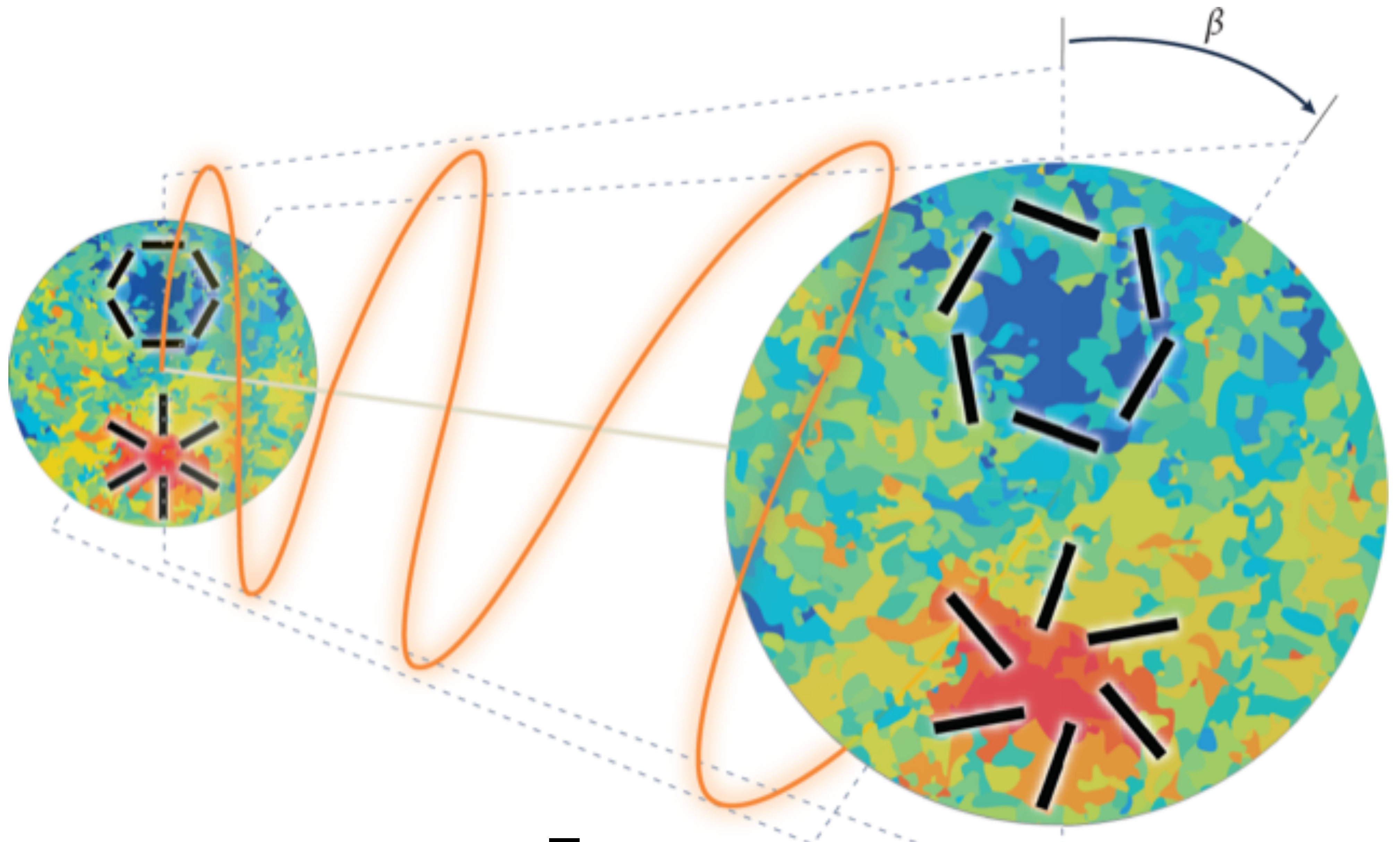
$$I_{\mathrm{CS}} = \int \mathrm{d}^4x \sqrt{-g}\left(-\frac{\alpha}{4f}\chi F\tilde{F}\right)$$



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Parity Violation in Cosmology

In search of new physics for the Universe

The lecture slides are available at
https://wwwmpa.mpa-garching.mpg.de/~komatsu/lectures--reviews.html

Day 7

Eiichiro Komatsu (Max Planck Institute for Astrophysics)

Nagoya University, June 6–30, 2023

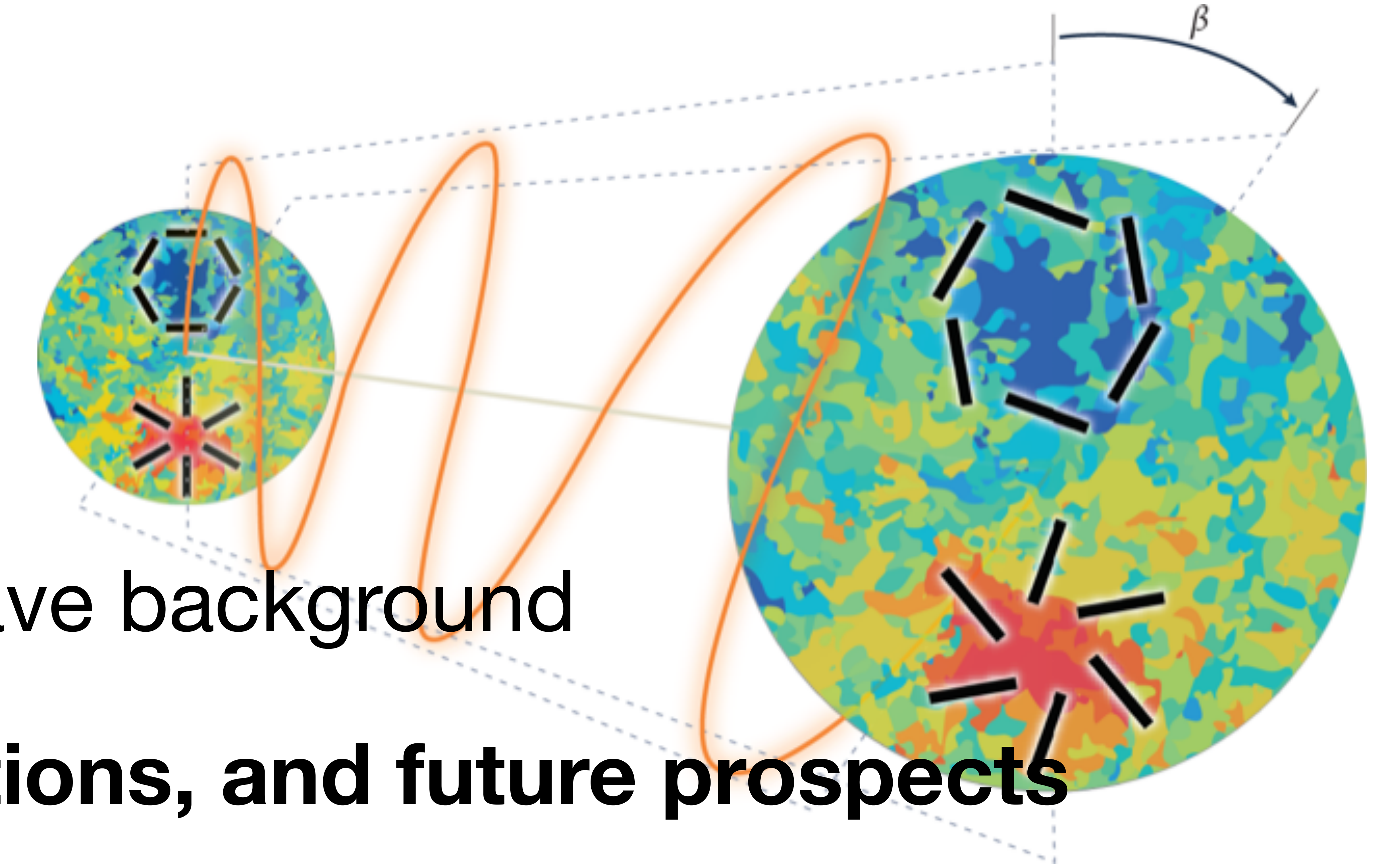
Topics

From the syllabus

1. What is parity symmetry?
2. Chern-Simons interaction
3. Parity violation 1: Cosmic inflation
4. Parity violation 2: Dark matter
5. Parity violation 3: Dark energy
6. Light propagation: birefringence
7. Physics of polarization of the cosmic microwave background

8. Recent observational results, their implications, and future prospects

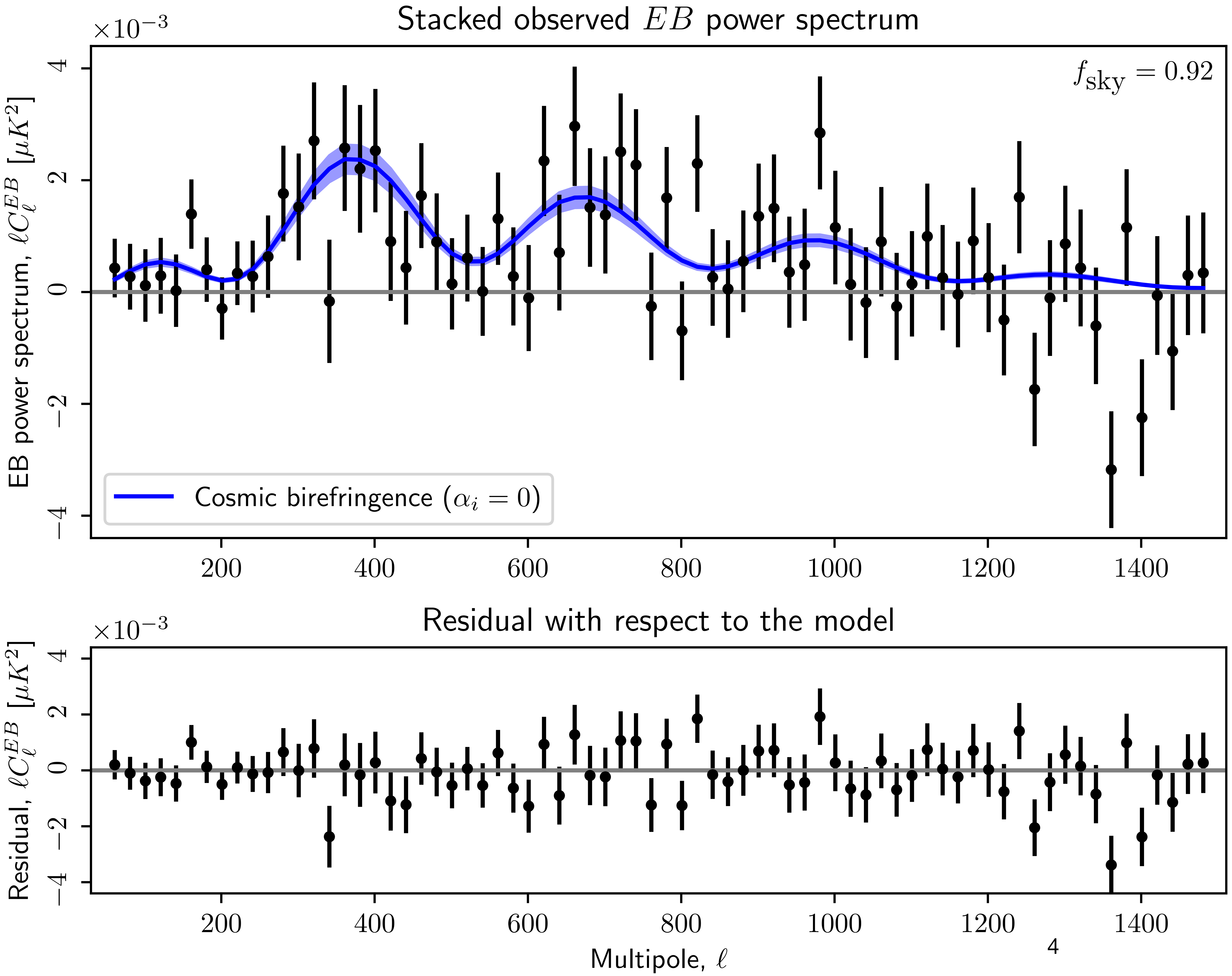
$$I_{\rm CS} = \int \mathrm{d}^4x \sqrt{-g} \left(-\frac{\alpha}{4f} \chi F \tilde{F} \right)$$

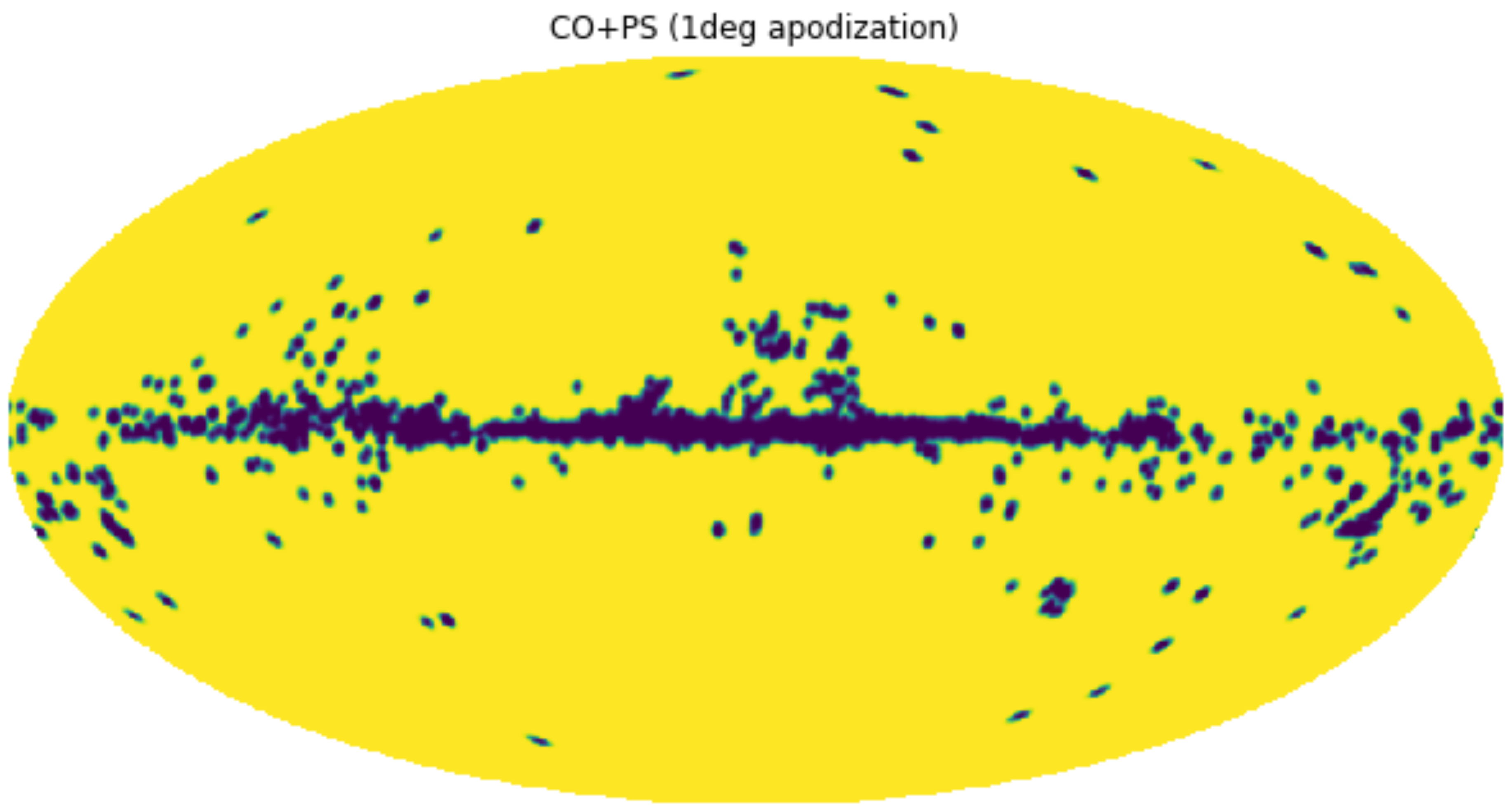


8.1 Possible sources of the observed EB power spectrum

Cosmic Birefringence fits well(?)

