Quantum Gravity

From black holes to the multiverse

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Why is the universe as we see today?

— Mathematics requires

— “We require”

Dramatic change of the view

Our universe is only a part of the “multiverse”

… suggested **both** from observation **and** theory

This comes with revolutionary change of the view on spacetime and gravity

- Holographic principle
- Horizon complementarity
- Multiverse as quantum many worlds
- …

… implications on particle physics and cosmology

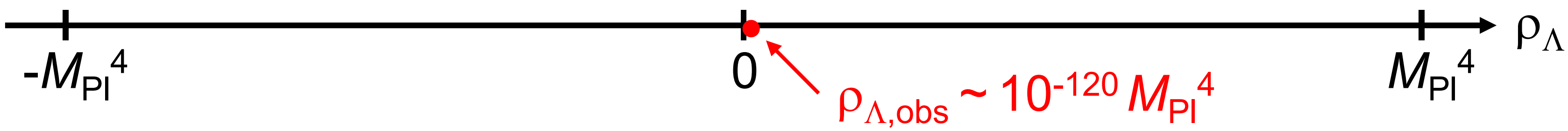
Shocking news in 1998

Expansion of the universe is accelerating: $\rho_\Lambda \sim (10^{-3}\text{ eV})^4$

— Why now?

Nonzero value completely changes the view !

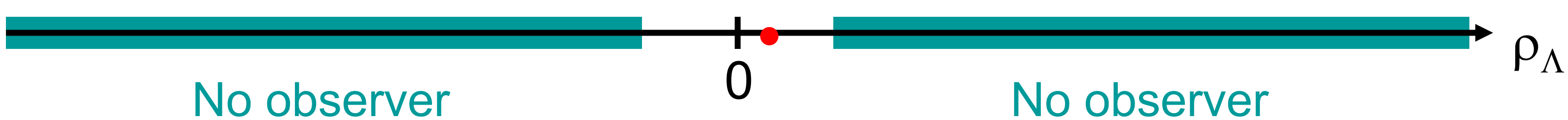
Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$



Unnatural (Note: $\rho_\Lambda = 0$ is NOT special from theoretical point of view)

⟹ Wait!

Is it really unnatural to *observe* this value?



It is quite "natural" to observe $\rho_{\Lambda,obs}$,

as long as different values of ρ_Λ are "sampled"

Weinberg ('87); also Banks, Linde, …

Theory also suggests

- String landscape

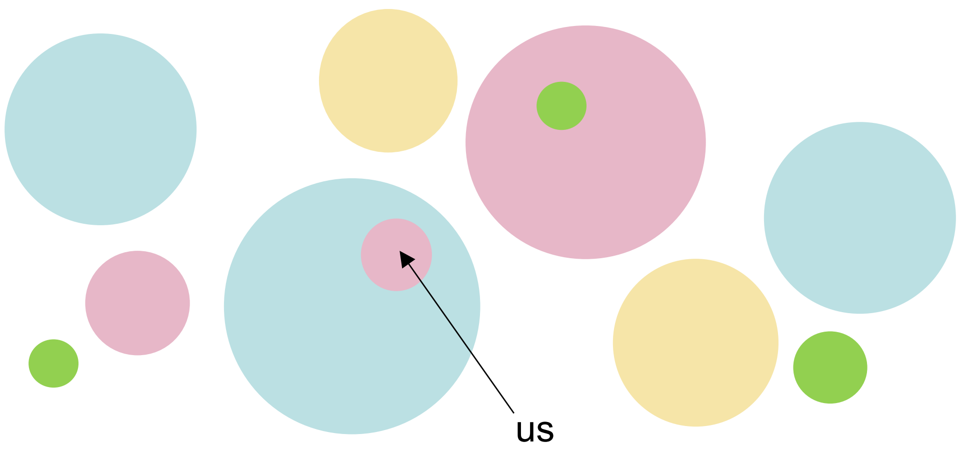
Compact (six) dimensions
$\rightarrow$ huge number of vacua

ex. $O(100)$ fields with $O(10)$ minima each
$\rightarrow O(10^{100})$ vacua

- Eternal inflation

Inflation is (generically) future eternal

$\rightarrow$ populate all the vacua



… Anthropic considerations **mandatory** (not an option)

$\Longrightarrow$ Eternally inflating multiverse

Full of "fine-tunings"

Examples:

- $y_{u,d,e}v \sim \alpha\,\Lambda_{QCD} \sim O(0.01)\,\Lambda_{QCD}$

  … otherwise, no nuclear physics or chemistry

(Conservative) estimate of the probability: $P \ll 10^{-3}$

- $\rho_{Baryon} \sim \rho_{DM}$

….

Some of them could be anthropic (and some may not)

$\Longrightarrow$ Implications?

- Observational / experimental (test, new scenarios, …)
- Fundamental physics (spacetime, gravity, …)

Full of "fine-tunings"

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⟹ Implications?

