Top-Down Overview

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Primordial Cosmology, KITP

April 23, 2013

9.5 years ago

KITP Conference: Superstring Cosmology (Oct 20-24, 2003)
Coordinators: T. Banks, S. Carroll, J. Maldacena, J. Polchinski, G. Veneziano

Speakers: Please lend your transparencies to the KITP staff members in the front office (Rm 1102) for scanning, or see us about file upload.

KITP news, 2004: “According to Polchinski, who is a string theorist, the KITP program that produced the test for string theory was the first sustained effort ever to bring cosmologists and string theorists together to advance the newly emerging field of string cosmology.”

Plan

I. Why pursue a top-down view of the early universe?

II. Inflation in string theory

- The task: compactification
- Lamppost example: D-brane inflation
- Many-field inflation
- Shift-symmetric example: axion monodromy

Quantum gravity and the early universe

- What can we hope to learn about Planck-scale physics through experimental cosmology? How can ideas about quantum gravity be used to interpret or guide observations?

Quantum gravity and the early universe

- What can we hope to learn about Planck-scale physics through experimental cosmology? How can ideas about quantum gravity be used to interpret or guide observations?
- Why is quantum gravity relevant at all?

Inflation is sensitive to Planck-scale physics.

- Inflationary dynamics is generically controlled by non-renormalizable contributions to the effective Lagrangian.
  - We expect contributions from integrating out massive degrees of freedom, with mass Λ, to which the inflaton couples.
  - The ultraviolet completion of gravity should furnish new d.o.f. with Λ at or below the Planck scale.
  - With $\mathcal{O}(1)$ couplings, even for $\Lambda = M_p$, operators with dimension $\Delta \leq 6$ make critical corrections to the dynamics.
- Thus, some properties of inflation are dictated by the ultraviolet completion of gravity.

Planck-sensitivity of inflation

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V_0(\phi)$$

$$\eta \equiv M_p^2 \frac{V''}{V} \ll 1$$

$$\Delta V \equiv \mathcal{O}_\Delta = V_0 \left(\frac{\phi}{\Lambda}\right)^{\Delta-4} \Longrightarrow \delta\eta \sim \left(\frac{M_p}{\phi}\right)^2 \left(\frac{\phi}{\Lambda}\right)^{\Delta-4}$$

$$\Delta = 6 : \quad \delta\eta \sim \left(\frac{M_p}{\Lambda}\right)^2 \gtrsim 1$$

For small inflaton displacements, $\Delta\phi \lesssim M_{pl}$, one must control corrections $\mathcal{O}_\Delta$ with $\Delta \lesssim 6$.

For large inflaton displacements, $\Delta\phi \gg M_{pl}$, one must control an infinite series of corrections, with arbitrarily large Δ.
(These large-field models we can identify unambiguously by detecting primordial tensors.)

Quantum gravity and the early universe

- What can we hope to learn about Planck-scale physics through experimental cosmology? How can ideas about quantum gravity be used to interpret or guide observations?
- Minimal goal: give quantum gravity stamp of approval to field theoretic models of inflation; lend legitimacy to EFT symmetry assumptions.
- Quantum gravitational consistency requirements may select a small subset of the vast space of EFT models, improving predictivity.
- Embedding into string theory can entail small modifications that lead to signatures: we will discuss this for axion monodromy inflation.

Quantum gravity and the early universe

- String theory has led to refining and expanding our ideas for inflationary mechanisms in EFT.
- Distant dream: discovering entirely new scenarios for the early universe, beyond EFT. Would likely require time-dependent solutions with string-scale curvatures.
- String theory can affect notions of naturalness and minimality. e.g. existence of many moduli, hidden sectors
- First task: understand inflation in string theory.

Still seeking a theory of INITIAL conditions

- Initial singularity
- Measures in eternal inflation
- Patch problem
- Low entropy initial state
- Overshooting? (some progress)
- Fine-tuning of Lagrangian (some progress)
- Predictivity (some progress)

In general, the Planck-suppressed contributions to the potential arise from integrating out massive fields that are part of the ultraviolet completion of gravity.

In string theory, the contributing massive fields notably include stabilized moduli.

Moduli and inflation in string theory

- String compactifications typically lead to 4d effective theories with many scalar fields corresponding to deformations of the internal space.
- Because their action originates in the 10d gravity sector, their couplings in 4d are of gravitational strength.
- These moduli fields are highly problematic in cosmology.
  - photodissociation during BBN; overclosure; decompactification; etc.

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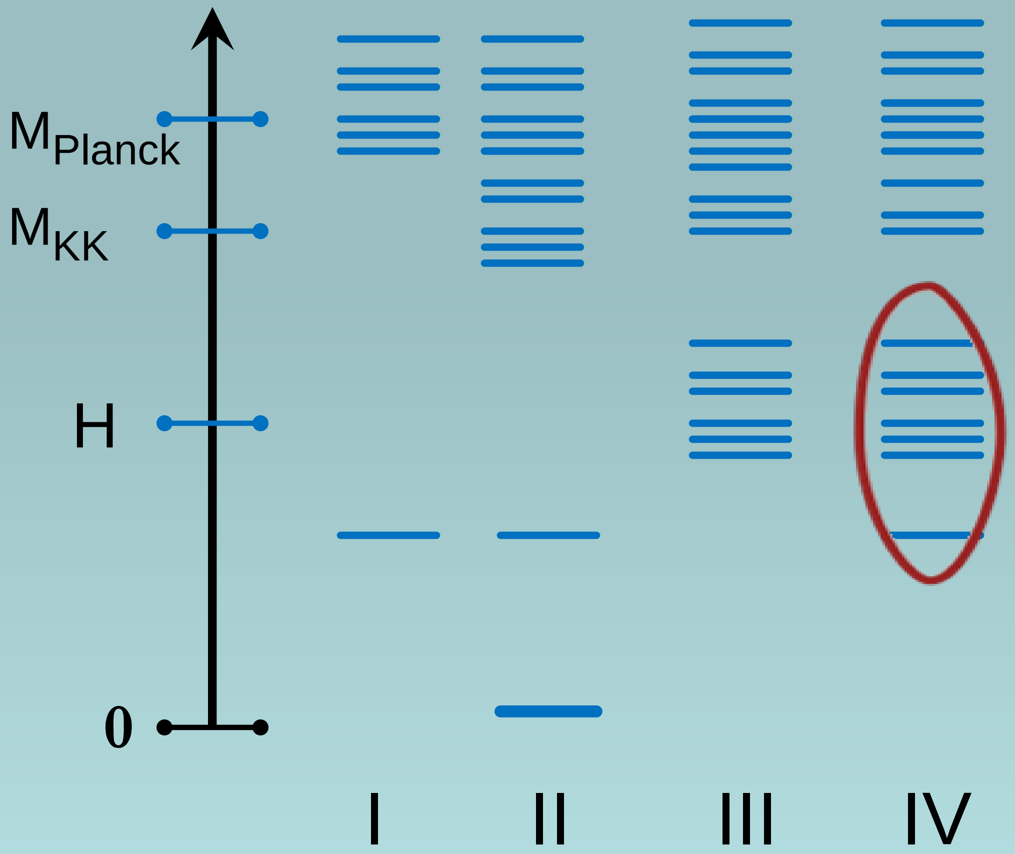
- A key achievement of the past decade: emerging understanding of effects that give masses to the moduli, i.e. of methods of moduli stabilization.
- These masses are finite! Integrating out the stabilized moduli yields critical contributions to the dynamics of the light fields.

