Closing the Loop in Early Universe Cosmology?

Chris Smeenk

University of Western Ontario, Philosophy
Rotman Institute

University of Toronto, Astronomy Colloquium
March 2023

(Work done partly in collaboration with Adam Koberinski and Jim Weatherall.)

Aim and Structure of Cosmological Theory (with Jim Weatherall)

Era of Precision Cosmology

New fundamental physics in ΛCDM model: dark matter, dark energy, early universe (inflaton field)

Aim and Structure of Cosmological Theory (with Jim Weatherall)

Era of Precision Cosmology

New fundamental physics in ΛCDM model: dark matter, dark energy, early universe (inflaton field)

Motivation

What implicit principles / ideas guide research? (E.g., views about explanation, what counts as a "good theory," what falls within theory's scope, ...)

Distinctive challenges in cosmology; principles and implicit philosophy guiding ΛCDM model

Two Themes

Modalities

Reliance on passive observations, often unique past events. Whether and how to establish laws?

Contrast between *theory* (possibilities) vs. *model* (description of actual universe)

Two Themes

Modalities

Reliance on passive observations, often unique past events. Whether and how to establish laws?

Contrast between *theory* (possibilities) vs. *model* (description of actual universe)

Principles

Example 1: Copernican Principle

Two Themes

Modalities

Reliance on passive observations, often unique past events. Whether and how to establish laws?

Contrast between *theory* (possibilities) vs. *model* (description of actual universe)

Principles

Example 1: Copernican Principle

Our observations are "representative sample," suitable for pursuing objective physical cosmology

Justification for standard (FLRW) models

Two Themes

Modalities

Reliance on passive observations, often unique past events. Whether and how to establish laws?

Contrast between *theory* (possibilities) vs. *model* (description of actual universe)

Principles

Example 2: "Indifference" Principle

Preference for explanations that are indifferent to initial state; dynamical evolution "washes away" features of initial state

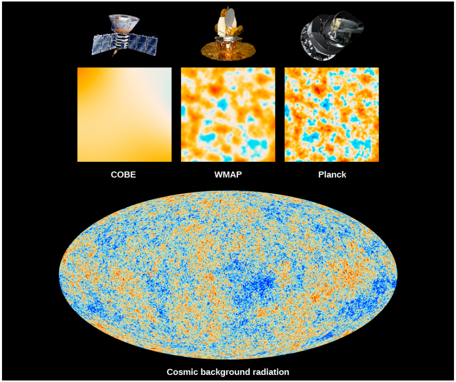


Image credit: NASA / ESA

Strikingly simple Early State

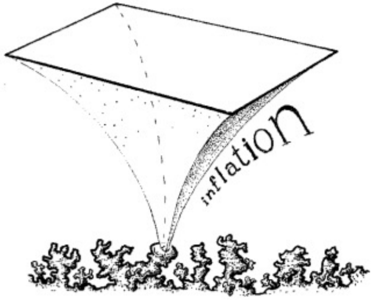
Maximally symmetric models with small perturbations.

(FLRW + Gaussian, adiabatic, nearly scale-invariant perturbations)

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

Inflationary Hypothesis:

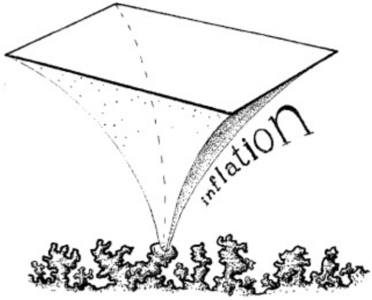
- Early universe dynamics dominated by scalar field, "inflaton" ϕ, $V(\phi)$
- Regions where inflaton is uniform, in false vacuum $\rightarrow$ effective cosmological constant



From Penrose, *Road to Reality*

Inflationary Hypothesis:

- Early universe dynamics dominated by scalar field, "inflaton" ϕ, $V(\phi)$
- Regions where inflaton is uniform, in false vacuum $\rightarrow$ effective cosmological constant



From Penrose, *Road to Reality*

Consequences:
Inflaton drives expansion, leading to quasi-De Sitter phase. Washes away features of pre-inflationary state.

(More loosely, "inflationary phase": $\ddot{R}(t) > 0$.)

