Aspects of flat/CCFT correspondence

Reza Fareghbal$^{1,2,3}$ and Ali Naseh$^2$

$^1$ Department of Physics, Shahid Beheshti University, G.C., Evin, Tehran 19839, Iran 
$^2$ School of Particles and Accelerators, Institute for Research in Fundamental Sciences (IPM), PO Box 19395-5531, Tehran, Iran

E-mail: r_fareghbal@sbu.ac.ir and naseh@ipm.ir

Received 19 October 2014, revised 6 May 2015
Accepted for publication 15 May 2015
Published 9 June 2015

Abstract

Flat/contracted conformal field theory (CCFT) is a correspondence between gravity in asymptotically flat backgrounds and a field theory which is given by contraction of conformal field theory. In order to find a dictionary for flat/CCFT correspondence one can start from the AdS/CFT and take the contraction of CFT in the boundary as the dual description of the flat-space limit (zero cosmological constant limit) of the asymptotically AdS spacetimes in the bulk side. In this paper we show that the Cardy-like formula of CCFT$_2$ is given by contraction of a proper formula in the CFT$_2$. This formula is the modified Cardy formula which gives the entropy of inner horizon of BTZ black holes.

Keywords: holography, flat spacetimes, AdS/CFT

1. Introduction

A possible way for generalizing the gauge/gravity duality for asymptotically flat spacetimes is using the AdS/CFT correspondence and taking flat-space limit (zero cosmological constant limit) of asymptotically AdS spacetimes and trying to find a proper interpretation of this limit in the boundary CFT. A proposal for this method has been introduced in [1, 2] where the flat-space limit of the bulk corresponds to the contraction of boundary CFT. The contracted conformal field theory (CCFT) which is dual to asymptotically flat spacetimes has the same symmetry as the asymptotic symmetry of the bulk geometry.

The correspondence between the flat-space limit in the bulk and contraction of the dual boundary theory can be used in defining a dictionary for the flat/CCFT correspondence. The first steps in this direction have already been performed in papers [1, 2] which showed that the Bondi–Metzner–Sachs (BMS) algebra [3, 4] as the asymptotic symmetry of asymptotically flat spacetimes at null infinity can be obtained by contraction of the Virasoro algebras as the symmetry of the two-dimensional CFT. Another important work in this context is [5] where a
Cardy-like formula for the CCFT\textsubscript{2} which is dual to the three-dimensional asymptotically flat spacetimes, has been introduced. The Cardy-like formula as an estimation of the CCFT degeneracy of states, gives the exact entropy of the cosmological horizon of the three-dimensional cosmological solutions. These geometries are the shifted-boost orbifold of the three-dimensional Minkowski spacetimes and can be found by taking the flat-space limit from the BTZ black holes [6].

Defining a field theory just by contracting a CFT has some advantages. Its correlation functions are given by contraction of correlation functions of the parent CFT [7]. This fact can also be used for finding the quasi local stress tensor of the asymptotically flat spacetimes. This idea has been followed in paper [8] for the three-dimensional asymptotically flat spacetimes and a stress tensor was introduced which gives correct charges for the gravity solutions. The stress tensor of [8] can also be used for computing the BMS\textsubscript{3} charge algebra.

The approach of using a contracted CFT in flat-space holography has been explored in many works. For example it can be used for finding higher-spin theories in three-dimensional asymptotically flat spacetimes [9, 10]. The reader can find a complete list of references in a recent work [11] where the current status of the problem and also future directions have been mentioned.

The point which we address in this paper, is the relation between the CCFT\textsubscript{2} Cardy-like formula and the modified Cardy formula of CFT\textsubscript{2}. The Cardy-like formula of CCFT has been derived in [5] by defining the partition function of CCFT and demanding its invariance under some novel modular transformations. In this paper we show that it is simply given by contracting a proper formula of the CFT. This formula is not the known Cardy formula which according to AdS\textsubscript{3}/CFT\textsubscript{2} correspondence gives the correct entropy of the outer horizon of the BTZ black holes but it is the formula which gives the entropy of the inner horizon [12, 13]. We elaborate on this point in the main text by using the flat-space limit of the BTZ black holes in the bulk side.

