Cosmological Observations and the Multiverse

Yasunori Nomura

UC Berkeley; LBNL; Kavli IPMU

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

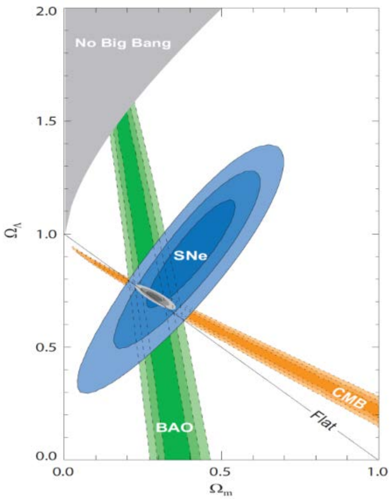
- Holographic principle
- Horizon complementarity
- Multiverse as quantum many worlds
- …

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

Shocking discovery in 1998 Supernova cosmology project; Supernova search team

Expansion of the Universe is accelerating!

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



Particle Data Group (2010)

Observationally,

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

Its smallness is already hard to understand

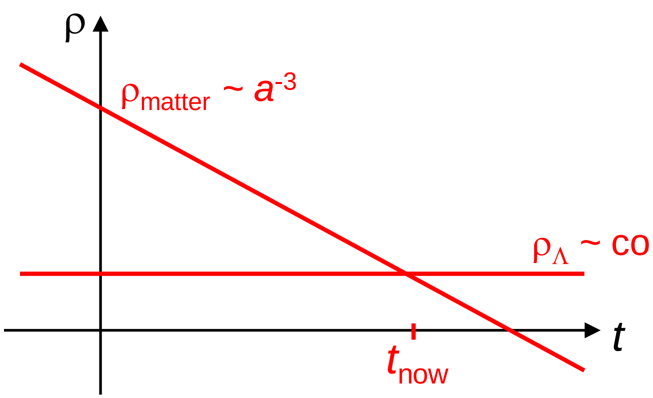
… natural size of $\rho_\Lambda \equiv \Lambda^2 M_{Pl}^2 \sim M_{Pl}^4$ (at the very least ~ TeV^4)

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

Moreover

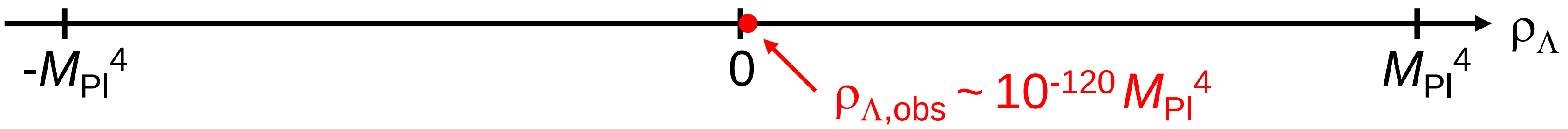
$$\rho_\Lambda \sim \rho_{matter}$$

— 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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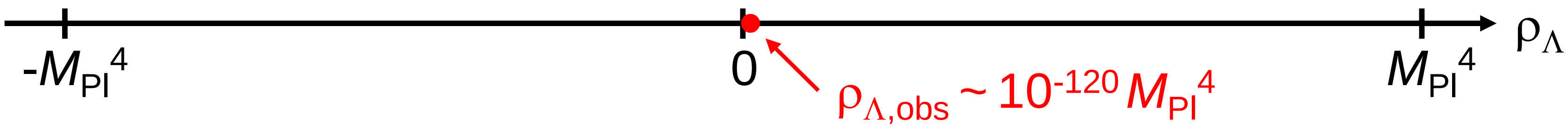
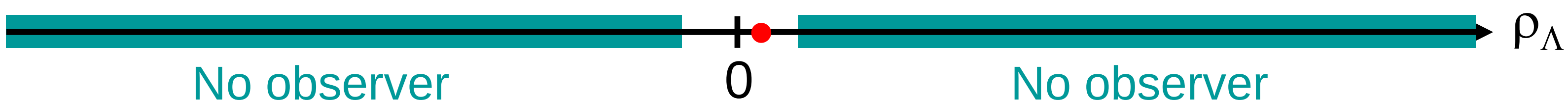


Unnatural (Note: $\rho_\Lambda = 0$ is NOT special from theoretical point of view)

$\Longrightarrow$ Wait!

Is it really unnatural to *observe* this value?



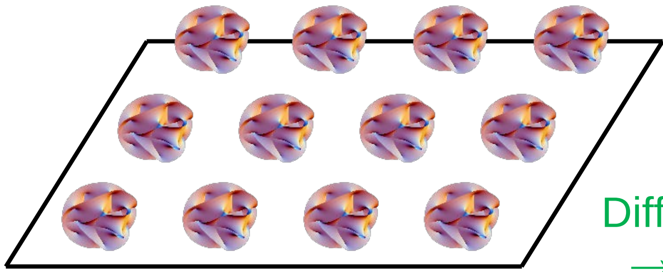
It is natural to observe $\rho_{\Lambda,obs}$,

as long as different values of ρ_Λ are "sampled" Weinberg ('87); also Banks, Linde, …

Theory also suggests:

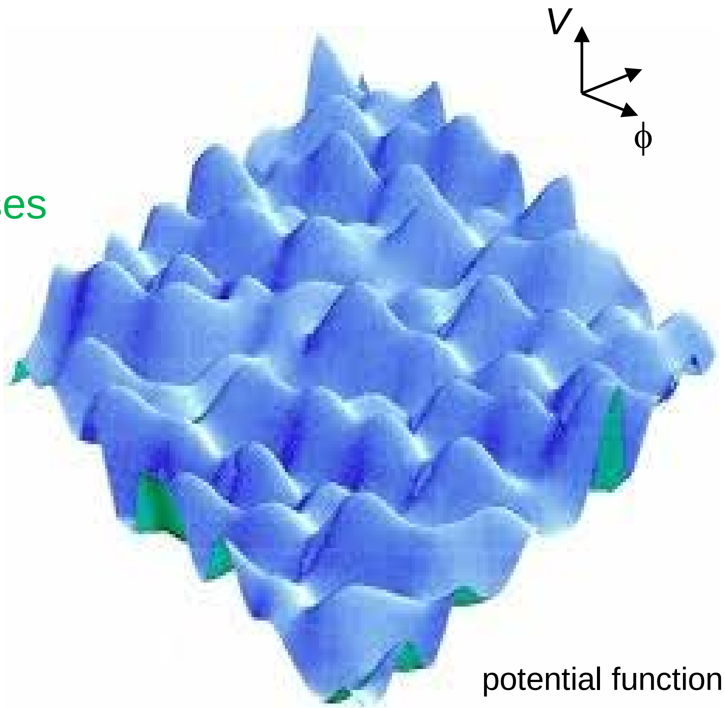
- String theory

  … 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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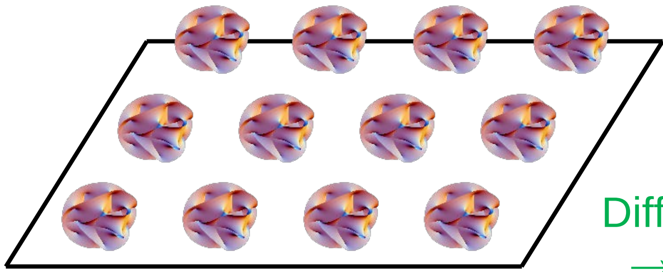

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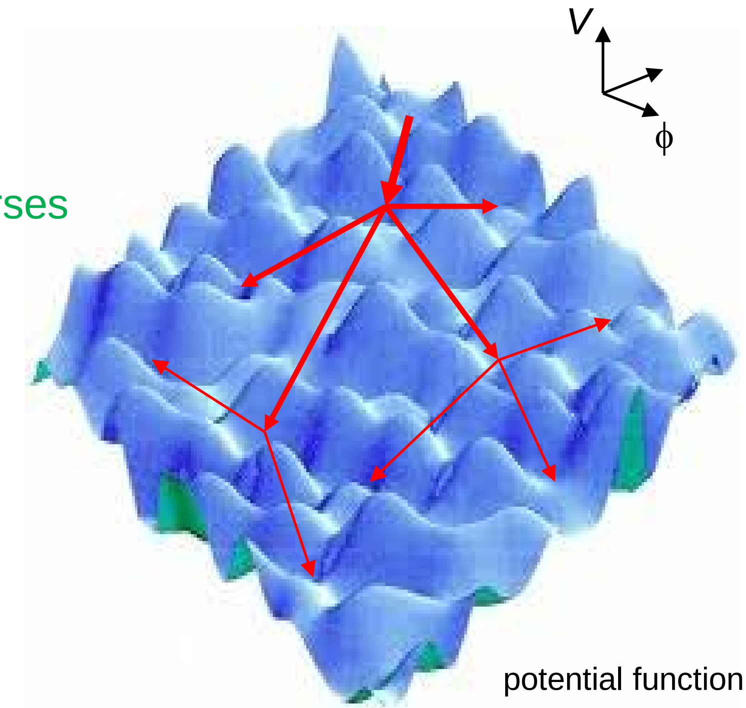

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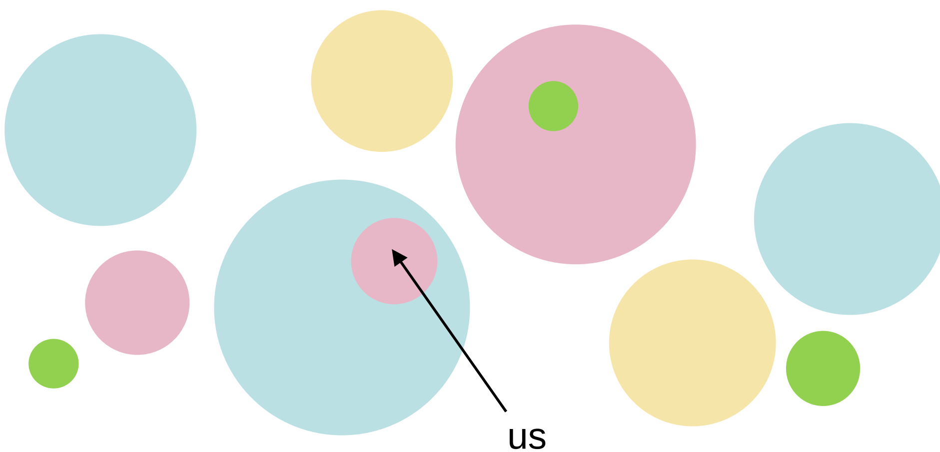
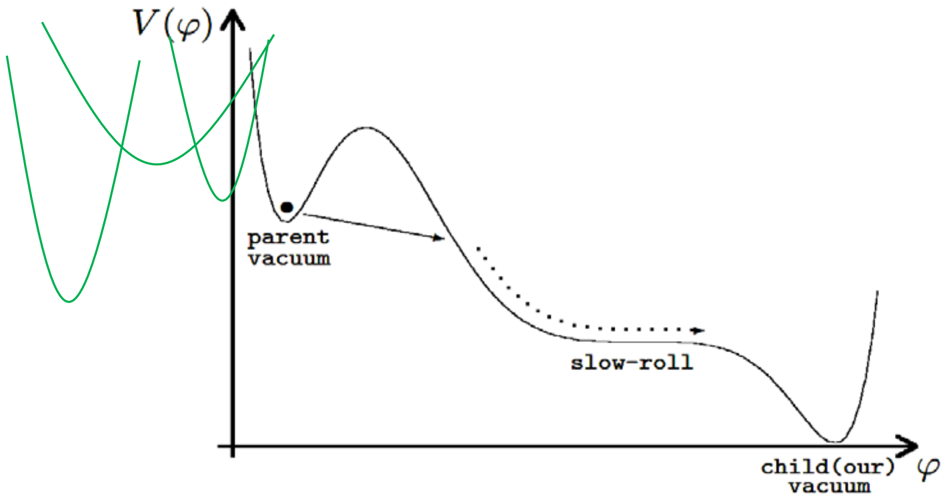
- Inflation

