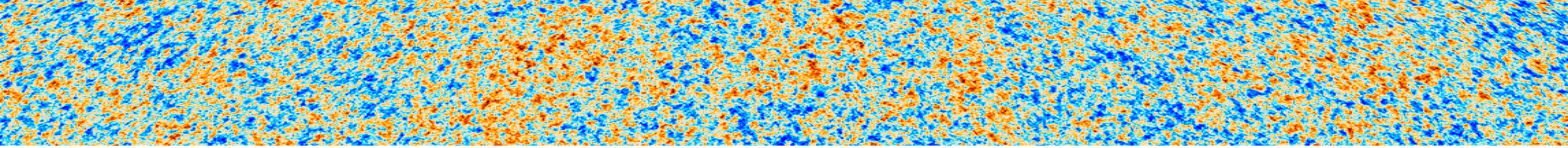


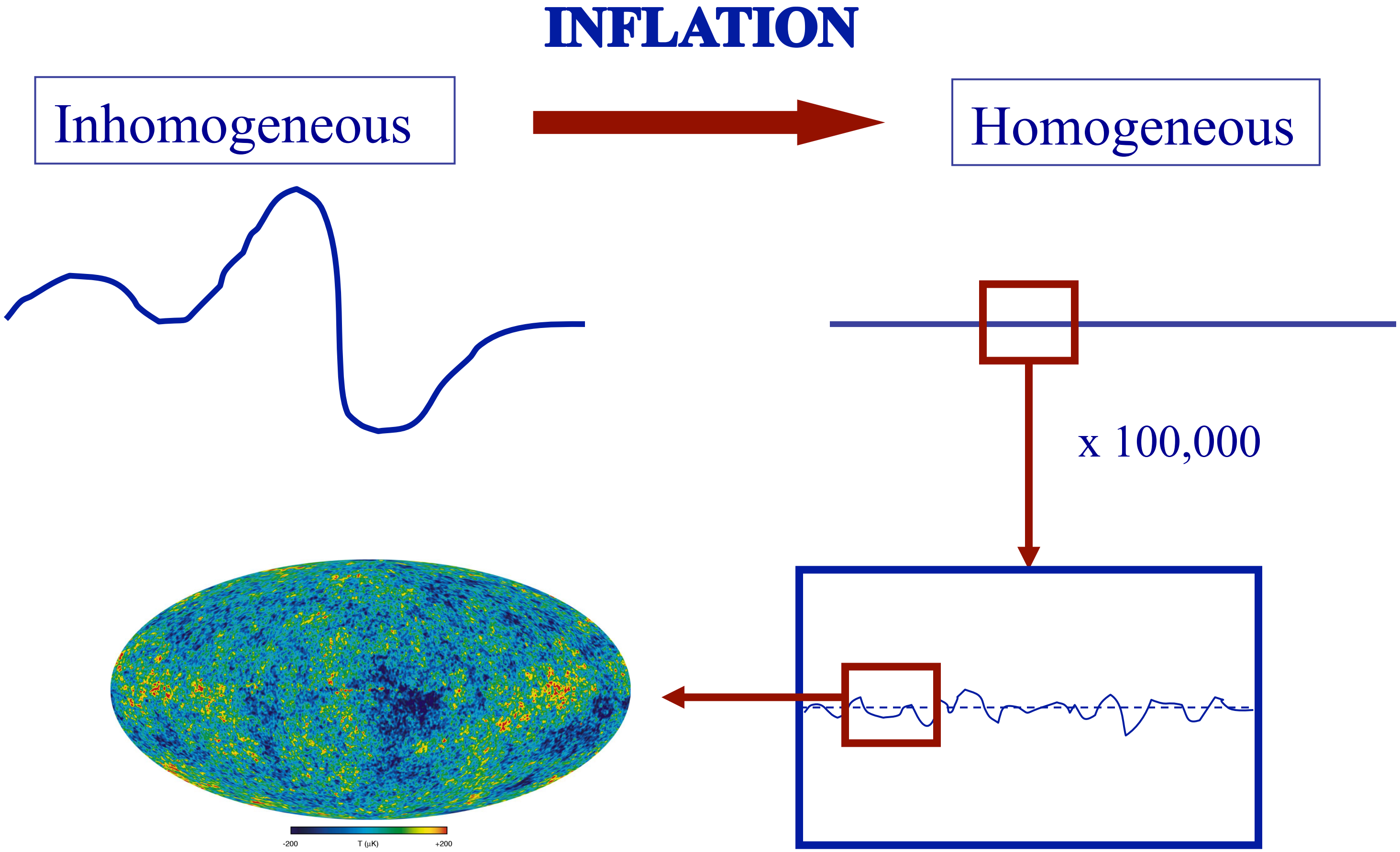
Primary CMB

Michele Liguori

University of Padova, INFN-Padova, INAF-OAPD

on behalf of the Italian CMB community

Primordial CMB: formation



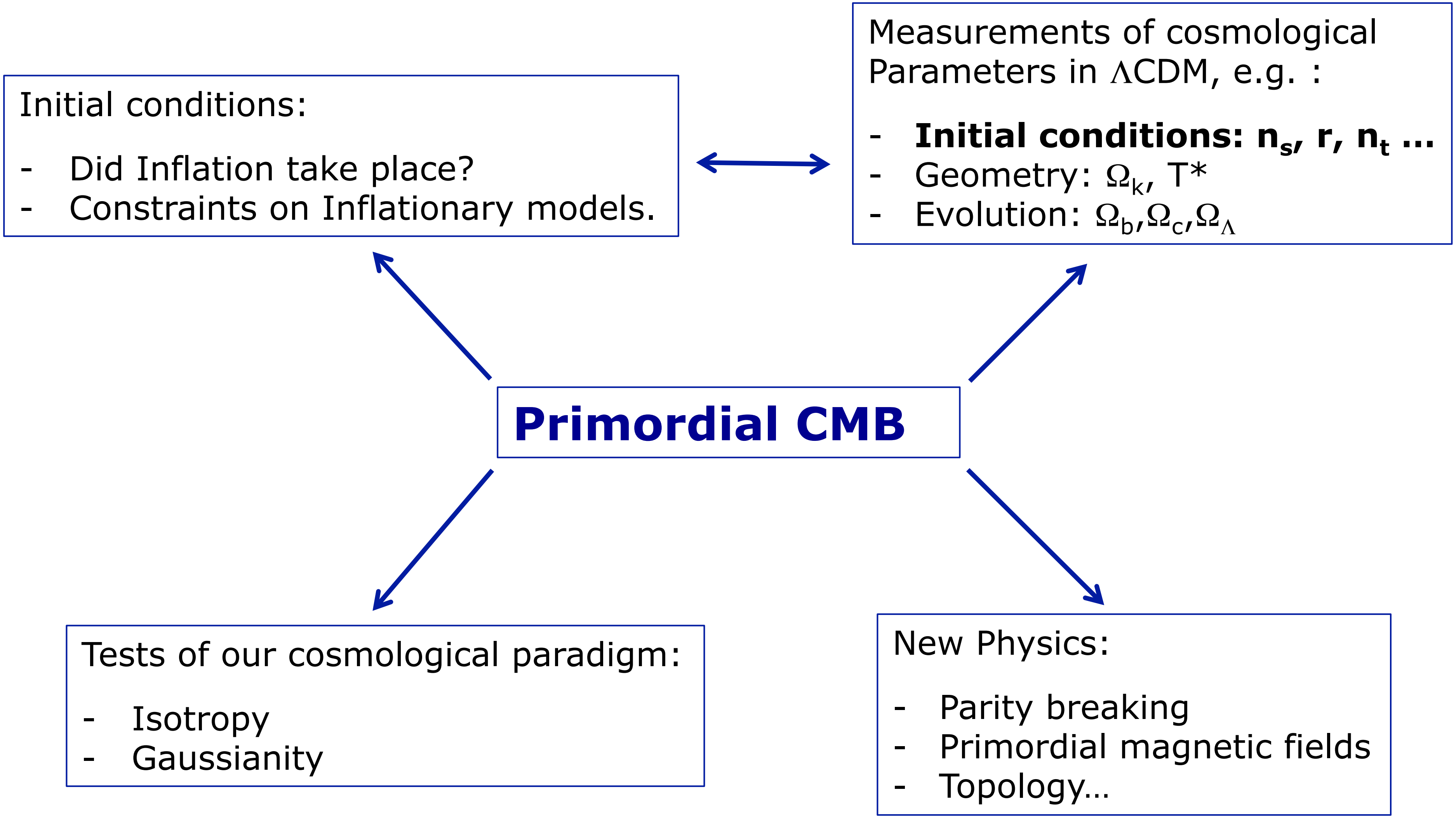
INFLATION

Inhomogeneous

Homogeneous

x 100,000

Scientific goals



Initial conditions:

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

Measurements of cosmological Parameters in ΛCDM, e.g. :

- **Initial conditions: n_s, r, n_t …**
- Geometry: Ω_k, T*
- Evolution: Ω_b,Ω_c,Ω_Λ

Primordial CMB

Tests of our cosmological paradigm:

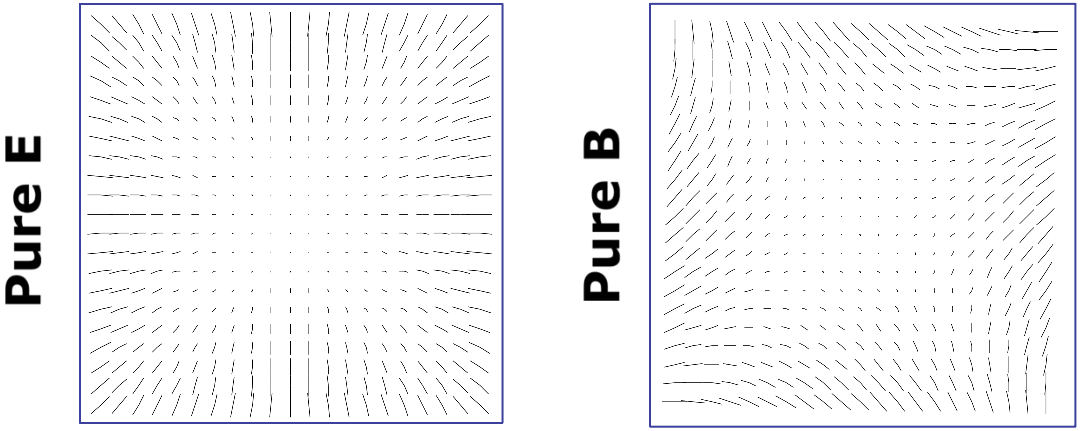
- Isotropy
- Gaussianity

New Physics:

- Parity breaking
- Primordial magnetic fields
- Topology…

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 Gravitational Waves (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.**

- **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*+BICEP2/Keck Arr.
  Primary goal for future CMB experiments.

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

Testing Inflation: power spectra.

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

$$\boxed{P_\varsigma(k) = A_\varsigma \left(\frac{k}{k_*}\right)^{n_S - 1}}$$

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

- Inflation also predicts a background of GW with spectrum

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

Tensor-to-scalar ratio $\boxed{r = \frac{P_t(k_*)}{P_\varsigma(k_*)}}$

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 < 0.07,** (95% C.L.)**,** Planck + BICEP2 + Keck Array.

