Physical predictions in 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
- …

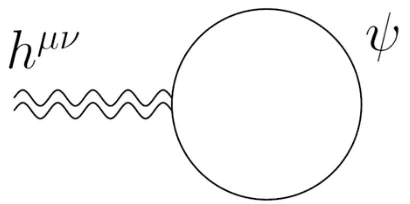
… implications on particle physics and cosmology

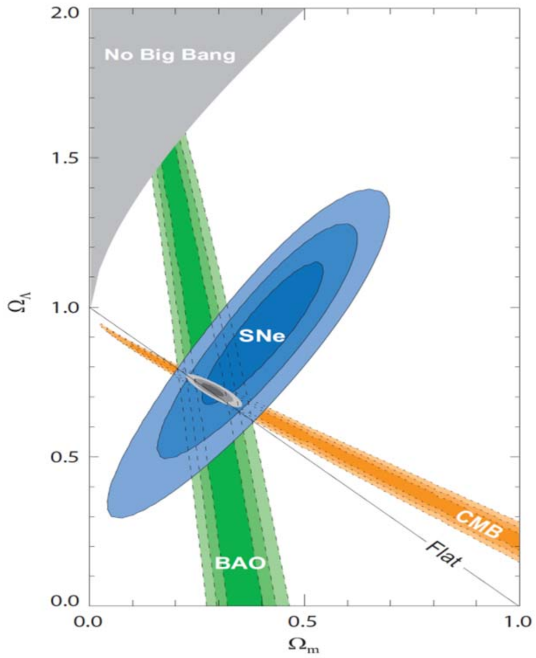
Shocking news in 1998

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)

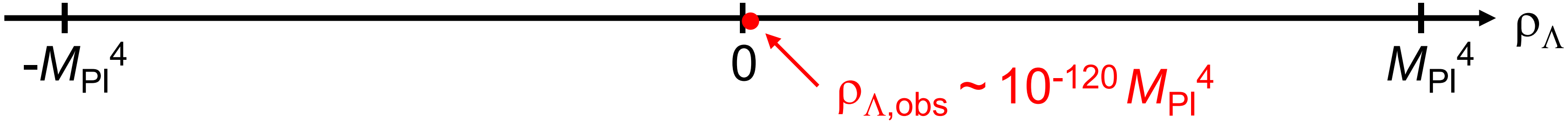
Observationally,

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

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

Nonzero value completely changes the view !

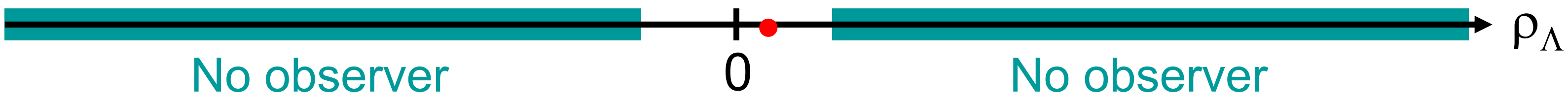
Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$



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

$\Longrightarrow$ 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

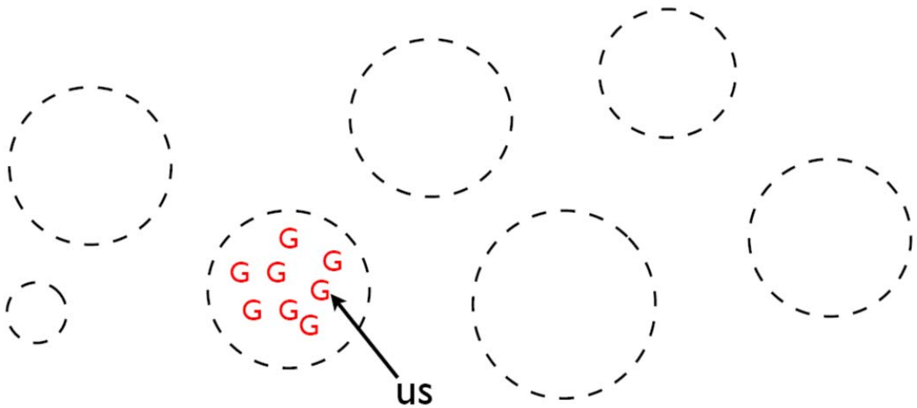
ex. $O(100)$ fields with $O(10)$ minima each

$\rightarrow$ $O(10^{100})$ 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: $P \ll 10^{-3}$

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

….

Some of them anthropic (and some may not)

$\Longrightarrow$ Implications?

