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**Probing Dark Matter in 2HDM+S with MeerKAT Galaxy Cluster
Legacy Survey**

by
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Declaration

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

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Date: 13 January 2023

Abstract

The unknown nature of dark matter remains an eyesore on our cosmological paradigm. As it is believed to constitute the majority of the matter content of the Universe, determining its properties is imperative to our understanding of the formation and evolution of the Universe. Weakly Interacting Massive Particles (WIMPs) are predicted to produce diffuse synchrotron emission as an indirect consequence of their annihilation. Radio frequency dark matter searches are gaining in prevalence due to the high sensitivity and resolution capabilities of the new generation of radio interferometers. MeerKAT is currently the best instrument of its kind in the southern hemisphere, making it a prime instrument for indirect dark matter searches. By making use of publicly available galaxy cluster data from the MeerKAT Galaxy Cluster Legacy Survey we are able to use the diffuse emission observed in clusters to constrain the dark matter parameter space. In this work we consider three generic WIMP annihilation channels ($b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$) as a representation of the larger total set of possible channels. Additionally, we probe the properties of the dark matter candidate within the 2HDM+S particle physics model, which was developed as an explanation to various anomalies observed in the Large Hadron Collider data from runs 1 and 2. This model has been considered as a potential explanation to various astrophysical anomalies due to the overlapping predicted mass ranges. We undertake a statistical analysis of the radio flux densities within galaxy clusters, considering radio halos, mini halos and a non-detection of diffuse emission, to produce upper limits on the dark matter annihilation cross section. We are able to exclude the thermal relic value for WIMP masses < 200 GeV. We show that within the uncertainty band of the dark matter density profile, 2HDM+S remains a viable explanation for the various astrophysical excesses. We produce some of the first WIMP dark matter constraints produced with MeerKAT, which are comparable to some of the most stringent limits to date.

To Mom, Dad and Jarod for the unending support through this journey.

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List of Acronyms

2HDM+S	2 Higgs Doublet Model + Singlet Scaler
AdvACTPol	Advanced Atacama Cosmology Telescope Polarimeter
APERTIF	Aperture Tile in Focus
ATCA	Australia Telescope Compact Array
ASKAP	Australian Square Kilometer Array Pathfinder
BCG	Brightest Central Galaxy
COUPP	Chicago land Observatory for Underground Particle Physics
CL	Confidence Level
COBE	Cosmic Background Explorer
CMB	Cosmic Microwave Background
CDMS	Cryogenic Dark Matter Search
CRESST	Cryogenic Rare Event Search with Superconducting Thermometers
DR1	Data Release 1
EMU	Evolutionary Map of Universe
EDELWEISS	Expérience pour Detector Les WIMPS En Site Souterrain
FITS	Flexible Image Transport System
FWHM	Full Width Half Maximus
GBT	Green Bank Telescope
HEPP	High Energy Particle Physics
HIFLUGCS	Highest X-ray Flux Galaxy Cluster Sample

LHC Large Hadron Collider

LOFAR Low Frequency Array

MHD Magnetohydrodynamics

MACHO Massive Compact Halo Objects

MGCLS Meerkat Galaxy Cluster Legacy Survey

NFW Navarro, Frenk and White

PICASSO Project In Canada to Search for Supersymmetric Objects

SPT-3G South Pole Telescope 3G

SKA Square Kilometer Array

SIMPLE Superheated Instrument for Massive Particle Experiments

SUMSS Sydney University Molonglo Sky Survey

WIMP Weakly Interacting Massive Particles

WRST Westerbork Synthesis Radio Telescope

WMAP Wilkinson Microwave Anisotropy Probe

Chapter 1

Introduction

Historically, radio frequency searches for indirect signals of dark matter have been disfavoured, due to complicating factors, such as the strong dependence of dark matter emission on the magnetic field configuration in the target object. Advancements of radio astronomy techniques and technology are beginning to overcome these obstacles. The new generation radio interferometers, such as MeerKAT, are able to probe faint diffuse fluxes due to their impressive sensitivity. These faint fluxes are ideal for comparing to dark matter predictions. It is expected that radio frequency dark matter searches will be able to produce highly competitive limits for the properties of dark matter models.

1.1 Dark Matter

In the current cosmological consensus dark matter constitutes roughly a quarter of the energy budget of the Universe. Due to this significant contribution it is expected that dark matter plays a key role in the formation of structures and the future evolution of the Universe. Without the presence of dark matter, the gravitational energy of baryonic matter would have been insufficient to slow the expansion from the Big Bang [1], inhibiting structure formation within the current timeline. However, the precise nature of this component remains an open question. Solving this long standing puzzle will be imperative to modern cosmology and to our potential for understanding the history and evolution of the Universe. Natural philosophers have postulated through out history that there may exist forms of matter unknown to us, either due to limitations in our observational capabilities or perhaps an intrinsic invisibility [2]. Friederich Bessel was one of the first to predict the existence of an unseen astronomical object in 1844, based solely on gravitational influence through an analysis of the proper motion of Sirius and Procyon [3]. An early and one of the most widely cited indications for dark matter was in the 1930's, when Zwicky noticed that galaxies in the Coma cluster were moving too fast to be supported by visible matter alone [4]. He then postulated the cluster had to contain an additional, invisible, mass component. Similar evidences were found in the following years, for example Kahn and Woltjier [5] noted that the motion of Andromeda was an indication of dark matter within our local group. However, it was not until the work of Rubin and Ford [6] that dark matter began to be widely accepted. Their argument for additional mass in the outer regions of galaxies was based on the comparison of the rotation curves predicted from photometry and those measured with the 21cm HI observations. This has since become one of the most well-known and cited results in literature. In modern literature dark matter is the proper noun of the most abundant type of matter, whose nature remains unknown. This is a stark contrast to historical mentions, where dark matter tended to mean any astrophysical material that was too faint to be observed. Many astronomers believed that dark matter may be composed of objects such as white dwarfs, neutron stars or cold clouds of gas. It was not until the 1980s that particle physicists became interested in the dark matter problem, eventually leading to the establishment of an unknown subatomic particle species as the dominant paradigm for dark matter [2].

1.1.1 Observational evidence

Over the last few decades observational evidence for the existence of dark matter has become overwhelming, and comes from various astrophysical measurements. As such, the standard model of cosmology includes dark matter as a constituent of the Universe. Below we review some of the evidences of dark matter in different astrophysical objects.

Rotation curves

A rotation curve plots the mean circular velocity as a function of distance from the centre of the galaxy (by extension this applies to clusters as well). Rotation curves of galaxies (and galaxy clusters) do not display the expected Keplerian fall-off [6], which implies, as the simplest explanation, the presence of additional mass.

The rotational velocities within galaxies are obtained via spectroscopic observations of emission lines from stars or gas in the optical disk. Some methods of this process are outlined in [7]. The resulting rotation curves were observed to increase rapidly with distance from the centre, then flatten out to an approximate constant value [8, 9]. This behaviour has continued to be observed in galaxies, including the Milky Way [10, 11]. The visible matter within these structures cannot account for this behaviour alone, as is evidenced by the inability of the luminous matter to trace the distribution of the gravitating matter. However, if it is assumed that the luminous matter was embedded within a dark matter spherical halo, the observed rotation curves are reproducible [12].

Some estimations of the dark matter content can be made by considering the mass-to-light ratio but this is subject to limitations. The outer regions of the rotation curves are not well sampled, due to the lack of emitting objects beyond the disk [13]. Thus rotation curves are only able to trace a small portion of the dark matter distribution.

Gravitational lensing

Einstein's Theory of General Relativity [14] predicts that light moving through a gravitational field will be deflected. As such, mass distributions in galaxies and clusters can be probed by observing the distortion, or lensing, of signals from distant emitters. This overcomes the limitations of rotation curves and is able to probe dark matter distributions out to much larger radii. Lensing can be broadly classified into two classes, strong and weak. Strong gravitational lensing occurs around a dense concentration of mass where a strong distortion, and even multiple images of a single source, is observed. Weak lensing applies far out from the core of a mass distribution. In this region the light deflection is very slight, and an ensemble of sources is required to obtain the lensing signal [15]. These two classes probe complementing regions of structure, as the strong lensing techniques will probe the central regions while the weak lensing techniques probe the outskirts. In principle these methods should be combined to obtain a detailed mass distributions of clusters, for example [16].

The Bullet Cluster

The Bullet Cluster is the prototype of observing a cluster-cluster merger as a method for inferring the existence of dark matter. It is also an ideal test of modified gravity models (MOND) that argue against the existence of dark matter. When comparing the scale of the individual galaxies to the scale of the cluster it is reasonable to treat them as point masses. Under this assumption within the cold dark matter paradigm, the galaxies and the dark matter halo of the cluster will act as effectively collisionless during the pass of the subcluster through the main cluster, while the gas is affected by ram pressure. When observed through lensing it is expected the peak mass will correspond spatially with the galaxies, as this

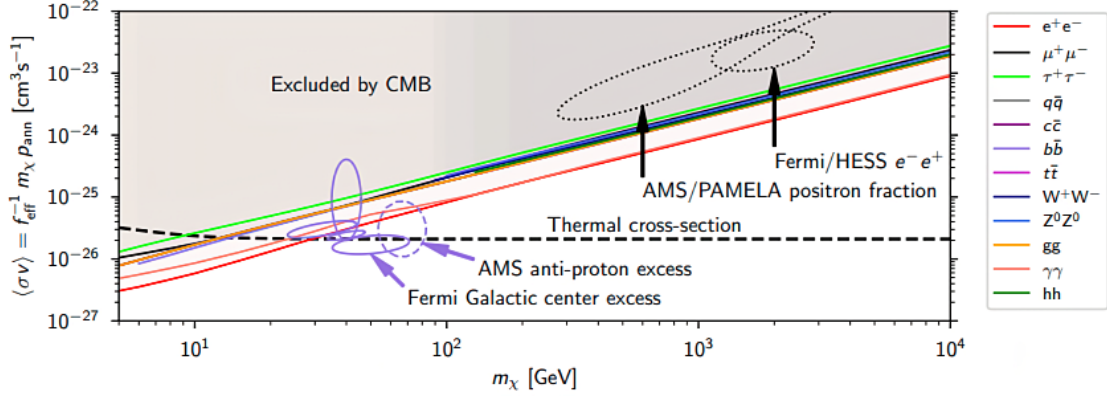


Figure 1.1: Upper limits on the dark matter mass and annihilation cross section obtained by the latest combined Planck collaboration results. Regions preferred by indirect detection experiments are overlaid for comparison, as well as the thermal-relic cross section. The purple regions assume annihilation into $b\bar{b}$, while the dotted regions assume annihilation into $\mu^+\mu^-$. Figure obtained from [22].

is where the dominant dark matter component will be situated. Correspondingly, in MOND the gas will be the dominant component, and thus the peak mass measured through lensing should be offset from the galaxies. In Clowe et al 2004 [17], the authors showed that the observations of the Bullet Cluster are in agreement with the cold dark matter situation, and not a MOND scenario.

CMB anisotropies

The cosmic microwave background (CMB) provides a powerful tool to probe the composition of the Universe at the time of recombination by observing acoustic oscillations of overdense regions. By observing the size and strength of these oscillations it is determined that matter composes approximately 30% of the energy density of the Universe, while baryons compose only 5%. Experiments, such as the Cosmic Background Explorer (COBE) [18], the Wilkinson Microwave Anisotropy Probe (WMAP) [19] and Planck [20], show that a Λ -CMB cosmology reproduces the observed anisotropies, providing strong evidence for dark matter.

Additionally, observations of the CMB anisotropies are able to probe and constrain the dark matter self-annihilation cross section of a Weakly Interacting Massive Particle (WIMP) dark matter candidate that is required to obtain the observed dark matter relic abundance [21]. The latest upper limits on dark matter mass and annihilation cross section are obtained by Planck [22] are obtained by combining the temperature anisotropies (TT), the polarization spectra (EE), the cross-correlation (TE), lensing reconstruction and baryon acoustic oscillations (BAO). These results are shown in Figure 1.1, with regions preferred by indirect detection experiments overlaid for comparison.

Newly operational or planned CMB experiments, such as BICEP3/KECK [23], the South Pole Telescope 3G (SPT-3G) [24] and the Advanced Atacama Cosmology Telescope Polarimeter (AdvACTPol) [25, 26], are expected to produce higher precision polarisation data, enhancing the sensitivity to dark matter annihilation. It is predicted that the constraints on dark matter properties may be improved by up to two orders of magnitude [27].

Primordial nucleosynthesis

The relic abundances of the lightest elements D , ${}^3\text{He}$, ${}^4\text{He}$ and ${}^7\text{Li}$ provide a probe of the contents and conditions of the very early Universe in which they were formed [28]. These abundances depend

on the baryon density and the expansion rate of the early Universe, parameters on which the CMB anisotropies depend as well. Predictions made by Standard Big Bang Nucleosynthesis (SBBN) appear to be in excellent agreement with current observationally inferred primordial abundances [29]. This supports Λ -CDM as well as the Standard Model of particle physics (introduced in Chapter 2)

1.1.2 Dark matter candidates

The evidences presented above provide a compelling argument for the existence of a dark matter component to the Universe that does not interact in the same way as baryonic matter. However, since dark matter interacts primarily through gravity, there is little information available on its nature or composition. It was initially thought that dark matter might be composed of stellar-like objects that were too faint to be observed, including dwarf stars, remnants, and primordial black holes [30]. This class of objects is known as massive compact halo objects (MACHOs). Many studies have since shown that if MACHOs are dark matter, they do not compose the dominant dark matter component within the Milky Way, from microlensing constraints placed on the matter budget that MACHOs would require if they were cosmologically significant e.g. [31, 32].

Considering the evidences provided by CMB anisotropies and the analysis of primordial nucleosynthesis it is evident that a majority of dark matter would be non-baryonic in nature. A simple solution would be to assume that this component would be composed of some composite undetected particles. Requirements for a particle model of dark matter are that the particle has mass, such that it is able to reproduce the gravitational evidences, it interacts very weakly with baryonic matter, and that the self interaction is able to reproduce the current observed abundances.

Particle dark matter candidates are broadly categorized as either hot or cold, with an additional intermediate category denoted warm, based on their velocity when they decouple from thermal equilibrium with the rest of the Universe. A relativistic particle would fall under hot dark matter, while a slow moving particle would be considered as cold. However, assuming large scale structures in the Universe form hierarchically, it has been shown that cosmologically significant dark matter must be cold in order to avoid early perturbations being damped by the effects of free streaming [33]. There are numerous candidates for particle dark matter, including sterile neutrinos, axions, supersymmetric candidates and most notably WIMPS [34]. Within this work we limit ourselves to WIMPS.

One of the most favoured and successful class of candidates are cold WIMPs. A WIMP solution to dark matter is attractive for a few reasons. They are found in many particle physics models, naturally reproduce the correct relic density when produced thermally, and have numerous potential methods of detection [35, 36]. A key property of these particles is their self-annihilation cross section. If one assumes a significant percentage of WIMP dark matter is produced thermally in the early Universe then the relic abundance would be produced during the freeze out mechanism [35] (when the dark matter particles cease to be in thermal equilibrium with the particles within the Standard Model). The annihilation rate is related to the present day abundance [37] through

$$\Omega_\chi h^2 \sim \frac{3 \times 10^{-27} \text{cm}^{-3} \text{s}^{-1}}{\langle \sigma_A v \rangle}, \quad (1.1)$$

where Ω_χ is the relic density of the χ particle in units of the critical density, h is defined as $\frac{H_0}{100 \text{km.s}^{-1} \text{Mpc}^{-1}}$ where H_0 is the Hubble constant consistent with the chosen cosmological framework, σ_A is the pair annihilation cross section and v is the relative velocity. The symbols $\langle$ and $\rangle$ indicate the quantity is averaged over the thermal velocity distribution. Following the practice in the literature, the quantity $\langle \sigma_A v \rangle$ is referred to as the annihilation cross section. Assuming that all dark matter is constituted of the particle

χ , then $\langle\sigma_{Av}\rangle$ is revealed by comparing with the present day abundance. For a generic WIMP the most often quoted value is $\langle\sigma_{Av}\rangle \sim 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ [38].

It is noted that there are other WIMP candidates besides thermally produced WIMPS. One such example are Two Higgs Doublet Models. The model this work considers falls in this category and will be discussed in detail in Chapter 2. Additional examples include the lightest neutralino in supersymmetric (SUSY) models, Sneutrinos which are the scalar partners of neutrinos within SUSY, and models with compactified universal extra dimensions [35].

1.1.3 Detection techniques

There are three categories of detection techniques for dark matter particles, direct detection, in which a dark matter particle would scatter off target material in a detector; indirect detection, that aims to detect the products of dark matter annihilation or decay in an astrophysical environment; and the detection of signatures that dark matter particles produce at particle colliders. These techniques are independent of each other, as well as being complementary. All three techniques require a coupling between dark matter and Standard Model particles, even if only very weakly, to produce visible signals.

Collider searches

Dark matter searches at particle colliders offer the possibility of producing WIMPs, either directly or through the decay of heavier exotic mediator particles. Due to the weak interactions dark matter has with Standard Model particles, any particles produced will not produce a visible signal. Instead the production of dark matter particles can be inferred by any imbalances in the transverse momentum [39]. The net momentum in the plane perpendicular to collider beams is zero, and momentum conservation requires that this remains true after the collision has taken place. An imbalance in this plane is a primary signal for the the production of dark matter [39]. This quantity is termed missing transverse momentum or missing transfer energy, $\cancel{E}_T$. Challenges for the measurement of this quantity include the rejection of fake missing transverse momentum due to the contribution of non-collision backgrounds to the tails of the spectrum. Additionally any contributions from the debris of concurring proton-proton interactions have to be excluded [40]. Such production events are typically accompanied by visible particles that will recoil off of the invisible particles. Such signals are often called mono-X, where X is a visible physical object such as a photon or a jet.

Mono-X searches do not target specific signals, but look for statistically significant deviations from the predicted background from well understood Standard Model processes. In mono-photon searches the signature is characterized as large missing transverse momentum recoiling against a high transverse momentum photon with no additional leptons, and at most one jet. The signature for the mono-jet channel is at least one energetic jet, large missing transverse momentum and no additional leptons. Mono-jet reactions are the most abundant of the mono-X reactions and are typically more sensitive to Beyond Standard Model (BSM) physics [41]. However these channels are subject to an irreducible background caused by the production of Z bosons decaying to neutrinos [41].

The Large Hadron Collider (LHC) is currently the best machine to search for new particle physics [42]. The two defining characteristics that make this machine powerful are the unprecedented collisions' centre-of-mass energy, up to 13 TeV in the latest run, allowing it to be sensitive to the production of new heavy mediators. The high instantaneous luminosity allows for the probing of extremely low cross sections [43]. Several dark matter searches have been performed at the Compact Muon Solenoid (CMS) [44] and A Toroidal LHC Apparatus (ATLAS) [45] experiments at the LHC. Limits on the dark matter

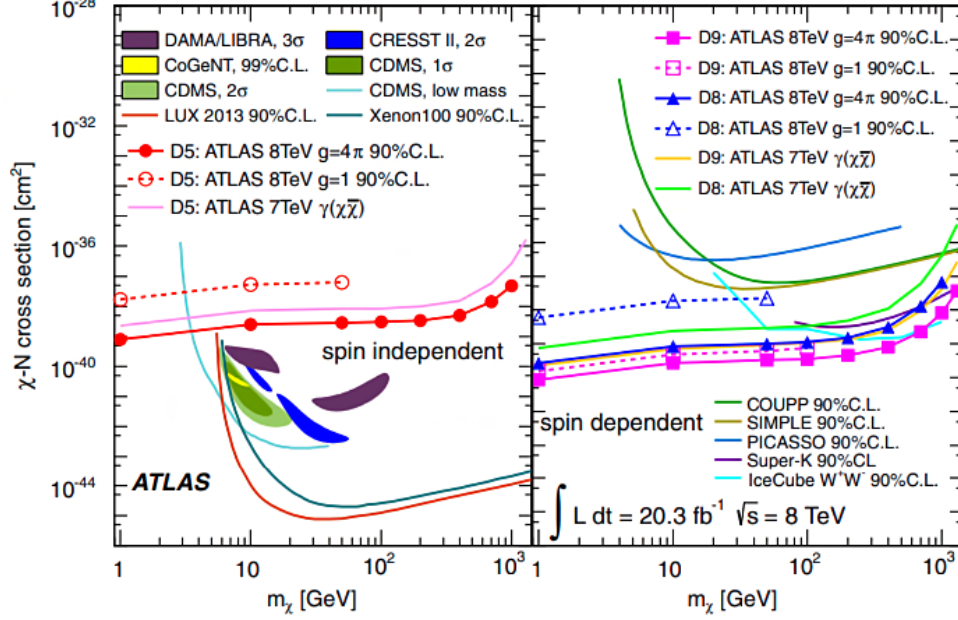


Figure 1.2: Upper limits at a 90% CL of the scattering cross section determined by the ATLAS experiment. Various direct detection limits are shown for comparison. Figure from [46].

scattering cross section with nucleons are displayed in Figure 1.2 and Figure 1.3 for ATLAS and CMS respectively.

Collider searches have the advantage of being sensitive to low WIMP masses, on the scale of a few GeV. Direct and indirect detection loses sensitivity as the WIMP mass decreases due to less energy being involved in the interaction, whereas lighter particles are more readily produced in colliders. Collider searches have the additional advantage of a well understood experimental environment, in contrast to the large uncertainties in initial state (e.g. velocity and density distribution of dark matter) experienced by direct and indirect searches [47]. However an uncertainty faced in collider searches is the time scale on which the produced particle is stable, since only the time spent within the collider can be probed [48].

In order to connect the discovery, or non-discovery, of invisible particles to dark matter, information from both direct and indirect experiments is required. A particle physics model must be assumed to make this connection, and then within the context of this model different types of information can be compared. One benefit of this connection might be more targeted collider searches [40].

Direct detection

This detection technique aims to detect the scattering of a dark matter particle off of a target nucleus through the interaction $\chi P \rightarrow \chi P$, where P is any standard model particle. It is expected that the elastic scattering of WIMPs in the mass range (10-1000) GeV/ c^2 will produce nuclear recoils in the energy range (1-100) keV [50]. The signature of a direct detection experiment would be the recoil spectrum of single scattering events. The differential recoil spectrum [50] can be expressed as

$$\frac{dR(E, t)}{dE} = \frac{\rho_\chi}{m_\chi m_A} \int v f(\mathbf{v}, t) \frac{d\sigma(E, v)}{dE} d^3v, \quad (1.2)$$

where m_χ is the mass of the dark matter candidate, ρ_χ is the local dark matter density, m_A is the mass of the nucleus, v is the speed of the particle, and $f(\mathbf{v}, t)$ denotes the velocity distribution of the dark matter

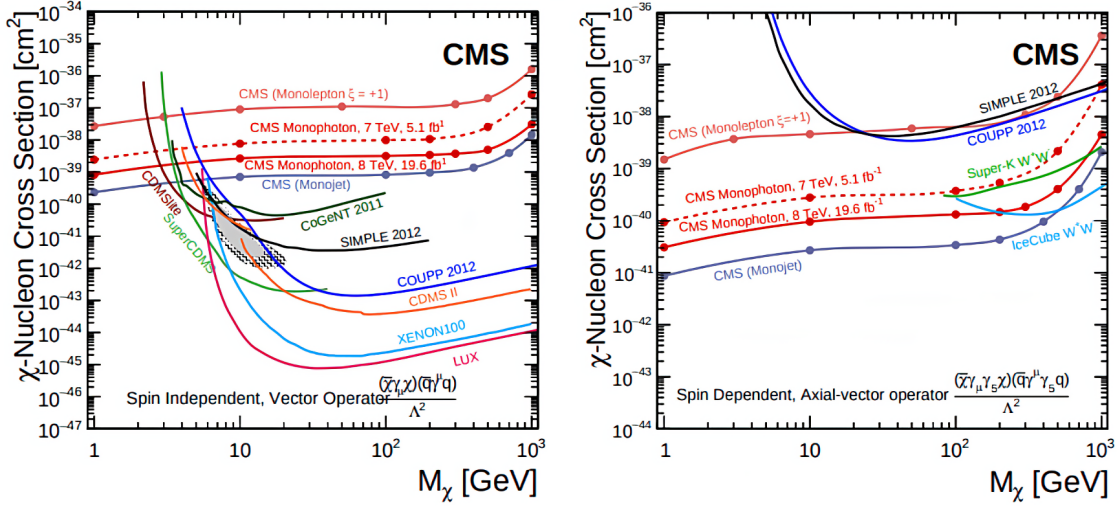


Figure 1.3: Upper limits at a 90% CL of the scattering cross section determined by the CMS experiment. Various direct detection limits are shown for comparison. Figure from [49].

particle within the reference frame of the detector. The differential cross section is denoted by $\frac{d\sigma}{dE}$. From this expression it can be seen that the cross section and mass of the candidate are the properties that can be probed with direct detection techniques [50].

A common approach of experiments is to attempt to measure the dependence on energy of the dark matter interactions. As shown in [51] the above equation can be approximated by

$$\frac{dR(E)}{dE} = \left(\frac{dR}{dE} \right)_0 F^2(E) \exp(-E/E_c), \quad (1.3)$$

where $\left(\frac{dR}{dE} \right)_0$ is the event rate for a zero momentum transfer, and E_c is a parameter that describes the energy scale [50]. Thus, it is expected that the signal will be dominant at low recoil energies, and becomes suppressed by the exponential term at higher energies.

