Theories of Origins

Chris Smeenk

University of Western Ontario
Department of Philosophy
Rotman Institute

Beyond Spacetime Summer Institute
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Theories of Origins ... of the Solar System

Indifference

[Even starting in] chaos as confused as any the poets could invent, by the laws of nature alone everything would in the course of time have come to be just as we now see it. The world as we now see it is entirely indifferent to the initial state.

Selection

Mere mechanical causes cannot account for the elegant system of the planets — with extremely regular motions of the planets and their satellites, all in the same direction and nearly in a single plane. This improbable arrangement can be best explained as the result of a specially chosen initial state.

Ensemble

Our planetary system is but one of an infinite number scattered throughout infinite space. Among this infinite ensemble there will be many that, like ours, have physical features suitable for life.

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Descartes

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Newton

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Giordano Bruno

Theories of Origins ... of the Solar System

Indifference	Selection	Ensemble
Attractor dynamics, indifference to initial state	Constraint on initial state, either lawlike or "by design"	Variation + anthropic selection

Methodological Principles

To what extent did they impact / guide inquiry into dynamics of the solar system and its formation?

To what extent should they have done so?

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Illusion of Contingency

What features should we treat as independent, apparently contingent facts → targets of explanation?

- Probability that the planets orbit with the same orientation, in the same plane?
- Stability of the solar system, comets?

Theories of Origins … of the Universe

Indifference	Selection	Ensemble
Attractor dynamics, indifference to initial state	Constraint on initial state, either lawlike or by design	Variation + anthropic selection

Methodological Principles

To what extent should they guide inquiry in early universe cosmology?

Motivating Questions

1. Reasons to expect that these principles lead to true theories?
   - Fertility, record of past successes
   - Metaphysical assumptions

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1. Reasons to expect that these principles lead to true theories?
   - Fertility, record of past successes
   - Metaphysical assumptions
2. Interplay between these principles and foundations of physics
   - Appropriate formulation in a specific theoretical context
   - Where to seek explanations?
     (In cosmology: physics at what energy scale accounts for property P?)

Outline

1. Background
   - Order to Chaos
   - Was there an “Origin”?
2. Selection
3. Ensemble
4. Indifference and Time’s Arrow

Standard Model of Cosmology

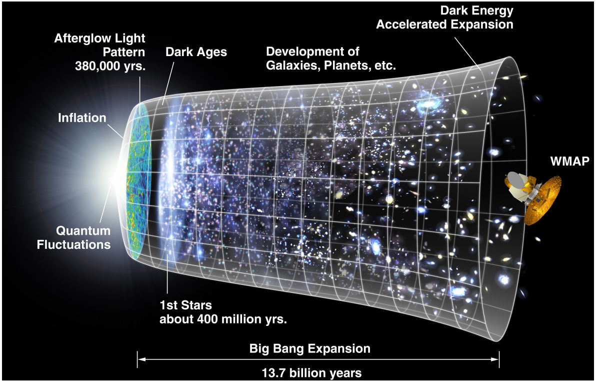

Image credit: NASA / WMAP

Our universe has been evolving from order to chaos.

Peebles (2020, 212)

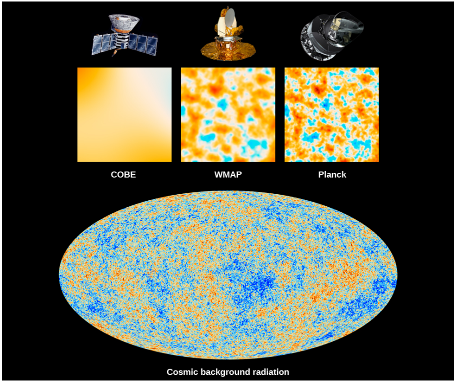

Image credit: NASA / ESA

Simple “Initial” State

FLRW models with Gaussian, adiabatic, nearly scale-invariant perturbations. Precision determination of cosmological parameters.

(see, e.g., Durrer (2021))

Targets for early universe theories:

- Why does the universe have specific light element abundances?
- Why is there a striking asymmetry between matter and anti-matter?
- Why does the universe have flat, almost FLRW geometry?
- Why are there Gaussian, nearly scale invariant perturbations?

(... among others ...)

Theory of Origins?

Why take an early universe theory to involve "origins" or "the initial state"?

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- Classical singularity theorems, but ...

  ... what are the limits of classical GR?

Big Bang Singularity (Tolman and Ward (1932), ...)

1. Focusing

   $\Lambda = 0$ and T_{ab} a perfect fluid with $\rho + 3p > 0$, Einstein's equations imply that cross sectional area of bundle of timelike geodesics decreases.

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2. Geometrical "initial condition"

   Isotropy and homogeneity (FLRW models), slice $\Sigma(t_0)$ with expansion $H_0 > 0$.

3. Causal structure

   Globally hyperbolic.

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Conclusion

There is a finite time T, such that the scale factor $R(t) \to 0$ as $t \to T$ (and $\rho(t) \to \infty$, etc.) All past-directed timelike geodesics have a finite length.

