Physical predictions in the Quantum 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
Universe is accelerating!

\[ \Lambda \neq 0 ! \]
The cosmological constant problem

- Every particle couples to gravity

\[ \rho_{\Lambda} \equiv \Lambda^2 M_{Pl}^2 \]

\[ \rho_{\Lambda} \sim \text{where new physics cuts loop integrals of } \psi \]

- Naively \( \rho_{\Lambda} \sim M_{Pl}^4 \)
- At the very least, \( \rho_{\Lambda} \sim \text{TeV}^4 \)

Observationally,

\[ \rho_{\Lambda} \sim (10^{-3} \text{ eV})^4 \]

Naïve estimates \( O(10^{120}) \) too large

Also, \( \rho_{\Lambda} \sim \rho_{\text{matter}} \) — Why now?

... the worst prediction ever made!
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 $\rho_{\Lambda,\text{obs}}$, as long as different values of $\rho_\Lambda$ are “sampled”

Weinberg (’87)
Many universes — multiverse — needed

• 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)
Full of “miracles”

Examples:

• $y_{u,d,e} \nu \sim \alpha \Lambda_{QCD} \sim O(0.01) \Lambda_{QCD}$
  
  ... 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 anthropic (and some may not)

→ Implications?

• Observational / experimental (test, new scenarios, …)
• Fundamental physics (spacetime, gravity, …)
Implications
—observation / experiment—
Cosmology

Our universe is a bubble formed in a parent vacuum:

\[ V(\varphi) \]

... 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
→ 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 !

"difficulty" of realizing a flat potential

$f(N) \sim 1/N^p$

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

Freivogel, Kleban, Rodriguez Martinez, Sussking ('05)
...
Guth, Y.N.
Particle Physics

Anthropic (could) affects how our universe looks
→Any change in our thinking? New scenario(s)?

Weak scale does affect environment

ex. Stability of complex nuclei

For fixed Yukawa couplings,
no complex nuclei for $v > 2 \, v_{\text{obs}}$

Possible that $v_{\text{obs}}$ arises as a result of environmental selection

Weak scale supersymmetry really “needed”?

… the scale of SUSY masses determined by statistics

$$d \mathcal{N} \sim f(\tilde{m}) \frac{v^2}{\tilde{m}^2} \, d\tilde{m}$$

$$f(\tilde{m}) \sim \tilde{m}^{p-1}$$

For $p < 2$, weak scale SUSY results, but for $p > 2$, $\tilde{m}$ prefers to be large
What if $\tilde{m}$ shoots up?

“Minimal” scenario — Standard Model!

Unification at the level of $\delta g_a^2 \sim 6\%$ at $E \sim 10^{14}$ GeV

Dark matter can be axions — $\theta_{\text{QCD}} \ll 1$ ... need mechanism

Doesn’t seem that bad...

(Note: no SUSY flavor problem, SUSY CP problem, $\mu$ problem, gravitino problem, axino problem, or …)

Hall, Y.N., arXiv:0910.2235
High scale SUSY — nothing left?

SUSY boundary condition on the Higgs quartic $\lambda$

$$\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \cos^22\beta$$

$$\lambda(m) \rightarrow \lambda(v) \rightarrow M_H \text{ prediction}$$

$M_H \approx (128 - 141) \text{ GeV}$

Many theories lead to this “edge value”

Crazy?

Do we know $\tilde{m}$?

What about threshold corrections?

$$\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \{1 + \delta(\tilde{m})\}$$

includes all threshold corrections

$\tilde{m}$: matching scale
Infrared convergence property

The fractional uncertainty reduced by ~ a factor of 6

\[ \delta = 0, \pm 0.1, \pm 0.2 \]
for \( \tilde{m} = 10^{14} \) GeV

Extreme insensitivity to \( \tilde{m} \)

Explicit dependence on \( \tilde{m} \) extremely mild!
Suppressed threshold corrections

SUSY corrections at $m \rightarrow$ very small!

Largest uncertainties

$\delta m_t|_{\text{exp}} = \pm 1.3 \text{ GeV}$ \quad $\rightarrow \quad \delta M_H = \pm 1.8 \text{ GeV}$

$\delta \alpha_s(M_Z)|_{\text{exp}} = \pm 0.002$ \quad $\rightarrow \quad \delta M_H = \mp 1.0 \text{ GeV}$

Precision Higgs mass prediction !!

$$M_H = 141.0 \text{ GeV} + 1.8 \text{ GeV} \left( \frac{m_t - 173.1 \text{ GeV}}{1.3 \text{ GeV}} \right) - 1.0 \text{ GeV} \left( \frac{\alpha_s(M_Z) - 0.1176}{0.002} \right)$$

$$+ 0.14 \text{ GeV} \left( \log_{10} \frac{\tilde{m}}{10^{14} \text{ GeV}} \right) + 0.10 \text{ GeV} \left( \frac{\delta}{0.01} \right) \pm 0.5 \text{ GeV}$$

$M_H = (141 \pm 2) \text{ GeV}$

... irreducible high energy errors only $\sim \pm 0.4 \text{ GeV}!$
Implications

— fundamental physics —
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 is robust

A metastable minimum with $\rho \ll M_{Pl}^4$ is enough!

