Decoupling from the Initial State?

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(Based on collaboration with Adam Koberinski)

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Two Aspects of Early Universe Cosmology

Theory of Origins

Quantum gravity: resolution of the initial singularity, emergence of classical spacetime

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Inflationary Phase

Exponential expansion driven by “inflaton” ϕ, described semiclassically.

To what extent does inflation “decouple” from assumptions about origins?

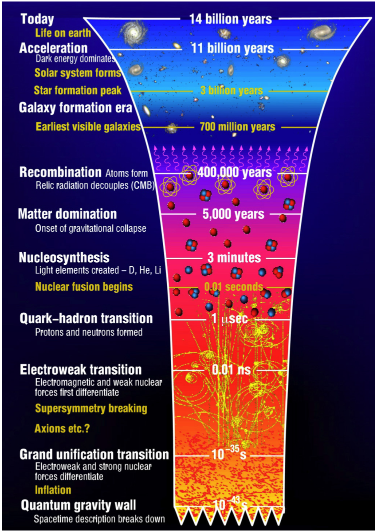

Image: SHCTC, Cambridge

“Indifference”

Inflation “washes away” imprint of earlier stages

Inflation at Forty

Observational Success ...

- Striking simplicity of early universe, revealed through CMBR observations
- Sufficient to rule out structure formation proposals
- Inflationary models compatible with all observations

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… Foundational Questions

- What is the inflaton field (or fields)?
- Is inflation generically eternal? If so, what is the appropriate measure to use in making predictions?
- How do fluctuations of the inflaton field transition to classical density perturbations?

…

More than fitting data...

Historical cases:

- Control of idealizations and physical assumptions used in constructing models → discrepancies with observations reveal further details, basis for ongoing inquiry
- Response to underdetermination threat

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

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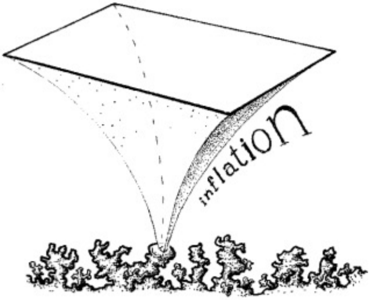
... applied to Inflationary Cosmology?

Obstacles: sensitivity to UV physics, failure to "decouple"; unclear connection to fundamental physics

Inflationary Hypothesis:

- Early universe includes scalar field ϕ, effective potential $V(\phi)$
- $\exists$ regions where ϕ is uniform, such that $T_{ab} \approx -V(\phi) g_{ab}$



From Penrose, *Road to Reality*

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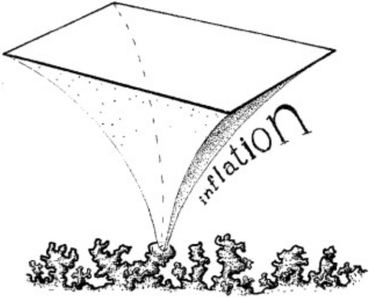

Consequence (?):
ϕ dominates expansion, leading to quasi-De Sitter phase.

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

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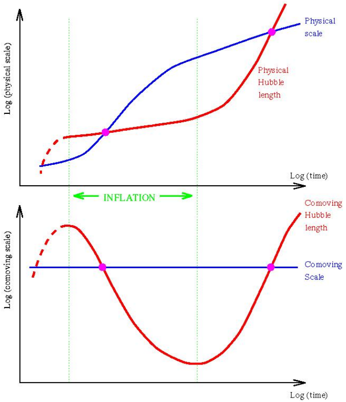
Structure Formation: Inflation

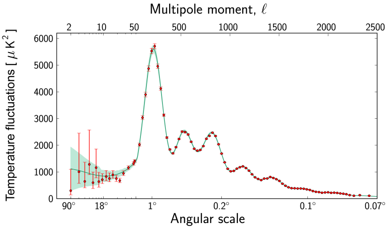


Horizon exit / re-entry (Liddle 1999)

Causal Account of Initial Fluctuations

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

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



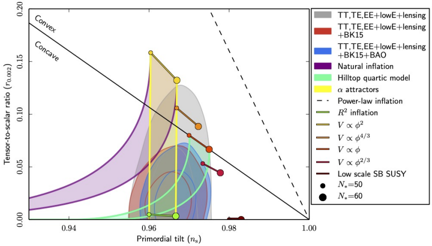


Fig. 8. Marginalized joint 68 % and 95 % CL regions for n_s and r at $k = 0.002\,\mathrm{Mpc}^{-1}$ from *Planck* alone and in combination with BK15 or BK15+BAO data, compared to the theoretical predictions of selected inflationary models. Note that the marginalized joint 68 % and 95 % CL regions assume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

