Gravitational lensing analysis from high-precision B-mode data

Toshiya Namikawa (Cambridge)

- This talk briefly highlights my recent completed and ongoing works on B-mode analysis

❑ T. Namikawa et al., "Evidence for the Cross-correlation between Cosmic Microwave Background Polarization Lensing from POLARBEAR and Cosmic Shear from Subaru Hyper Suprime-Cam", arXiv:1904.02116

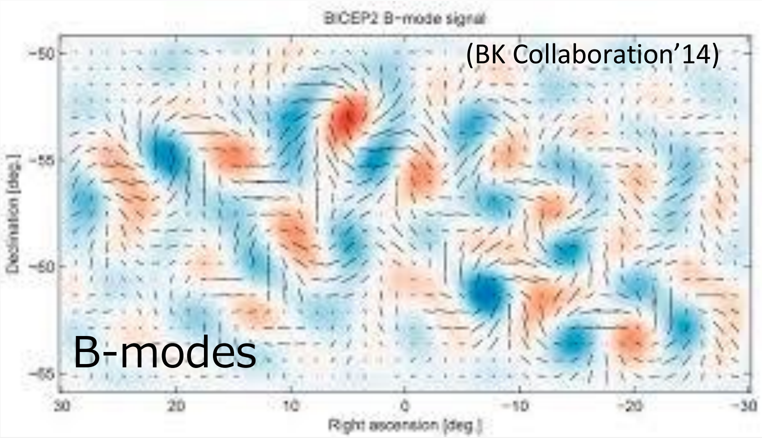
❑ BICEP2/Keck Array Collaborations (incl. T. Namikawa as corresponding author), "BICEP2 / Keck Array VIII: Measurement of gravitational lensing from large-scale B-mode polarization", arXiv:1606.01968

❑ BICEP2/Keck Array Collaborations (incl. T. Namikawa as corresponding author), "BICEP2 / Keck Array IX: New bounds on anisotropies of CMB polarization rotation and implications for axionlike particles and primordial magnetic fields", arXiv:1705.02523

❑ T. Namikawa, "CMB internal delensing with general optimal estimator for higher-order correlations", arXiv:1702.00169

CMB cosmology from high-precision B-modes

- In the coming decades, successful measurements of high precision B-modes will be of great interest for cosmology and high energy physics communities



  - B-modes provide a unique way to explore the early universe

    Inflationary physics, cosmic string, axion-like particles, primordial magnetic fields, ⋯

  - B-modes also provide a way to explore the late-time universe via lensing (next slide)

    Properties of Neutrinos, origin of dark matter and dark energy

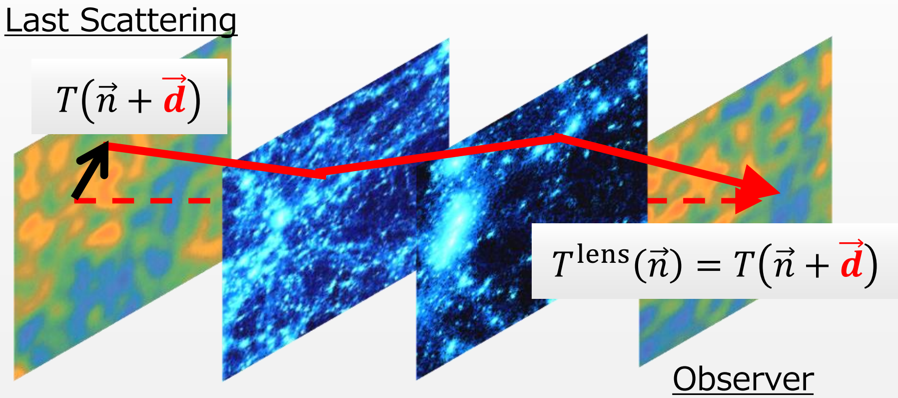
- B-mode analysis becomes very important for ongoing and future CMB experiments

  BICEP/Keck Array (**BK**) Simons Observatory (**SO**) CMB Stage-4 LiteBIRD

A quick review of gravitational lensing effect on polarization

(Reviews : Lewis&Challinor'06; Hanson+'10)

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

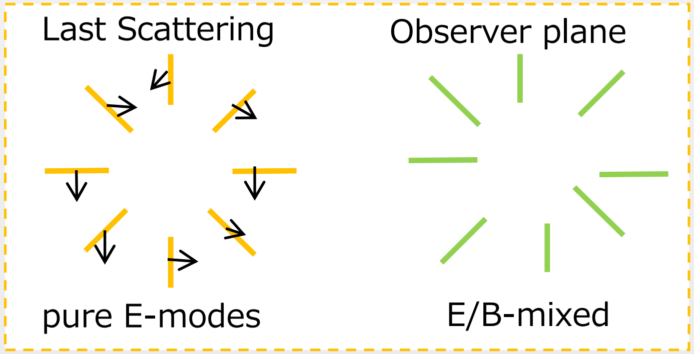


(convergence)

$$\kappa(\vec{n}) = -\frac{1}{2}\nabla\cdot\vec{d} = \int_0^{\chi_s} d\chi\, f(\chi,\chi_s)\underbrace{\nabla^2\Psi(\eta_0-\chi,\chi\vec{n})}_{\text{Gravitational potential of LSS}}$$

