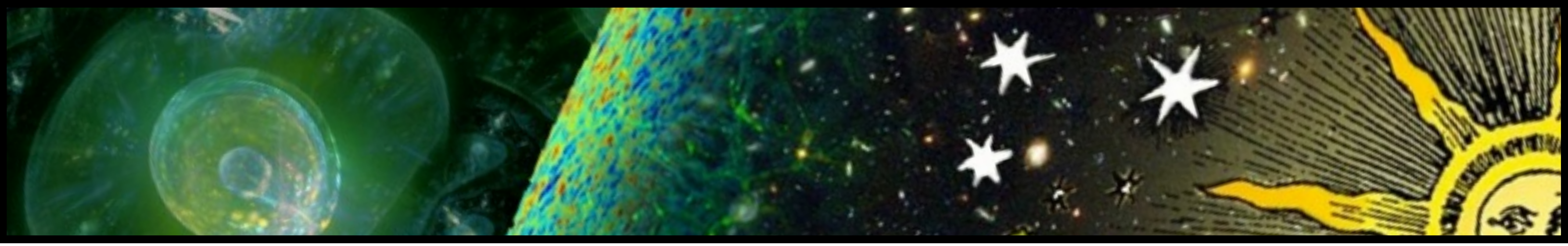


Testing inflation with Planck

Hiranya V. Peiris (UCL)

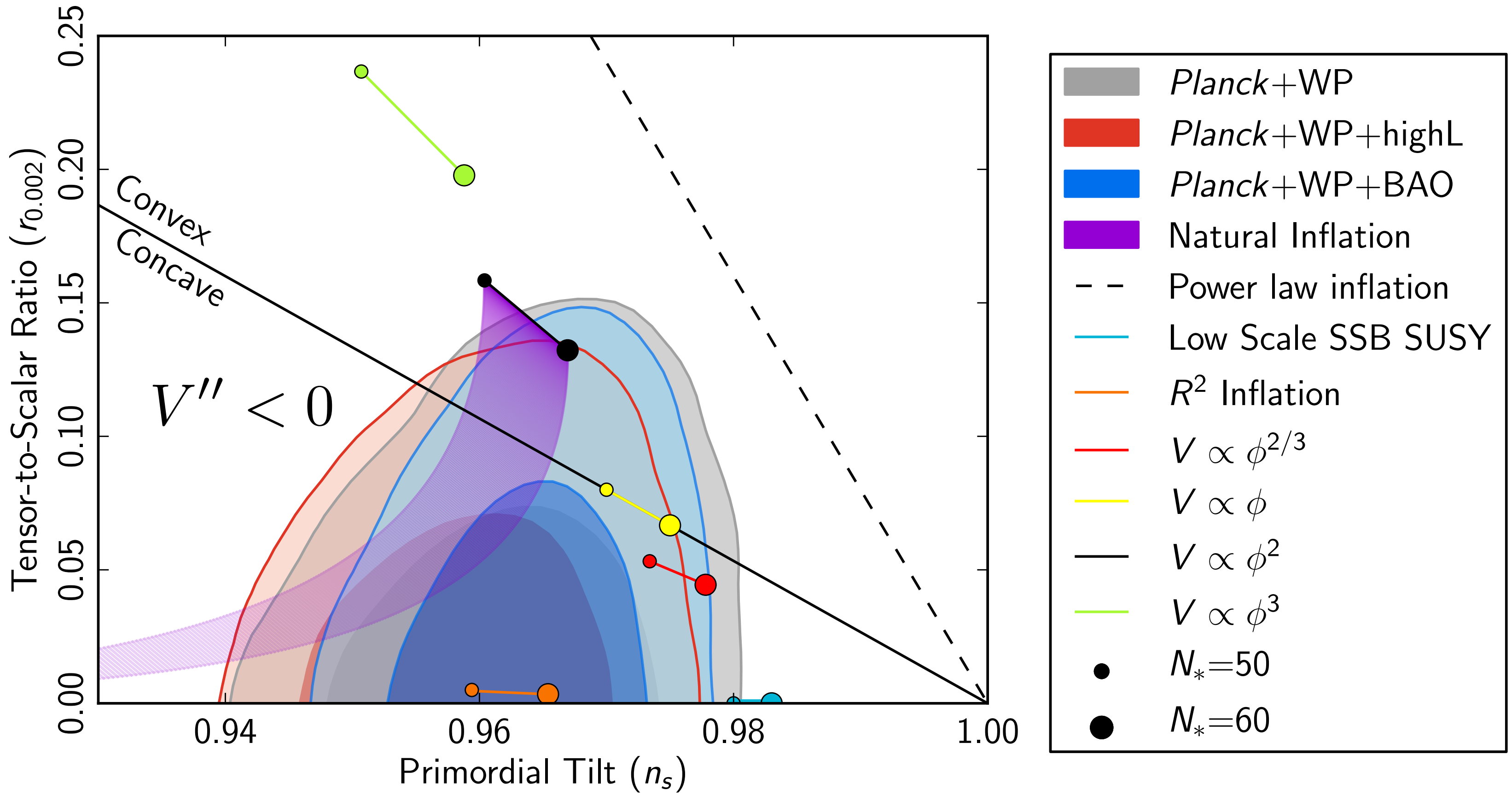
on behalf of
the Planck Collaboration

Planck 2013 Results XXII: Constraints on Inflation

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.

Constraints on slow roll models: n_s-r parameterization



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

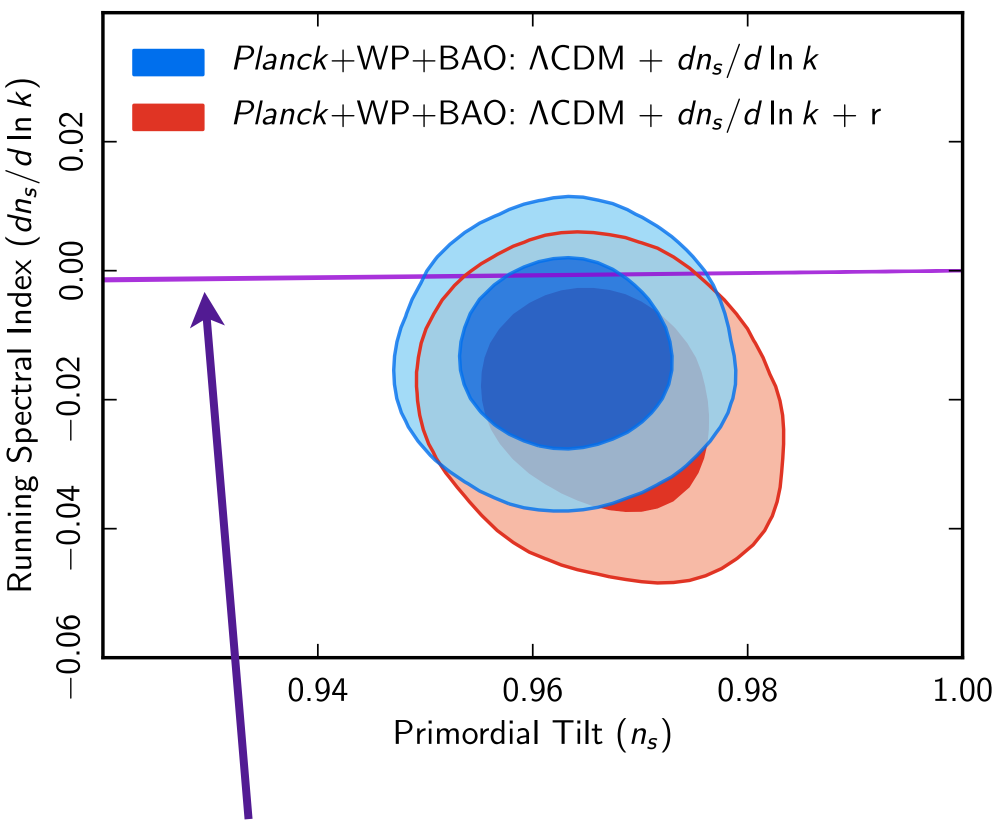
Energy scale of inflation: $V_* < (1.94 \times 10^{16} \mathrm{GeV})^4$

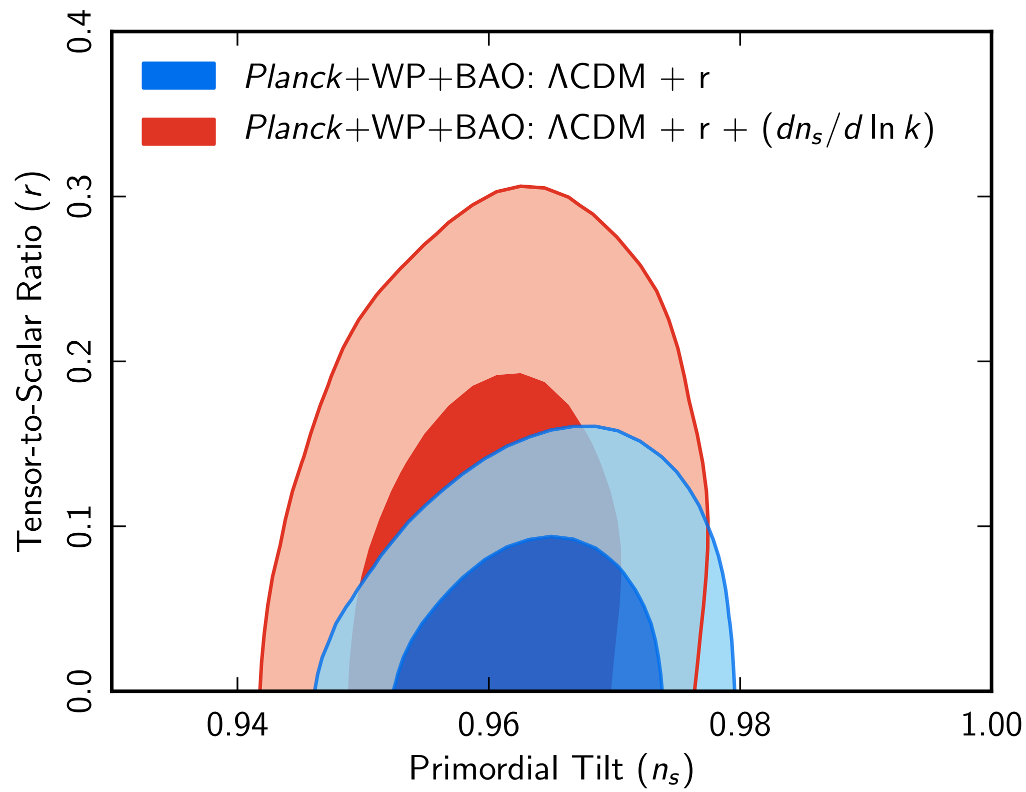
Ruling out exact scale invariance

	HZ	HZ + Y_P	HZ + N_{eff}	ΛCDM
$10^5\Omega_b h^2$	2296 ± 24	2296 ± 23	2285 ± 23	2205 ± 28
$10^4\Omega_c h^2$	1088 ± 13	1158 ± 20	1298 ± 43	1199 ± 27
$100\,\theta_{MC}$	1.04292 ± 0.00054	1.04439 ± 0.00063	1.04052 ± 0.00067	1.04131 ± 0.00063
τ	$0.125^{+0.016}_{-0.014}$	$0.109^{+0.013}_{-0.014}$	$0.105^{+0.014}_{-0.013}$	$0.089^{+0.012}_{-0.014}$
$\ln\left(10^{10}A_s\right)$	$3.133^{+0.032}_{-0.028}$	$3.137^{+0.027}_{-0.028}$	$3.143^{+0.027}_{-0.026}$	$3.089^{+0.024}_{-0.027}$
n_s	—	—	—	0.9603 ± 0.0073
N_{eff}	—	—	3.98 ± 0.19	—
Y_P	—	0.3194 ± 0.013	—	—
$-2\Delta\ln(\mathcal{L}_{max})$	27.9	2.2	2.8	0

- HZ model disfavored by $-2\,\Delta\ln L \sim 28$
- Main degeneracies: Y_P and N_{eff} (effect on damping tail mimics tilt)
- Requires helium fraction incompatible with direct astrophysical measurements + standard BBN / or needs extra relativistic d.o.f.
- With BAO, $-2\,\Delta\ln L \sim 39$ (HZ), 4.6 (HZ+Y_P), 8.0 (HZ + N_{eff})

Extending the primordial parameter set: running





predictions of monomial chaotic models with $N_* \sim [50,60]$

- Constraints pivot-dependent; shown at decorrelation scale k=0.04 Mpc^{-1}.