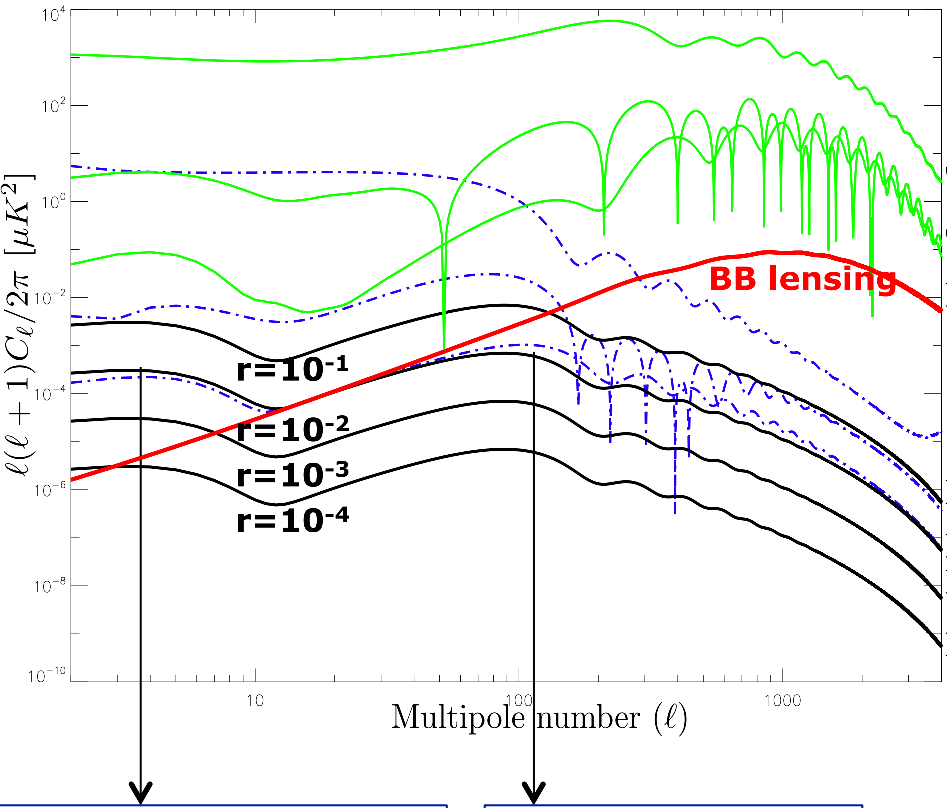
- From the **ground, claim: Δr ~ 0.01** maybe achievable.
  No self consistent result at present!

- **Main obstacles**: **astrophysical foreground, B-mode lensing signal.**
- **Best remedies**: full-sky, wide multi-frequency coverage => **SPACE**

- Next generation of **space missions aiming for Δr ~ 0.001**

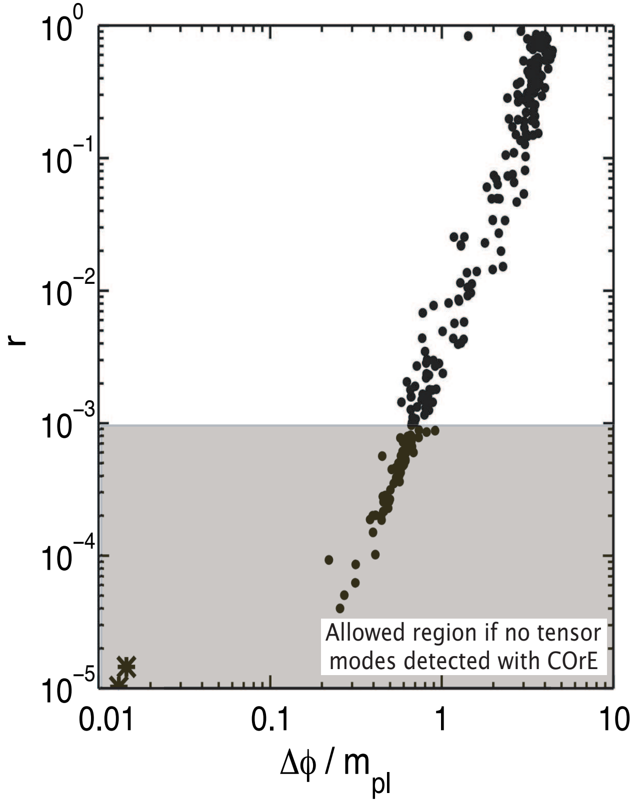
- Energy scale tested is ~12 order of magnitude, or more, larger than what probed in particle accelerators!

- Lyth bound $\frac{\Delta\phi}{M_{\mathrm{P}}} = \int \mathrm{d}N \sqrt{\frac{r}{8}}$ implies trans-Planckian excursion for $r > 2 \times 10^{-3}$



