Gravitational lensing analysis from Subaru HSC and POLARBEAR

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- This talk is based on https://arxiv.org/abs/1904.02116

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Our work

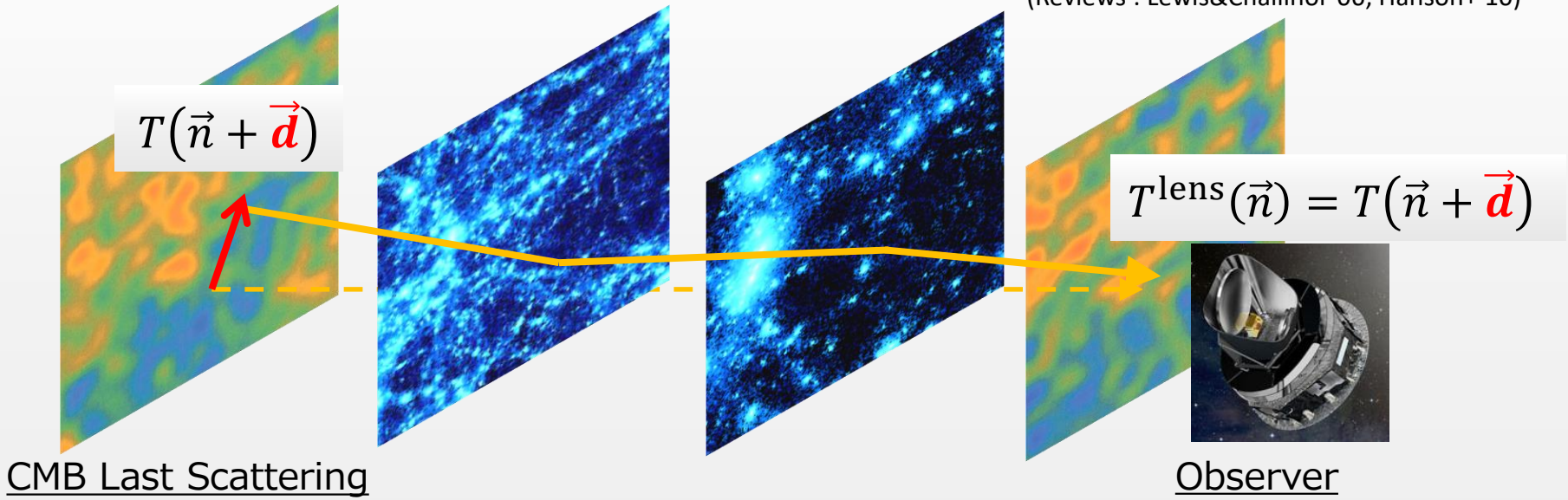
- We show the first evidence of correlations btw CMB *polarization* lensing and galaxy lensing

- We study in detail the systematics budget to show that residual systematics in our results are very small

- We reject the null hypothesis at 3.5σ and the lensing amplitude is consistent with the Planck 2018 LCDM prediction within 2σ

A quick review: Gravitational lensing effect on CMB

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



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

The lensing remaps the fluctuations by $\vec{d}$

(convergence) $$\kappa(\vec{n}) = -\frac{1}{2}\nabla\cdot\vec{d} = \int_0^{\chi_s} d\chi\, f(\chi,\chi_s)\nabla^2\Psi(\eta_0-\chi,\chi\vec{n})$$

Traces the gravitational potential of the large-scale structure (LSS)

A quick review: Gravitational lensing effect on polarization

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

- Distort small scale temperature / polarization fluctuations

- Create CMB B-modes in particular at small scales

- Correlation in and btw CMB E/B-modes (Mode-coupling of CMB E- and B-modes)

