

Testing inflationary models with Planck

Hiranya V. Peiris (UCL)
on behalf of
the Planck Collaboration

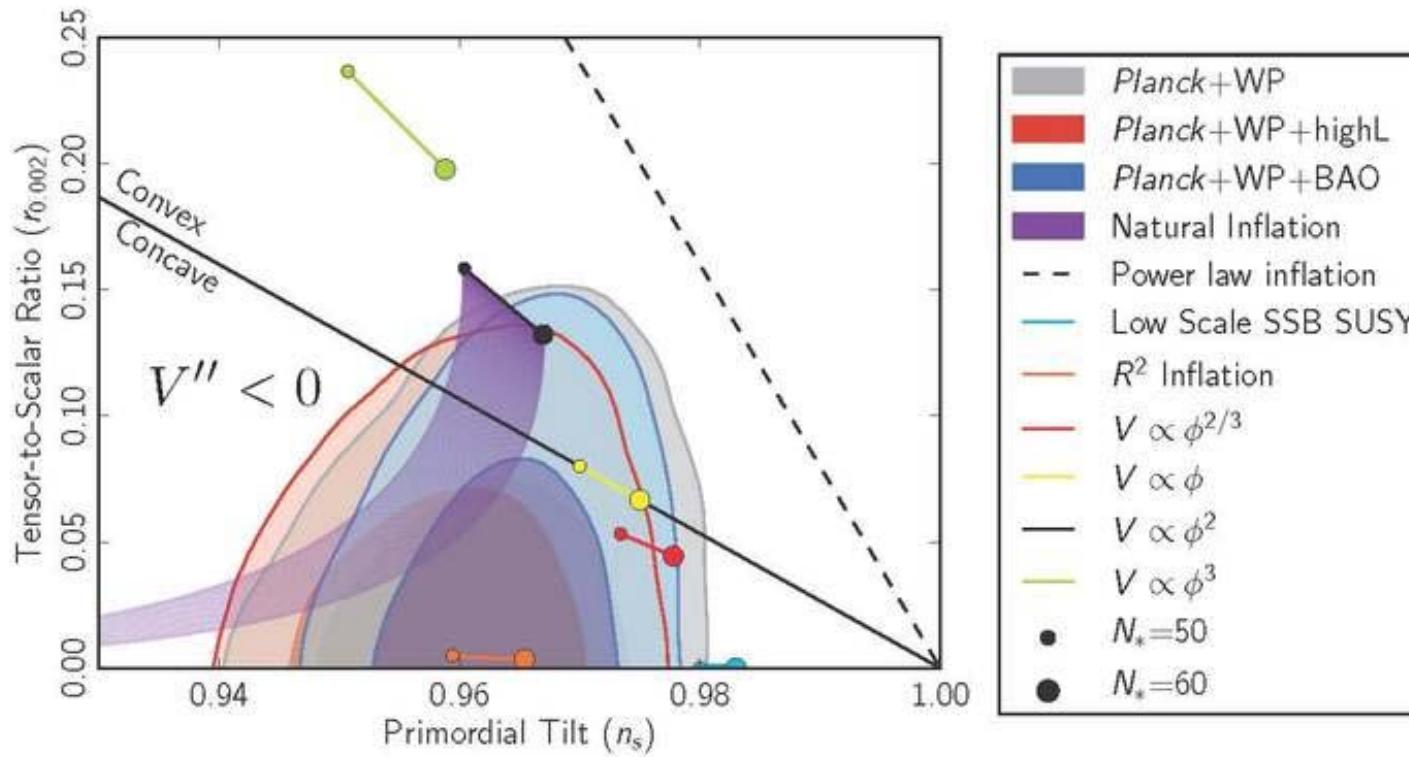
Planck 2013 Results XXII: Constraints on Inflation

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

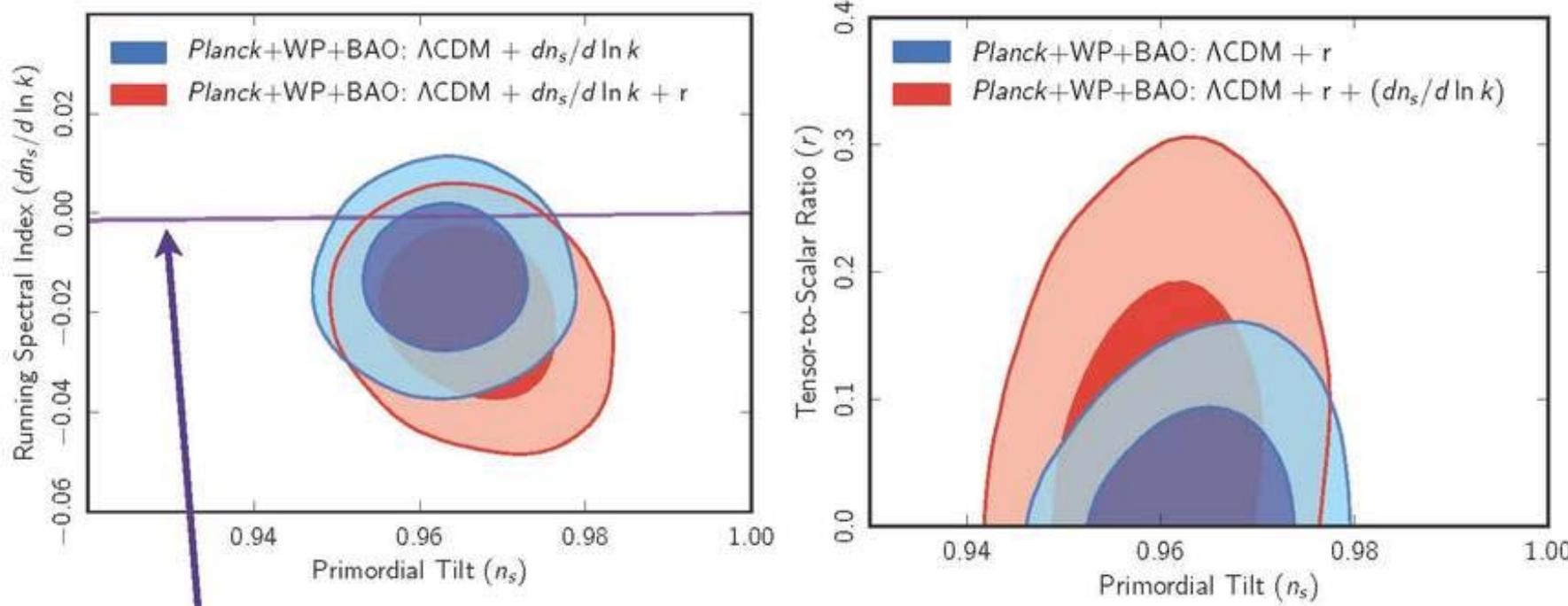
Energy scale of inflation: $V_* < (1.94 \times 10^{16} \text{ GeV})^4$

