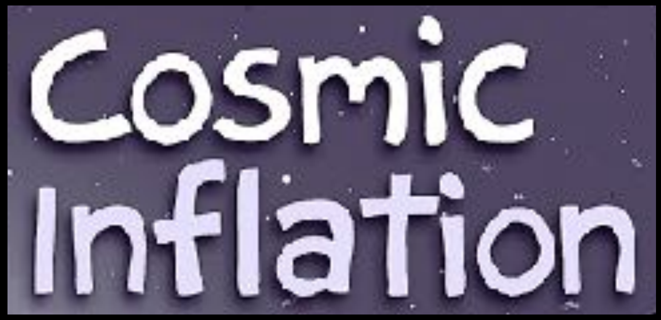
ISL

VS



Filippo Vernizzi - IPhT, CEA Saclay

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Diatribe: ISL *vs* inflation

Inflationary paradigm in trouble after Planck2013

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A B S T R A C T

Recent results from the *Planck* satellite combined with earlier observations from WMAP, ACT, SPT and other experiments eliminate a wide spectrum of more complex inflationary models and favor models with a single scalar field, as reported by the *Planck* Collaboration. More important, though, is that all the simplest inflaton models are disfavored statistically relative to those with plateau-like potentials. We discuss how a restriction to plateau-like models has three independent serious drawbacks: it exacerbates both the initial conditions problem and the multiverse-unpredictability problem and it creates a new difficulty that we call the inflationary "unlikeliness problem." Finally, we comment on problems reconciling inflation with a standard model Higgs, as suggested by recent LHC results. In sum, we find that recent experimental data disfavors all the best-motivated inflationary scenarios and introduces new, serious difficulties that cut to the core of the inflationary paradigm. Forthcoming searches for B-modes, non-Gaussianity and new particles should be decisive.

Diatribe: ISL *vs* inflation

Inflationary paradigm after Planck 2013

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ABSTRACT

Models of cosmic inflation posit an early phase of accelerated expansion of the universe, driven by the dynamics of one or more scalar fields in curved spacetime. Though detailed assumptions about fields and couplings vary across models, inflation makes specific, quantitative predictions for several observable quantities, such as the flatness parameter ($\Omega_k = 1 - \Omega$) and the spectral tilt of primordial curvature perturbations ($n_s - 1 = d\ln\mathcal{P}_{\mathcal{R}}/d\ln k$), among others—predictions that match the latest observations from the *Planck* satellite to very good precision. In the light of data from *Planck* as well as recent theoretical developments in the study of eternal inflation and the multiverse, we address recent criticisms of inflation by Ijjas, Steinhardt, and Loeb. We argue that their conclusions rest on several problematic assumptions, and we conclude that cosmic inflation is on a stronger footing than ever before.

Diatribe: ISL *vs* inflation

Inflationary schism after Planck2013

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(Dated: March 14, 2014)

Classic inflation, the theory described in textbooks, is based on the idea that, beginning from typical initial conditions and assuming a simple inflaton potential with a minimum of fine-tuning, inflation can create exponentially large volumes of space that are generically homogeneous, isotropic and flat, with nearly scale-invariant spectra of density and gravitational wave fluctuations that are adiabatic, Gaussian and have generic predictable properties. In a recent paper, we showed that, in addition to having certain conceptual problems known for decades, classic inflation is for the first time also disfavored by data, specifically the most recent data from WMAP, ACT and Planck2013. Guth, Kaiser and Nomura and Linde have each recently published critiques of our paper, but, as made clear here, we all agree about one thing: the problematic state of classic inflation. Instead, they describe an alternative inflationary paradigm that revises the assumptions and goals of inflation, and perhaps of science generally.

Diatribe: ISL *vs* inflation

COSMOLOGY

POP goes the universe

THE LATEST ASTROPHYSICAL MEASUREMENTS, COMBINED WITH THEORETICAL PROBLEMS, CAST DOUBT ON THE LONG-CHERISHED INFLATIONARY THEORY OF THE EARLY COSMOS AND SUGGEST WE NEED NEW IDEAS

