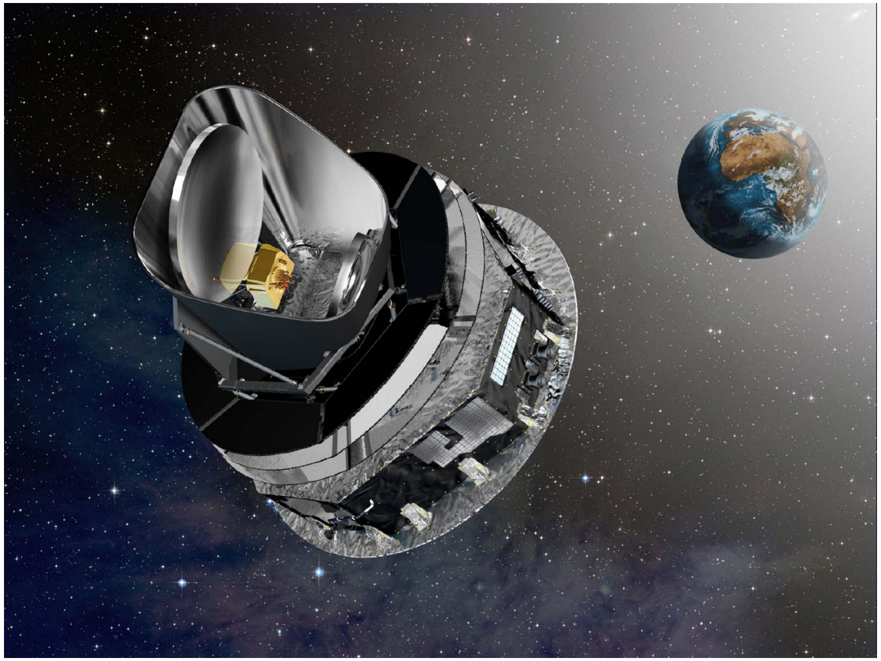


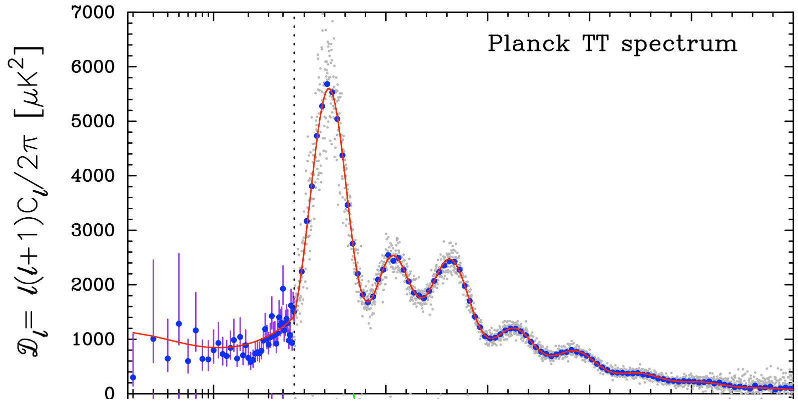
Planck implications for inflation

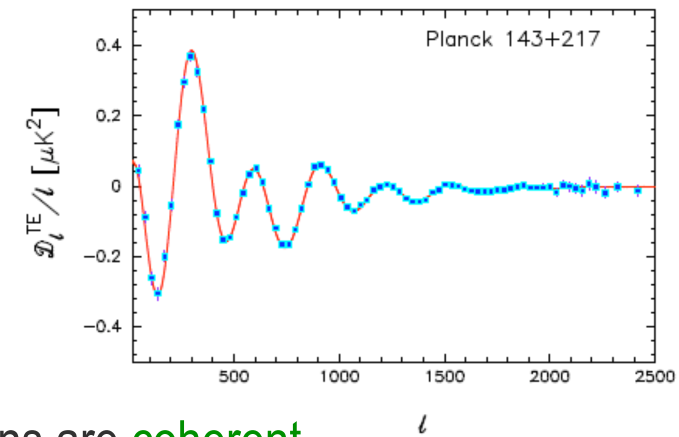
Invisible Universe TMR network, webinar, 18.06.2013

J. Lesgourgues (EPFL, CERN, LAPTh)

Why is inflation the favored paradigm?

- Fluctuations are correlated on scales that are super-Hubble at decoupling: Sachs-Wolfe plateau in temperature, and even more clear, large first multipoles in TE spectrum (while E-polarisation cannot come from integrated Sachs-Wolfe)



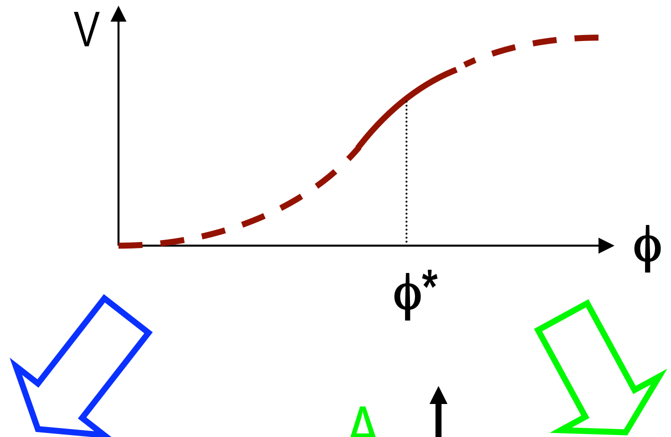


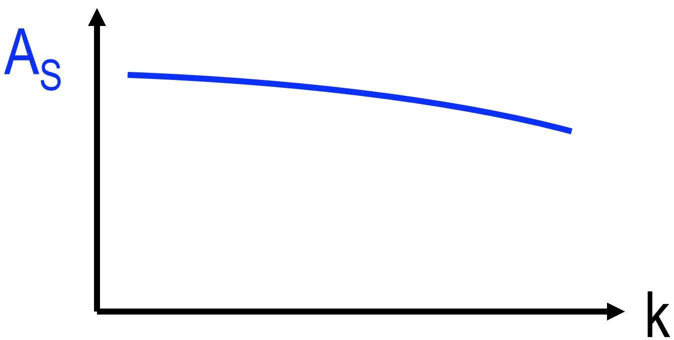
- Peak structure shows that acoustic oscillations are coherent
- Fluctuations seem to be nearly Gaussian, as in all simple inflationary models
- Peak location shows that early fluctuations are (at least mainly) adiabatic, as in single-field inflation
- At leading order, primordial spectrum close to scale-invariant

Slow-roll single-field inflation

Inflaton potential mapped

onto scalar/tensor spectra :



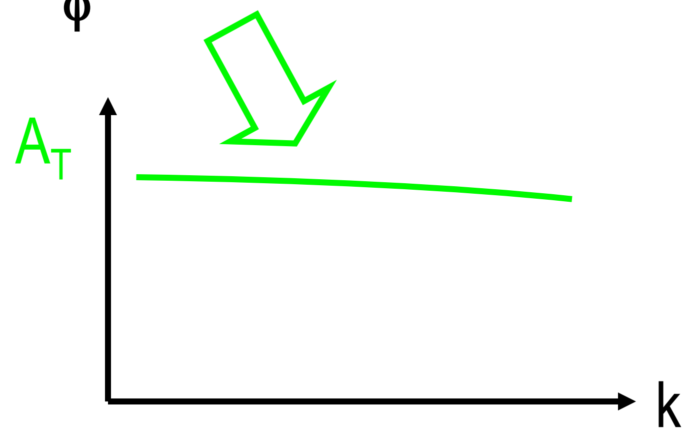


amplitude ↔ $V^{3/2}/V'$

tilt $(1-n_S)$ ↔ $(V'/V)^2$, V''/V

+ next-order corrections

(running of the tilt, …)



amplitude ↔ $V^{1/2}$

tilt n_T ↔ $(V'/V)^2$

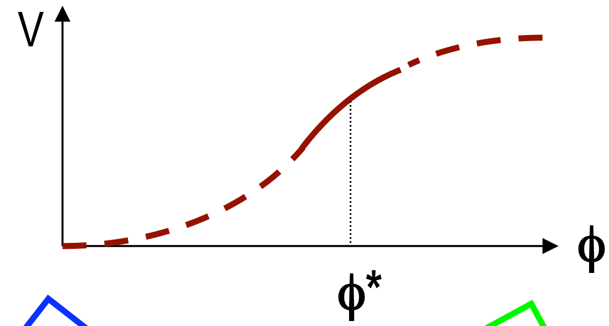
+ next-order corrections

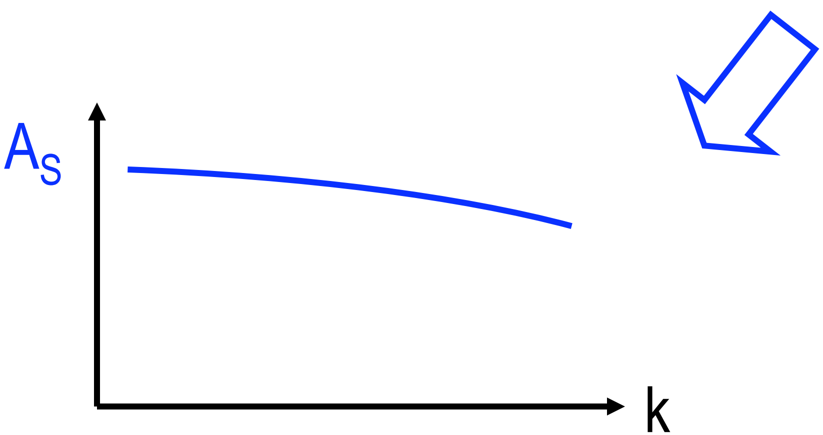
(running of the tilt, …)

