Exploring 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

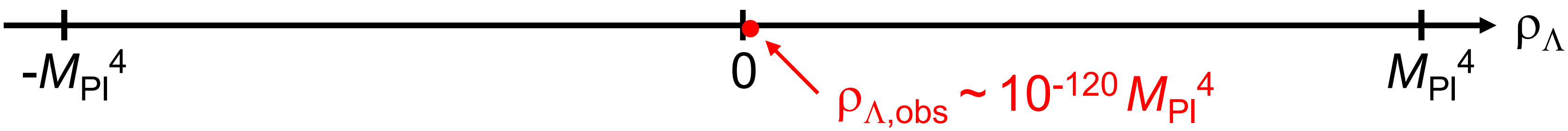
Shocking news in 1998

Expansion of the universe is accelerating: $\rho_\Lambda \sim (10^{-3}\ \mathrm{eV})^4$

— Why now?

Nonzero value completely changes the view!

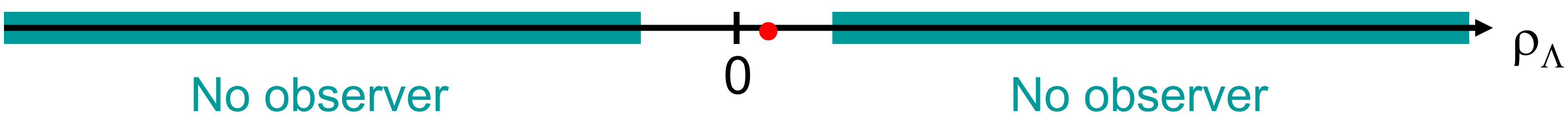
Natural size for vacuum energy $\rho_\Lambda \sim M_{Pl}^4$



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

⟹ 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); also Banks, Linde, …

Theory also suggests

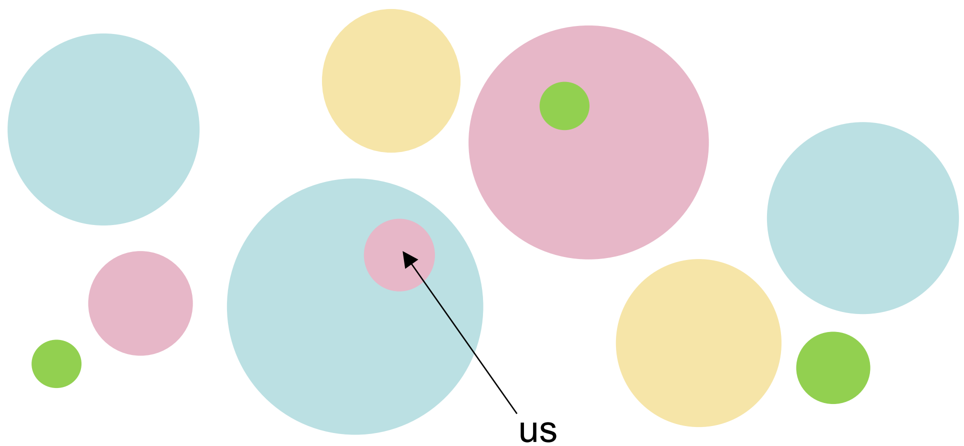
- String landscape

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)

⟹ Eternally inflating multiverse

Far-reaching implications

… The multiverse is “infinitely large” !

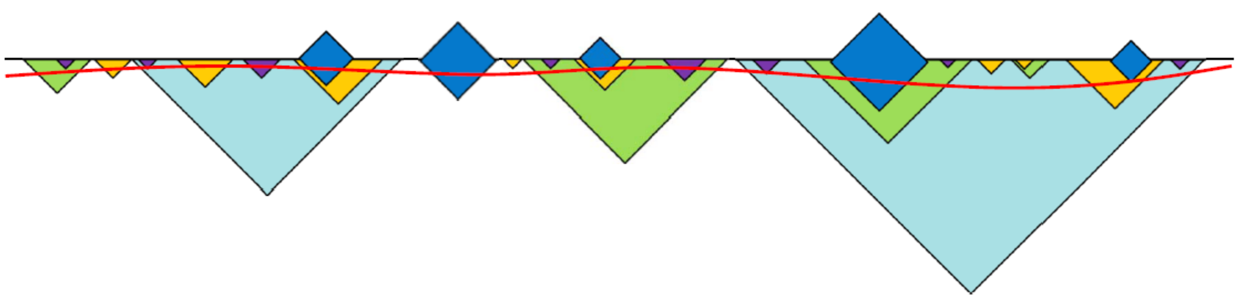
Predictivity crisis !