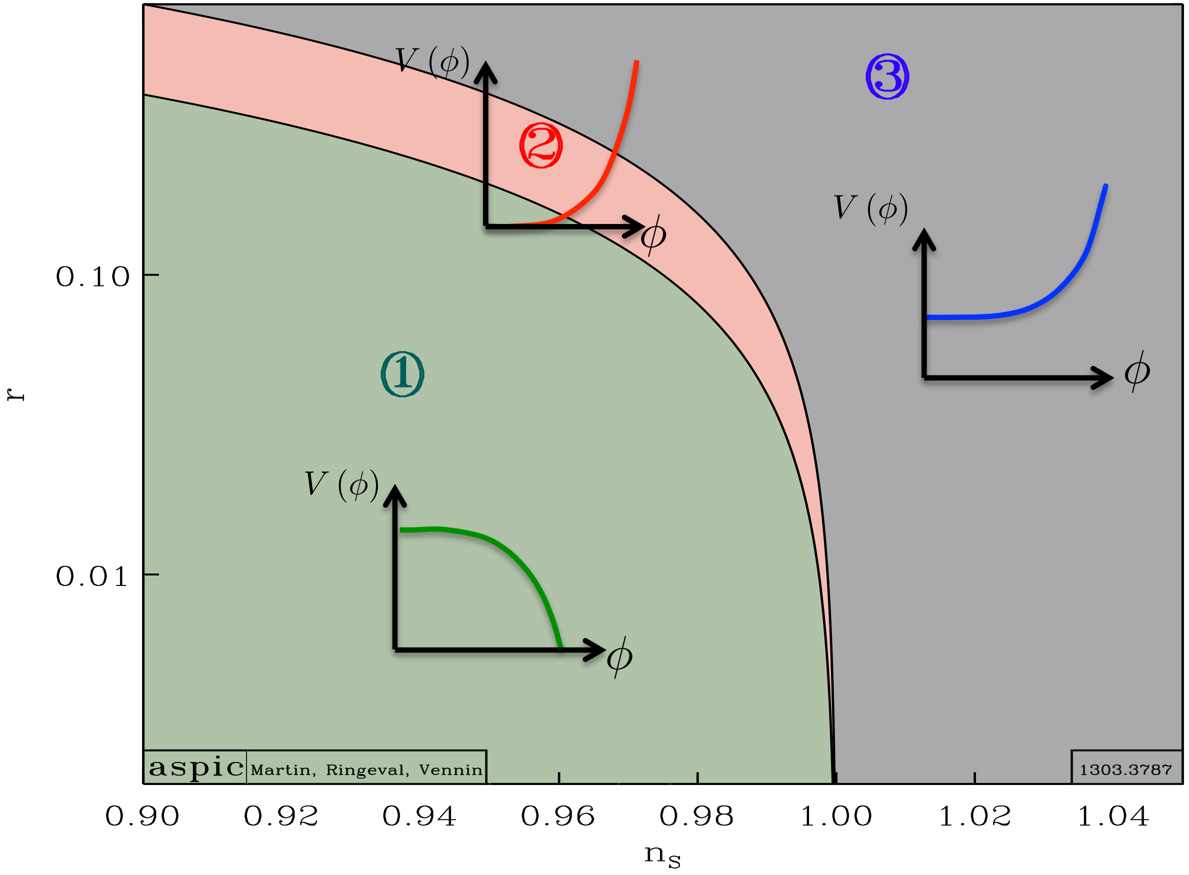
Reionization bump, **not** accessible from ground

