# CONSTRAINTS ON INFLATION FROM OBSERVATIONS OF THE PLANCK SATELLITE


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(based on Planck 2015 papers, mainly Planck 2015 XX)

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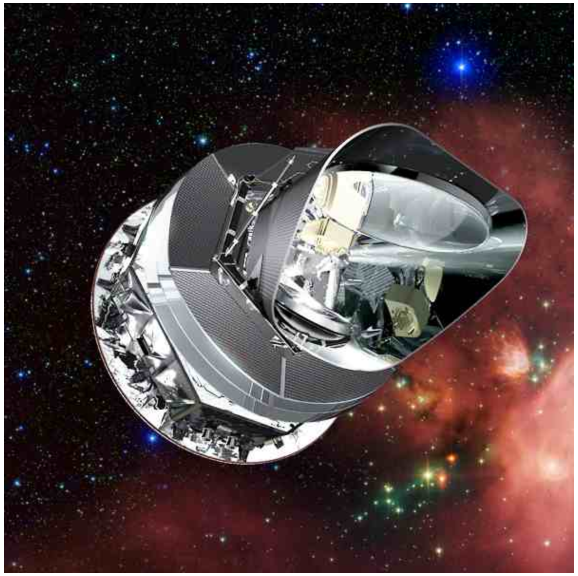
Advances in theoretical cosmology in light of data

Stockholm, July 4th 2017

# The Planck Satellite

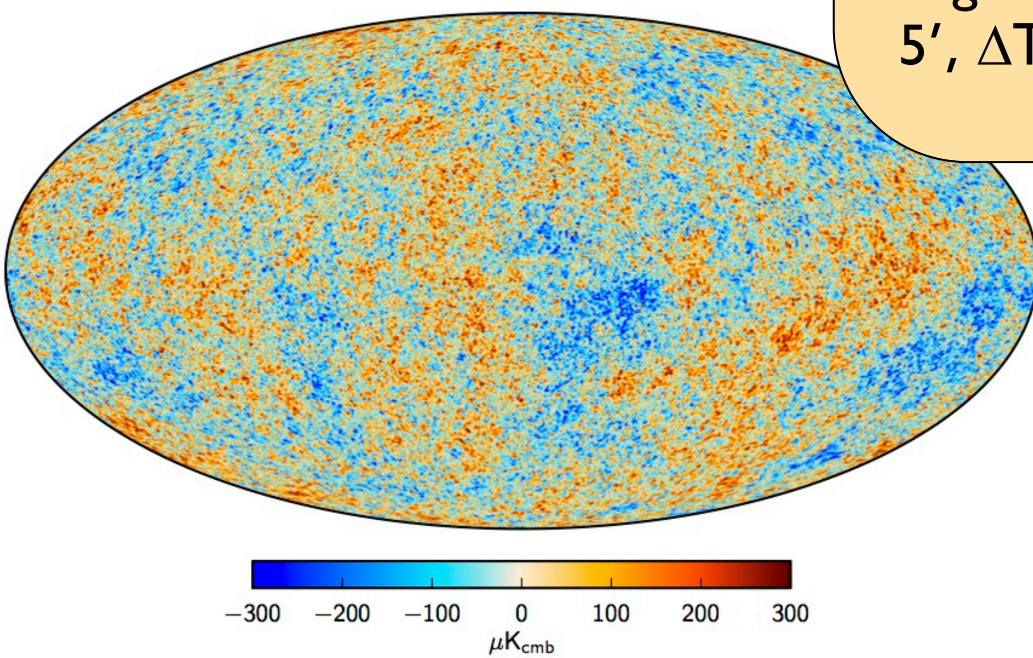


Planck is a 3rd generation ESA satellite devoted to CMB

Ultimate characterization of the temperature anisotropies

74 detectors (radiometers and bolometers) in 9 frequency bands from 30 to 857 GHz

angular resolution between 30’ and 5′, $\Delta T/T \sim 2 \times 10^{-6}$




Observed the full microwawe sky continously for 30 (HFI) and 48 (LFI) months

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Second cosmology data release in 2015, built from the full-mission temperature and polarization observations

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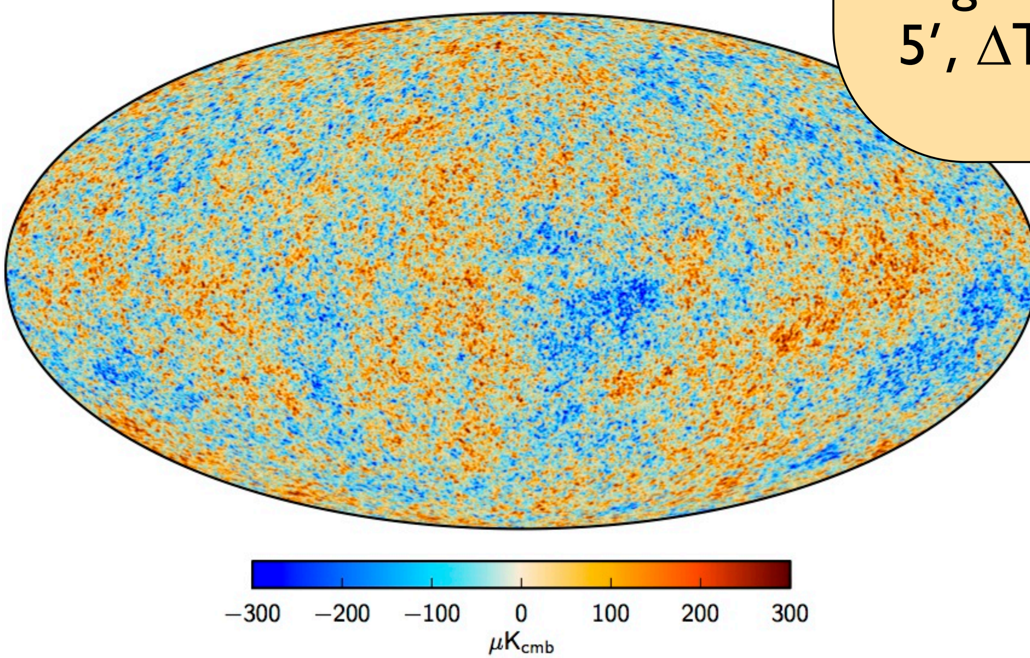