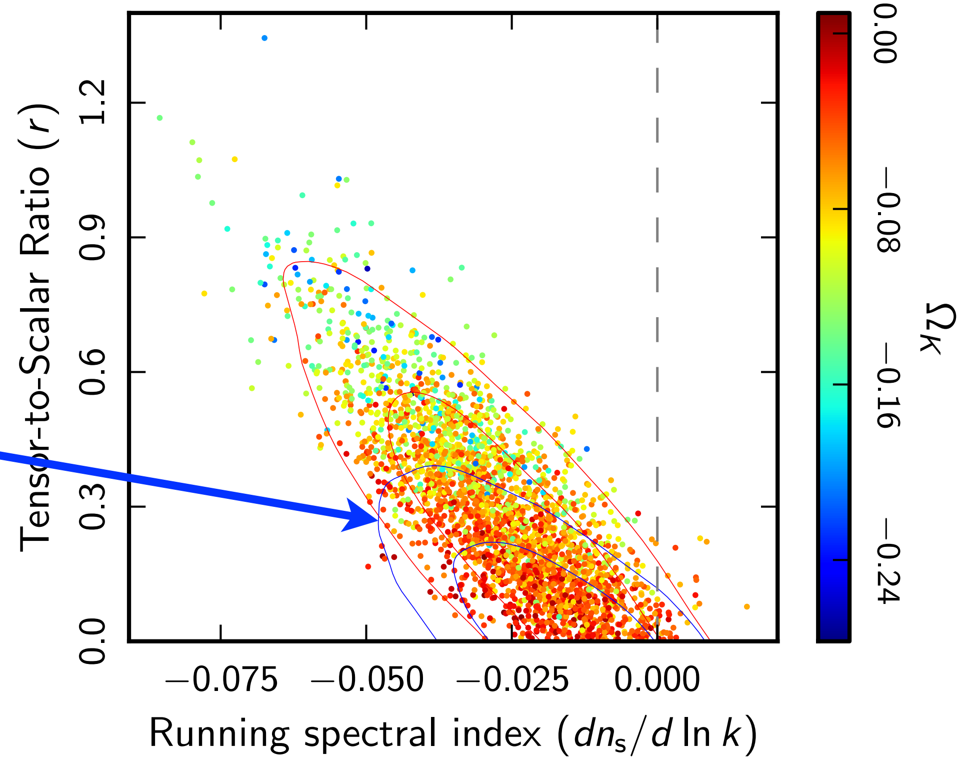
Planck+WP: $dn_s/d\ln k = -0.013 \pm 0.009$

Extending the primordial parameter set: curvature

- Simplest inflationary models predict $|\Omega_K| < 10^{-5}$
- Open inflation (e.g. bubble nucleation, landscape) can predict larger negative spatial curvature, O(10^{-4});
- positive curvature (closed universe) much harder to get in inflationary paradigm.

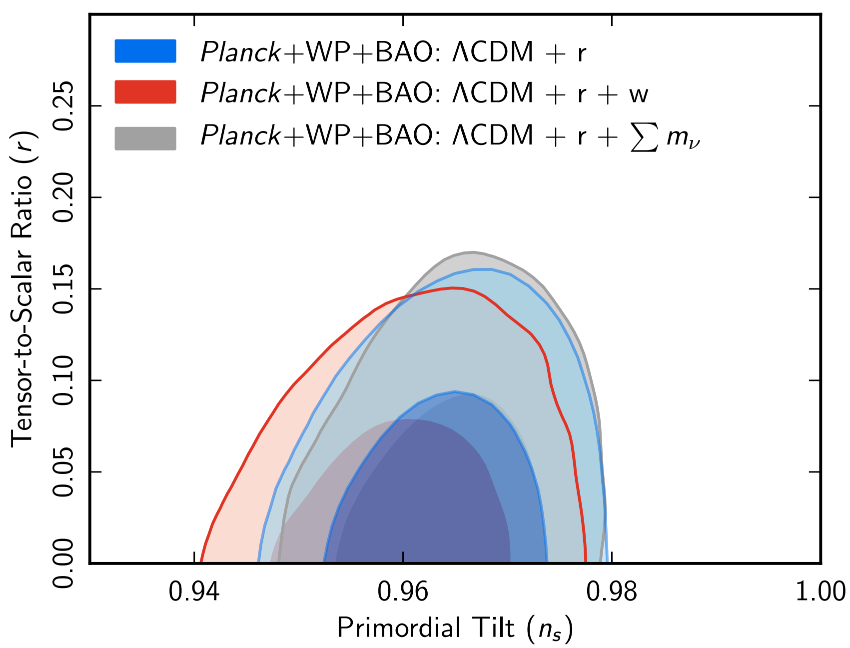
$$\Omega_K = -0.0004 \pm 0.0036$$

(Planck+WP+BAO)