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



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

Why do we care?

(I) A clue to deep questions in quantum gravity

→ Dramatic change of our view of spacetime and gravity

"Multiverse = Quantum many worlds"

(II) *Crucially* affect observational implications

Consider signals of the multiverse, e.g., bubble collisions, curvature, …

A naïve "volume weighted" measure

(more precisely, synchronous time cutoff measure)

Large volume → More observers → More likely

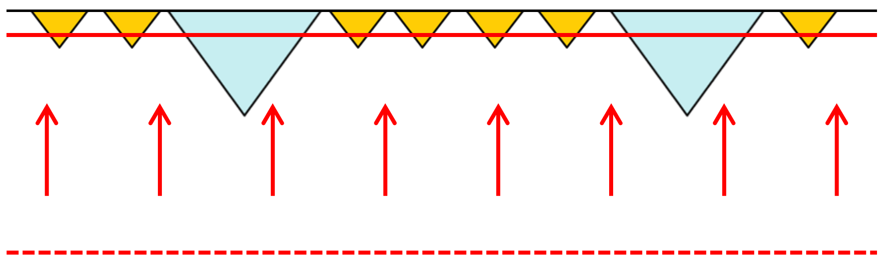
… This *would* exponentially "reward" longer e-folds of slow-roll inflation

$$P \sim e^{3N}$$

→ completely wipes out any signals
associated with large scale properties of the universe

Reasons to believe this is not the case

- Seems to lead to a strange (terribly wrong) consequence



Synchrinous (proper) time cutoff measure

Linde, Mezhlumian ('93)

$V \sim e^{3Ht}$

… vastly more younger universes than older ones

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

… Youngness paradox

Guth ('00); Tegmark ('04)

- Theoretical studies suggest the otherwise

Work addressing various aspects of the measure problem:

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

Below, based on my own view

Quantum mechanics is essential to answer these questions.

→ Dramatic change of our view of spacetime and gravity

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 principle:

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

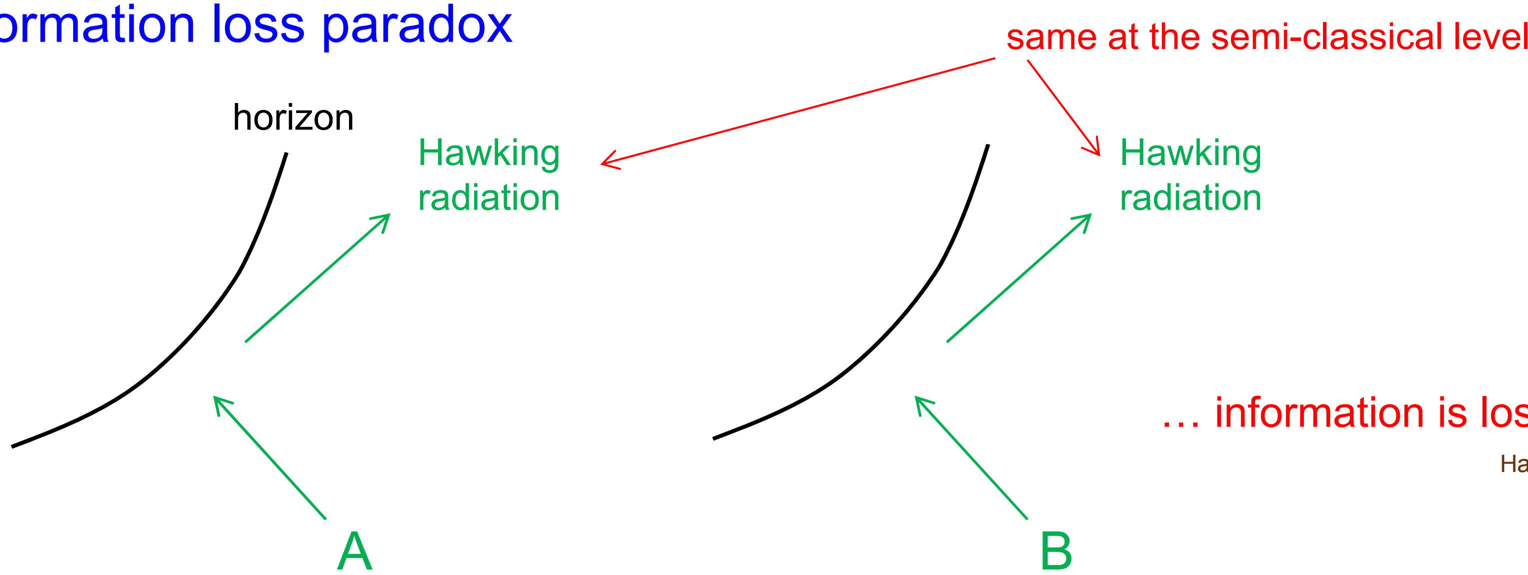
… provide simple regularization

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

Quantum Mechanics in a System with Gravity

Black Hole

Information loss paradox



… information is lost ??

Hawking ('76)

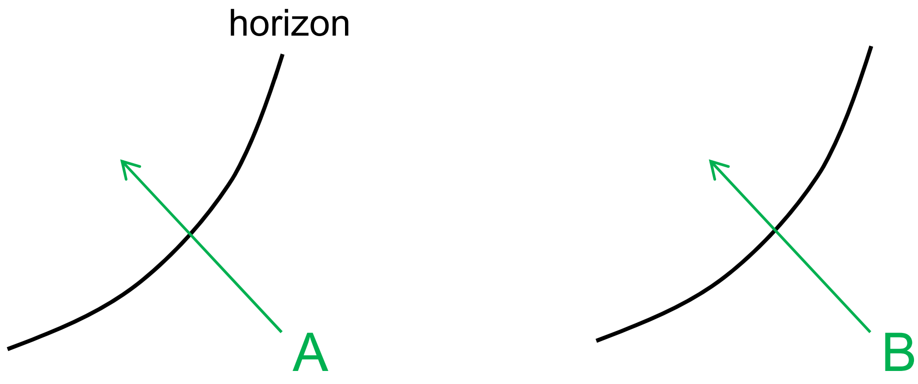
⟹ **No**

… 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)

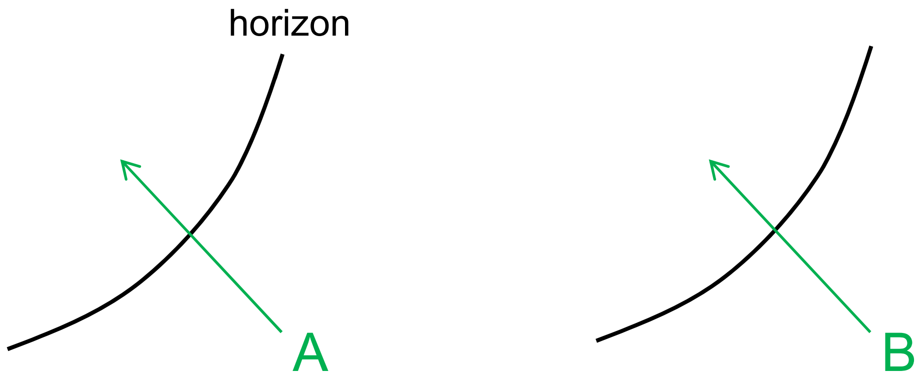
$|\uparrow\rangle \rightarrow |\uparrow\rangle|\uparrow\rangle$

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

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

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

From a falling observer's viewpoint:



… 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)

