# Baby de Sitter Black Holes and $dS_3/CFT_2$

Gaston Giribet

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Quantum Gravity in the Southern Cone VI

Based on arXiv:1308.5569, done in collaboration with

Sophie de Buyl, Stéphane Detournay, and Gim Seng Ng (Harvard University)

$$2 + 1 < 4$$

$$2 + 1 \simeq 4$$

# Playground for Holography

- AdS/CFT and the Microscopic derivation of Bañados-Teitelboim-Zanelli black holes thermodynamics

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- Flat space holography: $BMS_3$ algebra at null infinity.
- $dS_3/CFT_2$ correspondence: Black holes in dS space.

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Quantum Gravity in $d$-dimensional asymptotically de Sitter space $\longleftrightarrow$ Euclidean conformal field theory at future infinity $\mathcal{I}^+$

Witten 2001; Strominger 2001

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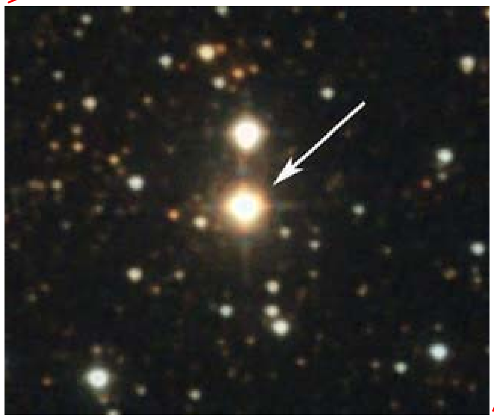

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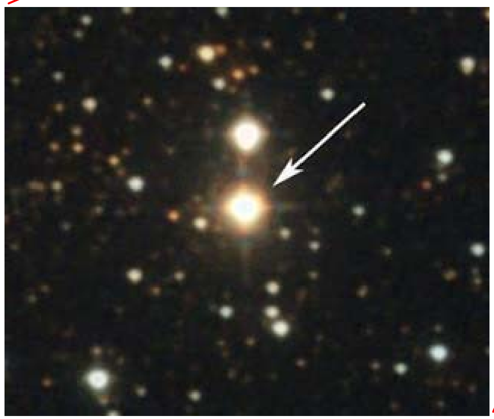

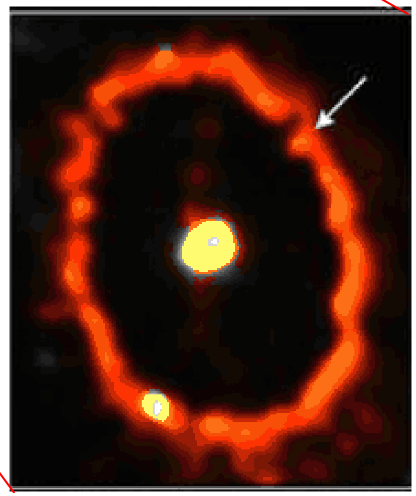

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# Three-Dimensional Massive Gravity

$$S = \frac{1}{16\pi G}\int_\Sigma d^3x\sqrt{-g}\,(R-2\Lambda) + \frac{1}{32\pi G\mu}\int_\Sigma d^3x\sqrt{-g}\epsilon^{\mu\nu\sigma}\Gamma^\eta_{\mu\beta}\left(\partial_\nu\Gamma^\beta_{\eta\sigma}+\Gamma^\beta_{\nu\rho}\Gamma^\rho_{\eta\sigma}\right)$$

$$+\frac{1}{16\pi G m^2}\int_\Sigma d^3x\sqrt{-g}\left(R_{\mu\nu}R^{\mu\nu}-\frac{3}{8}R^2\right).$$

Bergshoeff, Hohm & Townsend 2009

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$$l_+^2 \simeq \frac{1}{\Lambda} + \mathcal{O}(1/m^2),$$

$$l_-^2 \simeq \frac{1}{4m^2} + \mathcal{O}(1/m^4)$$

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$$l_+^2 = l_-^2 \longleftrightarrow \boxed{\Lambda = -m^2} \longleftrightarrow m^2 l^2 = -\frac{1}{2}$$

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# Asymptotia

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$$[\ell_n^{\pm}, \ell_m^{\pm}] = (n - m)\ell_{n+m}^{\pm}$$

$$n = \{-1, 0, +1\}$$

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| sl(2,$\mathbb{C}$) | $Vir \times Vir$ |
| $dS_3$ isometry algebra<br>$2d$ local conformal algebra | $dS_3$ asymptotic isometry algebra<br>$2d$ global conformal algebra |