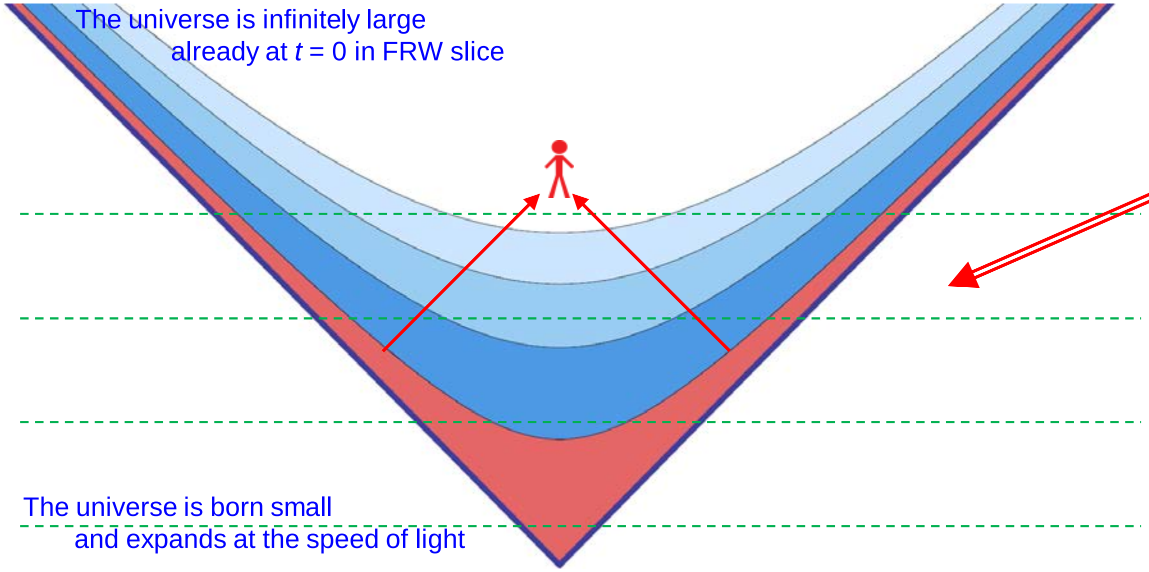
  … eternal to the future



… keep forming new “bubbles”

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

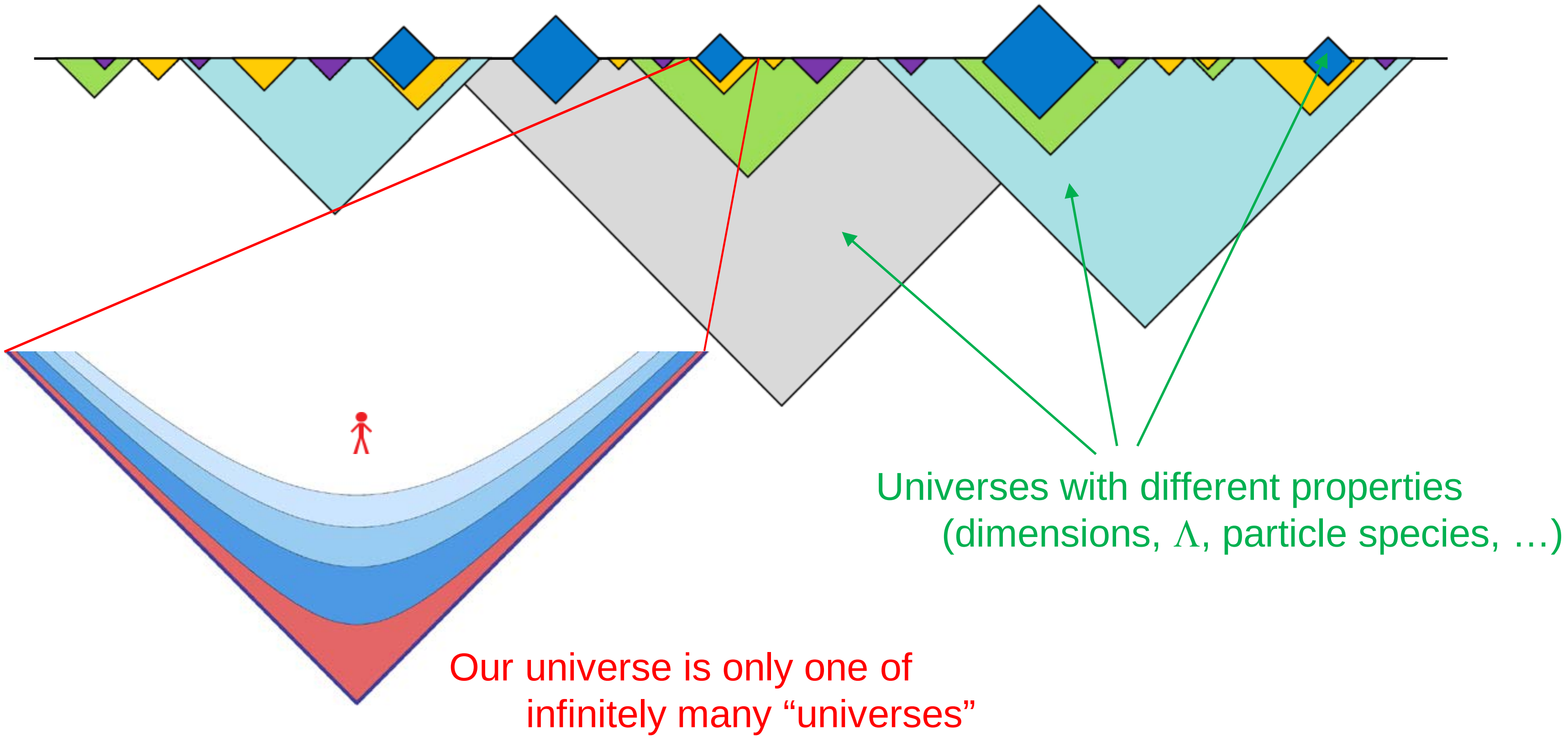




- What’s there before
  the universe was born?
- What’s there
  outside the universe?

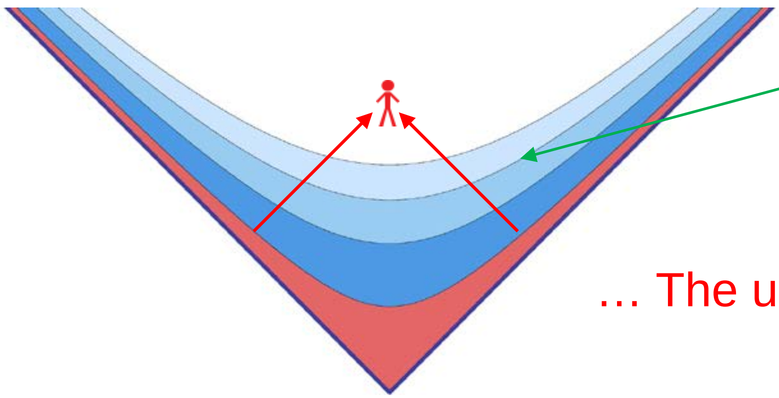
Coleman, De Luccia (’80)

Multiverse!



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

The curvature of our universe

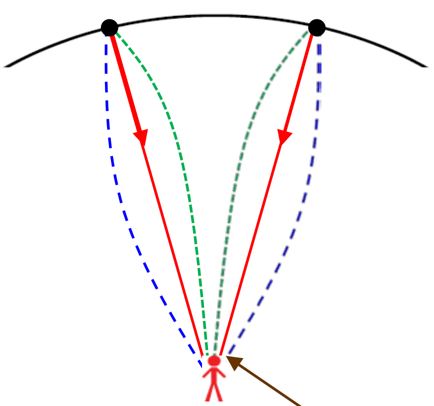


equal time for interior observers (FRW)

… The universe appears as “negatively curved”!