For answer to recent "firewall" challenge, see Y.N., Weinberg, arXiv:1406.1505

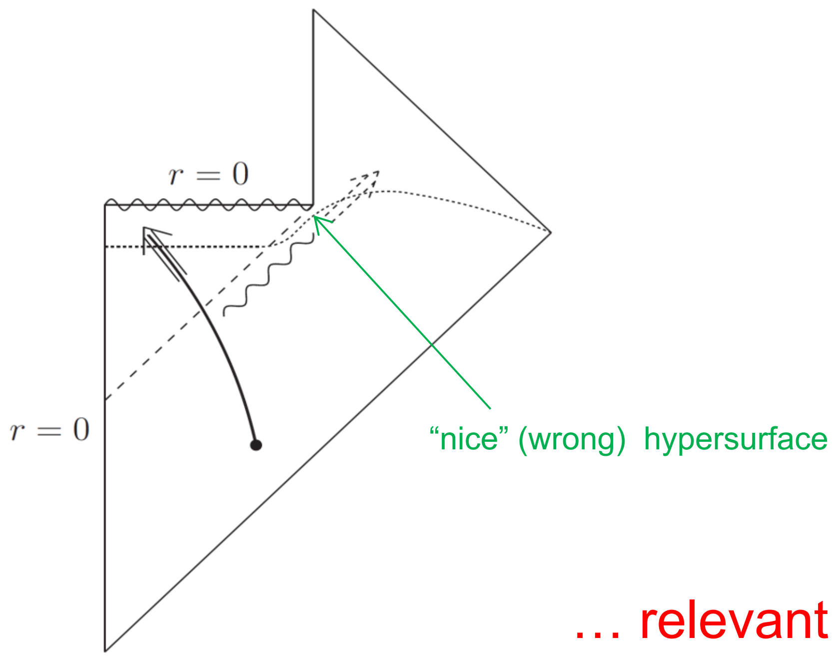
A Lesson:

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

To keep our description of nature to be **local** in space at long distances

(or, at least, to keep approximate locality in the description)

… Equal time hypersurface must be chosen carefully.



… relevant for formulating "measurements"

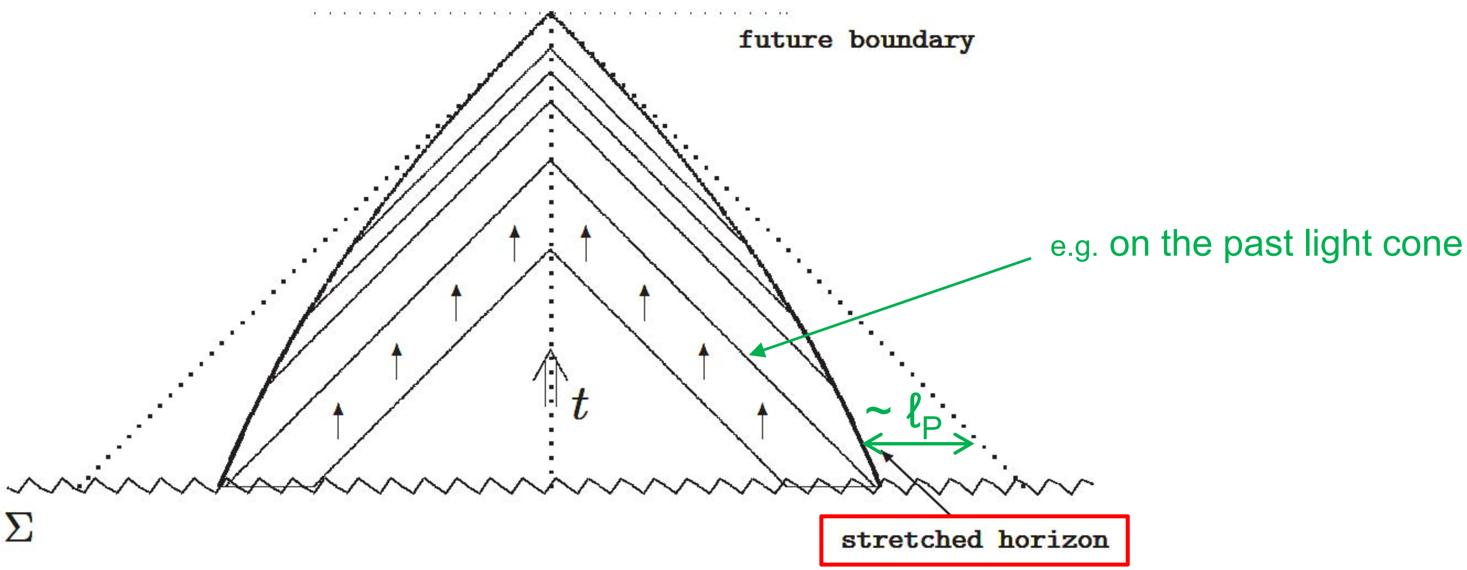
separating into subsystems, the basis for information amplification, …

Now, cosmology (eternal inflation)

… simply "inside-out" !