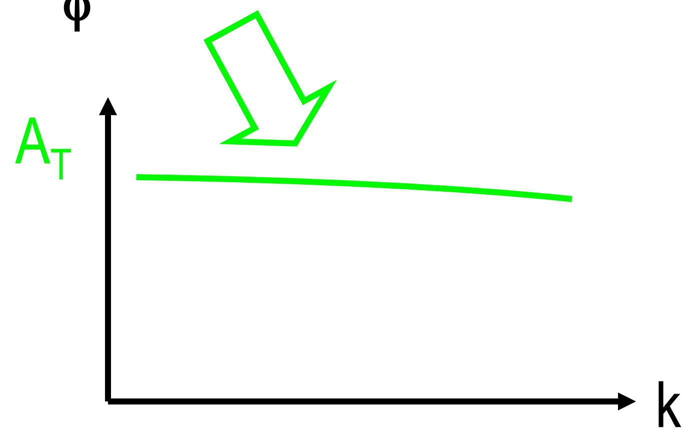
Slow-roll single-field inflation

Inflaton potential mapped

onto scalar/tensor spectra :







amplitude $\leftrightarrow$ $V^{3/2}/V'$

tilt $(1-n_S) \leftrightarrow (V'/V)^2 , V''/V$

+ next-order corrections

(running of the tilt, …)

Slow-roll expansion

amplitude $\leftrightarrow$ $V^{1/2}$

tilt $n_T \leftrightarrow (V'/V)^2$

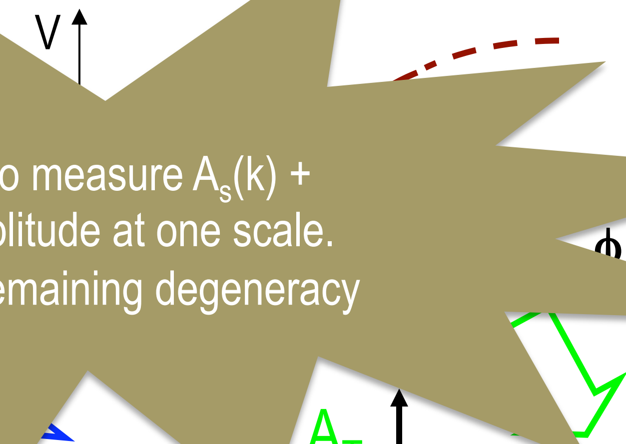
+ next-order corrections

(running of the tilt, …)

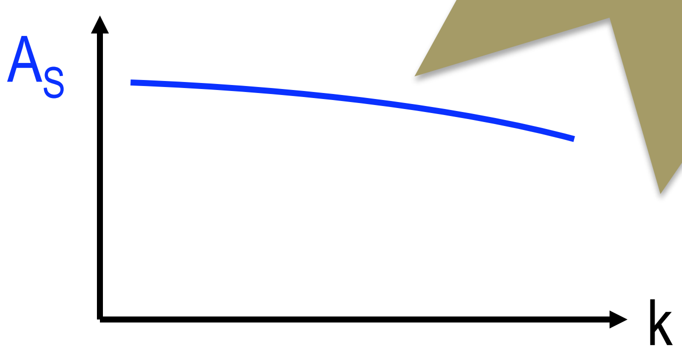
Slow-roll single-field inflation

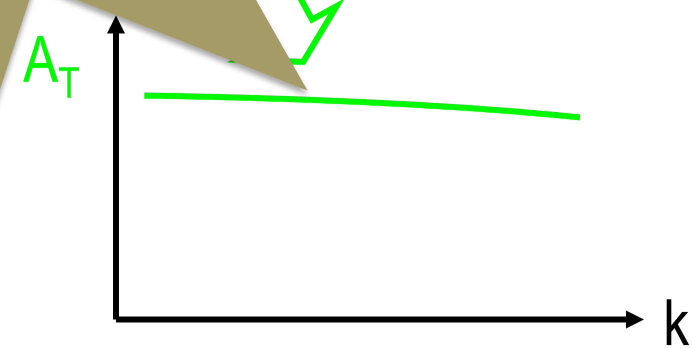
Inflaton poten... d

ont...



Need to measure $A_s(k)$ +
T/S amplitude at one scale.
If not… remaining degeneracy





amplitude ↔ $V^{3/2}/V'$

tilt $(1-n_S)$ ↔ $(V'/V)^2$, V''/V

+ next-order corrections

(running of the tilt, …)

amplitude ↔ $V^{1/2}$

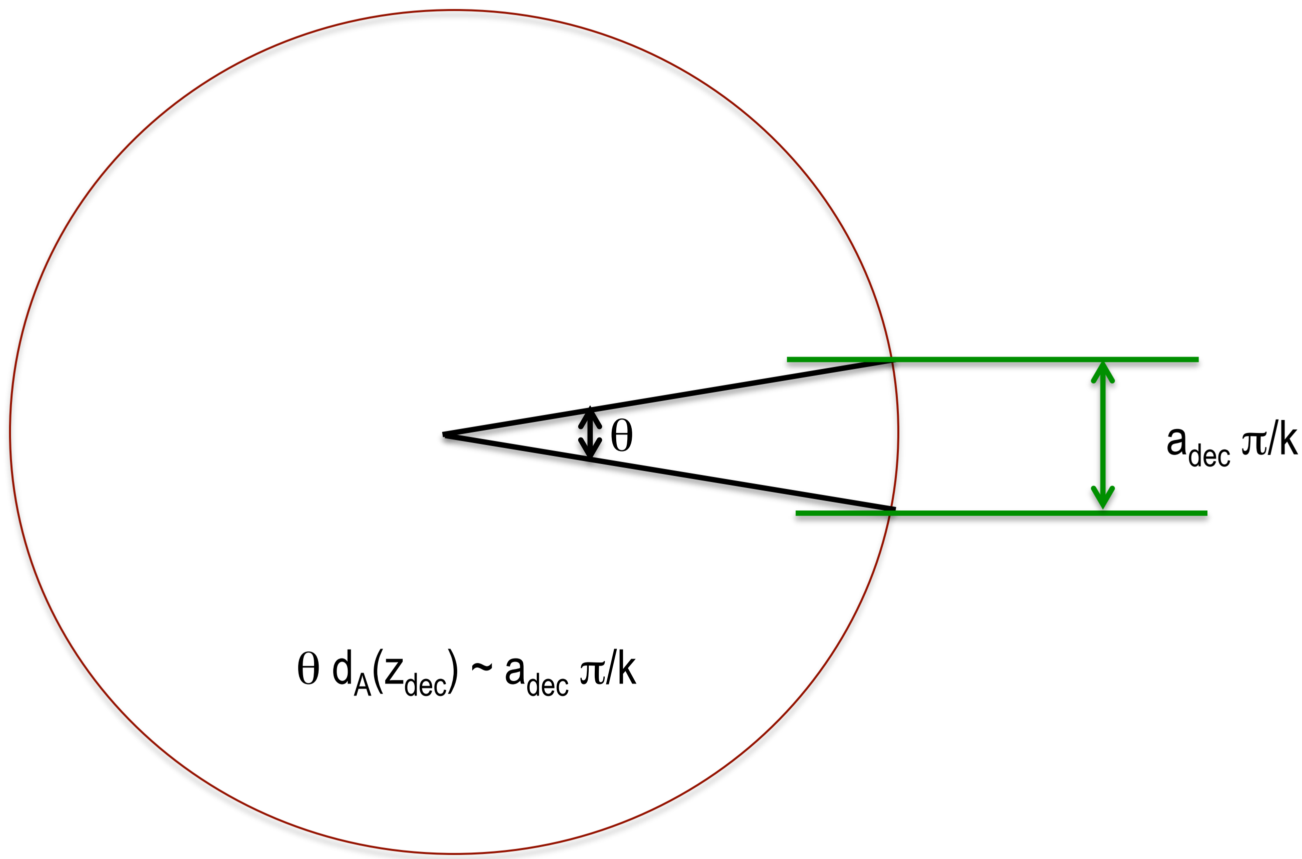
tilt n_T ↔ $(V'/V)^2$

+ next-order corrections

(running of the tilt, …)

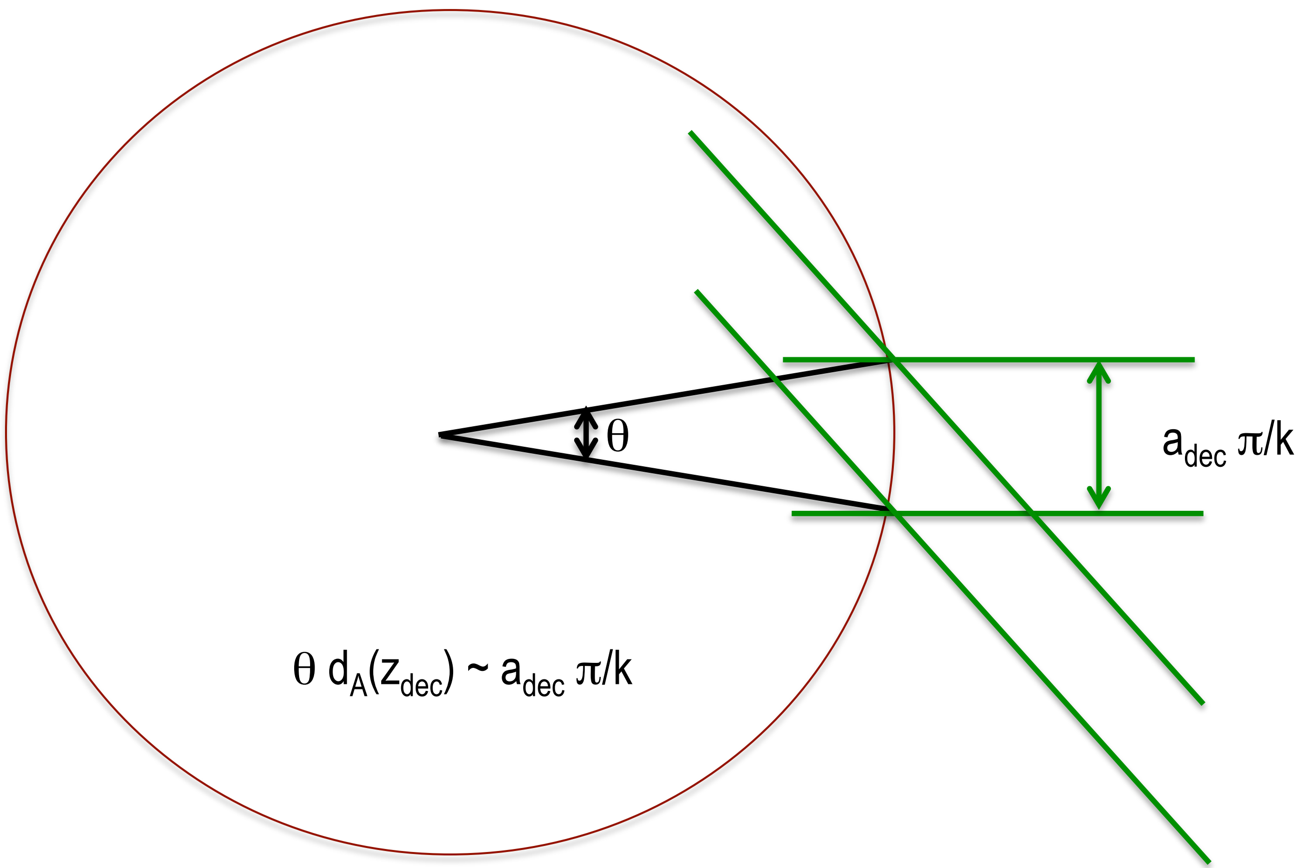
Slow-roll single-field inflation

- Scalar spectrum maps onto CMB temperature spectrum but in non-trivial way:



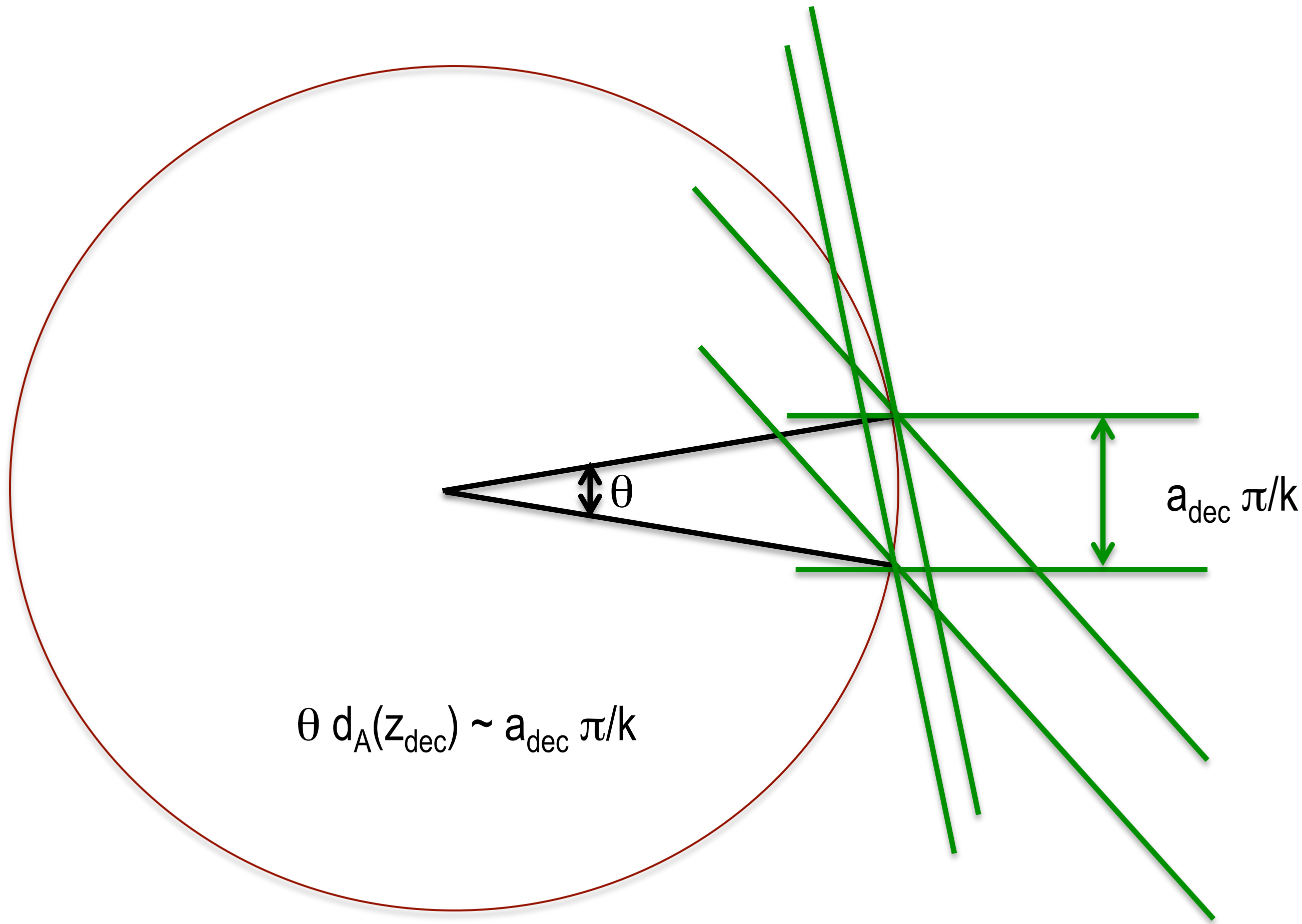
Slow-roll single-field inflation

- Scalar spectrum maps onto CMB temperature spectrum but in non-trivial way:



Slow-roll single-field inflation

- Scalar spectrum maps onto CMB temperature spectrum but in non-trivial way:



Slow-roll single-field inflation

- Scalar spectrum maps onto CMB temperature spectrum but in non-trivial way
- The same spectrum maps onto CMB E-polarisation

Slow-roll single-field inflation

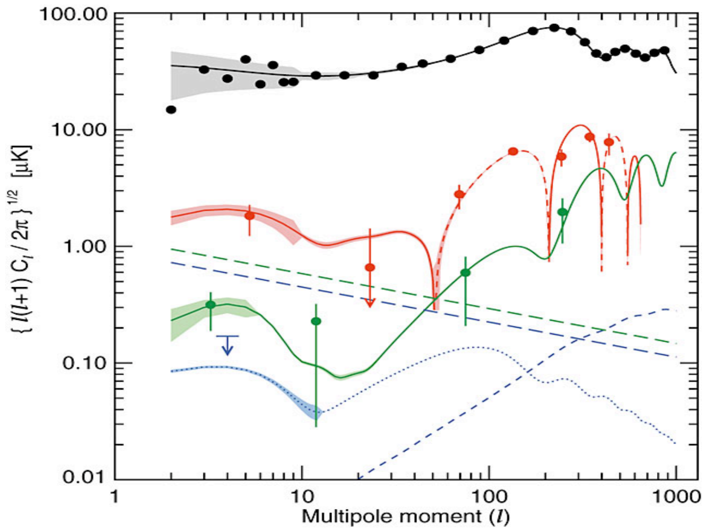
- Scalar spectrum maps onto CMB temperature spectrum but in non-trivial way
- The same spectrum maps onto CMB E-polarisation

- Tensor modes add up to the T and E spectrum. Appear as deficit of small scales versus large scales in T spectrum.

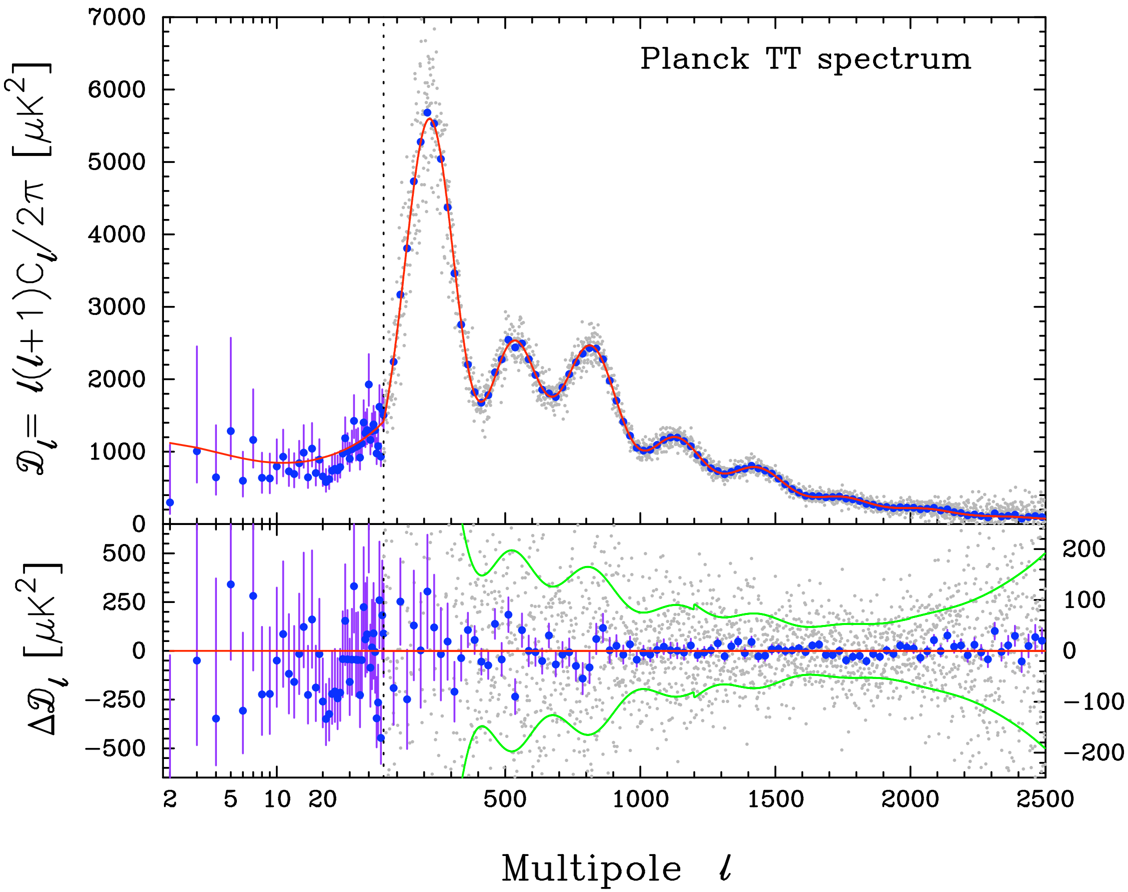
Slow-roll single-field inflation

- Scalar spectrum maps onto CMB temperature spectrum but in non-trivial way
- The same spectrum maps onto CMB E-polarisation