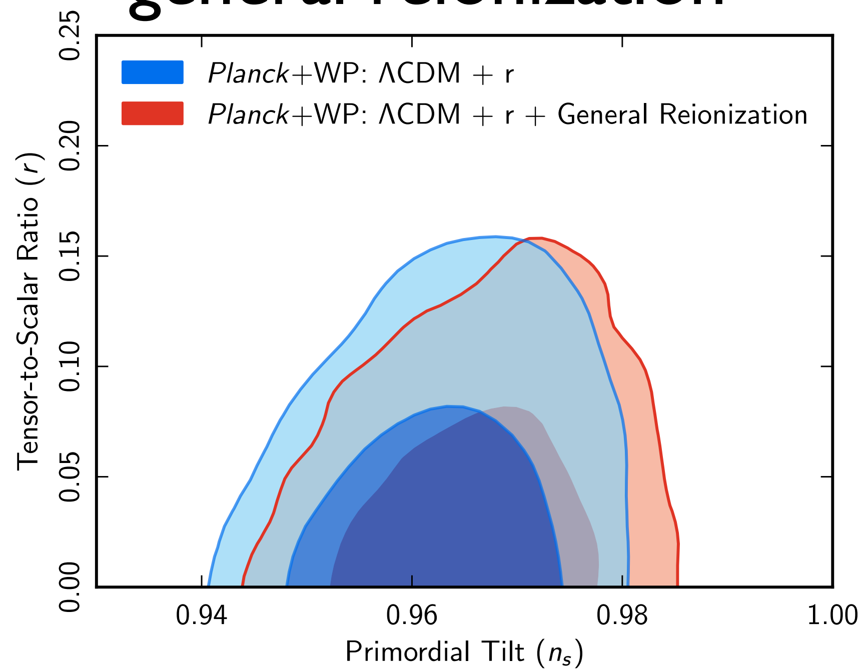


Robustness to cosmological model

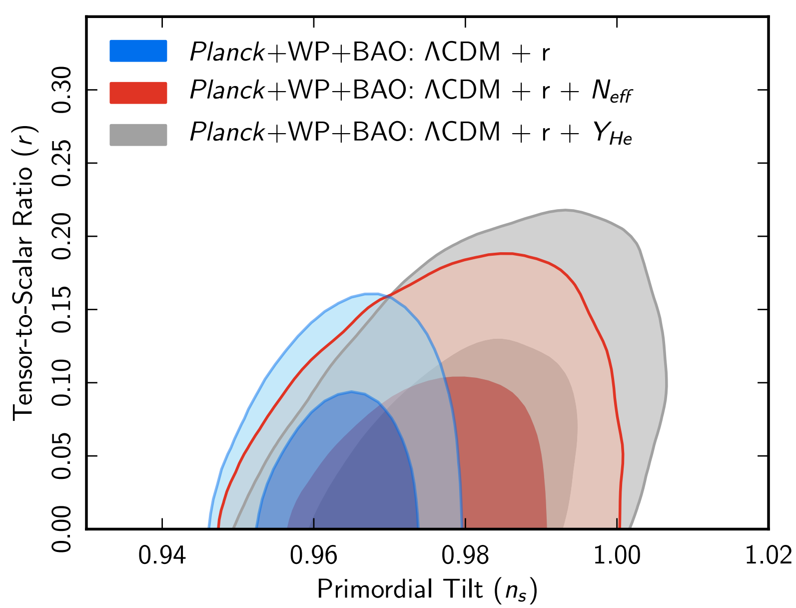
dark energy, υ mass



general reionization

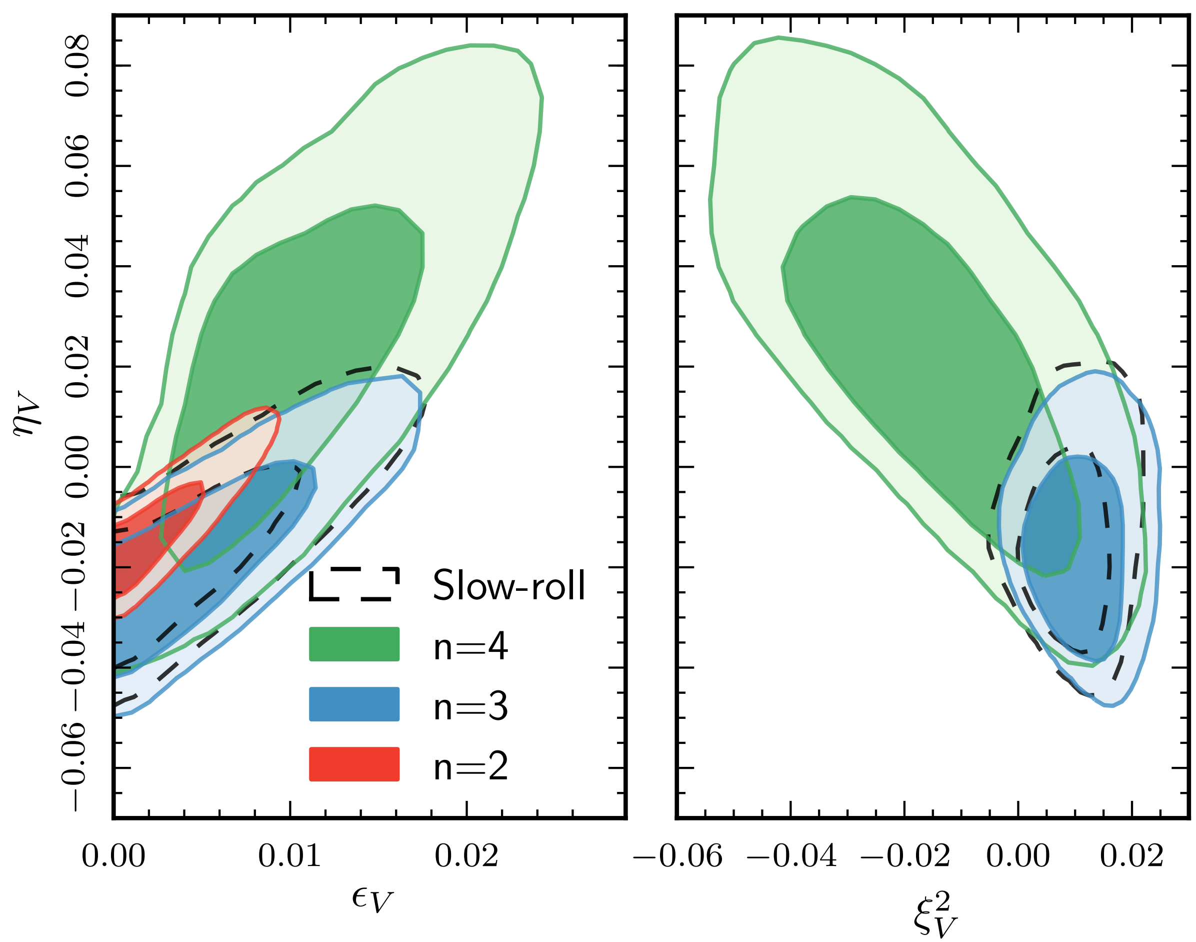


N_{eff}, Y_{He}

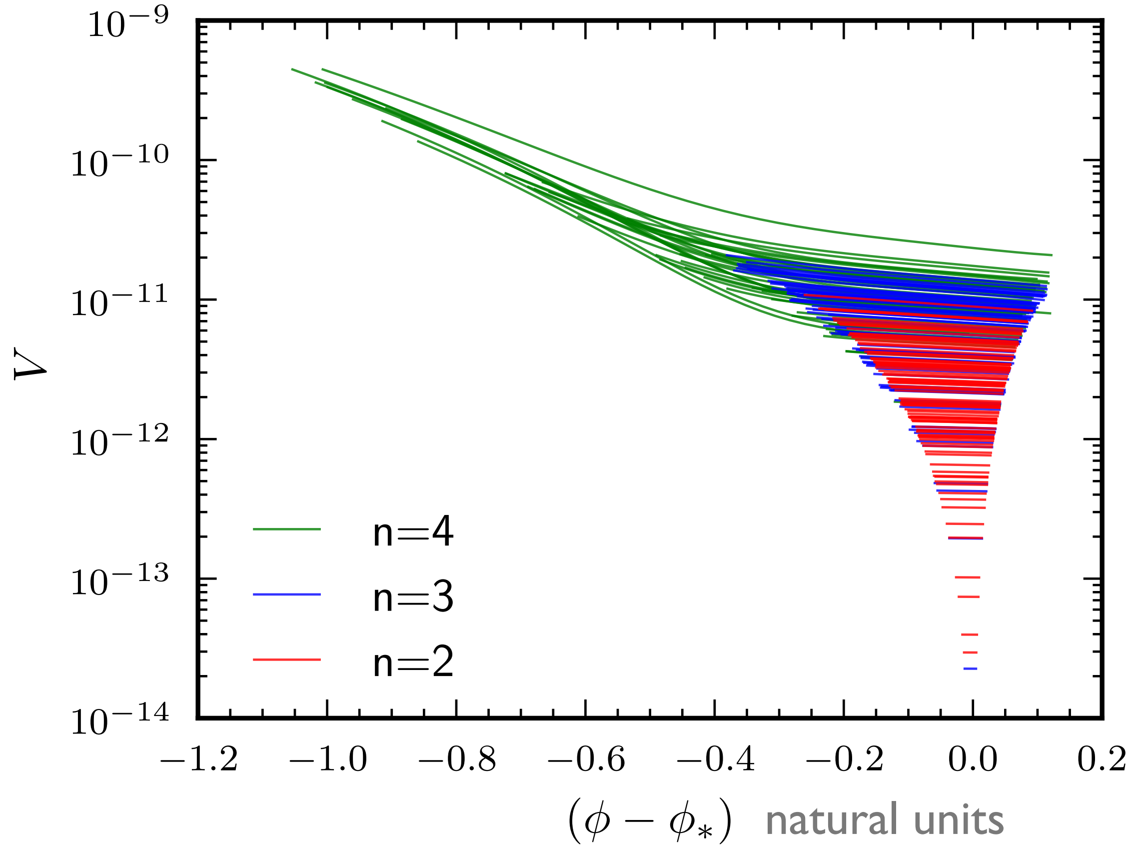


Observable window of inflation

- Taylor expansion of V(φ) in polynomials of order n=2,3,4 about φ_* ; uniform priors on (potential) slow roll parameters
- Direct numerical integration of modes (no slow roll approx); Consider few e-folds before and after observable window



Potential reconstruction in observable window



- Preference for concave potentials
- n=4 case exhibits running of running (acts to resolve low ell tension)
- sparsity of potentials with low V_0 reflects flat prior on V_0 rather than $\ln(V_0)$

Testing a subset of the inflationary zoo: priors

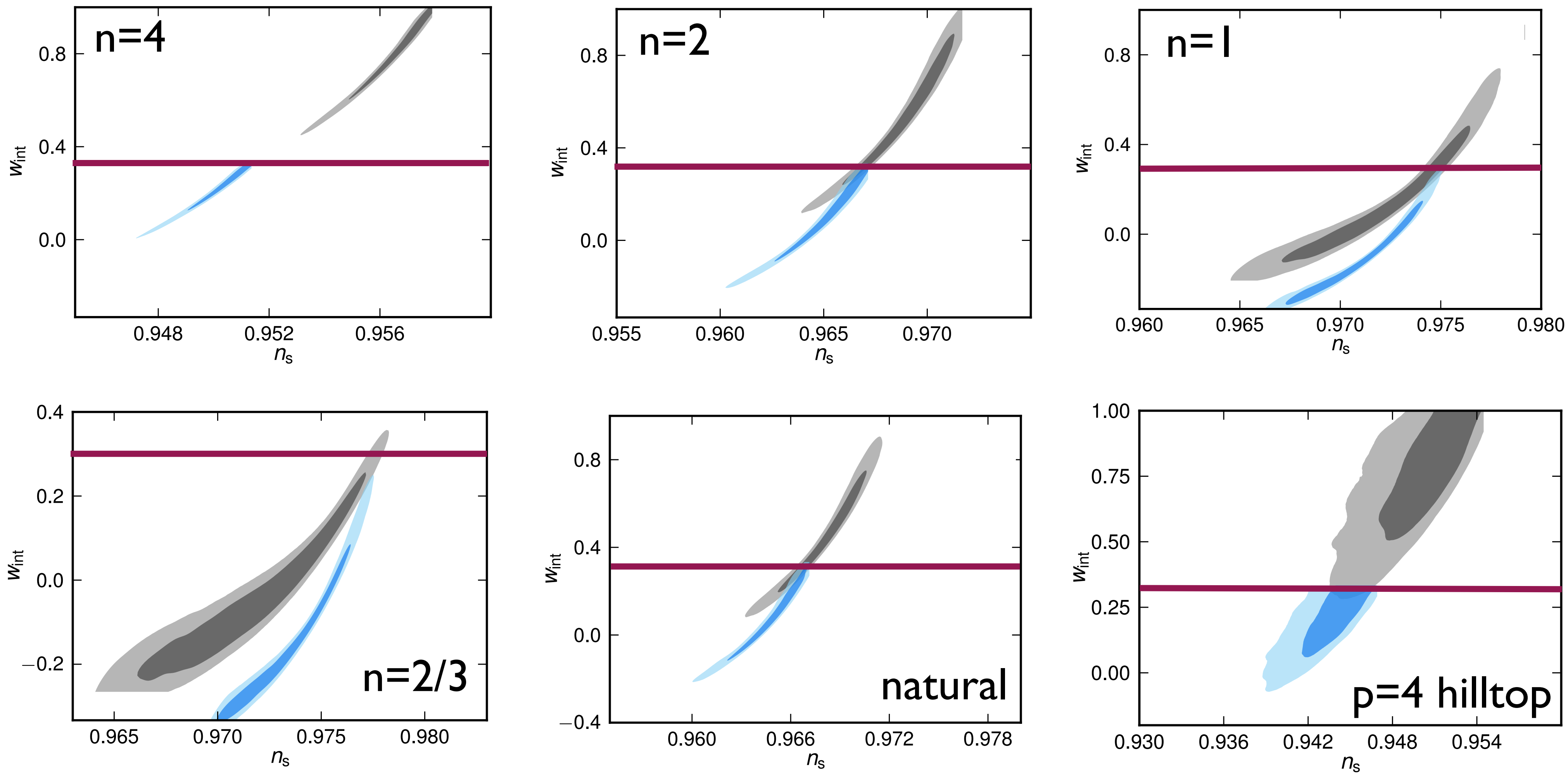
- Potential parameters are mass scales in particle physics; leads to logarithmic priors