Image credit: *Scientific American* – Ijjas, Steinhardt, and Loeb (2017)

Falsifiability of Inflation?

- Is inflation a just-so story?
- Plausibility of specific types of models?
- Plausibility of pre-inflationary state?
- Eternal Inflation and the Measure Problem

Recent versions: Ijjas, Steinhardt and Loeb (2013, 2014, 2017); replies from Guth et al. (2013), letter to *Scientific American*; Chowdhury et al. (2019)

Shift in focus of Assessment

- *Initial acceptance*: promise, feasibility, novel predictions, etc.

Shift in focus of Assessment

- *Initial acceptance*: promise, feasibility, novel predictions, etc.
- *Long-term evaluation:* how stringently is a theory tested by subsequent research based on accepting it?

Shift in focus of Assessment

- *Initial acceptance*: promise, feasibility, novel predictions, etc.
- *Long-term evaluation:* how stringently is a theory tested by subsequent research based on accepting it?

Closing the Loop

- Iterative refinement, leading to identification of new physical features of a system, provides decisive test

Shift in focus of Assessment

- *Initial acceptance*: promise, feasibility, novel predictions, etc.
- *Long-term evaluation:* how stringently is a theory tested by subsequent research based on accepting it?

Closing the Loop

- Iterative refinement, leading to identification of new physical features of a system, provides decisive test
- *Inflation*: possibility to pursue iterative refinement, probe details of early universe and inflationary dynamics? Is line of inquiry risky and constrained?

Outline

- Closing the Loop in Celestial Mechanics
- Closing the Loop in the Early Universe?
- Responses

More than phenomenological success...

Historical cases:

- Control of idealizations and physical assumptions used in constructing models $\rightarrow$ discrepancies with observations reveal further details, basis for ongoing inquiry
- Response to concern about flexibility of theory, underdetermination

(see especially Smith 2014; also CS 2017, 2019, Koberinski and CS 2020)

Challenges

1. *Underdetermination*: existence of many different theoretical representations compatible with a given body of data

Challenges

1. *Underdetermination*
2. *Circularity*: description of fundamental quantities and how they are measured depends on theory. Is this viciously circular?

Illustration: Celestial Mechanics

Accounts of Orbital Motion (ca. 1680)

	ORBITAL TRAJECTORY	LOCATION VS. TIME	MEAN DIST. FROM SUN
KEPLER	ellipse	area rule	from observations
BOULLIAU	ellipse	a geometric construction	from observations
HORROCKS	ellipse	area rule	via 3/2 power rule
STREETE	ellipse	Boulliau's construction	via 3/2 power rule
WING	ellipse	oscillating equant -------------- a geometric construction	from observations
MERCATOR	ellipse	a geometric construction	from observations

(from Smith 2014)

Illustration: Celestial Mechanics

Accounts of Orbital Motion (ca. 1680)

	ORBITAL TRAJECTORY	LOCATION VS. TIME	MEAN DIST. FROM SUN
KEPLER	ellipse	area rule	from observations
BOULLIAU	ellipse	a geometric construction	from observations
HORROCKS	ellipse	area rule	via 3/2 power rule
STREETE	ellipse	Boulliau's construction	via 3/2 power rule
WING	ellipse	oscillating equant ------------- a geometric construction	from observations
MERCATOR	ellipse	a geometric construction	from observations

(from Smith 2014)

Newton's Insight

Dynamics singles out Kepler's laws, as consequences of central force: gravity

(Kepler, *Astronomia Nova* (1609))

Contrast

- *Phenomenology*: (approximately) Keplerian orbits
- *Physics*: n-body gravitational interactions, further implications

(Kepler, *Astronomia Nova* (1609))

Successive Approximations (Smith 2014)

Idealized
description of Motions

Successive Approximations (Smith 2014)

