# 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
- …

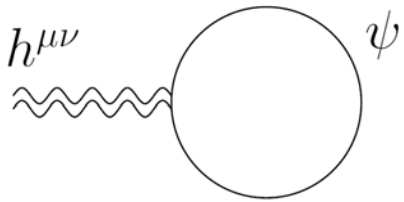
## … implications on particle physics and cosmology

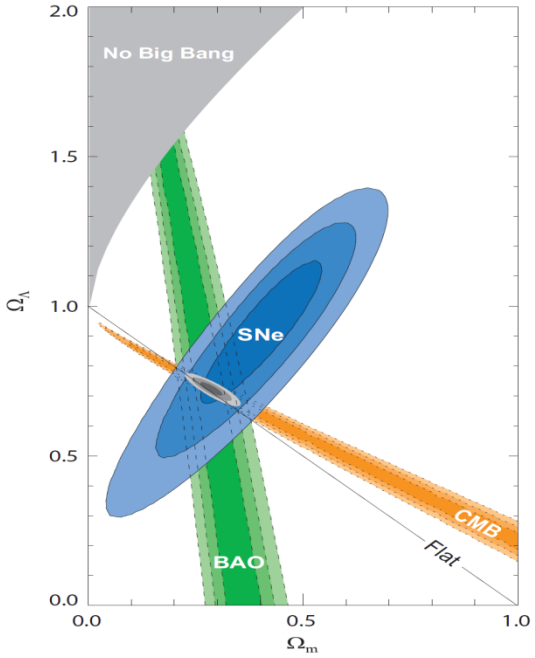
# Shocking news in 1998

Supernova cosmology project; Supernova search team

Universe is accelerating!

$\Lambda \neq 0$ !




Particle Data Group (2010)

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

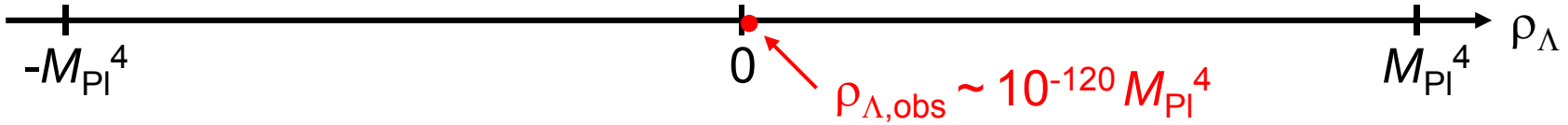
Observationally,

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

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

# Nonzero value completely changes the view !

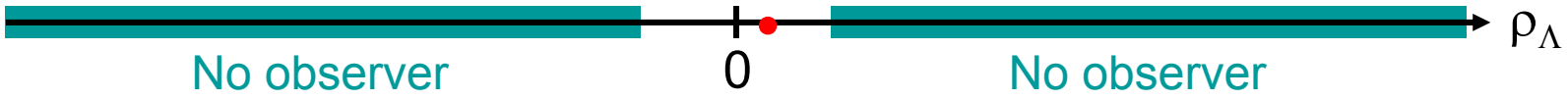
Natural size for vacuum energy $\rho_\Lambda \sim M_{\rm Pl}^4$




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 $\rho_{\Lambda,\rm obs}$,

**as long as** different values of $\rho_\Lambda$ are "sampled"

Weinberg ('87)

# Many universes — multiverse — needed

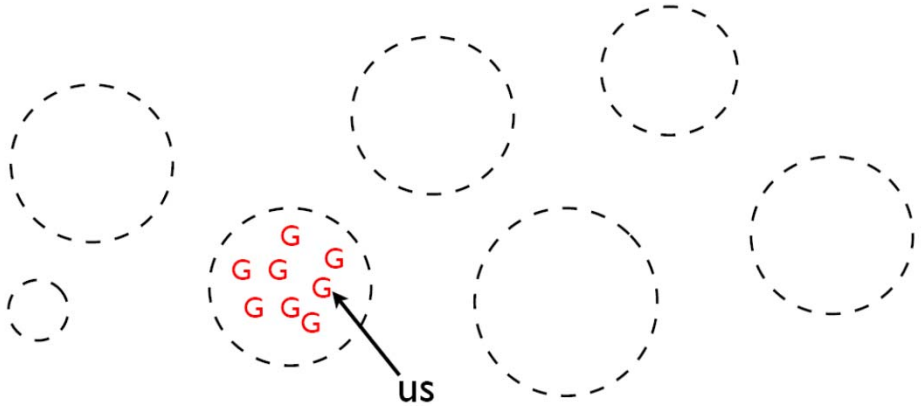
- String landscape

  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:

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

  … otherwise, no nuclear physics or chemistry

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

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

....

Some of them anthropic (and some may not)

$\Longrightarrow$ Implications?

