Lensing B-mode at low ell

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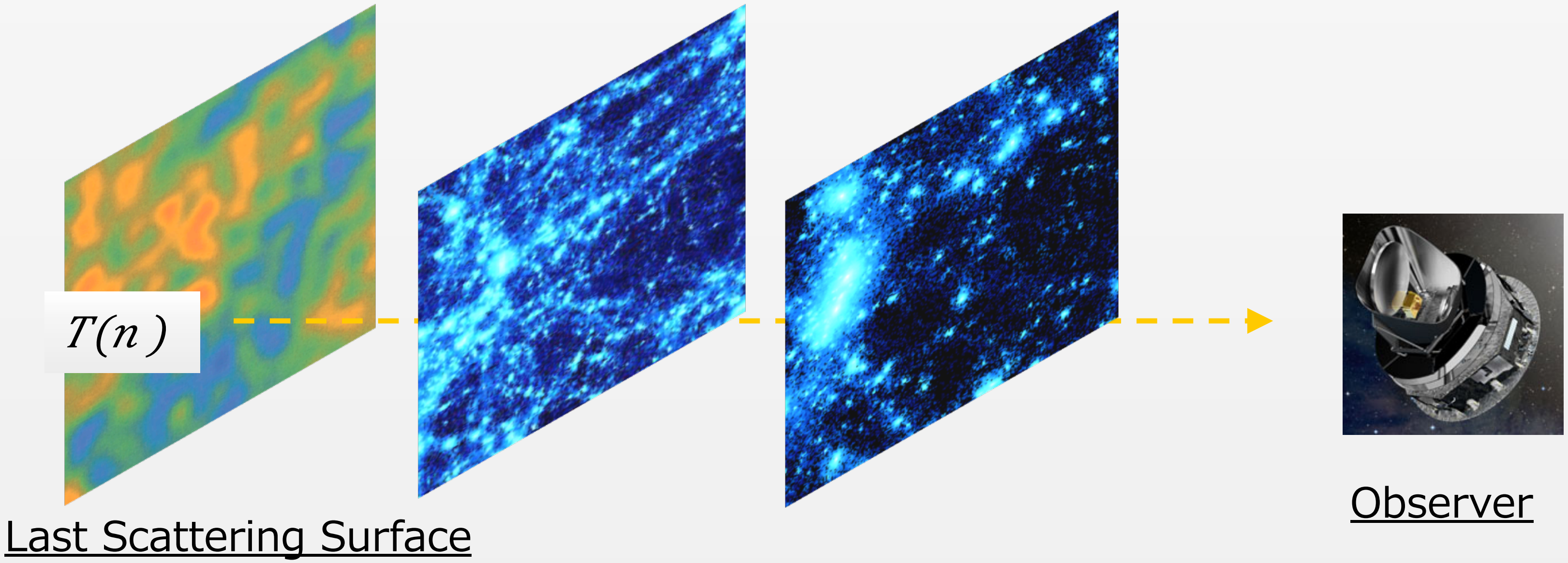
B-mode from Space WS (Dec 10-16, 2015)

Contents

CMB Lensing

The lensing effect on the CMB is well described by remapping of the CMB anisotropies.

(Reviews : Lewis&Challinor'06; Hanson+'10; Smith'11; TN'14)



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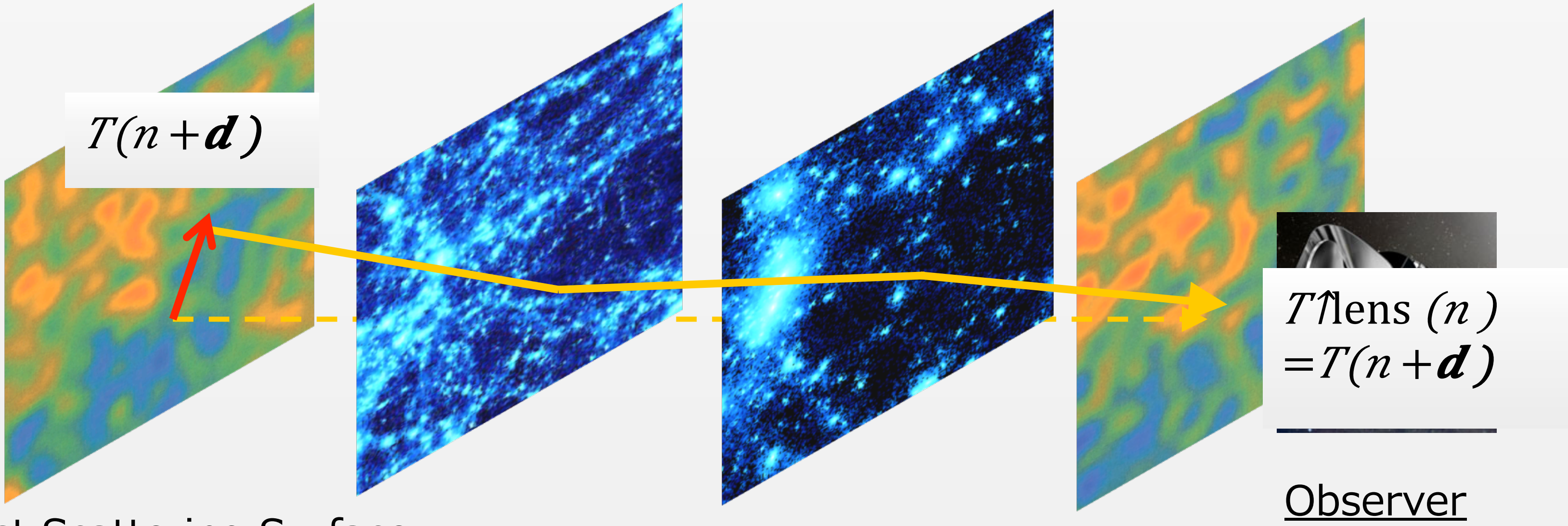

Last Scattering Surface

The lensing remaps the fluctuations by $\boldsymbol{d}=\nabla\boldsymbol{\phi}$

Lensing potential

Lensing B-modes

In ongoing and future CMB experiments, the polarization lensing is more important than the temperature lensing because the lensing produces B-modes

Only E-mode

Last Scattering Surface

(e.g., Zaldarriaga & Seljak, 1998)

Lensing B-modes

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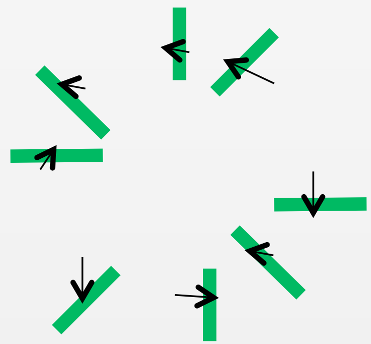
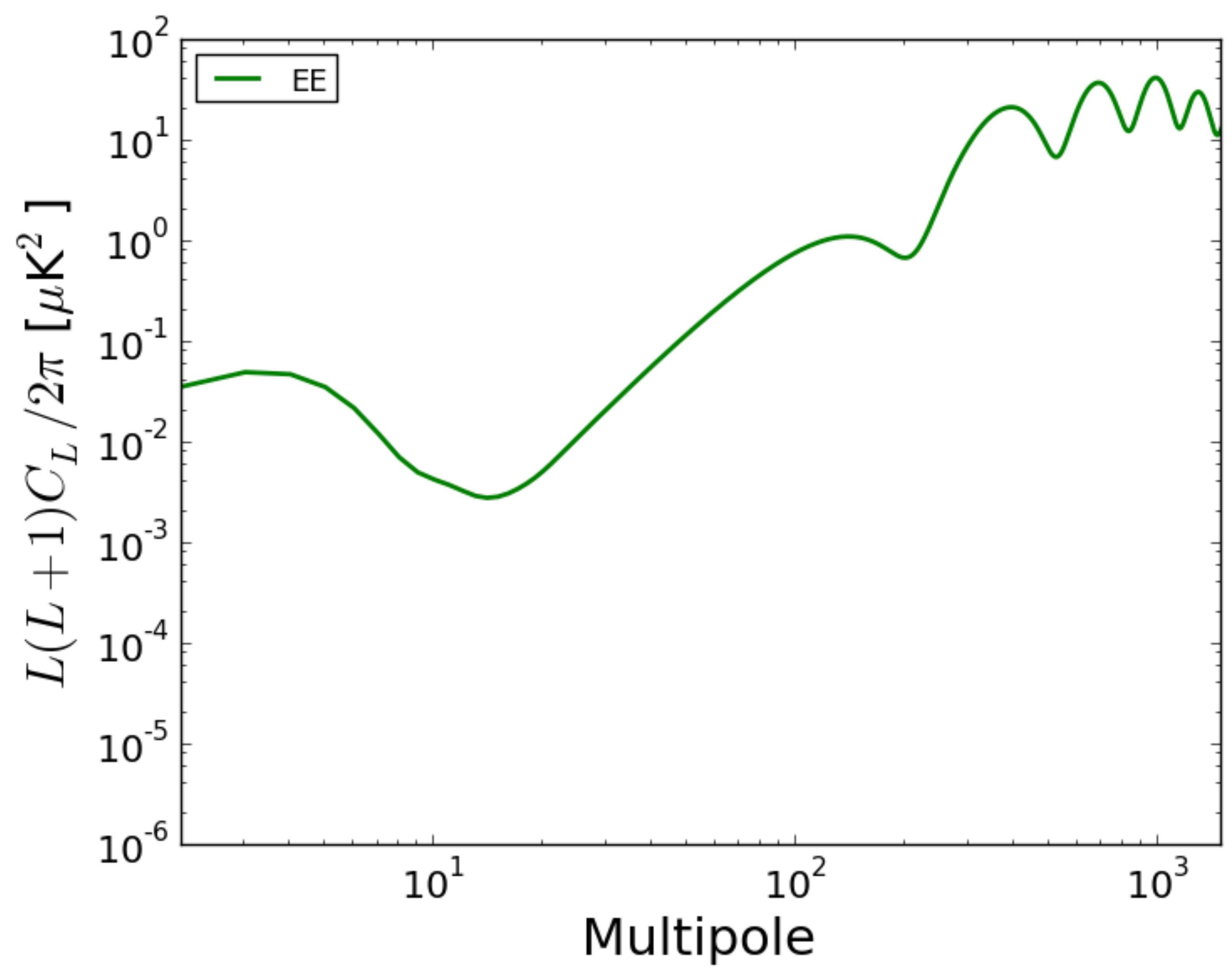


Observer

E/B mixed pattern
(no longer parity even)

(e.g., Zaldarriaga & Seljak, 1998)

