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

# New Physics from Polarised Light of the CMB

## Cosmic birefringence and primordial gravitational waves

**Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)**
**Guest lecture, Univ. Bonn, January 17, 2022**

# Standard Cosmological Model (ΛCDM) Requires New Physics

## Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy ($\Lambda$)?

- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?

- *Polarisation* of the CMB may hold the key to the answers.

# Standard Cosmological Model (ΛCDM) Requires New Physics

## Physics beyond Standard Model of elementary particles and fields

- **Dark Sector**: What is dark matter (*CDM*)? What is dark energy (*Λ*)?
    - **Cosmic birefringence** in cross-correlation of E- and B-mode polarisation
- **Early Universe**: What powered the Big Bang? What is the fundamental physics behind cosmic inflation?
    - Imprint of **primordial gravitational waves** in B-mode polarisation
- *Polarisation* of the CMB may hold the key to the answers.


Credit: WMAP Science Team
The surface of "last scattering" by electrons
(Scattering generates polarisation!)
What powered the Big Bang?
What is dark matter/energy?

# Part I: Cosmic Birefringence

*What is dark matter/energy?*

# How does the electromagnetic wave of the CMB propagate?

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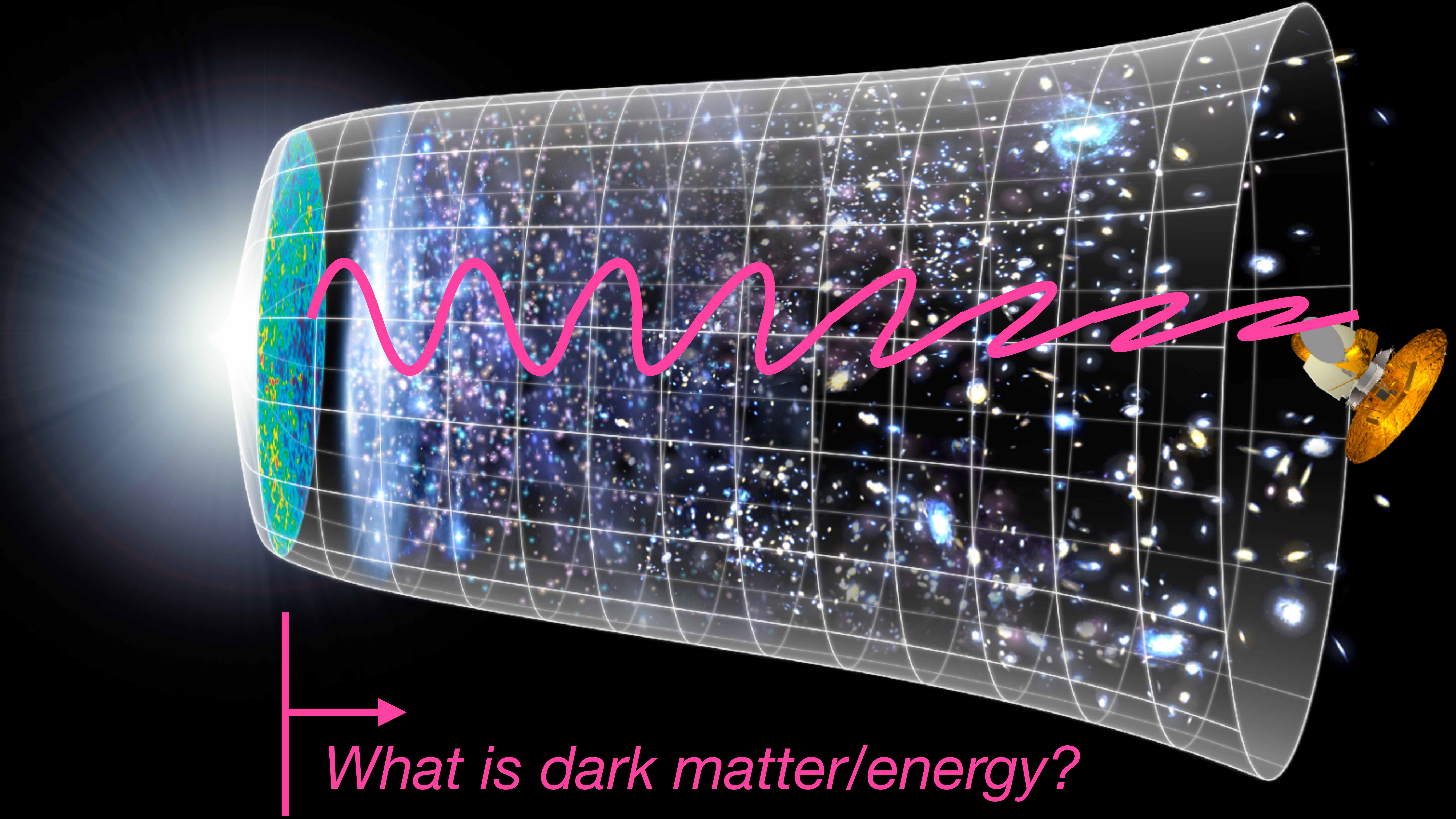

# How does the electromagnetic wave of the CMB propagate?

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

# Cosmic Birefringence

## The Universe filled with a “birefringent material”

*This “axion” field can be dark matter or dark energy!*

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

**Ni (1977); Turner & Widrow (1988)**

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta}\frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}}F_{\alpha\beta}$$

where $g_a$ is a coupling constant of the order $\alpha$, and the vacuum angle $\theta = \phi_a/f_a$ ($\phi_a$ = axion field). The equations

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\sum_{\mu\nu} F_{\mu\nu}F^{\mu\nu} = 2(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E})$$ **Parity Even**

$$\sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$ **Parity Odd**

- The axion field, θ, is a “pseudo scalar”, which is parity odd; thus, the last term in Eq.3.7 is parity even as a whole.

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

# Cosmic Birefringence

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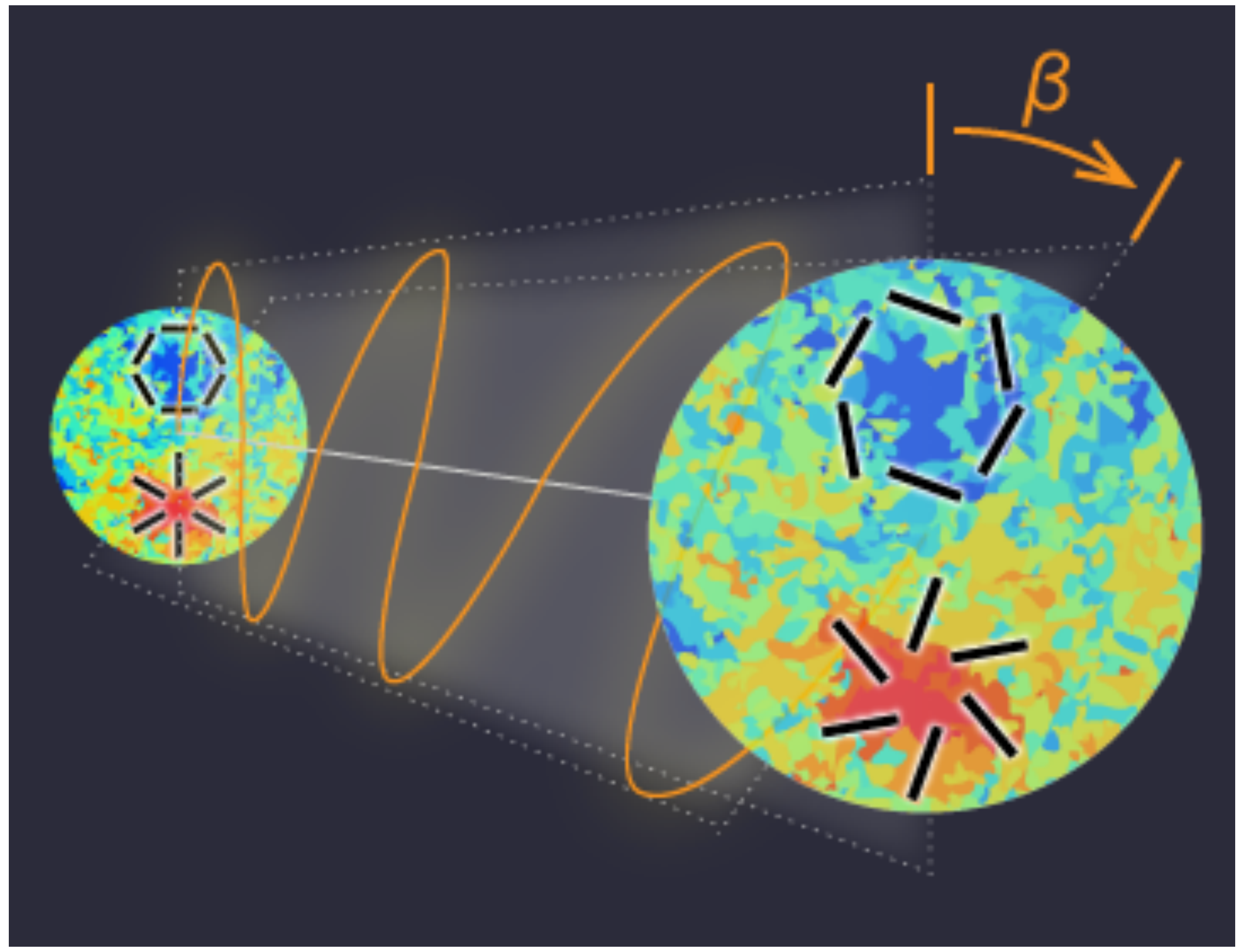



"Cosmic Birefringence"

This term makes the phase velocities of right- and left-handed polarisation states of photons different, leading to **rotation of the linear polarisation direction.**

# Standard Maxwell Theory

## Warm up (1)

- ***Technical, but an important note***: the standard electromagnetic theory is invariant under conformal transformation of the metric tensor:

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}$$

- To make the full advantage of this, we write the metric using the conformal time, η, rather than the physical time, t. That is to say,

$$ds^2 = a^2(-d\eta^2 + d\mathbf{x}^2) \quad \text{i.e.,} \quad g_{\mu\nu} = a^2(\eta)\mathrm{diag}(-1,1,1,1)$$

- What is this good for? If we choose Ω=1/a, **we can undo(*) expansion**, and the equation takes the same form as in Minkowski space!

(*) The effect of expansion is still remembered by the conformal time, $\eta = \int dt/a(t)$

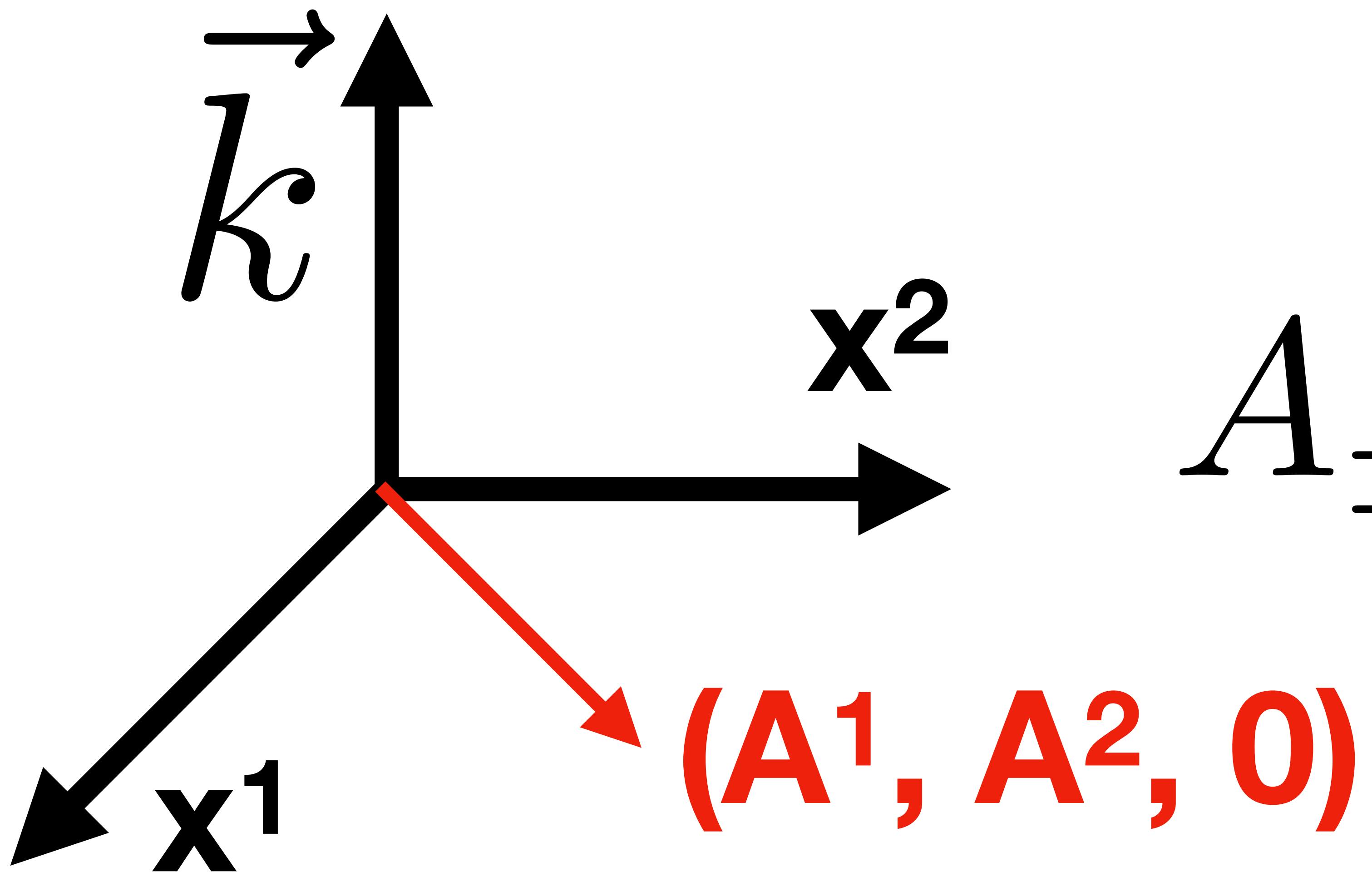
# Standard Maxwell Theory

## Warm up (2)

- To isolate a transverse wave, we require $A_0=0$ and $\mathrm{div}(A_i)=0$. Then, in vacuum,

$$\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right) A_i(\eta, \mathbf{x}) = 0$$

- Go to Fourier space, choose the propagation direction of $A_i$ to be in z-axis, and define right- and left-handed polarisation states as




$$A_\pm = \frac{A_1 \mp iA_2}{\sqrt{2}}$$

- $A_+$: Right-handed state
- $A_-$: Left-handed state

# Standard Maxwell Theory

## Warm up (3)

- To isolate a transverse wave, we require $A_0$=0 and div($A_i$)=0. Then, in vacuum,

$$\left(\frac{\partial^2}{\partial\eta^2} - \nabla^2\right) A_i(\eta, \mathbf{x}) = 0 \quad \Rightarrow \quad \left(-\omega_\pm^2 + k^2\right) A_\pm(\eta) = 0$$

Same dispersion relation for
right- and left-handed states

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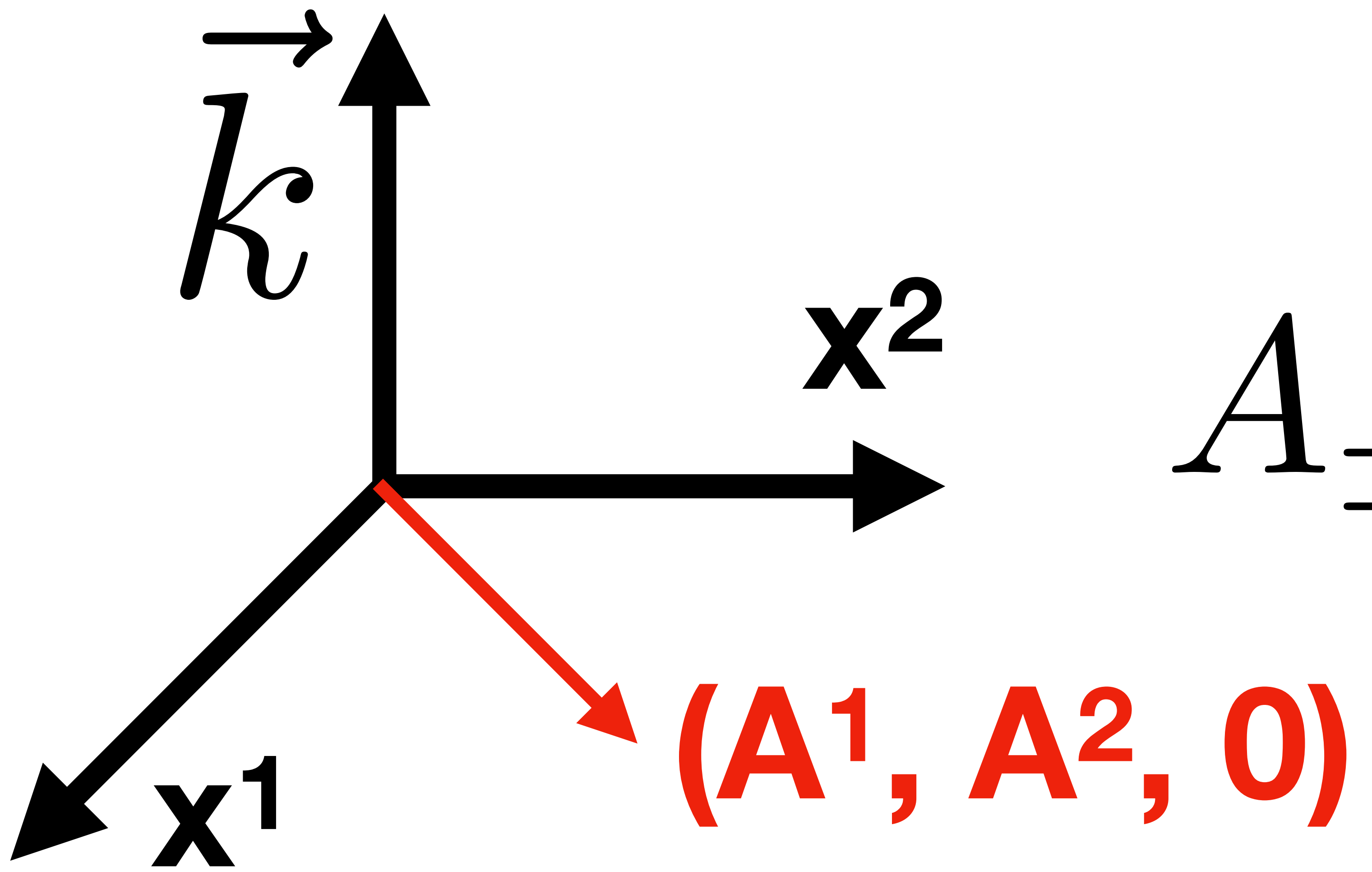


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Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998)

# Cosmic Birefringence

## Derivation (1)

- Now, include **the Chern-Simons term**!

> the effective Lagrangian for axion electrodynamics is
>
> Chern-Simons term
>
> $$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (3.7)$$
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> $$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta}\frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}}F_{\alpha\beta}$$
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> where $g_a$ is a coupling constant of the order $\alpha$, and the vacuum angle $\theta = \phi_a/f_a$ ($\phi_a$ = axion field). The equations

- The equation of motion is modified to

$$\left(-\omega_\pm^2 + k^2\right)A_\pm(\eta) = 0 \;\Rightarrow\; \left(-\omega_\pm^2 + k^2 \pm 4g_a k\theta'\right)A_\pm(\eta) = 0$$

$$\frac{\omega_\pm^2}{k^2} = 1 \pm \frac{4g_a\theta'}{k}$$

# Cosmic Birefringence

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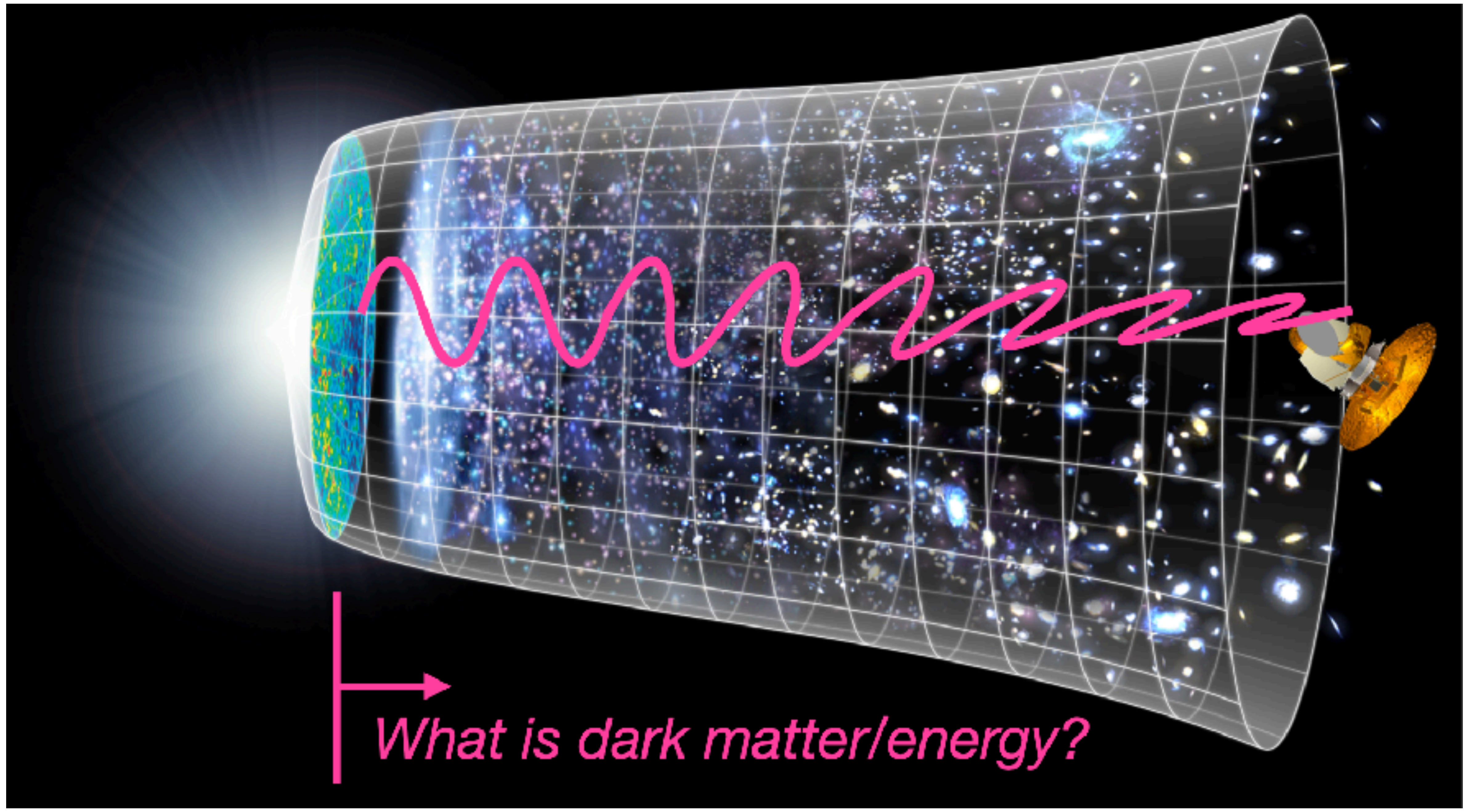
$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

Phase velocities of right- and left-handed states are slightly different!

# Cosmic Birefringence

## Derivation (2)




- With

$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

Phase velocities of right- and left-handed states are slightly different!