Recombination bump



Model predictions. Significant concentration of points for r>0.001

Constraining Inflation: the n_s-r plane

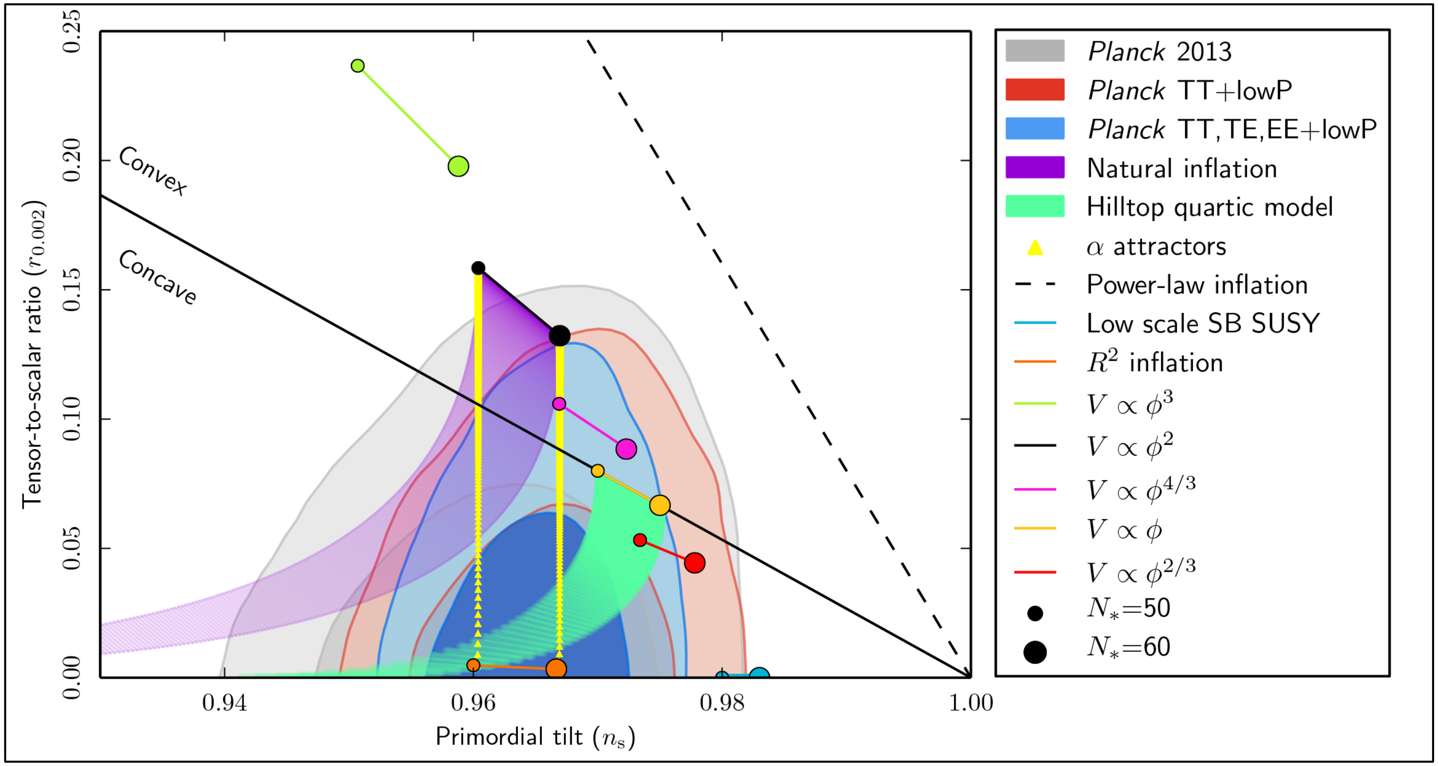


Picture from J. Martin et al. 2013

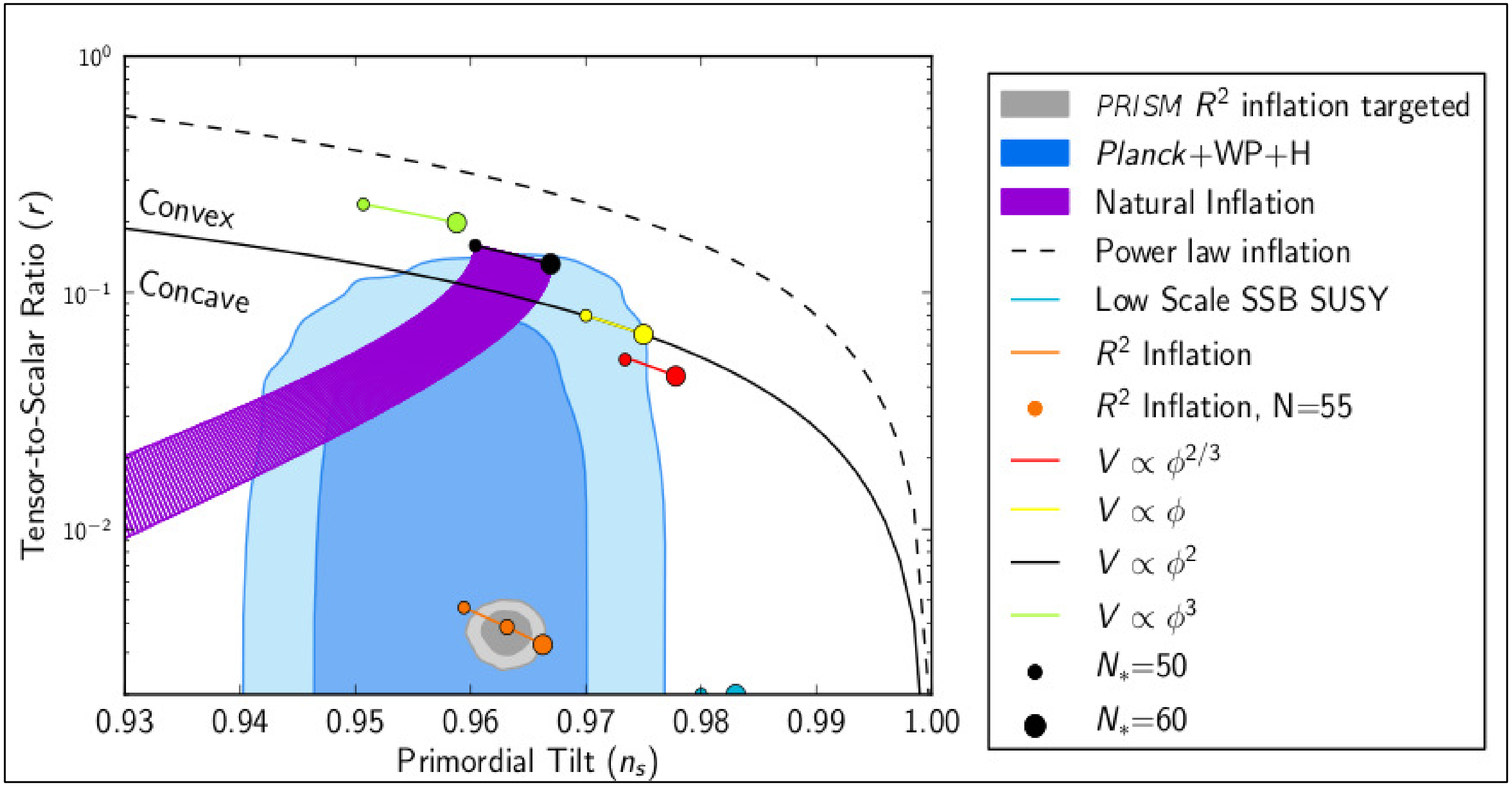
Current constraints on single-field slow-roll Inflation

Model	Parameter	*Planck* TT+lowP	*Planck* TT+lowP+lensing	*Planck* TT+lowP+BAO	*Planck* TT,TE,EE+lowP
ΛCDM+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
ΛCDM+r +$\mathrm{d}n_s/\mathrm{d}\ln k$	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
	$\mathrm{d}n_s/\mathrm{d}\ln k$	$-0.0126^{+0.0098}_{-0.0087}$	$-0.0076^{+0.0092}_{-0.0080}$	-0.0125 ± 0.0091	-0.0085 ± 0.0076
	$-2\Delta \ln \mathcal{L}_{\max}$	-0.81	-0.08	-0.87	-0.38

Planck 2015 results. XX. Constraints on inflation.



