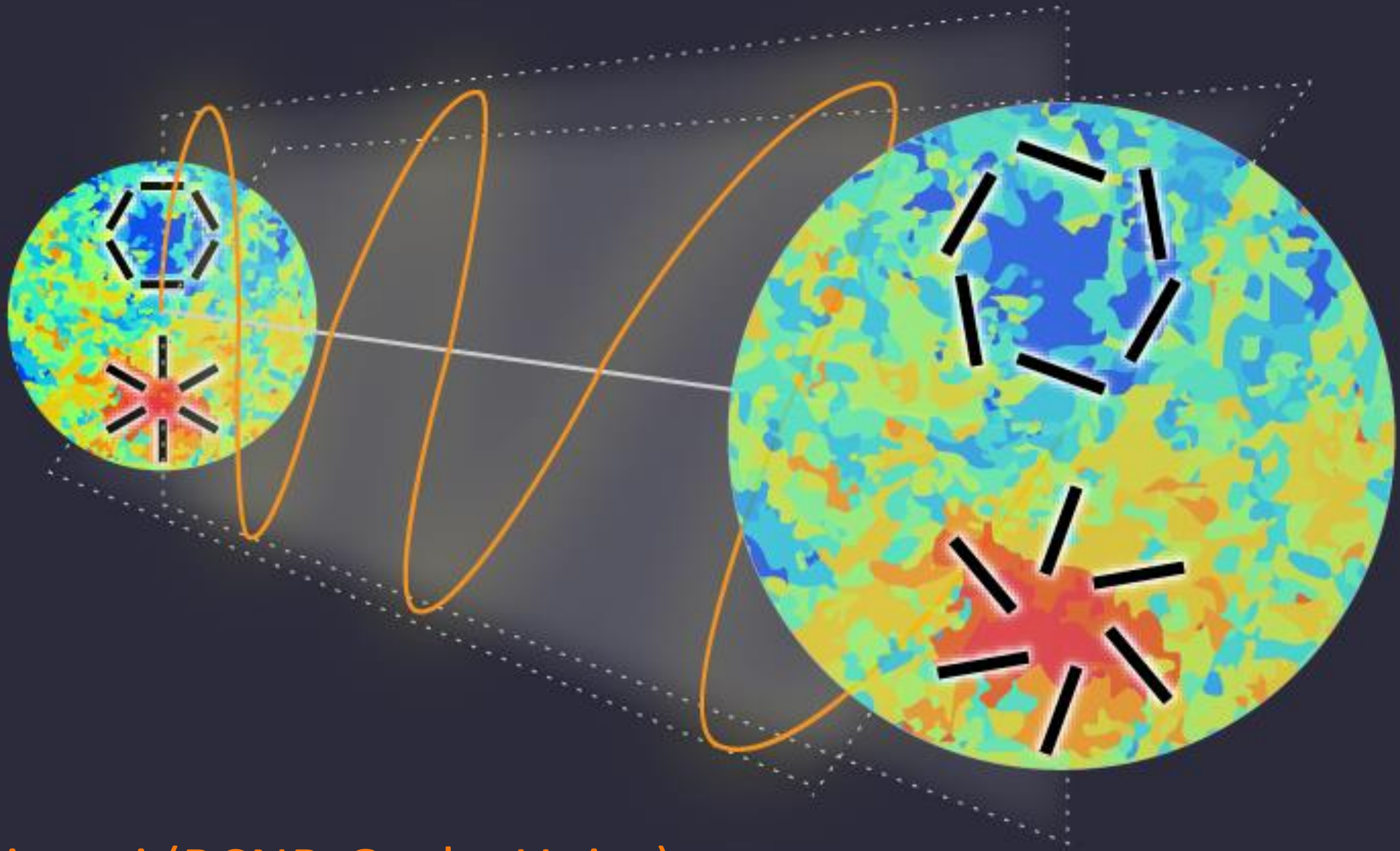
Cosmic Birefringence



Yuto Minami (RCNP, Osaka Univ.)

