Quantum Mechanics, Gravity, and 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

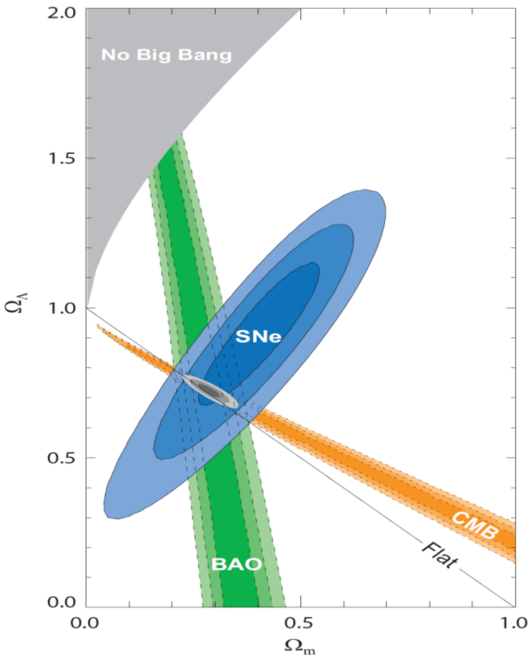
- Holographic principle
- Horizon complementarity
- Multiverse as quantum many worlds
- …

… implications on particle physics and cosmology

Shocking news in 1998

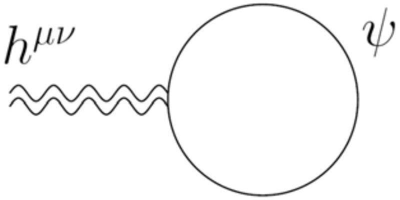
Supernova cosmology project; Supernova search team

Universe is accelerating!



Particle Data Group (2010)

$$\Lambda \neq 0 \; !$$



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

Observationally,

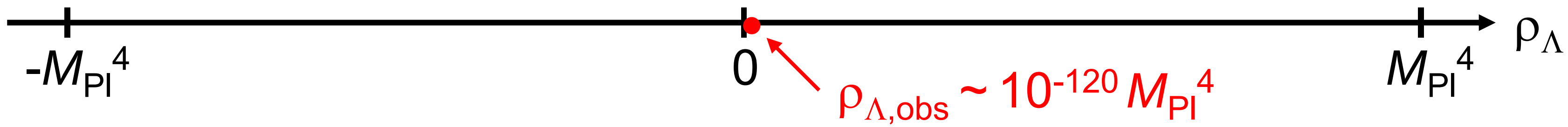
$$\rho_\Lambda \sim (10^{-3}\ \mathrm{eV})^4$$

Naïve estimates $O(10^{120})$ too large

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

Nonzero value completely changes the view !

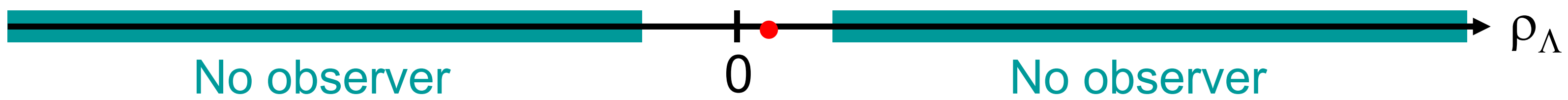
Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$



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) dimensins

$\rightarrow$ huge number of vacua

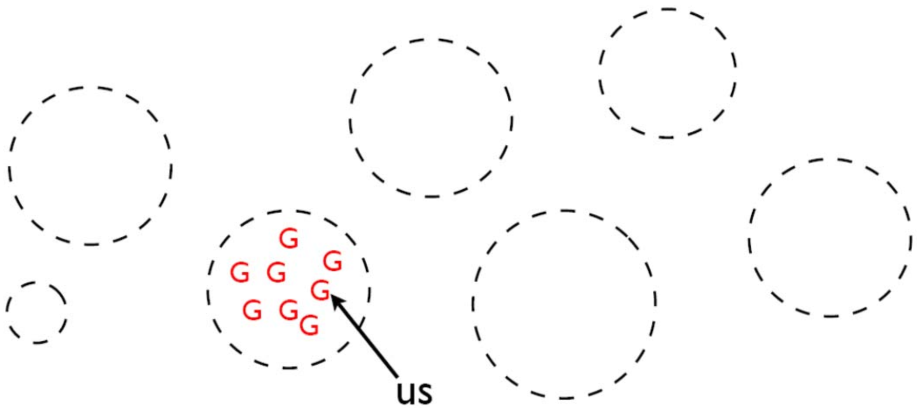
ex. $O(100)$ fields with $O(10)$ minima each

$\rightarrow O(10^{100})$ vacua

- Eternal inflation

Inflation is (generically) future eternal

$\rightarrow$ populate all the vacua



$\Longrightarrow$ Anthropic considerations **mandatory** (not an option)

Full of "miracles"

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: $P \ll 10^{-3}$

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

….

