Quantum Gravity Lessons from Black Hole Thermodynamics

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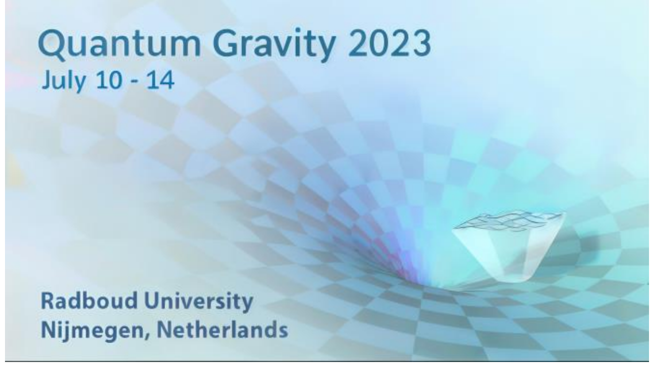
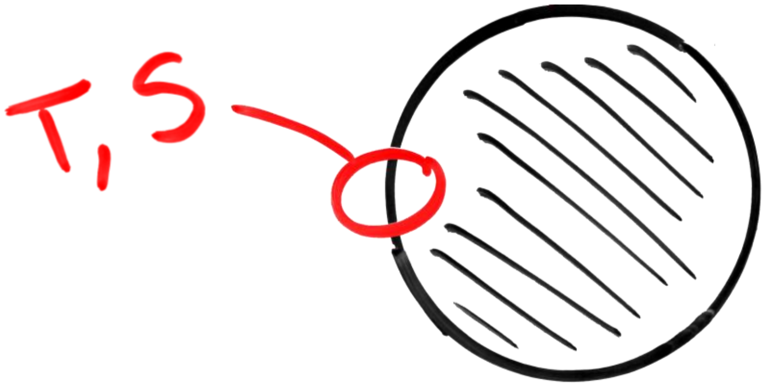
Astronomy, Astrophysics &
Astrophotonics

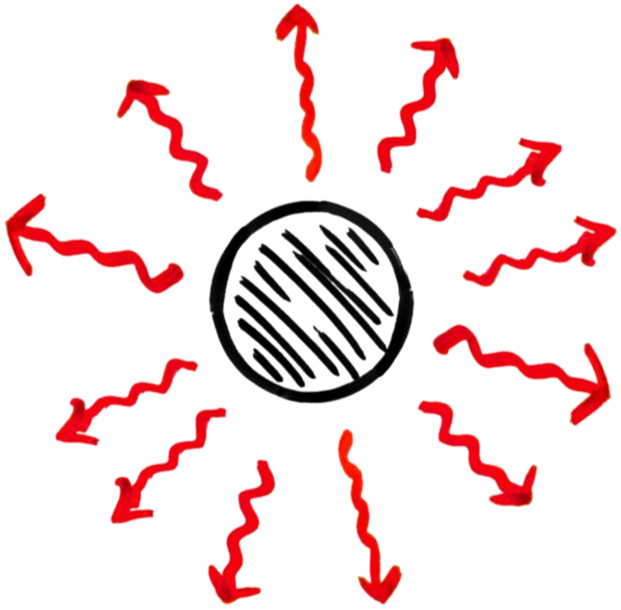


Why black holes?

- Black holes are one of the few objects in the universe where curved-space QFT and quantum gravity effects manifest.

- They appear to have thermodynamic properties:





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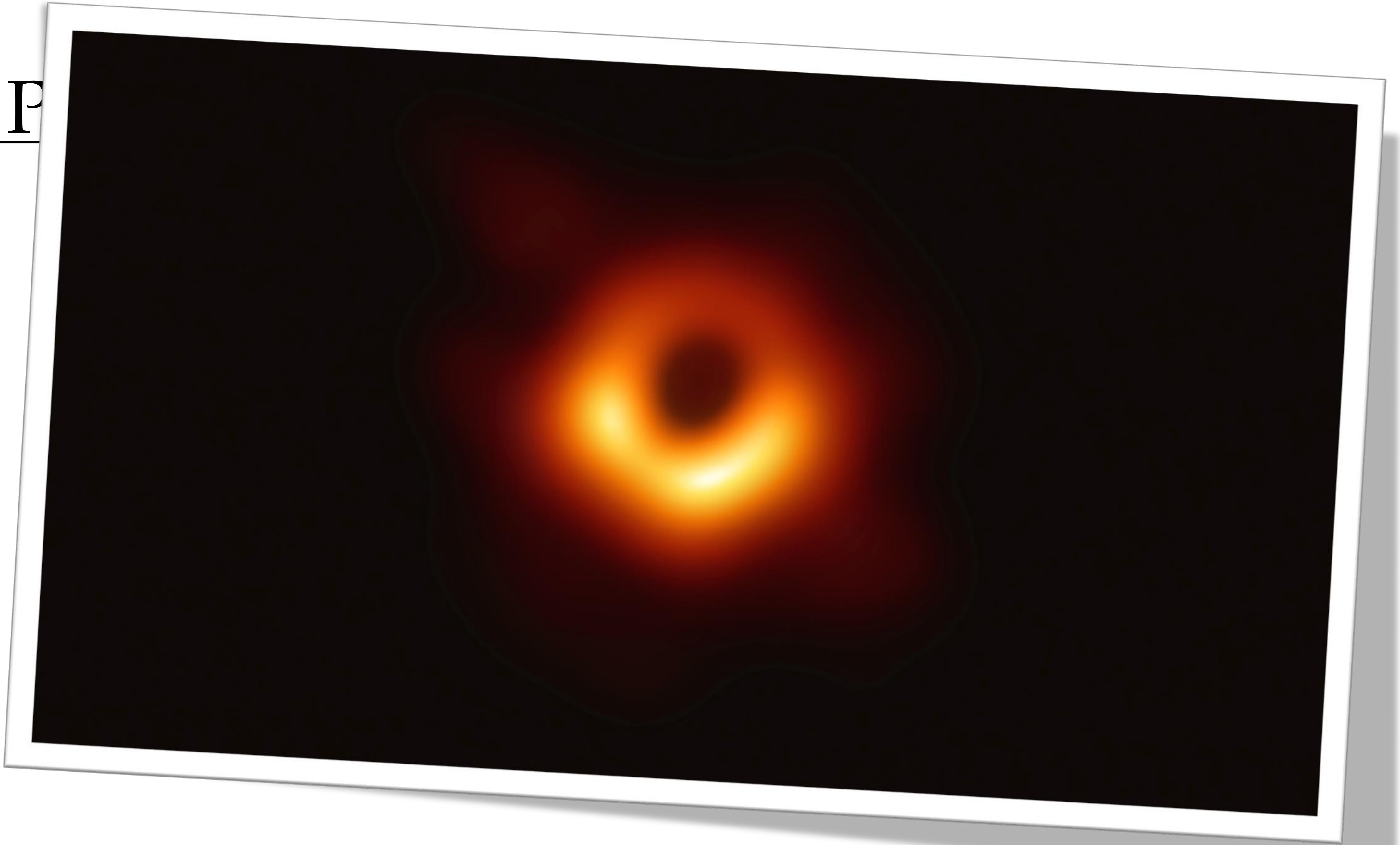


Laws of black hole mechanics

- In any Lagrangian theory of gravity:

Iyer, Wald 1994
Wald, Zoupas 2000

$$\delta H_\xi = \int_\Sigma \Omega(\phi, \delta\phi, \mathcal{L}_\xi \phi)$$

$$\int_\mathcal{B} \delta Q_\xi = \int_\infty \delta Q_\xi - i_\xi \theta$$

$$T_H = \frac{\kappa}{2\pi}\,, \qquad S = 2\pi \int_\mathcal{B} Q_\xi$$

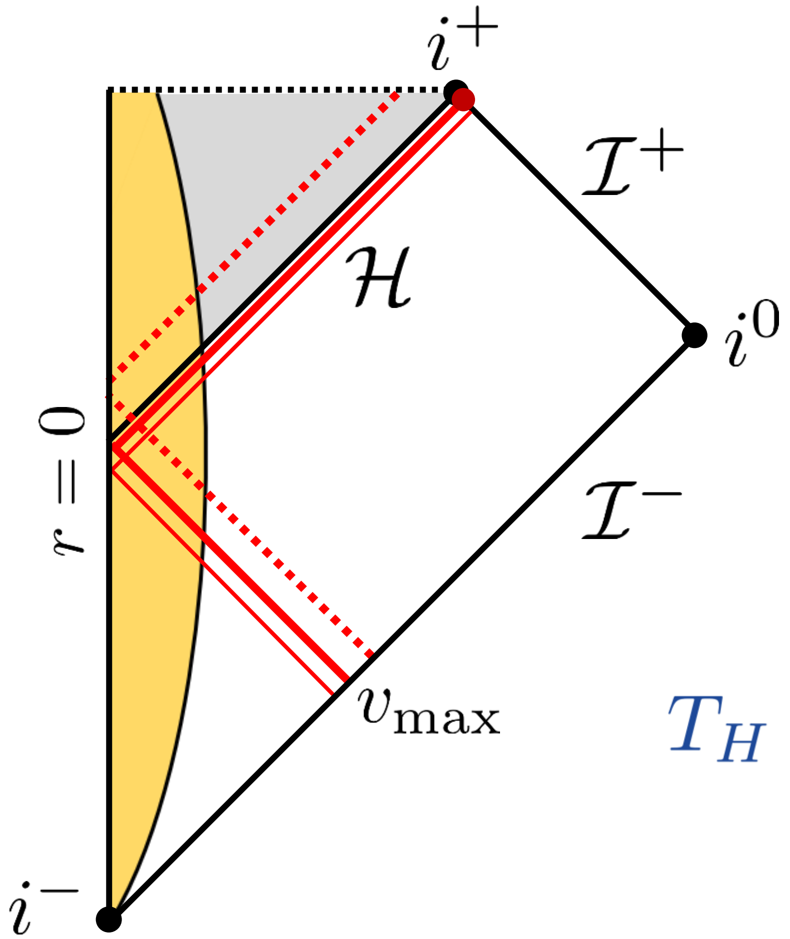
Entropy $\leftrightarrow$ Diffeos.

$$Q_\xi \sim -\frac{1}{16\pi}\epsilon_{abcd}\nabla^c \xi^d$$

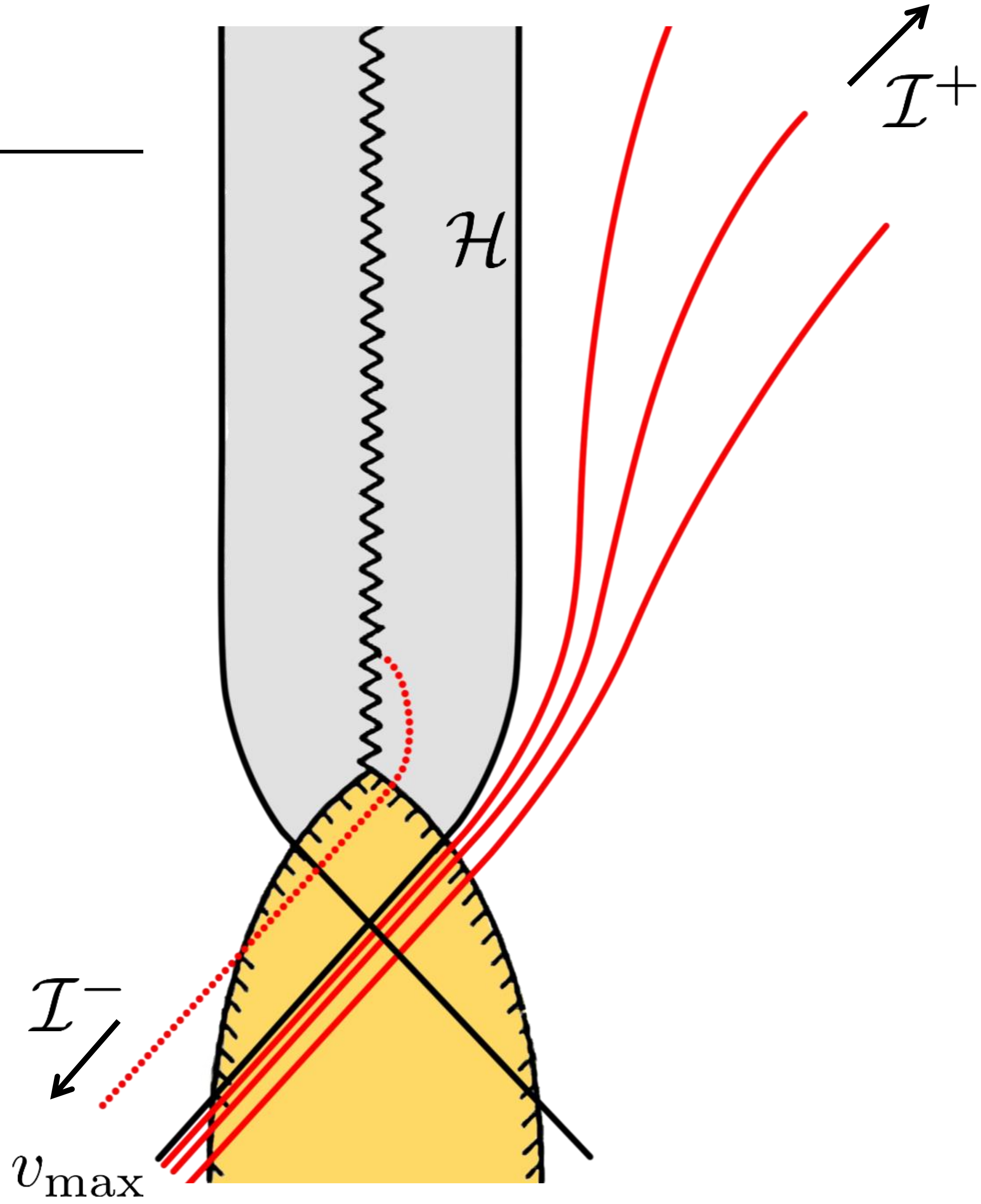
$$\boxed{T_H \delta S = \delta \mathcal{E} - \Omega_H \delta \mathcal{J}}$$

- Can be interpreted as a physical process or global state comparison.

