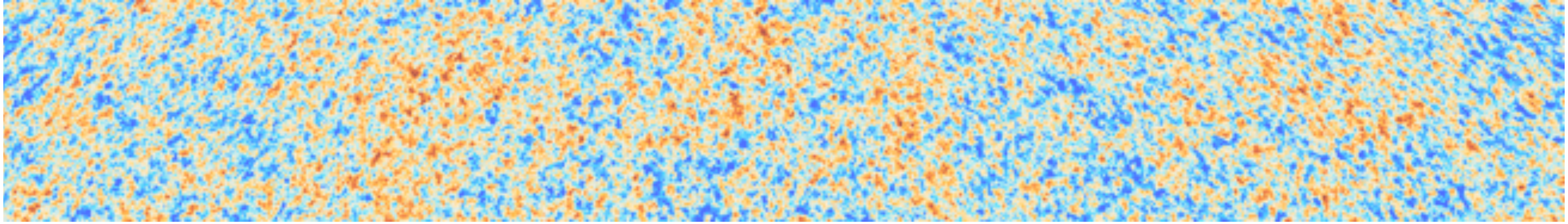

Implications of the next CMB space mission for the power spectrum of primordial fluctuations

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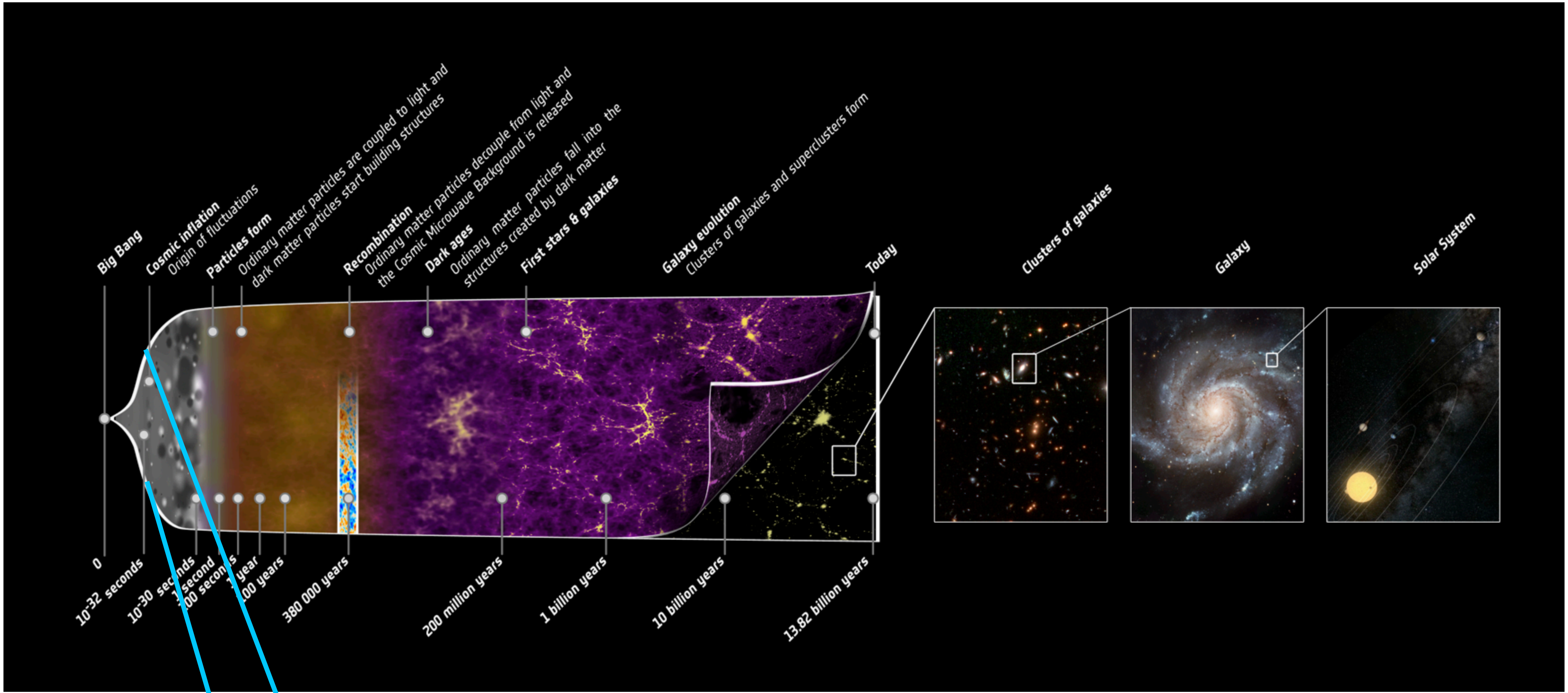
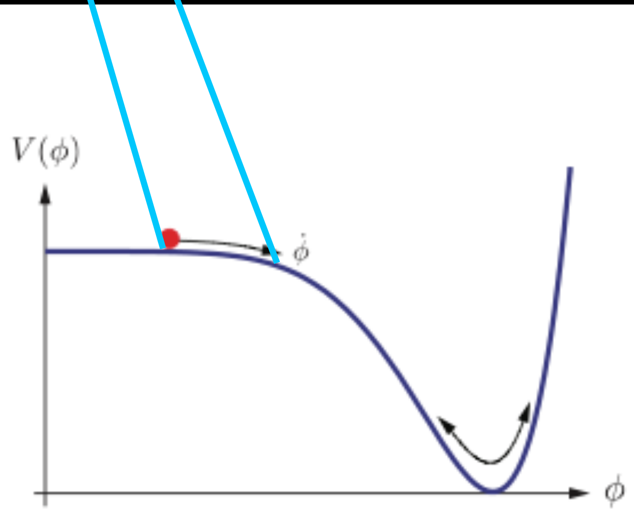
with inputs from Italian CMB community and CORE teams

Meeting INAF - Macroarea 1
Galassie e Cosmologia
Bologna, 16-17 Giugno 2016



Credit: ESA and the Planck Collaboration.



Generation of fluctuations

Scalar and tensor linear perturbations are amplified from the initial (Bunch-Davies) quantum vacuum to long-wavelength classical fluctuations.

