Quantum Mechanics of an Evaporating Black Hole

Yasunori Nomura

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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 event horizon smoothly?
- Are dynamics local outside the stretched 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 [arXiv:1207.3123 [hep-th]]

… involves all three pillars of modern physics:

Quantum mechanics, General relativity, and Statistical mechanics

In this talk, I present a coherent picture
that gives an affirmative answer to these questions.

We will see that a key to address these issues
is to understand the emergence of the semiclassical picture.

— d.o.f.s described by semiclassical theory is
only a *tiny* subset of the whole d.o.f.s (hard modes) in the microscopic theory.

— Physics of BH information concerns the other vast d.o.f.s (soft modes)
which must be viewed as *delocalized* from the semiclassical viewpoint.

— The entanglement structure of a system with a BH is intrinsically *multi-partite*,
involving hard modes, soft modes, and Hawking radiation.

→ • Black hole evolution is unitary;
• Interior spacetime is an effective coarse-grained concept;
• No wormhole connecting entangled BHs for falling semiclassical objects; …

Mostly based on

Y. Nomura, "Reanalyzing an Evaporating Black Hole," PR **D99** ('19) 086004 [arXiv:1810.09453 [hep-th]]

… earlier work with Varela and Weinberg, e.g., 1211.7033, 1304.0448, 1310.7564, 1406.1505;
with Sanches and Weinberg, 1412.7538, 1412.7539; with Salzetta, 1602.07673; …

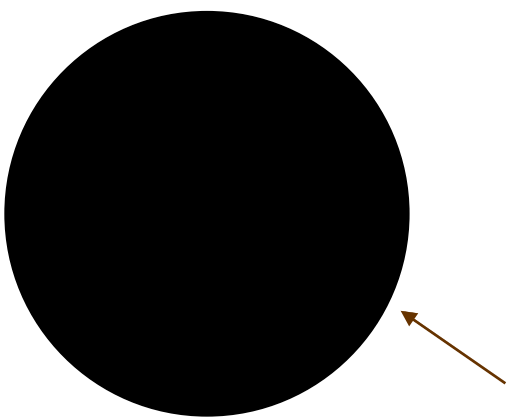
Thermodynamics of a Black Hole

One of the biggest discoveries in theoretical physics:

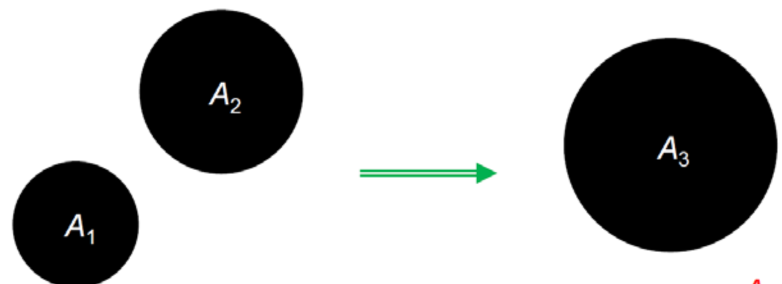
$$S_{\mathrm{BH}}(M) = \frac{\mathcal{A}(M)}{4 l_{\mathrm{P}}^2}$$

$$T_{\mathrm{H}}(M) = \frac{1}{8\pi M l_{\mathrm{P}}^2}$$

Bekenstein ('73); Hawking ('74)



- What happens to energy and entropy?



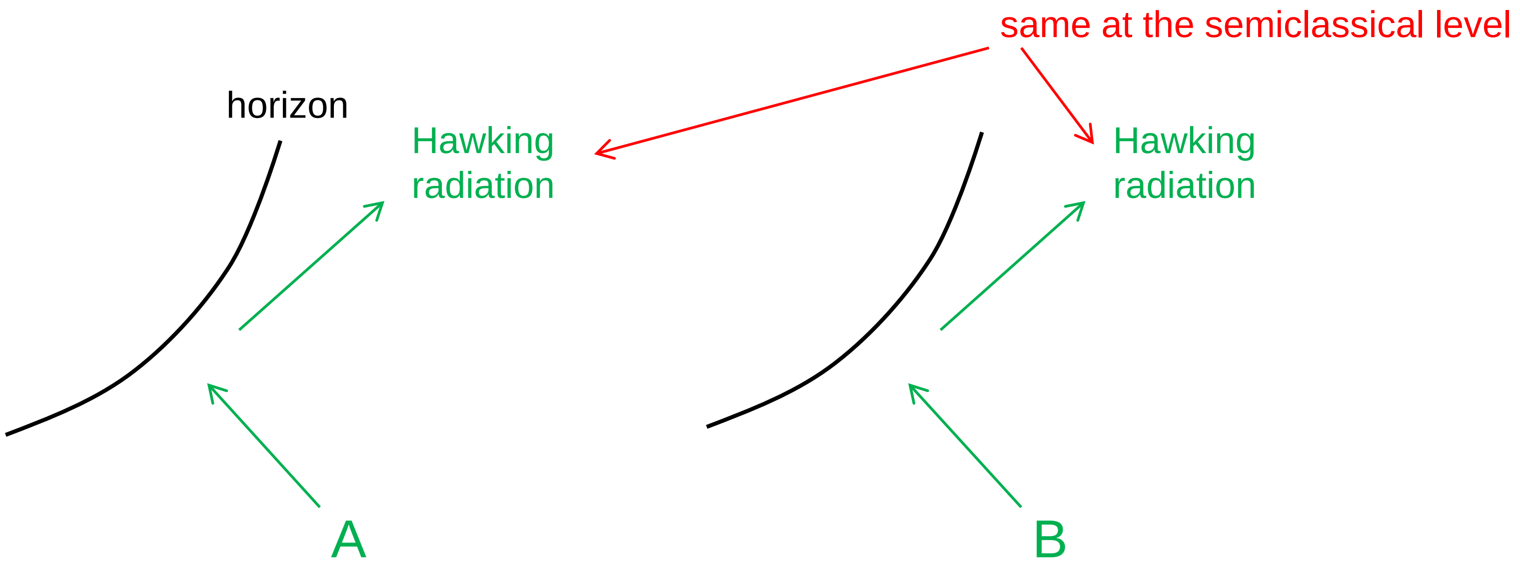
$A_3 \geq A_1 + A_2$

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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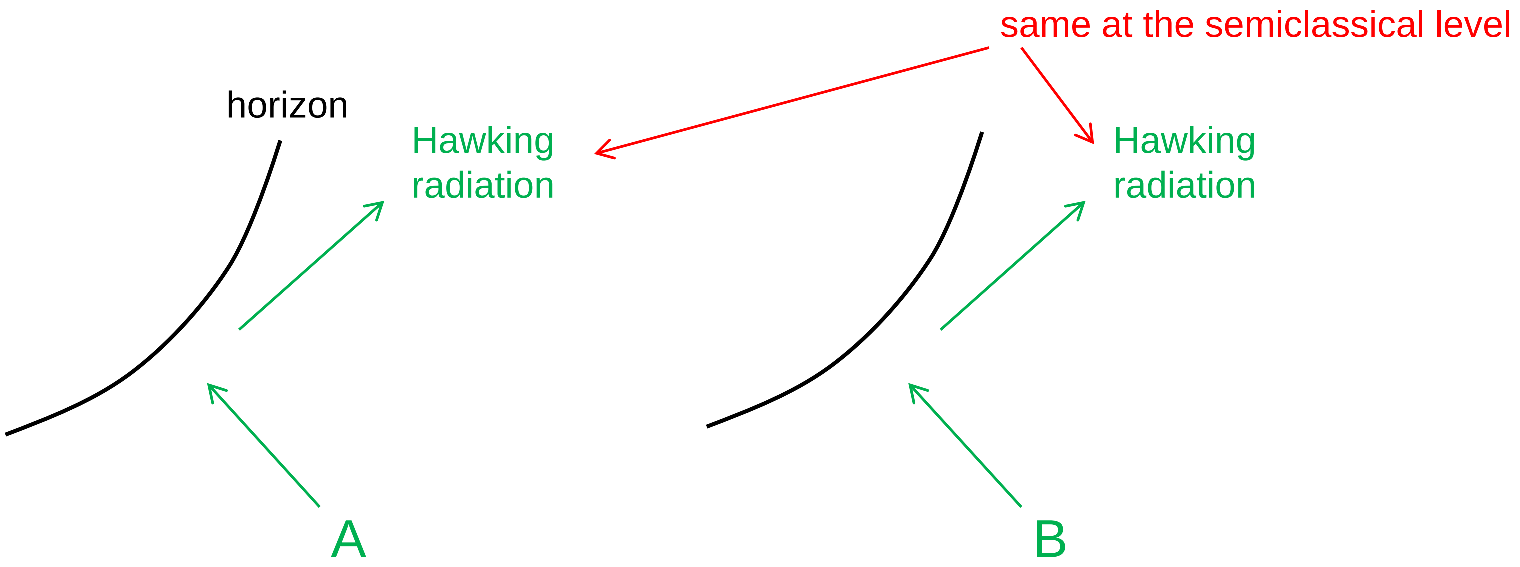


… information is lost ?? Hawking ('76)

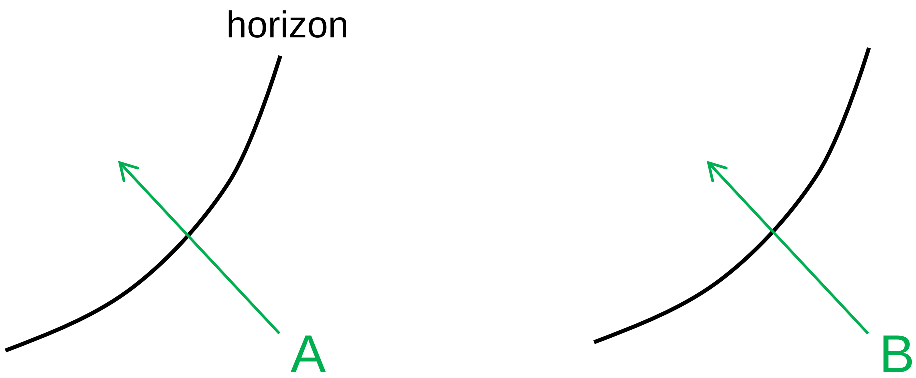
⟹ No

… 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)

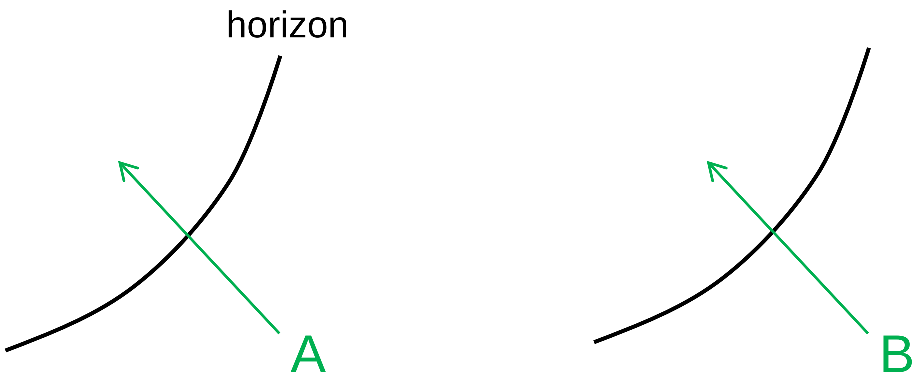
$$|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$$

$$|\downarrow\rangle \rightarrow |\downarrow\rangle|\downarrow\rangle$$

$$|\uparrow\rangle+|\downarrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle+|\downarrow\rangle|\downarrow\rangle$$ (superposition principle)

$$\neq (|\uparrow\rangle+|\downarrow\rangle)(|\uparrow\rangle+|\downarrow\rangle)$$

From a falling observer's viewpoint:



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- 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?

