Black Hole Information Problem as a Window into Quantum Gravity

Yasunori Nomura

UC Berkeley; LBNL; Kavli IPMU

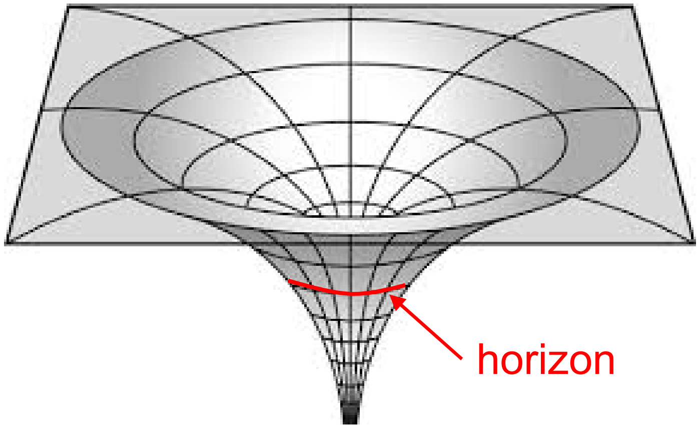
Quantum mechanics & Gravity

~ Quantum mechanics of spacetime

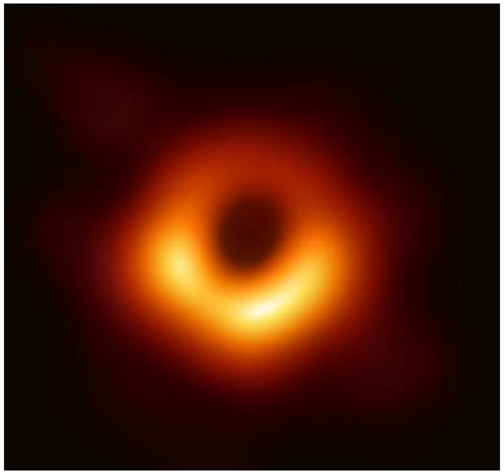
… has been elusive, despite many effort and progress

Black holes

– Objects showing the geometric nature of gravity most dramatically



– Ubiquitous in our universe



Why black holes?

"Testing grounds" for **theories of quantum gravity**

Even most basic questions remain debatable

- Do black holes evolve unitarily?
- Does an infalling observer pass the horizon smoothly?
- Are dynamics local outside the horizon?
- …

S.W. Hawking,
"Breakdown of predictability in gravitational collapse," *Phys. Rev.* **D14** (1976) 2460
...
A. Almheiri, D. Marolf, J. Polchinski, and J. Sully,
"Black holes: complementarity or firewalls?," *JHEP* **02** (2013) 062

… involves all three pillars of modern physics:

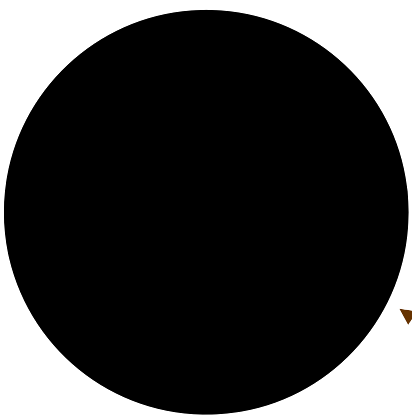
Quantum mechanics, General relativity, and Statistical mechanics

Thermodynamics of a Black Hole

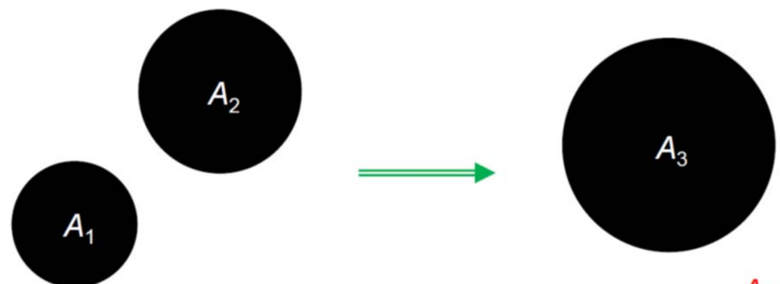
One of the biggest discoveries in theoretical physics:

$$\boxed{\begin{aligned} S_{\mathrm{BH}}(M) &= \frac{\mathcal{A}(M)}{4l_{\mathrm{P}}^2} \\ T_{\mathrm{H}}(M) &= \frac{1}{8\pi M l_{\mathrm{P}}^2} \end{aligned}}$$

Bekenstein ('73); Hawking ('74)



- What happens to energy and entropy?

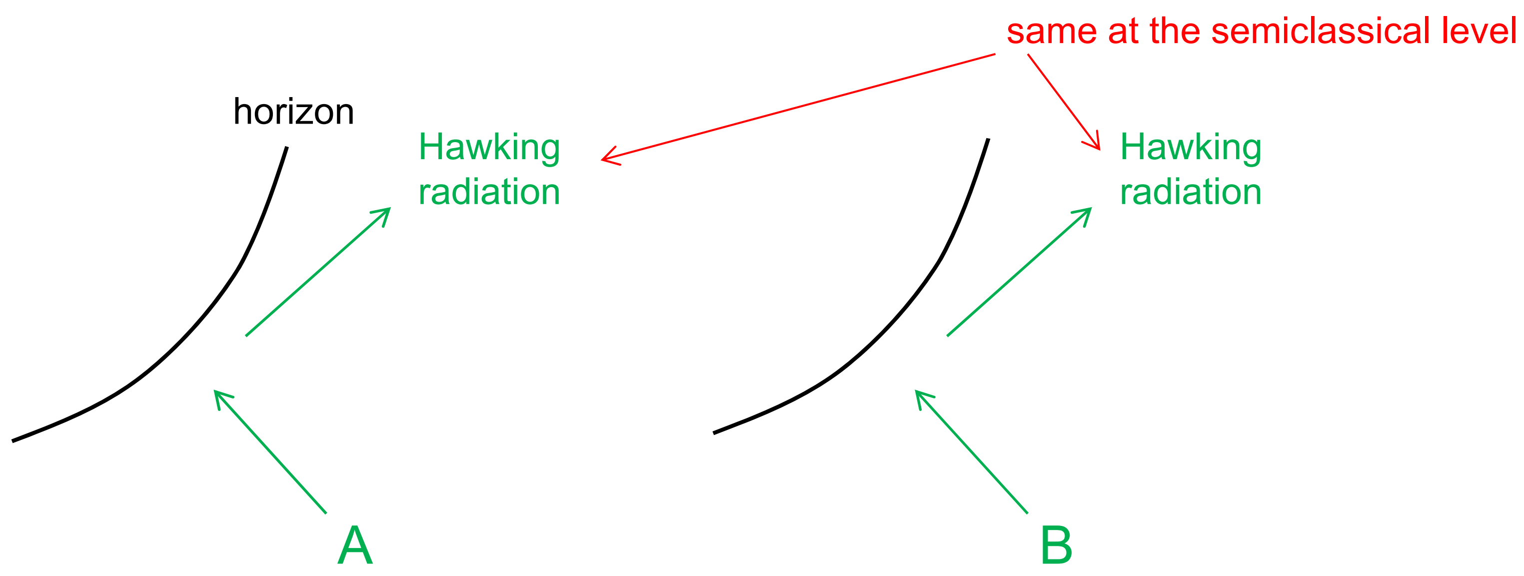


$A_3 \geq A_1 + A_2$

S(entropy) ~ A(area) → The fundamental degrees of freedom in quantum gravity live in lower-dimensional, *holographic* space! 't Hooft ('93); Susskind ('94); …; Bousso ('99); …

Mystery of Hawking Emission

Information loss paradox



… information is lost ?? Hawking (‘76)

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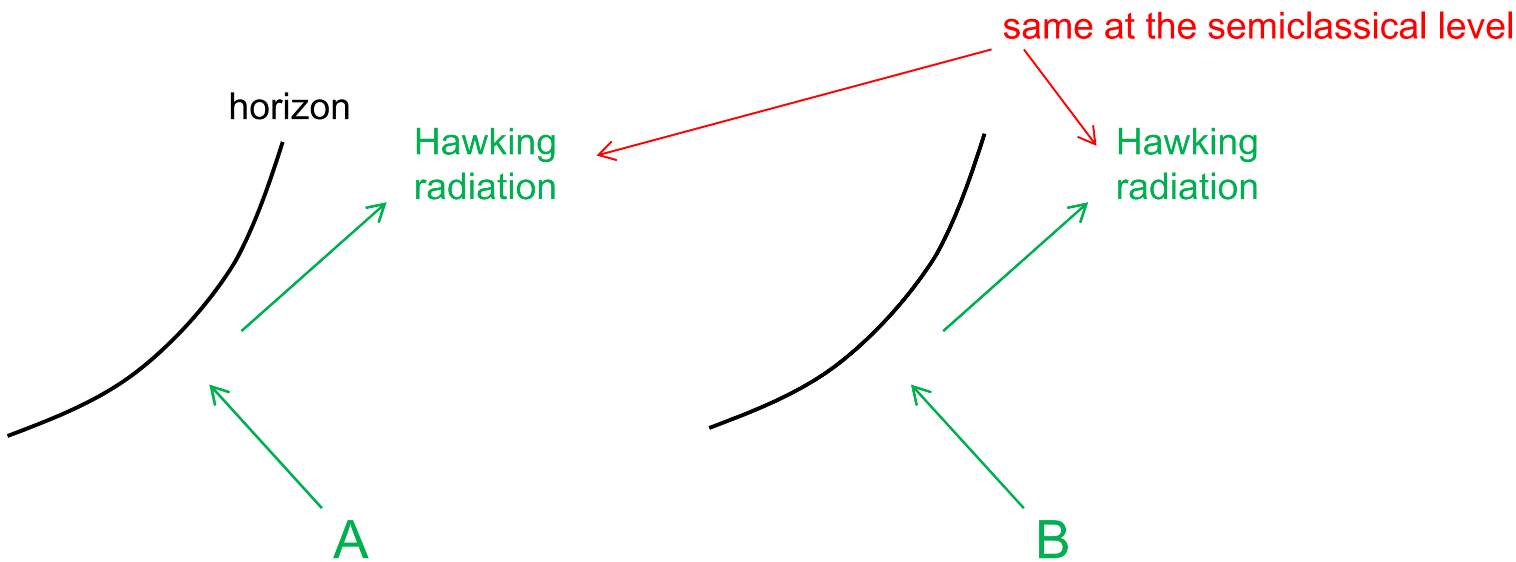


