The Quantum 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
- …

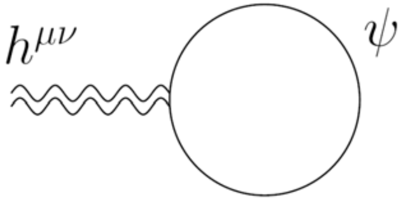
… implications on particle physics and cosmology

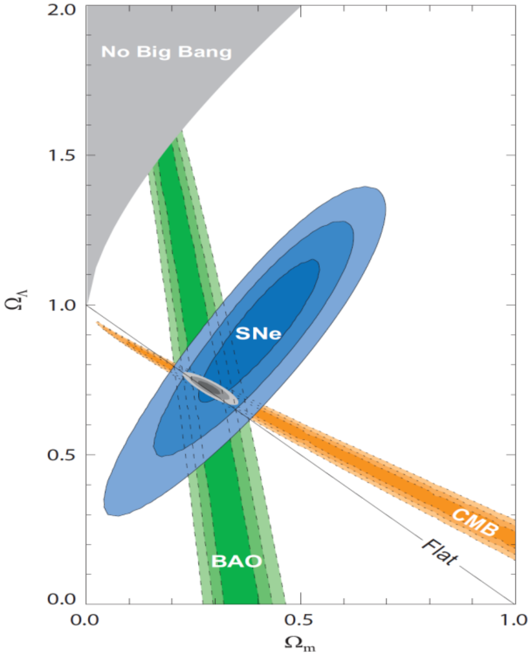
Shocking news in 1998

Supernova cosmology project; Supernova search team

Universe is accelerating!

$$\Lambda \neq 0 \ !$$





Particle Data Group (2010)

… natural size of $\rho_\Lambda \equiv \Lambda^2 M_{Pl}^2$ (naively) ~ M_{Pl}^4 (at the very least ~ TeV^4)

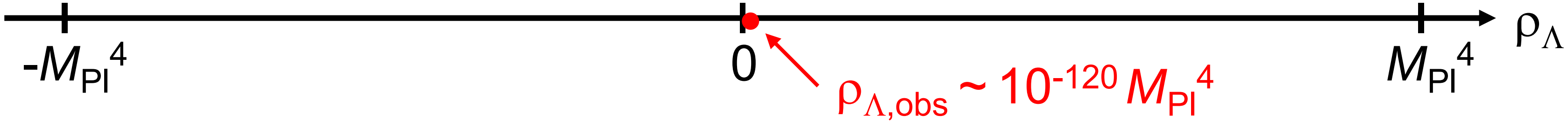
Observationally,

$\rho_\Lambda \sim (10^{-3}\ \mathrm{eV})^4$ Naïve estimates $O(10^{120})$ too large

Also, $\rho_\Lambda \sim \rho_{\mathrm{matter}}$ — Why now?

Nonzero value completely changes the view !

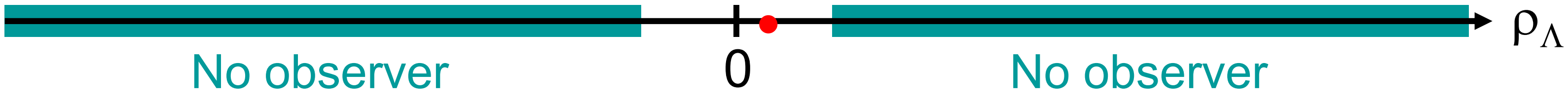
Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$



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)

Many universes — multiverse — needed

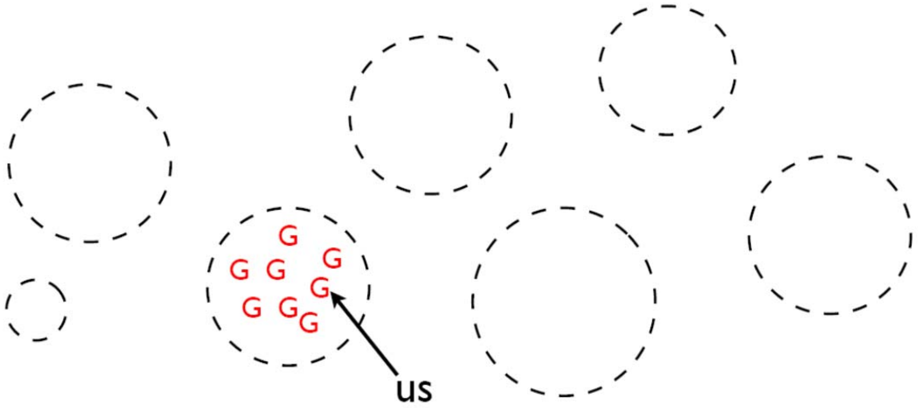
- String landscape

Compact (six) dimensions
→ huge number of vacua

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

- Eternal inflation

Inflation is (generically) future eternal → populate all the vacua



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

Full of "miracles"

Examples:

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

  … otherwise, no nuclear physics or chemistry

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

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

….

Some of them anthropic (and some may not)

$\Longrightarrow$ Implications?

