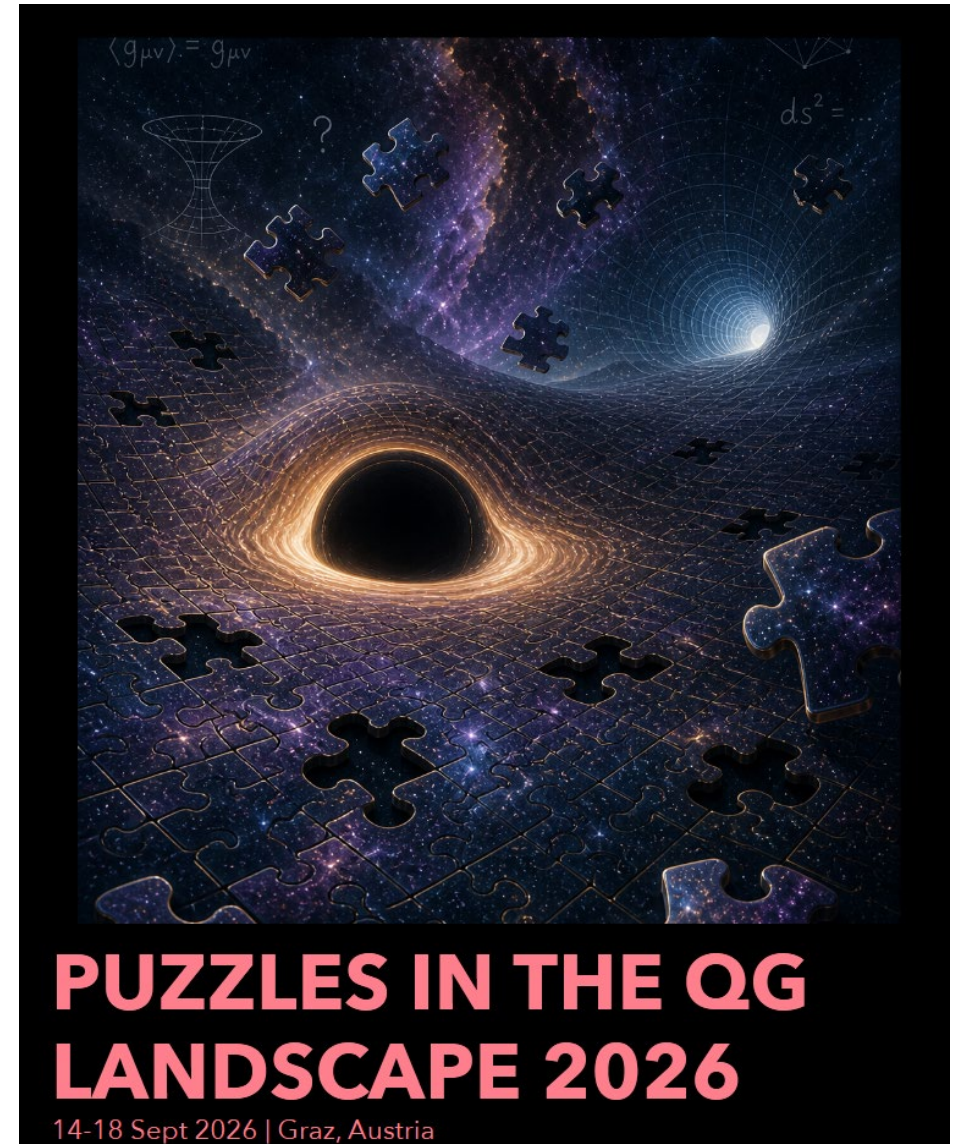


15 September 2026

An EFT perspective on gravity and black holes

(and What is Wrong with it)

Alessandra Gneccchi
INFN, Padova (Italy)



Outline

- Introduction and motivations
- Gravity as EFT
 - *Success and limitations in the string theory approach*
 - *Fundamental principles from IR physics*
- Black holes
 - *why are they our most promising theoretical laboratory?*
 - *why are they still a problem?*
- Outlook



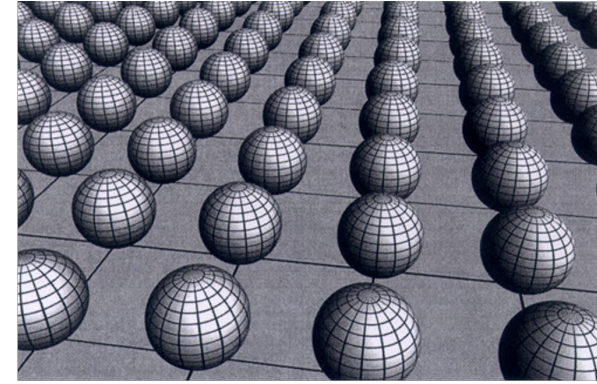
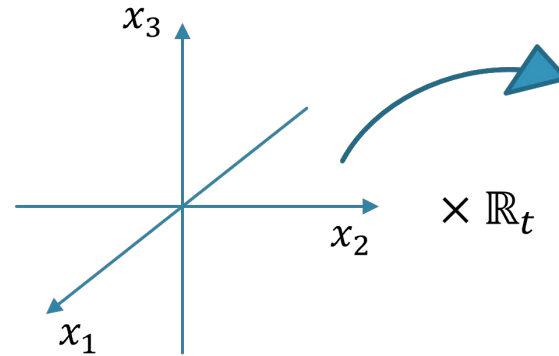
Motivations

- String theory provides a UV-complete theory of gravity, with classical geometries and black holes among its low-energy solutions.



- Gravitational EFT tells us what low-energy observers know, without access to the complete microscopic theory
- .. but fundamental properties of the UV-complete theory appear as constraints on the EFT, much below the Planck scale
- Black holes both realize these constraints and expose the limits of the EFT description

String Theory: what we love and hate



- It is consistent only in 10 (or 11) dimensions.
- Too many vacua! Too many particles!
- It is a supersymmetric theory
- We can engineer only some quantum field theories out of strings and branes
- We cannot directly predict the standard model

- $10 = d + (10-d)$ compactified extra dimensions
- A lot of concrete examples to study
- We can actually compute things!
- We can engineer quantum field theories out of strings and branes!
- We can directly address questions about QG

String Theory Landscape and the Swampland program

Depending on the geometry of the internal (10-d) compact space, and the strings and branes constituents, the resulting theory is a (strongly coupled) QFT.

