

Analysis of differential observations of the
cosmological radio background: Studying the
SZE-21cm



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Abstract

This thesis presents an analytical approach for studying the cosmological 21 cm background signal from the Dark Ages (DA) and subsequent Epoch of Reionization (EoR). Differential observations of a galaxy cluster are simulated to demonstrate how these epochs can be studied with a specific form of the Sunyaev-Zel'dovich Effect called the SZE-21cm. This work produces the first simulated maps of the SZE-21cm and shows that the SZE-21cm can be extracted from future observations with low-frequency radio interferometers such as the Hydrogen Epoch of Reionization Array (HERA) and the Square Kilometre Array (SKA). In order to simulate near realistic scenarios, we look into cosmic variance noise, incorporate and take into account the effects of foregrounds, thermal noise, and angular resolution for our simulated observations. We further extend this exploration by averaging over a sample of galaxy clusters to mitigate the effects of cosmic variance and instrumental noise. Studying the SZE-21cm for different plasma temperatures, a strategy is proposed to average the signal over multiple clusters of different plasma temperatures. The impact of point source contamination is also studied. The whole technique is applied to the results of the EDGES collaboration, which in 2018 reported an absorption feature of the global 21 cm background signal centred at 78 MHz. The thesis also investigated the impact of cosmological 21 cm background models on the SZE-21cm, considering cosmologies with Warm Dark Matter, Population II and Population III stellar heating in the early Universe, and excess cooling of the IGM at very high redshift, we find that the SZE-21cm is dependent on global 21 cm signal models and that it can be used to extract the distinct features imprinted on the cosmological signal during DA and EoR by physical processes described in these models. Moreover, differential observations of the SZE-21cm will enable us to rule out any inconsistent models of the global 21 cm signal, and allow for the SZE-21cm to probe the formation and nature of the first sources. Since the different models for the cosmological 21 cm background provide very similar results, the resulting SZE-21cm signals will also be very similar and it will be challenging to distinguish between them. Our approach demonstrates the potential of the SZE-21cm as an indirect probe for the DA and EoR, and we conclude that the spectral features of the SZE-21cm from our simulated observations yield results that are close to prior theoretical predictions and that the SZE-21cm can be used to test the validity of the EDGES detection. Early work showed the benefits of the differential analysis technique outside of the SZE-21cm, applying it to observations of radio galaxies from the GaLactic and Extra-galactic All-sky MWA survey to enhance features of sources in the continuum images, which can be beneficial for efforts of source finding, extraction, and characterisation and developing a preliminary pipeline that reduces the effects of contaminating backgrounds and foregrounds.

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Declaration

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signature:

A handwritten signature in black ink, appearing to be 'K. M. M.', written over a horizontal line.

Date: *17 December 2020*

CHAPTER 0. DECLARATION

This thesis comprises of work from the following papers submitted for publication during the PhD:

1. **Title:** Simulated differential observations of the Sunyaev-Zel'dovich Effect: Probing the Dark Ages and Epoch of Reionization
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CHAPTER 0. DECLARATION

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For Femidah, Malachi and Patricia

CHAPTER 0. ACKNOWLEDGMENTS

Chapter 1

Introduction

Our perceptive of the Universe is changing in the current era of modern astronomical observatories and ever improving instrument capabilities. The techniques that we use to study the Universe are evolving at a similar rate. With improving technologies and techniques we are in a position to explore answers to fundamental questions that will help us construct a clearer picture of the history of our Universe and understand the properties of the first luminous sources that powered it as well as the physical mechanisms that gave rise to these sources and the processes that shaped them into the state we observe today. Over the last three decades, our understanding of cosmology has matured considerably, despite the progress so far achieved, very little is well understood about the Dark Ages (DA) and the subsequent Epoch of Reionization (EoR), which are periods in Universe history related to a wide variety of fundamental questions in cosmology, to be specific: the properties of the first stars and galaxies, physical mechanisms occurring during these epochs and many subject issues central to both astrophysics and cosmology. Our theoretical understanding of processes occurring during the DA and EoR is well established, it is however untested by observations. There are efforts underway to construct larger and more sensitive instruments and that will be able to observe in their respective wavelengths.

At present, low radio frequency observations of the redshifted 21 cm neutral hydrogen line with interferometers are the popularly accepted probe for the DA and EoR (Furlanetto et al. 2006; Zaroubi 2013). The 21 cm signal can be studied by measuring the global or sky-averaged component, which tracks the average properties of the neutral hydrogen gas across the Universe as a function of redshift (Pritchard & Loeb 2012). An alternative approach to study the 21 cm signal is the measurement of the power spectrum, where angular variations in the neutral hydrogen gas evolution of matter distribution and the progress of reionization manifest (Morales & Wyithe

2010).

Direct observations of the 21 cm background are enormously challenged by the presence of a large number of astrophysical foregrounds including diffuse Galactic synchrotron emission, noise due to radio frequency interference, ionospheric distortions, cosmic variance and complex instrumental response (Ciardi & Madau 2003). It has been forecasted that contamination to the 21 cm signal due to these components is between 4 and 5 orders of magnitude greater than the cosmological 21 cm signal (Shaver et al. 1999; Jelić et al. 2010; Mellema et al. 2013), and unbundling the cosmological 21 cm signal from the contaminating foreground signals will be a non-trivial task and the use of foreground subtraction methods may leave additional contaminating residuals. Various proposals have been made to eliminate or avoid foreground contamination (Harker et al. 2009; Jelić et al. 2010; Chapman et al. 2016; Liu & Shaw 2019). Any method proposed for mitigation of foregrounds contamination needs to be exceptionally accurate and reliable as any error could conceivably decimate the possibility to derive information from the cosmological 21 cm signal. Considering the difficulties that can be confronted when measuring the global 21 cm background signal utilizing direct methods it is significant that we investigate possibilities to use indirect techniques that may enable us to establish properties of the global signal.

The work in this thesis uses differential analysis techniques for observations of the Sunyaev-Zel'dovich effect (SZE), which is an effective tool for cosmological and astrophysical studies, as an indirect technique to determine the global properties of the 21 cm radio background. This technique, called the SZE-21cm, was proposed by Cooray (2006) and Colafrancesco et al. (2016) as a probe for the DA and EoR, who also showed that the effect can be detected with upcoming interferometers at low radio frequencies (≤ 200 MHz). The SZE-21cm can also be used to verify detections made by current and future experiments, that are targeted for measuring the global 21 cm background signal using direct techniques, such as outcomes achieved in 2018 by the Experiment to Detect the Global EoR Signature (EDGES) collaboration (Bowman et al. 2018). This research also studies the advantages of differential techniques for continuum radio surveys, where the technique can be used to enhance features of low-surface brightness and extended radio sources.

This thesis is structured as follows: The theoretical background of the work covered in the thesis is given in Chapter 2. In Chapter 3 we simulate differential observations of the SZE-21cm, examine the detectability of the signal, show the benefits of measuring the SZE-21cm towards multiple individual galaxy clusters, and then calculating the average signal. This Chapter also looks at simulated cluster observations for the SZE-21cm with upcoming radio interferometers, namely the Hydrogen Epoch of Reionization Array (HERA) and the low-frequency Square Kilometer Array (SKA).

CHAPTER 1. INTRODUCTION

Chapter 4 looks at how we can expect different 21cm-background models to affect the SZE-21cm signal. In Chapter 5 we look at how different cluster plasma temperatures affect efforts to minimise expected errors by averaging the SZE-21cm towards multiple galaxy clusters. In Chapter 6 we apply differential observation analysis techniques to radio continuum data from a low-frequency radio survey and present a pipeline for such an implementation. The thesis summary, future work, and conclusions are presented in Chapter 7.

Chapter 2

Theoretical Background

2.1 The Universe after the Big Bang

It is now common knowledge that the Universe was born from the big bang about 13.8 billion years ago. Following the big bang, the Universe was hot, dense and opaque, and conditions did not allow for the formation of nuclei and neutral atoms. This means that the early Universe was ionized and scattered photons in any direction. Dark matter was not coupled to the radiation field as it only interacts via gravity. Approximately 380 000 years after the big bang, the temperature and density dropped such that protons and electrons begin to settle down forming hydrogen atoms. Photons could no longer scatter off free electrons and radiation decoupled from matter. During this cosmic event, gas in the Universe transitioned from an ionized to a neutral state, this epoch is known as recombination or the last scattering surface. The photons from this period travel to us and are detected as Cosmic Microwave Background (CMB). At recombination, the temperature of the Universe was approximately 3000 K, and since this period photons from the CMB have been redshifted to much longer wavelengths and are detectable in the microwave regime of the electromagnetic spectrum at a mean temperature of 2.725 K. By measuring properties of CMB photons, e.g. their polarizations and temperature, we can get important information about the early Universe. Following recombination, there were no luminous objects in the Universe. It became almost completely neutral and dark at this stage, and the only photons present were in the form of the CMB. This period in the history of the Universe is called the Dark Ages (DA). During the DA, early small perturbations in the matter density grew further under the influence of gravitational instability forming the first non-linear structures of baryonic and dark matter. This structure formation started a transition from a starless, neutral, and cold Universe to one that was

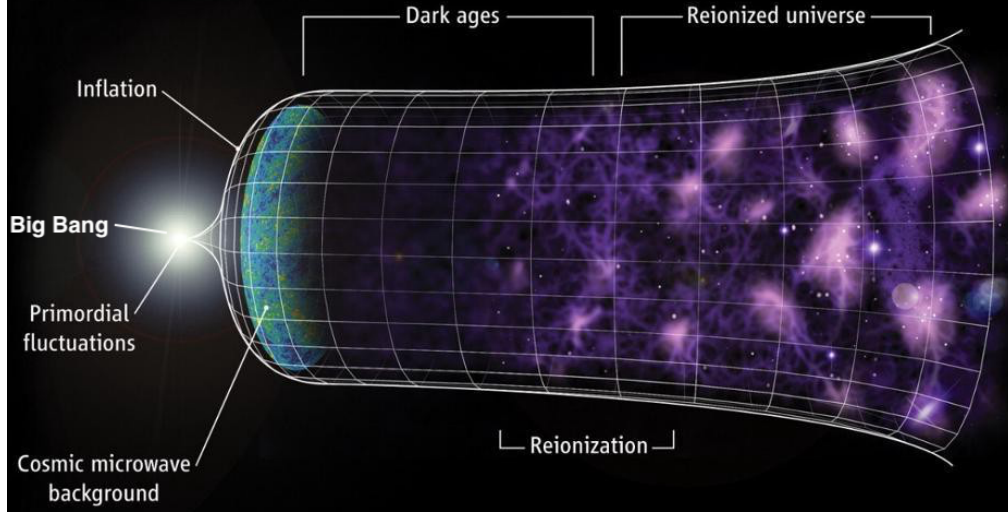


Figure 2.1: Schematic diagram of the evolution of the Universe, showing the big bang, the formation of the CMB at the last scattering surface, the Dark Ages and reionization. [Credit: [Faucher-Giguère et al. \(2008\)](#)]

gradually reionizing due to the emergence of the first luminous sources. This pivotal period in the history of the Universe is called the Epoch of Reionization (EoR). It is believed that the Universe was completely reionized by $z \sim 6$. However, small regions of neutral hydrogen still do exist within galaxies we observe. This Chapter will say more about the history of the Universe and various interesting astrophysical processes. The diagram in Figure 2.1 provides a good graphical representation of the evolution of the Universe from the Big Bang to its present reionized state.

2.2 The Cosmic Microwave Background

The Cosmic Microwave Background (CMB) radiation can be detected today as the afterglow of the Big Bang and is the oldest form of electromagnetic radiation in the Universe. [Penzias & Wilson \(1965\)](#) first observed the radiation while working on an experimental radiometer for satellite communications at Bell Telephone laboratories. The instrument showed excess noise of 3 K other than the antenna temperature, which they could not account for. It was later learned that this excess noise was from the relic radiation, which was predicted by [Gamow \(1946\)](#) and [Alpher & Herman \(1949\)](#), widely discussed by [Zel'dovich & Sunyaev \(1969\)](#) and [Dicke et al. \(1965\)](#). This observation by [Penzias & Wilson \(1965\)](#) served as a motivation to launch the Cosmic Background Explorer (COBE) satellite, which measured a near-perfect blackbody CMB spectrum that is shown in Figure 2.2 with a temperature of 2.725 ± 0.002

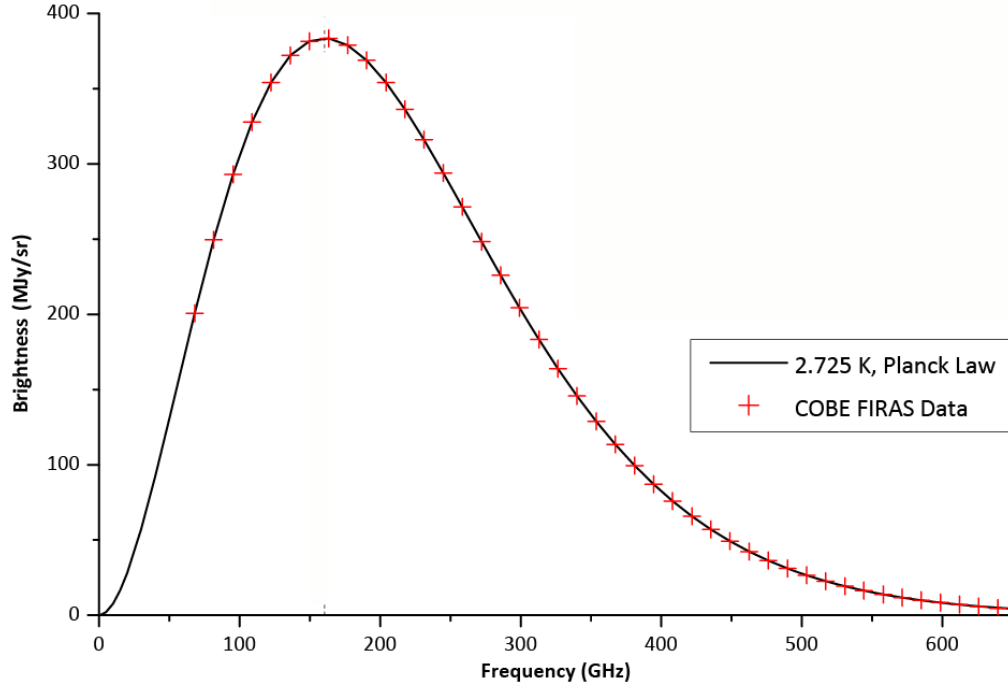


Figure 2.2: The CMB blackbody spectrum and data measured by the Far Infrared Absolute Spectrophotometer (FIRAS) instrument aboard the COBE satellite. [Credit: lambda.gsfc.nasa.gov]

K that was astonishingly uniform in all directions (see, [Fixsen et al. 1996](#)). The temperature of the radiation is astonishingly uniform in all directions due to an earlier phase of the Universe that was extremely dense and hot ([Smoot 1997](#); [Wands et al. 2016](#)). Later, more advanced satellite experiments such as the Wilkinson Microwave Anisotropy Probe (WMAP) ([Bennett et al. 2003](#); [Spergel et al. 2003](#); [Page et al. 2007](#)) and recently the Planck ([Planck Collaboration et al. 2015](#)) provided support for discoveries made by COBE. These experiments detected, measured and mapped the anisotropies of the CMB across the sky, and resulted in a highly constrained Λ CDM cosmological model with precise and accurate parameters.

The fluctuations in the CMB radiation across the sky are at the level of about 1 part in 100 000 ($\frac{\Delta T}{T} \approx 10^{-5}$) and are referred to as the microwave background anisotropies, they can be subdivided into primary and secondary anisotropies ([Bond et al. 1999](#)). By studying these anisotropies and their origins we can learn about the Universe content, the formation of large-scale structure and the overall evolution of the Universe. The primary CMB anisotropies are caused by effects at recombination and originate from the last scattering surface at $z \sim 1100$. On their path to us, CMB photons from the last scattering surface undergo various interactions that generate secondary anisotropies due to gravitational and scattering effects. Various physical processes

that occur subsequent to the recombination epoch leave an imprint on the CMB and allow us access epochs like the DA and EoR. The CMB interacts with the plasmas hosted by large-scale structures such as galaxy clusters, radio halos, and lobes of radio-galaxies during these epochs giving rise to the Sunyaev-Zel’dovich Effect, that this work uses as a probe of primordial physical processes using nearby large scale structures.

2.3 The standard cosmological model and formation of structures

The anisotropies detected in the CMB, which we briefly discussed in the previous section, are dependent on the amount of baryons in the Universe at the last scattering surface and are an indication of both the initial density perturbations that allowed for the formation of early gravitational wells as well as dynamics of the photon-baryon fluid (Spergel et al. 2003). While other models have been proposed, the Lambda Cold Dark Matter (Λ CDM) model is the current basis of the Standard Cosmological Model for structure formation, and according to this model gas and dark matter were gravitationally attracted to the areas of higher density and formed halos that resulted in a hierarchical process, which developed structures such as galaxies, groups, smaller clusters and then later larger galaxy clusters.

2.3.1 Galaxy Clusters

Galaxy clusters are among the most studied and interesting objects of our Universe, they are the largest virialized structures in the Universe (with mass $\sim 10^{15} M_{\odot}$), and can be used as probes to improve our understanding of the Universe at large scales (Walker et al. 2019). These cosmic structures contain a vast amount of galaxies, hot gas, and dark matter, and provide unique laboratories to test several astrophysical phenomena like particle acceleration in Mpc-scale shocks, galaxy evolution, and active galactic nuclei (AGN) feedback (Sarazin 1986). Clusters contain up to a few thousand galaxies. These galaxies constitute just a few percent of the overall cluster mass, with much of the baryonic cluster mass being provided by the hot ionized intracluster medium (ICM), held together by the clusters’ gravitational pull. Galaxy clusters have typical temperatures ($k_B T_e$) ranging from 2 to 12 keV (Perrenod & Henry 1981; Sarazin 1986). The velocities of galaxies inside clusters are too large for them to be gravitationally bound by their mutual attraction alone, which means that there is an additional mass component or additional forces in addition to gravity (Rubin

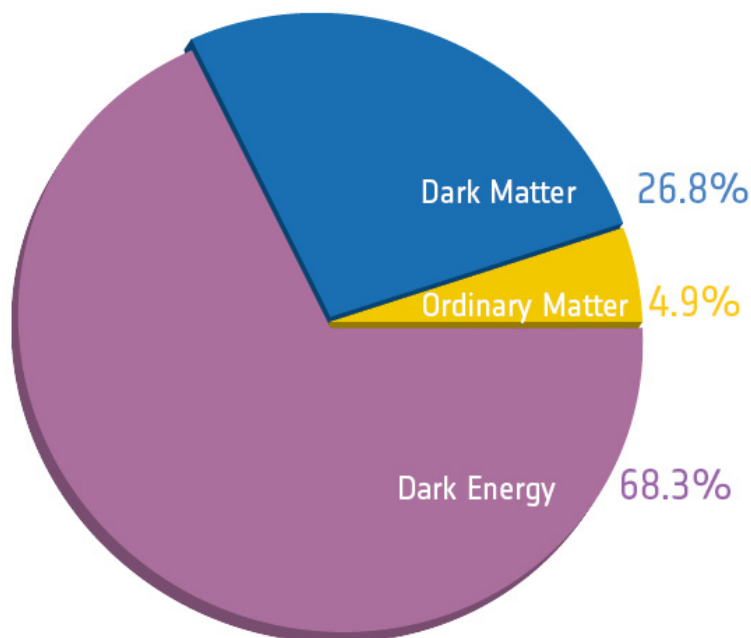


Figure 2.3: Energy density of the Universe attributed to baryonic matter, dark matter and dark energy from the latest results obtained by [Planck-Collaboration \(2018\)](#). [Credit: [planck.cf.ac.uk](#)]

1983). In the Λ CDM model, the matter content in galaxy clusters is explained by the presence of dark matter.

2.3.2 Elements of the Λ CDM model

The Λ CDM model is based on three main elements, which are dark matter, dark energy and inflation. The latest analysis of the CMB anisotropies ([Planck-Collaboration 2018](#)) tell us that about 31.7% of the total energy density is in the form of matter, where only around 4.9% of the density is in the form of baryonic matter and 26.8% is in the form of dark matter, the remaining 68.3% of the energy density is in the form of dark energy, see Figure 2.3.

Inflation is an epoch of accelerated expansion in the early Universe and is the element of the Λ CDM model that accounts for the homogeneity, isotropy, and flatness of the Universe ([Guth 2003](#)). This epoch of accelerated expansion occurred about 10^{-34} s after the big bang and led to a Universe with a density that appears to be equal to the critical one, providing a flat geometry on the length scales that we can probe (see, [Senatore 2016](#)). In other words, it is neither positively curved, like the 3-d equivalent of a sphere, nor negatively curved, like the 3-d equivalent of a hyperboloid. How-

ever, it is the 3-d equivalent of a plane, and the geometry is Euclidean. Cosmological parameters by both the WMAP (Bennett et al. 2003; Page et al. 2007) and Planck (Planck Collaboration et al. 2015) show that the Universe is close to flat in line with inflation. The latest measurement of the spatial curvature from Planck Collaboration et al. (2015) data only is $\Omega_K = -0.005^{+0.016}_{-0.017}$.

Often cited, Zwicky (1933) presented the first indication that our Universe is mostly composed of some form of unseen "Dark Matter". He measured the velocity dispersion of galaxies in the Coma Cluster and found that the velocities of the galaxies were about ten times larger than expected. Visible baryonic matter alone could not account for the mass of the Coma Cluster and accelerate the galaxies to higher velocities. Zwicky (1933) relied on the Hubble constant to obtain the distance to the Coma cluster. The Hubble constant was at that time overestimated by about an order of magnitude, which inflated the estimated mass to light ratio by the same factor. It was the ground-breaking work by Rubin et al. (1980) that confirmed the existence of dark matter and demonstrated that galaxies are embedded in dark-matter halos. This work showed that even at the periphery, the speed at which stars orbit around the centres of spiral galaxies remains high, which is contrary to the Newtonian theory of gravity which predicts that distant stars' speeds should drop when gravity pulls are decreased. The only logical scenario for the galactic flat rotation curves observed by Rubin et al. (1980) was that the mass of the galaxies invisibly extends beyond the most distant stars and gas of clouds.

Another piece of evidence is imprinted in the CMB anisotropies by the photon-baryon oscillation in the potential well of dark matter (see, Zackrisson 2005). Evidence of the existence of dark matter in clusters of galaxies is present through gravitational lensing of faraway galaxies. Observations by gravitational lensing experiments show that these background galaxies are distorted and the amount of mass that is responsible for this distortion is more than can be accounted for by visible baryonic matter (R. & Narayan 1992; Clowe et al. 2006). To this day the nature of dark matter is not fully understood, however, we know that it interacts via gravity and does not interact electromagnetically since it does not possess an electric charge (Bertone & Hooper 2016). Despite the indirect evidence of the existence of dark matter, our understanding of its amount and distribution on various astronomical scales, and our own galaxy have been improving over the years.

Dark matter may be classified into three groups: hot dark matter (HDM), warm dark matter (WDM), and cold dark matter (CDM) (see, Abazajian et al. 2001). Bond et al. (1984) and Primack & Blumenthal (1984) introduced the terminology of "Hot," "Warm," and "Cold" dark matter, which refer to the velocity of the particles after decoupling. HDM have minimal or close to no mass and move at relativistic speeds, CDM has more mass and moves at sub-relativistic speeds, and WDM is intermedi-

ate. It has been shown through N-body and analytic simulations that in a Universe of HDM, it is not possible to match the small-scale galaxy clustering structure we observe without an unrealistically late epoch of galaxy formation (White et al. 1983, 1984). CDM is currently the leading candidate to account for missing mass in the Universe, since the particles are too slow to travel all but a negligible distance out of a perturbation, keeping galactic scale density perturbations intact. A number of particles have been discussed as suitable candidates for dark matter with the most popular being axions and weakly interacting massive particles (WIMPs) (Goldman & Nussinov 1989; Fields et al. 1998; Bertone et al. 2004).

Observations by Riess et al. (1998) and Perlmutter et al. (1999) showed that type Ia supernova are dimmer than would be expected in a matter-only Universe, which means that they were farther away than expected and that the expansion rate of the Universe is increasing. While the nature of dark energy is mostly unknown, these observations led astronomers to assume the existence of dark energy, which unlike dark matter, leads to gravitational repulsion (Guendelman et al. 2012). According to these observations, there is a possibility that the Universe is accelerating with a large fraction of the cosmological density given by the cosmological term " Λ ", represented in Einstein's equations, with a strongly negative pressure given by

$$p = w\rho c^2, \quad (2.1)$$

which is known as the cosmic equation of state, where ρ is the energy density and w is a constant that is dependent on dark energy model being used (Peebles & Ratra 2003). For the cosmological term " Λ ", $w = -1$ implying that $\rho = \text{constant}$ (Zackrisson 2005). At largest scales, Friedmann-Lemaitre-Robertson-Walker (FLRW) metric is used to describe an expanding homogeneous and isotropic Universe:

$$ds^2 = c^2 dt^2 - a^2(t) \left(\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right), \quad (2.2)$$

where k is the curvature and the scale factor parametrizing the background expansion rate is a . The metric given as equation 2.2 can be used to compute the Friedmann equations from the Einstein equations:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}, \quad (2.3)$$

Table 2.1:: Cosmological parameters in the Λ CDM model.

Symbol	Parameters
H_0	Hubble parameter, which measure of the observable size of the Universe and its present age
Ω_Λ	Cosmological constant, which is the effective mass density of dark energy
Ω_m	Total matter density, which includes dark matter and baryonic mater
Ω_r	Radiation density term
Ω_K	Curvature term

where $g_{\mu\nu}$ is the metric, $R_{\mu\nu}$ is the Ricci tensor, G is Newtons gravitational constant, c is the speed of light, and $T_{\mu\nu}$ is the radiation matter-energy stress tensor. For the flat Universe scenario, we introduce the notion of critical energy density given by

$$\rho_c = \frac{3m_p^2 H^2}{8\pi}, \quad (2.4)$$

where m_p and H are the Planck mass and Hubble expansion rate, and define the ratio of the energy density for each fluid in the Universe to the critical energy density today,

$$\Omega_x = \frac{\rho_x}{\rho_c}. \quad (2.5)$$

The growth rate of the Universe is defined as the Hubble expansion rate:

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda c^2}{3} - \frac{Kc^2}{a^2}. \quad (2.6)$$

and the term evolves like

$$\frac{H(t)}{H_0} = \sqrt{\frac{a_0^3}{a^3}\Omega_m + \frac{a_0^4}{a^4}\Omega_r + \Omega_\Lambda + \frac{a_0^2}{a^2}\Omega_K}, \quad (2.7)$$

where H_0 and a_0 are the values of the Hubble parameter and the scale factor today, respectively. The cosmological parameters, that include the parameterization functions and numbers that describe the physical state of the Universe and its global

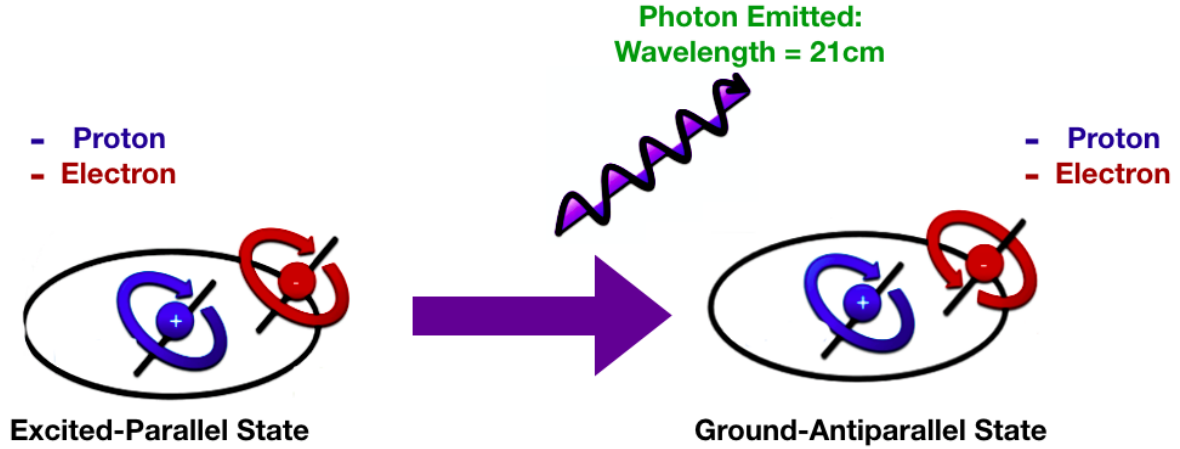


Figure 2.4: Visualisation of the hyperfine spin-flip transition of hydrogen from the higher energy spin state (triplet) to the lower (singlet) state, that produces radiation with a wavelength of 21cm.

dynamics, such as its composition, expansion rate and curvature are defined in table 2.1.

2.4 The cosmological 21 cm background: a probe for the DA and EoR

We have observational evidence on the epoch of recombination at $z \sim 1100$ from CMB experiments. However, when it comes to the subsequent periods, the DA and EoR, direct observational evidence is not possible because bright sources are not present during DA and are few in number at the beginning of EoR. Most of what we know about these epochs has been theorised and backed by simulations. This period between redshift 1100 to 6 is very important since this is when the initial density perturbations of the Universe grew gravitationally to eventually form the first structures. Many theoretical models predict that towards the end of the DA collapsed structures that emitted Ultraviolet (UV) and X-ray radiation started to form and caused the Inter-Galactic Medium (IGM) ionize, this transition from a homogeneous Universe marked the beginning of the EoR (Barkana & Loeb 2005; Furlanetto et al. 2006; Koopmans et al. 2015; Pritchard & Loeb 2012). As time and gravity advanced during the EoR more sources ignited, creating more ionized bubbles up to a point that the ionized bubbles started to overlap and gradually ionized the entire Universe at around $z \sim 6$.

2.4.1 The 21 cm line of neutral hydrogen

Neutral hydrogen that is abundant in the IGM prior to reionization; therefore, it provides a reliable tracer of gas properties which can help us in understanding major milestones in the first billion years following the big bang (Pritchard & Loeb 2012). Hydrogen undergoes a highly forbidden hyperfine transition that gives rise to the 21 cm line, with a mean lifetime of about 11 million years (Condon & Ransom 2016), and occurs due to the spin-spin interaction between the proton and the electron in hydrogen. A photon with a wavelength of 21 cm is emitted when the spins change from parallel to anti-parallel, this produces a signal with a temperature of $T_* = h\nu_{21}/k_B = 0.0681$ K at a line centre frequency of $\nu_{21} = 1420.405$ MHz (Hellwig et al. 1970), visualised in Figure 2.4. Here k_B and h are the Boltzmann and Planck constants, respectively. The expansion of the Universe results in the 21 cm signal emitted during the EoR and DA being redshifted to a frequency $\nu = \frac{\nu_{21}}{(1+z)}$ for Hydrogen located at a cosmological distance of a given redshift (z). The spin temperature characterizes the excitation temperature for the 21 cm transition with the ratio

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(\frac{-T_*}{T_S}\right), \quad (2.8)$$

where the ratio of the spin degeneracy factors of the two levels is $\frac{g_1}{g_0} = 3$, and n_0 and n_1 are the populations of the singlet and triplet ground state of HI atoms, respectively. Equation 2.8 tells us that the spin temperature is effectively a shorthand for the ratio between the occupation numbers of the two hyperfine levels which establishes the intensity of the radiation emanating from a cloud of neutral hydrogen (Zaroubi 2013).

For the 21 cm signal, the CMB is the background continuum radiation and the gas cloud is the neutral hydrogen in the IGM. Field (1958, 1959) calculated the spin temperature for a cloud of neutral hydrogen as the weighted average of T_{CMB} , the gas kinetic temperature (T_{kin}) and the temperature related to the existence of ambient Ly- α photons (T_α), assuming $T_{kin} = T_\alpha$, this can be written as

$$T_S = \frac{T_{CMB} + y_{kin}T_{kin} + y_\alpha T_{kin}}{1 + y_\alpha + y_{kin}}, \quad (2.9)$$

where the Ly- α coupling term y_α , is due to Ly α pumping (also known as the Wouthuysen-Field effect process (see, Wouthuysen 1952; Field 1958, 1959)), which occurs through collisions and scattering of Ly- α photons that couple the spin temperature to the gas temperature, T_{kin} . The kinetic coupling term y_{kin} , is due to

CHAPTER 2. THEORETICAL BACKGROUND

collisional excitations of the 21 cm transitions, and both y_α and y_{kin} depend on the rate of collisional and Ly- α pumping within the neutral hydrogen cloud.

