Entanglement Islands in the Eternally Inflating Multiverse

Yasunori Nomura

UC Berkeley; LBNL; Kavli IPMU

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- Measure Problem and Black Holes
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Eternally Inflating Multiverse

— a solution to the dark energy problem —

Dark energy and Why now?

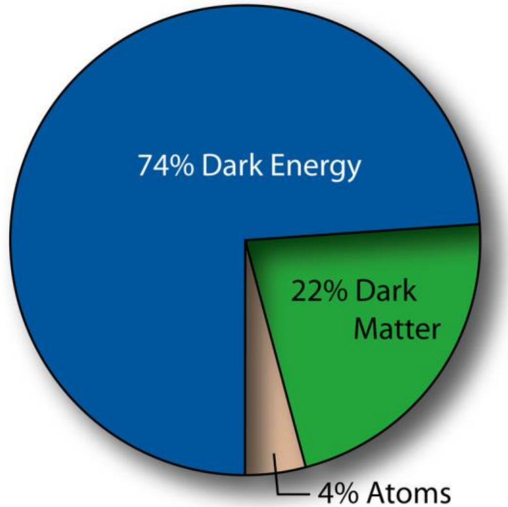
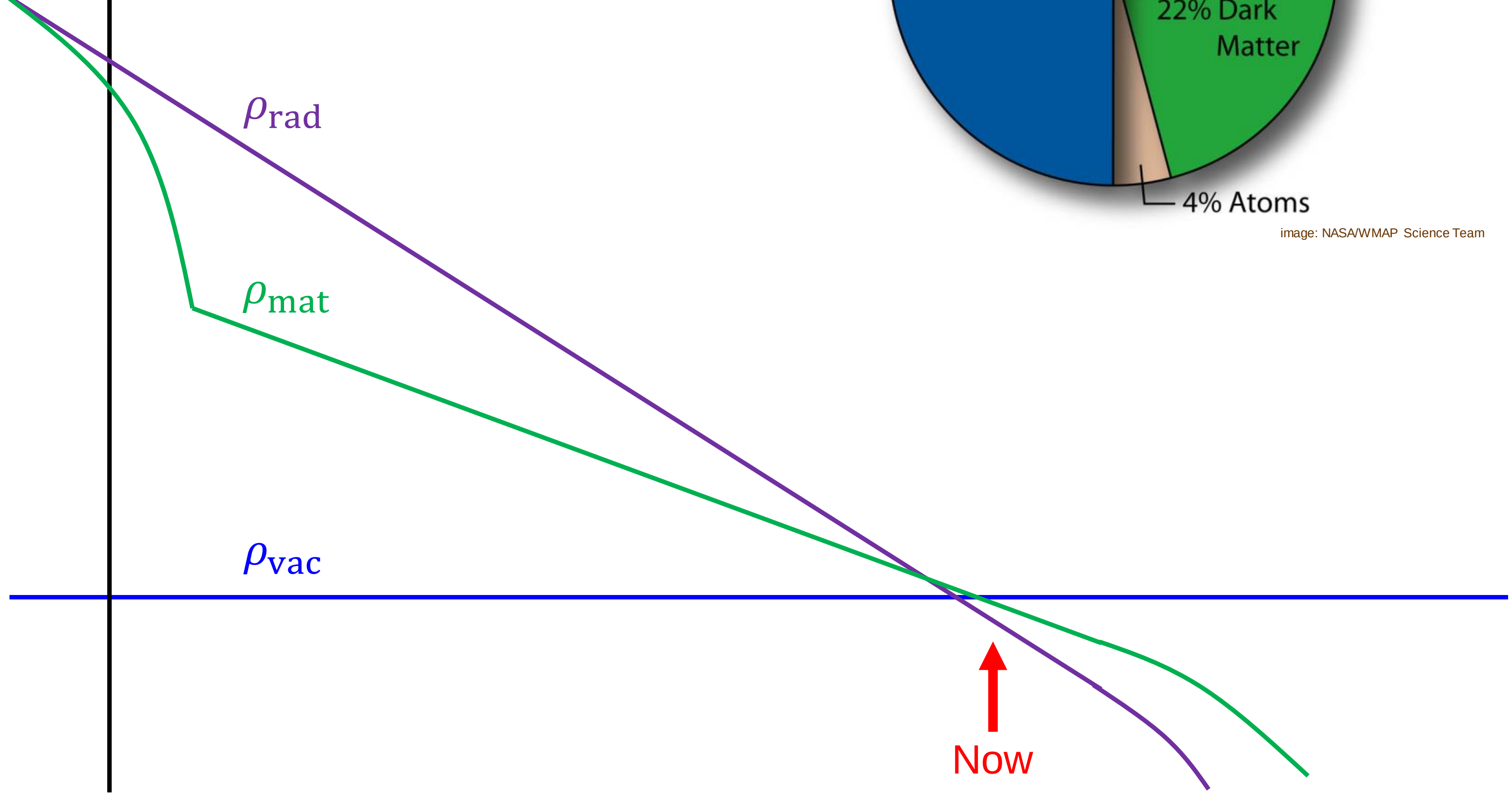
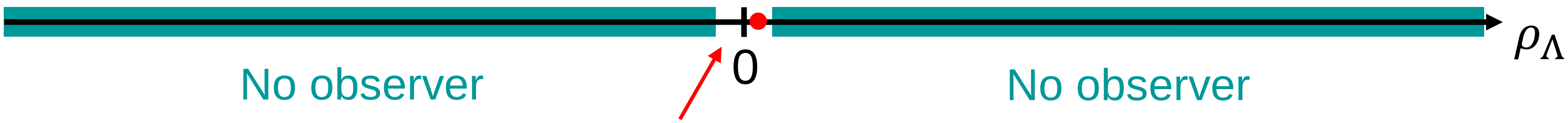


image: NASA/WMAP Science Team



Environmental selection in the Multiverse

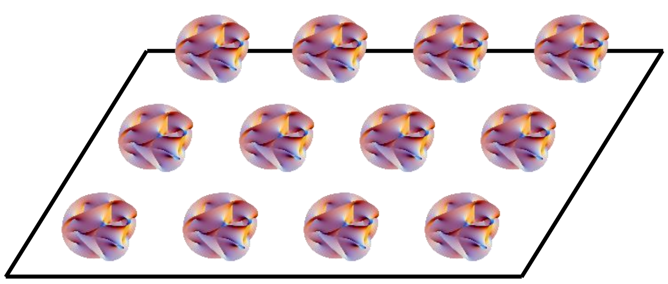


Observers (humans) arise
only in universe in this range.

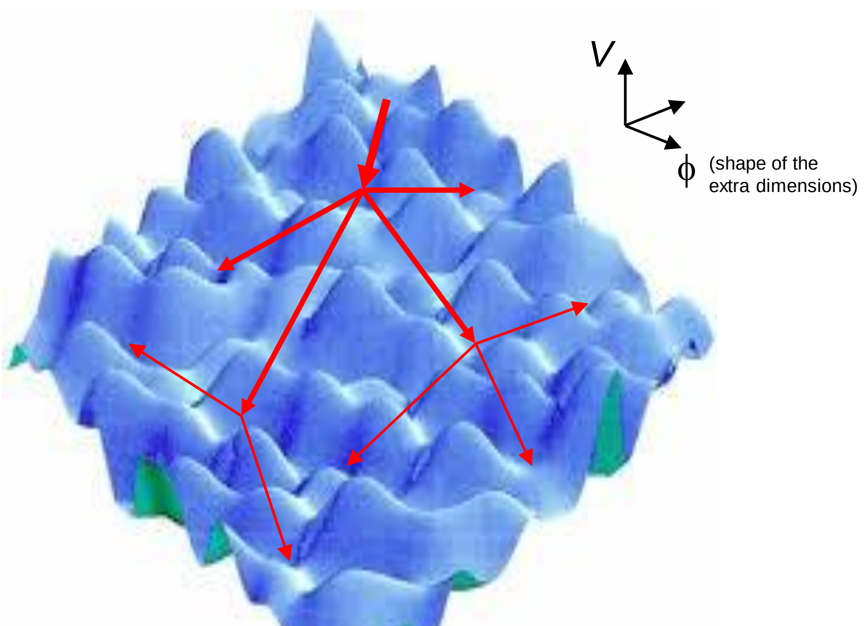
…; Weinberg ('87); …

… $\rho_\Lambda \neq 0$ indeed discovered in 1998

String landscape

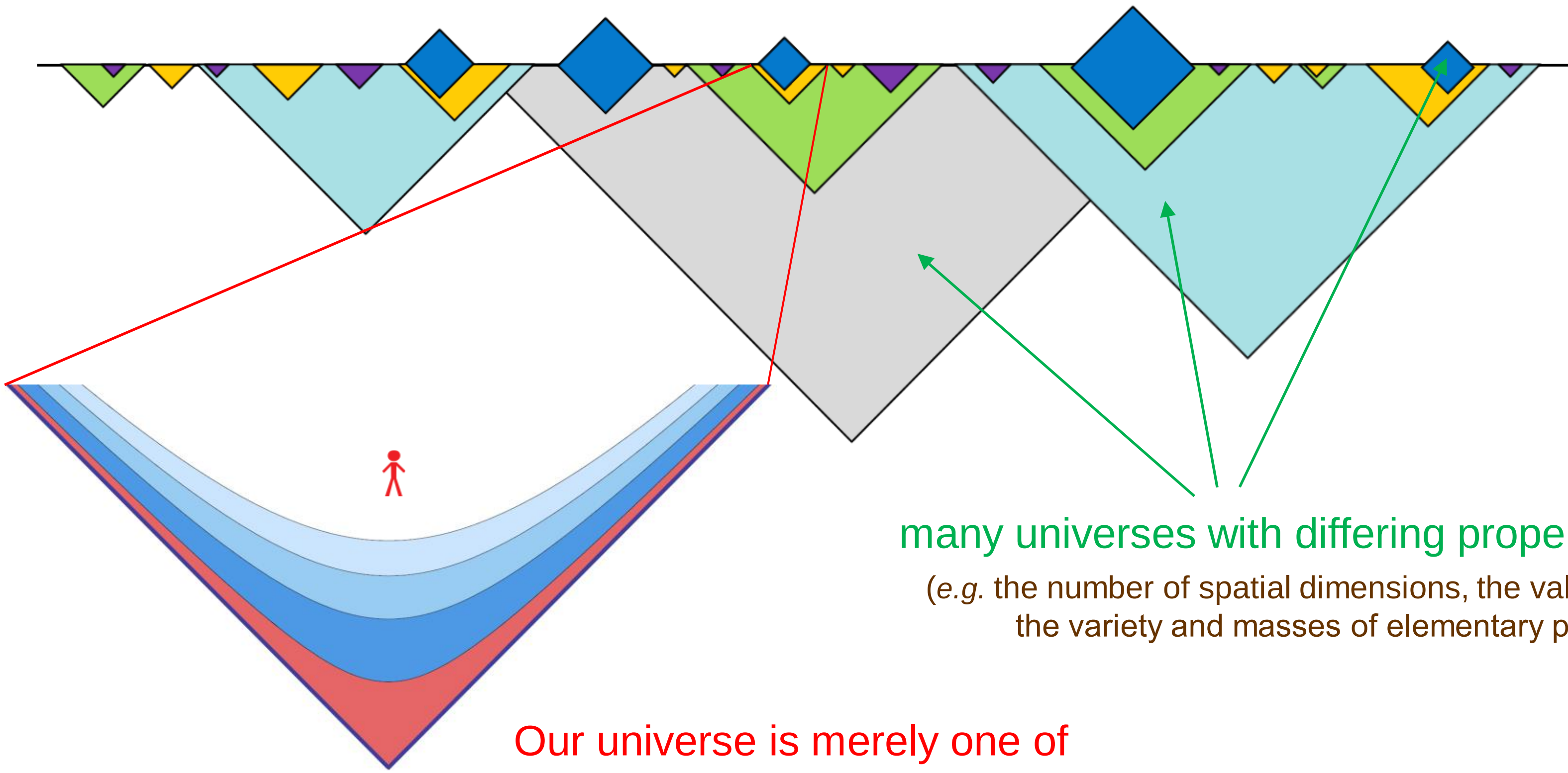


https://commons.wikimedia.org/wiki/File:Calabi-Yau-alternate.png



http://journalofcosmology.com/Multiverse9.html

Eternally inflating multiverse



many universes with differing properties

(*e.g.* the number of spatial dimensions, the value of ρ_Λ,
the variety and masses of elementary particles, …)

Our universe is merely one of
the (infinitely) many universes.