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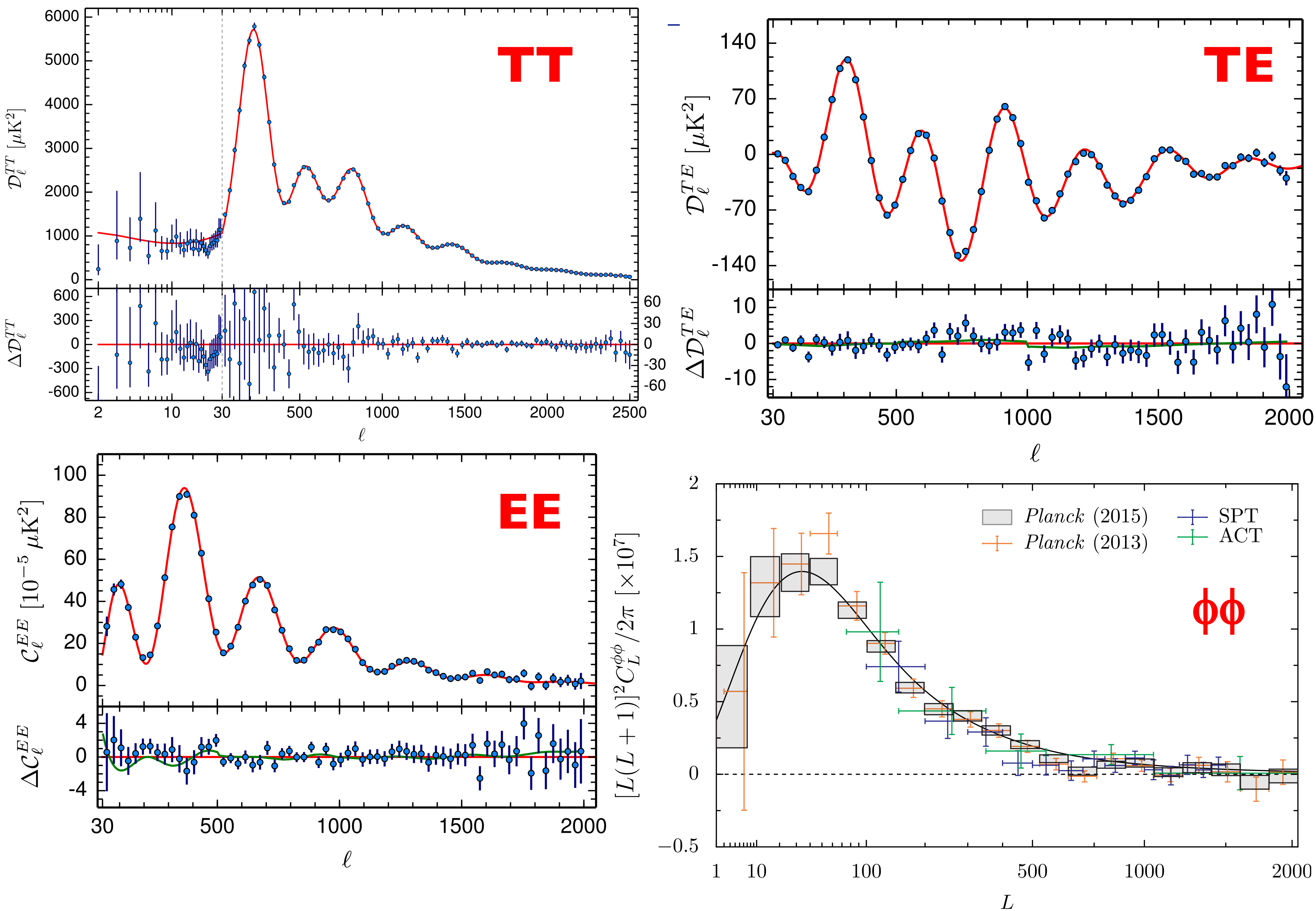
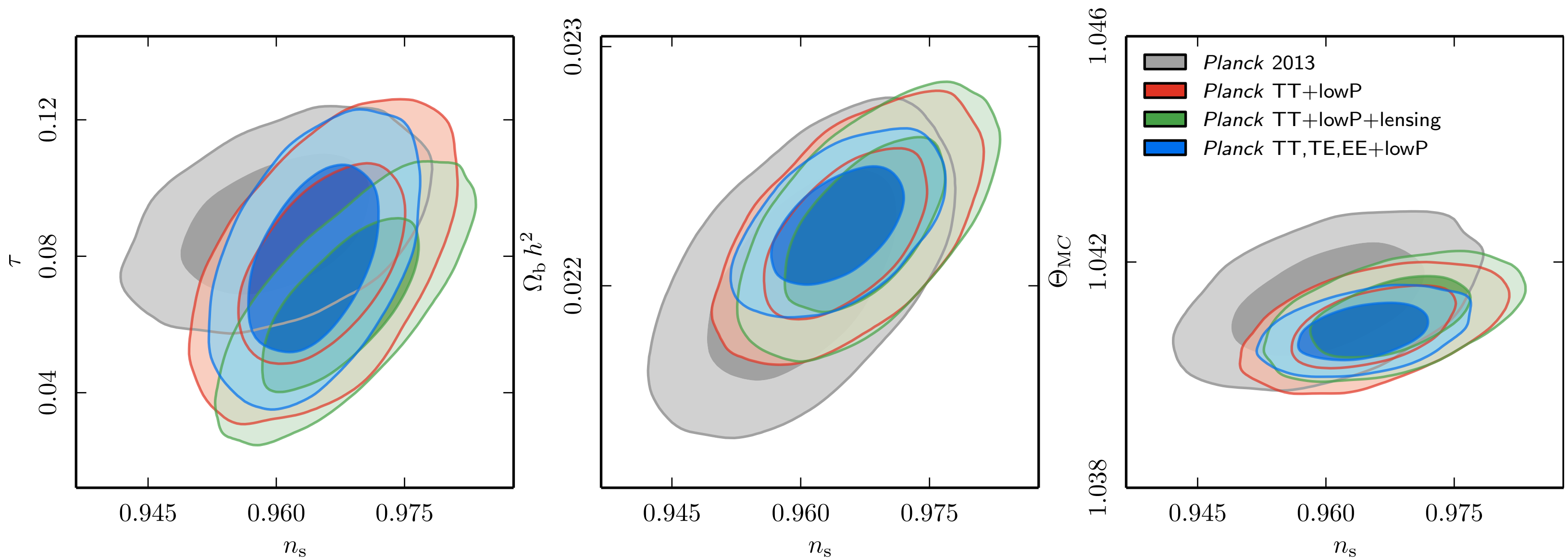

TT
TE
EE
ϕϕ
$\mathcal{D}_\ell^{TT}$ [$\mu$K$^2$]
$\Delta\mathcal{D}_\ell^{TT}$
$\mathcal{D}_\ell^{TE}$ [$\mu$K$^2$]
$\Delta\mathcal{D}_\ell^{TE}$
$\mathcal{C}_\ell^{EE}$ [$10^{-5}\,\mu$K$^2$]
$\Delta\mathcal{C}_\ell^{EE}$
$[L(L+1)]^2 C_L^{\phi\phi}/2\pi$ [$\times 10^7$]
$\ell$
$L$
Planck (2015)
Planck (2013)
SPT
ACT

# CONSTRAINTS ON THE PRIMORDIAL SPECTRUM




$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

assumes no tensor modes

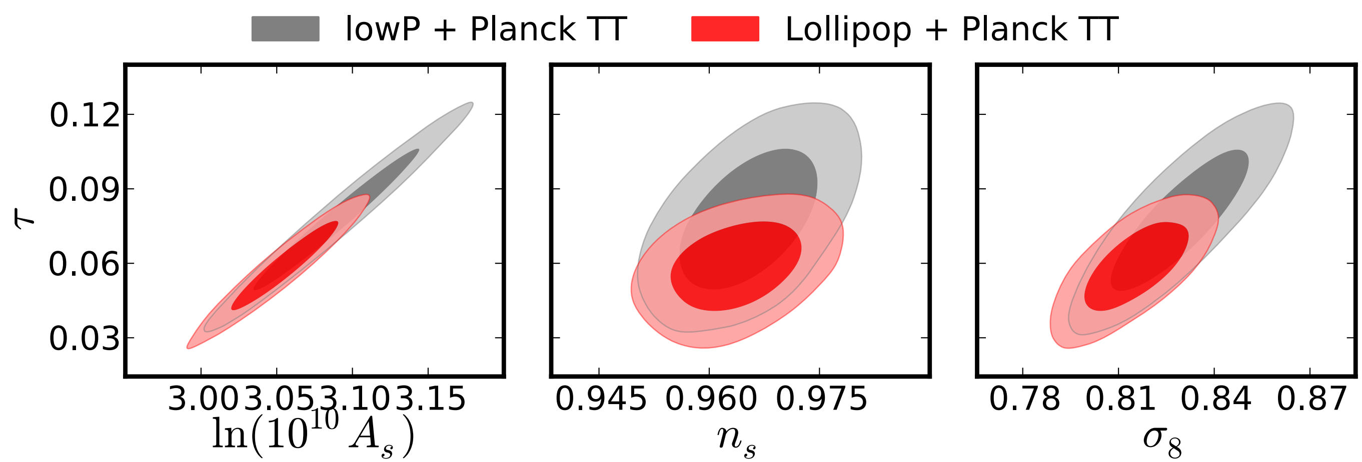
$k_* = 0.05$ Mpc$^{-1}$

$n_s$ = 0.9655 +/- 0.0062 (PlanckTT+lowP)
0.9645 +/- 0.0049 (PlanckTTTEEE+lowP)
0.9677 +/- 0.0060 (PlanckTT+lowP+lensing)