Cosmic Birefringence

Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998)

The Universe filled with a "birefringent material"

- If the Universe is filled with a pseudo-scalar field, ϕ,(e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

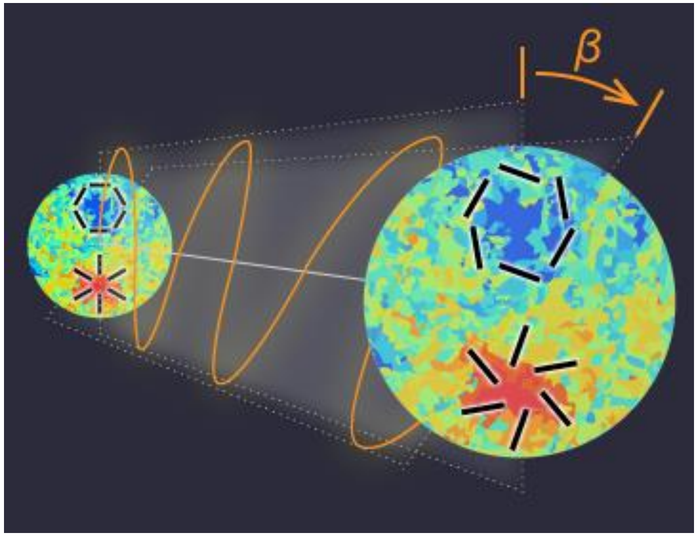
$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$

Chern-Simons term

$$\mathcal{L} \supset -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \cdots (1)$$

Turner & Widrow (1988)

$$\beta = \frac{g_{\phi\gamma}}{2}\int_{emission}^{observer} dt\,\dot{\phi} = \frac{g_{\phi\gamma}}{2}(\phi_{observer} - \phi_{emission}) \quad \cdots (2)$$



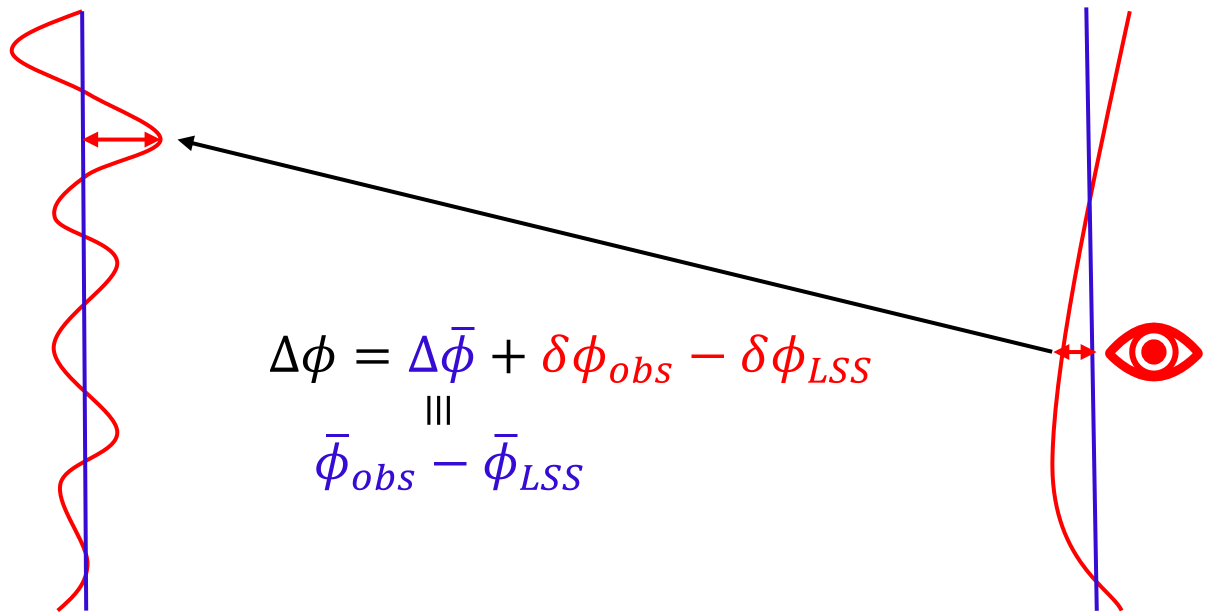
Difference of the field values rotates the linear polarization!

