# 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

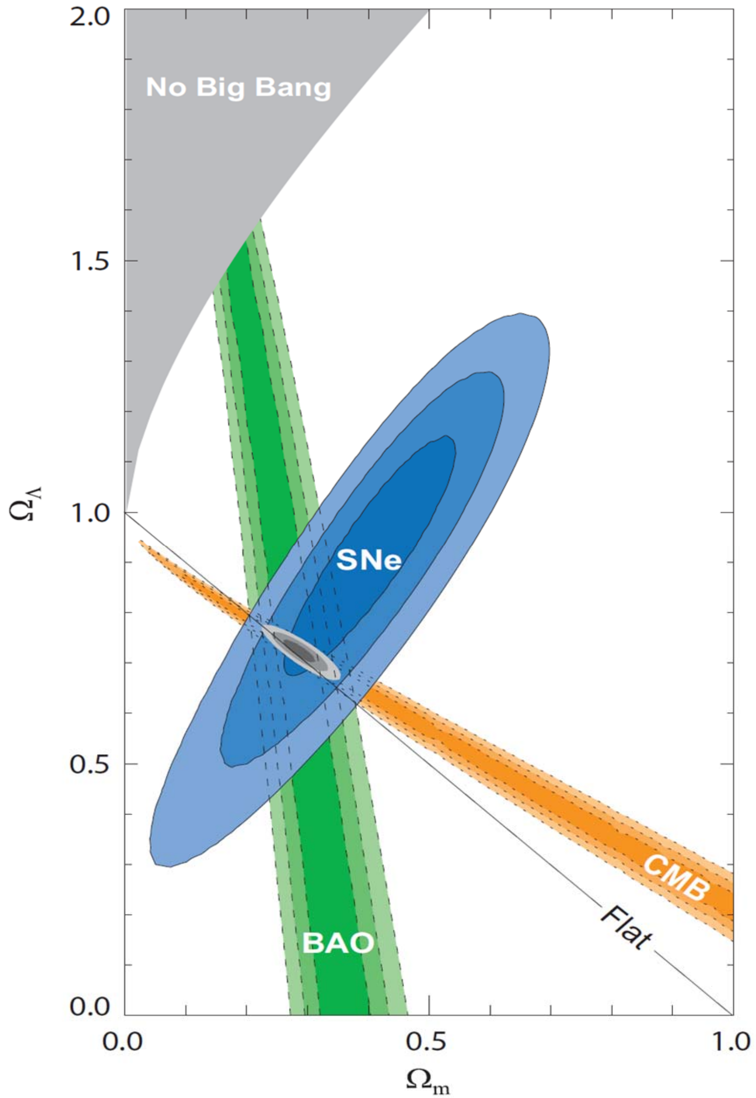
- Holographic principle
- Horizon complementarity
- Multiverse as quantum many worlds
- …

… implications on particle physics and cosmology

# Shocking news in 1998

Supernova cosmology project; Supernova search team

## Universe is accelerating!

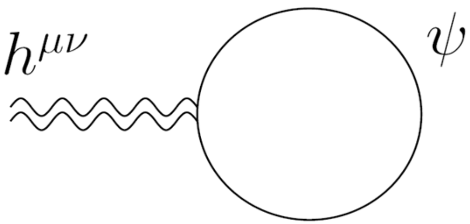



Particle Data Group (2010)

$$\Lambda \neq 0\,!$$

# The cosmological constant problem

- Every particle couples to gravity




*… generates $\mathcal{L} \sim \sqrt{-g}\, \rho_\Lambda$*
*by quantum corrections*

Natural size of $\rho_\Lambda \equiv \Lambda^2 M_{Pl}^2$

$\rho_\Lambda$ ~ where new physics cuts loop integrals of $\psi$

- Naively $\rho_\Lambda \sim M_{Pl}^4$
- At the very least, $\rho_\Lambda \sim \mathrm{TeV}^4$

Observationally,

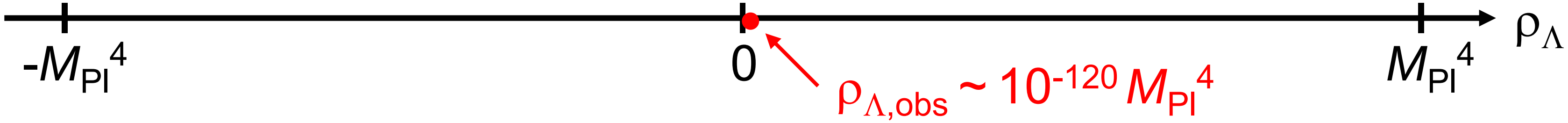
$\rho_\Lambda \sim (10^{-3}\ \mathrm{eV})^4$ Naïve estimates $O(10^{120})$ too large

… the worst prediction ever made !