What effective field theories can be consistently coupled to a theory of gravity in the UV **and why?**

What constraints String Theory imposes on the landscape EFT?

Develop a set of principles for an EFT to be compatible with a theory of quantum gravity

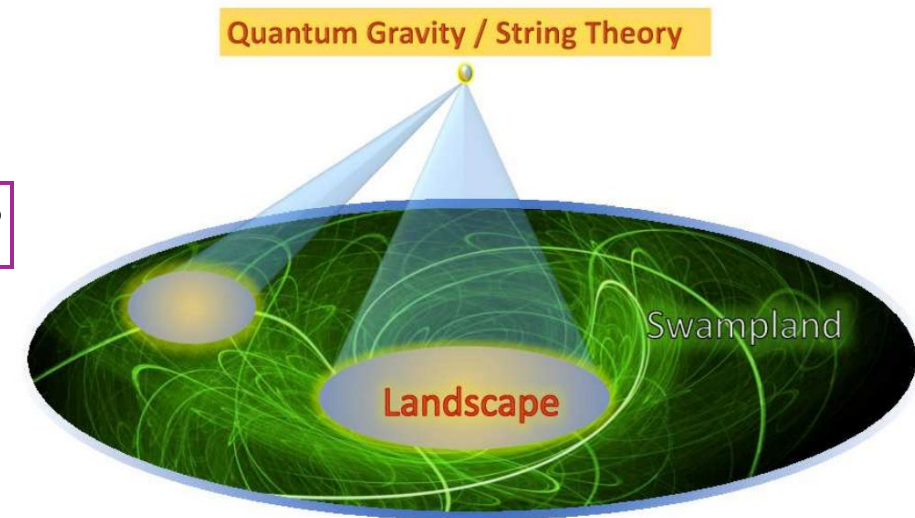


Image by E. Palti

UV-IR mixing

- Bekenstein bound

$$S_{QFT} \leq \frac{Area}{4G_N} \sim M_{Pl}^2 L^2$$

If $S_{matter} > S_{BH}$, by throwing more matter, one can create a BH, thus lower the entropy, violating the second law

- Origin of 't Hooft – Susskind **holographic** proposal: the QFT overcounts the number of states

$$S_{QFT}(\Lambda) \sim \Lambda^3 L^3$$

- Bekenstein bound implies that the states in the local QFT will collapse into black holes when their entropy reach $S \sim A$.

—————> UV and IR cutoffs in the Effective Field Theory are related due to gravity

UV – IR mixing *CKN bound*

[Cohen, Kaplan, Nelson '98]

- BB could be naively violated. In order to have a QFT that respects this bound we need to require that our QFT obeys

$$S_{QFT} \sim \Lambda^3 L^3 \leq \pi L^2 M_{Pl}^2$$

However, in order for the highly entropic states to be able to collapse into black holes, we must require that their Schwarzschild radius is contained in the volume of the system so

$$r_S = 2G_N M(L, \Lambda) \sim M_{Pl}^{-2} L^3 \Lambda^4 \leq L \quad \Rightarrow \quad \Lambda \leq \sqrt{\frac{M_{Pl}}{L}}$$

- the states that saturate this bound are the highest entropy states and, from the formula above one can see already that

$$S_{QFT}^{max} = S_{QFT}(r_S \sim L) \sim L^3 \Lambda_{UV*}^3 = (L^2 M_{Pl}^2)^{3/4} \sim \Lambda^{3/4}$$

UV – IR mixing *species scale*

The presence of light fields in the EFT lowers the QG cutoff

The gravitational effective theory has an effective cutoff lower than the Planck scale:

$$\Lambda_{UV} = \frac{M_{Pl}}{N^{1/(D-2)}}$$

- Perturbative argument: every particle species renormalizes the Planck mass by a factor Λ^2 .
- Non-perturbative argument: evaporation of a black hole of mass $M_{BH} = N\Lambda$ through heavy particles when its temperature drops to $T_H \sim \Lambda$

[Dvali '07] [Dvali, Redi '07]

- Bounds on Λ_{IR} using CEB from different towers of states M_{tower} [Castellano, Herráez, Ibáñez '22]
- Size of the smallest black hole in the theory, a thermodynamics associated to the species scale? [Basile, Cribiori, Lust, Montella, '24]
- Dependence on the massless/light modes [Long, Montero, Vafa, Valenzuela '21] [van de Heisteeg, Vafa, Wiesner, (Wu) '22-'23]....

EFT breakdown in String Theory

- Solutions of String Theory semiclassical equations of motion require *moduli stabilization*
- String Theory EFT are characterized by a choice of moduli
- What happens when we move in moduli space?

➤ Breakdown of the EFT at infinite distance in moduli space:

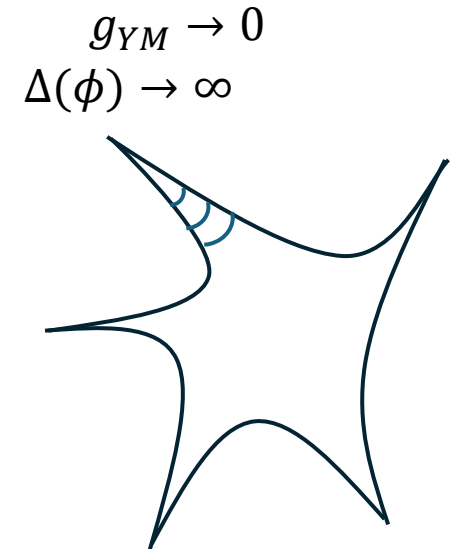
Swampland distance conjecture [Ooguri, Vafa '06]

Appearance of an asymptotic tower of light states, natural from a string theory perspective

Possibly a new, weakly coupled description of the theory is reached (string dualities)

Emergent string conjecture – only possibility is decompactification or tensionless string states (weakly coupled string theory limit)

[Lee, Lerche, Weigand '19]



