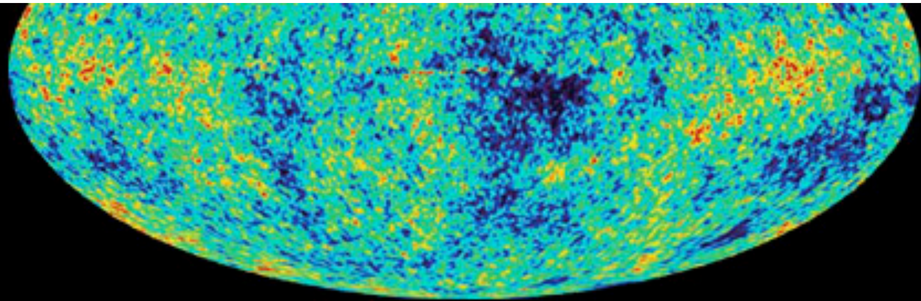
CMB and High Energy Physics
from Early Universe to clusters
of galaxies and Large Scale Structure
La Palma, July 16-24, 2012



Primordial Gravitational waves and the polarization of the CMB

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Outline

Lecture 1.

- Theory of CMB polarization.
  - E and B modes.
  - Primordial Gravitational waves.
- Observational status: CMB polarization measurements. E-mode detections and B-mode constraints.

Lecture 2.

- Foregrounds of the CMB.
- The future (CMB polarization experiments).
  - The Planck satellite.
  - QUIJOTE CMB experiment.
  - Core satellite.

Lecture 1. Bibliography

Books:

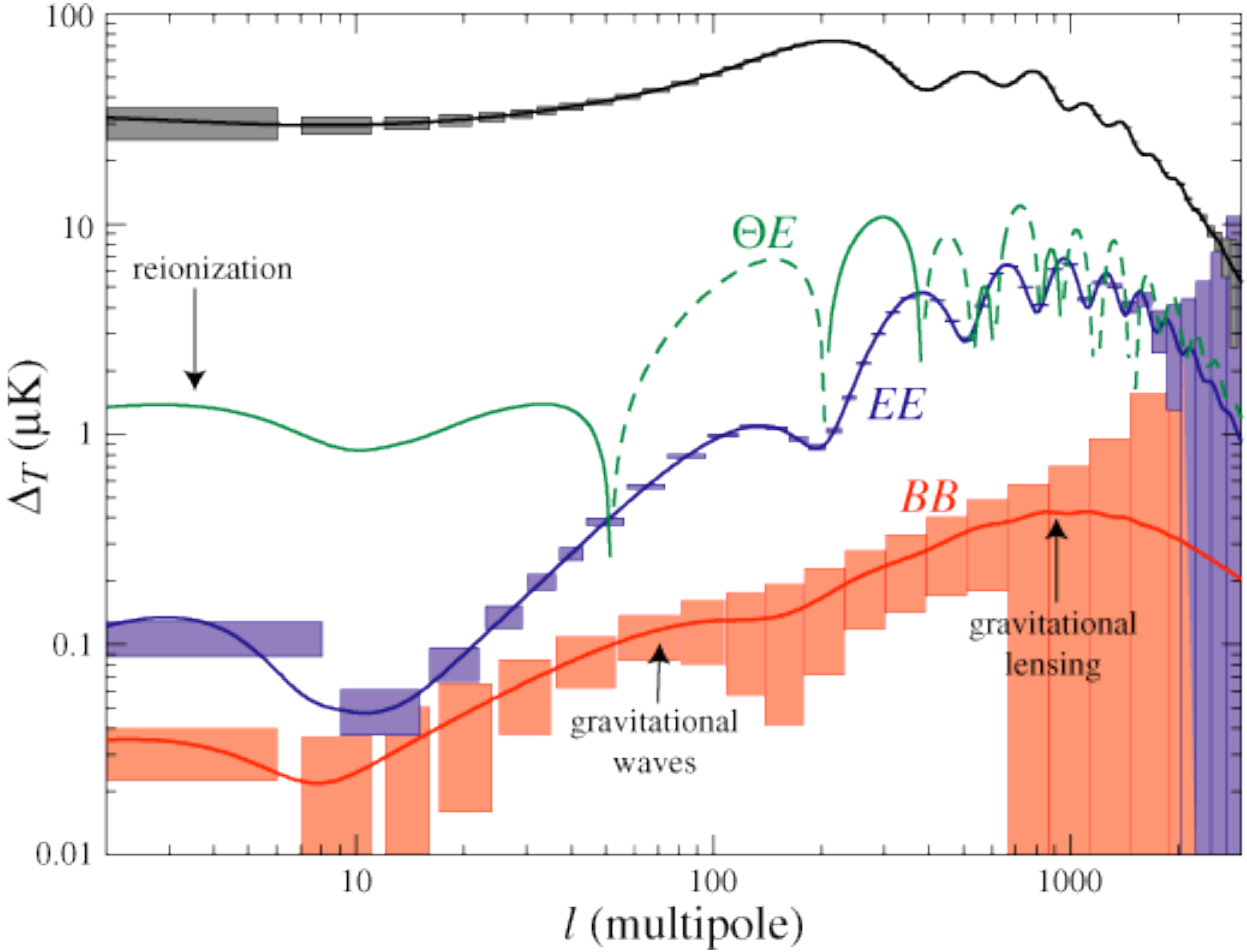
- ***Cosmological Inflation and Large Scale Structure.*** Liddle & Lyth (CUP 2000).
- ***Cosmology.*** S Weinberg (Oxford Univ. Press 2008)***.***
- ***The Cosmic Microwave Bakcground.*** Durrer (CUP 2008).
- ***The primordial density perturbation.*** Lyth & Liddle (CUP 2009)
- **The Cosmic Microwave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

Papers (Polarization of the CMB):

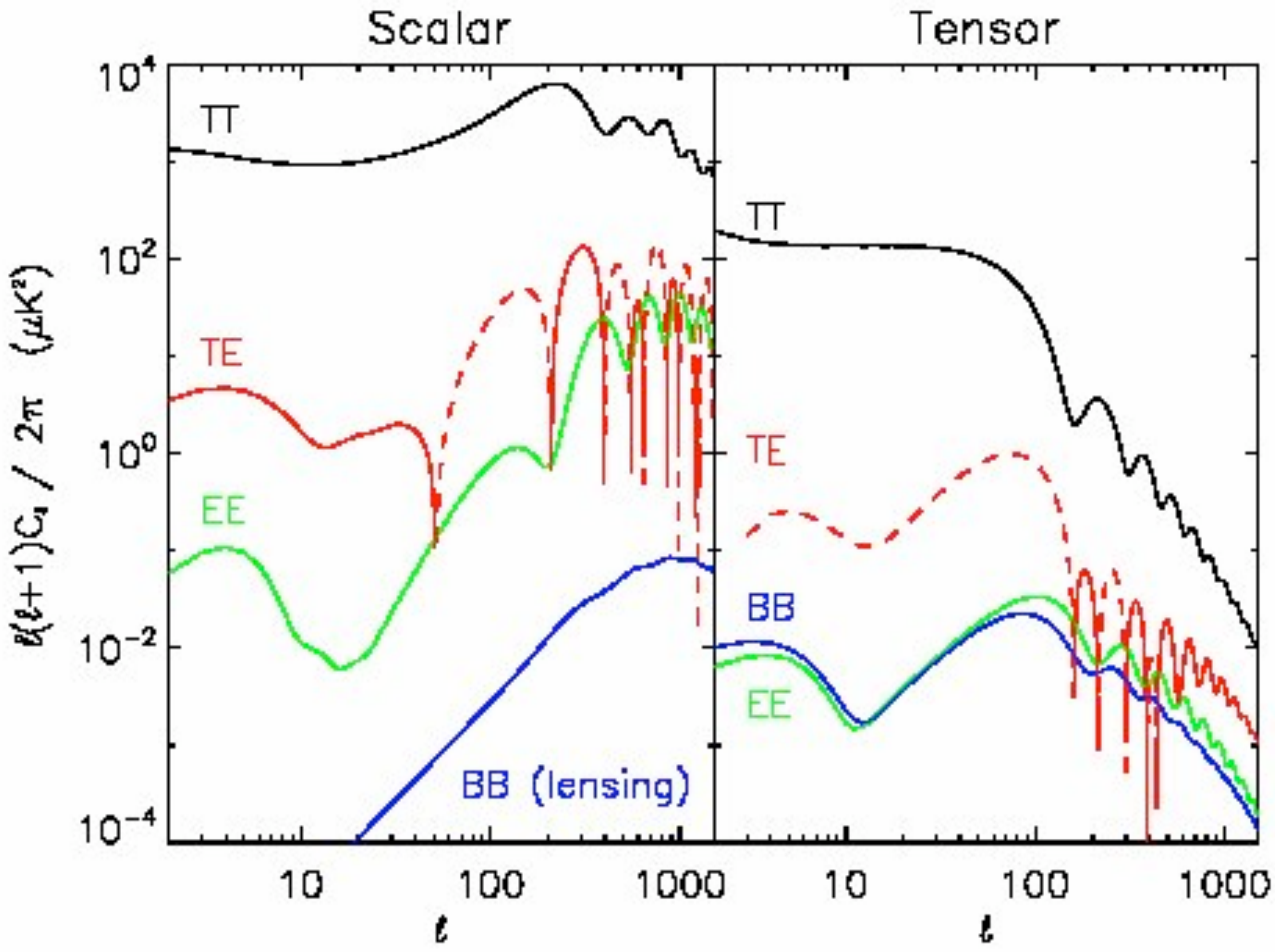
- Ma & Bertschinger (1995), ApJ, 455, 7.
- Hu & Sugiyama (1995), Phys. Rev. D 51, 2599
- Seljak & Zaldarriaga (1996), ApJ, 469, 437.
- Zaldarriaga & Seljak (1997), Phys. Rev. D. 55, 1830.
- Kamionkowski, Kosowsky & Stebbins (1997), Phys. Rev. D 55, 7368.

Remember A. Lasenby´s talk

Physics of the CMB anisotropies: the angular power spectrum



Power spectra - Theory



Stokes parameters

❖The polarization state of a electromagnetic wave propagating in a direction **n** can described by the intensity matrix

$$P_{ij} = \left\langle E_i(\hat{n}) E_j^*(\hat{n}) \right\rangle$$

where **E** is the electric field vector and the brackets denote time averaging.

❖ P is a hermitian 2x2 matrix and thus can be decomposed into the Pauli basis

$$P = I(\hat{n})\sigma_0 + Q(\hat{n})\sigma_3 + U(\hat{n})\sigma_1 + V(\hat{n})\sigma_2$$

$$\sigma_0 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \qquad \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

❖ In terms of the electric field, the Stokes parameters are defined as:

$$I = |E_1|^2 + |E_2|^2 \qquad Q = |E_1|^2 - |E_2|^2$$

$$U = (E_1^* E_2 + E_2^* E_1) = 2\mathrm{Re}(E_1^* E_2) \qquad V = 2\mathrm{Im}(E_1^* E_2)$$

Stokes parameters

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

❖ Q measures the different of intensities in the to 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

$$I' = I \qquad V' = V$$

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

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: ${}_sY_{\ell m} \longrightarrow e^{\pm si\psi}\,{}_sY_{\ell m}(\hat{n})$
- 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

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

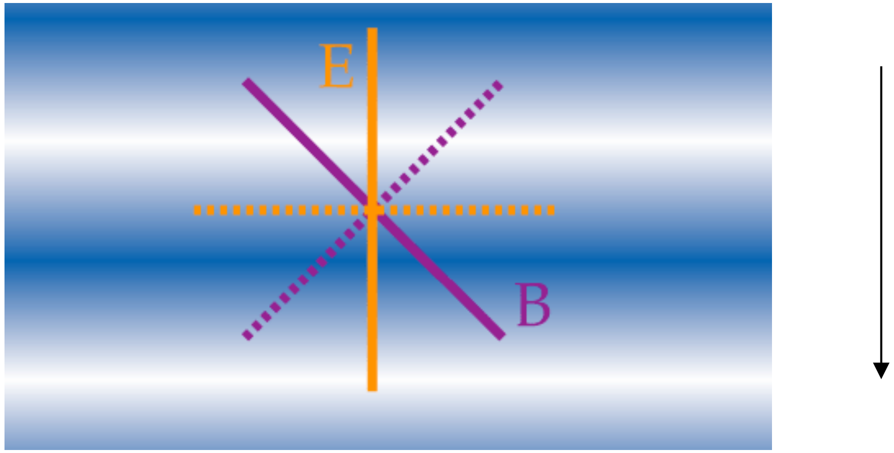
❖ In the last equality we have defined E- and B-modes:

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

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

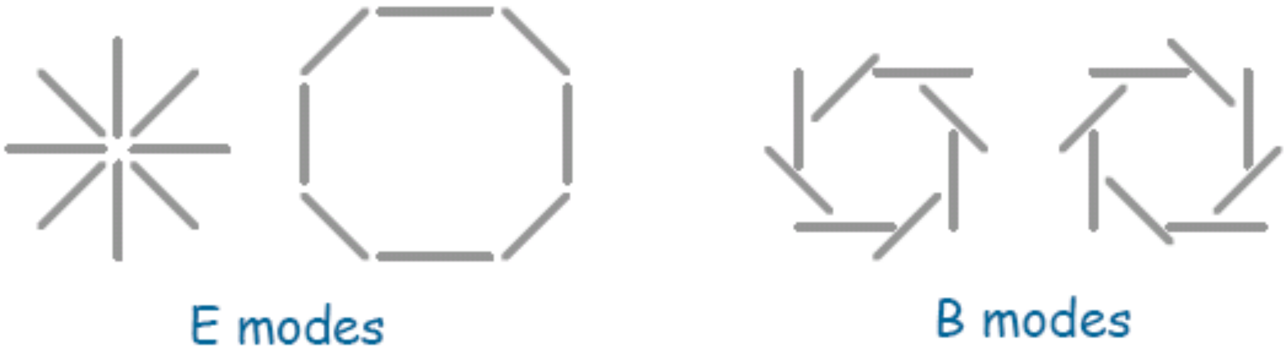
❖ Under parity transformations (**n→-n**), the E-modes remain invariant, while B-modes change sign.

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).

Angular power spectra

$$C_{Tl} = \frac{1}{2l+1} \sum_m \langle a^*_{T,lm} a_{T,lm} \rangle,$$

$$C_{El} = \frac{1}{2l+1} \sum_m \langle a^*_{E,lm} a_{E,lm} \rangle,$$

$$C_{Bl} = \frac{1}{2l+1} \sum_m \langle a^*_{B,lm} a_{B,lm} \rangle,$$

$$C_{Cl} = \frac{1}{2l+1} \sum_m \langle a^*_{T,lm} a_{E,lm} \rangle,$$

in terms of which,

$$\langle a^*_{T,l'm'} a_{T,lm} \rangle = C_{Tl} \delta_{l'l} \delta_{m'm},$$

$$\langle a^*_{E,l'm'} a_{E,lm} \rangle = C_{El} \delta_{l'l} \delta_{m'm},$$

$$\langle a^*_{B,l'm'} a_{B,lm} \rangle = C_{Bl} \delta_{l'l} \delta_{m'm},$$

$$\langle a^*_{T,l'm'} a_{E,lm} \rangle = C_{Cl} \delta_{l'l} \delta_{m'm},$$

$$\langle a^*_{B,l'm'} a_{E,lm} \rangle = \langle a^*_{B,l'm'} a_{T,lm} \rangle = 0.$$

The polarization of the CMB anisotropies

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

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

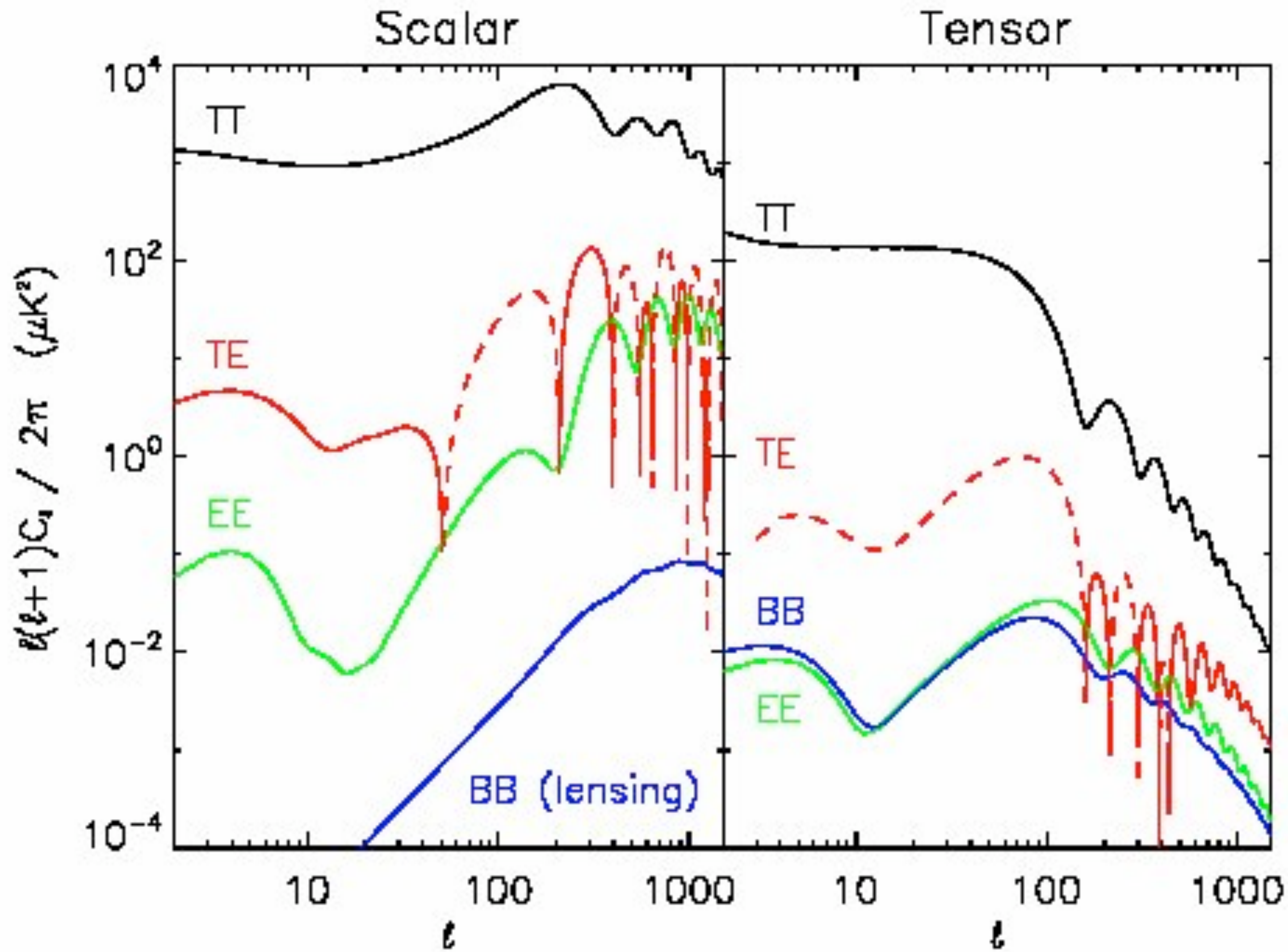
$$C_{EE} = \frac{1}{2l+1} \sum_m \left\langle a^*_{E,lm} \, a_{E,lm} \right\rangle \qquad C_{TE} = \frac{1}{2l+1} \sum_m \left\langle a^*_{T,lm} \, a_{E,lm} \right\rangle$$

- **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.**

Power spectra - Theory



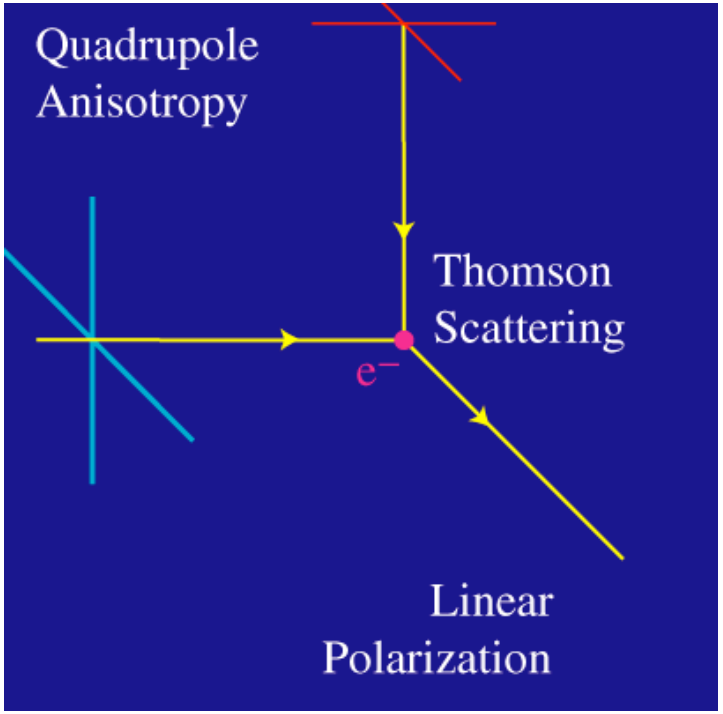
Thomson scattering

❖Differential cross-section

$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi}\left|\hat{\varepsilon}' \cdot \hat{\varepsilon}\right|^2 \sigma_T$$

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

❖ 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:



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

❖ 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.

