Features and anomalies in the primordial power spectrum

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CMB-DAY 2

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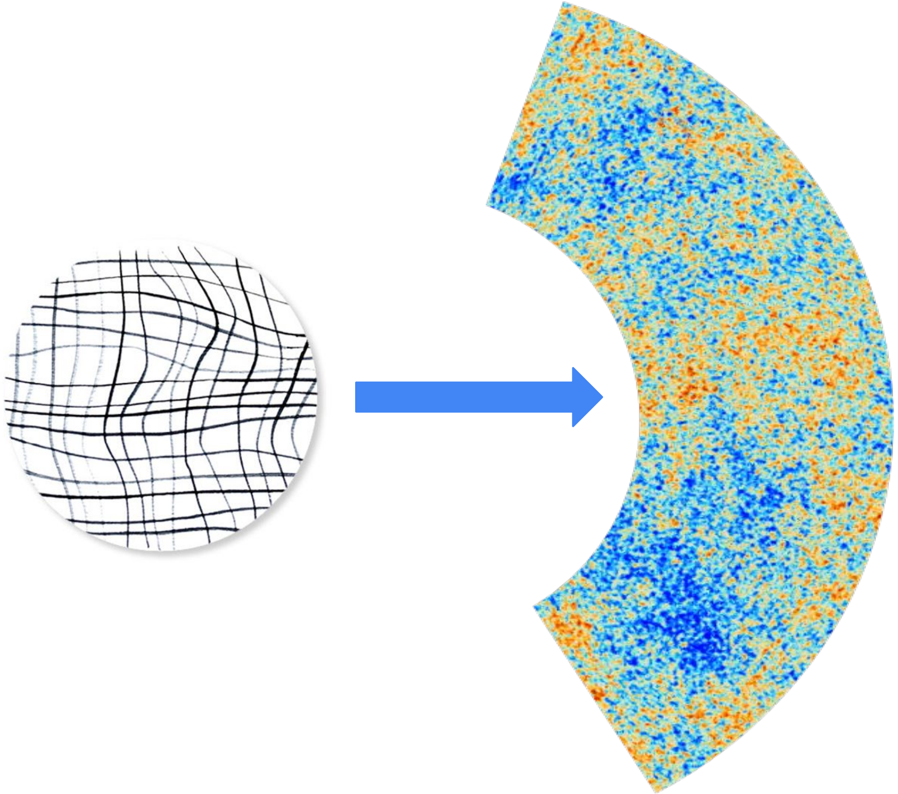
From primordial fluctuations to CMB anisotropies



Key predictions

Planck 2018 results. VI. Cosmological parameters
Planck 2018 results. IX. Constraints on primordial non-Gaussianity
Planck 2018 results. X. Constraints on inflation

1) At present the Universe has an almost perfect flat Euclidean geometry.

2) The produced inhomogeneities should be adiabatic.

3) The primordial inhomogeneities are nearly Gaussian.
   Acquaviva, Bartolo, Matarrese, Riotto, NPB 2003; Maldacena, JHEP 2003

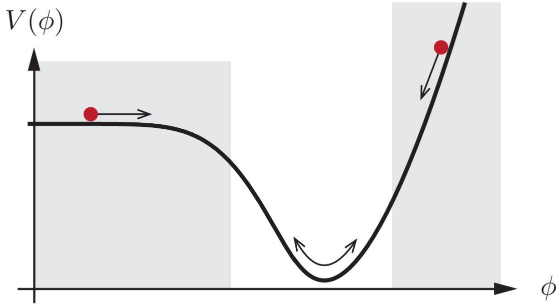
4) Inflationary perturbations generated during a slow-roll regime have a nearly flat power spectrum.

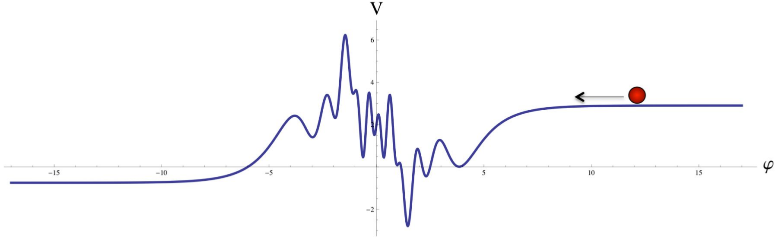
5) The existence of the long-wave gravitational waves.
   Starobinsky, SJETPL 1979

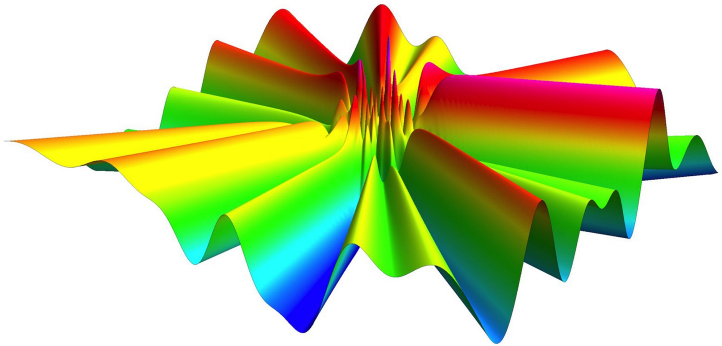
Primordial Gravitational Waves, not the perfect smoking gun:

1) Measuring such a tensor spectrum would not be enough to point to a specific inflationary models.
2) Not measuring such a tensor spectrum would not rule out cosmic inflation (e.g., very low-energy reheating temperature).