Hawking Radiation



$$T_H = \frac{\kappa}{2\pi}$$

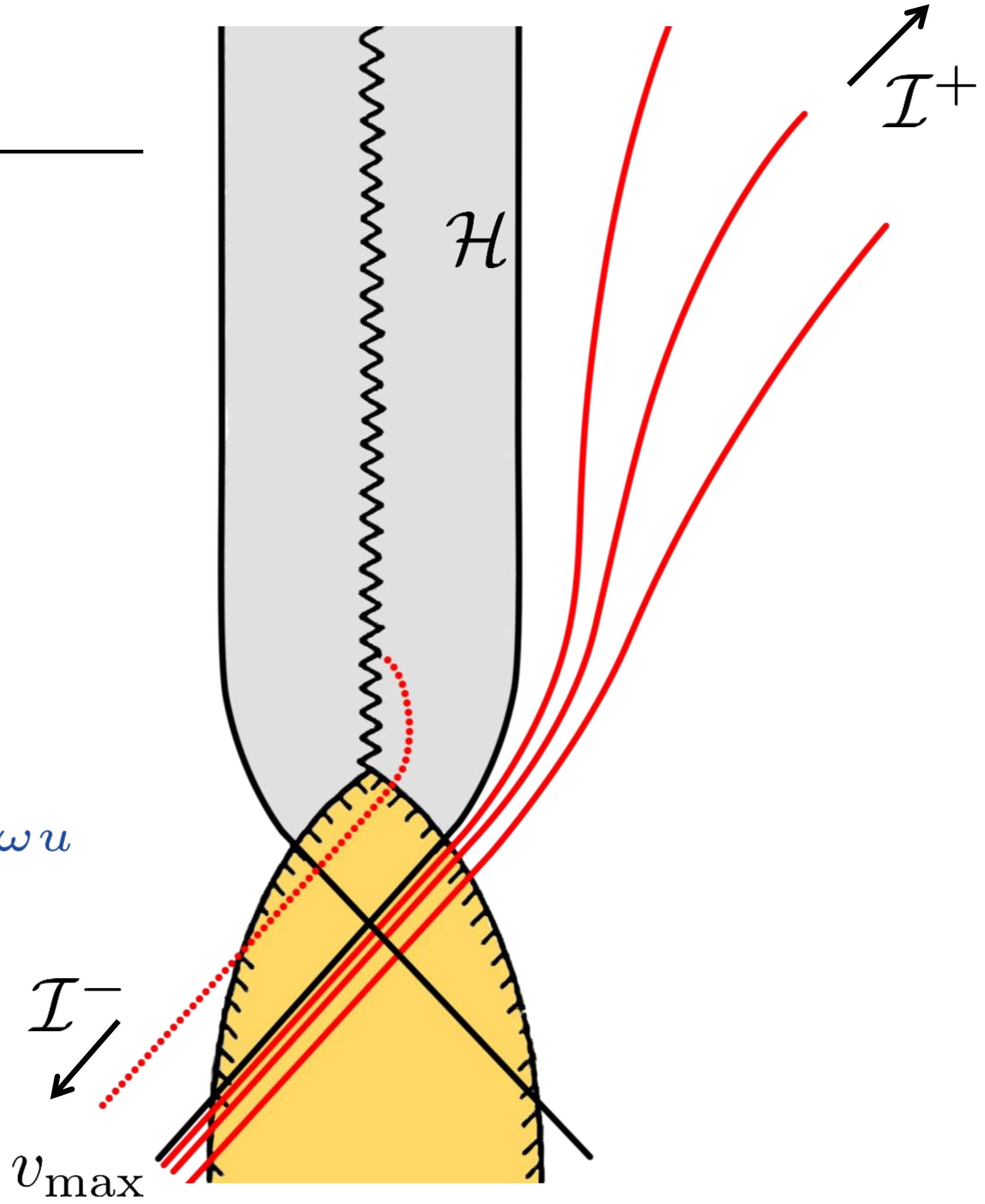


Hawking Radiation

- The evaporation process is ordinarily thought to be a feature particular to event horizons.
- Really all we need is a particular relation between null generators:

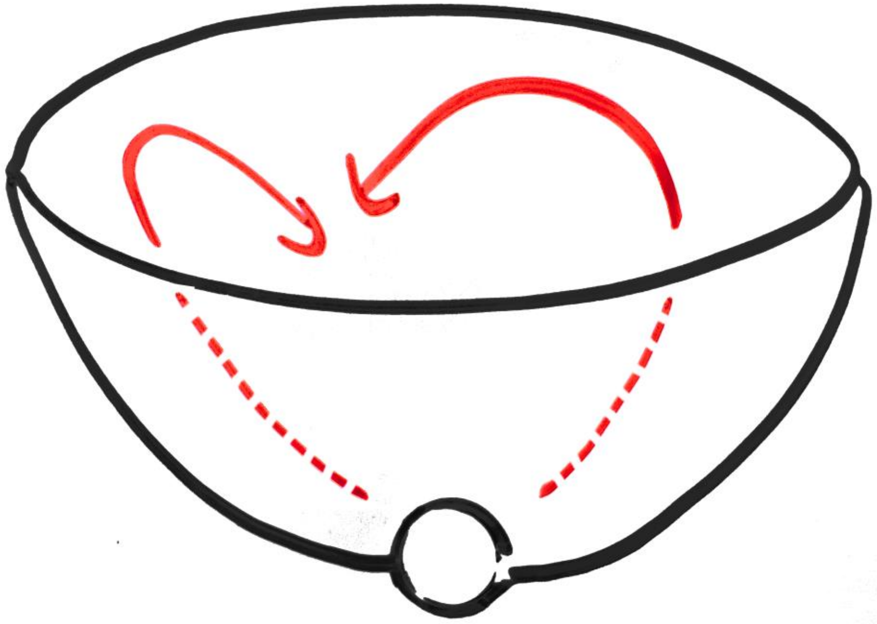
$$\beta_{\omega'\omega} = \frac{1}{2\pi}\sqrt{\frac{\omega}{\omega'}}\int du\, e^{-i\omega'\boxed{v(u)}}e^{-i\omega u}$$

$$v(u) \approx v_0 - Ce^{-\kappa u}$$



Anti-de Sitter Space

- Possesses nice boundary structure suitable for holography.
- Periodic (closed) orbits.
- A natural length scale separating two distinct regions.