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).

❖ The basic argument is:

❖ Consider a scattering ocurring at x_0. The mean free path is λ_T. Photons coming from a direction **n** roughly come from

$$x = x_0 + \lambda_T \hat{n}$$

❖ The photon-baryon fluid at that point was moving with velocity

$$v(x) = v(x_0) + \lambda_T \hat{n}_i \partial_i v(x_0)$$

❖ Due to Doppler effect, the temperature by the scatterer at x_0 is

$$\delta T(x_0, \hat{n}) = \hat{n} \cdot [v(x) - v(x_0)] \approx \lambda_T \hat{n}_i \hat{n}_j \partial_i v_j(x_0)$$

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:

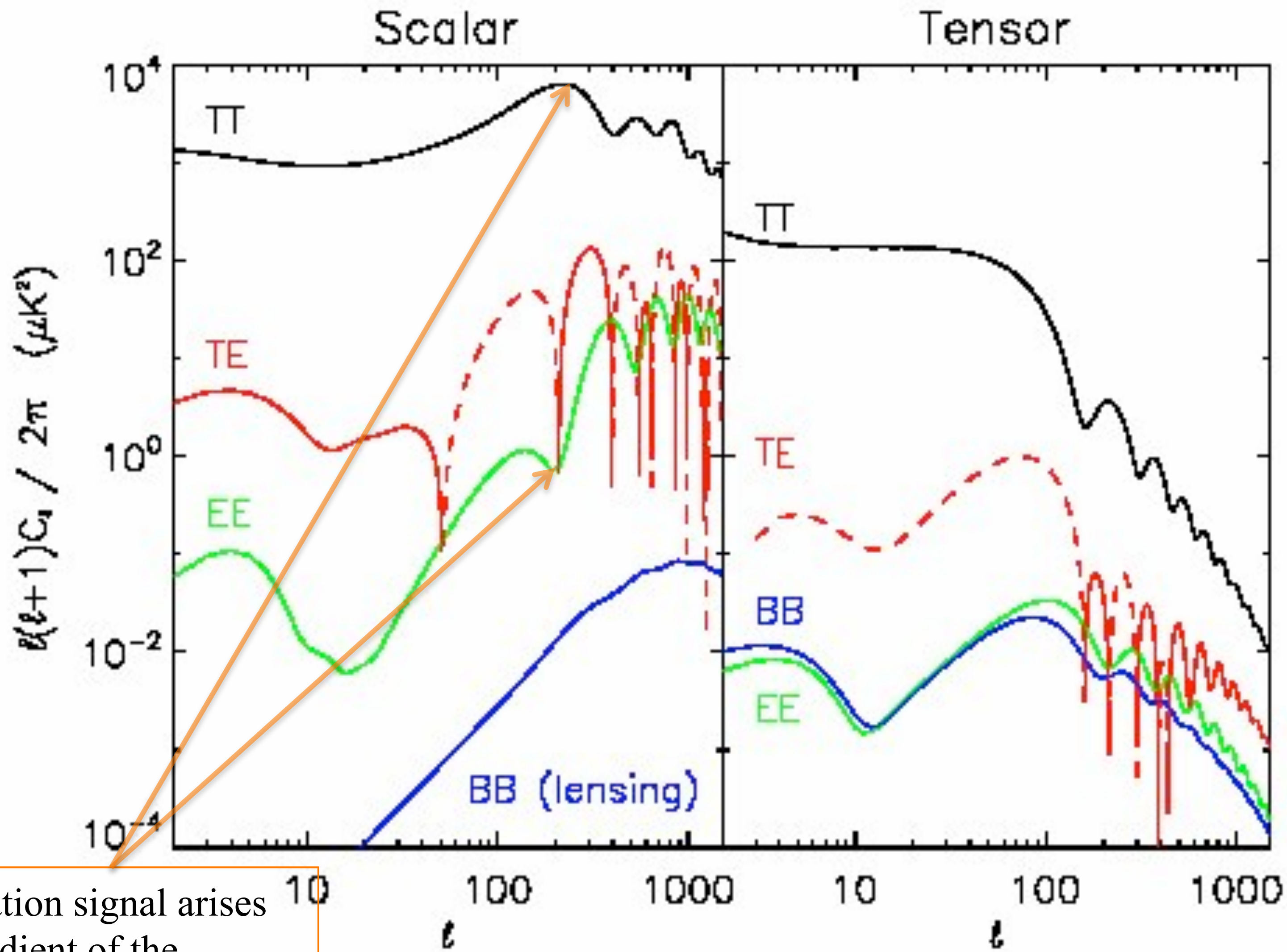
$$\Delta_E \approx -0.17(1-\mu^2)\Delta\eta_{dec} k v_\gamma(\eta_{dec})$$

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

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

- ❖ 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.

TE Polarization and acoustic peaks

❖Cross-correlation of temperature and polarization

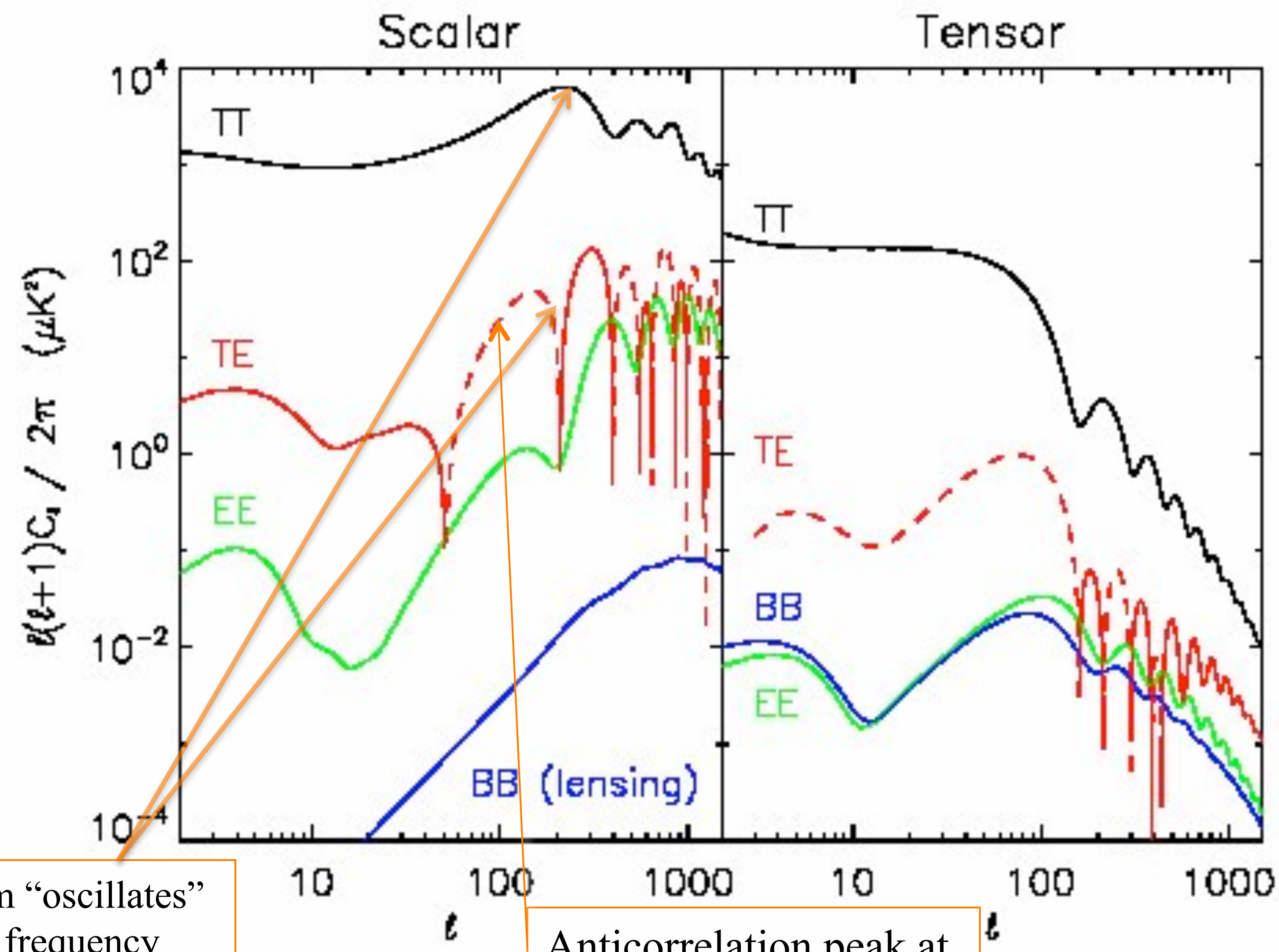
$$\Delta_T \Delta_E \propto \cos(kr_s)\sin(kr_s) \propto \sin(2kr_s)$$

❖ TE spectrum “oscillates” at twice the frequency

❖ TE correlation is radial or tangential around hot spots (see later, WMAP result).

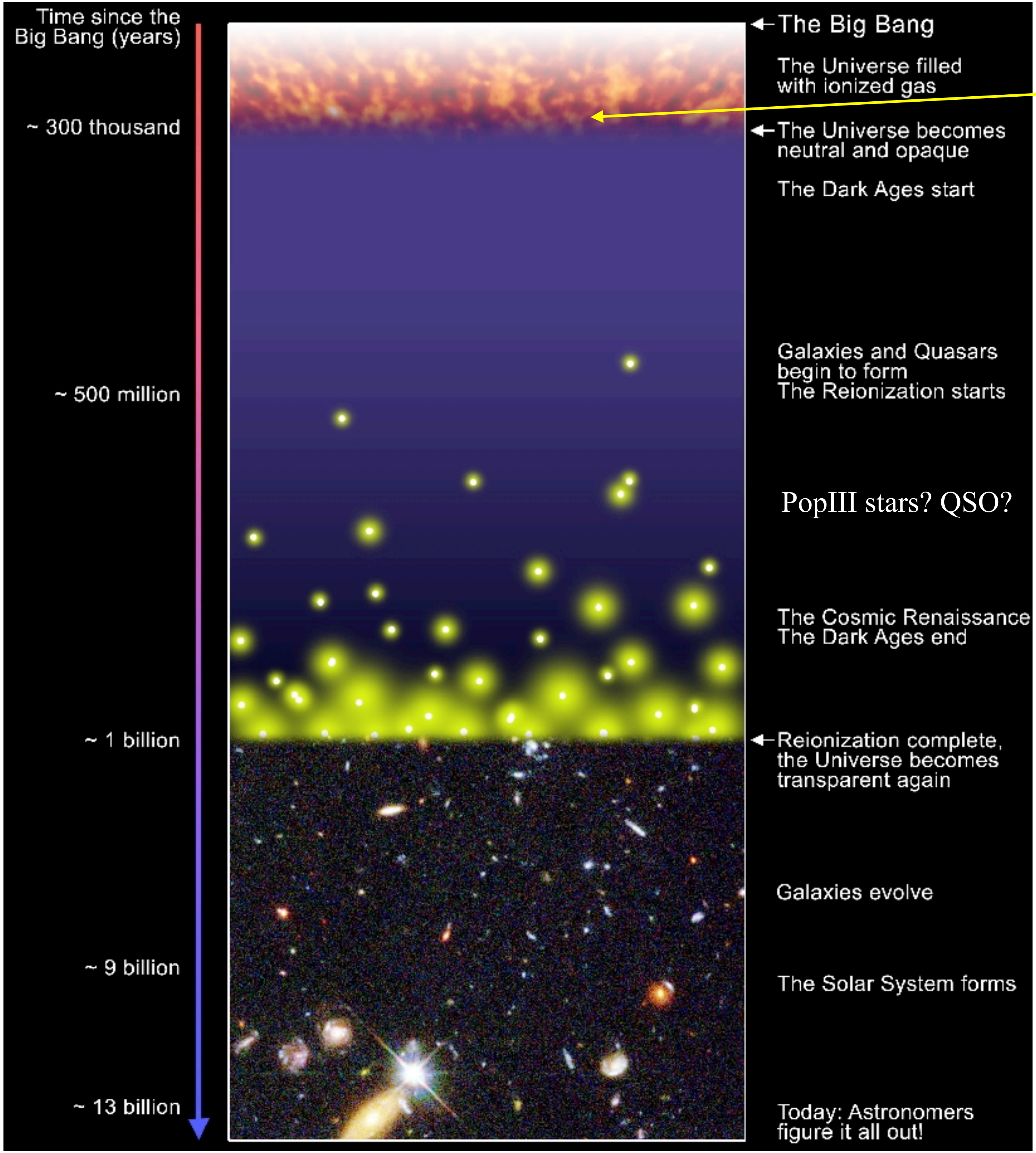
❖ Large scales: anticorrelation peak around l=150, a distinctive signature of primordial adiabatic fluctuations (Peiris et al. 2003).

Power spectra - Theory



TE spectrum "oscillates" at twice the frequency

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



Recombination (z ~ 1000)

(Microwave background)

Dark Ages

(Neutral hydrogen. Accesible with 21cm line surveys as SKA or LOFAR)

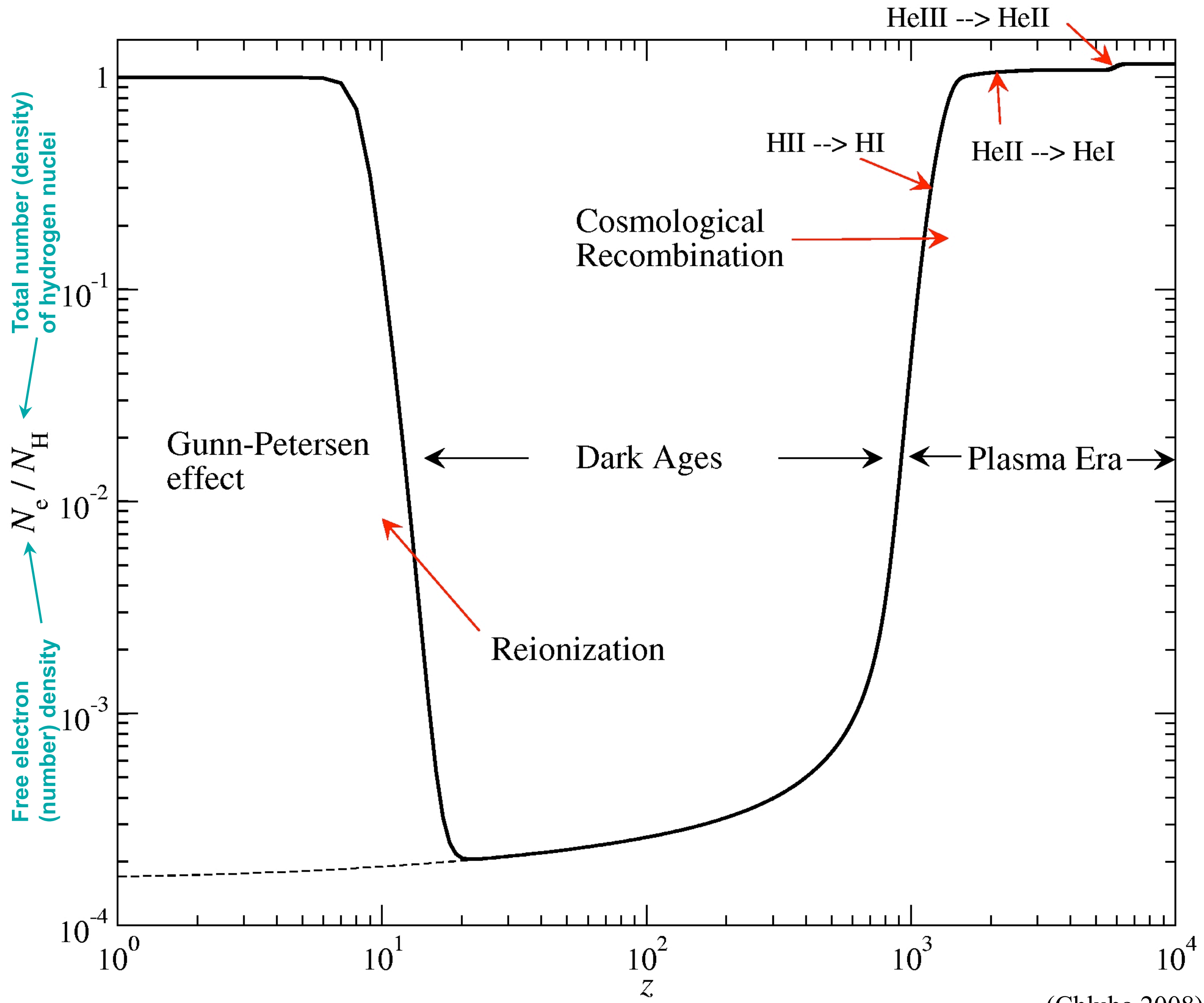
z~6

(GP trough observed in QSO)

