

Removal of lensing contributions in CMB polarization for ongoing and future experiments

Toshiya Namikawa

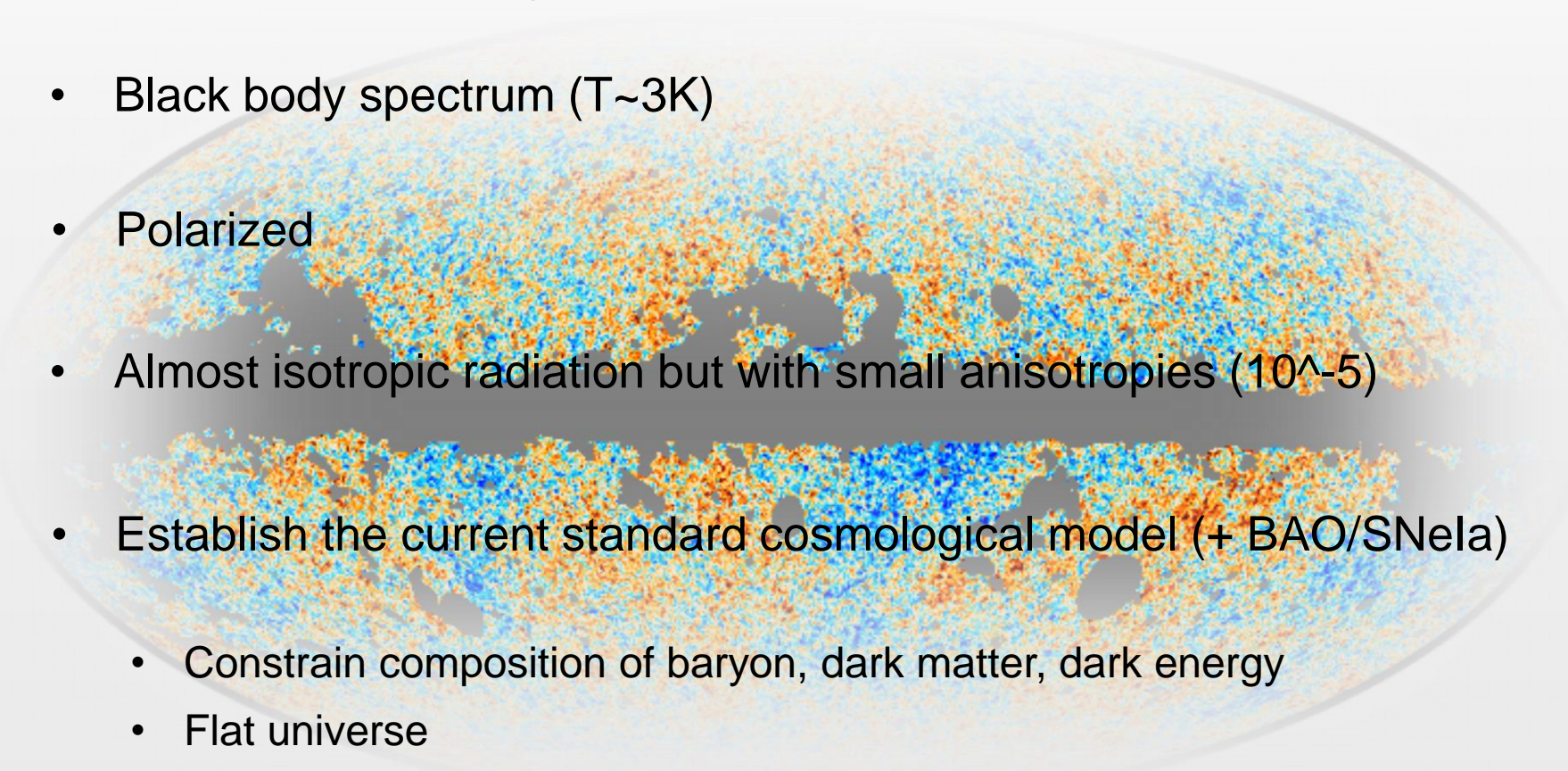
Based on

BICEP2/Keck Array Collaborations (in prep.)

Subaru-HSC and Polarbear Collaborations (in prep.)

TN, Yamauchi, Sherwin, Nagata (2016), PRD 93, 043527

Cosmic Microwave Background (CMB)

- Oldest accessible light ($z \sim 1100$)
 - Black body spectrum ($T \sim 3K$)
 - Polarized
 - Almost isotropic radiation but with small anisotropies (10^{-5})
 - Establish the current standard cosmological model (+ BAO/SNela)
 - Constrain composition of baryon, dark matter, dark energy
 - Flat universe
 - Gaussian fluctuations
 - Implying presence of dark energy from CMB data alone
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CMB cosmology from polarization

- In the near future:

No more information on primordial fluctuations from temperature

Polarization will be the best avenue to constrain cosmology from CMB

- Cosmological targets from CMB polarization

Inflationary physics

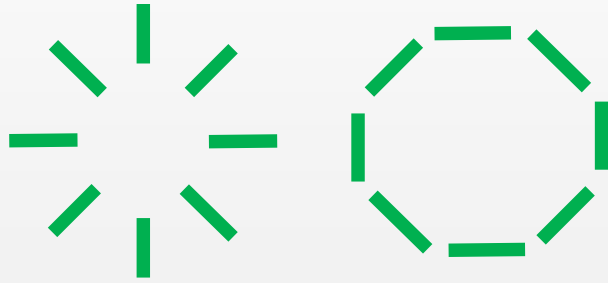
Properties of Neutrinos (+ BAO)

