Flat space higher spin holography

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COST Workshop "The String Theory Universe"
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FWF based on work with Afshar, Bagchi, Detournay, Fareghbal, Gary, Rey, Riegler, Rosseel, Salzer, Schöller, Simon, ...

Outline

Motivation (how general is holography?)

Simplification (3D)

Generalization (higher derivatives or spins)

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Motivation
How general is holography?

- Holographic principle, if correct, must work beyond AdS/CFT
  holographic principle: 't Hooft '93; Susskind '94

  AdS/CFT precursor: Brown, Henneaux '86
  AdS/CFT: Maldacena '97; Gubser, Klebanov, Polyakov '98; Witten '98

  non-unitary holography:
  AdS/log CFT '08-'13: review: DG, Riedler, Rosseel, Zojer '13
  Vafa '14

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- Does it work in flat space?
  Polchinski '99
  Susskind '99
  Giddings '00
  Gary, Giddings, Penedones '09; Gary, Giddings '09; ...

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- Holographic principle, if correct, must work beyond AdS/CFT
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- Can we find models realizing flat space/field theory correspondences?

  Barnich, Compere '06

  Barnich et al. '10-'14

  Bagchi et al. '10-'14

  Strominger et al. '13-'14

  ...

  flat space chiral gravity: Bagchi, Detournay, DG '12

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- Are there higher-spin versions of such models?
  Afshar, Bagchi, Fareghbal, DG, Rosseel '13
  Gonzalez, Matulich, Pino, Troncoso '13

  part of larger program: non-AdS holography in higher spin gravity
  Gary, DG, Rashkov '12
  Afshar, Gary, DG, Rashkov, Riegler '12
  Gutperle, Hijano, Samani '13
  Gary, DG, Prohazka, Rey '14

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  some aspects: yes; other aspects: no
  cannot just take the naive $\Lambda \to 0$ limit of 10^4 papers on AdS/CFT...

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- Relation between S-matrix and holographic observables?
  Strominger et al '13, '14

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Many interesting open issues in flat space holography!

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Address these issues in 3D!

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"Gravity 3D is a spellbinding experience"

… so let us consider 3D gravity!

Some properties of 3D gravity
AdS_3 gravity

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> Flat space analogues of these features?
> Does naive $\Lambda \to 0$ limit work?

Flat space limit
Example 1: Limit of geometries

Global AdS metric ($\varphi \sim \varphi + 2\pi$):

$$\mathrm{d}s^2_{\mathrm{AdS}} = \mathrm{d}(\ell\rho)^2 - \cosh^2\big(\tfrac{\ell\rho}{\ell}\big)\ \mathrm{d}t^2 + \ell^2 \sinh^2\big(\tfrac{\ell\rho}{\ell}\big)\ \mathrm{d}\varphi^2$$

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Limit $\ell \to \infty$ ($r = \ell\rho$):

$$\mathrm{d}s^2_{\text{Flat}} = \mathrm{d}r^2 - \mathrm{d}t^2 + r^2\ \mathrm{d}\varphi^2 = -\,\mathrm{d}u^2 - 2\,\mathrm{d}u\,\mathrm{d}r + r^2\ \mathrm{d}\varphi^2$$

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BTZ metric:

$$\mathrm{d}s^2_{\text{BTZ}} = -\frac{\big(\frac{r^2}{\ell^2} - \frac{r_+^2}{\ell^2}\big)(r^2 - r_-^2)}{r^2}\ \mathrm{d}t^2 + \frac{r^2\ \mathrm{d}r^2}{\big(\frac{r^2}{\ell^2} - \frac{r_+^2}{\ell^2}\big)(r^2 - r_-^2)} + r^2\ \Big(\mathrm{d}\varphi - \frac{\frac{r_+}{\ell}\, r_-}{r^2}\ \mathrm{d}t\Big)^2$$

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Limit $\ell \to \infty$ ($\hat{r}_+ = \frac{r_+}{\ell} = \text{finite}$):

$$\mathrm{d}s^2_{\text{FSC}} = \hat{r}_+^2\ \big(1 - \tfrac{r_-^2}{r^2}\big)\ \mathrm{d}t^2 - \frac{1}{1 - \frac{r_-^2}{r^2}}\ \frac{\mathrm{d}r^2}{\hat{r}_+^2} + r^2\ \Big(\mathrm{d}\varphi - \frac{\hat{r}_+\, r_-}{r^2}\ \mathrm{d}t\Big)^2$$