Lensing B-mode power spectrum



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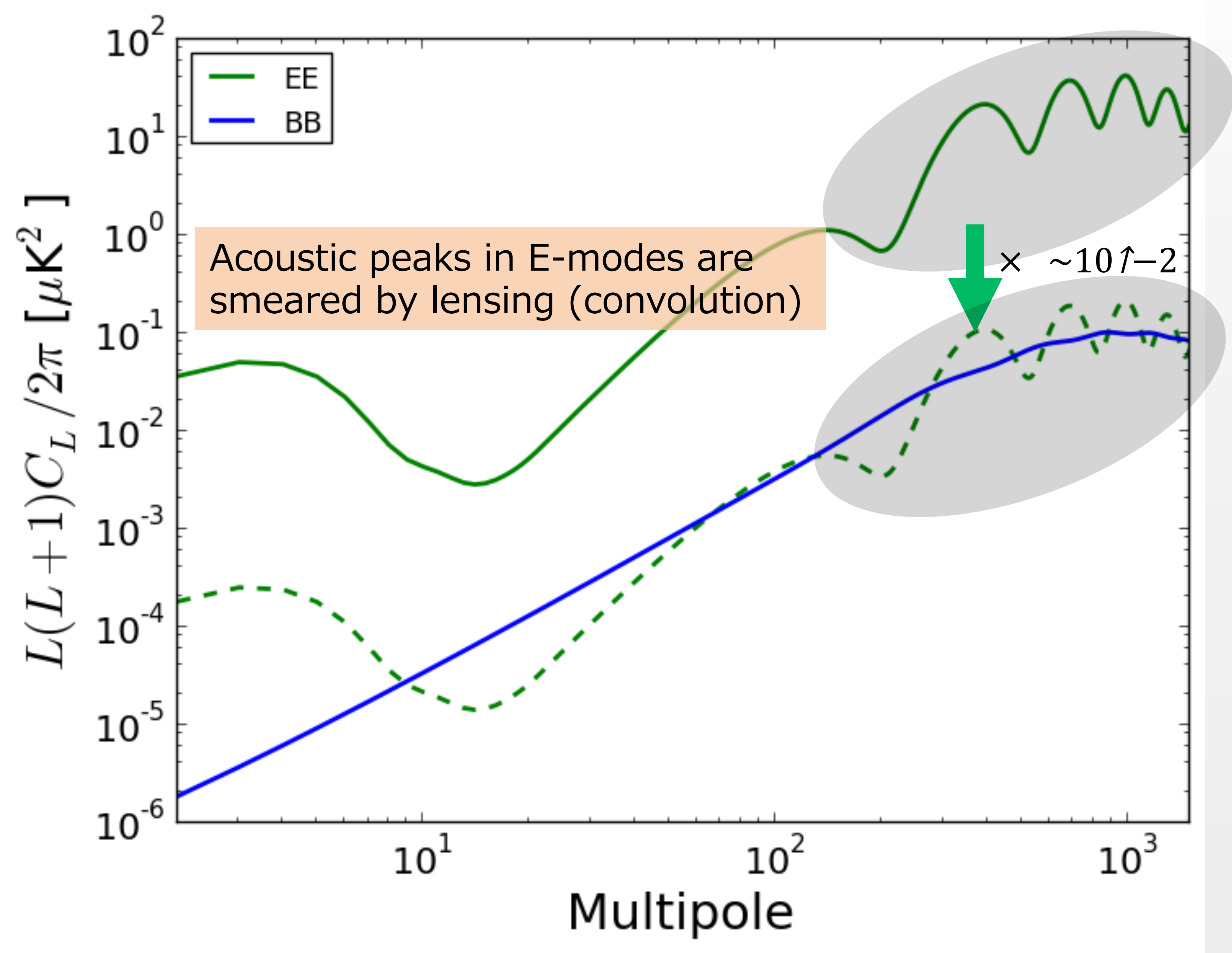

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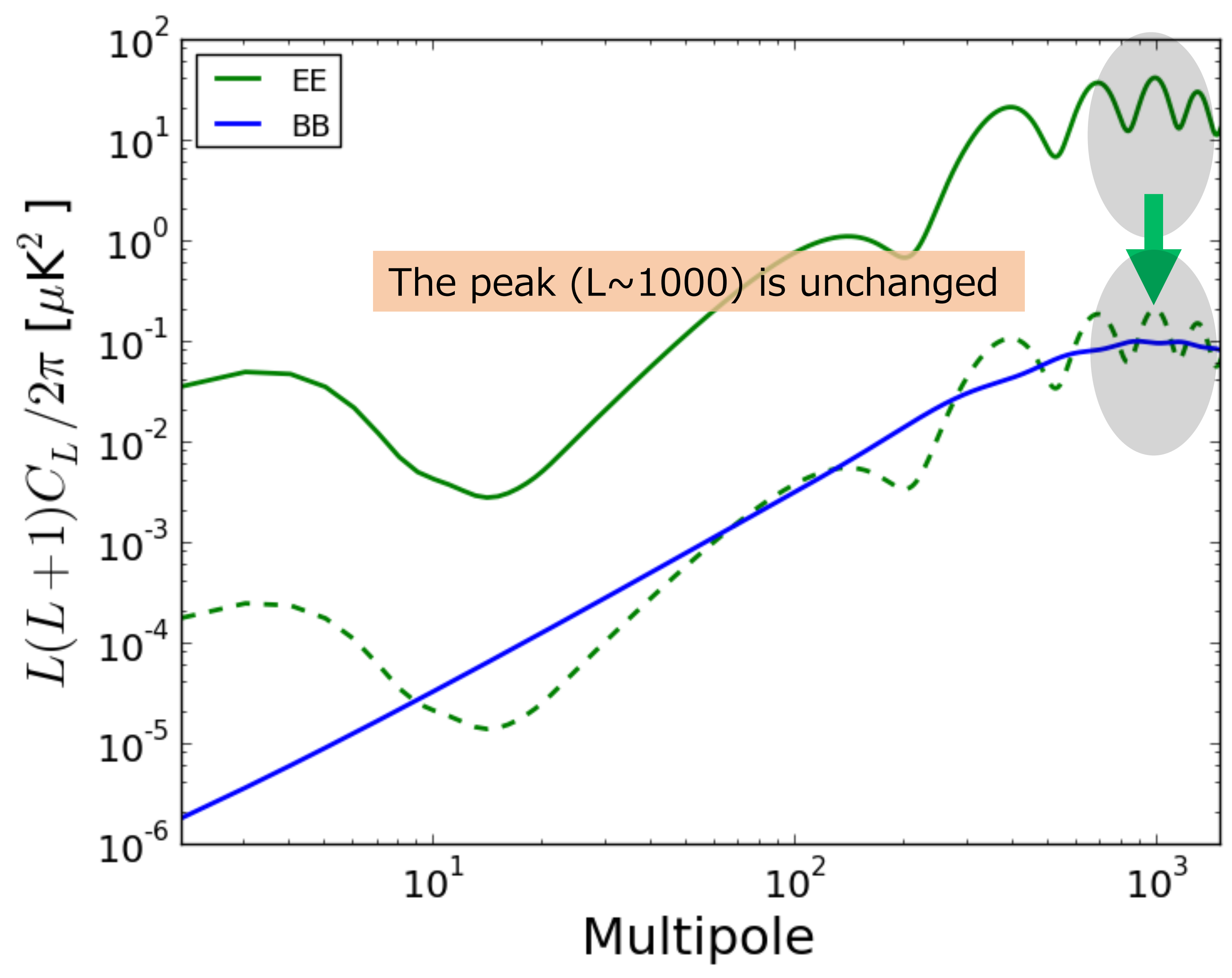

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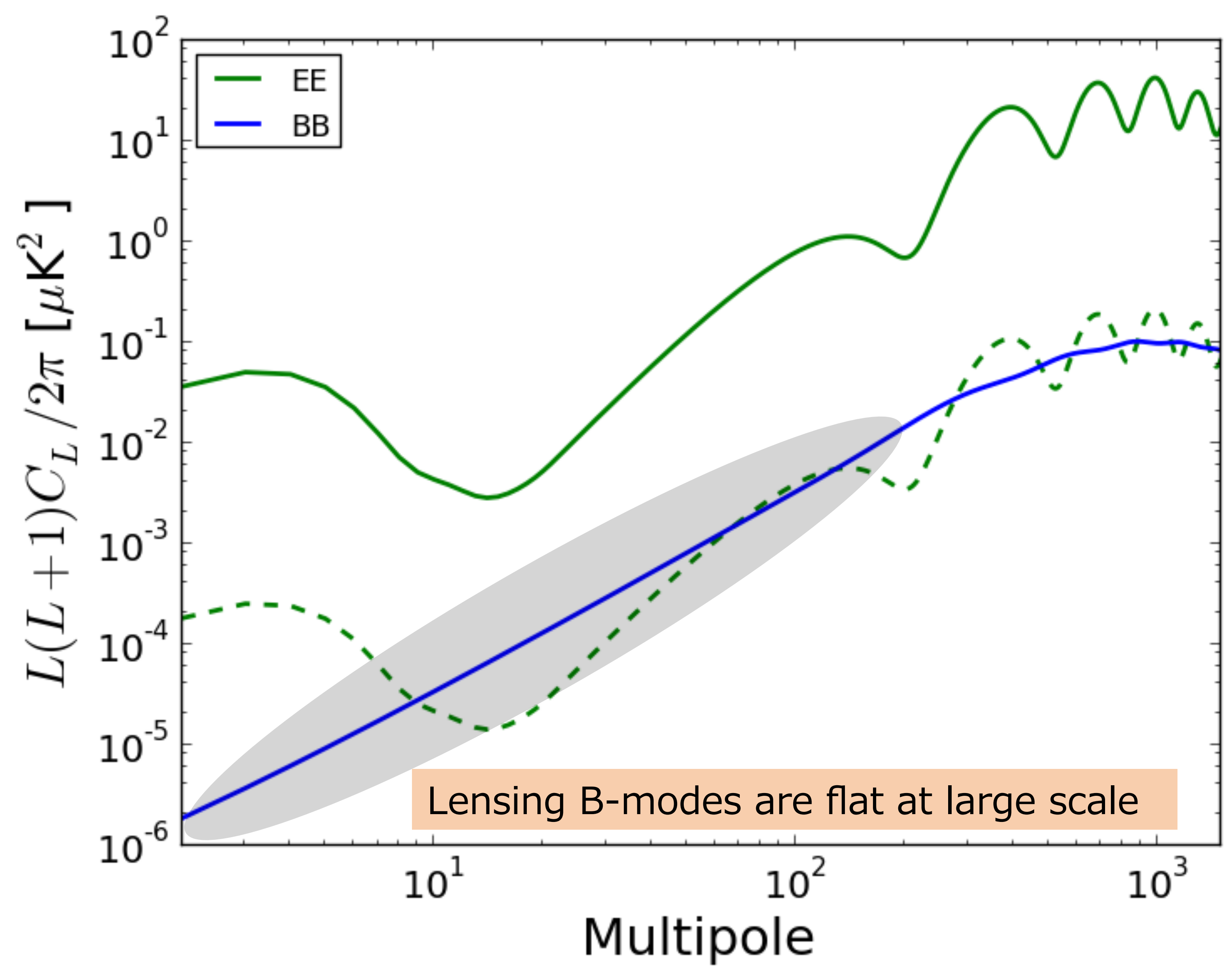
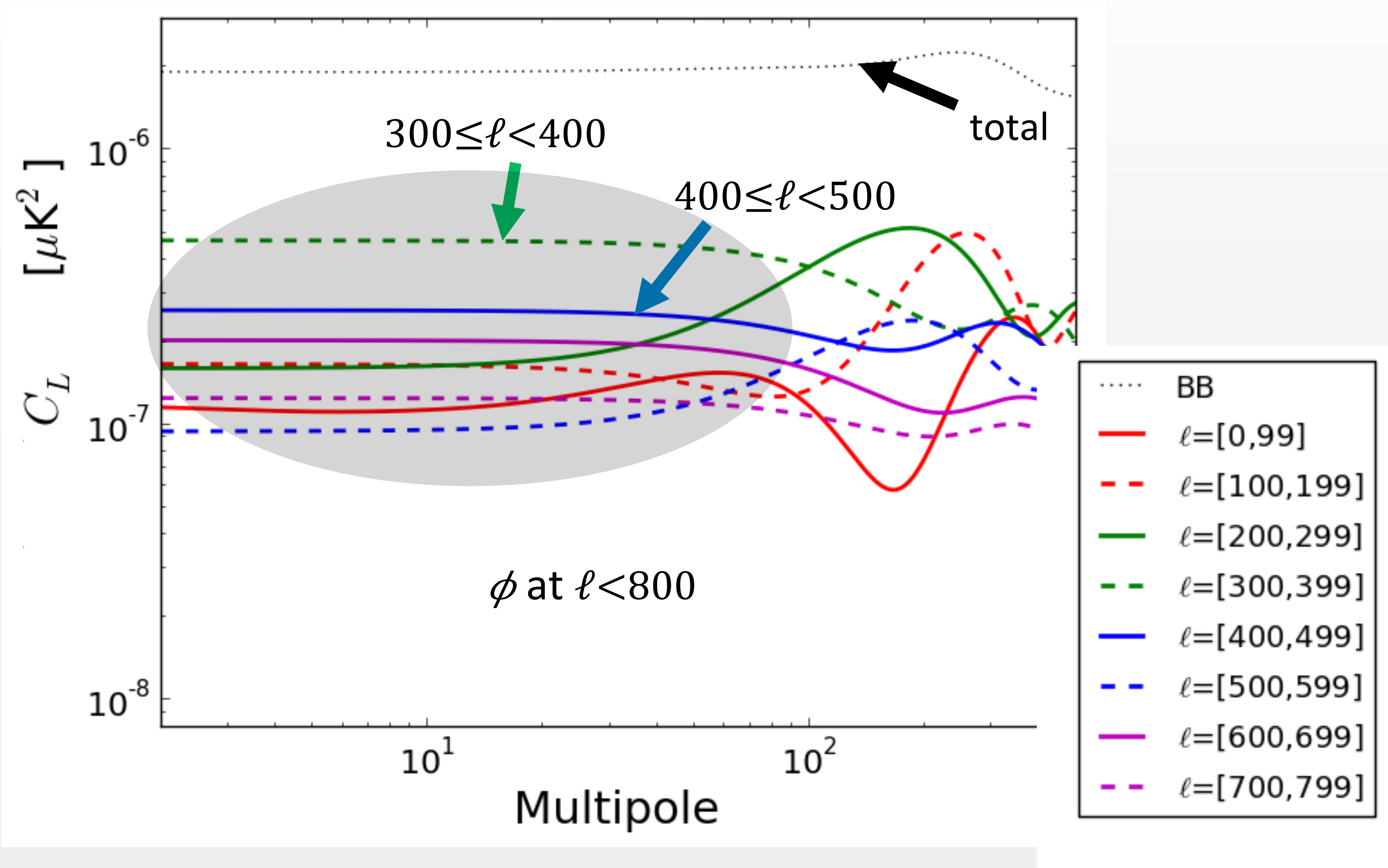