(though can’t predict how much)

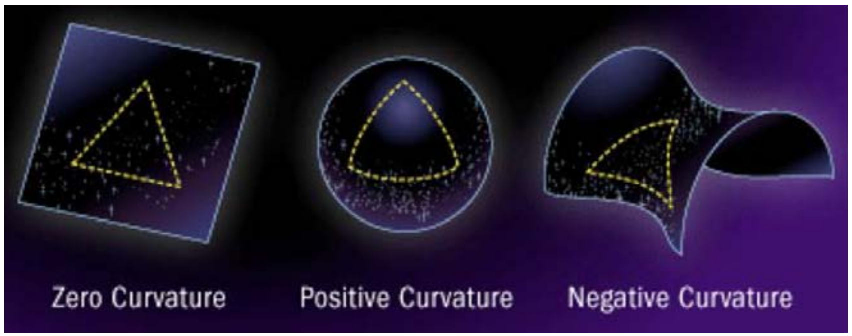
It can be measured



measure the angle

curvature

LD © 2008 HowStuffWorks



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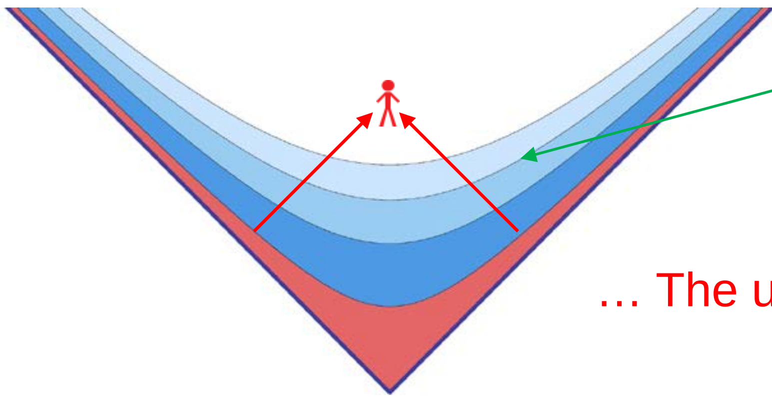

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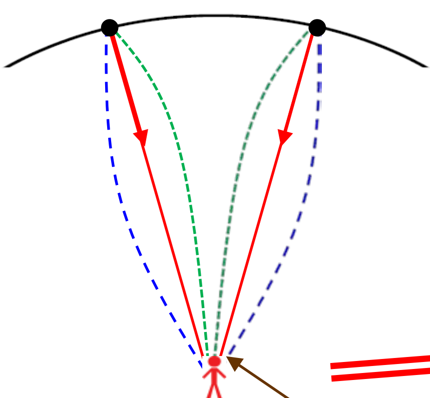

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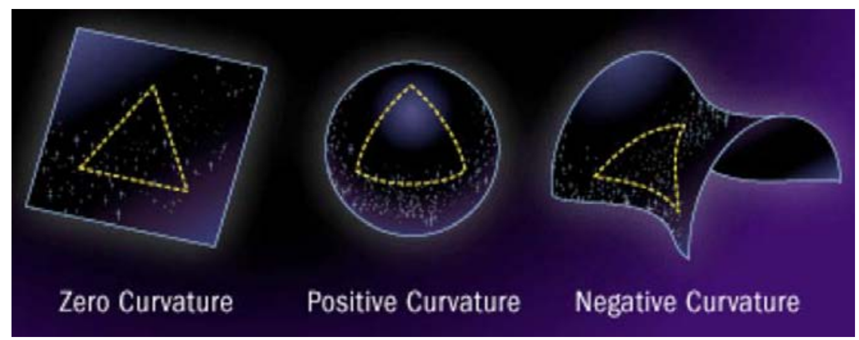


– X O

This would **exclude** the framework!

Far-reaching implications

… The multiverse is "infinitely large"!

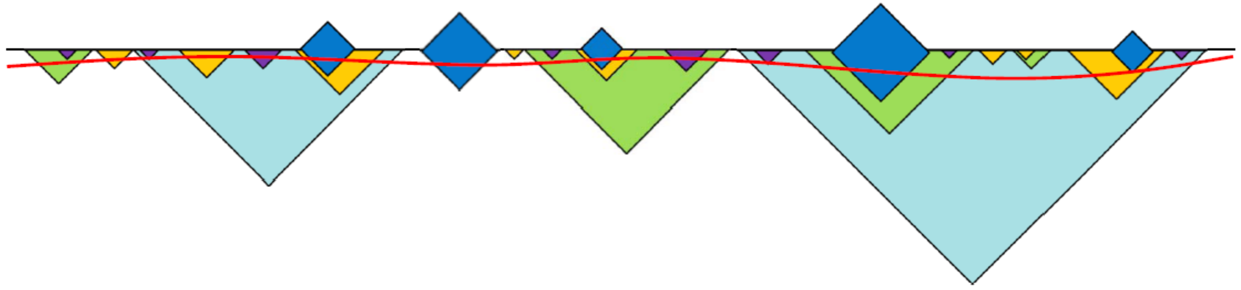
Predictivity crisis!

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

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

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 <u>**essential**</u>

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

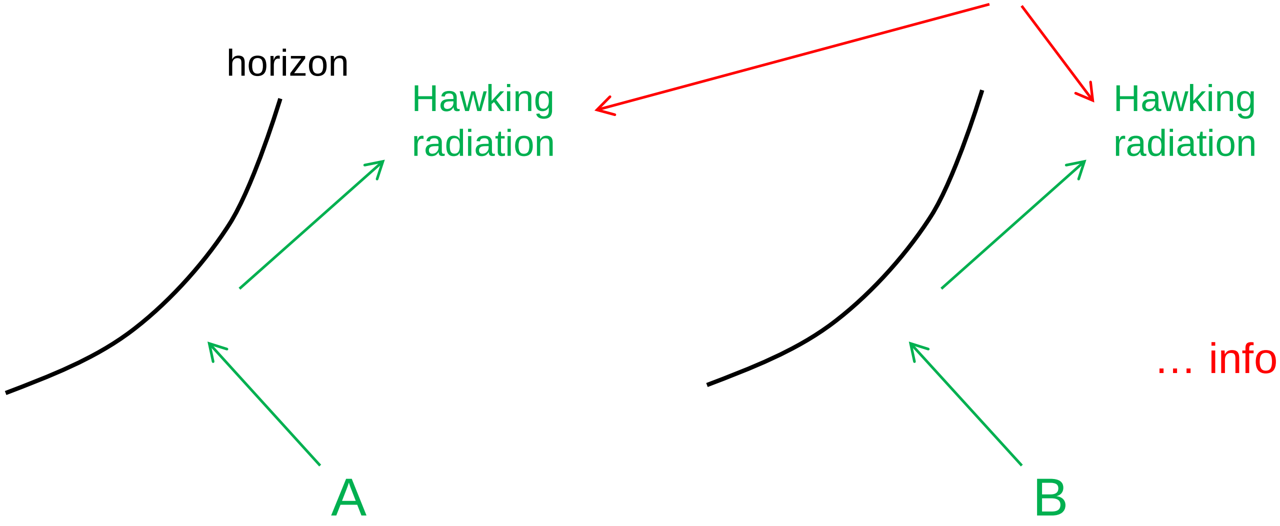
(Anything that can happen will happen *but not with equal probability*.)

Quantum mechanics in a system with gravity

Black Hole

Information loss paradox

same at the semi-classical level



… information is lost ??

Hawking ('76)

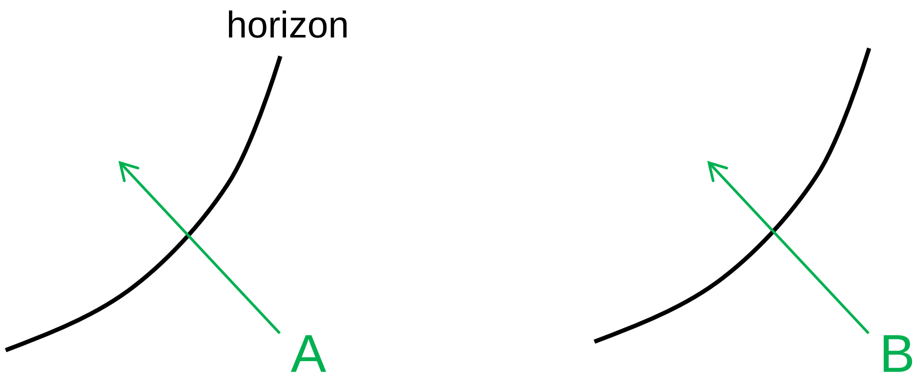
$\Longrightarrow$ No

… 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)

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

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

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

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

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?

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

There is no contradiction !

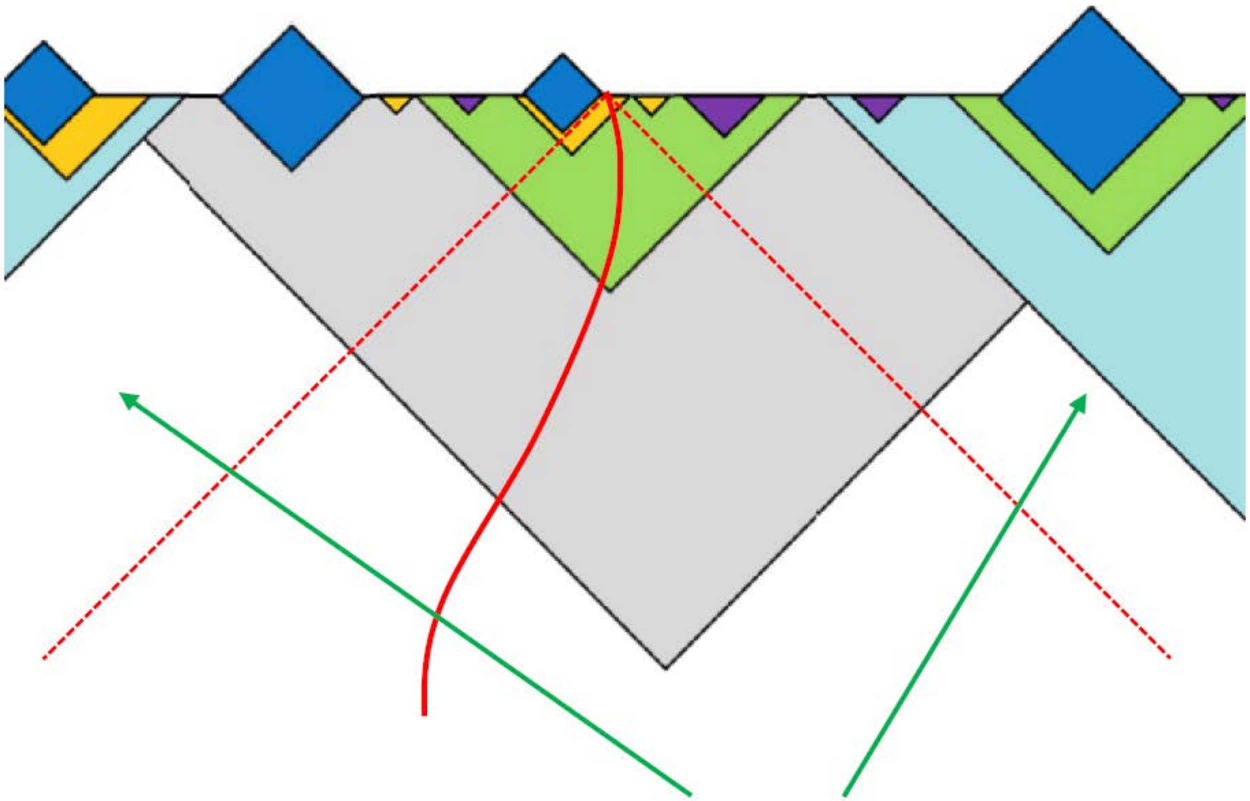
One cannot be *both* distant and falling observers *at the same time*.

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

… see "Reanalyzing an Evaporating Black Hole," Y.N., arXiv:1810.09453

A Lesson:

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



Does this region "exist"?

