Predictability Crisis in Early Universe Cosmology

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Motivating Questions

1. Is cosmology a science? What kind of science is cosmology?
   - Fundamental / law-seeking
   - Historical / descriptive
2. What are the appropriate aims of cosmology?
   - Detailed reconstruction of the physical properties, evolution within our Hubble volume
   - Assessment of probability of that account with respect to fundamental theory
   - Discovery and justification of new laws

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Predictability Crisis

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)

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1. Does *eternal* inflation make any predictions, and in what sense? (More generally, predictions from the multiverse?)
2. How should we define probabilities in cosmology?
3. How should we characterize empirical success of a cosmological theory?

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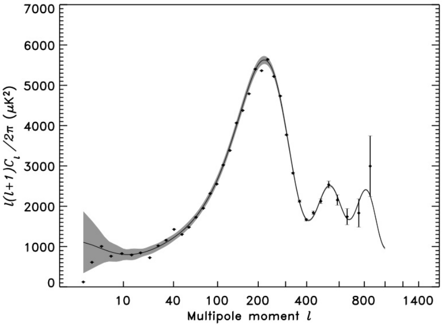
Outline

1. Background
   - Testability of Inflation
   - From Inflation to Eternal Inflation
2. Predictability Crisis
   - Recipe for Predictions in Eternal Inflation
   - Measure Problem
   - Status of the Measure
3. Responses
   - Response 1: Probabilities in Cosmology
   - Response 2: Reconsidering Empirical Success

Successes for Inflation



WMAP angular power spectrum (Spergel et al. 2006)

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

Consequences of dynamical evolution of "inflaton," scalar field ϕ

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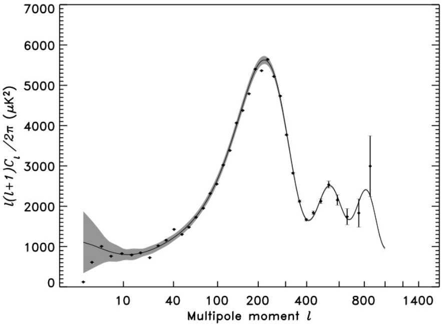

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Indifference Principle

Ernan McMullin (1924-2011)

This first version [Diogenes Laertius] of the cosmogonic indifference principle contains two elements: no special setting of the initial state is required (a ‘chaos’ will do), and no subsequent intervention of a purposive agency of any sort is required for order to appear out of the original disorder. The normal operation of what a later generation would call mechanical law suffices... (McMullin 1993)

Indifference and Inflation

- Conventional Wisdom: results of inflation “independent” of initial state, fixed by dynamical evolution of ϕ, replaces “finely-tuned” initial state
- Issues
  - How to make sense of claim that initial state in standard cosmology is “improbable” or “unnatural”?
  - How probable is it that inflation occurred? (Penrose 1986; Hollands and Wald, Turok et al.)
  - Exchange fine-tuning of ICs for specific properties of $V(\phi)$, initial state of ϕ
- Chaotic / Eternal Inflation
  - Linde: response to “fine-tuning” of $V(\phi), \phi$

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Eternal Inflation

"Inflation is generically eternal"

- Heuristic arguments: volume expansion rate >> rate of false vacuum decay
- Leads to universe with:
  - Regions of false vacua
  - "Pocket universes"

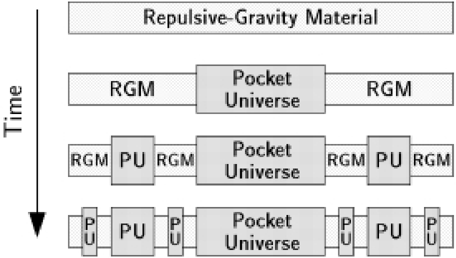

Image: Guth (2007)

Eternal Inflation

- Pocket universes with different low energy physics
- Variation based on "meta-law" governing generation of pocket universes

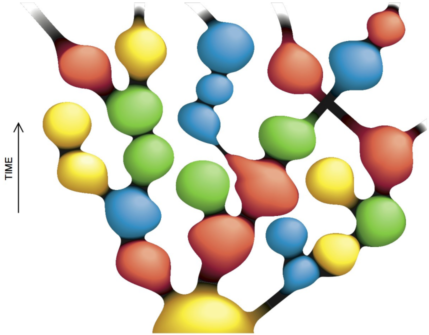

Image: Andrei Linde

Consequences of Eternal Inflation

"... anything is possible"

Scope of variation depends upon "meta-law" governing generation.