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

Specifically, the state can be defined to represent **only**
the spatial region **in and on the stretched (apparent) horizons**
as viewed from a freely falling reference frame. Y.N. ('11)



What is the multiverse? $\longrightarrow$ probability !!

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 region within the horizon

- Probability in cosmology has the origin in quantum mechanics

  … (a suitable generalization of) the Born rule will give the probability

  Multiverse = Quantum many worlds

- Global spacetime is an emergent (and "redundant") concept

  … probability is more fundamental

  — counting observers (with equal weight) may vastly overcount d.o.f.

  $\rightarrow$ provides natural and effective "regularization"

$\Longrightarrow$ The multiverse lives in probability space !!

No probability reward for volume increase !

cf. Fixing a reference frame

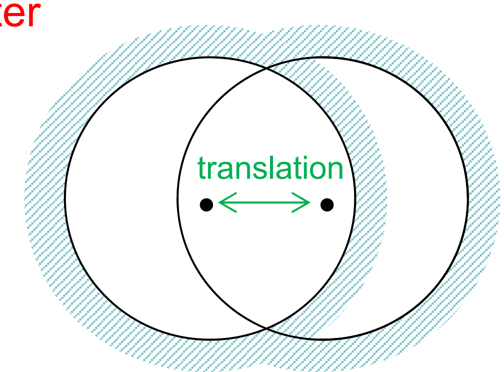
$\leftrightarrow$ eliminating / fixing a part of gauge redundancies in quantum gravity

There are residual ones:

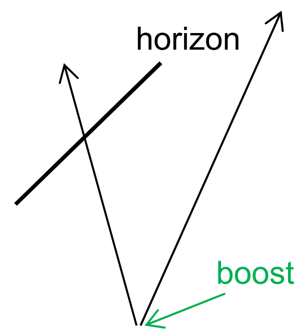
… Change of a reference frame (& time translation)

e.g.

de Sitter



Black hole



Spacetime $\leftrightarrow$ horizon d.o.f. !

This transf. $\overset{G_N \to 0}{\rightleftarrows}$ Poincaré (Lorentz) transf. $\overset{c \to \infty}{\rightleftarrows}$ Galilei transf.

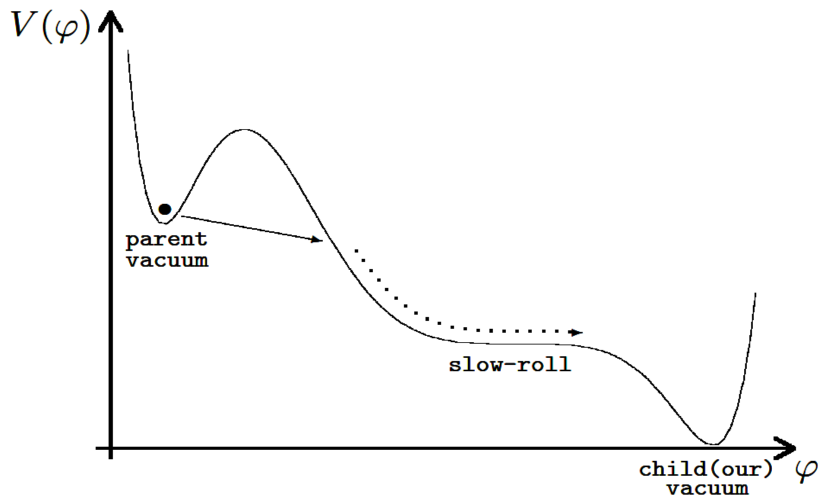
more “relativeness”

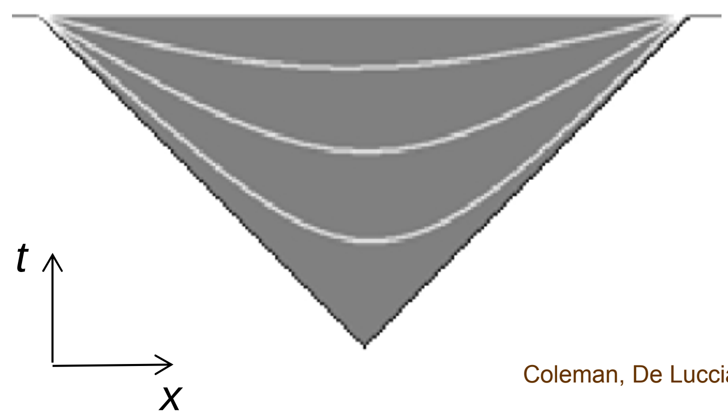
… What to do with this residual gauge redundancy ($t \to t + c$)?