$$E_{L_1} B_{L-L_1} \propto \text{signal } (\kappa_L) + \text{noise}$$

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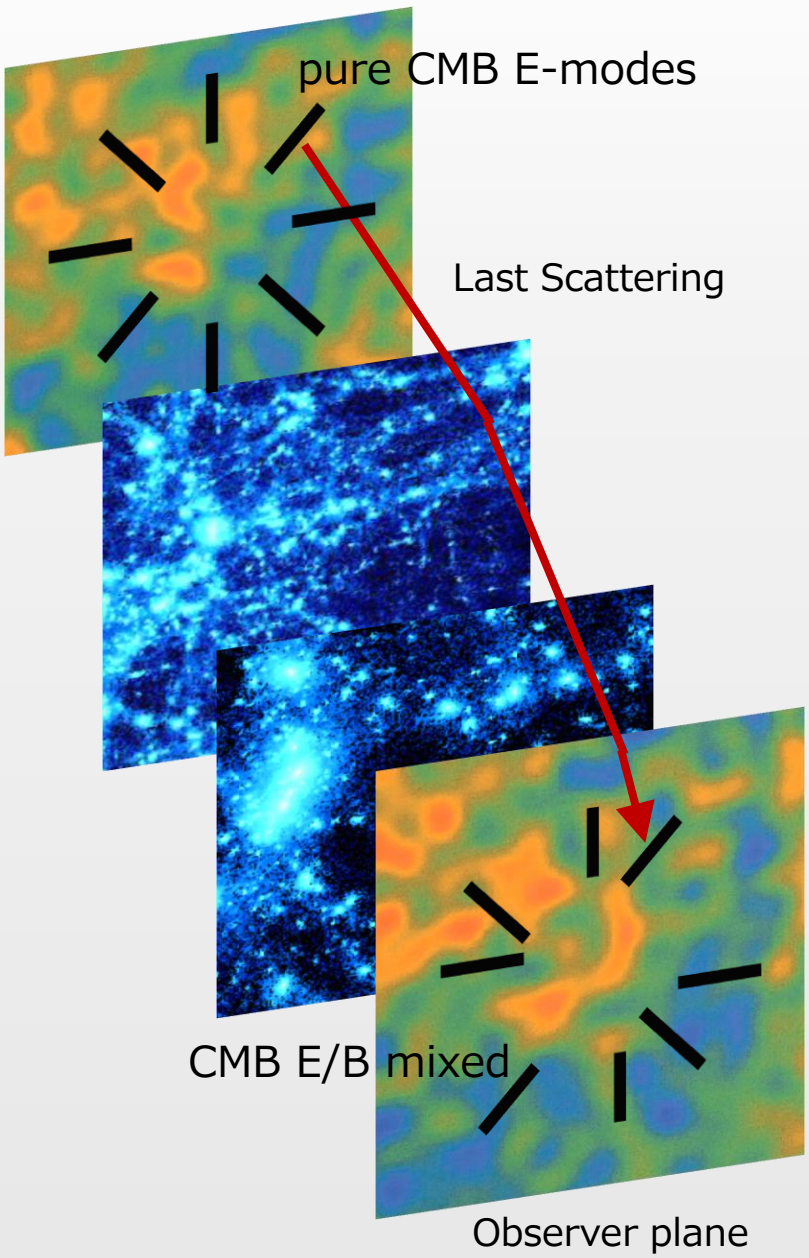
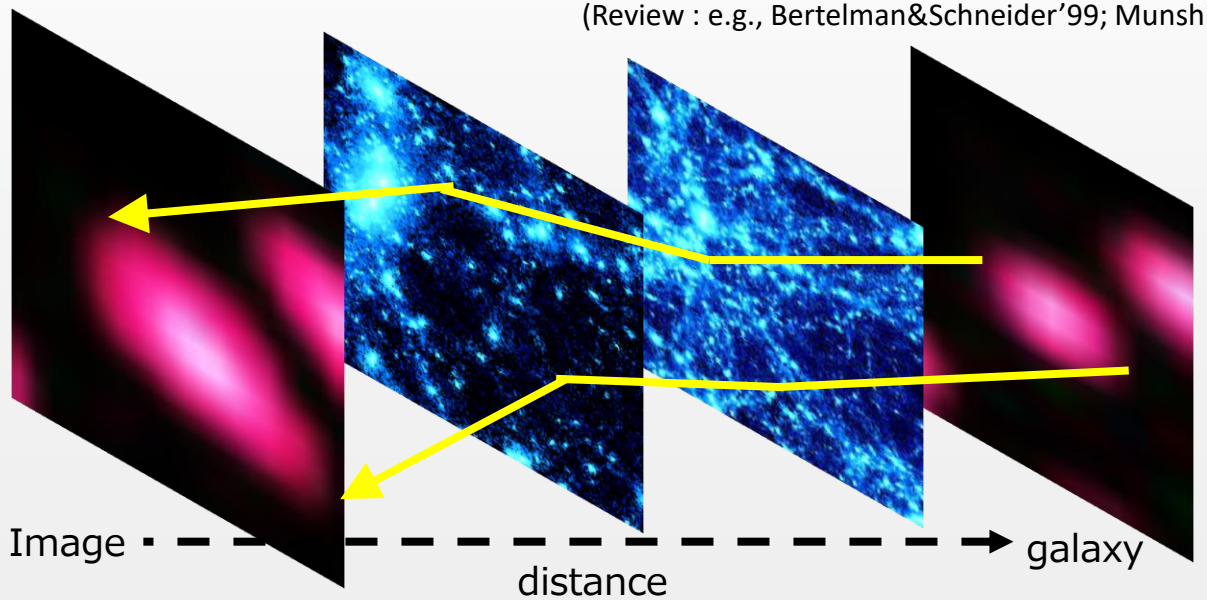


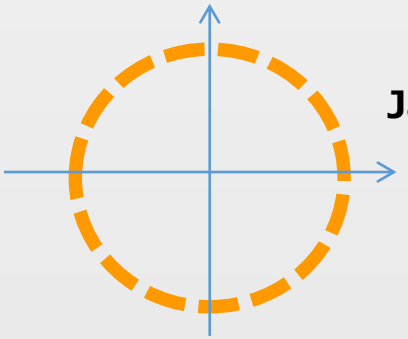
Galaxy Lensing

- Distorting images of galaxy shapes by lensing (cosmic shear)

(Review : e.g., Bertelman&Schneider'99; Munshi+'08)



- E/B-mode shear



Source plane

Jacobi matrix : D_{ab}

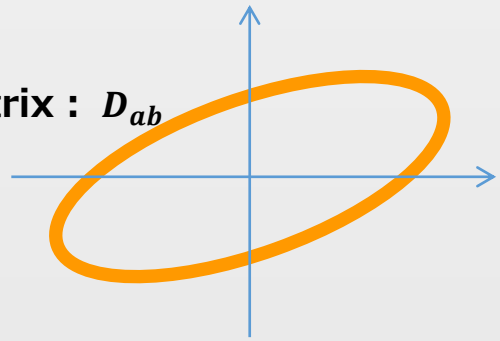


Image plane

$$D_{ab}^{TF} = \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & \gamma_1 \end{pmatrix}$$

$$\gamma_1, \gamma_2 \rightarrow \gamma^E, \gamma^B$$

γ^E traces gravitational potential of the LSS

Motivation

- Lensing

  Directly probes geometry and growth of the LSS

  Sensitive to the nature of dark matter, dark energy, neutrino masses

- Cross-correlation

  Immune to additive instrumental biases in each lensing measurement

  Important to cross-check auto-spectrum results (e.g., Vallinotto'12, Schaan+'17)

