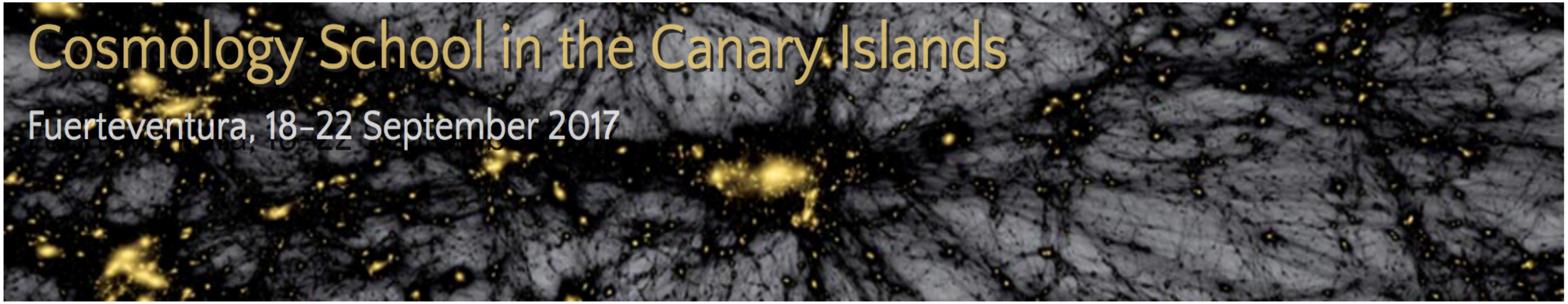


Theory of CMB polarization and current status of polarization experiments

José Alberto Rubiño Martín

(IAC, Tenerife)

RADIO FOREGROUNDS

Bibliography

Books:

- ***Cosmological Inflation and Large Scale Structure.*** Liddle & Lyth (CUP 2000).
- ***Cosmology.*** S Weinberg (Oxford Univ. Press 2008)***.***
- ***The Cosmic Microwave Bakcground.*** Durrer (CUP 2008).
- ***The primordial density perturbation.*** Lyth & Liddle (CUP 2009)
- **The Cosmic Microwave Background: from quantum fluctuations to the present Universe.** Eds. Rubiño-Martin, Rebolo, Mediavilla (Cambridge Univ. Press 2010).

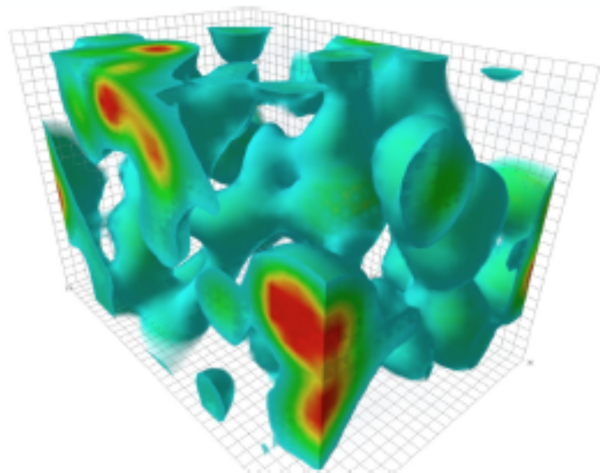
Papers (Polarization of the CMB):

- Ma & Bertschinger (1995), ApJ, 455, 7.
- Hu & Sugiyama (1995), Phys. Rev. D 51, 2599
- Seljak & Zaldarriaga (1996), ApJ, 469, 437.
- Zaldarriaga & Seljak (1997), Phys. Rev. D. 55, 1830.
- Kamionkowski, Kosowsky & Stebbins (1997), Phys. Rev. D 55, 7368.

Quantum fluctuations during inflation

- Any massless field experiences quantum fluctuations during inflation.

- Inflation stretches these to macroscopic scales.



(D. Baumann)

- Two massless fields are guaranteed to exist during inflation:

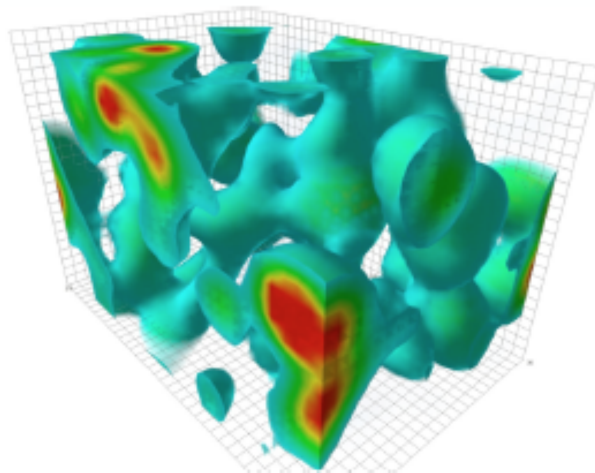
$$\mathrm{d}\ell^2 = e^{2Ht}\left[(1+\zeta)\delta_{ij} + h_{ij}\right]\mathrm{d}x^i\mathrm{d}x^j$$

expansion — $H(t) \approx const$

scalar — *isotropic stretching*

tensor — *anisotropic stretching*

Quantum fluctuations during inflation



(D. Baumann)

- Any massless field experiences quantum fluctuations during inflation.
- Inflation stretches these to macroscopic scales.
- Primordial power spectra:

inflation predicts

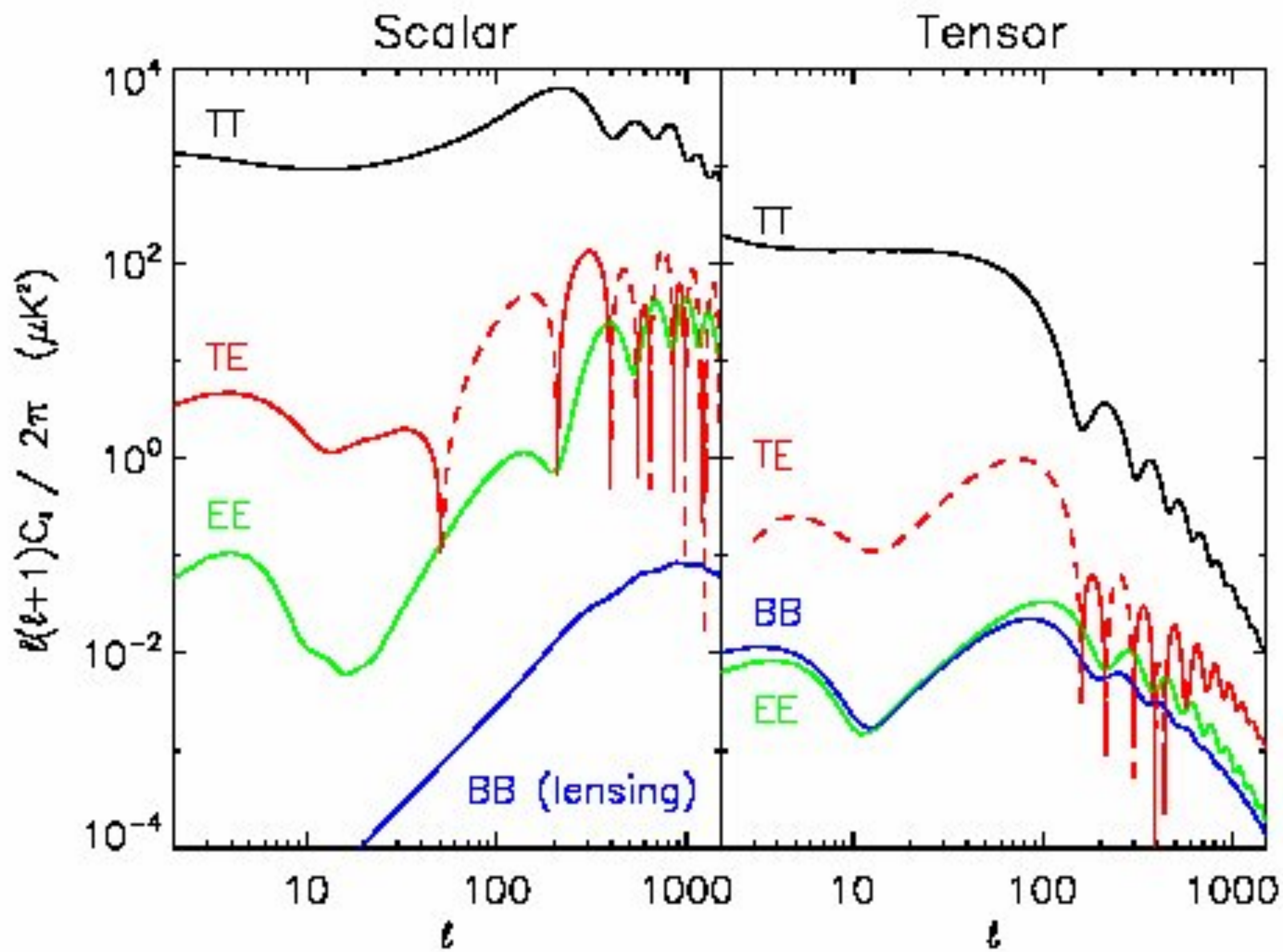
$$\langle \zeta^2 \rangle = \frac{1}{8\pi^2} \frac{H^4}{M_{\rm pl}^2 |\dot{H}|} \qquad \langle h_{ij}^2 \rangle = \frac{2}{\pi^2} \frac{H^2}{M_{\rm pl}^2}$$

↑ **observed** { adiabatic, Gaussian, superhorizon, scale-invariant

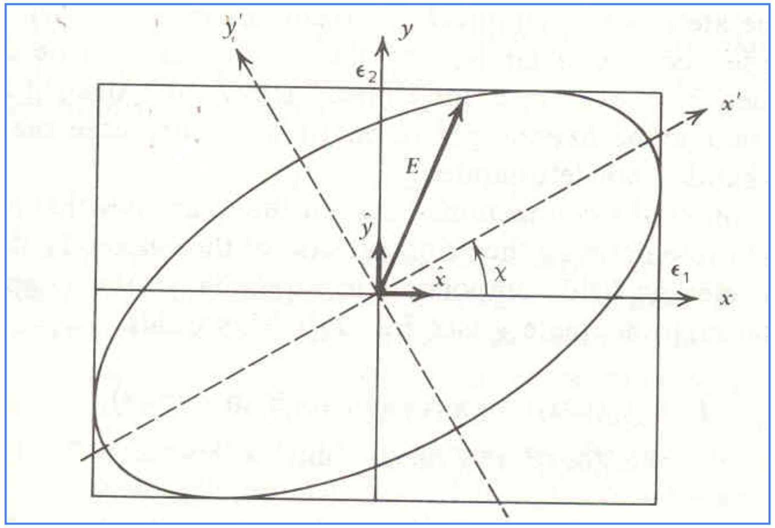
↑ **required** to show that

$$|\dot{H}| \ll H^2$$

Power spectra - Theory



Stokes parameters



❖The tip of the electric field vector **E** for a (monochromatic) electromagnetic wave propagating along a direction **n** traces out an elipse in a plane perpendicular to the direction of propagation.

$$\begin{cases} E_x = E_1 \cos(\omega t - \phi_1) \\ E_y = E_2 \cos(\omega t - \phi_2) \end{cases}$$

$$\begin{cases} E'_x = E_0 \cos(\beta) \cos(\omega t) \\ E'_y = -E_0 \sin(\beta) \sin(\omega t) \end{cases}$$

❖ **Stokes parameters** are defined as:

$$\begin{aligned} I &\equiv E_1^2 + E_2^2 &&= E_0^2 \\ Q &\equiv E_1^2 - E_2^2 &&= E_0^2 \cos(2\beta)\cos(2\chi) \\ U &\equiv 2E_1E_2\cos(\phi_1 - \phi_2) &&= E_0^2 \cos(2\beta)\sin(2\chi) \\ V &\equiv 2E_1E_2\sin(\phi_1 - \phi_2) &&= E_0^2 \sin(2\beta) \end{aligned}$$

$$E_0 = \sqrt{I} \qquad \sin(2\beta) = \frac{V}{I} \qquad \tan(2\chi) = \frac{U}{Q}$$

$$I^2 = Q^2 + U^2 + V^2.$$

Stokes parameters

❖ In the case of quasi-monochromatic waves, we can also define Stokes parameters.

$$\epsilon_1(t) = E_1(t)e^{i\phi_1(t)}$$
$$\epsilon_2(t) = E_2(t)e^{i\phi_2(t)}$$

❖ A real device measures time-averaged quantities (energy):

$$< \epsilon_i \epsilon_j^* >= \frac{1}{T}\int_0^T dt \epsilon_i(t)\epsilon_j^*(t)$$

❖ In analogy, **Stokes parameters** for quasi-monochromatic waves are defined as:

$$\begin{aligned} I &\equiv < \epsilon_1 \epsilon_1^* > + < \epsilon_2 \epsilon_2^* > \\ Q &\equiv < \epsilon_1 \epsilon_1^* > - < \epsilon_2 \epsilon_2^* > \\ U &\equiv < \epsilon_1 \epsilon_2^* > + < \epsilon_2 \epsilon_1^* > \\ V &\equiv \frac{1}{i}(< \epsilon_1 \epsilon_2^* > - < \epsilon_2 \epsilon_1^* >) \end{aligned}$$

$$I^2 \geq Q^2 + U^2 + V^2.$$

Stokes parameters

❖ Linear polarization is described by Stokes Q and U parameters.

❖ Q measures the different of intensities in the two axes x and y, while U measures the difference of intensities in a coordinate system at 45º.

❖ Not all Stokes parameters are rotationally invariant. Under a rotation of ψ degrees of the coordinate system, we have

$$I' = I$$

$$V' = V$$

$$Q' = Q\cos(2\psi) - U\sin(2\psi)$$

$$U' = U\cos(2\psi) + Q\sin(2\psi)$$

or in a more compact form

$$Q' \pm iU' = e^{\pm 2i\psi}(Q \pm iU)$$

❖Hence, (Q±iU) transforms like a spin-2 variable under rotations.

Spin weighted spherical harmonics

- Spin-s spherical harmonics.
- Under rotations, they transform as: ${}_sY_{\ell m} \to e^{\pm si\psi}\,{}_sY_{\ell m}(\hat{n})$
- Orthogonality and completeness

$$\int d\hat{\mathbf{n}}\,{}_sY^*_{\ell m}(\hat{\mathbf{n}})\,{}_sY_{\ell m}(\hat{\mathbf{n}}) = \delta_{\ell\ell'}\delta_{mm'}$$

$$\sum_{\ell m} {}_sY^*_{\ell m}(\hat{\mathbf{n}})\,{}_sY_{\ell m}(\hat{\mathbf{n}}') = \delta(\phi - \phi')\delta(\cos\theta - \cos\theta')$$

- Relation to Wigner rotation matrices:

$${}_sY_{\ell m}(\theta,\phi) = (-1)^m \sqrt{\frac{2\ell+1}{4\pi}}\, e^{-is\psi} D^{\ell}_{-m,s}(\phi,\theta,-\psi)$$

Statistical representation

❖ All-sky decomposition:

$$(Q \pm iU)(\hat{n}) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{+\ell} a_{\ell m}^{\pm 2} \ {}_{\pm 2}Y_{\ell m}(\hat{n}) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{+\ell} (a_{E,\ell m} \pm i a_{B,\ell m}) \ {}_{\pm 2}Y_{\ell m}(\hat{n})$$

❖ Here, $a_{lm}^{\pm 2}$ is a decomposition into positive and negative helicity. The helicity basis

$$e^{\pm} = \frac{1}{\sqrt{2}}(e_{\theta} \pm i e_{\phi})$$

❖ In the last equality we have defined E- and B-modes:

$$a_{E,\ell m} = \frac{1}{2}(a_{\ell m}^{+2} + a_{\ell m}^{-2})$$

$$a_{B,\ell m} = \frac{-i}{2}(a_{\ell m}^{+2} - a_{\ell m}^{-2})$$

❖ Under parity transformations (**n→-n**), the E-modes remain invariant, while B-modes change sign.

The polarization of the CMB anisotropies

- **Four parity-independent power spectra can be formed:**

$$C_{TT} = \frac{1}{2l+1}\sum_m \left\langle a^*_{T,lm}\, a_{T,lm} \right\rangle \qquad C_{BB} = \frac{1}{2l+1}\sum_m \left\langle a^*_{B,lm}\, a_{B,lm} \right\rangle$$

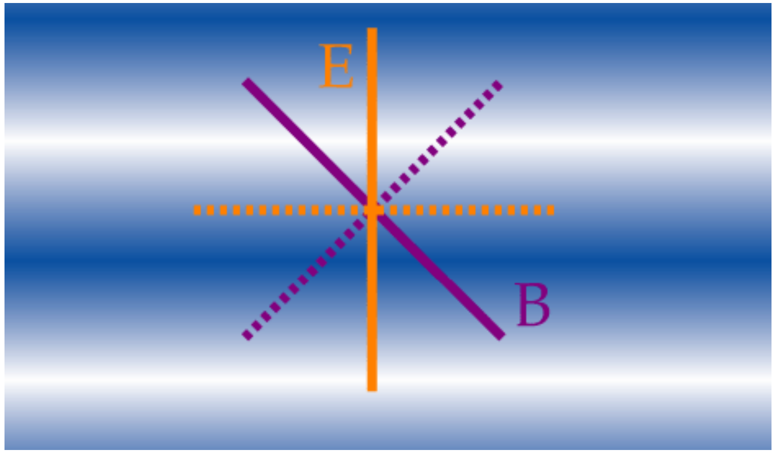
$$C_{EE} = \frac{1}{2l+1}\sum_m \left\langle a^*_{E,lm}\, a_{E,lm} \right\rangle \qquad C_{TE} = \frac{1}{2l+1}\sum_m \left\langle a^*_{T,lm}\, a_{E,lm} \right\rangle$$

- **Physics of generation of the Polarization.** Different sources of anisotropies generate different types of modes:

	Scalar (density perturbations)	Tensor (gravitational waves)
E-modes	Yes	Yes
B-modes	No	Yes

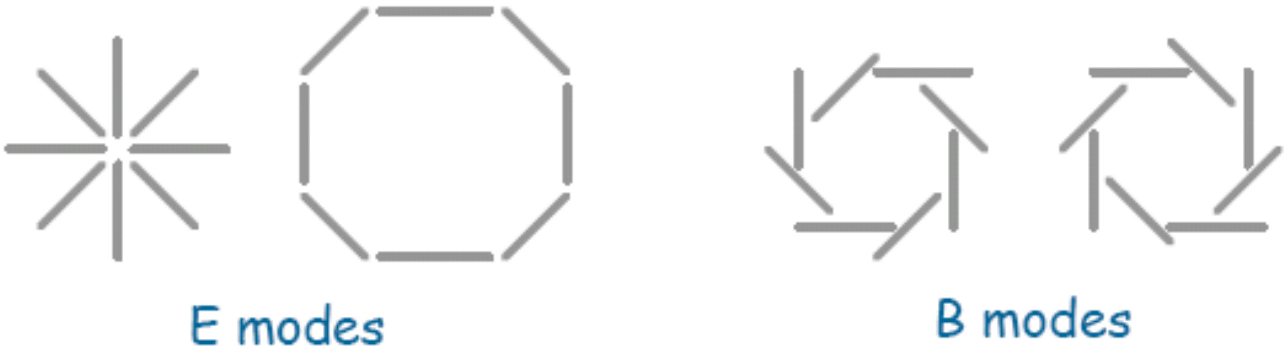
- **B-modes probe the existence of primordial gravitational waves.**

E and B modes



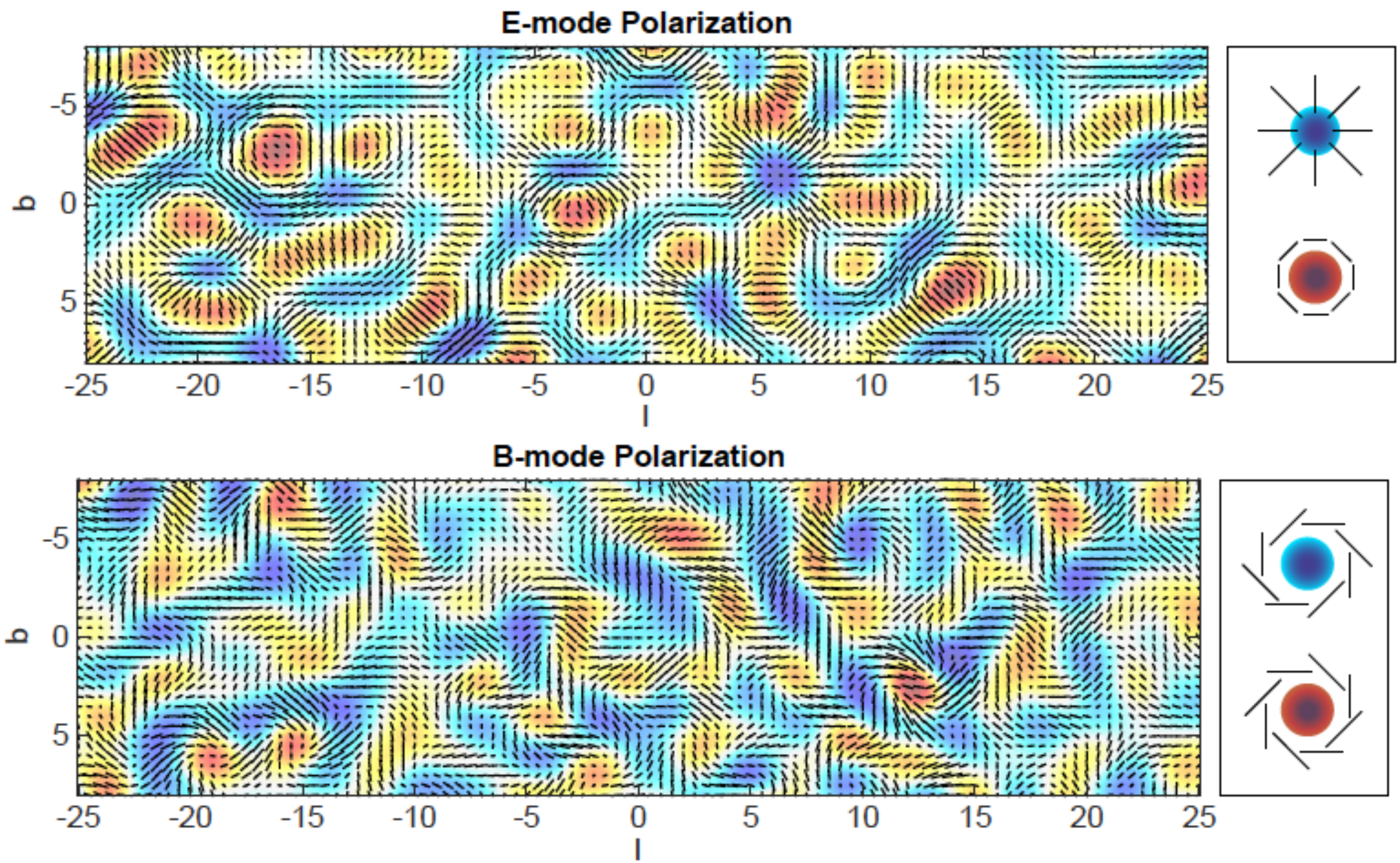
A plane wave moving from top to bottom. The direction of the polarization vector defines if they are E or B modes.