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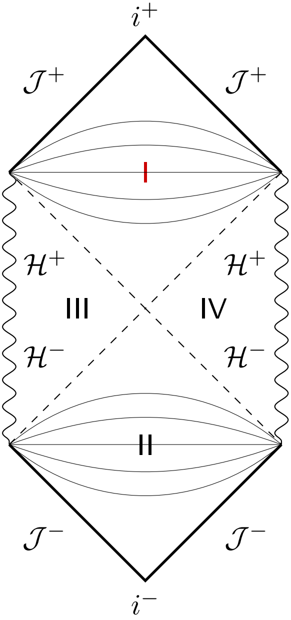
Shifted-boost orbifold studied by Cornalba & Costa more than decade ago
Describes expanding (contracting) Universe in flat space (horizon $r = r_-$)

FSC Penrose diagram (2D slice)



(graphics from Bagchi, DG, Salzer, Sarkar, Schöller '14)

- I: expanding cosmology
relevant patch for thermodynamics
- II: contracting cosmology
- III, IV: regions with access to singularity (wiggly line)

- i^+: future time-like infinity
- $\mathcal{J}^+$: future null infinity
- $\mathcal{H}^+$: horizon of expanding cosmology (dashed line)
- $\mathcal{H}^-$: horizon of contracting cosmology (dashed line)
- $\mathcal{J}^-$: past null infinity
- i^-: past time-like infinity

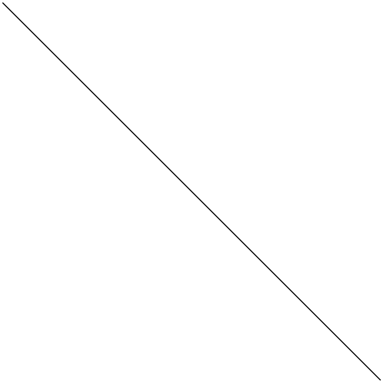
Flat space limit

Example 2: Limit of asymptotic boundaries (ultra-relativistic boost)

AdS-boundary:

Limit $\ell \to \infty$

Flat space boundary:



Null infinity holography!

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Example 3: Limit of asymptotic symmetries (Barnich, Compère '06)

- Take two copies of Virasoro, generators $\mathcal{L}_n$, $\bar{\mathcal{L}}_n$, central charges c, $\bar{c}$

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- Take two copies of Virasoro, generators $\mathcal{L}_n$, $\bar{\mathcal{L}}_n$, central charges c, $\bar{c}$
- Define superrotations L_n and supertranslations M_n

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

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- Make ultrarelativistic boost, $\ell \to \infty$ (İnönü–Wigner contraction)

$$[L_n,\, L_m] = (n-m)\, L_{n+m} + c_L\, \frac{1}{12}\left(n^3 - n\right)\delta_{n+m,\,0}$$
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- Is precisely the (centrally extended) BMS_3 algebra!
- Central charges:

$$c_L = c - \bar{c} \qquad c_M = (c + \bar{c})/\ell$$

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- $\text{BMS}_3 = \text{GCA}_2 = \text{URCA}_2$ Bagchi, Gopakumar '09, Bagchi '10

Chern–Simons formulation of AdS gravity

CS with weird boundary conditions (Achucarro & Townsend '86; Witten '88; Bañados '96)

- CS action:

$$S_{\rm CS} = \frac{k}{4\pi}\int {\rm CS}(A) - \frac{k}{4\pi}\int {\rm CS}(\bar A)$$

with

$${\rm CS}(A) = \langle A\wedge {\rm d}A + \tfrac{2}{3}\, A\wedge A\wedge A\rangle$$

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$$A(\rho,\, x^{\pm}) = b^{-1}(\rho) \big(\mathrm{d} + a(x^{\pm}) + o(1) \big)\, b(\rho)$$

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- Virasoro charges and algebra:

$$Q[\varepsilon]\sim\oint\varepsilon(x^+)\mathcal{L}(x^+) \qquad \delta_\varepsilon\mathcal{L} = \mathcal{L}'\,\varepsilon + 2\mathcal{L}\,\varepsilon' + \frac{c}{12}\,\varepsilon'''$$

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Barnich, Gonzalez '13, Afshar '13, Riegler '15 (part of PhD thesis)

- CS action:

$$S_{\text{CS}} = \frac{k}{4\pi} \int \text{CS}(\mathcal{A})$$

with iso$(2,1)$ connection

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

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Chern–Simons formulation of flat space gravity

Barnich, Gonzalez '13, Afshar '13, Riegler '15 (part of PhD thesis)

- CS action:

$$S_{\text{CS}} = \frac{k}{4\pi} \int \text{CS}(\mathcal{A})$$

with $\text{iso}(2,1)$ connection

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

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- BMS charges and BMS/GCA algebra:

$$Q[\varepsilon_M,\, \varepsilon_L] \sim \oint \big(\varepsilon_M(\varphi) M(\varphi) + \varepsilon_L(\varphi) L(\varphi)\big)$$

$$\delta_{\varepsilon_L} L = L'\, \varepsilon_L + 2L\, \varepsilon_L' + \tfrac{c_L}{12}\, \varepsilon_L''' \quad \delta_{\varepsilon_L} M = M'\, \varepsilon_L + 2M\, \varepsilon_L' + \tfrac{c_M}{12}\, \varepsilon_L''' \quad \delta_{\varepsilon_M} M = 0$$