Moduli mass spectra

(assuming SUSY spontaneously broken)



UV d.o.f.: integrate out

‘stabilized’ moduli:
dynamical, fluctuating

inflaton

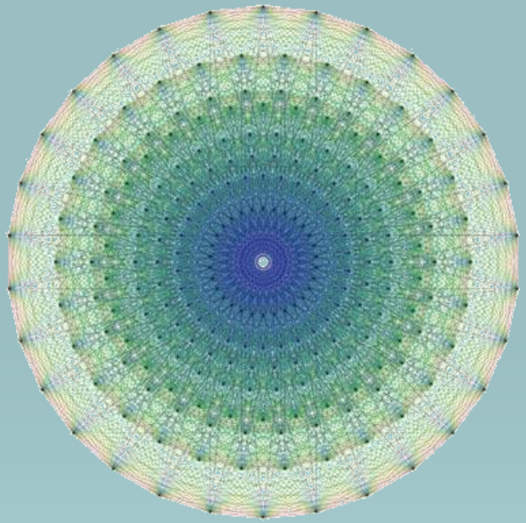
massless moduli

Task: Compactification

From geometric data, must derive 4d EFT (QFT+GR), including Planck-suppressed contributions.

But compact models with broken supersymmetry and many stabilized moduli are very difficult to analyze!

Two approaches to inflation in string theory



Compute the inflaton action by brute force, in a tractable example

Find a symmetry that simplifies the task

Lamppost example:
Warped D-brane inflation

Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi 03
Baumann, Dymarsky, Kachru, Klebanov, L.M. 08, 09, 10
Agarwal, Bean, L.M., Xu 11
Renaux-Petel, L.M., Xu 12

Warped D-brane inflation

Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi, 03

warped Calabi-Yau cone

D3-brane

stabilized compactification

Warped D-brane inflation

Kachru, Kallosh, Linde, Maldacena, L.M., Trivedi, 03

stabilized compactification

coefficients dictated by **unknown** details of bulk

Dimensions fixed by geometry of cone

$$V(r,\Psi) = \sum_i c_i r^{\Delta_i} h_i(\Psi)$$

$$\Delta = 1, \tfrac{3}{2}, 2, \sqrt{28}-3, \tfrac{5}{2}, \sqrt{28}-\tfrac{5}{2}, \ldots$$

Ceresole, Dall'Agata, D'Auria, Ferrara 99
Baumann, Dymarsky, Kachru, Klebanov, L.M. 08, 09, 10
Gandhi, L.M., Sjörs 11

Context: statistical approach to many-field inflation

- String theory strongly motivates considering inflation models with multiple light fields whose potential is controlled by Planck-suppressed contributions.
- Explicit computation of this potential is generally not possible. However, sometimes one can compute its ‘structure’, i.e. the list of contributing operators. Achieved so far only in this example of D3-brane inflation (N=6).
- But how to obtain signatures from the structure alone?
- Idea: when there are many fields and many terms in the potential, central limit behavior will take over, yielding a sort of universality.

Universality

- Practical definition: independence of the outputs on the inputs.

  e.g., central limit theorem for a sum of random variates. Input=some statistical distribution.

  Output=Gaussian distribution.

We conjecture – and verify – that taking

Input=some statistical distribution for the Wilson coefficients

one finds

Output=same inflationary phenomenology as if the input distribution were Gaussian.

In fact, our predictions are robust against more drastic changes of the potential (e.g., removing terms).

Method:

$$V(r, \Psi) = \sum_i c_i r^{\Delta_i} h_i(\Psi)$$

We truncate the potential at $\Delta<7.8$, retaining the first 334 terms.

We draw the coefficients c_i from a statistical distribution Ω, generating an ensemble of potentials.

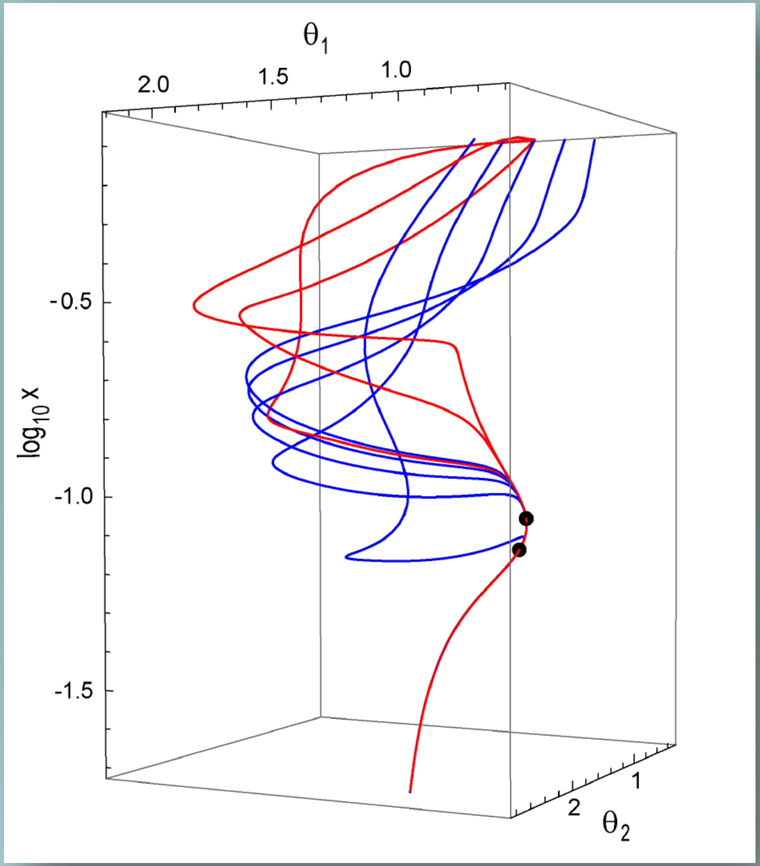
We draw a potential from the ensemble, choose a random initial condition (with appropriately bounded kinetic energy), and find the full six-field evolution of the homogeneous background. Repeat 7×10^7 times.

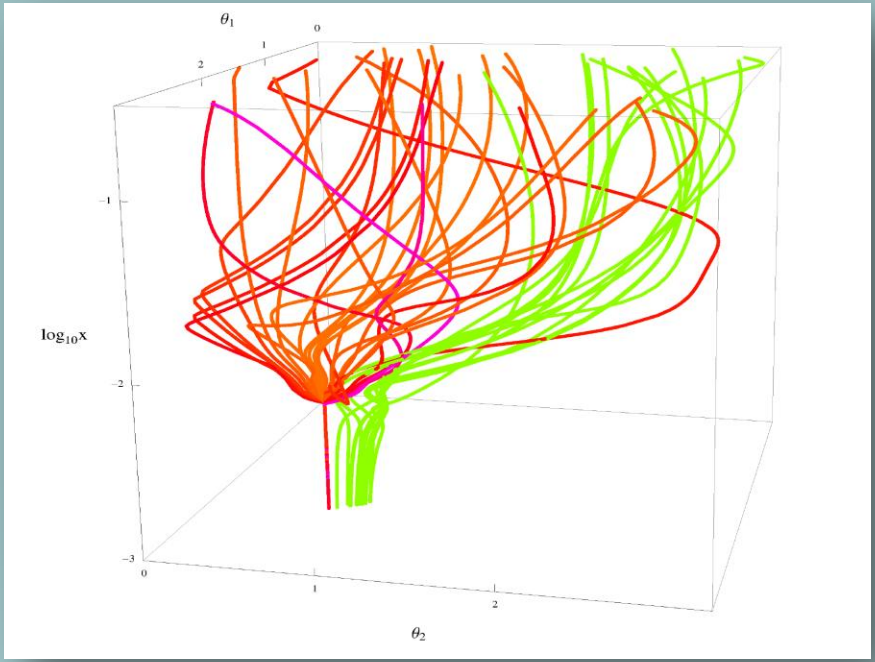
We then identify phenomenological properties that are demonstrably independent of Ω.

