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Gravitational description of the conformally invariant quantum mechanics of large matrices

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Jeffrey Hanmer (560921) List of Corrections: (Please note that the first 6 corrections were pointed out by the examiners and the remaining 33 corrections were identified by myself. All corrections are minor and were typographical errors.)

1. Page 11 First Paragraph: The factor of $-\frac{1}{2}$ was moved to the exponent:

$$ds^2 = H(r)^-1/2\eta_{\mu\nu}dx^\mu dx^\nu + H(r)^{1/2}\delta_{ij}dx^i dx^j$$

became

$$ds^2 = H(r)^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu + H(r)^{1/2}\delta_{ij}dx^i dx^j.$$

2. Page 17: Removed equation defining C from the paragraph above equation 29 and placed it below the paragraph as an equation (newly labeled as equation 29). This was done in order to emphasise the definition of C and to provide the defining equation with a number to which cross references can be made.

$$C = lH + mD + nK, \qquad l, n, m \in \mathbb{R}.$$

3. Page 19 Last Paragraph: The cross reference: "see definition of C ... below equation (28) " was replaced by "see definition of C - equation (29)", making use of the new equation (29) which defines C on page 17.

4. Page 31: In equation (102), which has become equation (103) post the addition of the defining equation of C on page 17, the factor $-dT^2 + dy^2$ has been moved to the numerator.

$$-d\tau^2 + d\sigma^2 = \frac{4}{\left(1+(T+y)^2\right)}\frac{1}{\left(1+(T-y)^2\right)\left(-dT^2+dy^2\right)}$$

became

$$-d\tau^2 + d\sigma^2 = \frac{4}{\left(1+(T+y)^2\right)}\frac{\left(-dT^2+dy^2\right)}{\left(1+(T-y)^2\right)}.$$

(Note that the examiner referred to equation 102 on page 32 while it is actually on page 31.)

5. In Reference [9]: The word Entropy was erroneously included in the reference [9]: "Sen, A. (2011) State Operator Correspondence and Entanglement Entropy in AdS_2/CFT_1. *Entropy* **13**, 1305-1323." This has been replaced with the correct title:

Sen, A. (2011) State Operator Correspondence and Entanglement in AdS_2/CFT_1. *Entropy* **13**, 1305-1323.

6. In Reference [16]: The author Simon Caron-Huot's name was incorrectly spelled as Caron-Hout: "Caron-Hout, S., Komargodski, Z., Sever, A. and Zhiboedov, A. (2016) Strings from Massive Higher Spins: The Asymptotic Uniqueness of the Veneziano Amplitude. [arXiv:1607.04253v1 [hep-th]]." This was corrected to read:

   Caron-Huot, S., Komargodski, Z., Sever, A. and Zhiboedov, A. (2016) Strings from Massive Higher Spins: The Asymptotic Uniqueness of the Veneziano Amplitude. [arXiv:1607.04253v1 [hep-th]].

7. Page 8: In the second last sentence of the first paragraph the word 'an' was used instead of 'a'. The sentence was:
   'Perhaps from this point of view, it would be possible to start with a one dimensional CFT and obtain an two dimensional theory of gravity with an AdS_2 spacetime.'
   This was corrected to read:
   'Perhaps from this point of view, it would be possible to start with a one dimensional CFT and obtain a two dimensional theory of gravity with an AdS_2 spacetime.'

8. Page 9: In the second last line of the page the word 'chaos' was incorrectly typed with a capital 'C' instead of a lower case one. The sentence was
   'There has also been recent work in the literature related to near-AdS_2 geometries and a breaking of the full conformal group of diffeomorphisms associated with the asymptotic symmetries of AdS_2 as well as the connection between Chaos and black holes which can be studied in this context.'
   This was corrected to read:
   'There has also been recent work in the literature related to near-AdS_2 geometries and a breaking of the full conformal group of diffeomorphisms associated with the asymptotic symmetries of AdS_2 as well as the connection between chaos and black holes which can be studied in this context.'

9. Page 10: In the third line from the top, the Minkowski manifold was referred to as $\mathbb{M}^{1,4}$. This typo was intended to be $\mathbb{M}^{1,3}$. The sentence was:
   'This expectation is based on the apparent duality between $\mathcal{N} = 4$ SYM on $\mathbb{M}^{1,4}$ and free Supergravity on $\mathbb{M}^{1,9}$ in the low energy limit of IIB superstring theory.'
   This was corrected to read:
   'This expectation is based on the apparent duality between $\mathcal{N} = 4$ SYM on $\mathbb{M}^{1,3}$ and free Supergravity on $\mathbb{M}^{1,9}$ in the low energy limit of IIB superstring theory.'