- Create B-modes in particular at small scales

(Zaldarriaga&Seljak'98)



- Anisotropic distortions = Create mode-couplings in CMB fluctuations

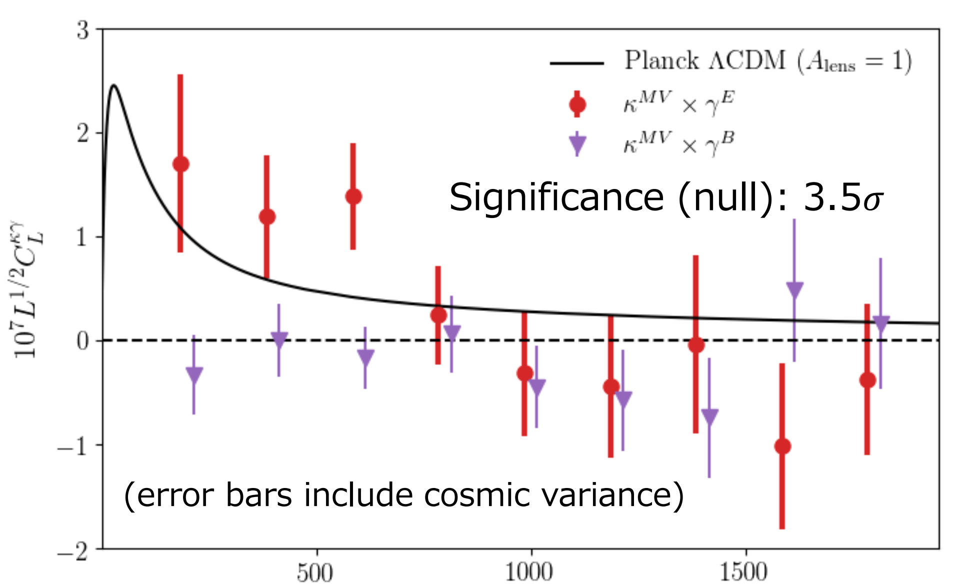
e.g. $E_{L_1}B_{L_2} \propto$ signal $\underline{(\kappa_{L_1+L_2})}$ + …

Correlating different modes allows us to reconstruct lensing signals (Hu&Okamoto'02, Hirata&Seljak'03)

CMB lensing measurements use non-Gaussian statistics, $\langle\gamma EB\rangle_c, \langle\delta_g EB\rangle_c, \langle EBEB\rangle_c, \langle EBEBEB\rangle_c, \ldots$

[1] Evidence for correlations btw CMB *polarization* lensing and cosmic shear
(CMB-CMB-shear bispectrum)

- Cross-spectrum is immune to additive instrumental biases in each lensing measurement
- CMB polarization is less contaminated by extragalactic foregrounds
- POLARBEAR (CMB lensing measurement) + Subaru HSC (cosmic shear) $EB\gamma + EE\gamma$



