From Quantum Gravity to Low Energy Physics

Yasunori Nomura

UC Berkeley; LBNL; Kavli IPMU

Quantum gravity

~ ’80s … the problem of renormalizability

— Physics around the Planck scale

… string theory (perturbative string theory, string dualities, …)

’90s ~ … revisions of the concept of spacetime at **long** distances

— Quantum mechanics of black holes

… holography (AdS/CFT, spacetime from entanglement, …)

Black holes provide keys

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?
- …

$\Longrightarrow$ A coherent picture is emerging

… Implications for particle physics and cosmology?

Thermodynamics of a Black Hole

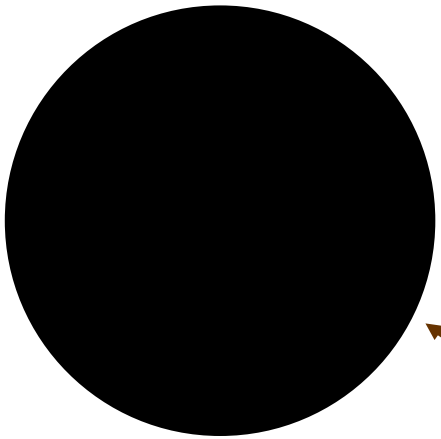
One of the biggest discoveries in theoretical physics:

horizon area

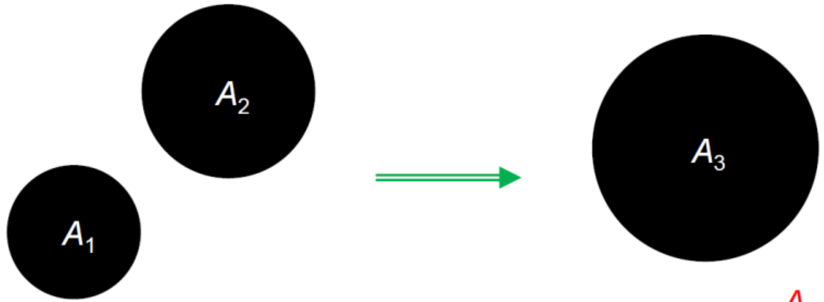
$$S_{\rm BH}(M) = \frac{\mathcal{A}(M)}{4 l_{\rm P}^2}$$

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

Bekenstein ('73); Hawking ('74)



- What happens to energy and entropy?

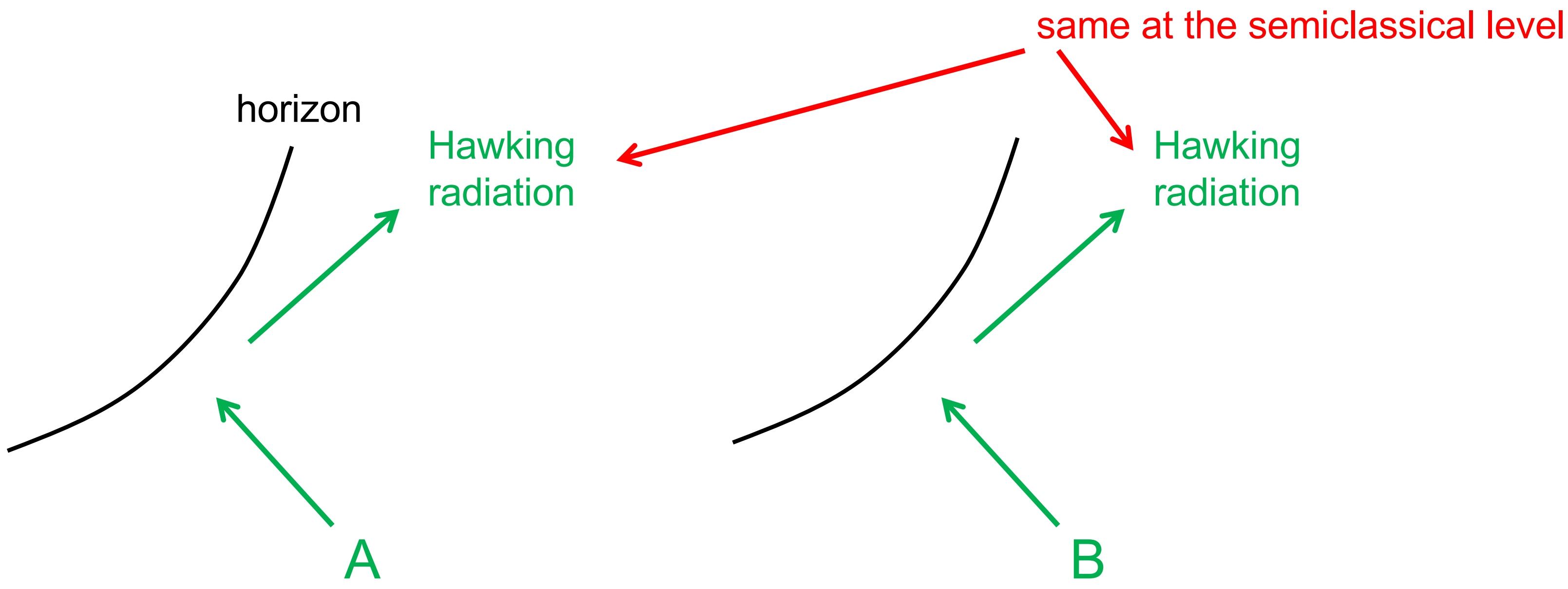


$A_3 \geq A_1 + A_2$

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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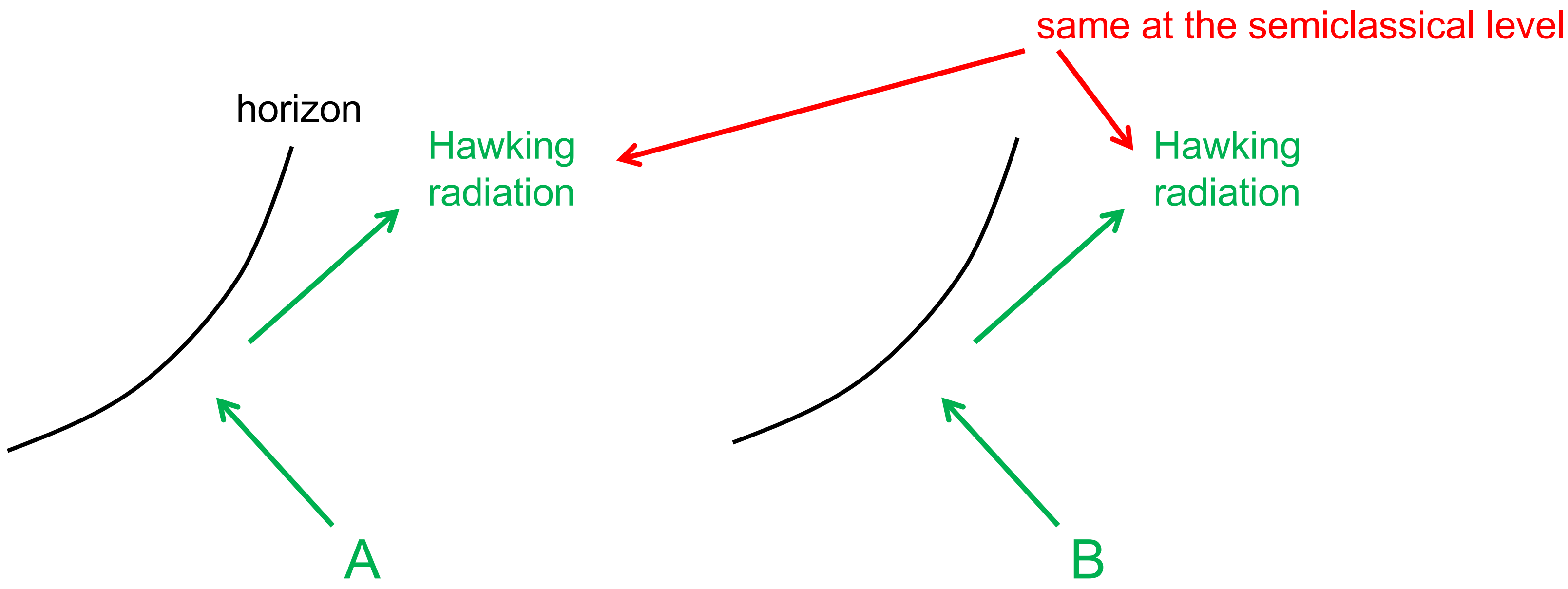