… information is lost ?? Hawking ('76)

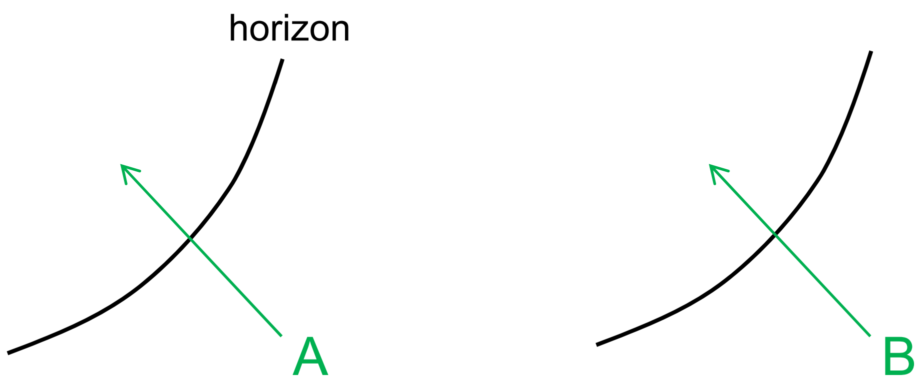
⟹ No

… Quantum mechanically different final states

The whole information is sent back in Hawking radiation (in a form of quantum correlations)

cf. AdS/CFT, classically "burning" stuffs, …

From a falling observer's viewpoint:



… Objects simply fall in

cf. equivalence principle

• **Distant observer:**

Information will be *out*side at late times.

(sent back in Hawking radiation)

• **Falling observer:**

Information will be *in*side at late times.

(carried with him/her)

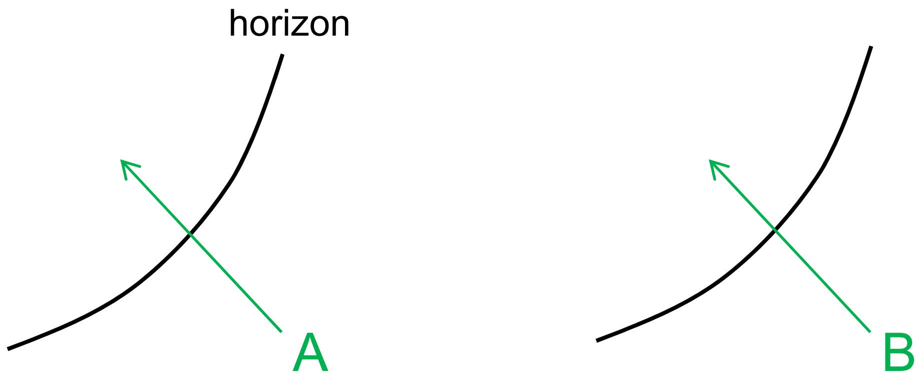
Which is correct?

Preskill ('93)

Note: Quantum mechanics prohibits faithful copy of information (no-cloning theorem)

$$|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$$
$$|\downarrow\rangle \rightarrow |\downarrow\rangle|\downarrow\rangle$$
$$|\uparrow\rangle+|\downarrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle+|\downarrow\rangle|\downarrow\rangle \quad \text{(superposition principle)}$$
$$\neq (|\uparrow\rangle+|\downarrow\rangle)(|\uparrow\rangle+|\downarrow\rangle)$$

From a falling observer's viewpoint:



… Objects simply fall in

cf. equivalence principle

- Distant observer:

  Information will be *out*side at late times.
  (sent back in Hawking radiation)

- Falling observer:

  Information will be *in*side at late times.
  (carried with him/her)

Which is correct?

$\Longrightarrow$ **Both are correct !**

There is no contradiction !

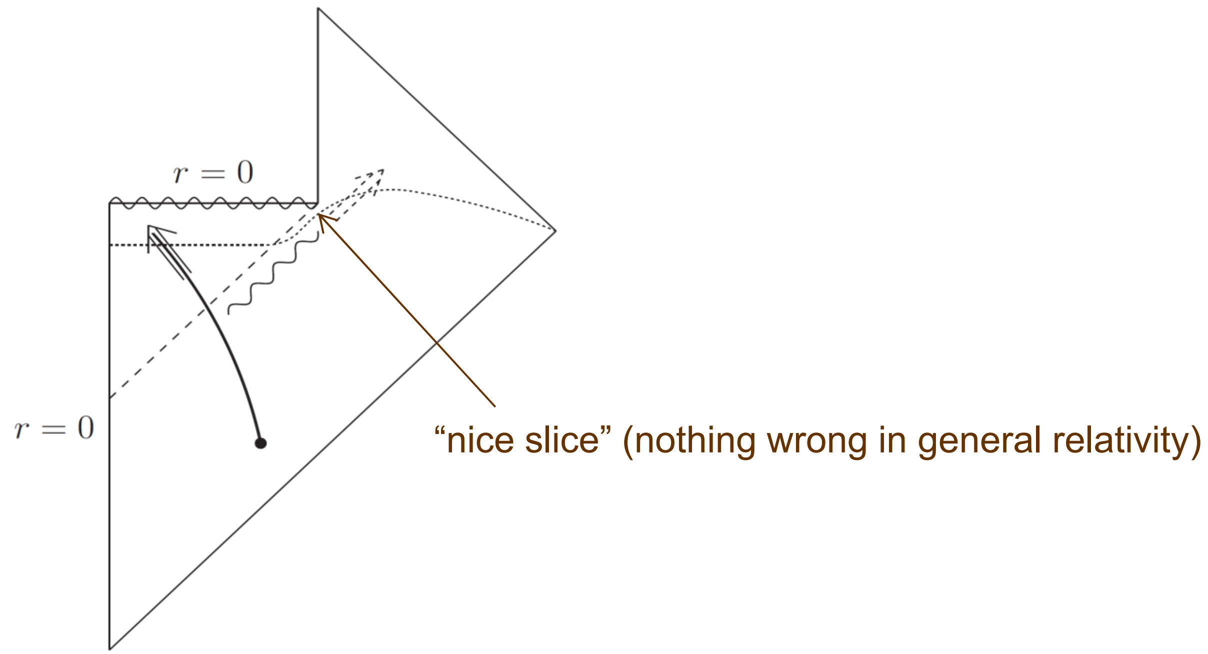
One cannot be *both* distant and falling observers *at the same time*.

… **"Black hole complementarity"** Susskind, Thorlacius, Uglum ('93); Stephens, 't Hooft, Whiting ('93)

Including both (late) Hawking radiation and
interior spacetime in a single description is overcounting !

… Equal-time hypersurfaces must be chosen carefully.

This is a hypothesis **beyond** QFT in curved spacetime.



A hope was that with such a careful choice,
semiclassical field theory gives a good (local) description of physics.

cf. Hayden, Preskil ('07); Sekino, Susskind ('08); …

Complementarity Is Not Enough

"Firewall" argument(s)

Almheiri, Marolf, Polchinski, (Stanford), Sully ('13–'14)

- Entanglement argument
  - — Monogamity of entanglement prevents unitarity and smoothness incompatible
- Typicality argument
  - — Typical states in quantum gravity do not seem to have smooth "interior"

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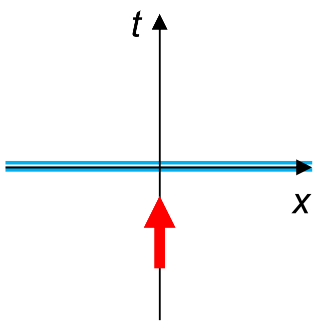
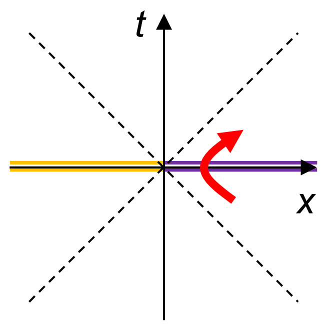
Smooth horizon:





$$|0\rangle \longleftrightarrow |0\rangle_L |0\rangle_R + |1\rangle_L |1\rangle_R + \ldots$$

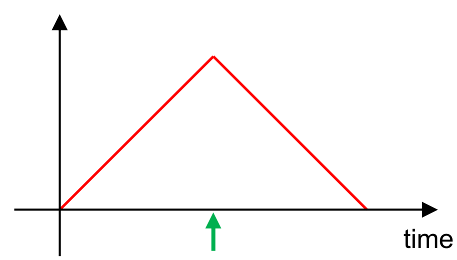
Minkowski (infalling)

Rindler (Schwarzschild)

Unitarity:

$$|BH\rangle|vac\rangle$$
$$\downarrow$$
$$|BH_1\rangle|rad_1\rangle + |BH_2\rangle|rad_2\rangle$$
$$\downarrow$$
$$|rad_1\rangle|rad_1\rangle + |rad_2\rangle|rad_2\rangle$$

entanglement between BH and radiation

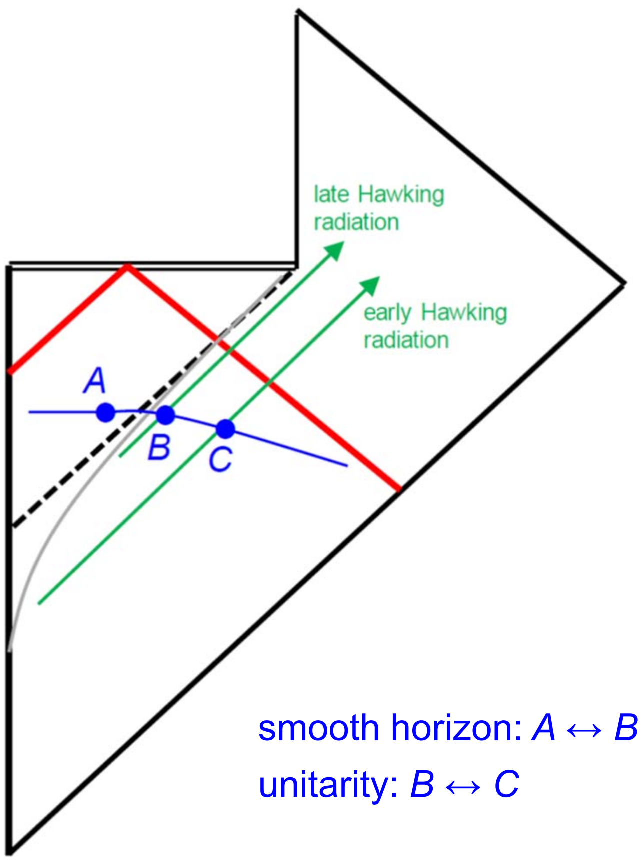


Page ('93)