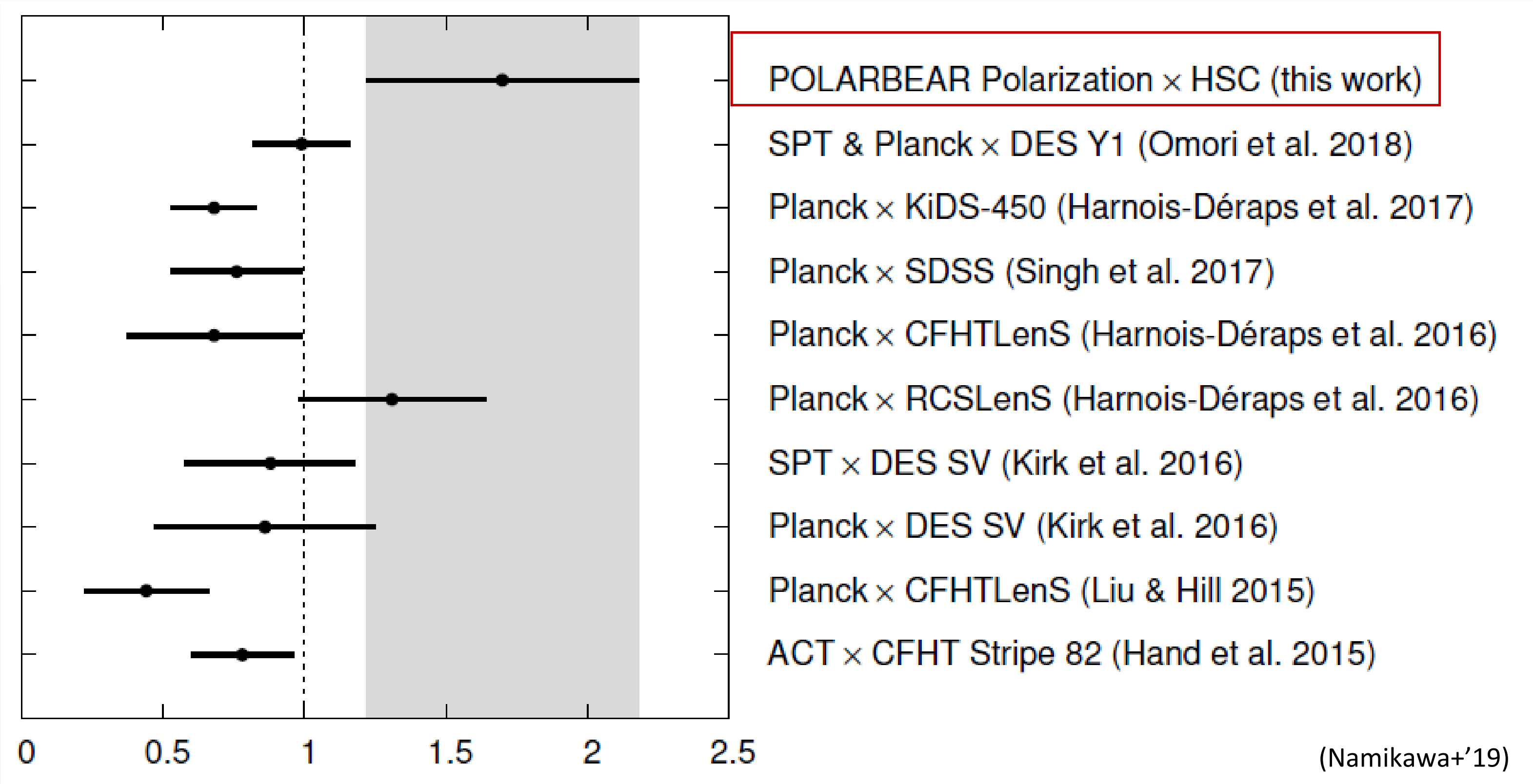
(Namikawa+'19)

Choice of the analysis method		$\widehat{A}_{\rm lens}$
Photo-z	Ephor	1.70 ± 0.48
	Frankenz	1.69 ± 0.48
	MLZ	1.83 ± 0.51
	Mizuki	1.69 ± 0.49
CMB multipoles	$\ell_{\rm max} = 2500$	1.64 ± 0.49
	$\ell_{\rm min} = 700$	1.89 ± 0.57
CMB estimator	EE	1.07 ± 0.93
	EB	1.65 ± 0.50
Cosmology	WMAP-9	1.99 ± 0.56
Baseline	**(Planck 2018)**	$\mathbf{1.70 \pm 0.48}$

(Namikawa+'19)

[1] Evidence for correlations btw CMB *polarization* lensing and cosmic shear
(CMB-CMB-shear bispectrum)

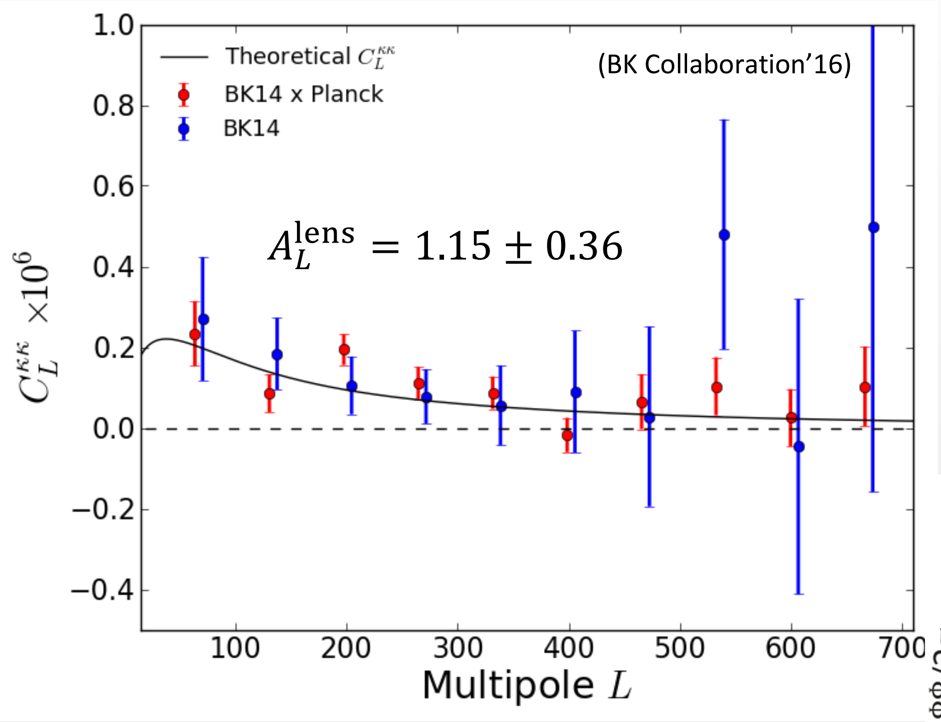
Cross-spectrum amplitude relative to the prediction from the Planck cosmology