… *a priori*, has nothing to do with quantum gravity, string landscape, beginning of spacetime, …

• The most naïve does NOT work!

\[ V \sim e^{3Ht} \]

… vastly more younger universes than older ones

\[
\frac{N_{T_{CMB}=3K}}{N_{T_{CMB}=2.725K}} \sim 10^{59} !!
\]

… Youngness paradox

Guth (’00); Tegmark (’04)

Synchrinous (proper) time cutoff measure

Linde, Mezhiumian (’93)
Any geometrical cutoff leads to peculiar “end” of time

Events in eternally inflating spacetime are dominated by late-time attractor regeme

→ The cutoff does not decouple!

\[ P_{\text{end}} \equiv 1 - \frac{N_2}{N_1} \rightarrow 0 \quad \text{Time does “end”!} \]

Bousso, Freivogel, Leichenauer, Rosenhaus (’10)

Something seems terribly wrong …
Multiverse as a Quantum Mechanical Universe

Quantum mechanics is **crucial**

The basic idea:

The laws of quantum mechanics are not violated (only) when physics is described from an observer’s point of view

Quantum mechanics in systems with gravity needs care

→ Dramatic change of our view on spacetime

- The measure problem is solved. (well-defined probabilities given by the Born rule)
- The multiverse and many worlds in QM are the same
- Global spacetime can be viewed as a derived concept
- The multiverse is a transient phenomenon while the system relaxing into a supersymmetric Minkowski state
- ....
What is “physical prediction”?

Two aspects
- Dynamical evolution
- Probabilities

Given what we know, *i.e.* condition $A$ imposed on a past light cone, what is the probability of this light cone to also have a property $B$?

"simulate" the multiverse many times

\[
\frac{\mathcal{N}_{A \cap B}}{\mathcal{N}_A} \rightarrow P(B|A)
\]

... semi-classical definition

$\ell \ll \ell_{Pl}$ — Does it make sense?
Holographic principle

't Hooft (’93); Susskind (’94); Bousso (’99)

The dimensions of states (# of d.o.f) bounded by the area

Black hole:

\[ S = \ln N = \frac{A}{4 \ell_{Pl}^2} \]

Bekenstein (’73); Hawking (’74)

de Sitter space:
The origin of different semi-classical universes cannot be attributed to the difference of initial conditions.

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

**multiverse:** \( \Psi(t = t_0) = |\Sigma\rangle \rightarrow \Psi(t) = \sum_i c_i |\text{cosmic history } i \text{ at time } t\rangle \)

The *single* state \( \Psi(t) \) describes the *entire* multiverse! ("no" global spacetime)

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How to define the state explicitly?
Horizon complementarity

A traveller falling into a black hole with some information

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

- **Falling traveller:**
  Information will be *inside* at late times.
  (carried with him/her)

Which is correct?

Both are correct!

— The two statements cannot be compared in principle.

A lesson: Equal time hypersurface must be chosen carefully.

Note: QM prohibits faithful copy of information (no-cloning theorem)
Multiverse state $|\Psi(t)\rangle$

Quantum observer principle:

*Physics obey the laws of quantum mechanics when described from the viewpoint of an “observer” (geodesic) traveling the multiverse, although this need not be the case if described in other ways, e.g., using the global spacetime picture with synchronous time slicing. The description involves only spacetime regions inside the (stretched) apparent horizons, as well as the degrees of freedom associated with these horizons.*

Y.N. (‘11)

Specifically, the state is defined on the observer’s past light cones bounded by the (stretched) apparent horizons.

How to define equal time hypersurfaces?