The entanglement argument for firewalls

… The problem of black hole information

can be formulated in a "single causal patch"



smooth horizon: $A \leftrightarrow B$

unitarity: $B \leftrightarrow C$

- Monogamity of entanglement

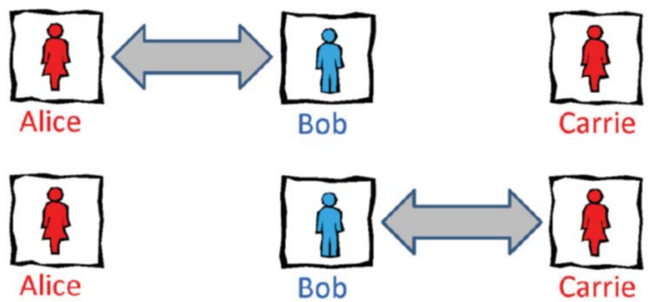


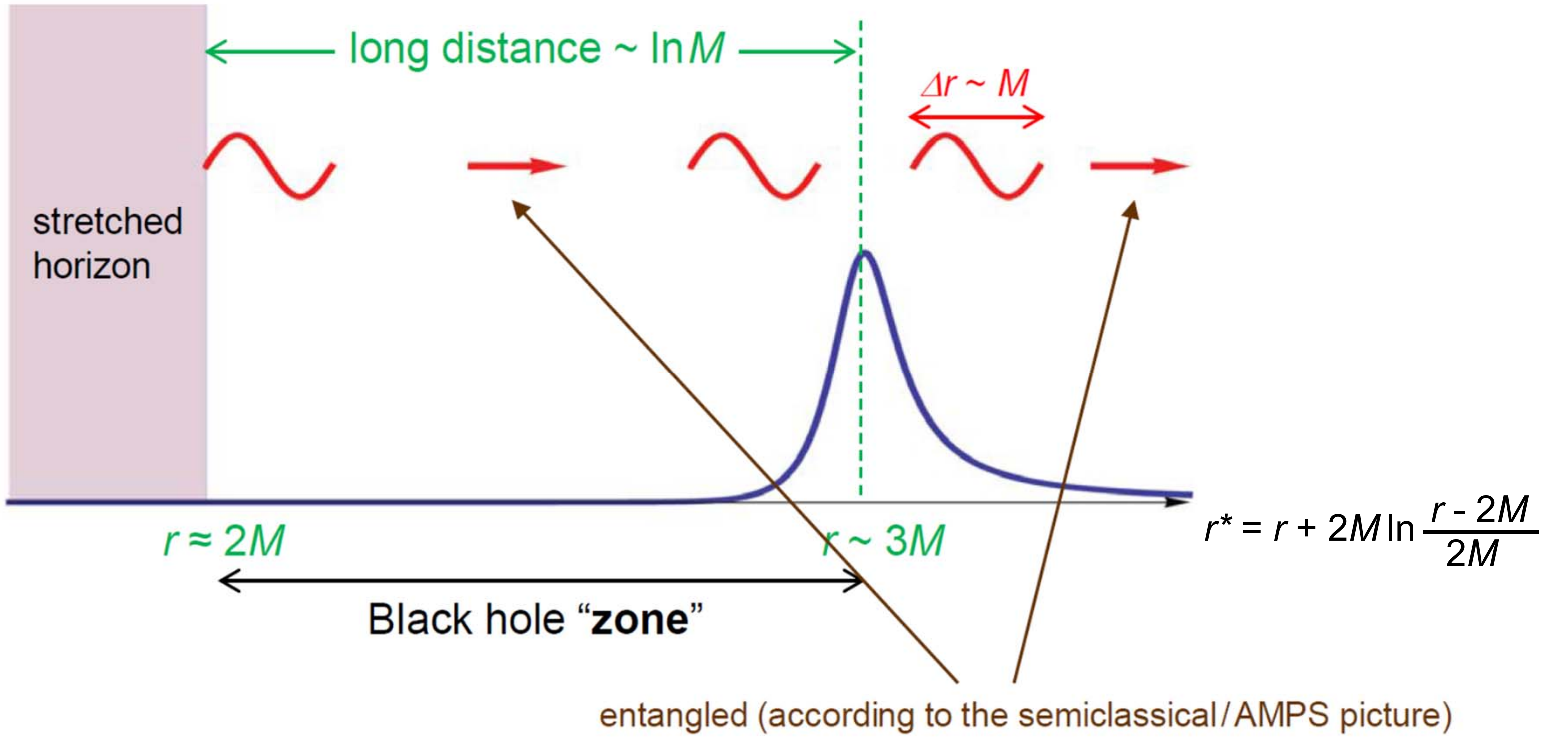
Fig. by Preskil

… These two structures cannot both be true.

Unitarity → ~~Smooth horizon~~ = "firewall"

Note: the black hole thermal atmosphere—**zone**—is "thick"

(below we set $\ell_P = 1$)



A clash of basic principles!

— Unitarity (of black hole evolution)

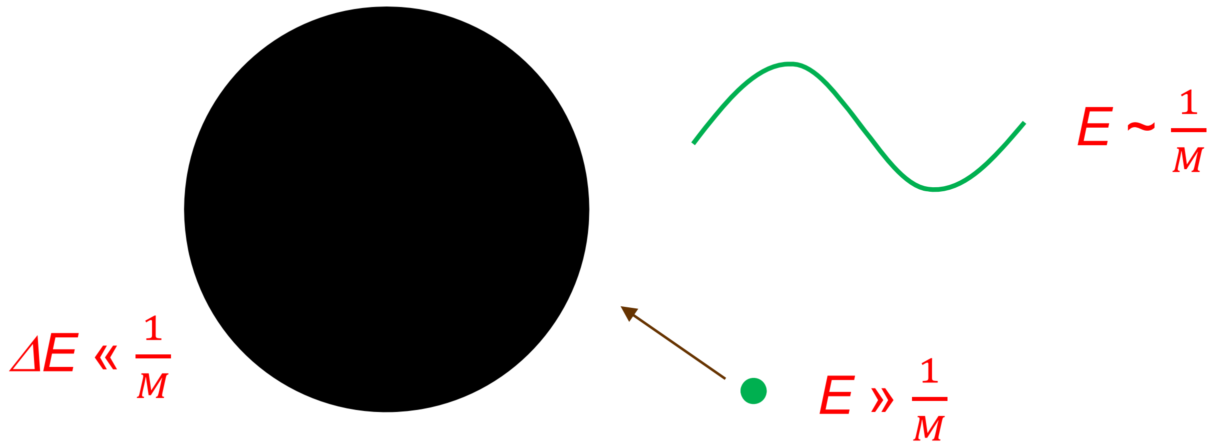
— Local physics outside the stretched horizon

— Equivalence principle (~ smooth horizon)

Reanalyzing an Evaporating BH

The origin of thermality

Y.N., "Reanalyzing an evaporating black hole," *Phys. Rev.* **D99** (2019) 086004;
"Spacetime and universal soft modes—black holes and beyond," arXiv:1908.05728 [hep-th]



Distinguish modes in the zone:

Hard modes: $E > \frac{1}{M}$ … described by semiclassical theory $|E\rangle$

Soft modes: $E < \frac{1}{M}$ … cannot be resolved (described only statistically) $|\psi_{i_E}\rangle$

$\Longrightarrow$ BH state: $|\psi(M)\rangle = \sum_E \sum_{i_E=1}^{\mathcal{N}(M-E)} c_{E i_E} |E\rangle |\psi_{i_E}(M-E)\rangle \quad \left(\mathcal{N}(M) \sim e^{S_{\rm BH}(M)} \right)$

Tracing out the soft modes → thermal density matrix with Hawking temperature T_H

… Thermality arises from **entanglement between the hard and soft modes**

How does information transfer from BH to ambient space occur?

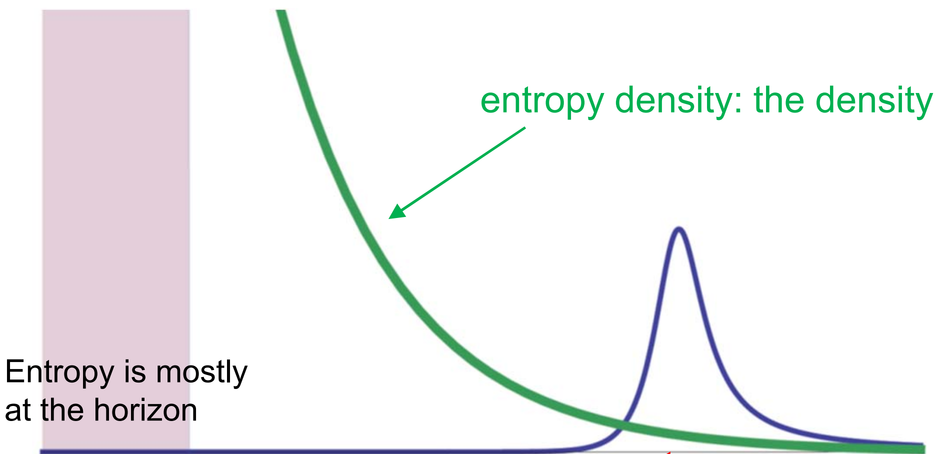
… need to understand the Hawking emission process

"Where" is the information?

In QM, information is stored nonlocally in general.

(A state is a nonlocal concept even if dynamics is local.)