HZ spectrum excluded at 5.6$\sigma$ in $\Lambda$CDM from PlanckTT+lowP
Strongly disfavoured also in simple extensions (e.g., $\Lambda$CDM+$N_{eff}$)

# 2016 Polarization data

New large-scale polarization data has been released in May 2016 (Planck int. res. XLVI)




Smaller $\tau$ means less overall power (thus smaller fluctuations) and less lensing

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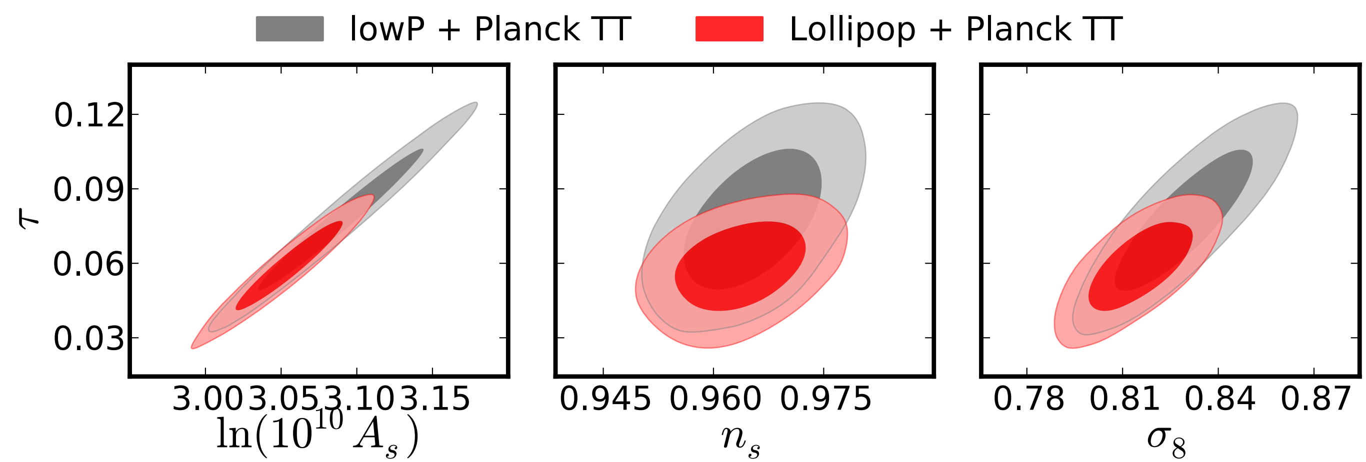


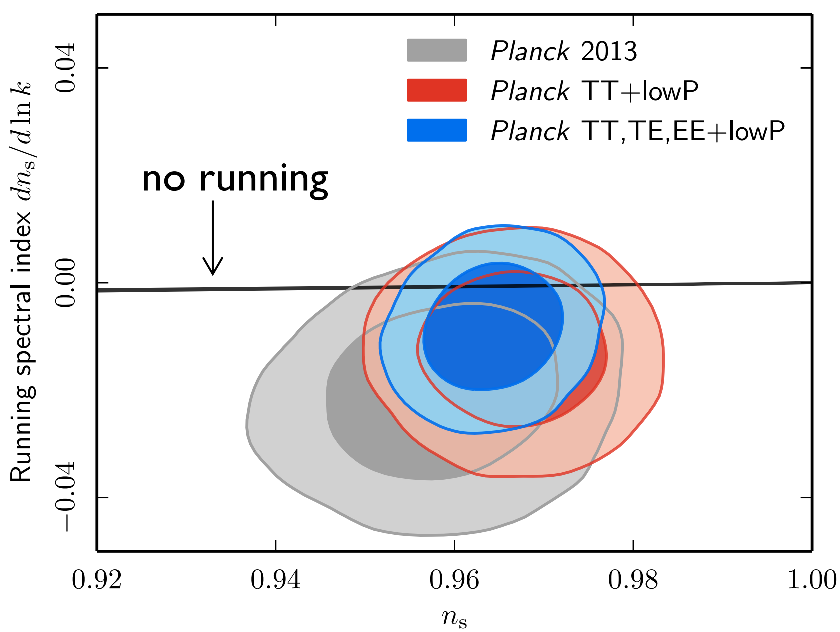

Smaller $\tau$ means less overall power (thus smaller fluctuations) and less lensing

$n_s$ = 0.9624 +/- 0.0057 (PlanckTT + SIMlow)

# CONSTRAINTS ON THE PRIMORDIAL SPECTRUM

Allowing for a running of the spectral index (and possibly running of the running)

$$\mathcal{P}_\mathcal{R}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2} dn_s/d\ln k \ln(k/k_*) + \frac{1}{6} d^2 n_s/d\ln k^2 [\ln(k/k_*)]^2}$$




$dn_s$/dlnk =

- 0.0084 +/- 0.0082 (PlanckTT+lowP)
- 0.0057 +/- 0.0071 (+TEEE)
- 0.0033 +/- 0.0074 (+ lensing)

Running is compatible with 0

Preference for negative values is driven by lack of power at large scales

# Constraints on the primordial spectrum

Allowing for a running of the spectral index (and possibly running of the running)

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2} dn_s/d\ln k \ln(k/k_*) + \frac{1}{6} d^2 n_s/d\ln k^2 [\ln(k/k_*)]^2}$$

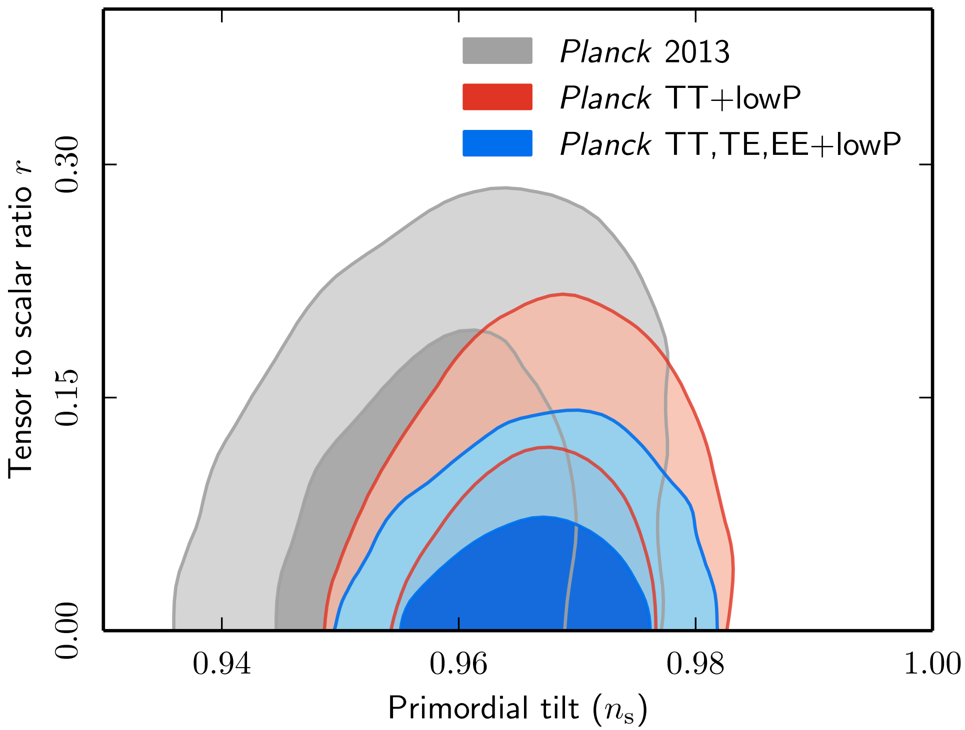
When running of the running is allowed:

$n_s = 0.9569$ +/- 0.077
$dn_s/d\ln k = 0.011$ +/- 0.014
$d^2n_s/d\ln k^2 = 0.029$ +/- 0.016

Other models with suppression of power at large scales (e.g. exponential cutoff) fit the data but are not preferred wrt $\Lambda$CDM

