BICEP2/Keck Array Results IX

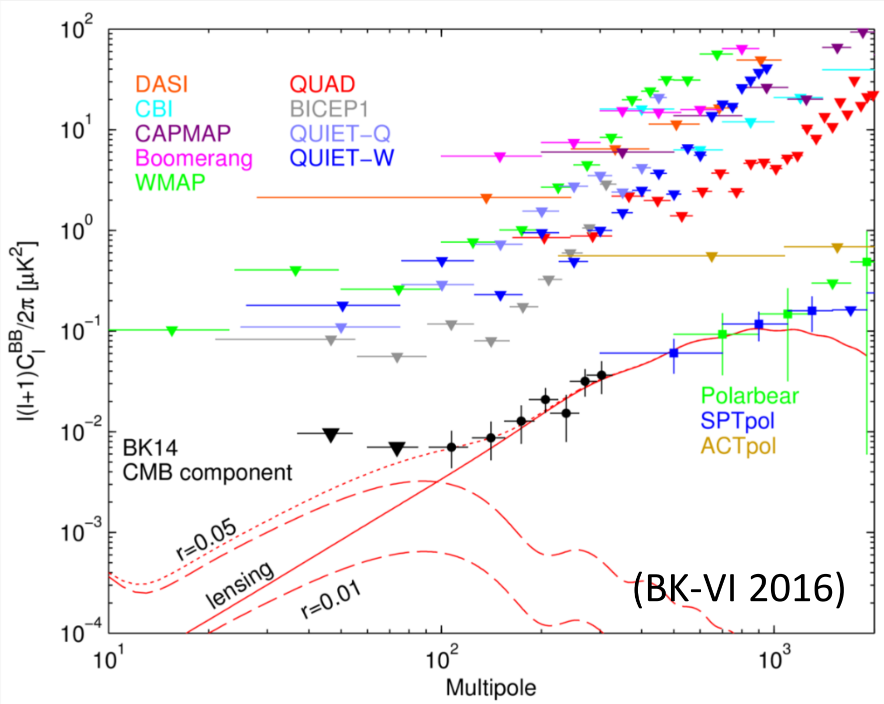
New Bounds on Anisotropies of CMB Polarization Rotation and Implications for Axionlike Particles and Primordial Magnetic Fields

Toshiya Namikawa

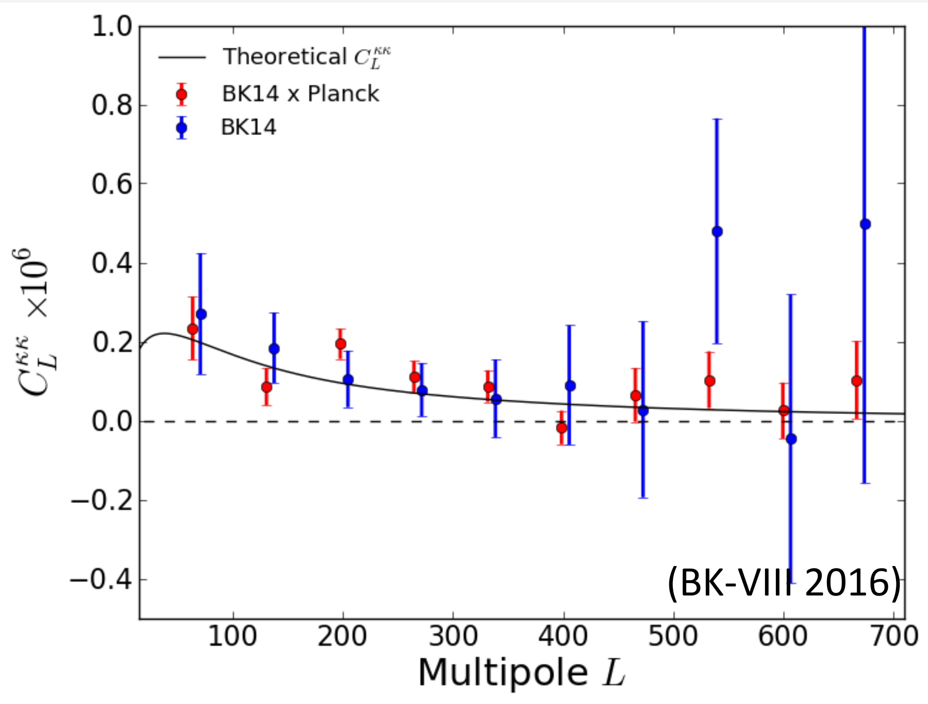
2nd B-mode from Space WS (Dec 4-6, 2017)

Measurements of Polarization

BICEP2/Keck Array (BK) has measured the large-scale polarization very precisely, providing tightest constraints on r and detecting lensing using polarization data alone



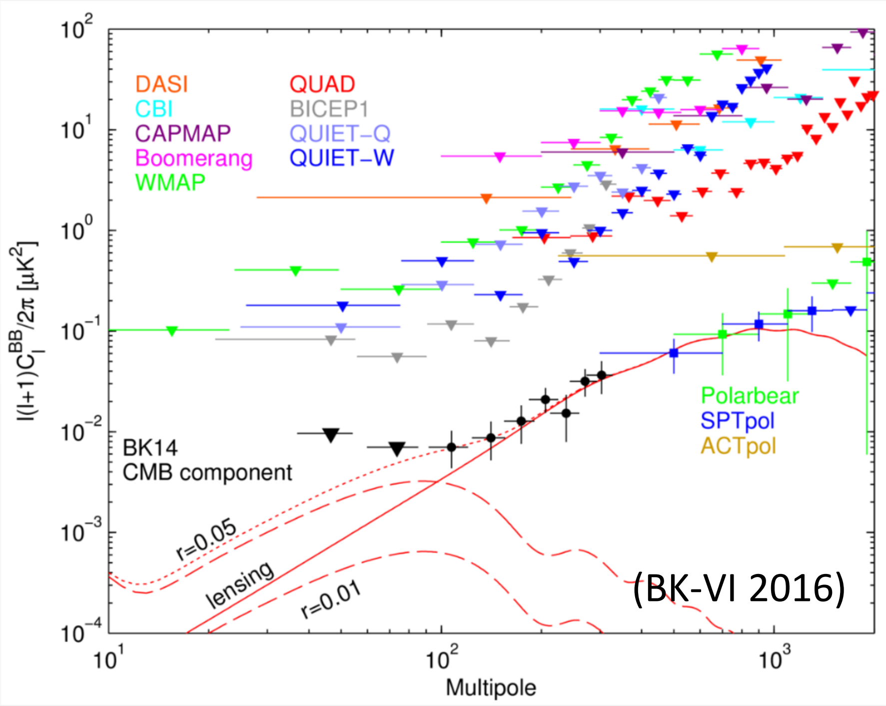
(BK-VI 2016)