Origin of dark energy/dark matter (+ Large-Scale Structure observables)

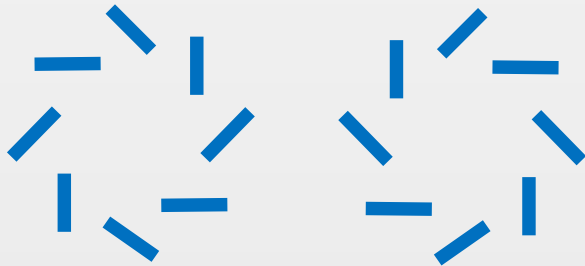
Cosmic string, axion, primordial magnetic fields, ...

E and B mode

E mode (even parity)

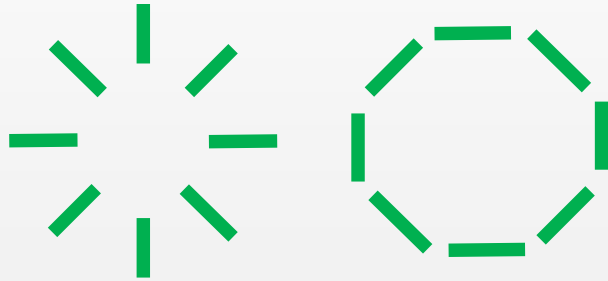


B mode (odd parity)



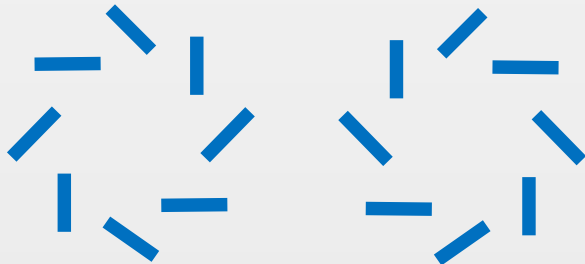
E and B mode

E mode (even parity)



Density fluctuations generate **only** E-mode

B mode (odd parity)



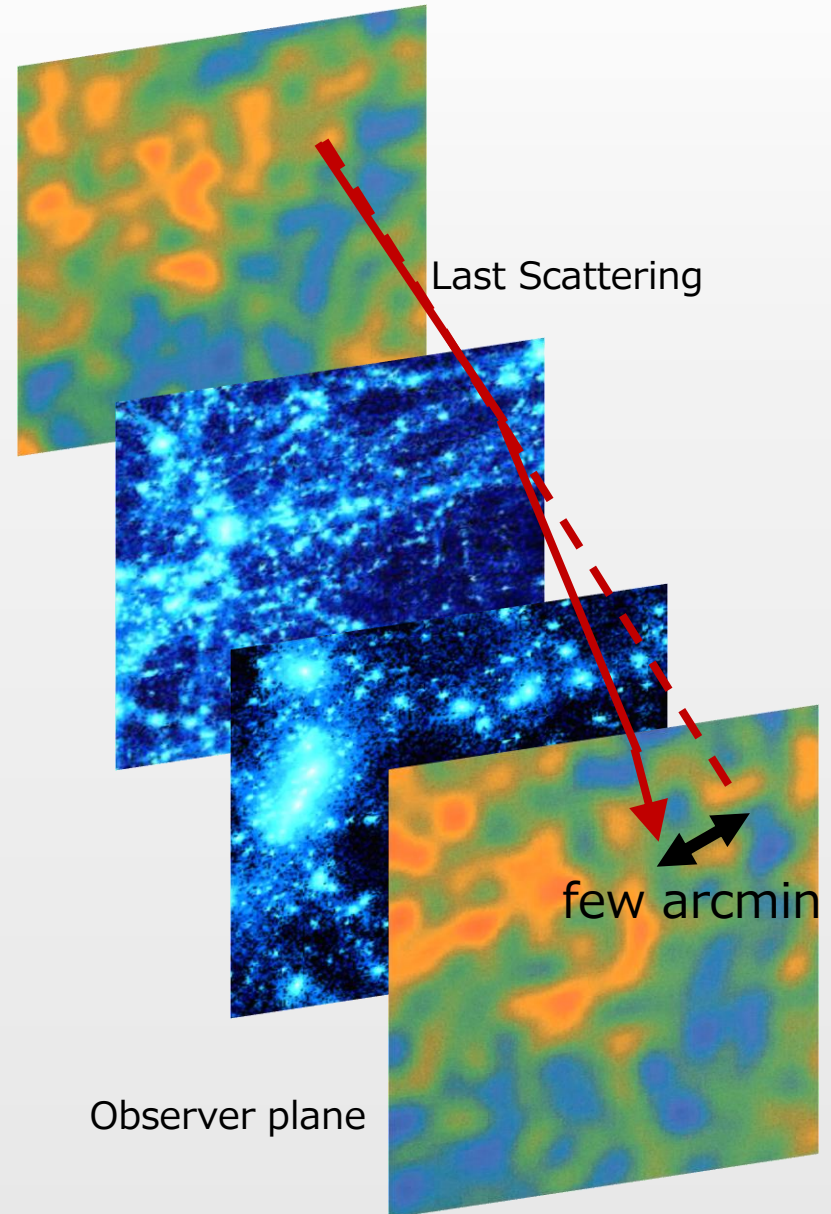
Inflationary gravitational waves (GWs) generate **not only** E mode **but also** B mode