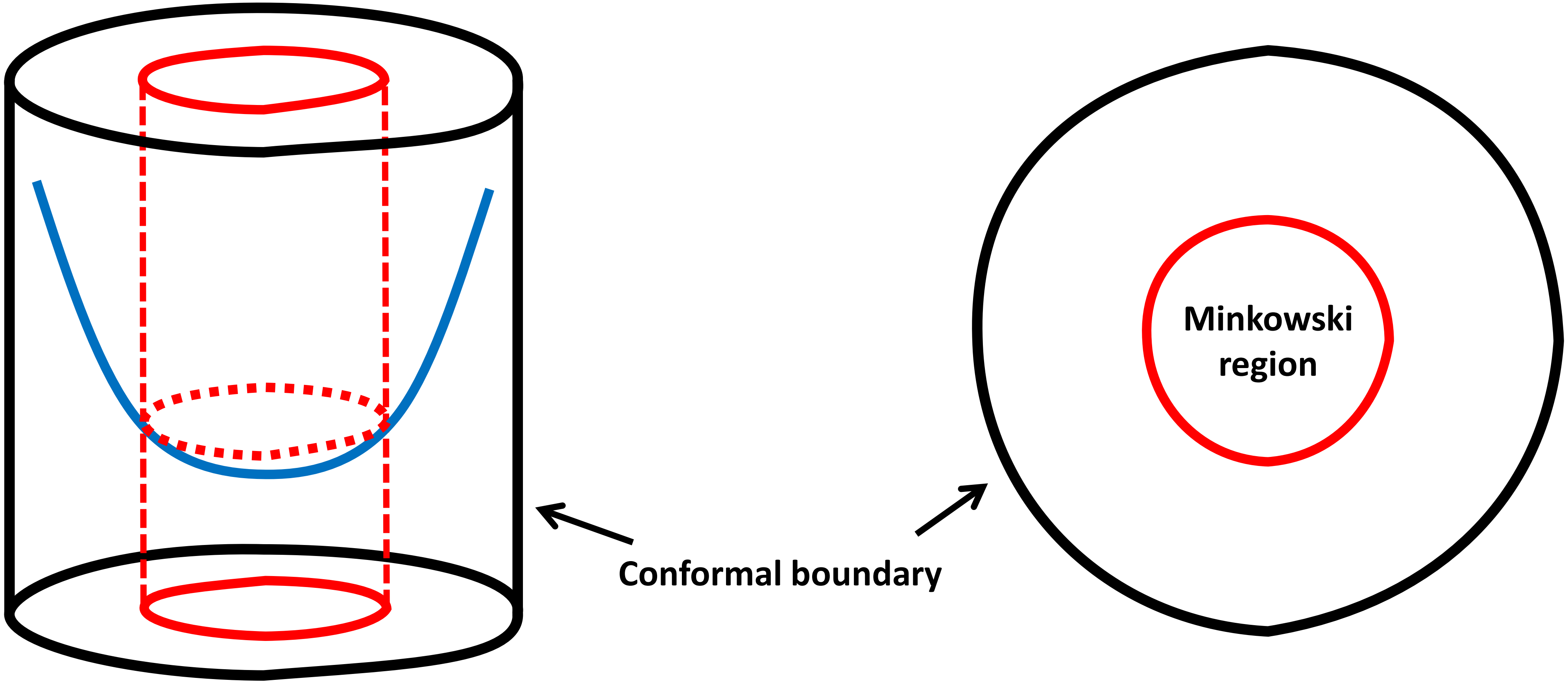
$$L = \frac{1}{2}\eta_{AB}\dot{X}^A\dot{X}^B - \lambda(\tau)(X_A X^A + a^2)$$

$$\implies \ddot{X}^A \pm \frac{1}{a^2}X^A = 0 \quad \text{and} \quad \ddot{X}^A = 0$$

(timelike) (null)

Anti-de Sitter Space

- The Ads length scale separates two regions:



Minkowski region

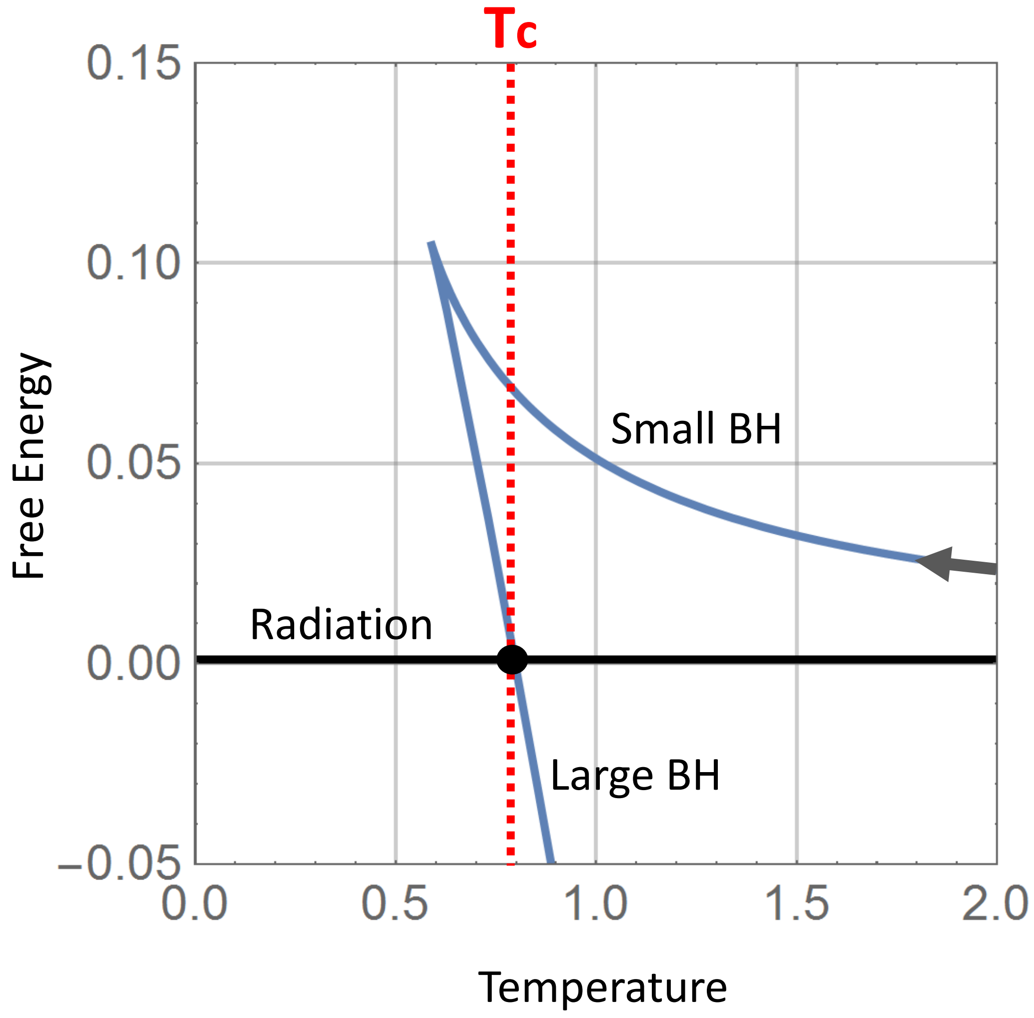
Conformal boundary

The Hawking-Page transition

- Consider an asymptotically AdS ($\Lambda < 0$) black hole spacetime.
- Can compute a free energy:

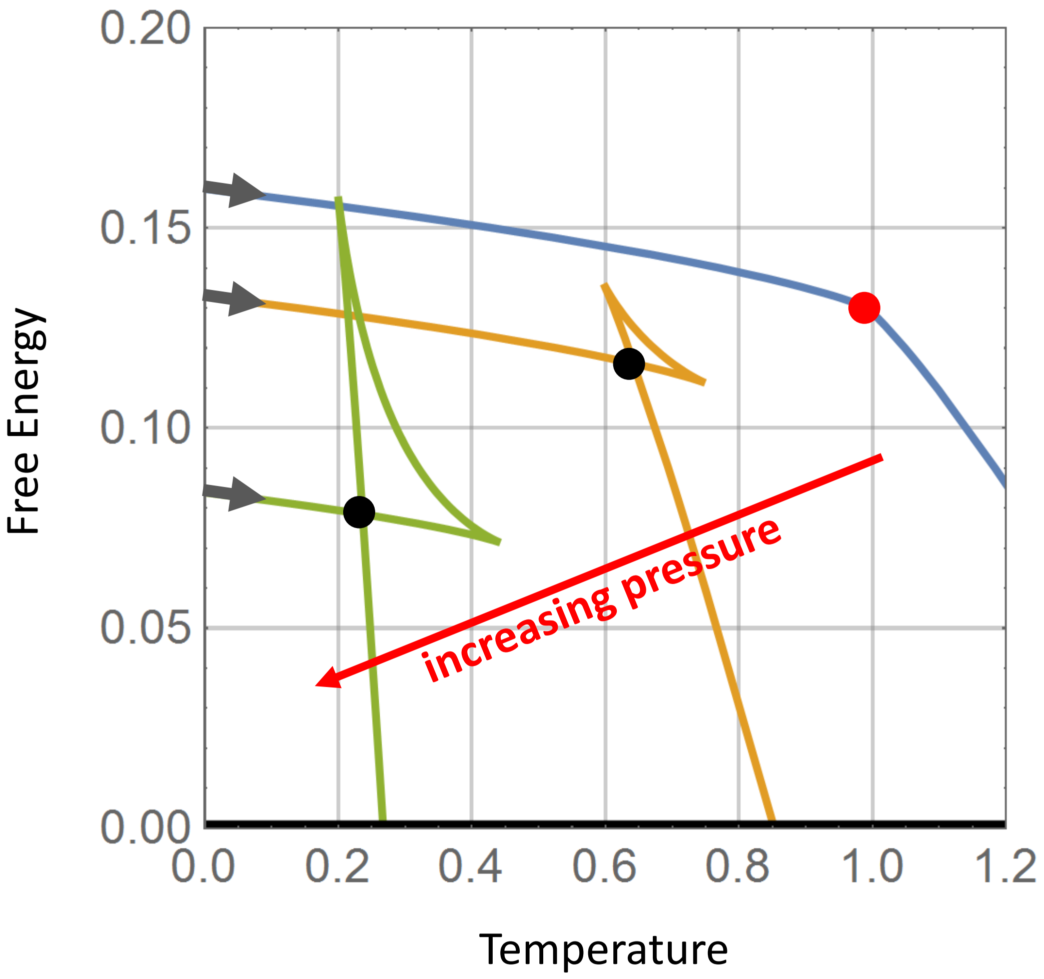
$$G = M_{ADM} - T_H S_{BH}$$

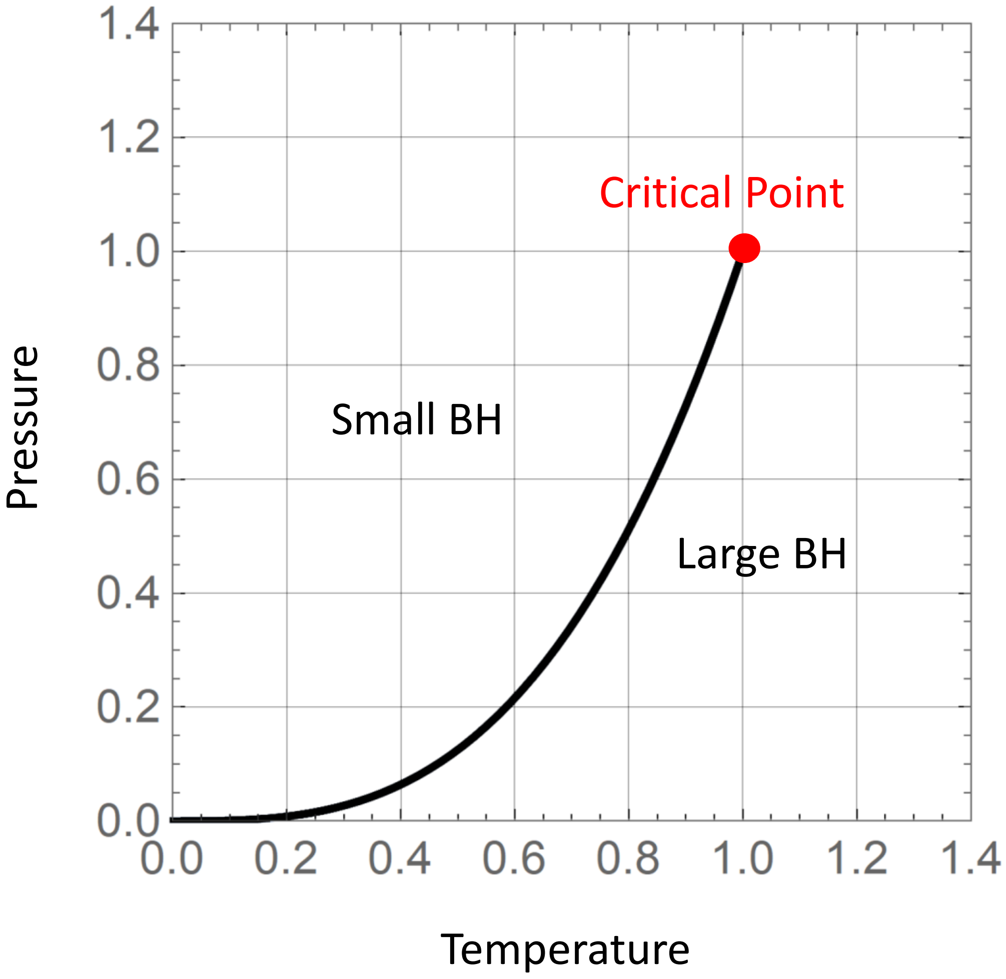
- When the temperature increases past Tc, a phase transition occurs.