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⟹ • Fundamental physics (spacetime, gravity, …)

Multiverse = Quantum many worlds, "constituents" of spacetime, …

Eternally Inflating Multiverse

Far-reaching implications

… The multiverse is "infinitely large"!

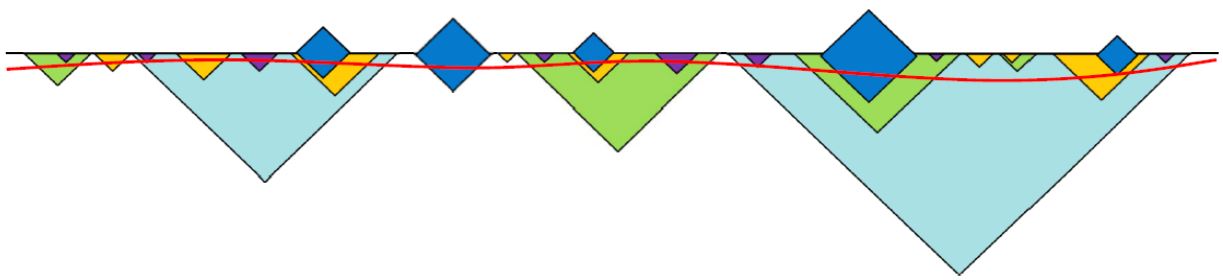
Predictivity crisis!

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?

— Problem of conditioning

… What is the "observation"?

Work addressing various aspects:

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

Below, my own view

Quantum mechanics is essential to answer these questions.

→ Dramatic change of our view of spacetime and gravity

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 principle:

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

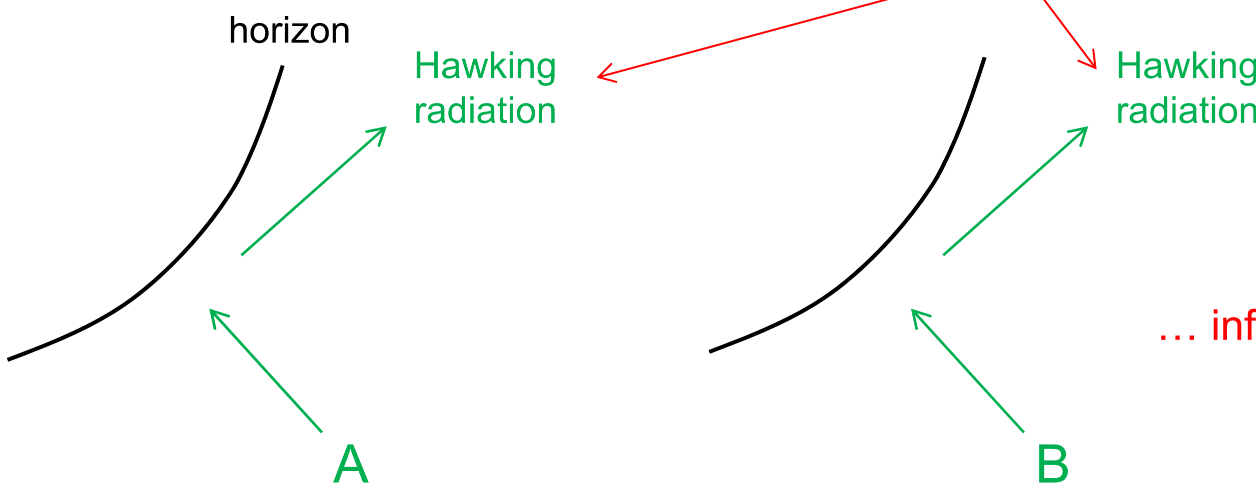
(Anything that can happen will happen *but not with equal probability*.)

Quantum mechanics in a system with gravity

Black Hole

Information loss paradox

same at the semi-classical level



… information is lost ??

Hawking ('76)

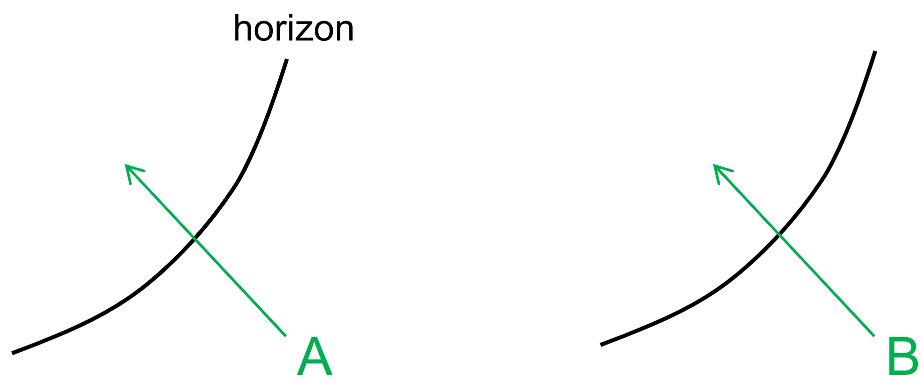
$\Longrightarrow$ No

… Quantum mechanically different final states

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

cf. AdS/CFT, classical "burning" of 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.