Ruling out exact scale invariance

	HZ	HZ + Y_p	HZ + N_{eff}	Λ CDM
$10^5 \Omega_b h^2$	2296 ± 24	2296 ± 23	2285 ± 23	2205 ± 28
$10^4 \Omega_c h^2$	1088 ± 13	1158 ± 20	1298 ± 43	1199 ± 27
$100 \theta_{\text{MC}}$	1.04292 ± 0.00054	1.04439 ± 0.00063	1.04052 ± 0.00067	1.04131 ± 0.00063
τ	$0.125^{+0.016}_{-0.014}$	$0.109^{+0.013}_{-0.014}$	$0.105^{+0.014}_{-0.013}$	$0.089^{+0.012}_{-0.014}$
$\ln(10^{10} A_s)$	$3.133^{+0.032}_{-0.028}$	$3.137^{+0.027}_{-0.028}$	$3.143^{+0.027}_{-0.026}$	$3.089^{+0.024}_{-0.027}$
n_s	—	—	—	0.9603 ± 0.0073
N_{eff}	—	—	3.98 ± 0.19	—
Y_p	—	0.3194 ± 0.013	—	—
$-2\Delta \ln(\mathcal{L}_{\text{max}})$	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 $k=0.04 \text{ Mpc}^{-1}$.

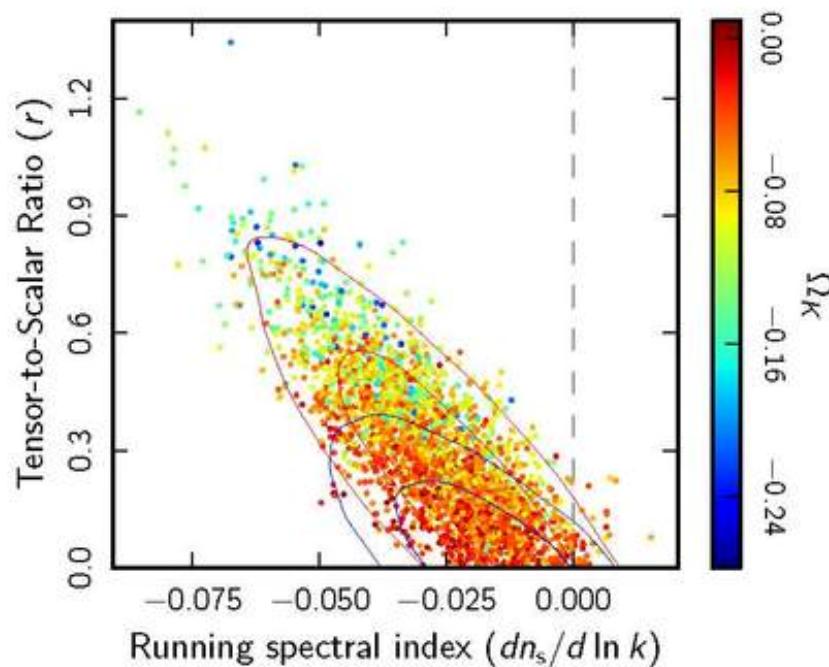
$$\text{Planck+WP: } dn_s/d \ln k = -0.013 \pm 0.009$$

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;
- positive curvature (closed universe) much harder to get in inflationary paradigm.

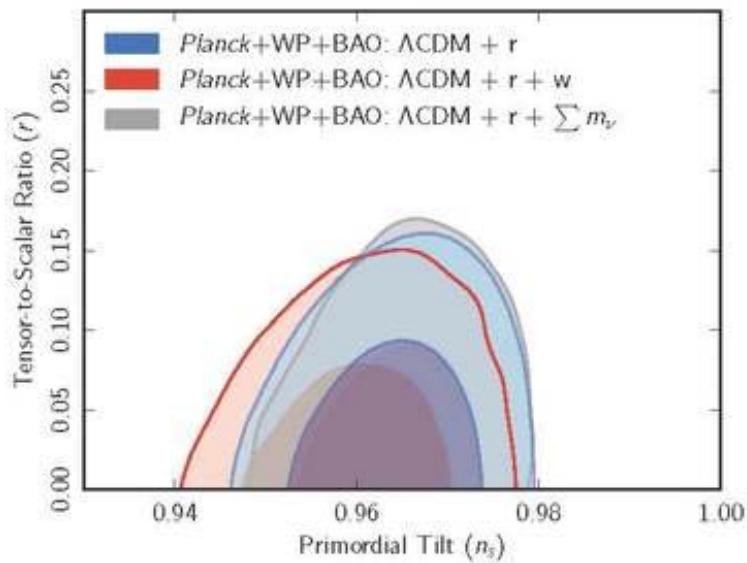
$$\Omega_K = -0.0004 \pm 0.0036$$

(Planck+WP+BAO)