The organization of this paper is as follows: in the next section we briefly review the flat/CCFT correspondence. The main point which we want to clarify in this section is the correspondence between the flat-space limit in the bulk and contraction of the CFT in the boundary. In section 3 we find the Cardy-like formula of CCFT\textsubscript{2} by contracting its counterpart in the parent CFT. The last section is devoted to conclusions and possible future directions.

2. A brief review of the flat/CCFT correspondence

Let us consider three-dimensional Einstein gravity with negative cosmological constant

$$S = \frac{1}{16\pi G} \int d^3x \sqrt{-\tilde{g}} \left( R + \frac{2}{\ell^2} \right).$$

(2.1)

The flat-space limit for this theory is defined by taking the zero cosmological constant limit which is given by the $\ell \to \infty$ limit. In order to make this limit well-defined we define the flat-space limit by using the dimensionless parameter $G/\ell$ and sending it to zero while keeping $G$ fixed. At the level of the metric, the flat-space limit is gauge dependent. An appropriate gauge that can capture properly the flat-space limit of the asymptotically locally AdS spacetimes is known as the BMS gauge [14–16]. For the asymptotically locally AdS\textsubscript{3} spacetimes the general solution of the equations of motion in the BMS gauge can be written as [16]
\[ ds^2 = \left( -\frac{r^2}{l^2} + \mathcal{M} \right) du^2 - 2du dr + 2dN d\phi + r^2 d\phi^2. \]  

(2.2)

where \( u \) is the retarded time coordinate, and \( \mathcal{M} \) and \( N \) are functions of \( u, \phi \) coordinates. Using the equations of motion, one then finds

\[
\partial_u \mathcal{M} = \frac{2}{l^2} \partial_\phi N, \quad 2\partial_u N = \partial_\phi \mathcal{M}.
\]

(2.3)

It is shown in [8] that by proper expansion of functions \( \mathcal{M} \) and \( N \) with respect to \( G/\ell \), one can find the general asymptotically flat metric as

\[ ds^2 = M du^2 - 2du dr + 2N d\phi + r^2 d\phi^2, \]

(2.4)

where

\[
M = \lim_{G/\ell \to 0} \mathcal{M} = \theta (\phi), \quad N = \lim_{G/\ell \to 0} \mathcal{N} = \chi (\phi) + \frac{u}{2} \theta' (\phi).
\]

(2.5)

The gauge (2.2) implies an asymptotic symmetry algebra which is given by two copies of the Virasoro algebra [16]:

\[
[ \mathcal{L}_m, \mathcal{L}_n ] = (m - n) \mathcal{L}_{m+n}, \quad [ \mathcal{L}_n, \tilde{\mathcal{L}}_n ] = (m - n) \tilde{\mathcal{L}}_{m+n}, \quad [ \mathcal{L}_m, \tilde{\mathcal{L}}_n ] = 0.
\]

(2.6)

In [16], the authors found the central extension of the surface charges algebra, computed with respect to AdS3 background, with \( c = \tilde{c} = 3l/2G \).

Using (2.6) and the explicit form of the generators \( \mathcal{L}_n \) and \( \tilde{\mathcal{L}}_n \) introduced in [16], one can easily check that the new generators

\[
L_n = \mathcal{L}_n - \tilde{\mathcal{L}}_{-n}, \quad M_n = \frac{G}{l} \left( \mathcal{L}_n + \tilde{\mathcal{L}}_{-n} \right),
\]

(2.7)

in the \( G/\ell \to 0 \) limit results in the BMS3 algebra

\[
[ L_m, L_n ] = (m - n) L_{m+n}, \quad [ L_n, M_m ] = (m - n) M_{m+n}, \quad [ M_m, M_n ] = 0,
\]

(2.8)

which is the asymptotic symmetry of the three-dimensional asymptotically flat spacetimes [4]. Moreover, the BMS3 charge algebra contains two central charges which are given by [4]

\[
C_{LL} = \lim_{\epsilon \to 0} \frac{c - \ell}{12}, \quad C_{LM} = \lim_{\epsilon \to 0} \frac{G}{l} \frac{c + \ell}{12}.
\]

(2.9)

Now let us focus on the boundary side and look for the equivalent procedure for the flat-space limit in the dual boundary CFT2 of the asymptotically AdS3 spacetimes.