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

Full of “miracles”

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- Observational / experimental (test, new scenarios, …)
- $\Longrightarrow$ • Fundamental physics (spacetime, gravity, …)

Implications on fundamental physics

– the multiverse as quantum many worlds –

Y.N., "Physical Theories, Eternal Inflation, and the Quantum Universe," JHEP **11**, 063 (2011) [arXiv:1104.2324];
"Quantum Mechanics, Spacetime Locality, and Gravity," arXiv:1110.4630;
"The Static Quantum Multiverse," arXiv:1205.5550.

For a review, "Quantum Mechanics, Gravity, and the Multiverse," AstRv. **7**, 36 (2012) [arXiv:1205.2675].

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

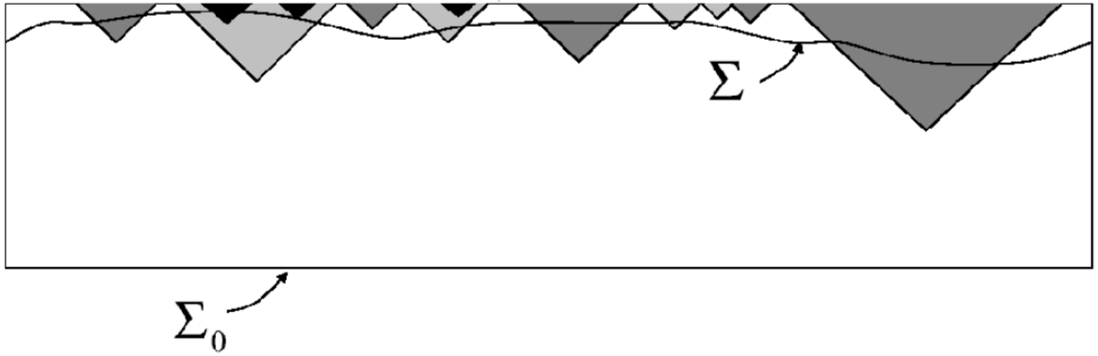
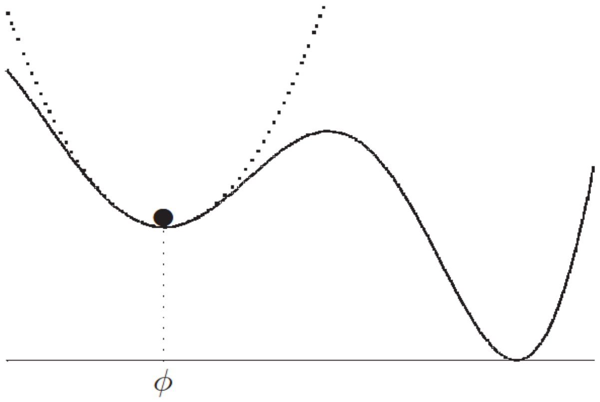


figure from Vilenkin ('06)

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

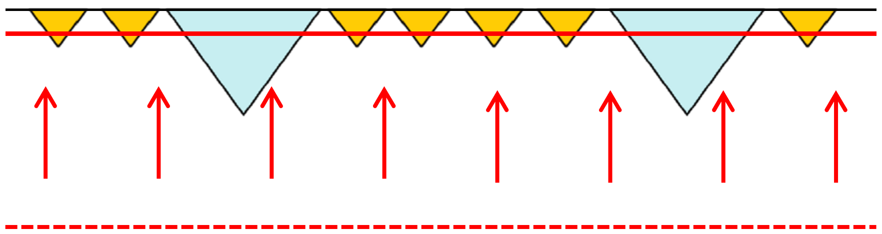
- The problem is robust



A metastable minimum
with $\rho \ll M_{Pl}^4$ is enough !

… *a priori*, has nothing to do with quantum gravity,
string landscape, beginning of spacetime, …

- The most naïve does NOT work !



Synchrinous (proper) time cutoff measure

Linde, Mezhlumian ('93)

$V \sim e^{3Ht}$

… vastly more younger universes
than older ones

$$\frac{N_{T_{\rm CMB}=3{\rm K}}}{N_{T_{\rm CMB}=2.725{\rm K}}} \sim 10^{10^{59}} \text{ !!}$$

… Youngness paradox

Guth ('00); Tegmark ('04)

Something seems terribly wrong …

Multiverse as a Quantum Mechanical Universe

Y.N. (2011)

Quantum mechanics is **crucial**

The basic principle:

The laws of quantum mechanics are not violated
when an appropriate description of physics is adopted