B mode is the best probe of inflationary GWs
(quantum gravity, beyond the standard model)

Gravitational lensing effect on CMB

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

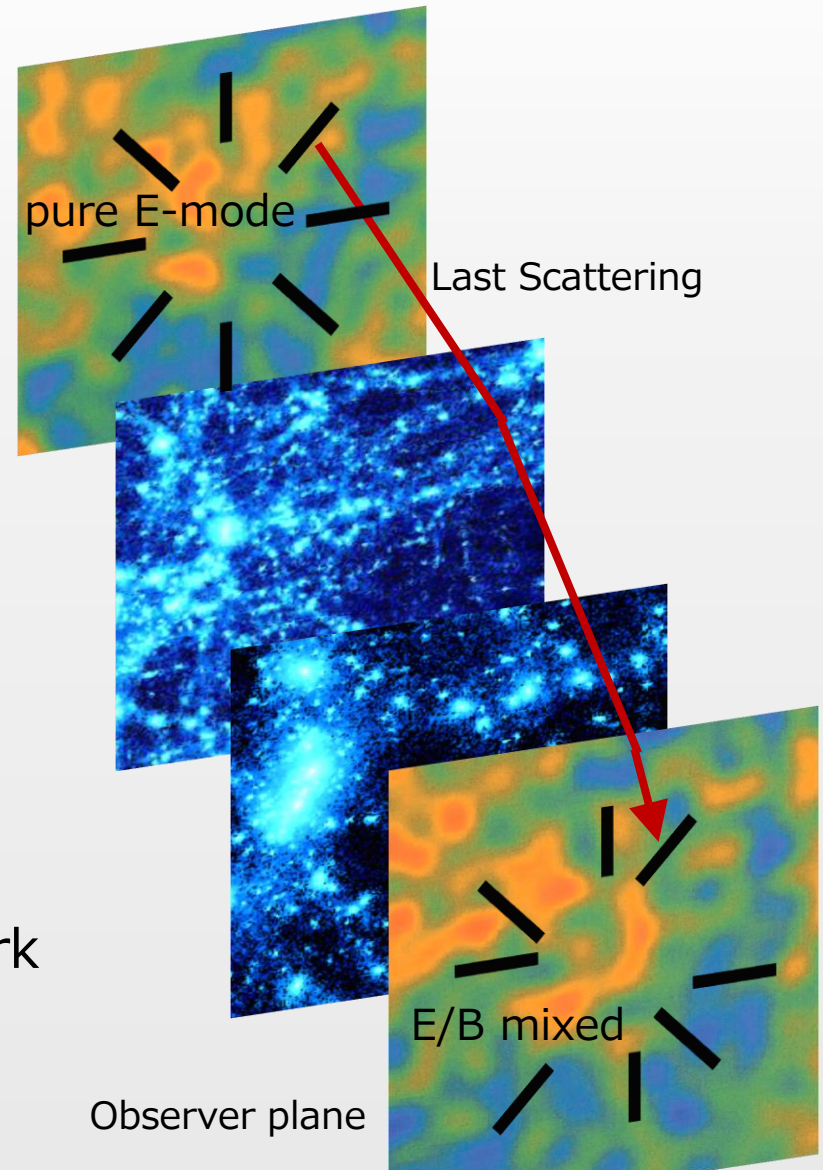
- Distort small scale temperature / polarization fluctuations



Gravitational lensing effect on CMB

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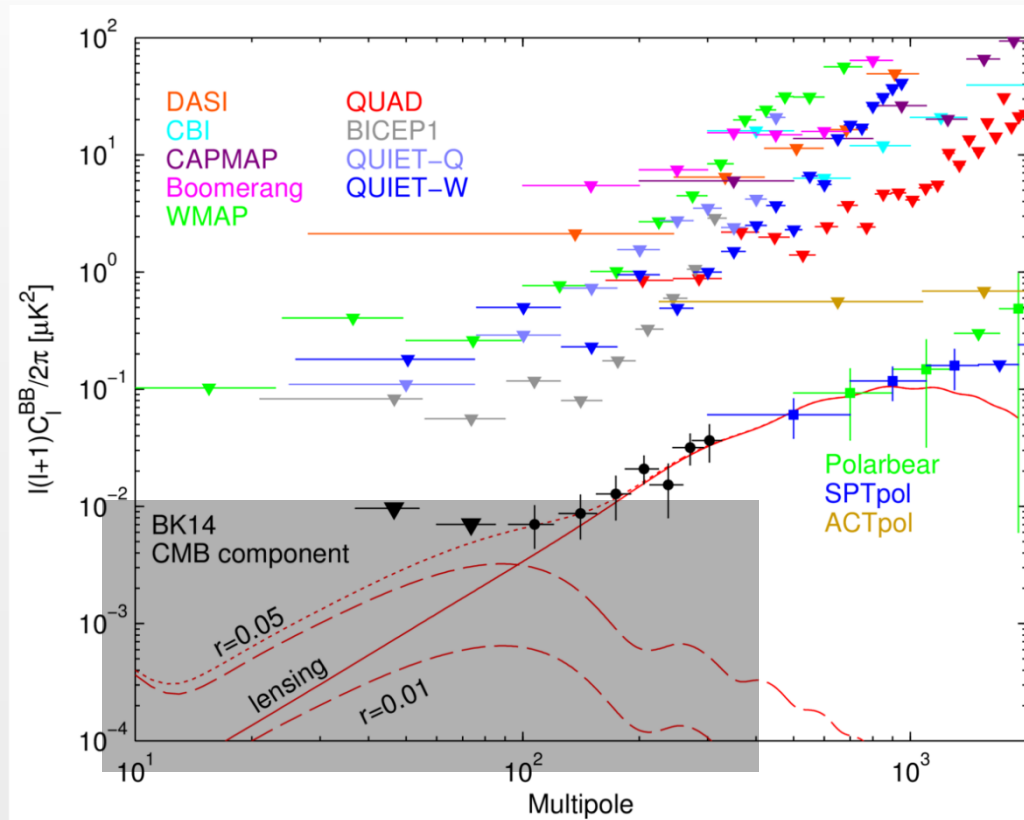
- Distort small scale temperature / polarization fluctuations
- Generate B mode in particular at small scales
Zaldarriaga & Seljak (1998)
- Probe of large-scale structure, e.g., massive neutrinos, dark energy, dark matter



