Eternally inflating multiverse and many worlds in quantum mechanics: same concept ?

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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
- …

… connection between cosmology and string (or any fundamental) theory

Shocking news in 1998

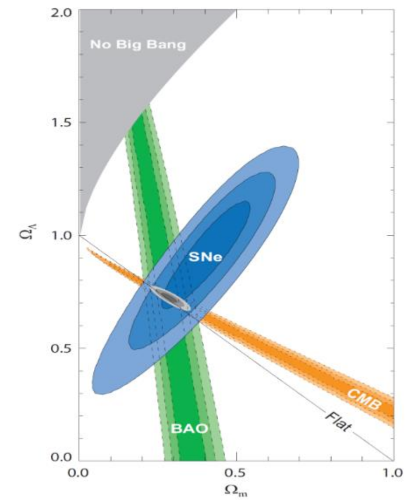
Supernova cosmology project; Supernova search team

Expansion of the Universe is accelerating!

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

Observationally,

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



Particle Data Group (2010)

Its smallness is already hard to understand

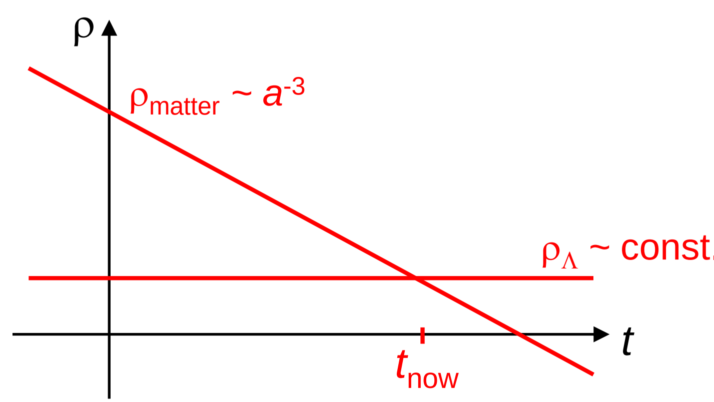
… natural size of $\rho_\Lambda \equiv \Lambda^2 M_{Pl}^2 \sim M_{Pl}^4$ (at the very least ~ TeV^4)

… Naïve estimate is $O(10^{120})$ too large

Moreover

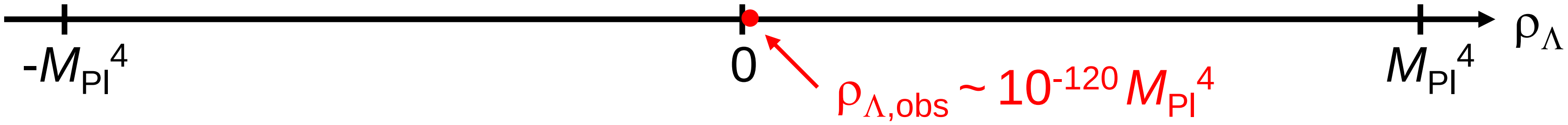
$$\rho_\Lambda \sim \rho_{matter}$$

— 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)

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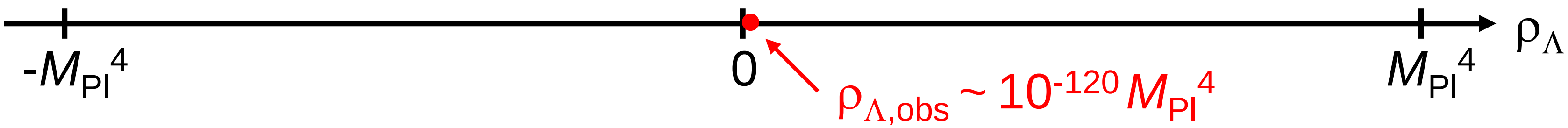
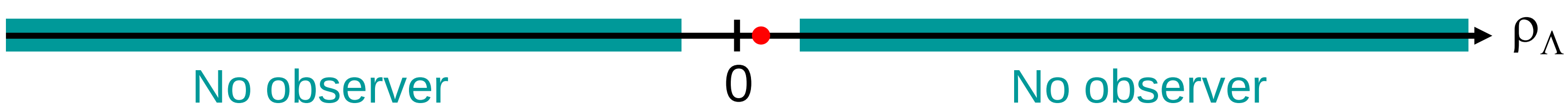
Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$



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 natural to observe $\rho_{\Lambda,obs}$,

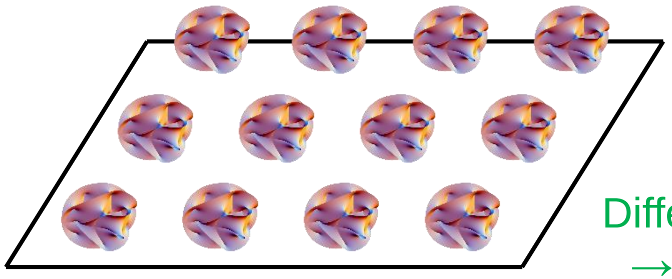
as long as different values of ρ_Λ are "sampled"

Weinberg ('87); also Banks, Linde, …

Theory also suggests:

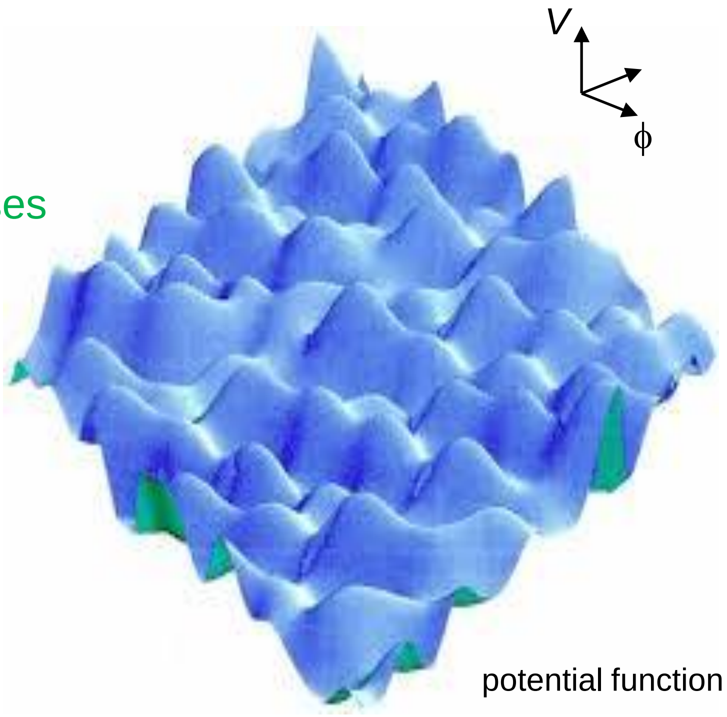
- String theory

… existence of extra dimensions



https://commons.wikimedia.org/wiki/File:Calabi-Yau-alternate.png

Different solutions
→ Different universes



http://journalofcosmology.com/Multiverse9.html

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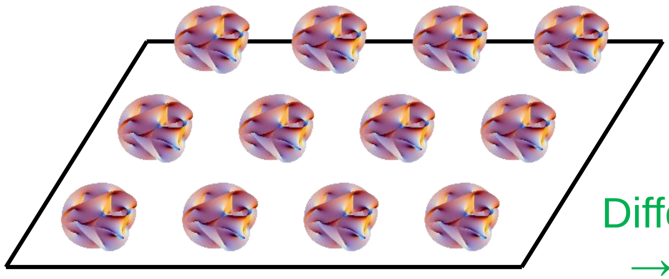

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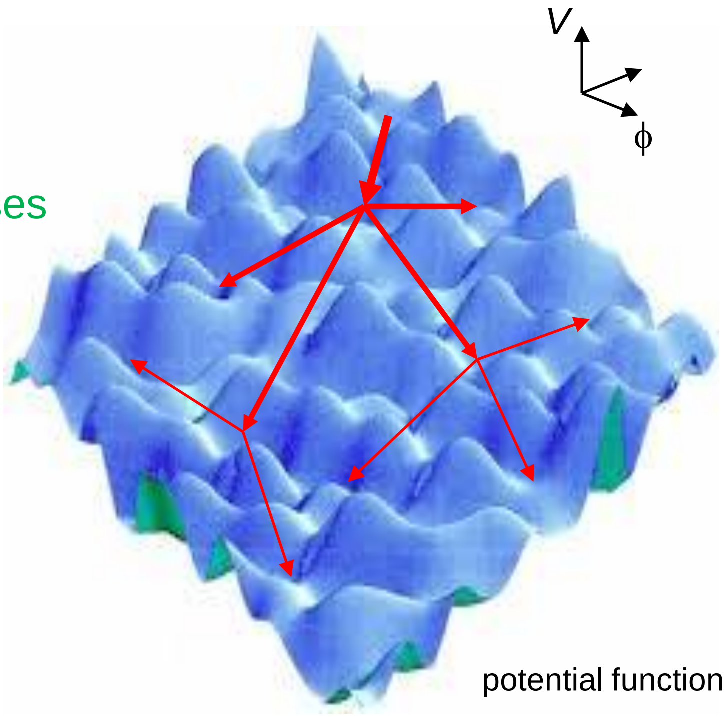