- Tensor modes add up to the T and E spectrum. Appear as deficit of small scales versus large scales in T spectrum.
- Tensors seed B-polarisation spectrum in a distinct way, but B-modes are much more difficult to measure than E-modes because they are smaller even for GUT-scale inflation… still little chance to see them with Planck

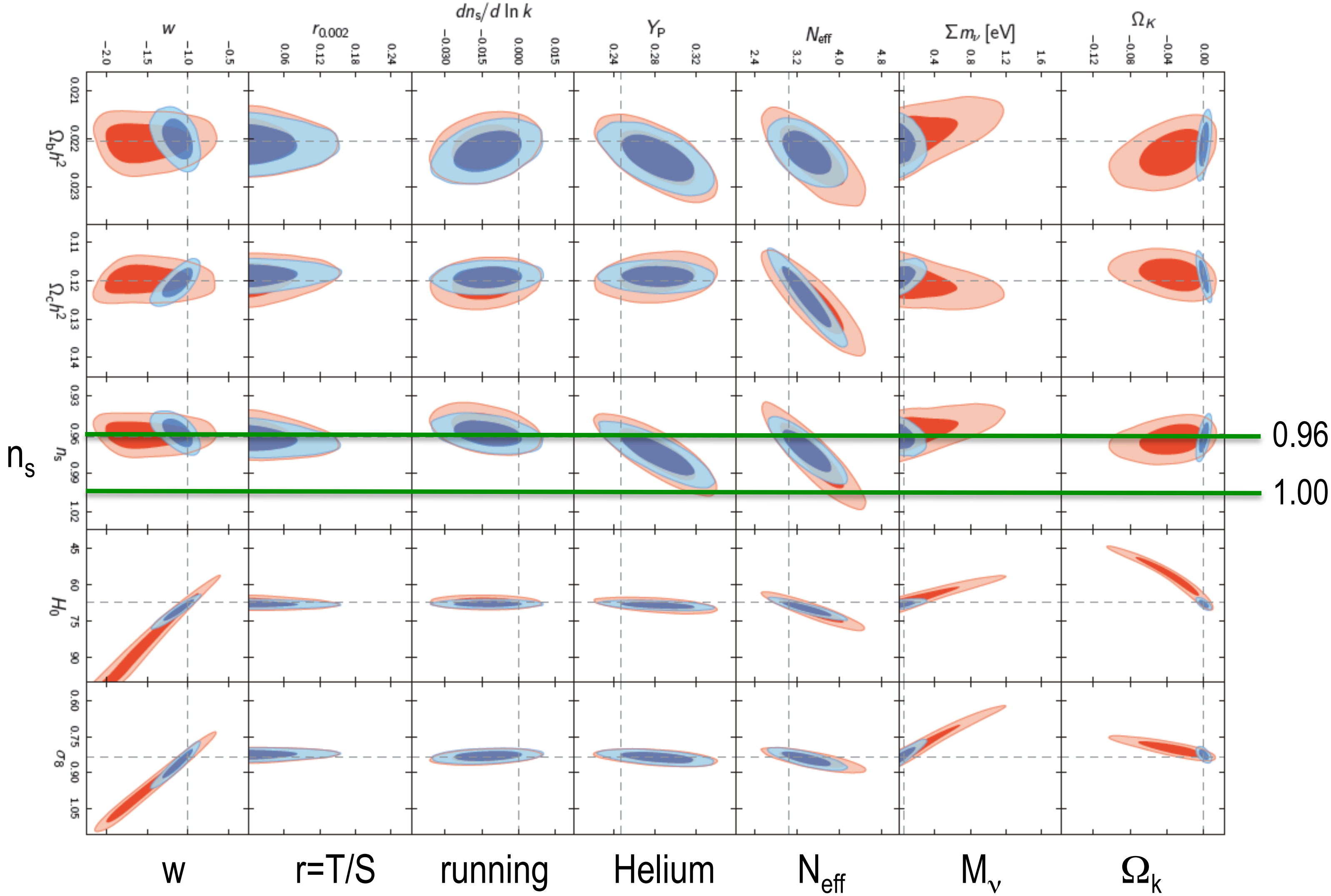


ΛCDM with power-law A_s is a good fit

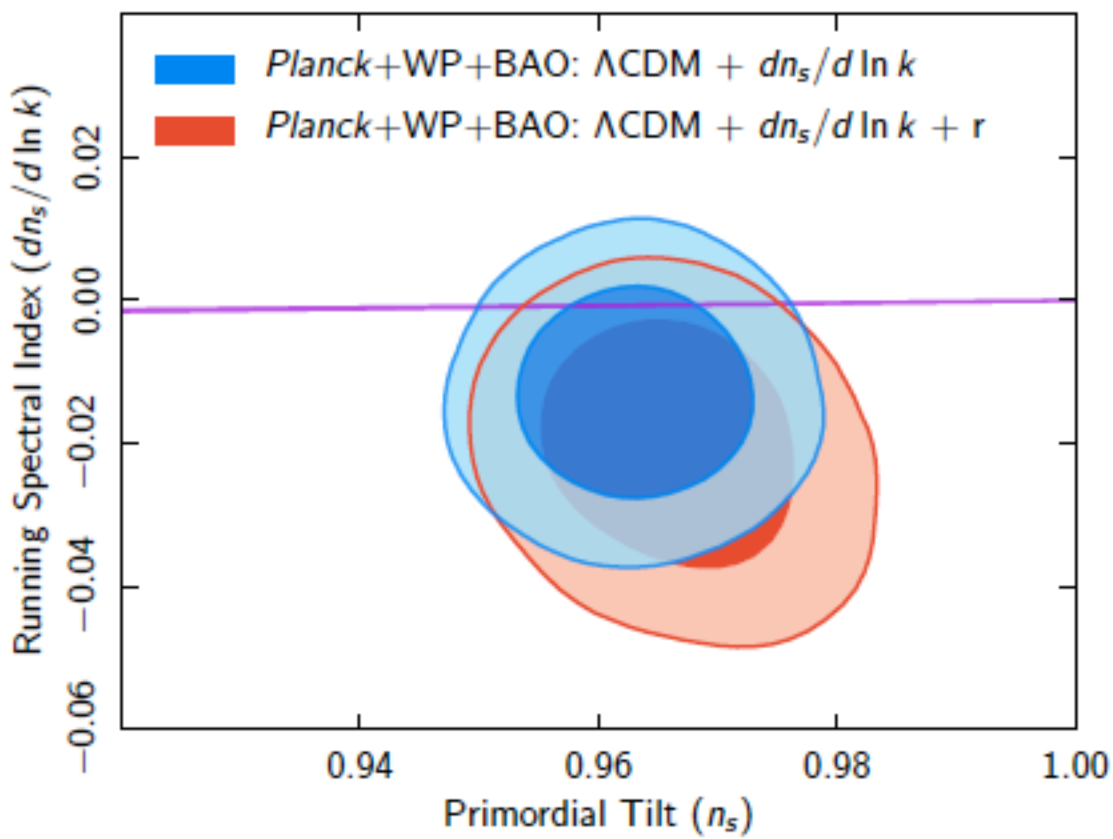


$n_s = 0.9603 \pm 0.0073$ (68%CL, Planck+WP), Harrison-Zel'dovitch is 5σ away

n_s< 1 is a robust result



Running spectral index not needed



Slow-roll single-field inflation

- We leave for the moment the possibility to constrain features or isocurvature modes

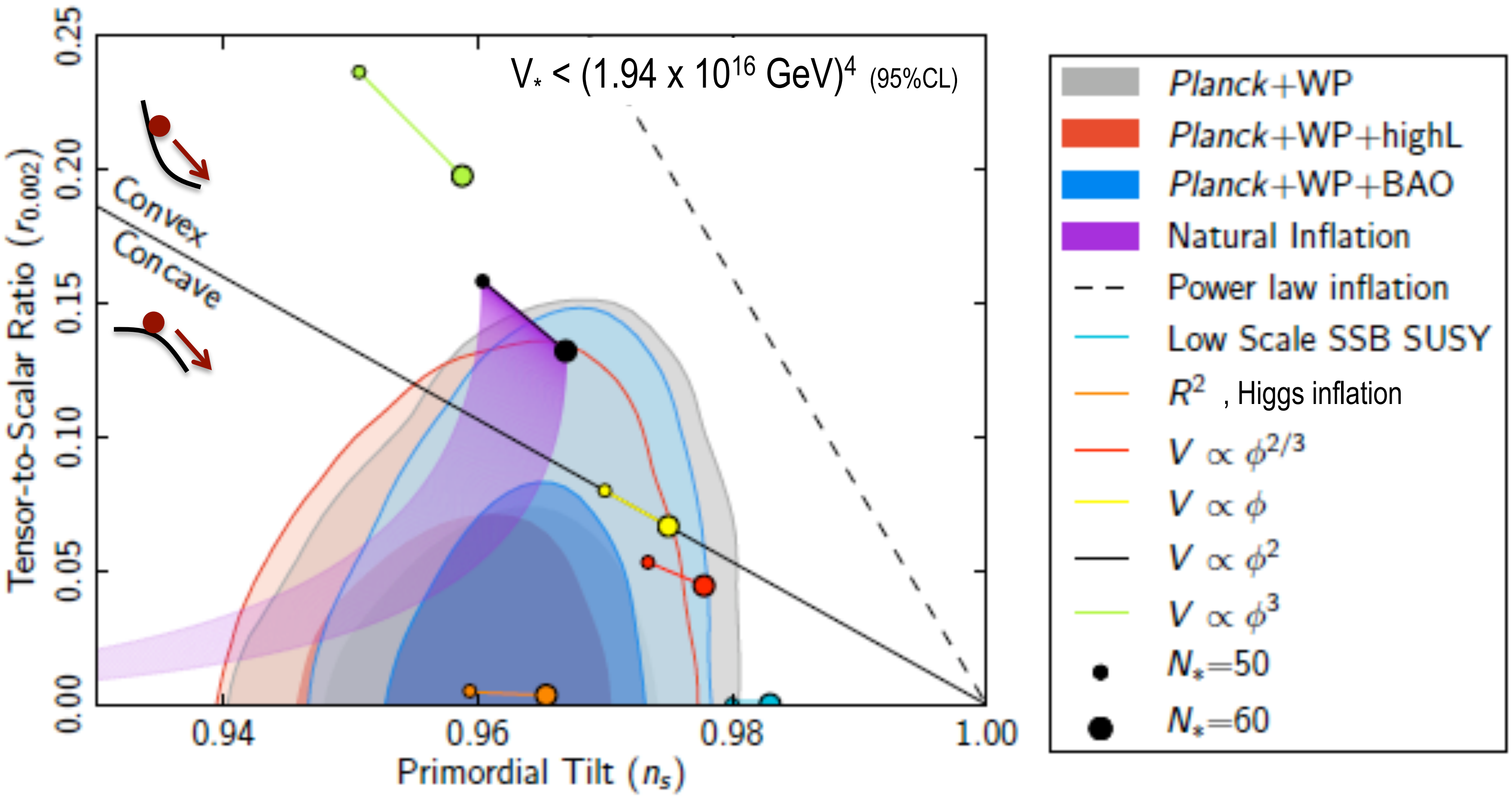
- We focus on single-field inflation, first with a slow-roll prior, then beyond this prior