Nearly full-sky data (92% of the sky)

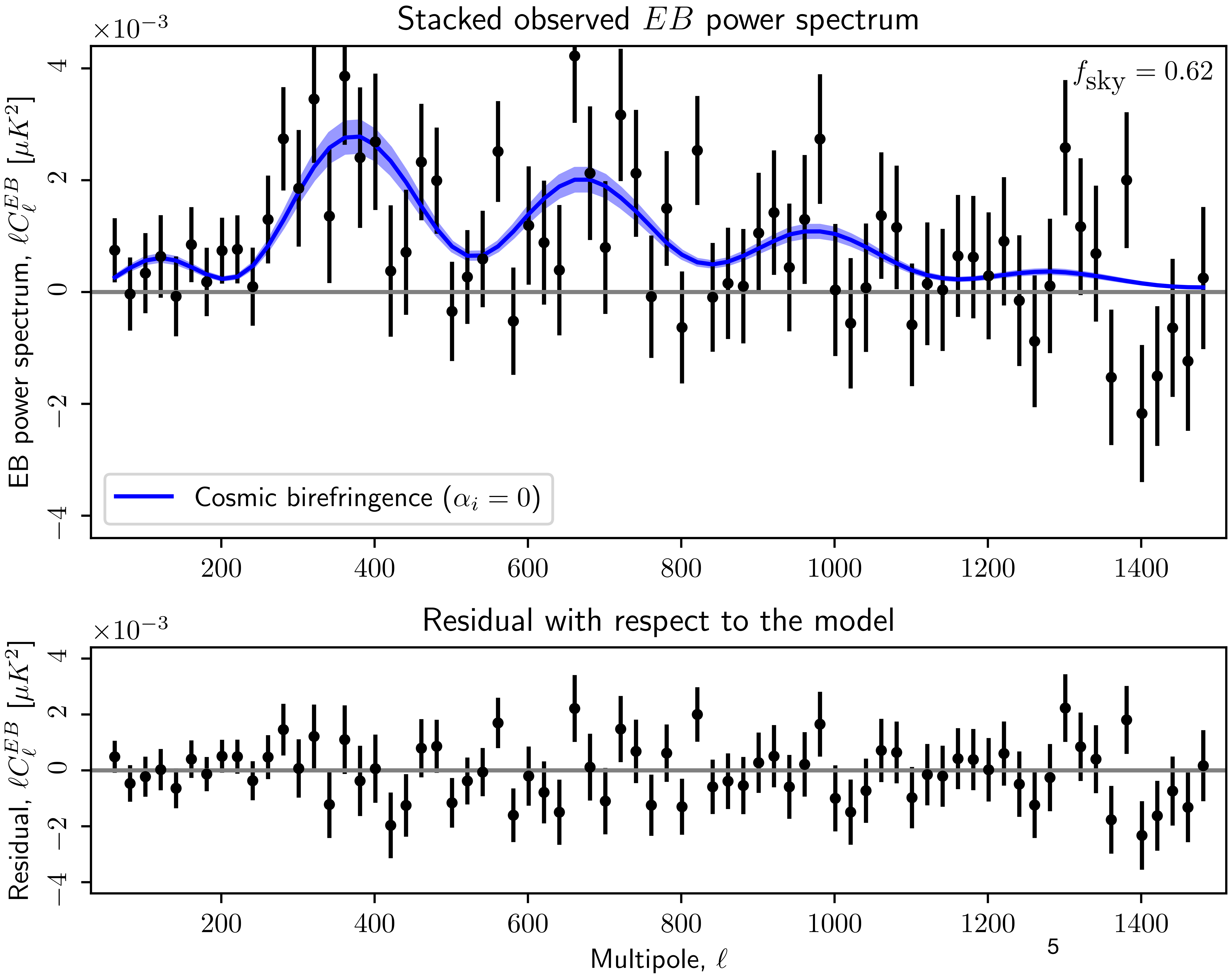


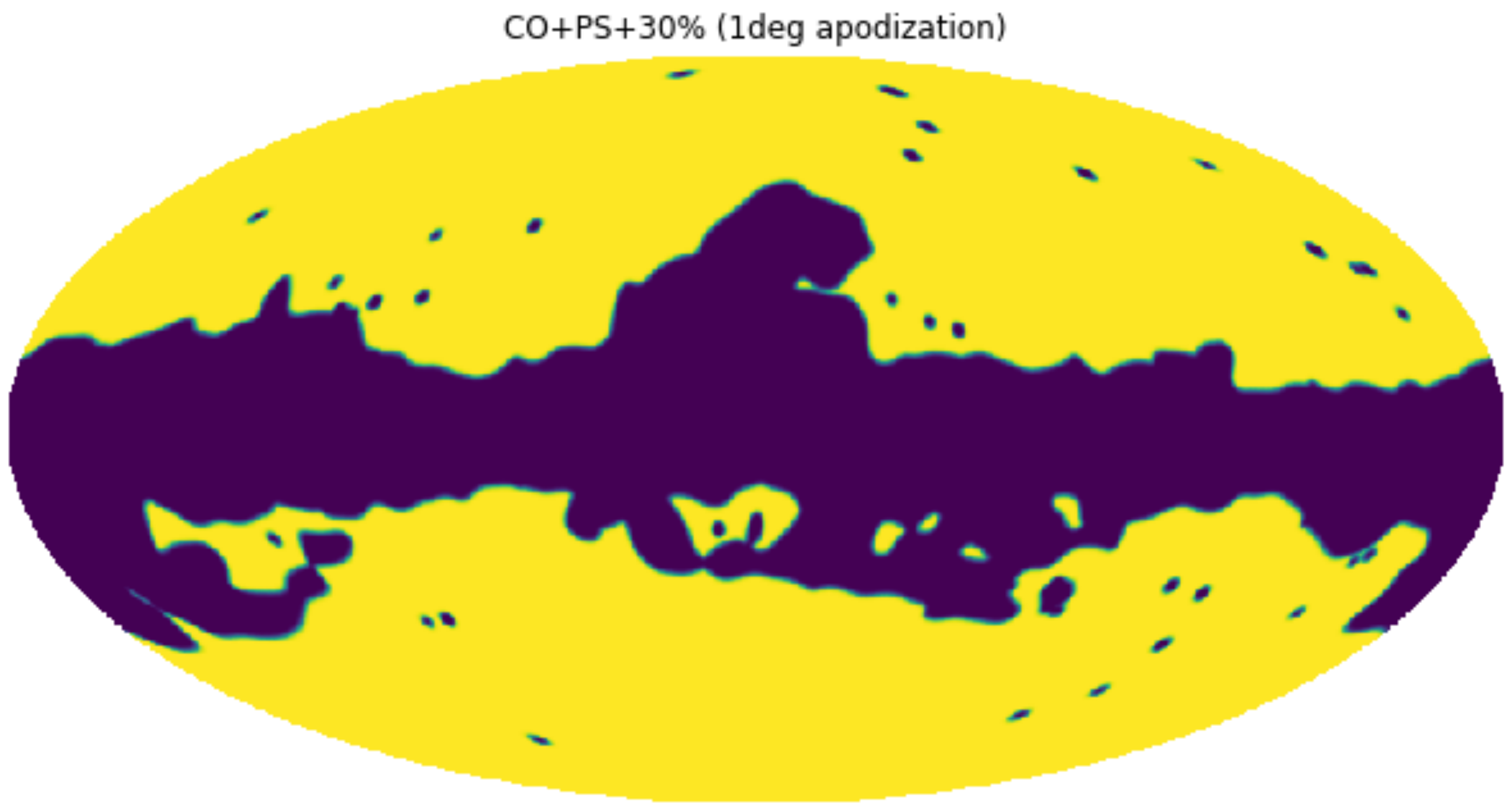


- $\beta = 0.288 \pm 0.032$ deg
- $\chi^2 = 66.1$
  - Good fit! 9σ detection?

Cosmic Birefringence fits well(?)

Galactic plane removed (62% of the sky)





- β = 0.330 ± 0.035 deg
- χ^2 = 64.5
- Signal is robust with respect to the Galactic mask.

The Biggest Problem: Miscalibration of detectors

Wu et al. (2009); Miller, Shimon, Keating (2009); EK et al. (2011)

Impact of miscalibration of polarization angles

Cosmic or Instrumental?

- Is the plane of linear polarization rotated by the genuine cosmic birefringence effect, or simply because the polarization-sensitive directions of the detectors are rotated with respect to the sky coordinates (and we did not know it)?

- If the detectors are rotated by α, it seems that we can measure only the **sum α+β**.

The past measurements

The quoted uncertainties are all statistical only (68%CL)

- $\alpha+\beta = -6.0 \pm 4.0$ deg (Feng et al. 2006) first measurement
- $\alpha+\beta = -1.1 \pm 1.4$ deg (WMAP Collaboration, EK et al. 2009; 2011)
- $\alpha+\beta = 0.55 \pm 0.82$ deg (QUaD Collaboration, Wu et al. 2009)
- …
- $\alpha+\beta = 0.31 \pm 0.05$ deg (Planck Collaboration 2016)
- $\alpha+\beta = -0.61 \pm 0.22$ deg (POLARBEAR Collaboration 2020)
- $\alpha+\beta = 0.63 \pm 0.04$ deg (SPT Collaboration, Bianchini et al. 2020)
- $\alpha+\beta = 0.12 \pm 0.06$ deg (ACT Collaboration, Namikawa et al. 2020)
- $\alpha+\beta = 0.07 \pm 0.09$ deg (ACT Collaboration, Choi et al. 2020)

Why not yet discovered?

The past measurements

Now including the estimated systematic errors on α

- β = –6.0 ± 4.0 ± **??** deg (Feng et al. 2006)
- β = –1.1 ± 1.4 ± **1.5** deg (WMAP Collaboration, EK et al. 2009; 2011)
- β = 0.55 ± 0.82 ± **0.5** deg (QUaD Collaboration, Wu et al. 2009)
- …
- β = 0.31 ± 0.05 ± **0.28** deg (Planck Collaboration 2016)
- β = –0.61 ± 0.22 ± **??** deg (POLARBEAR Collaboration 2020)
- β = 0.63 ± 0.04 ± **??** deg (SPT Collaboration, Bianchini et al. 2020)
- β = 0.12 ± 0.06 ± **??** deg (ACT Collaboration, Namikawa et al. 2020)
- β = 0.07 ± 0.09 ± **??** deg (ACT Collaboration, Choi et al. 2020)

Uncertainty in the calibration of α has been the major limitation

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

The Key Idea: The polarized Galactic foreground emission as a calibrator

ESA's Planck

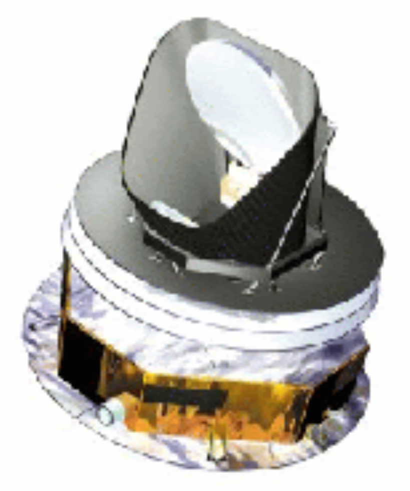
Credit: ESA

Polarized dust emission within our Milky Way!

$$\beta = +\frac{\alpha}{2f}\left[\chi(\tau_{\rm obs}) - \chi(\tau_{\rm em})\right]$$