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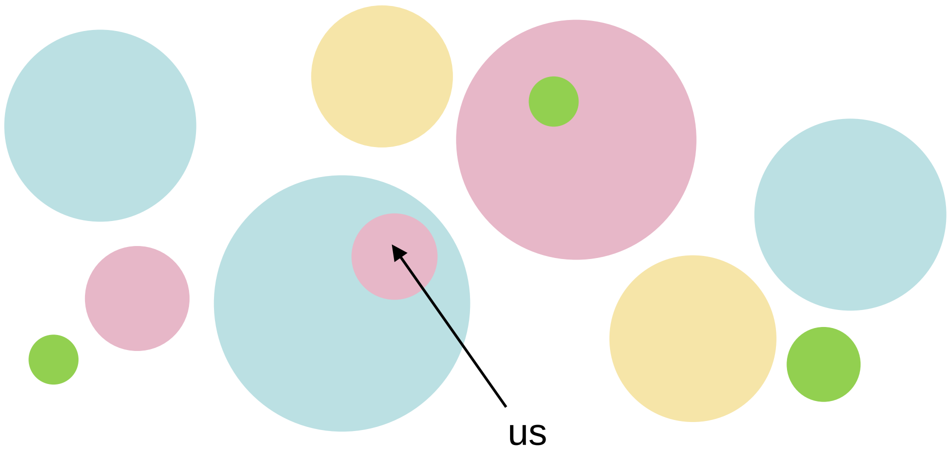
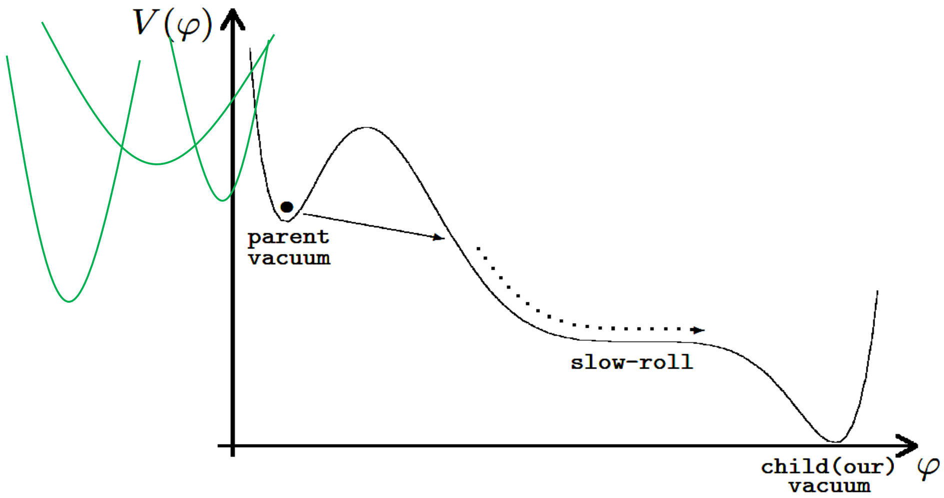
- Inflation

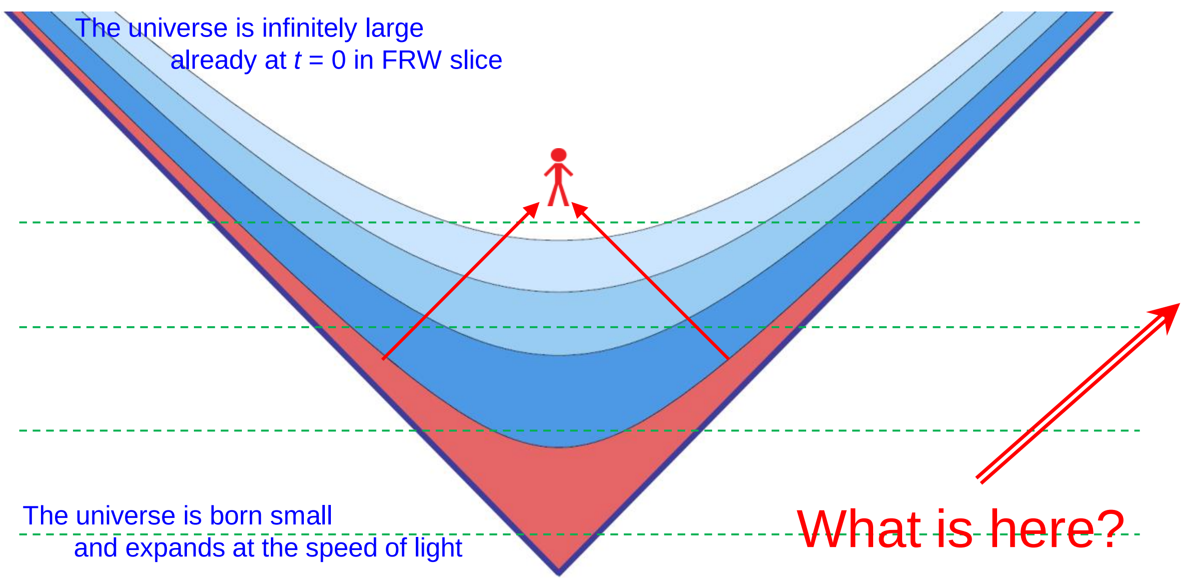
… eternal to the future



… keep forming new “bubbles”

Our universe is a “bubble” inside a larger structure!

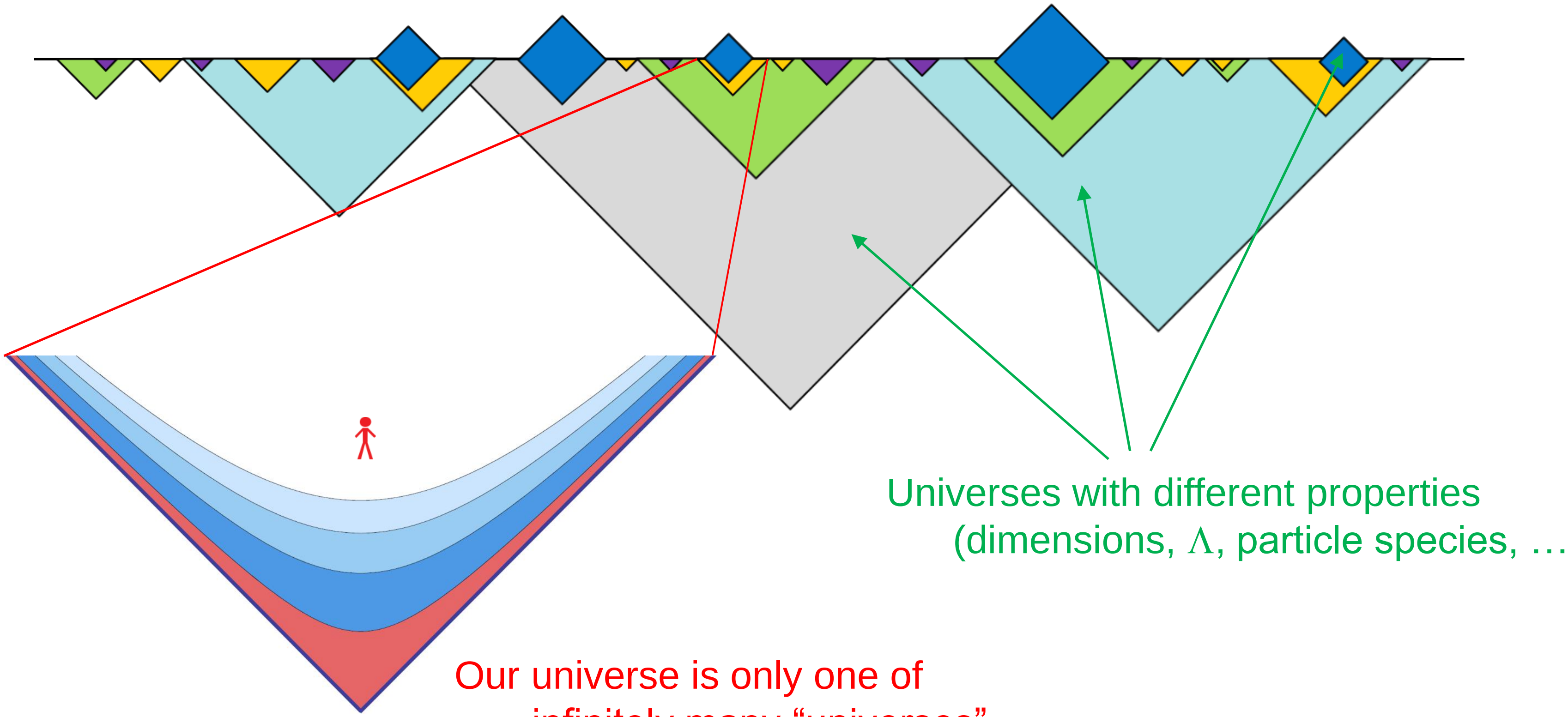




- What’s there before the universe was born?
- What’s there outside the universe?