EFT breakdown in String Theory

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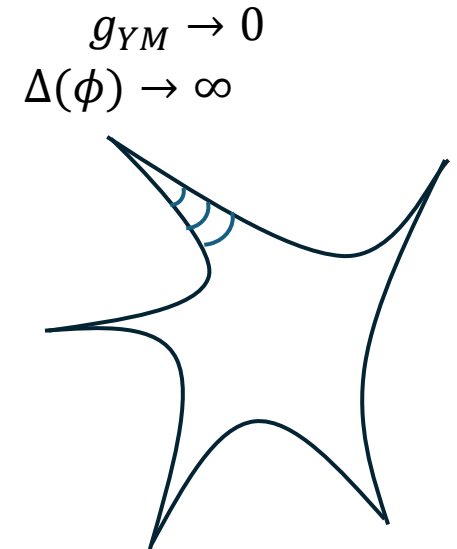
Swampland distance conjecture [Ooguri, Vafa '06]

Appearance of an asymptotic tower of light states, natural from a string theory perspective

$$mL_P \sim e^{-\lambda\Delta(\phi)}$$

If we decouple gravity, swampland constraints become irrelevant so the tower of states is identified by those states with mass

$$m \sim L_P^{-1} \text{ for } L_P \rightarrow 0$$



Black holes as a lamp in the Swampland

1. NO CONT. GLOBAL SYMMETRIES
Would not be conserved with black hole evaporation
2. ALL CHARGES IN THE SPECTRUM MUST BE REALIZED
3. GRAVITY IS THE WEAKEST FORCE

[N. Arkani-Hamed, L. Motl, A. Nicolis, C. Vafa, '07]

Extremal (BPS) bound: $M \geq Q$

In order not to have BPS black hole remnants,

$M-m, Q-q \longrightarrow m \leq q$

BPS states are the only ones for which $q=m$

Mass M , charge Q

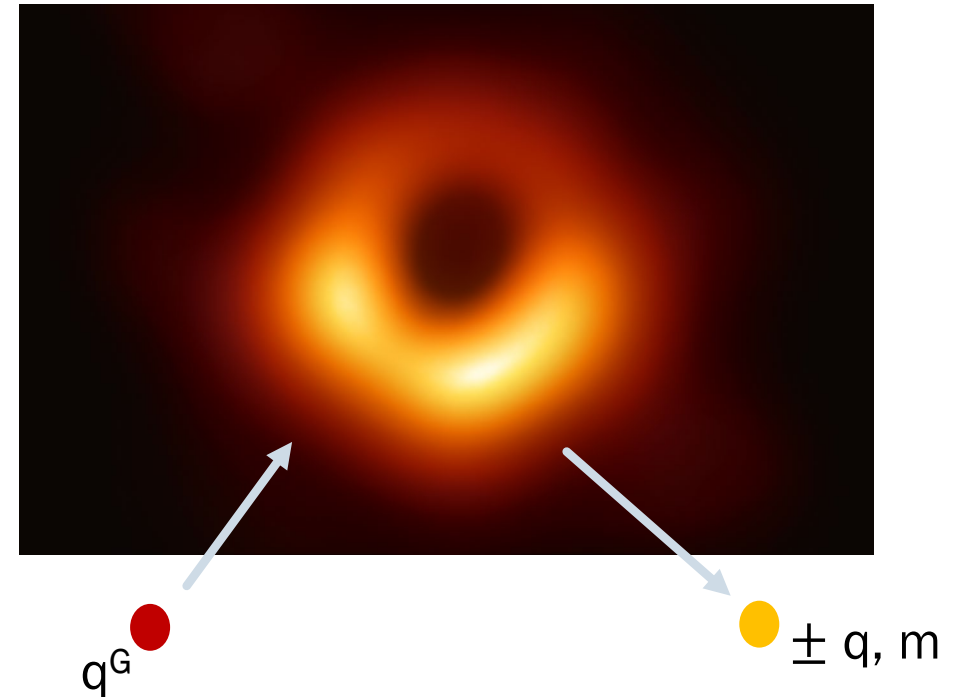
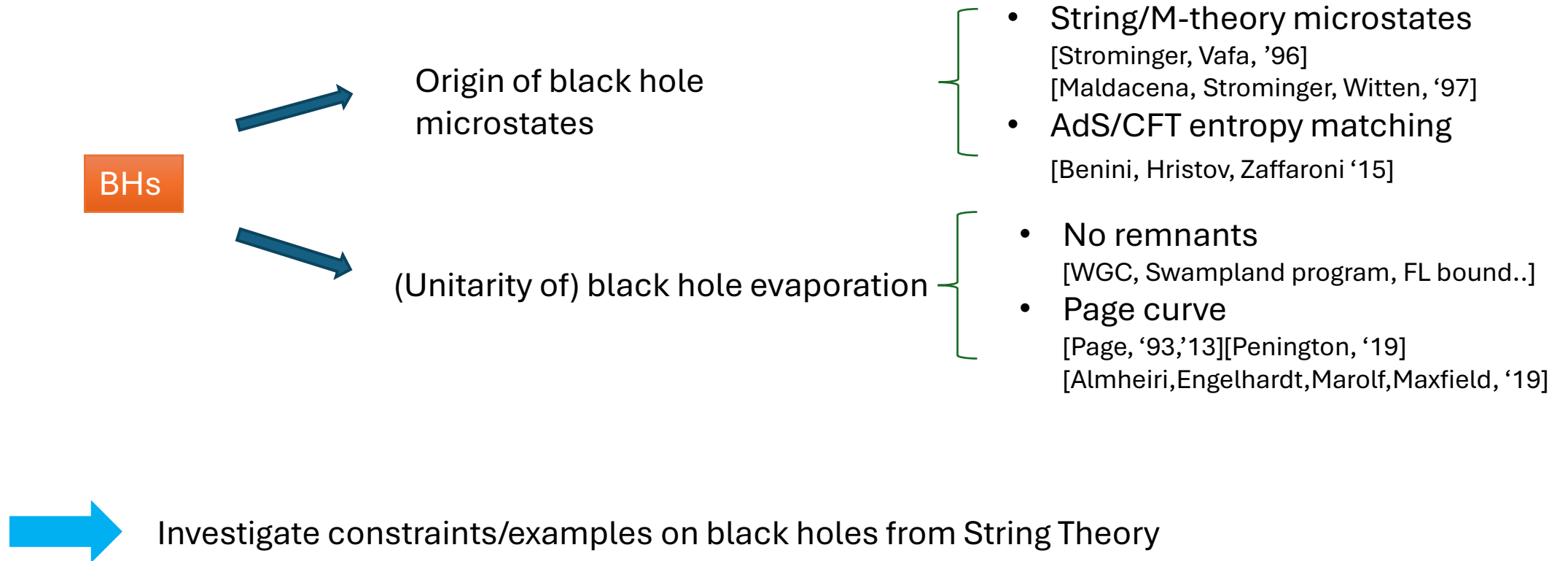


