Making predictions in the Quantum Multiverse

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We (seem to) live in the "multiverse"!

… suggested **both** from observation **and** theory

- Our universe is extremely "special"

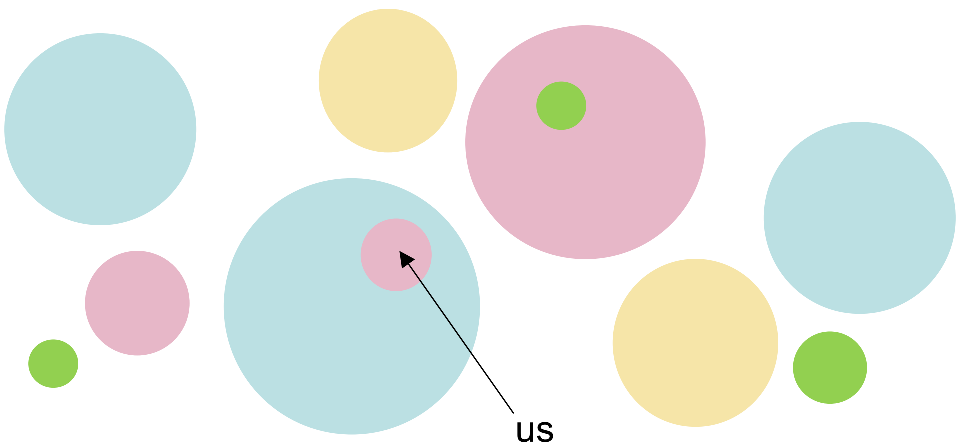
  e.g. $\rho_\Lambda \sim \rho_{matter}$ — why now?

… hard to understand unless our universe is only a part of the "multiverse"

cf. Weinberg ('87)

- Theory also suggests

  — eternal inflation



Inflation is (generically) future eternal

→ eternally creating "bubble" universes

String theory (landscape)

→ many universes with differing properties

… Anthropic considerations **mandatory** (not an option)

$\Longrightarrow$ Eternally inflating multiverse

Far-reaching implications

… The multiverse is “infinitely large” !

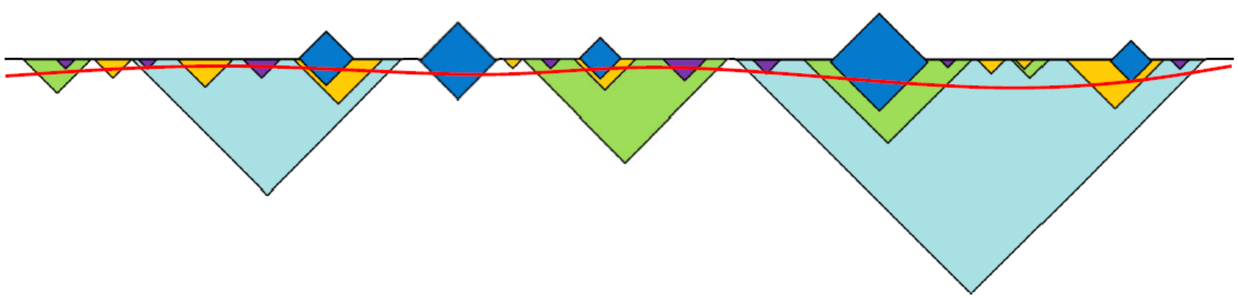
Predictivity crisis !

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)

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? … What is time?

— Problem of conditioning

… What is the "observation"? … information processing, entanglement, …

Work addressing various aspects:

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

Below, my own view

Quantum mechanics is essential to answer these questions.

A key role is played by "gauge fixing" (Multiverse = Quantum many worlds)

Remaining issues include that of conditioning (Measure problem ≈ Measurement problem)

Multiverse = Quantum many worlds

Y.N., "Physical theories, eternal inflation, and the quantum universe," arXiv:1104.2324
(see also Bousso, Susskind, 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

→ Fixing "gauge redundancies" associated with quantum gravity implies:

> The multiverse lives (only) in probability space

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

… provide simple regularization

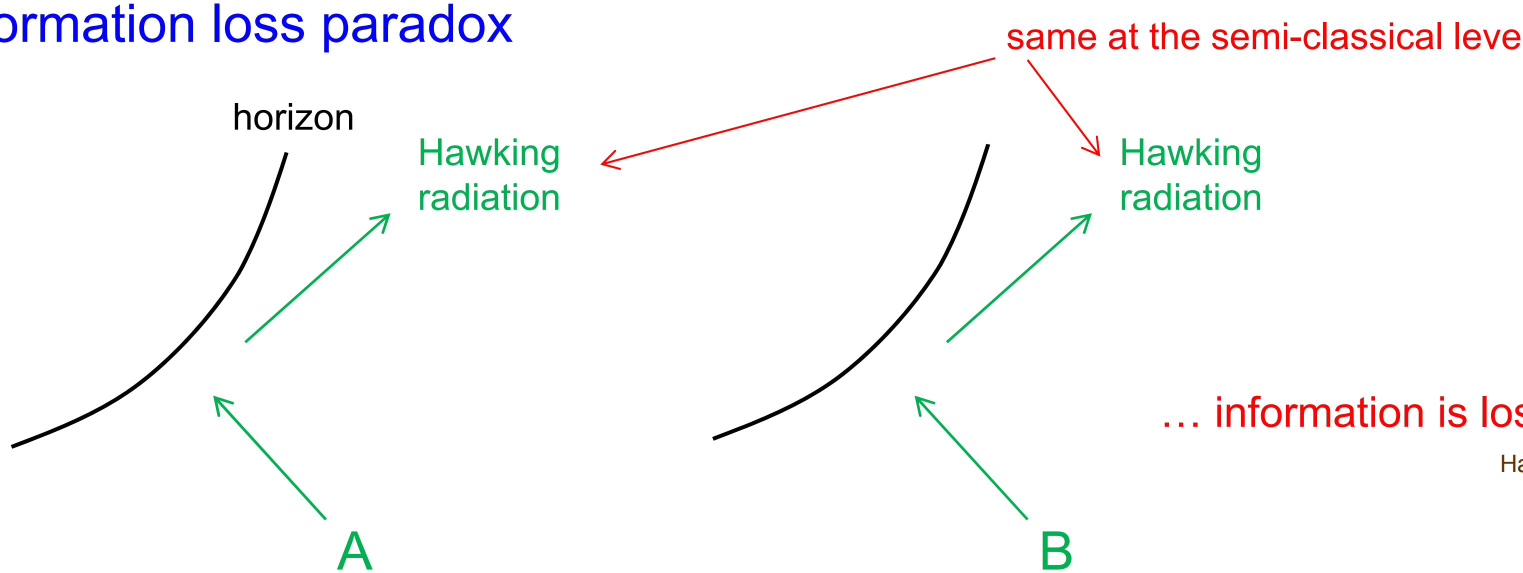
(Anything that can happen will happen but not with equal probability.)

$\Longrightarrow$ Dramatic change of our view of spacetime

Quantum Mechanics in a System with Gravity

Black Hole

Information loss paradox



… information is lost ??

Hawking ('76)

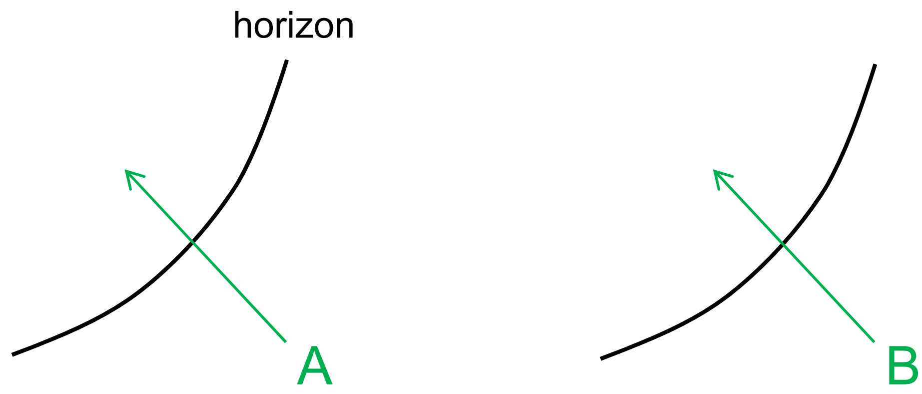
⟹ No

… 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:



… According to general relativity, objects simply fall in

(or might hit something dramatic—"firewall" cf. discussion on Thursday)

Can there be an *independent* interior picture?