⟹ **Both are correct !**

There is no contradiction !

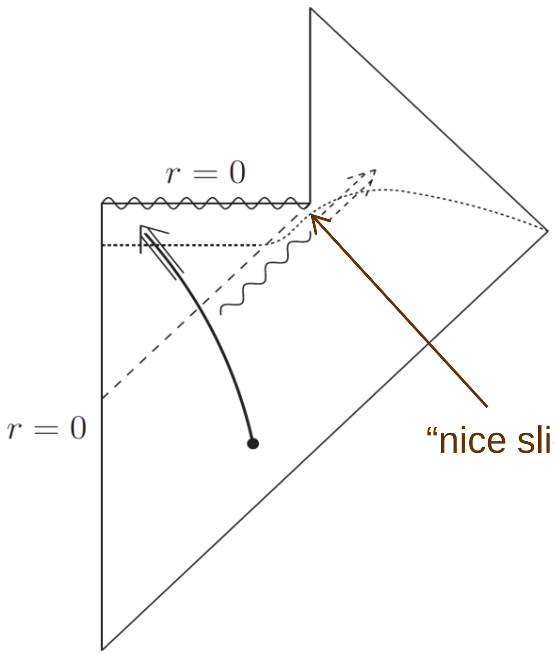
One cannot be *both* distant and falling observers *at the same time*.

… **"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.



"nice slice" (nothing wrong in general relativity)

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

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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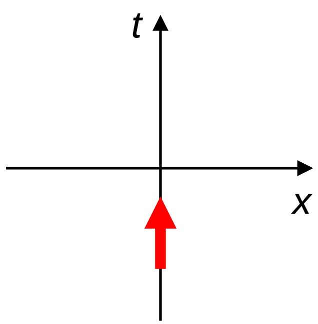
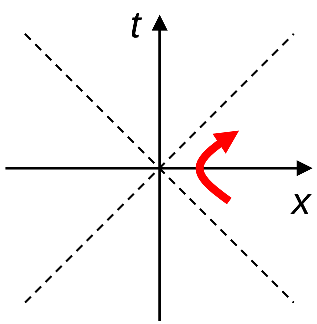
Smooth horizon:





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

Minkowski (infalling)

Rindler (Schwarzschild)

Unitarity:

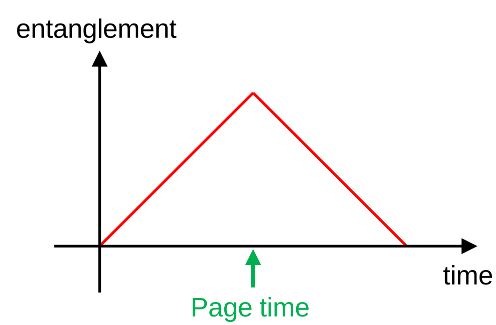
$|AB|0\rangle$

$\downarrow$

$|A|B\rangle + |B|A\rangle$

$\downarrow$

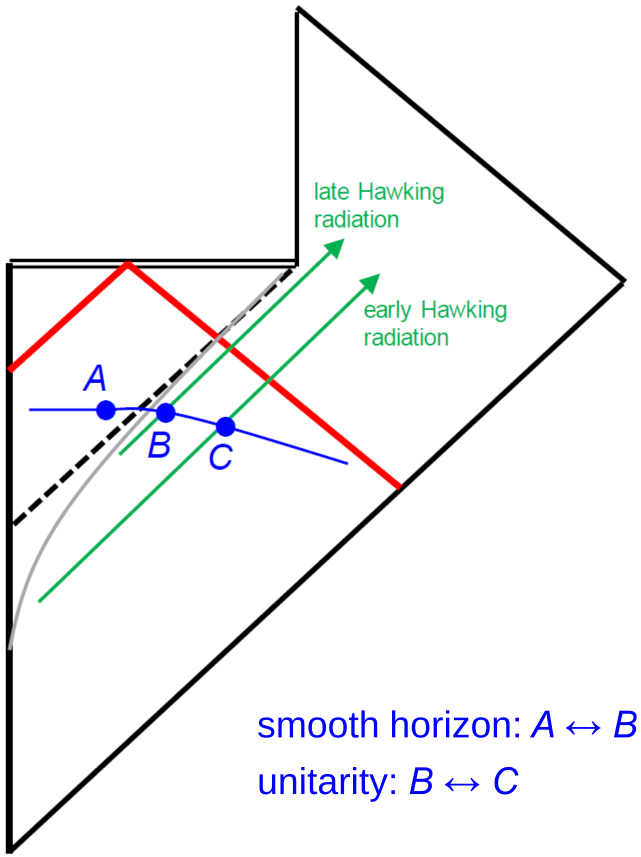
$|0|AB\rangle$



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

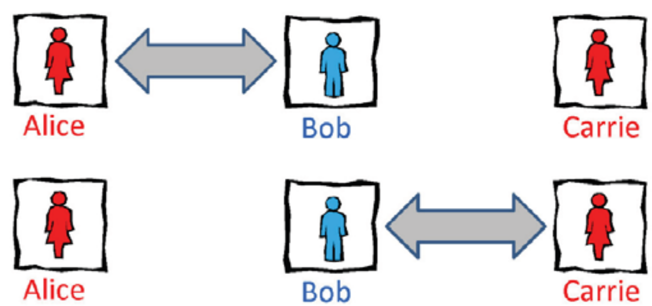


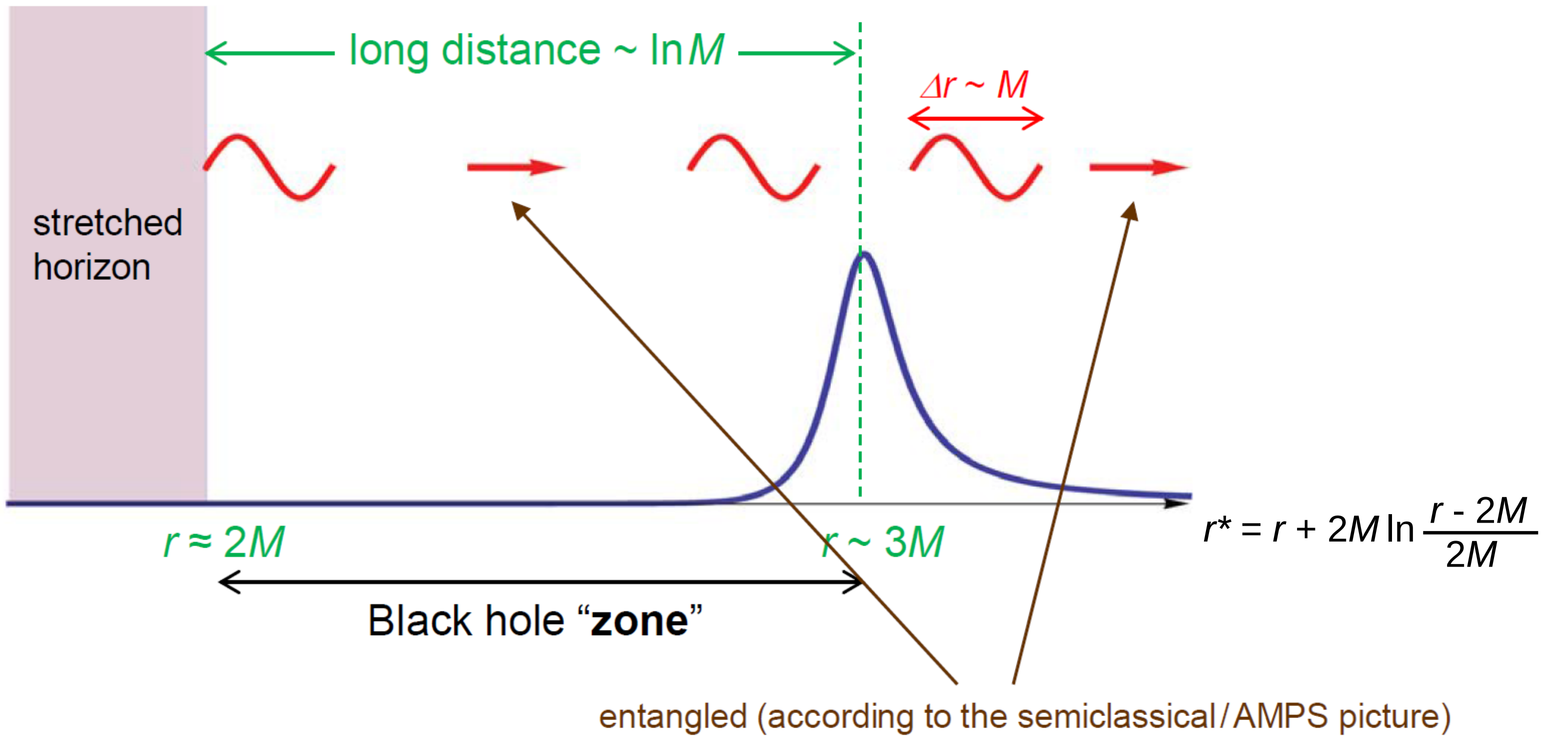
Fig. by Preskil

… 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)

State Dependence / “ER = EPR”

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.

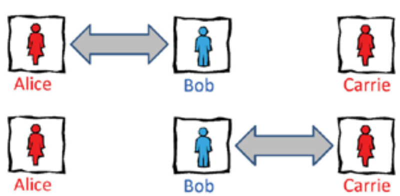
Since what the zone modes are entangled with depends on the microstate
of the system, operators describing the interior depend on the state.