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: $\Psi(t=t_0) = |\Sigma\rangle \quad \rightarrow \quad \Psi(t) = \sum_i c_i \,|\text{cosmic history } i \text{ at time } t\rangle$

eternally inflating

This by itself does **not** solve any of the problem

… What is the "state" (arbitrariness), an infinite # of events, …

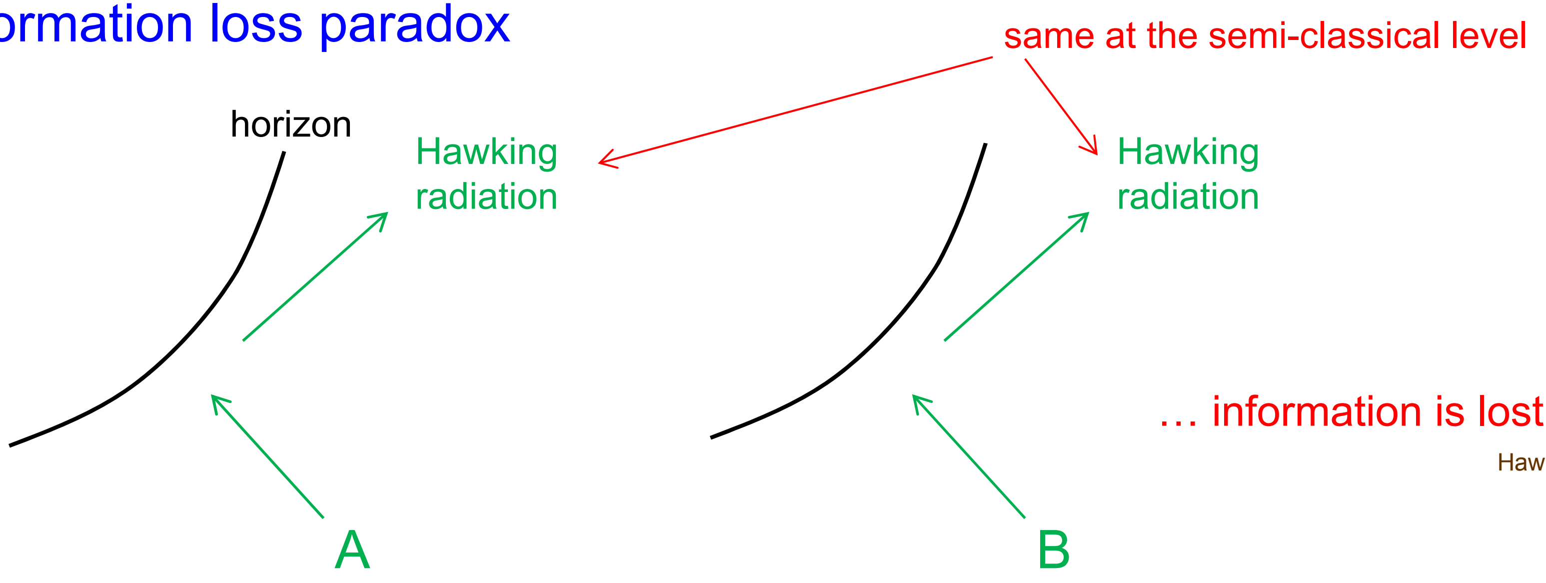
Quantum mechanics in gravitational systems

$\Longrightarrow$ Dramatic change of our view of spacetime

Quantum Mechanics in a System with Gravity

Black Hole

Information loss paradox



… information is lost ??

Hawking ('76)

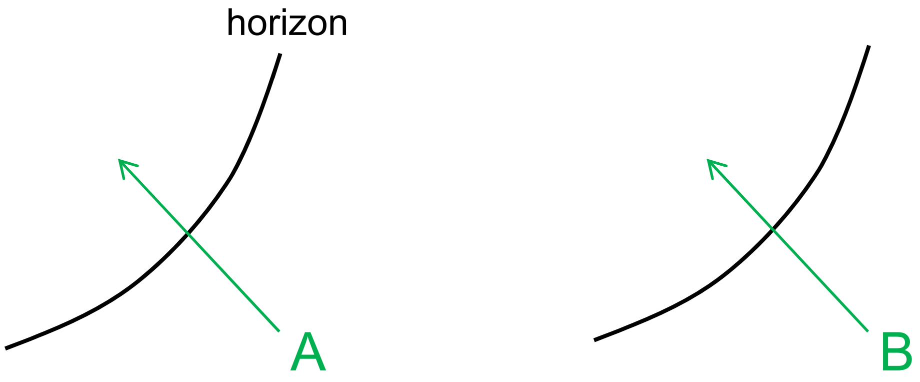
⟹ No

… Quantum mechanically different final states

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

cf. AdS/CFT, 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)

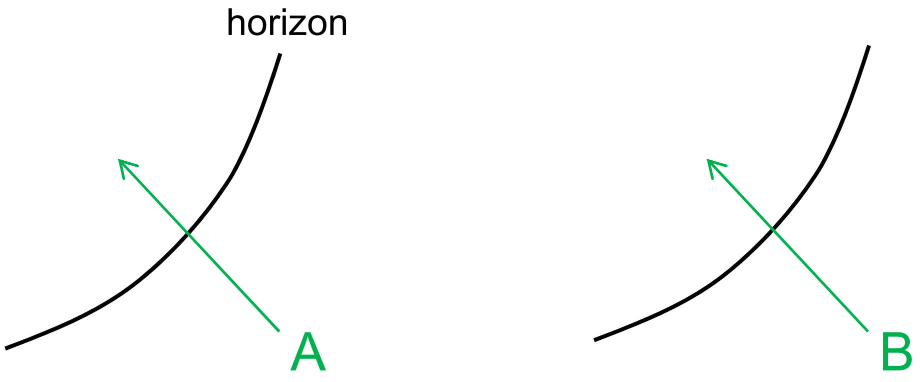
$|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$