- With a slow-roll prior, we fit the model ΛCDM + r

  - $n_s = 0.9624 \pm 0.0075$ (68%CL, Planck+WP)
  - $r < 0.12$ at $k_* = 0.002\ \mathrm{Mpc}^{-1}$ (95%CL, Planck+WP)

  - So $V_* < (1.96\times10^{16}\ \mathrm{GeV})^4$

Tensors, spectral index and inflation



- Also OK: Hill-top with p=2 or p≥4; also disfavored: inverse power-law

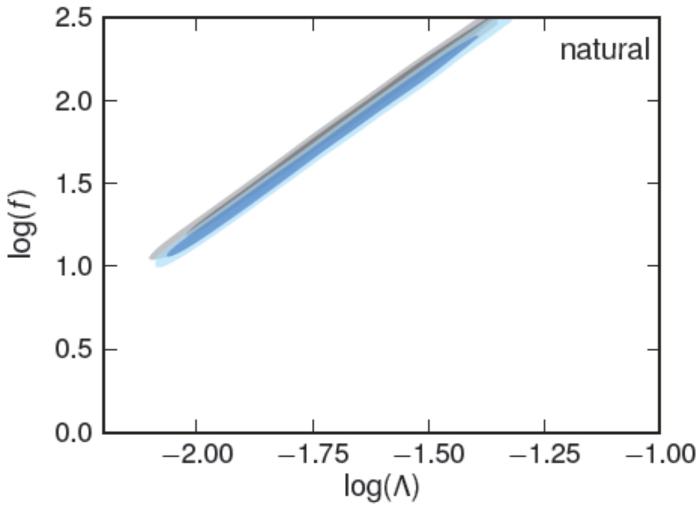
Inflationary model comparison

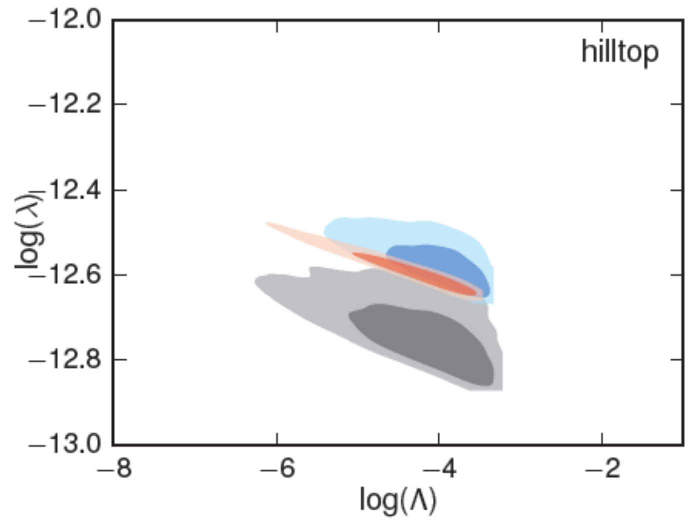
- Consider a few models: monomials, hilltop, natural inflation…
- Simulate them numerically (background evolved till the end of inflation; uncertainity on reheating marginalized out; T and S spectra computed numerically beyond slow-roll)
- Obtain Bayesian confidence limits on their free parameters
- Obtain Bayesian evidence ratio and $\Delta\chi^2_{\rm eff}$ w.r.t ΛCDM (with r=0)

Model	Instantaneous entropy generation		Restrictive entropy generation		Permissive entropy generation	
	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$	$\ln[\mathcal{E}/\mathcal{E}_0]$	$\Delta\chi^2_{\rm eff}$
$n = 4$	-14.9	25.9	-18.8	27.2	-13.2	17.4
$n = 2$	-4.7	5.4	-7.3	6.3	-6.2	5.0
$n = 1$	-4.1	3.3	-5.4	2.8	-4.9	2.1
$n = 2/3$	-4.7	5.1	-5.2	3.1	-5.2	2.3
Natural	-6.6	5.2	-8.9	5.5	-8.2	5.0
Hilltop	-7.1	6.1	-9.1	7.1	-6.6	2.4

Inflationary model comparison

- Consider a few models: monomials, hilltop, natural inflation…
- Simulate them numerically (background evolved till the end of inflation; uncertainty on reheating marginalized out; T and S spectra computed numerically beyond slow-roll)
- Obtain Bayesian confidence limits on their free parameter
- Obtain Bayesian evidence ratio and $\Delta\chi^2_{\rm eff}$ w.r.t ΛCDM (with r=0)



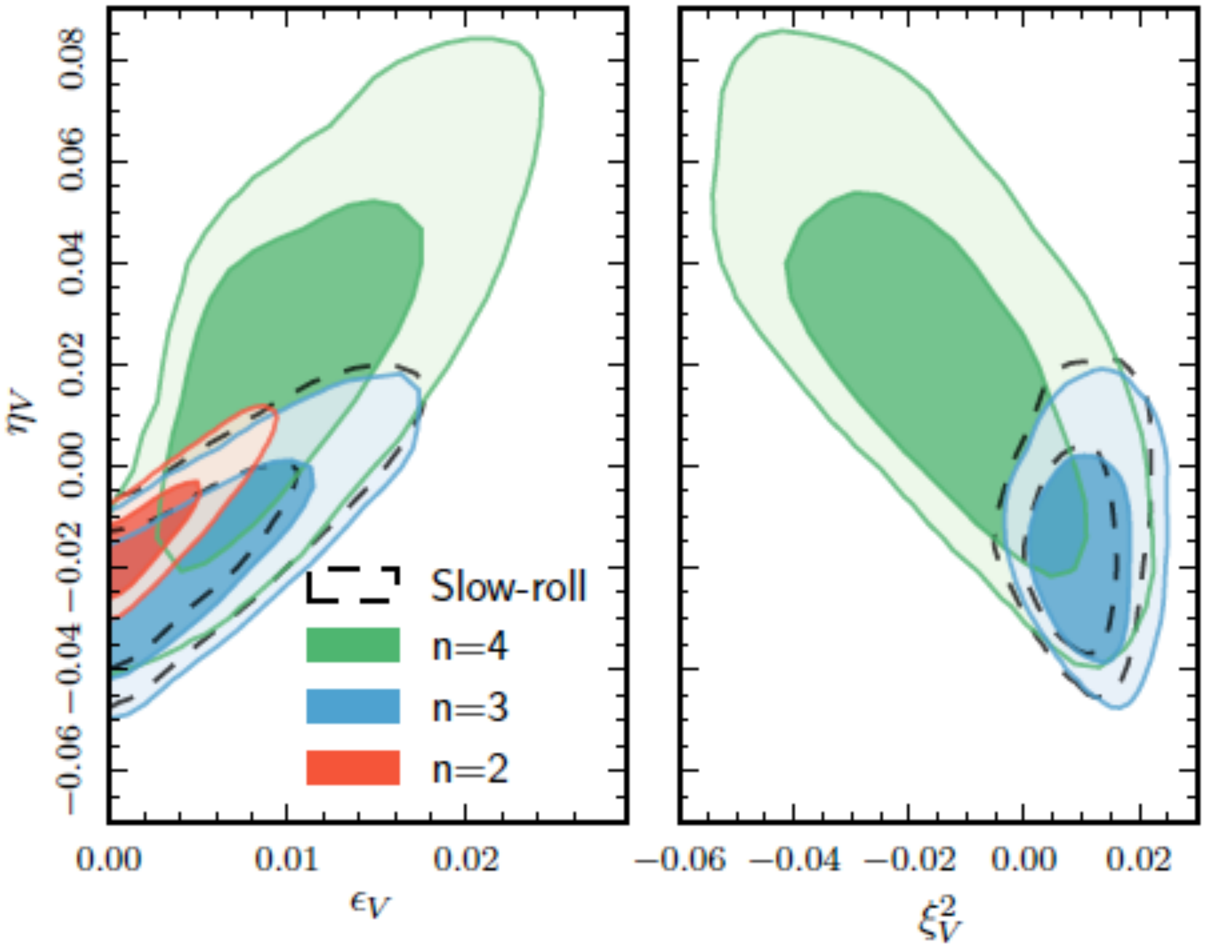


Inflation potential reconstruction

- Strictly speaking, we probe the inflaton potential only inside the “observable window”, and we extrapolate till the end of inflation using theoretical priors or an explicit for of the potential
- Most conservative approach: constrain a parametric form for $V(\phi)$ in the observable window and make no assumptions on the rest
- Compute spectrum numerically beyond slow-roll