$\to$ The “static” quantum multiverse (no time to talk; backup slides)

What observations?

Our universe is a bubble formed in a parent vacuum:





Coleman, De Luccia ('80)

… Infinite **open** universe

(negative curvature)

Why is our universe so flat?

If it is curved a bit more, no structure / observer $\rightarrow$ could be anthropic!

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

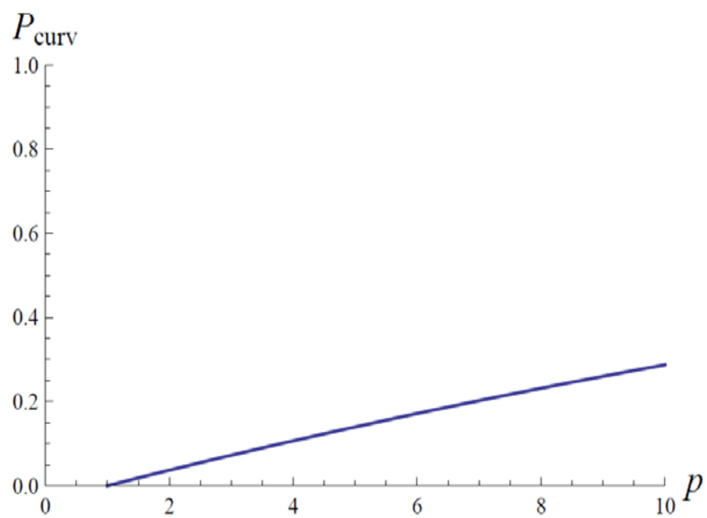
- Fine-tuning initial conditions
- Having a (accidentally) flat portion in the scalar potential

$\rightarrow$ (Observable) inflation

$\Longrightarrow$ 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
- $\Omega_{\rm curvature} < 0$ will exclude the framework!

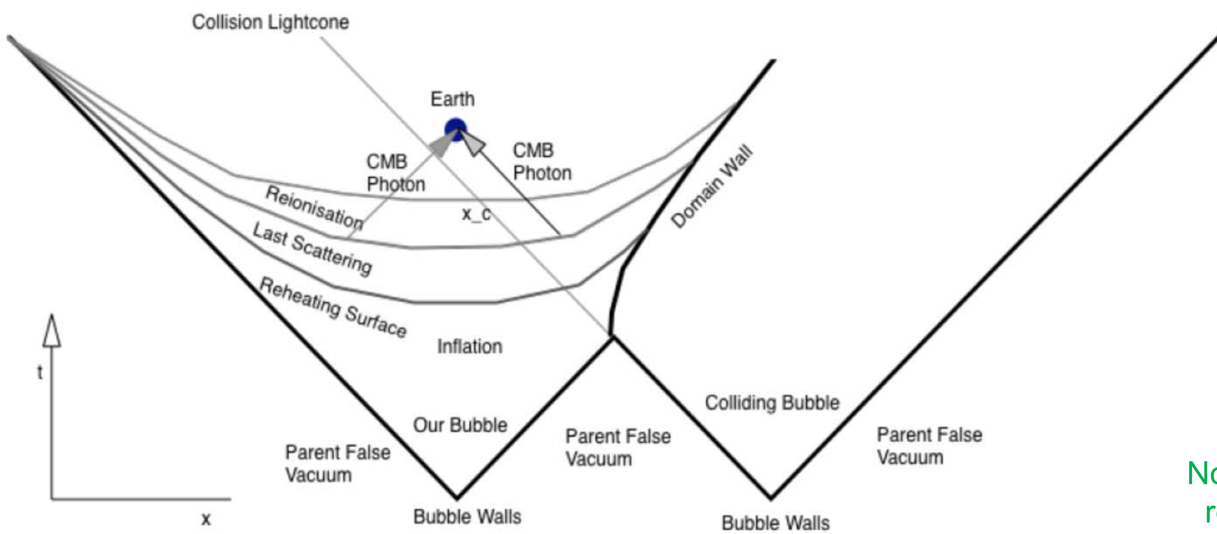
Freivogel, Kleban, Rodríguez Martínez, Susskind ('05)
….
Guth, Y.N. ('12)