By Anna Ijjas, Paul J. Steinhardt and Abraham Loeb

Diatribe: ISL *vs* inflation

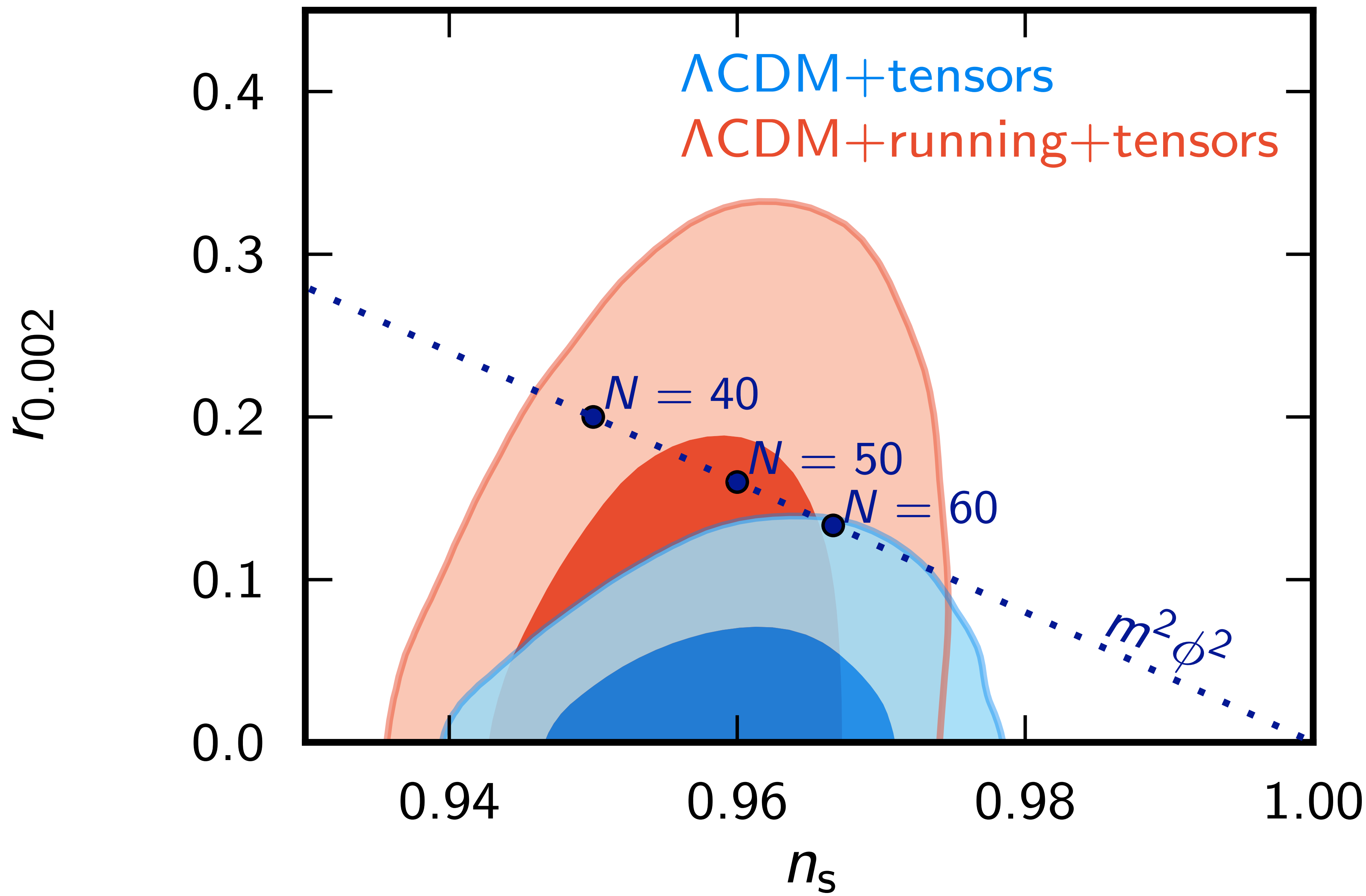
A Cosmic Controversy

A *Scientific American* article about the theory of inflation prompted a reply from a group of 33 physicists, along with a response from the article's authors

May 10, 2017

Alan H. Guth, David I. Kaiser, Andrei D. Linde, Yasunori Nomura, Charles L. Bennett, J. Richard Bond, François Bouchet, Sean Carroll, George Efstathiou, Stephen Hawking, Renata Kallosh, Eiichiro Komatsu, Lawrence M. Krauss, David H. Lyth, Juan Maldacena, John C. Mather, Hiranya Peiris, Malcolm Perry, Lisa Randall, Martin Rees, Misao Sasaki, Leonardo Senatore, Eva Silverstein, George F. Smoot, Alexei Starobinsky, Leonard Susskind, Michael S. Turner, Alexander Vilenkin, Steven Weinberg, Rainer Weiss, Frank Wilczek, Edward Witten, Matias Zaldarriaga

Planck 2013 results



$$r \equiv \frac{\text{tensor fluctuations}}{\text{scalar fluctuations}} \lesssim 0.12$$

Scalar and tensor fluctuations

The inflaton field and the metric fluctuations are generated during inflation:

$$\delta\phi_{\mathrm{quantum}} \sim H \qquad\qquad \frac{\gamma_{\mathrm{quantum}}}{\sqrt{16\pi G}} \sim H$$

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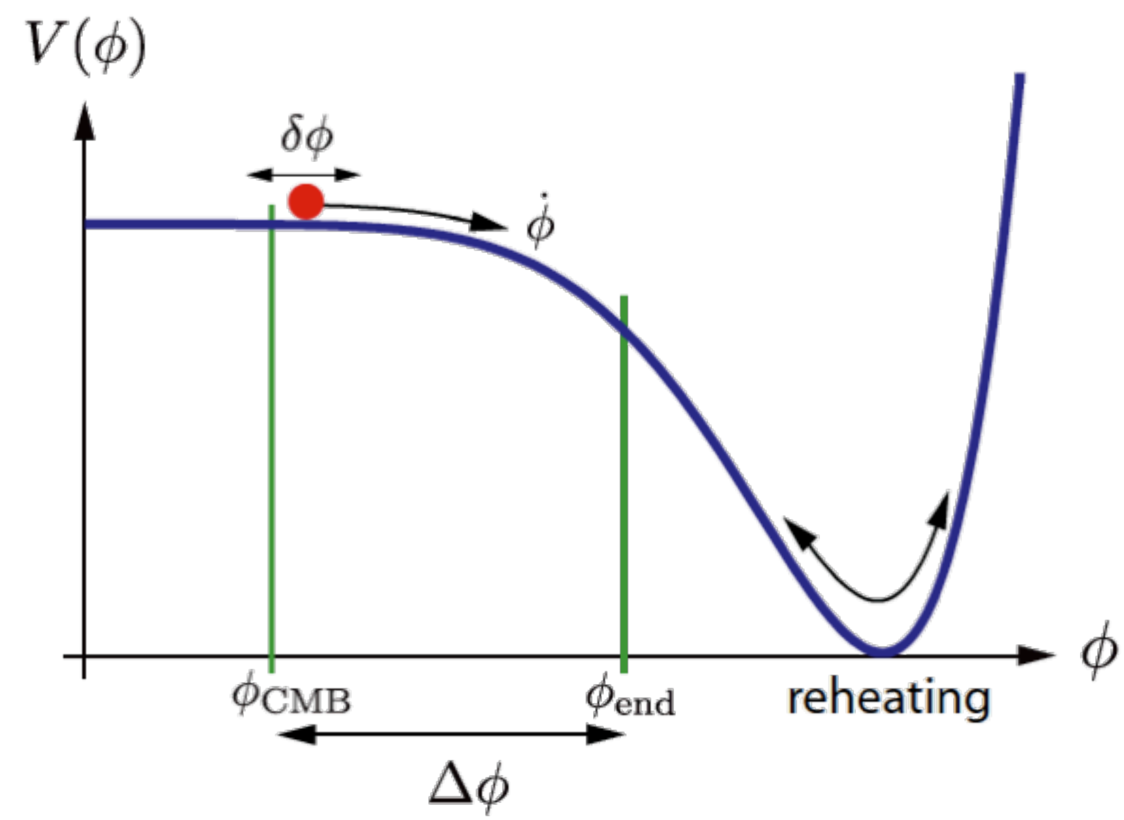
We observe a time delay:

$$\frac{\delta T}{T} = \frac{T(t+\delta t) - T(t)}{T(t)} \sim \frac{\delta\phi_{\text{quantum}}}{\dot{\phi}_{\text{classical}}/H}$$