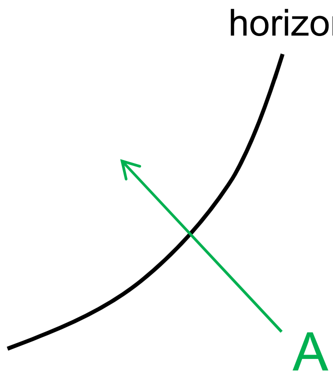
  (carried with him/her)

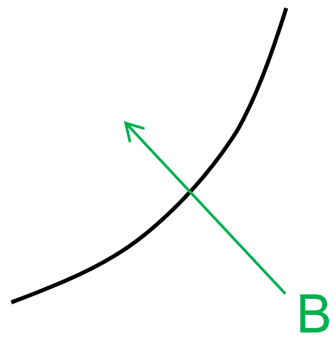
Which is correct?

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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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)

See later for the recent "firewall" challenge

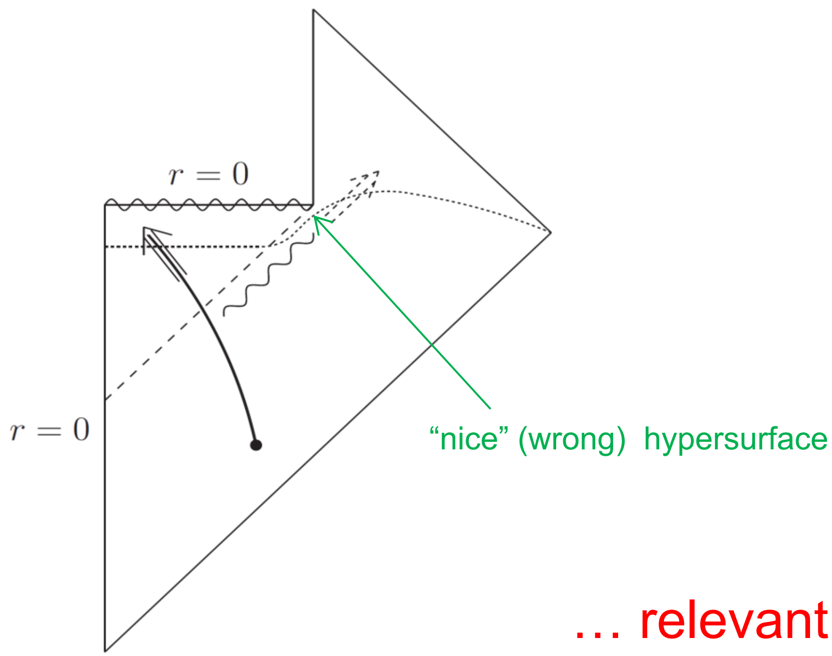
A Lesson:

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

To keep our description of nature to be **local** in space at long distances

(or, at least, to keep approximate locality in the description)

… Equal time hypersurface must be chosen carefully.



… relevant for formulating "measurements"

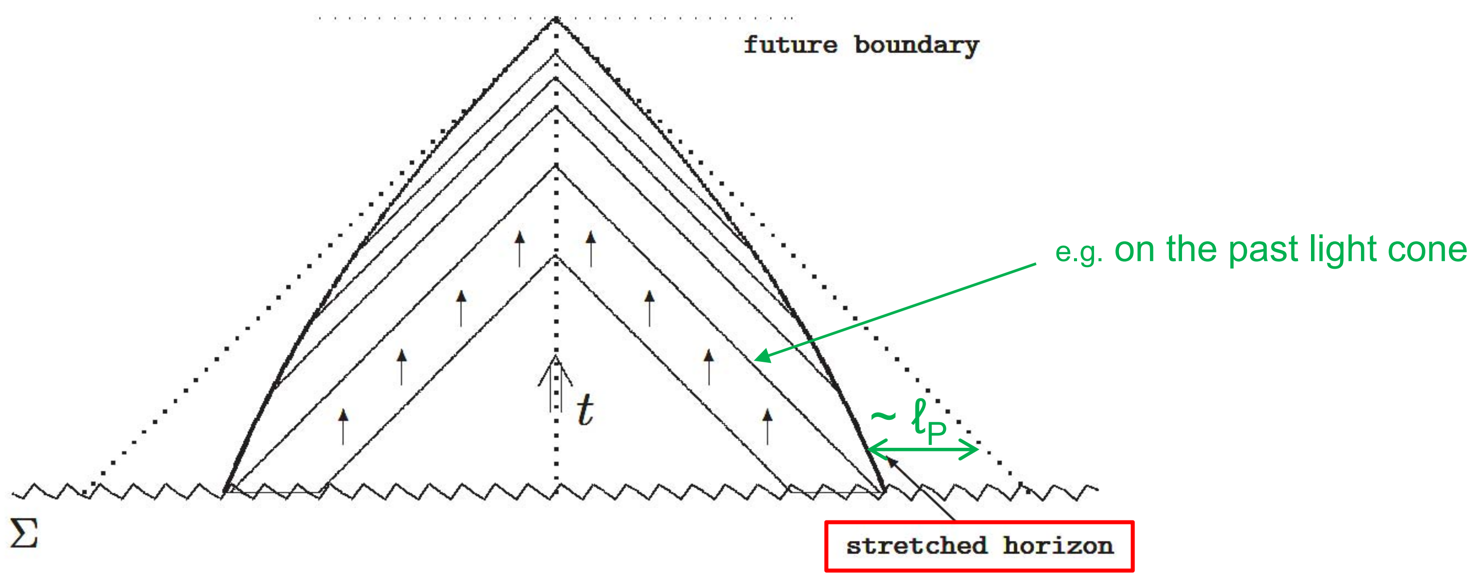
separating into subsystems, the basis for information amplification, …