In order to answer this question let us have a closer look at the generic solution (2.2) and try to find the conformal boundary for an arbitrary large \( \ell \). The metric of the conformal boundary is the same for all \( \mathcal{M} \) and \( \mathcal{N} \) and is given by:

\[ ds^2 = \frac{r^2}{G^2} \left( -\frac{G^2}{\ell^2} du^2 + G^2 d\phi^2 \right). \]

(2.10)

Thus, \( \ell \) can be absorbed in the definition of new time \( t = \frac{G}{\ell} u \). The dual CFT lives on a cylinder with coordinates \( \{ t, \phi \} \) and radius \( G \). It is clear that taking the flat-space limit, \( G \to 0 \), is equivalent to contract time as \( t \to \epsilon t \) with \( \epsilon \to 0 \), thus one may guess that the dual of asymptotically flat spacetimes is a CCFT. In two dimensions the symmetry of CCFT is

\footnote{We should emphasize that the flat-space limit in [8] is different from the modified Penrose limit defined in [16] and the Grassmannian method introduced in [17].}
isomorphic to the Galilean conformal algebra (GCA) [7]. In [1, 2], it has been argued that one can obtain the full GCA in two dimensions by contracting the symmetries of the two-dimensional CFT. In this approach the generators of the GCA and the parent CFT and also their central charges are related by

\[ M_n = \lim_{c \to 0} (L_n + \tilde{L}_{-n}), \quad L_n = \lim_{c \to 0} (L_n - \tilde{L}_{-n}), \quad (2.11) \]

\[ C_{LL} = \lim_{c \to 0} \frac{c - \bar{c}}{12}, \quad C_{LM} = \lim_{c \to 0} \left( \frac{c + \bar{c}}{12} \right). \quad (2.12) \]

Therefore, the connection between the flat-space limit in the bulk side and contraction of CFT in the boundary side is correct at the level of symmetries and one may propose a dual field theory for the asymptotically flat spacetimes which is a CCFT. We call this duality\(^5\) flat/CCFT\(^6\).

The flat/CCFT correspondence can be used for finding the quasi local stress tensor of asymptotically flat spacetimes. We expect the same dictionary as the AdS/CFT correspondence i.e. one-point function of the energy–momentum (EM) operator of the dual CCFT is the stress tensor of the bulk theory. This connection has been addressed in [8] where we have introduced the stress tensor of the asymptotically flat spacetimes using the flat/CCFT correspondence. The key point which has been used in [8] is that, therein, the authors used the previously known results about the one-point functions of the GCA and then constructed the flat-space stress tensor\(^7\). The EM of field theories which arise by contraction of conformal field theories is given by using the EM tensor of the original CFT. For example, for field theories with Galilean conformal symmetry, this connection has been worked out in paper [7]. The CCFT which is dual description of asymptotically flat spacetimes written in the BMS gauge, is defined by contracting time in the original CFT. Thus one would expect that the CCFT Hamiltonian is related to the Hamiltonian of the parent CFT by contracting time, while the momentum operators of both theories are the same, since the \(x\)-coordinate is not affected by the limiting procedure.

The flat-space stress tensor has been worked out in\(^8\) [8]

\[ \tilde{T}_{uu} = \frac{M}{16\pi G^2}, \quad \tilde{T}_{u\phi} = \frac{N}{8\pi G^2}, \quad \tilde{T}_{\phi\phi} = \frac{M}{16\pi}, \quad (2.13) \]

where the functions \(M\) and \(N\) are given by (2.5).

In [8] the above stress tensor (2.13) is used to find conserved charges of symmetry generators \(\xi^\mu\) by using the Brown and York definition [25].

\(^5\) Originally this correspondence was coined as BMS/GCA [1, 2] but since for bulk dimensions greater than three the BMS algebra is not exactly GCA while it is still related to a contracted conformal algebra, we call it flat/CCFT correspondence.

\(^6\) The coordinate which must be contracted can be determined by arguments related to those used for the conformal boundary which has been done in this section. It was the time coordinate which needed to be contracted for the dual of AdS written in the BMS gauge. As discussed in [18], for Rindler-AdS one should contract the \(x\)-coordinate in order to find the dual of the Rindler spacetime.

\(^7\) The holographic renormalization for the asymptotically flat spacetimes has also been worked out in papers [19] and [20] but none of them explored the connection between flat-space holography and CCFTs.

