3D quantum gravity, logarithmic CFT and its chiral truncation

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Outline

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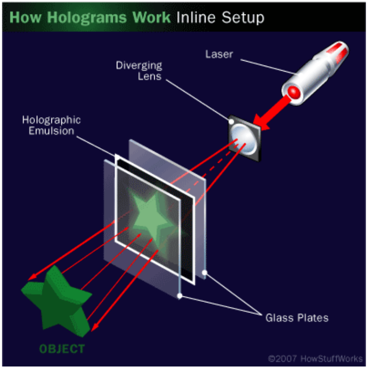
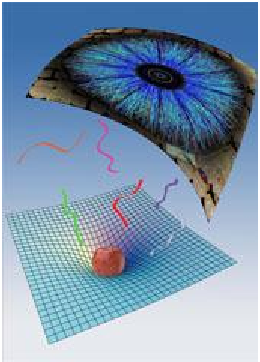
Holography – Main Idea

aka gauge/gravity duality, aka AdS/CFT correspondence





One of the most fruitful ideas in contemporary theoretical physics:

- The number of dimensions is a matter of perspective
- We can choose to describe the same physical situation using two different formulations in two different dimensions
- The formulation in higher dimensions is a theory with gravity
- The formulation in lower dimensions is a theory without gravity

Why Gravity?

The holographic principle in black hole physics

Boltzmann/Planck: entropy of photon gas in d spatial dimensions

$$S_{\text{gauge}} \propto \text{volume} \propto L^d$$

Bekenstein/Hawking: entropy of black hole in d spatial dimensions

$$S_{\text{gravity}} \propto \text{area} \propto L^{d-1}$$

Daring idea by 't Hooft/Susskind in 1990ies:

> Any consistent quantum theory of gravity could/should have a holographic formulation in terms of a field theory in one dimension lower

Discovery by Maldacena 1997:

> Holographic principle is realized in string theory in specific way

$$\text{e.g.} \quad \langle T_{\mu\nu}\rangle_{\text{gauge}} = T^{BY}_{\mu\nu} \qquad \delta\text{action} = \int \mathrm{d}^d x \sqrt{|h|}\, T^{BY}_{\mu\nu}\, \delta h^{\mu\nu}$$

Why should I care?

...and why were there > 6300 papers on holography in the past 12 years?

- Many applications!
- Tool for calculations
- Strongly coupled gauge theories (difficult) mapped to semi-cassical gravity (simple)
- Quantum gravity (difficult) mapped to weakly coupled gauge theories (simple)
- Sometimes both limits accessible: integrability of $N = 4$ SYM
- Examples of first type: heavy ion collisions at RHIC and LHC, superfluidity, type II superconductors (?), cold atoms (?), ...
- Examples of the second type: microscopic understanding of black holes, information paradox, Kerr/CFT (?), 3D quantum gravity (?), ...

We can expect many new applications in the next decade!

Outline

Why gravity in three dimensions?

"As simple as possible, but not simpler"

Gravity simpler in lower dimensions

$11D$: 1144 Weyl, 66 Ricci, $5D$: 35 Weyl, 15 Ricci, $4D$: 10 Weyl, 10 Ricci
$3D$: no Weyl, 6 Ricci, $2D$: no Weyl, 1 Ricci

2D gravity: black holes!

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Applications:

- Solve conceptual problems of (quantum) gravity
- Approximate geometry of cosmic strings/particles confined in plane
- Holographic tool for 2D condensed matter systems

pioneering work by Deser, Jackiw and Templeton in 1980ies
2007 Witten rekindled interest in 3D gravity

Outline

Attempt 1: Einstein–Hilbert

As simple as possible... but not simpler!

Let us start with the simplest attempt. `Einstein-Hilbert` action:

$$I_{\mathrm{EH}} = \frac{1}{16\pi\, G} \int \mathrm{d}^3x\sqrt{-g}\, R$$

Equations of motion:

$$R_{\mu\nu} = 0$$

Ricci-flat and therefore Riemann-flat – locally trivial!

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Properties of `Einstein-Hilbert`

- No gravitons (recall: in D dimensions $D(D-3)/2$ gravitons)
- No BHs
- `Einstein-Hilbert` in 3D is too simple for us!

Attempt 2: Topologically massive gravity

Deser, Jackiw and Templeton found a way to introduce gravitons!