Now, cosmology (eternal inflation)

… simply “inside-out” !

Including Gibbons-Hawking radiation, there is **no outside spacetime** !!

Specifically, the state can be defined to represent **only** the spatial region **in and on the stretched (apparent) horizons as viewed from** a freely falling reference frame. Y.N. (’11)



What is the multiverse? ⟶ probability !!

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

eternally inflating

each term representing only the region within the horizon

(temporarily taking time-evolution picture, which must arise effectively; see later)

- Probability in cosmology has the origin in quantum mechanics

  … (a suitable generalization of) the Born rule will give the probability

  Multiverse = Quantum many worlds

- Global spacetime is an emergent (and "redundant") concept

  … probability is more fundamental

  — counting observers (with equal weight) may vastly overcount d.o.f.

  $\rightarrow$ provides natural and effective "regularization"

$\Longrightarrow$ The multiverse lives in probability space!!

Fixing a reference frame

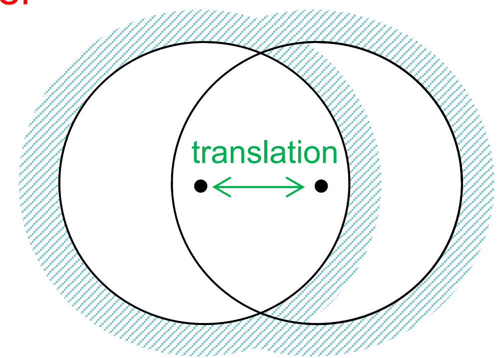
$\leftrightarrow$ eliminating / fixing a part of gauge redundancies in quantum gravity

There are residual ones:

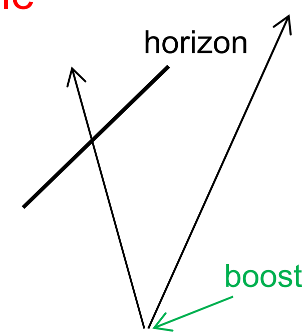
… Change of a reference frame (& time translation)

e.g.

de Sitter



Black hole



Spacetime $\leftrightarrow$ horizon d.o.f. !

This transf. $\underset{}{\overset{G_N \to 0}{\rightleftarrows}}$ Poincaré (Lorentz) transf. $\overset{c \to \infty}{\rightleftarrows}$ Galilei transf.

more "relativeness"

What to do with this residual gauge redundancy? … later

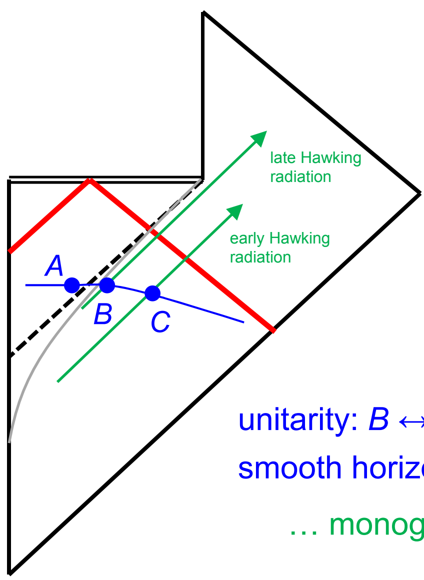
Obstacle for Complementarity?

Passed many consistency checks Hayden, Preskil ('07); Sekino, Susskind ('08); Y.N. ('11), …

but no explicit microscopic transformation laws

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

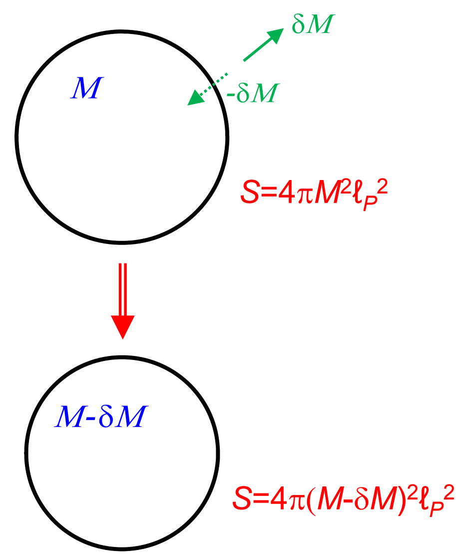
Problems can be formulated in a "single causal patch"



unitarity: $B \leftrightarrow C$

smooth horizon: $A \leftrightarrow B$

… monogamity of entanglement



… mismatch of Hilbert space dimensions

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

A Solution to the BH Information Problem

Y.N., Sanches, Weinberg, "Relativeness in quantum gravity: limitations and frame dependence of semiclassical descriptions," arXiv:1412.7538;
"The black hole interior in quantum gravity," arXiv:1412.7539

What is semiclassical theory?