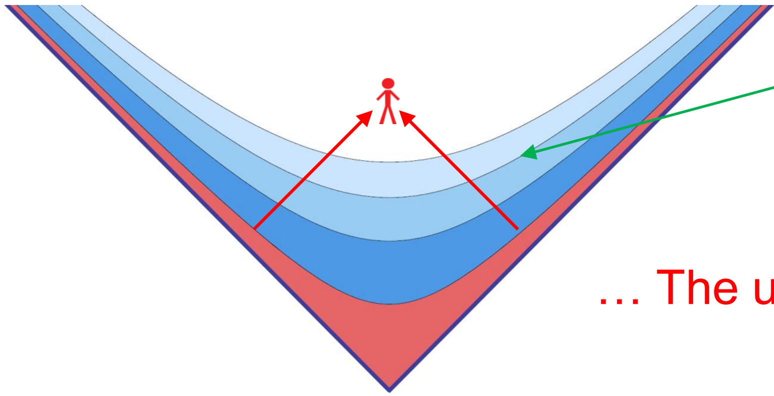
Coleman, De Luccia (’80)

Multiverse!



Many of the quantities we thought fundamental (Λ, particle species, …)
are properties of our "local environment" (universe)!

The curvature of our universe

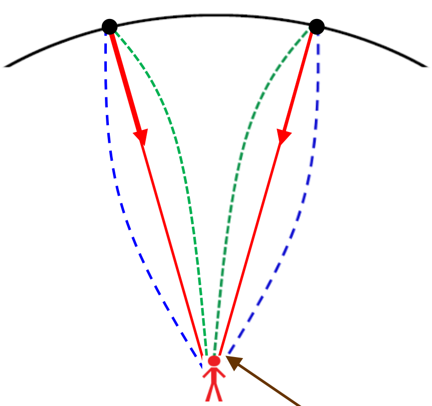


equal time for interior observers (us)

… The universe appears as “negatively curved”!

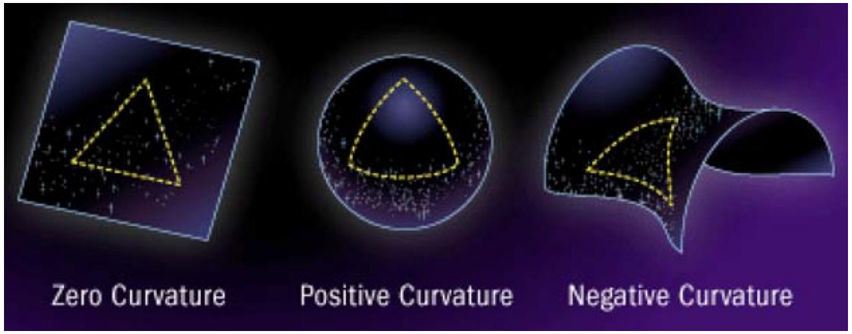
(though can’t predict how much)

It can be measured



measure the angle

curvature



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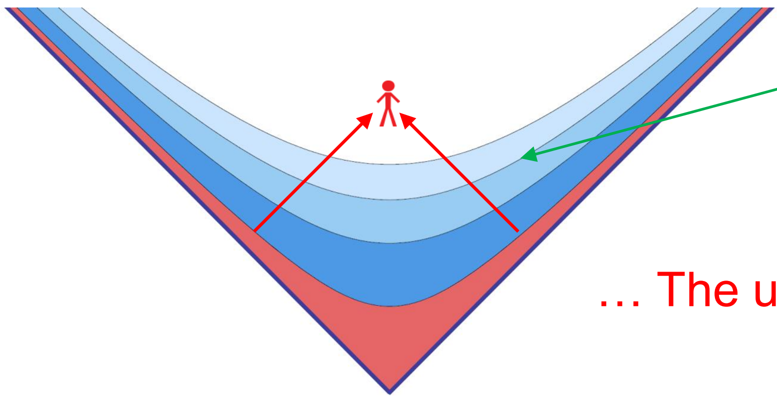

equal time for interior observers (FRW)

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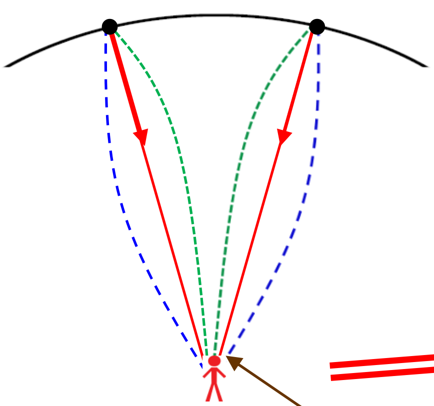
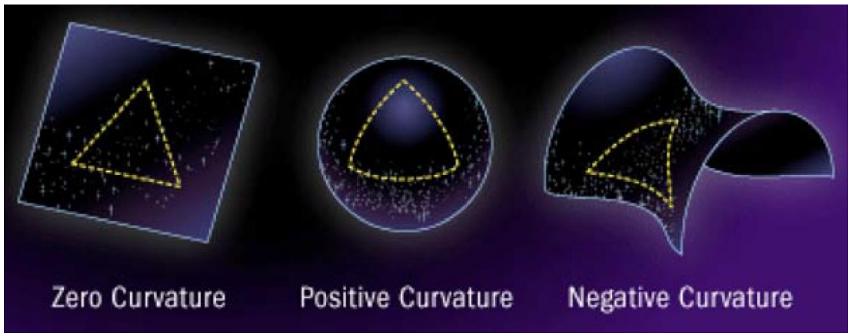


measure the angle

curvature

LD © 2008 HowStuffWorks



– X O

This would **exclude** the framework !

Far-reaching implications

… The multiverse is "infinitely large"!

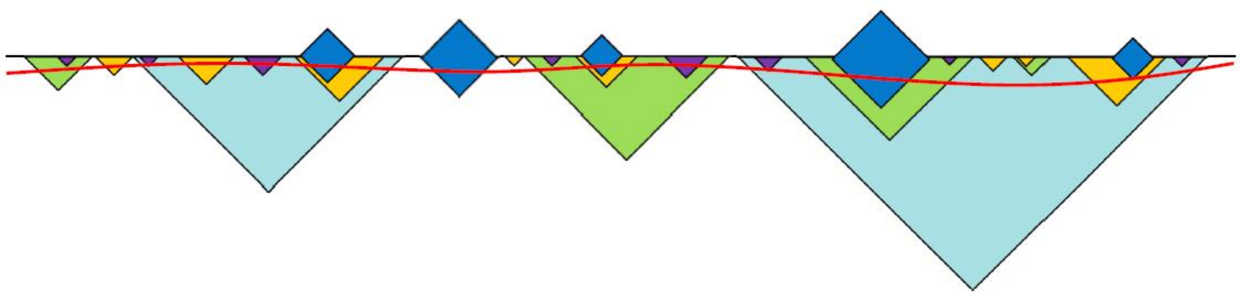
Predictivity crisis!

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*

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

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



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

The problem consists of several elements

— Problem of infinity

… How is the infinity regulated?

— Problem of arbitrariness

… What is the principle behind the regularization?

— Problem of selecting the state

… What is the initial condition of the multiverse?

— …

Work addressing various aspects:

Aguirre, Albrecht, Bousso, Carroll, Garriga, Guth, Linde, Nomura, Page, Susskind, Tegmark, Vilenkin, …

This can be a great opportunity !