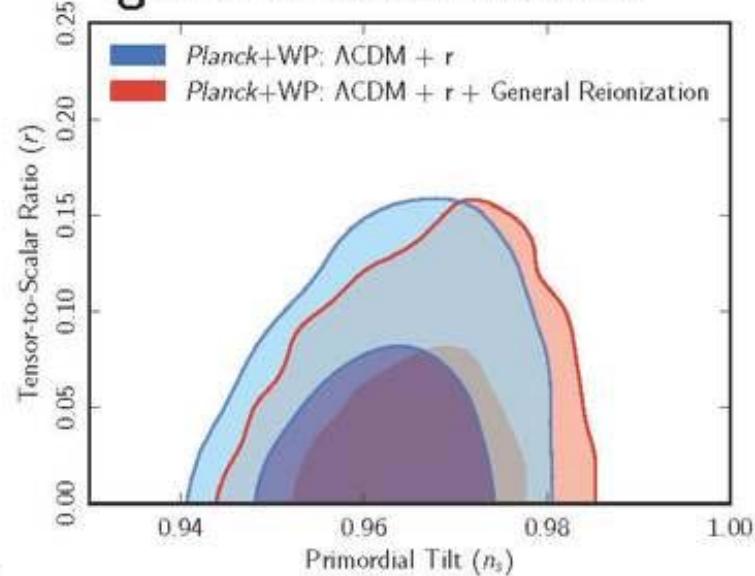


Robustness to cosmological model

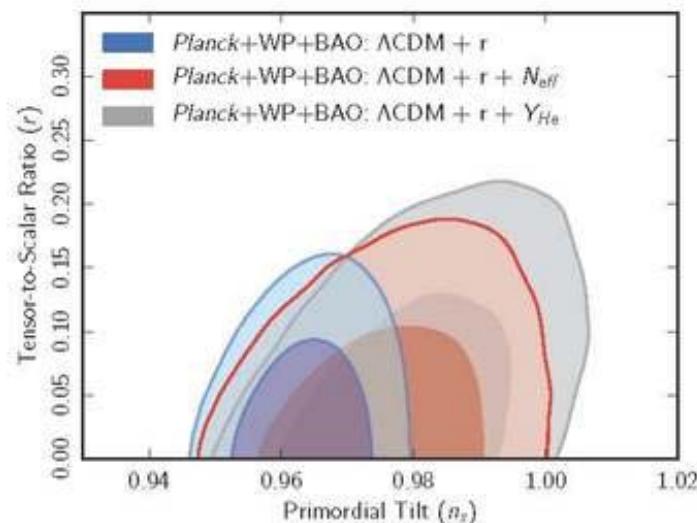
dark energy, v mass



general reionization

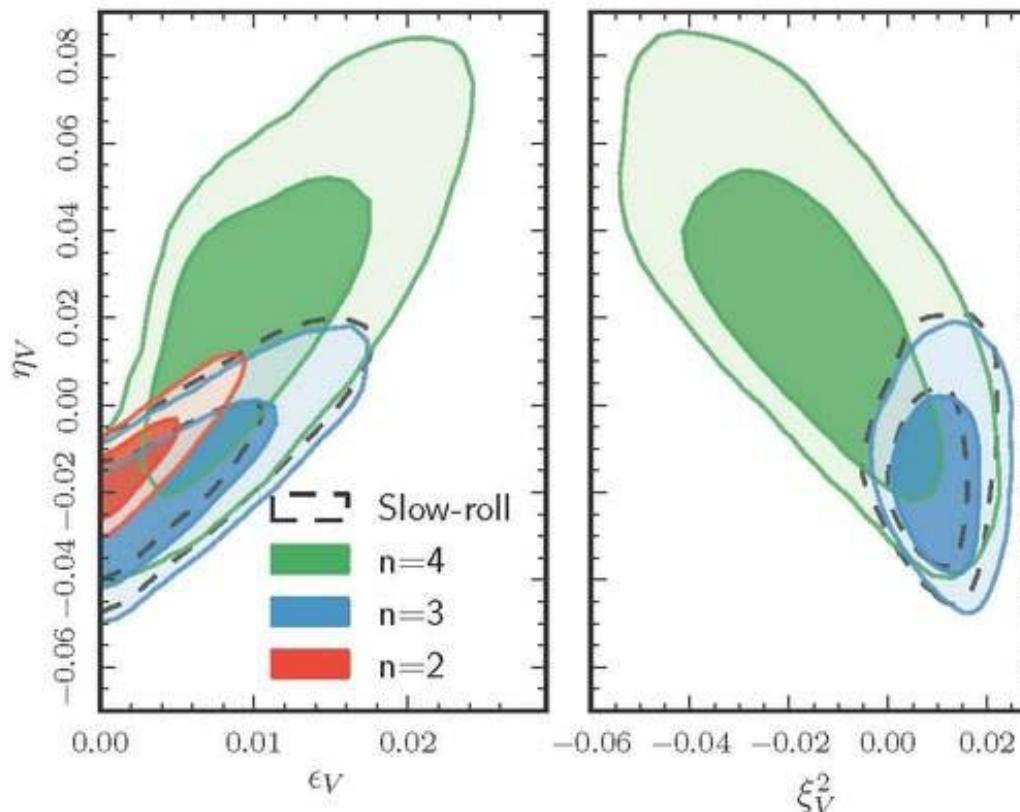


$N_{\text{eff}}, Y_{\text{He}}$

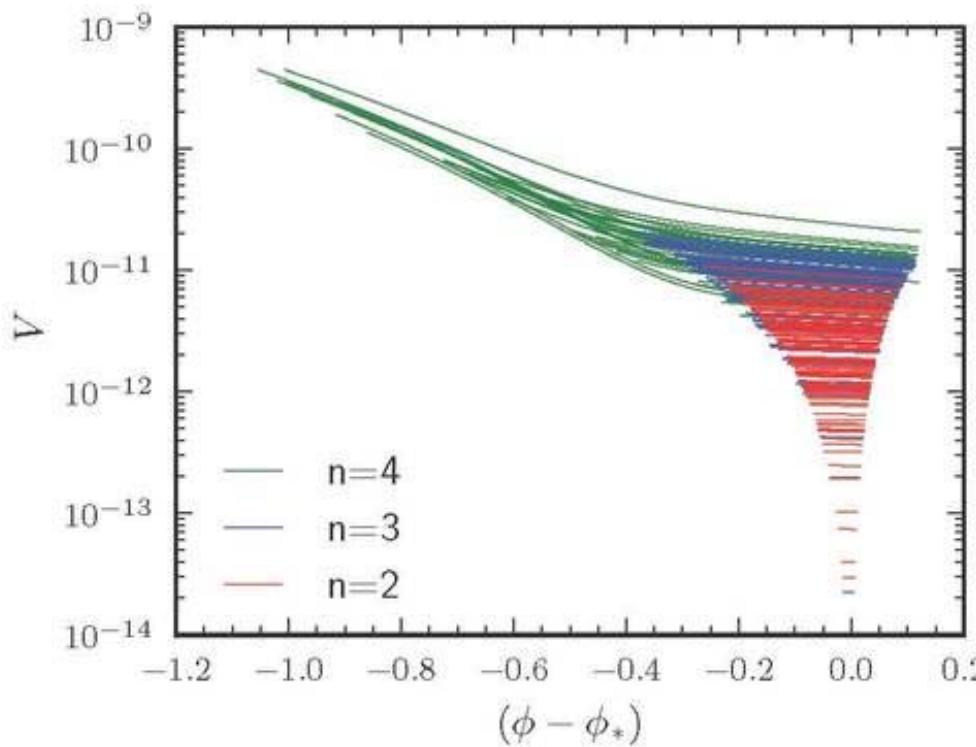


Observable window of inflation

- Taylor expansion of $V(\varphi)$ 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