The 21 cm signal depends on the radiative transfer through gas along the line of sight s for the specific intensity (per unit frequency ν) and the equation is given by (see, [Rybicki & Lightman 1986](#)),

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu, \quad (2.10)$$

where coefficients α_ν and j_ν , respectively describe the absorption and emission by the gas along the line of sight. Since the photon frequency of the 21 cm line is smaller than the peak frequency of the blackbody CMB, we can work in the Rayleigh-Jeans limit. In terms of the Rayleigh-Jeans law the relation between the brightness temperature (T_b) and specific intensity (I_ν) is given by

$$T_b(\nu) = \frac{I_\nu c^2}{2k_B \nu^2}, \quad (2.11)$$

Using the basic definition of the optical depth $\tau_\nu = \int ds \alpha_\nu(s)$ equation 2.10, the radiative transfer equation for light from a background radio source of brightness temperature T_{CMB} and spin temperature T_S , can be rewritten in terms of brightness temperature as

$$T_b(\nu) = T_S(1 - e^{-\tau_\nu}) + T_{CMB}(\nu)e^{-\tau_\nu}. \quad (2.12)$$

We note that when $T_S = T_{CMB}$ the brightness temperature will be that of the CMB due to the balance in absorption and emission. The three mechanisms that determine the spin temperature are (1) absorption of a 21 cm photon from the CMB by a hydrogen atom (CMB pumping), (2) collision of a hydrogen atom with another atom (collisional pumping), and (3) absorption of a Ly- α photon by a hydrogen atom to make a Ly- α transition, then decay to one of the hyperfine 21 cm levels (Ly- α pumping) (see, [Shapiro et al. 2006](#); [Zaroubi 2013](#)).

For a cloud of neutral hydrogen the optical depth is

$$\tau_\nu = \frac{3c^2 \hbar A_{10} n_{HI}}{16k_B \nu_{21}^2 T_S H(z)}. \quad (2.13)$$

CHAPTER 2. THEORETICAL BACKGROUND

Here n_{HI} is the local hydrogen density (see, [Zaldarriaga et al. 2004](#)), the spontaneous emission for the transition is $A_{10} = 2.85 \times 10^{-15} \text{s}^{-1}$ and assuming high redshifts ($z > 6$) the Hubble parameter is $H(z) \approx H_0 \Omega_m^{1/2} (1+z)^{3/2}$ in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and we can rewrite equation 2.13 as

$$\tau_\nu = 8.6 \times 10^{-3} (1 + \delta) x_{HI} \left[\frac{T_{CMB}(z)}{T_S} \right] \left(\frac{\Omega_b h^2}{0.02} \right) \times \left[\left(\frac{0.15}{\Omega_m h^2} \right) \left(\frac{1+z}{10} \right) \right]^{1/2}, \quad (2.14)$$

where the x_{HI} is the fraction of neutral hydrogen, $1 + \delta = \bar{\rho}/\rho$ is local baryon over density. The CMB temperature at redshift z is $T_{CMB} = 2.725(1+z) \text{K}$, and using equation 2.12 the quantity to be measured by radio interferometers is the differential brightness temperature $\delta T_b \equiv T_b - T_{CMB}$ given by

$$\delta T_b(\nu) = 23(1 + \delta) x_{HI} \left[\frac{T_S - T_{CMB}}{T_S} \right] \left(\frac{\Omega_b h^2}{0.02} \right) \times \left[\left(\frac{0.15}{\Omega_m h^2} \right) \left(\frac{1+z}{10} \right) \right]^{1/2} \text{mK}, \quad (2.15)$$

δT_b is also known as the global 21 cm signal, the spectrum as a function of frequency is in Figure 2.5. Equation 2.15 is a mixture of astrophysics and cosmology dependent terms, and is influenced by various contributions at different stages of its evolution. At low redshifts, the Universe is ionized and δT_b measurements are influenced by the contrast between the neutral and ionized regions, this probes the astrophysical source of ionization. At high redshifts the Universe is almost completely neutral, δT_b is proportional to the density fluctuations, and its measurements can help us understand how structures have grown through time, this makes it an excellent probe of cosmology. The detectability of the 21 cm signal rests on the spin temperature. Radiation of the 21cm-background can only be detected if it has a temperature different from that of the CMB, we do not expect to detect the 21 cm signal when $T_S \sim T_{CMB}$. The detailed derivations for equation 2.15 are covered by [Madau et al. \(1997\)](#); [Ciardi & Madau \(2003\)](#); [Furlanetto \(2006a\)](#); [Zaroubi \(2013\)](#). The 21 cm line at every observed frequency corresponds to a different distance, and we can use this to isolate each phase in the IGM's history, it emits energy at radio wavelengths and can be observed as a diffuse background redshifted to longer wavelengths due to the expansion of the Universe. The signal of the 21 cm line is sensitive to major transitions in the ionization and thermal history of the Universe, which constrain the surfacing of the first

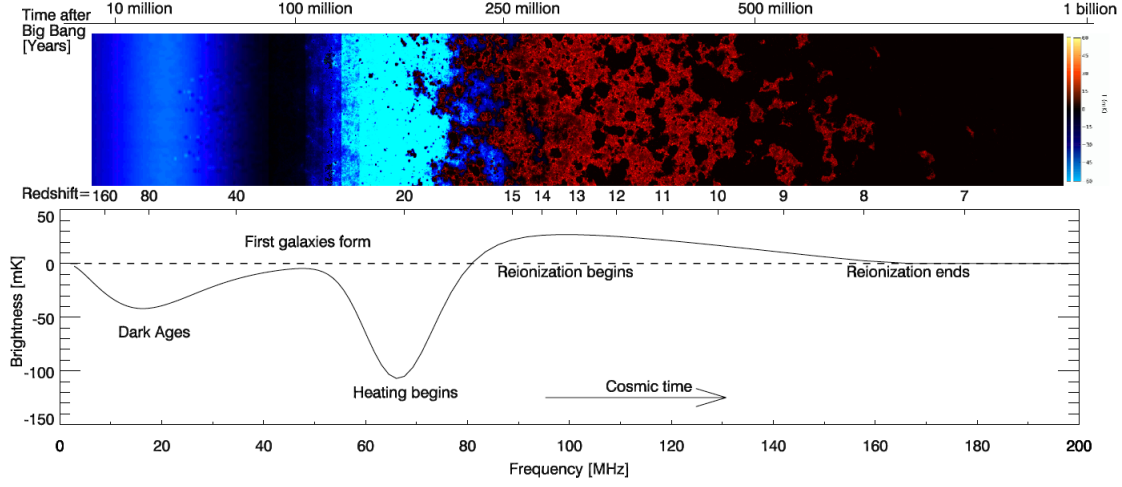


Figure 2.5: The global 21 cm cosmological signal of neutral hydrogen. **(Top)** Change of spectral shape of the 21 cm brightness over time, where the colours indicate the brightness of the 21 cm line, with blue corresponding to absorption and red to emission. **(Bottom)** *Solid curve:* The global 21 cm brightness temperature offset from the CMB spectrum as a function of frequency and redshift, *Dashed line* is at $\delta T_b = 0$. [Credit:Pritchard & Loeb (2012)]

generations of stars, black holes, quasars, and formation of large clusters. It maps the distribution of baryonic matter, hence mapping large comoving volumes of the Universe is more promising as a cosmological probe as compared to studies using the CMB and presents better sensitivity for cosmological probes of dark matter, dark energy, inflation and neutrino masses (Zheng et al. 2014).

2.4.2 The global history of the DA and EoR from the 21 cm cosmological signal

Changes in the kinetic temperature, CMB temperature, and spin temperature contribute to interesting physical features of the HI 21 cm signal. Paying close attention to equations 2.9 and 2.15, we now discuss key features of the global 21 cm signal as shown in Figure 2.5, which determine the redshift and corresponding frequency intervals where the cosmological signal is dominated by fluctuations in the different quantities:

- At redshifts $z \gtrsim 200$ ($\nu \lesssim 10$ MHz), Thomson scattering off residual free electrons and gas collisions maintain the equilibrium between T_S , T_{CMB} and

T_{kin} . Subsequent to recombination, the CMB temperature is coupled to that of neutral gas, and at this stage no changes can be observed in δT_b . Since all the temperatures are the same we do not expect any 21 cm signal as fluctuations of δT_b are negligible.

- The gas cools adiabatically at redshifts $40 \lesssim z \lesssim 200$ (35 – 10 MHz) such that $T_{kin} \propto (1+z)^2$, this results in the temperature of neutral gas dropping below that of the CMB ($T_{kin} < T_{CMB}$) and collisional coupling sets $T_S < T_{CMB}$, the CMB flux becomes resonantly absorbed by neutral Hydrogen through the spin-flip transition and $\delta T_b < 0$ (Field 1958; Loeb & Zaldarriaga 2004).
- At redshifts, $30 \lesssim z \lesssim 40$ (45 – 35 MHz), collisional coupling is no longer efficient and the density of the gas decreases and $T_S = T_{CMB}$. Therefore we do not expect a 21 cm signal (Pritchard & Loeb 2012).
- At redshifts, $15 \lesssim z \lesssim 30$ (90 – 45 MHz), the first stars and quasars switch on and the IGM begins to heat up as the first sources emitted both Ly α photons and X-rays (Chen & Miralda-Escude 2004; Furlanetto et al. 2004). The spin temperature is coupled to cold gas so that $T_S \sim T_{kin} < T_{CMB}$ and there is an absorption signal.
- At redshifts $8 \lesssim z \lesssim 15$ (160 – 90 MHz), heating becomes significant, T_S remains coupled to T_{kin} via scattering in the Ly α resonance (the Wouthuysen-Field effect). As the gas is heated above T_{CMB} , T_S stays with the gas so we expect a 21 cm emission signal (Pritchard & Loeb 2012; Wouthuysen 1952).
- At redshifts $6 \lesssim z \lesssim 8$ (200 – 160 MHz), reionization ends and the 21 cm signal is primarily expected from collapsed clumps of neutral hydrogen. The signal dies out after the full reionization of the Universe since $x_{HI} \equiv 0$ in equation 2.15.

2.5 Detection and observations of the 21 cm background from the DA and EoR

Several detection methods have been proposed to study the 21 cm signal from the DA and EoR, motivated by prospect of current and upcoming radio interferometers. Among these are, (1) studies of absorption features in spectra of bright, radio sources at high-redshift ($z \gtrsim 6$) (Carilli et al. 2002; Furlanetto & Loeb 2002), (2) the angular fluctuations on the sky (Madau et al. 1997; Ciardi & Madau 2003; Zaldarriaga et al.

2004; Furlanetto et al. 2004), (3) and features in the frequency spectrum of the global signal (Shaver et al. 1999).

Madau et al. (1997) and Shaver et al. (1999) have shown that the brightness temperature, δT_B , of the 21cm-background emission relative to the CMB can provide a direct probe for the DA and EoR. The 21 cm line from the DA and EoR will be observable between 30 and 200 MHz and is expected to be of the order of a few tens of milli-kelvin. There are two issues with detecting this faint signal from the DA and EoR, which are to do with the calibration of instruments and foreground contamination. For reliable detection of the cosmological signal, all data components and their influence on the desired signal must be well understood.

2.5.1 Experiments to detect the 21 cm signal from the DA and EoR

Large investments are being made into construction and development of experiments to measure the cosmological 21 cm signal from the DA and EoR. Here, we briefly discuss two complementary approaches for observations of the cosmological 21 cm signal that probe the evolution of this signal through cosmic history:

- The first approach is given by experiments that aim to improve our understanding of the spatial fluctuations in the 21 cm line by measuring the 21 cm brightness temperature power spectrum. Power spectrum measurement probes make use of brightness temperature fluctuations maps in all three dimensions, the sensitivity criteria to reach the expected amplitude of the cosmological 21 cm signal can only be achieved with long integration times (see, Liu et al. 2013). Interferometers have become the instrument of choice for experiments looking to measure spatial fluctuations in the 21 cm signal as they provide high angular resolution and rapid mapping speeds (Jelić et al. 2010; Zaroubi 2013). These interferometers include the Giant Metrewave Radio Telescope Epoch of Reionization (GMRT), the Low-Frequency Array (LOFAR), the 21 CentiMeter Array (21CMA), Precision Array for Probing the Epoch of Reionization (PAPER), the Hydrogen Epoch of Reionization Array (HERA), the Murchison Widefield Array (MWA), and the low-frequency Square Kilometer Array (SKA-Low).
- Another way to detect the 21 cm cosmological signal is to measure the global or sky averaged 21 cm signal (Furlanetto 2006a). Experiments that are currently targeting measurements of the global signal are single dipoles like the Experiment to Detect the Global EoR Signal (EDGES), which has already claimed

a detection (see, [Bowman et al. 2018](#)). Other examples of global signal experiments include the Long Wavelength Array (LWA), Shaped Antennas to measure the background RAdio Spectrum (SARAS), the Dark Ages Polarimetry Pathfinder (DAPPER) and the Probing Radio Intensity at high-Z from Marion (PRIZM) experiment.

2.5.2 Foreground contamination

The astrophysical foregrounds that present challenges for observations of the 21 cm signal include diffuse Galactic synchrotron emission, radio frequency interference, ionospheric distortions, and instrumental response ([Jelić et al. 2010](#)). Synchrotron emission is the most dominant form of foreground and originates from interaction between magnetic fields and relativistic charged particle. At 150 MHz galactic synchrotron emission accounts for about 70% of the total foreground emission, 27% is from extragalactic synchrotron radiation and 1% is due to galactic free-free emission ([Jelić 2010](#)). Extragalactic foregrounds are classified in two classes; (1) Point sources such as AGN producing synchrotron emission and HII regions in ionizing haloes producing free-free emission, (2) Extended sources which include cluster radio halos and relics as well as HII regions in the IGM producing free-free emission ([Di Matteo et al. 2004](#)). Some of these contaminants are not yet well-studied at angular scales ($\theta \lesssim 5$ arcmin) and frequencies ($\nu \lesssim 200$ MHz) relevant to studies of the 21 cm signal. On the other hand, the 21 cm signal has characteristics that make it distinguishable from foreground and noise, which can be extracted if proper statistics are used and taking advantage of that foreground contaminants mentioned above are spectrally smooth (see, [Zaldarriaga et al. 2004](#); [Furlanetto 2006a](#)). By contrast, the 21 cm signal from the DA and EoR is expected to show strong change of spectral shape over small ranges of frequency as illustrated in Figure 2.5.

Attempts to clean foregrounds from the data will require great sensitivity, accurate calibration, and beam modelling as compared to those currently available in the radio astronomy field (see, [Furlanetto et al. 2006](#); [Zheng et al. 2014](#)). Since these foregrounds dominate the cosmological signal, robust foreground subtraction techniques are essential. Various proposals have been made to remove or avoid foreground contamination ([Chapman et al. 2016](#); [Harker et al. 2009](#); [Liu & Shaw 2019](#)). One proposed method is to subtract foregrounds separately in each angular direction in the sky by fitting their total intensity dependence on frequency by a log-log polynomial ([Wang et al. 2006](#); [Li-Ping 2009](#)). Any fitting needs to be performed with caution as under fitting could result in the signal being dominated by residuals and over fitting could fit out the signal ([Mellema et al. 2013](#)). Examples of other foreground subtraction

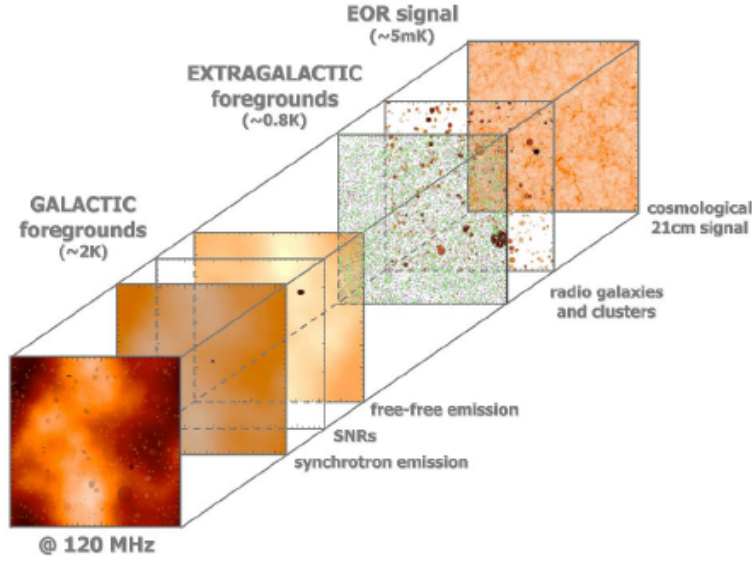


Figure 2.6: An illustration of galactic and extragalactic foreground components in the 21 cm experiments at 120 MHz. [Credit: Jelić et al. (2010)]

methods are: the Karhunen-Loeve transform (KL) (Shaw et al. 2014), independent component analysis (FASTICA) (Chapman et al. 2012), and singular value decomposition (SVD) (Burns et al. 2017). The KL transform makes use of models of statistical properties to separate foregrounds from the 21 cm signal while the latter (FASTICA and SVD) are blind search methods which decompose the data's independent components (Wolz et al. 2015). Foreground subtraction aims to fit and remove foreground contamination so the remaining data can be used, other methods include avoidance and suppression techniques. Discussions of these methods are beyond the scope of this text and can be found in more specialised texts (Matteo et al. 2002; McQuinn et al. 2006; Jelić et al. 2010; Jelić 2010; Barry et al. 2019).

2.5.3 Simulations

Scarcity in observational data presents a challenge for studies of the DA and EoR. Simulations have been playing a major role in modelling and understanding the 21 cm cosmological signal, painting for us a picture as what to expect when the signal is detected through observation. What we learn from simulations will play a crucial role in interpretation of any possible future detections. Two classes of simulations have been used to model small and large scale processes of the EoR and DA are: (1) Small volume, high resolution simulations that studying formation of early galaxies and associated processes these do not capture volumes large enough to study global

features of the DA and EoR, and (2) Large scale simulations (N-body simulations), that allow us to simulate and study large volumes on scales where the global evolution of the signal can be studied, these however lack resolution to resolve small-scale physics. In this work we focus on the later.

Numerical simulations offer detailed descriptions of the astrophysics at high redshifts from first principles by solving the non-linear physics of radiative transfer, gravitational collapse and hydrodynamics (McQuinn et al. 2006; Mesinger et al. 2010; Santos et al. 2010). Though numerical simulations allow us to simulate large volumes with large particle number they are slow and computationally expensive to run (Santos et al. 2010). Analytical models have been used to understand contributions to the 21 cm signal at high redshifts they are however unable to deal with spacial distribution of the reionization process (Mesinger et al. 2010), but they run faster than the numerical counterpart. Semi-numerical 21 cm simulations take a hybrid approach that follows spacial evolution provided by numerical simulations merging the speed and ease of analytical models. Results from semi-numerical simulations have been tested and are in good agreement with large scale numerical techniques, this is discussed in detail by Iliev et al. (2015); Mesinger et al. (2010); Santos et al. (2010). Simfast21 (Santos et al. 2010) and 21cmFAST (Mesinger et al. 2010) are publicly available semi-numerical large-scale simulations that use approximate physics to model the Universe during the DA and EoR in 3-dimensions. These simulation codes are very similar in nature and both produce δT_b cubes. In this thesis, we make use of 21cmFAST, and in Figure 2.7 we present an example of a 30 Mpc 3D volume of the 21 cm Brightness temperature cube simulated using 21cmFAST at 114.27 MHz, which was produced from one of the simulation runs used for the work presented in this thesis.

2.6 The Sunyaev-Zel’dovich effect

The CMB photons interact with the plasma residing in large-scale structures such as galaxy clusters, radio halos, and radio-galaxy lobes. This interaction through an inverse Compton scattering process induces a distortion that produces a change in the apparent brightness of the CMB radiation, known as the Sunyaev-Zel’dovich effect (SZE) (Zel’dovich & Sunyaev 1969; Sunyaev & Zel’dovich 1970, 1972, 1980). The interaction is illustrated in Figure 2.8. The scattering conserves photon number and produces a systematic shift of the CMB photons from the Rayleigh-Jeans (RJ) to the Wien side of the spectrum and introduces a small distortion to the CMB of order one-tenth of milli-Kelvin in temperature, see Figure 2.9, (Carlstrom et al. 2002; Colafrancesco et al. 2003). The SZE was first proposed in 1970 and is among the numerous methods to detect and characterize galaxy clusters and to estimate

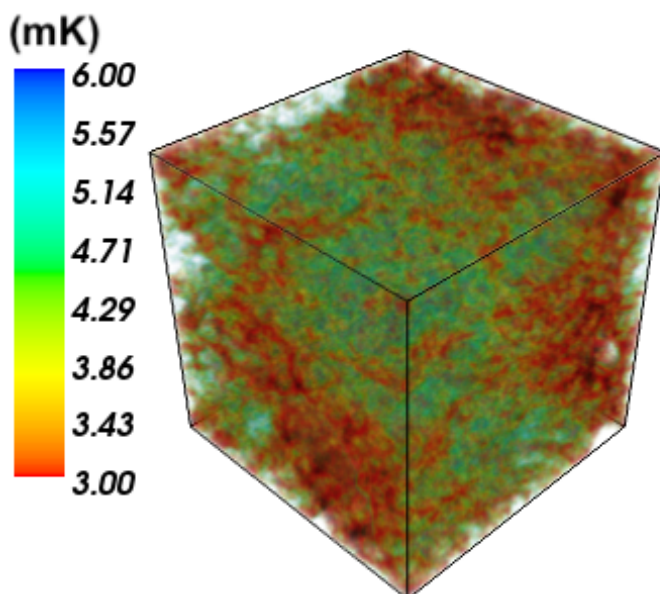


Figure 2.7: A 30 Mpc 3D volume of the 21 cm Brightness temperature cube simulated using 21cmFAST at 114.27 MHz

cosmological parameters, such as the Hubble constant. The SZE has been well covered and treated in literature (see, [Sunyaev & Zel'dovich 1980](#); [Rephaeli 1995](#); [Birkinshaw 1999](#)).

When a cluster has a peculiar velocity along the line of sight this results in a Doppler shift, that gives rise to a kinematic effect, which carries information about the electron bulk motion relative to the CMB rest frame. In addition to this, cluster atmospheres contain non-thermal electrons, which also scatter CMB photons and produce a non-thermal SZE ([Birkinshaw 1999](#); [Enßlin & Kaiser 2000](#); [Colafrancesco et al. 2003](#)). If the velocity of a cluster is zero, then the only signature imprinted on the spectrum of the CMB by the cluster is due to only the thermal and non-thermal SZE effect ([Rephaeli & Lahav 1991](#); [Colafrancesco et al. 2003](#)). In this work, we focus on the thermal SZE produced in galaxy cluster-hosted plasma, which typically has a temperature of several keV. The SZE is a powerful tool to study the Universe at low and high redshift as both the thermal and kinematic effects are redshift independent. Below we look at the calculations of the SZE in the non-relativistic limit as well as the relativistic corrections, which arise when we account for electron velocities in the intracluster medium (ICM) gas which may not be negligible with respect to the speed of light.

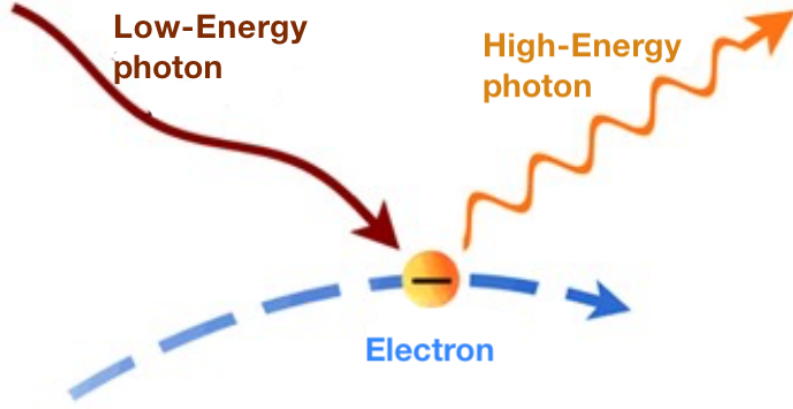


Figure 2.8: Inverse Compton scattering of photons that results in photons being moved from the lower to more energetic regions of the spectrum, giving rise to the SZE. [Credit: chandra.harvard.edu]

2.6.1 The SZE in the non-relativistic limit

The CMB consists mainly of low energy photons and for this reason, one may ignore quantum effects and energy transfers and use Thompson limit, $m_e c^2 \gg \gamma_e h\nu$, to describe the scattering process in the rest frame of the electron (Birkinshaw 1999; Enßlin & Kaiser 2000). Here, γ_e is the Lorentz factor, and m_e is the electron mass. The SZE can be obtained within the non-relativistic limit by solving the Kompaneets equation (see, Kompaneets 1957), and the spectral distortion of the CMB due to the SZE can, therefore, be expressed as an intensity change, $\Delta I(x)$, at the dimensionless frequency $x = \frac{h\nu}{k_B T_{CMB}}$ and is given by

$$\Delta I(x) = 2 \frac{(k_B T_{CMB})^3}{(hc)^2} y g(x), \quad (2.16)$$

where the Comptonization parameter, y , for a radiation field passing through a cloud of electrons is

$$y = \tau \frac{k_B T_e}{m_e c^2}. \quad (2.17)$$

Here scattering optical depth, τ , that depends on the properties the ICM, is defined as

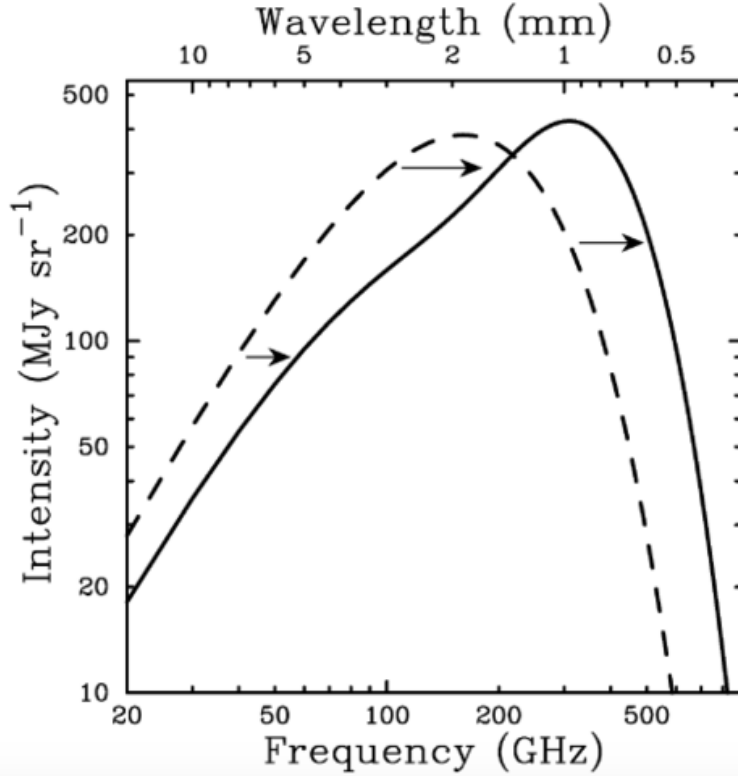


Figure 2.9: The impact of the SZE on the CMB spectrum. The dashed line is the undistorted blackbody spectrum of the CMB, and the solid line is the distorted spectrum after the CMB photons have been upscattered from the lower-energy part of the spectrum to higher energies due to the SZE. [Credit: [Carlstrom et al. \(2002\)](#)]

$$\tau = \int n_e \sigma_T ds, \quad (2.18)$$

the integration is calculated along the line of sight ds , and σ_T is Thomson's cross-section. The electron number density, n_e , varies with cluster radius r and can be expressed using different analytical approximated models (e.g. [Arnaud et al. 2010](#)); an usually adopted form is the Beta-profile (see, [Cavaliere & Fusco-Femiano 1976](#)):

$$n_e(r) = n_0 \left(1 + \frac{r^2}{r_c^2} \right)^{-\frac{3}{2}\beta}, \quad (2.19)$$

where r_c the cluster core radius, n_0 is the central number density, and the Beta-profile

parameter, β , can range between 0.5 and 1. The frequency dependence, $g(x)$, of the SZE in the non-relativistic limit is given by

$$g(x) = \frac{x^4 e^x}{e^x - 1} \left[x \frac{e^x + 1}{e^x - 1} - 4 \right]. \quad (2.20)$$

The Kompaneets approximation only holds for a thermal electron distribution and if the Compton y -parameter is small. This means that it is only valid for plasma of low temperature (up to $T_e \approx 2$ keV) and low optical depth ($\tau \ll 1$), therefore not taking into account multiple scatterings. Various literature (see e.g., [Wright 1979](#); [Fabbri 1981](#); [Rephaeli 1995](#); [Birkinshaw 1999](#); [Colafrancesco et al. 2003](#)) have considered this inadequacy of the Kompaneets equation for computing the SZE for hot clusters and have stressed the importance of computing the SZE in a full relativistic approach, which is valid for any general electron distributions.

2.6.2 The relativistic SZE

To compute the SZE spectrum with relativistic corrections we work with the Thomson limit approximation, in the electrons rest frame $m_e c^2 \gg \gamma_e h\nu$, where the SZE results from an inverse Compton interaction that causes a relativistic electron with momentum $p_e = \beta\gamma_e$, with $\beta = \frac{v}{c}$ and $\gamma_e = \frac{E_e}{m_e c^2}$ to increase the frequency of the scattered photon from an initial frequency (ν) to a final frequency (ν') by a factor of $t \equiv \frac{\nu'}{\nu}$. The resulting scattering can be expressed in terms of the logarithmic frequency shift as

$$s = \ln\left(\frac{\nu'}{\nu}\right), \quad (2.21)$$

and the probability that a single scattering of the photon causes a frequency shift, s , is given by

$$P(s; p_e) = \frac{3e^s(1+e^s)}{8p_e^5} \left[\frac{3+3p_e^2+p_e^4}{\sqrt{1+p_e^2}} - \frac{3+2p_e^2}{2p_e} (2\sinh^{-1}(p_e) - |s|) \right] - \frac{3|1-e^s|}{32p_e^6} [1 + (10+8p_e^2+4p_e^4)e^s + e^{2s}]. \quad (2.22)$$

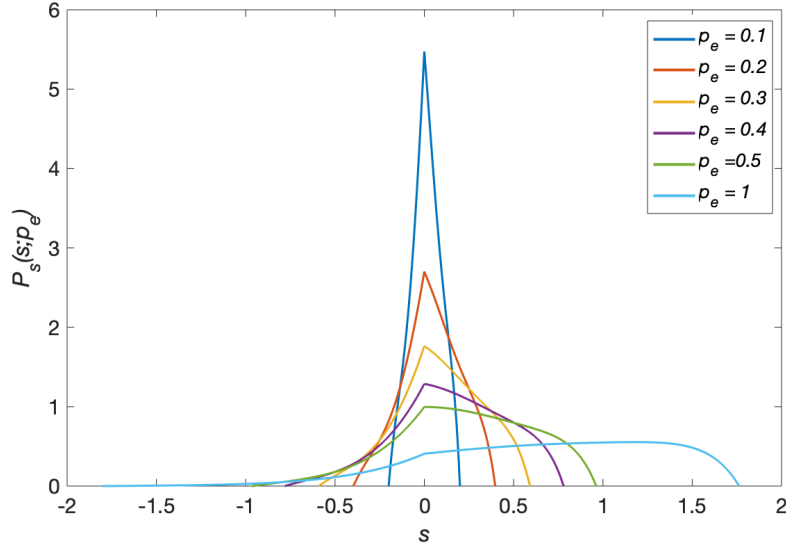


Figure 2.10: The scattering probability function $P(s, p_e)$, for $p_e = 0.1, 0.2, 0.3, 0.4, 0.5$, and 1 .