Below, my view

Quantum mechanics is essential to answer these questions.

Multiverse = Quantum many worlds

… Breakdown of the general relativistic spacetime picture **at long distances**

Multiverse = Quantum Many Worlds

Y.N., "Physical theories, eternal inflation, and the quantum universe," JHEP **11**, 063 ('11) [arXiv:1104.2324]

(see also Bousso, Susskind, PRD **85**, 045007 ('12) [arXiv:1105.3796])

— in what sense?

Quantum mechanics is **essential**

The basic assumption:

The basic structure of quantum mechanics persists when an appropriate description of physics is adopted

→ Quantum mechanics plays an important role even at largest distances:

$\boxed{\text{The multiverse lives (only) in probability space}}$

Probability in cosmology has the same origin as the quantum mechanical probability

… provide simple regularization

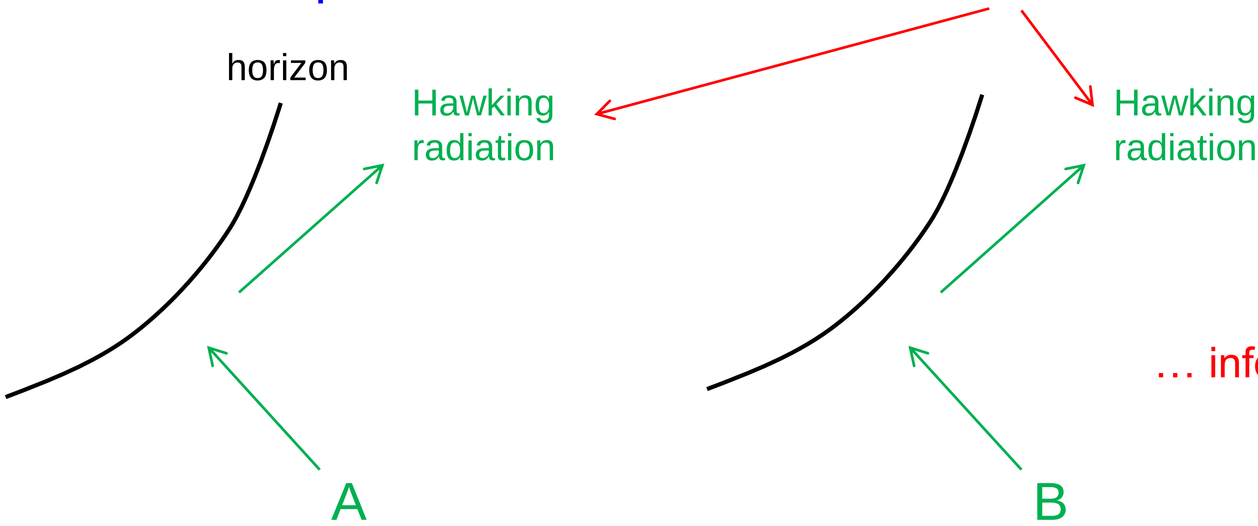
(Anything that can happen will happen *but not with equal probability*.)

Quantum mechanics in a system with gravity

Black Hole

Information loss paradox

same at the semi-classical level



… information is lost ??

Hawking ('76)

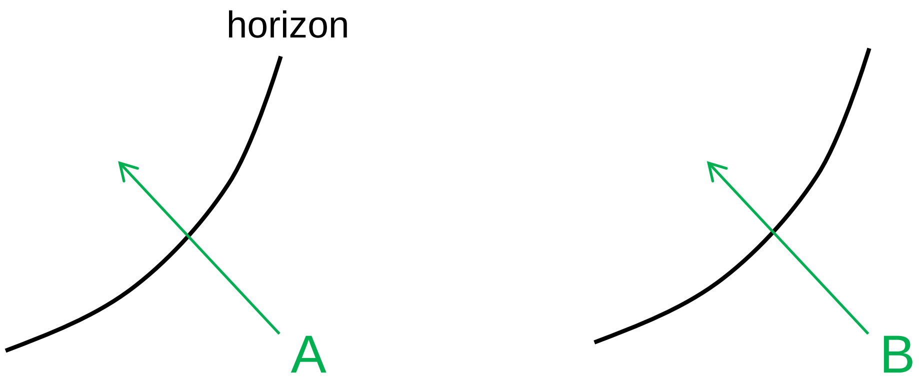
⟹ No

… 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)

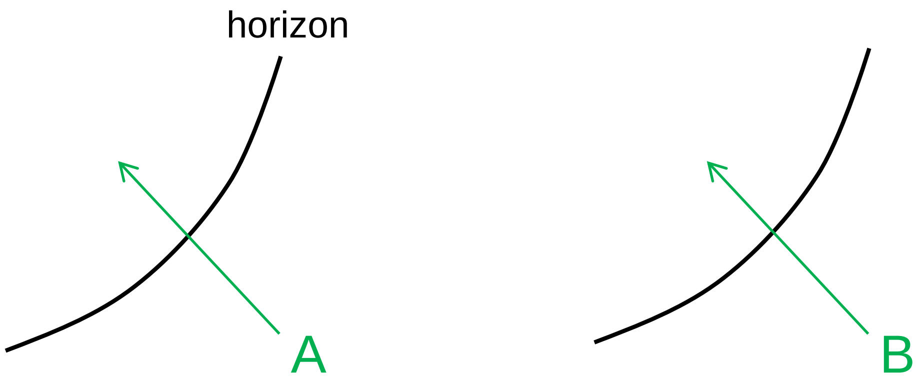
$|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$

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

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

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

From a falling observer's viewpoint:



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Which is correct?

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

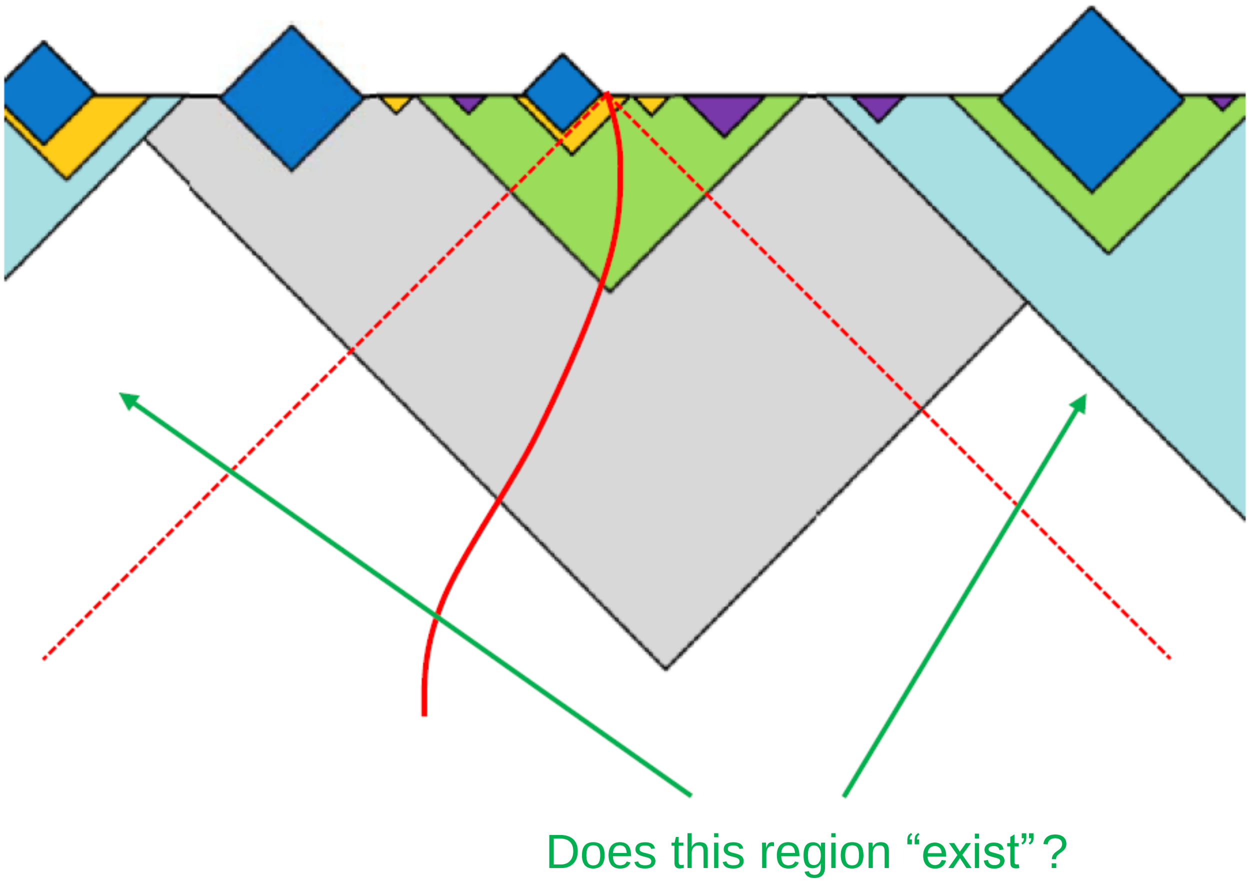
There is no contradiction !