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

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Implications

— fundamental physics —

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

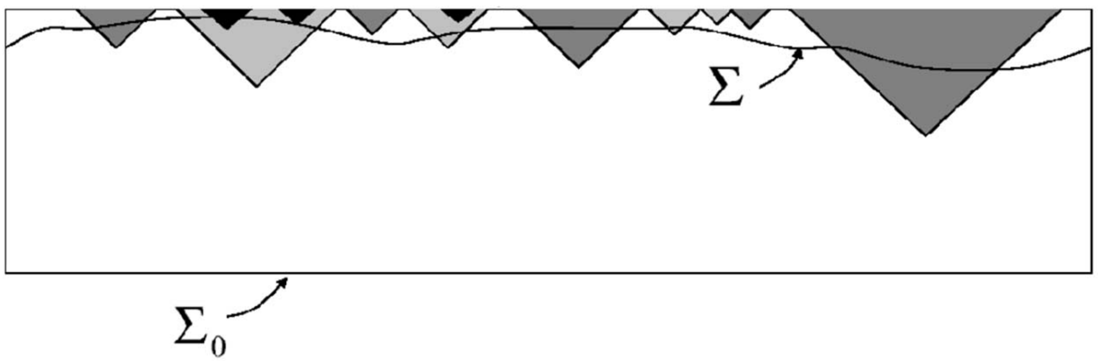
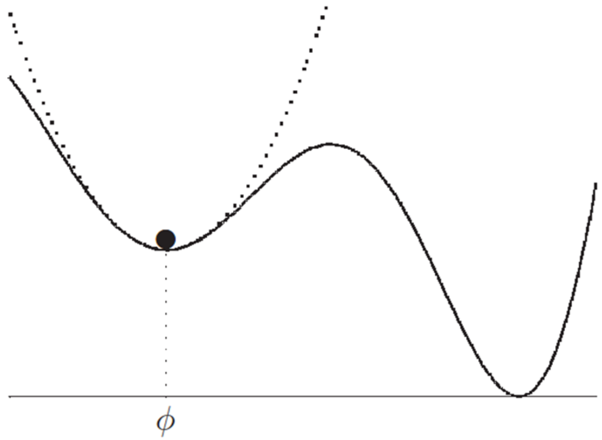


figure from Vilenkin ('06)

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

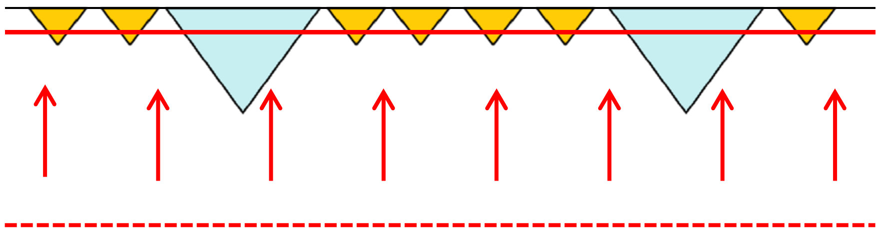
- The problem is robust



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)

$$V \sim e^{3Ht}$$

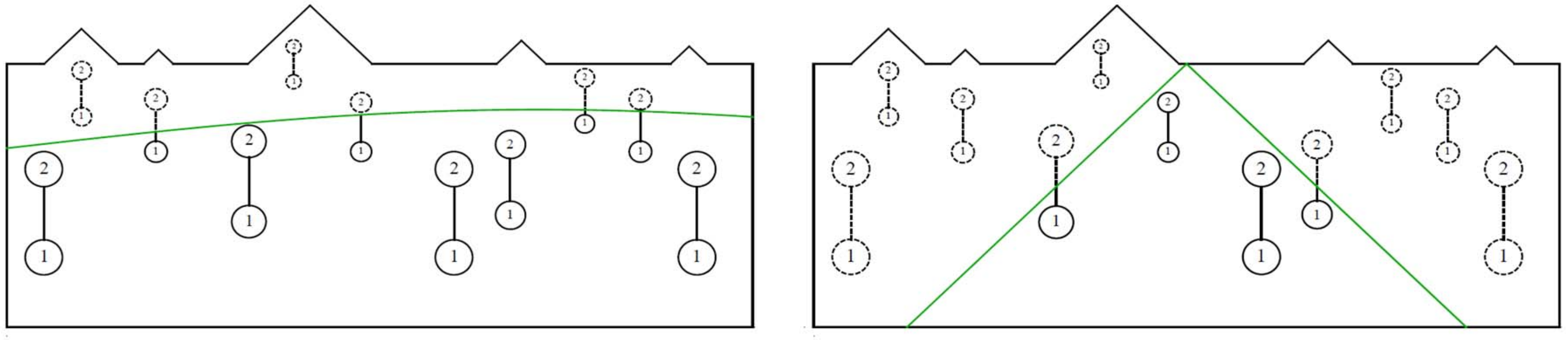
… vastly more younger universes than older ones