# Constraints on tensor modes

$$\mathcal{P}_t(k) = A_t \left(\frac{k}{k_*}\right)^{n_t + \frac{1}{2} dn_t/d\ln k \ln(k/k_*)} \qquad r \equiv \frac{\mathcal{P}_t(k_*)}{\mathcal{P}_\mathcal{R}(k_*)}$$




Planck TT+lowP+lensing

$n_s = 0.9688 \pm 0.0061$

$r_{0.002} < 0.11$

(<0.08 with BKP)

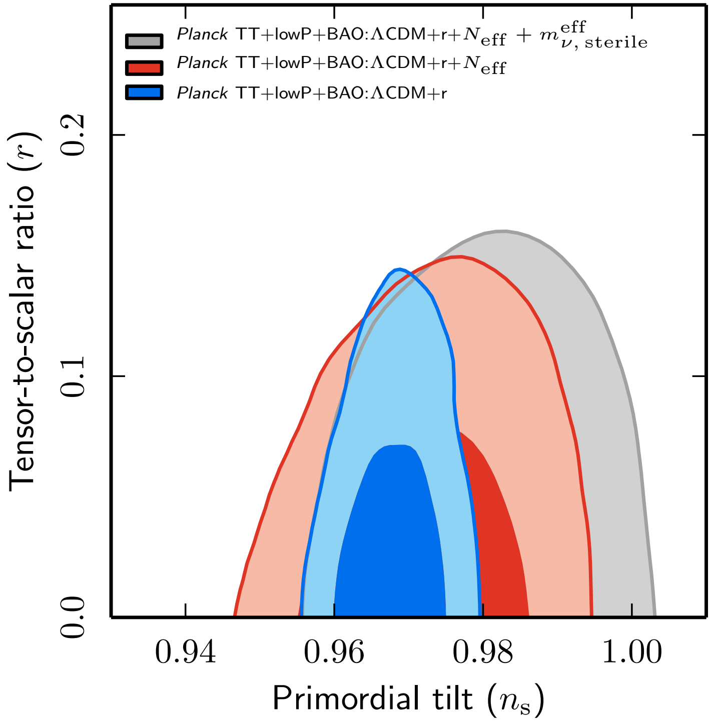
→ $V_{inf} < (1.9 \times 10^{16}\ \mathrm{GeV})^4$

Allowing for running of the spectral indices:

$r_{0.002} < 0.18$ (0.10 with BKP)

$dn_s/d\ln k = 0.013 \pm 0.010$

# CONSTRAINTS ON TENSOR MODES




Constraints can be relaxed in extended models (e.g., $r_{0.002}$ < 0.20 in $\Lambda$CDM+r+$\Omega_k$+dn$_s$/dlnk)

See Planck 2015 XX

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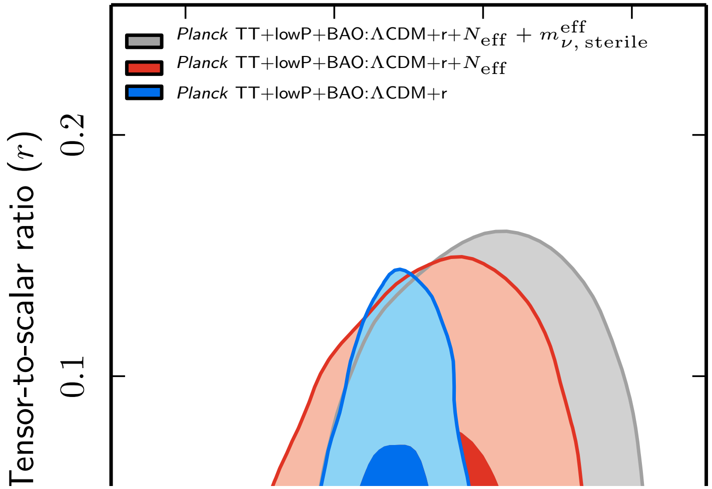


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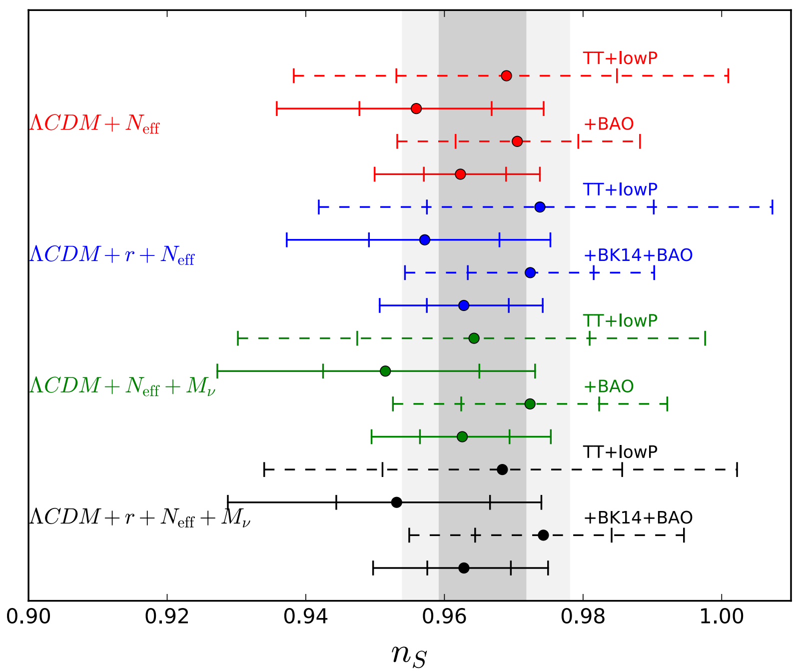
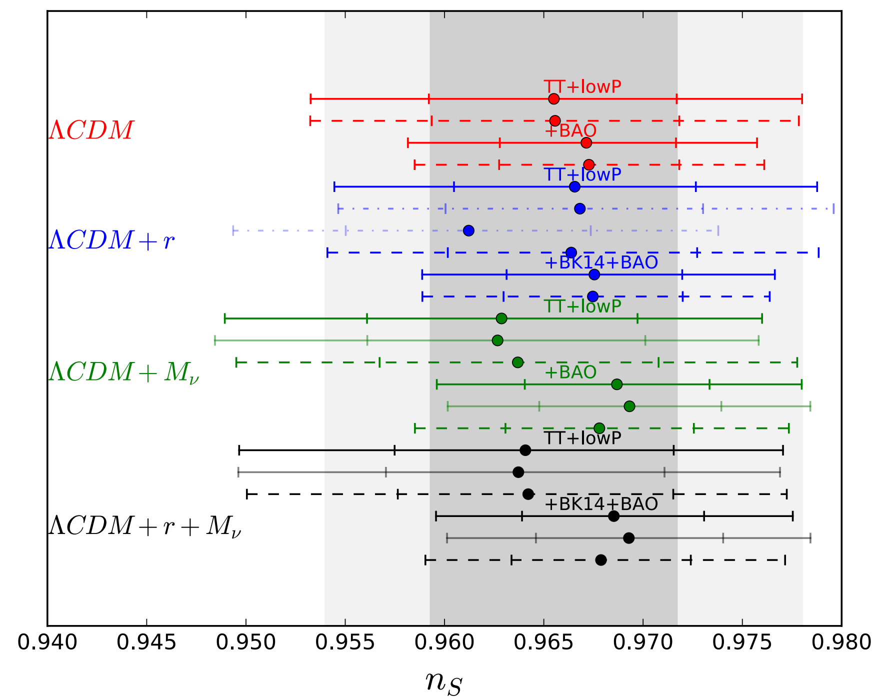
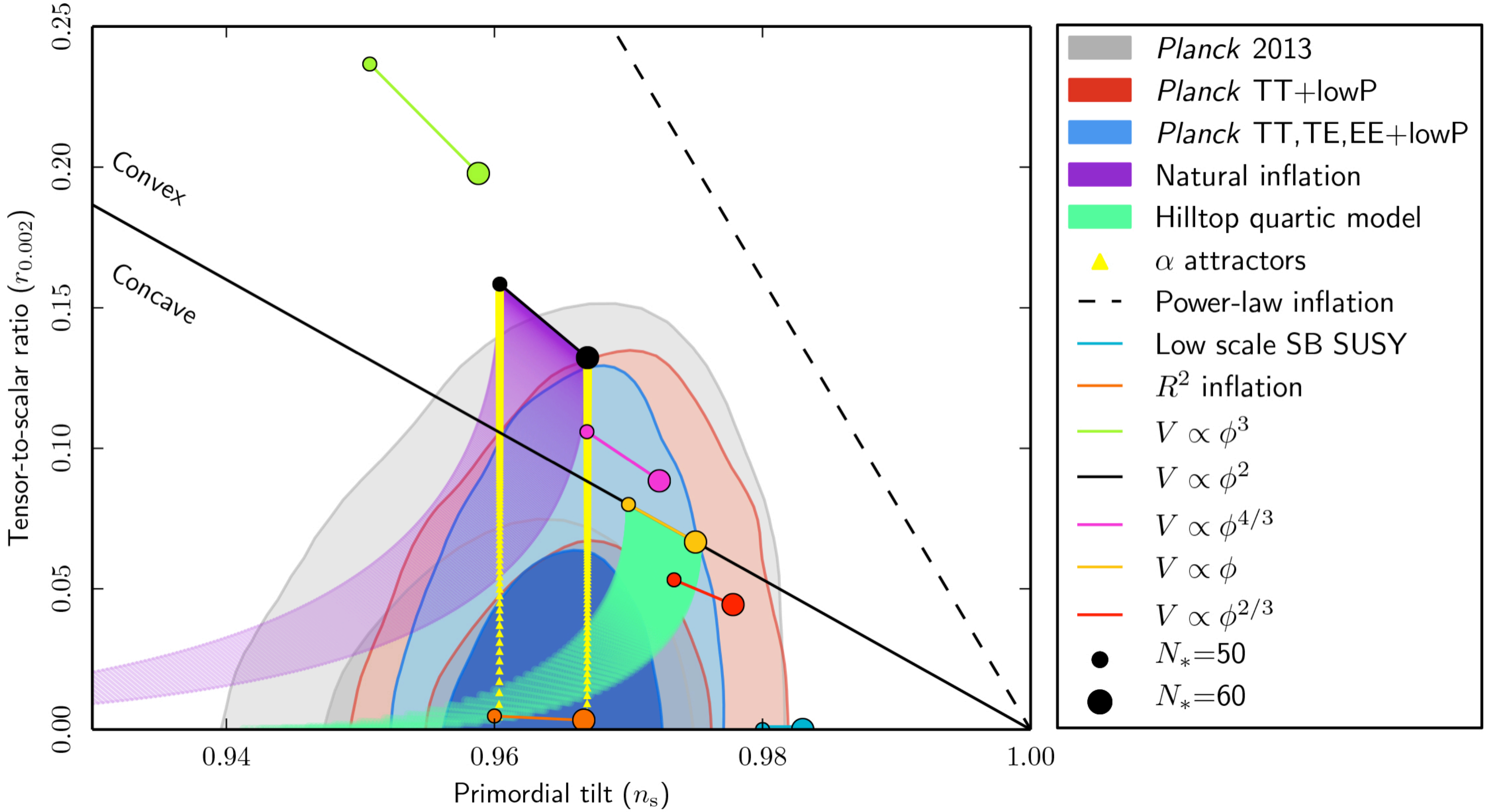
See Planck 2015 XX