Tensor perturbations (gravitational waves)

$$\mathcal{P}_{\rm t}(k) = A_{\rm t}\left(\frac{k}{k_*}\right)^{n_{\rm t}+\frac{1}{2}\frac{{\rm d}n_{\rm t}}{{\rm d}\ln k}\ln(\frac{k}{k_*})+\ldots}$$

$$A_{\rm t} \simeq \frac{2H^2}{\pi^2 M_{\rm pl}^2} \approx \frac{2V}{3\pi^2 M_{\rm pl}^4}$$

$$n_{\rm t} \simeq -2\epsilon_1 \approx -\frac{M_{\rm pl}^2 V_\phi^2}{V^2}$$

$$\epsilon_1 = -\frac{\dot{H}}{H^2} << 1$$

$$\frac{{\rm d}n_{\rm t}}{{\rm d}\ln k} \simeq -2\epsilon_1\epsilon_2$$

$$\epsilon_2 = -\frac{\dot{\epsilon}_1}{H\epsilon_1} << 1$$

Scalar perturbations

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\frac{1}{2}\frac{{\rm d}n_{\rm s}}{{\rm d}\ln k}\ln(\frac{k}{k_*})+\ldots}$$

$$A_{\rm s} \approx \frac{V^3}{12\pi^2 M_{\rm pl}^6 V_\phi^2}$$

$$\begin{aligned} n_{\rm s} - 1 &\simeq -2\epsilon_1 - \epsilon_2 \\ &\approx -3\frac{M_{\rm pl}^2 V_\phi^2}{V^2} + 2\frac{M_{\rm pl}^2 V_{\phi\phi}}{V} \end{aligned}$$

$$\frac{{\rm d}n_{\rm s}}{{\rm d}\ln k} \simeq -2\epsilon_1\epsilon_2 - \epsilon_2\epsilon_3$$

$$r = \frac{\mathcal{P}_{\rm t}(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)} \simeq 16\epsilon_1 \simeq -8n_{\rm t}$$

Planck results and key inflationary predictions

Planck TT + lowP

A spatially flat Universe (+ Planck lensing)	$\Omega_K = -0.005^{+0.016}_{-0.017}$	$95\%\mathrm{CL}$
A tilted power-law spectrum for density perturbations	$n_\mathrm{s} = 0.9655 \pm 0.0062$	$68\%\mathrm{CL}$
No statistical evidence of running	$dn_\mathrm{s}/d\ln k = -0.0084 \pm 0.0082$	$68\%\mathrm{CL}$
Small relative amount of gravitational waves	$r_{0.002} < 0.10$	$95\%\mathrm{CL}$

Nearly Gaussian perturbations (T + E)

$$f_\mathrm{NL}^\mathrm{local} = -0.8 \pm 5.0 \qquad 68\%\mathrm{CL}$$
$$f_\mathrm{NL}^\mathrm{equil} = -3.7 \pm 43$$
$$f_\mathrm{NL}^\mathrm{ortho} = -26 \pm 21$$

see Liguori talk

Planck 2015 results. XIX. Constraints on primordial non-Gaussianities

No need for additional fields: nearly adiabatic fluctuations $\beta_\mathrm{iso} < 0.035$ $95\%\mathrm{CL}$

Planck 2015 results. XX. Constraints on inflation

No strings and other topological defects $f_{10} < 0.020$ $95\%\mathrm{CL}$

Planck 2015 results. XIII. Cosmological parameters

A smoking gun for inflation: B-mode polarization

Current measurements including B-mode polarization

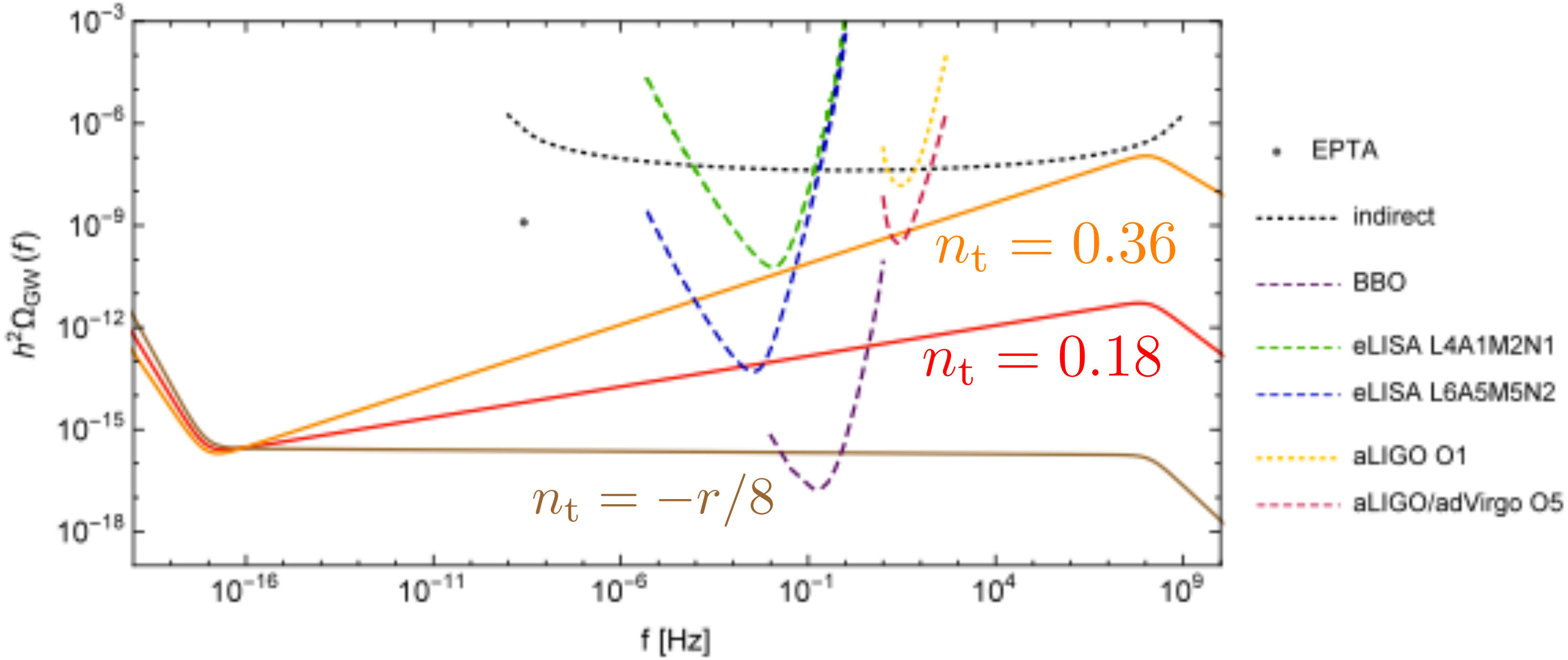
	(95 % CL)	
Bicep 2/Keck Array/Planck (BKP)	$r < 0.12$	
Planck 2015 + BKP	$r < 0.08$	
Planck 2015 + BKP incl. 95 GHz	$r < 0.07$	$V^{1/4} < 1.7 \times 10^{16}$ GeV (95 % CL)