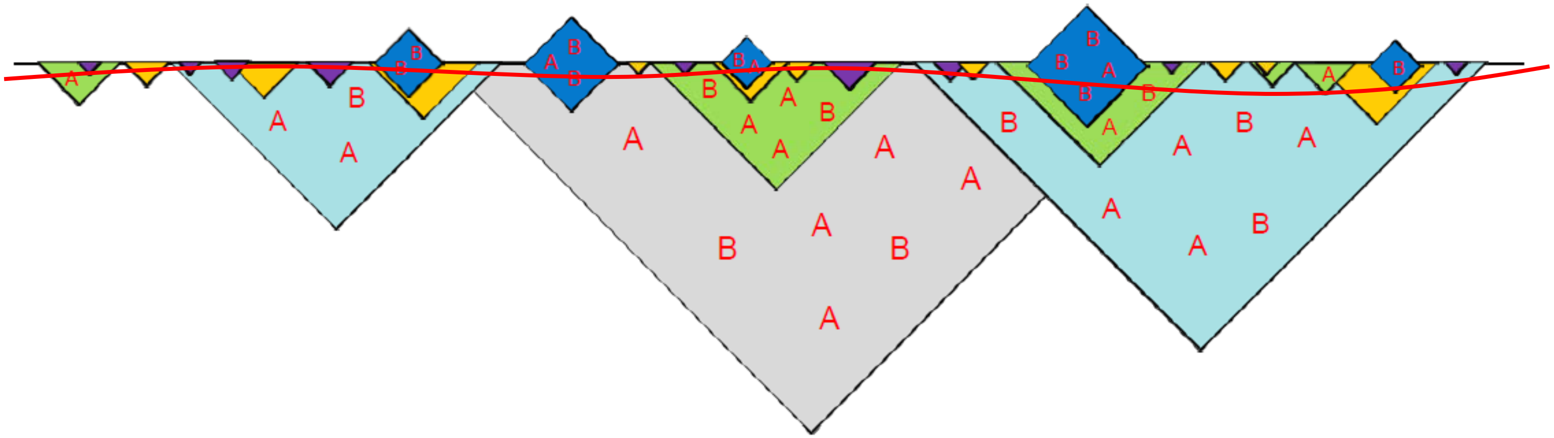
Anthropic consideration is **not** a choice

… mandatory for **logical consistency**

Measure Problem and Black Holes

— new view of spacetime in quantum gravity —

Cosmological measure problem



Problem of infinity: $P = \frac{N_A}{N_B} = \frac{\infty}{\infty}$

"regulate" spacetime at $t = t_c$ ($\to \infty$) ?

No $\to$ Predictions are highly sensitive to the regularization.

Linde, Linde, Mezhlumian ('93); Guth ('00); Vilenkin, Winitzki ('06); …

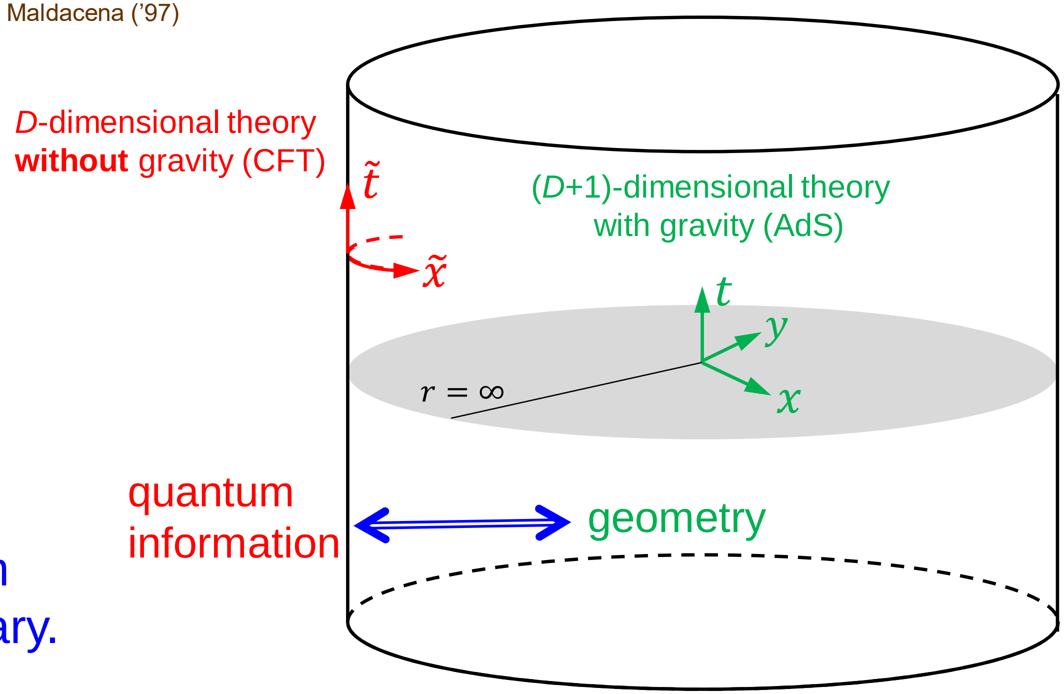
… What could be wrong?

Black Hole information problem

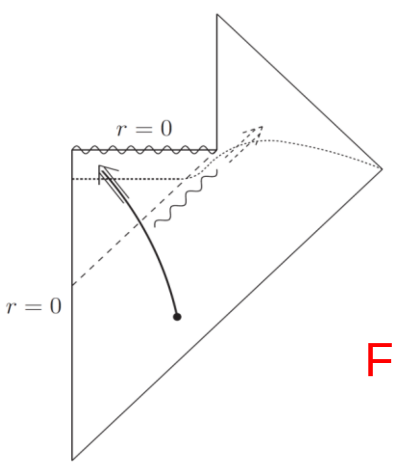
Hawking ('76); …; Almheiri, Marolf, Polchinski, Sully ('12); …

AdS/CFT correspondence

Maldacena ('97)



BH evolution as viewed from
the exterior must be unitary.

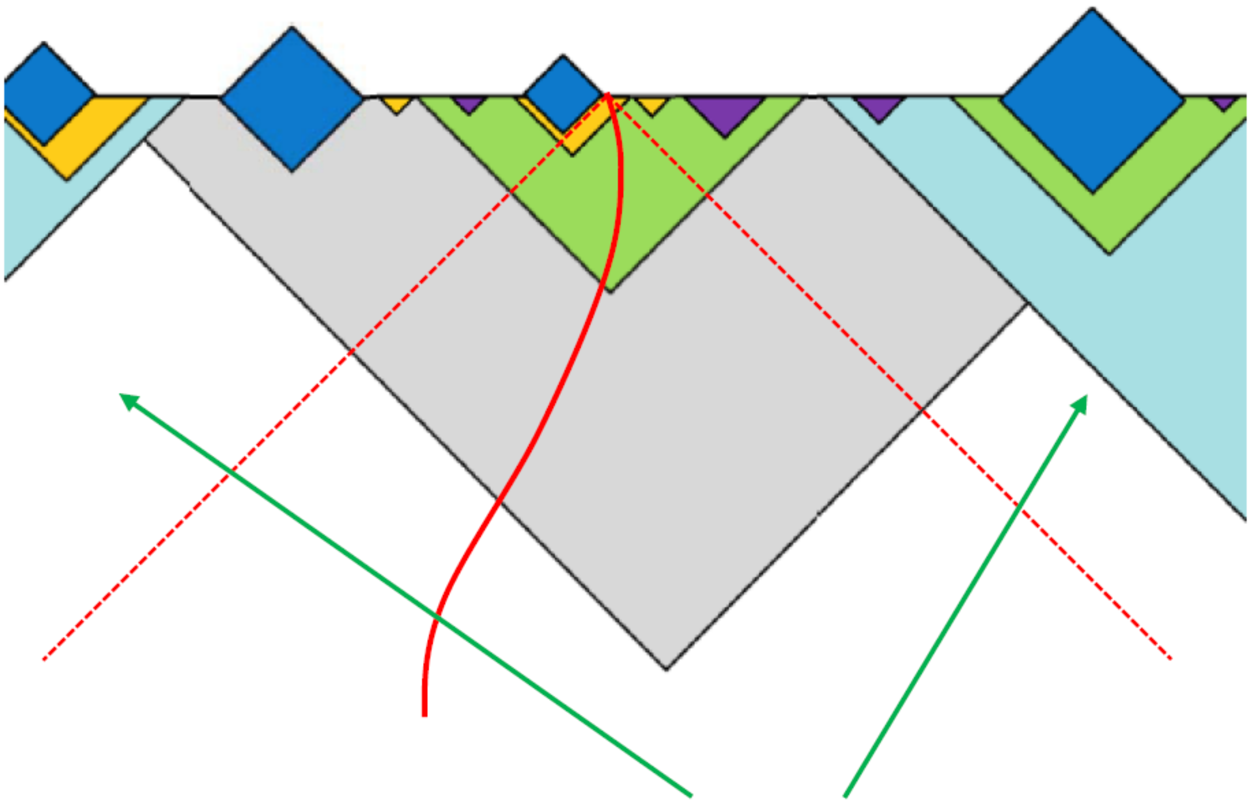


From the exterior point of view,
the interior of the BH must be viewed as **nonexistent**.

"Multiverse = Quantum many worlds" Y.N. ('11); Bousso, Susskind ('11)…

A Lesson from black hole physics:

Including both Hawking radiation and interior spacetime in a single description is **overcounting**.



Does this region "exist"?

“Multiverse = Quantum many worlds” Y.N. (’11); Bousso, Susskind (’11)…

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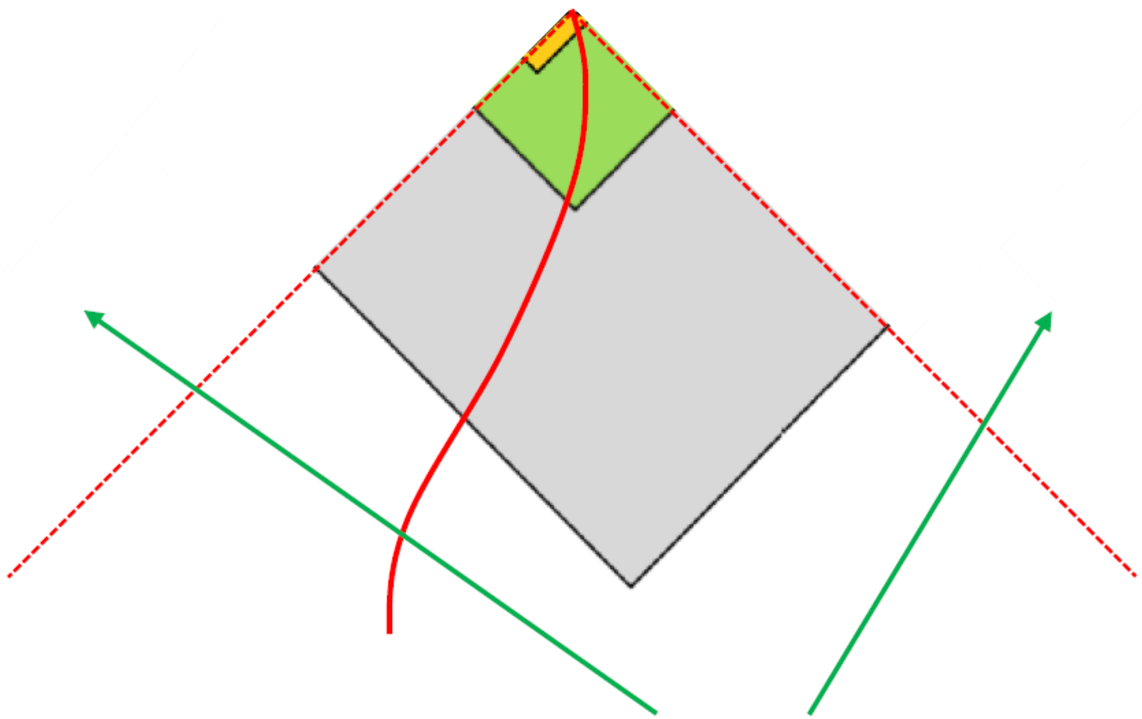
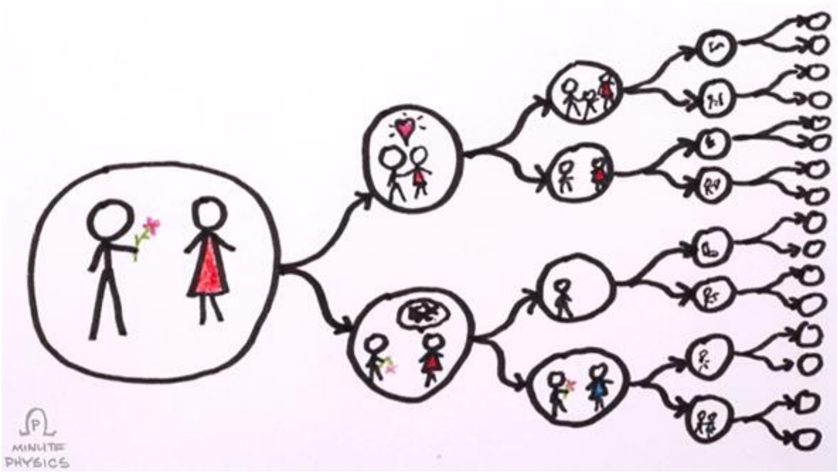
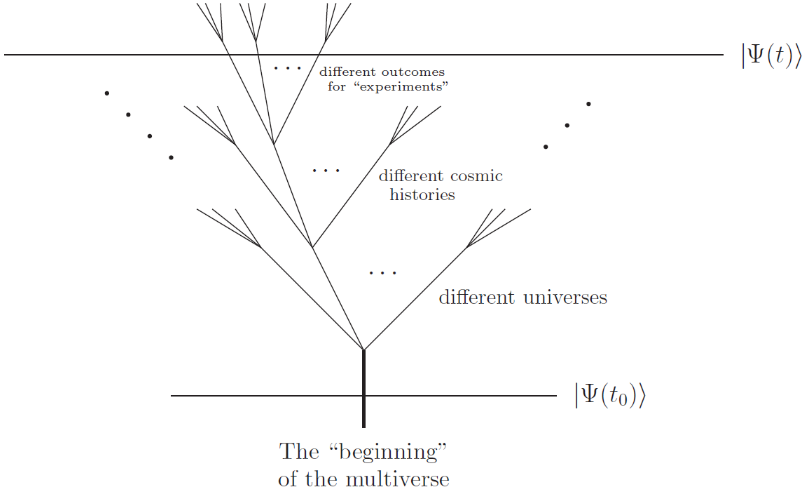