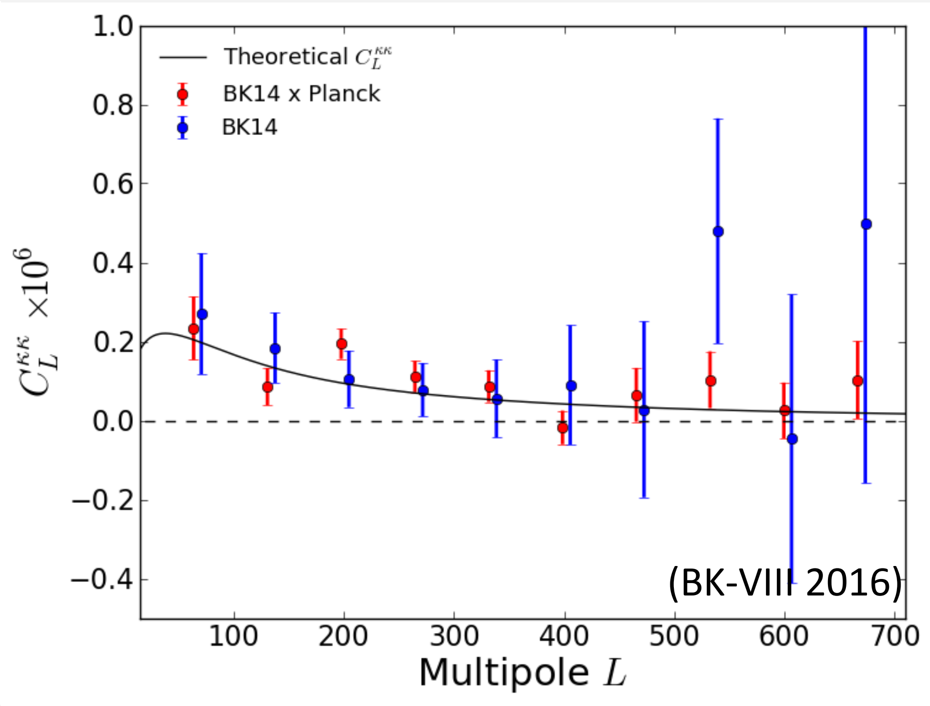


(BK-VIII 2016)

Measurements of Polarization

BICEP2/Keck Array (BK) has measured the large-scale polarization very precisely, providing tightest constraints on r and detecting lensing using polarization data alone





Polarization data can also be used to test parity-violating physics by measuring “anisotropic” rotation of polarization angle

Origins of anisotropies of polarization rotation

- **Axionlike particles**

String theory generally predicts presence of axionlike particles coupled with photons

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

Coupling constant → $g_{a\gamma}$

$$\text{Lagrangian} \supset \frac{g_{a\gamma} a}{4} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Origins of anisotropies of polarization rotation

- **Axionlike particles**

String theory generally predicts presence of axionlike particles coupled with photons

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

Coupling constant

$$\text{Lagrangian} \supset \frac{g_{a\gamma} a}{4} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

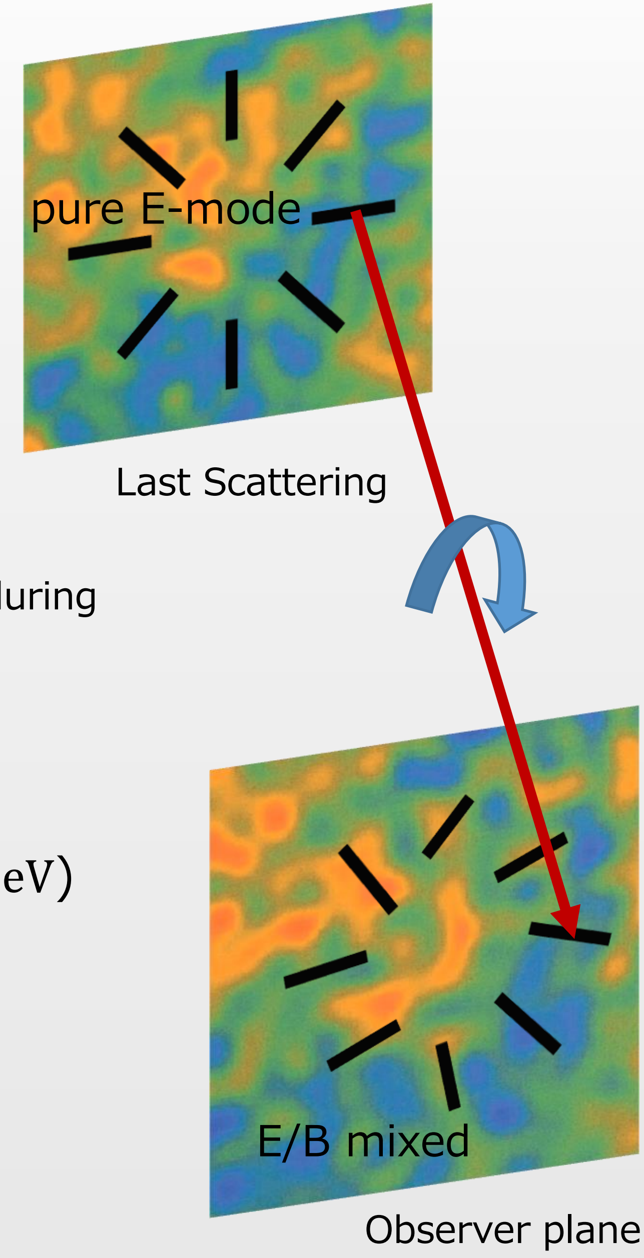
This leads to anisotropies in polarization angle

Total rotation angle

Changes in axion field during CMB propagation

$$\alpha(n) = \frac{g_{a\gamma} \Delta a(n)}{2}$$

(mass range: $10^{-33}\mathrm{eV} \leq m_a \leq 10^{-28}\mathrm{eV}$)



Origins of anisotropies of polarization rotation

- **Axionlike particles**

String theory generally predicts presence of axionlike particles coupled with photons

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

Coupling constant

$$\text{Lagrangian} \supset \frac{g_{a\gamma} a}{4} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

This leads to anisotropies in polarization angle

Total rotation angle

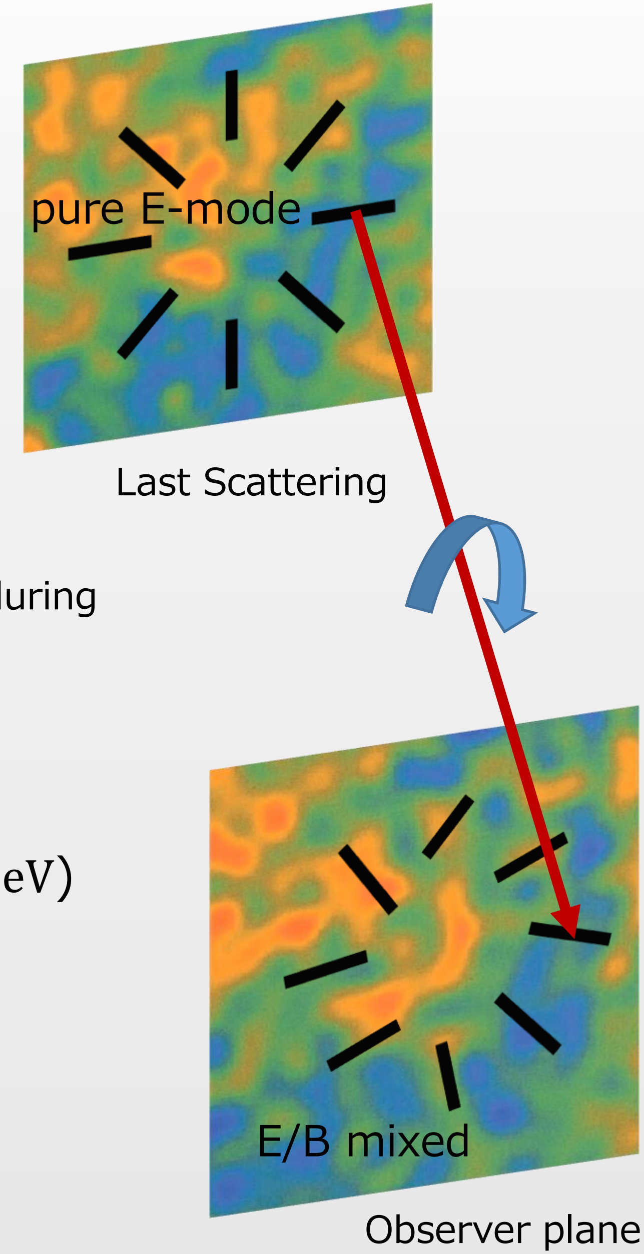
Changes in axion field during CMB propagation