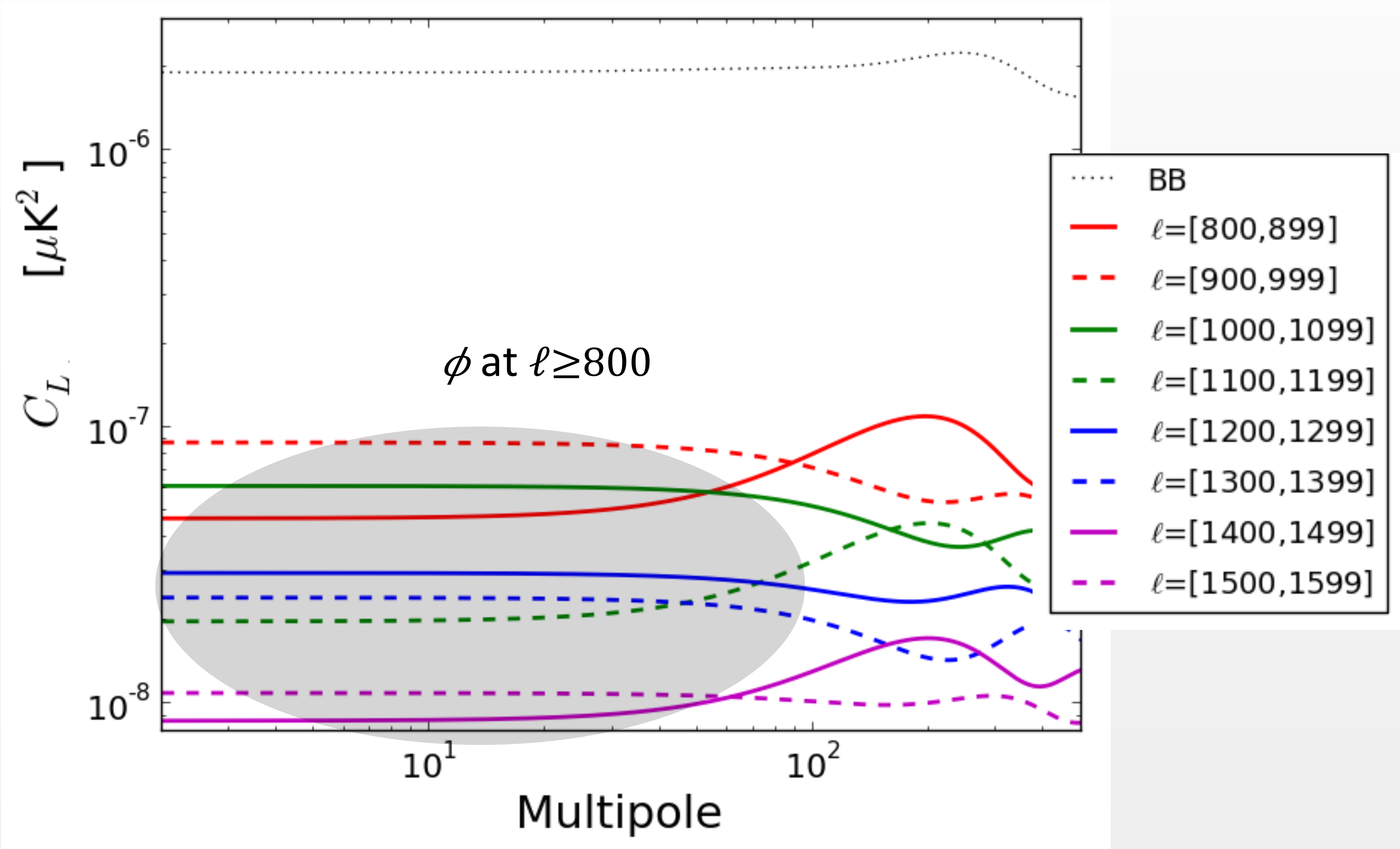
Which scales in ϕ source the lensing B modes



1) ϕ at $300 \leq \ell < 400$ is the most dominant source

2) Flat power spectrum at large scales

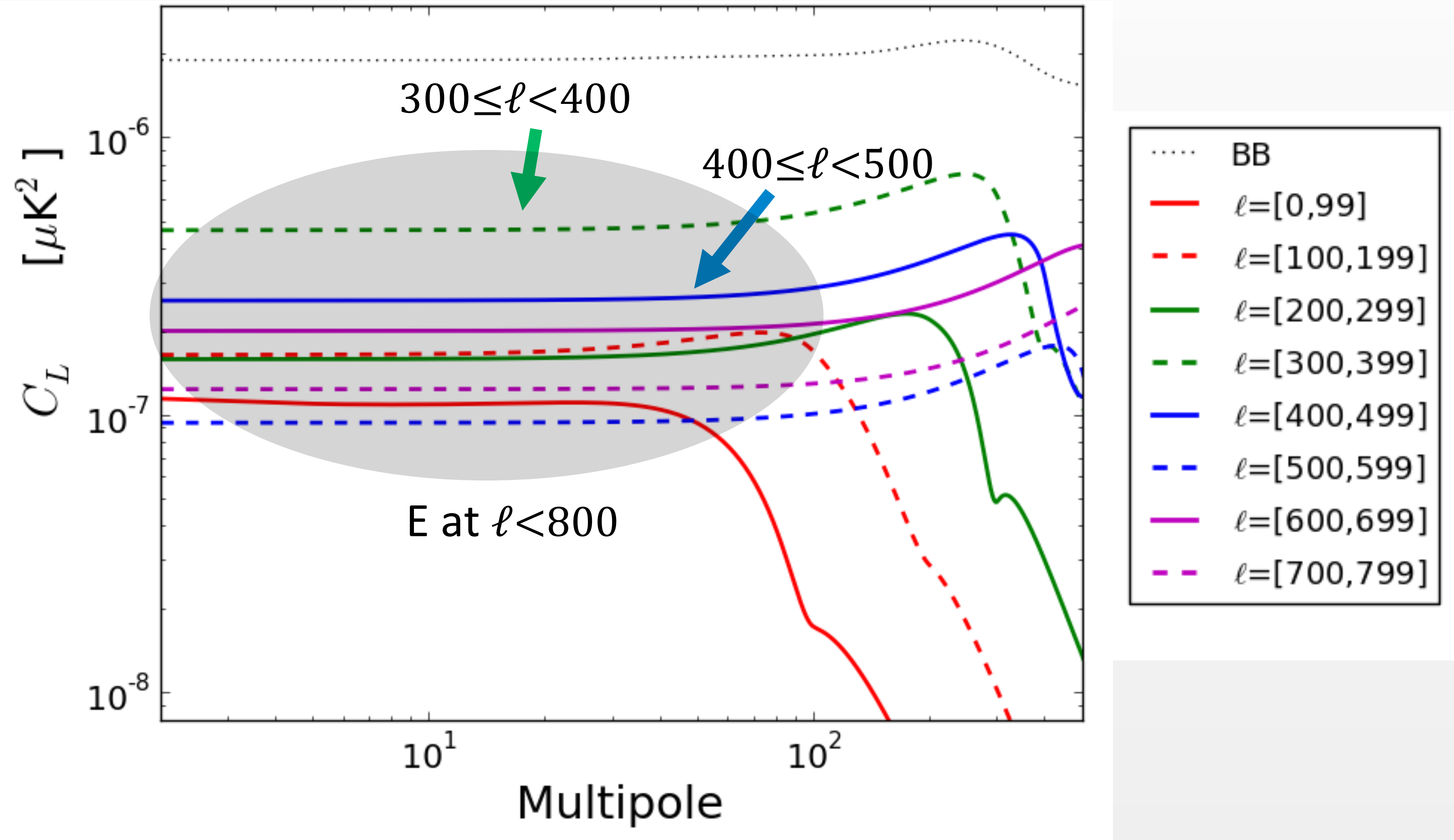
Which scales in ϕ source the lensing B modes



1) Contribution from ϕ at high-ℓ is not so significant

2) Flat power spectrum at large scales

Which scales in **E-modes** source the lensing B modes



1) Similar to the case of ϕ (at large scale)

2) Flat power spectrum at large scales

Flatness of the low-ℓ lensing B modes

From the previous figures, changes in the shape of C_ℓ^{EE} and $C_\ell^{\phi\phi}$ only affect amplitudes of C_ℓ^{BB} at low-ℓ

E-mode has little power at large scale, and only ~2′ shift can not produce significant correlation in large-scale E-mode pattern.