An additional common signature that is searched for is the so called ‘annual modulation’ of the total event rate. This modulation is caused due to Earth’s motion in the galactic rest frame. However the amplitude of the variation is expected to be on the order of the Earth’s rotational speed to the Sun’s circular speed ~ 0.07 [52]. To first order the differential rate can be expressed as [52]

$$\frac{dR(E, t)}{dE} \approx \frac{dR(E)}{dE} \left(1 + \Delta E \cos \left(\frac{2\pi(t - t_0)}{T} \right) \right), \quad (1.4)$$

$T = 1$ year, and the phase $t_0 = 150$ days. The sign of ΔE is negative for small recoil energies and positive for large recoil energies, and the energy at which the phase changes is referred to as the crossing energy. This value depends on the mass of the target nuclei as well, as that of the WIMP. In principle determining the crossing energy would allow for the determination of WIMP mass, however this requires low experimental energy thresholds [52].

A stronger signature would be the asymmetry in the directional signal [53], due to the Earth’s motion in the galaxy. The WIMP flux at the detector will be peaked in the direction of motion of the Sun, and as such the recoil spectrum should be peaked in the opposite direction. The interaction rate [54], expressed as a function of recoil energy and the angle between the WIMP velocity and the recoil velocity is

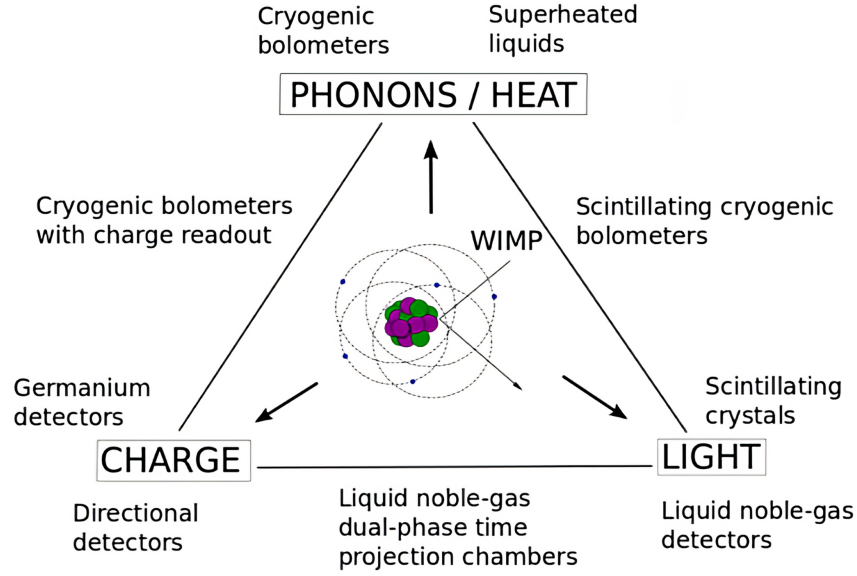


Figure 1.4: Schematic of potential signals measured in direct detector experiments depending on the type of detector. Figure from [50]

$$\frac{d^2 R}{dE d\cos\theta} = \frac{\rho_0 \sigma_{\text{WN}}}{\sqrt{\pi} \sigma_v^2} \frac{mN}{m_w m_r^2} \exp\left(\frac{-((v_{orb}^E + v_c) \cos\theta - v_{min})^2}{\sigma_v^2}\right). \quad (1.5)$$

This modulation should have an effect of the order ~ 1 [52]. However, observing this affect would require the ability to measure the direction of the incoming WIMP, as well as the axis and direction of the recoil. This is beyond current detector capabilities.

When a WIMP scatters off a target nucleus there are three potential signals that can be observed, depending on the detector in use. In solid detectors a recoil is observed through phonons and heat produced within a crystal as a result of transfer of kinetic energy in the scattering process. In liquid or gas detectors a recoil is observed through either scintillation photons released when a target nucleus de-excites, or through direct ionisation of the target atoms. Dual phase detectors that are able to detect two signals simultaneously have a higher discrimination against background signals [52].

The main challenges faced in direct detection include obtaining a low enough energy threshold in order to detect very small recoil energies, having a large detector mass to increase the probability of an interaction, as well as a low background in order to increase the significance of the signals. The background signals that affect direct detection experiments include external radiation in the form of gamma-rays, neutrons, neutrinos etc., as well as internal backgrounds that are detector specific. The background signals can be reduced with careful placement of the detector, typically in deep underground labs, as well as shielding the detector from cosmic rays, eg lead or large water tanks [50].

A synopsis of the various types of detectors and experiments is presented here. A more detailed review is given by Undagoitia et al [50]. A schematic of the signals searched for with the respective detectors is shown in Figure 1.4.

Successful examples of cryogenic detectors include Cryogenic Dark Matter Search (CDMS) [55], Cryo-

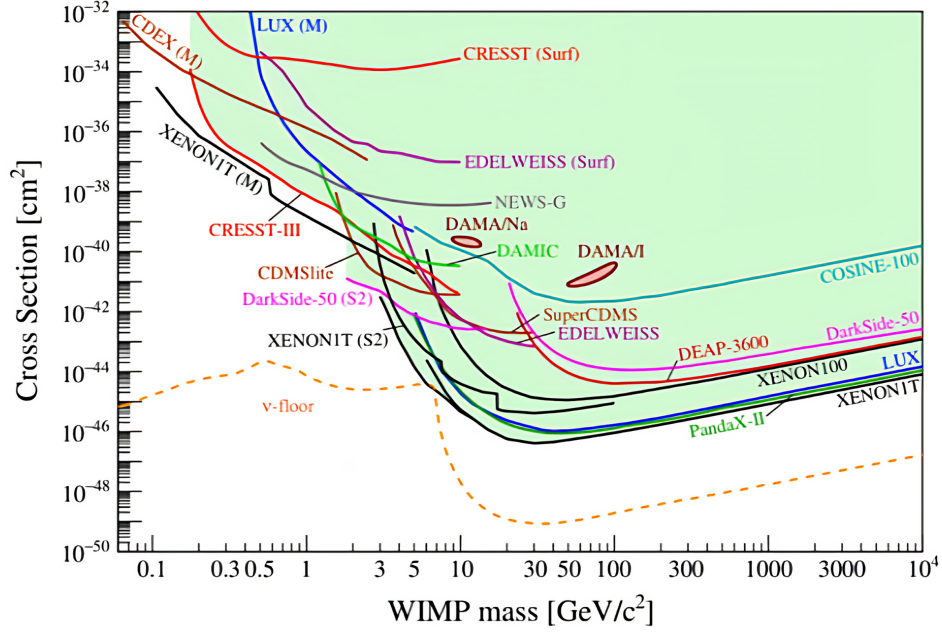


Figure 1.5: Current spin-independent WIMP-nucleon scattering cross section limits. Produced assuming an isothermal WIMP halo with $\rho_0 = 0.3 \text{ GeV/cm}^3$, $v_0 = 220 \text{ km/s}$, $v_{esc} = 544 \text{ km/s}$. Figure taken from [63]

genic Rare Event Search with Superconducting Thermometers (CRESST) [56] and Expérience pour Détecteur Les WIMPS En Site Souterrain (EDELWEISS) [57]. Such experiments have low energy thresholds ($\sim 10 \text{ keV}$), high energy resolution, and the added advantage to differentiate between nuclear and electronic recoils [52]. Germanium ionization detectors, such as Texono [58] and CoGeNT [59], have low backgrounds and are able to reach sub-keV energy thresholds. However, they have the disadvantage of being unable to differentiate between nuclear and electronic recoils.

Liquid noble gas experiments are excellent examples of dual phase scintillation and ionization detectors. Xenon and Argon have high light yields from scintillation as well as being good ionizers. Between these two elements Xenon is favoured for being radioactively clean, and having a wavelength of scintillation that is readily observable to commercial photocathodes [60]. A recent experiment in the XENON collaboration XENON1T [61] set an upper limit of the scattering cross section to $4.1 \times 10^{-47} \text{ cm}^2$ with an exposure of 1 ton year. Its successor XENONnT has increased the target mass to 5.9 tons, and is expected to improve these limits by an order of magnitude [62].

A collection of the scattering cross section for WIMP-nucleon interactions is shown in Figure 1.5.

If the scattering cross section depends on the spin of the particles, it is required that the target nuclei have an uneven total angular momentum [52]. Fluorine is a favoured target nucleus for these experiments, as the majority of the spin is carried by a unpaired proton, leading to constraints an order of a magnitude better than other target nuclei [52]. Superheated liquid detectors of this kind include the Project In Canada to Search for Supersymmetric Objects (PICASSO) [64], Chicagoland Observatory for Underground Particle Physics (COUPP) [65] and the Superheated Instrument for Massive Particle Experiments (SIMPLE) [66]. Upper limits for the spin-dependent scattering cross section are shown in Figure 1.6.

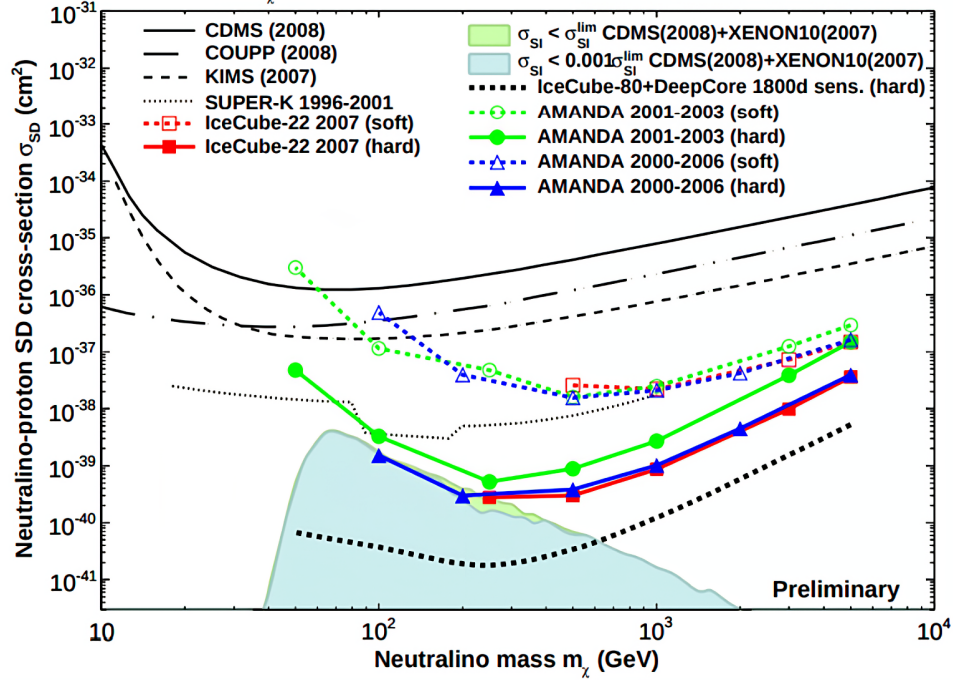


Figure 1.6: Upper limits on the spin-dependent WIMP-nucleon scattering cross section. The shaded region are predictions for neutralino dark matter in the general minimal supersymmetric standard model. Figure from [36].

Indirect detection

A fundamental property that indirect detection experiments hope to characterize is the self annihilation cross section of dark matter. Following the ‘thermal relic’ scenario of WIMP production, where dark matter was in thermal equilibrium with Standard Model particles, it is expected that dark matter will continue to annihilate and produce visible signals, characterized by the cross section. Products that can be observed through this process can be stable Standard Model particles, either produced directly or in the decay of intermediate unstable particles, or the secondary emission of these particles interacting with the astrophysical environment [67]. By observing the visible products of annihilation processes and determining the annihilation cross section, it may be possible to gain insight into the mechanisms that govern the dark matter abundance we see today.

The dark matter density distribution is a key input for the prediction of indirect dark matter signals. Unfortunately it is often the source of large uncertainties. Thus any constraints on the annihilation cross section depend heavily on the presumed density profile for the dark matter halo. A common choice is the universal fitting function obtained with high resolution N-body simulations by Navarro, Frenk and White (NFW) [68], namely

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right) \left(1 + \frac{r}{r_s}\right)^2}, \quad (1.6)$$

given in terms of the characteristic density ρ_s and the scale radius r_s . However, it must be noted that this function describes only the smooth component of the host halo. Within the Λ CDM paradigm structure forms hierarchically, with the smallest structures collapsing first and larger structure formed through smooth accretion or through the mergers of smaller structures. The density of the substructures resist the tidal forces present in mergers and remain bound, forming clumps within the host dark matter halo. The presence of these clumpy subhalos can strongly enhance the dark matter annihilation signal. This

enhancement is commonly referred to as the boost factor [37]. High resolution N-body simulations are unable to probe the full mass range of subhalos, requiring extrapolation for smaller masses. This introduces additional uncertainties when predicting annihilation signals.

For neutral particles the prompt, or primary, flux emitted in an annihilation process can be factored into a part that depends on the particle physics model and a part that depends on the dark matter distribution. This factor is commonly referred to as the J-factor, and can be expressed as in [37]:

$$J_{\text{ann}}(\phi) = \int_{\text{los}} \rho^2(\phi, l) dl \quad (1.7)$$

The J-factors characterize the relative size of expected annihilation signals. Neutral particles, specifically gamma-rays and neutrinos, will travel to us relatively undistorted, thus may carry spatial and spectral information. Gamma-rays in particular are thought of as a ‘golden channel’ for indirect WIMP detection. When the mass range of WIMPs is considered, it is expected that a large portion of the annihilation emission will correspond to gamma-ray energies. Below ~ 100 GeV, space based telescopes such as Fermi-LAT produce some of the strongest limits on the annihilation cross sections [69, 70]. At higher gamma-ray energies, ground based imaging atmospheric Cherenkov telescopes such as HESS, MAGIC and VERITAS, obtain the stronger bounds for WIMP annihilation [71, 72, 73, 74].

In contrast, any charged particles that are produced as a result of dark matter annihilation will diffuse within the astrophysical environment and can rapidly lose energy through secondary processes. The number density of these cosmic rays will be governed by a diffusion equation:

$$\frac{\partial}{\partial t} \frac{dn}{dE} = \nabla \cdot \left(D(E, \mathbf{x}) \nabla \frac{dn}{dE} \right) + \frac{\partial}{\partial E} \left(b(E, \mathbf{x}) \frac{dn}{dE} \right) + Q_e(E, \mathbf{x}). \quad (1.8)$$

In the above equation $\frac{dn}{dE}$ is the particle spectrum, the spatial diffusion is described with $D(E, \mathbf{x})$, $b(E, \mathbf{x})$ describes the rate of energy loss and the particle source function is given by the function $Q_e(E, \mathbf{x})$ [75].

Cosmic ray detectors can be highly sensitive as probes of dark matter annihilation, due to the low background of antimatter. Excesses observed by PAMELA [76] and later confirmed by AMS-02 [77] might be a possible signature of dark matter in the Galactic centre [78].

Additional secondary emission produced by the cosmic rays interacting with the production environment can be used to constrain properties of dark matter. Loss processes include Inverse Compton scattering, Coulomb scattering, synchrotron emission etc. In strong magnetic field environments synchrotron emission will be the primary energy loss process for electrons, allowing for the strongest bounds that can be obtained with secondary emission. This requires the constraint of the emission with the use of radio data. A collection of indirect search cross section upper limits is shown in Figure 1.7.

Galaxy clusters are ideal targets for indirect dark matter searches, due to their high dark matter content and the presence of large scale magnetic fields [79], and have been observed to contain diffuse extended emission. Secondary electrons produced by an annihilation event can interact with the cluster magnetic field and emit synchrotron radiation. The presence of faint diffuse emission within galaxy clusters is ideal for comparing to dark matter predictions.

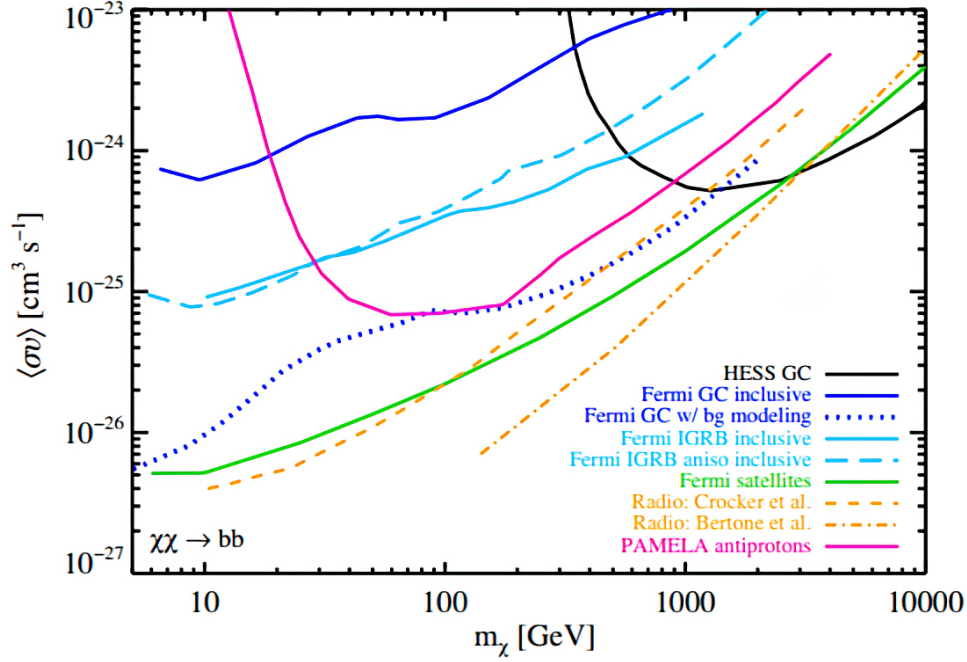


Figure 1.7: Upper limits on the annihilation cross section of WIMP dark matter models for various indirect detection experiments to the $b\bar{b}$ channel, at a 95% CL. Figure taken from [37].

1.2 Diffuse radio emission in galaxy clusters

An increasing number of galaxy clusters have been observed to contain diffuse extended radio sources. These sources are not associated with individual galaxies, but rather permeate the intra-cluster medium (ICM) and are indicative of the presence of both non-thermal cosmic rays and large scale magnetic fields [80]. They are characterised by a low surface brightness and a steep spectrum [81]. Traditionally there are three broad classifications of diffuse extended emission that depend upon the location of the emission within the cluster and the morphology [82]. These classifications are halos, mini-halos and radio relics. Halos are typically positioned at the centre of the cluster, mini-halos surround the brightest central galaxy (BCG), while radio relics are commonly located on the cluster periphery [80].

In this work we focus on halos and mini-halos, primarily due to their centralized location within clusters. The central regions of clusters have stronger magnetic fields, and a higher concentration of dark matter. As such, we expect the dark matter annihilation signal to be stronger in these regions than in the cluster periphery, where the magnitude of these properties is greatly reduced.

The production mechanism of the radio halos has historically been debated predominantly between two possibilities, primary and secondary electron models. In secondary, or hadronic models, it is postulated that the relativistic electrons are continuously injected into the ICM as a result of proton-proton collisions [83]. However, pure hadronic models have difficulty explaining observations, such as the steepening of the spectrum that has been observed in some halos [84], or the flat radio brightness distribution [85]. An additional consequence of hadronic interactions is the production of gamma-ray emission, arising from the decay of neutral pions [86]. Upper limits of gamma-ray emission from galaxy clusters are able to constrain the cosmic ray content, and thus test the hadronic nature of radio halos [87]. In primary electron models seed electrons present within the ICM are re-accelerated by cluster turbulence or shocks [88]. An open question within re-acceleration models is the source of the seed electrons. The electrons

could be secondary products of hadronic interactions [89], or injected by galaxy outflows or AGN activity [90]. Dark matter annihilation may also contribute to the population of relativistic electrons and positrons [91]. Additionally, it is possible that the origin of radio halos could arise from both primary and secondary electrons, in a hybrid of the two models [88].

1.2.1 Radio Halos

Giant radio halos are ~ 1 Mpc sized diffuse sources that are centrally located within massive dynamically disturbed clusters [80]. They tend to follow the distribution of the thermal X-ray emission and have a regular morphology [88]. They are unpolarized down to a few percent, in contrast to radio relics which exhibit high levels of polarization. The host clusters of radio halos typically display ongoing or recent merger activity [92]. The Coma cluster (Figure 1.8) was the first member of this source class that was discovered, and has become the most well studied [85, 93, 94, 95, 96]. Due to improved observational capabilities in recent years, smaller halos with irregular morphologies have been detected. These sources share the properties of giant halos. Giovannini et al [97] reported that the correlation between linear size and total radio power of a halo is continuous between small and giant scaled halos. This supports that these sources belong to the same class and have a common physical mechanism [88].

The production mechanism of giant radio halos has historically been debated between primary or secondary electron models [98]. In secondary models relativistic electrons are produced in hadronic interactions with cosmic ray protons and ICM protons. The same interactions are expected to induce a diffuse gamma-ray flux, as a result of the production and subsequent decay of neutral pions [80]. At present no significant detection of this emission has been reported [99, 100, 101, 102]. Gamma-ray observations and upper limits are able to constrain the cosmic ray proton content within the cluster, and test the hadronic nature of the radio halo. A joint likelihood analysis of Fermi-LAT data for 50 Highest X-ray Flux Galaxy Cluster Sample (HIFLUGCS) clusters performed by Ackerman et al [103] was able to constrain the contribution of cosmic ray protons to below a few percent within the viral radius. Investigations of the Coma radio halo show that a purely hadronic origin is incompatible with radio, including the Faraday rotation measures, and gamma-ray observations, as it would require a large magnetic field value that is in tension with rotation measure data [83, 104]. As such a turbulent re-acceleration scenario is the favoured candidate for the origin of giant radio halos.

In re-acceleration models a population of seed electrons is re-accelerated by turbulence that is produced as a consequence of cluster mergers [105, 106]. A critical point in re-acceleration models is the need for seed electrons in the ICM. These are possibly injected by AGN activity, supernova, starbursts or radio galaxies [107]. Hadronic interactions are also likely to contribute to the population of seed electrons [105]. It is possible that the products of dark matter annihilation events could potentially contribute to the seed electron population [79, 108].

1.2.2 Mini-halos

Mini-halos are found in relaxed cool-core clusters, and surround a bright central radio galaxy. Scales vary between ~ 100 to 500 kpc [80]. As with radio halos they are characterised by having a low surface brightness and a steep spectrum. The prototype of a mini-halo is the one found in the Perseus cluster [110] (Figure 1.9). As with radio halos the origin of the diffuse emission remains debated. While a mini-halo encompasses the central radio powerful galaxy, the activity of the galaxy would be insufficient to power the diffuse emission [111]. This can be confirmed by considering that the timescales required by the electrons to diffuse from the galaxy across the cooling region is much larger than the radiative lifetimes of the electrons [112]. Thus, as with giant halos in situ production or re-acceleration is required

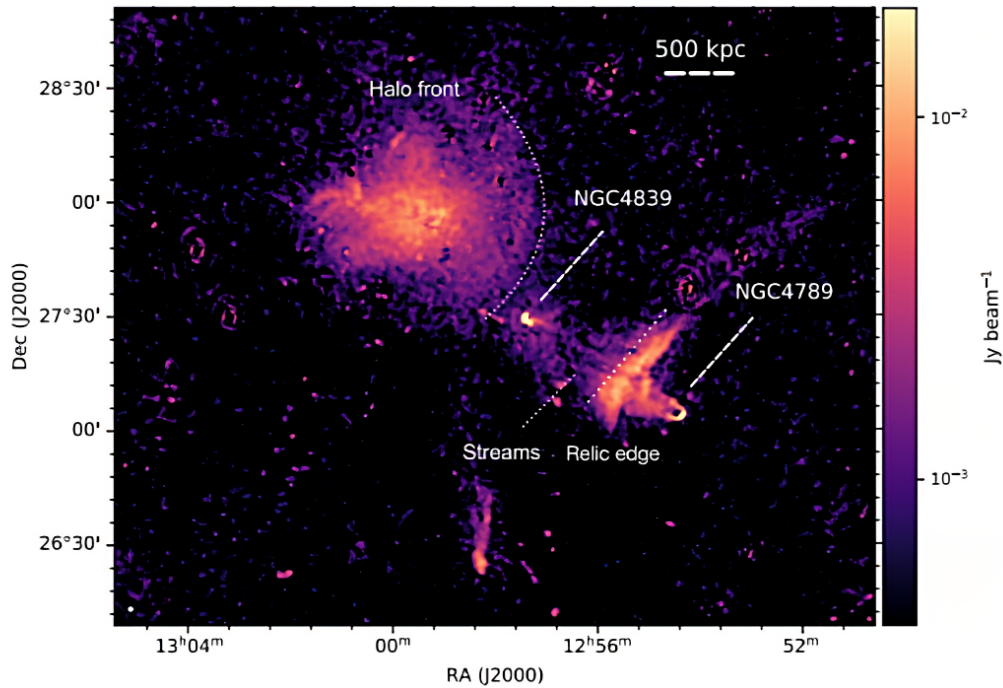


Figure 1.8: LOFAR emission of the Coma galaxy cluster field, at a $1'$ resolution. The units are Jy/beam, where the size of the restoring beam is shown in the lower left corner. Figure taken from [109].

to produce relativistic particles [113]. In contrast to gamma-ray upper limit studies that ruled out a pure hadronic origin for the giant radio halo in the Coma cluster, similar studies on the Perseus cluster [114, 115] show that a hadronic origin of the mini-halo is compatible with radio (including Faraday rotation measures) and gamma-ray observations. Thus, a hadronic model is a plausible explanation for the origin of mini-halos. Turbulent re-acceleration models are also a possible explanation. However, the origin of turbulence that may re-accelerates the seed particles cannot be due to merger activity in a relaxed cluster. One hypothesis is that the sloshing of gas within the cool core region generates the turbulence required [111]. Giacintucci et al [113] reported that clusters within their sample have Chandra X-ray images that indicate the presence of gas sloshing. When the synchrotron emissivity is compared to that of halos it is reported that mini-halos have values ~ 50 higher [88]. This suggests that mini-halo regions have a larger abundance of relativistic particles. It is possible that these are provided by past activity of the central galaxy.