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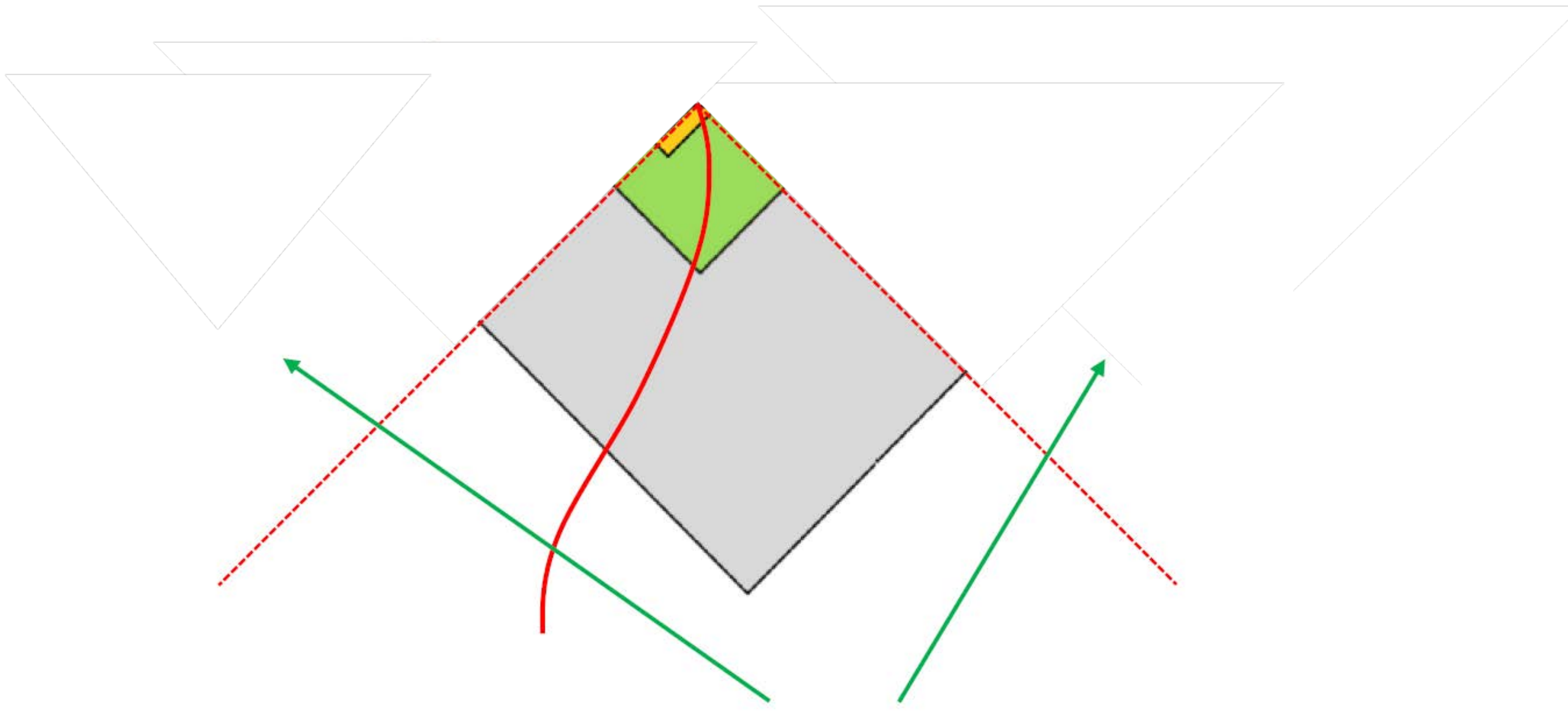
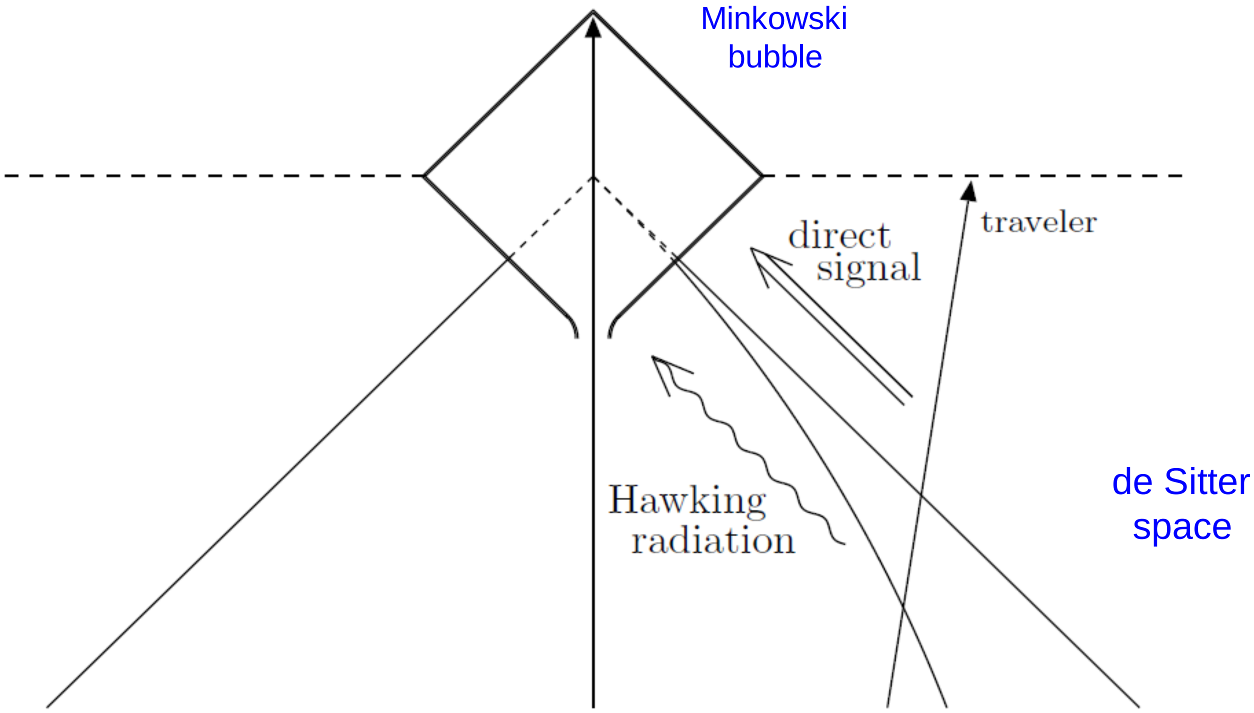


Does this region “exist”? → No!

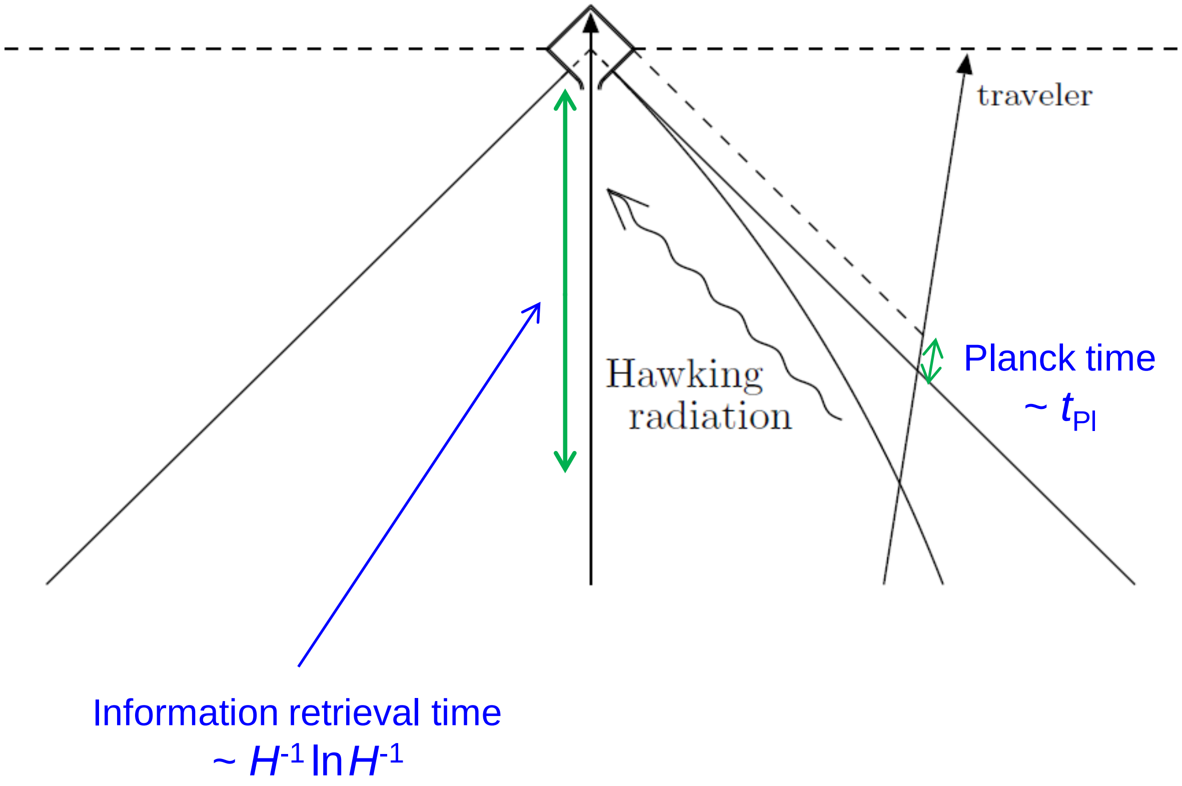
… What happened to the multiverse?

Consistent?



Doesn’t information duplicate?