10. Page 11: The fifth last line of the second paragraph. The word 'on' was a typo which was replaced with the word 'in'. The sentence was:
    'In the low energy limit ($\alpha' \to 0$) the description splits into two parts. Again, the warp factor plays an important role on an asymptotic ($r \to \infty$) observer's notion of energetic excitations in the two regions.'
    This was corrected to read:
    'In the low energy limit ($\alpha' \to 0$) the description splits into two parts. Again, the warp factor plays an important role in an asymptotic ($r \to \infty$) observer's notion of energetic excitations in the two regions.'

11. Page 11: The third last line of the third paragraph. The word 'to' was missing. The sentence was:
    'The various limits achieved through the tuning of these parameters allows one categorize the 'strength' of the statement of the correspondence as described above.'
    This was corrected by inserting the word 'to' as follows:
    'The various limits achieved through the tuning of these parameters allows one to categorize the 'strength' of the statement of the correspondence as described above.'

12. Page 11: In footnote 5 in the third last line. There is a typo where the word 'on' was used instead of 'one'. The sentence was:

'To recognize the correspondence between the point particle limit and supergravity (i.e. the low energy limit of string theory) on recalls that the string tension is $T = 1/2\pi l_s^2$ and the fact that the string spectrum is described by energy relations of the form $M^2 \propto 1/\alpha'$.'
This was corrected to read:
'To recognize the correspondence between the point particle limit and supergravity (i.e. the low energy limit of string theory) one recalls that the string tension is $T = 1/2\pi l_s^2$ and the fact that the string spectrum is described by energy relations of the form $M^2 \propto 1/\alpha'$.'

13. Page 11: Equation (1) read:

$$\mathcal{N} = 4 \text{ Super Yang-Mills in } \mathbb{M}^4$$

In accordance with my conventions, this was inconsistent as I have previously used $\mathbb{M}^{1,3}$. This was therefore corrected to read:

$$\mathcal{N} = 4 \text{ Super Yang-Mills in } \mathbb{M}^{1,3}.$$

14. Page 13: The word 'the' was inserted where it should not have been in the third line from the bottom of the paragraph above subsection 2.2. The sentence read:
'What the AdS/CFT correspondence teaches us is that matrix models are related to strings through the 't Hooft (Planar) limit but that at some point in the studying strings the planar limit breaks down (when the order of J exceeds powers of N to the half).'
This was corrected to read:
'What the AdS/CFT correspondence teaches us is that matrix models are related to strings through the 't Hooft (Planar) limit but that at some point in studying strings the planar limit breaks down (when the order of J exceeds powers of N to the half).'

15. Page 13: In the fourth line in the paragraph below the heading of subsection 2.2, the word 'to' was missing from the following sentence:
'We then introduce conformal quantum mechanics and derive its symmetry generators and show that they correspond the group $SL(2, \mathbb{R})$[2].'
The sentence was corrected to read:
'We then introduce conformal quantum mechanics and derive its symmetry generators and show that they correspond to the group $SL(2, \mathbb{R})$[2].'

16. Page 15: In the line above equation (8), the word 'well' was used when it should have been 'will'. The sentence was:
'In $d = -1$ (that is 1 length dimension) the theory becomes a relativistic one dimensional quantum field theory which we well refer to as conformal quantum mechanics...'
This was corrected to read:
"In $d = -1$ (that is 1 length dimension) the theory becomes a relativistic one dimensional quantum field theory which we will refer to as conformal quantum mechanics...'

17. Page 16: In point 1, the indefinite article 'an' was used when 'a' should have been used. The sentence was:
'For an generator T corresponding to the transformation in the Unitary representation U, it follows from (15) that...'
This was corrected to read:
'For a generator T corresponding to the transformation in the Unitary representation U, it follows from (15) that...'