The full treatment to derive equation 2.22 in this analytical form can be found in Birkinshaw (1999) and Enßlin & Kaiser (2000). Figure 2.10 shows the scattering probability function, $P(s, p_e)$, for electron momentum $p_e = 0.1, 0.2, 0.3, 0.4, 0.5$, and 1 . As we go up in values of p_e , the frequency shift related to a given photon angular deflection increases, causing $P(s, p_e)$ to become broader and asymmetric (discussed in detail by Birkinshaw 1999). For this work, we are interested in the momentum distribution of scattering electrons in plasma with temperature ($k_B T_e$) and a thermal relativistic distribution given by

$$f_e(p_e) = \frac{\beta_{th}}{K_2(\beta_{th})} p_e^2 e^{-\beta_{th} \sqrt{1+p_e^2}}, \quad (2.23)$$

where $K_2(\beta_{th})$ is the modified Bessel function of the second kind, $\beta_{th} = \frac{m_e c^2}{k_B T_e}$ is the normalized thermal beta-parameter, and $f_e(p_e)$ is normalised such that $\int f_e(p_e) dp_e = 1$ (Enßlin & Kaiser 2000). In Figure 2.11, we have the thermal relativistic distribution for plasma with temperature, $k_B T_e = 5, 10$, and 15 keV.

In light of equations 2.22 and 2.23, the redistribution function (also called the scattering kernel) of photons that undergo a single scattering by relativistic electrons in the ICM is given by

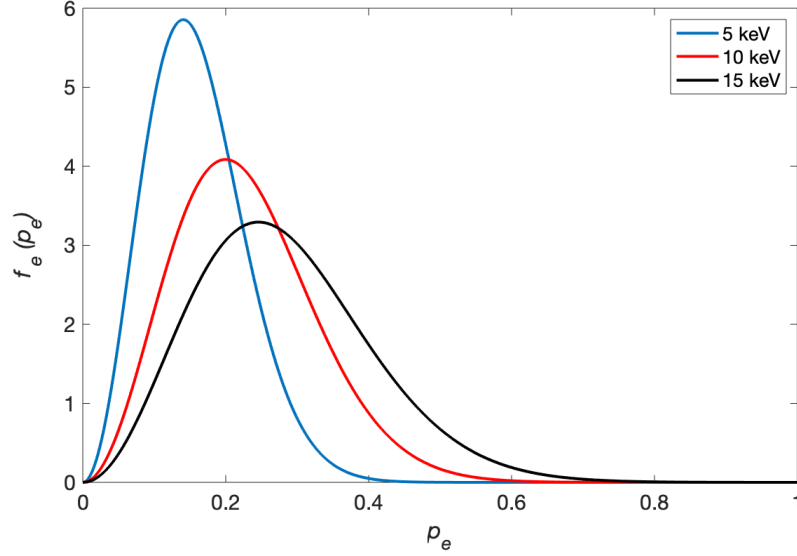


Figure 2.11: The thermal relativistic distribution for thermal populations with temperature $k_B T_e = 5, 10$ and 15 keV

$$P_1(s) = \int_{p_{min}}^{\infty} P(s; p_e) f_e(p_e) dp_e \quad (2.24)$$

where the minimum electron momentum needed to cause the shift, s , is $p_{min} = \sinh(|s|/2)$. See Figure 2.12 for the probability distribution function for plasma with temperature, $k_B T_e = 5, 10$, and 15 keV. The probability distribution function can be calculated for multiple scattering in the relativistic limit, the reader is referred to Birkinshaw (1999) and Colafrancesco et al. (2003) for further treatment in this regard. The spectral distortion of the CMB due to the SZE in relativistic limit can, therefore, be expressed as an intensity change:

$$\Delta I(x) = \tau \left[\int_{-\infty}^{+\infty} I_0(xe^{-s}) P_1(s) ds - I_0(x) \right], \quad (2.25)$$

to the first order in the optical depth, τ , where I_0 is the specific intensity of the CMB radiation given by

$$I_0(x) = 2 \frac{(k_B T_{CMB})^3}{(hc)^2} \frac{x^3}{e^x - 1}. \quad (2.26)$$

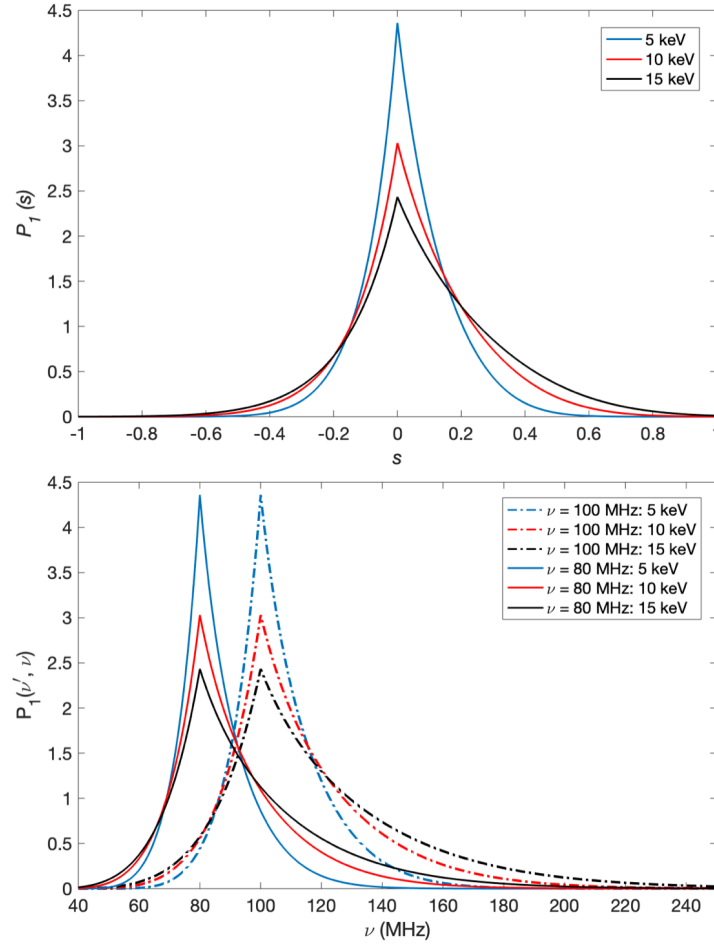


Figure 2.12: (Top) The probability distribution function, $P_1(s)$, for clusters with plasma of temperatures 5, 10, 15 keV. (Bottom) $P_1(s)$ for photons of initial frequency (ν) of 80 MHz (Solid) and 100 MHz (Dotted) for clusters with plasma of temperatures 5, 10, 15 keV.

In figure 2.13, we have the SZE spectrum for different plasma temperatures ($k_B T_e$) using both the relativistic (equation 2.26) and non-relativistic (equation 2.16) cases. It is evident that there exists a bigger discrepancy for higher plasma temperatures. However, the SZE with relativistic corrections is very close to the SZE calculated with the Kompaneets approximation at low temperatures. It is worth noting that taking the relativistic corrections into account allows the SZE to be computed for any sort of electron distribution, which means that it can be applied to computations of the spectrum for both the thermal and non-thermal electron distributions.

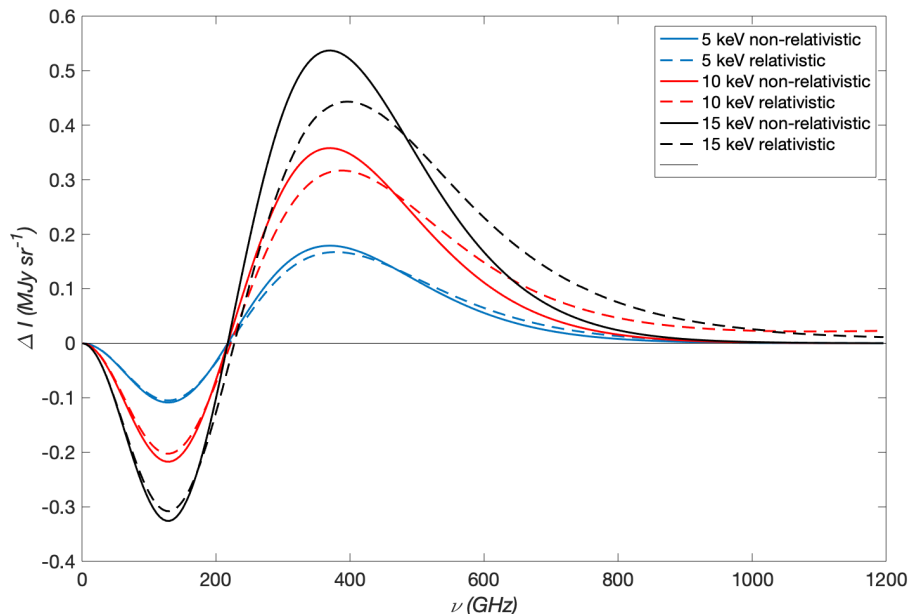


Figure 2.13: The SZE spectral distortion for the relativistic and non-relativistic cases computed for a thermal electron distribution of optical depth $\tau = 10^{-3}$ with plasma temperatures $k_B T_e = 5, 10, 15$ keV.

2.7 Observations of the SZE

Over the past 3-4 decades, there has been a tremendous increase in the study of galaxy clusters as cosmological probes through the SZE. To date, several experiments have been able to produce detailed images of the effect at X-ray frequencies and high radio frequencies. Radio observations have been obtained both from single dish and interferometer experiments (Birkinshaw 1999). Single dish radio telescopes were used for the first measurements of the SZE (Birkinshaw et al. 1984), and later interferometric techniques were used due to their ability to produce high quality images of the effect over larger ranges of angular scales and make it possible to remove contaminating emission from individual radio sources (Jones et al. 1993; Grainge et al. 1996; Carlstrom et al. 1999).

Observations of the SZE toward galaxy clusters are motivated by the ability to use combined SZE and X-ray emission data to determine the Hubble constant and the fraction of the total cluster mass contained in the hot gas. Using the SZE for measuring the Hubble constant is independent of other techniques and can be used to measure distances at high redshifts. Observations through non-targeted, sensitive SZE surveys of large areas of the sky have provided an inventory of clusters inde-

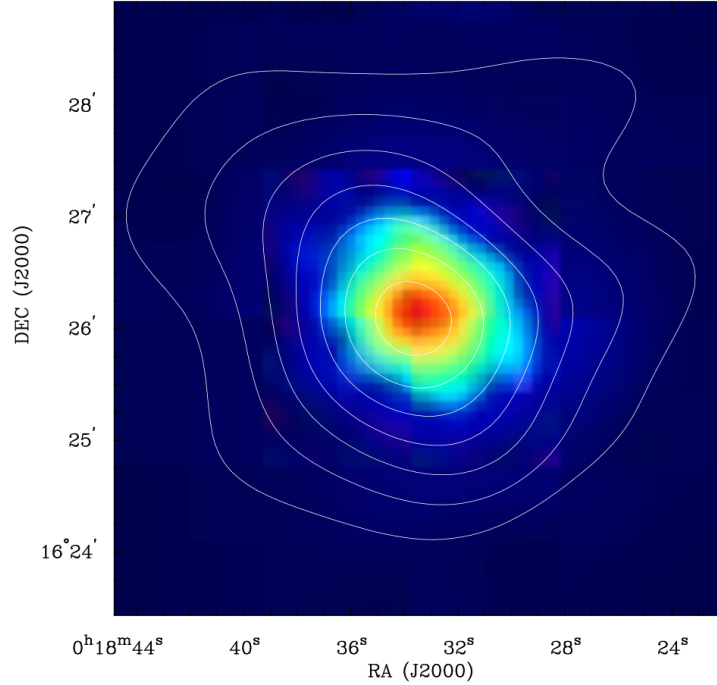


Figure 2.14: The SZE contours from data obtained with OVRO and BIMA, overlaid on the X-ray emission for the galaxy cluster CL 0016+16 obtained with the ROentgen SATellite (ROSAT). [Credit: [Carlstrom et al. \(1999\)](#)]

pendent of redshift ([Carlstrom et al. 1999](#)). Furthermore, the measurement of the SZE towards clusters gives a measure of the mass of the ICM, which is typically several times the mass responsible for the radiation from the galaxies ([Birkinshaw 1999](#)). [Carlstrom et al. \(1999\)](#) reported results from interferometric measurements of the SZE with millimeter arrays, the Owens Valley Radio Observatory (OVRO) and the Berkeley-Illinois-Maryland Association (BIMA) telescopes. They obtained a high quality image of a clusters SZE (see Figure 2.14) and obtained constraints for the Hubble and matter density cosmological parameters. Since then, the sensitivities of interferometers have improved and they yield higher S/N and confidence detections, observing techniques have also evolved. Interferometer observations of the SZE have shown potential and new and upcoming instruments are more sensitive to imaging at higher resolutions. Recently, observations from the Atacama Large Millimeter/submillimeter Array (ALMA) produced the highest angular and physical spatial resolutions achieved to date for imaging the SZE for RX J1347.5–1145 (see Figure 2.15).

Differential observations have been used and are sufficiently sensitive for the measure-

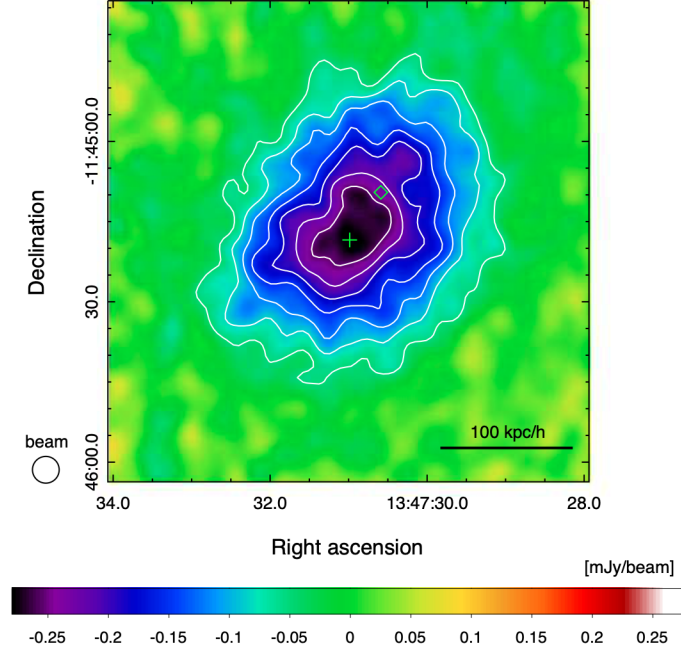


Figure 2.15: The SZE image of the galaxy cluster RX J1347.5–1145 from ALMA at the central frequency of 92 GHz at 5". [Credit: [Kitayama et al. \(2016\)](#)]

ment and detection of SZE that can be carried out by instruments, observing across the centimetre, millimetre, and sub-millimetre spectrum (see, [Carlstrom et al. 2002](#)). To measure the SZE with such differential techniques, cluster observations follow a procedure where a cluster is tracked for a certain amount of time and then the telescope is moved to a trailing empty patch of sky for the same amount of time (see, [Figure 2.16](#)). Galaxy clusters are extended low surface brightness objects and thus require precise differential measurements made towards widely separated directions on the sky. Differencing the on-source and off-source patches efficiently removes the contamination in the system (see, [Carlstrom 1996](#); [Lin et al. 2016](#)). With single dish observations this is achieved through beam switching techniques, examples of successful detections through such techniques are those of Birkinshaw and collaborators with the Owens Valley Radio Observatory (OVRO) 40 meter telescope ([Birkinshaw 1999](#); [Carlstrom et al. 2002](#)). In 2009, the first previously unknown cluster was discovered through its SZE signature by [Staniszewski et al. \(2009\)](#) with the South Pole Telescope (SPT). In recent times detection and imaging of the SZE has resulted in various catalogs from instruments such as the Atacama Cosmology Telescope (ACT) ([Hilton et al. 2018](#)), and the Planck telescope ([Planck Collaboration et al. 2014, 2016](#)).

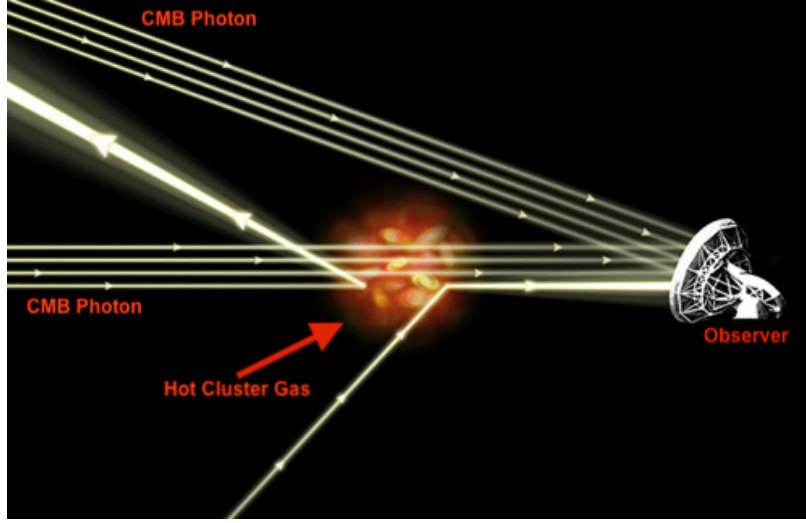


Figure 2.16: An illustration of the observational procedure of SZE with background photons interacting with energetic electrons that pervades the galaxy cluster. The photons acquire energy from this interaction, which distorts background signal in the direction of the cluster.[Credit: chandra.harvard.edu]

2.8 The SZE-21cm

In this Chapter we have given an introduction to the DA and EoR and how they can be studied using the 21 cm line of neutral hydrogen, we also learned that observations of the signal from these epochs are difficult due to the challenges that will be faced as the instruments suitable to study the signal require very accurate calibration and the foreground contamination is orders of magnitude greater than the cosmological signal. This Chapter also gave us a broad understanding of the SZE and how it has been used as a tool for cosmological and astrophysical studies.

[Cooray \(2006\)](#) discussed the feasibility to detect the global 21 cm spectrum from the DA and EoR modified by scattering off intervening electrons of foreground galaxy clusters through differential observations with low-frequency radio interferometers at frequencies below 200 MHz. This alternative probe for the global 21 cm signal using the SZE called the SZE-21cm was revisited by [Colafrancesco et al. \(2016\)](#) who addressed and refined calculations by [Cooray \(2006\)](#). The issues that [Colafrancesco et al. \(2016\)](#) identified in the preliminary results presented by [Cooray \(2006\)](#) are: (1) the baseline model of the global 21 cm spectrum used to describe the signal from the DA and EoR was unphysical and cannot be reconciled with recent models as it also contains a number of artificial discontinuities, and (2) the calculation of the SZE-21cm was performed in the non-relativistic limit, which made the result only

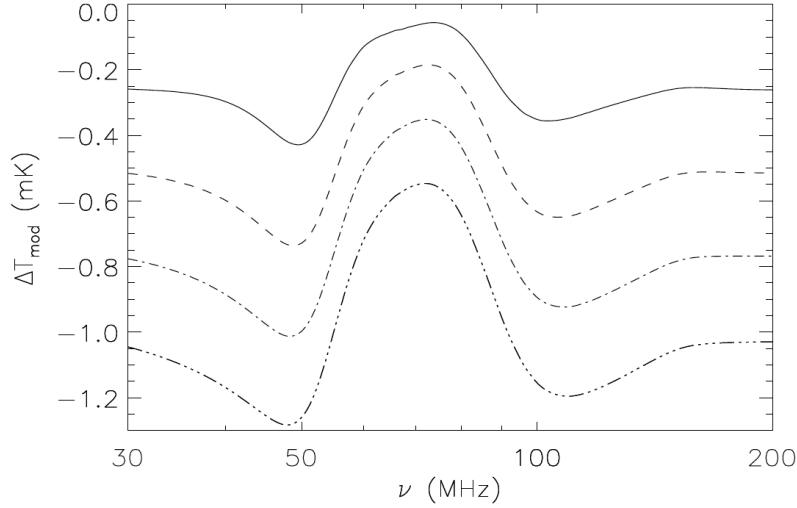


Figure 2.17: The SZE-21cm calculated for thermal electron distribution: 5 keV (solid), 10 keV (dashed), 15 keV (dot-dashed) and 20 keV (dash three dots) for an optical depth, $\tau = 5 \times 10^{-3}$. [Credit: Colafrancesco et al. (2016)]

applies to cluster with low plasma temperature, and (3) only thermal electrons were considered and the presence of non-thermal electrons in clusters was not accounted for.

Colafrancesco et al. (2016) recalculated the SZE-21cm using the full relativistic approach which is valid for any distribution of electrons and included additional mechanisms such as heating from dark matter annihilation using recent models of the global 21 cm signal (Evoli 2014). The results obtained by Colafrancesco et al. (2016) were also compared with the sensitivity of the upcoming low-frequency SKA telescope in Figure 2.18. This was done by calculating the loss of signal at small angular radii, produced by the finite extension of the SKA-low interferometer with a minimum baseline of 50 km and a reference resolution, $\theta_{min} = 11$ arcsec at 110 MHz (see, Dewdney et al. 2012). The optical depth at a projected distance θ from the center of an isothermal cluster with a gas density profile given by equation 2.19 is:

$$\tau(\theta) = \tau_0 \left(1 + \frac{\theta^2}{\theta_c^2} \right)^{\frac{1}{2} - \frac{3}{2}\beta} \quad (2.27)$$

(Colafrancesco et al. 2003). Calculating the flux up to $\theta_{max} = 10\theta_c$, the lack of sensitivity was estimated to be of order $\sim 1.1 \times 10^{-4}$, using the typical assumption of a near and rich Coma-like cluster with $\tau_0 = 5 \times 10^{-3}$, $\beta = 0.75$ to scales $\theta < \theta_{min}$ (Co-

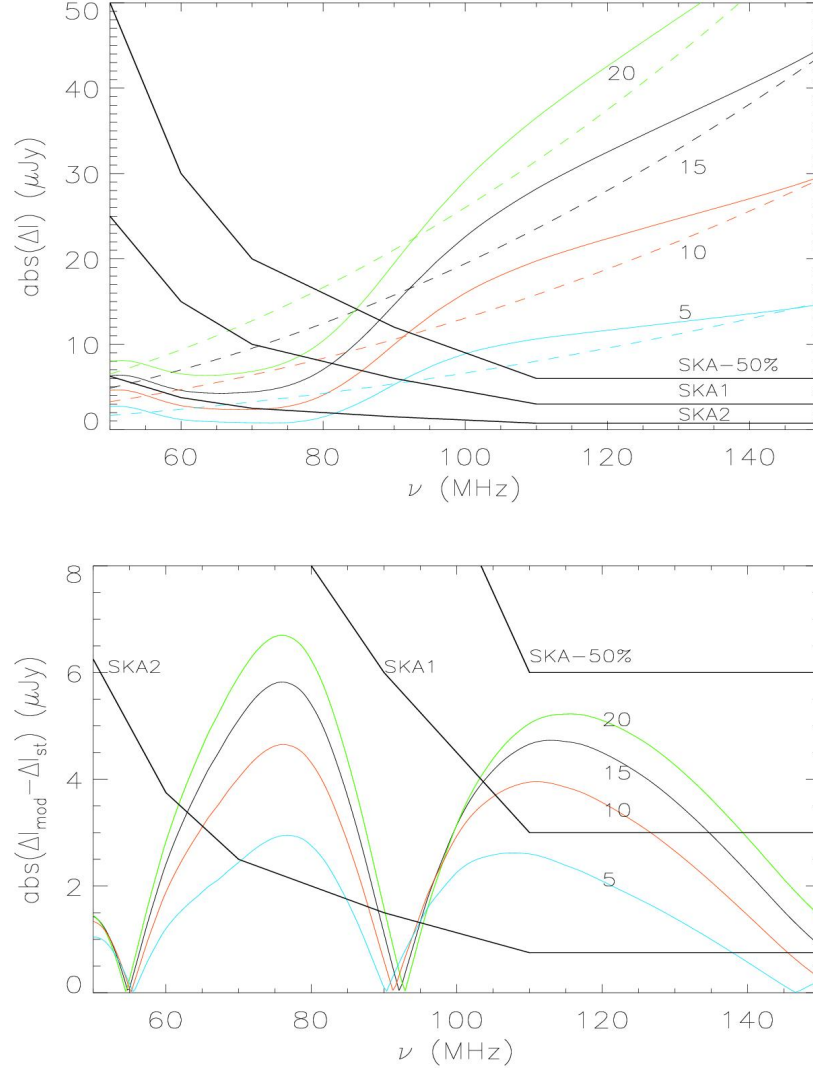


Figure 2.18: Top The spectra of the SZE-21cm and the SZE for a non-modified CMB ΔI_{st} (dashed lines). **Bottom** absolute value of the difference between the SZE-21cm and the standard SZE. Both plots are for thermal plasmas present in galaxy clusters with temperatures, 5 keV (cyan), 10 keV (red), 15 keV (black), and 20 keV (green). [Credit: Colafrancesco et al. (2016)]

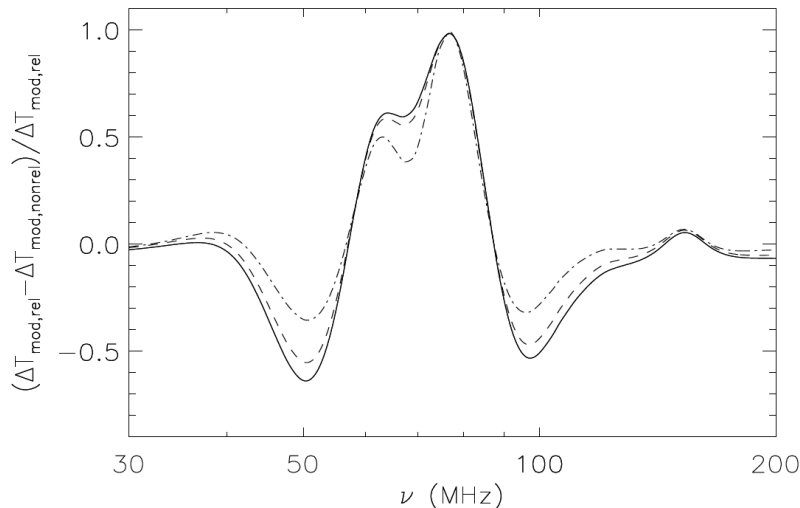


Figure 2.19: Fractional error calculated between for the relativistic and the non-relativistic SZE-21cm for thermal plasmas present in galaxy clusters with temperatures, 7 keV (dot-dashed line), 15 keV (dashed line), and 20 keV (solid line). [Credit: Colafrancesco et al. (2016)]

Colafrancesco & Marchegiani 2014; Colafrancesco et al. 2016). This work also showed the importance of the relativistic corrections by investigating the impact of relativistic effects on the SZE-21cm and found that the non-relativistic approach produces considerable errors over almost the frequency range that we expect to observe the SZE-21cm. The percentage difference between the two can go up to a 100%, see Figure 2.19. Work by Colafrancesco et al. (2016) also showed that it may be possible to derive information on the existence and the properties of the electron population in cosmic structures also from very low-frequency observations of the SZE.

Cooray (2006) and Colafrancesco et al. (2016) both emphasised that differential observations of the SZE-21cm with radio interferometers are less affected by the presence of galactic and extra-galactic foregrounds that are uniform over angular scales larger than a typical cluster and the observations would be less affected by exact calibration of the observed intensity using an external source. They also pointed out that multi-cluster SZE-21cm observations could be aided by the large instantaneous fields-of-view of upcoming instruments, which is expected to be about 100 square degrees, which can lead to simultaneous detection of hundreds, or more, massive clusters. The work that this thesis presents is deeply rooted in the works by Colafrancesco et al. (2016). In section 3.2.2, we revisit the derivation of the formalism they presented which is very relevant to this work.

Chapter 3

Simulated differential observations of the Sunyaev-Zel'dovich Effect: Probing the Dark Ages and Epoch of Reionization

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For this work, C. M. Takalana produced the simulated observation to measure the SZE-21cm and produced the written paper under the supervision of Dr. Paolo Marchegiani and Prof. Sergio Colafrancesco, and consulted with Dr. Geoff Beck.

Abstract

This work presents an analytical approach for studying the cosmological 21cm background signal from the Dark Ages (DA) and subsequent Epoch of Reionization (EoR). We simulate differential observations of a galaxy cluster to demonstrate how these epochs can be studied with a specific form of the Sunyaev-Zel'dovich Effect called the SZE-21cm. This work produces simulated maps of the SZE-21cm and shows that the SZE-21cm can be extracted from future observations with low-frequency radio interferometers such as the Hydrogen Epoch of Reionization Array (HERA)

and the Square Kilometre Array (SKA). In order to simulate near realistic scenarios, we look into cosmic variance noise, incorporate and take into account the effects of foregrounds, thermal noise, and angular resolution for our simulated observations. We further extend this exploration by averaging over a sample of galaxy clusters to mitigate the effects of cosmic variance and instrumental noise. The impact of point source contamination is also studied. Lastly, we apply this technique to the results of the EDGES collaboration, which in 2018 reported an absorption feature of the global 21cm background signal centred at 78 MHz. The challenges to be addressed in order to achieve the objectives of this work include errors that arise due to cosmic variation, instrumental noise and point source contamination. Our approach demonstrates the potential of the SZE-21cm as an indirect probe for the DA and EoR, and we conclude that the spectral features of the SZE-21cm from our simulated observations yield results that are close to prior theoretical predictions and that the SZE-21cm can be used to test the validity of the EDGES detection.

3.1 Introduction

The cosmic Dark Ages (DA) is an era of darkness in the Universe and the Cosmic Microwave Background (CMB) does not provide information about this period as baryonic matter and radiation have already decoupled prior to this epoch. Subsequently neutral hydrogen gas in the intergalactic medium (IGM) makes up the majority of baryonic matter in the Universe (Zaroubi 2013). The DA end with the formation of the first generation of stars, that are believed to have had significant effects on the Universe and subsequently initiate the Epoch of Reionization (EoR) (Bromm et al. 2009; Wise 2019). The first generation of stars and galaxies emit high-energy photons that permeate the IGM and gradually ionize the hydrogen, until at around $z \sim 6$ when the Universe is fully ionised (Fan et al. 2006). The process of reionization of the IGM enriches primordial galaxies with heavy elements, and seeds larger galaxies (Furlanetto 2006a).

Observations of the 21 cm hydrogen transition line promises to be an important probe into the DA and EoR. The 21 cm transition is a line, therefore the measured frequency corresponds to a particular redshift ($\nu = \frac{\nu_{21}}{(1+z)}$ with $\nu_{21} = 1420.405$ MHz), and by using this property we can isolate every phase in the history of the IGM. The signal is difficult to measure due to contamination by astronomical foregrounds (Furlanetto 2006a). Numerous efforts are nevertheless under-way to observe it and the experiments designed to measure it come in two different varieties namely power spectrum (Paciga et al. 2013; Jacobs et al. 2015, 2016; DeBoer et al. 2017; Mondal et al. 2019) and global signal (Burns et al. 2012; Bowman et al. 2009; Bowman et al. 2018).

The collaboration of the Experiment for the Detection of the Global EoR Signature (EDGES) recently reported the first observational results on the global 21 cm spectrum (Bowman et al. 2018). The results show an absorption feature with a remarkably large amplitude of about 500 mK at the redshift range of $z \sim 15-20$, which is nearly three times the predicted value. Until this detection is confirmed, it is essential that we evaluate the current theoretical models strictly and further explore the use of indirect techniques that can allow us to measure the 21 cm global background signal. Galaxy clusters are massive objects that provide powerful cosmological probes (Romer et al. 2001). Energetic electrons in the plasma of the galaxy clusters are responsible for inverse Compton scattering of background photons as they pass through the intracluster medium (ICM). This process produces a spectral distortion of the incident background radiation at the position of clusters on the sky and is known as the Sunyaev-Zel'dovich effect (SZE) (Zel'dovich & Sunyaev 1969; Sunyaev & Zel'dovich 1970, 1972, 1980). The SZE has been identified as an effective cosmological probe and can be measured at microwave and radio frequencies (Rephaeli 1995; Birkinshaw 1999; Holder & Carlstrom 1999).

Existing interferometers cannot be used to detect the global average sky background temperature using standard techniques as they are not sensitive to the spatially invariant global average (McKinley et al. 2018) but they are suitable to detect signal differences towards different directions in the sky with high precision, as in the case of the SZE. Based on this consideration, a specific form of the SZE called the SZE-21cm was proposed as an indirect technique to study the global 21 cm background signal (Colafrancesco et al. 2016). The SZE-21cm is a differential measurement towards and away from clusters of galaxies of the comptonized spectrum of the CMB as modified by physical processes occurring during the DA and the EoR. The idea to probe these epochs with the SZE-21cm was initially suggested by Cooray (2006) and later addressed by Colafrancesco et al. (2016), who concluded that the effect can be observed at low radio frequencies (40 MHz-200 MHz) with upcoming interferometers such as the Murchison Widefield Array (MWA)¹, Low Frequency Array (LOFAR)², Hydrogen Epoch of Reionization Array (HERA)³, and the Square Kilometre Array (SKA)⁴.