Uncorrelated random fields in real space correspond to a white spectrum

$$C_L^{BB} \sim \frac{1}{4\pi} \int \frac{d\ell}{\ell} \left[\ell^4 C_\ell^{\phi\phi}\right]\left[\ell^2 C_\ell^{EE}\right]$$

(independent of L)

Changes in C_L^{EE} and $C_L^{\phi\phi}$ can modify only the amplitudes

This feature is important to consider how the large scale B-modes are sensitive to the cosmology.

Accurate calculation of the large-scale lensing B-modes

- Non-linear growth of the large-scale structure : ~10%
  (compared to the linear theory) (Challinor & Lewis '05)

  [In addition, we can measure bispectrum of ϕ using S4,
  but this is rather relevant to the small-scale B-modes]

  For future high-sensitivity experiments, we may need to accurately treat the non-linearity in ϕ.

- Multiple lensing / Born appox. : < 1%
  (Hagstotz et al 2015; Calabrese et al 2015)

- Time delay (radial displacement) : 0.01% (Hu & Cooray 2000)

- Gravitational faraday rotation : 0.0001% x (r/0.13) (Dai 2014)

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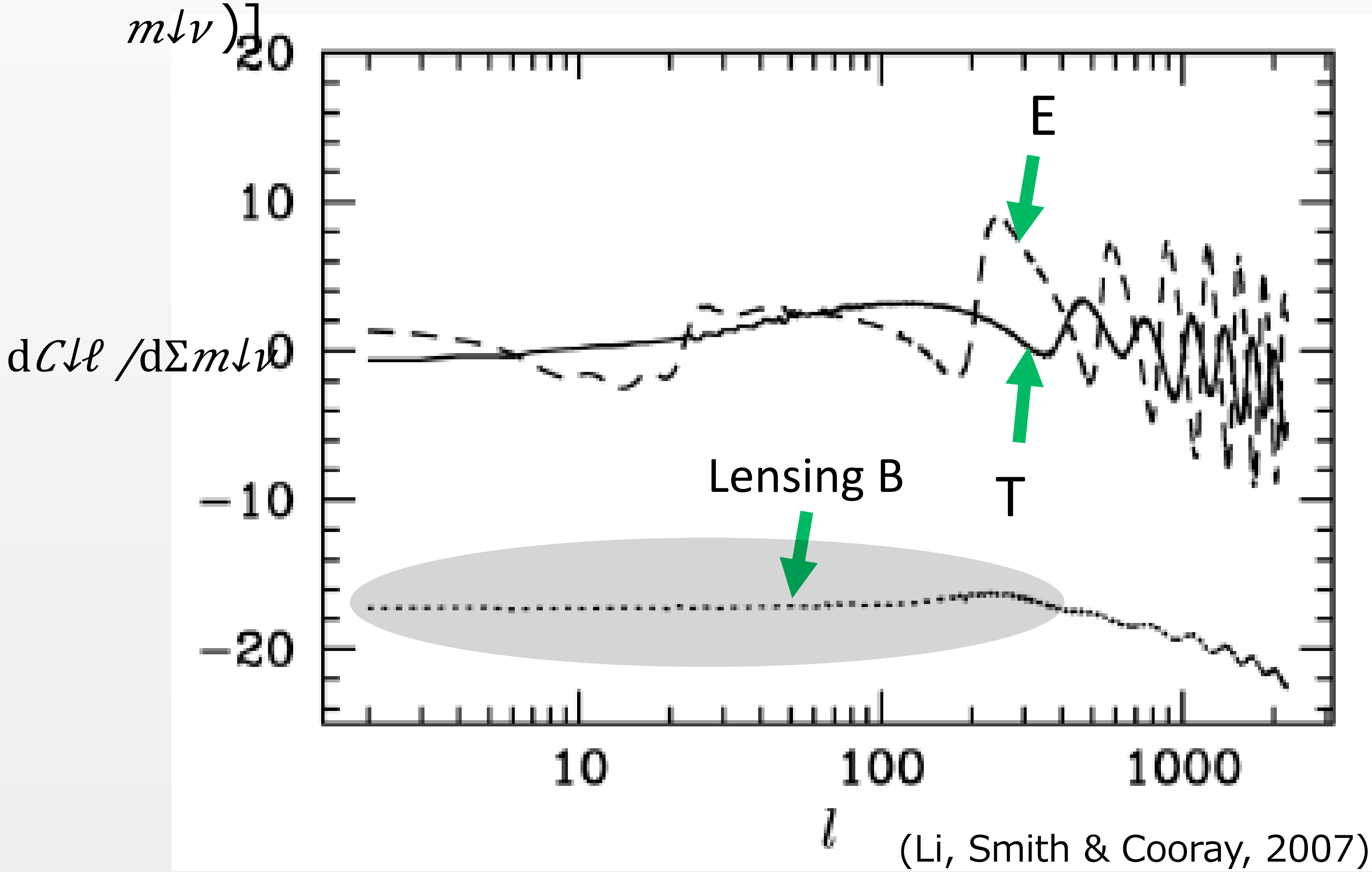
Cosmological information in large-scale lensing B-modes

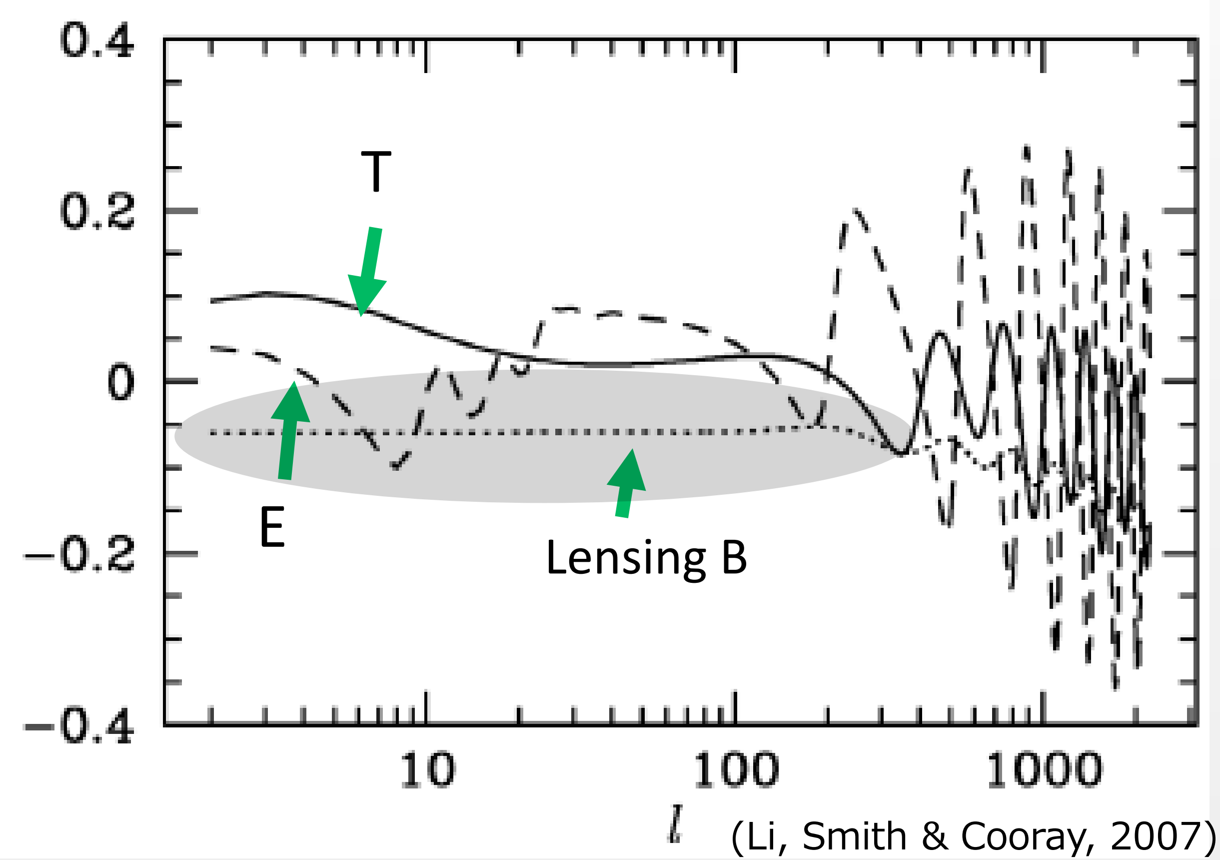
[Derivative with respect to the neutrino mass (Σm_ν)]



Sensitivity of C_ℓ^{BB} to Σm_ν is significant compared to that of E and T

Cosmological information in large-scale lensing B-modes

[Derivative with respect to the dark energy EoS (w)]



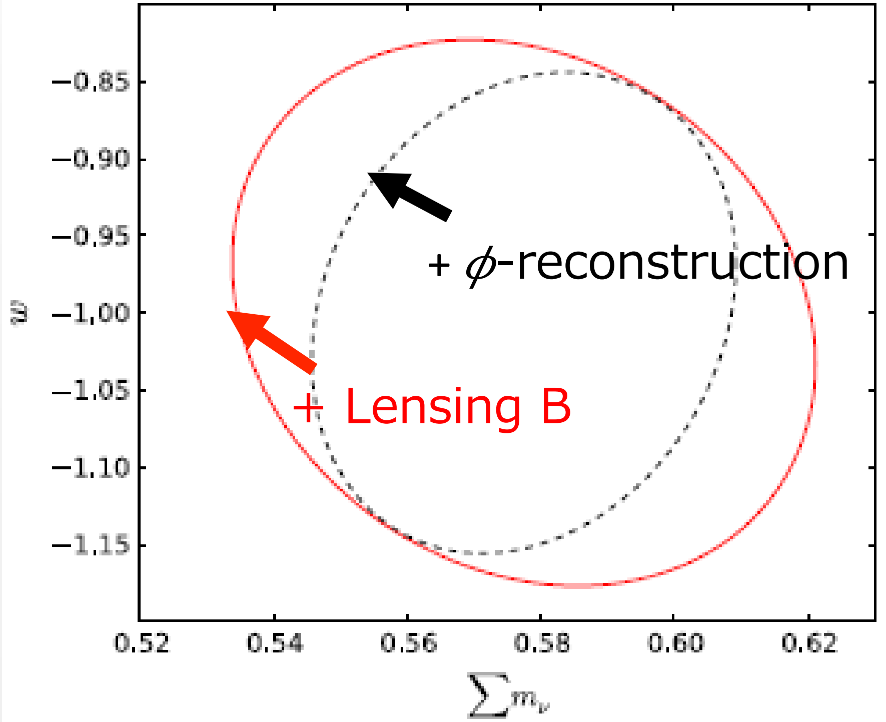
(Li, Smith & Cooray, 2007)

Derivative with respect to w is also flat which leads to strong parameter degeneracies

Cosmological information in the lensing B-modes

If we want to constrain Σm_ν and w, the reconstruction of ϕ is more useful than the lensing C_ℓ^{BB}

Benoit-Levi et al (2012)



If ϕ is modified at scales where the reconstruction noise is significant, the large-scale lensing C_ℓ^{BB} becomes better than the reconstruction (?)