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

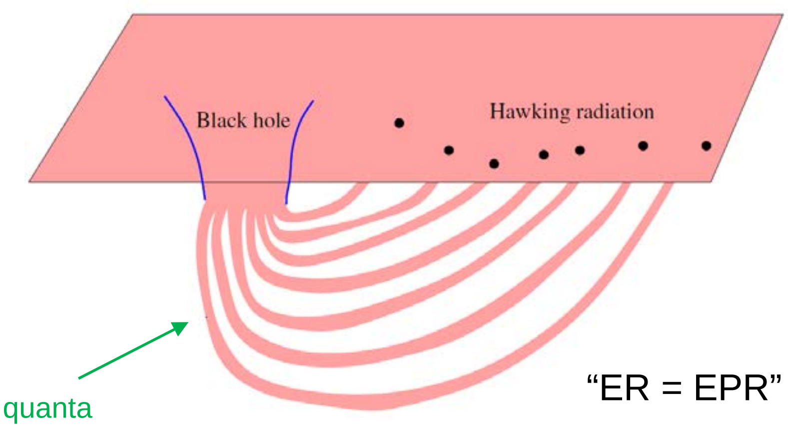
Specific realization Maldacena, Susskind (’13)

Before the Page time:

After the Page time:



⟹



Wormhole connecting
BH and early Hawking quanta

“ER = EPR”

Manipulation of early Hawking quanta can affect the interior !?

What Is Semiclassical Theory?

Y.N., "Reanalyzing an Evaporating Black Hole," arXiv:1810.09453 [hep-th]

What is Bekenstein-Hawking entropy?

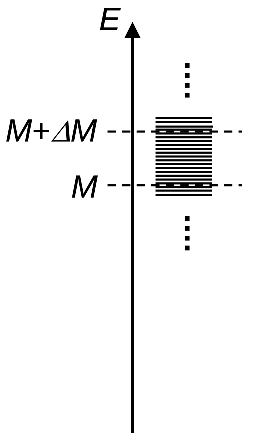
Dynamically formed black hole

Time scale of evolution (Hawking emission): $\Delta t \sim M$

→ The black hole state involves a superposition of $\Delta E \sim \Delta M \sim 1/M$

How many independent ways are there to superpose the energy eigenstates to obtain the same black hole geometry within this precision?

$$|\Psi(M)\rangle = c_1 |E_1\rangle + c_2 |E_2\rangle + c_3 |E_3\rangle + \dots$$



The logarithm of this number: $S_{BH} = \dfrac{A}{4}$

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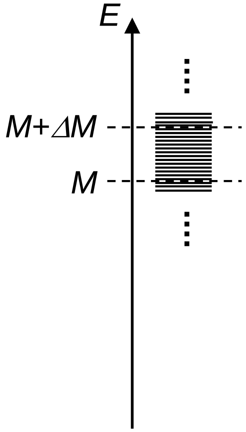
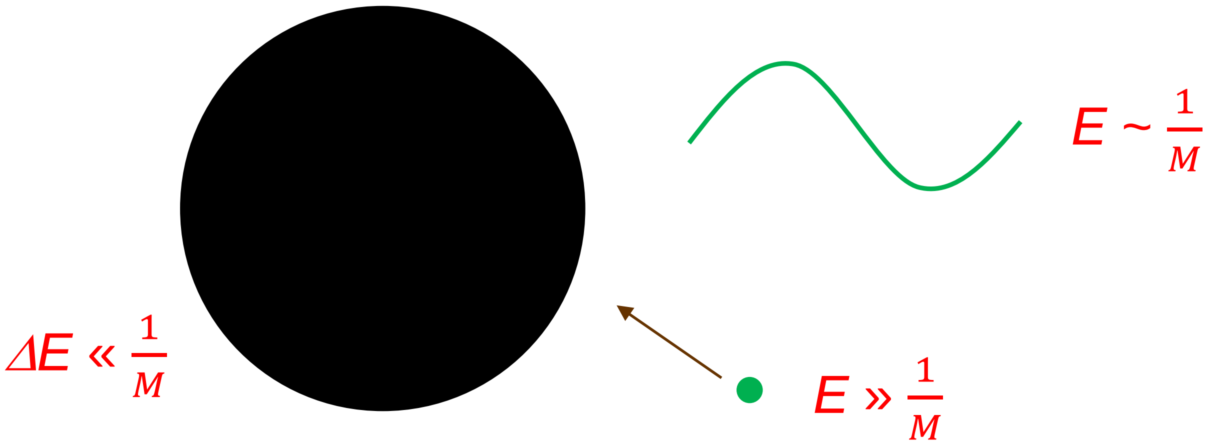


The logarithm of this number: $S_{\rm BH} = \dfrac{A}{4\hbar}$

Classically, the number is a continuous infinity!

… Quantum mechanics **reduces** the number of states (not a new “quantum hair”)

The origin of thermality



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) $|\psi_{i_E}\rangle$

⟹ 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

$$\rho(M) = {\rm Tr}_{\rm soft} |\psi(M)\rangle\langle\psi(M)| \simeq \frac{1}{\sum_E e^{-\frac{E}{T_{\rm H}}}} \sum_E e^{-\frac{E}{T_{\rm H}}} |E\rangle\langle E|$$

… thermal density matrix with Hawking temperature T_H

… Hard (semiclassical) modes are purified by the soft modes (but see below)

How does information transfer from BH to ambient space occur?

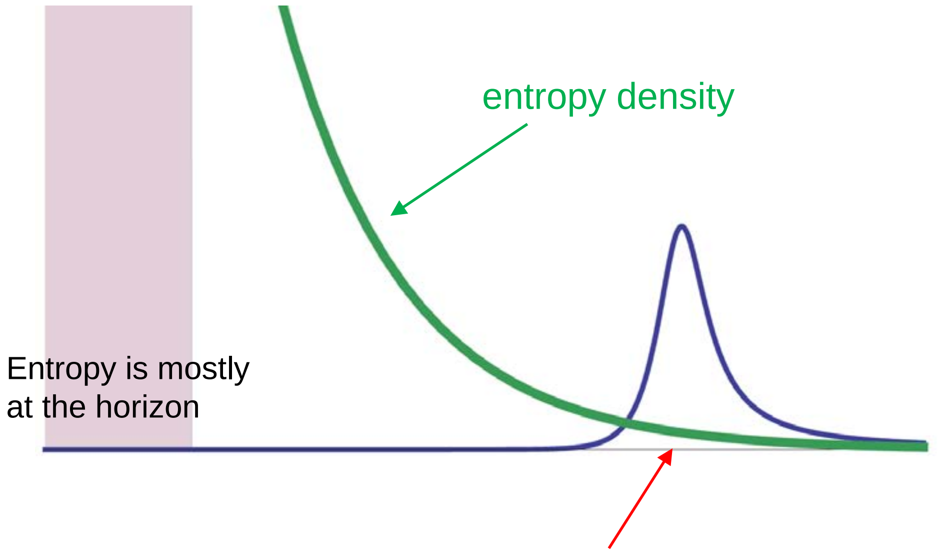
… need to understand the Hawking emission process

"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"



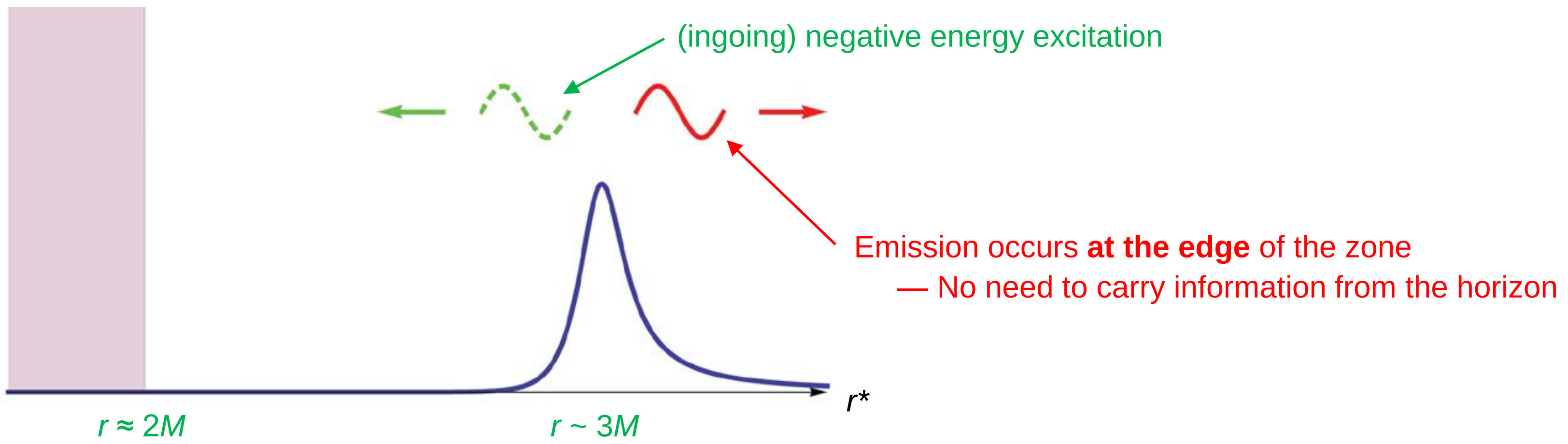
$$s(r) \propto T^3(r) = \frac{1}{(8\pi M)^3\,(1-2M/r)^{3/2}}$$

$O(1)$ 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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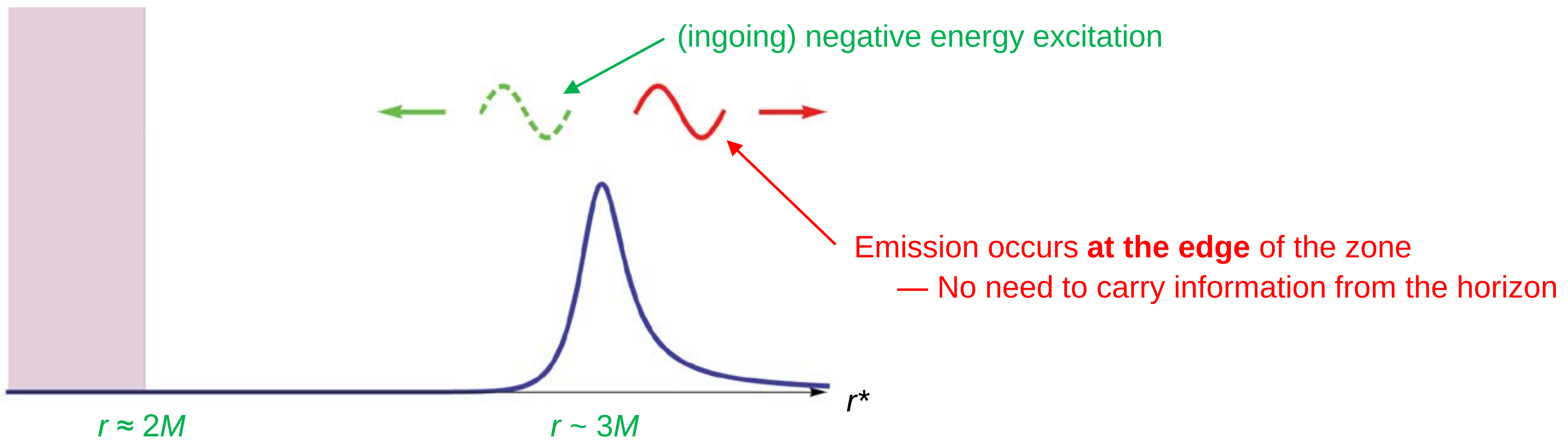

