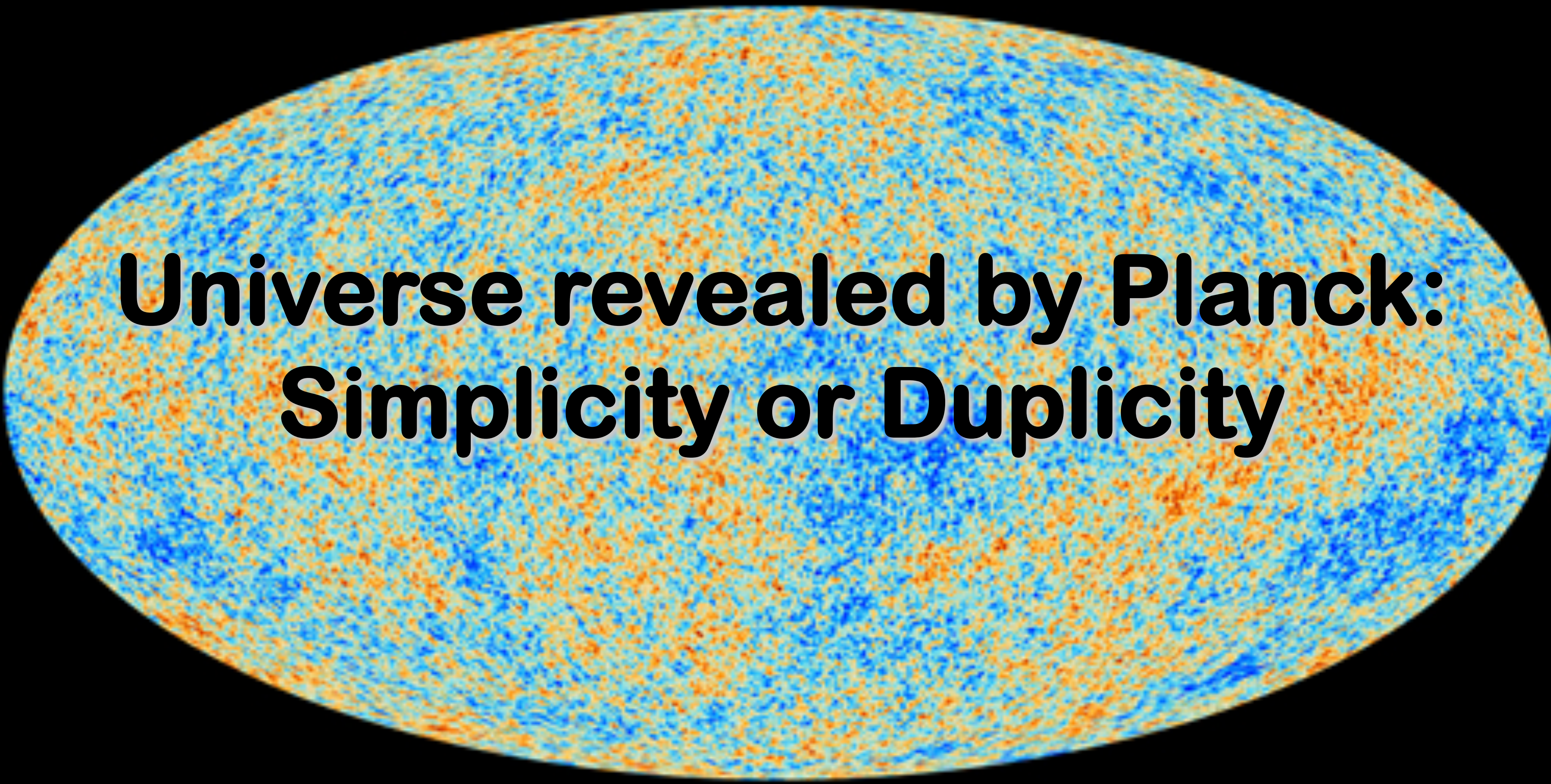
Universe revealed by Planck: Simplicity or Duplicity



Planck Day

ICTS, Bangalore

(Apr 16, 2013)

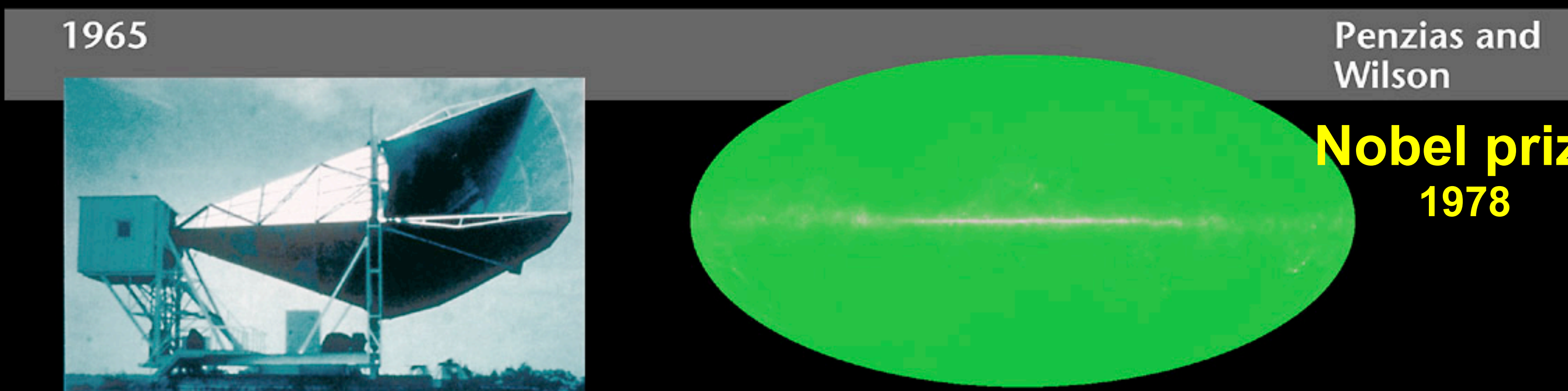
Tarun Souradeep

I.U.C.A.A., Pune

Planck HFI Core team

The Isotropic Universe

Cosmic Microwave Background

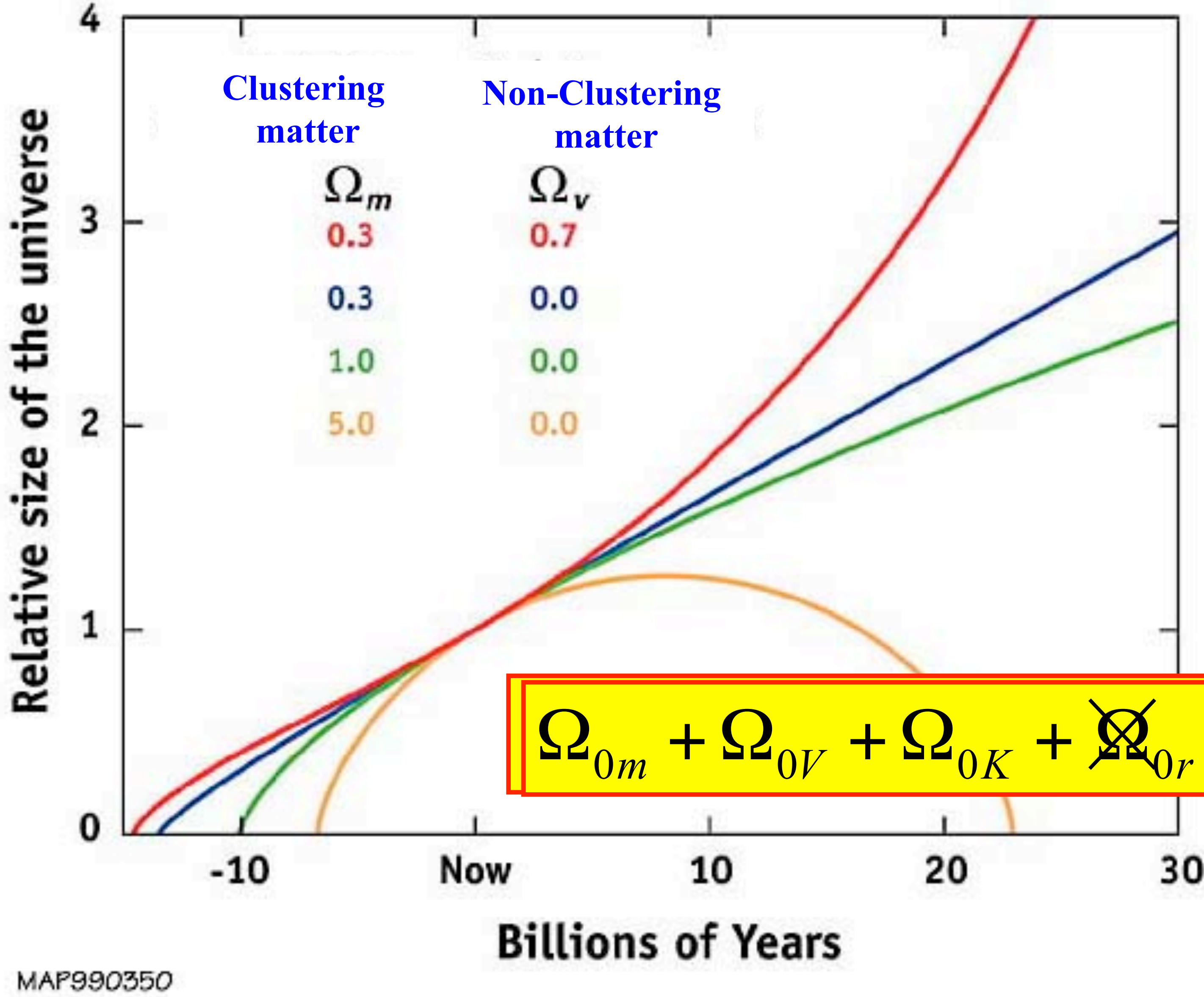


Nobel prize
1978

Serendipitous discovery of the dominant Radiation content of the universe as an extremely **isotropic**, **Black-body** bath at temperature T_0=2.725 (+/-0.002)K .

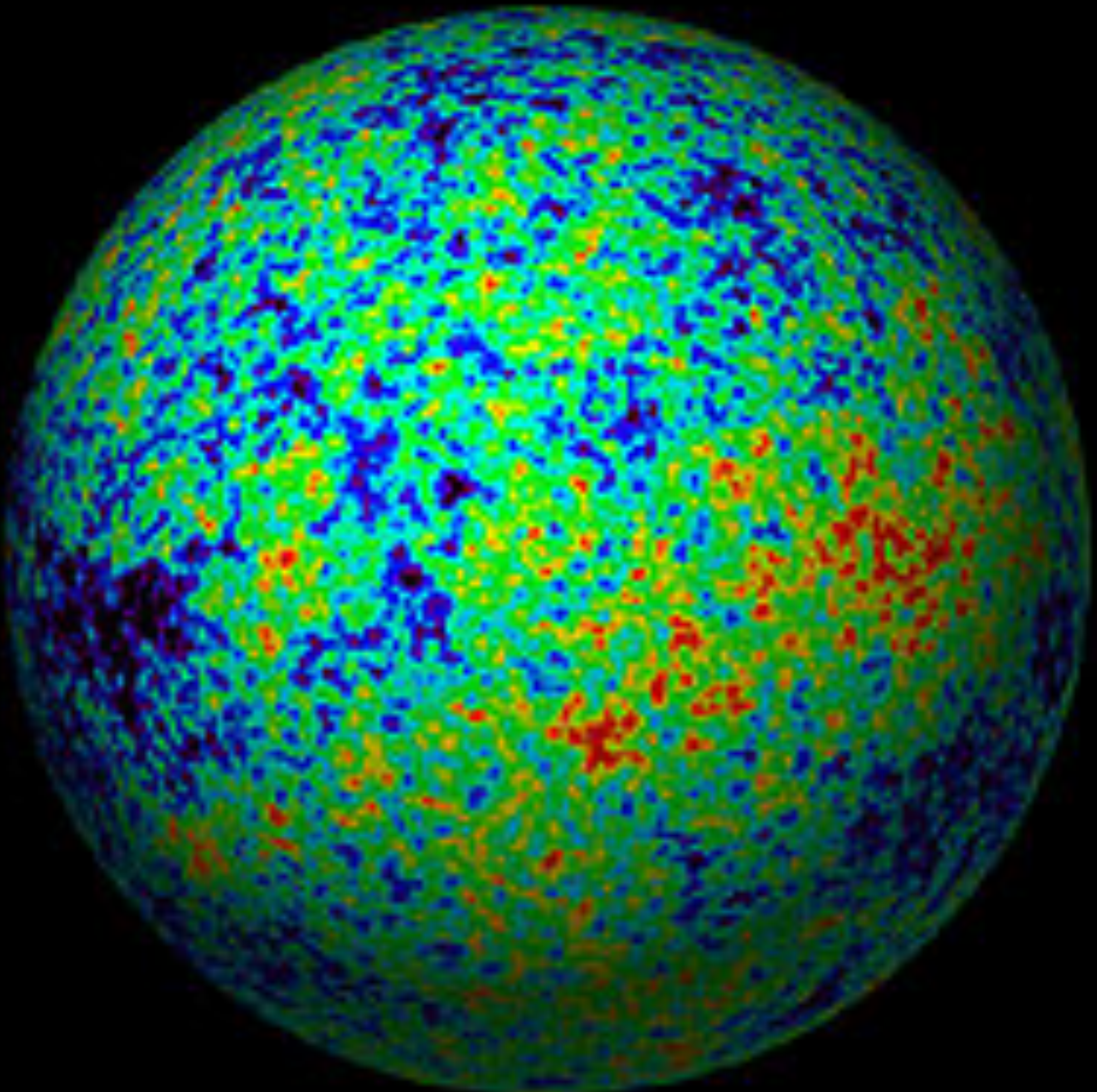
"Clinching support for Hot Big Bang model"

`Standard' cosmological model:
Geometry, Expansion & Matter

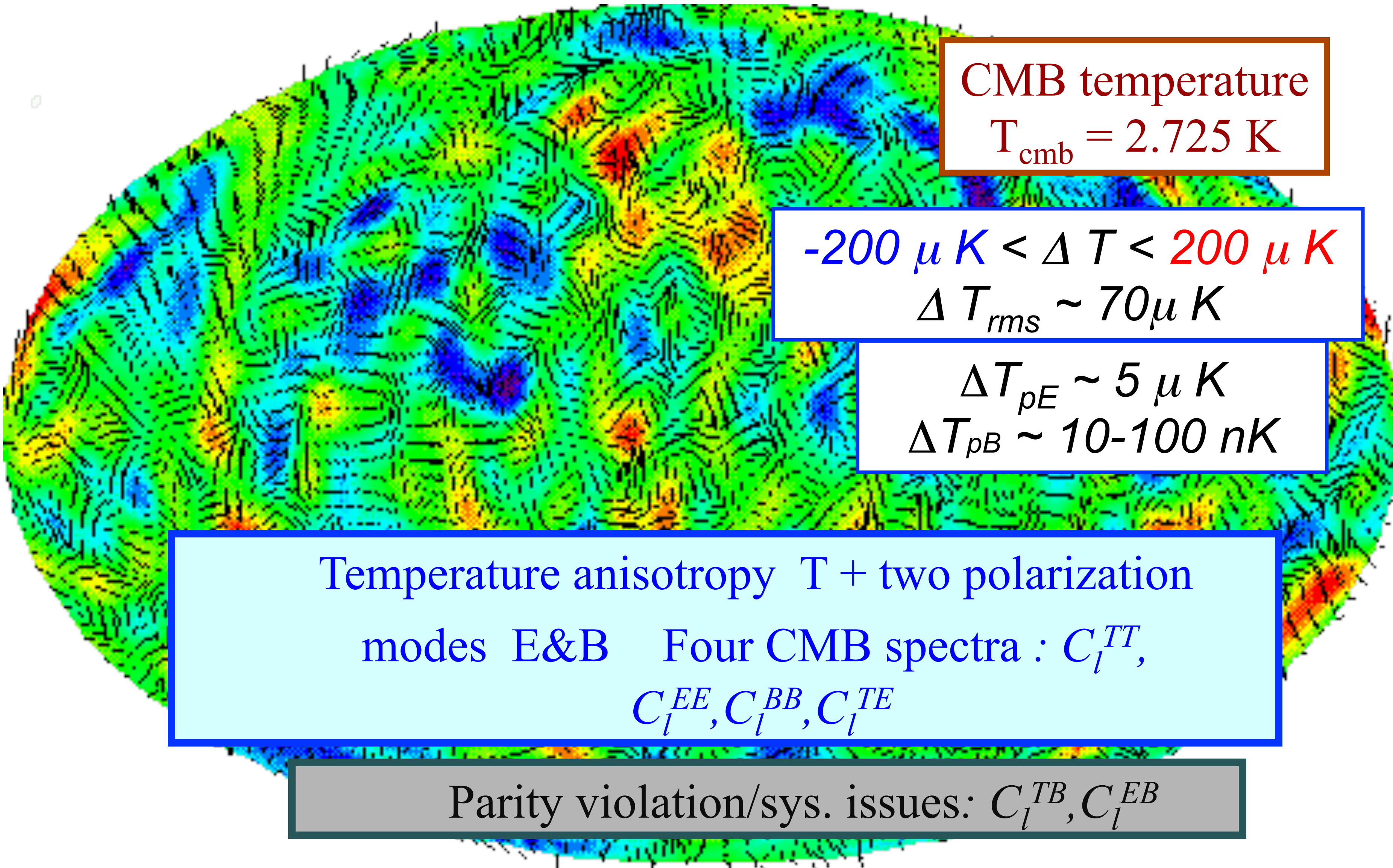


$$\Omega_{0m} + \Omega_{0V} + \Omega_{0K} + \Omega_{0r} + \ldots = 1$$

Cosmic “Super–IMAX” theater



CMB Anisotropy & Polarization



CMB temperature
$T_{cmb} = 2.725$ K

$-200\,\mu K < \Delta T < 200\,\mu K$
$\Delta T_{rms} \sim 70\mu K$

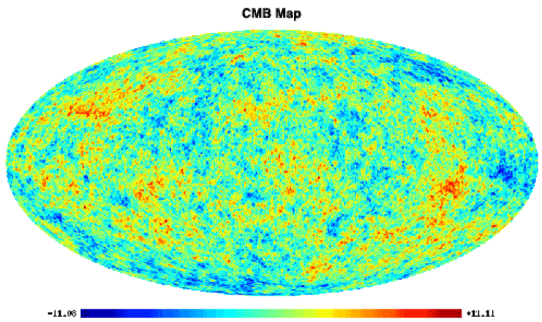
$\Delta T_{pE} \sim 5\,\mu K$
$\Delta T_{pB} \sim$ 10-100 nK

Temperature anisotropy T + two polarization modes E&B Four CMB spectra : C_l^{TT}, $C_l^{EE}, C_l^{BB}, C_l^{TE}$

Parity violation/sys. issues: C_l^{TB}, C_l^{EB}

Statistics of CMB

CMB Anisotropy Sky map => Spherical Harmonic decomposition



$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

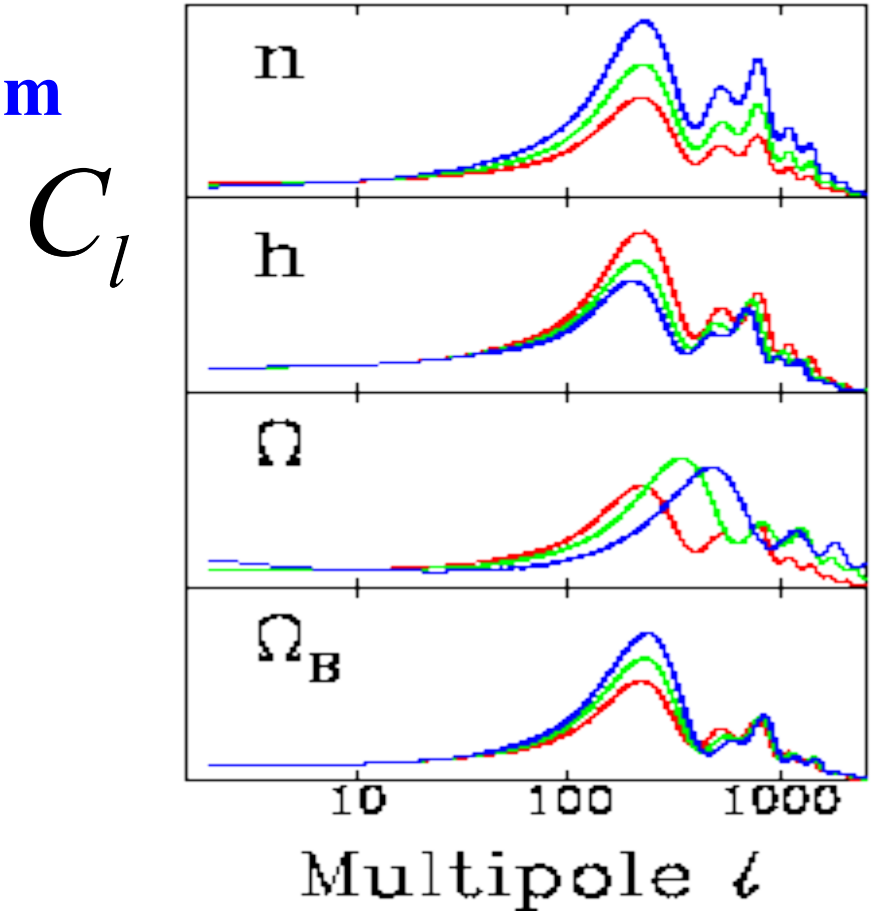
Statistical isotropic & Gaussian CMB anisotropy is completely specified by the

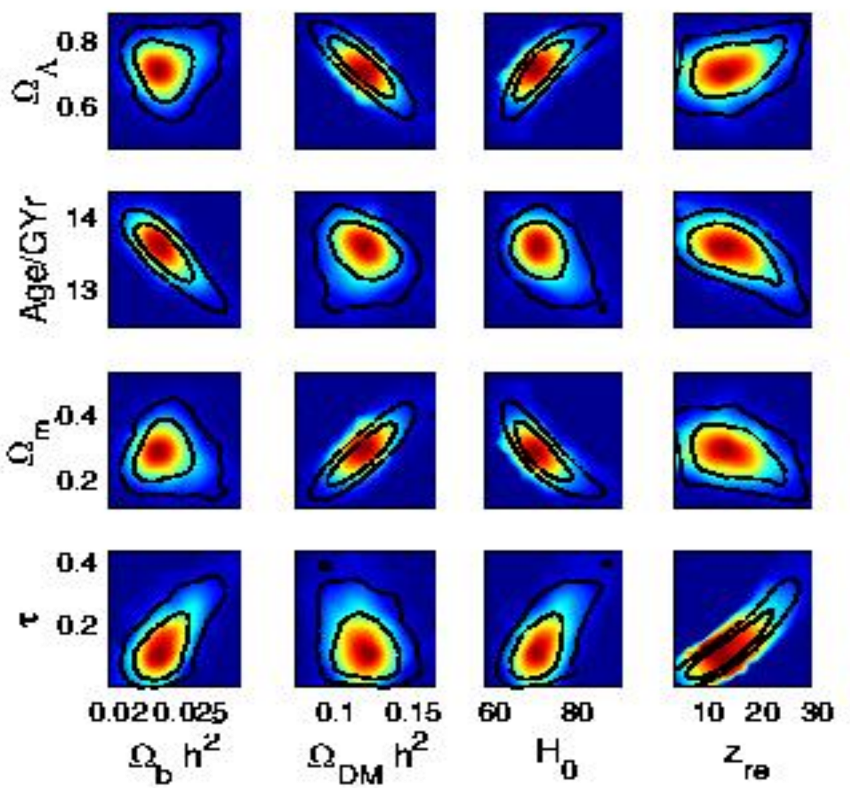
angular power spectrum

$$\langle a_{lm} \, a^{*}_{l'm'} \rangle = C_l \, \delta_{ll'} \delta_{mm'}$$

Fig. M. White 1997

The **Angular power spectrum** of CMB anisotropy depends sensitively on **Cosmological parameters**



