SEMI-CLASSICAL BLACK HOLES:

RECENT ADVANCES AND FUTURE PROSPECTS

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From Black Holes to the Cosmos: Matt Visser's journey through space and time, Trieste, 27 Aug 2026

MARIE CURIE ACTIONS

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Semi-classical gravity

- In the absence of a complete theory of quantum gravity, it is common to resort to solving the semi-classical Einstein equations:

$$G_{\mu\nu}(g_{\alpha\beta}) = 8\pi G \left\langle T_{\mu\nu}(g_{\alpha\beta}) \right\rangle$$

Einstein tensor for the quantum back-reacted metric $g_{\alpha\beta}$

renormalized stress tensor of quantum matter fields

- Computing $\left\langle T_{\mu\nu} \right\rangle$ and solving the coupled system of equations:

spacetime metric + **quantum correlators**

is often a ***daunting task*****,** because $\left\langle T_{\mu\nu} \right\rangle$ also depends on the metric.

Semi-classical gravity

- Typical approach: assume backreaction to be small and work perturbatively.
  - ➢ At zeroth order, solve the Einstein equations for the background,

$$G_{\mu\nu}(g^{(0)}_{\alpha\beta}) = 0$$

  - ➢ On this fixed background, compute the expectation value of the renormalized stress tensor,

$$\left\langle T_{\mu\nu}\left(g^{(0)}_{\alpha\beta}\right)\right\rangle$$

  - ➢ Quantum fields source the first-order perturbation in the metric,

$$G_{\mu\nu}\left(g^{(0)}_{\alpha\beta}, \delta g_{\alpha\beta}\right) = 8\pi G\left\langle T_{\mu\nu}\left(g^{(0)}_{\alpha\beta}\right)\right\rangle$$

Note: A cosmological constant can be included in the LHS.

Limitations of semi-classical gravity

- This approach can run into trouble.

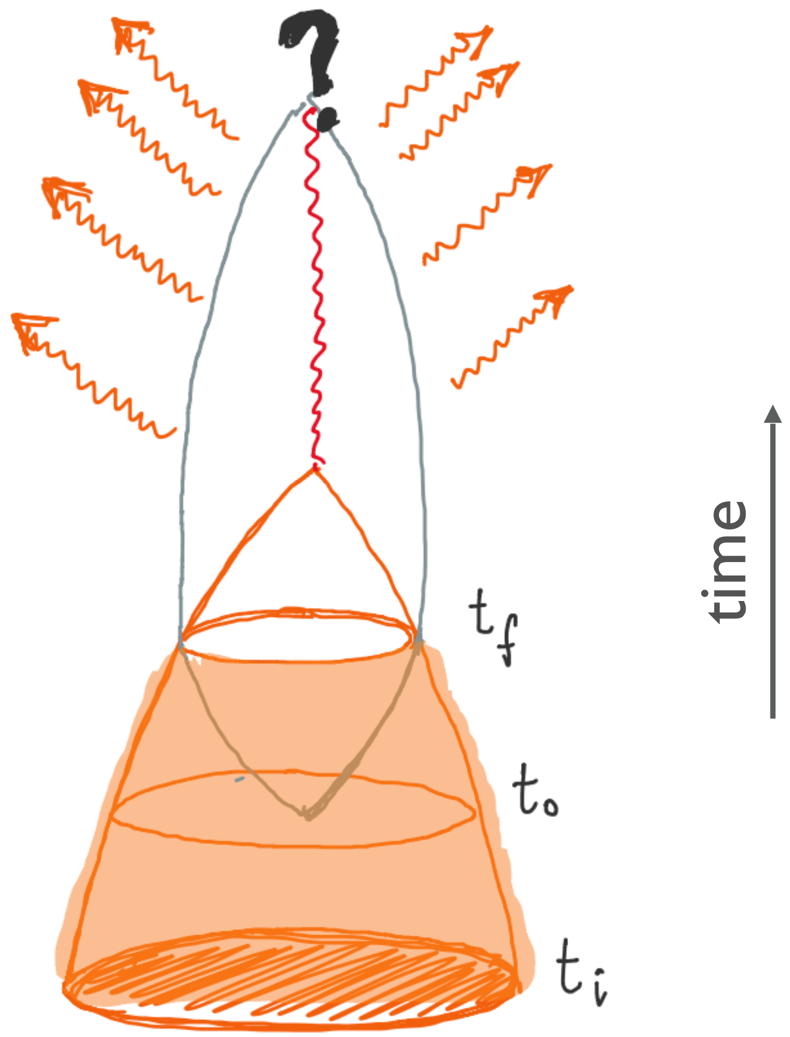
  E.g., the information paradox.

  ➢ In the semiclassical picture, black holes radiate thermally.

  Hawking (1974)

  ➢ This leads to non-unitary evolution.

  Hawking (1976)



- Non-perturbative effects, which could possibly resolve the information paradox, are not captured in this approach.

Holography (a non-perturbative tool)

In very special cases, alternative non-perturbative approaches are possible.

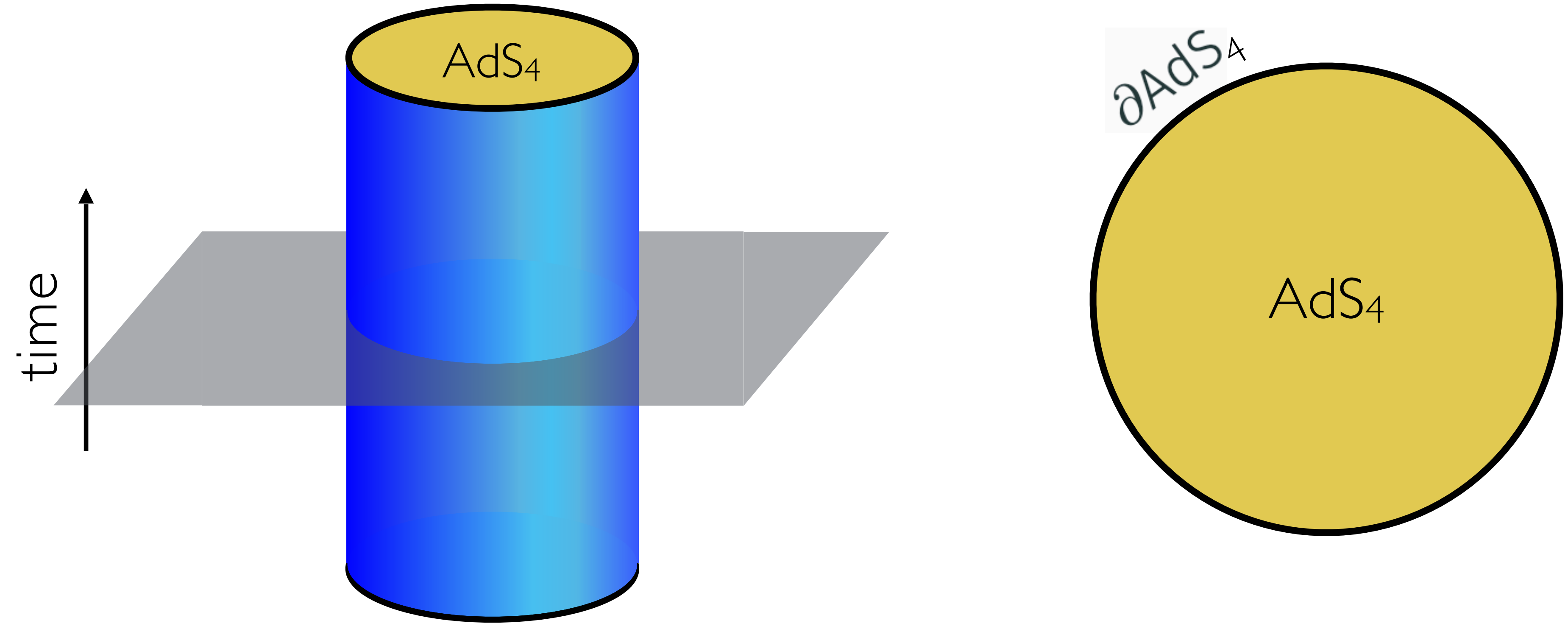
- One such approach is offered by 'holography':