Let us now add a gravitational Chern–Simons term. TMG action:

$$I_{\rm TMG} = I_{\rm EH} + \frac{1}{16\pi\, G}\int \mathrm{d}^3x\sqrt{-g}\,\frac{1}{2\mu}\,\varepsilon^{\lambda\mu\nu}\,\Gamma^\rho{}_{\lambda\sigma}\big(\partial_\mu\Gamma^\sigma{}_{\nu\rho}+\frac{2}{3}\,\Gamma^\sigma{}_{\mu\tau}\Gamma^\tau{}_{\nu\rho}\big)$$

Equations of motion:

$$R_{\mu\nu}+\frac{1}{\mu}\,C_{\mu\nu}=0$$

with the Cotton tensor defined as

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Properties of TMG

- Gravitons! Reason: third derivatives in Cotton tensor!
- No BHs
- TMG is slightly too simple for us!

Attempt 3: Einstein–Hilbert–AdS

Bañados, Teitelboim and Zanelli (and Henneaux) taught us how to get 3D BHs

Add negative cosmological constant to Einstein-Hilbert action:

$$I_{\Lambda\mathrm{EH}} = \frac{1}{16\pi\, G}\int \mathrm{d}^3x\sqrt{-g}\,\big(R + \frac{2}{\ell^2}\big)$$

Equations of motion:

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}\,g_{\mu\nu}R - \frac{1}{\ell^2}\,g_{\mu\nu} = 0$$

Particular solutions: BTZ BH with line-element

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

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Properties of Einstein-Hilbert-AdS

- No gravitons
- Rotating BH solutions that asymptote to AdS_3!
- Adding a negative cosmological constant produces BH solutions!

Cosmological topologically massive gravity

CTMG is a 3D theory with BHs and gravitons!

We want a 3D theory with gravitons and BHs and therefore take CTMG action

$$I_{\mathrm{CTMG}} = \frac{1}{16\pi\, G} \int \mathrm{d}^3x\sqrt{-g}\,\Big[R + \frac{2}{\ell^2} + \frac{1}{2\mu}\,\varepsilon^{\lambda\mu\nu}\,\Gamma^\rho{}_{\lambda\sigma}\big(\partial_\mu\Gamma^\sigma{}_{\nu\rho} + \frac{2}{3}\,\Gamma^\sigma{}_{\mu\tau}\Gamma^\tau{}_{\nu\rho}\big)\Big]$$

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Properties of CTMG

- Gravitons!
- BHs!
- CTMG is just perfect for us. Study this theory!

Einstein sector of the classical theory

Solutions of Einstein's equations

$$G_{\mu\nu} = 0 \qquad \leftrightarrow \qquad R = -\frac{6}{\ell^2}$$

also have vanishing Cotton tensor

$$C_{\mu\nu} = 0$$

and therefore are solutions of CTMG.

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Line-element of pure AdS:

$$\mathrm{d}s^2_{\mathrm{AdS}} = \bar{g}_{\mu\nu}\,\mathrm{d}x^\mu\,\mathrm{d}x^\nu = \ell^2\big(-\cosh^2\rho\,\mathrm{d}\tau^2 + \sinh^2\rho\,\mathrm{d}\phi^2 + \mathrm{d}\rho^2\big)$$

Isometry group: $SL(2,\mathbb{R})_L \times SL(2,\mathbb{R})_R$
Useful to introduce light-cone coordinates $u = \tau + \phi$, $v = \tau - \phi$

Cotton sector of the classical theory

Solutions of CTMG with

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necessarily have also non-vanishing Cotton tensor

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Few exact solutions of this type are known.

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Perhaps most interesting solution:

- Warped AdS (stretched/squashed), see `Bengtsson & Sandin`

Line-element of space-like warped AdS:

$$\mathrm{d}s^2_{\text{warped AdS}} = \frac{\ell^2}{\nu^2+3}\Big(-\cosh^2\rho\,\mathrm{d}\tau^2 + \frac{4\nu^2}{\nu^2+3}\,(\mathrm{d}u + \sinh\rho\,\mathrm{d}\tau)^2 + \mathrm{d}\rho^2\Big)$$

Sidenote: null-warped AdS in holographic duals of cold atoms:

$$\mathrm{d}s^2_{\text{null warped AdS}} = \ell^2\Big(\frac{dy^2 + 2\,\mathrm{d}x^+\,\mathrm{d}x^-}{y^2} \pm \frac{(\mathrm{d}x^-)^2}{y^4}\Big)$$

CTMG at the chiral point

...abbreviated as CCTMG

Definition: CTMG at the chiral point is CTMG with the tuning

$$\mu\,\ell = 1$$

between the cosmological constant and the Chern–Simons coupling.

