Predictions in Eternal Inflation

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Historical / philosophical question 1
What different lines of argument support Eternal Inflation (aka the Multiverse)? What is their character? How strong are they?
Historical / philosophical question 2

What are the prospects for using fine-tuning problems as a guide (sole guide?) for developing fundamental physics and cosmology?
Anthropic Predictions

Prediction $P_{obs}(\alpha_i)$ for parameter $\alpha$ (or set of parameters):

- Probability distribution $P_i(\alpha_i)$: variation of $\alpha_i$ across the multiverse (ensemble of “pocket universes”)
- “Typical” observer, chosen randomly from anthropic subset $A$
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Challenges

- Technical: measure problem, dealing with \( \infty \)
- Philosophical: what is the evidential value of anthropic predictions?
Claims about Anthropic Predictions

- Compatibility check rather than strong evidence, contrast with other cases of predictive success
- Weaker than other arguments in favor of Eternal Inflation
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1. Routes to Eternal Inflation
2. Anthropic Predictions
3. Other Arguments for EI
Routes to Eternal Inflation

Landscape Route

- Compactification $\rightarrow$ multiple minima, “scan” $\Lambda$
- Instability of dS to vacuum fluctuations, transition to lower minima
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Inflationary Cosmology Route
- Historically first (Vilenkin, Linde, ...)
- Expansion ends *locally*
Routes to Eternal Inflation

Landscape Route
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Assumption
Similar accounts of global causal structure of universe.

Inflationary Cosmology Route
- Historically first (Vilenkin, Linde, ...)
- Expansion ends \textit{locally}
Successes for Inflation

- Uniformity
- Flatness
- Spectrum of density perturbations (nearly scale invariant, Gaussian, adiabatic)

Consequences of dynamical evolution of “inflaton,” scalar field $\phi$

WMAP angular power spectrum (Spergel et al. 2006)
Starting Inflation

- Stochastic Inflation
  - Fluctuations “up the hill” → continued expansion
  - Inflation never ends globally

Image from Guth (2007)
Starting Inflation

- **Stochastic Inflation**
  - Fluctuations “up the hill” → continued expansion
  - Inflation never ends globally

- **Other Approaches**
  - Tunneling and bubble nucleation; topological inflation

Image from Guth (2007)
Eternal Inflation

- Pocket universes with different low energy physics
- Variation depends on mechanism generating pocket universes

Image: Andrei Linde
... what can we predict?

In an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times. Thus, the question of what is possible becomes trivial — anything is possible, unless it violates some absolute conservation law. To extract predictions from the theory, we must therefore learn to distinguish the probable from the improbable. (Guth 2007)
Exemplar: Weinberg on $\Lambda$

“What a typical observer (or other reference class) will measure for $\alpha_i$” (Principle of Mediocrity):

$$P_{obs}(\alpha_i) = N(\alpha_i)P_i(\alpha_i)$$

Ingredients (cf. Aguirre 2007)

- $\alpha$: vary $\Lambda$, other parameters fixed
- $N(\alpha) =$: normalized number of large gravitationally bound systems (proxy for observers); only non-zero in small window, due to $\Lambda$’s effect on structure formation
- $P_i(\alpha) =$: prior probability; expect this to be uniform, because anthropically allowed region small compared to particle physics energy scales
Anthropic Prediction vs. QFT Calculation

QFT calculation of vacuum energy

- $\Lambda$: quartically divergent, radiative corrections
- 120 orders of magnitude!
Anthropic Prediction vs. QFT Calculation

Anthropic Prediction

- Vacuum energy density close to:
  \[ \rho_v = 13.3 \rho_m \]

- Observed value: \( \rho_v = 2.3 \rho_m \)
  Probability = .156!

QFT calculation of vacuum energy

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Measure on the Multiverse

- Evaluating $N(\alpha), P_i(\alpha)$
  - Implicit choice of measure $\mu$
  - What is assigned “equal measure”: spacetime volume, “pocket” universe, length of world-line, ... ?
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- Measure Problem
  - Multiverse ensemble $\Sigma$ and measure $\mu$
  - Uniqueness: Causal structure sufficient to constrain $\mu$?
  - Probabilities:
    - non-normalizable $\mu(\Sigma) = \infty$, recover probabilities via regularization (limiting procedure)?
    - conditional probabilities (conglomerability)?
Example

Figure: Vilenkin 2006
## Debates regarding Measures

### Desiderata for Measure
- Independent of Initial Conditions
- “Calculable” \( N_O(\alpha_i) \)
- Foliation-independent
- ...