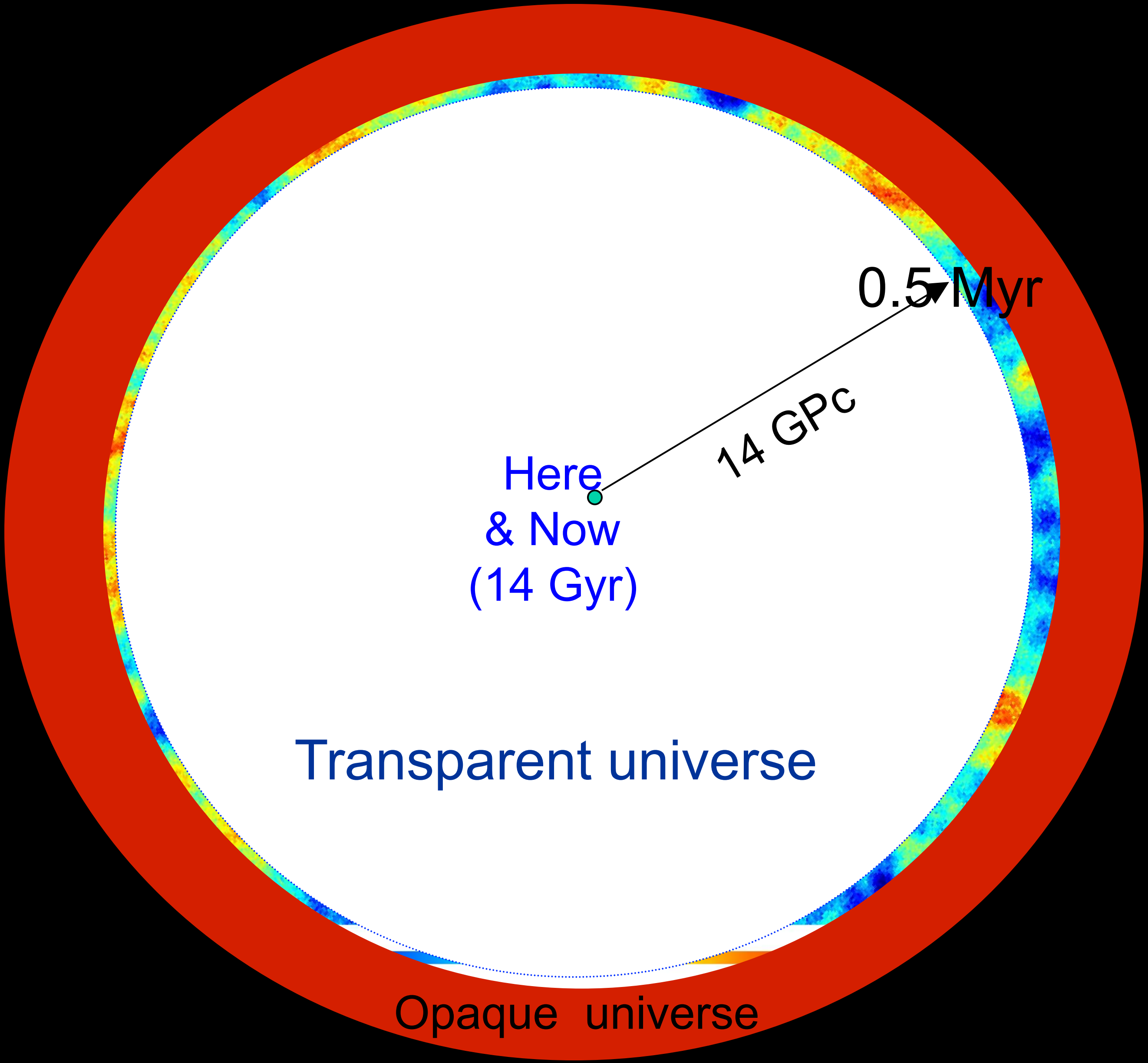


Multi-parameter Joint likelihood (MCMC)

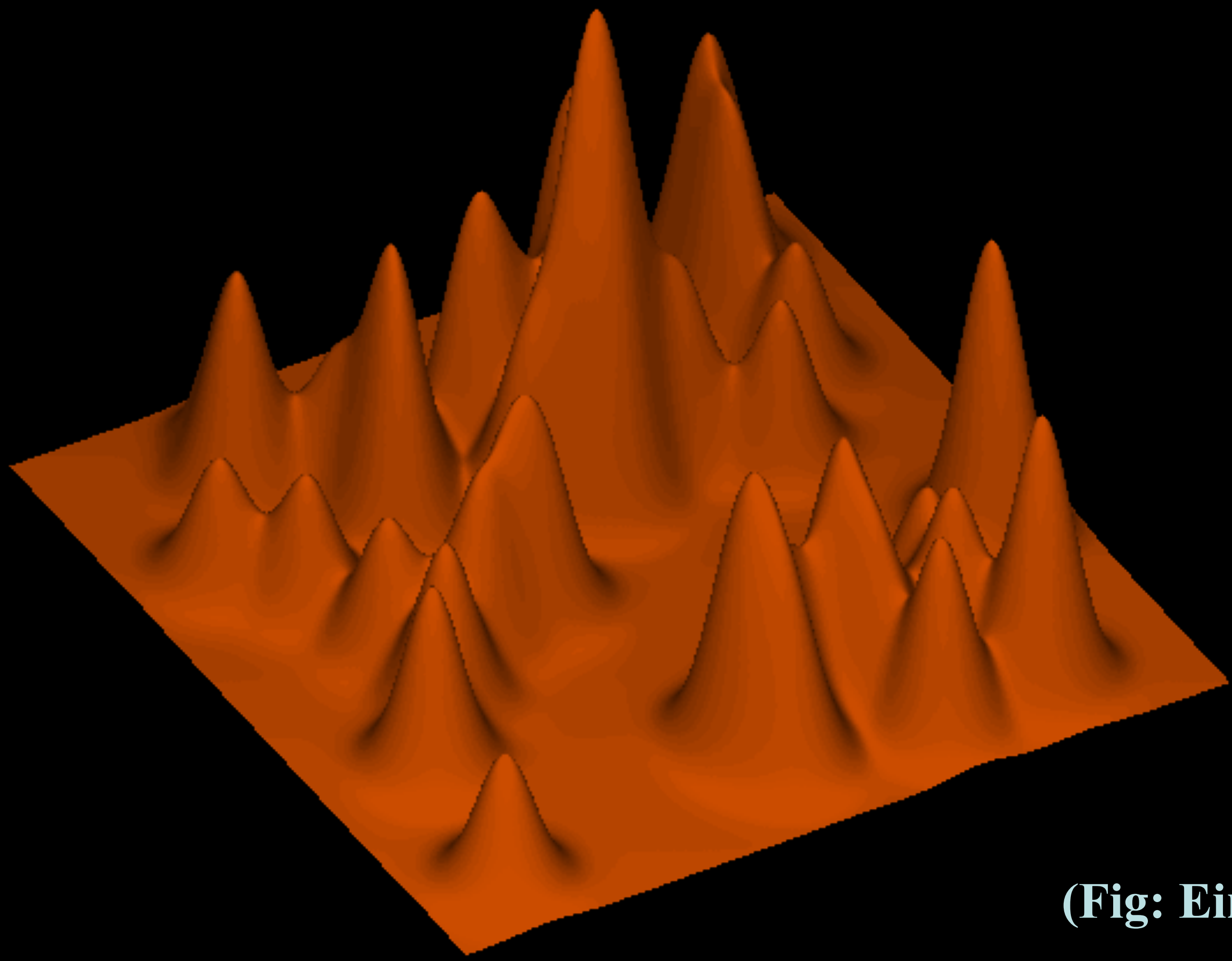
Hence, a **powerful tool** for constraining **cosmological parameters.**

Music of the Cosmic Drum

Cosmic "Super–IMAX" theater

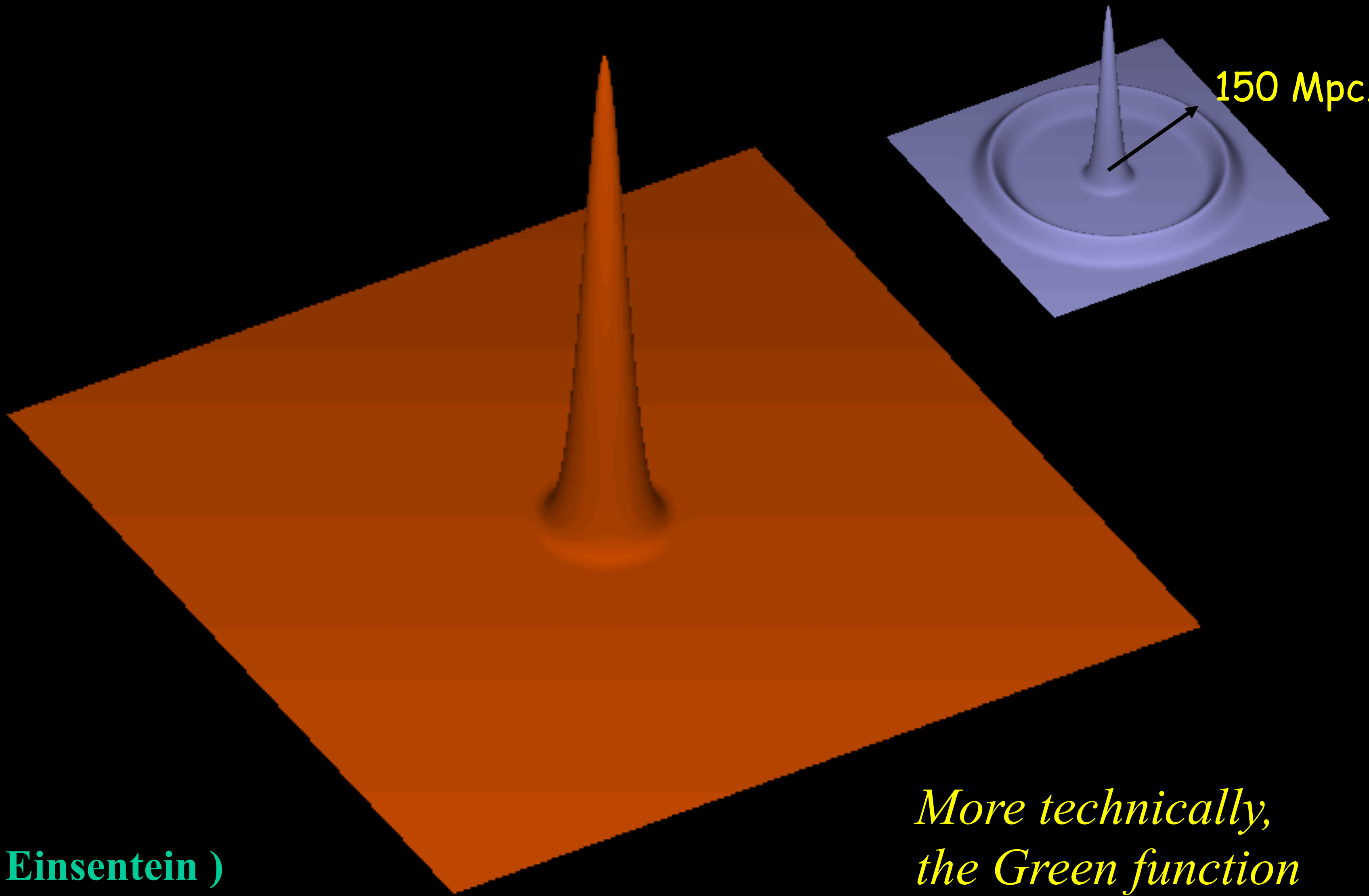


Perturbed universe: superposition of random `pings'



(Fig: Einsentein)

Ping the ‘Cosmic drum’

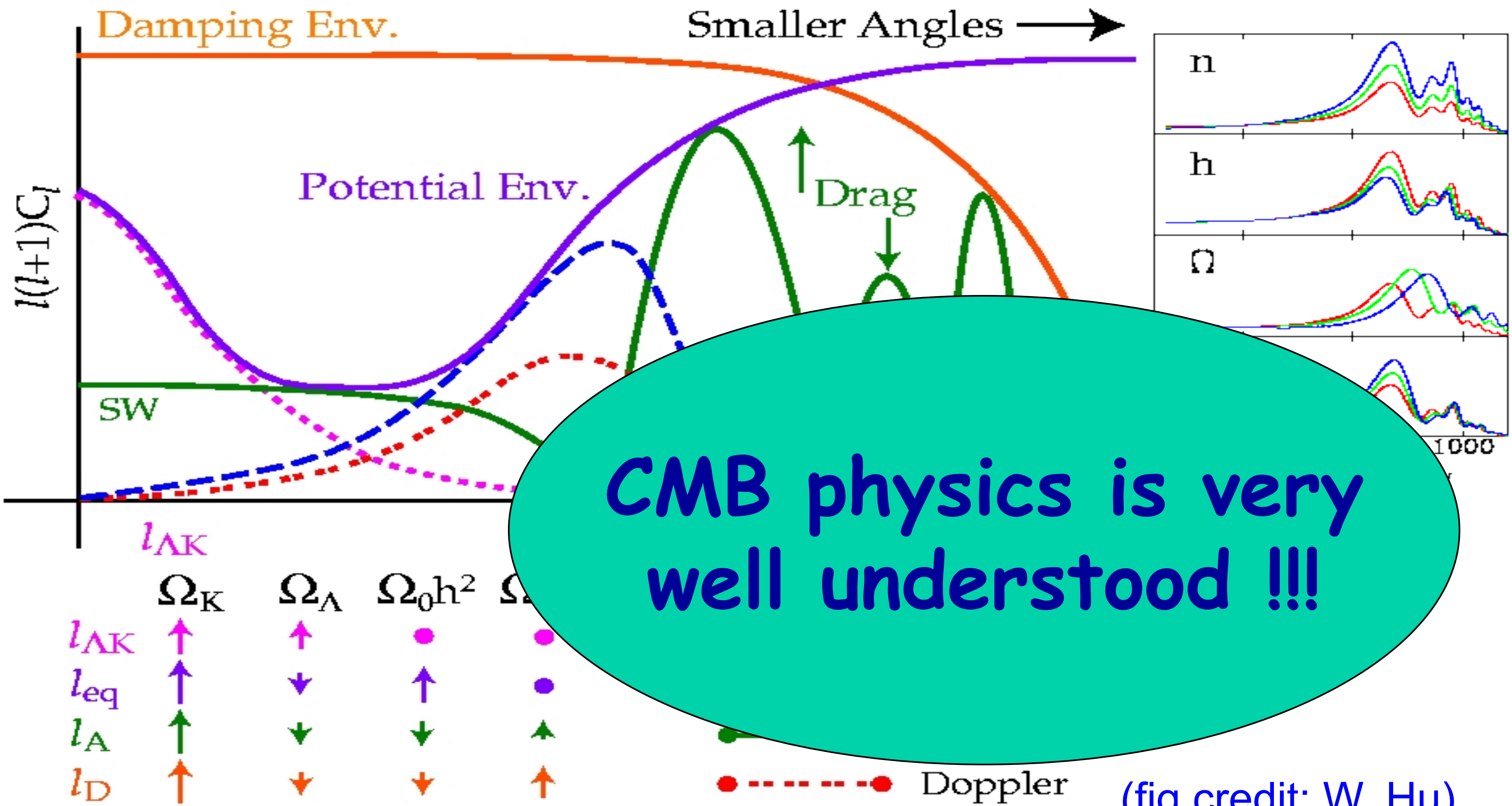


(Fig: Einsentein)

More technically,
the Green function

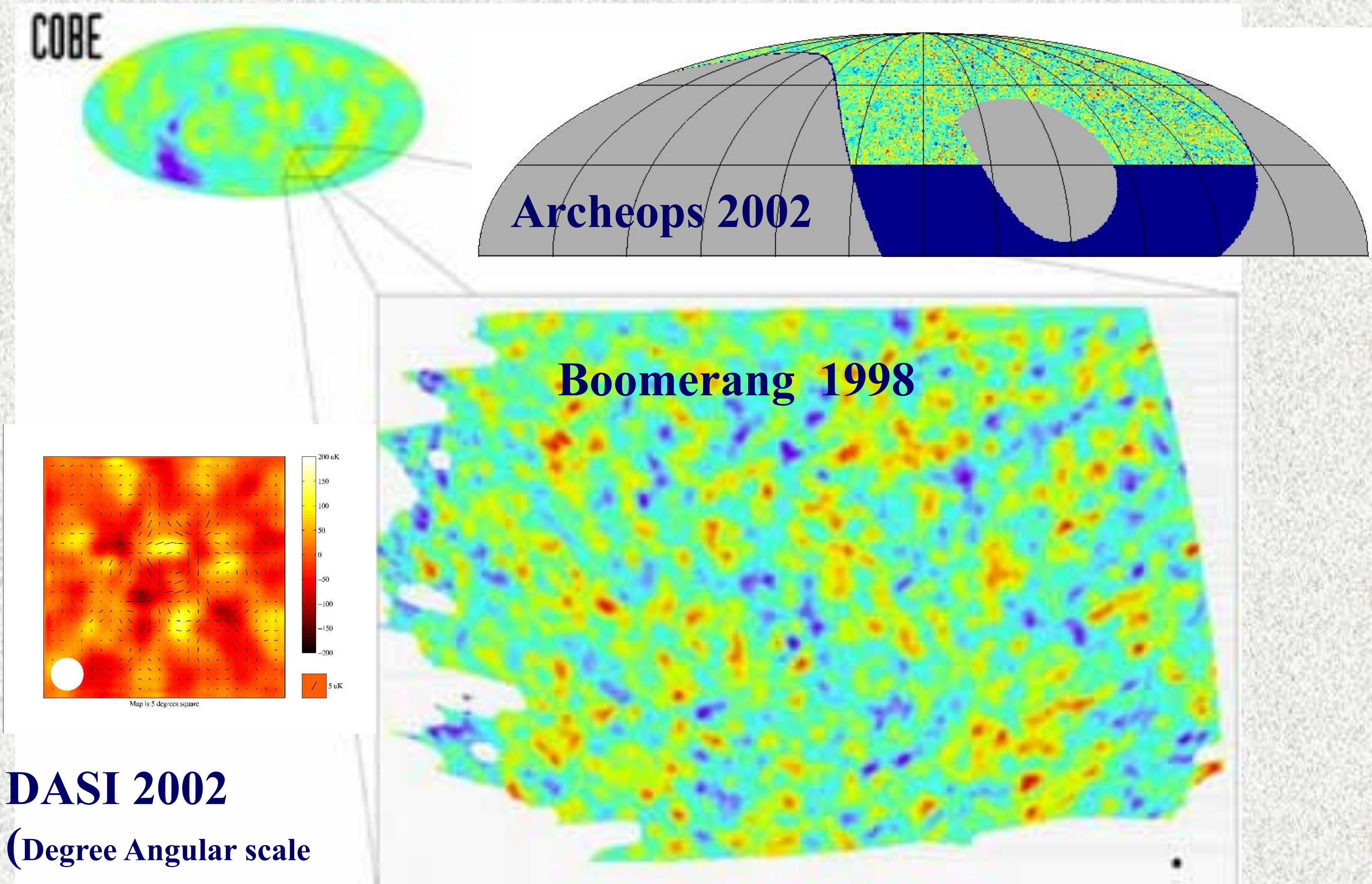
Dissected CMB Angular power spectrum

- **Low multipole : Sachs-Wolfe plateau**
- **Moderate multipole : Acoustic "Doppler" peaks**
- **High multipole : Damping tail**



(fig credit: W. Hu)

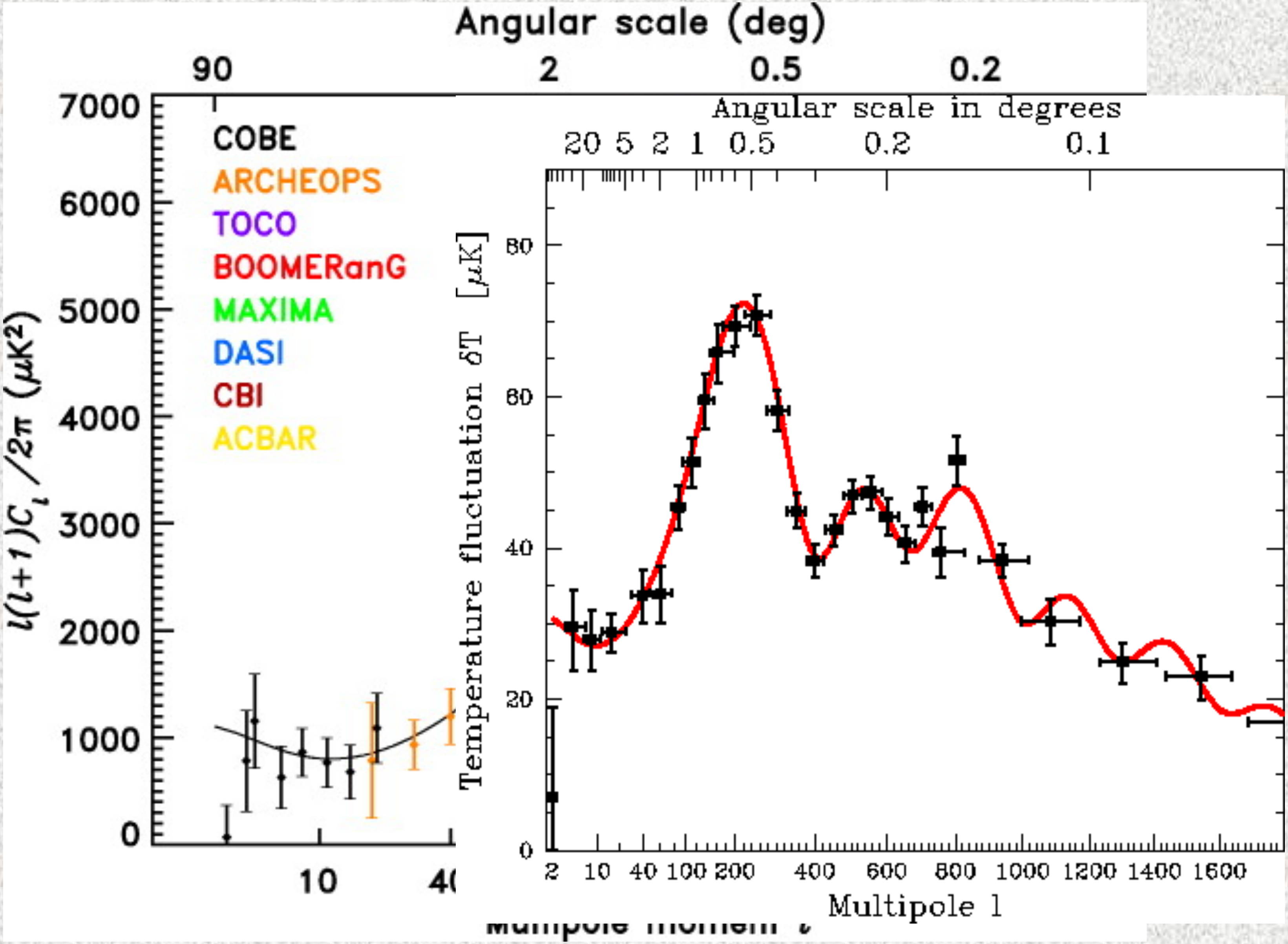
COBE, Post-COBE Ground & Balloon Experiments