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

# Nonzero value completely changes the view !

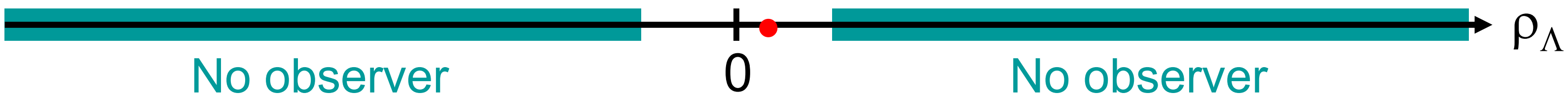
Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$




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 $\rho_\Lambda$ are "sampled"

Weinberg ('87)

# Many universes – multiverse – needed

- String landscape

Compact (six) dimensins

→ huge number of vacua

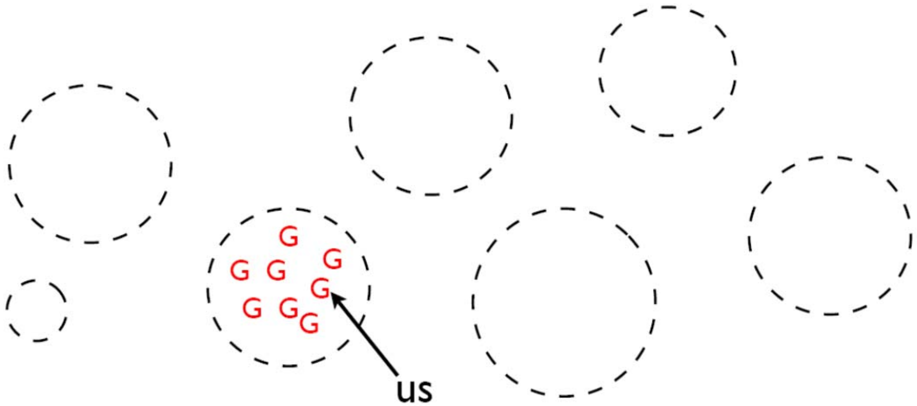
ex. $O(100)$ fields with $O(10)$ minima each

→ $O(10^{100})$ 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: $P \ll 10^{-3}$

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

….

Some of them anthropic (and some may not)

$\Longrightarrow$ Implications?

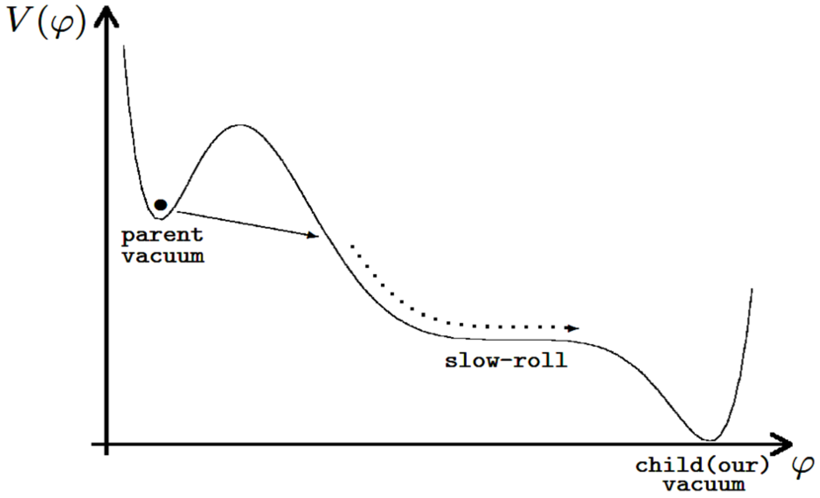
- Observational / experimental (test, new scenarios, …)
- Fundamental physics (spacetime, gravity, …)

# *Implications*

*—observation / experiment —*

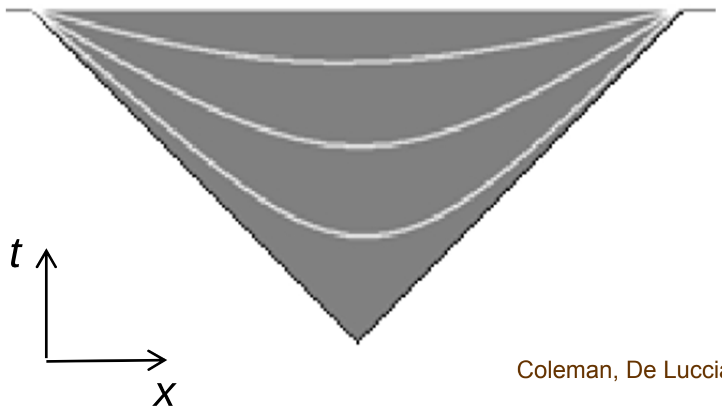
# Cosmology

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?

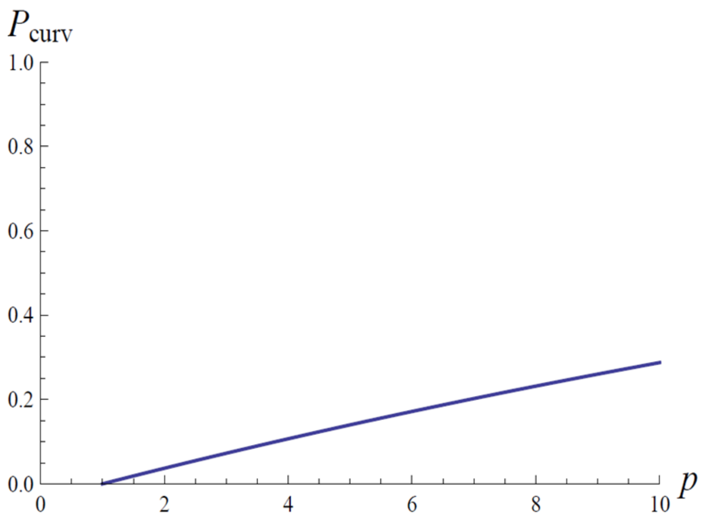
- Fine-tuning initial conditions
- Having a (accidentally) flat portion in the scalar potential

→ (Observable) inflation

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

"difficulty" of realizing a flat potential

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




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

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

….