- CMB polarization

  Extragalactic foregrounds cause significant biases in temperature-based reconstruction, while polarization is less contaminated by foregrounds

  (e.g., van Engelen+'14,Schaan&Ferraro'19)

  Future CMB lensing measurements will significantly rely on polarization

We demonstrate the lensing cross-spectrum between CMB and galaxies, using only polarization data

DATA (Area)

- Galaxy shapes from the Subaru Hyper Suprime-Cam (HSC) 1st year catalogue

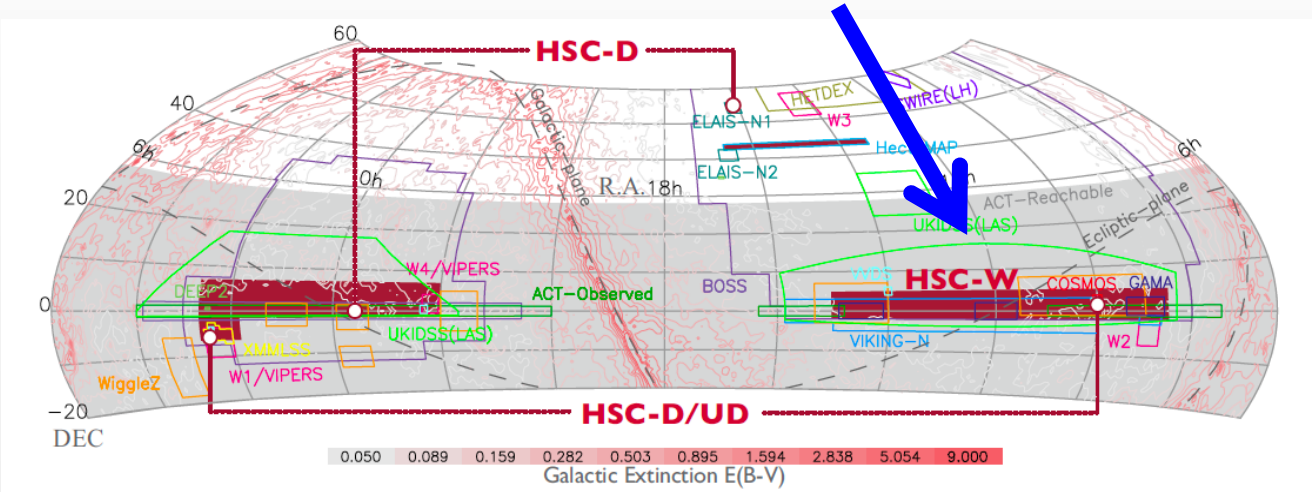
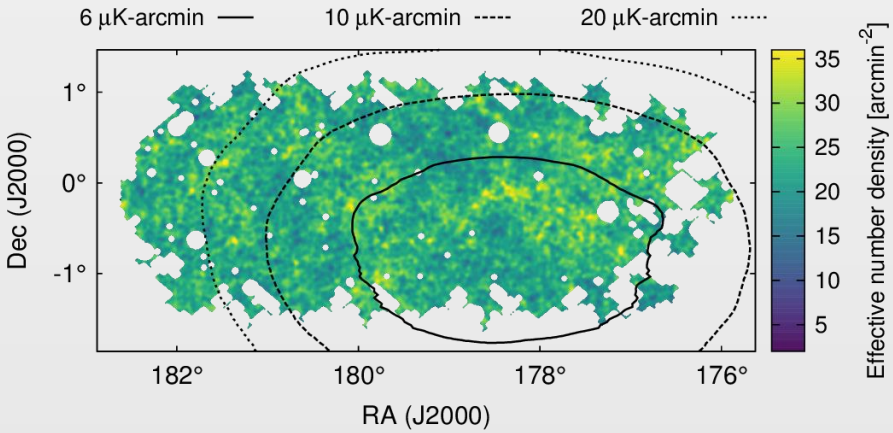


Figure 11: The location of the HSC-Wide, Deep (D) and Ultradeep (UD) fields on the sky in equatorial coordinates. A variety of external data sets and the Galactic dust extinction are also shown. The shaded region is the region accessible from the CMB polarization experiment, ACTPol, in Chile.