One cannot be *both* distant and falling observers *at the same time*.

… "Black hole complementarity" Susskind, Thorlacius, Uglum ('93); Stephens, 't Hooft, Whiting ('93)

A Lesson:

Including both Hawking radiation and
interior spacetime in a single description is **overcounting**!



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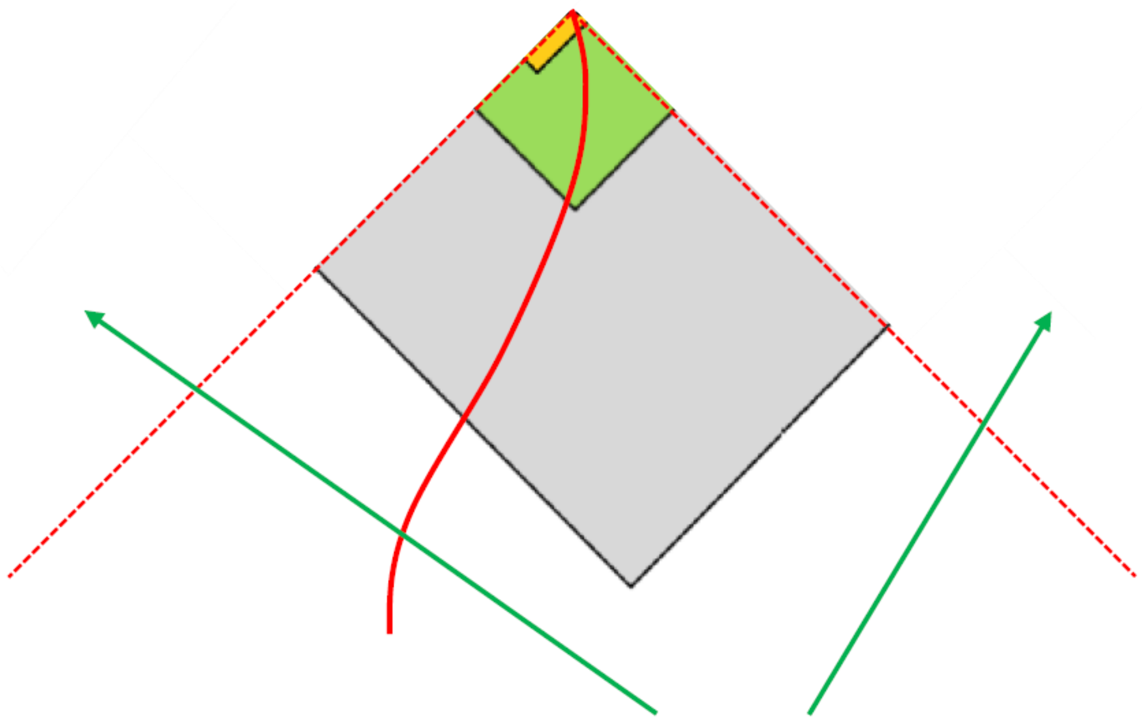
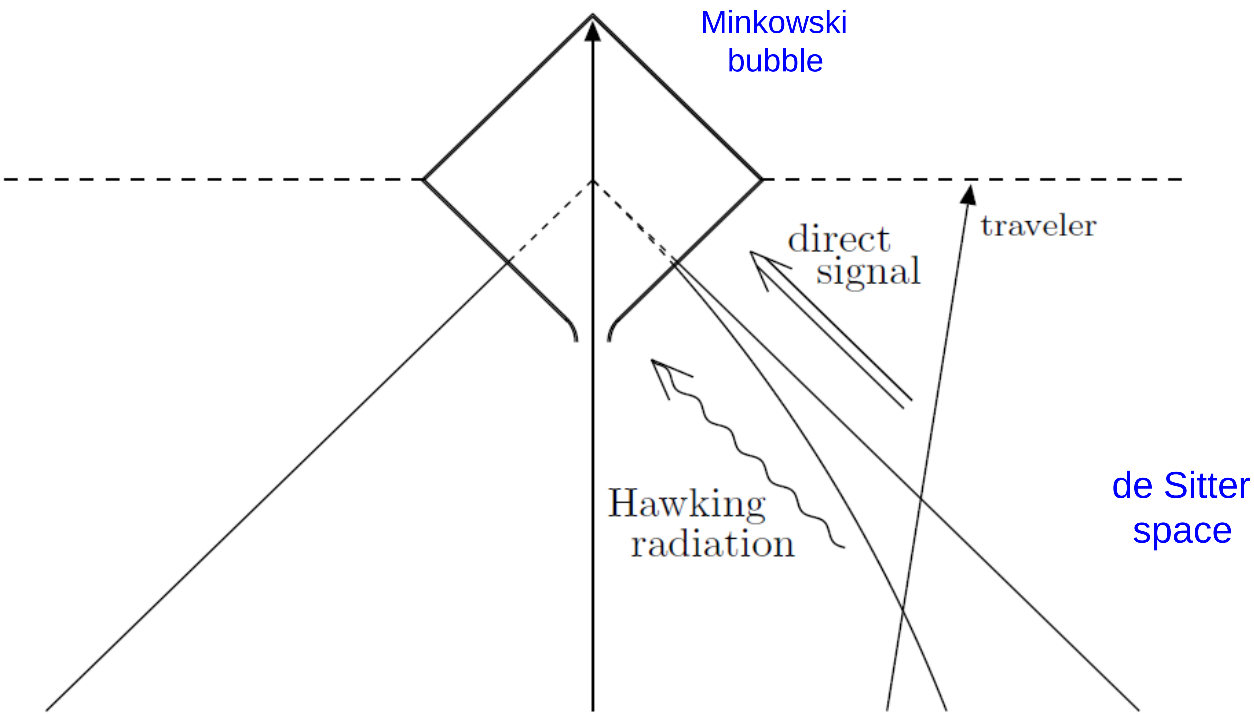


Does this region “exist”? → No!

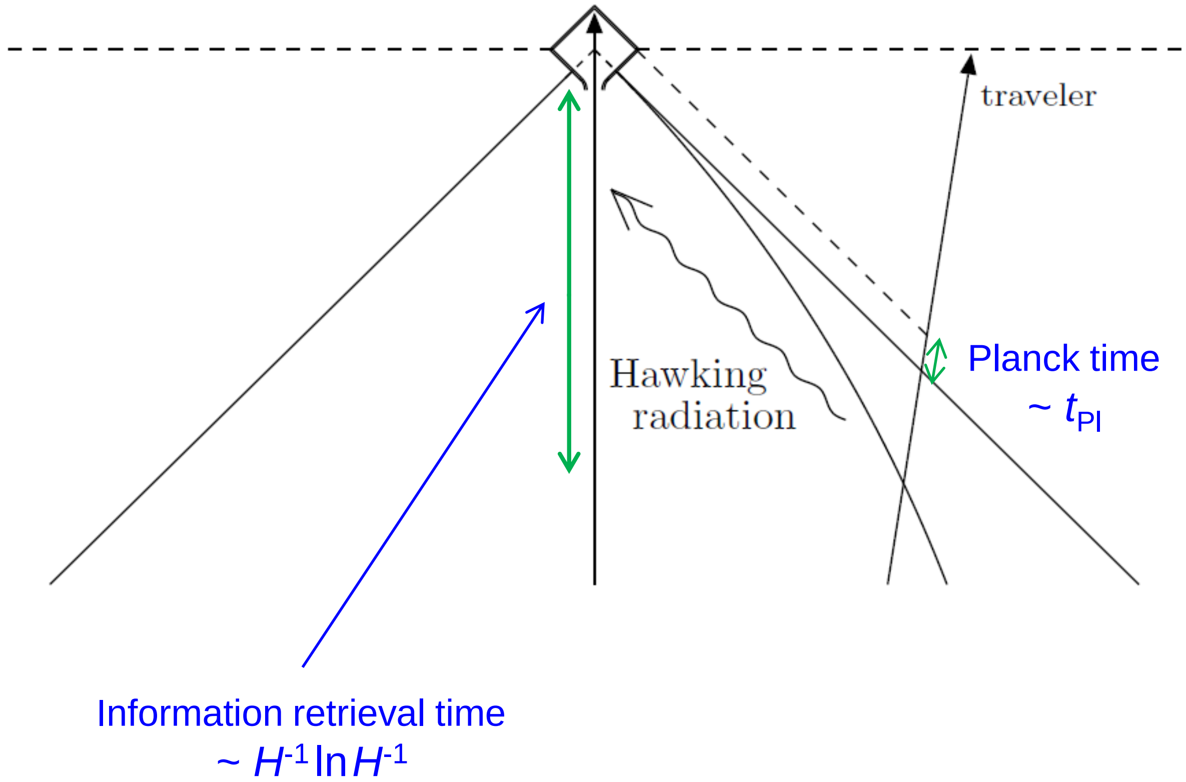
… What happened to the multiverse?