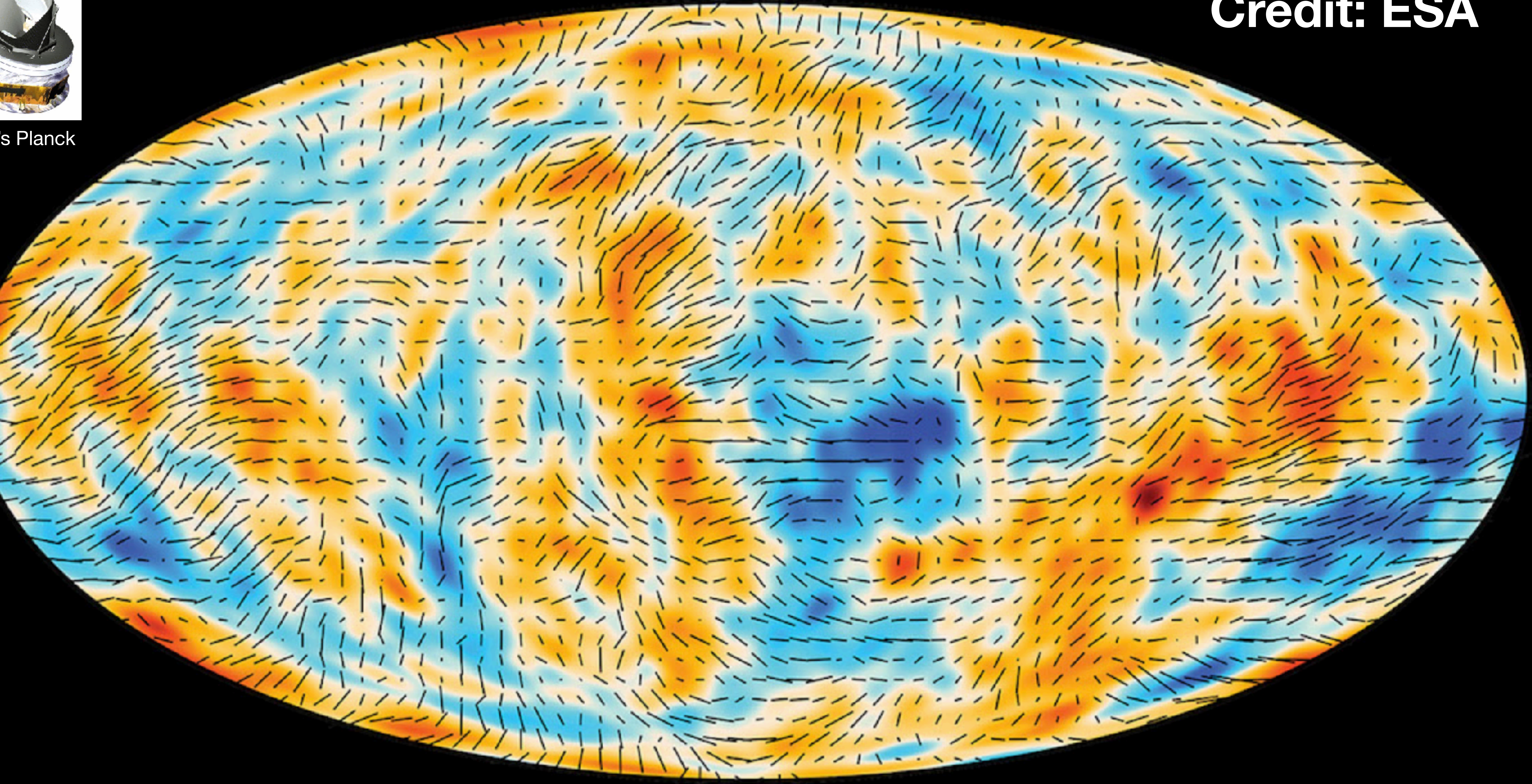
Emitted “right there” - it would not be affected by the cosmic birefringence.

Directions of the magnetic field inferred from polarization of the thermal dust emission in the Milky Way



ESA's Planck

Credit: ESA

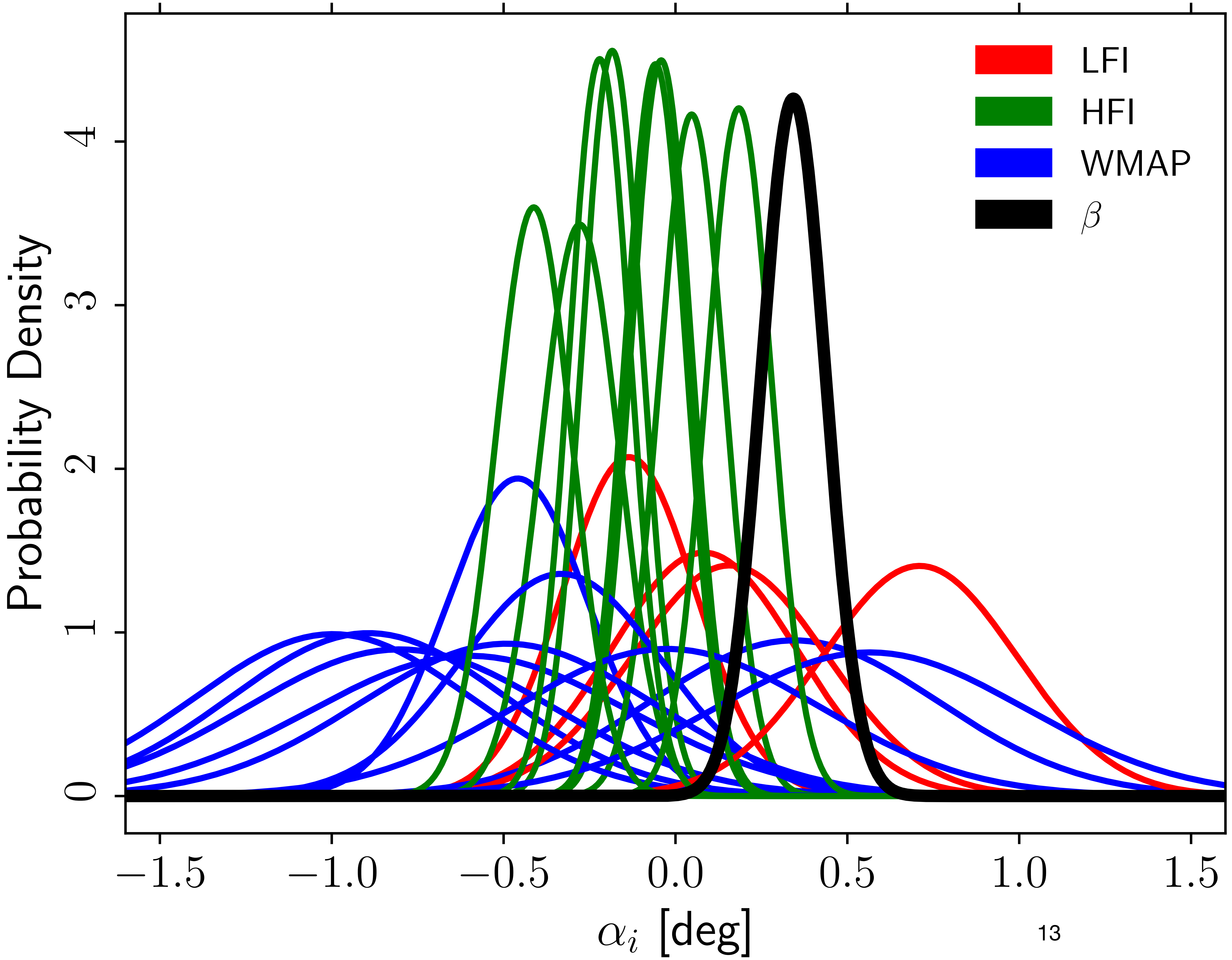


Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

Miscalibration angles (WMAP and Planck)

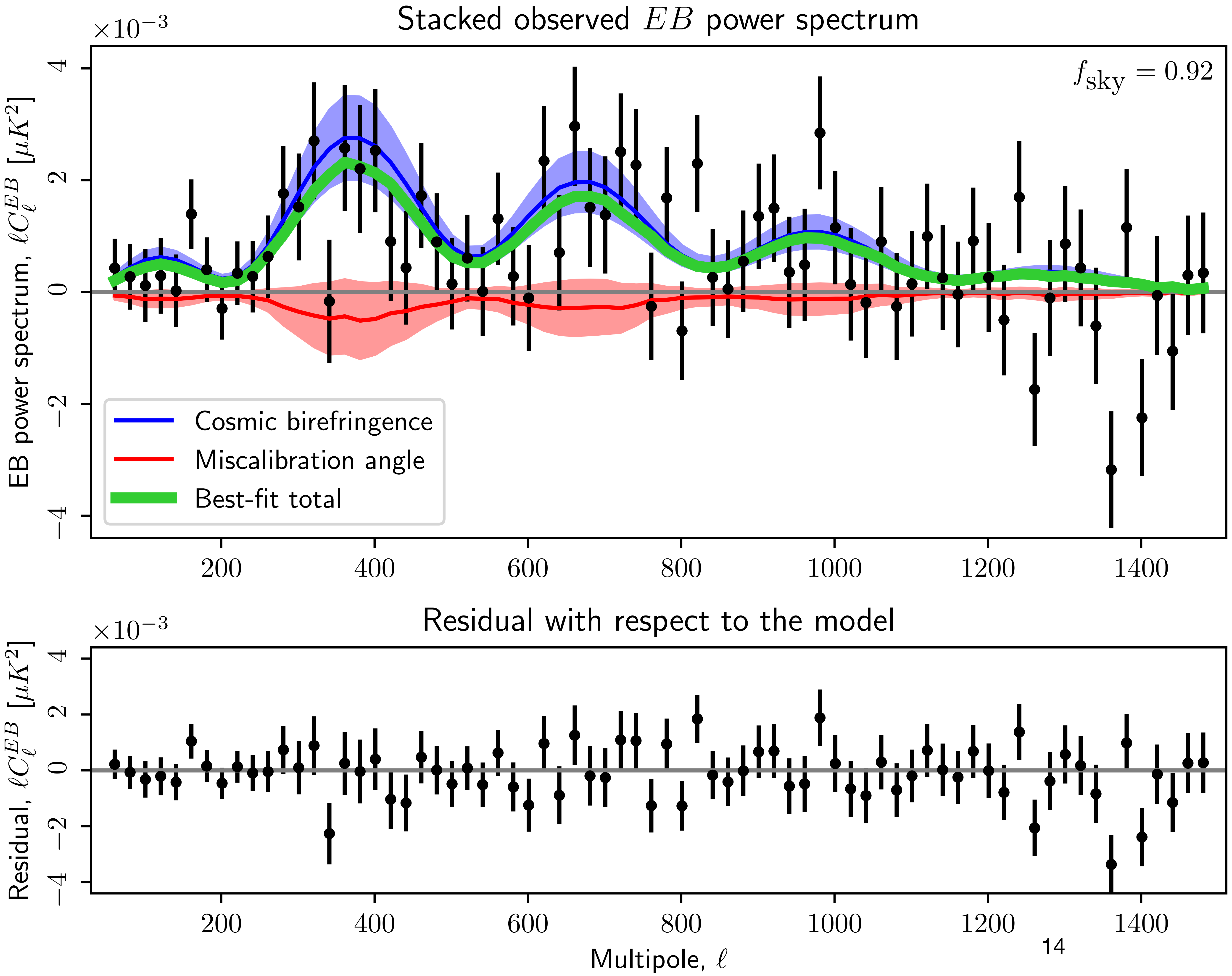
Nearly full-sky data (92% of the sky)

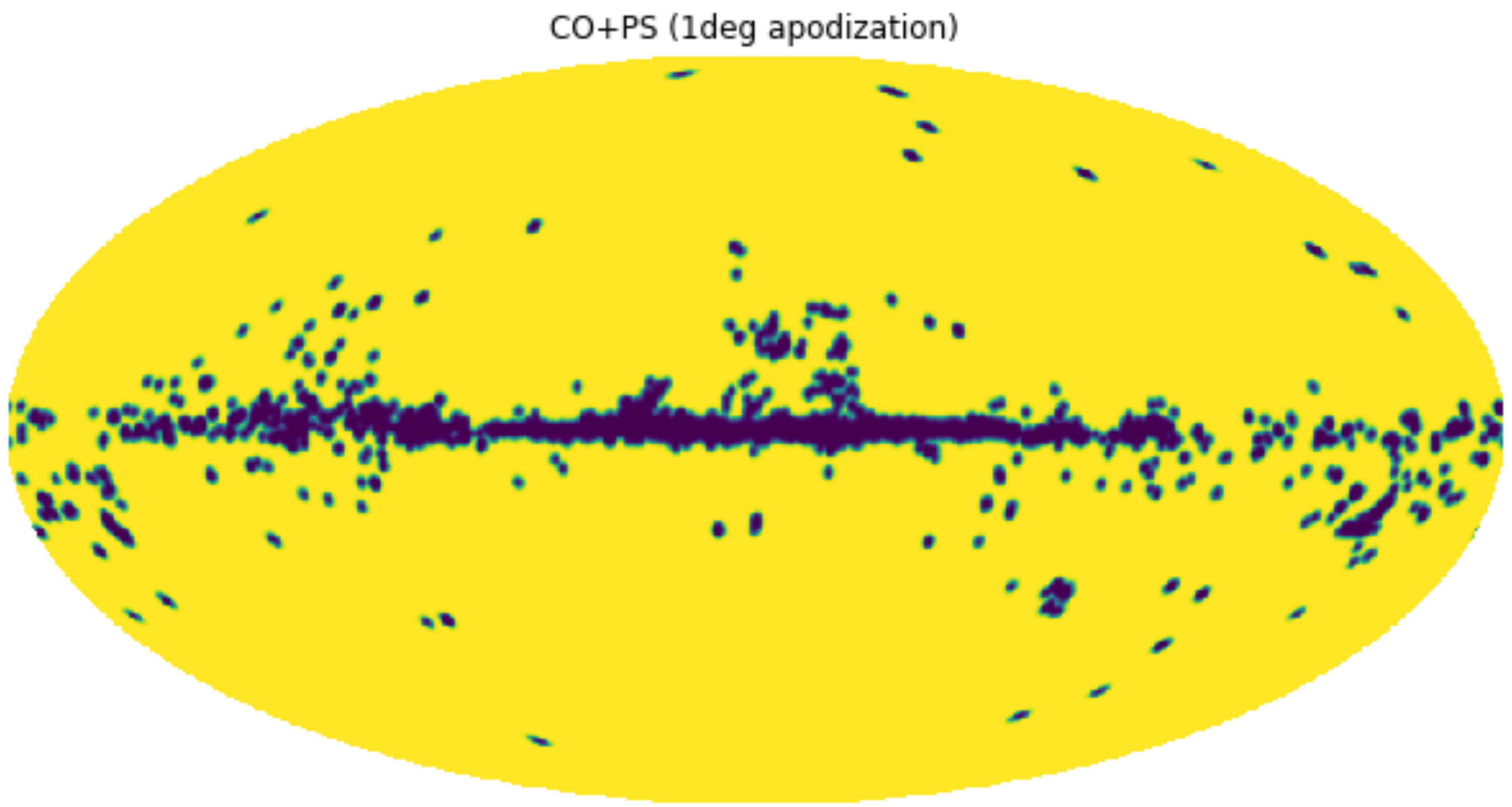


- The angles are all over the place, and are well within the quoted calibration uncertainty of instruments.
  - 1.5 deg for WMAP
  - 1 deg for Planck
- They cancel!
  - The power of adding independent datasets.

