

Primary CMB

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on behalf of the Italian CMB community



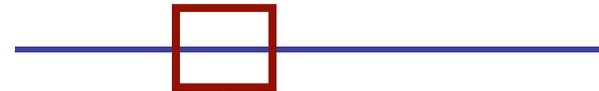
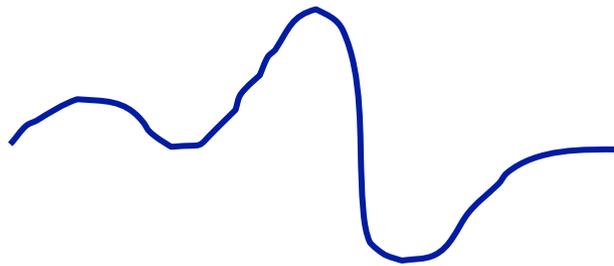
Primordial CMB: formation

INFLATION

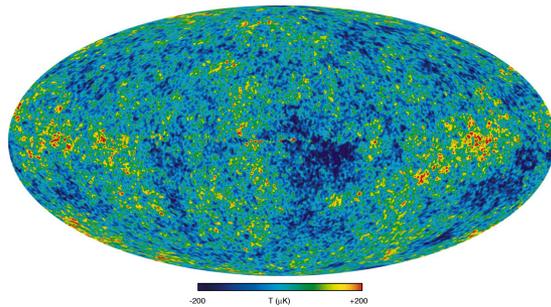
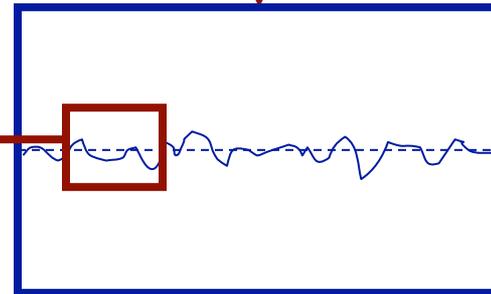
Inhomogeneous



Homogeneous



x 100,000



Scientific goals

Initial conditions:

- Did Inflation take place?
- Constraints on Inflationary models.

Measurements of cosmological Parameters in Λ CDM, e.g. :

- **Initial conditions:** $n_s, r, n_t \dots$
- Geometry: Ω_k, T^*
- Evolution: $\Omega_b, \Omega_c, \Omega_\Lambda$

Primordial CMB

Tests of our cosmological paradigm:

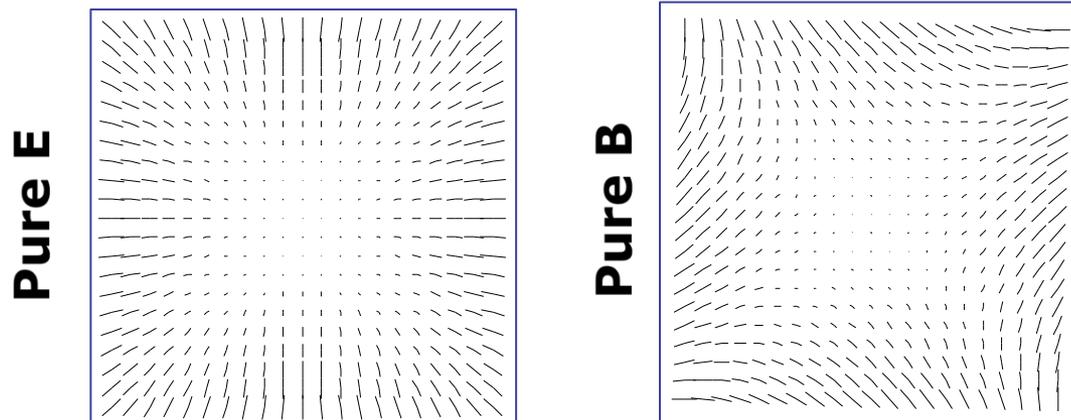
- Isotropy
- Gaussianity

Non-standard/new Physics:

- Parity breaking
- Topology
- Cosmic strings...

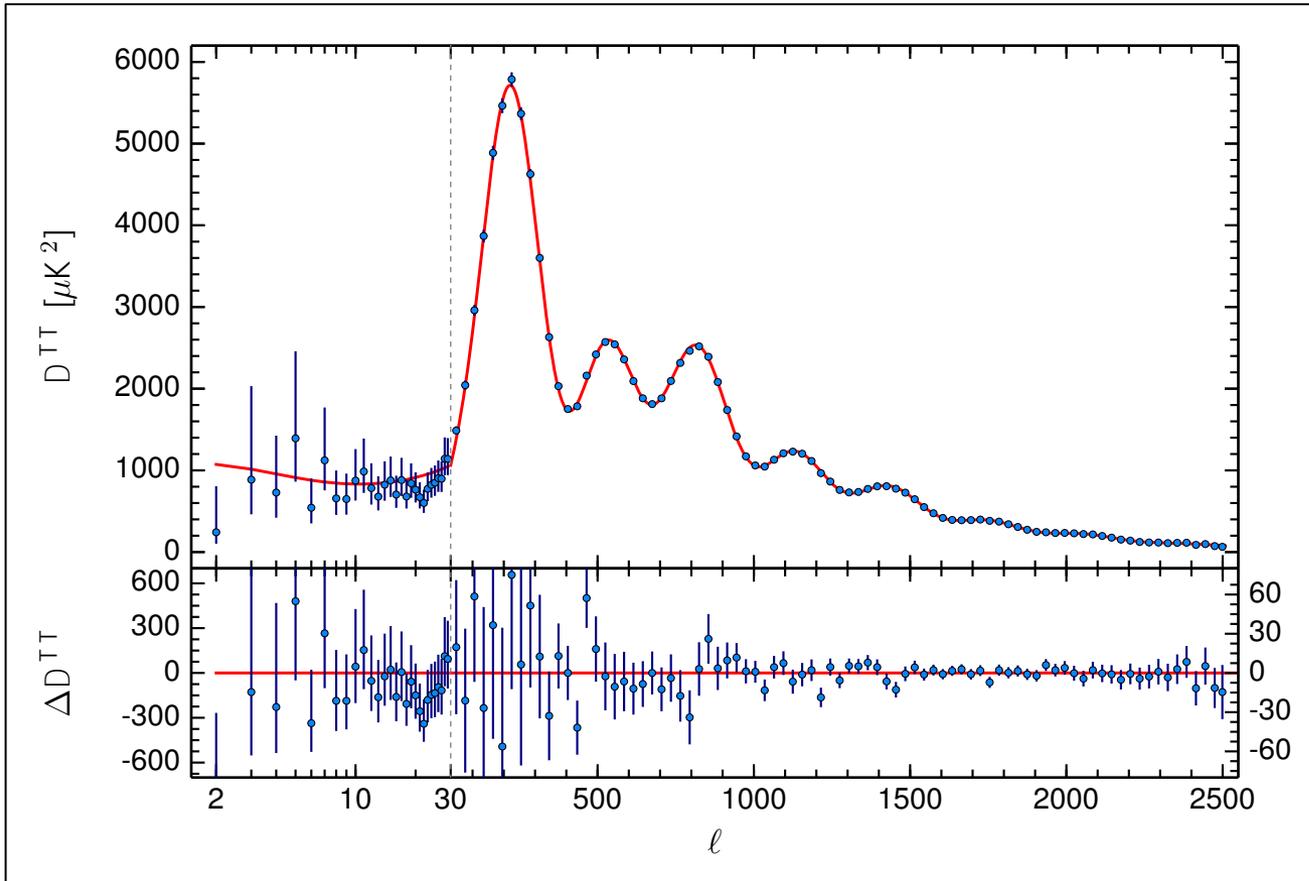
Observables

- Direction-dependent temperature fluctuations w.r.t to $T=2.725$ K blackbody
- Polarization fluctuations generated by Compton scattering at recombination
- Polarization is a spin-2 field. Can be decomposed in “gradient-curl”. Gradient part (E-mode) is generated by scalar perturbation. **Primordial curl (B-mode) is a smoking-gun signature of primordial GW (i.e. Inflation).**