Idealized
description of Motions

Comparison with Observations

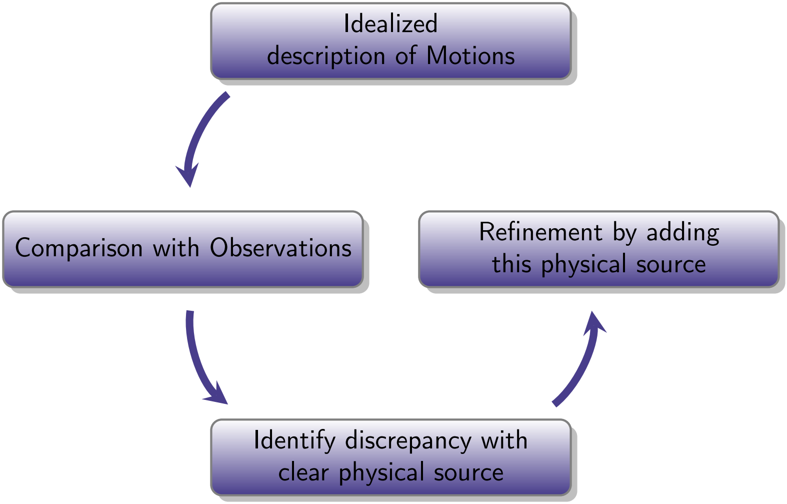
Successive Approximations (Smith 2014)

Idealized
description of Motions

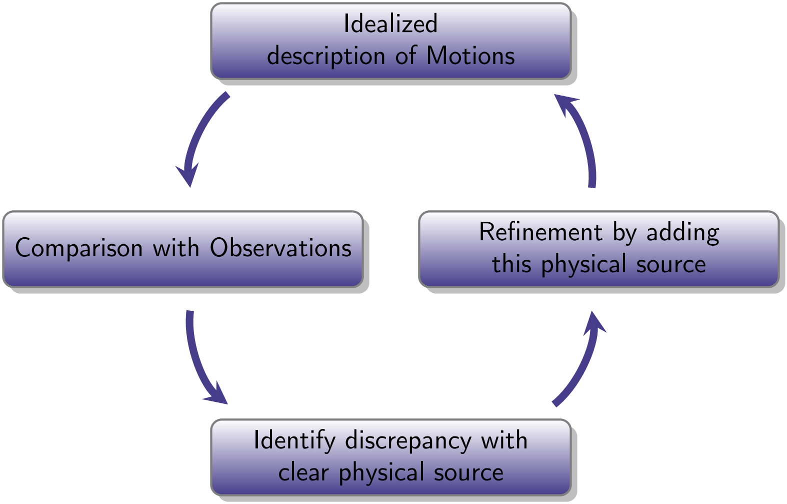
Comparison with Observations

Identify discrepancy with
clear physical source

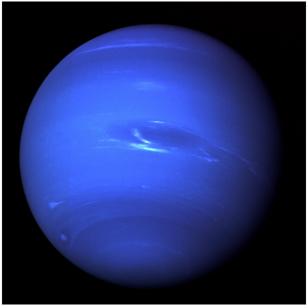
Successive Approximations (Smith 2014)



Successive Approximations (Smith 2014)



Robust Sources



(Image: NASA, Voyager II (1989))

Other cases:

- Jupiter-Saturn Great Inequality
- Secular acceleration of the Moon (Laplace, Adams, ...)
- "Great Empirical Term" (Brown, Jones, ...; varying rotational velocity of the Earth)

Nature of Evidence

Newton's Principia forced the test question within orbital astronomy for his theory of gravity to be not whether calculated locations of planets and their satellites agree with observations, but whether robust physical sources can be found for each systematic discrepancy between those calculations and observation – with the further demand of achieving closer and closer agreement with observation in a series of successive approximations in which more and more details of our solar system that make a difference become identified, along with the differences they make.

(Smith 2014)

Contrast with Phenomenological Success

1. *Underdetermination*:
   Recover reasoning involved in identifying discrepancies and their sources $\rightarrow$ limited scope of underdetermination, confirms theory (at some level of approximation, on suitably restricted domain)

Contrast with Phenomenological Success

1. *Underdetermination*:
   Recover reasoning involved in identifying discrepancies and their sources → limited scope of underdetermination, confirms theory (at some level of approximation, on suitably restricted domain)
2. *Circularity*:
   Independent ways to check sources of discrepancies

Closing the Loop in the Early Universe?