Measurement of B mode is very important in future cosmology

Why do we need delensing

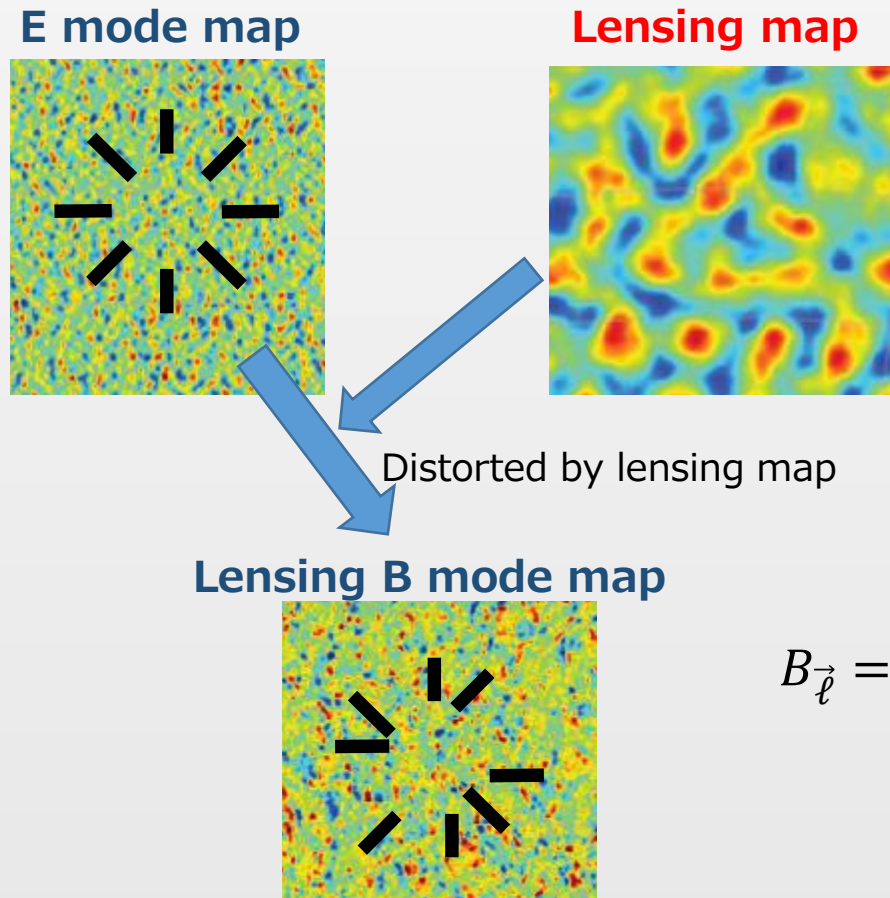
- Lensing B modes dominate over GW B modes



- Removal of lensing B mode (**delensing**) is required to detect primordial GWs in ongoing/future CMB experiments (e.g. BICEP/Keck, LiteBIRD).
- Delensing also helps to constrain non-lensing B modes (cosmic strings, axion, etc) at small scales

