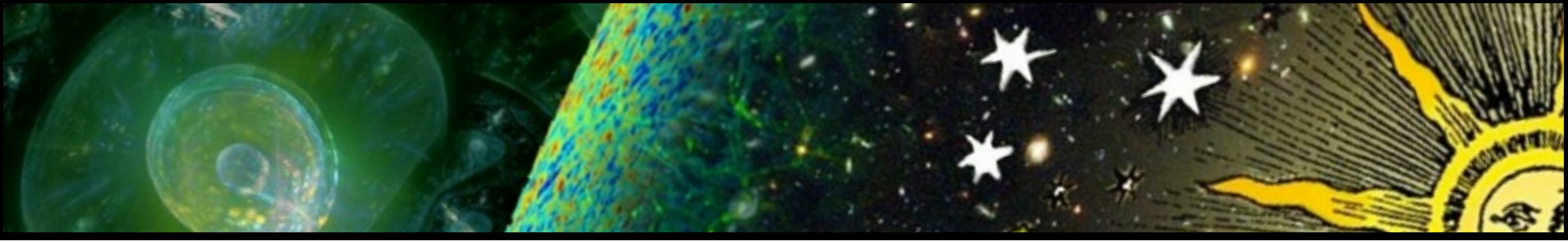


Testing inflation with combined power- and bispectrum

Hiranya V. Peiris (UCL)

on behalf of the Planck Collaboration

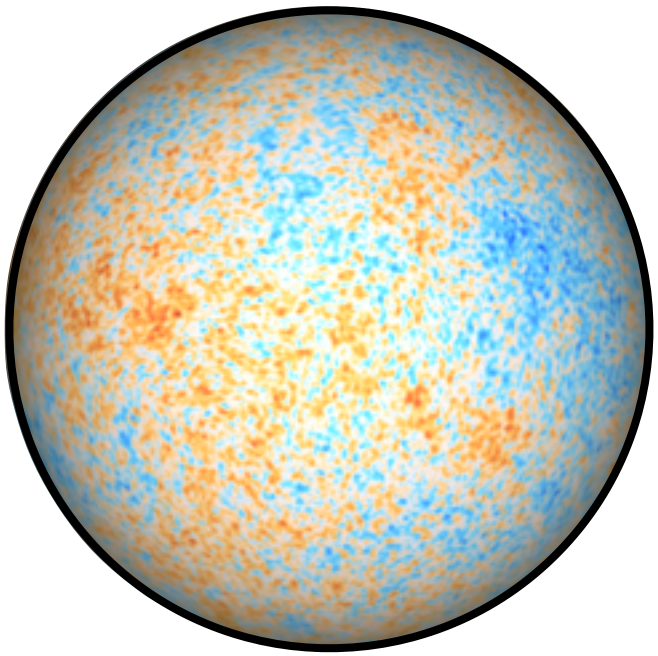
Planck 2013 Results XXII: Constraints on Inflation

Planck 2013 Results XXIV. Constraints on primordial non-Gaussianity

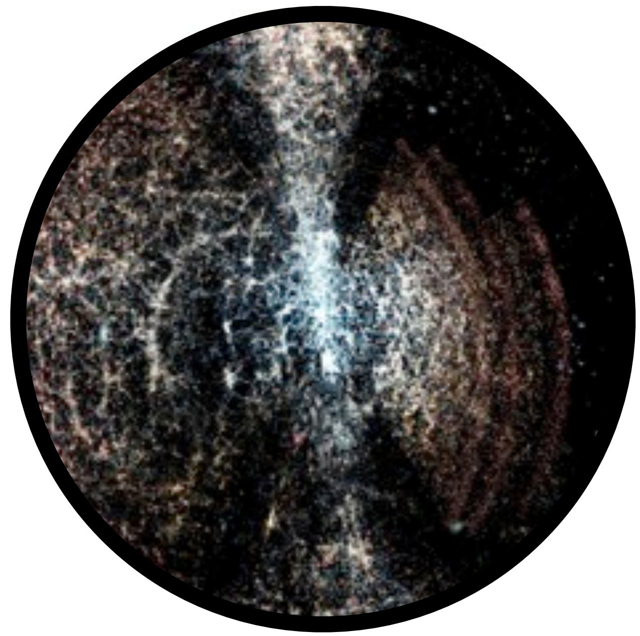
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

What is the physical origin of all the structure in the Universe?



Cosmic Microwave Background
image: Planck

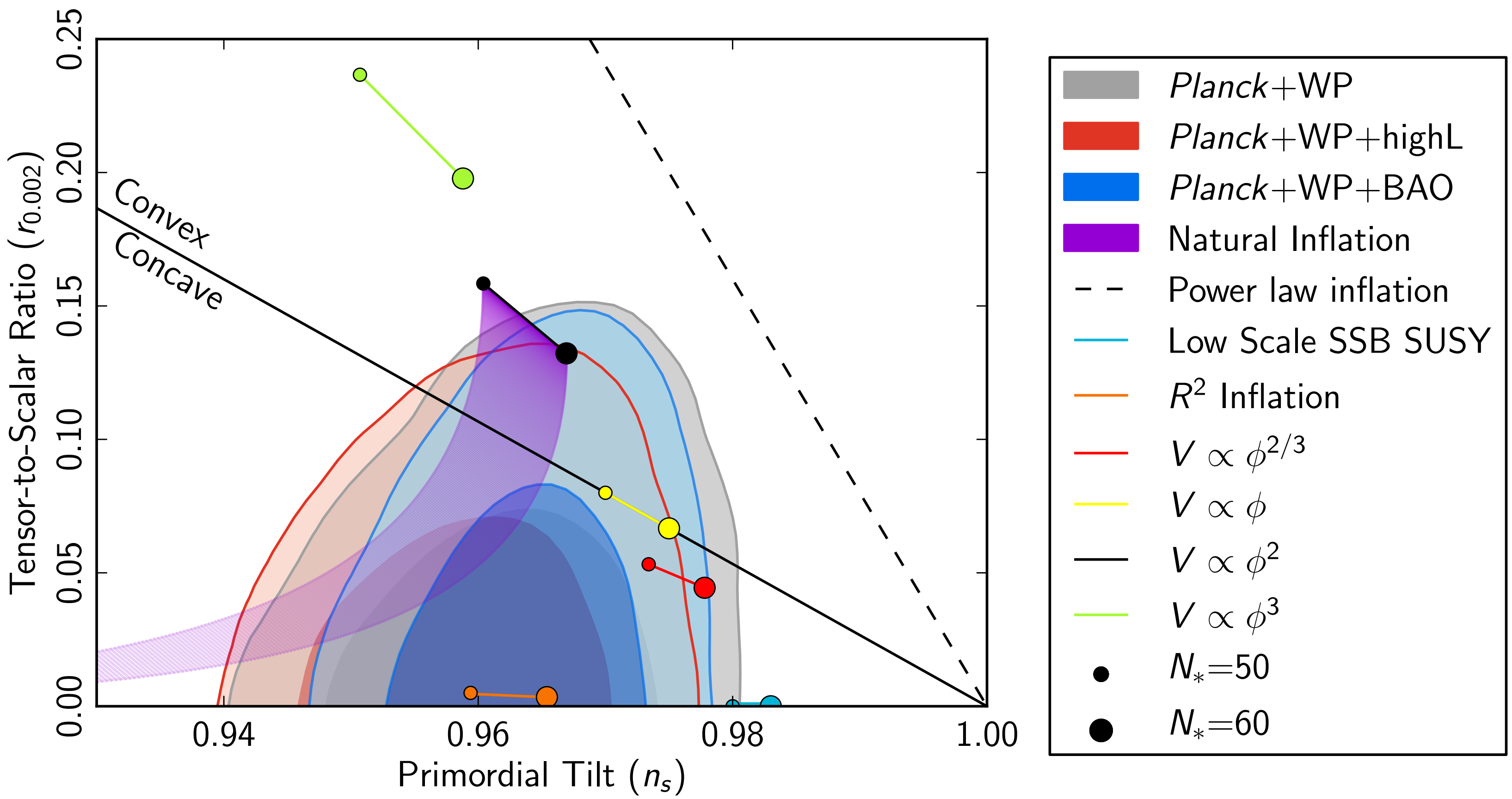


Large Scale Structure
image: SDSS

The simplest inflationary models have passed their most stringent test yet!

Inflationary models in a post-Planck world

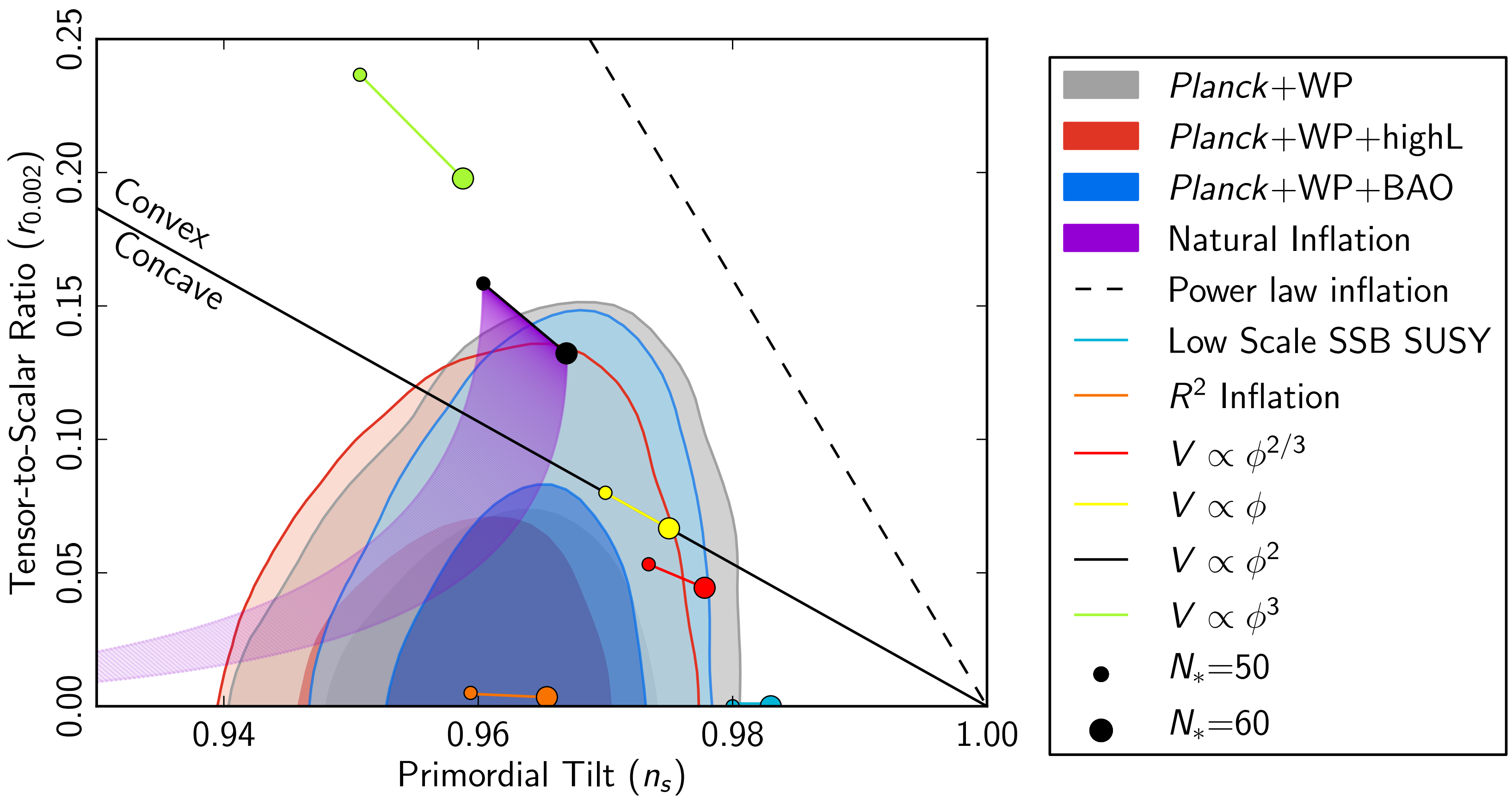
- Exact scale invariance (n_s=1) ruled out at >5σ by a single experiment
- While convex potentials are still allowed, Planck hints that flattened potentials are preferred