Reissner-Nordström-AdS

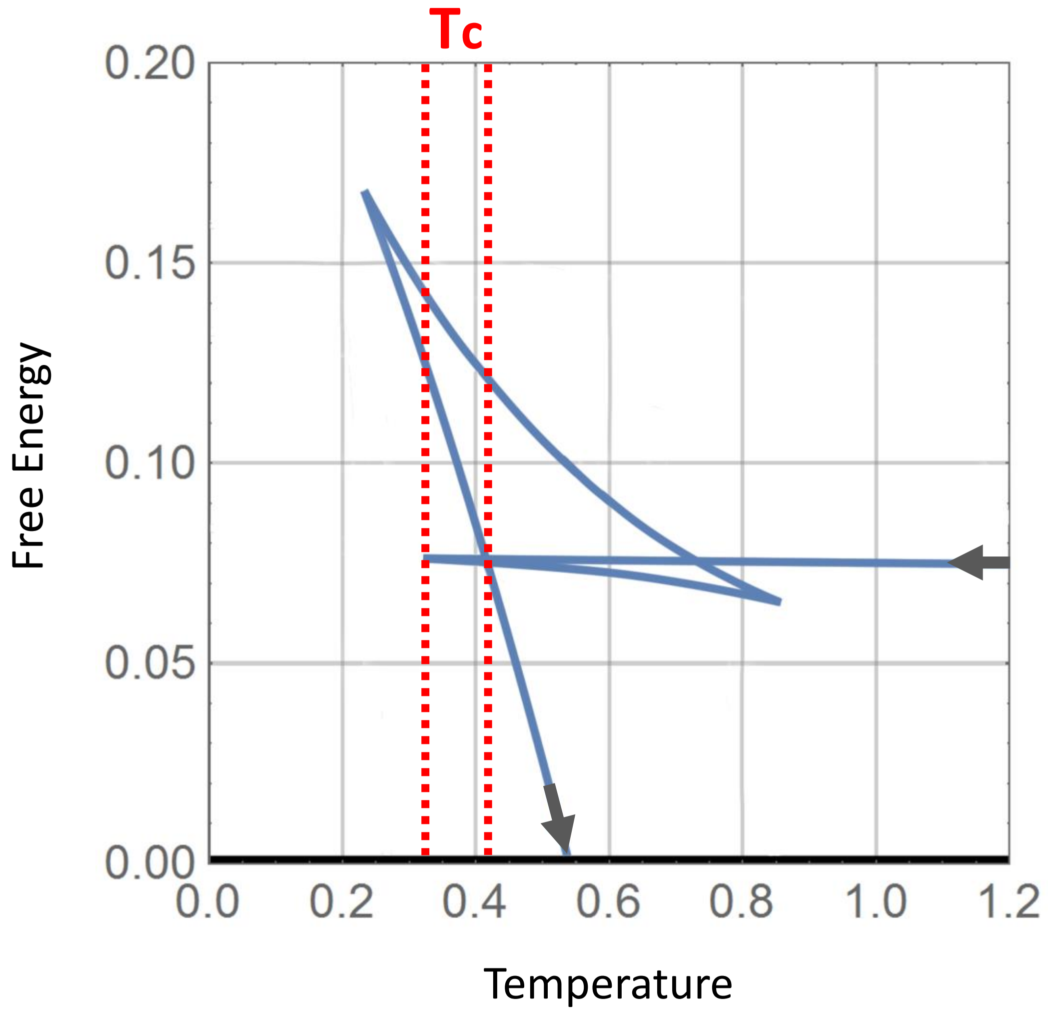
Kubiznak, Mann, Teo 2017
Mann, FS 2019

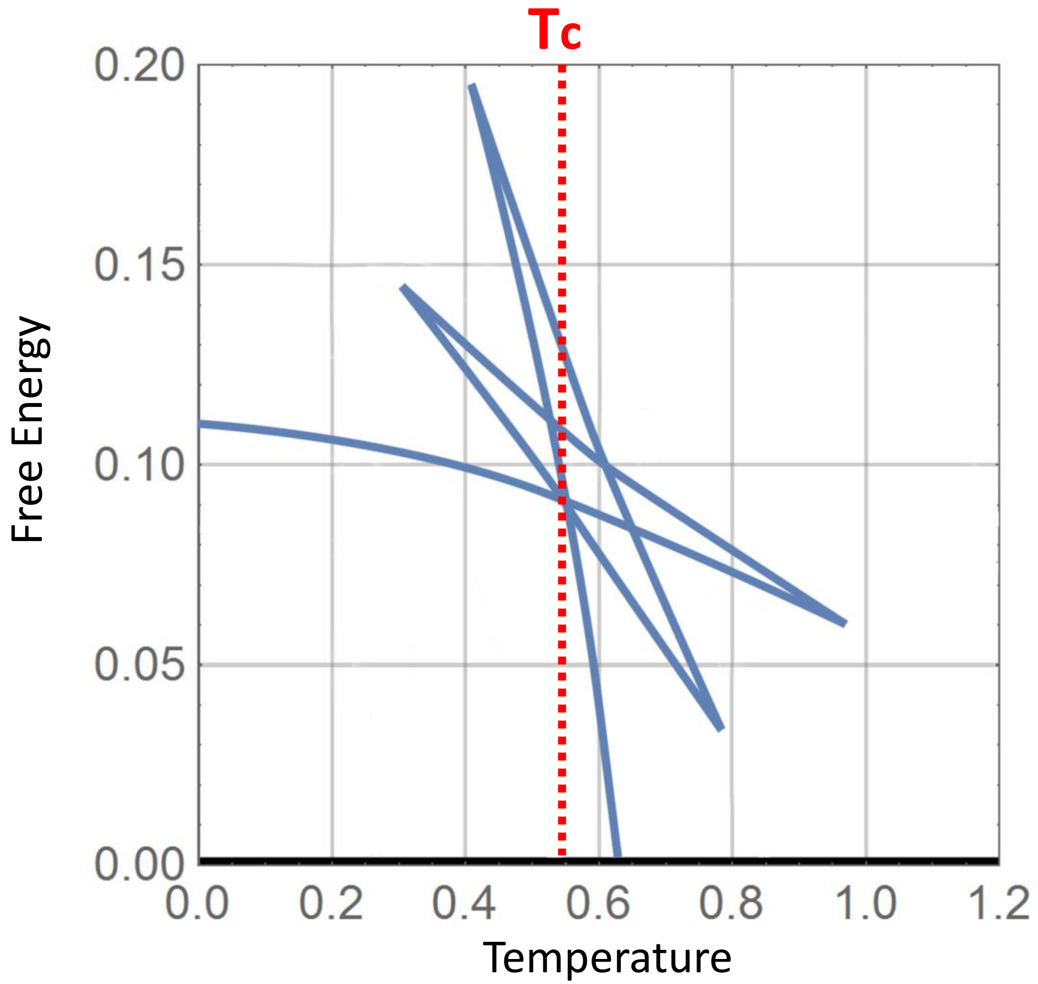




Gauss-Bonnet

$$\mathcal{L}_{GB} = \alpha\left(R_{abcd}R^{abcd} - 4R_{ab}R^{ab} + R^2\right)$$

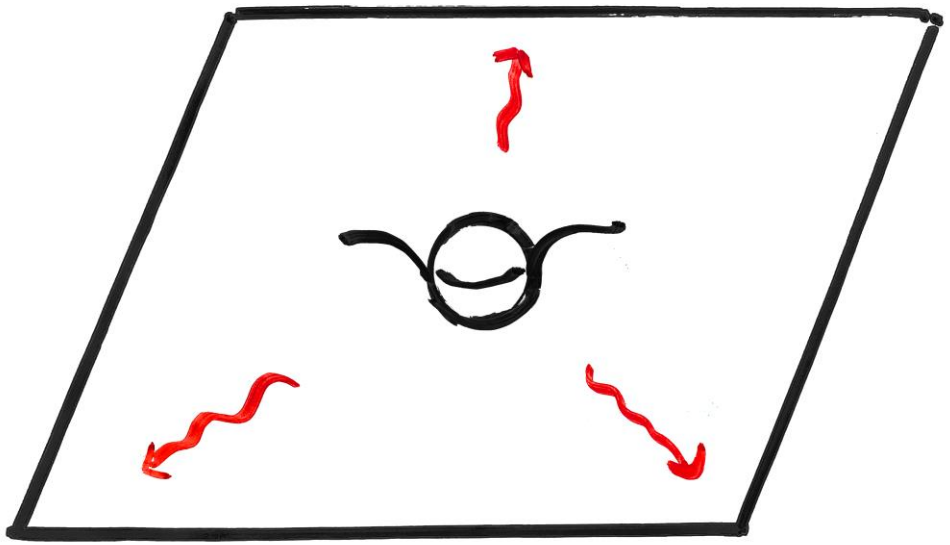




Haroon, Hennigar, Mann, FS 2020

What about de Sitter?