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Why special?
Calculating the central charges of the dual boundary CFT yields

$$c_L = \frac{3}{2G}\,\big(1 - \frac{1}{\mu\,\ell}\big)\,, \qquad c_R = \frac{3}{2G}\,\big(1 + \frac{1}{\mu\,\ell}\big)$$

Thus, at the chiral point we get

$$c_L = 0\,, \qquad c_R = \frac{3}{G}$$

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Notes:

- Abbreviate "CTMG at the chiral point" as CCTMG
- CCTMG sometimes called "chiral gravity" (misnomer!)

Gravitons around AdS_3 in CTMG

Linearization around AdS background

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

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leads to linearized EOM that are third order PDE

$$G^{(1)}_{\mu\nu} + \frac{1}{\mu}\,C^{(1)}_{\mu\nu} = (\mathcal{D}^R \mathcal{D}^L \mathcal{D}^M h)_{\mu\nu} = 0$$

with three mutually commuting first order operators

$$(\mathcal{D}^{L/R})_\mu{}^\nu = \delta^\nu_\mu \pm \ell\,\varepsilon_\mu{}^{\alpha\nu}\bar{\nabla}_\alpha\,, \qquad (\mathcal{D}^M)_\mu{}^\nu = \delta^\nu_\mu + \frac{1}{\mu}\varepsilon_\mu{}^{\alpha\nu}\bar{\nabla}_\alpha$$

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Three linearly independent solutions to linearized EOM:

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At chiral point left (L) and massive (M) branches coincide!

Degeneracy at the chiral point

`Li, Song & Strominger` found all regular nonrmalizable solutions of linearized EOM for $\mu\ell \neq 1$.

- Primaries: $L_0, \bar{L}_0$ eigenstates $\psi^{L/R/M}$ with

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- Linearized metric is then the real part of the wavefunction

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- At chiral point: L and M branches degenerate. Get new regular normalizable solution (Grumiller & Johansson)

$$\psi_{\mu\nu}^{\log} = \lim_{\mu\ell \to 1} \frac{\psi_{\mu\nu}^M(\mu\ell) - \psi_{\mu\nu}^L}{\mu\ell - 1}$$

with property

$$\big(\mathcal{D}^L \psi^{\log}\big)_{\mu\nu} = \big(\mathcal{D}^M \psi^{\log}\big)_{\mu\nu} \propto \psi^L\,, \qquad \big((\mathcal{D}^L)^2 \psi^{\log}\big)_{\mu\nu} = 0$$

Sign oder nicht sign?

That is the question. Choosing between Skylla and Charybdis.

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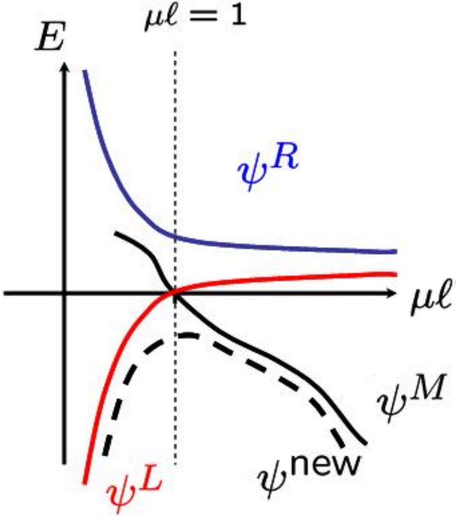
- Either way need a mechanism to eliminate unwanted negative energy objects – either the gravitons or the BHs
- Even at chiral point the problem persists because of the logarithmic mode. See Figure. (Figure: thanks to `N. Johansson`)

Energy for all branches:



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The LCFT conjecture

Observation:

$$L_0 \begin{pmatrix} \text{log} \\ \text{left} \end{pmatrix} = \begin{pmatrix} 2 & \frac{1}{2} \\ 0 & 2 \end{pmatrix} \begin{pmatrix} \text{log} \\ \text{left} \end{pmatrix},$$

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Such a Jordan form of $L_0, \bar{L}_0$ is defining property of a logarithmic CFT!
Logarithmic gravity conjecture (Grumiller & Johansson 2008):

> CFT dual to CTMG exists and is logarithmic

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> CFT dual to CTMG exists and is logarithmic

`Grumiller, Jackiw, Johansson, Henneaux, Maloney, Martinez, Song, Strominger, Troncoso, ... 2008/2009`:
Several non-trivial consistency checks that LCFT conjecture could be correct.