- The plane of linear polarisation rotates by an angle ψ:

$$\psi = \int d\eta \, \frac{\omega_+ - \omega_-}{2} = 2g_a \int d\eta \, \theta' = 2g_a \int dt \, \dot{\theta}$$

**The effect accumulates over the distance!**
**=> CMB polarisation is sensitive to this effect**

# Cosmic Birefringence

## Derivation (3)

- With

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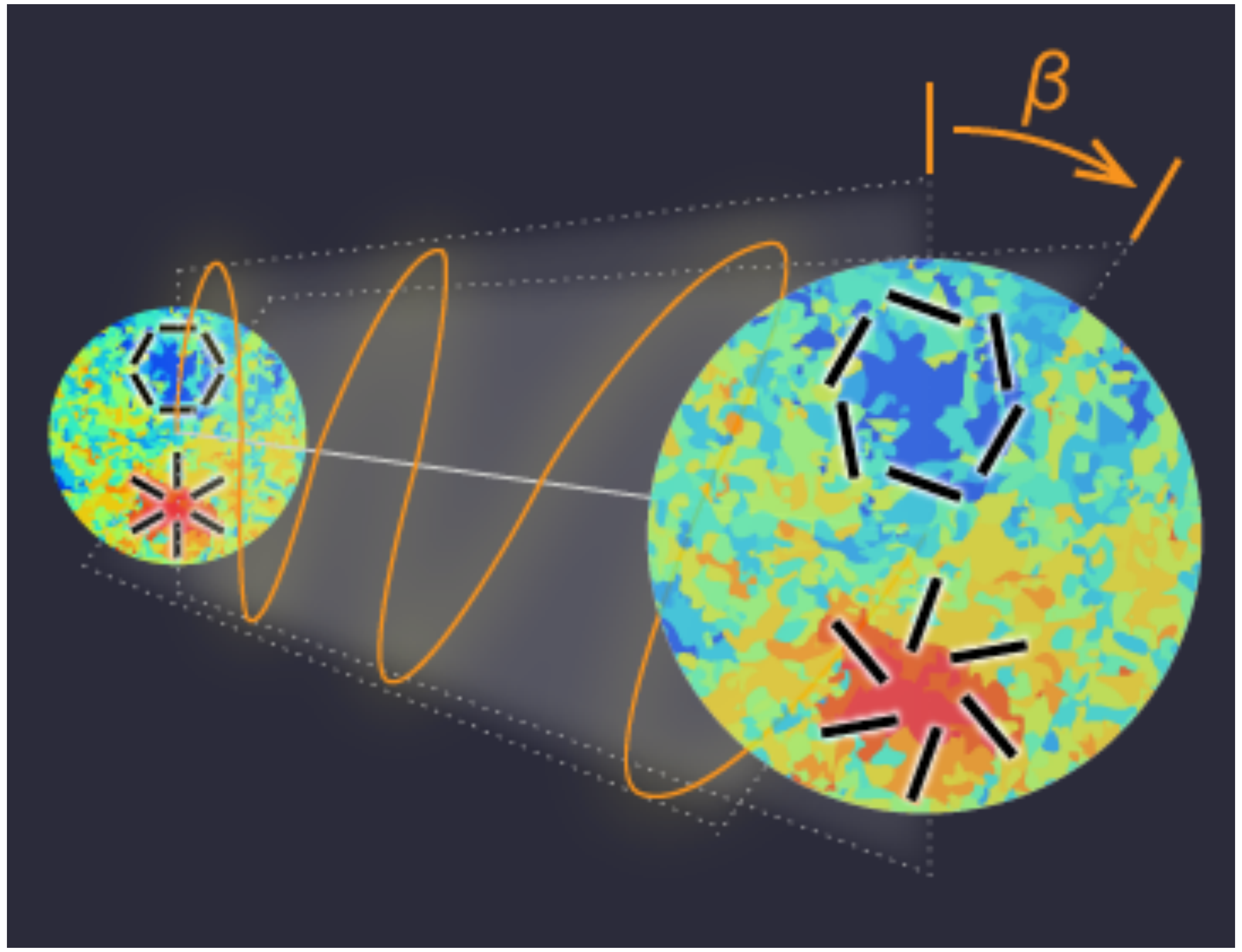
This is the convention for polarisation direction adopted by IAU

# Cosmic Birefringence

## Derivation (3)

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This is the convention for polarisation direction adopted by IAU

*However!*

The CMB community adopted the opposite sign convention…
**Thus, we shall use β = −ψ**

# Cosmic Birefringence

## Recap

*This "axion" field can be dark matter or dark energy!*

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

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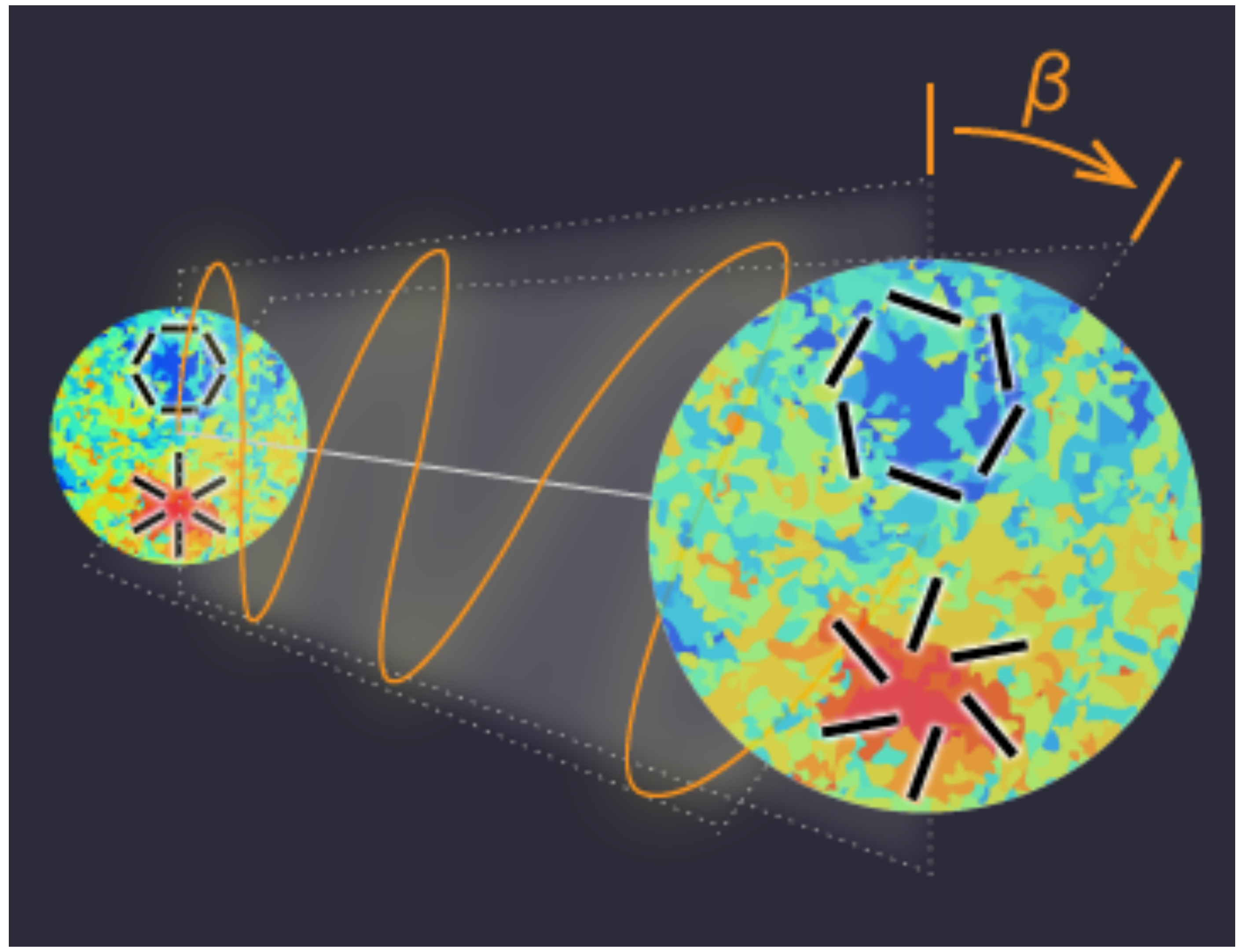
$$\beta = -2g_a \int_{t_{\text{emitted}}}^{t_{\text{observed}}} dt\ \dot{\theta}$$




The larger the distance the photon travels, the larger the effect becomes.

# Motivation

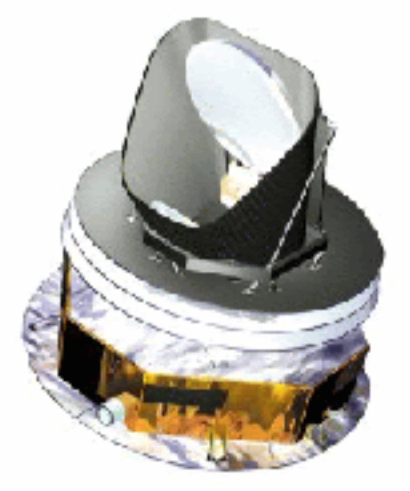
## Why study the cosmic birefringence?

- The Universe’s energy budget is dominated by two dark components:
    - Dark Matter
    - Dark Energy
- Either or both of these can be an axion-like field!
    - See Marsh (2016) and Ferreira (2020) for reviews.
- Thus, detection of parity-violating physics in polarisation of the cosmic microwave background can transform our understanding of Dark Matter/ Energy.

# (Simpler) Motivation

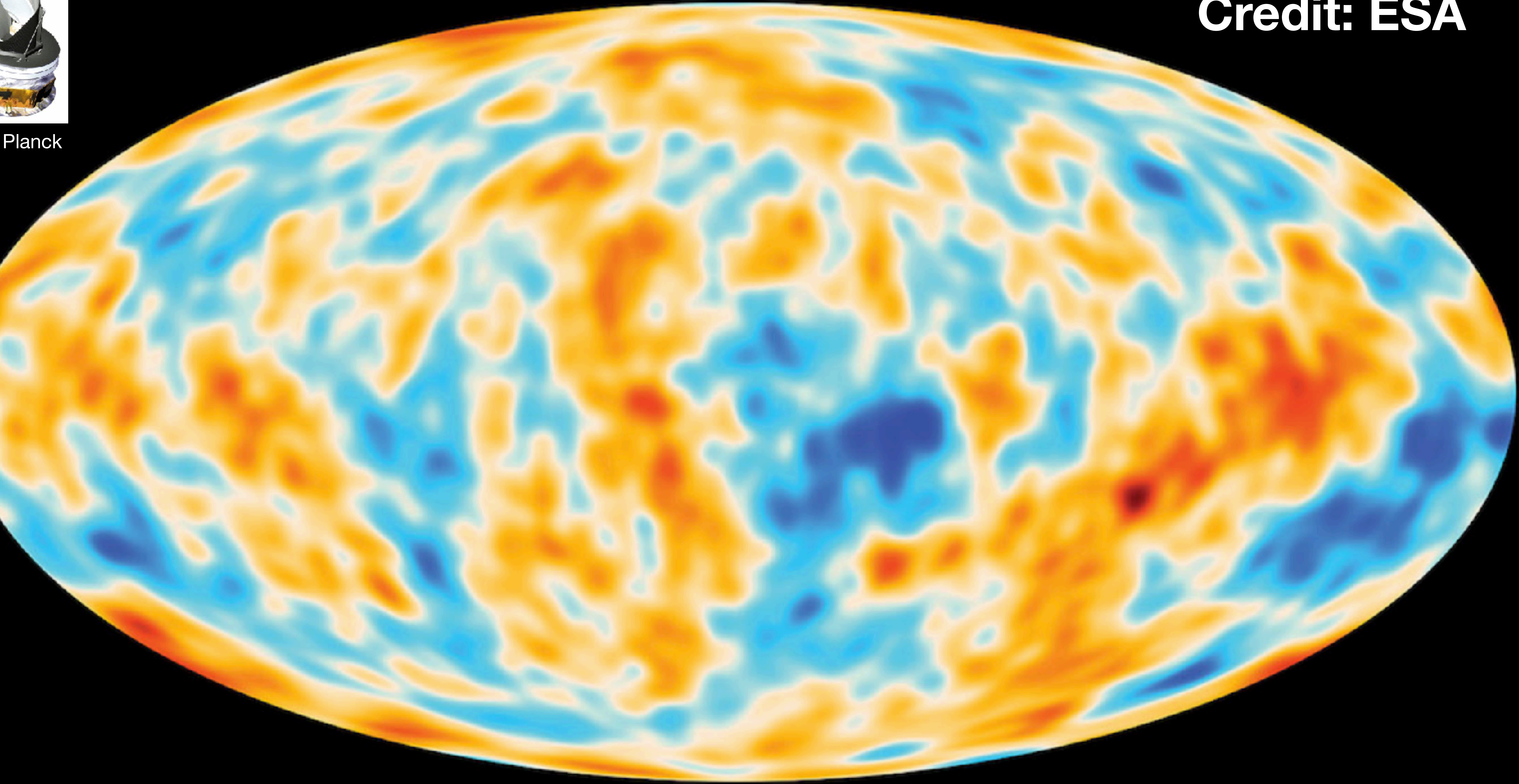
## Why study the cosmic birefringence?

- We know that the weak interaction violates parity (Lee & Yang 1956; Wu et al. 1957).
  - Why should the laws of physics governing the Universe conserve parity?
- Let's look!



ESA’s Planck

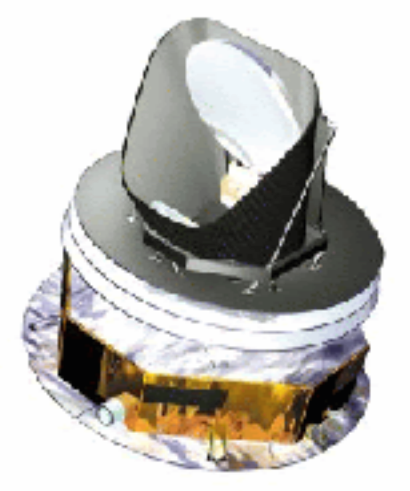
Credit: ESA



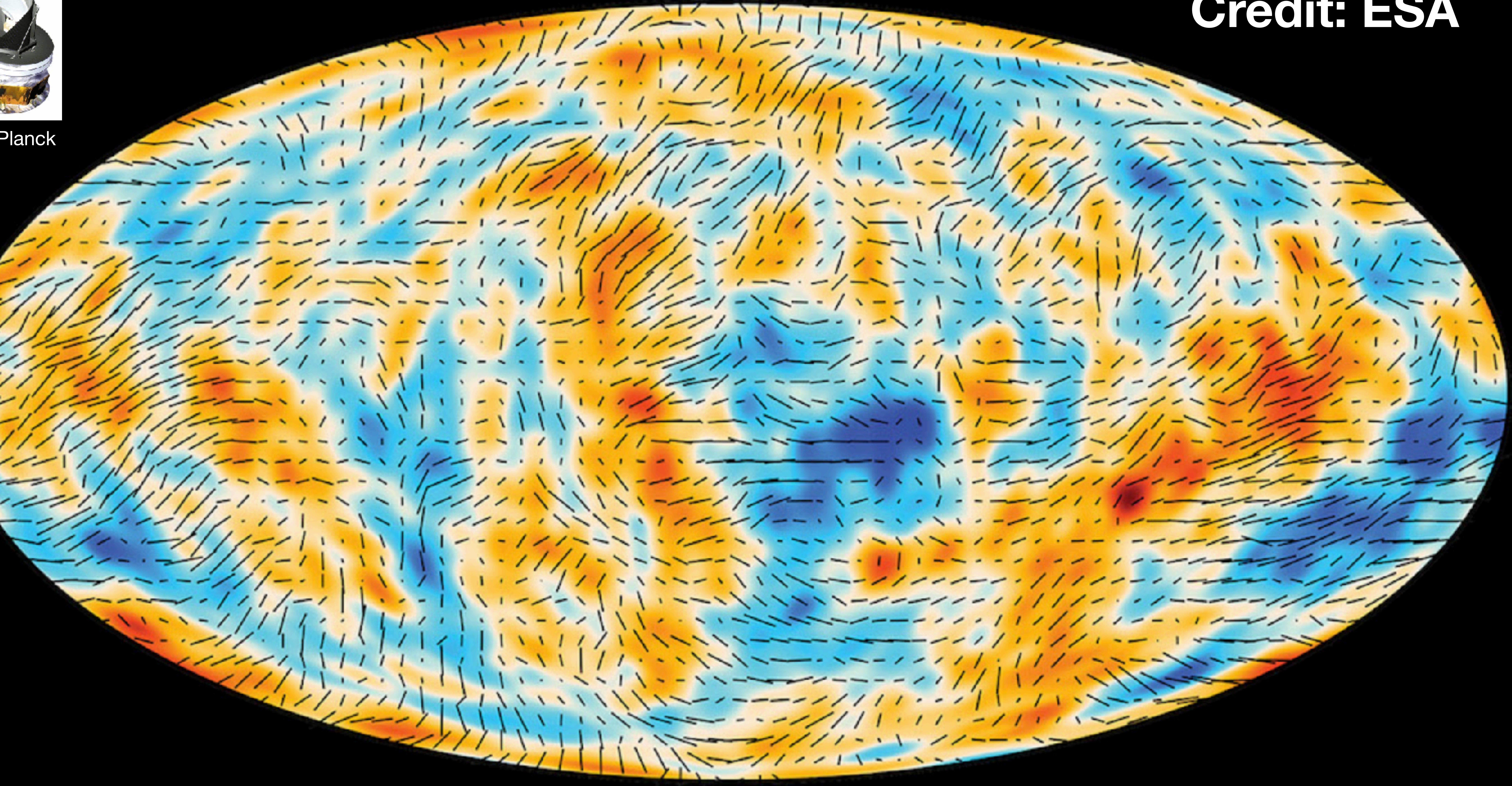
Foreground-cleaned Temperature (smoothed)

Emitted 13.8 billions years ago

# Credit: ESA



ESA's Planck



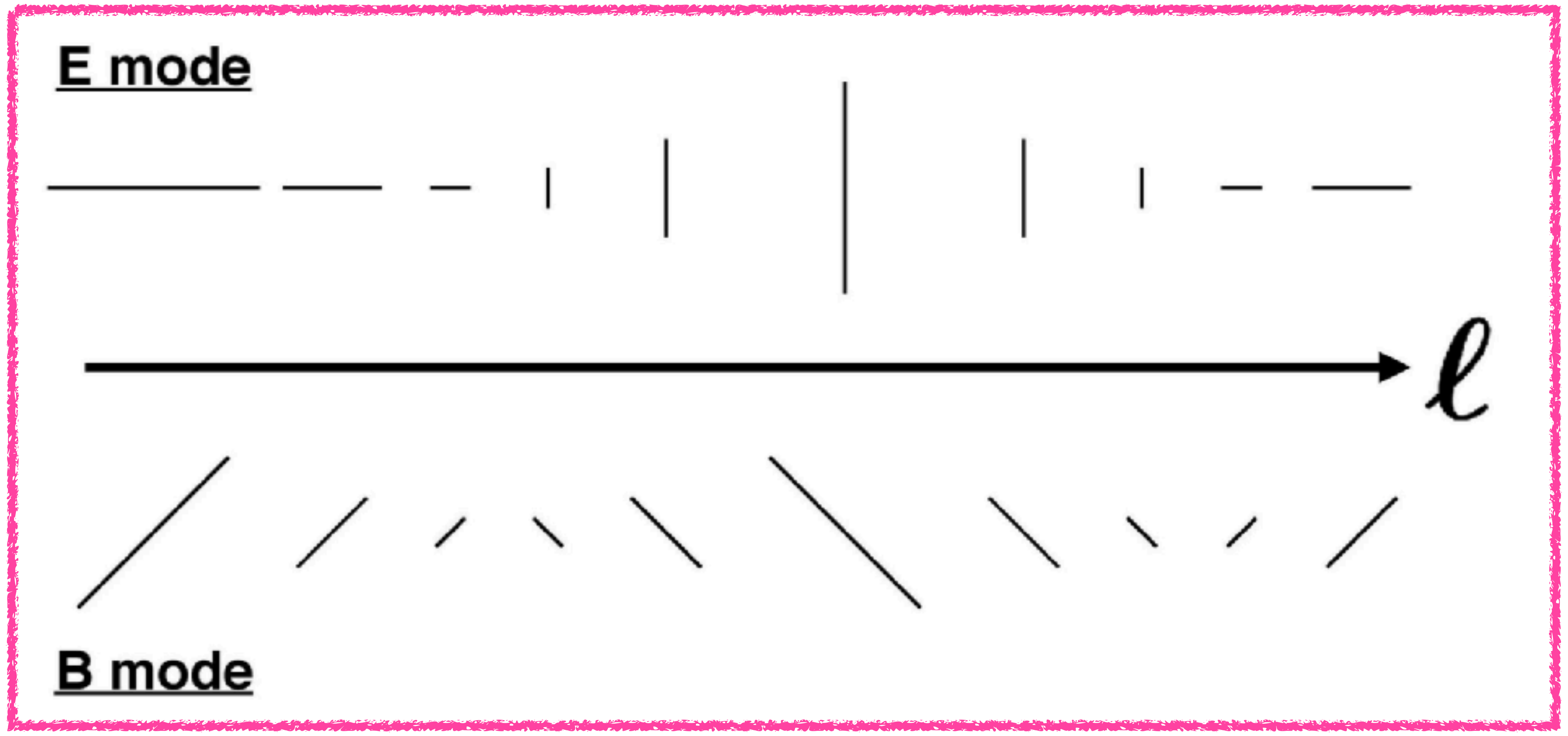
Foreground-cleaned Temperature (smoothed) + Polarisation

Emitted 13.8 billions years ago

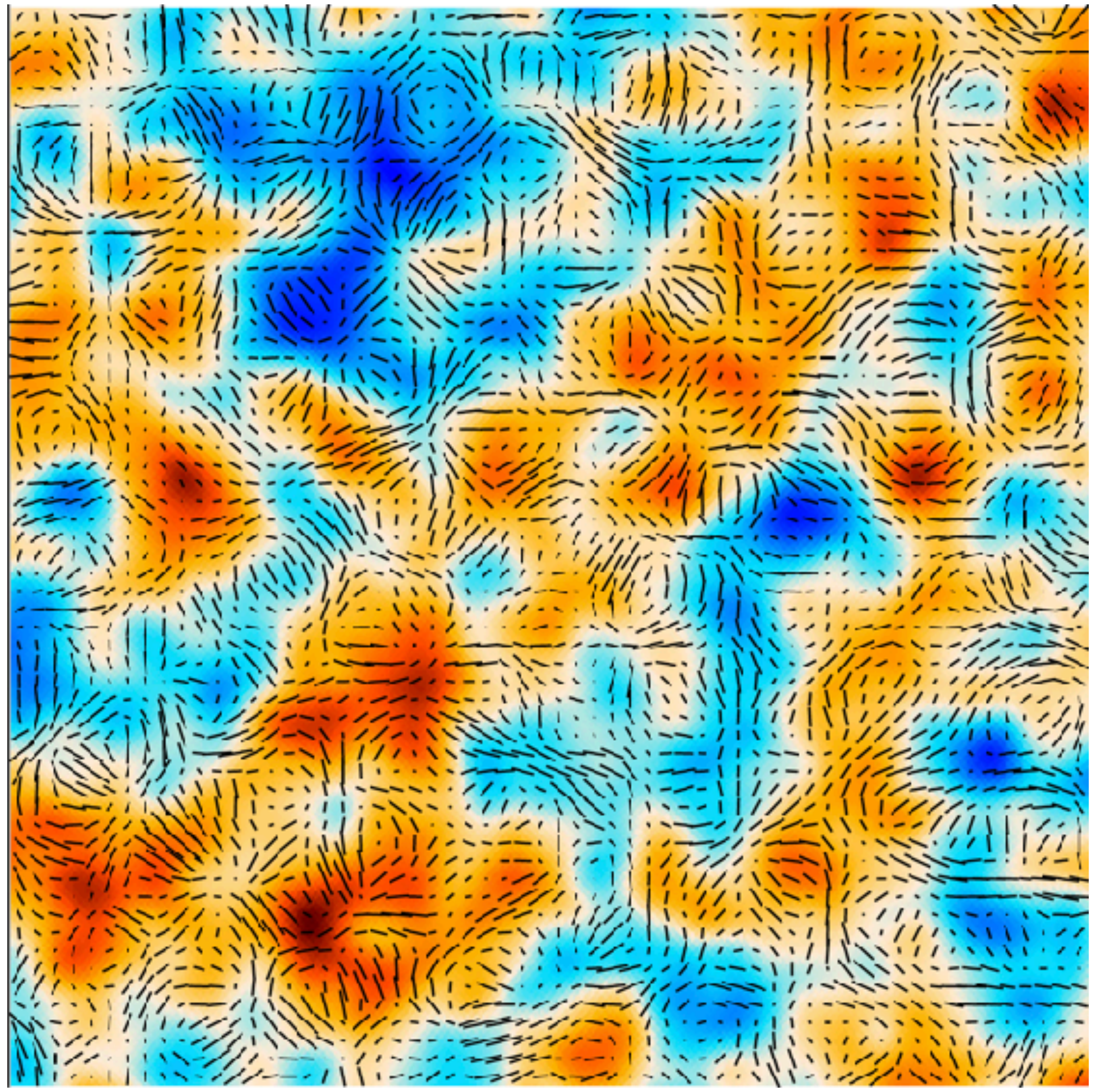
Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

# E- and B-mode decomposition of linear polarisation

## Concept defined in Fourier space




This map is dominated by E-mode polarisation

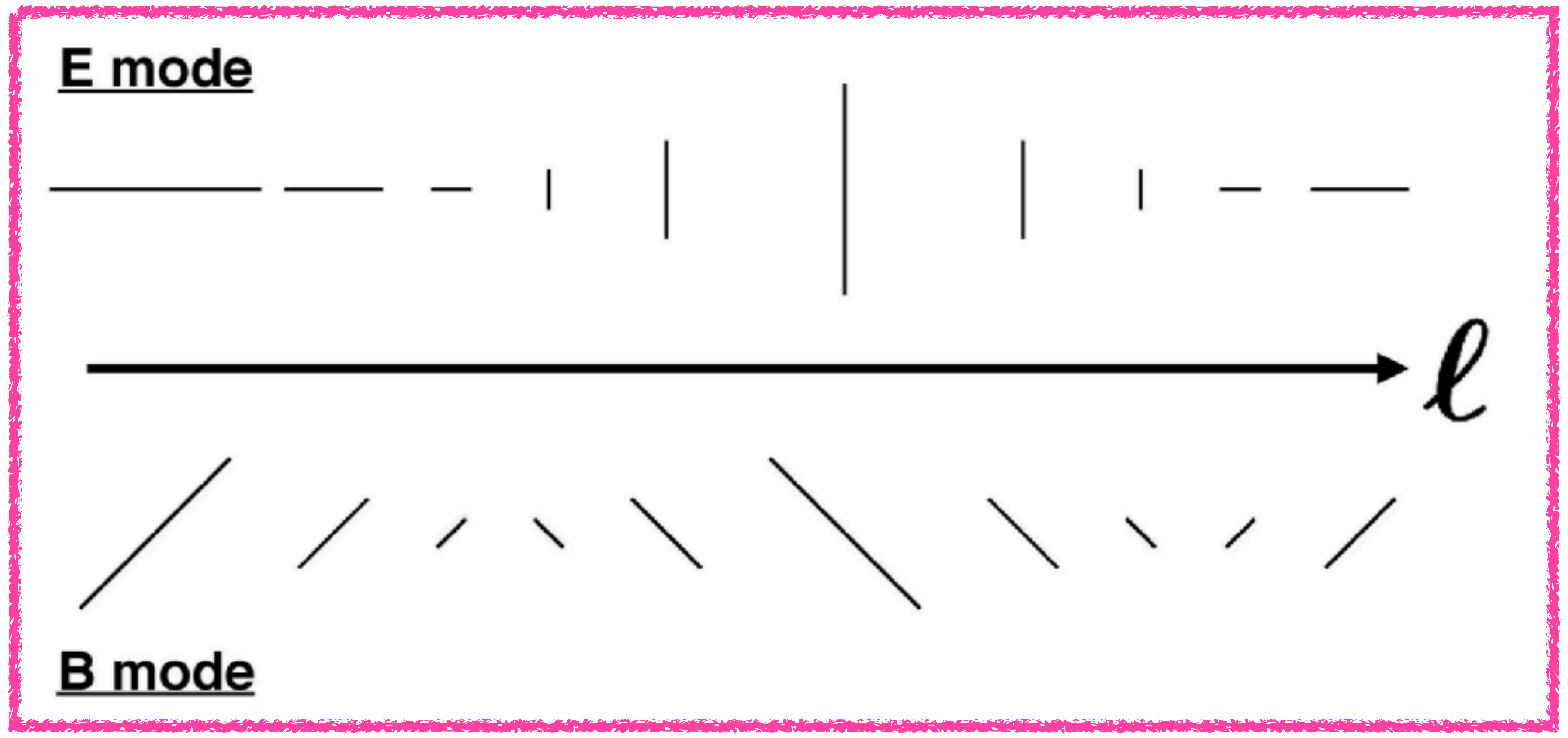


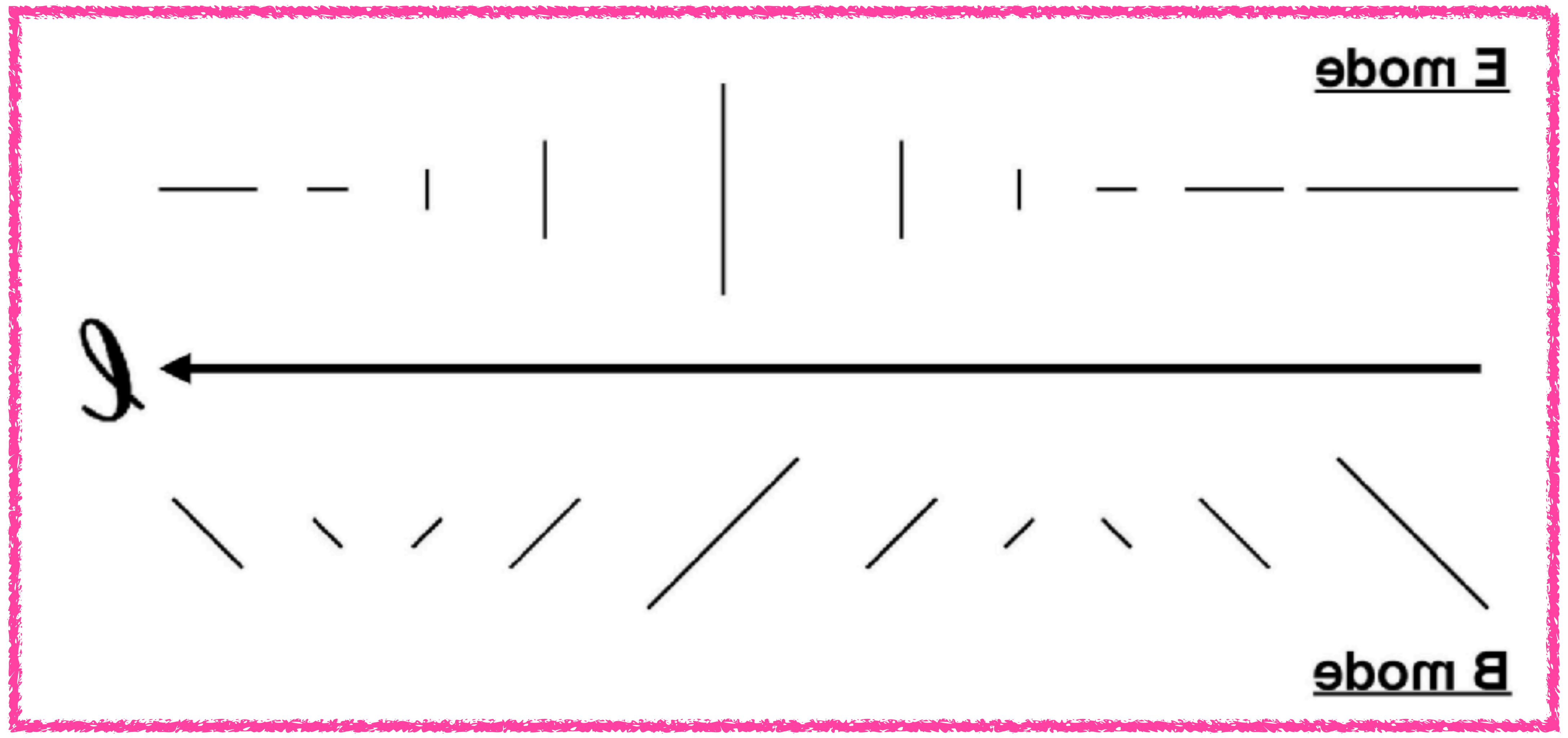
- **E-mode**：Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- **B-mode**：Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