- CMB polarization from POLARBEAR (PB) 2nd Paper Publication

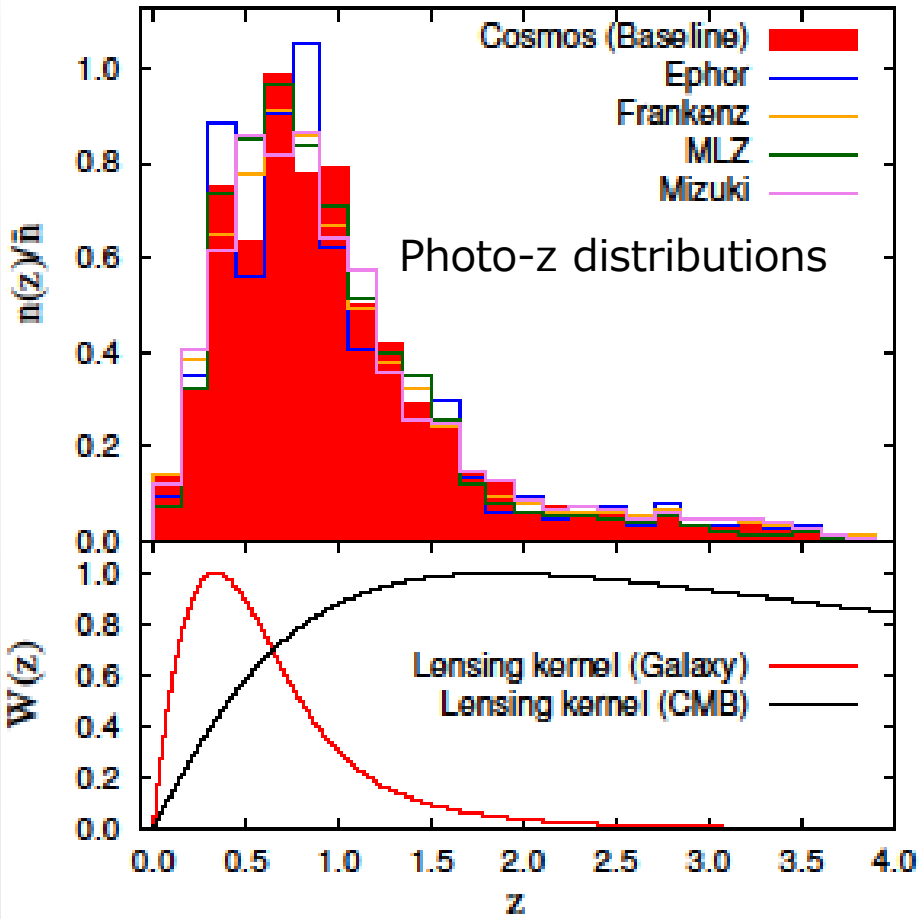


The overlapped region: ~ 9deg^2 effective area for 6uK-arcmin

DATA (Depth)

- HSC is one of the deepest wide-field optical imaging survey

  - Mean redshift: ~1.0
  - Galaxy number density: ~23/arcmin^2



$$W^{\kappa} = \int_{\chi}^{\infty} d\chi' p(\chi') \frac{\chi(\chi' - \chi)}{\chi'}$$

- Lensing obtained from HSC is suitable for CMB-galaxy lensing correlation study

Simulation & Analysis

- Simulation (for pipeline test and covariance)
  - Use fullsky ray-tracing simulation for lensed CMB and cosmic shear signals (Takahashi+17)
  - Scanned CMB map is made by PB pipeline
  - Galaxy shape catalogue is made based on Oguri+'18
  - Also, prepared simulations for various null tests, and instrumental systematics
- Cross-spectrum pipeline

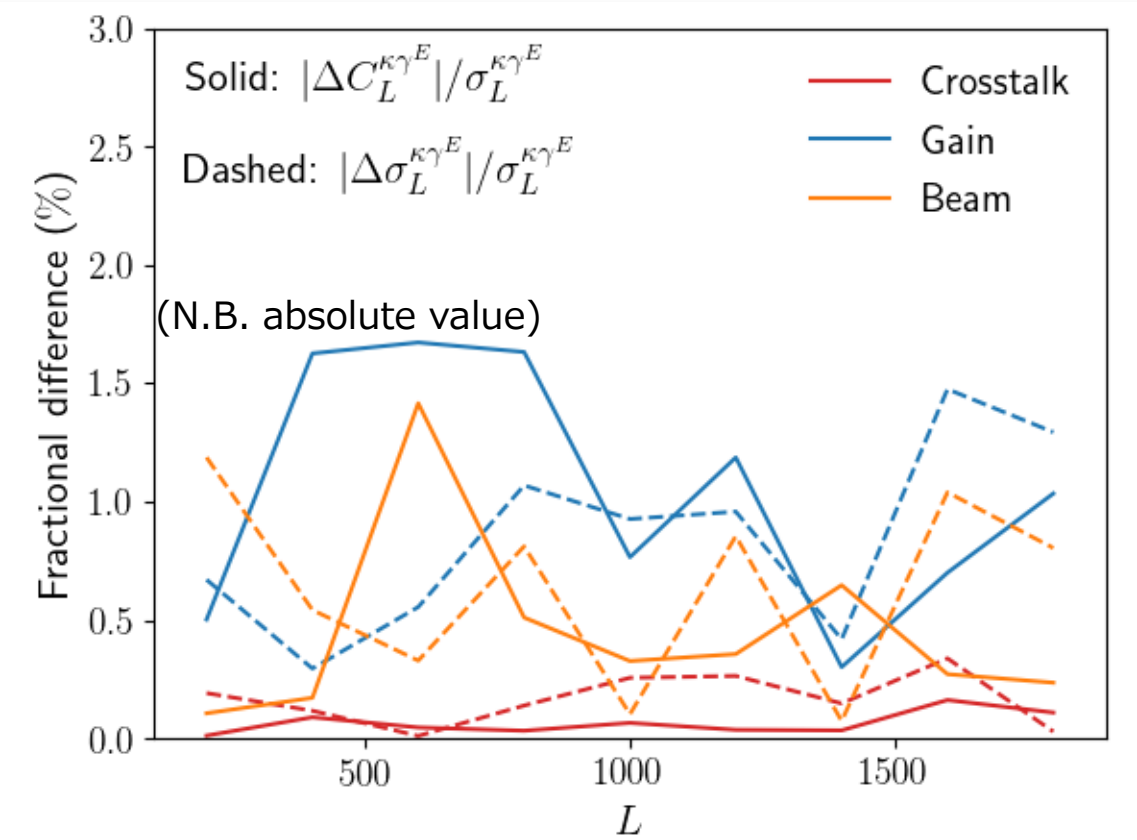
Galaxy shape catalogue → E/B-mode shear (e.g. Mandelbaum+'18)

