Flat Space Holography

Daniel Grumiller

Institute for Theoretical Physics
TU Wien

Gottfried Wilhelm Leibniz Universität Hannover, December 2015

based on work w. Afshar, Bagchi, Basu, Detournay, Fareghbal, Gary, Merbis, Riegler, Rosseel, Salzer, Sarkar, Schöller, Simon, ...

Some of our papers on flat space holography

A. Bagchi, D. Grumiller and W. Merbis,
"Stress tensor correlators in three-dimensional gravity,"
arXiv:1507.05620. [see `arXiv` today]

A. Bagchi, R. Basu, D. Grumiller and M. Riegler,
"Entanglement entropy in Galilean conformal field theories and flat holography,"
Phys. Rev. Lett. **114** (2015) 11, 111602 [arXiv:1410.4089].

H. Afshar, A. Bagchi, R. Fareghbal, D. Grumiller and J. Rosseel,
"Spin-3 Gravity in Three-Dimensional Flat Space,"
Phys. Rev. Lett. **111** (2013) 12, 121603 [arXiv:1307.4768].

A. Bagchi, S. Detournay, D. Grumiller and J. Simon,
"Cosmic Evolution from Phase Transition of Three-Dimensional Flat Space,"
Phys. Rev. Lett. **111** (2013) 18, 181301 [arXiv:1305.2919].

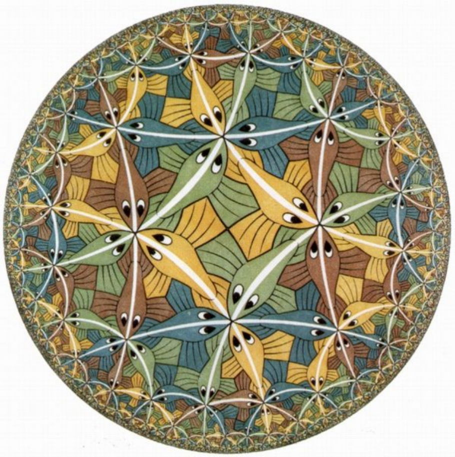
A. Bagchi, S. Detournay and D. Grumiller,
"Flat-Space Chiral Gravity,"
Phys. Rev. Lett. **109** (2012) 151301 [arXiv:1208.1658].

Outline

Outline

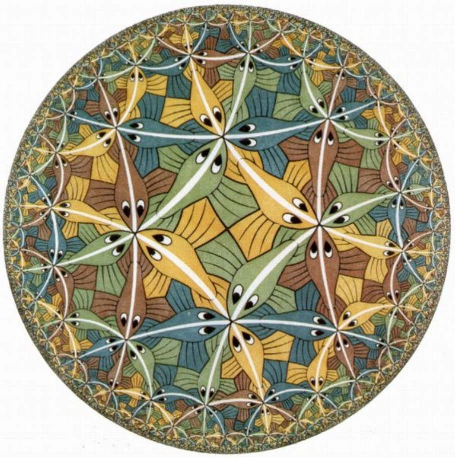
Holography beyond AdS/CFT?

This talk focuses on holography.



Holography beyond AdS/CFT?

This talk focuses on holography.



Main question: how general is holography?

Testing the holographic principle

How general is holography?

- Holographic principle realized in AdS/CFT correspondence
- Special case or generic lesson for quantum gravity?

AdS$_{d+1}$ $\to$ CFT$_d$

- Use (classical) gravity to learn more about CFTs
- Strong coupling large N limit: classical gravity
- Useful tool to calculate correlation functions
- Useful tool to calculate entanglement entropy

CFT$_d$ $\to$ AdS$_{d+1}$

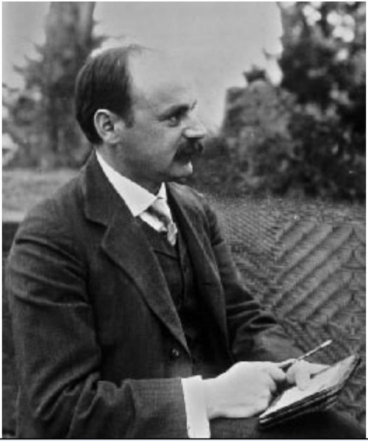
- Use CFTs to learn more about (quantum) gravity
- Gravity in ultra-quantum limit: simple CFT?
- Useful tool to address black hole microstates
- Useful tool for qu-gr puzzles (information paradox)

Testing the holographic principle

How general is holography?

Historical curiosity:

Karl Schwarzschild (1873-1916)



Simplest of all (classical) black holes:
Schwarzschild solution (22.12.1915)

$$\mathrm{d}s^2 = (1 - \gamma/R)\ \mathrm{d}t^2 - \frac{\mathrm{d}R^2}{1 - \gamma/R} - R^2 \left(\mathrm{d}\theta^2 + \sin^2\theta\ \mathrm{d}\phi^2 \right)$$

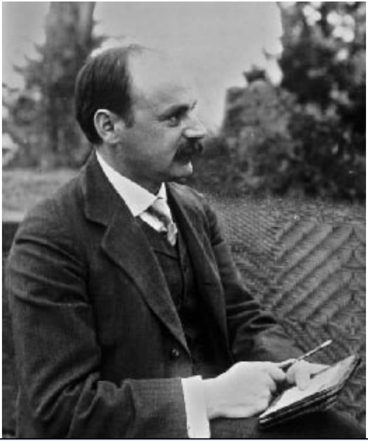
(Schwarzschild's conventions in letter to Einstein)

Testing the holographic principle

How general is holography?

Historical curiosity:

Karl Schwarzschild (1873-1916)



Simplest of all (classical) black holes:
Schwarzschild solution (22.12.1915)

$$\mathrm{d}s^2 = (1-\gamma/R)\ \mathrm{d}t^2 - \frac{\mathrm{d}R^2}{1-\gamma/R} - R^2\left(\mathrm{d}\theta^2 + \sin^2\theta\ \mathrm{d}\phi^2\right)$$

(Schwarzschild's conventions in letter to Einstein)

- Quantum mechanically: among least understood black holes!
- Microstates?
- Log corrections to entropy?
- Dual field theory??

Testing the holographic principle

How general is holography?

- To what extent do (previous) lessons rely on the particular constructions used to date?
- Are they tied to stringy effects and to string theory in particular, or are they general lessons for quantum gravity?

see numerous talks at KITP workshop “Bits, Branes, Black Holes” 2012

and at ESI workshop “Higher Spin Gravity” 2012

Testing the holographic principle

How general is holography?

- To what extent do (previous) lessons rely on the particular constructions used to date?
- Are they tied to stringy effects and to string theory in particular, or are they general lessons for quantum gravity?
- Does holography apply only to unitary theories?

- originally holography motivated by unitarity

Testing the holographic principle

How general is holography?

- To what extent do (previous) lessons rely on the particular constructions used to date?
- Are they tied to stringy effects and to string theory in particular, or are they general lessons for quantum gravity?
- Does holography apply only to unitary theories?

- originally holography motivated by unitarity
- plausible AdS/CFT-like correspondence could work non-unitarily
- AdS/log CFT first example of non-unitary holography DG, (Jackiw), Johansson '08; Skenderis, Taylor, van Rees '09; Henneaux, Martinez, Troncoso '09; Maloney, Song, Strominger '09; DG, Sachs/Hohm '09; Gaberdiel, DG, Vassilevich '10; ... DG, Riedler, Rosseel, Zojer '13
- recent proposal by Vafa '14

Testing the holographic principle

How general is holography?

- To what extent do (previous) lessons rely on the particular constructions used to date?
- Are they tied to stringy effects and to string theory in particular, or are they general lessons for quantum gravity?
- Does holography apply only to unitary theories?
- Can we establish a flat space holographic dictionary?

the answer appears to be yes — see my current talk and recent papers by Bagchi et al., Barnich et al., Strominger et al., '12-'15

Testing the holographic principle

How general is holography?

- To what extent do (previous) lessons rely on the particular constructions used to date?
- Are they tied to stringy effects and to string theory in particular, or are they general lessons for quantum gravity?
- Does holography apply only to unitary theories?
- Can we establish a flat space holographic dictionary?
- Generic non-AdS holography/higher spin holography?

non-trivial hints that it might work at least in 2+1 dimensions
Gary, DG Rashkov '12; Afshar et al '12; Gutperle et al '14-'15; Gary, DG, Prohazka, Rey '14; ...

Testing the holographic principle

How general is holography?

- To what extent do (previous) lessons rely on the particular constructions used to date?
- Are they tied to stringy effects and to string theory in particular, or are they general lessons for quantum gravity?
- Does holography apply only to unitary theories?
- Can we establish a flat space holographic dictionary?
- Generic non-AdS holography/higher spin holography?

- Address questions above in simple class of 3D toy models
- Exploit gauge theoretic Chern–Simons formulation
- Restrict to kinematic questions, like (asymptotic) symmetries

Goals of this talk

1. Review general aspects of holography in 3D

Goals of this talk

1. Review general aspects of holography in 3D
2. Discuss flat space holography

Goals of this talk

1. Review general aspects of holography in 3D
2. Discuss flat space holography
3. List selected open issues

Goals of this talk

1. Review general aspects of holography in 3D
2. Discuss flat space holography
3. List selected open issues

Address these issues in 3D!