The inflationary scenario





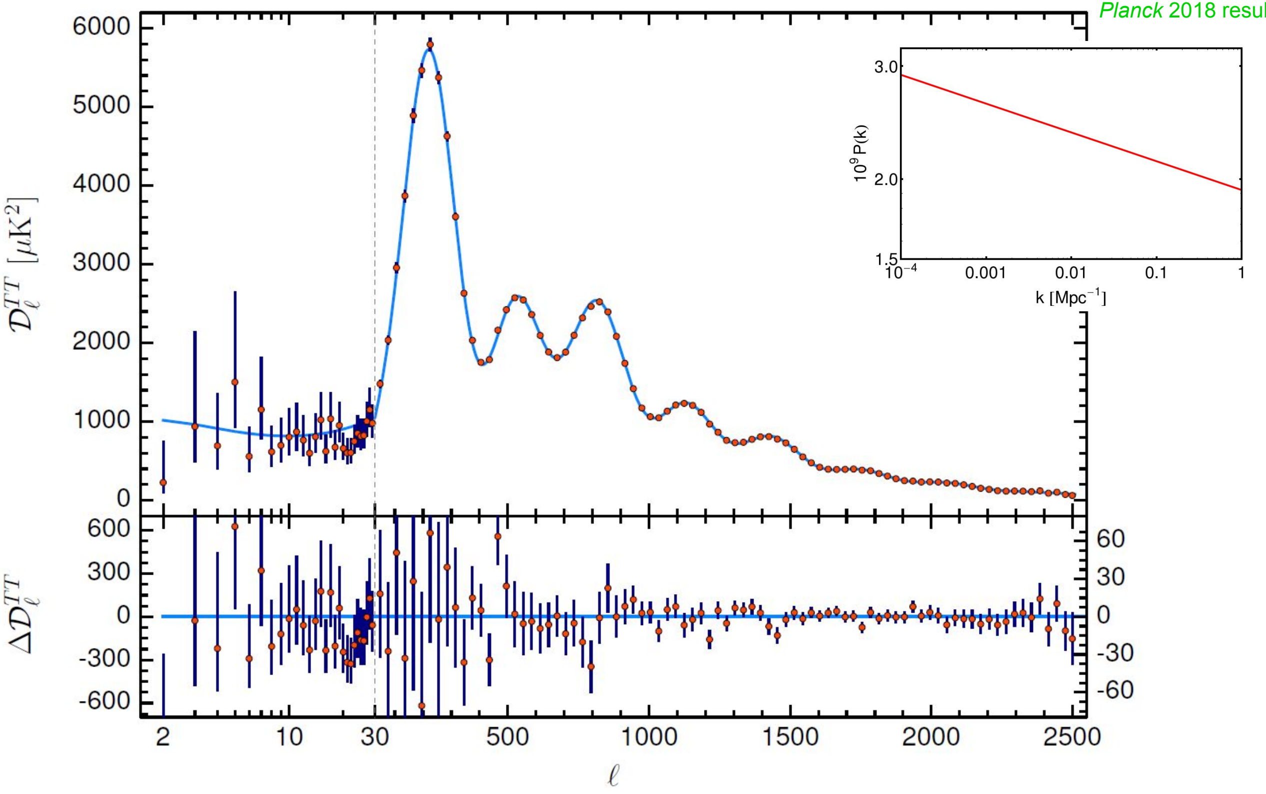


Single-field slow roll inflation is (most probably) a simplified model:

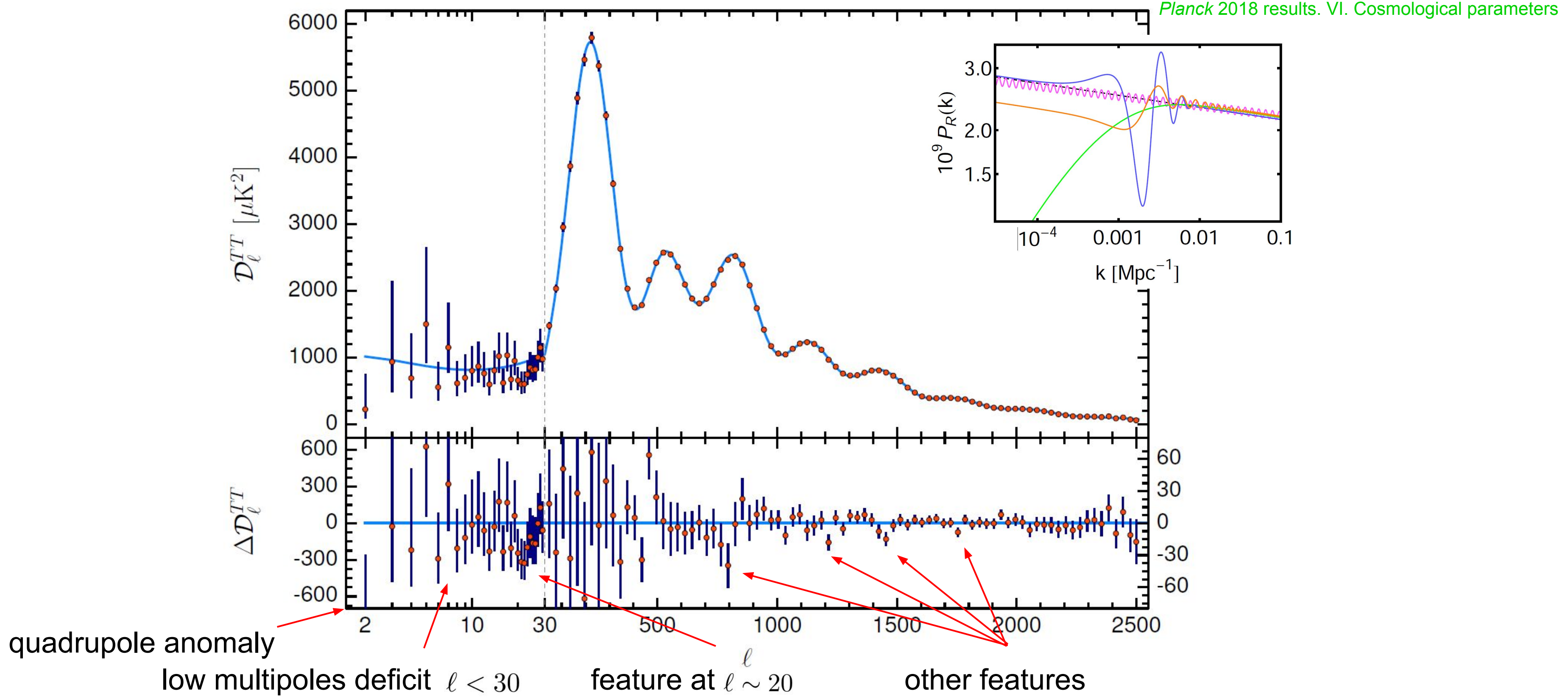
- Assumes a single-field slowly rolling down its potential.
- Assumes all other fields decoupled during inflation.
- Assumes a minimal coupling to gravity.