Agarwal, Bean, L.M., Xu 11
Renaux-Petel, L.M., Xu 12
Dias, Frazer, Liddle 12

cf. D=1 **Tegmark 04;** D=2 **Frazer, Liddle 11**

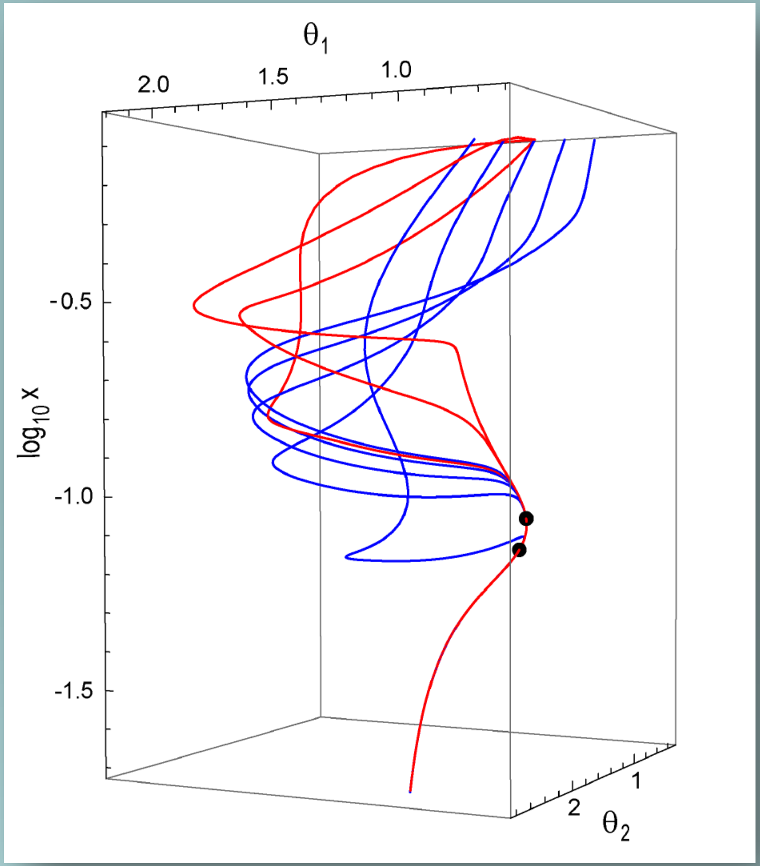
Attractor behavior

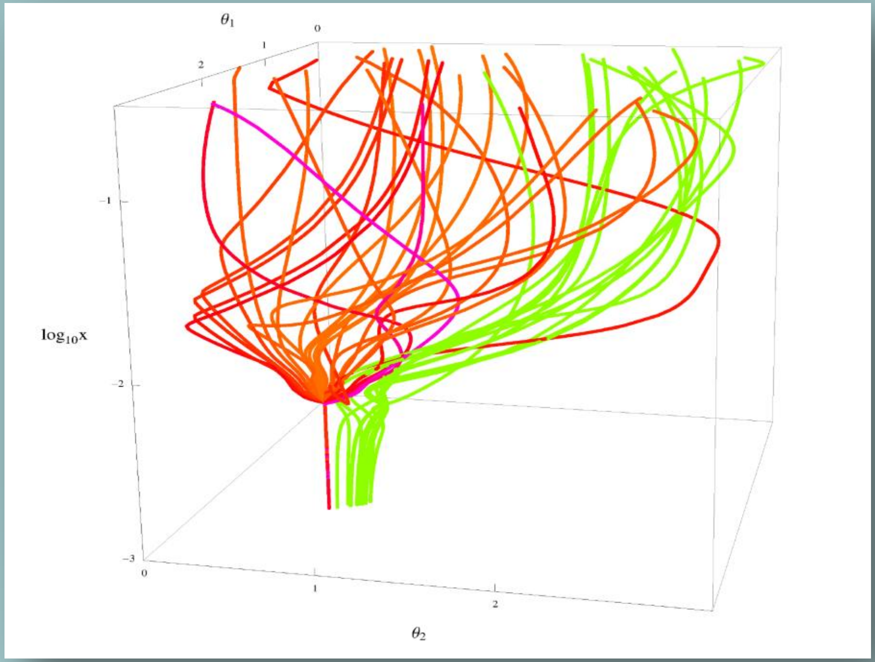




Typical successful trajectories. The fields are funneled into an angular minimum. Along this minimum, the potential has an approximate inflection point.