See also Gerbino, Freese, Vagnozzi, ML, Mena, Giusarma, Ho al. 2017 for an analysis focusing on neutrino parameters



# SINGLE FIELD SLOW-ROLL INFLATION

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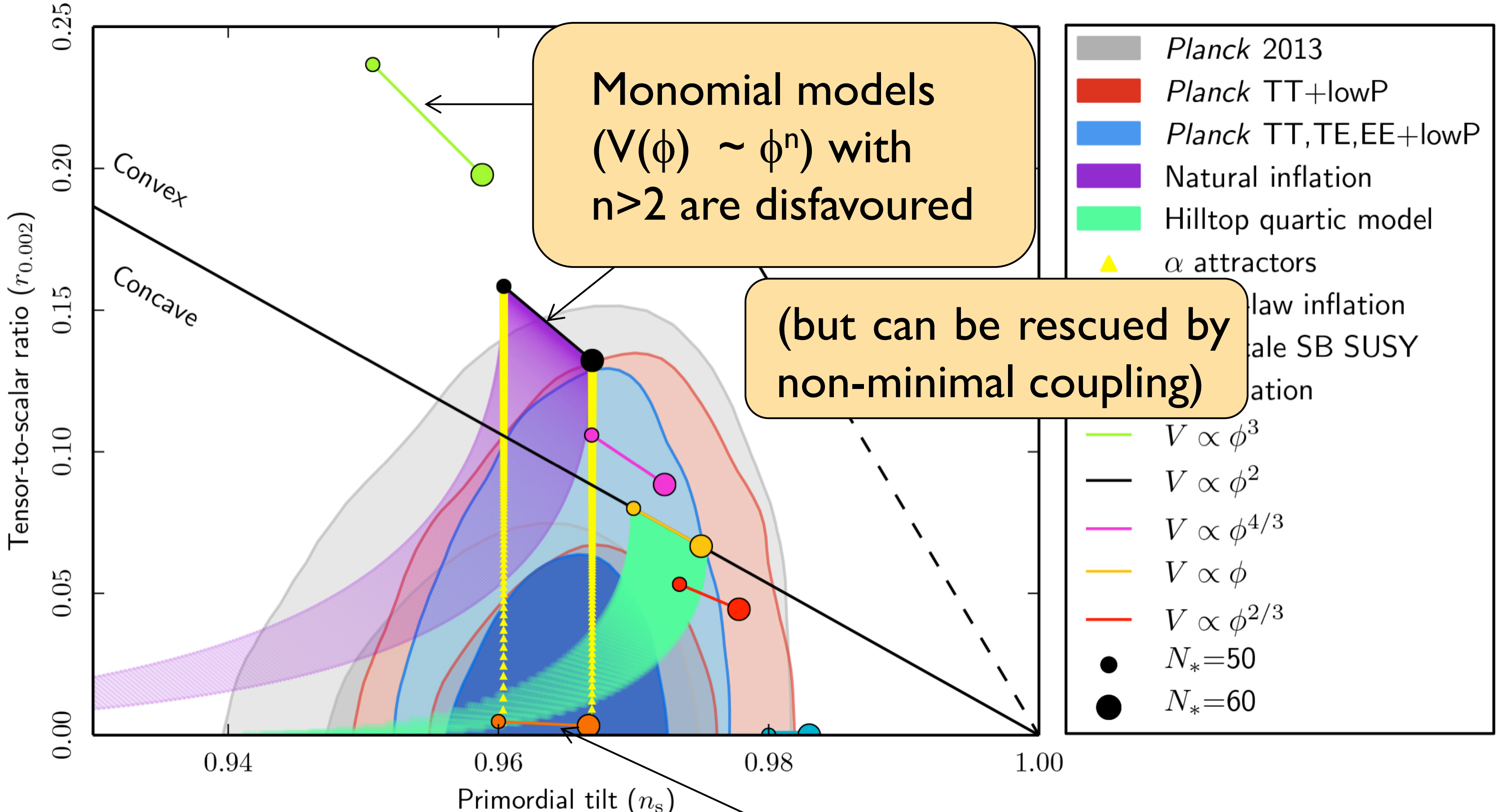



Monomial models ($V(\phi) \sim \phi^n$) with n>2 are disfavoured

(but can be rescued by non-minimal coupling)

Planck TT+lowP+lensing

$n_s = 0.9688 \pm 0.0061$

$r_{0.002} < 0.11$

$V_{inf} < (1.9 \times 10^{16}\ \mathrm{GeV})^4$

Model that predict smaller tensor-to-scalar ratio (e.g. $R^2$ inflation) are favoured