Image by EHT

Black holes as a powerful theoretical lab

Black hole physics raise puzzles that require extending the EFT

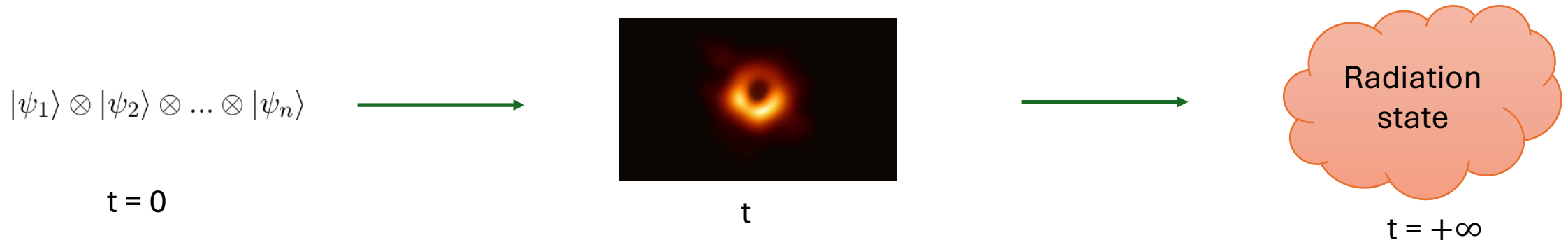


Entanglement and black hole evaporation

Quantum field theory in a black hole background, is in equilibrium with the BH at temperature $T_H = \frac{\kappa}{2\pi}$

First law: $T_H dS_{BH} = dM - \Phi dQ$

Bekenstein-Hawking entropy: $S_{BH} = \frac{k_B c^3}{\hbar} \frac{Area}{4G_N}$



The evolution is *Unitary*



At every time t the state is in a *pure state*

In order to ensure a pure state, the radiation must be *entangled* with the black hole interior

General Relativity and Quantum Cosmology

[Submitted on 15 Feb 2014]

1983 paper on entanglement entropy: "On the Entropy of the Vacuum outside a Horizon"

Rafael D. Sorkin

I introduce the concept of *entanglement entropy* (as it's now called) and point out that it follows an *area law* which renders it a suitable source of black hole entropy. I also suggest to conceive the latter as residing on the horizon at approximately one bit per "Planckian plaquette".

Comments: This is a verbatim copy of a paper published originally in 1983, before the existence of "arXiv". Also available at [this http URL](#)

Subjects: **General Relativity and Quantum Cosmology (gr-qc)**; Statistical Mechanics (cond-mat.stat-mech); High Energy Physics - Theory (hep-th); Quantum Physics (quant-ph)

Cite as: [arXiv:1402.3589 \[gr-qc\]](#)
(or [arXiv:1402.3589v1 \[gr-qc\]](#) for this version)
<https://doi.org/10.48550/arXiv.1402.3589> 

Journal reference: Tenth International Conference on General Relativity and Gravitation (held Padova, 4-9 July, 1983), Contributed Papers, vol. II, pp. 734-736

Entanglement and black hole evaporation

Initial state: infalling quantum matter



Pure quantum state

$$\rho = |\psi\rangle\langle\psi|$$

Black hole state +
Hawking radiation



$$B = A^c$$

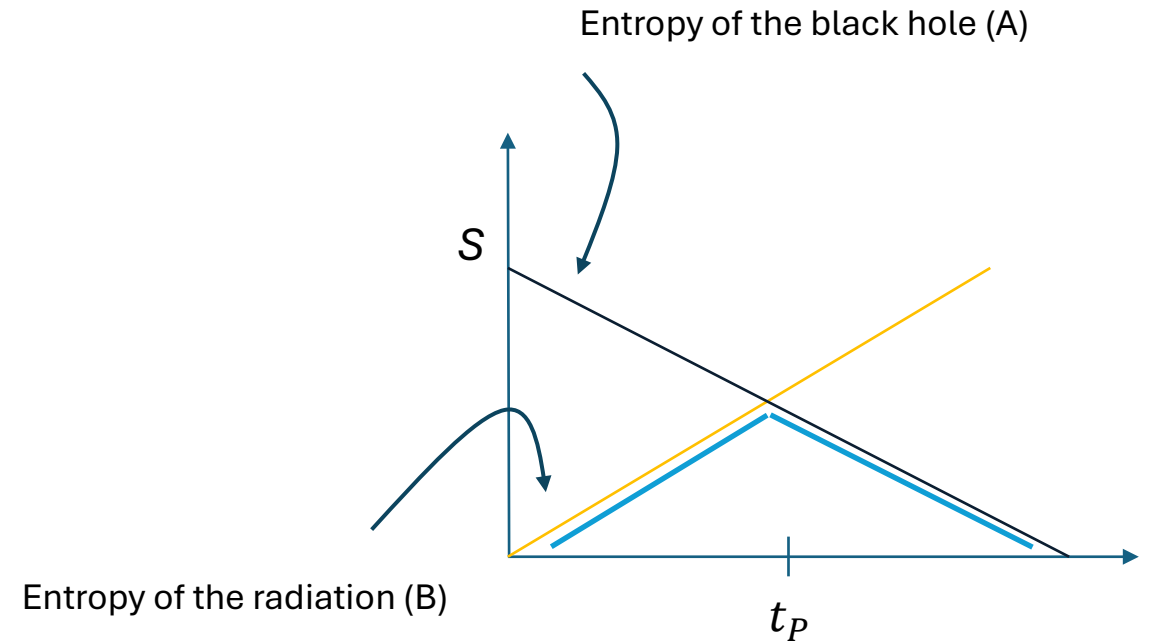
The information is in the **entanglement** of the radiation with the black hole interior

$$\rho_B = \text{tr}_A \rho$$

$$S_{VN} = S_B = -\text{tr} \rho_B \log \rho_B$$

Is the Von Neumann, or *Entanglement entropy*.