Delensing

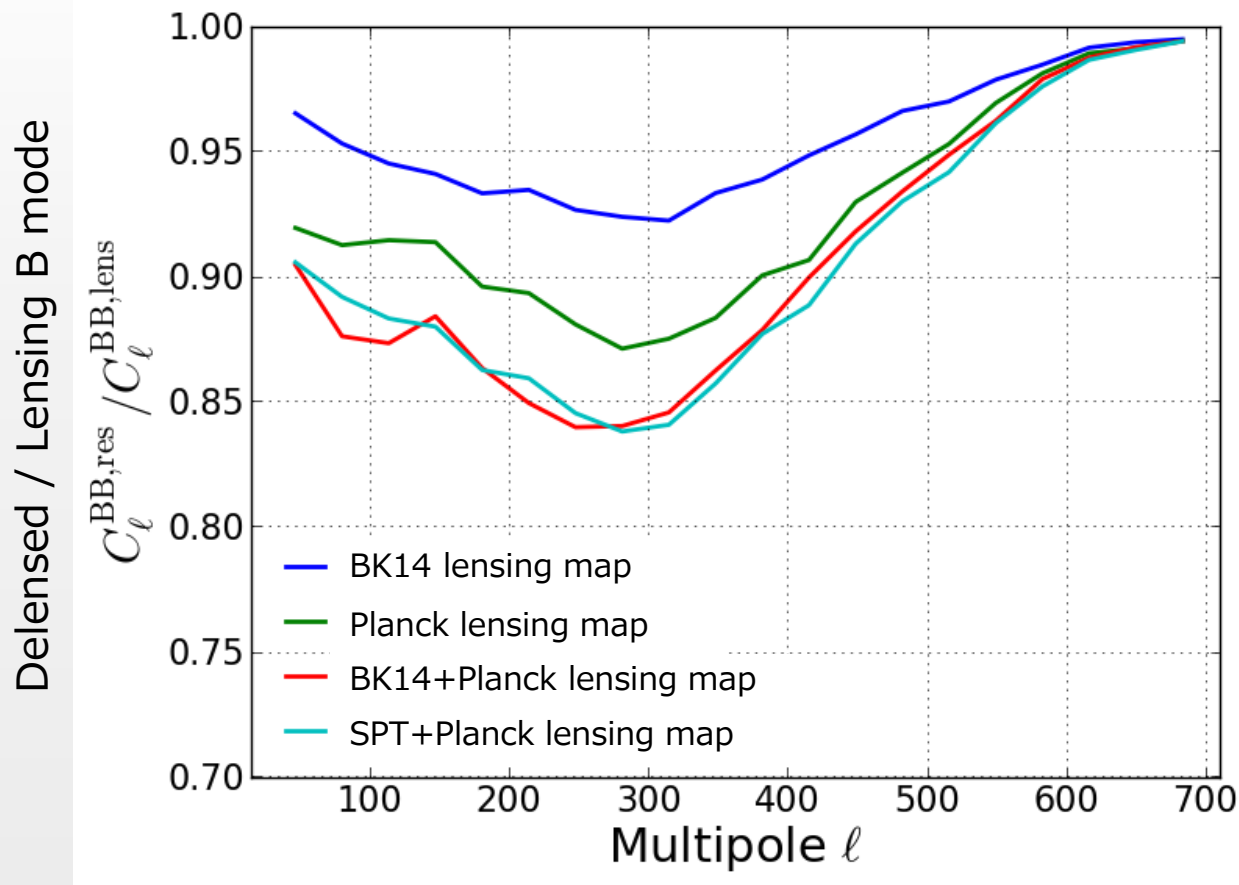
- How to remove lensing B mode
Estimate lensing B mode and subtract it from observed B mode
- Lensing B = distorting E mode map by **lensing map**



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

How efficiently can we remove lensing B mode?

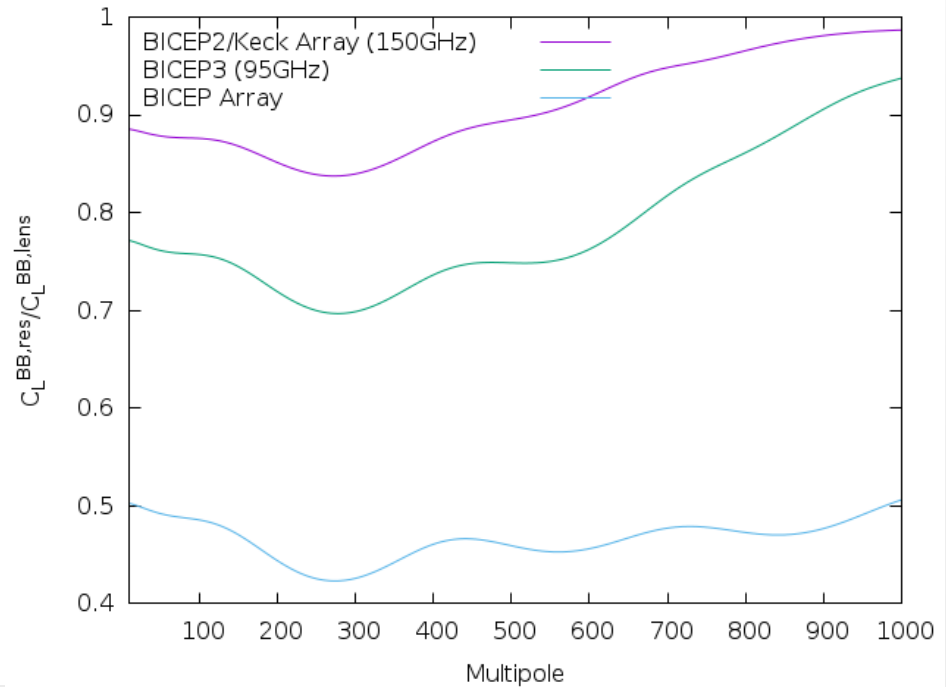
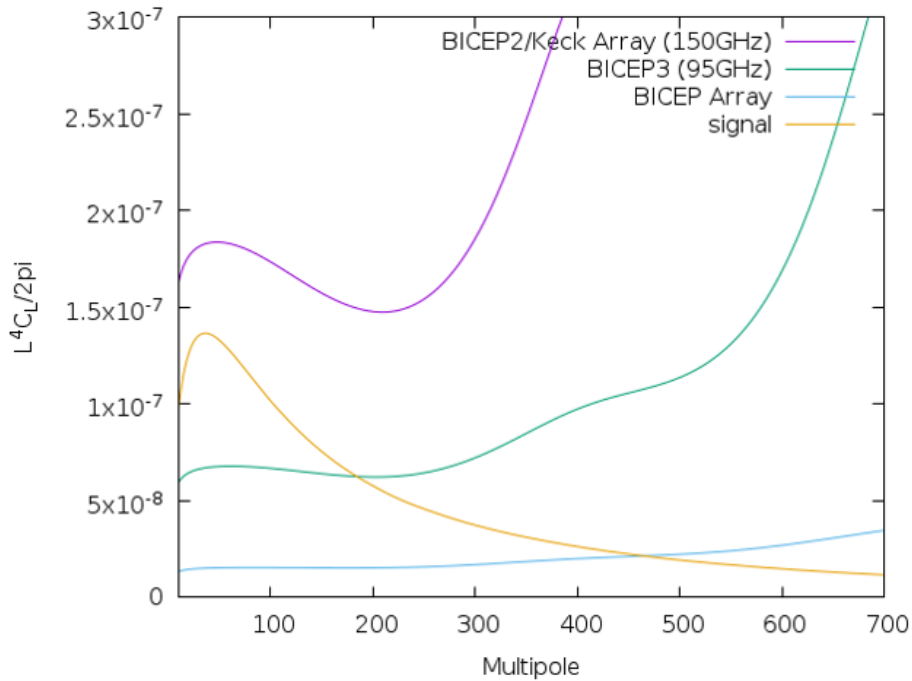
Delensing (BICEP/Keck = BK)