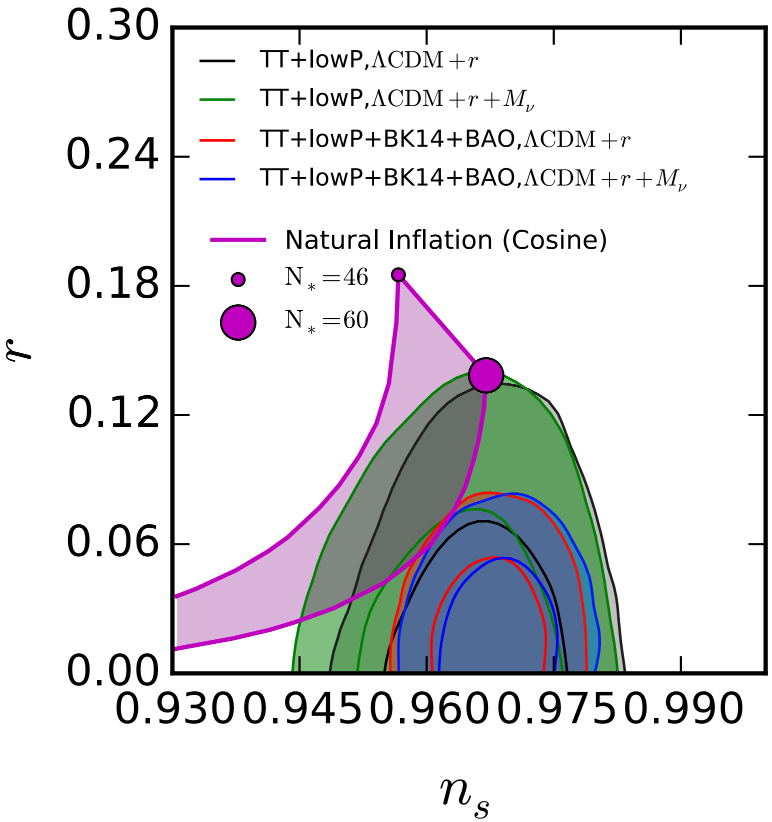
# SINGLE FIELD SLOW-ROLL INFLATION

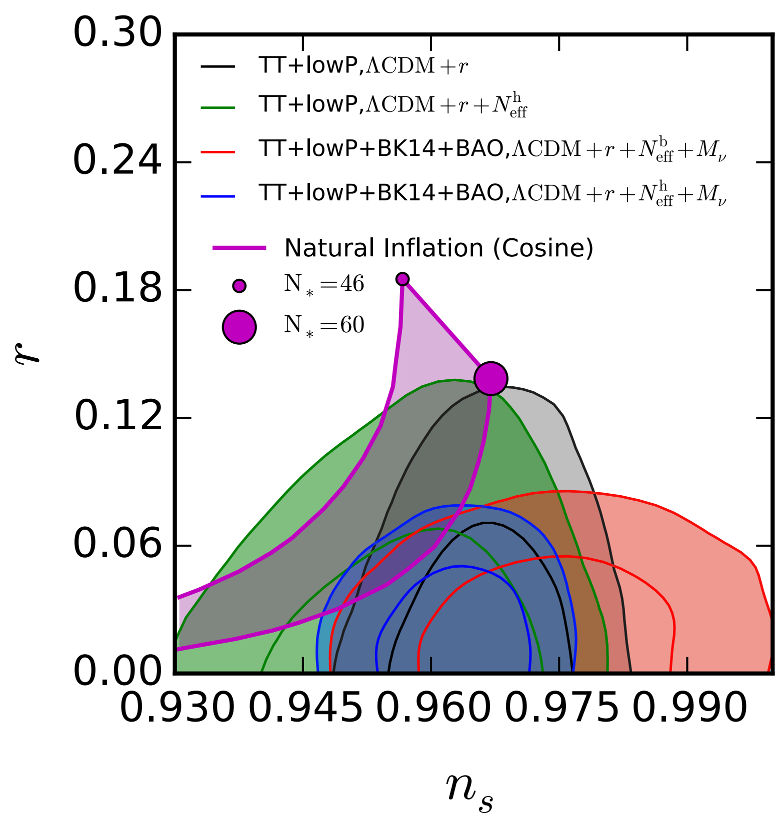
**Table 6.** Results of the inflationary model comparison. We provide $\Delta\chi^2$ with respect to base $\Lambda$CDM and Bayes factors with respect to $R^2$ inflation.

| Inflationary model | $\Delta\chi^2$ | | $\ln B_{0X}$ | |
|---|---|---|---|---|
| | $w_{\rm int} = 0$ | $w_{\rm int} \neq 0$ | $w_{\rm int} = 0$ | $w_{\rm int} \neq 0$ |
| $R + R^2/(6M^2)$ | +0.8 | +0.3 | ... | +0.7 |
| $n = 2/3$ | +6.5 | +3.5 | −2.4 | −2.3 |
| $n = 1$ | +6.2 | +5.5 | −2.1 | −1.9 |
| $n = 4/3$ | +6.4 | +5.5 | −2.6 | −2.4 |
| $n = 2$ | +8.6 | +8.1 | −4.7 | −4.6 |
| $n = 3$ | +22.8 | +21.7 | −11.6 | −11.4 |
| $n = 4$ | +43.3 | +41.7 | −23.3 | −22.7 |
| Natural | +7.2 | +6.5 | −2.4 | −2.3 |
| Hilltop ($p = 2$) | +4.4 | +3.9 | −2.6 | −2.4 |
| Hilltop ($p = 4$) | +3.7 | +3.3 | −2.8 | −2.6 |
| Double well | +5.5 | +5.3 | −3.1 | −2.3 |
| Brane inflation ($p = 2$) | +3.0 | +2.3 | −0.7 | −0.9 |
| Brane inflation ($p = 4$) | +2.8 | +2.3 | −0.4 | −0.6 |
| Exponential inflation | +0.8 | +0.3 | −0.7 | −0.9 |
| SB SUSY | +0.7 | +0.4 | −2.2 | −1.7 |
| Supersymmetric $\alpha$-model | +0.7 | +0.1 | −1.8 | −2.0 |
| Superconformal ($m = 1$) | +0.9 | +0.8 | −2.3 | −2.2 |
| Superconformal ($m \neq 1$) | +0.7 | +0.5 | −2.4 | −2.6 |