Cosmic Birefringence fits well (WMAP+Planck)

Nearly full-sky data (92% of the sky)



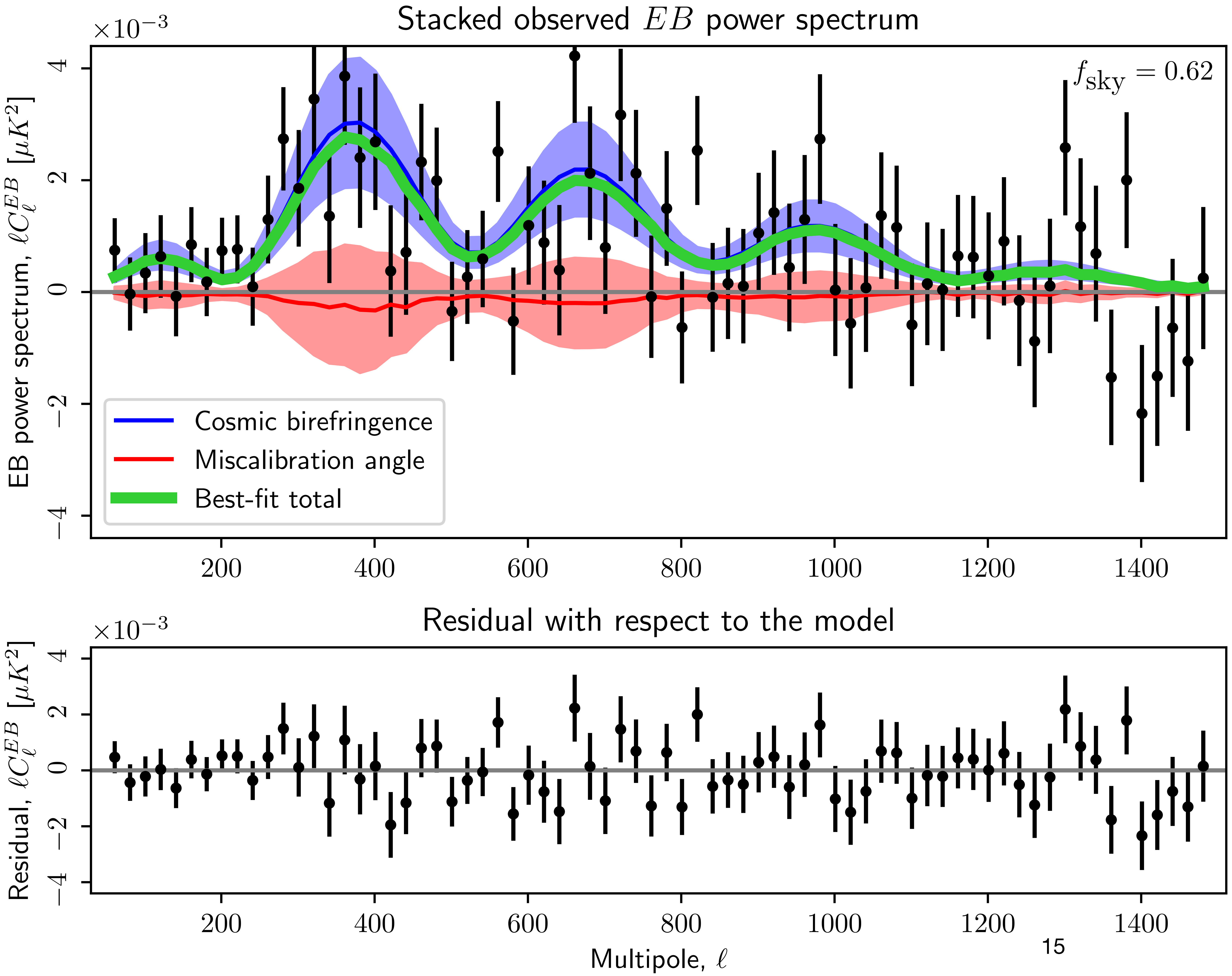


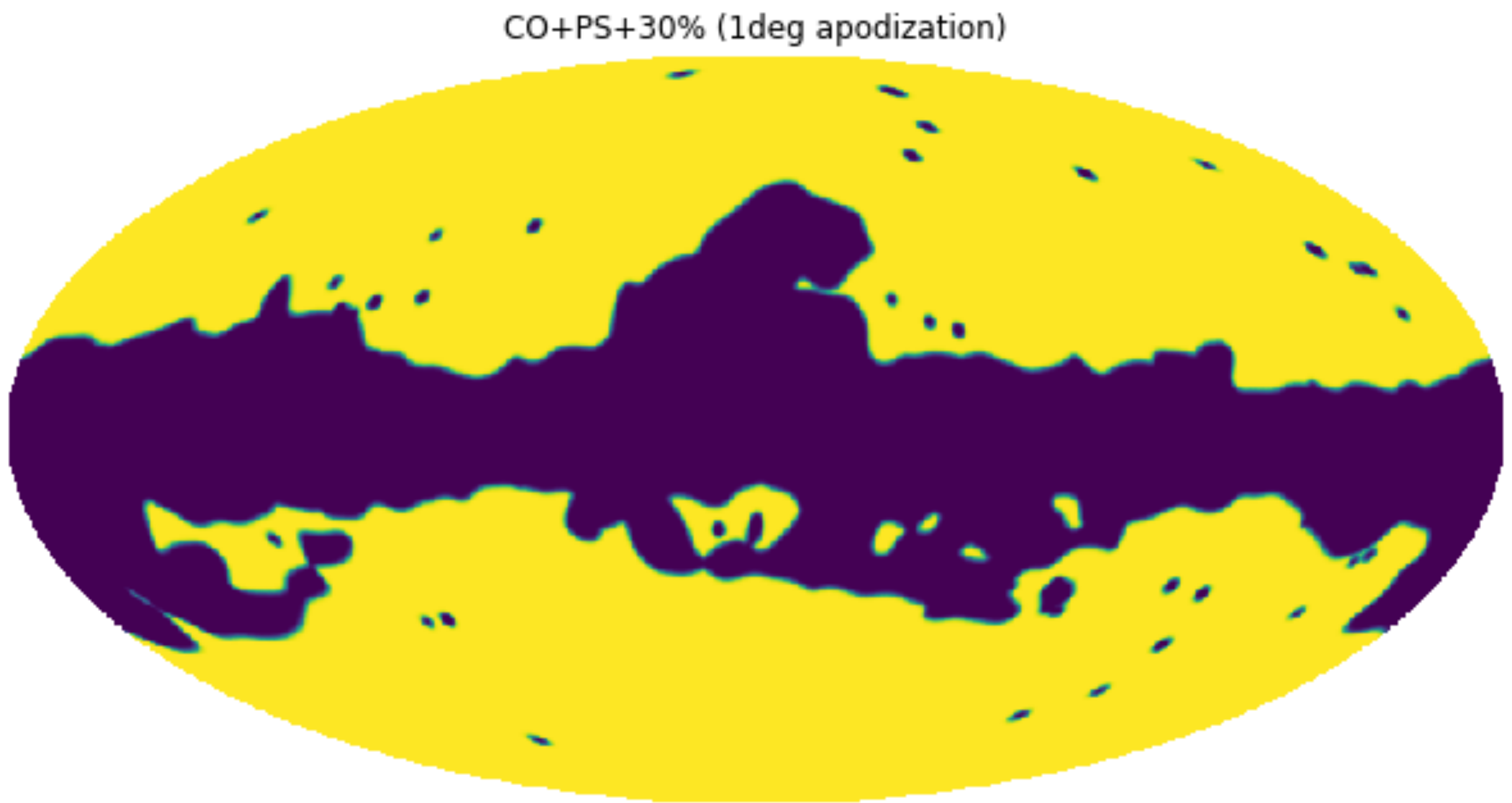
- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.34 ± 0.09 deg**
- χ^2 = 65.3 for DOF=72

Minami, EK (2020); Diego-Palazuelos et al. (2022); Eskilt, EK (2022)

Cosmic Birefringence fits well (WMAP+Planck)

Robust against the Galactic mask (62% of the sky)

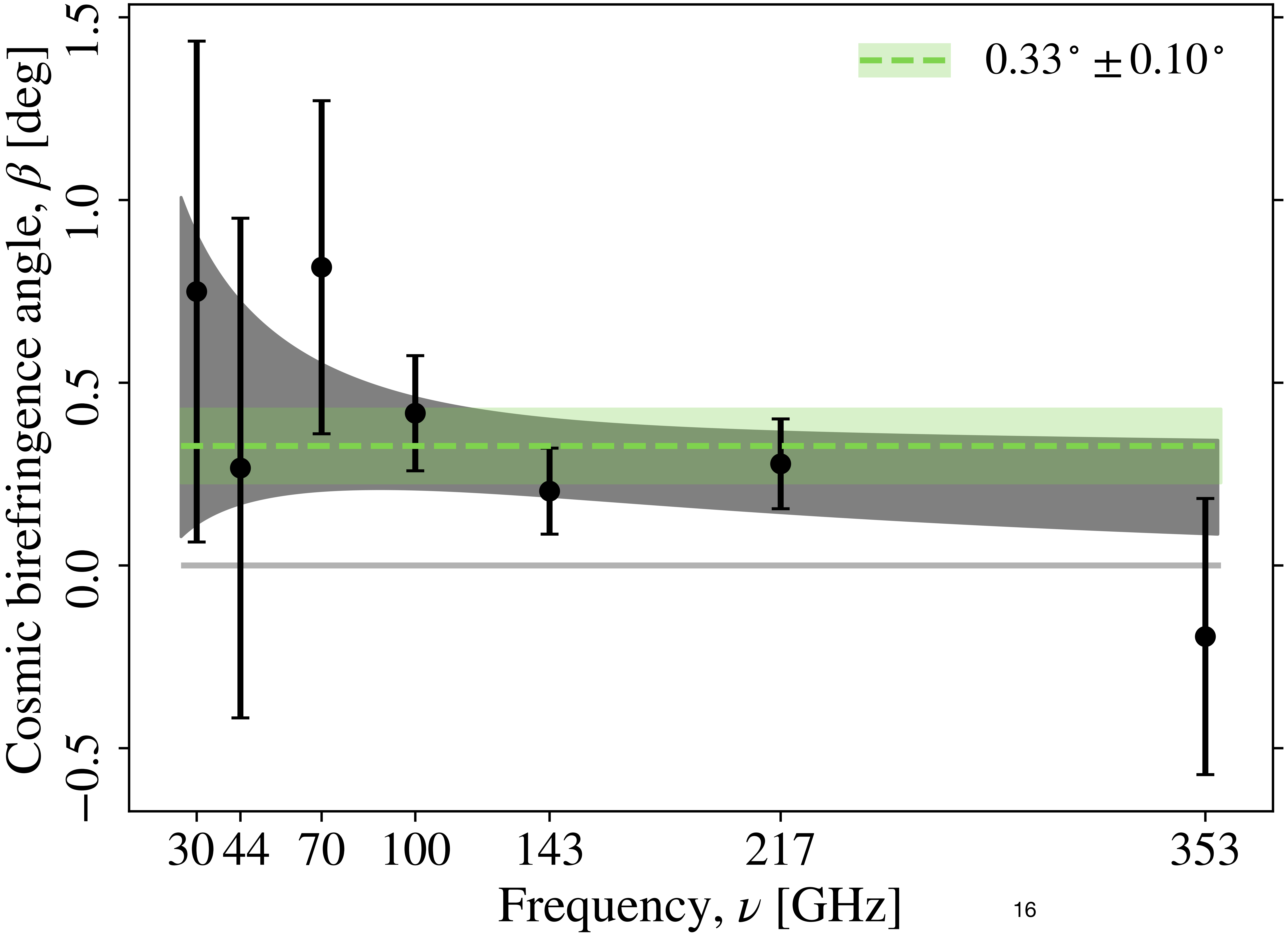




- **Miscalibration angles** make only small contributions thanks to the cancellation.
- **β = 0.37 ± 0.14 deg**
- χ^2 = 65.8 for DOF=72

No frequency dependence is found

Consistent with the expectation from cosmic birefringence



- Light traveling in a uniform magnetic field also experiences a rotation of the plane of linear polarization, called "**Faraday rotation**". However, the rotation angle depends on the frequency, as $\beta(\nu) \propto \nu^{-2}$.
- No evidence for frequency dependence is found!
  - For $\beta \propto \nu^n$, $n = -0.20^{+0.41}_{-0.39}$ (68% CL)
  - **Faraday rotation ($n = -2$) is disfavoured.**

Diego-Palazuelos et al. (2022, 2023); Eskilt et al., arXiv:2305.02268

Is β caused by non-cosmological effects?

We need to measure it in independent experiments.

- The **known** instrumental effects of the WMAP and Planck missions are shown to have negligible effects on β.
  - However, we can never rule out **unknown** instrumental effects… We need to measure β in independent experiments.
- The polarized Galactic foreground emission was used to calibrate the instrumental polarization angles, α. The intrinsic EB correlations of the Galactic foreground emission (**polarized dust and synchrotron emission**) could affect the results.
  - We need to measure β without relying on the foreground by calibrating α well, e.g., Cornelison et al. (BICEP3 Collaboration), arXiv:2207.14796.