Cosmic Birefringence with Cosmic Microwave Background (CMB)

Fujita, Minami, Murai, &Nakatsuka (2020)

- Birefringence from background and fluctuation

Last Scattering Surface (LSS) Observer



$$\phi_{LSS}(t = t_{LSS}, d_{LSS}\hat{\boldsymbol{n}}) = \bar{\phi}_{LSS} + \delta\phi_{LSS}(\hat{\boldsymbol{n}}) \qquad \phi_{obs}(t = t_0, \boldsymbol{0}) = \bar{\phi}_{obs} + \delta\phi_{obs}$$

$$\beta(\hat{\boldsymbol{n}}) = \frac{g_{\phi\gamma}}{2}\Big(\underbrace{\Delta\bar{\phi} + \delta\phi_{obs}}_{\beta\ \text{(isotropic)}} \underbrace{- \delta\phi_{LSS}(\hat{\boldsymbol{n}})}_{A_\alpha\text{(anisotropic)}}\Big) \quad \cdots (3)$$

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Last Scattering Surface (LSS) Observer

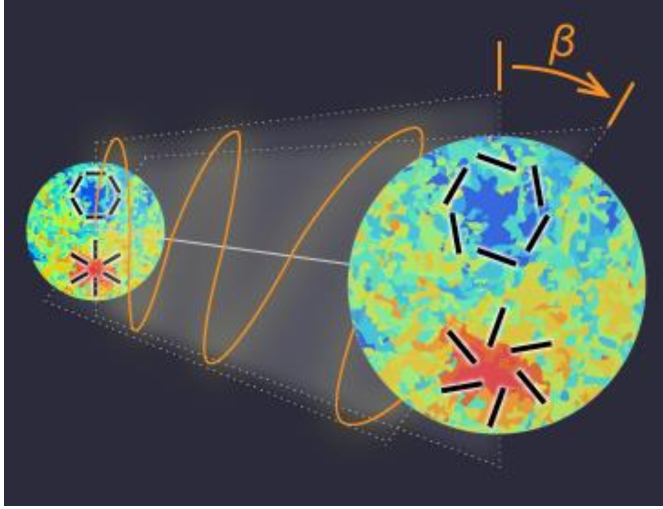
This talk only targets isotropic rotation β

$$\phi_{LSS}(t = t_{LSS}, d_{LSS}\hat{\boldsymbol{n}}) = \bar{\phi}_{LSS} + \delta\phi_{LSS} \qquad \phi_{obs}(t = t_0, \mathbf{0}) = \bar{\phi}_{obs} + \delta\phi_{obs}$$

$$\beta(\hat{\boldsymbol{n}}) = \frac{g_{\phi\gamma}}{2}\left(\underbrace{\Delta\bar{\phi} + \delta\phi_{obs}}_{\beta\ \text{(isotropic)}} - \underbrace{\delta\phi_{LSS}(\hat{\boldsymbol{n}})}_{A_\alpha\text{(anisotropic)}}\right) \quad \cdots (3)$$

EB correlation from the cosmic birefringence

Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)



- Cosmic birefringence convert E<-> B as

$$\begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}^{obs} = \begin{pmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix} \quad \cdots (4)$$

- In power spectra:

$$\langle C_\ell^{EB,obs} \rangle = \frac{1}{2} \left(\langle C_\ell^{EE} \rangle - \langle C_\ell^{BB} \rangle \right) \sin(4\beta) + \langle C_\ell^{EB} \rangle \cos(4\beta) \quad \cdots (5)$$

0

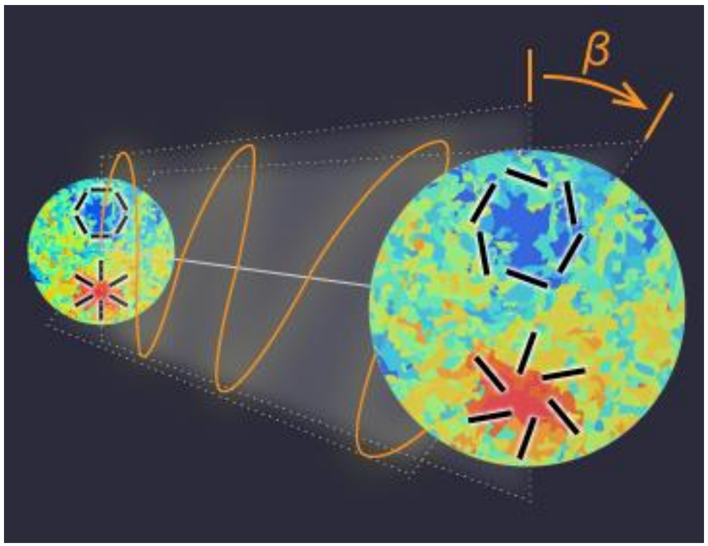
Need to assume a model!