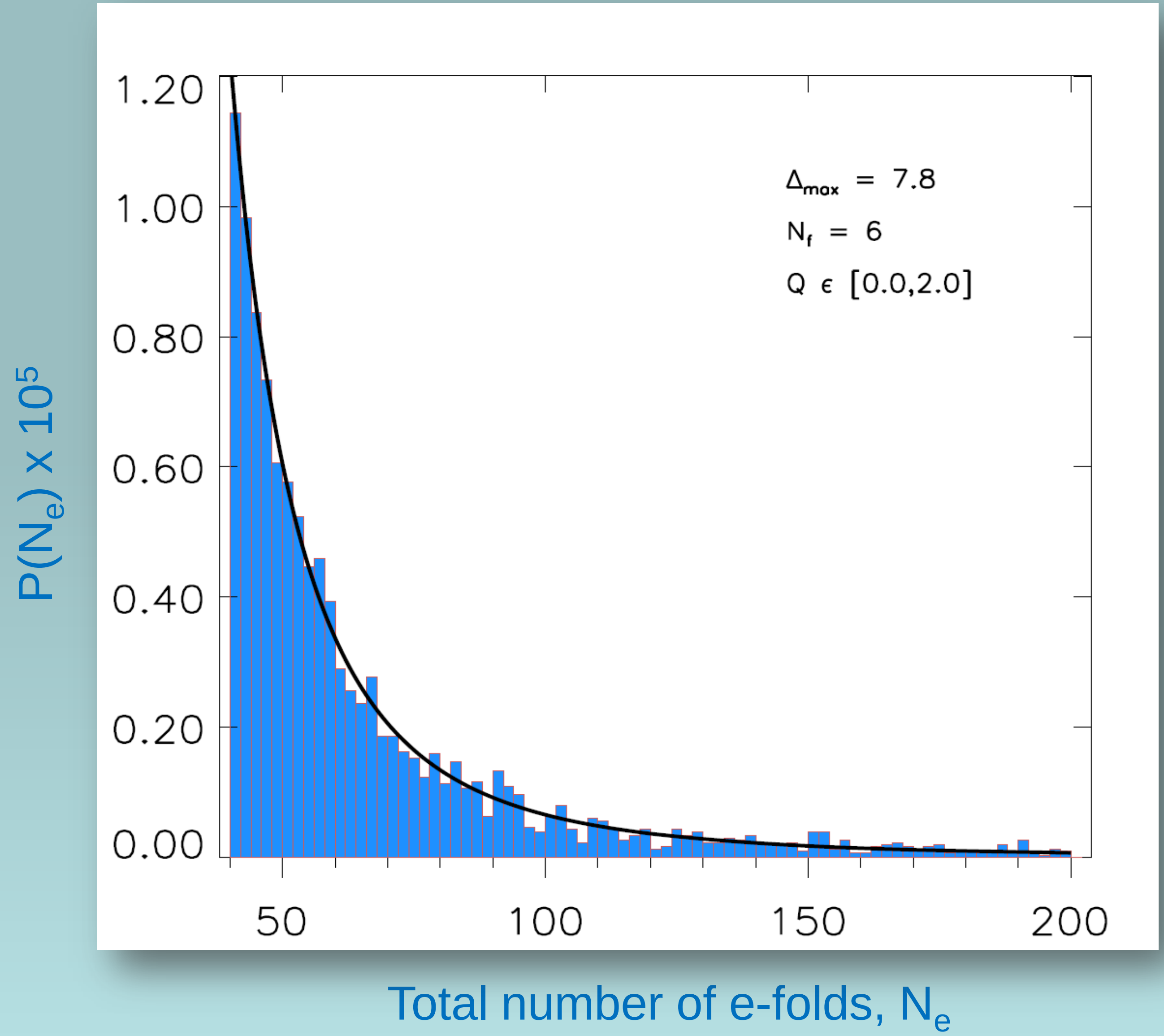
Attractor behavior





Overshooting the inflection point is rather rare; one can start far above it, contrary to expectations.

Success rate vs. number of e-folds



How likely is inflation?

- The probability of N e-folds is proportional to N^{-3}.
- We find 60+ e-folds of inflation approximately once in 10^3 trials.
- We find models consistent with all data approximately once in 10^5 trials.
- Caution: volume weighting? measure on phase space?

$$V(\phi) = c_0 + c_1\phi + c_3\phi^3 + \ldots$$

$$N_e \approx \frac{c_0}{\sqrt{c_1 c_3}}$$

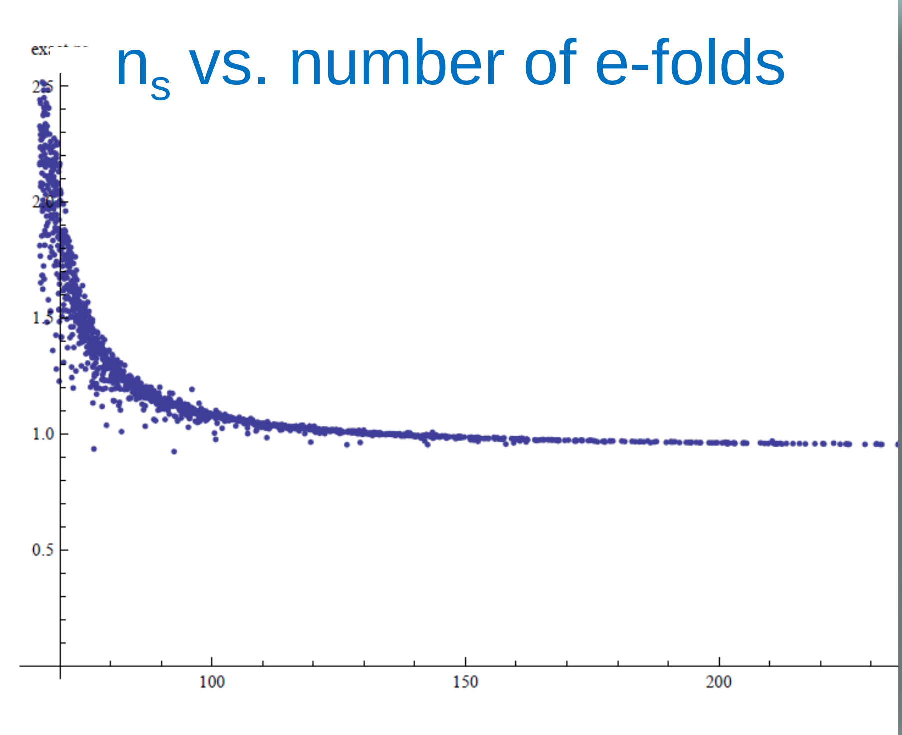
$$P(N_e) \approx -\frac{4c_0^2}{N_e^3}\log(c_0)$$

Agarwal, Bean, L.M., Xu 11

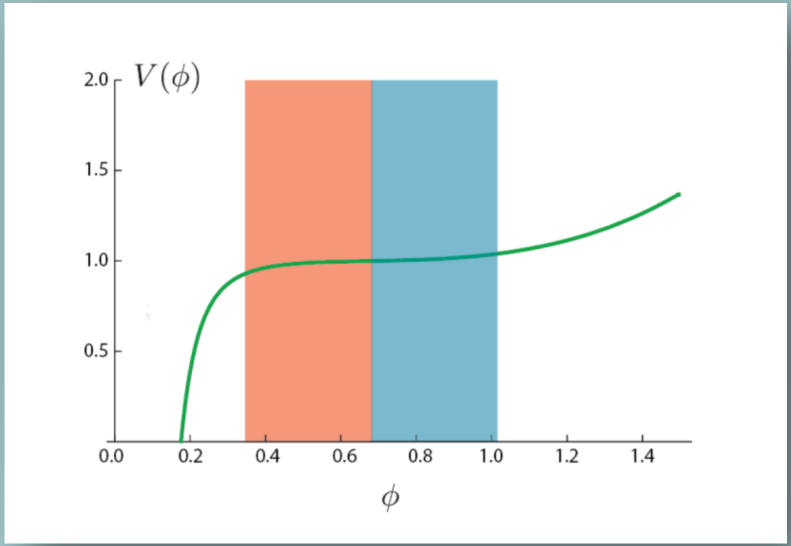
Freivogel, Kleban, Rodriguez Martinez, Susskind 05