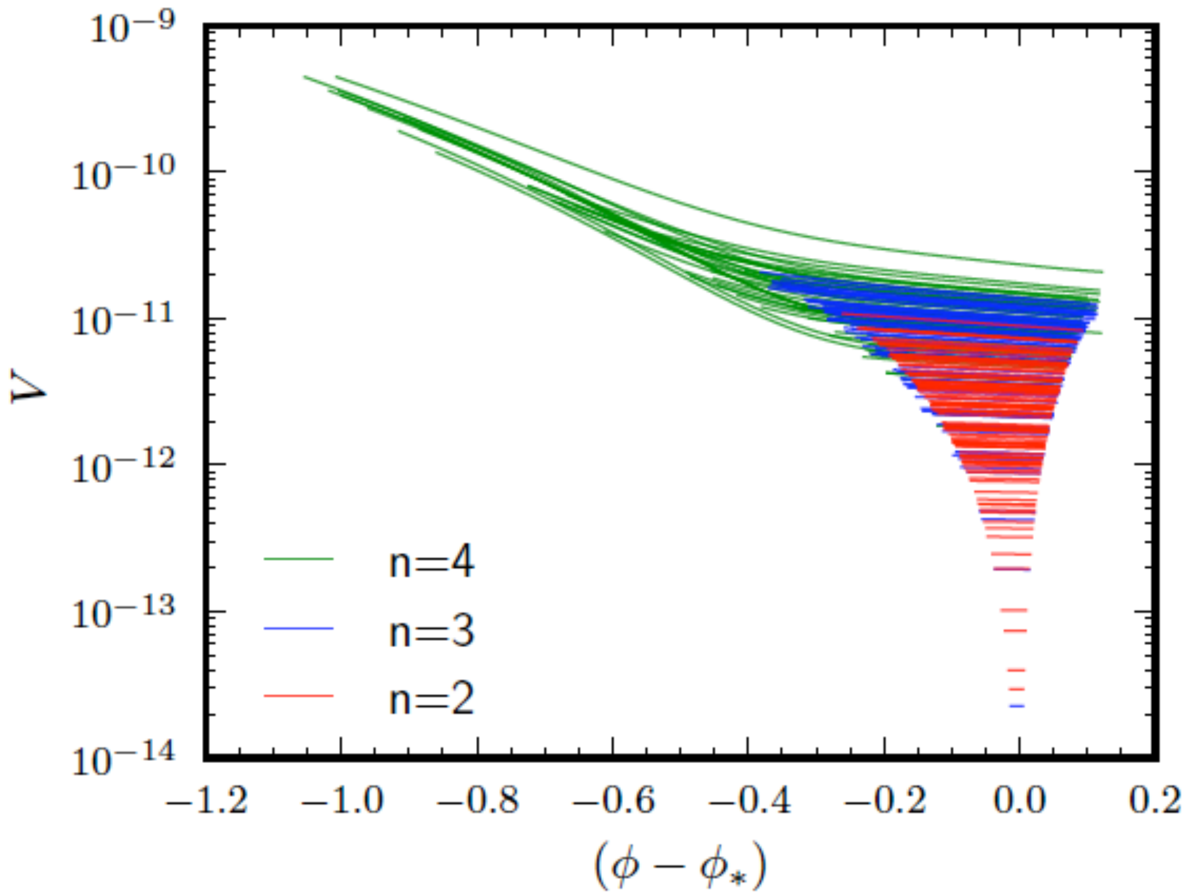
- Result only depends on parametric form. Since observable window is small: may try Taylor expansion at order n=2,3,4

Inflation potential reconstruction



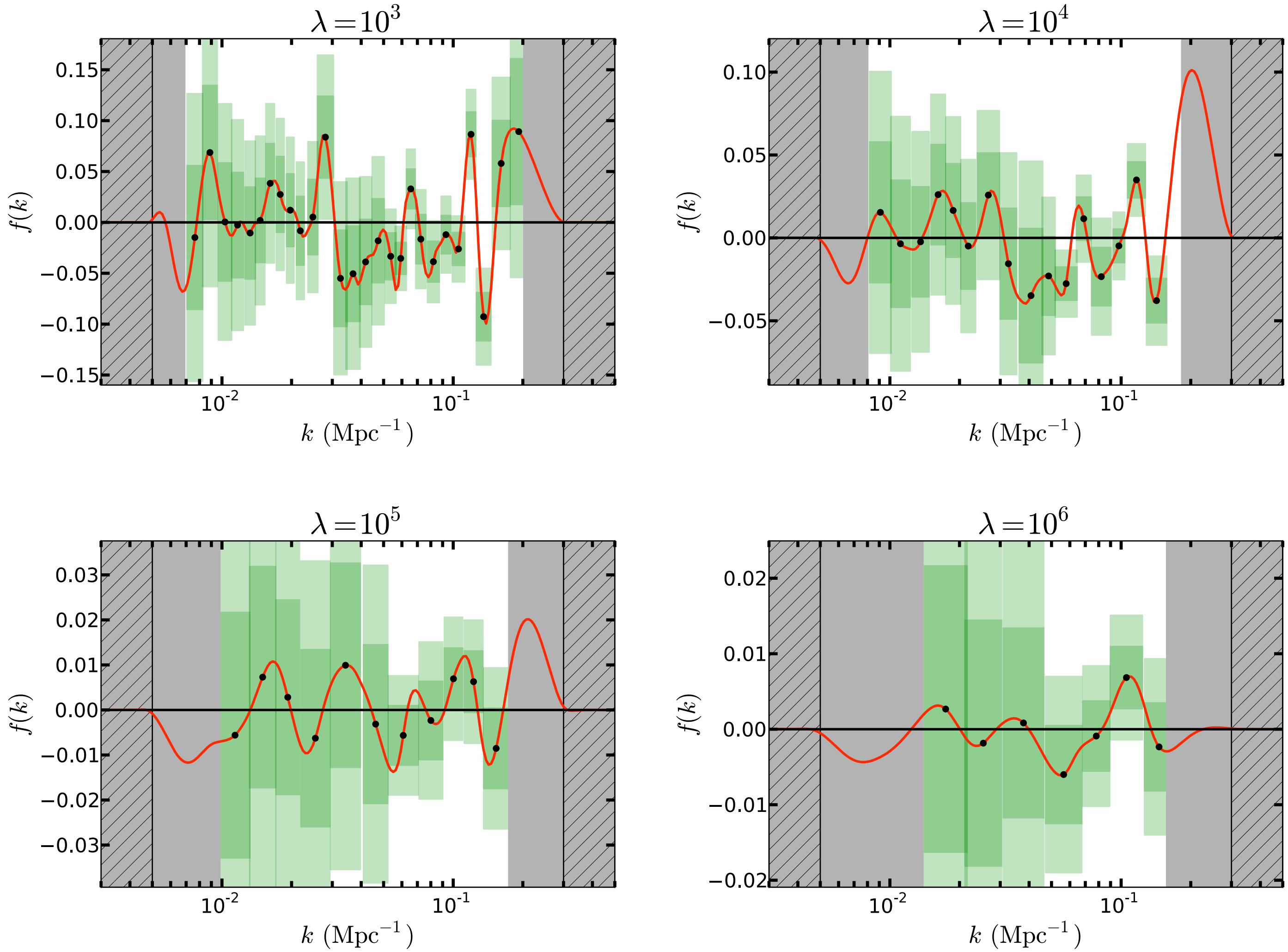
Slow-roll parameters at pivot scale using numerical reconstruction versus 2nd order slow-roll

Inflation potential reconstruction



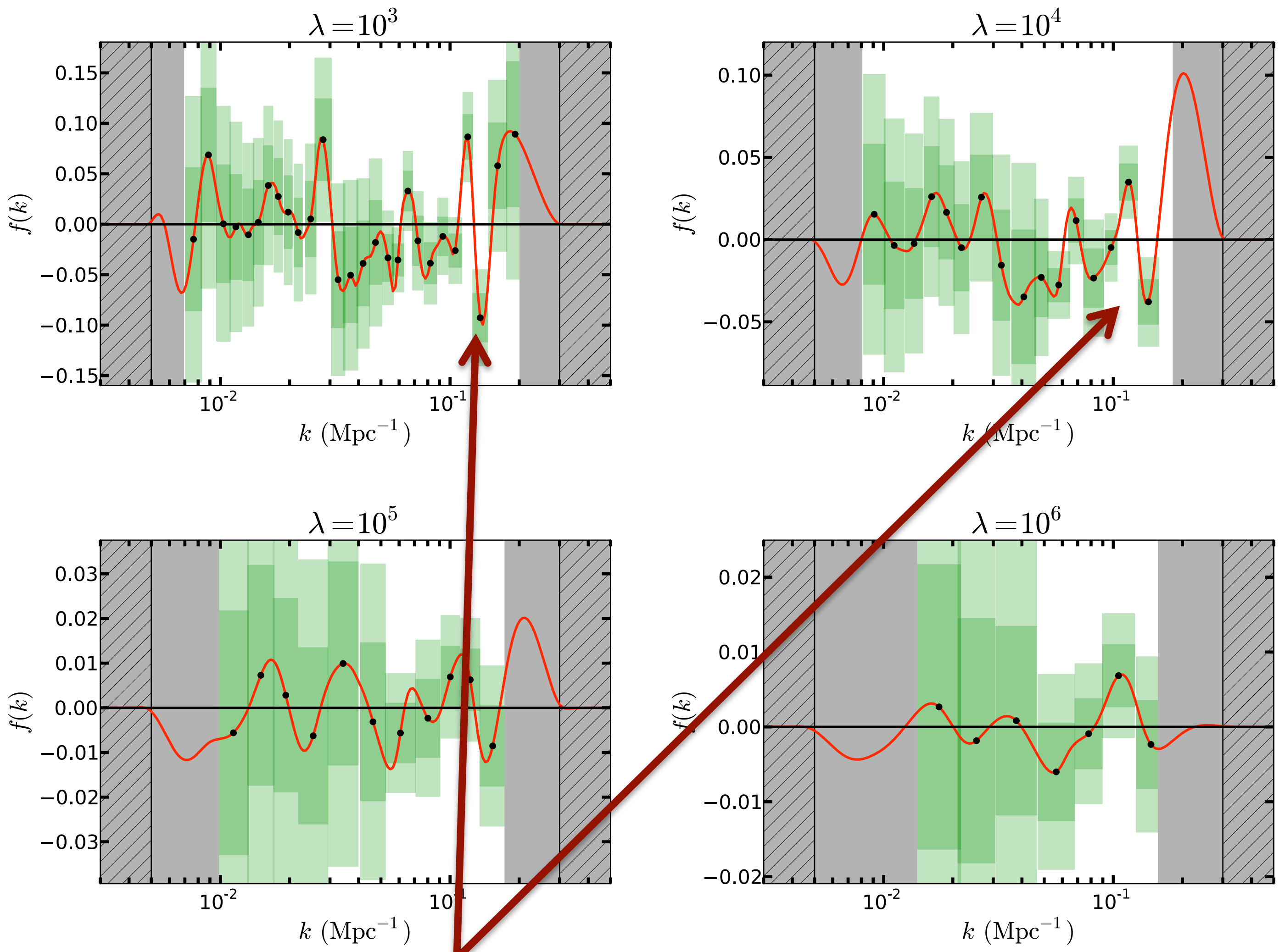
"observable window" of the inflaton potential, assuming that it can be Taylor-expanded inside this region at order n = 2, 3, 4 (units of true m_P)