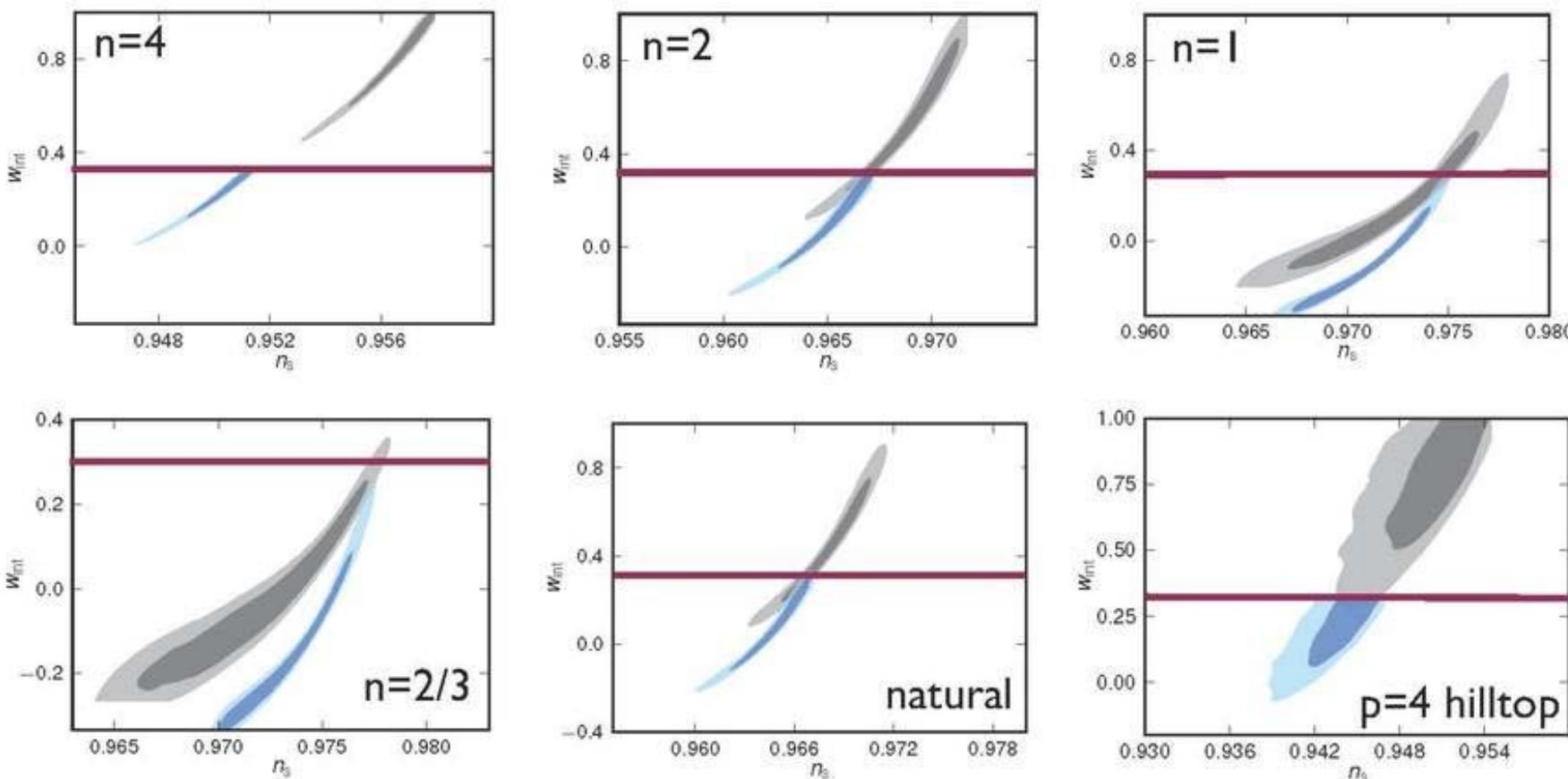
- Preference for concave potentials
- $n=4$ case exhibits running of running (acts to resolve low ell tension)
- sparsity of potentials with low V_0 reflects flat prior on V_0 rather than $\ln(V_0)$

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.

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

Constraints on post-inflationary epoch



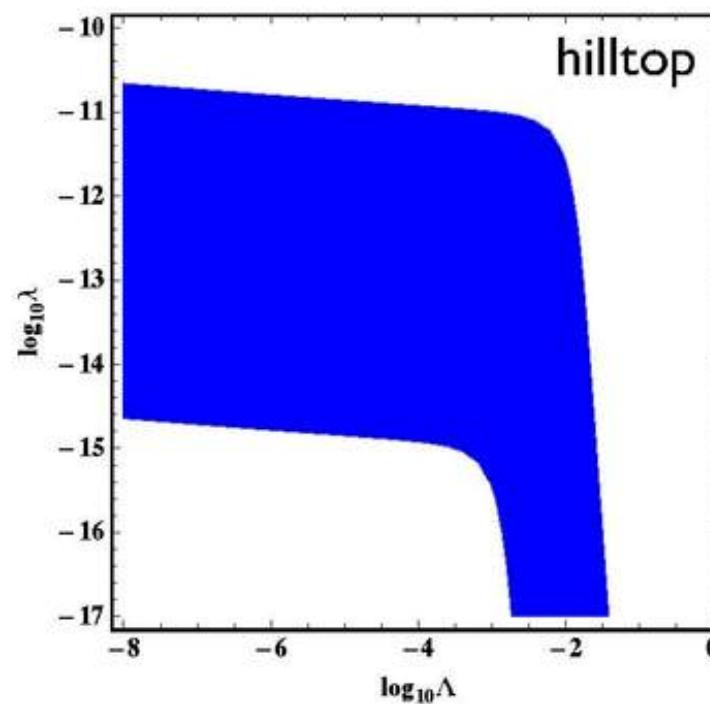
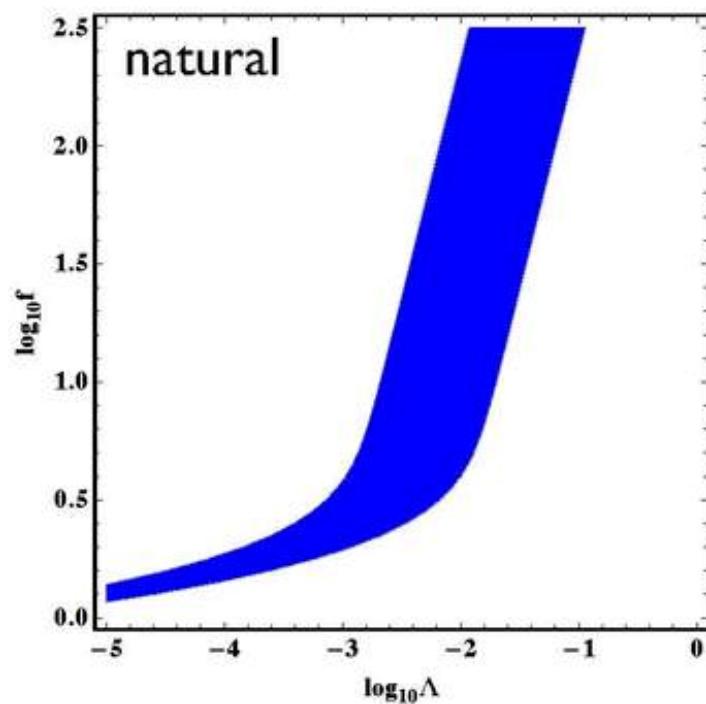
restrictive entropy generation