… quantum theory of matter on an **exact** spacetime background

But the uncertainty principle says there is no such thing!

ex.) Dynamically formed black hole

Time scale of evolution (Hawking emission): $\Delta t \sim M$ (below we set $\ell_P = 1$)

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

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

The logarithm of this number: $S_0 = \dfrac{A}{4}$ (at the leading order in $1/A$)

… the origin of the Bekenstein-Hawking entropy

There are e^{S_0} black hole **vacuum** states, labeled by k

… general black hole states: $|\Psi_{ak}(M)\rangle$

Two important assumptions

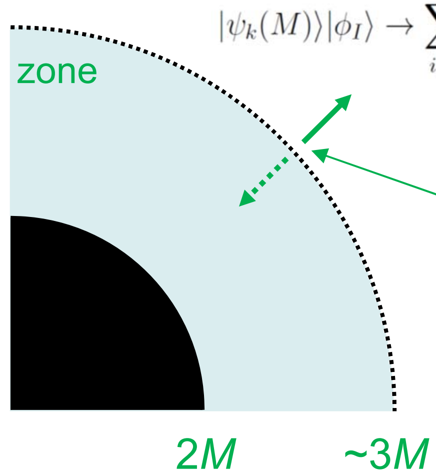
(motivated by the standard statistical interpretation of black hole thermodynamics)

- d.o.f. represented by *k*, which we call vacuum d.o.f., are course-grained **to obtain** the semiclassical theory
- These d.o.f. are viewed as distributed according to the thermal entropy calculated using the semiclassical theory

… BH information **delocalized** throughout the zone

The (correct) picture of Hawking emission:

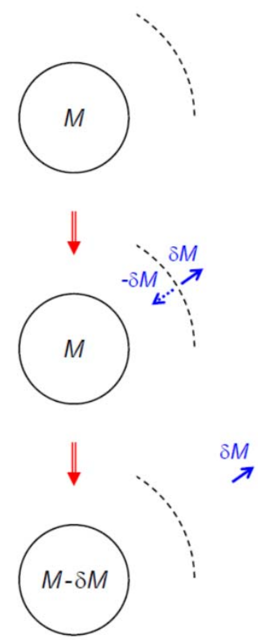
$$|\psi_k(M)\rangle|\phi_I\rangle \to \sum_{i,k_i} \alpha^k_{ik_i}|\psi_{k_i}(M-E_i)\rangle|\phi_{I+i}\rangle$$



occurs around the edge of the zone
(no outgoing Hawking quantum in the zone)

… early Hawking quantum entangled with *k*

(The monogamity argument does not apply.)



… Breakdown of semiclassical theory at **large** distances !!

Negative energy excitation carries a **negative** entropy

ex.) One q-bit of information release

negative energy excitation

$$|\psi_k(M)\rangle|\phi_0\rangle \to \begin{cases} |\psi_{a;\frac{k+1}{2}}(M)\rangle|\phi_1\rangle & \text{if } k \text{ is odd,} \\ |\psi_{a;\frac{k}{2}}(M)\rangle|\phi_2\rangle & \text{if } k \text{ is even,} \end{cases}$$

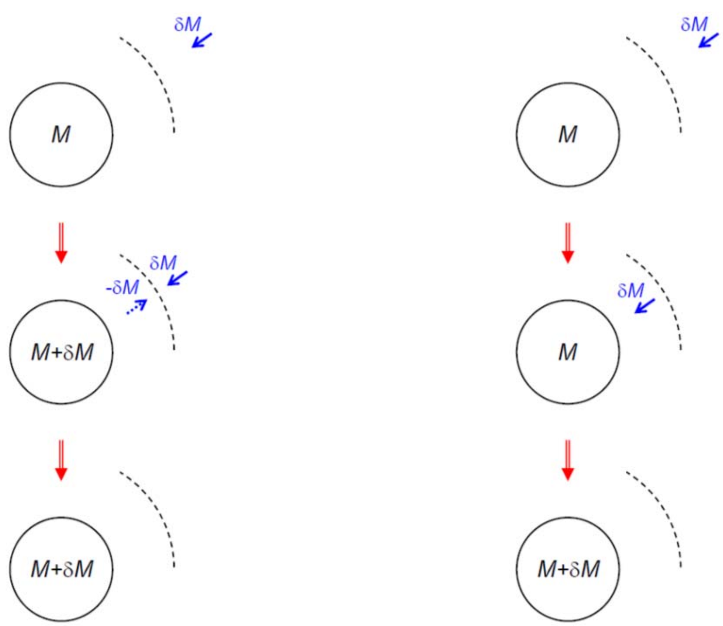
runs over 1,…, e^{S_0} runs over 1,…, $e^{S_0}/2$