… information is lost ?? Hawking ('76)

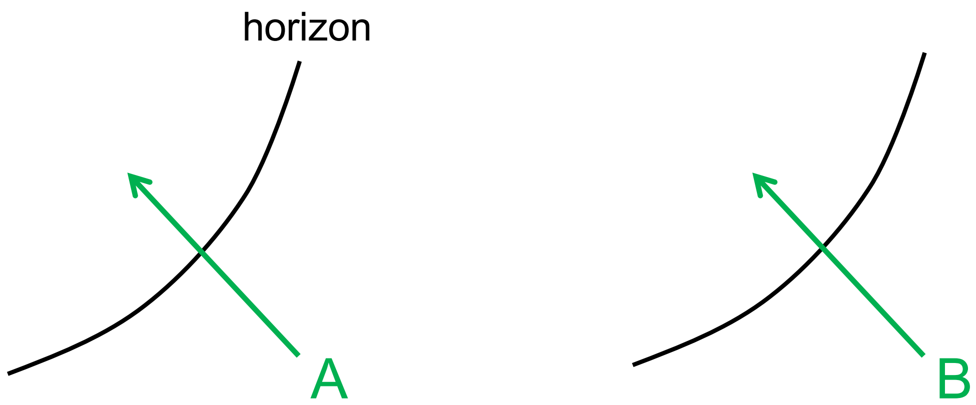
⟹ No

… 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)

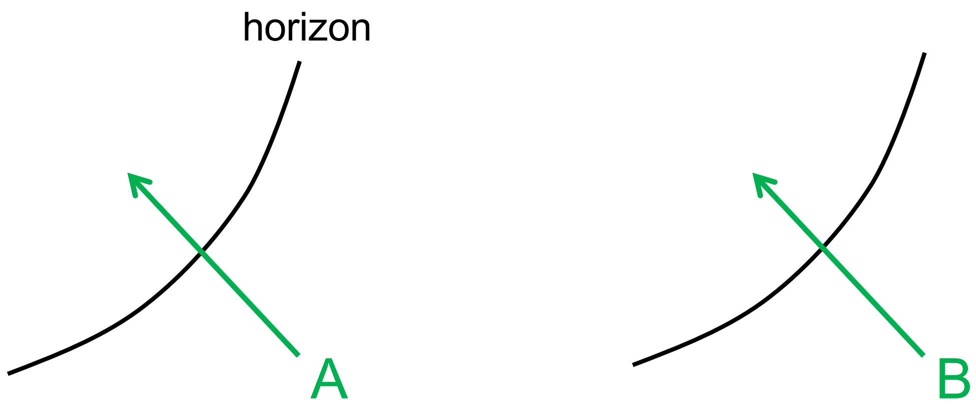
Which is correct?

Preskill ('93)

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

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

From a falling observer's viewpoint:



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  (carried with him/her)

Which is correct?

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

There is no contradiction !

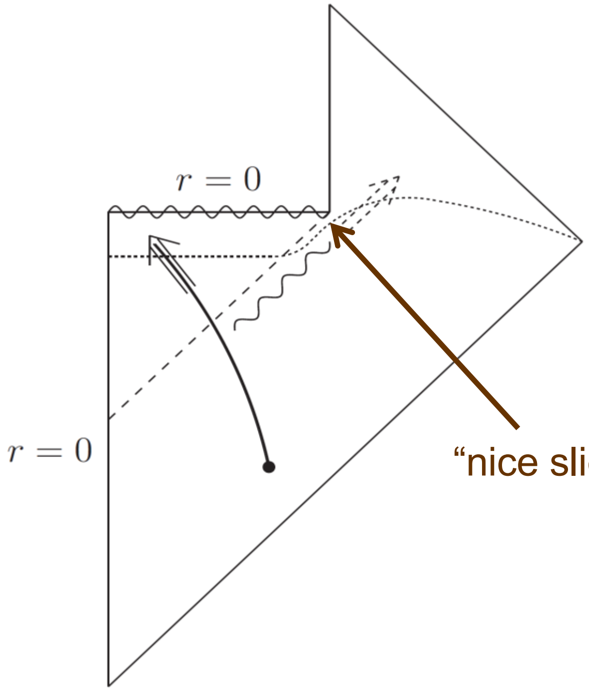
One cannot be *both* distant and falling observers *at the same time*.

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

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

… Physics must be described from the viewpoint of a **single** observer.

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



“nice slice” (nothing wrong in general relativity)

A hope was that by taking this into account,
semiclassical theory gives a good local description of physics.

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

The Interior of a Black Hole

The interior of a black hole is **not** independent
from the exterior (or Hawking radiation emitted earlier)!

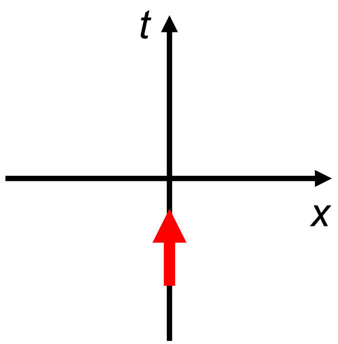
Papadodimas, Raju ('12–'15); Verlinde, Verlinde ('12–'13);
Y.N., Varela, Weinberg ('12–'13); Maldacena, Susskind ('13); …

… motivated by the "firewall" argument

(Complementarity is not enough) Almheiri, Marolf, Polchinski, Stanford, Sully ('13–'14)

A key is to get the (unique) thermal state in the exterior
without contradicting unitarity of black hole evolution.

Smooth horizon:

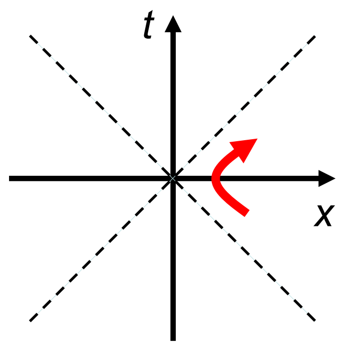


$|0\rangle$

Minkowski
(infalling description)

$\longleftrightarrow$

Thermal state:



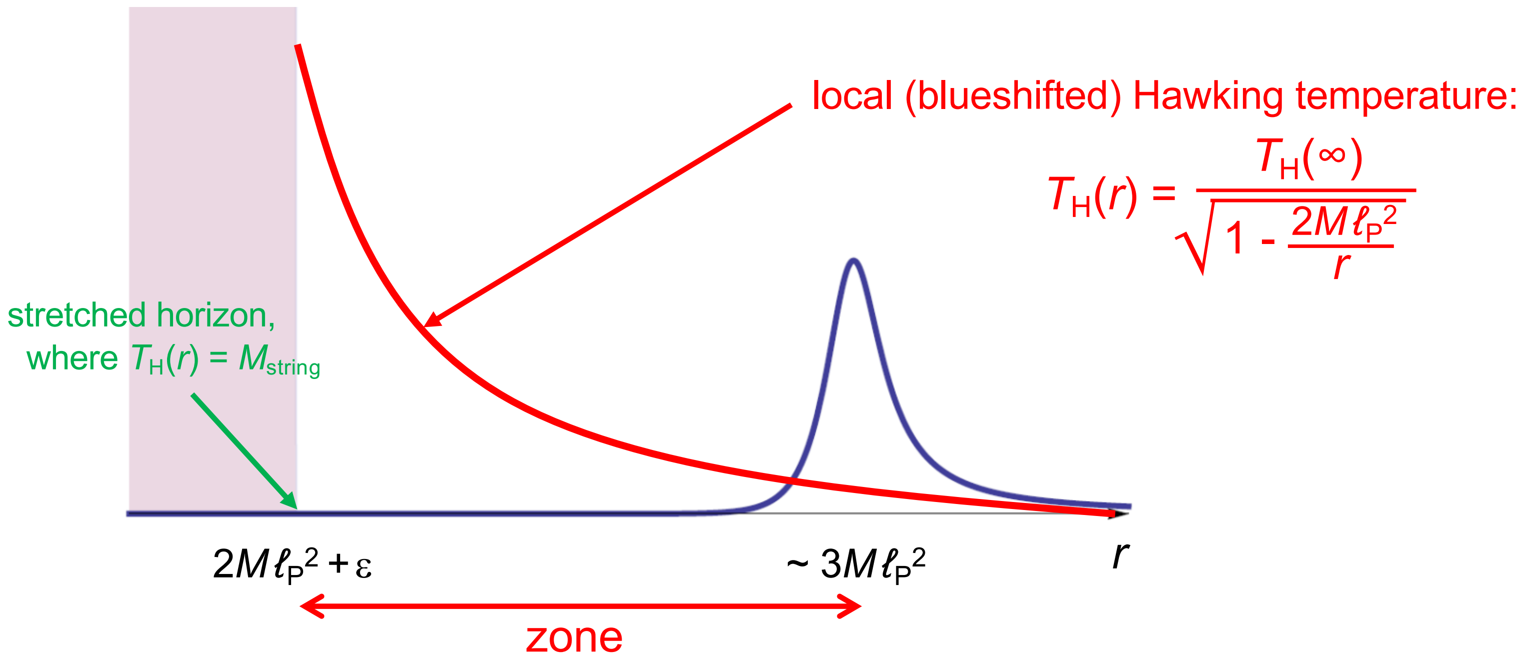
ρ_{thermal}

Rindler
(distant description)

Reanalyzing an Evaporating BH

Y.N., *Phys. Rev.* **D99** ('19) 086004 [arXiv:1810.09453 [hep-th]]

A black hole is "quasi static"

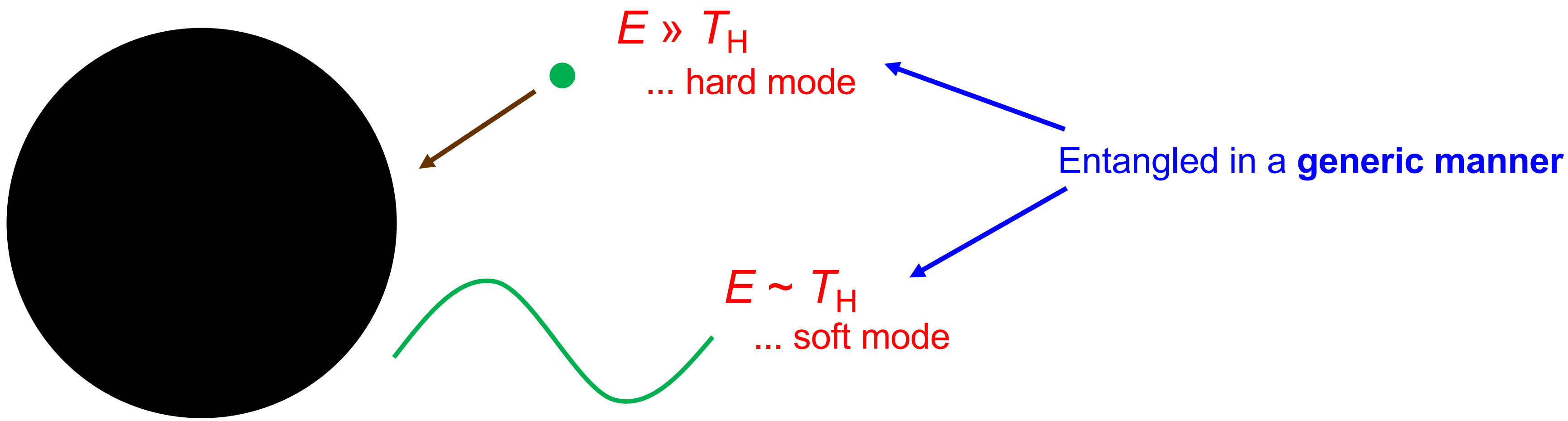


Distinguish modes in the zone:

Hard modes: $E > T_H$ … described by semiclassical theory

Soft modes: $E < T_H$ … cannot be resolved (described only statistically)

The origin of thermality



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

chaotic

Tracing out the soft modes

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

… thermal density matrix
with Hawking temperature T_H

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

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

… The **chaotic** nature of
the coefficients is still **crucial**.

Effective Theories of the BH Interior

Y.N., "Reanalyzing an evaporating black hole"
Phys. Rev. **D99** ('19) 086004 [arXiv:1810.09453 [hep-th]]

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

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

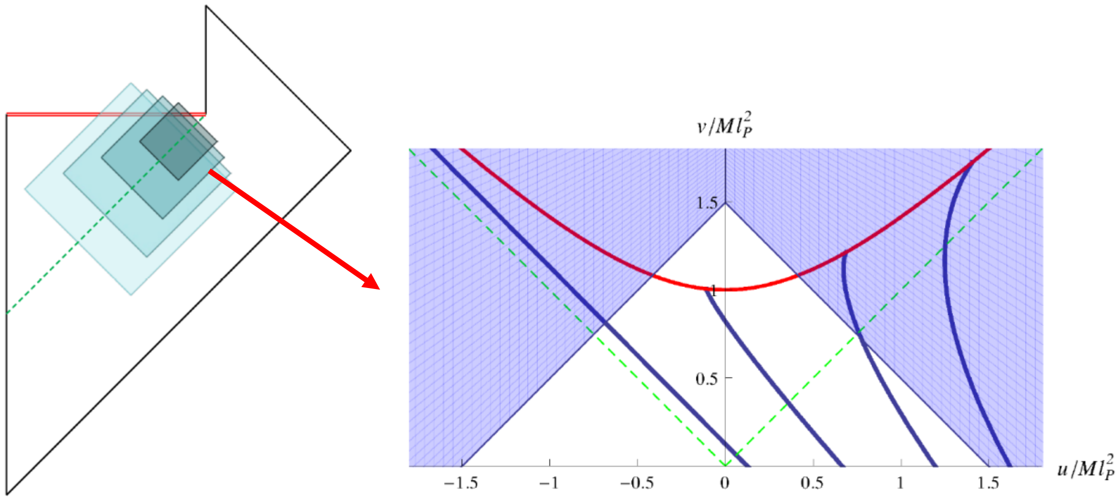
→ The *coarse-grained* state (for **chaotic** coefficients)