Information on pre-inflationary history, global structure of spacetime!, …

(Slow-roll) Inflation may be “just so”

… opens the possibility of many dramatic signals

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



Note: the number of relevant collisions ~ e^{-N}

… may leave signals in CMB and large scale structure

- Tunneling from a lower dimensional vacuum

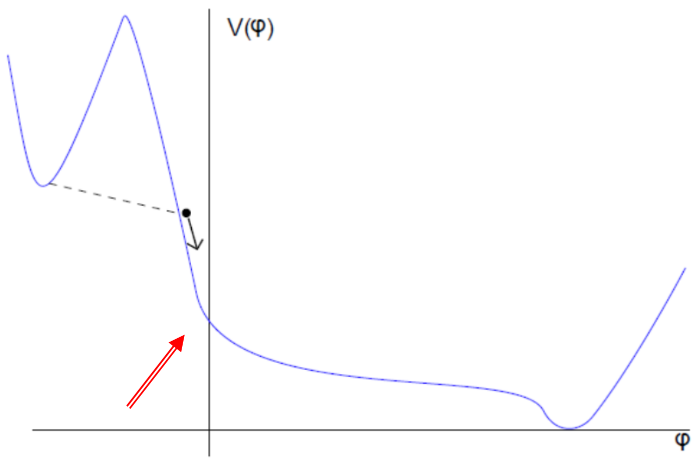
Graham, Harnik, Rajendran, arXiv:1003.0236

… may lead to signals in CMB through anisotropic curvature

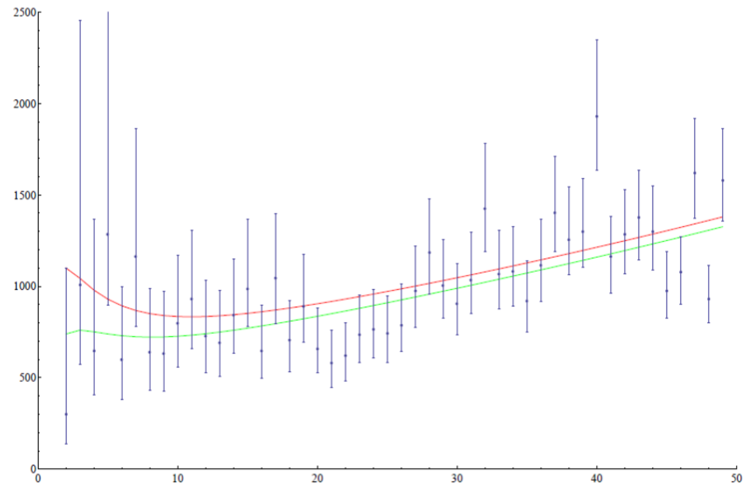
• Suppressions of low ℓ

Freivogel, Kleban, Rodriguez Martinez, Susskind, hep-th/0505232, arXiv:1404.2274; Bousso, Harlow, Senatore, arXiv:1309.4060, arXiv: 1404.2278

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



In PLANCK data?



(significance will increase if BICEP2 data is confirmed)

• 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, arXiv:0809.1206

Detection of any of these signals would provide evidence for the multiverse & information about the structure of spacetime

Future prospects?

Relation to observation

- Further signals supporting the multiverse — Axion dark matter with $f_a \sim M_{\rm GUT}$; What else can we imagine?
- Implications for physics beyond the standard model

cf. Arkani-Hamed, Dimopoulos; Hall, Y.N.; Giudice, Rattazzi; …

Emergent spacetime from quantum gravity

Y.N., Weinberg, "Black holes, entropies, and semiclassical spacetime in quantum gravity," arXiv:1406.1505

Bekenstein-Hawking entropy counts "constituents" of spacetime

— information delocalized quantum mechanically within the "zone"

→ implications for cosmology?

How to implement conditioning?