The true Hilbert space is smaller than naïve Fock space in the semiclassical theory

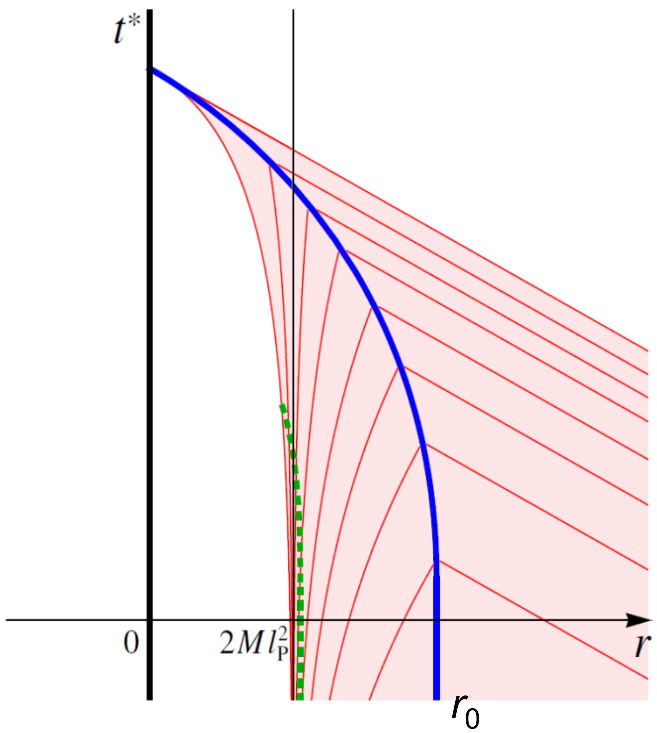
… Each of the emission & relaxation processes is separately (& locally) unitary

(no issue of Hilbert space dimensions)

cf.) Time reversal process vs generic incoming radiation



A successful reference frame change possible



A frame whose spatial origin
falls from a distance: $r_0 - 2M > O(M)$

… Space/time scale between
any “detector clicks” (even if blueshfited)
are ΔT ~ ΔX ~ $O(M)$ $\rightarrow$ approx. Minkowski

The **existence** of a reference frame in which the horizon region appears (approx.) Minkowski ensures that the horizon is smooth.

(consistently with unitarity of Hawking evaporation, BH mining, etc.)

… Satisfactory solution to the BH information problem without firewalls

The multiverse bootstrapped

Y.N., "The static quantum multiverse," PRD 86, 083505 ('12) [arXiv:1205.5550]

The picture so far:

Initial condition $|\Psi(t_0)\rangle$ $\xrightarrow[\text{dynamical evolution}]{}$ $|\Psi(t)\rangle \rightarrow$ Predictions

What is *the* "initial condition" *for the entire multiverse*?

The gauge fixing and the normalizability may be enough.

Time translation (as well as reference frame change) is gauge transformation

$\rightarrow$ Gauge conditions: $\mathcal{P}^{\mu}|\Psi(t)\rangle = \mathcal{J}^{\mu\nu}|\Psi(t)\rangle = 0$

$\Longrightarrow$ The multiverse *state* is static!

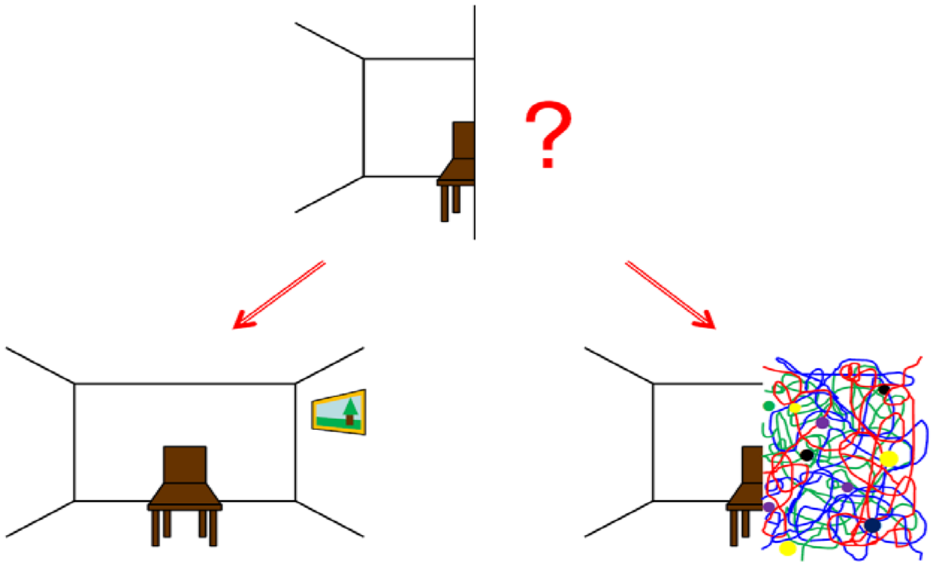
$$\boxed{H\,|\Psi(t)\rangle = 0 \quad \Leftrightarrow \quad \frac{d}{dt}|\Psi(t)\rangle = 0}$$

cf. Wheeler-DeWitt equation for a closed universe, but the system here is the "infinite" multiverse

- How does time evolution we observe arise?
- How can such a state be realized?