$\Delta \ln B_{0X} = 2.3$ corresponds to odds of 10:1

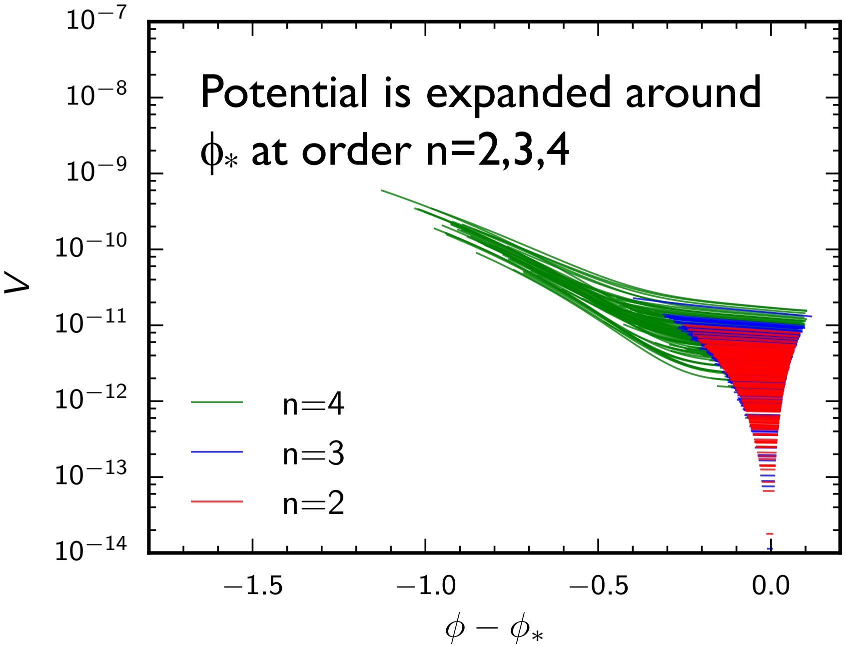
# SINGLE FIELD SLOW-ROLL INFLATION

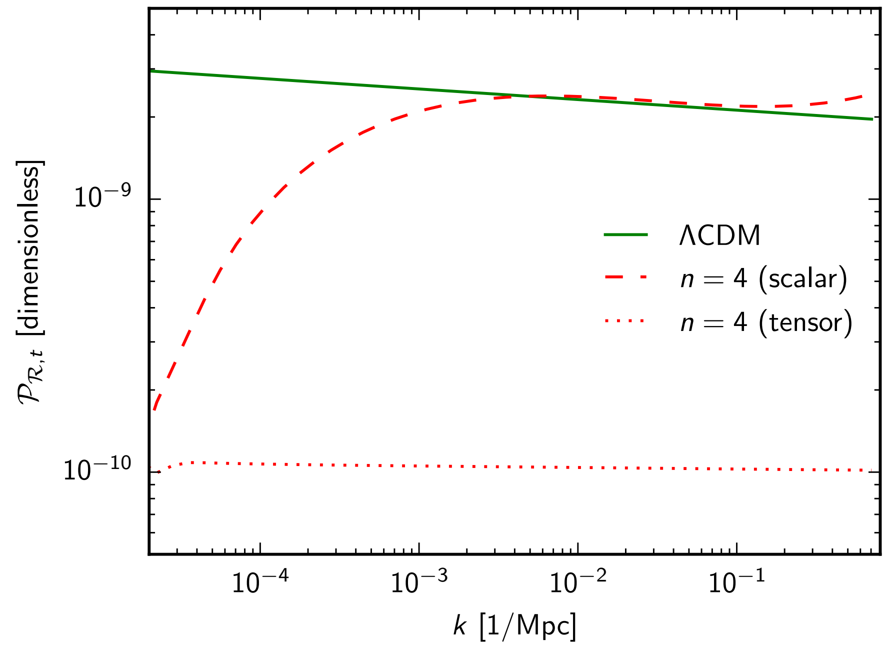


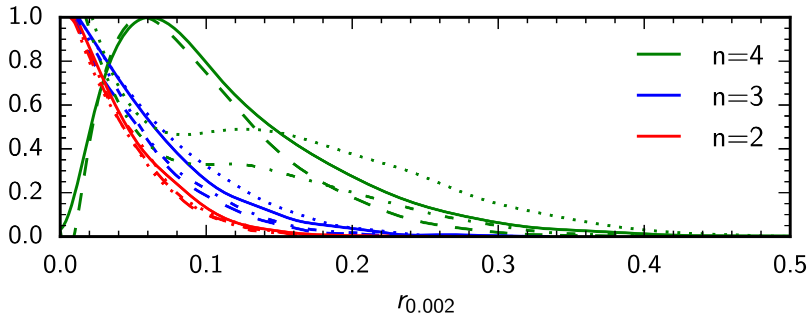



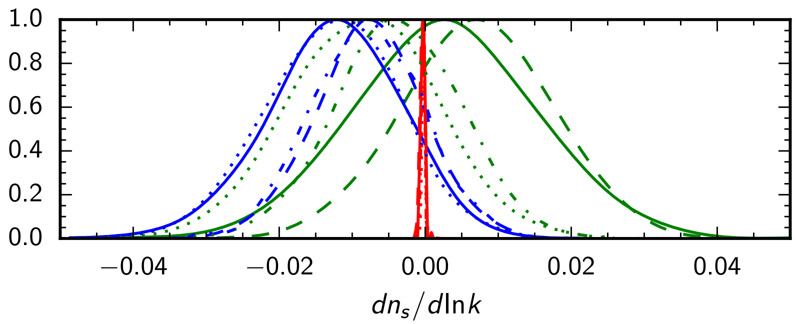

Gerbino et al. 2017

# Potential reconstruction beyond SR



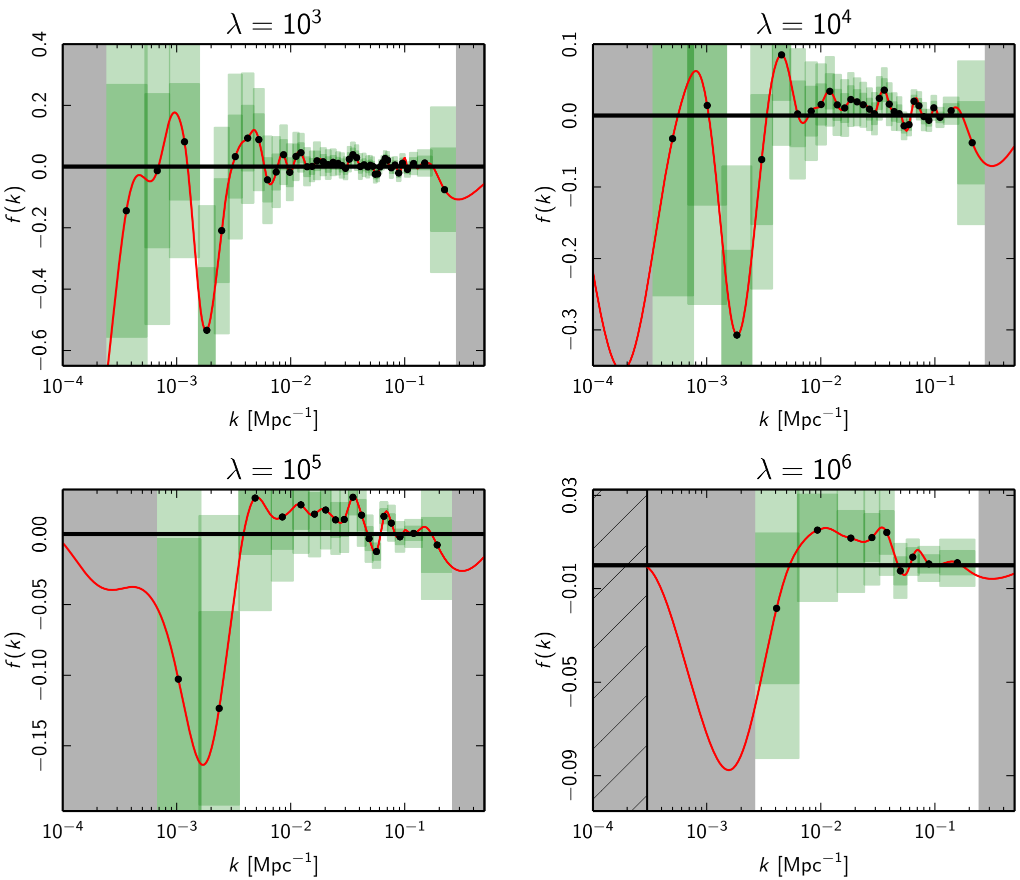




With more freedom in the potential, an initial phase of "marginal slow roll" still fits the data and allows for a larger tensor-to-scalar ratio.