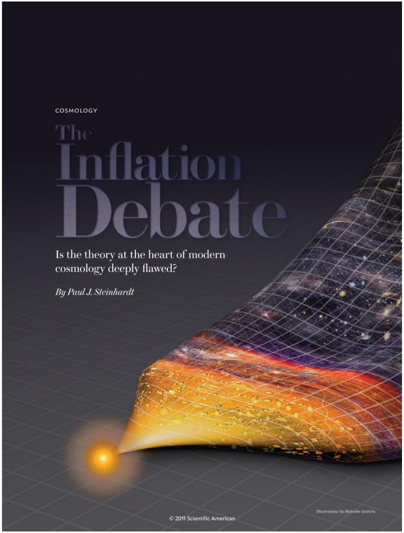
Planck Observations: (i) CMB angular power spectrum; (ii) Constraints on inflationary models from Planck observations, Planck Collaboration (2018)

Encyclopædia Inflationaris

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

- 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)



COSMOLOGY

The Inflation Debate

Is the theory at the heart of modern cosmology deeply flawed?

By Paul J. Steinhardt

Illustrations by Malcolm Godwin

Image credit: Steinhardt (2011)

Persistent Debates

- How plausible are the models favored by observations?
- Likelihood of initial state?
- Consequence of flexibility of inflationary “paradigm”?

Inflation as an Effective Field Theory?

- Standard Calculations
  - Evolution of perturbations: QFT in curved spacetime (fields evolving over fixed classical background), or semi-classical QG (including back-reaction effects)
  - Bunch-Davies vacuum state for ϕ

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- Standard Calculations
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  - Bunch-Davies vacuum state for ϕ
- How sensitive are these calculations to QG effects?

Decoupling in EFTs

Consider correlation functions $\langle O_1, ..., O_n \rangle$ among operators $\{O_i\}$ for a field theory with action S. Restrict to operators $\{O'_i\}$ at a lower energy scale. *EFT techniques*: construct S^{eff} such that $\langle O'_1, ..., O'_n \rangle$ calculated using S^{eff} agree with original correlation functions (up to some specified level of precision).

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- "Top-down"
  Explicitly integrate out high-energy degrees of freedom from existing theory to obtain S^{eff}.
- "Bottom-up"
  High-energy theory unknown, include all terms compatible with symmetries in S^{eff}.

Decoupling: high energy physics has limited impact on low-energy EFT, reflected in coupling constants

Senses of "Decoupling"

1. Inflationary Dynamics

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2. Indifference to Pre-Inflationary State

   How robust is the output to variations in the pre-inflationary state: (i) is an inflationary phase a dynamical attractor? (ii) are predictions robust to variations in initial state of ϕ?

Inflationary Attractor?

Form of results: from assumptions regarding (i) spacetime geometry; (ii) and properties of inflaton field in some patch; show that effective Λ term dominates. (Local but not global attractor.)

(Goldwirth and Piran (1992), ... Clough et al. (2019))

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Verdicts vary for different types of models, in particular "large field" seem robust and "small field" models have a more severe initial conditions problem

(See Brandenberger 2016 for a recent review)

Pre-Inflationary State

Structure formation predictions require ϕ in Bunch-Davies vacuum (or close to it); other states lead to non scale-invariant spectra. *Why* expect fluctuation modes to be in a (Minkowski) vacuum state?

"Trans-Planckian Problem": extrapolate mode with wavelength $\approx$ current Hubble radius back to 10^{16} GeV in standard FLRW model: on the order of *cm*. Inflationary phase: typically *much, much* below Planck length (depends on length of inflationary phase).

(Martin and Brandenberger 2001; see also LQG calculations by Agullo, et al.)

TransPlanckian Censorship Conjecture (Bedroya et al. 2020a, b; Brandenberger 2021)

- Fluctuation modes with trans-Planckian wavelength never "classicalize" (exceeds Hubble radius)

$$\frac{R(t)}{R(t_i)} L_P \leq H^{-1}(t) \forall t > t_i$$

For inflation: implies constraints on energy scale, shape of potential.

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  For inflation: implies constraints on energy scale, shape of potential.
- "Swampland Conjectures": proposed constraints on low-energy EFTs, based on string theory

EFTs for Cosmology?

- EFT Techniques applied to Gravity (e.g., Burgess 2004, 2017; Donoghue 2012)
    - Applied in regimes with symmetries (e.g. static, asymptotically flat), basis for separation of energy scales (and other features of EFT constructions)

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- General cosmological case?
  - Lacks symmetries used in existing constructions; expansion

EFTs for Cosmology?