$$V = \frac{3\pi^2 A_\mathrm{s}}{2} \, r \, M_\mathrm{pl}^4$$

CORE specifications are currently designed to reach a sensitivity on r of the order of 2 x 10^{-4} (preliminary) **based on noise sensitivity and BB delensing** as the ultimate measurement of B-mode polarization.

CORE can probe the energy scale of inflation in the GUT range down to 6 x 10^{15} GeV.

Synergy with direct search of GWs



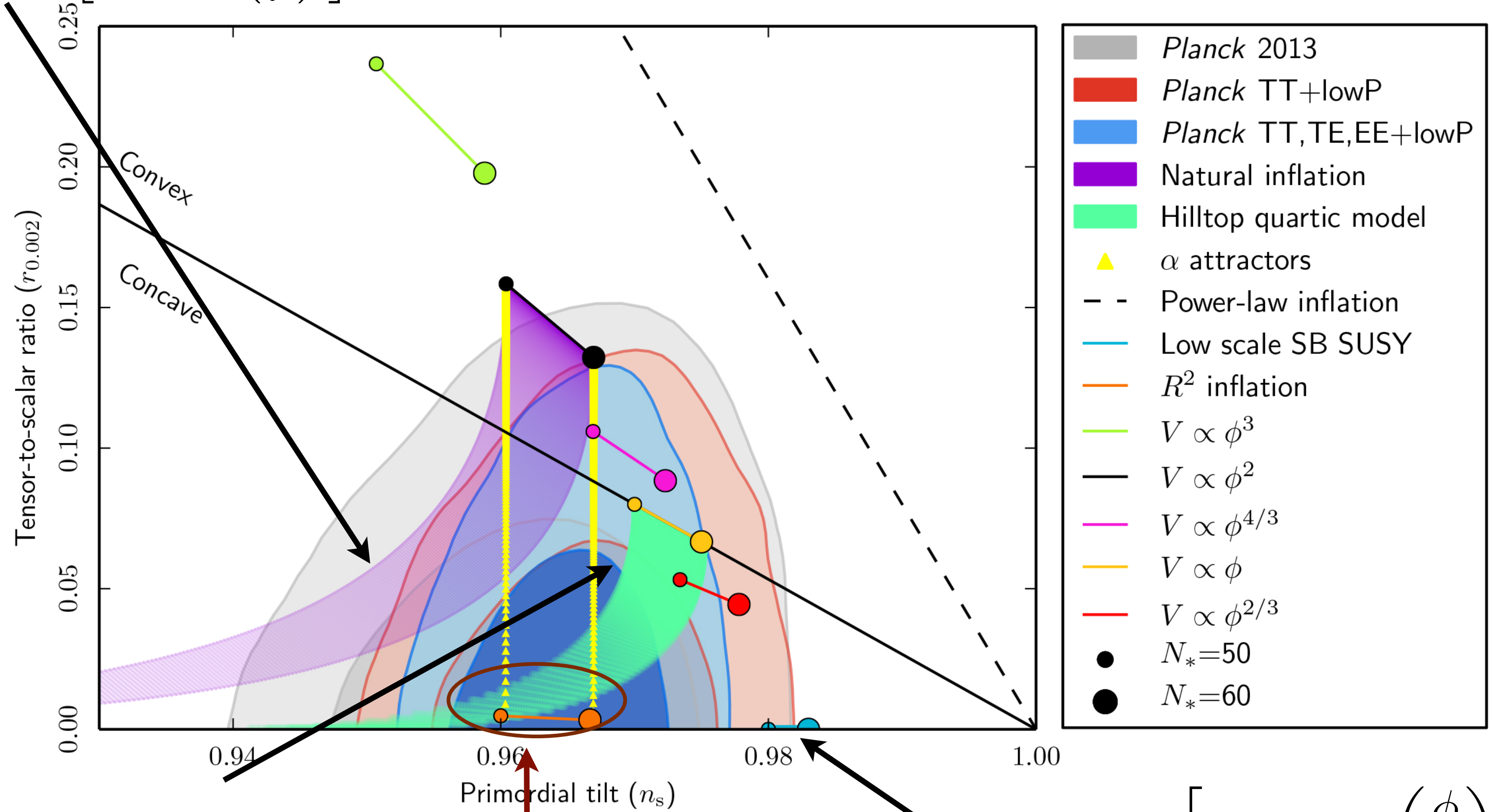
Guzzetti, Bartolo, Liguori e Matarrese, 2016, arXiv:1605.01615