The arrow of time can emerge dynamically

The fact that we see time flowing in a definite direction
does **not** mean that $|\Psi>$ must depend on *t*



The dominance of extremely rare configurations (ordered ones; left) $\leftrightarrow$ time's arrow

… Correlation among physical subsystems

cf. DeWitt ('67)

Consistency conditions *on the form of H*:

J: vacuum that can support any observer

$$\frac{\langle\Psi|\,\mathcal{O}_{\mathrm{BB},J}\,|\Psi\rangle}{\langle\Psi|\,\mathcal{O}_{\mathrm{OO},J}\,|\Psi\rangle} \sim \frac{\Gamma_{\mathrm{BB},J}}{\epsilon_J \Gamma_J} \lll 1$$

The rate of producing "fluke" observers: Boltzmann brain (BB)

The probability of leading to ordinary observers

The vacuum decay rate

In |Ψ>, various "micro-processes" must balance

e^{iHt} is not diagonal in the Hilbert space basis in which locality is manifest

usual "time evolution"

$$|\Psi\rangle = \underbrace{|\quad\rangle + \cdots + |\quad\rangle}+ \cdots + \underbrace{\left|\begin{matrix}\text{slow-roll}\\ \text{inflation}\end{matrix}\right\rangle + |\text{big-bang}\rangle + |\text{galaxies}\rangle + \cdots}_{\text{our universe}} + \cdots + \underbrace{|\quad\rangle + \cdots + |\quad\rangle}$$

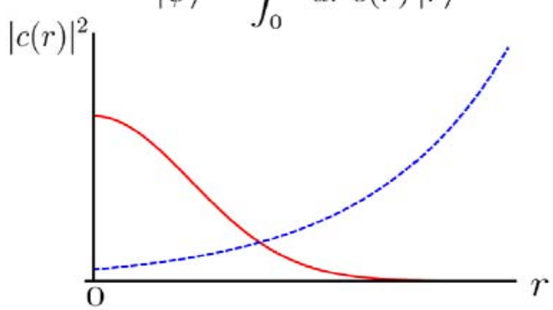
How to prevent "dissipation" into Minkowski/singularity worlds?

… processes *exponentially suppressed* at the semi-classical level

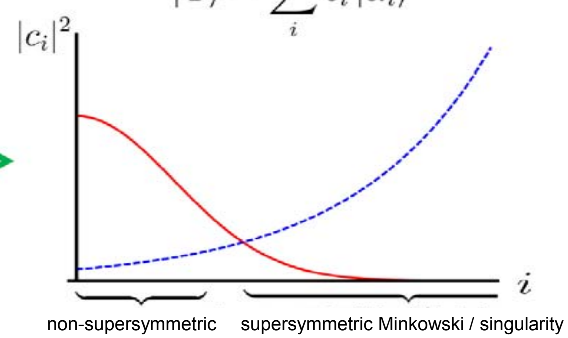
The normalizability may select the (possibly unique, non-ergodic) state

Analogy with the hydrogen atom:

$$|\psi\rangle = \int_0^\infty dr\, c(r)\, |r\rangle \qquad\qquad |\Psi\rangle = \sum_i c_i\, |\alpha_i\rangle$$



The hydrogen atom

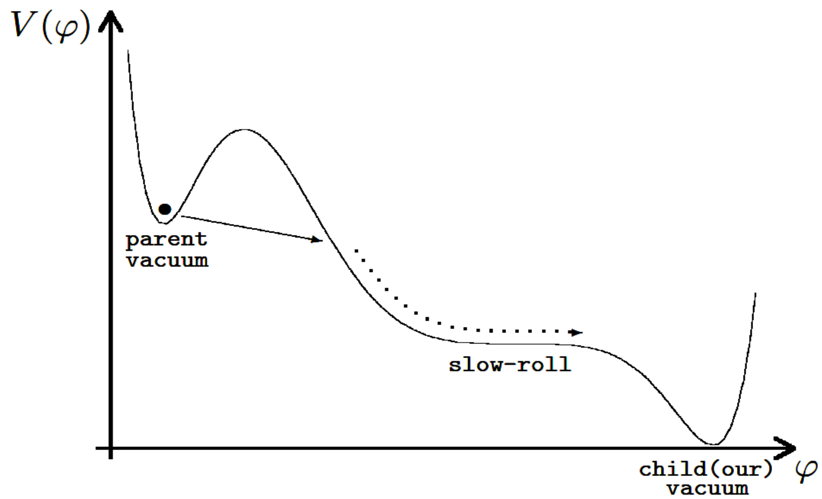


The quantum multiverse

- Quantum mechanics is crucial for the very *existence* of the system!
- Relevant Hilbert space is effectively *finite-dimensional* → normalized probability…