Galaxies form and evolve

(Universe accesible with optical/IR telescopes)

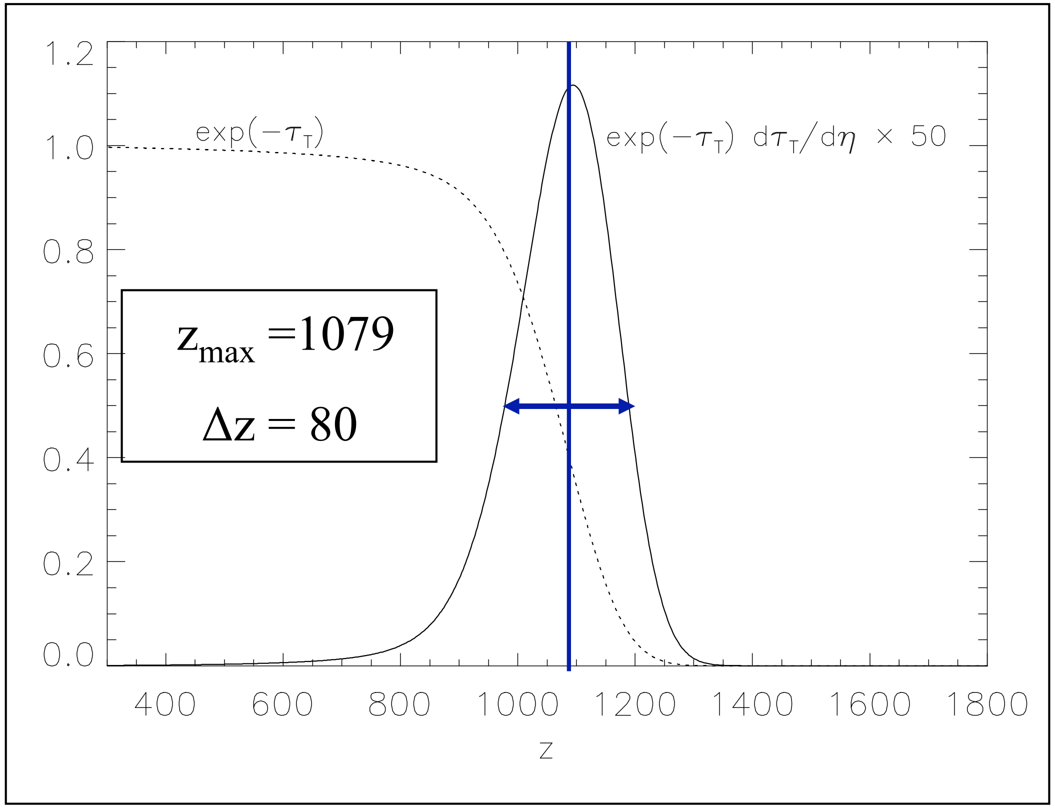
How did the Universe became neutral? Sketch of the Ionization History



(Chluba 2008)

The Thomsom visibility function

Prior to the recombination epoch, the photons and the electrons are tighly coupled due to Thomson scattering. When the number density of electrons decreases, the photons are released and the CMB is formed.



•The relevant quantity is the Thomson optical depth.

$$\tau = \int \sigma_T \, n_e \, dl$$

•The **visibility function** gives the probability that a photon observed now was last scattered at redshift z:

$$V = \exp(-\tau)\, d\tau/d\eta$$

Reionization

❖Optical depth to Thomson scattering to reionization

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

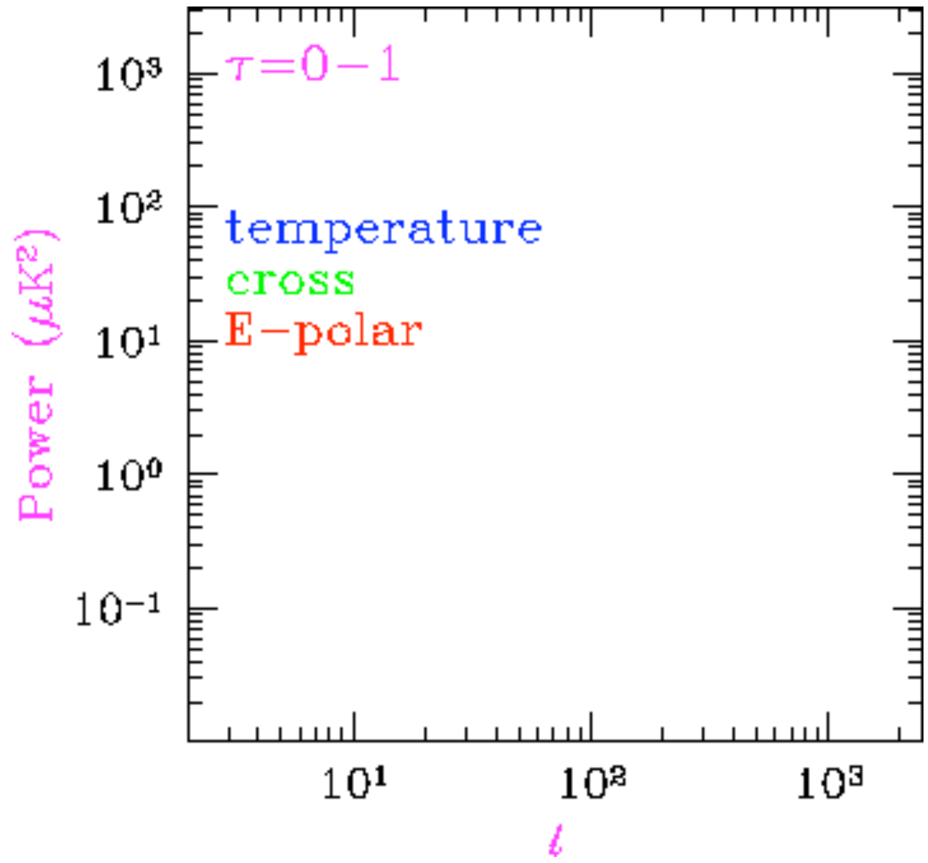
$$= \left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{\Omega_m h^2}{0.15}\right)^{-1/2}\left(\frac{1+z}{61}\right)^{3/2}$$

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

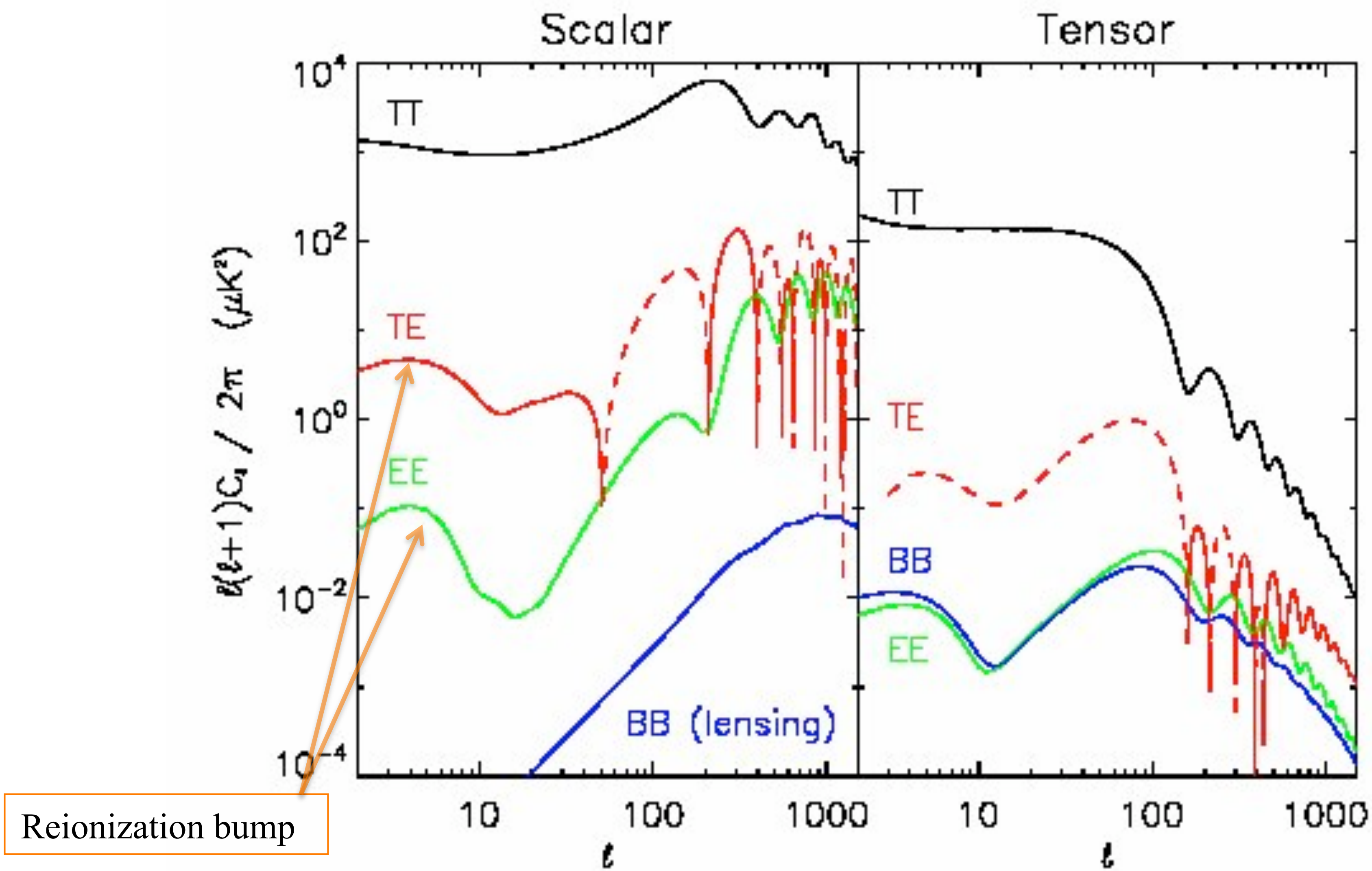
$$\Delta_T \rightarrow \Delta_T e^{-\tau} \qquad \Delta_E \rightarrow \Delta_E \tau$$

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

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



Power spectra - Theory



Gravitational lensing

❖ Large scale density fluctuations in the Universe induce random deflections in the direction of CMB photons as they propagate from last scattering surface to us. In the small scale limit, we have

$$Q(\boldsymbol{\theta}) = \tilde{Q}(\boldsymbol{\theta} + \delta\boldsymbol{\theta}) = (2\pi)^{-2} \int d^2\boldsymbol{l} e^{i\boldsymbol{l}\cdot(\boldsymbol{\theta}+\delta\boldsymbol{\theta})}$$

$$\times [E(\boldsymbol{l})\cos(2\phi_l) - B(\boldsymbol{l})\sin(2\phi_l)],$$

$$U(\boldsymbol{\theta}) = \tilde{U}(\boldsymbol{\theta} + \delta\boldsymbol{\theta})$$

$$= (2\pi)^{-2} \int d^2\boldsymbol{l} e^{i\boldsymbol{l}\cdot(\boldsymbol{\theta}+\delta\boldsymbol{\theta})}$$

$$\times [E(\boldsymbol{l})\sin(2\phi_l) + B(\boldsymbol{l})\cos(2\phi_l)].$$

(Zaldarriaga & Seljak 1998)

Gravitational lensing

❖ Zaldarriaga & Seljak (1998), PRD 58, 23003.

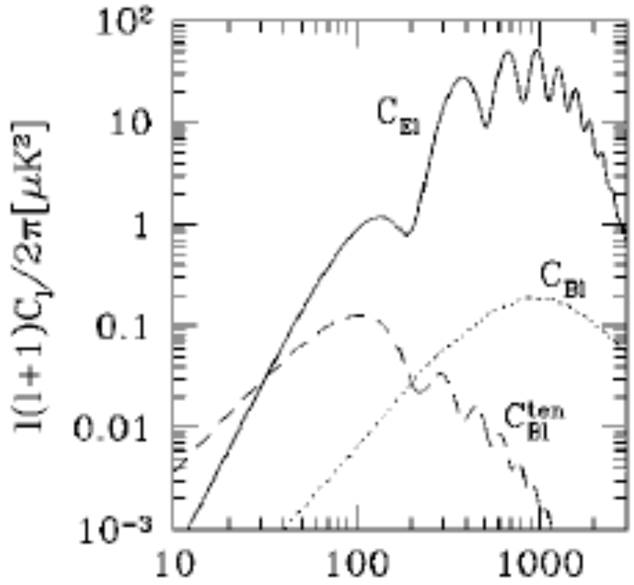
$$C_{Tl} = C_{\tilde{T}l} + W_{1l}^{l'} C_{\tilde{T}l'} ,$$

$$C_{El} = C_{\tilde{E}l} + \frac{1}{2}[W_{1l}^{l'} + W_{2l}^{l'}] C_{\tilde{E}l'} + \frac{1}{2}[W_{1l}^{l'} - W_{2l}^{l'}] C_{\tilde{B}l'} ,$$

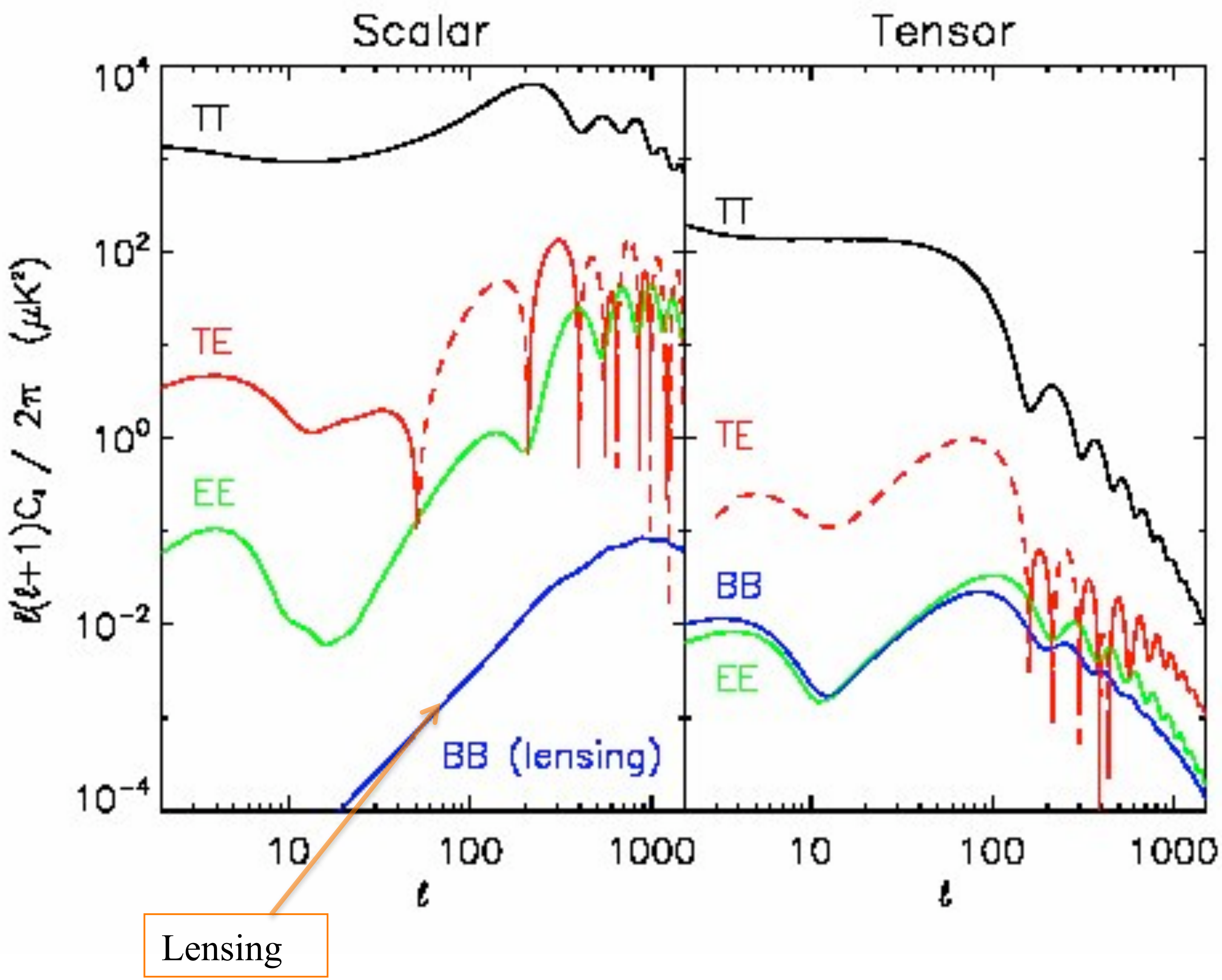
$$C_{Bl} = C_{\tilde{B}l} + \frac{1}{2}[W_{1l}^{l'} - W_{2l}^{l'}] C_{\tilde{E}l'} + \frac{1}{2}[W_{1l}^{l'} + W_{2l}^{l'}] C_{\tilde{B}l'} ,$$

$$C_{Cl} = C_{\tilde{C}l} + W_{3l}^{l'} C_{\tilde{C}l'} ,$$

❖ Lensing mixes E and B polarization modes. Even for pure scalar fluctuations, B-modes are generated at small scales.



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).