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

… Youngness paradox

Guth ('00); Tegmark ('04)

Any geometrical cutoff leads to peculiar "end" of time



(a) Global Cutoff (b) Causal Patch Cutoff

Events in eternally inflating spacetime
are dominated by late-time attractor regeme

→ The cutoff does not decouple !

$$P_{\text{end}} \equiv 1 - \frac{N_2}{N_1} \not\rightarrow 0$$

Time does "end" !

Bousso, Freivogel, Leichenauer, Rosenhaus ('10)

Something seems terribly wrong …

Multiverse as a Quantum Mechanical Universe

Y.N., "Physical Theories, Eternal Inflation, and Quantum Universe," arXiv:1104.2324

Quantum mechanics is **crucial**

The basic idea:

The laws of quantum mechanics are not violated (only) when physics is described from an observer's point of view

Quantum mechanics in systems with gravity needs care

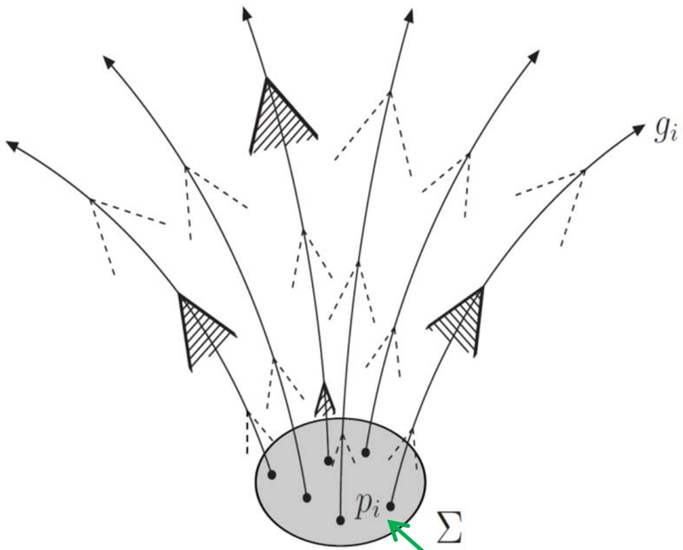
$\Longrightarrow$ Dramatic change of our view on spacetime

- The measure problem is solved. (well-defined probabilities given by the Born rule)
- The multiverse and many worlds in QM are the same
- Global spacetime can be viewed as a derived concept
- The multiverse is a transient phenomenon while the system relaxing into a supersymmetric Minkowski state
- ….

What is “physical prediction”?

Two aspects → Dynamical evolution
→ Probabilities ⟸

Given what we know, *i.e.* condition *A* imposed on a past light cone, what is the probability of this light cone to also have a property *B*?



“simulate” the multiverse many times

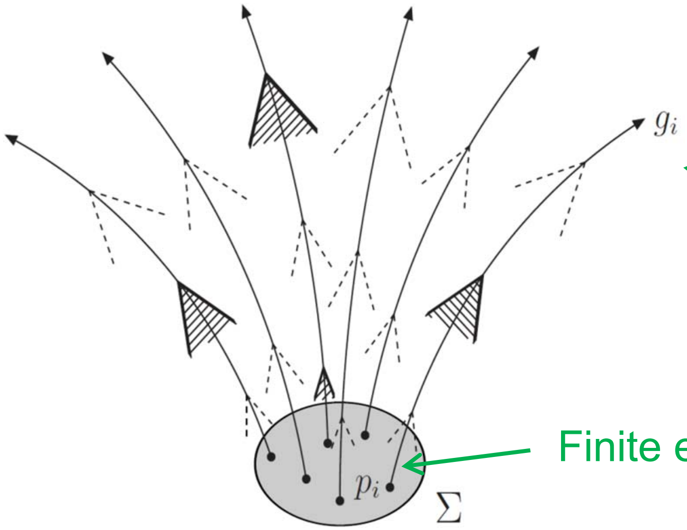
$$\frac{\mathcal{N}_{A\cap B}}{\mathcal{N}_A} \to P(B|A)$$

(*not* counting events)

… semi-classical definition

$\ell \ll \ell_{Pl}$ — Does it make sense?