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

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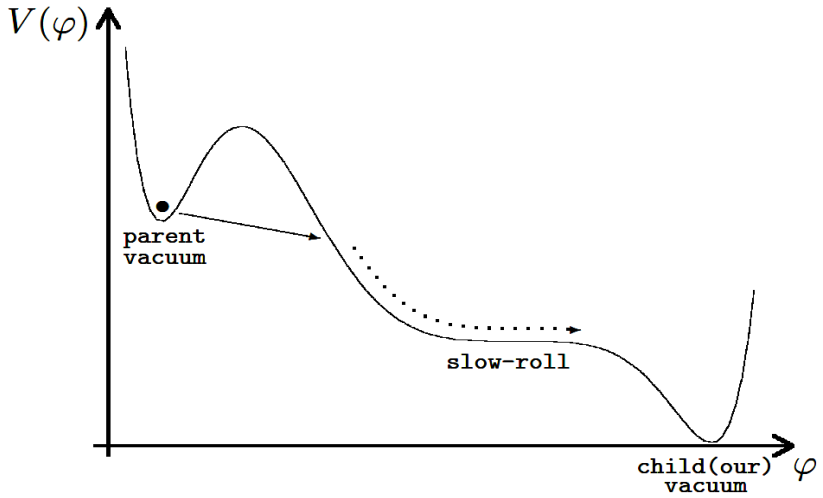
# *Implications*

## —observation / experiment —

... new ways of thinking physics

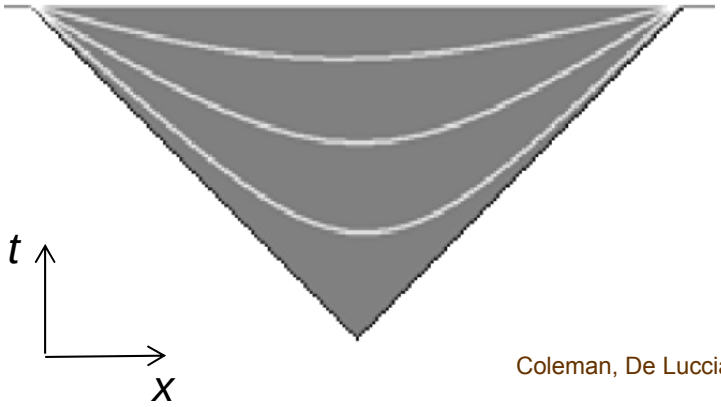
# Cosmology

## 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

→ anthropic !

What is the “cheapest” way to realize the required flatness?

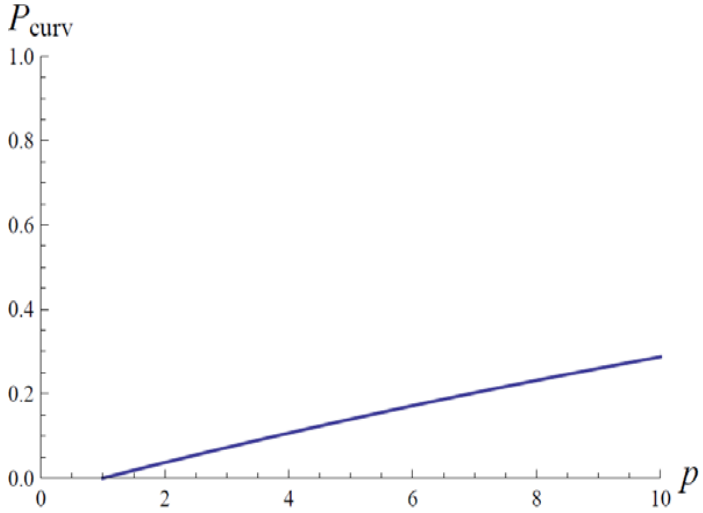
- Fine-tuning initial conditions
- Having a (accidentally) flat portion in the scalar potential

→ (Observable) inflation

⟹ The flatness will not be (much) beyond needed !

“difficulty” of realizing a flat potential

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




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

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

# Particle Physics

Anthropic (could) affects how our universe looks

→ 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 $v > 2\, v_{obs}$ Damour, Donoghue ('07)

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

Weak scale supersymmetry really "needed"?

No … the scale of SUSY masses determined by statistics

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

$f(\tilde{m}) \sim \tilde{m}^{p-1}$ → e.g. "Spread" / "Mini-split" SUSY

Hall, Y.N. ('11); Arvanitaki, Craig, Dimopoulos, Villadoro ('12)

# Can anthropic explain *everything*?

⟹ **No !**

ex. Strong CP problem in QCD

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

… mechanism needed → "axion"

(more "robust" problem than the hierarchy problem)

## Implication for Dark Matter (DM)

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

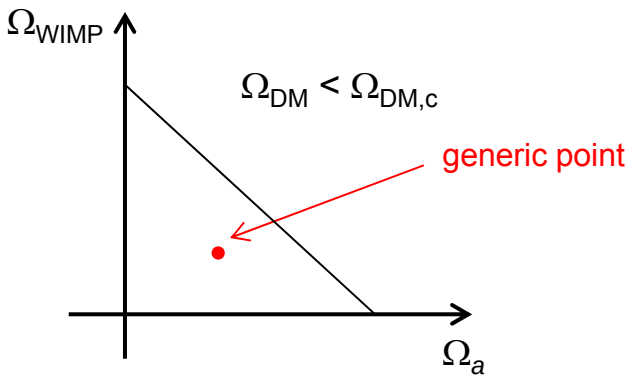
… forced by $\Omega_{DM} < \Omega_{DM,c}$

Linde ('88); Tegmark, Aguirre, Rees, Wilczek ('05)

DM already present! → no "need" for WIMP

WIMP?