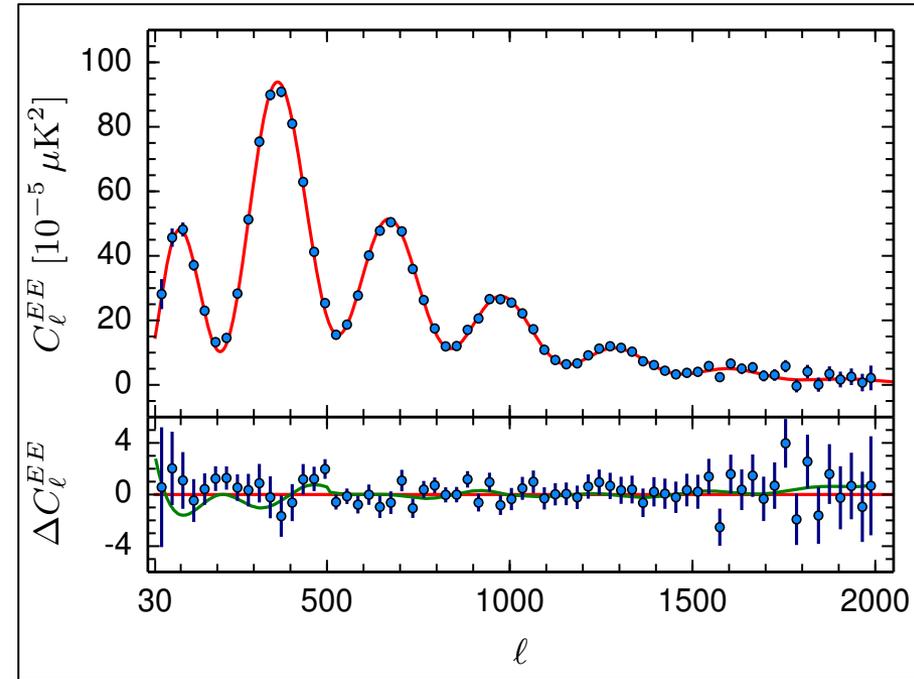
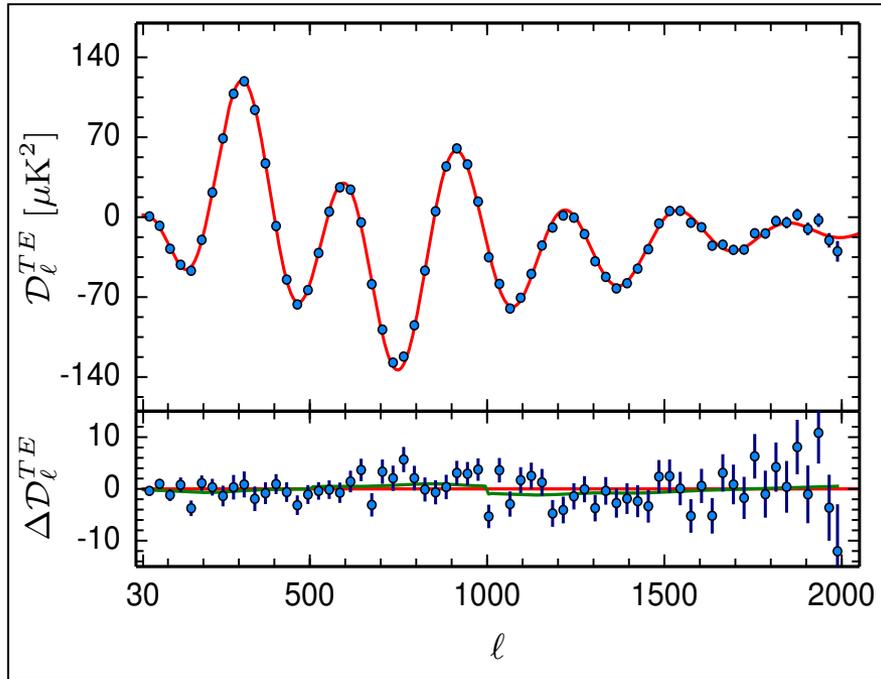
- Small deviations from perfect blackbody, in the frequency domain. **Spectral distortions generate a very promising, yet nearly completely unexploited observational window!**

Current status: temperature



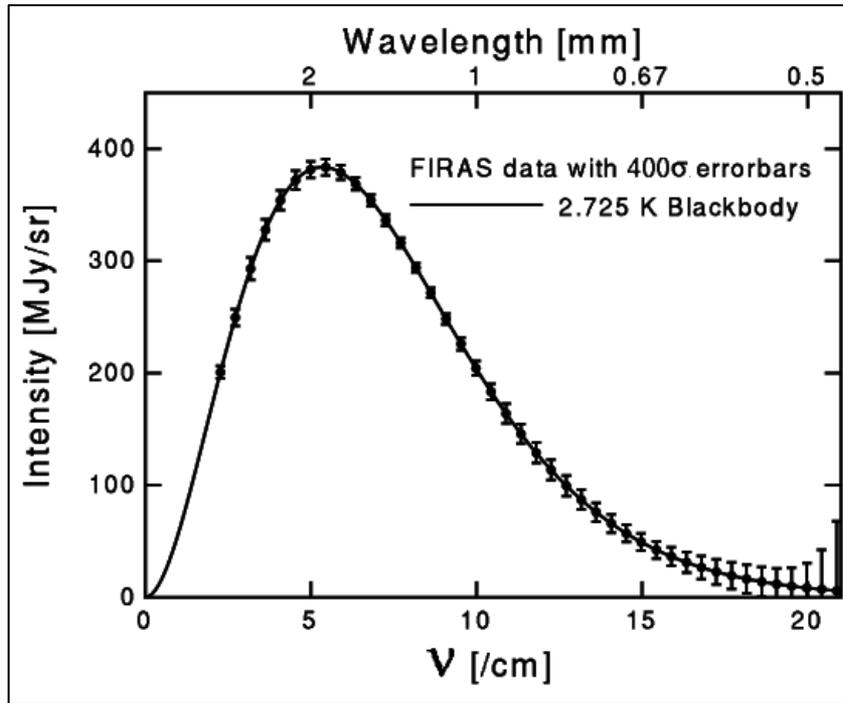
- As long as *primordial* fluctuations are concerned, Planck has essentially fully and optimally extracted all information from temperature.

Current status: polarization



- **Primordial E-mode** Not optimal yet, error budget dominated by instrumental noise. **Important gains are possible in the future.**
- **Primordial B-mode undetected**, best upper limits from Planck+BICEP. **Primary goal for future CMB experiments.**

Current status: distortions



No distortion detected
(except γ -distortions from
SZ-effect, not primordial).