Outline

Motivations

Assumptions

Flat space holography basics

Recent results

Generalizations & open issues

Assumptions

Working assumptions:

- 3D

Assumptions

Working assumptions:

- 3D
- Restrict to "pure gravity" theories

Assumptions

Working assumptions:

- 3D
- Restrict to "pure gravity" theories
- Define quantum gravity by its dual field theory

Interesting dichotomy:

- Either dual field theory exists $\rightarrow$ useful toy model for quantum gravity
- Or gravitational theory needs UV completion (within string theory) $\rightarrow$ indication of inevitability of string theory

Assumptions

Working assumptions:

- 3D
- Restrict to "pure gravity" theories
- Define quantum gravity by its dual field theory

Interesting dichotomy:

- Either dual field theory exists $\rightarrow$ useful toy model for quantum gravity
- Or gravitational theory needs UV completion (within string theory) $\rightarrow$ indication of inevitability of string theory

This talk:

- Remain agnostic about dichotomy
- Focus on generic features of dual field theories that do not require string theory embedding

Gravity in 3D
AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons

Gravity in 3D
AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci

Gravity in 3D
AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons

Gravity in 3D
AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons
- Formulation as topological gauge theory (Chern–Simons)

Gravity in 3D

AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons
- Formulation as topological gauge theory (Chern–Simons)
- Dual field theory (if it exists): 2D

Gravity in 3D

AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons
- Formulation as topological gauge theory (Chern–Simons)
- Dual field theory (if it exists): 2D
- Infinite dimensional asymptotic symmetries (Brown–Henneaux)

Gravity in 3D

AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons
- Formulation as topological gauge theory (Chern–Simons)
- Dual field theory (if it exists): 2D
- Infinite dimensional asymptotic symmetries (Brown–Henneaux)
- Black holes as orbifolds of AdS_3 (BTZ)

Gravity in 3D

AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons
- Formulation as topological gauge theory (Chern–Simons)
- Dual field theory (if it exists): 2D
- Infinite dimensional asymptotic symmetries (Brown–Henneaux)
- Black holes as orbifolds of AdS_3 (BTZ)
- Simple microstate counting from AdS_3/CFT_2

Gravity in 3D

AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons
- Formulation as topological gauge theory (Chern–Simons)
- Dual field theory (if it exists): 2D
- Infinite dimensional asymptotic symmetries (Brown–Henneaux)
- Black holes as orbifolds of AdS_3 (BTZ)
- Simple microstate counting from AdS_3/CFT_2
- Hawking–Page phase transition hot AdS $\leftrightarrow$ BTZ

Gravity in 3D
AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons
- Formulation as topological gauge theory (Chern–Simons)
- Dual field theory (if it exists): 2D
- Infinite dimensional asymptotic symmetries (Brown–Henneaux)
- Black holes as orbifolds of AdS_3 (BTZ)
- Simple microstate counting from AdS_3/CFT_2
- Hawking–Page phase transition hot AdS $\leftrightarrow$ BTZ
- Simple checks of Ryu–Takayanagi proposal

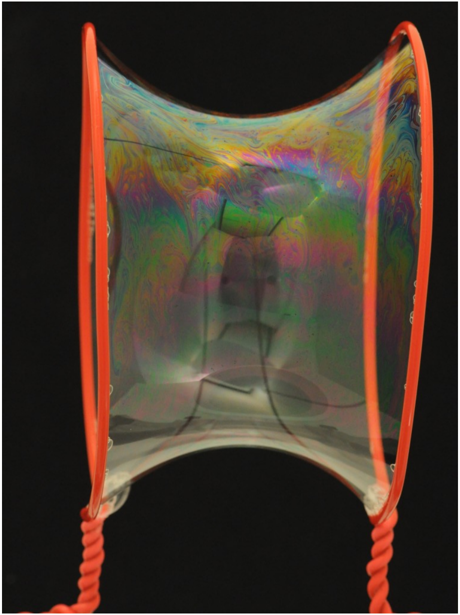
Gravity in 3D

AdS_3 gravity

- Lowest dimension with black holes and (off-shell) gravitons
- Weyl $= 0$, thus Riemann $=$ Ricci
- Einstein gravity: no on-shell gravitons
- Formulation as topological gauge theory (Chern–Simons)
- Dual field theory (if it exists): 2D
- Infinite dimensional asymptotic symmetries (Brown–Henneaux)
- Black holes as orbifolds of AdS_3 (BTZ)
- Simple microstate counting from AdS_3/CFT_2
- Hawking–Page phase transition hot AdS $\leftrightarrow$ BTZ
- Simple checks of Ryu–Takayanagi proposal

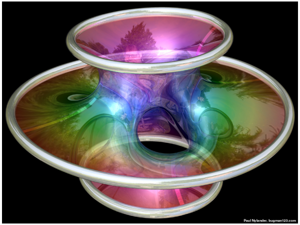
Caveat: while there are many string compactifications with AdS_3 factor, applying holography just to AdS_3 factor does not capture everything!

Picturesque analogy: soap films



Both soap films and Chern–Simons theories have

- essentially no bulk dynamics
- highly non-trivial boundary dynamics
- most of the physics determined by boundary conditions
- esthetic appeal (at least for me)



Outline

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true $\Rightarrow$ must work in flat space

Just take large AdS radius limit of 10^4 AdS/CFT papers?

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true $\Rightarrow$ must work in flat space

Just take large AdS radius limit of 10^4 AdS/CFT papers?

- Works straightforwardly sometimes, otherwise not

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true $\Rightarrow$ must work in flat space

> Just take large AdS radius limit of 10^4 AdS/CFT papers?

- Works straightforwardly sometimes, otherwise not
- Example where it works nicely: asymptotic symmetry algebra

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true $\Rightarrow$ must work in flat space

> Just take large AdS radius limit of 10^4 AdS/CFT papers?

- Works straightforwardly sometimes, otherwise not
- Example where it works nicely: asymptotic symmetry algebra
- Take linear combinations of Virasoro generators $\mathcal{L}_n$, $\bar{\mathcal{L}}_n$

$$L_n = \mathcal{L}_n - \bar{\mathcal{L}}_{-n} \qquad M_n = \frac{1}{\ell}\left(\mathcal{L}_n + \bar{\mathcal{L}}_{-n}\right)$$

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true $\Rightarrow$ must work in flat space

Just take large AdS radius limit of 10^4 AdS/CFT papers?

- Works straightforwardly sometimes, otherwise not
- Example where it works nicely: asymptotic symmetry algebra
- Take linear combinations of Virasoro generators $\mathcal{L}_n$, $\bar{\mathcal{L}}_n$

$$L_n = \mathcal{L}_n - \bar{\mathcal{L}}_{-n} \qquad M_n = \frac{1}{\ell}\left(\mathcal{L}_n + \bar{\mathcal{L}}_{-n}\right)$$

- Make Inönü–Wigner contraction $\ell \to \infty$ on ASA

$$[L_n,\, L_m] = (n-m)\, L_{n+m} + \frac{c_L}{12}\,(n^3 - n)\,\delta_{n+m,\,0}$$

$$[L_n,\, M_m] = (n-m)\, M_{n+m} + \frac{c_M}{12}\,(n^3 - n)\,\delta_{n+m,\,0}$$

$$[M_n,\, M_m] = 0$$

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true ⇒ must work in flat space

Just take large AdS radius limit of 10^4 AdS/CFT papers?

- Works straightforwardly sometimes, otherwise not
- Example where it works nicely: asymptotic symmetry algebra
- Take linear combinations of Virasoro generators $\mathcal{L}_n$, $\bar{\mathcal{L}}_n$

$$L_n = \mathcal{L}_n - \bar{\mathcal{L}}_{-n} \qquad M_n = \frac{1}{\ell}\left(\mathcal{L}_n + \bar{\mathcal{L}}_{-n}\right)$$

- Make Inönü–Wigner contraction $\ell \to \infty$ on ASA

$$[L_n,\, L_m] = (n-m)\, L_{n+m} + \frac{c_L}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$

$$[L_n,\, M_m] = (n-m)\, M_{n+m} + \frac{c_M}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$

$$[M_n,\, M_m] = 0$$

- This is nothing but the BMS_3 algebra (or GCA_2, URCA_2, CCA_2)!
  Ashtekar, Bicak, Schmidt, '96; Barnich, Compere '06
  L_n: diffeos of circle, M_n: supertranslations, $c_{L/M}$: central extensions

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true $\Rightarrow$ must work in flat space

> Just take large AdS radius limit of 10^4 AdS/CFT papers?

- Works straightforwardly sometimes, otherwise not
- Example where it works nicely: asymptotic symmetry algebra
- Take linear combinations of Virasoro generators $\mathcal{L}_n$, $\bar{\mathcal{L}}_n$

$$L_n = \mathcal{L}_n - \bar{\mathcal{L}}_{-n} \qquad M_n = \frac{1}{\ell}\left(\mathcal{L}_n + \bar{\mathcal{L}}_{-n}\right)$$

- Make Inönü–Wigner contraction $\ell \to \infty$ on ASA

$$[L_n,\, L_m] = (n-m)\,L_{n+m} + \frac{c_L}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$
$$[L_n,\, M_m] = (n-m)\,M_{n+m} + \frac{c_M}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$
$$[M_n,\, M_m] = 0$$

- This is nothing but the BMS_3 algebra (or GCA_2, URCA_2, CCA_2)!
  If dual field theory exists it must be a 2D Galilean CFT!
  Bagchi et al., Barnich et al.

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true ⇒ must work in flat space

> Just take large AdS radius limit of 10^4 AdS/CFT papers?