18. Page 17: In point 3, the exponent of 1 should have been -1. The equation was

$$t \to t' = (1 + \epsilon t)^1 t = t - \epsilon t^2$$

and it was corrected to read

$$t \to t' = (1 + \epsilon t)^{-1} t = t - \epsilon t^2.$$

19. Page 19: In line 7 of the last paragraph, 'when ever' was used when the correct word would be 'whenever'. The sentence read:
'$C\psi$ is a solution to the time dependent Schrodinger equation when ever ψ is, which is true for all time; this is a consequence of the fact that C is a constant of motion.'
This was corrected to read:
'$C\psi$ is a solution to the time dependent Schrodinger equation whenever ψ is, which is true for all time; this is a consequence of the fact that C is a constant of motion.'

20. Page 35: In the fourth line of the first paragraph, the word 'of' was missing. The sentence was:
'A second point, located at a proper distance $\delta > 0$ away from that point on the same geodesic and parameterized by δ, is additionally defined in terms two functions: $x(\delta)^\mu = (\alpha^+(\delta), \alpha^-(\delta))$.'
This was corrected to read:
'A second point, located at a proper distance $\delta > 0$ away from that point on the same geodesic and parameterized by δ, is additionally defined in terms of two functions: $x(\delta)^\mu = (\alpha^+(\delta), \alpha^-(\delta))$.'

21. Page 40: There was a full stop below equation (150) that should not have been there:

$$[L_o, L_{\pm 1}] = \mp L_{\pm 1}, \qquad\qquad [L_{+1}, L_{-1}] = 2L_o.$$

.

and it was removed so that the equation read

$$[L_o, L_{\pm 1}] = \mp L_{\pm 1}, \qquad\qquad [L_{+1}, L_{-1}] = 2L_o.$$

22. Page 45: There was a ρ missing in the argument of the sinh function in equation (171):

$$E = TR^{d-2} V_{d-2} \left(\sinh^{d-2} \rho \cosh \rho - \underline{q \sinh^{d-1}} \right).$$

This was corrected as follows:

$$E = TR^{d-2} V_{d-2} \left(\sinh^{d-2} \rho \cosh \rho - \underline{q \sinh^{d-1} \rho} \right)$$

23. Page 48: In the fourth line of the first paragraph the word 'of' was erroneously included twice:
'The so-called 'very-near-horizon' limit of of the S^1 compactification of AdS_3 reduces to AdS_2.'
This was corrected to read:
'The so-called 'very-near-horizon' limit of the S^1 compactification of AdS_3 reduces to AdS_2.'

24. Page 66: In footnote 76, the word 'to' was missing. The sentence was:
'Strictly speaking it is correct refer to this algebra as the $so(1,2)$ algebra rather than the $sl(2,\mathbb{R})$ algebra, however due to their equivalence we shall sometimes relax this restriction.'
This was corrected to read:
'Strictly speaking it is correct to refer to this algebra as the $so(1,2)$ algebra rather than the $sl(2,\mathbb{R})$ algebra, however due to their equivalence we shall sometimes relax this restriction.'

25. Page 70: In the sixth line of the paragraph below equation (266) the word 'theory' was missing. The sentence was:
'That is, the dimensional reduction of the multi-matrix in the radial fermionization has been mapped to a second quantized formulation of ordinary conformal quantum mechanics.'
This was corrected to read:
'That is, the dimensional reduction of the multi-matrix theory in the radial fermionization has been mapped to a second quantized formulation of ordinary conformal quantum mechanics.'

26. Page 76: In the first sentence of subsection 5.2.2 the word 'the' was missing. The sentence was:
'We now consider the possibility of writing down a density description of the conformal algebra associated with free multi-matrix model.'
This was corrected to read:
'We now consider the possibility of writing down a density description of the conformal algebra associated with the free multi-matrix model.'

27. Page 80: The metric $G_{\mu\nu}$ in equation (322) has a factor of 'x' which should not be there.

$$G_{\mu\nu} = \begin{pmatrix} \Phi_o(r) & 0 \\ 0 & \frac{-1}{\pi^2 x \Phi_o(r)} \end{pmatrix}$$

This was corrected to the following:

$$G_{\mu\nu} = \begin{pmatrix} \Phi_o(r) & 0 \\ 0 & \frac{-1}{\pi^2 \Phi_o(r)} \end{pmatrix}$$

28. Page 82: In the third line of the paragraph below equation (327) the word 'the' begins with a capital letter when it should be a lower case 't'. The sentence was:
' Alternatively, The two boundaries could be suggestive of AdS_2 features directly; given the two boundaries we may take the interpretation that: the inner boundary corresponds to an event horizon and the outer corresponding to the boundary of AdS.'
This was corrected to read:
' Alternatively, the two boundaries could be suggestive of AdS_2 features directly; given the two boundaries we may take the interpretation that: the inner boundary corresponds to an event horizon and the outer corresponding to the boundary of AdS.'