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

permissive entropy generation

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

Constraints on specific models: examples I

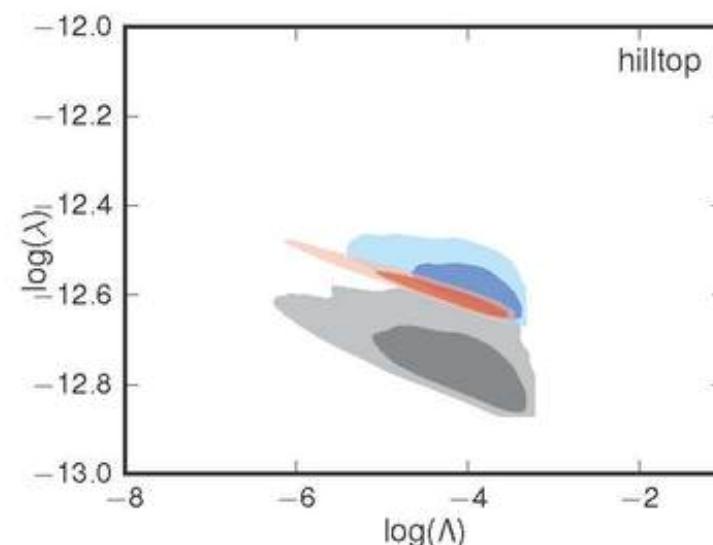
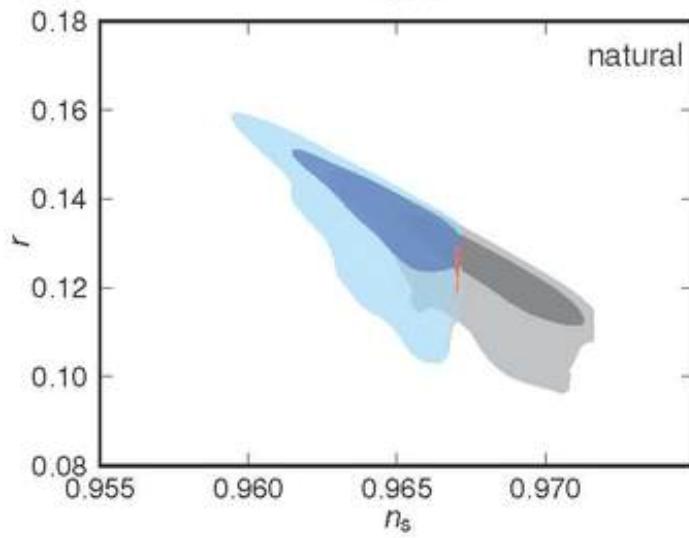
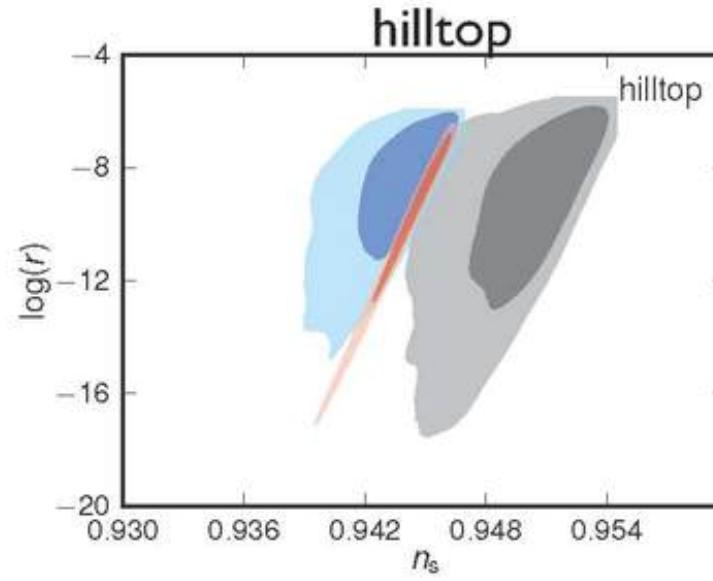
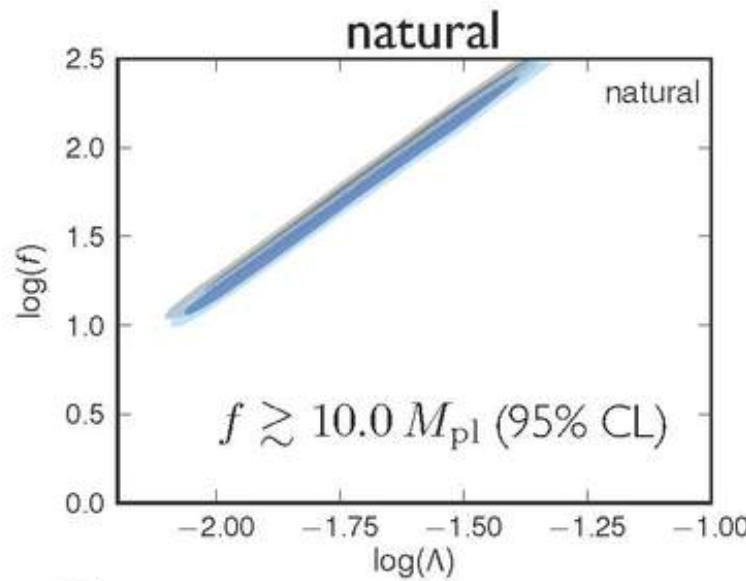


$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right) \right]$$

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

natural units in reduced Planck mass

Constraints on specific models: examples II



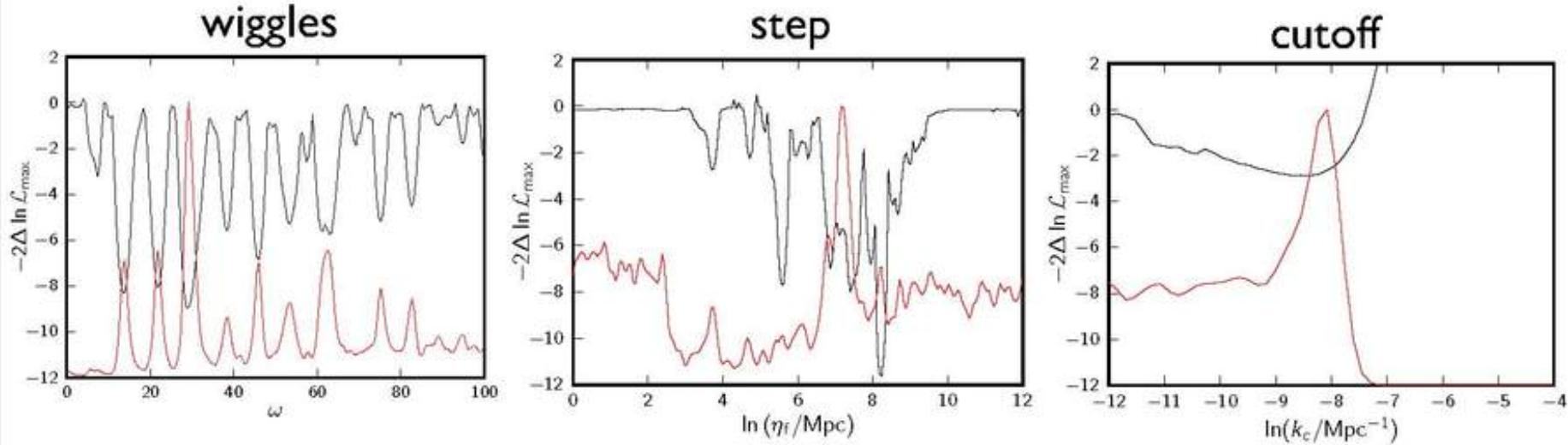
instant / restrictive / permissive entropy generation