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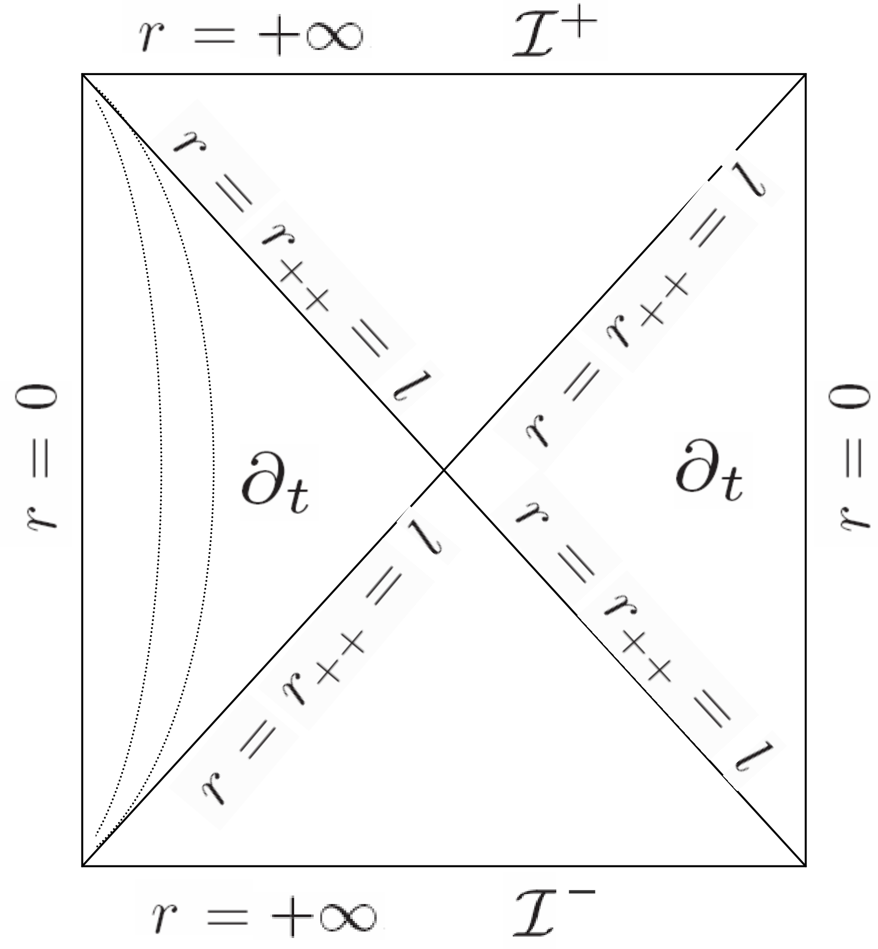

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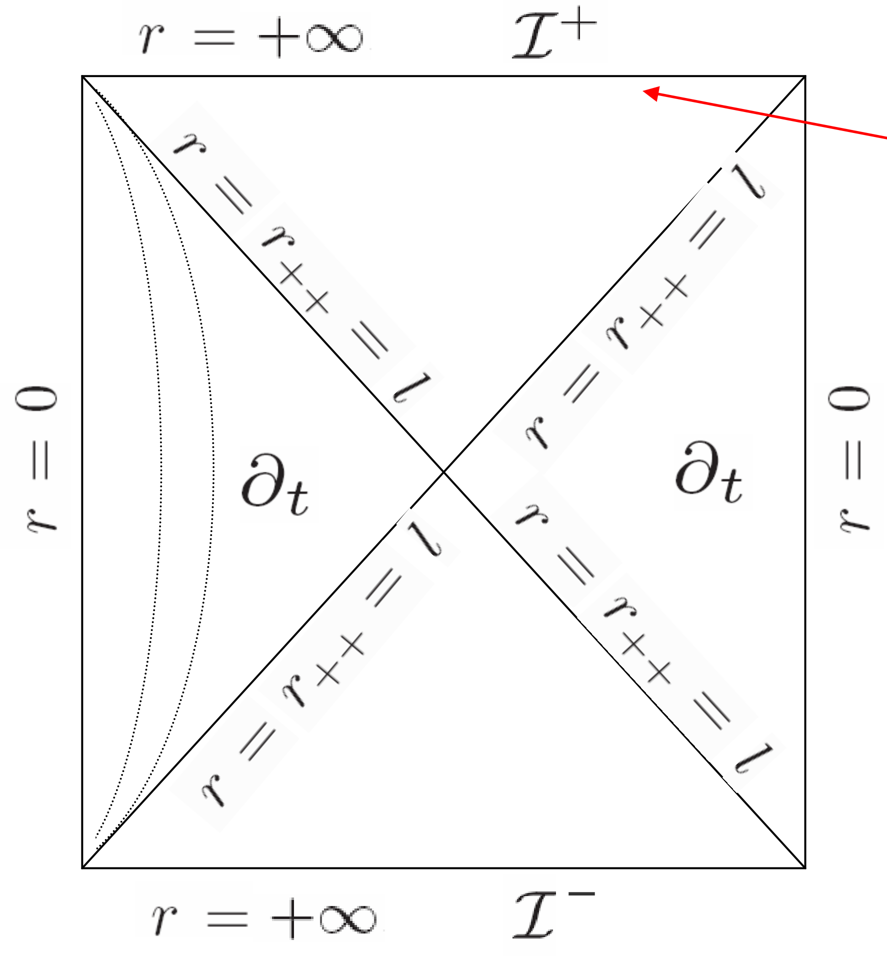