- 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



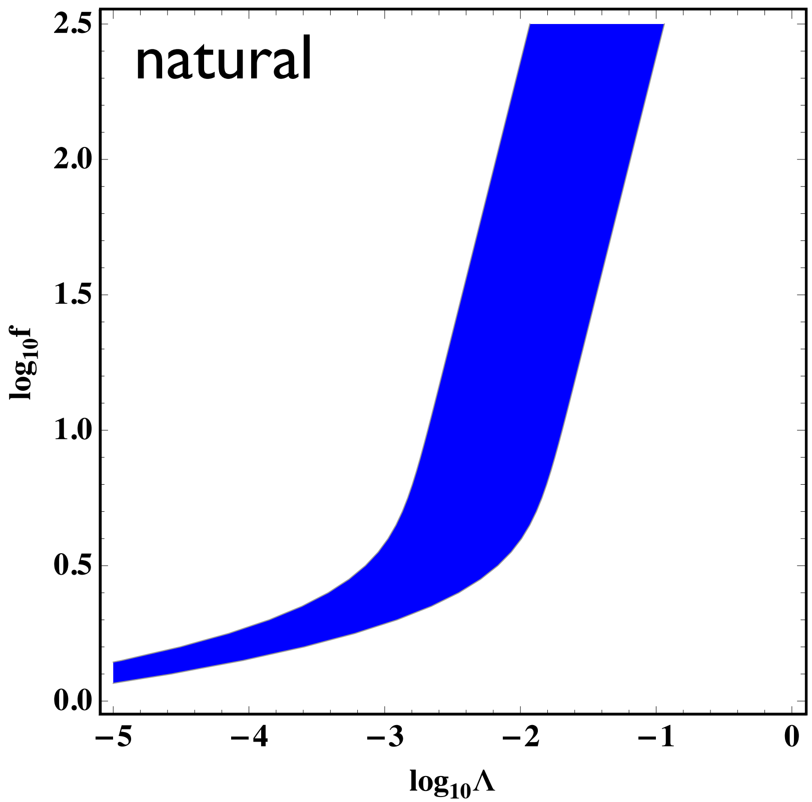
restrictive entropy generation

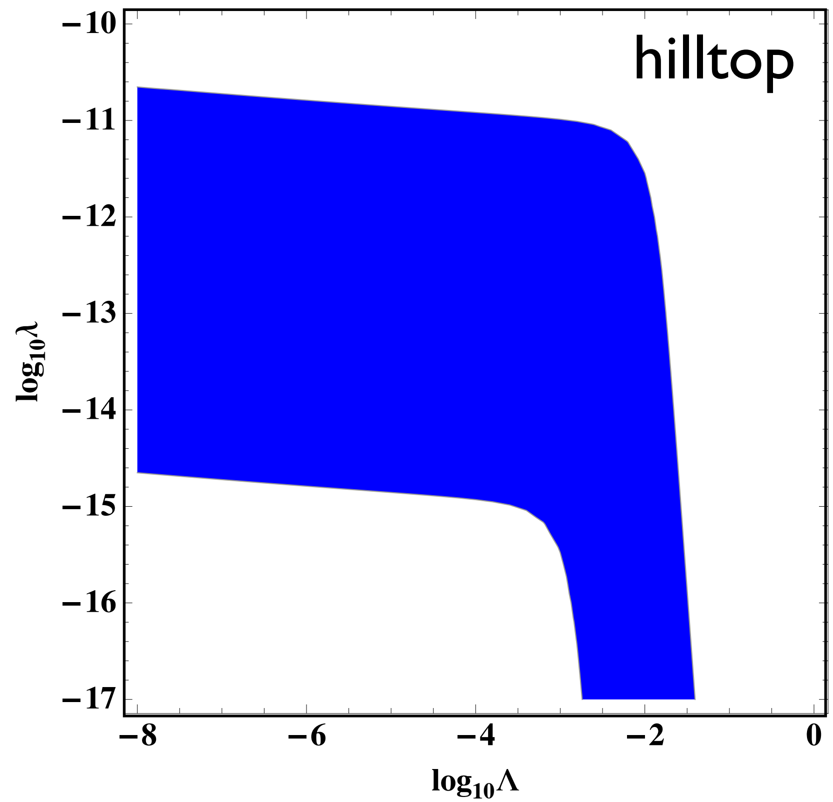
$$\rho_{\rm th}^{1/4} = 10^9 \text{ GeV} \quad w_{\rm int} \in [-1/3, 1/3]$$

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



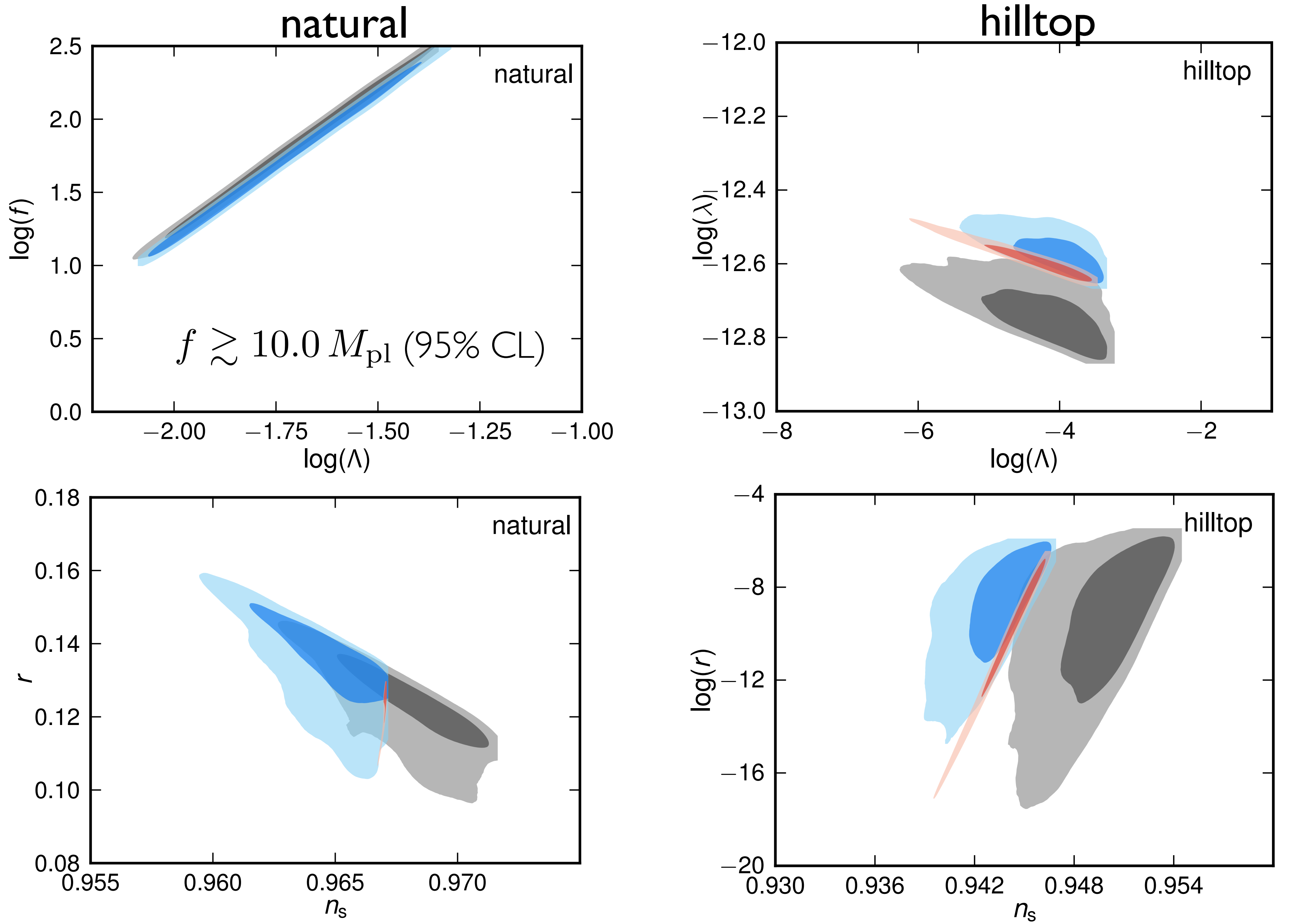


$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

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

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

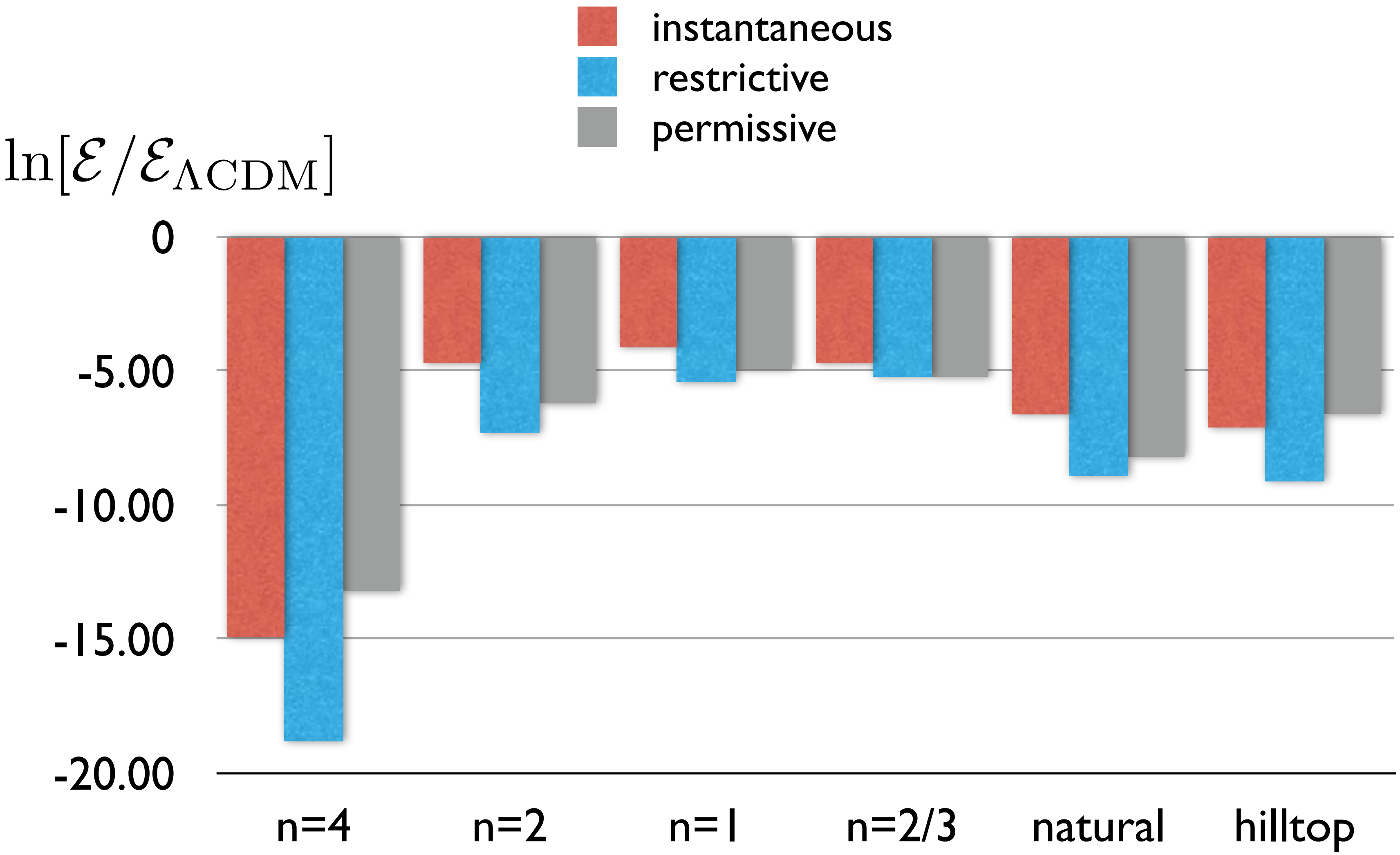
prior probability

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

Evidence: normalizing factor

Evidence: model-averaged likelihood

Model comparison



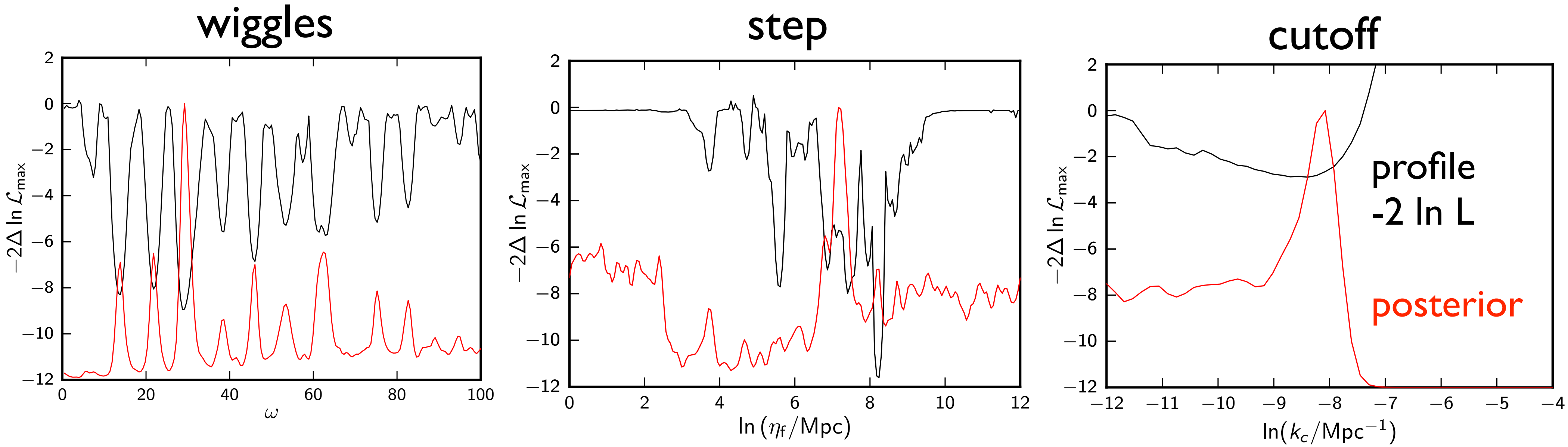
ln[evidence ratio] of ~5 (~150:1 odds)
considered decisive in this context