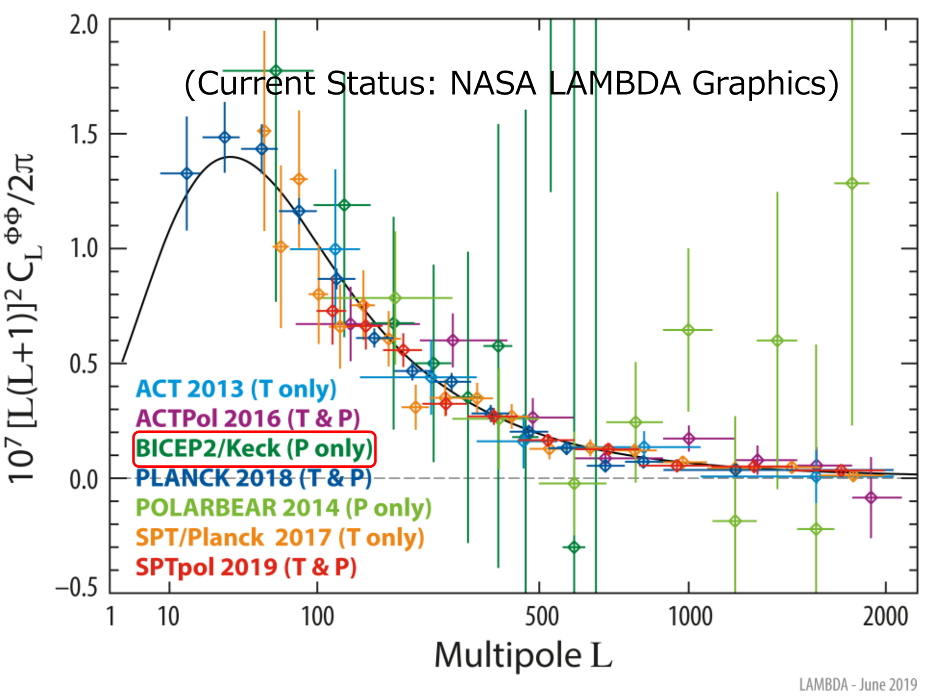
(N.B. the redshift distributions of source galaxies are different)

- We show a first measurement of correlations btw CMB *polarization* lensing and shear
- CMB-galaxy lensing cross-spectra agree with the standard cosmology

[2] Lensing spectrum measurement from polarization
(CMB trispectrum)



- Use BK data taken from 2010-2014 season at 150GHz
- The very deep (~3μK') Q/U maps make it possible to reconstruct κ from larger angular scale B-modes



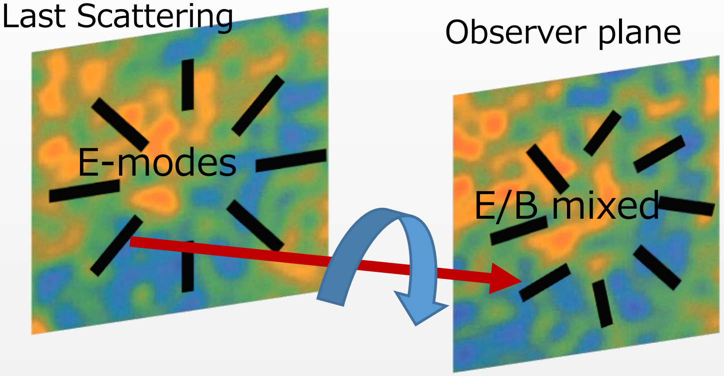
- κ is reconstructed from the BK data and we then compute auto-spectrum and cross-spectrum with Planck, finding that they are consistent

(BK collaboration'18 shows lensing updates)

[3] Constraints on anisotropies of cosmic birefringence
(CMB trispectrum)