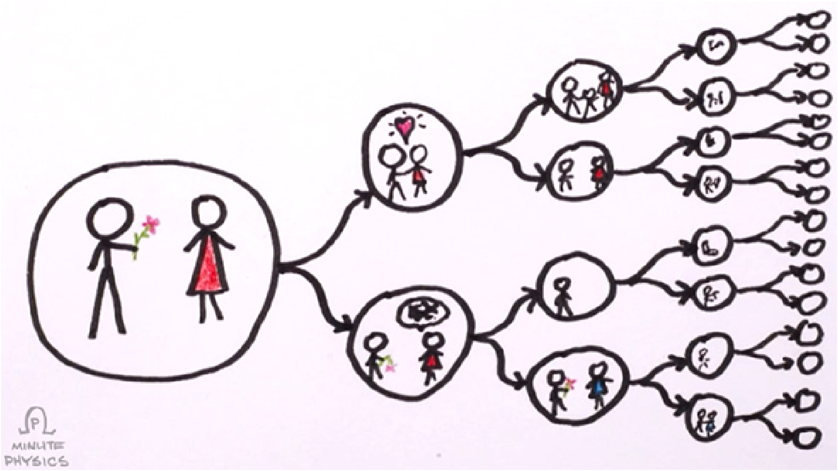
Consistent? — Yes



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

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

eternally inflating

each term representing only the causally accessible region

… provides natural and effective "regularization"

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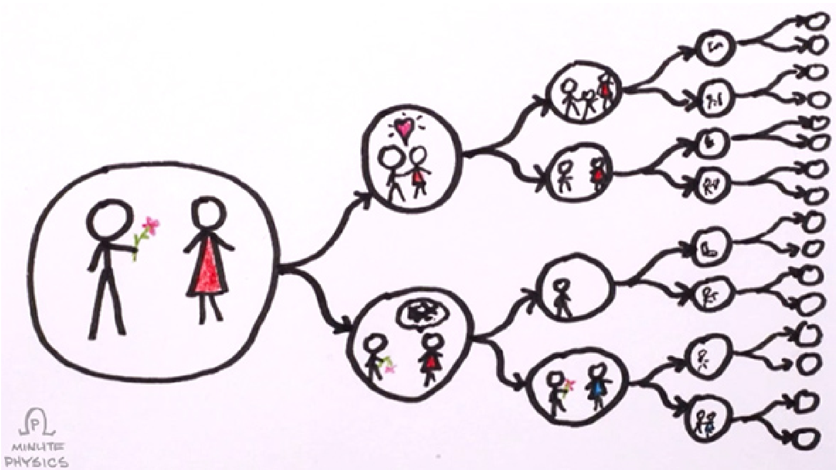

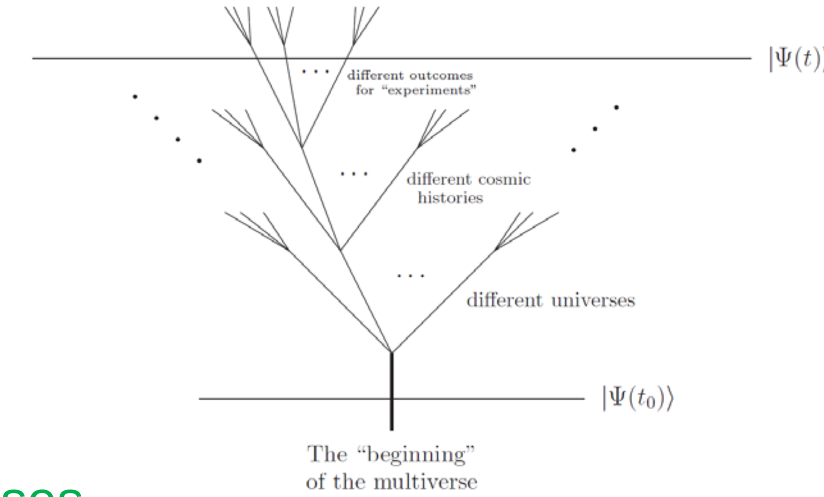

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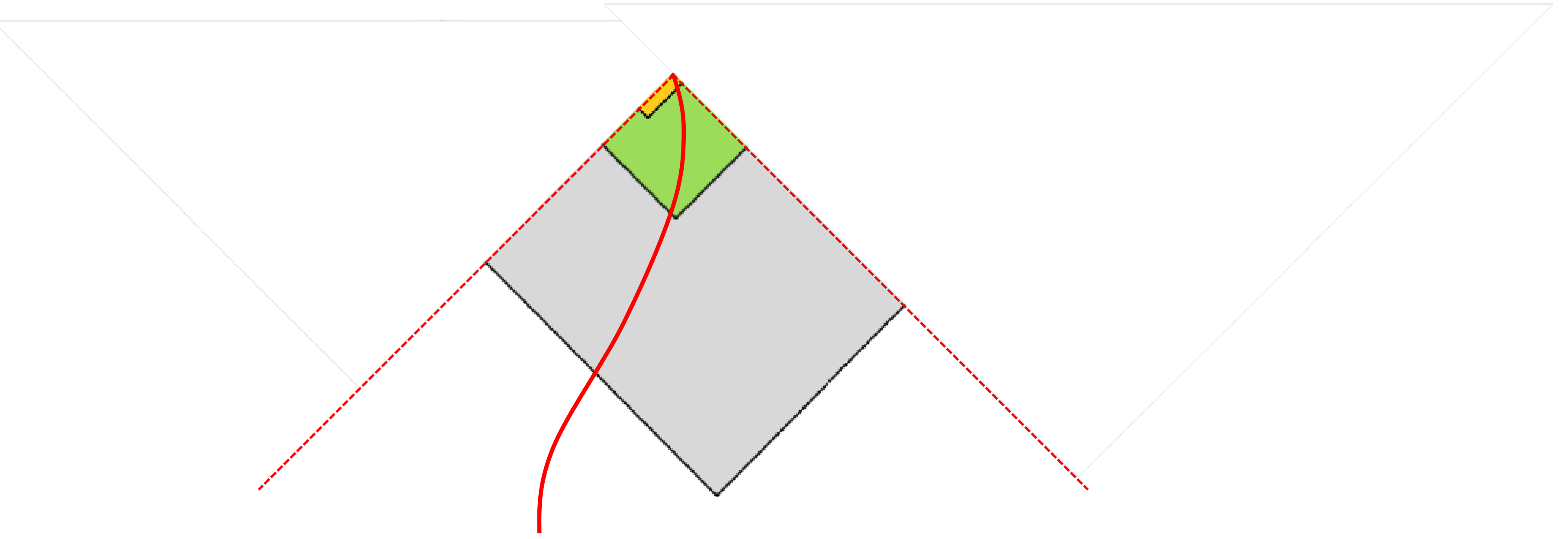
Multiverse = Quantum many worlds

… The multiverse lives (only) in probability space!

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



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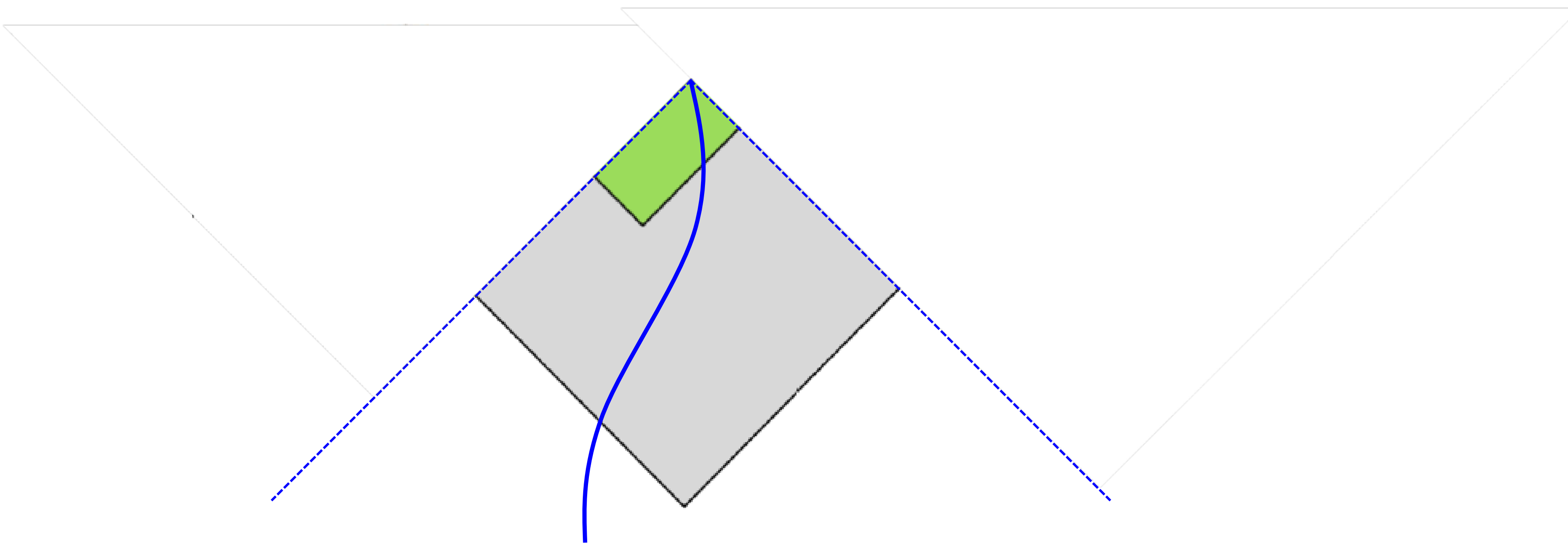

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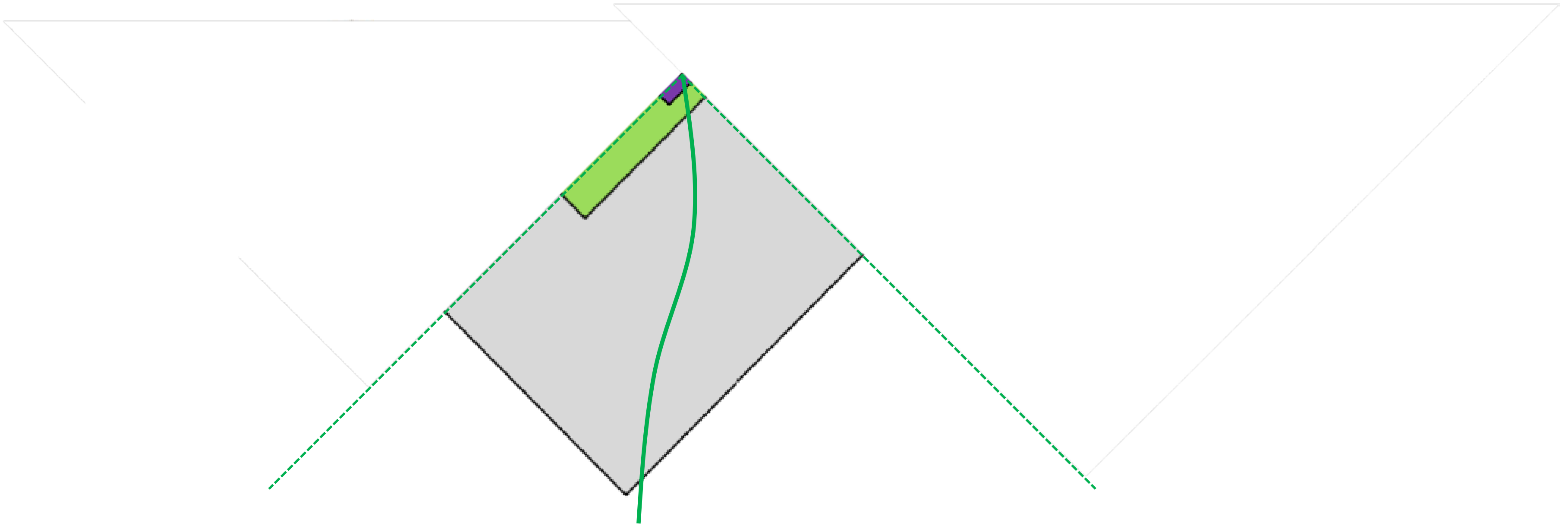