Observed CMB map → Reconstruction of CMB lensing map (EE/EB quadratic estimators) (e.g. Hu&Okamoto+'02)

→ $C_L^{\gamma^E \kappa}$ Cross-spectrum

- Compared with theory and obtain lensing amplitudes $A_{Lens} = \Sigma_b w_b C_b^{obs} / C_b^{fid}$
- Shear multiplicative bias had been blinded until we passed all of the tests

Validation test (CMB)

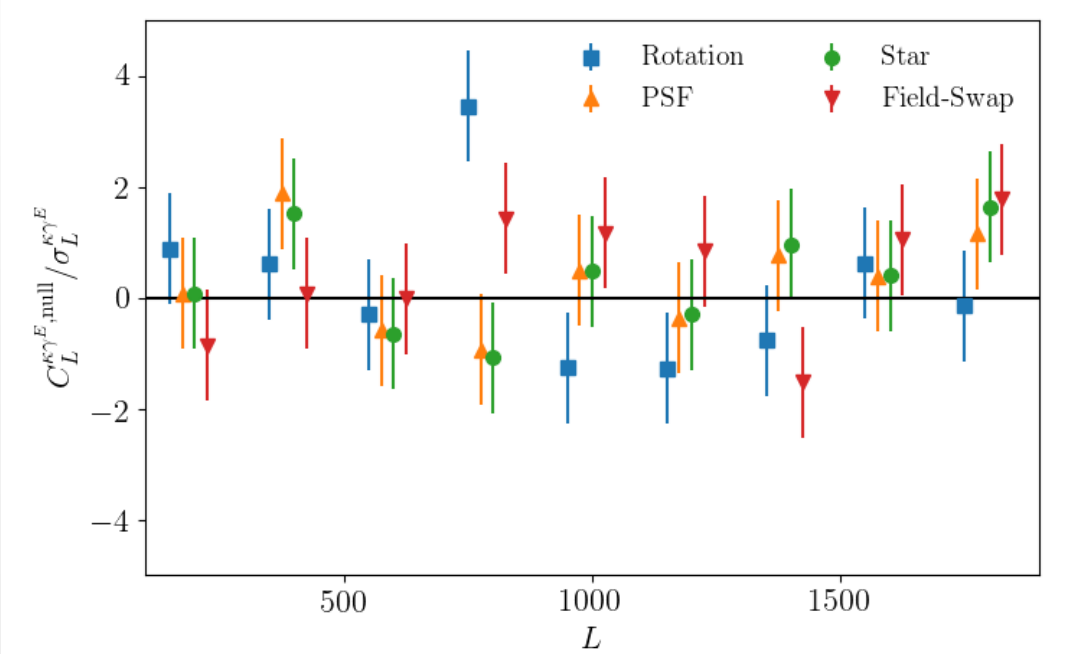


- Instrumental systematic uncertainties on the cross-spectrum:

  At most 1.5% in the power spectrum, and 1.3% bias in A_lens (~4% of statistical error)

- Passed the same types of null tests for $C_L^{\gamma^E\kappa^{CMB}}$ as the PB (2017) paper done

Validation test (Shear)



	χ-PTE	χ^2-PTE
Rotation	0.52	0.10
Star	0.26	0.43
PSF	0.46	0.49
Field Swap	0.20	0.33

Rotation: randomly rotating ellipticities of galaxies (which removes the cosmic shear signal)