Need a suitable extension of the Born rule … in "space*time*", must involve operators e.g. H

… separation into subsystems, extracting suitable correlations, what's the observation, information processing?, …

… may have to be done in an (effectively) finite-dimensional Hilbert space

cf. Page; Y.N.; Bousso, Susskind; Aguirre, Tegmark, Layzer; Carroll, Sebens; …

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*?

$\boxed{\text{The gauge fixing and the normalizability may be enough.}}$

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!

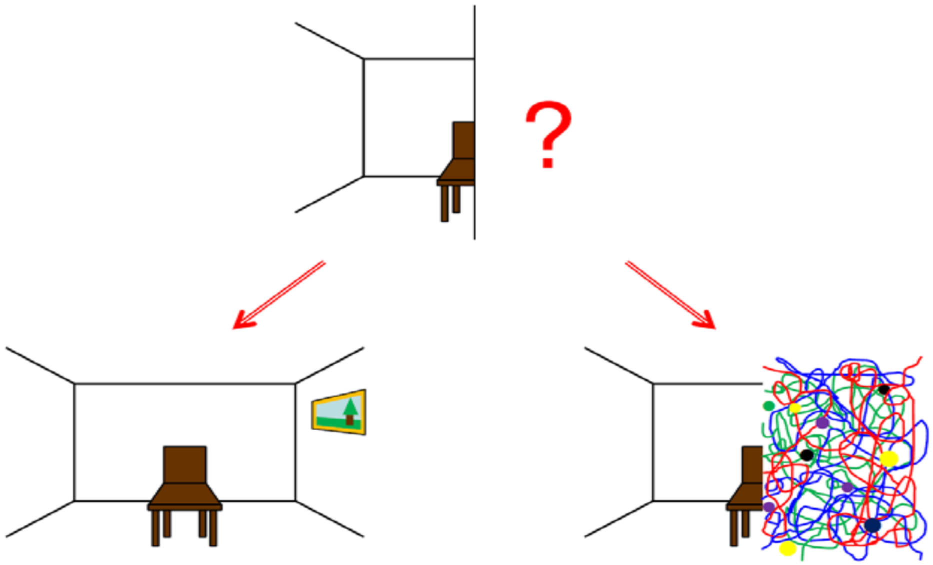
$$\boxed{H\,|\Psi(t)\rangle = 0 \quad \Leftrightarrow \quad \frac{d}{dt}|\Psi(t)\rangle = 0}$$

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) $\leftrightarrow$ time's arrow

… Correlation among physical subsystems

cf. DeWitt ('67)

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

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"

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

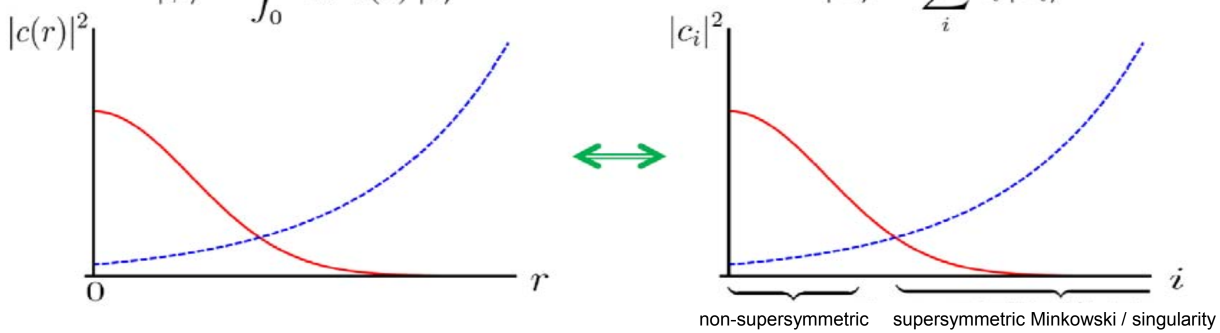
How to prevent "dissipation" into Minkowski/singularity worlds?

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

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

Analogy with the hydrogen atom:

$$|\psi\rangle = \int_0^\infty dr\, c(r)\, |r\rangle \qquad\qquad |\Psi\rangle = \sum_i c_i\, |\alpha_i\rangle$$



The hydrogen atom — The quantum multiverse

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