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

… standard thermofield double form

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

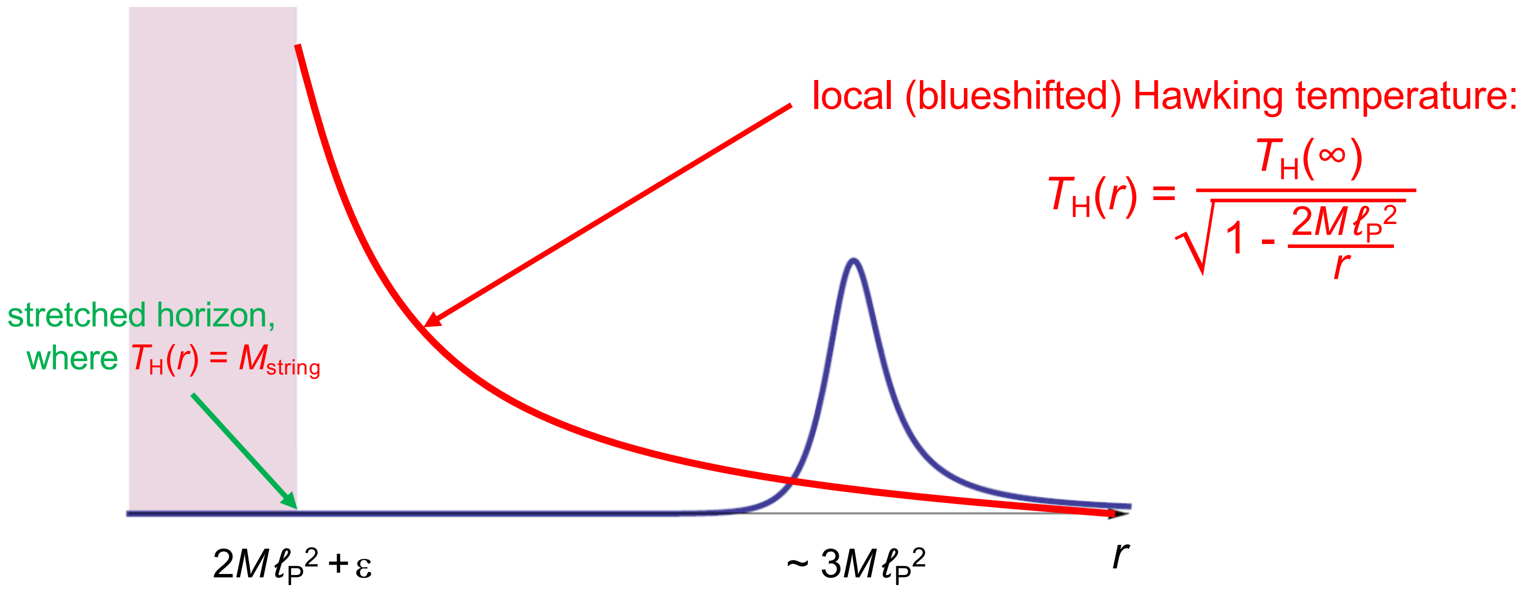
The black hole interior
emerges (only) effectively
at the semiclassical level.



Implication for Particle Physics

Y.N., "Spacetime and universal soft modes — black holes and beyond," arXiv:1908.05728 [hep-th]]

Physics at the string scale must be chaotic **across all low energy species**.



There should **not** be a mechanism preventing universal distribution of energy (mass) to low energy quantum fields.

$\Longrightarrow$ Global symmetry must be broken **with ~ $O(1)$ strength** at the string scale!

… much stronger than e.g. Harlow, Ooguri ('19)

Allowed global symmetries

– Already nonlinearly realized at M_{string}

e.g. String axions, …

– Accidental symmetry due to gauge invariance

$$\mathcal{L} = \mathcal{L}_{\text{symmetric}} + \frac{c}{M^n_{\text{string}}}\mathcal{O}_{\text{dim}=4+n}, \quad c \sim O(1)$$

e.g. Baryon number, lepton number, …

Implications for the QCD axion

- String axion

… $f_a \sim 10^{15\text{-}18}$ GeV

- Accidental Peccei-Quinn symmetry due to gauge invariance

… $f_a \ll 10^{15}$ GeV

… and many more

Implication for Cosmology

Eternally inflating multiverse

… The multiverse is "infinitely large"!

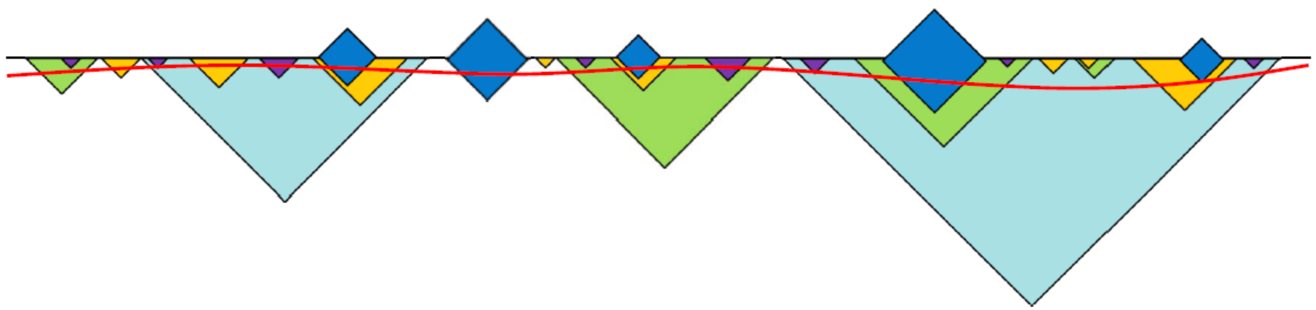
Predictivity crisis!

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)

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])

Quantum mechanics is **essential**

— in what sense?

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

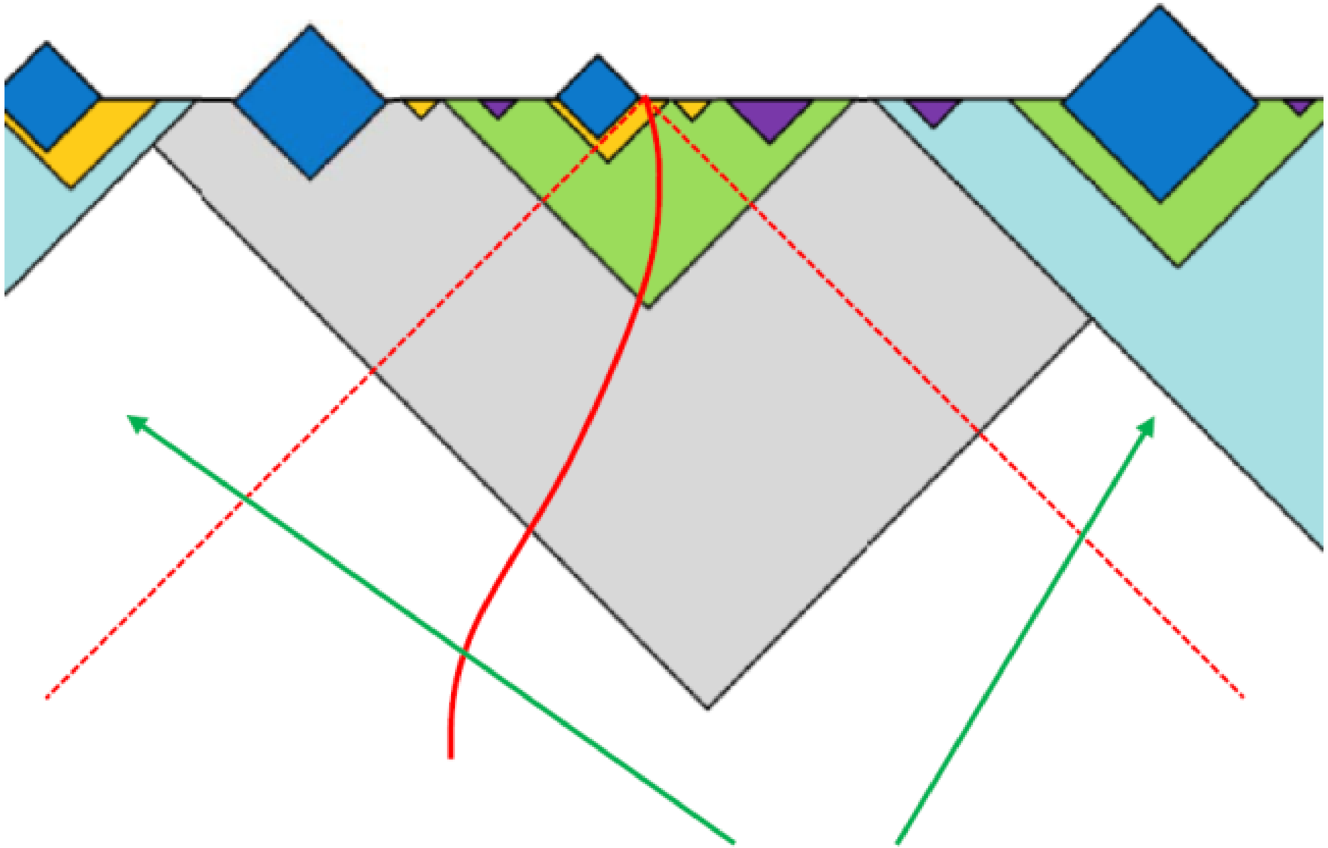
Probability in cosmology has the same origin as the quantum mechanical probability