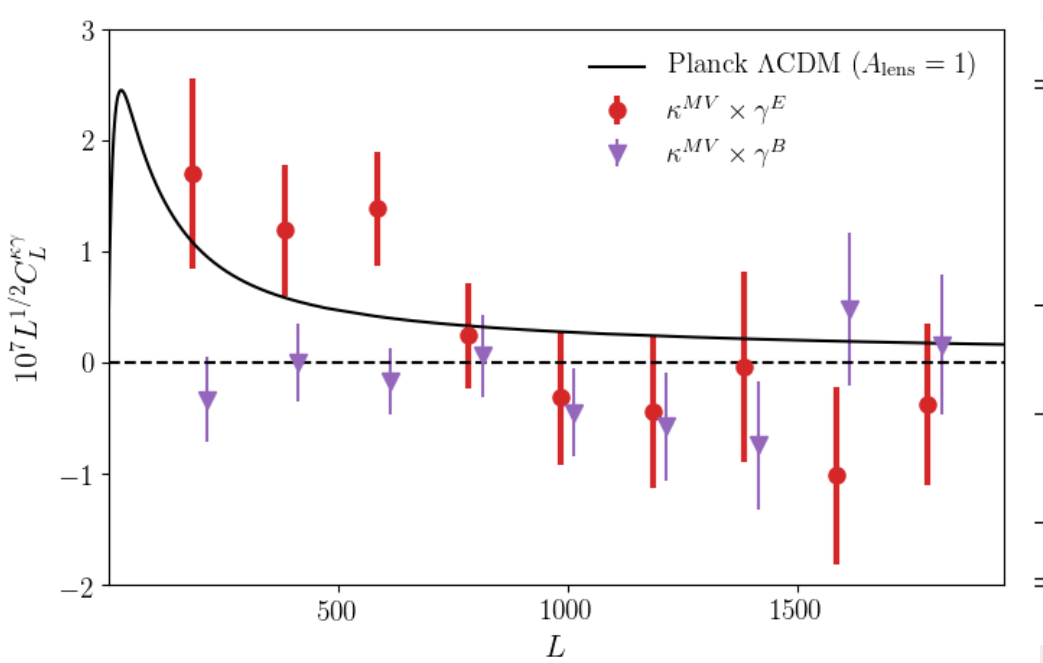
Star: ellipticities of stars for reconstructing the Point Spread Function (PSF)

PSF: PSFs reconstructed at the star position

Field Swap: a shear map measured in another field

- Passed the null tests for shear

Results

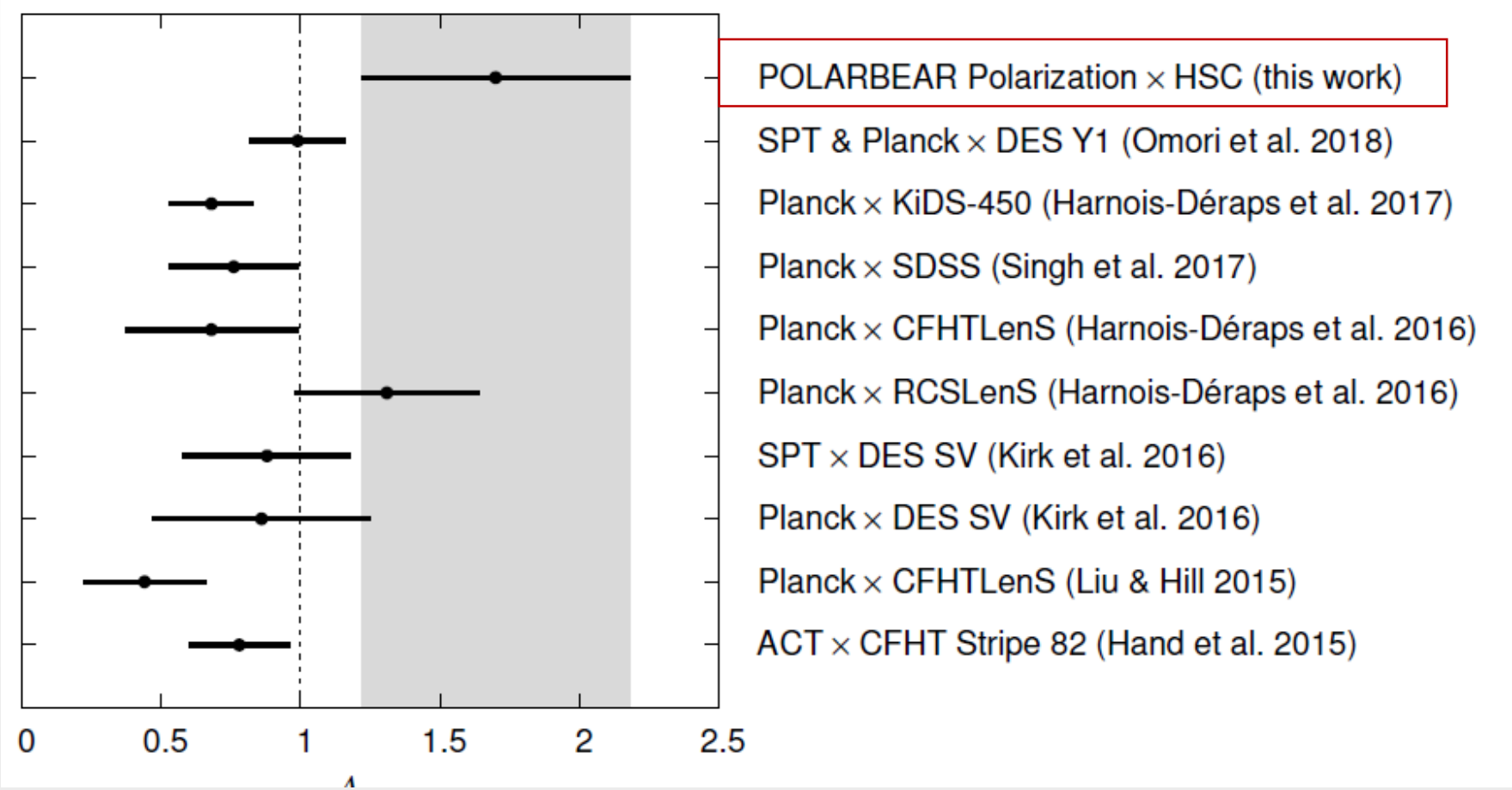


Choice of the analysis method		$\widehat{A}_{\rm lens}$
Photo-z	Ephor	1.70 ± 0.48
	Frankenz	1.69 ± 0.48
	MLZ	1.83 ± 0.51
	Mizuki	1.69 ± 0.49
CMB multipoles	$\ell_{\rm max} = 2500$	1.64 ± 0.49
	$\ell_{\rm min} = 700$	1.89 ± 0.57
CMB estimator	EE	1.07 ± 0.93
	EB	1.65 ± 0.50
Cosmology	WMAP-9	1.99 ± 0.56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