Guth, Y.N.

# Particle Physics

Anthropic (could) affects how our universe looks

$\rightarrow$ Any change in our thinking? New scenario(s)?

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

ex. Stability of complex nuclei

For fixed Yukawa couplings,

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

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

Weak scale supersymmetry really "needed"?

… the scale of SUSY masses determined by statistics

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

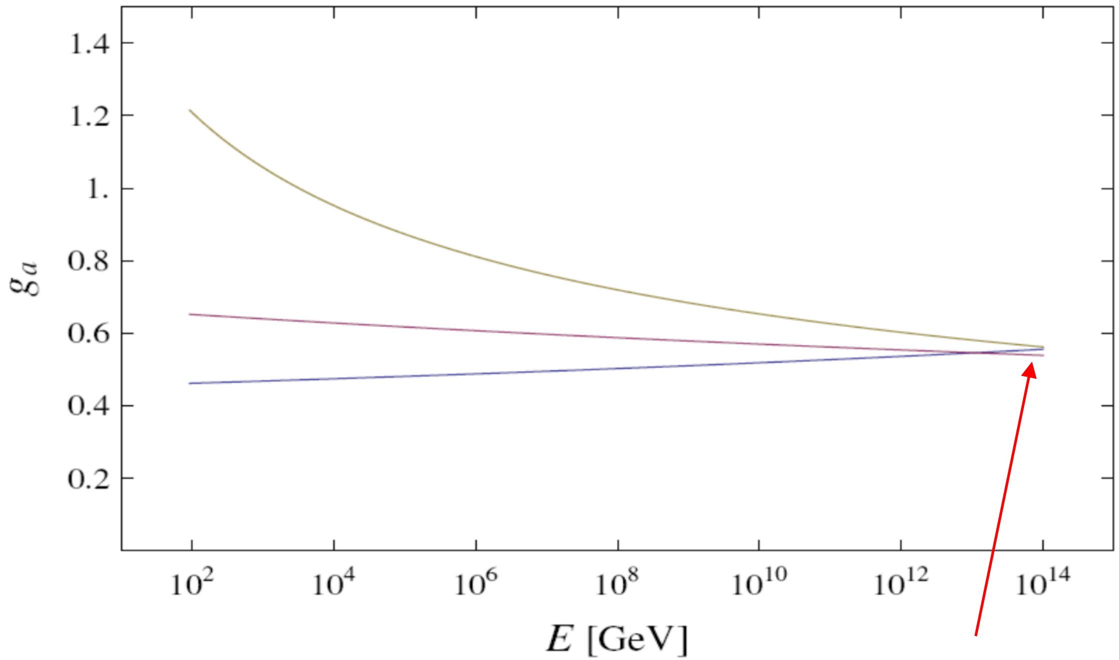
$f(\tilde{m}) \sim \tilde{m}^{p-1}$

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

# What if $\tilde{m}$ shoots up?

Hall, Y.N., arXiv:0910.2235

## "Minimal" scenario — Standard Model !




Unification at the level of $\delta g_a^2 \sim 6\%$ at $E \sim 10^{14}$ GeV

unification
~~SUSY~~
~ $10^{14}$ GeV

Dark matter can be axions — $\theta_{QCD} \ll 1$ … need mechanism

## Doesn't seem that bad…

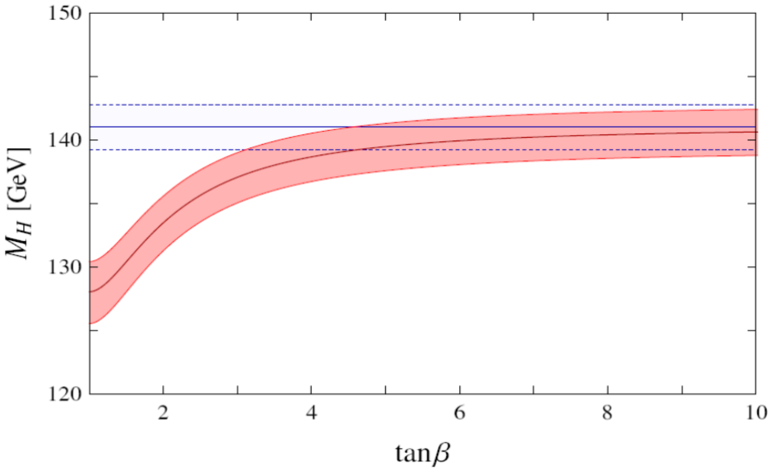
(Note: no SUSY flavor problem, SUSY CP problem, $\mu$ problem, gravitino problem, axino problem, or …)

# High scale ~~SUSY~~ — nothing left?

SUSY boundary condition on the Higgs quartic $\lambda$

$$\boxed{\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8}\cos^2 2\beta}$$

$\lambda(m) \;\rightarrow\; \lambda(v) \;\rightarrow\; M_H$ prediction




2-loop RGE + 1-loop threshold
QCD threshold up to 3 loops

$m_t = 173.1 \pm 1.3$ GeV
$\alpha_s(M_Z) = 0.1176 \pm 0.002$

$M_H \approx (128 - 141)$ GeV

Many theories lead to this "edge value"

# Crazy?

Do we know $\tilde{m}$?