IMPORTANT”: These “E and B modes” are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

# Parity Flip

## E-mode remains the same, whereas B-mode changes the sign



- Two-point correlation functions invariant under the parity flip are

$$\langle E_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{EE}$$

$$\langle B_{\boldsymbol{\ell}} B^*_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{BB}$$

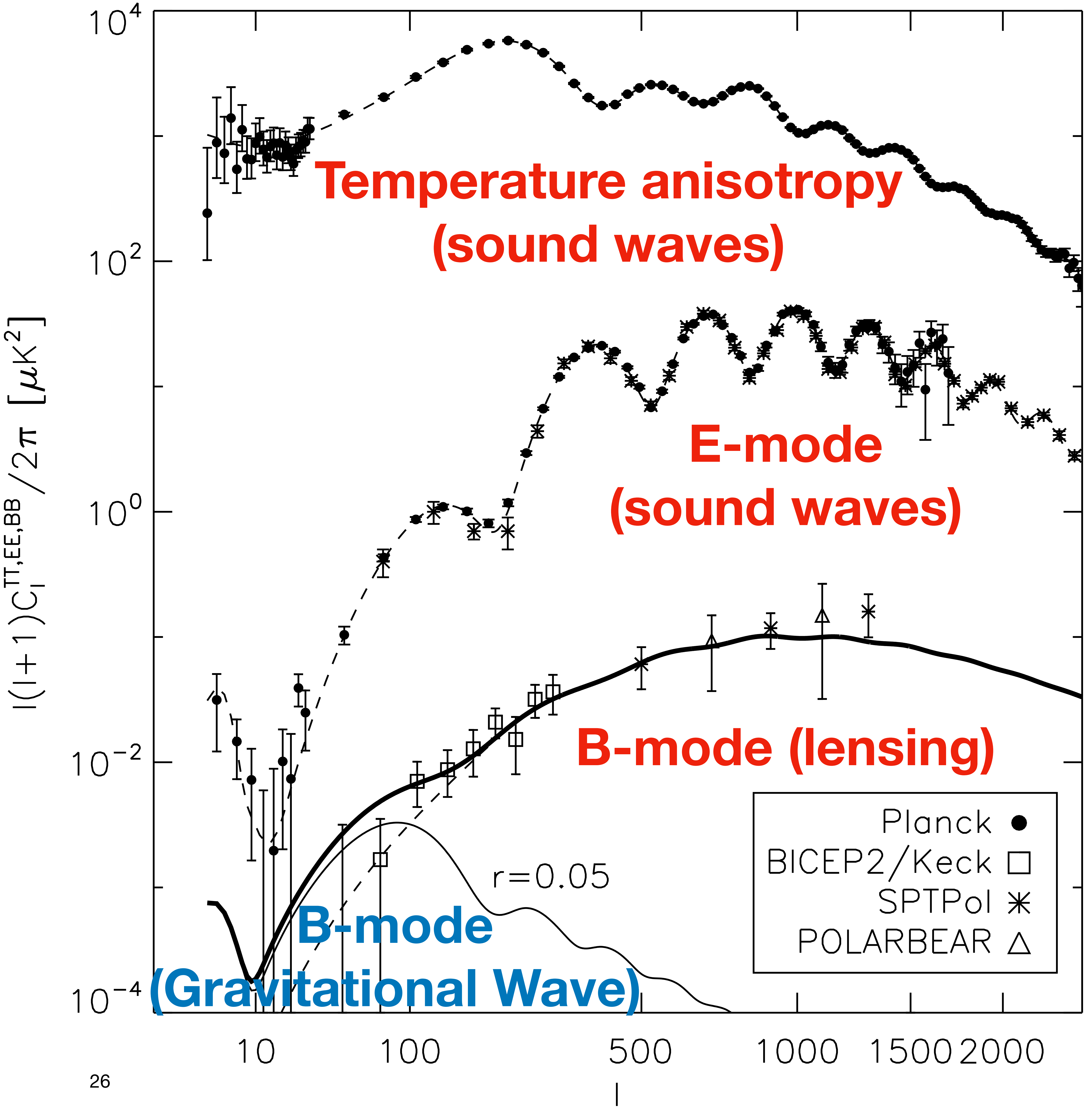
$$\langle T_{\boldsymbol{\ell}} E^*_{\boldsymbol{\ell}'} \rangle = \langle T^*_{\boldsymbol{\ell}} E_{\boldsymbol{\ell}'} \rangle = (2\pi)^2 \delta_D^{(2)}(\boldsymbol{\ell} - \boldsymbol{\ell}') C_\ell^{TE}$$

- The other combinations <TB> and <EB> are not invariant under the parity flip.
  - **We can use these combinations to probe parity-violating physics (e.g., axions)**

# Power Spectra

## A lot have been measured

- This is the typical figure that you find in talks and lectures on CMB.
    - The temperature power spectrum and the E- and B-mode polarisation power spectra have been measured well.
- **Our focus is the EB spectrum, which is not shown here.**



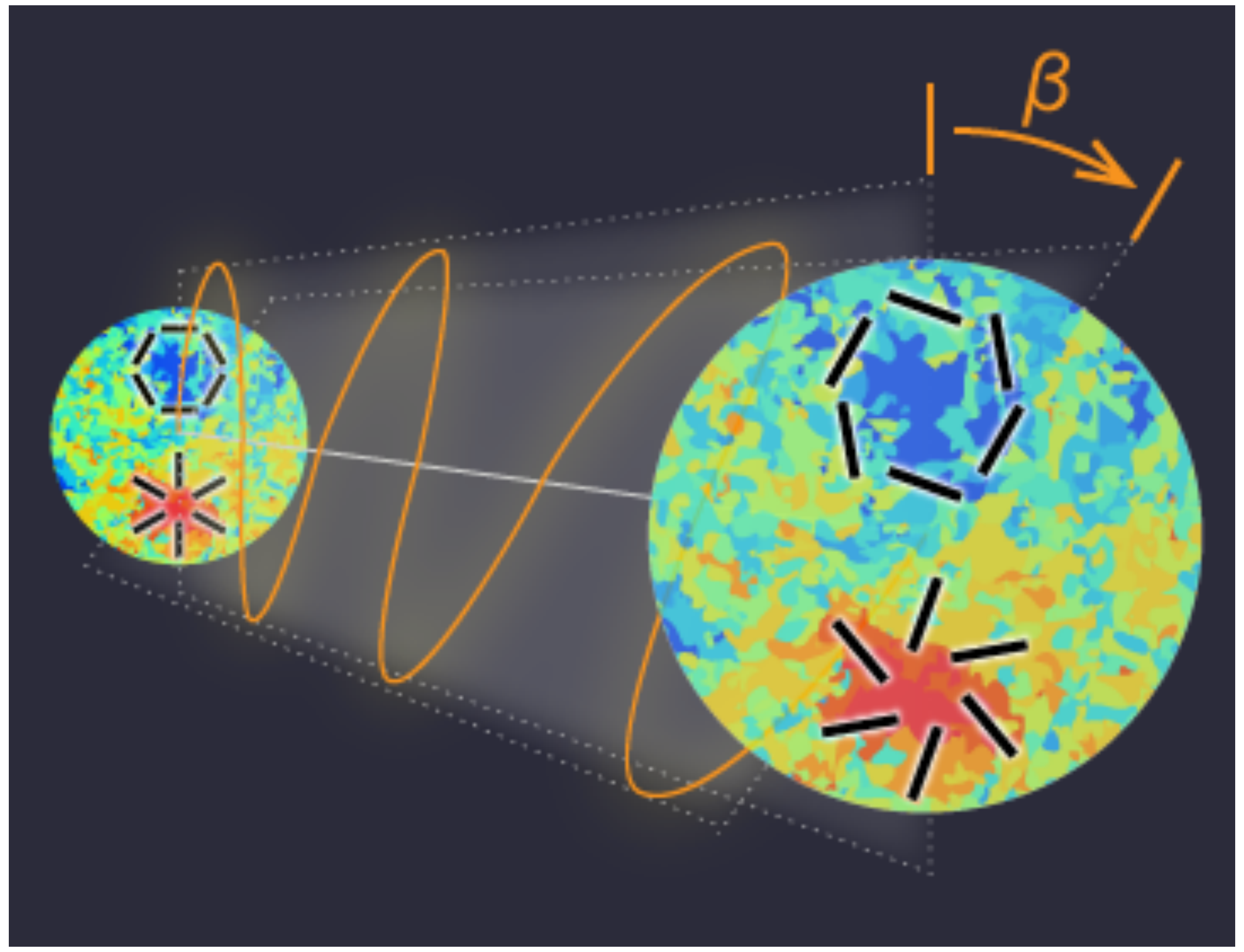
Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

# EB correlation from the cosmic birefringence

## E <-> B conversion by rotation of the linear polarisation plane

- The intrinsic EE, BB, and EB power spectra 13.8 billion years ago would yield the observed EB as

$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

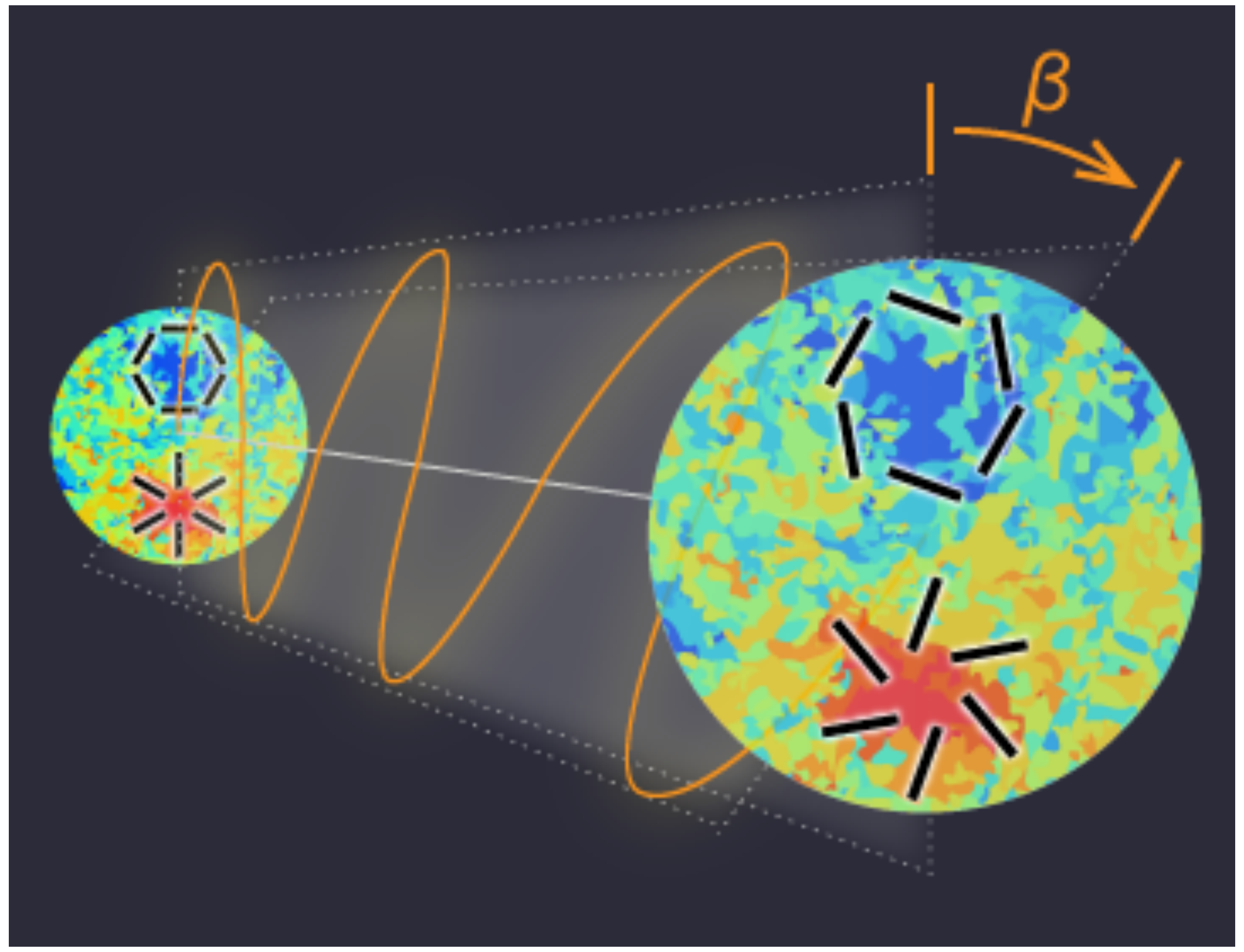



- **How do we infer β from the observational data?**

- Traditionally, one would find β by fitting $C_l^{EE,CMB} - C_l^{BB,CMB}$ to the observed $C_l^{EB,obs}$ using the best-fitting CMB model, and assuming the intrinsic EB to vanish, $C_l^{EB}=0$.

# Searching for the birefringence

**Improvement #1** (Zhao et al. 2015)




- If we look at how EE and BB spectra are also modified,

$$C_\ell^{EE,\mathrm{obs}} = C_\ell^{EE}\cos^2(2\beta) + C_\ell^{BB}\sin^2(2\beta) - C_\ell^{EB}\sin(4\beta)$$

$$C_\ell^{BB,\mathrm{obs}} = C_\ell^{EE}\sin^2(2\beta) + C_\ell^{BB}\cos^2(2\beta) + C_\ell^{EB}\sin(4\beta)$$

- We find

$$C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}} = (C_\ell^{EE} - C_\ell^{BB})\cos(4\beta) - 2C_\ell^{EB}\sin(4\beta)$$

- Thus,

$$C_\ell^{EB,\mathrm{obs}} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

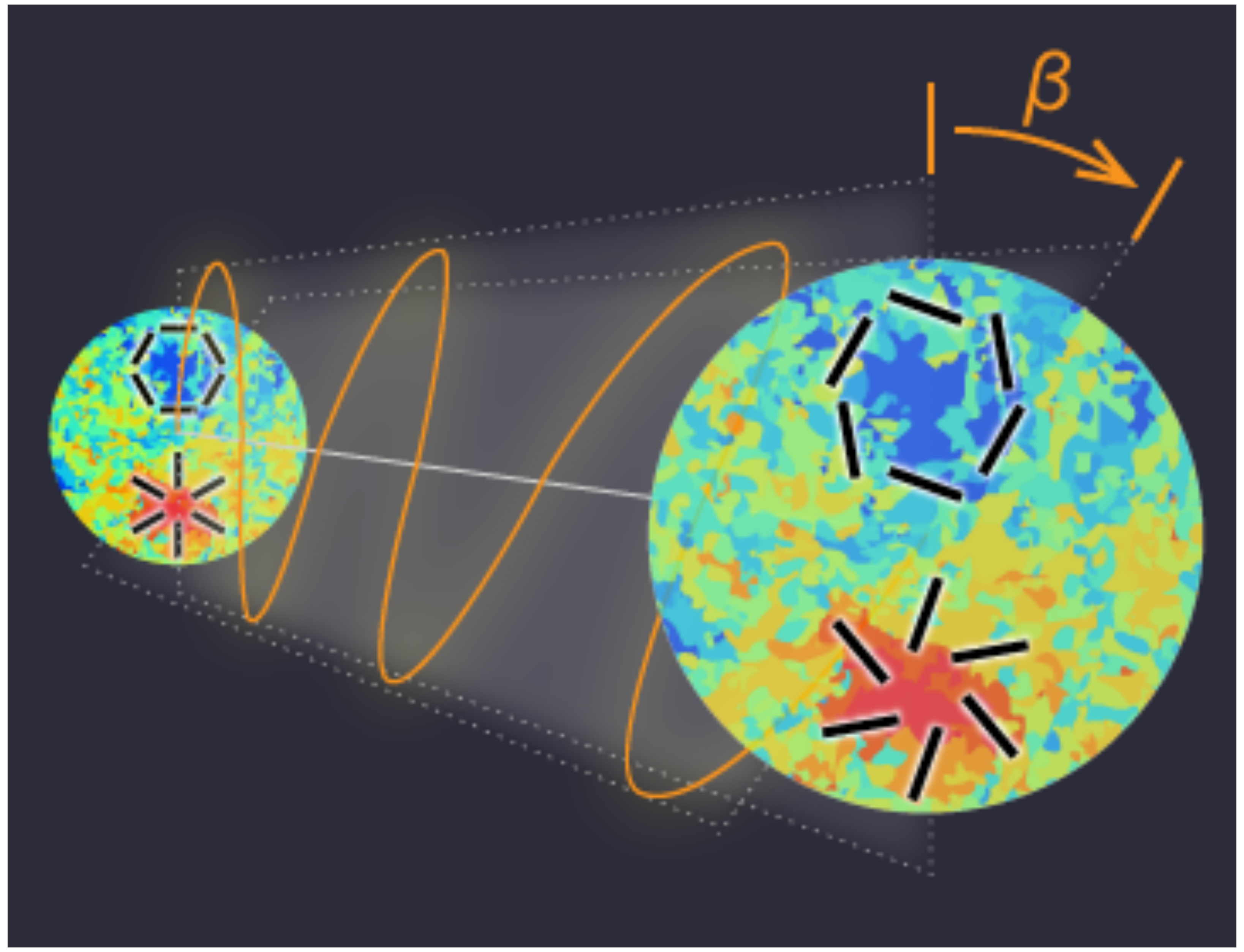
$$= \frac{1}{2}\boxed{(C_\ell^{EE,\mathrm{obs}} - C_\ell^{BB,\mathrm{obs}})}\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

No need to assume a model

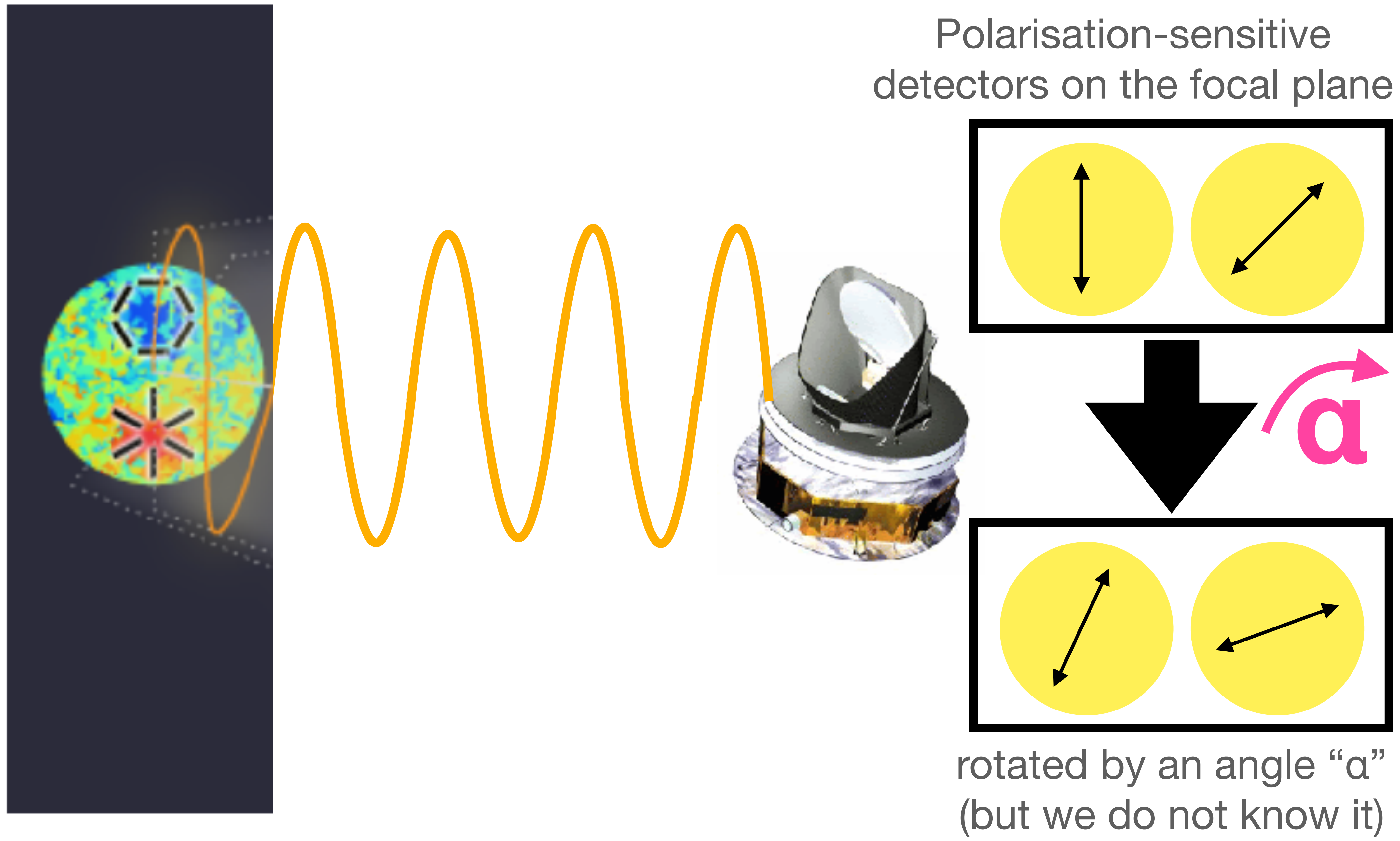
# The Biggest Problem: Miscalibration of detectors

# Impact of miscalibration of polarisation angles

## Cosmic or Instrumental?




OR




- Is the plane of linear polarisation rotated by the genuine cosmic birefringence effect, or simply because the polarisation-sensitive directions of 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, Komatsu 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, Komatsu 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)
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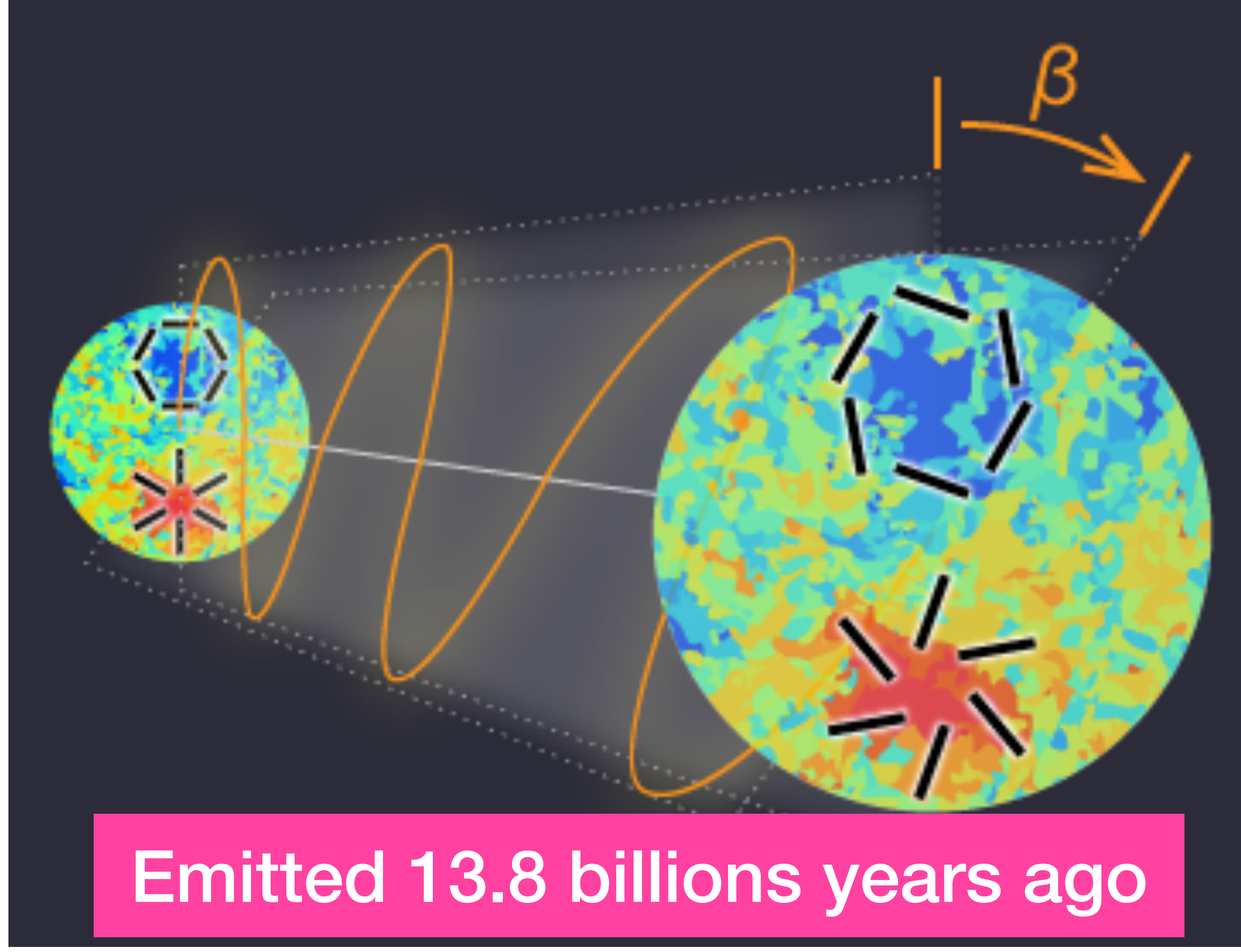
Uncertainty in the calibration of α has been the major limitation

# The Key Idea: The polarised Galactic foreground emission as a calibrator


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

# Searching for the birefringence

## Improvement #2 (Minami et al. 2019)




But the source of foreground is much closer!