❖ GW correspond to spatial metric perturbations. From A. Lasenby´s talk:

- Tensor metric perturbations $ds^2 = a^2[d\eta^2 - (\delta_{ij} + 2h_{ij})dx^i dx^j]$ where h_{ij} is traceless and transverse
- If substitute this into Einstein equations, and use modes of the form $\exp(ik_i x^i)$, then find

$$\ddot{h}_{ij} + 2aH\dot{h}_{ij} + k^2 h_{ij} = 8\pi G \Sigma^T_{ij}$$

  where Σ^T_{ij} is the transverse and traceless part of the anisotropic stress
- Express h_{ij} in terms of the two independent gravitational wave polarization components, h_+ and $h_\times$

Polarization and tensor modes: Gravitational waves

❖From A. Lasenby´s lecture:

- Two independent solutions:

$$h \propto \frac{1}{\eta^3}(\cos(k\eta)k\eta - \sin(k\eta)) \quad \text{and} \quad h \propto \frac{1}{\eta^3}(\cos(k\eta)k\eta + \sin(k\eta))$$

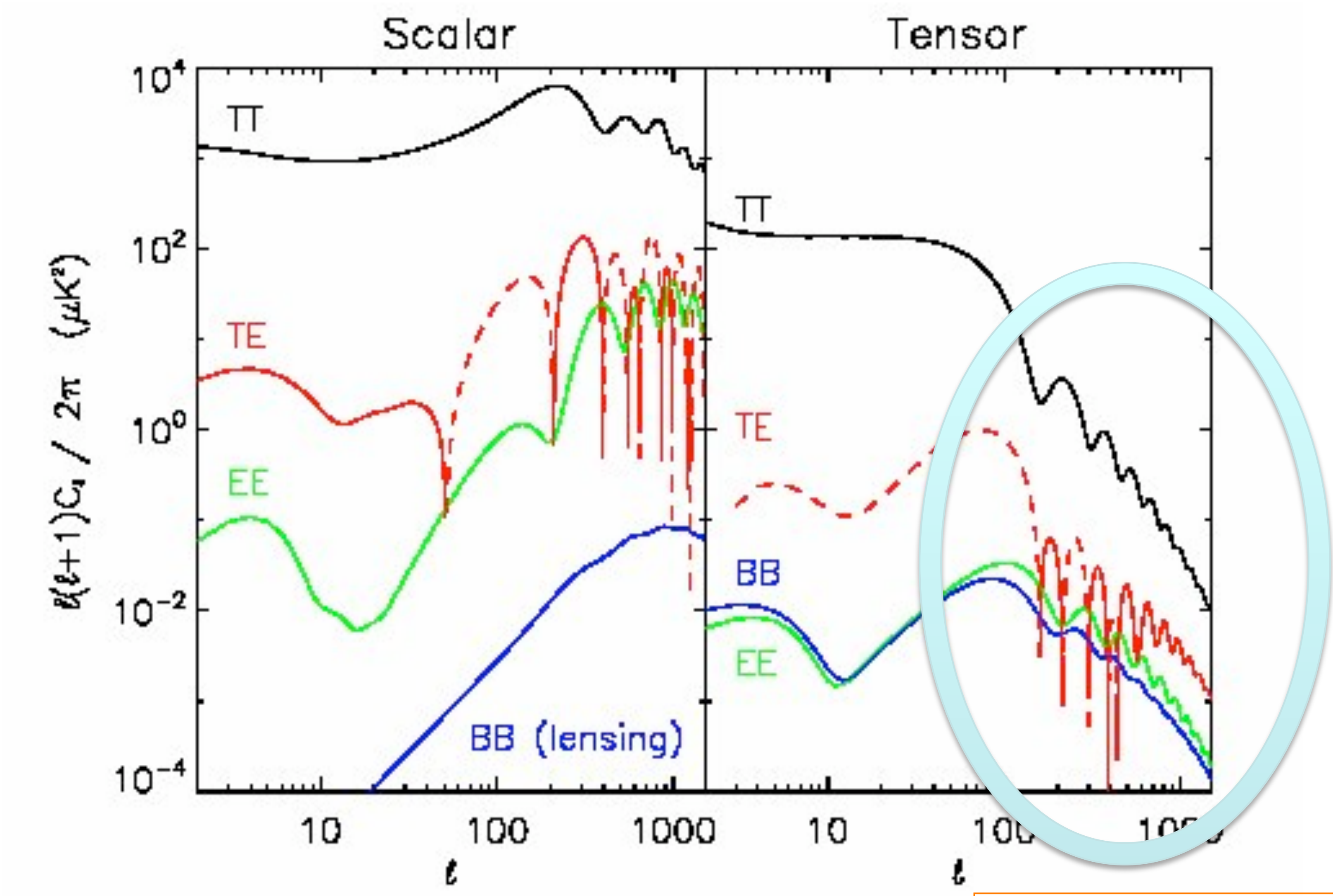
- Find following behavior as one goes back in time: only one of these is non-singular, and here can write

$$h_{+,\times}(\eta) = -\frac{3}{k^3\eta^3}(\cos(k\eta)k\eta - \sin(k\eta))h_{+,\times}(0) = 3\sqrt{\frac{\pi}{2}}\frac{J_{3/2}(k\eta)}{(k\eta)^{3/2}}h_{+,\times}(0)$$

- So this is solution for scales entering the horizon well after matter domination
- Note that overall η dependence for large η is $1/\eta^2 \propto 1/t^{2/3} \propto 1+z$, so the gravitational perturbations redshift away inside the horizon — quite unlike the scalar perturbations
- Therefore only important at degree scales and above

❖ GW oscillate and decay at horizon crossing.

Power spectra - Theory



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

Polarization and tensor modes: Gravitational waves

❖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.

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

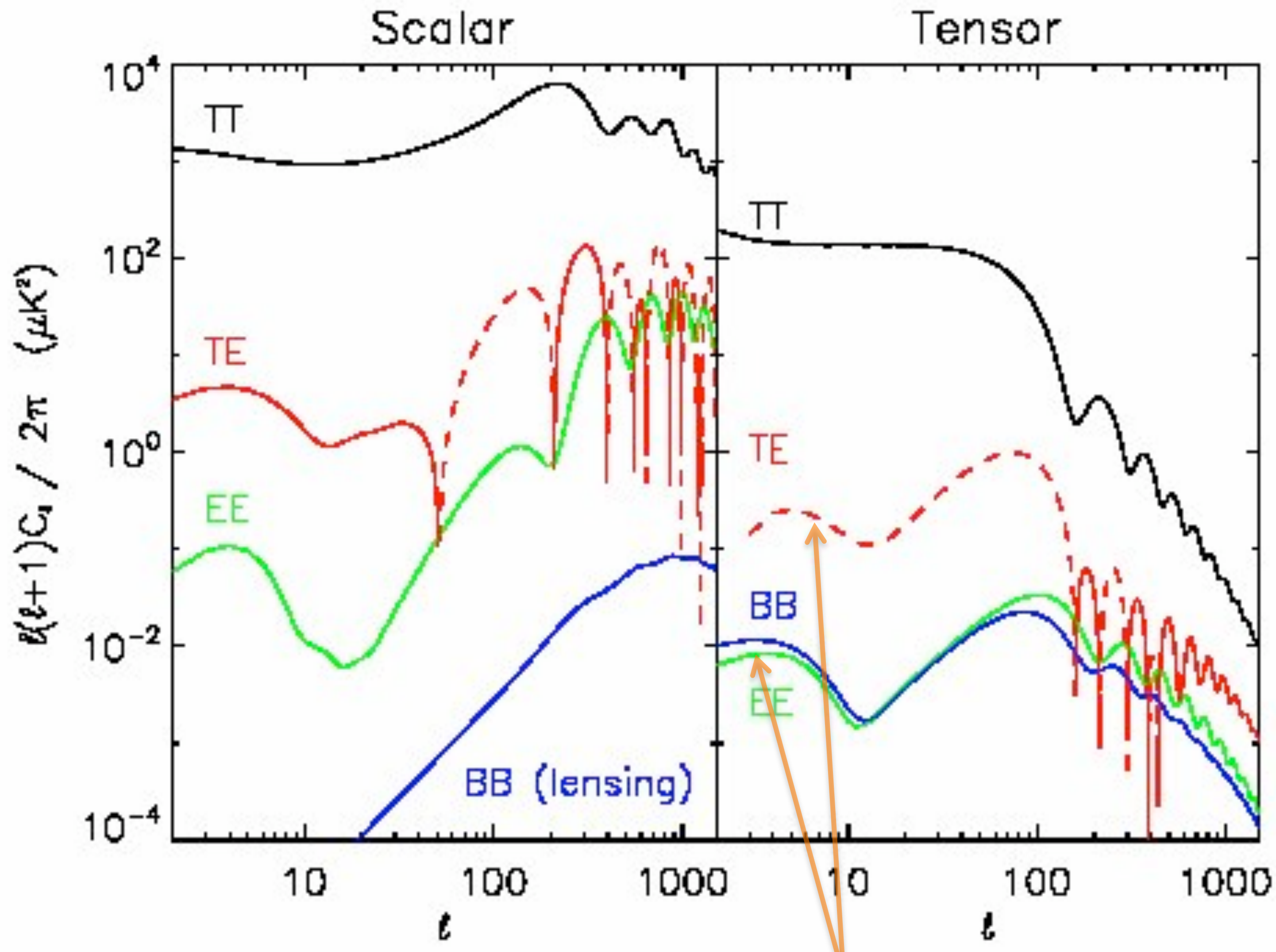
$$C_{Bl}^{(T)} = (4\pi)^2 \int k^2\, dk\, P_h(k) \left| \int d\tau\, g(\tau) \Psi(k,\tau) \left[2j_l'(x) + \frac{4j_l}{x} \right] \right|^2,$$

(Seljak & Zaldarriaga 1997)

❖ E and B modes have similar amplitude.

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

Power spectra - Theory



E and B modes of similar amplitude. Reionization bump

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.

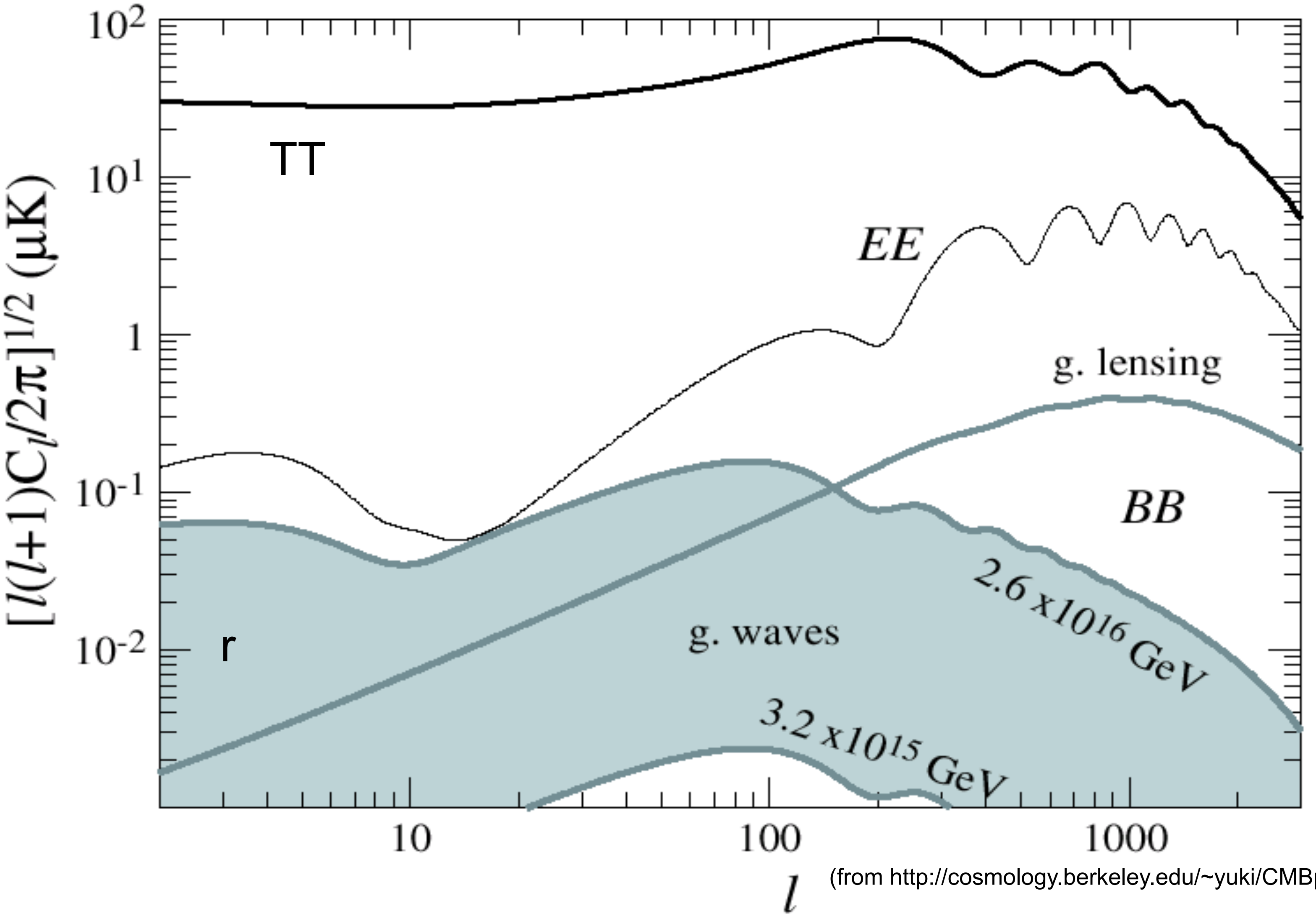
$$P_{tensor} = \frac{8}{m_{Pl}^2}\left(\frac{H}{2\pi}\right)^2 \propto E_{\inf}^4$$

- 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!

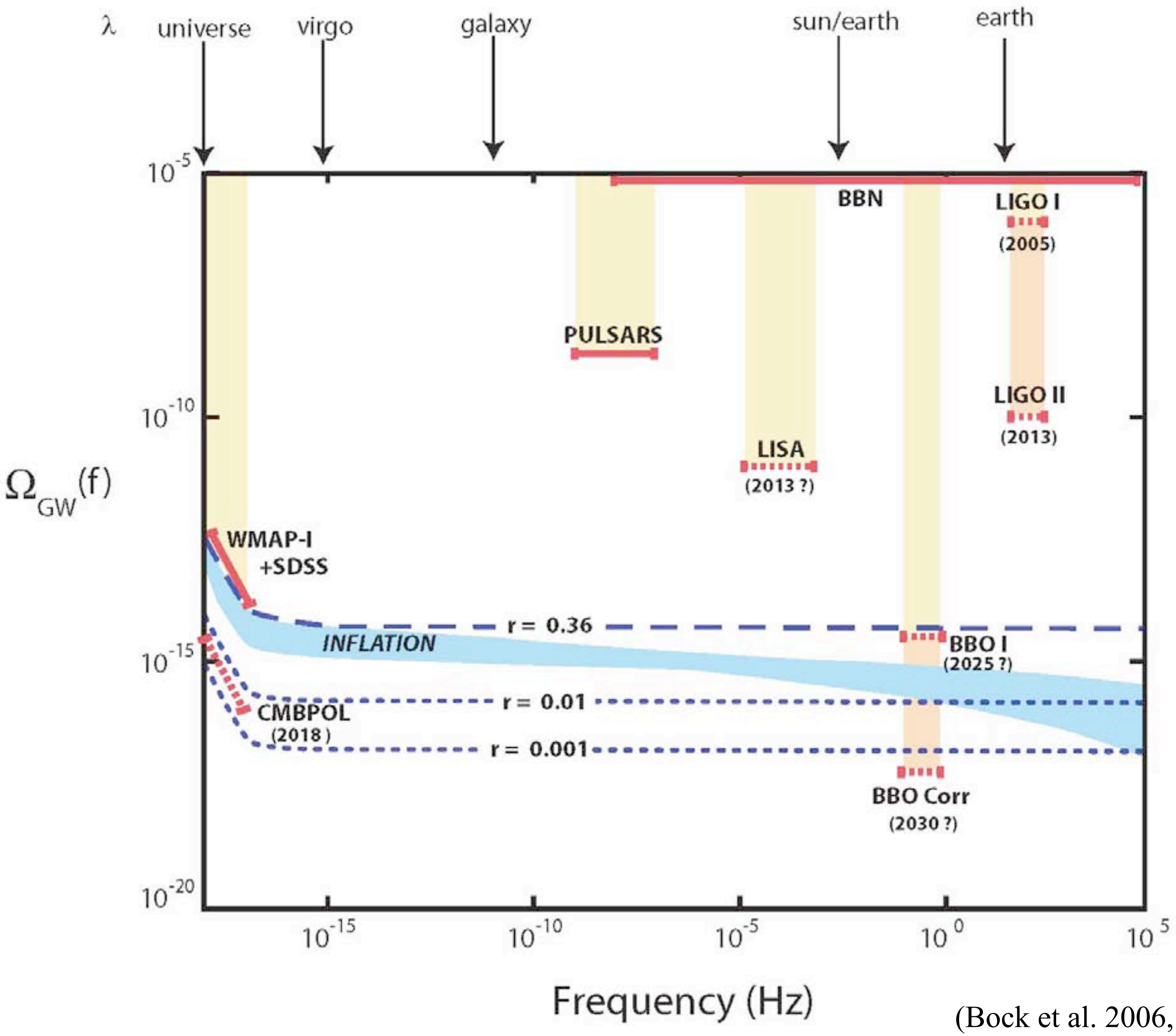
Primordial gravitational waves and B-modes



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

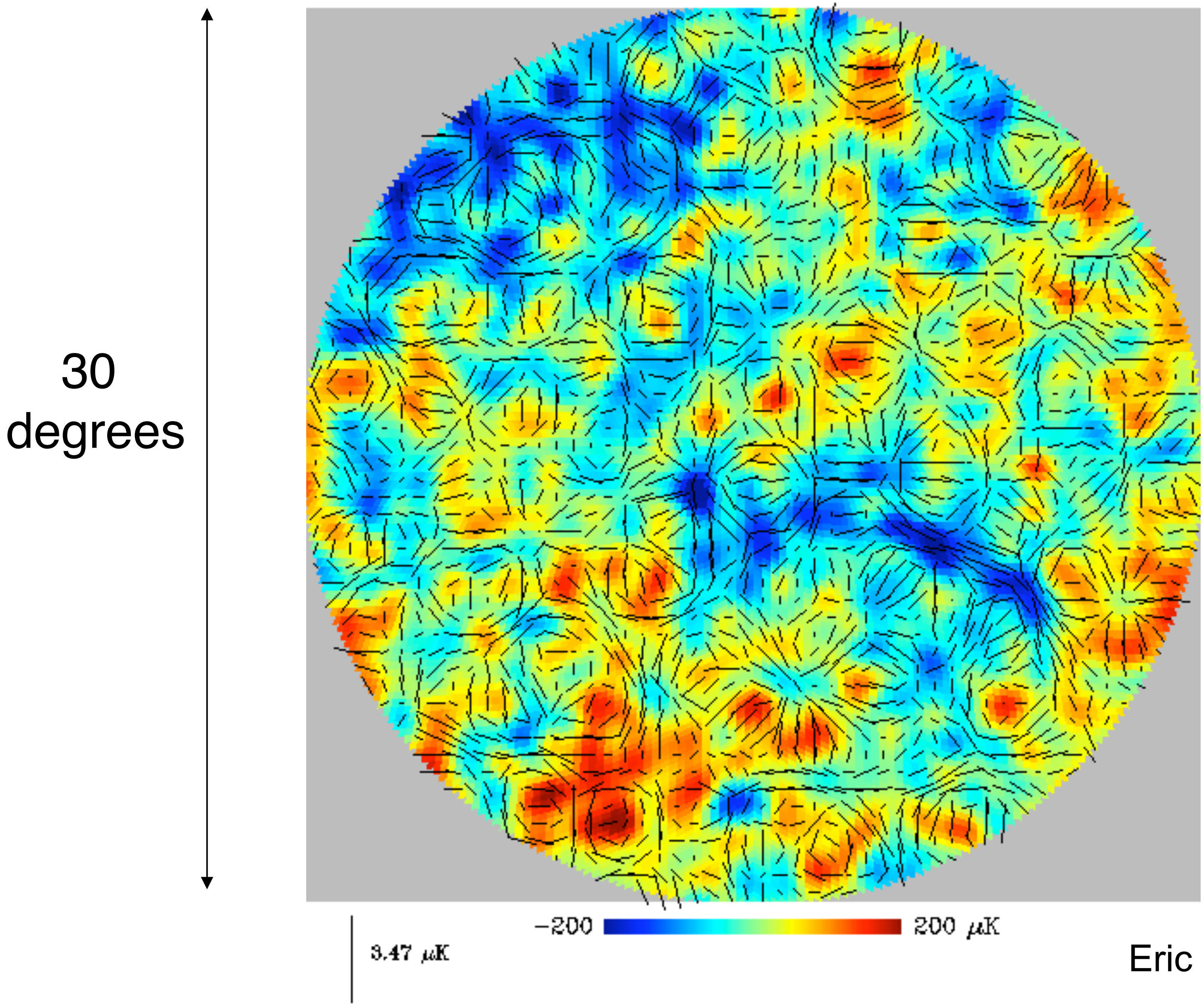
- r=0.1 corresponds to an energy scale of inflation around 2×10^{16} GeV.