Using large-scale lensing B-modes, we can reconstruct the large-scale ϕ map, and constrain, e.g., fNL by cross-correlating galaxy clustering

Contents

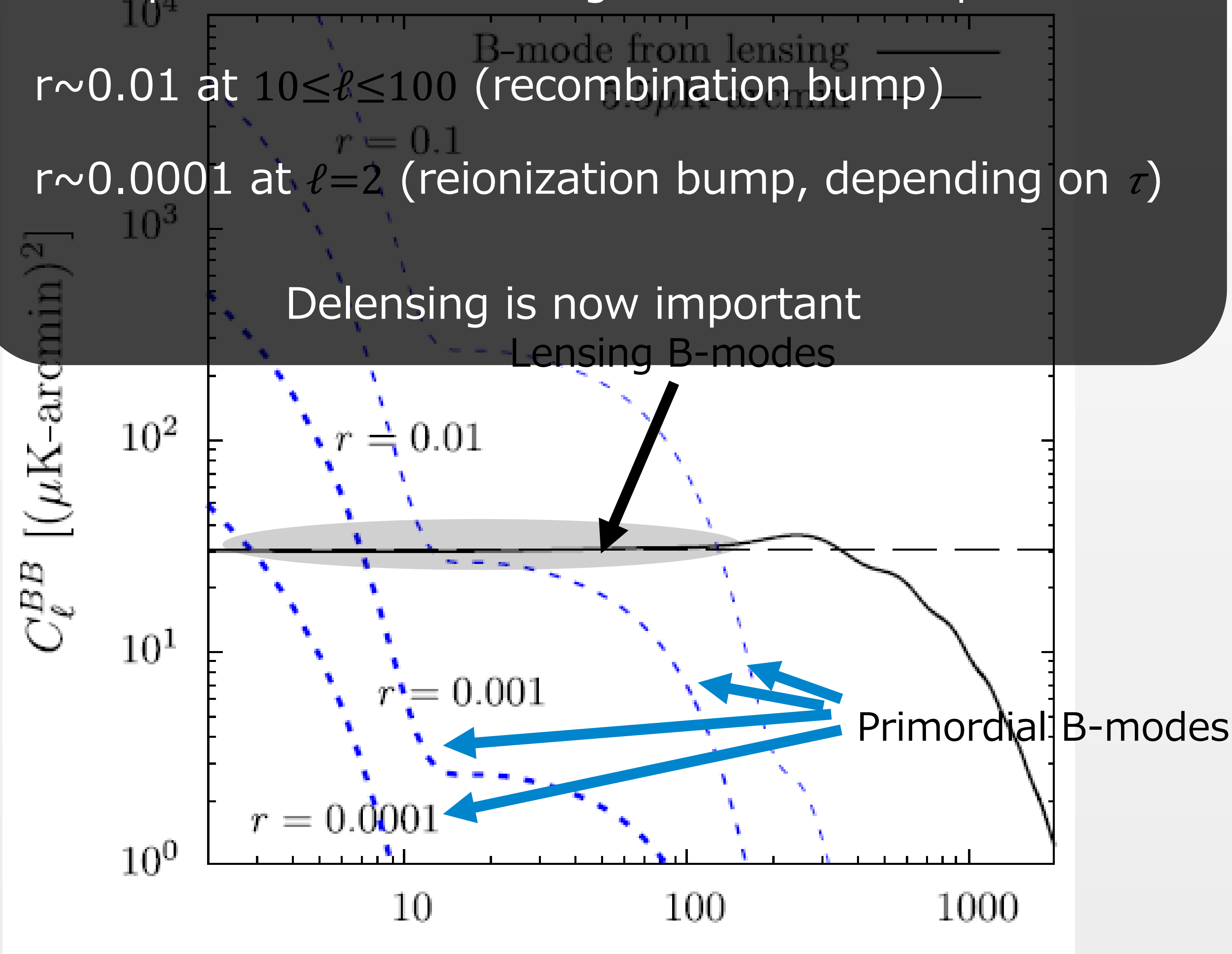
Lensing B-mode power spectrum

Amplitudes of the lensing B-modes correspond to

r~0.01 at $10 \le \ell \le 100$ (recombination bump)

r~0.0001 at $\ell=2$ (reionization bump, depending on τ)

Delensing is now important



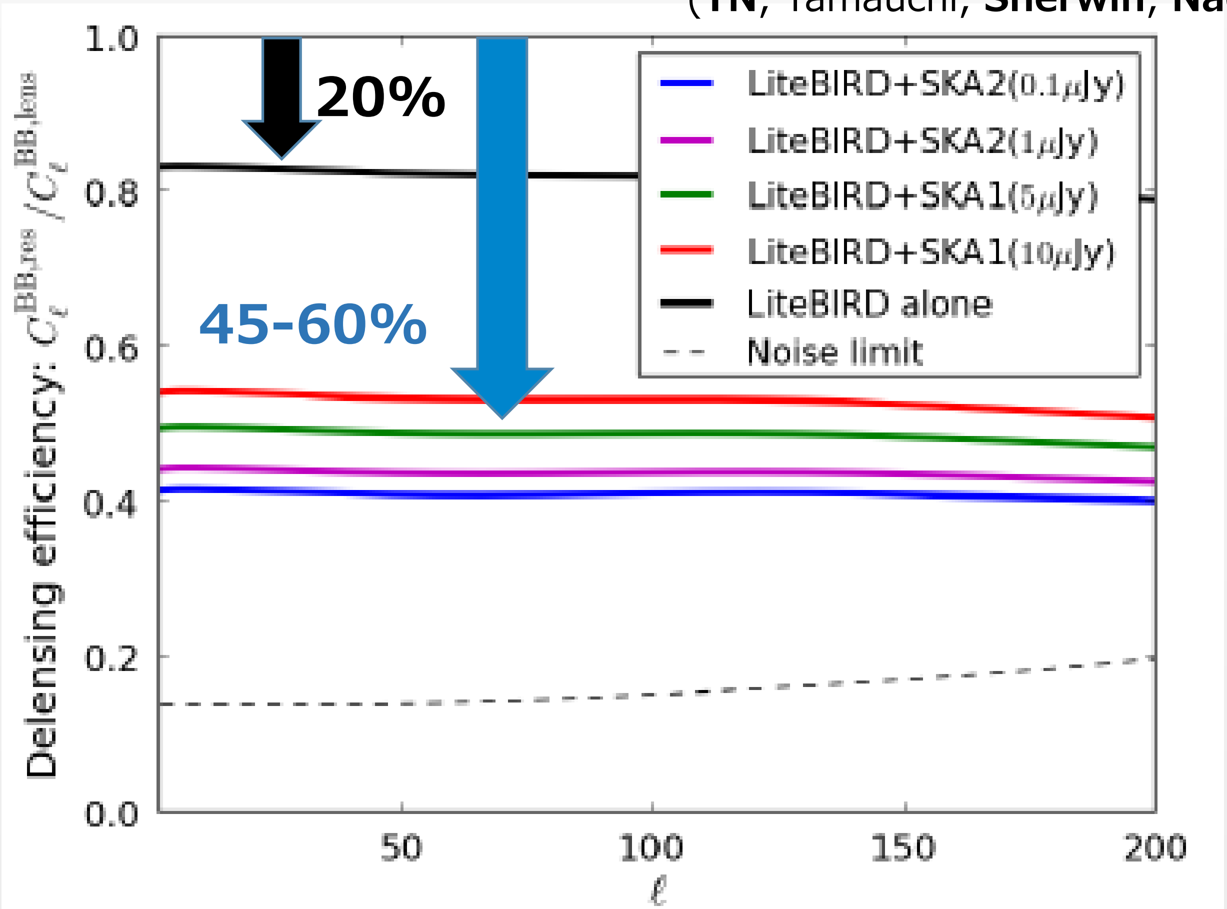
(TN '14)

Delensing LiteBIRD B-modes

See Blake's talk

Once we measure ϕ (+noise), we can remap observed E-modes to get lensing B-mode template, and subtract it from observed B-modes

(**TN**, Yamauchi, **Sherwin**, **Nagata** 2014)



For LiteBIRD, mass tracers will be useful for delensing.

Delensing LiteBIRD B-modes

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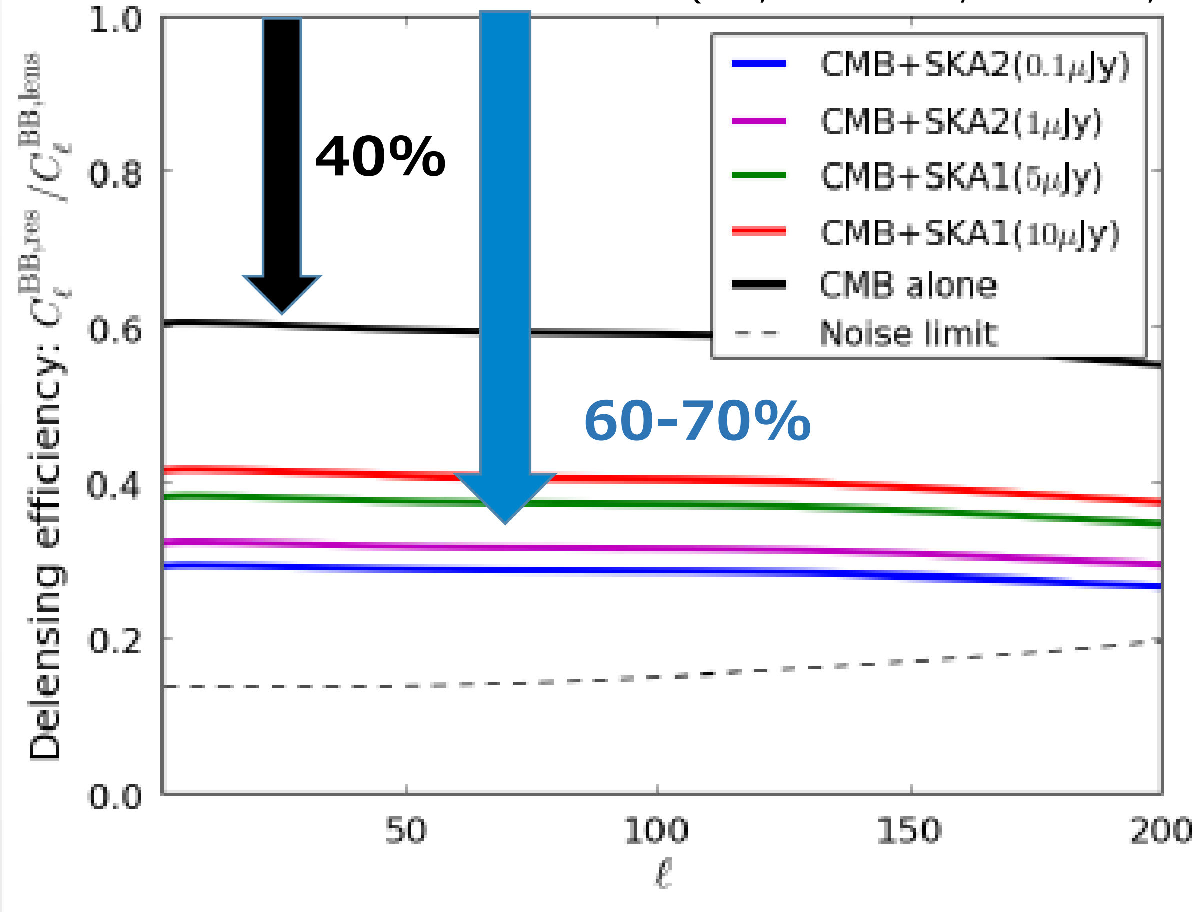