Colafrancesco et al. (2016) derived the SZE-21cm in a general relativistic approach

¹<http://www.mwatelescope.org>

²<http://lofar.org>

³<http://reionization.org>

⁴<http://www.skatelescope.org>

and studied how its spectral shape can be used to establish the global features in the mean 21 cm spectrum generated during, and prior to, the EoR. Additionally, the aforementioned work also outlined how the effect depends on the properties of plasma in cosmic structures. [Takalana et al. \(2018\)](#) described the first version of a procedure to observe the SZE-21cm with upcoming interferometers. While the past work on this topic is mainly theoretical, in this work we perform new simulations of the background signal and study instrumental effects for HERA and SKA. We simulate differential observations of a low redshift galaxy cluster as a function of frequency for a theoretical 21 cm background model to show that by measuring the SZE-21cm we can derive the properties of the global 21 cm background spectrum generated during the DA and EoR. Our simulated observations explore the impact of cosmic variance (or sample variance) and point sources and take into account the effects of foregrounds, thermal noise, and angular resolution for upcoming interferometers. We also consider the observation and computation of the SZE-21cm towards multiple clusters as a method to ultimately reduce the uncertainty and improve the signal-to-noise. This work takes into consideration newer models of the 21 cm background, both theoretical and observational.

The EDGES experiment reported a 21 cm background signal that challenges cosmological models and instrumental precision. We use the EDGES detection results to make predictions for the SZE-21cm and make comparisons with the simulated theoretical 21 cm background model results to show that differential observation techniques for the SZE-21cm can be used to confirm detections made by experiments similar to EDGES. Lastly, we explore the feasibility of detecting the SZE-21cm with the upcoming SKA telescope.

In section 3.2 we present the theoretical background and mathematical formalism for studies of the 21 cm transition signal and the SZE-21cm. In section 3.3 we simulate differential observations of a galaxy cluster with upcoming radio interferometers and from this establish the relationship between the SZE-21cm spectrum and the global 21 cm background spectrum using a theoretical 21 cm model. In section 3.4 we use the global 21 cm background signal measured by EDGES to make predictions for the SZE-21cm and make comparisons with the signal obtained through our simulations using the theoretical 21 cm model. In section 3.5 we discuss the simulation results and look at possible challenges for observations of the SZE-21cm presented by instrumental effects, cosmic variance, and point sources. We summarize our findings and conclude in section 3.6. We assume a Λ CDM cosmology throughout this work with the following Planck 2015 parameters: $h_{100} = 0.673$, $\Omega_m = 0.315$, $\Omega_b = 0.0491$, $\Omega_\Lambda = 0.685$, $\sigma_8 = 0.815$ and $n_s = 0.968$ ([Planck Collaboration et al. 2015](#)).

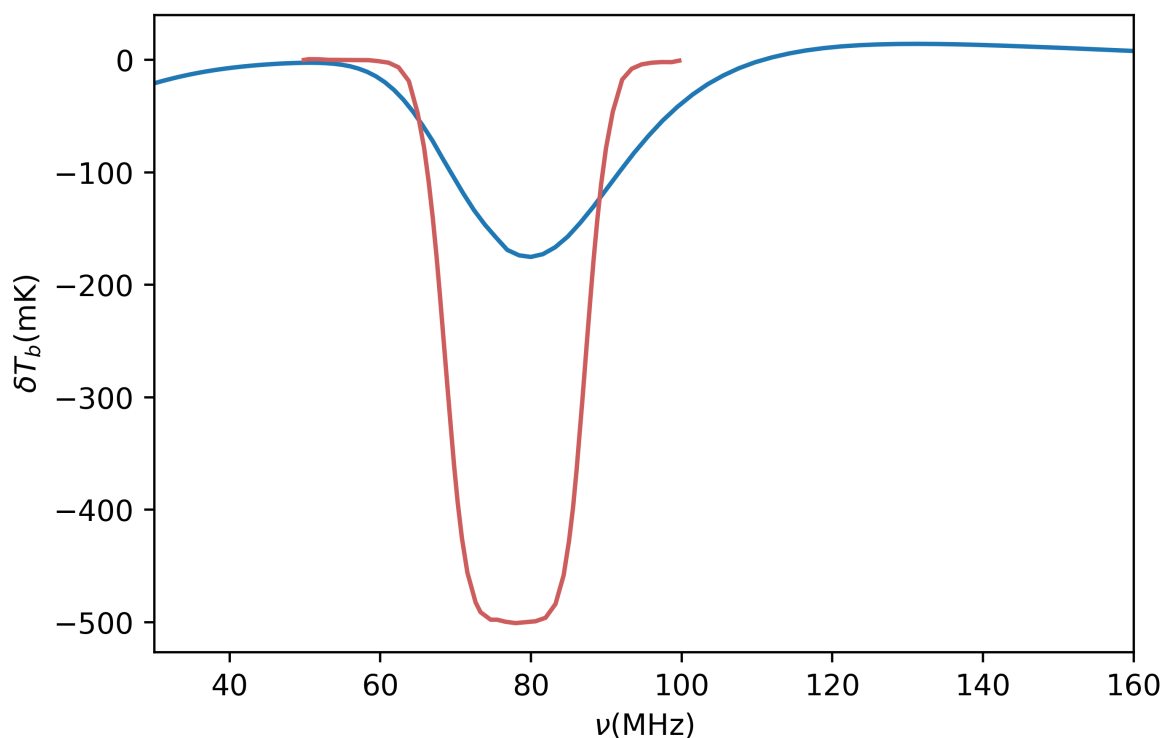


Figure 3.1: The mean 21 cm background brightness temperature offset from the CMB spectrum as a function of frequency. The *Blue* curve is for a theoretical 21 cm model simulated for this work and the *Red* curve for the best-fitting 21 cm profile model derived from the EDGES observations (Bowman et al. 2018).

3.2 The SZE-21cm: a probe for the DA and EoR

In this section, we present theoretical background and formalism for studies of the 21 cm transition signal and discuss the detection of the signal claimed by the EDGES collaboration in 2018, and look at the concerns raised about the results. We also provide the theoretical background of the SZE-21cm and revisit the formalism derived by Colafrancesco et al. (2016). Lastly, we discuss observations of the 21 cm to probe the DA and EoR.

3.2.1 The cosmological 21 cm background signal

Neutral hydrogen atoms undergo a quantum mechanical transition between the hyperfine energy levels (spin-flip transition) resulting from magnetic interaction between the electron and the spin of the proton. When the spins change from parallel to anti-parallel, a photon with a wavelength of 21 cm is emitted, producing a signal with

a line center frequency of $\nu_0 = 1420.405$ MHz (van de Hulst 1945; Ewen & Purcell 1951; Muller & Westerhout 1957). The intensity of the 21 cm radiation from a population of neutral hydrogen is dependent on the spin temperature (T_S) defined through the ratio between the number densities of hydrogen atoms in the $1S$ triplet and $1S$ singlet levels (Pritchard & Loeb 2012). The quantity of interest that radio interferometers will measure is the offset of the 21 cm brightness temperature from the CMB temperature, $T_{CMB} = 2.73(1+z)$ K, along a line of sight at the observed frequency (Furlanetto 2006a), which is written as

$$\delta T_b \simeq 23x_{HI} \left[\left(\frac{0.15}{\Omega_m} \right) \left(\frac{1+z}{10} \right) \right]^{1/2} \left(\frac{\Omega_b h^2}{0.02} \right) \left[1 - \frac{T_R}{T_s} \right] \text{mK}, \quad (3.1)$$

where x_{HI} is the neutral fraction of hydrogen, h is the Hubble parameter in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and Ω_b and Ω_m are the baryon and matter densities respectively. T_R is the temperature of the background radiation, which this work assumes to be from the CMB, hence $T_R = T_{CMB}$. Predicted by Shaver et al. (1999), this global 21 cm background signal is sensitive to both astrophysical and cosmological processes in the early Universe, which makes it a good probe of the physics between the CMB decoupling, the DA and the EoR (see Field 1958; Shaver et al. 1999; Barkana & Loeb 2005; Furlanetto 2006a; Pritchard & Loeb 2012, for detailed discussions and formalism derivations for the 21 cm background signal).

This work focuses on a theoretical model of the 21 cm background signal that we simulate under standard cosmological assumptions using a semi-numeric modeling tool Mesinger et al. (2010) and one based on the best-fitting 21 cm profile model from recent EDGES results (Bowman et al. 2018). For both cases, the brightness temperature offset from the CMB is shown in Figure 3.1 as a function of frequency. Equation 3.1 tells us that the amplitude of the absorption signal can be increased by reducing T_s . The claimed EDGES detection exhibits a much larger flat-bottomed amplitude of -500^{+200}_{-300} mK with a Full-Width at Half-Maximum of 19^{+4}_{-2} MHz centred at around 78 MHz (corresponding to $z \sim 17$) (Bowman et al. 2018). Various proposals have been made to explain the larger than expected amplitude observed by EDGES. One of the proposals argues that the anomaly could be a new signal of baryon-dark matter interaction as scattering processes that may cool neutral hydrogen with respect to the standard expectations from the CMB measurements (see Barkana 2018; Fialkov et al. 2018). Another suggestion argues that the anomaly may be related to an additional radio background with likely causes of this excess ranging from instrumental systematics to new astrophysics as may have been observed by ARCADE 2 (see Fixsen et al. 2011; Ewall-Wice et al. 2018).

Motivated by the unexpected nature of the EDGES claim, concerns were raised re-

garding the modelling of the EDGES data. These concerns arise from the following findings:

- [Hills et al. \(2018\)](#); [Singh & Subrahmanyan \(2019\)](#); [Sims & Pober \(2019b\)](#) suggest the potential presence of an uncalibrated sinusoidal-form systematic in the data.
- [Hills et al. \(2018\)](#) also highlight the use of a modeling process that implies unphysical parameters in the data for foreground emission, where the degeneracy between signal and foreground modeling allows a wide range of signals to be consistent with the data.
- Work by [Singh & Subrahmanyan \(2019\)](#) enforces a maximally smooth polynomial foreground model, constant amplitude sinusoidal systematic model, white noise and a Gaussian parametrisation of the global 21 cm signal, and found evidence for a different 21 cm signal, substantially more in agreement with the standard predictions.
- [Bradley et al. \(2019\)](#) report on a possible systematic artifact within the ground plane due to resonance modes beneath the antenna that may produce spurious broad absorption features in the spectra.

While the above ideas may not perfectly describe the detection, they illustrate the efforts of the community to use the results of [Bowman et al. \(2018\)](#) to explore possible exotic physics and new source populations as extensions to standard models for cosmology and particle physics. They also explore possible unmodeled systematic effects present in the data as we have seen above. Later in this work, we make predictions for the SZE-21cm using a 21 cm background signal described by the [Bowman et al. \(2018\)](#) data to test the usefulness of the SZE-21cm as a technique that can potentially be used to verify the EDGES detection and other such claims in the future.

3.2.2 *The SZE-21cm*

The interaction between photons and free electrons by inverse Compton scattering results in the SZE ([Zel'dovich & Sunyaev 1969](#); [Sunyaev & Zel'dovich 1970, 1972, 1980](#)). The SZE is produced when the free electrons in the dense cores of galaxy clusters that contain hot ionized gas ($\sim 10^7$ K) ([Cavaliere & Fusco-Femiano 1976](#)) up-scatter CMB photons causing a change in the apparent brightness of the CMB photons, which modifies the incident Planck spectrum (see [Birkinshaw 1999](#), for a review). This scattering results in a systematic shift of the CMB photons from the

Rayleigh-Jeans to the Wien side of the spectrum (Birkinshaw 1999; Carlstrom et al. 2002; Colafrancesco et al. 2003).

This work examines the use of low-frequency SZE observations (< 200 MHz) to study the global properties of the universe during the DA and EoR with the 21 cm line of neutral hydrogen. In this section, we summarise the formalism for the SZE-21cm as derived by Colafrancesco et al. (2016) as this forms the basis of the simulated observations we present in the sections that follow. For the full treatment of the formalism in the relativistic limit, the reader is referred to Colafrancesco et al. (2003) for the standard SZE and Colafrancesco et al. (2016) for the SZE-21cm. Here we consider the SZE due only to the thermal electrons in a hot cluster, which requires the appropriate relativistic corrections to be taken into account.

Any energy injecting process occurring during the EoR and DA modifies the CMB spectrum as described in Section 3.2.1 and subsequently modifies the SZE. The incident CMB radiation field modified during the DA and EoR is given by the specific intensity as:

$$I_{0,mod}(\nu) = I_{0,st}(\nu) + \delta I(\nu), \quad (3.2)$$

where $\delta I(\nu)$ is the radiation intensity corresponding to the differential brightness temperature (δT_b) in equation 3.1 obtained by applying the Rayleigh-Jeans law, $\delta I(\nu) = \frac{2K_B\nu^2}{c^2}\delta T_b(\nu)$, and the unperturbed or standard CMB spectrum ($I_{0,st}$) is given by

$$I_{0,st}(x) = 2 \frac{(k_B T_{CMB})^3}{(hc)^2} \frac{x^3}{e^x - 1}, \quad (3.3)$$

where c is the speed of light, h is the Planck constant, k_B is the Boltzmann constant, and $x = \frac{h\nu}{k_B T_{CMB}}$ is the a-dimensional frequency. The spectral distortion due to the SZE of the CMB radiation field as modified during the DA and EoR is given by

$$I_{mod}(x) = \int_{-\infty}^{+\infty} I_{0,mod}(xe^{-s})P(s)ds, \quad (3.4)$$

where $P(s)$ is the photon redistribution function that is dependent on the electrons spectrum producing the CMB Comptonization (Birkinshaw 1999; Enßlin & Kaiser 2000; Colafrancesco et al. 2003, 2016), and is essentially the scattering kernel giving

the probability of a scattering to shift a photon from a frequency ν to ν' (with $s = \ln(\frac{\nu'}{\nu})$). The SZE-21cm is then given as the difference between the scattered spectrum (I_{mod}) and the incoming radiation ($I_{0,mod}$):

$$\Delta I_{mod}(\nu) = I_{mod}(\nu) - I_{0,mod}(\nu). \quad (3.5)$$

This equation can then be transformed in terms of brightness temperature by applying the Rayleigh-Jeans law and be rewritten as

$$\Delta T_{mod}(\nu) = T_{mod}(\nu) - T_{0,mod}(\nu). \quad (3.6)$$

3.2.3 *Observations of the 21 cm signal from the DA and EoR*

The 21 cm background signal from the DA and EoR is weak and may be observed as a faint, diffuse background detectable at frequencies below 200 MHz. Previous and current generation interferometer experiments attempt to measure a statistical power spectrum of the signal over the sky, rather than to image the signal directly, by measuring a range of aggregate spatial scales on the sky. There are several challenges associated with observations of the 21 cm background. The main problem is that the signal is weak, at a characteristic scale of ~ 10 to 100 mK, and the task is further complicated by the much stronger foreground continuum emission due to sources such as galactic diffuse synchrotron, free-free emission, and emissions from extragalactic radio sources (Santos et al. 2005; Sims & Pober 2019a). These contaminating signals are five orders of magnitude stronger than the 21 cm emission, making its observation extremely complex to study, and requiring very precise calibration and knowledge of various foregrounds (see e.g., Furlanetto 2006a). Several ideas have been presented to overcome the various problems identified above, including foreground avoidance and removal techniques. These strategies rely on the spectral smoothness and spatial characteristics of foreground sources; we do not discuss the various approaches here but refer the reader to other texts (see e.g., Barkana & Leob 2005; Furlanetto 2006a; McQuinn et al. 2006).

All observations that are sufficiently sensitive to detect the SZE are differential (Carlstrom et al. 2002). Consequently, differential observations of the SZE-21cm towards galaxy clusters have been proposed as one way to overcome the above-mentioned problems by Cooray (2006) and Colafrancesco et al. (2016). Unlike an experiment

to directly determine the cosmological 21 cm background spectrum involving a total intensity measurement on the sky, differential observations with an interferometer are less affected by the confusion from galactic foregrounds that are smooth over angular scales larger than a typical cluster and by issues such as the exact calibration of the observed intensity using an external source (Cooray 2006; Colafrancesco et al. 2016). In the next section, we simulate differential observations of a galaxy cluster to compute the SZE-21cm.

3.3 Simulations of differential observations of the SZE-21cm

3.3.1 *Simulations of the 21 cm background*

We simulate the 21 cm cosmological background using the publicly available semi-numerical code 21cmFAST⁵. 21cmFAST takes into account the necessary physical processes and produces large-scale simulations utilizing perturbation theory, the excursion set formalism (which specifies the location and mass of collapsed dark matter haloes), and analytic prescriptions to produce evolved 3D realizations of density, spin temperature fields, ionization, and peculiar velocity, which when combined, can be used to deduce the global 21 cm brightness temperature at a given redshift as described by equation 3.1.

Each simulation cube in our runs is 30 Mpc on a side down-sampled from the high-resolution initial conditions generated on a 460^3 grid and computed on a 115^3 grid corresponding to a cell resolution of 0.26 Mpc, in the frequency range $\nu = 30 - 160$ MHz. Our model assumes that Population II stars are responsible for early heating with parameters in Table 3.1. The parameters are the ionizing photons per stellar baryon N_γ , the ionizing efficiency (the number of photons per baryon per dark matter halo) ζ , the fraction of baryons converted to stars f_* , the minimum virial temperature for all sources $T_{vir,min}$, the maximum horizon for ionizing photons R_{max} , the efficiency parameter corresponding to the number of photons per solar mass in stars ζ_X , and the clumping factor on the scale of the simulation cell C . We refer the reader to Mesinger et al. (2010) for detailed information and discussions on the code, relevant parameters, and the formalism.

⁵<https://github.com/andreimesinger/21cmFAST>

Table 3.1.: Summary of parameters used in our run of the 21cmFAST simulation run.

Parameter	
N_γ	4300
ζ	20
f_*	0.05
$T_{vir,min}$	10^4 K
R_{max}	50 Mpc
ζ_X	$10^{56} M_\odot$
C	2

3.3.2 Procedure for simulated observations of the SZE-21cm

This work makes use of only the 21 cm brightness temperature $\delta T_b(\nu)$ cubes from the 21cmFAST simulations. We use equation 3.3 to compute unperturbed CMB intensity cubes ($I_{0,st}(\nu)$), and Rayleigh-Jeans law to calculate it in terms of brightness temperature ($T_{0,st}(\nu)$), and add this signal to each cube of $\delta T_b(\nu)$, which gives us the CMB radiation field modified during the DA and EoR ($T_{0,mod}(\nu)$). To conduct our mock observations of the SZE-21cm we insert a typical rich cluster with a temperature of 10 keV, an optical depth of 10^{-3} , and a radius of 2 Mpc ⁶. The incoming background radiation field ($T_{0,mod}(\nu)$) is scattered by energetic electrons in the cluster, resulting in a modified signal ($T_{mod}(\nu)$) calculated according to equations 3.4 - 3.6.

One of the issues that we will face measuring the SZE-21cm is that the 21 cm background has variations on angular scales comparable to that of the galaxy clusters and their intrinsic level presents a potentially significant contaminant to SZE-21cm observations as the variations may be comparable to the expected signal of the SZE-21cm as computed by Colafrancesco et al. (2016). The variations ($\frac{\Delta T}{T}$) in our cubes are computed to be of orders between 10^{-1} - 10^{-3} . They arise from significant degeneracies between parameters that control the average 21 cm global temperature spectrum, which lead to inhomogeneities (McQuinn et al. 2006), and are greater than the CMB primordial fluctuations that are of the order of 10^{-5} . To quantify the cosmic variance noise that arises from the finite volume of the universe accessible to 21 cm experiments we plot the 21 cm signal (versus frequency) incident on each of the cluster-sized angular regions in the simulations, along with the global average (see Figure 3.2). The

⁶For the cluster region simulated in this work, we use the radius in which the mean over-density of the cluster is 200 times the critical density of the universe, r_{200} . To approximate r_{200} we use the scaling relations from Neumann (2005).

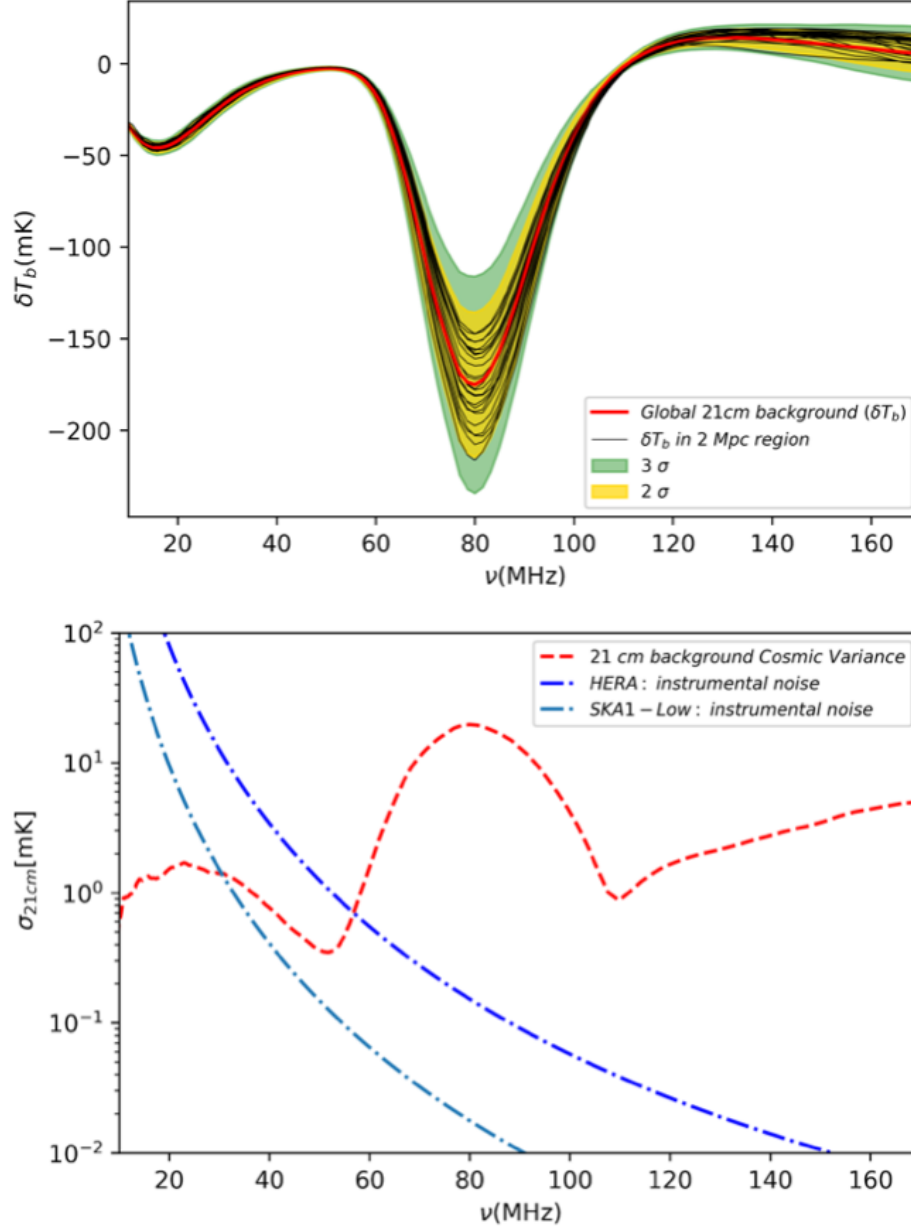


Figure 3.2: **Top:** The mean 21 cm background brightness temperature offset from the CMB spectrum as a function of frequency incident on each of the cluster-sized regions (**Black**), along with the simulation global mean (**Red**). The shaded areas correspond to 2σ and 3σ standard deviations in the cluster-sized regions. **Bottom:** Noise on the 21 cm Global signal as a function of frequency (y-axis in log-scale). The (**Red**)-dashed lines represent the cosmic-variance. For comparison, we also have the instrumental noise for the HERA and SKA1-Low experiments calculated using equation 3.13.

Table 3.2:: Summary of parameters used in this work for HERA and SKA.

	HERA	SKA1-low
Antennae design	350 hexagonally packed dishes	512 stations
Antenna/station diameter (m)	14	35
Collecting area (m^2)	53,878	416,595
A_{eff} (m^2)	153.93	962.11
$T_{sys}(K)(= T_{sky} + T_{rcvr})$	$T_{sky} + 100$	$1.1T_{sky} + 40$

Figure illustrates how the global signal measured over the cluster-sized region can significantly depart from the average signal. Each of the cluster-sized regions provides an estimator for the $\delta T_b(\nu)$, which varies from one to another, showing variance produced to the signal in a finite region. We note that cosmic variance noise increases the error budget resulting in a decrease in the significance of any detection. Hence, by allowing observations of many more samples we will reduce the overall error budget and effects of cosmic variance.

Observations of the SZE at microwave frequencies will aid in distinguishing the SZE-21cm fluctuations from intrinsic degeneracies between parameters that control the mean 21 cm brightness temperature spectrum and CMB fluctuations, and we can use information from these observations as a way to normalise low-frequency signals that will be crucial to establishing signatures related to the 21cm signal. Contamination from point sources is also a major concern and for our mock observations, it is, therefore, useful that we detect and discard point-source contaminated pixels. To do this we apply a threshold approach to avoid contamination in the SZE-21cm computation, identifying possible point sources in these fields above a given threshold and replacing those pixels with the mean background value; this also helps us account for the cube fluctuations. Later in the section 3.5, we will focus on how possible sources of contamination can be handled.

Simulating 21cm instruments

To include realistic 21 cm instrumental effects we follow the methodology of [Hassan et al. \(2018\)](#) that accounts for the finite angular resolution of the instrument, foreground cleaning, and the presence of instrumental noise. This methodology produces mock observations using the 21cmSense⁷ package ([Poher et al. 2013, 2014](#)), which creates realisations of thermal noise taking into account the antenna configuration,

⁷<https://github.com/jpoher/21cmSense>

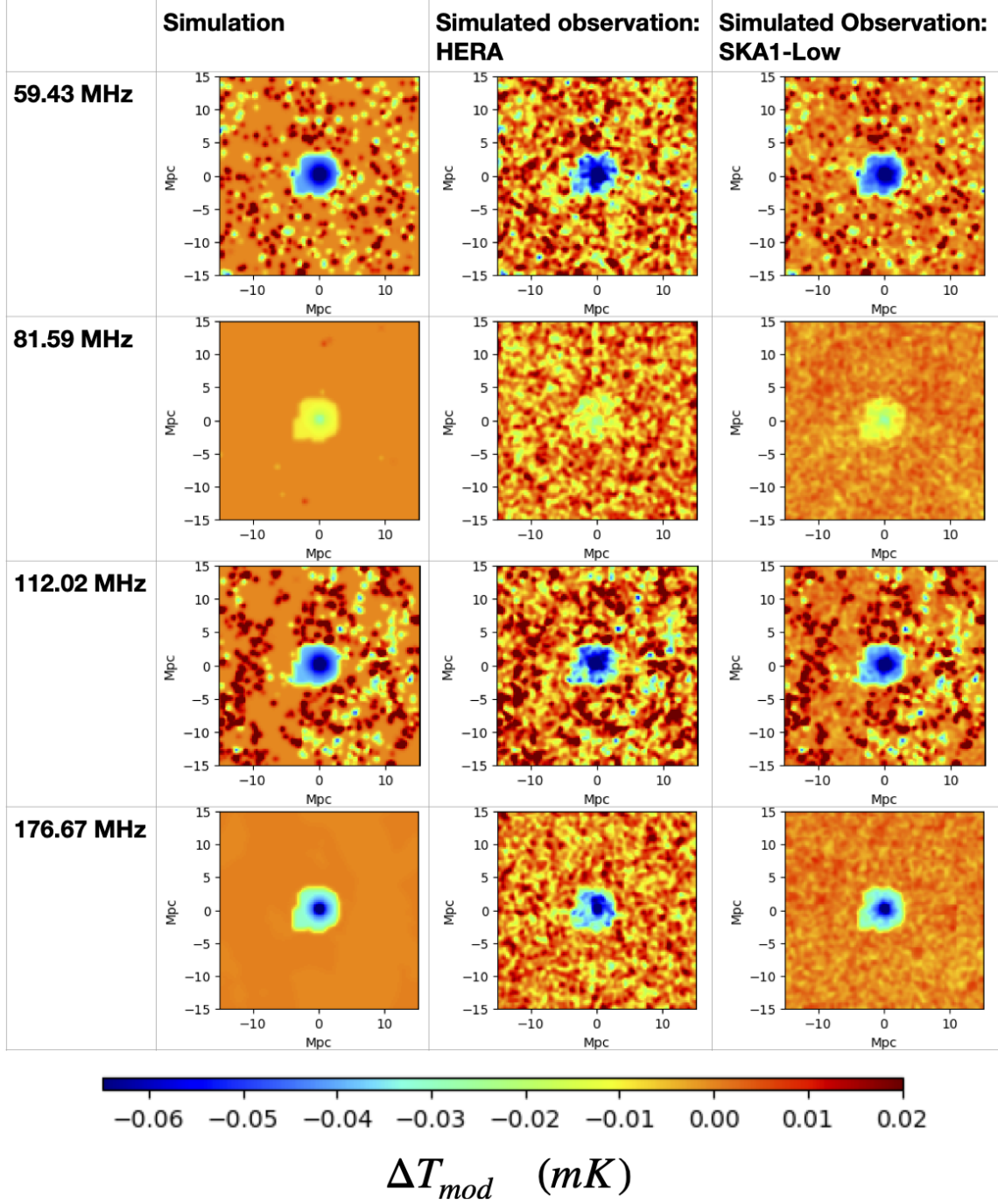


Figure 3.3: Simulated SZE-21cm cluster maps from our mock differential observations at 59.43 MHz, 81.59 MHz, 112.02 MHz, and 176.67 MHz for a cluster with a plasma temperature of 10 keV, a radius of 2 Mpc, and optical depth of 10^{-3} . The maps are shown for simulated differential observations without instrumental effects and simulated observations with HERA and SKA1-Low.

system temperature, and station/dish size to calculate expected sensitivities of 21 cm experiments. For this work, we produce mock observations with HERA and the low-frequency SKA1 (SKA1-low) instruments. The summary of our assumed HERA and SKA array designs are in Table 3.2.

We take a 3D-Fourier transform of each cube, this gives us the magnitude of the cube as a function of wave vector $\mathbf{k}$; k , the magnitude of $\mathbf{k}$ vector, is $k = |\mathbf{k}| = \sqrt{k_{\perp}^2 + k_{\parallel}^2}$, where $k_{\perp}$ is the co-moving component on the plane of the sky and $k_{\parallel}$ is the co-moving component along the line of sight. It is expected that foreground contamination of 21 cm measurements will be spectrally smooth and should only affect the lowest $k_{\parallel}$ modes (Bowman et al. 2009). However, due to the frequency dependence of an interferometer’s response, the contamination will leak into higher k modes through “mode mixing”, which is stronger for long baselines (high values of $k_{\perp}$) that have higher fringe rates. This mode mixing causes the foregrounds to become confined to a wedge-shaped region in the $k_{\perp} - k_{\parallel}$ space (Liu et al. 2009, 2014).