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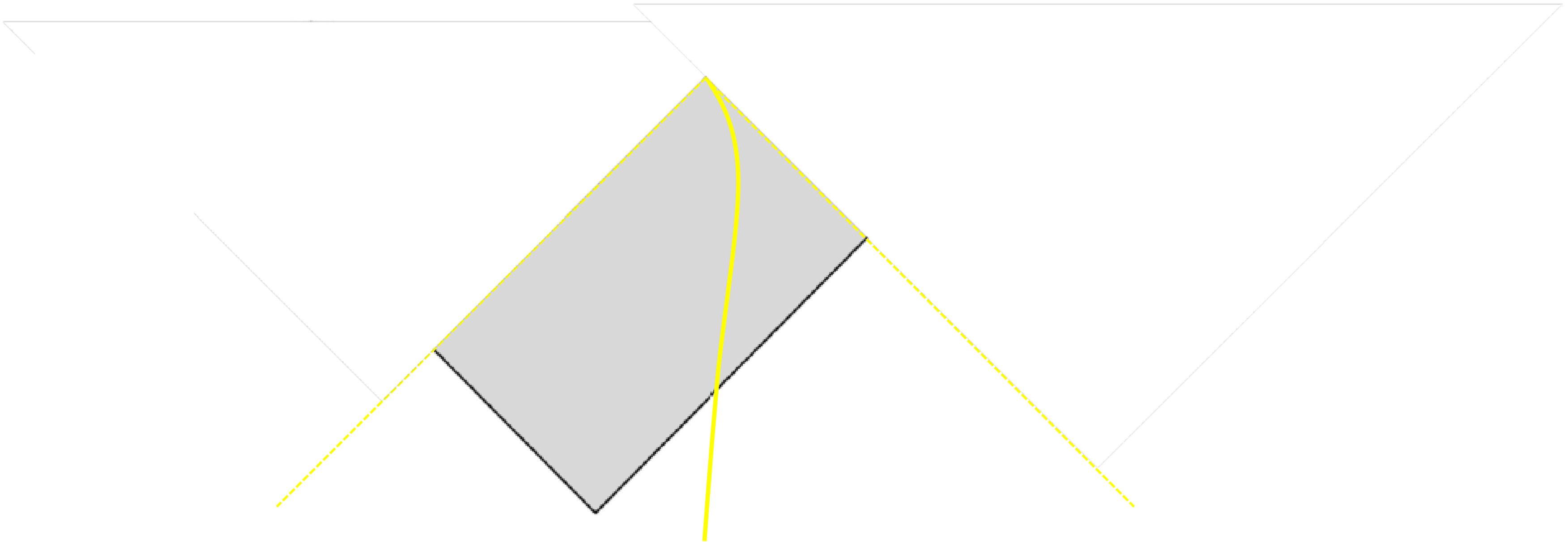

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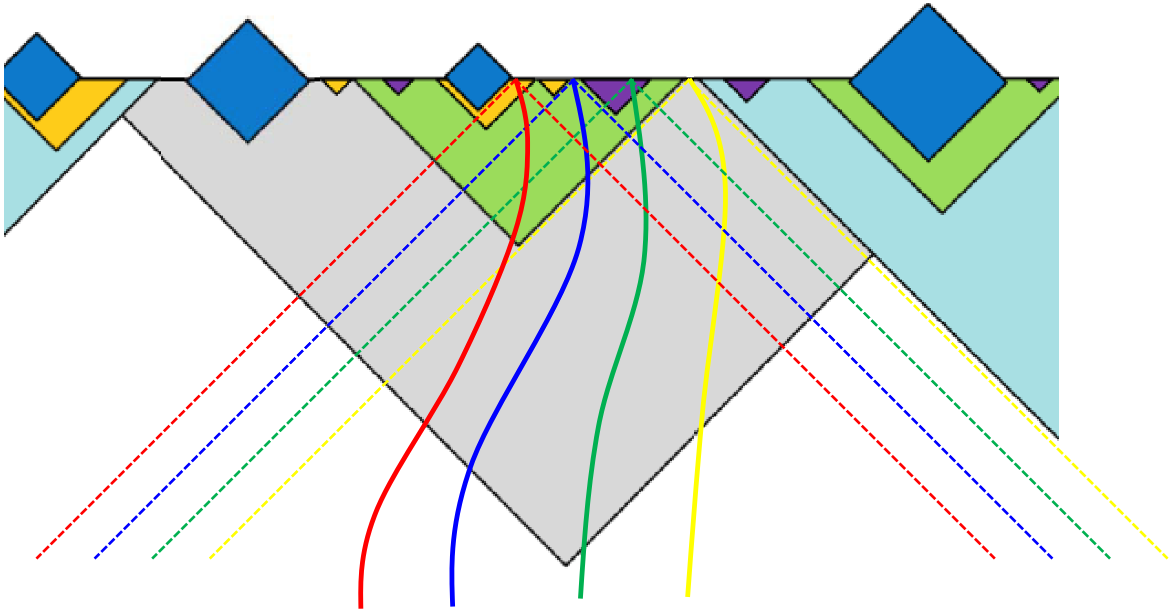

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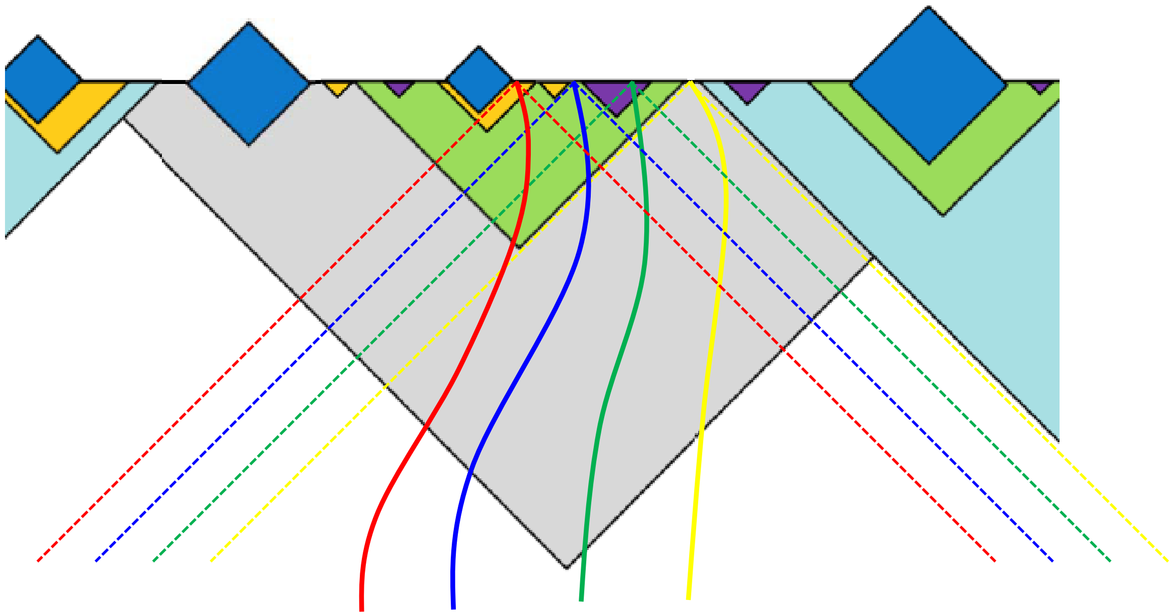


… probability is more fundamental

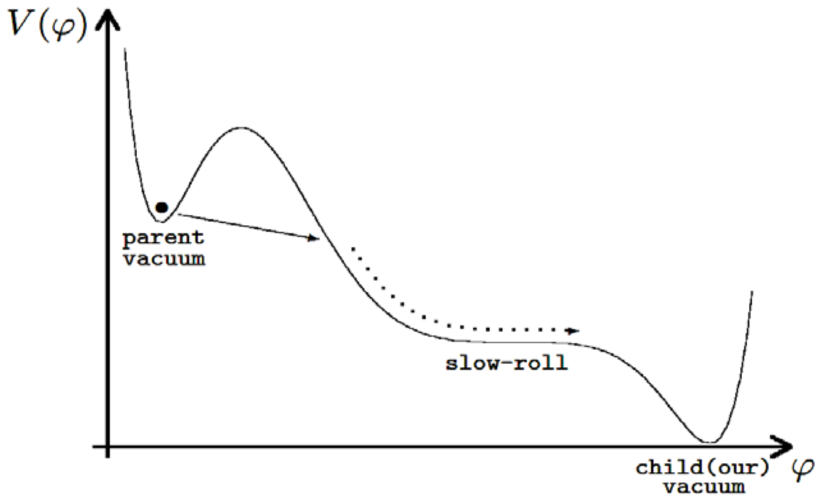
— counting observers (with equal weight) vastly overcounts d.o.f.s

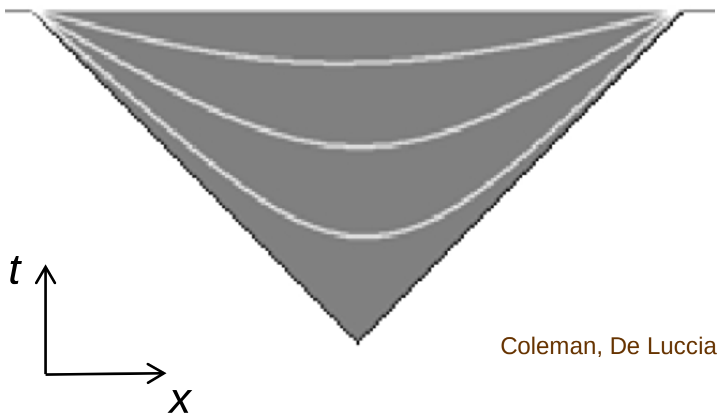
The picture of infinitely large multiverse arises
only after patching different branch worlds artificially.

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

The universe in the multiverse

Our universe is a bubble formed in a parent vacuum:





Coleman, De Luccia ('80)

… Infinite open universe

(negative curvature: $\Omega_{\text{curvature}} > 1$)

- Finding $\Omega_{\text{curvature}} < 0$ will **exclude** the framework!