The test question within cosmology for the inflationary model is not whether calculated features of the early universe, including the overall uniformity and temperature anisotropies in the CMB, can be fit with a particular choice of the "inflaton" field, but whether robust physical sources can be found for each systematic discrepancy between calculations and observation – with the further demand of achieving closer agreement with observation in a series of successive approximations in which more and more details of the universe that make a difference become identified, along with the differences they make.

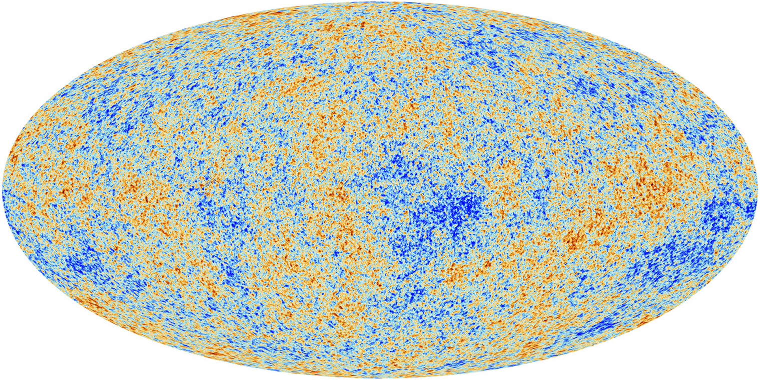
(... with apologies to Smith)

Closing the Loop in the Early Universe?

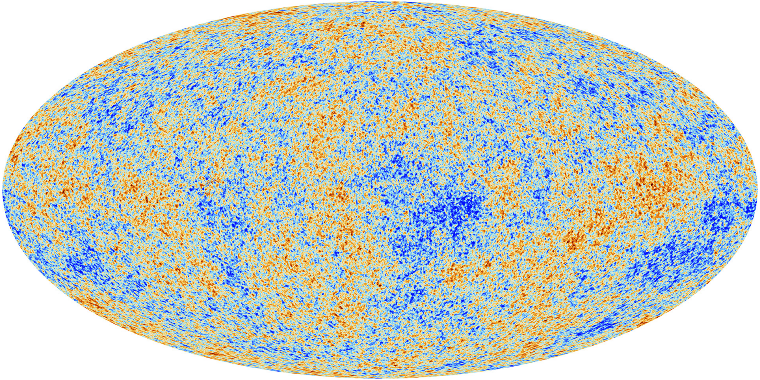
> *The test question within cosmology for the inflationary model is not whether calculated features of the early universe, including the overall uniformity and temperature anisotropies in the CMB, can be fit with a particular choice of the "inflaton" field, but whether robust physical sources can be found for each systematic discrepancy between calculations and observation – with the further demand of achieving closer agreement with observation in a series of successive approximations in which more and more details of the universe that make a difference become identified, along with the differences they make.*
>
> *(... with apologies to Smith)*

Contrast with Solar System Case

What are the prospects for an iterative approach in early universe cosmology?



(ESA Planck: CMB temperature anisotropies)



(ESA Planck: CMB temperature anisotropies)

Contrast

- *Phenomenology*: Gaussian, linear, nearly scale invariant, adiabatic density perturbations
- *Physics*: dynamics of inflaton field; what are the further implications?

Stages of Inflation

1. Pre-inflationary state
2. Inflationary Stage: Structure Formation
   - Horizon exit / re-entry of fluctuation modes of inflaton field (see, e.g., Mukhanov, Feldman, Brandenberger 1992; Liddle and Lyth 2000)
   - "Squeezing" of fluctuations, quantum to classical transition
   - Several characteristic features: near scale invariance ($n_s \approx .96$), tensor-scalar consistency relationship, small non-Gaussianities (Maldacena 2003)
3. "Graceful exit": Reheating