1.2.3 Cluster magnetic fields

It is widely acknowledged that μG -level magnetic fields permeate large volumes of galaxy clusters [88, 117, 118, 119, 120]. It is expected that these fields would play key roles in the particle re-acceleration processes, for example magnetohydrodynamics (MHD) may be the origin of the gas sloshing in cool core regions [121]. However these fields are difficult to measure. Techniques used to measure the field strengths include studies of the synchrotron emission [117], inverse Compton X-ray analysis [122] and Faraday rotation methods [123]. Estimates of magnetic fields within radio emitting regions rely on the assumption of equipartition of energy between cosmic rays and magnetic fields within the region. It is expected that surveys, such as MGCLS [124], will increase the sample size of polarized radio sources that can be utilized for magnetic field studies and the improved statistics of a larger sample size can be utilized for ICM magnetic field studies [80]. Though many clusters do not have detailed magnetic field profiles as of yet, it is often assumed that the magnetic field amplitude follows that of the gas density [118, 125] when modelling the cluster environment.

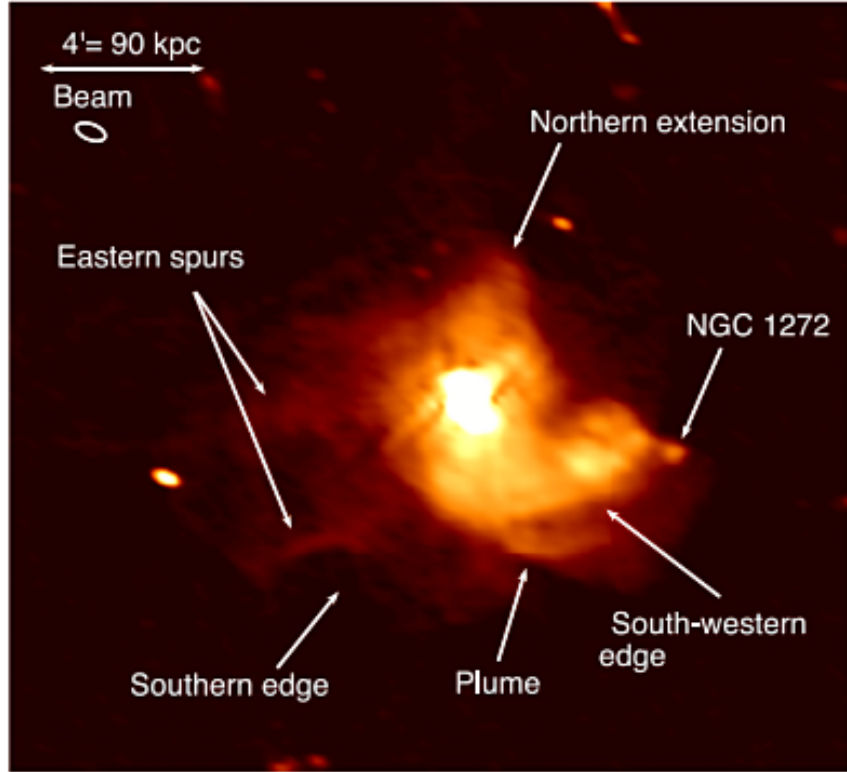


Figure 1.9: Emission in the Perseus galaxy cluster, surrounding NGC1275. The image is zoomed into the mini-halo from a larger 270-430 MHz radio map, available in the source. The main structures of the mini-halo are indicated by the white labels on the image. Figure taken from [116].

1.3 Previous $\langle\sigma V\rangle_A$ upper limits from radio data

Previous indirect dark matter searches performed with radio data have primarily focused on nearby dwarf spheroidal galaxies, for example: [79, 126, 127, 128, 129, 130]. These studies use either faint detection of diffuse emission or non-detection, to place constraints on dark matter properties, by requiring that the modelled dark matter induced synchrotron emission does not exceed the observations. All conclude that radio observations are able to place competitive bounds and are complementary to gamma-ray indirect dark matter searches, and may even outperform in objects with a low astrophysical radio diffuse background [131].

However, due to the small size of dwarf spheroidal galaxies, spatial diffusion plays an important role in the propagation of charged particles, and therefore on the predicted surface brightnesses [126]. Investigations of larger structures, on the scale of clusters of galaxies, have the advantage that the effect of diffusion is less significant. Clusters of galaxies are promising targets for synchrotron signals of dark matter annihilations, as they are massive, dark matter dominated, and are known to host μG -scale magnetic fields.

Storm et al [132] determined upper limits on a sample of galaxy clusters. The sample was chosen based on available radio, X-ray and magnetic field data from literature at the time. Upper limits are shown in Figure 1.10. The authors concluded that the derived limits of the annihilation cross section are better than non-detections of gamma-rays for the same sub-structure model, by up to a factor of 3.

In Storm et al [133] the authors investigated the sensitivity of radio surveys to dark matter annihila-

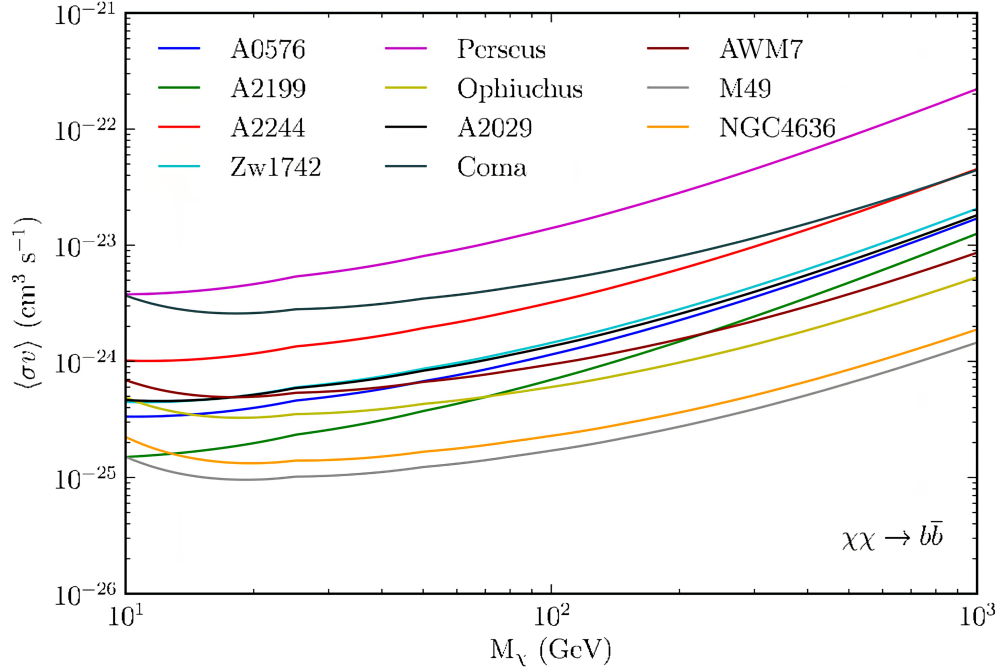


Figure 1.10: Upper limits on the annihilation cross section for galaxy clusters determined by Storm et al (2013) [132], where a smooth NFW density profile is assumed

tion. The radio surveys considered in the paper are the Tier 1 survey with the Low Frequency Array (LOFAR) [134], the Evolutionary Map of the Universe (EMU) survey with Australian Square Kilometer Array Pathfinder (ASKAP) [135] and legacy surveys with Aperture Tile in Focus (APERTIF) installed on the Westerbork Synthesis Radio Telescope (WRST) [136]. The derived upper limits are stronger than limits determined from non-detection of gamma-rays for the muon and tau annihilation channels, for low WIMP masses. An interesting, and useful, conclusion the authors are able to draw is that the redshift does not have a strong effect on the predictions, for $0 < z < 0.5$. This allows for a larger sample size of future radio survey works when compared to gamma-ray studies. The authors noted that surveys performed by the SKA in the future will be able to go deeper, in terms of sensitivity, by a factor of 3 or more.

In this work we consider the SKA pathfinder MeerKAT, and obtain constraints on the dark matter properties by utilizing the products of the MeerKAT Galaxy Cluster Legacy Survey. We investigate the sensitivity of this South African based instrument with legacy survey data of galaxy clusters.

1.4 MeerKAT and the MGCLS

MeerKAT is the precursor for the Square Kilometer Array (SKA) mid-frequency telescope. It is currently the most sensitive decimetre wavelength radio interferometer array in the world, until SKA1-MID becomes operational. Operating with 64 antennas of 13.5 m diameter with an offset Gregorian feed (Figure 1.11), the array spans 8 km. A schematic of the array layout is shown in Figure 1.12. The concentration of short baselines in the central region provides the brightness sensitivity required to recover faint extended emission, while the longer baselines provide the high resolution required to disentangle compact sources. MeerKAT is a powerful instrument for wide area surveys, and has a high sensitivity over a wide range of angular scales.

MeerKAT observes the sky at a declination below $+45^\circ$ [139], and operates in the UHF (580-1015 MHz),



Figure 1.11: A MeerKAT antenna, with offset Gregorian feed. Source: [137]

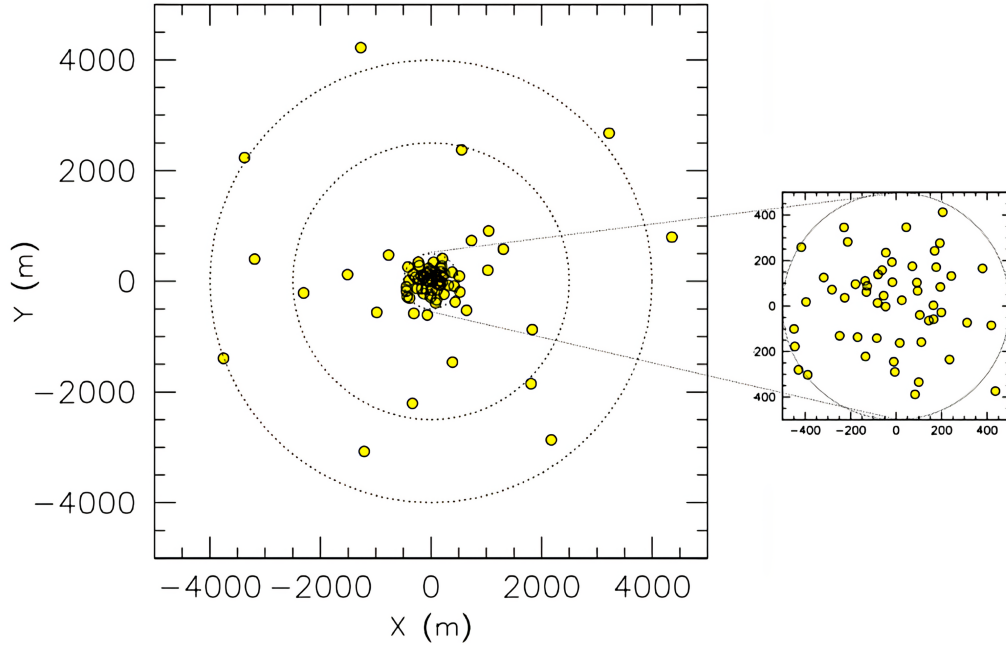


Figure 1.12: The MeerKAT telescope array configuration. The inner component of the array contains 70% of the dishes with a dispersion of 300 m where the longest baseline is 1 km and the shortest baseline is 29 m. The outer component of the array contains 30% of the dishes with a dispersion of 2.5 km and a longest baseline of 7.7 km. The shortest baseline is 29 m. The circular regions depicted have diameters of 1, 5 and 8 km. The inset shows the inner core in more detail. Source: [138]. The array configuration of MeerKAT allows for exceptional simultaneous sensitivity to a wide range of angular scales.

L (900-1670 MHz) and S (1.75-3.5 GHz) bands. The L-band system was commissioned first and has a primary beam full width at half max (FWHM) of 1.2° at a central frequency of 1.28 GHz. The primary beam FWHM of the UHF and S bands at the central frequencies (~ 798 MHz and 2.63GHz) are approximately 1.8° and 0.6° respectively [140].

Dark matter searches performed with MeerKAT will benefit from the higher sensitivity available than searches performed with instruments such as Green Bank Telescope (GBT) and the Australia Telescope Compact Array (ATCA) [128, 130, 141]. The improved sensitivity will be able to observe faint diffuse sources, thus expanding the dark matter parameter space that can be probed. The higher angular resolution provided by the long-baselines allows for the simultaneous detection of large and small scale sources, thus reducing confusion caused by point sources.

Since galaxy clusters are dark matter-dominated and are less affected by the effects of electron diffusion than smaller scale structures, they are ideal candidates for dark matter searches. High angular resolution observations of clusters have the potential to place powerful constraints of the dark matter parameter space, despite the presence of a baryonic background. MeerKAT provides the high resolution observations required.

The MeerKAT Galaxy Cluster Legacy Survey [124], consists of ~ 1000 hours of observations in the L-band, and contains observations of 115 galaxy clusters. The sample is heterogeneous, with no redshift or mass criteria applied in the selection. The sample is categorized into two groups, termed ‘radio selected’ and ‘X-ray selected’. Clusters within the radio selected group have been previously searched for diffuse cluster radio emission. Due to the high mass restrictions imposed by the previous studies, this sub-sample contains clusters with $M \gtrsim 6 \times 10^{14} M_\odot$, and has a bias towards clusters that host radio halos and relics. The X-ray selected sub-sample contains clusters selected from the Meta-Catalogue of X-ray-detected Clusters (MCXC) [142], with the intention to form a sample without any bias to radio properties.

Details of the data reduction process are available in [124]. MGCLS DR1 products are now publicly available through a DOI ¹, including primary beam-corrected images, referred to as the enhanced products. There are two types of enhanced products available: 5-plane cubes consisting of the intensity at the reference frequency (typically 1.28 GHz), spectral index, brightness uncertainty estimate, spectral index uncertainty and the χ^2 of the least squares fit, as well as a frequency cube of intensity images with 12 frequency planes. At present we limit this investigation to the reference frequency, and utilize the intensity plane of the 5-plane cube. It is noted that the uncertainty estimates in the 5-plane cubes contain only the statistical noise component [124]. There are two resolutions provided in DR1, $7''$ and $15''$. The full resolution images ($7''$) are used for the identification of compact point sources, while the convolved ($15''$) images are used to identify the faint diffuse emission of halos or mini halos.

Of the 115 clusters observed, 62 have been found to contain a form of diffuse cluster emission, many of which had not been previously detected. The authors classified the diffuse emission as radio halos, relics or mini halos. Structures classified as a candidate form of diffuse emission are those with marginal detection, or when the classification is uncertain. These diffuse emission detections can be used to constrain the dark matter parameter space, by requiring that a potential dark matter signal is hidden behind the diffuse emission.

¹<https://doi.org/10.48479/7epd-w356>

1.5 This dissertation

This dissertation investigates the potential of MeerKAT to probe and constrain the parameter space of WIMP dark matter candidates within galaxy clusters. This is performed with the use of MGCLS data products. Alongside annihilation channels $b\bar{b}$, $\mu^+\mu^-$ and $\tau^+\tau^-$, which are representative of the larger set of possible channels, we also investigate the annihilation channel of the dark matter candidate contained within 2HDM+S. This work presents some of the first WIMP dark matter constraints produced with MeerKAT. MeerKAT will be incorporated into SKA1-MID [143]. The SKA1-MID is expected to be able to observe radio emissions with sensitivity of $\mathcal{O}(\mu\text{Jy})$ [144]. As such this work serves as proof of concept for the use of SKA1-MID for more sensitive dark matter radio searches.

In Chapter 2 we introduce 2HDM+S, a particle physics model that contains a dark matter candidate. Chapter 3 provides all of the theoretical considerations required in order to model the radio emission from a dark matter annihilation event. In Chapter 4 we outline the methodology and present the the physical parameters of the chosen galaxy clusters required to model the dark matter-induced radio signal. In Chapter 5 we present and discuss the results, and we conclude in Chapter 6. Throughout this work we assume a Λ -CDM cosmology, with $\Omega_m = 0.3089$, $\Omega_\Lambda = 0.6911$ and the Hubble constant $H_0 = 67.74 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Chapter 2

2HDM+S and Dark Matter

2.1 The Standard Model and Beyond

The Standard Model (SM) of particle physics [145] is one of the most successful theories in physics. It comprises of all of elementary particles of visible matter, as well as the gauge bosons that mediate interactions. Elementary particles are broadly classified as either quarks or leptons, each class containing six particles. Three of the four fundamental forces (strong, weak, electromagnetic and gravitational) result from the exchange of bosons, and are described within the SM (gravity cannot be explained within the SM [146]). The photon mediates the electromagnetic interaction, the W and Z bosons mediate the weak interaction and gluons mediate the strong interaction [145]. A representation is shown in Figure 2.1.

Development of the SM of particle physics began in the 1970s, and has had great experimental success thus far. The most recent achievement is the discovery of the Higgs boson [148], where the scalar nature of the Higgs field induces spontaneous symmetry breaking, and in turn imparts mass to most particles in the SM, barring neutrinos. [149, 150, 151, 152].

Despite the success of the SM in its description of the subatomic world, it is incomplete. There are some open questions that the SM is unable to answer, leading many to believe there is much still to be discovered. These questions include the composition of dark matter and dark energy, the asymmetry between matter and anti-matter, and the path required to unify the four fundamental forces [153]. The numerous problems within the SM, for example the inability of gravity to be unified with the other interactions, or the existence of heavier families of fermions that do not have an obvious role in nature [146], have led to the development of models beyond the SM.

Beyond Standard Model (BSM) physics can be searched for at particle colliders. Searches for BSM look for any new resonances (e.g. of heavy exotic bosons), non-resonant states (e.g. the presence of an invisible particle yielding large missing transverse energy), or any deviations in final states from the precise predictions of the SM [153].

Run 1 and 2 data at ATLAS and CMS have reported various anomalies in multi-lepton final states, as well as a distortion of the Higgs transverse momentum spectrum. These anomalies prompted the introduction of many BSM models that aim to provide an explanation. One such model is a two-Higgs doublet model with an additional singlet scalar (2HDM+S) [154], which is considered in this work.¹

¹The sensitivity of BSM searches at particle colliders is expected to increase substantially following planned upgrades to ATLAS and CMS [155].

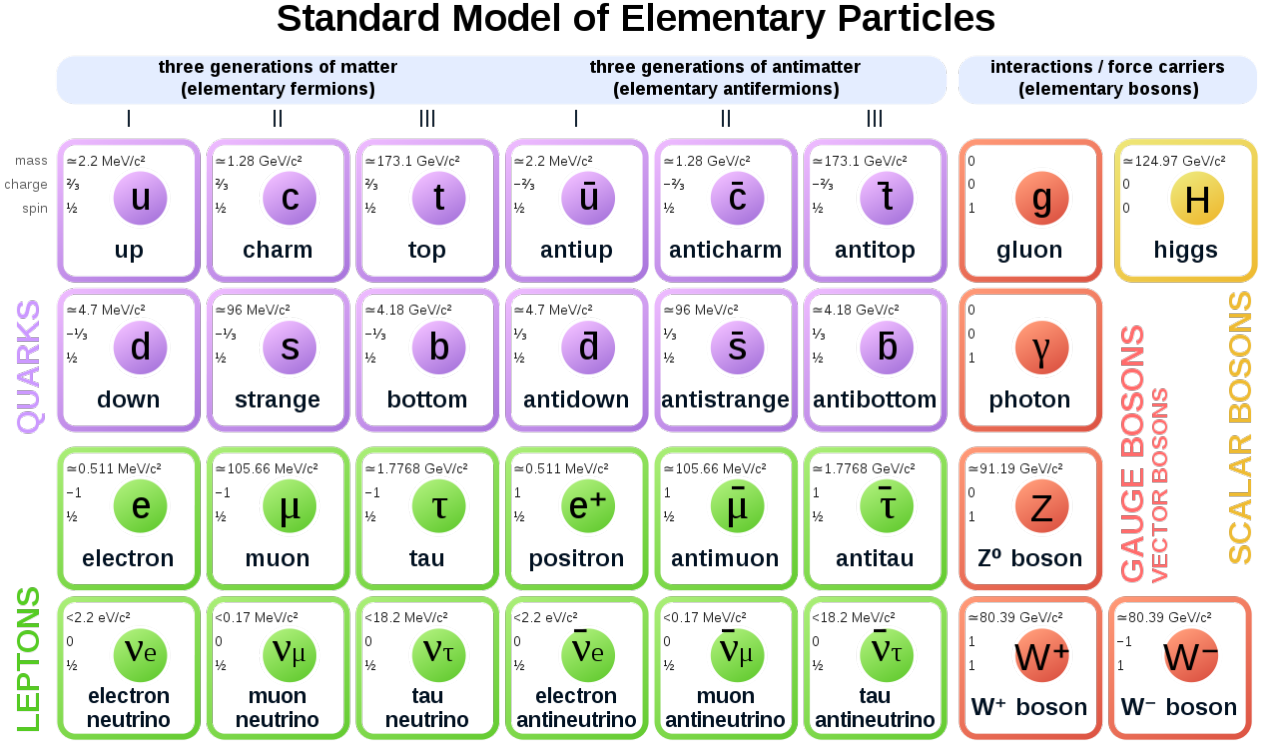


Figure 2.1: The Standard Model of particle physics with antimatter. The 3 generations or families of fermions are shown in sequential columns, with mass increasing from left to right. Source: [147]

2.2 2HDM+S

Following the various anomalies observed at the LHC, the WITS-HEPP group put forward an effective model that introduced a heavy scalar boson H and a dark matter candidate χ [156], where $m_H = 270 \text{ GeV}$. In this simplified model the origin of the coupling between H and χ is unknown, but appeared to be strong. Further work [157, 158, 159, 160] found that a two-Higgs doublet model extension to the SM, along with two scalars S and χ , might prove more fitting to the observed anomalies. In this updated formalism S acts as a mediator to the dark sector and the initial focus on $H \rightarrow h\chi\chi$ is shifted to $H \rightarrow hS, SS$ and $S \rightarrow \chi\chi$ [161]. One implication of this model is the production of multiple leptons through the decay chain of H quoted above. Excesses in multi-lepton final states were examined in [159] and the best fit to the data was obtained for $m_S = 150 \pm 5 \text{ GeV}$. Statistically compelling excesses in numerous leptonic final states (opposite and same sign di-leptons, and the three lepton channel with and without the presence of b-tagged jets) have been reported by [160] [162], and [163]. In addition to this, evidence for the production of a candidate for S with mass 151 GeV was obtained by combining side band data from SM Higgs searches [164]. When all decay channels are included a global significance of 4.8σ was reported for the required mass range (130 -160 GeV) to explain the anomalies as described above [164].

2.2.1 Formalism

Following [154] the potential of the two-Higgs doublet model with an additional singlet scalar is given by:

$$\begin{aligned}
V(\Phi_1, \Phi_2, \Phi_S) = & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + h.c. \right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\
& + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + h.c. \right] \\
& + \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} \left(\Phi_1^\dagger \Phi_1 \right) \Phi_S^2 + \frac{\lambda_8}{2} \left(\Phi_2^\dagger \Phi_2 \right) \Phi_S^2 \quad (2.1)
\end{aligned}$$

In the above equation the fields Φ_1 and Φ_2 are the $SU(2)_L$ Higgs doublets. Terms involving these fields are the contributions from the real 2HDM potential. Terms involving the subscript S are the contributions from the singlet field. Models with multiple Higgs doublets generally contain tree-level flavour changing neutral currents, where a hypothetical interaction changes the flavour of a fermion while preserving the electrical charge. This has not been observed in experiments yet, and as such the authors prevented this occurring by imposing $\mathbb{Z}_2$ symmetry, that can be softly broken with the term m_{12}^2 [154]. Readers interested in a more in-depth presentation of the formalism of this model, as well as interaction Lagrangians and constraints of the parameter space are referred to [161, 154].

The interaction of the scalar S with various types of dark matter candidates can be encoded within a Lagrangian. If the dark matter candidate is considered to have spin 0, 1/2 or 1 the Lagrangian of the interaction can be written as [165]:

$$\mathcal{L}_0 = \frac{1}{2} m_\chi g_\chi^S \chi \chi S \quad (2.2)$$

$$\mathcal{L}_{1/2} = \bar{\chi} (g_\chi^S + i g_\chi^P \gamma_5) \chi S \quad (2.3)$$

$$\mathcal{L}_1 = g_\chi^S \chi^\mu \chi_\mu S \quad (2.4)$$

In the above the factor g_χ^S describes the strength of the scalar coupling between S and the dark matter candidate, g_χ^P is the strength of the pseudo-scalar coupling to S, and m_χ is the mass of the dark matter candidate.

Yield functions

WIMP like dark matter particles can annihilate into pairs of quarks, leptons, Higgs and other bosons. The hadronization and further decay of these particles then lead to electrons/positrons considered in this work (e.g. $\chi\chi \rightarrow b\bar{b} \rightarrow e^-e^+$). For the 2HDM+S model the simplest interactions that can be considered are $\chi\bar{\chi} \rightarrow S \rightarrow X$ and $\chi\bar{\chi} \rightarrow S \rightarrow HS/h \rightarrow X$, where X represents the SM products of the annihilation, e^-/e^+ here. The lowest dark matter mass that can be probed with these reactions is that that can produce S, or H and h together respectively. For the former process this value is approximately 75 GeV, while the latter has a lower limit of approximately 200 GeV. For simplicity of labelling we refer to $\chi\bar{\chi} \rightarrow S \rightarrow HS/h \rightarrow X$ as $2 \rightarrow 3$.