Vanish at the LSS

- Traditionally, one would find β by fitting $C_\ell^{EE,CMB} - C_\ell^{BB,CMB}$ to the observed $C_\ell^{EB,obs}$ using the best-fitting CMB model
  - Assuming the intrinsic $\langle C_\ell^{EB} \rangle = 0$, at the last scattering surface (LSS) (justified in the standard cosmology)

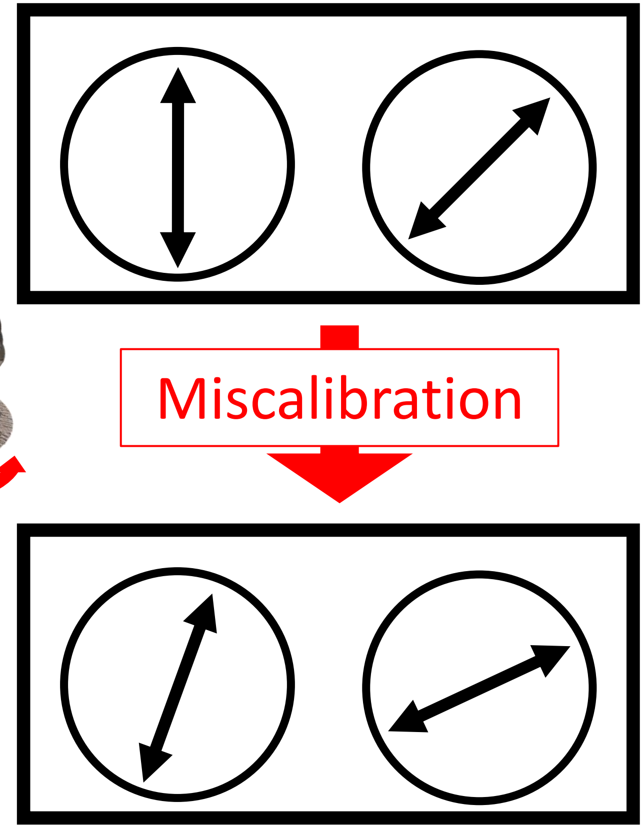
The Biggest Problem in observations: Miscalibration of detectors

Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)



OR

Polarisation-sensitive detectors on the focal plane



rotated by an angle "α"
(but we do not know it)

- Is the polarization plane rotated by the genuine cosmic birefringence, β ?
- Are the polarisation-sensitive detectors rotated by miscalibration, α, on the sky coordinate (and we did not know)?

We can only measure the sum, $\alpha + \beta$

The past measurements with the traditional way

Systematic errors on α limited the measurements

Measurement	β + stat. + sys. (deg.)
Feng et al. 2006	$-6.0 \pm 4.0 \pm$??
WMAP Collaboration, Komatsu et al. 2009; 2011	$-1.1 \pm 1.4 \pm \mathbf{1.5}$
QUaD Collaboration, Wu et al. 2009	$-0.55 \pm 0.82 \pm \mathbf{0.5}$
…	…
Planck Collaboration 2016	$0.31 \pm 0.05 \pm \mathbf{0.28}$
POLARBEAR Collaboration 2020	$-0.61 \pm 0.22 +$??
SPT Collaboration, Bianchini et al. 2020	$0.63 \pm 0.04 +$??
ACT Collaboration, Namikawa et al. 2020	$0.12 \pm 0.06 +$??
ACT Collaboration, Choi et al. 2020*	$0.09 \pm 0.09 +$??

First measurement

Uncertainty in the calibration of α has been the major limitation

*used optical model , "as-designed" angles

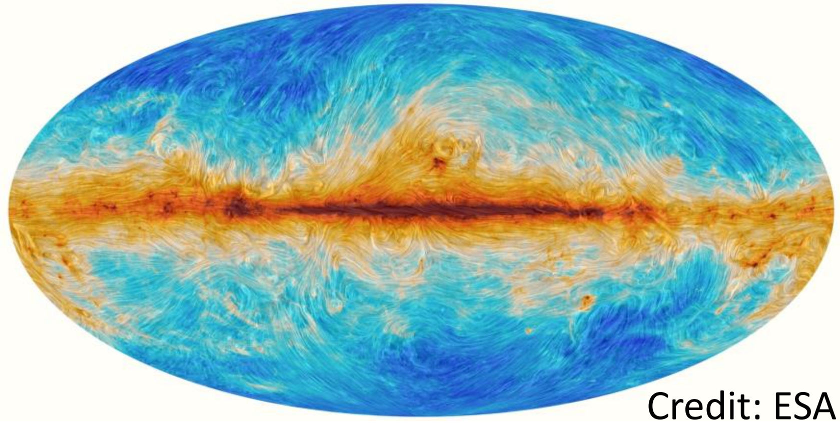
- Other way to calibrate?