A black hole is "quasi static"



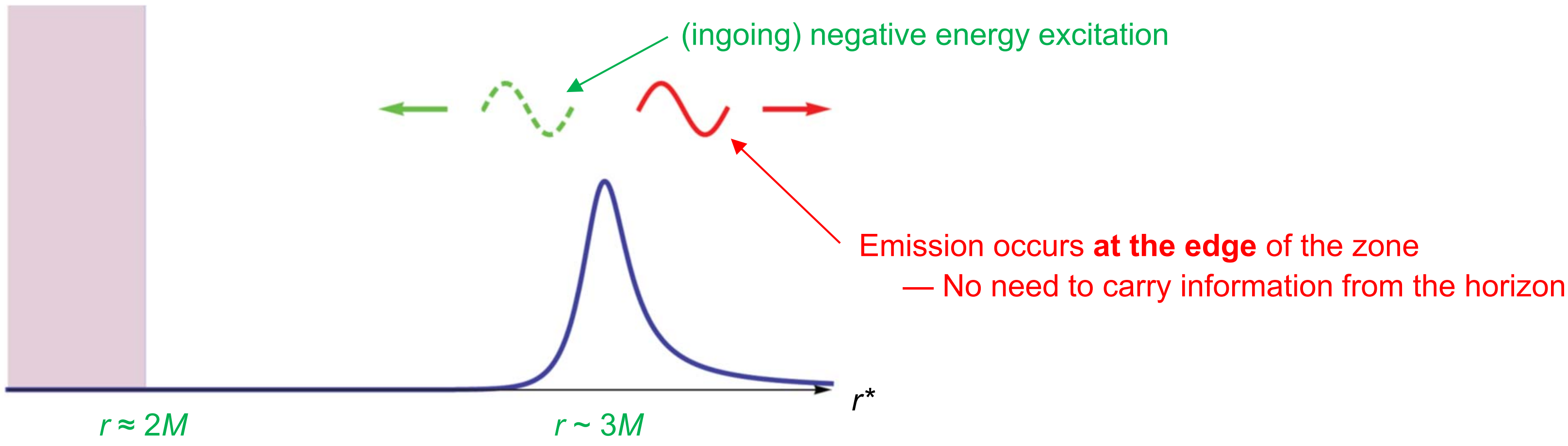
$$s(r) \propto T^3(r) = \frac{1}{(8\pi M)^3\,(1-2M/r)^{3/2}}$$

$O(1)$ entropy at the edge of the zone — **not** « $O(1)$

… fractionally only ~ O($1/A$), but enough to affect evaporation!

There are $O(M^2 \sim A)$ steps!

The (correct) picture of Hawking emission:



There is no outgoing mode in the zone in the semiclassical picture.

Note: difference from the previous, AMPS picture

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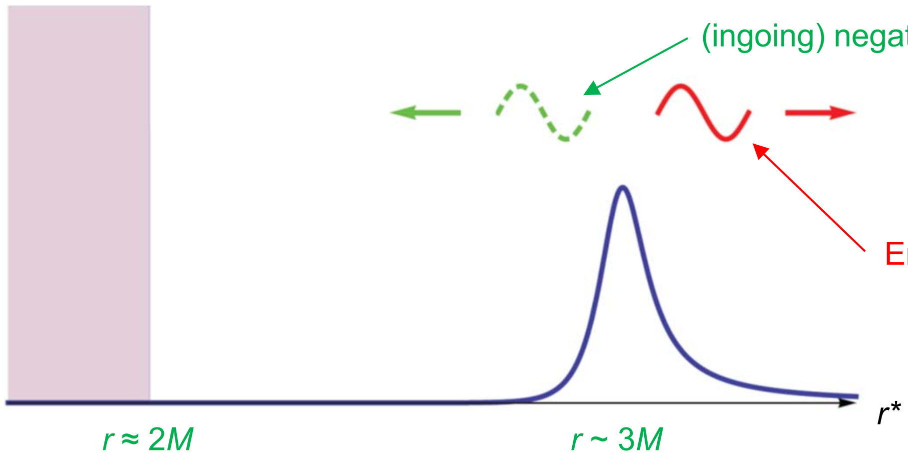

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At the microscopic level

$|\Psi_1(M)>$

$|\Psi_2(M)>$

$|\Psi_3(M)>$ $\overset{?}{\Longrightarrow}$

$|\Psi_4(M)>$

$\vdots$

$|\Psi_{2n}(M)>$

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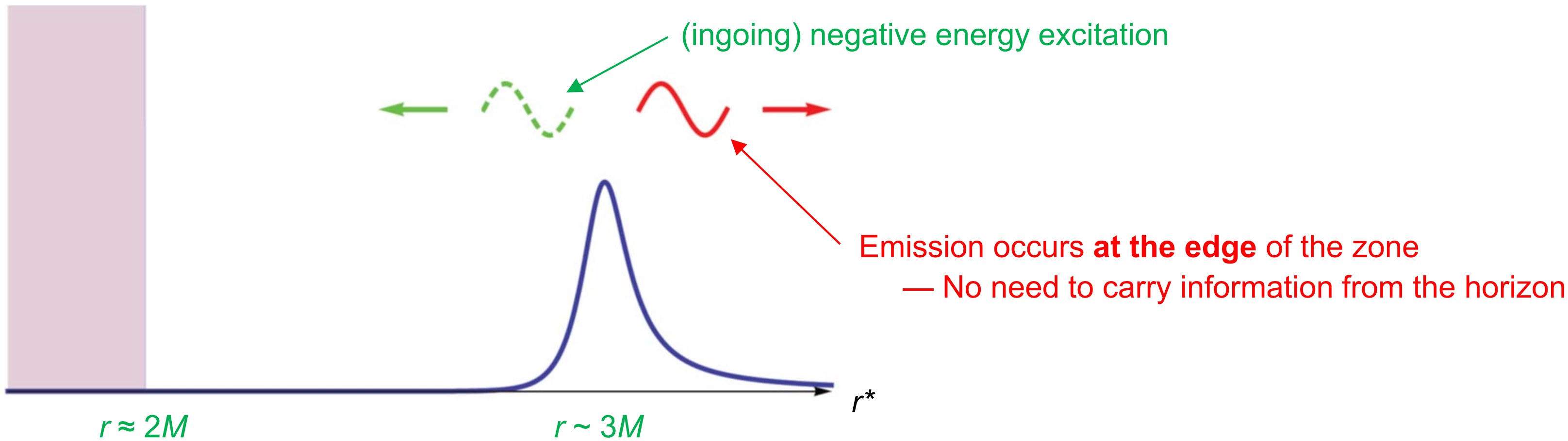

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At the microscopic level

$$
\begin{array}{ccc}
|\Psi_1(M)\rangle & & |\Psi^*_1(M)\rangle\,|r_1\rangle \\
|\Psi_2(M)\rangle & & |\Psi^*_2(M)\rangle\,|r_2\rangle \\
|\Psi_3(M)\rangle & \overset{?}{\Longrightarrow} & |\Psi^*_3(M)\rangle\,|r_1\rangle \\
|\Psi_4(M)\rangle & & |\Psi^*_4(M)\rangle\,|r_2\rangle \\
\vdots & & \vdots \\
|\Psi_{2n}(M)\rangle & & |\Psi^*_{2n}(M)\rangle\,|r_2\rangle
\end{array}
$$

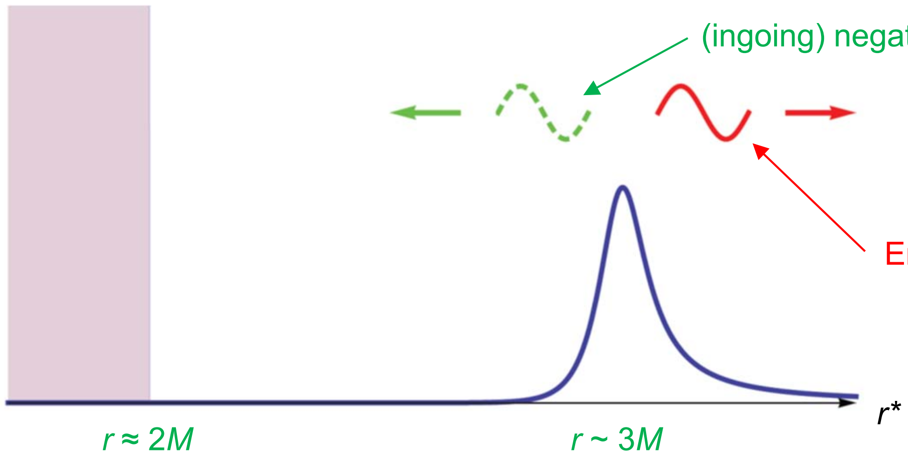
$*$: negative energy excitation

But the relaxation afterward

$$
\begin{array}{ccc}
|\Psi^*_1(M)\rangle & & |\Psi_1(M-\delta M)\rangle \\
|\Psi^*_2(M)\rangle & \longrightarrow & |\Psi_2(M-\delta M)\rangle \\
\vdots & & \vdots \\
|\Psi^*_{2n}(M)\rangle & & |\Psi_n(M-\delta M)\rangle
\end{array}
$$

does not seem to be possible…

The (correct) picture of Hawking emission:



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|\Psi_3(M)\rangle & \Longrightarrow & |\Psi^*_2(M)\rangle\,|r_1\rangle \\
|\Psi_4(M)\rangle & & |\Psi^*_2(M)\rangle\,|r_2\rangle \\
\vdots & & \vdots \\
|\Psi_{2n}(M)\rangle & & |\Psi^*_n(M)\rangle\,|r_2\rangle
\end{array}$$

Negative energy excitation
carries *negative* entropy!

$$E \sim S$$

… Information extraction from BHs occurs through ingoing **negative information**.

Unitary Evolution

Y.N., “Reanalyzing an evaporating black hole,” *Phys. Rev.* **D99** (2019) 086004;
“Spacetime and universal soft modes—black holes and beyond,” arXiv:1908.05728 [hep-th]

As a black hole evolves, entanglement
between soft modes and Hawking radiation develops quickly.

$$\boxed{|\Psi(M)\rangle = \sum_{E} \sum_{i_E=1}^{\mathcal{N}(M-E)} \sum_{a=1}^{e^{S_{\rm rad}}} c_{E i_E a} |E\rangle |\psi_{i_E}(M-E)\rangle |r_a\rangle}$$

The entanglement structure is intrinsically multi-partite (Soft modes–Hard modes–Hawking radiation)
whether the age of the black hole is larger or smaller than the Page time.

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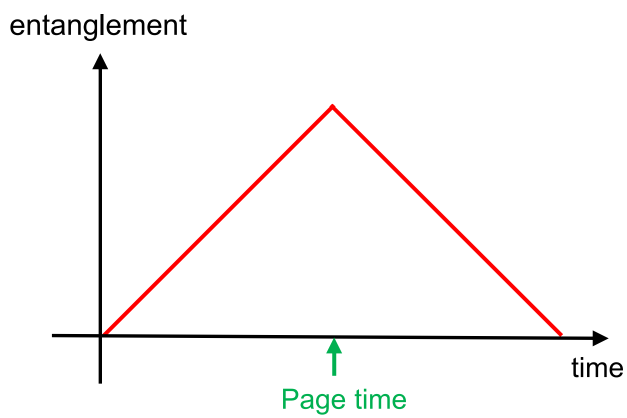
The entanglement structure is intrinsically multi-partite (Soft modes–Hard modes–Hawking radiation)
whether the age of the black hole is larger or smaller than the Page time.