n_s-r: foreseeable improvements



Forecasts for PRISM: arXiv:1306.22951

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

More inflationary parameters: running

Running spectral index

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

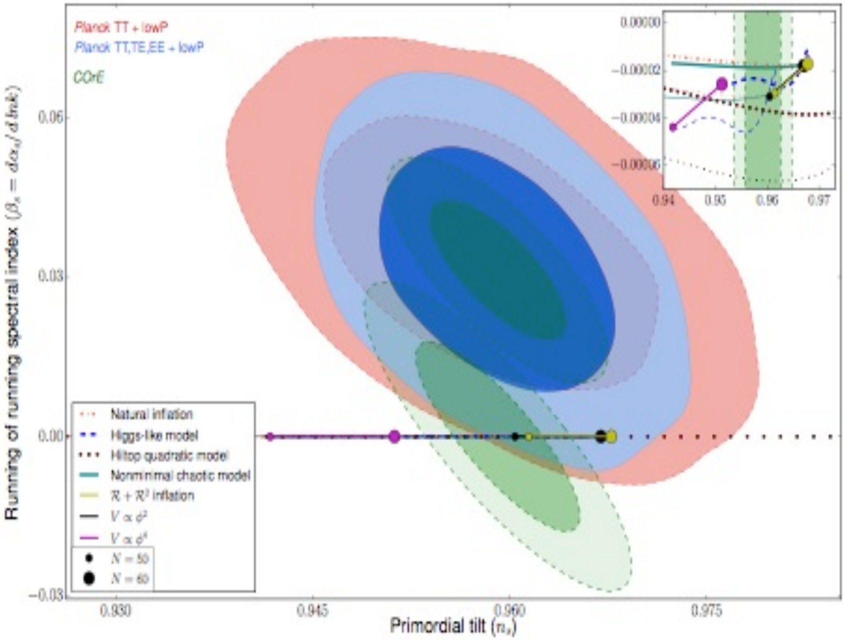
running

running of running

Planck

$$\begin{cases} \alpha_s = 0.009 \pm 0.010 \\ \beta_s = 0.025 \pm 0.013 \end{cases}$$

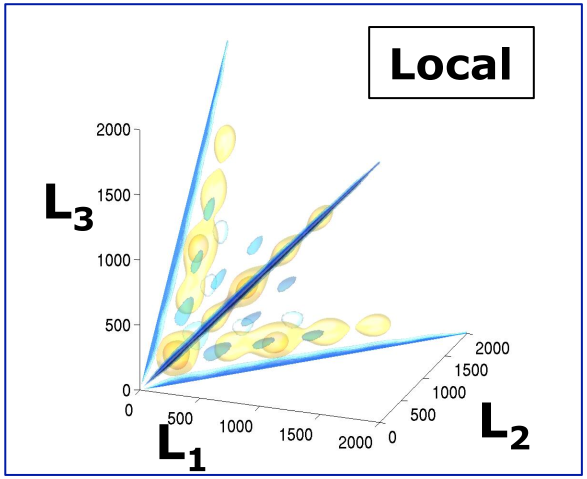
- Future CMB surveys (e.g. CORE) can achieve factor ~3 improvement **(Errard et al. 2015, arXiv:1509.06770)**
- Allows to further tighten constraints on inflationary models

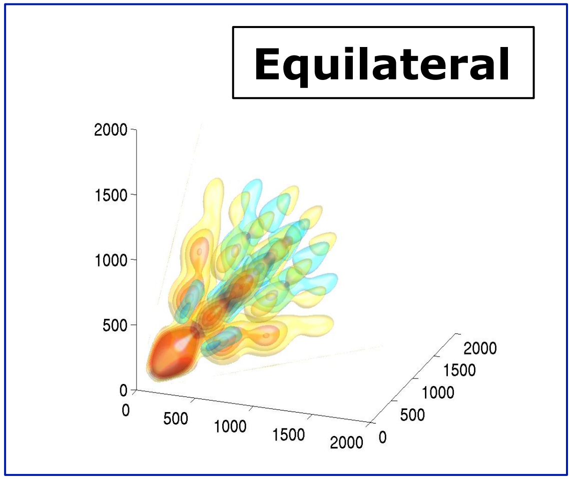


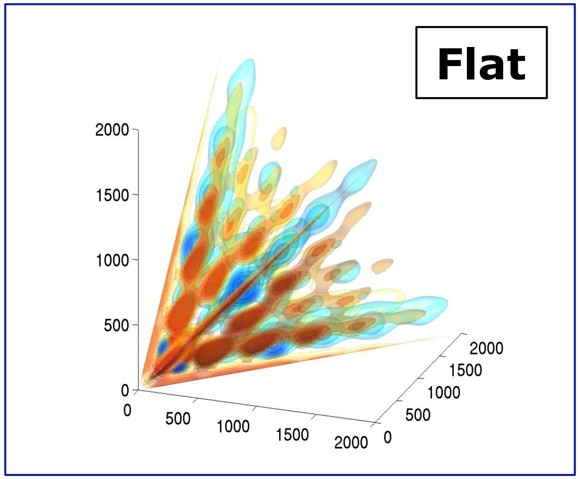
Escudero et al. 2016, arXiv: 1509.05419

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.**


Local


Equilateral


Flat

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

Non-Gaussianity: foreseeable improvements

- Still room for improvement on NG parameters from future CMB data. Achievable by increasing sensitivity for E-mode.

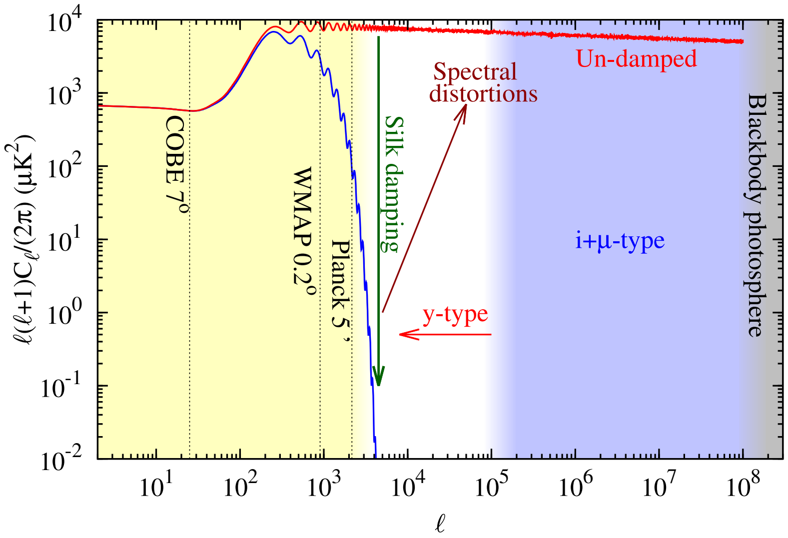
- A cosmic variance dominated E-mode reconstruction up to $l_{max} \sim 3000$ (PRISM, CMBpol) allows an **improvement in f_{NL} error bars by a factor ~3 for all shapes** (*no other cosmological observable can do that, except futuristic 21 cm surveys*).