- Cosmic birefringence

Rotation of CMB polarization angle



- Sources of anisotropic cosmic birefringence

Axionlike particles at $m_a \sim 10^{-33} - 10^{-28}$eV

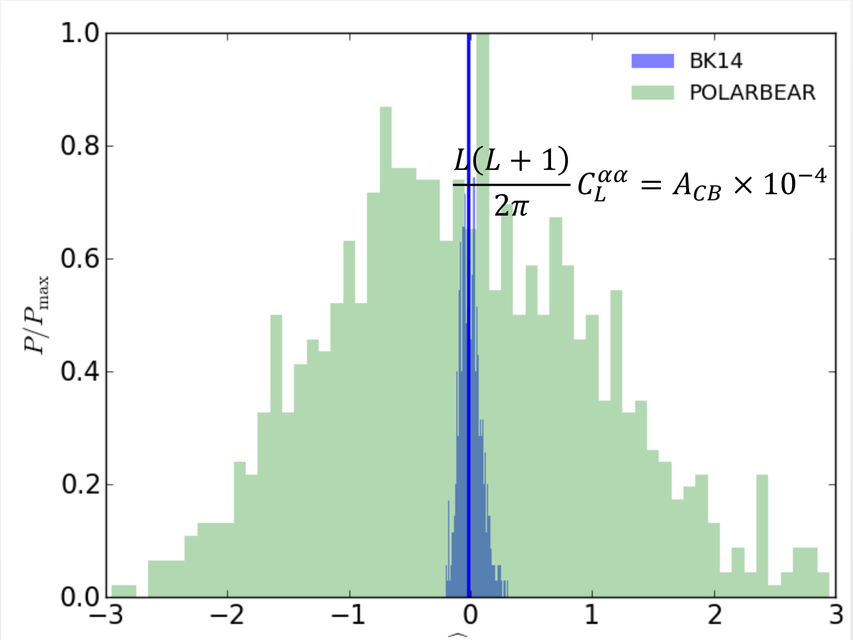
String theory generally predicts presence of axionlike particles coupled with photons

See e.g. Pospelov+'09, Caldwell+'11

Primordial magnetic fields

by the Faraday rotation

See e.g. Kosowsky & Loeb'96, Harari+'97



(BK Collaboration'17)

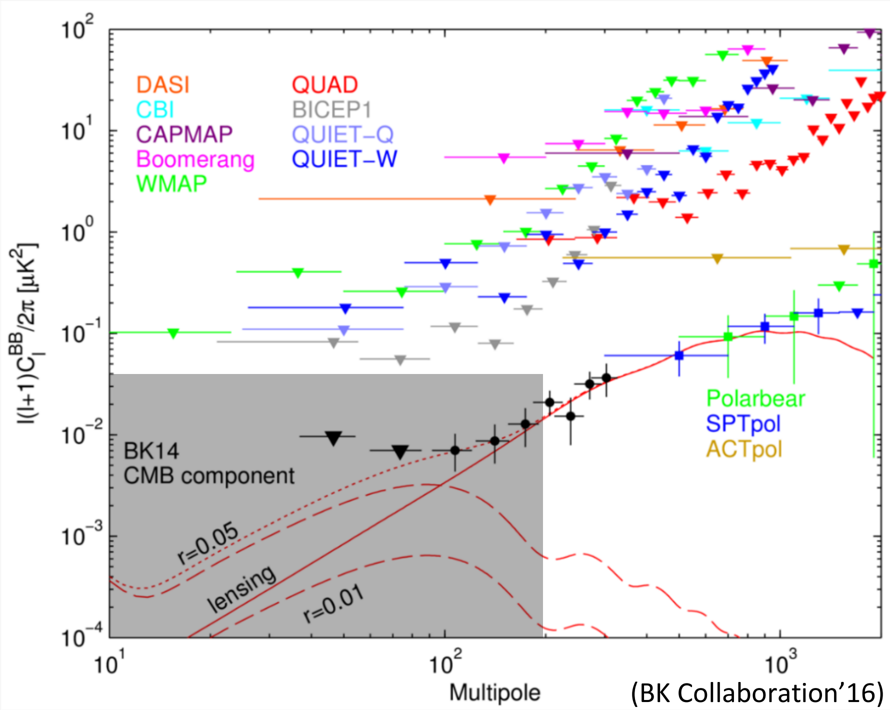
- The BK constraint is an order of magnitude better than the previous attempts