Best limits essentially date back
to COBE/FIRAS:

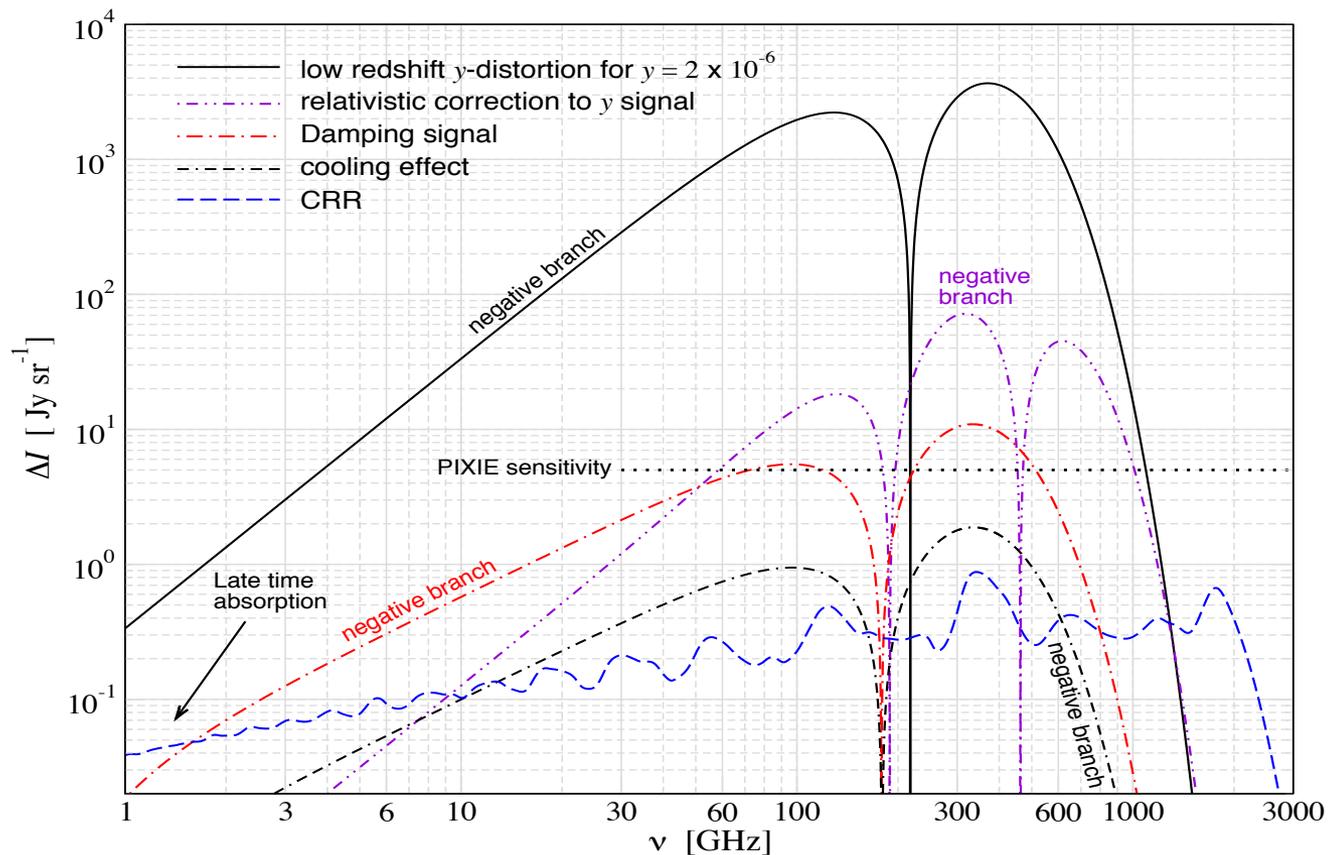
$$\Delta I_{\nu}/I_{\nu} < 10^{-4}$$

$$\mu < 9 \times 10^{-5}$$

$$\gamma < 1.5 \times 10^{-5} \quad (95\% \text{ C.L.})$$

Spectral distortions yet undetected. They are expected in standard Cosmology, from a variety of mechanisms.

Expected CMB distortions in Λ CDM



Chluba 2016, arXiv:1603.02496

Large amount of information. Not accessible from ground.

Testing Inflation: power spectra.

- The primordial curvature perturbation from inflation is described by a Gaussian random field with nearly scale invariant spectrum

$$P_{\zeta}(k) = A_{\zeta} \left(\frac{k}{k_*} \right)^{n_s - 1}$$

Spectral index, n_s . Describes slope. Defines deviation from perfect scale invariance

- Inflation also predicts a background of GW with spectrum

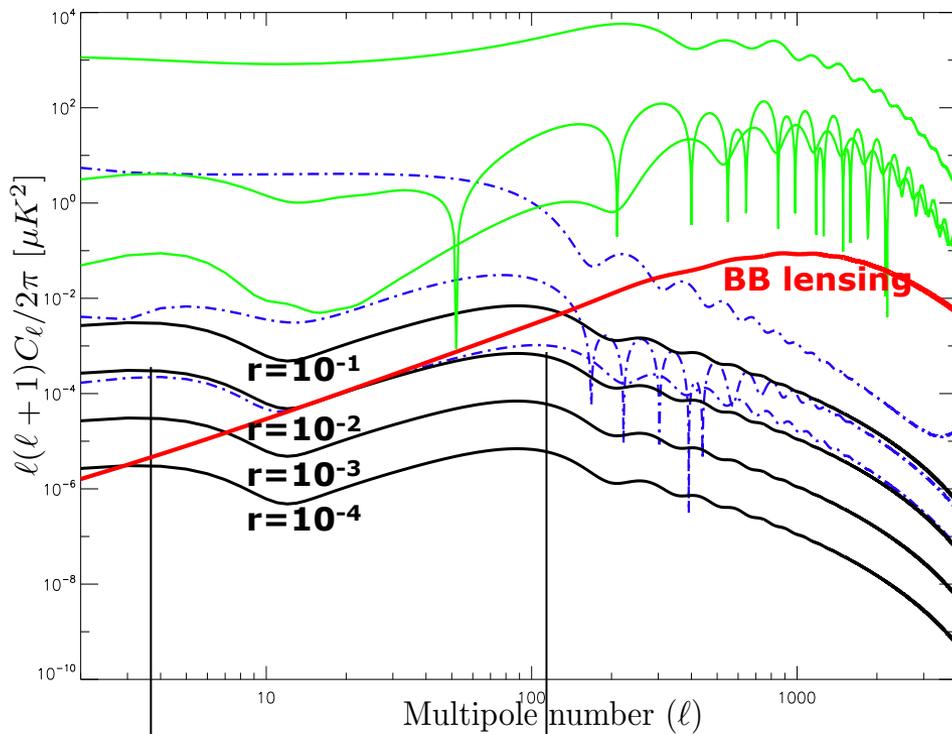
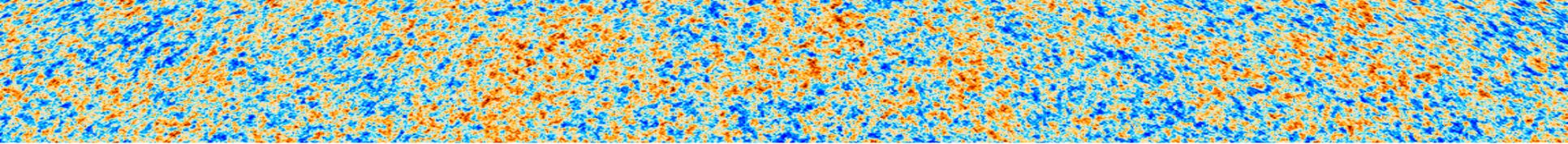
$$P_t(k) = A_t \left(\frac{k}{k_*} \right)^{n_t}$$

Tensor-to-scalar ratio $r = \frac{P_t(k_*)}{P_{\zeta}(k_*)}$ **Parametrizes strength of primordial GW signal**

- Detecting $r > 0$, via B-mode detection would be a smoking-gun confirmation of Inflation
- We can constrain slow-roll inflationary models through measurements of n_s and r (from CMB power spectra).