Consistent?



Doesn’t information duplicate?

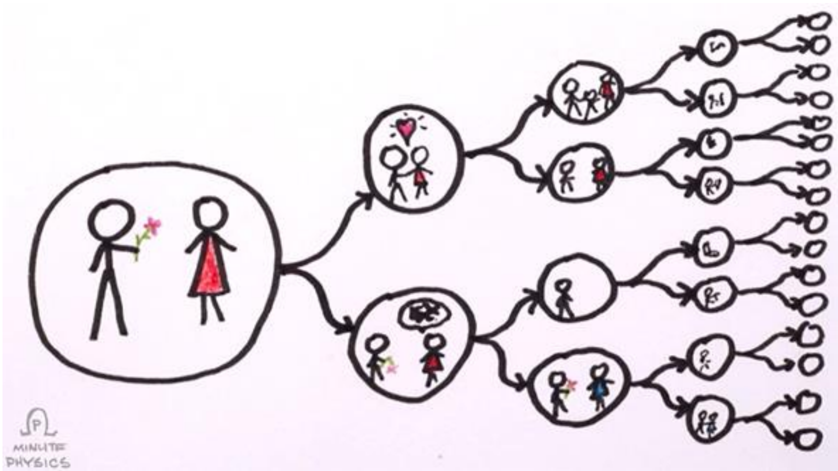
Consistent? — Yes



The information duplication does *not* occur!

Information can be obtained *either* from Hawking radiation *or* from direct signal, but *not from both*.

We live in a quantum mechanical world!



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: $\Psi(t=t_0) = |\Sigma\rangle \quad \rightarrow \quad \Psi(t) = \cdots + c\left|\begin{smallmatrix} 321 \\ \rho_\Lambda \end{smallmatrix}\right\rangle + c'\left|\begin{smallmatrix} 321 \\ \rho'_\Lambda \end{smallmatrix}\right\rangle + \cdots + d\left|\, 41 \,\right\rangle + \cdots$

eternally inflating

each term representing only the causally accessible region

… provides natural and effective "regularization"

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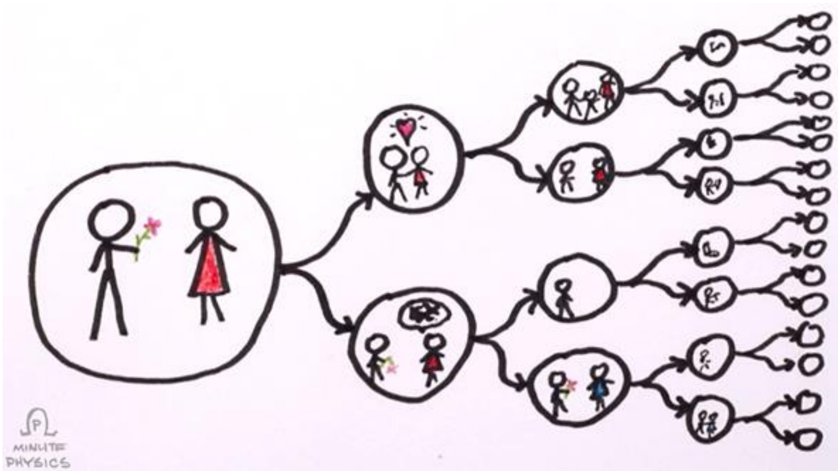

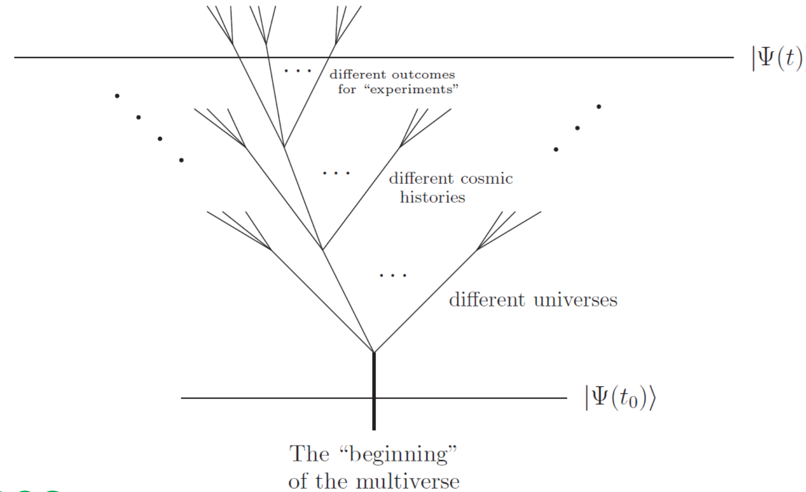

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eternally inflating

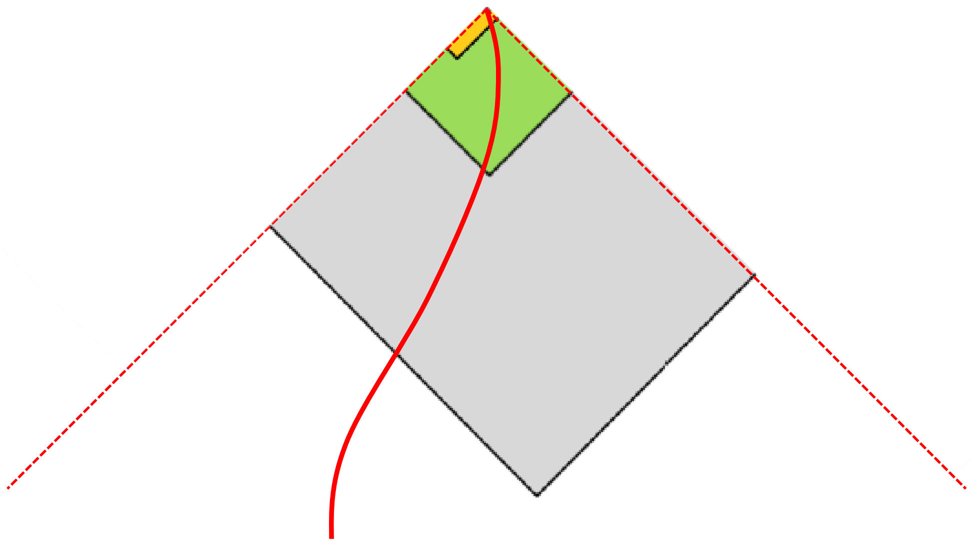
each term representing only the causally accessible region

… provides natural and effective "regularization"

Multiverse = Quantum many worlds

… The multiverse lives (only) in probability space!

Global spacetime of general relativity
is an emergent (and “redundant”) concept!