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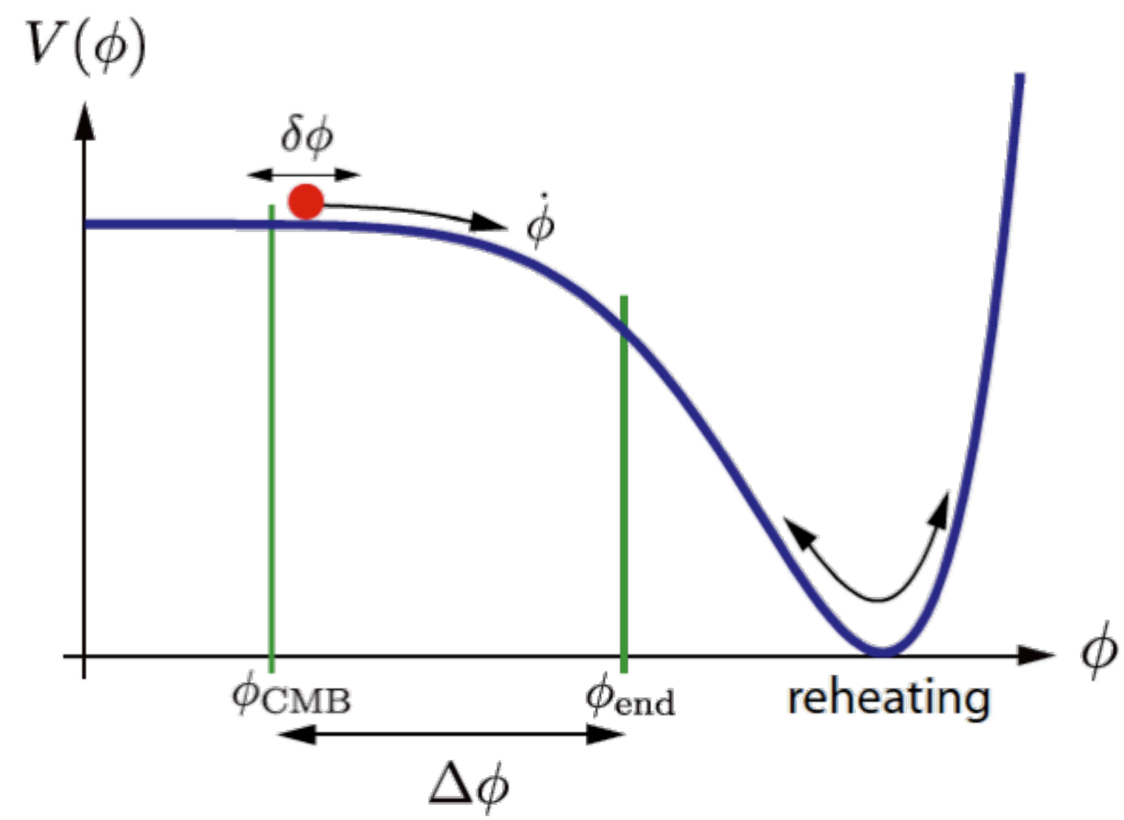
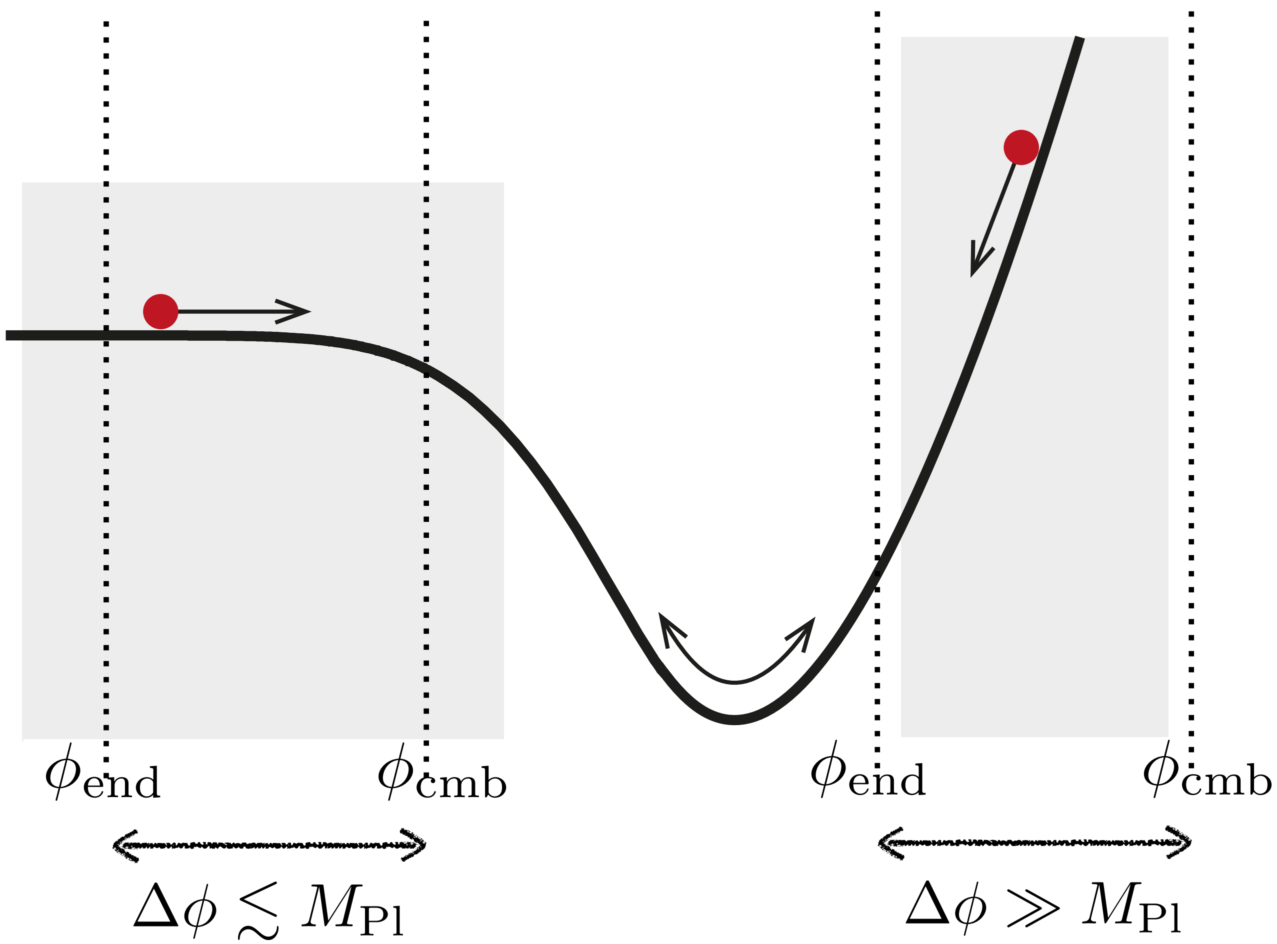