- ACTpol can further improve the sensitivity by ~ 1 order of magnitude

[4] B-mode delensing and primordial GWs

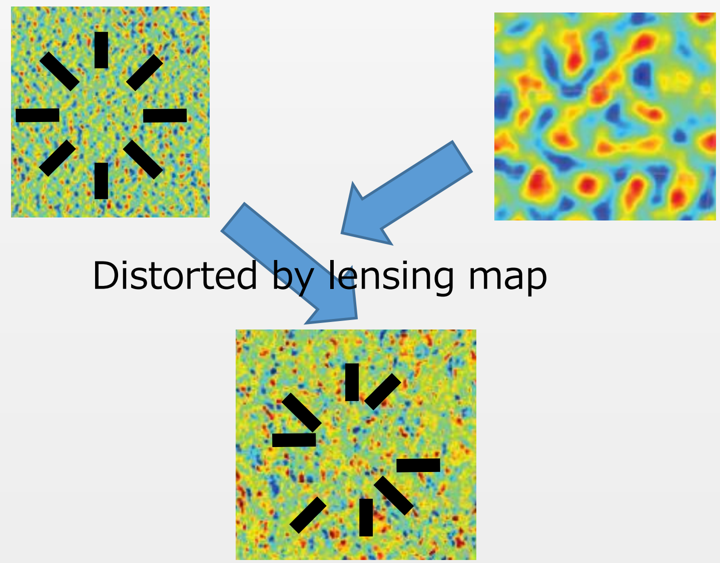
(Up to CMB six-point)

- Constraints on primordial GWs is already limited by lensing contaminants in ground-based CMB experiments (e.g. BK Collaboration'18)



E mode map

Lensing map



Lensing B-mode template

$$B^{\mathrm{LT}}_{\vec{\ell}} = \int d^2\vec{L}\, w_{\vec{\ell},\vec{L}} E_{\vec{L}} \kappa_{\vec{\ell}-\vec{L}}$$

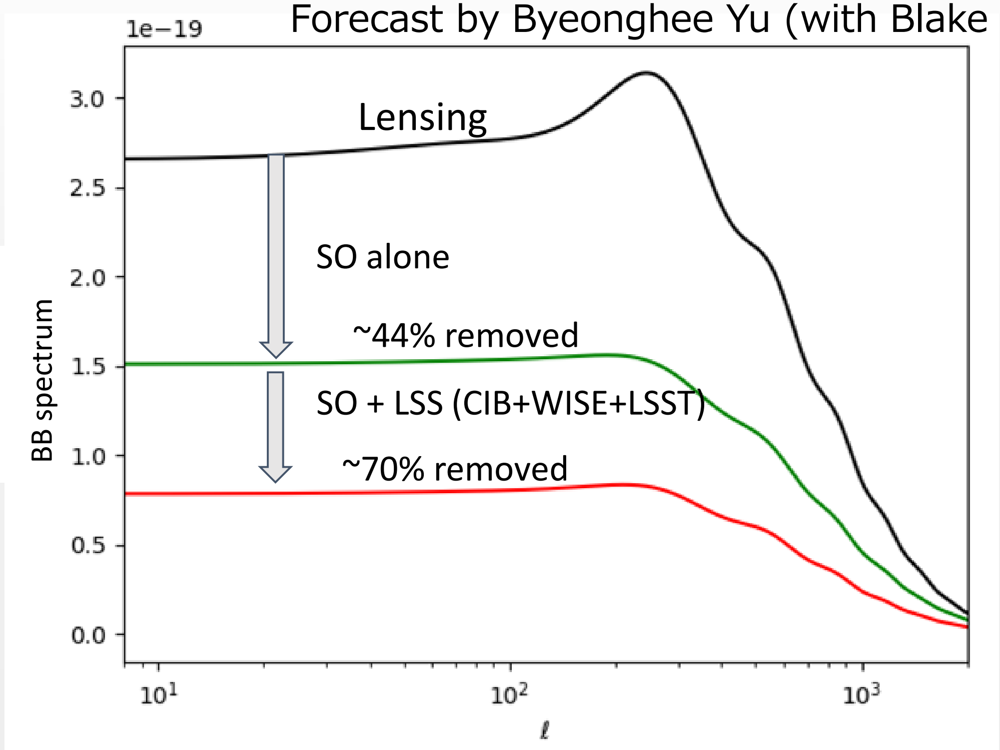
$$B^{\mathrm{res}}_{\vec{\ell}} = B^{\mathrm{obs}}_{\vec{\ell}} - B^{\mathrm{LT}}_{\vec{\ell}}$$

Removal of lensing B-modes (**delensing**) significantly improve detection significance of primordial GWs in ongoing/future CMB experiments (e.g. BK, SO).

[4] B-mode delensing and primordial GWs

(Up to CMB six-point)

Forecast by Byeonghee Yu (with Blake and Colin)



- Capable of removing ~70% of the lensing B-modes using LSST+CIB contamination

  (a factor 2 improvement on $\sigma(r)$ compared to no-delensing)

- Some uncertainties in mass-tracers could be a potential issue. They could be constrained by auto/cross spectra, and do not significantly bias on r, but we need quantitative studies.

  Anton's talk ?