See also Lasky et al., 2016, Phys. Rev. X 6

Inflationary Models

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

Planck 2015 results XX: Constraints on inflation

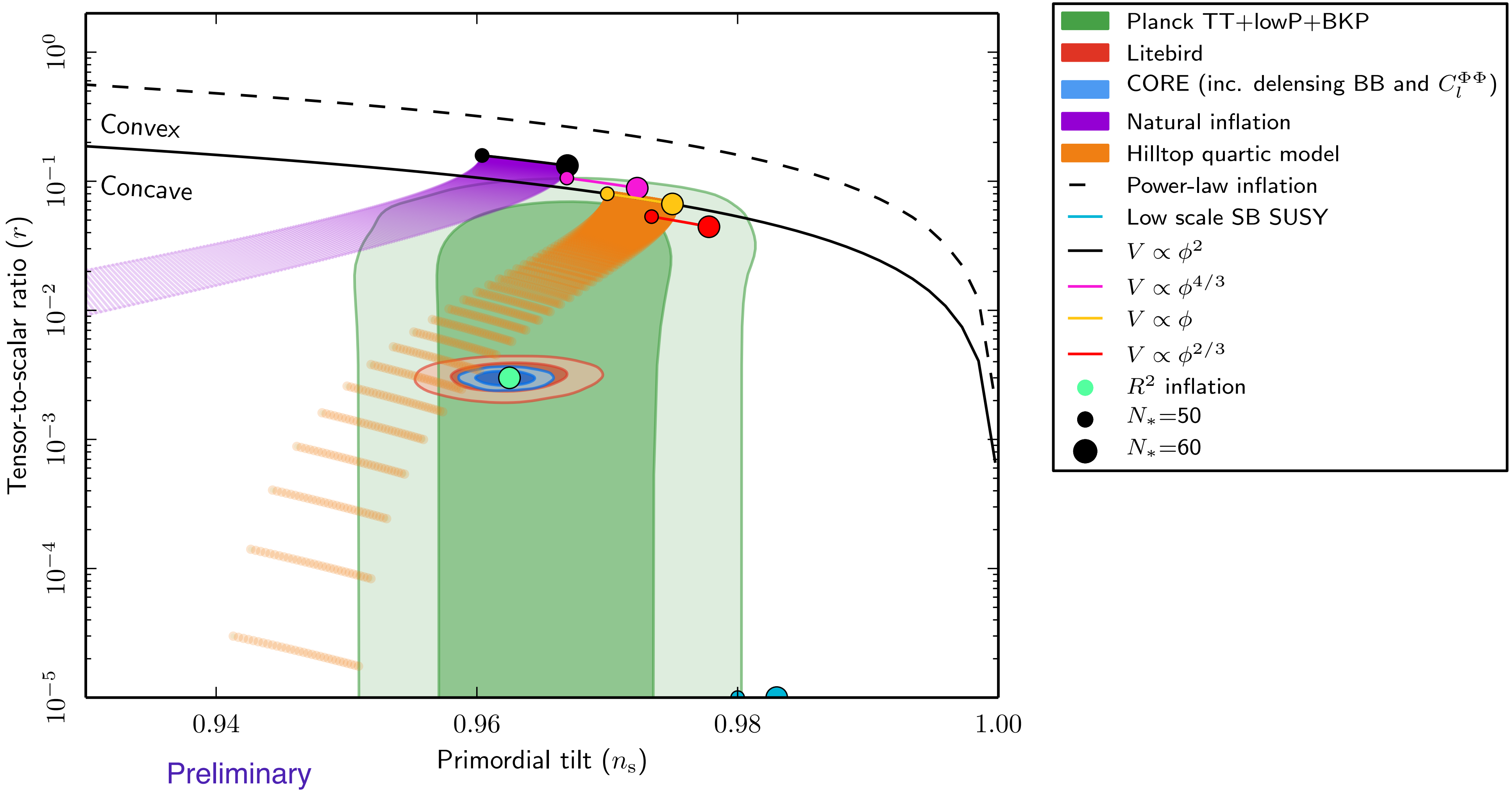


$$V(\phi) = \Lambda^4 \left(1 - \frac{\phi^4}{\mu^4} + \ldots\right)$$

$$V(\phi) = \Lambda^4 \left[1 + \alpha_{\rm h} \ln\left(\frac{\phi}{\mu}\right)\right]$$

$$V(\tilde{\phi}) = \frac{\Lambda^4}{4} \left(1 - e^{-2\tilde{\phi}/\sqrt{6}M_{\rm pl}}\right)^2$$

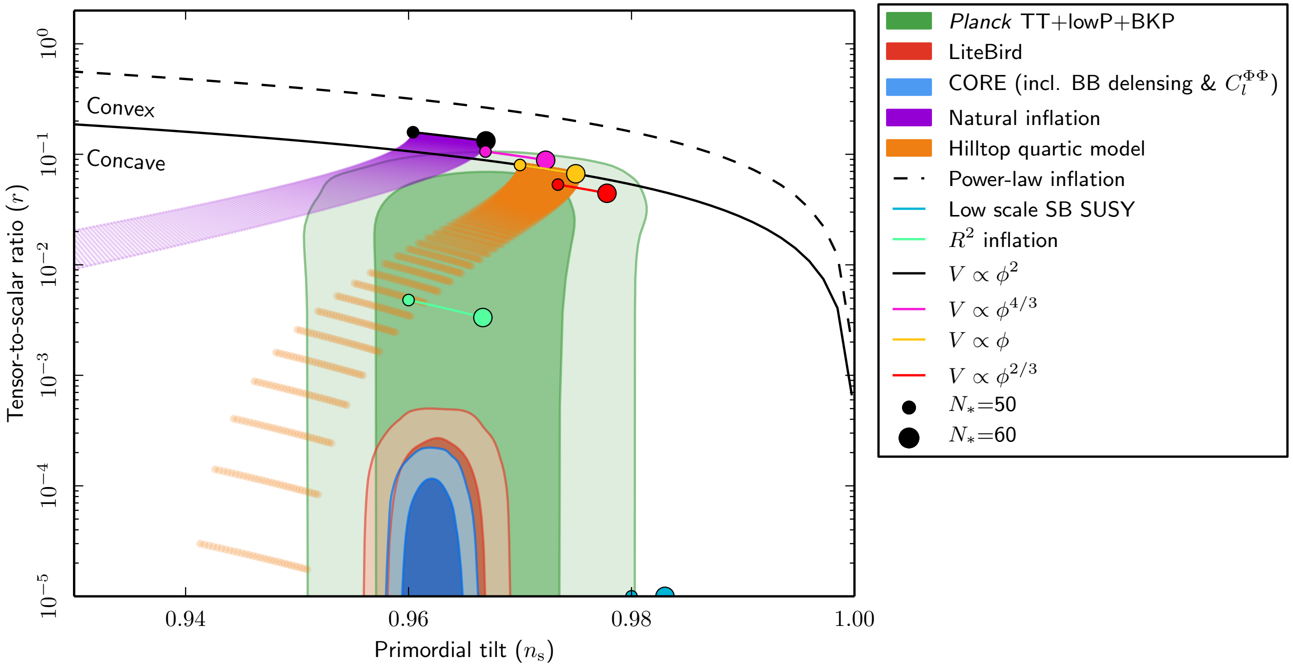
The Starobinsky model unveiled !



A detection at high statistical significance of the best inflationary model after Planck (Starobinsky, 1980; Mukhanov & Chibishov, 1981) which predicts $r \sim 3 \times 10^{-3}$

An upper limit to r?