- **Full-sky** polarization maps can be decomposed into two components usually called **E-modes** (analog of the gradient component) and **B-modes** (analog of the curl component) (see Kamionkowski et al. 1997; Seljak & Zaldarriaga 1997).
- These modes are <u>independent on the coordinate system</u>, and are related to the Q and U Stokes parameters by a non-local transformation.



(A pure E-mode turns into pure B-mode if we turn all polarization vectors by 45º).

E and B modes

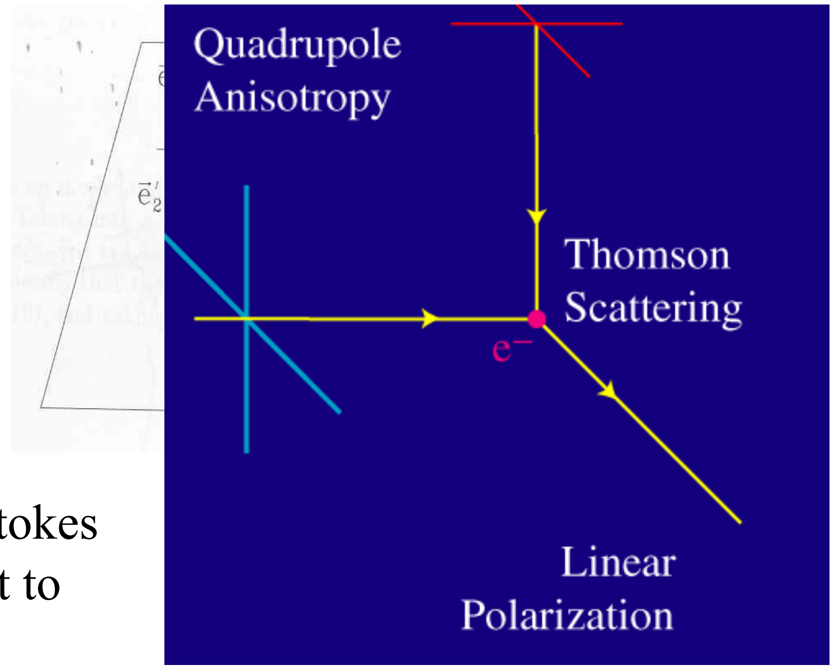


(Kamionkowski & Kovetz 2016)

Thomson scattering

❖Differential cross-section gives:

$$\begin{pmatrix} E_1 \\ E_2 \end{pmatrix} = -\frac{r_c}{R} \begin{pmatrix} 1 & 0 \\ 0 & \cos\theta \end{pmatrix} \begin{pmatrix} E_1' \\ E_2' \end{pmatrix}$$



❖ Defining the y-axes of the incoming and outgoing coordinate systems to be in the scattering plane, the Stokes parameters of the outgoing beam, defined with respect to the x-axis, we have:

$$I = \frac{3\sigma_T}{8\pi R^2} I'(1+\cos^2(\beta)) \qquad Q = \frac{3\sigma_T}{8\pi R^2} I' \sin^2(\beta) \qquad U = V = 0$$

❖ For unpolarized light, linear polarization is generated, perpendicular to scattering plane (Q>0).

❖ The net polarization produced by the scattering of an incoming, unpolarized ratiation field of intensity I′(θ,ϕ) is determined by integrating over all incoming directions.

$$I(\hat{z}) = \frac{3\sigma_T}{8\pi R^2} \int d\Omega \, I'(\theta,\phi)(1+\cos^2(\theta))$$

$$Q(\hat{z}) - iU(\hat{z}) = \frac{3\sigma_T}{8\pi R^2} \int d\Omega \, \sin^2(\theta) e^{i2\phi} I'(\theta,\phi)$$

Only a_{2m} components contribute.

❖ A net polarization is generated if there is a quadrupole anisotropy in the radiation field.

Polarization: scalar perturbations

❖Breakdown of tight-coupling leads to a quadrupole anisotropy.

❖ For scalar perturbations, the polarization signal arises from the gradient of the peculiar velocity of the photon fluid (e.g. Zaldarriaga & Harari 1995).

❖ Gradient of the velocity is along the direction of the wavevector, so the polarization is purely E-mode:

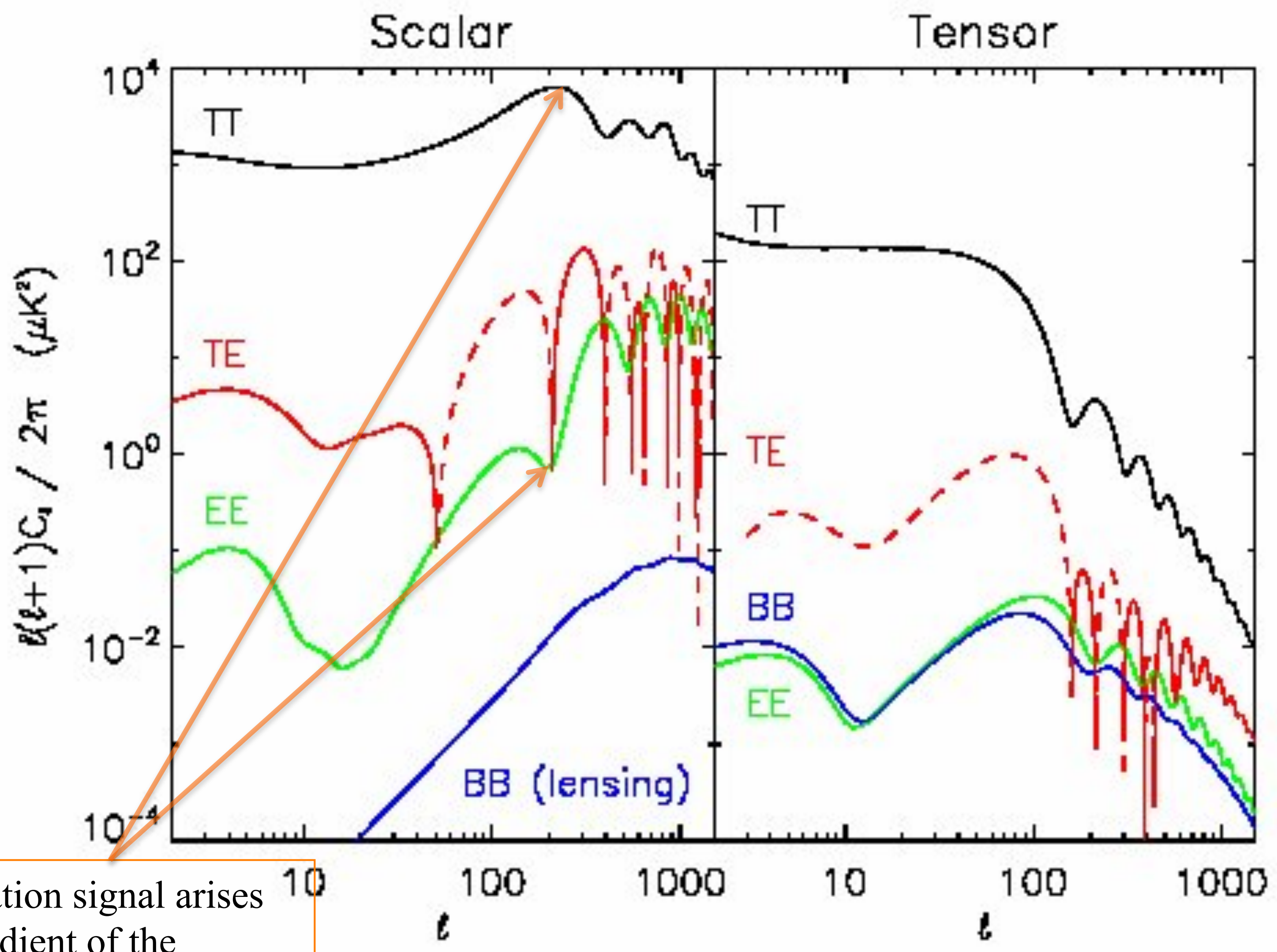
$$\Delta_E \approx -0.17(1-\mu^2)\Delta\eta_{dec} k\, v_\gamma(\eta_{dec})$$

❖ Velocity is 90º out of phase with respect to temperature – turning points of oscillator are zero points of velocity:

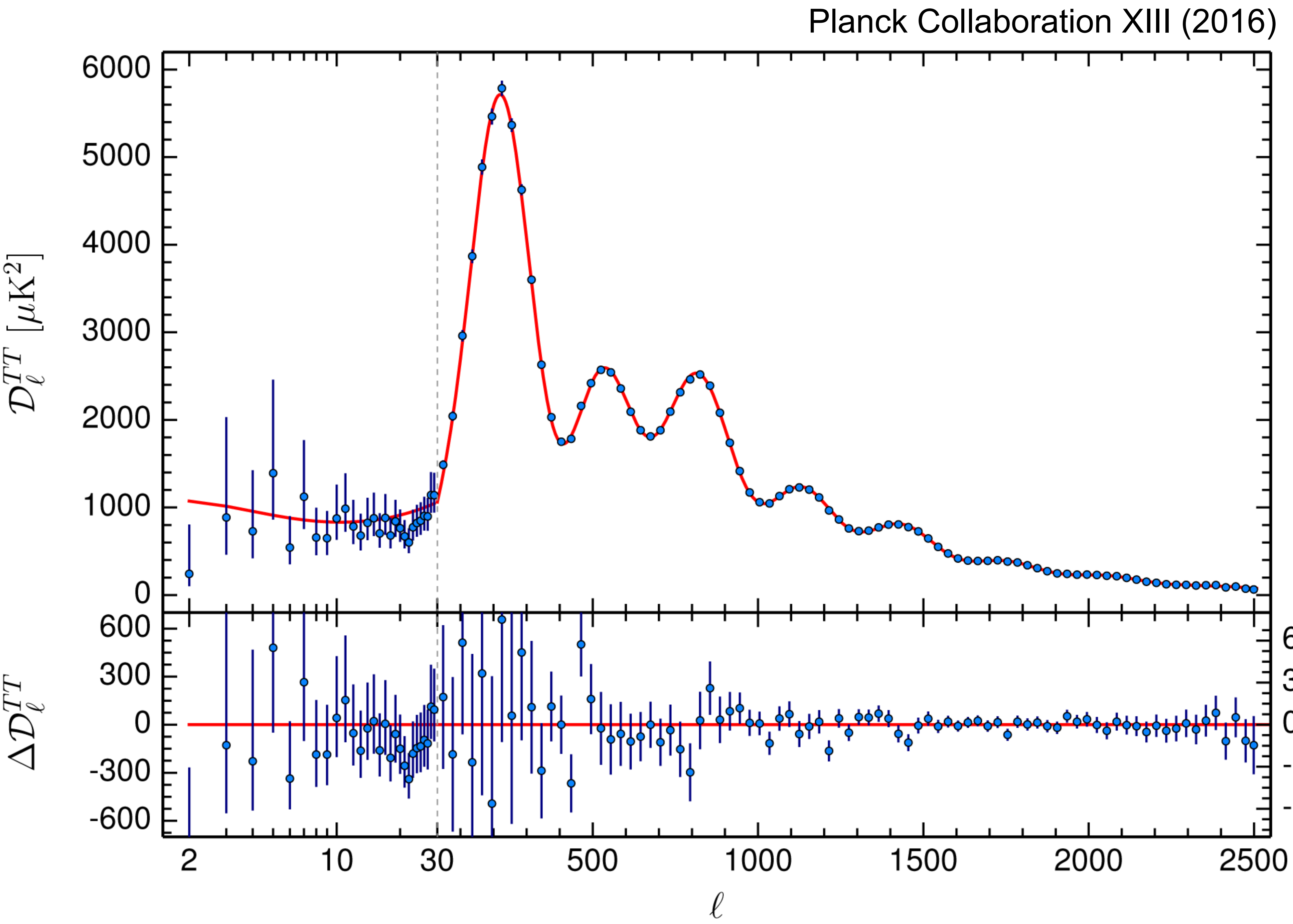
$$\Delta_T \propto \cos(kr_s) \qquad\qquad v_\gamma \propto \sin(kr_s)$$

❖ Polarization peaks are at troughs of temperature peaks.

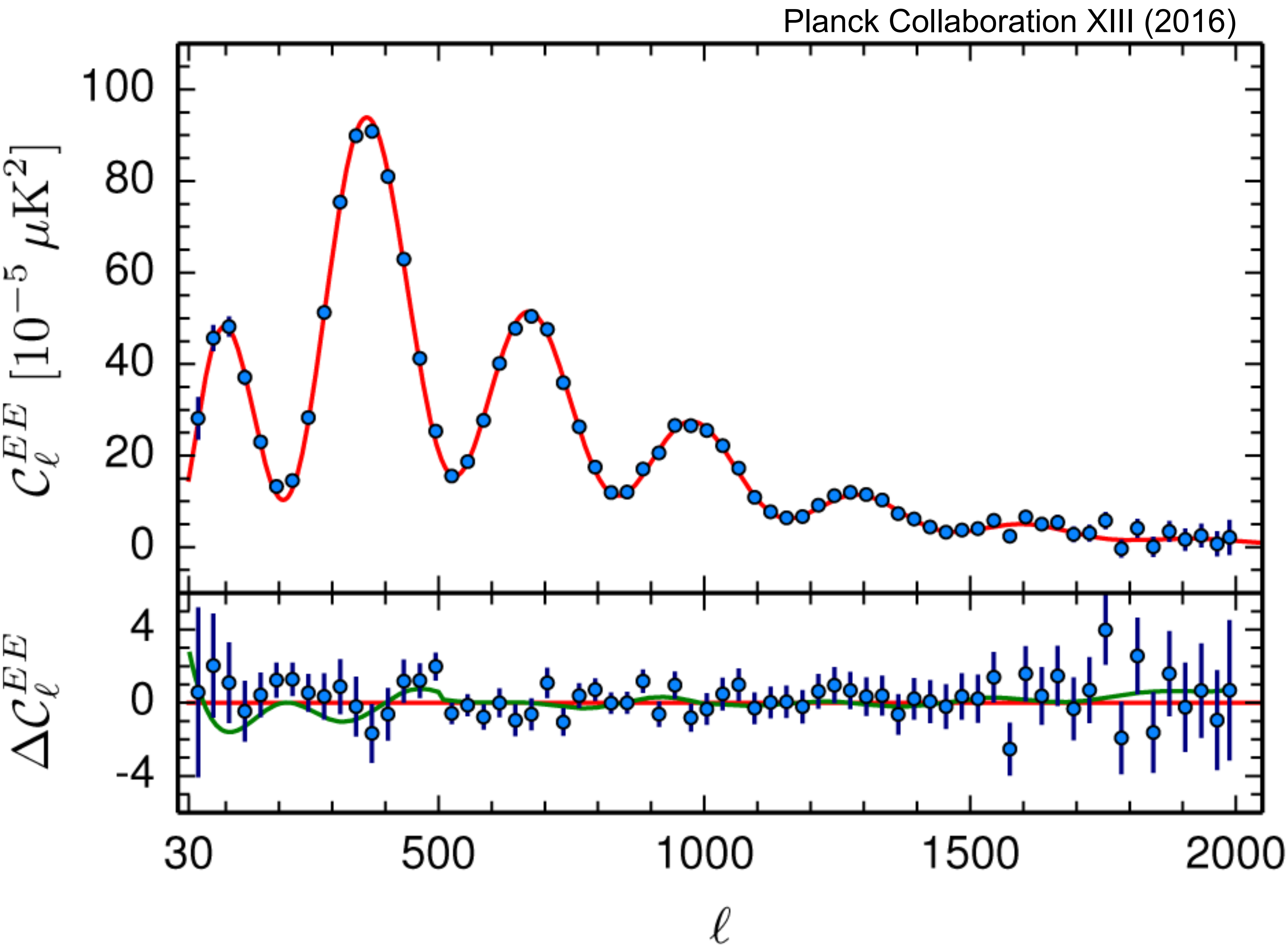
Power spectra - Theory



The polarization signal arises from the gradient of the peculiar velocity of the photon fluid => TT and EE peaks are out of phase.



Planck Collaboration XIII (2016)
$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$
ℓ
6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500


Planck Collaboration XIII (2016)
C_ℓ^{EE} [10^{-5} μK^2]
ΔC_ℓ^{EE}
ℓ
100
80
60
40
20
0
4
0
-4
30
500
1000
1500
2000

TE Polarization and acoustic peaks

❖ Cross-correlation of temperature and polarization

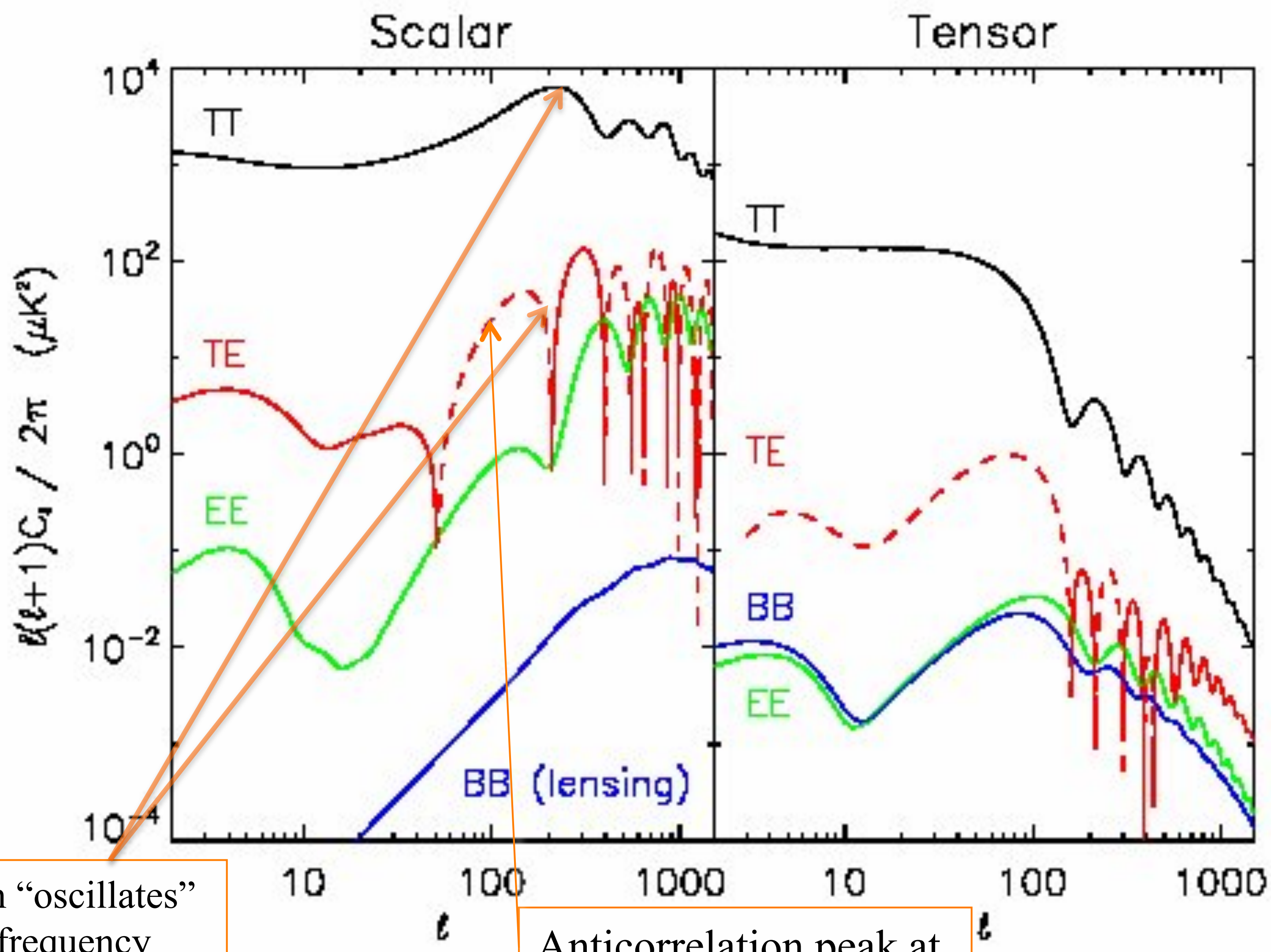
$$\Delta_T \Delta_E \propto \cos(kr_s)\sin(kr_s) \propto \sin(2kr_s)$$

❖ TE spectrum “oscillates” at twice the frequency

❖ TE correlation is radial or tangential around hot spots.