Parametric searches for features in the primordial spectrum

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

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

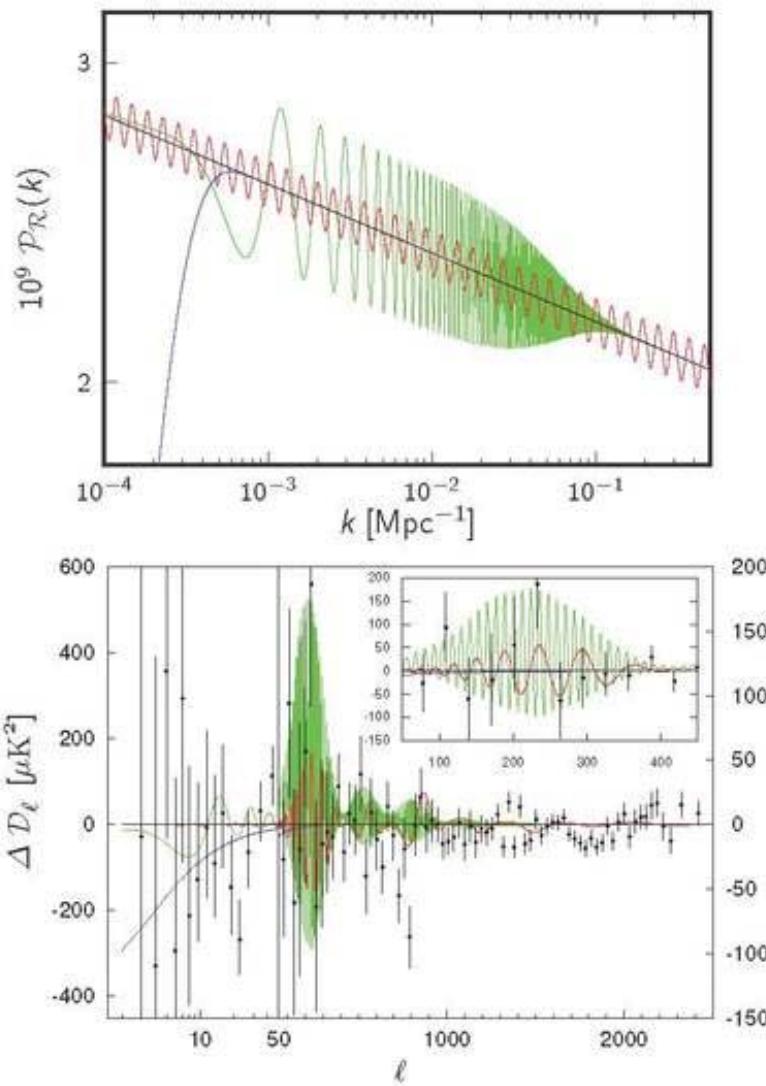
cutoff: $\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k) \left\{ 1 - \exp \left[- \left(\frac{k}{k_c} \right)^{\lambda_c} \right] \right\}$



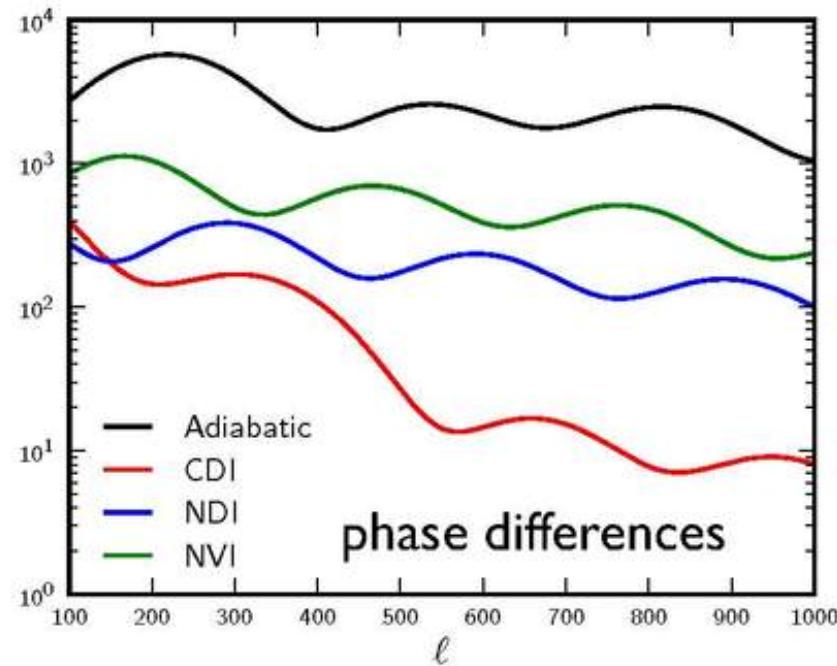
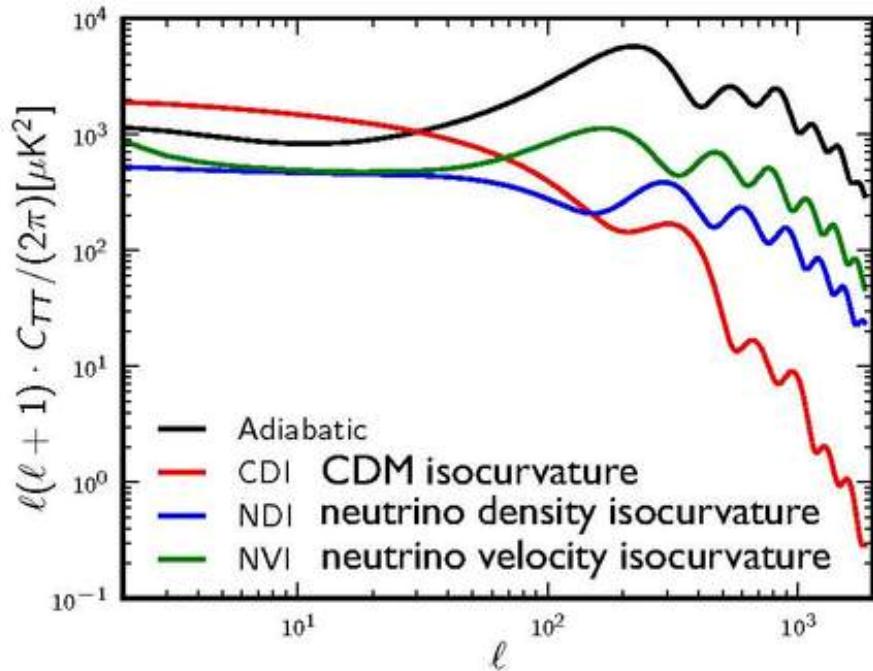
Parametric searches for features in the primordial spectrum

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?
- Complementary non-parametric search performed (see paper!)