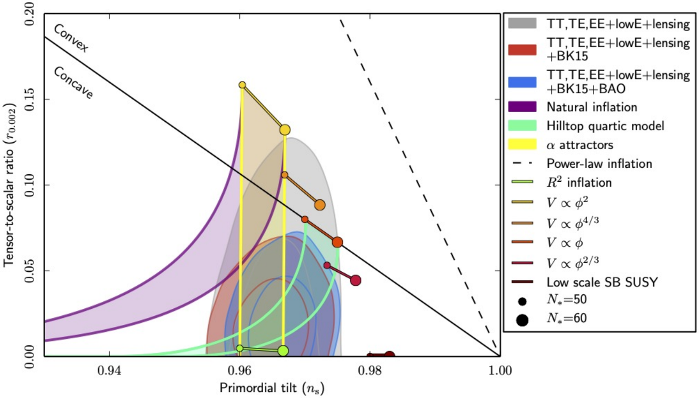


Fig. 8. Marginalized joint 68 % and 95 % CL regions for n_s and r at $k = 0.002\,\mathrm{Mpc}^{-1}$ from *Planck* alone and in combination with BK15 or BK15+BAO data, compared to the theoretical predictions of selected inflationary models. Note that the marginalized joint 68 % and 95 % CL regions assume $dn_s/d\ln k = 0$.

Constraints on inflationary models from Planck observations, Planck Collaboration (2018)

Phenomenology of Inflation

- *Horizon, flatness*: lower bound on how long inflationary expansion lasts (number of e-folds).
- *Structure Formation*: $V(\phi), V'(\phi), V''(\phi)$ roughly 60 e-folds before the end of inflationary phase. (Ongoing: polarization, test scalar-tensor ratio; non-Gaussianities.)
- *Reheating*: $V(\phi), \mathcal{L}_I$ at end of inflationary phase

Phenomenology of Inflation

- *Horizon, flatness*: lower bound on how long inflationary expansion lasts (number of e-folds).
- *Structure Formation*: $V(\phi), V'(\phi), V''(\phi)$ roughly 60 e-folds before the end of inflationary phase. (Ongoing: polarization, test scalar-tensor ratio; non-Gaussianities.)
- *Reheating*: $V(\phi), \mathcal{L}_I$ at end of inflationary phase
- *Other constraints?*: (... if inflaton = specific field, or other constraints)

… Learning about the Details of Inflation?

- *Phenomenological Success*: many inflationary models compatible with CMB data, imply constraints on properties of candidates $(\phi, V(\phi))$

... Learning about the Details of Inflation?

- *Phenomenological Success*: many inflationary models compatible with CMB data, imply constraints on properties of candidates $(\phi, V(\phi))$
- *Discrepancies with Robust Sources?*

What is the "Inflaton"? (1990s version)

A glaring problem, in my opinion, is our lack of being able to fully integrate inflation into a unification scheme or any scheme having to do with our fundamental understanding of particle physics and gravity. ... An inflaton as an inflaton and nothing else can only be viewed as a toy, not a theory.

(Olive 1990, p. 389)

What is the "Inflaton"? (2010s version)

... an Effective Field Theory

Low energy EFT describing the matter sector, coupled to Einstein gravity.

Challenges in applying EFT techniques in cosmological case: lack of separation of energy scales; expansion of the universe (time dependent Hilbert space, unitarity)

… Learning about the Details of Inflation?

- *Phenomenological Success*: many inflationary models compatible with CMB data, imply constraints on properties of candidates $(\phi, V(\phi))$
- *Discrepancies with Robust Sources?*
  - Lack of constraints on inflaton $\rightarrow$ can always go "back to the drawing board" in light of discrepancies
    (Other sources of flexibility: pre-inflationary state, eternal inflation and the measure problem)

Limitation of Theory?

Features of inflationary cosmology that pose obstacles to further progress? (Flexibility, lack of physical constraints, ...)

Our Limitations?

Inaccessibility *to us* of novel further consequences (energy scales, features of early universe that are unobservable in practice)

Responses

- Too Soon?
  - Still at early stage of inquiry, prospects to reveal and constrain details of inflation.

Responses

- Too Soon?
  - Still at early stage of inquiry, prospects to reveal and constrain details of inflation. But flexibility undermines possibility of risky, constrained further inquiry.