The CMB temperature anisotropies

Planck 2018 results. VI. Cosmological parameters

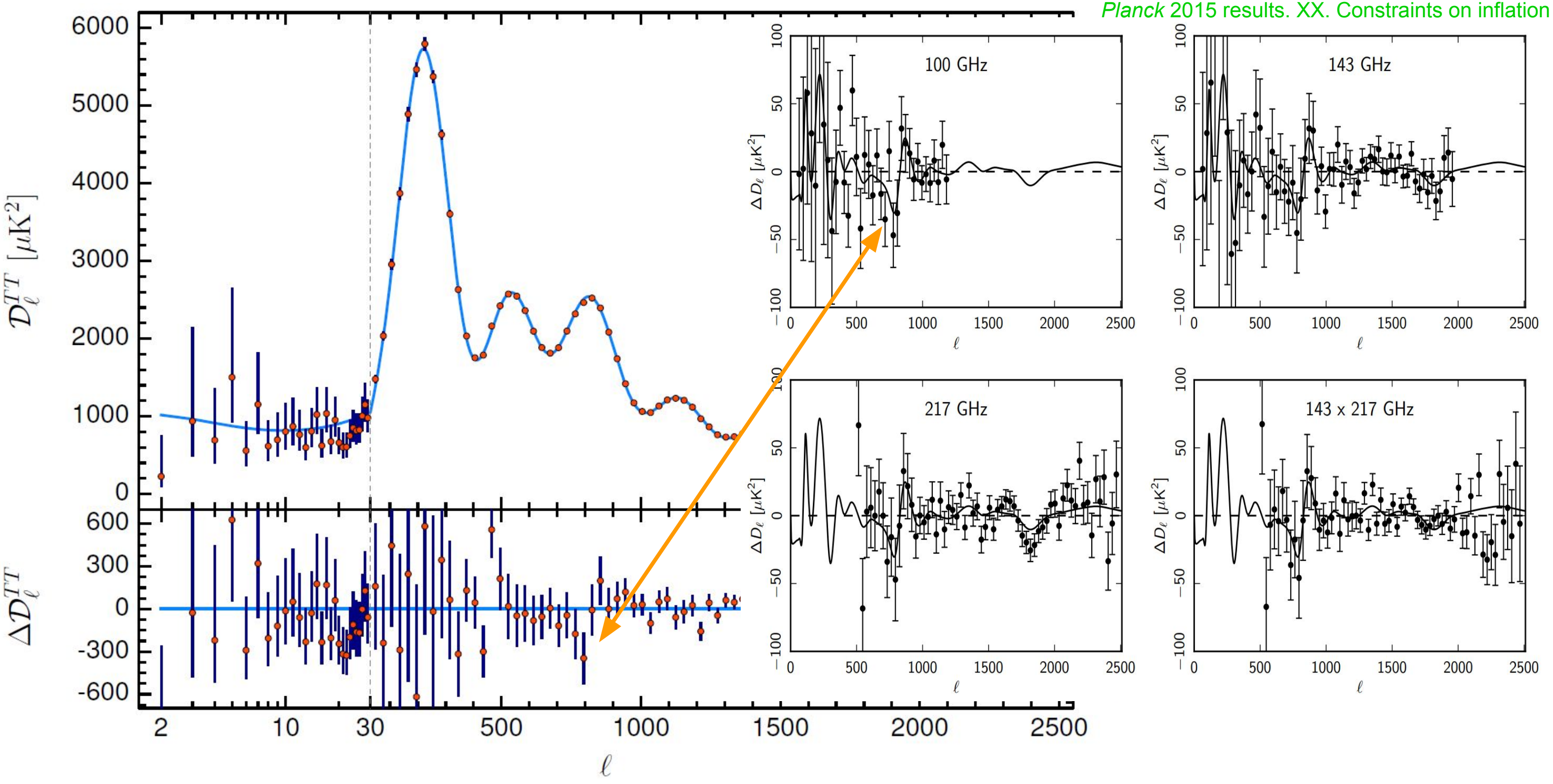


Features in the CMB temperature anisotropies

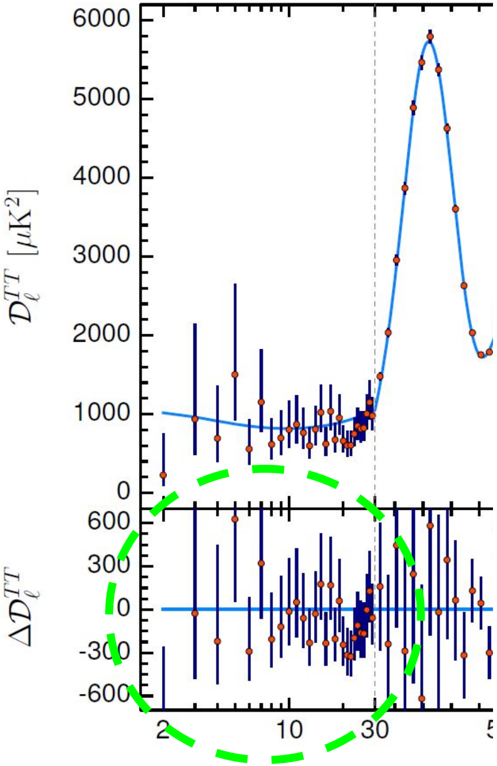


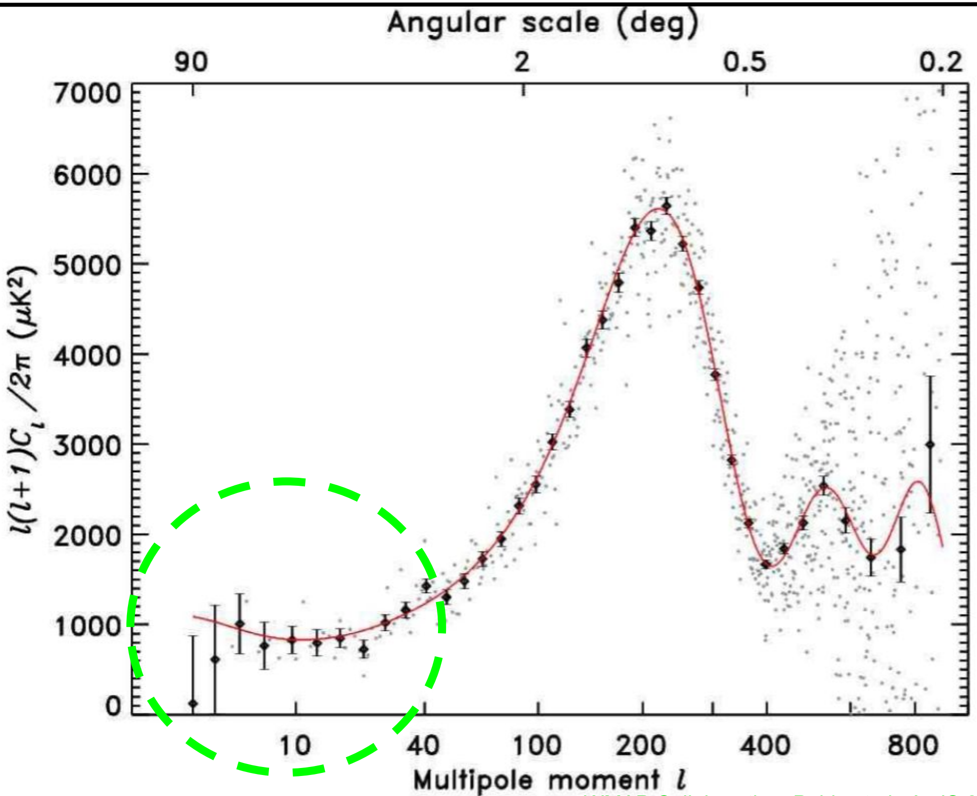
Features in the CMB temperature anisotropies

Planck 2015 results. XX. Constraints on inflation



For 15 year…





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WMAP Collaboration, Peiris et al., ApJS 2003

Primordial oscillatory features

For a single clock:

- Excitations in time (changing equation-of-state during inflation at fixed time or speed of sound change) lead to linear oscillations (also known as sharp feature).
  Starobinsky, SJETPL 1992
  Adams, Cresswell, Easther, PRD 2001
  Achucarro, Gong, Hardeman, Palma, Patil, JCAP 2011
  Chen, 2011