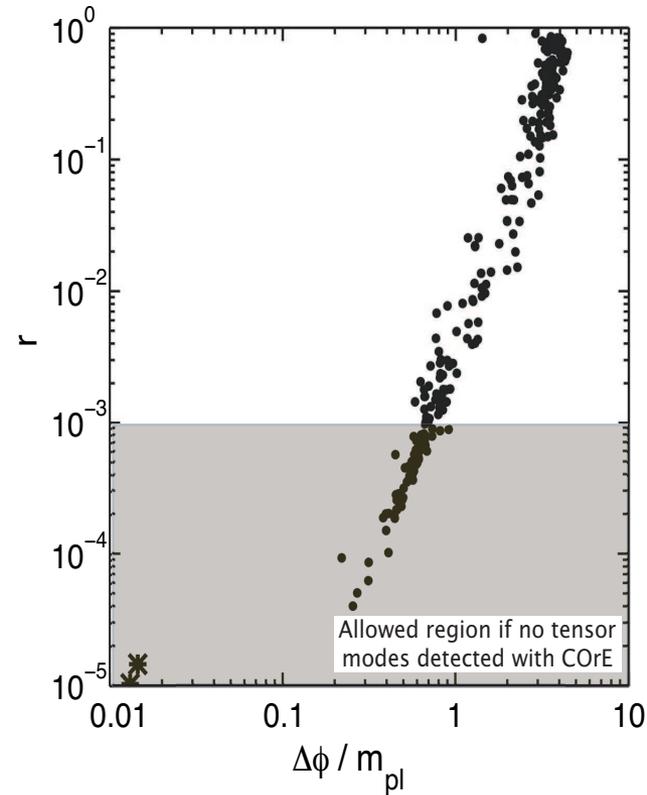
The Inflation smoking-gun: B-modes

- The search for B-modes will be the main target for most future CMB surveys.
- **Current** constraints $r < 0.1$ (Planck + BICEP).
- From the **ground**, $\Delta r \sim 0.01$ maybe achievable.
- **Main obstacles**: astrophysical foreground, B-mode lensing signal.
- **Best remedies**: full-sky, wide multi-frequency coverage => **SPACE**
- Next generation of **space missions aiming for $\Delta r \sim 0.001$**
- Energy scale tested is ~ 12 order of magnitude, or more, larger than what probed in particle accelerators!
- **Lyth bound** $\frac{\Delta\phi}{M_{\text{P}}} = \int dN \sqrt{\frac{r}{8}}$ implies **trans-Planckian** excursion for $r > 2 \times 10^{-3}$



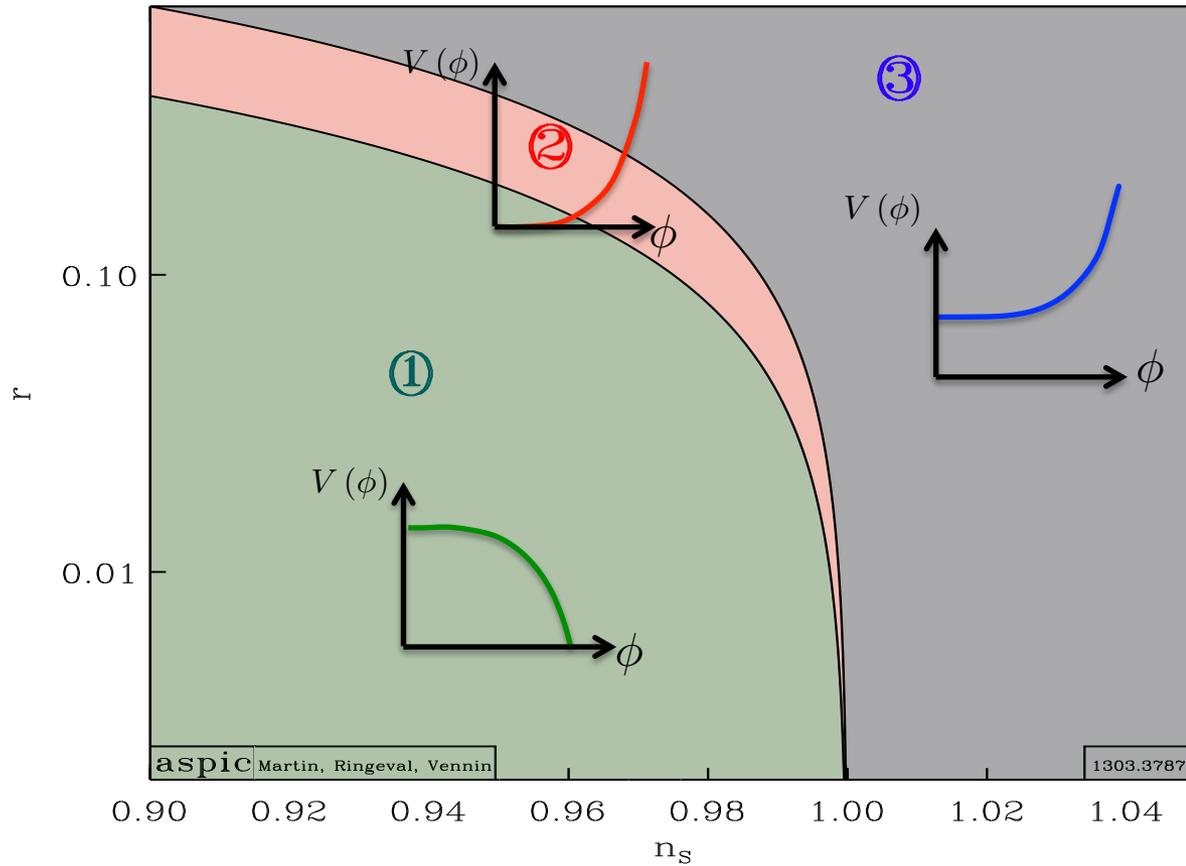
Reionization bump,
not accessible from
ground

Recombination
bump



Model predictions.
Significant concentration
of points for \$r > 0.001\$

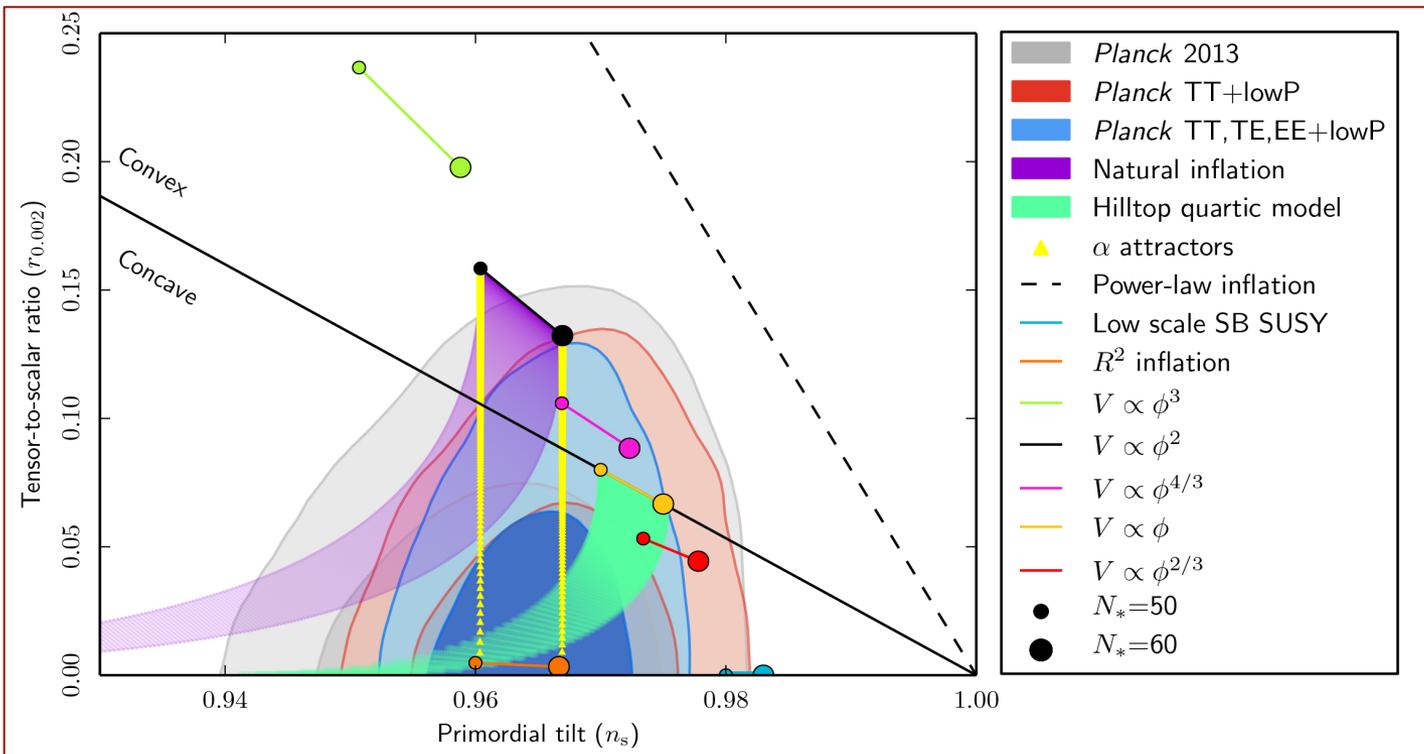
Constraining Inflation: the n_s - r plane