Does this region “exist”? → No!

What happened to the multiverse?

We live in a quantum mechanical world





Bubble nucleation … probabilistic processes

usual QFT: $\Psi(t=-\infty) = |e^+e^-\rangle \quad \rightarrow \quad \Psi(t=+\infty) = c_e\,|e^+e^-\rangle + c_\mu\,|\mu^+\mu^-\rangle + \cdots$

multiverse: $\Psi(t=t_0) = |\Sigma\rangle \quad \rightarrow \quad \Psi(t) = \cdots + c\left|\begin{smallmatrix}321\\ \rho_\Lambda\end{smallmatrix}\right\rangle + c'\left|\begin{smallmatrix}321\\ \rho'_\Lambda\end{smallmatrix}\right\rangle + \cdots + d\left|41\right\rangle + \cdots$

eternally inflating

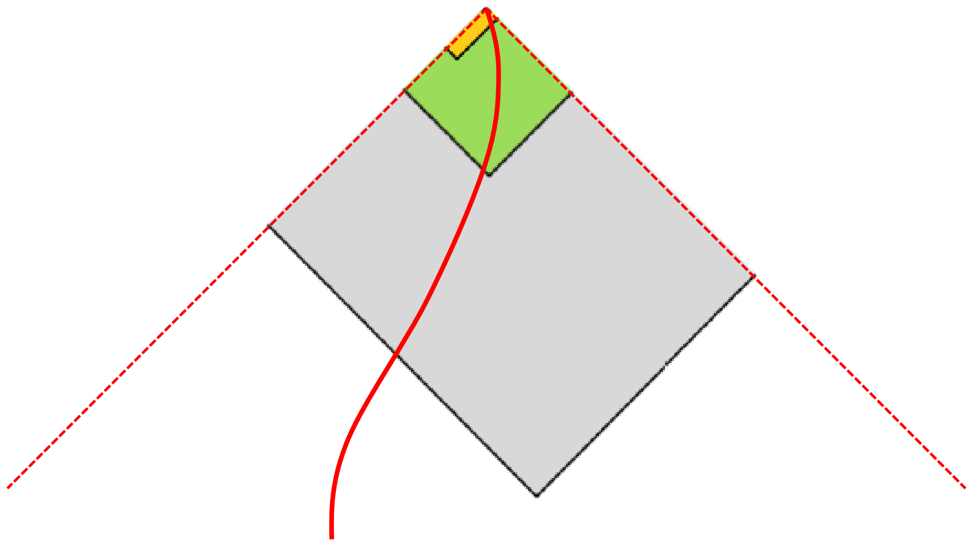
each term representing only the causally accessible region

… provides natural and effective "regularization"

… The multiverse lives (only) in probability space !

Global spacetime of general relativity

is an emergent (and "redundant") concept!



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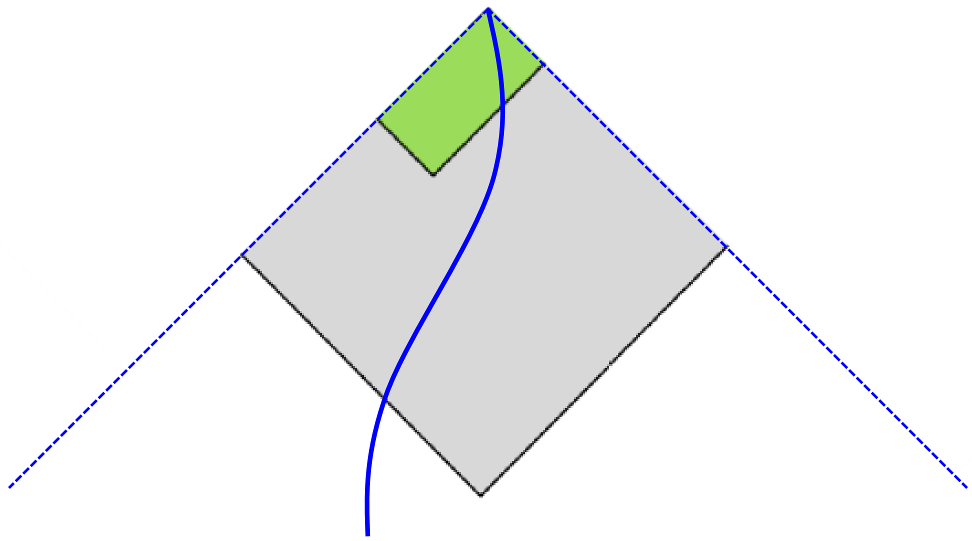

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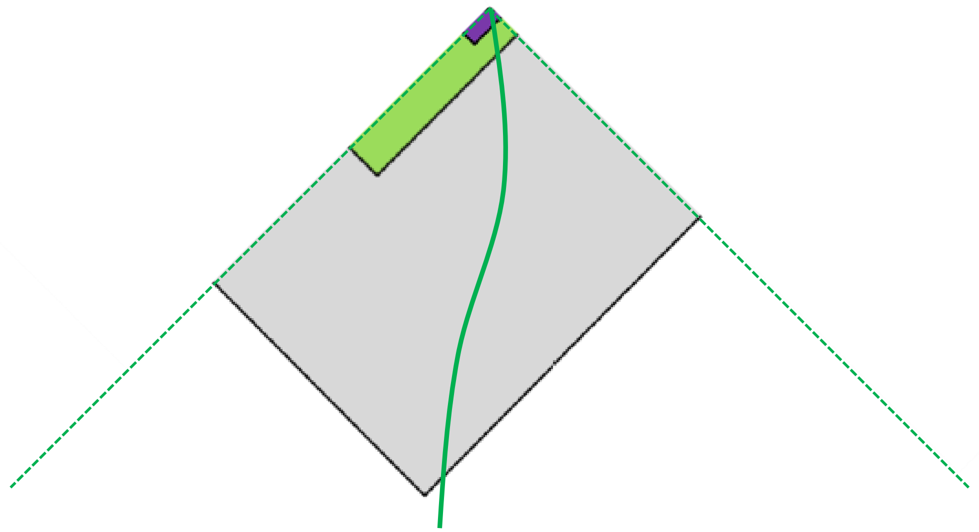

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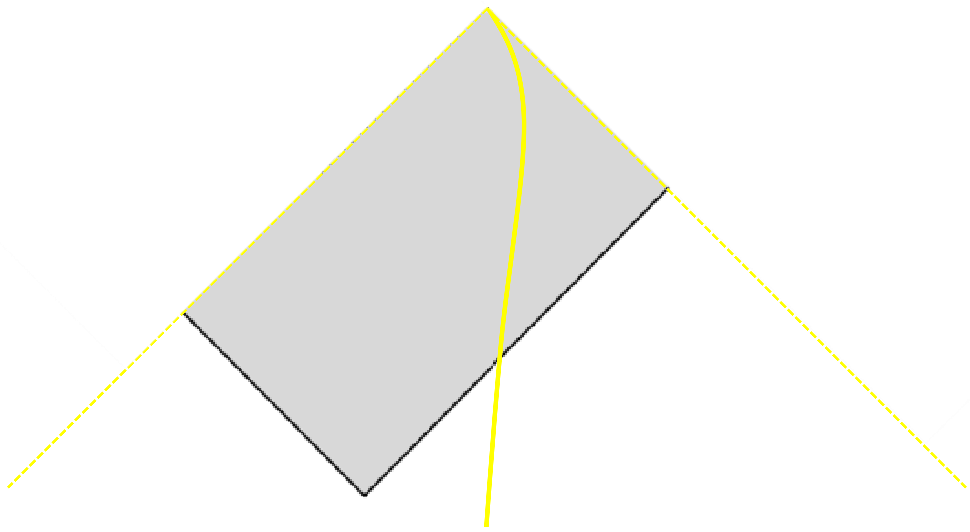

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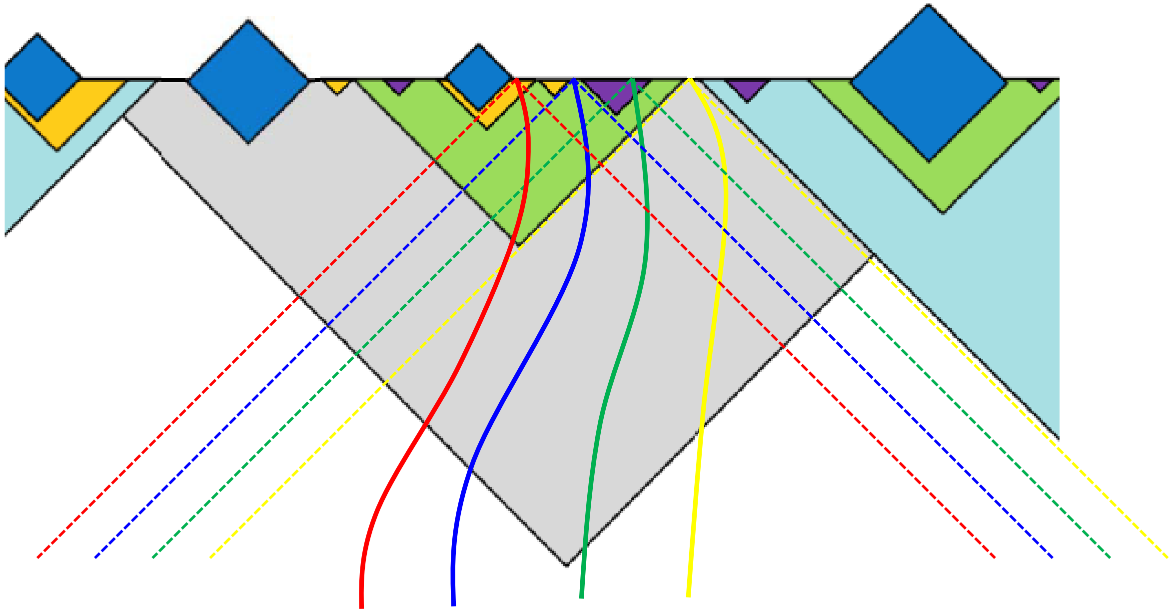


… probability is more fundamental

— counting observers (with equal weight) vastly overcounts d.o.f.s

The picture of infinitely large multiverse arises

only after patching different branch worlds artificially.