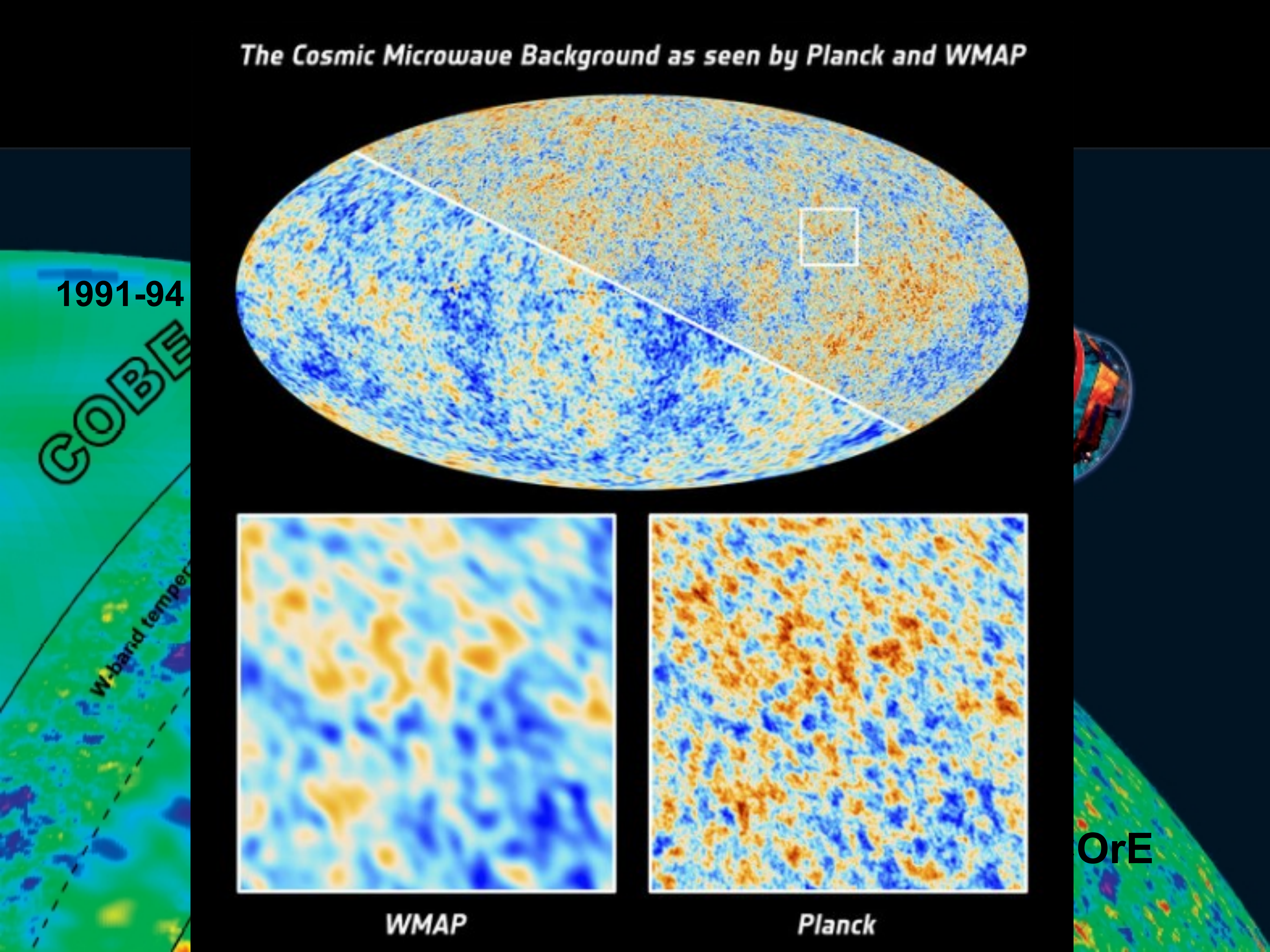


DASI 2002

(Degree Angular scale Interferometer)

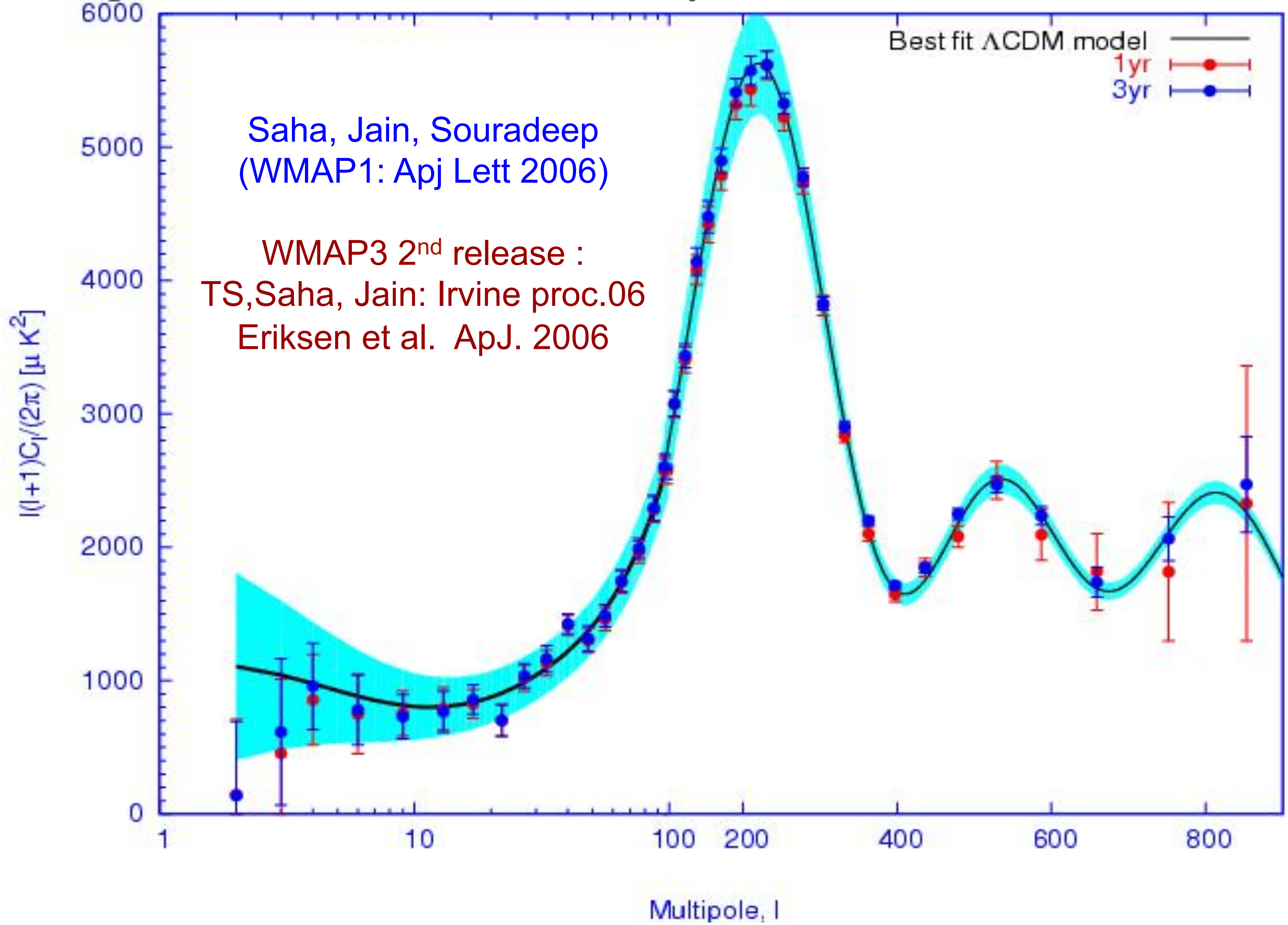
Highlights of CMB Anisotropy Measurements (1992- 2002)




The Cosmic Microwave Background as seen by Planck and WMAP
1991-94
COBE
WMAP
Planck

WMAP: Angular power spectrum

Independent, self contained analysis of WMAP multi-frequency maps



Pre-Planck Angular power spectrum

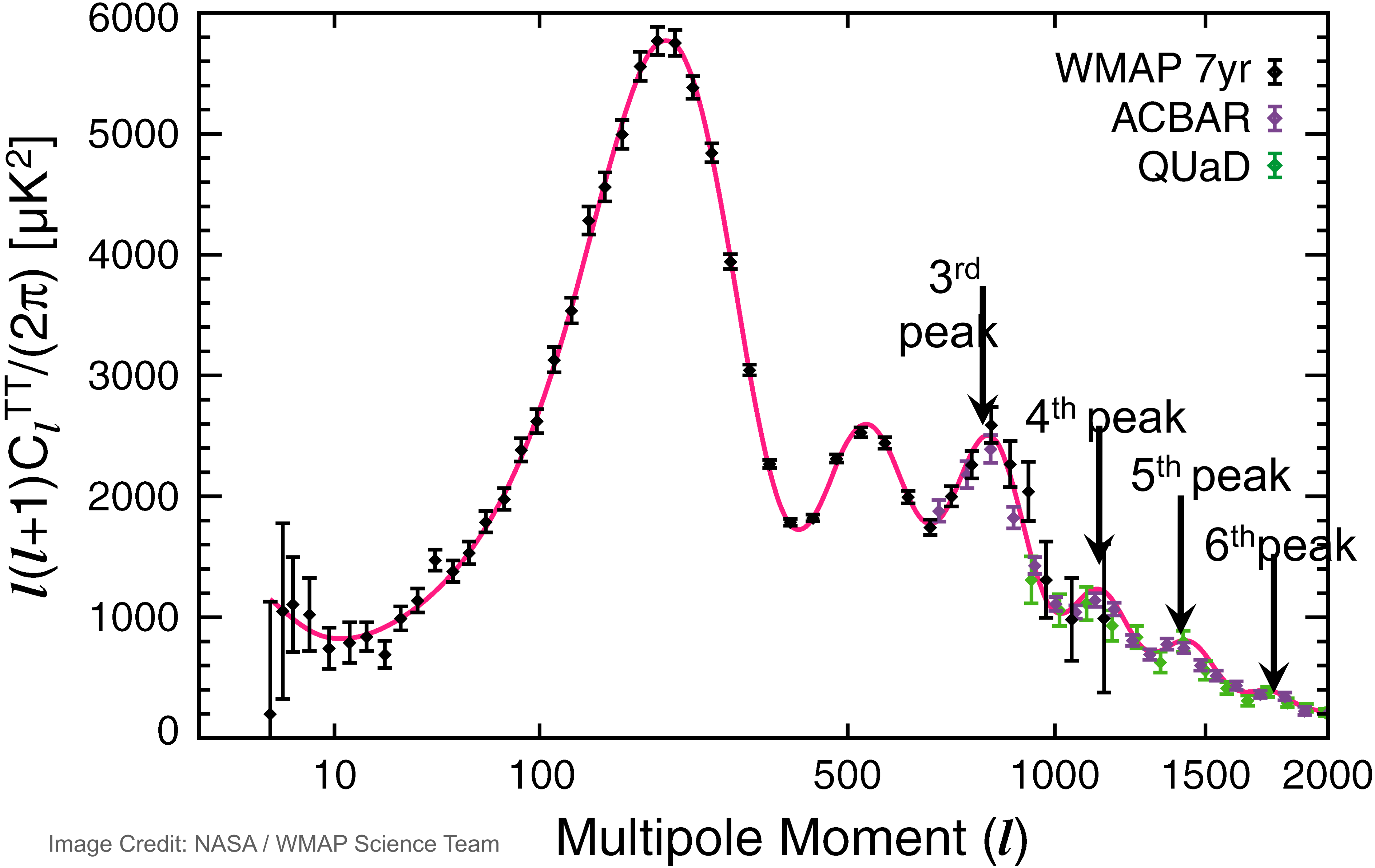
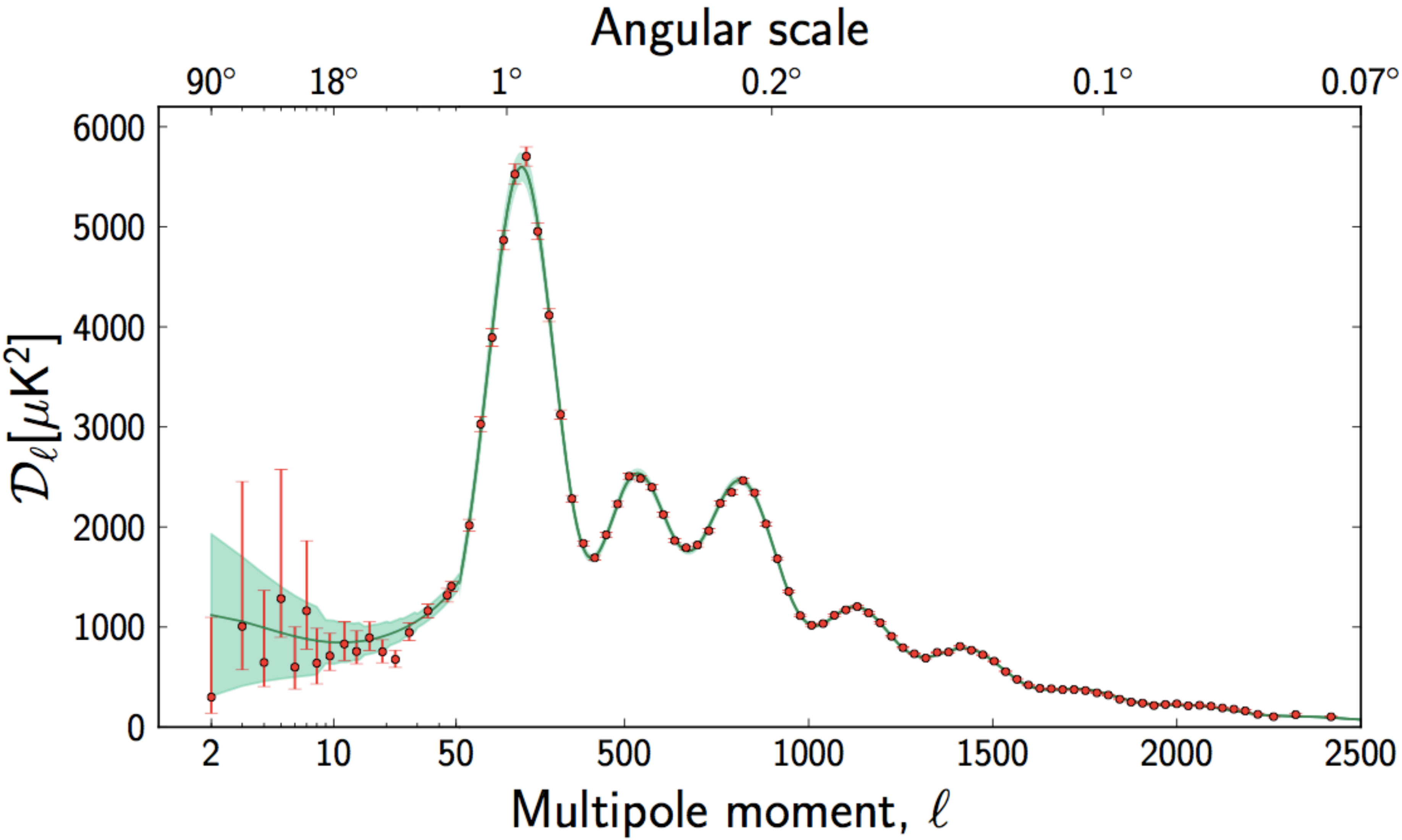
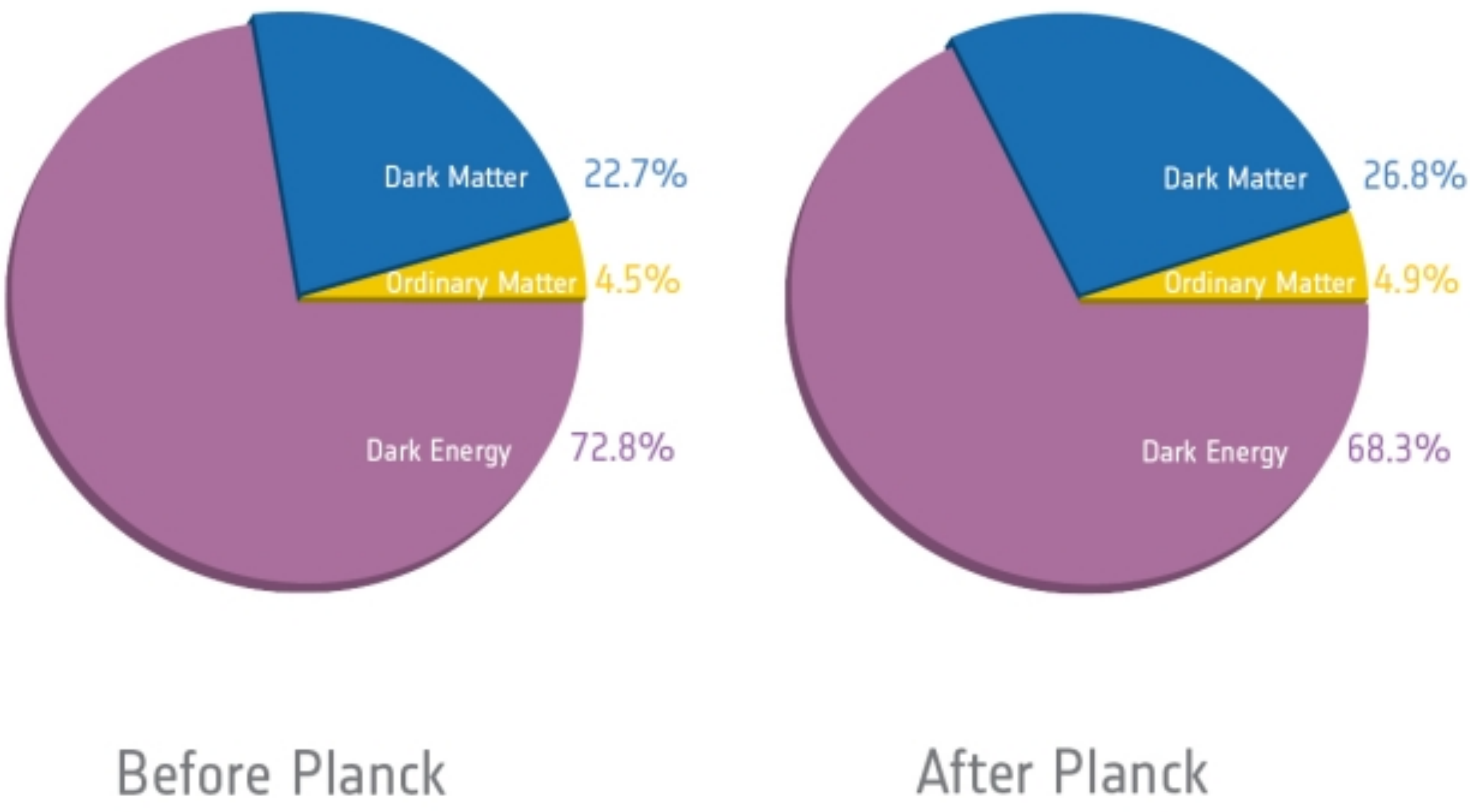