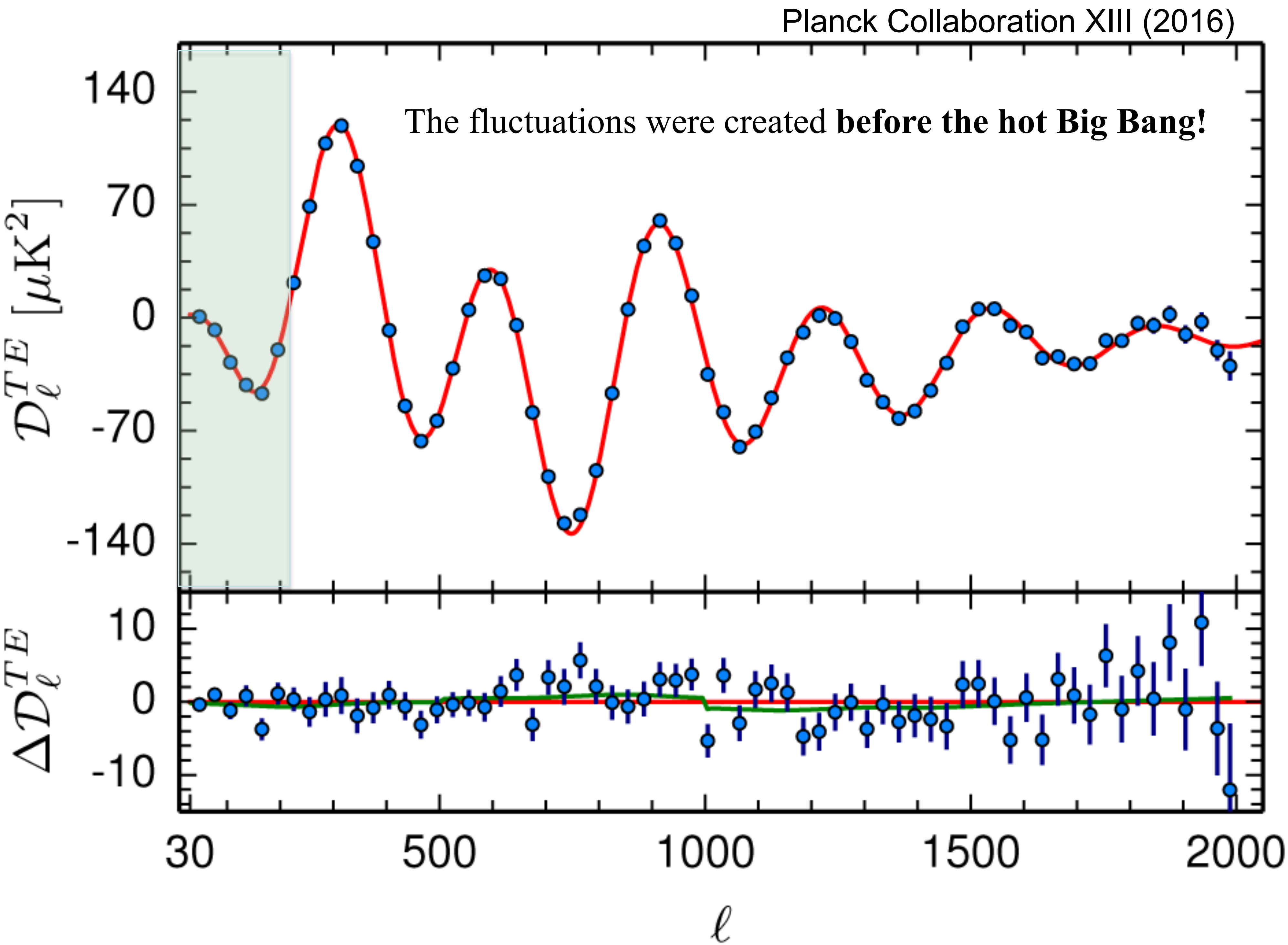
❖ Large scales: anticorrelation peak around l=150, **a distinctive signature of primordial adiabatic fluctuations** (Peiris et al. 2003).

Power spectra - Theory

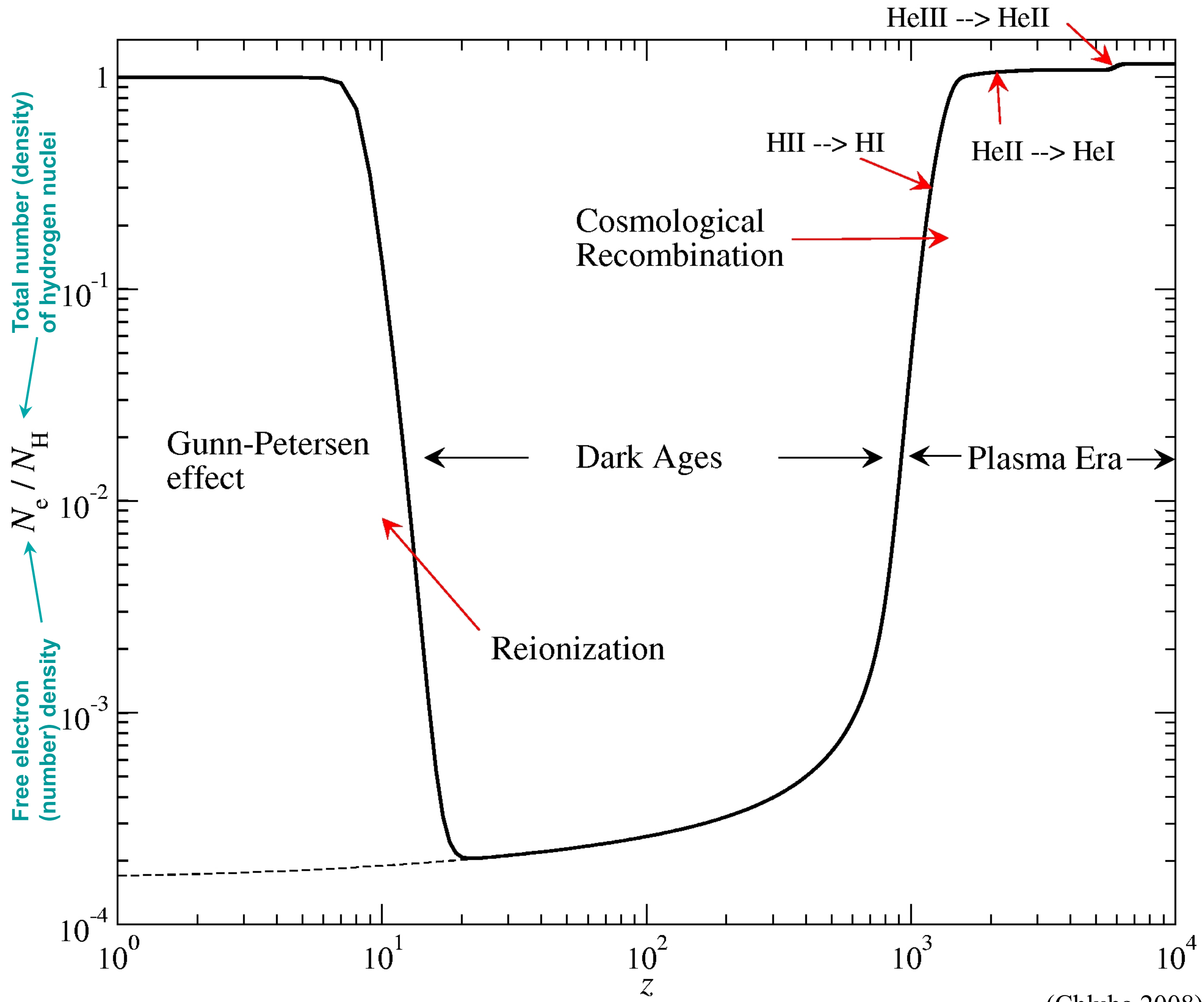


TE spectrum "oscillates" at twice the frequency

Anticorrelation peak at l=150 is a signature of superhorizon adiabatic fluctuations


Planck Collaboration XIII (2016)
The fluctuations were created **before the hot Big Bang!**
$\mathcal{D}_\ell^{TE}\ [\mu K^2]$
$\Delta\mathcal{D}_\ell^{TE}$
140
70
0
-70
-140
10
0
-10
30
500
1000
1500
2000
ℓ

How did the Universe became neutral? Sketch of the Ionization History



(Chluba 2008)

Reionization

❖Optical depth to Thomson scattering to reionization

$$\tau(z) = \int d\eta n_e \sigma_T a = \int d\ln a \frac{n_e \sigma_T}{H(a)} \propto (\Omega_b h^2)(\Omega_m h^2)^{-1/2}(1+z)^{3/2}$$

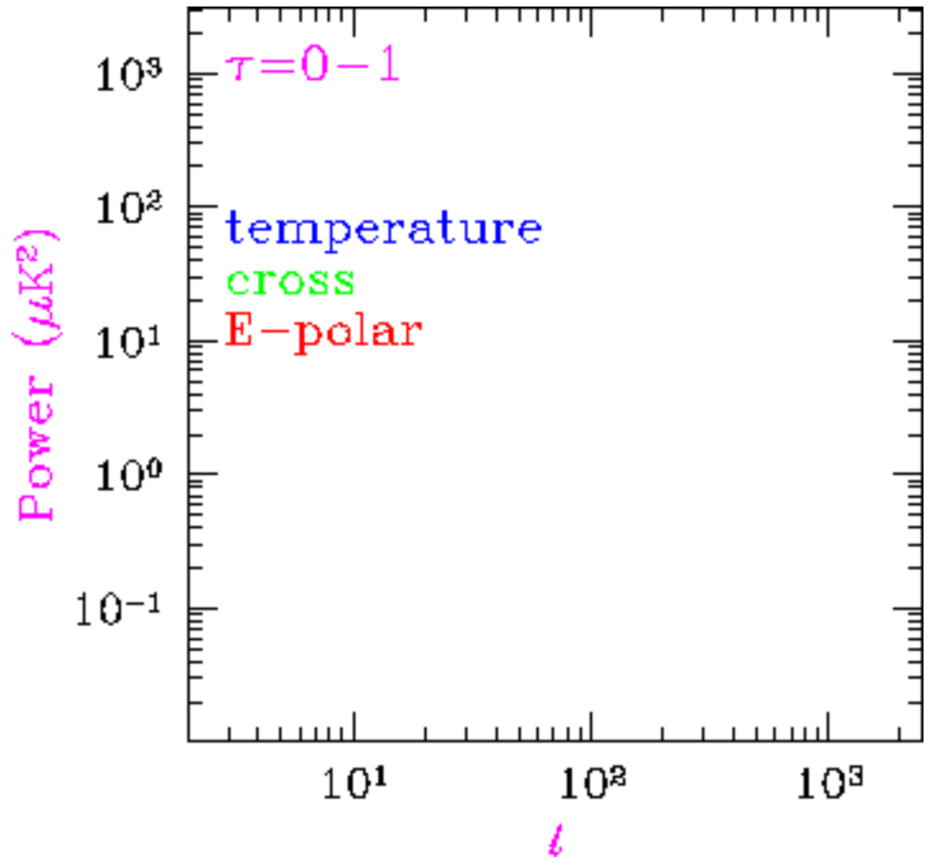
$$= \left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{\Omega_m h^2}{0.15}\right)^{-1/2}\left(\frac{1+z}{61}\right)^{3/2}$$

❖ CMB re-scatters off re-ionized gas. Generation of new anisotropies at large scales (Doppler) and absorption at small scales:

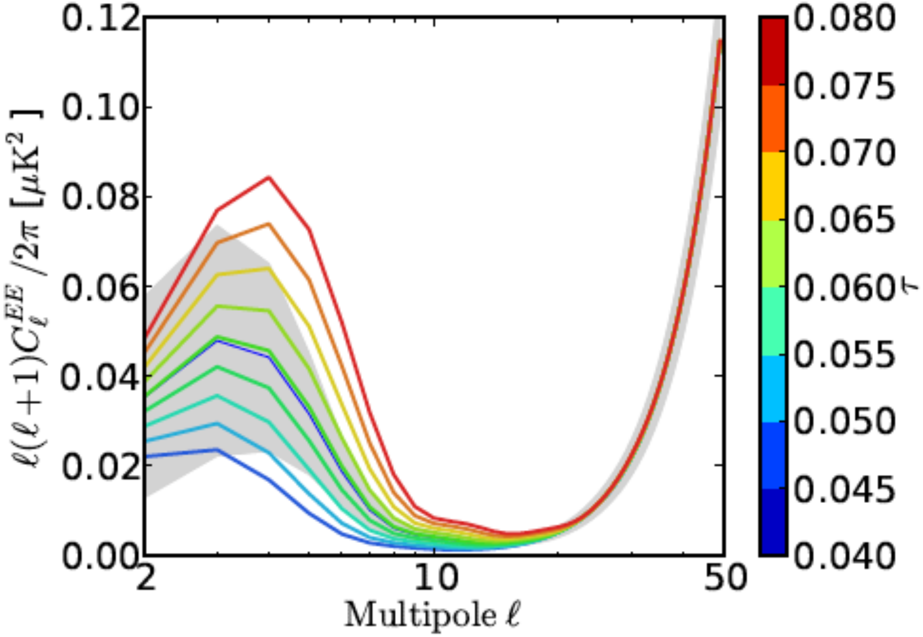
$$\Delta_T \rightarrow \Delta_T e^{-\tau} \qquad \Delta_E \rightarrow \Delta_E \tau$$

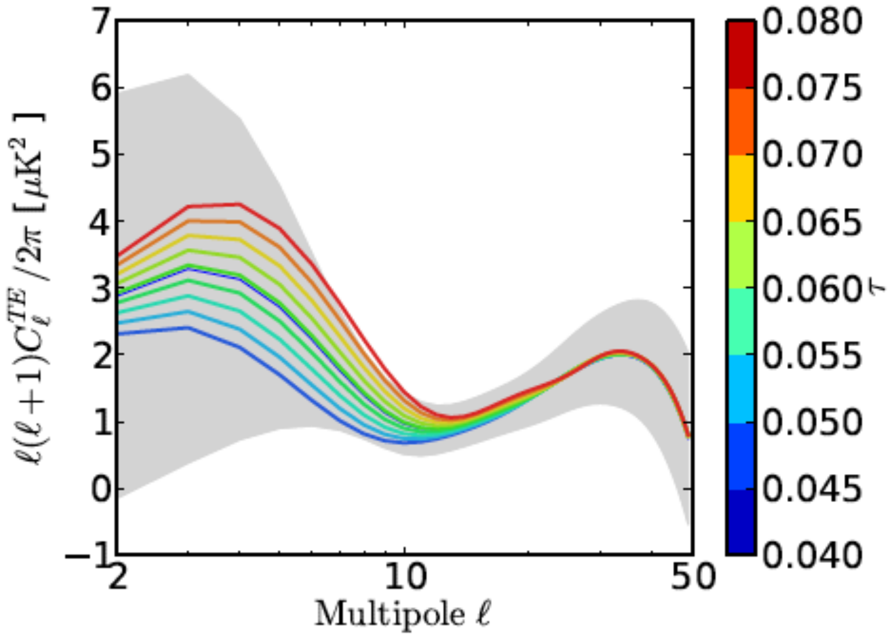
$$C_\ell^{TE} \propto \tau e^{-\tau} \qquad C_\ell^{EE} \propto \tau^2$$

❖ Effect peaks at horizon scale at recombination (l≈2-3). If the optical depth is very large, primordial anisotropies are erased.