Crab nebula, Tau A (Celestial source)	0.27 deg. (Aumont et al.(2018))
Wire grid (Planck / Tajima et al. (2011))	1.00 deg.? / 0.8 deg.

Simultaneous determination of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$

Minami et al. (2019); Minami (2020);Minami & Komatsu (2020a); Minami & Komatsu (2020b)

- The key idea: use the polarised Galactic foreground emission as a calibrator
  - FG is rotated by α
  - CMB is rotated by $\alpha + \beta$



Credit: ESA

$$\langle C_\ell^{EB,\mathrm{o}} \rangle = \frac{\tan(4\alpha)}{2} \left(\underbrace{\langle C_\ell^{EE,\mathrm{o}} \rangle - \langle C_\ell^{BB,\mathrm{o}} \rangle}_{\text{Measured}} \right) + \frac{\sin(4\beta)}{2\cos(4\alpha)} \left(\underbrace{\langle C_\ell^{EE,\mathrm{CMB}} \rangle - \langle C_\ell^{BB,\mathrm{CMB}} \rangle}_{\text{Known accurately}} \right) + \frac{1}{\cos(4\alpha)} \langle C_\ell^{EB,\mathrm{fg}} \rangle + \frac{\cos(4\beta)}{\cos(4\alpha)} \langle C_\ell^{EB,\mathrm{CMB}} \rangle. \quad \cdots (6)$$

- When we ignore the intrinsic EB correlations of the FG and the CMB, we can determine both $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$
  - The latter is justified but the former is not
- Using Planck PR3 data, **$\boldsymbol{\beta}$ = 0.35 ± 0.14 [Minami & Komatsu 2020b]**
  - **$\boldsymbol{\beta}$ > 0 at 99.2%C.L. (2.4σ)**

How about the foreground $\boldsymbol{EB}$?

Minami et al. (2019); Minami (2020);Minami & Komatsu (2020b)

If the intrinsic foreground (FG) *EB* exists, our method interprets it as a miscalibration angle $\boldsymbol{\alpha}$

- Thus, $\alpha \to \alpha + \gamma$, where γ is the parameter of the intrinsic EB
  - The sign of γ is the same as the sign of the foreground EB
- We thus can determine:

FG: $\alpha + \gamma$

CMB: $\alpha + \beta$

$$\boldsymbol{\beta - \gamma = 0.35 \pm 0.14}\ \textbf{deg.}$$

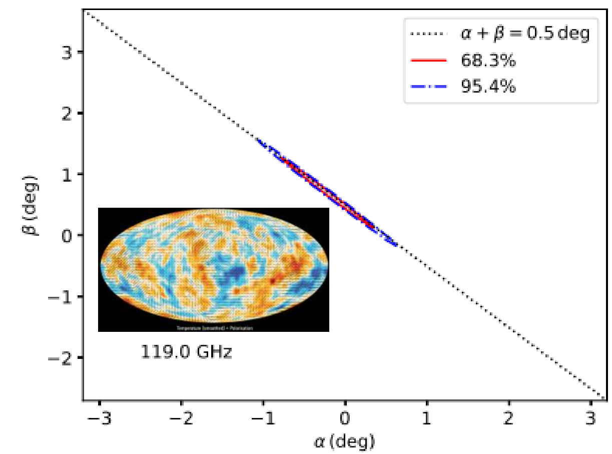
- There is evidence for the dust-induced $TE_{dust} > 0$ & $TB_{dust} > 0$; then, we'd expect $EB_{dust} > 0$ [Huffenberger et al.], i.e., $\gamma > 0$. If so, β increased further…
  - We can give a lower bound on β