- In asymptotically flat and de Sitter spacetimes, black holes evaporate and there is no thermal equilibrium.



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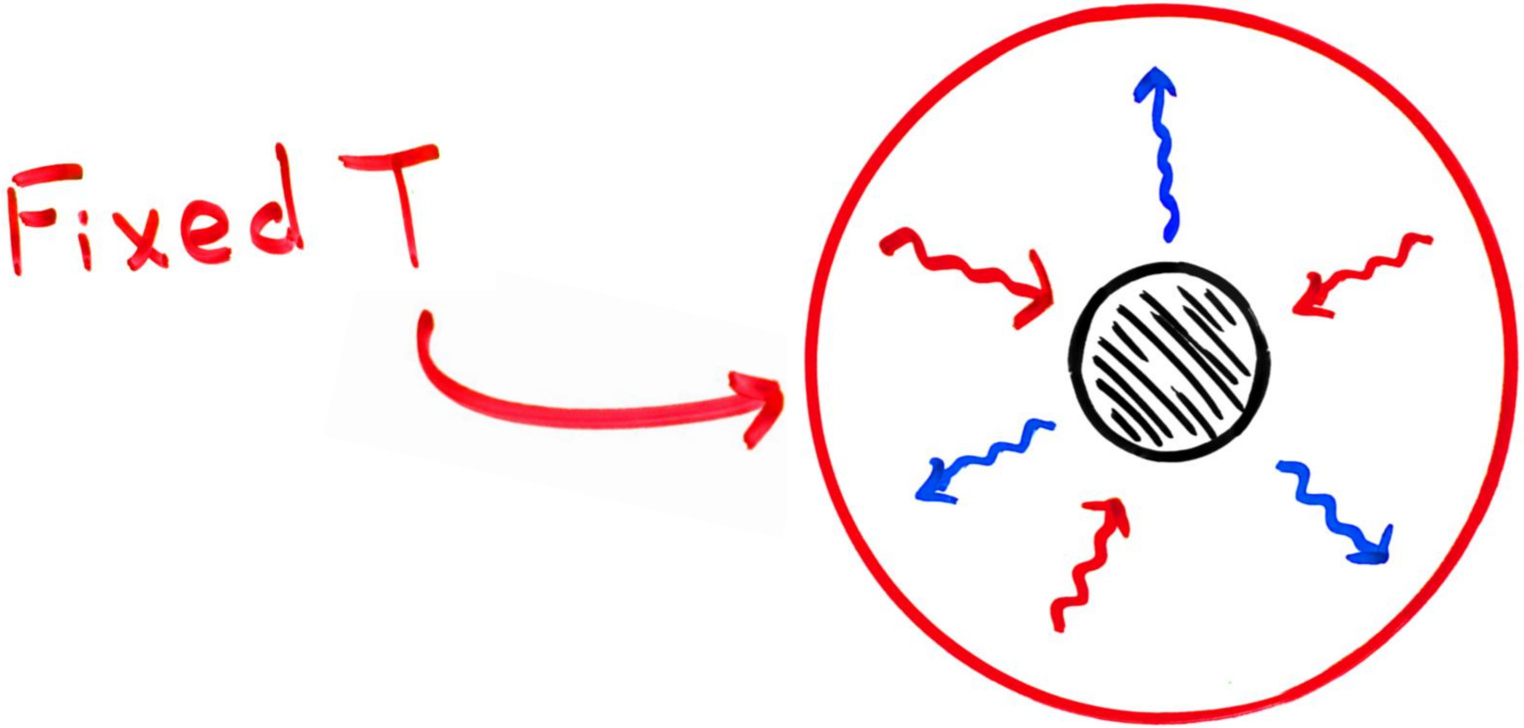


What about de Sitter?

- Take a semi-classical path integral approach:

$$\mathcal{Z} = \mathrm{Tr}\; e^{-\beta H} \sim \int \mathcal{D}[g]\; e^{-I_E/\hbar} \approx e^{-I_E[g_{cl}]/\hbar}$$

Gibbons, Hawking 1977
York et al 1986
Whiting York 1988
Carlip, Vaidya 2003

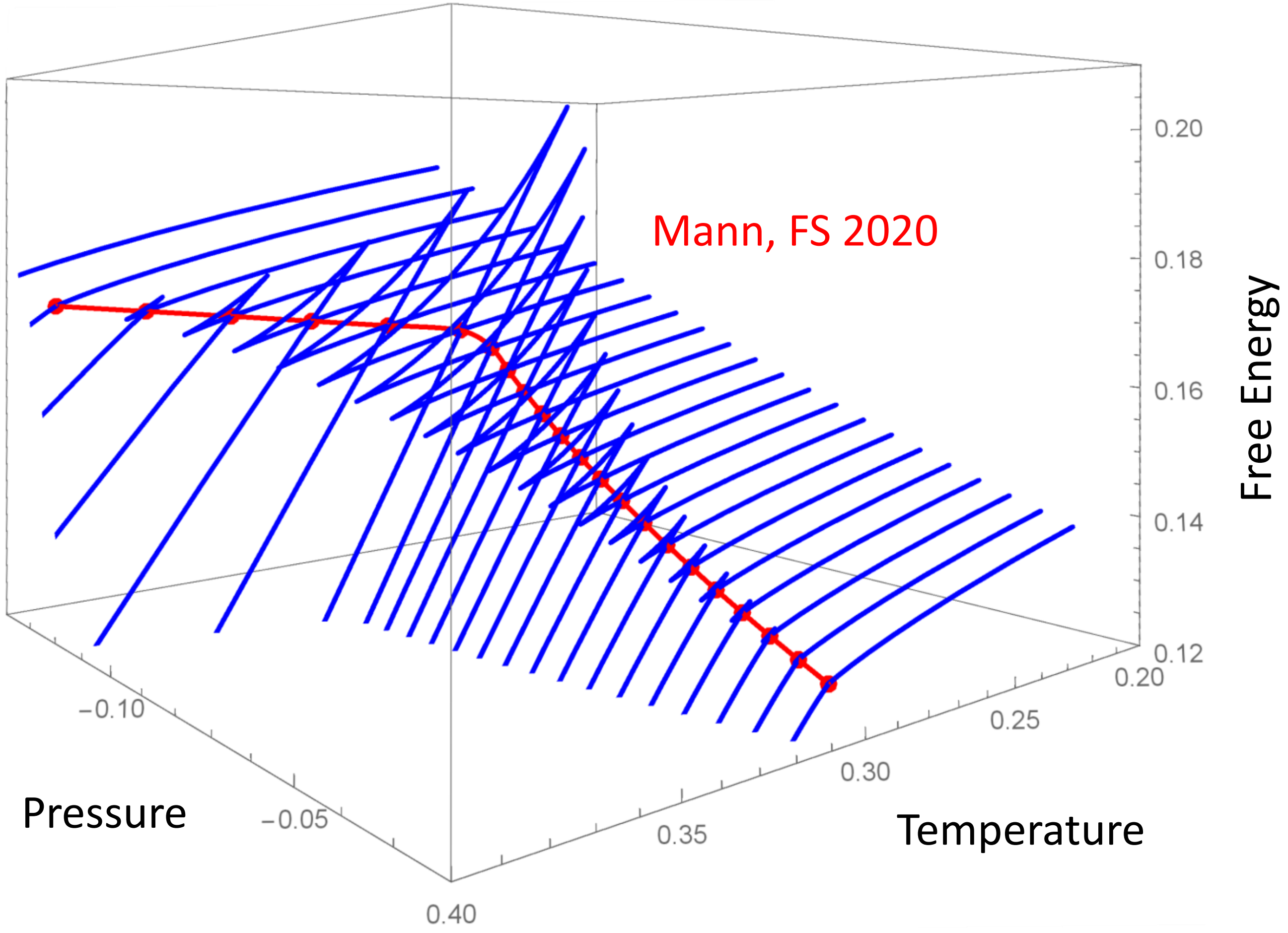
- Data is fixed at a finite boundary in the spacetime:

$$I_{\mathrm{E}} = -\frac{1}{16\pi}\int_{\mathcal{M}} d^4x\sqrt{g}\,(R-2\Lambda) - \frac{1}{8\pi G}\int_{\partial\mathcal{M}} d^3x\sqrt{k}\;K - I_0$$

$$\langle E\rangle = \frac{\partial I_E}{\partial\beta}\,, \qquad S = \beta\left(\frac{\partial I_E}{\partial\beta}\right) - I_E\,, \qquad F = T I_E$$

What about de Sitter?

- Coexistence line is bounded from above and below due to the presence of the cosmological horizon.
- Need to be careful about how the thermodynamic ensemble is defined.



Mann, FS 2020

Banihashemi, Jacobson 2022
Banihashemi, Jacobson, Svesko, Visser 2022

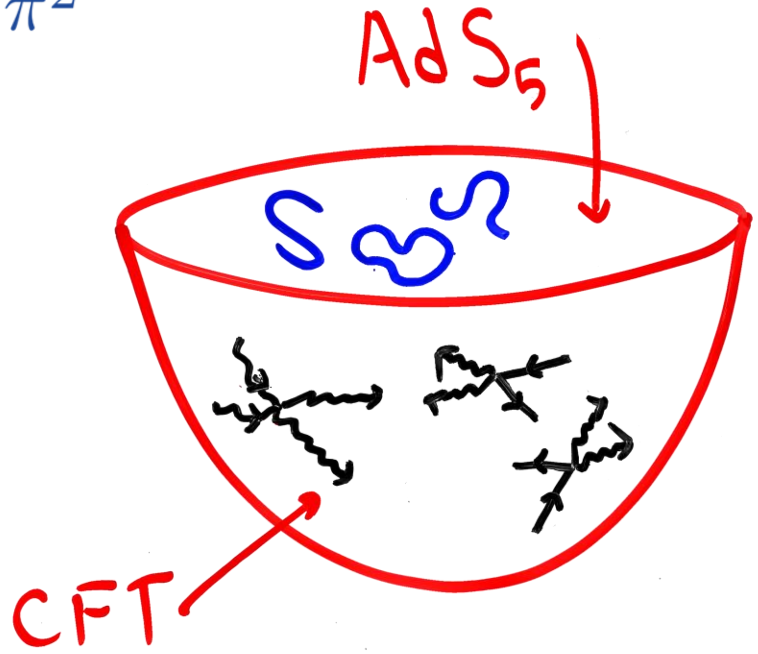
The dual description

- Pressure arises from variable Λ:

$$P = -\frac{\Lambda}{8\pi G_N} = \frac{(D-1)(D-2)}{16\pi\, l_{AdS}^2\, G_N} \,, \qquad l_{AdS}^4 = \frac{\sqrt{2}\, l_{Pl}^4 N}{\pi^2}$$

- Corrections to the bulk have implications for the boundary theory:

$$\alpha_{GB} \quad \rightarrow \quad \eta_{\partial\mathcal{M}} = \frac{(1-8\alpha)b^3}{16\pi l_{Ads}^3}$$



Studied examples

- Scalar fields: $\mathcal{L} = -\frac{1}{2}(\partial\phi)^2 - \frac{1}{12}\phi^2 R - V(\phi)$

  Fusco, Mann, FS 2021

- 4D Gauss-Bonnet: $\mathcal{L} = \psi\mathcal{G} - 2G^{ab}\nabla_a\psi\nabla_b\psi - \frac{1}{4}(\nabla\psi)^4 - (\nabla\psi)^2\Box\psi$

  Marks, Mann, FS 2021

- Exotic black holes: $\mathcal{L} = \frac{1}{16\pi}\sum_k \frac{\hat{\alpha}_k}{2^k}\delta^{a_1 b_1 \ldots a_k b_k}_{c_1 d_1 \ldots c_k d_k} R_{a_1 b_1}{}^{c_1 d_1} \ldots R_{a_k b_k}{}^{c_k d_k}$

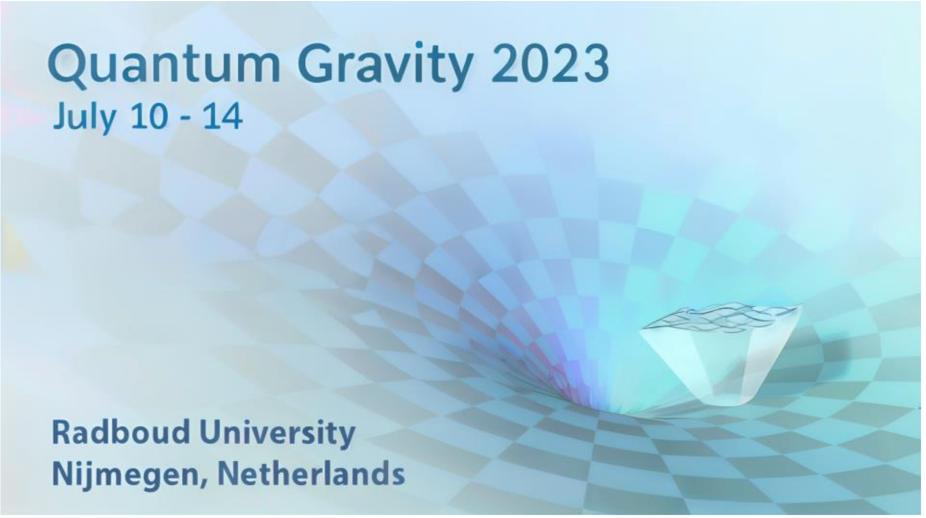
  Hull, FS 2022

- Regular black holes: $\mathcal{L} = \frac{4\mu}{\alpha}(\alpha F_{\mu\nu}F^{\mu\nu})^{\frac{\mu+3}{4}}\left(1 + (\alpha F_{\mu\nu}F^{\mu\nu})^{\frac{\mu}{4}}\right)^{-2}$

  Soranidis, FS 2023 (forthcoming)

Something to think about…

- Black holes continually provide fertile ground for understanding both classical and quantum gravity, and the potential for observations of quantum gravity effects.
- Beyond Ads/CFT… dS/CFT, local and quasi-local holography?
- Where do the microscopic degrees of freedom live?
- Information loss? Boundary unitarity?



IN·DEI·NOMINE·FELICITER

Radboud Universiteit

Thank you

Béatrice Bonga, Timothy Budd, Badri Krishnan, Renate Loll, Antonio Pereira, and Frank Saueressig

NWO
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