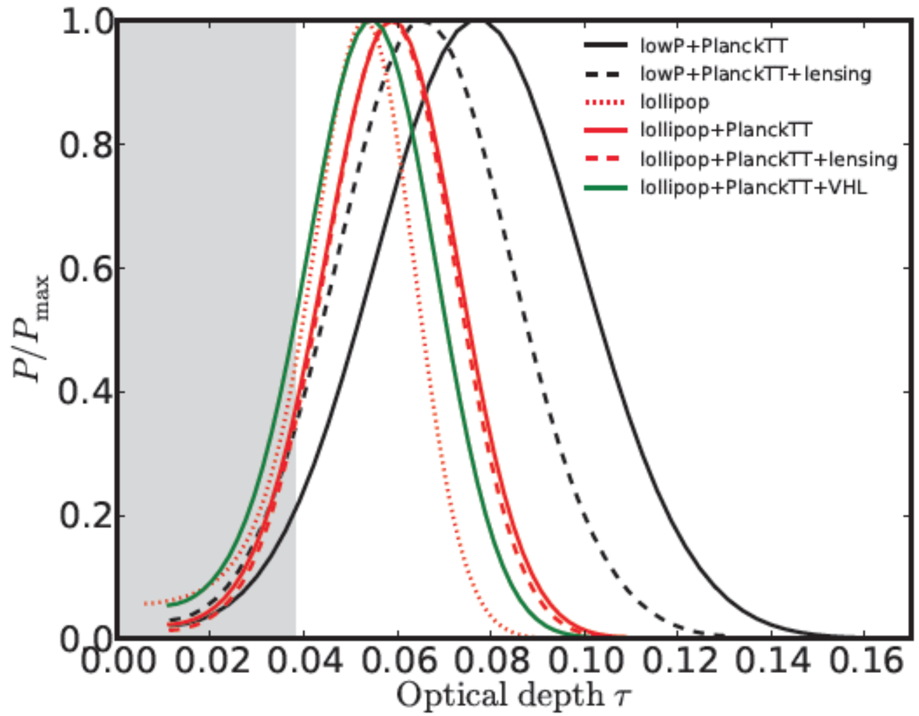


Reionization

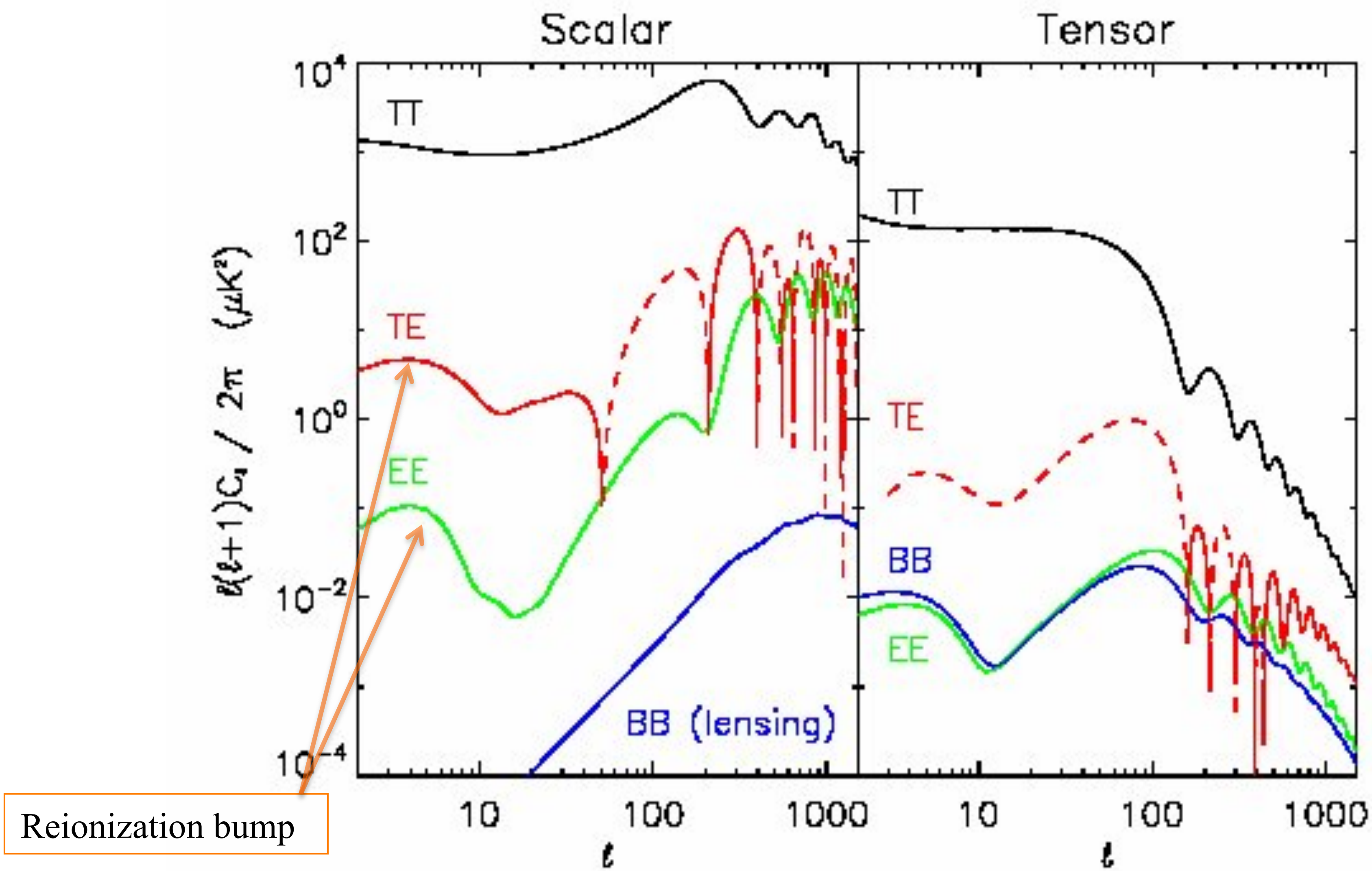




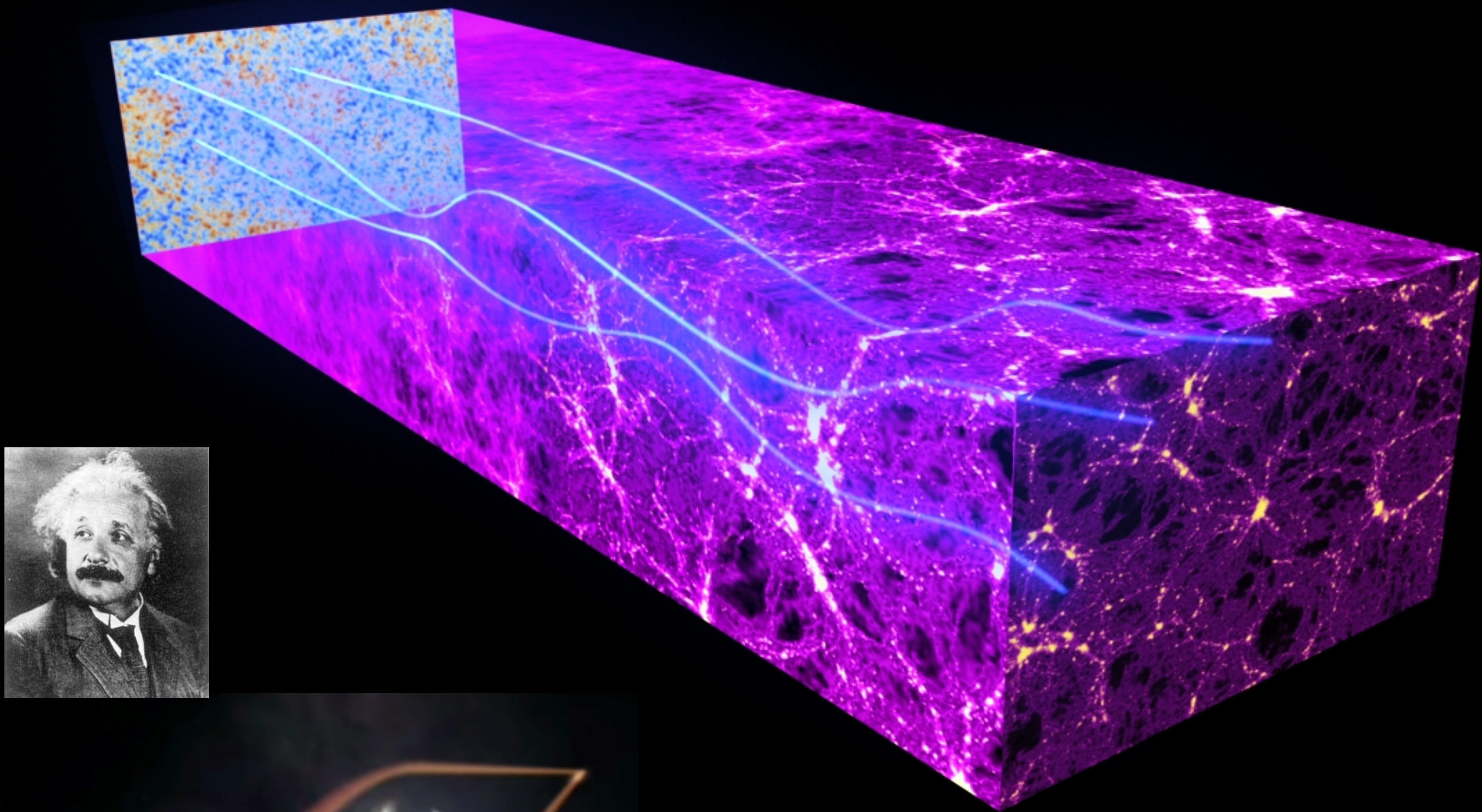
- ❖ Planck Collaboration XLVII (2016).
- ❖ $\tau = 0.058 \pm 0.012$ (assuming instantaneous reionization).
- ❖ Redshift of reionization is model dependent: z_{re}~8.5. Complementary to 21cm studies.
- ❖ Needed to break degeneracies with other parameters (r).



Power spectra - Theory



Gravitational lensing as seen by Planck



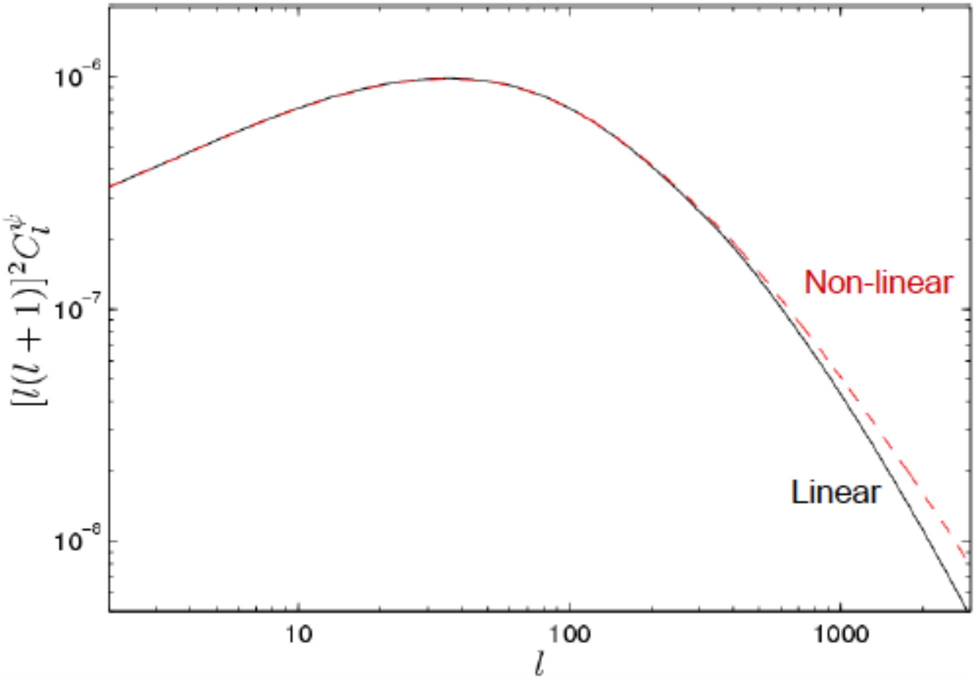
$$T(\hat{n}) = T^{\rm unl}(\hat{n} + \nabla\phi(\hat{n})),$$
$$= T^{\rm unl}(\hat{n}) + \sum_i \nabla^i\phi(\hat{n})\nabla_i T(\hat{n}) + O(\phi^2),$$

Gravitational lensing

Deflection angle power spectrum

Large-scale lenses: potentials nearly linear, clean physics

$$\boldsymbol{\alpha} = \nabla\psi$$

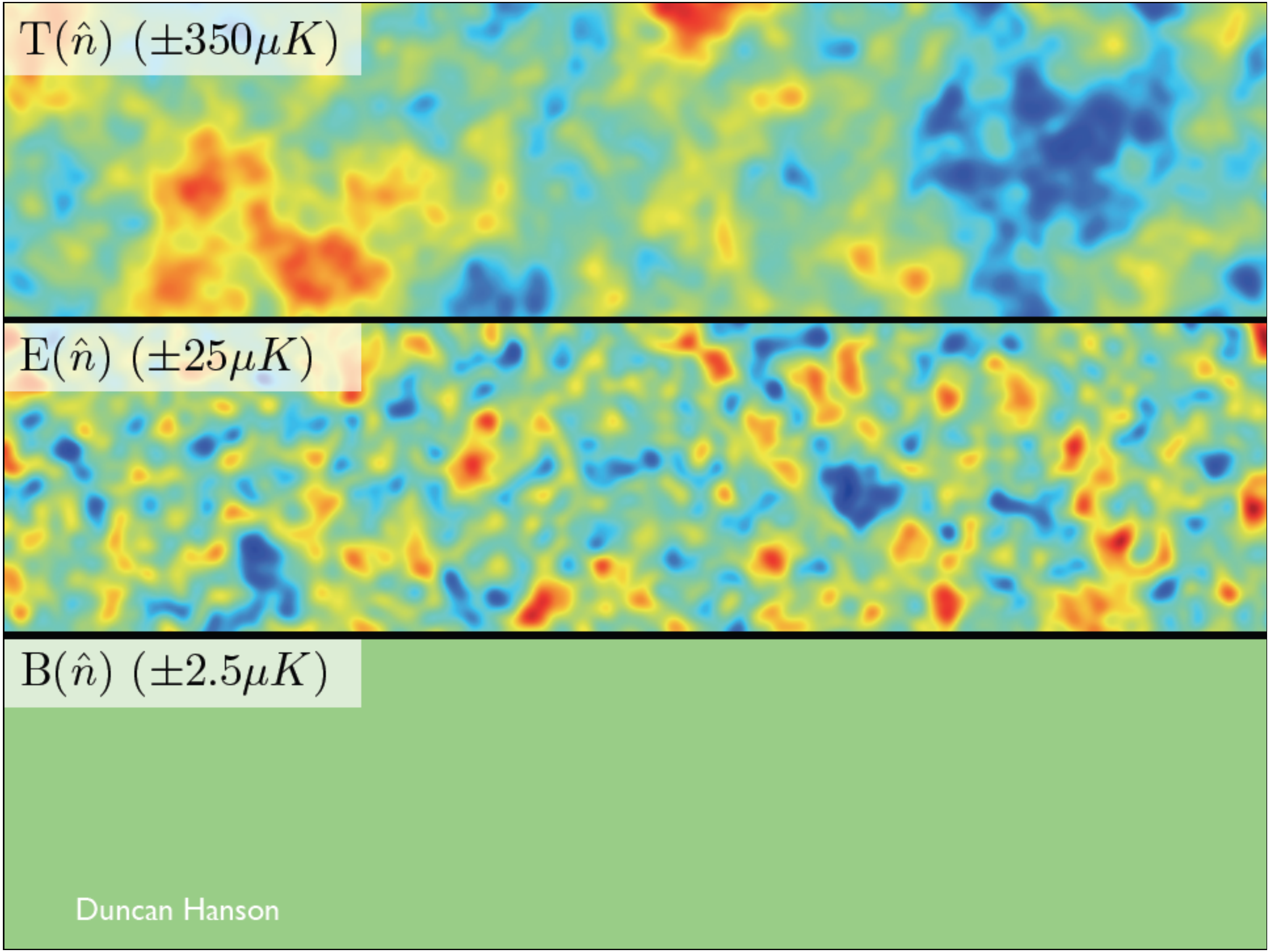


Deflections O(10^{-3}) , but coherent on degree scales

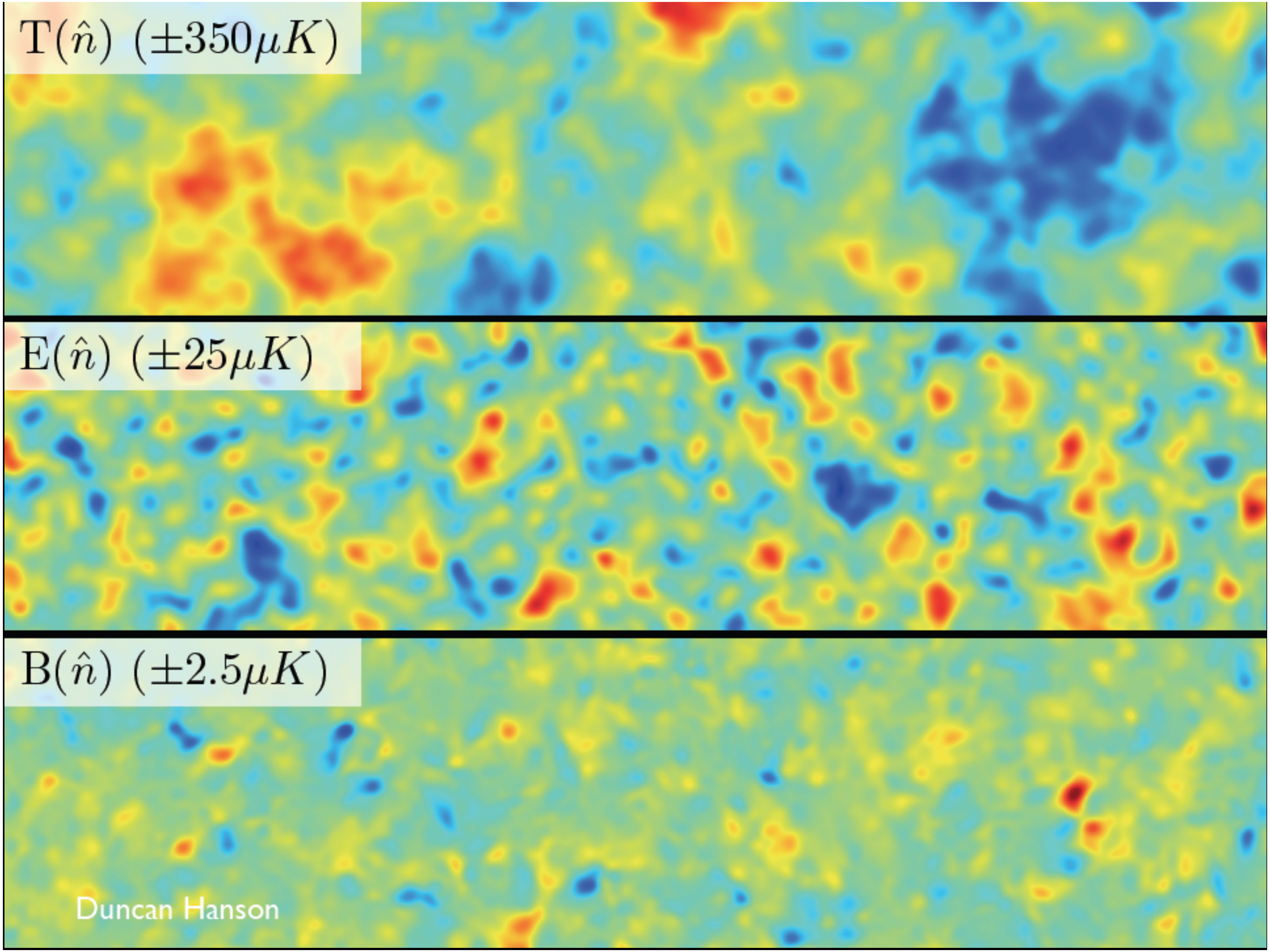
Probes matter distribution at roughly $0.5 < z < 6$ depending on l

Non-linear structure growth effects not a major headache

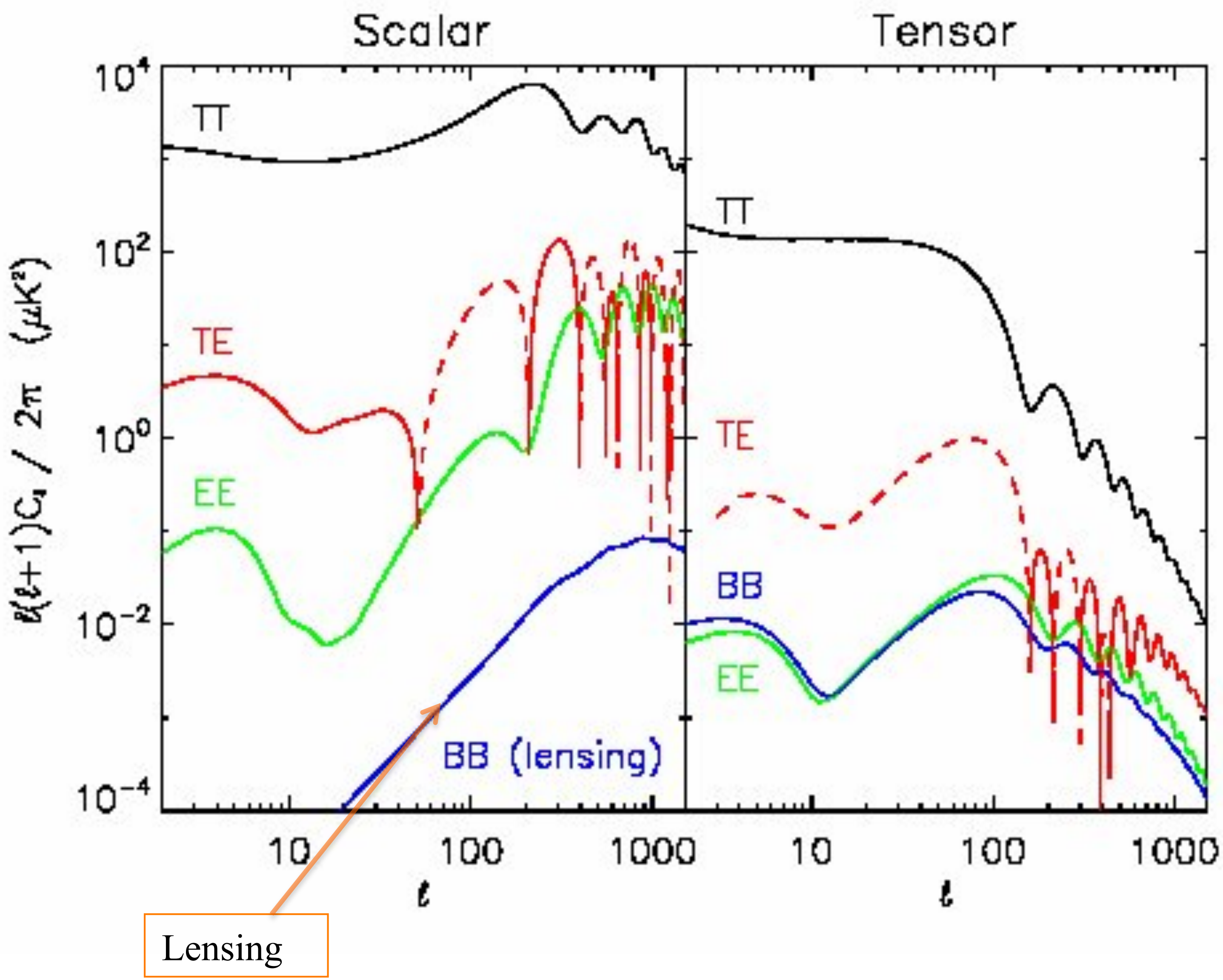
(Slide from A. Lewis, https://indico.in2p3.fr/event/14661/timetable/#all)



$T(\hat{n})$ ($\pm 350 \mu K$)
$E(\hat{n})$ ($\pm 25 \mu K$)
$B(\hat{n})$ ($\pm 2.5 \mu K$)
Duncan Hanson


$T(\hat{n})$ $(\pm 350\mu K)$
$E(\hat{n})$ $(\pm 25\mu K)$
$B(\hat{n})$ $(\pm 2.5\mu K)$
Duncan Hanson

Power spectra - Theory



Polarization and tensor modes: Gravitational waves

❖ Gravitational waves are a natural consequence of inflationary models (Grishchuk 1974; Rubakov et al. 1982; Starobinsky 1982, 1983; Abbott & Wise 1984).

❖ GW created as vacuum fluctuations (exactly as density perturbations).

- **Evolution at large scales**. Similar to temperature fluctuations. Flat power at large scales.
- **Evolution at small scales**. After re-entering the horizon, fluctuations evolve like radiation (a^{-4}), so their ratio keeps constant. $\Omega_{GW} \sim \Omega_r (H/m_{pl})^2 \sim 10^{-4} V/m_p^4$. → GW oscillate and decay at horizon crossing.

❖ Gravitational waves produce a quadrupolar distortion in the temperature of the CMB.