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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- Fundamental physics (spacetime, gravity, …) $\Longleftarrow$

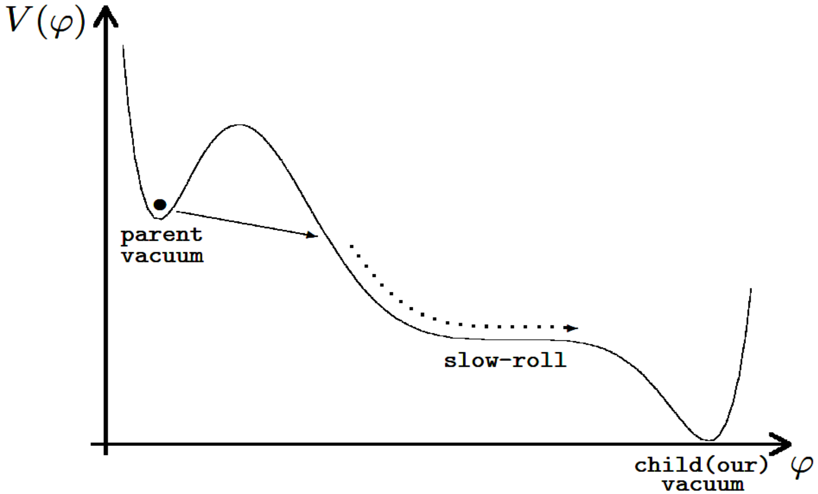
Implications

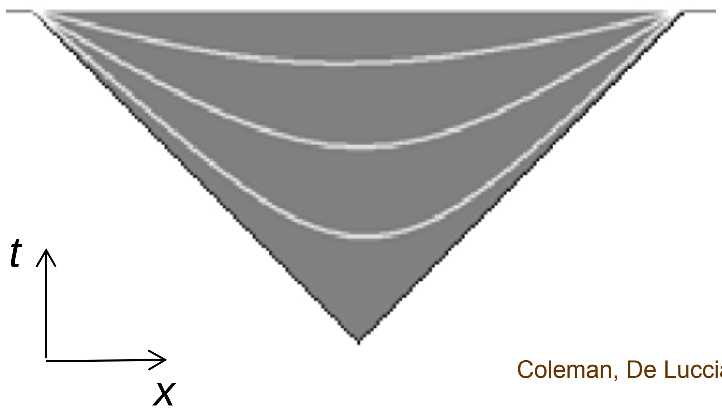
—observation / experiment —

... new ways of thinking physics

Cosmology

Our universe is a bubble formed in a parent vacuum:





Coleman, De Luccia ('80)

… Infinite **open** universe

(negative curvature)

Why is our universe so flat?

If it is curved a bit more, no structure / observer

$\rightarrow$ anthropic !

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

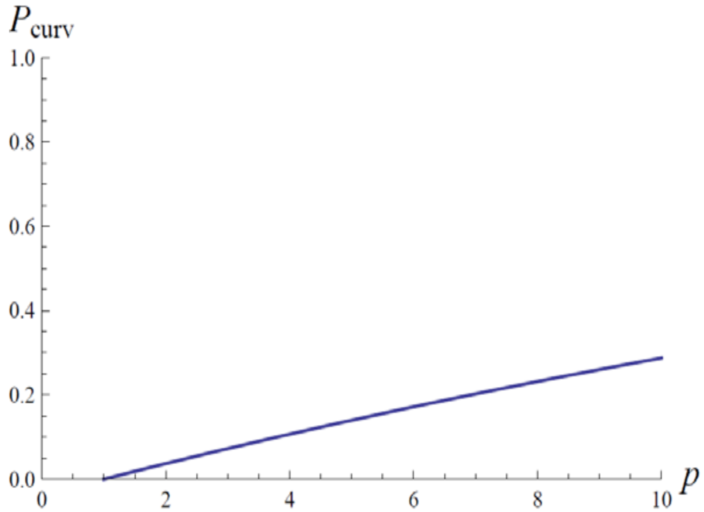
- Fine-tuning initial conditions
- Having a (accidentally) flat portion in the scalar potential

$\rightarrow$ (Observable) inflation

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

"difficulty" of realizing a flat potential

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



$\Omega_{\text{curvature}} > 0$ may be seen

Freivogel, Kleban, Rodriguez Martinez, Susskind ('05)

….

Guth, Y.N.

Particle Physics

Anthropic (could) affects how our universe looks

$\longrightarrow$ Any change in our thinking?

Weak scale *does* affect environment Agrawal, Barr, Donoghue, Seckel ('97)

ex. Stability of complex nuclei

For fixed Yukawa couplings,

no complex nuclei for $v > 2\, v_{\rm obs}$ Damour, Donoghue ('07)

Possible that $v_{\rm obs}$ arises as a result of environmental selection

Weak scale supersymmetry really "needed"?

No … the scale of SUSY masses determined by statistics

$$\boxed{d\mathscr{N} \sim f(\tilde{m})\, \frac{v^2}{\tilde{m}^2}\, d\tilde{m}}$$

$f(\tilde{m}) \sim \tilde{m}^{p-1}$

For $p < 2$, weak scale SUSY results,
but for $p > 2$, $\tilde{m}$ prefers to be large

Can anthropic explain *everything*?