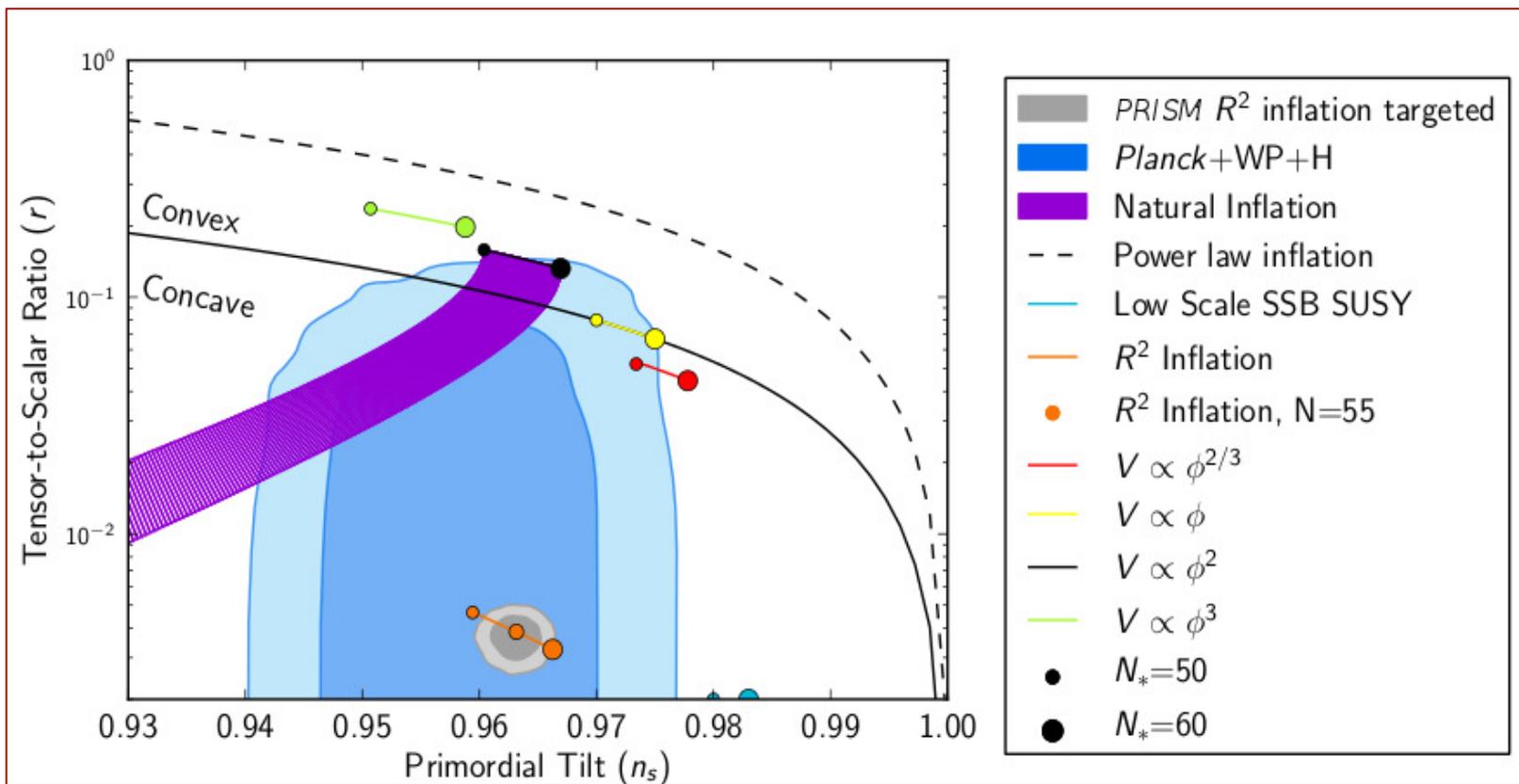
Picture from J. Martin et al. 2013

Current constraints on single-field slow-roll Inflation

Model	Parameter	Planck TT+lowP	Planck TT+lowP+lensing	Planck TT+lowP+BAO	Planck TT,TE,EE+lowP
Λ CDM+r	n_s	0.9666 ± 0.0062	0.9688 ± 0.0061	0.9680 ± 0.0045	0.9652 ± 0.0047
	$r_{0.002}$	< 0.103	< 0.114	< 0.113	< 0.099
	$-2\Delta \ln \mathcal{L}_{\max}$	0	0	0	0
Λ CDM+r	n_s	0.9667 ± 0.0066	0.9690 ± 0.0063	0.9673 ± 0.0043	0.9644 ± 0.0049
	$r_{0.002}$	< 0.180	< 0.186	< 0.176	< 0.152
	r	< 0.168	< 0.176	< 0.166	< 0.149
+ $dn_s/d \ln k$	$dn_s/d \ln k$	$-0.0126^{+0.0098}_{-0.0087}$	$-0.0076^{+0.0092}_{-0.0080}$	-0.0125 ± 0.0091	-0.0085 ± 0.0076
	$-2\Delta \ln \mathcal{L}_{\max}$	-0.81	-0.08	-0.87	-0.38



n_s - r : improvement potential



Forecasts for PRISM: arXiv:1306.22951

Vast improvement achievable from future polarization data (TE, EE, BB)