- 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.*

CMB spectral distortions: a new window



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

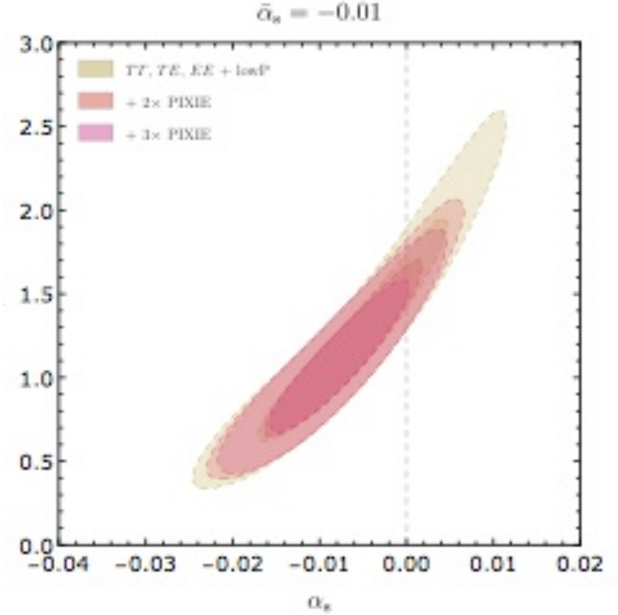
Many additional modes!

Kathri and Sunyaev 2013, arXiv: 1303.7212

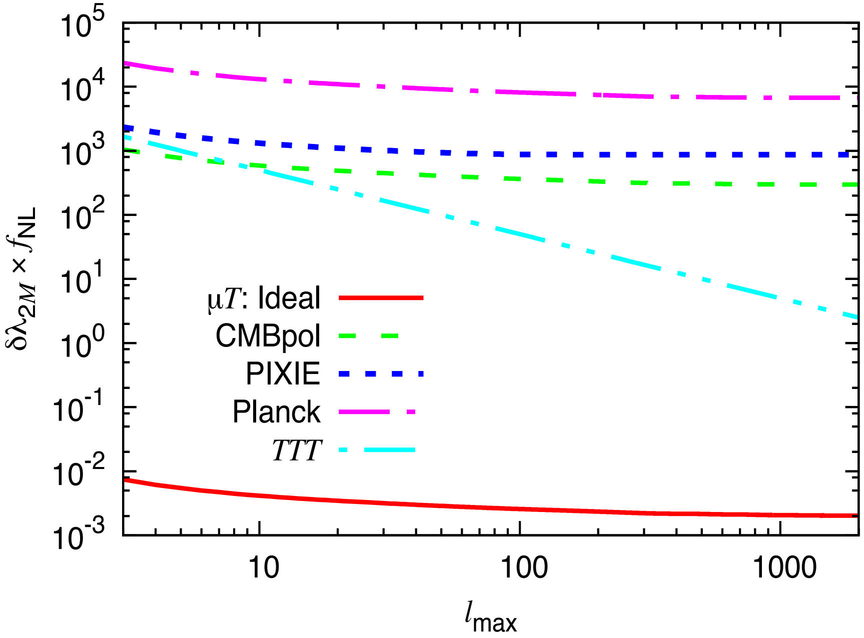
- Power spectrum and running spectral index
  (Khatri and Sunyaev 2013, Cabass, Melchiorri, Pajer 2016)

- If μ-*anisotropies* are measured (no absolute calibration needed):
  - ✓ $T\mu$ correlation: primordial local f_{NL} (or other squeezed bispectra)
    (Pajer and Zaldarriaga 2013)
  - ✓ $\mu\mu$ correlation: primordial local trispectrum, τ_{NL}
  - ✓ $TT\mu$ bispectrum: primordial local trispectrum, g_{NL}
    (Bartolo, ML, Shiraishi 2016)