$$\alpha(n) = \frac{g_{a\gamma} \Delta a(n)}{2}$$

(mass range: $10^{-33}\mathrm{eV} \leq m_a \leq 10^{-28}\mathrm{eV}$)

Power spectrum (assuming result of inflationary fluctuations)

$$\frac{L(L+1)}{2\pi} C_L^{\alpha\alpha} = \left(\frac{H_I g_{a\gamma}}{4\pi} \right)^2$$



Origins of anisotropies of polarization rotation

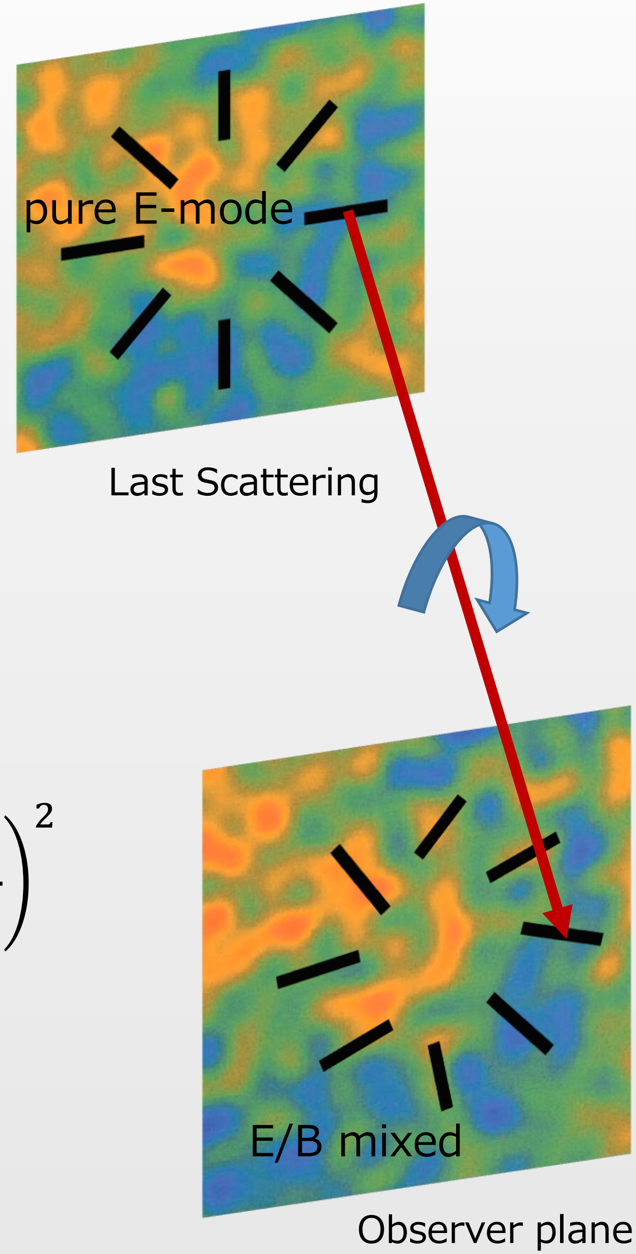
- **Primordial magnetic fields**

Primordial magnetic fields can also lead to a rotation of polarization by the Faraday rotation

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

$$\alpha(n) = \frac{3c^2}{16\pi e^2}\nu^{-2}\int \dot{\tau}\,\vec{B}\cdot d\vec{l}$$

Magnetic field



Power spectrum See e.g. Yadav+12, Pogosian+'13

$$\frac{L(L+1)}{2\pi}C_L^{\alpha\alpha} = 3.6\times 10^{-8}\left(\frac{\nu}{150\mathrm{GHz}}\right)^{-4}\left(\frac{B_{1\mathrm{Mpc}}}{1\mathrm{nG}}\right)^2$$

Our Work

- Several Works have constrained the anisotropies of the polarization rotation using $C_L^{\alpha\alpha}$

  Gluscevic+'13, Polarbear'15

- Some works used BB spectrum

  Gruppuso+'12, Li&Yu'13, Alighieri+'14, Li+'15, Mei+'15, Pan+'17

- **We significantly improve the constraints on the models by measuring $C_L^{\alpha\alpha}$**

  We specifically constrain the amplitude of the scale-invariant spectrum, A_{CB}

$$\frac{L(L+1)}{2\pi} C_L^{\alpha\alpha} = A_{CB} \times 10^{-4}$$

How to measure polarization rotation

Details are given by Namikawa'17 (1612.07855)

- Anisotropies in α generate mode couplings between E and B modes (similar to lensing)

$$\mathrm{e}^{\pm 2\mathrm{i}\alpha(\hat{\boldsymbol{n}})}[Q \pm \mathrm{i}U](\hat{\boldsymbol{n}}).$$

$\Rightarrow$

$$E'_\ell = E_\ell + \int \frac{\mathrm{d}^2\boldsymbol{L}}{(2\pi)^2} 2\alpha_{\boldsymbol{L}} \times [E_{\ell-\boldsymbol{L}} \cos 2(\varphi_{\ell-\boldsymbol{L}} - \varphi_\ell) + B_{\ell-\boldsymbol{L}} \sin 2(\varphi_{\ell-\boldsymbol{L}} - \varphi_\ell)]$$

$$B'_\ell = B_\ell + \int \frac{\mathrm{d}^2\boldsymbol{L}}{(2\pi)^2} 2\alpha_{\boldsymbol{L}} \times [E_{\ell-\boldsymbol{L}} \sin 2(\varphi_{\ell-\boldsymbol{L}} - \varphi_\ell) - B_{\ell-\boldsymbol{L}} \cos 2(\varphi_{\ell-\boldsymbol{L}} - \varphi_\ell)].$$

- $\alpha(n)$ can be reconstructed by correlating different modes of E and B

$$\widehat{\alpha_L} = A_L \int d^2L_1 f_{L,L_1} E_{L_1} B_{L-L_1} = \alpha_L + \text{noise}$$

How to measure polarization rotation

Details are given by Namikawa'17 (1612.07855)

- Reconstruction of polarization rotation power spectrum

$$\hat{C}_L^{\alpha\alpha} = \sum_M \frac{|\hat{\alpha}_{LM}|^2}{2L+1} - \widehat{N}_L^{(0)} - N_L^{lens}$$

lensing trispectrum

disconnected 4pt function

How to measure polarization rotation

Details are given by Namikawa’17 (1612.07855)