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

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

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

From a falling observer's viewpoint:



… 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 !**

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

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

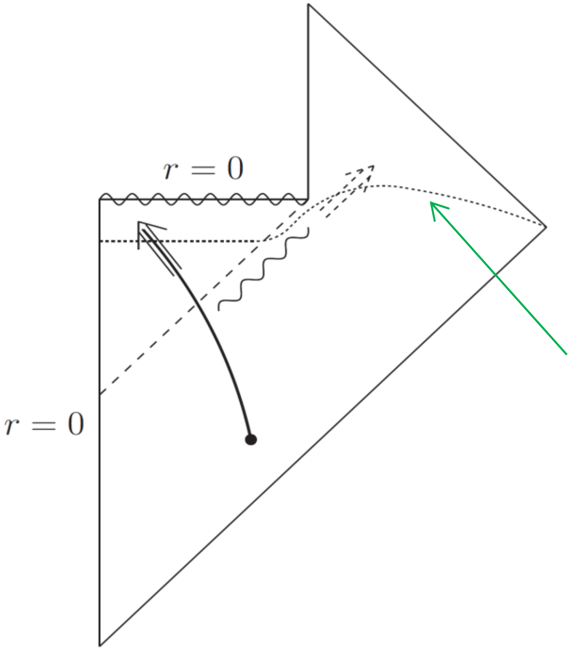
The two statements cannot be compared *in principle*.

(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 inside spacetime is **overcounting** !!



“nice” (wrong) hypersurface

… Equal time hypersurface
must be chosen carefully.

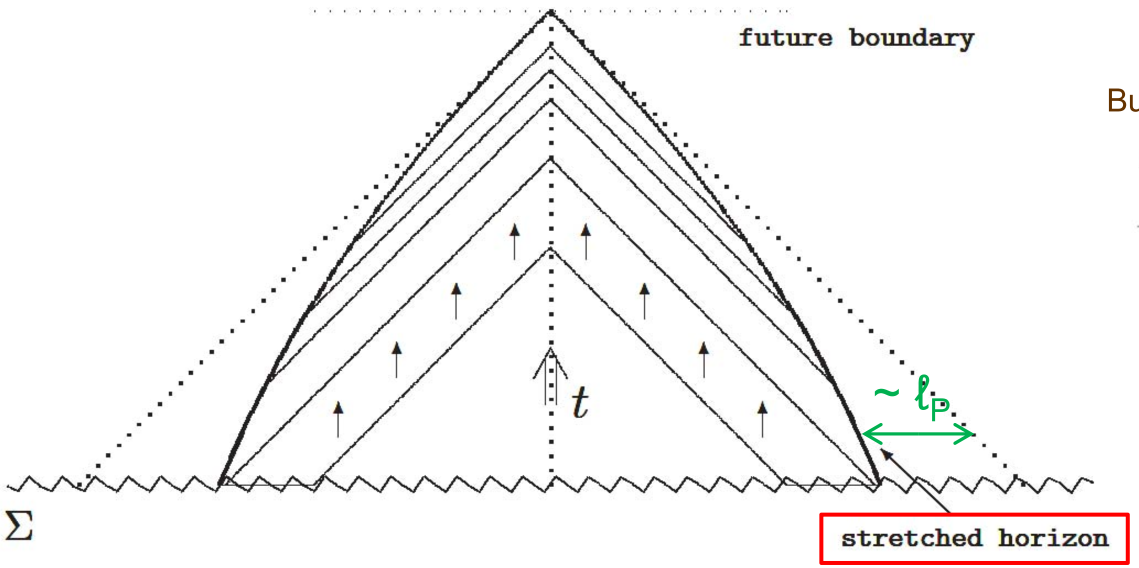
Now, eternal inflation

… simply "inside-out" !

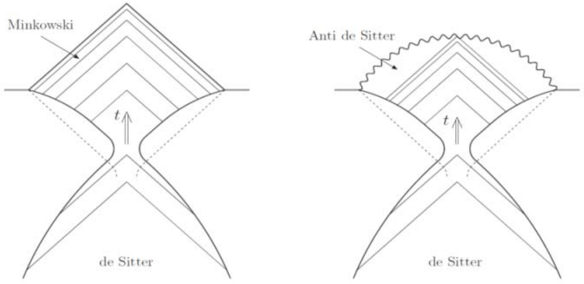
Including Gibbons-Hawking radiation, there is **no outside spacetime** !!

Specifically, the state is defined on the observer's past light cones **bounded by the (stretched) apparent horizons**.