Combining, e.g., Simons Array and AdvACT will also help delensing

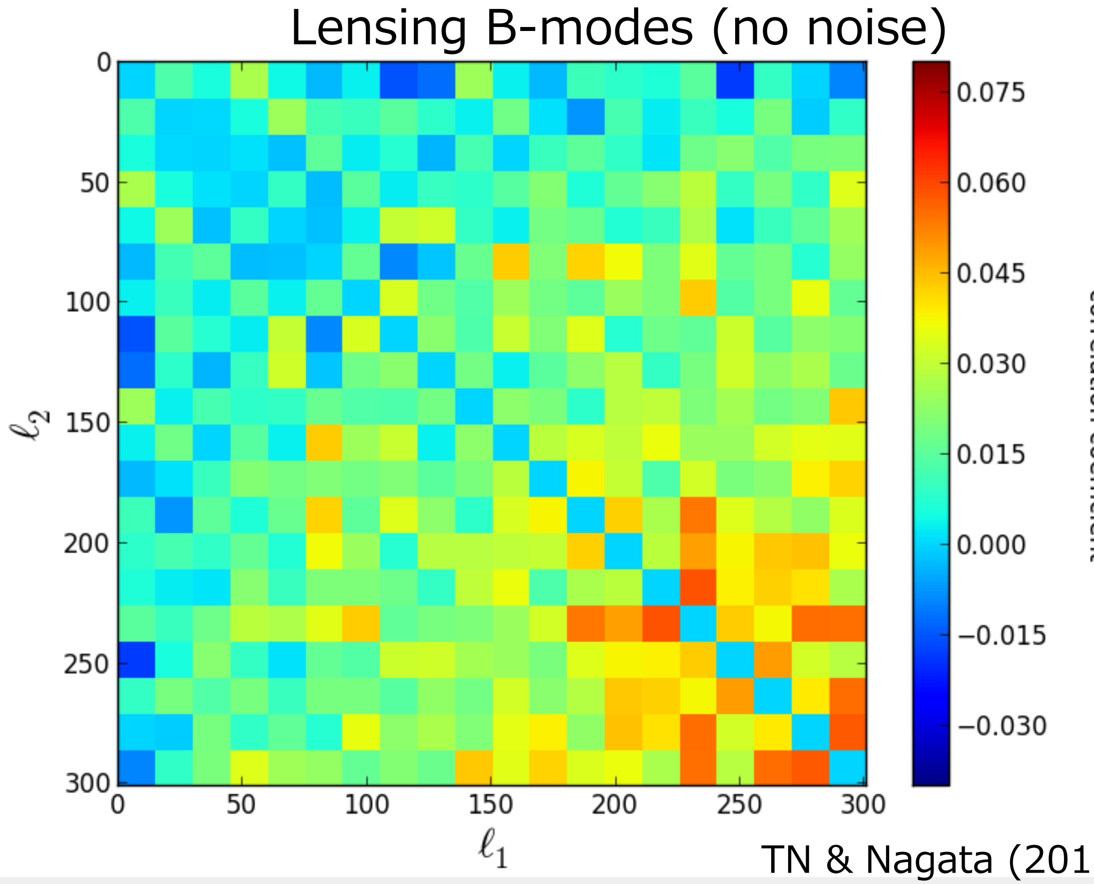
Statistical property

Lensing B-modes = non-Gaussian field

Non-Gaussian covariance may degrade the sensitivity to r

The delensing process may enhance the impact of the non-Gaussian covariance

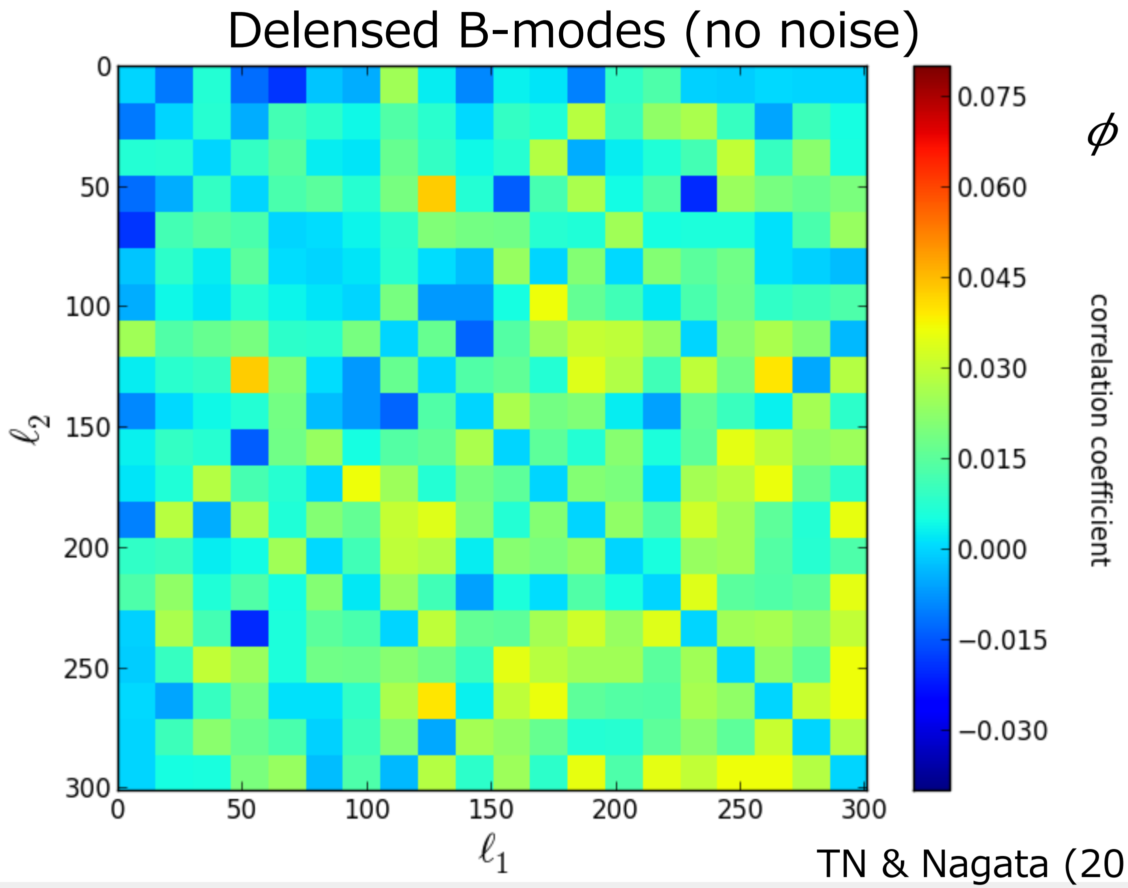
Power Spectrum Covariance



TN & Nagata (2015)

The typical values are <1% at $\ell < 100$ and 6-8% at $\ell = 200 - 300$

Power Spectrum Covariance



ϕ from Simons Array

TN & Nagata (2015)

The values are smaller than those of the lensing B-modes

The non-Gaussian covariance degrades $\sigma(r)$ by only few percent

But the results depend on the precision of ϕ measurement

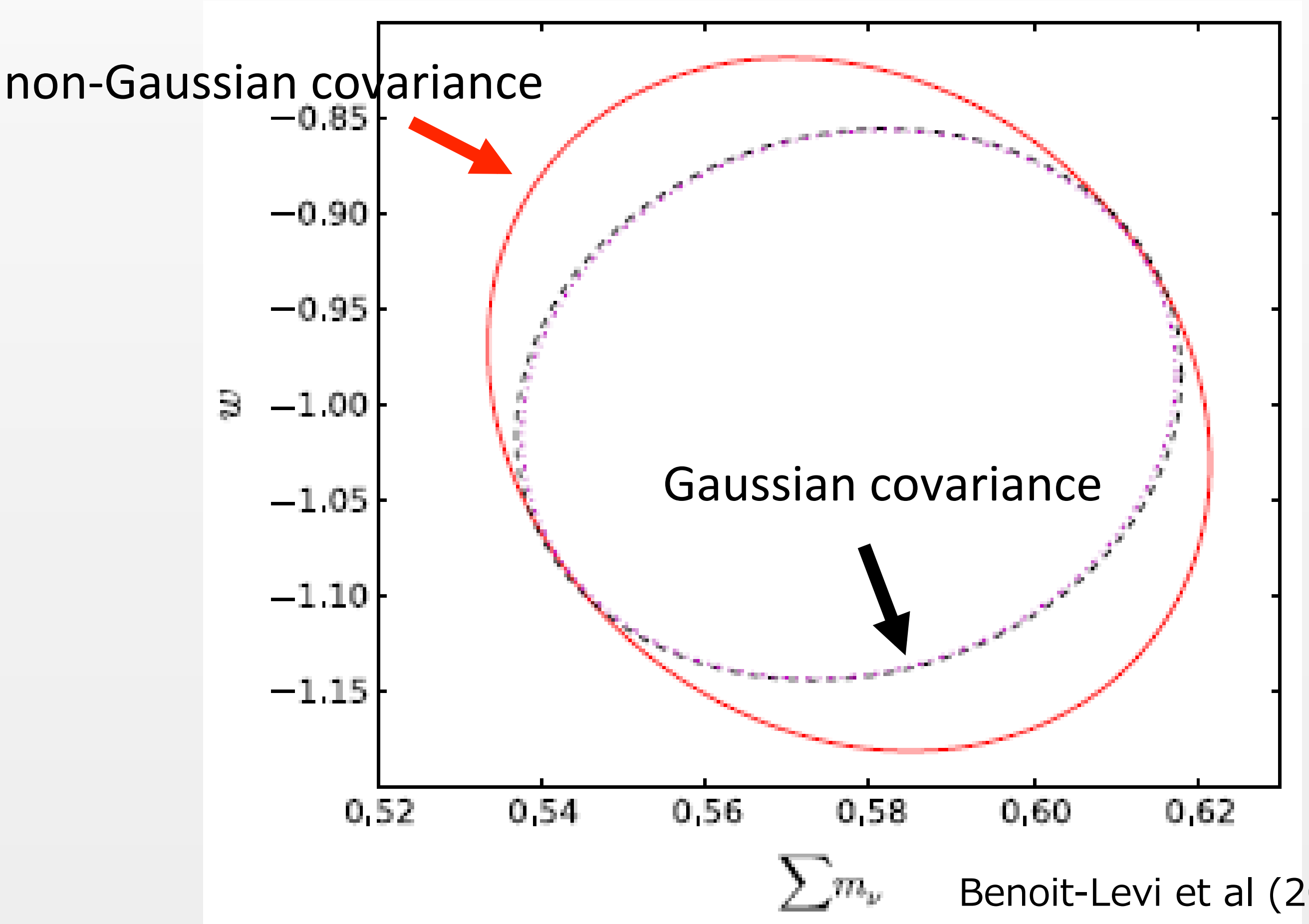
Summary

- Large scale lensing B-modes are mostly sourced from E-modes and ϕ at $300 \leq \ell < 400$
- Using large-scale lensing B-modes to parameter constraints suffer from the strong parameter degeneracy, but useful to reconstruct the large-scale ϕ
- Delensing is now important and mass tracers are useful for LiteBIRD, if S4 data will be not available