Parametric searches for features in the primordial spectrum

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

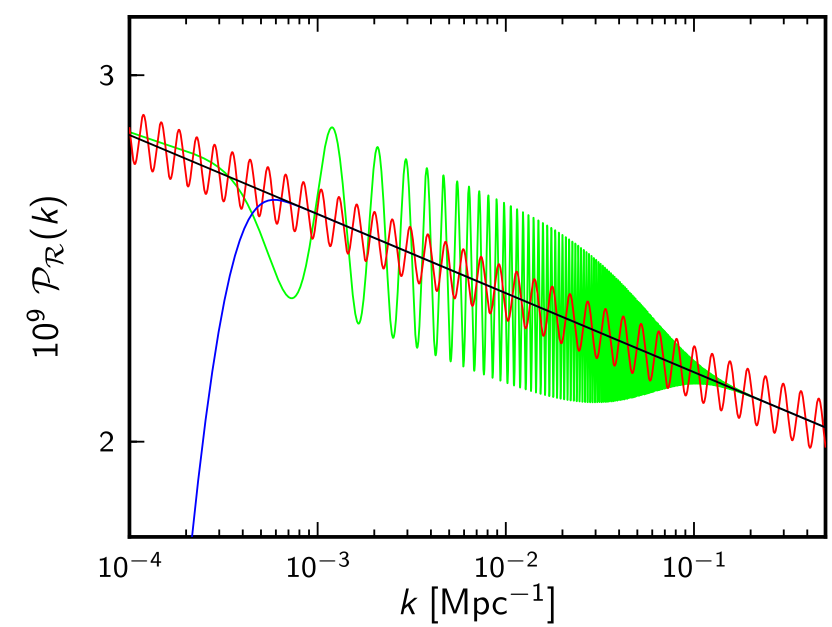
step: $$\mathcal{P}_{\mathcal{R}}(k) = \exp\left[\ln\mathcal{P}_0(k) + \frac{\mathcal{A}_{\rm f}}{3}\frac{k\eta_{\rm f}/x_d}{\sinh(k\eta_{\rm f}/x_{\rm d})}W'(k\eta_{\rm f})\right]$$

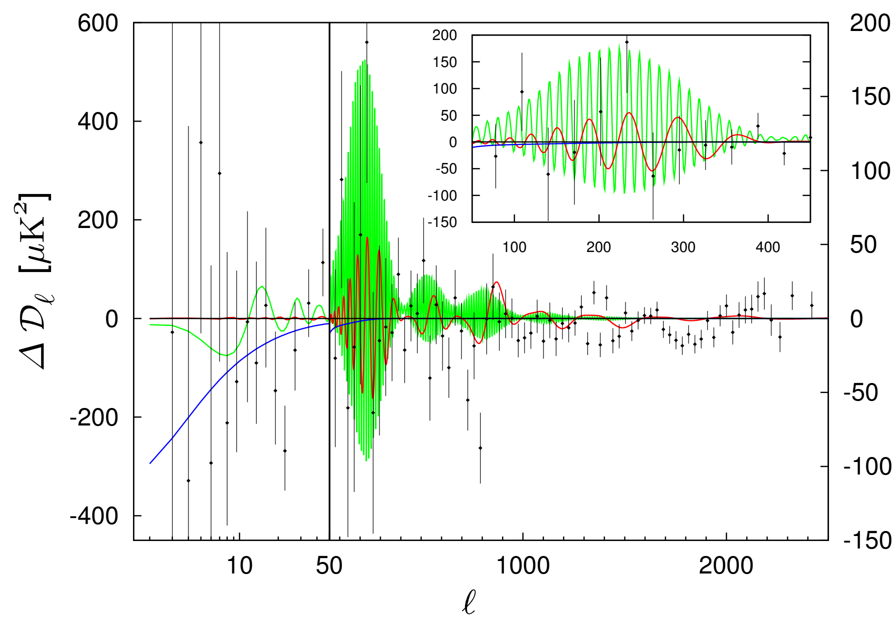
cutoff: $$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 - \exp\left[-\left(\frac{k}{k_{\rm c}}\right)^{\lambda_{\rm c}}\right]\right\}$$



Parametric searches for features in the primordial spectrum

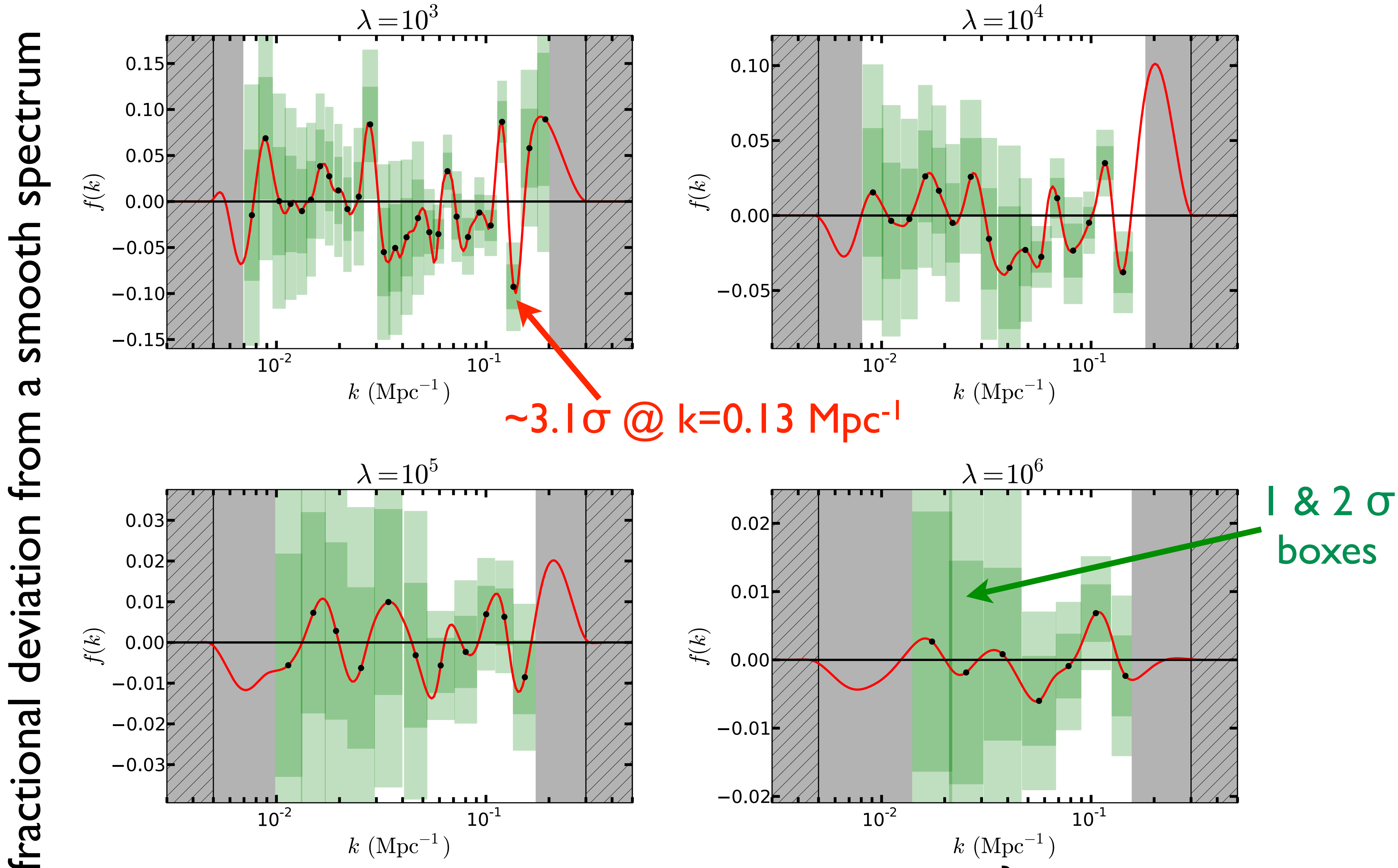
Model	$-2\Delta \ln \mathcal{L}_{\max}$	$\ln B_{0X}$
Wiggles	-9.0	1.5
Step-inflation	-11.7	0.3
Cutoff	-2.9	0.3





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

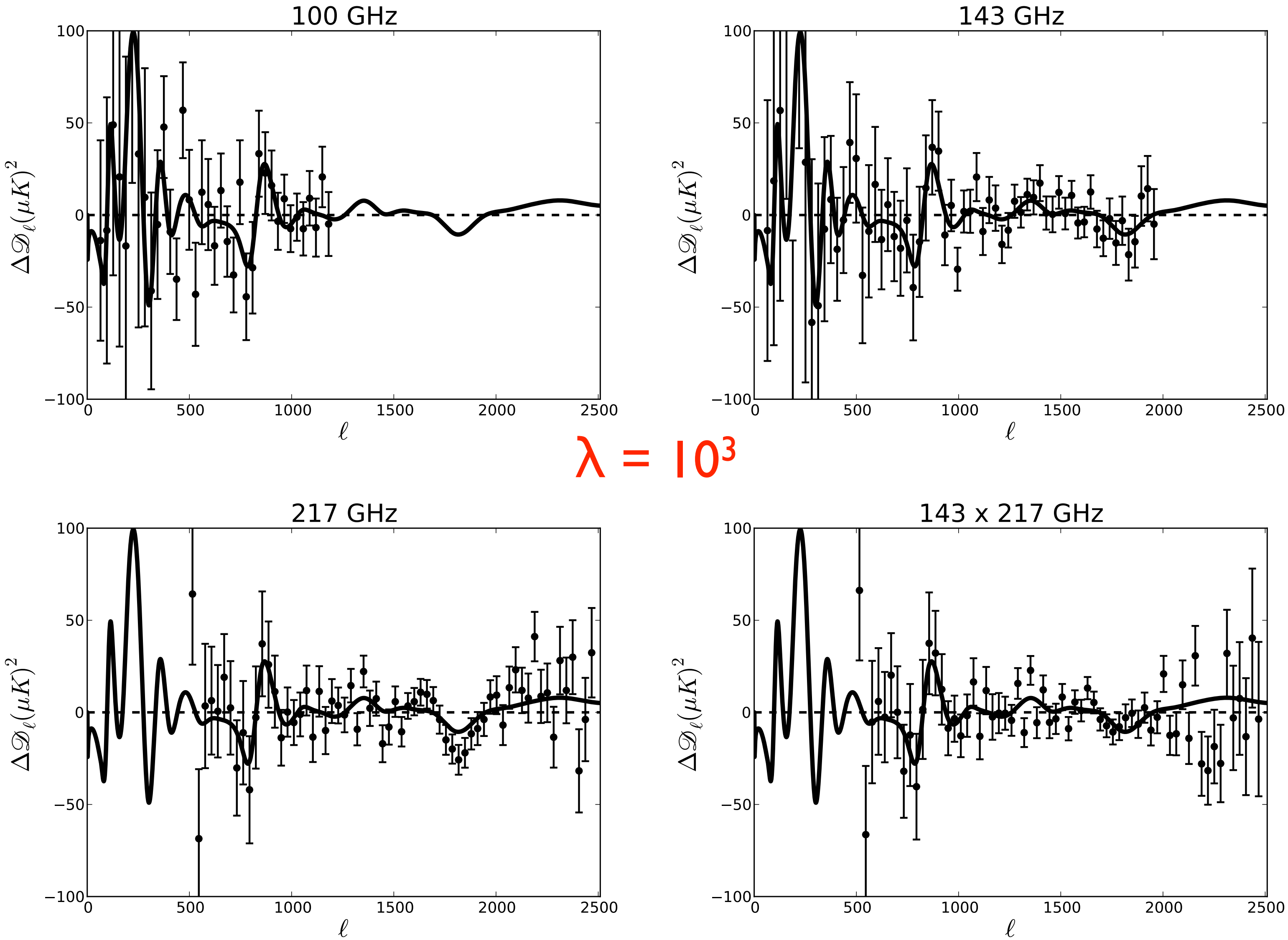
Non-parametric searches for features in the primordial spectrum