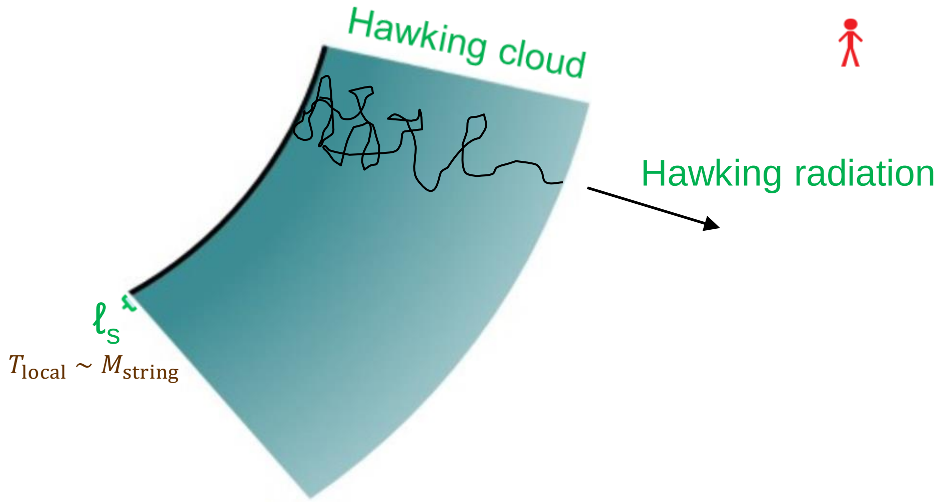
(at the cost of overcounting the true quantum mechanical d.o.f.s)

Recent Progress in Black Hole Physics

— two equivalent descriptions of spacetimes —

c.f. Y.N., “From the black hole conundrum to the structure of quantum gravity,” arXiv:2011.08707

Unitary description (Quantum Mechanics; holography)



The horizon behaves
as the surface of regular material.

… no issue with unitarity

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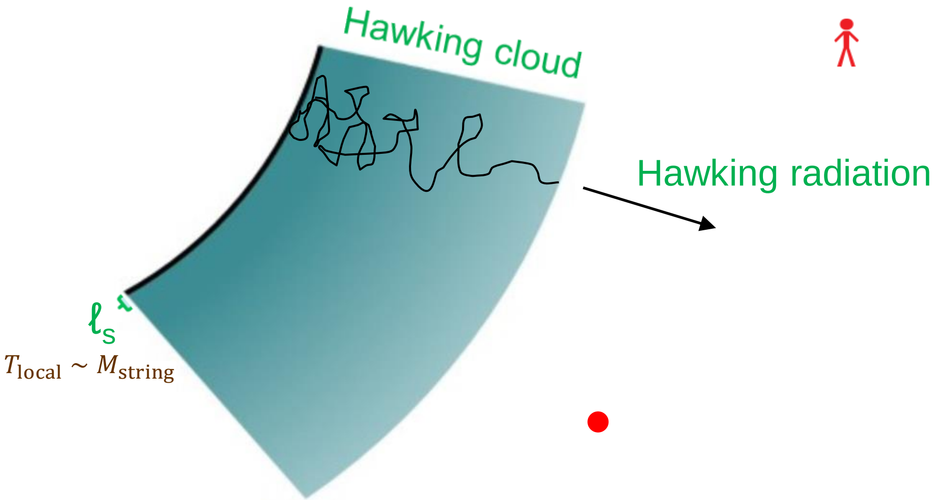

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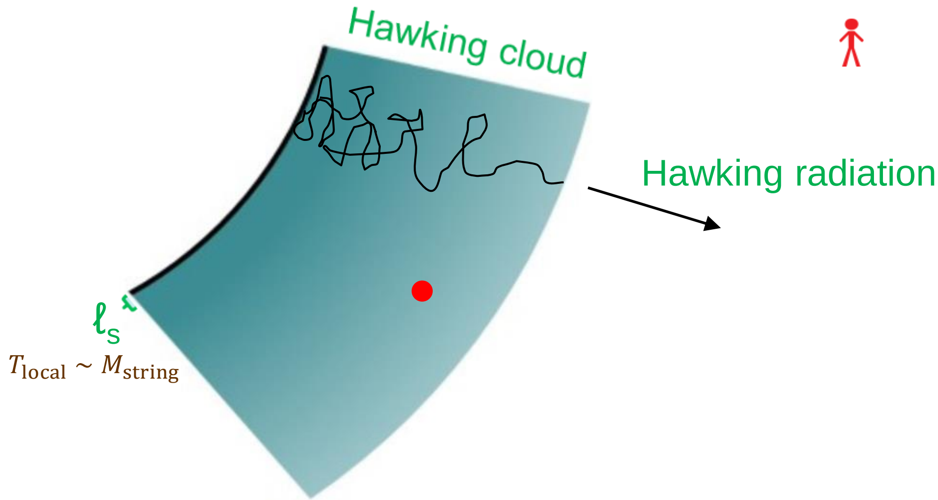

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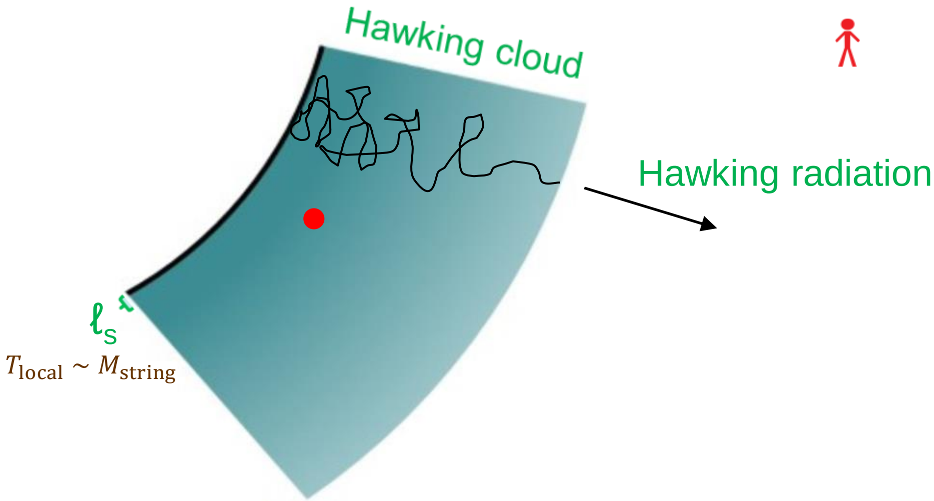

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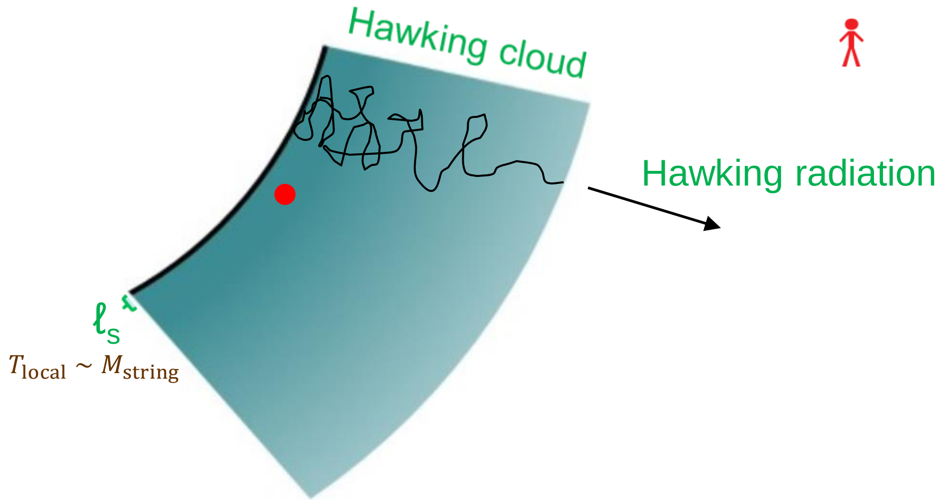

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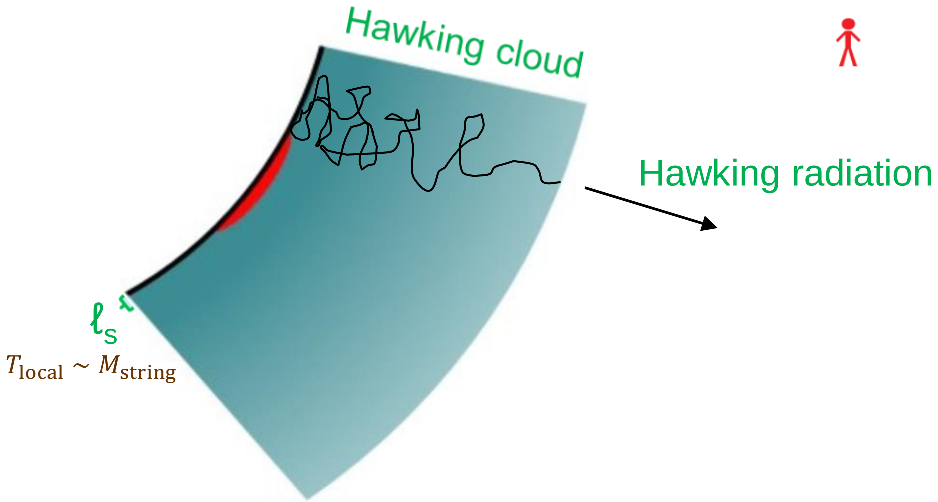

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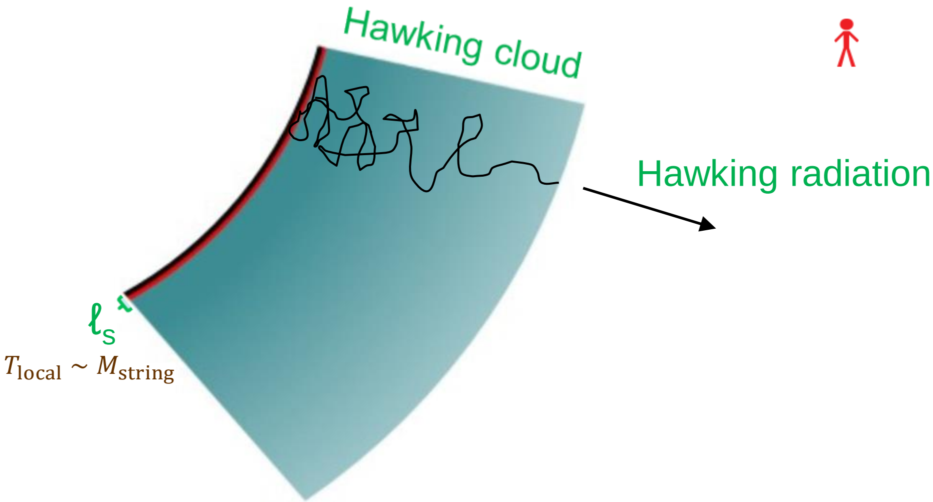

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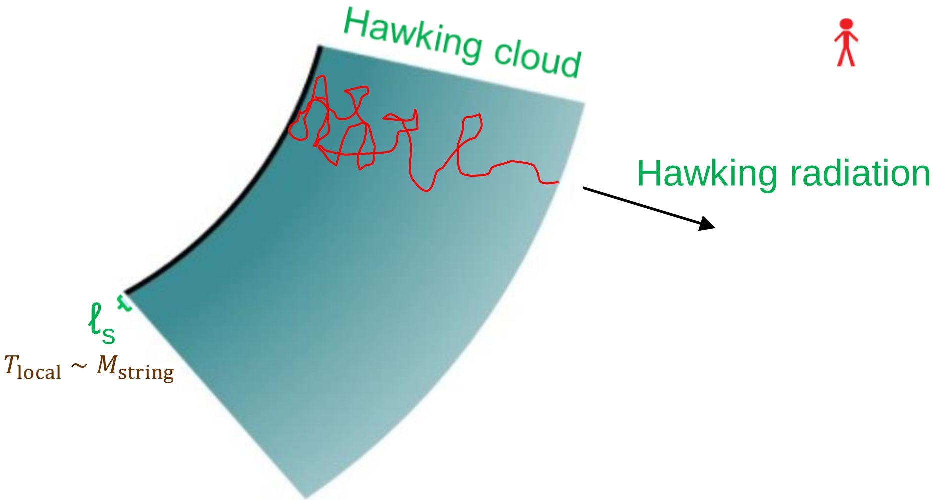