BACKUP

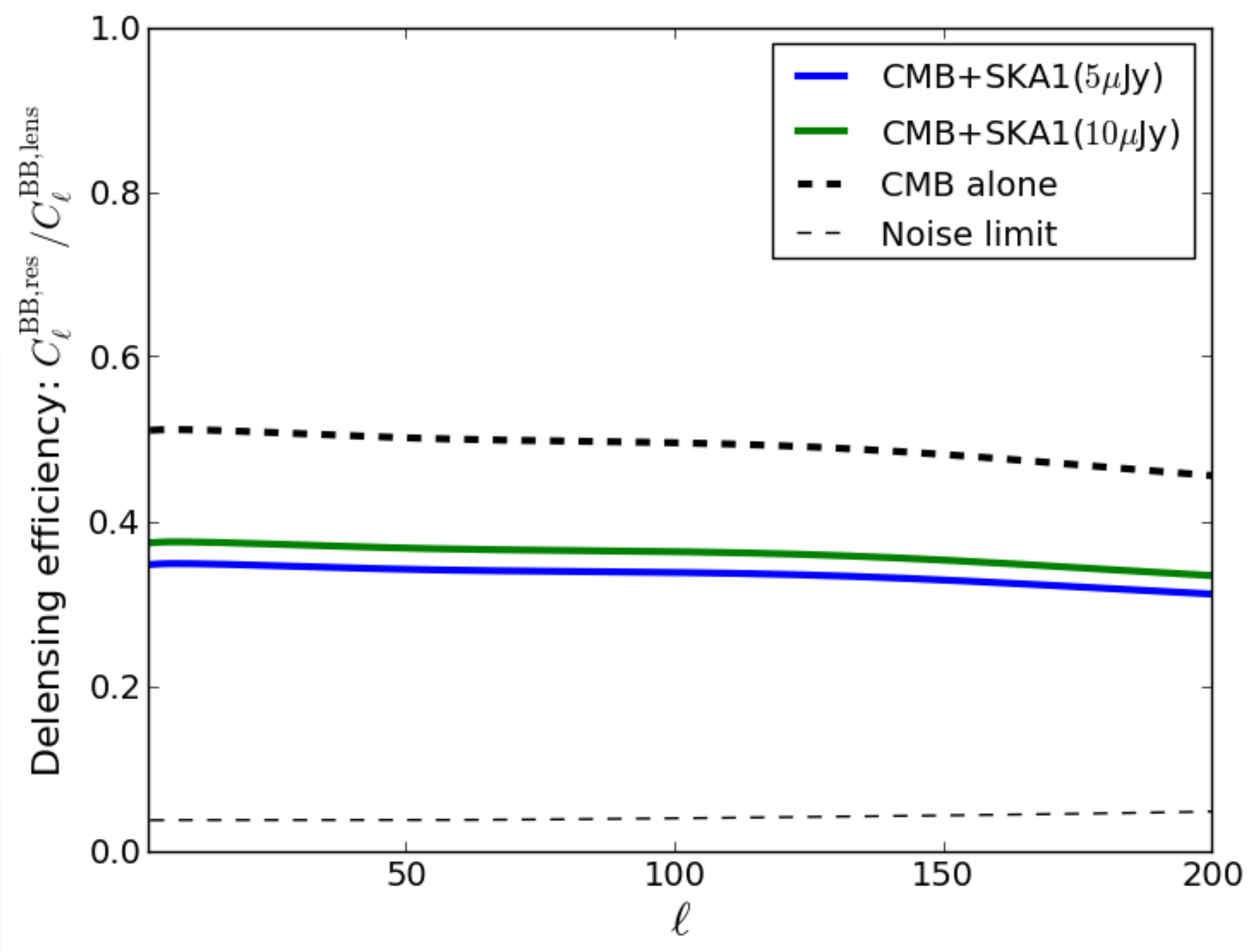
Cosmological information in the lensing B-modes

Moreover, the lensing B-modes are non-Gaussian (especially at small scales) which degrades parameter constraints



Benoit-Levi et al (2012)

Delensing



Using BICEP/Keck + SPT and other mass tracers, the lensing B-modes are significantly suppressed.

Measuring lensing potential

Primordial CMB is statistically isotropic, and different multipoles are uncorrelated:

$$\langle T_{L_1} T_{L_2} \rangle = 0 \qquad (L_1 \neq L_2)$$

A lensing potential leads to statistical anisotropy in the primordial CMB, generating mode couplings:

$$\langle T^{\rm lens}_{L_1} T^{\rm lens}_{L_2} \rangle \propto \phi_{L_1 - L_2} \qquad (L_1 \neq L_2)$$

The lensing potential is estimated from the off-diagonal elements

$$\phi^{\rm obs}_{L} = \int \mathrm{d}^2 \ell \; F_{\ell, L} \; T^{\rm obs}_{L-\ell} \, T^{\rm obs}_{\ell}$$

(Hu & Okamoto, 2002)

though some non-lensing anisotropies cause non-negligible biases

(e.g., TN, Hanson & Takahashi 2013)

Measuring lensing potential

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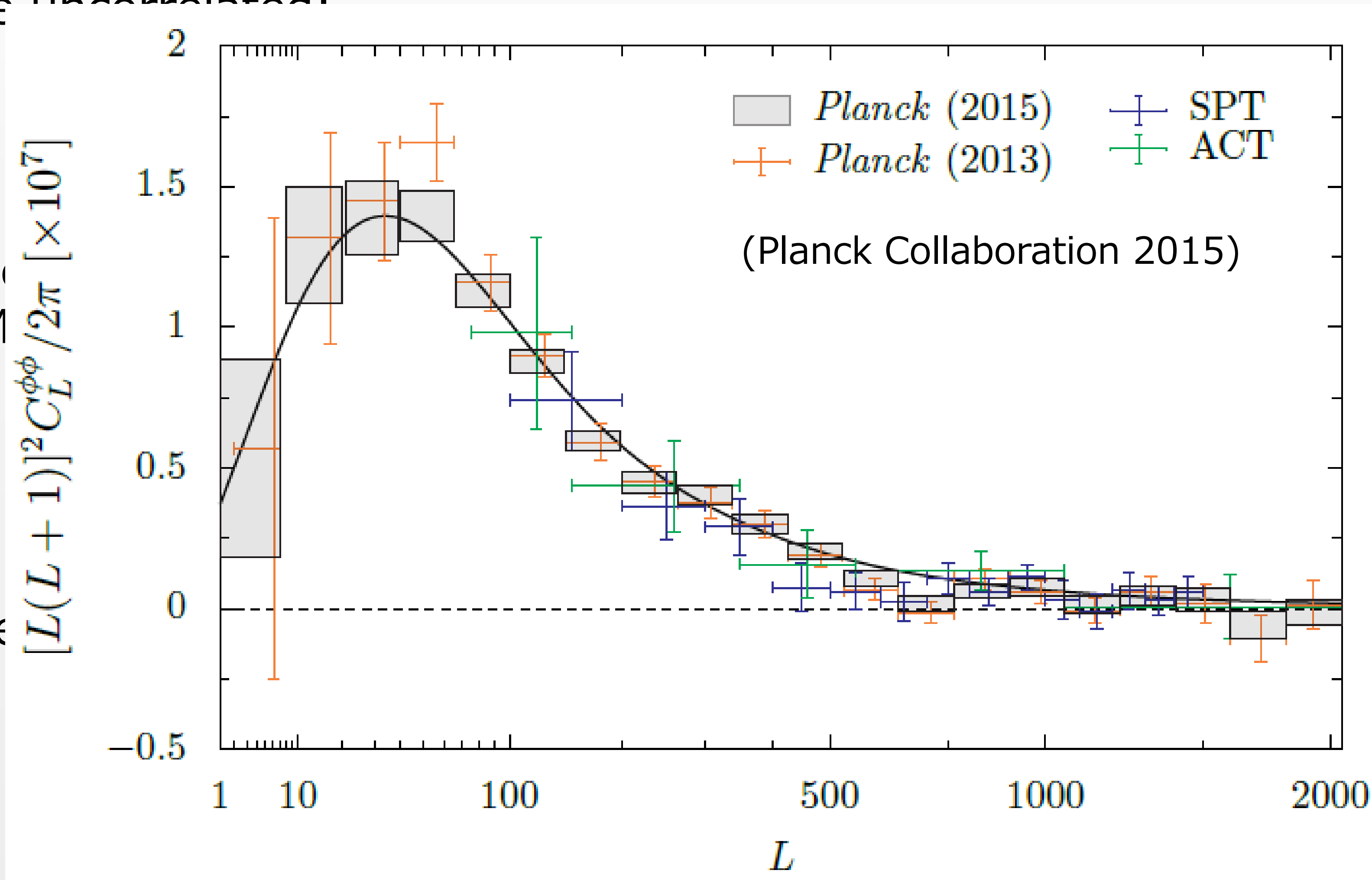

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Lensing Cosmology with LiteBIRD

Using the lensing B-modes, the lensing potential can be measured without small scale anisotropies

Planck provides phi at 40<=L<=400 (8<=L<=2048) as a conservative (aggressive) range

LiteBIRD will be able to measure nearly fullsky lensing potential, and has possibility to measure the phi map at the largest scales

Lensing Cosmology with LiteBIRD

Using the lensing B-modes, the lensing potential can be measured without small scale anisotropies