- ML solution for "smoothing parameter" λ

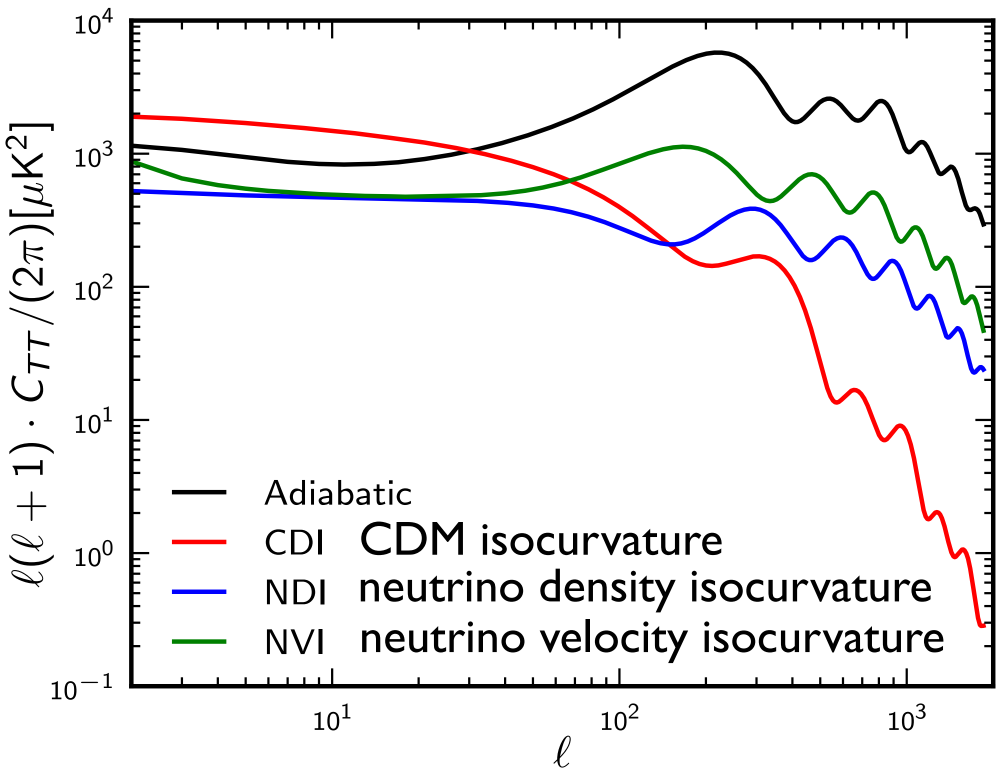
Nuisance parameters (beams) fixed to best fit values

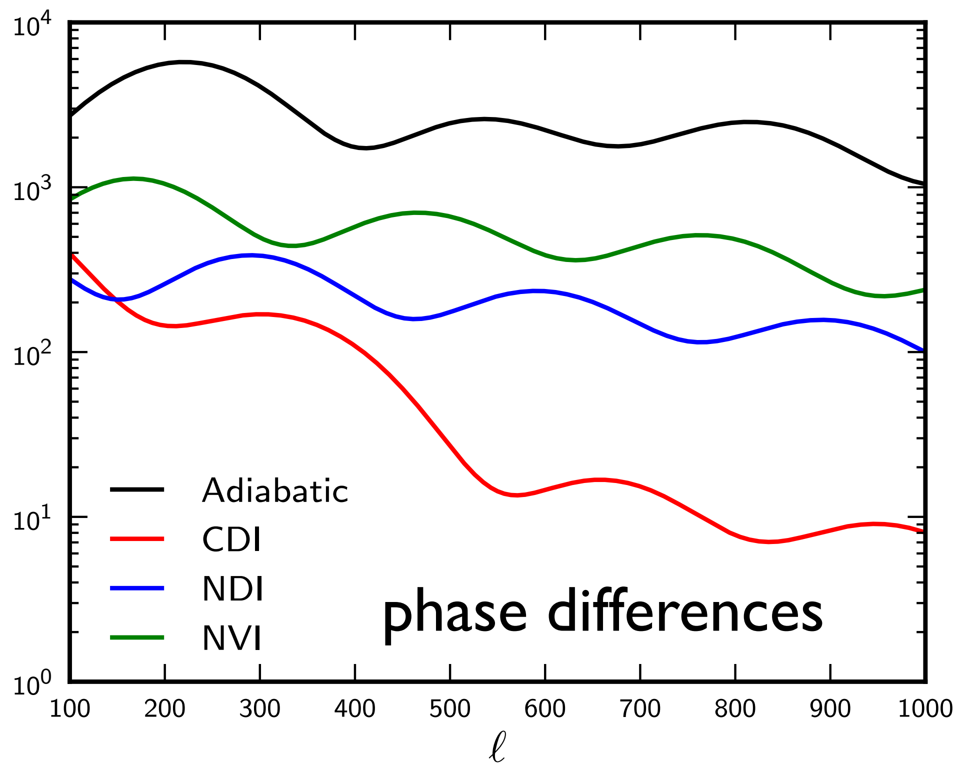
Non-parametric searches for features in the primordial spectrum



Broad dip at ℓ ~1800 not explained by known systematics propagated through data analysis pipeline. Needs further investigation with full mission data.

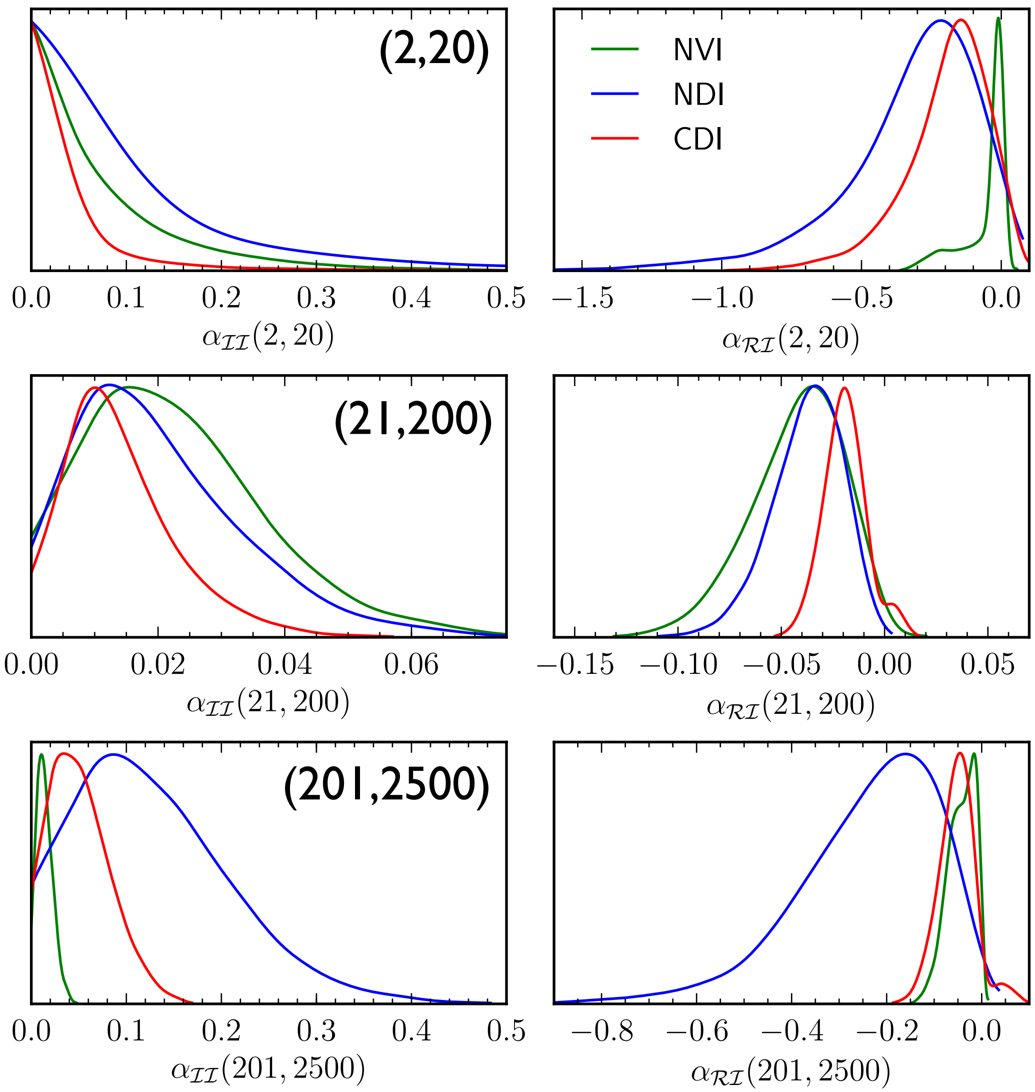
Isocurvature: spectra





- arise from spatial variations in the eq. of state or between relative velocities of components
- might be excited in e.g. multifield scenario
- expect correlations between adiabatic and isocurvature d.o.f.