Problem Set 7

Parity transformation of Fourier coefficients

- Show that the coefficients of the Fourier transform of a real function, $f^*(\mathbf{x}) = f(\mathbf{x})$, where * denotes its complex conjugate, satisfy

$$f^*_{\mathbf{k}} = f_{-\mathbf{k}}$$

Hint:
$$f_{\mathbf{k}} = \int d^3\mathbf{x}\ f(\mathbf{x}) e^{-i\mathbf{k}\cdot\mathbf{x}}$$

- Under parity transformation, $\mathbf{x} \to \mathbf{x}' = -\mathbf{x}$, show that the Fourier coefficients are transformed as

$$f_{\mathbf{k}} \to f_{\mathbf{k}'} = f_{-\mathbf{k}}$$

Hint:
$$f(\mathbf{x}) = \int \frac{d^3\mathbf{k}}{(2\pi)^3}\ f_{\mathbf{k}}\ e^{i\mathbf{k}\cdot\mathbf{x}}$$

8.2 Is cosmic birefringence due to dark matter or dark energy?

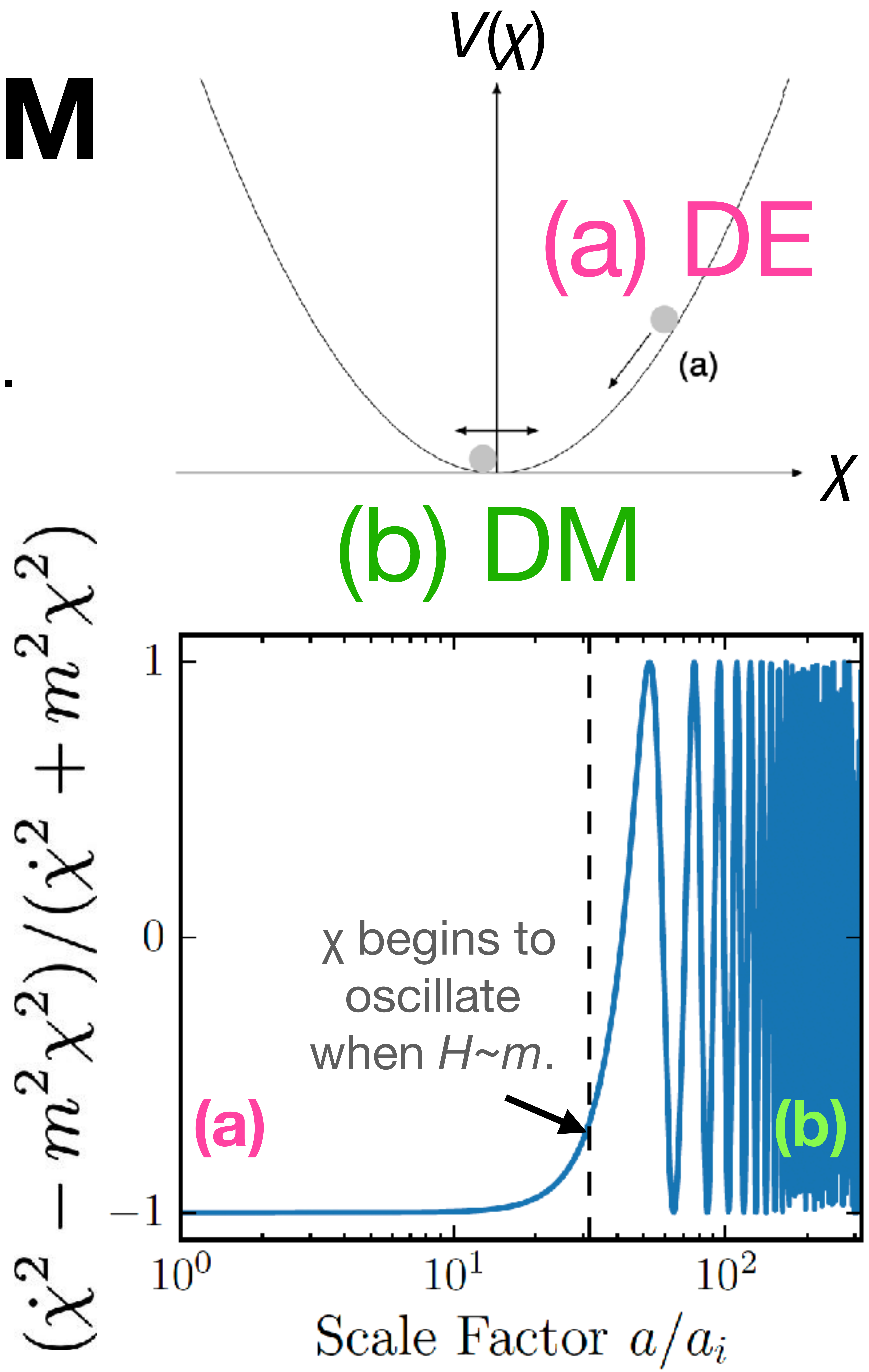
Distinction between DE and DM

How small is its mass?

- The useful criterion is the equation of state parameter, *w*.

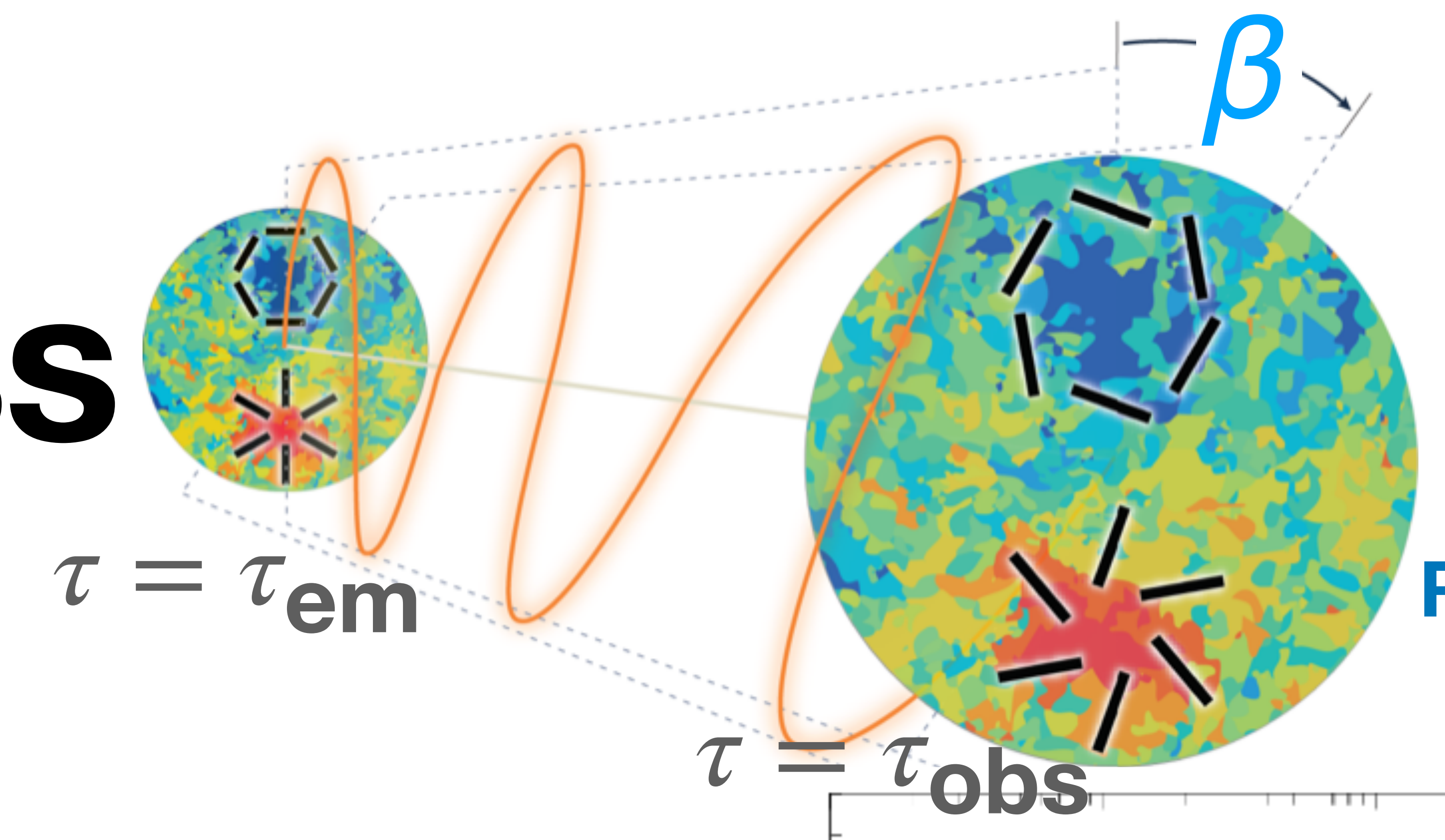
$$w = \frac{P}{\rho} = \frac{\langle \dot{\chi}^2 \rangle - m^2 \langle \chi^2 \rangle}{\langle \dot{\chi}^2 \rangle + m^2 \langle \chi^2 \rangle}$$

- $w \simeq -1$: Dark Energy (DE)
  - $m \lesssim H_0 \simeq 10^{-33}$ eV
- $w \simeq 0$: Dark Matter (DM)
  - $m \gtrsim H_0$



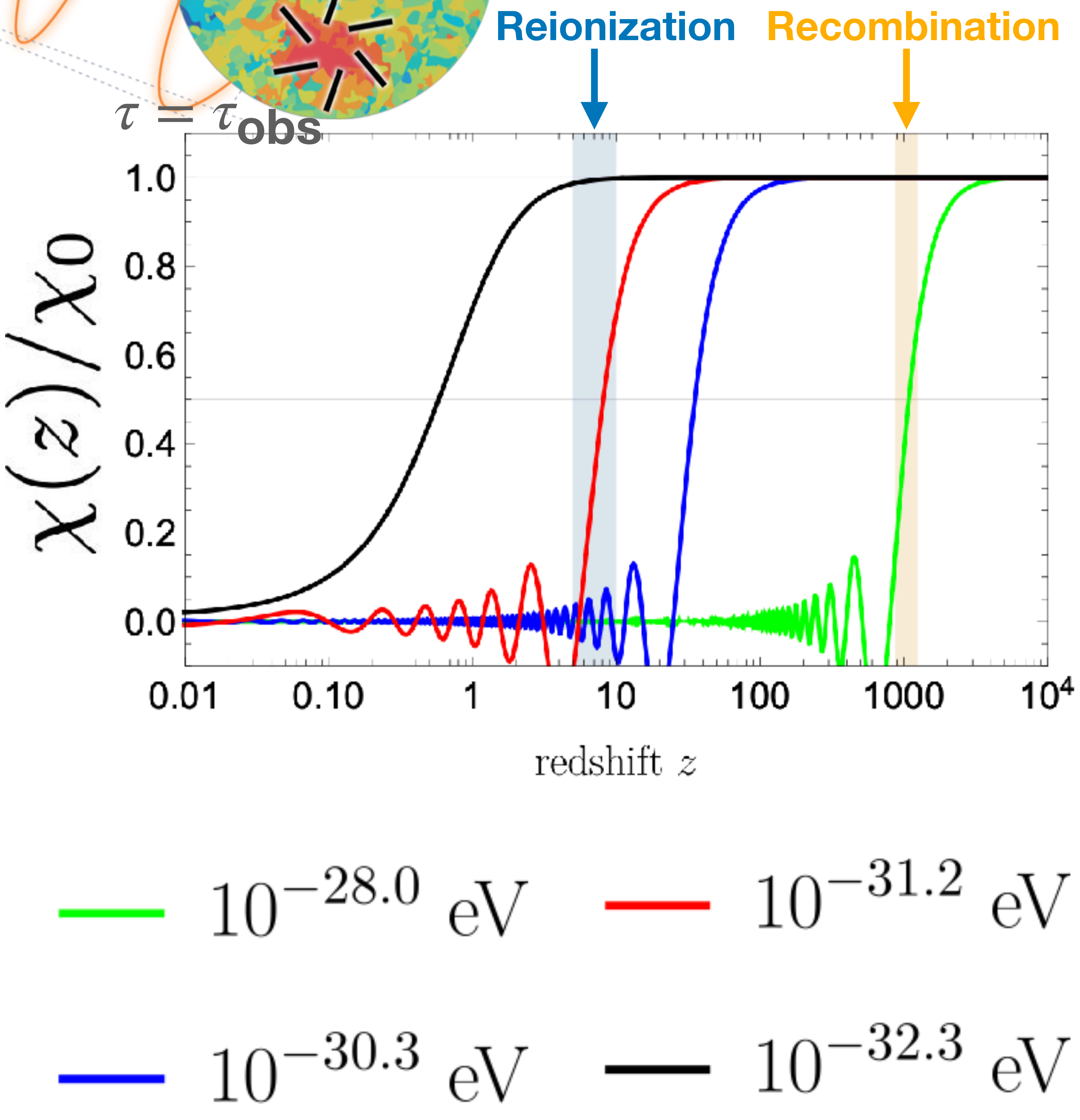
Nakatsuka, Namikawa, EK (2022)

How to measure mass



$$\beta = +\frac{\alpha}{2f}\left[\chi(\tau_{\text{obs}}) - \chi(\tau_{\text{em}})\right]$$