(error bars include cosmic variance)

- Significance: 3.5σ
- Not sensitive to photo-z estimation methods
- Intrinsic alignment is less than 10% of the statistical error
- Chi and chi^2-PTE of kappa x shear B: 0.26 and 0.68

Results

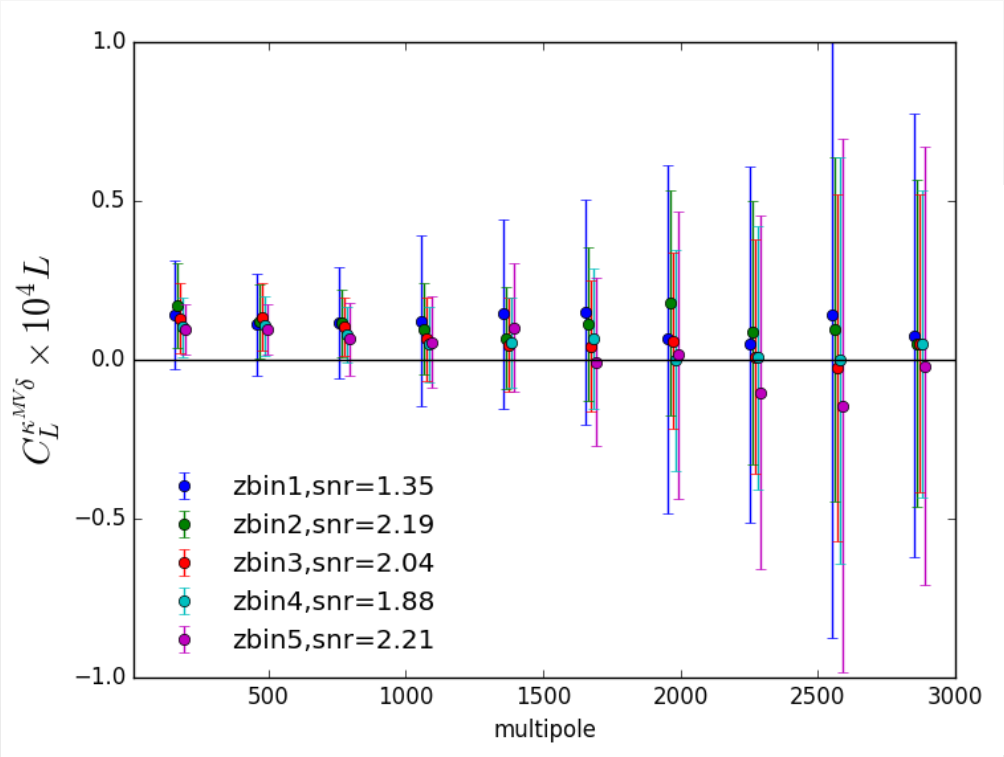


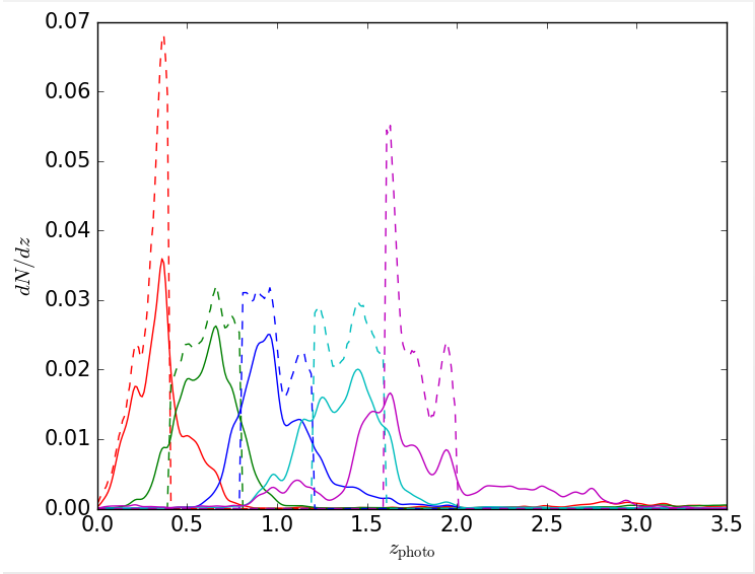
(N.B. the redshift distributions of source galaxies are different)

- CMB-galaxy lensing cross-spectra agree with the standard cosmology

Future directions: galaxy density – CMB lensing correlation

A forecast of expected galaxy number density x CMB lensing from the same data set we used





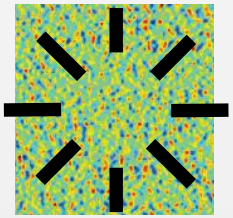
Galaxy density - CMB lensing correlation is detectable at ~3-4 sigma

Future directions: B-mode delensing for PB+HSC

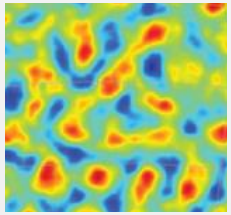
- Primordial GWs search from B mode is already limited by lensing contaminants from ground-based experiments (e.g. BICEP2/KeckArray 2018)