We would be happy if CMB-S4 can test this

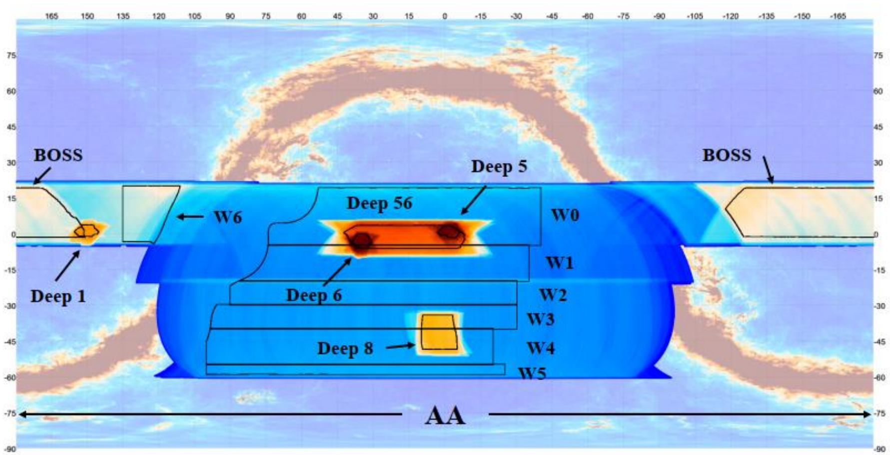
With CMB channels

Minami et al. (2019); Minami (2020)

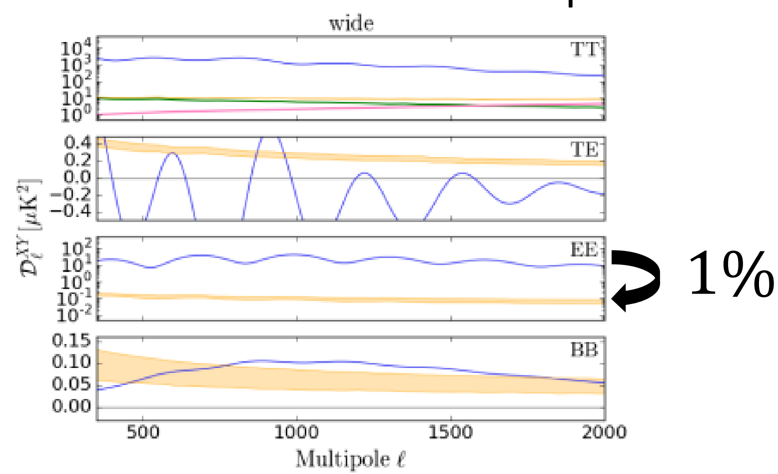
- At least, we need to observe bright FG region
  - FG is needed to determine α
- Most of the ground based experiments didn't observe foreground dominated regions
  - lose sensitivity



Demonstration with a LiteBIRD like experiment



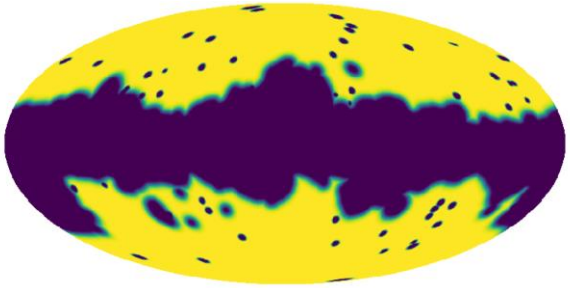
ACT DR4 coverage [Choi et.al (2020)]



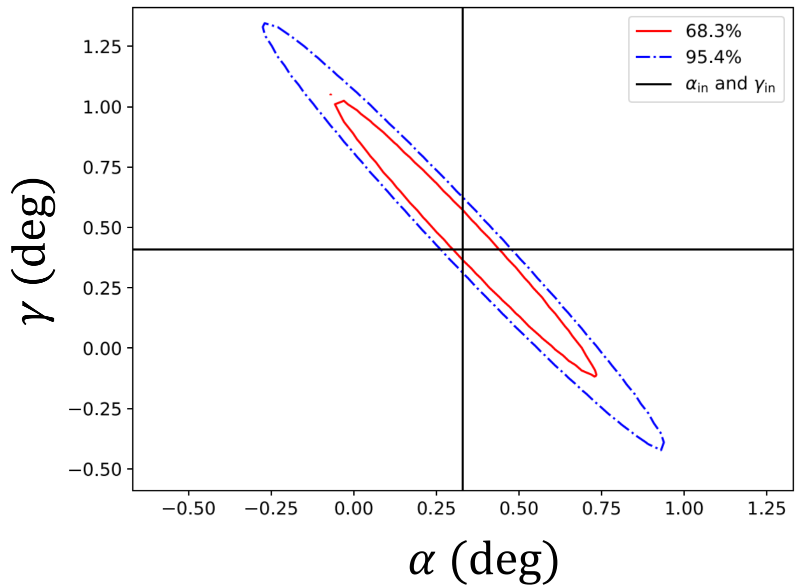
Foreground level (band) and CMB power spectra [Choi et.al (2020)]