Maldacena (1998)
Witten (1998)
Gubser, Klebanov, Polyakov (1998)

gravity in a 4D AdS spacetime ⟷ **quantum theory of 3D conformal fields**

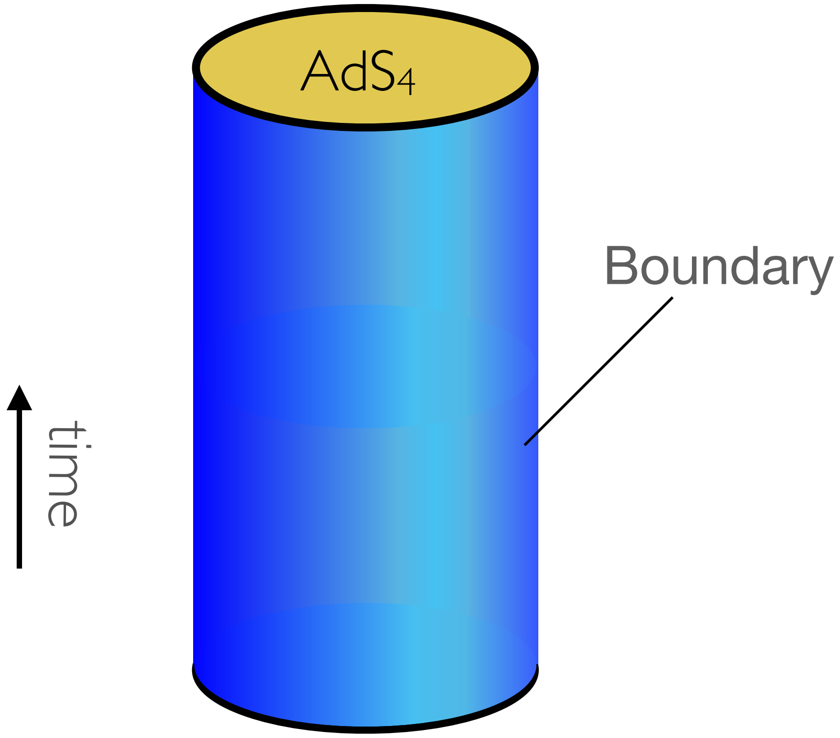
AdS_4/CFT_3

duality



Why study black holes in AdS?

- AdS is spatially a box (because light rays reach infinity in a finite time — the boundary of AdS is timelike)
- It comes with a scale related to the cosmological constant Λ: the constant curvature radius L_4.



→ The extended thermodynamic framework

Extending the standard framework of black hole thermodynamics to include the effect of a dynamical cosmological constant.

- **The idea:** pressure can be associated with a negative cosmological constant Λ

$$P = -\frac{\Lambda}{8\pi} = \frac{3}{8\pi L_4^2} \qquad V = \left(\frac{\partial M}{\partial P}\right)_S \qquad dM = T\,dS + V\,dP$$

Robert B. Mann, *"Black hole chemistry: The first 15 years"* (2025)

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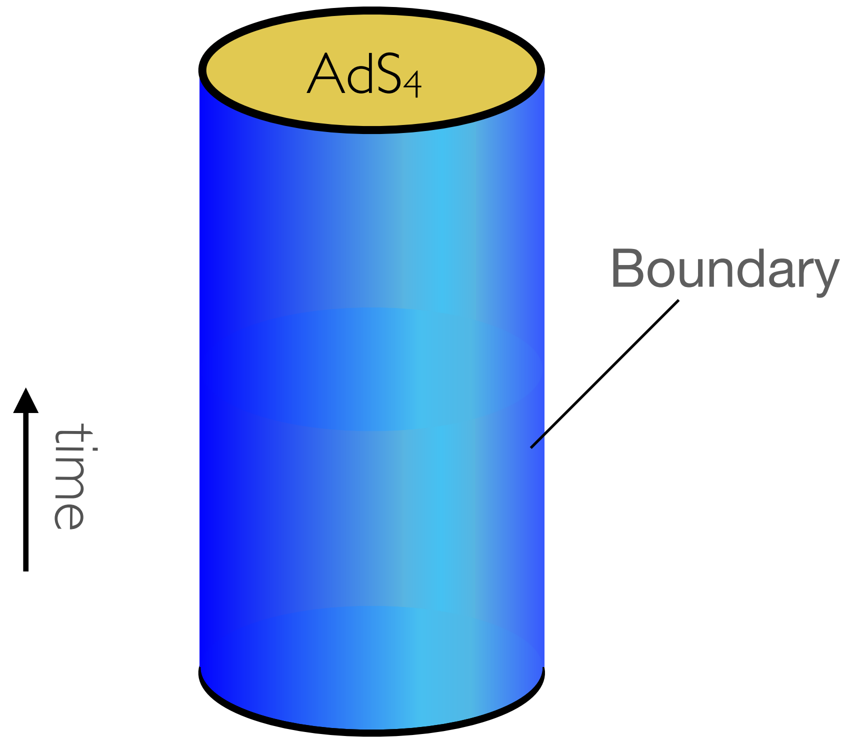

➡ The extended thermodynamic framework

- There are two distinguishable classes of BHs in AdS: small and large.
- Small AdS black holes are thermodynamically unstable and evaporate.

➡ Large AdS black holes are thermodynamically stable and don't evaporate.

➡ The AdS/CFT correspondence from string theory (quantum gravity).

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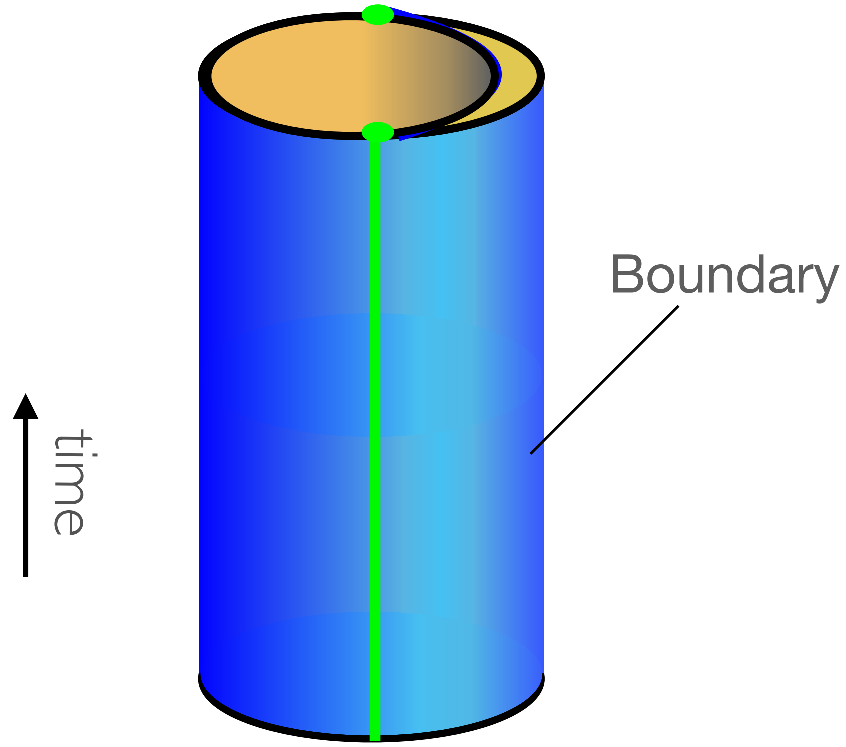