- **Idea:** *Miscalibration of the polarization angle α rotates both the foreground and CMB, but β affects only the CMB.*

$$E^{\rm o}_{\ell,m} = E^{\rm fg}_{\ell,m}\cos(2\alpha) - B^{\rm fg}_{\ell,m}\sin(2\alpha) + E^{\rm CMB}_{\ell,m}\cos(2\alpha+2\beta) - B^{\rm CMB}_{\ell,m}\sin(2\alpha+2\beta) + E^{\rm N}_{\ell,m}$$

$$B^{\rm o}_{\ell,m} = E^{\rm fg}_{\ell,m}\sin(2\alpha) + B^{\rm fg}_{\ell,m}\cos(2\alpha) + E^{\rm CMB}_{\ell,m}\sin(2\alpha+2\beta) + B^{\rm CMB}_{\ell,m}\cos(2\alpha+2\beta) + B^{\rm N}_{\ell,m}$$

noise

- Thus,

$$\langle C^{EB,{\rm o}}_\ell\rangle = \frac{\tan(4\alpha)}{2}\left(\underbrace{\langle C^{EE,{\rm o}}_\ell\rangle - \langle C^{BB,{\rm o}}_\ell\rangle}_{\text{measured}}\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\underbrace{\langle C^{EE,{\rm CMB}}_\ell\rangle - \langle C^{BB,{\rm CMB}}_\ell\rangle}_{\text{known accurately}}\right)$$

$$+ \frac{1}{\cos(4\alpha)}\langle C^{EB,{\rm fg}}_\ell\rangle + \frac{\cos(4\beta)}{\cos(4\alpha)}\langle C^{EB,{\rm CMB}}_\ell\rangle\,.$$

Key: No explicit modelling of the foreground EE and BB is necessary

# Assumption for the baseline result

## What about the intrinsic EB correlation of the foreground emission?

$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$
$$+ \frac{1}{\cos(4\alpha)}\boxed{\langle C_\ell^{EB,\mathrm{fg}}\rangle} + \frac{\cos(4\beta)}{\cos(4\alpha)}\boxed{\langle C_\ell^{EB,\mathrm{CMB}}\rangle}.$$

- For the baseline result, we ignore the intrinsic EB correlations of the foreground $\langle C_\ell^{EB,\mathrm{fg}}\rangle$ and the CMB $\langle C_\ell^{EB,\mathrm{CMB}}\rangle$.
    - The latter is justifiable but the former is not. We will revisit this important issue at the end.

Minami et al. (2019)

# Likelihood for the simplest case

## Single-frequency case, full sky data

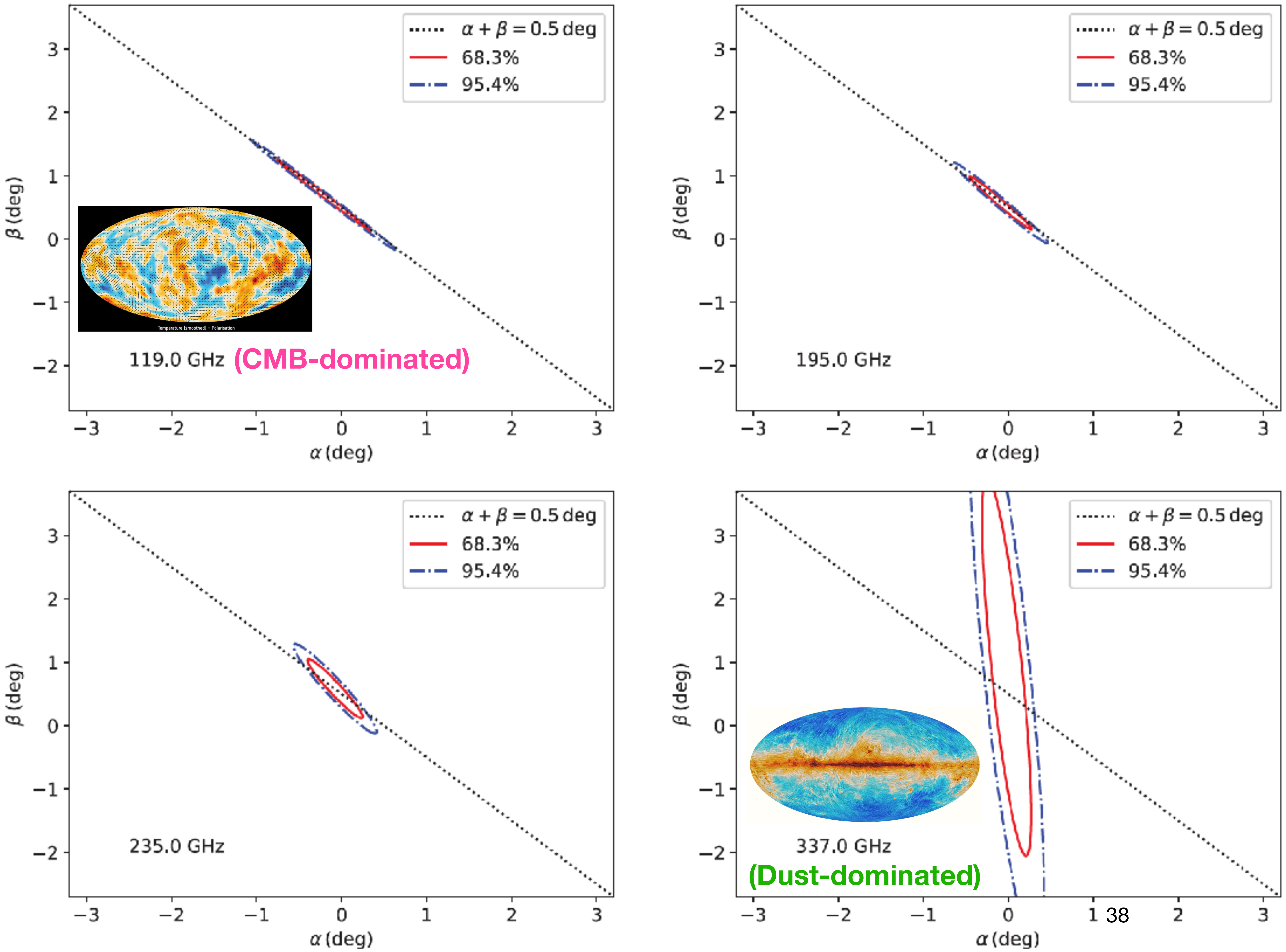
$$-2\ln\mathcal{L} = \sum_{\ell=2}^{\ell_{\max}} \frac{\left[C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right) - \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\mathrm{CMB}} - C_\ell^{BB,\mathrm{CMB}}\right)\right]^2}{\mathrm{Var}\left(C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)\right)}$$

- We determine α and β simultaneously from this likelihood.
- We first validate the algorithm using simulated data.
- For analysing the Planck data, we use the multi-frequency likelihood developed in Minami and Komatsu (2020a).

*Minami et al. (2019)*

# How does it work?

## Simulation of future CMB data (LiteBIRD)




- When the data are dominated by CMB, the sum of two angles, α+β, is determined precisely.
    - This is the diagonal line.
- The foreground determines α with some uncertainty, breaking the degeneracy. Then σ(β) ~ σ(α) because σ(α+β) << σ(α).
- When the data are dominated by the foreground, it can determine α but not β due to the lack of sensitivity to the CMB.

# Application to the Planck Data (PR3)

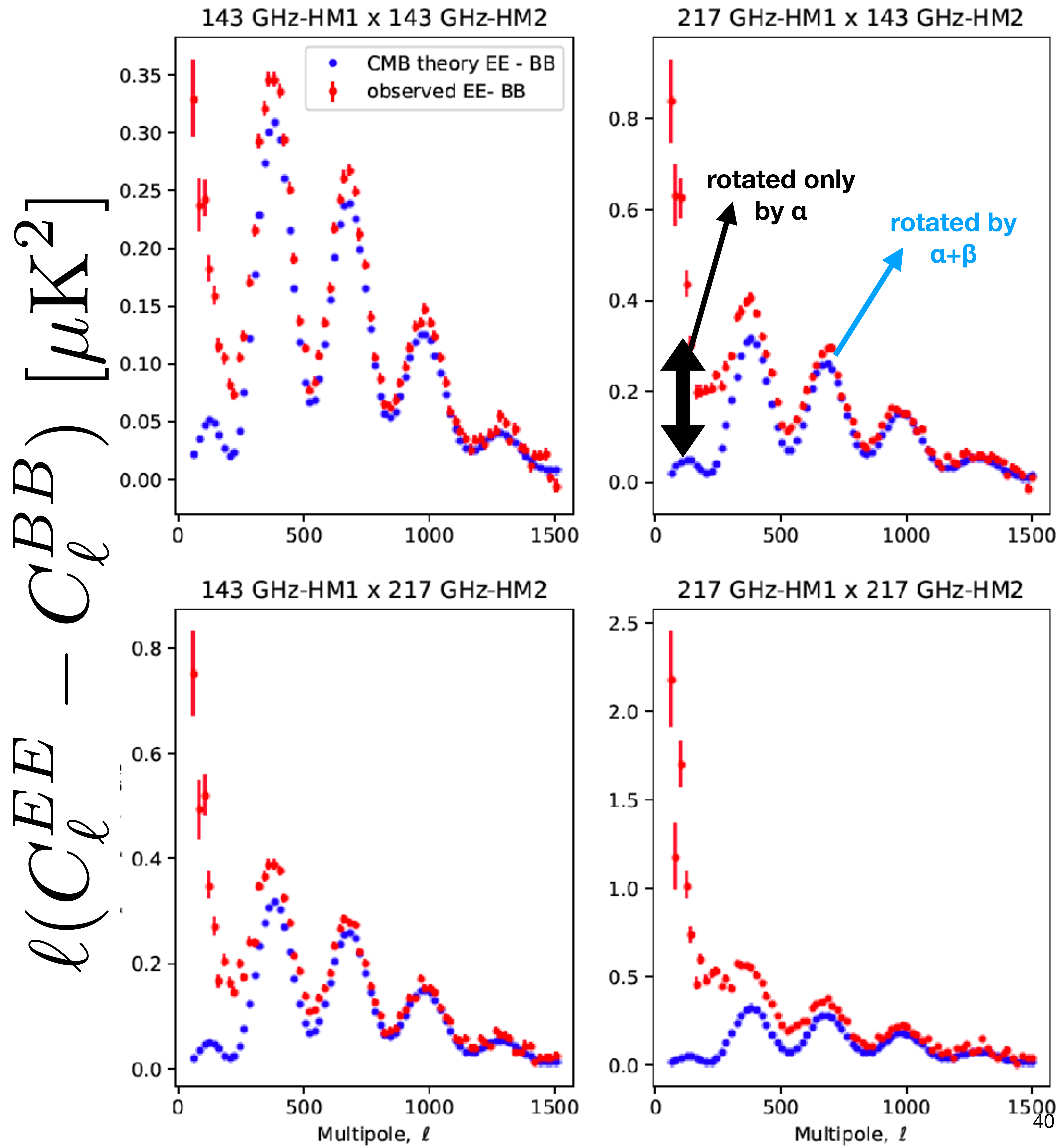
## lmin = 51, lmax = 1500 (the same as those used by the Planck team)

- Planck High Frequency Instrument (HFI) data (100, 143, 217, 353 GHz)

# Main Result: β > 0 at 2.4σ

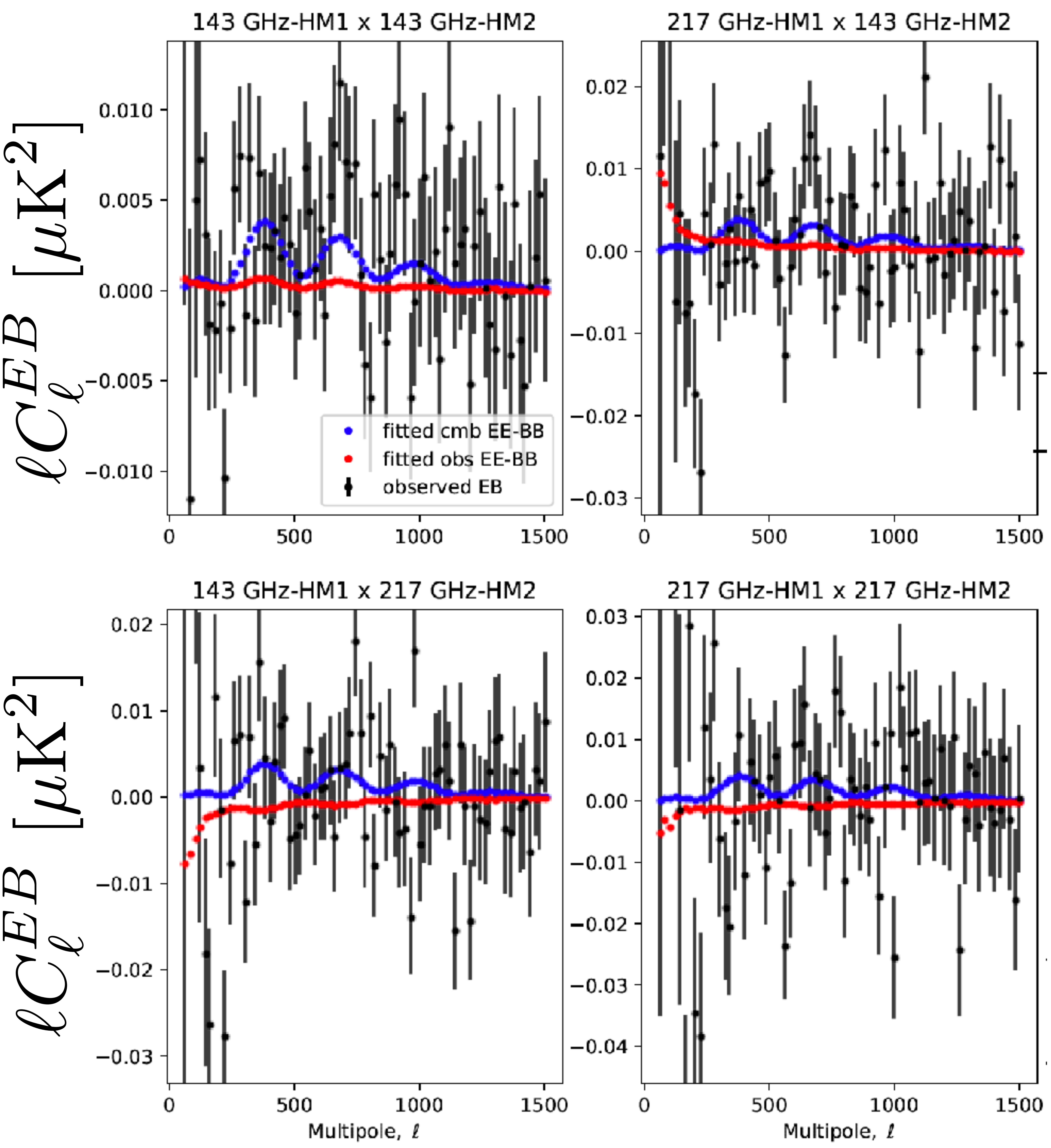
TABLE I. Cosmic birefringence and miscalibration angles from the Planck 2018 polarization data with $1\sigma$ (68%) uncertainties

| Angles | $\alpha_\nu$=0 | Results (deg) |
|---|---|---|
| $\beta$ | 0.289 ± 0.048 (This agrees with the result of the Planck team) | $0.35 \pm 0.14$ |
| $\alpha_{100}$ | | $-0.28 \pm 0.13$ |
| $\alpha_{143}$ | | $0.07 \pm 0.12$ |
| $\alpha_{217}$ | | $-0.07 \pm 0.11$ |
| $\alpha_{353}$ | | $-0.09 \pm 0.11$ |




$$\langle C_\ell^{EB,o}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,o}\rangle - \langle C_\ell^{BB,o}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$

- Can we see β = 0.35 ± 0.14 deg by eyes?
- First, take a look at the observed EE–BB spectra.
  - Red: Total
  - Blue: The best-fitting CMB model
  - *The difference is due to the FG (and maybe unknown systematics)*




*Minami & Komatsu (2020b)*

$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right)$$

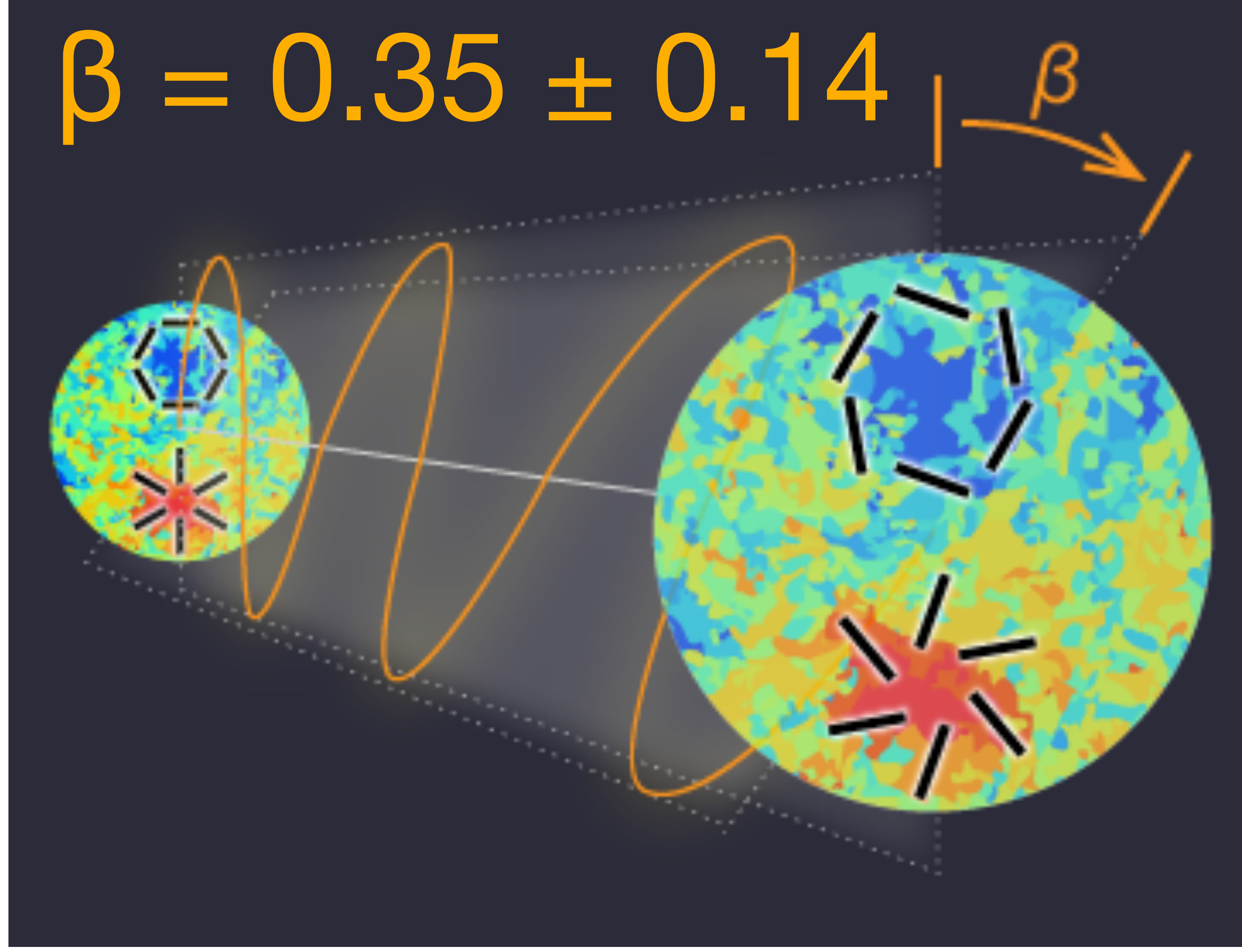
- Can we see β = 0.35 ± 0.14 deg by eyes?
  - Red: The signal attributed to the miscalibration angle, $\alpha_\nu$
  - Blue: The signal attributed to the cosmic birefringence, β
- Red + Blue is the best-fitting model for explaining the data points

# How about the foreground EB?

- If the intrinsic foreground EB power spectrum exists, our method interprets it as a miscalibration angle α.
- Thus, α -> α+γ, where γ is the contribution from the intrinsic EB.
  - The sign of γ is the same as the sign of the foreground EB.
- From FG: α+γ. From CMB: α+β.
  - Thus, our method yields **β–γ = 0.35 ± 0.14 deg.**
- There is evidence for the dust-induced $TE_{dust} > 0$ and $TB_{dust} > 0$. Then, we'd expect $EB_{dust} > 0$ (Huffenberger et al. 2020), i.e., γ>0. If so, β increases further…

# Conclusion: Part I

**$\beta = 0.35 \pm 0.14$ (68%CL)**

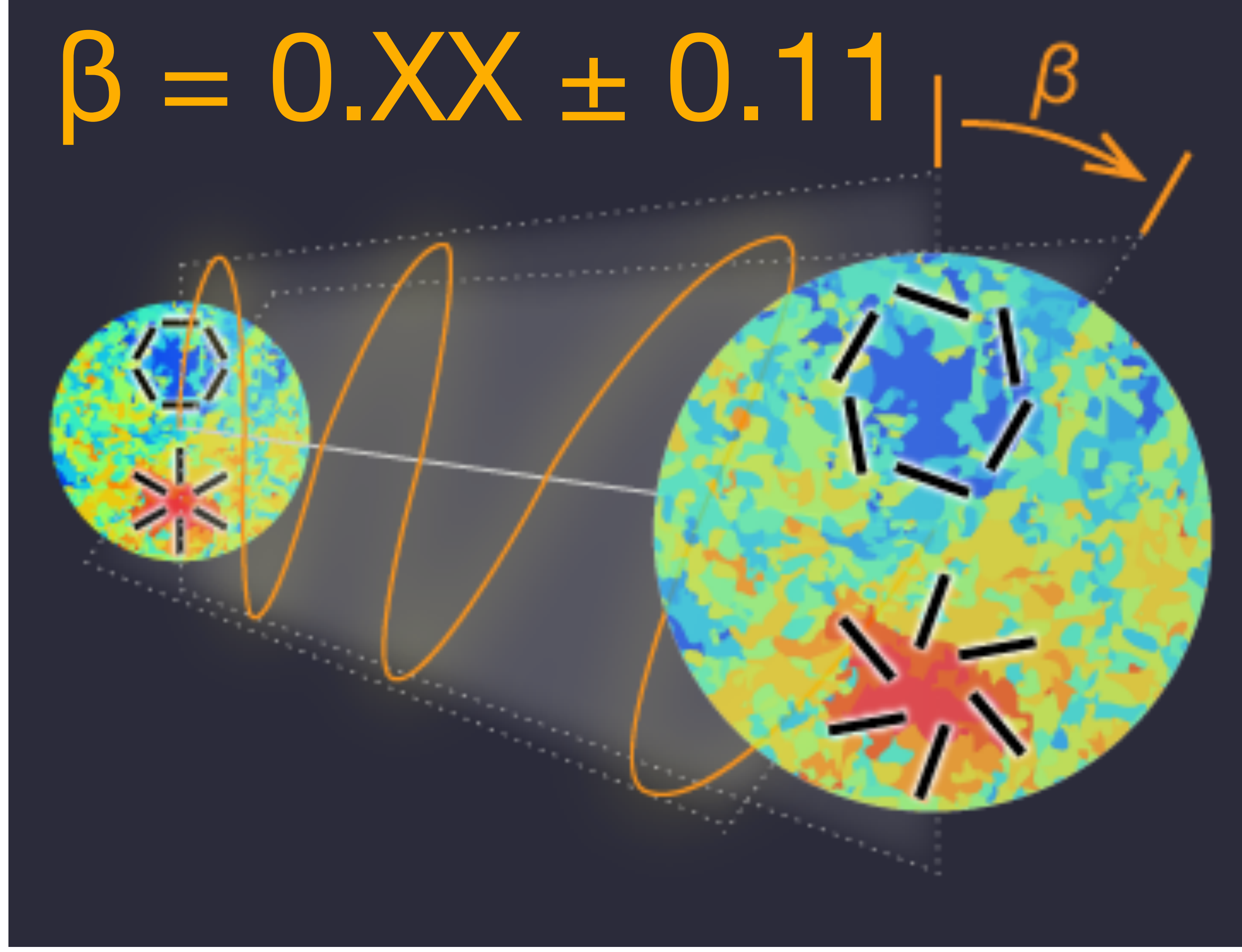



- We perfectly understand what 2.4σ means!
  - Higher statistical significance is need to confirm this signal.
- Our new method finally allowed us to make this "impossible" measurement, which may point to new physics.
  - Our method can be applied to any of the existing and future CMB experiments.
  - The confirmation (or otherwise) of the signal should be possible immediately.
- If confirmed, it would have important implications for dark matter/energy.