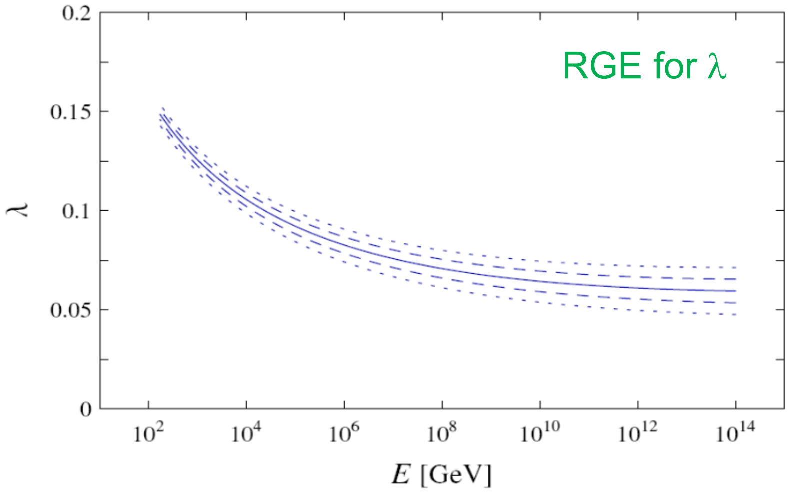
What about threshold corrections? $\Rightarrow$

$$\boxed{\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8}\{1 + \delta(\tilde{m})\}}$$

includes all threshold corrections

$\tilde{m}$: matching scale

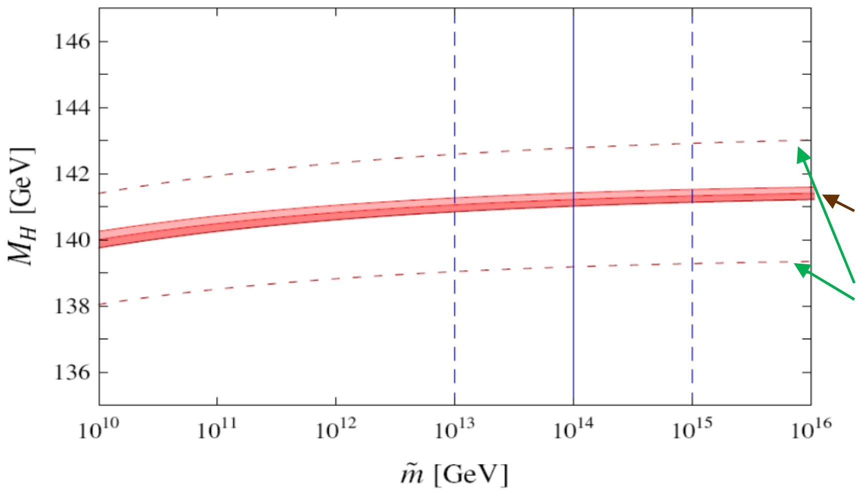
# Infrared convergence property




$\delta$ = 0, ±0.1, ±0.2
for $\tilde{m}$ = $10^{14}$ GeV

The fractional uncertainty
reduced by ~ a factor of 6

# Extreme insensitivity to $\tilde{m}$




fixed $\delta$ = 0, 0.02, 0.04

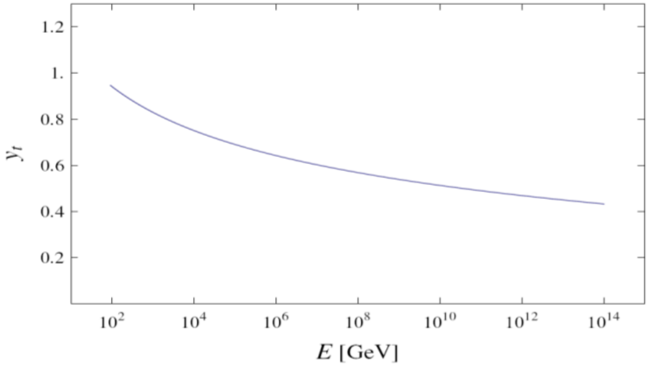
1$\sigma$ $m_t$ error

$$\delta M_H = 0.14\,\mathrm{GeV}\left(\log_{10}\frac{\tilde{m}}{10^{14}\,\mathrm{GeV}}\right)$$

Explicit dependence
on $\tilde{m}$ extremely mild !

# Suppressed threshold corrections

SUSY corrections at *m* $\rightarrow$ very small !