Flat space cosmologies

Graphics by Barnich, Gomberoff, Gonzalez '12

- Physical states characterized by two functions $\mathcal{M}(\varphi)$ and $\mathcal{L}(\varphi)$

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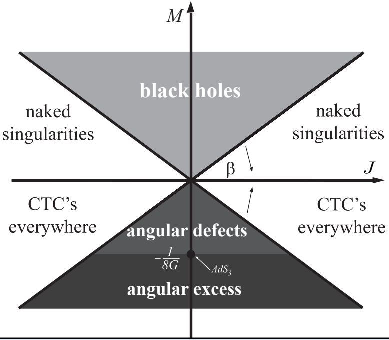

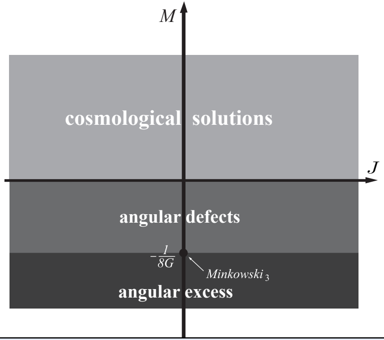

Microstate counting

Cardy-like formula?

- Direct calculation of Cardy-like formula in GCA_2 with $c_L = 0$ (Bagchi, Detournay, Simón '12, Barnich '12)

$$S_{\text{GCA}} = \pi h_L \sqrt{\frac{c_M}{6h_M}}$$

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$$S_{\text{macro}} = S_{\text{A}_{\text{int}}} = \frac{A_{\text{int}}}{4G} = 2\pi\sqrt{\frac{ch}{6}} - 2\pi\sqrt{\frac{\bar{c}\bar{h}}{6}} = S_{\text{inner}} = S_{\text{micro}}$$

Note the unusual sign between the two terms!

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- Einstein gravity: $c_L = 0$ reproduces correct formula for S_{GCA} of Bagchi, Detournay, Simón '12, Barnich '12

Phase transitions

Statement of main result

Hot flat space $(\varphi \sim \varphi + 2\pi)$

$$\mathrm{d}s^2 = \pm\,\mathrm{d}t^2 + \mathrm{d}r^2 + r^2\,\mathrm{d}\varphi^2$$

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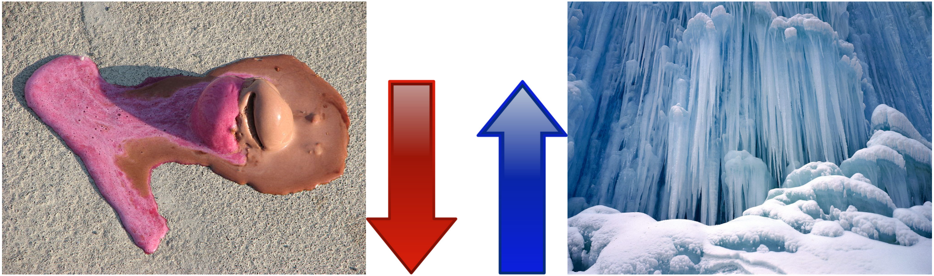

$$\mathrm{d}s^2 = \pm\,\mathrm{d}\tau^2 + \frac{(E\tau)^2\ \mathrm{d}x^2}{1+(E\tau)^2} + \big(1+(E\tau)^2\big)\Big(\mathrm{d}y + \frac{(E\tau)^2}{1+(E\tau)^2}\ \mathrm{d}x\Big)^2$$

Flat space cosmology $(y \sim y + 2\pi r_0)$

Bagchi, Detournay, Grumiller, Simón '13

Phase transitions

Derivation from Euclidean path integral

- Evaluate Euclidean partition function in semi-classical limit

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

boundary conditions specify temperature T, angular velocity Ω

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For this to work need full action Γ!

Towards a holographic dictionary

0-point function (Detournay, DG, Schöller, Simón '14)

- Full (holographically renormalized) action:

$$\Gamma = -\frac{1}{16\pi G}\int_M \mathrm{d}^3x\sqrt{g}\,R - \frac{1}{16\pi G}\int_{\partial M}\mathrm{d}^2x\sqrt{\gamma}\,K$$

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- Phase transition at self-dual point $(r_+ = 1)$:

$$2\pi\,T_c = \Omega \qquad T > T_c : \text{FSC stable} \quad T < T_c : \text{HFS stable}$$

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- M and J coincide precisely with zero-point canonical charges!

Outline

Motivation (how general is holography?)