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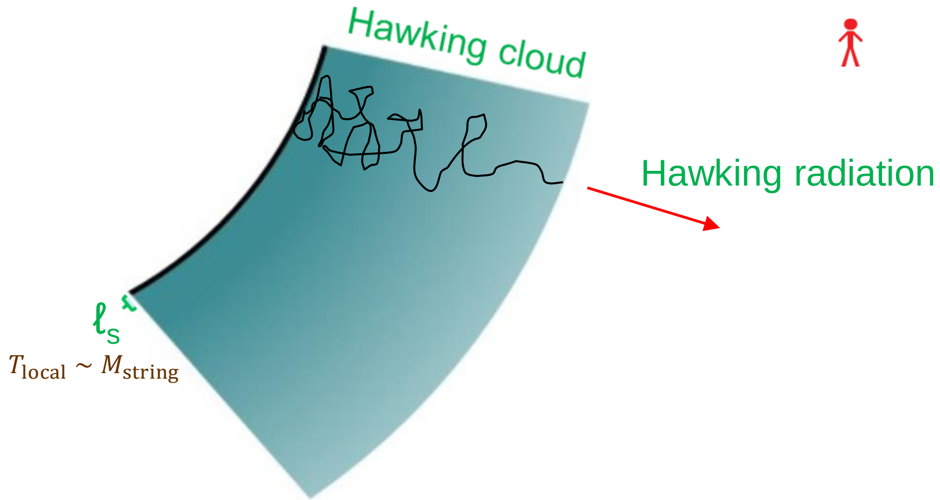

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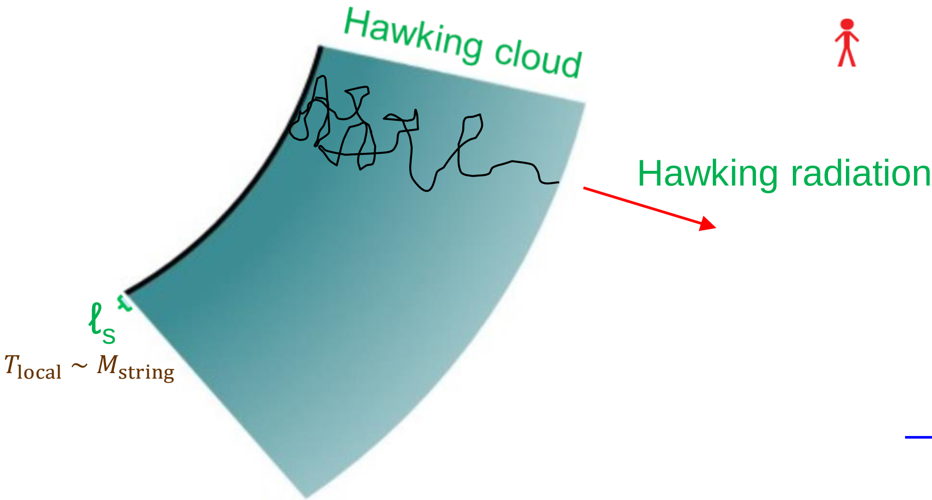

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→ What about the interior?

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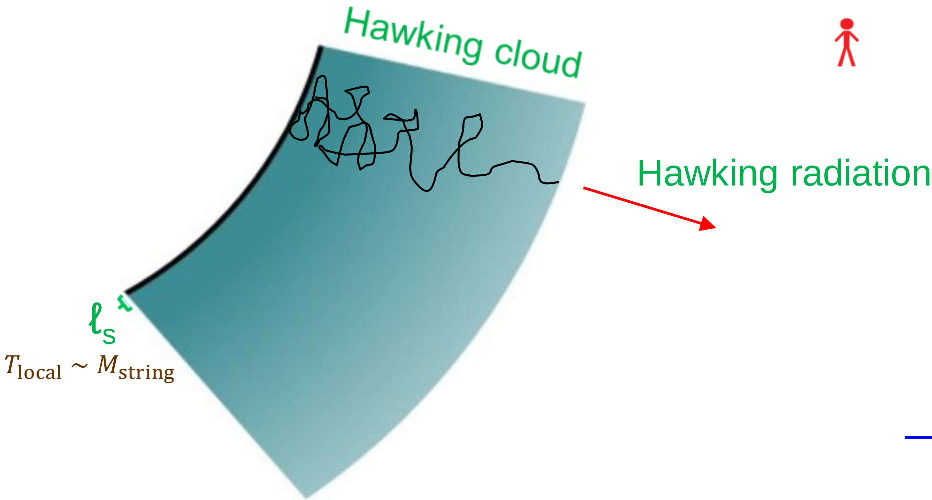

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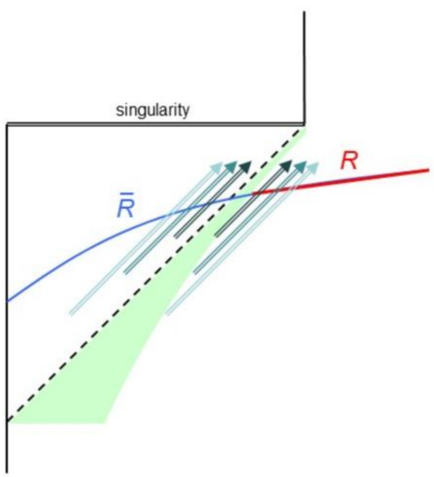
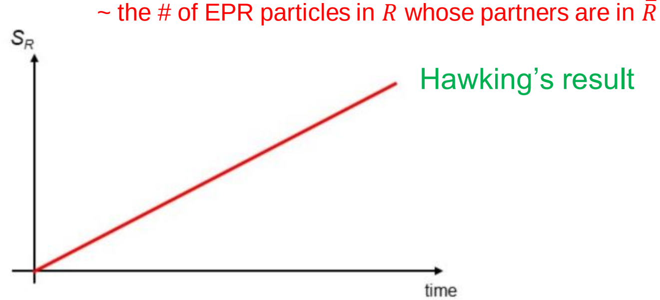
Global description (General Relativity)



$S_R = -\mathrm{Tr}[\rho_R \ln \rho_R] \quad (\rho_R = \mathrm{Tr}_{\bar{R}} |\Psi\rangle\langle\Psi|)$

~ the # of EPR particles in R whose partners are in $\bar{R}$



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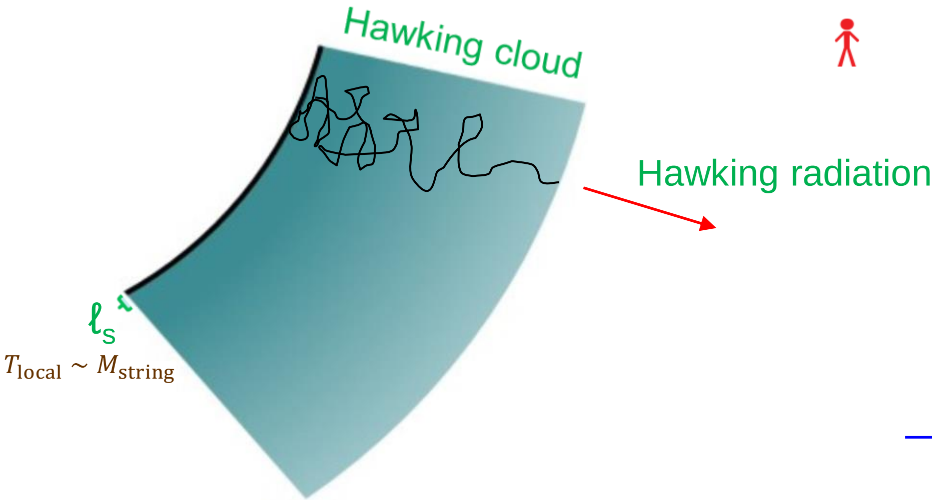

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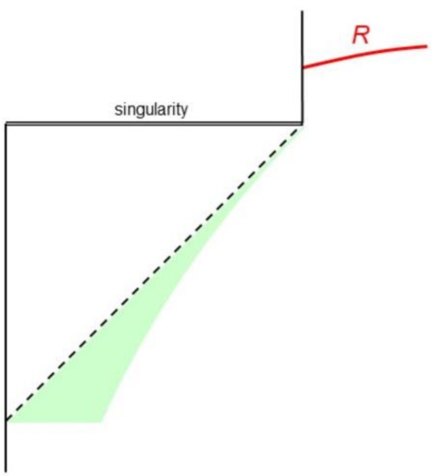

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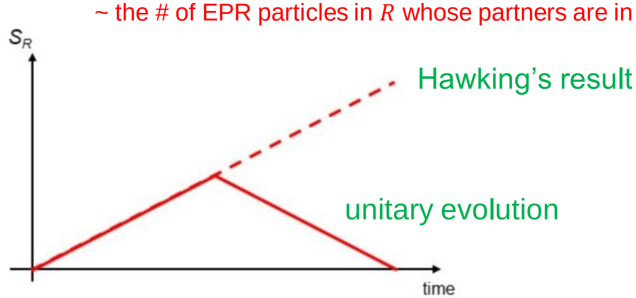

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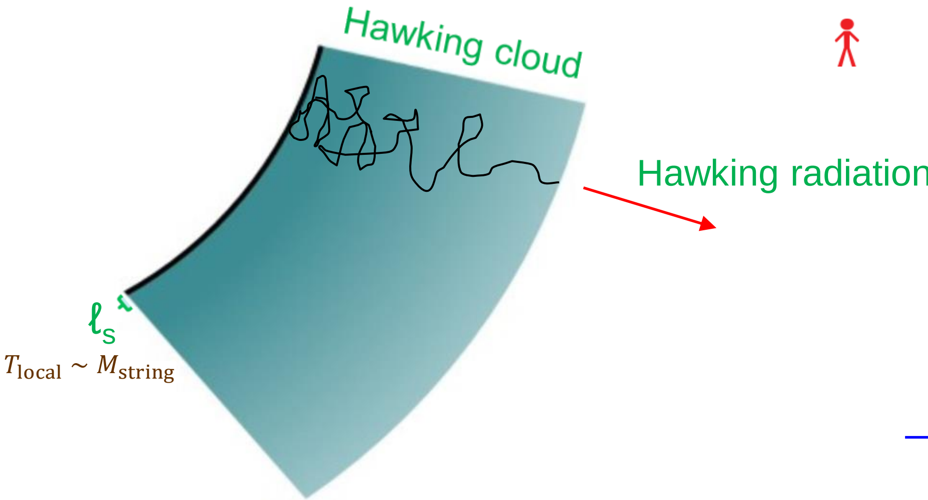

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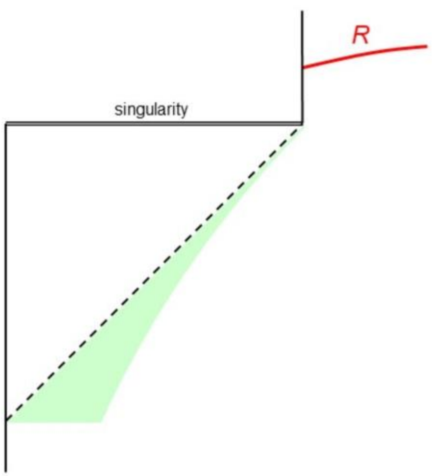

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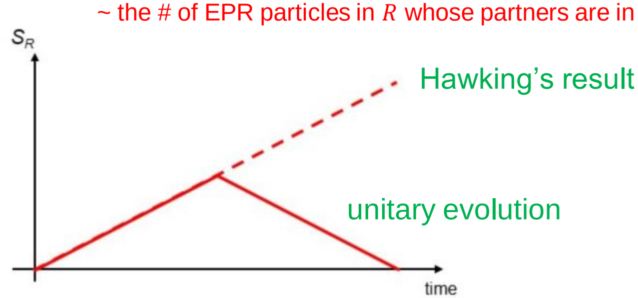
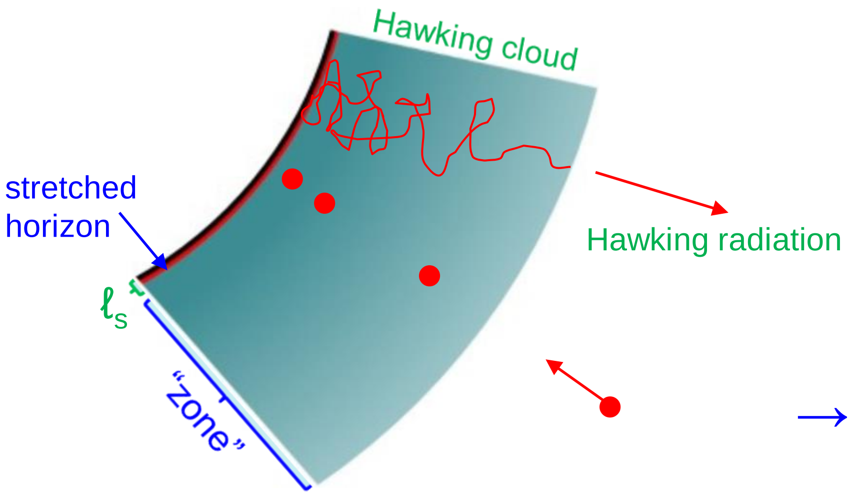


→ What was wrong with Hawking's analysis?