Tensor-to-scalar ratio: $$r \equiv \frac{\langle|\gamma|^2\rangle}{\langle|\delta T/T|^2\rangle} = 64\pi G \left(\frac{d\phi}{dN}\right)^2 \simeq 8\left(\frac{\Delta\phi}{M_{\text{Pl}}}\right)^2 \frac{1}{\Delta N^2}$$

Small *r* implies small field excursion: $$\frac{\Delta\phi}{M_{\text{Pl}}} \sim \sqrt{\frac{r}{0.002}}$$

Large and small field models

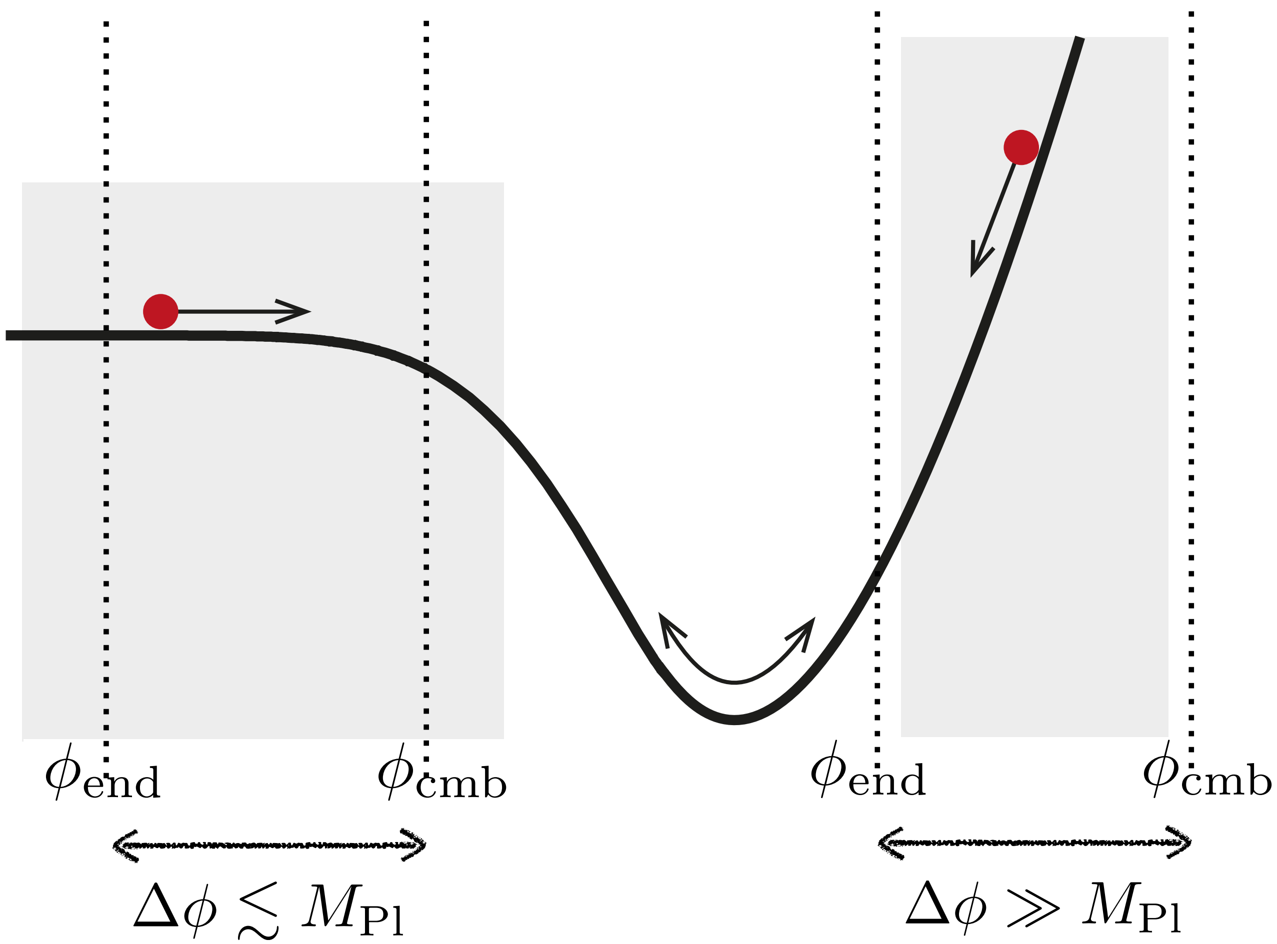


Large-field models:

$$V \propto \phi^n$$

$$r \sim \left(\frac{M_{\rm Pl}}{\phi}\right)^2 \sim \frac{1}{N}$$

Large and small field models



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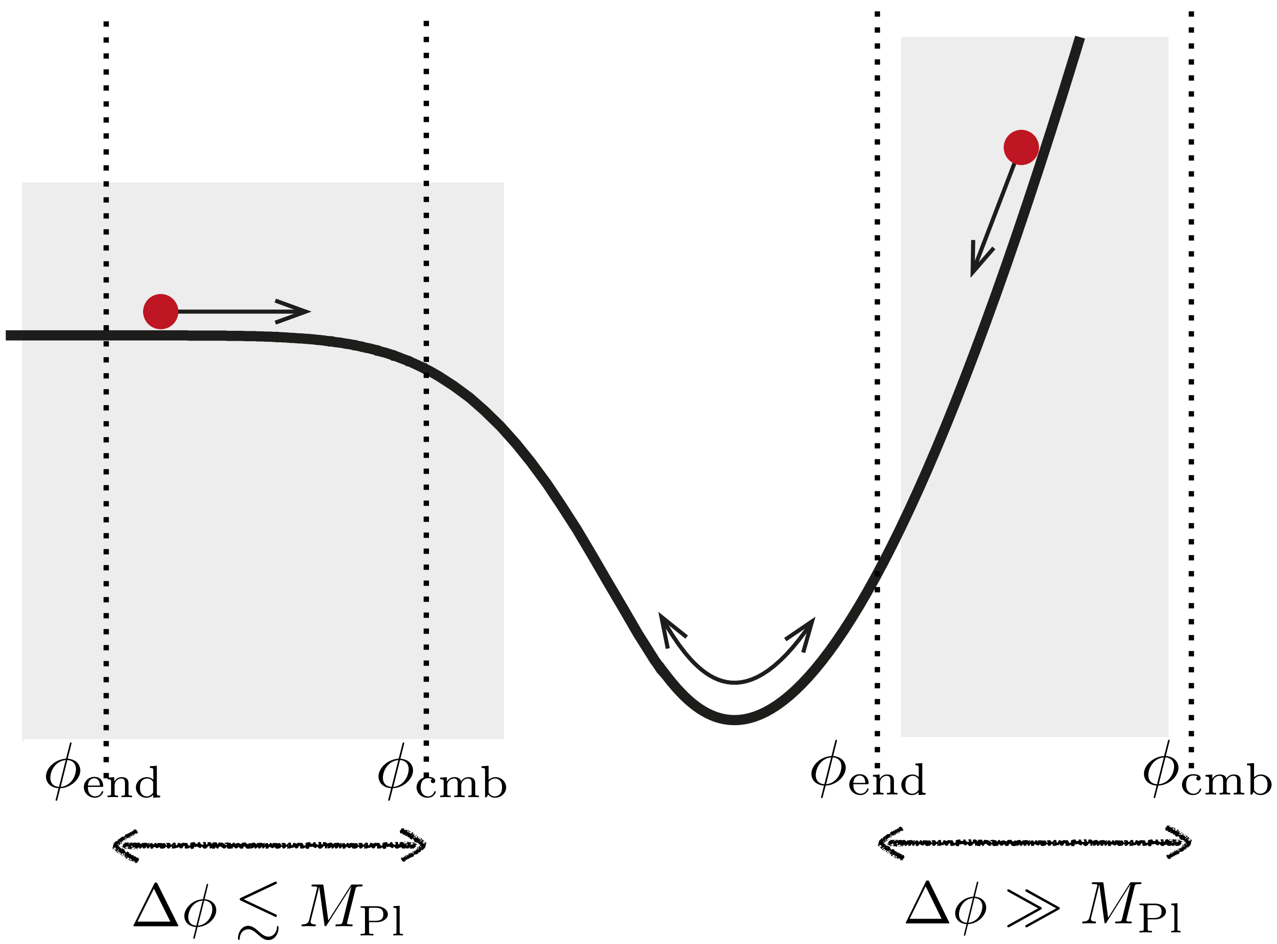
Small-field models:

$$V \propto 1 - \left(\frac{\phi}{\mu}\right)^n + \ldots\,, \quad \phi \lesssim M_{\rm Pl} \lesssim \mu$$

$$r \sim \left(\frac{M_{\rm Pl}}{\mu}\right)^2 \left(\frac{\phi}{\mu}\right)^{n-1} \sim \frac{1}{N^\alpha}\,, \quad \alpha > 1$$