$O(M^2)$ … most of entanglement between BH and Hawking quanta

… obeys the Page curve



→ BH evolution viewed from the outside is unitary.

Effective Theories of the Interior

Y.N., “Reanalyzing an evaporating black hole,” *Phys. Rev.* **D99** (2019) 086004;
“Spacetime and universal soft modes—black holes and beyond,” arXiv:1908.05728 [hep-th]

At *each time*, the BH mirror modes can be identified as

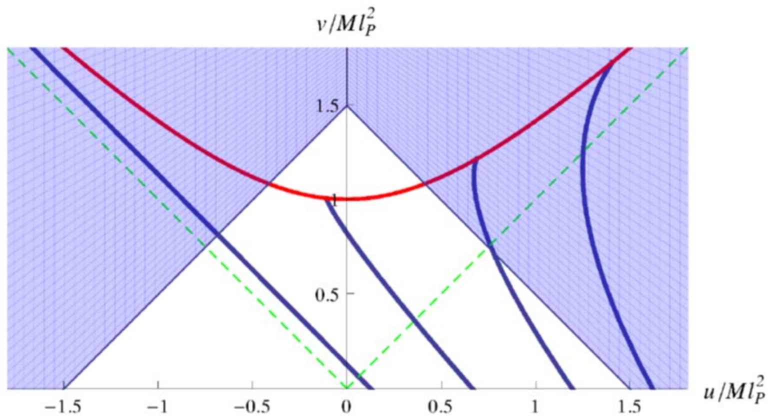
$$\boxed{|\Psi(M)\rangle = \sum_E \boxed{\sum_{i_E=1}^{\mathcal{N}(M-E)} \sum_{a=1}^{e^{S_{\rm rad}}} c_{E i_E a}} \boxed{|E\rangle} \boxed{|\psi_{i_E}(M-E)\rangle |r_a\rangle}} \xrightarrow{\text{coarse-grain}} \|E\rangle\!\rangle$$

→ The **coarse-grained** state

$$\|\Psi(M)\rangle\!\rangle = \frac{1}{\sqrt{\sum_E e^{-\frac{E}{T_{\rm H}}}}} \sum_E e^{-\frac{E}{2T_{\rm H}}} |E\rangle \|E\rangle\!\rangle$$

… standard thermofield double (Rindler) form

represents the causal region associated with the zone and its mirror:



… The description is intrinsically semiclassical.

The black hole interior emerges **only effectively** at the coarse-grained level!

Relation to Earlier Work

State-dependent identification of the interior modes

Papadodimas, Raju ('12–'15);
also Verlinde, Verlinde ('12–'13); Y.N., Varela, Weinberg ('12–'13)

No matter what the modes in the zone are entangled with,
that could play a role of the corresponding interior ("mirror") modes.

Since what the zone modes are entangled with depends on the microstate
of the system, operators describing the interior depend on the state.

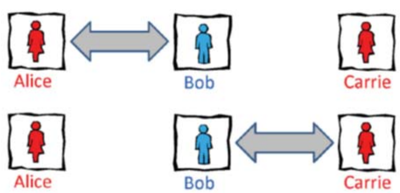
(This is in contrast with the standard linear operators in quantum mechanics.)

A specific realization

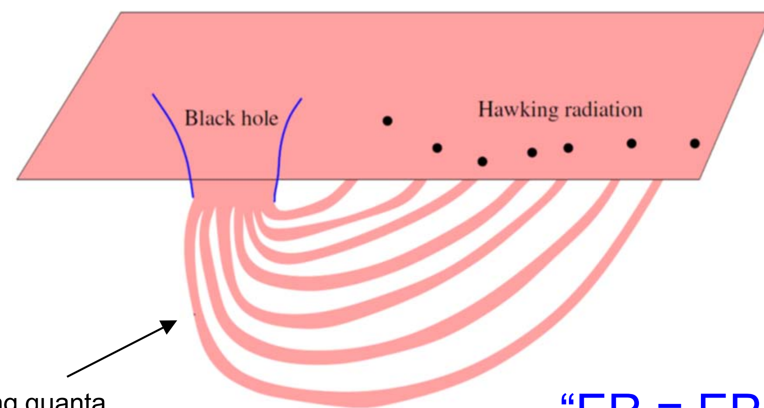
Maldacena, Susskind ('13)

Before the Page time:

After the Page time:



⟹



Wormhole connecting
BH and early Hawking quanta

"ER = EPR"

⟷ The structure we identified is multi-partite: Hard ~ Soft ~ Radiation

- Soft modes must be universal:

$$|\Psi(M)\rangle = \sum_E \sum_{i_E=1}^{\mathcal{N}(M-E)} \sum_{a=1}^{e^{S_{\rm rad}}} c_{Ei_Ea} |E\rangle |\psi_{i_E}(M-E)\rangle |r_a\rangle \xrightarrow{\text{coarse-grain}} \| \Psi(M) \rangle\!\rangle = \frac{1}{\sqrt{\sum_E e^{-\frac{E}{T_{\rm H}}}}} \sum_E e^{-\frac{E}{2T_{\rm H}}} |E\rangle \| E \rangle\!\rangle$$

… Importance of chaotic dynamics **across low energy species**

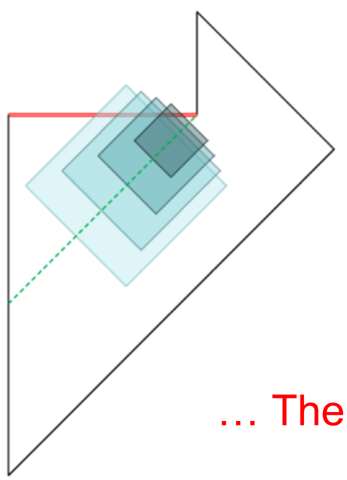
— Global symmetry must be *O*(1) broken. c.f. Harlow, Ooguri ('18)

(Nonlinearly realized symmetries are OK … cf. axion)

- BH "self repairs" its horizon

… Chaotic dynamics recovers generic coefficients c_{Ei_Ea}

- Global interior spacetime emerges only using multiple effective theories:



… The whole BH interior emerges only by "patching" views of multiple effective theories.

Relation to Cosmology

Y.N., "Physical theories, eternal inflation, and the quantum universe," *JHEP* **11** (2011) 063

Eternally inflating multiverse

… The multiverse is "infinitely large"!

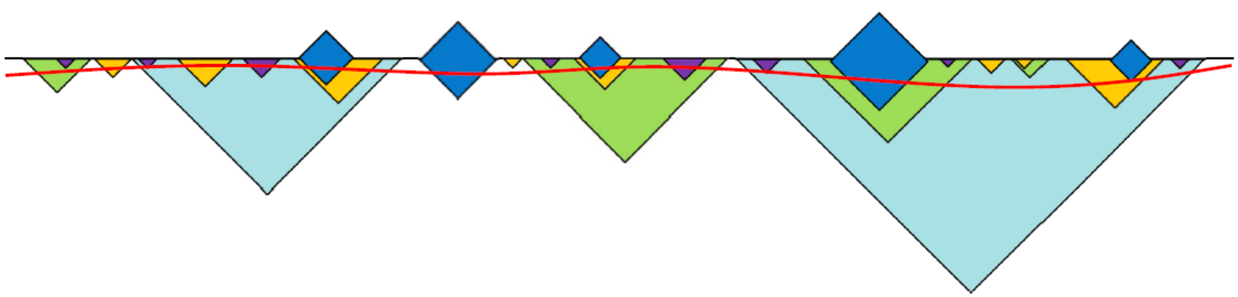
Predictivity crisis!

In an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times. Guth ('00)

ex. Relative probability of events *A* and *B*

$$P = \frac{N_A}{N_B} = \frac{\infty}{\infty} \;!!$$

Why don't we just "regulate" spacetime at $t = t_c$ ($\to \infty$)



… highly sensitive to regularization!! (The measure problem)

Multiverse = Quantum Many Worlds

Y.N., "Physical theories, eternal inflation, and the quantum universe," JHEP **11** (2011) 063
(see also Bousso, Susskind, *Phys. Rev.* D**85** ('12) 045007)

— in what sense?

Quantum mechanics is **essential**

BHs have told us:

The basic structure of quantum mechanics persists
only when an appropriate description of physics is adopted.

… Breakdown of the general relativistic spacetime picture **at long distances**.

$\Longrightarrow$ The multiverse lives **(only)** in probability space.

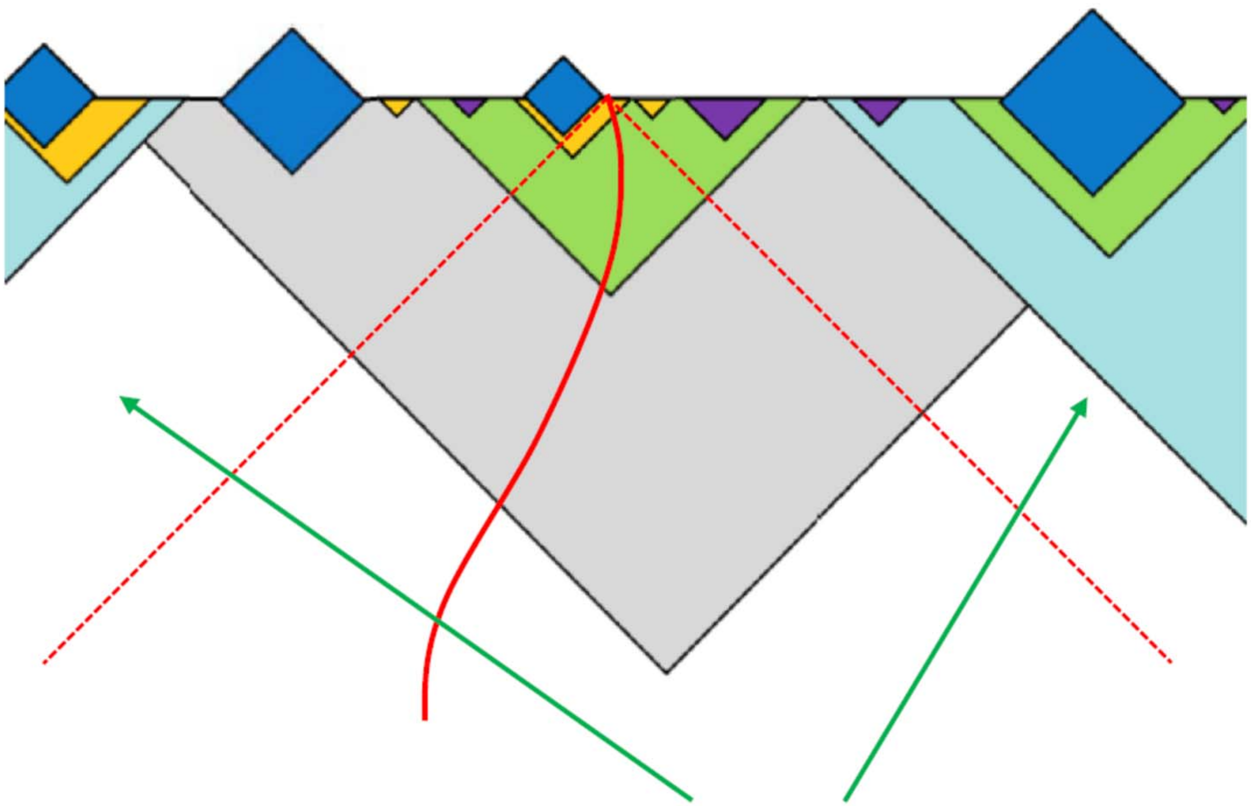
Probability in cosmology has the same origin
as the quantum mechanical probability

… provide simple regularization

(Anything that can happen will happen *but not with equal probability*.)