Inflection point inflation

$$V(\phi) = c_0 + c_1\phi + c_3\phi^3 + \ldots$$

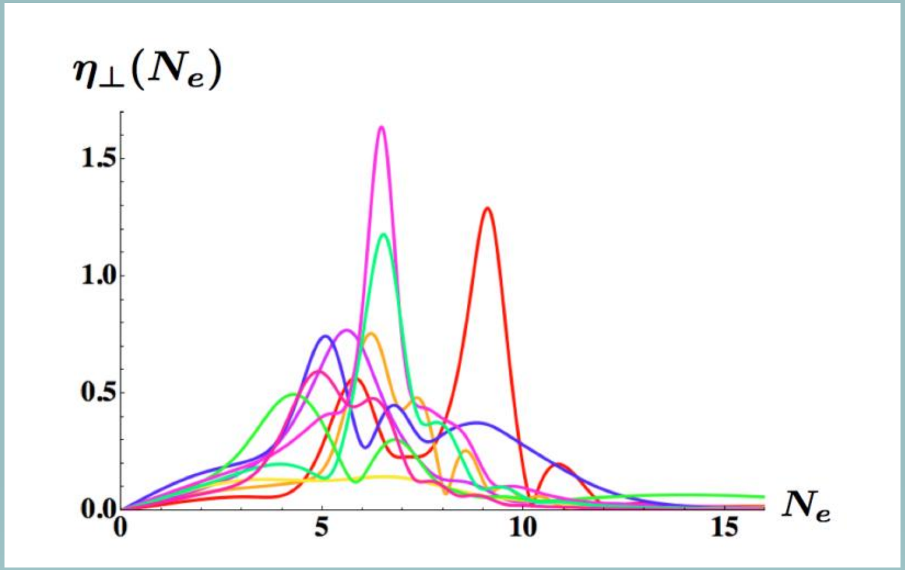


n_s vs. number of e-folds



Krause and Pajer 07
Baumann, Dymarsky, Klebanov, L.M. 07
Linde and Westphal 07

Bending trajectories

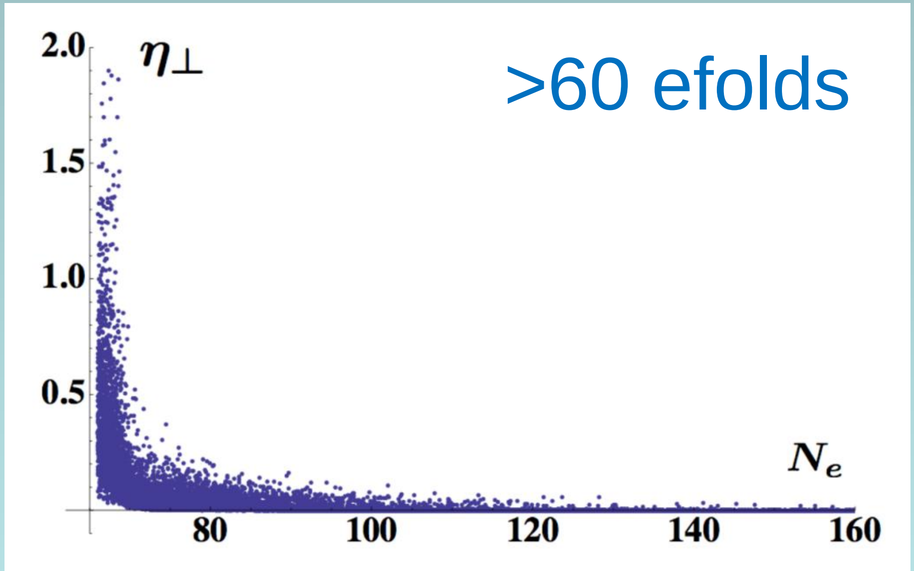


Bending drives conversion of entropy perturbations to curvature perturbations.