\(^8\) The results of [8] predict a symmetric structure for the CCFT EM tensor. On the other hand one may expect a non-symmetric EM tensor due to absence of Lorentz symmetry for the CCFT. We should emphasize that the symmetric structure of the CCFT EM tensor in the current case is a direct consequence of zero off-diagonal terms for the components of the parent CFT EM tensor written in the light-cone gauge. Any improvement to the generic case requires a clear understanding of the EM tensor of a theory with Galilean conformal symmetry which may be achieved along the lines of recent papers [21–24].
where $u^\nu$ is the unit timelike vector normal to $\Sigma$. The variation of charges under the symmetry generators yields the BMS$_3$ algebra with exactly the same central extension as [4]. Using the results of [8], we can find the corresponding charges of the generators $M_0$ and $L_0$ as

$$Q_{M_0} = -\frac{1}{8G}, \quad Q_{L_0} = 0.$$  \hspace{1cm} (2.15)

We will use these charges in the next section to compute the entropy of the cosmological solution using the CCFT Cardy-like formula.

3. A Cardy-like formula for the CCFT by contraction of the modified Cardy formula

Interpreting the entropy of the black holes as the degeneracy of microstates of the dual theory is an important issue which must be addressed carefully in any gauge/gravity correspondence. The flat/CCFT correspondence as a duality between gravity in the asymptotically flat spacetimes and contracted CFTs must provide a clear understanding for the entropy of the asymptotically flat black holes using microstates of the dual CCFT.

Let us concentrate on the flat/CCFT$_2$ and consider the three-dimensional asymptotically flat spacetimes. It was shown in [27] that no asymptotically flat black hole exists in three-dimensional Einstein gravity. However, there are other interesting solutions in three-dimensional Einstein gravity which have a cosmological horizon. They are called cosmological solutions and are given by the following metric:

$$ds^2 = \hat{t}_+^2 dr^2 - \frac{r^2}{\hat{r}_+^2} \left( r^2 - r_0^2 \right) + r^2 d\phi^2 + 2\hat{r}_0 d\tau d\phi. \hspace{1cm} (3.1)$$

These solutions are characterized by two parameters $\hat{r}_+$ and $r_0$ which are related to the mass $M$ and the angular momentum $J$ as $\hat{r}_+ = \sqrt{8GM}$ and $r_0 = \frac{2G}{M} |J|$. Moreover, $r = n_0$ is the radius of the cosmological horizon and one can define the entropy of the cosmological solution by using the area of the cosmological horizon as

$$S = \frac{A}{4G} = \frac{\pi n_0}{2G}. \hspace{1cm} (3.2)$$

It was shown that the solution (3.1) is the boost-shift orbifold of the three-dimensional Minkowski spacetimes and it can be obtained by taking the flat-space limit of the BTZ black hole [6]. The connection between BTZ black holes and cosmological solutions is important for us in this paper. The idea that the flat-space limit in the bulk corresponds to the contraction of CFT in the boundary can be used to find a Cardy-like formula for the states of CCFT which yields the entropy of the cosmological solution. In fact this idea was first used in paper [5] where a Cardy-like formula was introduced for the CCFT$_2$. The idea of contraction of time for the CFT has been entered in an unusual transformation of the modular parameters of the CCFT. Invariance of the partition function under these new modular transformations along with a saddle point approximation resulted in a formula for the degeneracy of states which correctly reproduces entropy of the cosmological horizon [5]. In this paper we want to argue that the Cardy-like formula of CCFT$_2$ can be obtained by taking a direct contraction of the modified Cardy formula of CFT. Before making this connection we need to have a closer look at the bulk and study the flat-space limit of the BTZ black hole.
The cosmological solution is given by taking the flat-space limit of the BTZ black hole with metric
\[
ds^2 = -\left(\frac{r^2 - r_+^2}{r^2 \ell^2}\right) \, dt^2 + \frac{r^2 \ell^2}{(r^2 - r_+^2)(r^2 - r_-^2)} \, dr^2 + r^2 \left( d\phi + \frac{r_+ r_-}{\ell r^2} \, dt \right)^2, \tag{3.3}
\]
where
\[
r_{\pm} = \sqrt{2G \ell (\ell M + J)} \pm \sqrt{2G \ell (\ell M - J)} \tag{3.4}
\]
are the radii of the horizons and \(M\) and \(J\) are related to the mass and the angular momentum of the black hole. It is easy to see that \(r_0\) in the cosmological solution is given by taking the \(\ell \to \infty\) limit of \(r_-\) but \(r_+\) goes to infinity in the flat-space limit. On the other hand according to AdS\(_3\)/CFT\(_2\) correspondence, the Cardy formula of CFT results in the correct entropy of the outer horizon \(r_+\). We can rewrite (3.5) using (2.11) and take the \(\epsilon \to 0\) limit which corresponds to the \(\ell \to \infty\) limit in the bulk. The final answer diverges as expected because in the bulk side the entropy of the outer horizon diverges in the \(\ell \to \infty\) limit. If we want to find a Cardy-like formula which gives the entropy of the cosmological horizon we should contract a formula in the CFT which corresponds to the entropy of the inner horizon of the BTZ.