First, we remove the foreground contaminated k modes from the cubes assuming that foregrounds are confined to some regions in Fourier space along the line-of-sight. This confinement is expressed in terms of spatial Fourier wave-numbers for Fourier modes $k_{\perp}$ and $k_{\parallel}$. Foreground contaminants are expected to be mostly in modes that satisfy the following condition:

$$k_{\parallel} < k_{\parallel}^0 \frac{H_0 D_c \theta [\Omega_m (1+z)^3 + \Omega_{\Lambda}]^{\frac{1}{2}}}{c(1+z)} k_{\perp}, \quad (3.7)$$

where D_c is the co-moving line-of-sight distance, θ is the angle between the line of sight and the direction of the Fourier mode $\mathbf{k}$, and $k_{\parallel}^0$ is an offset constant (detailed derivations of this may be found in Liu et al. 2014, 2016). The modes of the signal that are contaminated by foregrounds lie inside a foreground wedge in the $k_{\perp} - k_{\parallel}$ plane. The foreground wedge slope is given by:

$$m = \frac{H_0 D_c [\Omega_m (1+z)^3 + \Omega_{\Lambda}]^{\frac{1}{2}} \sin \theta}{c(1+z)}. \quad (3.8)$$

For our cubes, we zero out all the modes that are inside the wedge to clean the foregrounds. More modes are removed at lower frequencies since m increases with decreasing frequency. To account for the angular resolution we compute the uv-coverage antennae distribution for the HERA and SKA1-Low designs using the 21cmSense package. The uv-coverage gives the total number of baselines that observe a given u-v pixel. The angular direction is given by $k_x = 2\pi k_y$, where the sky along x and y

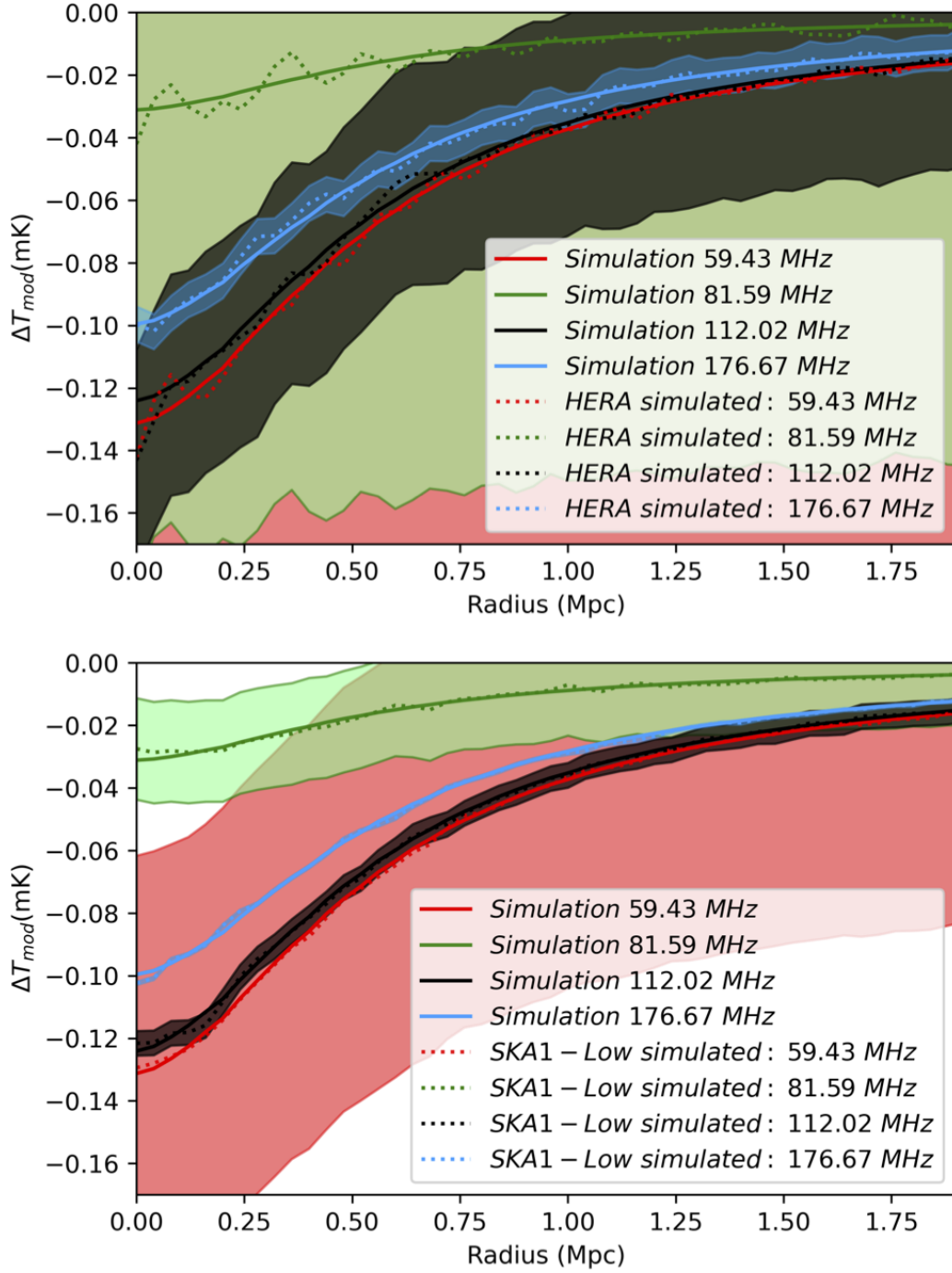


Figure 3.4: The SZE-21cm temperature decrement radial profile from a cluster of radius of 2 Mpc, a core radius (r_c) of 0.248 Mpc and $\beta = \frac{3}{5}$ at 59.43 MHz, 81.59 MHz, 112.02 MHz, and 176.67 MHz. **Top:** simulation without instrumental effects and simulated observations with HERA. **Bottom:** simulation without instrumental effects and simulated observations with SKA1-Low. The shaded errors regions assume observations with HERA (**Top**) and SKA1-Low (**Bottom**).

coordinates can be converted in terms of baseline length in u and v coordinates. We compute the u - v coverage for HERA and SKA1-Low from the antenna distribution and convert the uv coordinates into corresponding k_x and k_y modes. We then obtain a Fourier transform of $T_{mod}(\nu)$ and $T_{0,mod}(\nu)$ maps, and zero out the Fourier modes that correspond to null u - v coverage at k_x and k_y . We smooth down the maps using a Gaussian filter with a full width half maximum of $\text{FWHM} = \frac{21\text{cm}(1+z)}{B}$, where B is the maximum baseline length for HERA and SKA1-Low. Thereafter, we obtain the angular resolution limited $T_{mod}(\nu)$ and $T_{0,mod}(\nu)$ maps and we inverse Fourier transform back to real space. We simulate a noise map whose pixel values are obtained from a Gaussian distribution with a zero mean and standard deviation that is set to thermal noise for HERA and SKA1-Low (see, [Zaldarriaga et al. 2004](#); [Hassan et al. 2018](#)):

$$\sqrt{\langle |N|^2 \rangle} [Jy] = \frac{2k_B T_{sys}}{A_{eff} \sqrt{\Delta\nu t_{int}}}, \quad (3.9)$$

where A_{eff} is the effective area of a single antenna, $\Delta\nu$ is the frequency resolution, t_{int} is the integration time, and $T_{sys} = T_{sky} + T_{rcvr}$ is the system temperature, where T_{rcvr} is the receiver temperature and the sky temperature is, $T_{sky} = 120 \left(\frac{\nu}{150}\right)^{-2.55} \text{K}$, see Table 3.2. Our simulated experiments assume $t_{int} = 1000$ hours, and $\Delta\nu = 97.8$ kHz for HERA and $\Delta\nu = 50$ kHz for SKA⁸. The noise is suppressed by our u - v coverage (N_{uv}) by a factor of $\frac{1}{\sqrt{N_{uv}}}$, we inverse Fourier transform the noise map to real space. This is then added to our foreground and angular resolution corrected $T_{mod}(\nu)$ and $T_{0,mod}(\nu)$ maps.

Mock differential observation

We perform mock observations in the direction of the cluster $T_{mod}(\nu)$ and compare this with an empty sky region located away from the cluster region $T_{0,mod}(\nu)$ to obtain SZE-21cm maps with HERA and SKA1-Low. The empty sky region away from the cluster has the same size as the region of the cluster to allow for pixel-by-pixel operations. The differential observation that gives us the SZE-21cm as in equation 3.6 can be written as:

$$\Delta T_{SZE-21cm} = T_{ON} - T_{OFF}, \quad (3.10)$$

⁸The total simultaneously processed bandwidth in this work is 100 MHz for HERA ([DeBoer et al. 2017](#)) and 300 MHz for SKA1-low ([Labate et al. 2017](#))

where T_{ON} is the value obtained when observing the cluster signal (hereafter titled signal ON), from which we subtract the background (empty sky), T_{OFF} (hereafter titled signal OFF). To account for correlation and position-dependent offsets, we use two background regions and let $T_{OFF} = \frac{T_{OFF1} + T_{OFF2}}{2}$. We perform the differential observation as set out by equation 3.10, which gives us the SZE-21cm at the cluster as $\Delta T_{mod} = \Delta T_{SZE-21cm}$, which is the modification of the initial background signal. Assuming that the mock cluster's gas is isothermal, we use the isothermal β -model to model its density profile (see e.g., [Cavaliere & Fusco-Femiano 1976](#)), which varies as a function of cluster radius, r :

$$n_e(r) = n_{e,0} \left(1 + \frac{r^2}{r_c^2} \right)^{-\frac{3}{2}\beta}, \quad (3.11)$$

where $n_{e,0}$ is the electron number density at the center of the spherical symmetric cluster gas distribution; β is the power-law index and r_c is the core radius. This electron density distribution leads to the following analytic form of SZE-21cm brightness temperature profile:

$$\Delta T_{mod}(\nu) = \Delta T_{mod,0} \left(1 + \frac{r^2}{r_c^2} \right)^{\frac{1}{2} - \frac{3}{2}\beta}, \quad (3.12)$$

$\Delta T_{mod,0}$ is the central temperature decrement. We model the SZE-21cm brightness temperature, ΔT_{mod} , at the cluster using the model in equation 3.12, with $\beta = \frac{3}{5}$ and $r_c = 0.248$ Mpc for a typical rich cluster.

We generate cluster maps and measure the SZE-21cm at the cluster, and use the measured signal to construct the SZE-21cm spectrum. The simulated maps are shown in Figure 3.3 and the cluster radial profiles are in Figure 3.4. The mock observations are made in the frequency range between 30 and 160 MHz, but here we only show the simulated maps and cluster radial profiles at 59.43 MHz, 81.59 MHz, 112.02 MHz, and 176.67 MHz as these are the frequencies where we can see the strongest decrements or increments in the SZE-21cm signal. The SZE-21cm spectrum is shown in Figure 3.5 and is discussed at length in section 3.3.3.

3.3.3 Discussion: HERA and SKA simulated observations of the SZE-21cm for the theoretical model

According to [Cooray \(2006\)](#) and [Colafrancesco et al. \(2016\)](#), detailed measurement of the SZE-21cm will allow us to derive precise information on the epochs at which the

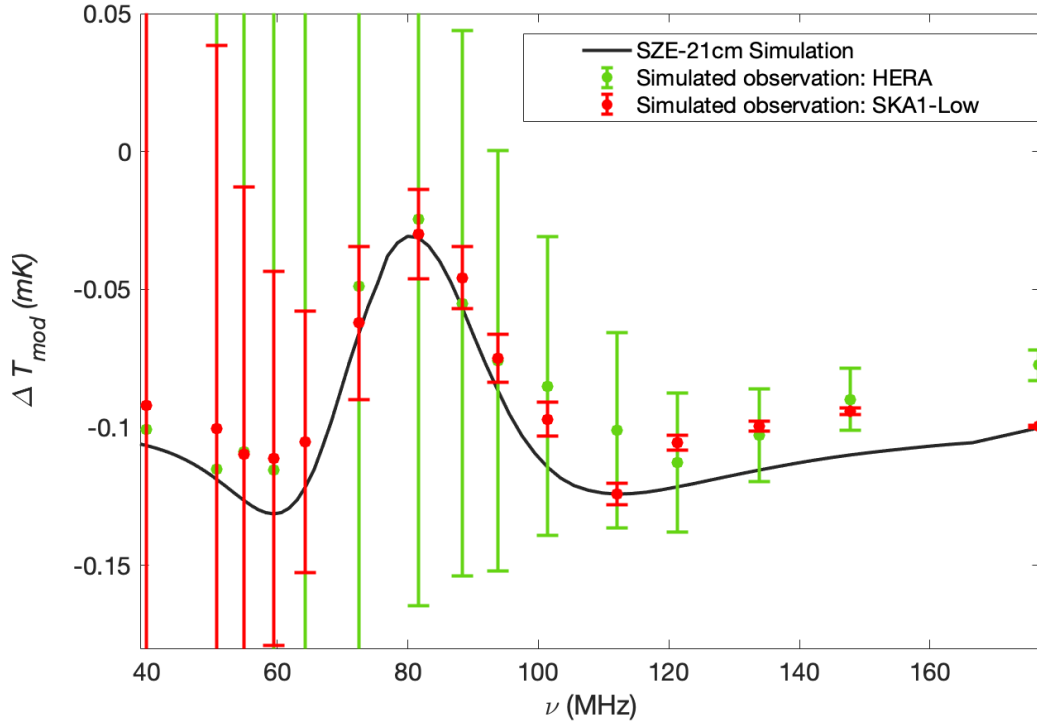


Figure 3.5: The SZE-21cm spectrum from our mock differential observations of a galaxy cluster with a plasma temperature 10 keV and $\tau = 10^{-3}$. The **Black** solid line is the theoretically expected value calculated for our simulated cluster. The **Green** points and error bars are from the SZE-21cm measurement of the simulated observations for HERA, and the **Red** points and error bars are from the SZE-21cm measurement of the simulated observations for SKA1-Low.

CMB was modified (i.e., DA and EoR) and on the physical mechanisms that imprint distinct features on the global 21 cm background (δT_b) that are present in the SZE-21cm spectrum. Figure 3.3 in the work presented here shows images resulting from the simulated differential observations of a galaxy cluster at different frequencies, and Figure 3.5 gives us the SZE-21cm measured at the cluster without instrumental effects and also taking into account the effects of foregrounds, thermal noise, and angular resolution observing with HERA and SKA1-Low, which gives us a good idea of the impact that instrumental effects have on the differential observations. For our simulated observations using a low-frequency radio interferometer, we employ a simple strategy to provide order of magnitude approximations to the noise errors at the frequencies of relevance. The system temperature (T_{sys}) for HERA and SKA1-Low can be found in Table 3.2. The instrumental noise on the brightness temperature, ΔT^N , measured by an interferometer is given by [Furlanetto \(2006a\)](#)

$$\Delta T^N = \frac{T_{sys}}{\eta_f \sqrt{\Delta \nu t_{int}}}. \quad (3.13)$$

The array filling factor is given by $\eta_f = A_{eff}/D_{max}^2$, where D_{max} and A_{eff} are the maximum baseline and total effective area of the array respectively.

We realise that the SZE-21cm spectrum almost resembles an inverted δT_b spectrum. As the SZE-21cm changes as a function of frequency, its features correspond to some changes in the δT_b spectrum. For example, the minimum point of the input spectrum at approximately 80 MHz, Figure 3.1, corresponds to the maximum point of the SZE-21cm spectrum, Figure 3.5. The spectrum shows absorption of the SZE-21cm between 40-60 MHz, as a result, we observe a decrement in the SZE-21cm map at 59.43 MHz, this followed by emission in the SZE-21cm spectrum between 60-90 MHz and as a result, we observe an increment on the SZE-21cm map at 81.59 MHz. Between 80-110 MHz there is absorption in the SZE-21cm spectrum and as a result, we observe another decrement at 112.02 MHz. At $\nu > 110$ MHz the SZE-21cm spectrum starts to pick-up and this is evident in the SZE-21cm map at 176.67 MHz. Notably, we have a deviation between the simulated observation and the true signal at high frequencies in Figure 3.5, and the deviation is more substantial for SKA1-Low than for HERA, contrary to expectations, and it is not clear what produced this effect.

The cluster is easily identifiable in all the simulated maps thanks to the angular resolution of our simulated HERA and SKA1-Low designs and the uv-coverage that extends small scales at the frequencies of interest. The noise for SKA1-Low is less as compared to HERA and the lower angular resolution for HERA makes it slightly more challenging to resolve the cluster. Figure 3.4 also shows that we can recover the cluster radial profile with both HERA and SKA as the simulated observation results with instrumental effects are compatible with the model. At higher frequencies, SKA1-Low will be able to produce good results, however, at low frequencies, the errors are larger. SKA1-Low may be an ideal instrument to conduct studies of the SZE-21cm as compared to HERA, which promises to be instrumental in making the first detections of the effect as it will come online ahead of SKA1-Low. Minimising the errors when observing with HERA will require significant amount of integration time, this work simulate the observations assuming 1000 hours with both instruments.

The SZE-21cm from multiple clusters

The SZE-21cm, which is our quantity of interest, is a faint signal and the best way to deal with such a signal would be to average it over as many clusters as possible.

We demonstrate the feasibility of reducing the error budget that arises due to instrumental effects by averaging the SZE-21cm observed towards multiple galaxy clusters with the low-frequency SKA telescope, we estimate the expected error for cluster observations of the SZE-21cm by scaling and combining observations towards multiple clusters to improve the signal-to-noise which is given by equation 3.13. The expected errors in Figure 3.6 are determined assuming observations towards one cluster and the improvement by computing the average over signals towards ten and then one hundred clusters. To give a sense of the impact this may have on reducing the error budget, we assume an improvement in ΔT with $\sqrt{N_{cl}}$ of the number of clusters (N_{cl}) used (Cooray 2006; Clanton et al. 124). In each of the clusters, the SZE-21cm signal is present, thereby adding to it its contribution. Whereas, noise is random and therefore does not add but begins to cancel as the number of clusters we average increases. For this reason, we can expect that the signal-to-noise improvement obtained by averaging the SZE-21cm from multiple galaxy clusters to be proportional to the square root of the number of clusters averaged. Measuring the SZE-21cm observed towards multiple galaxy clusters and obtaining an average as described here will also be beneficial to reduce the uncertainty that arises due to cosmic variance on the 21 cm background signal incident on each of the cluster-sized angular regions in the simulations, see Figure 3.2, which we begin to suppress stacking up to a few hundred clusters.

The SZE-21cm computation requires prior knowledge of the cluster’s electron temperature and optical depth profile, which can be obtained from observations of the SZE related to the CMB spectrum alone at much higher radio and microwave frequencies, possible with the Planck telescope (see e.g., Hansen et al. 2002). Colafrancesco et al. (2016) pointed out that the SZE-21cm as a function of frequency is dependent on the temperature of the intracluster plasma, mathematically this can be written in terms of the Compton parameter as $y \propto k_B T \cdot \tau$. We propose two solutions to overcome the challenge that arises from the SZE-21cm varying for clusters with different plasma temperatures. To average the SZE-21cm of clusters with different plasma temperatures, we can study and measure the Compton y parameter at higher frequencies and factor it in our computations, alternatively we can average the SZE-21cm for clusters with the same plasma temperatures only. In this regard, we expect the low-frequency SKA array to have large fields-of-view of approximately 2.5 – 10 degree from 200 MHz down to 50 MHz (Mellema et al. 2013), which will enable us to identify large cluster samples to study the SZE-21cm by selecting the ones having similar plasma temperatures as can be derived from X-ray observations. Detecting a larger number of sources will also strengthen the statistical studies of the DA and EoR and the cosmological radio backgrounds.

To better derive information on the SZE-21cm produced by low redshift galaxy clus-

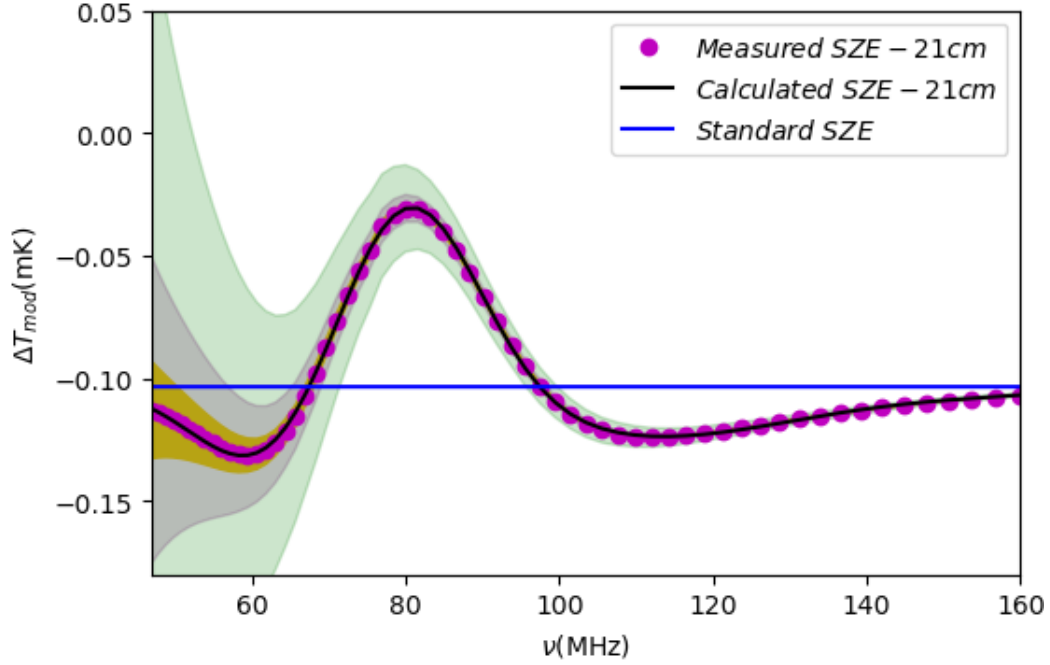


Figure 3.6: The SZE-21cm spectrum from our mock differential observations of a galaxy cluster with a plasma temperature 10 keV and $\tau = 10^{-3}$. The shaded errors regions assume observations with an interferometer similar to SKA. The **Green** error region is for differential observations towards a single cluster, **Grey** area towards 10, and the **Gold** area towards 100 clusters (see e.g., Cooray 2006). The **Black** solid line is the best-fit to theoretically calculated data points, the **Magenta** dots are points measured from our simulated mock observations and the **Blue** solid line is the standard SZE (ΔT_{st}) for comparison.

ters, multi-frequency measurements of the SZE at X-ray and microwave bands are highly desirable for the extraction of additional information from its spectral shape, and for separating the signal from the various sources of contamination and confusion. Such multi-frequency measurements will also be useful in finding suitable cluster candidates for low-frequency studies based on the strength of the SZE signal at high-frequencies and will be instrumental in estimating the profile of the optical depth and the temperature of the cluster gas, which must be known when computing the SZE-21cm.

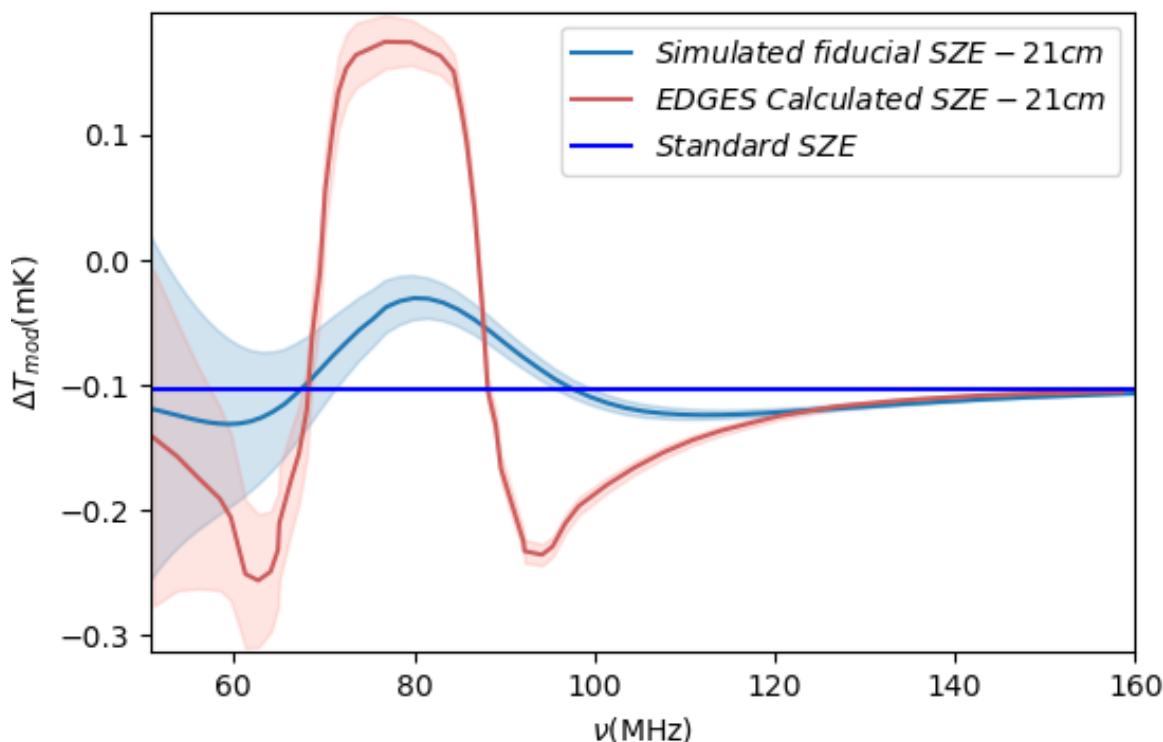


Figure 3.7: The SZE-21cm computed for the simulated fiducial 21 cm background model from Figure 3.1 (*Blue*) compared to the SZE-21cm computed using the 21cm background spectrum detection claimed by the EDGES experiment (*Red*). The shaded errors regions assume observations with an interferometer similar to SKA for differential observations towards a single cluster. The SZE-21cm spectrum computed from the EDGES input spectrum is only reliable between 70-90 MHz due to the edge effects of the frequency range of the input spectrum. For both cases, we assume a cluster with a plasma temperature of 10 keV and an optical depth of $\tau = 10^{-3}$.

3.4 The SZE-21cm in the EDGES era

In this section, we compare our results for the SZE-21cm obtained using the fiducial 21 cm background model in section 3.3 to the results we calculate using the 21 cm background spectrum claimed by the EDGES experiment (Bowman et al. 2018). To calculate the SZE-21cm with the input spectrum being the 21 cm background signal claimed by the EDGES collaboration we used the formalism in section 3.2.2. We show the spectra in Figure 3.7. We note that the SZE-21cm spectrum computed from the EDGES input spectrum is accurate only in the frequency range (70-90 MHz) due to the edge effects of the frequency range.

The EDGES 21 cm background spectrum in Figure 3.1 implies that gas temperatures during DA and EoR were cooler by orders of 2 to 3 as compared to predictions by any

prior models. The peak of the SZE-21cm for the EDGES detected background signal and the troughs of the SZE-21cm are also amplified by orders 2 to 3 compared to the theoretical model. Figure 3.7 therefore, demonstrates that the SZE-21cm spectrum can be used to establish the amplitude of the input background spectrum and features that probe the corresponding epochs.

In Figure 3.8 we plot the low-frequency SKA telescope sensitivity compared to the standard SZE and the SZE-21cm. We note that the EDGES background is reliable only in the band 70-90 MHz. We list our findings below:

- With SKA1-low-50% the SZE-21cm can be detected for the fiducial model at $\nu \gtrsim 90$ MHz and the EDGES-like background at $\nu \gtrsim 75$ MHz. Good frequency channels to distinguish between the standard SZE and the SZE-21cm signals are 110 - 140 MHz for the fiducial model and 90 - 130 MHz for an EDGES-like background spectrum.
- With SKA1-low the SZE-21cm can be detected for the fiducial model at $\nu \gtrsim 70$ MHz and the EDGES-like background at $\nu \gtrsim 60$ MHz. Good frequency channels to distinguish between the standard SZE and the SZE-21cm signals is $\nu \gtrsim 75$ MHz for the fiducial model and $\nu \gtrsim 70$ MHz for an EDGES-like background spectrum.
- With SKA2 the SZE-21cm can be detected for both the fiducial model and EDGES-like background at $\nu \gtrsim 50$ MHz. Good frequency channels to distinguish between the standard SZE and the SZE-21cm signals is $\nu \gtrsim 70$ MHz for the fiducial model and $\nu \gtrsim 55$ MHz for an EDGES-like background spectrum.

To match the unexpectedly large extent of the SZE-21cm computed using the EDGES signal without recourse to any form of new physics we may need to change the conditions for the source of the background radiation in our simulated models. Apart from concerns raised on the foreground model and systematics, the EDGES detection has been discussed extensively and potential explanations consider new physics, radio background in excess of the CMB at redshifts related to the DA and EoR, interaction between baryons and dark-matter particles (Barkana 2018), and new modes of star formation such as metal-free Pop III stars (see e.g., Mebane et al. 2019). While this detection has yet to be confirmed by other techniques and experiments, it exhibits features that are inconsistent with existing theoretical predictions. Independent experiments and methods are needed to verify this EDGES result, therefore, we propose measuring the SZE-21cm with upcoming instruments like the SKA as this method probes the features of the input 21 cm background spectrum.

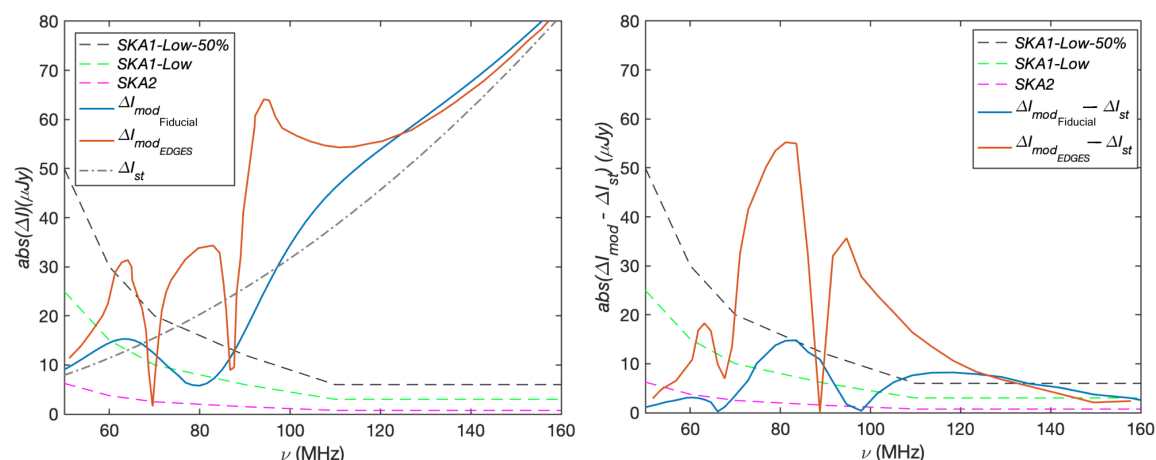


Figure 3.8: Right: The spectra of the SZE-21cm ΔI_{mod} . The **blue** solid line represents the SZE-21cm for our simulated fiducial 21 cm background model and the **Red** line for a 21 cm background spectrum similar to the EDGES detection. The **Grey** dotted and dashed line represents the SZE for a non-modified CMB ΔI_{st} . **Left:** The absolute value of the difference between the SZE-21cm and the standard SZE. The **Blue** solid line for our simulated fiducial model and the **Red** line for the SZE-21cm calculated from the spectrum similar to the EDGES detection. For both figures, we compared with the SKA1-low-50% (**Black**), SKA1-low (**Green**), and SKA2 (**Magenta**) sensitivities for 100 kHz bandwidth, 1000 hrs of integration, 2 polarizations, no taper, and no weight.