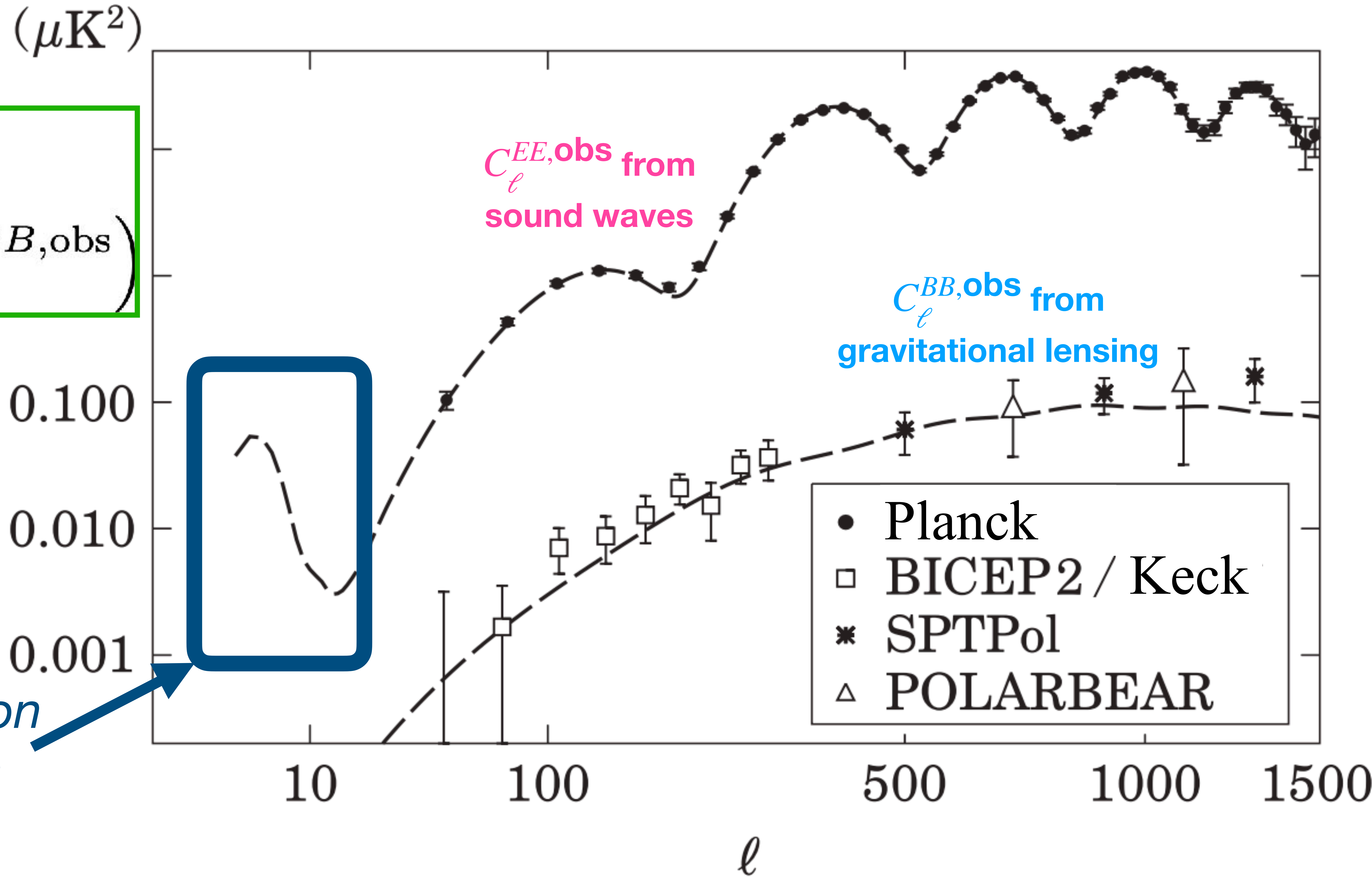
- There are 2 epochs when the CMB polarization was produced.
  - ***z~1100: Recombination***
  - ***z~10: Reionization***
- *β* from these 2 epochs can be different!



“Reionization bump” at low multipoles ($\ell \lesssim 10$)

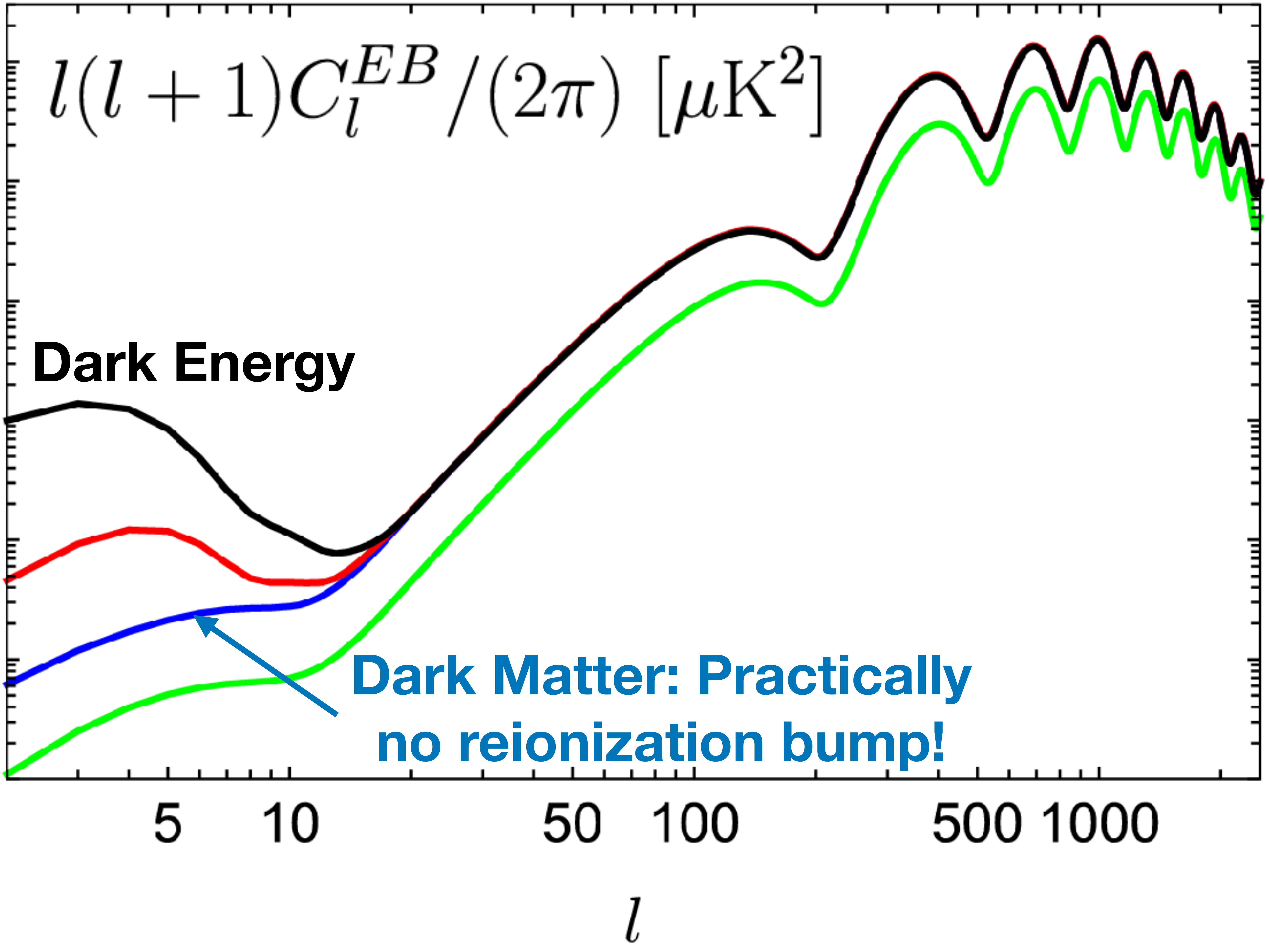
Do we find this?

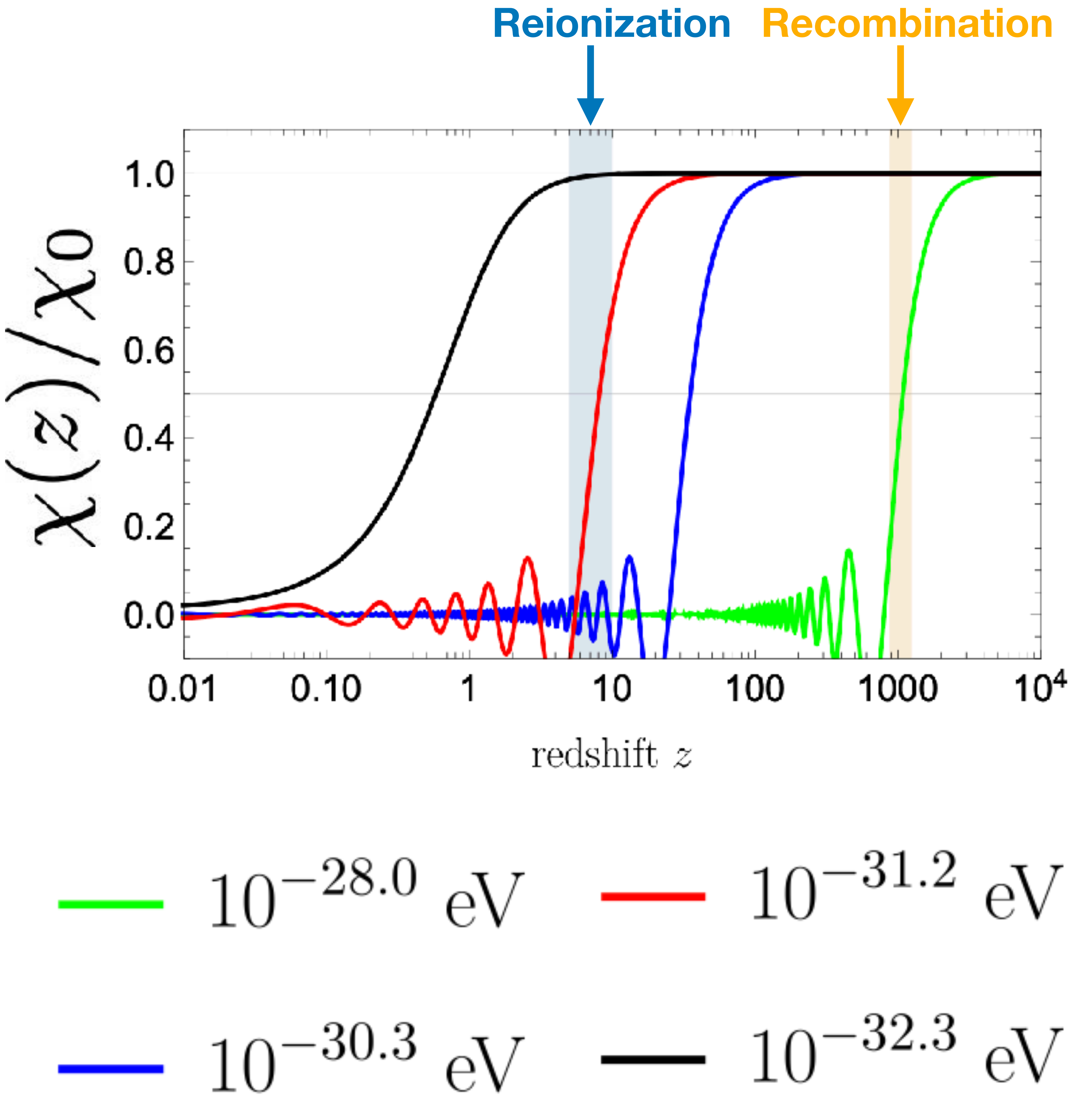
$$C_\ell^{EB,\mathrm{obs}} = \frac{\tan(4\beta)}{2}\left(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}}\right)$$



Nakatsuka, Namikawa, EK (2022)

Cosmic Birefringence "Tomography"





8.3 Signature of parity violation in the density fluctuations

Parity violation in the density field?

What is right and left?

- The CMB polarization has directions from which one could construct parity eigenstates, such as E and B modes.
- How can we construct parity eigenstates for the density field, which is a scalar field and has no directions?
- **Important**: We continue to assume that physics is invariant under spatial translation and rotation (homogeneity and isotropy).

Is the power spectrum sensitive to parity?

No.

- The power spectrum is related to the 2-point correlation function as (Problem Set 4)

$$P(\mathbf{k}) = \int d^3\mathbf{r}\ \xi(\mathbf{r}) e^{-i\mathbf{k}\cdot\mathbf{r}}$$

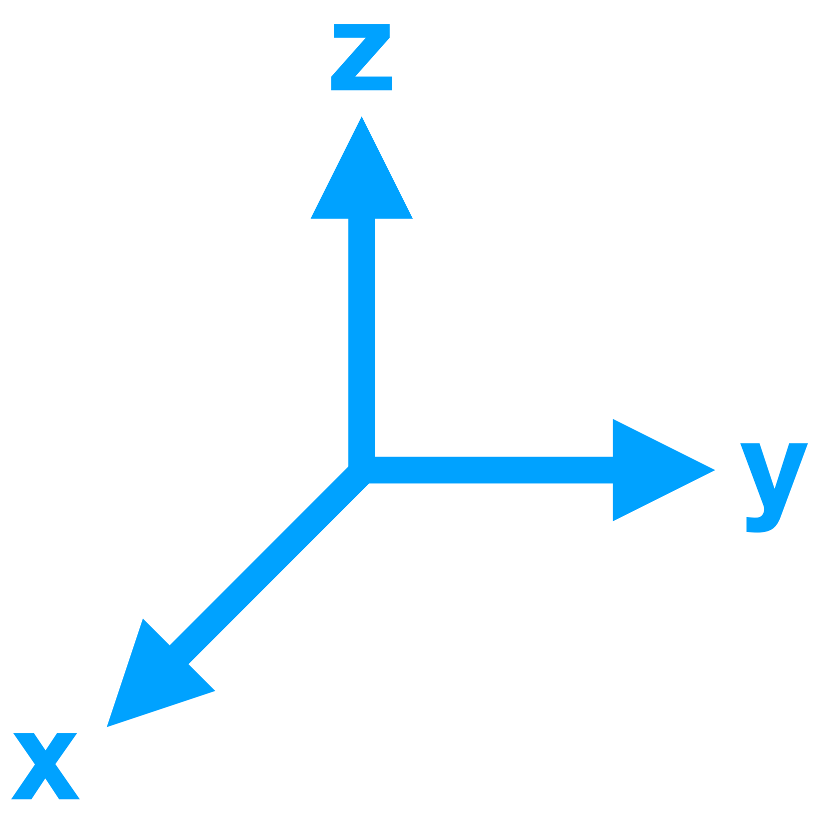
- Rotational invariance means that $\xi(\mathbf{r})$ does not depend on the direction of $\mathbf{r}$, but only on the magnitude, $r = |\mathbf{r}|$. Then the parity transformation, $\mathbf{k} \to -\mathbf{k}$, simply gives