More inflationary parameters: running

Running spectral index

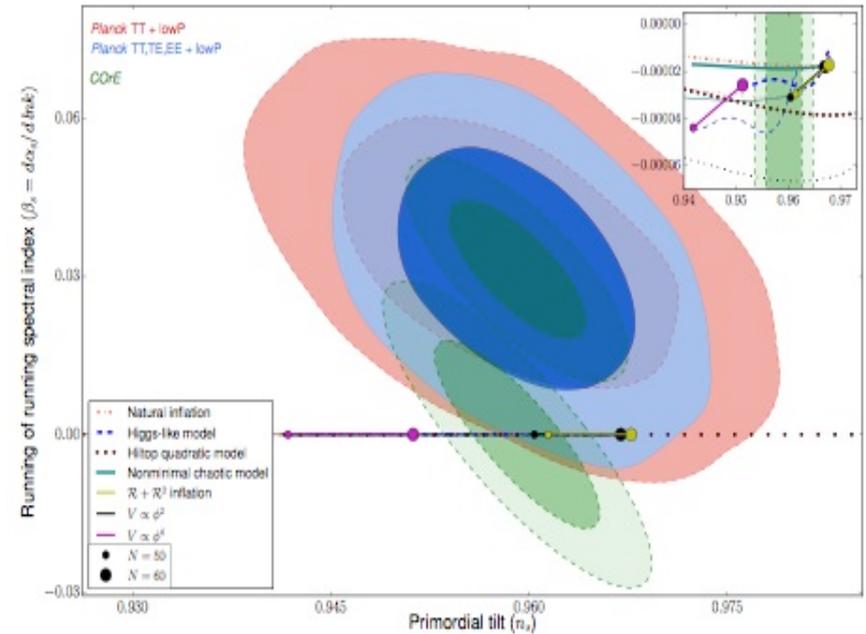
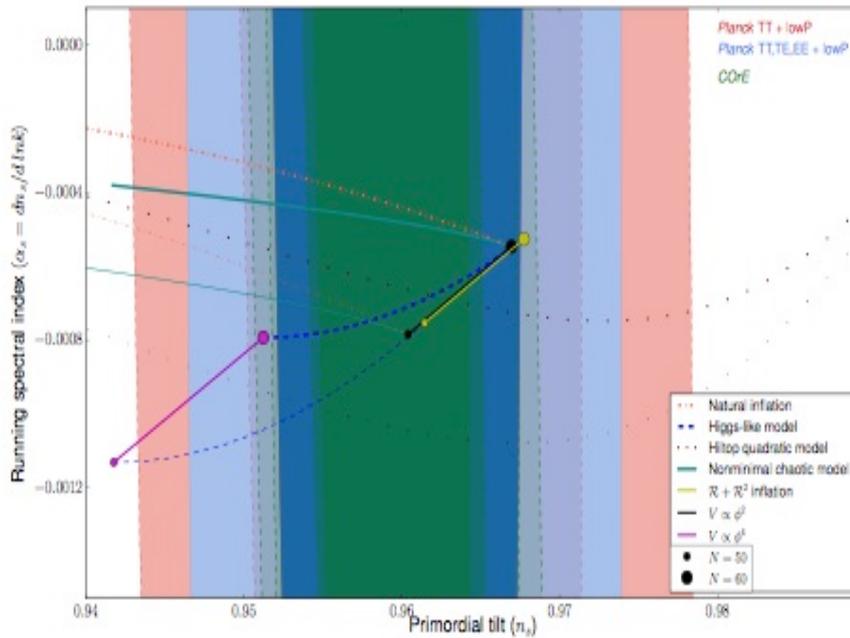
$$\Delta_{\zeta}^2(k) = \Delta_{\zeta}^2(k_*) \left(\frac{k}{k_*} \right)^{n_s - 1 + \frac{1}{2} \alpha_s \ln(k/k_*) + \frac{1}{3!} \beta_s \ln^2(k/k_*)}$$

Planck

$$\left\{ \begin{array}{l} \alpha_s = 0.009 \pm 0.010 \\ \beta_s = 0.025 \pm 0.013 \end{array} \right.$$

running

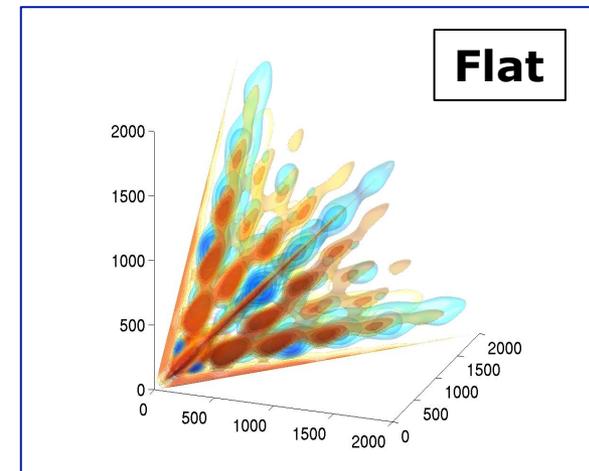
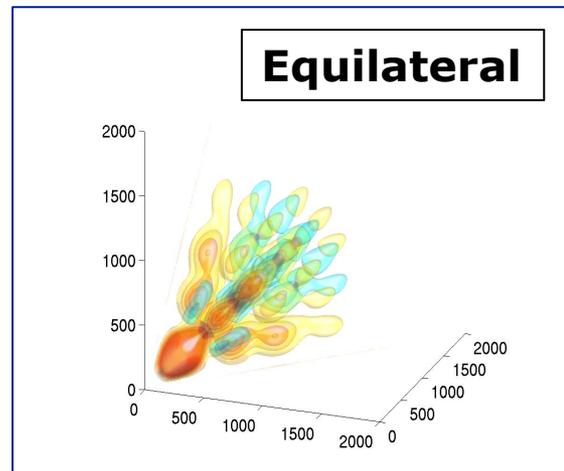
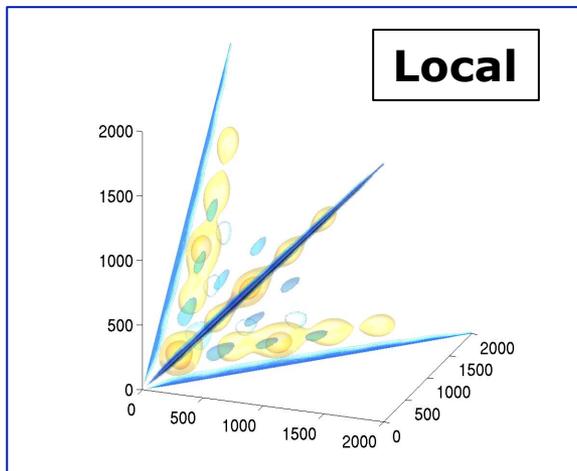
running of running



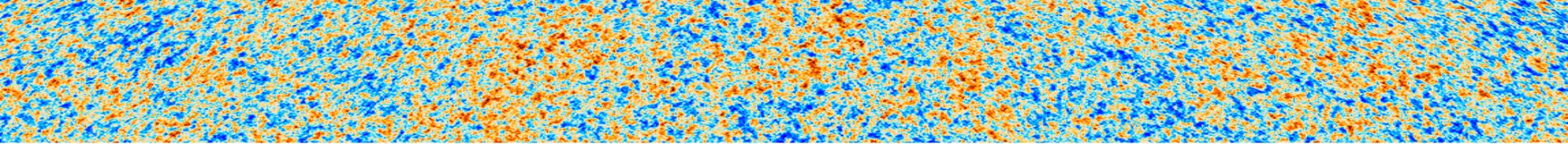
Escudero et al. 2016, arXiv: 1509.05419

Beyond power spectra: non-Gaussianity

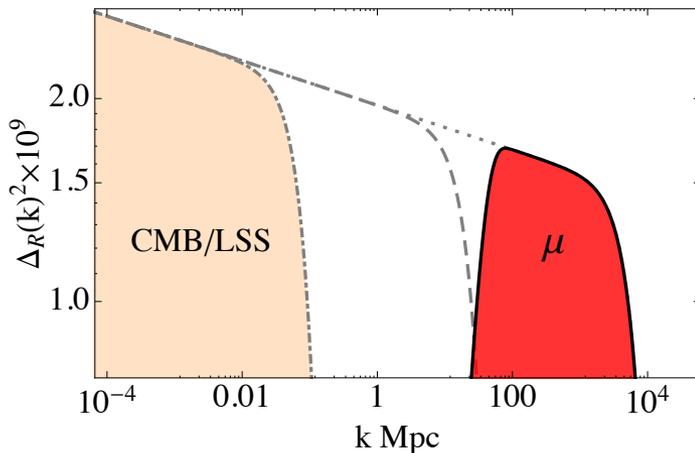
Primordial non-Gaussianity. Many inflationary scenarios (notably, multi-field Inflation) predict small, **model-dependent deviations from Gaussianity.** **Additional information in 3-point (bispectrum) and 4-point (trispectrum) correlation functions.**