❖ B-mode polarization is produced, because the symmetry of a plane wave is broken by the transverse nature of gravity wave polarization.

$$C_{El}^{(T)} = (4\pi)^2 \int k^2\, dk\, P_h(k) \left| \int d\tau\, g(\tau) \Psi(k,\tau) \left[-j_l(x) + j_l''(x) + \frac{2j_l(x)}{x^2} + \frac{4j_l'(x)}{x} \right] \right|^2,$$

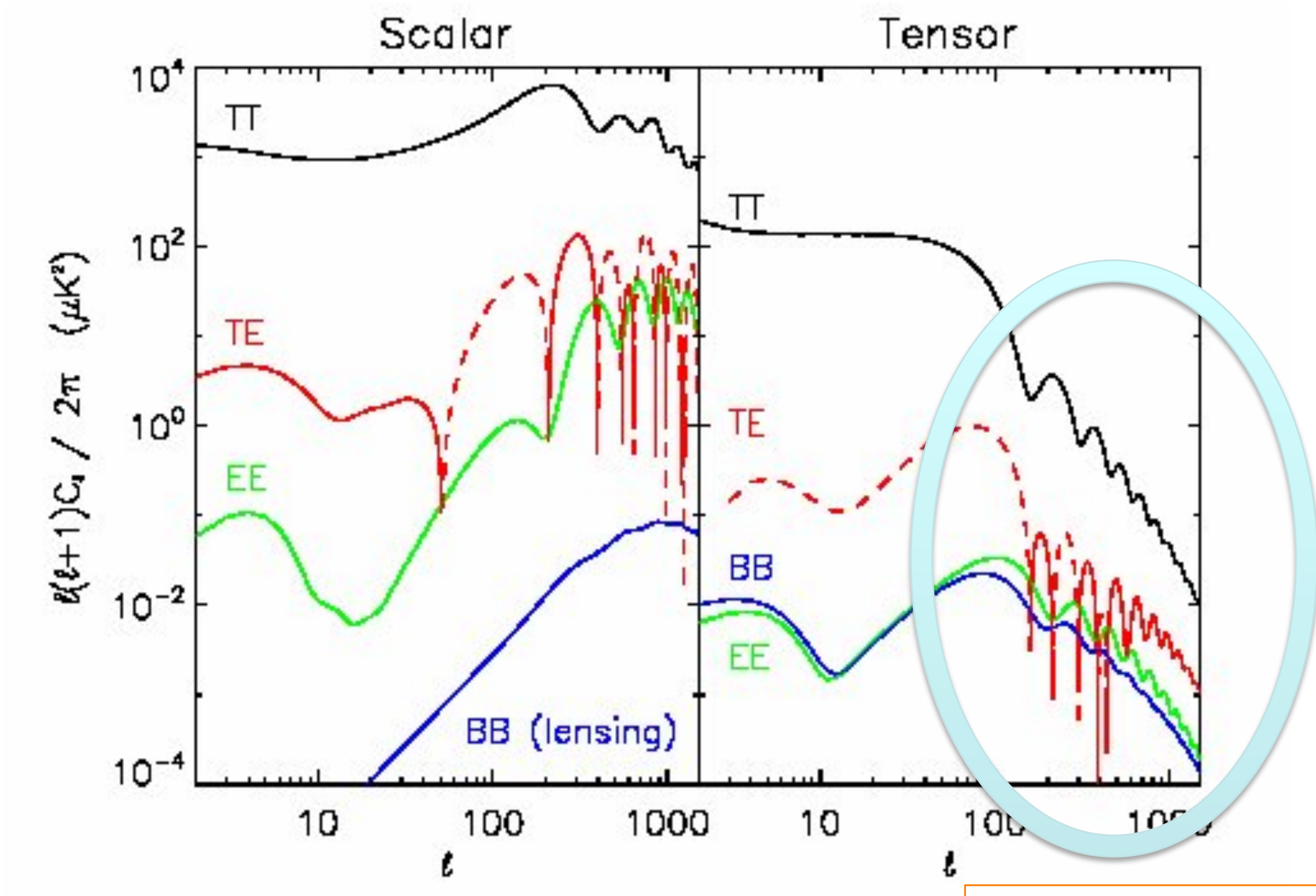
$$C_{Bl}^{(T)} = (4\pi)^2 \int k^2\, dk\, P_h(k) \left| \int d\tau\, g(\tau) \Psi(k,\tau) \left[2j_l'(x) + \frac{4j_l}{x} \right] \right|^2,$$

(Seljak & Zaldarriaga 1997)

❖ E and B modes have similar amplitude.

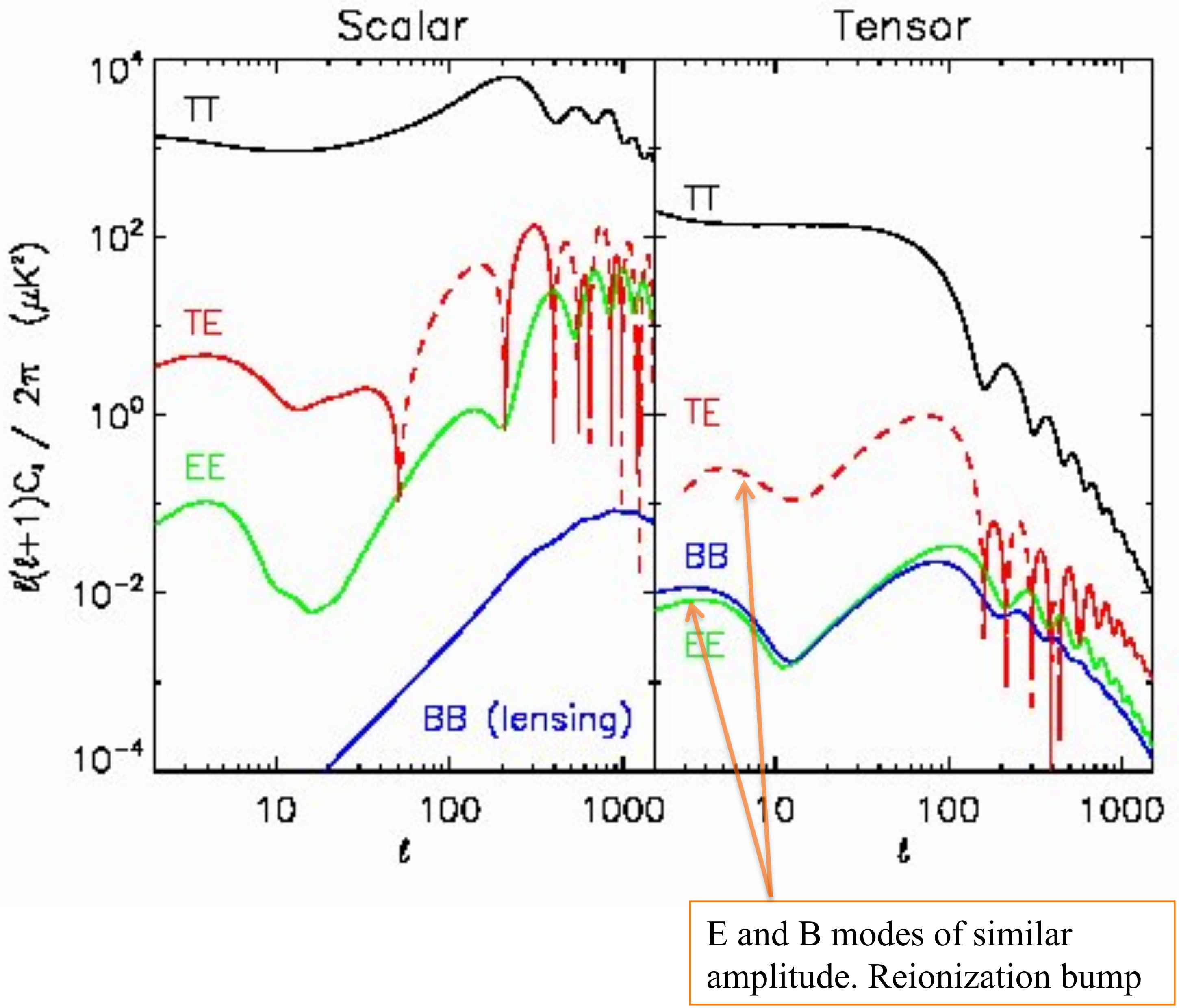
❖ Again, polarization is only generated at last scattering surface (or reionization).

Power spectra - Theory



Effects only on large scales because gravity waves damp inside horizon.

Power spectra - Theory



What would a detection of GW tell us?

- It would provide strong evidence that inflation happened!
- The amplitude of the power spectrum is a (model-independent) measurement of the energy scale of inflation.

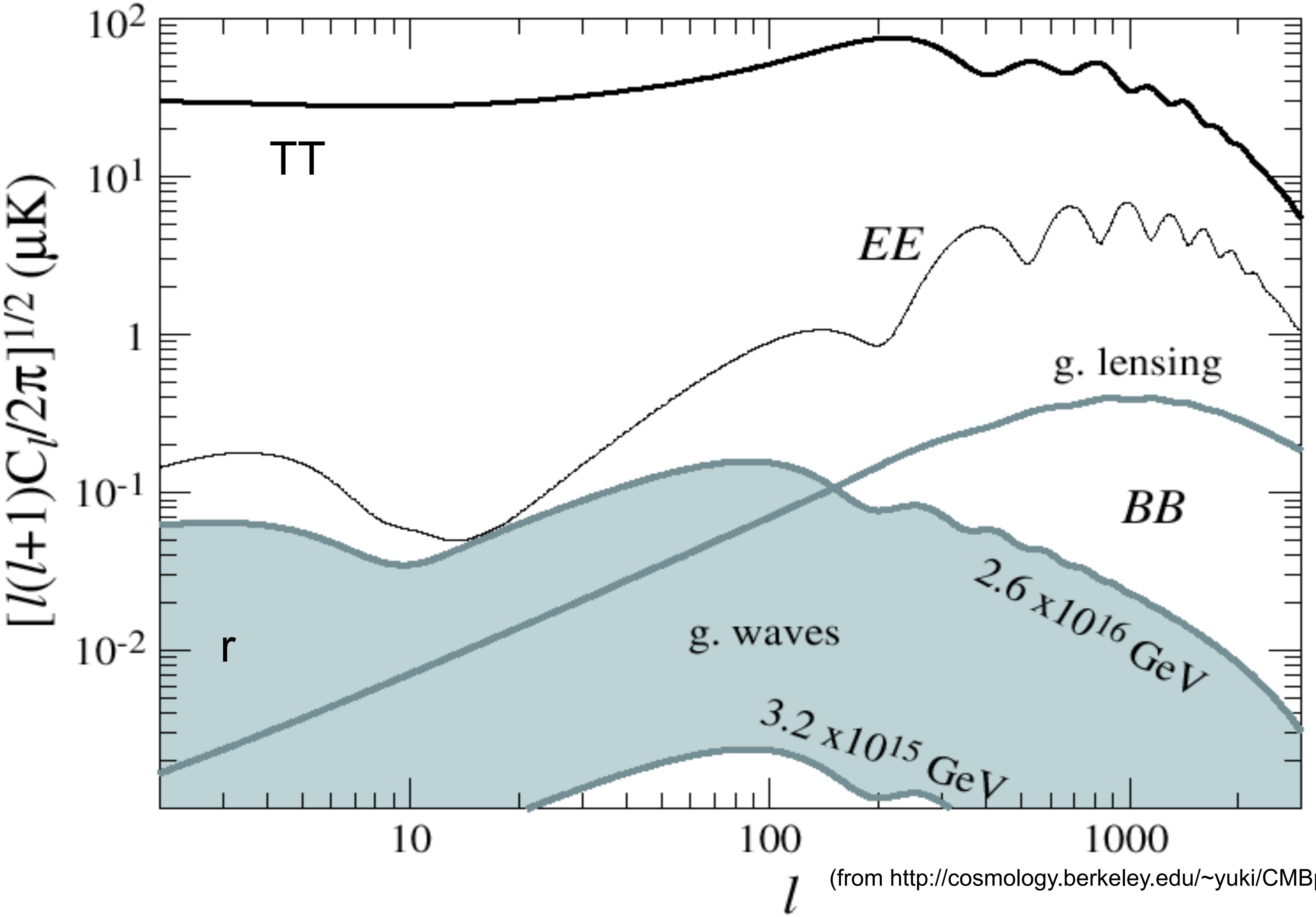
$$P_{tensor} = \frac{8}{m_{Pl}^2}\left(\frac{H}{2\pi}\right)^2 \propto E_{\inf}^4$$

- Defining the tensor-to-scalar ratio (r) at a certain scale k_0 (typically 0.001 Mpc^{-1}), we have

$$r \equiv \frac{P_{tensor}(k_0)}{P_{scalar}(k_0)} = 0.008\left(\frac{E_{\inf}}{10^{16}\,GeV}\right)^4$$

- Values of r of the order of 0.01 or larger would imply that inflation occurred at the GUT scale.
- These scales are 12 orders of magnitude larger than those achievable at LHC!

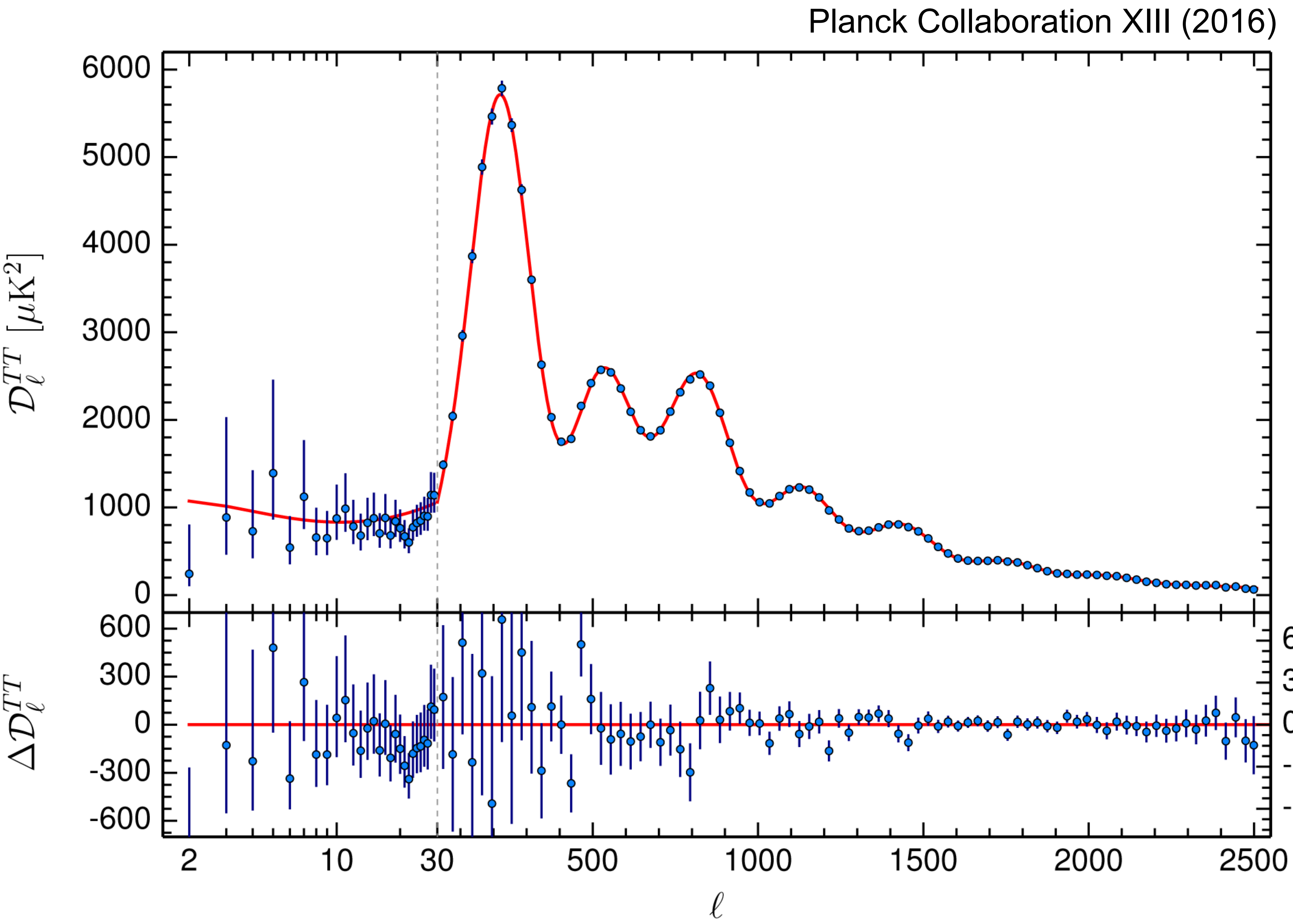
Primordial gravitational waves and B-modes



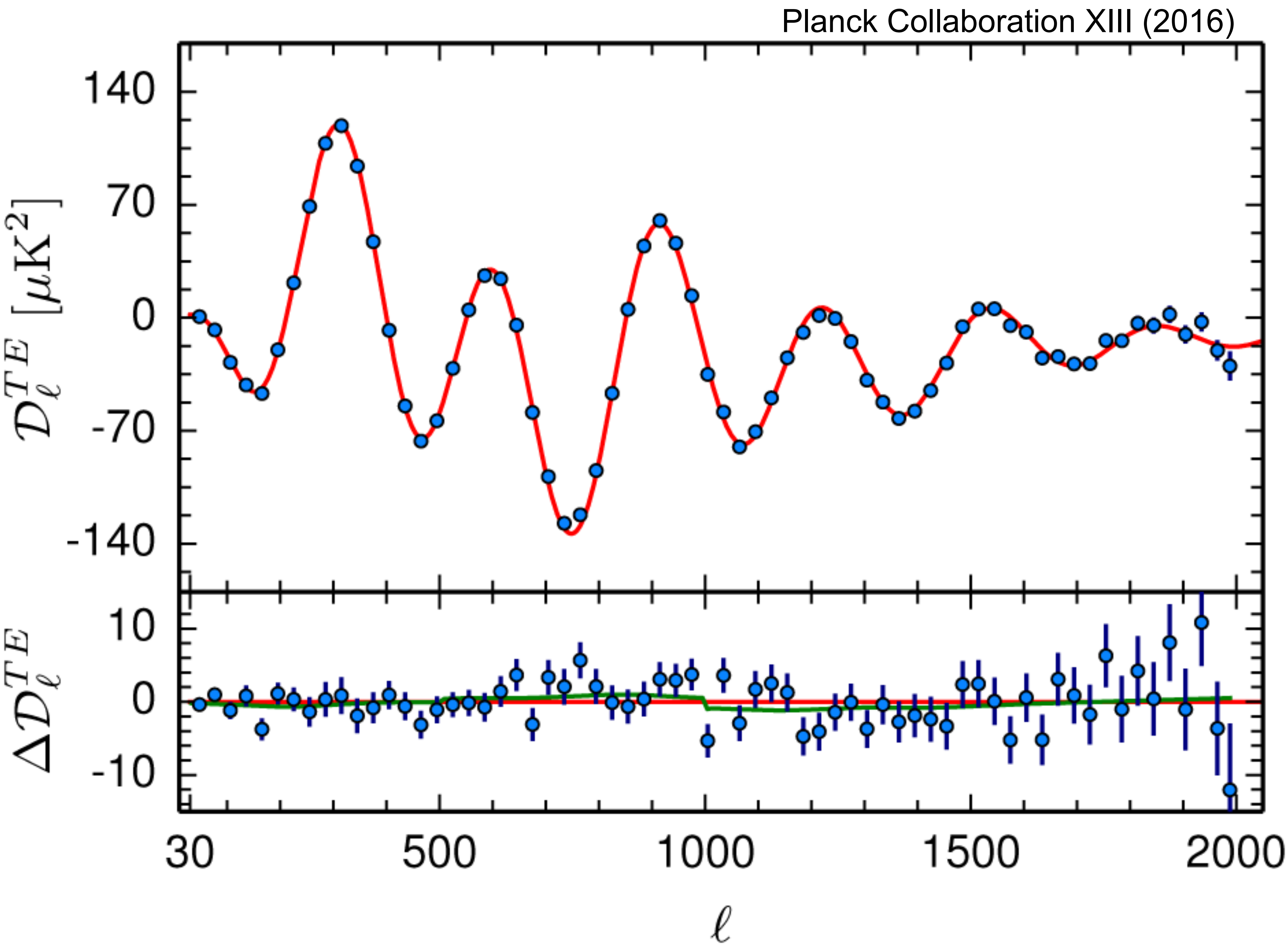
(from http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm)

- r=0.1 corresponds to an energy scale of inflation around 2×10^{16} GeV.