N.B. Nonlinear growth of LSS does not degrade the efficiency (Namikawa&Takahashi'19)

[5] An optimal estimator for polyspectra

(N-point correlations)

Bispectrum

For given temperature fluctuations T,

(e.g. Creminelli+'06) $\hat{k}_{\{\vec{L}_1 \dots \vec{L}_3\}} = A_{\{\vec{L}_1 \dots \vec{L}_3\}} [\bar{T}_{\vec{L}_1} \bar{T}_{\vec{L}_2} \bar{T}_{\vec{L}_3} - p_2^3]$

$$\bar{T}_{\vec{L}} = [C^{-1} T]_{\vec{L}}$$

$$p_2^3 = \langle \bar{T}^1_{\vec{L}_1} \bar{T}^1_{\vec{L}_2} \rangle \bar{T}_{\vec{L}_3} + (2 perms.)$$

(Applied to e.g. f_{NL} constraints)

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(Applied to e.g. f_{NL} constraints)

Trispectrum

(e.g. Regan+'10)

$$\hat{k}_{\{\vec{L}_1 \ldots \vec{L}_4\}} = A_{\{\vec{L}_1 \ldots \vec{L}_4\}}[\bar{T}_{\vec{L}_1}\bar{T}_{\vec{L}_2}\bar{T}_{\vec{L}_3}\bar{T}_{\vec{L}_4} - p_2^4 + p_4^4]$$

$$p_2^4 = \langle \bar{T}_{\vec{L}_1}^1 \bar{T}_{\vec{L}_2}^1 \bar{T}_{\vec{L}_3} \bar{T}_{\vec{L}_4} + (5 perms.) \rangle_1$$

$$p_4^4 = \langle \bar{T}_{\vec{L}_1}^1 \bar{T}_{\vec{L}_2}^1 \bar{T}_{\vec{L}_3}^2 \bar{T}_{\vec{L}_4}^2 + (2 perms.) \rangle_{1,2}$$

(Applied to e.g. the lensing spectrum estimation)

[5] An optimal estimator for polyspectra

(N-point correlations)

Bispectrum

For given temperature fluctuations T,

(e.g. Creminelli+'06) $\hat{k}_{\{\vec{L}_1 \ldots \vec{L}_3\}} = A_{\{\vec{L}_1 \ldots \vec{L}_3\}}[\bar{T}_{\vec{L}_1}\bar{T}_{\vec{L}_2}\bar{T}_{\vec{L}_3} - p_2^3]$ $\quad \bar{T}_{\vec{L}} = [C^{-1}T]_{\vec{L}}$

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(Applied to e.g. f_{NL} constraints)

Trispectrum

(e.g. Regan+'10)

$$\hat{k}_{\{\vec{L}_1 \ldots \vec{L}_4\}} = A_{\{\vec{L}_1 \ldots \vec{L}_4\}}[\bar{T}_{\vec{L}_1}\bar{T}_{\vec{L}_2}\bar{T}_{\vec{L}_3}\bar{T}_{\vec{L}_4} - p_2^4 + p_4^4]$$

$$p_2^4 = \langle \bar{T}^1_{\vec{L}_1} \bar{T}^1_{\vec{L}_2} \bar{T}_{\vec{L}_3} \bar{T}_{\vec{L}_4} + (5 perms.) \rangle_1$$

$$p_4^4 = \langle \bar{T}^1_{\vec{L}_1} \bar{T}^1_{\vec{L}_2} \bar{T}^2_{\vec{L}_3} \bar{T}^2_{\vec{L}_4} + (2 perms.) \rangle_{1,2}$$

(Applied to e.g. the lensing spectrum estimation)

N-point

For given $x_{i_1}, \ldots, x_{i_n}$, we can derive an estimator which maximizes a likelihood expanded as Edgewoth series including nth order cumulant, k, and the result is

T. Namikawa, Phys. Rev. D 95 (2017) 103514

$$\hat{k}_{\{i_1 \ldots i_n\}} = A_{\{i_1 \ldots i_n\}}[\bar{T}_{\vec{L}_1} \cdots \bar{T}_{\vec{L}_n} - \Sigma_{m=1}(-1)^{m+n+1} p_m^n]$$

$$p_m^n = \langle \bar{x}^1_{i_1} \ldots \bar{x}^m_{i_{2m}} \bar{x}_{i_{2m+1}} \ldots \bar{x}_{i_n} + (perms.) \rangle_{1,\ldots,m} \qquad p_m^n = 0 \; (n < m)$$

Applications:
- Delensed BB spectrum (4pt + 6pt)
- Lensing κ bisepectrum (6pt), trispectrum (8pt), …
- Lensing κ x other mass map cross-bisepectrum (5pt), …

Summary

I have analyzed non-Gaussian signatures in polarization to extract cosmological signals