3.5 Challenges for observations of the SZE-21cm

Work by Cooray (2006) and Colafrancesco et al. (2016) showed that contamination from background and foreground emissions on scales larger than a typical galaxy cluster has less impact on differential observational measures of the SZE-21cm. However, radio point sources have historically been the main source of contamination in the SZE measurements (Carlstrom et al. 2002), and synchrotron radio emissions from the host galaxy cluster can also lead to contamination at frequencies relevant to the DA and EoR studies. The measurements of the SZE-21cm can be contaminated by the emission of point sources along the sightline to the galaxy cluster, which could contribute to the underestimation or overestimation of the SZE signal. A strategy that could be used to remove point sources is to identify possible point sources in radio catalogs and follow up with pointed observations at high angular resolution. The point source removed should be much smaller than the extent of the SZE signal for the amount of the removed SZE-21cm flux to be negligible; this will be achievable with the SKA telescope, which should be capable of making high angular resolution

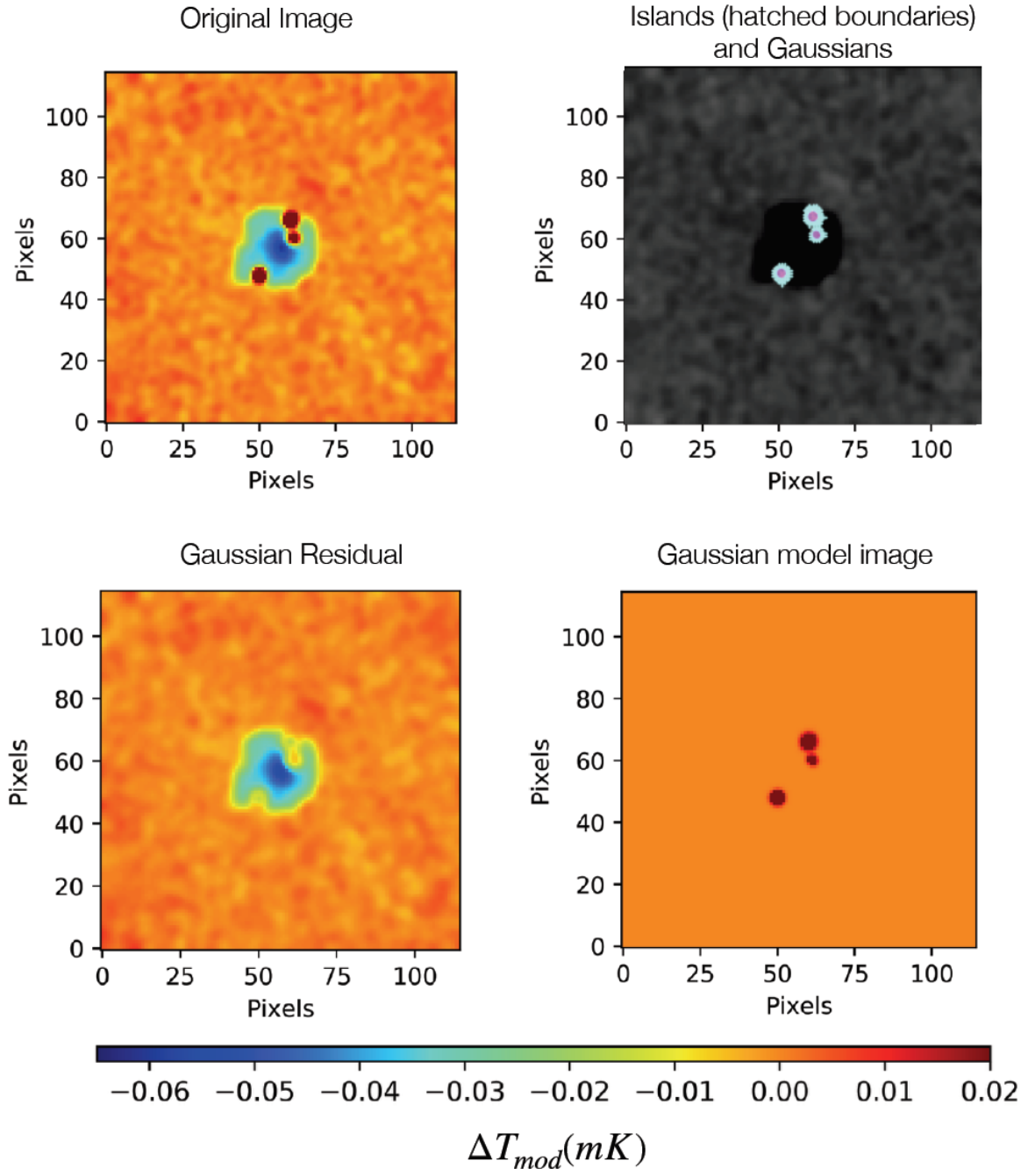


Figure 3.9: Simulated SZE-21cm cluster maps at 176.67 MHz: with point sources in the original image, the model image, and the residual which is original minus model image. Boundaries of the regions/island of emission found by code are shown in light blue and the fitted Gaussians the shaded areas shown for each region as small ellipses.

measurements (< 0.1 arcsecond).

Radio point sources are abundant in galaxy clusters, which leads to a significant fraction of the SZE signal being affected by the contamination as discussed above. Two modes can lead to the dilution of the SZE: point sources that are not removed can fill the SZE signal, and the removal of the point sources can result in removal of the SZE signal (Cooray et al. 1998; Birkinshaw 1999). Experiments to measure the SZE only needs to remove about two bright point sources to be confident that the measurement is not contaminated by radio emission from galaxy cluster members (Holder 2002). We simulated an observation towards a galaxy cluster at $z = 0.1$ with point sources assuming the typical spectral index is about $\alpha = -0.7$, where $S(Jy) \propto \nu^\alpha$ at 176.67 MHz with radio flux ranging from 30 to 290 mJy (see e.g., George et al. 2017), which is of the order of magnitude of some of brightest galaxies in clusters at frequencies relevant to this work. We make use of a code designed to decompose radio interferometry images into sources called PyBDSF (the Python Blob Detector and Source Finder, formerly PyBDSM) (N & Rafferty 2015). The code reads in the input image, calculates background rms and mean images, finds regions of emission, fits Gaussians to the regions, and groups them into sources. We left the PyBDSF parameters at their default values during this source extraction. We obtain a percentage error of 6% for the SZE-21cm simulated for observation with the SKA1-low beam after point source subtraction compared to the SZE-21cm computed at the same frequency in Section 3.3. The presence of the point source and the subtraction thus has an impact on the SZE-21cm signal that we measure. The point source subtraction removes flux within the point source subtraction beam area from the cluster map at the position of the point source. Figure 3.9 illustrates the simulated point source and subtraction described here.

Another possible issue is due to the presence of diffuse emission in the radio band (Radio halos, mini-halo and relics) that have been detected and studied in galaxy clusters (see review, Feretti et al. 2012). This may be one order of magnitude higher at frequencies relevant to observations of the SZE-21cm. It is also worth noting that contamination due to synchrotron emission in the cluster decreases for objects at large distances, since radio synchrotron emission changes with luminosity distance, whereas the SZE does not change as a function of redshift and distance of the source (see., Colafrancesco et al. 2016). By using this property, Multi-frequency and spatially resolved analysis with upcoming interferometers will allow us to reduce the importance of intrinsic radio emission from the clusters. It is important, however, that we study and analyse both contributions to distinguish and separate them.

3.6 Conclusions

Further simulations and observations are necessary to pinpoint the best strategy for observing and measuring the SZE-21cm to probe the DA and EoR, which will require very deep, thorough observations and highly accurate theoretical analysis. The detection of the SZE-21cm with the upcoming HERA and SKA instruments has the potential to yield insightful information on the history and physical mechanisms occurring during the DA and the subsequent EoR as they are sensitive. The SKA will particularly play a large role in the study of cosmological radio backgrounds by providing SZE data with high accuracy. Cosmic variance and instrumental noise have potential to contaminate and decrease chances for a clean detection of the SZE-21cm signal. Averaging the signal from a number of clusters has been demonstrated as a method to suppress the noise and deal with the challenges we may face observing towards a individual cluster. To identify ideal clusters and obtain cluster plasma temperatures, X-ray measurements of the ICM properties will be of great importance and will form a crucial part of our observational strategy for studies of the SZE-21cm, particularly clusters that are in the Southern hemisphere, where HERA and the SKA will observe. In this regard, the next step would be to identify clusters in Microwave source catalogs from the SPT, Planck and, ACT. Furthermore, we have shown that point source removal is crucial to address the issue of contamination that may fill the SZE-21cm signal. We also noted a deviation between the true signal and simulated observation with HERA and SKA at high frequencies, which is particularly contrary to expectations for observations with SKA-low. The source of this deviation needs to be investigated and adequately addressed. This work has shown that HERA and Low-frequency SKA will be able to obtain maps of the SZE-21cm. The outcomes from our simulations and calculations make us optimistic that the SKA telescope will detect the SZE-21cm spectrum and will be instrumental in following-up on the EDGES result.

Acknowledgments

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Chapter 4

The impact of cosmological 21cm background models on the SZE-21cm

Abstract

The exact shape and amplitude of the global 21 cm background signal and fluctuations are still highly uncertain, and in this Chapter, we investigate the impact of cosmological 21 cm background models on the SZE-21cm. The models we consider are for cosmologies with Warm Dark Matter, Population II and Population III stellar heating in the early Universe, and excess cooling of the IGM at very high redshift. We find that the SZE-21cm obtained through simulated differential observations is dependent on global 21 cm signal models that we use and that the SZE-21cm can be used to extract the distinct features imprinted on the cosmological signal during DA and EoR by physical processes described in these models. Moreover, when inferring the global signal using the differential observations of the SZE-21cm we will also be able to rule out any inconsistent model, allowing the SZE-21cm to probe the formation and nature of the first sources.

4.1 Introduction

In the previous Chapters, we have already established that the cosmological 21 cm signal arises from the radiation effects produced by the first generation of sources in

the Universe, including stars, accreting black holes, and galaxies. The evolution of the global signal, δT_b , given by equation 2.15, is driven by a number of important physical processes. These include (1) Ultra-Violet (UV) radiation from the first sources; (2) X-ray heating, as a result of gas accreting into primordial black holes; and (3) ionizing photons from the first galaxies (see, [Wouthuysen 1952](#); [Fields et al. 1998](#); [Madau et al. 1997](#); [Shaver et al. 1999](#)). It is worth mentioning that the first generation stars to form in the Universe are different compared to stars we observe today, as no prior generation of stars had existed to enrich the IGM with heavy elements ([Mirocha et al. 2018](#)). Since our knowledge of the first sources is very limited, it is not possible to make robust predictions for the global 21 cm background. Instead, over the years there have been efforts to study how relevant processes that affect the mean signal, which can give us some insight on these first sources.

In section 2.3, we briefly discussed the hierarchical structure formation under the Λ CDM model, which gives us a good picture of the Universe at large scales within a range ~ 10 Mpc - 1 Gpc. However, some concerns have been raised relating to this model at sub-Mpc scales on whether it provides an adequate fit to data on these scales as simulations using this model have yielded results that are inconsistent with observations of our galaxy and its satellites (see, [Klypin et al. 1999](#); [Moore et al. 1999](#); [de Blok et al. 2001](#); [Boylan-Kolchin et al. 2011, 2012](#)). To account for this change in properties, Warm Dark Matter (WDM) models instead of CDM have been considered to alleviate the issues at small scales as a result of dark matter with higher velocities (see, [Sitwell et al. 2014](#)).

The first generation of metal-free stars, known as Population III stars are thought to form since around $z = 40 - 20$ inside dark matter mini-haloes of mass around $10^6 M_\odot$. The high Jeans mass of metal-free gas suggests a top-heavy or bimodal initial mass function (IMF), which is different from that of their successors, namely Population II and Population I stars that form in metal-enriched gas, where the Jeans mass is lower (see, [Bromm et al. 1999](#); [Abel et al. 2000](#); [Yoshida et al. 2003](#)). The feedback mechanisms in the first stars may have been more intense, leading to the release of great amounts of ionizing radiation ([Tumlinson & Shull 2000](#)). Population II stars are the second generation of stars created through the metallicity increasing cycles of the Universe, where each generation is more metal-rich and with evolving nucleosynthetic properties ([Corazza 2017](#)). Population I are young stars with high metallicity and form as a result of several generations of low metallicity Population II supernovae. Since the first star-forming halos were very small and consisted only of pristine gas, it is possible that Population III stars are massive, of the order of hundreds of solar masses, and formed in isolation ([Wise & Abel 2007](#)), emitting copious amounts of ionizing UV radiation. These Population III stars played a vital role in the evolution of

early galaxies as they introduced the first heavy elements required for more traditional star formation (Population II) into the universe by the Supernova explosions, thereby adding metals to gas, which increased the number of atomic and molecular transitions and increased its ability to cool. It is currently unclear when this transition from stars of Population III to stars of Population II happened and how prolonged it was over time. However, while the majority of star formation has transitioned to Population II, it is plausible that the formation of Population III has continued even to $z \sim 6$ in pristine gas pockets, before being ultimately shut off by cosmic reionization (Muratov et al. 2013). At present ($z = 0$), Population I and Population II stars populate our Universe (Baade 1944).

A Population III cluster (with 100-260 $M_{\odot}$ Salpeter IMF) produces more hydrogen-ionizing photons by order of magnitude than a Population II cluster (with 0.1-100 $M_{\odot}$ Salpeter IMF) with the same mass (Schaerer 2002). In this regard, Population II could have played a role in the reionization of the Universe and if they were responsible for the reionization process they would need to supply at least an order of magnitude more number of ionizing photons per baryon than Population II stars we observe today (Sokasian et al. 2003; Wyithe et al. 2005; Bromm et al. 2009). Hence, to reconcile this, Population III reionization models have been studied and have been an area of great interest for a number of decades (see, Furlanetto 2006a; Mirocha et al. 2018). These stars have been shown to modify the intensity of the 21 cm signal through the Wouthuysen field effect (discussed in section 2.4), that couples the neutral hydrogen hyperfine structure levels to the gas temperature (see, Bromm 2013). Despite having advanced simulations of Population III stars, there is a lack of understanding of their formation over an extensive range of physical conditions and redshift range as there are no observations. The UV photons from either Population II or Population III stars ionize the IGM and bubbles of high temperature ionized hydrogen form around the sources and as they grow they eventually overlap until they ionize larger parts of the Universe (Thomas & Zaroubi 2010). The Population III star population declines as Population II increases and supernovae gradually enrich the IGM with metals. Population I stars are too young to have even contributed to reionization.

Complementary to efforts to understand stellar systems and the nature of dark matter during the DA and EoR are radio interferometric experiments designed to detect the redshifted cosmological 21 cm radiation. These should enable us to study how primordial star formation significantly changed conditions in the early Universe, during the first billion years.

The various models that study different stellar populations and forms of dark matter show that the processes introduced by these models will leave an imprint on the 21 cm global signal. As a proposed indirect probe for the global 21 cm signal, we expect to observe the imprints of these physical processes on the SZE-21cm spectrum as well.

This Chapter aims to compute the SZE-21cm for different cosmologies and to identify those properties from the global 21 cm background that become imprinted on the SZE-21cm spectrum. We incorporate a selection of theoretical models of possible signals from different classes, which differ by the generation of stars whose contribution governs the signal behaviour (particularly Population II and Population III stars), we also look at the effects of WDM, and added cooling channels that can result in global signal with an amplitude similar to the EDGES detection.

This Chapter is structured as follows. In section 4.2 we present the simulations of the global signal with 21cmFAST for models considering WDM, and Population II and III stellar population, we look at how these models affect the global 21 cm signal and thereafter present our expectations on how these models impact the SZE-21cm from our simulated differential observations and discuss the implications. Section 4.3 presents a comparison of the SZE-21cm for the EDGES detection (Bowman et al. 2018) and a model that considers added cooling of the IGM as an attempt to account for the signal reported by the EDGES collaboration. We present our conclusions for this Chapter in section 4.4.

4.2 The global 21 cm signal considering Warm Dark Matter, Population II and Population III star cosmologies

In Figure 4.1 we have the global 21 cm brightness temperature from the best-fitting profile model from recent EDGES results (Bowman et al. 2018), and deviations from standard 21 cm Λ CDM cosmology models for phenomenological models that include effects of warm dark matter (WDM), Population III stars, and a model with added cooling to the primordial neutral hydrogen. This section focuses on a fiducial standard 21 cm CDM cosmology model with Population II stars dominating and responsible for early heating in the Universe, a CDM model with Population III stars dominating and responsible for early heating in the Universe, and a model with WDM with Population II stars dominating responsible for early heating.

To simulate the effects of a WDM model, Population II and Population III stars on the global 21 cm signal we made use of the publicly available 21cmFAST semi-numerical code (Mesinger et al. 2010), which is an efficient tool for modelling the early universe and is essential for us to make sense of upcoming observations. As in the previous Chapter, the simulation cube in our runs is 30 Mpc on a side down-sampled from the high-resolution initial conditions generated on a 460^3 grid and computed

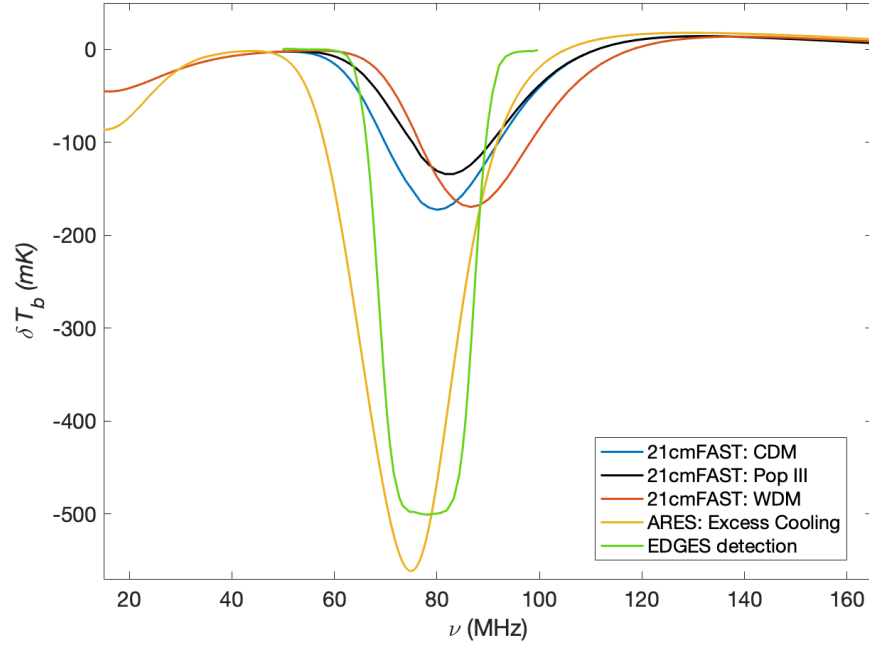


Figure 4.1: Global 21 cm brightness temperature offset from the CMB spectrum as a function of frequency: **Gold** - Signal with added cooling simulated using the Accelerated Reionization Era Simulations (ARES), in section 4.3. **Green** - The best-fitting 21 cm profile model derived from the EDGES observations (Bowman et al. 2018). **Blue** - Simulated fiducial CDM model with Population II stars responsible for early heating. **Red** - WDM model with $m_\chi = 3$ keV and Population II stars responsible for early heating. **Black** - Simulated CDM model with Population III stars (Pop III) responsible for early heating.

on a 115^3 grid corresponding to a cell resolution of 0.26 Mpc, in the redshift range $z = 138 - 7$ (corresponding to frequency range 10 – 176 MHz). We compute mean 21 cm brightness temperature $\delta T_b(\nu)$ from our cubes simulated using 21cmFAST, this is presented in Figure 4.1 as a function of frequency.

4.2.1 21cmFAST: Cases considering Warm Dark Matter, Population II and Population III stars

Considering stellar population responsible for early heating we simulated the cases for Population II and Population III stars. For the WDM case we assume a dark matter particle mass of $m_\chi = 3$ keV as it is within the detection limits of current radio interferometers, future experiments should be able to measure the difference for other relevant WDM models (see, Sitwell et al. 2014).

Below we compare the fiducial CDM 21 cm global signal where the star formation rate (SFR) is dominated by Population II stars with a CDM 21 cm global signal where the SFR is dominated by Population III stars, and also compare WDM 21 cm global signal with that in fiducial CDM model:

- **Case considering Population II and Population III stars:** The option between Population II and much more massive Population III stellar populations has an impact on the ratio of Ly α photons to ionizing photons and moves the initiation of Ly α coupling relative to reionization (Furlanetto 2006b). If the early Universe is dominated by Population II stars, the global 21 cm signal has a strong absorption epoch, which is followed by emission that is weaker and begins to fade during the reionization epoch. This is a result of the Wouthuysen-Field coupling rendering the IGM visible ahead of being heated by X-rays leading up to reionization. This absorption signature of the global signal can give us information on the emergence and spectral properties of the first sources and the impact of Wouthuysen-Field coupling and X-ray heating. The thermal history for the Population III case is similar to that of Population II. However, if the much hotter and larger Population III stars dominate they push this transition forward in time and compress them into a shorter time interval, which results in a decline of the amplitude and a weaker absorption in the global signal, with the emission of the global signal remaining mostly unchanged (see, Furlanetto 2006a,b, 2016; Mebane et al. 2019). The weaker absorption could make detecting the cosmological 21 cm signal slightly more difficult if Population III stars dominate throughout the EoR. Furlanetto (2006a) and Mirocha et al. (2018) expand on these cases of Population II and III stars dominating early phase of stellar evolution in greater detail .
- **Case considering WDM:** WDM delays early star formation as it suppresses the growth of structures on small scales and its presence in significant quantities could potentially alter and leave a trace on the cosmological 21 cm signal. This results in the delay of production of UV and X-ray backgrounds, which modifies the Wouthuysen-Field, X-ray heating and reionization. The global 21 cm brightness temperature spectrum for the WDM model with $m_\chi = 3$ keV shows that considering WDM even with a particle mass of a few keV alters the evolution of the signal. Sitwell et al. (2014) has shown that decreasing m_χ for WDM models results in an increase the gradients of the global signal. Since structure formation is delayed but faster in WDM, the absorotion trough is delayed, and is deeper and narrow compared to the CDM case. This case is expanded in detail by Sitwell et al. (2014).

Furlanetto (2006a), Mesinger et al. (2010), Sitwell et al. (2014) & Mirocha et al. (2018) also give detailed information on how these cases can be simulated with semi-numerical code such as 21cmFAST.

4.2.2 The SZE-21cm: Cases considering Warm Dark Matter, Population II and Population III stars

To compute the SZE-21cm for the presented cases, we follow the same procedure as in the previous Chapter. We simulate a typical rich cluster with a temperature of 10 keV, a radius of 2 Mpc, and optical depth of 10^{-3} that scatters the incoming radiation field ($T_{0,mod}(\nu)$), which we computed using the brightness temperature spectrum for each of the cases. The resulting modified signal ($T_{mod}(\nu)$) is then calculated according to equations 3.4 - 3.6 and we conduct a mock observation in the direction of the cluster and compare this with an empty sky region located away from the source region. This is followed by cleaning the individual patches off any source of contamination that may lead to an inaccurate measure of the SZE-21cm by masking all sources and replacing the affected pixels in the empty sky patches with the mean background. The differential observation procedure that is described by equations 3.6 and 3.10 is then used to obtain the SZE-21cm. We make the assumption that the mock cluster's gas is isothermal and make use of the isothermal β model to derive the SZE-21cm brightness temperature profile (see equation 3.12). We use the same cluster size as in the previous Chapter, the values of the power law index, $\beta = \frac{3}{5}$, and $r_c = 0.248$ Mpc, remain unchanged. The simulated observations yield 2D maps of the cluster from which we measure the SZE-21cm at the cluster and construct the SZE-21cm spectrum. The simulated 2D maps of differential observations performed in the frequency range between 10 and 176 MHz are in Figure 4.2, where we only show the simulated maps at 59.43 MHz, 81.59 MHz and 112.02 MHz as these are the frequencies where we see the strongest decrements or increments in the SZE-21cm signal. In this Chapter, we present only the simulated maps without accounting for instrumental effects such as the finite angular resolution of the instrument, foreground cleaning, and the presence of instrumental noise as we did in Chapter 3. The SZE-21cm spectrum for the presented cases is shown in Figure 4.3 and is discussed extensively for each of the cases below.

Discussion

The SZE-21cm derived from simulated differential observations (Figure 4.3), measured at the cluster differs for each global 21 cm spectrum (δT_b) from the models

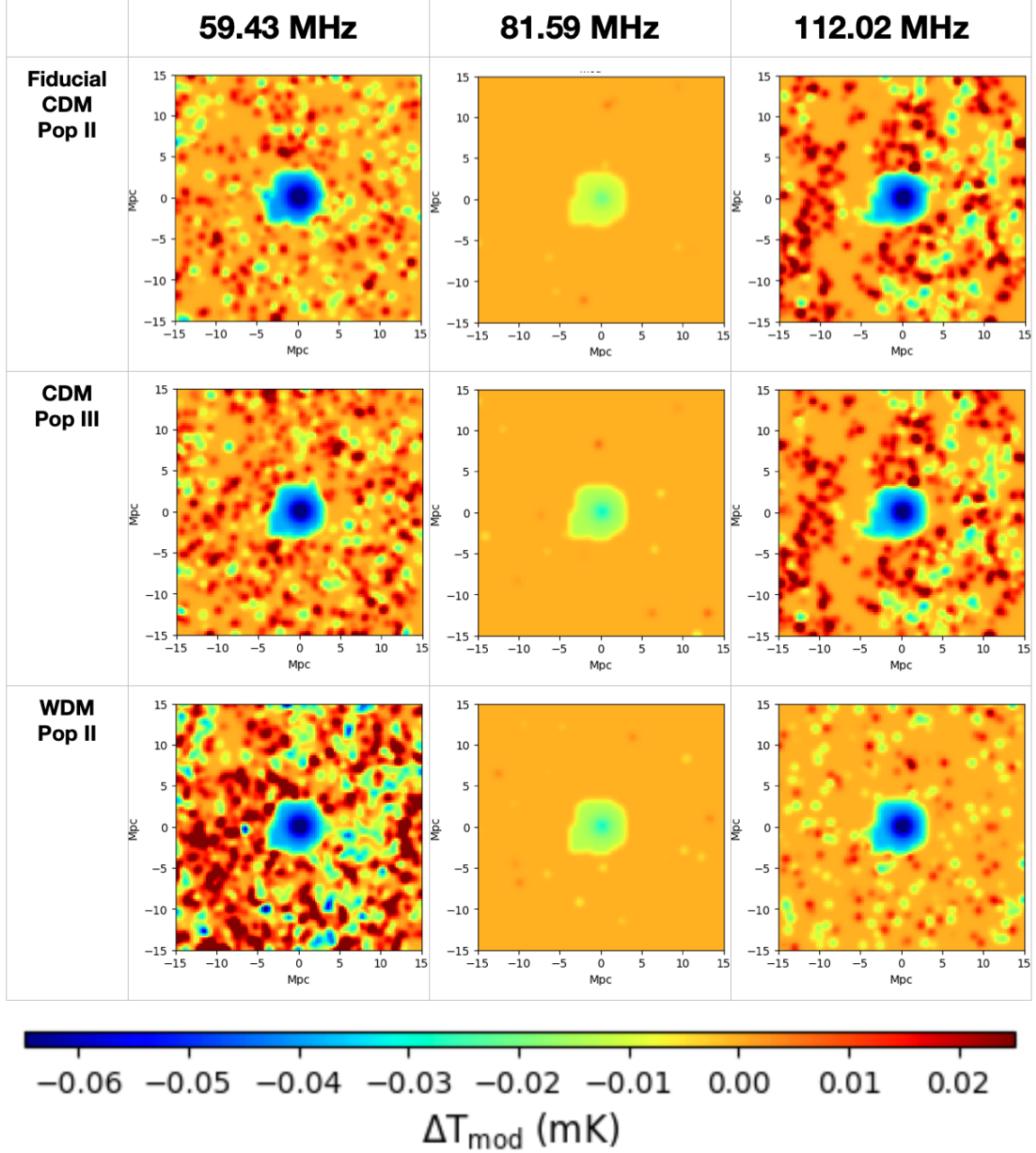


Figure 4.2: Simulated SZE-21cm cluster maps from our mock differential observations at: 59.43 MHz, 81.59 MHz, and 112.02 MHz, for maps that are 30 Mpc a side **Top** - Fiducial CDM model with Population II stars responsible for early heating. **Middle** - CDM model with Population III stars responsible for early heating. **Bottom** - WDM model with $m_\chi = 3$ keV and Population II stars responsible for early heating.

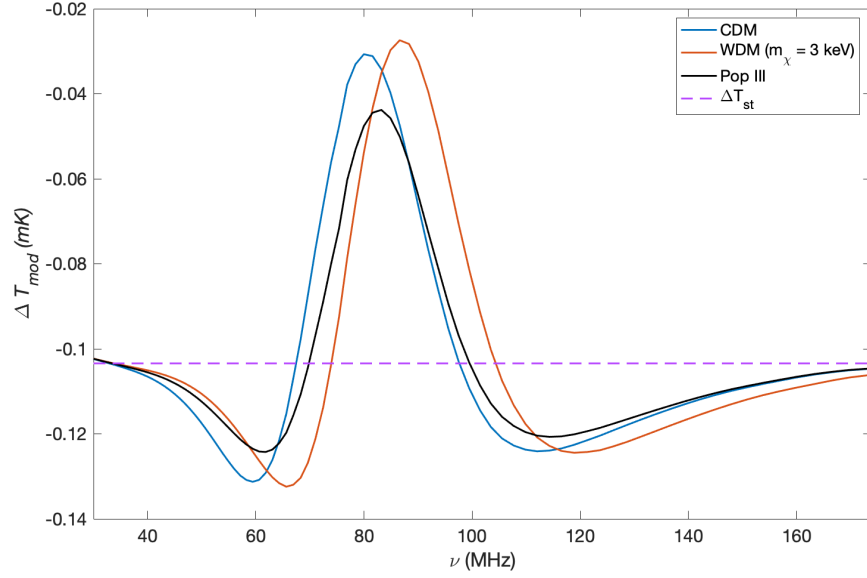


Figure 4.3: The SZE-21cm spectrum from our mock differential observations of a galaxy cluster with a plasma temperature 10 keV and $\tau = 10^{-3}$. **Blue** - The SZE-21cm computed for the Fiducial CDM model where the SFR is dominated by Population II stars. **Black** - The SZE-21cm computed for the CDM model where the SFR is dominated by Population III stars. **Red** - The SZE-21cm computed for the WDM model with $m_\chi = 3$ keV where the SFR is dominated by Population II stars. **Magenta** - dashed line is the standard SZE (ΔT_{st}) for comparison.

studied by this work. Each model imprints distinct features on the SZE-21cm spectrum. There is an approximately 30 MHz frequency range where the SZE-21cm dominates the standard SZE for each model, which corresponds to the absorption feature of the global spectrum: (1) for our fiducial model which considers CDM where the SFR is dominated by Population II stars this range is between 68 - 98 MHz, (2) for the model which considers a CDM where the SFR is dominated by Population III stars this range is between Population III 70 - 100 MHz, (3) and for the model which considers WDM where the SFR is dominated by Population II stars this range is between 75 - 105 MHz. In these ranges it will be easier to distinguish the SZE-21cm from the standard SZE with upcoming radio interferometers, we show this in Figure 4.4. The standard SZE dominates the SZE-21cm outside these ranges, and signals differ by an order of a few μJy (see right panel in Figure 4.4).

One can easily distinguish between any of the input models in most parts of the SZE-21cm spectra. The CDM SZE-21cm signal peaks at a lower frequency compared with the WDM SZE-21cm and corresponds to earlier star formation. The WDM model also has a higher amplitude compared to the SZE-21cm measured for the CDM model

and it appears that it will be easier to distinguish from the standard SZE model (see Figure 4.4). The CDM model where the SFR is dominated by Population III stars has a weaker SZE-21cm signal and may be more difficult to detect as compared to the CDM fiducial case where the SFR is dominated by Population II stars. The emission signal of the Population III input spectrum, δT_b , remains mostly unchanged as compared to the fiducial Population II case, however, this is not the case in the same frequency range, where we observe absorption in the SZE-21cm spectrum. These features are characteristic and can be seen in the input spectra, δT_b , and give evidence that this information is also imprinted in the SZE-21cm. Sensitivity to a WDM case can be best achieved at the frequencies where the SZE-21cm amplitude is stronger and shifted from that of the CDM case, detection of the SZE-21cm for this shift in the amplitude could point towards the presence of WDM. Sensitivity to stellar populations (Population II and Population III) can be achieved by studying the peak of the SZE-21cm in the 68 - 100 MHz frequency range, and can also probe the heating rate influenced by either stellar population. These above-mentioned features show that the SZE-21cm can be viewed as a suitable tool to probe the nature of dark matter and of the first sources in the Universe and their abundance.

The SZE-21cm for the different models is detectable with the SKA instrument; Figure 4.4 shows detectability for the standard SZE and the SZE-21cm for all the simulated models, which is put up with the sensitivities of SKA instrument, SKA1-Low-50%, SKA1-Low, and SKA- 2. We used the SKA1 System Baseline document to extract the instrument performances (Dewdney et al. 2012). Looking at all the models we simulated, the SZE-21cm for a cluster with an optical depth of $\tau = 10^{-3}$ and temperature of 10 keV should be detectable using SKA1-Low-50% at frequencies $\gtrsim 88 MHz$, SKA1-Low at $\gtrsim 60 MHz$ and SKA2-Low at $\gtrsim 50 MHz$, observing at 100 kHz bandwidth, with 1000 hours integration time, 2 polarizations, no taper, no weight. We are more likely to be able to distinguish between the SZE-21cm and the standard SZE for the case with WDM as this should already be detectable with SKA1-Low-50%. To detect this difference for the other two models SKA-1-Low and SKA2-Low are more suitable instruments, with SKA2-Low this should already be possible at frequencies as low as 65 MHz.