Predictions and Probabilities

- In what sense can we make predictions?
- What do we need to introduce to do so?

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Recipe for Multiverse Predictions (e.g., Aguirre 2006)

Ingredients

- O: reference class for conditionalization, e.g. "observers" (or some proxy)
- α_i: parameters taken to vary in different regions of multiverse
- $N_O(\alpha_i)$: number of "observers"
- $P(\alpha_i)$: prior probability

"What a typical member of reference class will observe" (Principle of Mediocrity):

$$P_O(\alpha_i) = N_O(\alpha_i)P(\alpha_i) \tag{1}$$

Exemplar: Weinberg on Λ

Ingredients

- O: large gravitationally bound systems (as proxy for observers)
- α: consider varying Λ, other parameters all fixed
- $N_O(\alpha) =$: only non-zero in small window, due to Λ's effect on structure formation
- $P(\alpha) =$: expect this to be uniform, because anthropically allowed region small compared to particle physics energy scales

Result: expect to something close to "median value" of Λ (calculation in 2005)

$$\rho_V = 13.3\rho_m \qquad (2)$$

Observed value: $\rho_V = 2.3\rho_m$. Probability $= .156$.

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Questionable Ingredients

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- $N_O(\alpha_i)$: number of “observers”
- $P(\alpha_i)$: prior probability

- Reasonable estimates of $N_O(\alpha_i)$, $P(\alpha_i)$?
- Principle of Mediocrity?
- “Measure Problem”: implicit choice of measure. What is the appropriate measure over the multiverse?

Measure Problem

- What should be given "equal weight" by the measure?
  - Distinct pocket universe
  - Spacetime volume
  - Each distinct pocket universe generated from a given starting region
  - Length of a given world-line in each distinct pocket universe
- Dealing with infinity: require some way of "regulating" infinities

Example

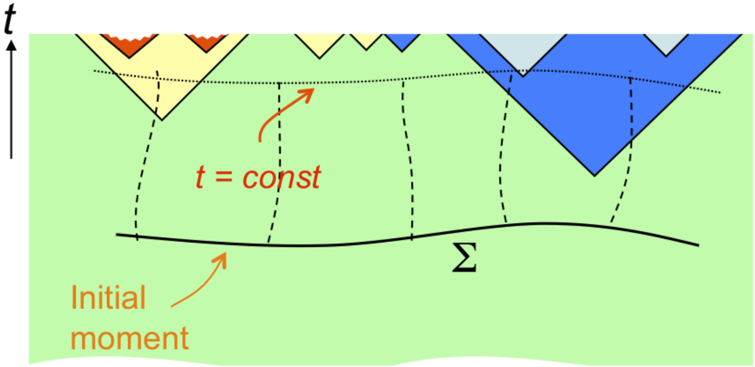

Figure: Vilenkin 2006

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

Getting Predictions out of Nothing?

- “Phenomenological” approach
  - Measures proposed *without* underlying dynamics
- Indifference principle revisited
  - Independent of initial conditions (*some* take as a desiderata)

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Eternal Inflation is Self-Undermining?

- Does EI predict *anything*?
  - Original predictions of inflation undermined
  - Response (?): don't abandon successful theory due to open problems
- Reconsider claim that inflation $\longrightarrow$ EI
- "Fair treatment" of competing theories

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Probabilities in Cosmology

- Contrast with statistical mechanics
  - Active debates regarding nature of probability in SM
  - Measure plays a central role in predictive success of the theory
- Change inductive methodology in EI?
  - Bayesian methodology to calculate conditional probabilities (subjective credences)
  - Should this depend on infinite extent of the universe? (cf. Neal 2006)

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- Possible response to incorrect "prediction" of parameter value α_i?
  - *Some* parameters will have unusual values
  - Reject measure
  - Reject estimate of $N_O(\alpha_i)$, consider different reference class
  - Reconsider calculation varying more parameters
- Contrast with more informative cases
  - Set of clearly motivated sufficient conditions to derive a particular claim
  - Systematic discrepancies revealing; possibility of refinement and further empirical testing

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Concluding Remarks

- Pessimism about Measure Problem
  - Not clear how the debates about appropriate measure can be resolved
  - Extracting predictions from EI requires accepting dubious principles such as the Principle of Mediocrity, specification of a reference class
- Connection with broader questions
  - Justifying new fundamental physics based on its role in reconstruction in cosmic history
  - Modalities in cosmology: laws and initial conditions, probabilities