Direct measurements of primordial Gravitational Waves



(Bock et al. 2006, arXiv:0604101)

No gravitational waves (r = 0)



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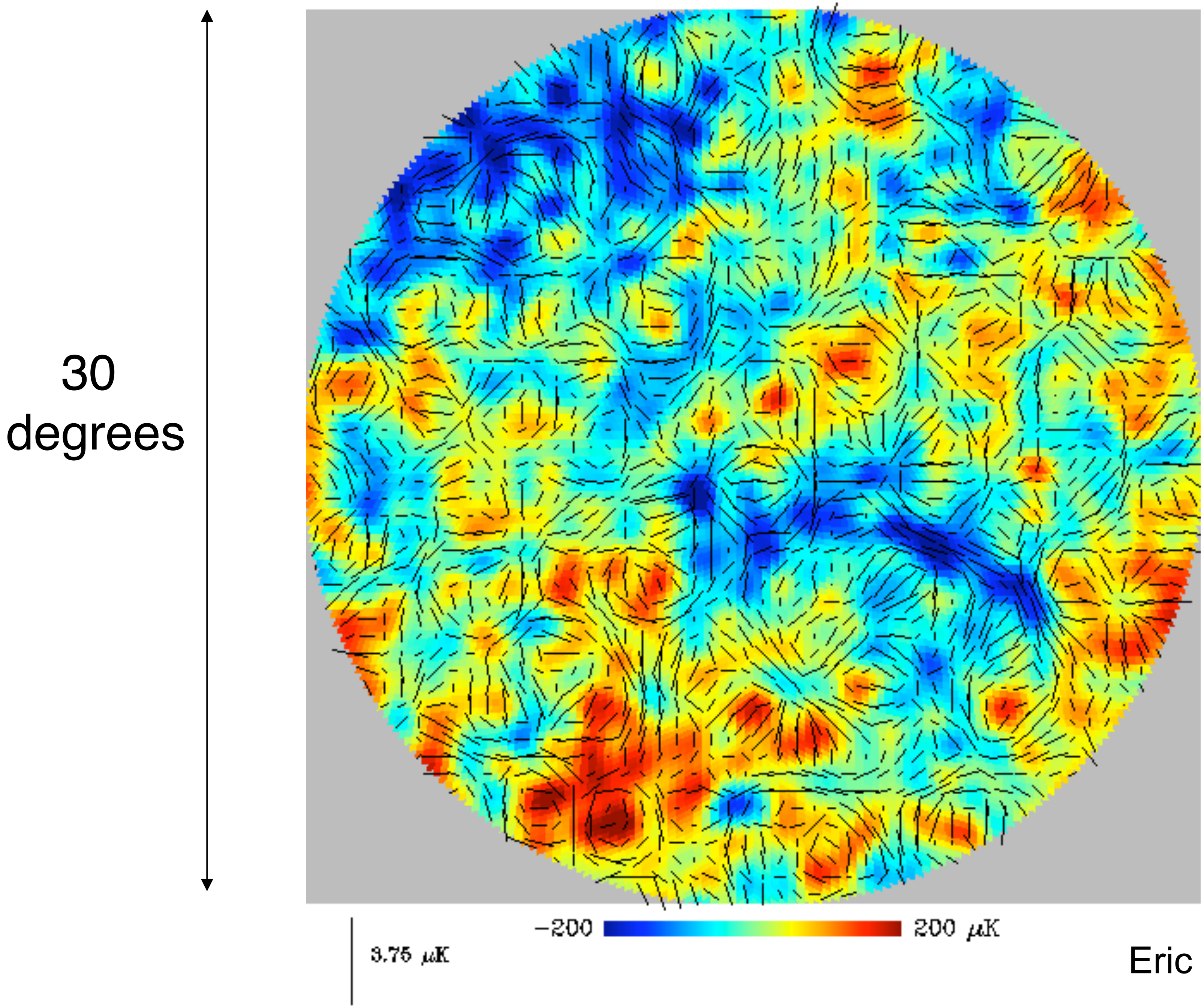
Gravitational waves (r = 0.3)



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Raising/lowering operators

An important property of spin-s functions is that there exists a spin raising (lowering) operator ð ($\bar{ð}$) with the property of raising (lowering) the spin weight of a function, $(ð_s f)' = e^{-i(s+1)\psi} ð_s f$, $(\bar{ð}_s f)' = e^{-i(s-1)\psi} \bar{ð}_s f$. Their explicit expression is given by

$$ð_s f(\theta,\phi) = -\sin^s(\theta)\left[\frac{\partial}{\partial\theta} + i\csc(\theta)\frac{\partial}{\partial\phi}\right]\sin^{-s}(\theta)\,{}_s f(\theta,\phi),$$

$$\bar{ð}_s f(\theta,\phi) = -\sin^{-s}(\theta)\left[\frac{\partial}{\partial\theta} - i\csc(\theta)\frac{\partial}{\partial\phi}\right]\sin^s(\theta)\,{}_s f(\theta,\phi). \tag{A2}$$

Raising/lowering operators

- They can be used to define spin zero quantities:

$$\bar{\eth}^{\,2}(Q+iU)(\hat{\boldsymbol{n}})=\sum_{lm}\left[\frac{(l+2)!}{(l-2)!}\right]^{1/2} a_{2,lm} Y_{lm}(\hat{\boldsymbol{n}}),$$

$$\eth^{2}(Q-iU)(\hat{\boldsymbol{n}})=\sum_{lm}\left[\frac{(l+2)!}{(l-2)!}\right]^{1/2} a_{-2,lm} Y_{lm}(\hat{\boldsymbol{n}}).$$

- For real-space computations, it is useful to define:

$$\begin{aligned}\chi_E &\equiv [\bar{\eth}\,\bar{\eth}(Q+iU)+\eth\eth(Q-iU)]/2\\ &= -\sum_{lm}[(l+2)!/(l-2)!]^{1/2} a_{E,lm} Y_{lm},\\ \chi_B &\equiv i[\bar{\eth}\,\bar{\eth}(Q+iU)-\eth\eth(Q-iU)]/2\\ &= \sum_{lm}[(l+2)!/(l-2)!]^{1/2} a_{B,lm} Y_{lm}.\end{aligned}$$

E/B mixing

❖In finite patches of sky, the separation between E and B modes can not be done perfectly.

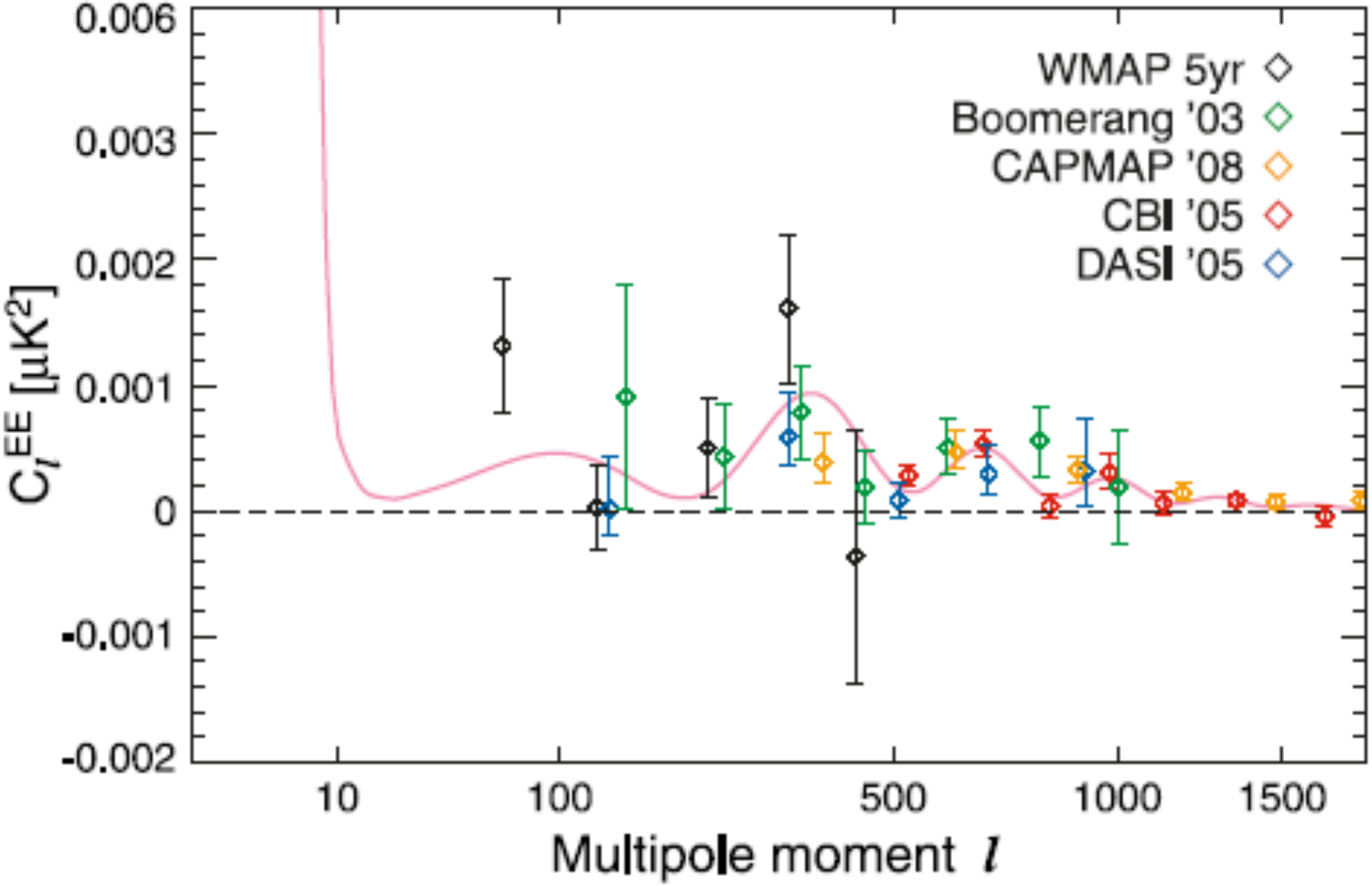
❖ Aliasing effects from E modes into B modes are very important, as E-mode spectrum is much larger in amplitude.

❖Specific methods in Fourier space or real space to minimize this problem.

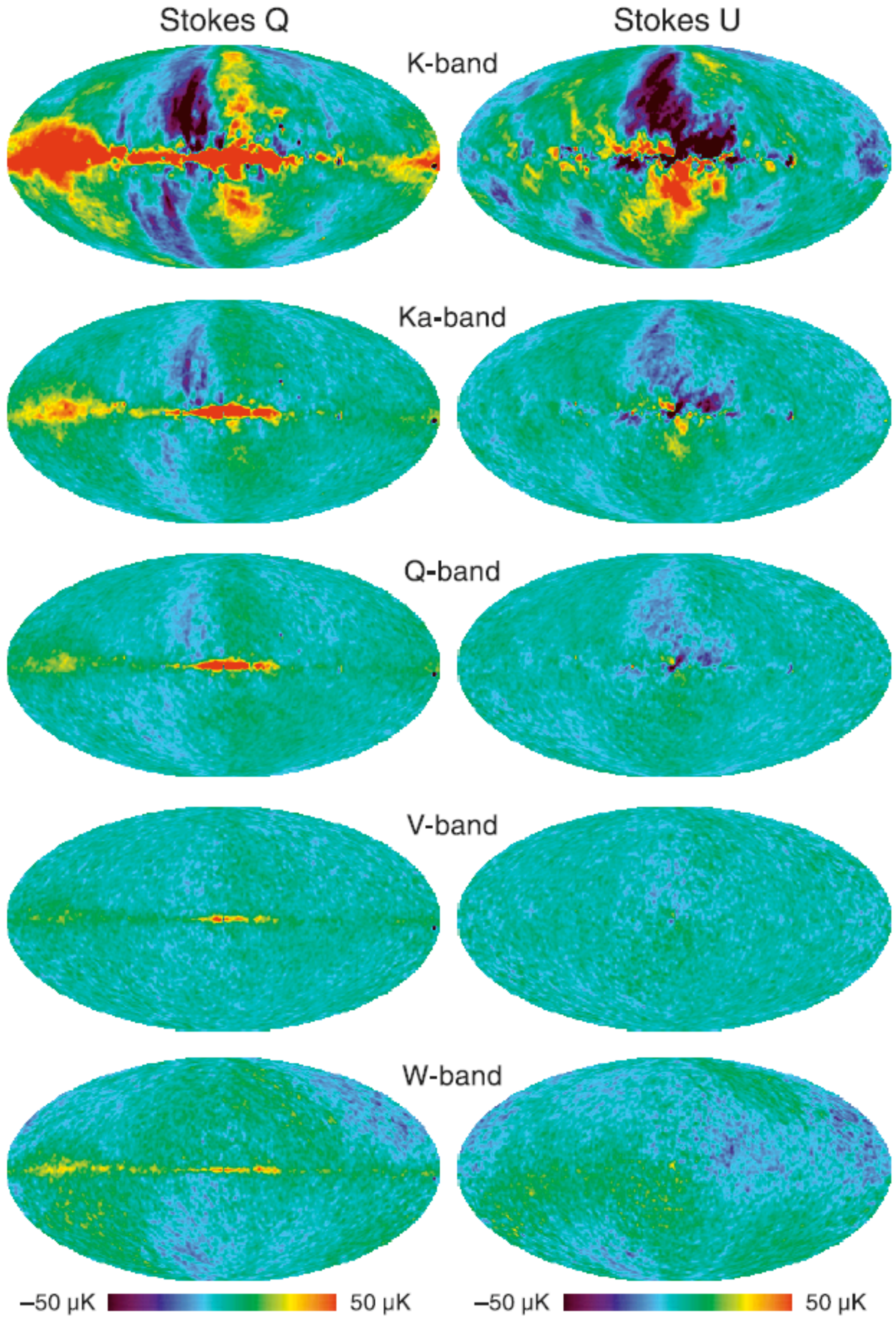
Observational status:
polarization of the CMB

First Observations of CMB polarization

E-mode detections: DASI (Kovac et al. 2002, Nature), WMAP, CAPMAP, CBI, Boomerang.