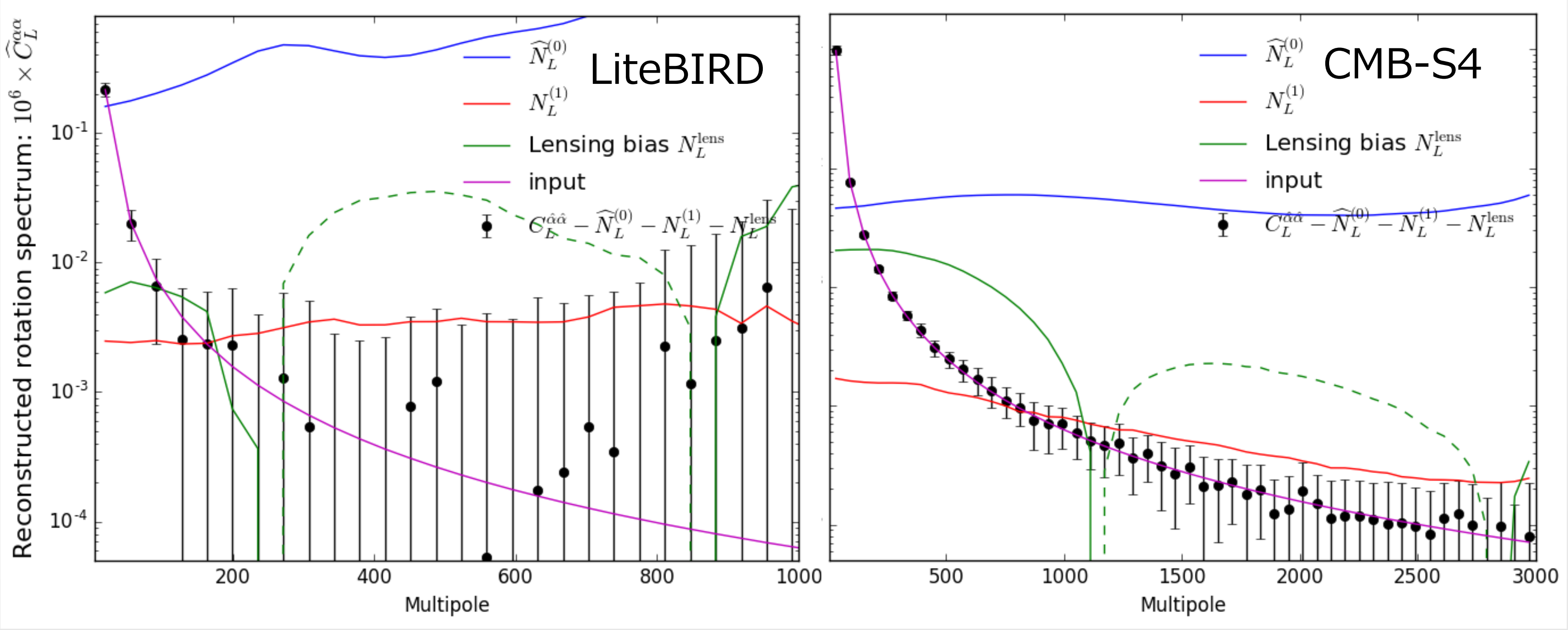
- Reconstruction of polarization rotation power spectrum

$$\hat{C}_L^{\alpha\alpha} = \sum_M \frac{|\hat{\alpha}_{LM}|^2}{2L+1} - \widehat{N}_L^{(0)} - N_L^{lens}$$

lensing trispectrum

disconnected 4pt function

- Test the method by simulation (recovery of input spectrum)



(including N1 bias correction)

How to measure polarization rotation

Details are given by Namikawa'17 (1612.07855)

- Reconstruction of polarization rotation power spectrum

$$\hat{C}_L^{\alpha\alpha} = \sum_M \frac{|\hat{\alpha}_{LM}|^2}{2L+1} - \widehat{N}_L^{(0)} - N_L^{lens}$$

lensing trispectrum

disconnected 4pt function

- For BK analysis

  - Disconnected bias is estimated by a realization-dependent way

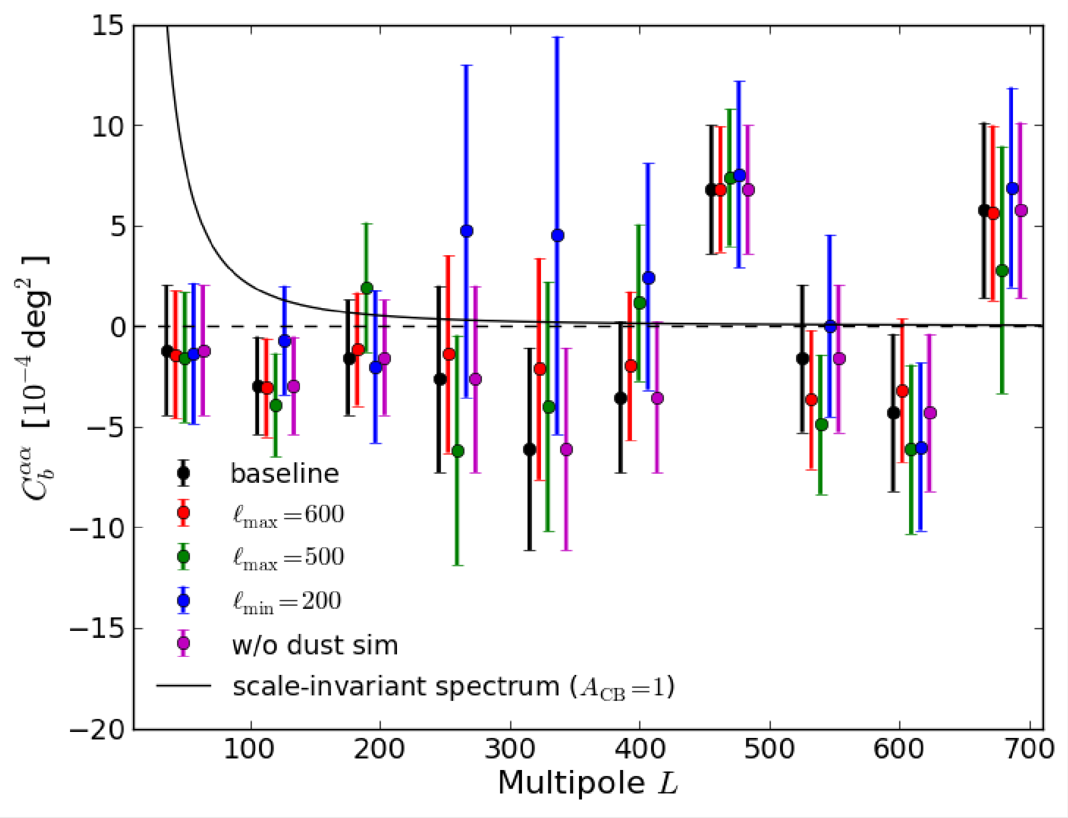
    (Less sensitive to inaccuracy of simulated covariance)

  - Lensing bias is negligible

  - Mean-field bias, $\langle\hat{\alpha}_L\rangle$, from lensing and survey boundary is negligible (due to the difference of parity symmetry at linear order)