Cosmological Constant Problem

> *It is surely an act of cosmic chutzpah to use this dismal theoretical failure [in understanding vacuum energy and the cosmological constant Λ] as a base for erecting theoretical superstructures, but of course this is exactly what is done in current inflationary models.*
>
> *Wilczek, in Hawking et al. 1983*

(See Bianchi and Rovelli 2010; Koberinski 2017, Schneider 2020)

Reconsidering “Indifference”

Can we forget about the early state? No! (Appealing prospect: possibility of further insights into QG.)

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Foundational Challenges to Inflation

Persistent foundational debates reflect, in part, challenges in connecting inflation with fundamental physics, clarifying domains of applicability of EFTs. (Needed to assess inflation by contrast with variety of other early universe scenarios.)

Thank You!

John Templeton Foundation

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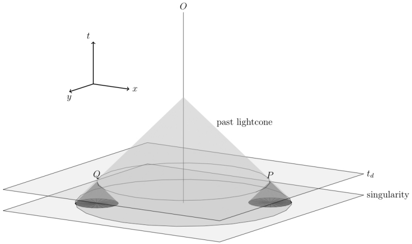
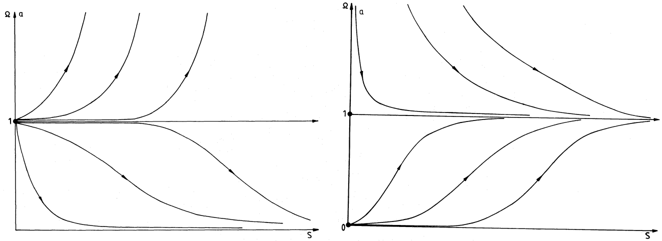
Horizon Problem



Flatness Problem



Density parameter $\Omega = \frac{\rho_c}{\rho}$ evolves away from 1 with expansion ($S(t) =:$ scale factor)

Problems with Initial State

Due to causal structure (horizon) and dynamics (flatness), standard cosmology requires pre-established harmony, fine tuning ...

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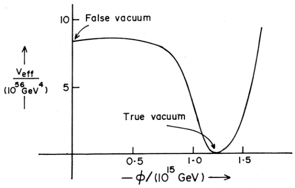
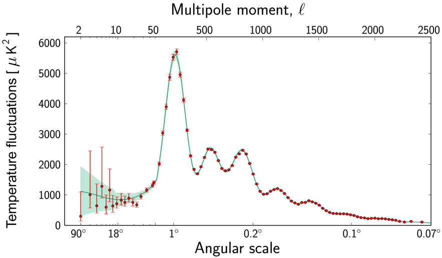
Due to causal structure (horizon) and dynamics (flatness), standard cosmology requires pre-established harmony, fine tuning ...

... Solved by 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 the "generic" post-inflationary state, for sufficiently large $\mathcal{N}$
- Vacuum fluctuations of inflaton field → classical density perturbations (Gaussian, nearly scale-invariant)



$V(\phi)$ for "new inflation" model (Albrecht & Steinhardt 1982)



Planck power spectrum

- Inflation: $V(\phi)$, parameters appearing in Lagrangian $\mathcal{L}$
- Features of power spectrum: Amplitude, spectral index for scalar, tensor perturbations; non-Gaussianities

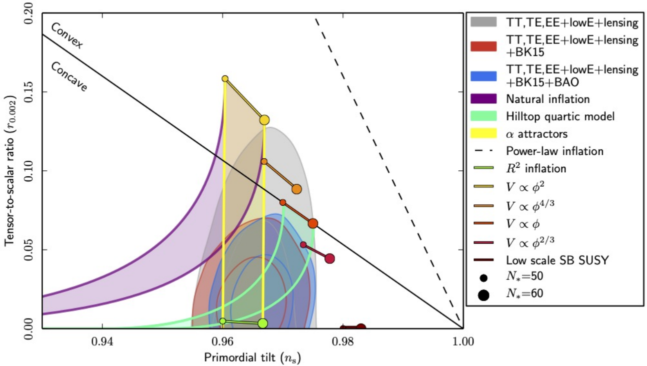


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Image Credit: constraints on inflationary models from Planck observations, Planck Collaboration (2018)

> *But approximate theories are not merely approximately true. They can make a statement that, though it refers to an approximation, is nevertheless precisely true. For instance, although Maxwell's equations give only an approximate account of electric and magnetic fields, it is precisely true that the error introduced by using Maxwell's equations to calculate these fields can be made as small as one likes by considering fields that are sufficiently weak and slowly varying. This is part of the reason that Maxwell's equations are a permanent part of physical science.*
>
> *Steven Weinberg (discussing Kuhn, in NYRB)*