Planck+WP: $n_s = 0.9603 \pm 0.0073 \quad r_{0.002} < 0.12$ (95% CL)

Inflationary models in a post-Planck world

- Planck does not exclude or suggest many active fields during inflation
- However, single-field models are arguably "simplest" allowed by data



Planck+WP: $n_s = 0.9603 \pm 0.0073 \quad r_{0.002} < 0.12$ (95% CL)

Inflationary models in a post-Planck world

- Bispectrum now a routine observable, like the spectral index
- Standard bispectrum configurations not detected by Planck; stringent constraints on local/equilateral/orthogonal etc shapes

Shape	ISW-lensing subtracted KSW
Local	2.7 ± 5.8
Equilateral	-42 ± 75
Orthogonal	-25 ± 39

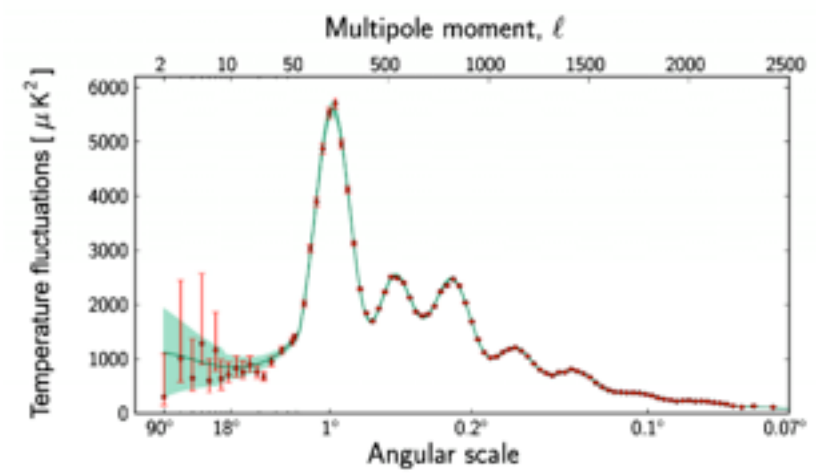
DBI	11 ± 69
EFT1	8 ± 73
EFT2	19 ± 57
Ghost	-23 ± 88

Inflationary models in a post-Planck world

- No NG detection: stalls progress via "bottom up" approach (e.g. reconstruction via measuring EFT observables...).

- "Top down" approach (model-building first) looks more promising.

- Non-generic correlations between 2pt+3pt+... observables provide powerful constraints on such models



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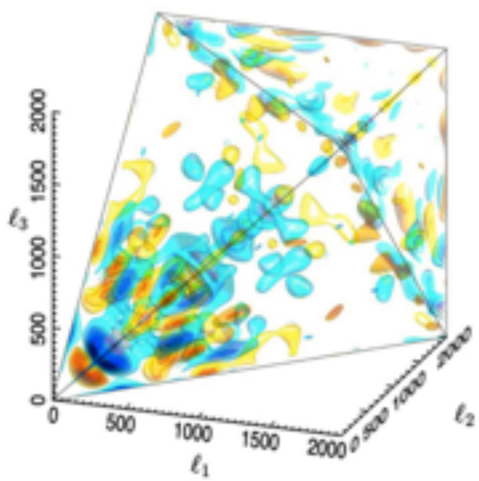
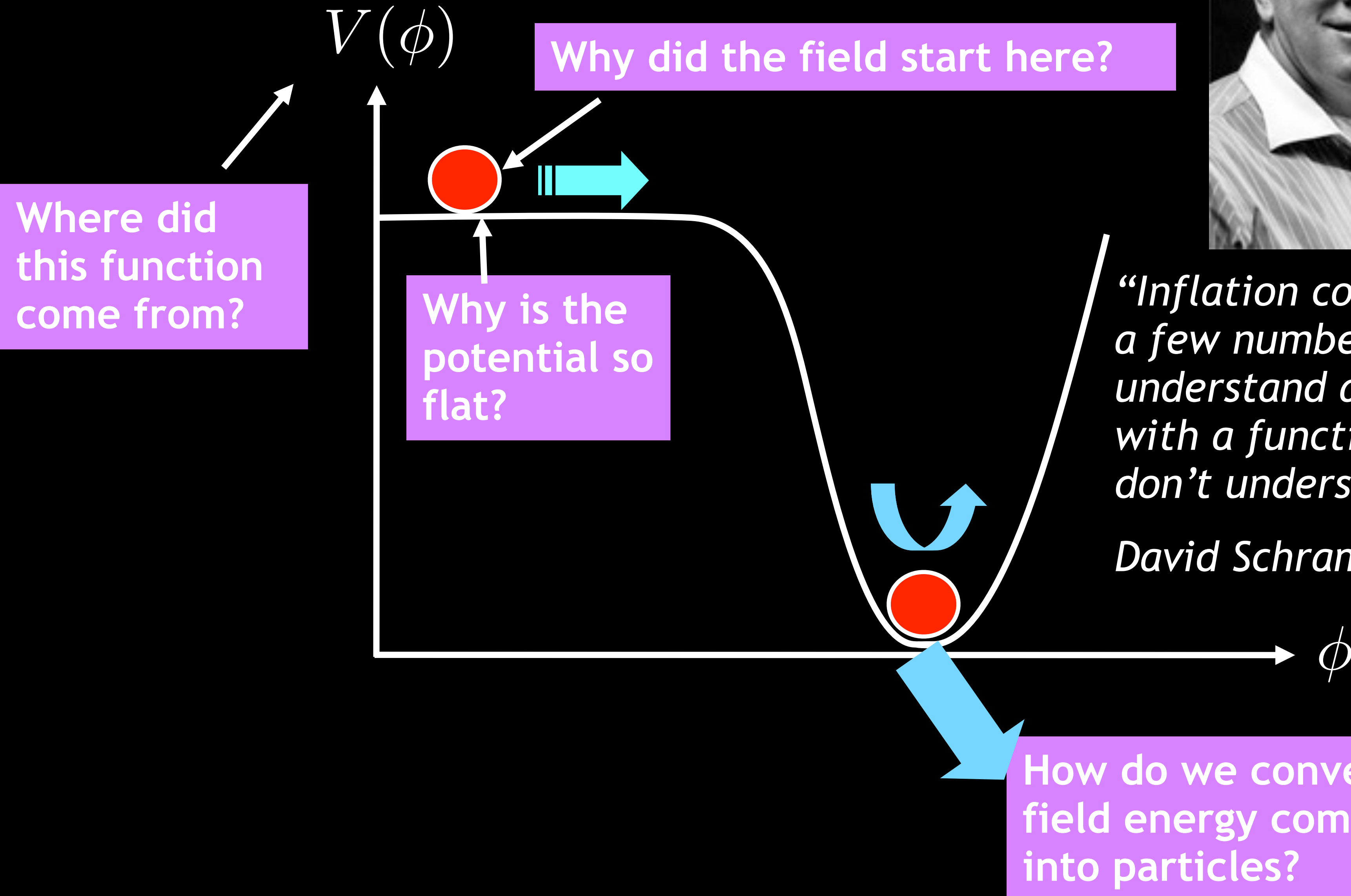


Outline

- Testing inflation with the Planck power spectrum and bispectrum

- A case study of the "top down" approach with multiple non-generic observables: constraining monodromy inflation

What is the physics of inflation?



"Inflation consists of taking a few numbers that we don't understand and replacing it with a function that we don't understand"