Data seem to exclude power laws and favour plateau-like

Large and small field models



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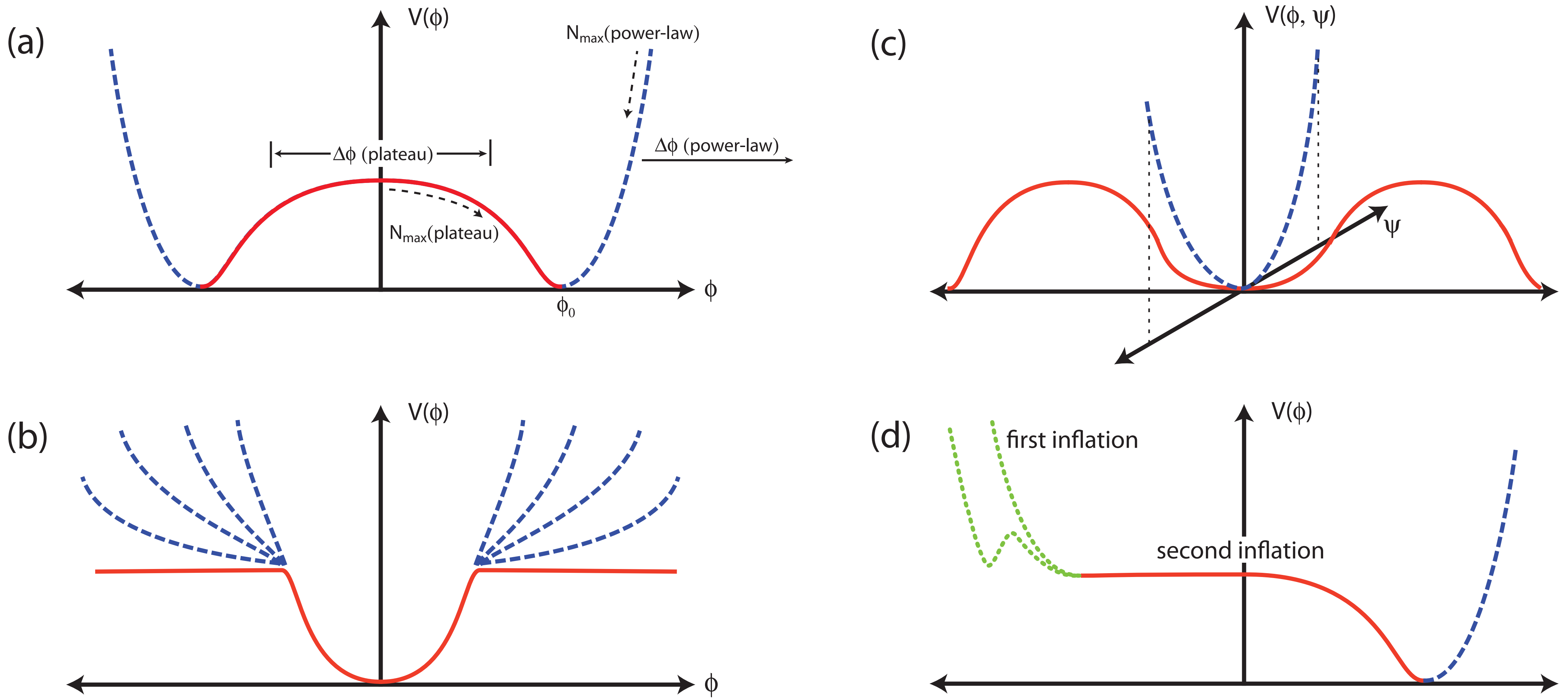
Data seem to exclude power laws and favour plateau-like

Caveats: Assumes single field and slow-roll inflation

Inflationary problems after 2013

	Inflaton Potential +	Initial Conditions +	Measure ⟹	Predictions
Classic inflationary paradigm	**Simple –** Single, continuous stage of inflation governed by potentials with the fewest degrees of freedom, fewest parameters, least tuning.	**Insensitive –** Inflation transforms typical initial conditions emerging from the big bang into a flat, smooth universe with certain generic properties.	**Common-sense –** It is more likely to live in an inflated region because inflation exponentially increases volume $\Rightarrow$ measure = volume	**Generic –** Based on simplest potentials: - red tilt: $n_S \sim .94 - .97$, - large $r \sim .1 - .3$*, - negligible f_{NL}, - flatness & homogeneity
Conceptual problems known prior to WMAP, ACT & Planck2013	**Not so simple –** Even simplest potentials require fine-tuning of parameters to obtain the right amplitude of density fluctuations.	**Sensitive –** The initial conditions required to begin inflation are entropically disfavored/exponentially unlikely. There generically exist more homogeneous and flat solutions without inflation than with.	**Catastrophic failure –** Inflation produces a multiverse in which most of the volume today is inflating and, among non-inflating volumes (bubbles), Inflation predicts our universe to be exponentially unlikely.	**Predictability problem –** No generic predictions; "anything can happen and will happen an infinite number of times." The probability by volume of our observable universe is less than $10^{-10^{55}}$.
Observational problems after WMAP, ACT & Planck2013 [1]***	**Unlikeliness problem –** *Simplest* inflaton potentials disfavored by data; favored (plateau) potentials require more parameters, more tuning, and produce less inflation.	**New initial conditions problem –** Favored plateau potentials require an initially homogeneous patch that is a billion times** larger than required for the simplest inflaton potentials.	**New measure problem –** All favored models predict a multiverse yet data fits predictions assuming no multiverse.	**Predictability problem unresolved –** Potentials favored by data do not avoid the multiverse or the predictability problems above. Hence, no generic predictions.

"Unlikeliness problem"



$$N_{\max}(\text{power-law}) \quad \gg \quad N_{\max}(\text{plateau}).$$

Need tuning of parameters to have a plateau. Plateau predicts less e-folds, so less amount of inflationary expansion, so it is less likely.

Reply to unlikeliness problem

The story is more complicated…

No way of knowing if inflation occurred on the plateau or power-law part

The plateau could have been preceded by tunnelling from a metastable vacuum (where N could be very large) and the center be a point of enhanced symmetry in a multi-field space

The concept of “likeliness” must be addressed in the context of the multiverse (see later)

No measure to compute probabilities has been satisfactorily defined

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New initial condition problem

In chaotic (power law) inflation, one starts with generic initial conditions at the Planck scale:

$$\frac{1}{2}\dot{\phi}^2 \sim \frac{1}{2}|\nabla\phi|^2 \sim V \sim M_{\rm Pl}^4$$

Evolving forward in time, potential comes to dominate over the kinetic and gradient energy (which decrease in time) and inflation starts. One just needs a region of homogeneity of order H^{-1}

$$\frac{1}{2}\dot{\phi}^2 \propto \frac{1}{a^6} \qquad\qquad \frac{1}{2}|\nabla\phi|^2 \propto \frac{1}{a^2}$$

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Given δT/T, tensor-to-scalar ratio fixes the energy scale of inflation

$$\frac{\delta T}{T} \sim \frac{\gamma}{\sqrt{r}} \sim \frac{1}{\sqrt{r}}\frac{H}{M_{\rm Pl}} \sim \frac{1}{\sqrt{r}}\left(\frac{E_{\rm infl}}{M_{\rm Pl}}\right)^2 \quad \Rightarrow \quad E_{\rm infl} \lesssim 10^{-3} M_{\rm Pl}\left(\frac{r}{0.12}\right)^{1/4}$$

In the plateau, difficult for the potential to dominate. One must require an initial region of homogeneity much larger than H^{-1}

$$\frac{1}{2}\dot{\phi}^2 \sim \frac{1}{2}|\nabla\phi|^2 \gg V \sim E_{\rm infl}^4$$

Reply to IC problem

Assuming inflation only occurred on the plateau…

Do not agree with the estimate, because the region of homogeneity and H^{-1} scale in the same way

Anyway, estimate is based on the assumption that the potential is featureless. Potential can be more complicated: tunnelling, multi-field with many local minima, etc. Details of this previous phase are anyway not observable…

The situation can be even more complicated in the multiverse picture: inflation may have been preceded by other inflationary phases, etc.