The per annihilation spectra of these two processes can be computed through Monte Carlo simulations and compared to generic WIMP annihilation channels for various final states. The focus of this working being synchrotron emission for electrons and positrons, we limit this comparison to the spectra of these particle final states. Figure 2.2 shows the differential particle spectra for the channels considered later in this work. For the 2HDM+S channel the spectra are obtained from [165], and the spectra for the other channels is obtained from [166]. The particle spectra depicted are continuous, and relatively featureless,

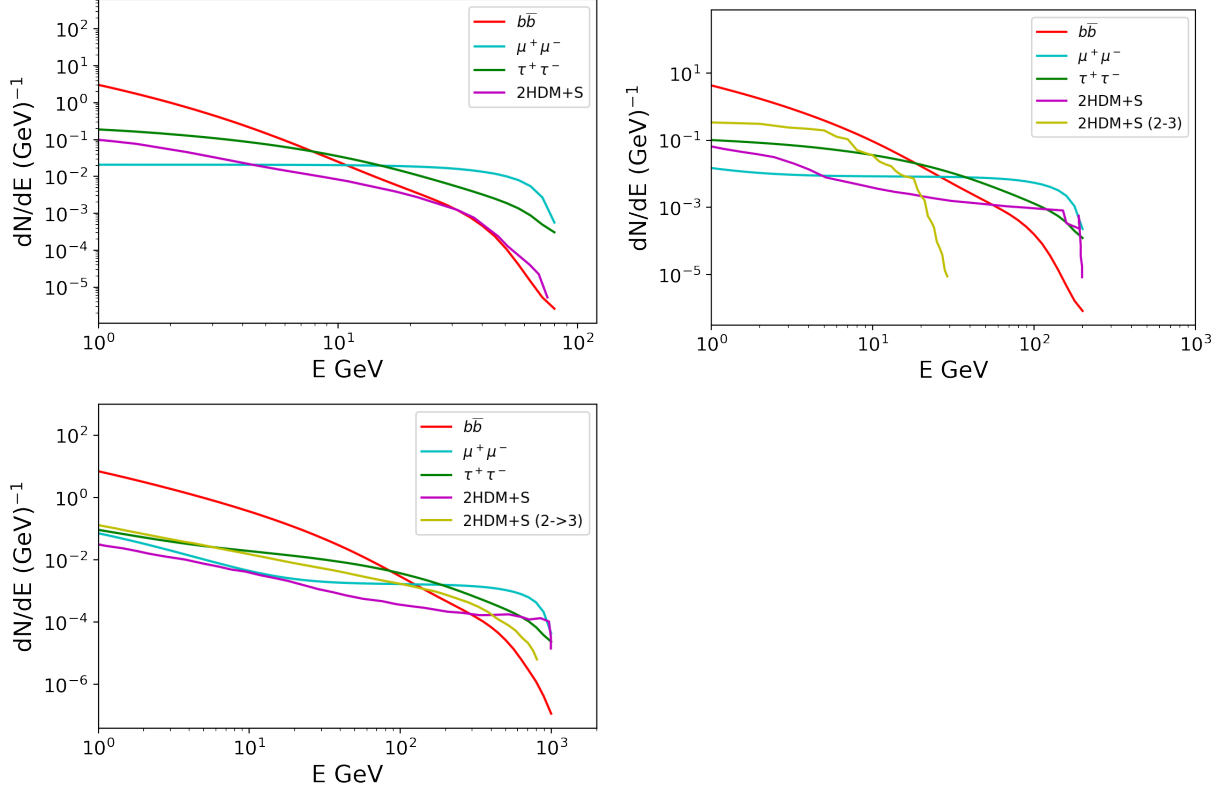


Figure 2.2: Differential particle spectra for positrons, three comparing generic WIMP annihilation channels, 2HDM+S channel and 2HDM+S $2 \rightarrow 3$. The panels have WIMP masses 80 GeV(75 GeV for 2HDM+S), 200 GeV and 1000 GeV.

in the sense that they do not have resonant peaks. All spectra do show an exponential cutoff at the kinematical limit, where $E = M_\chi$, since the energy of the products cannot exceed the energy of the original particle. The yield function of the 2HDM+S model behaves similar to the leptonic channel at lower energies and the hadronic channels at higher energies for the lower WIMP masses. For WIMP masses above a few hundred GeV the behaviour is more similar to the leptonic channel.

A notable result from [165] is that the particle yield functions per annihilation for 2HDM+S channels do not vary significantly for the choice of spin of the dark matter candidate, when spin 0, 1/2 and 1 are considered. As such, in this work we limit our calculations to a spin-0 candidate.

2.2.2 Connection to astrophysics

The properties of the dark matter candidate contained within 2HDM+S are unconstrained by any data from the LHC. As such it is intriguing to probe the validity of the model in astrophysical contexts. This can be achieved with the use of indirect dark matter searches in regions where the dark matter density is expected to be high. Beck et al [165] considered the anti-proton [167] and positron [168] excesses observed with AMS-02, as well as the gamma-ray excesses observed by Fermi-LAT [169]. These excesses have been considered as potential signatures of dark matter in various studies, for example [170, 171, 172].

Beck et al [165] probed the dark matter parameter space of the 2HDM+S model. Figure 2.3 shows the author's parameter space fitting for $\chi\bar{\chi} \rightarrow S \rightarrow X$ to AMS-02 positron data, and the overlapping regions of anti-proton and Fermi-LAT galactic centre gamma ray parameter spaces, for an NFW dark matter density profile for the Milky Way. On this plot the thermal relic value is depicted as a band, accounting

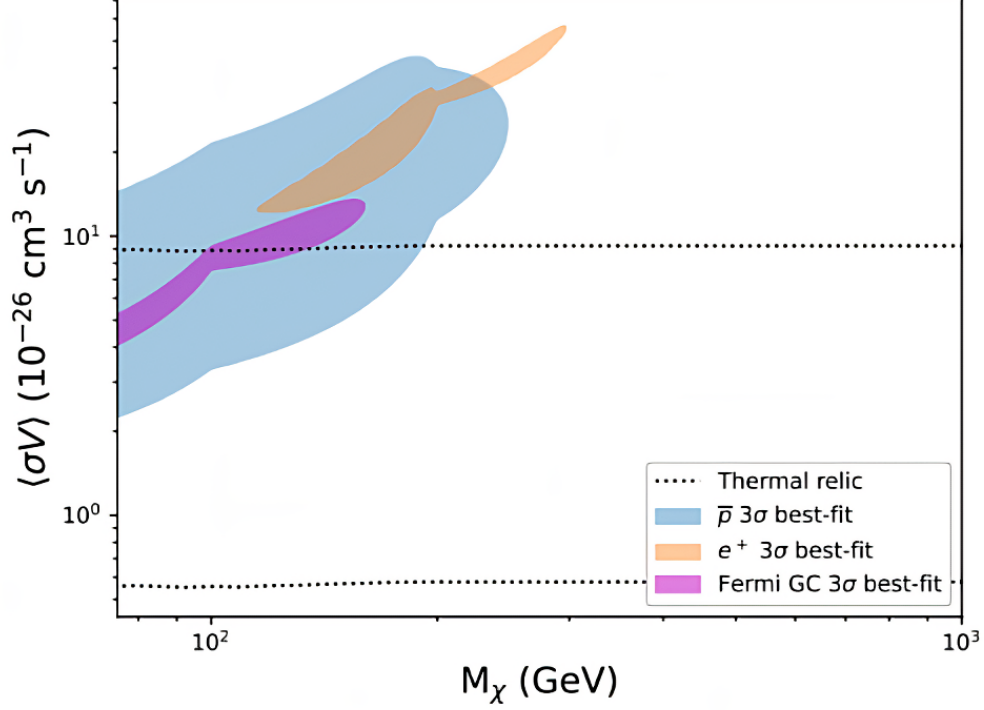


Figure 2.3: The parameter space fitting of $\chi\bar{\chi} \rightarrow S \rightarrow X$ scattering to AMS-02 positron data, with overlaid anti-proton and Fermi-LAT galactic centre excess parameter spaces for an NFW density profile. The two dotted lines represent the uncertainty in the thermal relic value due to the local dark matter density and the halo profile. Figure taken from [165].

for the uncertainties in the normalization of the local dark matter density. Models within this band remain compatible to the thermal relic value up to systematic uncertainties. A more contracted density profile was disfavoured by this fitting procedure. Despite the inclusion of positron background sources, the favoured cross sections were large. This indicated that the parameter space of the 2HDM+S model that describes the LHC anomalies and astrophysical data cannot be excluded by indirect detection [165].

The authors found that the best fits of 2HDM+S to the observed excesses are for dark matter masses below 200 GeV. As such we choose 75 GeV – 200 GeV for our analysis within galaxy clusters, the lower limit being the WIMP mass that can produce S. The reaction $\chi\bar{\chi} \rightarrow S \rightarrow HS/h \rightarrow X$ requires larger dark matter masses, and the analysis of this channel is left to future works.

Chapter 3

Astrophysical modelling for dark matter radio emission

Radio emission can be produced through dark matter annihilation when relativistic electrons and positrons are products of the annihilation process. These particles then interact with the cluster magnetic field and release synchrotron emission that can be measured in the radio band. Within this work the potential radio emission from dark matter annihilation is modelled using a tool developed by Beck et al [75, 165, 173, 174, 175, 176] This chapter will detail the theoretical considerations required.

Electrons and positrons are expected to be injected into the environment through each dark matter annihilation. The general way to describe the production of these particles is through a source function. This function describes the number of particles produced per unit volume per unit time per unit energy. For annihilation this can be expressed as,

$$Q(r, E) = \langle \sigma V \rangle \sum_f \frac{dN^f}{dE} \mathcal{B}_f \mathcal{N}_\chi(r), \quad (3.1)$$

where $\langle \sigma V \rangle$ is the velocity averaged annihilation cross section for dark matter, $\mathcal{B}_f$ is the branching ratio to state f, and the particle production spectra for each state is $\frac{dN^f}{dE}$. In this work we consider annihilation through $b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$ and 2HDM+S chains (e.g. $\chi\chi \rightarrow b\bar{b} \rightarrow e^-e^+$). The per annihilation yield function for the generic WIMP annihilation channels can be found in [166], and for 2HDM+S in [165]. The factor of $\mathcal{N}_\chi(r)$ details the dark matter pair density, which can be further expressed as $\mathcal{N}_\chi(r) = \frac{\rho_\chi^2}{M_\chi^2}$. Here we see the dark matter density distribution, and the mass of the dark matter particle come into play.

There are various common dark matter density profiles. One of the most notable is the Navarro-Frenk-White (NFW) [68], determined through high resolution N-body simulations,

$$\rho_{NFW} = \frac{\rho_s}{\frac{r}{r_s} \left(1 + \frac{r}{r_s}\right)^2}. \quad (3.2)$$

Here the scale density and radius are denoted by the subscript s. This profile can be generalised to accommodate either shallower or steeper inner profiles, expressed as:

$$\rho_{gNFW} = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\alpha \left(1 + \frac{r}{r_s}\right)^{3-\alpha}}. \quad (3.3)$$

There are some tensions between simulations, which indicate a cuspy profile, and observations, which indicate a core profile such as the Burkert profile [177],

$$\rho_B = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)}, \quad (3.4)$$

where ρ_0 and r_0 represent the central dark matter density and the scale radius respectively. However, these tensions are predominantly valid on galactic scales. When considering galaxy clusters, there appears to be some evidence of NFW-like density profiles [176, 178, 179]. Additionally, authors of [178] rule out cored-profiles, such as the Burkert cored profile, for clusters of galaxies. In this work we utilize standard NFW profiles for the modelling of the dark matter halos.

The spectra of injected electrons will evolve with time, as the particles diffuse and lose energy. It is imperative to consider these processes, as the position and energy distributions of the particles effect the predicted synchrotron emission. The equilibrium distributions can be obtained by solving the diffusion-loss equation under the assumption of vanishing time derivatives, also known as the equilibrium form,

$$0 = \frac{\partial}{\partial t} \frac{dn_e}{dE} = \nabla \left(D(E, \mathbf{x}) \nabla \frac{dn_e}{dE} \right) + \frac{\partial}{\partial E} \left(b(E, \mathbf{x}) \frac{dn_e}{dE} \right) + Q_e(E, \mathbf{x}). \quad (3.5)$$

In the above $D(E, \mathbf{x})$ is the diffusion function, and $b(E, \mathbf{x})$ is the energy loss function. There are two main methods employed to solve this equation. The first is a semi-analytical formalism that uses Green's functions, while the second uses the Crank-Nicolson scheme to discretise the derivatives (see [75]). In this work the Green's function method is utilized. This method requires that the diffusion and loss functions have no spatial dependence. In contrast, a Crank-Nicolson scheme investigated by Beck et al [176] allows these functions to retain their spatial dependence. The authors compared the upper limits on the annihilation cross-section determined through these two methods, and found that for integrated flux measurements the assumption that the diffusion and loss functions have no spatial dependence does not overly affect the results. The diffusion function can be expressed as in [176],

$$D(E) = D_0 \left(\frac{d_0}{1 \text{ kpc}} \right)^{2/3} \left(\frac{\bar{B}}{1 \mu\text{G}} \right)^{-1/3} \left(\frac{E}{1 \text{ GeV}} \right)^{1/3}, \quad (3.6)$$

with the diffusion constant set as $D_0 = 3 \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$, the factor d_0 is the coherence length of the magnetic field, and $\bar{B}$ is the average magnetic field. The energy loss function is given by:

$$b(E) = b_{\text{IC}} \left(\frac{E}{1 \text{ GeV}} \right)^2 + b_{\text{sync}} \left(\frac{E}{1 \text{ GeV}} \right)^2 \left(\frac{\bar{B}}{1 \mu\text{G}} \right)^2 + b_{\text{Coul}} \left(\frac{\bar{n}}{1 \text{ cm}^{-3}} \right) \left(1 + \frac{1}{75} \log \left(\frac{\gamma}{\bar{n}/1 \text{ cm}^{-3}} \right) \right) + b_{\text{brem}} \left(\frac{\bar{n}}{1 \text{ cm}^{-3}} \right) \left(\frac{E}{1 \text{ GeV}} \right). \quad (3.7)$$

In this expression $\gamma = \frac{E}{m_e c^2}$ and the average gas density $\bar{n}$. The coefficients of each term are the energy loss rates of the given loss process, these being Inverse Compton scattering, synchrotron emission, Coulomb scattering and bremsstrahlung in the order they appear. The values of these quantities are $0.25 \times 10^{-16} (1+z)^4$ for CMB photons, 0.0254×10^{-16} , 6.13×10^{-16} and 4.7×10^{-16} respectively in units of GeV s^{-1} .

The average gas density and magnetic field are calculated within the scale radius of the dark matter halo, to ensure they reflect the environment in which the majority of the annihilations will occur [176]. They are able to take on different functional forms with radial dependencies within the model. These profiles are flat,

$$n_e(r) = n_0, \quad (3.8)$$

power law,

$$n_e(r) = n_0 \left(\frac{r}{r_e} \right)^{q_e}, \quad (3.9)$$

beta profile,

$$n_e(r) = n_0 \left(1 + \left(\frac{r}{r_e} \right)^2 \right)^{3\beta_e/2}, \quad (3.10)$$

a double beta profile

$$n_e(r) = n_0 \left(1 + \left(\frac{r}{r_e} \right)^2 \right)^{3\beta_e/2} + n_{0,2} \left(1 + \left(\frac{r}{r_{e,2}} \right)^2 \right)^{3\beta_{e,2}/2}, \quad (3.11)$$

or an exponential profile

$$n_e(r) = n_0 \exp^{-r/r_e}, \quad (3.12)$$

where the normalization n_0 , scale r_e and any indices have to be sourced in available literature on the relevant target. The magnetic field profiles have the same available forms.

The equilibrium solution for the particle spectra, under the assumption of spherical symmetry for the dark matter and baryon distributions is then [75],

$$\frac{dn_e}{dE}(r, E) = \frac{1}{b(E)} \int_E^{M_x} dE' G(r, E, E') Q(r, E'). \quad (3.13)$$

The Green's function has the form

$$G(r, E, E') = \frac{1}{\sqrt{4\pi\Delta\nu}} \sum_{n=-\infty}^{\infty} (-1)^n \int_0^{r_h} dr' \frac{r'}{r_n} f_{G,n}, \quad (3.14)$$

where r_h is the diffusion limit, where it is expected that $\frac{dn_e}{dE}$ approaches zero, and n is an integer.

$$f_{G,n} = \left(\exp^{-(r'-r_n)^2/4\Delta\nu} - \exp^{-(r'+r_n)^2/4\Delta\nu} \right) \frac{Q(r')}{Q(r)} \quad (3.15)$$

with internal functions expressed as in [75, 176]:

$$\Delta\nu = \nu(u(E)) - \nu(u(E')) \quad (3.16)$$

$$\nu(u(E)) = \int_{u_{\min}}^{u(E)} D(x) dx \quad (3.17)$$

$$u(E) = \int_E^{E_{\max}} \frac{dx}{b(x)}. \quad (3.18)$$

With the equilibrium solution to the particle spectra in hand, we can begin to model the synchrotron emission. Synchrotron emission is produced when the high energy electrons, of energy E , interact with the a magnetic field, of strength B . The power of this emission has dependences on the observed frequency ν , as well as the redshift, z , of the source. It is given by [180] as:

$$P_{\text{sync}}(\nu, E, r, z) = \int_0^\pi d\theta \frac{\sin^2 \theta}{2} 2\pi \sqrt{3} r_e m_e c \nu_g F_{\text{sync}} \left(\frac{\kappa}{\sin \theta} \right), \quad (3.19)$$

with m_e as the mass of an electron, $r_e = \frac{e^2}{m_e c^2}$ the classical radius of an electron, and the non-relativistic gyro-frequency $\nu_g = \frac{cB}{2\pi m_e c}$. The parameter κ is defined as:

$$\kappa = \frac{2\nu(1+z)}{3\nu_0\gamma} \left(1 + \left(\frac{\nu_p\gamma}{\nu(1+z)} \right)^2 \right)^{3/2}, \quad (3.20)$$

here ν_p is the plasma frequency, which is directly dependent on the electron density of the environment being modelled. The function F_{sync} gives the synchrotron kernel, with form

$$F_{\text{sync}}(x) = x \int_x^\infty dy K_{5/3}(y) \approx 1.25x^{1/3} \exp^{-x} (648 + x^2)^{1/12}. \quad (3.21)$$

The synchrotron emissivity at a radius r within the dark matter halo is then found to be

$$j_{\text{sync}}(\nu, r, z) = \int_{m_e}^{M_\chi} dE \left(\frac{dn_{e^-}}{dE} + \frac{dn_{e^+}}{dE} \right) P_{\text{sync}}(\nu, E, r, z), \quad (3.22)$$

where $\frac{dn_{e^-}}{dE}$ and $\frac{dn_{e^+}}{dE}$ are the equilibrium solutions to the electron and positron spectra respectively. The emissivity is then used to calculate the flux density and the azimuthally averaged surface brightness that would be observed. These quantities have the form as given in [75]

$$S_{\text{sync}}(\nu, z) = \int_0^r d^3r' \frac{j_{\text{sync}}(\nu, r, z)}{4\pi D_L^2}, \quad (3.23)$$

with D_L the luminosity distance to the target, and

$$I_{\text{sync}} = (\nu, \Theta, \Delta\Omega, z) = \int_{\Delta\Omega} d\Omega \int_{l.o.s} \frac{j_{\text{sync}}(\nu, r, z)}{4\pi} \quad (3.24)$$

respectively.

The flux density and the surface brightness predicted through this modelling can then be compared to measurements of astrophysical sources to probe the dark matter parameter space. A common way to go about this is to compare integrated fluxes of a region of interest. However, the model of the flux density assumes a smooth dark matter profile, and it is reasonable to expect that the presence of sub-structure will effect the strength of the signal. This is evident when the dependency of prompt flux of an annihilation on the dark matter density, $J_{\text{ann}}(\phi) = \int_{l.o.s} \rho^2(\phi, l) dl$, is recalled.

Moliné et al 2017 [181] investigated the effect of substructure on the annihilation signal. The authors presented a parametric equation for the boost factor as a function of host halo mass. The boost is given by

$$\log B_{\text{sub}}(M) = \sum_{i=0}^5 b_i \left[\log \left(\frac{M}{M_\odot} \right) \right]^i, \quad (3.25)$$

where the best fit parameters b_i are presented for two values of the slope of the subhalo mass function, $\alpha = 1.9$ and $\alpha = 2$. In this work we utilize the parametric equation with $\alpha = 2$ to calculate the full boost factor within the virial radius, denoted by f_{boost} . Here, elaboration is required for the use of the term ‘full boost’. It must be noted that the authors formulated the expression for this factor with primarily γ -ray annihilation signals in mind. On the contrary, synchrotron emission cannot benefit from this enhancement in signal. This is due to the fact that sub-halos are more common on the outskirts of the host halo [182], where magnetic fields are weaker. Thus, it is necessary to scale the boost to the regions where synchrotron emission is more likely. This is achieved through the consideration of the spatial distribution of substructure within the host halo, as well as the magnetic field distribution. This leads to the scaled boost taking the form presented in Beck et al 2022 [176]:

$$\mathcal{B}(R) = 4\pi \int_0^R dr r^2 f_{\text{boost}} \left(\frac{B(r)}{B_0} \right) \tilde{\rho}_{\text{sub}}(r), \quad (3.26)$$

where $\tilde{\rho}_{\text{sub}}(r)$ is the sub-halo mass density normalized to 1 between 0 and the virial radius. It can be understood as the host halo mass density multiplied by a modifier function from [182]. The factor f_{boost} is the full boost factor described above. The cluster fluxes appear to exhibit a dependency on B rather than B^2 , and it is possible this is due to the effect of the energy losses [176].

The flux from the host halo is then multiplied by $\mathcal{B}(R)$ to account for the presence of substructure, and obtain the total expected flux from dark matter annihilation. It is noted however that the uncertainties of the sub-halo distribution will affect any constraints of dark matter properties that are deduced through comparisons of integrated fluxes.

Chapter 4

Methodology

This chapter serves to outline the methods utilized to obtain upper limits on the dark matter annihilation cross section for the various analyses.

4.1 Radio flux measurements with SAOImage DS9

Throughout this work we make use of the python plugin `radioflux`¹ to determine the total flux in a region of interest. The package can be used with the radio software `SAOImageDS9` [183] or stand-alone. This section gives a brief description of the package and how it is utilized in this work.

The program requires the region of interest to be fed in by the user, and is then able to determine the total flux within the boundary of the region. This is accomplished by summing the value of all the pixels that fall within the region of interest. Noting that the pixel values are in units of Jy/beam, a conversion factor of the beam area to a solid angle in units of steradians is required. The beam is a Gaussian, and its area is defined by its 2-dimensional integral,

$$\Omega = \frac{\pi \theta_{\text{MAJ}} \theta_{\text{MIN}}}{4 \ln 2}, \quad (4.1)$$

where θ_{MAJ} and θ_{MIN} are the full width half maximums (FWHMs) along the major and minor axes respectively, in terms of pixels [184]. Therefore the total flux in the region is obtained by the sum of all pixels divided by the solid angle of the beam, resulting in units of Jy.

The statistical uncertainty in this measurement is estimated by taking the noise into account. This requires that a background region is supplied. We require that the background region has a minimum radius three times the beam width, for the calculated statistics to be an accurate representation of the local noise. It is imperative that the region does not contain point sources, or astrophysical signals, in order to be a good representation of the image noise. The noise can be variable across the images, and as such we chose a background area that is near to the region of interest.

The output values of the total flux and its statistical uncertainty are then used in our calculations for the dark matter annihilation cross section.

¹<https://www.extragalactic.info/~mjh/radio-flux.html>

4.2 Integrated flux comparison

In clusters with a radio halo, a 2σ confidence level for the annihilation cross section can be obtained through

$$\langle\sigma V\rangle = \frac{S + 2\sigma_{\text{uncertainty}}}{S'_{\chi}\mathcal{B}}, \quad (4.2)$$

where S is the measured flux density of the radio halo, $\sigma_{\text{uncertainty}}$ is the uncertainty in the measured flux, S'_{χ} is our modelled dark matter induced flux density as given in equation 3.23 where the cross section dependence has been extracted and $\mathcal{B}$ is the boost factor due to the presence of substructure within the dark matter halo (see equation 3.26).

In order to obtain upper limits on the dark matter annihilation cross section from the integrated flux values the primary requirement is to obtain the flux density of the diffuse emission of the radio halo from the MGCLS data products, S . In order to determine a region that is spanned by the radio a 3σ contour is applied, where σ is the average local RMS noise value. To simplify the comparison to the modelled dark matter signal, which is circular, we consider a circular region extended to encompass the 3σ contours. The total flux of the region is given by `radioflux`. The lower resolution of the available products will be more sensitive to the faint diffuse emission. As such, the above process is performed on the convolved ($15''$ resolution) image. The selected region may be extended past the contours of the radio halo, in order to include the full contribution of compact sources. This is done in an attempt to reduce the impact of over subtraction when removing these contributions. An example is shown in the left panel of Figure 4.1.

Compact sources are identified with Python Blob Detector Source Finder (PyBDSF) [185]², using the full resolution primary beam corrected MGCLS data products. The superior resolution allows for PyBDSF to more accurately identify compact sources. PyBDSF searches for islands of emission, and then fits one or more elliptical Gaussian functions to the island. Gaussians are then grouped into sources. Following the source identification utilised in MGCLS [124], we use the default parameters of PyBDSF. This is a $3\sigma_{\text{RMS}}$ island boundary, and a $5\sigma_{\text{RMS}}$ source detection threshold. Note that σ_{RMS} is the local RMS, calculated within PyBDSF. The resulting source catalogue is used to identify the compact sources that fall within the circular region defined above and the flux contributions summed. The total compact source flux is then manually subtracted from the total flux of the region provided by `radioflux`. The residual image produced by PyBDSF can be seen in the right panel of Figure 4.1.