If the system is in a pure state $S_A = S_{A^c}$



'Page curve'

Hawking radiation and entanglement

Entanglement grows with the size of the subsystem B until it is half of the full system, after which it starts decreasing

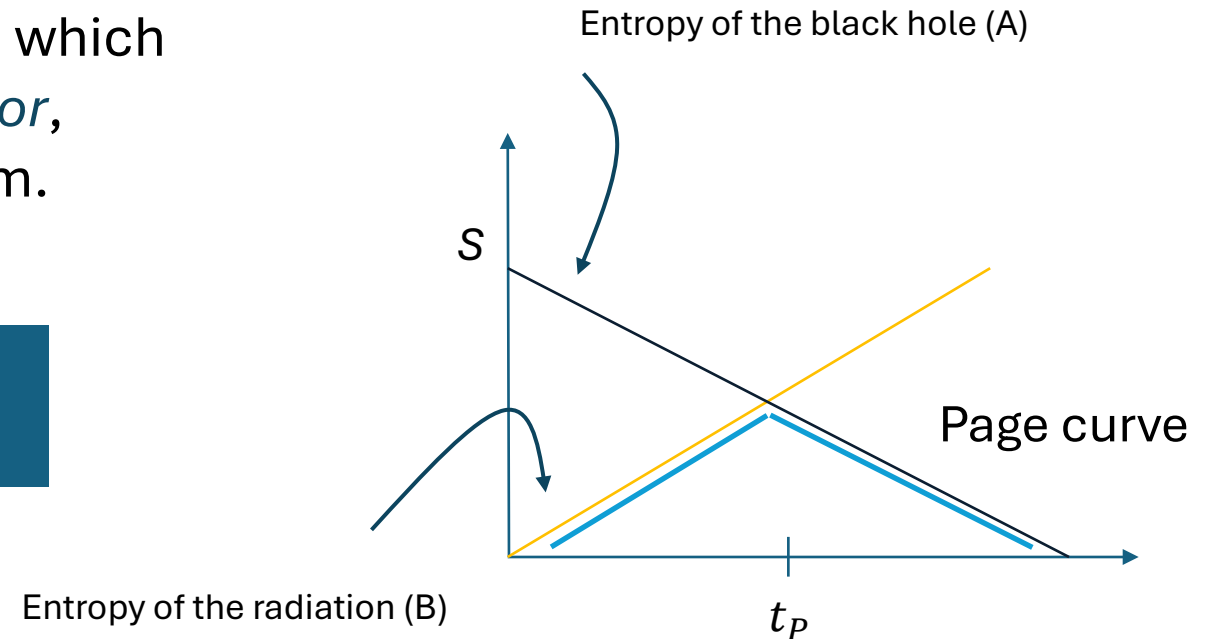
$$\text{For a pure system: } S = S_{AA^c} = 0$$

In the case of a black hole, the horizon is what separates the subsystem *Hawking radiation*, which is accessible to us, with the *black hole interior*, which is its complement quantum subsystem.

Reproducing the Page curve would prove that black hole evolution is unitary.



(If the subsystem B is much larger than A, it already contains most of the dof of the full system)



Quantifying entanglement

[RT,HRT,EW]

[Penington,Almehiri-Engelhardt-Marolf-Maxfield,..]

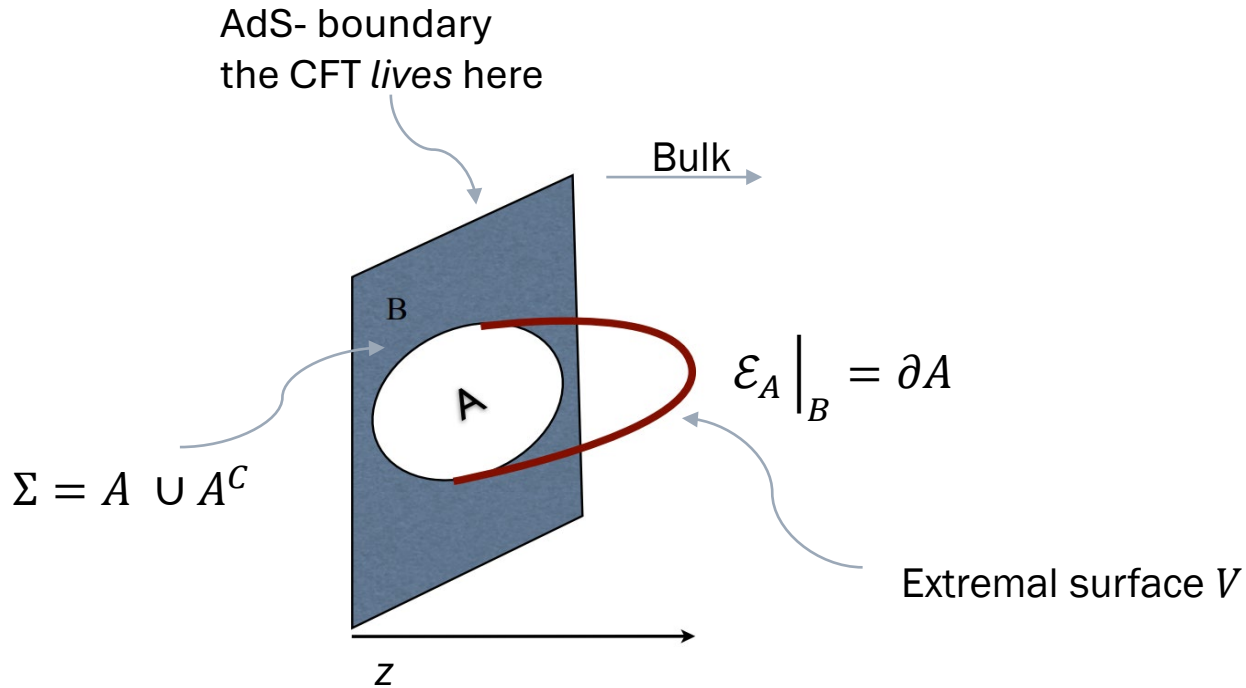
- Compute entanglement in CFT using extremal surfaces
- Different types of extremal surfaces competing in different regimes
- Competition among different extremal surfaces gives different phases of entanglement

Different extremal surfaces correspond to different saddles of the gravitational path integral realizing different structures of entanglement

[Lewkowycz,Maldacena'13][Saad,Shenker,Stanford'19]

[Almheiri,Hartman,Maldacena,Shaghoulian,Tajdini'19]