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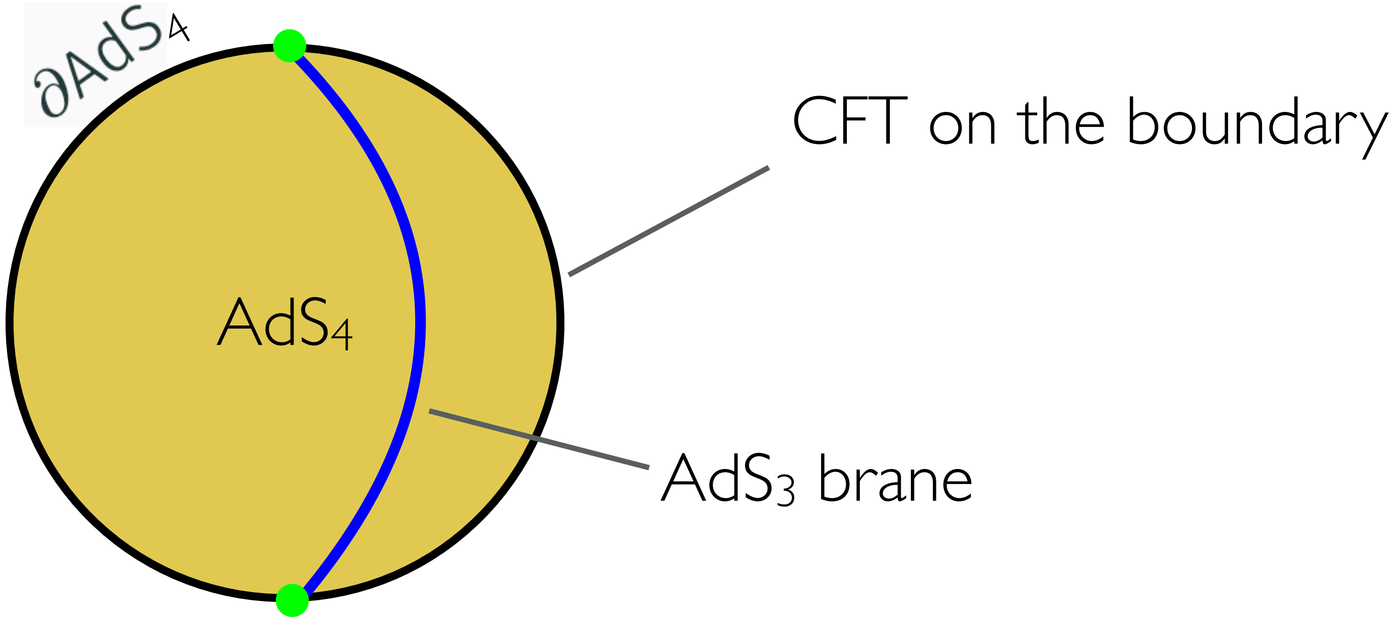
→ The AdS/CFT correspondence from string theory (quantum gravity).

→ Natural embedding for braneworld scenarios.

Braneworld Gravity

- In the simplest incarnation of the gauge-gravity correspondence, the conformal field theory is formulated on a **non-dynamical spacetime**. (Not promising if one wants to study quantum backreaction on black holes…)



- A notable setup that describes **a CFT coupled to dynamical AdS gravity** is the **Karch–Randall (KR) model.**

Karch, Randall (2001)

➡ Gravity is recovered on a 3D braneworld supporting the quantum fields.

➡ Originally considered a 5D bulk and a 4D brane, where (massive) gravity is recovered, along with CFT fields.

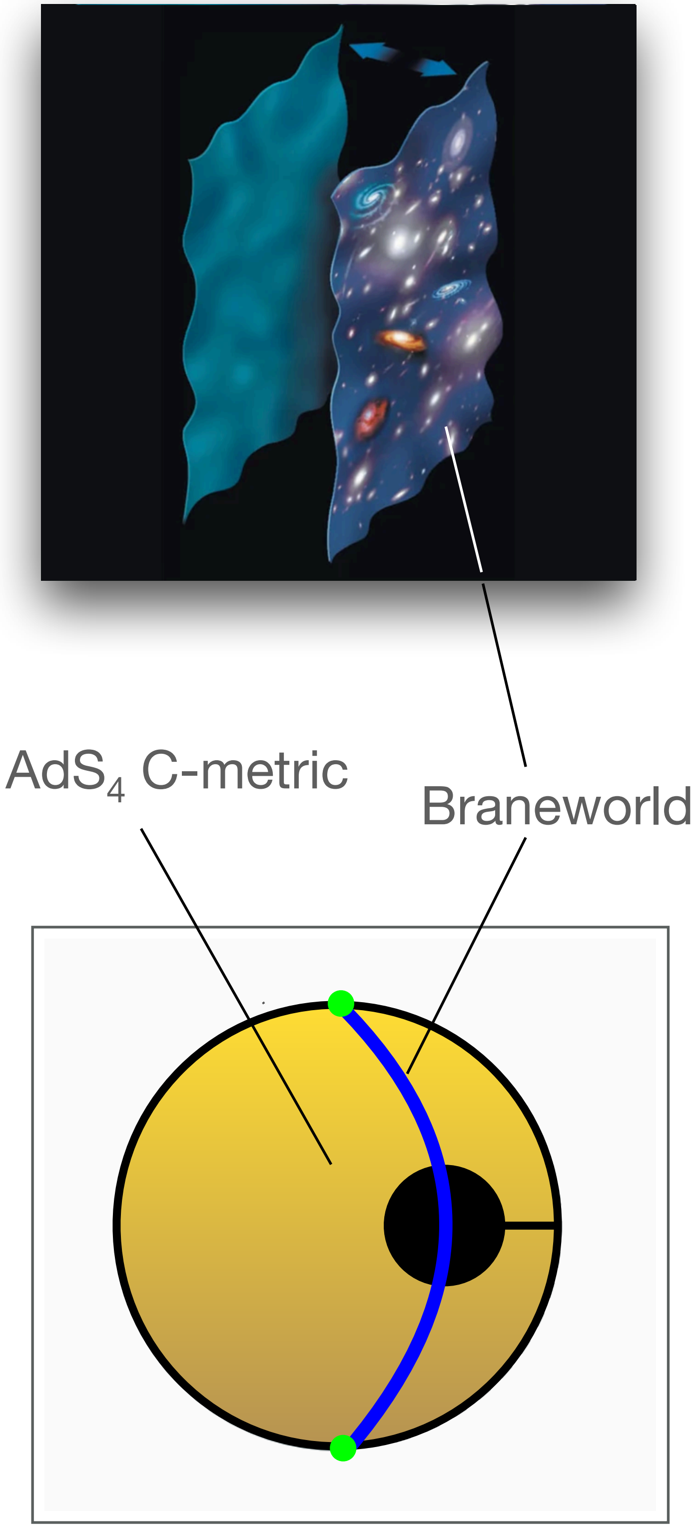
The main idea:

- One can improve over the semi-classical approximation, by **combining holography and braneworld** ideas with special exact (classical) black hole solutions (the AdS C-metric), to obtain quantum-corrected black holes.