The dark matter-induced flux is obtained by integrating the dark matter signal over a radius equal to the radius of the circular region used to measure the diffuse emission flux.

There are various sources of uncertainty that accumulate through this procedure, and it is non-trivial to accurately account for their effects. A statistical estimate of the uncertainty of the flux within the circular region is obtained by accounting for the noise. The systematic uncertainty is estimated to be $\sim 6\%$ of the measured flux, obtained via a flux density comparison of the MGCLS compact sources to the corresponding sources in the NRAO VLA Sky Survey (NVSS) and the Sydney University Molonglo Sky Survey (SUMSS) [124]. A simple estimation of the uncertainty is obtained by adding these two quantities in quadrature,

$$\sigma_{\text{uncertainty}} = \sqrt{\sigma_{\text{statistical}}^2 + \sigma_{\text{systematic}}^2}. \quad (4.3)$$

An additional source of uncertainty comes from the identification of the compact sources by PyBDSF. We recall that PyBDSF attempts to fit Gaussian functions to bright islands of emission. However, it does not take into consideration that a peak in emission might have contributions from both compact

²<https://github.com/lofar-astron/PyBDSF>

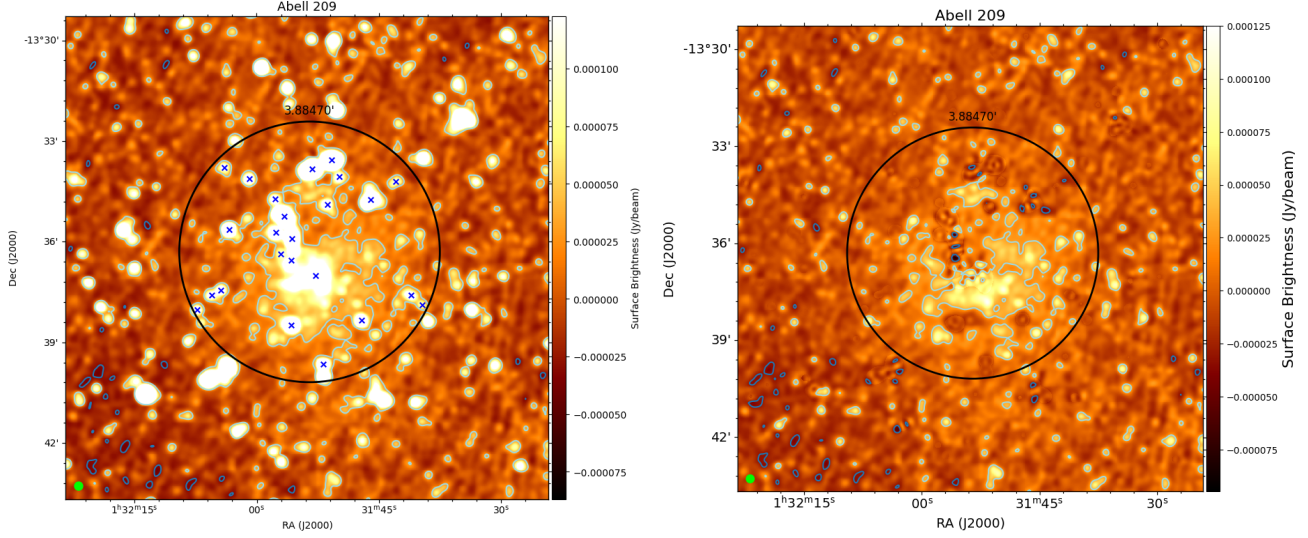


Figure 4.1: Illustrative example of the procedure for obtaining the diffuse flux, depicting Abell 209. The contours shown are -3σ and 3σ in dark and light blue respectively, where σ is the local RMS noise. The black circular region is the region chosen, that aims to contain the entire radio halo. The beam is shown in the lower left corner. *Left:* The surface brightness at $15''$ resolution. The crosses indicate the presence of point sources identified by PyBDSF in the full resolution image, which are then removed. *Right:* The residual image produced by PyBDSF of region of the radio halo.

sources and the diffuse emission present in the region. This can lead to over-subtraction when removing the contributions from compact sources. This effect can be seen in the right panel of Figure 4.1. This uncertainty is non-trivial to quantify, but we make note that the effect of over-subtracting may be lowering the diffuse flux density measurement, and biasing our obtained upper limits on the annihilation cross section to lower values.

A second method of obtaining the diffuse flux is investigated as a comparison to the method detailed above. For this the contributions of compact sources are removed from the full resolution ($7''$) with PyBDSF. The residual image produced as an output of the PyBDSF is then convolved to $15''$ resolution through the `casa` task `convolve2d`. A 3σ contour of the local RMS value is then used to identify the region of interest around the radio halo. The `radioflux` package is then used to determine the integrated flux of the diffuse emission that remains. The noise is taken into account by utilizing the background selection option provided within `radioflux`. In Figure 4.2 the full resolution MeerKAT map is used to identify and remove sources, and is shown in the first panel. The source subtracted image is then convolved to a $15''$ resolution which shown in the second panel.

4.3 Dark matter signal injection

In an attempt to produce more constraining upper limits on the dark matter annihilation cross section clusters with fainter diffuse emission were considered. These sources were two mini-halos and a non-detection of diffuse emission. Additionally, we investigate the potential of a different technique than that used for the radio halos for determining dark matter constraints.

This approach requires modelling the predicted dark matter annihilation signal, and injecting this into the image in the region of the galaxy cluster centre. To reduce the required computation time, the full MGCLS surface brightness plane is cropped to a $20'$ by $20'$ square, around the MeerKAT pointing coordinates of the cluster given in [124]. The contributions from the compact sources are removed with the use

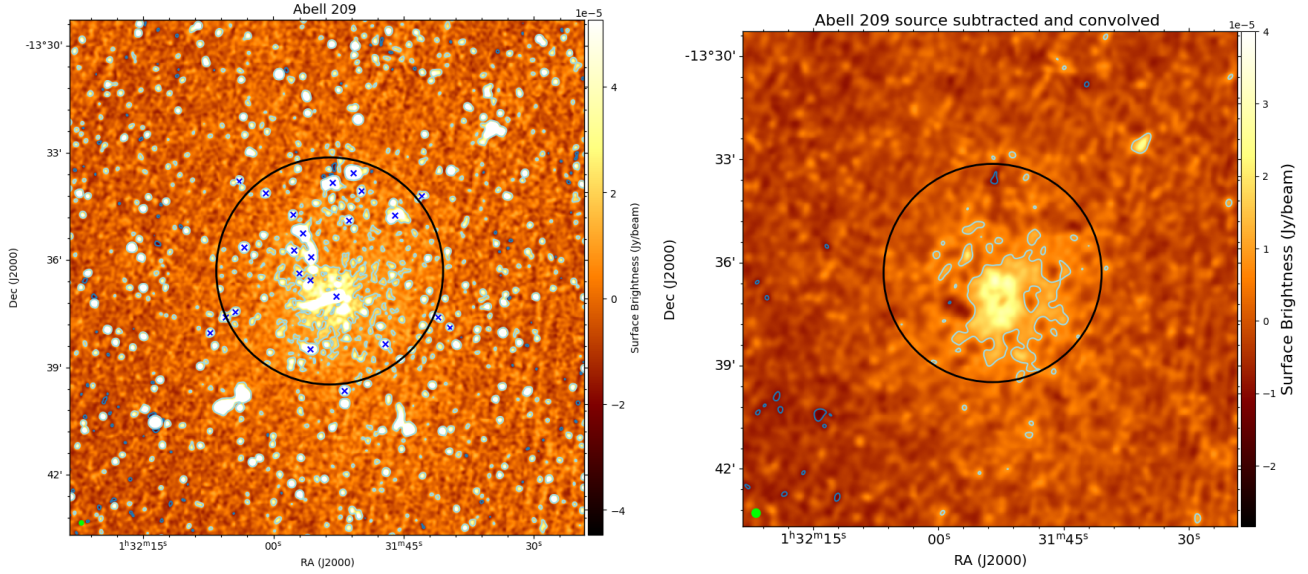


Figure 4.2: Illustrative example of the procedure for obtaining the diffuse flux, depicting Abell 209. The contours shown are -3σ and 3σ in dark and light blue respectively, where σ is the local RMS noise. The black circular region is the region chosen, that aims to contain the entire radio halo. The beam is shown in the lower left corner. *Left:* The surface brightness at $7''$ resolution. The crosses indicate the presence of point sources identified by PyBDSF in the full resolution image, which are then removed. *Right:* The residual image produced by PyBDSF of region of the radio halo which in then convolved to $15''$ resolution.

of PyBDSF³, as described in section 4.2. The residual image is then used as the parent surface brightness image, reminiscent of the process of injecting a modelled halo into a visibility file [186]. Injecting into the surface brightness image is done as calibrated visibilities are not provided in DR1 in order to perform this injection in visibility space. In the era of the SKA such image-based analysis might be the only option, due to the vast volume of visibility data expected.

The tool used for the predictions of dark matter emission creates a surface brightness Flexible Image Transport System (FITS) image, with units of Jy/pixel, of the dark matter radio halo. To be able to perform the halo injection, the FITS image needs to be processed to have the same properties of the MeerKAT FITS image of the relevant galaxy cluster. For this we utilize the Common Astronomy Software Applications package (CASA) [187].

The initial processing step is to apply a beam to the image of the dark matter signal in order to convert the surface brightness units from Jy/pixel to Jy/beam. Here, we note that we are utilizing the full resolution data product, which defines the size of the beam we are applying. The `convolve2d` function in CASA performs a Fourier based convolution using a provided 2D kernel. Here we provide a kernel that corresponds to the beam size of the image, which can be extracted from the FITS header of the parent image. It is then necessary to regrid the coordinate system to that of the parent image. This can be achieved with `imregrid`, where the parent image is the template for the regridding procedure. Once this step has been performed, our dark matter induced flux FITS file has the units of Jy/beam, as well as the coordinate grid and pixel size of the MeerKAT image. To inject the dark matter radio halo into the parent image we can simply add the brightnesses on a pixel by pixel basis. In general this was performed on the residual image, where the compact sources have been removed.

Once the dark matter signal has been injected into the MeerKAT image it is necessary to trial a method

³<https://pybdsf.readthedocs.io/en/latest/>

of analysis that will constrain the dark matter parameter space. Below we detail the analysis procedure utilized in order to place an upper limit on the dark matter annihilation cross section.

4.3.1 Flux uncertainty exclusion limit

In typical radio halo injection upper limit techniques, such as in [186, 188, 189, 190], the integrated flux in a region is compared before and after the injection is performed. The region of integration is comparable to the size of the injected halo. George et al [186] argued that a 10% excess in flux density in the injected halo region compared to the input image is a reasonable estimator for the upper limit of a radio halo, in line with the experience of authors in earlier works [188, 189].

We attempt to adapt this method noting some keys differences. The primary difference is that we are injecting our modelled dark matter signal directly into the surface brightness image, also known as the image plane. The reason for this is twofold. First, the MGCLS DR1 products do not include uv datasets and secondly our modelled signal is in units of surface brightness. The linear nature of the Fourier transform between the planes means that it should be possible to perform the injection in either plane. Injection of the signal into the image plane is computationally inexpensive when compared to injection into the visibilities. This is because the modelled image would have to be convolved to a visibility, added to the existing uv data, and the modified visibility would have to be deconvolved to the image plane. This is a computationally expensive process. However, due to the nature of interferometers the transform is not ideal. If the injection is performed in the visibility space, the recovered flux of an injected source depends largely on the uv sampling. As any measured visibility function is a limited subset of the true visibility function it is unlikely to recover the full signal from an injected source. Thus, if the signal was injected into the visibility plane we expect to recover a weaker signal in the image plane, and therefore obtain less constraining upper limits of the annihilation cross section. A detailed investigation will be performed in future work.

Another key difference is that in other radio halo upper limit calculations, determination of the upper limit requires that the injected halo has visible extent in the modified images. In our case the dark matter signal is more peaked than a standard Gaussian source, as shown in Figure 4.3, and therefore does not have a large spatial extent.

We recall that dark matter halos, and therefore their signals, do not have a defined size. In order to choose an appropriate radius over which to measure the total flux we consider the relative size of the expected annihilation signal's dependency on the integration radius. We recall that the signal can be characterized by the J-factor as given in equation 1.7, an integral of the square of the density distribution. Noting that the density distribution is spherically symmetric we can perform a volume integral of the profile to determine how much of the annihilation signal will be contained within a given radius. The contained signal is proportional to

$$\int_0^a \frac{x^2}{x^2(1+x)^4} = \frac{1}{3} - \frac{1}{3(a+1)^3}, \quad (4.4)$$

where $a = r/r_s$. From this we are able to deduce that approximately 70% of the anticipated dark matter signal is contained within $r = 0.5r_s$, or $a = 0.5$. We chose this to be the default choice for the region of integration.

The upper limit on the annihilation cross section is found through

$$\langle \sigma V \rangle = 10^{-26} \text{cm}^3 \text{s}^{-1} \frac{2\sigma_{\text{uncertainty}}}{S_{\text{Injected}} - S_{\text{Original}}}, \quad (4.5)$$

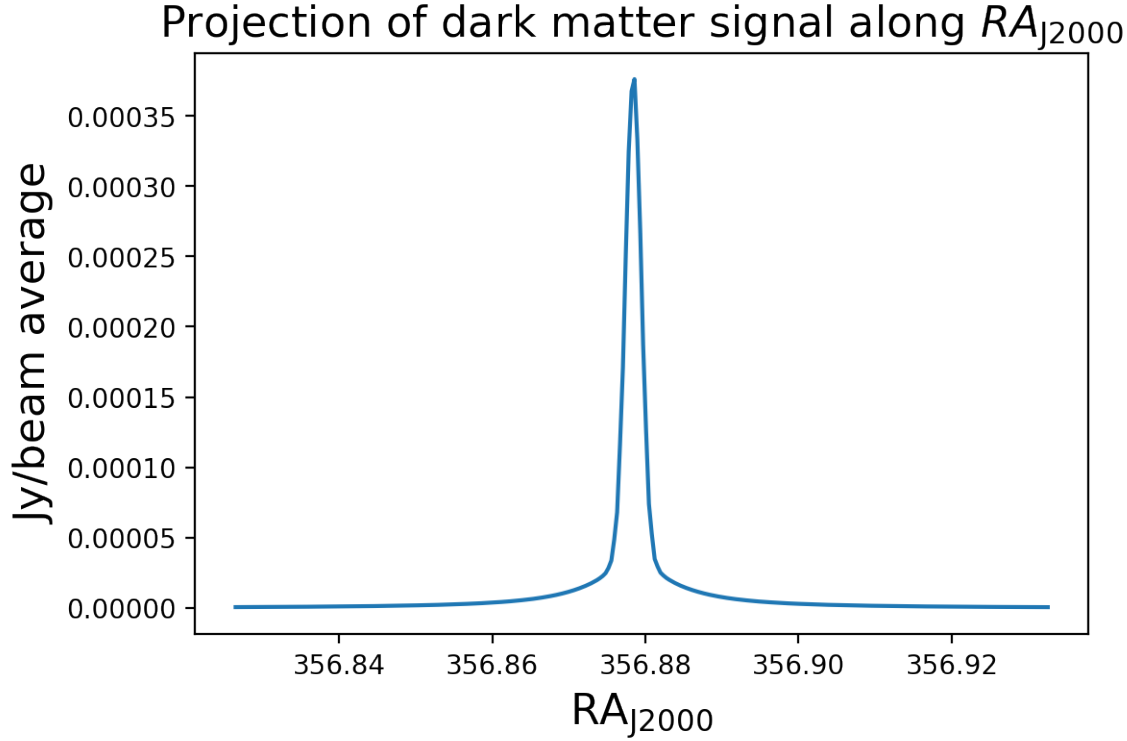


Figure 4.3: Projection of the dark matter signal across RA_{J2000} for Abell 4038. This signal is produced assuming annihilation through $b\bar{b}$, WIMP mass of 75 GeV and $\langle\sigma V\rangle = 10^{-26}$

where S_{Injected} and S_{original} are the total fluxes in the same region in the modified image and the original sky image respectively, and $\sigma_{\text{uncertainty}}$ is the statistical uncertainty of S_{original} . Requiring that the excess flux after the injection is twice the uncertainty approximates a 95% confidence level. The factor 10^{-26} assumes that the injection is performed with a modelled dark matter signal that has $\langle\sigma V\rangle = 10^{-26}\text{cm}^3\text{s}^{-1}$.

The total flux within $0.5r_s$ was obtained with `radioflux`⁴, where the statistical uncertainty accounts for the noise. The modelled dark matter signals and the cluster region before and after injection can be seen in Figure 4.5 and 4.4.

The central region of Abell 133 contains an extremely bright radio galaxy, with an extended radio tail. We attempted to remove this emission with `PyBDSF`. However, it was unable to adequately deal with the extended emission, leading to regions where there was extreme over subtraction, and regions with residual emission from the central galaxy. This can be seen in the top right panel of Figure 4.6. When the integrated flux was calculated in the region of interest, a non-physical value was obtained. Unrealistically low flux values will bias the calculated upper limits to be overly constraining. Residual emission in contrast will tend to weaken the upper limits by obscuring the dark matter signal, but is still considered the more conservative option. For this reason we chose to use the MeerKAT image with the compact emission, including the contributions from the bright central galaxy, intact for the dark matter signal injection. A more refined source subtraction in the case of an extended source with a complex morphology has been investigated by Hale et al [191]. The authors investigated the ability of `ProFound` [192] to accurately model complex sources. A source subtraction for Abell 133 with `ProFound` will be attempted in future work.

⁴<https://www.extragalactic.info/~mjh/radio-flux.html>

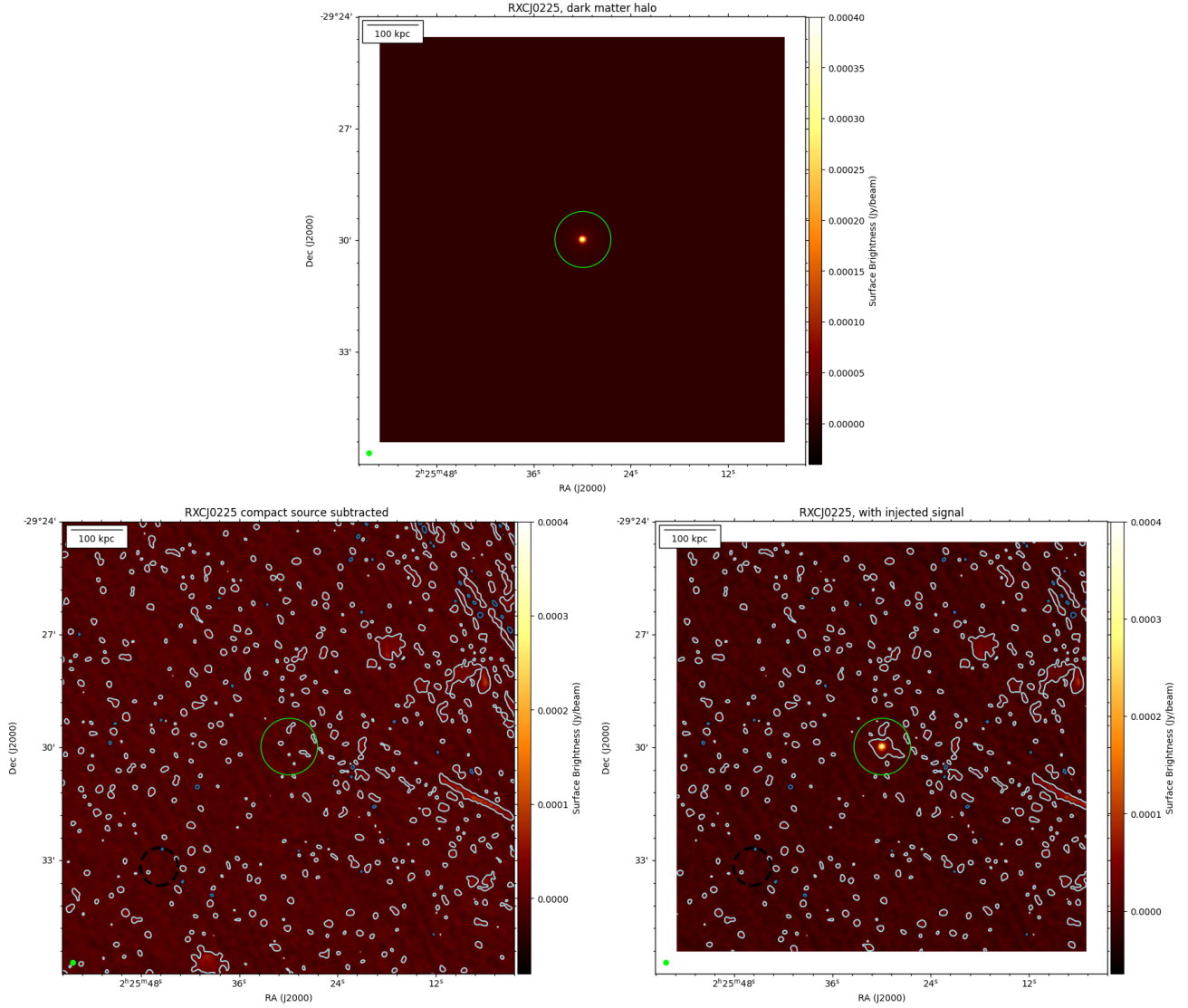


Figure 4.4: RXCJ0225.1-2928 focused on the MeerKAT pointing coordinates, cropped to a $20' \times 20'$ square. *Top:* The modelled dark matter signal in the RXCJ0225.1-2928 dark matter halo, for a WIMP mass of 75 GeV, $\langle\sigma V\rangle = 10^{-26}\text{cm}^3\text{s}^{-1}$ and annihilation channel $b\bar{b}$. The region over which the flux density is integrated is shown by the green circle, and is defined as half the scale radius, r_s , of the dark matter halo. *Bottom Left:* The original image used for the signal injection. This is the MGCLS image with compact sources removed. *Bottom Right:* The same region of sky after the dark matter signal has been injected. The dashed black circle is used as a background region used to calculate the statistical uncertainty of the radio flux in the two maps. The beam size is shown in the lower left corner of all maps. The dark and light contours correspond to -2σ and 2σ of the local average RMS respectively.

4.3.2 Brightest pixel value

As an additional test of the sensitivity of radio maps to dark matter induced radio halos we perform a comparison of the brightest flux density pixel value of the dark matter radio halo to the mean local RMS of the MeerKAT image. This requires convolving the FITS image of the dark matter signal with a kernel corresponding to the MeerKAT beam of the given cluster. This is done with `convolve2D`, as described in section 4.3. This ensures that the pixel value will be in units of Jy/beam, in order to be compared to the RMS value.

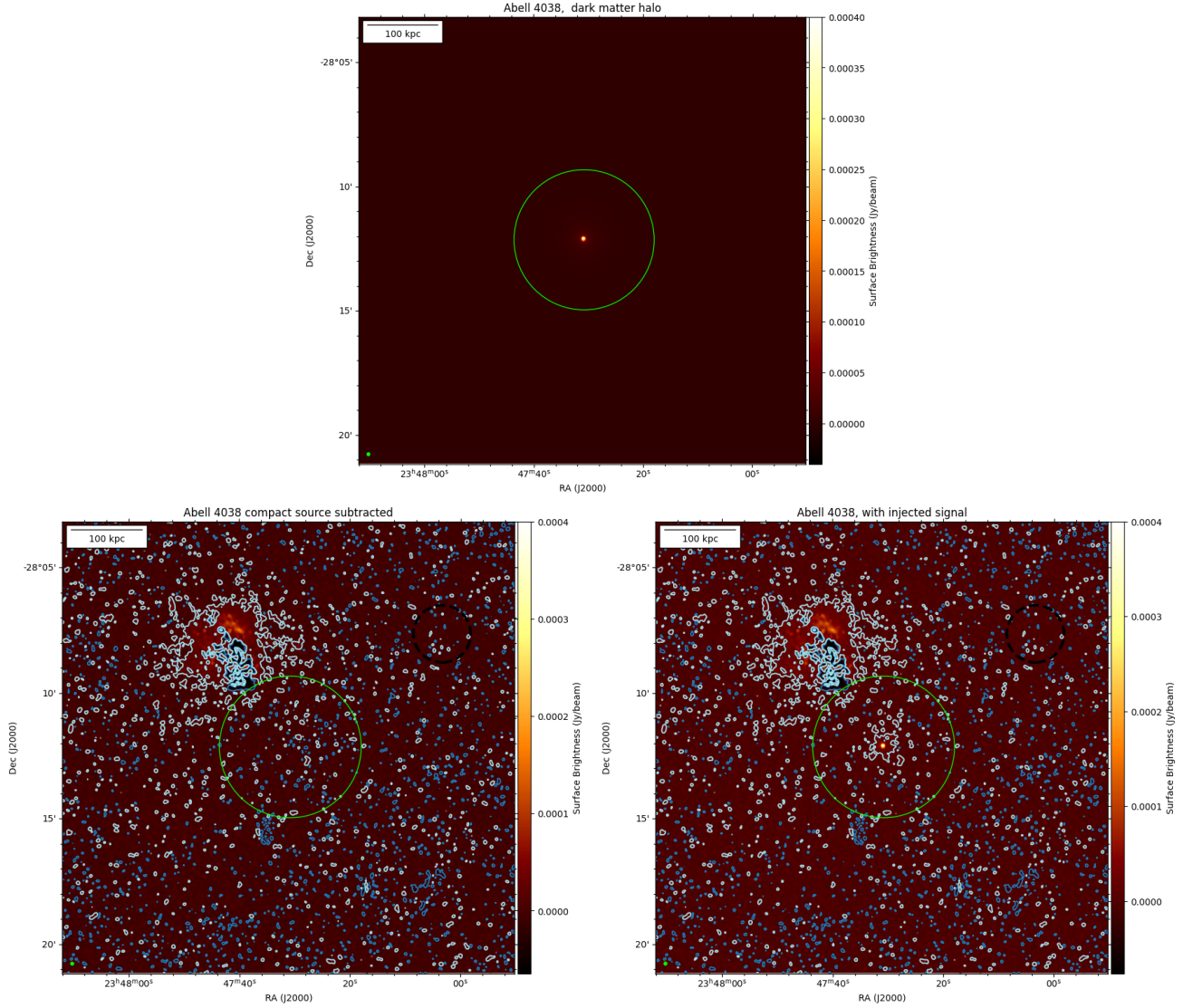


Figure 4.5: Abell 4038 focused on the MeerKAT pointing coordinates, cropped to a $20' \times 20'$ square. *Top:* The modelled dark matter signal in the Abell 4038 dark matter halo, for a WIMP mass of 75 GeV, $\langle\sigma V\rangle = 10^{-26} \text{cm}^3 \text{s}^{-1}$ and annihilation channel $b\bar{b}$. In this cluster we choose a slightly smaller region of integration than $r_s/2$ to avoid the emission and over subtraction in the region of the brightest radio galaxy. *Bottom-Left:* The original image used for the signal injection. This is the MGCLS image with compact sources removed. *Bottom-Right:* The same region of sky after the dark matter signal has been injected. The dashed black circle is used as a background region used to calculate the statistical uncertainty of the radio flux in the two maps. The beam size is shown in the lower left corner of all maps. The dark and light contours correspond to -2σ and 2σ of the local average RMS respectively.