→ Past light cones
Bubble nucleations:

Apparent horizon:
- NOT depend on low energy physics
- always exists in any FRW universes
- "locally" determined within a bubble
- plays a role of the "preferred screen"

Deterministic, unitary evolution

\[ |\Psi(t_1)\rangle = U(t_1, t_2) |\Psi(t_2)\rangle \]

This duplication does not occur!
Hilbert space

$|\Psi(t)>$: superposition of semi-classical spacetimes

(evolution not along the axes determined by operators local in spacetime)

$$\mathcal{H} = \bigoplus_{\mathcal{M}} (\mathcal{H}_{\mathcal{M},\text{bulk}} \otimes \mathcal{H}_{\mathcal{M},\text{horizon}})$$

Probabilities

$$P(B|A) = \frac{\int dt \langle \Psi(t)| \mathcal{O}_{A \cap B} |\Psi(t)\rangle}{\int dt \langle \Psi(t)| \mathcal{O}_A |\Psi(t)\rangle}$$

- well-defined
- “gauge invariant”

Semi-classical approximation:

$$\rho_{\text{bulk}}(t) = \text{Tr}_{\text{horizon}} |\Psi(t)\rangle \langle \Psi(t)|$$

$$P(B|A) = \frac{\int dt \text{Tr} [\rho_{\text{bulk}}(t) \mathcal{O}_{\text{bulk},A \cap B}]}{\int dt \text{Tr} [\rho_{\text{bulk}}(t) \mathcal{O}_{\text{bulk},A}]}$$

... information loss
Quantum-to-classical transition

Multiverse: (intrinsically) quantum mechanical
↔ Our daily experience: (almost) classical

How does this dichotomy arise?

ex. Rotationally invariant theory

A chair: \( |\Psi\rangle \sim \left( |\text{chair}\rangle + |\text{man}\rangle + \cdots \right) \)

A chair + a man: \( |\Psi\rangle \sim \left( |\text{chair}\rangle + |\text{man}\rangle + \cdots \right) \otimes \left( |\text{chair}\rangle + |\text{man}\rangle + \cdots \right) \) \( \rightarrow \) No

\[
\left( \langle \text{chair} | \langle \text{man} \rangle \right) \hat{H} \left( |\text{chair}\rangle \right) = \begin{pmatrix} A & B \\ B & A \end{pmatrix} \quad \text{Eigenstates } \left( |\text{chair}\rangle \pm |\text{man}\rangle \right)/\sqrt{2} \text{ with eigenvalues } A \pm B
\]

For a macroscopic object, \( B \ll A \)

\( |\Psi\rangle \sim \left( |\text{chair}\rangle \otimes |\text{man}\rangle + |\text{man}\rangle \otimes |\text{chair}\rangle + \cdots \right) \)

The chair always has a definite orientation with respect to the man.

(The man, \( \approx \) we, do not see a superposition of chairs.)
Multiverse as quantum many worlds

The evolution of the multiverse state is deterministic, but not along the axes determined by operators local in spacetime:

The resulting multiverse state, \(|\Psi(t)\rangle \approx \sum_i |\text{possible world } i \text{ at time } t\rangle\), is everything. (Even we ourselves appear as a part.)

Once we have \(|\Psi(t)\rangle\), we can make predictions using our master formula. (No need of wavefunction collapse, environmental decoherence, or anything like those.)

The questions may be about global properties of the universe, or about outcomes of a specific experiment.

→ Unified treatment of quantum measurements and the multiverse
Problems in Geometric Cutoffs Solved

• Youngness paradox
• Boltzmann brains
• What’s observer?
• ambiguities in quantum probabilities
• “end” of time
• …

The ultimate future

The components that hit big crunch or black hole singularities “disappear.”

- covariant entropy conjecture
- consistency w/ the idea of stretched horizons
- string theory — no global symmetries
- reversibility of quantum evolution

\[ |\Psi(t)\rangle \xrightarrow{t \to \infty} \sum_i |\text{Supersymmetric Minkowski world } i\rangle \]
The “beginning”

\[ |\alpha_{\text{beginning}}\rangle \rightarrow |\Psi(t)\rangle = \sum_i c_i(t) |\alpha_i\rangle \]

contains \( |\alpha_{\text{beginning}}\rangle \) at some time \( t \)

\[ \rightarrow \text{restart the whole multiverse from there as a branch of } |\Psi(t)\rangle \]

Why can’t we identify \( |\alpha_{\text{beginning}}\rangle \) as a component of a “larger” structure?

Our multiverse is a fluctuation in a larger structure:

\[ S_{\text{beginning}} \sim 0 \rightarrow S_{\text{Minkowski}} = \infty \]

… the arrow of time

Two possibilities:

• The multiverse with a beginning
  
  (e.g. creation from “nothing”)

• The stationary, fractal “mega-multiverse”
  
  (Quantum mechanics satisfied *all* the time — no beginning or end)
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

→ surprising, quantum natures of spacetime and gravity
(black hole physics, eternal inflation, …)

Wide range of implications

cosmology, particle physics, (philosophy), …

Further experimental / theoretical support strongly desired

ex. spatial curvature, the Higgs boson mass, …