Emparan, Horowitz, Myers (2000)
Emparan, Fabbri, Kaloper (2002)

- This is a **non-perturbative approach** that accounts for **backreaction from quantum fields** in an **exact** manner.

All such quantum black holes obtained so far are **three-dimensional**.



Outline

- ➢ Motivation: beyond semi-classical gravity
- ➢ Construction of the qBTZ black hole
- ➢ Thermodynamics of the qBTZ
- ➢ Testing weak cosmic censorship with the qBTZ black hole
- ➢ Conclusions and outlook

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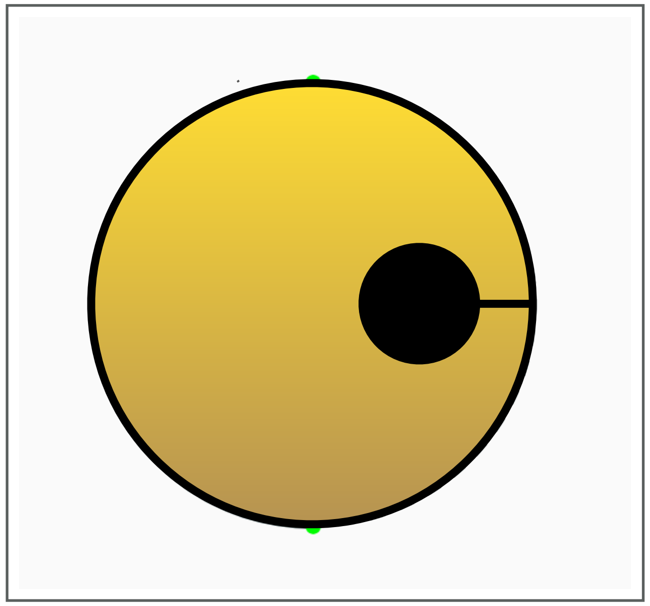
Accelerated black holes in AdS



- The AdS4 C–metric, which describes accelerating black holes in a 4D anti–de Sitter spacetime:

$$ds^2 = \frac{\ell^2}{(\ell + xr)^2}\left[-H(r)dt^2 + \frac{dr^2}{H(r)} + r^2\left(\frac{dx^2}{G(x)} + G(x)d\phi^2\right)\right]$$

- The parameter ℓ — inversely related to the acceleration — controls the tension of the cosmic string that pulls on the black hole.
  - ➡ It can be tuned so that the KR brane (at $x = 0$) slices the bulk black hole.

- In this setup, the surface $x = 0$ is totally umbilic, i.e. the extrinsic curvature K_{ij} and the induced metric on the brane satisfy:

$$K_{ij} = -\frac{1}{\ell}h_{ij}$$

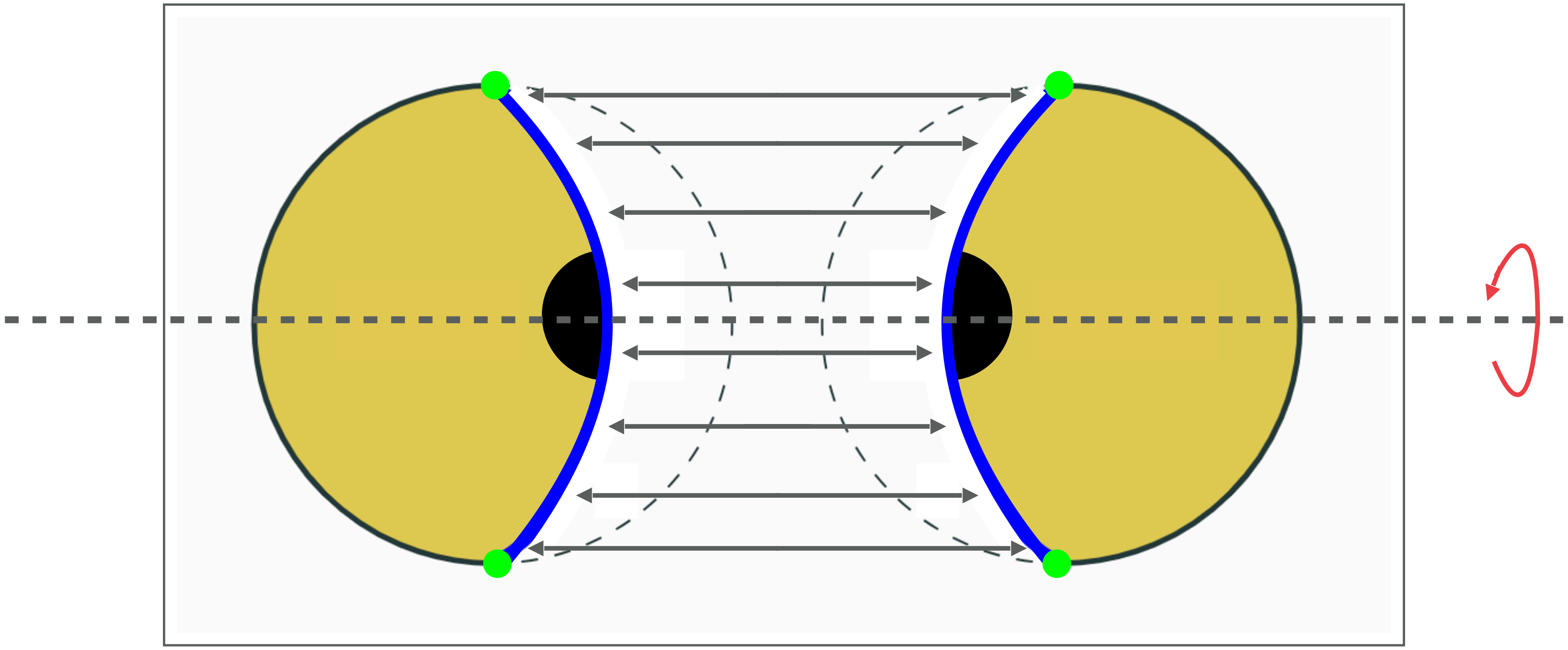
This coefficient is proportional to the brane's tension

Braneworld Black Holes

The accelerated black hole solution plus the braneworld scenario allows the construction of quantum black holes:

Emparan, Horowitz, Myers (2000)
Emparan, Fabbri, Kaloper (2002)
Tanaka (2003)
Emparan, AMF, Way (2020)

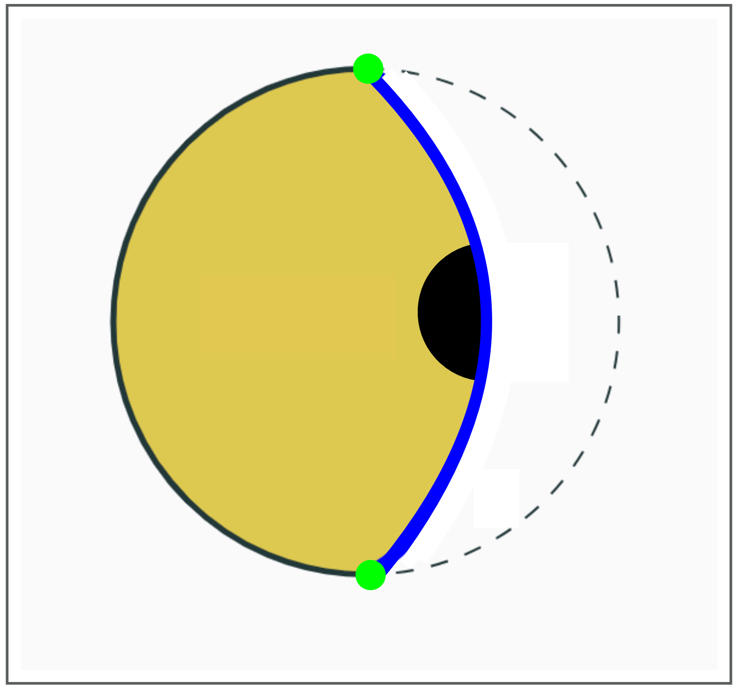
- Instead of starting with pure AdS$_4$ spacetime, now take an accelerated black hole in AdS (the AdS C-metric) and slice it with a Karch-Randall brane.



rotation can be included

- Discard the side containing the cosmic string.
- Then glue along the brane with another copy to obtain a two-sided brane.