The requirement we imposed to determine the upper limit of the annihilation cross section is that the brightest pixel of the dark matter radio halo is at least twice as bright as the mean RMS value. This requirement approximates to a 2σ confidence level for the upper limit of the annihilation cross section.

4.4 Galaxy cluster sample

This section serves to introduce the galaxy clusters used in the analysis and detail all the required parameters to model the dark matter signal. We study 12 clusters with giant radio halos, 1 cluster with a

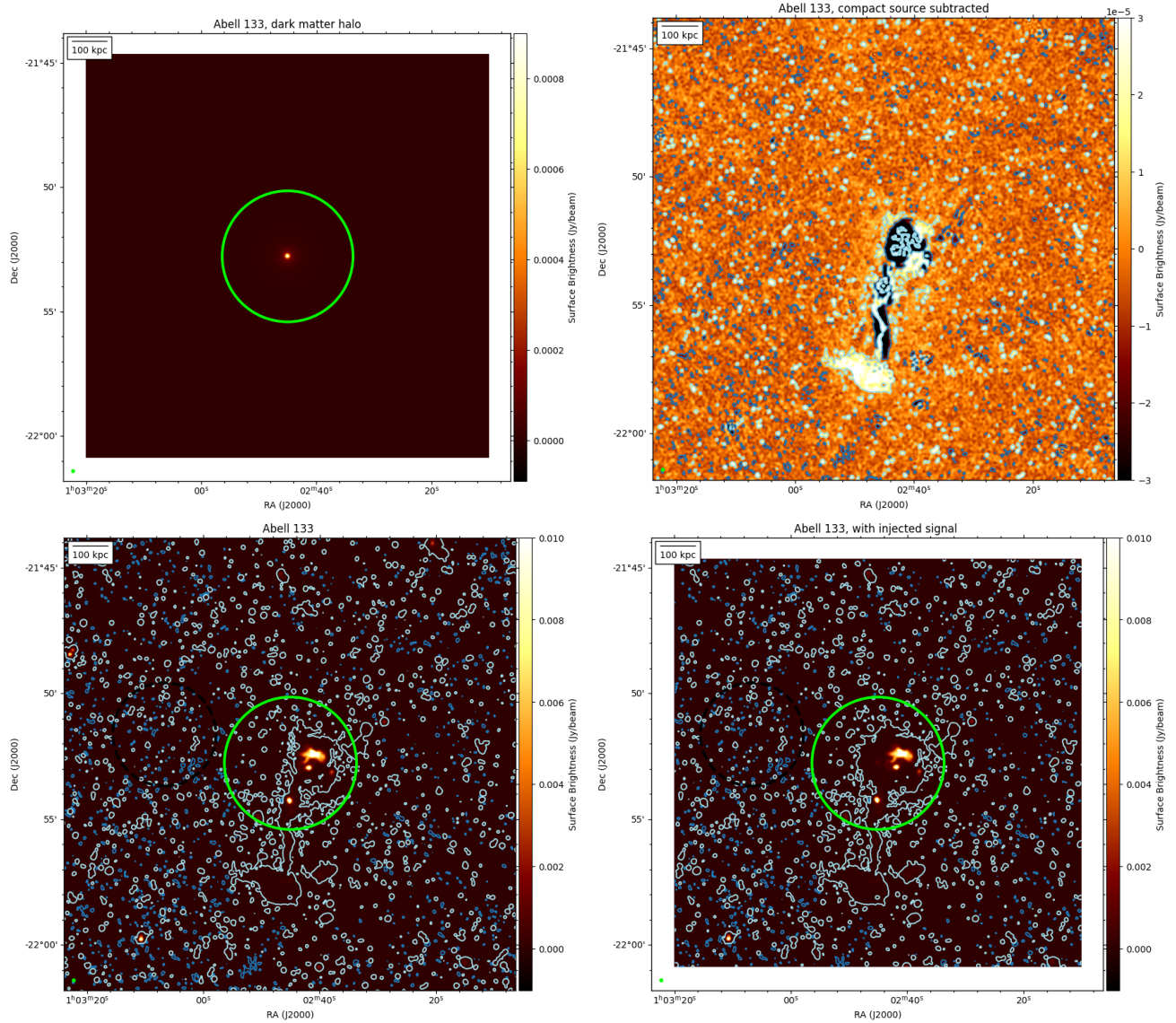


Figure 4.6: Abell 133 focused on the MeerKAT pointing coordinates, cropped to a $20' \times 20'$ square. *Top-Left:* The modelled dark matter signal in the Abell 133 dark matter halo, for a WIMP mass of 75 GeV, $\langle\sigma V\rangle = 10^{-25}\text{cm}^3\text{s}^{-1}$ and annihilation channel $b\bar{b}$. $r_s/2$ is shown by the green circle. *Top-Right:* The cluster centre with source subtraction with PyBDSF. The regions of over subtraction are shown by the dark regions. *Bottom-Left:* The original image used for the signal injection. This is the MGCLS image of the cluster centre. *Bottom Right:* The same region of sky after the dark matter signal has been injected. The dashed black circle is used as a background region used to calculate the statistical uncertainty of the radio flux in the two maps. The beam size is shown in the lower left corner of all maps. The dark and light contours correspond to -2σ and 2σ of the local average RMS respectively.

mini halo and 1 with a non-detection. These clusters were selected from the MGCLS catalogue due to the availability of the dark matter halo parameters in current literature.

4.4.1 Radio Halos

For the integrated flux comparison, as described in Section 4.2, clusters with giant radio halos are used. The 12 clusters utilized are selected from MGCLS due to the availability of the dark matter halo pa-

rameters in current literature. The tool used to model the dark matter radio signal requires an input describing the mass and size of the dark matter halo. The halo modelling function is able to take in either the characteristic density and the scale radius, or the virial mass and radius. In cases where the virial properties are readily available in the literature these properties are used. In cases where only M_{500} is found in literature we utilize a conversion between M_{500} and M_{vir} derived in Hu and Kravtsov [193], which assumes a standard NFW dark matter density profile. The equations are adapted to include the redshift dependence.

M_{500} can be used to determine r_{500} , from which the virial parameters can be obtained through the following equations:

$$\frac{M_{500}}{M_{\text{vir}}} = \frac{\Delta_{500}}{\Delta_c} \left(\frac{r_{500}}{c r_s} \right)^3, \quad (4.6)$$

where r_s is the scale radius of the dark matter halo, $c = r_{\text{vir}}/r_s$ and $\Delta_{500} = 500$ is the over-density used to define r_{500} . We define Δ_c as the over-density of the perturbation at the time of gravitational collapse, with respect to the critical density. This can be expressed as:

$$\Delta_c = 18\pi^2 - 82x - 39x^2, \quad (4.7)$$

where $x = 1 - \Omega_m(z)$. The two radii are related as

$$f\left(\frac{r_s}{r_{500}}\right) = \frac{\Delta_{500}}{\Delta_c} f\left(\frac{1}{c}\right), \quad (4.8)$$

where

$$f(x) = x^3 \left[\ln(1 + x^{-1}) - (1 + x)^{-1} \right]. \quad (4.9)$$

Therefore the ratio of the two radii requires inverting the function f . Hu and Kravtsov [193] provide a fitting formula for this inversion, given as

$$x(f) = [a_1 f^{2p} + 0.75^2]^{-0.5} + 2f, \quad (4.10)$$

with $p = a_2 + a_3 \ln f + a_4 (\ln f)^2$ and $a = [0.5116, -0.4283, -3.31 \times 10^{-3}, -3.52 \times 10^{-5}]$. In order to avoid degeneracies in this conversion we impose the condition on the virial concentration, $c = 6$. This is an estimation based on the concentration-mass relation for galaxy clusters [194]. The scaled boost factor is calculated within the radius of integration with equation 3.26. The physical properties of the dark matter halos of these clusters are provided in the first section of Table 4.3.

Additionally, to model the synchrotron emission we must model the electron distribution and the magnetic field. For this the gas density normalization factor, scale radius and the index of the radial profile are required and similarly for the magnetic field. At present these properties are not available for many of the target galaxy clusters. In the case of the clusters classified as containing a radio halo this information was unavailable and the properties of the Coma cluster are scaled to the size of the target.

For the gas density normalization, n_0 , the scaling relation used is

$$n_0 = n_{\text{Coma},0} \left(\frac{M_{\text{virial}}}{M_{\text{Coma,virial}}} \right)^{1/3} = 3.49 \times 10^{-3} \text{cm}^{-3} \left(\frac{M_{\text{virial}}}{1.24 \times 10^{15} M_{\odot}} \right)^{1/3}. \quad (4.11)$$

The gas scale, r_e , and magnetic field scale, r_B , are assumed to have the same value, following the behaviour displayed by Coma. This factor is scaled with the virial radius using the following relation

Table 4.1: Properties of the Coma cluster used in the scaling relations to obtain values for similar clusters

Property	Value	Reference
B_0	$4.7 \mu G$	[125]
η	0.5	[125]
n_0	$3.49 \times 10^{-3} \text{cm}^{-3}$	[195]
β	-0.654	[195]
r_e	253 kpc	[195]
M_{vir}	$1.24 \times 10^{15} M_{\odot}$	[196]
r_{vir}	2.7 Mpc	[196]

$$r_{e/B} = r_{e/B, \text{Coma}} \left(\frac{r_{\text{virial}}}{r_{\text{virial, Coma}}} \right) = 253 \text{ kpc} \left(\frac{r_{\text{virial}}}{2.7 \text{ Mpc}} \right). \quad (4.12)$$

The magnetic field normalization factor is slightly more ambiguous, as it is not expected to have any mass scaling, but rather depends on the dynamical activity within the galaxy cluster [197]. A key technique that is used in order to obtain information about the magnetic field strength is Faraday rotation (FR) analysis of radio sources within or behind the cluster. Govoni et al [117] summarises the results of FR studies on clusters. It is found that for in galaxy clusters with cool cores the rotation measure (RM) values are extremely high, approximately proportional to the cooling rate. The derived magnetic field strengths range from $\sim 5 \mu G$ up to $30 \mu G$ in extreme cases. Galaxy clusters without cool cores have FR data that is consistent with μG magnetic fields, with values $\sim 2 - 8 \mu G$ [117]. Recalling that radio halos occur in dynamically disturbed clusters, we choose the value of $5 \mu G$ as the normalization factor for this sample.

As there are no details on the shape of the gas density or magnetic field for these clusters, we use the model that best fits Coma for both profiles. This is a beta profile, with form given in equation 3.10.

4.4.2 Mini-halos and non-detections

The sample of clusters used in the halo injection contains fainter diffuse sources, either in the form of mini halos or a non-detection of diffuse emission. The physical properties of the dark matter halos are provided in the second section of Table 4.3. For these clusters, information on the electron distribution was sourced from literature. For Abell 4038 the parameters required for a beta profile were found. For Abell 133 and RXCJ0225.1-2928 the electron distributions were presented graphically in [198] and [199] respectively. This data was extracted and the best fit beta and double beta profiles were fitted. The parameters resulting from this fitting procedure are reported in Table 4.2. The double beta profile appears to provide an improved description of the data, however for RXCJ0225.1-2928 the beta value of -2.56×10^3 is unrealistic. Therefore we utilize the double beta profile for Abell 133, and the more realistic single beta profile for RXCJ0225.1-2928.

As the magnetic field parameters are currently unavailable we rely on general scaling relations noted by various Faraday rotation measure studies performed on clusters of galaxies, such as [118, 202, 203]. The common choice is that the magnetic field radial distribution follows that of the gas density with form

$$B(r) = B_0 \left(\frac{n_e(r)}{n_0} \right)^{\eta}, \quad (4.13)$$

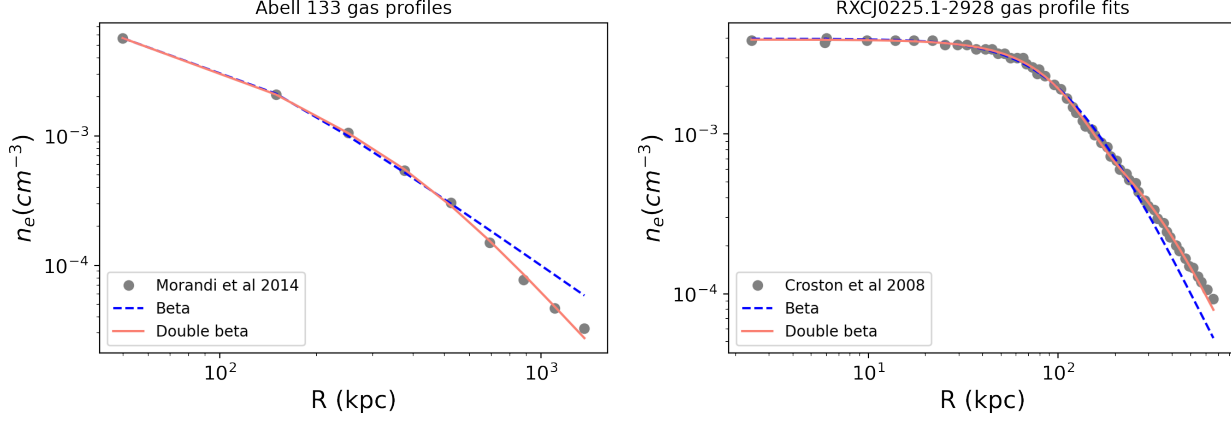


Figure 4.7: Best fit beta and double beta radial profiles to gas density data extracted from literature.

Table 4.2: Electron distribution properties of the clusters analysed by surface brightness. (2): The gas normalization factor. (3): The second gas normalization factor applicable in a double beta profile. (4): The gas scale, where (5) gives the second gas scale for the double beta profile. (6) gives the exponent of the profile and the second exponent for the double beta profile given in (7).

Cluster name (1)	$n_0 \text{ (cm}^{-3}\text{)}$ (2)	$n_{0,2} \text{ (cm}^{-3}\text{)}$ (3)	$r_e \text{ (kpc)}$ (4)	$r_{e,2} \text{ (kpc)}$ (5)	β_e (6)	$\beta_{e,2}$ (7)	References (8)
Abell 4038	0.022	-	75.87	-	-0.54	-	[200] [201]
Abell 133							[198]
Beta profile	0.008	-	82.29	-	-0.57		
Double beta profile	0.007	0.001	81.18	391	-0.75	-1.08	
RXCJ0225.1-2928							[199]
Beta profile	0.004	-	112	-	-0.8		
Double beta profile	0.003	0.001	6×10^3	250	-2.56×10^3	-0.87	

predicted through both cosmological simulations and the comparison between thermal and radio brightness profiles [88]. Typically $\eta = 0.5$ corresponds to a magnetic field that decreases with radius in the same way as the gas density [118]. We note that in previous works this value is often assumed, and is only derived from comparison to observations for the case of the Coma cluster. In the modelling of the magnetic field profile we utilize $\beta_B = 0.5\beta_e$, as well as assuming that the scale radius takes on the same value. We take a conservative estimation of $8 \mu G$ on the central value of the magnetic field for the mini halos, as these can take on extreme values. Following the conclusions of Feretti et al [88] of rotation measure studies, the magnetic field strengths of clusters are similar between cases with or without detected diffuse halos, we utilize the value of $5 \mu G$ for the central magnetic field value of RXCJ0225.1-2928, to match the value we have chosen for radio halos. Abell 133 is classified as a mini-halo, and thus should have the central magnetic field value of $8 \mu G$. Requiring that the two normalization factors sum to this central value and that

$$B_{0,2} = B_0 \left(\frac{n_{0,2}}{n_0} \right)^{\beta_e/\beta_B}, \quad (4.14)$$

we determine that $B_0 = 5.79 \mu G$ and $B_{0,2} = 2.21 \mu G$.

Table 4.3: Physical properties of the dark matter halo within the cluster. (2): Redshift. (3)-(4): MeerKAT pointing coordinates. (5): Mass contained within the virial radius. (6): Scale radius of the dark matter halo. (7): Presence of diffuse emission (DE) and the form. (8) Classification. (9) The scaled boost factor. (10) Alternate names. (11) References. The mass value with the asterisk is calculated using M_{500} and $c_{500} = r_{500}/r_s$. The table is separated according to the clusters used in the analysis following section 4.2 and 4.3.

Cluster name (1)	z (2)	R.A. _{J2000} (deg) (3)	Dec. _{J2000} (deg) (4)	$M_{\text{vir}}(10^{15} M_{\odot})$ (5)	r_s (Mpc) (6)	DE (7)	Class (8)	Scaled Boost (9)	Alternate name (10)	References (11)
Abell 209	0.206	22.9896	-13.5764	1.35	0.62	✓	Halo	5.69		[124] [204]
Abell 370	0.375	39.9604	-1.5856	3.03	0.36	✓	Halo	5.78	G172.98-53.55	[124] [205] [206]
Abell 545	0.154	83.1017	-11.5431	0.507	0.32	✓	Halo	5.30	J0532.3-1131	[124] [207]
Abell 2667	0.230	357.9196	-26.0836	1.48	0.438	✓	Halo	1.92	J2351.6-2605	[124] [208]
Abell 2813	0.29	10.8517	-20.6214	1.241	0.61	✓	Halo	2.84	J0043.4-2037	[124] [204]
Abell S295	0.3	41.4	-53.0380	0.51	0.44	✓	Halo	5.58	J0245.4-5302	[124] [204]
Abell S1063	0.348	342.1813	-44.5289	1.49	0.66	✓	Halo	5.74	J2248.7-4431	[124] [204]
J0303.7-7752	0.274	45.9433	-77.8692	1.10	0.387	✓	Halo	4.34	G294.66-37.02	[124] [208]
J0528.9-3927	0.284	82.2346	-39.4628	1.64	0.65	✓	Halo	1.82		[124] [209]
J0638.7-5358	0.233	99.6938	-53.9717	1.09	0.394	✓	Halo	5.28	Abell S592	[124] [208]
J0645.4-5413	0.167	101.3721	-54.2189	1.24	0.61	✓	Halo	4.27	Abell 3404	[124] [204]
J1601.7-7544	0.153	240.4446	-75.7461	1.24	0.431	✓	Halo	3.06	G313.88-17.12	[124] [208]
Abell 4038	0.028	356.8796	-28.2028	0.46	0.391	✓	Mini halo			[124] [210]
Abell 133	0.057	15.6879	-21.8800	0.389	0.361	✓	Mini halo			[124] [211]
RXCJ0225.1-2928	0.060	36.3750	-29.5000	0.138*	0.108	-				[124] [212] [213]

Chapter 5

Results and discussions

In this chapter the upper limits of the dark matter annihilation cross section are presented and the results of this work are compared to those of earlier works. We discuss how these results could potentially be improved upon in future work.

5.1 Upper limits on $\langle\sigma V\rangle$ determined with giant radio halos

We probe WIMP annihilation into bottom quarks, muons, tau leptons and through the 2HDM+S chain, for WIMP masses 75-200 GeV. This mass range is chosen as it overlaps with the mass range of the 2HDM+S dark matter candidate expected from kinematic considerations [161], and the mass fitting to various astrophysical excesses [167, 168, 214, 215]. 12 galaxy clusters containing giant radio halos were investigated for the integrated flux comparison. The results are depicted in Figure 5.8 and Figure 5.9.

For comparison we determine upper-limits on the annihilation with a varied method of removing the contribution to the point sources. This entailed removing the compact sources in the full resolution image with PyBDSF, and then convolving the source subtracted image to a $15''$ resolution. The integrated flux of the region of interest determined by $3\sigma_{\text{RMS}}$ contours around the pointing coordinates. It was found that the integrated fluxes in the region of interest were an order of magnitude lower than those determined in the previous method. This is likely due to an under-subtraction of the compact source contribution when using the $15''$ resolution images in the initial processing. These findings support that performing the source subtraction on the full resolution image and then convolving to the lower resolution is a superior method for obtaining the diffuse flux of the radio halo. The reduction of the flux values to which the dark matter flux is compared strengthens the upper limits on the annihilation cross section by approximately an order of magnitude. The results are depicted in Figure 5.10 and Figure 5.11.

The upper limits on the annihilation cross sections for the four channels are well above the thermal relic cross section. As such, these results cannot exclude these dark matter models at a 2σ confidence level. This is likely due to the high flux values of the giant radio halos, allowing many possible dark matter signals to be hidden beneath the halo emission. Despite this, the upper limits determined with MGCLS radio data are more stringent than those determined with gamma-ray data. Ando et al [216] analysed Fermi-LAT data of 49 galaxy clusters. The authors used the non-detection of gamma-ray excesses to constrain the dark matter annihilation cross section. In Figure 5.1 the stacked constraints for bottom quarks and tau leptons obtained through the comparison of integrated fluxes of giant radio halos are presented alongside the stacked results determined with gamma-ray observations [216]. Here we note that these are the stacked results of the weaker limits (Figure 5.8 and 5.9). Despite this, the results of this work are a vast improvement over those obtained in Ando et al [216].

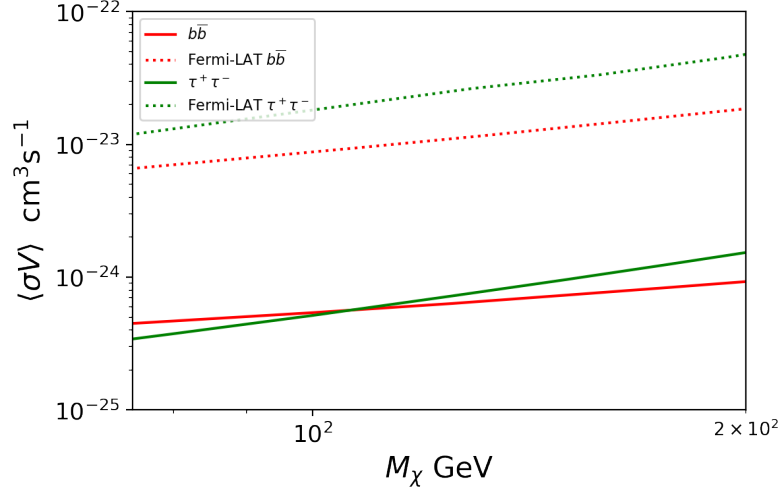


Figure 5.1: Upper limits of the dark matter annihilation cross section for the bottom quark and tau lepton annihilation channels. The solid lines show the statistically stacked results of the 12 giant radio halos investigated in this work, while the dotted lines show the statistically stacked results of 38 clusters investigated by Ando et al [216] observed with Fermi-LAT.

More constraining limits on dark matter properties can be obtained from clusters with giant radio halos by removing the contribution to the flux density due to normal diffuse cosmic rays. This would require radio continuum spectral data and has been attempted by Chan et al [217, 218, 219]. In these works it is argued that radio continuum spectrum data could be used to differentiate the contributions of cosmic rays and dark matter to the diffuse emission as the spectral index could be different. However, the spectral shape of the cosmic ray contribution depends on the assumed model for the production mechanism, primary electron emission models, secondary electron emission model or in situ acceleration. Parametric equations [217] for the cosmic ray contributions are:

$$S_{\text{CR}} = S_{\text{CR},0} \left(\frac{\nu}{\text{GHz}} \right)^{-\alpha} \left[\frac{1}{1 + \left(\frac{\nu}{\nu_s} \right)^\Gamma} \right], \Gamma = 0.5 \text{ or } 1 \quad (5.1)$$

$$S_{\text{CR}} = S_{\text{CR},0} \left(\frac{\nu}{\text{GHz}} \right)^{-\alpha} \quad (5.2)$$

$$S_{\text{CR}} = S_{\text{CR},0} \left(\frac{\nu}{\text{GHz}} \right)^{-\alpha} \exp(-\nu^{1/2}/\nu_s^{1/2}) \quad (5.3)$$

respectively. In the above $S_{\text{CR},0}$, ν_s and α are free parameters for the fitting to the observed radio spectrum. Such an analysis assumes that the measured flux with its uncertainty is the expected flux density. This is valid in cases where the contribution from star formation is negligible [220], but should be used with caution, particularly for smaller scaled structures where the contribution from star formation is significant.

5.2 Upper limits on $\langle\sigma V\rangle$ determined with mini radio halos and non-detections

This section presents the results determined by injecting the dark matter signal into an image of the central cluster region.