Primordial spectrum reconstruction



λ = penalisation factor. Disfavors variations below a given scale.

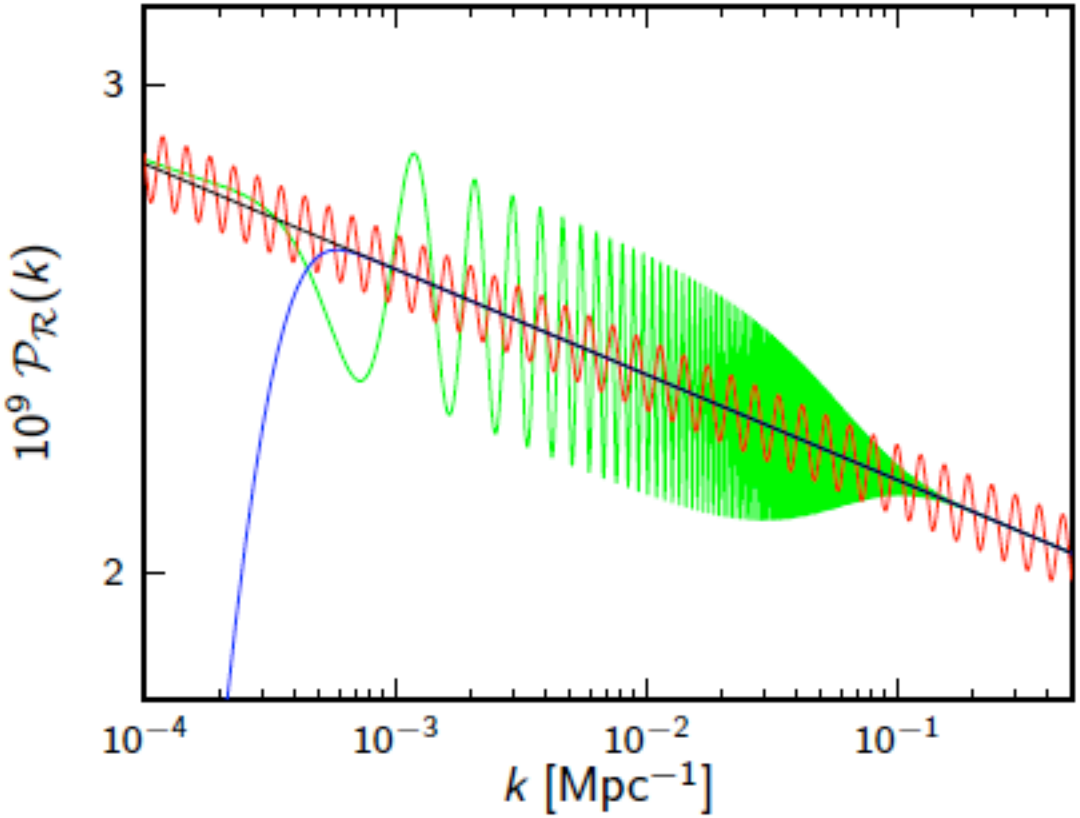
Primordial spectrum reconstruction



Feature at k~0.13 Mpc^{-1} related to dip in C_l with l~1800 . 3-4 σ effect.

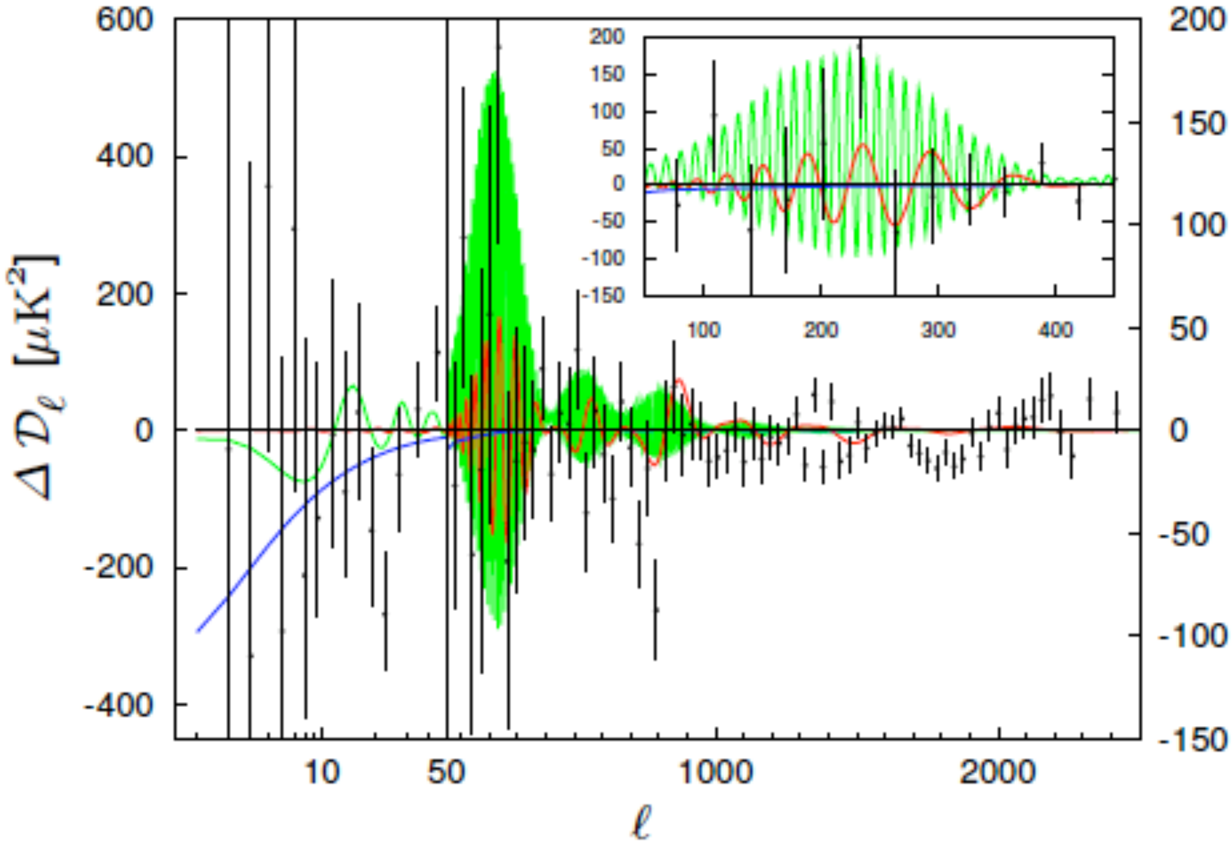
Primordial spectrum with parametric features

- Search for: - constant oscillation in log(P) versus log(k) (3 extra parameters)
  - localised oscillations from step in inflaton potential (3 extra parameters)
  - exponential cut-off for short inflation (2 extra parameters)



Primordial spectrum with parametric features

- best fits compared to ΛCDM residuals:



Primordial spectrum with parametric features

- Improvement is not worth the price to pay, Bayesian evidence in favor of power-law:

Model	$-2\Delta \ln \mathcal{L}_{max}$	$\ln B_{0X}$	Parameter	Best fit value
Wiggles	-9.0	1.5	α_w	0.0294
			ω	28.90
			φ	$0.075\ \pi$
Step-inflation	-11.7	0.3	$\mathcal{A}_f$	0.102
			$\ln(\eta_f/\mathrm{Mpc})$	8.214
			$\ln x_d$	4.47
Cutoff	-2.9	0.3	$\ln\left(k_c/\mathrm{Mpc}^{-1}\right)$	-8.493
			λ_c	0.474