Raychaudhuri Equation

Considering a congruence of timelike geodesics, parametrized by proper time τ with tangent vectors ξ^a.

Expansion of the congruence (θ) evolves as follows:

$$\frac{d\theta}{d\tau} = -\frac{1}{3}\theta^2 - \sigma_{ab}\sigma^{ab} + \omega_{ab}\omega^{ab} - R_{cd}\xi^c\xi^d \tag{1}$$

- σ_{ab} – shear; ω_{ab} – twist
- R_{ab}: Ricci tensor

Focusing

Consider congruence orthogonal to a hypersurface Σ, such that $\omega_{ab} = 0$. The second term $(\sigma_{ab}\sigma^{ab})$ is non-negative. Finally, it is plausible to suppose that $R_{cd}\xi^c\xi^d \geq 0$ ("gravity is a force of attraction").

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Then the equation simplifies to:

$$\frac{d\theta}{d\tau} + \frac{1}{3}\theta^2 \leq 0 \quad (2)$$

If θ_0 (initial value) is negative, $\theta \to -\infty$ within time $\tau \leq \frac{3}{|\theta_0|}$

Schematic Singularity Theorem

1. Focusing / convergence due to positive curvature
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Reductio

1 and 2: initial conditions, subsequent focusing sufficient for conjugate points.

Contradicts existence of geodesics implied by 3.

Singularity theorems (Hawking, Geroch, Ellis, ...)

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- Generality: singularities persist with significantly weaker versions of assumptions (1 - 3) than Tolman (and others), without symmetries
- Reveal $\exists$ incomplete geodesic; not particularly informative regarding further structure

From a purely philosophical standpoint it is difficult to believe that physical singularities are a fundamental and unavoidable feature of our universe. On the contrary, when faced with a theory which predicts the evolution of a singular state, one is inclined to discard or modify that theory rather than accept the suggestion that the singularity actually occurs in nature.

(Thorne 1967, p. 415)

Incompleteness of GR

Curvature Singularity

FLRW case: blow-up of curvature invariants, mass density, ... along all past-directed geodesics.

Other Cases

Curvature pathologies not linked to geodesic incompleteness (see Curiel (1999, 2019))

Cauchy horizons (CS and Wüthrich 2009, 2020)

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Additional grounds for incompleteness?

FLRW (and other cases with curvature blow-up) $\rightarrow$ strong gravitational fields, expectation that quantum effects relevant.

Further reasons for incompleteness, rationale to avoid singularities?

Theory of Origins?

Singularity resolution requires modifying GR, modifying the matter sector (violation of null energy condition), or both. Two general issues:

- Continuity / matching conditions
- "Control" of the new physics (stability, emergence of classical GR, ...)

(... also discussed by Crowther, Sakellariadou, Vidotto)

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For this talk: take "initial state" to be specified at "limit of domain of applicability of GR".

Indifference

Attractor dynamics, indifference to initial state

Selection

Constraint on initial state, either lawlike or by design

Ensemble

Variation + anthropic selection

Formulation and status in modern cosmology?

Versions of all three pursued after discovery of CMB

Past as Prologue: Boltzmannian Themes

Boltzmann (1844-1906)'s tomb.
Image credit: wikimedia

- Derivation of Time Asymmetry?
  - Boltzmann transport equation (1872): Dilute gas approaches Maxwell-Boltzmann distribution
  - H-theorem: quantity (H), stationary for Maxwell-Boltzmann distribution

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- Derivation of Time Asymmetry?
  - Boltzmann transport equation (1872): Dilute gas approaches Maxwell-Boltzmann distribution
  - H-theorem: quantity (H), stationary for Maxwell-Boltzmann distribution
- Complications:
  - Reversibility (Lohschmidt 1876)
  - Recurrence (Zermelo 1896)

Past as Prologue: Boltzmannian Themes

Two speculative cosmological hypotheses:

Selection "...the entire universe finds itself at present in a very improbable state"

Universe began in low entropy state, which has increased but is still low compared to maximum entropy

Boltzmann 1897, translated in Brush (2003)

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Selection "...the entire universe finds itself at present in a very improbable state"
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Ensemble "[the universe] is in thermal equilibrium as a whole and therefore dead," but for "relatively small regions of the size of our galaxy (which we call worlds) which, during the relatively short time of eons, deviate significantly from thermal equilibrium"

Boltzmann 1897, translated in Brush (2003)

Modern Versions of Selection

- Weyl Curvature Hypothesis (Penrose (1979))
- Wave function for the universe (No boundary, Hawking-Hartle 1983; tunneling, Vilenkin 1983)
- CPT universe (Boyle, Finn, Turok 2018, 2019...)

  ... (And others) ...