Y.N. ('11)

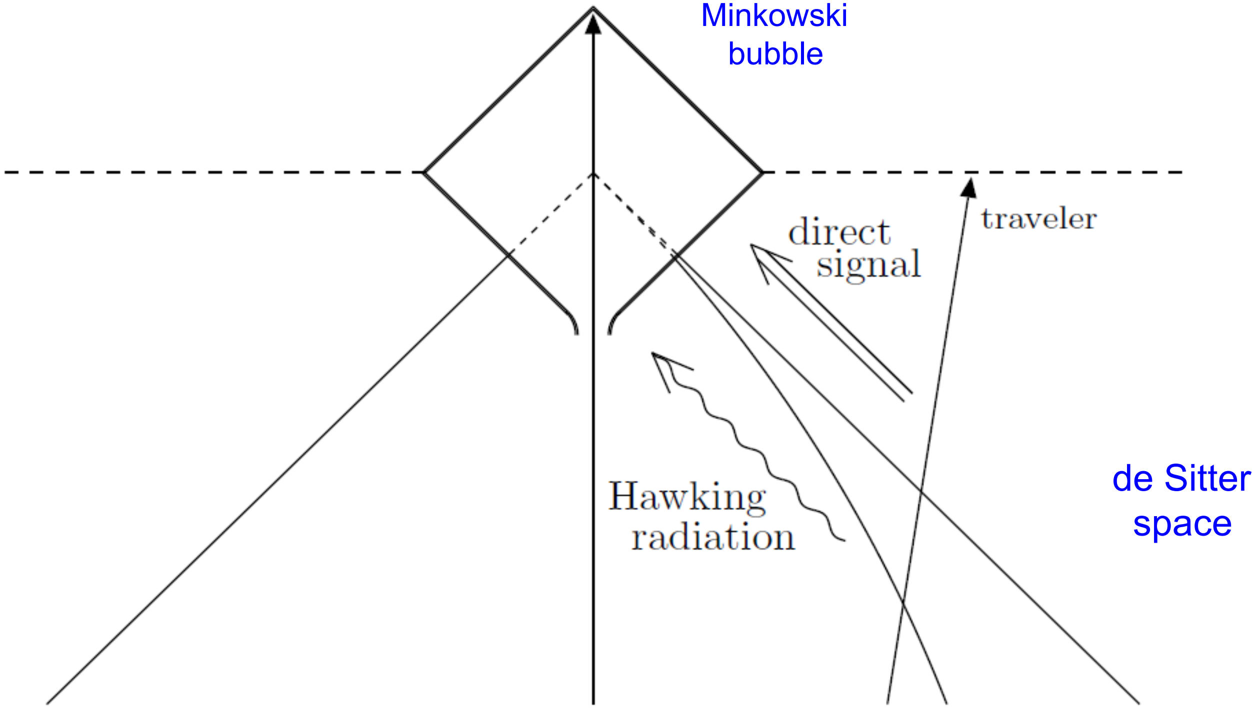


Bubble nucleation:



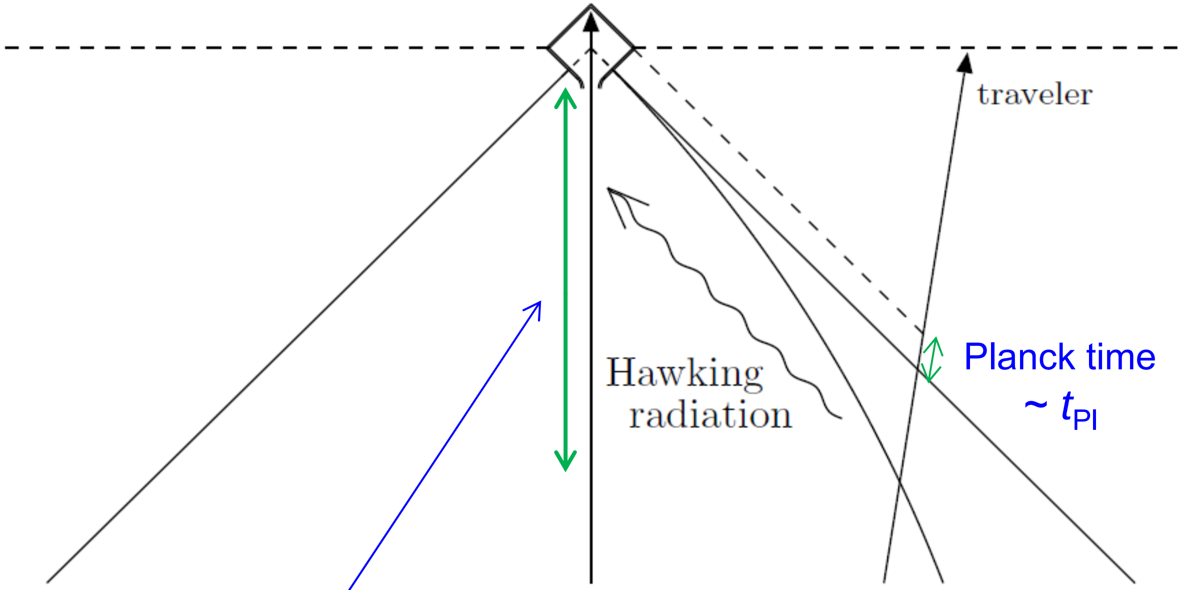
What is the multiverse? ⟹ probability !!

Consistent?



Doesn’t information duplicate?

Consistent? — Yes



Planck time
~ t_{Pl}

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*.

How to formulate all these?