Preliminary



Self-consistent delensing for CORE is important to push the ultimate sensitivity (before foreground subtraction) for r to 10^{-4}, compared to 3 x 10^{-4} which LiteBird can reach.

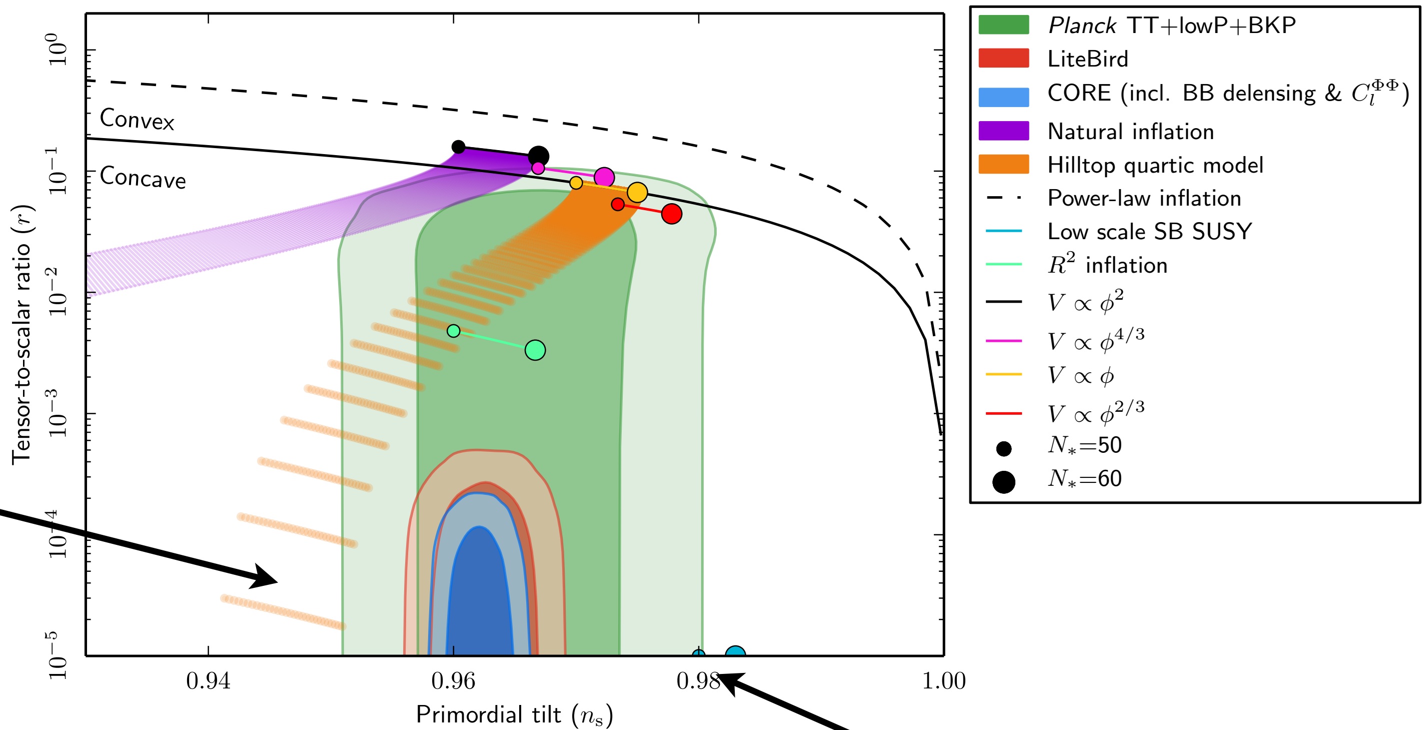
In case of a null detection for primordial GW, this means that inflation would have occurred at scales below 10^{16} GeV, 12 orders of magnitude larger than @ LHC !

The Lyth bound connects r to the change of the inflaton value from the CMB scale to the end of inflation

$$\frac{\Delta\phi}{M_{\rm pl}} \approx \int_{N_{\rm end}}^{N_{\rm CMB}} {\rm d}N \sqrt{\frac{r}{8}} \approx \mathcal{O}(1) \left(\frac{r}{0.01}\right)^{1/2}$$

The change in the value of inflaton would be sub-Planckian under quite conservative assumptions. This would be a result of key importance for model building since would establish that radiative corrections to the potential are under control.

An upper limit to r? (2)



$$V(\phi) = \Lambda^4 \left(1 - \frac{\phi^4}{\mu^4} + \ldots\right)$$

Preliminary

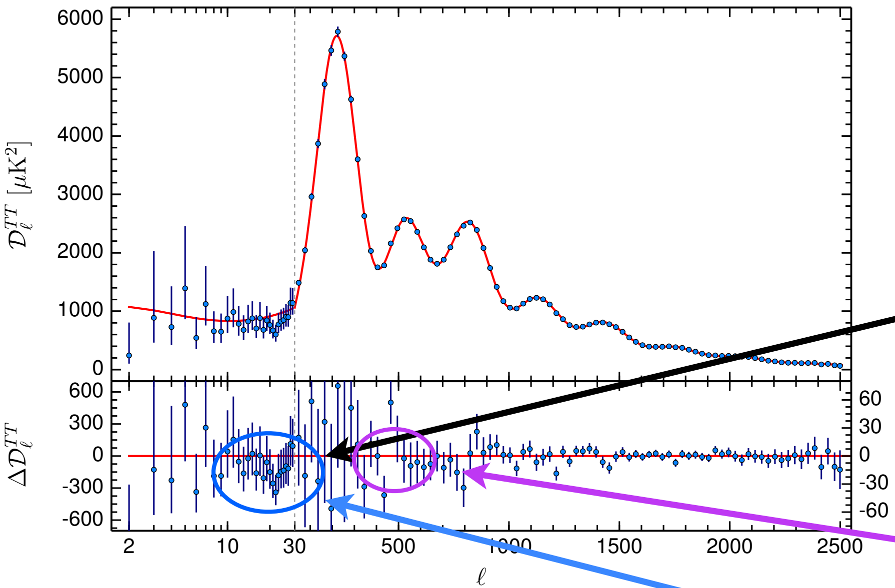
$$V(\phi) = \Lambda^4 \left[1 + \alpha_{\rm h} \ln\left(\frac{\phi}{\mu}\right)\right]$$