Geometrization of entanglement



➤ Holographic entanglement entropy

$$S_A = \min_V \frac{\text{Area}(\mathcal{E}_A)}{4G_N}$$

➤ Quantum corrections to holographic extremal surfaces

$$S = \min_X \left\{ \text{ext}_X \left[\frac{\text{Area}(X)}{4G_N} + S_{\text{semi-class}}(\Sigma_{\text{rad}}) \right] \right\}$$

[Ryu, Takayanagi '06]
[Hubeny, Rangamani, Takayanagi '07]

[Faulkner, Lewkowycz, Maldacena, '13]
[Engelhardt, Wall, '14]

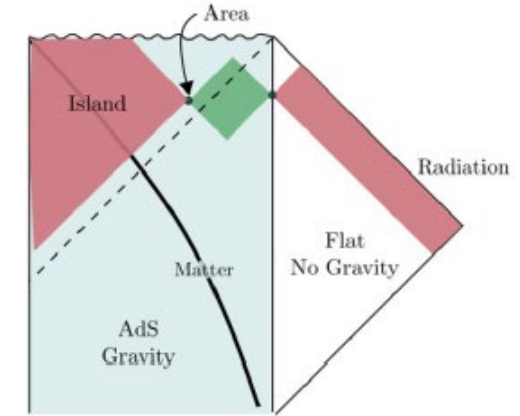
[Penington, '19]
[Almheiri, Engelhardt, Marolf, Maxfield '19]

Geometrization of entanglement

- ▶ Time dependent systems: extremal surface which dominates may change with time
- ▶ At late times *islands* appear whose entropy decreases with black hole evaporation

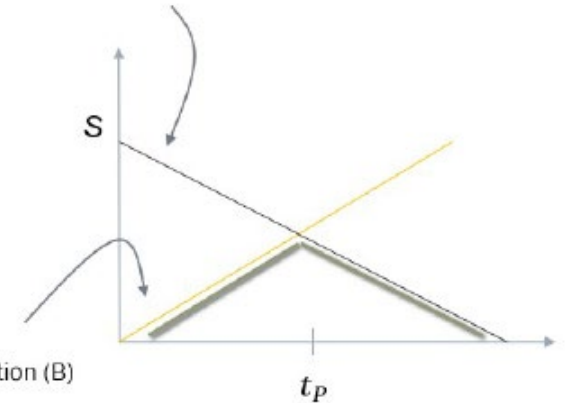
[Almheiri, Mahajan, Maldacena, Zhao '19]

[Penington'19][Almheiri,Engelhardt,Marolf,Maxfield'19]



Entropy of the black hole (A)

$$S_{rad} = \min_X \left\{ \text{ext}_X \left[\frac{\text{Area}(X)}{4G_N} + S_{\text{semi-class}}(\Sigma_{rad} \cup \Sigma_{\text{island}}) \right] \right\}$$



Entropy of the radiation (B)

Black holes on Branes

Quantum BTZ black hole

Exploiting the C-metric in AdS_4 , compute backreaction of quantum conformal fields on BTZ backgrounds.

[Emparan, Frassino, Way '20]

Higher dimensional realization of black holes coupled to a thermal bath

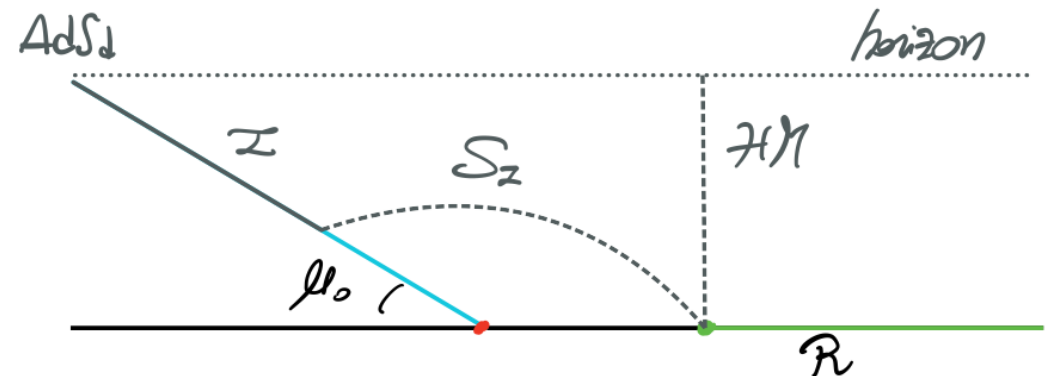
[Almheiri, Mahajan, Santos, '19][Chen, Myers, Neuenfeld & Reyes, Sandor '20] [Geng, Karch '20]

[Geng, Karch, Perez-Pardavila, Raju, Randall '20-'21]

Two classes of QES

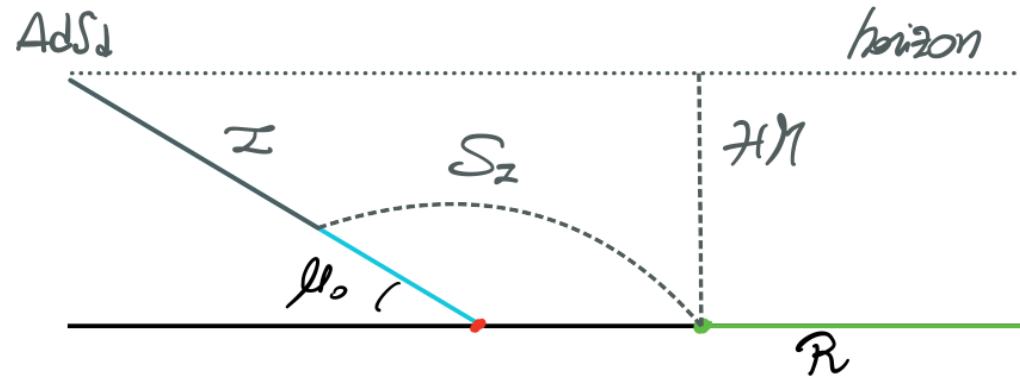
- ▶ Hartman-Maldacena
- ▶ Island surfaces

→ Geometrization of extremal surfaces



Braneworlds

[Karch, Randall '01] [Randall, Sundrum '99]



- Transparent boundary conditions induce a graviton mass [Porrati'01,'01][Porrati,Starinets'02]
- Critical angle needed to localize gravity on the AdS_4 brane

$$\mu \sim m_g$$

- Maybe a graviton mass is required in higher dimensional islands setups..