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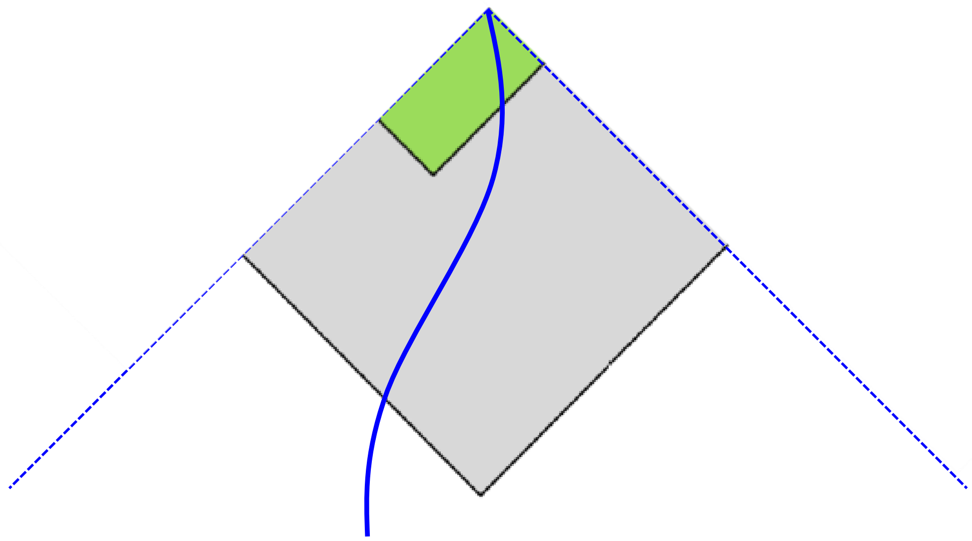

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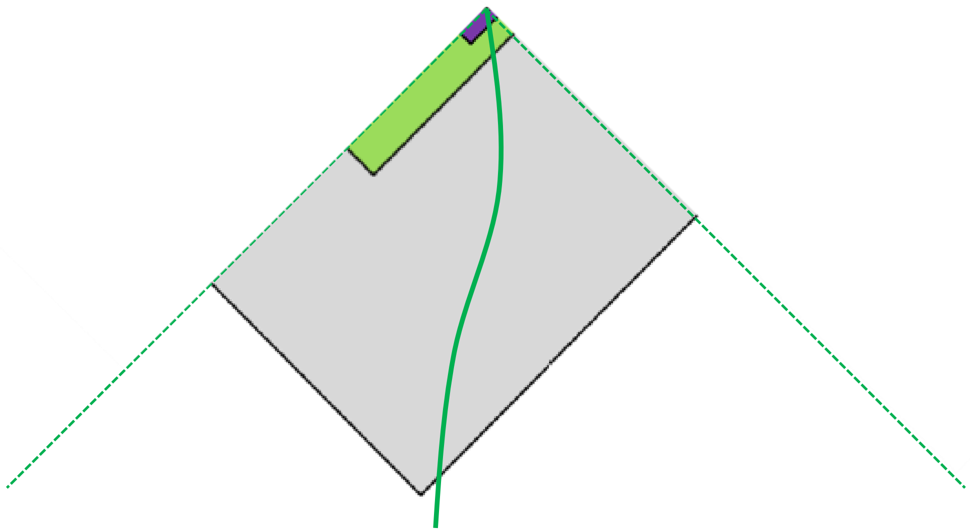

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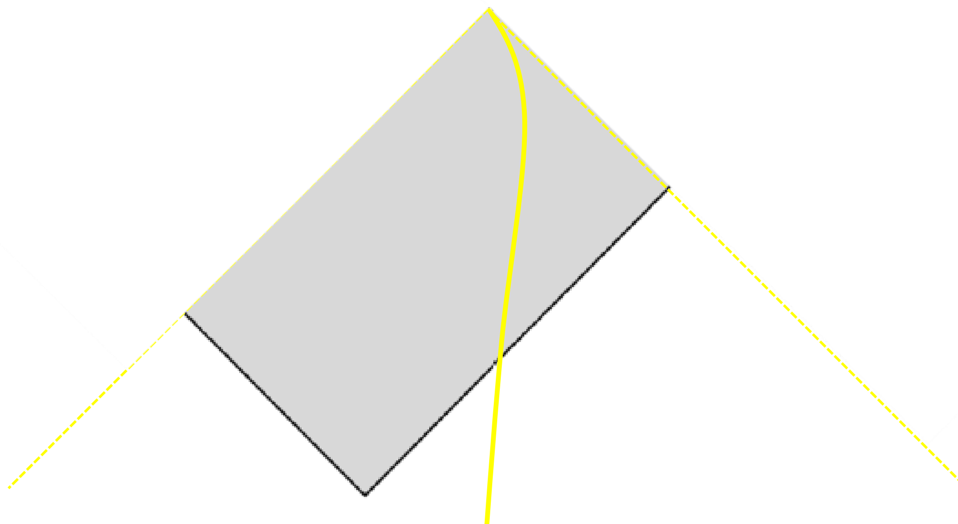

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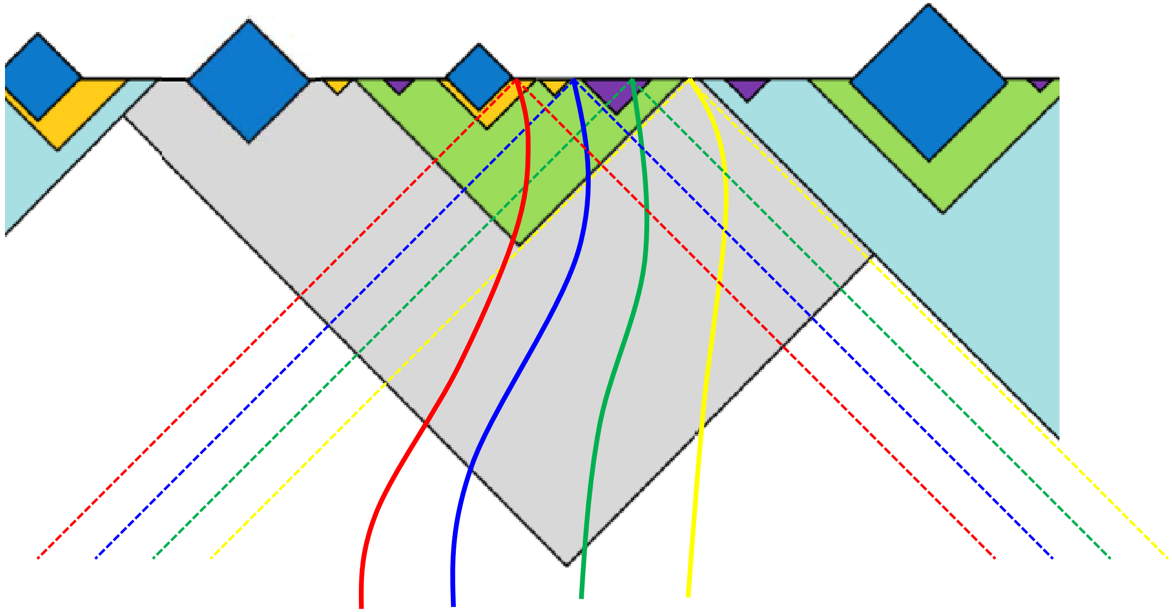

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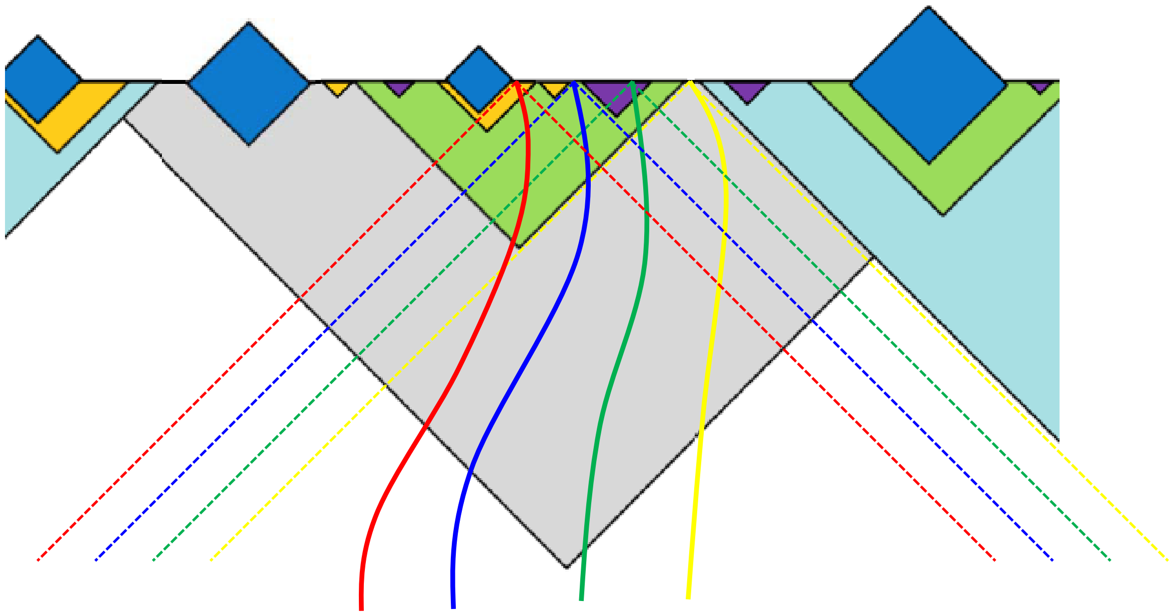


… probability is more fundamental

— counting observers (with equal weight) vastly overcounts d.o.f.s

The picture of infinitely large multiverse arises
only after patching different branch worlds artificially.