The entropy of the inner horizon of the BTZ black hole in terms of the dual CFT parameters, can be written as [12, 13]:
\[
S = 2\pi \sqrt{\frac{1}{6} \mathcal{L}_0} + 2\pi \sqrt{\frac{1}{6} \mathcal{L}_0} \tag{3.6}
\]
Now if we use (2.11) and take the \(\epsilon \to 0\) limit the final answer is well-defined and is exactly the Cardy-like formula which was introduced in [5] i.e.
\[
S = 2\pi \left( C_{LL} \sqrt{\frac{M_0}{2C_{LM}}} + L_0 \sqrt{\frac{C_{LM}}{2M_0}} \right). \tag{3.7}
\]
This is another check that the flat limit in the bulk corresponds to contraction of CFT in the boundary.

The Cardy-like formula for the CCFTs can also be given in another form. The point is that there is another form for the Cardy formula (see appendix of [28] and the references therein). Now one can use this new formulation and take the limit from it.

The alternative form of the Cardy formula which gives the degeneracy of states of the CFT is given by
\[
S_{\text{CFT}} = 2\pi \sqrt{-(H_{\text{vac}} + J_{\text{vac}})(H + J)} + 2\pi \sqrt{-(H_{\text{vac}} - J_{\text{vac}})(H - J)}. \tag{3.8}
\]
States are characterized by the eigenvalues of the Hamiltonian and the momentum \((H, J)\) and ‘vac’ denotes the vacuum state. Using the AdS/CFT correspondence, the above formula (3.8) gives the entropy of the outer horizon of the BTZ black holes [28]. However, if we want to find a similar formula for the CCFT, similar to the previous subsection, we should look for a formula in terms of CFT parameters which gives the correct entropy of the inner horizon of BTZ black holes. Using [28], one can easily check that the formula
\[\begin{aligned}
S &= 2\pi \sqrt{-(H_{\text{vac}} + J_{\text{vac}})(H + J) - 2\pi \sqrt{- (H_{\text{vac}} - J_{\text{vac}})(H - J)},}
\end{aligned}\] (3.9)

results in an entropy which matches the entropy of the inner horizon.

Now we can contract (3.9). As discussed in section 2, the Hamiltonian of CCFT is given by contracting the corresponding Hamiltonian of CFT but momenta are the same for both of the theories. If we use this correspondence between \(H, J\) of CFT and \(\tilde{H}, \tilde{J}\) of CCFT, we can write

\[\begin{aligned}
S_{\text{CCFT}} &= \lim_{\epsilon \to 0} \left[ 2\pi \sqrt{\left( \frac{\tilde{H}_{\text{vac}}}{\epsilon} + J_{\text{vac}} \right)} \left( \frac{\tilde{H}}{\epsilon} + J \right) - 2\pi \sqrt{\left( \frac{\tilde{H}_{\text{vac}}}{\epsilon} - J_{\text{vac}} \right)} \left( \frac{\tilde{H}}{\epsilon} - J \right) \right],
\end{aligned}\]

\[\begin{aligned}
&= \lim_{\epsilon \to 0} \left[ 2\pi \sqrt{- \frac{2}{\epsilon}\left( \tilde{H}_{\text{vac}} + \epsilon J_{\text{vac}} \right)} \right] = 2\pi \sqrt{\frac{\tilde{H}_{\text{vac}}}{\tilde{H}}} \tilde{J} + 2\pi \sqrt{\frac{\tilde{H}}{\tilde{H}_{\text{vac}}} \tilde{J}_{\text{vac}}}.
\end{aligned}\] (3.10)