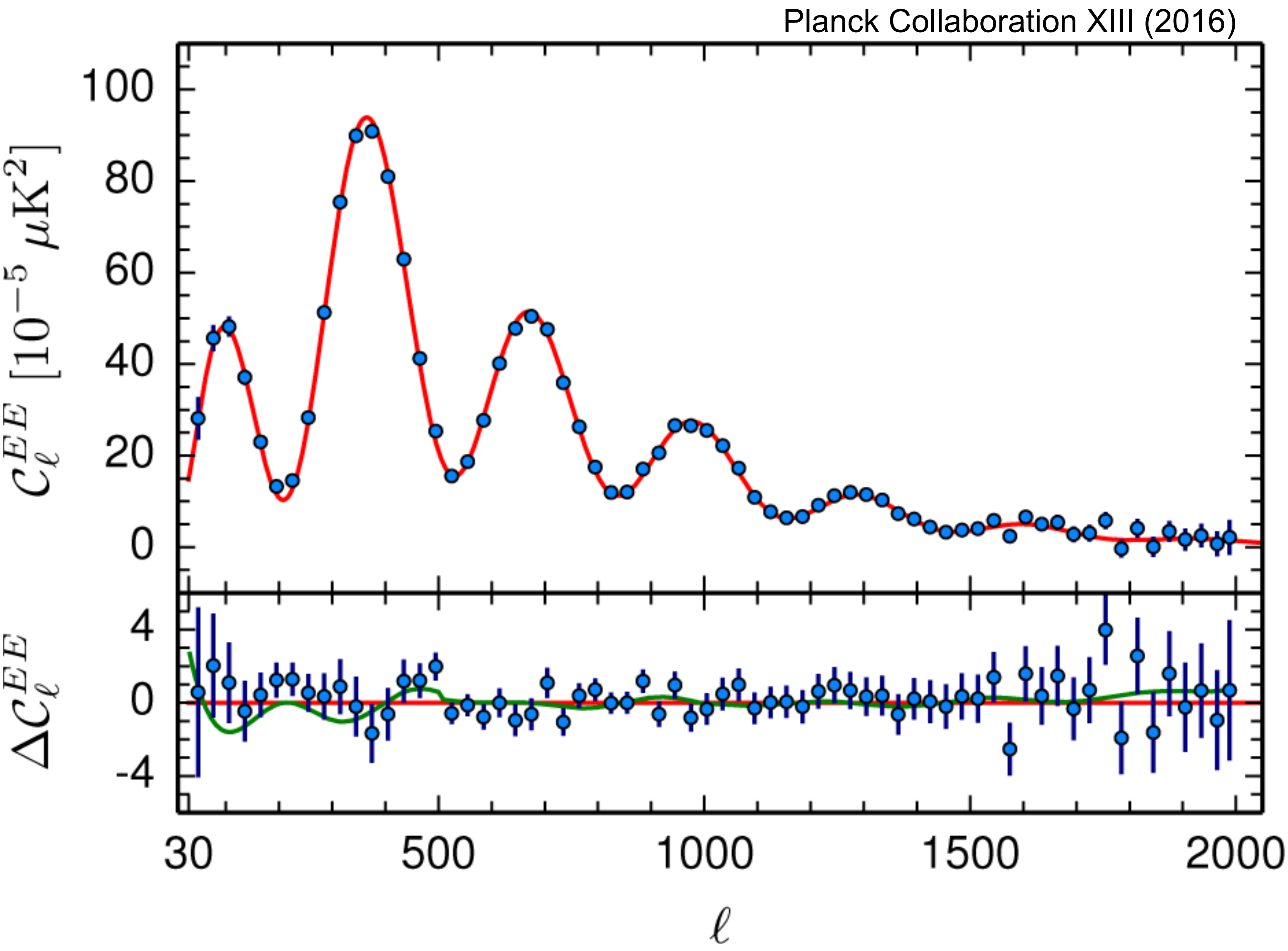
CMB polarization experiments. Present and future



Planck Collaboration XIII (2016)
$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

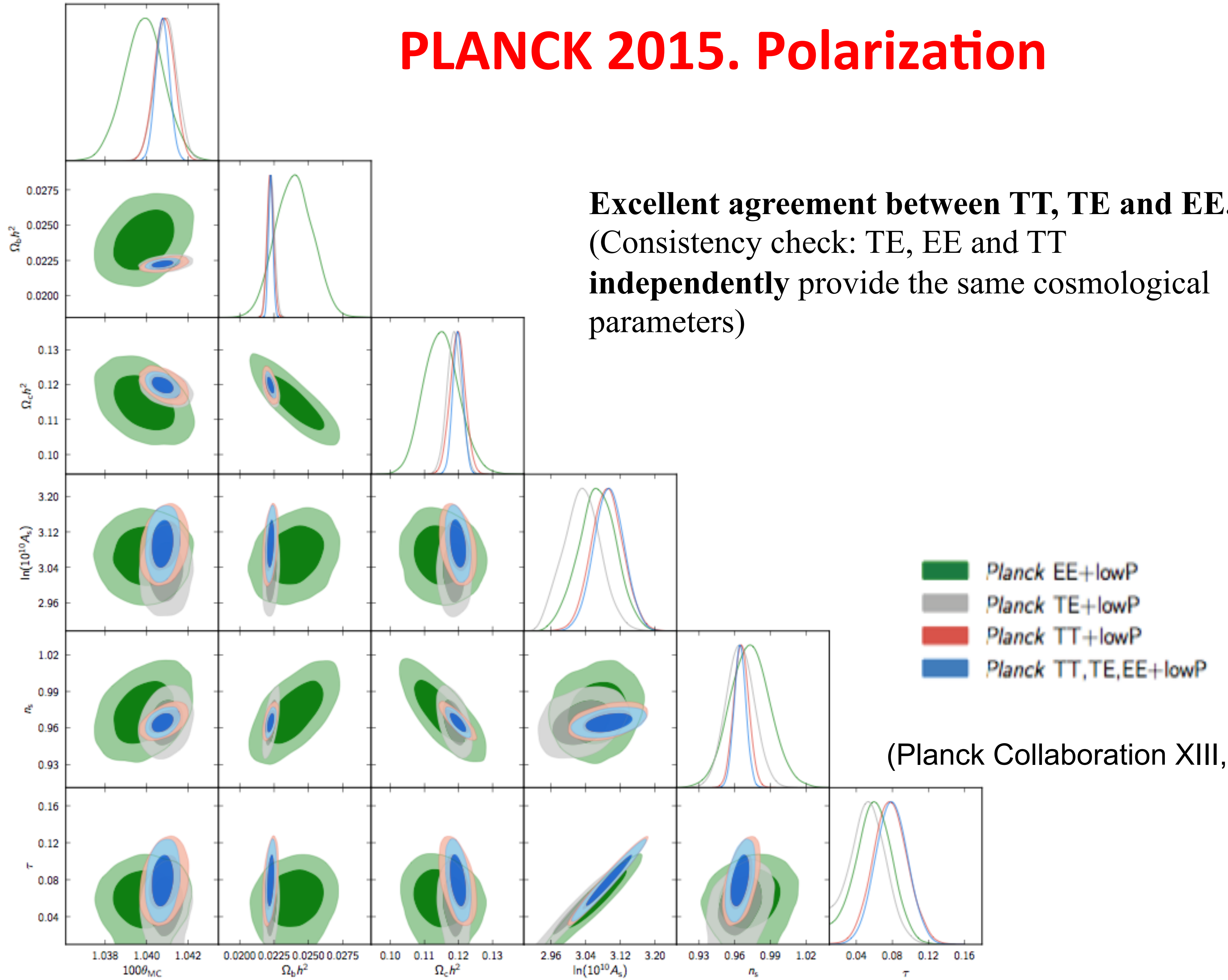


Planck Collaboration XIII (2016)
140
70
0
-70
-140
$\mathcal{D}_\ell^{TE}$ [μK^2]
10
0
-10
$\Delta\mathcal{D}_\ell^{TE}$
30
500
1000
1500
2000
ℓ



Planck Collaboration XIII (2016)
C_ℓ^{EE} [10^{-5} μK^2]
ΔC_ℓ^{EE}
100
80
60
40
20
0
4
0
-4
30
500
1000
1500
2000
ℓ

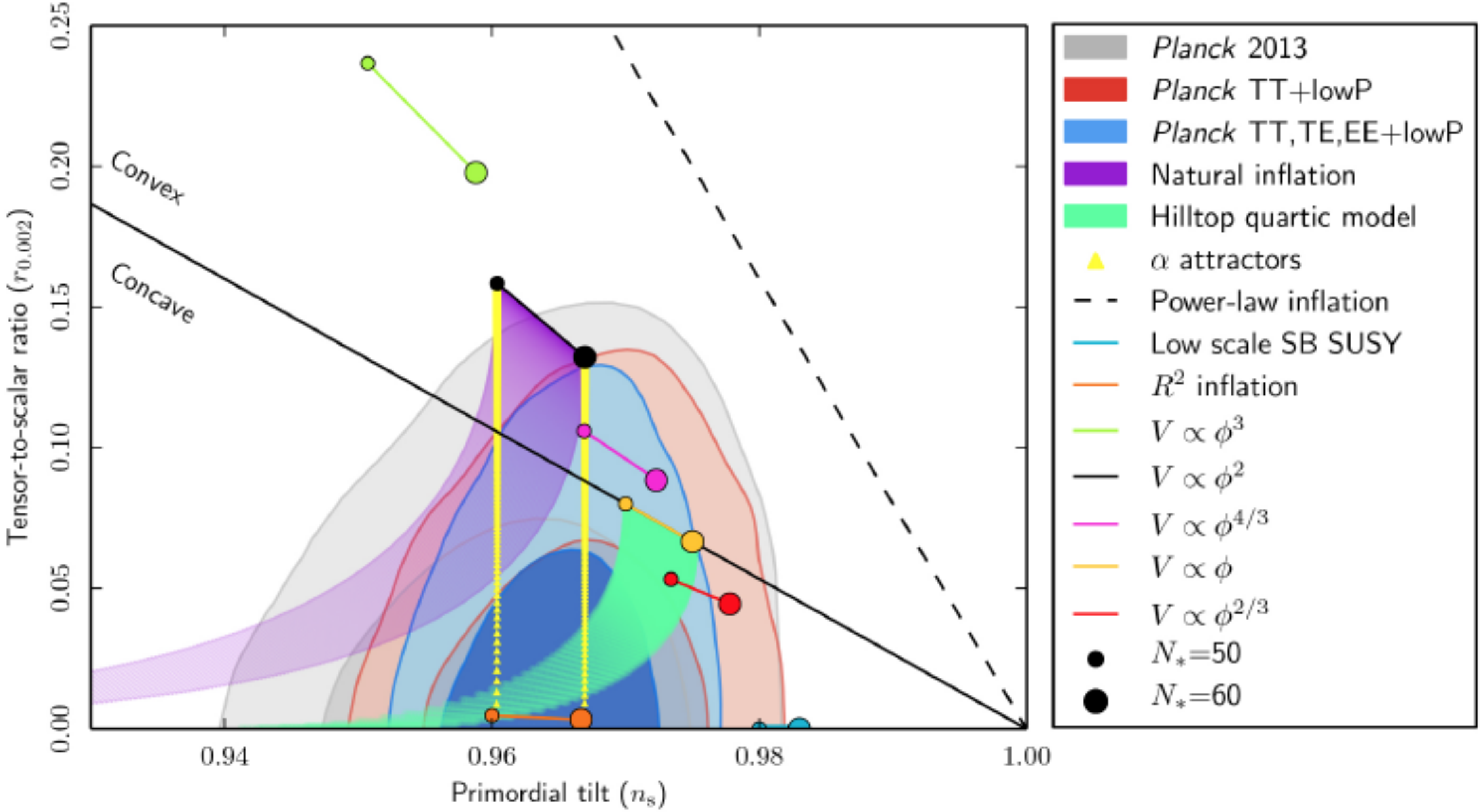
PLANCK 2015. Polarization



Excellent agreement between TT, TE and EE.
(Consistency check: TE, EE and TT **independently** provide the same cosmological parameters)

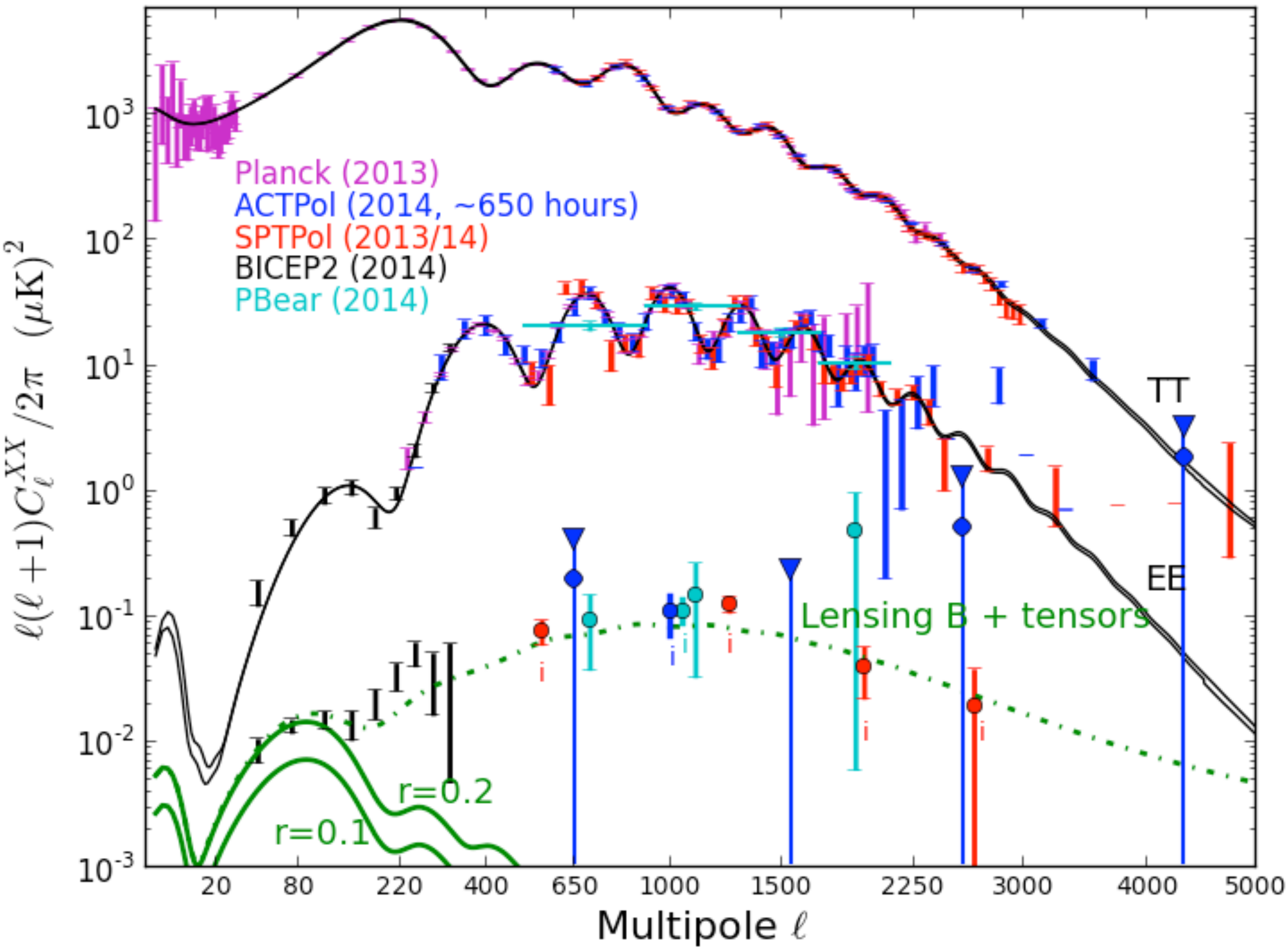
(Planck Collaboration XIII, 2016)

PLANCK 2015. Implications on inflation

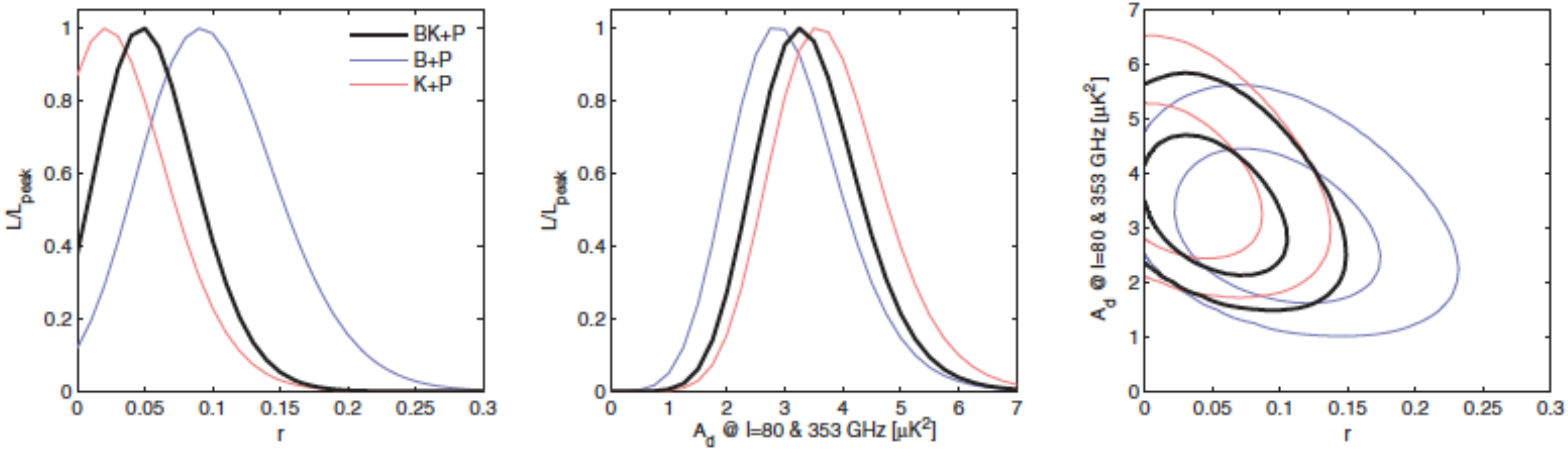


(Planck Collaboration XX, 2016)

State of TT, EE, BB – early 2015



Joint analysis of BICEP2/Keck and PLANCK

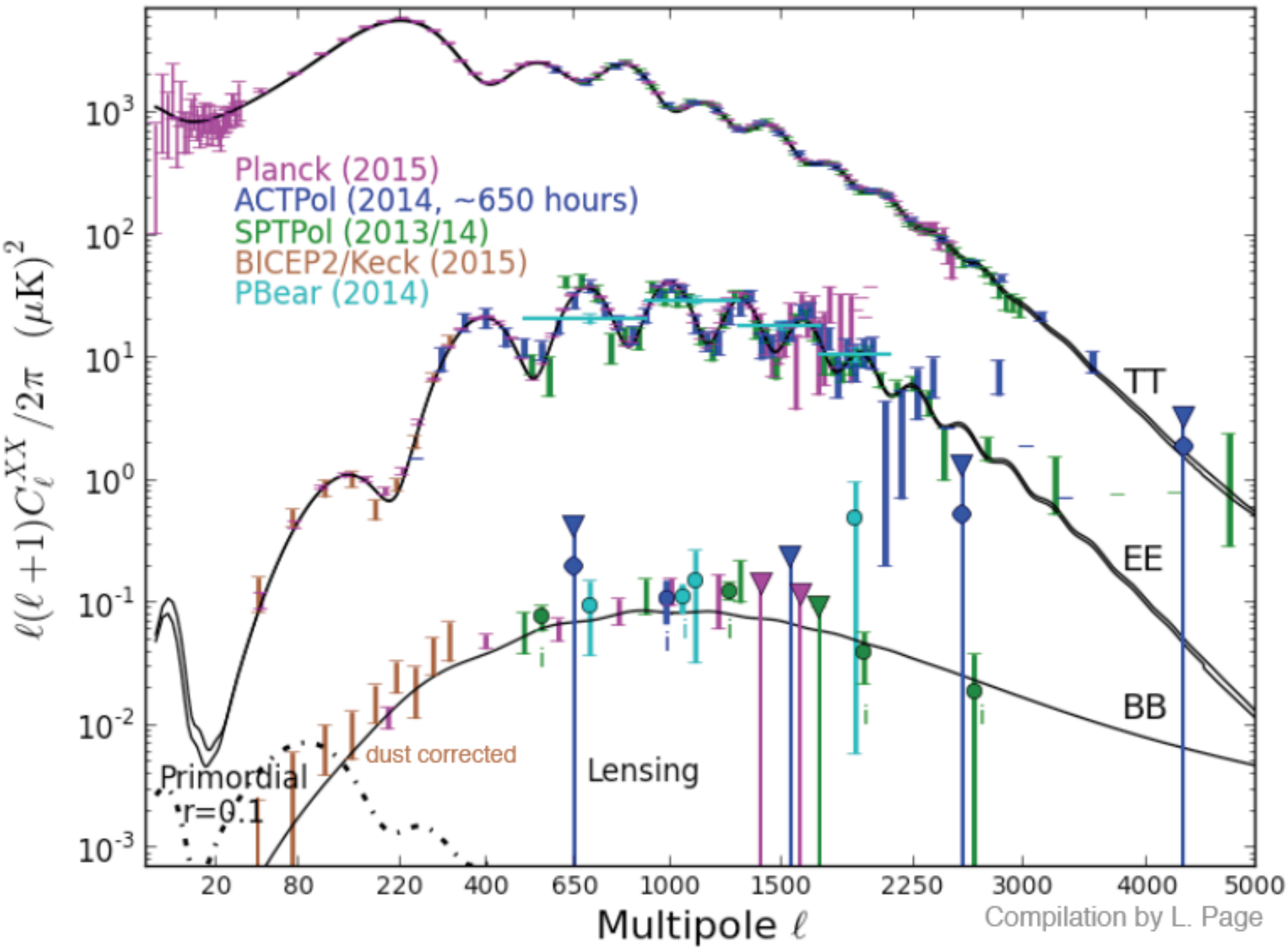


- r=0.048 +-0.035 → r<0.12 at 95% C.L.
- 5.1 sigma detection of **dust emission**→ foregrounds!
- Other lines: BICEP alone, Keck alone.