Responses

- Too Soon?
  - Still at early stage of inquiry, prospects to reveal and constrain details of inflation. But flexibility undermines possibility of risky, constrained further inquiry.
- Integrate inflation with high energy physics / quantum gravity
  - Optimistic view: inflationary model building depends on various assumptions about QG; possible source of insights and constraints (see, e.g., Brandenberger's recent work)

Responses

- Too Soon?
  - Still at early stage of inquiry, prospects to reveal and constrain details of inflation. But flexibility undermines possibility of risky, constrained further inquiry.
- Integrate inflation with high energy physics / quantum gravity
  - Optimistic view: inflationary model building depends on various assumptions about QG; possible source of insights and constraints (see, e.g., Brandenberger's recent work)
- "Post-empirical" science (e.g. Dawid 2013, re. string theory)
  - For some domains of physics, relevant phenomena inaccessible. Should we regard theories of these domains as, at best, "how-possibly" accounts?

Thank You!

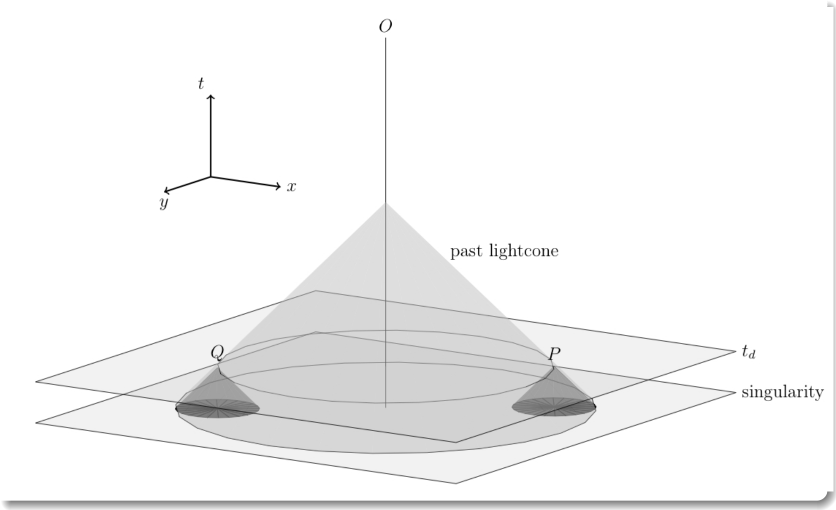
This work was supported by a grant from the John Templeton Foundation. The views expressed do not necessarily represent those of the Foundation.

Questions regarding the “initial” state

- 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?
- What produced the perturbations, and why do they have the features that they do?

  (... among others ...)

Causality and the Horizon Problem



Causality in Early Universe

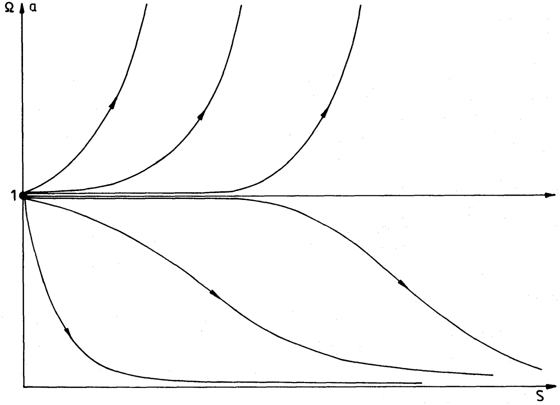
Horizons block causal explanation of super-horizon scale correlations (uniformity, large scale perturbations).

Causality in Early Universe

Horizons block causal explanation of super-horizon scale correlations (uniformity, large scale perturbations).

Correlations between physical conditions at points like P and Q should not be due to "influences from infinity"; instead due to common causal past. (Similar to Sommerfeld radiation condition – no "source-free" radiation.)

"Fine-Tuning": Flatness Problem



Density parameter $\Omega = \frac{\rho_c}{\rho}$ evolves away from 1 with expansion ($S(t) =:$ scale factor). Why is Ω close to 1 today?

Two Principles

Causality

Correlations between physical states at (space-like separated) regions trace back to common causal past.

(Law of Conditional Independence, O. Penrose and Percival 1962)

Two Principles

Causality

Correlations between physical states at (space-like separated) regions trace back to common causal past.