Image Credit: NASA / WMAP Science Team

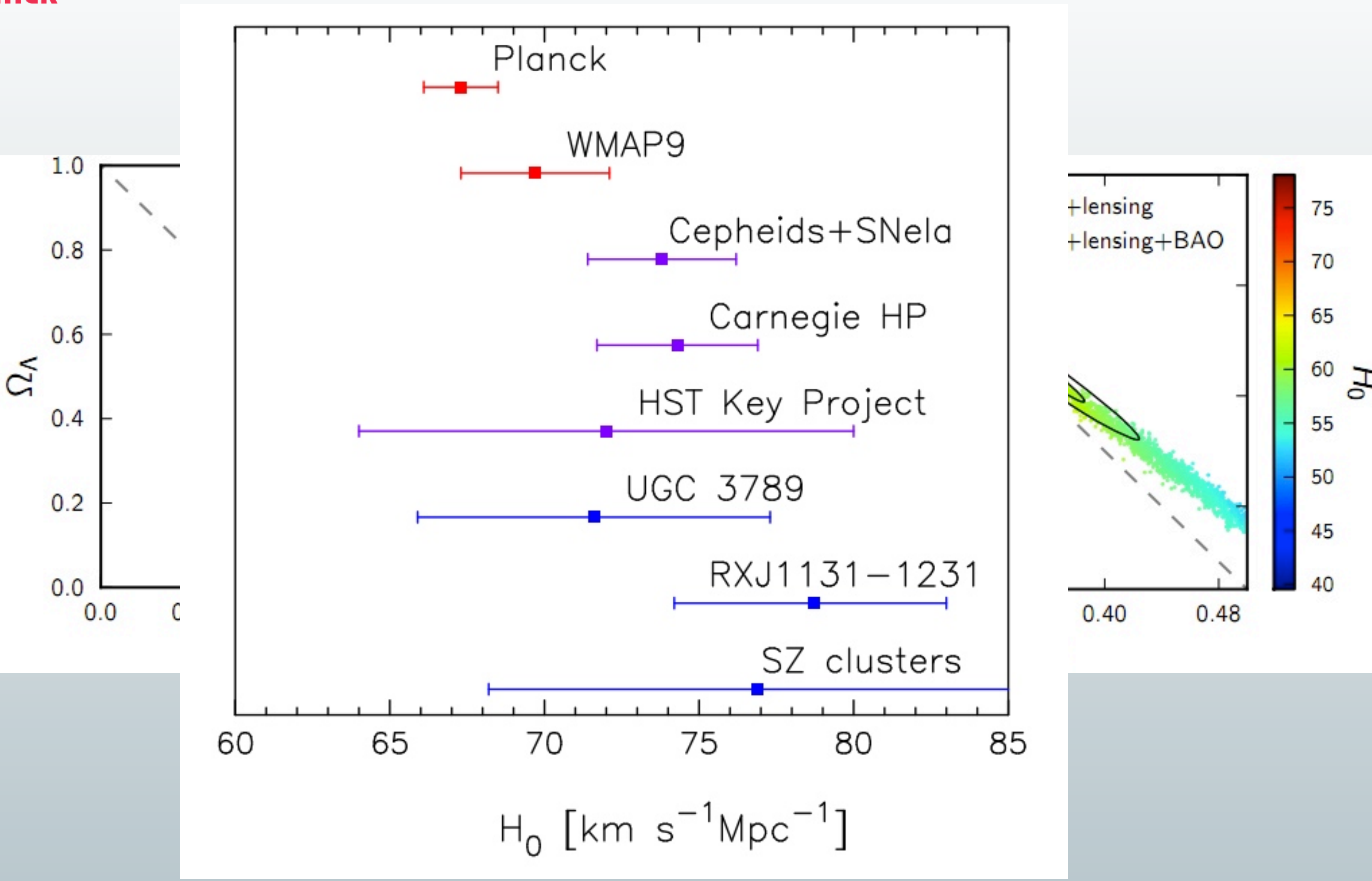
Planck Angular power spectrum



Cosmic content post-Planck



Revised Hubble constant



Cosmological Parameters

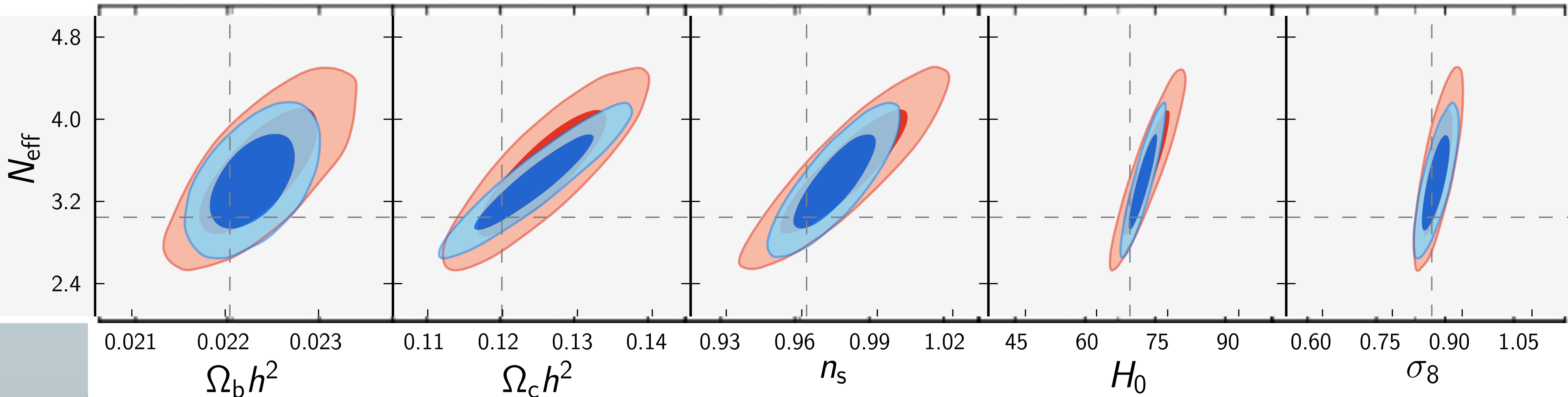
6-Parameter ΛCDM

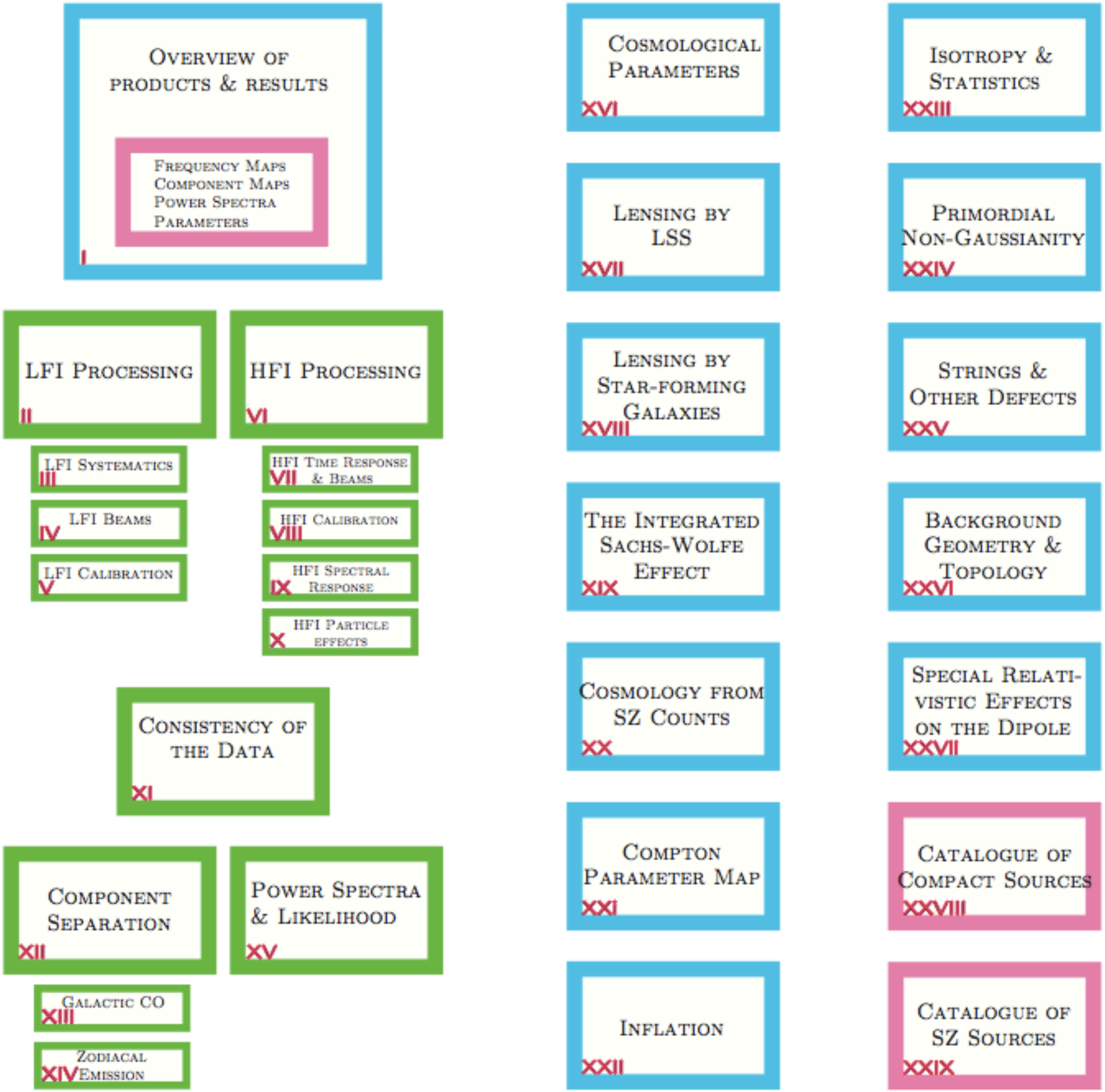
Parameter	*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
	Best fit	68% limits	Best fit	68% limits
$100\Omega_b h^2$				
$\Omega_c h^2$	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$10^9 A_s$	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
n_s				
τ	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
$100\theta_*$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
Ω_Λ				
H_0	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054

Cosmological Parameters

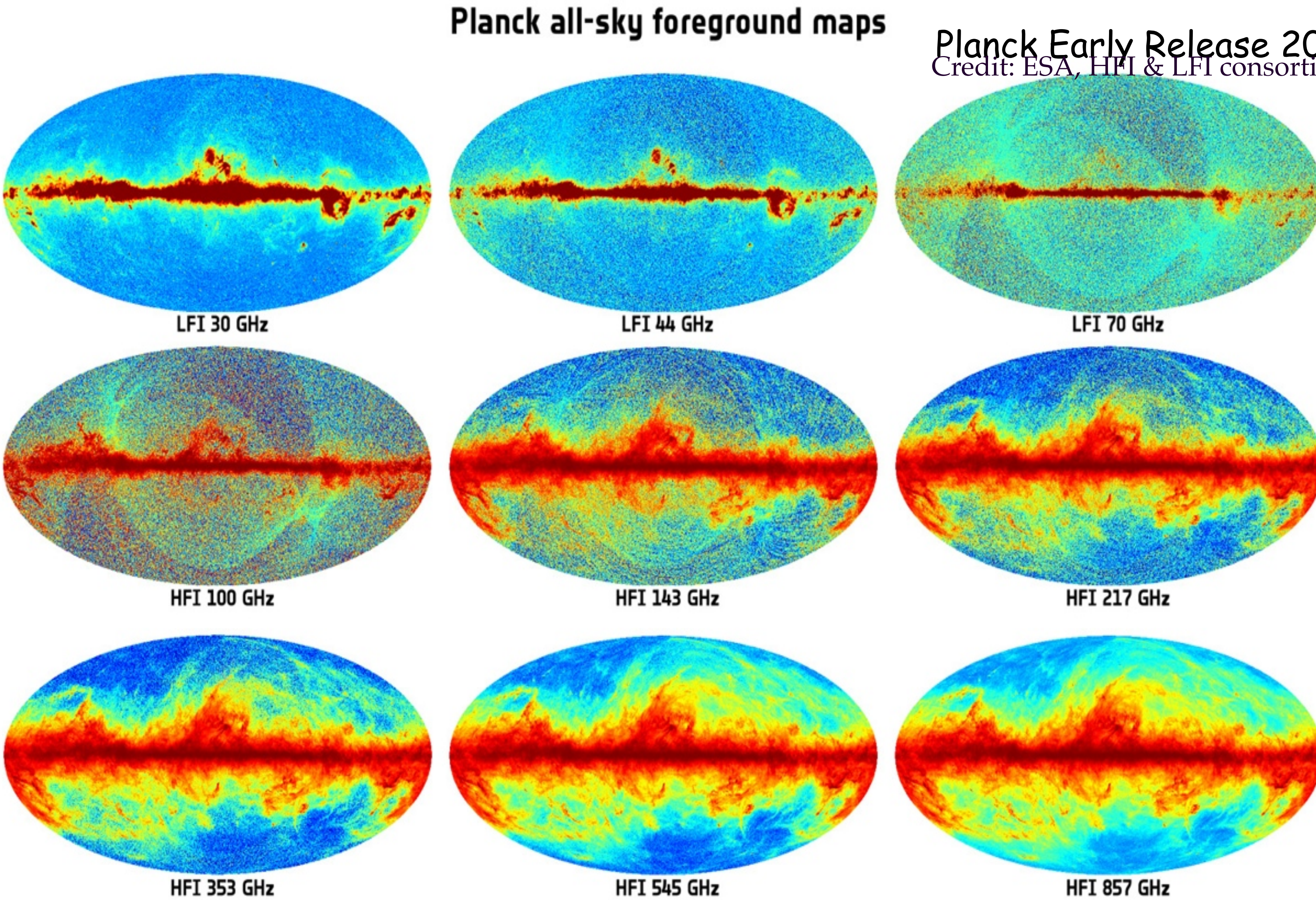
Limits on 1-parameter extensions to 6-p ΛCDM

	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\rm s}/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$




Overview of products & results
Frequency Maps
Component Maps
Power Spectra
Parameters
I
LFI Processing
II
HFI Processing
VI
LFI Systematics
III
HFI Time Response & Beams
VII
LFI Beams
IV
HFI Calibration
VIII
LFI Calibration
V
HFI Spectral Response
IX
HFI Particle effects
X
Consistency of the Data
XI
Component Separation
XII
Power Spectra & Likelihood
XV
Galactic CO
XIII
Zodiacal Emission
XIV
Cosmological Parameters
XVI
Lensing by LSS
XVII
Lensing by Star-forming Galaxies
XVIII
The Integrated Sachs-Wolfe Effect
XIX
Cosmology from SZ Counts
XX
Compton Parameter Map
XXI
Inflation
XXII
Isotropy & Statistics
XXIII
Primordial Non-Gaussianity
XXIV
Strings & Other Defects
XXV
Background Geometry & Topology
XXVI
Special Relativistic Effects on the Dipole
XXVII
Catalogue of Compact Sources
XXVIII
Catalogue of SZ Sources
XXIX

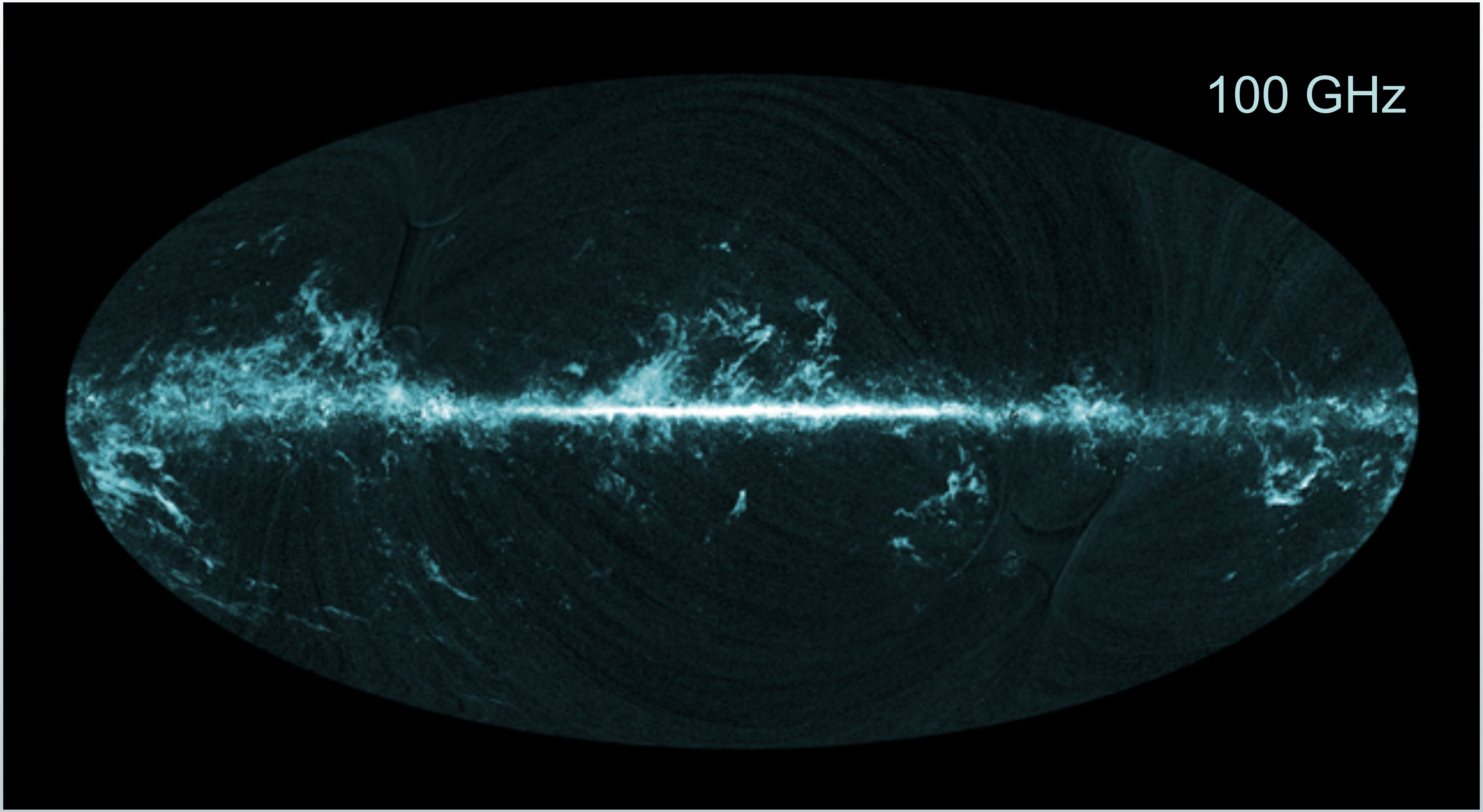
CMB Maps at Planck Frequencies



Planck Early Release 2011

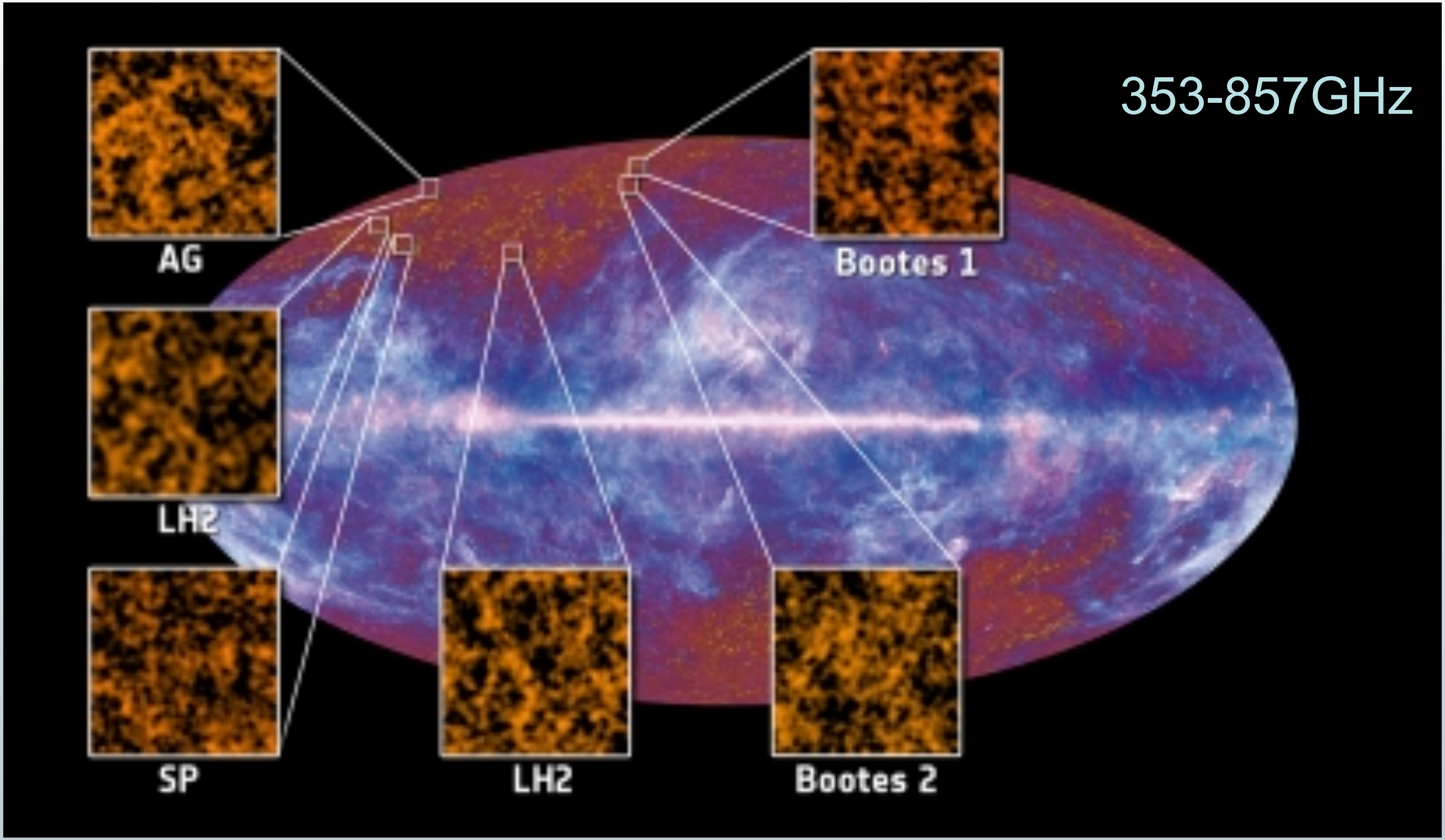
Credit: ESA, HFI & LFI consortia

Fringe benefit: First CO map of the full sky



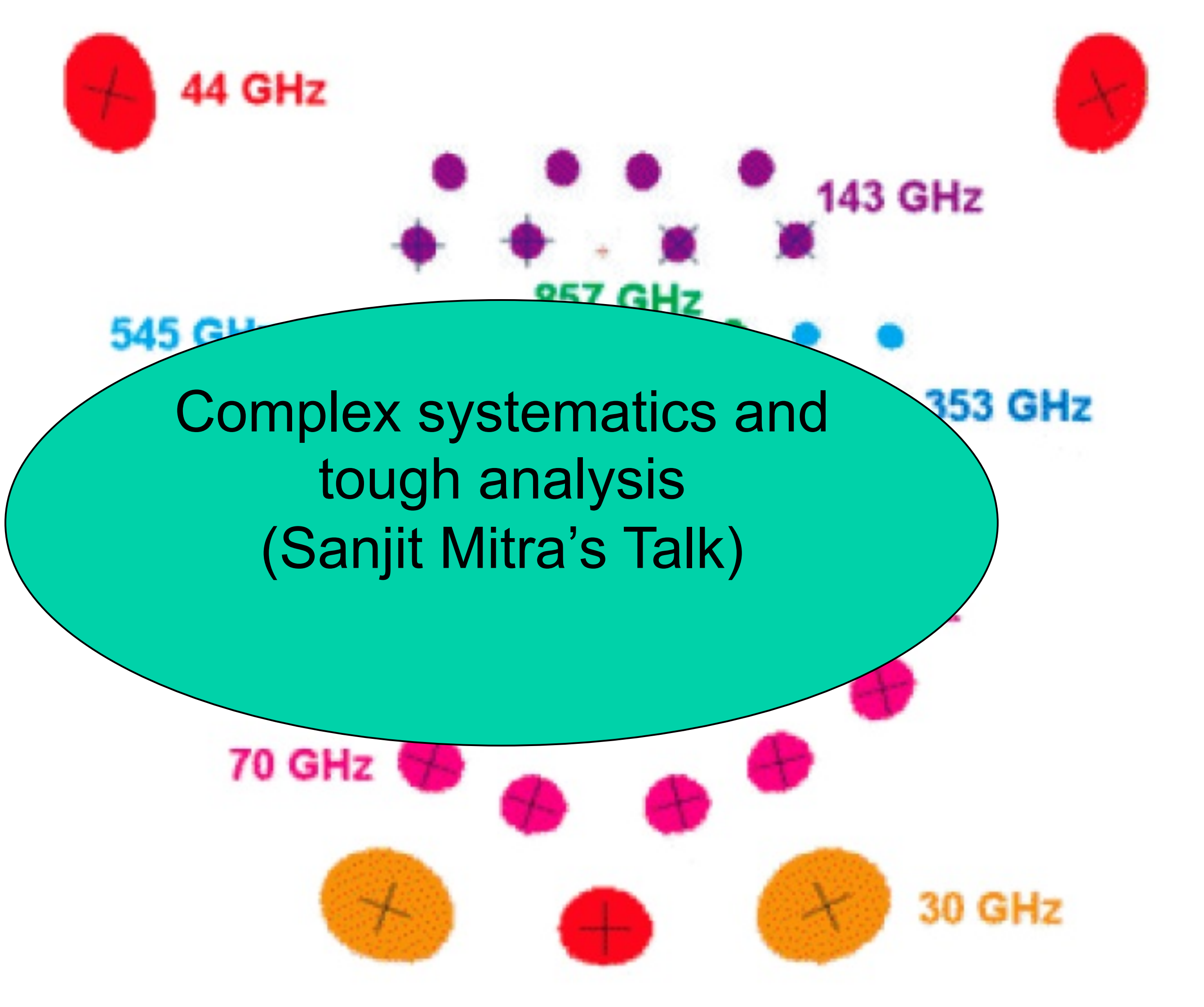
Location of cold molecular clouds in our galaxy