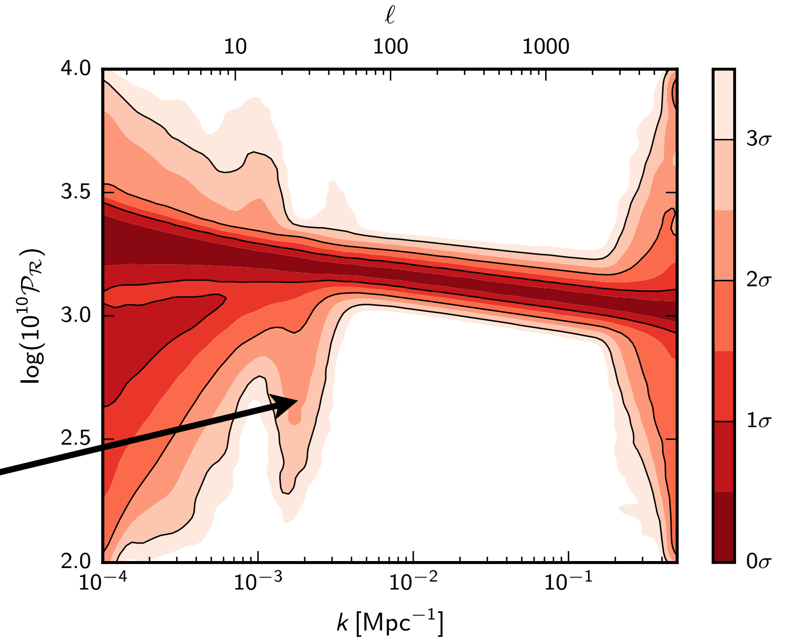
Either the higher angular resolution and the inclusion CMB lensing information drive the uncertainty on n_s down to 0.0015 compared to what can be reached by Planck + Euclid P(k), which is around 0.0024.

Several models predicting a low r would be ruled out at high statistical significance!

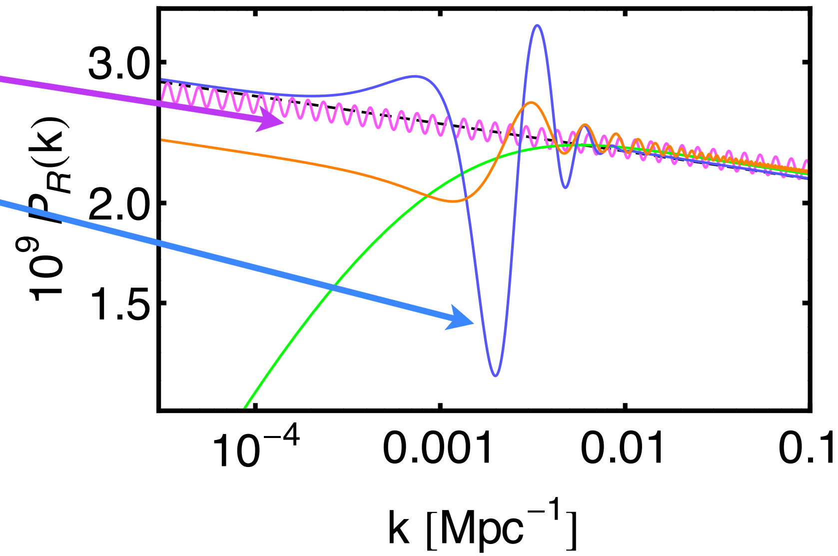
The observational uncertainty on ns will be closer to the theoretical uncertainties due to our ignorance for the expansion history from the end of inflation to now. We'll enter in a new era in which inflationary models will be tested also through the predictions for the post-inflationary expansion (i.e. reheating temperature).

Deviations from a simple power-law spectrum for primordial fluctuations



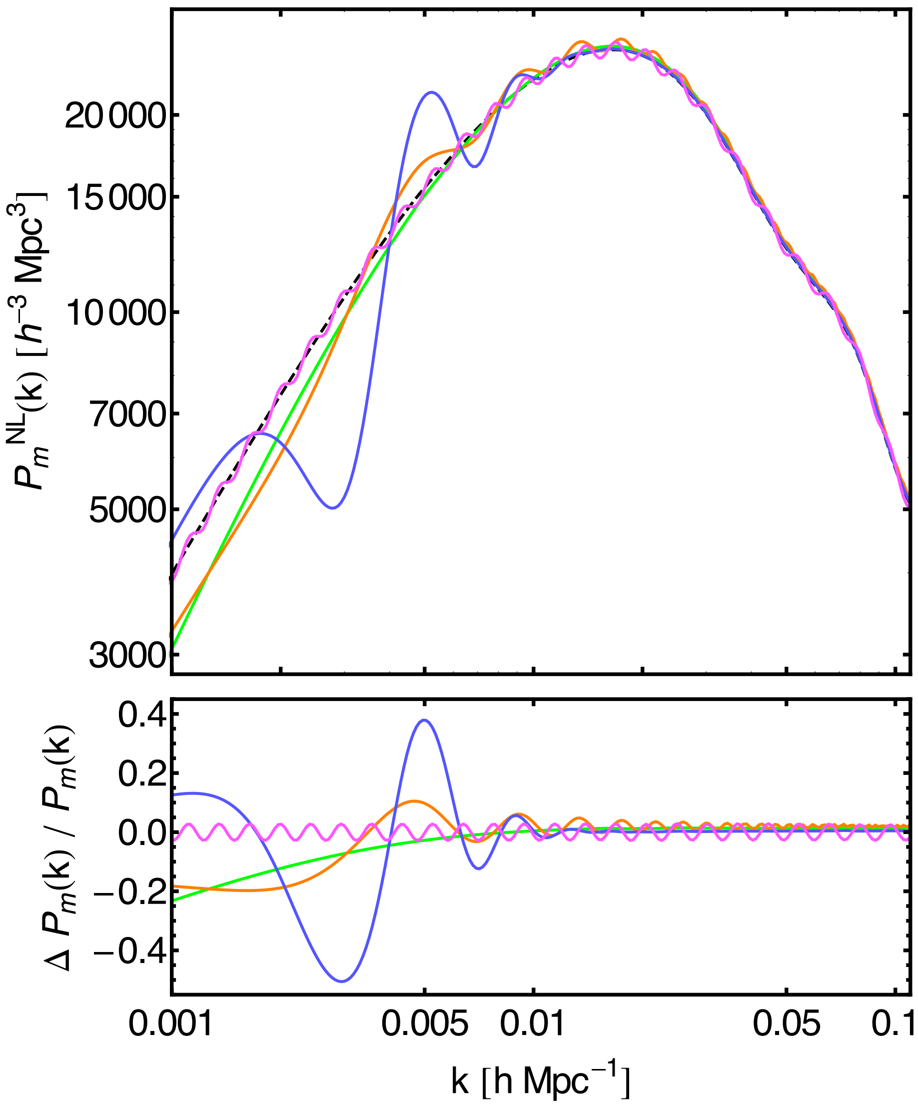


Are these departures in the Planck temperature power spectrum just statistical fluctuations and noise or are of primordial origin?