(at the cost of overcounting the true quantum mechanical d.o.f.s)

- A new picture for slow-roll inflation (in our universe)

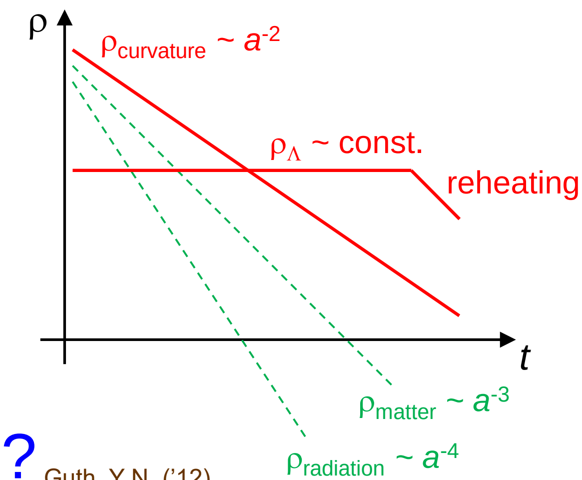
Problems in small-field (low energy) inflation avoided:

e.g. Guth, Kaiser, Y.N. ('13)

$|\nabla\phi|^2 \rightarrow 0$ … Coleman-De Luccia instanton (homogeneity by tunneling)

$|\dot{\phi}|^2 \rightarrow 0$ … Early curvature domination (damping effect)

The almost only way to get
a nontrivial universe after bubble nucleation

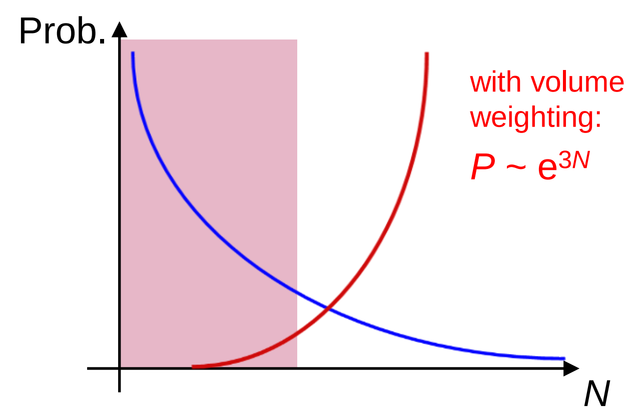


- What can we learn if $\Omega_{\text{curvature}} > 0$ is found? Guth, Y.N. ('12)

  – Our universe begins with bubble nucleation

  – Slow-roll inflation occurs "accidentally"
  (without e.g. a shift symmetry over a wide field range)

  – No volume weighting in probability
  ($\rightarrow$ Global spacetime in GR is an "artifact")



… nontrivial connections between cosmology and fundamental theory

The multiverse bootstrapped

Y.N., "The static quantum multiverse," PRD 86, 083505 ('12) [arXiv:1205.5550]

The picture so far:

Initial condition $|\Psi(t_0)\rangle$ $\xrightarrow[\text{dynamical evolution}]{}$ $|\Psi(t)\rangle \rightarrow$ Predictions

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

The gauge fixing and the normalizability may be enough.

Time translation (as well as reference frame change) is gauge transformation

$\rightarrow$ Gauge conditions: $\mathcal{P}^\mu |\Psi(t)\rangle = \mathcal{J}^{\mu\nu} |\Psi(t)\rangle = 0$

$\Longrightarrow$ The multiverse *state* is static !

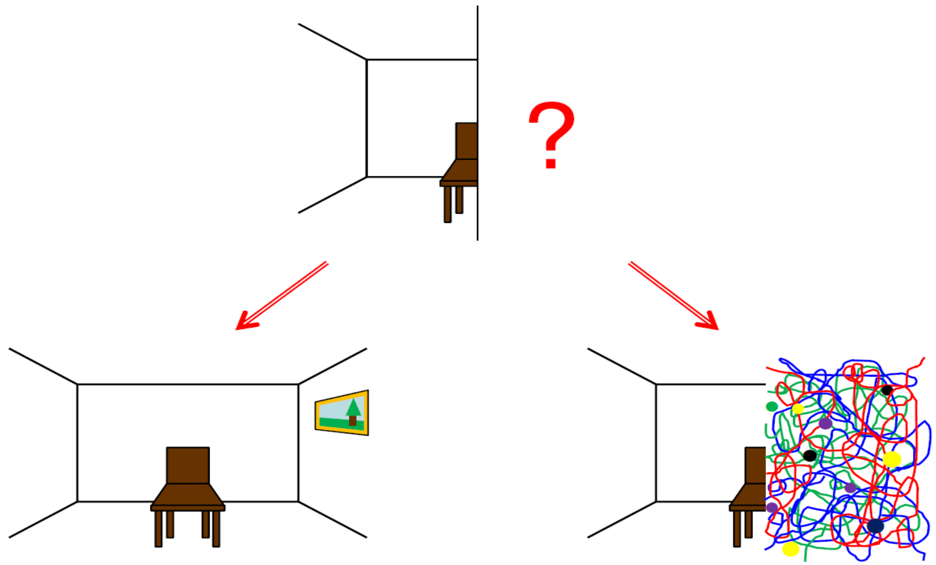
$$\boxed{H\,|\Psi(t)\rangle = 0 \quad \Leftrightarrow \quad \frac{d}{dt}|\Psi(t)\rangle = 0}$$

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

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

The arrow of time can emerge dynamically

The fact that we see time flowing 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*:

… Correlation among physical subsystems

cf. DeWitt ('67)

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

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 probability of leading to ordinary observers

The vacuum decay rate

In |Ψ>, various "micro-processes" must balance

e^{iHt} is not diagonal in the Hilbert space basis in which locality is manifest

usual "time evolution"

$$|\Psi\rangle = \underbrace{\big| \quad \big\rangle + \cdots + \big| \quad \big\rangle}_{} + \cdots + \underbrace{\left|\begin{smallmatrix}\text{slow-roll}\\ \text{inflation}\end{smallmatrix}\right\rangle + |\text{big-bang}\rangle + |\text{galaxies}\rangle + \cdots}_{\text{our universe}} + \cdots + \underbrace{\big| \quad \big\rangle + \cdots + \big| \quad \big\rangle}_{}$$

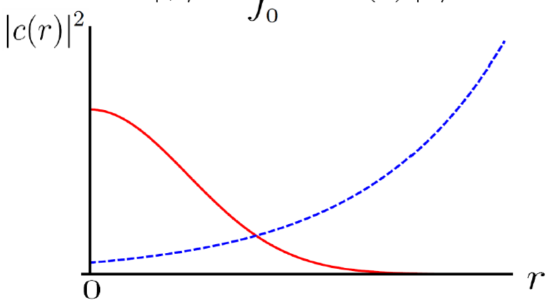
How to prevent "dissipation" into Minkowski/singularity worlds?

… processes *exponentially suppressed* at the semi-classical level

The normalizability may select the (possibly unique, non-ergodic) state

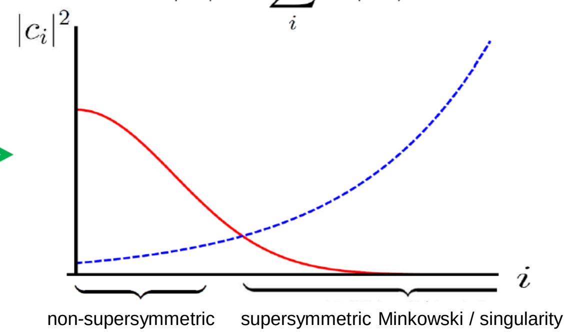
Analogy with the hydrogen atom:

$$|\psi\rangle = \int_0^\infty dr\, c(r)\, |r\rangle$$



The hydrogen atom

$$|\Psi\rangle = \sum_i c_i\, |\alpha_i\rangle$$



The quantum multiverse

- Quantum mechanics is crucial for the very *existence* of the system !
- Relevant Hilbert space is effectively *finite-dimensional* → normalized probability…

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 (naturalness), …

Further experimental / theoretical support strongly desired

ex. spatial curvature,
the holographic description of cosmological spacetime, …