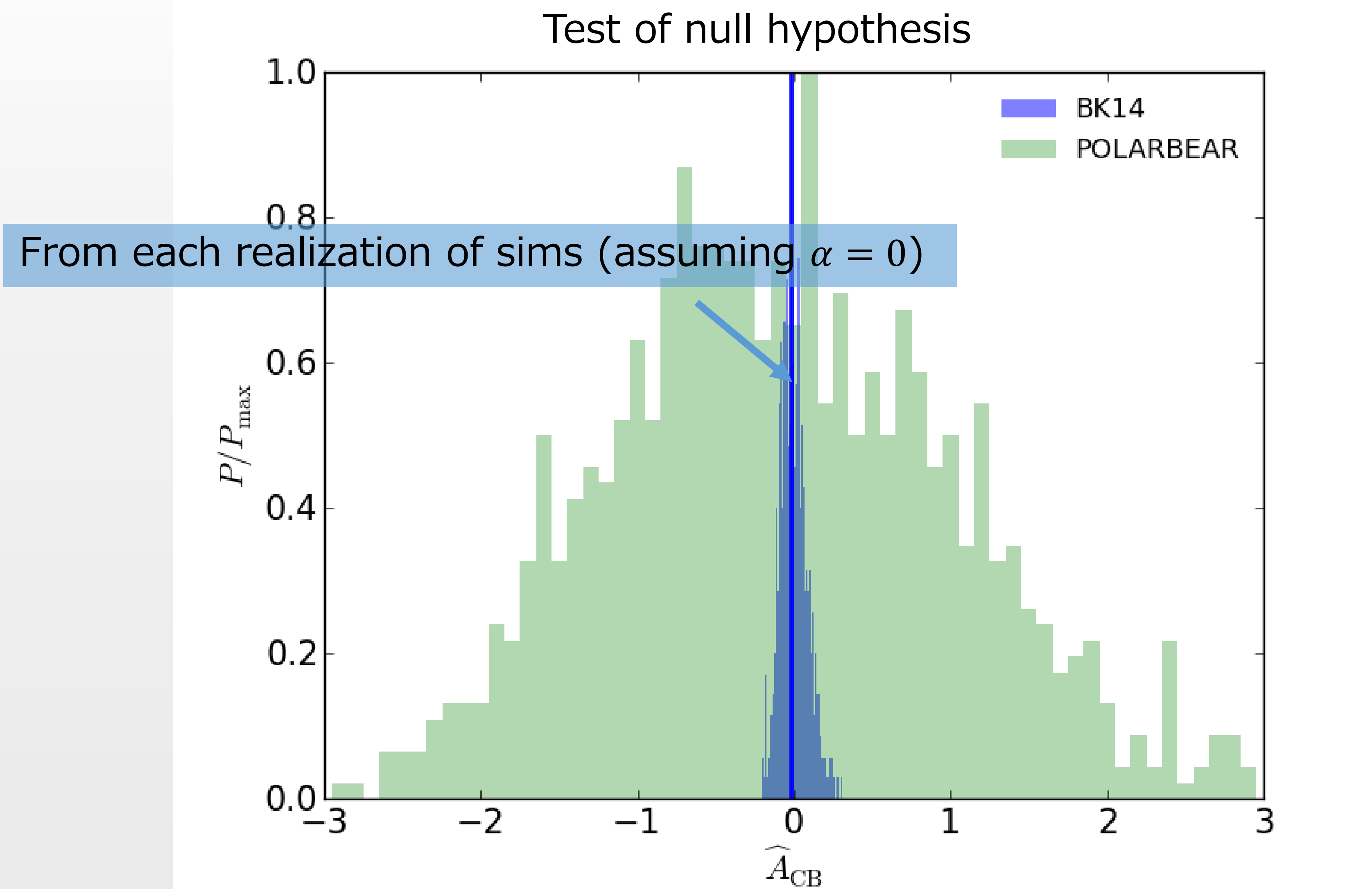
Results

- Use BK14 150GHz Q/U maps



$$\frac{L(L+1)}{2\pi} C_L^{\alpha\alpha} = A_{CB} \times 10^{-4}$$

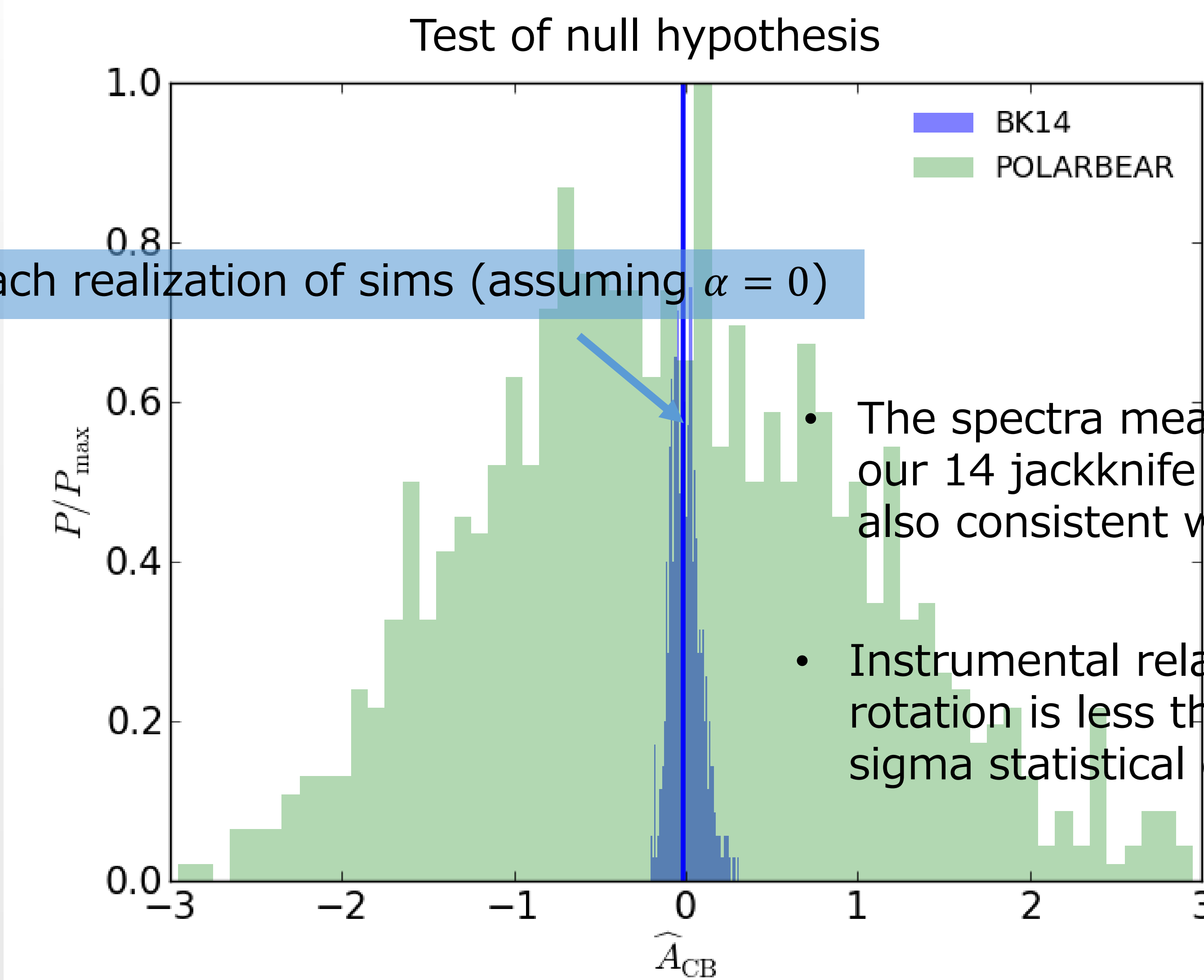
Results



Consistent with null ($A_{CB} = 0$)