Metric of the quantum BTZ black hole



- The 3D metric induced on the brane at $x = 0$ is:

$$ds^2|_{x=0} = -H(r)dt^2 + \frac{dr^2}{H(r)} + r^2 d\phi^2$$

$$H(r) = \frac{r^2}{L_3^2} - 8\mathcal{G}_3 M - \frac{F(M)\ell}{r}$$

- In the corresponding geometry on the 3D brane:
  - ➡ The acceleration is proportional to the tension τ of the 3D brane and controls the backreaction effects, parametrized by

$$\nu = \frac{\ell}{L_3} \qquad \tau \propto \frac{1}{\nu}$$

Interpretation: *This is a solution of a theory of 3D gravity coupled to a large number of quantum conformal fields, namely, the holographic CFT dual to the 4D bulk.*

Emparan, Fabbri, Kaloper (2002)

Semiclassical gravity on the brane

- **From the brane perspective,** the induced theory may thus be interpreted as **a semi-classical theory of gravity where the higher-derivative corrections incorporate backreaction effects due to the CFT living on the brane.**

$$\mathscr{G}_{\mu\nu}(g_{\alpha\beta}) = 8\pi\, G_3 \left\langle T_{\mu\nu}(g_{\alpha\beta}) \right\rangle_{\text{planar}}$$

Einstein tensor including the Λ_3 induced cosmological constant on the brane + higher-curvature terms

Holographic CFT stress-tensor in the planar limit

- Going beyond the planar limit corresponds to including bulk quantum effects (conventional perturbative backreaction problem in the four-dimensional bulk).

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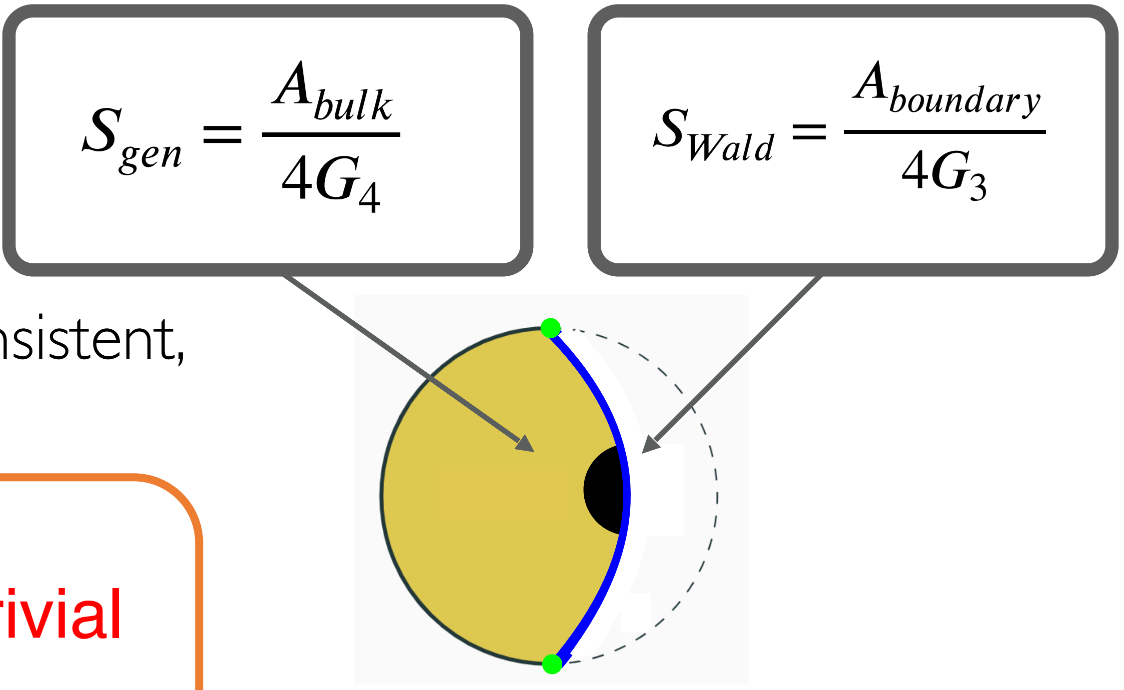
Induced thermodynamics of qBTZ

- Some bulk BH thermodynamic quantities duplicate as thermodynamics of qBTZ:

$$T = T_{qBTZ} \qquad S_{gen} \equiv S_{Wald} + S_{outside}$$



$$S_{gen} = \frac{A_{bulk}}{4G_4}$$

$$S_{Wald} = \frac{A_{boundary}}{4G_3}$$

- If the holographic interpretation of braneworld is consistent, then:

$$T dS_{\text{gen}} = dM - \Omega dJ$$

1st law: Not trivial

In the bulk

On the brane w/ higher curvature gravity

$$\Delta S_{\text{gen}} \geqslant 0$$

2nd law: Trivial

- S_{Wald} alone will not satisfy these relations.
- Thermodynamics with fixed tension.

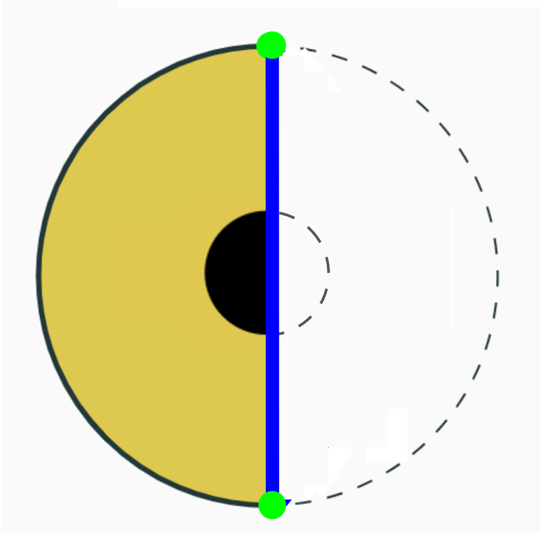
Emparan, AMF, Way (2020)

Variation of the tension

- From the bulk perspective, it is very natural to vary the tension of the brane, since it is a physical parameter of the system.

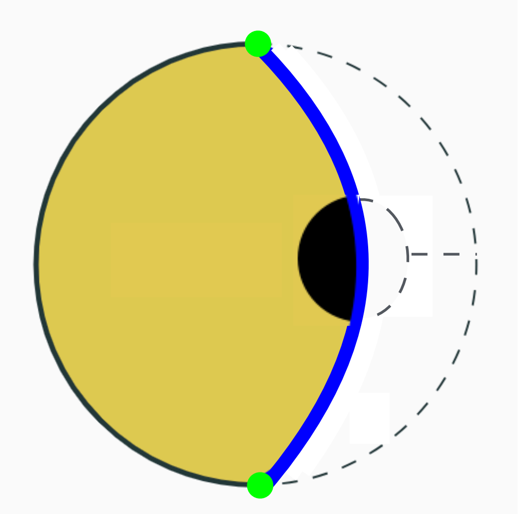
- The tension determines the position of the brane via Israel junction conditions, thence varying the tension changes the position.