- Works straightforwardly sometimes, otherwise not
- Example where it works nicely: asymptotic symmetry algebra
- Take linear combinations of Virasoro generators $\mathcal{L}_n$, $\bar{\mathcal{L}}_n$

$$L_n = \mathcal{L}_n - \bar{\mathcal{L}}_{-n} \qquad M_n = \frac{1}{\ell}\left(\mathcal{L}_n + \bar{\mathcal{L}}_{-n}\right)$$

- Make Inönü–Wigner contraction $\ell \to \infty$ on ASA

$$[L_n,\, L_m] = (n-m)\, L_{n+m} + \frac{c_L}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$
$$[L_n,\, M_m] = (n-m)\, M_{n+m} + \frac{c_M}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$
$$[M_n,\, M_m] = 0$$

- This is nothing but the BMS_3 algebra (or GCA_2, URCA_2, CCA_2)!
- Example where it does not work easily: boundary conditions

Flat space holography (Barnich et al, Bagchi et al, Strominger et al, ...)

if holography is true $\Rightarrow$ must work in flat space

Just take large AdS radius limit of 10^4 AdS/CFT papers?

- Works straightforwardly sometimes, otherwise not
- Example where it works nicely: asymptotic symmetry algebra
- Take linear combinations of Virasoro generators $\mathcal{L}_n$, $\bar{\mathcal{L}}_n$

$$L_n = \mathcal{L}_n - \bar{\mathcal{L}}_{-n} \qquad M_n = \frac{1}{\ell}\left(\mathcal{L}_n + \bar{\mathcal{L}}_{-n}\right)$$

- Make Inönü–Wigner contraction $\ell \to \infty$ on ASA

$$[L_n,\, L_m] = (n-m)\, L_{n+m} + \frac{c_L}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$
$$[L_n,\, M_m] = (n-m)\, M_{n+m} + \frac{c_M}{12}\,(n^3-n)\,\delta_{n+m,\,0}$$
$$[M_n,\, M_m] = 0$$

- This is nothing but the BMS_3 algebra (or GCA_2, URCA_2, CCA_2)!
- Example where it does not work easily: boundary conditions
- Example where it does not work: highest weight conditions

Flat space Einstein gravity as isl(2) Chern–Simons theory

For details, references and spin-3 generalization see Gary, DG, Riegler, Rosseel '14

See also talk by Mirah Gary two days ago (Junior plenary session)

Flat space Einstein gravity as isl(2) Chern–Simons theory

For details, references and spin-3 generalization see Gary, DG, Riegler, Rosseel '14

- AdS gravity in CS formulation: sl$(2)\oplus$sl(2) gauge algebra

  Achucarro, Townsend '86; Witten '88

Flat space Einstein gravity as isl(2) Chern–Simons theory

For details, references and spin-3 generalization see Gary, DG, Riegler, Rosseel '14

- AdS gravity in CS formulation: sl$(2)\oplus$sl(2) gauge algebra
- Flat space: isl(2) gauge algebra

$$S_{\rm CS}^{\rm flat} = \frac{k}{4\pi} \int \langle \mathcal{A}\wedge \mathrm{d}\mathcal{A} + \tfrac{2}{3}\,\mathcal{A}\wedge\mathcal{A}\wedge\mathcal{A}\rangle$$

with isl(2) connection ($a = 0, \pm 1$)

$$\mathcal{A} = e^a M_a + \omega^a L_a$$

isl(2) algebra (global part of BMS/GCA)

$$[L_a,\, L_b] = (a-b) L_{a+b}$$
$$[L_a,\, M_b] = (a-b) M_{a+b}$$
$$[M_a,\, M_b] = 0$$

Note: e^a dreibein, ω^a (dualized) spin-connection

Bulk EOM: gauge flatness $\to$ Einstein equations

$$\mathcal{F} = \mathrm{d}\mathcal{A} + \mathcal{A}\wedge\mathcal{A} = 0$$

Flat space Einstein gravity as isl(2) Chern–Simons theory

For details, references and spin-3 generalization see Gary, DG, Riegler, Rosseel '14

- AdS gravity in CS formulation: sl$(2)\oplus$sl(2) gauge algebra
- Flat space: isl(2) gauge algebra

$$S_{\rm CS}^{\rm flat} = \frac{k}{4\pi}\int\langle\mathcal{A}\wedge\mathrm{d}\mathcal{A}+\tfrac{2}{3}\,\mathcal{A}\wedge\mathcal{A}\wedge\mathcal{A}\rangle$$

with isl(2) connection $(a=0,\,\pm1)$

$$\mathcal{A}=e^aM_a+\omega^aL_a$$

- Boundary conditions in CS formulation:

$$\mathcal{A}(r,\,u,\,\varphi)=b^{-1}(r)\left(\mathrm{d}+a(u,\,\varphi)+o(1)\right)b(r)$$

Flat space Einstein gravity as isl(2) Chern–Simons theory

For details, references and spin-3 generalization see Gary, DG, Riegler, Rosseel '14

- AdS gravity in CS formulation: sl$(2)\oplus$sl(2) gauge algebra
- Flat space: isl(2) gauge algebra

$$S_{\rm CS}^{\rm flat} = \frac{k}{4\pi}\int\langle\mathcal{A}\wedge\mathrm{d}\mathcal{A}+\tfrac{2}{3}\,\mathcal{A}\wedge\mathcal{A}\wedge\mathcal{A}\rangle$$

with isl(2) connection ($a=0,\,\pm1$)

$$\mathcal{A} = e^a M_a + \omega^a L_a$$

- Boundary conditions in CS formulation:

$$\mathcal{A}(r,\,u,\,\varphi) = b^{-1}(r)\,\big(\mathrm{d}+a(u,\,\varphi)+o(1)\big)\,b(r)$$

- Flat space boundary conditions: $b(r)=\exp\big(\frac12\,rM_{-1}\big)$ and

$$a(u,\,\varphi) = \big(M_1 - M(\varphi)M_{-1}\big)\,\mathrm{d}u + \big(L_1 - M(\varphi)L_{-1} - N(u,\,\varphi)M_{-1}\big)\,\mathrm{d}\varphi$$

with $N(u,\,\varphi)=L(\varphi)+\frac{u}{2}\,M'(\varphi)$

Flat space Einstein gravity as isl(2) Chern–Simons theory

For details, references and spin-3 generalization see Gary, DG, Riegler, Rosseel '14

- AdS gravity in CS formulation: sl$(2)\oplus$sl(2) gauge algebra
- Flat space: isl(2) gauge algebra

$$S_{\text{CS}}^{\text{flat}} = \frac{k}{4\pi} \int \langle \mathcal{A} \wedge \mathrm{d}\mathcal{A} + \tfrac{2}{3}\, \mathcal{A} \wedge \mathcal{A} \wedge \mathcal{A} \rangle$$

with isl(2) connection $(a = 0,\, \pm 1)$

$$\mathcal{A} = e^a M_a + \omega^a L_a$$

- Boundary conditions in CS formulation:

$$\mathcal{A}(r,\, u,\, \varphi) = b^{-1}(r) \big(\mathrm{d} + a(u,\, \varphi) + o(1) \big)\, b(r)$$

- Flat space boundary conditions: $b(r) = \exp\big(\frac{1}{2}\, r M_{-1}\big)$ and

$$a(u,\, \varphi) = \big(M_1 - M(\varphi) M_{-1}\big)\, \mathrm{d}u + \big(L_1 - M(\varphi) L_{-1} - N(u,\, \varphi) M_{-1}\big)\, \mathrm{d}\varphi$$

with $N(u,\, \varphi) = L(\varphi) + \frac{u}{2}\, M'(\varphi)$

- metric

$$g_{\mu\nu} \sim \tfrac{1}{2}\, \widetilde{\mathrm{tr}} \langle \mathcal{A}_\mu \mathcal{A}_\nu \rangle \quad \to \quad \mathrm{d}s^2 = M\, \mathrm{d}u^2 - 2\, \mathrm{d}u\, \mathrm{d}r + 2N\, \mathrm{d}u\, \mathrm{d}\varphi + r^2\, \mathrm{d}\varphi^2$$

Outline

Correlation functions in flat space holography

AdS/CFT good tool for calculating correlators
What about flat space/Galilean CFT correspondence?

Correlation functions in flat space holography

AdS/CFT good tool for calculating correlators
What about flat space/Galilean CFT correspondence?

- What is flat space analogue of

$$\langle T(z_1)T(z_2)\dots T(z_{42})\rangle_{\text{CFT}} \sim \frac{\delta^{42}}{\delta g^{42}}\Gamma_{\text{EH-AdS}}\Big|_{\text{EOM}}$$

?

Correlation functions in flat space holography

AdS/CFT good tool for calculating correlators
What about flat space/Galilean CFT correspondence?

- What is flat space analogue of

$$\langle T(z_1)T(z_2)\dots T(z_{42})\rangle_{\text{CFT}} \sim \frac{\delta^{42}}{\delta g^{42}}\Gamma_{\text{EH-AdS}}\Big|_{\text{EOM}}$$

  ?
- Does it work?

Correlation functions in flat space holography

AdS/CFT good tool for calculating correlators
What about flat space/Galilean CFT correspondence?

- What is flat space analogue of

$$\langle T(z_1)T(z_2)\dots T(z_{42})\rangle_{\text{CFT}} \sim \frac{\delta^{42}}{\delta g^{42}}\Gamma_{\text{EH-AdS}}\Big|_{\text{EOM}}$$

  ?
- Does it work?
- What is the left hand side in a Galilean CFT?

Correlation functions in flat space holography

AdS/CFT good tool for calculating correlators
What about flat space/Galilean CFT correspondence?

- What is flat space analogue of

$$\langle T(z_1)T(z_2)\dots T(z_{42})\rangle_{\text{CFT}} \sim \frac{\delta^{42}}{\delta g^{42}}\Gamma_{\text{EH-AdS}}\Big|_{\text{EOM}}$$

  ?
- Does it work?
- What is the left hand side in a Galilean CFT?
- Shortcut to right hand side other than varying EH-action 42 times?