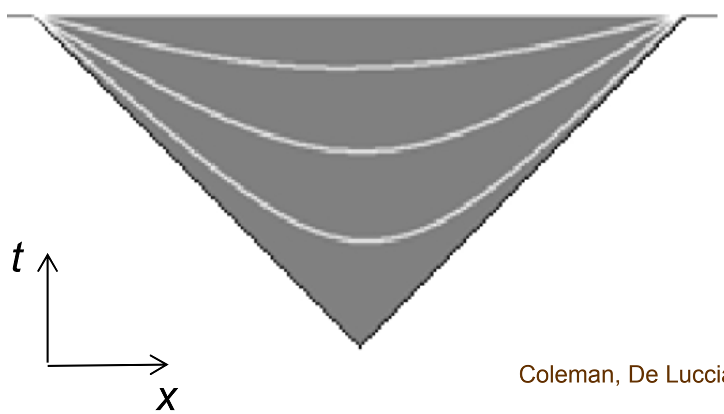
Relation to Observations?

Our universe is a bubble formed in a parent vacuum:



… Infinite **open** universe

(negative curvature)



Coleman, De Luccia ('80)

Why is our universe so flat?

If it is curved a bit more, no structure / observer $\rightarrow$ could be anthropic !

What is the "cheapest" way to realize the required flatness?

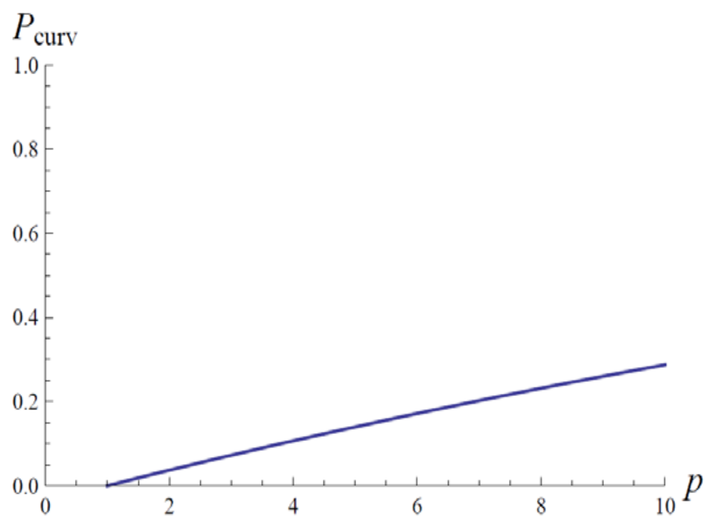
- Fine-tuning initial conditions
- Having a (accidentally) flat portion in the scalar potential

$\rightarrow$ (Observable) inflation

$\Longrightarrow$ The flatness will not be (much) beyond needed !

"difficulty" of realizing a flat potential

$f(N) \sim 1/N^p$



- $\Omega_{\rm curvature} > 0$ may be seen
- $\Omega_{\rm curvature} < 0$ will exclude the framework !

Freivogel, Kleban, Rodriguez Martinez, Susskind ('05)
….
Guth, Y.N. ('12)

Information on pre-inflationary history, probability measure, …

Summary and future directions

The multiverse seems "real"

— picture suggested both from observation and theory

It raises a challenge of making (top-down) predictions for
why we live in the universe we observe

(the structure of low-energy Lagrangians, values of cosmological parameters, etc.)

The "infinitely large" multiverse $\rightarrow$ How to define probabilities?

Quantum mechanics + Gauge invariance of quantum gravity

Multiverse = Quantum Many Worlds

The multiverse lives (only) in probability space

… a new viewpoint for the global spacetime

… provides a framework to address further questions

(the origin / "beginning" of the multiverse, what is time, …)

Emergent spacetime from quantum gravity

Bekenstein-Hawking entropy counts microscopic d.o.f. that play
dual roles of “constituents” of spacetime and thermal radiation

— information delocalized quantum mechanically within the “zone”

— unexpected breakdown of semiclassical theory at **large** distances

→ satisfactory solution to the BH information problem without firewalls

Future Prospects?

Relation to observation

- Further signals supporting the multiverse Cosmic bubble collisions; suppression of low ℓ modes; …
- Implications for physics beyond the standard model

cf. Arkani-Hamed, Dimopoulos; Hall, Y.N.; Giudice, Rattazzi; …

Subtlety in conditioning

Need a suitable extension of the Born rule … in “space*time*”, must involve operators e.g. H

… separation into subsystems, extracting suitable correlations,
what’s the observation, information processing?, …

… may have to be done in an (effectively) finite-dimensional Hilbert space

cf. Page; Y.N.; Bousso, Susskind; Aguirre, Tegmark, Layzer; Carroll, Sebens; …