- Using current available data, ~ 10 - 15% of lensing B mode can be removed
= $\sim 10\%$ improvement on r constraint

Delensing (BK)

Near Future Lensing Analysis in BK



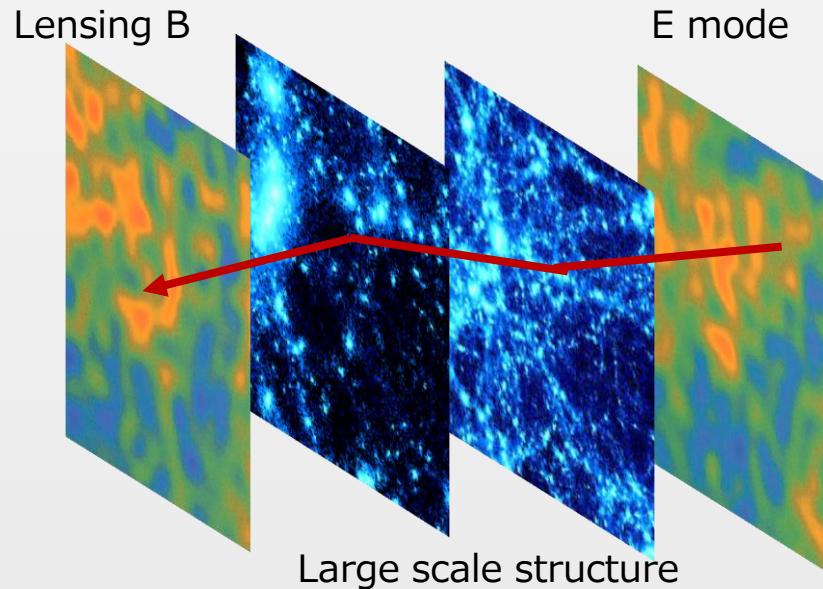
BICEP2/Keck Array: $\Delta_p = 3\mu K'$, $\theta = 30'$
BICEP3 $\Delta_p = 2\mu K'$, $\theta = 24'$
BICEP Array: 95GHz: $\Delta_p = 1\mu K'$, $\theta = 24'$
150GHz: $\Delta_p = 1.4\mu K'$, $\theta = 15'$
220GHz: $\Delta_p = 7\mu K'$, $\theta = 11'$
270GHz: $\Delta_p = 10\mu K'$, $\theta = 9'$