Correlation functions in flat space holography

AdS/CFT good tool for calculating correlators
What about flat space/Galilean CFT correspondence?

- What is flat space analogue of

$$\langle T(z_1)T(z_2)\dots T(z_{42})\rangle_{\text{CFT}} \sim \frac{\delta^{42}}{\delta g^{42}}\Gamma_{\text{EH-AdS}}\Big|_{\text{EOM}}$$

  ?
- Does it work?
- What is the left hand side in a Galilean CFT?
- Shortcut to right hand side other than varying EH-action 42 times?

Start slowly with 0-point function

0-point function (on-shell action)

Not check of flat space holography but interesting in its own right

- Calculate the full on-shell action Γ

0-point function (on-shell action)

Not check of flat space holography but interesting in its own right

- Calculate the full on-shell action Γ
- Variational principle?

$$\Gamma = -\frac{1}{16\pi G_N}\int \mathrm{d}^3x\sqrt{g}\,R - -\frac{1}{8\pi G_N}\int \mathrm{d}^2x\sqrt{\gamma}\,K - I_{\text{counter-term}}$$

with $I_{\text{counter-term}}$ chosen such that

$$\delta\Gamma\big|_{\text{EOM}} = 0$$

for all δg that preserve flat space bc's

0-point function (on-shell action)

Not check of flat space holography but interesting in its own right

- Calculate the full on-shell action Γ
- Variational principle?

$$\Gamma = -\frac{1}{16\pi G_N}\int \mathrm{d}^3x\sqrt{g}\,R - -\frac{1}{8\pi G_N}\int \mathrm{d}^2x\sqrt{\gamma}\,K - I_{\text{counter-term}}$$

with $I_{\text{counter-term}}$ chosen such that

$$\delta\Gamma\big|_{\text{EOM}} = 0$$

for all δg that preserve flat space bc's

Result (Detournay, DG, Schöller, Simon '14):

$$\Gamma = -\frac{1}{16\pi G_N}\int \mathrm{d}^3x\sqrt{g}\,R - \underbrace{\frac{1}{16\pi G_N}}_{\frac{1}{2}\text{GHY!}}\int \mathrm{d}^2x\sqrt{\gamma}\,K$$

follows also as limit from AdS using Mora, Olea, Troncoso, Zanelli '04
independently confirmed by Barnich, Gonzalez, Maloney, Oblak '15

0-point function (on-shell action)

Not check of flat space holography but interesting in its own right

- Calculate the full on-shell action Γ
- Variational principle?
- Phase transitions?

  Standard procedure (Gibbons, Hawking '77; Hawking, Page '83)

  Evaluate Euclidean partition function in semi-classical limit

  $$Z(T,\,\Omega) = \int \mathcal{D}g\, e^{-\Gamma[g]} = \sum_{g_c} e^{-\Gamma[g_c(T,\,\Omega)]} \times Z_{\text{fluct.}}$$

  path integral bc's specified by temperature T and angular velocity Ω

  Two Euclidean saddle points in same ensemble if

  - same temperature $T = 1/\beta$ and angular velocity Ω
  - obey flat space boundary conditions
  - solutions without conical singularities

  Periodicities fixed:

  $$(\tau_E,\,\varphi) \sim (\tau_E + \beta,\,\varphi + \beta\Omega) \sim (\tau_E,\,\varphi + 2\pi)$$

0-point function (on-shell action)

Not check of flat space holography but interesting in its own right

- Calculate the full on-shell action Γ
- Variational principle?
- Phase transitions?
  3D Euclidean Einstein gravity: for each T, Ω two saddle points:
  - Hot flat space
    $$\mathrm{d}s^2 = \mathrm{d}\tau_E^2 + \mathrm{d}r^2 + r^2\,\mathrm{d}\varphi^2$$
  - Flat space cosmology
    $$\mathrm{d}s^2 = r_+^2\left(1 - \frac{r_0^2}{r^2}\right)\mathrm{d}\tau_E^2 + \frac{r^2\,\mathrm{d}r^2}{r_+^2\,(r^2 - r_0^2)} + r^2\left(\mathrm{d}\varphi - \frac{r_+ r_0}{r^2}\,\mathrm{d}\tau_E\right)^2$$
    shifted-boost orbifold, see Cornalba, Costa '02

0-point function (on-shell action)

Not check of flat space holography but interesting in its own right

- Calculate the full on-shell action Γ
- Variational principle?
- Phase transitions?
- Plug two Euclidean saddles in on-shell action and compare free energies

$$F_{\text{HFS}} = -\frac{1}{8G_N} \qquad F_{\text{FSC}} = -\frac{r_+}{8G_N}$$

0-point function (on-shell action)

Not check of flat space holography but interesting in its own right

- Calculate the full on-shell action Γ
- Variational principle?
- Phase transitions?
- Plug two Euclidean saddles in on-shell action and compare free energies

$$F_{\text{HFS}} = -\frac{1}{8G_N} \qquad F_{\text{FSC}} = -\frac{r_+}{8G_N}$$

- Result of this comparison
  - $r_+ > 1$: FSC dominant saddle
  - $r_+ < 1$: HFS dominant saddle

  Critical temperature:

$$T_c = \frac{1}{2\pi r_0} = \frac{\Omega}{2\pi}$$

  HFS "melts" into FSC at $T > T_c$

  Bagchi, Detournay, DG, Simon '13

1-point functions (conserved charges)

First check of entries in holographic dictionary: identification of sources and vevs

In AdS_3:

$$\delta\Gamma\big|_{\text{EOM}} \sim \int_{\partial\mathcal{M}} \text{vev} \times \delta\,\text{source} \sim \int_{\partial\mathcal{M}} T^{\mu\nu}_{\text{BY}} \times \delta g^{\text{NN}}_{\mu\nu}$$

Note that $T^{\mu\nu}_{\text{BY}}$ follows from canonical analysis as well (conserved charges)

1-point functions (conserved charges)

First check of entries in holographic dictionary: identification of sources and vevs

In AdS_3:

$$\delta\Gamma\big|_{\text{EOM}} \sim \int_{\partial\mathcal{M}} \text{vev} \times \delta\,\text{source} \sim \int_{\partial\mathcal{M}} T^{\mu\nu}_{\text{BY}} \times \delta g^{\text{NN}}_{\mu\nu}$$

Note that $T^{\mu\nu}_{\text{BY}}$ follows from canonical analysis as well (conserved charges)

In flat space:

- non-normalizable solutions to linearized EOM?
- analogue of Brown–York stress tensor?
- comparison with canonical results

1-point functions (conserved charges)

First check of entries in holographic dictionary: identification of sources and vevs

In AdS_3:

$$\delta\Gamma\big|_{\text{EOM}} \sim \int_{\partial\mathcal{M}} \text{vev} \times \delta\,\text{source} \sim \int_{\partial\mathcal{M}} T^{\mu\nu}_{\text{BY}} \times \delta g^{\text{NN}}_{\mu\nu}$$

Note that $T^{\mu\nu}_{\text{BY}}$ follows from canonical analysis as well (conserved charges)

In flat space:

- non-normalizable solutions to linearized EOM?
- analogue of Brown–York stress tensor?
- comparison with canonical results

everything works (Detournay, DG, Schöller, Simon, '14)

mass and angular momentum:

$$M = \frac{g_{tt}}{8G} \qquad N = \frac{g_{t\varphi}}{4G}$$

full tower of canonical charges: see Barnich, Compere '06

2-point functions (anomalous terms)

First check sensitive to central charges in symmetry algebra

Galilean CFT on cylinder ($\varphi \sim \varphi + 2\pi$):

$$\langle M(u_1, \varphi_1)\, M(u_2, \varphi_2)\rangle = 0$$

$$\langle M(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_M}{2s_{12}^4}$$

$$\langle N(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_L - 2c_M\tau_{12}}{2s_{12}^4}$$

with $s_{ij} = 2\sin[(\varphi_i - \varphi_j)/2]$, $\tau_{ij} = (u_i - u_j)\,\cot[(\varphi_i - \varphi_j)/2]$

Fourier modes of Galilean CFT stress tensor on cylinder:

$$M := \sum_n M_n e^{-in\varphi} - \frac{c_M}{24}$$

$$N := \sum_n \big(L_n - inuM_n\big)e^{-in\varphi} - \frac{c_L}{24}$$

Conservation equations: $\partial_u M = 0$, $\partial_u N = \partial_\varphi M$

2-point functions (anomalous terms)

First check sensitive to central charges in symmetry algebra

Galilean CFT on cylinder ($\varphi \sim \varphi + 2\pi$):

$$\langle M(u_1, \varphi_1)\, M(u_2, \varphi_2)\rangle = 0$$

$$\langle M(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_M}{2s_{12}^4}$$

$$\langle N(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_L - 2c_M\tau_{12}}{2s_{12}^4}$$

with $s_{ij} = 2\sin[(\varphi_i - \varphi_j)/2]$, $\tau_{ij} = (u_i - u_j)\,\cot[(\varphi_i - \varphi_j)/2]$
Short-cut on gravity side:

- Do not calculate second variation of action

2-point functions (anomalous terms)