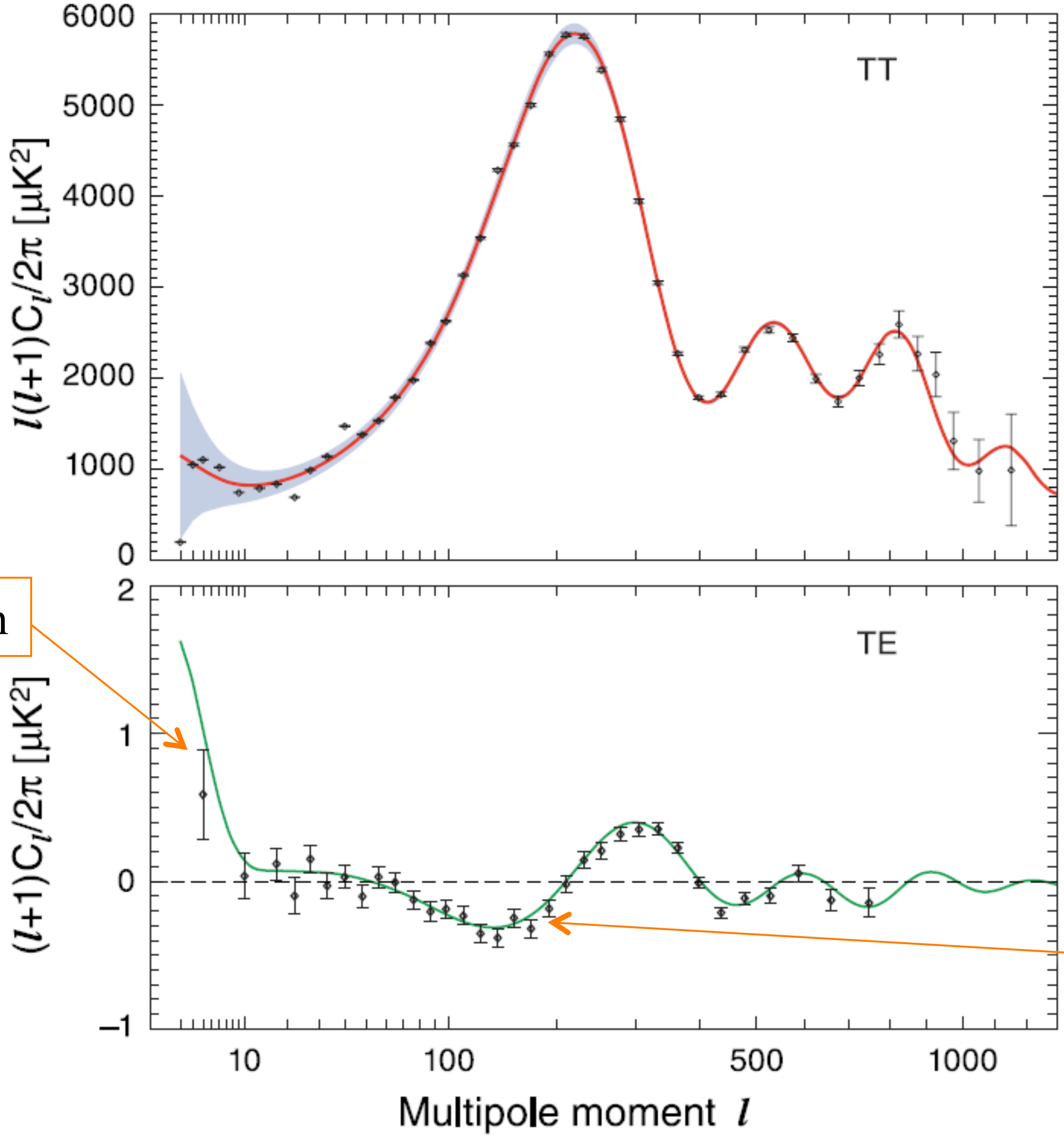


WMAP 7yr results



Jarosik et al. 2010

WMAP7 power spectrum



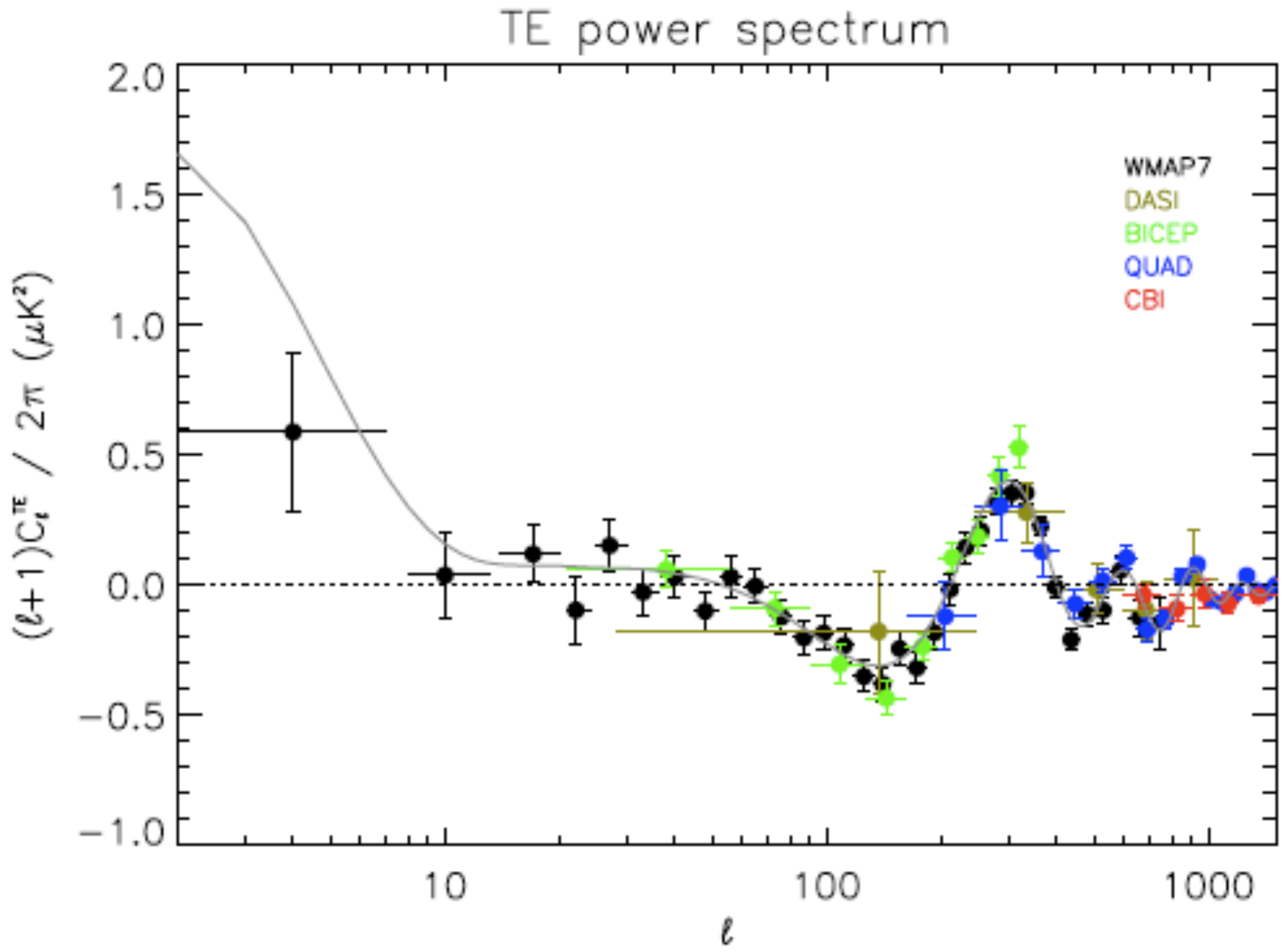
(Larson et al. 2011)

Reionization

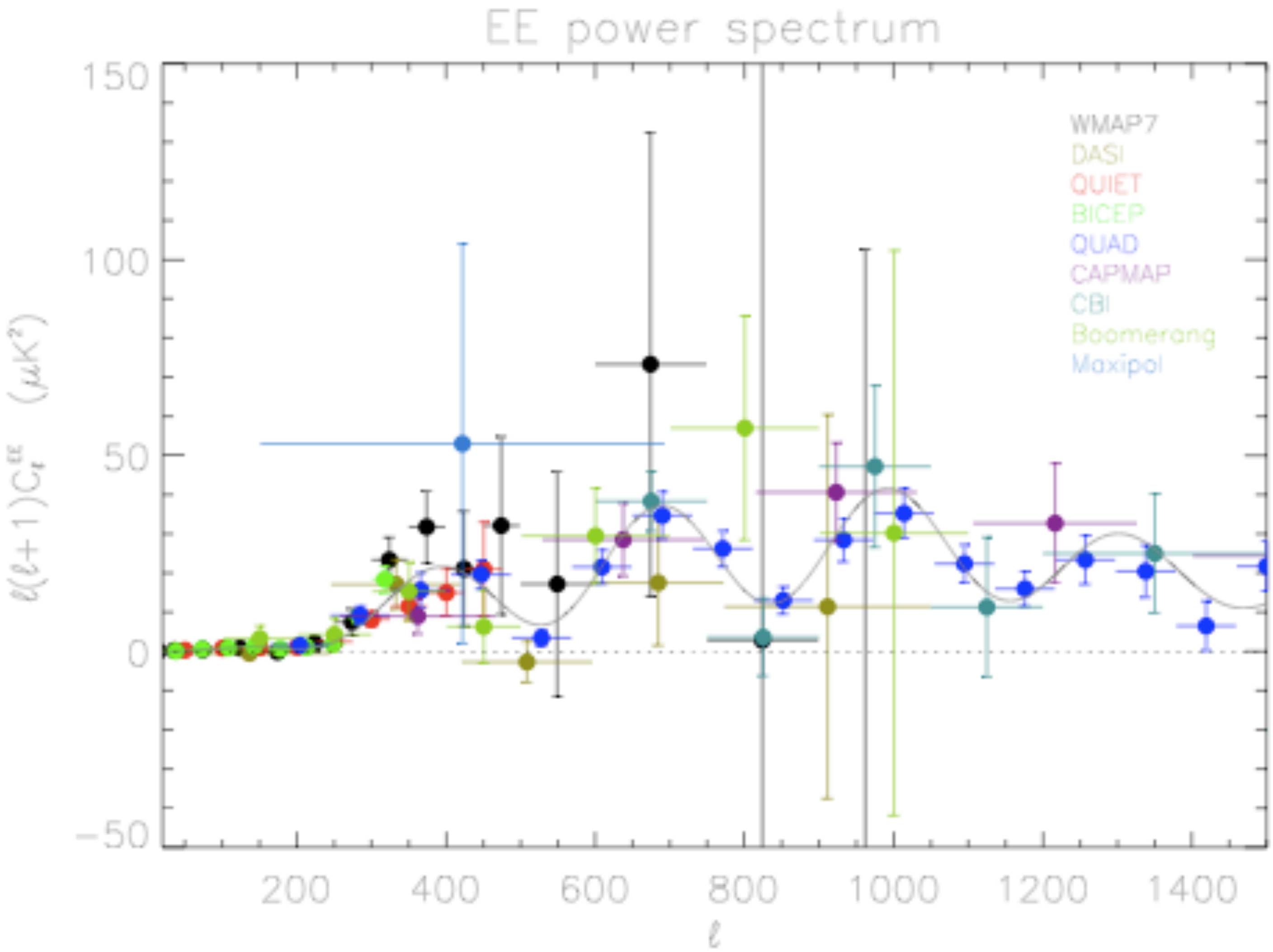
Green line is the ΛCDM prediction!

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

CMB polarization. TE spectrum



CMB polarization. EE spectrum



Real space correlations

$$\langle T_i T_j \rangle \equiv \sum_l \left(\frac{2l+1}{4\pi}\right) P_l(z) C_l^T$$

$$\langle T_i Q_j \rangle \equiv -\sum_l \left(\frac{2l+1}{4\pi}\right) F_l^{10}(z) C_l^{TE},$$

$$\langle T_i U_j \rangle \equiv -\sum_l \left(\frac{2l+1}{4\pi}\right) F_l^{10}(z) C_l^{BT},$$

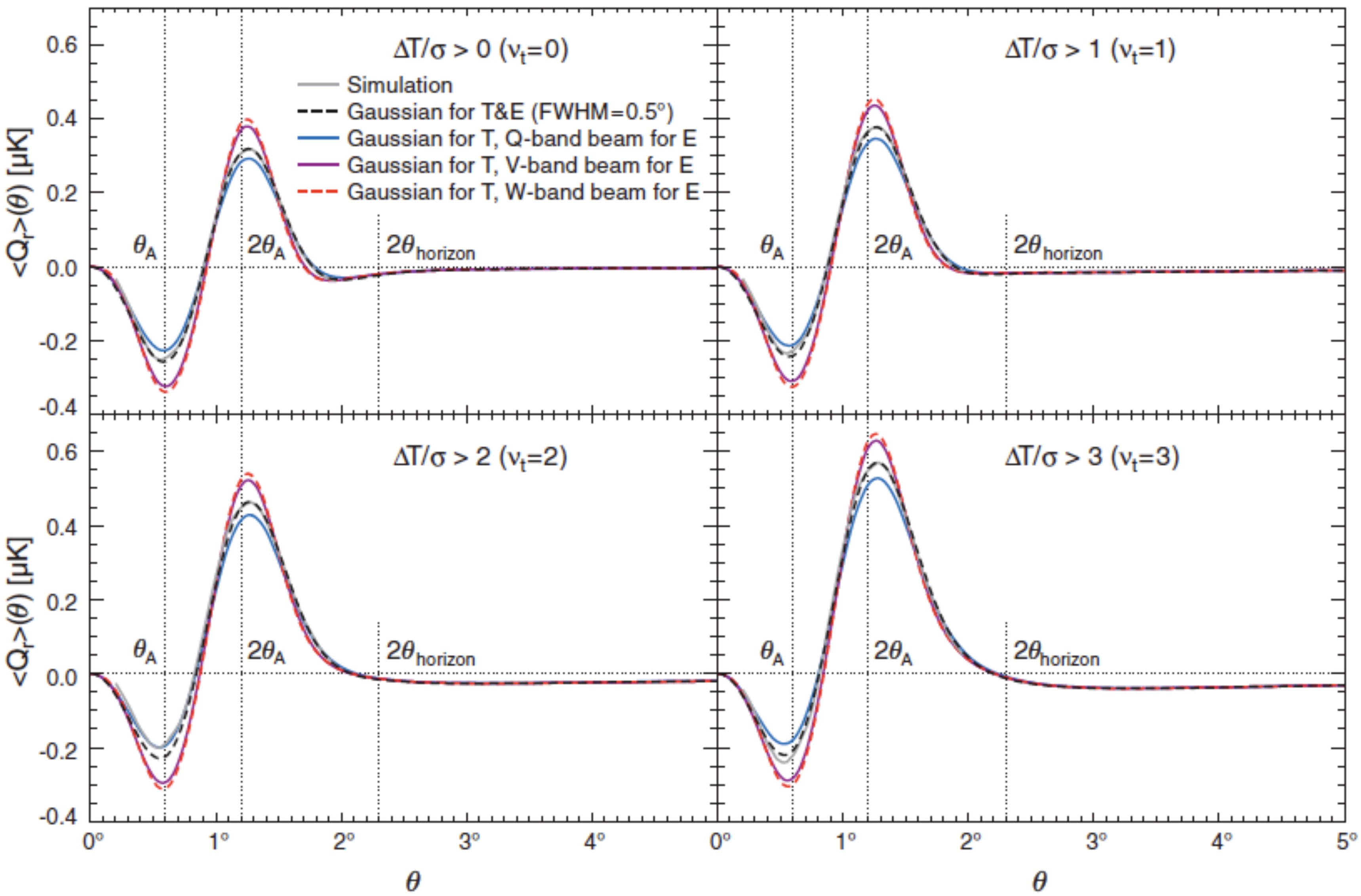
$$\langle Q_i Q_j \rangle \equiv \sum_l \left(\frac{2l+1}{4\pi}\right) [F_l^{12}(z) C_l^E - F_l^{22}(z) C_l^B],$$

$$\langle U_i U_j \rangle \equiv \sum_l \left(\frac{2l+1}{4\pi}\right) [F_l^{12}(z) C_l^B - F_l^{22}(z) C_l^E],$$

$$\langle Q_i U_j \rangle \equiv \sum_l \left(\frac{2l+1}{4\pi}\right) [F_l^{12}(z) + F_l^{22}(z)] C_l^{EB},$$

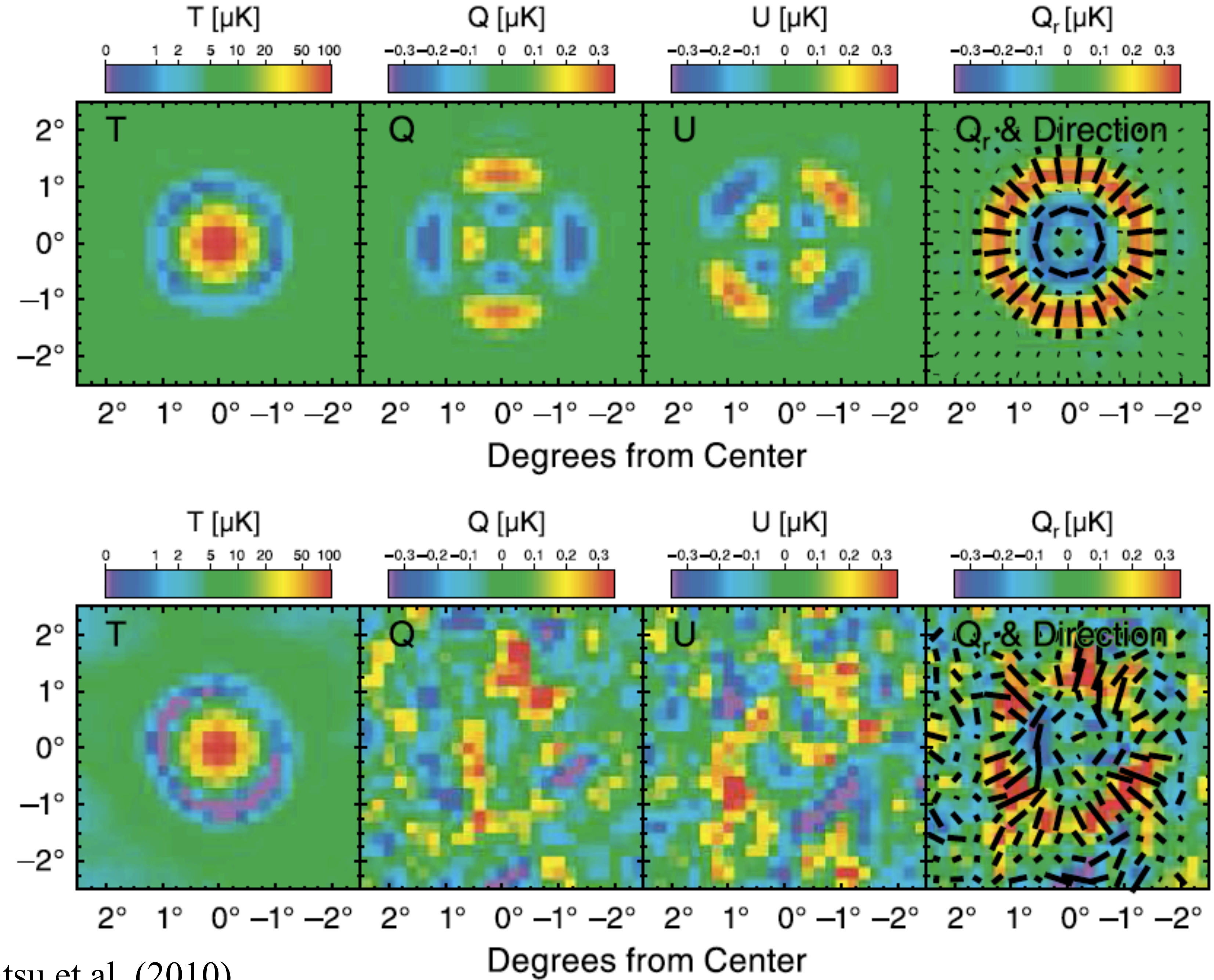
(See e.g. Tegmark et al. 2006)

WMAP7: real space correlations



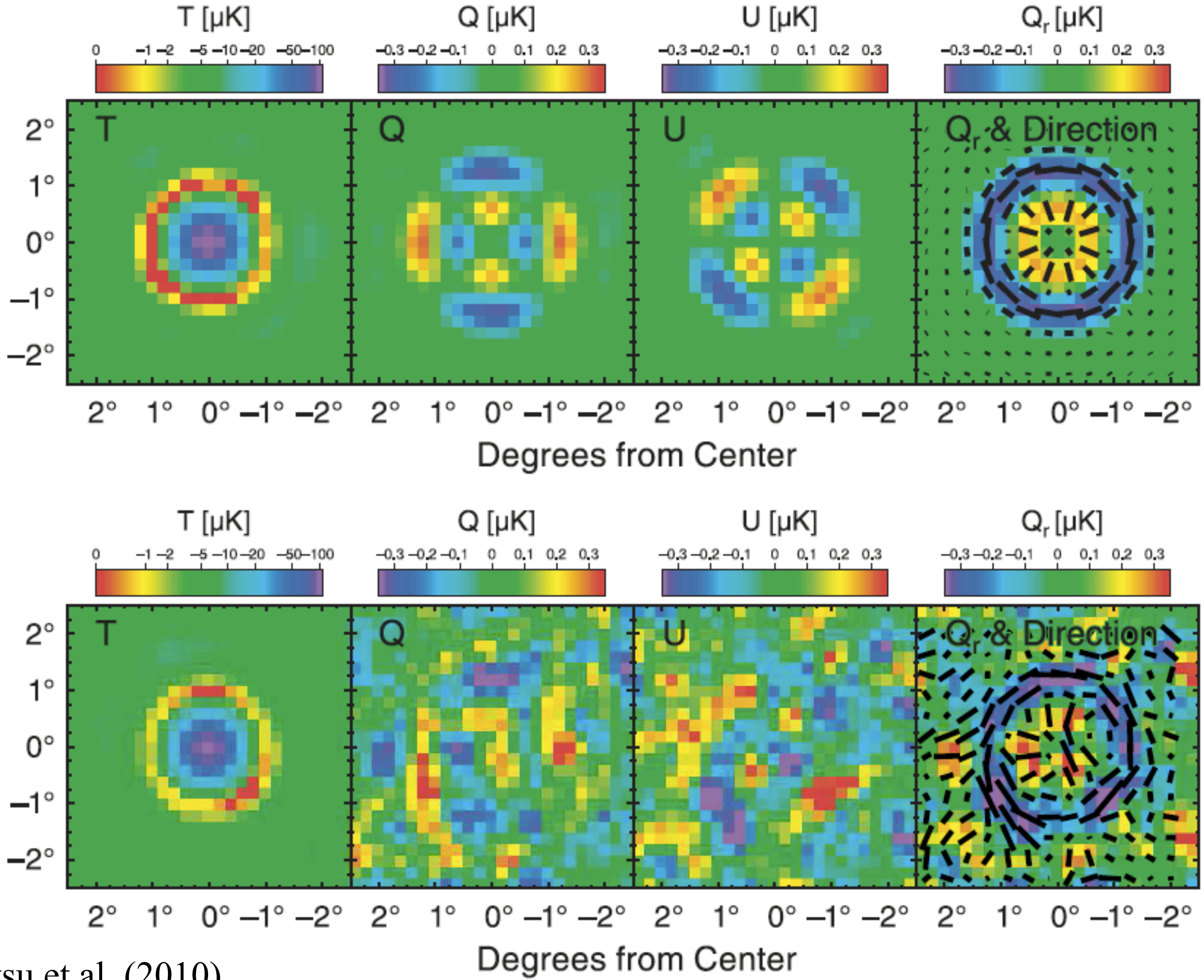
Komatsu et al. (2010)