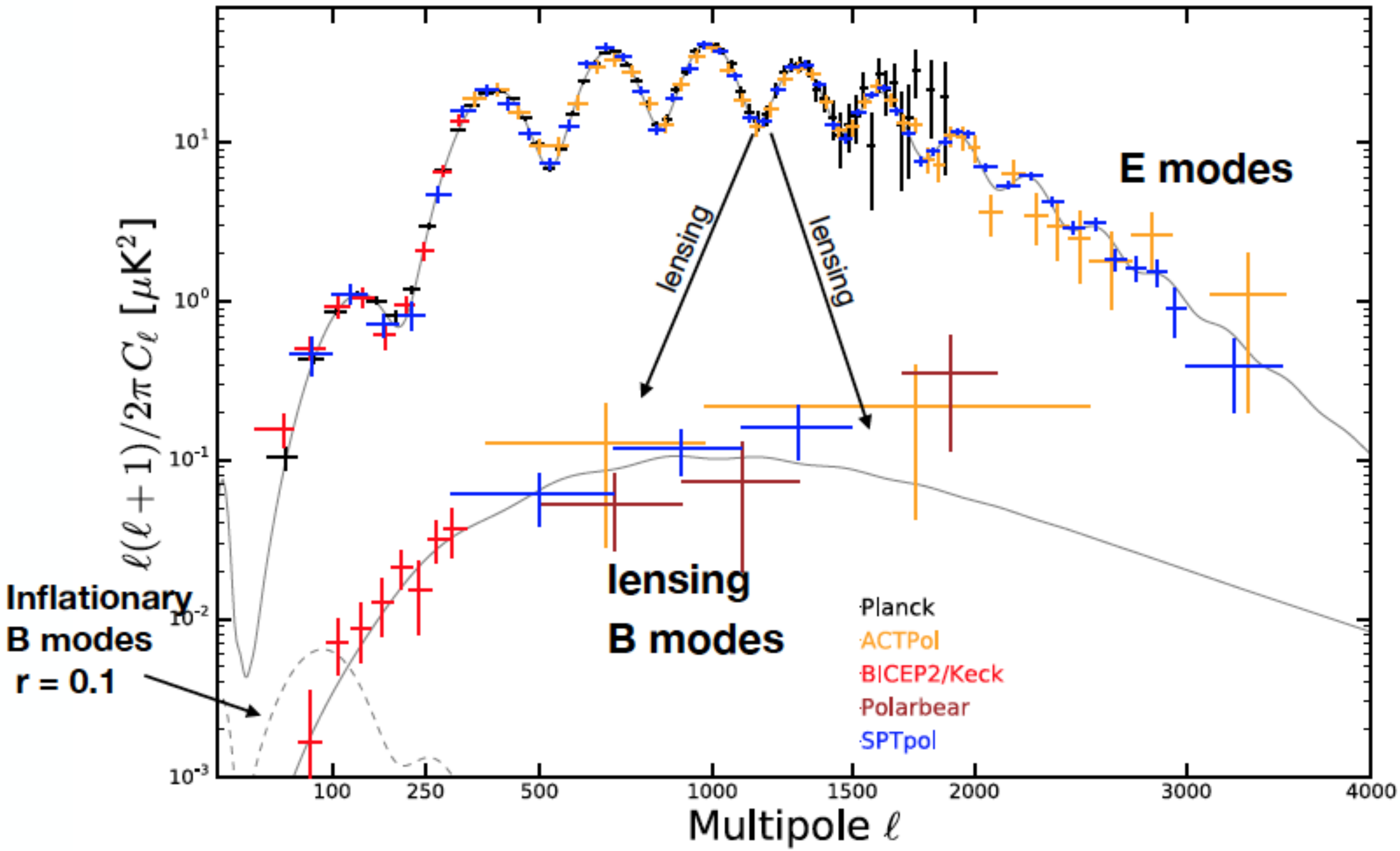
- Other results: 7 sigma detection of lensing B modes.

BICEP2 Keck and Planck Collaborations (2015), PRL 114, 101301.

State of TT, EE, BB – mid 2015

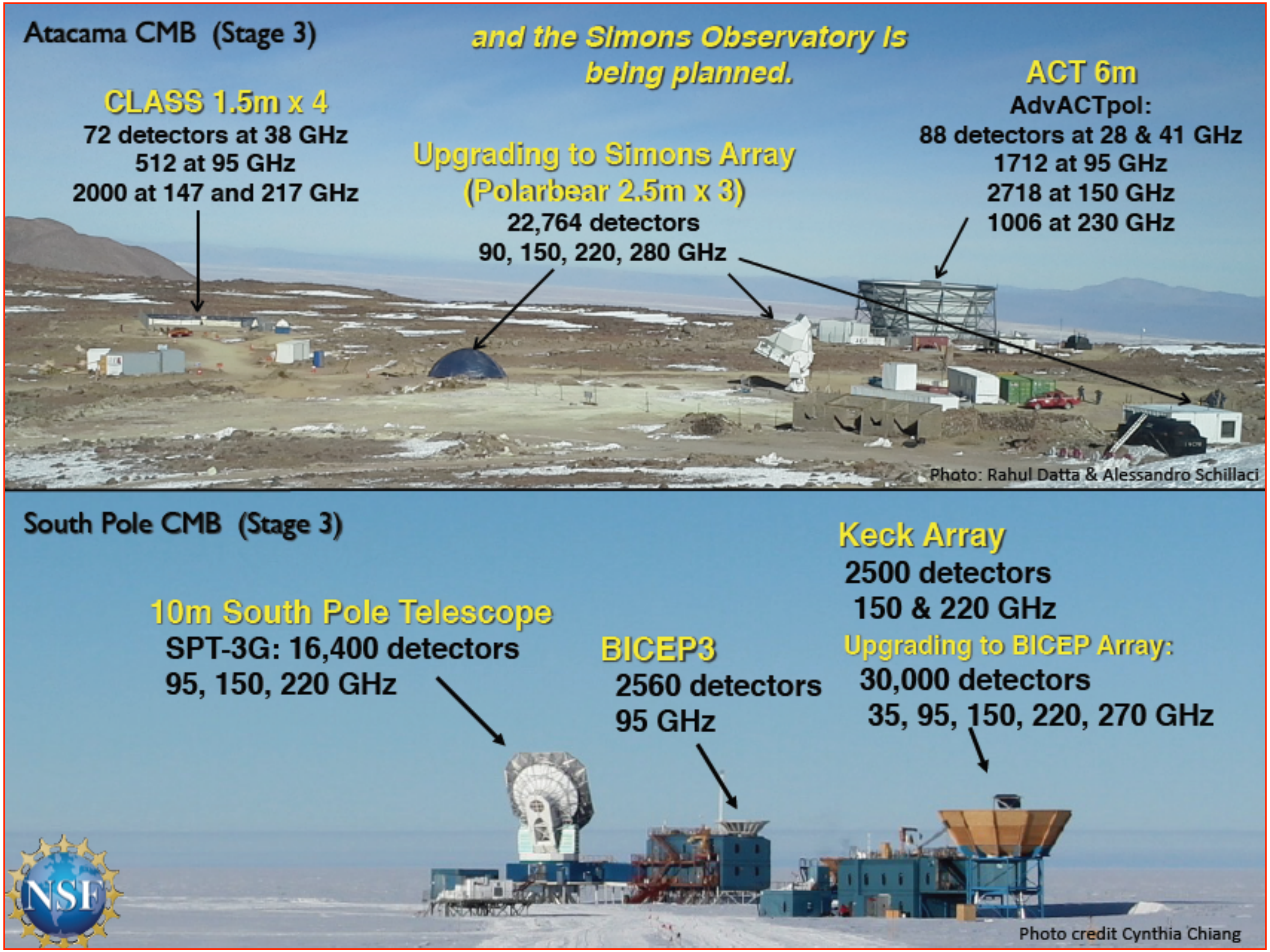


State of EE, BB – 2017



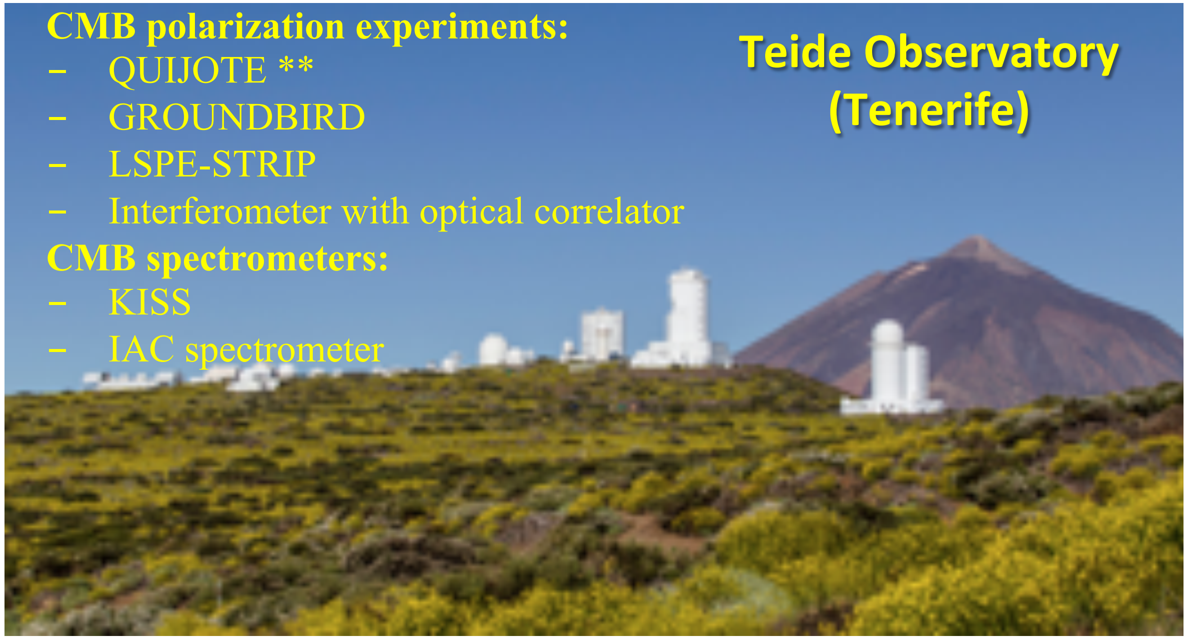
Rapid progress. All within last few years.

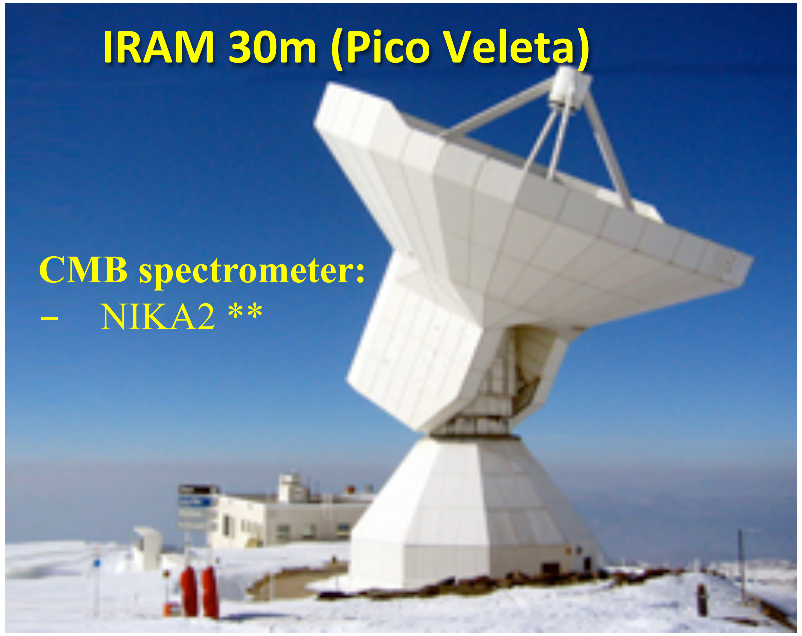
CMB Stage 3 experiments

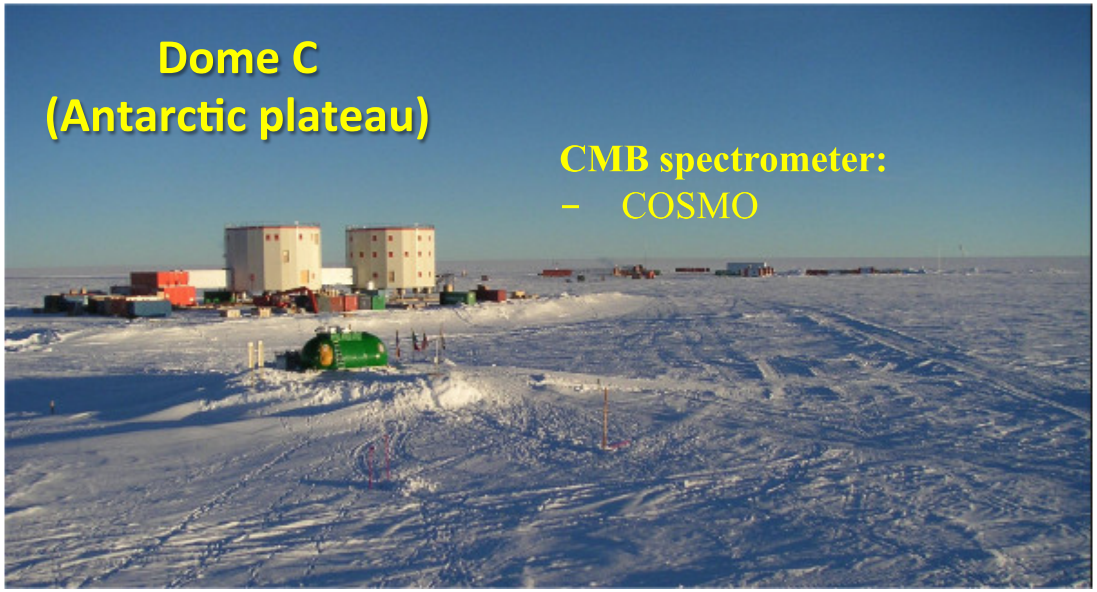


(Slide from J. Carlstrom. Florence 2017. https://indico.in2p3.fr/event/14661/timetable)

CMB experiments at European sites

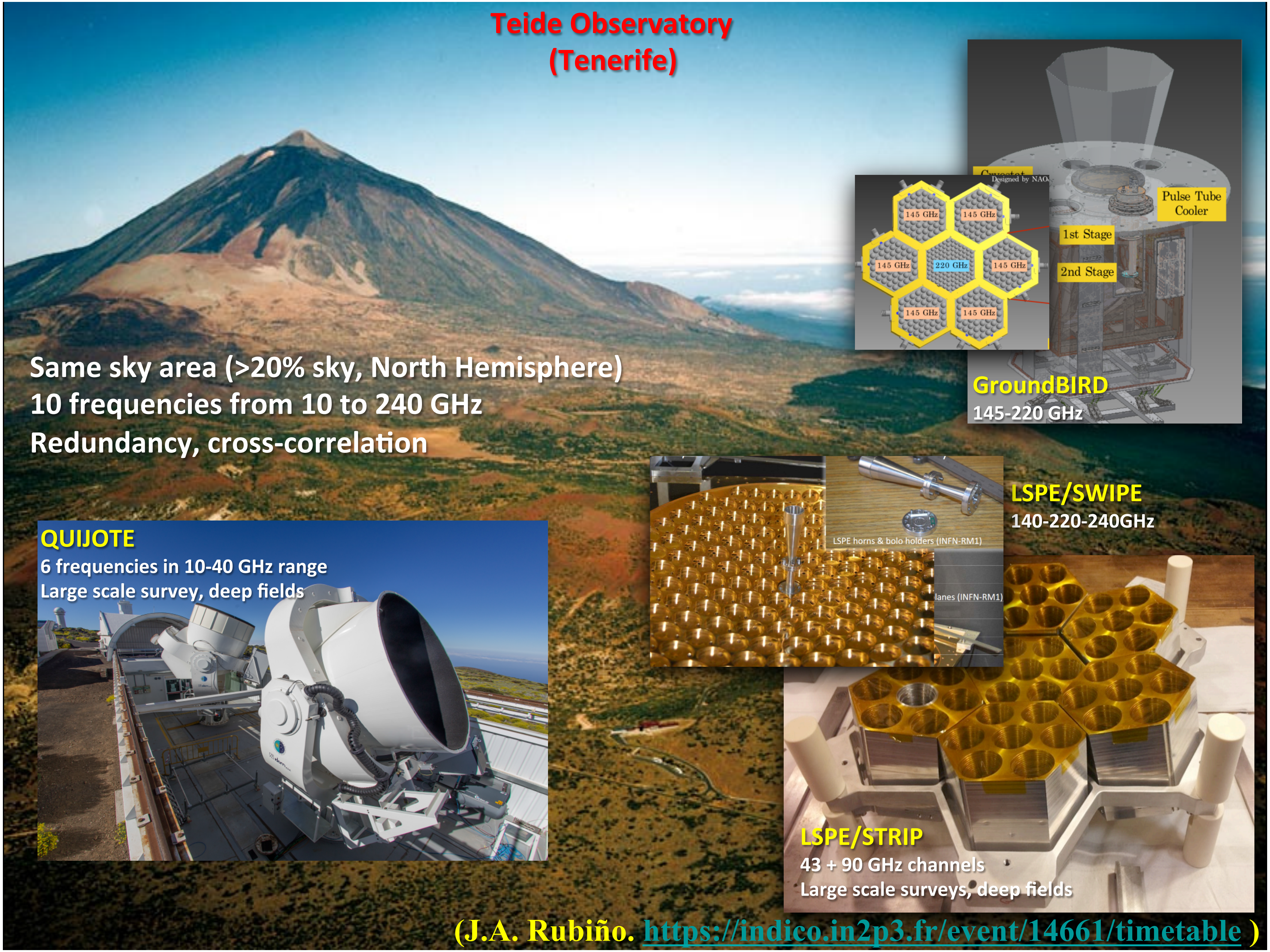






(** = in operation)

(J.A. Rubiño. https://indico.in2p3.fr/event/14661/timetable)


Teide Observatory
(Tenerife)
Same sky area (>20% sky, North Hemisphere)
10 frequencies from 10 to 240 GHz
Redundancy, cross-correlation
Pulse Tube Cooler
1st Stage
2nd Stage
145 GHz
220 GHz
GroundBIRD
145-220 GHz
LSPE/SWIPE
140-220-240GHz
LSPE horns & bolo holders (INFN-RM1)
QUIJOTE
6 frequencies in 10-40 GHz range
Large scale survey, deep fields
LSPE/STRIP
43 + 90 GHz channels
Large scale surveys, deep fields
(J.A. Rubiño. https://indico.in2p3.fr/event/14661/timetable)

Moore's law for detectors

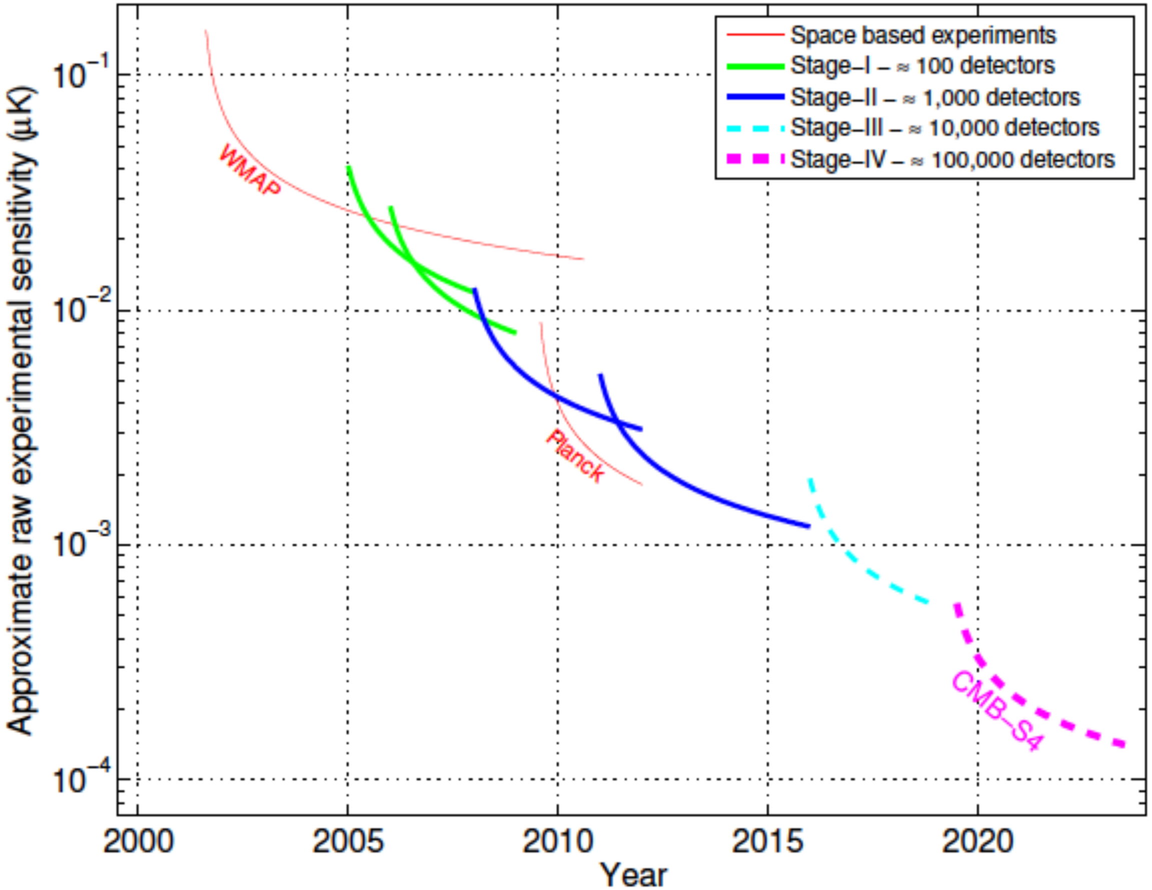
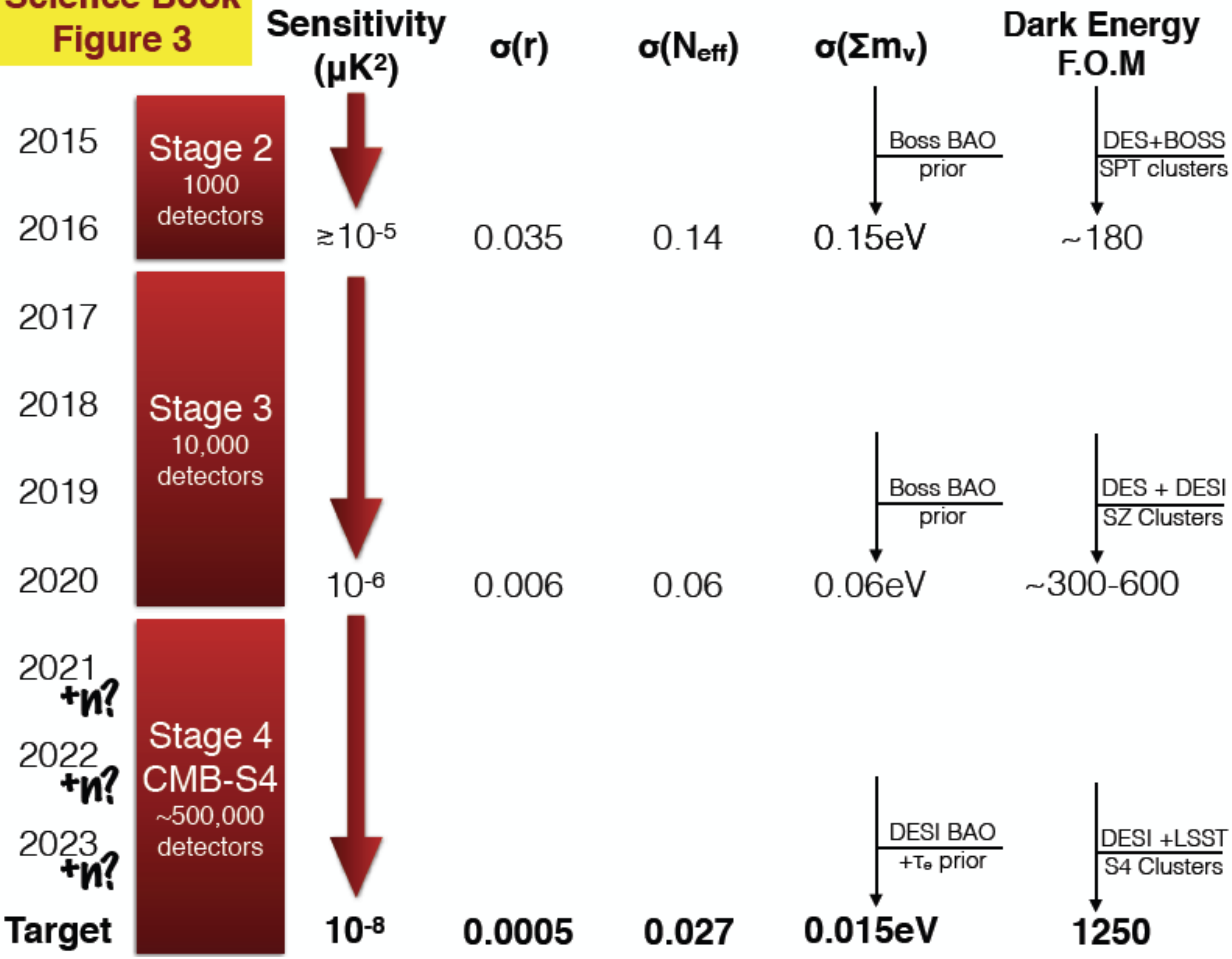