- Excitations in scale (oscillatory potential or initial state modifications at some fixed scale) lead to logarithmic oscillations (also known as resonant model).
  Freese, Frieman, Olinto, PRL 1990
  Chen, Easther, Lim, JCAP 2008

Planck searches for parameterized oscillatory features

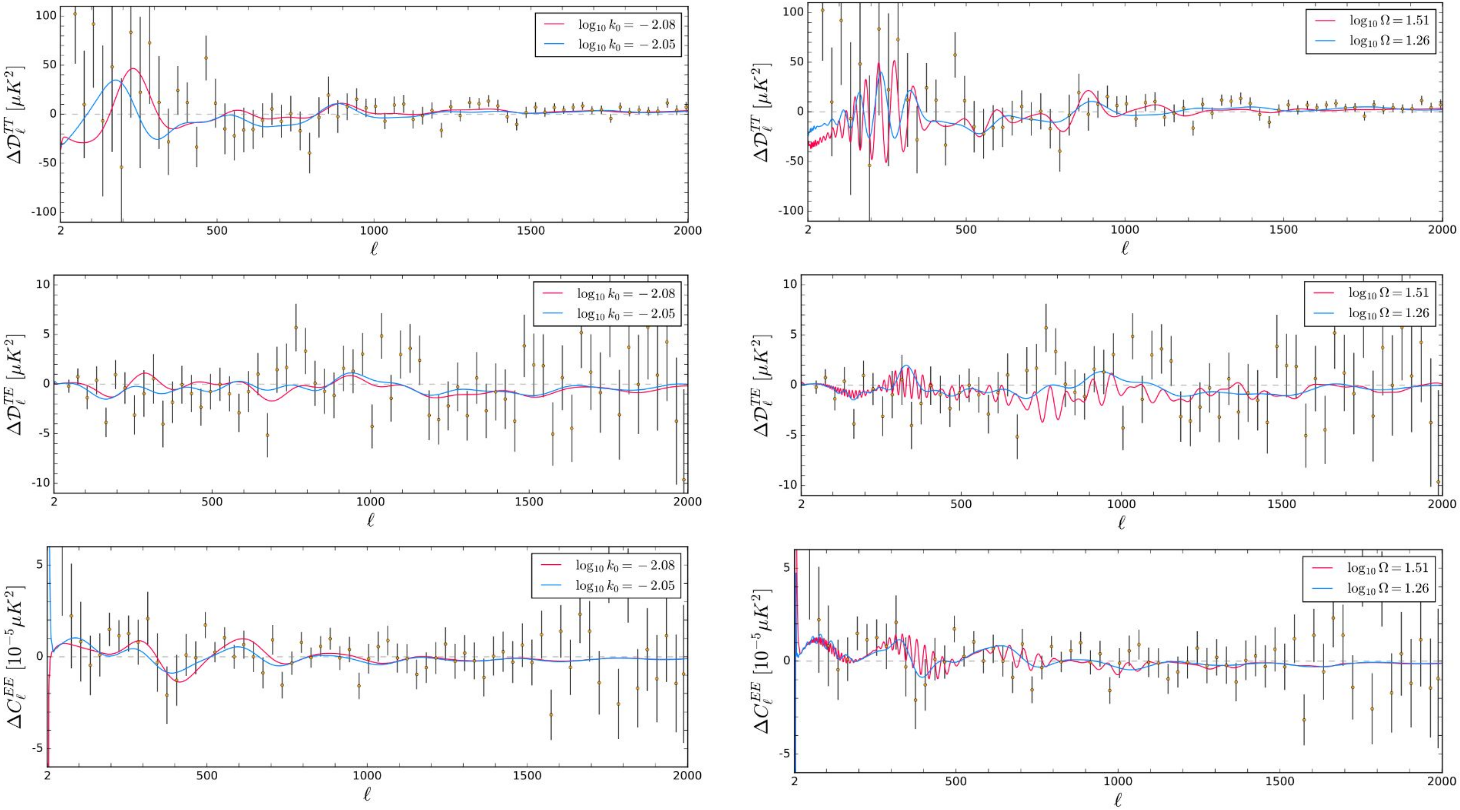
Planck 2018 results. X. Constraints on inflation

$$P_\zeta(k) = P_{\zeta,0}(k)\left[1 + \mathcal{A}_{\rm lin}\cos\left(\omega_{\rm lin}\frac{k}{k_*} + \phi\right)\right]$$

$$P_\zeta(k) = P_{\zeta,0}(k)\left[1 + \mathcal{A}_{\rm log}\cos\left(\omega_{\rm log}\log\frac{k}{k_*} + \phi\right)\right]$$

	Lin osc			Log osc		
	TT	EE	TT,TE,EE	TT	EE	TT,TE,EE
$\Delta\chi^2_{\rm eff}$	−4.2	−9.0	−10.8	−8.5	−13.5	−11.0
$\ln B$	−1.8	−1.3	−0.8	−1.5	−0.2	−0.9
$\mathcal{A}_X$	0.024	0.046	0.015	0.024	0.073	0.014
$\log_{10}\omega_X$	1.74	1.84	1.05	1.51	1.72	1.26
$\varphi_X/(2\pi)$	0.34	0.81	0.56	0.60	0.07	0.07
$\alpha_{\rm rf}$	...	...	...	...	...	...

