Quantum Gravity

From black holes to 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
• …

… implications on particle physics and cosmology
Shocking news in 1998

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

— Why now?

Nonzero value completely changes the view!

Natural size for vacuum energy \( \rho_\Lambda \sim M_{\text{Pl}}^4 \)

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

Wait!

Is it really unnatural to observe this value?

It is quite “natural” to observe \( \rho_{\Lambda,\text{obs}} \),

as long as different values of \( \rho_\Lambda \) 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
Full of “fine-tunings”

Examples:

- \( y_{u,d,e} \nu \sim \alpha \Lambda_{\text{QCD}} \sim O(0.01) \Lambda_{\text{QCD}} \)
  
  ... otherwise, no nuclear physics or chemistry

(Conservative) estimate of the probability: \( P \ll 10^{-3} \)

- \( \rho_{\text{Baryon}} \sim \rho_{\text{DM}} \)

....

Some of them could be anthropic (and some may not)

\[ \rightarrow \quad \text{Implications?} \]

- Observational / experimental (test, new scenarios, …)
- Fundamental physics (spacetime, gravity, …)
Full of “fine-tunings”

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  …. 

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$\Rightarrow$ Implications?

• Observational / experimental (test, new scenarios, …)
$\Rightarrow$• Fundamental physics (spacetime, gravity, …)

Multiverse = Quantum many worlds, “constituents” of spacetime, …
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 \( t = t_c \) (\( \to \infty \))

… 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?

— Problem of conditioning
  … What is the “observation”? 

Work addressing various aspects:

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

Below, my own view

Quantum mechanics is essential to answer these questions.

→ Dramatic change of our view of spacetime and gravity
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**

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

**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

→ 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:

• Distant observer:
  Information will be outside at late times.
  (sent back in Hawking radiation)

• Falling observer:
  Information will be inside at late times.
  (carried with him/her)

Which is correct?

Note: Quantum mechanics prohibits faithful copy of information (no-cloning theorem)
From a falling observer’s viewpoint:

... Objects simply fall in
  cf. equivalence principle

• Distant observer:
  Information will be outside at late times.
    (sent back in Hawking radiation)

• Falling observer:
  Information will be inside at late times.
    (carried with him/her)

Which is correct?

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 later for the recent “firewall” challenge
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.

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: \( \Psi(t = t_0) = |\Sigma\rangle \rightarrow \Psi(t) = \cdots + c |\frac{\phi_1}{\phi_2}\rangle + c' |\frac{\phi_2}{\phi_3}\rangle + \cdots + d |\frac{41}{101}\rangle + \cdots \)

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 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.
  
  → provides natural and effective “regularization”

  → 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.

[Diagram: de Sitter vs. 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? … later
Obstacle for Complementarity?

Passed many consistency checks Hayden, Preskil ('07); Sekino, Susskind ('08); Y.N. ('11), …
but no explicit microscopic transformation laws

“Firewall” argument Almheiri, Marolf, Polchinski, (Stanford), Sully ('13–'14)

Problems can be formulated in a “single causal patch”

Unitarity → Smooth horizon = “firewall”

\[ S = 4\pi M^2 \ell_P^2 \]
\[ S = 4\pi (M-\delta M)^2 \ell_P^2 \]

... monogamy of entanglement

... mismatch of Hilbert space dimensions
A Solution to the BH Information Problem

What is semiclassical theory?

… quantum theory of matter on an exact spacetime background

But the uncertainty principle says there is no such thing!

ex.) Dynamically formed black hole

Time scale of evolution (Hawking emission): $\Delta t \sim M$ (below we set $\ell_P = 1$)

→ The black hole state involves a superposition of $\Delta E \sim 1/M$

How many independent ways are there to superpose the energy eigenstates to obtain the same black hole geometry within this precision?

The logarithm of this number: $S_0 = \frac{A}{4}$ (at the leading order in $1/A$)

… the origin of the Bekenstein-Hawking entropy

There are $e^{S_0}$ black hole vacuum states, labeled by $k$

… general black hole states: $|\Psi_{ak}(M)>$
Two important assumptions
(motivated by the standard statistical interpretation of black hole thermodynamics)

• d.o.f. represented by $k$, which we call vacuum d.o.f.,
  are course-grained **to obtain** the semiclassical theory

• These d.o.f. are viewed as distributed according to
  the thermal entropy calculated using the semiclassical theory

... BH information **delocalized** throughout the zone

The (correct) picture of Hawking emission:

occurs around the edge of the zone
(no outgoing Hawking quantum in the zone)

... early Hawking quantum entangled with $k$
(The monogamy argument does not apply.)

... Breakdown of semiclassical theory at **large** distances!!
Negative energy excitation carries a **negative** entropy

ex.) One q-bit of information release

\[ |\psi_k(M)\rangle|\phi_0\rangle \rightarrow \begin{cases} 
|\psi_\alpha^{k+1}(M)\rangle|\phi_1\rangle & \text{if } k \text{ is odd,} \\
|\psi_\alpha^{k+2}(M)\rangle|\phi_2\rangle & \text{if } k \text{ is even,}
\end{cases} \]

(CF:) Time reversal process vs generic incoming radiation

The true Hilbert space is smaller than naïve Fock space in the semiclassical theory

… Each of the emission & relaxation processes is separately (& locally) unitary

(no issue of Hilbert space dimensions)
A successful reference frame change possible

The existence of a reference frame in which the horizon region appears (approx.) Minkowski ensures that the horizon is smooth.

(consistently with unitarity of Hawking evaporation, BH mining, etc.)

A frame whose spatial origin falls from a distance: $r_0 - 2M > O(M)$

... Space/time scale between any “detector clicks” (even if blueshifted) are $\Delta T \sim \Delta X \sim O(M) \rightarrow$ approx. Minkowski

... Satisfactory solution to the BH information problem without firewalls
The multiverse bootstrapped

Y.N., “The static quantum multiverse,”
PRD 86, 083505 (’12) [arXiv:1205.5550]

The picture so far:

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

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

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

\[ \rightarrow \text{The multiverse state is static!} \]

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

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 $|\Psi\rangle$ must depend on $t$.

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

Consistency conditions on the form of $H$:\n\[
\frac{\langle \Psi | \mathcal{O}_{BB,J} | \Psi \rangle}{\langle \Psi | \mathcal{O}_{OO,J} | \Psi \rangle} \approx \frac{\Gamma_{BB,J}}{\epsilon_J \Gamma_J} \ll 1
\]

$J$: vacuum that can support any observer

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

The probability of leading to ordinary observers

The vacuum decay rate

$\cdots$ Correlation among physical subsystems

cf. DeWitt (’67)
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 $\rightarrow$ normalized probability…
Relation to Observations?

Our universe is a bubble formed in a parent vacuum:

... Infinite open universe
(negative curvature)

Coleman, De Luccia ('80)
Why is our universe so flat?

If it is curved a bit more, no structure / observer → 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
  → (Observable) inflation

→ The flatness will not be (much) beyond needed!

Information on pre-inflationary history, probability measure, …
Summary and future directions

The multiverse seems “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 probabilities?

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, …)
Emergent spacetime from quantum gravity

Bekenstein-Hawking entropy counts microscopic d.o.f. that play dual roles of “constituents” of spacetime and thermal radiation

— information delocalized quantum mechanically within the “zone”
— unexpected breakdown of semiclassical theory at large distances

→ satisfactory solution to the BH information problem without firewalls

Future Prospects?

Relation to observation

• Further signals supporting the multiverse
• Implications for physics beyond the standard model

Subtlety in 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 be done in an (effectively) finite-dimensional Hilbert space