$$ds^2/l^2 = e^{2t}dzd\bar{z} - dt^2$$

$$r \equiv e^t$$

$$t \to +\infty$$

$$g_{z\bar{z}} = l^2 e^{2t}/2 + \mathcal{O}(e^{+t}),$$

$$g_{tt} = -l^2 + \mathcal{O}(e^{-t}),$$

$$g_{zz} = \mathcal{O}(e^t),$$

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$$ds^2 = -\frac{l^2 d\rho^2}{\rho^2} + \sum_{p \in \mathbb{N}} g_{ij}^{(p)} \rho^{2-p} dx^i dx^j$$

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$$\begin{aligned} Q_{\ell_n^+} &= \frac{1}{4\pi G l}\int d\phi\, e^{-inx^+}(g^{(2)}_{++} - \frac{1}{l^2}g^{(1)}_{++}g^{(1)}_{+-}) \\ Q_{\ell_n^-} &= \frac{1}{4\pi G l}\int d\phi\, e^{inx^-}(g^{(2)}_{--} - \frac{1}{l^2}g^{(1)}_{--}g^{(1)}_{+-}) \end{aligned}$$

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

$$c^\pm = -\frac{3l}{2G}\left(1 - \frac{1}{2m^2 l^2}\right)$$

à la Brown & Henneaux

# Black Holes in $dS_3$ Space

$$S = \frac{1}{16\pi G}\int_{\Sigma} d^3x\sqrt{-g}\,(R-2\Lambda) + \frac{1}{16\pi G m^2}\int_{\Sigma} d^3x\sqrt{-g}\left(R_{\mu\nu}R^{\mu\nu} - \frac{3}{8}R^2\right).$$

Oliva, Tempo & Troncoso 2009

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$$ds^2 = -N^2(r)F(r)dt^2 + \frac{dr^2}{F(r)} + r^2\left(d\phi + N^\phi(r)dt\right)^2$$

$$F(r) = \frac{\hat{r}^2}{r^2}\left[-\frac{\hat{r}^2}{l^2} + \frac{b}{2}(1+\eta)\,\hat{r} - \frac{b^2l^2}{16}(1-\eta)^2 - 4MG\eta\right]$$

$$N(r) = 1 - \frac{bl^2}{4\hat{r}}(1-\eta), \quad N^\phi(r) = -\frac{a}{2r^2}(4GM - b\hat{r}),$$

$$\hat{r}^2 = r^2 + 2MGl^2(1-\eta) - (b^2l^4/16)(1-\eta)^2 \qquad \eta = \pm\sqrt{1 + a^2/l^2}$$

Oliva, Tempo & Troncoso 2009

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$$M$$

Oliva, Tempo & Troncoso 2009

# Black Holes in $dS_3$ Space

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$M$ $a$ $b$ Oliva, Tempo & Troncoso 2009

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$$ds^2 = -\frac{(r - r_+)(r_{++} - r)}{l^2} dt^2 + \frac{l^2 dr^2}{(r - r_+)(r_{++} - r)} + r^2 d\phi^2$$

$$\begin{aligned} r_{++} + r_+ &\equiv bl^2, \\ r_{++} r_+ &\equiv 4MGl^2 \\ 0 &\equiv a \end{aligned}$$

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Oliva, Tempo & Troncoso 2009

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$$R = 6/l^2 - 2b/r$$

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# Black Holes in $dS_3$ Space