First check sensitive to central charges in symmetry algebra

Galilean CFT on cylinder ($\varphi \sim \varphi + 2\pi$):

$$\langle M(u_1, \varphi_1)\, M(u_2, \varphi_2)\rangle = 0$$

$$\langle M(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_M}{2s_{12}^4}$$

$$\langle N(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_L - 2c_M \tau_{12}}{2s_{12}^4}$$

with $s_{ij} = 2\sin[(\varphi_i - \varphi_j)/2]$, $\tau_{ij} = (u_i - u_j)\,\cot[(\varphi_i - \varphi_j)/2]$

Short-cut on gravity side:

- Do not calculate second variation of action
- Calculate first variation of action on non-trivial background

2-point functions (anomalous terms)

First check sensitive to central charges in symmetry algebra

Galilean CFT on cylinder ($\varphi \sim \varphi + 2\pi$):

$$\langle M(u_1, \varphi_1)\, M(u_2, \varphi_2)\rangle = 0$$
$$\langle M(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_M}{2s_{12}^4}$$
$$\langle N(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_L - 2c_M\tau_{12}}{2s_{12}^4}$$

with $s_{ij} = 2\sin[(\varphi_i - \varphi_j)/2]$, $\tau_{ij} = (u_i - u_j)\,\cot[(\varphi_i - \varphi_j)/2]$
Short-cut on gravity side:

- Do not calculate second variation of action
- Calculate first variation of action on non-trivial background
- Can iterate this procedure to higher n-point functions

2-point functions (anomalous terms)

First check sensitive to central charges in symmetry algebra

Galilean CFT on cylinder ($\varphi \sim \varphi + 2\pi$):

$$\langle M(u_1, \varphi_1)\, M(u_2, \varphi_2)\rangle = 0$$
$$\langle M(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_M}{2s_{12}^4}$$
$$\langle N(u_1, \varphi_1)\, N(u_2, \varphi_2)\rangle = \frac{c_L - 2c_M \tau_{12}}{2s_{12}^4}$$

with $s_{ij} = 2\sin[(\varphi_i - \varphi_j)/2]$, $\tau_{ij} = (u_i - u_j)\,\cot[(\varphi_i - \varphi_j)/2]$
Short-cut on gravity side:

- Do not calculate second variation of action
- Calculate first variation of action on non-trivial background
- Can iterate this procedure to higher n-point functions

Summarize first how this works in the AdS case

2-point functions (anomalous terms)

Illustrate shortcut in $\text{AdS}_3/\text{CFT}_2$ (restrict to one holomorphic sector)

- On CFT side deform free action S_0 by source term μ for stress tensor

$$S_\mu = S_0 + \int \mathrm{d}^2 z\, \mu(z, \bar{z}) T(z)$$

2-point functions (anomalous terms)

Illustrate shortcut in AdS_3/CFT_2 (restrict to one holomorphic sector)

- On CFT side deform free action S_0 by source term μ for stress tensor

$$S_\mu = S_0 + \int \mathrm{d}^2 z\, \mu(z, \bar{z}) T(z)$$

- Localize source

$$\mu(z, \bar{z}) = \epsilon\, \delta^{(2)}(z - z_2, \bar{z} - \bar{z}_2)$$

2-point functions (anomalous terms)

Illustrate shortcut in AdS_3/CFT_2 (restrict to one holomorphic sector)

- On CFT side deform free action S_0 by source term μ for stress tensor

$$S_\mu = S_0 + \int \mathrm{d}^2 z \, \mu(z, \bar{z}) T(z)$$

- Localize source

$$\mu(z, \bar{z}) = \epsilon \, \delta^{(2)}(z - z_2, \bar{z} - \bar{z}_2)$$

- 1-point function in μ-vacuum $\to$ 2-point function in 0-vacuum

$$\langle T^1 \rangle_\mu = \langle T^1 \rangle_0 + \epsilon \, \langle T^1 \, T^2 \rangle_0 + \mathcal{O}(\epsilon^2)$$

2-point functions (anomalous terms)

Illustrate shortcut in $\text{AdS}_3/\text{CFT}_2$ (restrict to one holomorphic sector)

- On CFT side deform free action S_0 by source term μ for stress tensor

$$S_\mu = S_0 + \int \mathrm{d}^2 z\, \mu(z,\bar z) T(z)$$

- Localize source

$$\mu(z,\bar z) = \epsilon\, \delta^{(2)}(z - z_2, \bar z - \bar z_2)$$

- 1-point function in μ-vacuum $\to$ 2-point function in 0-vacuum

$$\langle T^1 \rangle_\mu = \langle T^1 \rangle_0 + \epsilon\, \langle T^1\, T^2 \rangle_0 + \mathcal{O}(\epsilon^2)$$

- On gravity side exploit sl(2) CS formulation with chemical potentials

$$A = b^{-1}(\mathrm{d}+a)b \qquad\qquad b = e^{\rho L_0}$$

$$a_z = L_+ - \frac{\mathcal{L}}{k} L_- \qquad\qquad a_{\bar z} = \mu L_+ + \dots$$

Drinfeld, Sokolov '84, Polyakov '87, H. Verlinde '90
Bañados, Caro '04

2-point functions (anomalous terms)

Illustrate shortcut in $\mathrm{AdS}_3/\mathrm{CFT}_2$ (restrict to one holomorphic sector)

- On CFT side deform free action S_0 by source term μ for stress tensor

$$S_\mu = S_0 + \int \mathrm{d}^2 z\, \mu(z,\bar z) T(z)$$

- Localize source

$$\mu(z,\bar z) = \epsilon\, \delta^{(2)}(z - z_2, \bar z - \bar z_2)$$

- 1-point function in μ-vacuum $\to$ 2-point function in 0-vacuum

$$\langle T^1 \rangle_\mu = \langle T^1 \rangle_0 + \epsilon\, \langle T^1\, T^2 \rangle_0 + \mathcal{O}(\epsilon^2)$$

- On gravity side exploit sl(2) CS formulation with chemical potentials

$$A = b^{-1}(\mathrm{d}+a)b \qquad\qquad b = e^{\rho L_0}$$

$$a_z = L_+ - \frac{\mathcal{L}}{k} L_- \qquad\qquad a_{\bar z} = \mu L_+ + \dots$$

- Expand $\mathcal{L}(z) = \mathcal{L}^{(0)}(z) + \epsilon \mathcal{L}^{(1)}(z) + \mathcal{O}(\epsilon^2)$

2-point functions (anomalous terms)

Illustrate shortcut in $\mathrm{AdS}_3/\mathrm{CFT}_2$ (restrict to one holomorphic sector)

- On gravity side exploit CS formulation with chemical potentials

$$A = b^{-1}(d+a)b \qquad\qquad b = e^{\rho L_0}$$

$$a_z = L_+ - \frac{\mathcal{L}}{k} L_- \qquad\qquad a_{\bar{z}} = \mu L_+ + \dots$$

- Expand $\mathcal{L}(z) = \mathcal{L}^{(0)}(z) + \epsilon\mathcal{L}^{(1)}(z) + \mathcal{O}(\epsilon^2)$
- Write EOM to first subleading order in ϵ

$$\bar{\partial}\mathcal{L}^{(1)}(z) = -\frac{k}{2}\,\partial^3\delta^{(2)}(z-z_2)$$

2-point functions (anomalous terms)

Illustrate shortcut in AdS_3/CFT_2 (restrict to one holomorphic sector)

- On gravity side exploit CS formulation with chemical potentials

$$A = b^{-1}(d+a)b \qquad\qquad b = e^{\rho L_0}$$

$$a_z = L_+ - \frac{\mathcal{L}}{k} L_- \qquad\qquad a_{\bar z} = \mu L_+ + \dots$$

- Expand $\mathcal{L}(z) = \mathcal{L}^{(0)}(z) + \epsilon \mathcal{L}^{(1)}(z) + \mathcal{O}(\epsilon^2)$
- Write EOM to first subleading order in ϵ

$$\bar\partial \mathcal{L}^{(1)}(z) = -\frac{k}{2}\, \partial^3 \delta^{(2)}(z - z_2)$$

- Solve them using the Green function on the plane $G = \ln(z_{12}\bar z_{12})$

$$\mathcal{L}^{(1)}(z) = -\frac{k}{2}\, \partial^4_{z_1} G(z_{12}) = \frac{3k}{z_{12}^4}$$

2-point functions (anomalous terms)

Illustrate shortcut in $\text{AdS}_3/\text{CFT}_2$ (restrict to one holomorphic sector)

- On gravity side exploit CS formulation with chemical potentials

$$A = b^{-1}(d+a)b \qquad\qquad b = e^{\rho L_0}$$

$$a_z = L_+ - \frac{\mathcal{L}}{k} L_- \qquad\qquad a_{\bar{z}} = \mu L_+ + \dots$$

- Expand $\mathcal{L}(z) = \mathcal{L}^{(0)}(z) + \epsilon \mathcal{L}^{(1)}(z) + \mathcal{O}(\epsilon^2)$
- Write EOM to first subleading order in ϵ

$$\bar{\partial} \mathcal{L}^{(1)}(z) = -\frac{k}{2}\, \partial^3 \delta^{(2)}(z - z_2)$$

- Solve them using the Green function on the plane $G = \ln\left(z_{12}\bar{z}_{12}\right)$

$$\mathcal{L}^{(1)}(z) = -\frac{k}{2}\, \partial_{z_1}^4 G(z_{12}) = \frac{3k}{z_{12}^4}$$

- This is the correct CFT 2-point function on the plane with $c = 6k$

2-point functions (anomalous terms)

Illustrate shortcut in $\mathrm{AdS}_3/\mathrm{CFT}_2$ (restrict to one holomorphic sector)

- On gravity side exploit CS formulation with chemical potentials

$$A = b^{-1}(d+a)b \qquad\qquad b = e^{\rho L_0}$$

$$a_z = L_+ - \frac{\mathcal{L}}{k} L_- \qquad\qquad a_{\bar z} = \mu L_+ + \dots$$