- But can be checked independently with future polarisation

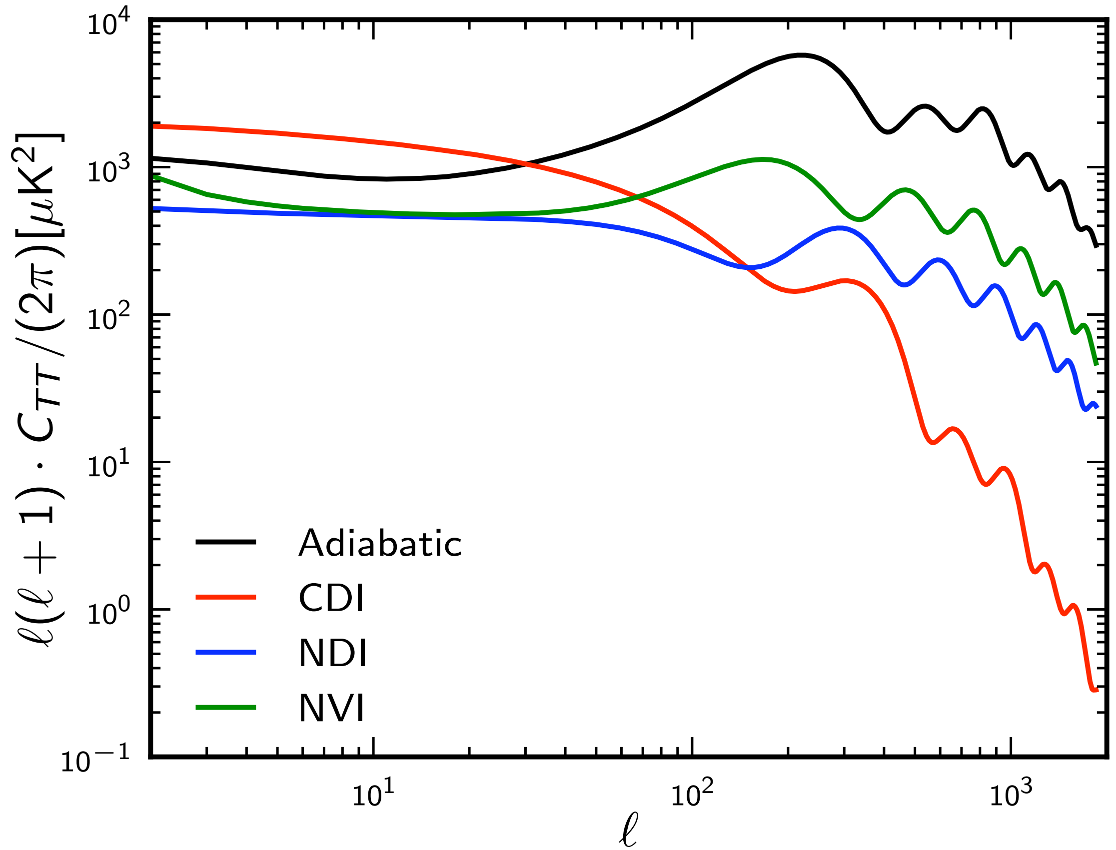
Inflation with non-canonical kinetic term

- Sound speed $c_s^2 < 1$
- Scalar spectrum modified by different sound speed
- Tensor to scalar ratio affected
- Generates primordial non-gaussianity: f_{NL} usually proportional to $(1-c_s^{-2})$

- Paper investigates constraints on c_s^2 and on slow-roll parameter under various assumption
- From f_{NL} and from the temperature spectrum: no evidence for $c_s^2 < 1$

Isocurvature modes

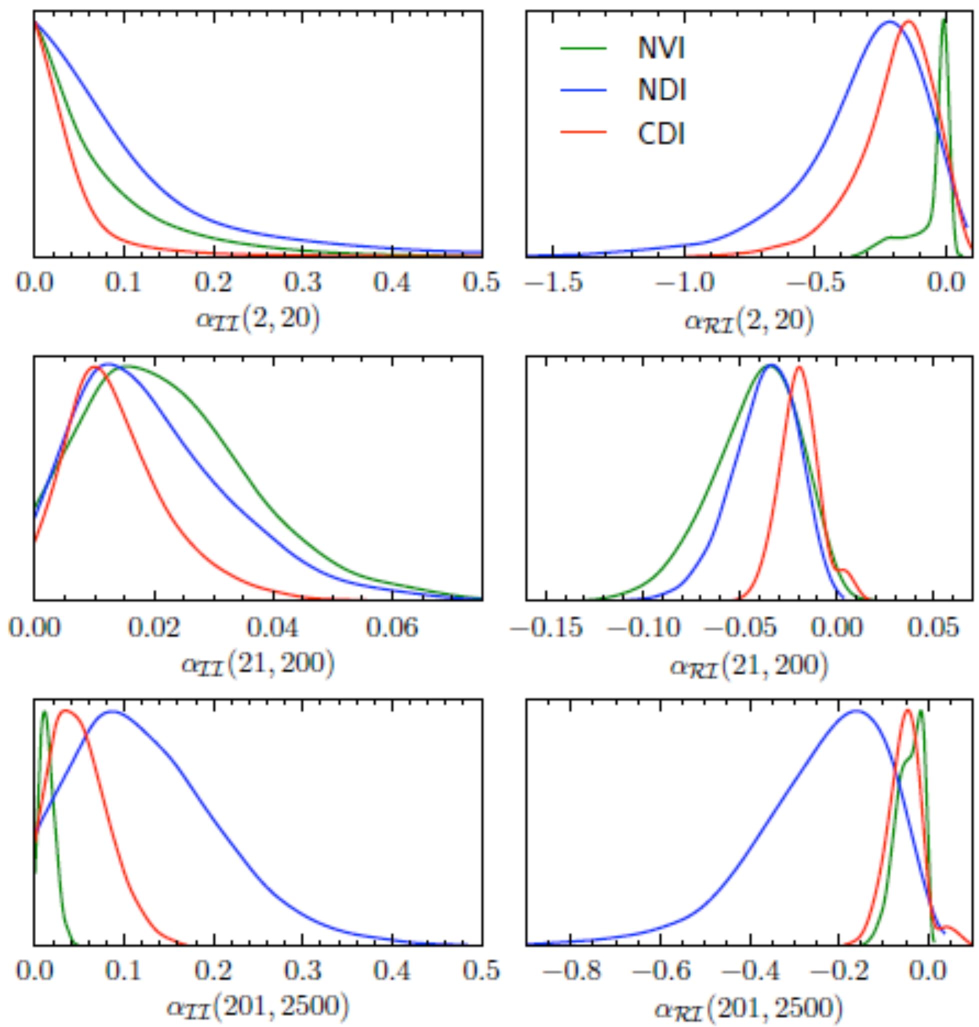
- General case:
  adiabatic mode plus
  - CDM isocurvature
  - Neutrino density
  - Neutrino velocity



Isocurvature modes

- General case:
  adiabatic mode plus
  - CDM isocurvature
  - Neutrino density
  - Neutrino velocity

New improved bounds.



Isocurvature modes

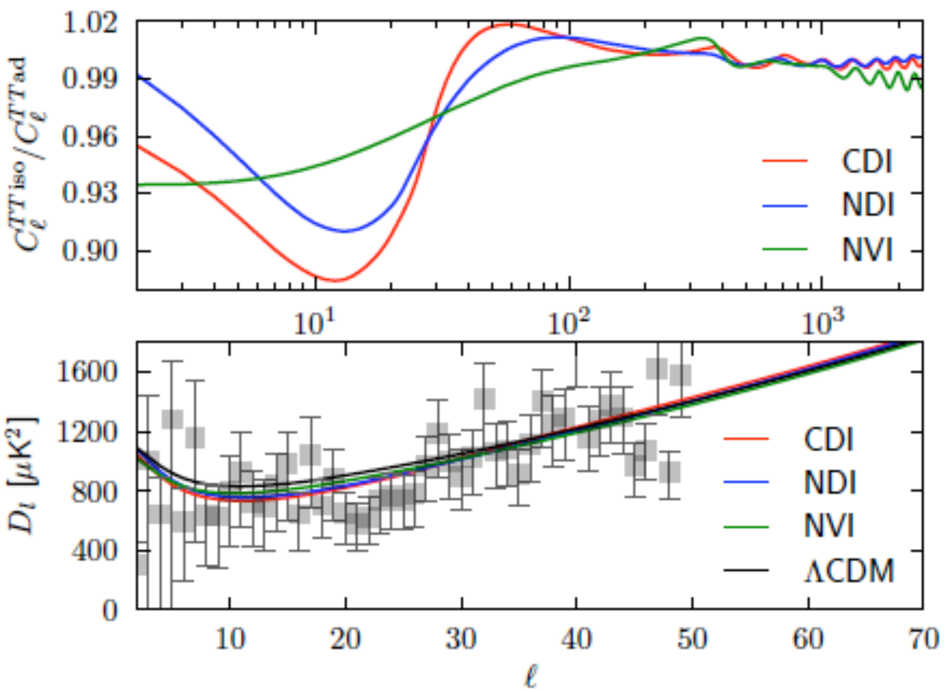
- General case:

  - CDM isocurvature
  - Neutrino density
  - Neutrino velocity

  New improved bounds.

$\Delta\chi^2_{\rm eff}$ ~ 4 from large scales:

No clue for isocurvature modes!



Isocurvature modes

- specific case of axion.

  Under various assumptions:
  - Inflation takes place after PQ symmetry breaking
  - PQ symmetry not restored by quantum or thermal corrections during inflation/reheating
  - Axion = CDM after at QCD transition due to misalignment angle

  … then uncorrelated adiabatic + CDI modes with $n_{iso}\approx 1$

Got no evidence for this situation. Improved bound leading to

$$H_{\mathrm{inf}} \leq 0.87 \times 10^{7}\ \mathrm{GeV} \left(\frac{f_{\mathrm{a}}}{10^{11}\ \mathrm{GeV}} \right)^{0.408} \ (95\%\ \mathrm{CL})\ .$$

In this scenario.

Isocurvature modes

- specific case of curvaton.

  Under various assumptions:
  - Light scalar field during inflation, not contributing to background
  - Curvaton decays into CDM at a time when it does contribute as a fraction r of total pressure

… then fully correlated adiabatic + CDI modes with $n_{iso} = n_{ad}$ and $f_{NL}(r)$

Got no evidence for this situation. Improved bound leading to $0.98 < r < 1$

Conclusions

- Paper contains much more information…
- Maximally Boring Universe or Maximally Elegant Model ?
  - [Actually none of them if anomalies are taken seriously !!]
- Potential of improvement for next year's release:
  - From nominal survey to full survey data
  - Polarization
  - Possible improvement of foreground modeling, mask reduction, manoeuvres inclusion
- Likelihoods are released. Under assumption of FL universe: you can immediately run your favorite models with the last versions of CAMB + CosmoMC (www.cosmologist.info) or CLASS + Monte Python (class-code.net) (include numerical modules simulating inflation)