… 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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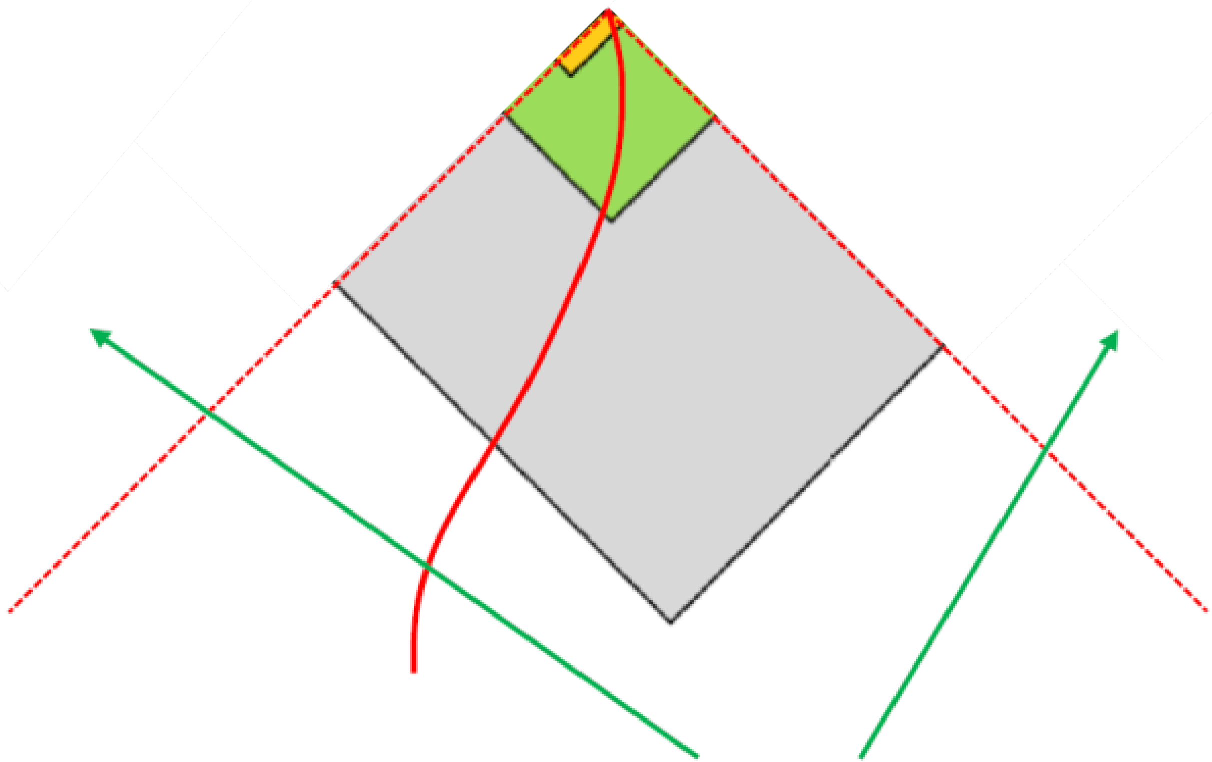
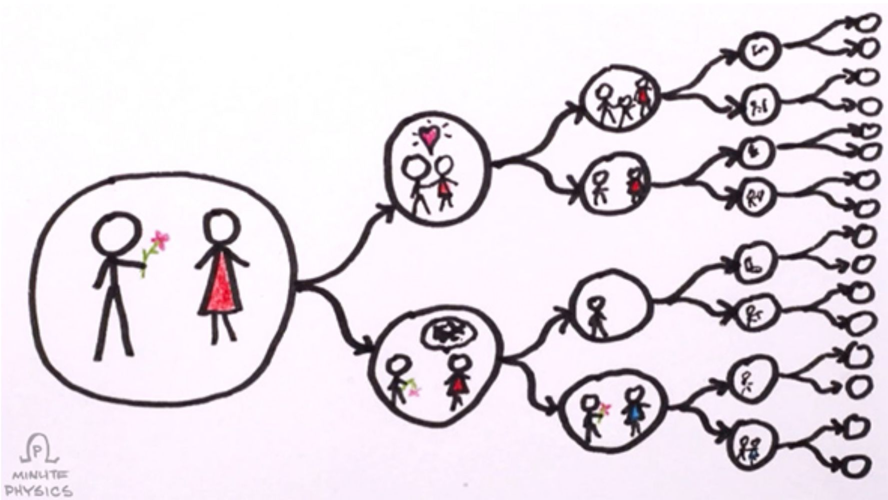


Does this region “exist”? → No!

… What happened to the multiverse?

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"

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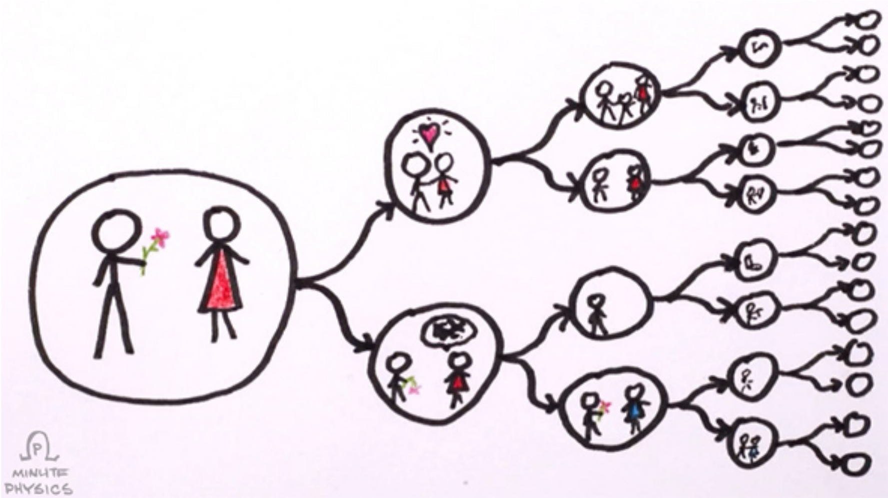