$\nu \to \infty$



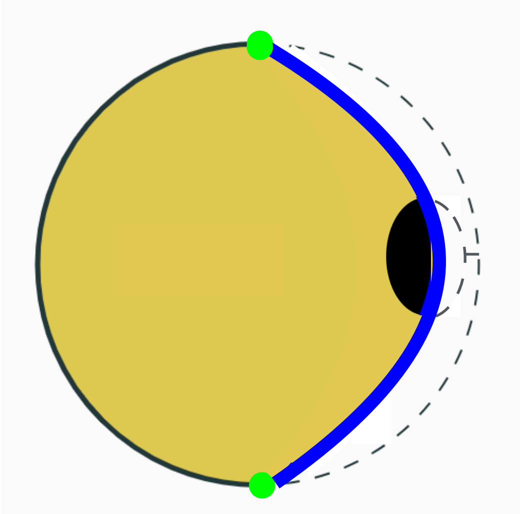
AdS4 BH
(only Z_2 symmetry)

$0 < \nu < \infty$



BH+CFT

$\nu \to 0$



$\kappa = -1$ bd geometry
is BTZ

$$\tau \propto \frac{1}{G_3 \nu}$$

- Accordingly, varying the tension alone corresponds to varying the CC on the brane:

$$d\tau = \frac{d\Lambda_3}{8\pi G_3}$$

Induced extended thermodynamics

- Consider the case when the brane tension is treated as a thermodynamic variable, similar to the surface tension of liquids.

- The effect is that the brane will do work on the black hole system, such that the bulk first law becomes:

$$dM = TdS + A_\tau d\tau$$

$$\boxed{A_\tau \equiv \left(\frac{\partial M}{\partial \tau}\right)_S}$$

- **The bulk first law maps to the brane first law:**

Generalization of the quantum 1st law at fixed tension

$$dM = TdS_{gen} + V_3 dP_3$$

$$\boxed{P_3 \equiv -\frac{\Lambda_3}{8\pi G_3} \qquad V_3 \equiv \left(\frac{\partial M}{\partial P_3}\right)_S}$$

AMF, Pedraza, Svesko, Visser PRL (2023)
AMF, Hennigar, Pedraza, Svesko PRL (2024)

AMF, Mann, Mureika, PRD (2015)

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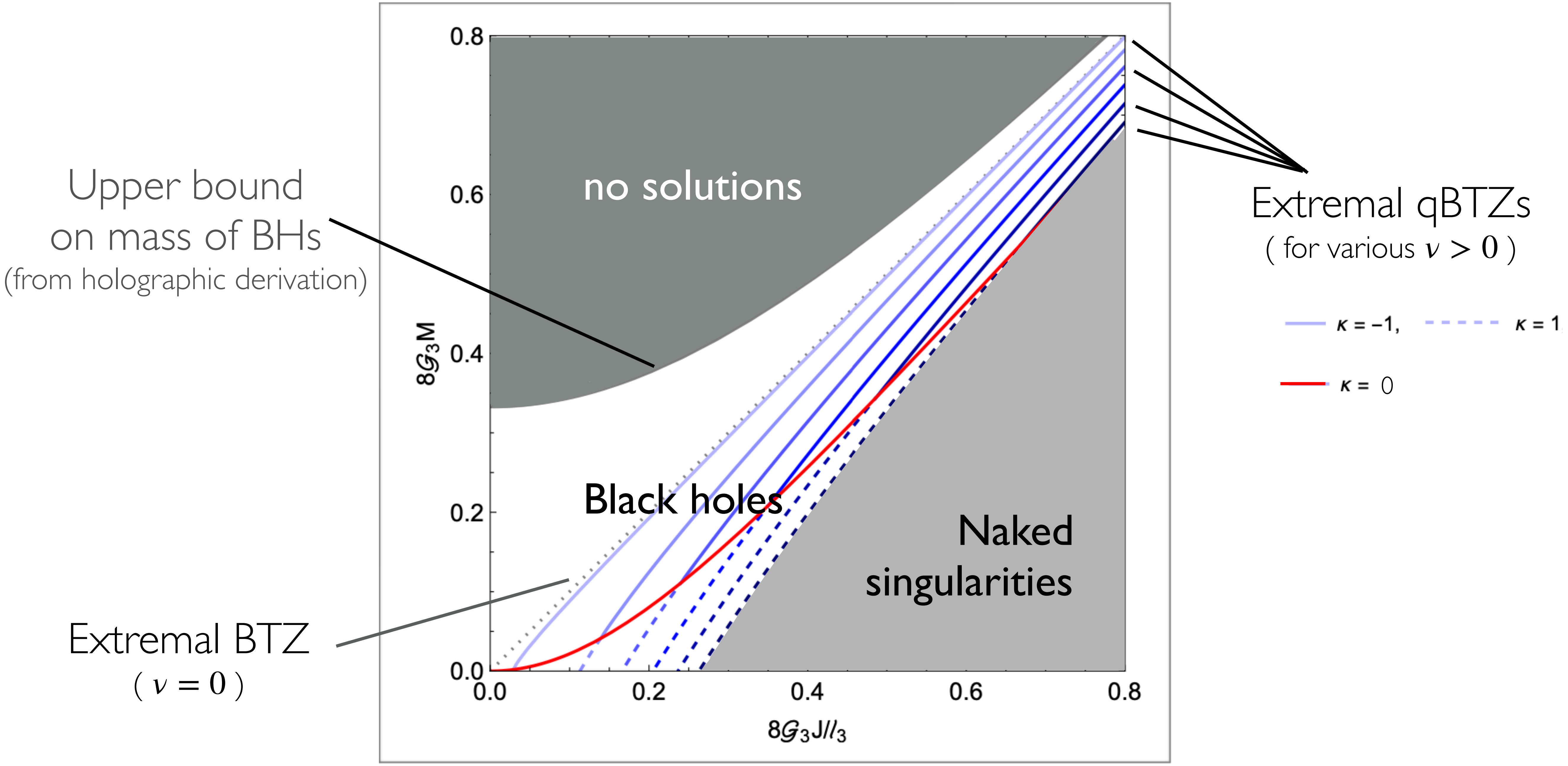
Mass vs. spin diagram of the quantum BTZ spacetime



Upper bound
on mass of BHs
(from holographic derivation)

Extremal BTZ
($\nu = 0$)

Extremal qBTZs
(for various $\nu > 0$)

- Curve of extremal qBTZ spacetimes depends on the backreaction parameter ν
- The region of parameter space occupied by black holes grows with backreaction.