… The eternally inflating multiverse **is** falsifiable

Guth, Y.N., Phys. Rev. **D86** (2012) 023534
See also Kleban, Schillo ('12)

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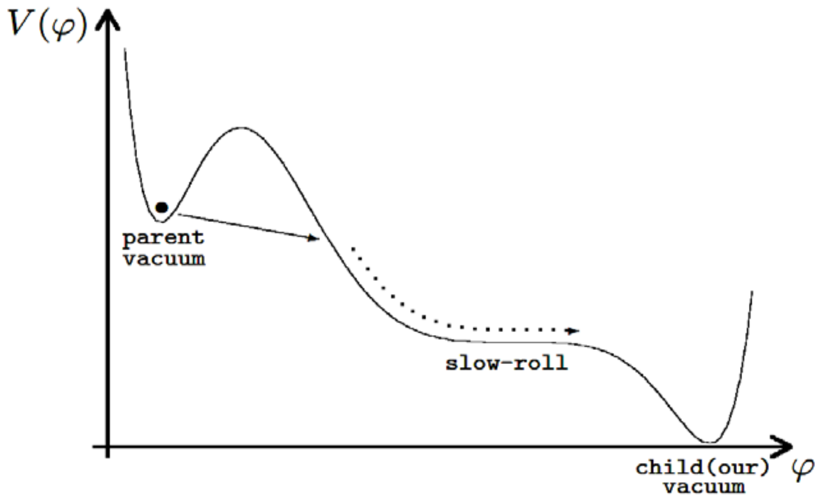

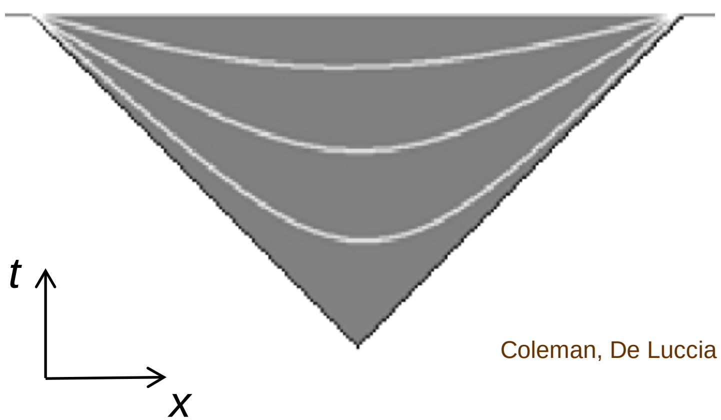

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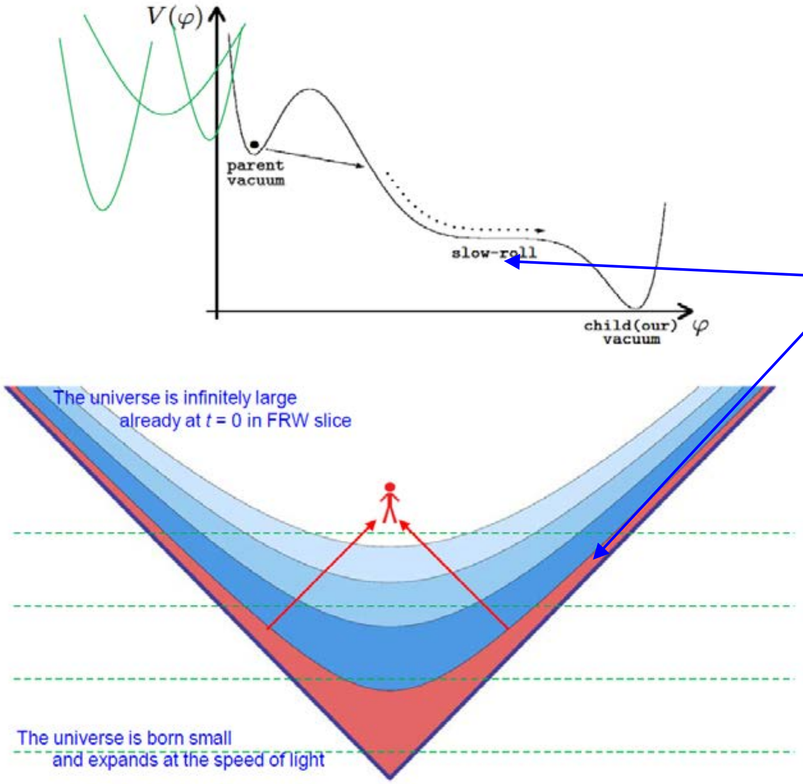
… Can we expect?

A modern view

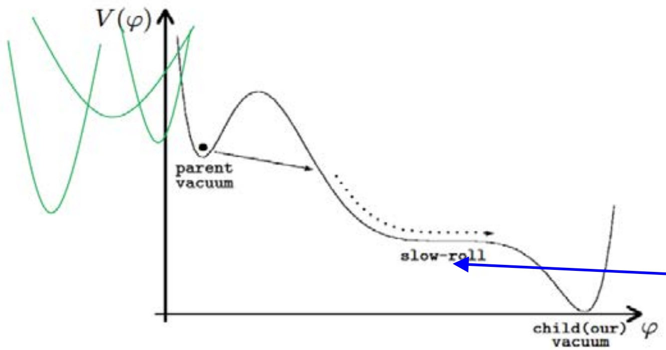
Guth, Kaiser, Y.N., Phys. Lett. **B733** (2014) 112

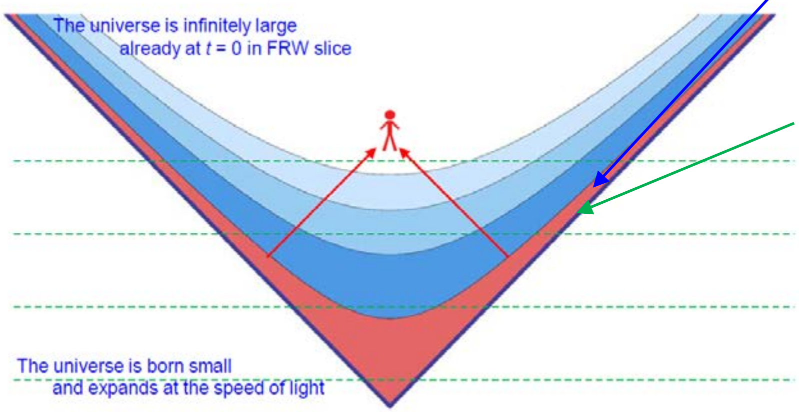


Observable (slow-roll) inflation

A modern view

Guth, Kaiser, Y.N., Phys. Lett. **B733** (2014) 112





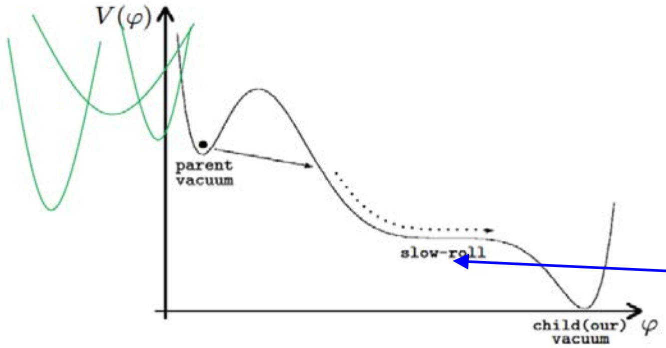
Observable (slow-roll) inflation

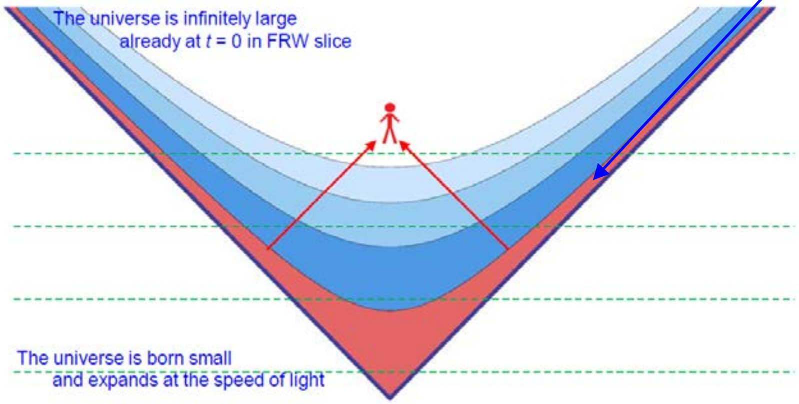
Why did this need to happen?

Bubble nucleation may provide a special initial condition of our universe e.g. homogeneity

A modern view

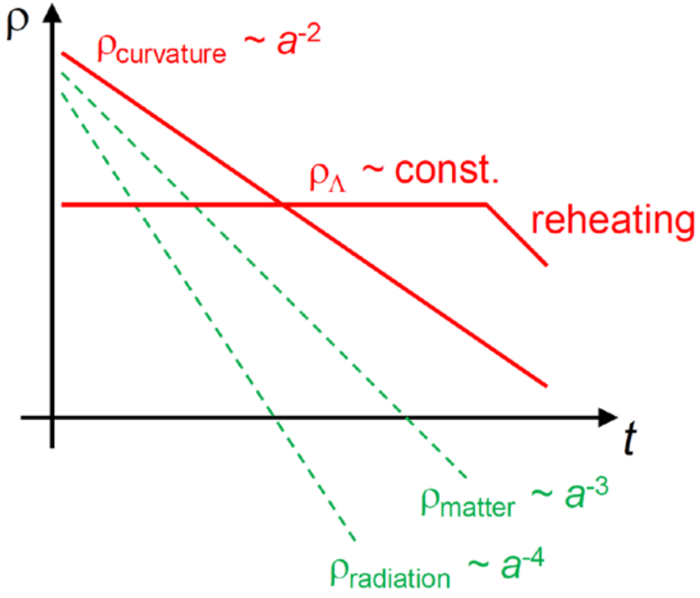
Guth, Kaiser, Y.N., Phys. Lett. **B733** (2014) 112





Observable (slow-roll) inflation

… **needed** to dilute curvature



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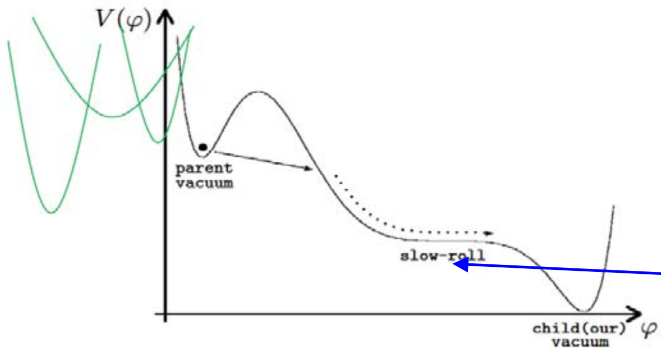