The quantum state

— defined on the past light cone **in** and **on** the stretched horizon

Hilbert space for dynamical spacetime

For a fixed background $\mathcal{M}$

$$\mathcal{H}_{\mathcal{M}} = \mathcal{H}_{\mathcal{M},\text{bulk}} \otimes \mathcal{H}_{\mathcal{M},\text{horizon}}$$

← too semi-classical ?

$$\left[\ \dim \mathcal{H}_{\mathcal{M},\text{bulk}} = \dim \mathcal{H}_{\mathcal{M},\text{horizon}} = \exp\left(\frac{\mathcal{A}_{\partial\mathcal{M}}}{4l_P^2}\right)\ \right]$$

Full Hilbert space

Fock space

n particle states

$$\mathcal{H} = \bigoplus_{\mathcal{M}} \mathcal{H}_{\mathcal{M}} \quad \underset{\text{analogy}}{\longleftrightarrow} \quad \mathcal{H} = \bigoplus_{n} \mathcal{H}_{n}$$

$$\Psi(t=t_0) = |\Sigma\rangle \quad \to \quad \Psi(t) = \sum_i c_i(t)\,|(\text{cosmic})\ \text{configuration}\ i\rangle$$

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

A state evolves deterministically and unitarily

Horizon viewed from who?

— What we are doing is to fix **a reference frame** (the origin of the coordinates)

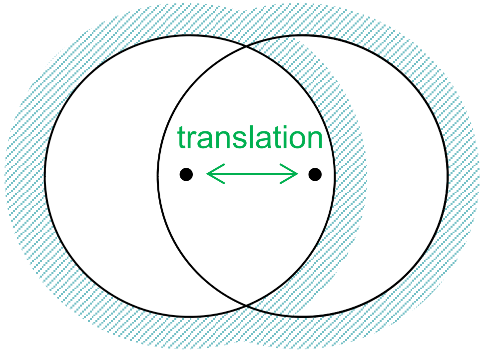
Why?

Hamiltonian quantum mechanics

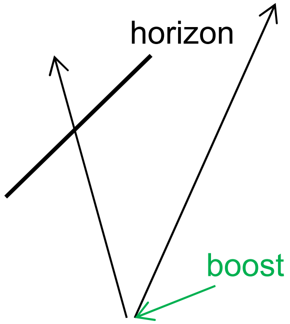
→ gauge fixing → gauge = coordinate transformation

Change of a reference frame

de Sitter



Black hole



observer dependence of horizon

complementarity

unified understanding

Spacetime ↔ horizon d.o.f. !!

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

more “relativeness”

Probability

$$\boxed{P(B|A) = \frac{\int dt \, \langle \Psi(t) | \, \mathcal{O}_{A \cap B} \, | \Psi(t) \rangle}{\int dt \, \langle \Psi(t) | \, \mathcal{O}_{A} \, | \Psi(t) \rangle}}$$

$$|\Psi(t)\rangle = \sum_i c_i(t) \, |\alpha_i\rangle$$

$$\mathcal{O}_A = \sum_i |\alpha_{A,i}\rangle \langle \alpha_{A,i}|$$

- well-defined (finite)
- no problem associated with geometric cutoff

The measure problem is solved.

… (extended) Born rule

For *B*, a question about

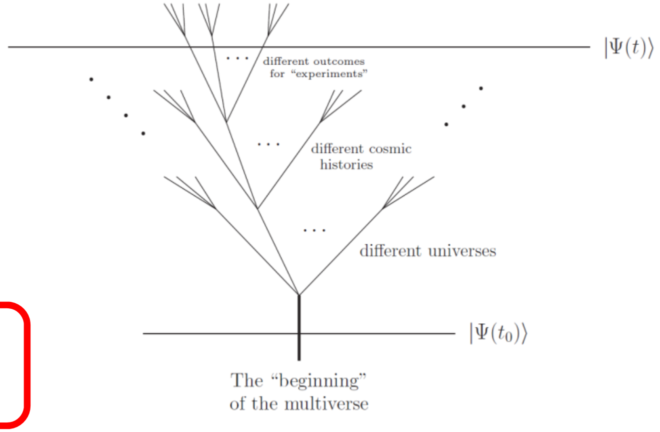
global properties → Multiverse

e.g. cosmological constant, e^- mass, …

local properties → Quantum many worlds

e.g. result of a particular experiment, …

Multiverse = Quantum many worlds



Quantum measurement

— *Dynamical* process:

$$|\Sigma\rangle \;\to\; |A\rangle + |B\rangle \;\to\; |aa\rangle + |bb\rangle + |cc\rangle + |dd\rangle \;\to\; |\alpha\alpha\cdots\alpha\rangle + |\beta\beta\cdots\beta\rangle + \cdots$$

involving

- branching

$$|e^+e^-\rangle \;\to\; |e^+e^-\rangle + |\mu^+\mu^-\rangle + \cdots + |e^+e^-e^+e^-\rangle + \cdots \;\to\; \cdots$$

… many worlds / multiverse

and

- amplification

$|\uparrow\rangle \;\to\; |\uparrow\rangle\,|\textcircled{\uparrow}\rangle \;\to\; |\uparrow\rangle\,|\textcircled{\uparrow}\rangle\,|$  $\rangle \;\to\; \cdots$