BICEP Array alone can remove half of lensing B mode

Delensing with external data

- Galaxy clustering can be also used to estimate lensing map

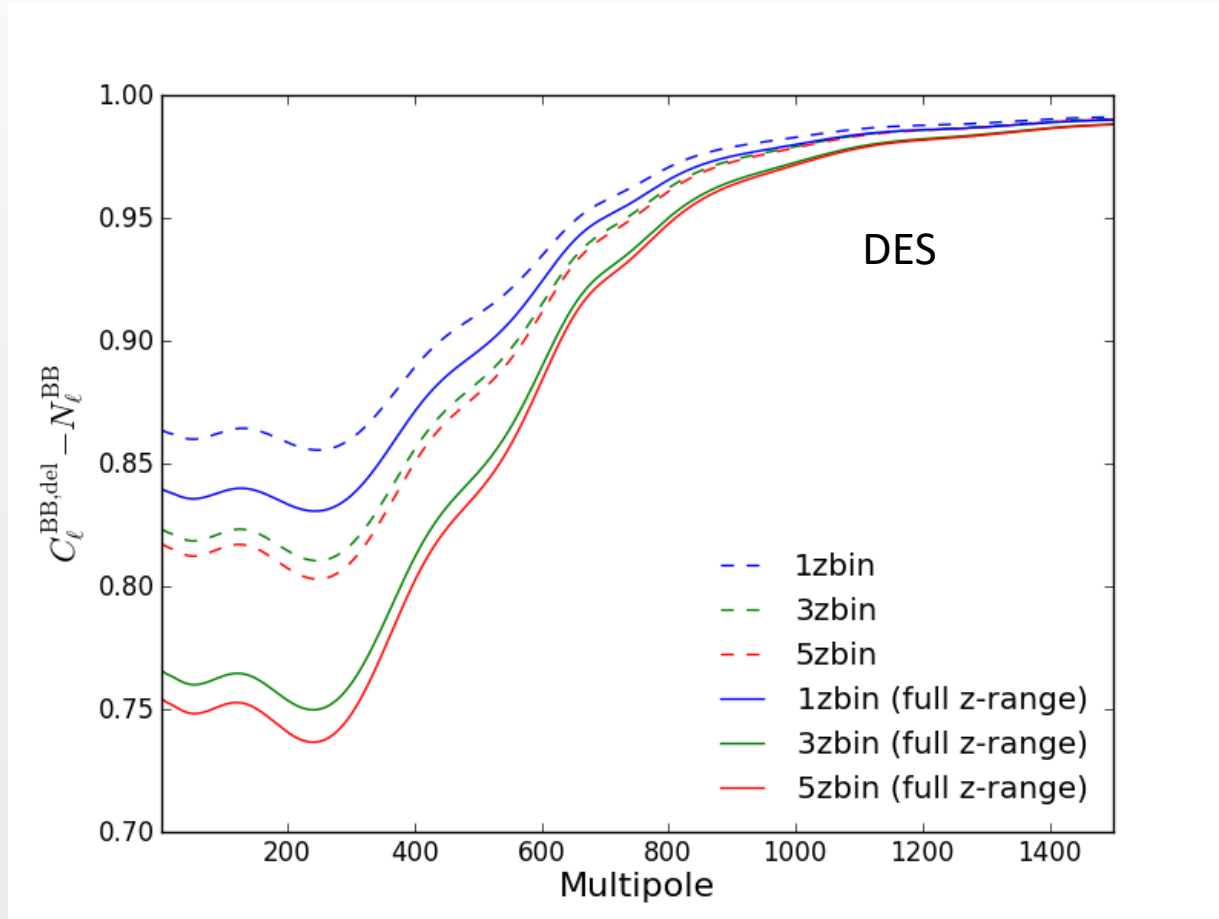
Galaxy clustering \approx density fluctuations \approx gravitational potential



(this is also the same for cosmic infrared background, optical lensing etc)

Delensing with external data (BK)

Forecast: BK + Dark Energy Survey (DES)