- Fit primordial bispectrum (trispectrum) template to the data and measure the degree of correlation via a dimensionless parameter f_{NL} ($g_{\text{NL}}, \tau_{\text{NL}}$).
- Large f_{NL} for a given shape selects specific scenarios. E.g. **large local f_{NL} would rule out standard single-field models.**

- 
- Still room for improvement on NG parameters from future CMB data. Achievable by increasing sensitivity for E-mode.
 - A cosmic variance dominated E-mode reconstruction up to $l_{\max} \sim 3000$ (PRISM, CMBpol) allows an **improvement in f_{NL} error bars by a factor ~ 3 for all shapes** (no other cosmological observable can do that, except futuristic 21 cm surveys).
 - Similar improvement expected for trispectra (can test consistency relations).
 - Allows to test alternatives to Inflation (e.g. ekpyrosis)
 - All these measurements require full-sky, high-sensitivity, accurate foreground subtraction.

"A new window"



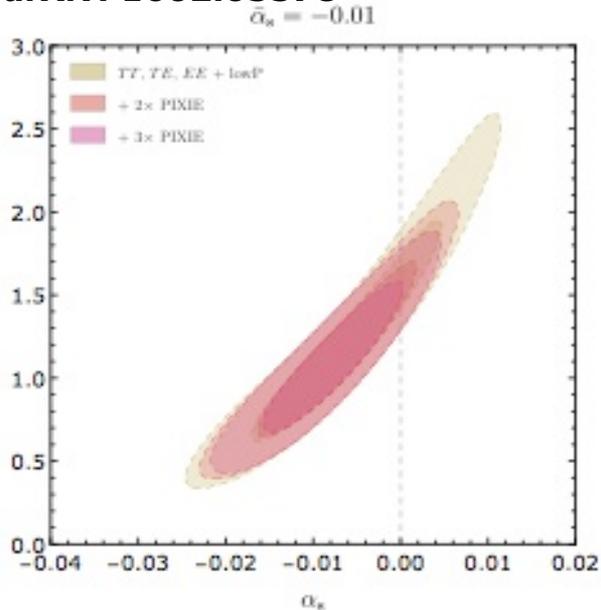
CMB spectral distortions from acoustic wave dissipation probe a large range of scales, much smaller than CMB/LSS

Many additional modes!

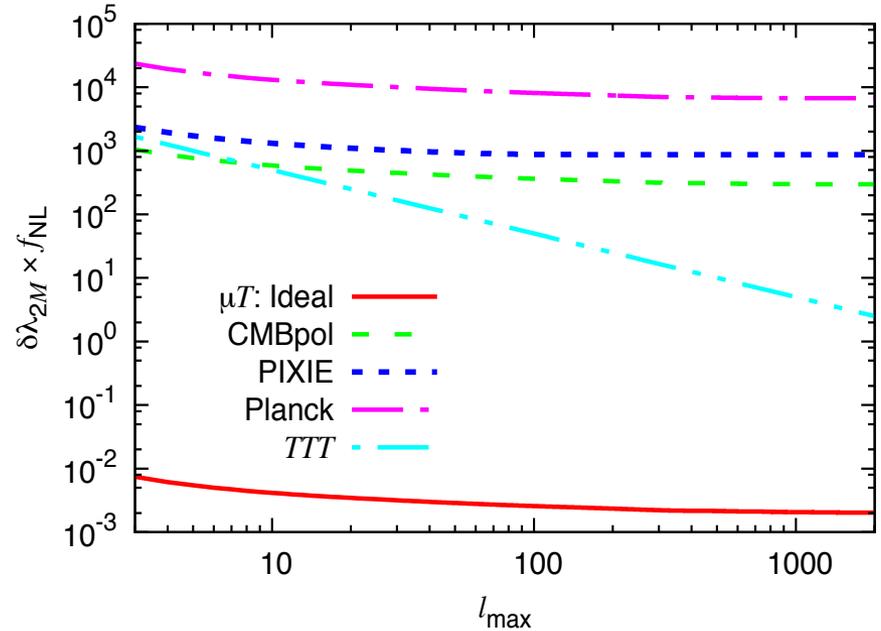
Pajer and Zaldarriaga 2013, arXiv:1201.5375

- Running spectral index
- If μ -anisotropies are measured (no absolute calibration needed):
 - ✓ $T\mu$ correlation: primordial local f_{NL} (or other squeezed bispectra)
 - ✓ $\mu\mu$ correlation: primordial local trispectrum, τ_{NL}
 - ✓ $\mathbb{T}\mu$ bispectrum: primordial local trispectrum, g_{NL}

**Cabass, Melchiorri and Pajer (2016),
arXiv: 1602.05578**



**Shiraishi, ML and Bartolo (2015),
arXiv: 150606670**



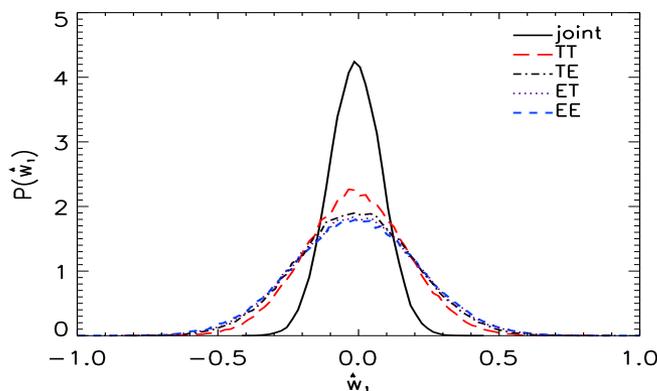
- With “PIXIE x 3”, either detection of μ , or detection of running
- Cosmic variance dominated observation of μ anisotropies (futuristic) can achieve, for standard local shape $f_{NL}, \tau_{NL} \ll 1$ (local) and $g_{NL} \sim$ a few (local), as well as testing several other models and scenarios.
- Specific models produce enhanced signals that can be observed also with PIXIE-like sensitivity.