$\Longrightarrow$ **No !**

ex. Strong CP problem in QCD

θ_{QCD} already way too small $(< 10^{-10})$

… mechanism needed $\rightarrow$ "axion"

(more "robust" problem than the hierarchy problem)

Implication for Dark Matter (DM)

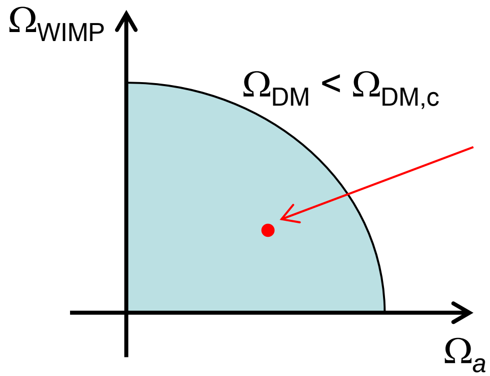
$f_a \sim M_{GUT}$ $\rightarrow$ overabundant $\rightarrow$ fine with $\theta_{init} \ll 1$

… forced by $\Omega_{DM} < \Omega_{DM,c}$

DM already present! $\rightarrow$ no "need" for WIMP

WIMP?

— possible



$\Longrightarrow$ Multi-component DM !

Implications

— fundamental physics —

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

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

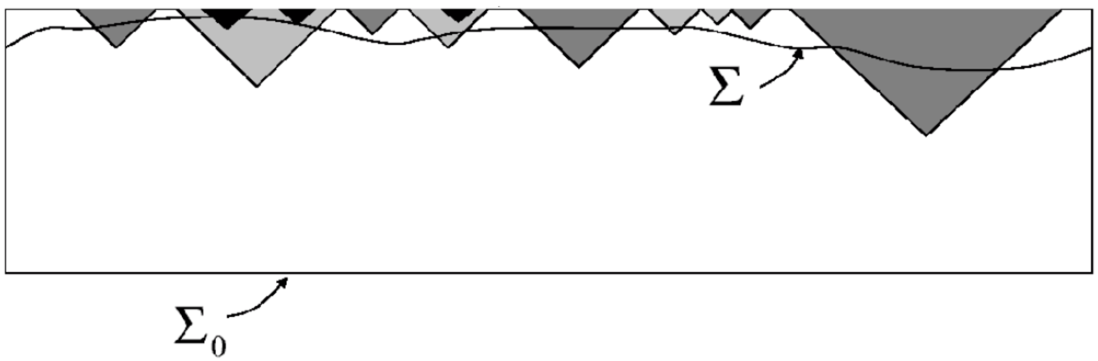
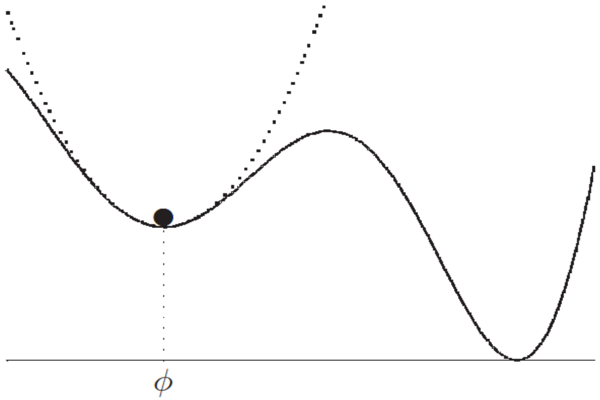


figure from Vilenkin ('06)

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

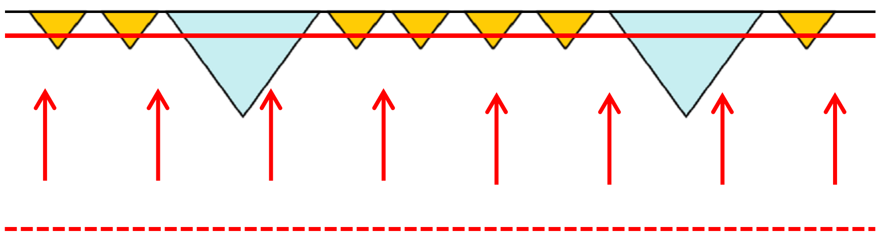
• The problem is robust



A metastable minimum
with $\rho \ll M_{\mathrm{Pl}}^4$ 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