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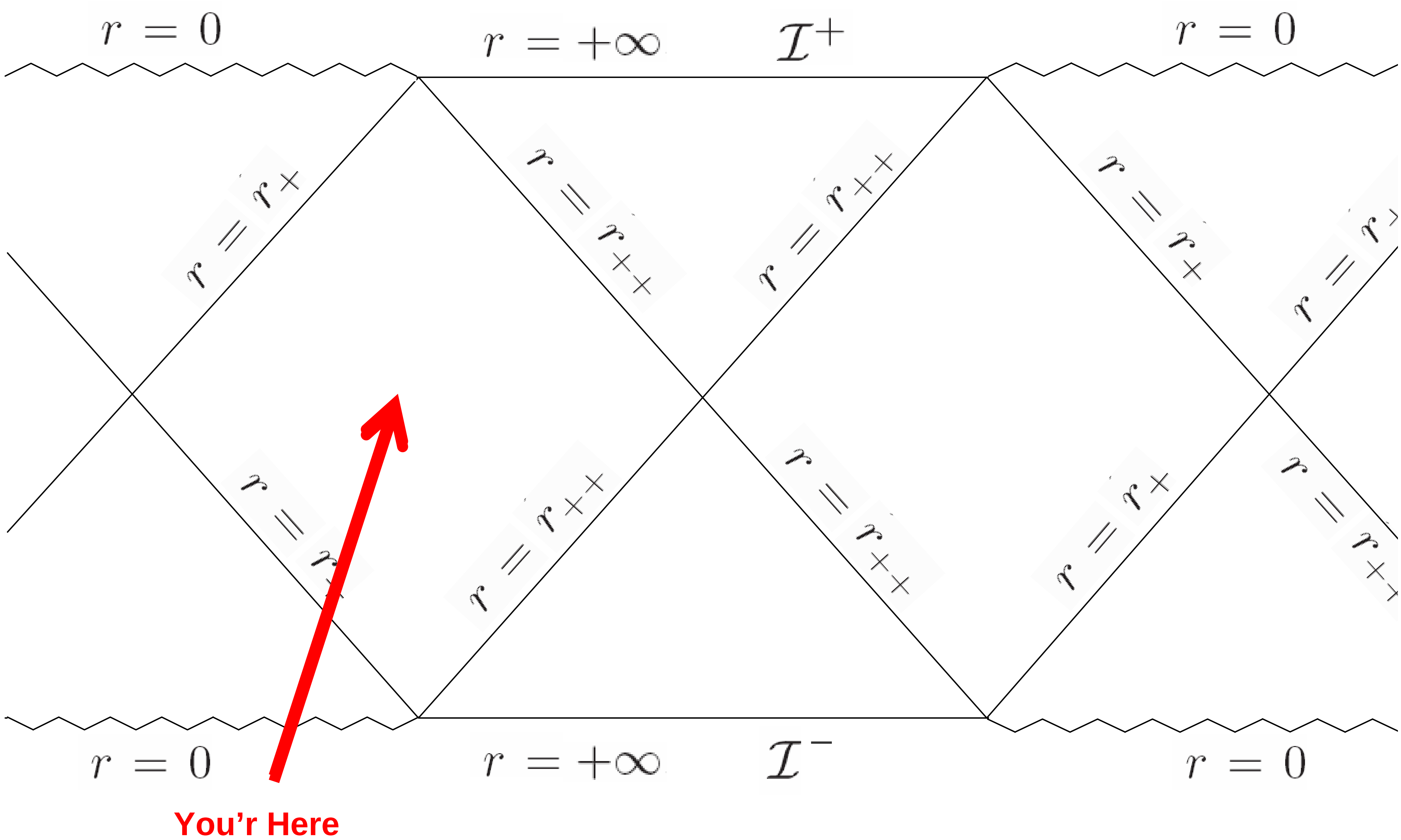
$$2 + 1 \simeq 4$$

# Black Holes in $dS_3$ Space



# Conserved Charges

$$ds^2 = -\frac{l^2 d\rho^2}{\rho^2} + \sum_{p\in\mathbb{N}} g_{ij}^{(p)} \rho^{2-p} dx^i dx^j \qquad g_{\pm\pm}^{(0)} = 0,\, g_{+-}^{(0)} = l^2/2$$

$$\begin{aligned} Q_{\ell_n^+} &= \frac{1}{4\pi G l} \int d\phi \, e^{-inx^+} (g_{++}^{(2)} - \frac{1}{l^2} g_{++}^{(1)} g_{+-}^{(1)}) \\ Q_{\ell_n^-} &= \frac{1}{4\pi G l} \int d\phi \, e^{inx^-} (g_{--}^{(2)} - \frac{1}{l^2} g_{--}^{(1)} g_{+-}^{(1)}) \end{aligned}$$