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At the microscopic level

$|\Psi_1(M)\rangle$

$|\Psi_2(M)\rangle$

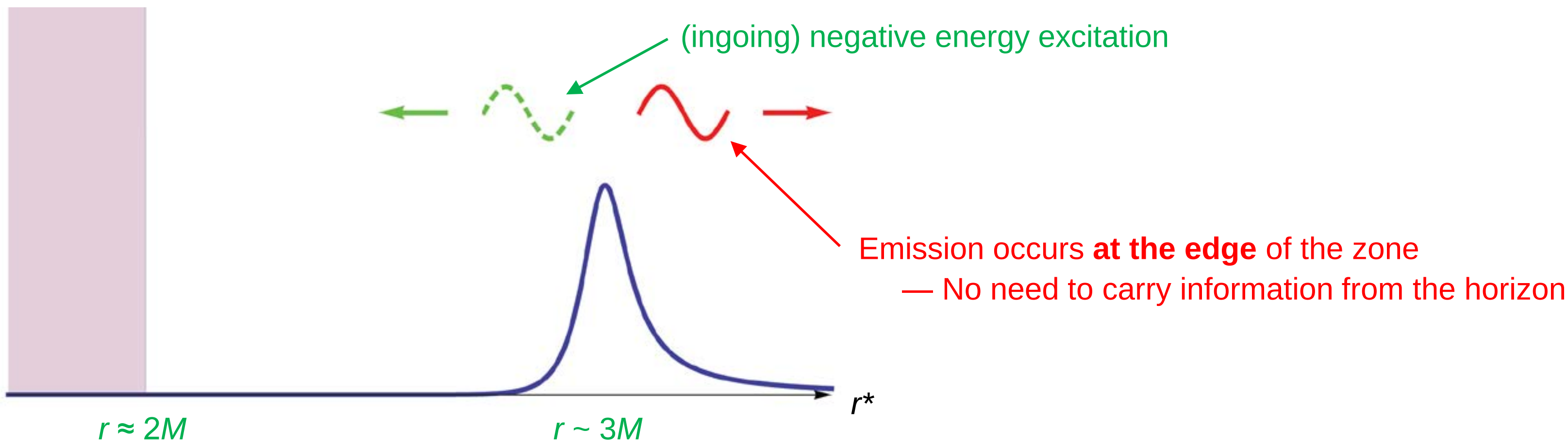
$|\Psi_3(M)\rangle$ $\xrightarrow{?}$

$|\Psi_4(M)\rangle$

$\vdots$

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

The (correct) picture of Hawking emission:



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At the microscopic level

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

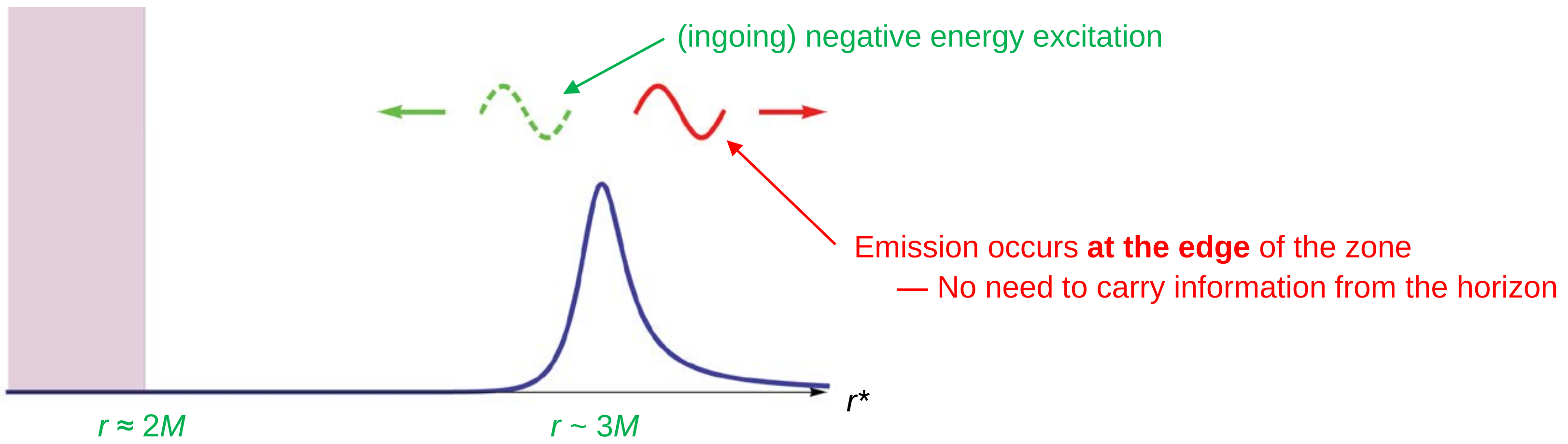
$*$: negative energy excitation

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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Note: difference from the previous, AMPS picture

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\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.**

Entanglement of an Evaporating BH

Y.N., “Reanalyzing an Evaporating Black Hole,” arXiv:1810.09453 [hep-th]

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

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

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.

(This does not change the form of the density matrix of the hard modes.)

In more detail,

In dim: $O(M^{p<2})$ $\qquad$ $O(M^2)$

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

most of entanglement between BH and Hawking quanta

Effective Theories of the Interior

Y.N., “Reanalyzing an Evaporating Black Hole,” arXiv:1810.09453 [hep-th]

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

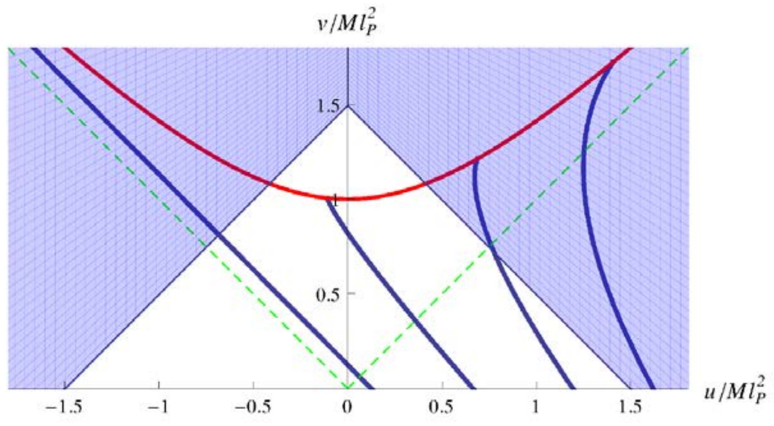
$$|\Psi(M)\rangle = \sum_E \sum_{i_E=1}^{\mathcal{N}(M-E)} \sum_{a=1}^{e^{S_{\rm rad}}} c_{E i_E a} |E\rangle |\psi_{i_E}(M-E)\rangle |r_a\rangle \quad \xrightarrow{\text{coarse-grain}} \quad \|E\rangle\!\rangle$$

→ 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 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 semiclassical level!

- Entanglement structure is intrinsically multi-partite (regardless of the “age”):

trace out

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

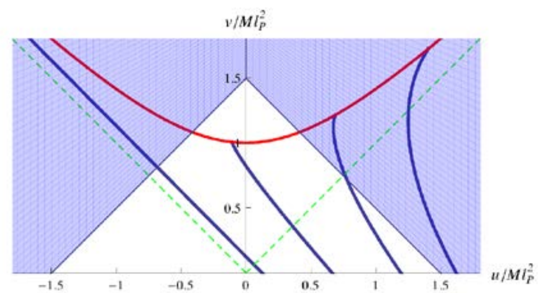
only classical correlation

trace out

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

only classical correlation

- A new, simpler solution to the cloning problem becomes available:



If information retrieval time satisfies

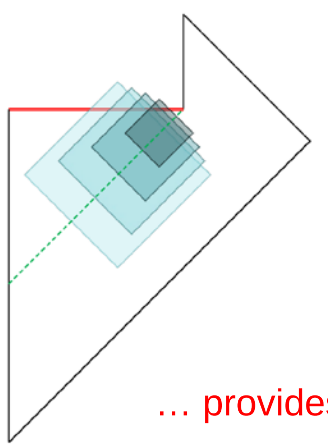
$$t_{\rm I} \geq \frac{1}{2\pi T_{\rm H}} \ln S_{\rm BH} = \frac{1}{\lambda_{\rm L,max}} \ln S_{\rm BH}$$

($\lambda_{\rm L,max}$: Lyapulov exponent)

there is no cloning of information in *any single description*.

in contrast with what are envisioned in Hayden, Preskill (’07), Harlow, Hayden (’13)

- Global interior spacetime emerges only using multiple effective theories:



… provides a specific realization of the complementarity picture

Other Issues

Y.N., "Reanalyzing an Evaporating Black Hole," arXiv:1810.09453 [hep-th]

- Black hole mining can be analyzed in a similar manner:

  … The information extraction rate can be accelerated because of an increased number of angular momentum modes, but the rest are all analogous.

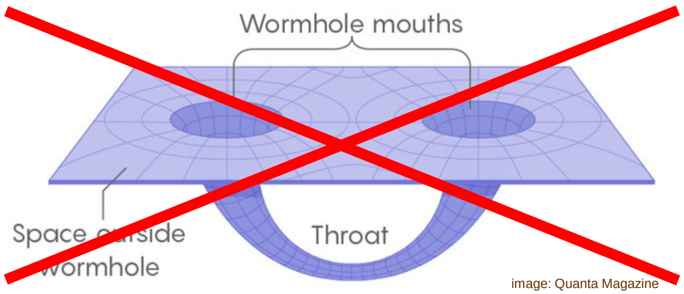
- Rindler limit can be taken smoothly:

  The impossibility of extracting information from the Minkowski vacuum

  → The Rindler space corresponds to an infinitely young black hole.