David Schramm 1945 -1997

Testing a subset of the inflationary zoo: priors

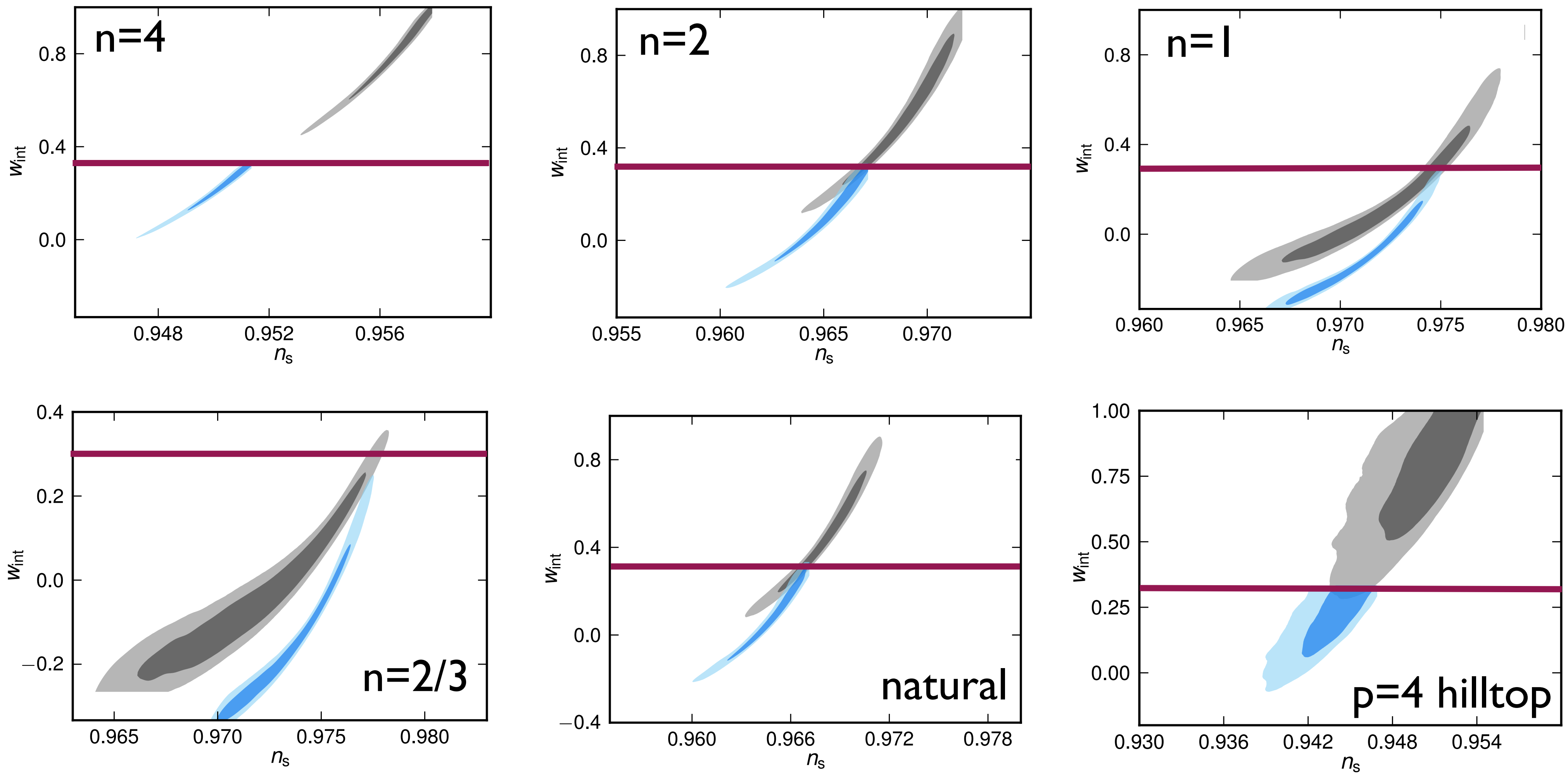
- Potential parameters are mass scales in particle physics; leads to logarithmic priors

- Evaluate models on equal footing by requiring amplitude of primordial fluctuations within 2 orders of mag of observations.

- **Reheating**: uniform prior on number of e-folds; accept models that achieve thermalisation by a given energy scale, plus effective post-inflationary equation of state within specified range.

$$N_* \approx 71.21 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_{\rm hor}}{M_{\rm pl}^4}\right) + \frac{1}{4}\ln\left(\frac{V_{\rm hor}}{\rho_{\rm end}}\right) + \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\ln\left(\frac{\rho_{\rm rh}}{\rho_{\rm end}}\right)$$

Constraints on post-inflationary epoch



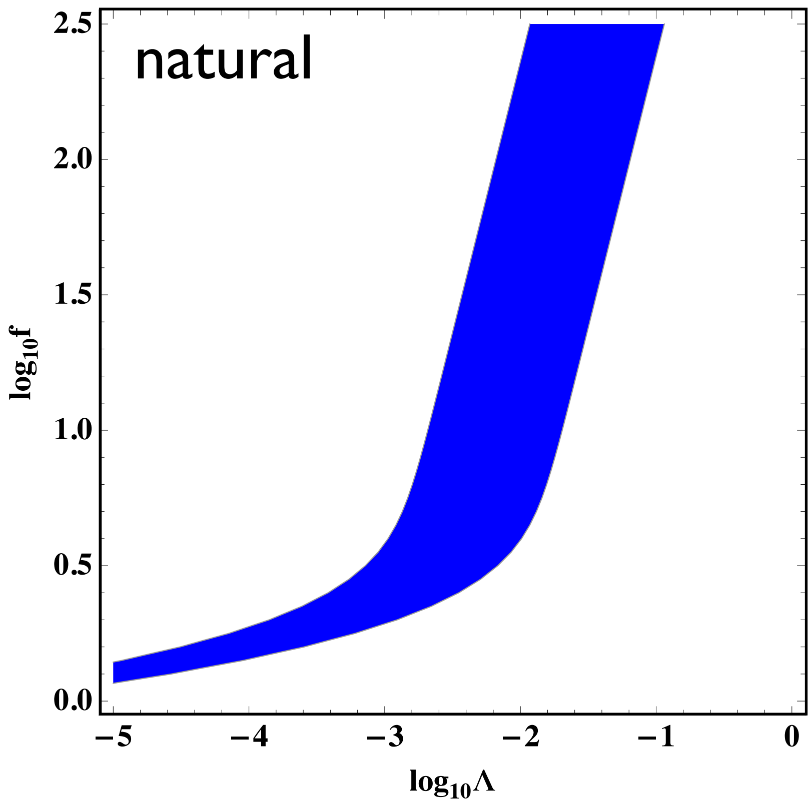
restrictive entropy generation

$$\rho_{\rm th}^{1/4} = 10^9 \text{ GeV} \quad w_{\rm int} \in [-1/3, 1/3]$$

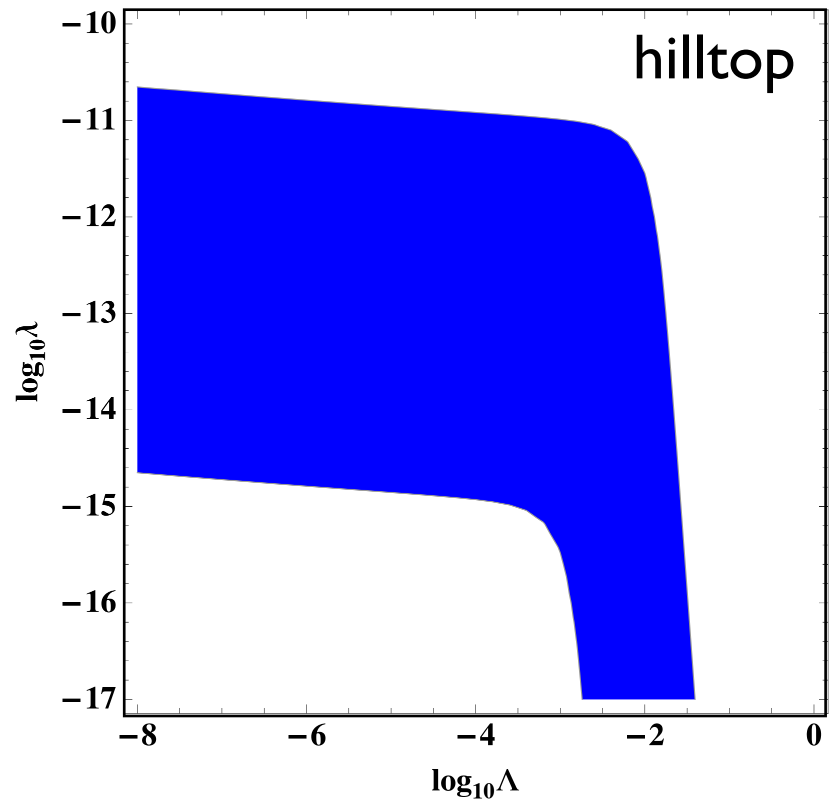
permissive entropy generation

$$\rho_{\rm th}^{1/4} = 10^3 \text{ GeV} \quad w_{\rm int} \in [-1/3, 1]$$

Constraints on specific models: examples I



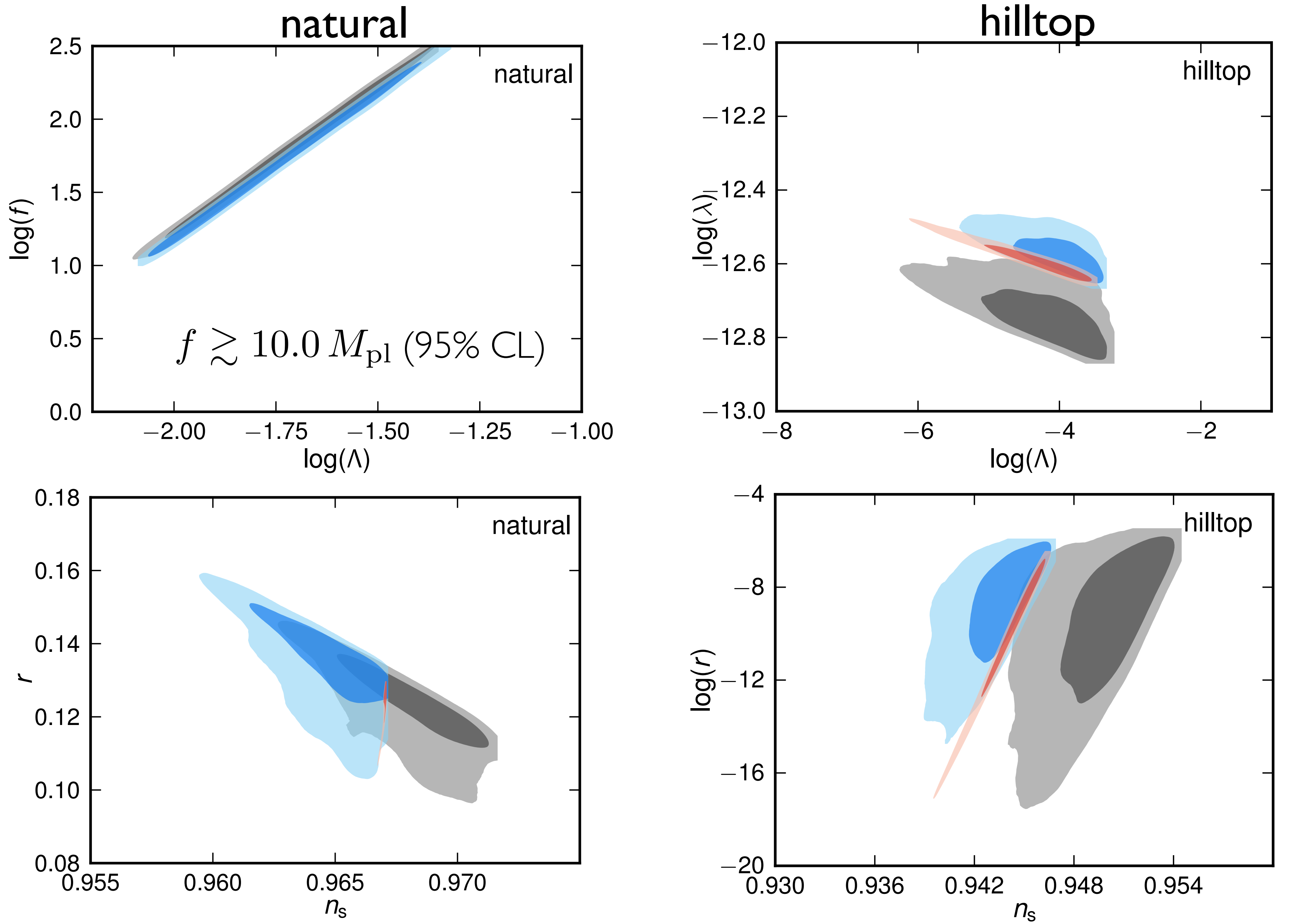
$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$