(BK constraints ~ 0.1 x POLARBEAR constraints)

Results



From each realization of sims (assuming $\alpha = 0$)

- The spectra measured from our 14 jackknife maps are also consistent with null
- Instrumental relative pol. rotation is less than 1% of 1 sigma statistical error

Consistent with null ($A_{CB} = 0$)

(BK constraints ~ 0.1 x POLARBEAR constraints)

Implications

Compared to previous attempts, we improve the constraints on the scale-invariant spectrum by an order of magnitude

$$A_{CB} \leq 0.33 \text{ (95\%CL)}$$

(Planck data also provides the similar upper bounds, see Contreras+'17)

- **Axionlike particles**

$$g_{a\gamma} \leq \frac{7.2 \times 10^{-2}}{H_I} \quad \text{(at } 10^{-33}\text{eV} \leq m_a \leq 10^{-28}\text{eV)}$$

An order of magnitude better than Pospelov+09

- **Primordial magnetic fields**

$$B_{1\text{Mpc}} \leq 30\text{nG}$$

(c.f. $B_{1\text{Mpc}} \leq 3.9\text{nG}$ using BB by Polarbear team)

Discussion

- **Coupling constant of axionlike particles**

(see e.g. Marsh 2016)

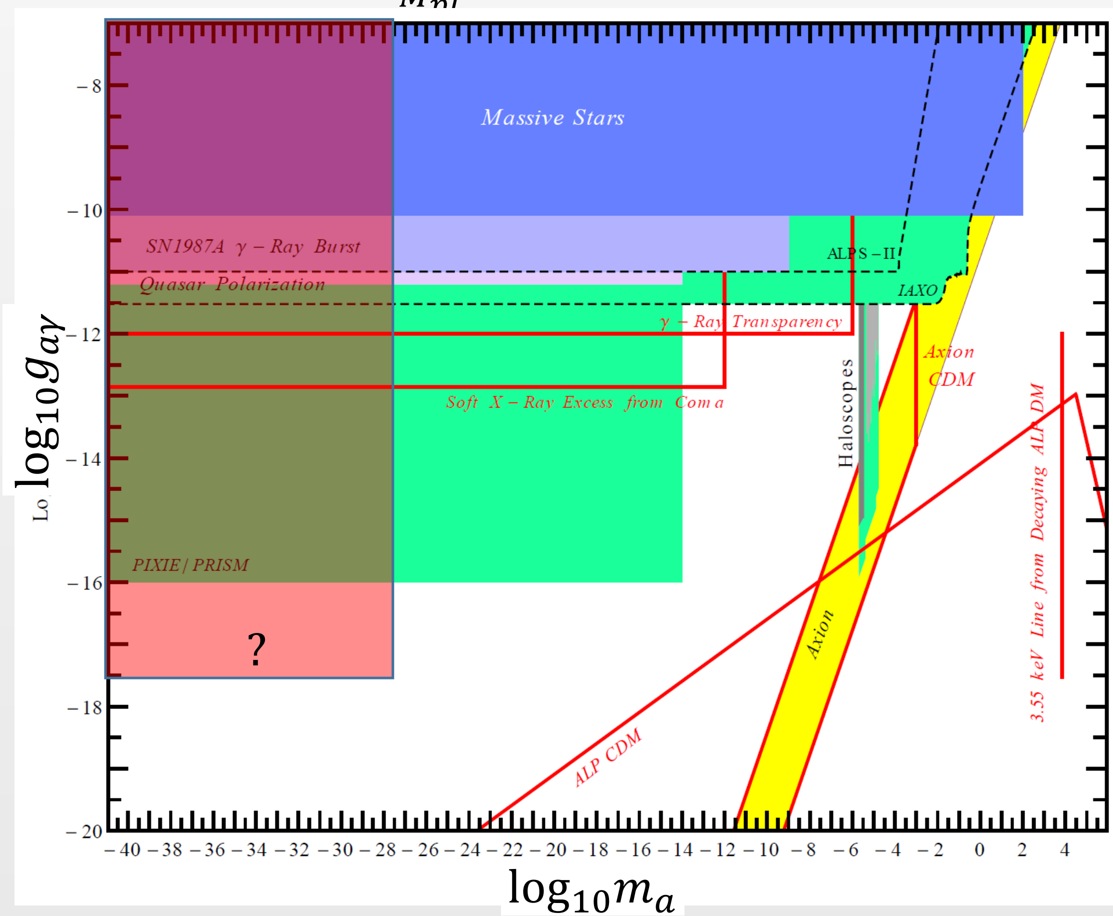
Typically $g_{a\gamma} \sim 10^{-19}$/GeV but in general $g_{a\gamma} \geq \frac{10^{-3}}{M_{pl}} \sim 10^{-22}$/GeV