Fringe benefit: Cosmic Infrared background



Signature of star formation in the universe

Planck Focal Plane

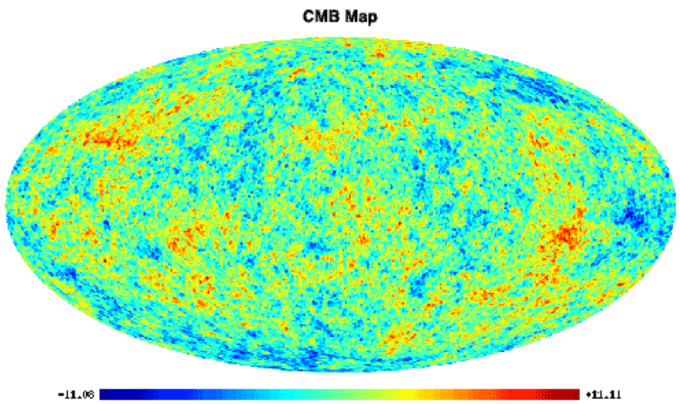


Complex systematics and tough analysis
(Sanjit Mitra's Talk)

Credit: ESA, HFI & LFI consortia

Gravitational Instability

Mildly Perturbed universe at z=1100



Cosmic matter content

Ω_{tot}

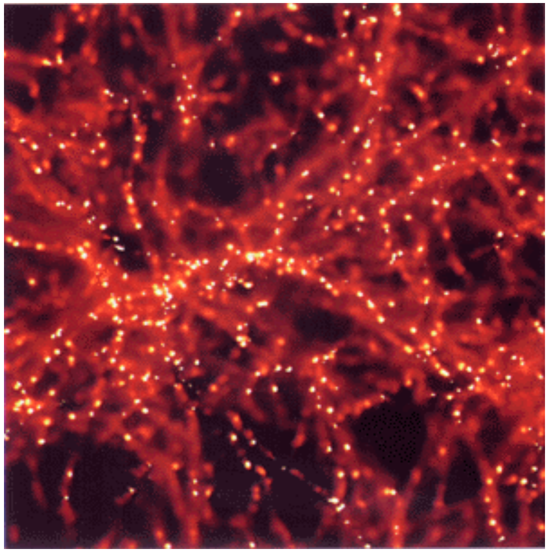
Ω_b

Ω_{DM}

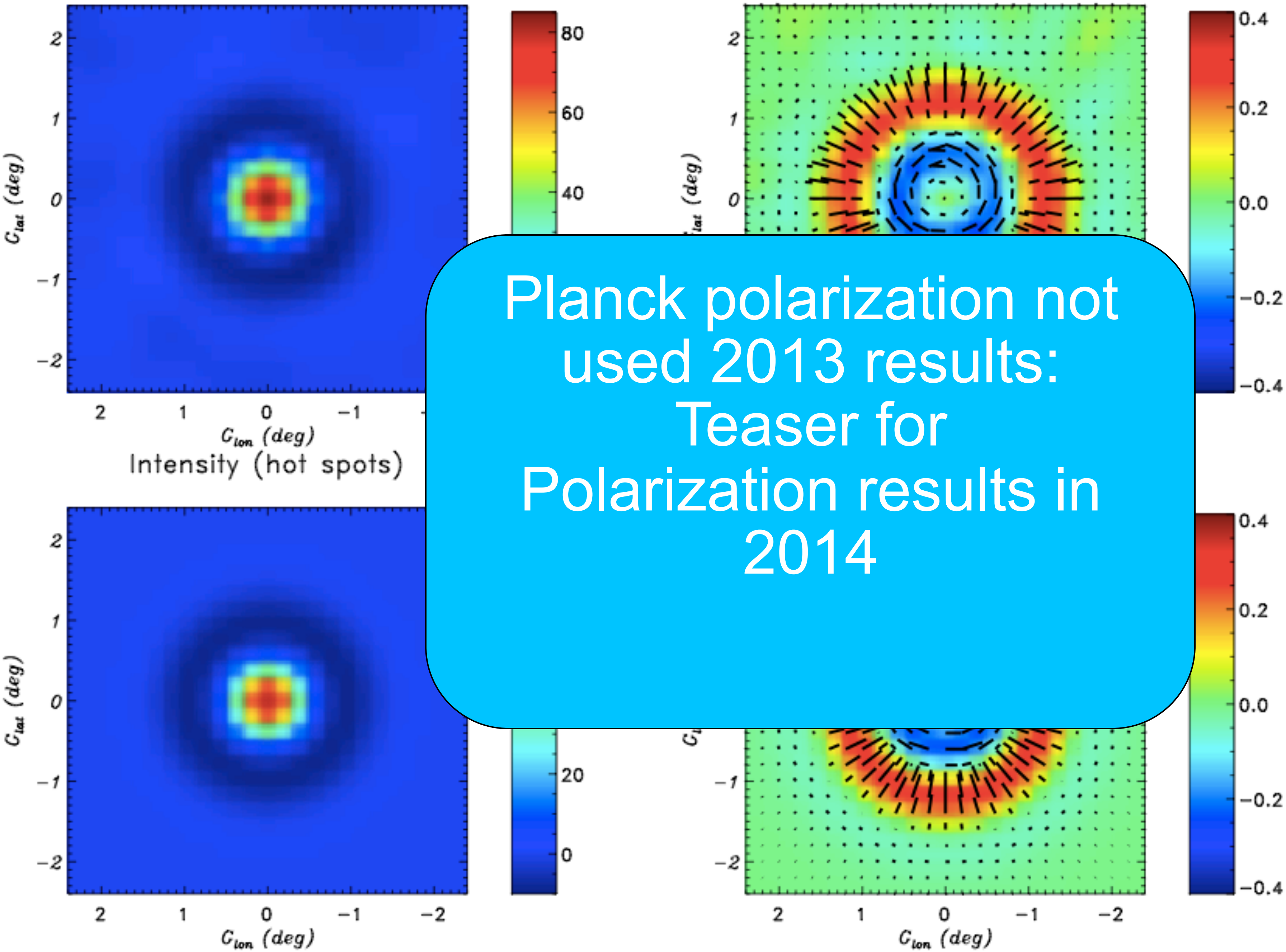
Ω_Λ

H_0

Present universe at z=0



(credit: Virgo simulations)



Planck polarization not used 2013 results:
Teaser for
Polarization results in
2014

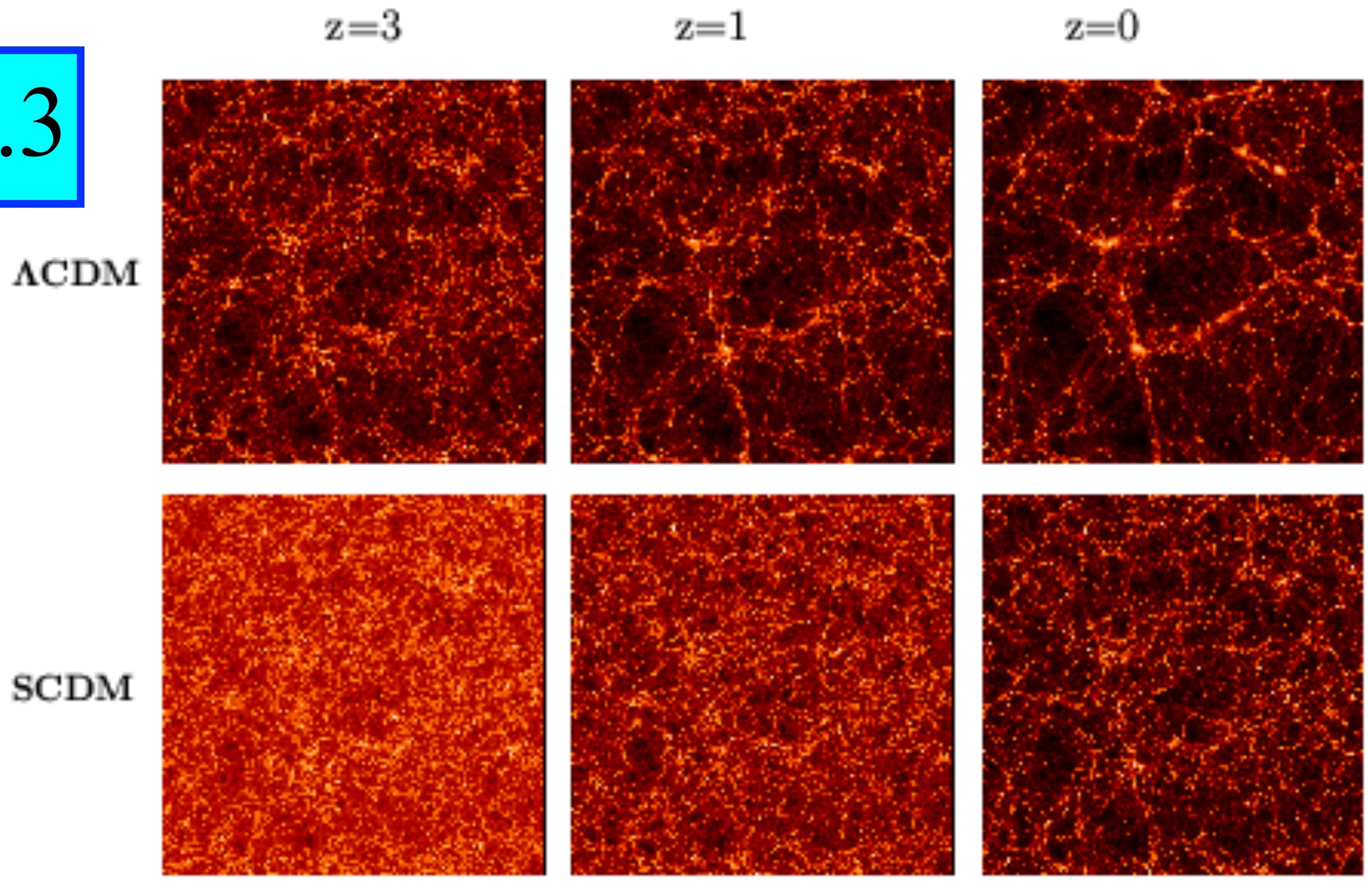
Gravitational Instability

Time →

$$\Omega_{0m} = 0.3$$

Cosmological constant + cold dark matter

Standard cold dark matter

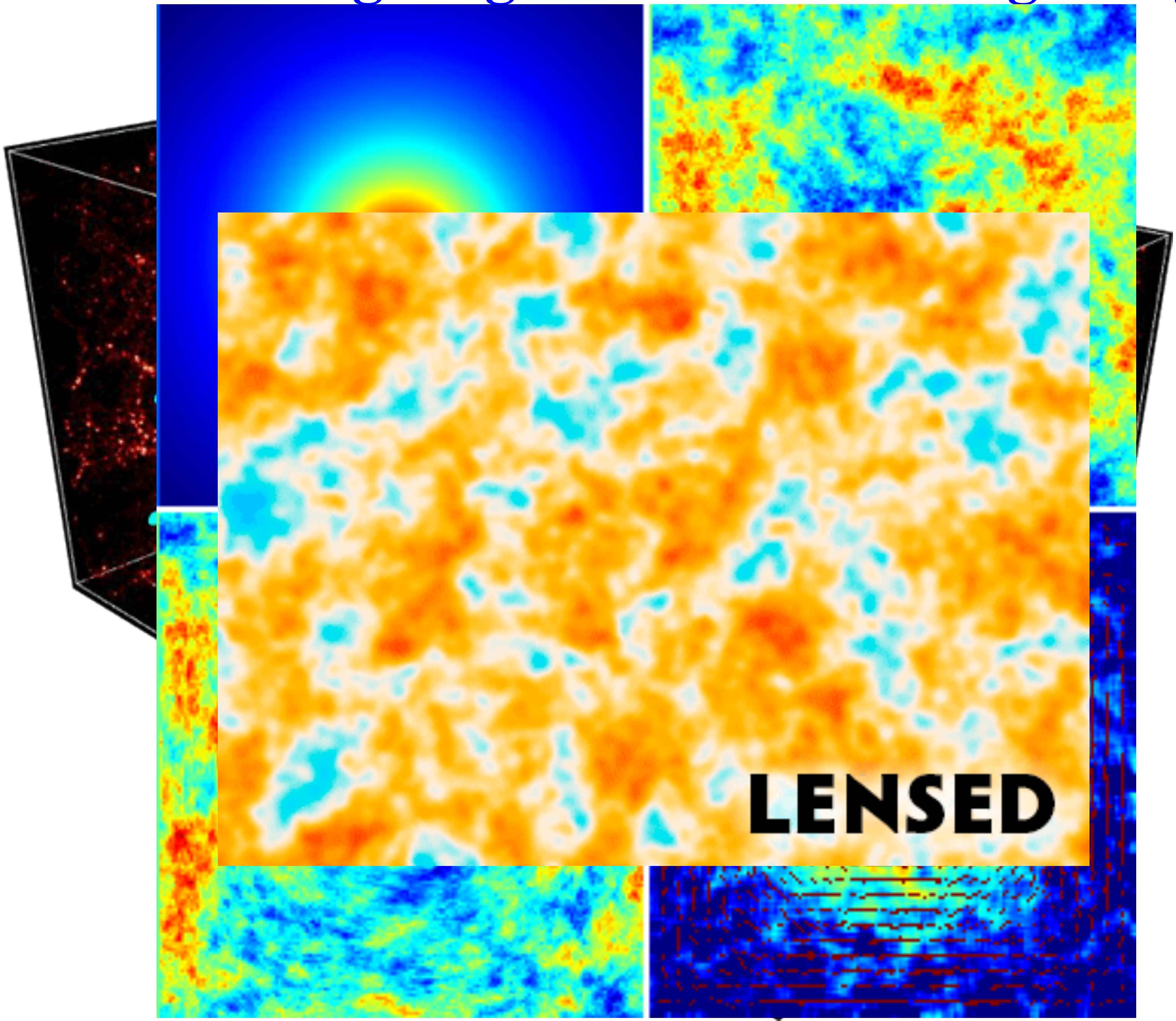


(quarter size) *(half size)* *(now)*

expansion →

(fig: Virgo simulations)

Weak lensing: Light deflects due to gravity



Projected matter density from Planck

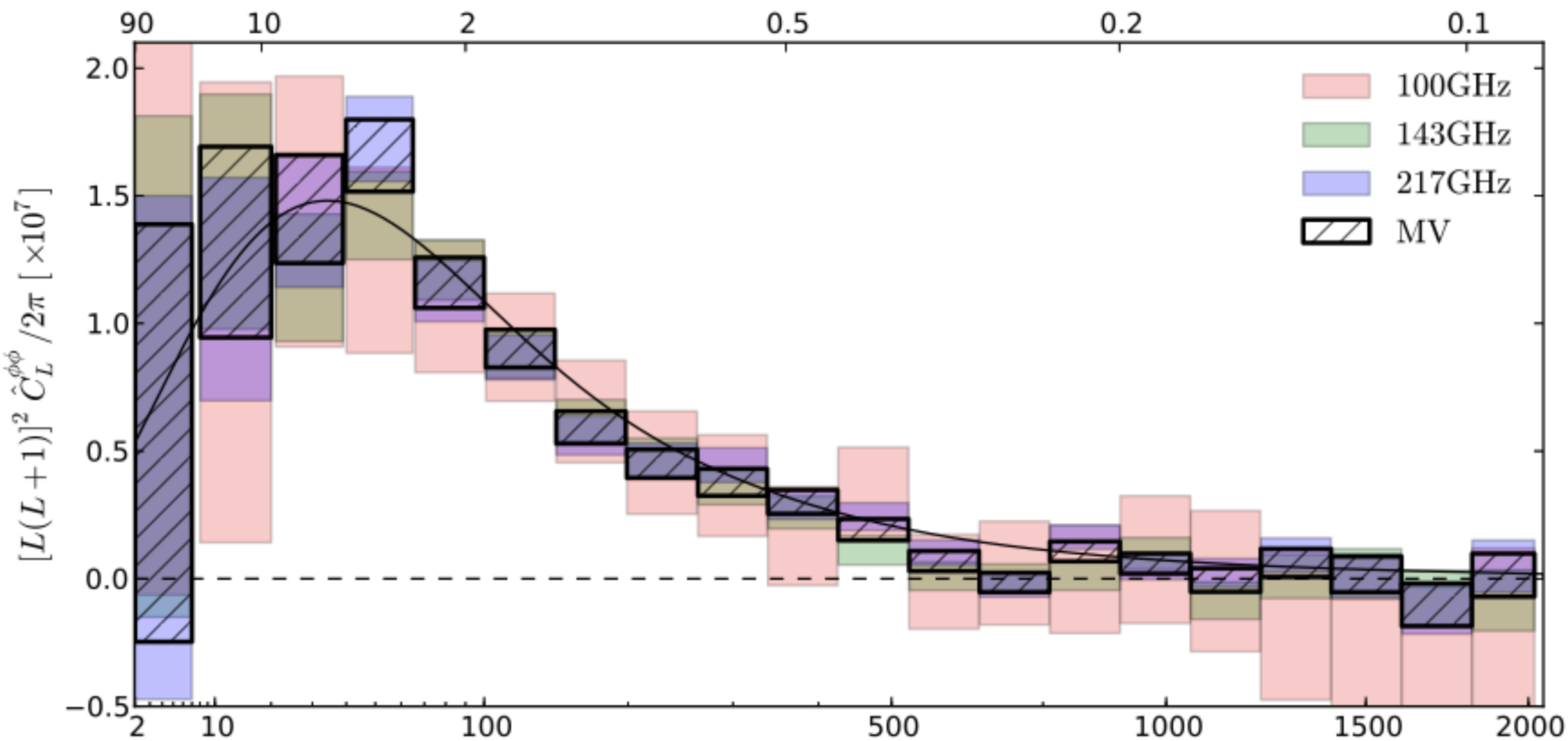
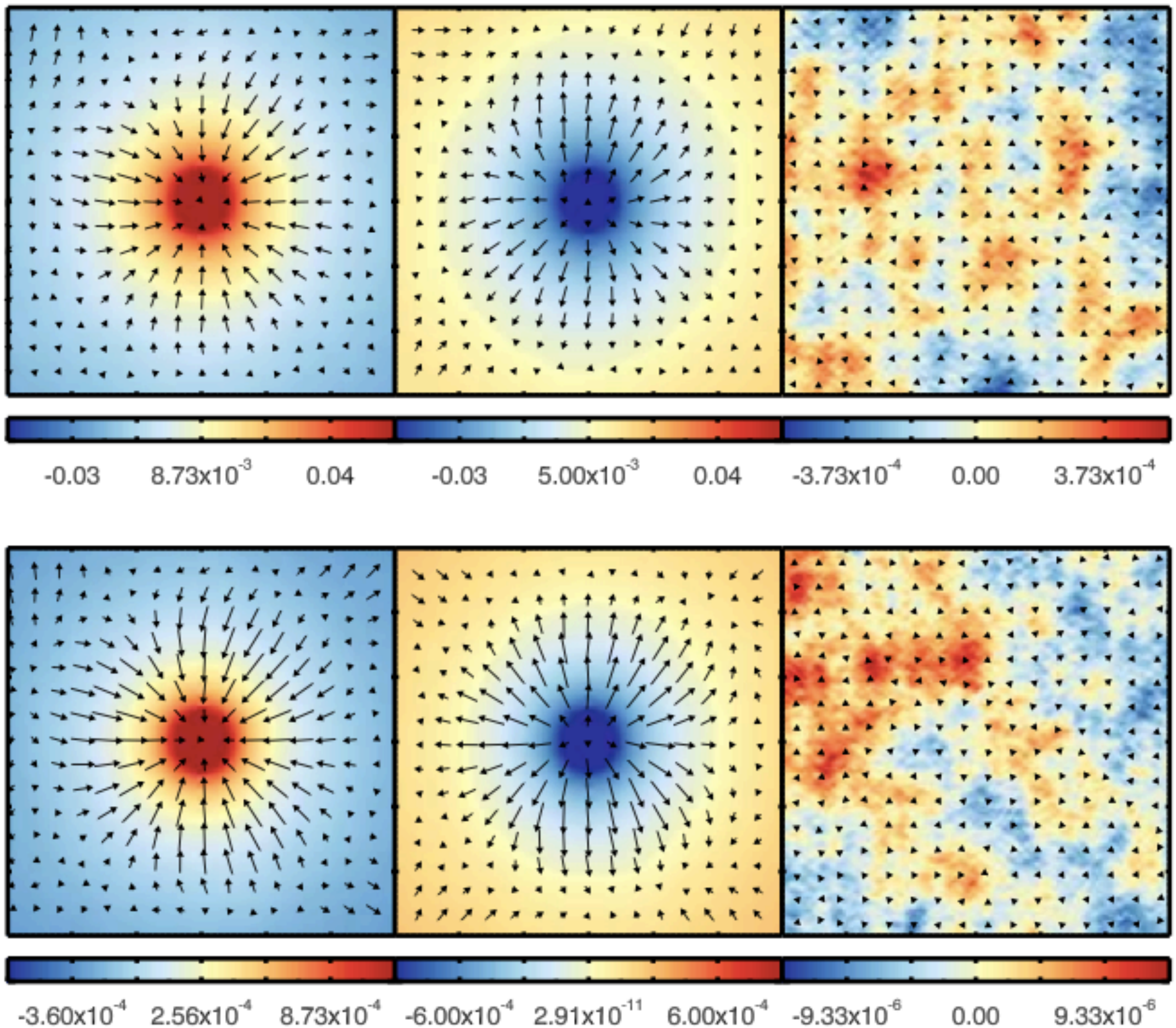


Fig. 18. Fiducial lensing power spectrum estimates based on the 100, 143, and 217 GHz frequency reconstructions, as well as the minimum-variance reconstruction that forms the basis for the *Planck* lensing likelihood.