Planck searches for parameterized oscillatory features



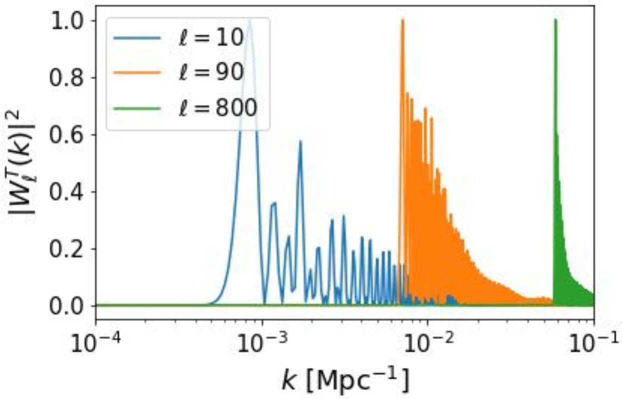
Features and the CMB temperature

- Projection effect from momentum space to multipole space:

$$\frac{\ell(\ell+1)}{2\pi} C_\ell^{XX'} = \int \mathrm{d}\ln k\, W_\ell^X W_\ell^{X'} \Delta_{\mathcal{R}}^2(k)$$

$$\frac{\ell(\ell+1)}{2\pi} C_\ell^{TT} \approx \frac{\Delta_{\mathcal{R},0}^2}{25}\left[1 + \mathcal{A}\sqrt{\frac{\pi}{2}\frac{D_{\rm rec}}{\Omega\ell}}\cos\left(\frac{\Omega\ell}{D_{\rm rec}} + \frac{\pi}{4}\right)\right]$$

- The actual (normalized) transfer function differs from the SW approximation: ISW, Doppler, ...



Features and the CMB E-mode polarization

- Projection effect from momentum space to multipole space:

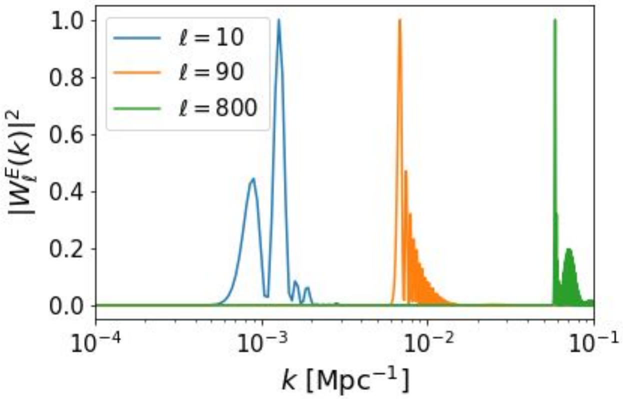
$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{XX'} = \int \mathrm{d}\ln k W_\ell^X W_\ell^{X'} \Delta^2_{\mathcal{R}}(k)$$

$$j_\ell(kD_{\mathrm{rec}}) \to \sqrt{\frac{3(\ell+2)!}{8(\ell-2)!}}\frac{j_\ell(kD_{\mathrm{rec}})}{(kD_{\mathrm{rec}})^2}$$

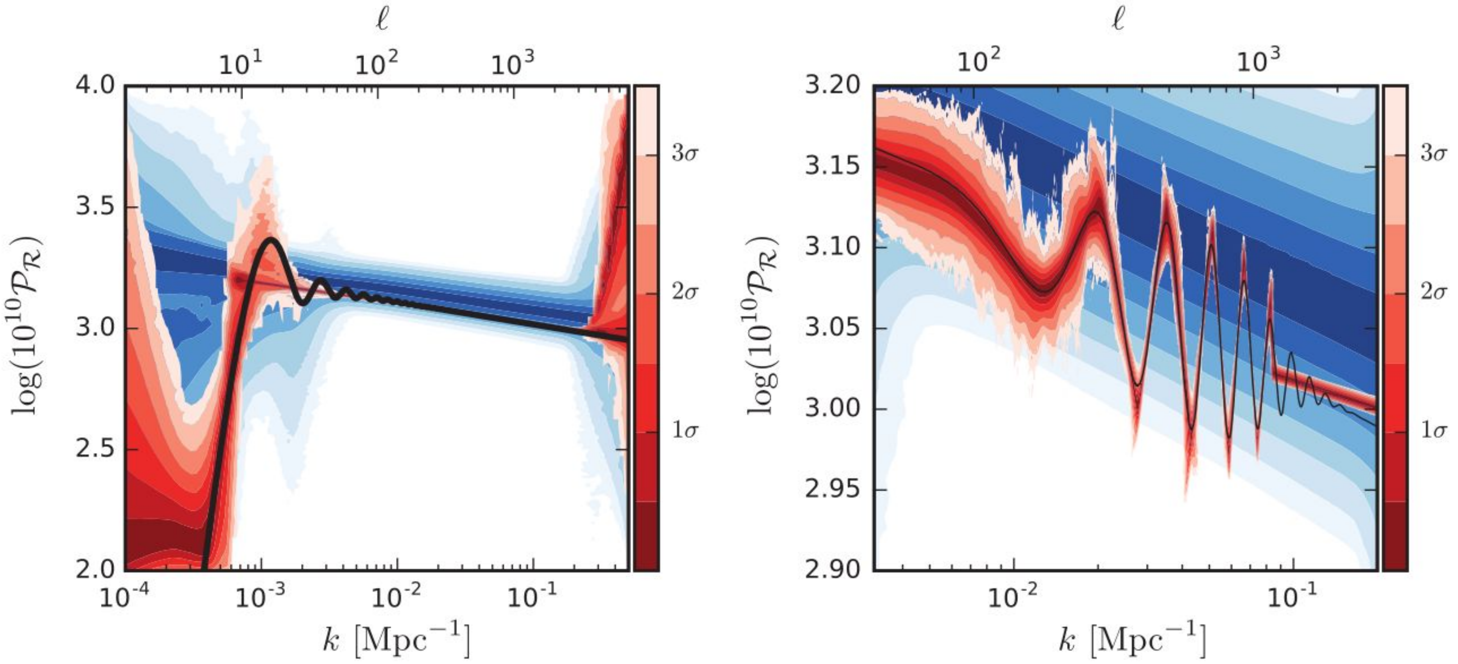
- Limitations of the temperature power spectrum are largely removed with polarization information. The (normalized) polarization transfer is modulated according to velocity.