Inflationary problems after 2013

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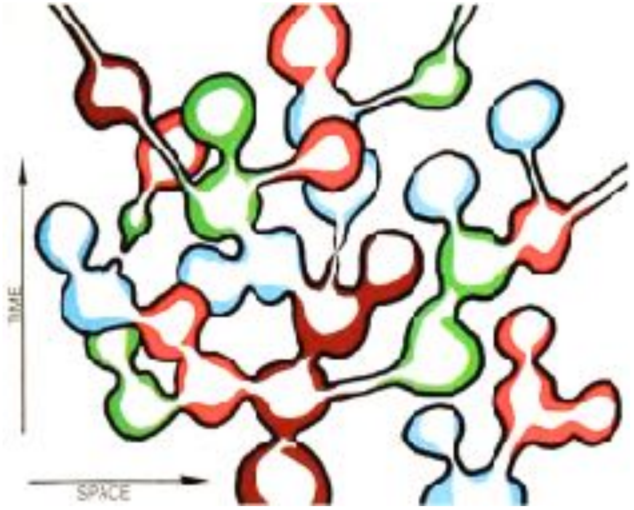
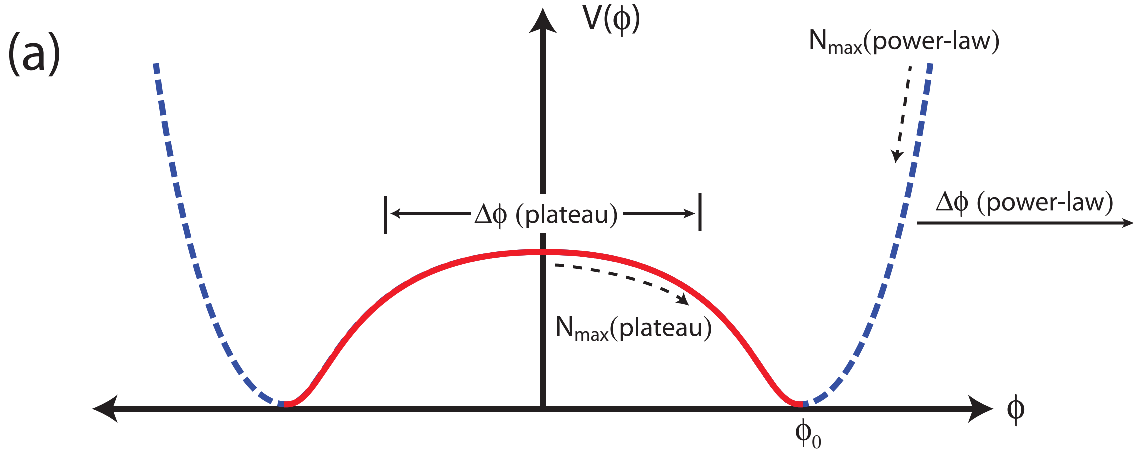
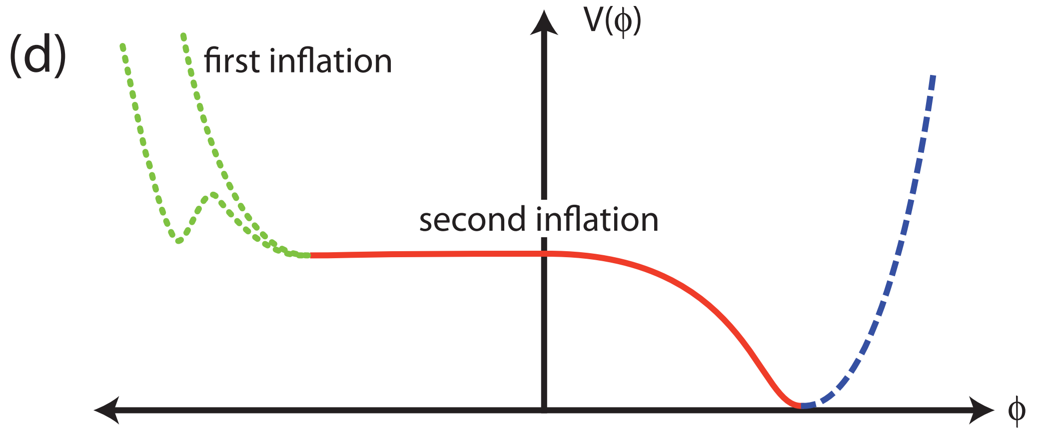
New measure problem

Eternal inflation: quantum fluctuations dominate over the classical evolution:

$$\frac{\delta\phi_{\text{quantum}}}{\dot{\phi}_{\text{classical}}/H} \gg 1$$







Most of the volume occupied by many (infinite) inflating regions. Since anything can happen, large deviations from naive predictions should be observed and we do not

Multiverse, but probabilities must be defined. Using the volume on proper time hypersurfaces lead to very small probabilities for our universe

Reply to new measure problem

Probability laws work also with large (infinite) numbers. (In quantum mechanics anything can happen but cars do not tunnel from their garages.)

They agree that no measure has been satisfactorily defined, so difficult to distinguish common from rare events.