… basis selection

A state branches into separate, decohered worlds

$\Longrightarrow$ The origin of classical objectivity

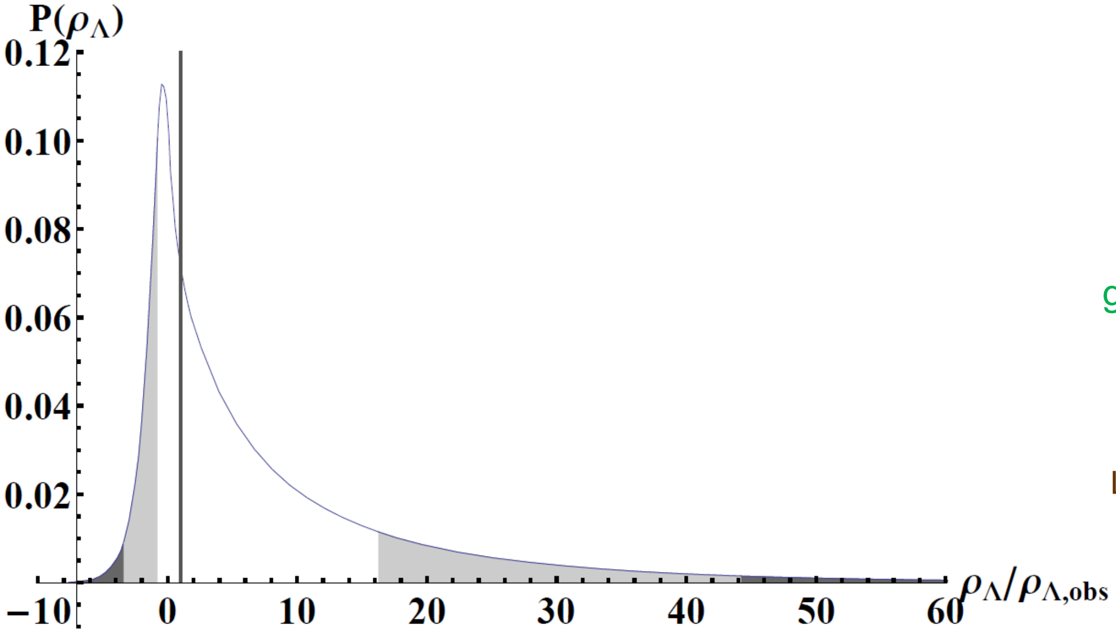
cf. Quantum Darwinism: Ollivier Poulin, Zurek (‘03); Blume-Kohout, Zurek (‘05)

Predictions?

The cosmological constant

… likely to be insensitive to the initial condition cf. Weinberg ('87)

The distribution is calculated by the dynamics within "our universes" alone



galaxy formation
+ metalicity

Larsen, Y.N., Roberts, arXiv:1107.3556

In contrast with earlier "measures" (which typically prefer $\Lambda < 0$ with > 99.9% probability)

the positive vacuum energy is preferred, consistent with observation!

The Static Quantum Multiverse

Y.N. (2012)

The framework developed so far allows

$$\text{Initial condition } |\Psi(t_0)\rangle \xrightarrow[\text{dynamics: “Hamiltonian”}]{} \text{Predictions}$$

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

One idea — physical theory only allows for relating $|\Psi(t_1)>$ to $|\Psi(t_2)>$

as in Newtonian mechanics & (usual formulation of) quantum mechanics

→ Problems:

- Quantum mechanics does not allow us to observationally determine $|\Psi(t_0)>$, *which includes ourselves.*

(Also, practically, $|\Psi(t)>$ contains terms that represent semi-classically different universes.)

$\Longrightarrow$ need *theoretical* input for the “boundary condition,” *e.g.* initial condition $|\Psi(0)>$

The beginning of the multiverse?

$\Longrightarrow$ violation of quantum mechanics (unitarity) at the initial moment…

Related discussions: Mithani, Vilenkin (‘12);
Susskind (‘12)

What is the right condition to select the state?

Physical predictions do not depend on
the reference frame one chooses to describe the multiverse

(↔ There is no center or absolute rest frame in the multiverse.)

reference frame change

The states $|\Psi>$ and $U|\Psi>$ lead to the same predictions

→ $|\Psi>$ must be eigenstates of P_i (translations) and K_i (boosts).

⇓ Poincaré algebra

$|\Psi>$ must be a simultaneous eigenstate of $J_{[ij]}$, Pi, Ki, and H

with eigenvalue zero: $J_{[ij]}\,|\Psi\rangle = K_i\,|\Psi\rangle = P_i\,|\Psi\rangle = H\,|\Psi\rangle = 0$

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

probability:

$$P(B|A) = \frac{\langle\Psi|\,\mathcal{O}_{A\cap B}\,|\Psi\rangle}{\langle\Psi|\,\mathcal{O}_{A}\,|\Psi\rangle}$$

… The multiverse state must be static !

cf. What we are really doing:

previous picture: (only) constraints corresponding to the local (x^μ-dep.) coordinate transformations

static picture here: also constraints on the coordinate transformations ↔ assumption about the “boundary” (horizons)