- Expand $\mathcal{L}(z) = \mathcal{L}^{(0)}(z) + \epsilon \mathcal{L}^{(1)}(z) + \mathcal{O}(\epsilon^2)$
- Write EOM to first subleading order in ϵ

$$\bar\partial \mathcal{L}^{(1)}(z) = -\frac{k}{2}\, \partial^3 \delta^{(2)}(z - z_2)$$

- Solve them using the Green function on the plane $G = \ln\left(z_{12}\bar z_{12}\right)$

$$\mathcal{L}^{(1)}(z) = -\frac{k}{2}\, \partial^4_{z_1} G(z_{12}) = \frac{3k}{z_{12}^4}$$

- This is the correct CFT 2-point function on the plane with $c = 6k$
- Generalize to cylinder

2-point functions (anomalous terms)

Apply shortcut to flat space/Galilean CFT (Bagchi, DG, Merbis '15)

- Exploit results for flat space gravity in CS formulation in presence of chemical potentials (Gary, DG, Riegler, Rosseel '14)

2-point functions (anomalous terms)

Apply shortcut to flat space/Galilean CFT (Bagchi, DG, Merbis '15)

- Exploit results for flat space gravity in CS formulation in presence of chemical potentials (Gary, DG, Riegler, Rosseel '14)
- Localize chemical potentials $\mu_{M/L} = \epsilon_{M/L}\,\delta^{(2)}(u-u_2,\,\varphi-\varphi_2)$

2-point functions (anomalous terms)

Apply shortcut to flat space/Galilean CFT (Bagchi, DG, Merbis '15)

- Exploit results for flat space gravity in CS formulation in presence of chemical potentials (Gary, DG, Riegler, Rosseel '14)
- Localize chemical potentials $\mu_{M/L} = \epsilon_{M/L}\, \delta^{(2)}(u - u_2,\, \varphi - \varphi_2)$
- Expand around global Minkowski space

$$M = -k/2 + M^{(1)} \qquad N = N^{(1)}$$

2-point functions (anomalous terms)

Apply shortcut to flat space/Galilean CFT (Bagchi, DG, Merbis '15)

- Exploit results for flat space gravity in CS formulation in presence of chemical potentials (Gary, DG, Riegler, Rosseel '14)
- Localize chemical potentials $\mu_{M/L} = \epsilon_{M/L}\,\delta^{(2)}(u - u_2,\, \varphi - \varphi_2)$
- Expand around global Minkowski space

$$M = -k/2 + M^{(1)} \qquad N = N^{(1)}$$

- Write EOM to first subleading order in $\epsilon_{M/L}$

$$\partial_u M^{(1)} = -\,k\,\epsilon_L\big(\partial_\varphi^3\delta + \partial_\varphi\delta\big)$$
$$\partial_u N^{(1)} = -\,k\,\epsilon_M\big(\partial_\varphi^3\delta + \partial_\varphi\delta\big) + \partial_\varphi M^{(1)}$$

2-point functions (anomalous terms)

Apply shortcut to flat space/Galilean CFT (Bagchi, DG, Merbis '15)

- Exploit results for flat space gravity in CS formulation in presence of chemical potentials (Gary, DG, Riegler, Rosseel '14)
- Localize chemical potentials $\mu_{M/L} = \epsilon_{M/L}\,\delta^{(2)}(u-u_2,\,\varphi-\varphi_2)$
- Expand around global Minkowski space

$$M = -k/2 + M^{(1)} \qquad N = N^{(1)}$$

- Write EOM to first subleading order in $\epsilon_{M/L}$

$$\partial_u M^{(1)} = -\,k\,\epsilon_L\big(\partial_\varphi^3\delta + \partial_\varphi\delta\big)$$
$$\partial_u N^{(1)} = -\,k\,\epsilon_M\big(\partial_\varphi^3\delta + \partial_\varphi\delta\big) + \partial_\varphi M^{(1)}$$

- Solve with Green function on cylinder

$$M^{(1)} = \frac{6k\epsilon_L}{s_{12}^4} \qquad N^{(1)} = \frac{6k(\epsilon_M - 2\epsilon_L\,\tau_{12})}{s_{12}^4}$$

2-point functions (anomalous terms)

Apply shortcut to flat space/Galilean CFT (Bagchi, DG, Merbis '15)

- Exploit results for flat space gravity in CS formulation in presence of chemical potentials (Gary, DG, Riegler, Rosseel '14)
- Localize chemical potentials $\mu_{M/L} = \epsilon_{M/L}\,\delta^{(2)}(u - u_2,\, \varphi - \varphi_2)$
- Expand around global Minkowski space

$$M = -k/2 + M^{(1)} \qquad N = N^{(1)}$$

- Write EOM to first subleading order in $\epsilon_{M/L}$

$$\partial_u M^{(1)} = -\,k\,\epsilon_L\big(\partial_\varphi^3\delta + \partial_\varphi\delta\big)$$
$$\partial_u N^{(1)} = -\,k\,\epsilon_M\big(\partial_\varphi^3\delta + \partial_\varphi\delta\big) + \partial_\varphi M^{(1)}$$

- Solve with Green function on cylinder

$$M^{(1)} = \frac{6k\epsilon_L}{s_{12}^4} \qquad N^{(1)} = \frac{6k(\epsilon_M - 2\epsilon_L\,\tau_{12})}{s_{12}^4}$$

- Correct 2-point functions for Einstein gravity with $c_L = 0$, $c_M = 12k$

3-point functions (check of symmetries)

First non-trivial check of consistency with symmetries of dual Galilean CFT

Check of 2-point functions works nicely with shortcut; 3-point too?

3-point functions (check of symmetries)

First non-trivial check of consistency with symmetries of dual Galilean CFT

Check of 2-point functions works nicely with shortcut; 3-point too?

- Yes: same procedure, but localize chemical potentials at two points

$$\mu_{M/L}(u_1,\,\varphi_1)=\sum_{i=2}^{3}\epsilon^i_{M/L}\,\delta^{(2)}(u_1-u_i,\,\varphi_1-\varphi_i)$$

3-point functions (check of symmetries)

First non-trivial check of consistency with symmetries of dual Galilean CFT

Check of 2-point functions works nicely with shortcut; 3-point too?

- Yes: same procedure, but localize chemical potentials at two points

$$\mu_{M/L}(u_1,\,\varphi_1)=\sum_{i=2}^{3}\epsilon^i_{M/L}\,\delta^{(2)}(u_1-u_i,\,\varphi_1-\varphi_i)$$

- Iteratively solve EOM

$$\partial_u M=-k\partial_\varphi^3\mu_L+\mu_L\partial_\varphi M+2M\partial_\varphi\mu_L$$

$$\partial_u N=-k\partial_\varphi^3\mu_M+(1+\mu_M)\partial_\varphi M+2M\partial_\varphi\mu_M+\mu_L\partial_\varphi N+2N\partial_\varphi\mu_L$$

3-point functions (check of symmetries)

First non-trivial check of consistency with symmetries of dual Galilean CFT

Check of 2-point functions works nicely with shortcut; 3-point too?

- Yes: same procedure, but localize chemical potentials at two points

$$\mu_{M/L}(u_1,\,\varphi_1)=\sum_{i=2}^{3}\epsilon^i_{M/L}\,\delta^{(2)}(u_1-u_i,\,\varphi_1-\varphi_i)$$

- Iteratively solve EOM

$$\partial_u M=-k\partial_\varphi^3\mu_L+\mu_L\partial_\varphi M+2M\partial_\varphi\mu_L$$

$$\partial_u N=-k\partial_\varphi^3\mu_M+(1+\mu_M)\partial_\varphi M+2M\partial_\varphi\mu_M+\mu_L\partial_\varphi N+2N\partial_\varphi\mu_L$$

- Result on gravity side matches precisely Galilean CFT results

$$\langle M^1\,N^2\,N^3\rangle=\frac{c_M}{s_{12}^2s_{13}^2s_{23}^2}\qquad\langle N^1\,N^2\,N^3\rangle=\frac{c_L-c_M\,\tau_{123}}{s_{12}^2s_{13}^2s_{23}^2}$$

provided we choose again the Einstein values $c_L=0$ and $c_M=12k$

4-point functions (enter cross-ratios)

First correlators with non-universal function of cross-ratios

- Repeat this algorithm, localizing the sources at three points

4-point functions (enter cross-ratios)

First correlators with non-universal function of cross-ratios

- Repeat this algorithm, localizing the sources at three points
- Derive 4-point functions for Galilean CFTs (Bagchi, DG, Merbis '15)

$$\langle M^1\, N^2\, N^3\, N^4\rangle = \frac{2c_M\, g_4(\gamma)}{s_{14}^2 s_{23}^2 s_{12} s_{13} s_{24} s_{34}}$$

$$\langle N^1\, N^2\, N^3\, N^4\rangle = \frac{2c_L\, g_4(\gamma) + c_M \Delta_4}{s_{14}^2 s_{23}^2 s_{12} s_{13} s_{24} s_{34}}$$

with the cross-ratio function

$$g_4(\gamma) = \frac{\gamma^2 - \gamma + 1}{\gamma} \qquad \gamma = \frac{s_{12}\, s_{34}}{s_{13}\, s_{24}}$$

and

$$\Delta_4 = 4g_4'(\gamma)\eta_{1234} - (\tau_{1234} + \tau_{14} + \tau_{23})g_4(\gamma)$$

$$\eta_{1234} = \sum (-1)^{1+i-j}(u_i - u_j)\sin(\varphi_k - \varphi_l)/(s_{13}^2 s_{24}^2)$$

4-point functions (enter cross-ratios)

First correlators with non-universal function of cross-ratios

- Repeat this algorithm, localizing the sources at three points
- Derive 4-point functions for Galilean CFTs (Bagchi, DG, Merbis '15)

$$\langle M^1\, N^2\, N^3\, N^4\rangle = \frac{2c_M\, g_4(\gamma)}{s_{14}^2 s_{23}^2 s_{12} s_{13} s_{24} s_{34}}$$

$$\langle N^1\, N^2\, N^3\, N^4\rangle = \frac{2c_L\, g_4(\gamma) + c_M \Delta_4}{s_{14}^2 s_{23}^2 s_{12} s_{13} s_{24} s_{34}}$$

with the cross-ratio function

$$g_4(\gamma) = \frac{\gamma^2 - \gamma + 1}{\gamma} \qquad \gamma = \frac{s_{12}\, s_{34}}{s_{13}\, s_{24}}$$

and

$$\Delta_4 = 4g_4'(\gamma)\eta_{1234} - (\tau_{1234} + \tau_{14} + \tau_{23}) g_4(\gamma)$$

$$\eta_{1234} = \sum (-1)^{1+i-j} (u_i - u_j) \sin(\varphi_k - \varphi_l)/(s_{13}^2 s_{24}^2)$$

- Gravity side yields precisely the same result!