- Pair created Schwarzschild BHs are not connected by a wormhole:

  BHs being entangled does not mean that their hard modes are entangled.



- ….

Relation to Cosmology

Y.N., "Physical theories, eternal inflation, and the quantum universe," arXiv:1104.2324

Eternally inflating multiverse

… The multiverse is "infinitely large" !

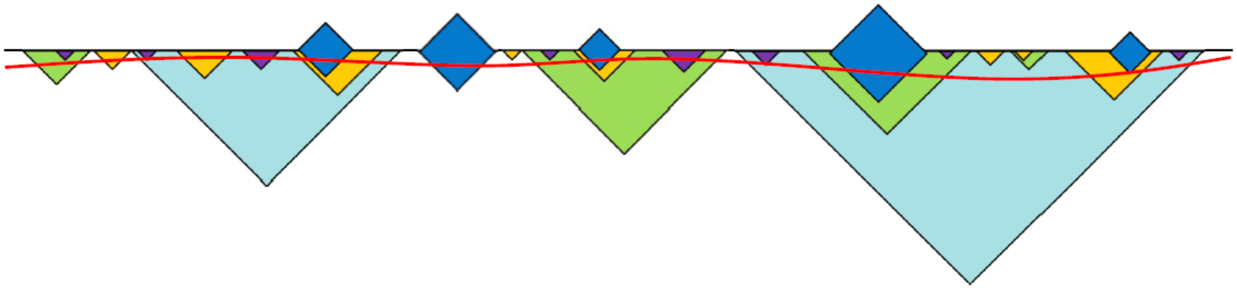
Predictivity crisis !

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 $t = t_c$ ($\rightarrow \infty$)



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

The problem consists of several elements

— Problem of infinity

… How is the infinity regulated?

— Problem of arbitrariness

… What is the principle behind the regularization?

— Problem of selecting the state

… What is the initial condition of the multiverse?

— …

Work addressing various aspects:

Aguirre, Albrecht, Bousso, Carroll, Garriga, Guth, Linde, Nomura, Page, Susskind, Tegmark, Vilenkin, …

This can be a great opportunity !

Below, my view

Quantum mechanics is essential to answer these questions.

Multiverse = Quantum many worlds

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

Multiverse = Quantum Many Worlds

Y.N., "Physical theories, eternal inflation, and the quantum universe," JHEP **11**, 063 ('11) [arXiv:1104.2324]

(see also Bousso, Susskind, PRD **85**, 045007 ('12) [arXiv:1105.3796])

— in what sense?

Quantum mechanics is **essential**

The basic assumption:

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

→ Quantum mechanics plays an important role even at largest distances:

The multiverse lives **(only)** in probability space

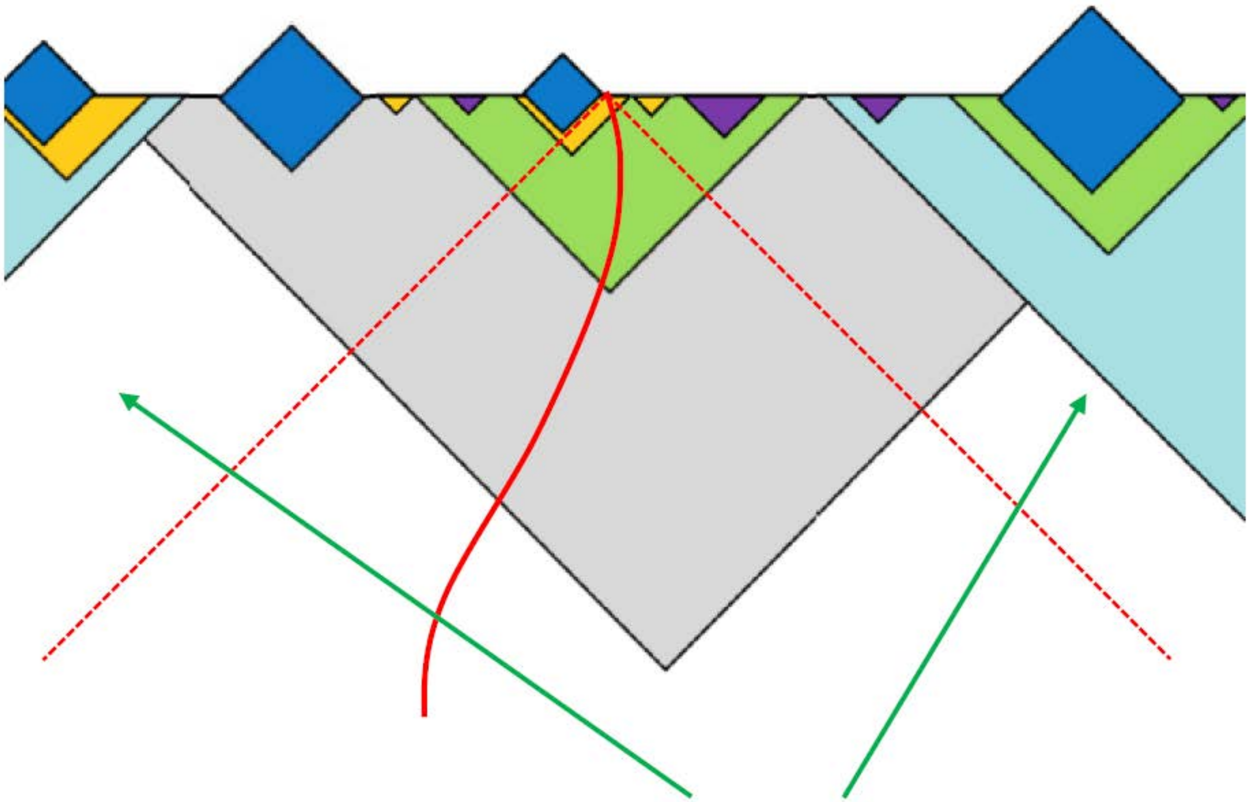
Probability in cosmology has the same origin as the quantum mechanical probability

… 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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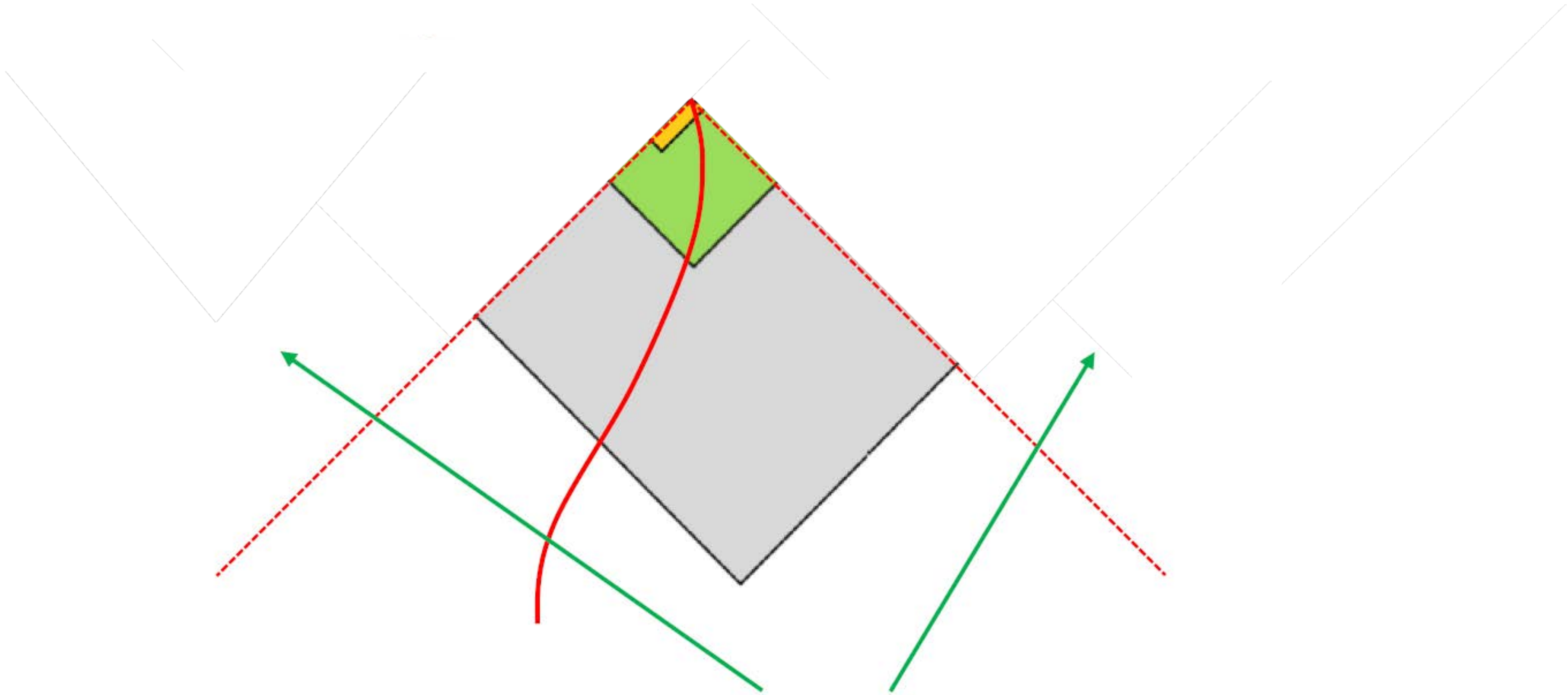
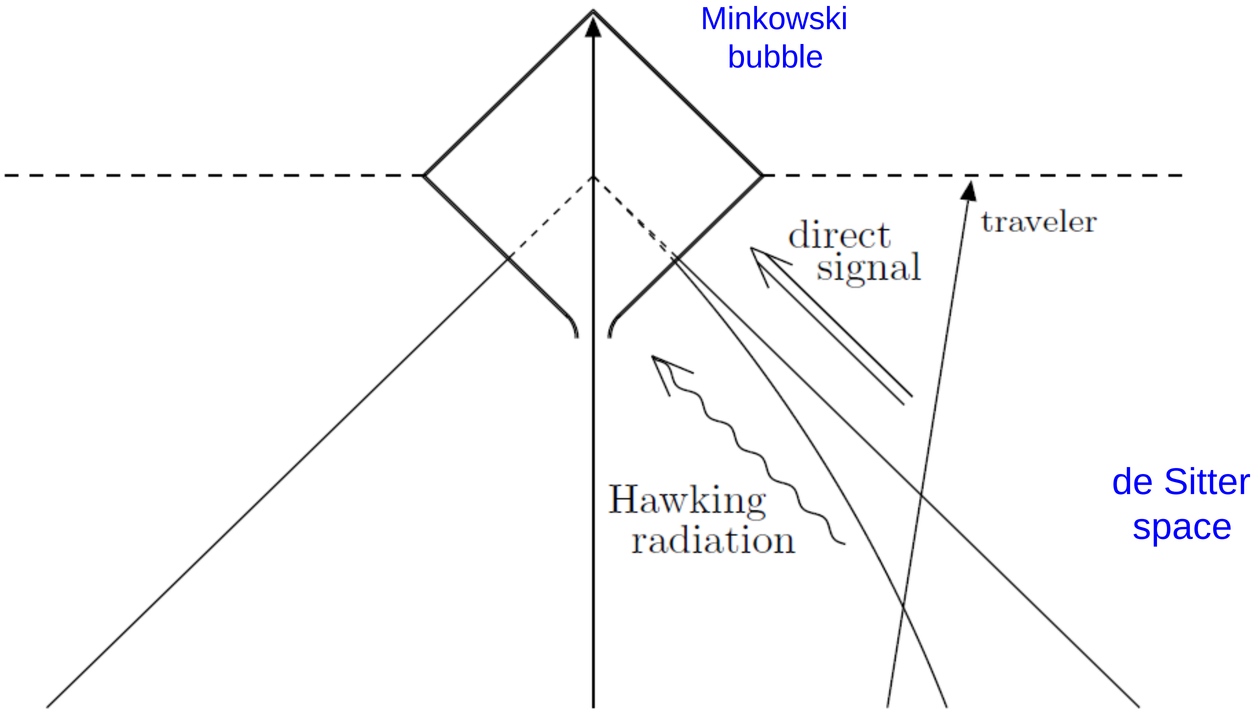