With FG-dominated channels

- We can use strong foreground signal even with Galactic mask
  - We can determine β
- Assuming Simons Observatory Large Aperture Telescope's 280 GHz channel
  - α and γ are well determined



Planck's LR42 mask
(fsky~0.4)

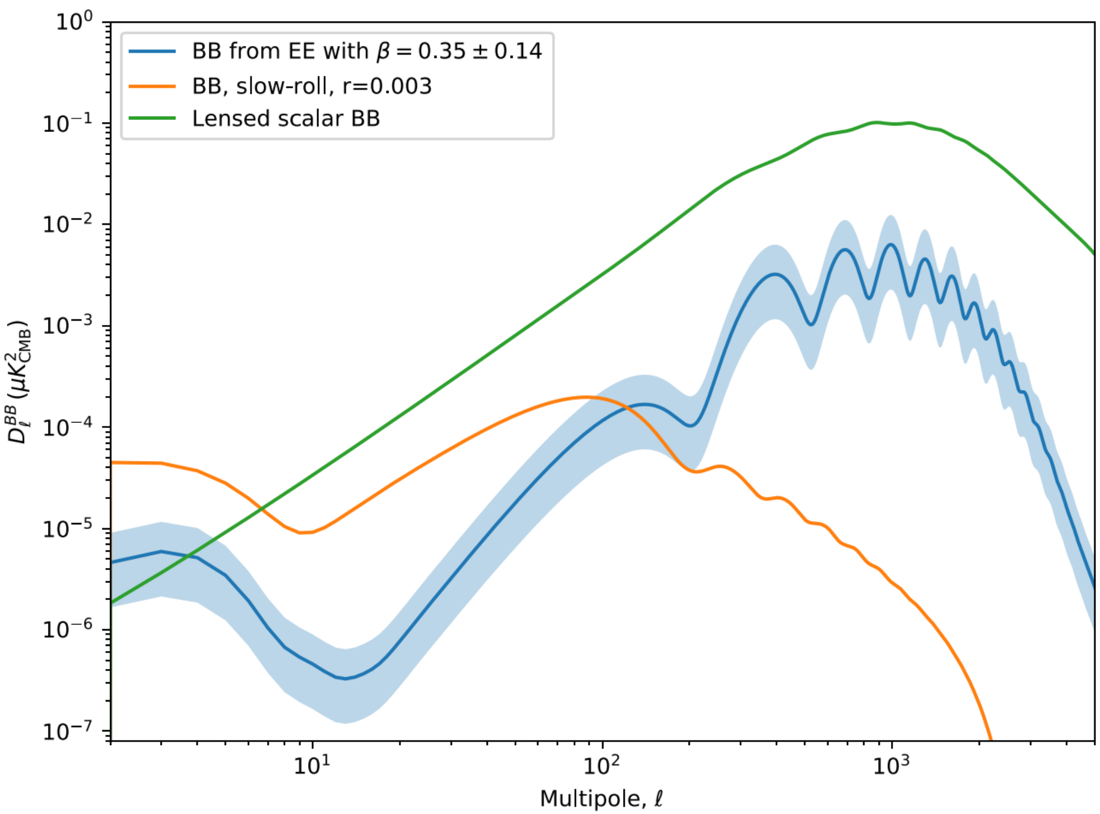


Summary

- Cosmic birefringence: difference of field values with Chern-Simons coupling rotates linear polarization of the CMB photons
  - $\beta = \frac{g_{\phi\gamma}}{2}(\phi_{obs} - \phi_{LSS})$
- Calibration uncertainty on detector rotation α has limited the measurements of β
- When we use the Galactic foreground as a calibrator, we can determine α and β simultaneously
  - $\beta = 0.35 \pm 0.14$
- The measurements with CMB-S4 are highly expected
  - Reducing calibration uncertainty with the ground calibrator
  - Observing FG-dominated regions and channels

Bonus:

➢ Does β = 0.35 ± 0.14 deg. disturb the measurement of primordial *B*-mode?



Backups