(I) Unitary description



The d.o.f.s outside the horizon comprise the **entire** system.

→ The evolution is unitary.

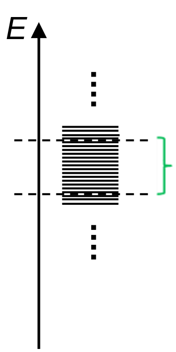
→ How does the "interior" emerge?

Papadodimas, Raju ('12–'15); Verlinde, Verlinde ('12–'13);
Y.N., Sanches, Varela, Weinberg ('12–'15); …
Y.N. ('19, 20)

Key features of the horizon Y.N. ('19, 20)

— defining characteristics of BHs

- Exponentially dense spectrum



$$e^{S_{\rm BH}} \;\rightarrow\; \Delta E \sim e^{-S_{\rm BH}}$$

- Dynamics at the stretched horizon

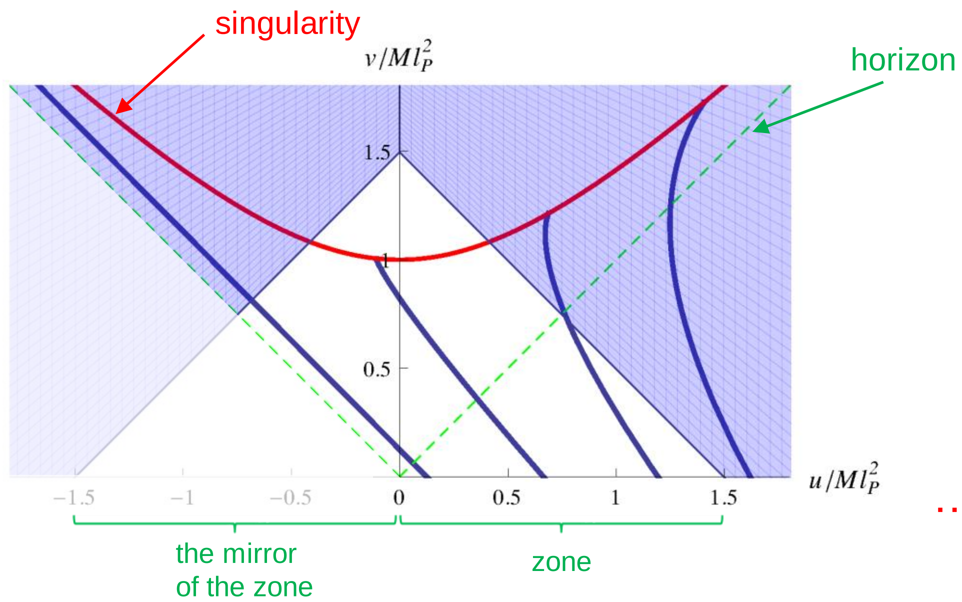
$$T_{\rm local} \sim M_{\rm string}$$

… string dynamics

- quantum chaos Maldacena, Shenker, Stanford ('15)
- fast scrambling Hayden, Preskil ('07); Sekino, Susskind ('08)
- universal Banks, Seiberg ('10); …; Harlow, Ooguri ('18)

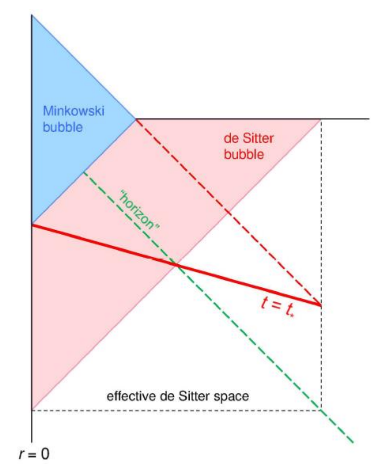
These features allow for Hawking cloud (and early Hawking radiation) to respond to an infalling object **as if** it falls through into the interior.

→ Effective theory of the interior



… erected at each time t

The same construction works for de Sitter space outside the horizon.

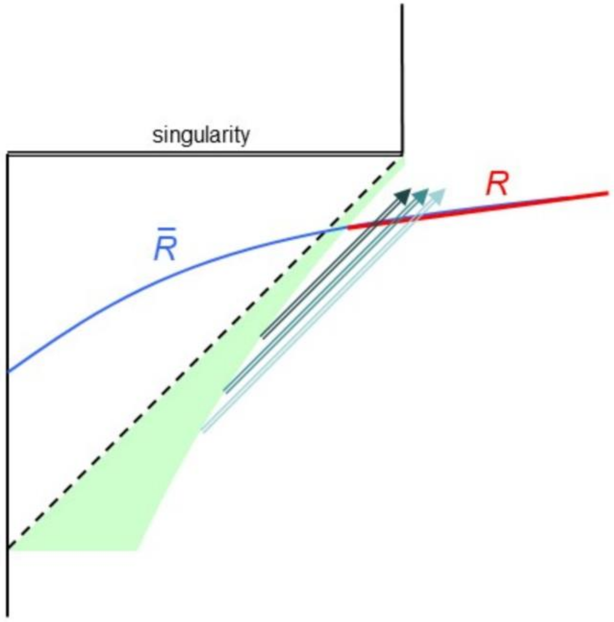


Y.N., 1908.05728

(II) Global description

Penington ('19); Almheiri, Engelhardt, Marolf, Maxfield ('19); Almheiri, Mahajan, Maldacena, Zhao ('19); …

What was the problem?



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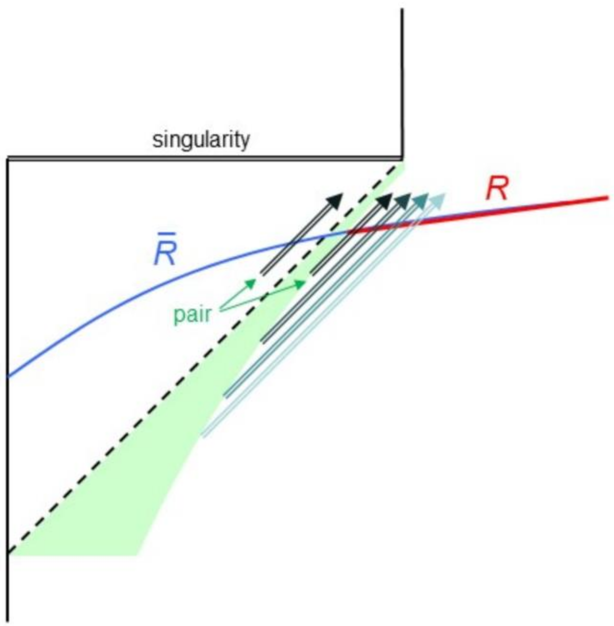

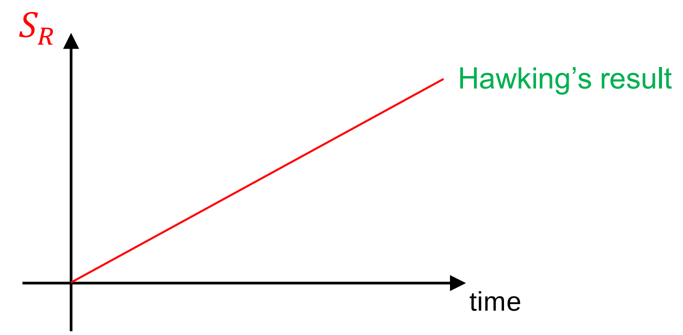

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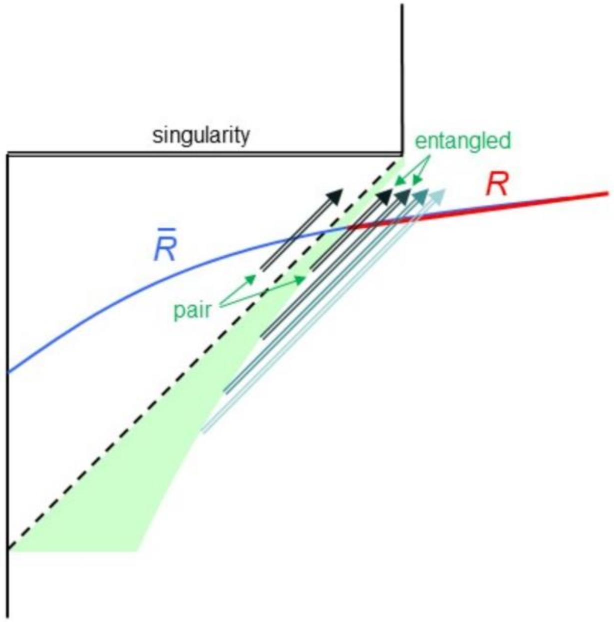

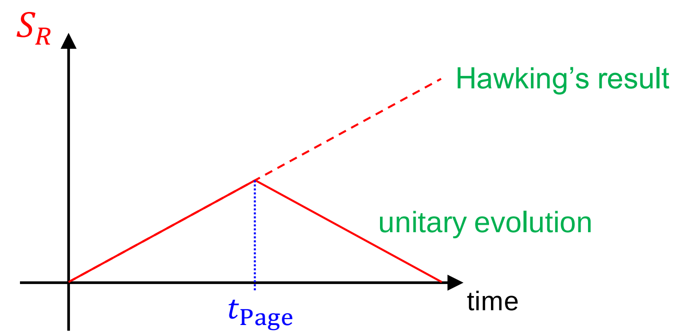

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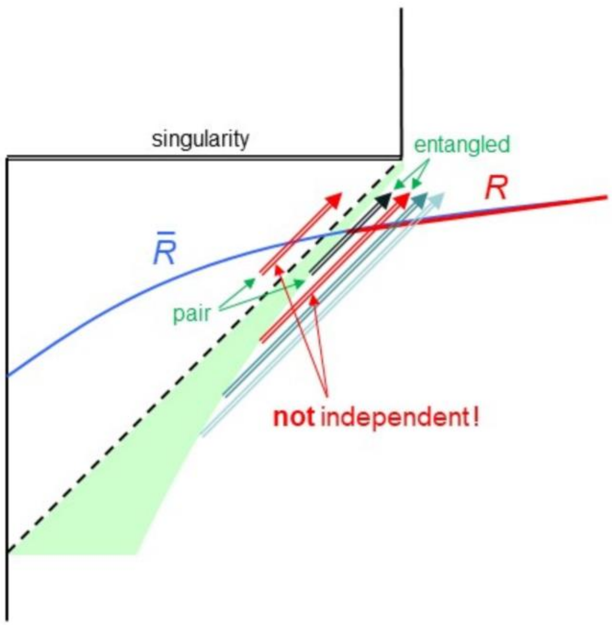

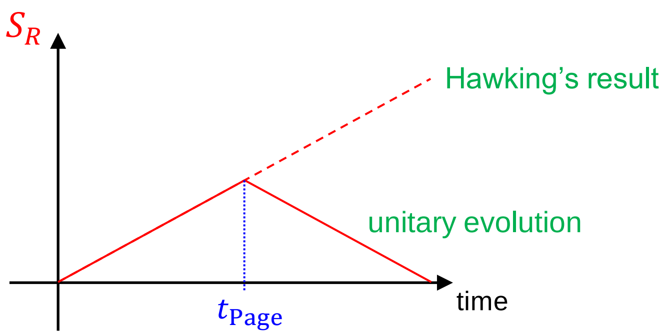

→ Hawking radiation emitted earlier is **not** independent of the interior d.o.f.s!