⟹ No

… The Information cannot exist both in the interior and exterior

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

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)

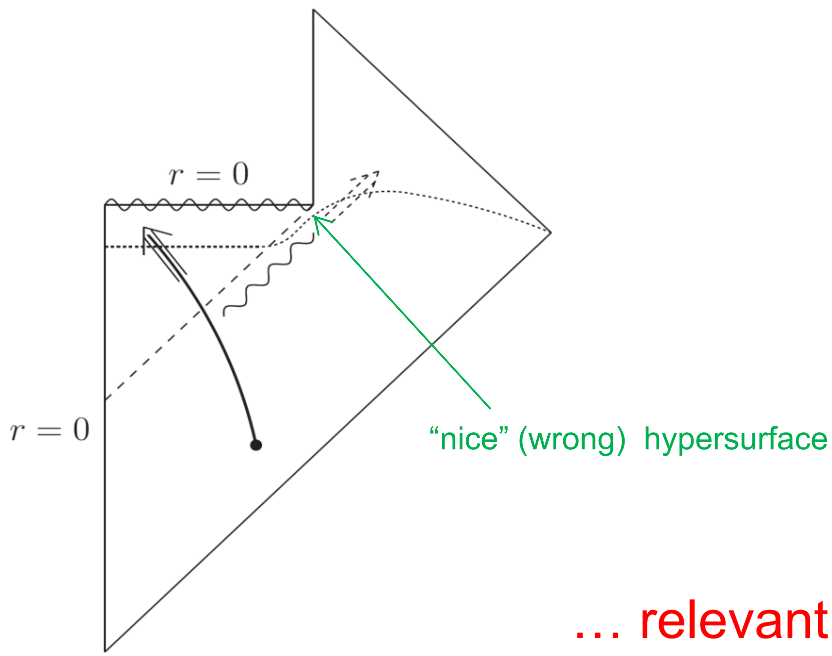
A Lesson:

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

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"

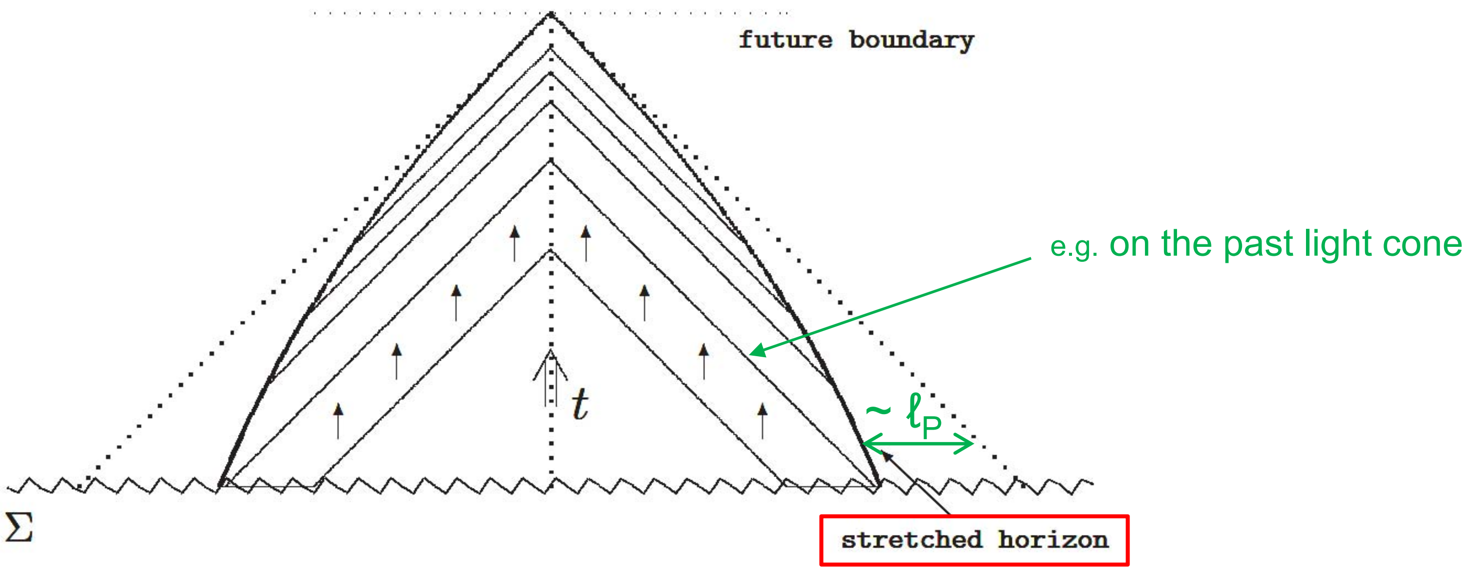
separating into subsystems, the basis for information amplification, …

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? ⟶ probability !!