Does this region “exist”? → No!

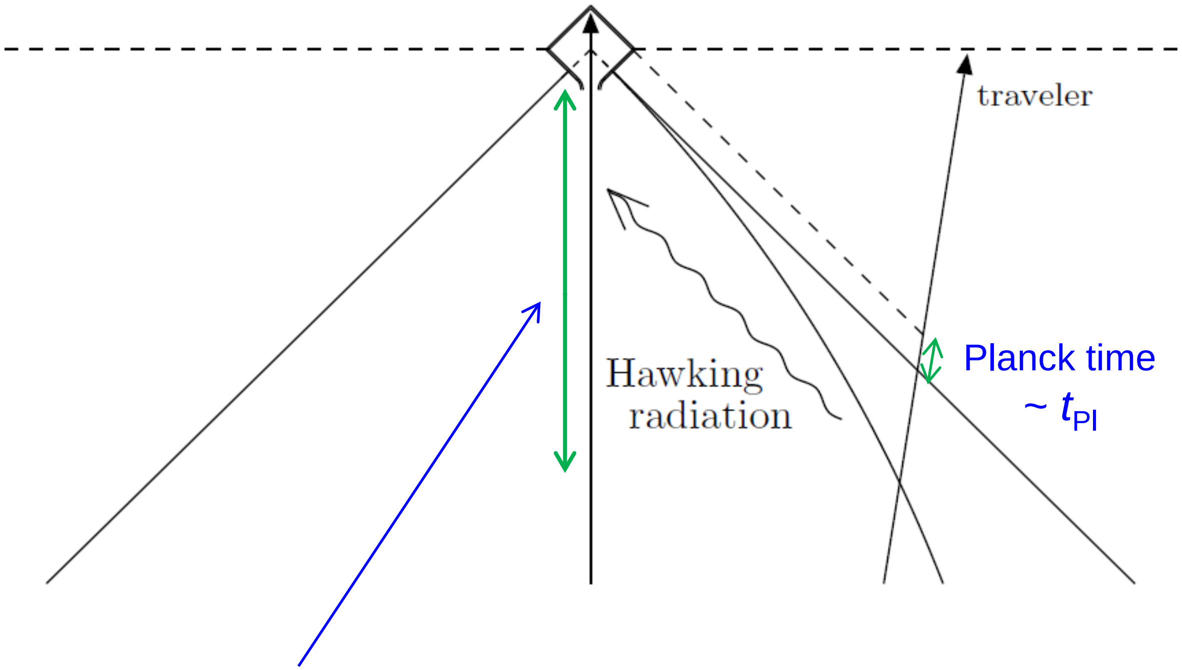
... What happened to the multiverse?

Consistent?



Doesn't information duplicate?

Consistent? — Yes

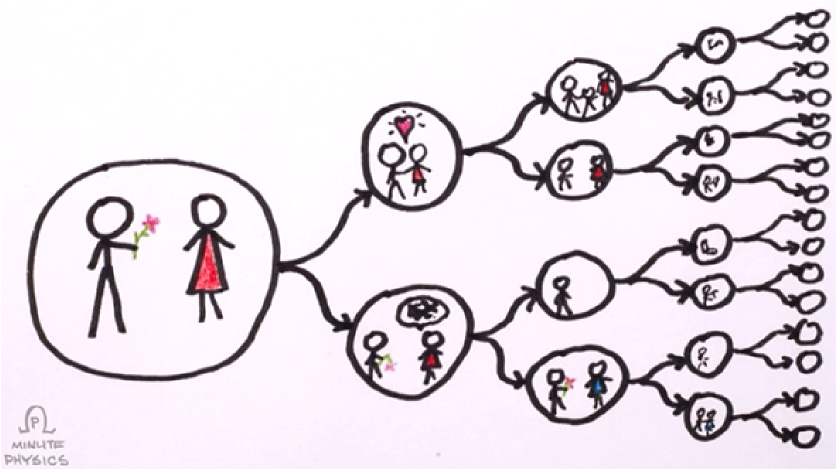


Information retrieval time
~ $H^{-1} \ln H^{-1}$

The information duplication does *not* occur!

Information can be obtained *either* from Hawking radiation *or* from direct signal, but *not from both*.

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”

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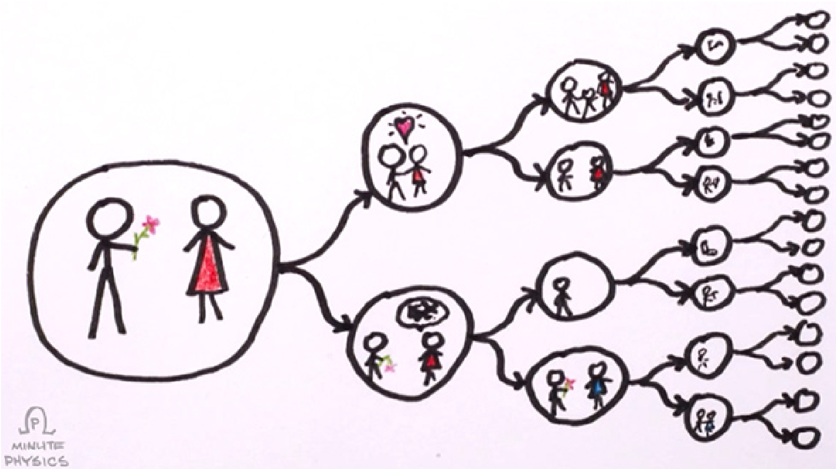

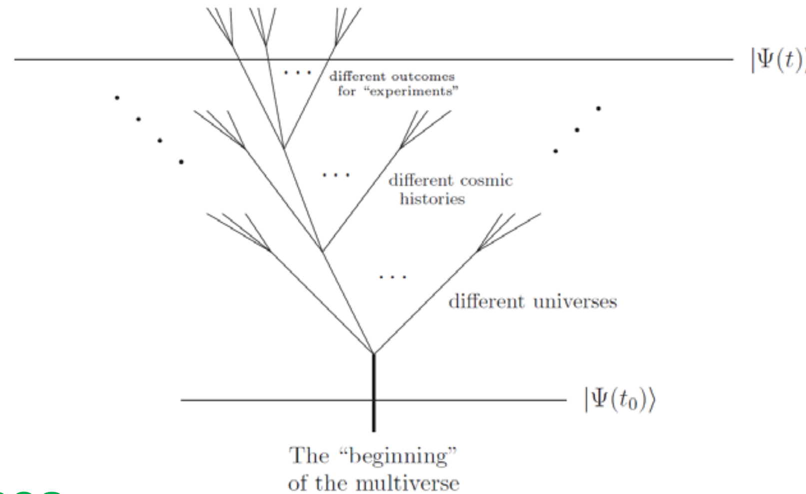

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eternally inflating

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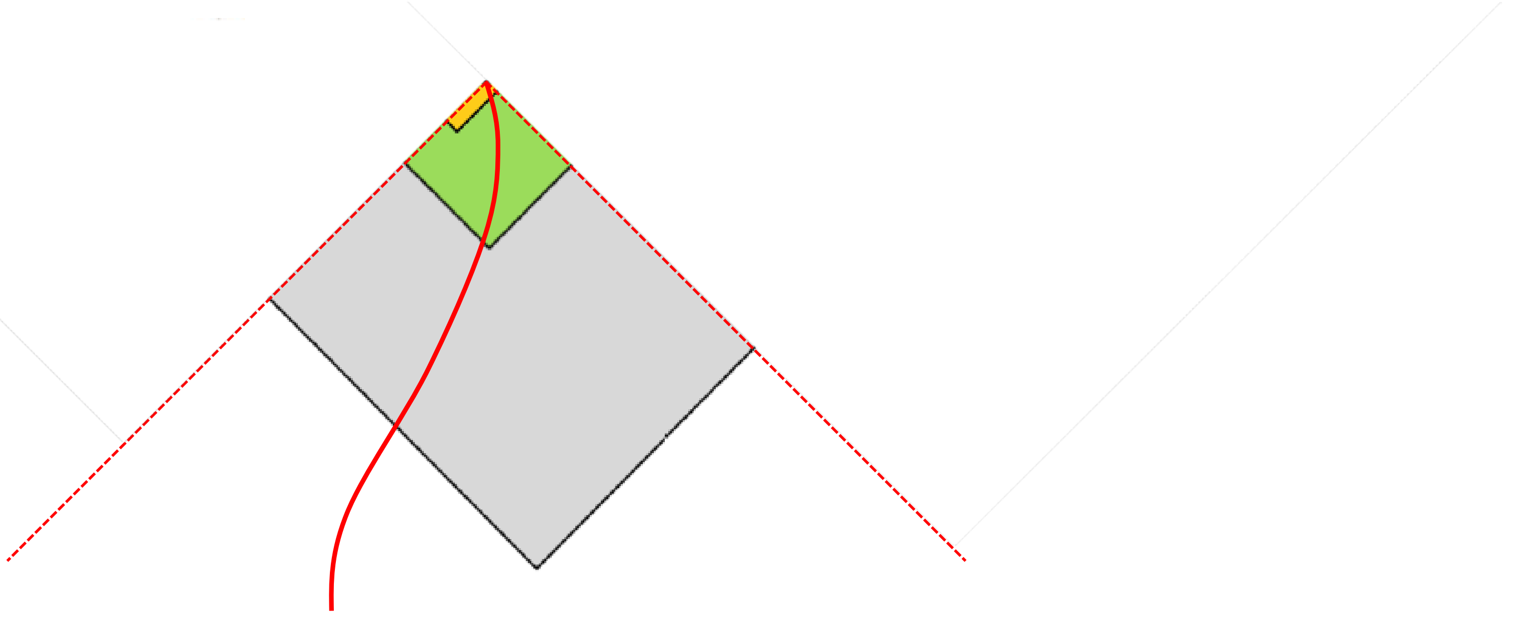
Multiverse = Quantum many worlds

… The multiverse lives (only) in probability space!