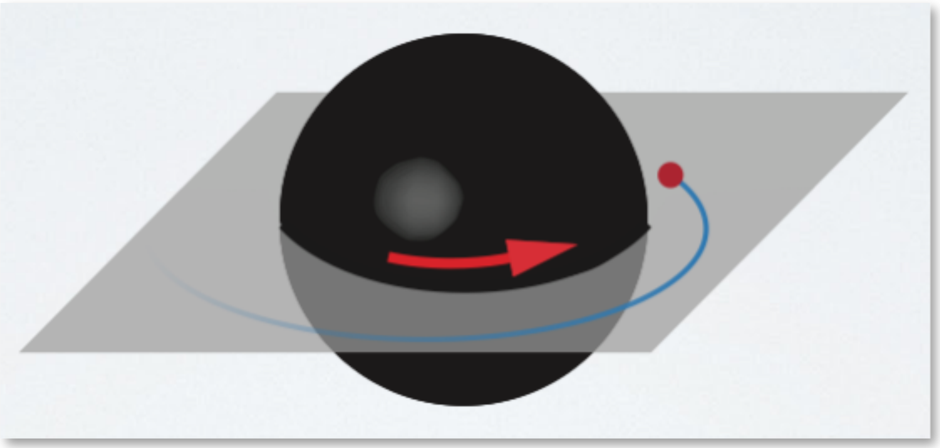
Weak Cosmic Censorship Conjecture (WCCC)

- Penrose famously conjectured that, under time evolution with regular generic initial conditions and matter respecting standard energy conditions, spacetime singularities should remain hidden from asymptotic observers, cloaked by event horizons.

Penrose (1969)

- If true, this conjecture offers protection to the deterministic picture of classical evolution in gravitational collapse.

- Wald's Gedanken experiment: Wald (1974)
  Try to destroy the event horizon of extremal rotating (and/or charged) BHs with test particles.



- WCCC is respected:
  Point particles with dangerously high spin/charge bounce before reaching the black hole, instead of disrupting the horizon.

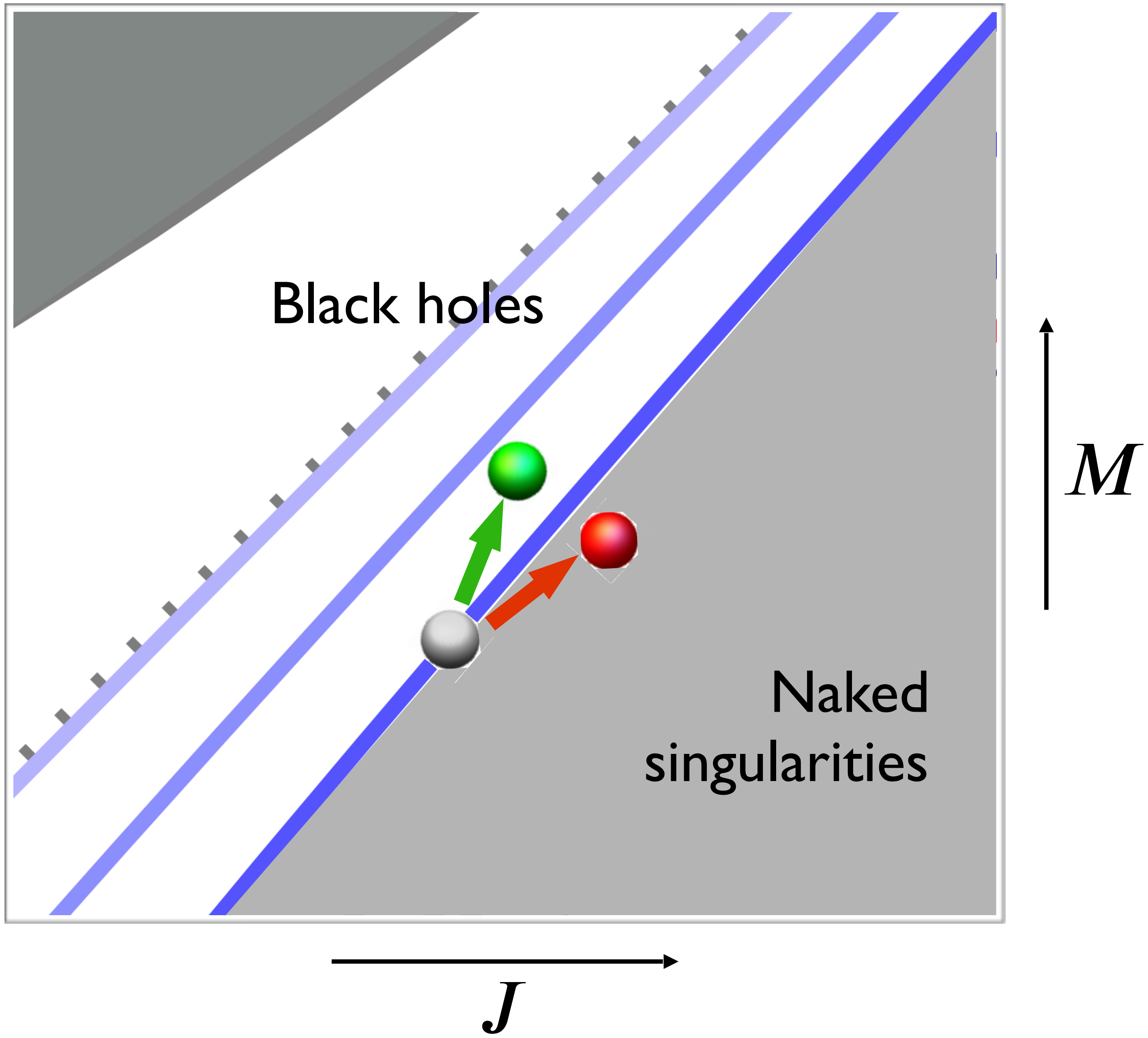
Wald’s Gedanken Experiment on qBTZ

- Assume the test-particle approximation, with the absorbed particle imparting linear perturbations on the mass and the angular momentum of the BH.

1. Pick an extremal background BH.

2. Compute the variations δM and δJ.

3. Check if final BH lies above or below the extremality curve.



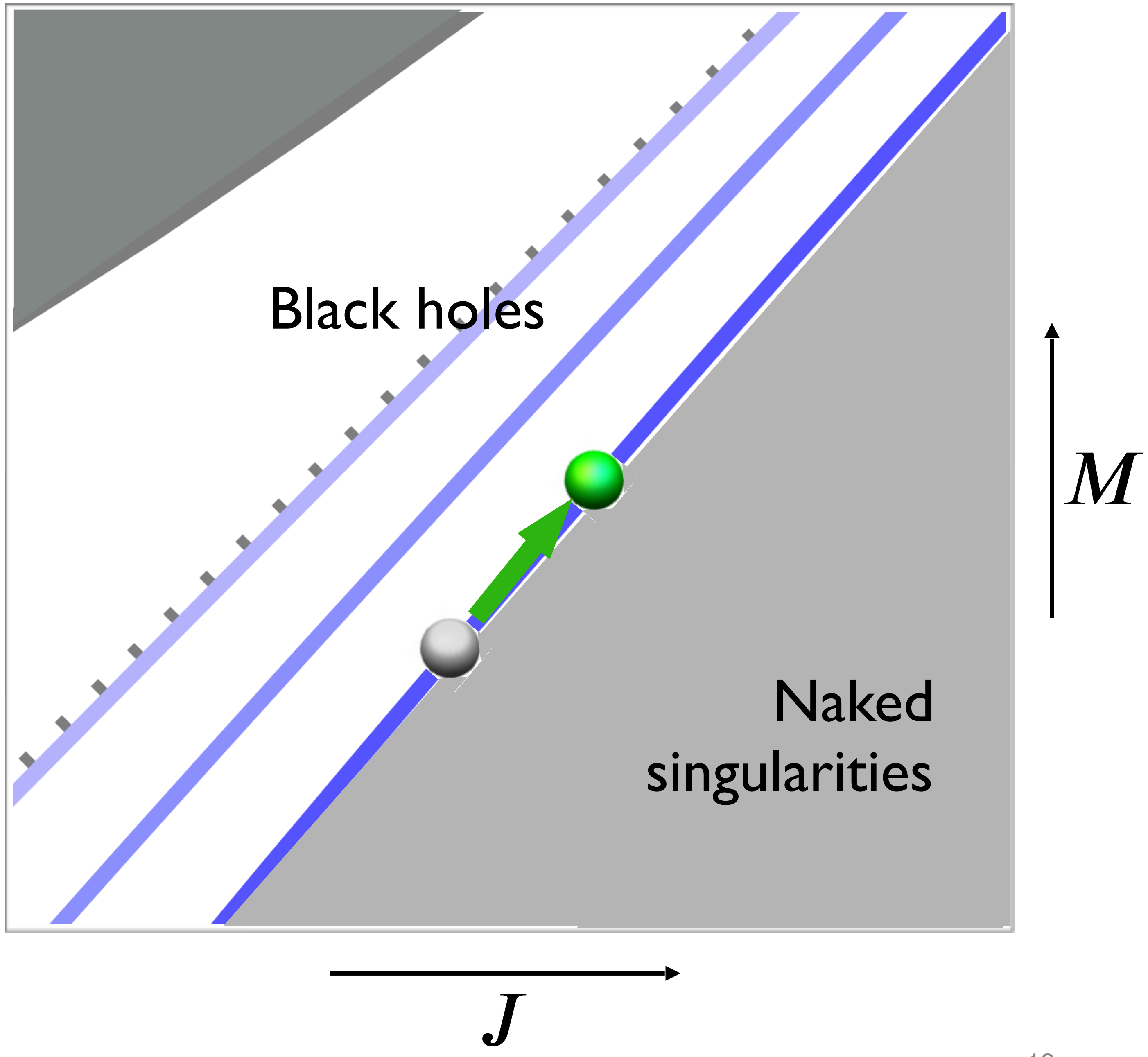
Testing weak Cosmic Censorship with qBTZ