— possible




⟹ Multi-component DM !

# *Implications on fundamental physics*

## *– the multiverse as quantum many worlds –*

Y.N., arXiv:1104.2324; arXiv:1110.4630; arXiv:1205.5550; ….

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

# Predictivity crisis !

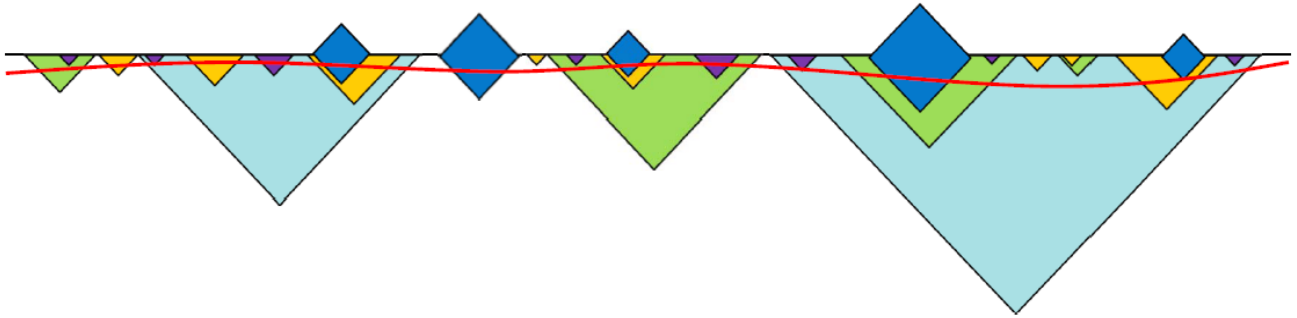
*In an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times.*

Guth ('00)

ex. Relative probability of events *A* and *B*

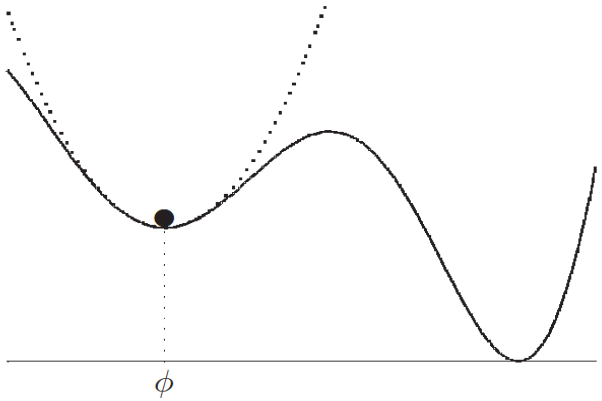
$$P = \frac{N_A}{N_B} = \frac{\infty}{\infty} \;\; !!$$