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Challenges

- Derivation / consistency with full theory of quantum gravity
- Mathematical content and further implications
  (See, e.g., recent debates regarding no boundary proposal: Feldbrugge, Lehners and Turok 2018, various replies)

Modern Versions of Ensemble

- “Multiverses” of many kinds: eternal inflation, Smolin’s evolutionary model, Tegmark, ...
  (Some involve “fluctuations away from equilbrium” as in Boltzmann’s proposal, e.g. vacuum decays)

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Challenges

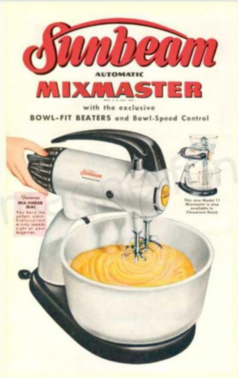
- What generates the ensemble and variation among regions?
- Grounds for probabilities to yield "anthropic predictions" (e.g. Weinberg 1987 for Λ)
- Anthropic pre-emption (aka Boltzmann brains): lower entropy cost for small fluctuations from equilibrium, so these have (??) much higher probability than Hubble-region sized fluctuations

Modern Version of Indifference

Misner's Chaotic Cosmology (1967 - ~1975)

Aim to "predict the observed universe" independent of "chaotic" initial conditions:

- Neutrino viscosity
- Chaotic "mixmaster" oscillations (in light of horizon problem)



Sunbeam Mixmaster

Dynamics and Indifference

Dynamical phase "washes away" initial state:

$\underline{\text{arbitrary initial state}} \rightarrow \underline{\text{later state, properties } P_i}$

Dynamics renders P_i "more probable," by contrast with finely-tuned initial state

Thermal History

- Statistical Mechanics in Cosmology
  - Irreversible dynamics

    Freeze out, decoupling of particle species; structure formation via gravitational clumping; etc.

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- Statistical Mechanics in Cosmology
  - Irreversible dynamics

    Freeze out, decoupling of particle species; structure formation via gravitational clumping; etc.
- Historical inferences, probabilities in this context?

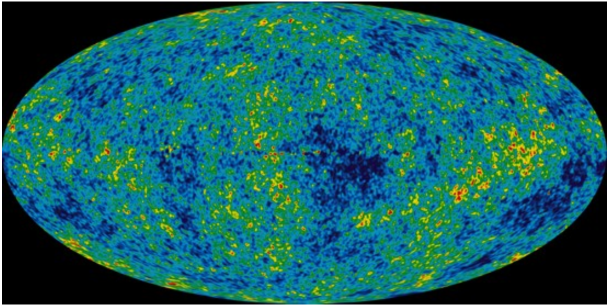

Figure: WMAP observations of CMB temperature anisotropies

Retrodictions

CMB photons decouple, evolve approximately adiabatically.
Present state + dynamics (backwards-evolve) $\rightarrow$ surface of last scattering

Thermal History

Effects of Expansion

Temporal asymmetry: expansion of the universe.

Too fast to maintain equilibrium!

Rate of interactions Γ vs. Rate of expansion H

- $\Gamma >> H$: interaction maintains local thermal equilibrium, adiabatic expansion
- $\Gamma \approx H$: "freeze out," decoupling

Boltzmann equation (or coupled set of equations)

Big Bang Nucleosynthesis

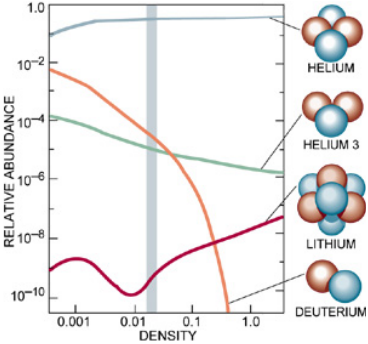

Image credit: Martin White

1. Neutrons, protons start in local equilibrium (insensitive to earlier states)
2. Irreversible dynamics leads to mass fractions for light elements

How Probable is Big Bang Nucleosynthesis?

Trajectory Counting

Consider α_f: macro-state of the system some time after BBN.

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Time-reversal invariant microscopic dynamics $\rightarrow$ vast majority of trajectories through α_f did not pass through pre-BBN, lower-entropy state α_i. α_f local entropy minimum for vast majority of trajectories.

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These arguments always fail when applied to retrodictions!
(Can fix this by taking probabilities conditional on "Past Hypothesis...")

Dynamical Attractors (e.g. Wallace 2012, Myrvold 2021)

- Attractor Dynamics (e.g. Boltzmann equation): initial distributions converge towards equilibrium
- Probabilities apply on time scales $>$ relaxation time
- Initial states with "delicate correlations" do not satisfy irreversible dynamics

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Historical Inference

- Propose initial state, forward-evolve and check consequences
- Plausibility of restriction that initial state lacks "delicate correlations"?

How Probable is Big Bang Nucleosynthesis (take two)?

- Plausible initial state α_i
  - Earlier evolution leads to partial equilibrium, "washes out" correlations for some set of physical variables

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- Plausible initial state α_i
  - Earlier evolution leads to partial equilibrium, "washes out" correlations for some set of physical variables
- Predictions based on forward-evolving dynamics
  - Physics at the relevant energy scales well understood
  - Mass fractions for light elements (as a function of total baryon density, etc.)

Reconsidering "Indifference"

- Standard rhetoric: flawed application of probabilities to thermal history
- Assessment of proposed dynamical phase: plausibility of initial state, forward-evolved consequences