Towards a proof of the LCFT conjecture

Calculate correlators on the gravity side

If $AdS_3/LCFT_2$ works then the following algorithm must work:

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- Construct non-normalizable modes related to left-, right- and log-branches

$$\mathcal{D}^{L/R}\psi^{L/R} = 0 \qquad \psi^{L/R} \sim e^{2\rho}$$
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- Take the n-th variation of the full on-shell action

$$\delta S^{(2)}(\psi_1, \psi_2) = \text{boundary} \qquad \delta S^{(n)}(\psi_1, \psi_2, \ldots, \psi_n) = \text{bulk}$$

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- Insert above n non-normalizable modes as sources
- Compare with LCFT correlators, e.g.

$$\langle \mathcal{O}^L(z, \bar{z})\, \mathcal{O}^{\log}(0)\rangle = -\frac{b}{2\, z^4} + \dots$$

`Skenderis, Taylor & van Rees 2009`: $n = 2$
`Grumiller & Sachs 2009`: $n = 2, 3$

Non-normalizable modes

Constructed with `Ivo Sachs` in global coordinates:

Non-normalizable modes

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- Separation Ansatz with $SL(2,\mathbb{R})$ weights $h, \bar{h}$:

$$\psi_{\mu\nu} = e^{-ihu-i\bar{h}v}\, F_{\mu\nu}(\rho) \qquad \mathcal{D}^{L/R/M}\psi = 0$$

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- Non-normalizable: $(-1+n, -1-m)$ and $(-1-n, -1+m)$
- Exploit $SL(2,\mathbb{R})$ algebra to related modes of different weights:

$$\big[\mathcal{D}^{L/R}, L_\pm\big]\psi^L = \big[\mathcal{D}^{L/R}, \bar{L}_\pm\big]\psi^L = 0$$

$$\big[\big(\mathcal{D}^L\big)^2, L_\pm\big]\psi^{\log} = \big[\big(\mathcal{D}^L\big)^2, \bar{L}_\pm\big]\psi^{\log} = 0$$

In words: $L_\pm$, $\bar{L}_\pm$ act as ladder operators

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- Exploit trick above and partial integrations to simplify 3-point correlators

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- Keep track of all numerical factors:
$$\langle L \log \rangle = -\frac{b}{2\, z^4} = \langle \mathcal{O}^L(z, \bar{z}) \, \mathcal{O}^{\log}(0) \rangle$$

Examples for 3-point correlators

Without log insertions reduce to Einstein gravity correlators:

$$\langle R\,R\,R\rangle \sim \delta^{(3)}S(R,R,R) \sim 2\delta^{(3)}S_{\text{EH}}(R,R,R)$$

$$\langle L\,L\,L\rangle \sim \delta^{(3)}S(L,L,L) \sim 0\delta^{(3)}S_{\text{EH}}(L,L,L) = 0$$

With single log insertions after some manipulations reduce to Einstein gravity correlators:

$$\langle L\,L\,\log\rangle \sim \delta^{(3)}S(L,L,\log) \propto \delta^{(3)}S_{\text{EH}}(L,L,L)$$

$$\langle L\,R\,\log\rangle \sim \delta^{(3)}S(L,R,\log) \sim 0 + \text{contact terms}$$

With multiple log insertions calculations still very lengthy:

$$\langle \log\log\log\rangle \sim \delta^{(3)}S(\log,\log,\log) = \text{lengthy!}$$

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- 3-point correlators:
  Calculated 7 of 10 correlators so far — all of them match precisely. Plan to calculate one more. Will not calculate $\langle L \log\log\rangle$ and $\langle \log\log\log\rangle$ (lengthy!)

Outline

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> CTMG might be a good gravity dual to strongly coupled LCFTs!

Literature

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Thank you for your attention!

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