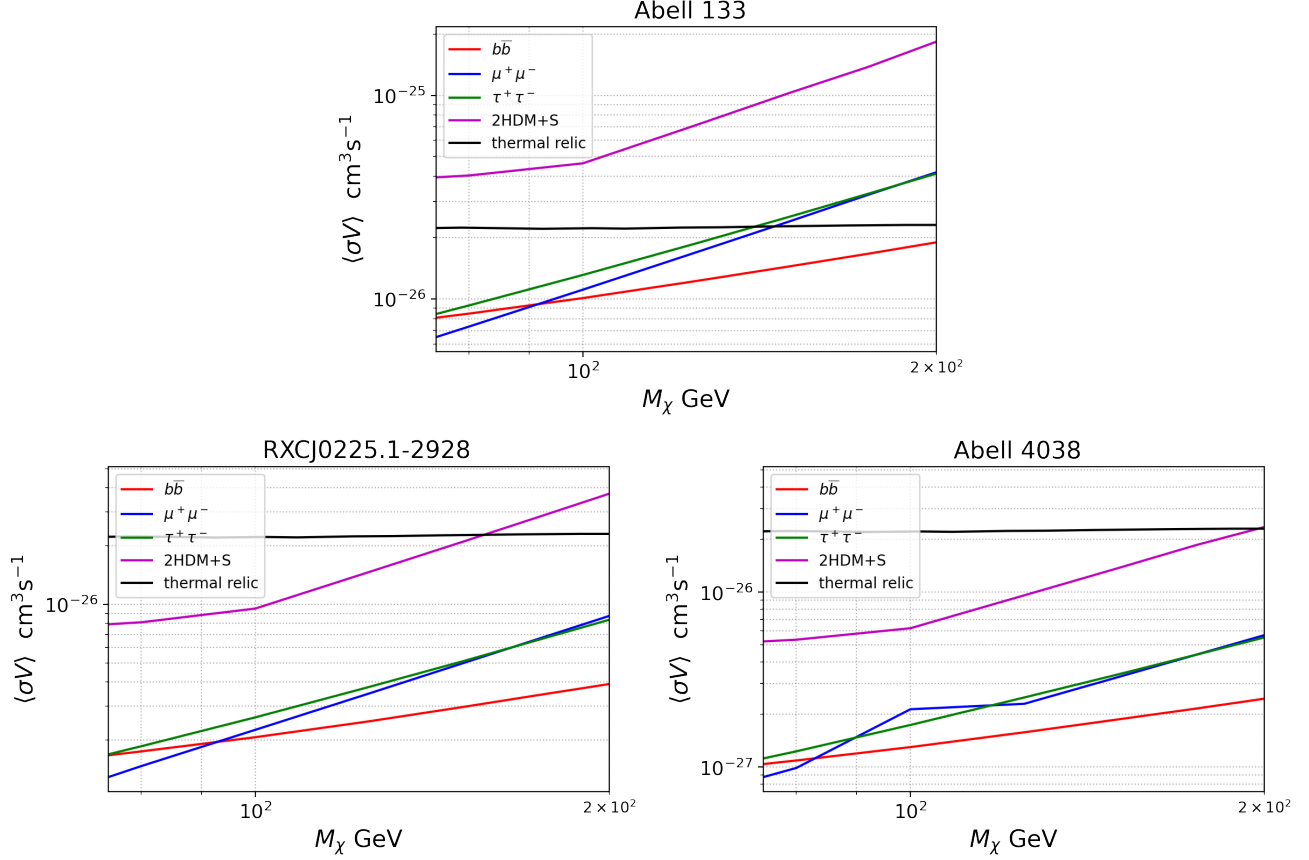


Figure 5.2: Upper limits of the dark matter annihilation cross section at a 95% confidence level, determined by requiring that the difference in total flux within $r_s/2$ once the dark matter signal has been injected is twice the uncertainty. The solid black line represents the thermal relic value, below which models can be excluded.

5.2.1 Flux uncertainty exclusion limits

The upper limits of the dark matter annihilation cross section determined with Equation 4.5, requiring that the difference in total flux within $r_s/2$ after the dark matter signal has been injected into the image of the cluster is twice the uncertainty, are presented in Figure 5.2. We recall that the parent image for Abell 133 contained the radio lobes from the bright central radio galaxy. This resulted in the flux of the integration region being much larger compared to RXCJ0225.1-2928 and Abell 4038. We present the constraints derived with Abell 133, despite the bright central flux, as a demonstration of the usefulness of fainter diffuse sources as well as non-detections.

From the results of RXCJ0225.1-2928 and Abell 4038 we are able to rule out the thermal relic value for bottom quarks, muons and tau leptons for masses between 75 – 200 GeV. In the case of Abell 4038 the 2HDM+S channel is also excluded across this mass range, while for RXCJ0225.1-2928 this is excluded for masses $\lesssim 156$ GeV. For Abell 133 we are able to exclude the thermal relic for bottom quarks across the mass range, while muons and tau leptons are excluded for masses $\lesssim 140$ GeV. The results for 2HDM+S channel for this cluster are unable to exclude the thermal relic.

5.2.2 Brightest pixel comparison

The constraints derived by requiring that the brightest pixel of the modelled dark matter emission is twice as bright as the average local RMS noise are shown with coloured lines. It is expected that these would be the best possible upper limits that could be obtained with these radio maps. The results of the annihilation cross section upper limits are shown in Figure 5.3.

5.2.3 The effects of uncertainties in the modelling parameters

Uncertainties in various modelling parameters may impact the upper limits on the annihilation cross sections. In this section we investigate the impact of the assumed density profile, magnetic field strengths and the diffusion constant on the constraints.

The previous results have assumed that the dark matter density follows a cuspy NFW profile. This assumption was made following evidences that support NFW profiles for galaxy clusters [176, 178, 179]. To investigate the affect of the density profile on the produced constraints, the generalised NFW profile (Equation 3.3) is considered. We consider two values for the halo index, $\alpha = 1$ which corresponds to a cuspy NFW profile and $\alpha = 0.5$ which describes a more shallowly cusped profile. We feel that these profiles should adequately cover the uncertainties of the modelling of the dark matter density profiles for these targets. The results are depicted in Figure 5.4. It can be seen that assuming a more shallowly cusped density profile weakens the constraints of the annihilation cross section. This behaviour is expected, as the cuspiest the profile the more concentrated the dark matter within the central regions of the dark matter halo. This in turn causes stronger emissions, and therefore stronger constraints.

In Figure 5.5 the affect of magnetic field strength on the constraints of the annihilation cross section is depicted. We consider an example taking a NFW dark matter density profile, a WIMP mass of 100 GeV and annihilation through bottom quarks with Abell 4038 as the target object. The magnetic field strength is varied between 2 and 10 μG . This range is chosen as it covers the range of strengths found for clusters in various studies [117, 221]. At small magnetic field strengths the upper limit of the cross section scales with the inverse square of the magnetic field strength. As the magnitude increase the constraints flatten out. These results are in agreement with what is found by Regis et al [131] for the LMC.

In the modelling of the dark matter signal the diffusion constant was assumed to be $D_0 = 3 \times 10^{28} \text{cm}^2 \text{s}^{-1}$ following [222, 223, 79]. There is however some uncertainty for the use of this value in extragalactic targets. We investigate the dependence of the results on the choice of this value by varying D_0 between $3e \times 10^{27} \text{cm}^2 \text{s}^{-1}$ and $3 \times 10^{29} \text{cm}^2 \text{s}^{-1}$. We find there is a negligible difference between the annihilation cross sections for these values. This is due to the large size of the galaxy clusters, where the effects of diffusion are less significant. Beck et al [176] investigated two diffusion scenarios, namely Kolmogorov and Bohmian [224]. The authors found a negligible affect even with these differing diffusion scenarios. We can therefore conclude that our results are robust to changes in the diffusion constant.

5.2.4 Comparison to previous works

A key objective of this work is to showcase MeerKAT's ability to constrain the dark matter parameter space. Therefore, it is beneficial to compare the results to those of previous studies. Some of the most stringent dark matter constraints to date were derived by Regis et al [131] for the Large Magellanic Cloud (LMC), which was processed as part of the Evolutionary Map of the Universe (EMU) survey performed with the Australian Square Kilometre Array Pathfinder (ASKAP). In Figure 5.6 we display the annihilation cross section upper limits determined in Section 5.2.1 assuming an NFW density profile, overlaid

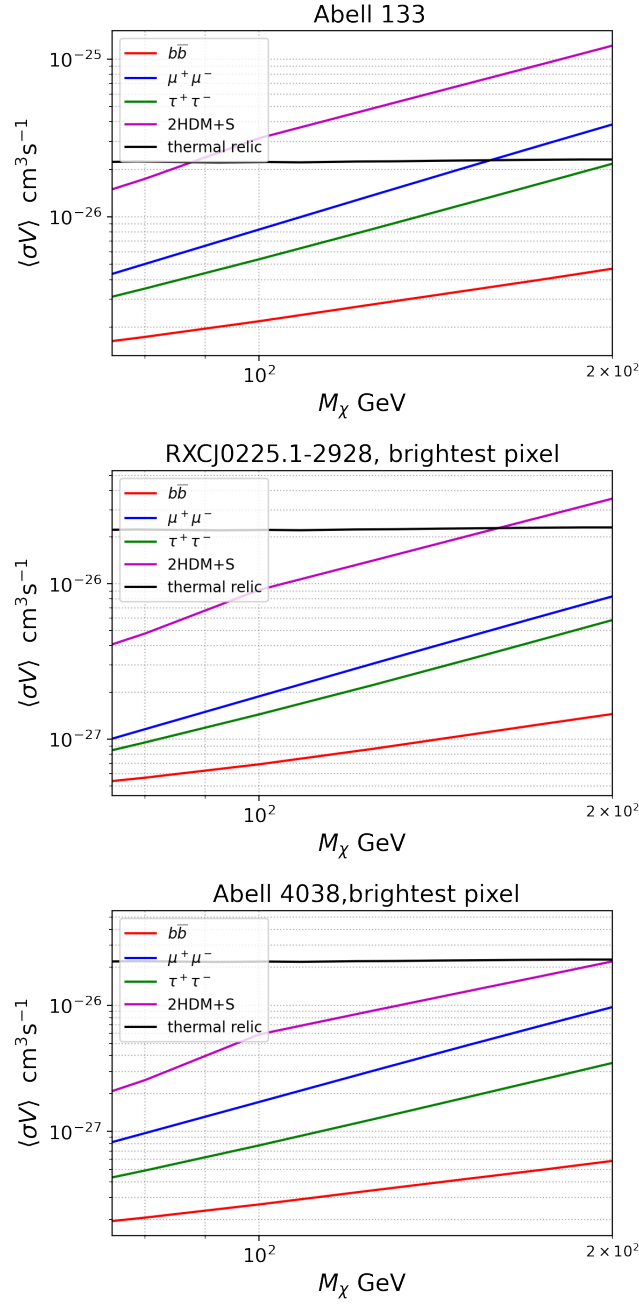


Figure 5.3: Upper limits of the dark matter annihilation cross section at a 95% confidence level, determined by comparing the brightest pixel of the dark matter signal to twice the local RMS noise level. The solid black line represents the thermal relic value, below which models can be excluded.

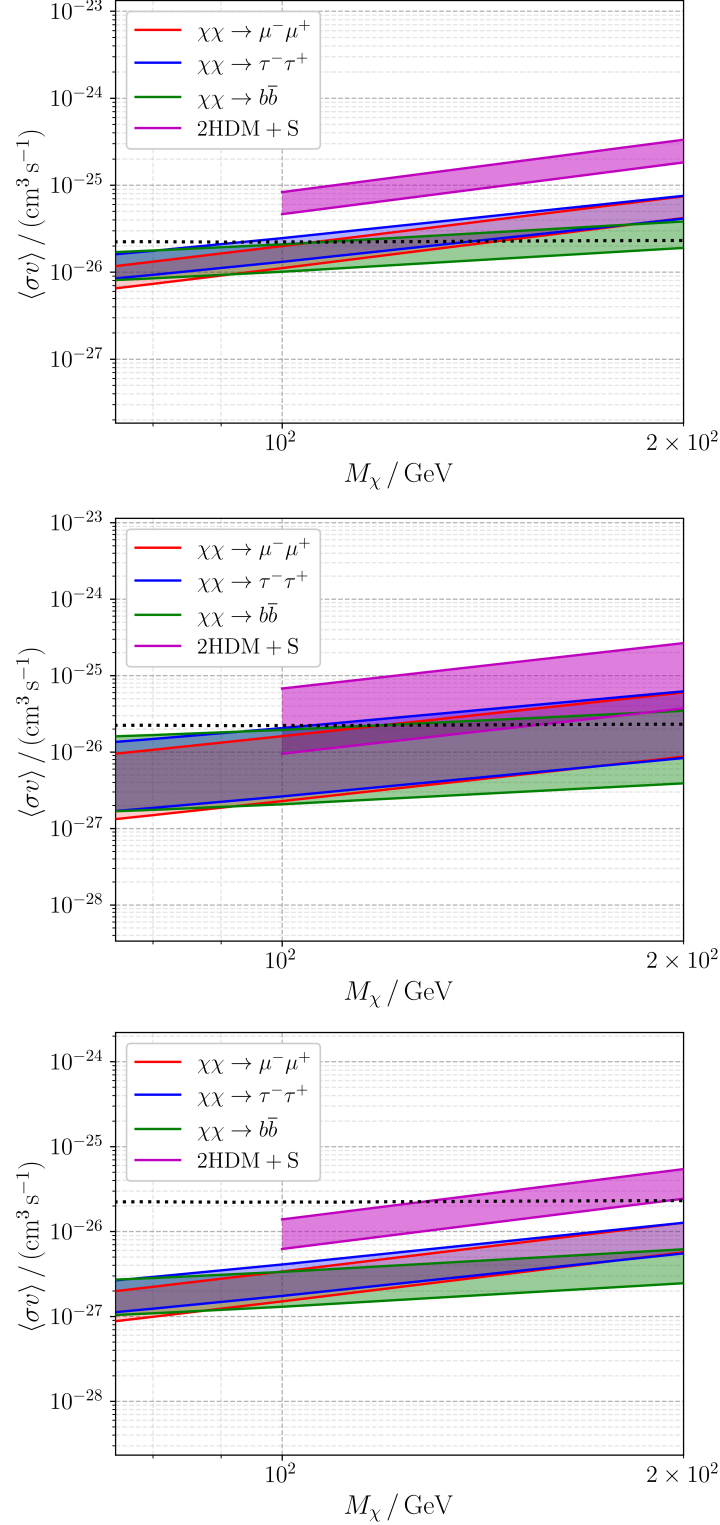


Figure 5.4: Upper limits of the dark matter annihilation cross section at a 95% confidence level, determined by requiring that the difference in total flux within $r_s/2$ once the dark matter signal has been injected is twice the uncertainty. The lower bound of the uncertainty band assumes a cuspy NFW density profile ($\alpha = 1$), and the upper bound assumes a more shallowly cusped profile ($\alpha = 0.5$). The solid black line represents the thermal relic value, below which models can be excluded. *Top:* Abell 133. *Middle:* RXCJ0225.1-2928. *Bottom:* Abell 4038.

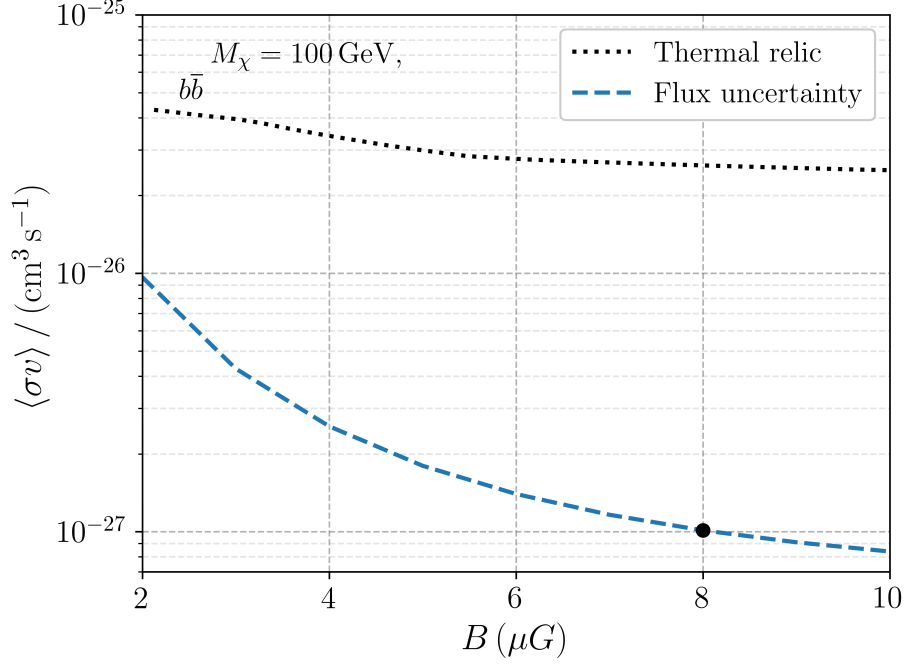


Figure 5.5: The 2σ exclusion limits on the annihilation cross section for Abell 4038 with varying magnetic field strength. An NFW dark matter density profile is assumed, and annihilation through bottom quarks for WIMP mass 100 GeV is considered as an example. The black dot shows the reference value assumed for Abell 4038 in this work. The dotted line is the thermal relic value.

with the constraints from Regis et al [131]. Additionally some of the latest constraints derived using Fermi-LAT observations of dwarf spheroidal galaxies by Hoof et al [225] are shown.

A key metric for dark matter constraints is the maximum mass at which we can exclude the thermal relic cross section. In Figure 5.6 we can see that for dwarf galaxies observed with Fermi-LAT the maximum mass below which we can exclude the thermal relic is ~ 100 GeV for annihilation through quarks. The results of this work are able to exclude all the channels considered up to the maximum mass we have considered (200 GeV), comparable to the masses that are excluded by Regis et al [131]. We note that the annihilation constraints for the LMC determined by Regis et al [131] are obtained by taking the lower limits for the dark matter profile and magnetic field while taking the upper limits for the diffusion coefficient, interstellar radiation field and gas density. This results in conservative bounds for the WIMP signal. The more stringent constraints are produced by assuming a cuspy dark matter profile (NFW and Hernquist) while the upper bound is produced by considering a cored dark matter profile (Burkert and Isothermal). The varying dark matter profiles are considered due to the poor knowledge of dark matter physics on small scales, valid for the LMC. From this we are able to conclude that our results from the signal injection technique are competitive to those determined by Regis et al [131] while surpassing those determined with gamma-ray data [225].

By studying dark matter induced radio signals in galaxy clusters we are able to reduce some of the uncertainties faced by studies on dwarf galaxies, such as the dark matter density profile and halo mass, the magnetic field profile and the diffusion coefficient. Galaxy clusters appear to have NFW-like density profiles [176, 178, 179] while there are still tensions between cored and cuspy profiles in smaller structures. The largest uncertainty faced in this work is the magnetic field strength. Faraday rotation measure studies within clusters [117] provide a range of magnetic field strengths, approximately $2.5 - 7.5 \mu\text{G}$ for non-cool core clusters and $5 - 15 \mu\text{G}$ for cool core clusters. This results in a relative

error of approximately 0.5. Rotation measures are more challenging to obtain in dwarf galaxies due to their low gas and dust content, and therefore the magnetic field remains largely unconstrained [127]. For the three galaxy clusters considered for the flux uncertainty exclusion limit technique the gas density profiles have an empirical grounding. This in turn provides an empirical grounding for the magnetic field profile utilized. Future polarization studies will be able to determine the magnetic field structures of astrophysical objects. Additionally, dark matter emission in clusters is dominated by energy-loss effects, in contrast to smaller scaled structures, such as dwarf galaxies, that have significant uncertainties due to the effects of diffusion. Regis et al [131] face large uncertainties for the virial mass, magnetic field structure and the diffusion coefficient for the LMC. The authors circumvented these uncertainties by only integrating over a very small central region, 1.3 kpc in radius. This allows the authors to assume a constant magnetic field of $4.3 \mu\text{G}$, and reduces the effects of diffusion.

At present the only constraints of the dark matter candidate within the 2HDM+S model have been determined by a parameter space fitting of $\chi\bar{\chi} \rightarrow S \rightarrow X$ to AMS-02 positron data [165], and the overlapping regions of anti-proton and Fermi-LAT galactic centre gamma ray parameter spaces, see Section 2.2.2. In Figure 5.7 we overlay the results of the annihilation cross section upper limits obtained in Section 5.2.1 on the parameter space fittings of Beck et al [165]. The upper limits derived for Abell 4038 and RXCJ0225.1-2928 exceed the predictions of potential upper limits for a non-detection with MeerKAT with 100 hours of observational data, at a 2σ confidence level produced by Beck et al [165]. This is achieved with less than 10 hours on target observation. Additionally, the results indicate that 2HDM+S dark matter models can be excluded as explanations for the positron, anti-proton and galactic centre gamma ray excesses if an NFW density profile is assumed. However with the more shallowly cusped density profile a significant overlap can be seen between the parameter space fittings and the uncertainty bands. Therefore, within the uncertainty of the dark matter density profiles for galaxy clusters, 2HDM+S remains a viable explanation for the various astrophysical excesses. The upper limits of the annihilation cross section can be translated to limits on the coupling between the scalar mediator, S , and the dark matter candidate, χ , which is denoted by g_χ^S . This can be achieved through the relation:

$$\langle\sigma V\rangle = \int \sigma_{\chi\chi}(g_\chi^S = 1) (g_\chi^S)^2 v f(v) dv, \quad (5.4)$$

where $\sigma_{\chi\chi}(g_\chi^S = 1)$ is the annihilation cross section when the coupling is unity and $f(v)$ is a Maxwell-Boltzmann distribution of the velocity dispersion of the dark matter halo [165]. At present this coupling remains unconstrained by collider data.

5.3 Future improvements

By improving the sensitivity of the data products obtained with MeerKAT, we should in principle be able to produce more stringent upper limits. Sensitivity scales as a function of integration time. Stokes I point source sensitivity with natural weighting is given by the radiometer equation:

$$\frac{SEFD}{\sqrt{2\Delta\nu t_{\text{int}} N(N-1)}}. \quad (5.5)$$

From this it can be seen that thermal noise scales as a function of integration time, where an increase in the integration time can improve the sensitivity. However, after a sufficient time the field will be dominated by confusion noise. Confusion noise can be understood as the fluctuations of the background brightness below which sources cannot be detected individually [226]. This represents a fundamental limit to continuum detections with MeerKAT. Using the MeerKAT continuum sensitivity calculator ¹

¹<https://apps.sarao.ac.za/calculators/continuum>

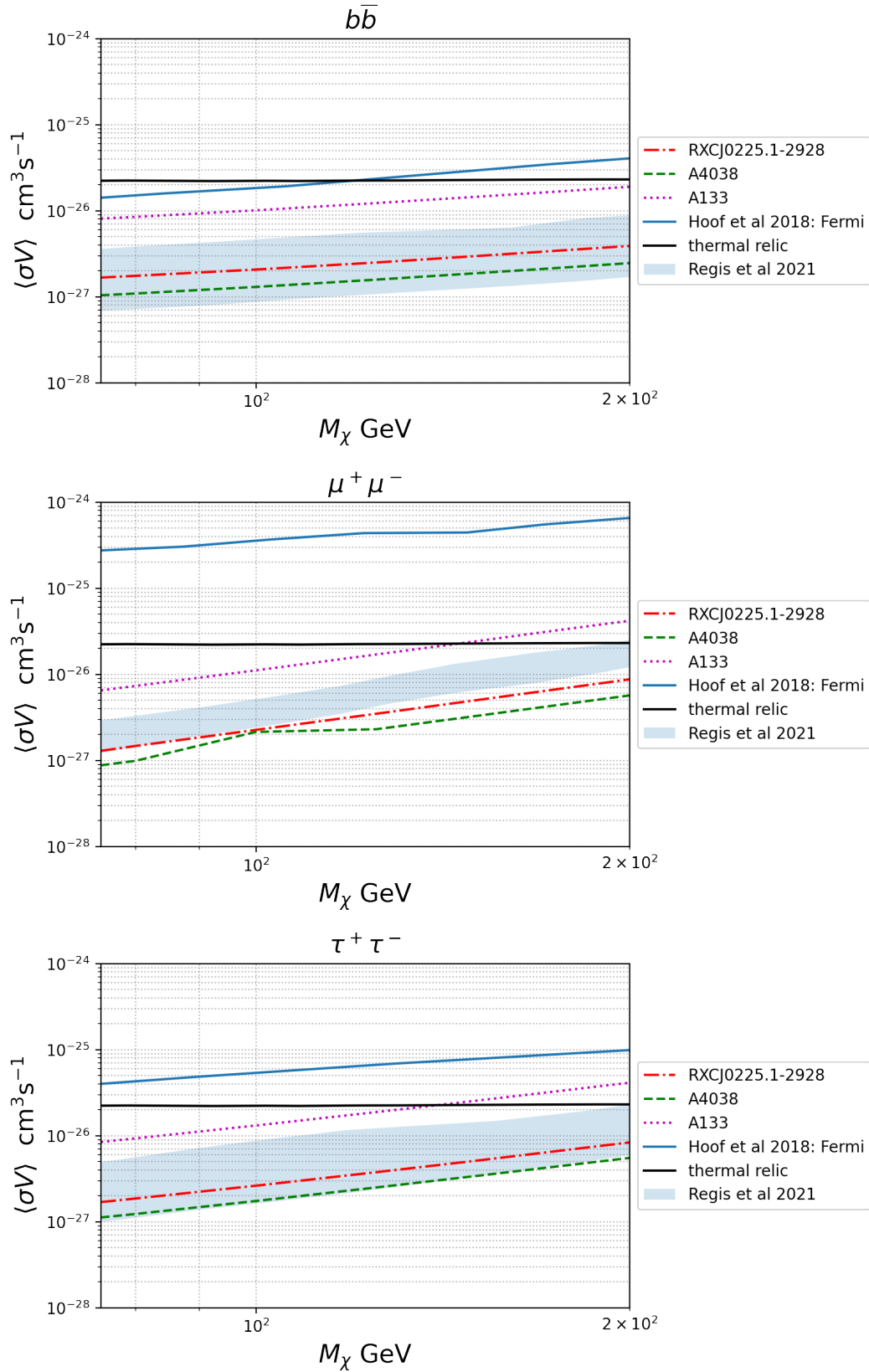


Figure 5.6: The upper limits of WIMP annihilation channels derived in this work (dotted, dashed, dot-dashed lines) from the flux uncertainty exclusion limit method assuming an NFW profile, with the constraints derived by Regis et al [131] for the LMC observed as part of the EMU survey with ASKAP and from Fermi-LAT observations of dwarf spheroidal galaxies by Hoof et al [225]. The black line represents the thermal relic value, below which models can be excluded. *Top:* annihilation via b-quarks. *Middle:* annihilation via muons. *Bottom:* annihilation via tau leptons.