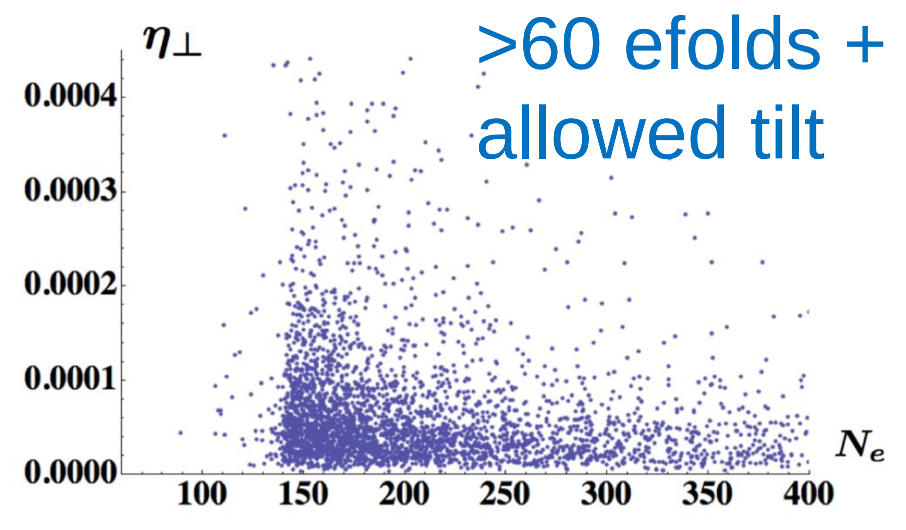
Gordon, Wands, Bassett and Maartens, 01

Conversion controlled by $\eta_\perp$

Groot Nibbelink and van Tent, 01



>60 efolds



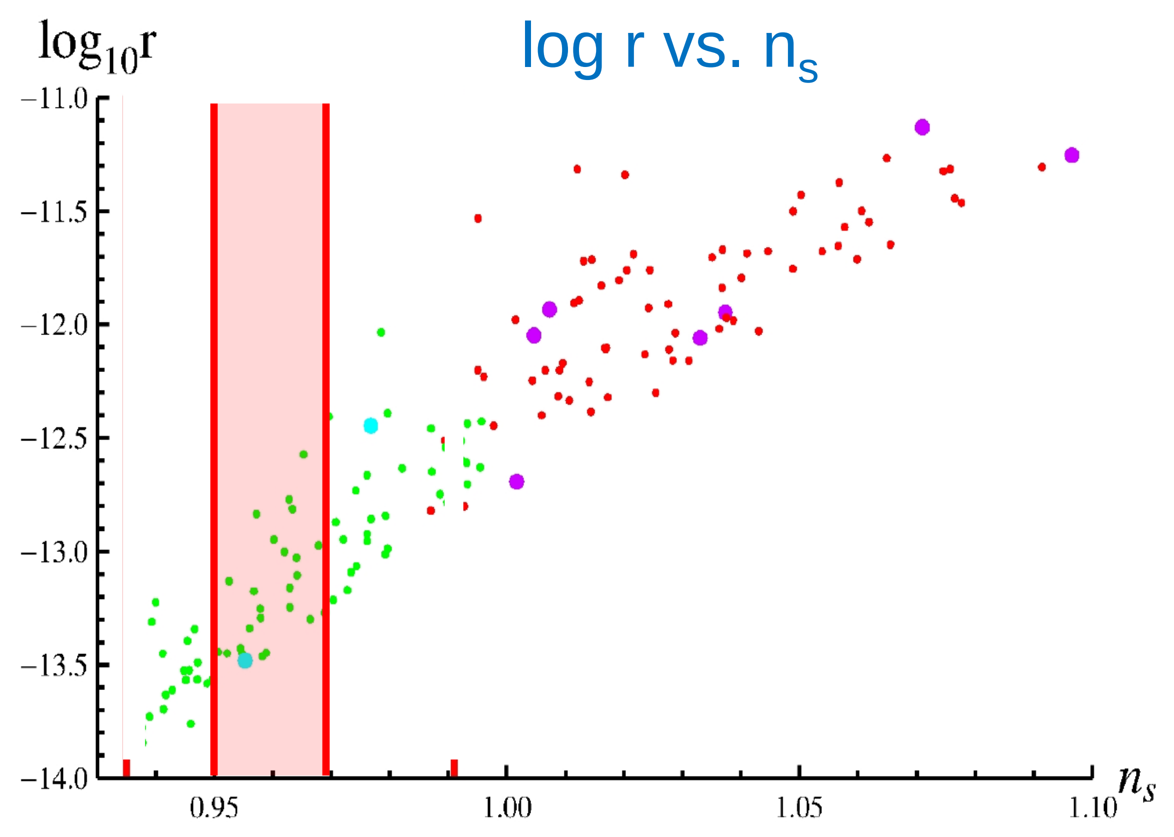
>60 efolds + allowed tilt

Low tensors in inflection point inflation

$$V(r,\Psi) = \sum_i c_i r^{\Delta_i} h_i(\Psi)$$

Agarwal, Bean, L.M., Xu 11
Renaux-Petel, L.M., Xu 12

$$r \lesssim 10^{-12}$$



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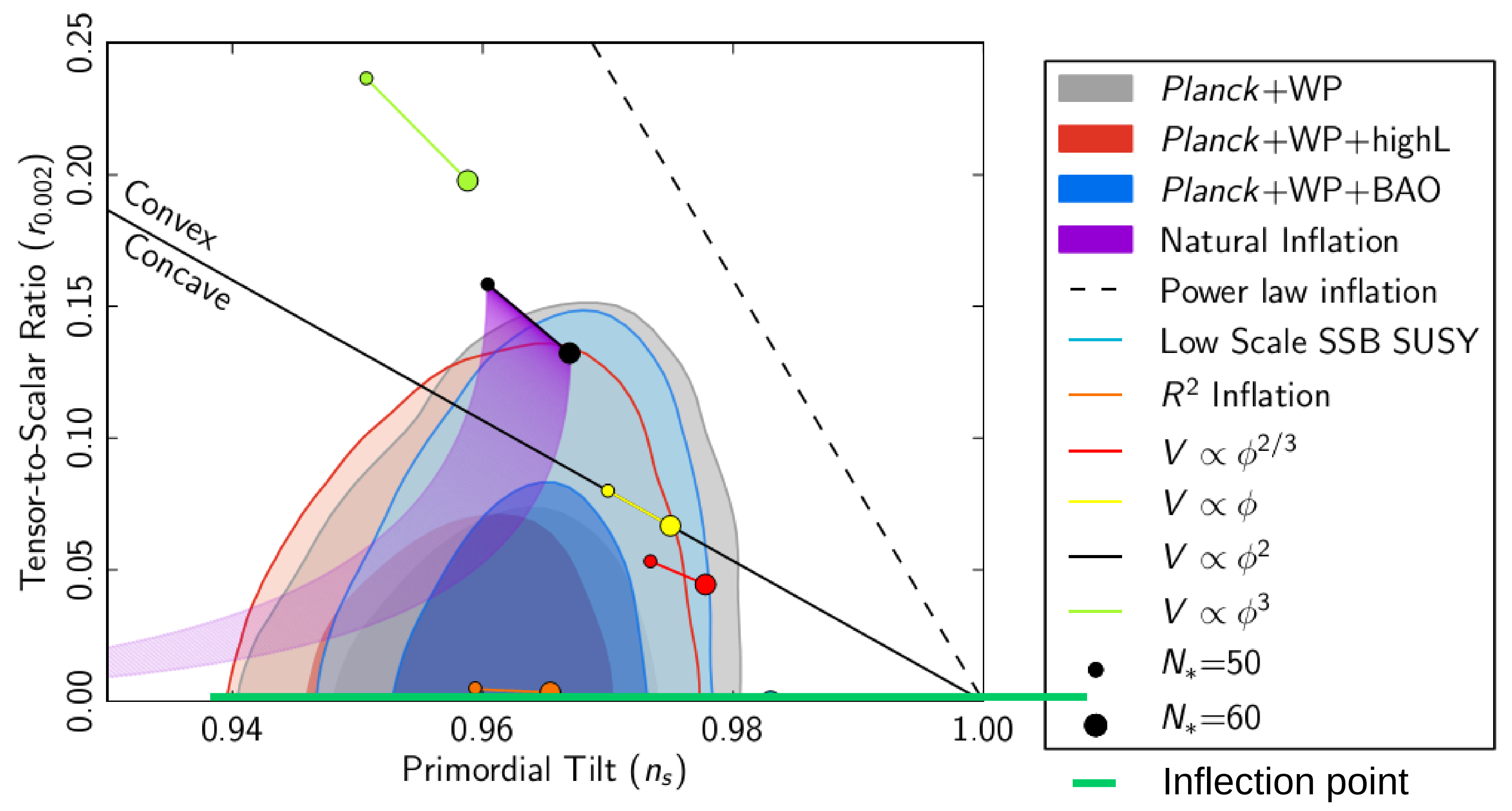


Summary for D3-brane inflation

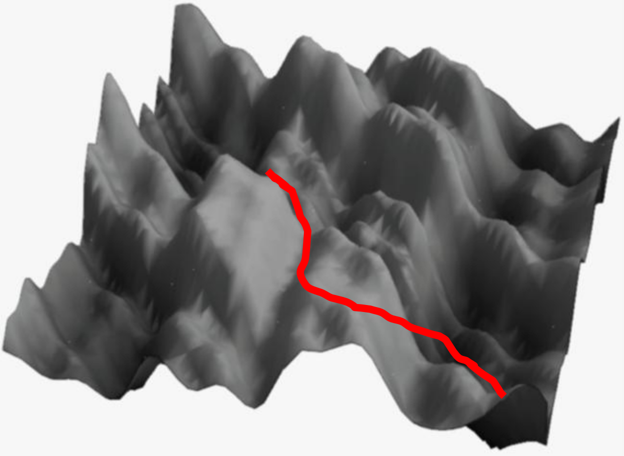
- Inflation occurs occurs by chance at an inflection point.
- No overshoot problem; attractor behavior.
- Primordial tensors are negligible: $r \lesssim 10^{-12}$
- The probability of N_e e-folds is a power law, N_e^{-3} .
- One trial in 10^5 consistent with WMAP (Planck tbd)
- Coulomb + moduli potential not steep enough, in this setting, to drive a DBI phase.

Silverstein, Tong 03;
Alishahiha, Silverstein, Tong 04
Bean, Chen, Peiris, Xu 07;
Bean, Shandera, Tye, Xu 07

- Significant multifield (and even many-field) effects present in 10% of trials solving the horizon problem. However, constraints from *spectrum* require N_e>120, and multifield effects are absent in most such cases.

Many-field inflation

- Success here motivates extension to more general, higher-dimensional systems. What is the dynamics in a random landscape with N fields?



cost: e^N

Marsh, L.M., Pajer, Wrase to appear

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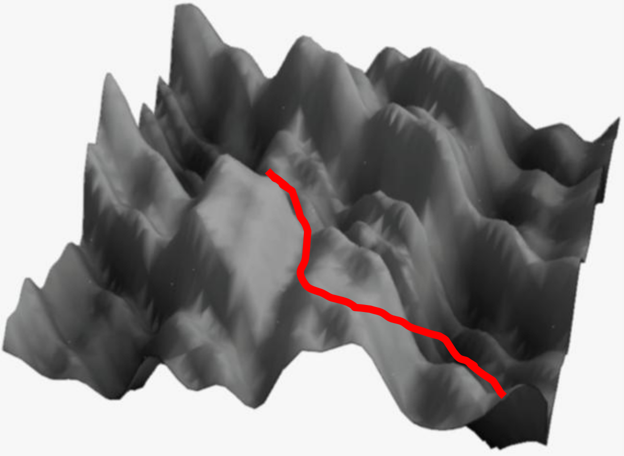

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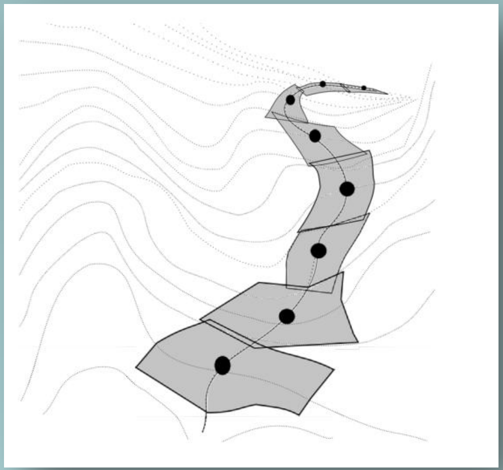
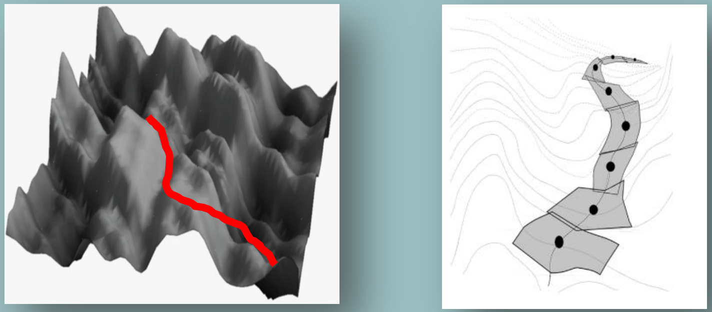


cost: N^2

Marsh, L.M., Pajer, Wrase to appear

Random matrix theory for many-field inflation

- Need a rule describing change from patch to patch.
- Powerful tool:
  random matrix theory



- Determine V, V’ by specifying statistics of Hessian. For large N, Hessian is an element of a random matrix ensemble. Universality+analytic control.
- Natural evolution of eigenvalues: Dyson Brownian motion.