Bubble nucleation … probabilistic processes

usual QFT: $\Psi(t=-\infty) = |e^+e^-\rangle \quad \to \quad \Psi(t=+\infty) = c_e\,|e^+e^-\rangle + c_\mu\,|\mu^+\mu^-\rangle + \cdots$

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

eternally inflating

each term representing only the region within the horizon

(temporarily taking time-evolution picture, which must arise effectively; see later)

- Probability in cosmology has the origin in quantum mechanics

  … (a suitable extension 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 !!

Fixing a reference frame

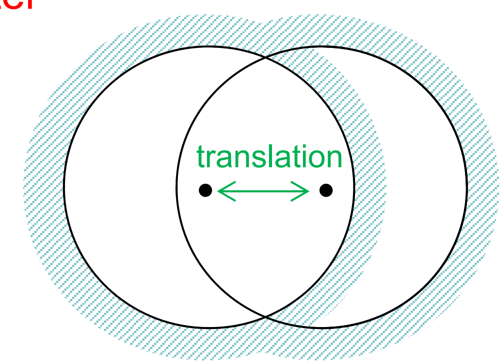
$\leftrightarrow$ eliminating / fixing a part of gauge redundancies in quantum gravity

There are residual ones:

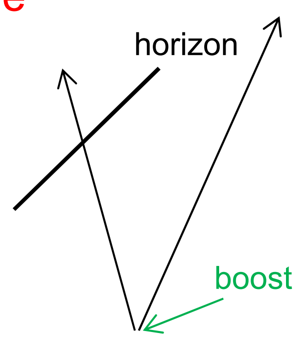
… Change of a reference frame (& time translation)

e.g.

de Sitter



Black hole



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

This transf. $\underset{\longleftarrow}{\xrightarrow{G_N \to 0}}$ Poincaré (Lorentz) transf. $\underset{\longleftarrow}{\xrightarrow{c \to \infty}}$ Galilei transf.

more "relativeness"

… What to do with this residual gauge redundancy?

The multiverse bootstrapped

Y.N., "The static quantum multiverse," 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!

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

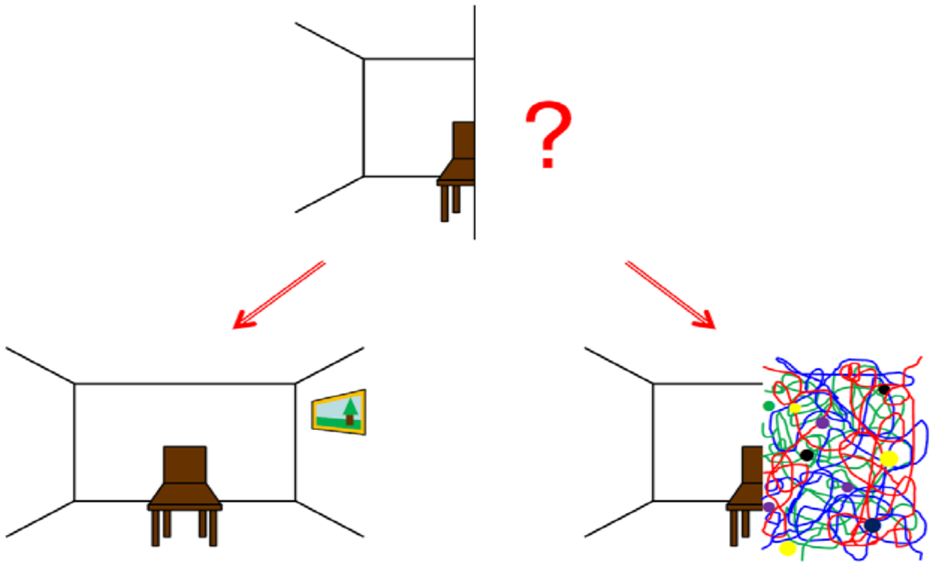
cf. Wheeler-DeWitt equation for a closed universe,
but the system here is the "infinite" multiverse

- 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 $|\Psi>$ must depend on *t*



The dominance of extremely rare configurations (ordered ones; left) $\leftrightarrow$ time's arrow

Consistency conditions *on the form of H*:

J: vacuum that can support any observer

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

$$\frac{\langle\Psi|\,\mathcal{O}_{\mathrm{BB},J}\,|\Psi\rangle}{\langle\Psi|\,\mathcal{O}_{\mathrm{OO},J}\,|\Psi\rangle} \sim \frac{\Gamma_{\mathrm{BB},J}}{\epsilon_J \Gamma_J} \lll 1$$

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"

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

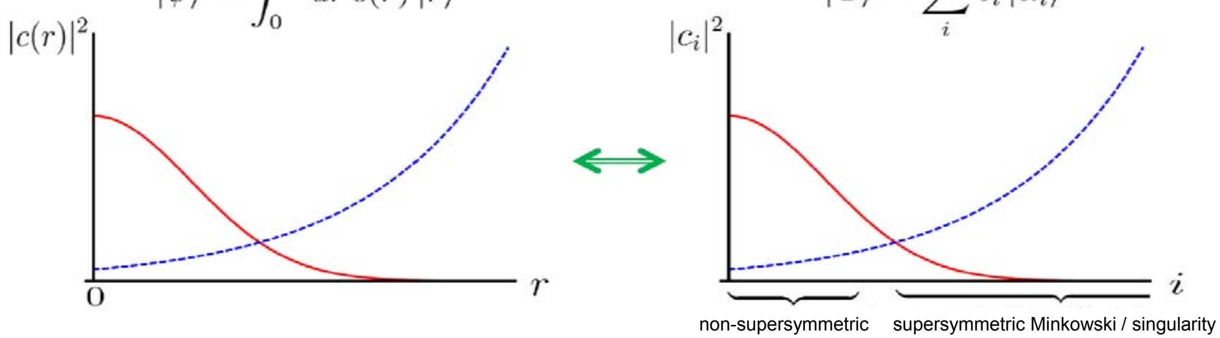
How to prevent "dissipation" into Minkowski/singularity worlds?

… 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…

Summary and future directions

The multiverse is "real"

— picture suggested both from observation and theory

It raises a challenge of making (top-down) predictions for
why we live in the universe we observe

(the structure of low-energy Lagrangians, values of cosmological parameters, etc.)

The "infinitely large" multiverse $\rightarrow$ How to define the probability?

Quantum mechanics + Gauge invariance of quantum gravity

$\boxed{\text{Multiverse = Quantum many worlds}}$

The multiverse lives (only) in probability space

… a new viewpoint for the global spacetime

… provides a framework to address further questions

(the origin / "beginning" of the multiverse, what is time, …)

The multiverse *state* may be static

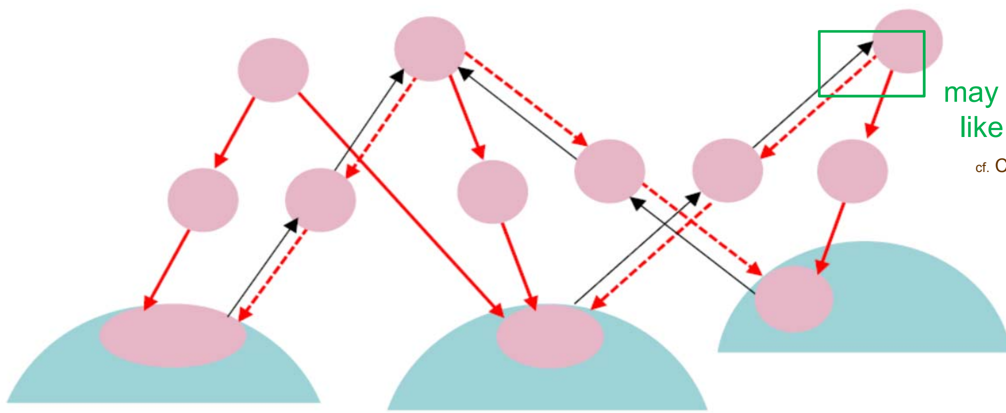
$$\boxed{H\,|\Psi\rangle = 0}$$

… Gauge invariance and the normalizability may select a unique state.

(may not be pure, $\rho = \Sigma_i\,|\Psi_i\rangle\langle\Psi_i|\,/\,N$)

The arrow of time emerges dynamically:

How does the state look from the "insider" viewpoint?



may *locally* look like "dual time"

cf. Carroll, Chen ('04)

… collection of initial and final states / vacua

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 done in an (effectively) finite-dimensional Hilbert space

→ connection to semi-classical, effective methods of regularization