$y_t(\tilde{m}) \approx 0.5\, y_t(v)$

($\delta_s$ proportional to $y_t^4$)

## $\Longrightarrow$ Largest uncertainties

$\delta m_t|_{exp} = \pm 1.3$ GeV $\Longrightarrow$ $\delta M_H = \pm 1.8$ GeV

$\delta\alpha_s(M_Z)|_{exp} = \pm 0.002$ $\Longrightarrow$ $\delta M_H = \mp 1.0$ GeV

# Precision Higgs mass prediction !!

$$\boxed{\begin{aligned} M_H \;=\; & 141.0\ \mathrm{GeV} + 1.8\ \mathrm{GeV}\left(\frac{m_t - 173.1\ \mathrm{GeV}}{1.3\ \mathrm{GeV}}\right) - 1.0\ \mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1176}{0.002}\right) \\ & + 0.14\ \mathrm{GeV}\left(\log_{10}\frac{\tilde{m}}{10^{14}\ \mathrm{GeV}}\right) + 0.10\ \mathrm{GeV}\left(\frac{\delta}{0.01}\right) \pm 0.5\ \mathrm{GeV} \end{aligned}}$$

$M_H = (141 \pm 2)$ GeV

… irreducible high energy errors only ~ ±0.4 GeV !

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

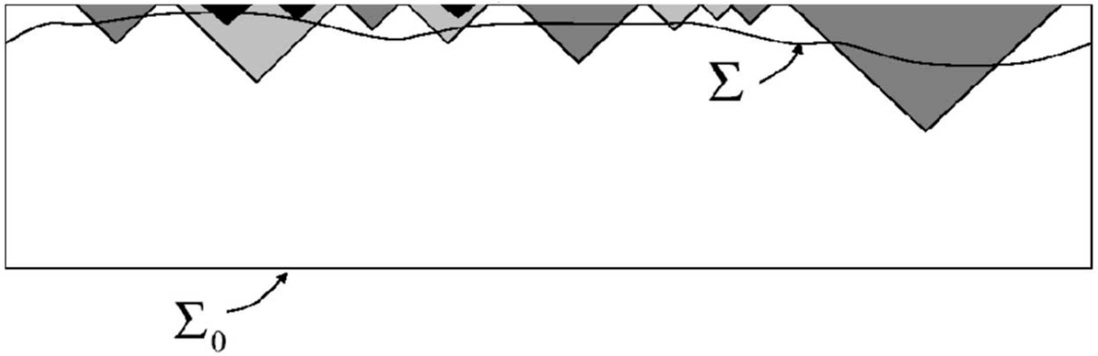
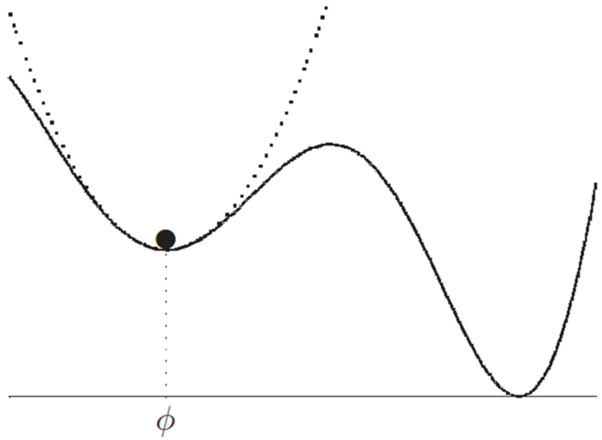



figure from Vilenkin ('06)

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

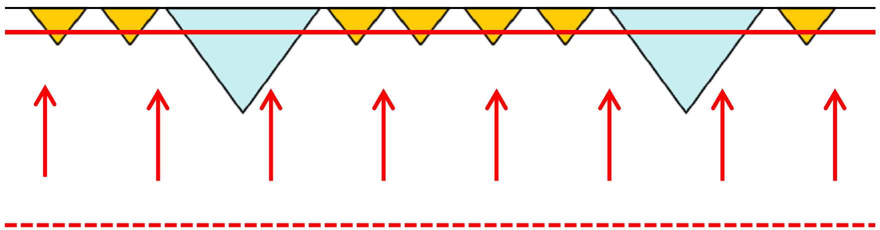
- The problem is robust




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)

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

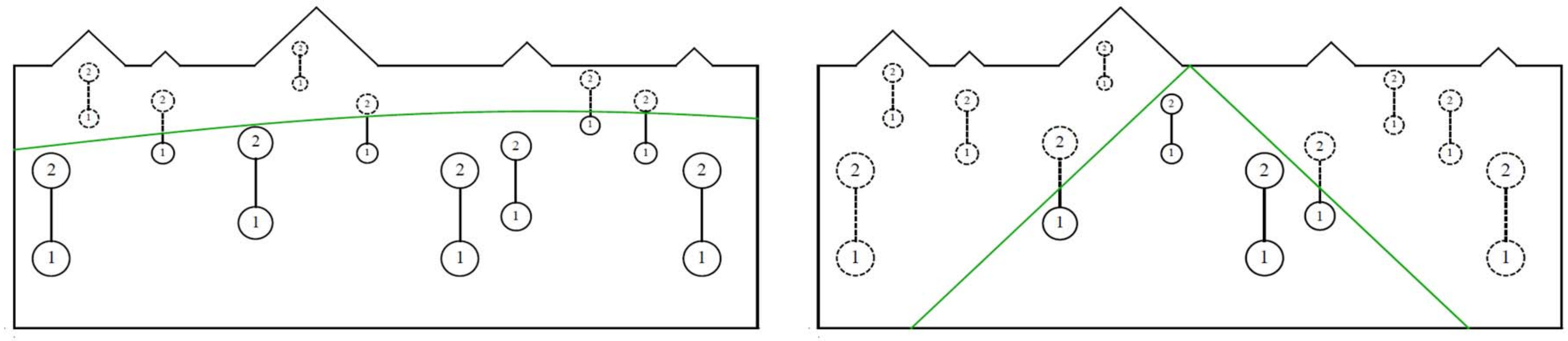
… vastly more younger universes than older ones