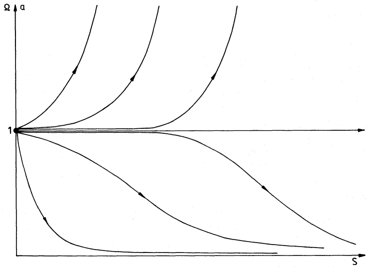
(Law of Conditional Independence, O. Penrose and Percival 1962)

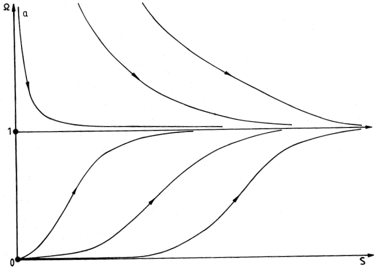
Indifference / "No Miracles"

Finely-tuned properties explained via dynamical evolution that "washes away" initial state:

arbitrary initial state $\rightarrow$ *later state, properties* P_i

Dynamics renders P_i natural, more probable.





Consequences of Inflation

- Horizon distance stretched by a factor of $e^{\mathcal{N}}$ for $\mathcal{N}$ e-foldings
- During inflation dynamics drives $\Omega \to 1$
- Uniform, flat patch as "generic" post-inflationary state, for large $\mathcal{N}$
- Vacuum fluctuations of inflaton field $\to$ classical density perturbations

Indifference Reconsidered

Fine-Tuning problems reflect conflict between:

- *Chaotic Initial State*: "random choice" from among space of physically possible models. No correlation among causally disjoint patches, arbitrary value of Ω and other parameters, ...

Indifference Reconsidered

Fine-Tuning problems reflect conflict between:

- *Chaotic Initial State*: "random choice" from among space of physically possible models. No correlation among causally disjoint patches, arbitrary value of Ω and other parameters, ...
- *Observations*: Striking uniformity of the CMBR, "unnatural" parameter values

Indifference Reconsidered

Fine-Tuning problems reflect conflict between:

- *Chaotic Initial State*: "random choice" from among space of physically possible models. No correlation among causally disjoint patches, arbitrary value of Ω and other parameters, ...
- *Observations*: Striking uniformity of the CMBR, "unnatural" parameter values

Indifference Reconsidered

Fine-Tuning problems reflect conflict between:

- *Chaotic Initial State*
- *Observations*

Two Objections

- *Ambiguity*: Random choice from which space of "physically possible models"? (GR, quantum gravity, ...) Why uniform probability over parameter values?

Indifference Reconsidered

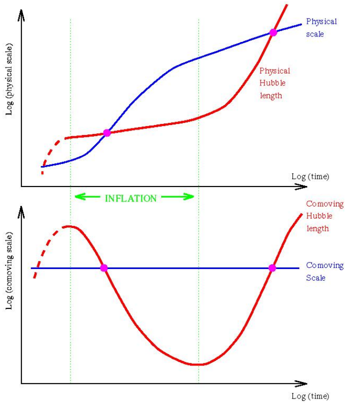
Fine-Tuning problems reflect conflict between:

- *Chaotic Initial State*
- *Observations*

Two Objections

- *Ambiguity*: Random choice from which space of "physically possible models"? (GR, quantum gravity, ...) Why uniform probability over parameter values?
- *Past Hypothesis* (e.g., Penrose): Require constraint on initial state for any system exhibiting thermodynamic asymmetry. (Constrasting view about historical inferences, probabilities.)

Structure Formation: Inflation



Horizon exit / re-entry (Liddle 1999)

Causal Account of Initial Fluctuations

- Mukhanov-Sasaki equation: adiabatic evolution for sub-Hubble modes; overdamped (squeezing) for super-Hubble modes
- Horizon exit / re-entry (post-inflation)

Leads to predictions for $\{n_s, r, ...\}$ given state of ϕ, shape of potential $V(\phi)$

(See e.g. Mukhanov, Feldman, Brandenberger 1992; Liddle and Lyth 2000)

Encyclopædia Inflationaris

$$\mathcal{L} = -\frac{1}{2}g^{ab}\partial_a\phi\partial_b\phi - V(\phi) + \mathcal{L}_I(\phi, A_a, \psi, ...),$$

- Consider 74 types of inflationary models (small field, large field, multi-field, ...), nearly 200 individual models. (For simplest models: specifying $V(\phi)$ and $\mathcal{L}_I$.)
- Use Bayesian inference to find preferred models: "plateau" models favored (e.g., Starobinsky 1980)

(Martin et al. 2013)