A Lesson from black hole physics:

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



Does this region “exist”?

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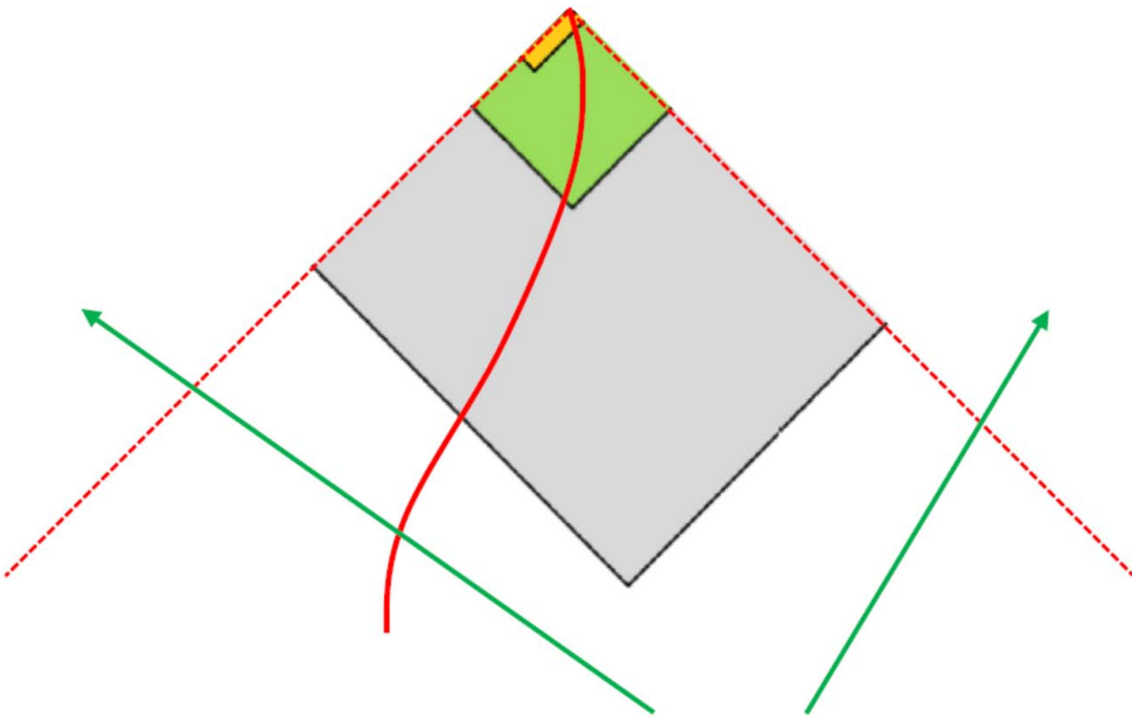
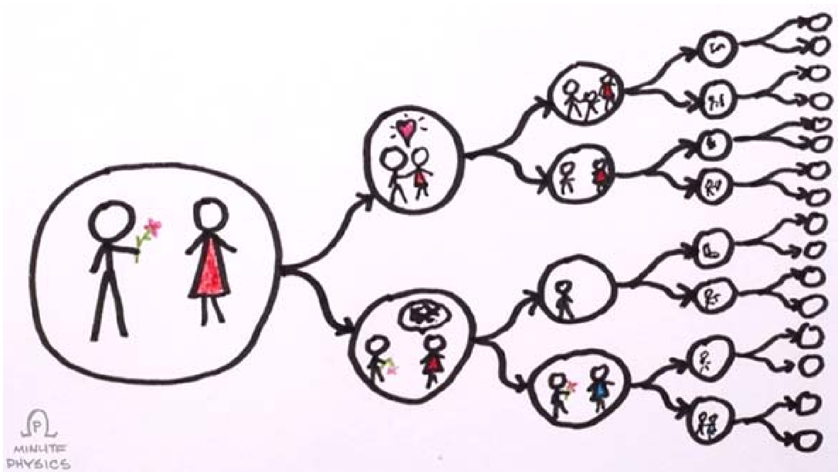


Does this region “exist”? → No!

… What happened to the multiverse?

We live in a quantum mechanical world!



Bubble nucleation … probabilistic processes

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

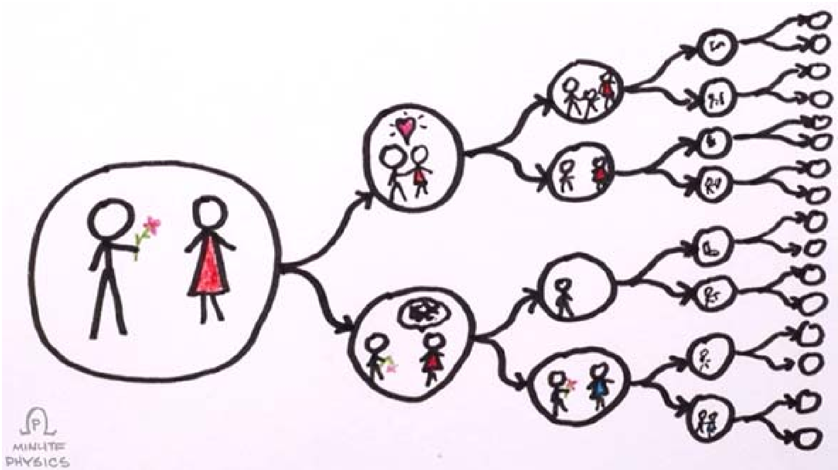
multiverse: $\Psi(t=t_0) = |\Sigma\rangle \quad \rightarrow \quad \Psi(t) = \cdots + c\left|\begin{smallmatrix}321\\ \rho_\Lambda\end{smallmatrix}\right\rangle + c'\left|\begin{smallmatrix}321\\ \rho'_\Lambda\end{smallmatrix}\right\rangle + \cdots + d\left|41\right\rangle + \cdots$

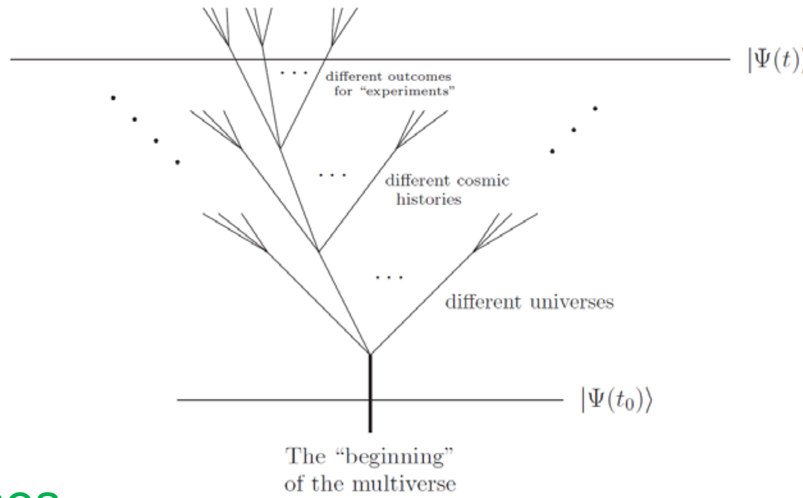
eternally inflating

each term representing only the causally accessible region

… provides natural and effective "regularization"

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

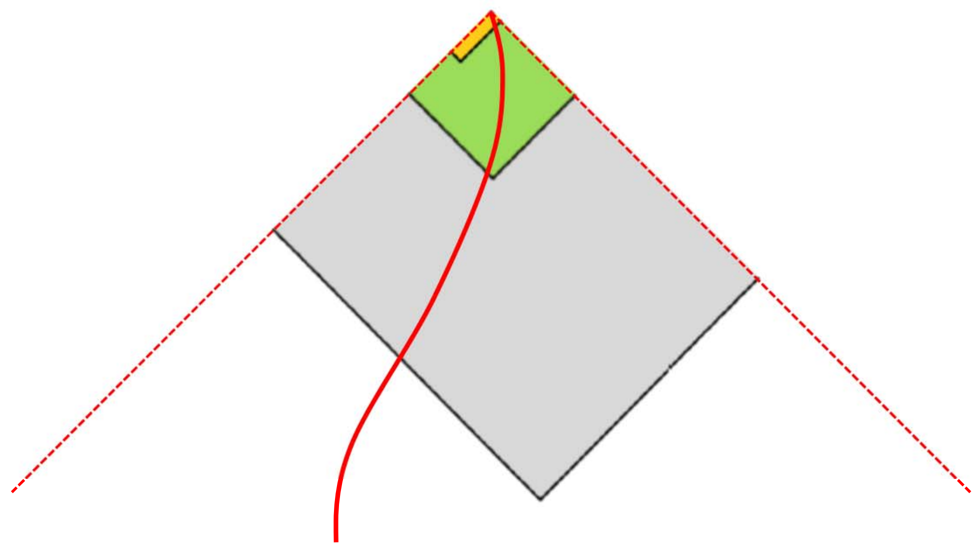
… provides natural and effective "regularization"

Multiverse = Quantum many worlds

… The multiverse lives (only) in probability space!