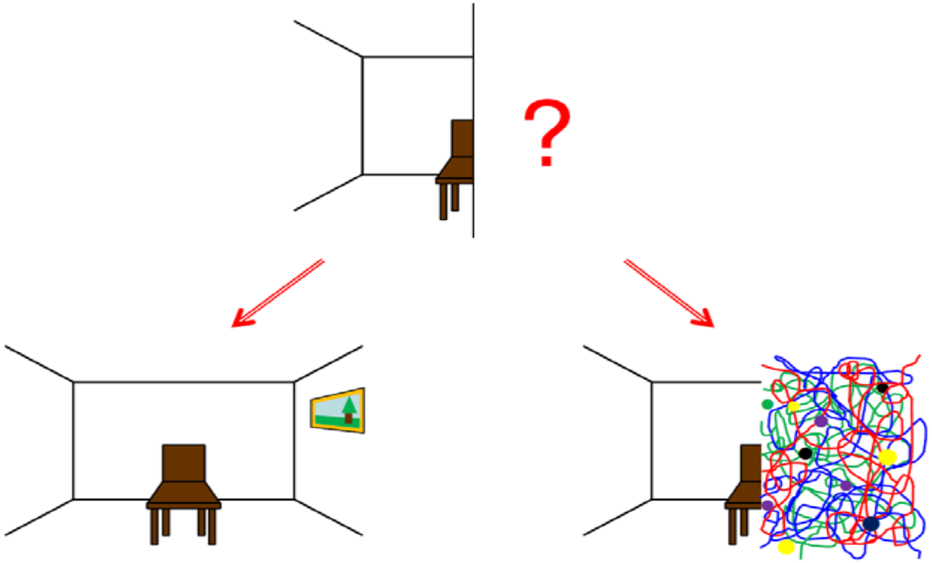
cf. Wheeler-DeWitt equation for a closed universe

Consistent?

The arrow of time

The fact that we see time flows in a definite direction

does **not** mean that |Ψ> must depend on *t*



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

Consistency conditions *on the form of H*:

J: vacuum that can
support any observer

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

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

The probability of leading to
ordinary observers

The vacuum decay rate

How does this avoid the “beginning”?

The (normalized) static state |Ψ>:

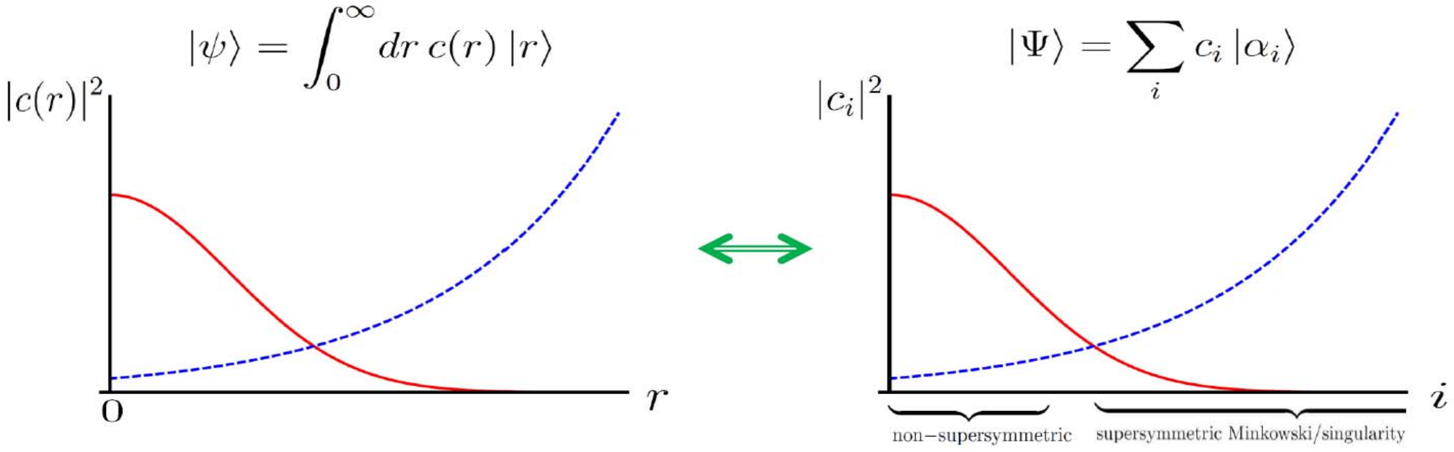
… the state in which various “micro-processes” balance

What are the processes that can put the system back from a Minkowski vacuum?

… processes that are *exponentially suppressed* in the usual semi-classical analysis

⟶ cannot see in the semi-classical considerations of the multiverse

Analogy with the hydrogen atom:



The hydrogen atom

The quantum multiverse

… Quantum mechanics is crucial even for the very existence of the system !

Summary

The revolutionary change of our view in the 21st century

Our universe is a part of the multiverse

(cosmological constant, string landscape, …)

Quantum mechanics + General relativity

→ surprising, quantum nature of spacetime and gravity

(black hole physics, eternal inflation, …)

Wide range of implications

cosmology, particle physics, (philosophy), …

Further experimental / theoretical support desired

ex. spatial curvature, multi-component dark matter (e.g. axion + WIMP), …