[Geng,Karch'20][Geng, Karch, Perez-Pardavila, Raju, Randall '21]

Braneworlds

Properties

- ▶ No sharp Hilbert space factorization $\Rightarrow$ no well-defined entanglement
- ▶ Effective massive graviton: information can leak into a bath
- ▶ Subsystems become well-defined, and entanglement behaves as in QFT
- ▶ $\Rightarrow$ Islands are allowed

In this frameworks, graviton mass is an IR effect

Problem of defining local observables in the bulk

microscopic realization

[D'Hoker, Estes, Gutperle '07][Aharony, DeWolfe, Freedman, Karch '03]



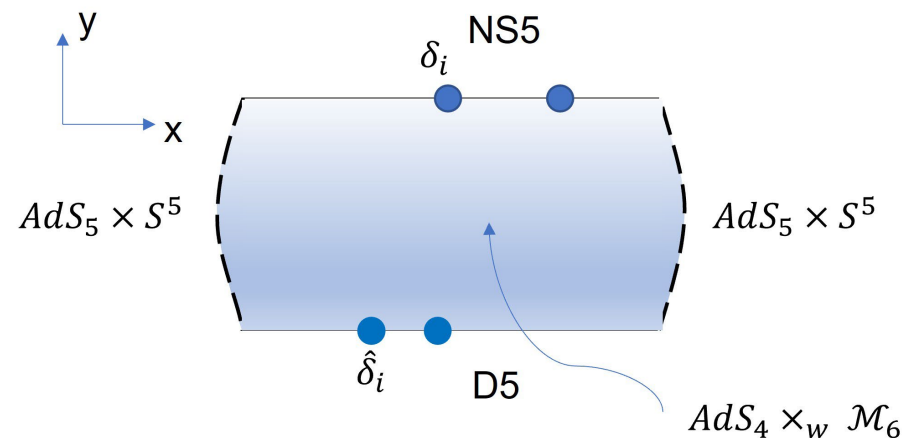
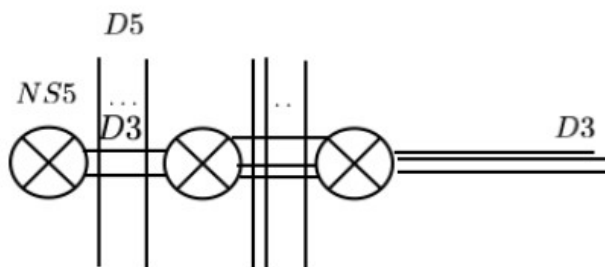
CFT in presence of a (planar) interface or defect, or boundary
Dual to N=4 SYM with a defect

$$AdS_4 \times S^2 \times S^2 \times \Sigma$$

- ▶ Σ is a Riemann surface with a boundary, where the geometry develops AdS_5 throats
- ▶ Janus solutions with D5 and NS5 branes
- ▶ May preserve supersymmetry

type IIB embedding

[Aharony, Berdychovsky, Berkooz, Shamir, '11] [Assel, Bachas, Estes, Gomis, '11]



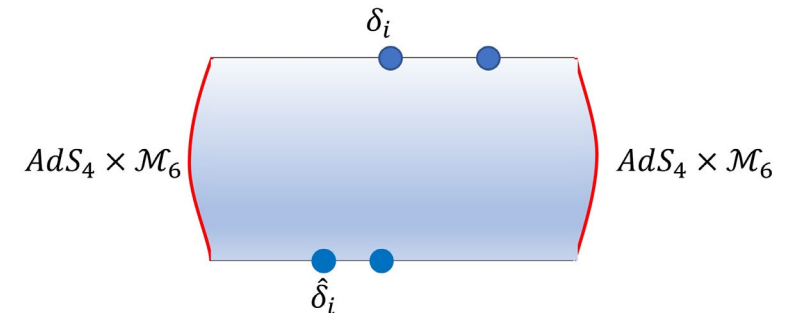
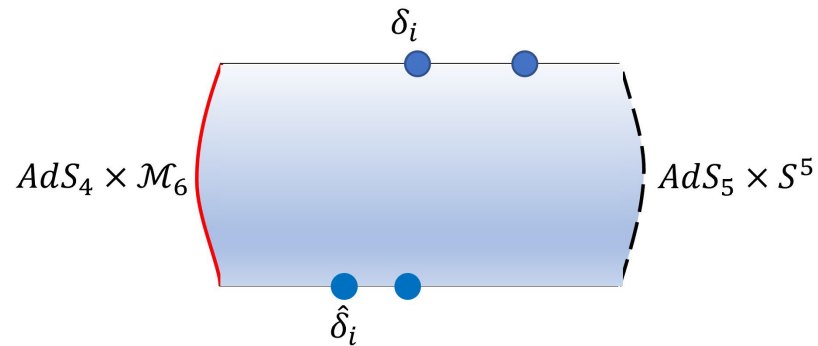
- Linear quivers constructions of D3-D5-NS5 branes dual to 1/4 BPS type IIB solutions of [D'Hoker, Estes, Gutperle '07]
- The theory flows in the IR to a strongly coupled 3d SCFT

microscopic realization

- EOW brane tension translates in the parameter

$$\mu^{-1} \quad \leftrightarrow \quad \alpha \sim \frac{F_3}{F_4} \sim \frac{\text{dof BCFT}}{\text{dof CFT}}$$

- Bag region as a *composite* Karch-Randall brane
- Transparent boundary conditions correspond to leaking into the AdS_5 region where gravity is non-dynamical: non gravitating bath
- When both regions are capped off, the internal geometry is compact and the graviton is massless