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

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

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

eternally inflating

This by itself does not solve any of the problem

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

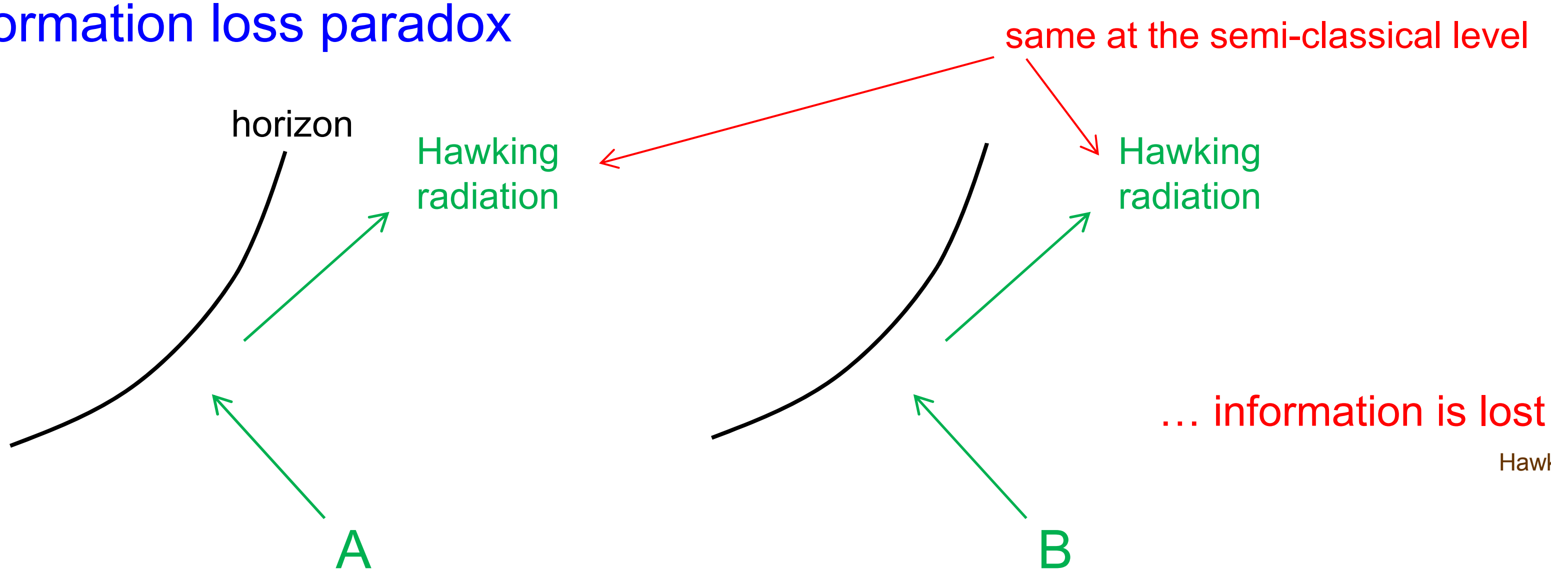
Quantum mechanics in gravitational systems

$\Longrightarrow$ Dramatic change of our view on spacetime

Quantum Mechanics in a System with Gravity

Black Hole

Information loss paradox



… information is lost ??

Hawking ('76)

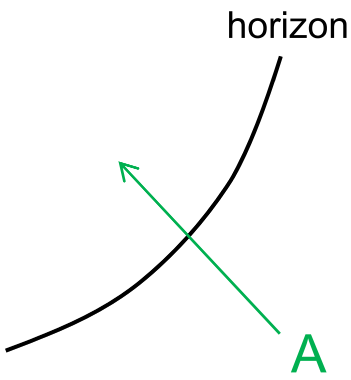
$\Longrightarrow$ No

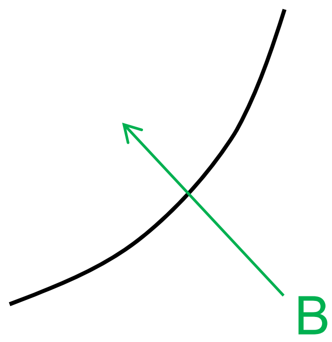
… Quantum mechanically different final states

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.

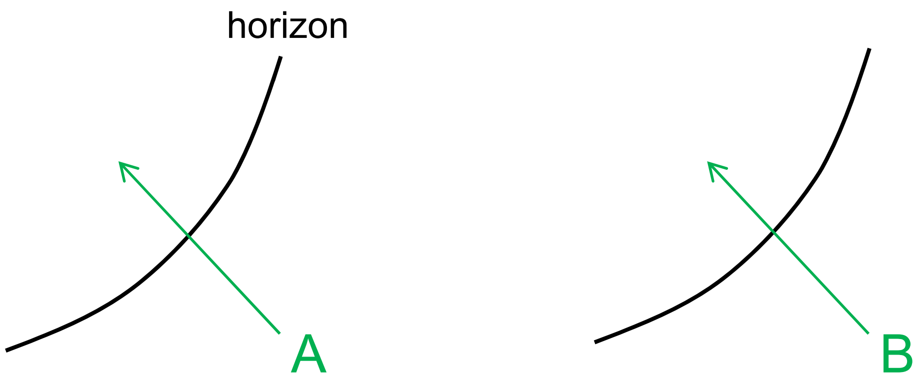
  (carried with him/her)

Which is correct?

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

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

From a falling observer's viewpoint:



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- Distant observer:

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- Falling observer:

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  (carried with him/her)

Which is correct?

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

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

$|\uparrow\rangle \;\to\; |\uparrow\rangle|\uparrow\rangle$

$|\downarrow\rangle \;\to\; |\downarrow\rangle|\downarrow\rangle$

$|\uparrow\rangle+|\downarrow\rangle \;\to\; |\uparrow\rangle|\uparrow\rangle+|\downarrow\rangle|\downarrow\rangle$ (superposition principle)