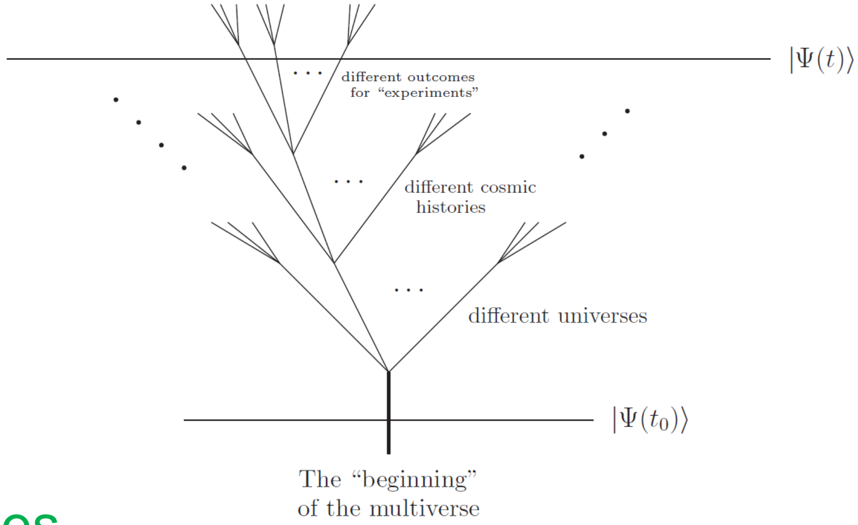

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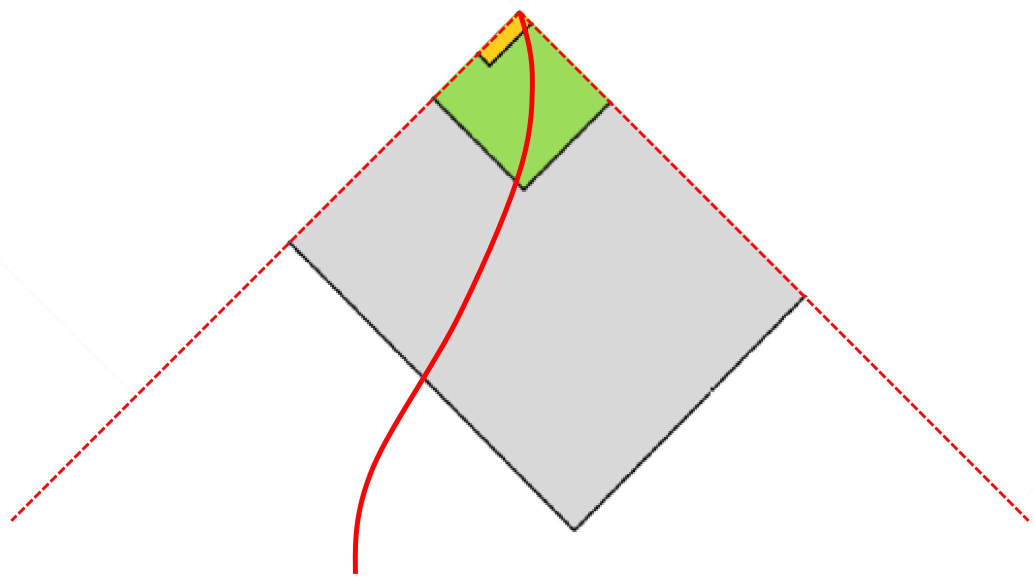
Global spacetime of general relativity

is an emergent (and “redundant”) concept!



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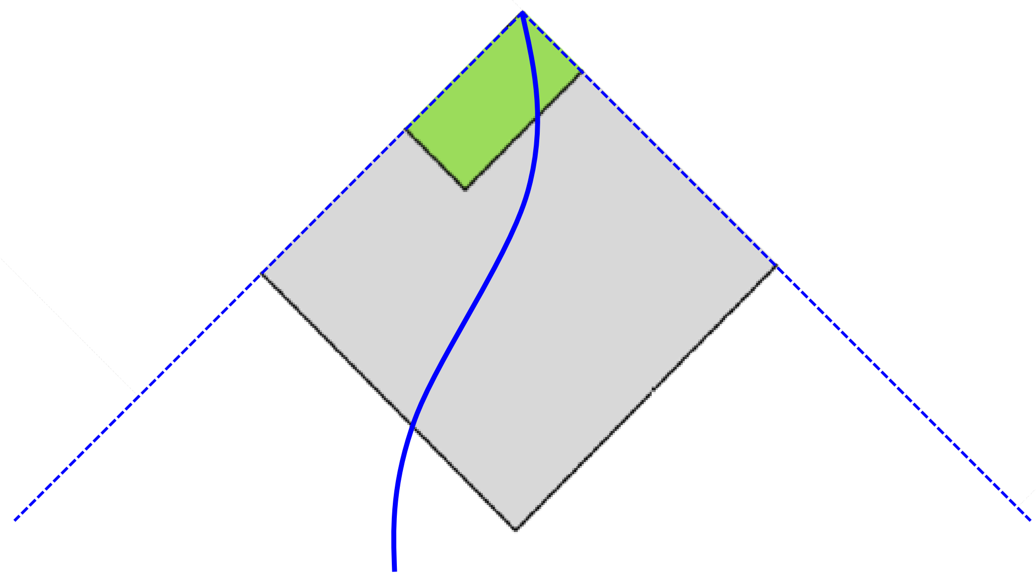

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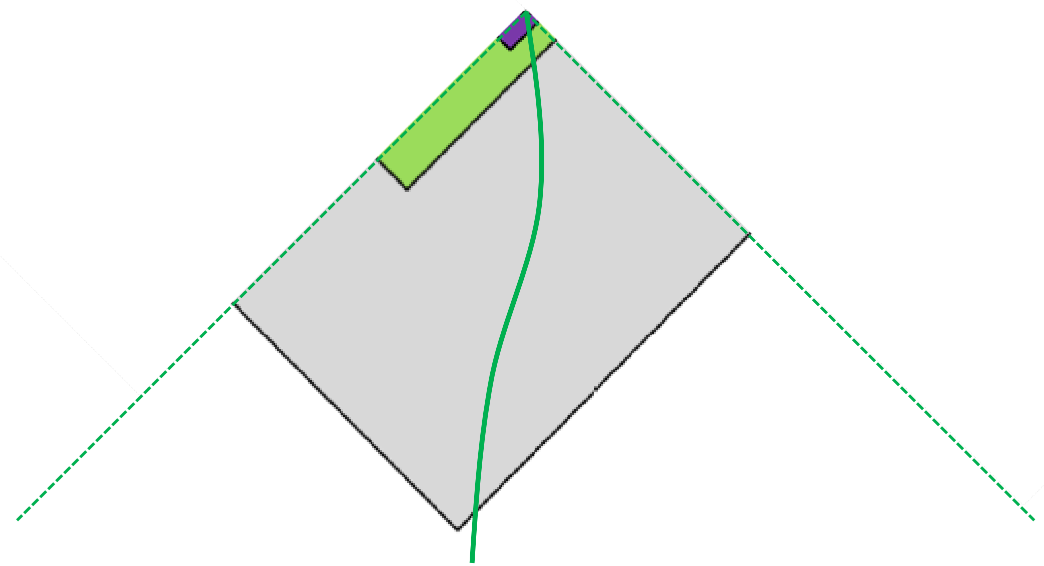

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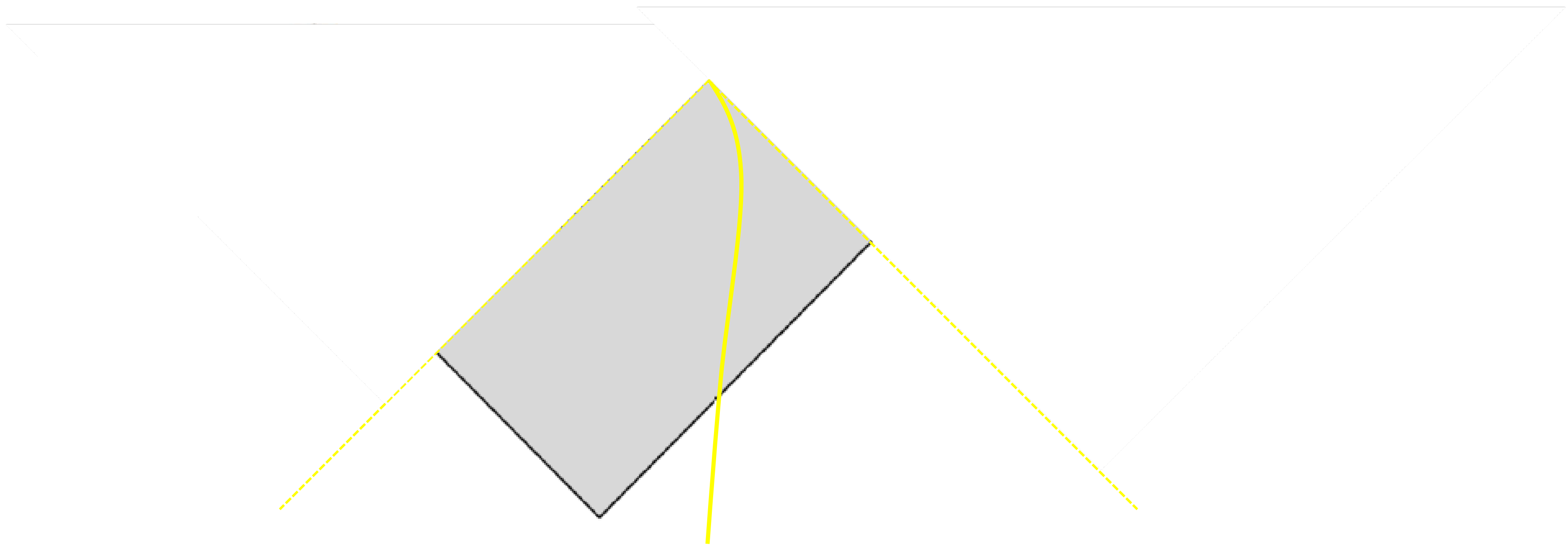