- E-mode polarization peaks follow the velocity fluid making the turning points of temperature peaks corresponding to zero points of velocity (this implies a π/2 shift in phase).
Ballardini, Finelli, JCAP 2022

- Mild degeneracies between large scale features and non-standard reionization histories.
Mortonson, Dvorkin, Peiris & Hu, PRD 2009
Hazra, Paoletti, MB, Finelli, Shafieloo, Smoot & Starobinsky, JCAP 2017

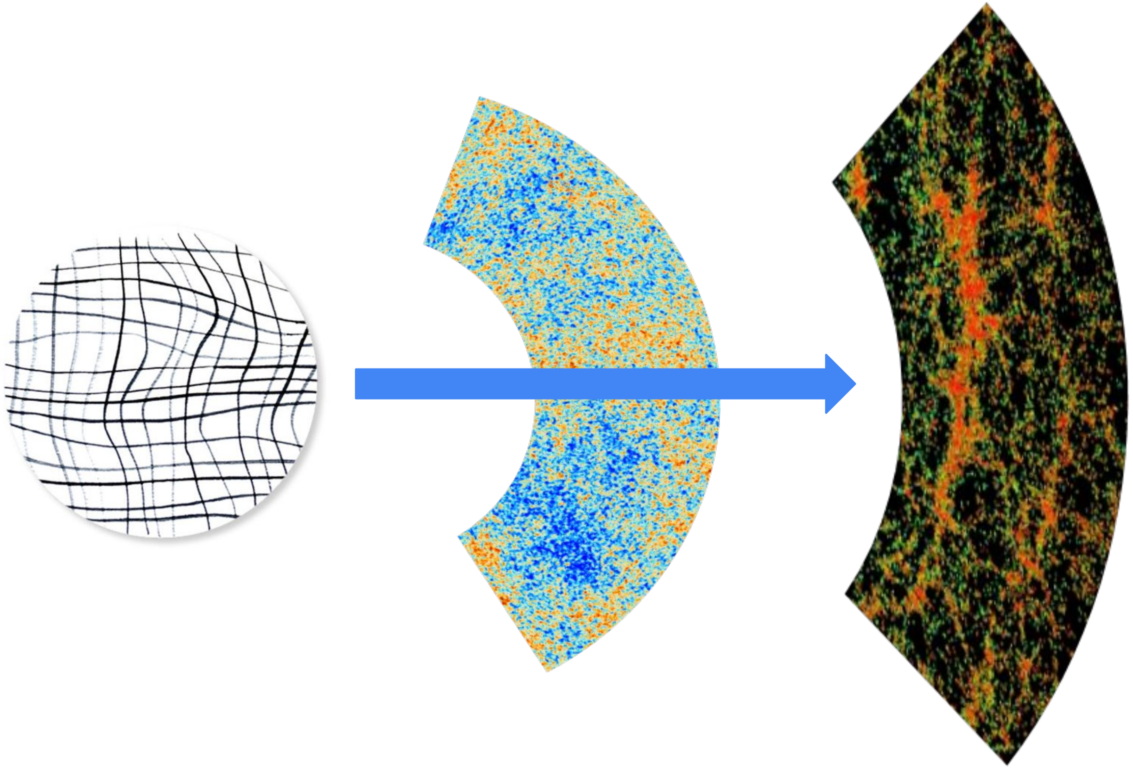


Future CMB constraints



Exploring cosmic origins with CORE, JCAP 2018

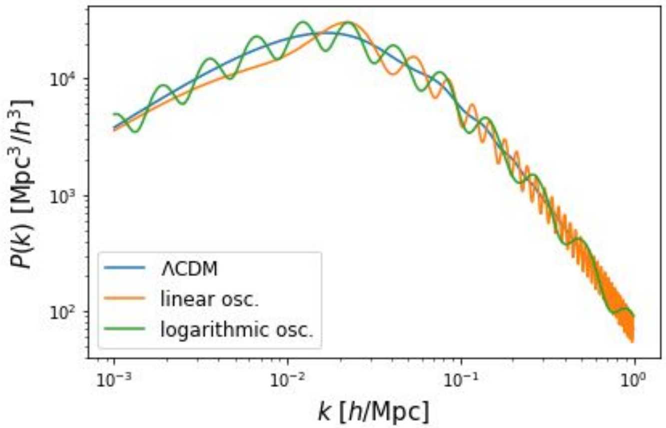
From primordial fluctuations to LSS



Early Universe constraints from large-scale structures

- Large-scale structure (LSS) clustering measurements can be used to further test the primordial origin of the CMB's hints of deviations from a nearly scale-invariant primordial power spectrum.
  Wang, Spergel, Strauss, ApJ 1999
  Huang, Verde, Vernizzi, JCAP 2012
  Chen, Dvorkin, Huang, Namjoo, Verde, JCAP 2016
  Ballardini, Finelli, Fedeli, Moscardini, JCAP 2016

- Major challenge: beating non-linearities.