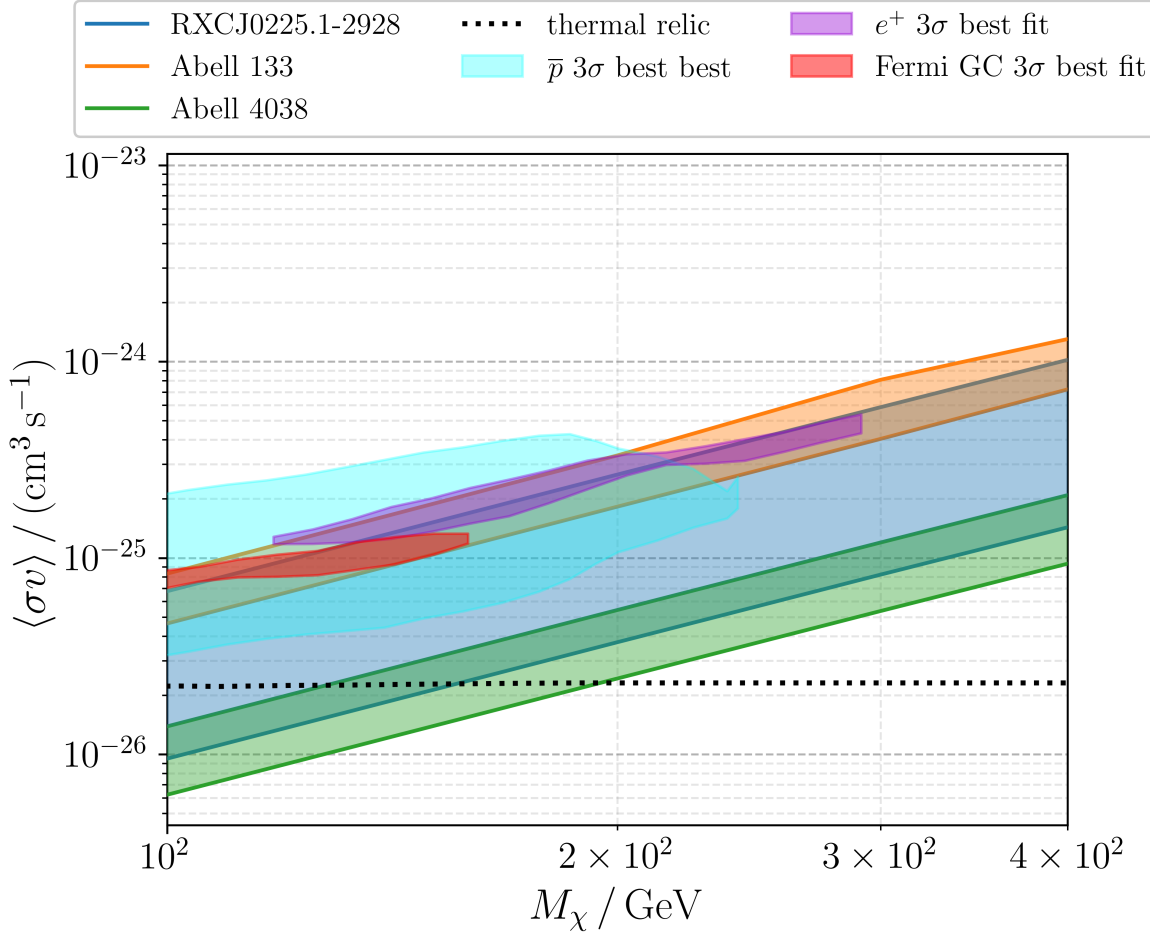


Figure 5.7: Upper limits of the dark matter annihilation cross section determined at a 95% confidence level for the 2HDM+S annihilation channel from the flux uncertainty exclusion limit method, overlaid with the parameter space fittings for the positron, anti-proton and gamma-ray excesses determined by Beck et al [165]. The lower bound of the uncertainty band for each target assumes an NFW density profile ($\alpha = 1$) and the upper bound assumes a more shallowly cusped profile ($\alpha = 0.5$). The solid black line represents the thermal relic value, below which models can be excluded.

it is possible to estimate the integration time above which the sensitivity cannot be improved. Using RXCJ0225.1-2829 as an example, between 6 and 10 hours on target the robust weighted thermal noise varies approximately between 4 and 3 $\mu\text{Jy}/\text{beam}$ respectively. For 70 hours on target the robust weighted thermal noise approaches the confusion limit of 1 $\mu\text{Jy}/\text{beam}$. Here we note that the values calculated depend on the declination of the source, where we have used -30° , which is approximately the declination of the three clusters studied with the signal injection technique. Additionally a robust weighting factor of -0.5 is input, as this is a good default for continuum imaging and provides a compromise between natural and uniform weighting [227], and roughly corresponds to the weighting of the MGCLS [124] data products. With this improvement on the sensitivity we expect that the upper limits on the annihilation cross section can be improved by approximately an order of magnitude.

An additional challenge faced in this investigation is the uncertainty of strength, radial profile and power spectrum of the magnetic fields of galaxy clusters. At present, the exact properties and origins of the magnetic fields of clusters are still uncertain. Faraday rotation measures are one of the most powerful methods of constraining magnetic fields. The observation of background or embedded sources of galaxy

clusters will be able to probe the magnetic field properties. MeerKAT has demonstrated its ability to sample large sources at a high resolution and derive polarization and spectral information with only a few hours of observational data [228]. These capabilities will only become more powerful with the SKA [229], thus allowing for more detailed magnetic field constraints for many galaxy clusters such as those derived for the Coma cluster [125], which was observed with the Very Large Array (VLA).

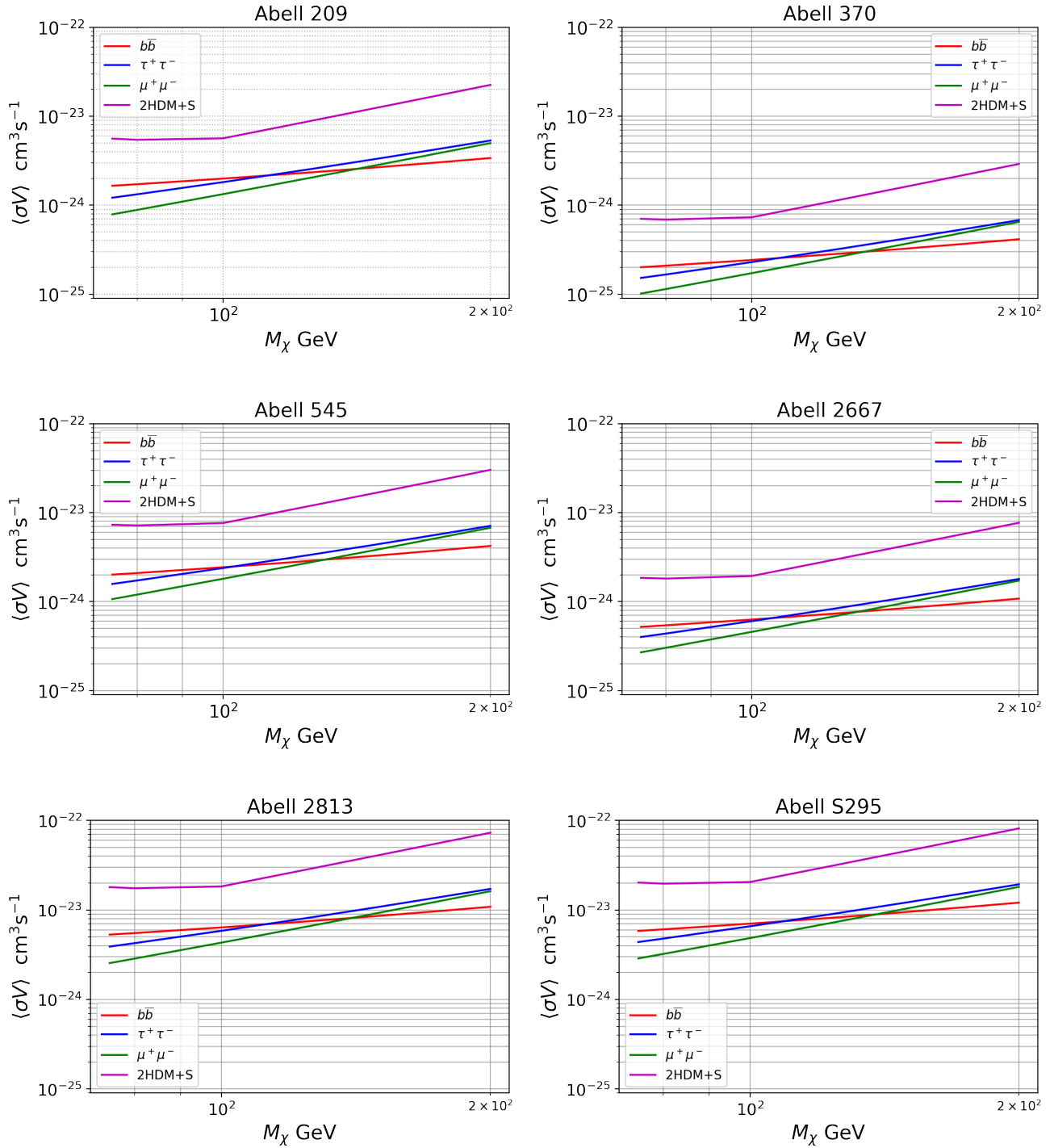


Figure 5.8: Upper limits of the dark matter annihilation cross section at a 95% confidence level, determined by integrated flux comparison method on a sample of clusters containing giant radio halos. Galaxy clusters and their properties are listed in Table 4.3.

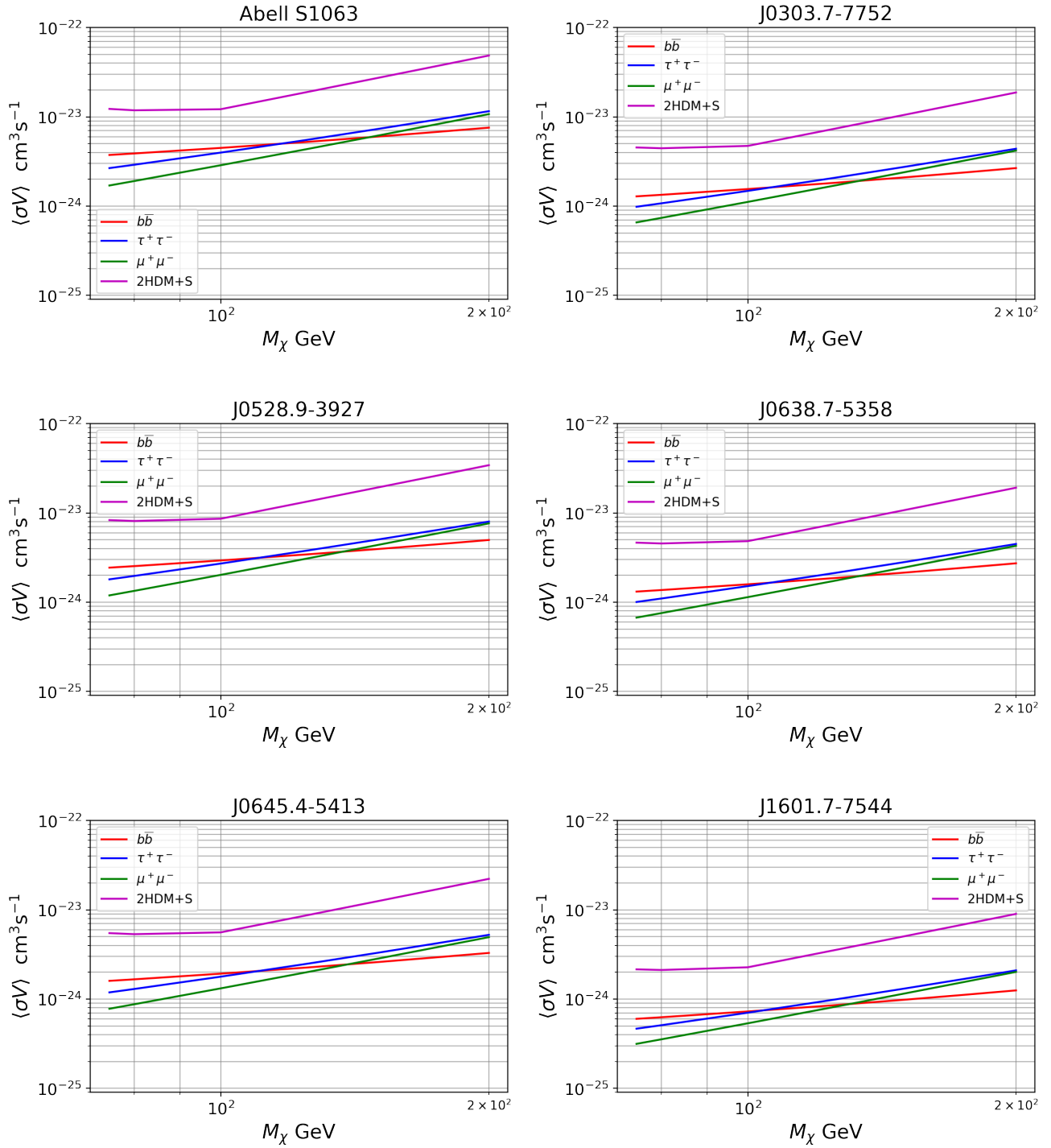


Figure 5.9: Upper limits of the dark matter annihilation cross section at a 95% confidence level, determined by integrated flux comparison method. Galaxy clusters and their properties are listed in Table 4.3.

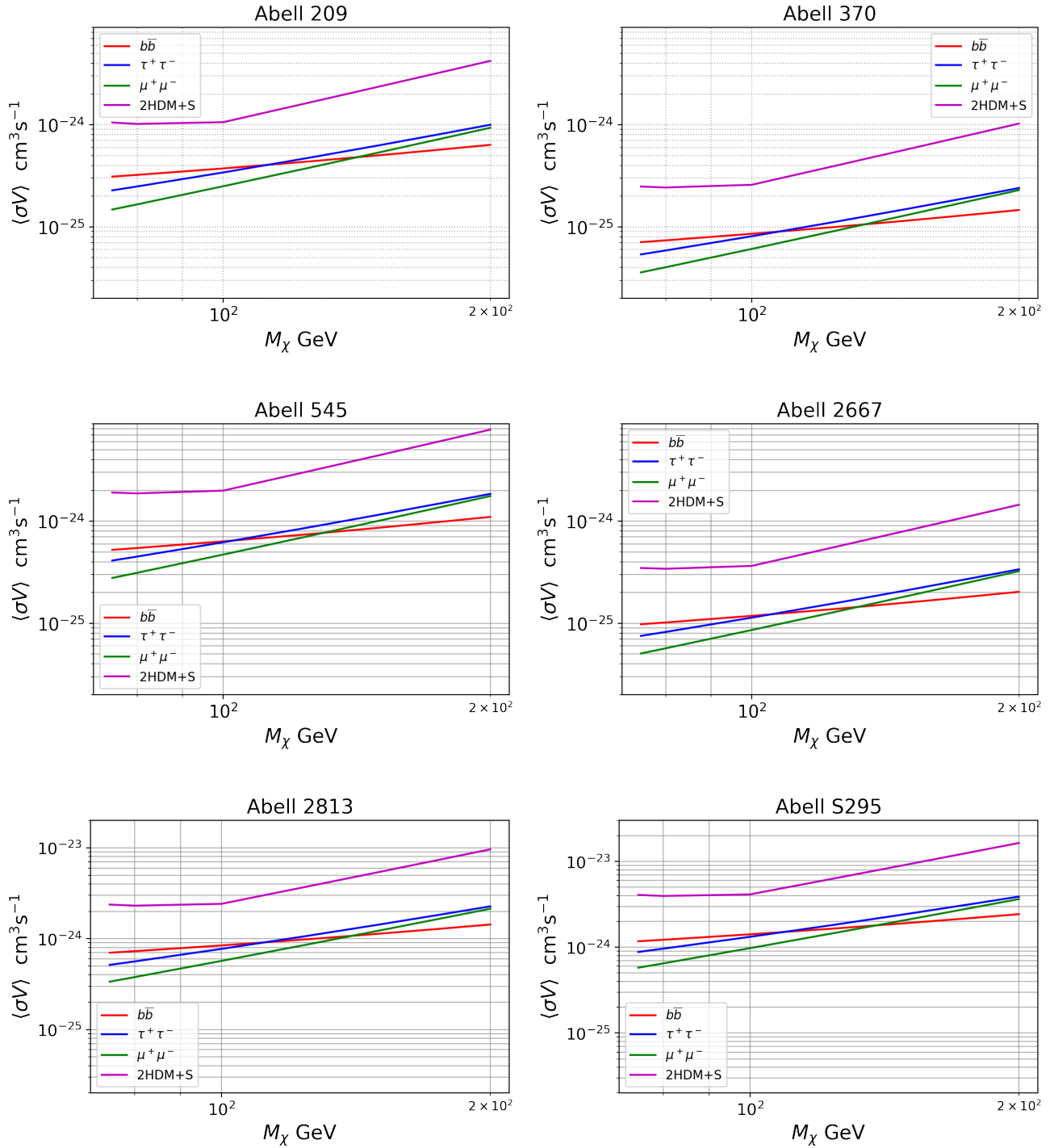


Figure 5.10: Upper limits of the dark matter annihilation cross section at a 95% confidence level, determined by integrated flux comparison method on a sample of clusters containing giant radio halos, through a convolution of the source subtracted full resolution image. Galaxy clusters and their properties are listed in Table 4.3.

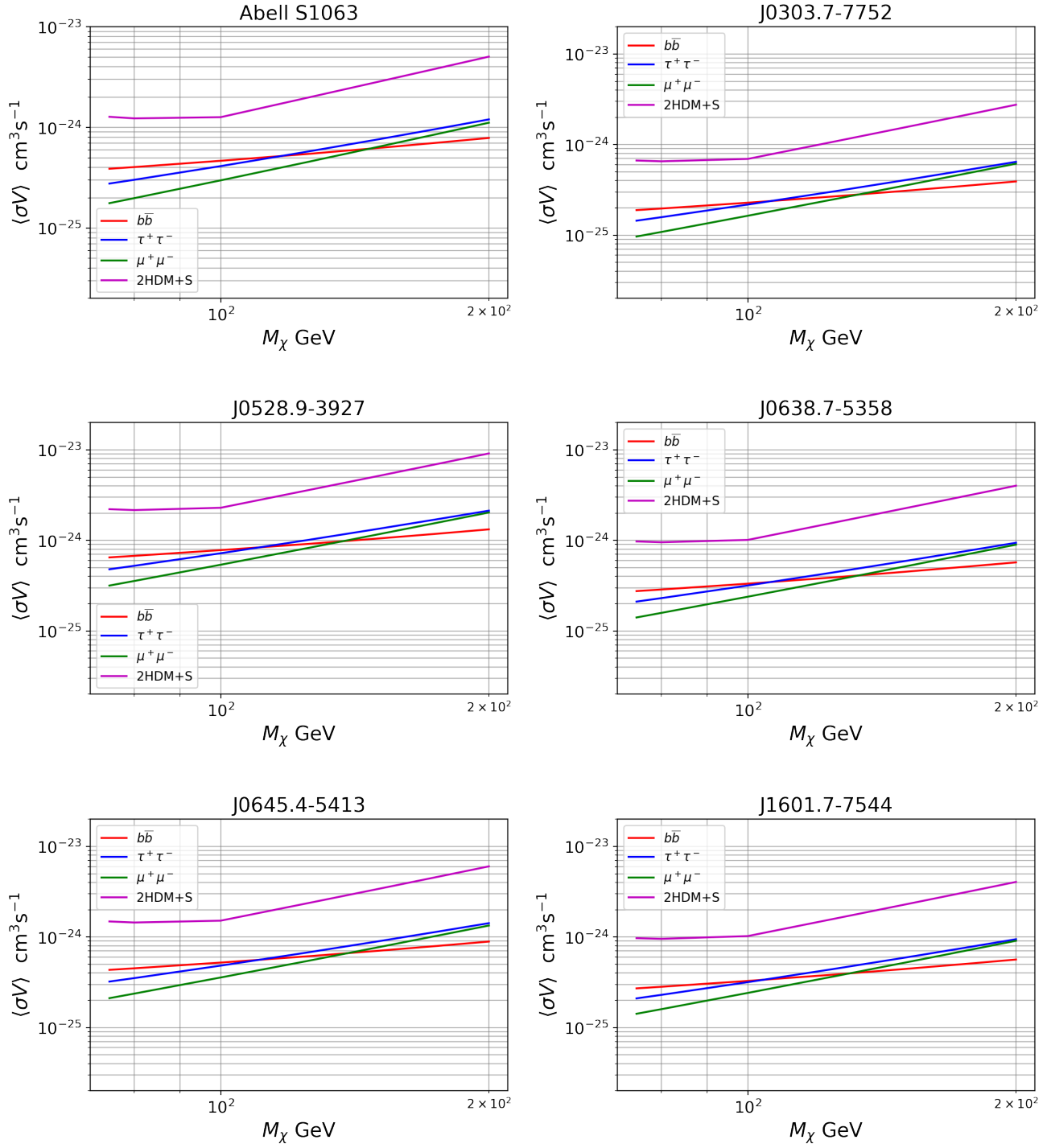


Figure 5.11: Upper limits of the dark matter annihilation cross section at a 95% confidence level, determined by integrated flux comparison method, through a convolution of the source subtracted full resolution image. Galaxy clusters and their properties are listed in Table 4.3.

Chapter 6

Conclusion

In this work we presented a radio search for WIMP dark matter in galaxy clusters. Our images were obtained with MeerKAT and processed as part of the MeerKAT Galaxy Cluster Legacy Survey. The use of public MeerKAT data have allowed us to present some of the first WIMP dark matter constraints produced using this instrument. Galaxy clusters are promising targets for WIMP searches at radio frequencies due to their high concentration of dark matter and the presence of substantial magnetic fields. In our analysis we considered clusters that contain giant radio halos, mini halos and a non-detection of diffuse emission. Alongside a representative subset of generic WIMP annihilation channels we investigate annihilation through 2HDM+S. The model dependent study of 2HDM+S aimed to constrain parameters that are at present unconstrained by LHC data.

The results found for clusters containing giant radio halos were unable to exclude the thermal relic. Despite this, the results are roughly an order of magnitude improved over non-detections of gamma-rays in galaxy clusters. The upper limits on the annihilation cross section determined on the analysis of mini-halos and a non-detection are competitive with some of the tightest constraints determined for an astrophysical object by Regis et al [131]. We are able to exclude the generic WIMP annihilation channels investigated ($b\bar{b}$, $\mu^+\mu^-$, $\tau^+\tau^-$) up to the maximum mass we have probed (200 GeV). This is a factor of two larger than the maximum mass that can be excluded by the Fermi-LAT data of dwarf galaxies, and comparable to the masses excluded by Regis et al [131]. The upper limits for the annihilation cross section for 2HDM+S indicate that this model remains a viable explanation to the positron, anti-proton and Galactic centre gamma-ray excesses that have been observed by AMS-02 and Fermi-LAT respectively within the uncertainties of the dark matter density profile. Our upper limits on the annihilation cross section can be used to constrain the coupling between the dark matter candidate and the scalar mediator, S , introduced within the model.

Due to the injection directly into the image plane we consider these results as the case of an ideal visibility sampling. As true uv sampling will be a limited subset, the upper limits presented here are expected to weaken if the modelled signal is injected into the visibility space.

A central uncertainty faced is the magnetic field structure in the target environments. Since the annihilation cross section scales inversely with the magnetic field strength, an underestimation of the magnetic field can lead to less stringent constraints on the dark matter parameter space, where the converse is equally as likely. Additional uncertainty is added through the subtraction of compact sources. In future work a more refined source subtraction will be investigated. This will be especially beneficial if the field contains an extended source with a complex morphology. MeerKAT's polarimetry and rotation measure capabilities can be utilized to determine the magnetic field structure of a target object. This will allow for a more accurate analysis, and potentially produce more stringent constraints on the dark matter

parameter space.

We have demonstrated the ability of MeerKAT to constrain the WIMP parameter space by searching for diffuse synchrotron emission in galaxy clusters. It can be expected that more accurate upper limits will be obtained once detailed polarization studies of galaxy clusters with MeerKAT begin. Future works can extend the analysis to other dark matter particle candidates, as well as probe a larger dark matter mass range. Our results serve as proof of concept for more sensitive dark matter searches in the upcoming SKA era.

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