Why don't we just "regulate" spacetime at $t = t_c \; (\rightarrow \infty)$



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

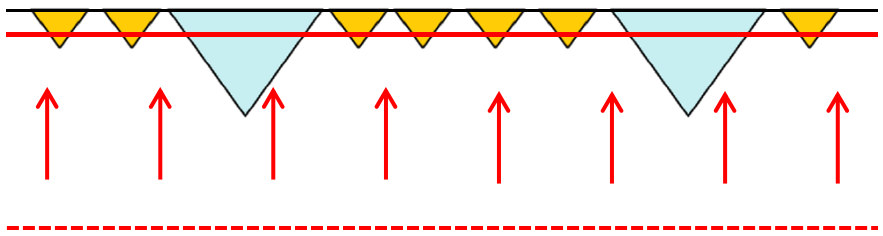
- The problem is robust




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

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

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

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

eternally inflating

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

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

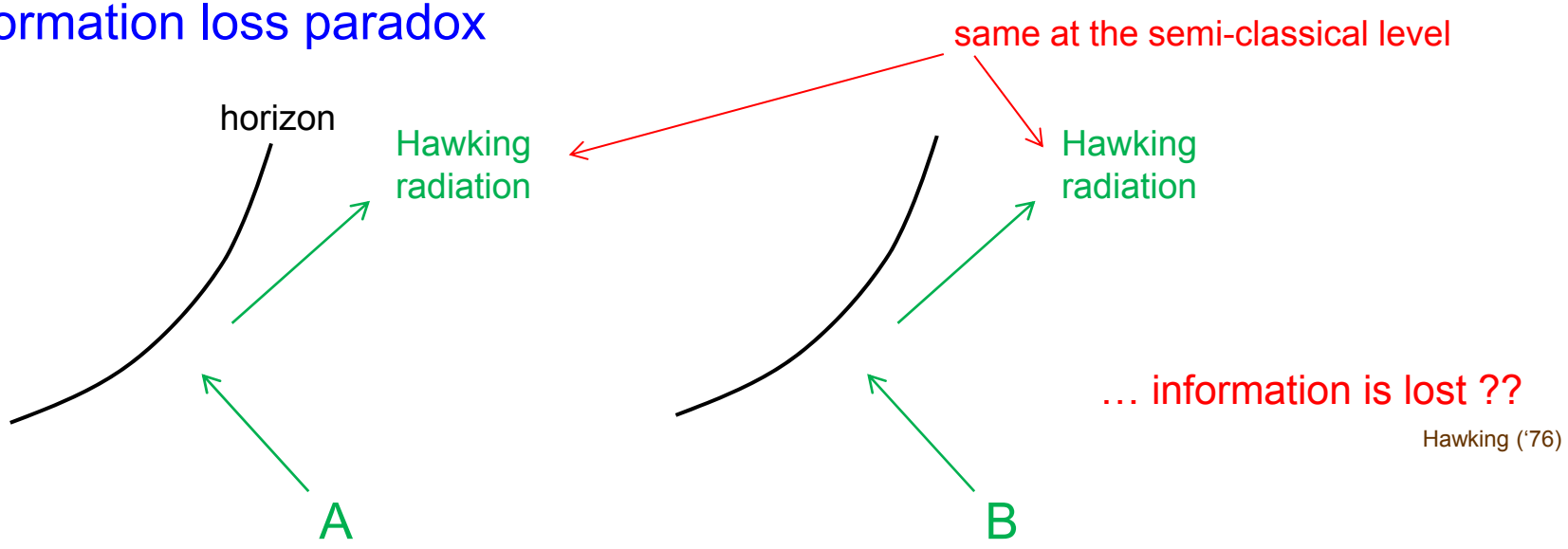
## Quantum mechanics in gravitational systems

$\Longrightarrow$ Dramatic change of our view of spacetime

# Quantum Mechanics in a System with Gravity

## Black Hole

### Information loss paradox




… information is lost ??

Hawking ('76)

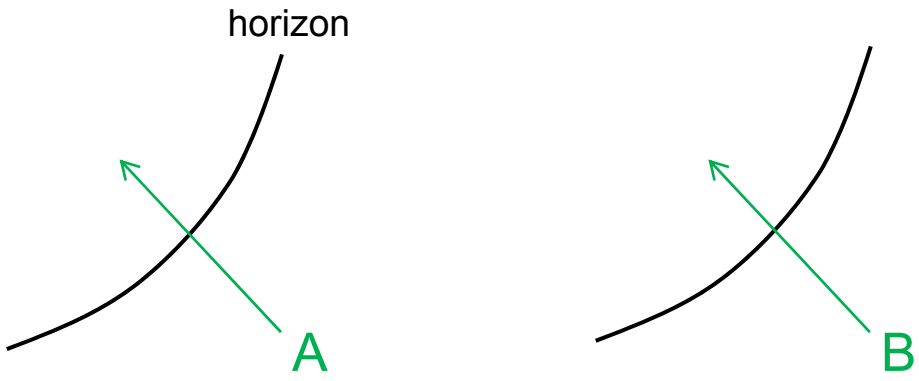
⟹ No

… 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)

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

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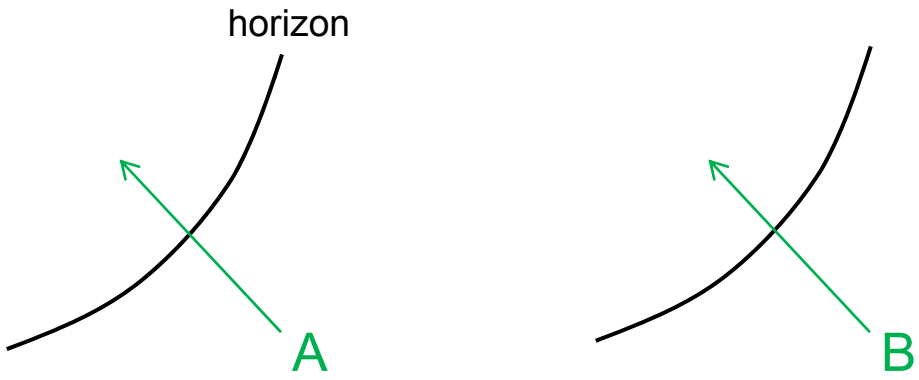