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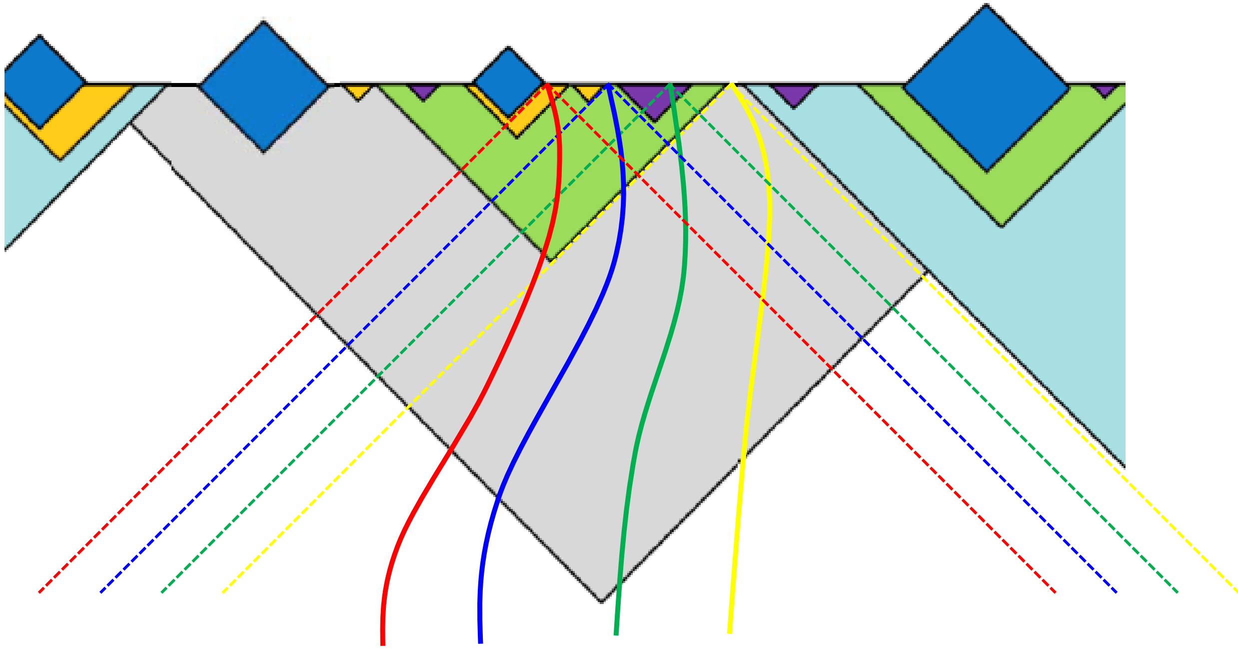

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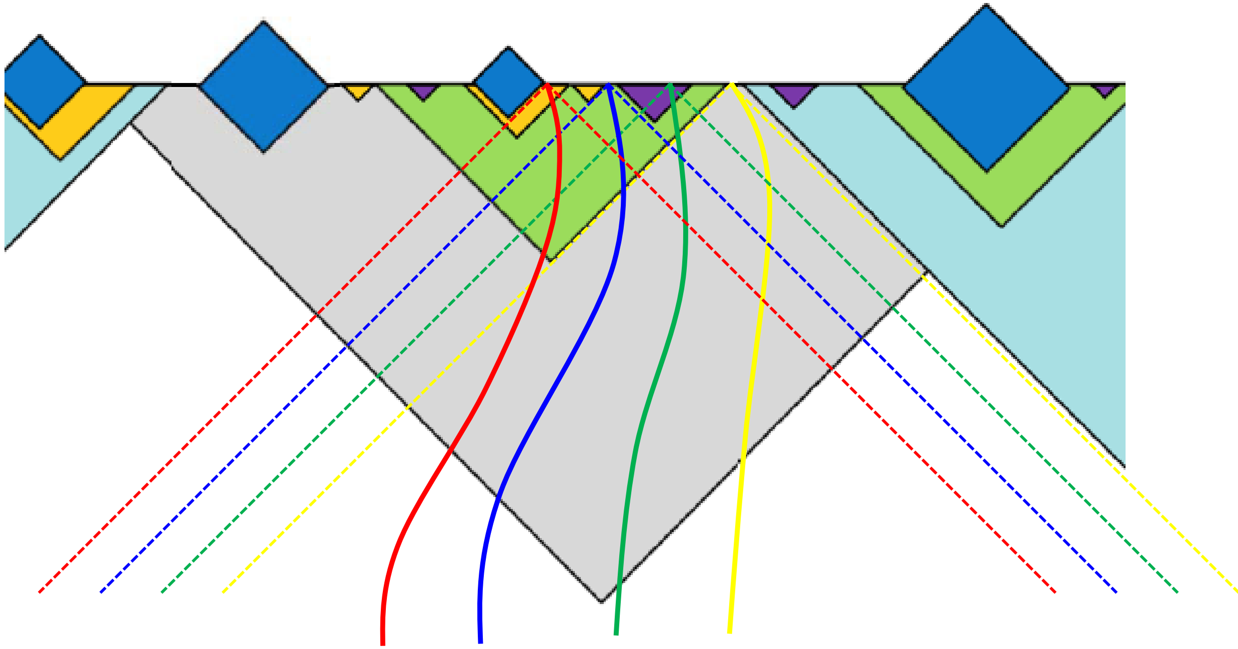

… probability is more fundamental

— 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)

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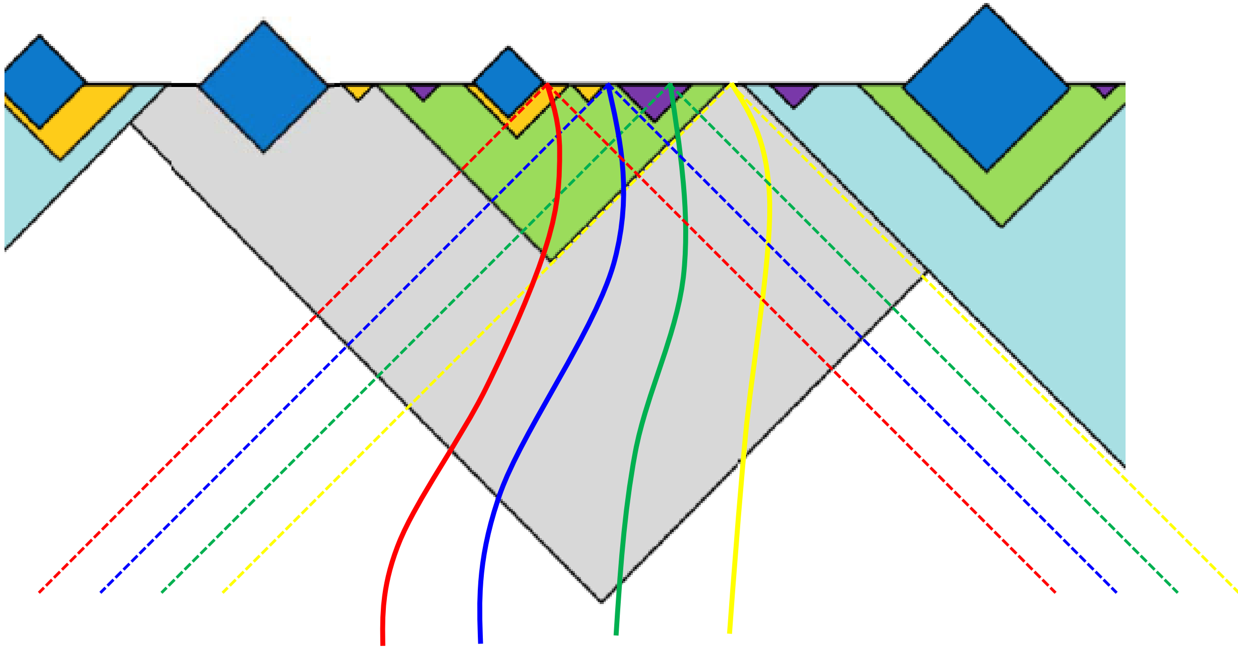

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– No "volume weighting" → Slow-roll eternal inflation is an illusion.