Perturbative description of the non-linear damping

$$P_{\rm lin}(z,k) = D^2(z)\left[P_{\rm nw}(k) + P_{\rm w}(k)\right]$$

$$P_{\rm w}(k) \equiv P_{\rm nw}\left[\delta P_{\rm w}^{\rm BAO}(k) + \delta P_{\rm w}^{\rm X}(k) + \delta P_{\rm w}^{\rm BAO}(k)\delta P_{\rm w}^{\rm X}(k)\right]$$

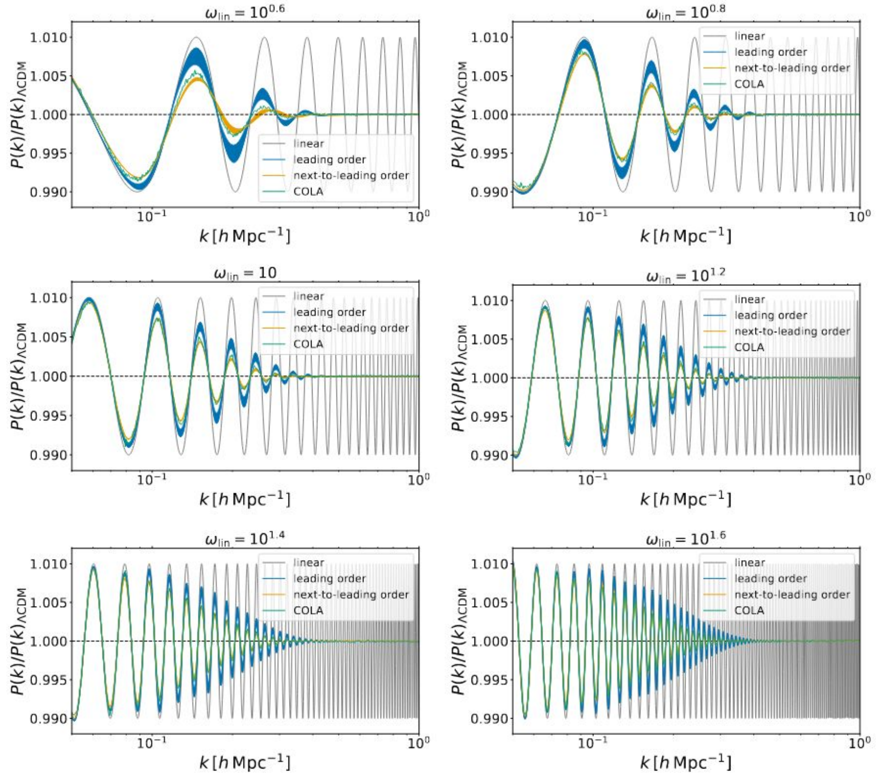
$$P^{\rm IR\,res,\,LO}(z,k) = D^2(z)P_{\rm nw}(k) \cdot \left[1 + e^{-k^2D^2(z)\Sigma^2_{\rm BAO}}\delta P_{\rm w}^{\rm BAO}(k) + e^{-k^2D^2(z)\Sigma^2_{\rm lin}}\delta P_{\rm w}^{\rm lin}(k)\right]$$

$$P^{\rm IR\,res,\,LO+NLO}(z,k) = D^2(z)P_{\rm nw}(k) \cdot \left\{1 + \left[1 + k^2D^2(z)\Sigma^2_{\rm BAO}\right]e^{-k^2D^2(z)\Sigma^2_{\rm BAO}}\delta P_{\rm w}^{\rm BAO}(k) + \left[1 + k^2D^2(z)\Sigma^2_{\rm lin}\right]e^{-k^2D^2(z)\Sigma^2_{\rm lin}}\delta P_{\rm w}^{\rm lin}(k)\right\} + D^4(z)P^{1-{\rm loop}}\left[P^{\rm IR\,res,\,LO}(k)\right],$$

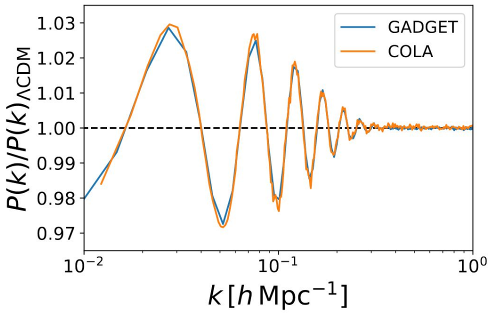
Model for the matter power spectrum based on 1-loop perturbation theory taking into account both the damping of baryonic acoustic oscillations (BAO) and the one of primordial oscillations by infrared resummation of the large-scale bulk flows.

Vasudevan, Ivanov, Sibiryakov, Lesgourgues, JCAP 2019
Beutler, Biagetti, Green, Slosar, Wallisch, PRR 2019
Ballardini, Finelli, JCAP 2022
Euclid Collaboration, Ballardini et al., A&A 2023

Perturbation theory versus N-body simulations



Differences ~ 1% (slightly larger for frequencies lower than the BAO one) at Leading Order and < 1% at Next-to-Leading Order.

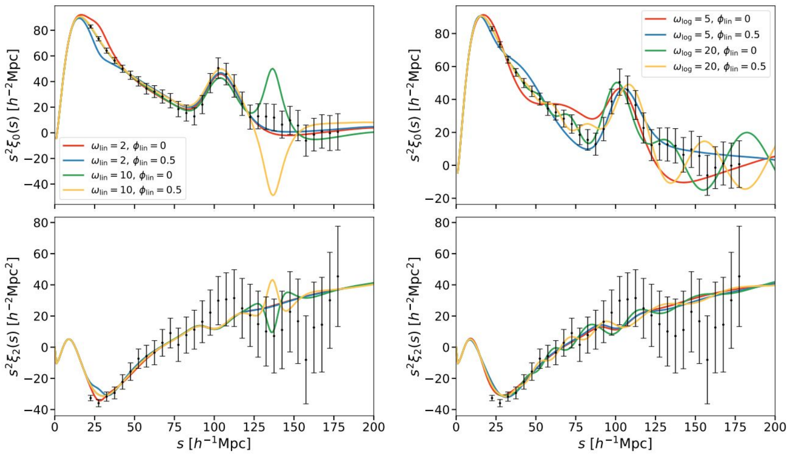


Ballardini, Murgia, Baldi, Finelli, Viel, JCAP 2020
Euclid Collaboration, Ballardini et al., A&A 2023