Global spacetime of general relativity
is an emergent (and "redundant") concept!



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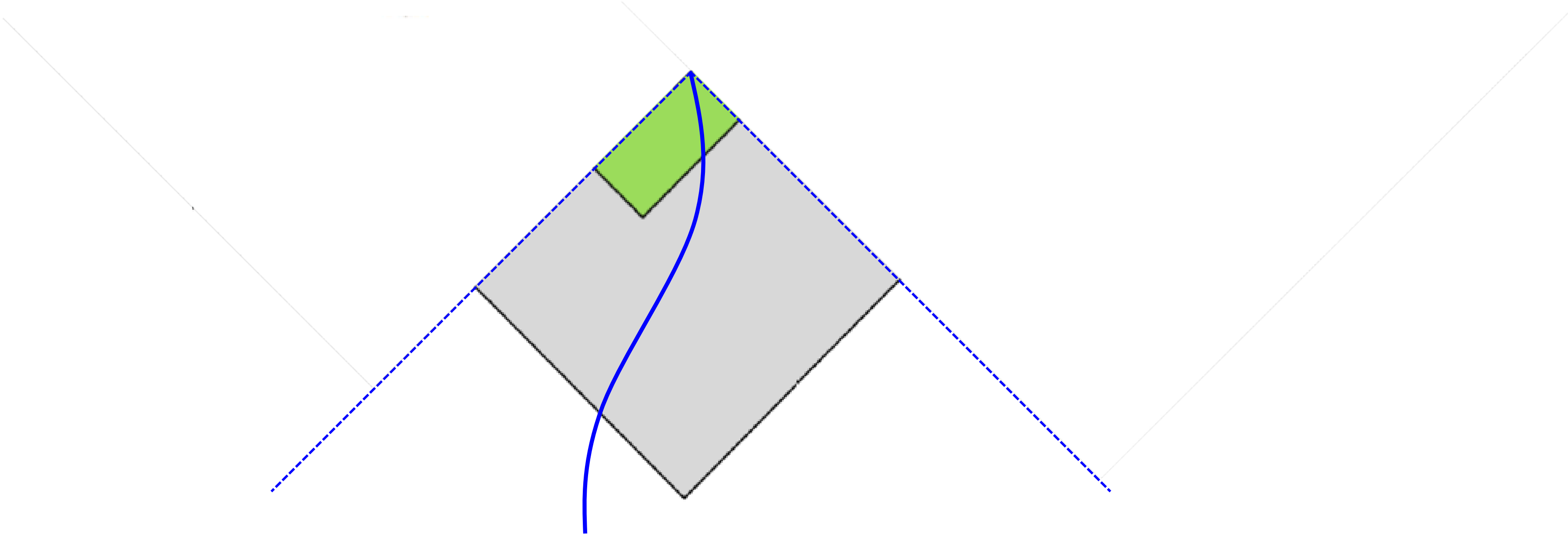

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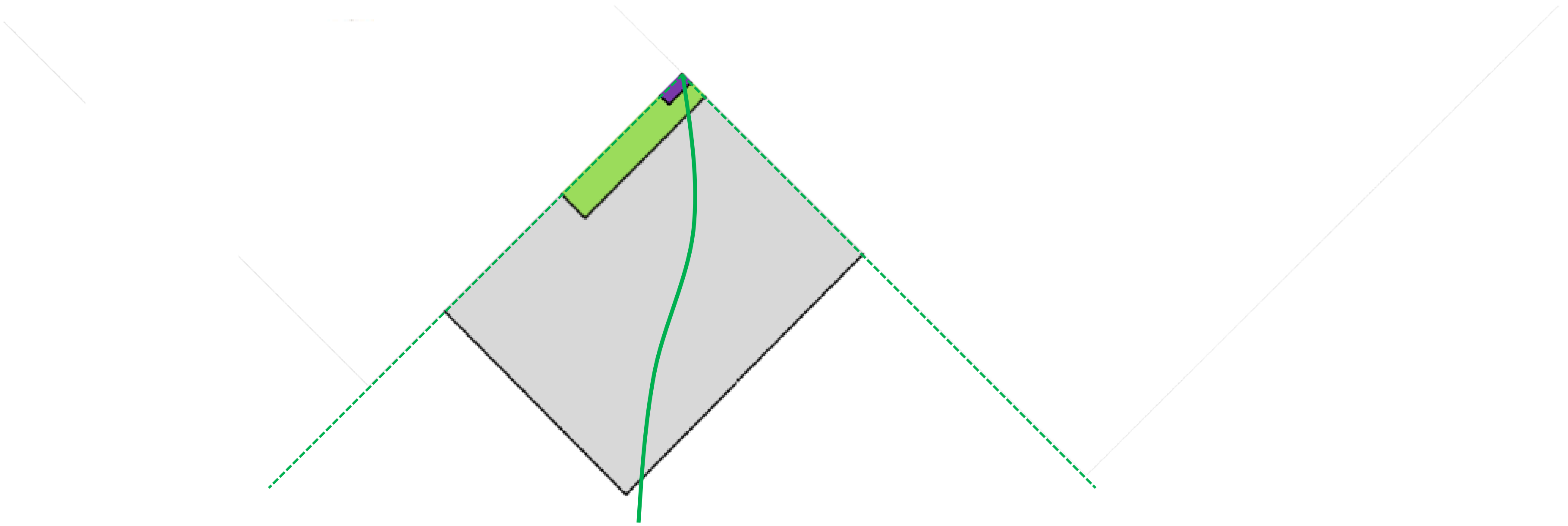

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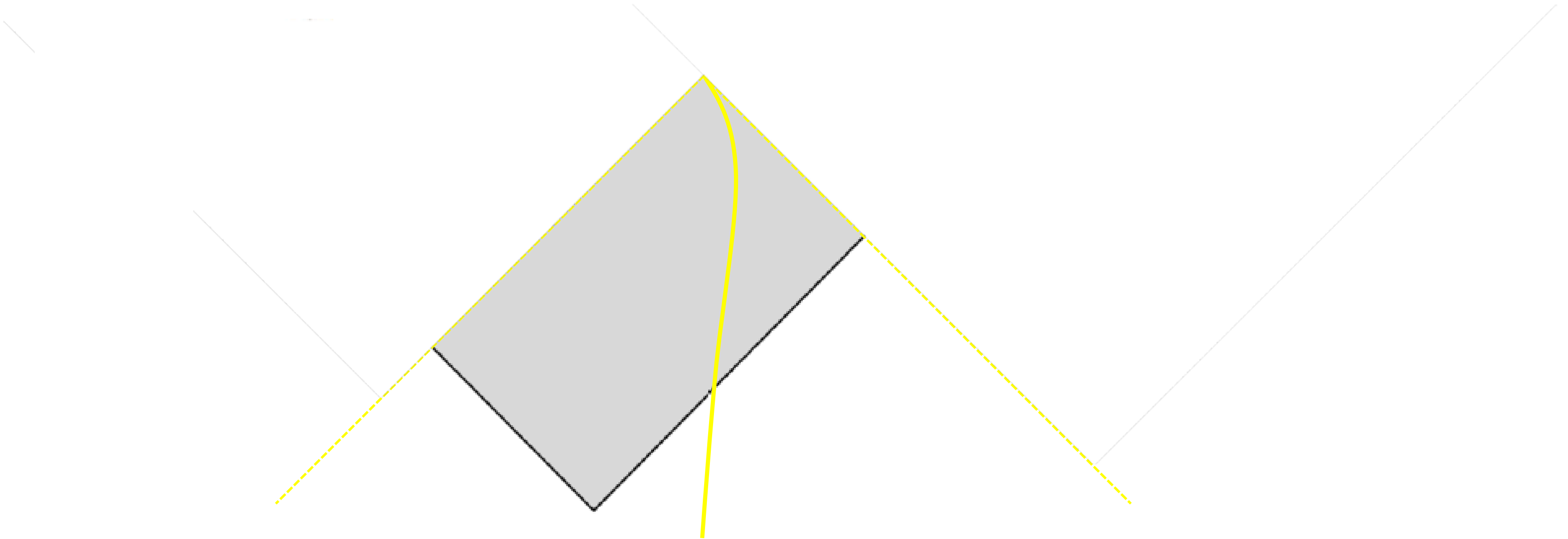

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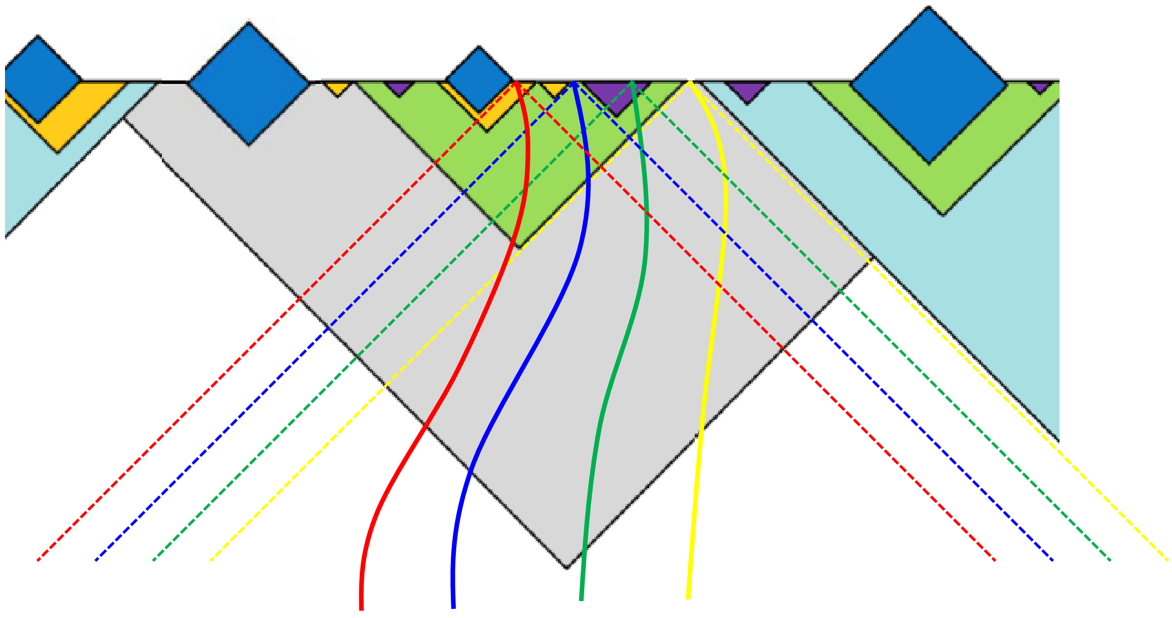