Figure 2. *Plot illustrating the evolution of the raw sensitivity of CMB experiments, which scales as the total number of bolometers. Ground-based CMB experiments are classified into Stages with Stage II experiments having O(1000) detectors, Stage III experiments having O(10,000) detectors, and a Stage IV experiment (such as CMB-S4) having O(100,000) detectors. Figure from Snowmass CF5 Neutrino planning document.*

CMB-S4 Science Book – arXiv:1610.02743

Science Book Figure 3

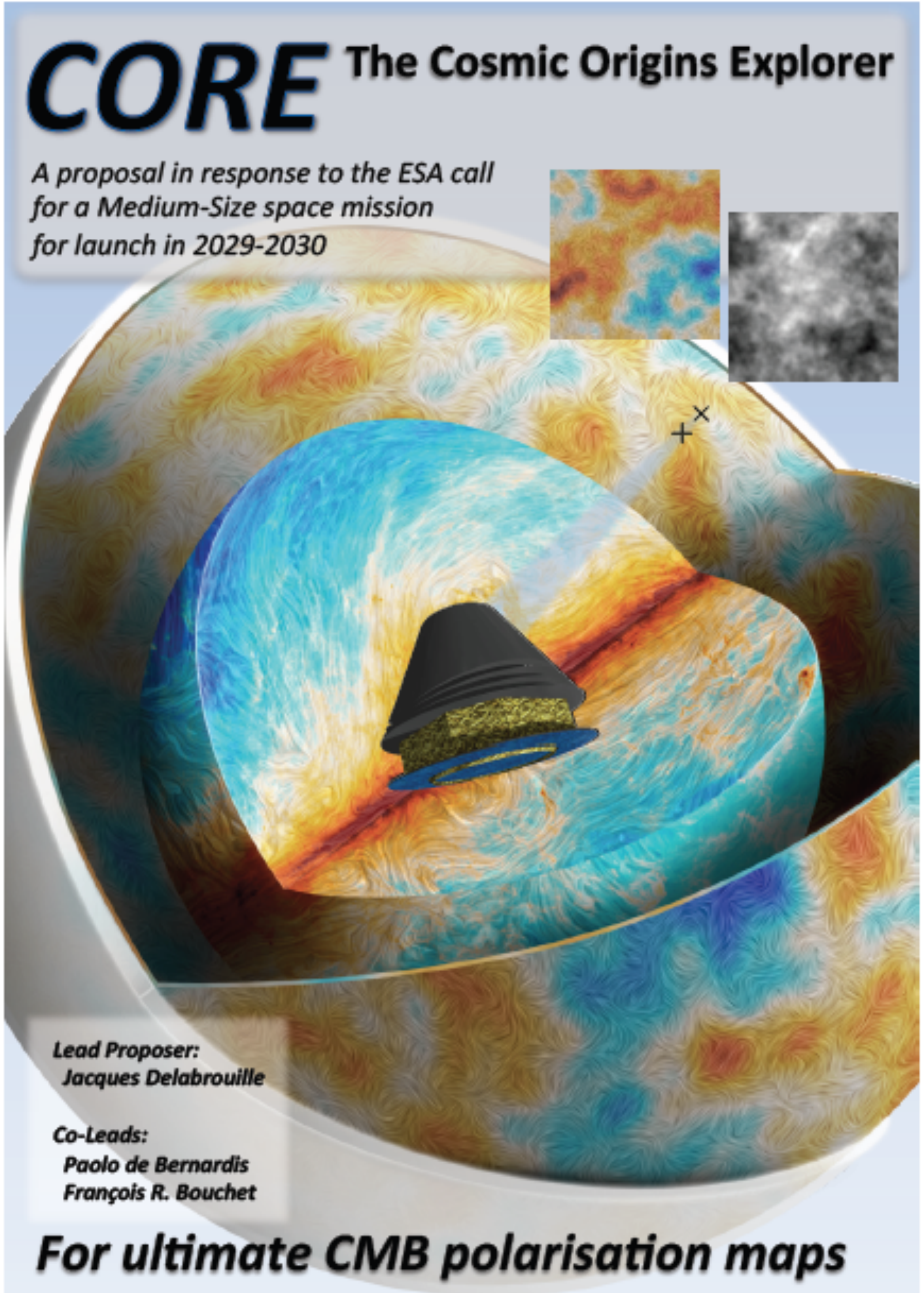
(slide from J. Carlstrom´s talk in Florence 2017)



A European "whitepaper" (in preparation)

http://wiki.e-cmb.org

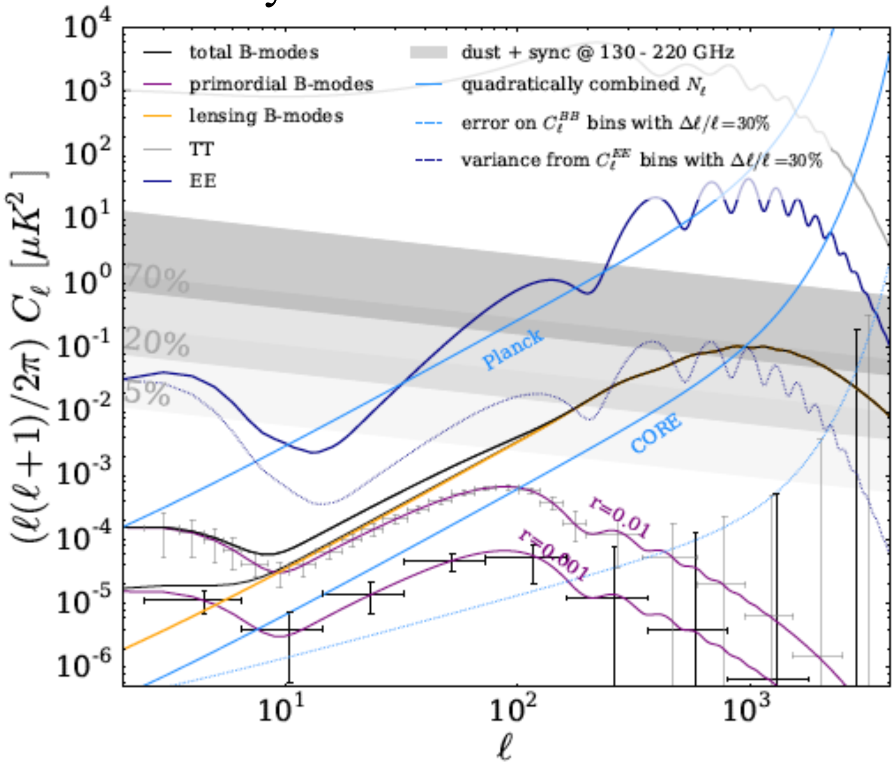
- Introduction
- The Scientific Questions
  - Neutrino Sector, Dark Sector, Inflation, ...
- The Requirements to answer these questions
  - What do we need to do?
- The Community
- The State of the Art Today
  - Planck, the S3 experiments, European experiments, ...
- The Scientific Landscape for the Coming Years
  - S4?, LiteBIRD?, others?
- Near Term Roadmap
- Mid Term Roadmap
- Long Term Roadmap



Submitted to M5 ESA call, but not accepted.

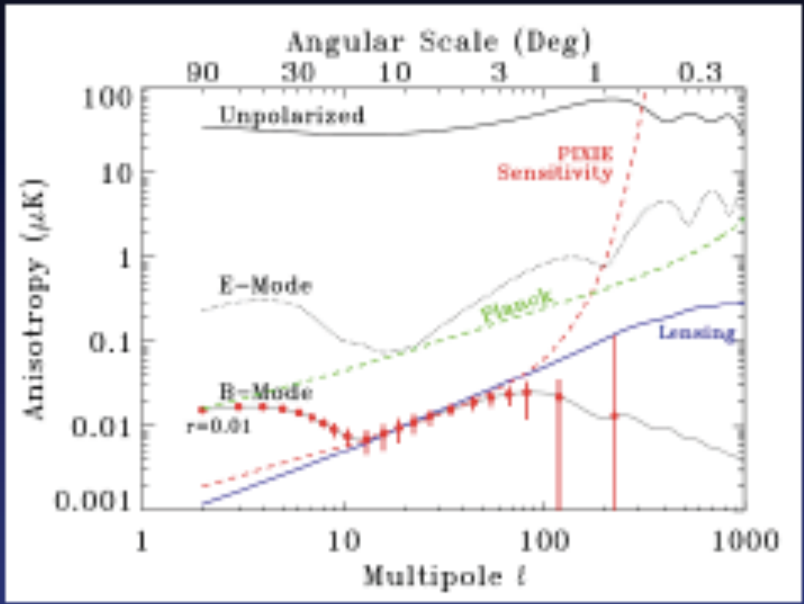
Science case:

- Inflation
- Gravitational lensing (neutrino masses < 44meV).
- DE (FoM increased x10 wrt EUCLID)
- Neff with error <0.04
- Galaxy clusters.

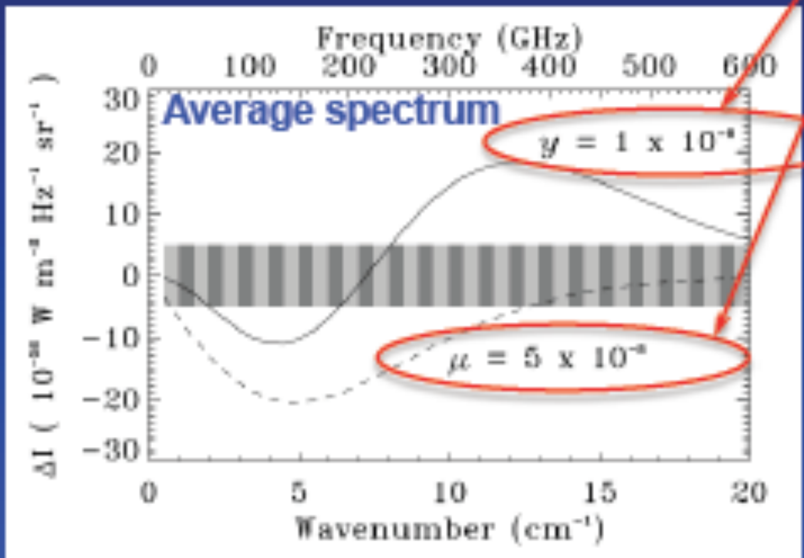


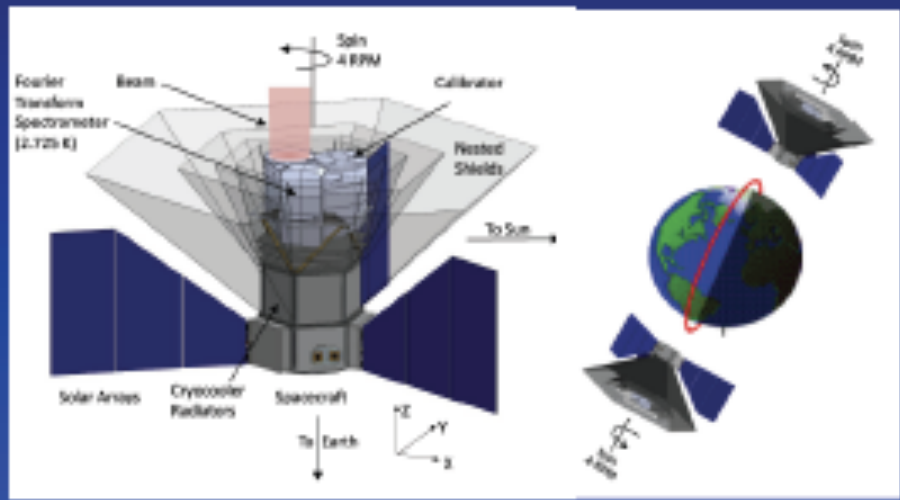
arXiv:170604516

PIXIE: Primordial Inflation Explorer



- 400 spectral channel in the frequency range 30 GHz and 6THz ($\Delta\nu \sim$ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)



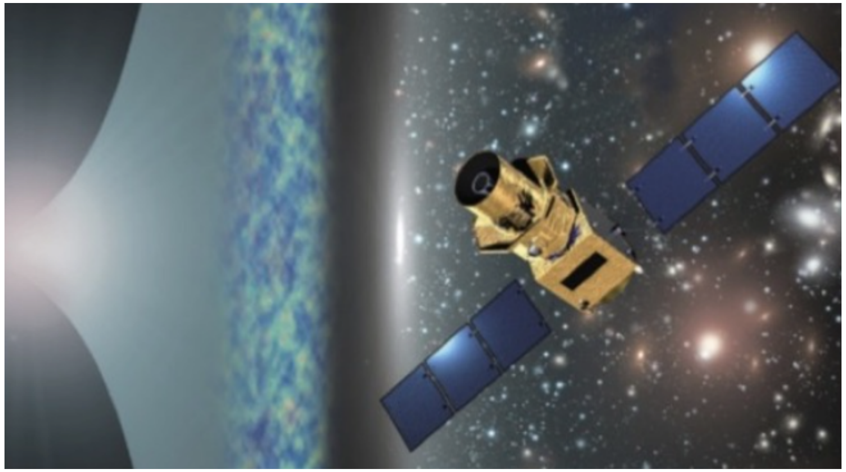


Kogut et al, JCAP, 2011, arXiv:1105.2044

(Slide from J. Chluba)

LiteBIRD

Lite *(Light) Satellite for the Studies of* ***B****-mode Polarization and* ***I****nflation from Cosmic Background* ***R****adiation* ***D****etection – Japanese PI: Masashi Hazumi, US PI: Adrian Lee*



Focused mission:
- Detect r with σ(r=0)<0.001, without the help of delensing
- Multipole coverage 2<l<200

Status: Phase A.

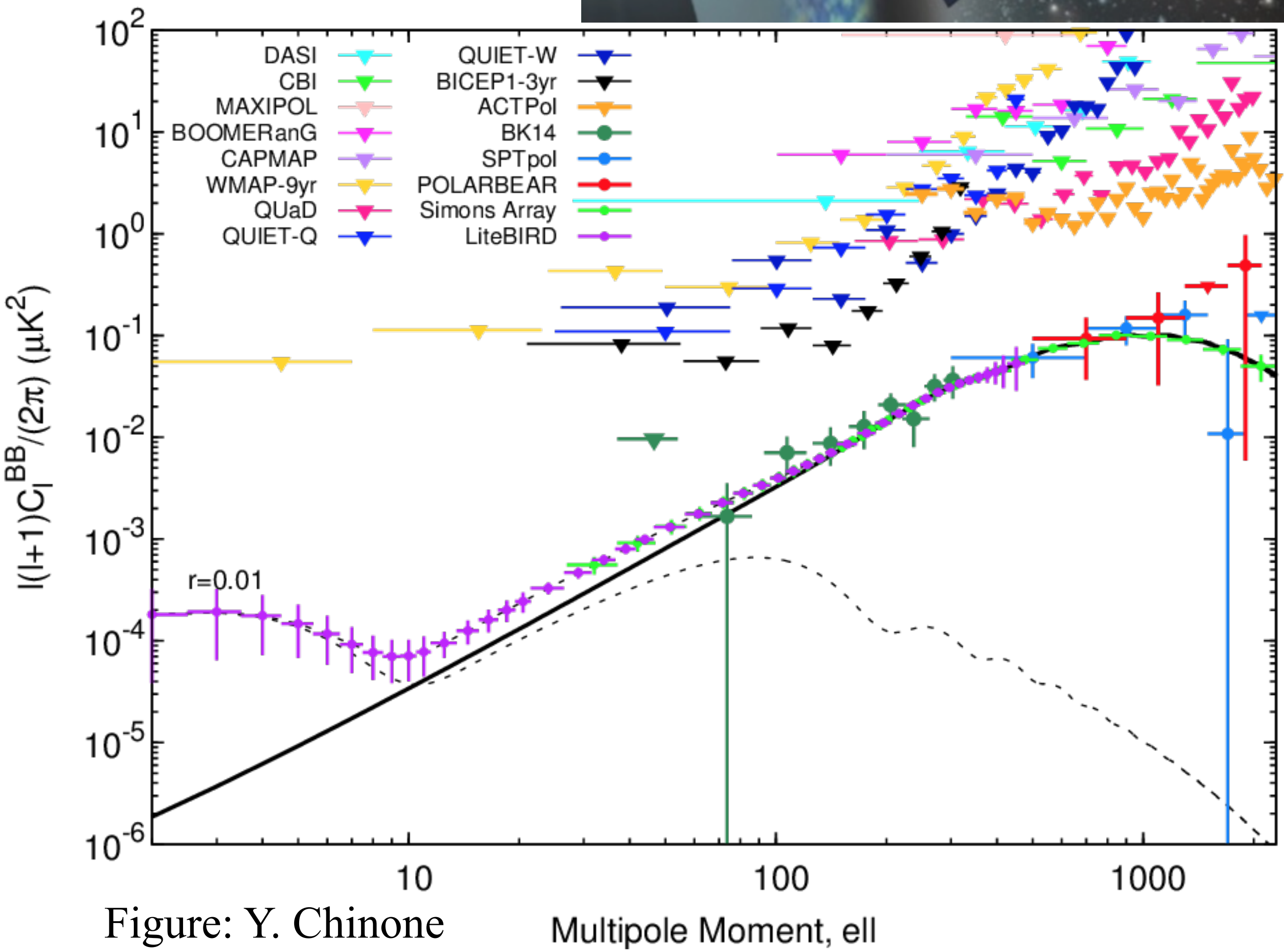


Figure: Y. Chinone

Conclusions

- A very significant fraction of all the information in cosmology over the last 20 years has come from the study of the CMB anisotropies.
- Still a wealth of information encoded in the polarization of the CMB.
    - Inflation: origin of primordial perturbations. But not only this!
    - Light relics from early universe (Neff)
    - Neutrino: setting the mass scale and testing the 3-neutrino paradigm
    - Reionization: complementary way to 21cm studies.
    - Primordial magnetic fields, Cosmic strings.
    - CMB lensing: mapping all mass in the universe. → X-correlation studies.
    - Dark matter, dark energy
    - Unknowns: CMB anomalies at low multipoles, tensions between high & low z universe (H_0, sigma8), lensing, …