# Spoiler!

## β = 0.35 ± 0.14 => 0.XX ± 0.11 (68% CL)

*Diego-Palazuelos, Eskilt, Minami, et al.,*
*to appear in Physical Review Letters soon*




- We have measured β from the latest data release of Planck (PR4)
  - PR4 (“NPIPE” reprocessing of the Planck data) has lower noise.
  - The statistical uncertainty went down from 0.14 to 0.11.
  - What about the best-fitting value? Wait for publication of the paper!
  - ***We will post the paper to arXiv on Monday next week at the latest - most likely sooner.***

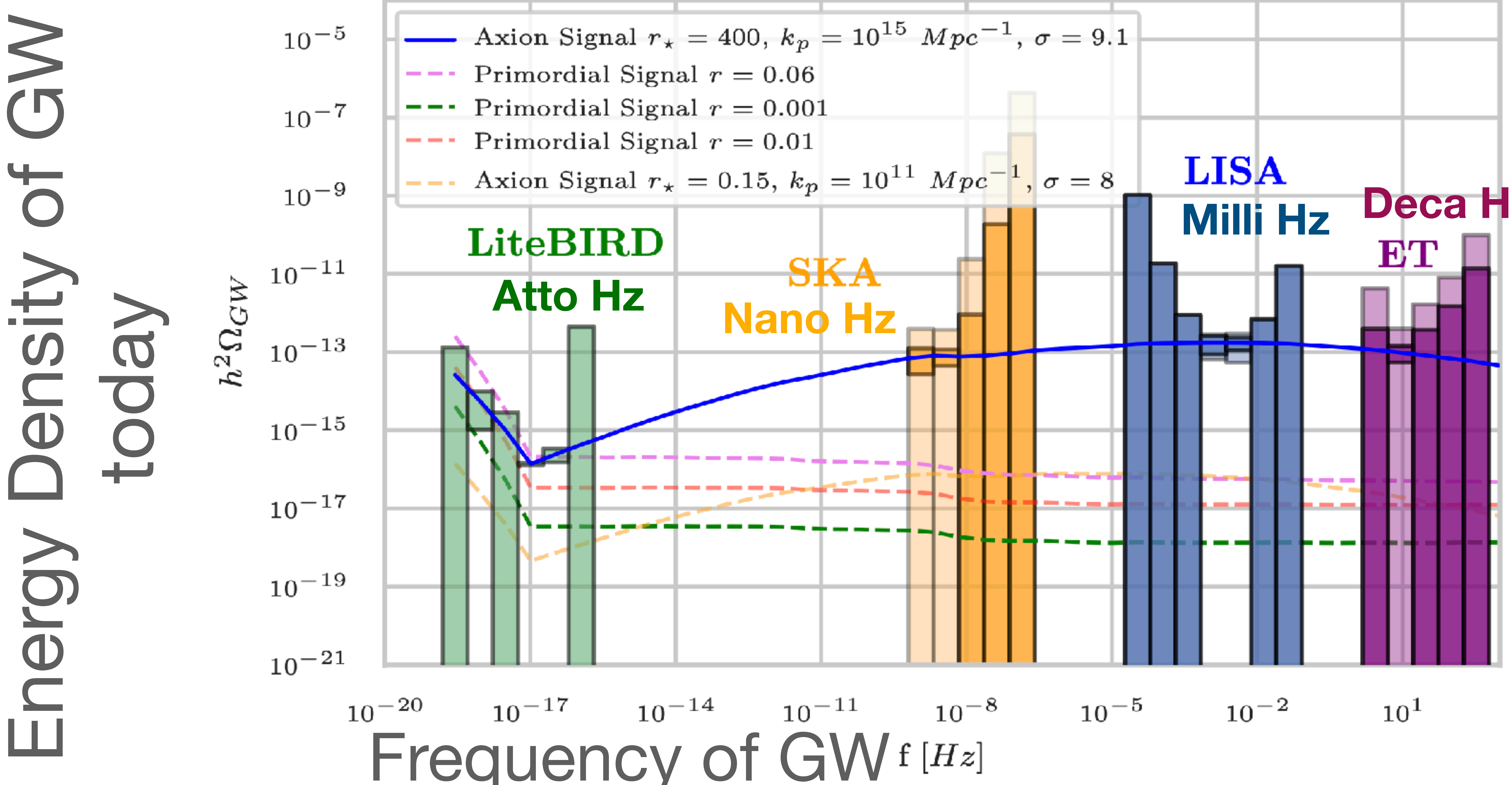
# Part II: Primordial Gravitational Waves

*What powered the Big Bang?*

Campeti, EK, Poletti, Baccigalupi (2021)

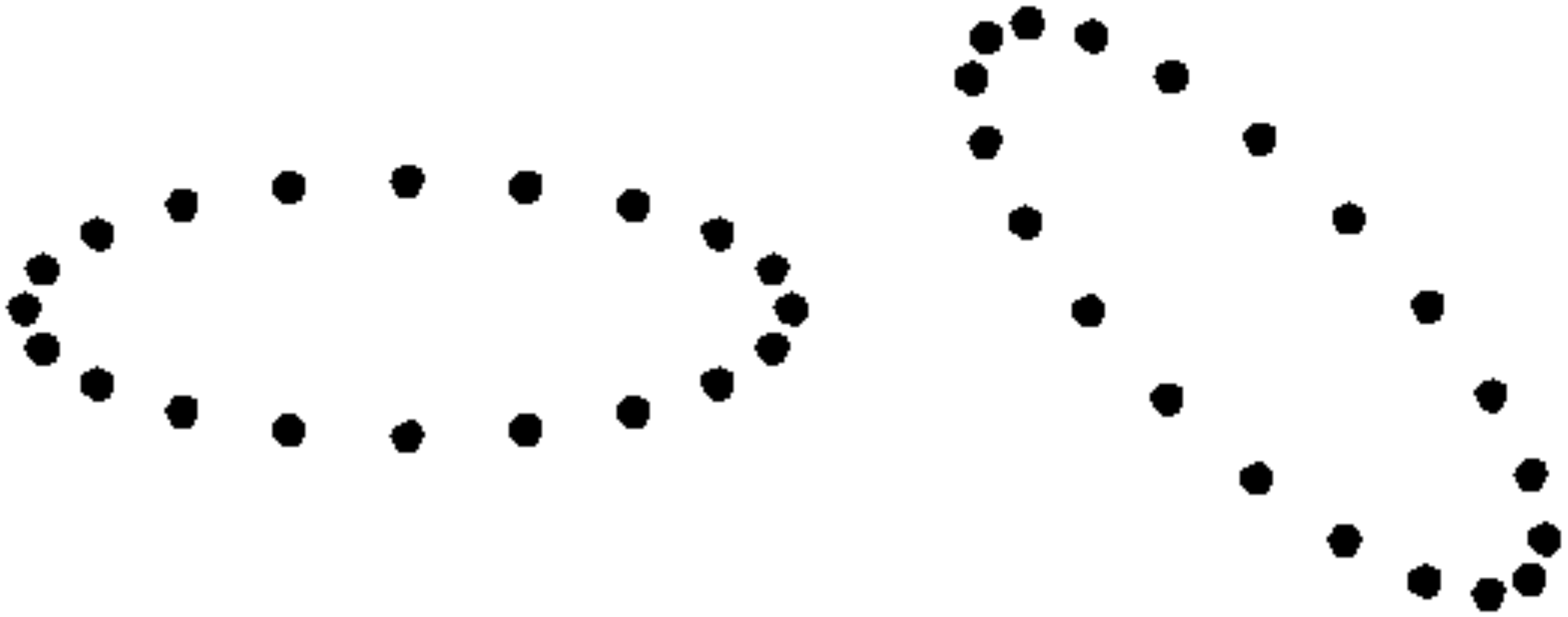
# GWs from the early Universe are everywhere!

## We can measure it across 21 orders of magnitude in the GW frequency



# Gravitational waves are coming towards you!

## To visualise the waves, watch motion of test particles.



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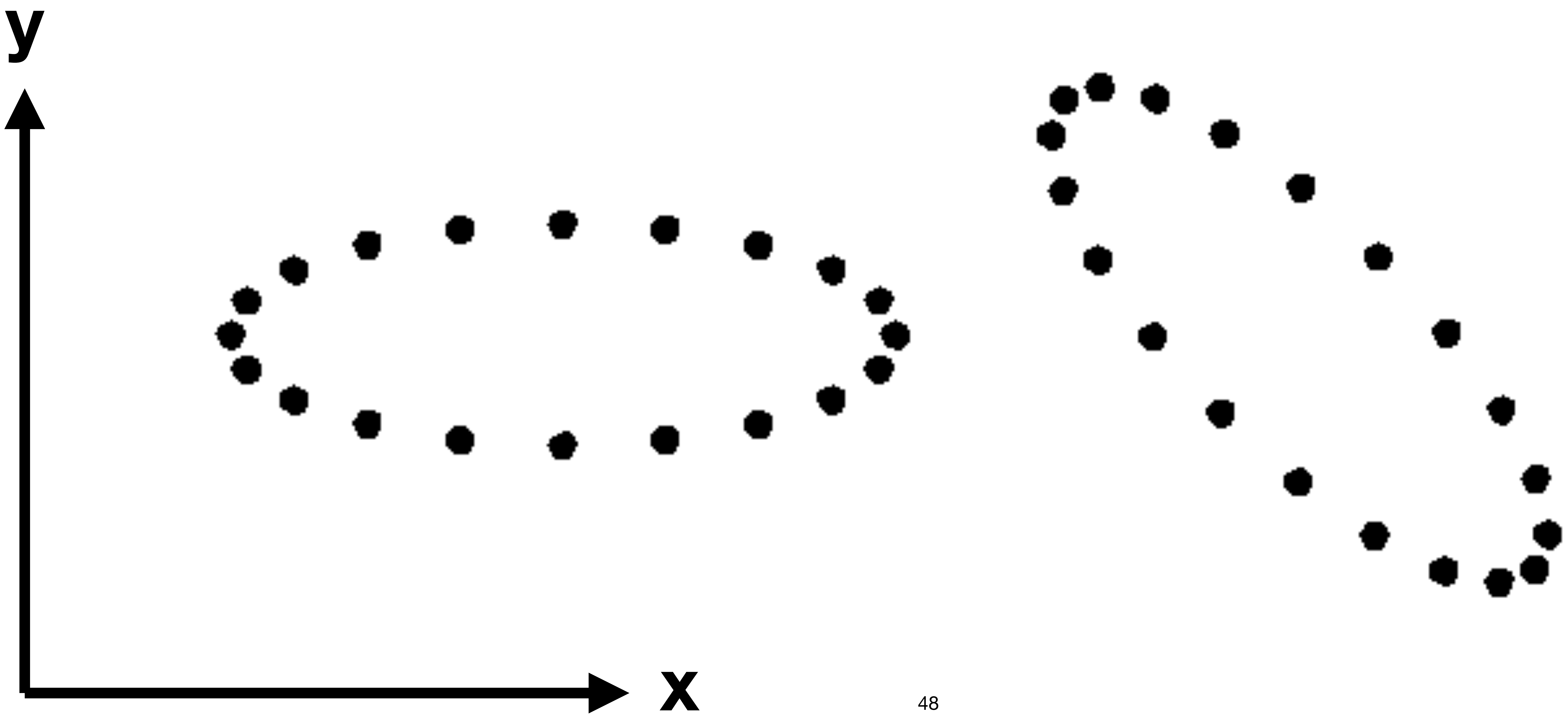


# Distance between two points

- In Cartesian coordinates, the distance between two points in Euclidean space is

$$ds^2 = dx^2 + dy^2 + dz^2$$

- To include the isotropic expansion of space,

$$ds^2 = \boxed{a^2(t)}(dx^2 + dy^2 + dz^2)$$

Scale Factor

# Distortion in space

$x^2$

- Compact notation using Kronecker's delta symbol:

$$ds^2 = a^2(t) \sum_{i=1}^{3} \sum_{j=1}^{3} \delta_{ij} \, dx^i \, dx^j$$

$$\boldsymbol{x} = (x, y, z)$$

$\delta_{ij}$ = 1 for i=j;
$\delta_{ij}$ = 0 otherwise

- To include distortion in space,

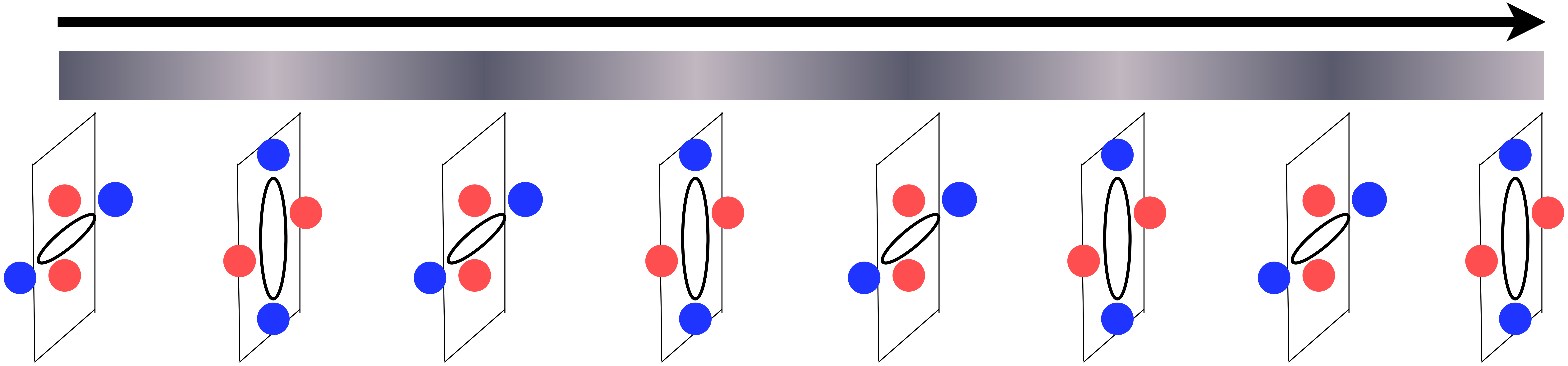
$$ds^2 = a^2 \sum_{i=1}^{3} \sum_{j=1}^{3} (\delta_{ij} + \boxed{h_{ij}}) dx^i dx^j$$

$x^1$

**Distortion in space!**

# Four conditions for gravitational waves

- **The gravitational wave shall be transverse.**
  - The direction of distortion is perpendicular to the propagation direction $\vec{k}$

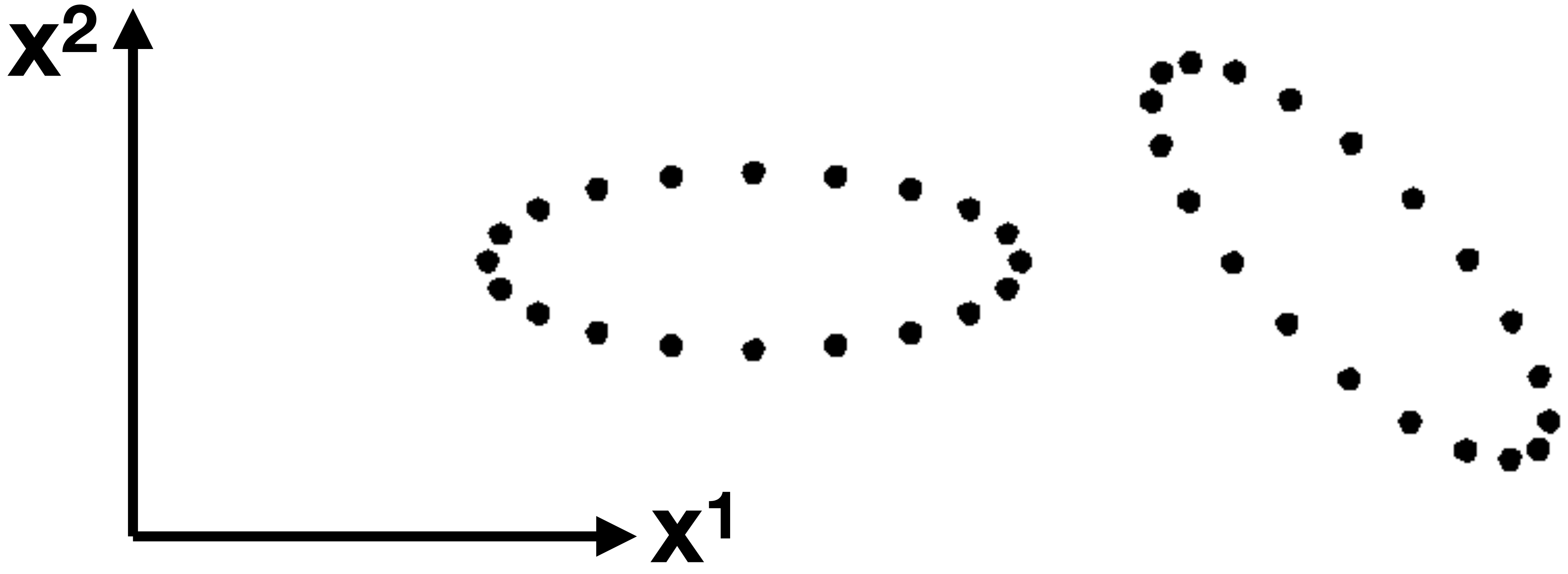


Thus, $$\sum_{i=1}^{3} k^i h_{ij} = 0$$ 3 conditions for $h_{ij}$

# Four conditions for gravitational waves

- **The gravitational wave shall <u>not change the area</u>**
  - The determinant of $\delta_{ij}+h_{ij}$ is 1

$$ds^2 = a^2 \sum_{i=1}^{3} \sum_{j=1}^{3} (\delta_{ij} + h_{ij}) dx^i dx^j$$




Thus, $$\sum_{i=1}^{3} h_{ii} = 0$$

**1 condition for $h_{ij}$**

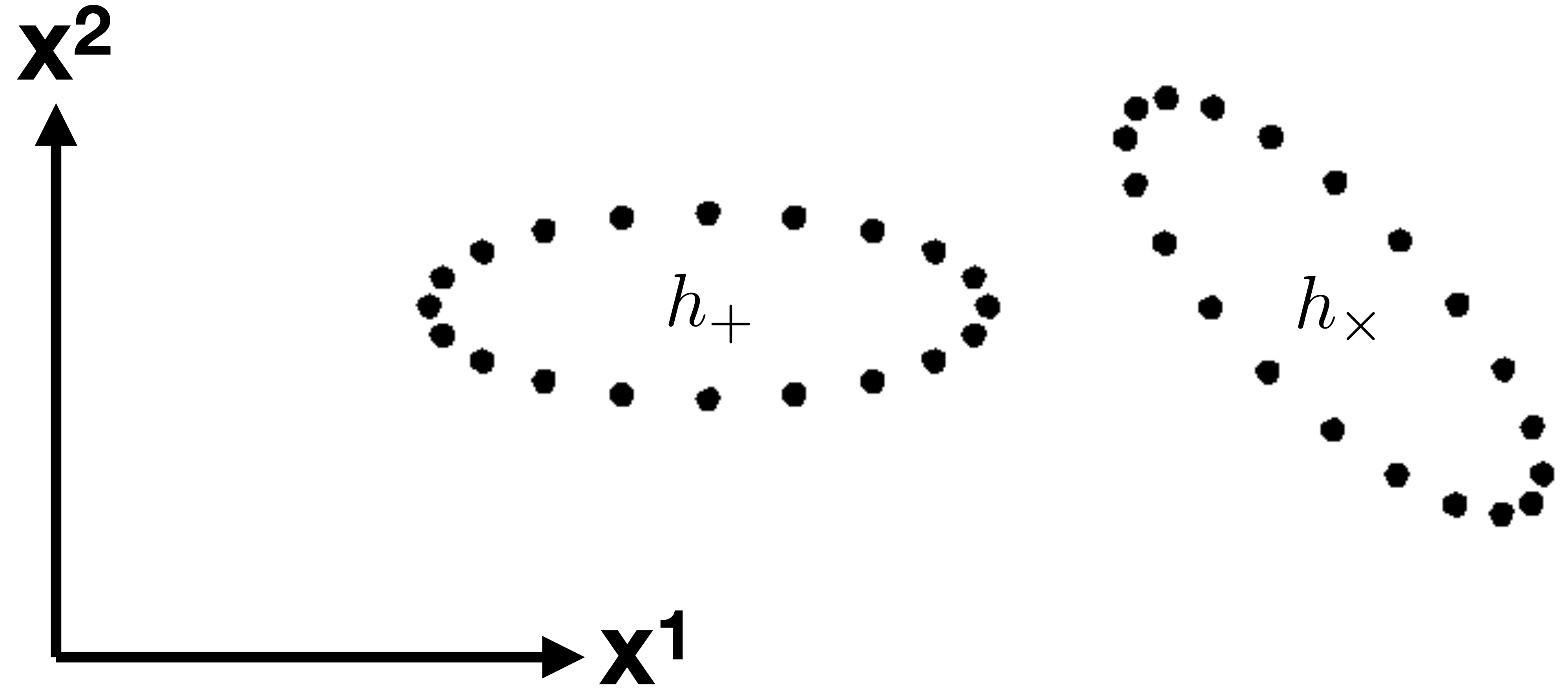
# 6 – 4 = 2 degrees of freedom for GW

## We call them “plus” and “cross” modes

- The symmetric matrix $h_{ij}$ has 6 components, but there are 4 conditions. Thus, we have two degrees of freedom.

- If the GW propagates in the $x^3$=z axis, non-vanishing components of $h_{ij}$ are

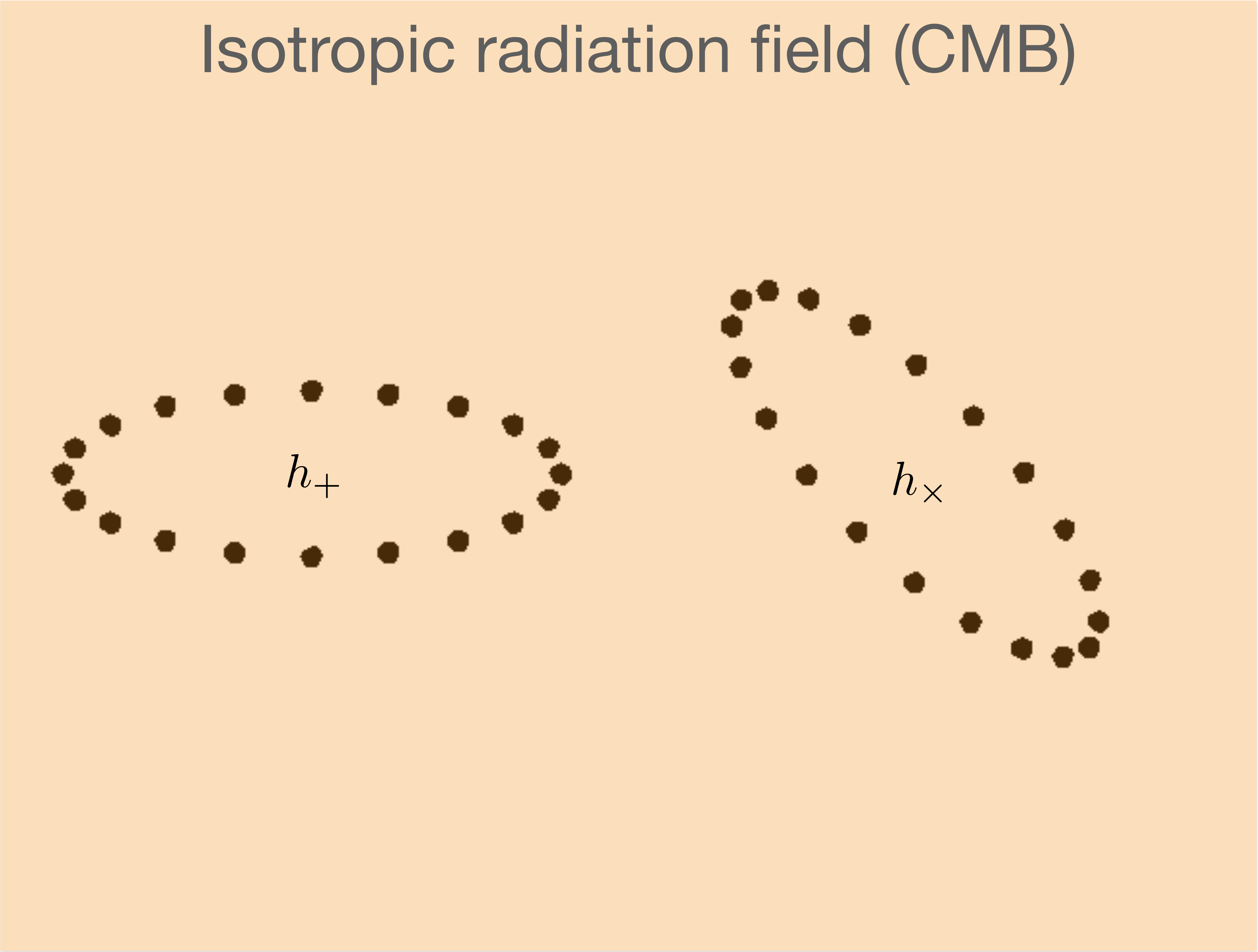
$$h_{ij} = \begin{pmatrix} h_+ & h_\times & 0 \\ h_\times & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

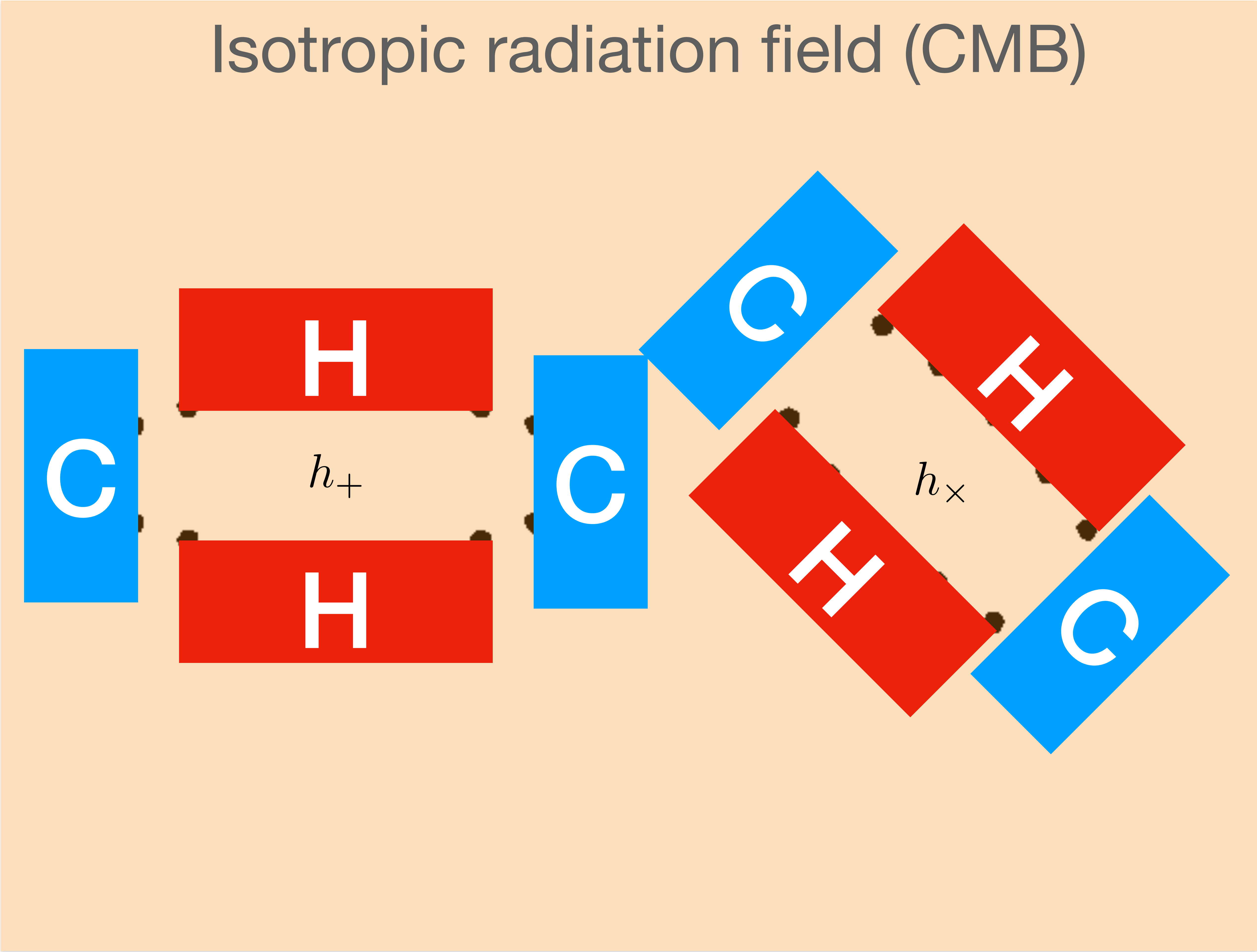



Propagation direction of GW $\vec{k}$
z
$h_+=\cos(kz)$
$h_\times=\cos(kz)$

# Detecting GW by CMB

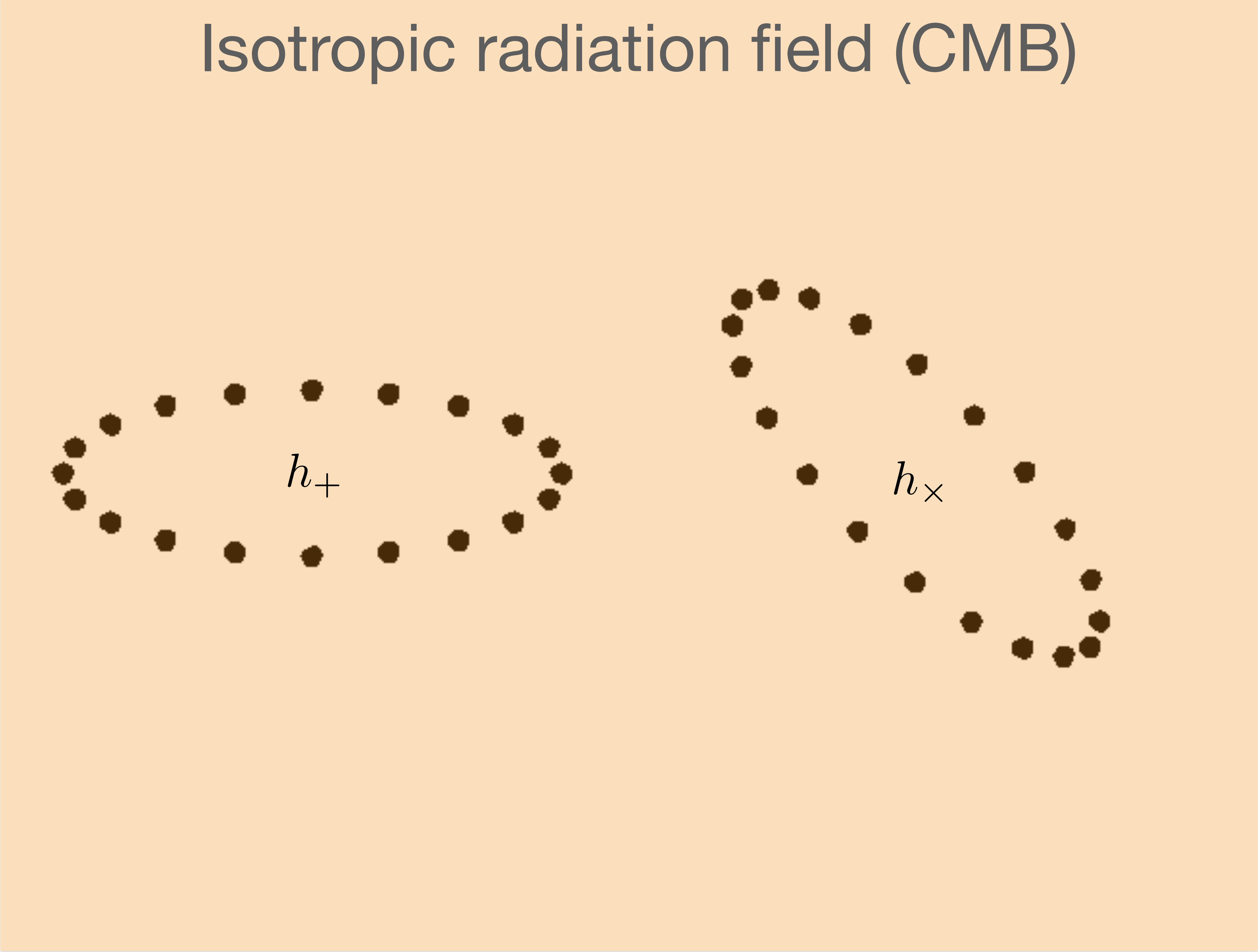
## Quadrupole temperature anisotropy generated by red- and blue-shifting of photons