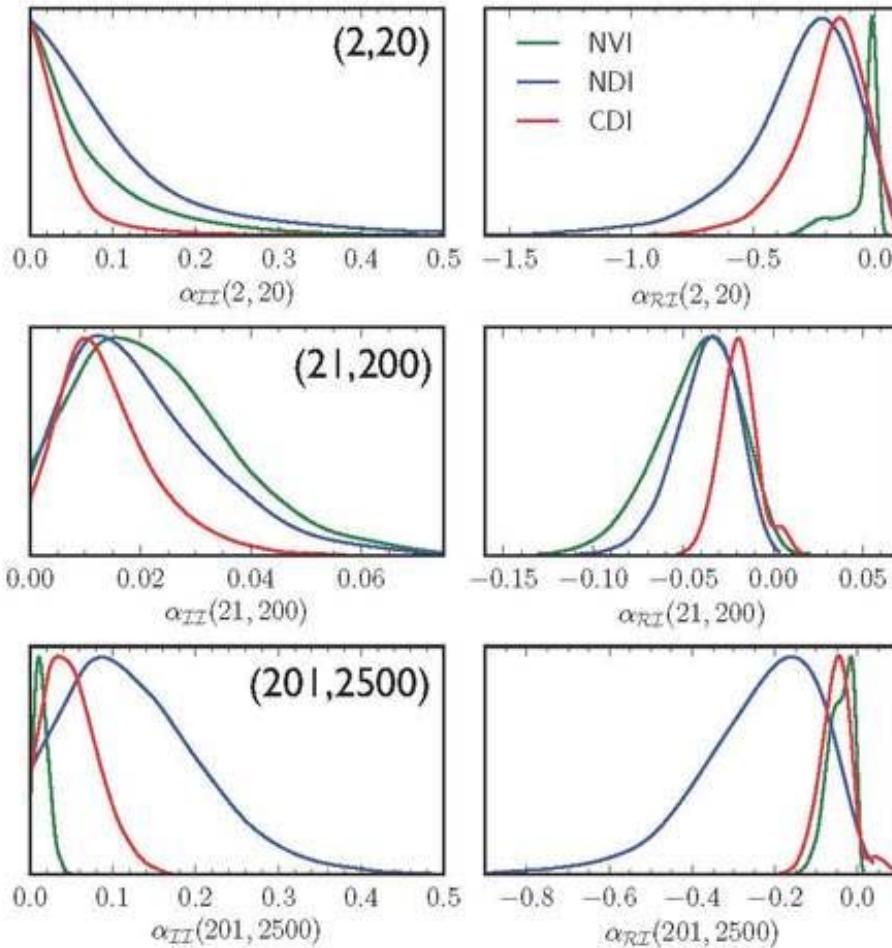


Isocurvature: spectra



- 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



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

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

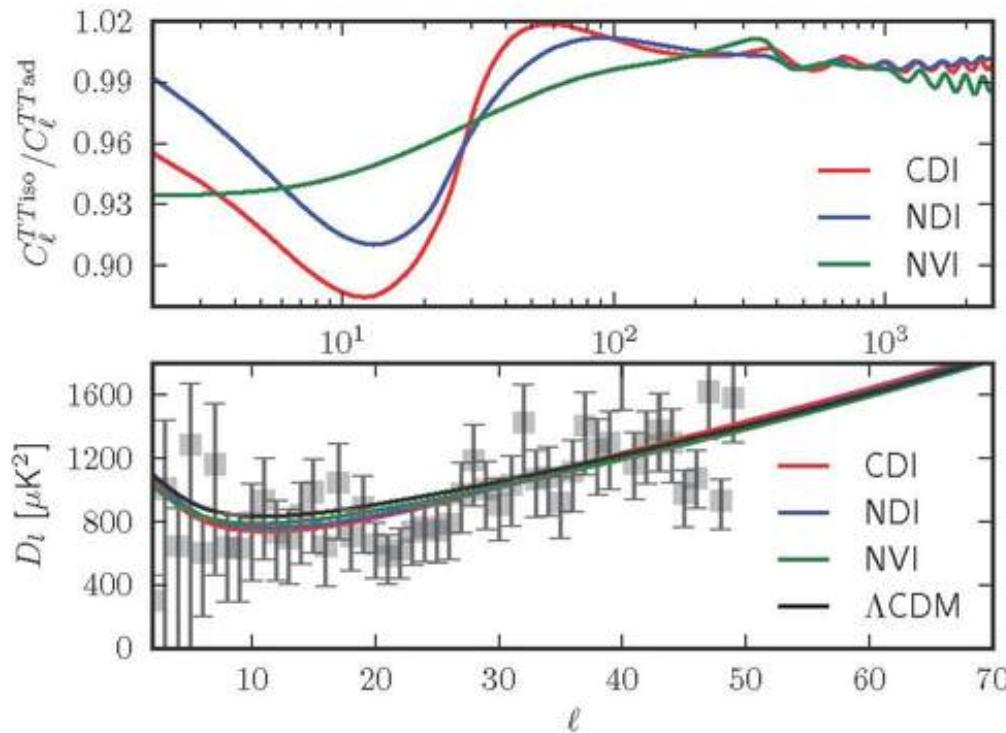
$$\alpha_{II}(\ell_{\min}, \ell_{\max}) = \frac{(\Delta T)_{II}^2(\ell_{\min}, \ell_{\max})}{(\Delta T)_{\text{tot}}^2(\ell_{\min}, \ell_{\max})},$$