B-mode de-lensing becomes important for future missions as well

E mode map

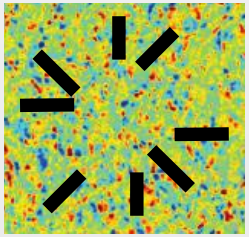


Lensing map



Distorted by lensing map

$$B_{\vec{\ell}} = \int d^2\vec{L}\, w_{\vec{\ell},\vec{L}} E_{\vec{L}} \kappa_{\vec{\ell}-\vec{L}}$$



Lensing B mode map

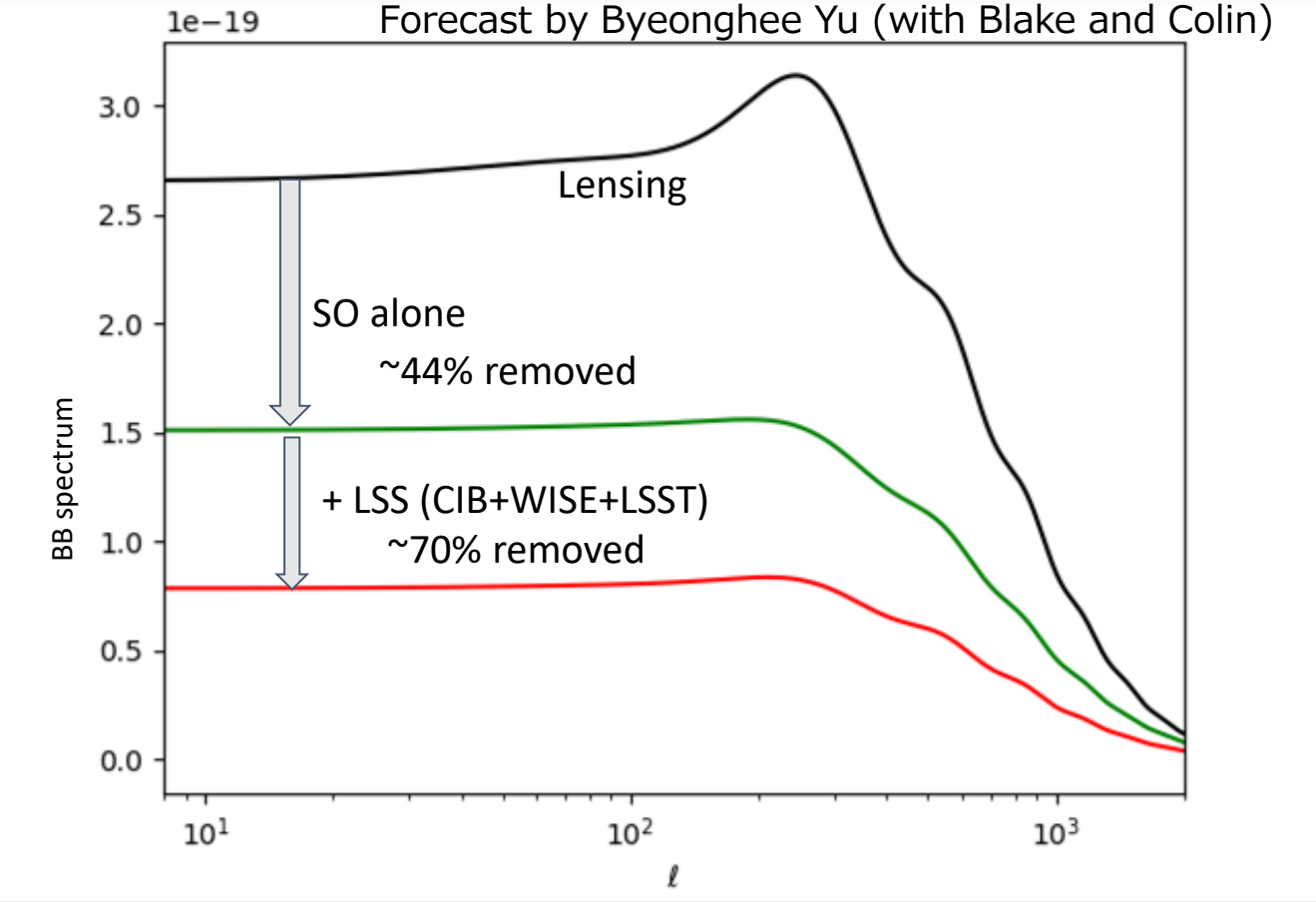
- Galaxy density can be used to estimate part of lensing noise in B-modes

Galaxy density ≃ density fluctuations ≃ gravitational potential
(this is also the same for cosmic infrared background, optical lensing etc)

- Using currently available data, half of the lensing B mode can be removed

(Cosmic shear traces matter fluctuations at lower-z and less effective for delensing)

Future directions: B-mode delensing for SO



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

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

Summary

- We measured CMB-lensing – galaxy lensing cross-spectrum with *polarization* only
  - Less sensitive to instrumental systematics, foregrounds
  - Performed various systematics and null tests
  - Significance of 3.5σ, the first evidence of this kinds of correlations, consistent with the Planck cosmology
- Future directions
  - Cross-correlation between galaxy density and CMB lensing
  - B-mode delensing (SO, BKSPT)