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$$\mathcal{M} \equiv Q_{\partial_t} = M - \frac{b^2 l^2}{16G}$$

$$\mathcal{J} \equiv Q_{\partial_\phi} = -a\mathcal{M}$$

# Thermodynamics

$$T_{++} = T_{+} = \frac{\eta}{\pi l}\sqrt{\frac{-2G\mathcal{M}}{1+\eta}} \qquad \eta = \sqrt{1 + a^2/l^2}$$

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$$-d\mathcal{M} = T_{+} dS_{+} + \Omega_{+} d\mathcal{J}$$

$$\Omega_{+} = -\frac{1}{l}\sqrt{\frac{\eta - 1}{\eta + 1}}$$

$dS_3$

**$\mathbf{CFT}_2$**

# Holographic Renormalization

$$S = \frac{1}{16\pi G}\int_\Sigma d^3x\sqrt{-g}\,(R-2\Lambda) + \frac{1}{16\pi G m^2}\int_\Sigma d^3x\sqrt{-g}\left(R_{\mu\nu}R^{\mu\nu} - \frac{3}{8}R^2\right)$$

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$$S_{\rm B} = -\frac{1}{8\pi G}\int_{\mathcal{I}+} d^2x\sqrt{|\gamma|}\left(K + \frac{1}{2}\hat{f}^{ij}(K_{ij} - \gamma_{ij}K)\right)$$

$$ds^2 = -N^2dr^2 + \gamma_{ij}(dx^i + N^i dr)(dx^j + N^j dr)$$

$$f^{\mu\nu} = \begin{pmatrix} f^{ij} & h^j \\ h^i & s \end{pmatrix} \qquad \hat{f}^{ij} \equiv f^{ij} + 2h^{(i}N^{j)} + sN^iN^j$$

# Holographic Renormalization

$$ds^2 = -N^2 dr^2 + \gamma_{ij}(dx^i + N^i dr)(dx^j + N^j dr)$$

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$$S_{\mathrm{C}} = \frac{1}{8\pi G} \int_{\mathcal{I}^+} d^2x \sqrt{|\gamma|} (\alpha_0 + \alpha_1 \hat{f} + \alpha_2 \hat{f}^2 + \beta_2 \hat{f}_{ij} \hat{f}^{ij} + \ldots)$$

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$$T_{zz} = \sum_{n\in\mathbb{Z}} L_n^+\ z^{-n-2}$$

$$\boxed{L_0^+ + L_0^- = -l\mathcal{M},\ \ L_0^+ - L_0^- = i\mathcal{J}}$$

# Cardy-ology

$$Z(\tau) \equiv \sum_{h,\overline{h}} \rho\left(L_0^+, L_0^-\right) e^{2\pi i(L_0^+ - c^+/24)\tau} e^{-2\pi i(L_0^- - c^-/24)\overline{\tau}}$$

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$$S_{\mathrm{CFT}} \equiv \log \rho\left(L_0^+, L_0^-\right) \simeq 2\pi \sqrt{\frac{|c^+|L_0^+}{6}} + 2\pi \sqrt{\frac{|c^-|L_0^-}{6}}$$

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# Cardy-ology

$$S_{\mathrm{CFT}} = S_{++} = S_{+}$$

# Conclusions

Unlike three-dimensional General Relativity, three-dimensional massive gravity does admit asymptotically de Sitter black holes.

These black holes exhibit several features that are reminiscent of those of higher-dimensional dS black holes:

They possess a curvature singularity at the origin and interesting thermodynamical properties both at the black hole event horizon and at the cosmological horizon.

Unlike the black holes in $dS_{d>3}$ space, the $dS_3$ black holes are always in thermal equilibrium with respect with the cosmological horizon of the spacetime that hosts them.

This invites us to study these black holes in the context of dS/CFT.

# Conclusions

We studied the asymptotic $dS_3$ isometry group and showed that it is generated by two copies of the conformal algebra in two-dimensions.

The algebra of the charges associated to the asymptotic Killing vectors consists of two copies of Virasoro algebra with negative central charge.

We defined the regularized boundary stress-tensor and identified it with that of the dual conformal field theory.

We showed that Cardy formula in the dual $CFT_2$ exactly reproduces the entropy of both the black hole and the cosmological horizon.

The fact that Cardy entropy formula matches the entropy of black holes in the bulk of $dS_3$ is remarkable because of the existence of an extra hair parameter. All the black hole parameters conspire in a way that numerical matching holds.

**Obrigado, Gracias, Thanks**


**Sept. 11$^{th}$ 1973 – Sept. 11$^{th}$ 2013**

**It's taking 40 years to recover their right...**