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**Which is correct?**

**⟹ Both are correct !**

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

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

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

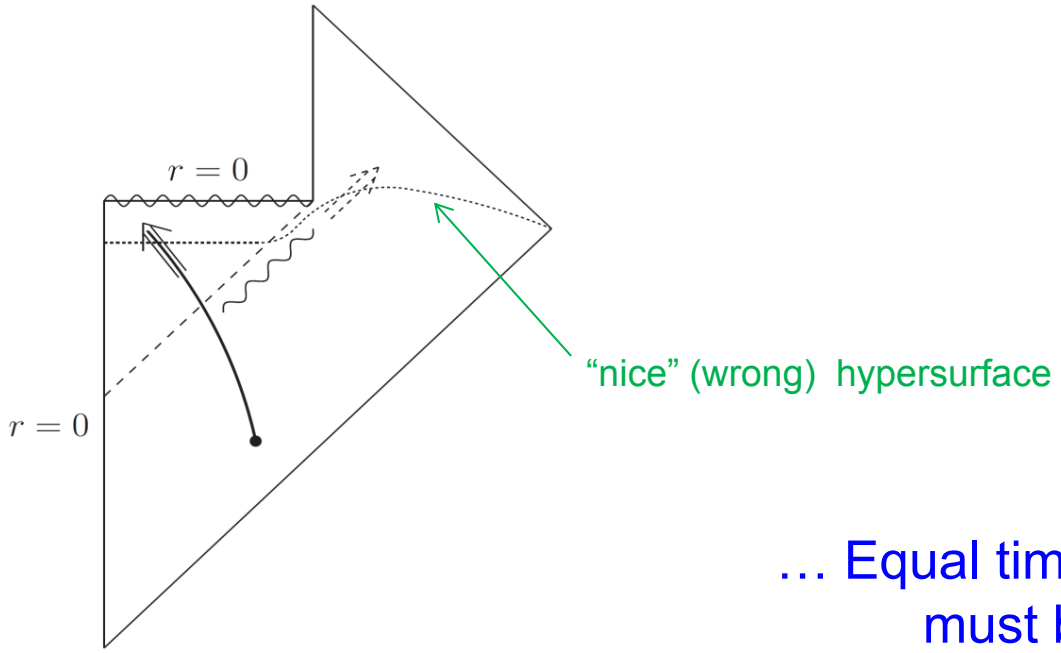
The two statements cannot be compared *in principle*.

(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.

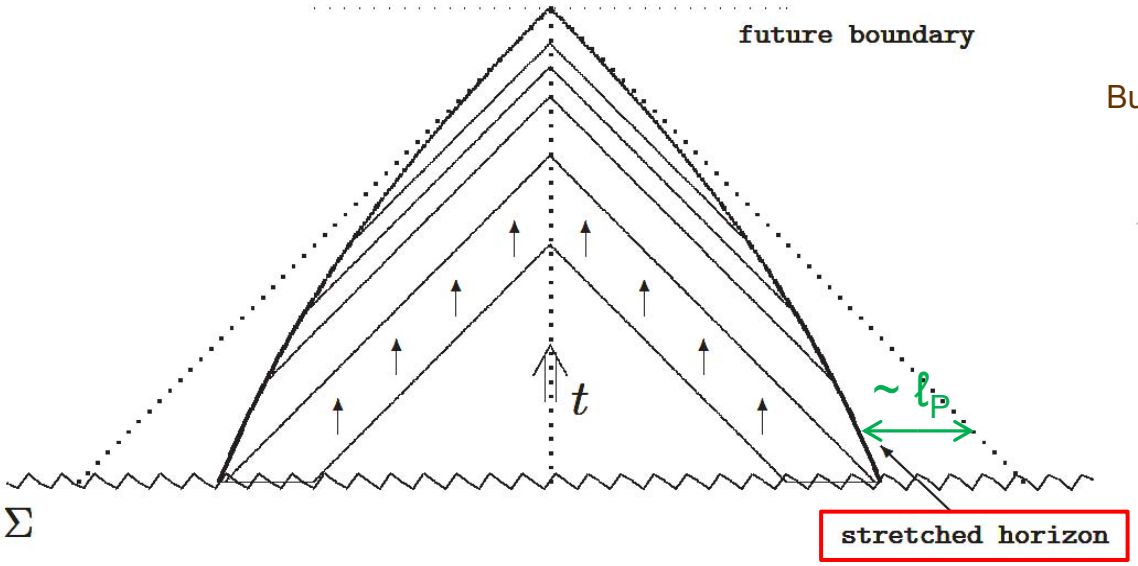
# Now, eternal inflation

… simply “inside-out” !

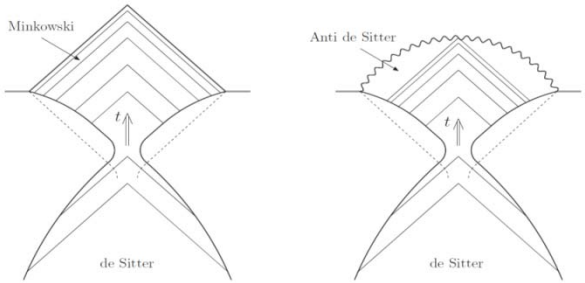
Including Gibbons-Hawking radiation, there is **no outside spacetime** !!