Isocurvature: constraints



$$\alpha_{\mathcal{RR}}(\ell_{\min},\ell_{\max}) = \frac{(\Delta T)^2_{\mathcal{RR}}(\ell_{\min},\ell_{\max})}{(\Delta T)^2_{\text{tot}}(\ell_{\min},\ell_{\max})},$$

$$\alpha_{\mathcal{II}}(\ell_{\min},\ell_{\max}) = \frac{(\Delta T)^2_{\mathcal{II}}(\ell_{\min},\ell_{\max})}{(\Delta T)^2_{\text{tot}}(\ell_{\min},\ell_{\max})},$$

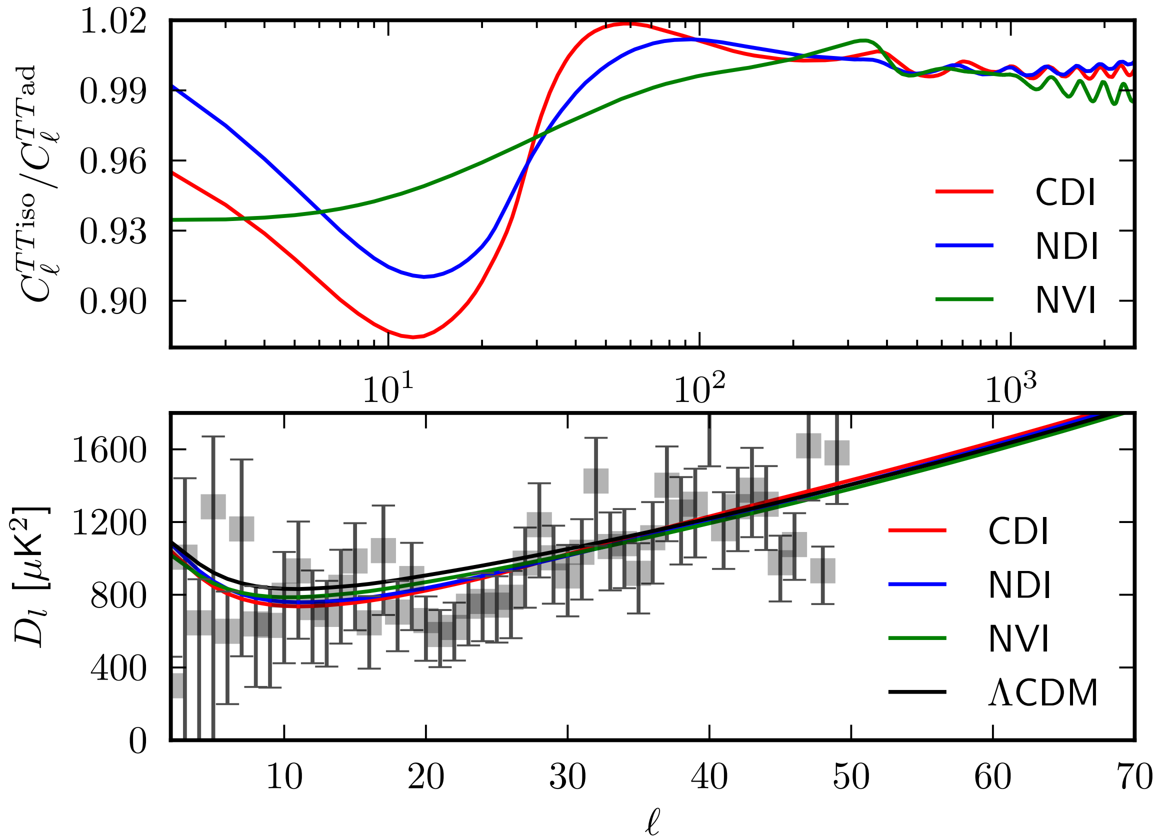
$$\alpha_{\mathcal{RI}}(\ell_{\min},\ell_{\max}) = \frac{(\Delta T)^2_{\mathcal{RI}}(\ell_{\min},\ell_{\max})}{(\Delta T)^2_{\text{tot}}(\ell_{\min},\ell_{\max})},$$

$$(\Delta T)^2_X(\ell_{\min},\ell_{\max}) = \sum_{\ell=\ell_{\min}}^{\ell_{\max}} (2\ell+1) C^{TT}_{X,\ell}.$$

$\alpha_{\mathscr{RR}}$ for l~(2,2500) (95% CL): non-adiabatic fraction can be as high as [7%, 9%, 5%] (CDI, NDI, NVI)

$$\boldsymbol{\mathcal{P}}(k) = \begin{pmatrix} \mathcal{P}_{\mathcal{R}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{R}\mathcal{I}_{\rm CDI}}(k) & \mathcal{P}_{\mathcal{R}\mathcal{I}_{\rm NDI}}(k) & \mathcal{P}_{\mathcal{R}\mathcal{I}_{\rm NVI}}(k) \\ \mathcal{P}_{\mathcal{I}_{\rm CDI}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{I}_{\rm CDI}\mathcal{I}_{\rm CDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm CDI}\mathcal{I}_{\rm NDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm CDI}\mathcal{I}_{\rm NVI}}(k) \\ \mathcal{P}_{\mathcal{I}_{\rm NDI}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NDI}\mathcal{I}_{\rm CDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NDI}\mathcal{I}_{\rm NDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NDI}\mathcal{I}_{\rm NVI}}(k) \\ \mathcal{P}_{\mathcal{I}_{\rm NVI}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NVI}\mathcal{I}_{\rm CDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NVI}\mathcal{I}_{\rm NDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NVI}\mathcal{I}_{\rm NVI}}(k) \end{pmatrix}$$

Isocurvature: best fits



- result driven by "low" l<40 (data prefer anticorrelated isocurvature to fit Sachs-Wolfe amplitude), delta chisq ~ 4.6 improvement.

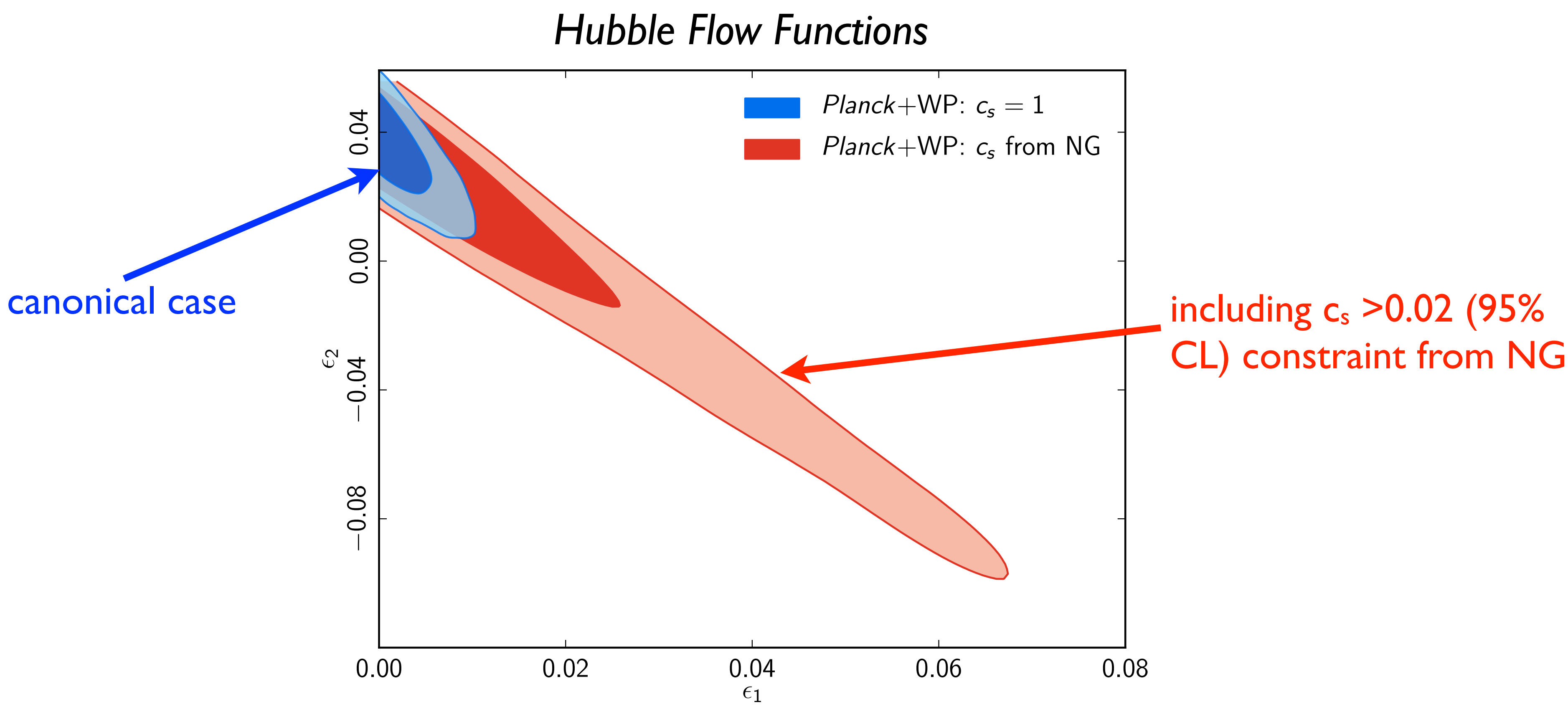
- interpret with care! peak phase shift not detected.

Joint constraints from 2-pt and 3-pt

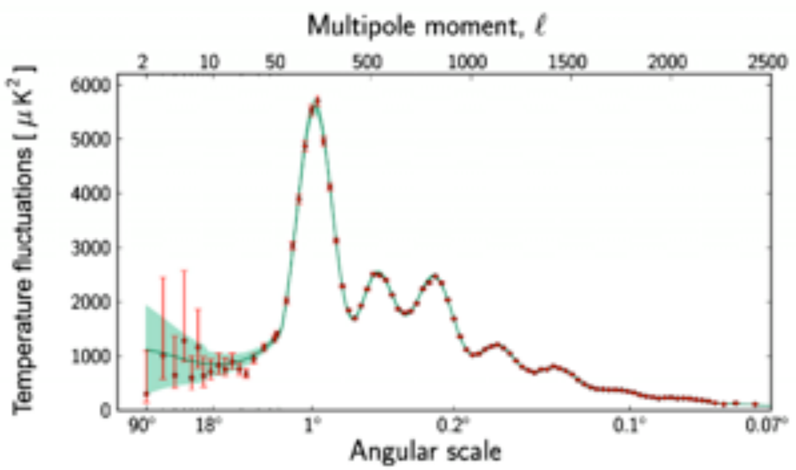
- Consider general class of inflationary models where Lagrangian is general function of the scalar inflaton field and its first derivative.

- 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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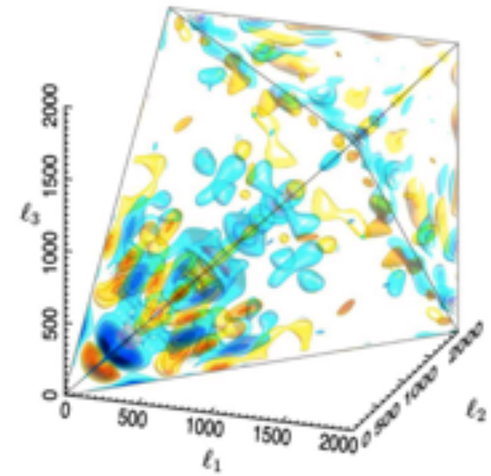


•**IR DBI**: DBI model where inflaton moves from IR to DBI side, with potential

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

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

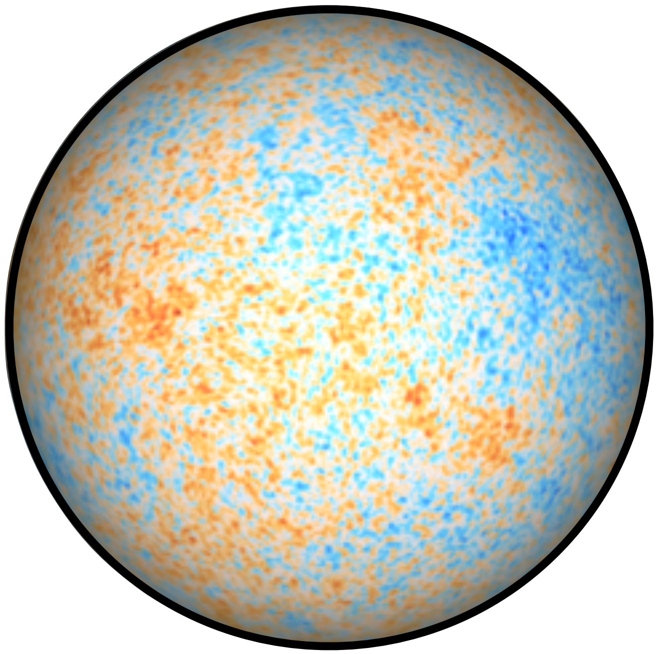
•**k-inflation**: One class depends on a single parameter γ (Amendariz-Picon et al, 99).