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

… 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 !

$$P_{\mathrm{end}} \equiv 1 - \frac{N_2}{N_1} \not\to 0$$

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 quamtum mechanics are not violated (only) when physics is described from an observer's point of view**

## Quantum mechanics in systems with gravity needs care

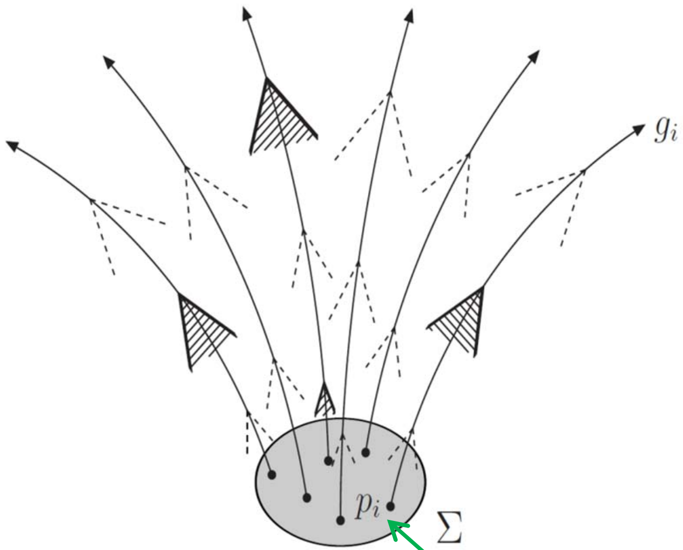
$\Longrightarrow$ Dramatic change of our view on spacetime

- 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

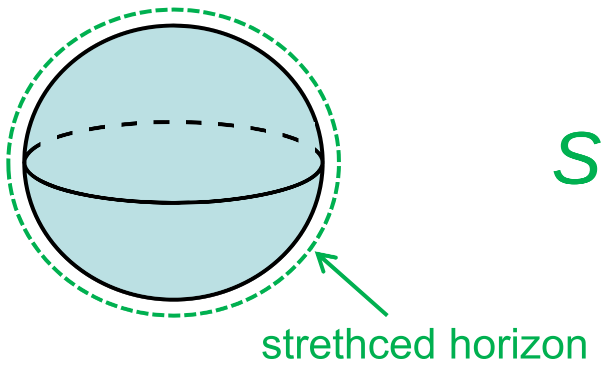
$\ell \ll \ell_{\rm Pl}$ — Does it make sense?

# Holographic principle

't Hooft ('93); Susskind ('94); Bousso ('99)

The dimensions of states (# of d.o.f) bounded by the **area**

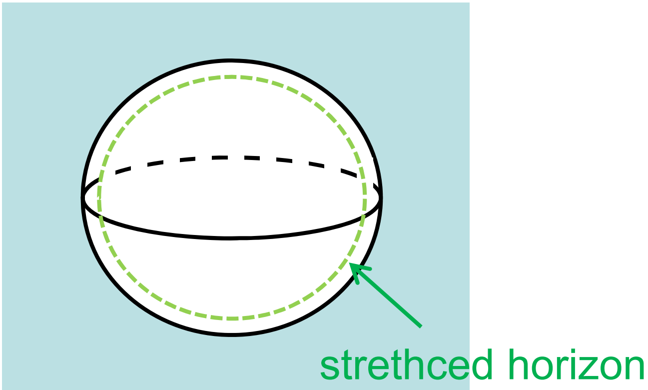
Black hole:



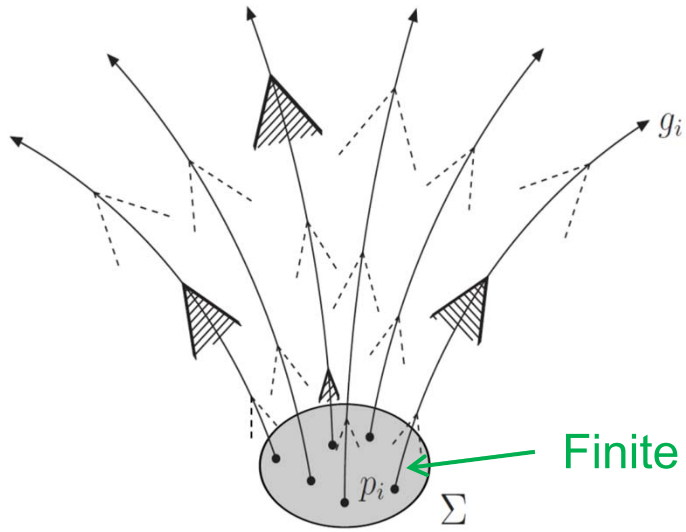

$$S = \ln \mathscr{N} = \frac{A}{4\,\ell_{Pl}^{\,2}}$$

Bekenstein ('73); Hawking ('74)

de Sitter space:



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

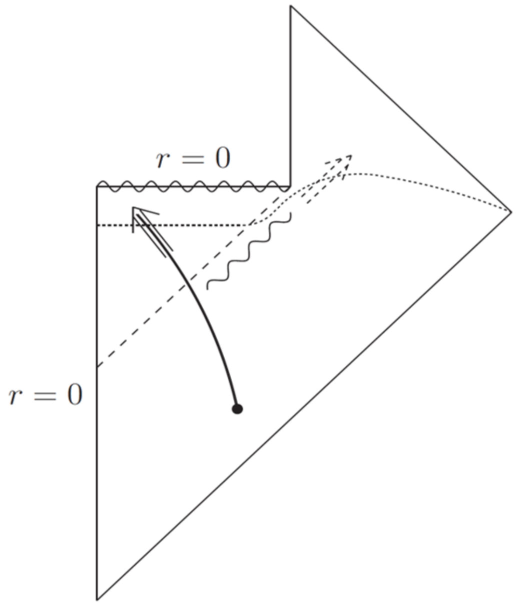
The *single* state $\Psi$(t) describes the *entire* multiverse ! (“no” global spacetime)

$\Longrightarrow$ How to define the state explicitly?

# 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.

A lesson: Equal time hypersurface must be chosen carefully.

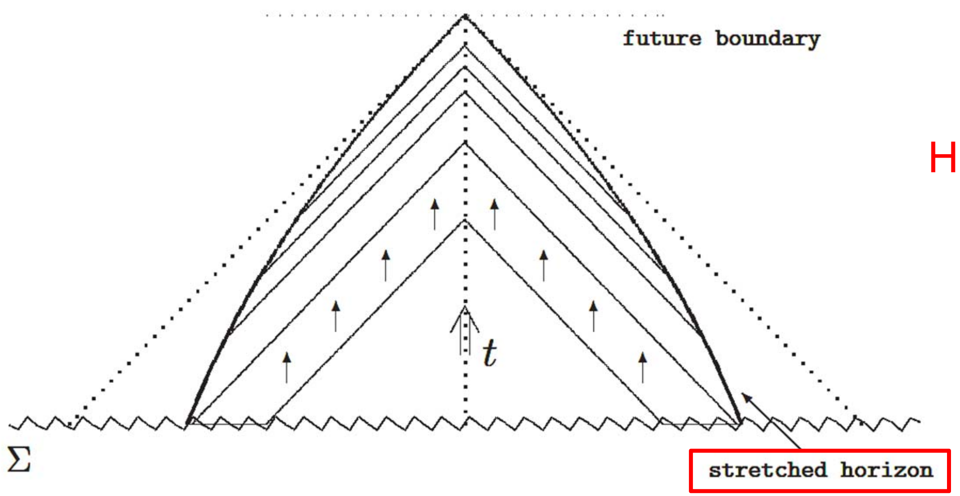
# Multiverse state |Ψ(t)>

## 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)

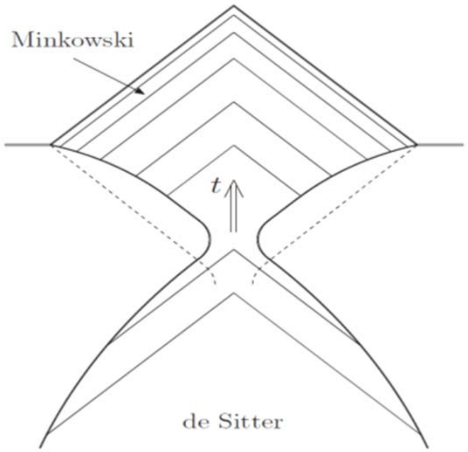
Specifically, the state is defined on the observer's past light cones bounded by the (stretched) apparent horizons.

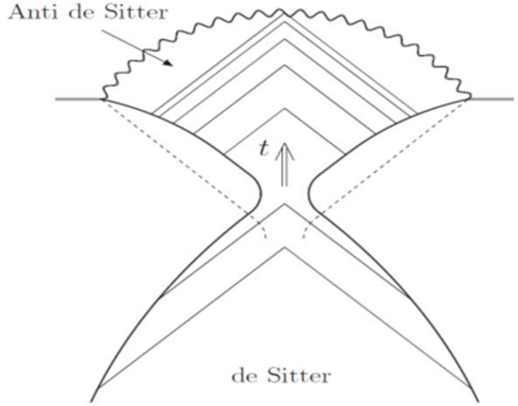



How to define equal time hypersurfaces?

→ Past light cones

# Bubble nucleations:



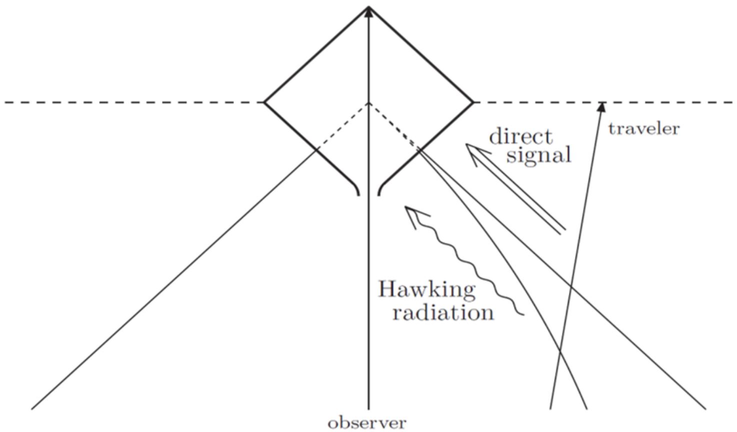




Apparent horizon:

- NOT depend on low energy physics
- always exists in any FRW universes
- "locally" determined within a bubble
- plays a role of the "preferred screen"

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

# Consistent!




This duplication
does *not* occur !