Global spacetime of general relativity

is an emergent (and "redundant") concept!



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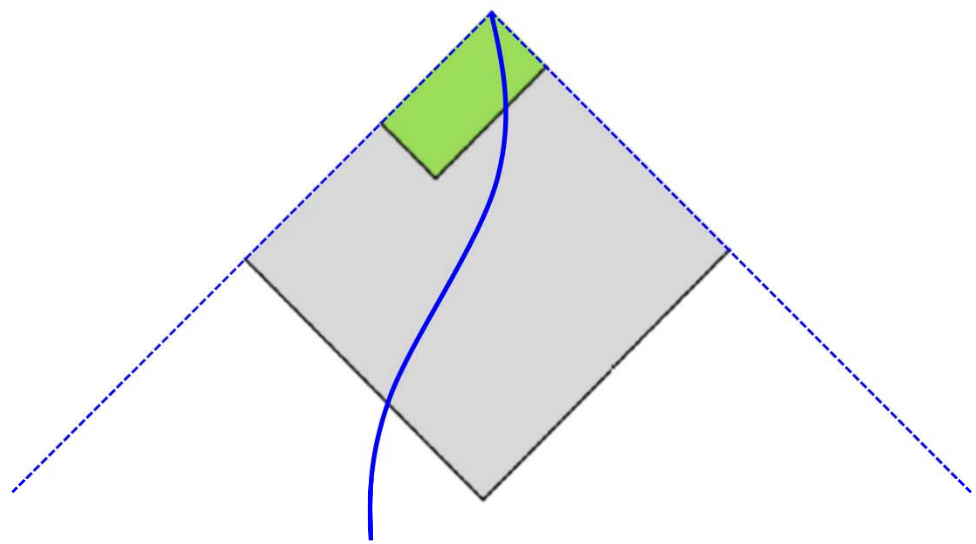

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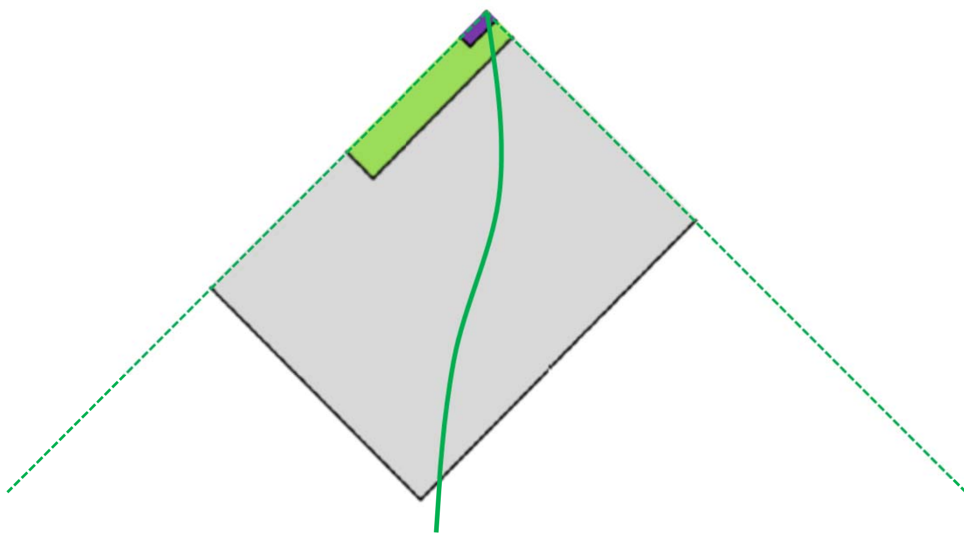

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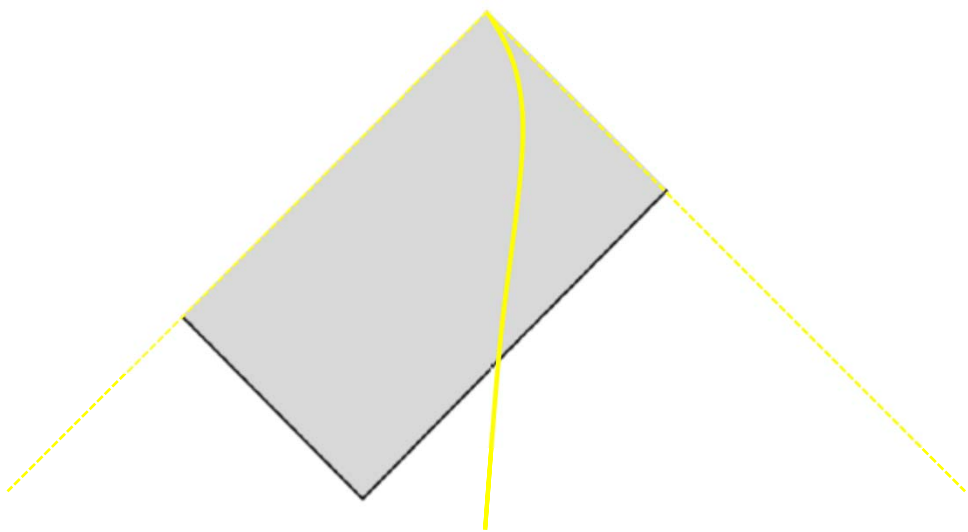

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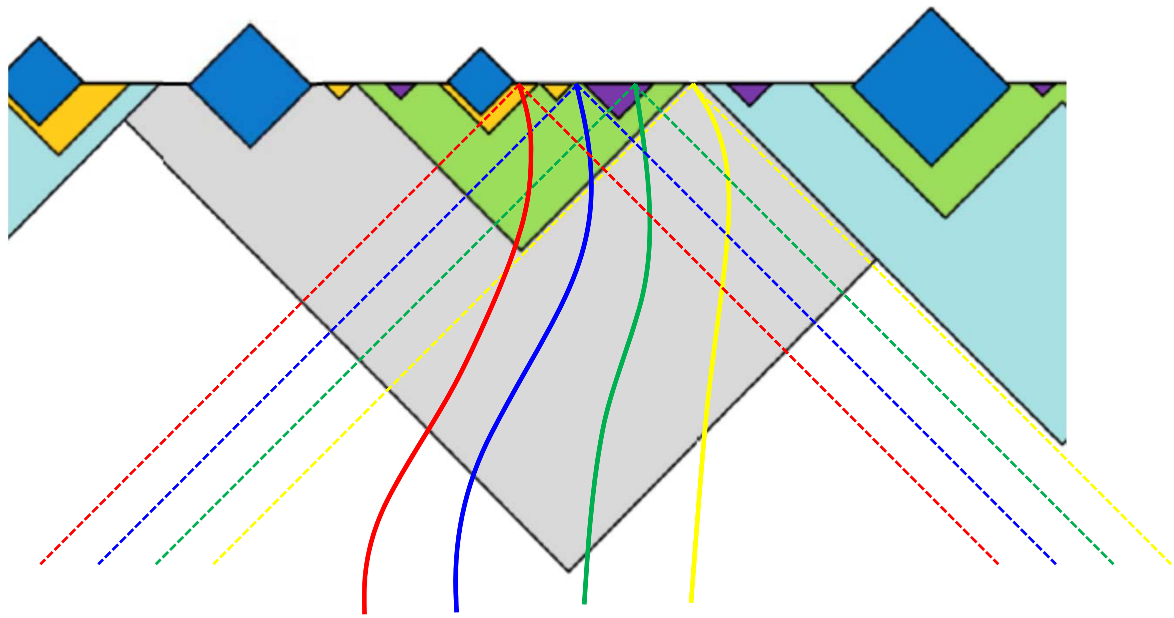

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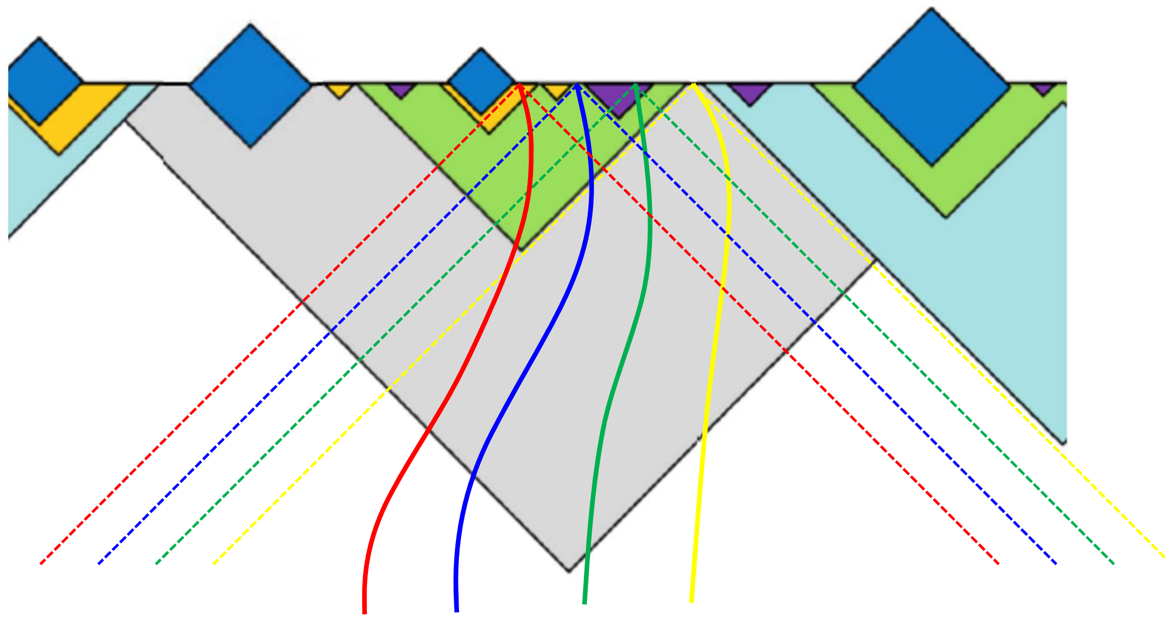


… probability is more fundamental

— 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.