Falsifiability

	Inflaton Potential +	Initial Conditions +	Measure $\Longrightarrow$	Predictions
Postmodern inflationary paradigm	**Complex** – with many fields, parameters, dips, minima, and hence many metastable states, leading to multiple phases of inflation [GKN10-11] and making eternal inflation unavoidable [GKN12]	**Not important** – in considering validity of inflation; any problems can be compensated by adjusting the measure [GKN19]	**To be determined** – from some combination of probability weighting and anthropic selection [GKN13,17,20]	**Generic** – predictions should generically agree with observations once the right complex potential and combination of measure and anthropic weighting is identified [GKN6,15]
Problems	**Unpredictability. Part I** – A complex energy landscape allows virtually any outcome and provides no way to determine which inflaton potential form is most likely. [GKN17]	**Unpredictability. Part II** – Without knowing initial conditions cannot make predictions even if energy landscape is known. [GKN14]	**Paradigm rests entirely on the measure** – yet, to date, no successful measure has been proposed and there is no obvious way to solve this problem. [GKN13]	**No predictions** – the simplest (volume) measure gives catastrophic results and different landscapes, initial conditions, and measures give different predictions [GKN6].

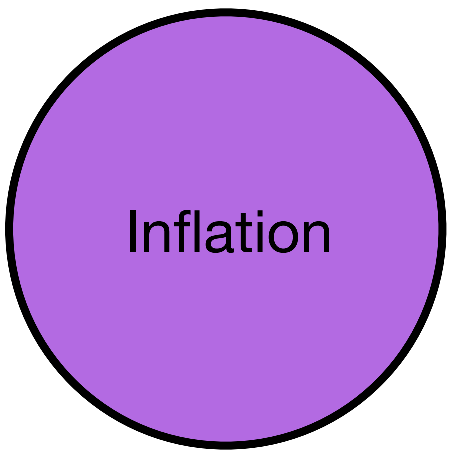
Reply to falsifiability

1) A physical theory has parameters (in this case shape of the potential, initial conditions, etc.). These are not predicted but fixed *a posteriori* with data. Example: Standard Model: particle content and 19 or more numbers.

2) Any physical theory relies on assumptions. E.g., big bang cosmology assumes initial homogeneity and small scale-invariant fluctuations (explained by inflation). But it makes predictions (relative abundance of light elements).

3) The multiverse does not interfere with testability. Standard Model and inflation would be understood as a description of physics of our Universe.

Thoughts on falsifiability



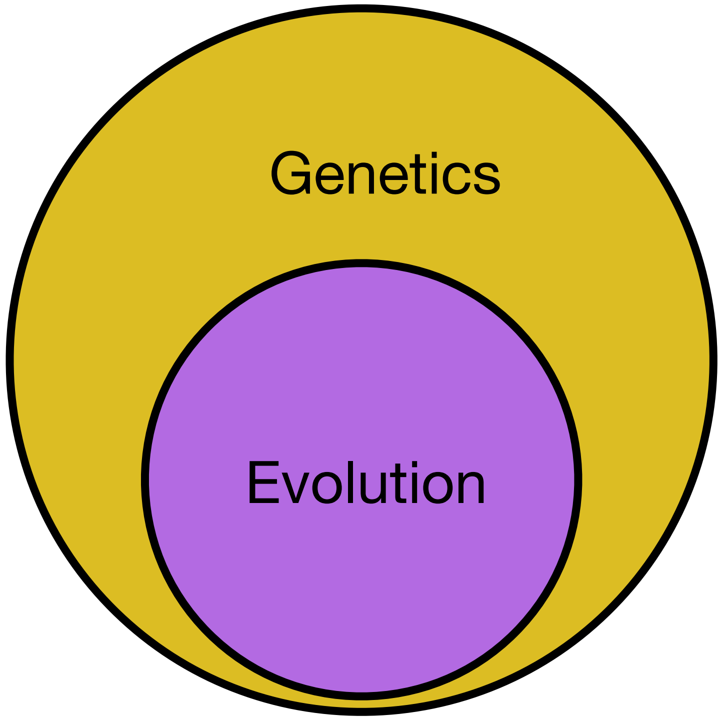
Inflation: early accelerated expansion of at least 60 e-folds.
Predictions: flat and smooth universe, quasi-scale invariant spectrum of adiabatic and gaussian fluctuations, tensor modes.
Assumptions: it started in our observable universe at some high energy.
Parameters: field space, parameters in inflaton action.

Thoughts on falsifiability

Evolution

Evolution: species change and new species form through natural selection.
Predictions: speciation, anagenesis, extinctions (e.g. fossils).
Assumptions: Traits can be inherited and new traits can form.
Parameters: sizes of animals, characteristics of adaptations, etc.

Thoughts on falsifiability



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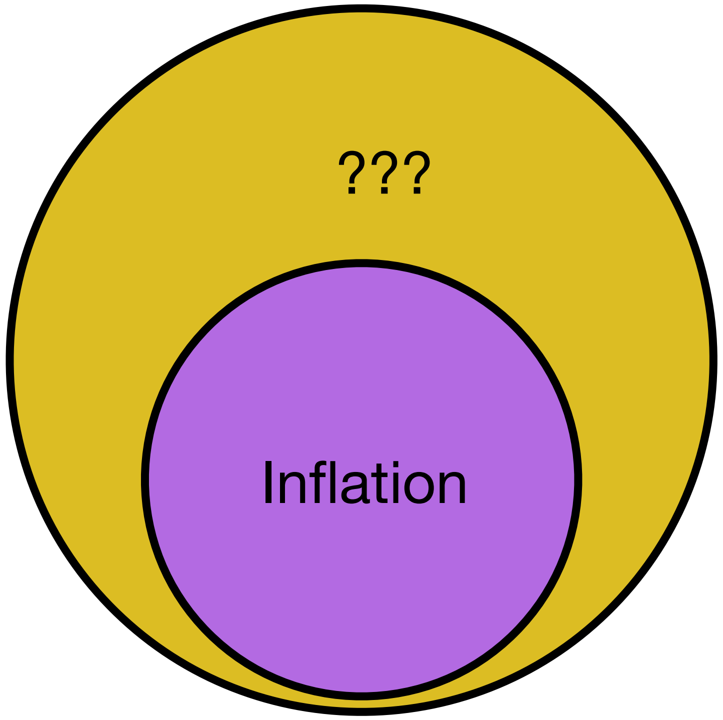

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