…; Maldacena, Susskind ('13); …

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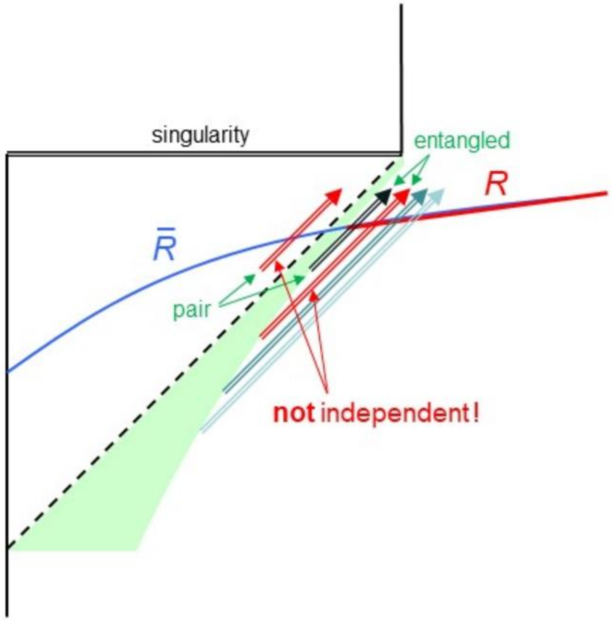
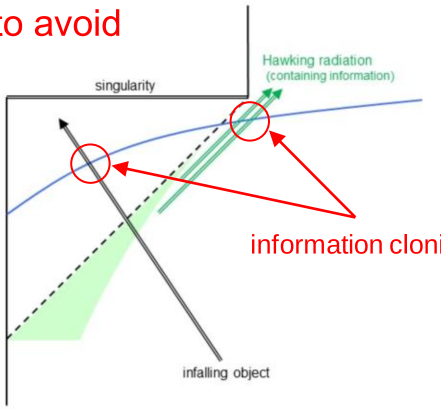


- needed to avoid



- consistent because of causality

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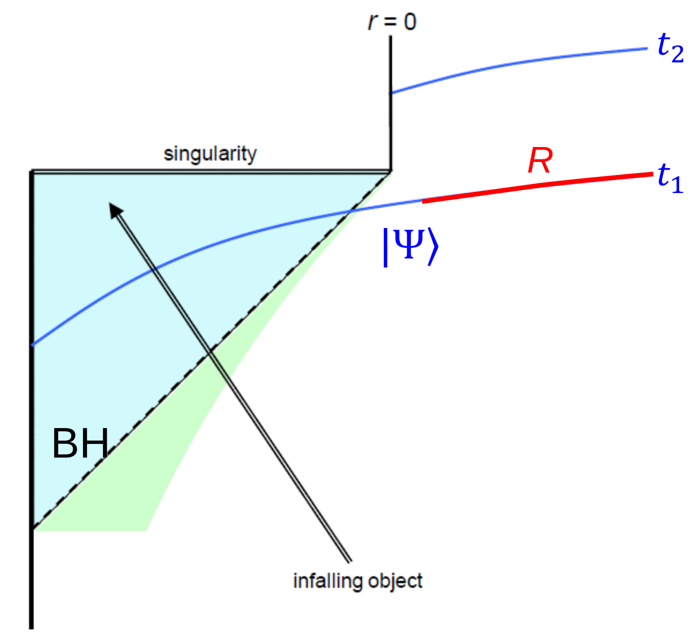


- The existence of the interior is manifest.
- The **fundamental** d.o.f.s in R represent physics in $\boldsymbol{R} \cup \boldsymbol{I}$.

$$S(\mathbf{R}) = \min_I \operatorname{ext} S_{\rm gen}(I \cup R)$$

$$S_{\rm gen}(X) = \frac{\mathcal{A}(\partial X)}{4G_{\rm N}} + S_{\rm bulk}(X)$$

semiclassical von Neumann entropy

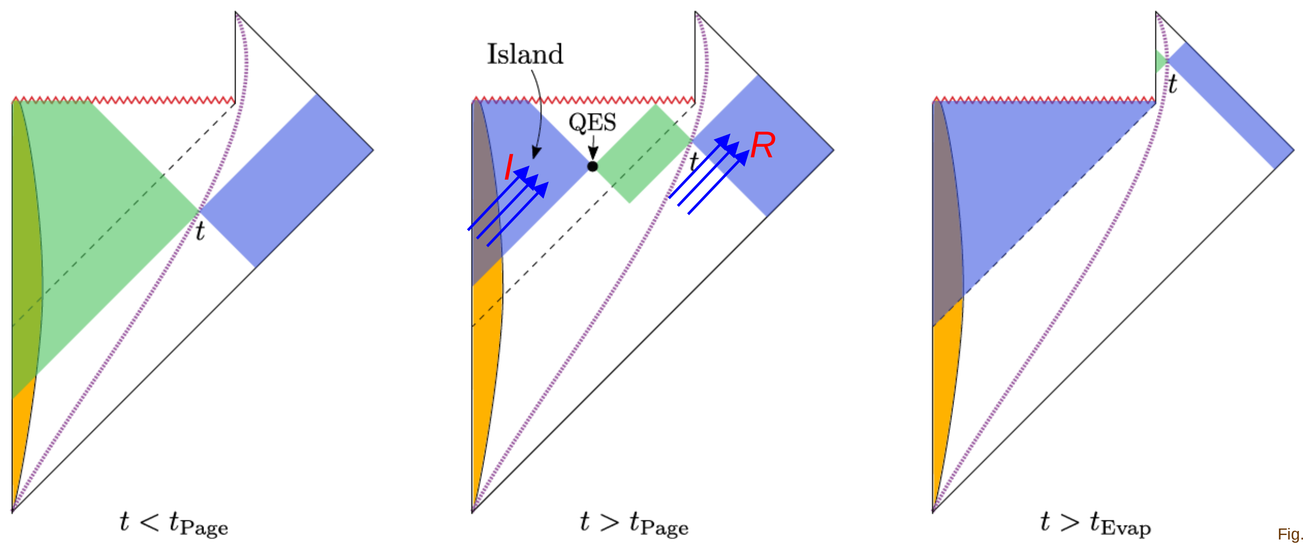


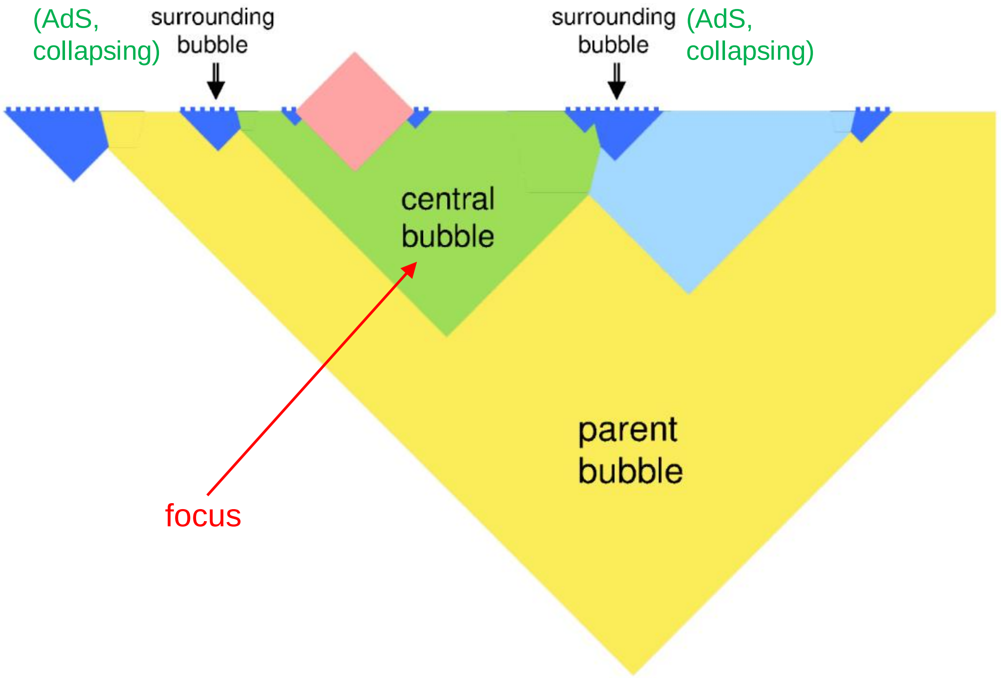
Fig. from Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini

Entanglement Islands in the Multiverse

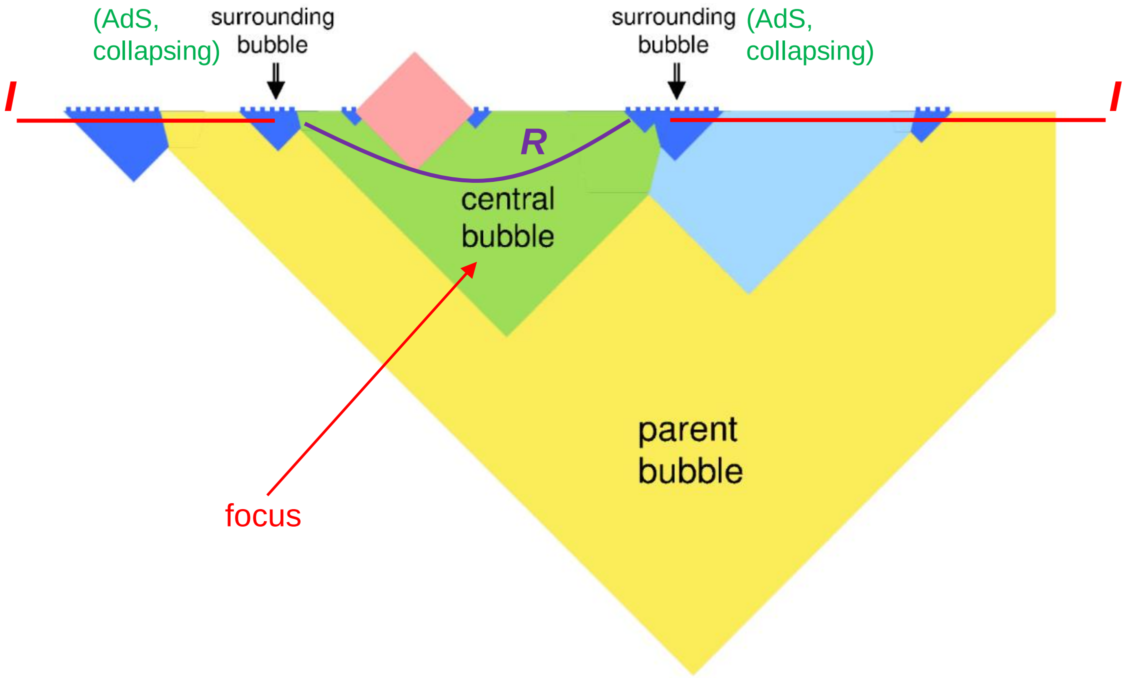
— redundancy of infinitely large spacetime —