- The first evidence of correlations btw CMB polarization lensing and galaxy lensing, which is consistent with the Planck cosmology
- Detected lensing from BK B-modes
- Significant improvement on constraining anisotropies of cosmic birefringence

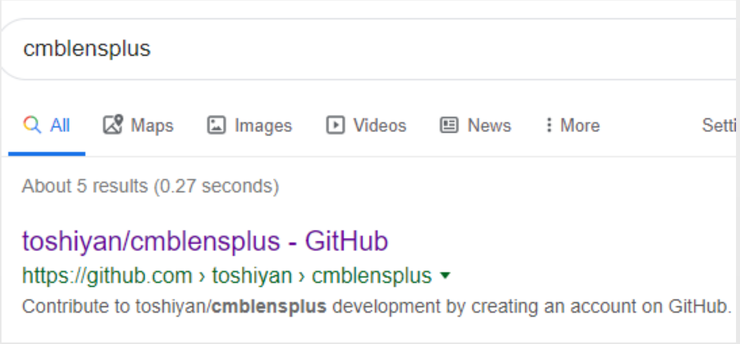
Ongoing works, Future directions

- B-mode delensing (SO, BKSPT)
- Constraining tensor non-Gaussianity, $f_{NL}^{\rm tens}$, using BK data
- Lensing and cosmic birefringence analysis

Others

A python package of interfacing Fortran codes to reconstruct lensing, cosmic birefringence, delensing, bispectrum, ⋯, in full and flat sky:

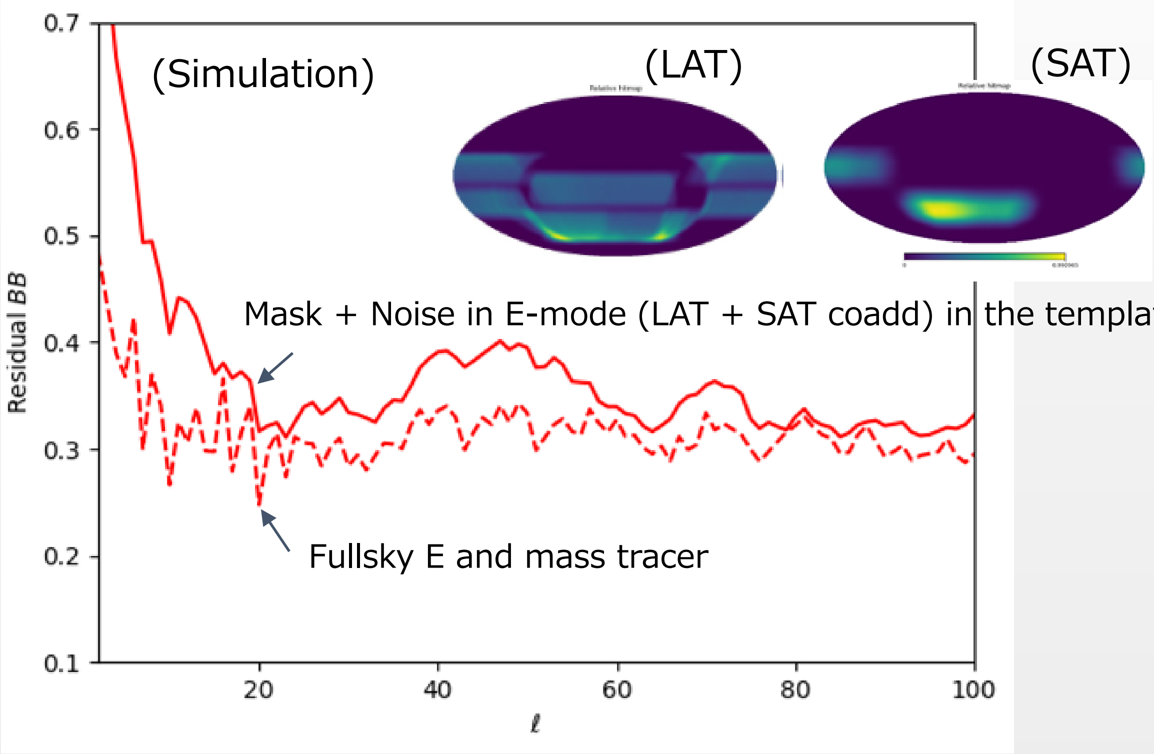
https://github.com/toshiyan/cmblensplus



Backup slides

[4] B-mode delensing and primordial GWs

(Up to CMB six-point)



- SO survey mask only (not shown above):
  The simulation well agrees with the analytic expectation at $\ell > 10$
- SO survey mask + anisotropic noise:
  The E-mode noise decreases the efficiency by up to ~5%, but improvements may be possible (now implementing Wiener filtering on curvedsky)