Simplification (3D)

Generalization (higher derivatives or spins)

Flat space chiral gravity

Bagchi, Detournay, DG '12

Conjecture:

Conformal Chern–Simons gravity at level $k = 1 \simeq$ chiral extremal CFT with central charge $c = 24$

$$I_{CSG} = \frac{k}{4\pi} \int \left(\Gamma \wedge \mathrm{d}\Gamma + \tfrac{2}{3}\Gamma \wedge \Gamma \wedge \Gamma\right) + \text{flat space bc's}$$

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Missing: full partition function on gravity side

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

Flat space higher spin gravity

Afshar, Bagchi, Fareghbal, DG, Rosseel '13, Gonzalez, Matulich, Pino, Troncoso '13

- AdS gravity in CS formulation: spin 2 $\to$ spin 3 $\sim$ sl$(2) \to$ sl(3)

Flat space higher spin gravity

Afshar, Bagchi, Fareghbal, DG, Rosseel '13, Gonzalez, Matulich, Pino, Troncoso '13

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$$S_{\text{CS}}^{\text{flat}} = \frac{k}{4\pi} \int \text{CS}(\mathcal{A})$$

with isl(3) connection ($e^a =$ "zuvielbein")

$$\mathcal{A} = e^a T_a + \omega^a J_a \qquad T_a = (M_n,\, V_m) \quad J_a = (L_n,\, U_m)$$

isl(3) algebra (spin 3 extension of global part of BMS/GCA algebra)

$$[L_n,\, L_m] = (n-m)L_{n+m}$$
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- Spin 3 charges:

$$Q[\varepsilon_M,\, \varepsilon_L,\, \varepsilon_V,\, \varepsilon_U] \sim \oint \left(\varepsilon_M(\varphi) M(\varphi) + \varepsilon_L(\varphi) L(\varphi) + \varepsilon_V(\varphi) V(\varphi) + \varepsilon_U(\varphi) U(\varphi)\right)$$

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Asymptotic symmetry algebra at finite level k Afshar, Bagchi, Fareghbal, DG, Rosseel '13

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$$\Lambda_n = \sum_p :L_p\,M_{n-p}: \, - \tfrac{3}{10}\,(n+2)(n+3)M_n \qquad \Theta_n = \sum_p M_p\,M_{n-p}$$

other commutators as in isl(3) with $n \in \mathbb{Z}$

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- Note quantum shift and poles in central terms!
- Analysis generalizes to flat space contractions of other W-algebras

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Unitarity leads to further contraction DG, Riegler, Rosseel '14

Facts:

- Unitarity in GCA requires $c_M = 0$ (see paper for caveats!)

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Higher spin states decouple and become null states!

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Generic flat space W-algebras DG, Riegler, Rosseel '14

1. NO–GO:

Generically (see paper) you can have only two out of three:

- Unitarity
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Example:

Flat space chiral gravity

Bagchi, Detournay, DG, 1208.1658

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Minimal model holography

Gaberdiel, Gopakumar, 1011.2986, 1207.6697

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Flat space higher spin gravity (Galilean W_3 algebra)

Afshar, Bagchi, Fareghbal, DG and Rosseel, 1307.4768

Gonzalez, Matulich, Pino and Troncoso, 1307.5651

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2. YES–GO:

There is (at least) one counter-example, namely a Vasiliev-type of theory, where you can have all three properties!

> Unitary, non-trivial flat space higher spin algebra exists!
> Vasiliev-type flat space chiral higher spin gravity?

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Flat space W_∞-algebra compatible with unitarity DG, Riegler, Rosseel '14

- We do not know if flat space chiral higher spin gravity exists...

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- ...but its existence is at least not ruled out by the no-go result!
- If it exists, this must be its asymptotic symmetry algebra:

$$[\mathcal{V}^i_m, \mathcal{V}^j_n] = \sum_{r=0}^{\lfloor \frac{i+j}{2} \rfloor} g^{ij}_{2r}(m,n)\, \mathcal{V}^{i+j-2r}_{m+n} + c^i_{\mathcal{V}}(m)\, \delta^{ij}\, \delta_{m+n,0}$$

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where

$$c^i_{\mathcal{V}}(m) = \#(i,\, m) \times c \qquad \text{and} \qquad c = -\bar{c}$$

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- Vacuum descendants $\mathcal{W}^i_m|0\rangle$ are null states for all i and m!
- AdS parent theory: no trace anomaly, but gravitational anomaly (Like in conformal Chern–Simons gravity $\to$ Vasiliev type analogue?)

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- holographic entanglement entropy in flat space (higher spin) gravity
- ...

- Long way to go before fully understanding flat space holography
- Part of the path now seems clear and may lead to new insights
- Other parts probably will require novel techniques

Selected references

Thanks for your attention!

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