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

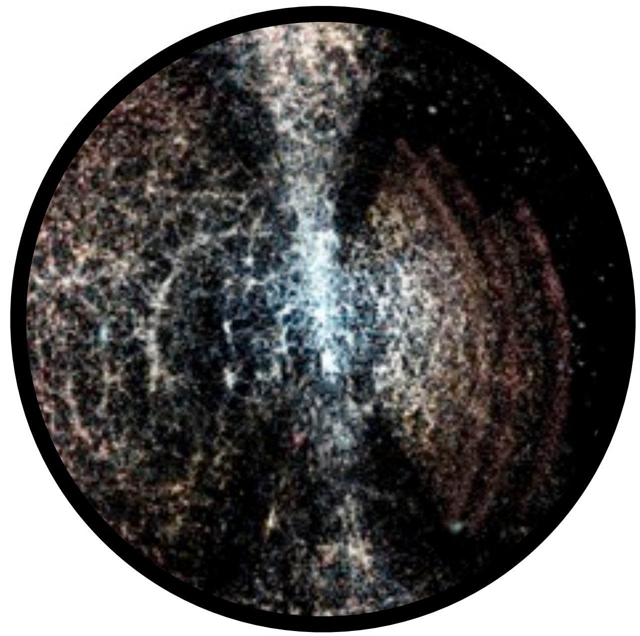
Planck f_{NL}(equil): $\gamma > 0.05$ (95% CL).

Inconsistent!

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



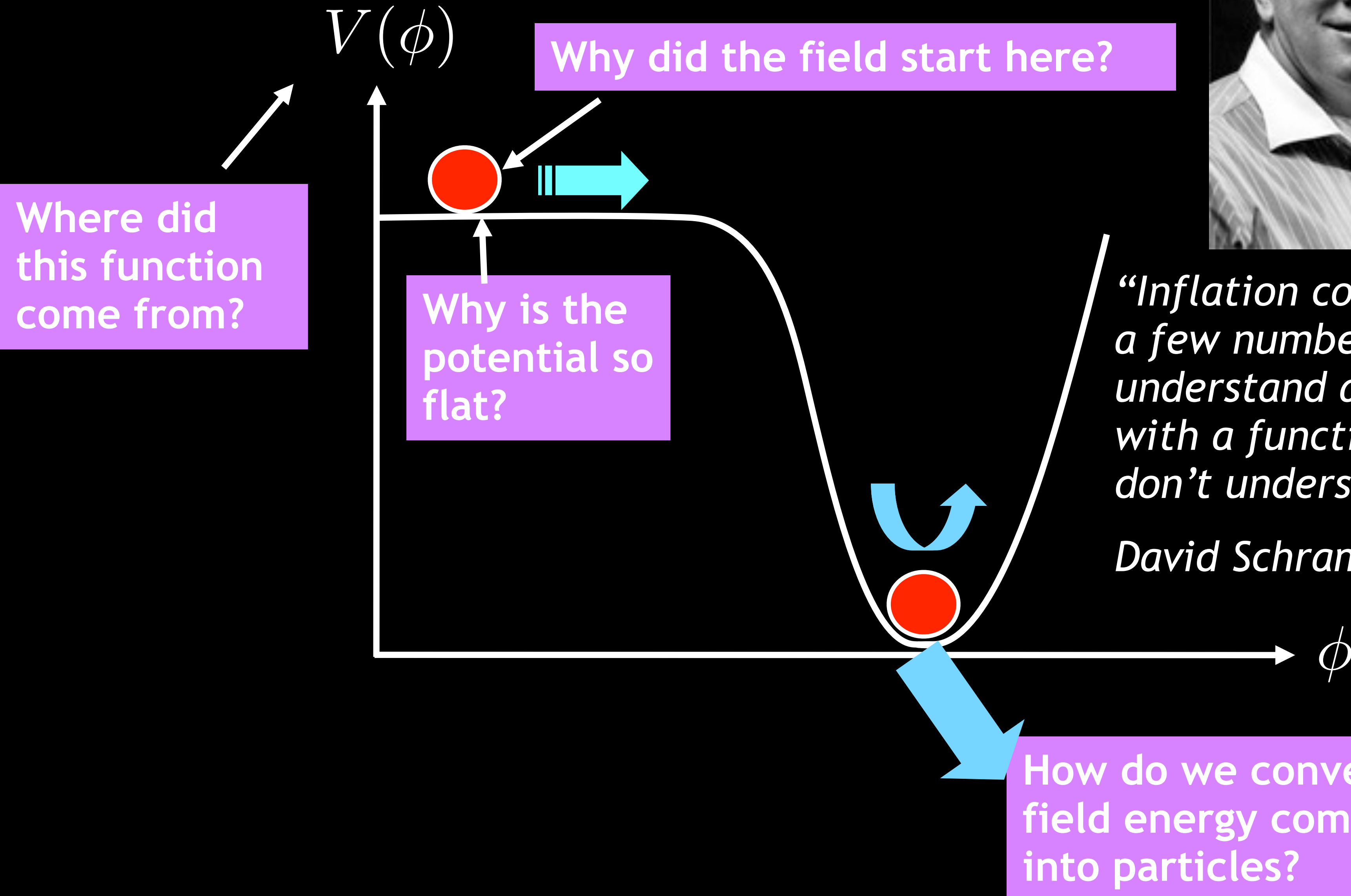
Cosmic Microwave Background
image: Planck



Large Scale Structure
image: SDSS

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

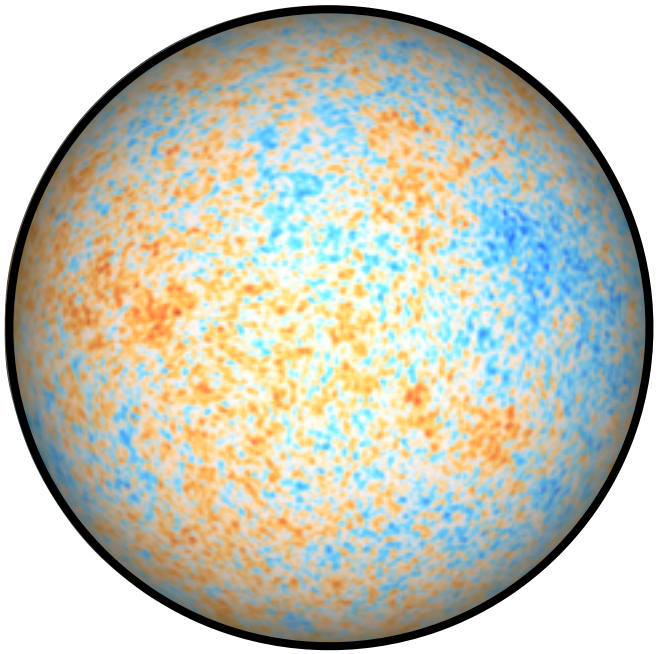
What is the physics of inflation?



"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

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



Cosmic Microwave Background
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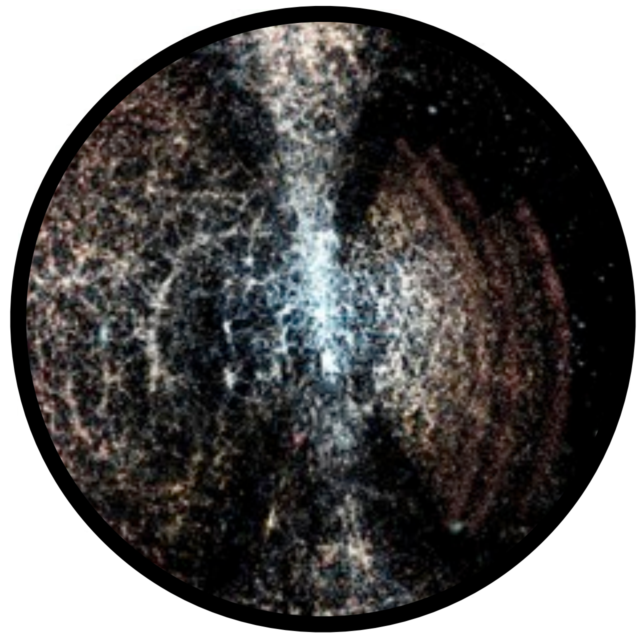
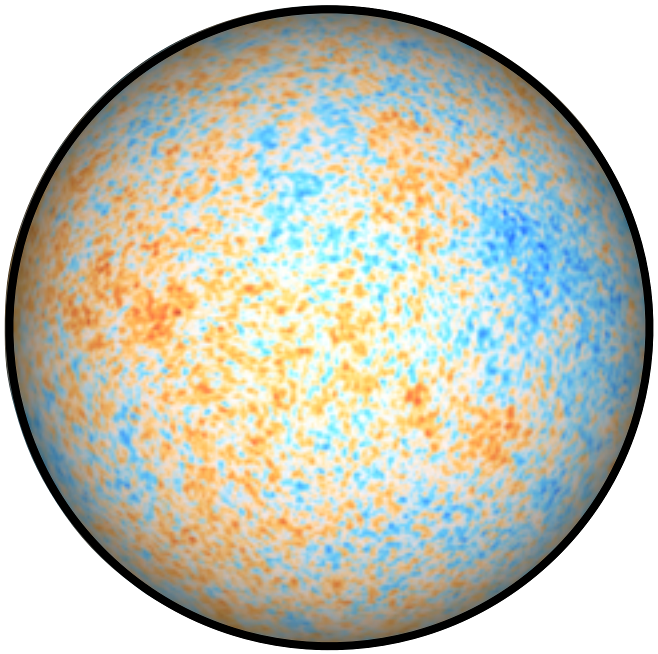


Large Scale Structure
image: SDSS

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?



Cosmic Microwave Background
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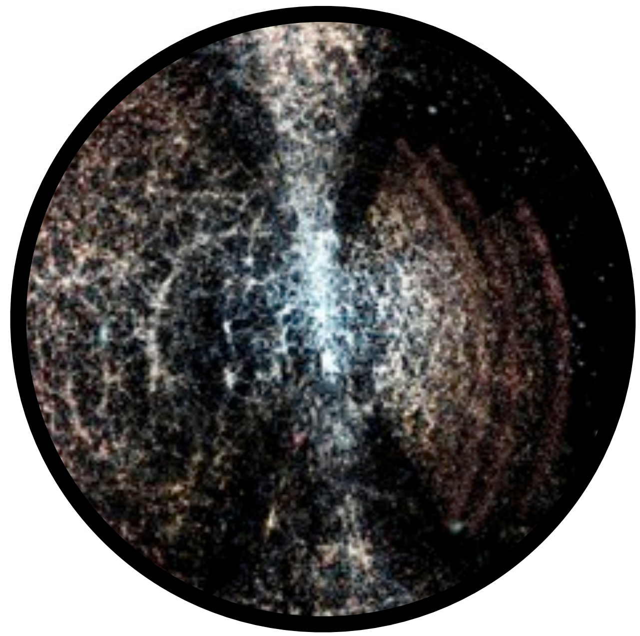

Large Scale Structure
image: SDSS

Does inflation work in principle?