5-point functions (further check of consistency of flat space holography)

Last new explicit correlators I am showing to you today (I promise)

- Repeat this algorithm, localizing the sources at four points

5-point functions (further check of consistency of flat space holography)

Last new explicit correlators I am showing to you today (I promise)

- Repeat this algorithm, localizing the sources at four points
- Derive 5-point functions for Galilean CFTs (Bagchi, DG, Merbis '15)

$$\langle M^1\, N^2\, N^3\, N^4\, N^5\rangle = \frac{4c_M\, g_5(\gamma,\,\zeta)}{\prod_{1\le i<j\le 5} s_{ij}}$$

$$\langle N^1\, N^2\, N^3\, N^4\, N^5\rangle = \frac{4c_L\, g_5(\gamma,\,\zeta) + c_M \Delta_5}{\prod_{1\le i<j\le 5} s_{ij}}$$

with the previous definitions and ($\zeta = \frac{s_{25}\, s_{34}}{s_{35}\, s_{24}}$)

$$g_5(\gamma,\,\zeta) = \frac{\gamma+\zeta}{2(\gamma-\zeta)} - \frac{(\gamma^2-\gamma\zeta+\zeta^2)}{\gamma(\gamma-1)\zeta(\zeta-1)(\gamma-\zeta)} \times \big([\gamma(\gamma-1)+1][\zeta(\zeta-1)+1]-\gamma\zeta\big)$$

$$\Delta_5 = 4\partial_\gamma g_5(\gamma,\zeta)\eta_{1234} + 4\partial_\zeta g_5(\gamma,\zeta)\eta_{2345} - 2g_5(\gamma,\zeta)\tau_{12345}$$

5-point functions (further check of consistency of flat space holography)

Last new explicit correlators I am showing to you today (I promise)

- Repeat this algorithm, localizing the sources at four points
- Derive 5-point functions for Galilean CFTs (Bagchi, DG, Merbis '15)

$$\langle M^1\, N^2\, N^3\, N^4\, N^5\rangle = \frac{4c_M\, g_5(\gamma,\,\zeta)}{\prod_{1\leq i<j\leq 5} s_{ij}}$$

$$\langle N^1\, N^2\, N^3\, N^4\, N^5\rangle = \frac{4c_L\, g_5(\gamma,\,\zeta) + c_M \Delta_5}{\prod_{1\leq i<j\leq 5} s_{ij}}$$

with the previous definitions and ($\zeta = \frac{s_{25}\, s_{34}}{s_{35}\, s_{24}}$)

$$g_5(\gamma,\,\zeta) = \frac{\gamma+\zeta}{2(\gamma-\zeta)} - \frac{(\gamma^2-\gamma\zeta+\zeta^2)}{\gamma(\gamma-1)\zeta(\zeta-1)(\gamma-\zeta)} \times \big([\gamma(\gamma-1)+1][\zeta(\zeta-1)+1]-\gamma\zeta\big)$$

$$\Delta_5 = 4\partial_\gamma g_5(\gamma,\zeta)\eta_{1234} + 4\partial_\zeta g_5(\gamma,\zeta)\eta_{2345} - 2g_5(\gamma,\zeta)\tau_{12345}$$

- Gravity side yields precisely the same result!

n-point functions (holographic Ward identities and recursion relations)

Shortcut to 42 (Bagchi, DG, Merbis '15)

Smart check of all n-point functions?

- Idea: calculate n-point function from $(n-1)$-point function

n-point functions (holographic Ward identities and recursion relations)

Shortcut to 42 (Bagchi, DG, Merbis '15)

Smart check of all n-point functions?

- Idea: calculate n-point function from $(n-1)$-point function
- Need Galilean CFT analogue of BPZ-recursion relation

$$\langle T^1\, T^2 \dots T^n \rangle = \sum_{i=2}^{n} \left(\frac{2}{s_{1i}^2} + \frac{c_{1i}}{2}\, \partial_{\varphi_i} \right) \langle T^2 \dots T^n \rangle + \text{disconnected}$$

n-point functions (holographic Ward identities and recursion relations)

Shortcut to 42 (Bagchi, DG, Merbis '15)

Smart check of all n-point functions?

- Idea: calculate n-point function from $(n-1)$-point function
- Need Galilean CFT analogue of BPZ-recursion relation

$$\langle T^1 \, T^2 \dots T^n \rangle = \sum_{i=2}^{n} \left(\frac{2}{s_{1i}^2} + \frac{c_{1i}}{2} \, \partial_{\varphi_i} \right) \langle T^2 \dots T^n \rangle + \text{disconnected}$$

- After small derivation we find ($c_{ij} := \cot[(\varphi_i - \varphi_j)/2]$)

$$\langle M^1 \, N^2 \dots N^n \rangle = \sum_{i=2}^{n} \left(\frac{2}{s_{1i}^2} + \frac{c_{1i}}{2} \partial_{\varphi_i} \right) \langle M^2 \, N^3 \dots N^n \rangle + \text{disconnected}$$

$$\langle N^1 N^2 \dots N^n \rangle = \frac{c_L}{c_M} \langle M^1 N^2 \dots N^n \rangle + \sum_{i=1}^{n} u_i \partial_{\varphi_i} \langle M^1 N^2 \dots N^n \rangle$$

n-point functions (holographic Ward identities and recursion relations)

Shortcut to 42 (Bagchi, DG, Merbis '15)

Smart check of all n-point functions?

- Idea: calculate n-point function from $(n-1)$-point function
- Need Galilean CFT analogue of BPZ-recursion relation

$$\langle T^1\, T^2 \dots T^n \rangle = \sum_{i=2}^{n} \Big(\frac{2}{s_{1i}^2} + \frac{c_{1i}}{2}\, \partial_{\varphi_i} \Big) \langle T^2 \dots T^n \rangle + \text{disconnected}$$

- After small derivation we find ($c_{ij} := \cot[(\varphi_i - \varphi_j)/2]$)

$$\langle M^1\, N^2 \dots N^n \rangle = \sum_{i=2}^{n} \Big(\frac{2}{s_{1i}^2} + \frac{c_{1i}}{2} \partial_{\varphi_i} \Big) \langle M^2\, N^3 \dots N^n \rangle + \text{disconnected}$$

$$\langle N^1 N^2 \dots N^n \rangle = \frac{c_L}{c_M} \langle M^1 N^2 \dots N^n \rangle + \sum_{i=1}^{n} u_i \partial_{\varphi_i} \langle M^1 N^2 \dots N^n \rangle$$

- We can also derive same recursion relations on gravity side!

n-point functions in flat space holography

Summary

- EH action has variational principle consistent with flat space bc's (iff we add half the GHY term!)

n-point functions in flat space holography
Summary

- EH action has variational principle consistent with flat space bc's (iff we add half the GHY term!)
- 0-point function shows phase transition exists between hot flat space and flat space cosmologies

n-point functions in flat space holography
Summary

- EH action has variational principle consistent with flat space bc's (iff we add half the GHY term!)
- 0-point function shows phase transition exists between hot flat space and flat space cosmologies
- 1-point functions show consistency with canonical charges and lead to first entries in holographic dictionary

n-point functions in flat space holography
Summary

- EH action has variational principle consistent with flat space bc's (iff we add half the GHY term!)
- 0-point function shows phase transition exists between hot flat space and flat space cosmologies
- 1-point functions show consistency with canonical charges and lead to first entries in holographic dictionary
- 2-point functions consistent with Galilean CFT for $c_L = 0$, $c_M = 12k = 3/G_N$

n-point functions in flat space holography
Summary

- EH action has variational principle consistent with flat space bc's (iff we add half the GHY term!)
- 0-point function shows phase transition exists between hot flat space and flat space cosmologies
- 1-point functions show consistency with canonical charges and lead to first entries in holographic dictionary
- 2-point functions consistent with Galilean CFT for $c_L = 0$, $c_M = 12k = 3/G_N$
- 42^{nd} variation of EH action leads to 42-point Galilean CFT correlators

n-point functions in flat space holography
Summary

- EH action has variational principle consistent with flat space bc's (iff we add half the GHY term!)
- 0-point function shows phase transition exists between hot flat space and flat space cosmologies
- 1-point functions show consistency with canonical charges and lead to first entries in holographic dictionary
- 2-point functions consistent with Galilean CFT for $c_L = 0$, $c_M = 12k = 3/G_N$
- 42$^{\text{nd}}$ variation of EH action leads to 42-point Galilean CFT correlators
- all n-point correlators of Galilean CFT reproduced precisely on gravity side (recursion relations!)