29. Page 84: The word 'background' in the heading of figure 5 was written with a capital 'B' when it should have been a lower case 'b'. The sentence was:
'Plot of the Background collective field for integer values of q with $R = 1$. (Plots generated in Mathematica)'
This was corrected to read:
'Plot of the background collective field for integer values of q with $R = 1$. (Plots generated in Mathematica)'

30. Page 85: The word 'Firstly' in the first line of the last paragraph should have a lower case 'f'. The sentence was changed from:
'We emphasize three new results: Firstly, there is an induced scale parameter, R, in the free matrix model..'
to
'We emphasize three new results: firstly, there is an induced scale parameter, R, in the free matrix model...'

31. Page 86: In the fifth line from the bottom of the first paragraph, there was a full stop incorrectly placed before the reference. The sentence was:
'Since the symmetries are asymptotic to AdS_2 they are spontaneously broken to the $SL(2,\mathbb{R})$ group in pure AdS_2 and are explicitly broken for any deviation of the form $AdS_2 \to NAdS_2$.[49].'
This full stop was removed so that the sentence read:
'Since the symmetries are asymptotic to AdS_2 they are spontaneously broken to the $SL(2,\mathbb{R})$ group in pure AdS_2 and are explicitly broken for any deviation of the form $AdS_2 \to NAdS_2$[49].'

32. Page 86: Footnote 102 was missing a full stop. The sentence was:
'See appendix F for details'
The full stop was appended to the end of the sentence as follows:
'See appendix F for details.'

33. Page 86: In the third paragraph, ten lines down, the sentence structure has been improved. The sentence was:
'In the case of the free multi-matrix collective field Hamiltonian, we have not imposed the 'UV' turning point it is inherited in the metric due to the emergent $1/r^2$ term.'
This was modified to read:
'In the case of the free multi-matrix collective field Hamiltonian we have not imposed the 'UV' turning point- it is inherited in the metric due to the emergent $1/r^2$ term.'

34. Page 87: The first sentence of the second paragraph is missing the word 'to'. The sentence was:
'While the metric generated by L_0 has the appearance of a charged black hole one would like to be able lift the restriction to the radial sector and introduce angular degrees of freedom...'
The word 'to' was inserted as follows:
'While the metric generated by L_0 has the appearance of a charged black hole one would like to be able to lift the restriction to the radial sector and introduce angular degrees of freedom...'

35. Page 100: In footnote 109, the plural of matrix was used instead of the singular:
'For the case of 1 complex matrices a restriced Wigner distribution is obtained but for $m \geq 2$ the distribution is no longer of the Wigner type.'
The plural was replaced with 'matrix':
'For the case of 1 complex matrix a restriced Wigner distribution is obtained but for $m \geq 2$ the distribution is no longer of the Wigner type.'

36. Page 111: There was a bracket missing in equation (449).

$$0 = \left[-\frac{1}{t'} \left(\frac{t'\phi_R)'}{t'} \right)' \right]' .$$

Was replaced by:

$$0 = \left[-\frac{1}{t'} \left(\frac{(t'\phi_R)'}{t'} \right)' \right]' .$$

37. Page 114: 't Hooft's S-matrix ansatz should not include the word 'at' in the first sentence. The sentence was:
' *Processes involving free particles/states at in asymptotically flat spacetime at extremely early and late times should be described by an S-matrix.*'
The 'at' was removed so that the sentence now reads:
' *Processes involving free particles/states in asymptotically flat spacetime at extremely early and late times should be described by an S-matrix.*'

38. Page 115: The exponent in footnote 128 should be -1. The footnote was:
'The tortoise coordinate has the usual definition $\frac{dr*}{dr} = (1 - \frac{2GM}{r})^{-}1$ that describes the black hole exterior.'
This was corrected to the following:
'The tortoise coordinate has the usual definition $\frac{dr*}{dr} = (1 - \frac{2GM}{r})^{-1}$ that describes the black hole exterior.'

39. Page 118: The last sentence of footnote 136 has an extra full stop:
'There is therefore a clear difference between the perturbation expansion in the topology and one in the matrix model coupling, g.[74].'
This was corrected to read:
'There is therefore a clear difference between the perturbation expansion in the topology and one in the matrix model coupling, g[74].'