QM $\rightarrow$ deterministic, unitary evolution



Infinitely many different universes

Finite entropy (# of quantum states)

The origin of different semi-classical universes cannot be attributed to the difference of initial conditions

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

The *single* state Ψ(t) describes the *entire* multiverse ! ("no" global spacetime)

How to define the multiverse state |Ψ(t)> ?

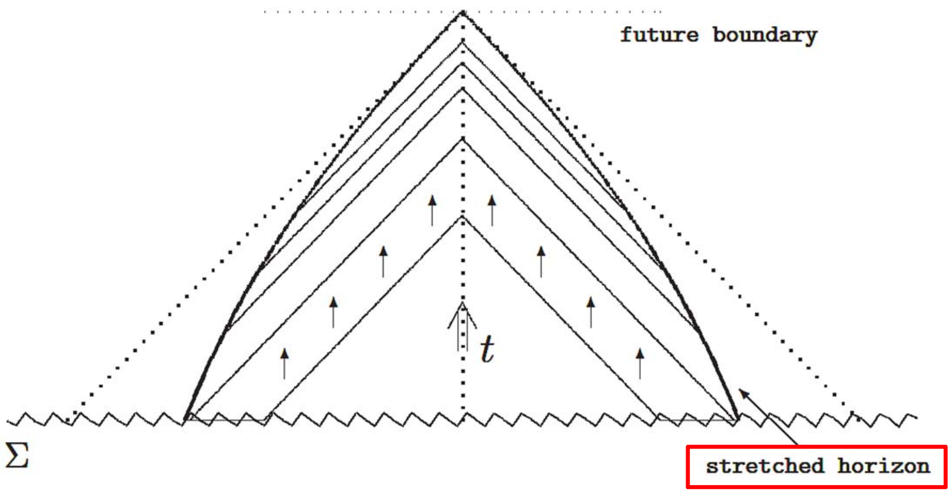
= How to define equal time hypersurfaces?

Quantum observer principle:

Physics obey the laws of quantum mechanics when described from the viewpoint of an "observer" (geodesic) traveling the multiverse, although this need not be the case if described in other ways, e.g., using the global spacetime picture with synchronous time slicing. The description involves only spacetime regions inside the (stretched) apparent horizons, as well as the degrees of freedom associated with these horizons.

Y.N. ('11)

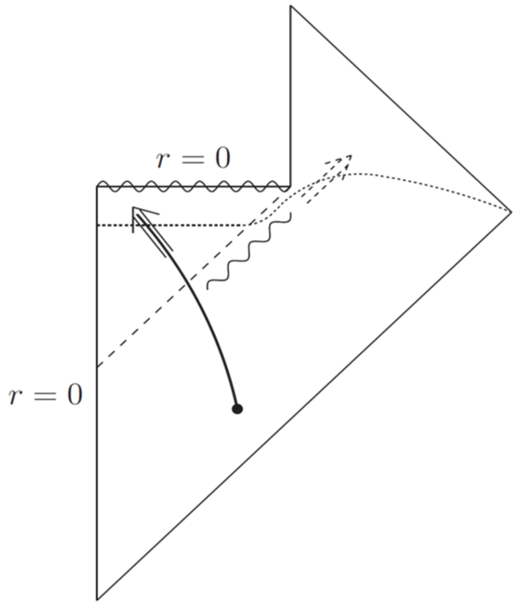
Specifically, the state is defined on the observer's past light cones **bounded by the (stretched, apparent) horizons**.



Horizon complementarity

Susskind, Thorlacius, Uglum ('93);
Stephens, 't Hooft, Whiting ('93)

A traveller falling into a black hole with some information



- Distant observer:

  Information will be *out*side at late times.

  (sent back in Hawking radiation)

- Falling traveller:

  Information will be *in*side at late times.

  (carried with him/her)

Which is correct?

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

Both are correct !