Our constraint leads to

$$10^{-3} \leq M_{pl} g_{a\gamma} \leq 10^{-2} \frac{M_{pl}}{H_I}$$

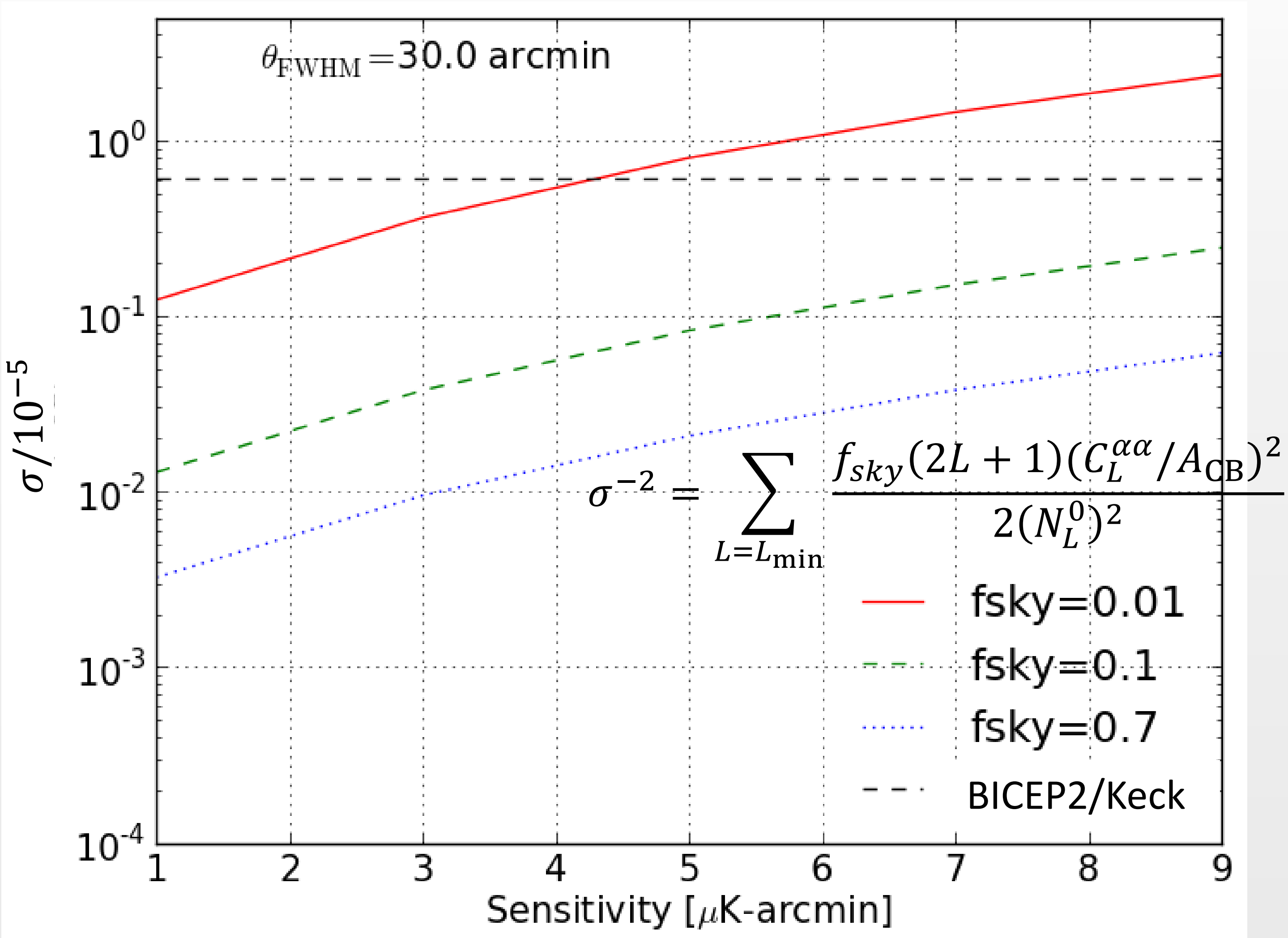
E.g. if $r = 0.01$,

$$10^{-3} \leq M_{pl} g_{a\gamma} \leq 10^{3}$$



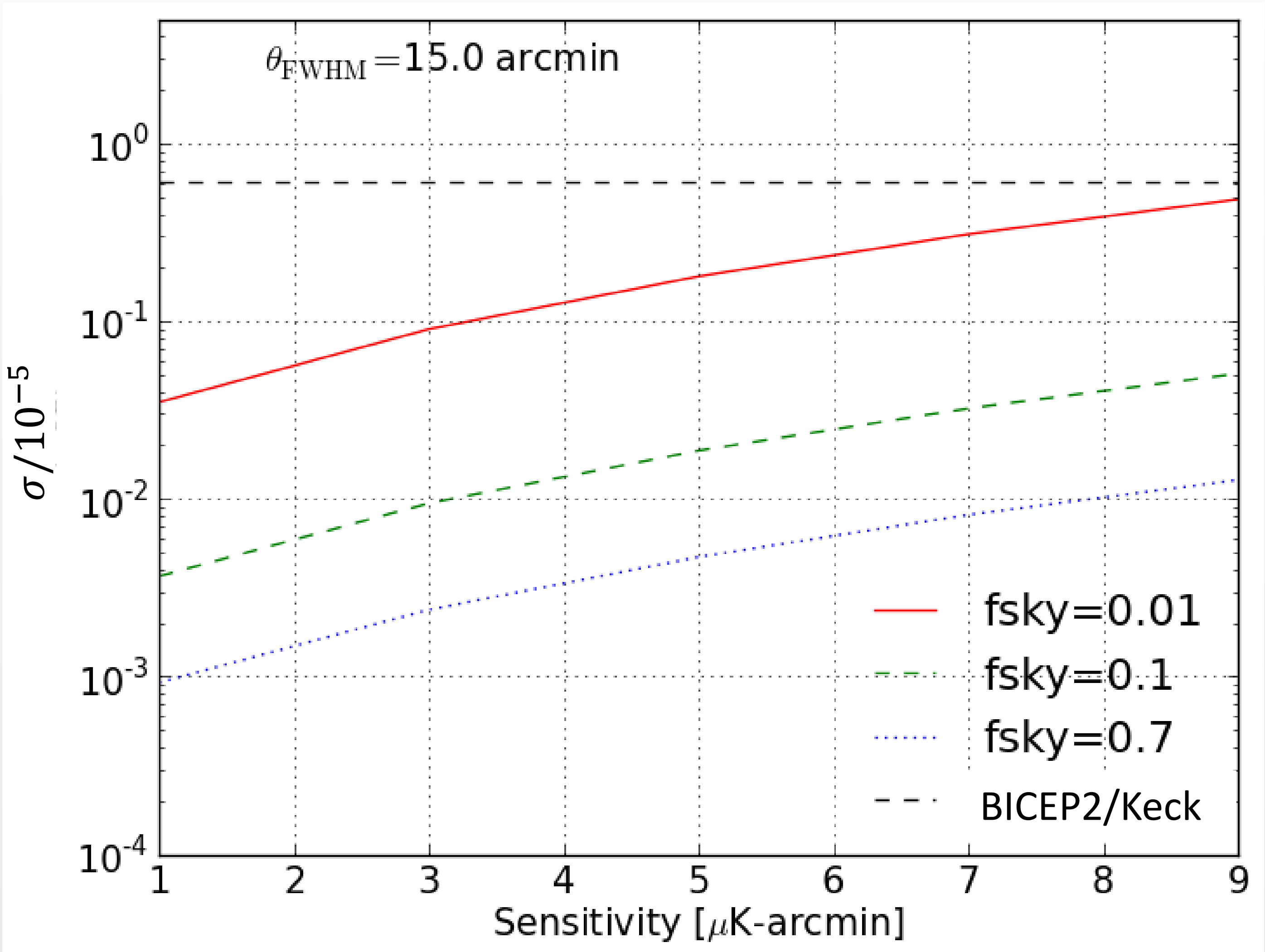
Detection of r is important to constrain $g_{a\gamma}$