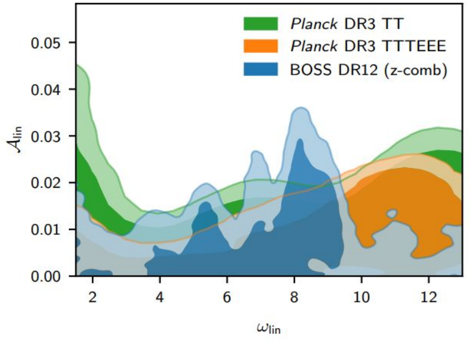
Constraints from BOSS DR12 galaxy 2PCF

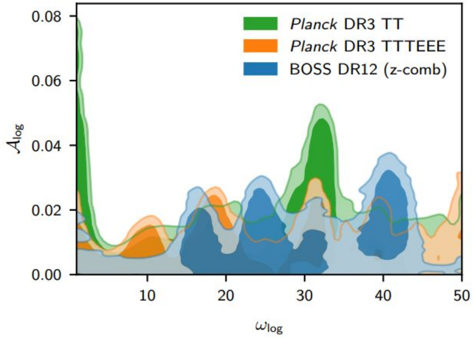
$$\xi_0(s) = B_0 \xi_0^{\rm CDM}(s, \alpha_\perp, \alpha_\parallel) + A_0^0 + \frac{A_0^1}{s} + \frac{A_0^2}{s^2}$$

$$\xi_2(s) = \frac{5}{2}\left[B_2 \xi_2^{\rm CDM}(s, \alpha_\perp, \alpha_\parallel) - B_0 \xi_0^{\rm CDM}(s, \alpha_\perp, \alpha_\parallel)\right] + A_2^0 + \frac{A_2^1}{s} + \frac{A_2^2}{s^2}$$



Ballardini, Finelli, Marulli, Moscardini, Veropalumbo, PRD 2023





Power spectrum and bispectrum combination

- Oscillatory primordial features also generate highly correlated signals in terms of non-Gaussianities and specific features appear also in the bispectrum. Indeed, primordial features can also be searched for in the bispectrum, or jointly in the power spectrum and bispectrum.

- The bispectrum will have preserved scaling argument (linear vs logarithmic).

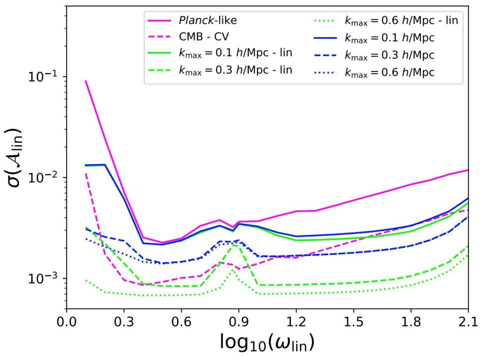
$$B^{lin}(k_1, k_2, k_3) = f_{NL}^{lin} \frac{6A^2}{k_1^2 k_2^2 k_3^2} \sin\left[\omega_{\rm lin}^B \frac{K}{k_*} + 2\pi\phi_{\rm lin}^B\right]$$

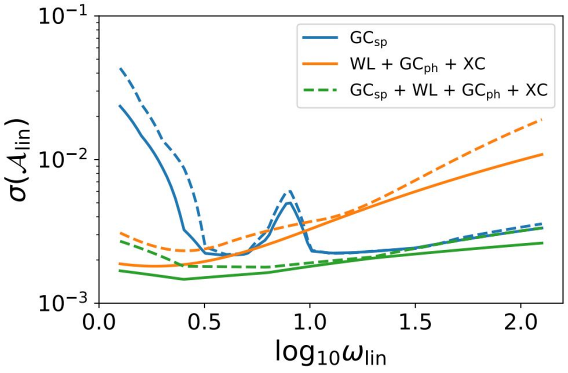
$$B_\Phi^{log}(k_1, k_2, k_3) = f_{NL}^{log} \frac{6A^2}{k_1^2 k_2^2 k_3^2} \sin\left[\omega_{\rm log}^B \ln\left(\frac{K}{k_*}\right) + 2\pi\phi_{\rm log}^B\right]$$

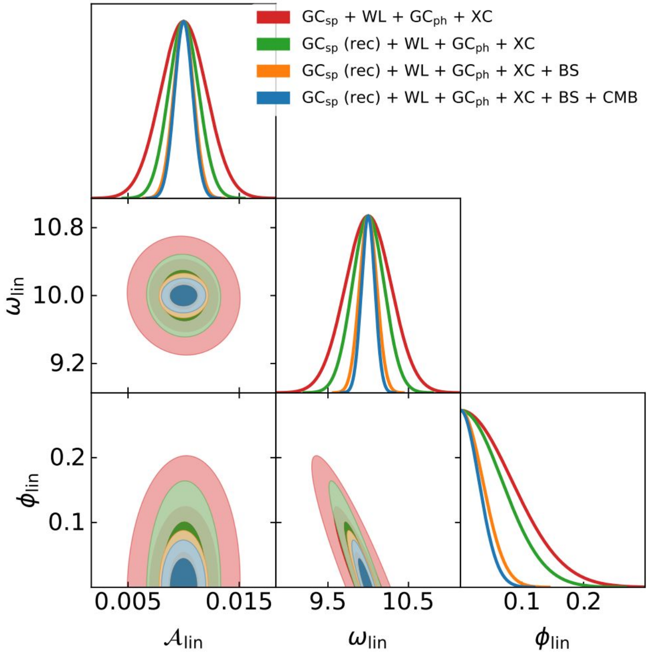
Chen, Easther, Lim, JCAP 2007
Euclid Collaboration, Ballardini et al., A&A 2023
Karagiannis et al. (including Ballardini and Bartolo), in preparation

Future uncertainties

- Forecasts for linear features.
- Synergies between different observables and different probes.







Ballardini, Murgia, Baldi, Finelli, Viel, JCAP 2020
Euclid Collaboration, Ballardini et al., A&A 2023

$\mathcal{A}_{lin} = 0.0100 \pm 0.0008$ at 68.3% CL

Conclusions

- Primordial features provide a variety of valuable information on the physics of the early Universe ranging from detecting new heaviest particles, the presence of a fast-roll stage, to the details in the inflationary dynamics. They can also be used to discriminate between inflation and alternative scenarios in presence of signals oscillatory in time.

- CMB data from *Planck* are consistent with a smooth, power-law primordial spectrum as predicted by the simplest models of cosmic inflation; however, intriguing anomalies are present in the temperature power spectrum (not statistically preferred!).

- Future CMB polarization measurements (from both small and large angular scales) and future galaxy surveys will help us to reach a more complete picture of the physics of the early Universe and to improve the current bounds on the primordial feature amplitude. In addition, the expected observations from LSS will allow us to scrutinise the primordial interpretation of some of the anomalies in the CMB temperature angular power spectra.