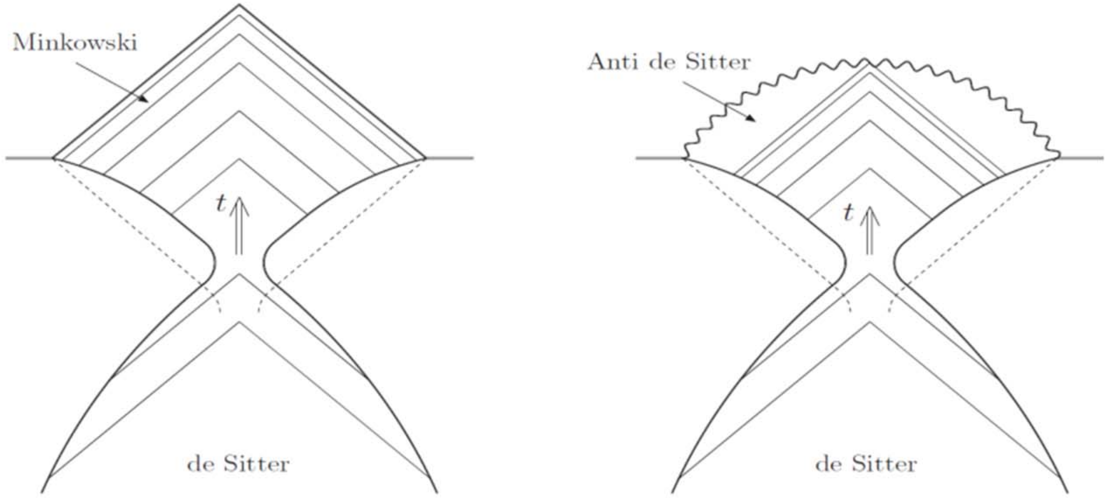
— The two statements cannot be compared in principle.

$\Longrightarrow$ We **must** restrict the spacetime region to what we can actually observe

We must fix a “reference frame”

(need gauge fixing to do quantum mechanics!)

e.g.
bubble nucleation



⟹ Deterministic, unitary evolution $\boxed{|\Psi(t_1)\rangle = U(t_1,t_2)\,|\Psi(t_2)\rangle}$

Hilbert space

|Ψ(t)>: superposition of semi-classical spacetimes

(evolution not along the axes determined by operators local in spacetime)

$$\boxed{\mathcal{H} = \oplus_{\mathcal{M}}\left(\mathcal{H}_{\mathcal{M},\mathrm{bulk}} \otimes \mathcal{H}_{\mathcal{M},\mathrm{horizon}}\right)}$$

cf. Fock space in usual QFT

Probabilities

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

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

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

- well-defined

  … The probability of multiple occurrence of an event is exponentially small

- "gauge invariant"

  … The parameter *t* is simply an auxiliary parameter

  cf. parameterizing a curve in 2D: (x(t), y(t))

Semi-classical approximation:

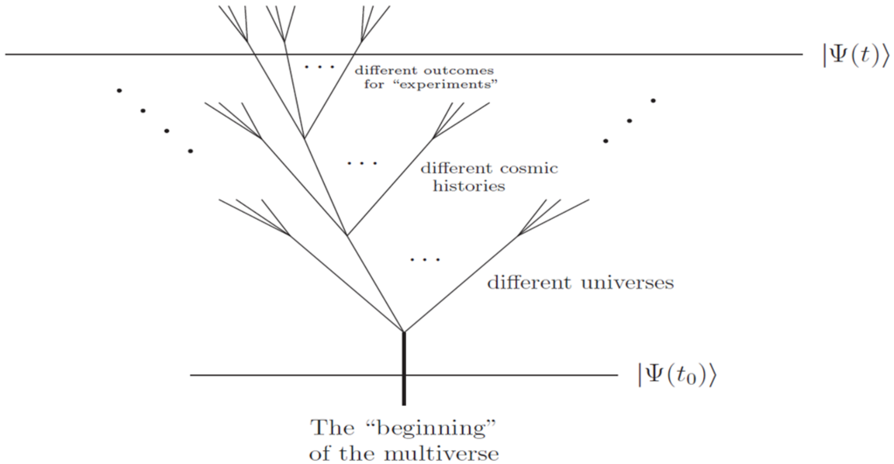
$$\boxed{\rho_{\text{bulk}}(t) = \mathrm{Tr}_{\text{horizon}}\,|\Psi(t)\rangle\,\langle\Psi(t)|} \;\longrightarrow\; P(B|A) = \frac{\int dt \, \mathrm{Tr}\left[\rho_{\text{bulk}}(t)\,\mathcal{O}_{\text{bulk},A\cap B}\right]}{\int dt \, \mathrm{Tr}\left[\rho_{\text{bulk}}(t)\,\mathcal{O}_{\text{bulk},A}\right]}$$

… allows semi-classical calculations at the cost of information loss

Multiverse as quantum many worlds

The evolution of the multiverse state is deterministic,

but not along the axes determined by operators local in spacetime:



The resulting multiverse state, $|\Psi(t)\rangle \approx \sum_i |\text{possible world } i \text{ at time } t\rangle$, is *everything*.