Using (2.15), in the bulk side we have

\[\begin{aligned}
Q_{M_0} &= \tilde{H}_{\text{vac}} = -\frac{1}{8G},
Q_{L_0} &= \tilde{J}_{\text{vac}} = 0,
\end{aligned}\] (3.11)

where \(\tilde{H}_{\text{vac}}\) exactly matches the free-energy of the cosmological solution that can be obtained from the Euclidean on-shell action [29]. Therefore, from (3.10) the entropy of the cosmological solution is found to be

\[\begin{aligned}
S &= \frac{\pi}{2G} \sqrt{\frac{2G}{M}}.
\end{aligned}\] (3.12)

Using \(n_0 = J \sqrt{\frac{2G}{M}}\), we end up with the known result of the entropy for the cosmological solution [5],

\[\begin{aligned}
S &= \frac{\pi n_0}{2G}.
\end{aligned}\] (3.13)

### 4. Conclusion

This work is another check for the correspondence between the flat-space limit in the bulk and contraction of the boundary field theory. We considered three-dimensional Einstein gravity which admits asymptotically flat geometries, namely cosmological solutions. The asymptotic symmetry group of the asymptotically flat solutions at null infinity is infinite dimensional. The next step is studying four-dimensional asymptotically flat spacetimes which also have an infinite dimensional asymptotic symmetry group [4]. The lessons from the three-dimensional analysis can be used for finding the quasi local stress tensor of the four-dimensional spacetimes and one can also calculate the BMS$_4$ charge algebra using our approach and get insight about the possible central extension of the BMS$_4$ algebra.

Moreover, a Cardy-like formula in the form (3.10) may exist for the CCFT$_3$ which also has infinite dimensional symmetry. We should note that formulas (3.6) and (3.9), which give the inner horizon entropy, are phenomenological observations and there is no proof for them in the CFT side. We just wrote the inner horizon entropy of the BTZ in terms of the CFT parameters but what this counting means, is an open question.
Acknowledgments

The authors would like to especially thank Mahmoud Safari and Seyed Morteza Hosseini for their comments on the manuscript and Stephane Detournay for useful comments. We also thank Arjun Bagchi, Daniel Grumiller and Joan Simon for a continuing collaboration in the flat-spacetime holography project.

Note added in proof. When this paper was ready for submission, we became aware that Max Riegler also has pointed out the limit of the modified Cardy formula which results in (3.7) [30].

References

[1] Bagchi A 2010 Correspondence between asymptotically flat spacetimes and nonrelativistic conformal field theories Phys. Rev. Lett. 105 171601
Bagchi A 2010 The BMS/GCA correspondence (arXiv:1006.3354 [hep-th])

[2] Bagchi A and Fareghbal R 2012 BMS/GCA redux: towards flatspace holography from non-relativistic symmetries J. High Energy Phys. JHEP10(2012)092

[3] Bondi H, van der Burg M G and Metzner A W 1962 Gravitational waves in general relativity: 7. Waves from axisymmetric isolated systems Proc. R. Soc. London A 269 21
Sachs R K 1962 Gravitational waves in general relativity: 8. Waves in asymptotically flat spacetimes Proc. R. Soc. London A 270 103
Sachs R K 1962 Asymptotic symmetries in gravitational theory Phys. Rev. 128 2851

[4] Barnich G and Compere G 2007 Classical central extension for asymptotic symmetries at null infinity in three spacetime dimensions Class. Quantum Grav. 24 F15 (arXiv:gr-qc/0610130)
Barnich G and Compere G 2007 Class. Quantum Grav. 24 3139 (erratum)
Barnich G and Troessaert C 2010Symmetries of asymptotically flat 4 dimensional spacetimes at null infinity revisited Phys. Rev. Lett. 105 111103 (arXiv:0909.2617 [gr-qc])
Barnich G and Troessaert C 2010 Aspects of the BMS/CFT correspondence J. High Energy Phys. JHEP05(2010)062 (arXiv:1001.1541 [hep-th])

[5] Bagchi A, Detournay S, Fareghbal R and Simon J 2013 Holography of 3d flat cosmological horizons Phys. Rev. Lett. 110 141302

[6] Corinalba L and Costa M S 2002 A new cosmological scenario in String theory Phys. Rev. D 66 066001