Langhoff, Murdia, Y.N., “Multiverse in an inverted island,” arXiv:2106.05271

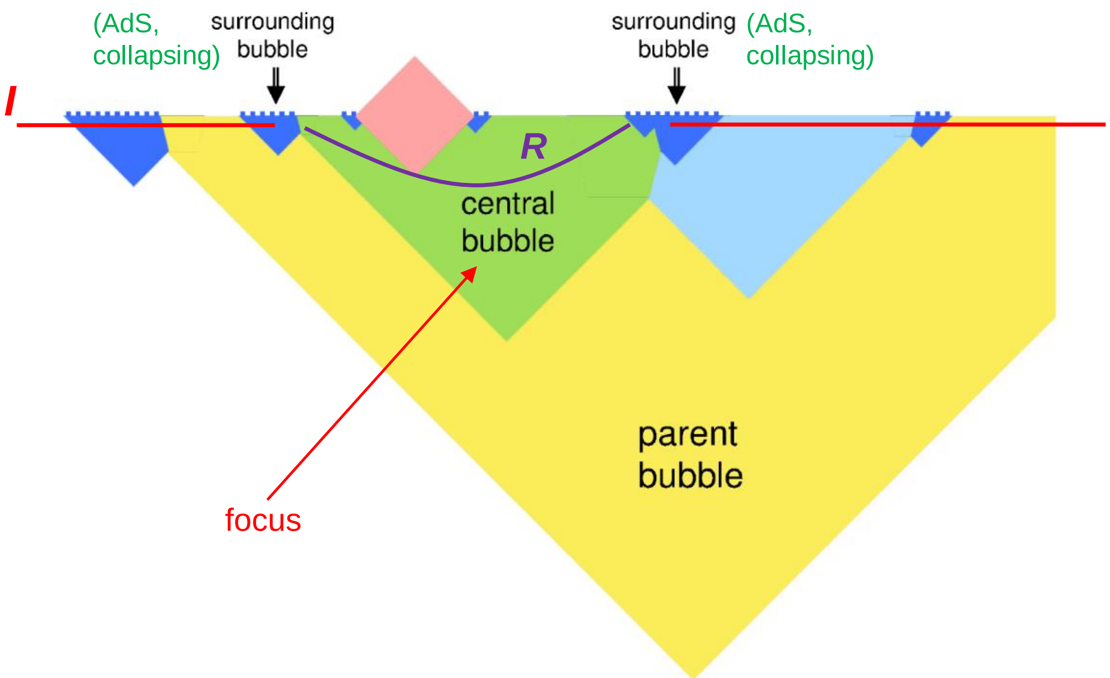
Begin with global spacetime



Begin with global spacetime



Begin with global spacetime

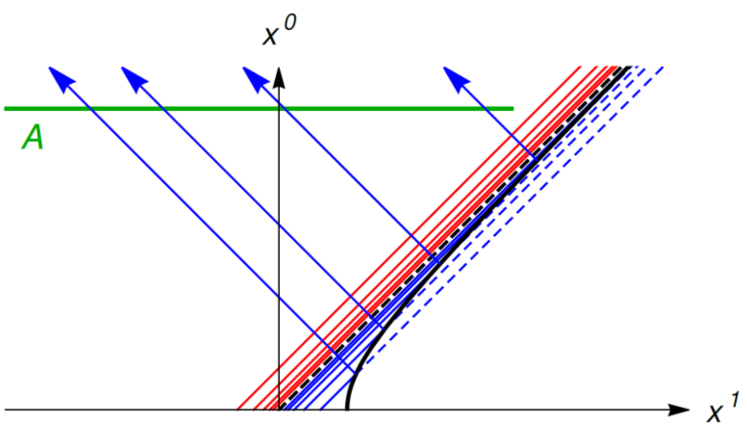


- Origin of S_{bulk}

… need a major source of
entropy associated with spacetime

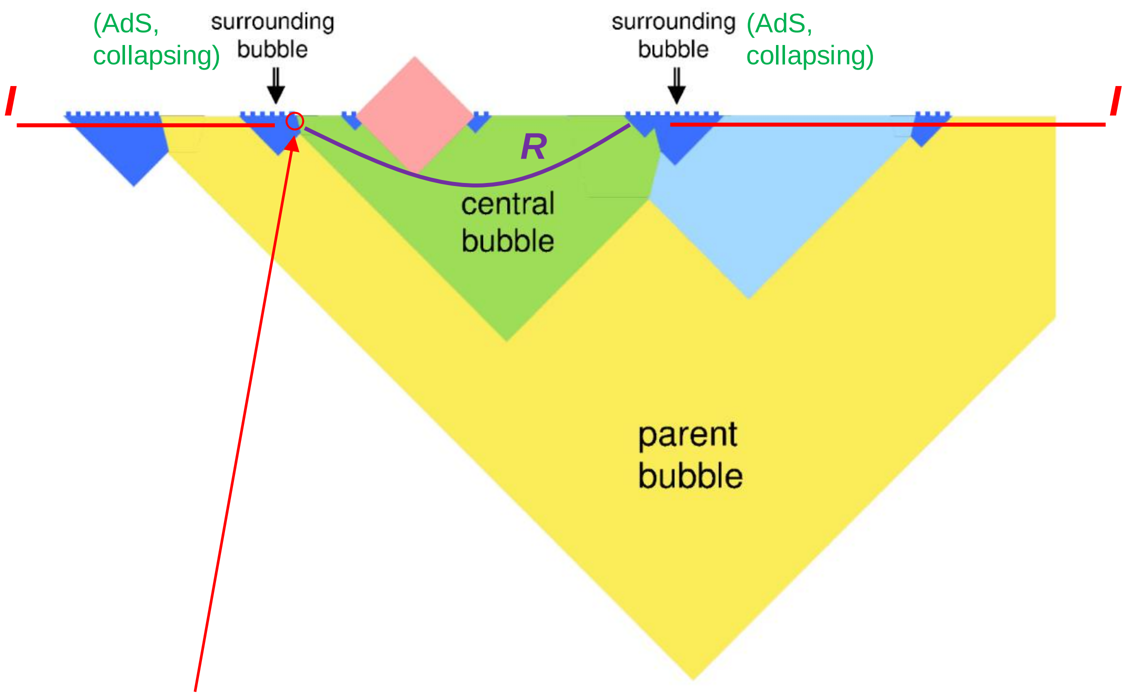
e.g. Hawking radiation, reheating, …

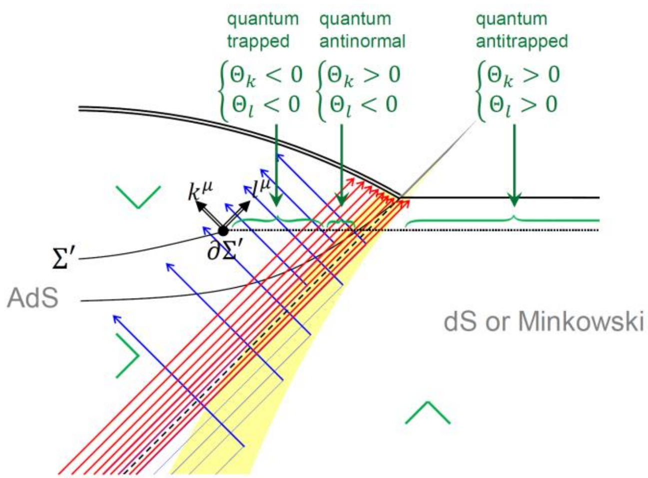
→ Unruh radiation from
accelerating domain walls

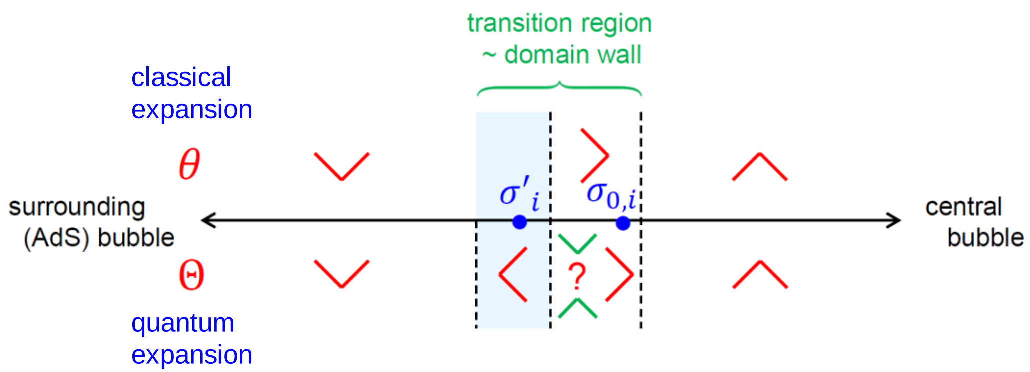


… keep harvesting vacuum entanglement

Begin with global spacetime

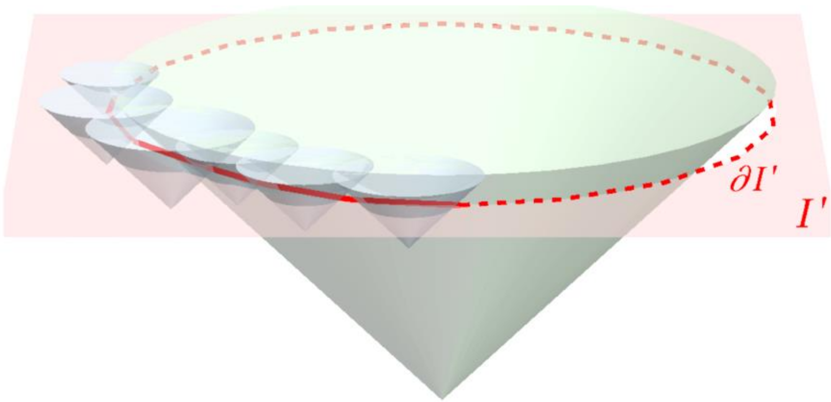






… Singularities in AdS bubbles are important.

Inverted island around the bubble



The existence of

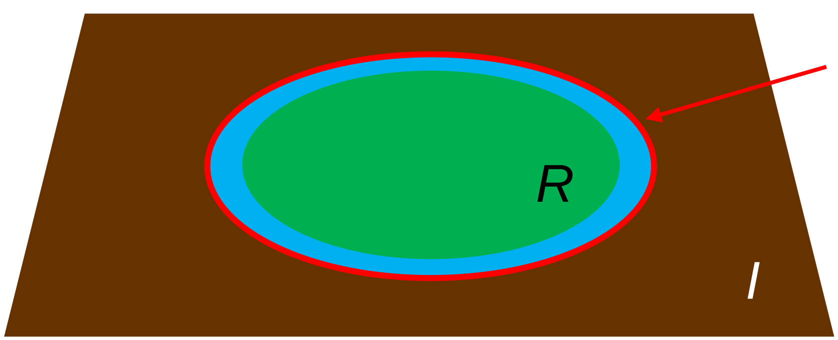
I' • spacelike separated from R
• $S_{\text{gen}}(I' \cup R) < S_{\text{gen}}(R)$
• $\partial I'$: quantum antinormal w.r.t. $S_{\text{gen}}(I' \cup R)$

as well as

I_0 • spacelike separated from R
• $D(I_0) \supset I'$
• ∂I_0: quantum normal w.r.t. $S_{\text{gen}}(I_0 \cup R)$

$\Downarrow$ "Island finder" Bousso, Shahbazi-Moghaddam ('21)

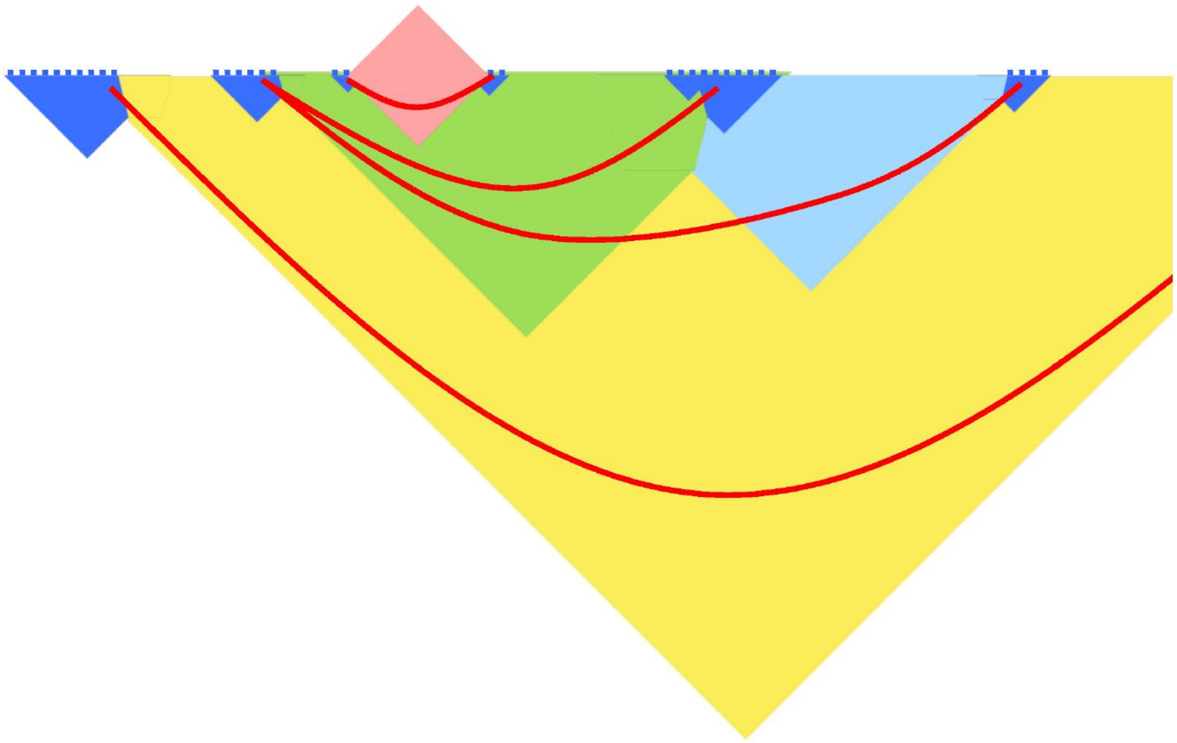
$\exists$ Quantum extremal surface



Fundamental d.o.f.s inside this is enough to describe the **entire** multiverse!

c.f. For an analysis of lower dimensional models, Aguilar-Gutierrez, Chatwin-Davies, Hertog, Pinzani-Fokeeva, Robinson, 2108.01278

Cosmological evolution



Cauchy surface Ξ $\rightarrow$ effective Cauchy surface $\Xi \setminus I_\Xi$ $[\, I_\Xi = D(I) \cap \Xi \,]$

$$|\Psi(\Upsilon_1)\rangle \xrightarrow[\text{evolution}]{\text{time}} \sum_{i \in \text{geometries}} c_i |\Psi(\Upsilon_{2,i})\rangle_{\mathcal{M}_i}$$

… enough to describe time evolution

Summary

Eternally Inflating Multiverse

- provides (arguably) the best understanding of $\rho_{\Lambda,\mathrm{obs}}$
- well motivated by theory (string theory)

Recent Progress in Quantum Gravity

- new understanding of spacetime
  - Black holes
  - de Sitter spacetime
  - …

Implications for the Multiverse

- addresses a major problem in cosmology (measure problem)