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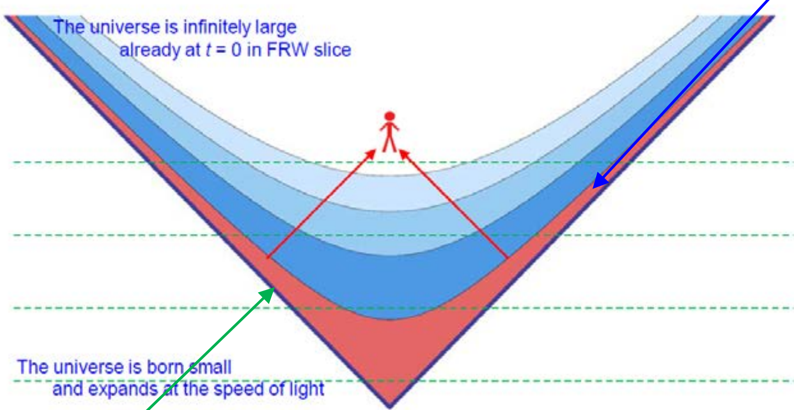
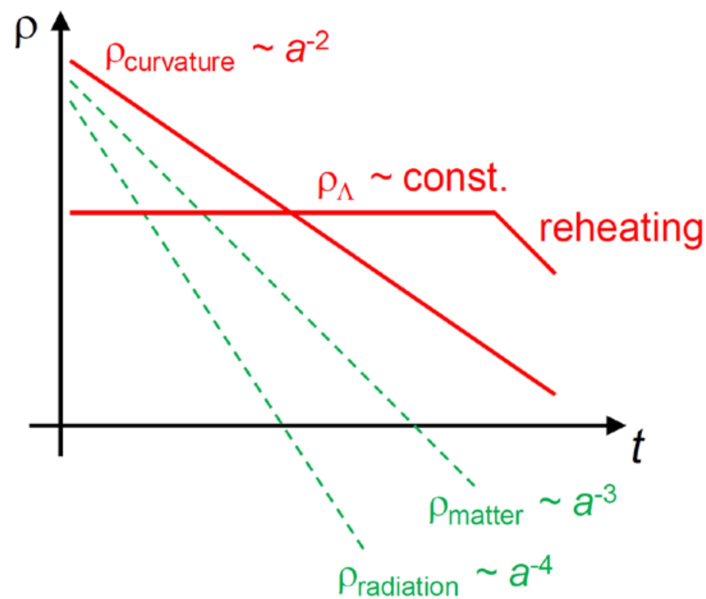




Bubble nucleation

$|\nabla\phi|^2 \to 0$ … symmetric instanton (homogeneity by tunneling)

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

… may provide an initial condition
for observable inflation

Origin of structure (fluctuation)
$\to$ **our universe**

A possible scenario

Why is **our** universe so flat?

... required by anthropic

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

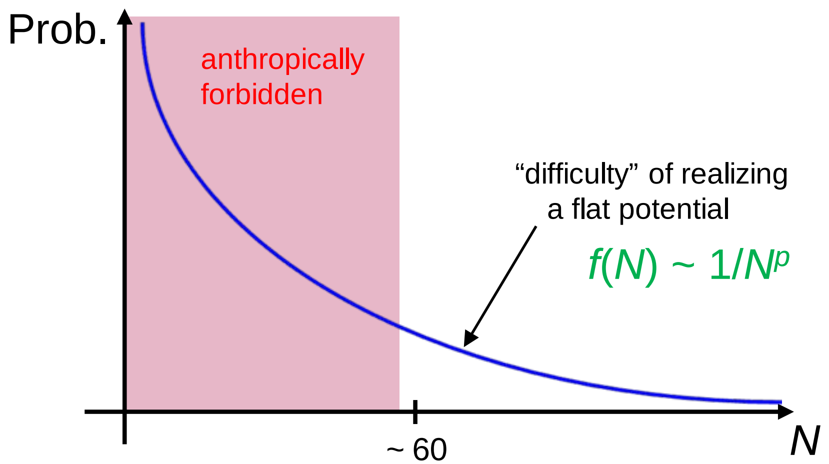
Does this mean there is no slow-roll inflation? $\Longrightarrow$ No!

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

– Fine-tuning initial conditions **or**

– Having (accidentally) a flat portion in the potential $\rightarrow$ observable inflation

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

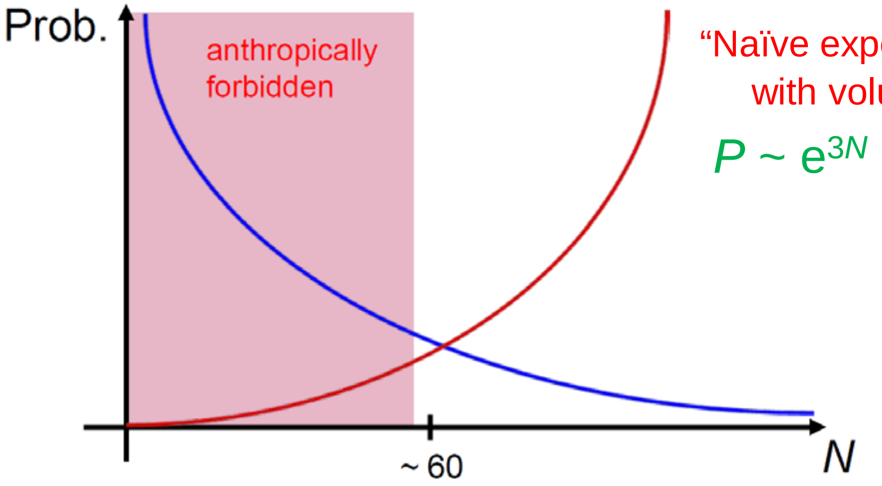


$\Omega_{\text{curvature}} > 0$ may be seen

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

Slow-roll inflation may be "just-so"

Things are not as simple as one might think



"Naïve expectation"
with volume weighting:

$P \sim e^{3N}$

What can we learn if $\Omega_{\text{curvature}} > 0$ is found? Guth, Y.N., Phys. Rev. **D86** (2012) 023534

– 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

(→ Global spacetime in general relativity is an "artifact")

… nontrivial connections between cosmology and fundamental theory

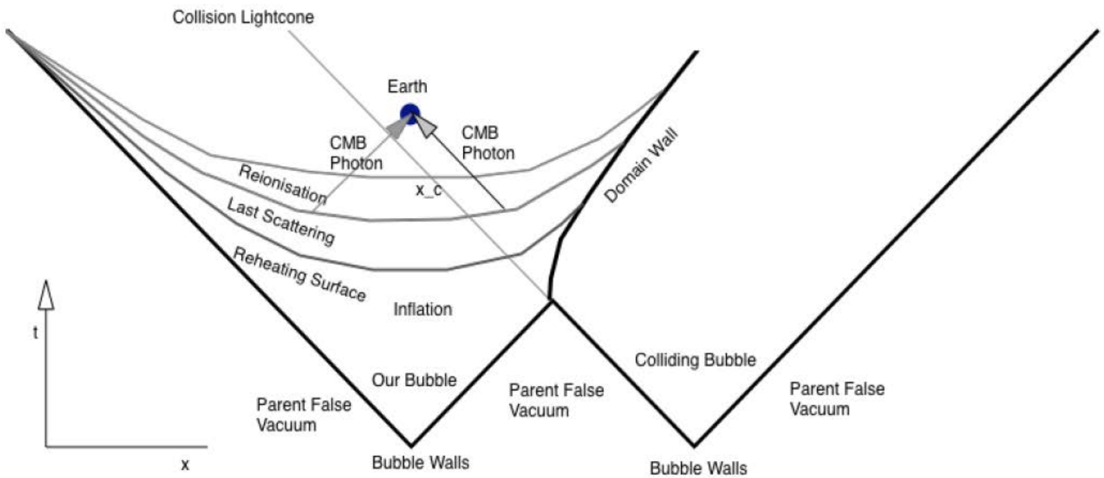
A variety of possible signatures

… opens the possibility of many signatures

• Nonzero spacetime curvature

e.g. 21 cm might probe down to $\Omega_{curv} \sim 10^{-4}$

• Cosmic bubble collisions e.g. Kleban, arXiv:1107.2593



Note: the number of relevant collisions $\sim e^{-N}$

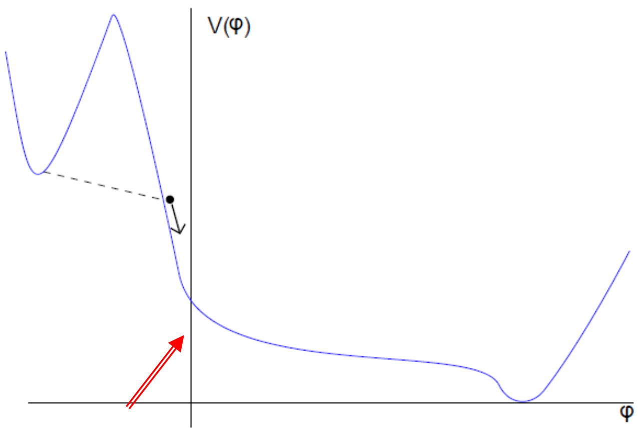
… may leave signals in CMB and large scale structure

• Tunneling from a lower dimensional vacuum Graham, Harnik, Rajendran ('10)

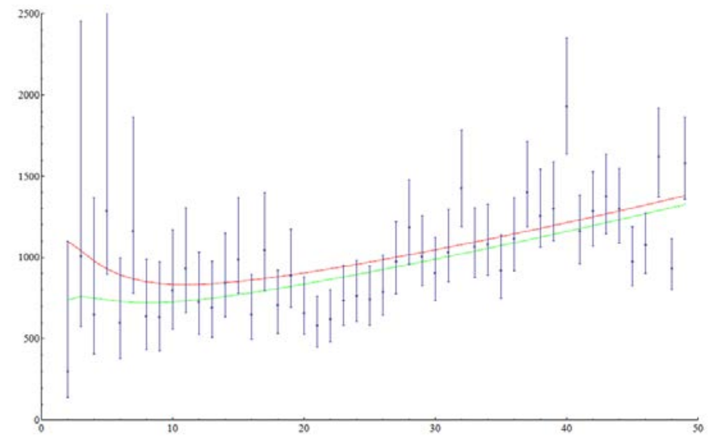
… may lead to signals in CMB through anisotropic curvature

• Suppressions of low ℓ Freivogel, Kleban, Rodriguez Martinez, Susskind ('05, '14); Bousso, Harlow, Senatore, ('13, '14); …

… may be able to probe a faster-roll phase during the onset of inflation



In PLANCK data?



• Remnants of the pre-inflationary history

ex. Peccei-Quinn phase transition before inflation

→ may lead to a tilt between the rest frames of CMB and matter

D.B. Kaplan, Nelson, ('08)

Detection of any of these signals would be suggestive of the multiverse & give us information about the structure of spacetime

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 (naturalness), …

A possible observational window into fundamental physics

ex. spatial curvature (“just-so” inflation), …

Further theoretical explorations: the holographic description of cosmological spacetime, …