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

Y.N. (‘11)

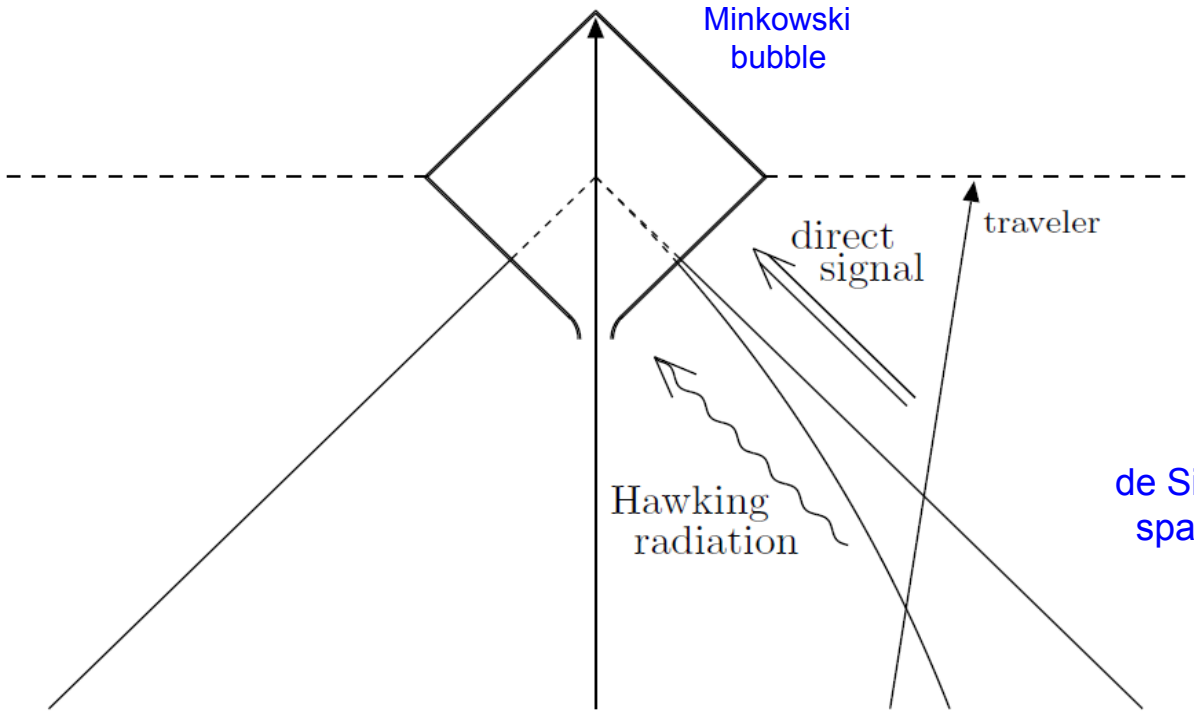



Bubble nucleation:



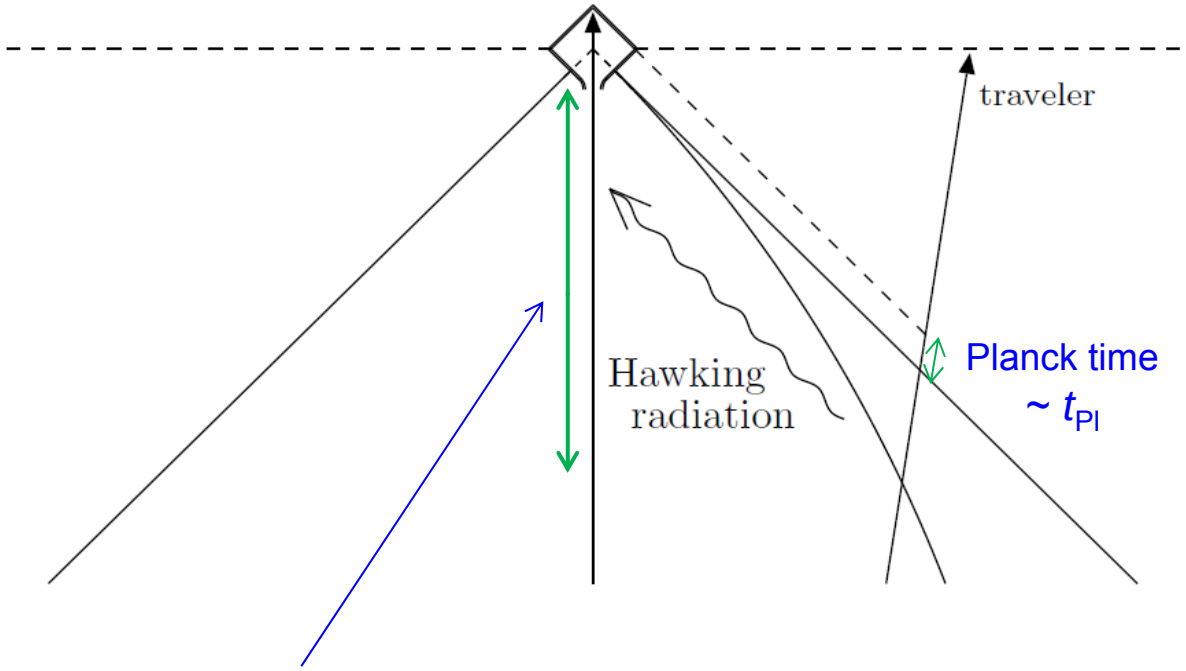

What is the multiverse? ⟹ probability !!