[7] Bagchi A and Gopakumar R 2009 Galilean conformal algebras and AdS/CFT J. High Energy Phys. JHEP07(2009)037
Alishahiha M, Davody A and Vahedi A 2009 On AdS/CFT of Galilean conformal field theories J. High Energy Phys. JHEP08(2009)022
Bagchi A and Mandal I 2009 On representations and correlation functions of Galilean conformal algebras Phys. Lett. B 675 393
Bagchi A, Gopakumar R, Mandal I and Miwa A 2010 GCA in 2d J. High Energy Phys. JHEP08 (2010)004
Bagchi A 2011 Topologically massive gravity and Galilean conformal algebra: a study of correlation functions J. High Energy Phys. JHEP02(2011)091

[8] Fareghbal R and Naseh A 2014 Flat-space energy–momentum tensor from BMS/GCA correspondence J. High Energy Phys. JHEP03(2014)005

[9] Afshar H, Bagchi A, Fareghbal R, Grumiller D and Rosseel J 2013 Higher spin theory in 3-dimensional flat space Phys. Rev. Lett. 111 121603

[10] Gonzalez H A, Matulich J, Pino M and Troncoso R 2013 Asymptotically flat spacetimes in three-dimensional higher spin gravity J. High Energy Phys. JHEP09(2013)016

[11] Bagchi A, Basu R and Mehra A 2014 Galilean conformal electrodynamics J. High Energy Phys. JHEP1411(2014)061 (arXiv:1408.0810 [hep-th])

[12] Detournay S 2012 Inner mechanics of 3d black holes Phys. Rev. Lett. 109 031101

[13] Castro A and Rodriguez M J 2012 Universal properties and the first law of black hole inner mechanics Phys. Rev. D 86 024008
[14] Isenberg J and Moncrief V 1983 Symmetries of cosmological Cauchy horizons Commun. Math. Phys. 89 387–413
[15] Friedrich H, Racz I and Wald R M 1999 On the rigidity theorem for space-times with a stationary event horizon or a compact Cauchy horizon Commun. Math. Phys. 204 691
[16] Barnich G, Gomberoff A and Gonzalez H A 2012 The flat limit of three-dimensional asymptotically anti-de Sitter spacetimes Phys. Rev. D 86 024020
[17] Krishnan C, Raju A and Roy S 2014 A Grassmann path from AdS3 to flat space J. High Energy Phys. JHEP03(2014)036 (arXiv:1312.2941 [hep-th])
[18] Fareghbal R and Naseh A 2014 Rindler/contracted-CFT correspondence J. High Energy Phys. JHEP06(2014)134
[19] Caldeira Costa R N 2014 Aspects of the zero Λ limit in the AdS/CFT correspondence Phys. Rev. D 90 104018 (arXiv:1311.7339 [hep-th])
[20] Detournay S, Grumiller D, Schöller F and Simón J 2014 Variational principle and one-point functions in three-dimensional flat space Einstein gravity Phys. Rev. D 89 084061 (arXiv:1402.3687 [hep-th])
[21] Christensen M H, Hartong J, Obers N A and Rollier B 2014 Boundary stress–energy tensor and Newton–Cartan geometry in Lifshitz holography J. High Energy Phys. 1401 JHEP01(2014)057
[22] Jensen K 2014 On the coupling of Galilean-invariant field theories to curved spacetime (arXiv:1408.6855 [hep-th])
[23] Hartong J, Kiritsis E and Obers N A 2014 Lifshitz space-times for Schrödinger holography (arXiv:1409.1519 [hep-th])
[24] Hartong J, Kiritsis E and Obers N A 2014 Schrödinger invariance from Lifshitz isometries in holography and field theory (arXiv:1409.1522 [hep-th])
[25] Brown J D and York J W Jr 1993 Quasilocal energy and conserved charges derived from the gravitational action Phys. Rev. D 47 1407
[26] Barnich G 2012 Entropy of three-dimensional asymptotically flat cosmological solutions J. High Energy Phys. JHEP10(2012)095
[27] Ida D 2000 No black hole theorem in three-dimensional gravity Phys. Rev. Lett. 85 3758
[28] Detournay S, Hartman T and Hofman D M 2012 Warped conformal field theory Phys. Rev. D 86 124018
[29] Bagchi A, Detournay S, Grumiller D and Simon J 2013 Cosmic evolution from phase transition of three-dimensional flat space Phys. Rev. Lett. 111 181301
[30] Riegler M 2015 Flat space limit of higher-spin Cardy formula Phys. Rev. D 91 024044