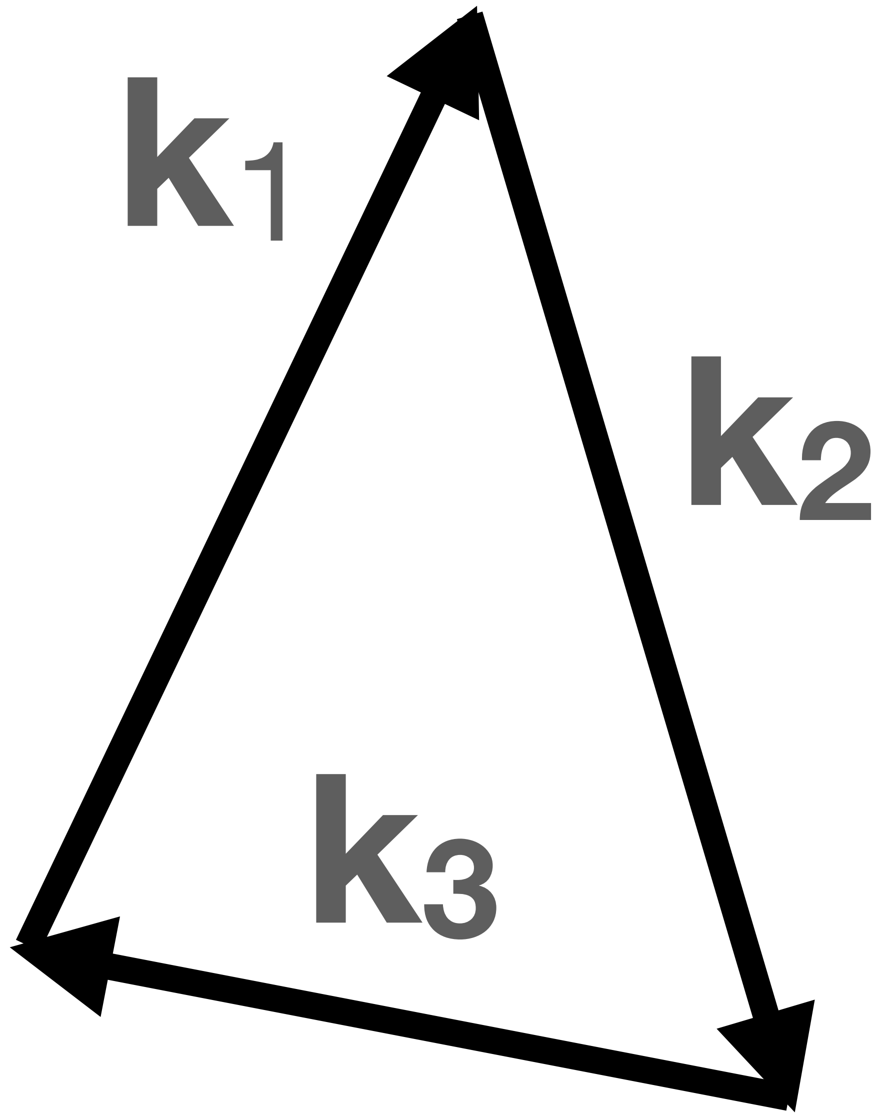
$$P(-\mathbf{k}) = P(\mathbf{k}) = P(k) \quad \text{where} \quad k = |\mathbf{k}|$$

Higher-order Statistics (*N*-point functions)

Many wavenumber vectors –> Right- and left-handed?

- The 2-point function correlates 2 points in space. The 3-point function correlates 3 points in space.
- The Fourier transform of the 2-point function is the power spectrum. The Fourier transform of the 3-point function is the **bispectrum**.





$$\langle \delta_{\mathbf{k}_1} \delta_{\mathbf{k}_2} \delta_{\mathbf{k}_3} \rangle \quad \text{with} \quad \mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 = 0$$

where

$$\delta(t, \mathbf{x}) = \frac{\rho(t, \mathbf{x}) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

Mass density fluctuations

Higher-order Statistics (*N*-point functions)

Many wavenumber vectors –> Right- and left-handed?

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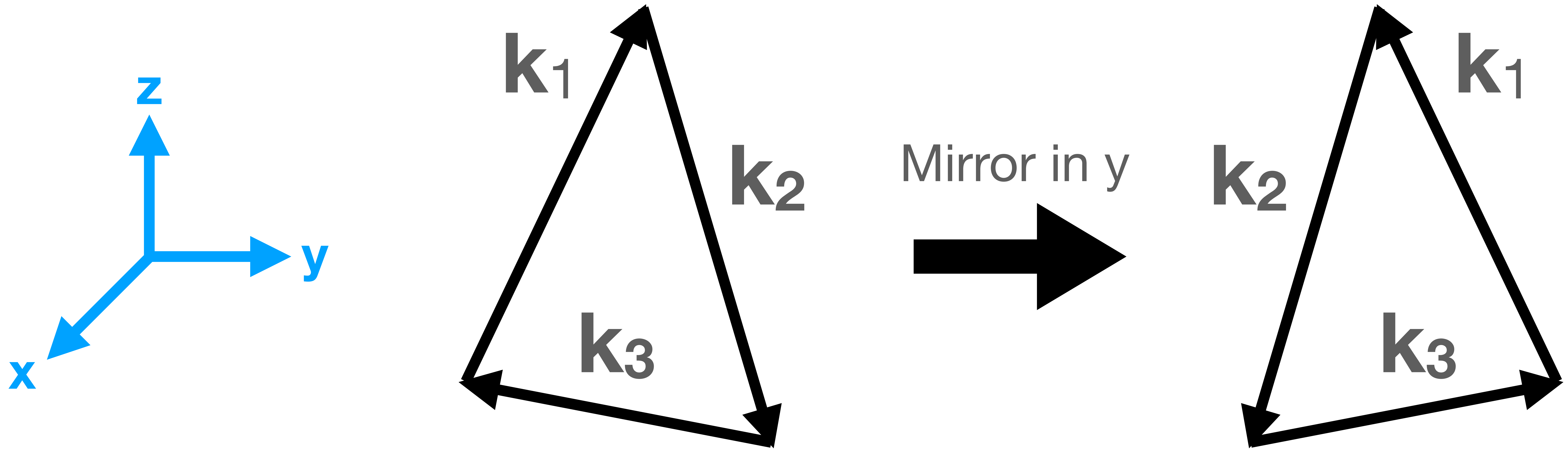

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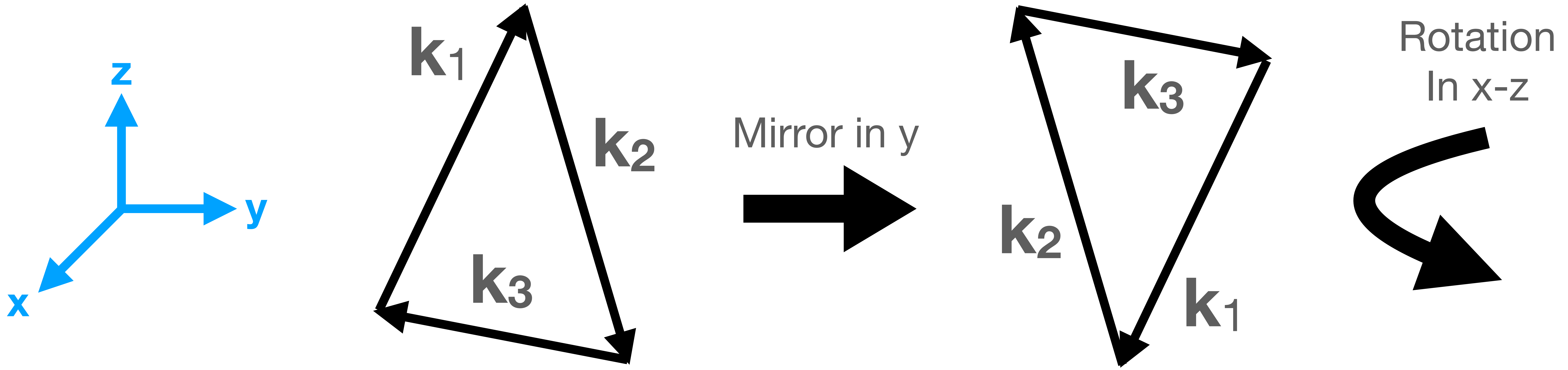

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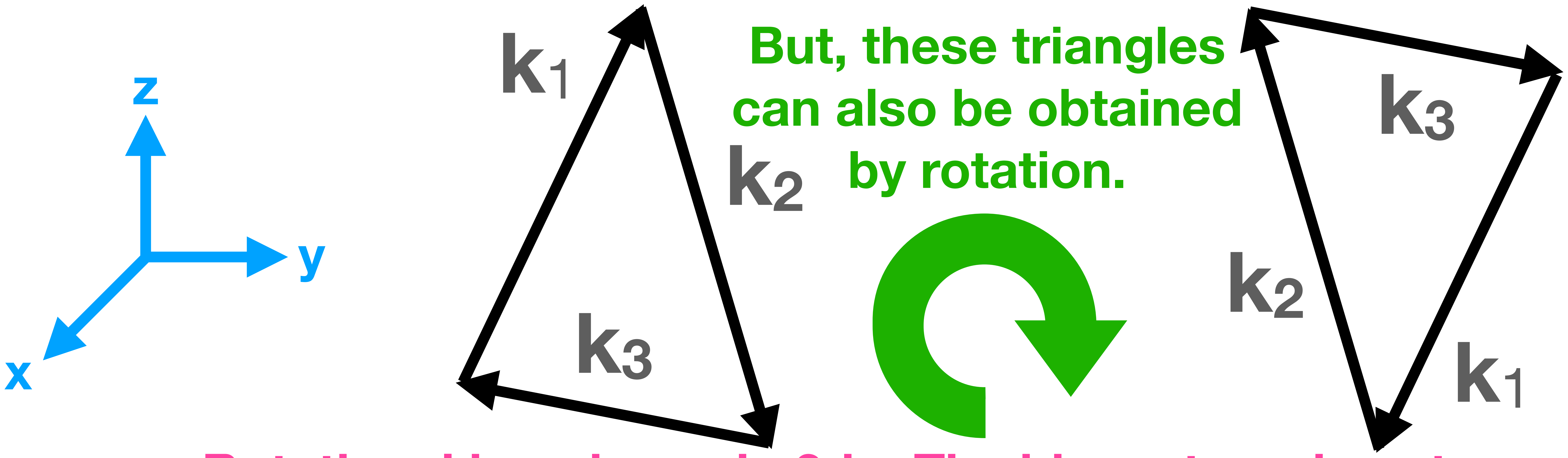

Rotational invariance in 3d = The bispectrum is not sensitivity to parity.

Higher-order Statistics (*N*-point functions)

Many wavenumber vectors –> Right- and left-handed?

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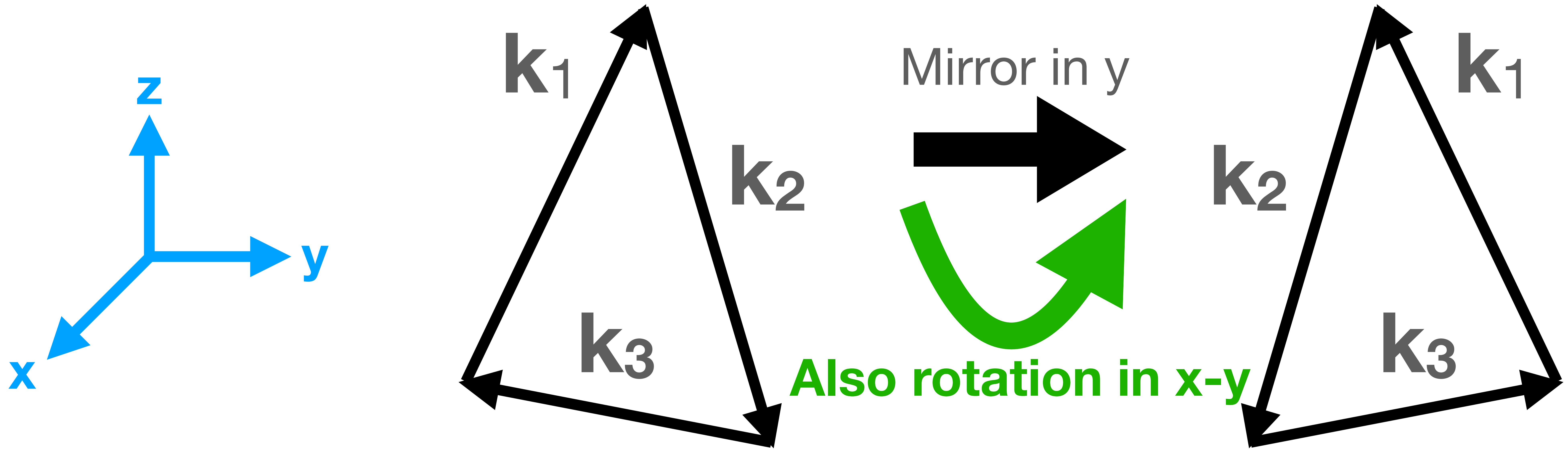
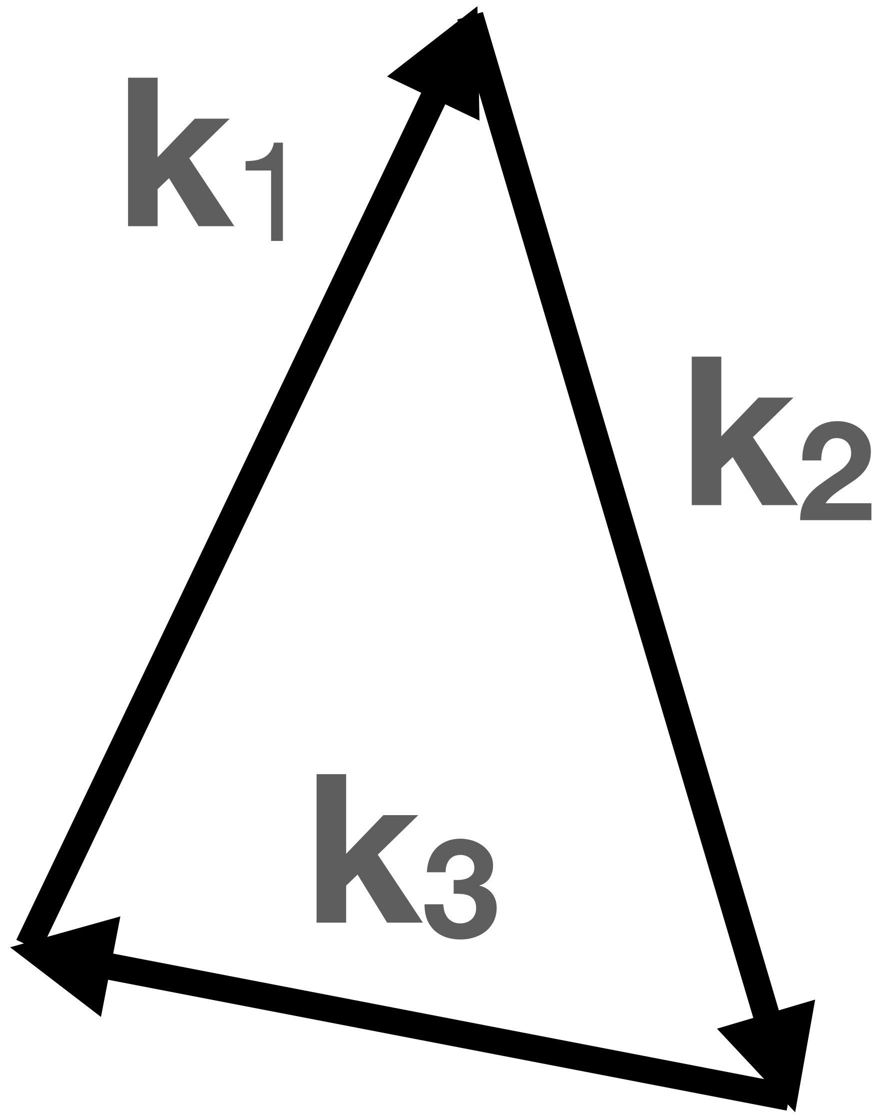


Rotational invariance in 3d = The bispectrum is not sensitivity to parity.