WMAP7 hot spots



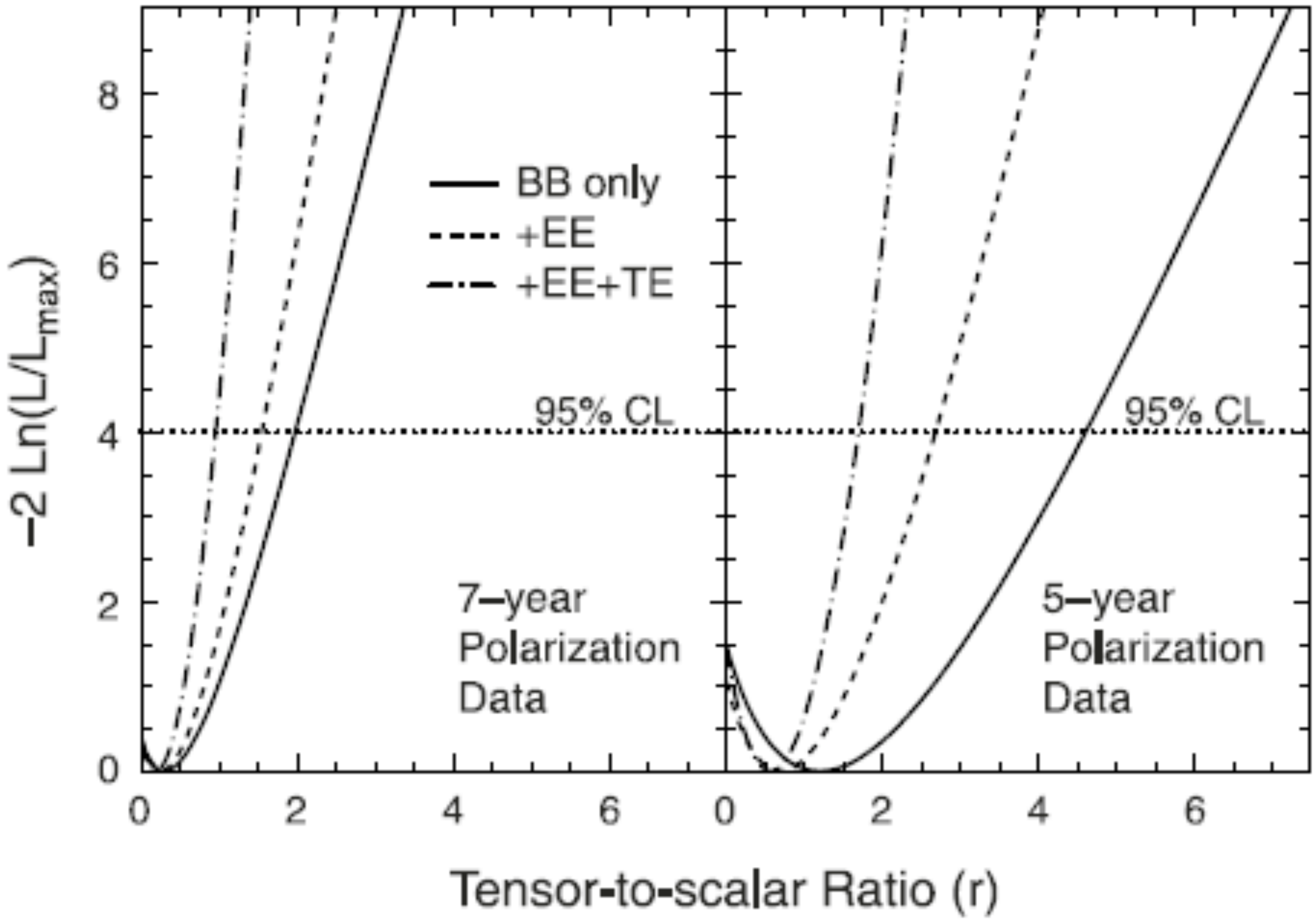
Komatsu et al. (2010)

WMAP7 cold spots



Komatsu et al. (2010)

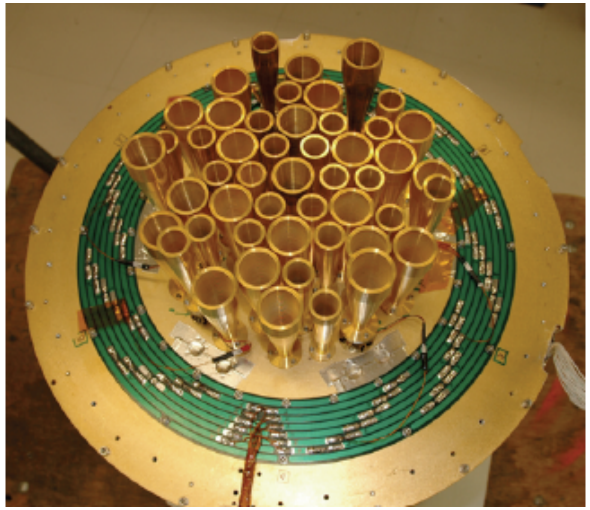
WMAP7 constraints on r



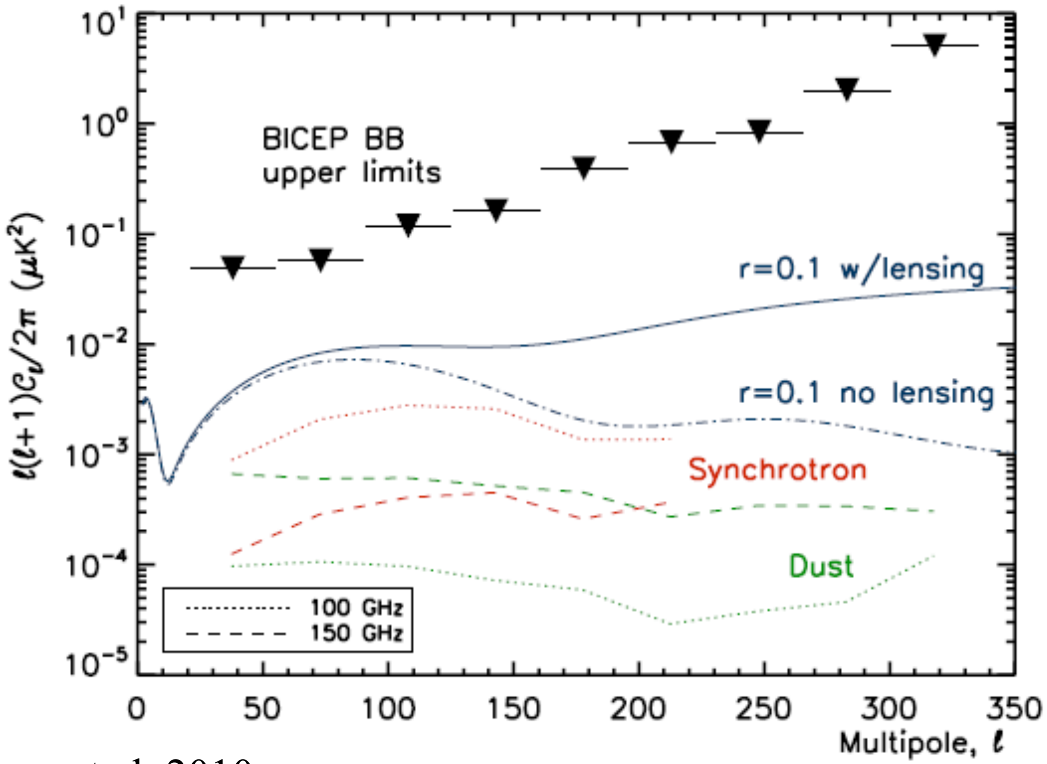
Komatsu et al. (2010)

BICEP results

• BICEP (Background Imaging of Cosmic Extragalactic Polarization). Caltech, Princeton, JPL, Berkeley and others collaboration.
• Uses 100GHz and 150GHz polarization sensitive bolometers. Operates from South Pole.

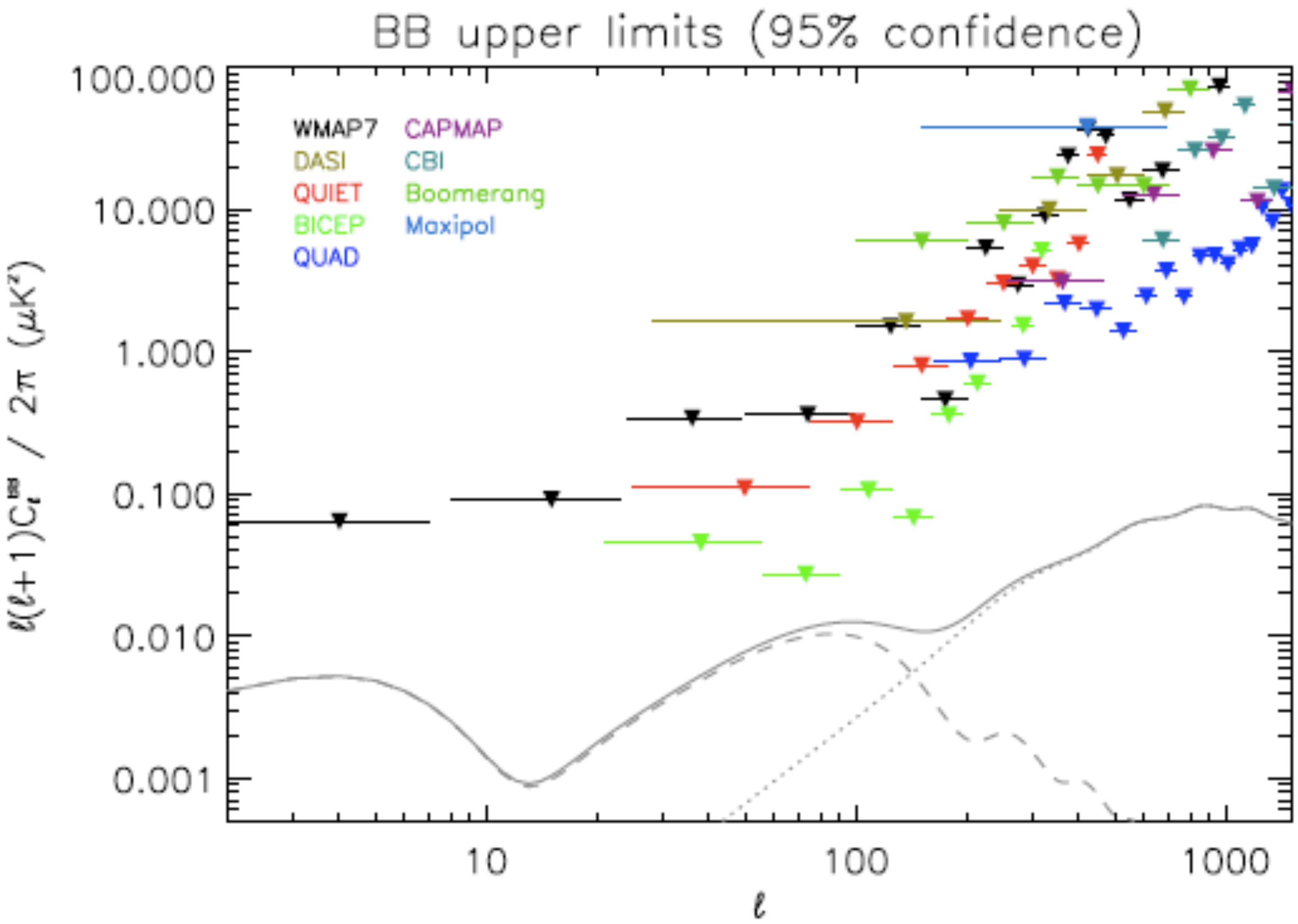


• Detection of E-mode signal.
• Upper limit on r, based on BB spectrum only:
r<0.72 at 95% confidence (Chiang et al. 2010).