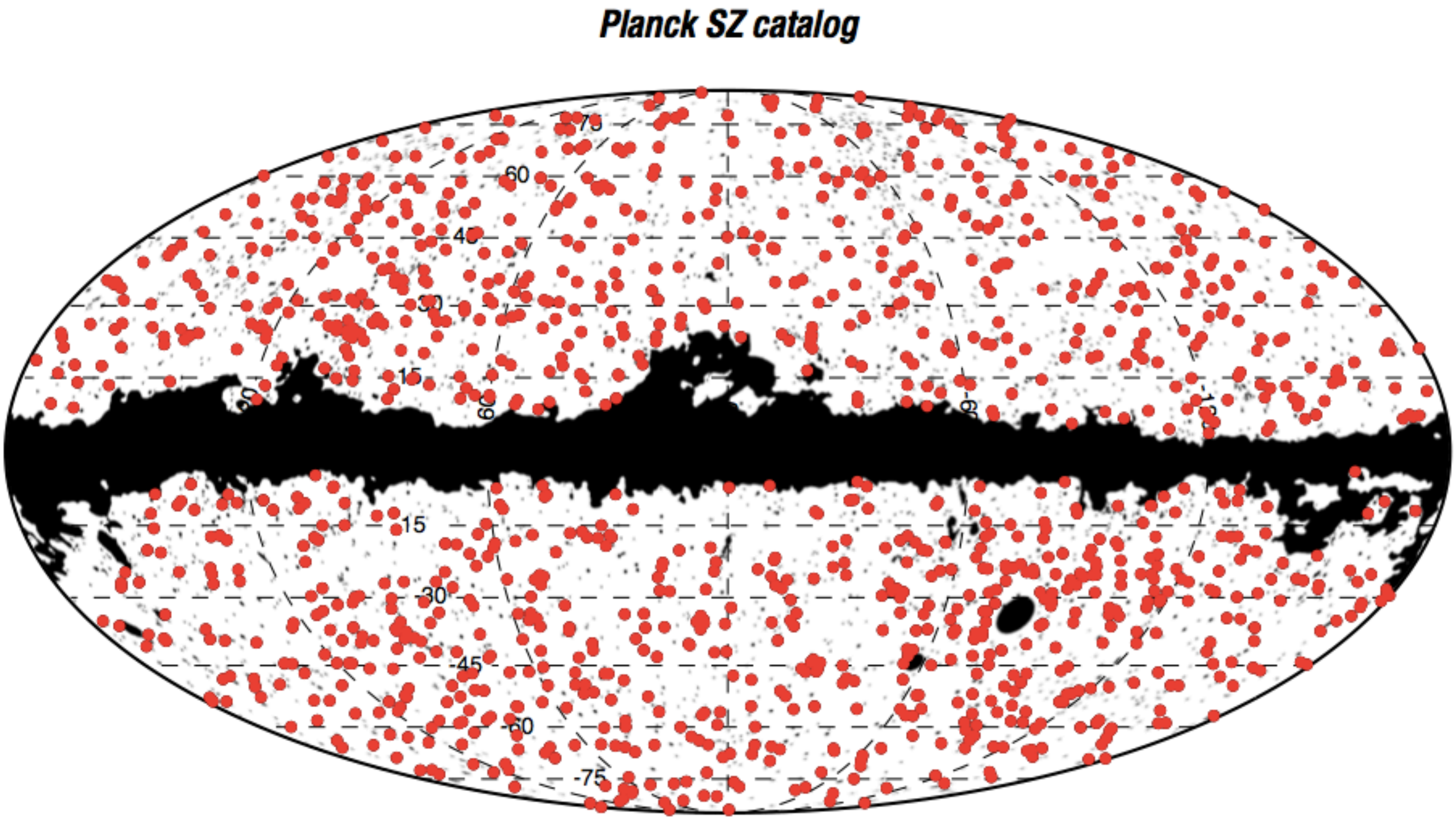
Stacked weak lensing field

857 GHz

545 GHz



SZ clusters from Planck



Simple… yet, an exotic universe

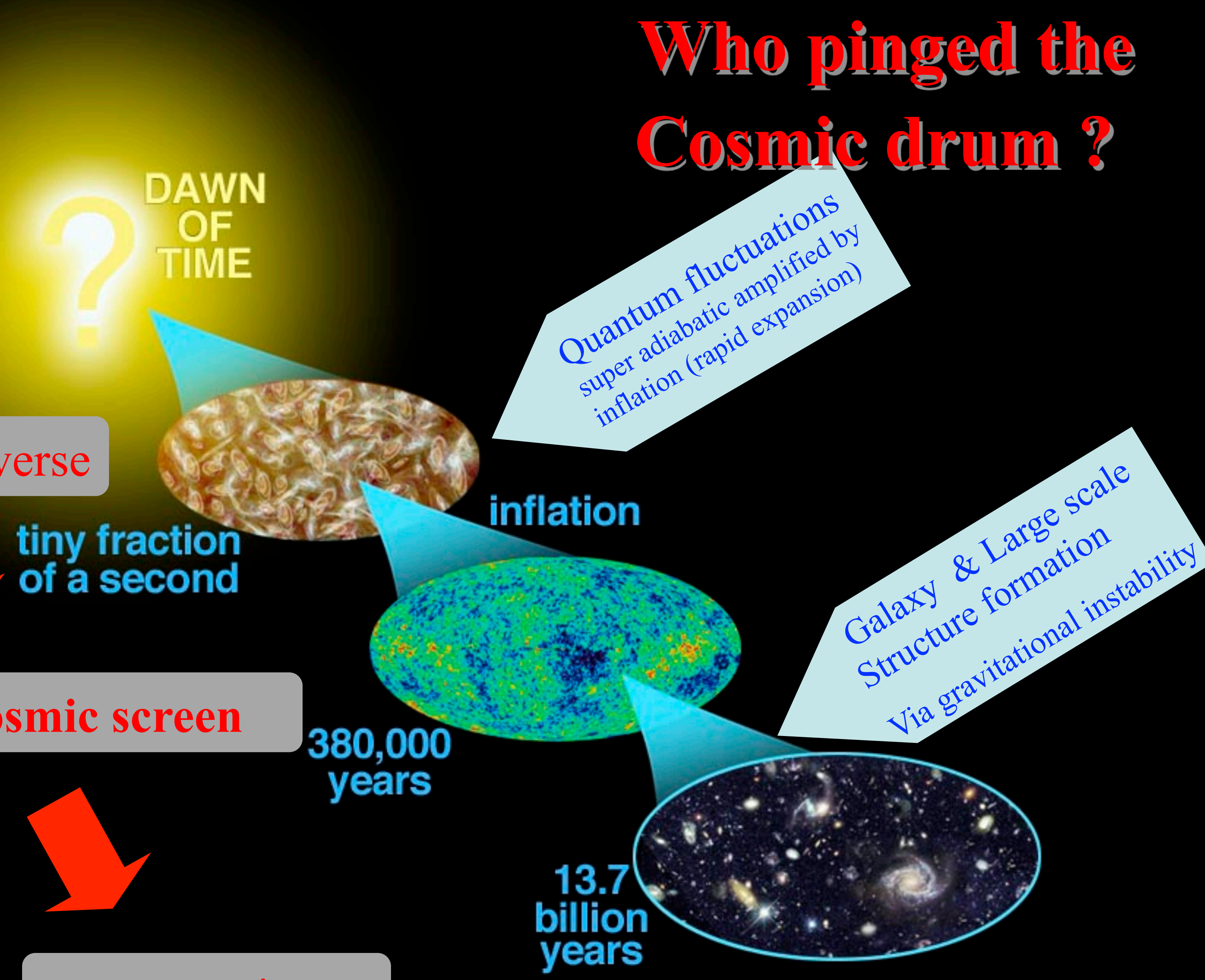
- 95% of the energy of the universe is in some exotic form
- Dark Matter: we cannot see it directly, only via its gravitational affect.
- Dark Energy: smooth form of energy which acts repulsively under gravity.
- Some new Ultra-high energy (possibly, fundamental) physics for generating primordial perturbations.

Who pinged the Cosmic drum ?

Early Universe

The Cosmic screen

Present Universe



Early Universe in CMB

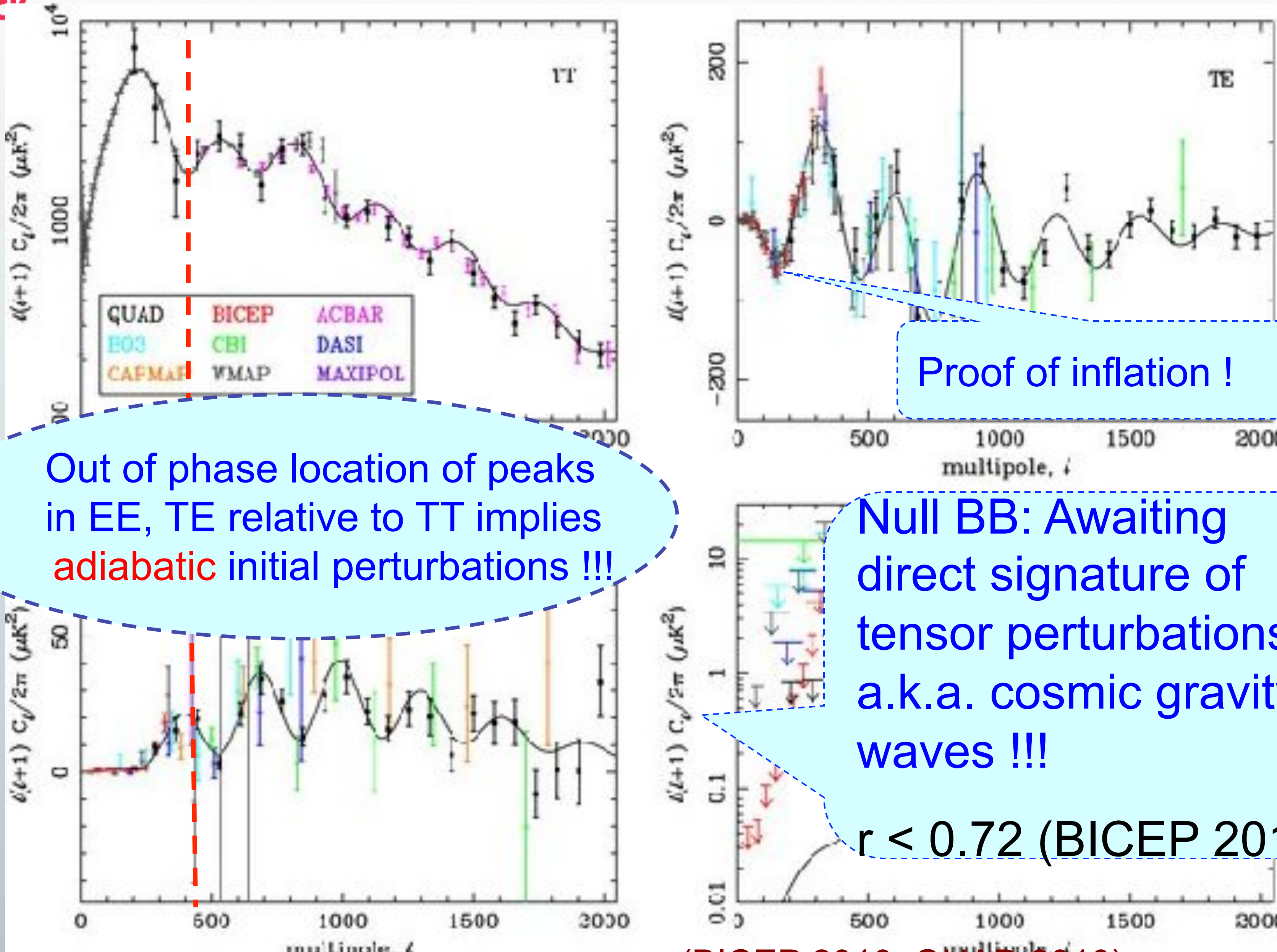
The Background universe

- Homogeneous & isotropic space: *Cosmological principle* ✓ ?
- Flat (Euclidean) Geometry ✓ … *but global topology?*

The nature of initial/primordial perturbations

- **Power spectrum :** *'Nearly' Scale invariant /scale free form* ✓
  … *but are there features ?*
- **Spin characteristics: (*Scalar) Density perturbations*** ✓
  … *cosmic (Tensor) Gravity waves ?*
- **Type of scalar perturbation:** *Adiabatic – no entropy fluctuations* ✓
- **Underlying statistics:** *Gaussian* ✓

Pre-Planck status of CMB Spectra



Proof of inflation !

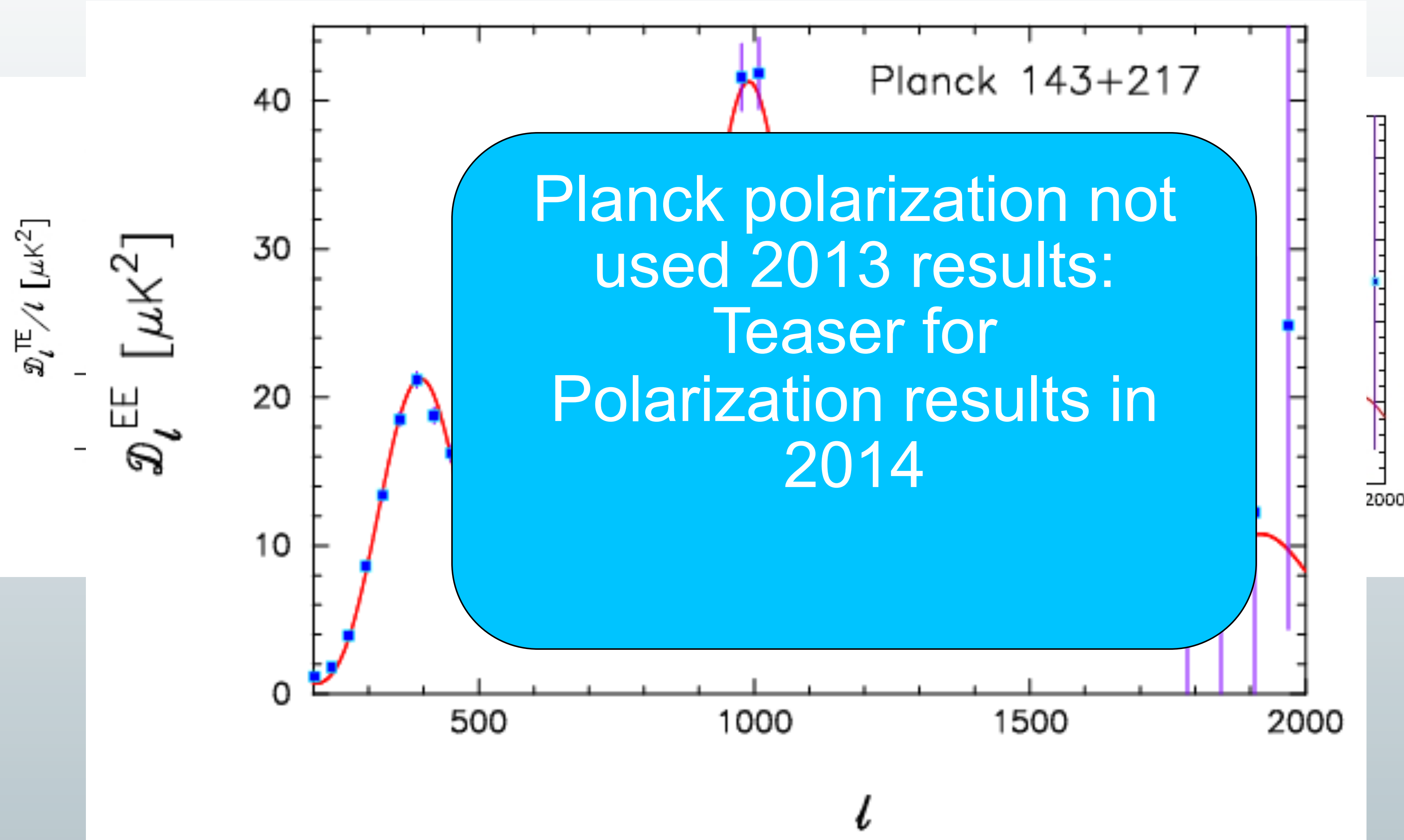
Out of phase location of peaks in EE, TE relative to TT implies adiabatic initial perturbations !!!

Null BB: Awaiting direct signature of tensor perturbations, a.k.a. cosmic gravity waves !!!

r < 0.72 (BICEP 2010)

(BICEP 2010, QUAD 2010)

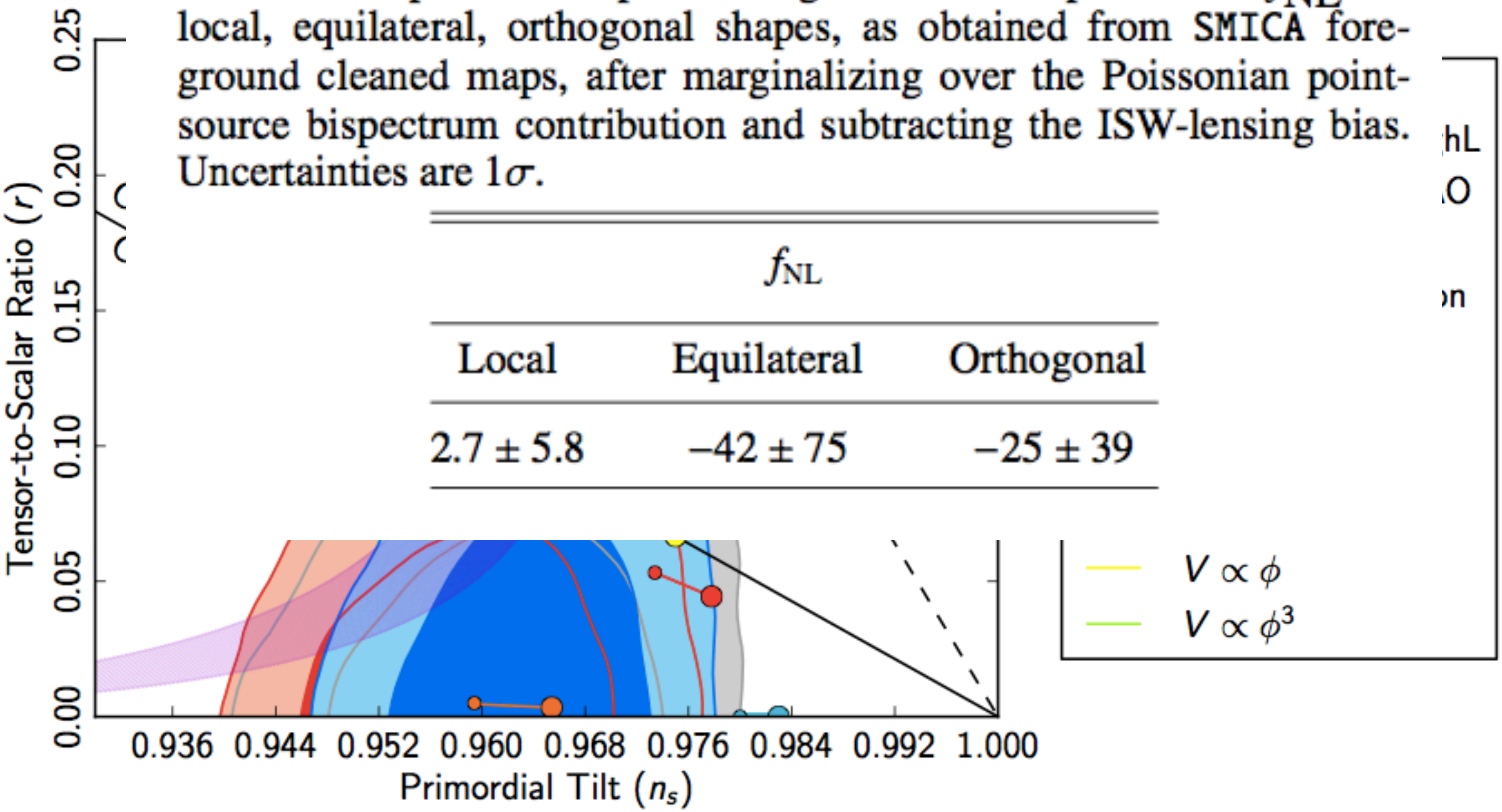
CMB Polarization spectra



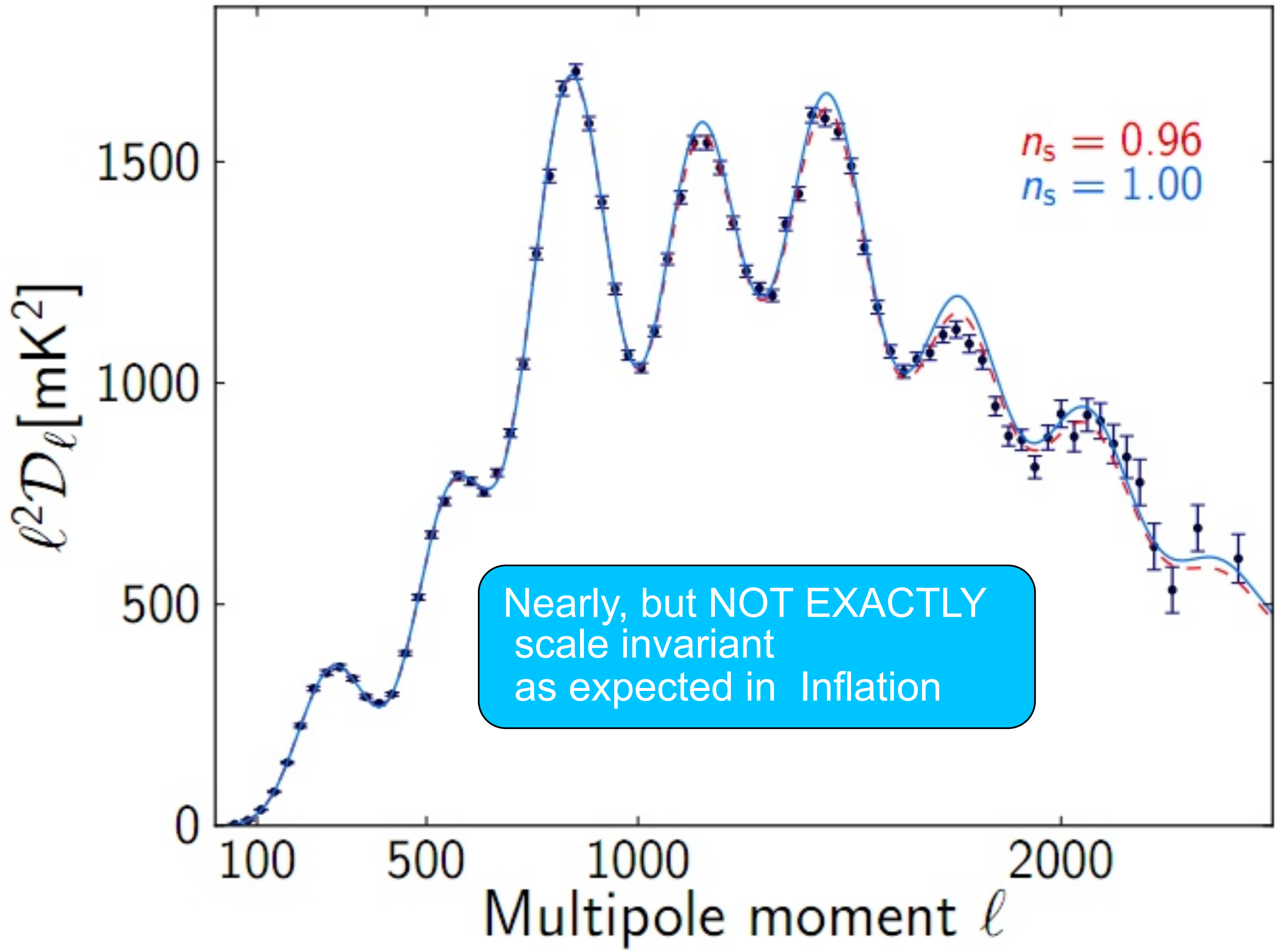
Status of Inflationary models

Table 10. Separable template-fitting estimates of primordial $f_{\rm NL}$ for local, equilateral, orthogonal shapes, as obtained from `SMICA` foreground cleaned maps, after marginalizing over the Poissonian point-source bispectrum contribution and subtracting the ISW-lensing bias. Uncertainties are 1σ.