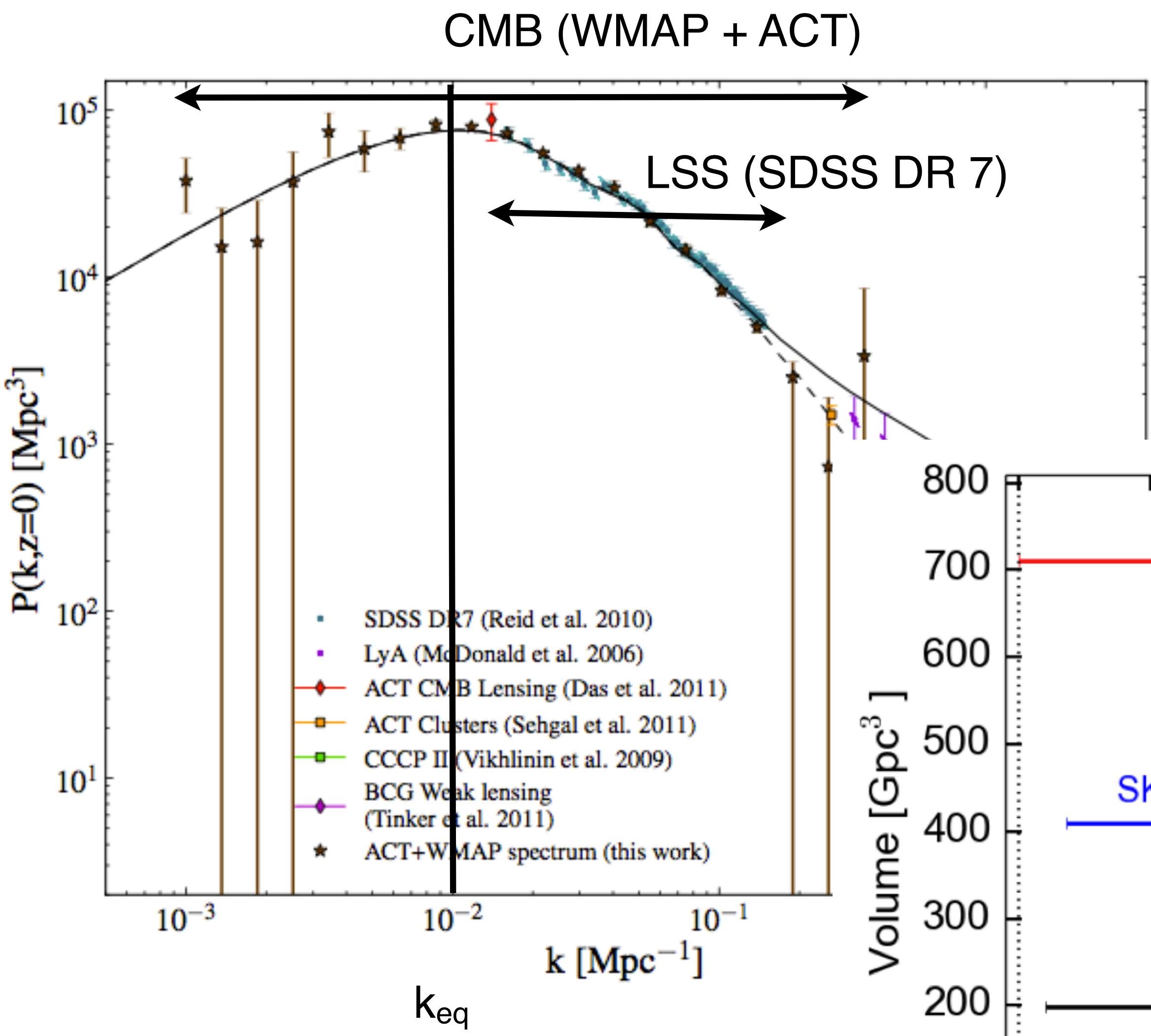
Best-fits motivated by a short inflationary stage, by non-perturbative effect in the inflaton potential, ...

