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. $\rho_\Lambda \sim \rho_{\text{matter}}$ — 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)

  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 $B$

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

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

— 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.)

→ Dramatic change of our view of spacetime

(see also Bousso, Susskind, arXiv:1105.3796)
Quantum Mechanics in a System with Gravity

Black Hole

Information loss paradox

→ 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:

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.

... *nice* (wrong) hypersurface

... 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.

What is the multiverse? → probability!!
Bubble nucleation … probabilistic processes

usual QFT: \[ \Psi(t = -\infty) = |e^+e^-\rangle \rightarrow \Psi(t = +\infty) = c_e |e^+e^-\rangle + c_\mu |\mu^+\mu^-\rangle + \cdots \]

multiverse: \[ \Psi(t = t_0) = |\Sigma\rangle \rightarrow \Psi(t) = \cdots + c \left| \begin{array}{c} 321 \\ \rho_A \end{array} \right\rangle + c' \left| \begin{array}{c} 321 \\ \rho_B \end{array} \right\rangle + \cdots + d \left| \begin{array}{c} 41 \end{array} \right\rangle + \cdots \]

(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.

  \[ \rightarrow \text{provides natural and effective “regularization”} \]

  \[ \Longrightarrow \text{The multiverse lives in probability space}!! \]
Fixing a reference frame
↔ 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 ↔ horizon d.o.f.!

This transf. $G_N \rightarrow 0$  Poincaré (Lorentz) transf. $c \rightarrow \infty$  Galilei transf.
more “relativeness”

… What to do with this residual gauge redundancy?
The multiverse bootstrapped


The picture so far:

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

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

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

\( \rightarrow \text{The multiverse state is static!} \)

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

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

Cf. Wheeler-DeWitt equation for a closed universe, but the system here is the “infinite” multiverse.
The arrow of time can emerge dynamically

The fact that we see time flowing in a definite direction does not mean that $|\Psi\rangle$ 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

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

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

The probability of leading to ordinary observers

The vacuum decay rate
In $|\Psi\rangle$, various “micro-processes” must balance.

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:

- Quantum mechanics is crucial for the very *existence* of the system!
- Relevant Hilbert space is effectively *finite-dimensional* $\to$ 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 → How to define the probability?

Quantum mechanics + Gauge invariance of quantum gravity

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

\[ H |\Psi\rangle = 0 \]

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

The arrow of time emerges dynamically:

How does the state look from the “insider” viewpoint?

... collection of initial and final states / vacua

How to implement conditioning?

Need a suitable extension of the Born rule ... in “spacetime”, 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

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