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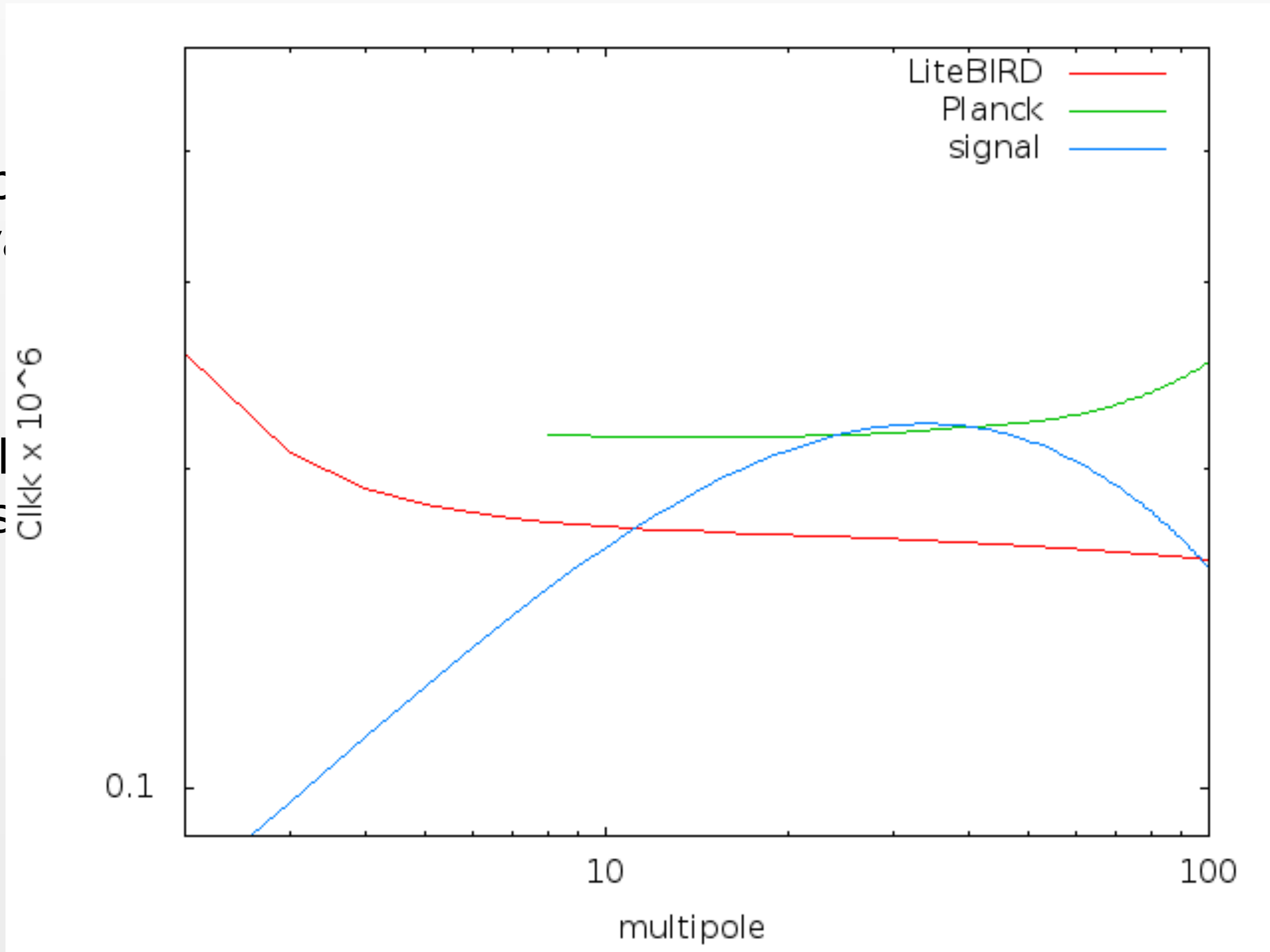


Lensing Cosmology with LiteBIRD

Using "large-scale" lensing mass map, we can probe

Primordial non-gaussianity — CMB lensing x galaxy clustering

Dark energy sound speed

Modified gravity

CMB lensing

CMB lensing x ISW

CMB lensing x galaxy

Other possibilities

CMB Lensing x E-modes — Reionization

Lensing at reionization epoch causes correlations between E-mode and lensing potential at very large scale

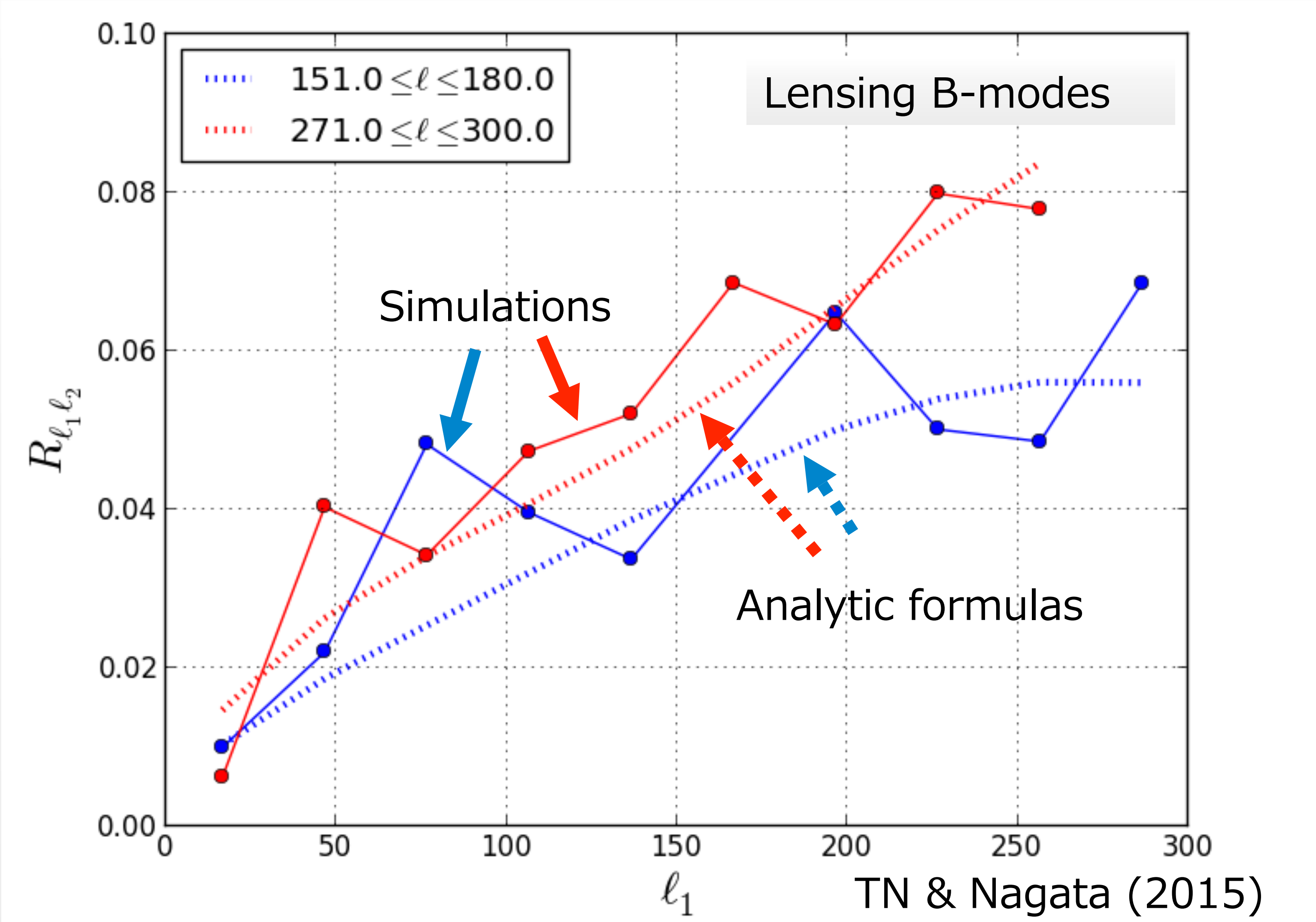
CMB Lensing Curl-Mode — Cosmic String, Magnetic field, post recombination GWs, etc

Curl mode of the lensing potential has large amplitudes at large scales

Polarization Lensing Bispectrum — Primordial non-gaussianity; Parity violation

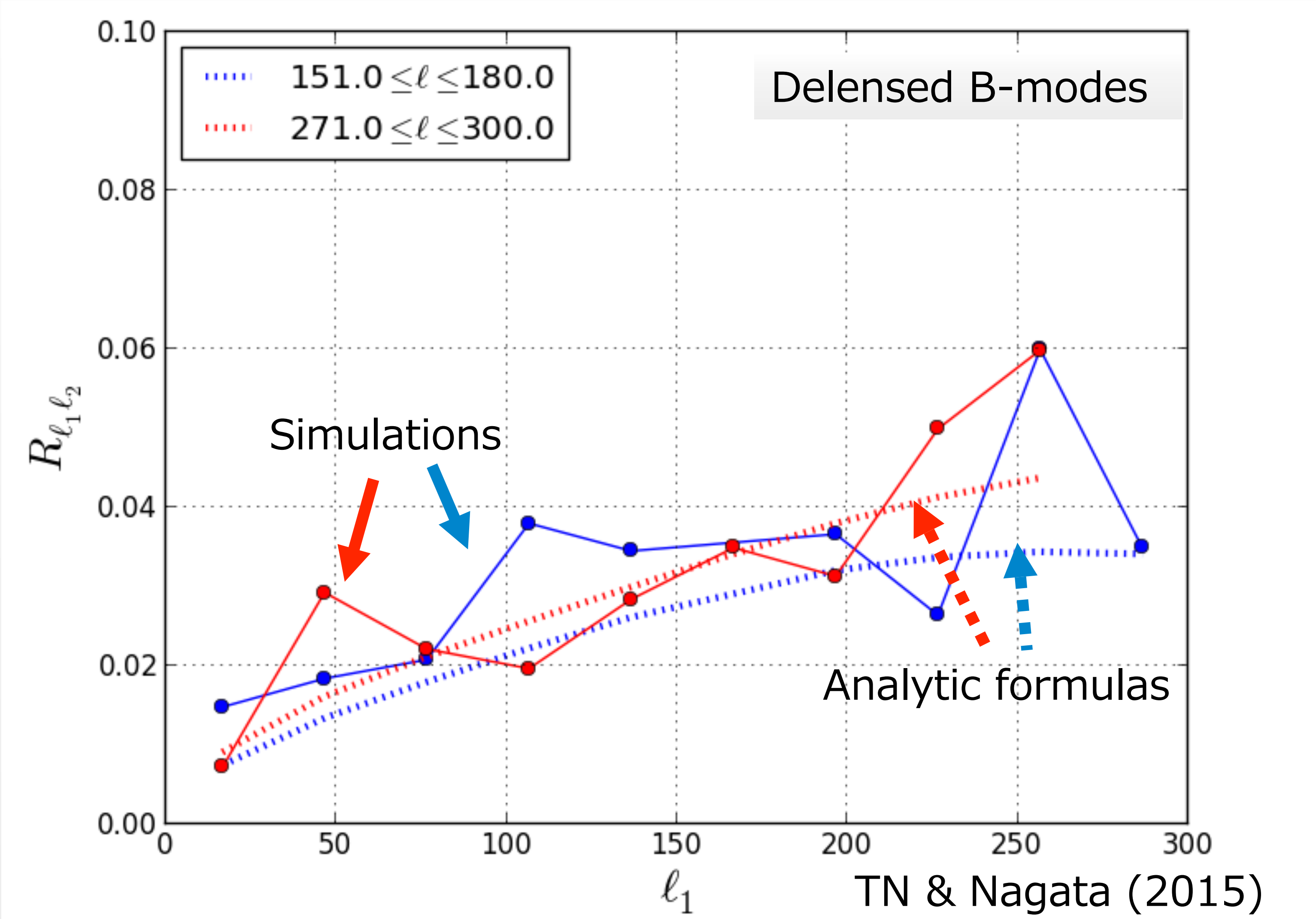
BBE, BBϕ, etc can be generated by non-Gaussianity, and BBB, $\cdots$ are generated by further violating parity.

Power Spectrum Covariance



The analytic formula including up to trispectrum well capture the behaviors of the simulation results

Power Spectrum Covariance



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