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- Status of Quantum Gravity (opinionated)
- The problem of renormalizability

– Deriving the low energy theory

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    String landscape

- The emergence of spacetime
  - Revisions of the concept of naturalness

    Bousso, Polchinski; Kachru, Kallosh, Linde Trivedi; Susskind; Denef, Douglas; …
  - General consequences for low energy physics

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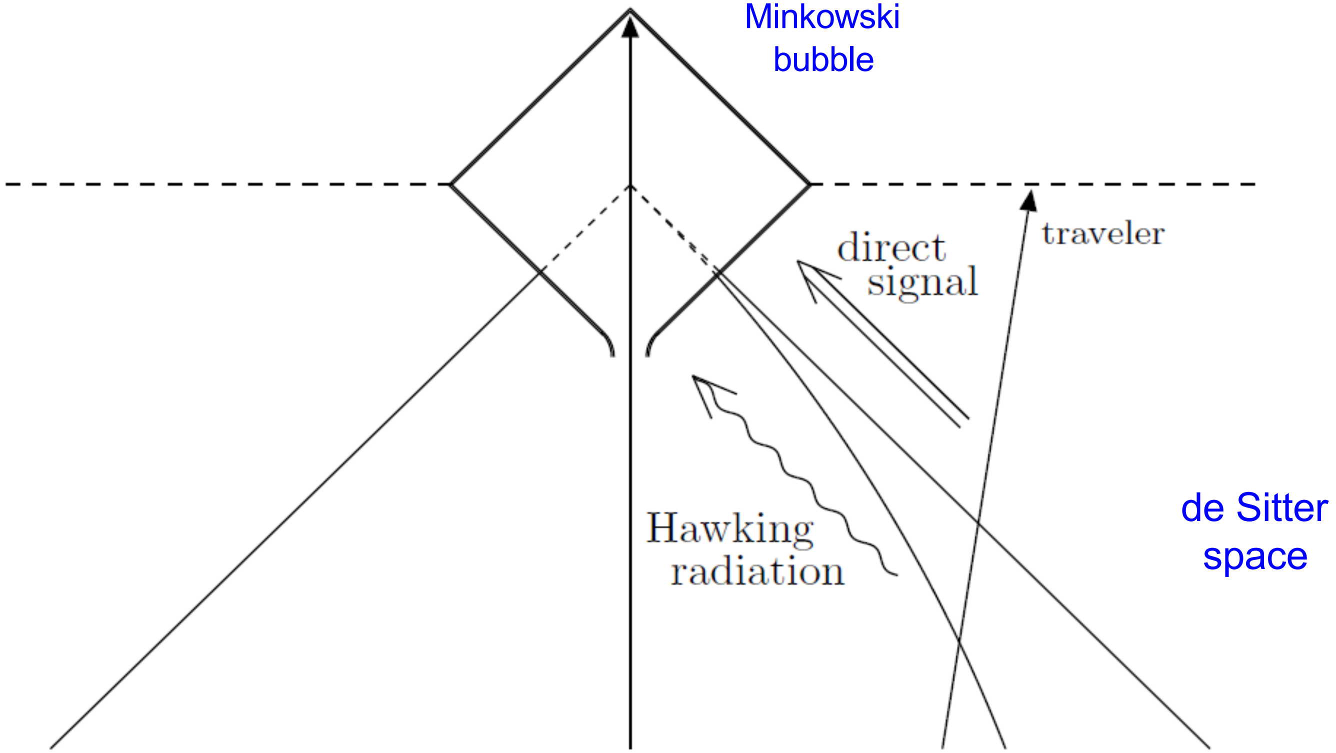
- Implications for Particle Physics and Cosmology

  — "$O(1)$" breaking of global symmetries at M_{string} … QCD axion

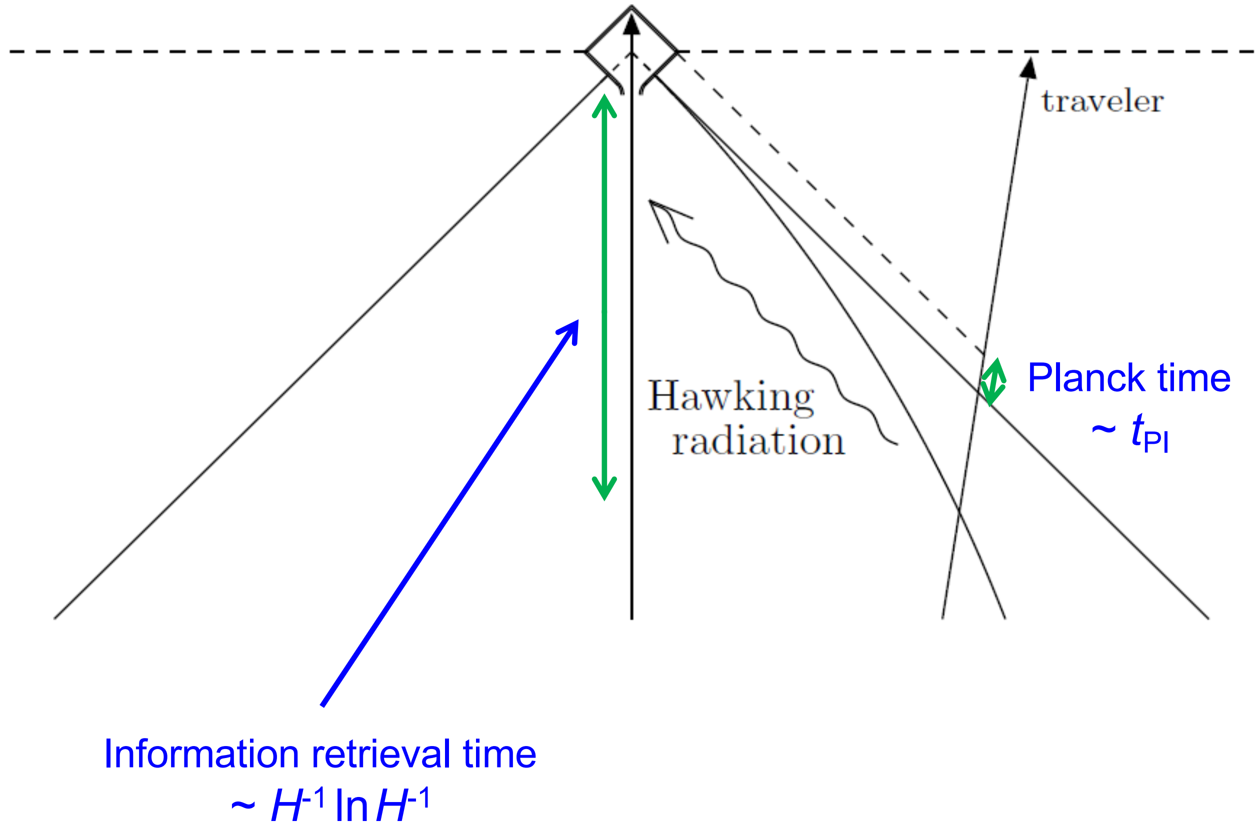
  — The lack of "global spacetime" … measure problem in multiverse cosmology

Consistent?



Doesn't information duplicate?

Consistent? — Yes



The information duplication does *not* occur!

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