Tests of isotropy: CMB anomalies

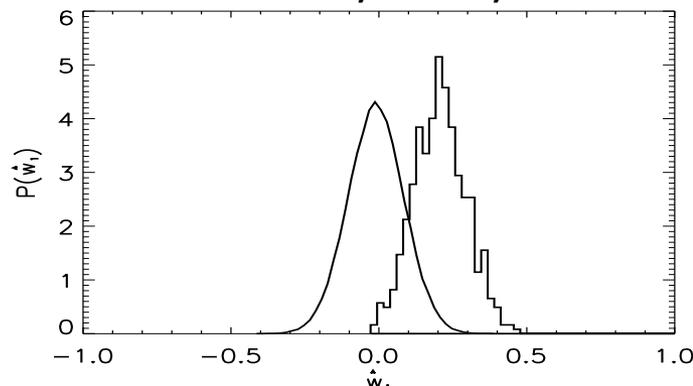
feature	p-value	data	reference
in angular space			
low variance ($N_{\text{side}} = 16$)	$\leq 0.5\%$	Planck 15	Tab. 12 [7]
2-pt correlation $\chi^2(\theta > 60^\circ)$	$\leq 3.2\%$	Planck 15	Tab. 14 [7]
2-pt correlation $S_{1/2}$	$\leq 0.5\%$	Planck 15	Tab. 13 [7]
2-pt correlation $S_{1/2}$	$\leq 0.3\%$	Planck 13 & WMAP 9yr	Tab. 2 [31]
2-pt correlation $S_{1/2}$ (larger masks)	$\leq 0.1\%$	Planck13	Tab. 2 [31]
	$\leq 0.1\%$	WMAP 9yr	[31, 32]
hemispherical variance asymmetry	$\leq 0.1\%$	Planck 15	Tab. 20 [7]
cold spot	$\leq 1.0\%$	Planck 15	Tab. 19 [7]
in harmonic space			
quadrupole-octopole alignment	$\leq 0.5\%$	Planck 13	Tab. 7 [33]
$\ell = 1, 2, 3$ alignment	$\leq 0.2\%$	Planck 13	Tab. 7 [33]
odd parity preference $\ell_{\text{max}} = 28$	$< 0.3\%$	Planck 15	Fig. 20 [7]
odd parity preference $\ell_{\text{max}} < 50$ (LEE)	$< 2\%$	Planck 15	Text [7]
dipolar modulation for $\ell = 2 - 67$	$\leq 1\%$	Planck 15	Text [7]

- Three main “families”: lack of large angle correlation, multipole alignments, Hemispherical asymmetry. All on large scales.
- Statistical fluke, “a posteriori”, look elsewhere, or real? Cosmological or not? Primordial or late time?
- **Ways forward:**
 - ✓ Find primordial models explaining the anomalies and fit parameters.
 - ✓ **Cross-check temperature anomalies using different observables.**

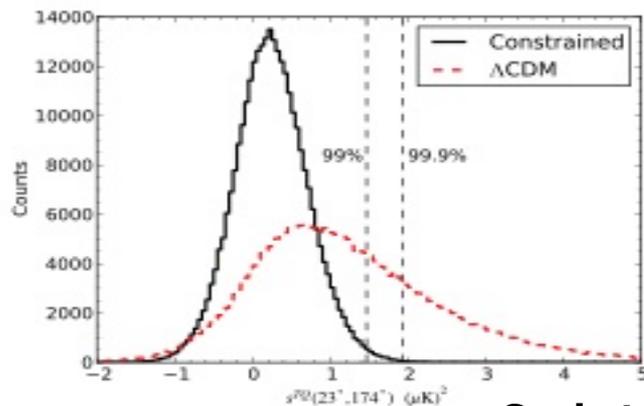
- Current data provide reliable polarization power spectra (but foreground contamination at low l is difficult to handle).



Dvorkin, Peiris, Hu 2007



- Need better S/N and excellent level of foreground subtraction to produce additional tests at the level of Q, U maps.

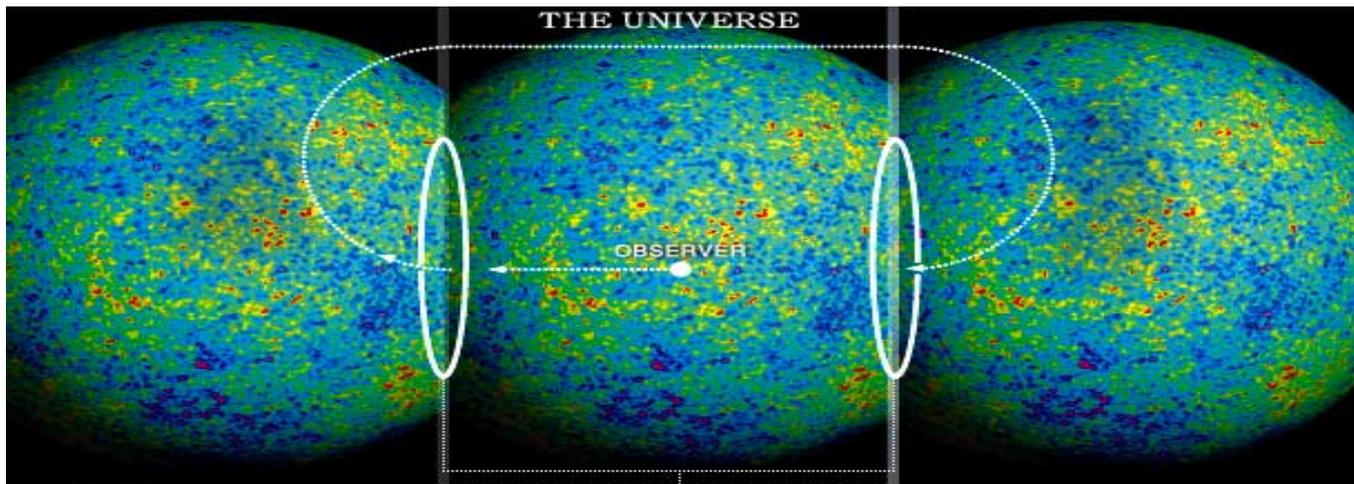
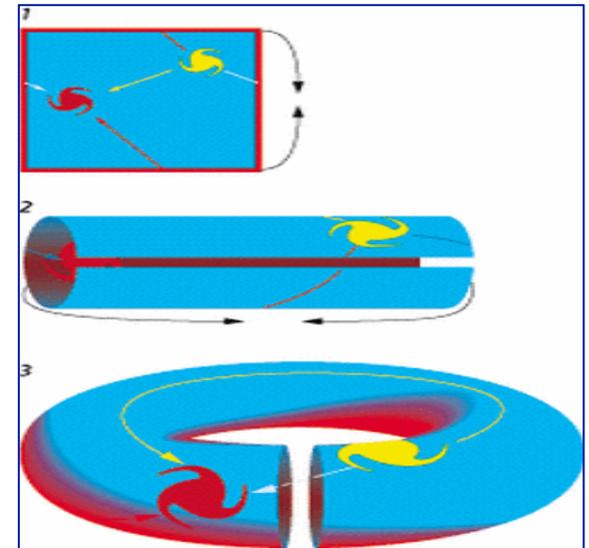


TQ statistics

Copi et al. 2013

Topology

- Multi-connected Universe => matched circles in the CMB sky
- Accurate polarization maps allow important cross-check of temperature searches and accuracy improvement.
- Sensitivity improvements, full sky and foreground subtraction are again crucial



Parity breaking

If fundamental Physics is **parity-breaking** in the electromagnetic sector, there are **observational consequences**, e.g.:

- Non-vanishing EB and TB
- Cosmic birefringence (rotation of polarization angle)
- Parity-odd bispectra

These signatures were all tested using Planck data.

Better polarization data can lead to significant improvements

Summary

- CMB studies projected Cosmology into a new, data-driven, high-precision era.
- Much information still awaits to be extracted. For primary CMB:
 - ✓ Polarization (primordial B-mode spectrum, accurate E-mode maps)
 - ✓ Spectral distortions
- This additional information, would allow to, e.g.:
 - ✓ Strongly improve our understanding of the Early Universe (e.g. tight constraints on Inflation)
 - ✓ Possibly provide a smoking-gun evidence of Inflation
 - ✓ Test energy scales well above particle accelerators' reach
 - ✓ Test fundamental assumptions of standard Cosmology
 - ✓ Search for exotic/non-standard Physics(and much more if we consider late-time Physics, secondary effects etc. see coming talks)
- *Accurate foreground subtraction (i.e. wide frequency coverage), tight control of systematics, high sensitivity and full sky coverage are key to a fully successful achievement of the above scientific goals*