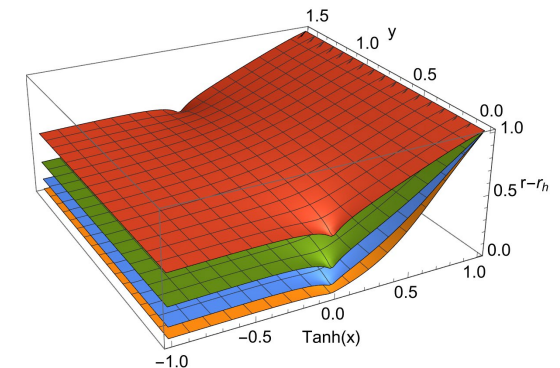
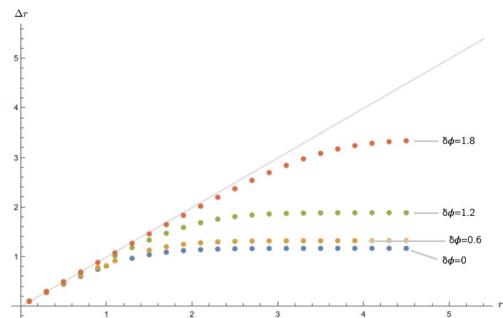
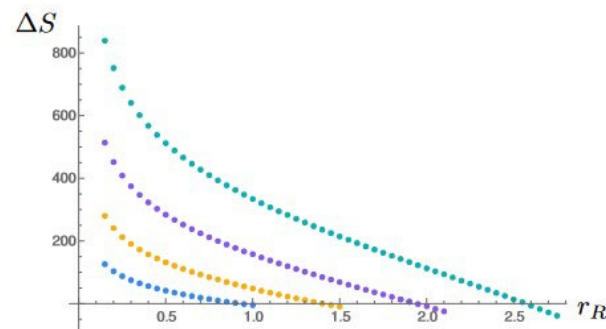
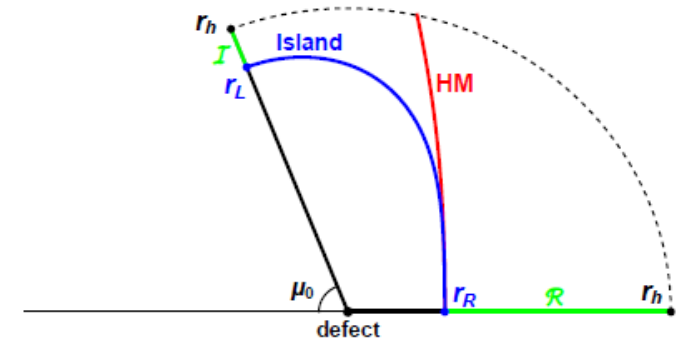


Results from double holography

[Geng, Karch,..][Uhlemann,'21]
[Demulder,AG,Lavdas,Lüst,'23]
[AG, Billiato, '24]

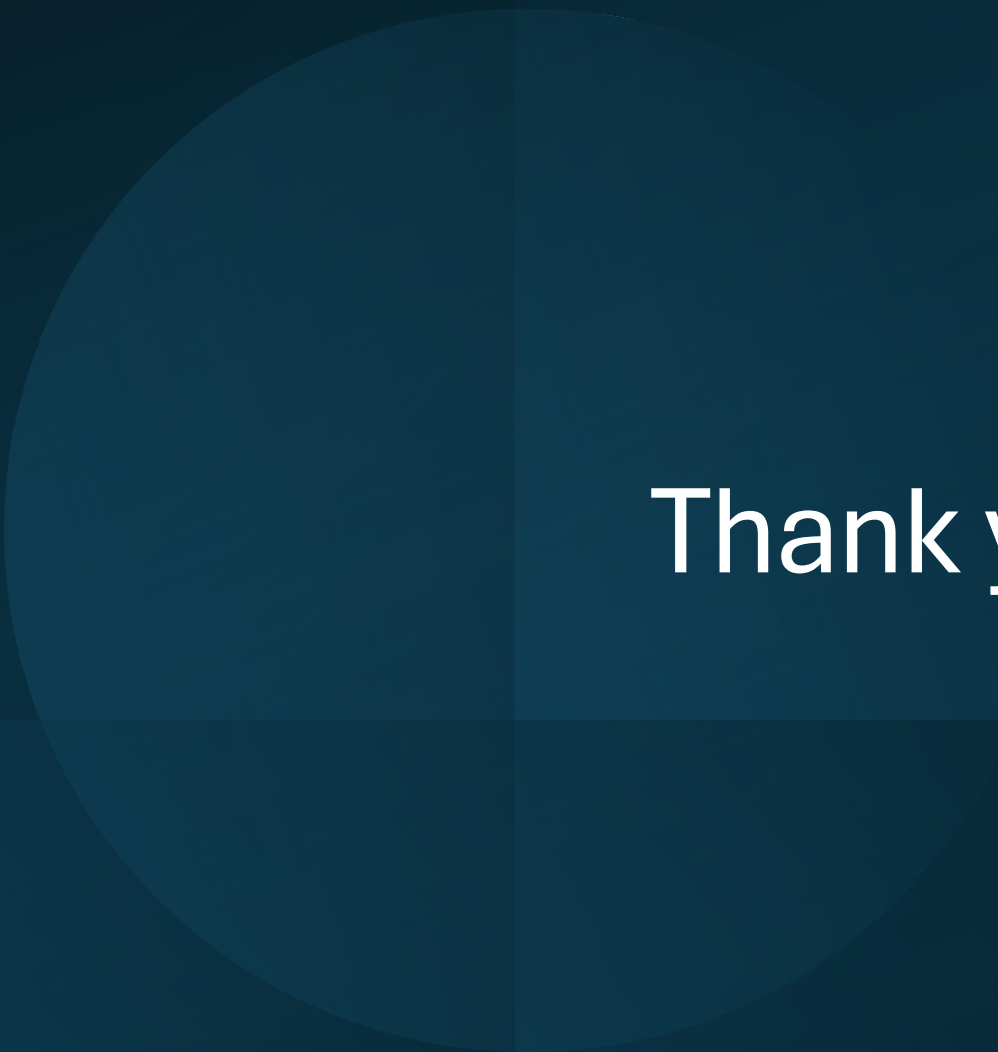
Competition between surfaces indicates different ways for the system to partition information between the brane and the bath

- ▶ There is always a phase transition
- ▶ Extremal surfaces are not always well defined
- ▶ They can end on particular regions of the boundary
- ▶ Their anchoring points determine their properties



Summary

- Quantum gravity constrains its low-energy EFT far below the Planck scale.
- Black holes both realize these constraints and expose the limits of local semiclassical observables.
- Islands recover the expected entropy evolution in settings where gravity becomes effectively massive and subsystems can be approximately localized.
- What is missing may be a language adapted to the quantum state space, rather than a further correction to the local EFT.



Thank you