# Hilbert space

$|\Psi(t)>$: superposition of semi-classical spacetimes

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

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

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
- “gauge invariant”

## Semi-classical approximation:

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

… information loss

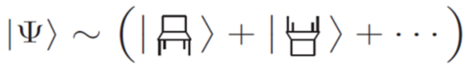
# Quantum-to-classical transition

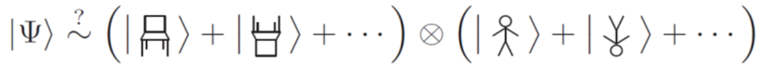
Multiverse: (intrinsically) quantum mechanical

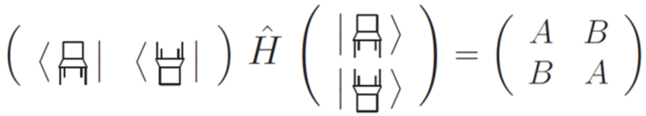
$\leftrightarrow$ Our daily experience: (almost) classical

How does this dichotomy arise?

ex. Rotationally invariant theory

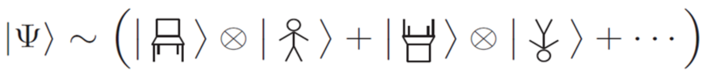
A chair: 

A chair + a man:  $\Longrightarrow$ No

 $\longrightarrow$ Eigenstates 

with eigenvalues $A \pm B$

For a macroscopic object, $B \ll A$

$\Longrightarrow$ 

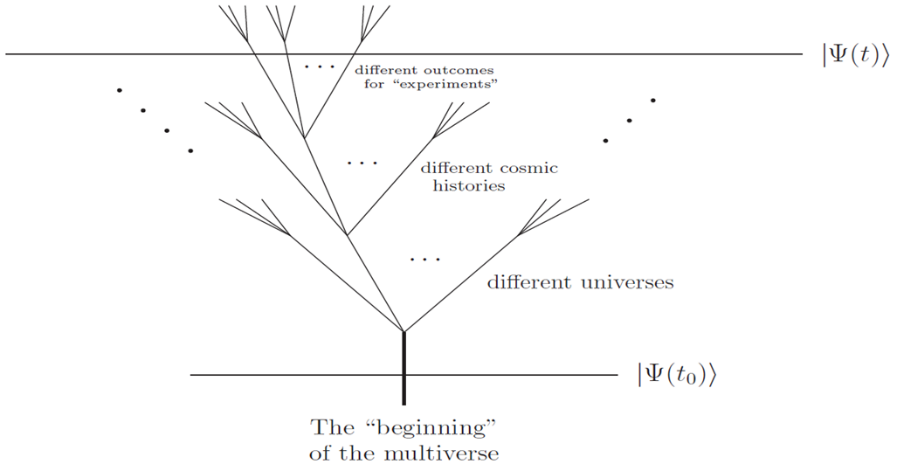
The chair always has a definite orientation *with respect to* the man.

(The man, ≈ we, do not see a superposition of chairs.)

# 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.

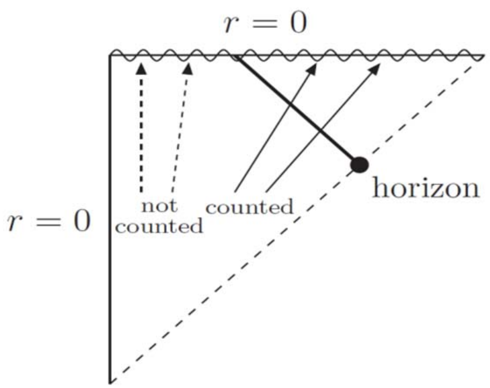
→ Unified treatment of quantum measurements and the multiverse

# Problems in Geometric Cutoffs Solved

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

# The ultimate future

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

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

infinite entropy reservoir

# The "beginning"

$$|\alpha_{\text{beginning}}\rangle \quad \rightarrow \quad |\Psi(t)\rangle = \sum_i c_i(t)\, |\alpha_i\rangle$$

contains $|\alpha_{\text{beginning}}>$ at some time *t*

$\rightarrow$ restart the whole multiverse from there as a branch of $|\Psi(t)>$

Why can't we identify $|\alpha_{\text{beginning}}>$ as a component of a "larger" structure?

# Our multiverse is a fluctuation in a larger structure:

$$\boxed{S_{\text{beginning}} \sim 0 \quad \rightarrow \quad S_{\text{Minkowski}} = \infty}$$

… the arrow of time

Two possibilities:

- The multiverse with a beginning

  (e.g. creation from "nothing")

- The stationary, fractal "mega-multiverse"

  (Quantum mechanics satisfied *all* the time — no beginning or end)

# 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 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, …