$f_{\rm NL}$		
Local	Equilateral	Orthogonal
2.7 ± 5.8	-42 ± 75	-25 ± 39

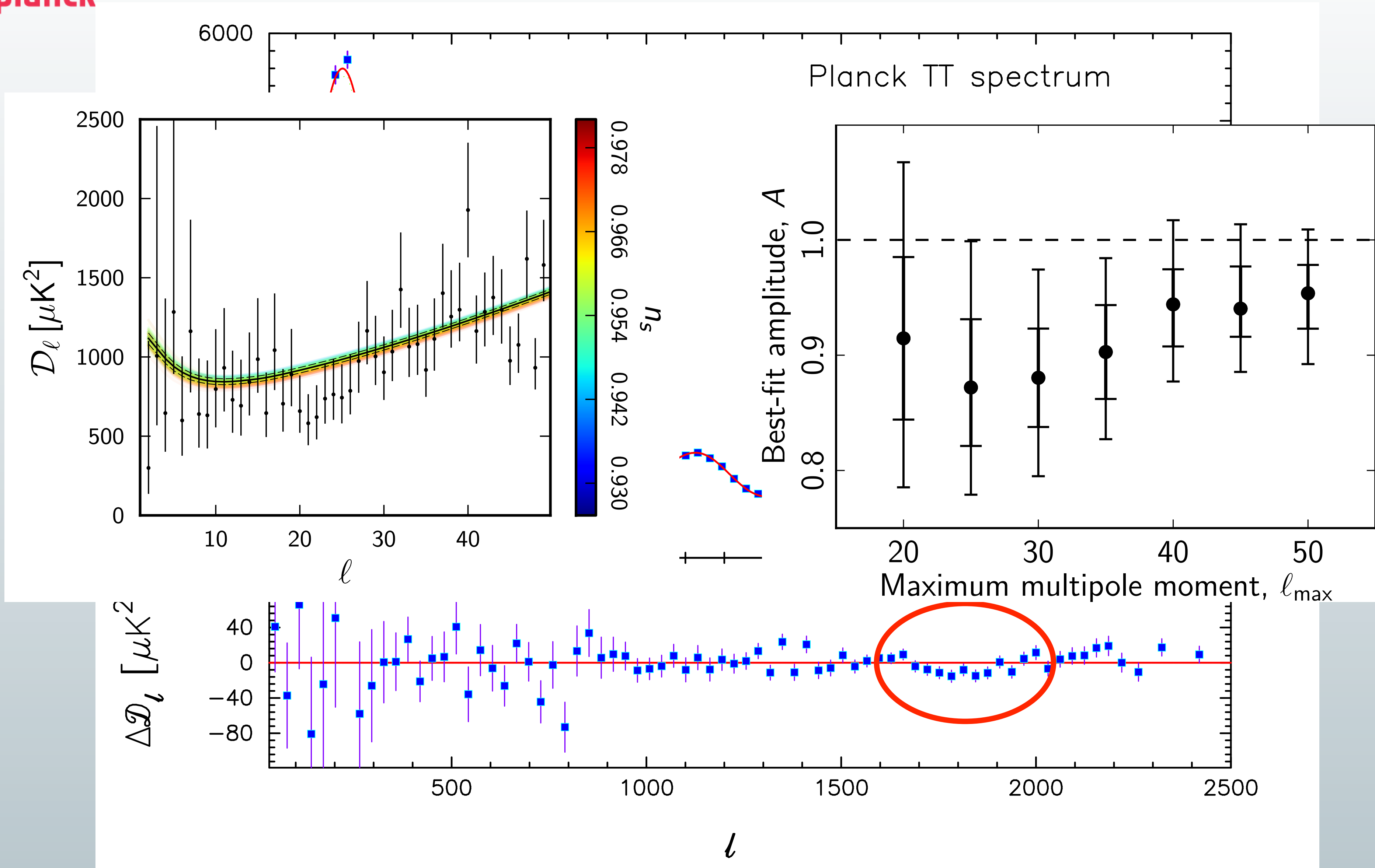


Spectral index of perturbations



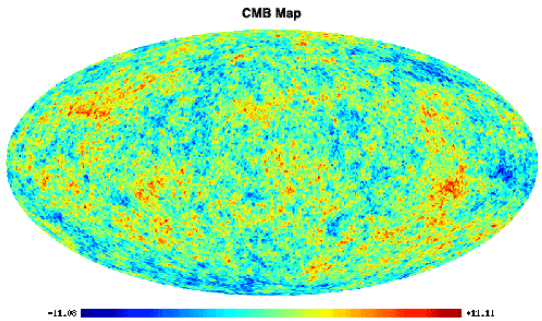
Nearly, but NOT EXACTLY scale invariant as expected in Inflation

Room for improved fit?



Statistics of CMB

CMB Anisotropy Sky map => Spherical Harmonic decomposition



$$\Delta T(\theta,\phi) = \sum_{l=2}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

Gaussian CMB anisotropy completely specified by the ***angular power spectrum*** IF

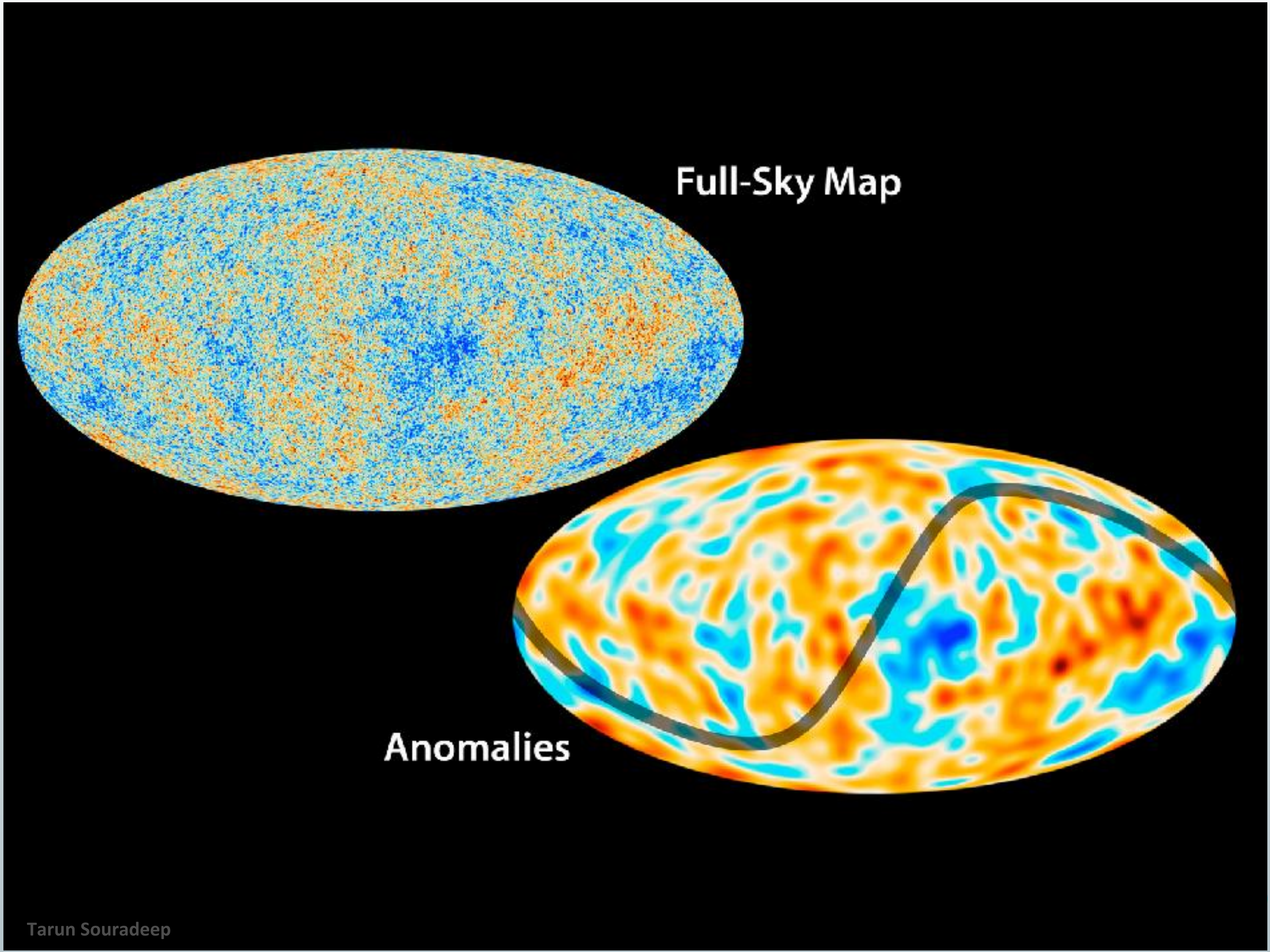
Statistical isotropy

$$\langle a_{lm}\, a^{*}_{l'm'} \rangle = C_l\ \delta_{ll'}\delta_{mm'}$$

=>Correlation function C(n,n')=<ΔT(n) ΔT(n')>

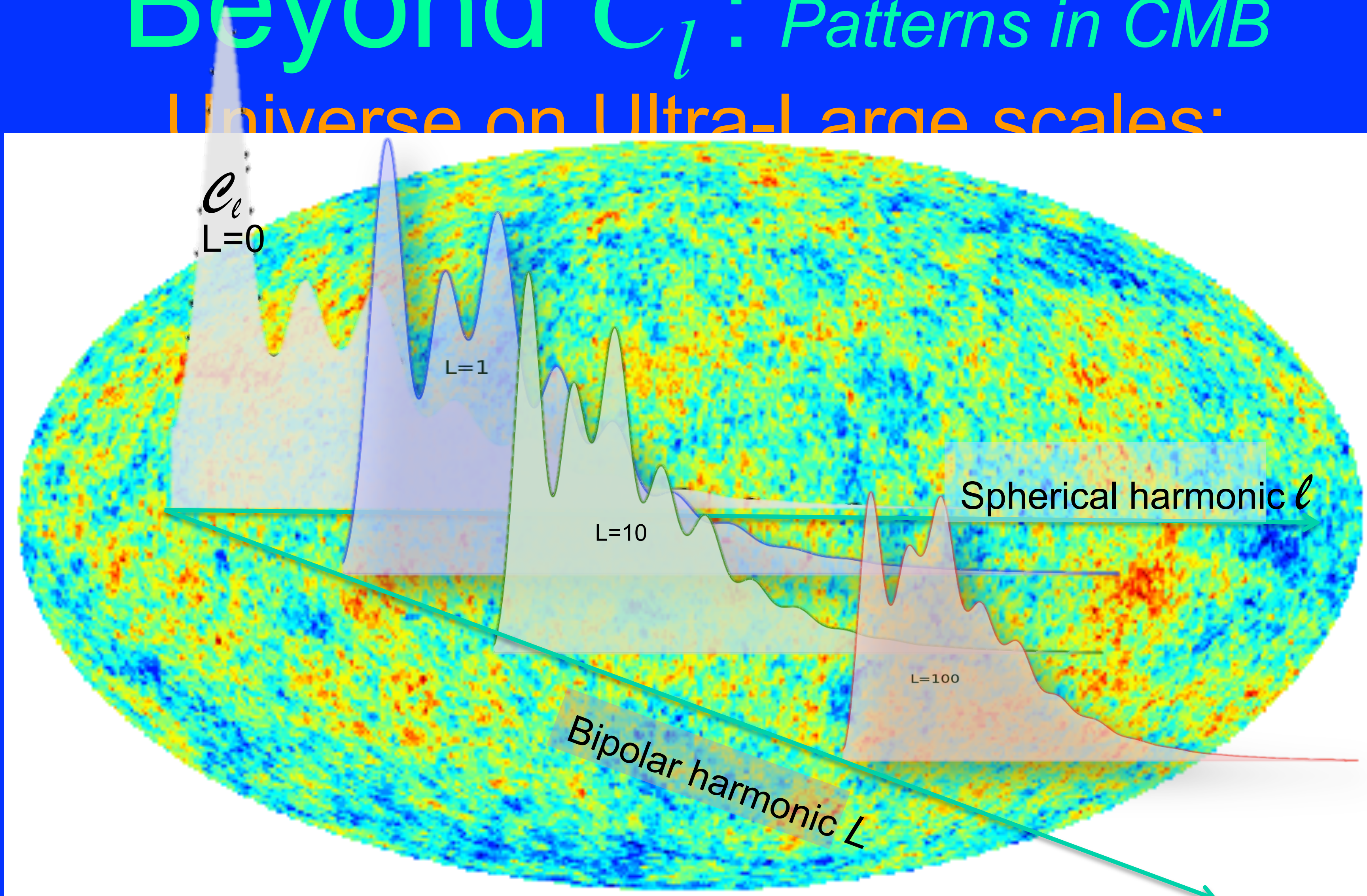
is **Rotationally Invariant**

Hemispherical asymmetry



Beyond C_l : *Patterns in CMB*

Universe on Ultra-Large scales:



BipoSH : Natural generalization of C_ℓ

Bipolar Spherical Harmonic representation

Amir Hajian & Souradeep 2003

$$C(n_1 \bullet n_2) = \sum \frac{2l+1}{4\pi} C_l P_l(n_1 \bullet n_2)$$

$$C_\ell = \langle a_{\ell m} a^*_{\ell m} \rangle$$

$$C(\hat{n}_1, \hat{n}_2) = \sum_{l_1 l_2 LM} A^{LM}_{l_1 l_2} \{Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2)\}_{LM}$$

Bipolar spherical harmonics.

BipoSH
Coefficients

$$A^{LM}_{l_1 l_2} = \sum_m \left\langle a^*_{l_1 m} a_{l_2 m+M} \right\rangle C^{LM}_{l_1 m_1 l_2 m_{+M}}$$

Linear combination of off-diagonal elements
BipoSH provide complete representation of SH space correlation matrix

BipoSH : *Natural* generalization of C_ℓ

Bipolar Spherical Harmonic representation

Amir Hajian & Souradeep 2003

A *complete* representation of two-point correlation

- Modulation of CMB sky $\Delta T(\hat{n}) = [1 + M(\hat{n})]\Delta T^{\rm SI}(\hat{n})$

- non-uniform variance (e.g., inhomo. noise, anomaly in XXIII)

$$\langle \Delta T(\hat{n})^2 \rangle = \mathcal{R}(\hat{n}) = \sum_{LM} \mathcal{R}_{LM} Y_{LM}(\hat{n})$$

$$\mathcal{R}_{LM} = \sum_{l_1 l_2} A^{LM}_{l_1 l_2} \frac{\Pi_{l_1}\Pi_{l_2}}{\sqrt{4\pi}\Pi_L} \mathcal{C}^{L0}_{l_1 0 l_2 0}$$

- Weak lensing
  - *Scalar & Tensor lens*

    Books, Kamionkowski, TS 2012

  - *Weak lensing of non-SI map affects C_ℓ*

$$A^{(+)LM}_{\ell\ell'} = \phi_{LM}\ \left[C_\ell G^L_{\ell\ell'} + (\ell \leftrightarrow \ell')\right]$$

$$A^{(-)LM}_{\ell\ell'} = \Omega_{LM}\ \left[C_\ell G^L_{\ell\ell'} - (\ell \leftrightarrow \ell')\right]$$

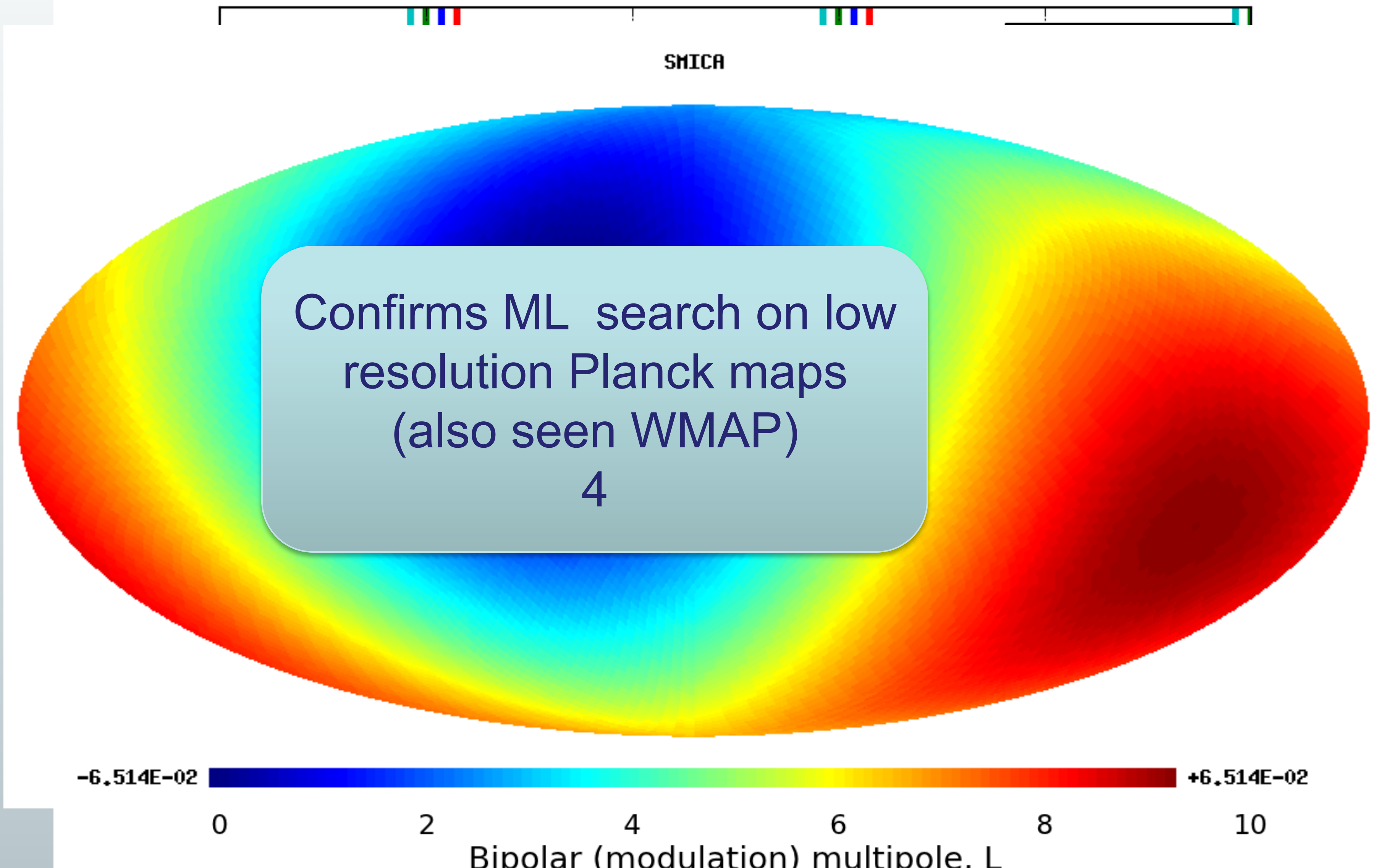
- Beam non-circularity

  Joshi, Das, Rotti, Mitra, TS 2012

$$A^{L0}_{l_1 l_2} = \sum_{l'} C_{l'} \sum_{L_1 L_2} B^{L_1 0}_{l_1 l'} B^{L_2 0}_{l_2 l'} (-1)^{l_1+L_1} \sqrt{(2L_1+1)(2L_2+1)} C^{L0}_{L_1 0 L_2 0} \begin{pmatrix} l' & l_2 & L_2 \\ L & L_1 & l_1 \end{pmatrix}$$

- Cosmic topology, Magnetic fields , Lorentz violation…

BipoSH Power spectrum of reconstructed modulation maps.

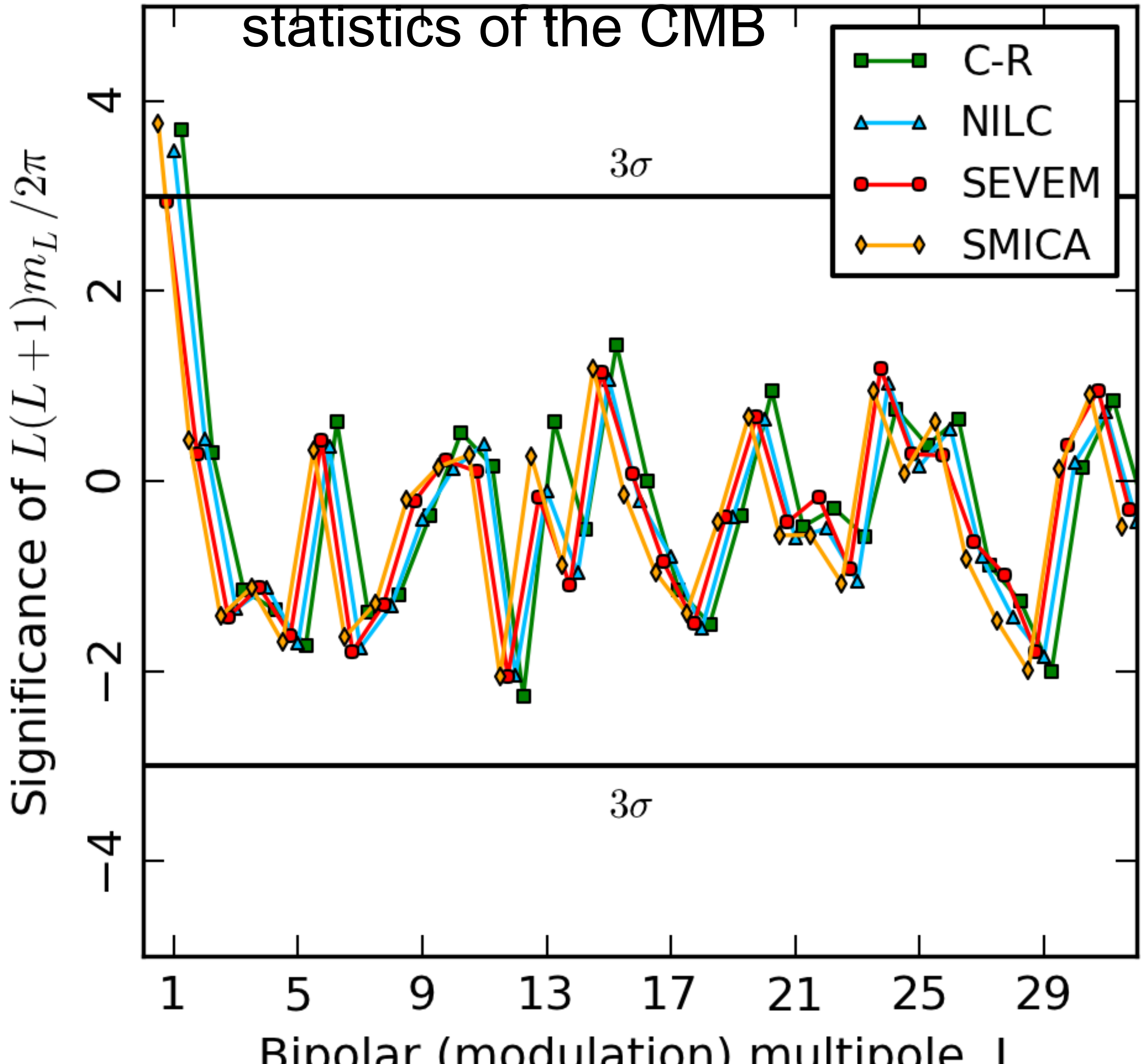


Confirms ML search on low resolution Planck maps (also seen WMAP)

4

Significance of Modulation Power.