$$V(\phi) = \Lambda^4 - \frac{\lambda}{4}\phi^4$$

natural units in reduced Planck mass

Constraints on specific models: examples II



instant / restrictive / permissive entropy generation

Reminder:
parameter estimation vs model comparison

posterior: probability of the model given the data

probability of the data given the model

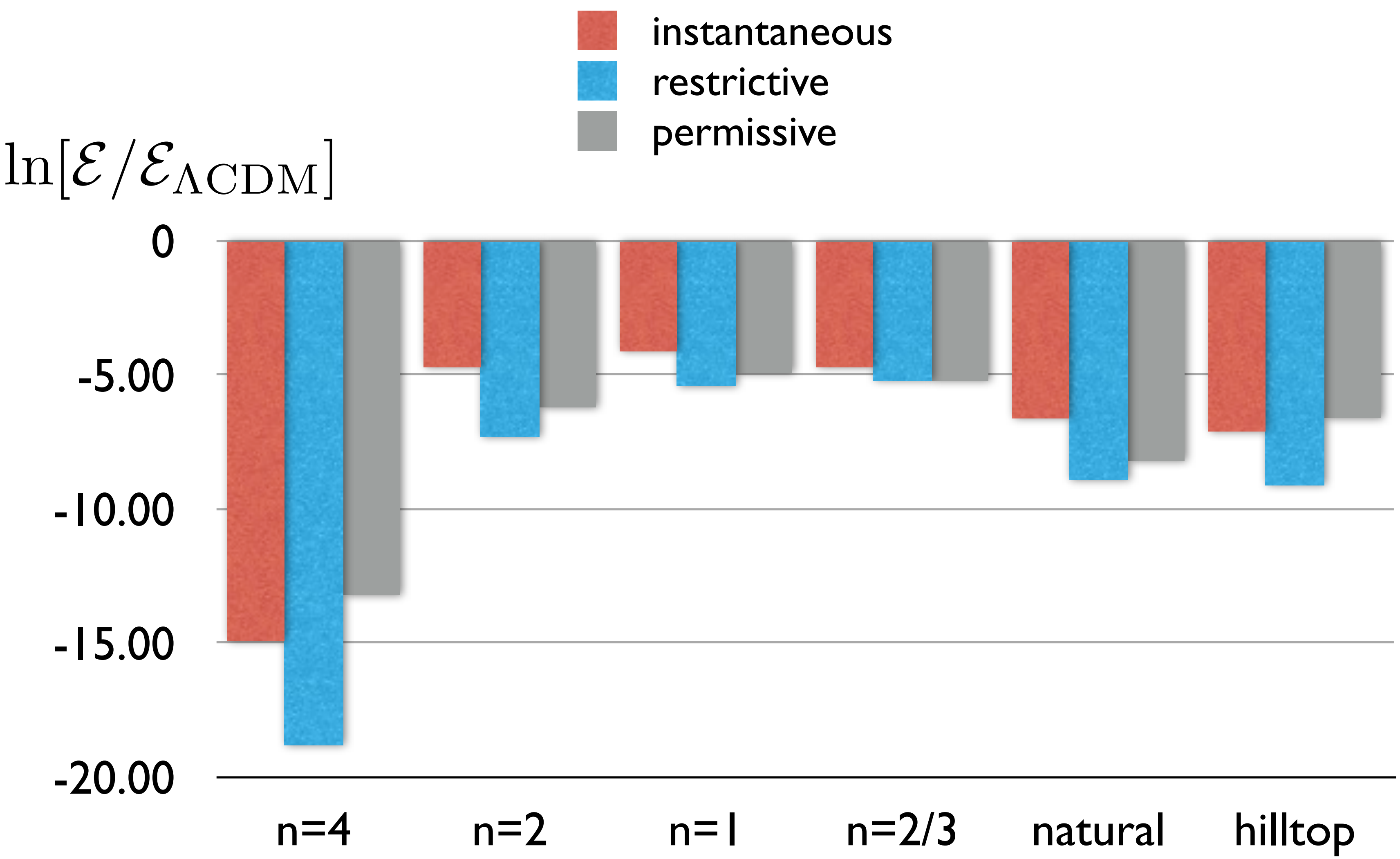
prior probability

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{\int P(D|\theta)P(\theta)d\theta}$$

Evidence: normalizing factor

Evidence: model-averaged likelihood

Model comparison



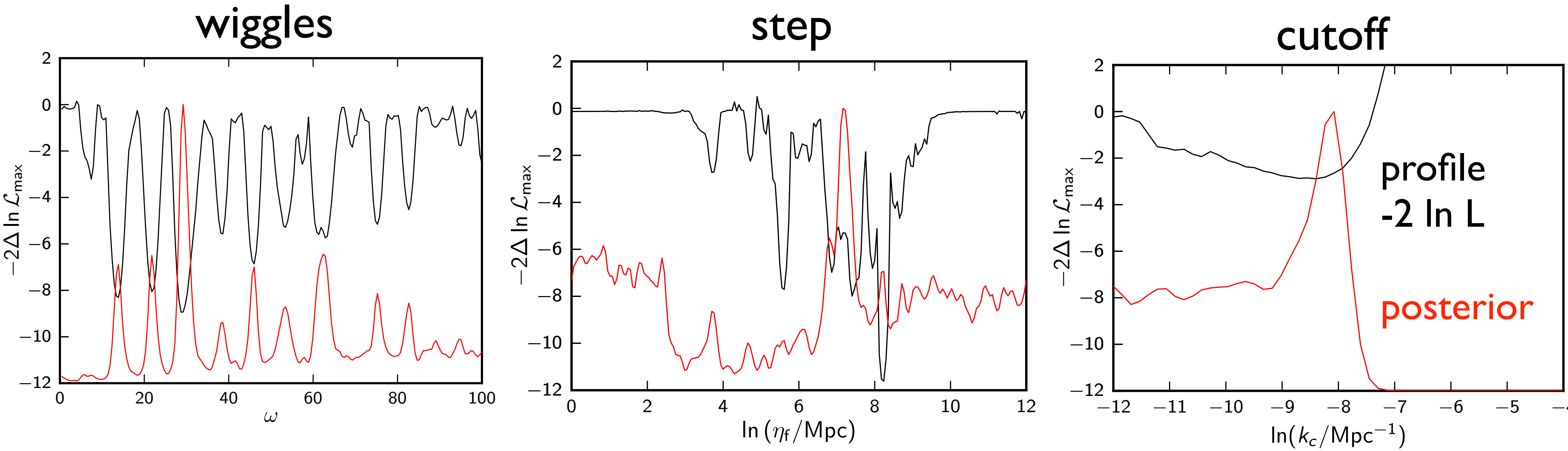
ln[evidence ratio] of ~5 (~150:1 odds)
considered decisive in this context

Parametric searches for features in the primordial spectrum

wiggles: $$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\ \left\{1 + \alpha_{\mathrm{w}}\ \sin\left[\omega \ln\left(\frac{k}{k_*}\right) + \varphi\right]\right\}$$

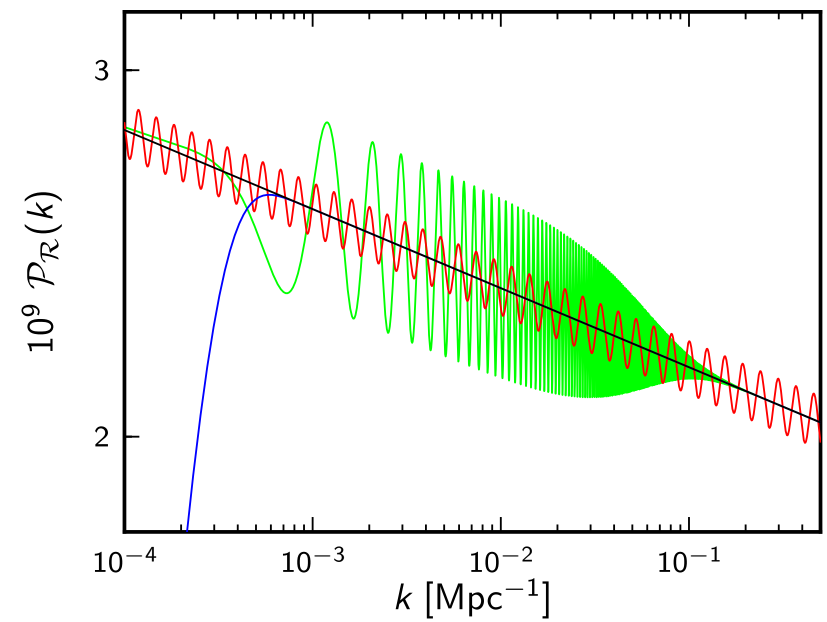
step: $$\mathcal{P}_{\mathcal{R}}(k) = \exp\left[\ln \mathcal{P}_0(k) + \frac{\mathcal{A}_{\mathrm{f}}}{3}\ \frac{k\eta_{\mathrm{f}}/x_d}{\sinh(k\eta_{\mathrm{f}}/x_{\mathrm{d}})} W'(k\eta_{\mathrm{f}})\right]$$

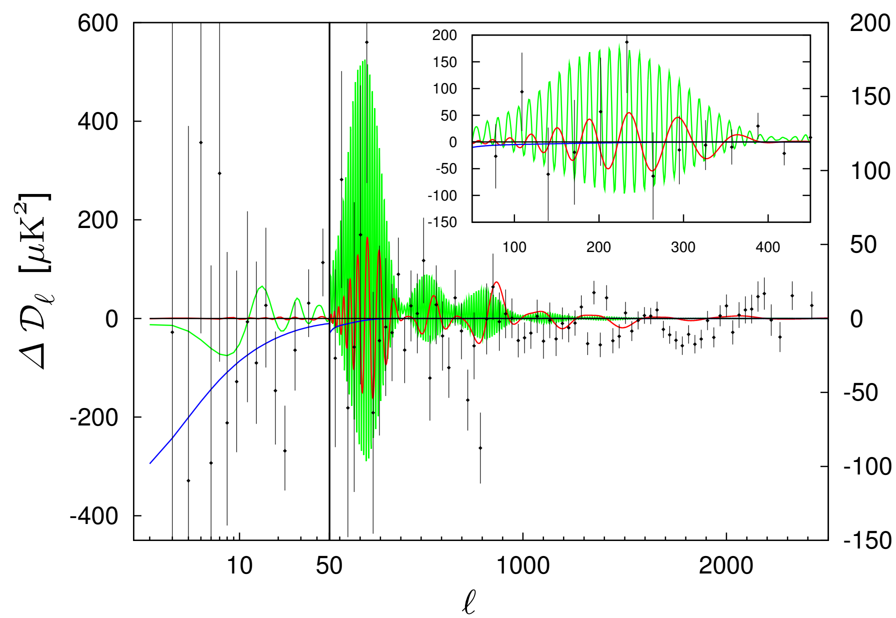
cutoff: $$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 - \exp\left[-\left(\frac{k}{k_{\mathrm{c}}}\right)^{\lambda_{\mathrm{c}}}\right]\right\}$$