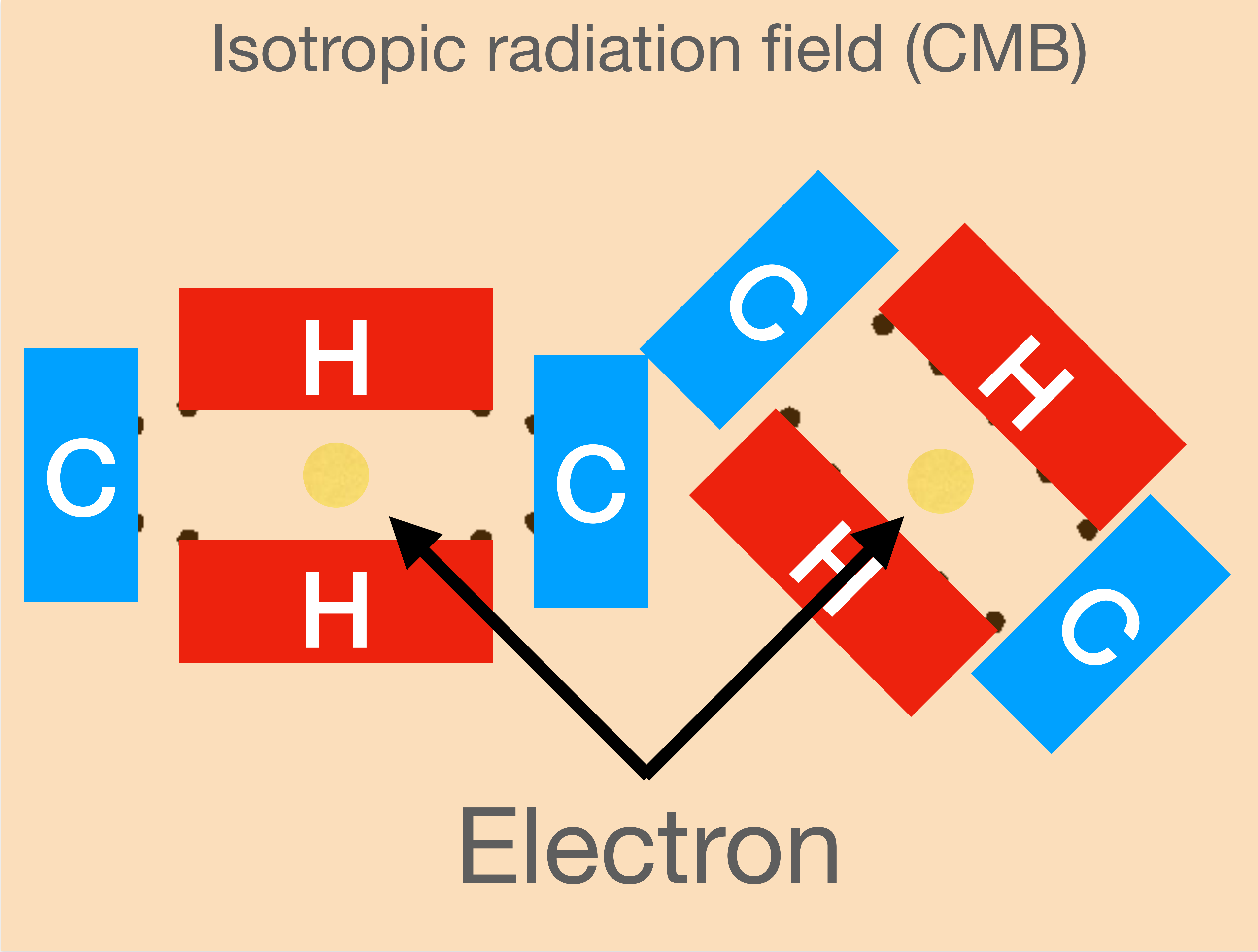


# Detecting GW by CMB

**Quadrupole temperature anisotropy generated by red- and blue-shifting of photons**



*Polnarev (1985)*

# Detecting GW by CMB *Polarisation*

## Quadrupole temperature anisotropy scattered by an electron

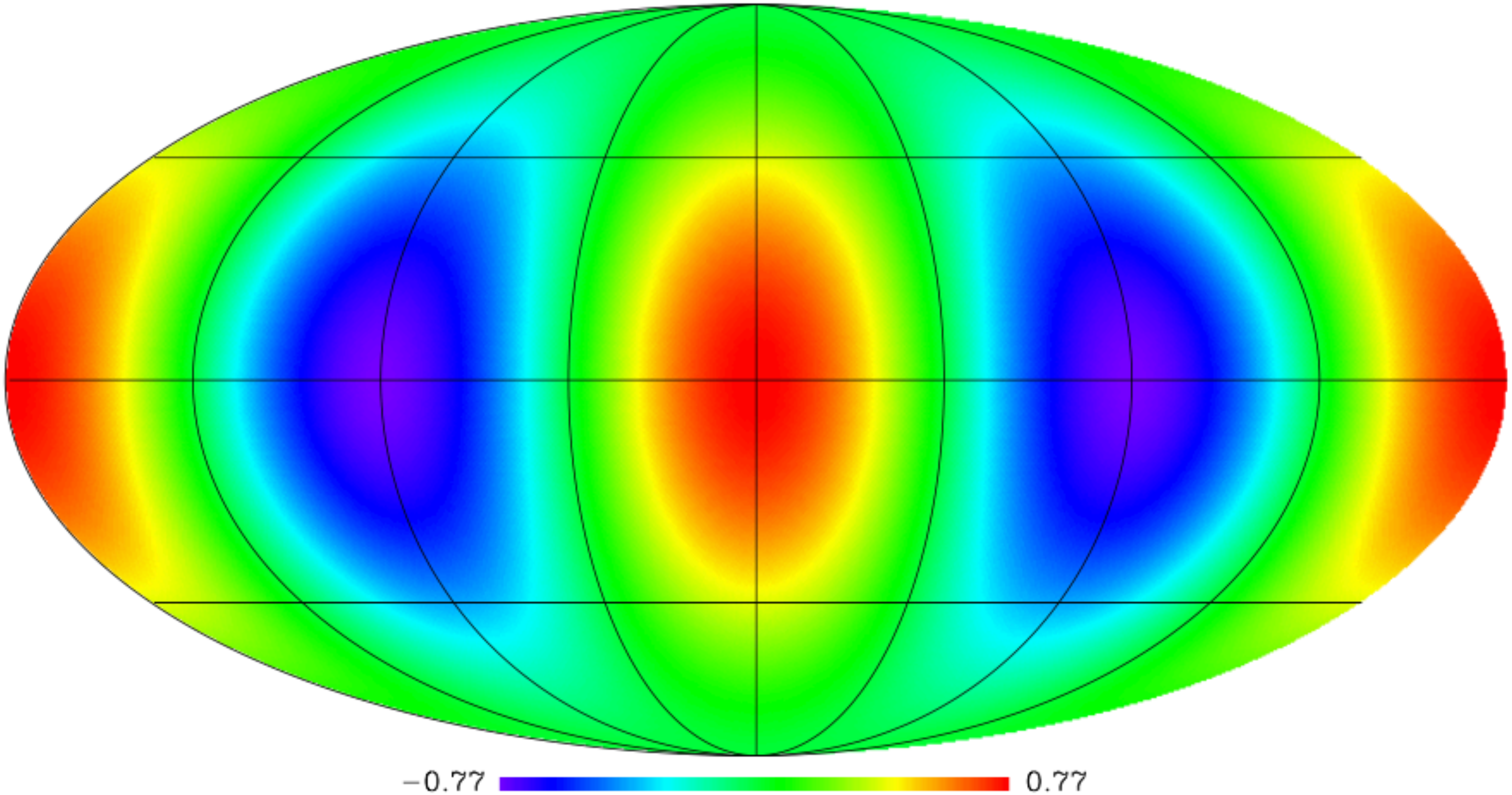
# Physics of CMB Polarisation

## Necessary and sufficient condition: Scattering and Quadrupole Anisotropy


Credit：Wayne Hu

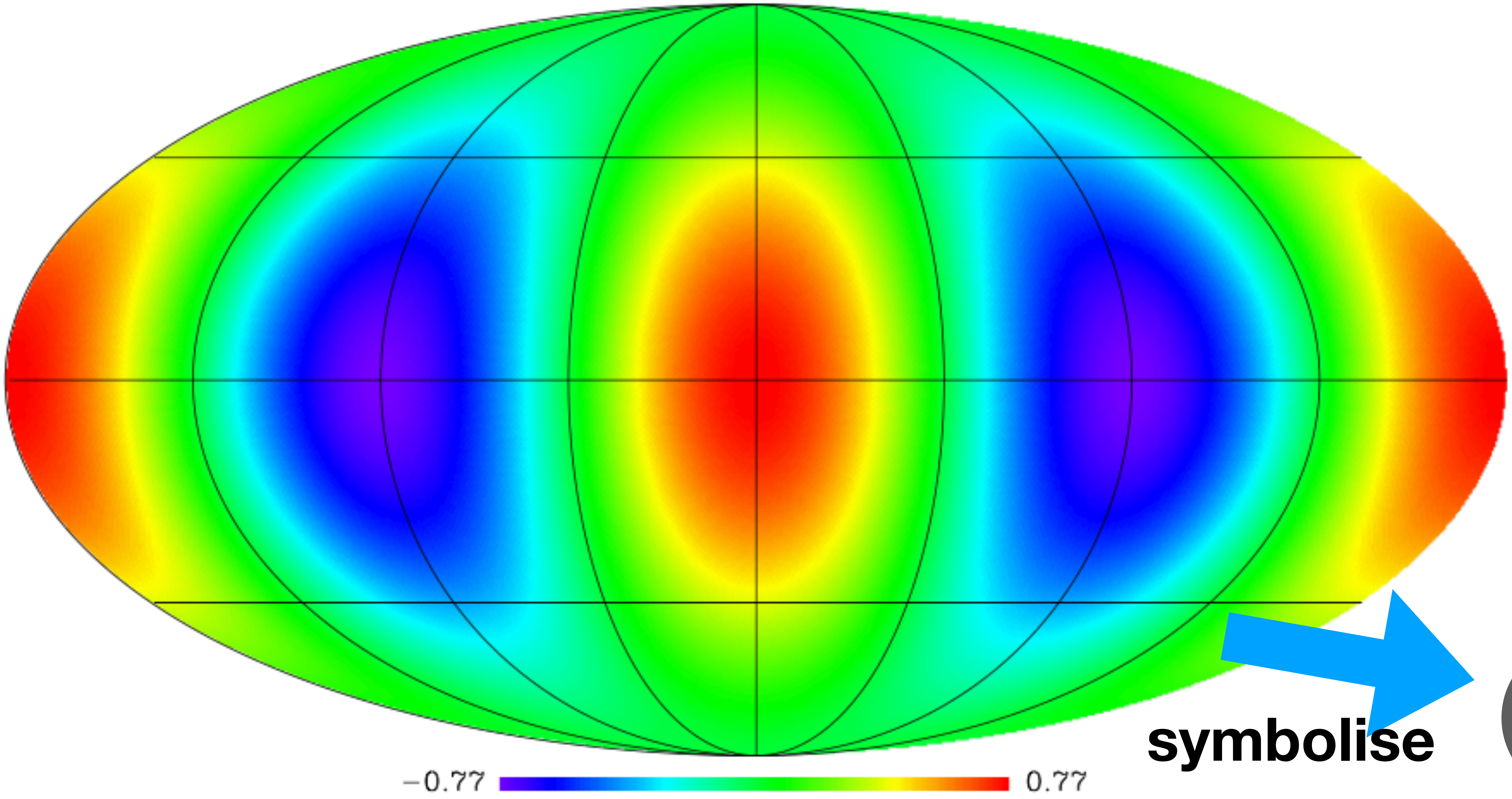
# Local quadrupole seen by an electron

## Imagine you are an electron, observing light over the "full sky"...

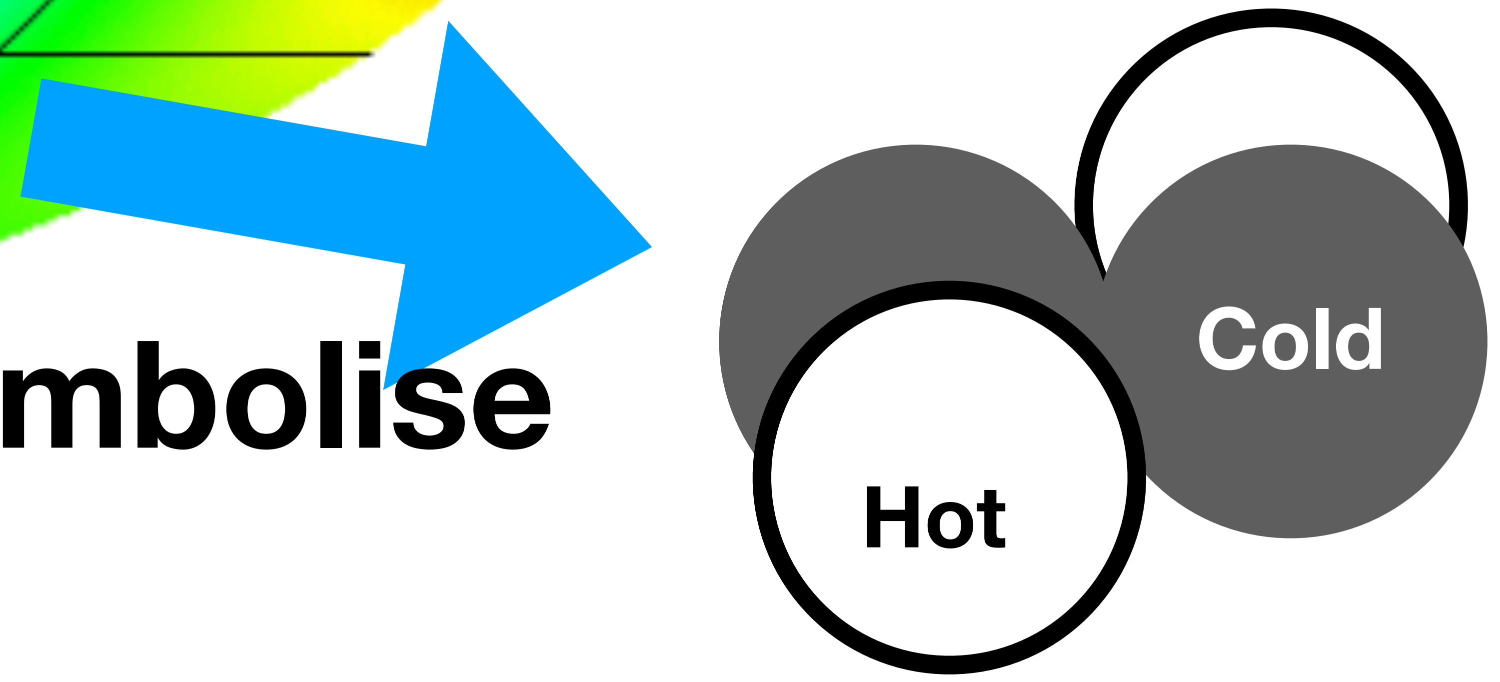


# Local quadrupole seen by an electron

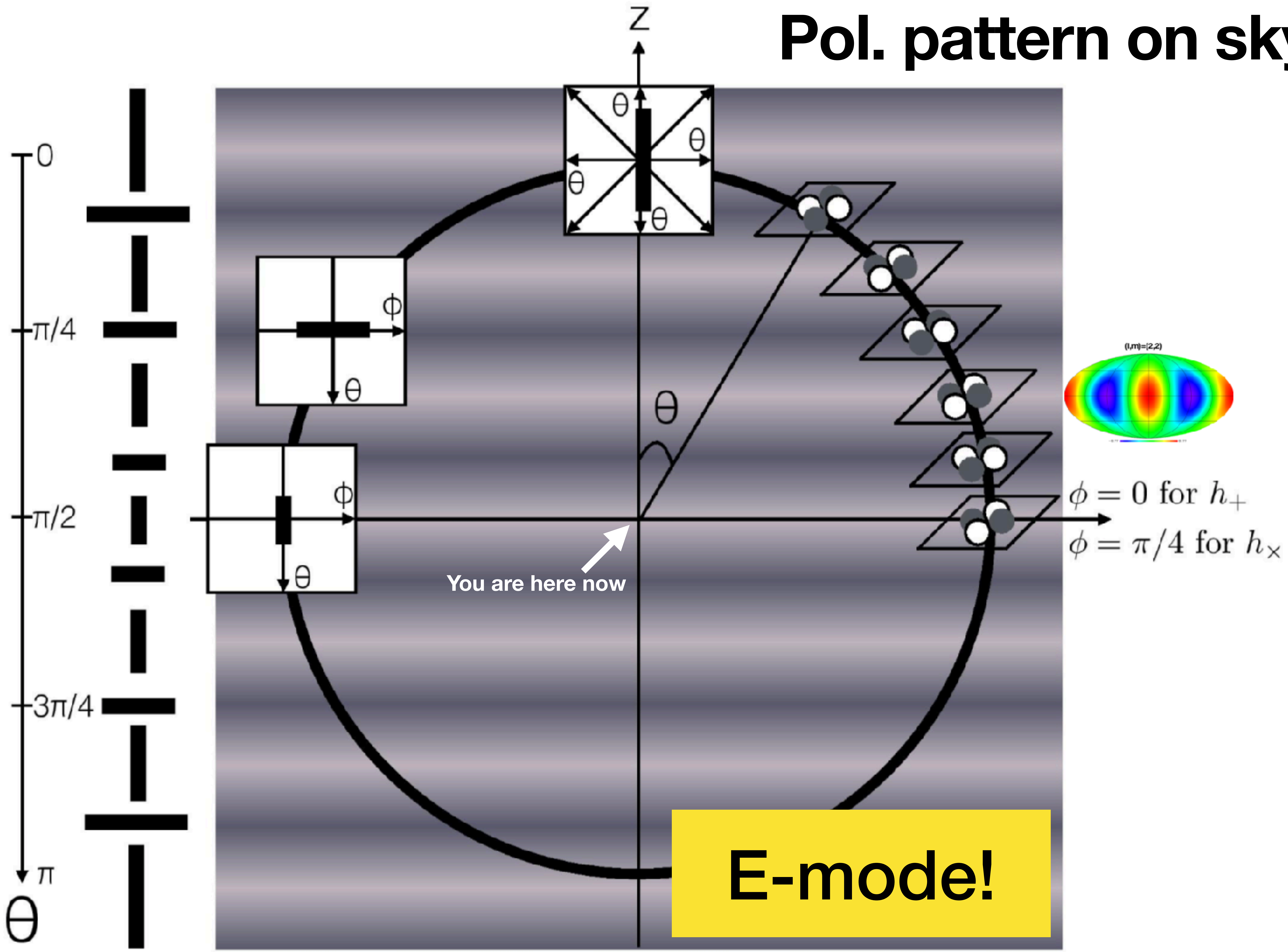
## Imagine you are an electron, observing light over the "full sky"...