Marsh, L.M., Pajer, Wrase to appear

Aazami and Easther 05
Easther and L.M. 05
Marsh, L.M., Wrase 11

Symmetry example: Axion monodromy inflation

L.M., Silverstein, Westphal 08

cf. Silverstein and Westphal 08
Berg, Pajer, Sjors 09
Kaloper, Lawrence, Sorbo 11

Symmetries and large field inflation

Large-field inflation is interesting and important, because it is particularly sensitive to ultraviolet physics, and because it makes testable predictions.

Task: identify a robust symmetry in string theory that protects the inflaton over a super-Planckian range.

Axion monodromy

String theory contains many axions enjoying all-orders shift symmetries.

Nonperturbative effects break the continuous shift symmetry, generating a periodic potential:

$$V = \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

A fivebrane wrapping a curve introduces small explicit breaking. As axion shifts by a period, potential undergoes a monodromy that unwraps the axion circle.

$$V(\phi) = \mu^3 \phi + \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

Result: asymptotically linear potential with large field range.

Prediction: r=0.07

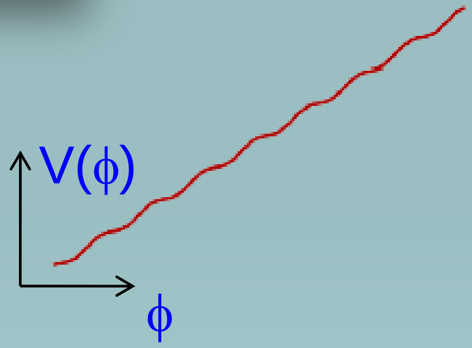
L.M., Silverstein, Westphal 08

Modulated power spectrum

$$V(\phi) = \mu^3 \phi + \Lambda^4 \cos\left(\frac{\phi}{f}\right)$$

The modulations produce a driving force that resonates with the oscillations of modes inside the horizon.

Chen, Easther, Lim 06, 08



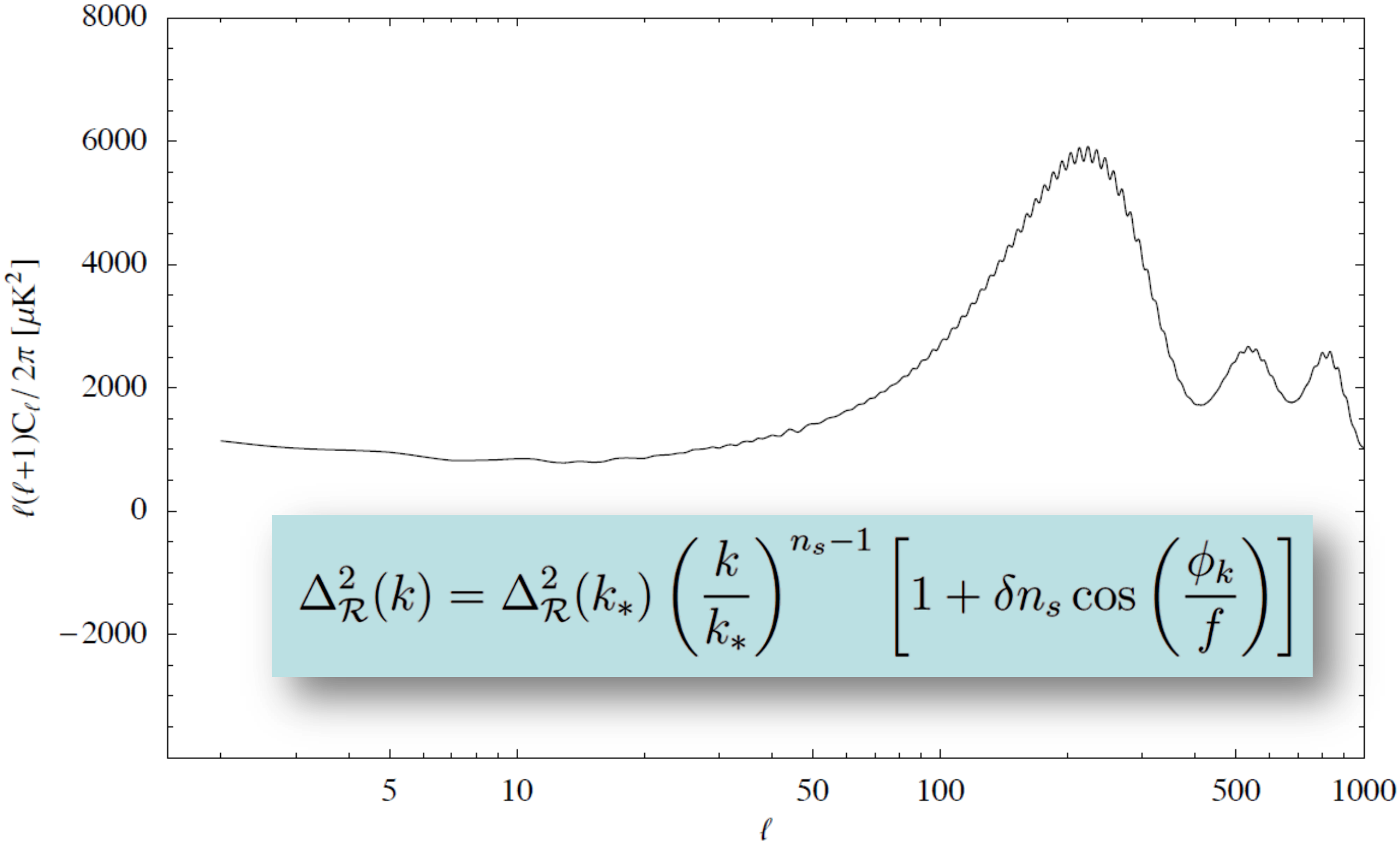
Result: resonant perturbations of the spectrum and bispectrum.

This is a single-field, canonical kinetic term, slow roll model that can have a detectable (resonant) bispectrum. **Flauger and Pajer 10**

This signature comes from confronting constraints of UV completion.