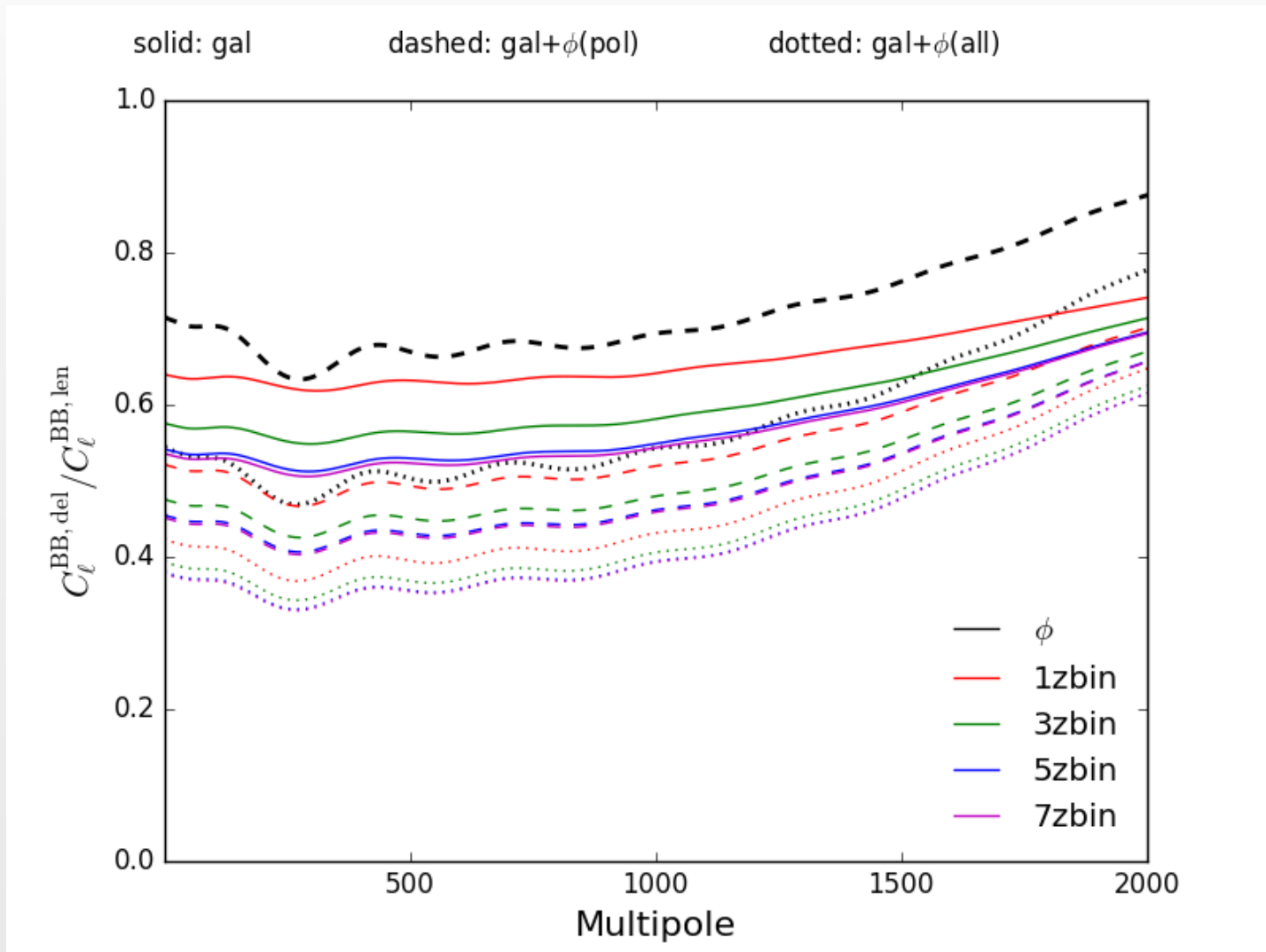


Dashed: only $0.2 \leq z \leq 1.2$ are used (dashed)

Using DES data, $\sim 20\text{-}25\%$ of lensing B mode can be removed

Delensing with external data (PolarBear)

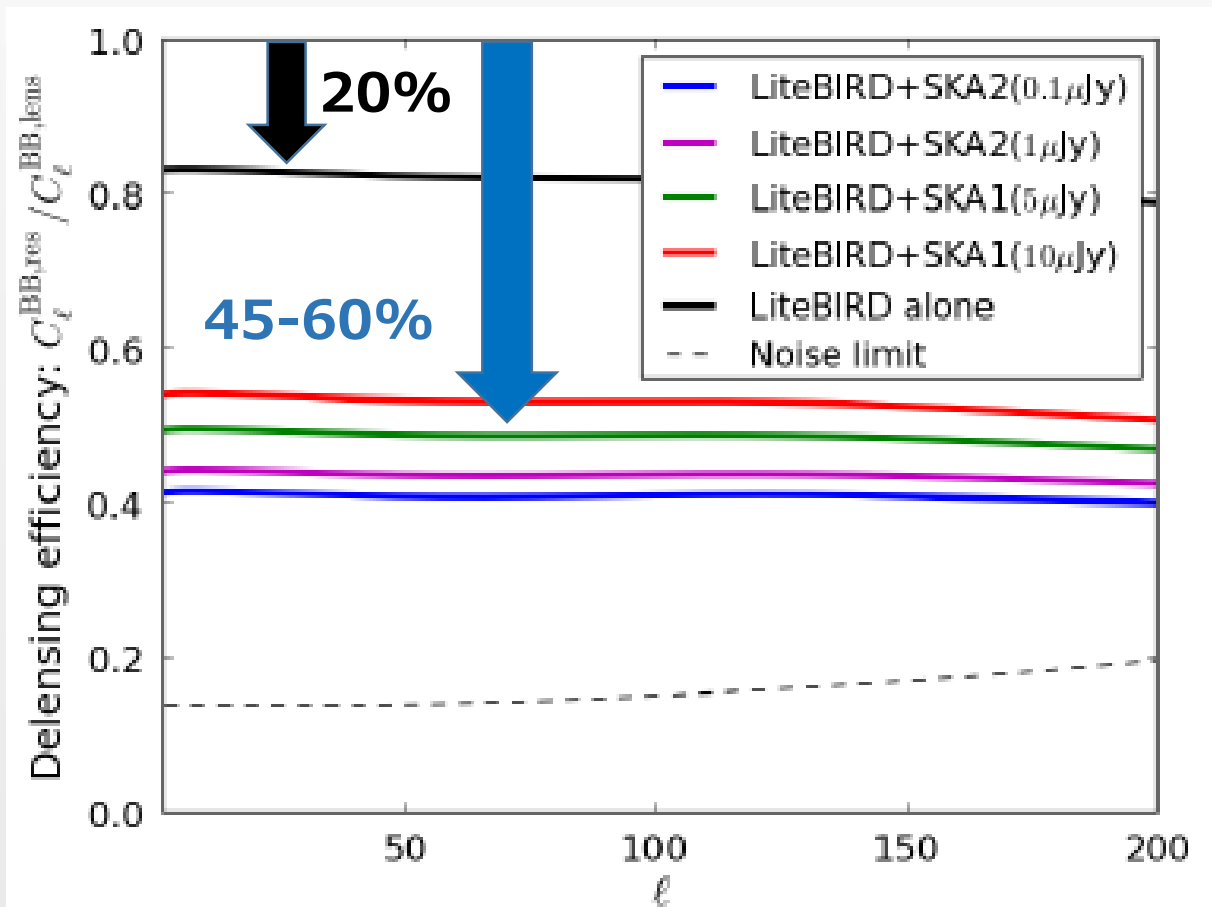
- Delensing Polarbear B mode with Subaru HSC data (Ongoing)



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

Delensing with external data (LiteBIRD)

(TN, Yamauchi, Sherwin, Nagata 2016)



Mass tracers will be also useful for delensing LiteBIRD B-mode.

Summary

- **Polarization will be soon the forefront of cosmological probes**
- **Delensing is necessary to improve the sensitivity to primordial GWs**
- **How efficiently can we remove lensing B mode?**
 - Using current CMB data of BK+SPT+Planck, delensing will improve the constraints on r by $\sim 10\%$
 - Using external data, delensing will further improve the constraints on r significantly