Parametric searches for features in the primordial spectrum

Model	$-2\Delta \ln \mathcal{L}_{\max}$	$\ln B_{0X}$
Wiggles	-9.0	1.5
Step-inflation	-11.7	0.3
Cutoff	-2.9	0.3





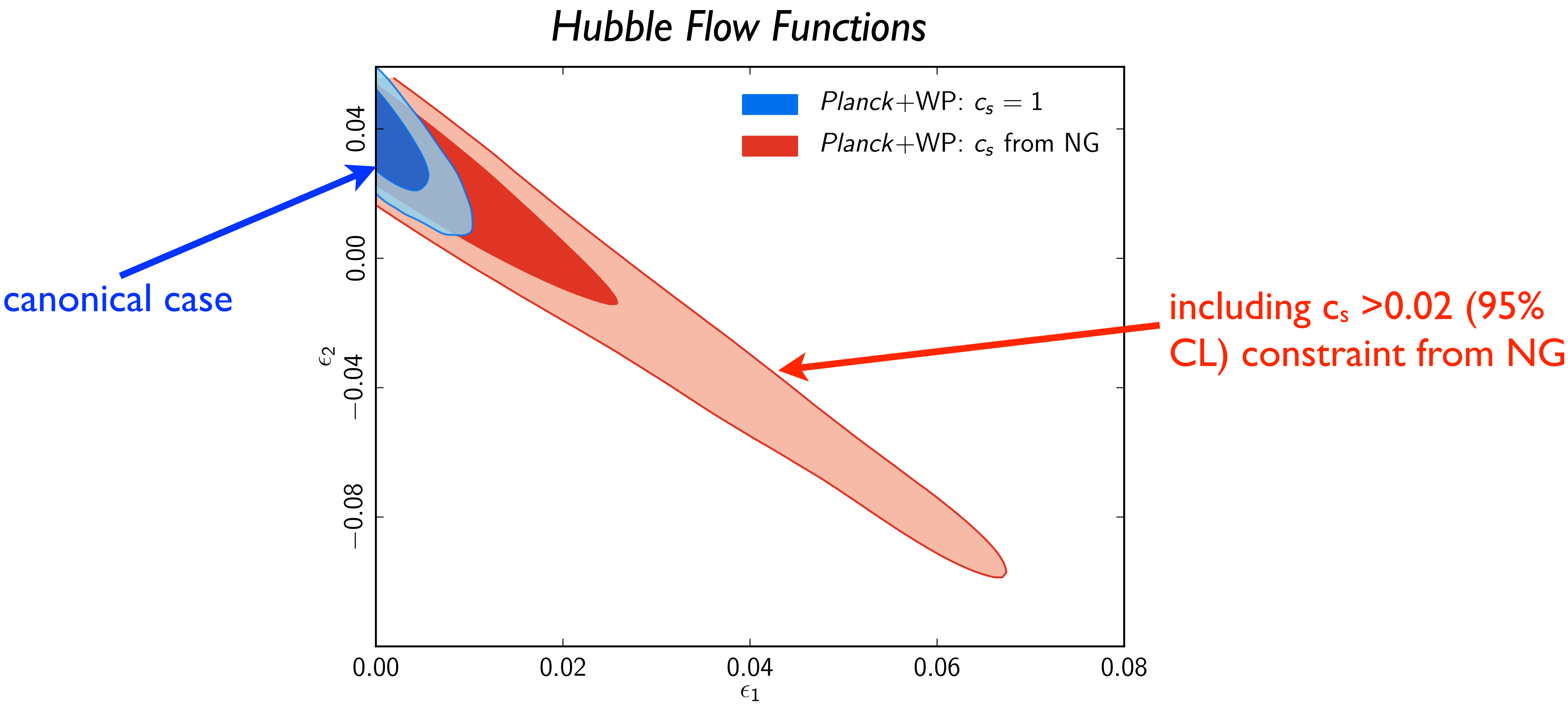
- higher frequencies?
- complementary signals in polarization and NG?

Joint constraints from 2-pt and 3-pt

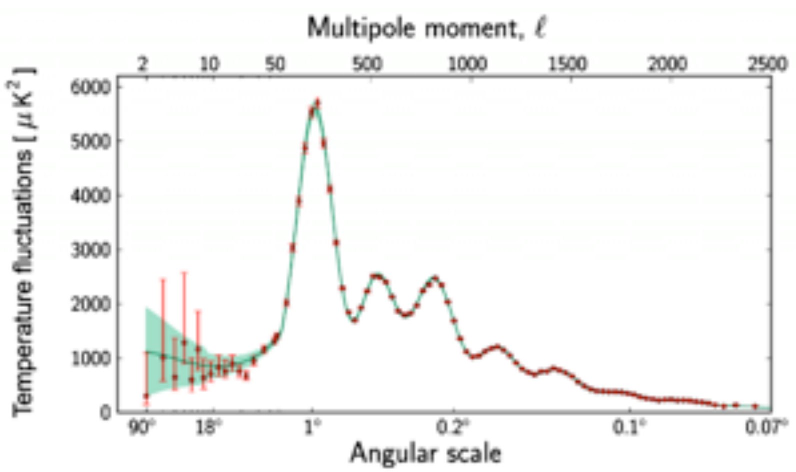
- Consider general class of inflationary models where Lagrangian is general function of the scalar inflaton field and its first derivative.

- Inflationary sound speed can be $c_s < 1$ (canonical case: $c_s=1$).

- Full parameter set (A_s, ϵ_1, ϵ_2, c_s) assuming constant sound speed degenerate without NG info.



Joint constraints from 2-pt and 3-pt: some other examples



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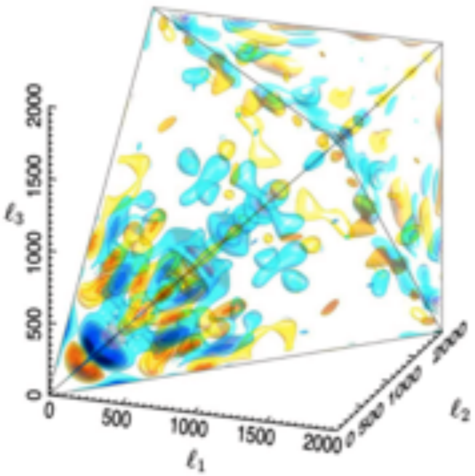


•**IR DBI**: DBI model where inflaton moves from IR to DBI side, with potential

$$V(\phi) = V_0 - \frac{1}{2}\beta H^2 \phi^2$$

where $0.1 < \beta < 10^9$. Planck n_s + f_{NL}(DBI) constrains $\beta < 0.7$ (95% CL).

•**k-inflation**: One class depends on a single parameter γ (Amendariz-Picon et al, 99).

Planck n_s: $0.01 < \gamma < 0.02$ (95% CL);

Planck f_{NL}(equil): $\gamma > 0.05$ (95% CL).

Inconsistent!

A "top down" case study*: Constraining monodromy inflation

with Richard Easther (Auckland) & Raphael Flauger (IAS Princeton/NYU)

arXiv:1303.2616 (JCAP in press)

***pre-Planck**

Flattened potentials

- "Technical naturalness" ('tHooft & Wilson): theory considered untuned

    -if its small numbers are generated dynamically

    -if quantum corrections are suppressed by symmetry principle.

- flattened potentials included in Wilsonian-natural subset of inflationary models.
- The approximate shift symmetry involved can arise from pseudo-Nambu goldstone bosons (axions).

Theoretical Background and Motivation

Monodromy inflation

- Silverstein and Westphal: arXiv:0803.3085
- Flauger, McAllister, Pajer, Westphal and Xu: arXiv:0803.3085
- Flauger and Pajer: arXiv:1002.0833

Key features

- Large field range, wrapped around a compact direction
- High scalar, detectable tensors, theoretical “control”
- Wrapping provides extra scale: modulated spectrum?

Approximation to the potential...

$$V(\phi) = \mu^3 \left[\phi - bf\left(\cos\left(\frac{\phi}{f} + \psi\right) - c\right)\right]$$

- Amplitude of perturbations set by μ
- Axion decay constant f: sub-Planckian, f > few x 10-4
- Modulations: 0 ≤ b < 1 to prevent trapping