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

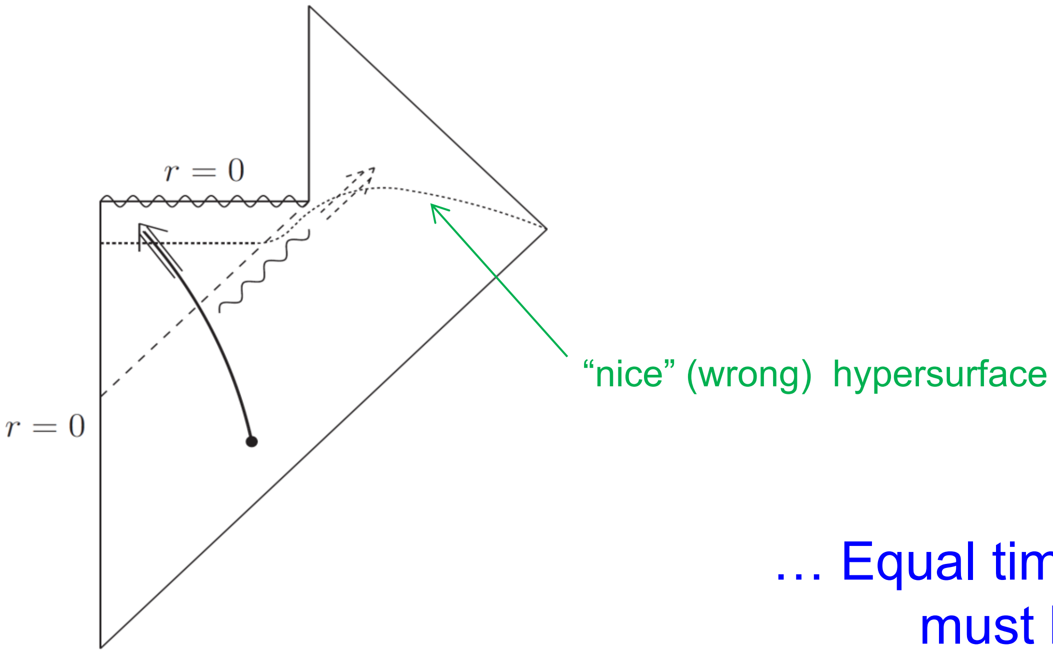
The two statements cannot be compared *in principle*.

(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** !!



… Equal time hypersurface
must be chosen carefully.

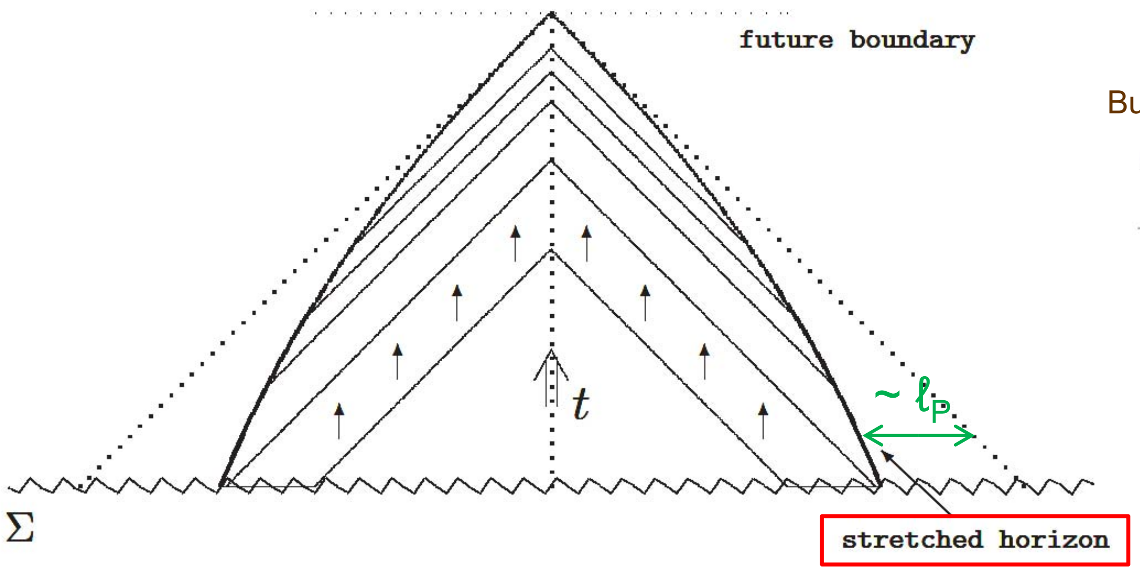
Now, eternal inflation

… simply "inside-out" !

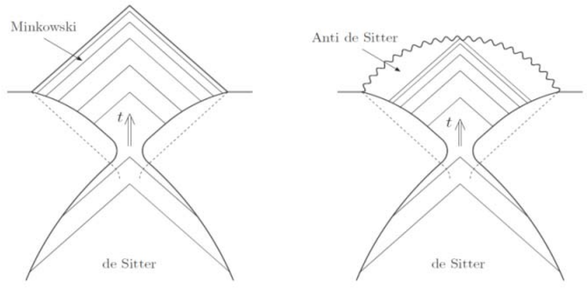
Including Gibbons-Hawking radiation, there is **no outside spacetime** !!