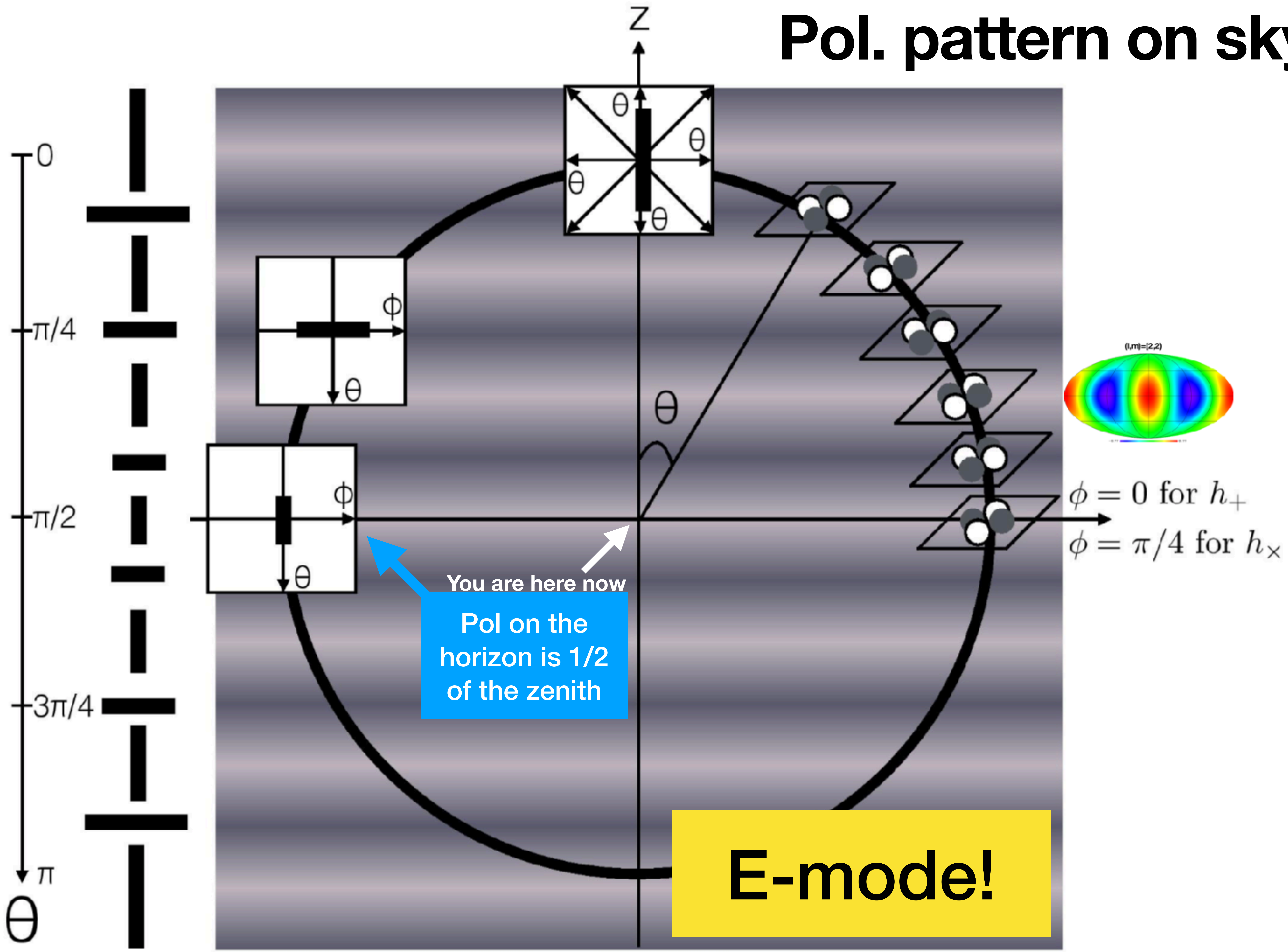

symbolise



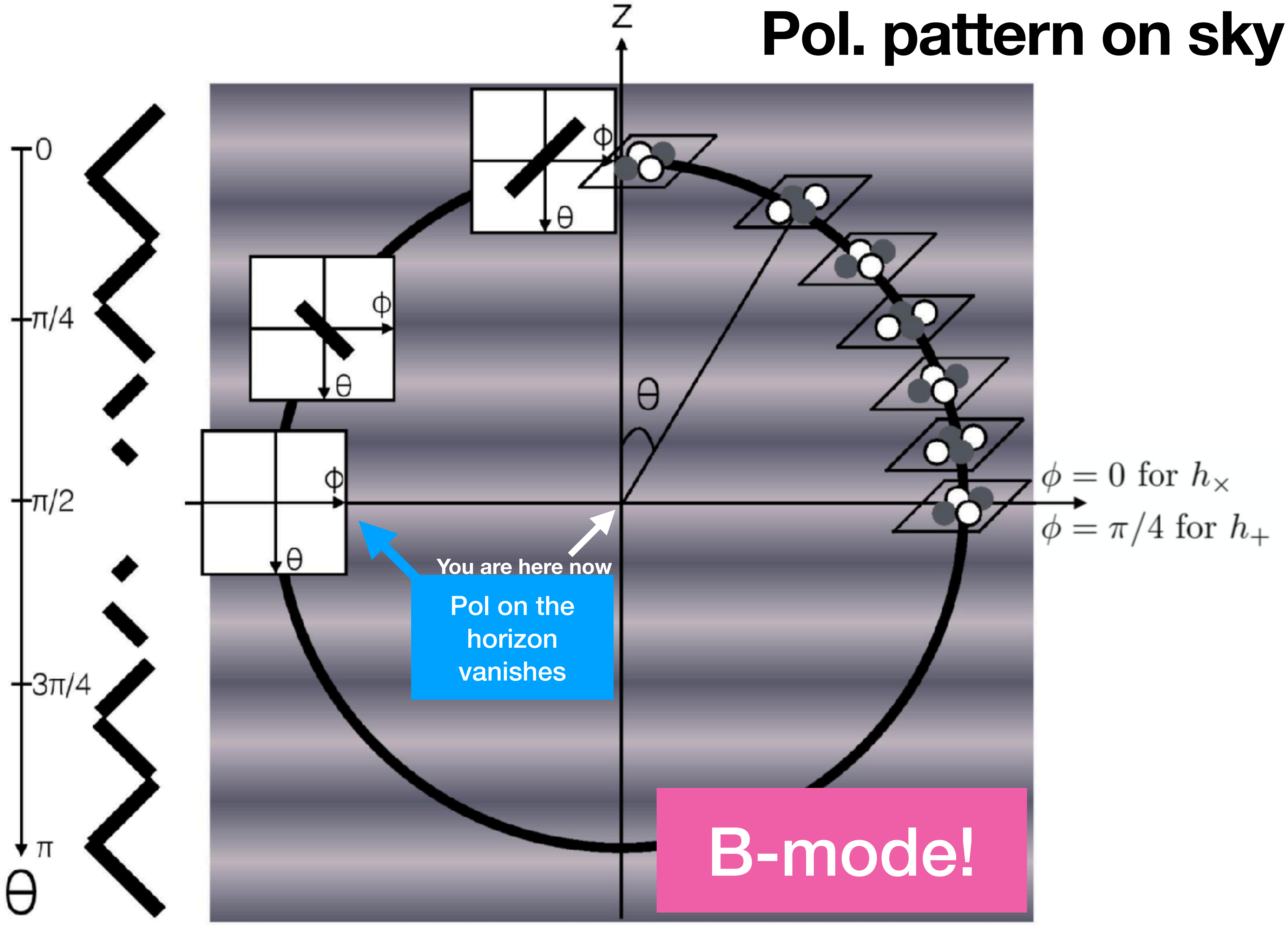
# Pol. pattern on sky today

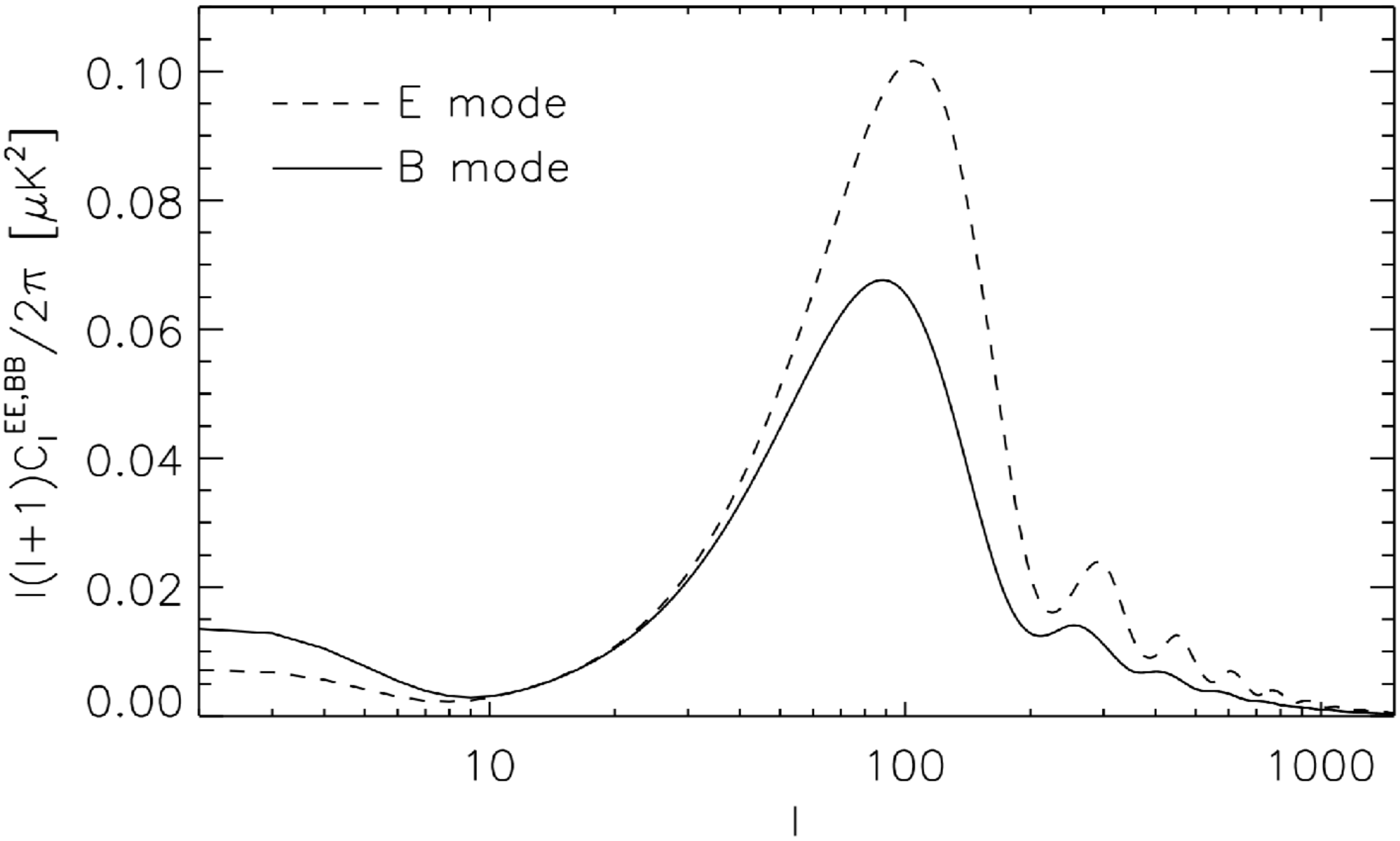


# Pol. pattern on sky today



# Pol. pattern on sky today





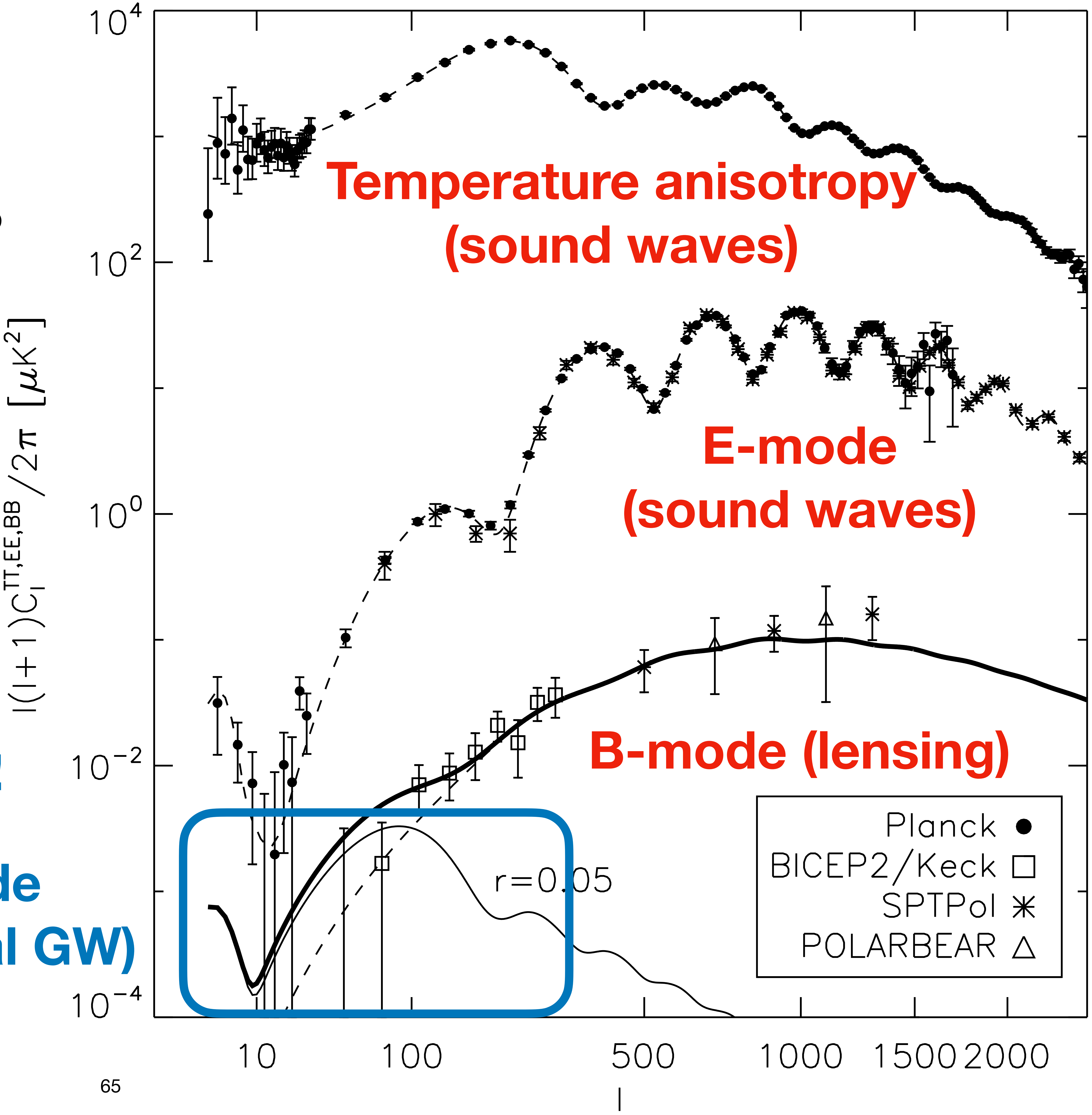

- E and B modes are produced nearly equally, but on small scales B is smaller than E because B vanishes on the horizon

# Power Spectra

## Where are we? What is next?

- The temperature and polarisation power spectra originating from **the scalar (density) fluctuation** have been measured.

- The next quest: **B-mode power spectrum from the primordial GW!**

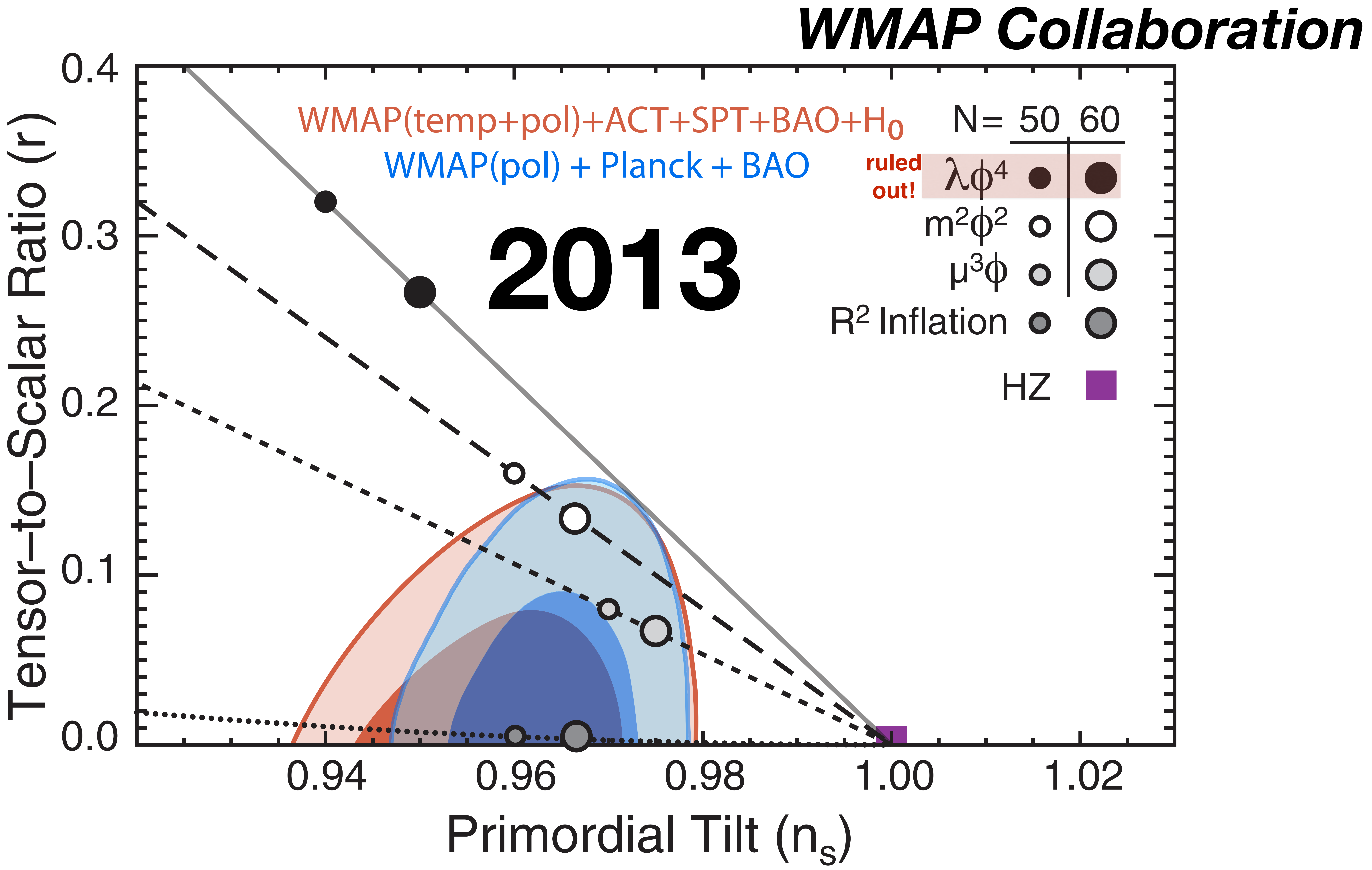


# Tensor-to-scalar Ratio

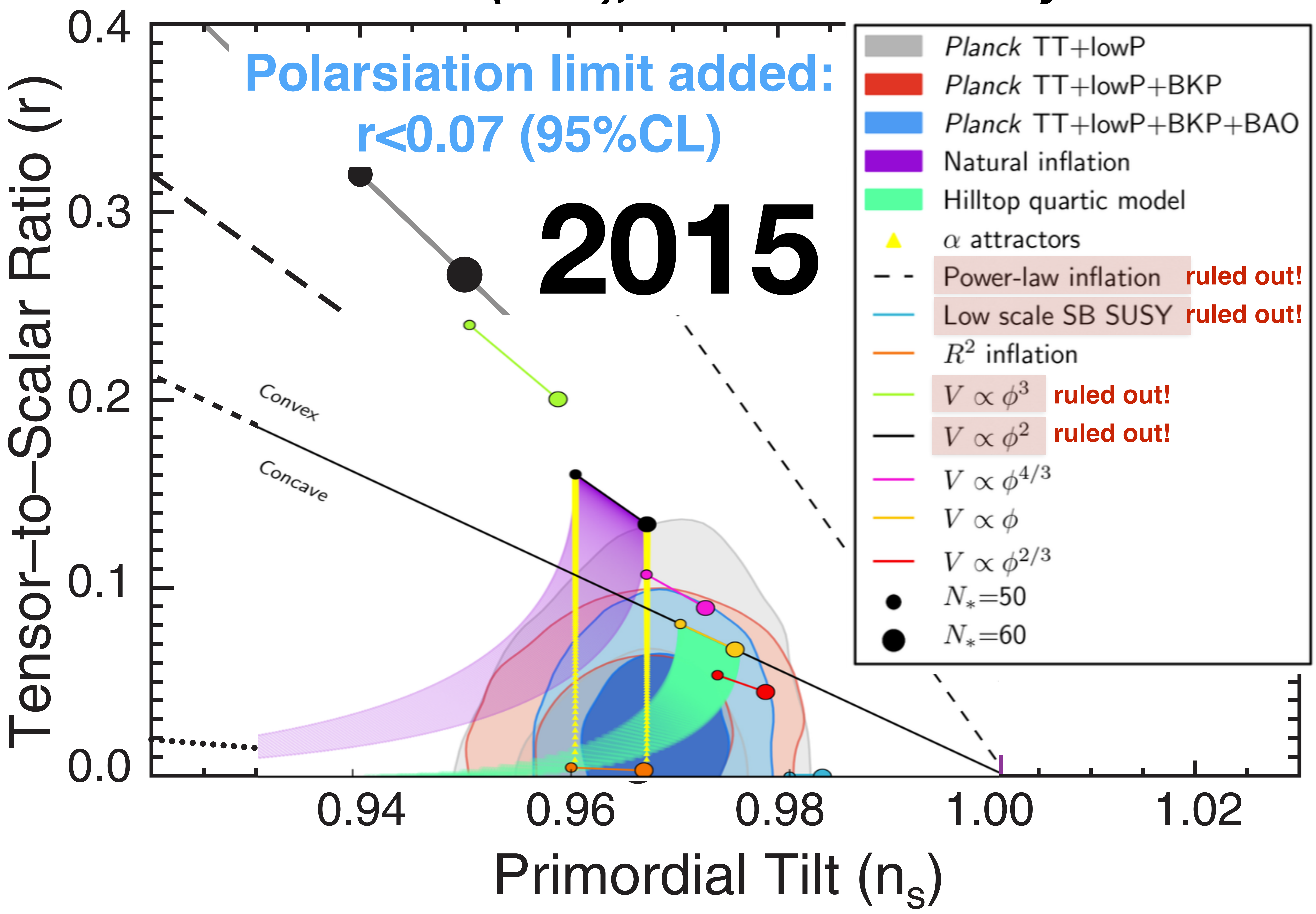
$$r \equiv \frac{\langle h_{ij} h^{ij} \rangle}{\langle \zeta^2 \rangle}$$

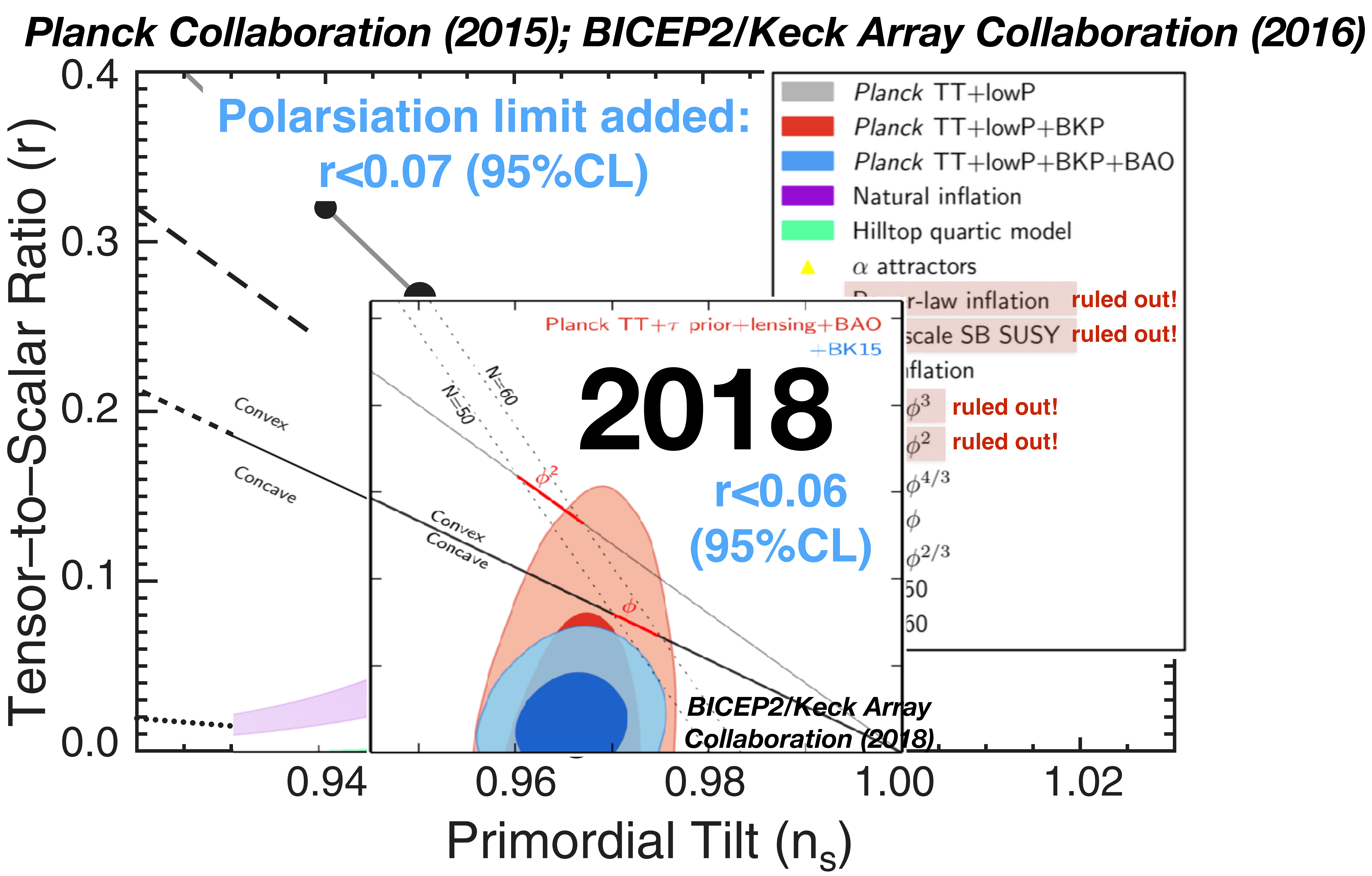
Scalar mode

- We really want to find this! The current upper bound is **r<0.036** [95%CL; *BICEP2/Keck Array Collaboration (2021)*]

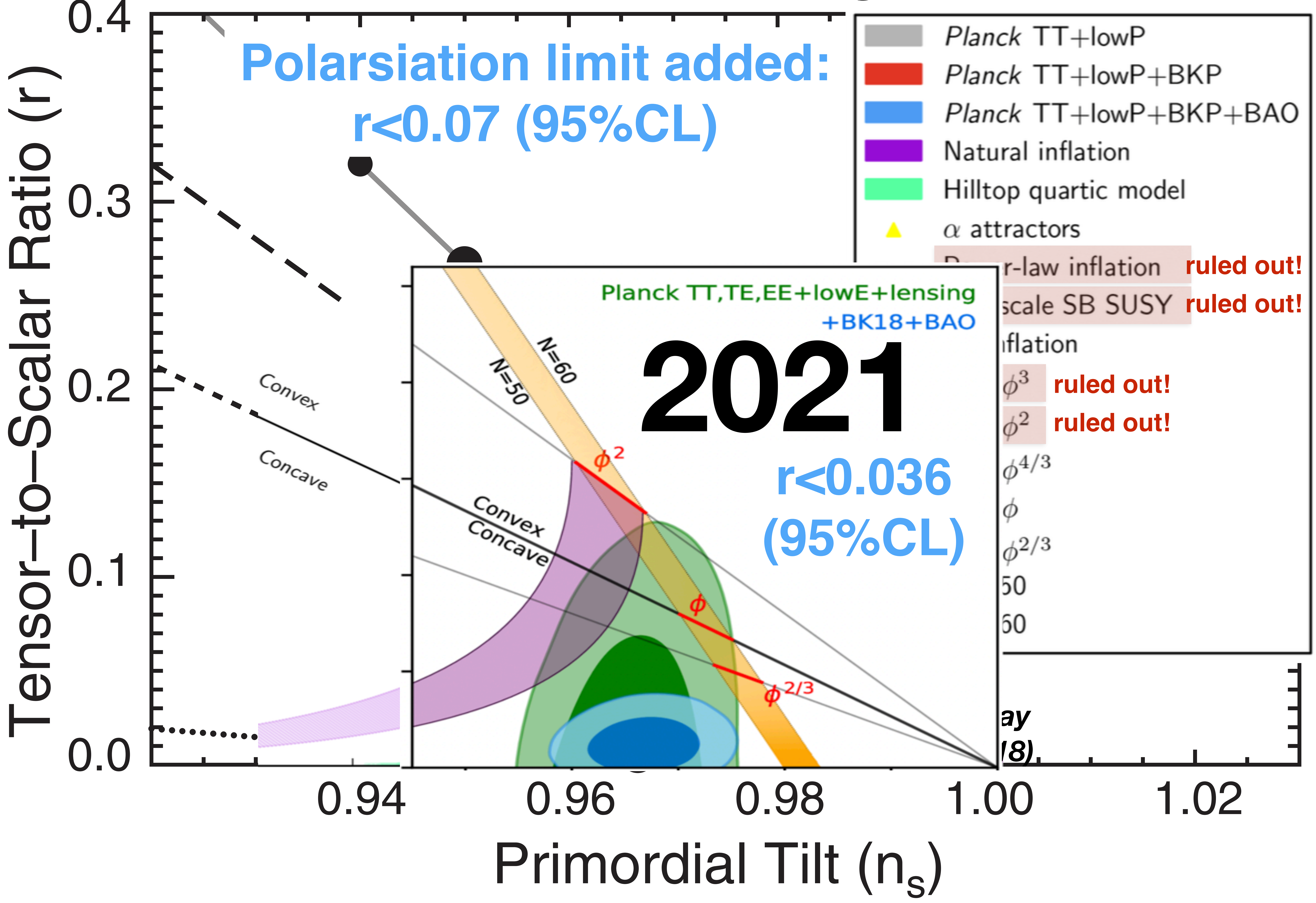

WMAP Collaboration
WMAP(temp+pol)+ACT+SPT+BAO+$H_0$
WMAP(pol) + Planck + BAO
2013
N= 50 60
ruled out!
$\lambda\phi^4$
$m^2\phi^2$
$\mu^3\phi$
$R^2$ Inflation
HZ
Tensor-to-Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt ($n_s$)

*Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)*




Planck Collaboration (2015); BICEP2/Keck Array Collaboration (2016)
Polarsiation limit added:
r<0.07 (95%CL)
Tensor-to-Scalar Ratio (r)
Primordial Tilt ($n_s$)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
$\alpha$ attractors
ruled out!
ruled out!
ruled out!
ruled out!
Convex
Concave
Planck TT+$\tau$ prior+lensing+BAO
+BK15
2018
r<0.06
(95%CL)
N=60
N=50
$\phi^2$
$\phi$
$\phi^3$
$\phi^{4/3}$
$\phi^{2/3}$
BICEP2/Keck Array
Collaboration (2018)