(Even we ourselves appear as a part.)

Once we have $|\Psi(t)\rangle$, we can make predictions using our master formula.

(No need of wavefunction collapse, environmental decoherence, or anything like those.)

The questions may be about global properties of the universe,

or about outcomes of a specific experiment.

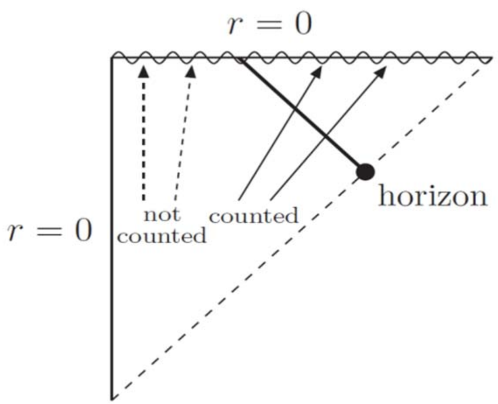
→ **Complete** unification of the multiverse and quantum many worlds !

Problems in Geometric Cutoffs Solved

Youngness paradox, Boltzmann brains, What's observer?, ambiguities in quantum probabilities, "end" of time, …

The ultimate future (What spacetime singularities mean?)

The components that hit big crunch or black hole singularities "disappear."



- covariant entropy conjecture
- consistency w/ the idea of stretched horizons
- string theory — no global symmetries
- reversibility of quantum evolution

$$\boxed{|\Psi(t)\rangle \quad \xrightarrow{t\to\infty} \quad \sum_i |\text{Supersymmetric Minkowski world } i\rangle}$$

infinite entropy reservoir

… the ultimate origin of the finiteness

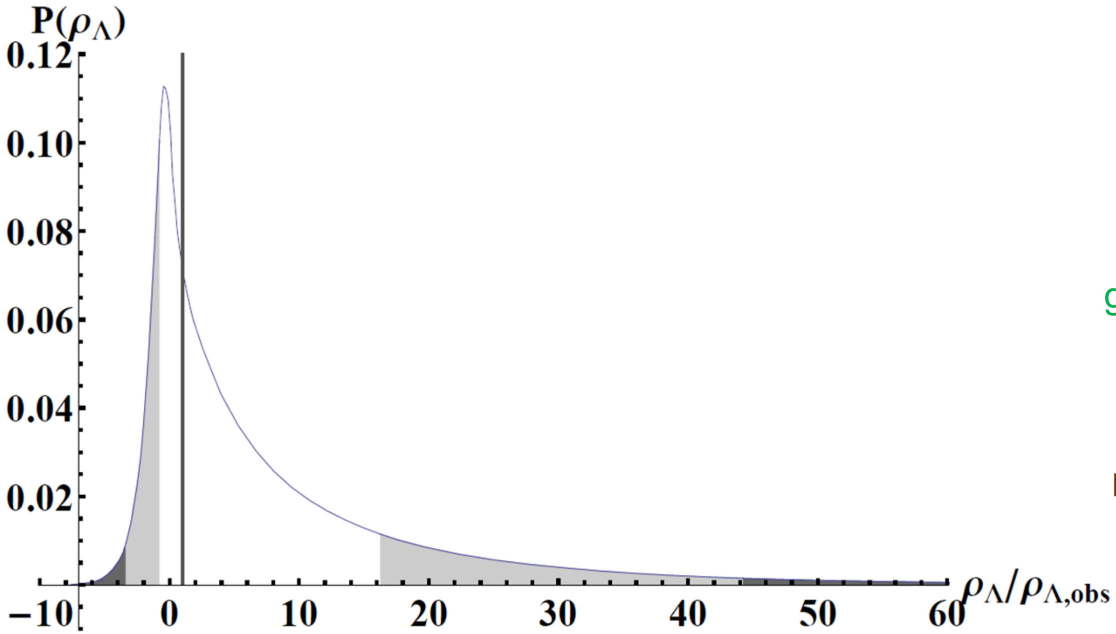
The "beginning" — see the paper

So what? — 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!

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

$\rightarrow$ surprising, quantum natures of spacetime and gravity

(black hole physics, eternal inflation, …)

Wide range of implications

cosmology, particle physics, (philosophy), …

Further experimental / theoretical support strongly desired

ex. spatial curvature, the Higgs boson mass, …