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

Y.N. ('11)

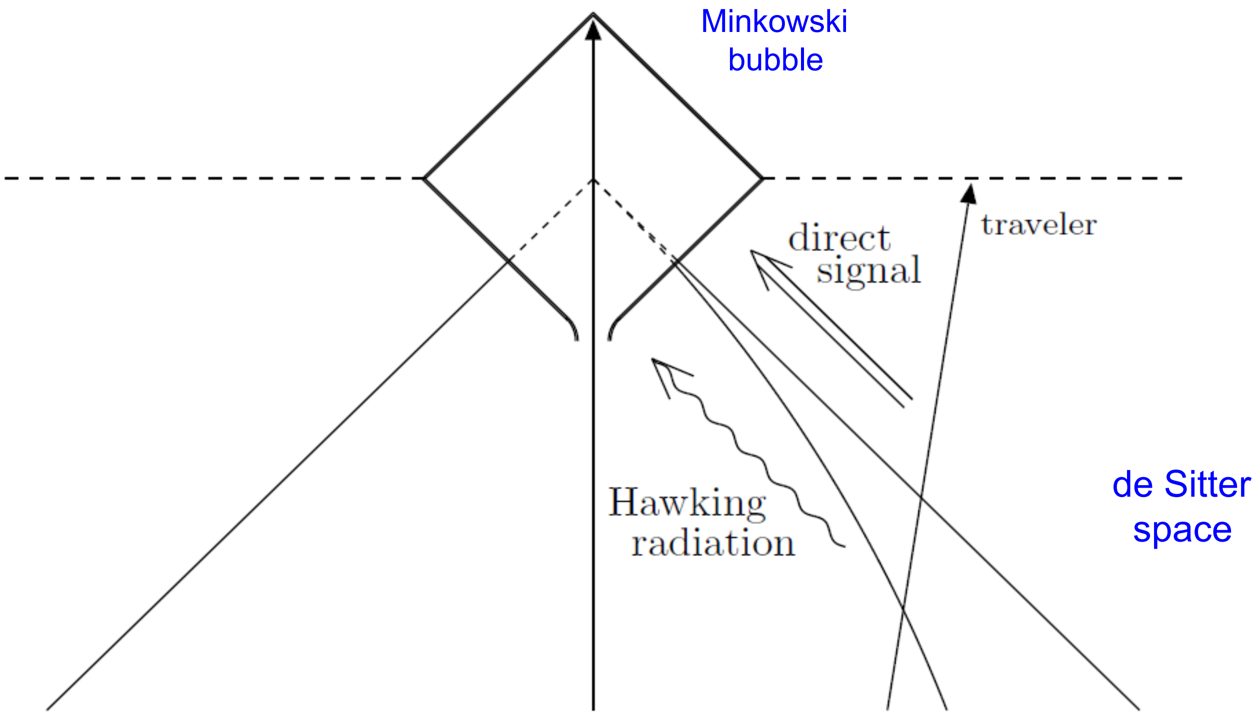


Bubble nucleation:



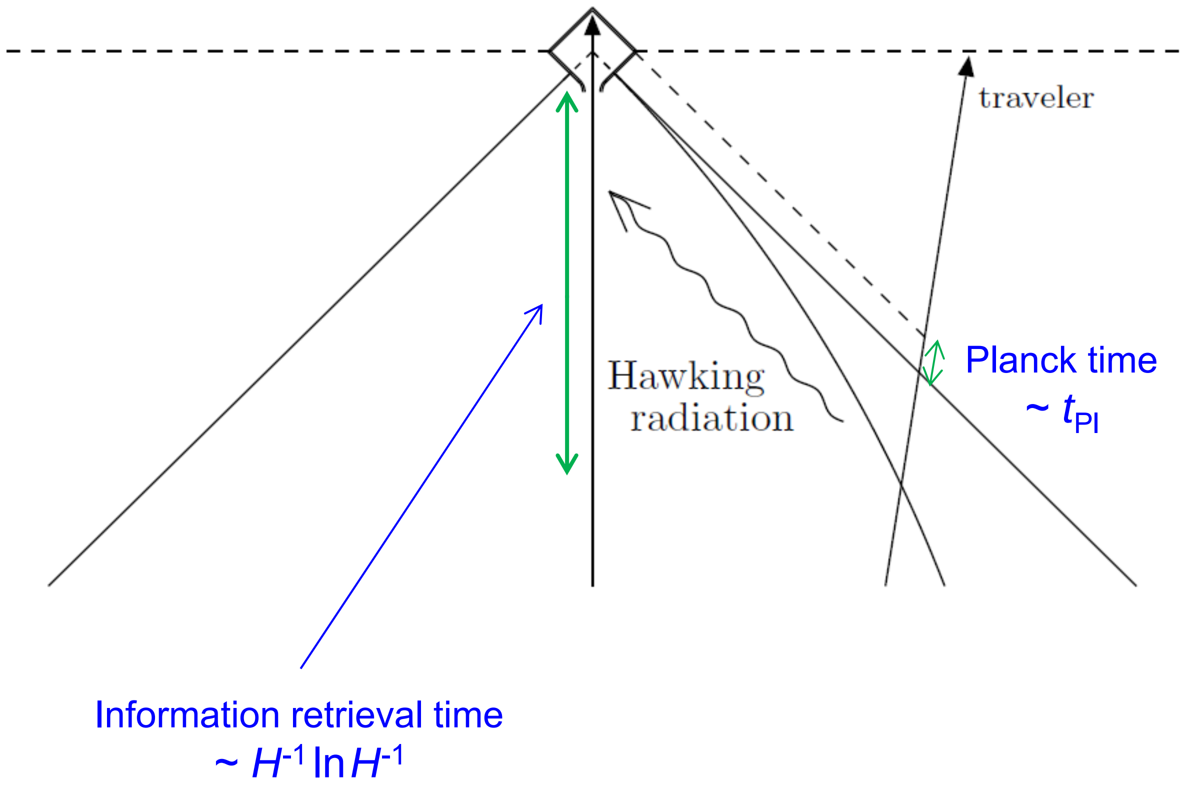
What is the multiverse? $\Longrightarrow$ probability !!