# 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 ?

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

## Full Hilbert space

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


## Fock space

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

*n* particle states

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

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

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)

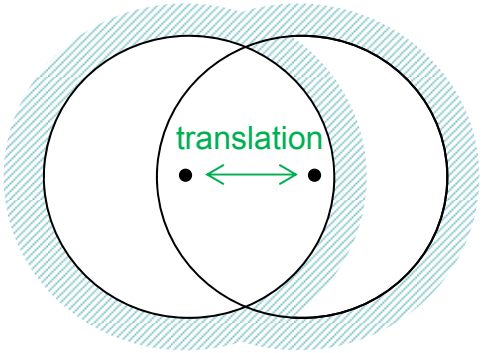
Why?

Hamiltonian quantum mechanics

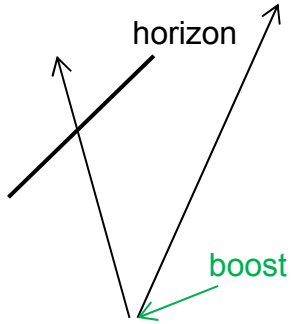
→ gauge fixing → gauge = coordinate transformation

## Change of a reference frame

de Sitter




Black hole




observer dependence of horizon ↖ ↗ complementarity

unified understanding

Spacetime ↔ horizon d.o.f. !!

This transf. $\xrightarrow[\longleftarrow]{G_N \to 0}$ Poincaré (Lorentz) transf. $\xrightarrow[\longleftarrow]{c \to \infty}$ Galilei transf.

more “relativeness”

# Probability

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

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

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

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

**The measure problem is solved.**

… (extended) Born rule

For *B*, a question about

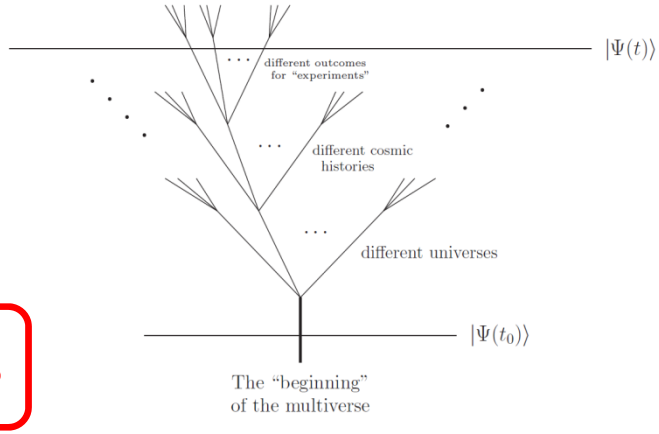
global properties → Multiverse

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

local properties → Quantum many worlds

e.g. result of a particular experiment, …

**Multiverse = Quantum many worlds**

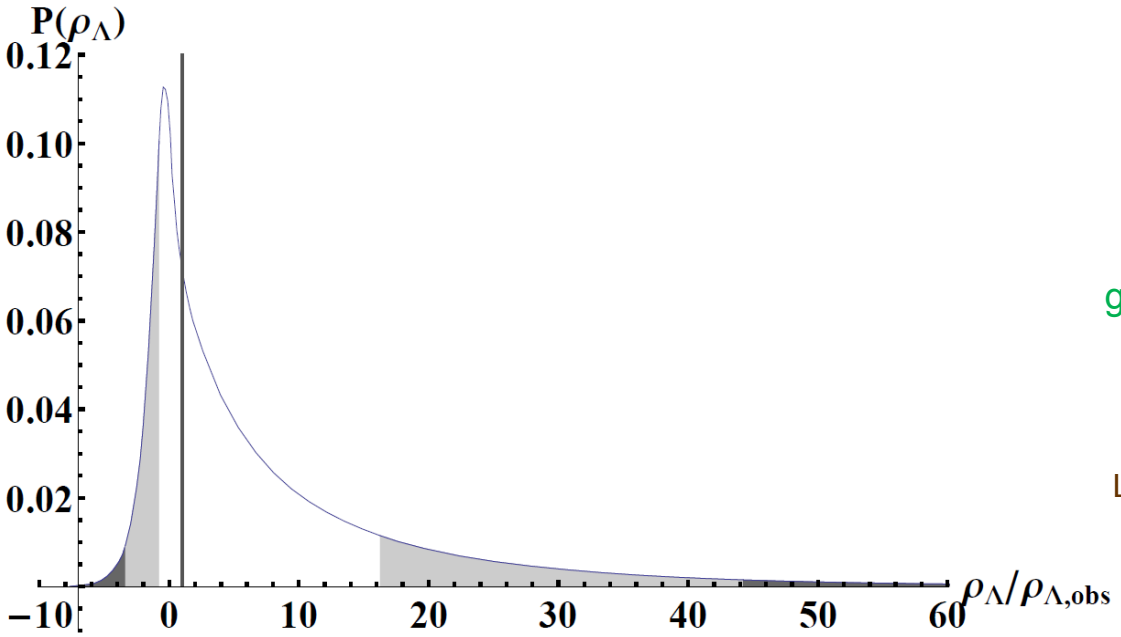


# Predictions?

## 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!

# The Static Quantum Multiverse

Y.N. (2012)

The framework developed so far allows

Initial condition $|\Psi(t_0)\rangle$ ⟶ Predictions

dynamics: "Hamiltonian"

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

⟹ The multiverse state can be static!