- EH action has variational principle consistent with flat space bc's (iff we add half the GHY term!)
- 0-point function shows phase transition exists between hot flat space and flat space cosmologies
- 1-point functions show consistency with canonical charges and lead to first entries in holographic dictionary
- 2-point functions consistent with Galilean CFT for $c_L = 0$, $c_M = 12k = 3/G_N$
- 42^{nd} variation of EH action leads to 42-point Galilean CFT correlators
- all n-point correlators of Galilean CFT reproduced precisely on gravity side (recursion relations!)

Fairly non-trivial check that 3D flat space holography can work!

Other selected recent results

Some further checks that dual field theory is Galilean CFT:

Other selected recent results

Some further checks that dual field theory is Galilean CFT:

- Microstate counting?

Other selected recent results

Some further checks that dual field theory is Galilean CFT:

- Microstate counting?

  Works! (Bagchi, Detournay, Fareghbal, Simon '13, Barnich '13)

$$S_{\text{gravity}} = S_{\text{BH}} = \frac{\text{Area}}{4G_N} = 2\pi h_L \sqrt{\frac{c_M}{2h_M}} = S_{\text{GCFT}}$$

  Also as limit from Cardy formula (Riegler '14, Fareghbal, Naseh '14)

Other selected recent results

Some further checks that dual field theory is Galilean CFT:

- Microstate counting?

  Works! (Bagchi, Detournay, Fareghbal, Simon '13, Barnich '13)

$$S_{\text{gravity}} = S_{\text{BH}} = \frac{\text{Area}}{4G_N} = 2\pi h_L \sqrt{\frac{c_M}{2h_M}} = S_{\text{GCFT}}$$

  Also as limit from Cardy formula (Riegler '14, Fareghbal, Naseh '14)
- (Holographic) entanglement entropy?

Other selected recent results

Some further checks that dual field theory is Galilean CFT:

- Microstate counting?

  Works! (Bagchi, Detournay, Fareghbal, Simon '13, Barnich '13)

  $$S_{\text{gravity}} = S_{\text{BH}} = \frac{\text{Area}}{4G_N} = 2\pi h_L \sqrt{\frac{c_M}{2h_M}} = S_{\text{GCFT}}$$

  Also as limit from Cardy formula (Riegler '14, Fareghbal, Naseh '14)

- (Holographic) entanglement entropy?

  Works! (Bagchi, Basu, DG, Riegler '14)

  $$S_{\text{EE}}^{\text{GCFT}} = \underbrace{\frac{c_L}{6}\,\ln\frac{\ell_x}{a}}_{\text{like CFT}} + \underbrace{\frac{c_M}{6}\,\frac{\ell_y}{\ell_x}}_{\text{like grav anomaly}}$$

  Calculation on gravity side confirms result above (using Wilson lines in CS formulation)

Outline

Recent generalizations:

- adding chemical potentials

  Works! (Gary, DG, Riegler, Rosseel '14)

  In CS formulation:

$$A_0 \to A_0 + \mu$$

  See also talk by Mirah Gary two days ago (Junior plenary session)

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)

  Conformal CS gravity at level $k = 1$ with flat space boundary conditions conjectured to be dual to chiral half of monster CFT. Action (gravity side):

  $$I_{\rm CSG} = \frac{k}{4\pi} \int \mathrm{d}^3x \sqrt{-g}\, \varepsilon^{\lambda\mu\nu}\, \Gamma^\rho{}_{\lambda\sigma} \big(\partial_\mu \Gamma^\sigma{}_{\nu\rho} + \frac{2}{3}\, \Gamma^\sigma{}_{\mu\tau} \Gamma^\tau{}_{\nu\rho}\big)$$

  Partition function (field theory side, see Witten '07):

  $$Z(q) = J(q) = \frac{1}{q} + 196884\, q + \mathcal{O}(q^2)$$

  Note: $\ln 196883 \approx 12.2 = 4\pi +$quantum corrections

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity

  Works! (Barnich, Donnay, Matulich, Troncoso '14)

  Asymptotic symmetry algebra = super-BMS_3

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity
- flat space higher spin gravity

Remarkably it exists! (Afshar, Bagchi, Fareghbal, DG, Rosseel '13; Gonzalez, Matulich, Pino, Troncoso '13)

New type of algebra: W-like BMS ("BMW")

$$[U_n,\,U_m] = (n-m)(2n^2+2m^2-nm-8)L_{n+m} + \frac{192}{c_M}(n-m)\Lambda_{n+m}$$

$$-\frac{96\big(c_L+\frac{44}{5}\big)}{c_M^2}(n-m)\Theta_{n+m} + \frac{c_L}{12}\,n(n^2-1)(n^2-4)\,\delta_{n+m,\,0}$$

$$[U_n,\,V_m] = (n-m)(2n^2+2m^2-nm-8)M_{n+m} + \frac{96}{c_M}(n-m)\Theta_{n+m}$$

$$+\frac{c_M}{12}\,n(n^2-1)(n^2-4)\,\delta_{n+m,\,0}$$

$[L,L]$, $[L,M]$, $[M,M]$ as in BMS_3 $\qquad$ $[L,U]$, $[L,V]$, $[M,U]$, $[M,V]$ as in isl(3)

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity
- flat space higher spin gravity

Some open issues:

- Further checks in 3D (n-point correlators, partition function, ...)

  Barnich, Gonzalez, Maloney, Oblak '15: 1-loop partition function matches BMS_3 character

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity
- flat space higher spin gravity

Some open issues:

- Further checks in 3D (n-point correlators, partition function, ...)
- Further generalizations in 3D (massive gravity, adding matter, ...)

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity
- flat space higher spin gravity

Some open issues:

- Further checks in 3D (n-point correlators, partition function, ...)
- Further generalizations in 3D (massive gravity, adding matter, ...)
- Generalization to 4D? (Barnich et al, Strominger et al)

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity
- flat space higher spin gravity

Some open issues:

- Further checks in 3D (n-point correlators, partition function, ...)
- Further generalizations in 3D (massive gravity, adding matter, ...)
- Generalization to 4D? (Barnich et al, Strominger et al)
- Flat space limit of usual $\mathrm{AdS}_5/\mathrm{CFT}_4$ correspondence?

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity
- flat space higher spin gravity

Some open issues:

- Further checks in 3D (n-point correlators, partition function, ...)
- Further generalizations in 3D (massive gravity, adding matter, ...)
- Generalization to 4D? (Barnich et al, Strominger et al)
- Flat space limit of usual $\text{AdS}_5/\text{CFT}_4$ correspondence?

> - holography seems to work in flat space

Generalizations & open issues

Recent generalizations:

- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity
- flat space higher spin gravity

Some open issues:

- Further checks in 3D (n-point correlators, partition function, ...)
- Further generalizations in 3D (massive gravity, adding matter, ...)
- Generalization to 4D? (Barnich et al, Strominger et al)
- Flat space limit of usual $\text{AdS}_5/\text{CFT}_4$ correspondence?

> - holography seems to work in flat space
> - holography more general than AdS/CFT

Generalizations & open issues

Recent generalizations:

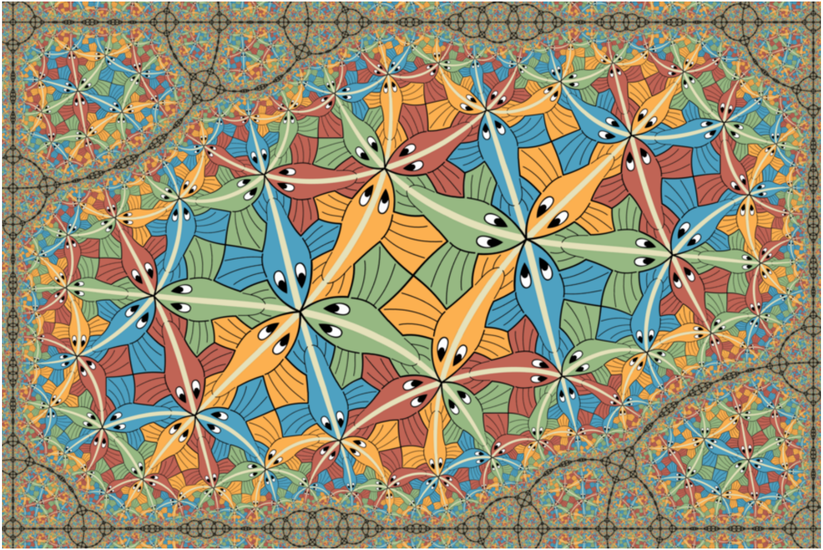
- adding chemical potentials
- 3-derivative theory: flat space chiral gravity (Bagchi, Detournay, DG '12)
- generalization to supergravity
- flat space higher spin gravity

Some open issues:

- Further checks in 3D (n-point correlators, partition function, ...)
- Further generalizations in 3D (massive gravity, adding matter, ...)
- Generalization to 4D? (Barnich et al, Strominger et al)
- Flat space limit of usual $\text{AdS}_5/\text{CFT}_4$ correspondence?

> - holography seems to work in flat space
> - holography more general than AdS/CFT
> - (when) does it work even more generally?

Thanks for your attention!



Vladimir Bulatov, M.C.Escher Circle Limit III in a rectangle