4.3 Impact of an EDGES like model on the SZE-21cm

Throughout this work, we have used 21 cm background spectra obtained by early predictions for the 21 cm global signal (Furlanetto 2006a; Mesinger et al. 2010; Pritchard

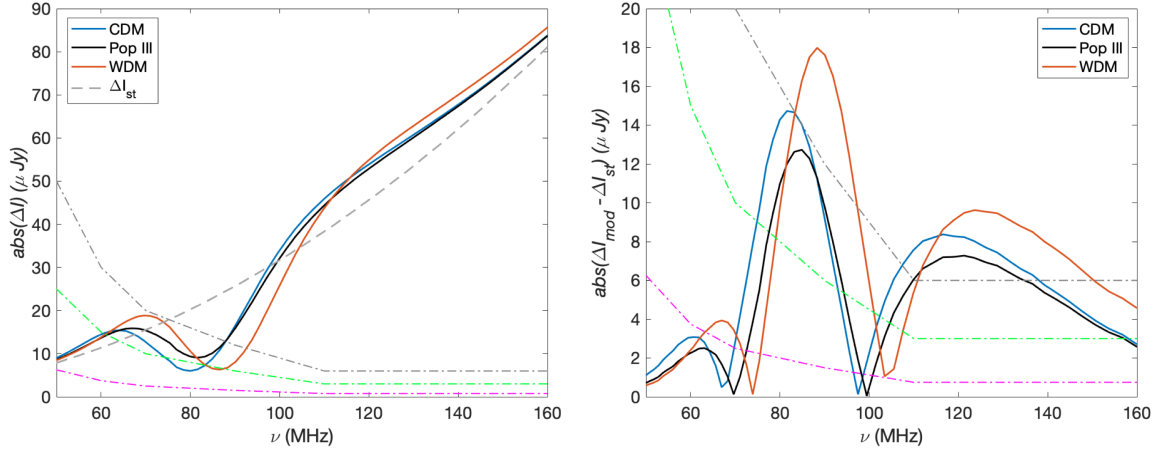


Figure 4.4: Left: The spectra of the absolute fluxes of the SZE-21cm ΔI_{mod} (in μJy). The **Blue** solid line is the SZE-21cm for our simulated fiducial CDM model where the SFR is dominated by Population II stars, the **Black** solid line is the SZE-21cm for our simulated CDM model where the SFR is dominated by Population III stars, and **Red** the line is the SZE-21cm for our simulated WDM model where the SFR is dominated by Population II stars. The **Grey** dashed line is the SZE for a non-modified CMB ΔI_{st} . **Right:** The absolute value of the difference between the SZE-21cm and the standard SZE. The **Blue** solid line is the SZE-21cm for our simulated fiducial CDM model dominated by Population II stars, the **Black** solid line is the SZE-21cm for our simulated CDM model where the SFR is dominated by Population III stars, and the **Red** line is the SZE-21cm for our simulated WDM model where the SFR is dominated by Population II stars. For both Figures we compare with the SKA1-low-50% (**Grey**), SKA1-low (**Green**), and SKA2 (**Magenta**) sensitivities for 100 kHz bandwidth, 1000 hrs of integration, 2 polarizations, no taper and no weight.

& Loeb 2012; Sitwell et al. 2014), which yielded an SZE-21cm with strong emission of the signal at around 80 MHz, consistent with the recent EDGES detection (Bowman et al. 2018), these were theoretical and not tied to any observations. To make more quantitative predictions for potential future observations we must study the SZE-21cm using models that have been considered to explain the EDGES detection.

Presently, the focus of many experiments that are targeted at measuring the global 21 cm signal is to confirm the detection by the EDGES collaboration (Bowman et al. 2018). This can be achieved by another single antenna experiment to measure global 21 cm, by measuring the spatially fluctuating 21 cm signal using interferometers in the same redshift range as EDGES or by measuring the SZE-21cm (as we have shown in the previous Chapter). To match the EDGES signal, models need to include processes that increase the amplitude of the global 21 cm absorption signal beyond the

expectations of an adiabatically cooling IGM. This will have some impact on the expected SZE-21cm spectrum and as a result, we can try to infer the thermal history and radio background that might be responsible for the EDGES signal by measuring the SZE-21cm at the relevant frequencies. In Chapter 3 we discussed some of the proposed processes and models that attempt to explain the amplitude signal measured by EDGES. Considering that origin of the excess cooling that can result in an EDGES-like is still up for debate. Rather than appeal to particular physical models proposed to explain this detection, Mirocha & Furlanetto (2019) instead parametrized the thermal history by allowing it to depart from the predictions of standard recombination codes in Λ CDM (see, Chluba & Thomas 2011), and allowing for cooling to happen at much faster rates at earlier times than in traditional models.

Unlike 21cmFAST, which simulates the cosmological 21 cm signal by generating 3D realizations of the 21 cm brightness temperature, the Accelerated Reionization Era Simulations (ARES) code generates only models for the global 21 cm signal (Mirocha et al. 2018; Mirocha & Furlanetto 2019). ARES does not include any DM models to account for the amplitude of the EDGES signal (see, e.g. Barkana 2018). However, Mirocha & Furlanetto (2019) explored two general possibilities, which are; (1) a parametric excess cooling model, and; (2) scenarios of astrophysically generated radio backgrounds. Both these possibilities result in very similar EDGES-like global signal, for this reason, we only work with the excess cooling model, which we use to compute the SZE-21cm. Both of these should produce a global signal consistent with a colder than that expected IGM before the universe is reionized.

4.3.1 ARES: Excess cooling cosmological 21 cm signal

The temperature of a collapsing gas parcel evolves between $T(z) \propto (1+z)$ and $T(z) \propto (1+z)^2$ at high redshifts. The $(1+z)$ dependence is a signature of the coupled kinetic, spin, and CMB temperatures via Compton scattering, and the $(1+z)^2$ dependence is a signature that indicates that Compton scattering has become inefficient, allowing for adiabatic cooling of the gas (see, Mirocha & Furlanetto 2019). Using the log-cooling rate, $\frac{d \log T}{d \log t}$, of a mean density parcel between $-\frac{2}{3}$ and $-\frac{4}{3}$ in a matter dominated cosmology, Mirocha & Furlanetto (2019) modelled the thermal history by taking

$$\frac{d \log T}{d \log t} = \frac{\alpha}{3} - \frac{2+\alpha}{3} \left\{ 1 + \exp \left[- \left(\frac{z}{z_0} \right)^\beta \right] \right\}, \quad (4.1)$$

where z_0 (referred to as the decoupling redshift) indicates the redshift at which the cooling rate is midway between the asymptotic limits, β indicates how fast the cooling

rate decreases after Compton scattering becomes inefficient. $\frac{d \log T}{d \log t}$ declines sharply for larger values of β . Equation 4.1 is constructed such that changing α alters the late-time cooling rate when $\alpha = -4$ it reproduces the typical thermal history. During the recombination epoch, to preserve the thermal history, the cooling rate tends to $\frac{d \log T}{d \log t} = -\frac{2}{3}$ as $z \rightarrow \infty$. The following parameters are adopted to reproduce the standard Λ CDM result: $\alpha = -4$, $z_0 = 189.6$, and $\beta = 1.27$, which the ARES code obtains from CosmoRec (Chluba & Thomas 2011), yielding a global 21 cm signal similar to the fiducial model from 21cmFAST in Figure 4.1. We use the exact models presented in Mirocha & Furlanetto (2019) to produce the excess cooling global signal in Figure 4.1, by summoning the requisite parameters within the ARES code. Though the ARES signal with excess cooling replicates the amplitude of the EDGES signal, like other physically reasonable models, it cannot reconcile the sharp walls and flat-bottom of the EDGES detection. This section focuses on computing the SZE-21cm from this model and we refer the reader to Mirocha & Furlanetto (2019) for the detailed procedure that goes into obtaining the excess cooling 21 cm global spectrum using ARES as we have done for purposes of this work. The excess cooling 21 cm global signal which we generated using ARES is presented in Figure 4.1 along with other models generated using 21cmFAST and the actual EDGES detection, for comparison.

4.3.2 The SZE-21cm: ARES Excess cooling model

We compute the SZE-21cm from an input spectrum, δT_b , for the excess cooling model obtained from ARES, to do this we make use of equations 3.2 - 3.6. The ARES SZE-21cm spectrum is in Figure 4.5. The ARES added cooling model yields an SZE-21cm spectrum similar to the one we calculated for the best fit to the EDGES signal in Chapter 3. The ARES signal peak appears slightly earlier than that of the EDGES detection, this is a consequence of the mechanisms for increasing the amplitude input spectrum and how the star formation efficiency evolves. The resulting SZE-21cm cannot match its shape of the SZE-21cm calculated EDGES detection as the ARES SZE-21cm spectrum has broader wings and lacks the flat EDGES peak.

To estimate the expected observational errors for SZE-21cm spectrum for the ARES signal presented in Figure 4.5, we assume observations using an interferometer similar to the proposed SKA1-Low array using equation 3.13 and parameters in table 3.2. The errors were determined, assuming observations towards one cluster and the improvement by computing the average over signals towards ten and then one hundred clusters (following the procedure as in section 3.3.3). Looking at Figure 4.6, the SZE-21cm signal computed for the excess cooling model is much more amplified in

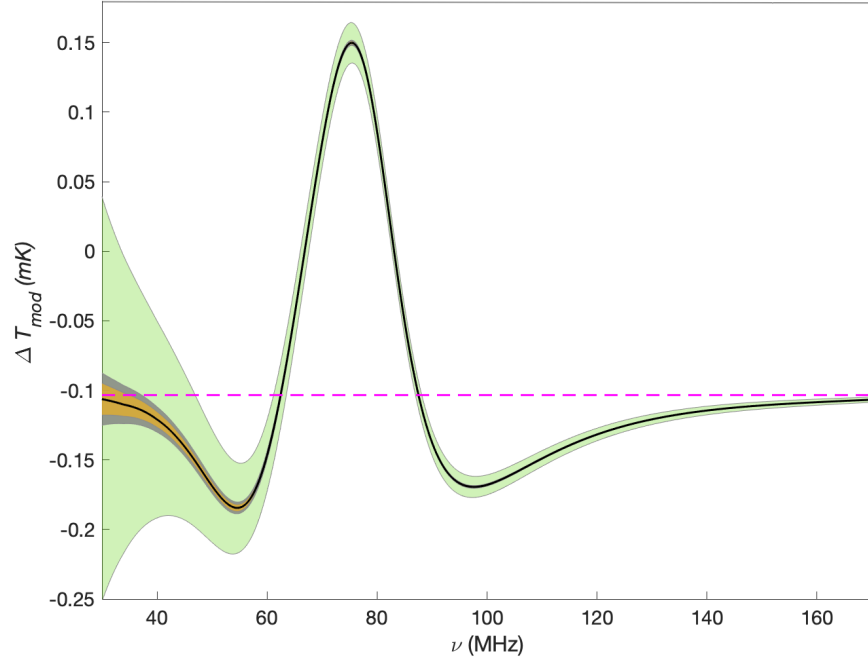


Figure 4.5: The SZE-21cm computed using the global 21 cm spectrum from our ARES simulation run for a cluster with a plasma temperature of 10 keV and an optical depth $\tau = 10^{-3}$. The **Magenta** dashed line is the standard SZE (ΔT_{st}) for comparison. The **Green** error region is for differential observations towards a single cluster, **Grey** area towards 10, and the **Gold** area towards 100 clusters.

both absorption and emission when compared to the SZE-21cm for the fiducial CDM model where the SFR is dominated by Population II stars, the CDM model where the SFR is dominated by Population III stars, and WDM model we have discussed in the previous section. The peak of the SZE-21cm for the EDGES detection and excess cooling model is amplified by nearly an order of 2 compared to any of the models that we used for our simulated differential observations. It is also worth mentioning that peak has resulted in an SZE-21cm with a positive brightness temperature, whereas previous works (Colafrancesco et al. 2016; Takalana et al. 2018) had predicted an SZE-21cm signal with a non-positive brightness temperature. The SZE-21cm amplitude is dependent on the photon distribution at the respective frequencies. At the frequencies where we have the peak on the ARES SZE-21cm signal, a larger number of photons are present with respect to the standard SZE and SZE-21cm for models we assessed in the previous section, here the ARES signal peak is larger by a factor of about 2; on the other hand, at the frequencies where we observe absorption on the ARES SZE-21cm signal, a smaller number of photons are present with respect to the standard SZE and the SZE-21cm for models we assessed in the previous section, here the absorption of the ARES SZE-21cm signal is about 2 orders of magnitude

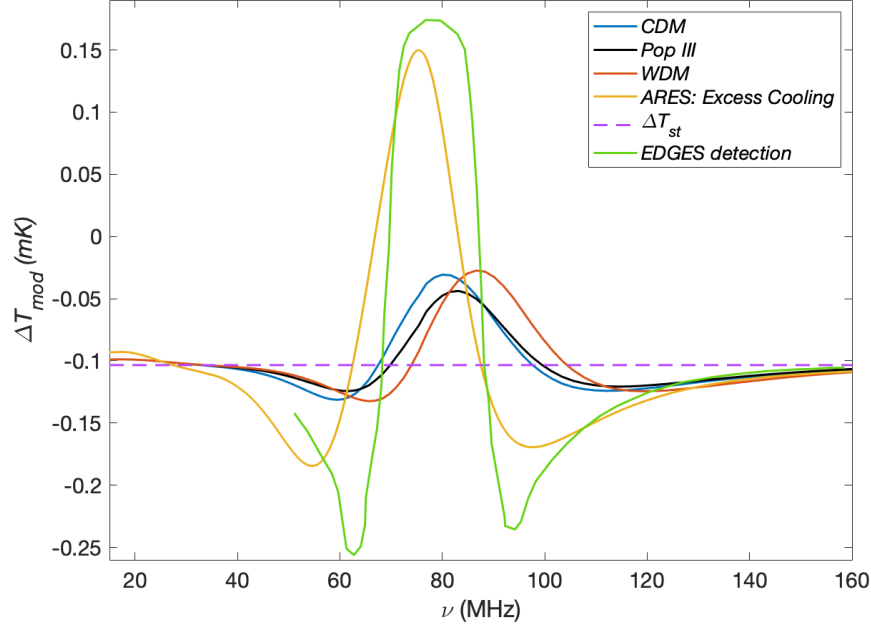


Figure 4.6: The SZE-21cm spectrum from our mock differential observations of a galaxy cluster with a plasma temperature 10 keV and $\tau = 10^{-3}$ for the ARES excess cooling input spectrum (**Gold**), the Fiducial CDM model where the SFR is dominated by Population II stars (**Blue**), the CDM model where the SFR is dominated by Population III stars (**Black**), the WDM model with $m_\chi = 3$ keV (**Red**), the SZE-21cm computed using the 21 cm background spectrum detection claimed by the EDGES collaboration (**Green**). The SZE-21cm spectrum computed from the EDGES input spectrum is only reliable between 70-90 MHz due to the edge effects of the frequency range of the input spectrum.

larger. Also, the SZE-21cm dominates the standard SZE between 62 - 88 MHz, which is a narrower frequency range as compared to the range we measured for the models presented in section 4.2. If this were to be observed, it would be evidence that the source of excess cooling, cooled the IGM earlier and more rapidly than for the models presented in section 4.2.

The SZE-21cm detectability of the ARES excess cooling model with the SKA is similar to that of the EDGES signal (see Figure 4.7), we have already discussed the detectability of the EDGES signal in the previous Chapter using the best fit model. It is worth noting that in comparison to the models we studied in section 4.2 there is a higher chance of detecting the SZE-21cm and distinguishing it from the standard SZE for a case of a Universe with excess cooling processes or scenarios that produce astrophysical radio backgrounds that yield an EDGES-like signal.

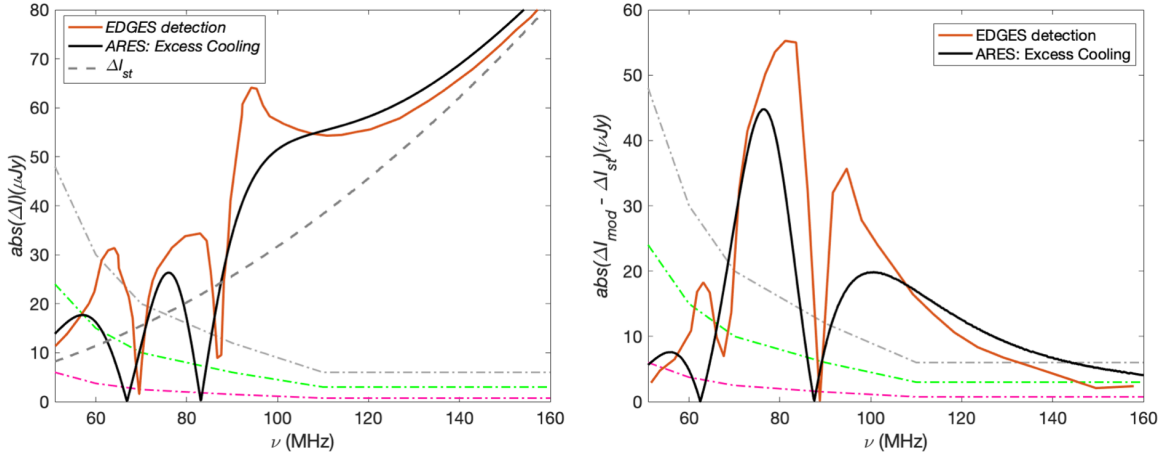


Figure 4.7: Left: The spectra of the absolute fluxes of the SZE-21cm ΔI_{mod} (in μJy). The **Black** solid line is the SZE-21cm for our simulated excess cooling model with ARES. The **Grey** dashed line is the SZE for a non-modified CMB ΔI_{st} . **Right:** The absolute value of the difference between the SZE-21cm and the standard SZE. The **Black** solid line for our simulated excess cooling model, and the **Orange** line for the SZE-21cm calculated for the EDGES detection. For both Figures we compare with the SKA1-low-50% (**Grey**), SKA1-low (**Green**), and SKA2 (**Magenta**) sensitivities for 100 kHz bandwidth, 1000 hrs of integration, 2 polarizations, no taper and no weight.

4.4 Conclusion

This Chapter has shown that different models of the cosmological 21 cm signal that affect the timing, shape, and amplitudes of the global 21 cm signal make distinct imprints on the SZE-21cm, and as a result, make the SZE-21cm inviting as an indirect probe for different cosmologies and to close in on proposed models that aim to paint a picture of physical mechanisms and processes occurring during the DA and subsequent EoR. The features imprinted on the SZE-21cm as a result of the global 21 cm signal models also allow the SZE-21cm to probe the nature of the early sources and dark matter in the DA and EoR. Each of the models that we studied has a distinct SZE-21cm and this can be exploited by future observations to rule out those models that are inconsistent with experimental data. Furthermore, we studied the detectability of SZE-21cm for the various models and found that the best frequency range for observations in the future is 62 - 105 MHz, where it is easier to distinguish the SZE-21cm from the standard effect. It is pressing that we take advantage of observations in this frequency range as these correspond to the EDGES result and could aid in using SZE-21cm to confirm this detection and possibly others in the near future.

Chapter 5

Observations of the SZE-21cm towards multiple clusters of different plasma temperatures with upcoming experiments

Abstract

In Chapter 3 we have shown that by averaging the SZE-21cm signal from different clusters we can decrease the expected errors, thus increasing the significance of the signal per frequency, for observations with upcoming interferometers. The SZE-21cm is directly connected to cluster thermal energy and it is therefore important that we understand how the signal behaves for clusters with different plasma temperatures. In this Chapter, we study the SZE-21cm for different plasma temperatures and propose a strategy to average the signal over multiple clusters.

5.1 Introduction

The wide range of theoretical models and simulations of the DA and EoR have allowed us to study expectations for observations from 21 cm surveys when they become available. These future 21 cm observations will supply us with large datasets of 21 cm images that will contain encoded information on the global signal itself and imprints of the signal buried in other forms of signatures such as the SZE-21cm. The

SZE-21cm is a faint signal and the expected errors for observations with upcoming interferometers may have significant impact on the measurement of the signal, it has therefore been proposed that averaging the signal over multiple clusters could potentially decrease the errors in the measurements and take care of effects introduced by cosmic variance (see, Cooray 2006; Colafrancesco et al. 2016; Takalana et al. 2018, 2020). In Chapter 3, this was well illustrated by Figure 3.6 and discussed in section 3.3.3. The large field of view of the SKA will make it possible to study the SZE-21cm towards multiple numbers of clusters and with data from microwave and X-ray frequencies the plasma temperature of the clusters can be estimated, which is useful for our low-frequency studies. In Chapter 3 we also noted that the SZE-21cm varies with plasma temperature, and we calculated the expected error when averaging the SZE-21cm signal over multiple clusters, in that particular case we assumed the case of the signal from clusters with the same temperature to avoid the complexities introduced by stacking the signal from clusters with different plasma temperatures. With the SZE-21cm depending on the plasma temperature ($k_B T$) of the galaxy cluster being observed it is essential that we account for this when averaging the signal from multiple clusters, not doing this could lead to underestimates or overestimates of the signal.

A high-significance detection of the SZE-21cm is possible using statistical analysis of a large number of galaxy clusters. In this Chapter, we study maps and spectra from simulated differential observations of the SZE-21cm for clusters with different plasma temperature and we attempt to obtain an averaged SZE-21cm and model it as though it is for a single cluster temperature. The Chapter is structured as follows. In section 5.2 we look at and study the SZE-21cm for clusters with different plasma temperatures and in section 5.3 we use this analysis to obtain the SZE-21cm for the stacked clusters. We give the discussions and conclusion in section 5.4.

5.2 The SZE-21cm for clusters with different plasma temperatures

For work presented in this section, we make use of the fiducial 21 cm-background model from Chapter 4 for a Λ CDM model where the SFR is dominated by Population II stars. We simulate differential observations towards clusters of galaxies with different plasma temperatures using the procedure described for differential observations of the SZE-21cm in Chapter 3. We insert clusters with plasma temperatures of 5, 10 and 15 keV into our simulated cubes and select empty sky regions away from the cluster that contains the background signal. This is followed by cleaning the

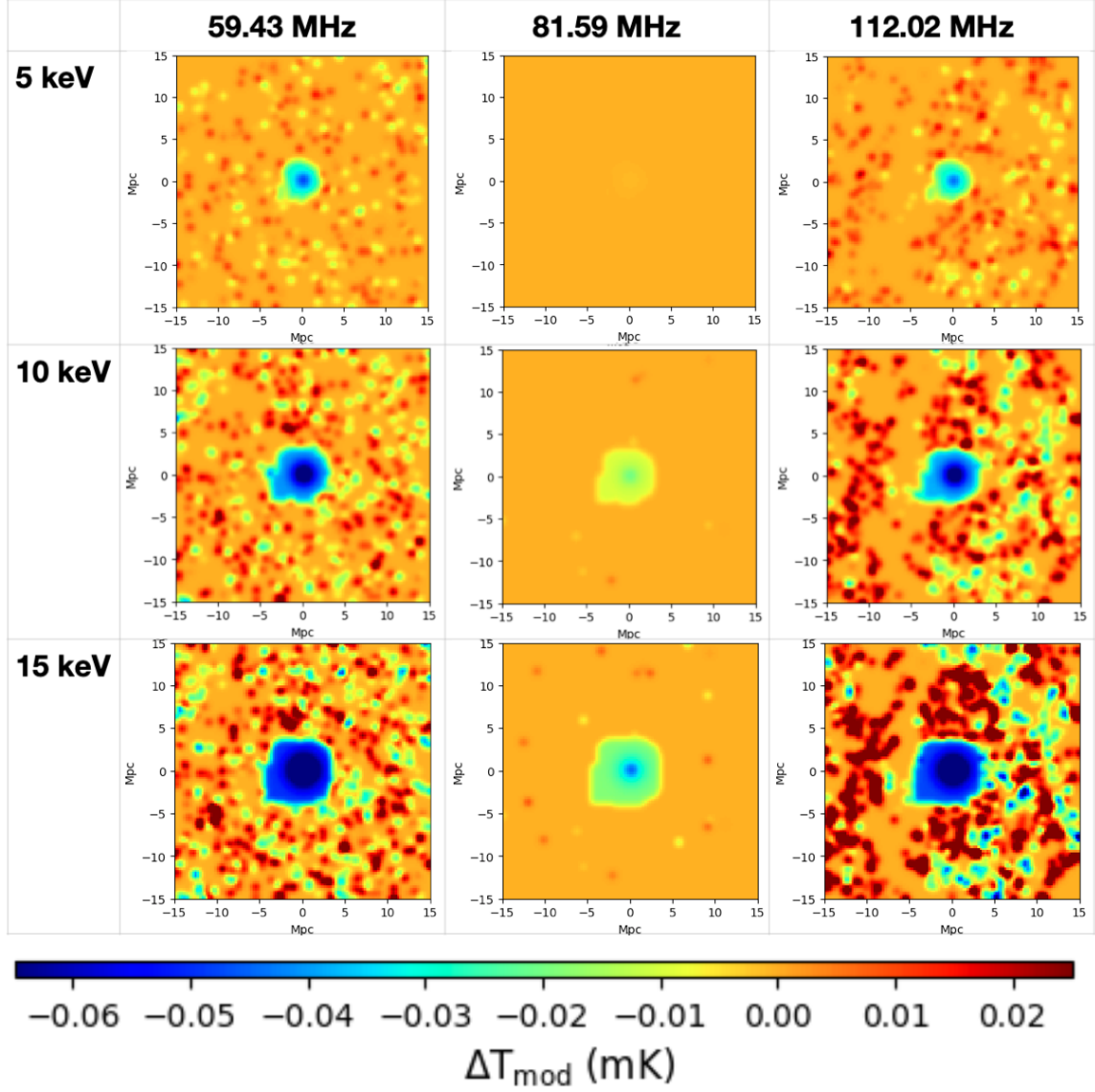


Figure 5.1: Simulated SZE-21cm cluster maps from our mock differential observations at: 59.43 MHz, 81.59 MHz, and 112.02 MHz, for a cluster with plasma temperatures of 5, 10 and 15 keV, and an optical depth of 10^{-3} . The maps are 30 Mpc a side.

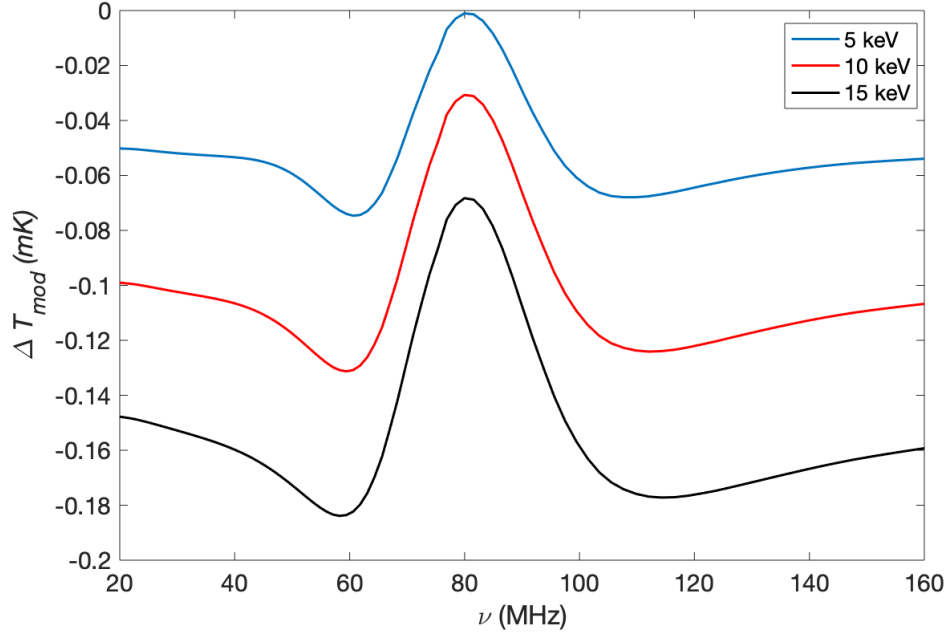


Figure 5.2: The SZE-21cm computed for the simulated fiducial 21 cm-background model from Chapter 4 for cases with a cluster with a plasma temperature of 5 keV (**Blue**), 10 keV (**Red**) and 15 keV (**Black**), the optical depth is $\tau = 10^{-3}$.

individual patches off any source of contamination that may lead to an inaccurate measure of the SZE-21cm by masking all sources and replacing the affected pixels in the empty sky patches with the mean background. As before, we then perform the simulated differential observation using equation 3.10. The simulated cluster optical depth (τ) is 10^{-3} and the radii was approximated using the r_{200} scaling relations from Neumann (2005), these correspond to about 1.5 Mpc for the 5 keV cluster, 2 Mpc for the 10 keV cluster and 2.5 Mpc for the 15 keV cluster. The images of the simulated differential observation of the clusters are in Figure 5.1, and Figure 5.2 shows the SZE-21cm spectrum as a function of the frequency for plasma temperatures of 5, 10 and 15 keV. In this Chapter, we present only the simulated maps without accounting for instrumental effects such as the finite angular resolution of the instrument, foreground cleaning, and the presence of instrumental noise as we did in Chapter 3 and only show the simulated cluster images at 59.43 MHz, 81.59 MHz, and 112.02 MHz, which are the frequencies where we observe the strongest increments and decrements in the SZE-21cm signal.

From Figures 5.1 and 5.2, we observe that the amplitude of the SZE-21cm brightness temperature increases with the cluster temperature. In addition to this, the signatures imprinted on the SZE-21cm by the global 21 cm signal, that contains information on

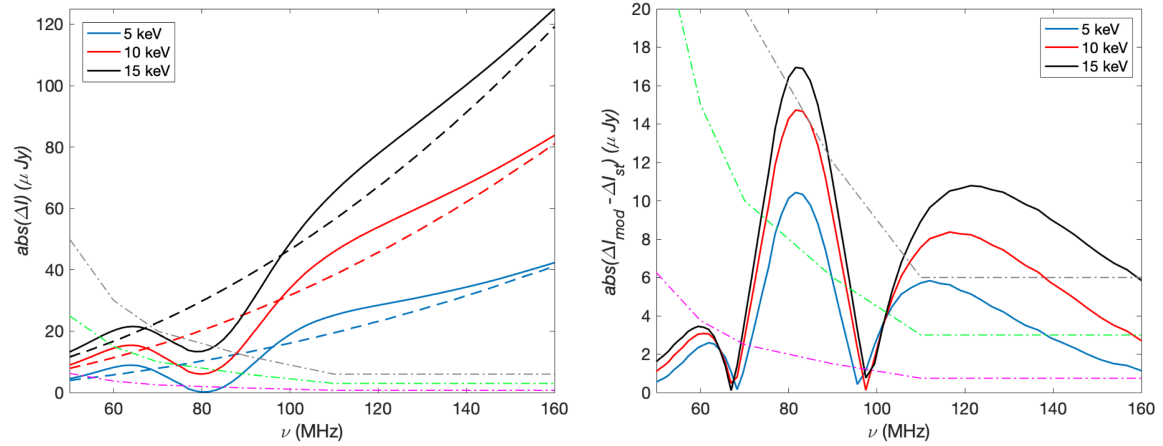


Figure 5.3: Left: The spectra of the absolute fluxes of the SZE-21cm ΔI_{mod} (in μJy) for cases with a cluster with a plasma temperature of 5 keV (**Blue**), 10 keV (**Red**) and 15 keV (**Black**), the optical depth is $\tau = 10^{-3}$. The dashed lines are the SZE for a non-modified CMB ΔI_{st} . **Right:** The absolute value of the difference between the SZE-21cm and the standard SZE for cases with a cluster with a plasma temperature of 5 keV (**Blue**), 10 keV (**Red**) and 15 keV (**Black**). For both Figures we compare with the SKA1-low-50% (**Grey**), SKA1-low (**Green**), and SKA2 (**Magenta**) sensitivities for 100 kHz bandwidth, 1000 hrs of integration, 2 polarizations, no taper and no weight.

processes occurring during the DA and EoR, are preserved. The positions of temperature decrements and increments remain unchanged in frequency for all cases of the cluster plasma temperature, the SZE-21cm temperature decrements are at $\nu \leq 68$ MHz and $\nu \geq 98$ MHz and the increment is at $68 \text{ MHz} \leq \nu \leq 98$ MHz.