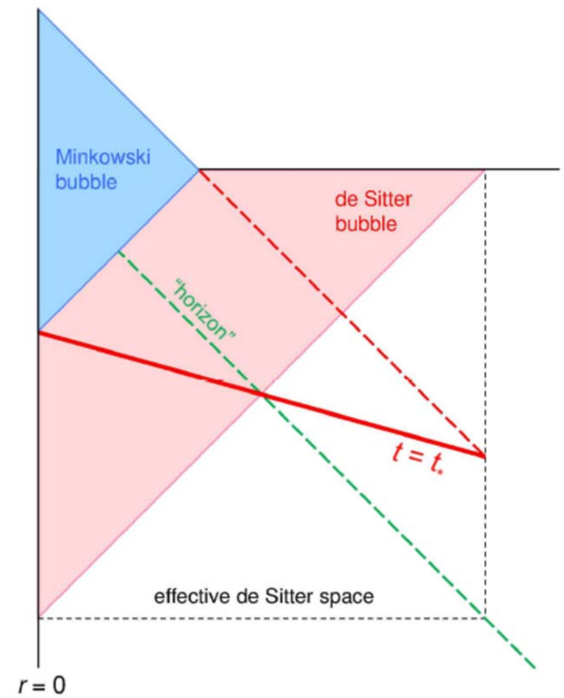
(at the cost of overcounting the true quantum mechanical d.o.f.s)

Isn't it possible to see the outside of the horizon even within a single branch?

Coarse-graining leads to the emergence of the other hemisphere.

$$|\Psi(H)\rangle = \sum_n \boxed{\sum_{i_n=1}^{\mathcal{N}(n)} c_{n i_n} \boxed{|\{n_\alpha\}\rangle} \boxed{|\psi_{i_n}(n)\rangle}} \xrightarrow{\text{coarse-grain}} \|\{n_\alpha\}\rangle\!\rangle$$

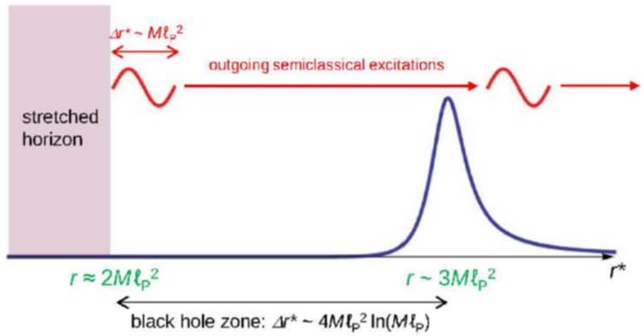
… enough to describe the future fate of the branch



	Evaporating black hole	Cosmological de Sitter space
microscopic level {	zone region	inside the horizon
	far region	—
effective theory {	two-sided black hole	pure de Sitter space
	the second exterior	the other hemisphere

Conclusions

- Hawking emission from the semiclassical viewpoint



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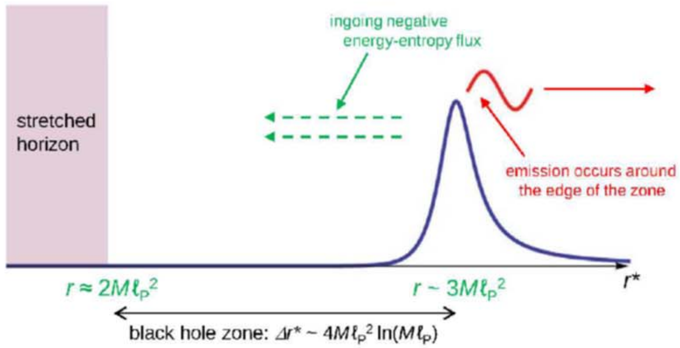

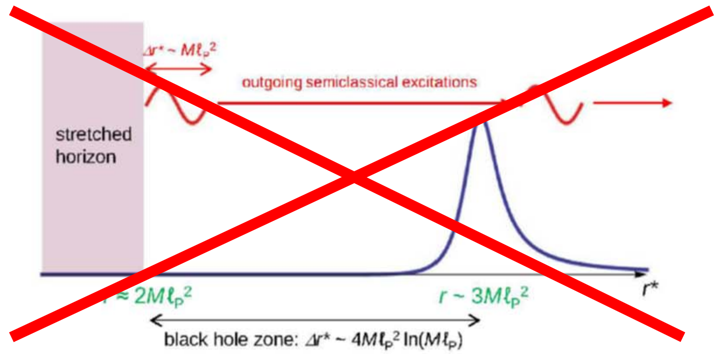

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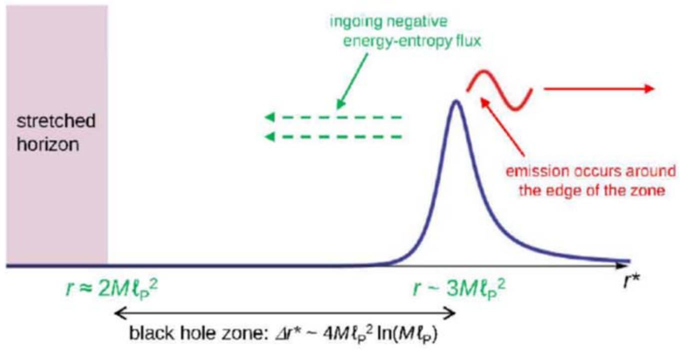

Hard modes: “matter”

Soft modes: “spacetime”

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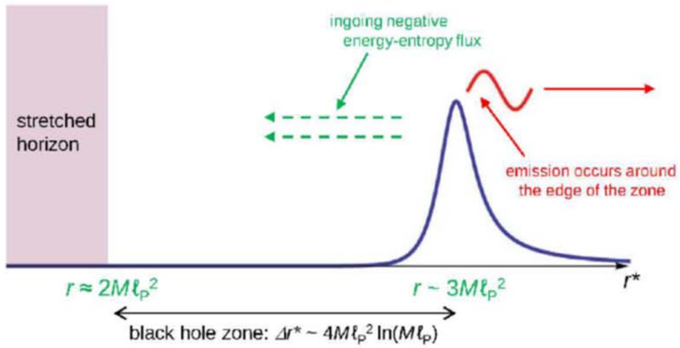

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- Microscopic entanglement structure of a BH

$$\boxed{|\Psi(M)\rangle = \sum_{E} \sum_{i_E=1}^{\mathcal{N}(M-E)} \sum_{a=1}^{e^{S_{\rm rad}}} c_{E i_E a} |E\rangle |\psi_{i_E}(M-E)\rangle |r_a\rangle}$$

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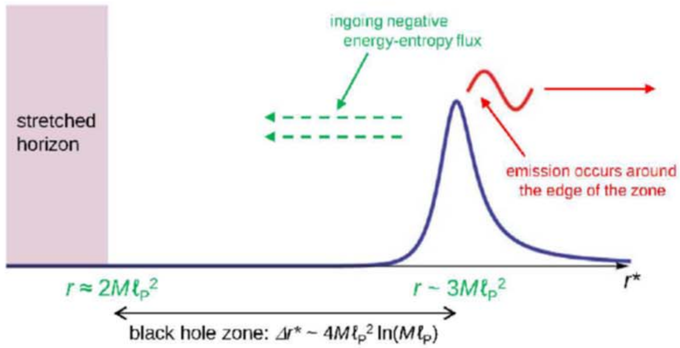

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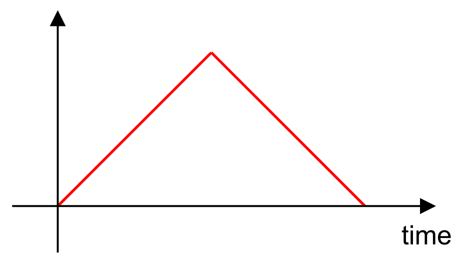
entanglement



… Page curve
→ Unitary evolution

Conclusions

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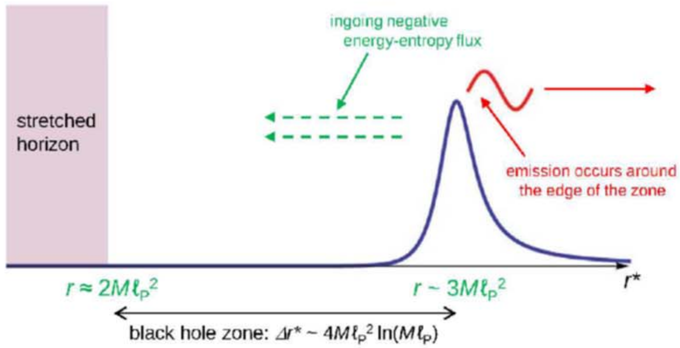

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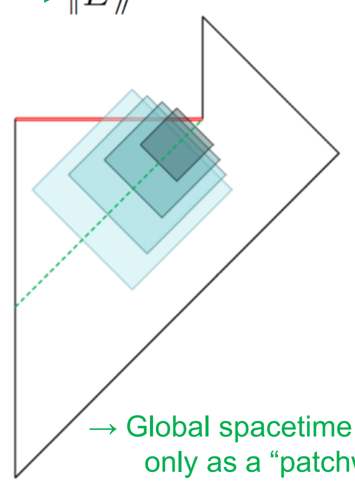
- Effective emergence of the interior

… effective theories erected **at each time**



→ Global spacetime of general relativity emerges only as a “patchwork” of multiple effective theories.

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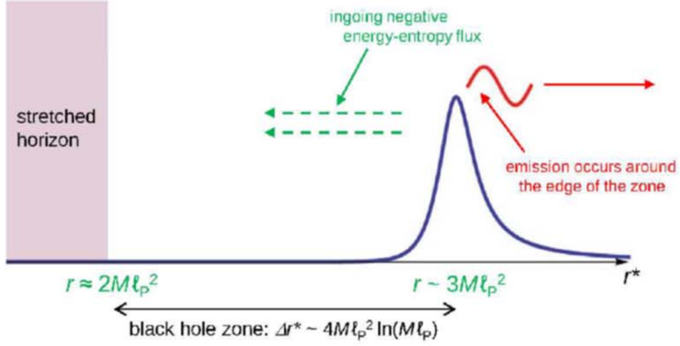

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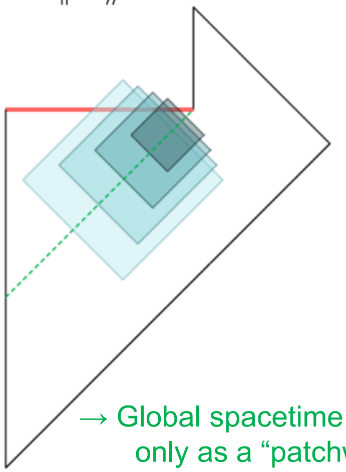

→ Global spacetime of general relativity emerges only as a "patchwork" of multiple effective theories.

- Implication for cosmology (multiverse)