Forecast



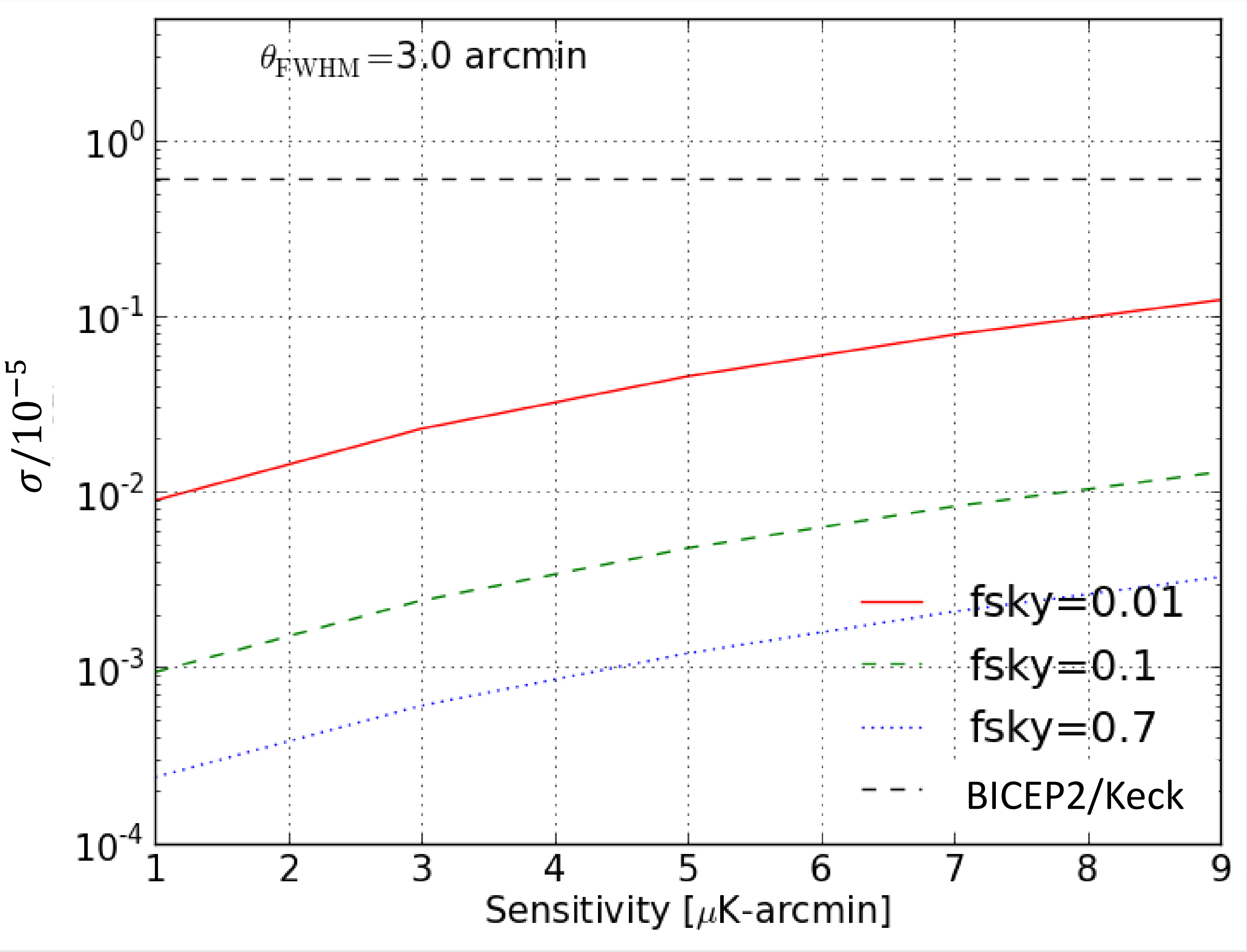
1-2 orders of magnitude improvement by LiteBIRD

Forecast



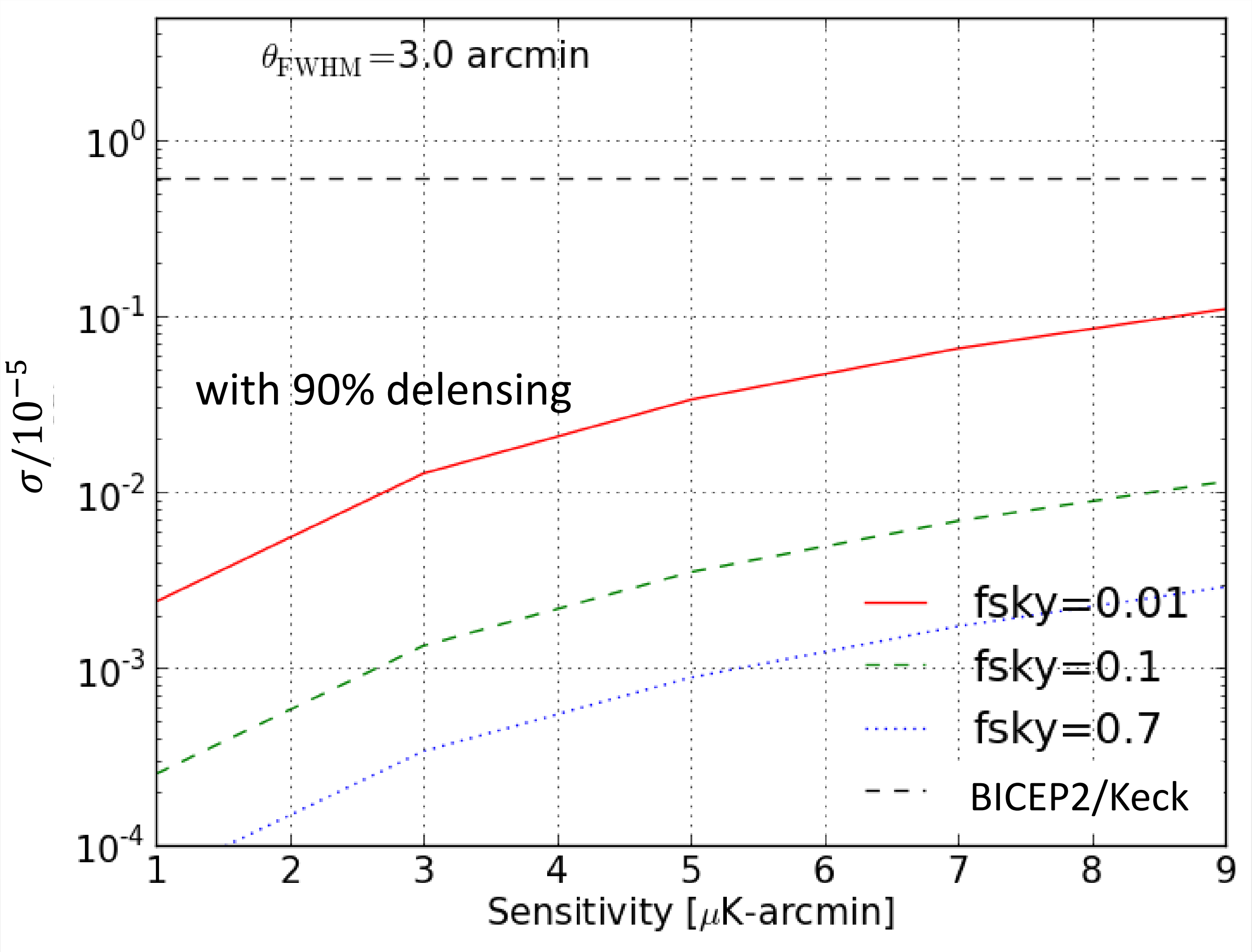
~1 order of magnitude improvement by BICEP Array

Forecast



$\theta_{\rm FWHM}=$3.0 arcmin
$\sigma/10^{-5}$
10^0
10^-1
10^-2
10^-3
10^-4
1 2 3 4 5 6 7 8 9
Sensitivity [μK-arcmin]
fsky=0.01
fsky=0.1
fsky=0.7
BICEP2/Keck

Forecast



~ 4 orders of magnitude improvement by S4

Summary

- We present the strongest constraints to date on anisotropies of CMB polarization rotation using BK data
- Our results lead to an order of magnitude improvement of better constraint on the coupling constant of the axionlike particle, $g_{a\gamma} \leq 7.2 \times 10^{-2}/H_I$ (95% CL)
(If r=0.01, this corresponds to $M_{Pl} g_{a\gamma} \leq 10^3$ at $10^{-33} \leq m_a \leq 10^{-28}$ eV)
- The upper bound on the PMFs is 30nG (95% CL)
- S4 will improve the constraints by ~4 orders of magnitude better than our results