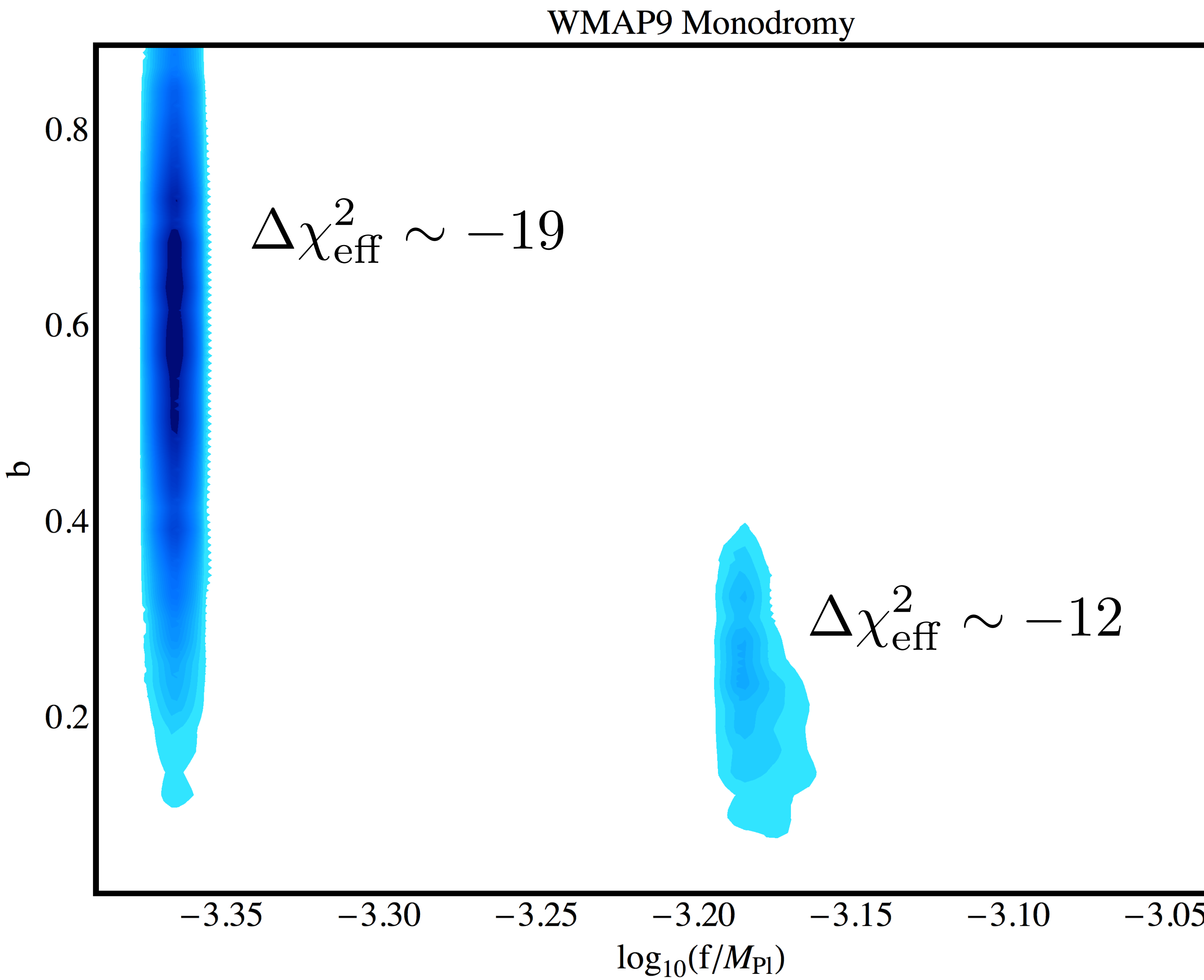
Analysis

- Uses MODECODE (Peiris, Easther & others)
  - Directly solves perturbation equations
  - There is also a good approximate solution
- CAMB slowed down by oscillatory spectrum
  - Uses interpolation when it can; not safe here
  - Boosted accuracy settings in CAMB (checked convergence)
- Sampling done by MultiNest
  - Massively parallel; samples prior not posterior

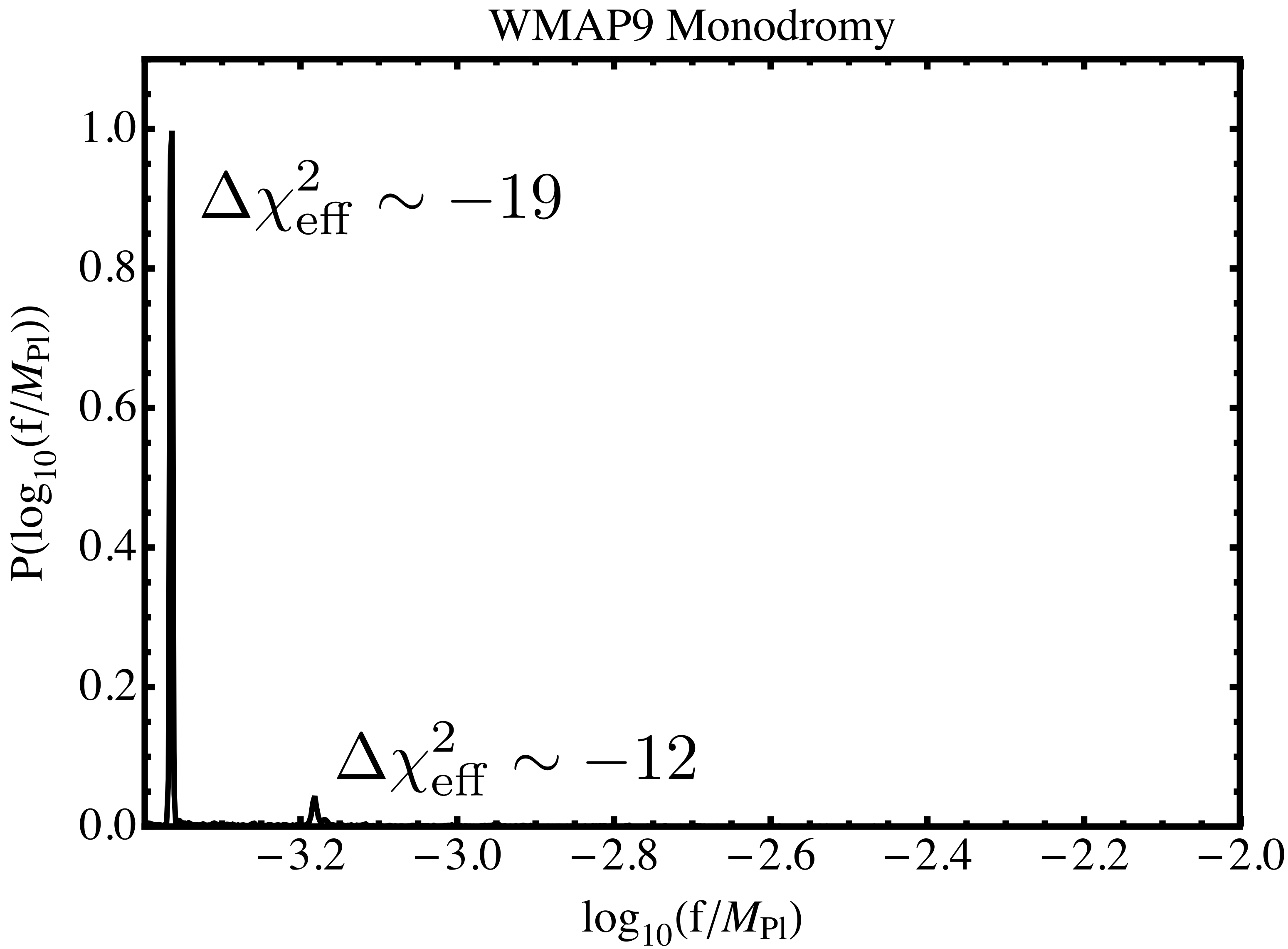
Priors

Inflation	
Mass scale	$-3.615 < \log_{10}(\mu/M_{\rm Pl}) < -3.015$
Axion coupling	$-3.4 < \log_{10}(f/M_{\rm Pl}) < -2.0$
Oscillation amplitude	$0 < b < 0.9$
Phase	$-\pi < \psi < \pi$
Matching	
e-foldings	$N = 55$
Astrophysics	
Baryon fraction	$0.0218859 < \Omega_{\rm b} h^2 < 0.02378859$
Dark matter	$\Omega_{\rm dm} h^2 = 0.1145$
Reionization	$\tau = 0.0874$
Projected acoustic scale	$\theta = 1.040$
Sunyaev-Zel'dovich Amplitude	$A_{\rm SZ} = 0.10078$