- ✦ Endow the test particle with the maximum angular momentum that still allows it to reach the horizon. (This is the sharpest challenge toWCCC.)

- For this threshold case, an analytic calculation reveals that the perturbed BH remains extremal.

The event horizon is not destroyed.

AMF, Rocha, Sanna, JHEP (2024)

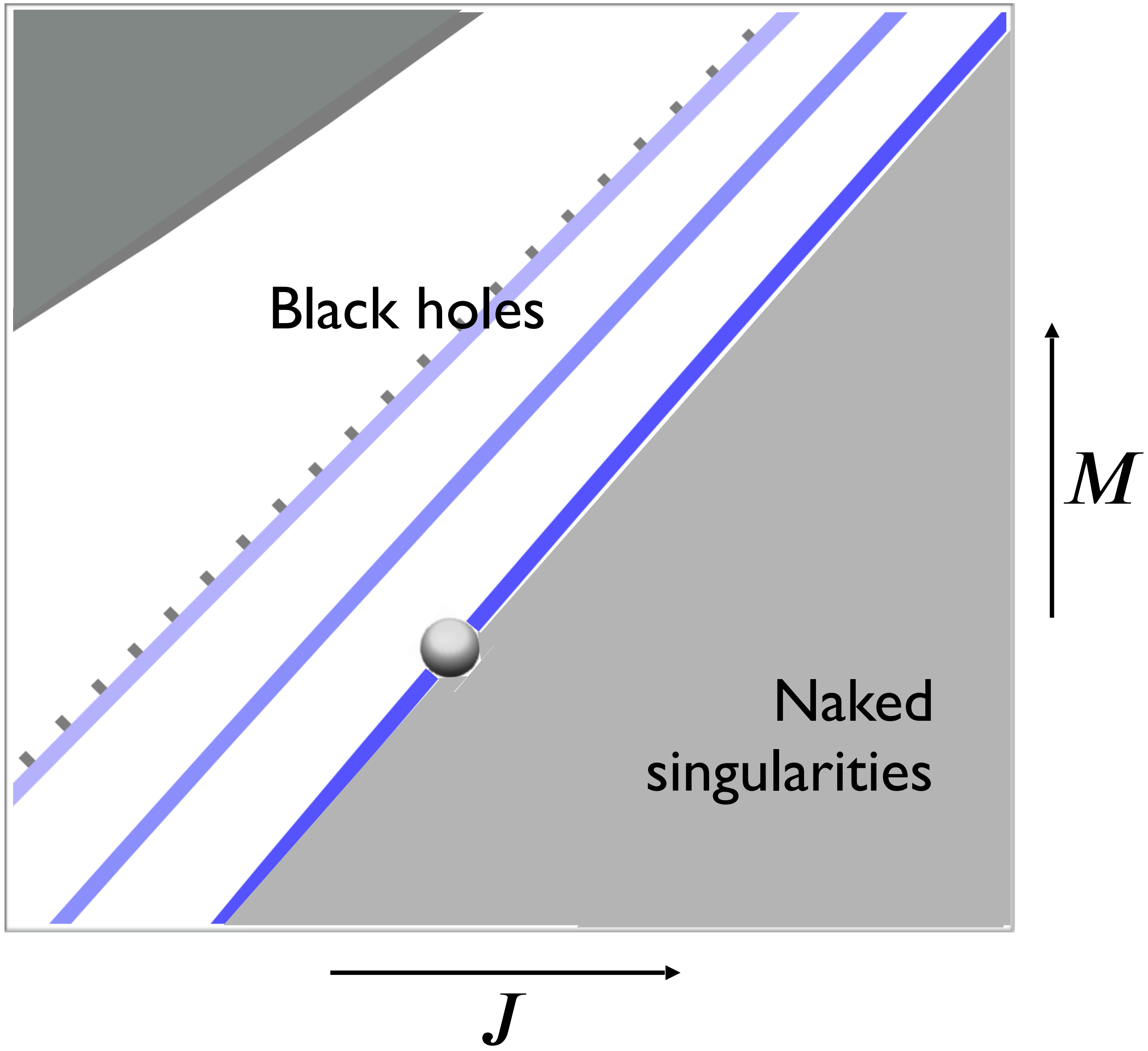


Testing weak Cosmic Censorship with qBTZ

- A non-linear numerical assessment of Wald gedanken experiment with qBTZ reveals that extremal back holes become sub-extremal upon the absorption of generic test particles.

- **Cosmic censorship is respected.**
- **Quantum backreaction typically strengthens cosmic censorship.**

AMF, Rocha, Sanna, JHEP (2024)



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Conclusions

- **Braneworld holography** allows to study quantum effects on black hole geometries and its relation to cornerstone mathematical results in GR such as:
  - **Black hole thermodynamics**
    - It offers a natural framework to explore extended black hole thermodynamics.

      AMF, Pedraza, Svesko, Visser PRL (2023)
  - **Geometric inequalities (e.g. Penrose inequality)**

    AMF, Hennigar, Pedraza, Svesko PRL (2024)
  - **Weak cosmic censorship**

    AMF, Rocha, Sanna, JHEP (2024)

Outlook

- Quantum back reaction for regular BTZ black hole?

- A quantum corrected AdS$_3$-soliton can be constructed by slicing the AdS C-metric with a different umbilical brane (one that does not intersect the bulk BH).

  Hennigar, Patra, Ross, JHEP (2026)

- dS quantum black holes are also possible to obtain upon careful Wick rotation and brane-slicing the bulk differently.

  Emparan, Pedraza, Svesko, Tomašević, Visser, JHEP (2022)

- One can also consider point particles falling into the BH directly from the bulk, for instance, a spinning partile falling along the axis of rotation of the BH, with spins aligned.

  AMF, Rocha, Sanna, PLB (2025)