Imprints of Planck features on the matter power spectrum

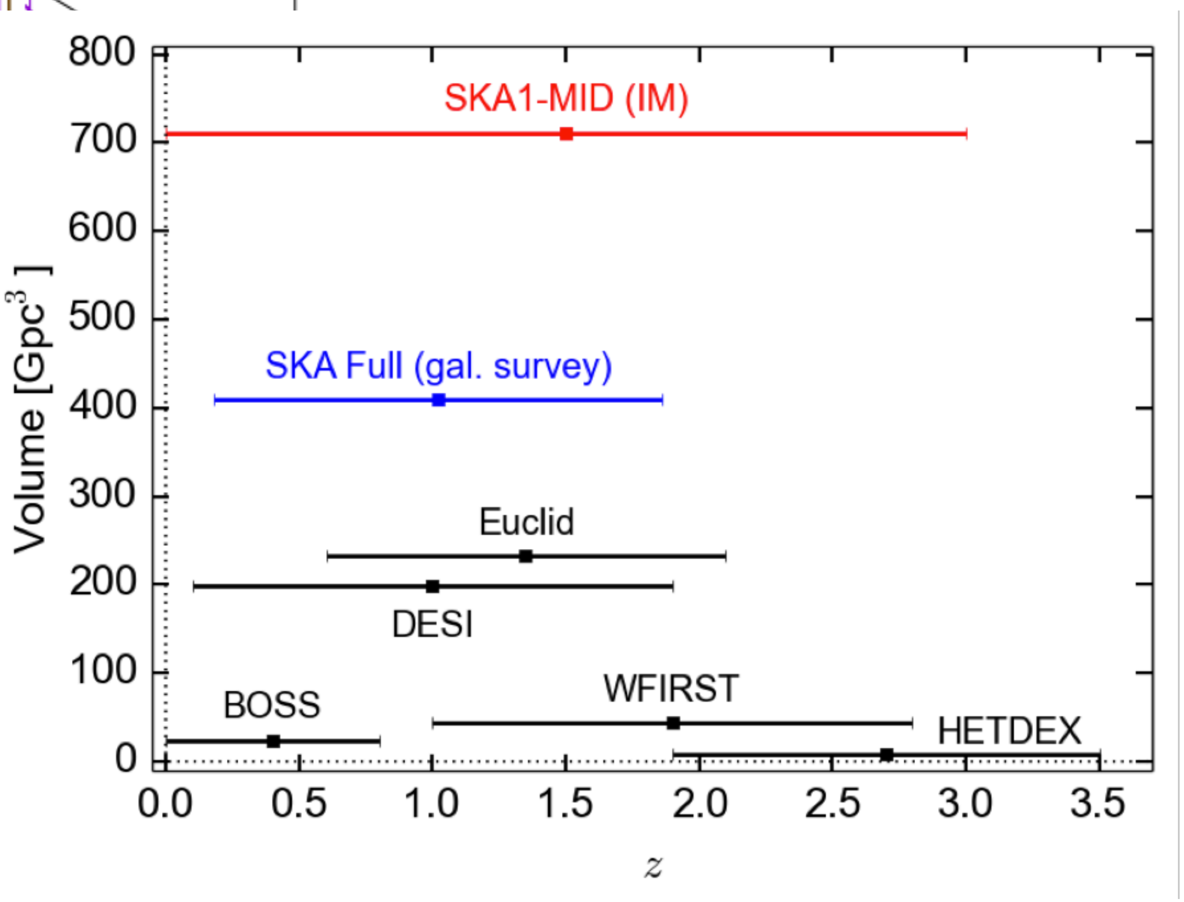


If primordial, these features leave imprints in the matter power spectrum as well.

Future galaxy surveys perspective

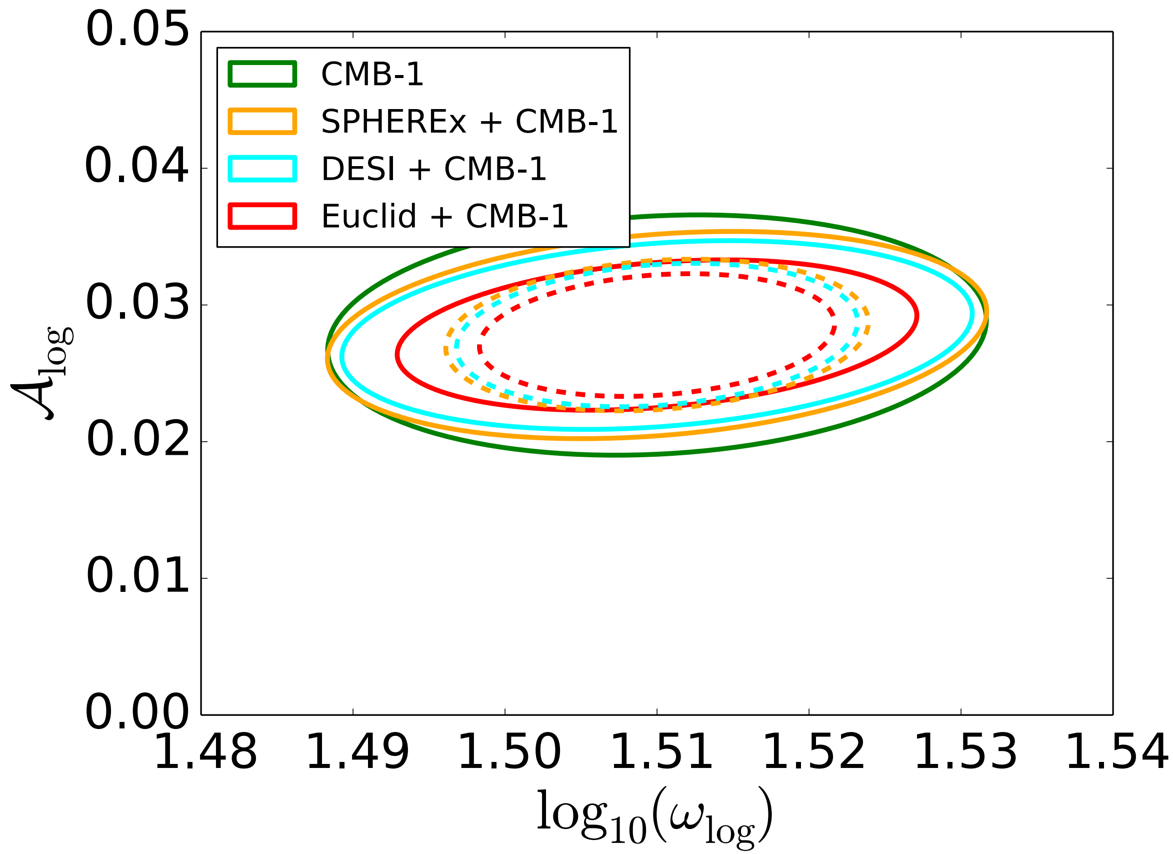


Hlozek et al., ACT collaboration, 2012, ApJ 749



Santos et al., arXiv:1501.03989 (2015)

Future galaxy surveys perspective (2)



Ballardini et al., 2016, arXiv:1606.03747

Future galaxy surveys can determine if the origin of some of the features we see in Planck temperature power spectrum is primordial!

Conclusions

- Detecting B-modes from primordial gravitational waves would be a definitive confirmation of inflation.

- CORE is designed to be the ultimate CMB space mission to explore the energy scale of GUTs in synergy with the direct search of gravitational waves.

- CMB is one of the key observables to improve significantly the current status of the phenomenology of inflation. CORE sensitivity can confirm or rule out inflationary models favoured by Planck (such as R^2 model) at hight statistical significance.

- CORE can probe the physics of inflation beyond the simplest slow-roll models alone or in combination with future galaxy surveys.