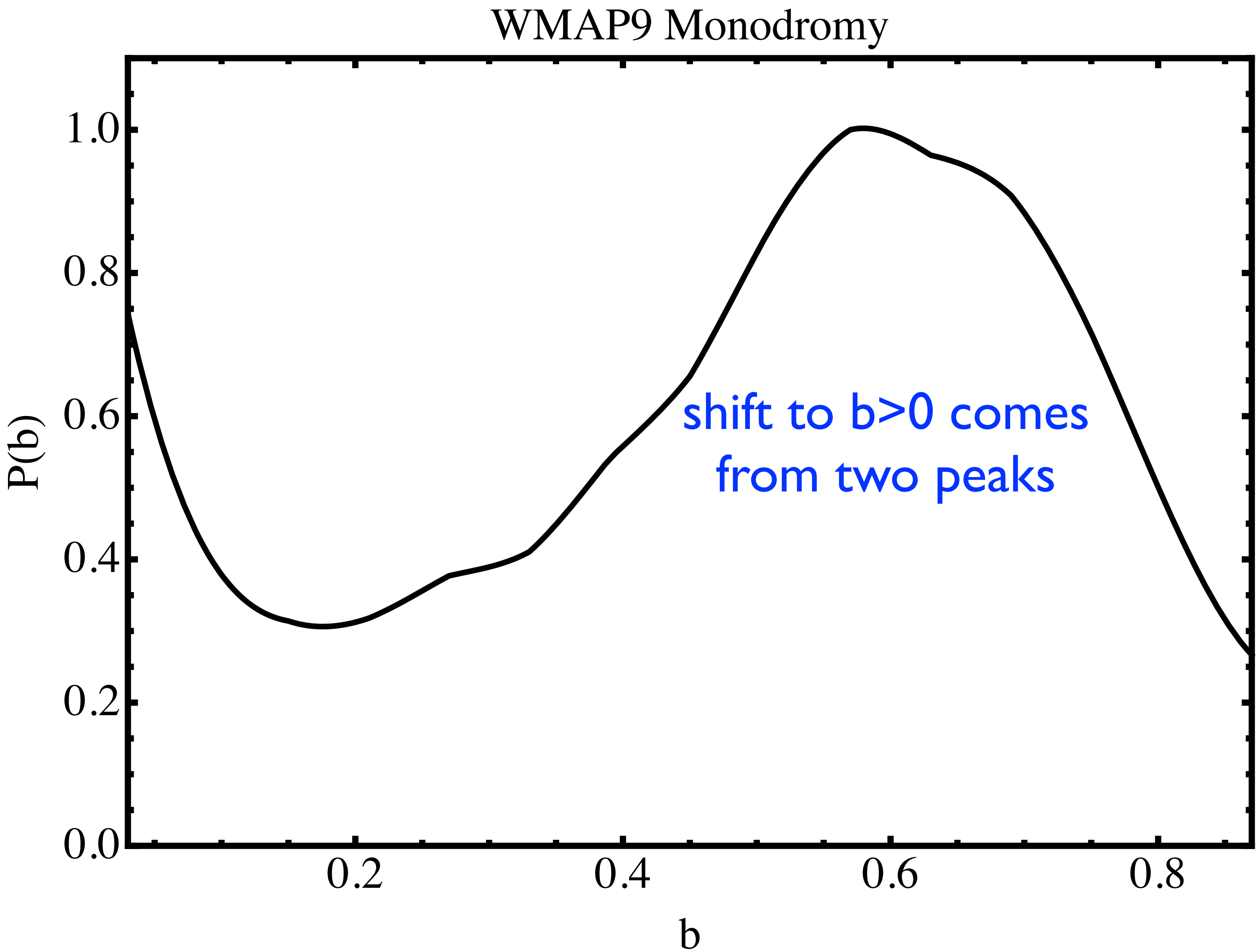
Marginalised posterior



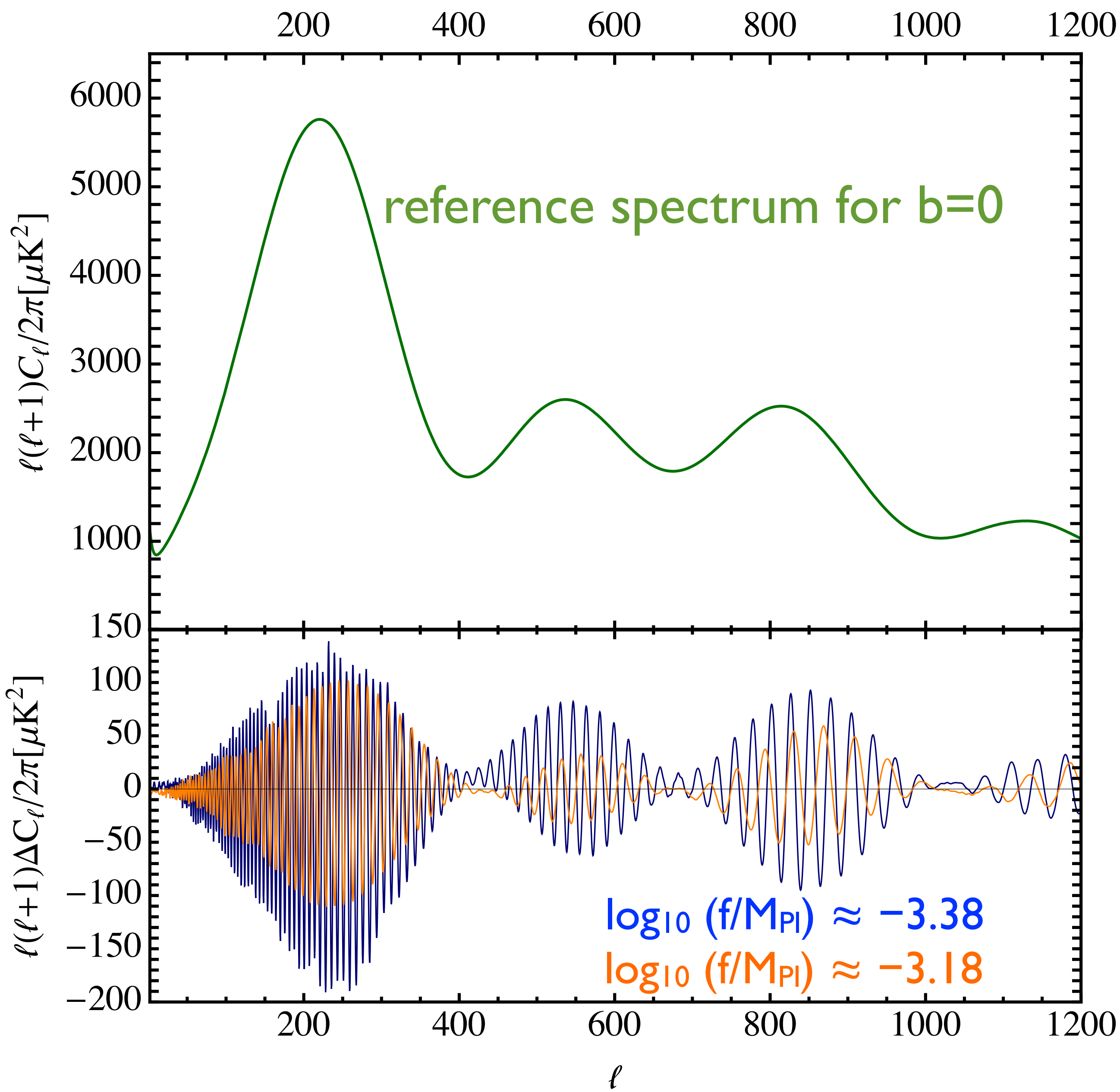
Marginalised posterior



Marginalised posterior



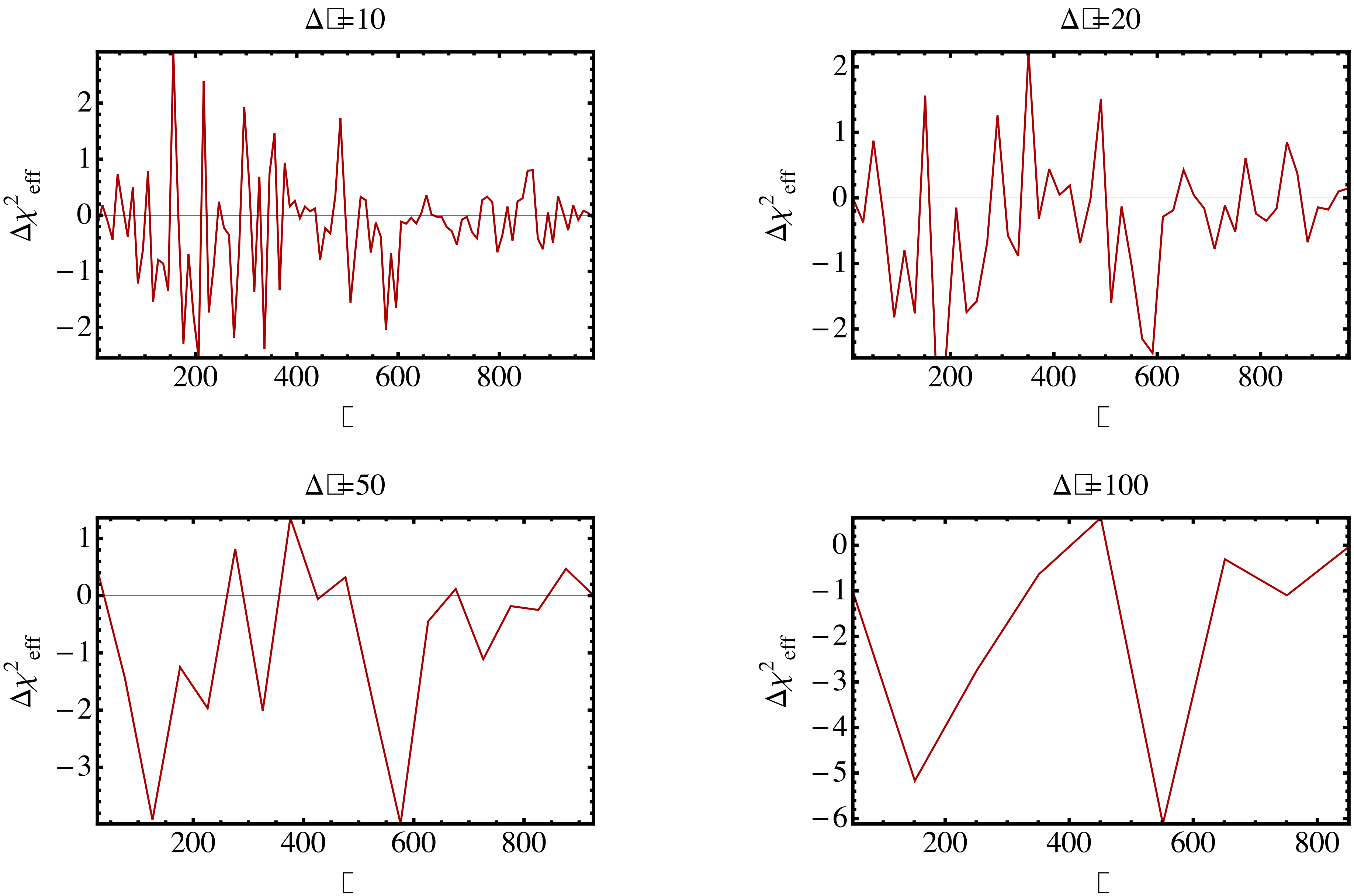
Effect on power spectrum



Significance

- Bayesian evidence: 0.6 in favor of modulated model (not significant)
- Maximum likelihood: $-2\,\Delta \ln L \sim 19$ for high peak; 12 for low peak
  - Relative to both b=0 and ΛCDM
  - Significant improvement, but not compelling
  - Both peaks: $-2\,\Delta \ln L \sim 11$ with μ fixed

Locating the improvement...



improvement comes from full l-range where WMAP has S/N

Non-Gaussianity

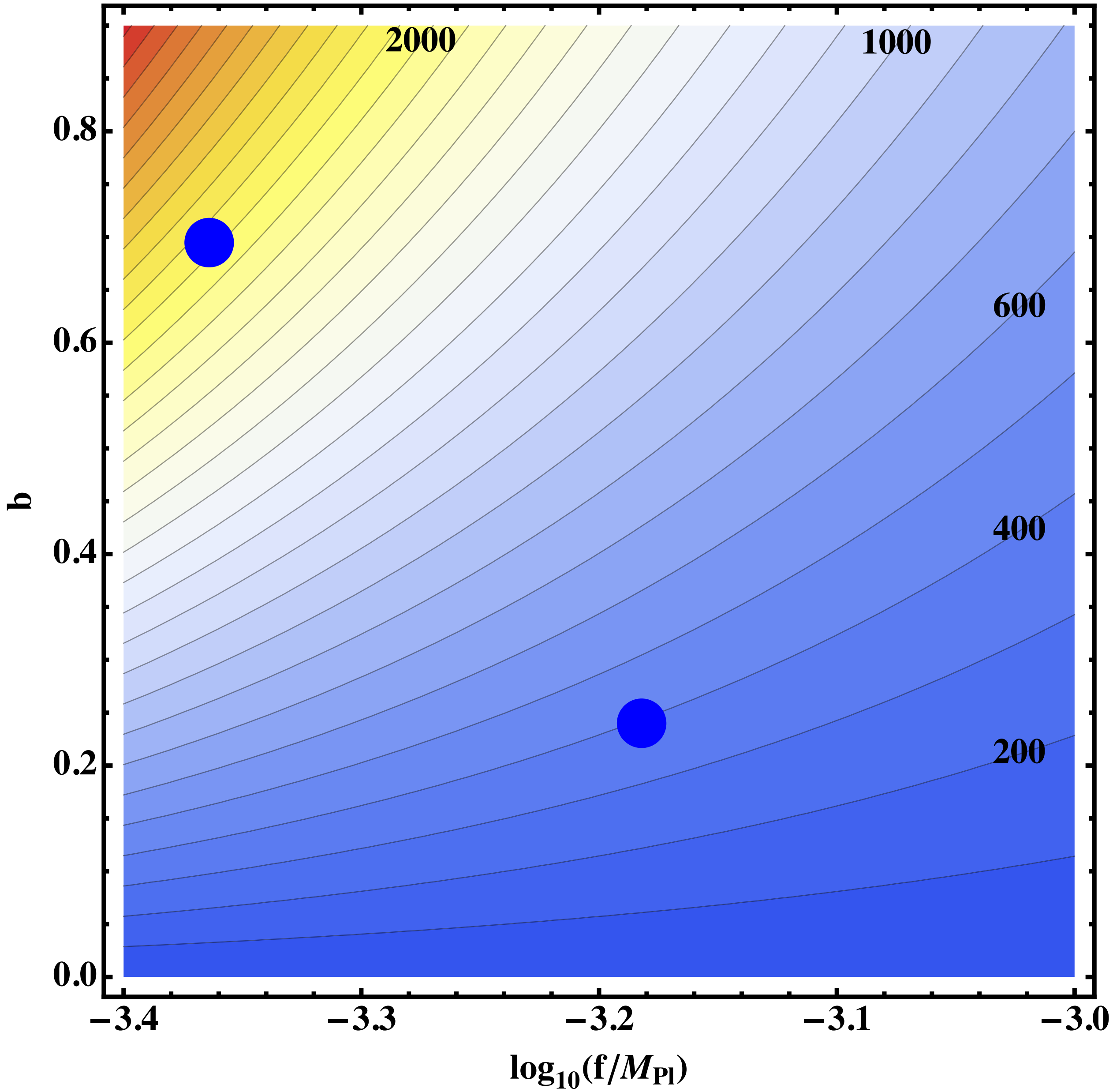
Resonant non-Gaussianity

- Chen, Easther and Lim − arXiv:0801.3295
- Generated inside the horizon
- Considered generic interaction terms for 3-point function