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

probability:

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

This can be regarded as a gauge condition

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

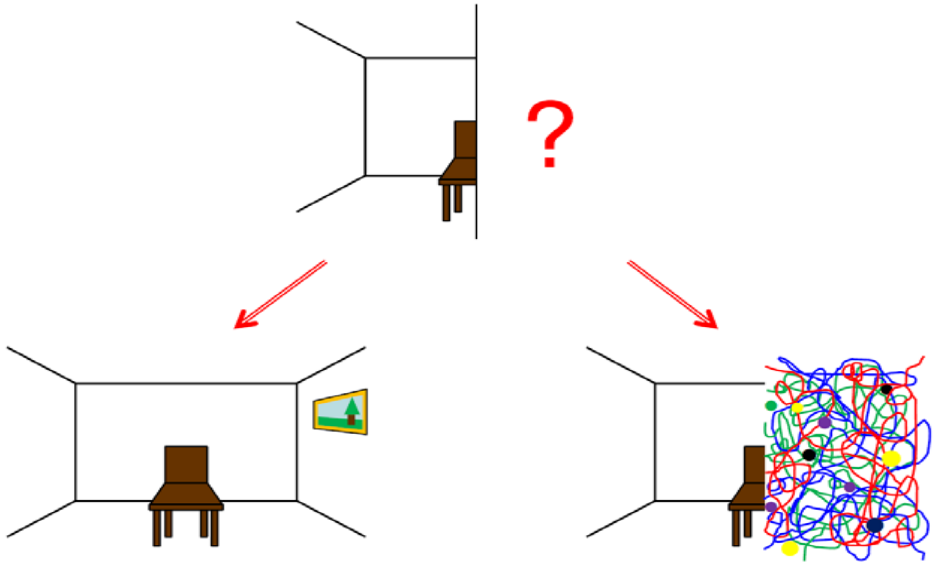
The multiverse does not have a beginning or end

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

# The arrow of time can emerge dynamically

The fact that we see time flows in a definite direction

does **not** mean that $|\Psi\rangle$ 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

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

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

The probability of leading to ordinary observers

The vacuum decay rate

# How does this avoid the “beginning”?

## The (normalized) static state |Ψ>:

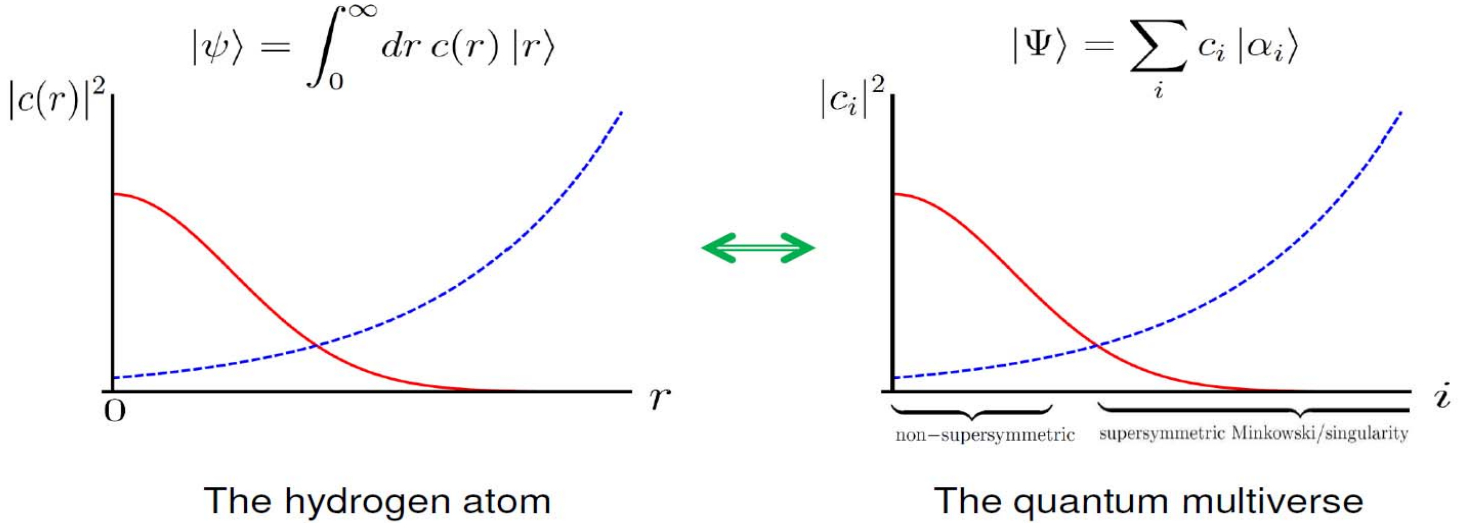
… the state in which various “micro-processes” balance

## What are the processes preventing “dissipation” into Minkowski/singularity worlds?

… 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), …