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*.

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 ?

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

Full Hilbert space

$$\mathcal{H} = \bigoplus_{\mathcal{M}} \mathcal{H}_{\mathcal{M}}$$

$\longleftrightarrow$ analogy

Fock space

n particle states

$$\mathcal{H} = \bigoplus_{n} \mathcal{H}_{n}$$

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

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

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)

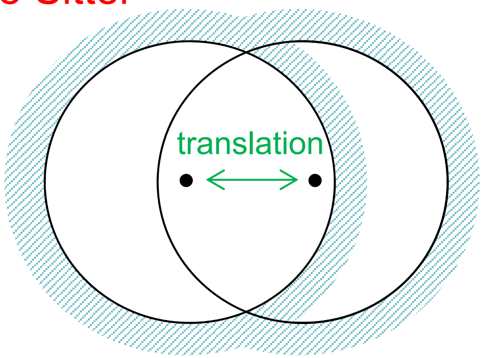
Why?

Hamiltonian quantum mechanics

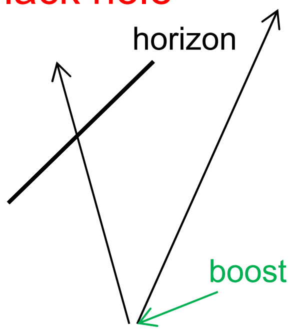
→ gauge fixing → gauge = coordinate transformation

Change of a reference frame

de Sitter



Black hole



observer dependence of horizon

complementarity

unified understanding

Spacetime ↔ horizon d.o.f. !!

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

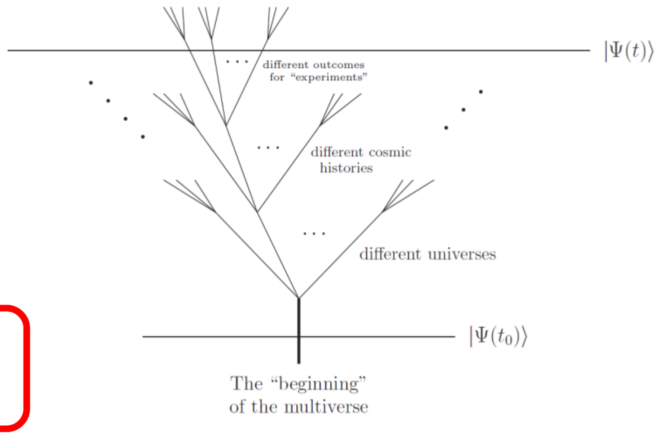
global properties → Multiverse

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

local properties → Quantum many worlds

e.g. result of a particular experiment, …

Multiverse = Quantum many worlds

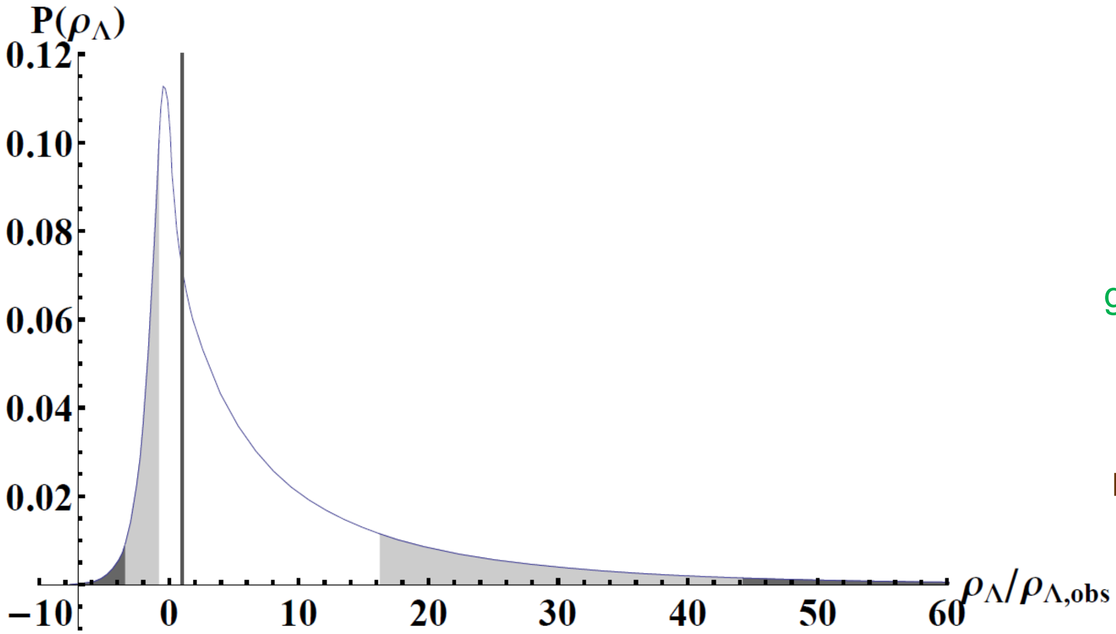


Predictions?