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

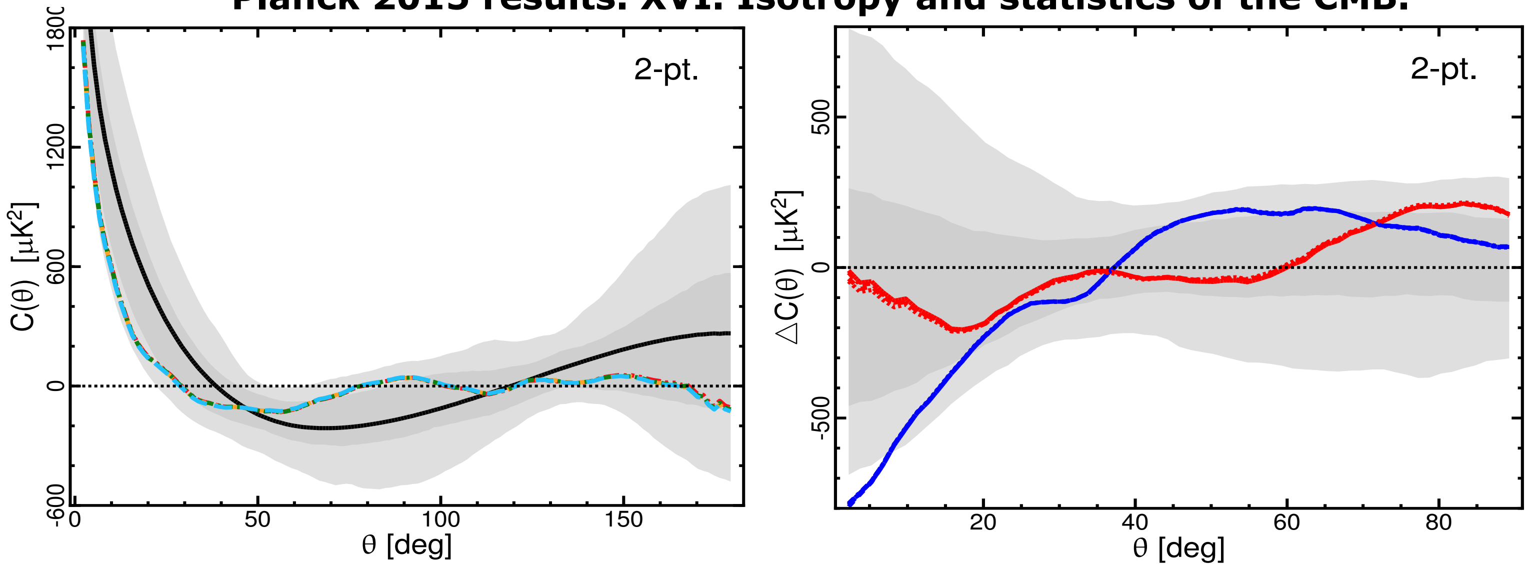


Shiraishi, ML and Bartolo (2015), arXiv: 150606670



- 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},τ_{NL} << 1 (local) and g_{NL} ~ 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



Planck 2015 results. XVI. Isotropy and statistics of the CMB.

- Three main “families”: lack of large angle correlation, multipole alignments, Hemispherical asimmetry. 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 e.g**. CMB polarization.**

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. Birefringence *Planck* paper in preparation. *Planck* statistical uncertainty on rotation angle ~ 0.03 deg

- Better polarization data can lead to significant improvements **A CORE-like survey can improve statistical uncertainty by a factor ~ 10**

Primordial magnetic fields

- **Primordial Magnetic Fields (PMF)**, could be generated in the Early Universe by different mechanisms, such as inflation or phase transitions.

- **The study of PMF may open a new observational window** on the early universe.

- At later times, these PMF could have contributed to the generation of the observed large scale magnetic fields in galaxies and clusters.

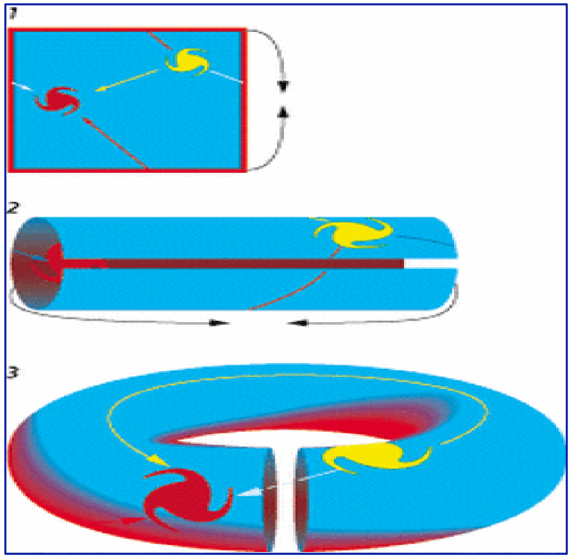
- PMF leave different signatures on the CMB anisotropies, in temperature, polarization and non-Gaussianities, including parity-breaking features. Therefore **the CMB is the best laboratory to investigate and constrain PMF.**

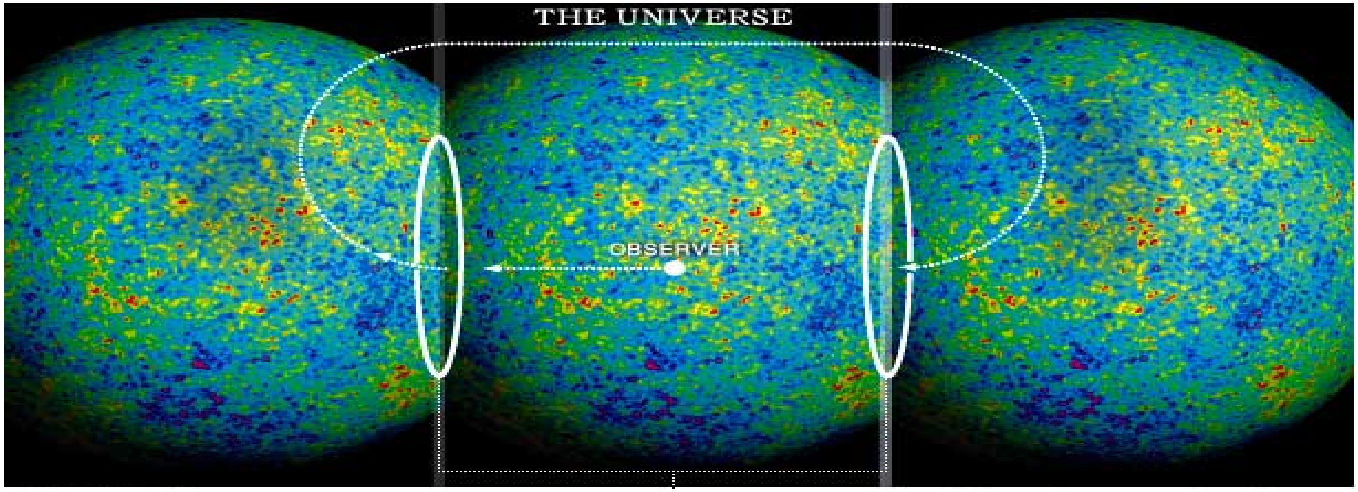
- Current constraints at nG level (*Planck* 2015 results XIX, Paoletti and Finelli, 2011, 2013).

- **Future polarization surveys can improve by one order of magnitude.**

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





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)
  - ✓ Possibily provide a smoking-gun evidence of Inflation
  - ✓ Test energy scales well above particle accelerators’ reach
  - ✓ Test fundamental assumptions of standard Cosmology
  - ✓ Search for new 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 => SPACE***