Monodromy

- Flauger, McAllister, Pajer, Westphal & Xu
- Detailed look at non-Gaussianity (also Flauger & Pajer)
- Little "overlap" with standard shapes; not constrained

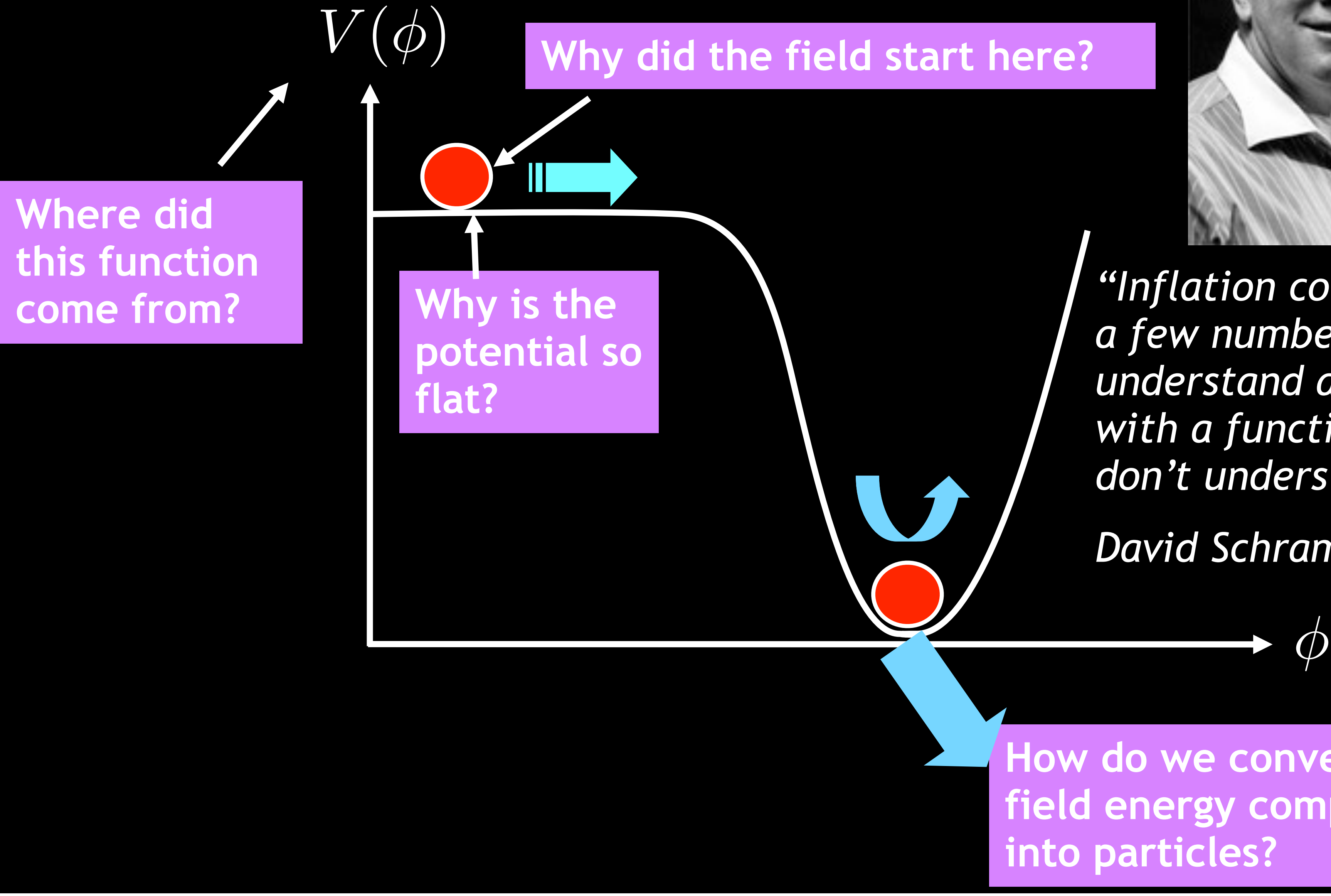
Non-Gaussianity



Post-Planck update

- Large, high frequency oscillation seen in WMAP9
  - Similar analysis by Planck; but not at this frequency
  - WMAP and Planck appear different in several relevant aspects
- Larger than most "anomalies"
  - But not compelling
  - And even if it is "real", it could be a systematic
- Interesting model, eminently testable through predictions for scalar/tensor spectra + bispectrum...

What is the physics of inflation?



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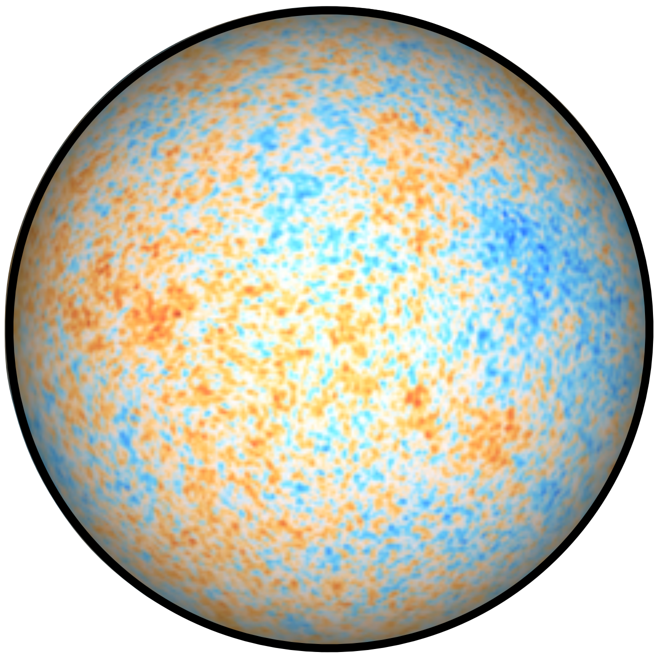
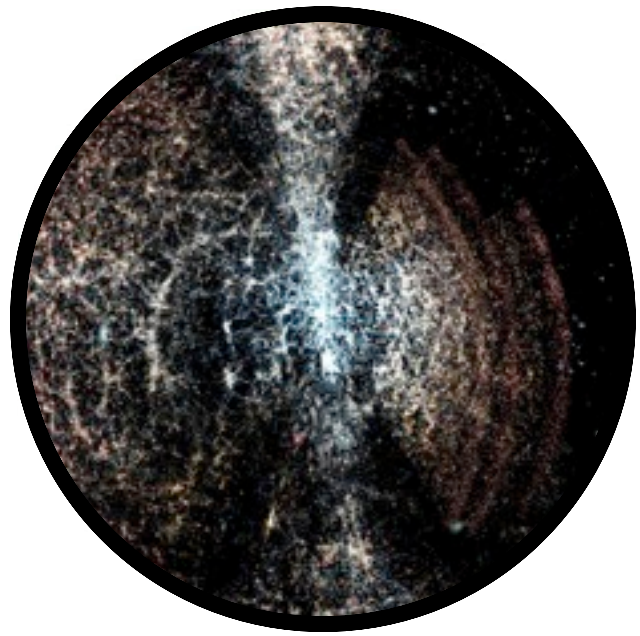
What is the physical origin of all the structure in the Universe?



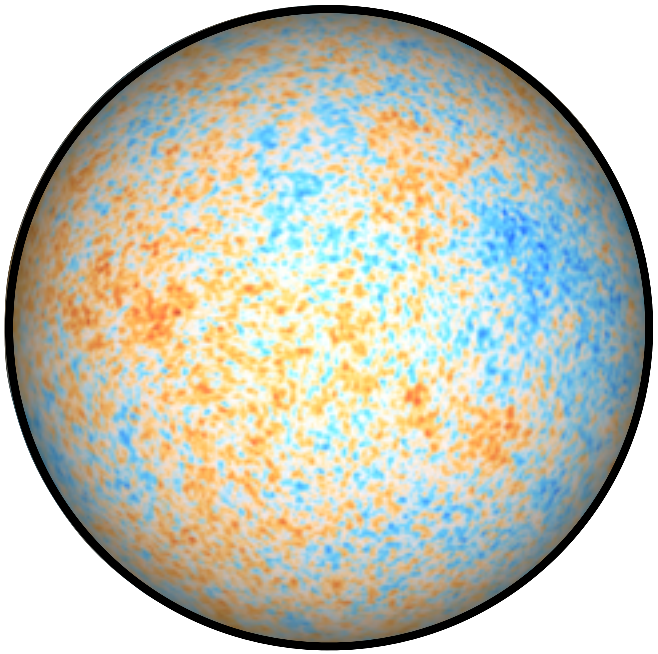
Cosmic Microwave Background
image: Planck



Large Scale Structure
image: SDSS

We see a model working in practice. How does it work in principle?

What is the physical origin of all the structure in the Universe?



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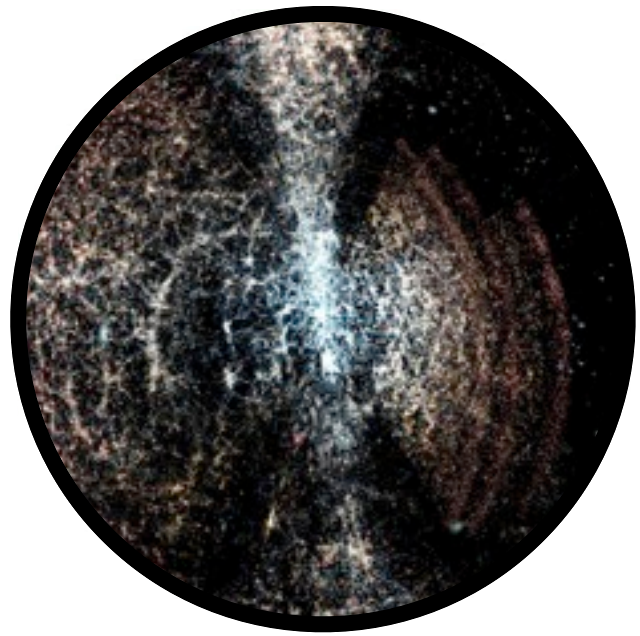

Large Scale Structure
image: SDSS

Does inflation work in principle?