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

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

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

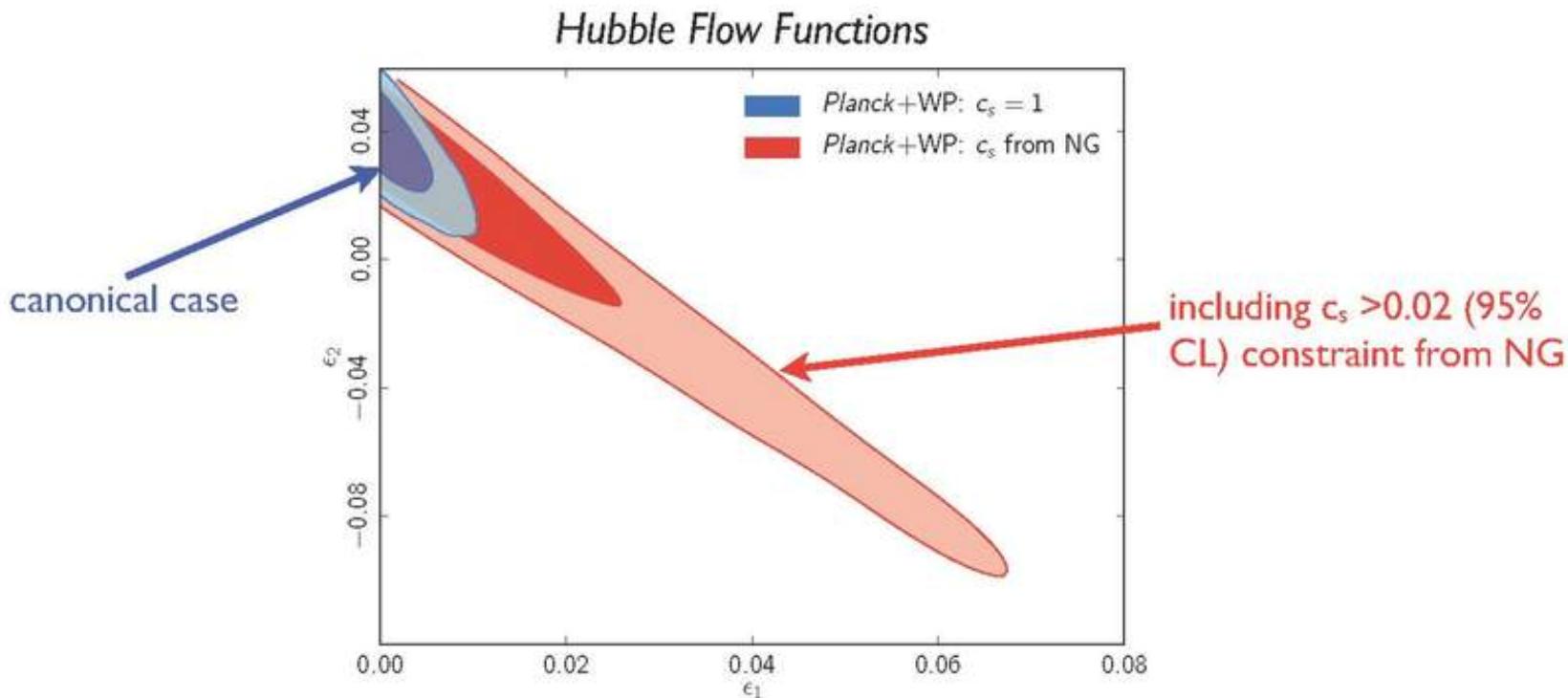
Isocurvature: best fits



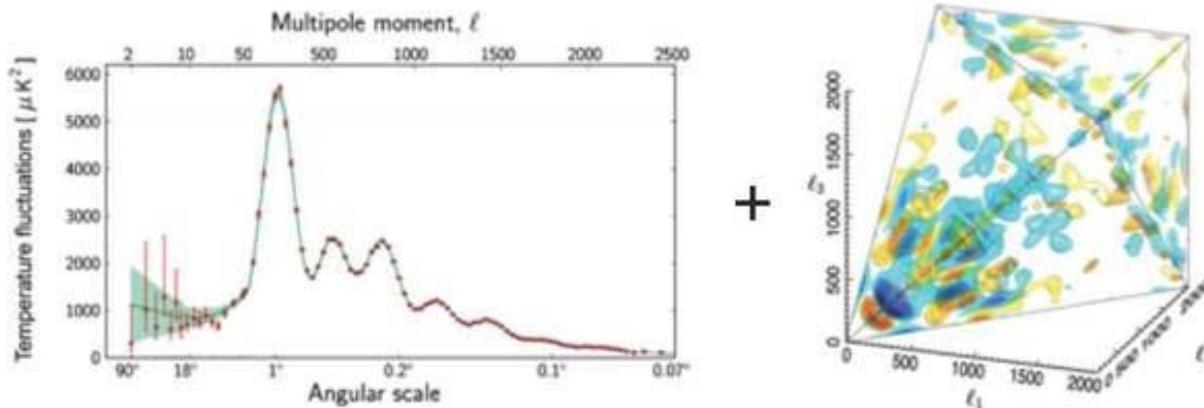
- result driven by “low” $|\ell| < 40$ (data prefer anticorrelated isocurvature to fit Sachs-Wolfe amplitude), $\Delta \chi^2 \sim 4.6$ improvement.
- interpret with care! peak phase shift not detected.

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 $(A_s, \epsilon_1, \epsilon_2, c_s)$ assuming constant sound speed **degenerate** without NG info.



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



- **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 $n_s + f_{NL}(\text{DBI})$ constrains $\beta < 0.7$ (95% CL).

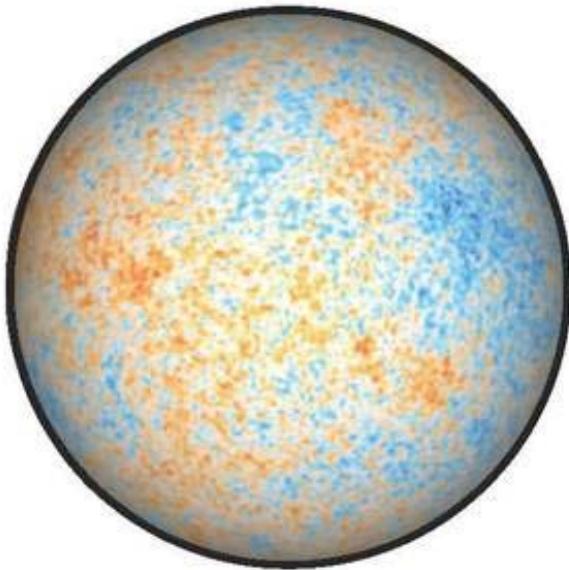
- **k-inflation:** One class depends on a single parameter γ (Amendariz-Picon et al, 99).

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

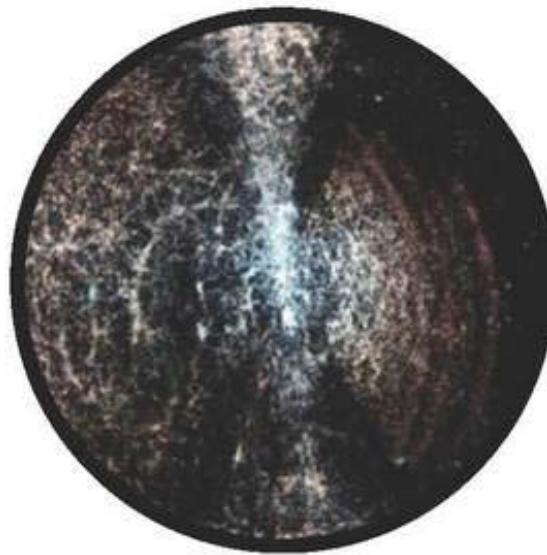
Planck $f_{NL}(\text{equil})$: $\gamma > 0.05$ (95% CL).

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!