Flauger, L.M., Pajer, Westphal, Xu 09

Modulated power spectrum



$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_*)\left(\frac{k}{k_*}\right)^{n_s-1}\left[1+\delta n_s \cos\left(\frac{\phi_k}{f}\right)\right]$$

Chen, Easther, Lim 06, 08
Flauger, L.M., Pajer, Westphal, Xu 09
Peiris, Easther, Flauger 13

A Window on Hidden Sectors

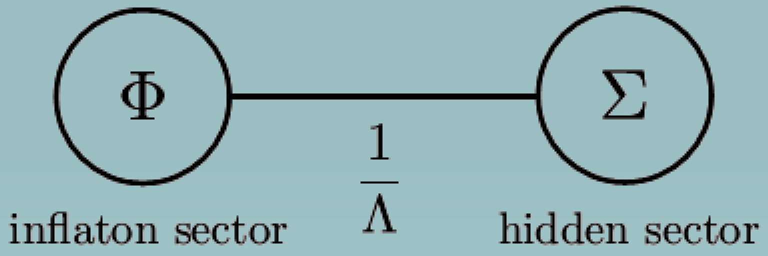
- String theory strongly motivates considering scenarios with many light (m~H) fields.
- If there were light fields in a hidden sector, could we tell?

Green, Lewandowski, Silverstein, Senatore, Zaldarriaga 13

Assassi, Baumann, Green, L.M. 13

A Window on Hidden Sectors

- Consider a shift-symmetric inflaton coupled to a hidden sector field by nonrenormalizable interactions.



- Leading mixing: $\mathcal{L}_{\text{mix}} = -\frac{1}{2}\frac{(\partial\Phi)^2\Sigma}{\Lambda}\ .$

- Hidden-sector self-interactions, e.g. $\mathcal{L}_{\Sigma} \supset -\mu\Sigma^3$ lead to NG in the curvature perturbations.

Assassi, Baumann, Green, L.M. 13

Planck-suppressed operators

- Generic case for moduli: $$m \sim H$$ $$\mu \sim H$$

- Planck limits give $\Lambda > 10^5 H$ for $\mu \sim H$.
- In terms of the Planck scale,

$$\Lambda \gtrsim 0.5 \left(\frac{|\mu|}{H}\right)^{1/3} \left(\frac{r}{0.01}\right)^{1/2} M_{\rm pl} \ .$$

- In fact even a Gaussian hidden sector sources NG, leading to the universal bound $\Lambda > 10^2 H$.

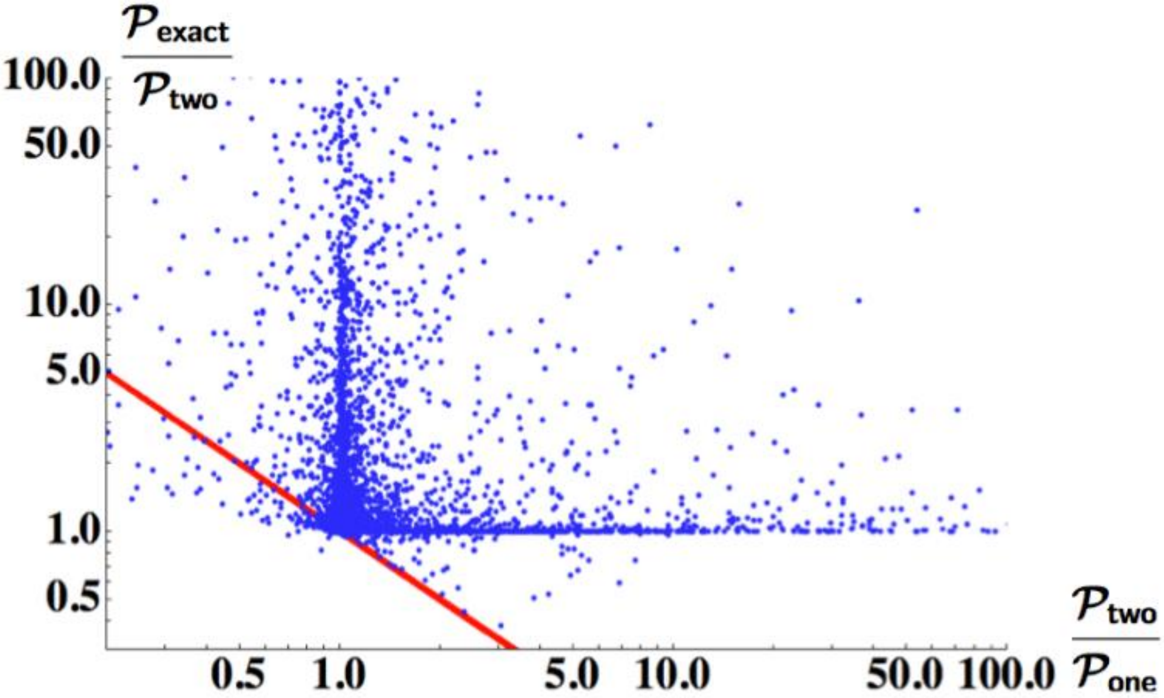
Assassi, Baumann, Green, L.M. 13

Conclusions

- Models of the early universe are sensitive to Planck-scale physics.
- String theory realizations of inflation have suggested novel mechanisms and signatures. A few scenarios are now realistic enough to be falsifiable.
- These connections have the potential to turn observational cosmology into a window on string theory.
- Much work remains before we can understand what sort of cosmological dynamics is generic in string theory.

Backup

Two-field and many-field effects



- Multifield effects make O(1) corrections to the spectrum in 10% of cases, while many-field effects are O(1) in 6% of cases.
- But constraint from n_s excludes >97% of cases with multifield dynamics.

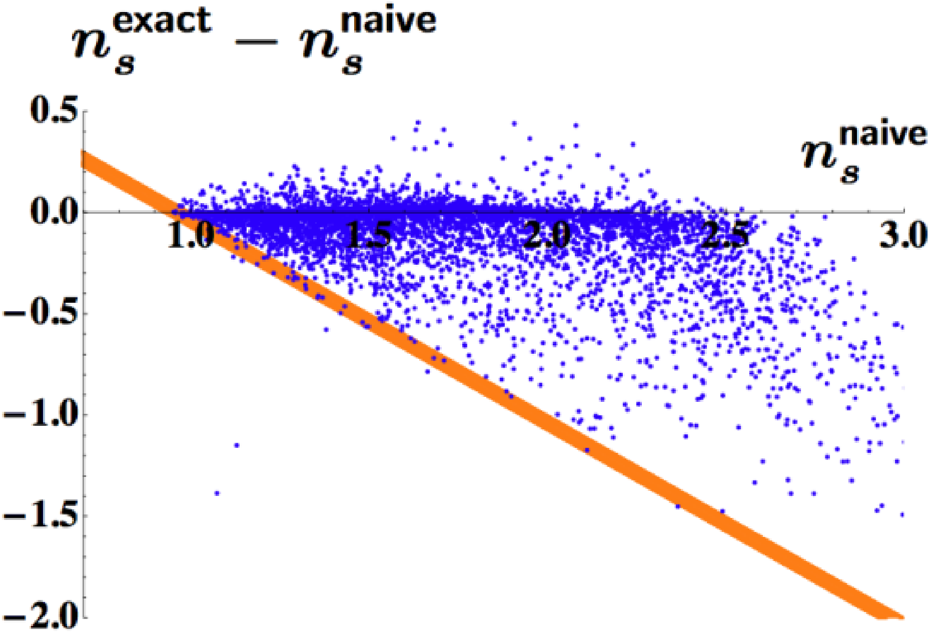


Figure 15: The difference δn_s between the exact and naive results for the tilt n_s, versus the naive tilt, for effectively multifield realizations (see §2.3.4). Notice that multifield contributions typically shift the spectrum toward scale invariance, and the more blue the naive spectrum, the larger the scatter of δn_s. The orange band corresponds to the window allowed at 2σ by WMAP7.