Planck 2013 results. XXIII. Isotropy and statistics of the CMB



I

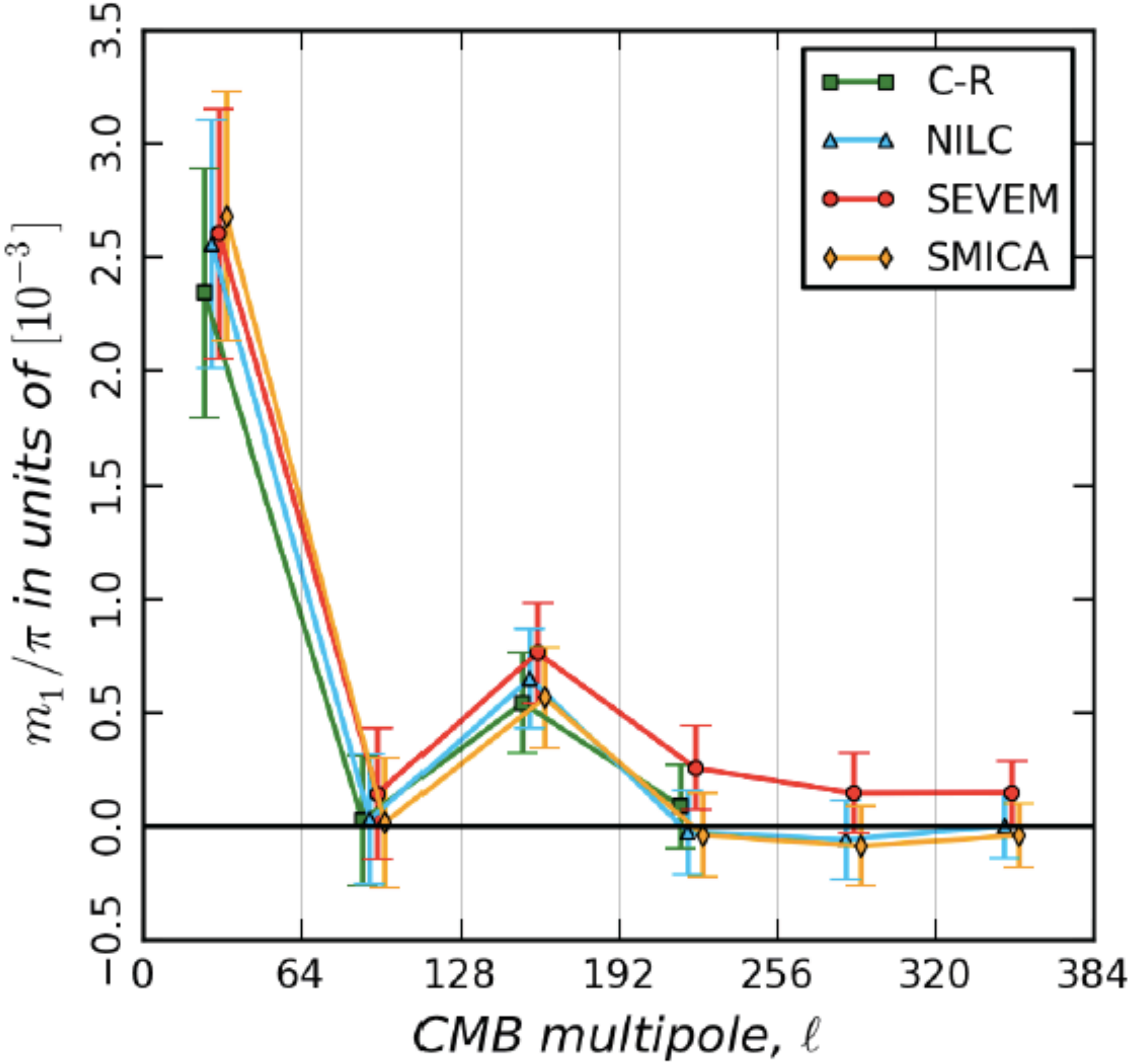
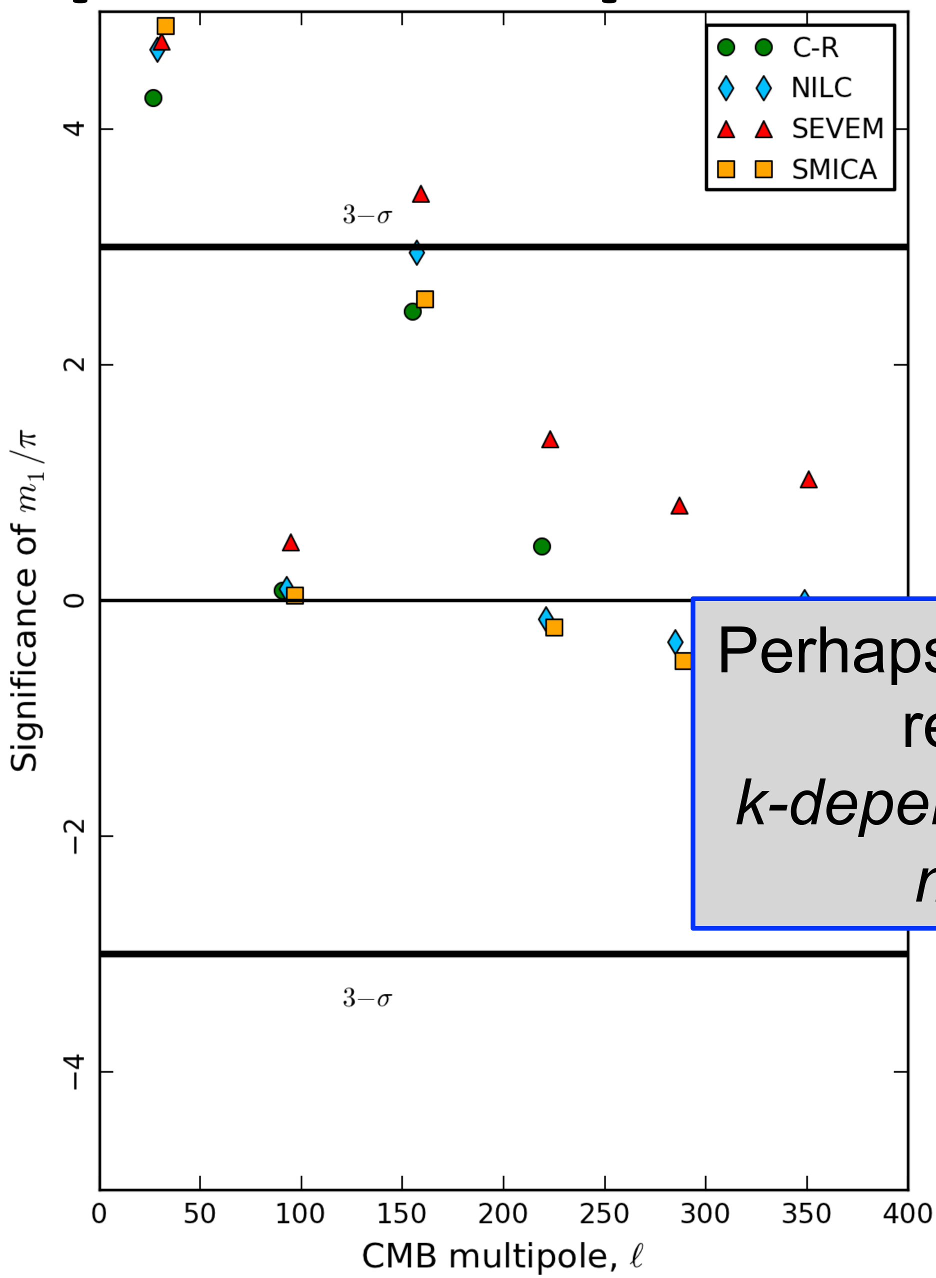


Fig. 33. The CMB multipole dependence of the BipoSH (modulation)

Scale dependent dipole modulation.



$A \to A(\ell)$

Perhaps Physically more reasonable?
k-dependent modulation mechanism

BIPOLAR measurements by WMAP-7 team

(Bennet et al. 2010)

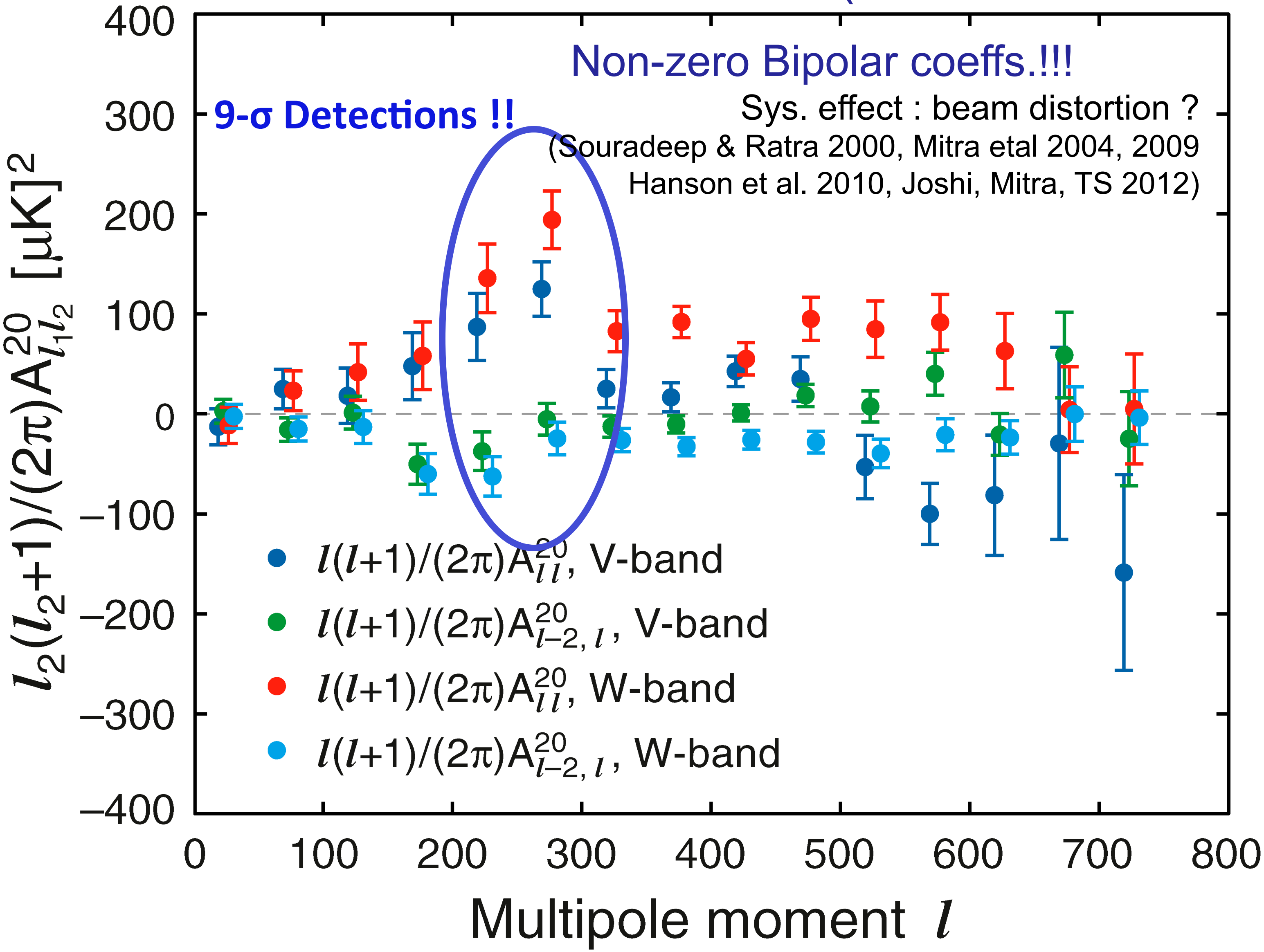
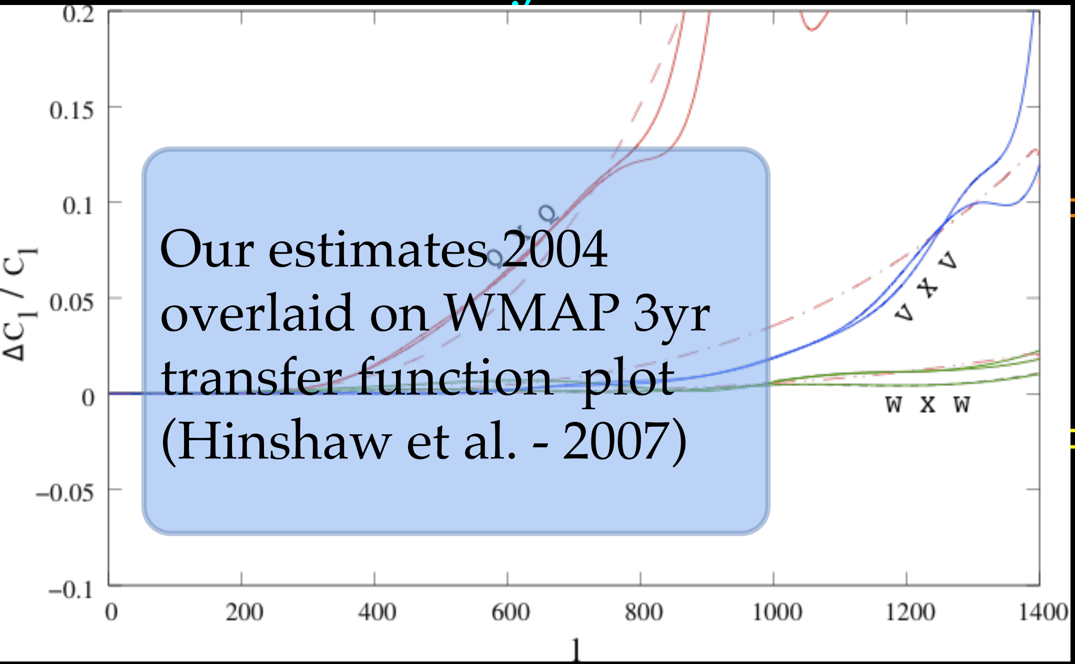


Image Credit: NASA / WMAP Science Team

Non-circular Beam Systematics

$$\Delta T^{\rm obs}(\hat{n}) = \int d\Omega \Delta T(\hat{n}') B(n', n)$$

TS&Ratra 2000, Mitra, Sengupta,TS 2004,….



$$B(\hat{n}', \hat{n}) \equiv B(\hat{n} \cdot \hat{n}')$$

$$\Rightarrow C_l^{\rm obs} = B_l^2 C_l$$

$$B(\hat{n}', \hat{n}) \not\equiv B(\hat{n} \cdot \hat{n}')$$

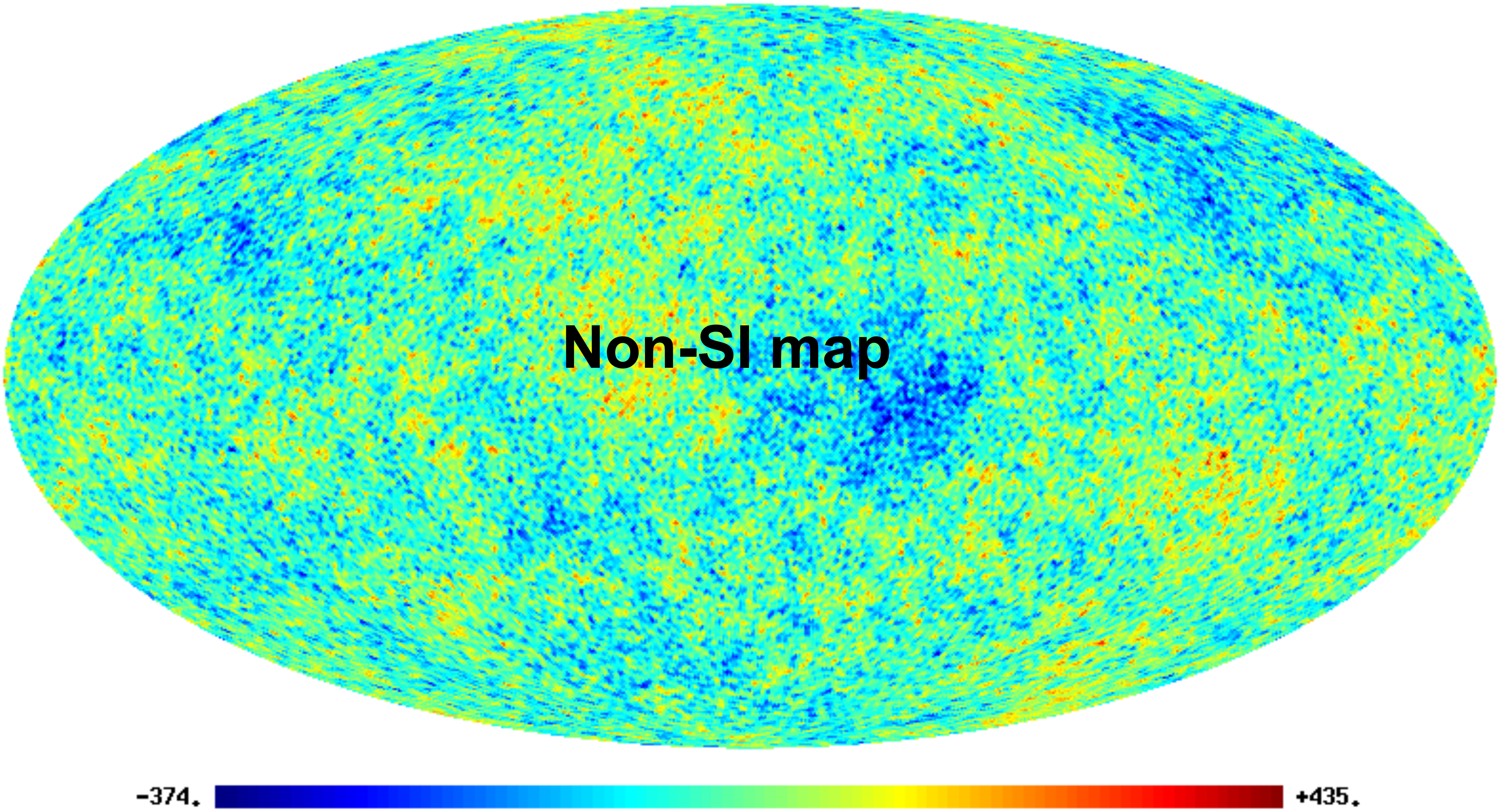
$$\Rightarrow C_l^{\rm obs} = \sum_{l'} A_{ll'}^2 C_{l'}$$

- Non-circular beam induces off-diagonal correlations in the covariance matrix.
- **BipoSH allows WMAP beam non-circularity to be detected at 9-σ !!!**

(Nidhi Joshi, Santanu Das, Aditya Rotti, Sanjit Mitra, TS : arXiv:1210.7318)

Non-SI by eye

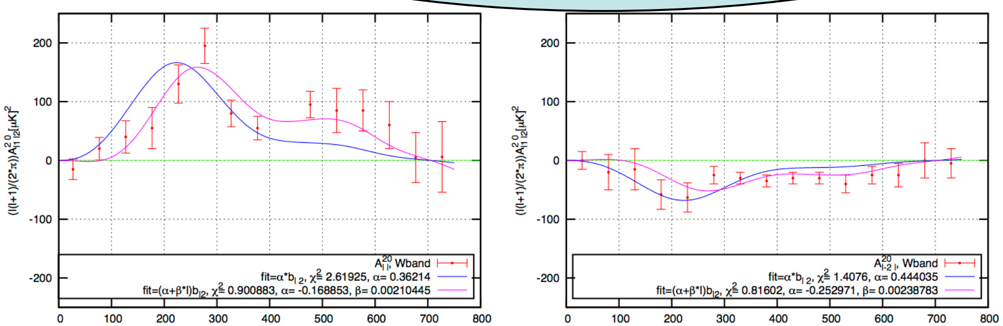
(a very subtle effect !!!)



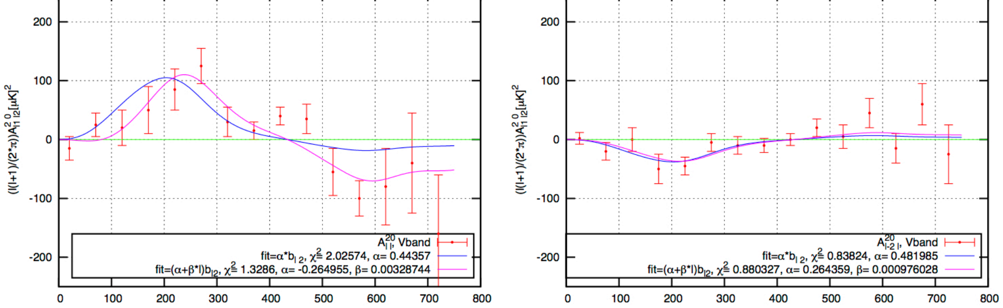
Non-SI map generation for given BipoSH: Suvodip Mukherjee

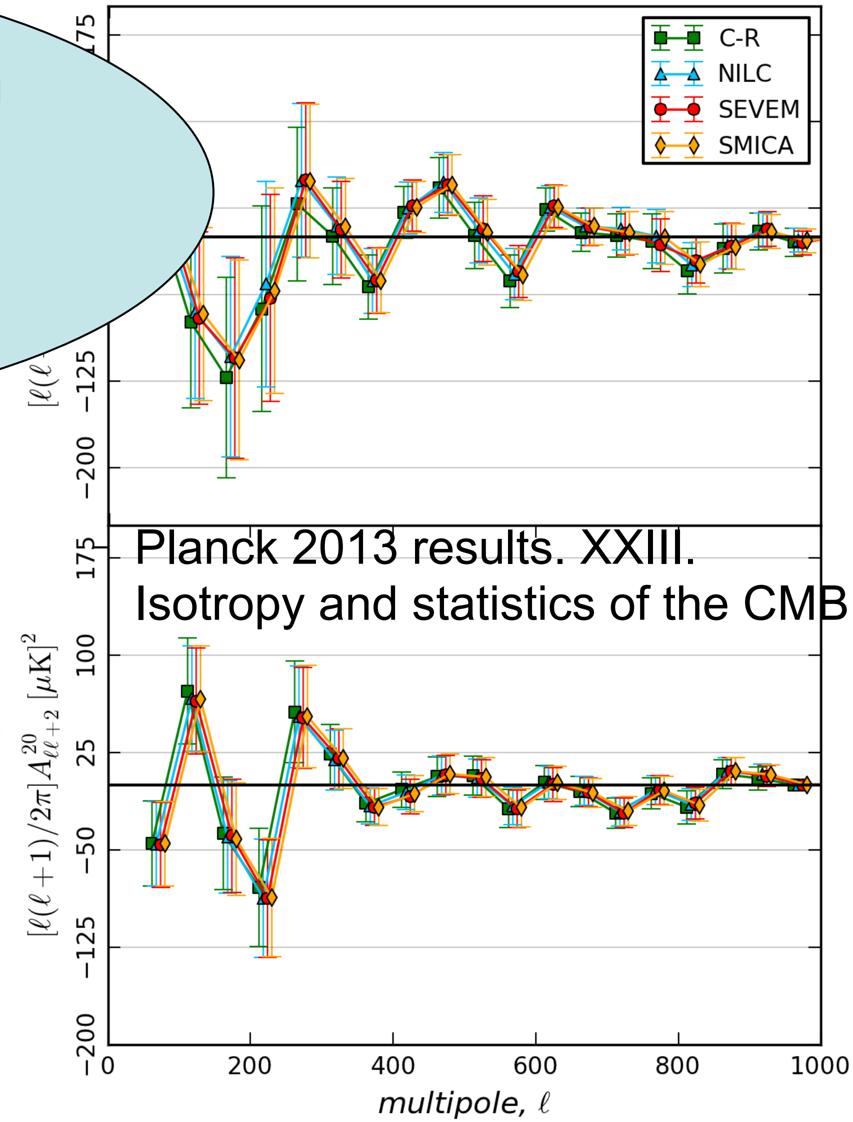
Quadrupolar BipoSH anomaly in WMAP-7

Beam asymmetry correction for Planck used FebeCoP (Sanjit Mitra @JPL/ IUCAA)



(Nidhi Joshi, Santanu Das, Aditya Rotti, Sanjit Mitra, TS : arXiv:1210. 7318)





Planck 2013 results. XXIII. Isotropy and statistics of the CMB

Summary

Thank you !!!

- Planck confirms with high confidence the 'simplest' version of cosmology & structure formation
- This cosmos is exotic enough – DM, DE, quantum origin of structure !!!
- Possible surprise from unexpected quarter –