However, statistical significance is low – no higher order derivatives are needed

# PPS Reconstruction

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1} \exp\left[f(k)\right]$$

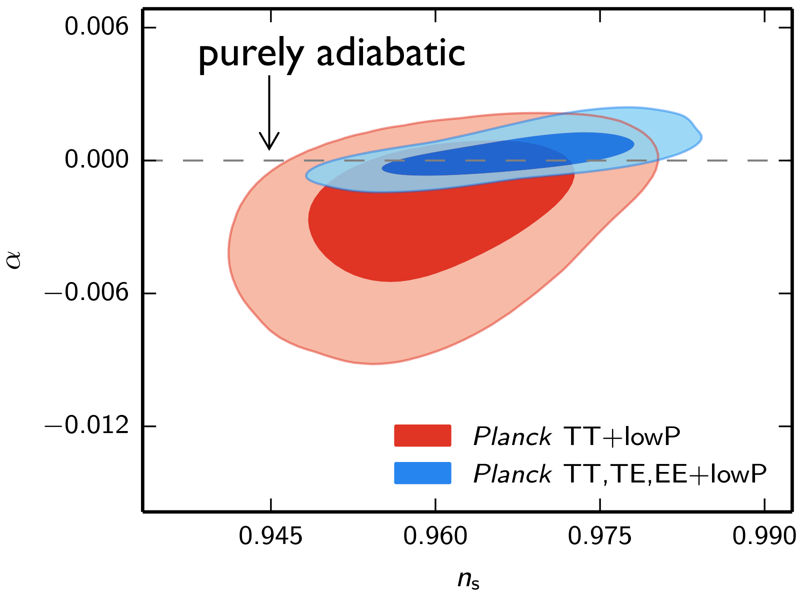



No deviations from a smooth power law except around k ~ 0.002 Mpc$^{-1}$

The deviations, however, are not statistically significant (less than 2σ level)

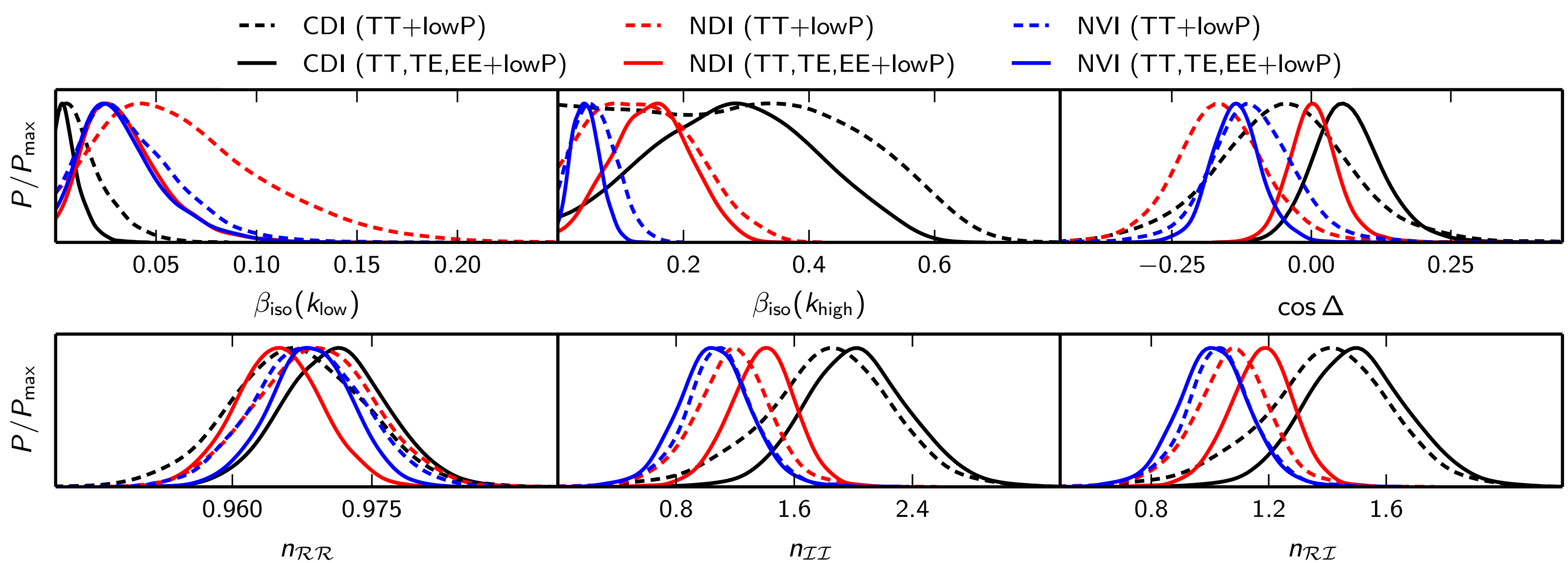
Similar results obtained with different methods.

# ADIABATICITY OF INITIAL CONDITIONS

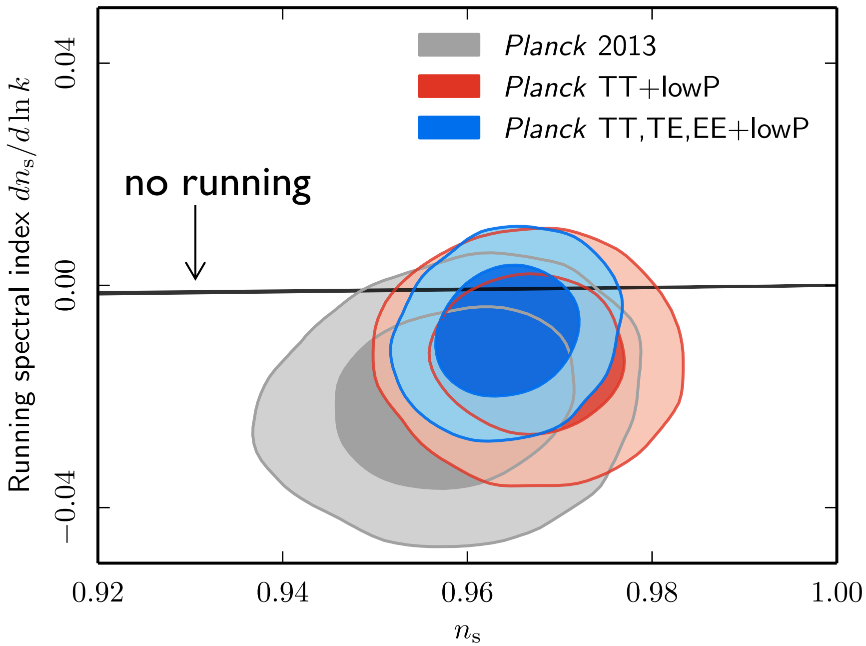



Adiabatic initial conditions are strongly favoured (ΔlnB < - 5 for nearly all models and data combinations)

Isocurvature fractions are constrained to be below the ~ few percent level



# SUMMARY

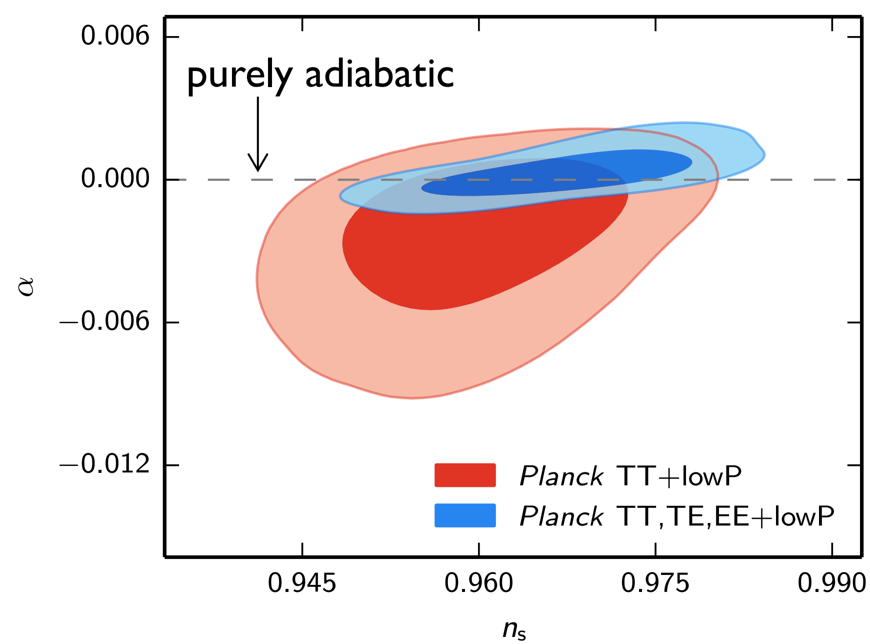



Planck data are consistent with purely adiabatic initial scalar pertubations with a nearly scale-invariant power-law spectrum

Consistent with single-field slow-roll inflation

No evidence for

- isocurvature modes
- running of the spectral index
- primordial non-gaussianities
- features in the primordial PS



**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.