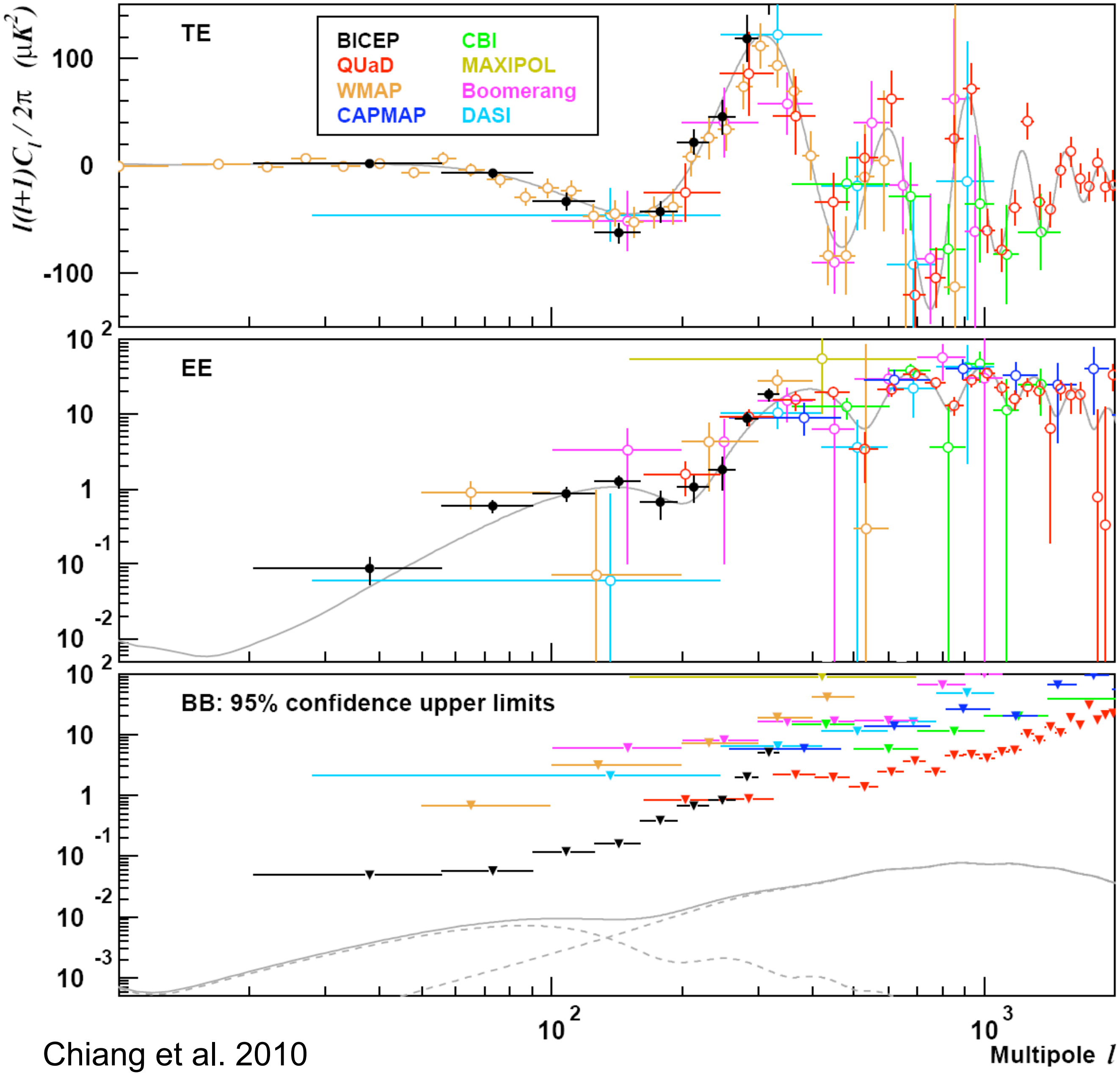


Chiang et al. 2010

CMB polarization. BB spectrum



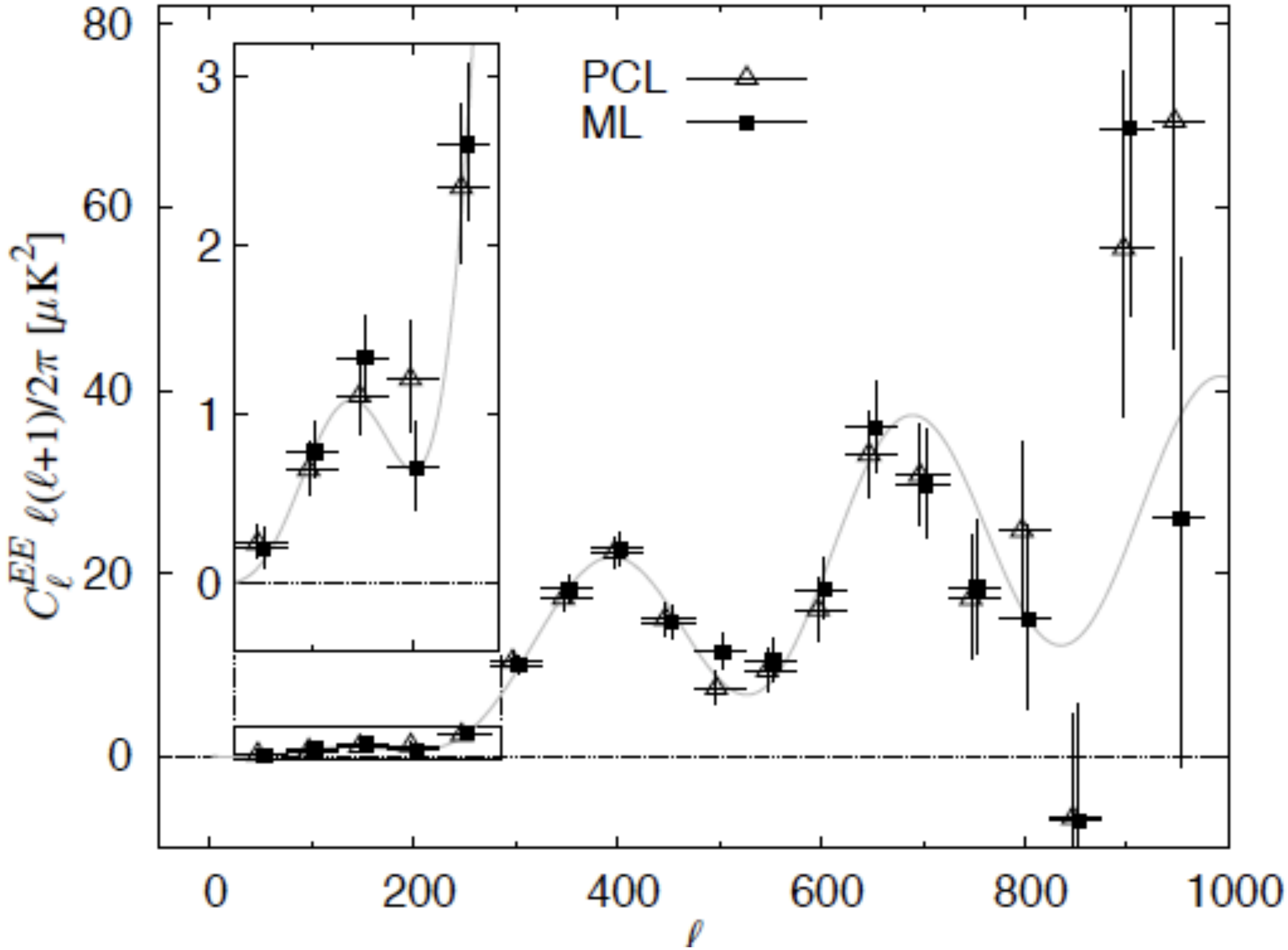
CMB polarization: observational status



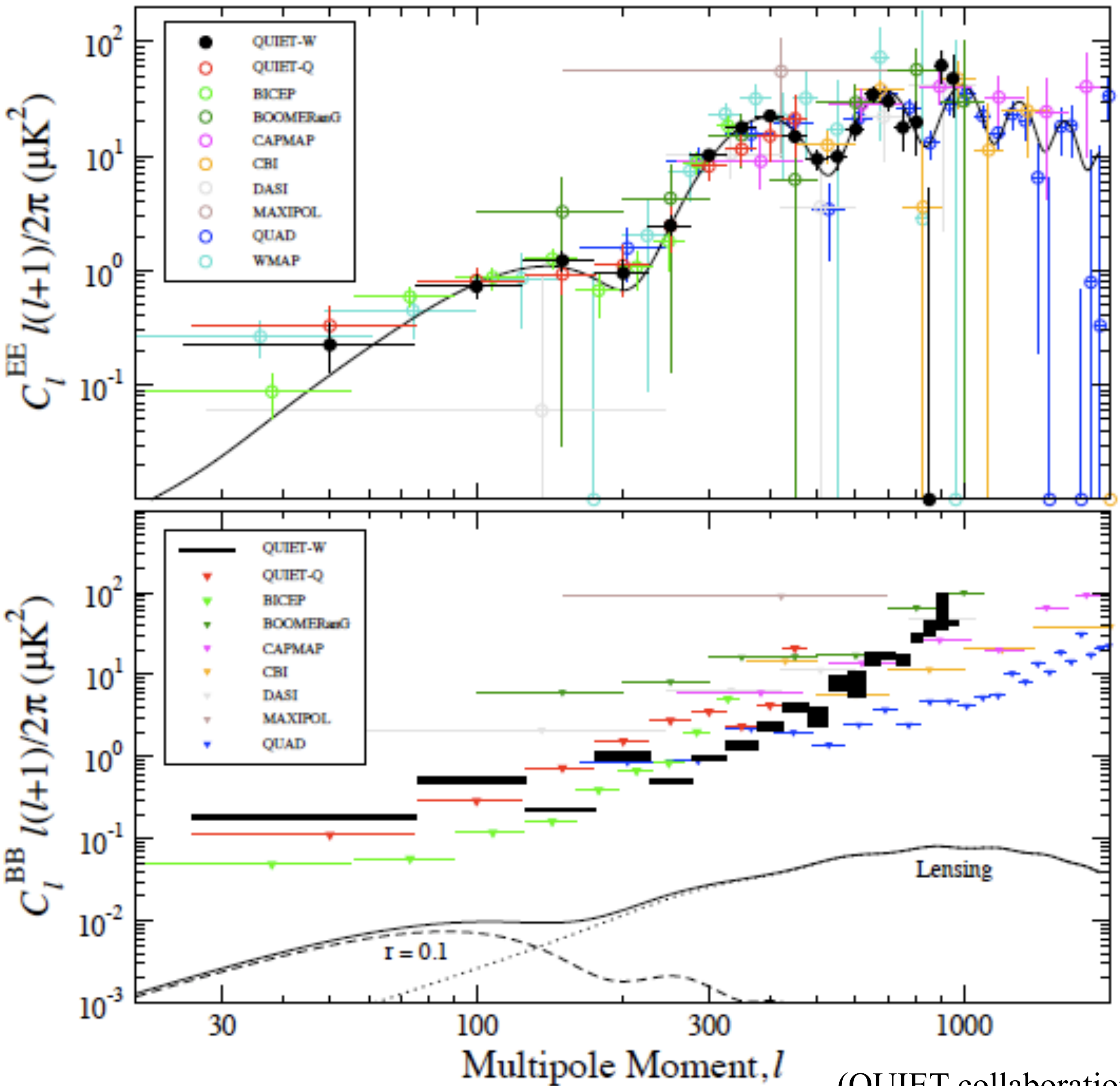
Chiang et al. 2010

- Several E-mode detections: DASI, CBI, CAPMAP, Boomerang, WMAP, QUAD, BICEP, QUIET, etc.
- WMAP7 gives r<0.93 at 95% using TE/EE/BB, and r<2.1 at 95% with BB alone.
- WMAP7+BAO+SN gives r<0.2 (Komatsu et al. 2010).
- BICEP: r<0.72 at 95% with BB only (Chiang et al. 2010).
- QUIET: $r=0.35^{+1.06}_{-0.87}$ with BB only (Bischoff et al. 2010)

QUIET results at 95 GHz



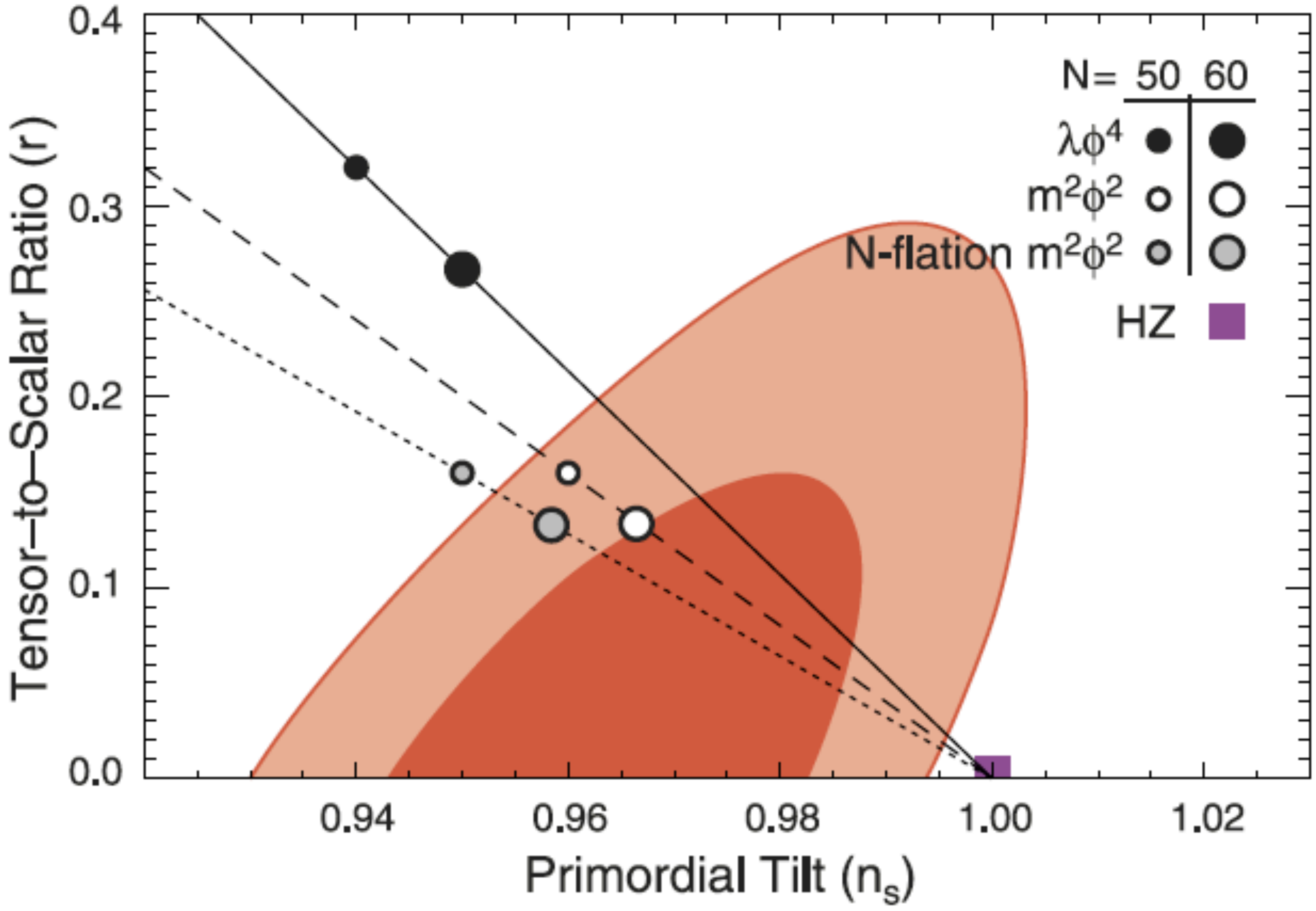
(QUIET collaboration: arXiv1207.5034)



r < 2.7 at 95% C.L.

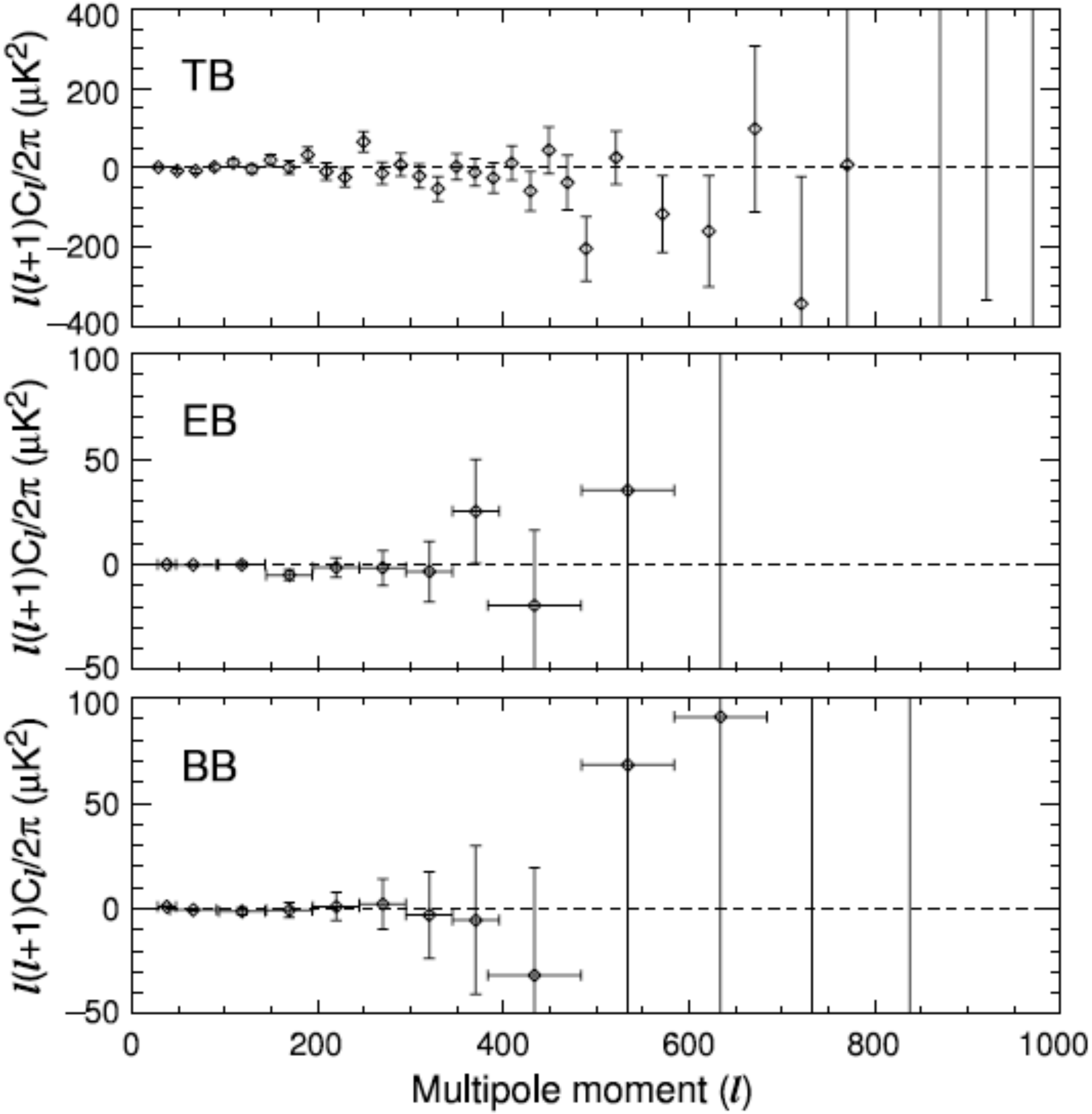
(QUIET collaboration: arXiv1207.5034)

Probing inflation



- Komatsu et al. (2010): $r<0.24$ (at 95% C.L.) using WMAP7+BAO+H_0
- For chaotic inflationary models with $V=\lambda\phi^p$ and N e-folds of inflation, the predicted tensor-to-scalar ratio is $r=4p/N$, with $n_S=1-(p+2)/2N$. Data excludes $p>3$ for $N=60$ at 95% C.L.

TB, EB and BB spectra: hints for new physics?



(WMAP3: Kogut et al. 2007)

TB, EB and BB spectra: hints for new physics?

Testing CPT Symmetry

if terms like Chern-Simons have to be added to the standard electrodynamic Lagrangian, than Lorentz, P and CPT symmetries will be violated. This will induce a rotation of the polarization direction of each photon as it propagates from the LSS to us. This effect is called "Cosmic Birefringence"

$$C_\ell^{\mathrm{TE,obs}} = C_\ell^{\mathrm{TE}} \cos(2\Delta\alpha),$$

$$C_\ell^{\mathrm{TB,obs}} = C_\ell^{\mathrm{TE}} \sin(2\Delta\alpha),$$

$$C_\ell^{\mathrm{EE,obs}} = C_\ell^{\mathrm{EE}} \cos^2(2\Delta\alpha),$$

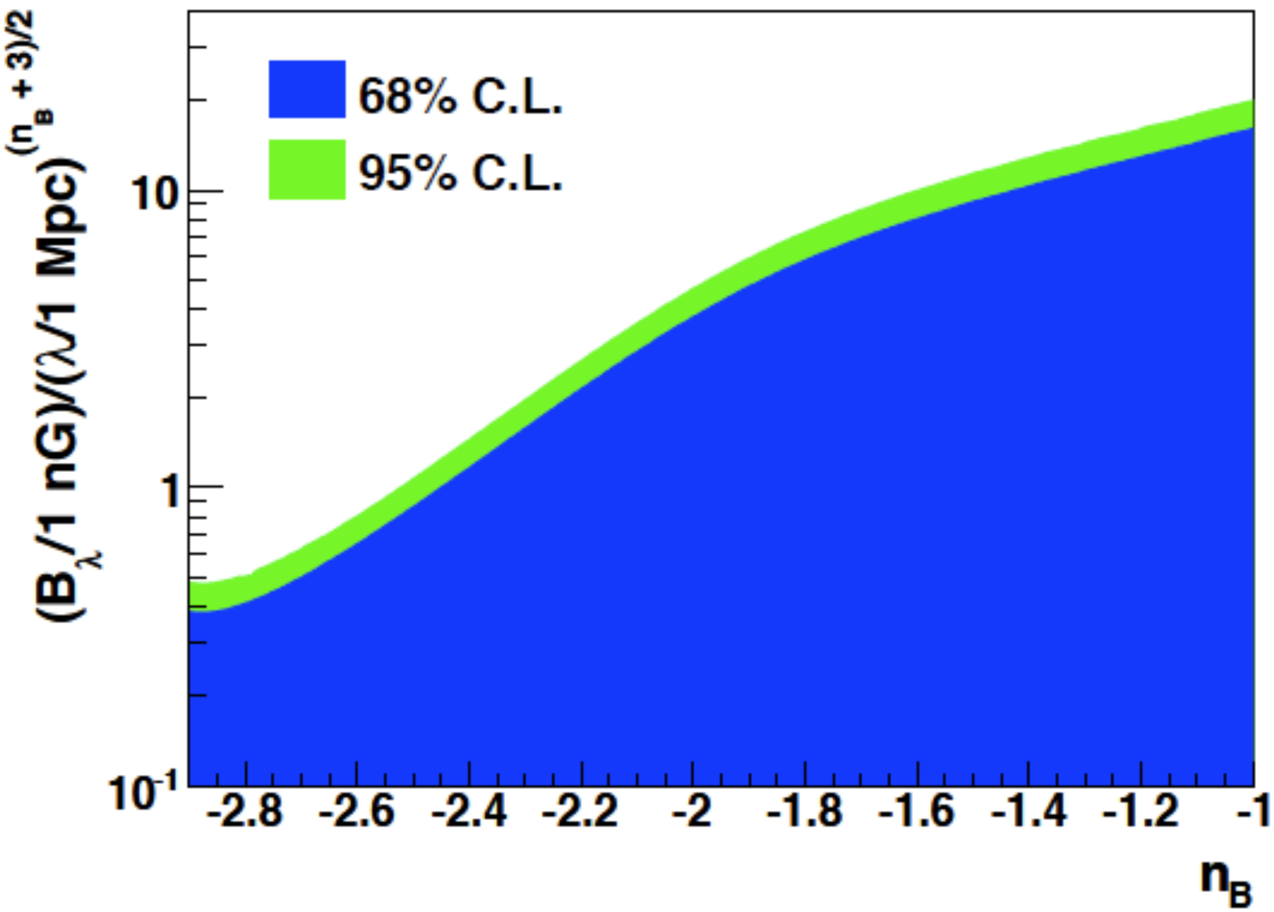
$$C_\ell^{\mathrm{BB,obs}} = C_\ell^{\mathrm{EE}} \sin^2(2\Delta\alpha),$$

$$C_\ell^{\mathrm{EB,obs}} = \tfrac{1}{2}(C_\ell^{\mathrm{EE}}) \sin(4\Delta\alpha).$$

alpha = Birefringence angle

From these equations it is possible to build estimators for alpha (as long as it is zero these violating terms are excluded)

Constraining Primordial magnetic fields



• Faraday rotation by a primordial magnetic field produce B-mode polarization.

• Kahniashvili et al. (2008). At scales of 1 Mpc and n_B=-2.9, constraints are better than 1nG (extrapolated to present).

Observability of B-modes

- **Signals are extremely small** ⇒ large number of receivers with large bandwidths are required.
- Accurate **control of systematics** (cross-pol, spillover,...) is mandatory.
- **Foregrounds**. B-mode signal is subdominant over Galactic foregrounds
  - Free-free, low-freq, not polarized
  - Synchrotron, low-freq, pol ~10%
  - Thermal dust, high-freq, pol ~10%
  - Anomalous emission, 20-60 GHz, pol ~3%?
  - Point sources, low-freq, pol ~5%