Why is the 3d bispectrum insensitive to parity?

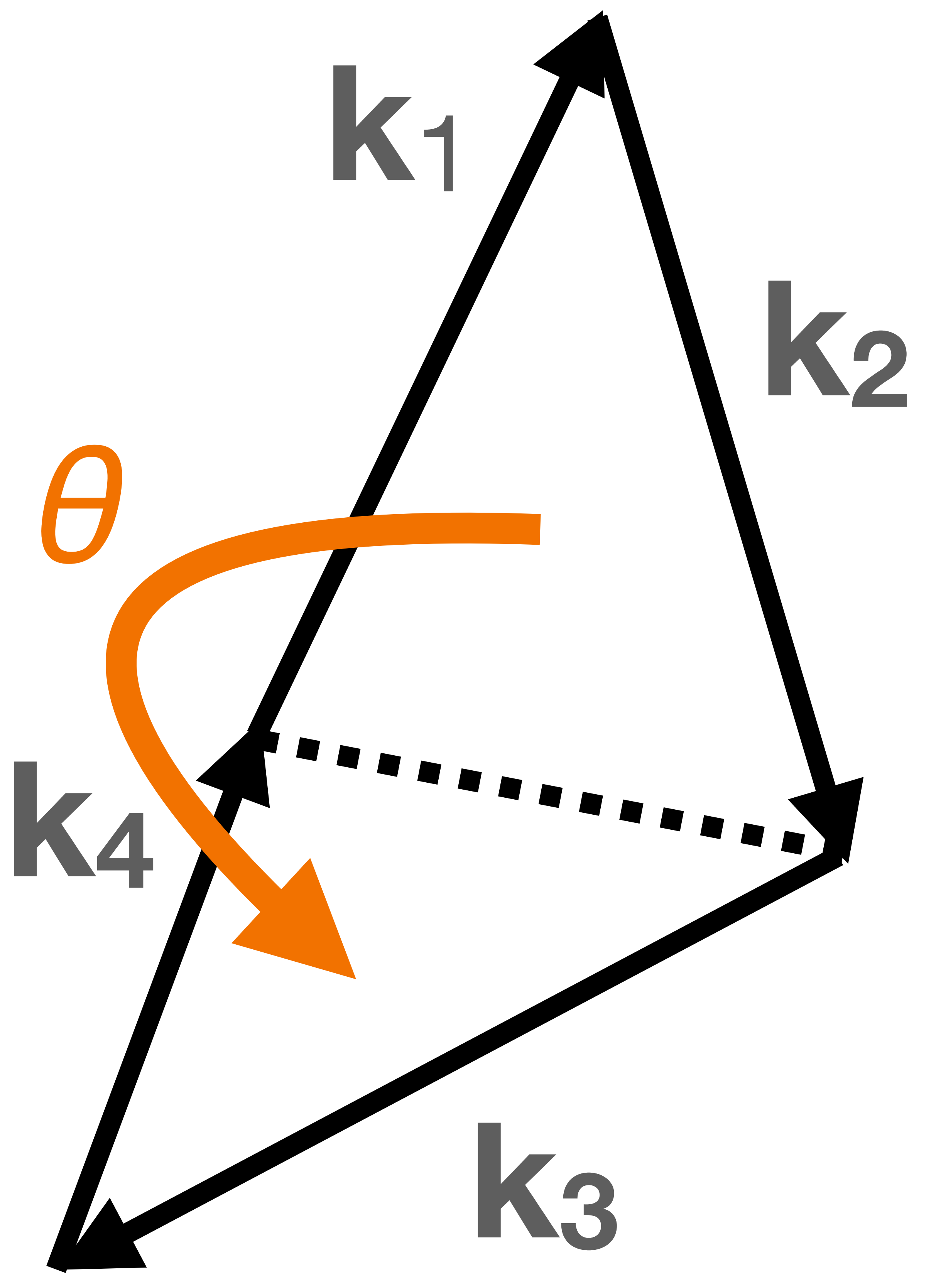
Because the triangle forms a plane.



- 3 vectors form a plane ($\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 = 0$).
- To define handedness, a pseudoscalar (like helicity) is required.
    - The only possible pseudoscalar is $(\mathbf{k}_a \times \mathbf{k}_b) \cdot \mathbf{k}_c$.
    - However, this vanishes because $\mathbf{k}_c = -\mathbf{k}_a - \mathbf{k}_b$!
- There is no unique handedness for triangles in 3d.
- **How about the 4-point function?**

4-point function in 3d is sensitive to parity

…unless it forms a plane.



- The Fourier transform of the 4-point function is the **trispectrum**.
  - There are 4 vectors and one can form a pseudoscalar, $(\mathbf{k}_a \times \mathbf{k}_b) \cdot \mathbf{k}_c$, that does not vanish!
  - …unless it forms a plane, $\theta = 0$ or π.
- The 4-point function is the lowest-order statistics that is parity-sensitive in 3 dimensions.
- The Chern-Simons term can generate this via

Parity violation in the density fluctuation

$$\Box\chi - \frac{\partial V}{\partial \chi} = -\frac{\alpha}{f}\mathbf{E}\cdot\mathbf{B}$$

Parity-odd Trispectrum: Density Fluctuation

Imaginary part

- As shown in Problem Set 7, the Fourier coefficients satisfy $\delta^*_{\mathbf{k}} = \delta_{-\mathbf{k}}$ for a real function $\delta(\mathbf{x})$.
- Under the parity transformation, $\mathbf{k} \rightarrow -\mathbf{k}$, and the trispectrum is transformed as

$$\langle \delta_{\mathbf{k}_1} \delta_{\mathbf{k}_2} \delta_{\mathbf{k}_3} \delta_{\mathbf{k}_4} \rangle$$

$$\rightarrow \langle \delta_{-\mathbf{k}_1} \delta_{-\mathbf{k}_2} \delta_{-\mathbf{k}_3} \delta_{-\mathbf{k}_4} \rangle = \langle \delta^*_{\mathbf{k}_1} \delta^*_{\mathbf{k}_2} \delta^*_{\mathbf{k}_3} \delta^*_{\mathbf{k}_4} \rangle$$

- **The imaginary part, Im$(\langle \delta_{\mathbf{k}_1} \delta_{\mathbf{k}_2} \delta_{\mathbf{k}_3} \delta_{\mathbf{k}_4} \rangle)$, is sensitive to parity violation.**

Philcox (2022); Hou, Slepian, Cahn (2023)

Observational hints?

New and exciting research area

These find similar results, with the rank test giving a detection probability of 99.6% (2.9σ).

PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

Probing parity violation with the four-point correlation function of BOSS galaxies

Oliver H. E. Philcox

Phys. Rev. D **106**, 063501 – Published 6 September 2022

In LOWZ, we find 3.1σ evidence for a non-zero parity-odd 4PCF, and in CMASS we detect a parity-odd 4PCF at 7.1σ.

JOURNAL ARTICLE

Measurement of parity-odd modes in the large-scale 4-point correlation function of Sloan Digital Sky Survey Baryon Oscillation Spectroscopic Survey twelfth data release CMASS and LOWZ galaxies

Jiamin Hou, Zachary Slepian, Robert N Cahn

Monthly Notices of the Royal Astronomical Society, Volume 522, Issue 4, July 2023, Pages 5701–5739, https://doi.org/10.1093/mnras/stad1062

Published: 22 May 2023 **Article history** ▾

Shiraishi (2016)

Parity-odd Trispectrum: CMB Temperature

$\ell_1 + \ell_2 + \ell_3 + \ell_4 =$ **odd**

- Under the parity transformation, $\hat{n} \to -\hat{n}$, the spherical harmonics coefficients of CMB temperature anisotropy, $\Delta T(\hat{n}) = \sum a_{\ell m} Y_\ell^m(\hat{n})$, are transformed as $a_{\ell m} \to (-1)^\ell a_{\ell m}$ (Day 6).

- Therefore, the temperature trispectrum is transformed as

$$\langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} \rangle$$
$$\to (-1)^{\ell_1+\ell_2+\ell_3+\ell_4} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} a_{\ell_4 m_4} \rangle$$

- **The configuration with $\sum \ell_i =$ odd is sensitive to parity violation.**

Philcox, arXiv:2303.12106

Observational constraints

New and exciting research area

Do the CMB Temperature Fluctuations Conserve Parity?

Oliver H. E. Philcox[1,2,*]

[1] *Center for Theoretical Physics, Department of Physics, Columbia University, New York, NY 10027, USA*

[2] *Simons Society of Fellows, Simons Foundation, New York, NY 10010, USA*

The measured trispectra can be used to constrain physical models of inflationary parity violation, including Ghost Inflation, Cosmological Collider scenarios, and Chern-Simons gauge fields. Considering eight such models, we find no evidence for new physics, with a maximal detection significance of 2.0σ.

What else should we look at?

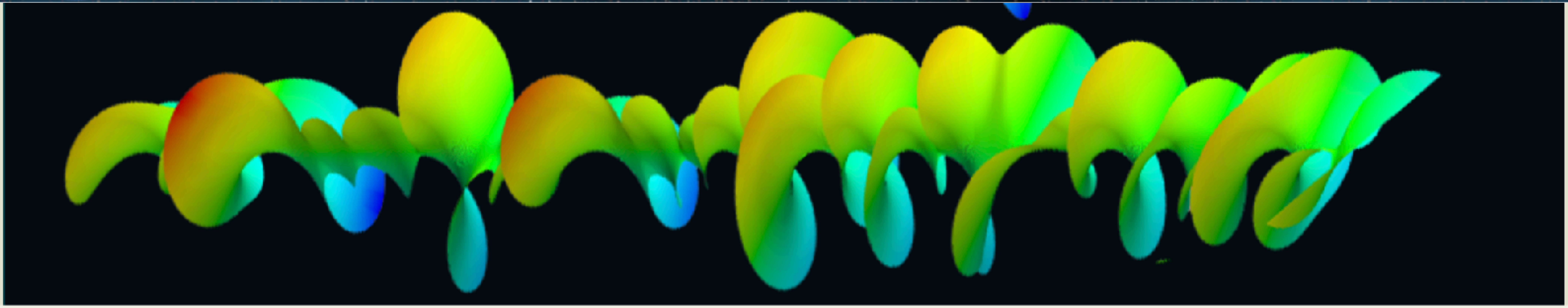
To confirm violation of parity symmetry in the density fluctuations

- Weak lensing shear field?
- Intrinsic alignment of galaxies?
- Angular momentum of galaxies and dark matter halos?
- etc…

- **This is the opportunity for new topics of research. We need new ideas!**

中央研究院
天文及天文物理研究所
ACADEMIA SINICA
Institute of Astronomy and Astrophysics

The registration will be open around middle of July.



Large-scale Parity Violation Workshop

December 4(Mon)-7(Thu), 2023

ASIAA, Taipei, Taiwan

December 4-7 in Taipei

https://events.asiaa.sinica.edu.tw/workshop/20231204/index.php

Purpose

In recent few years, studies of parity violation at cosmological scales have been attracting a lot of attention, with the observations of birefringence in CMB, galaxy spins, and four-point correlation functions of galaxies and CMB. Investigating violation of parity at such scales enables us to probe new physics beyond the standard model of cosmology, potentially nature of dark matter and dark energy. This workshop aims to bring together experts in numerical, observational and theoretical aspects of parity violation in cosmology.

The registration will be open around middle of July.

Recap: Day 7

- To show that β is not caused by non-cosmological effects, we need to measure it in independent experiments.
- The shape of the EB power spectrum can be used to distinguish between dark matter and dark energy as the origin of cosmic birefringence.
- The 4-point function of the density fluctuations is sensitive to the violation of parity symmetry, whereas the 3-point function is not, if rotational symmetry is not violated.
- **What else should we look at? New and great topics of research.**

Further reading

Let’s find new physics!

- The Chern-Simons term of **SU(2) gauge fields**
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- The **gravitational** Chern-Simons term
  - Alexander, Yunes, Physics Reports, 480, 1 (2009)
- **LiteBIRD**: JAXA-led space mission to measure the CMB polarization
  - LiteBIRD collaboration, Progress of Theoretical and Experimental Physics, 2023, 042F01 (2022)