In Figure 5.3 we show the detectability of the SZE-21cm for the different plasma temperatures and find that we can maximise both the SZE-21cm signal and the difference between the standard SZE by carrying out future observations of clusters that have higher plasma temperature, particularly observing clusters of plasma temperatures in the range 10 - 15 keV promises a better characterization of the SZE-21cm spectral shape and more precise determination of the global signal from the DA and EoR.

5.3 Method for stacking the SZE-21cm for clusters with different plasma temperatures

From the simulated differential observations in the frequency range 10 – 176 MHz, we measure the SZE-21cm for clusters with plasma temperatures of 5, 10, 15 keV. At each frequency, we obtain the relationship between SZE-21cm and plasma temperature by

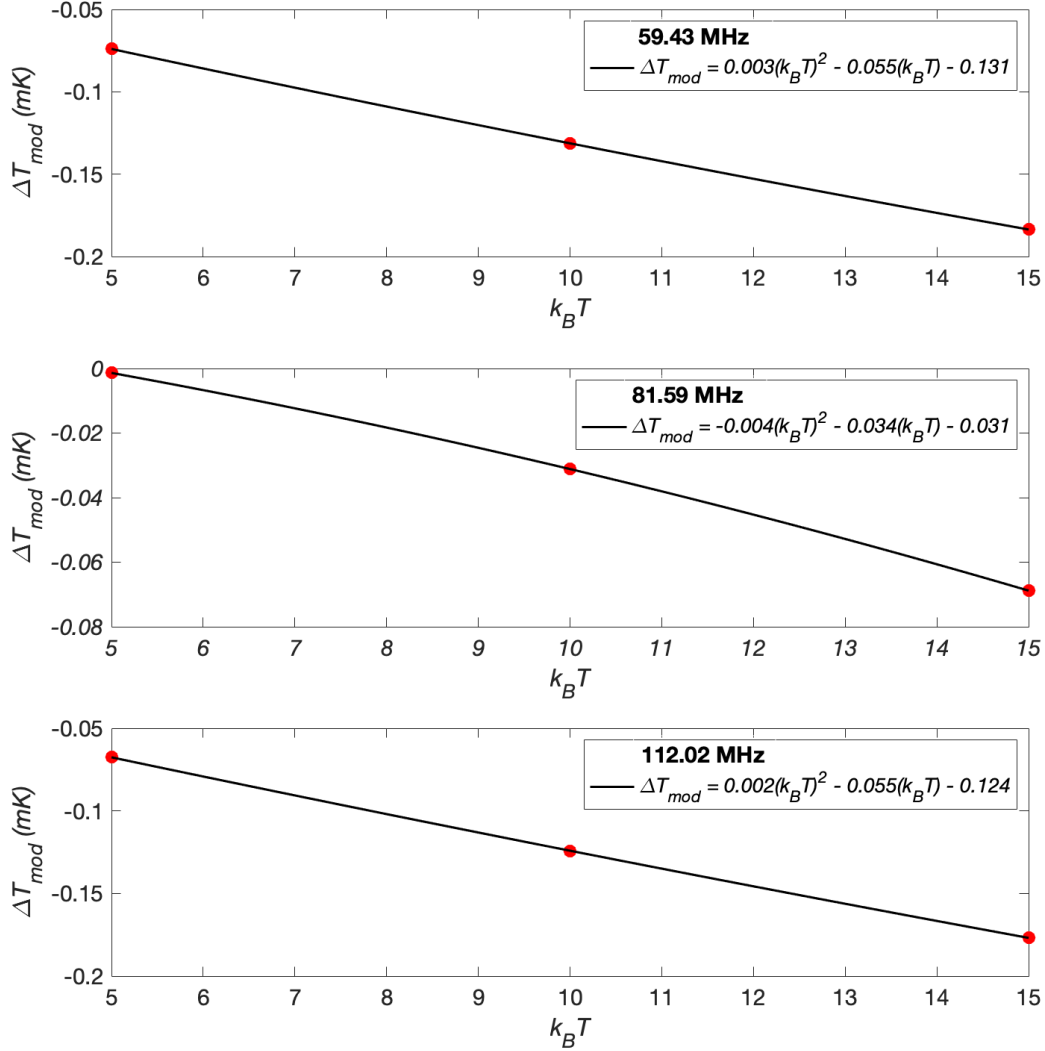


Figure 5.4: The SZE-21cm measured for the galaxy clusters simulated and shown in Figure 5.1 as a function of plasma temperature ($k_B T$). The top Figure is SZE-21cm at 59.43 MHz, the middle is at 81.59 MHz and the bottom at 112.02 MHz. The cluster optical depth is $\tau = 10^{-3}$. The red points are the SZE-21cm at plasma temperatures of 5, 10 and 15 keV, and the black line is the best fit line.

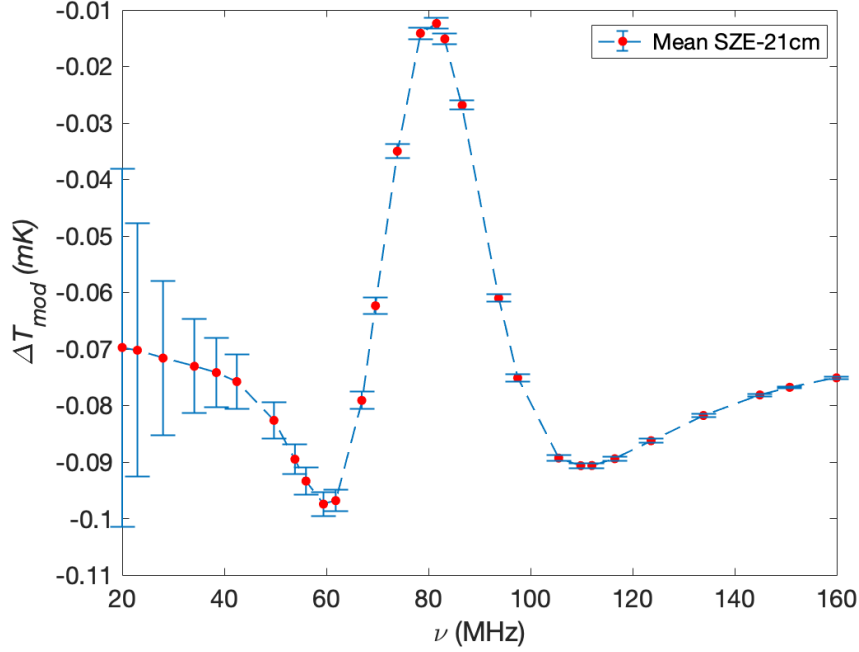


Figure 5.5: The average SZE-21cm for clusters with plasma temperature between $k_B T_{min} = 6$ and $k_B T_{max} = 8$ keV and an optical depth of $\tau = 10^{-3}$. To obtain the error bars we assume stacked observations of 100 clusters within the plasma temperature range with SKA1-low.

making fits through the points. We present the fits through the points at 59.43 MHz, 81.59 MHz and 112.02 MHz in Figure 5.4, these frequencies were chosen as an illustration. The best fits through the points at all the frequencies were second-order polynomials and we stress that this quasi-polynomial behaviour of the SZE-21cm spectral distortion with respect to $k_B T$ is only used to motivate a stacking analysis. Assuming this quasi-polynomial behaviour, we create a mock SZE-21cm sample with cluster plasma temperatures between $k_B T_{min} = 6$ and $k_B T_{max} = 8$ keV. To obtain an average of the SZE-21cm we apply the mean value theorem for integrals, according to this theorem there is at least one point in the interval $[k_B T_{min}, k_B T_{max}]$ where the polynomial $\Delta T_{mod}(k_B T)$ attains its average value:

$$\Delta \bar{T}_{mod} = \frac{1}{k_B T_{max} - k_B T_{min}} \int_{k_B T_{min}}^{k_B T_{max}} \Delta T_{mod}(k_B T) dk_B T. \quad (5.1)$$

We perform this integration for the SZE-21cm polynomial fits at each frequency and plot the average SZE-21cm in Figure 5.5 with error bars assuming 100 clusters observed with the low-frequency SKA as in previous Chapters, using equation 3.13.

5.4 Discussions and Conclusion

The averaging procedure preserves the shape of the SZE-21cm, which is essential to establish the global properties of the sky-averaged 21 cm background signal. While the quasi-polynomial fits permit for us to calculate the SZE-21cm for any single plasma temperature, equation 5.1 allows us to obtain an approximation of the average SZE-21cm for any number of clusters in a given range of plasma temperature, this method is useful in that it incorporates the SZE-21cm from these different plasma temperature clusters into a single spectrum from which we can infer properties of the global 21 cm spectrum. The error for this method primarily depends on the goodness of the fits of ΔT_{mod} vs $k_B T$ at each frequency. The R-square value for our fits is 1 at each indicating that a great proportion of variance is accounted for by the fits. In our case we chose the plasma temperature range between $k_B T_{min} = 6$ and $k_B T_{max} = 8$ because it is within temperature range from which we obtained our fits. Real data from upcoming observations that include systematics will put this method to the ultimate test.

Chapter 6

Differential analysis techniques for low frequency radio observations of galaxies

The work presented in this chapter includes results that has been published as:

- 1. C.M. Takalana, P. Marchegiani & S. Colafrancesco, Proceedings of Science, 2019, 338, PoS(HEASA2018)006*
- 2. C.M. Takalana, S. Colafrancesco & P. Marchegiani, RAF 2018 Proceedings: FAST-MeerKAT and SKA Pathfinder Synergies*

Abstract

Differential techniques enabled us to measure the SZE-21cm signal from galaxy cluster observations, which can be used to obtain the global features of the 21 cm background from the Dark Ages and Epoch of Reionization. This work applies the differential technique to observations of radio galaxies from the GaLactic and Extra-galactic All-sky MWA survey, which consists of low-surface brightness and extended radio sources. In this work we perform differential analysis on 2 galaxies; NGC 1534 and IC 4296, and present a preliminary pipeline that helps us reduce the effects of contaminating backgrounds and foregrounds that present challenges in low-frequency radio observations and we find that the differential technique can be used to enhance of features of sources in the continuum images, which is promising to be beneficial for efforts of source finding, extraction, characterisation, and improving the signal to noise.

6.1 Introduction

Differential observation analysis techniques involve the acquisition of measurements on a targeted cosmic structure and an empty sky region away from the target, which we refer to as the background. Computing the difference between the target region and the background region can be used to reveal changes in the brightness of the target region less the background region and to increase the signal-to-noise levels towards our targeted cosmic structure. Such a computation can be key for both improving our knowledge of the source itself and our understanding of the environment that hosts it. There is limited literature on the use of differential techniques for continuum radio surveys and much can be learned from optical pipelines with similar goals in this regard. Over the last two decades our knowledge of radio continuum emission from extended and low-surface brightness sources has improved (see, [Das et al. 2007](#); [Subrahmanyan et al. 2008](#); [Vacca et al. 2011](#); [Shimwell et al. 2014](#); [van Weeren et al. 2019](#)), and differential techniques can potentially contribute further to extraction and characterisation of these sources in low-frequency radio astronomical surveys.

This work adapts and slightly modifies the procedure proposed for observations to measure SZE-21cm. We apply it to existing continuum radio observations and present a preliminary pipeline, which is rooted and closely related to pipelines that are currently available for optical experiments (see e.g., [Tomaney & Crofts 1996](#); [Levesque & Lelievre 2007](#)). We make use of an iterative computation to estimate and eliminate effects of the background and foregrounds from target/sources in the data image cut-outs, which we obtained from the Murchison Widefield Array (MWA), GaLactic and Extra-galactic All-sky MWA (GLEAM), survey¹. This Chapter is structured as follows. We use section 6.2 to familiarise the reader with the MWA-GLEAM survey. Section 6.3 describes the pipeline that we use for our differential techniques for low-frequency radio astronomical surveys and our results. In section 6.4 we present our discussion and we conclude in section 6.5.

6.2 The Murchison Widefield Array GLEAM survey

The MWA is a phased interferometric array that operates between 72 and 300 MHz. The instrument is situated in Western Australia’s Murchison Radio Astronomy Observatory (MRO) as a precursor to the SKA low-band telescope with an instantaneous

¹<http://gleam-vo.icrar.org>

bandwidth of 30.32 MHz and a wide field-of-view of between 15° and 50° , it consists of 128 32-dipole antenna tiles that are spread out over an area of 3 km in diameter (Tingay et al. 2013). In addition to the aforementioned, the instrument’s short-medium baselines make it a suitable instrument for observing the 21 cm line of neutral hydrogen from the DA and EoR (For et al. 2018; Bowman et al. 2013). The MWA dipole arrays are fixed and for this reason, a drift scan observing strategy is used.

The data used in this work are from the GLEAM survey observed with the MWA, which mapped the entire southern sky below declination of $+25^\circ$. Observations of the GLEAM survey was at the observing bandwidth of 72-231 MHz, which was covered by shifting frequencies by 30.72 MHz every two minutes in week-long drift scan campaigns that observe a single declination (Dec) strip each night (Hurley-Walker et al. 2017). The sensitivity of the GLEAM survey is between 6 - 10 mJy/beam, covering a sky area of 30 000 deg² with an angular resolution of about 100 arcsec. The observations of this survey consist of approximately an hour of integration time per pointing at each frequency (Wayth et al. 2015).

6.3 Procedure and Results for differential analysis for radio observations

To test out our differential technique we selected two sources; IC 4296 and NGC 1534 from the GLEAM survey (see details in table 6.1):

- **NGC 1534** is a lenticular low redshift galaxy at $z = 0.017802$ (da Costa et al. 1991). It is part of LDC 292 and HDC 269 group of galaxies. The source is associated with a nearby Giant Radio Galaxy (GRG) with diffuse low-surface brightness emission, which was discovered with the MWA and is extensively discussed by Hurley-Walker et al. (2015) and Duchesne & Johnston-Hollitt (2019).
- **IC 4296** is a giant elliptical low redshift galaxy at $z = 0.012601$. It is part of the HG22 group of galaxies in the central region of the Abell 3565 galaxy cluster (see, Huchra & Geller 1982; Grossová et al. 2019).

We identified regions hosting these sources in the GLEAM survey ², then selected a patch with the sources as the main target and selected six empty patches (hereafter titled "the background") with minimal bright sources (see, Figure 6.1).

²<http://gleam-vo.icrar.org>

Table 6.1:: Sources selected from the GLEAM survey to test the differential technique for low frequency radio surveys.

	Source Name	RA	DEC	Gleam Frequency Range
1.	NGC 1534	04 08 40.78	-62 49 12.20	154-162 MHz
2.	IC 4296	13 36 38.58	-33 57 45.81	216-223 MHz

We first work on the selected background regions and make an assumption that the regions are relatively smooth and that any signal in the regions is very sharp. Then, using an iterative process illustrated in Figure 6.2, we attempt to refine the background regions. In the first step, the signal is almost zero everywhere and any signal above this background is the first estimation of a source signal. To obtain a good background estimation, we clip the background image at $2\sigma_n$ and replace the affected pixels with the local mean, while preserving the unaffected background pixels. The signal is attenuated before estimating the background again. The sigma clipping at each iteration causes the resultant image to converge toward the true background. We defined exclusion zones as where the pixels are greater than $2\sigma_n$ and 0 elsewhere, these pixels are systematically ignored in the analysis. No exclusion zones were identified were identified in our runs. We stop the iterations when no more improvements can be made to the background region or when the residual error is less than the noise level. The final background is the clipped image, where no further improvements can be made to the background.

Once all the selected background regions have been put through the iterative signal clipping pipeline we compute a mean background image by,

$$I_{Background} = \frac{1}{N} \sum_{i=1}^N I_{Background_i}. \quad (6.1)$$

Where N is the number of selected background regions. We then subtract the mean background from our target source image through,

$$\Delta I = I_{Source} - I_{Background}. \quad (6.2)$$

Using the mean background region in our differential technique mitigates the introduction of spurious artefacts and ensures that the variation that we measure effectively originates from the main target source and not from the background. Figure

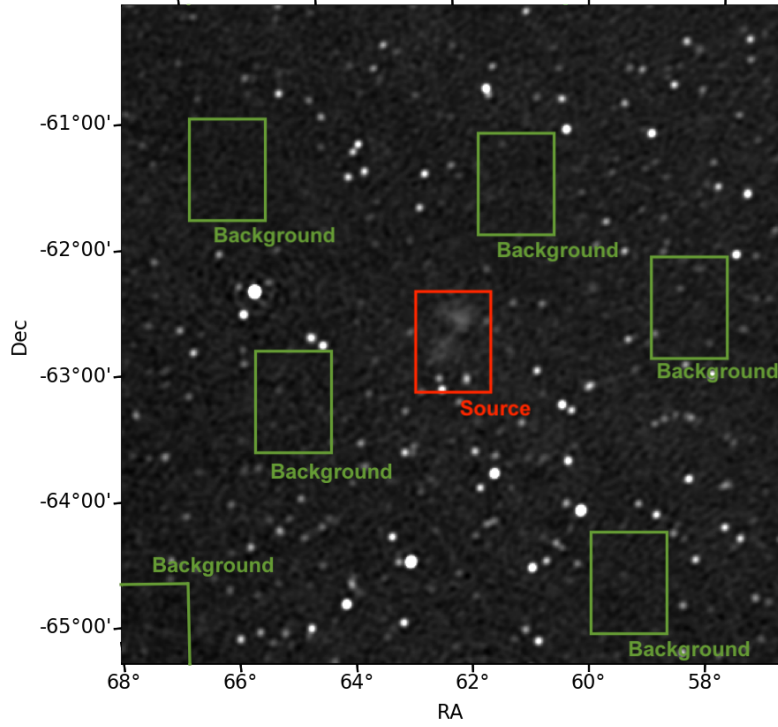


Figure 6.1: Image cut-out of NGC 1534 from the GLEAM survey with the main target source in the red region and the six background regions in green.

6.3 shows the main target sources (NGC 1534 and IC 4296) before (top) and after (bottom) the application of the differential technique. In this work, we do not analyse the main target sources fully but look at the efficiency and effectiveness of the differential technique instead.

6.4 Discussion

Comparing the before and after images in Figure 6.3 we find that elements that were not apparent in the original target image are now visible, we can observe these differences in images through the radio contours. While allowing us to investigate the accuracy and usefulness of the technique, the contours allow us to link or relate the emission to a parent source and to trace the distribution of the radio emission in the field of interest. The signal-to-noise ratio for NGC 1534 increases by a factor of 1.4 and 1.3 for IC 4296 compared to the original target images. For NGC 1534 the southern lobe appears larger than it was in the image prior to application of the differential technique, and some of the areas with emission have also been extended.

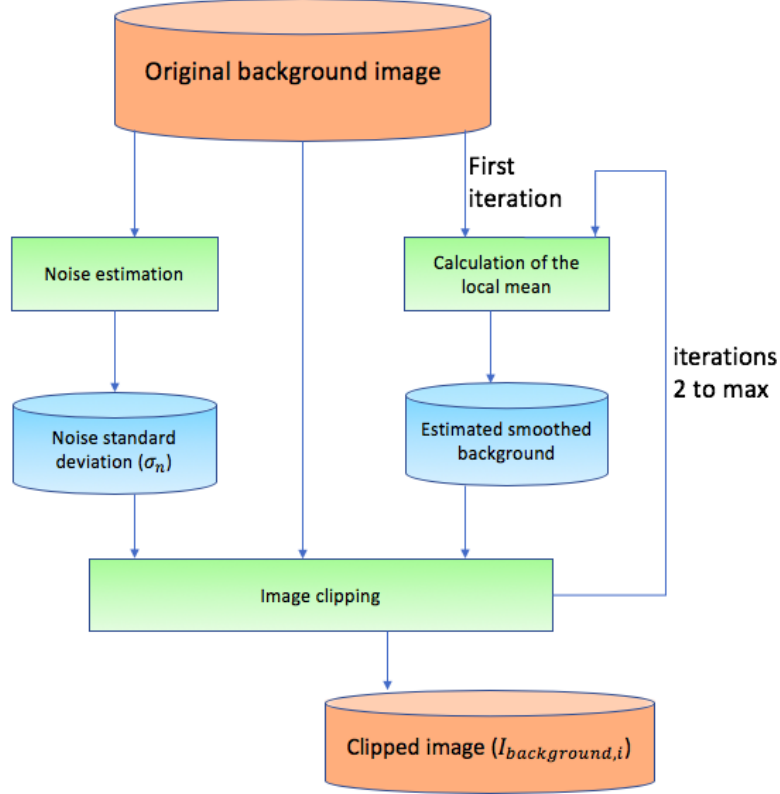


Figure 6.2: Illustrative diagram of the iterative background estimation pipeline.

The lobes on the NGC 1534 image now also appear nearly symmetric in size and very similarly diffuse. For IC 4296, the initial image shows a definite connection between the two source regions in the western direction of the extended radio emission. Though one could assume that the emission in the eastern direction seems to be related to the other two in the western direction, it is only following the differential operation that we observe a definite connection in the contours of all three bright regions of the extended radio source, we also observe that the source is well-collimated with nearly symmetric jets that re-brighten away from the central region. For both cases (NGC 1534 and IC 4296), the contours on the new images show signals that did not appear as strong in the images before putting the image through the pipeline. We also note that none of the features of the initial images were destroyed but have in-fact become enhanced. The full pipeline for the differential techniques for radio emission involves the background estimate calculation on the individual empty sky region, the acquisition of the mean background, and subtracting the mean background image from the target source image. The pipeline still requires further development to perfect the technique. However, some of the advantages of the technique has been shown in this work.

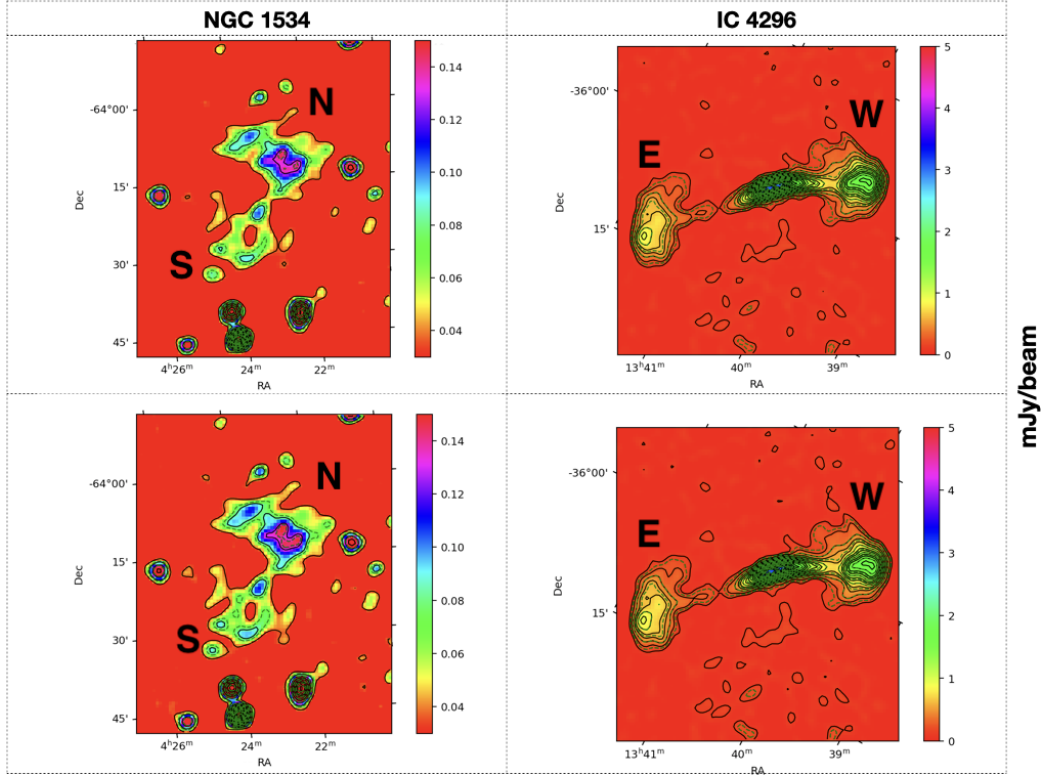


Figure 6.3: Illustration of the differential technique using observations of the target sources selected from the GLEAM survey, NGC 1534 and IC 4296, where the green dashed contour is at 3σ and the black contour starts at 2σ with 2σ increments. **Top:** before subtracting the calculated background. **Bottom:** after subtracting the calculated background.

6.5 Conclusion

Our approach to this work is based on a differential analysis of the cosmic radio background to measure the SZE-21cm of the DA and EoR. This work presented the preliminary pipeline of a differential technique for radio astronomical images. While the differential technique is relatively straightforward to implement, the examples are shown here demonstrate the applicability of the proposed technique to improve the signal-to-noise and to some extent, the pipeline can be considered, among other techniques, for source detection, extraction, characterization, and those aimed at enhancing the features of sources in radio continuum images. However, it is also important to check if artefacts are introduced when employing this technique.

Chapter 7

Summary, future work, and thesis conclusion

7.1 Summary and discussions

Following the detection claimed by the EDGES collaboration ([Bowman et al. 2018](#)) of the surprisingly deep absorption trough in the 21 cm global spectrum, several models have been explored to explain it. This measured signal, if confirmed, would give us a completely new perspective into the physics of the Universe’s evolution, probing the DA and EoR. Detection of this signal is challenging as it is orders of magnitude fainter than systematic effects. The work presented in this thesis aimed to probe these epochs using the distortions of the global 21 cm signal due to the Sunyaev-Zeldovich, the SZE-21cm ([Colafrancesco et al. 2016](#)). The SZE-21cm is intrinsically a differential measure between two directions, conducted through a procedure where a galaxy cluster is tracked for a certain amount of time and then the telescope is moved to a trailing empty patch of sky for the same amount of time. Amongst the advantages of this type of differential observations to detect the SZE-21cm, is the weak dependence by issues like exact calibration of the observed intensity and the confusion from galactic foregrounds, which are generally spatially smooth over angular scales larger than clusters.

Using simulated galaxy cluster differential observations, maps of the SZE-21cm were produced and the SZE-21cm at the cluster was measured, taking into account effects of foregrounds, thermal noise, angular resolution, and point sources. The spectral features of the SZE-21cm from our simulated observations with HERA and SKA1-low yielded results that are close to prior theoretical predictions ([Colafrancesco et al. 2016](#); [Takalana et al. 2018](#)). Studying the detectability of the SZE-21cm generated

from a theoretical model of the 21 cm global signal and the EDGES signal in Figure 3.8, we find that the SKA1-low and SKA2-low interferometers will be able to detect the signal from both the EDGES and theoretical 21 cm global spectra. The SZE-21cm can therefore be seen as a viable technique to confirm the EDGES result. In the caveat where the EDGES SZE-21cm is reliable (70-90 MHz), SKA1-low and SKA2-low interferometers can distinguish the SZE-21cm from the theoretical model and the one resulting from an EDGES-like background at a level between 2σ and 3.5σ , assuming sensitivities for 100 kHz bandwidth, 1000 hours of integration, 2 polarizations, no taper, and no weight (Dewdney et al. 2012). In Chapter 4, we further explored the use of the SZE-21cm. Here, it can also be used to distinguish between different models of the cosmological 21 cm signal that affect the timing, shape, and amplitudes of the global 21 cm signal make distinct imprints on the SZE-21cm. This feature can be exploited by future observations to rule out those models that are inconsistent with experimental data. However, we do caution that, if the different models for the background give very similar results, this may result in SZE-21cm spectra that are also very similar and it will be hard to distinguish between the models.

Using updated parameters for the SKA-low interferometer and its sensitivity, we confirm the claim by Cooray (2006), that by stacking observations of the effect over a sample of clusters we should be able to decrease the total expected error budget when observing with radio interferometers (see, Figure 3.6). However, since the SZE-21cm is dependent on the temperature of the intracluster plasma we can not get away with stacking clusters with different plasma temperatures. One way to get around this is to average the SZE-21cm for clusters with the same plasma temperatures only as we assumed for Figure 3.6. We proposed a method to average the SZE-21cm for clusters with different plasma temperatures, which involves using quasi-polynomial fits to calculate the SZE-21cm for any plasma temperature and then obtaining an approximation of the average SZE-21cm for any number of clusters in a given range of plasma temperature.

A method of possibly clean radio images was presented in Chapter 6 of this work aiming to reduce the effects of contaminating backgrounds and foregrounds that present challenges in low-frequency continuum radio observations and we found that while the procedure contributes to a signal-to-noise improvement, the features of extended, low-surface brightness sources may only moderately improve overall, this is a result of large-scale background signals being completely filtered out by interferometric observations, and as such, background subtraction may not be necessary to see any further improvements in the features.

7.2 Future work

We have identified the challenges that need to be addressed to detect the SZE-21cm with upcoming interferometers; these include errors that arise due to cosmic variation, instrumental noise, and point source contamination. The data for this work was generated via simulations and we found that to detect the SZE-21cm we will need to have a good understanding of the systematics at the frequencies of interest. For example, in this work we obtained a percentage error of 6% for the SZE-21cm simulated for observation with the SKA1-low beam after point source subtraction, it is now pressing that we further study point sources hosted by clusters at the relevant frequencies to develop a robust strategy to mitigate contamination as a result of point sources. This can be done in the coming years with data from the MWA which is already operational and HERA when it comes online, and leading up to the roll-out of SKA1-low. Furthermore, we need to study for synchrotron emission, which is predicted to be an order of magnitude stronger than the SZE-21cm at the relevant frequencies. X-ray and Microwave data will also be obtained to find clusters with strong SZE signal at higher redshifts ($z > 1$). This can be done from readily available public data from SPT, Planck, ACT, and ALMA. We will also need to understand the instruments that will be used to obtain these large data sets. For example, we expect better sensitivity observing at a wider channel width as this can help detect and derive information on the SZE-21cm. In this work, we assumed 1000 hours of integration time per cluster. The HERA and SKA1-low beams are about 10 degrees at 150 MHz (DeBoer et al. 2017) and 5 degrees at 110 MHz (Labate et al. 2017), respectively. A cluster will spend between 40 to 60 minutes per day in the primary beam, translating to about 3 years of observation with SKA1-low and about 4 years with HERA. We might need to come up with observing strategies that decrease the integration time without compromising on the sensitivity of the observations.

Colafrancesco et al. (2015) has also shown that SKA1-MID, SKA-LOW, and MeerKAT can measure the SZE modified by non-Planckian effects (SZ-NP) during recombination ($z=1500$), by observing the peak of the SZ-NP located exactly at the plasma frequency at that epoch, independent of the cluster parameters. This will allow us to open a unique window for the experimental exploration of plasma effects in the early universe using SKA, and at the same time help us understand the SZE signal at frequencies between 350 and 1050 MHz. For the SZE in general, the variations of the temperature inside a cluster need to be studied and understood to correctly measure the SZE produced by the cluster (Colafrancesco & Marchegiani 2010). This will require us to use interferometers with good spatial resolution so that the temperature variation can be accounted for well when conducting observations to detect the SZE.

The pipeline proposed for low-frequency radio observations for purposes of source detection, extraction, characterization, and enhancing the features of sources in radio continuum images as-presented in Chapter 6 reduces the signal to noise. However, it does not effectively enhance sources and the pipeline may need to be redesigned. One way to do this may be to determine a robust estimator between the mean and median background for the true background. Furthermore, there is a need to investigate if any boosting effects of faint source by noise to go over the threshold come into play (see, [Yoho et al. 2013](#)), which may result in biases.

7.3 Conclusion

Moving from simulations to real data is necessary to study systematics and find the best strategy for observing and measuring the SZE-21cm to probe the DA and EoR. It will also help us to understand the results from our simulations, for example, the deviation between the true signal and simulated observation with HERA and SKA at high frequencies, which is unexpected for observations with SKA1-low. The detection of the SZE-21cm with the upcoming HERA and SKA instruments is promising and will yield insightful information on the history and physical mechanisms occurring during the DA and the subsequent EoR. Furthermore, the simulations have helped us examine possible models that probe the origins of the EDGES signal and the SZE-21cm has been demonstrated as a viable technique to confirm the EDGES result and other results that may be released in the near future pertaining to the global 21 cm signal. The differential technique presented by this work will also be important for developing methods to detect other forms of the SZE such as the SZ-NP.

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