### Paradoxes
- Youngness paradox
- \( Q \) catastrophe
- Boltzmann brains / freak observers
- ...

### State of the Debate (?)
- “Testing” different proposed measures by considering paradoxes
- Disagreement regarding desiderata
  (e.g., Aguirre et al. 2007; Winitzki 2009; Freivogel 2011; Vilenkin)
Assume that a suitable $\mu$ has been found ...

- Agreement on list of desiderata for $\mu$
- Uncontroversially satisfies all desiderata
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... what would we then be able to discover about EI?
From Measure to Probability

What justifies “equal measure with respect to $\mu$” $\rightarrow$ equal probability?
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What justifies “equal measure with respect to $\mu$” $\rightarrow$ equal probability?

- **Objective Probabilities**
  - “Phase space measure” $\mu$ (Gibbons, Hawking and Stewart 1987; Ashtekar and Sloan 2011; Schiffrin and Wald 2012)
  - Statistical mechanics arguments connecting $\mu$ to physical probability $\rightarrow$ cosmology

- **Epistemic Probabilities**
  - SSA: cosmologists should reason as if they are “typical” (w/r/t $\mu$) among reference class $A$
  - Dependent on reference class
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Value of Anthropic Predictions

- Multiverse ensemble $\Sigma$
  - How does this differ from “random” ensemble – “anything goes” (variation of all parameters $\alpha_i$)?
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  - Well-motivated? (Jerry-mandering to insure correct predictions)
  - Unique? (Testing measure + theory, or theory)
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- Anthropic subset $A$
  - $\Sigma|_A \approx \Sigma'|_A$?
  - Extent of anthropic subset: isolated “islands” in parameter space
Generic Predictions

- Anthropic predictions “robust” to changes in $\Sigma, \mu, A$
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  ... vice rather than virtue. Do not support specific multiverse theory in detail, as opposed to compatibility check of general proposal.

On the Importance of Being Exact

Contrast with exemplary historical cases:

- Successful predictions quantitatively sharp
- Relationship to phenomena tightly constrains theory
Alternative Arguments for EI

1. Metaphysical
2. Theoretical Consequence
3. Eliminative
Metaphysical Argument

Mathematical Universe Hypothesis (e.g., Tegmark 2007)

- MUH: “Our external physical reality is a mathematical structure”
- MUH $\rightarrow$ multiverse hierarchy, including EI (among all other consistent mathematical structures!)
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As a defense of EI?

- Depends on contentious views regarding application of mathematics, metaphysics
- EI and empirical results in cosmology need not play any role
Indirect Argument

Implied by Successful Theory?

- “Inflation is generically eternal”
Indirect Argument

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- “Inflation is generically eternal”
  - What is the domain of validity of theoretical calculations of onset of inflation?
  - Validity of semi-classical picture of EI?
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- String theory and the landscape
Eliminative Argument

How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth? (Sherlock Holmes)
Eliminative Argument

How often have I said to you that when you have eliminated all dynamical solutions to the cosmological constant problem as impossible, whatever remains — the multiverse — however improbable, must be the truth?
Eliminative Arguments

- Question 1: complete list of suspects?
  - Explore space of possible theories
  - Example: PPN formulation of solar system tests of GR
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- Question 2: criteria for elimination?
  - Empirical anomalies or logical inconsistencies
  - Heuristics: naturalness
What different lines of argument support Eternal Inflation?

- Anthropic predictions as compatibility check, not detailed positive evidence.
- Other lines of argument: consequence of inflation / string theory; eliminative argument. Explicitly theoretical.
Fine-tuning problems as a guide for developing physics and cosmology?

- Some features of fundamental physics as “environmental:” legitimate explanatory stopping point
- Not sufficient to support development and refinement of theories