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!

So far

Eternal inflation ...... measure problem

Quantum mechanics

Now

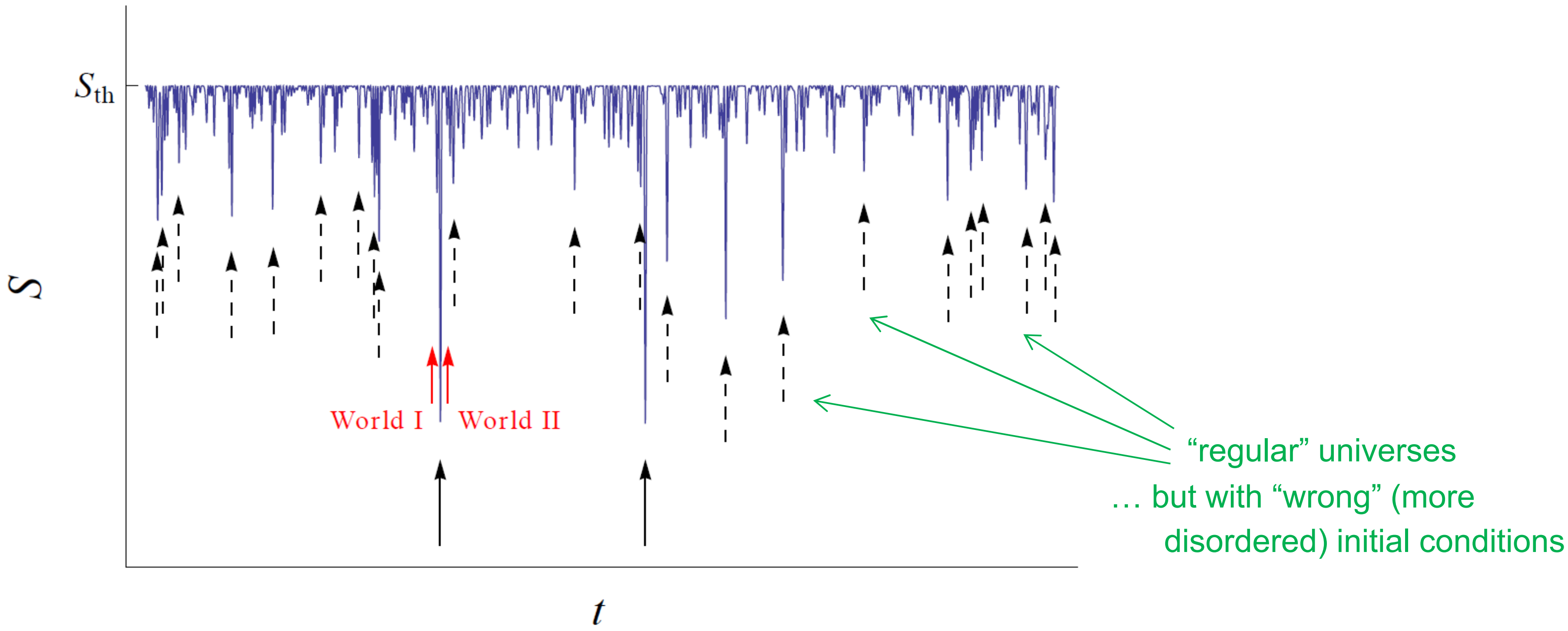
Eternal inflation ...... measure problem

Quantum mechanics ...... measurement problem

"Necessity" of the multiverse

Suppose we live in a stable vacuum with $\rho_{\Lambda,\mathrm{obs}} \sim (10^{-3}\,\mathrm{eV})^4$

$\Longrightarrow$ $\ln \dim \mathcal{H} \sim 1/(\rho_{\Lambda,\mathrm{obs}} G_N^2)$ … finite



If dim $\mathcal{H}$ = finite,

then the problem is unavoidable !!

cf. the Boltzmann brain problem

In the multiverse

$$\dim \mathcal{H} = \infty$$

since $\dim \mathcal{H}_{\text{Minkowski}} = \infty$ cf. 10D SUSY vacua in string theory

This explains the fact that we observe the ordered world !

Quantum measurement

— dissipation of coherence into (infinitely) large Hilbert space

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

- branching

and $\left|e^+e^-\right\rangle \rightarrow \left|e^+e^-\right\rangle + \left|\mu^+\mu^-\right\rangle + \cdots + \left|e^+e^-e^+e^-\right\rangle + \cdots \rightarrow \cdots$ … many worlds / multiverse

- amplification

$|\uparrow\rangle \rightarrow |\uparrow\rangle\,|\uparrow\rangle \rightarrow |\uparrow\rangle\,|\uparrow\rangle\,|\quad\rangle \rightarrow \cdots$ … basis selection

Because of $\dim \mathcal{H} = \infty$, different branches do not recohere.

$\rightarrow$ A state branches really into separate worlds!

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), …