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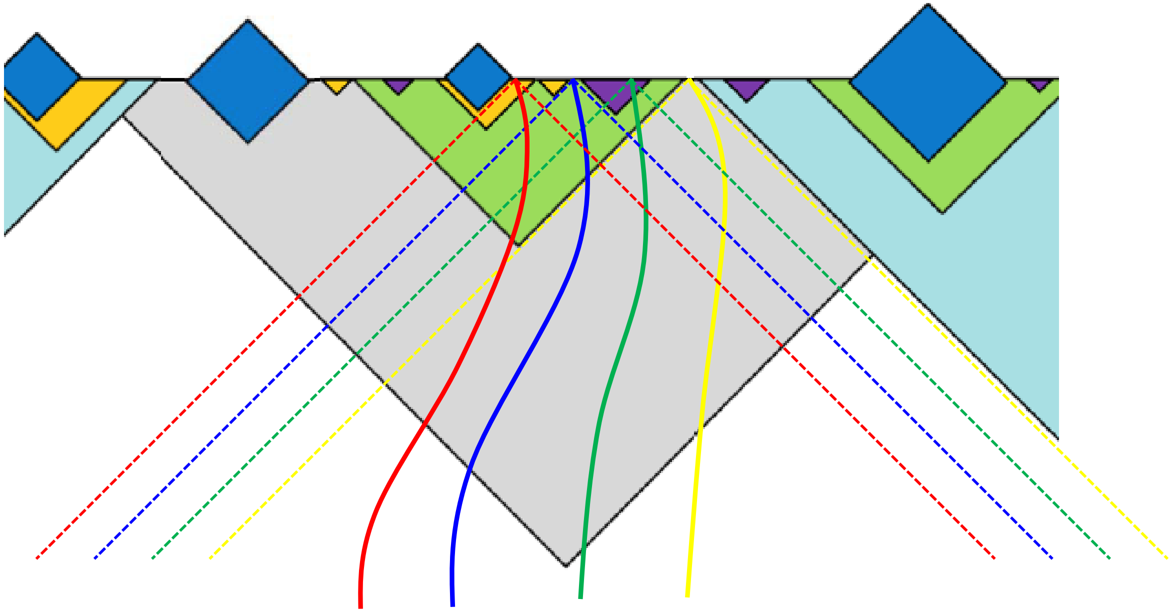


… probability is more fundamental

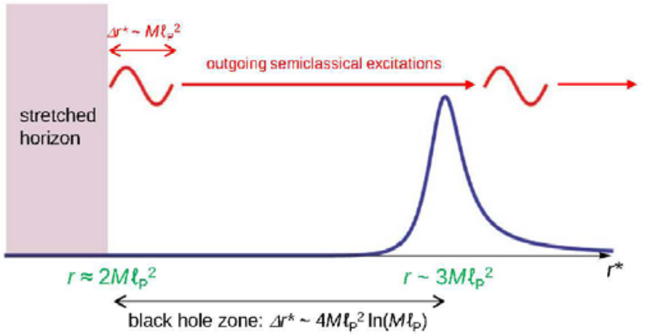
— counting observers (with equal weight) vastly overcounts d.o.f.s

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)

Conclusions

- Hawking emission from the semiclassical viewpoint



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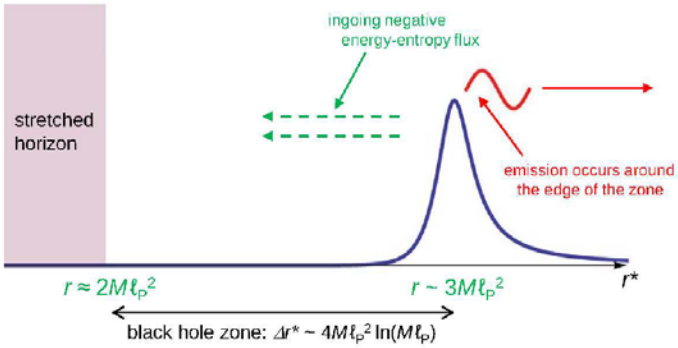

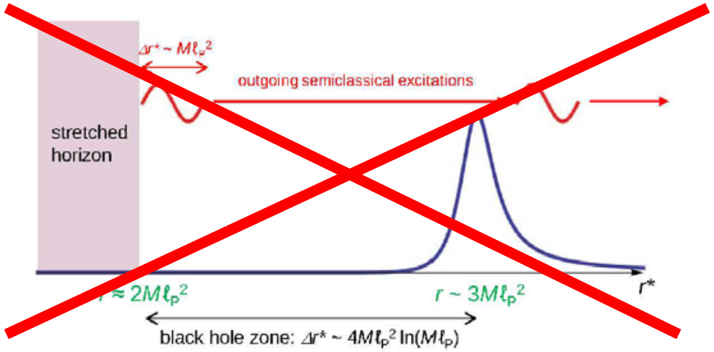

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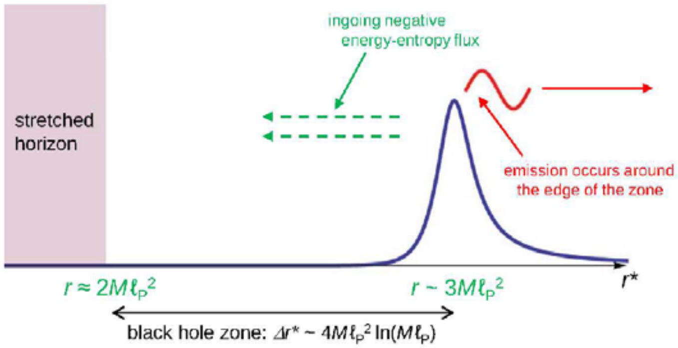

Hard modes: “matter”

Soft modes: “spacetime”

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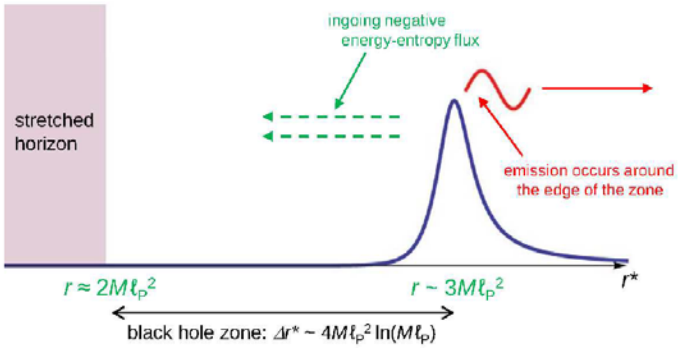

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$$|\Psi(M)\rangle = \sum_{E} \sum_{i_E=1}^{\mathcal{N}(M-E)} \sum_{a=1}^{e^{S_{\rm rad}}} c_{E i_E a} |E\rangle |\psi_{i_E}(M-E)\rangle |r_a\rangle$$

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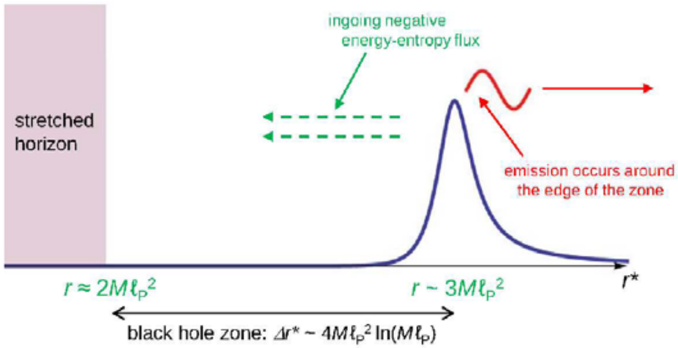

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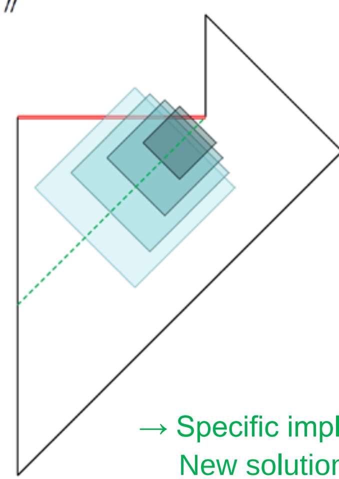
… effective theories erected **at each time**



→ Specific implementation of complementarity,
New solution to the cloning problem, …

Conclusions

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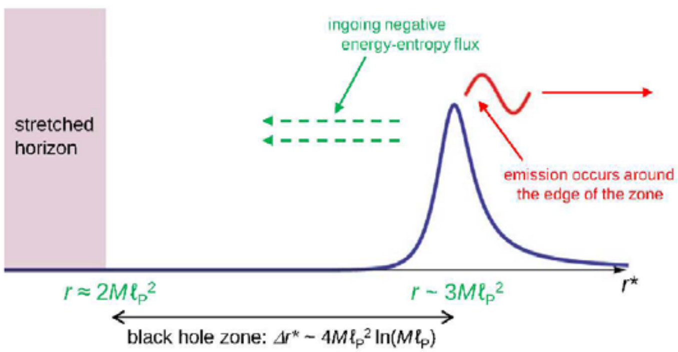

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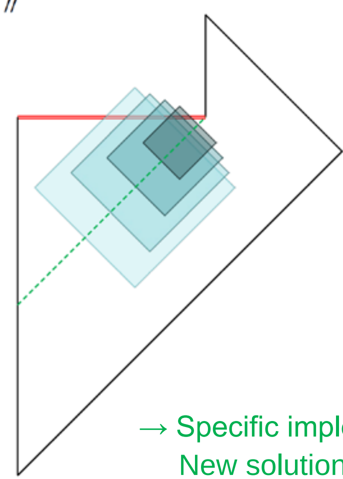

- Implication for cosmology (multiverse)

→ Specific implementation of complementarity,
New solution to the cloning problem, …