# BICEP2/Keck Array Collaboration (2021)



# Experimental Landscape

# CMB Stages

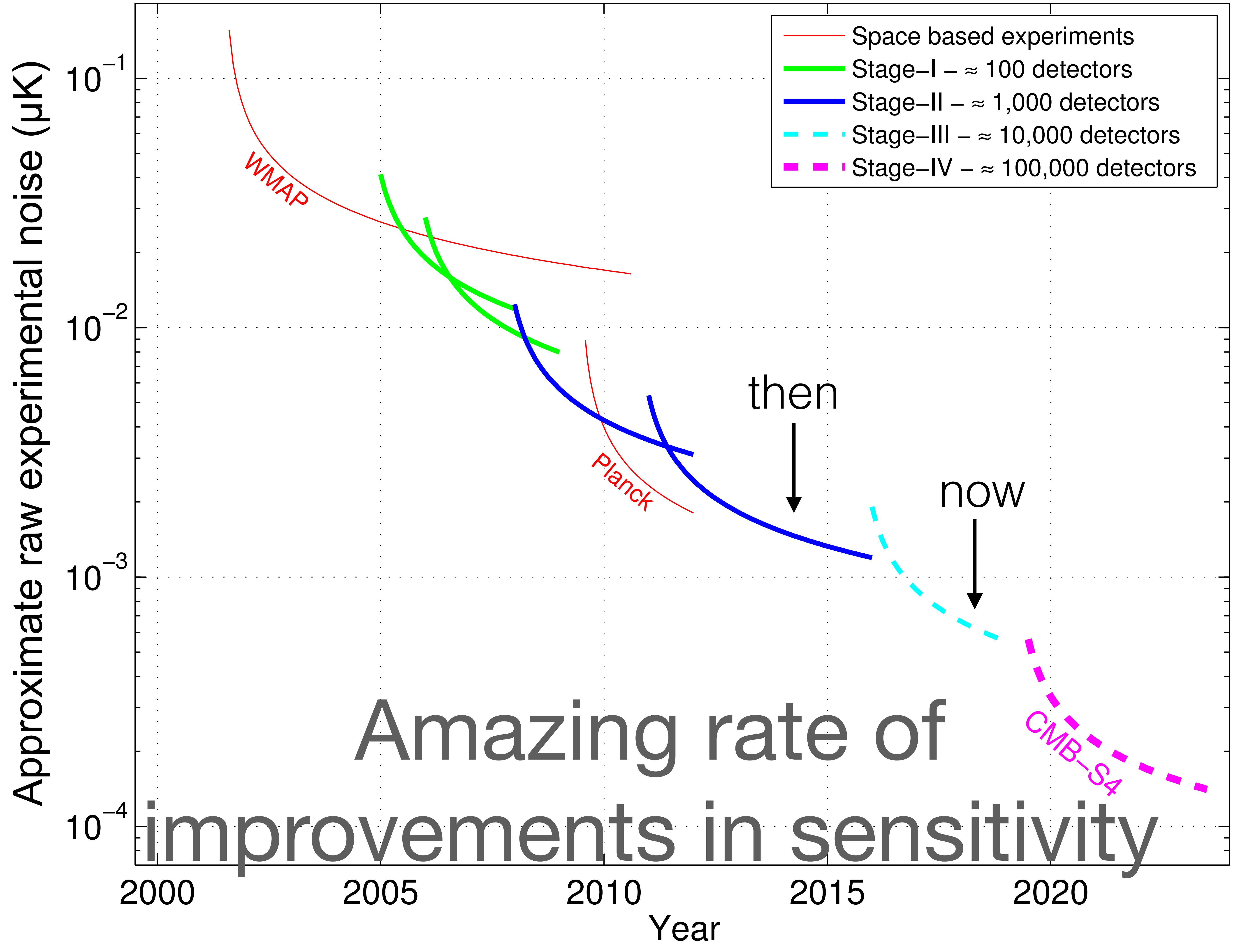
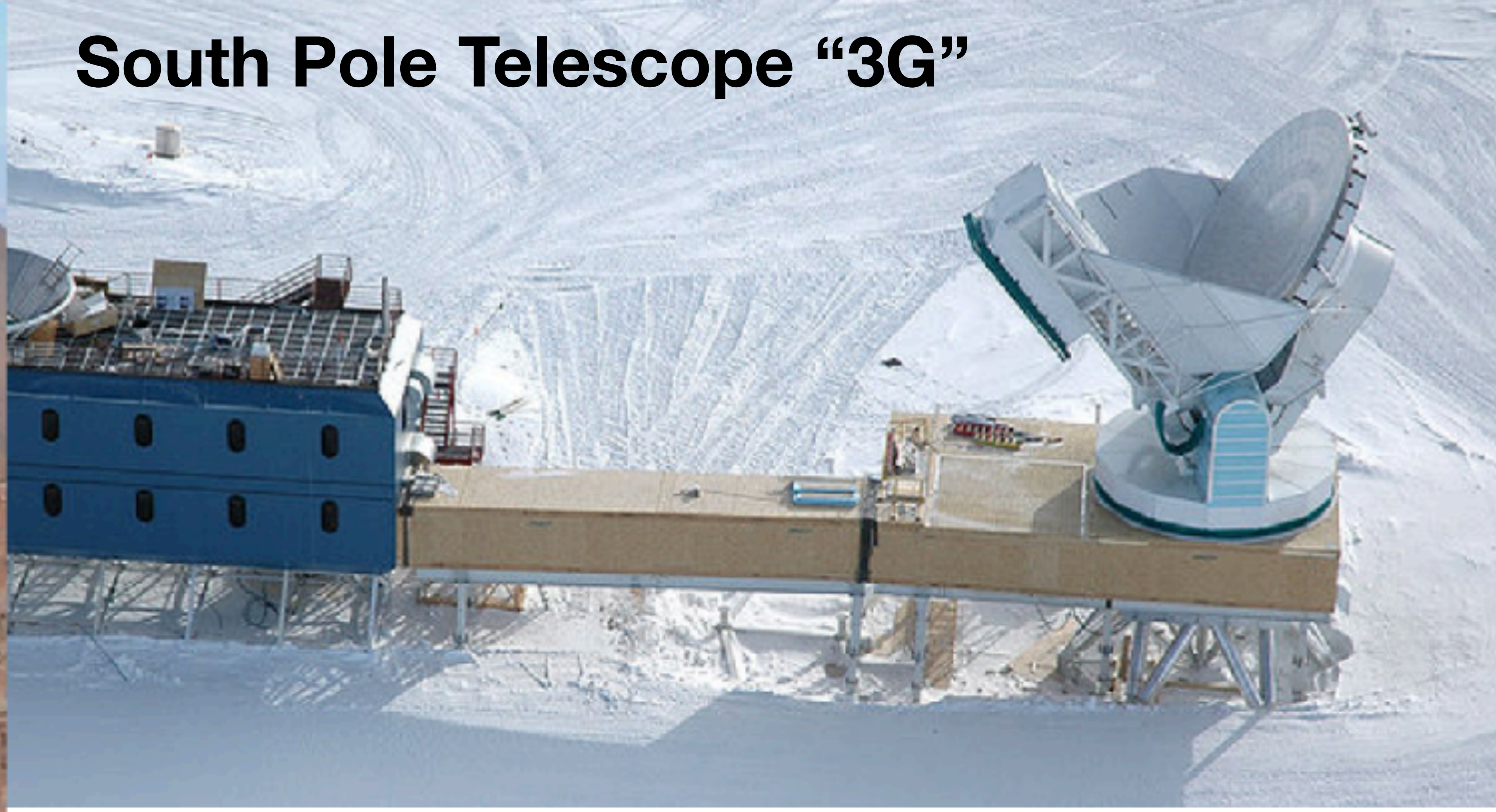
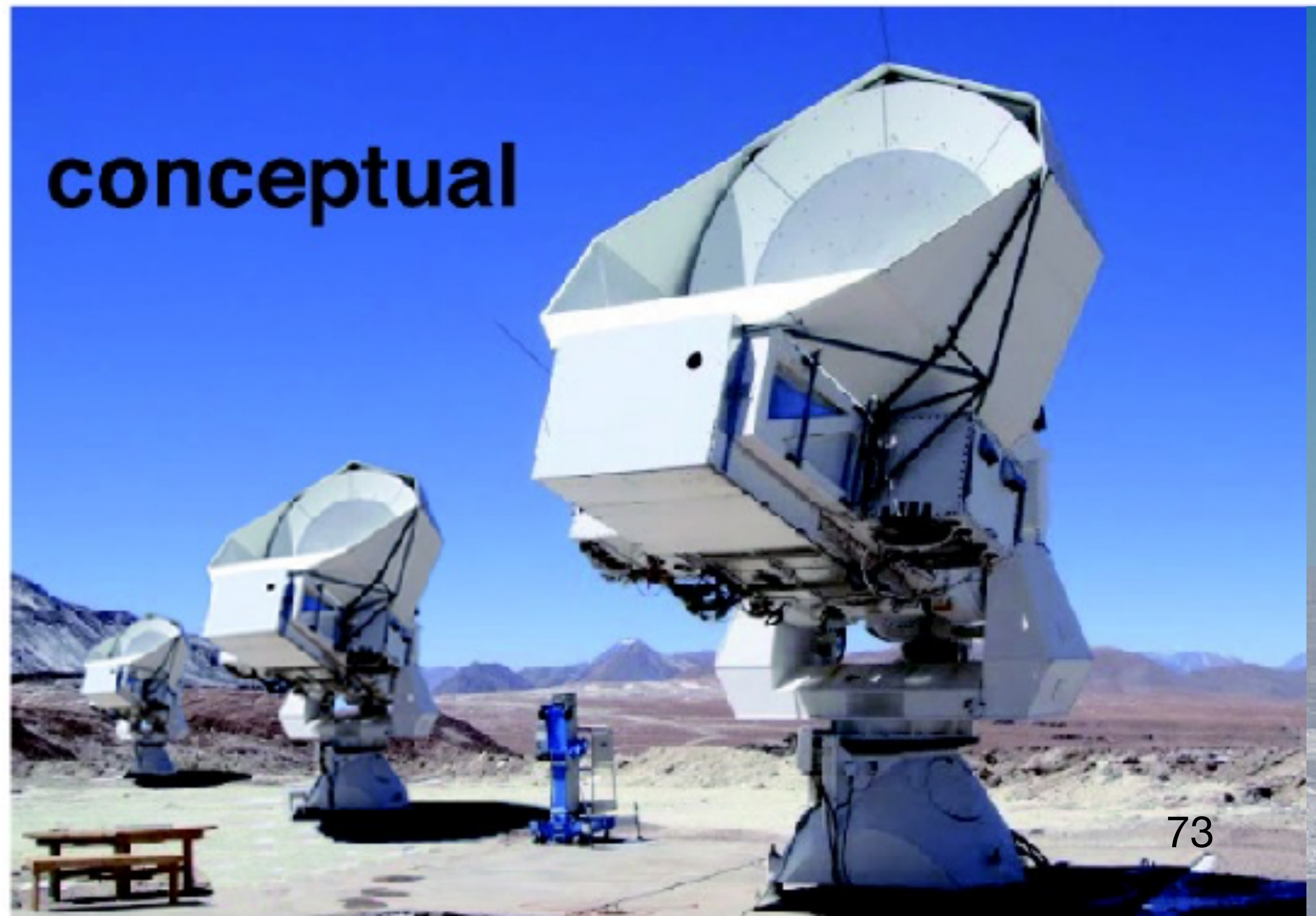



Figure by Clem Pryke for 2013 Snowmass documents

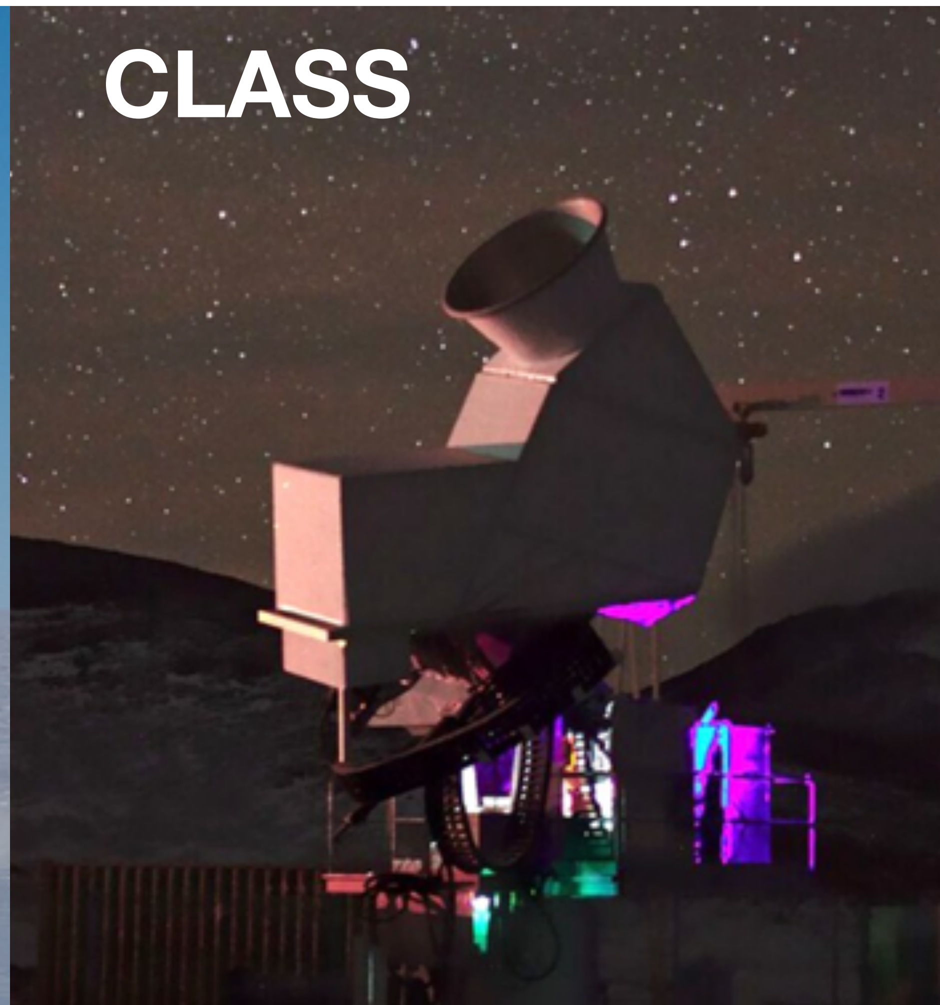
# On-going Ground-based Experiments

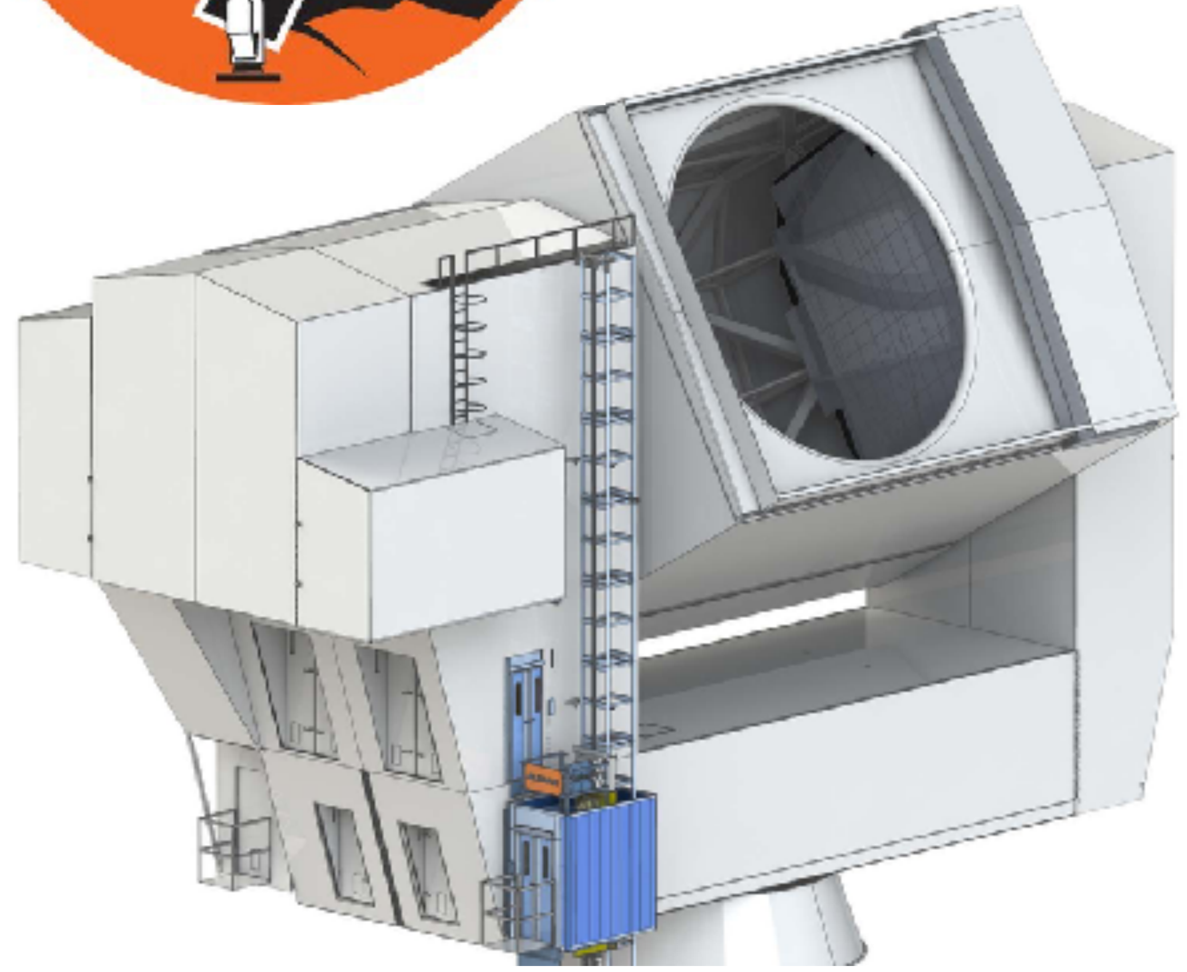

The Simons Array







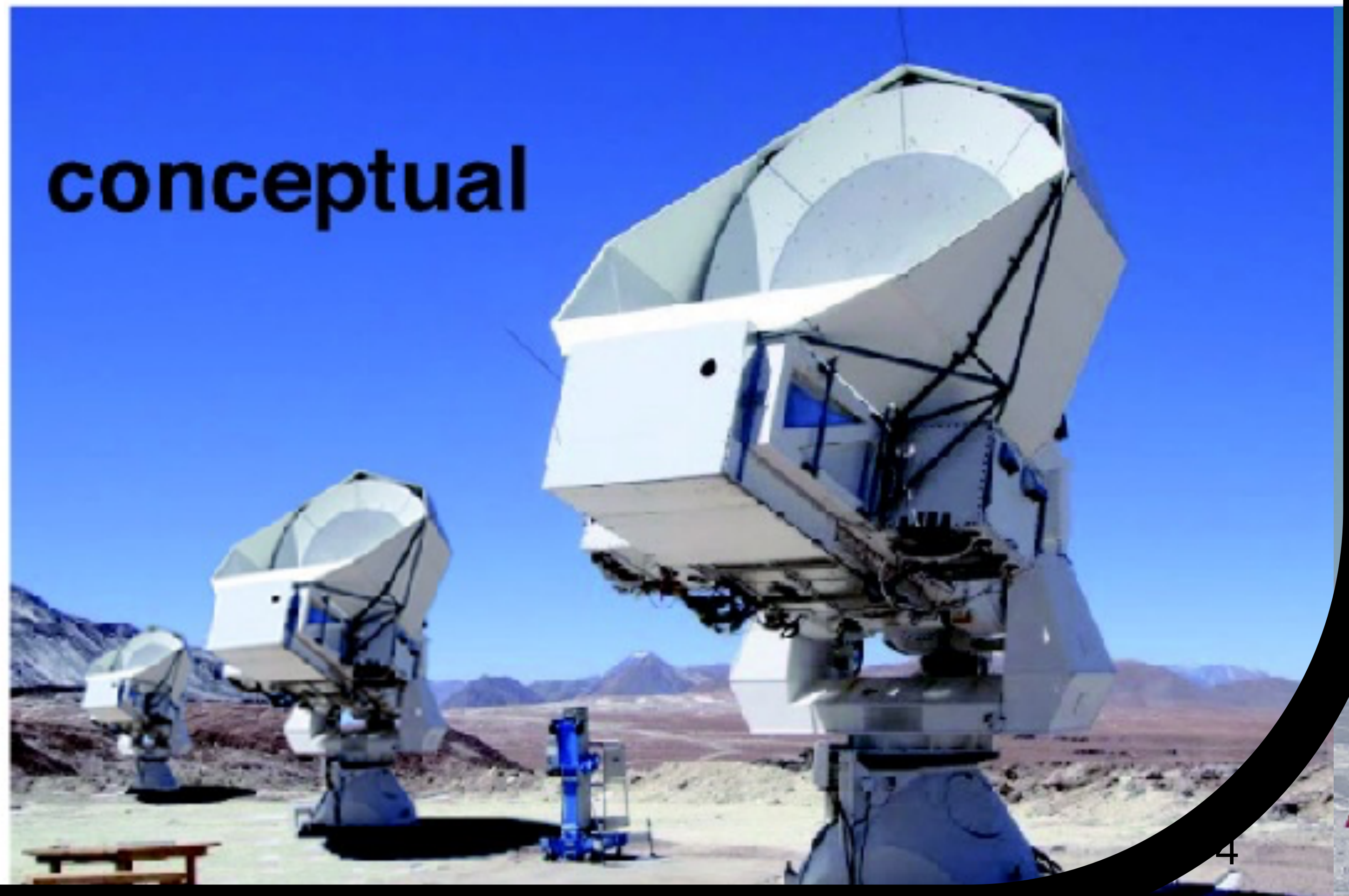
SIMONS OBSERVATORY

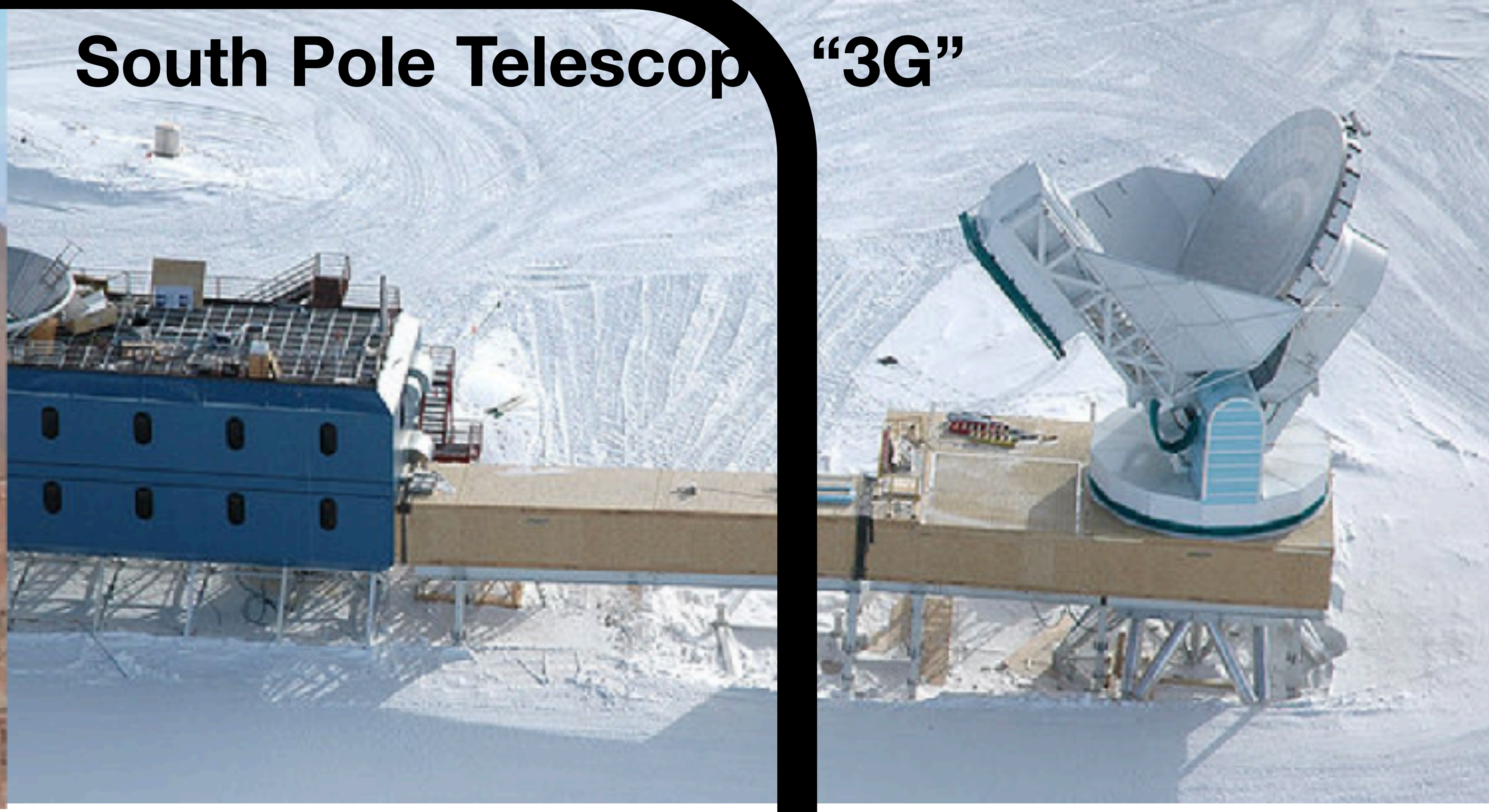


# Early 2020s

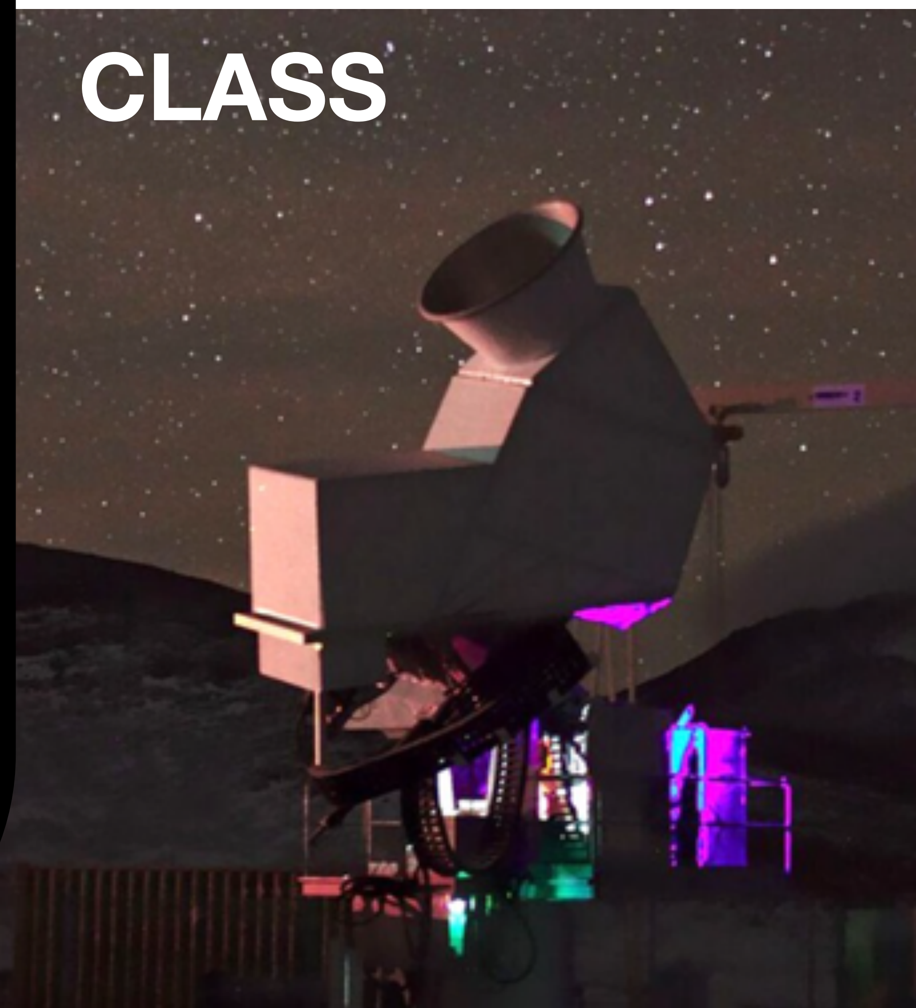
~$100M


The Simons Array

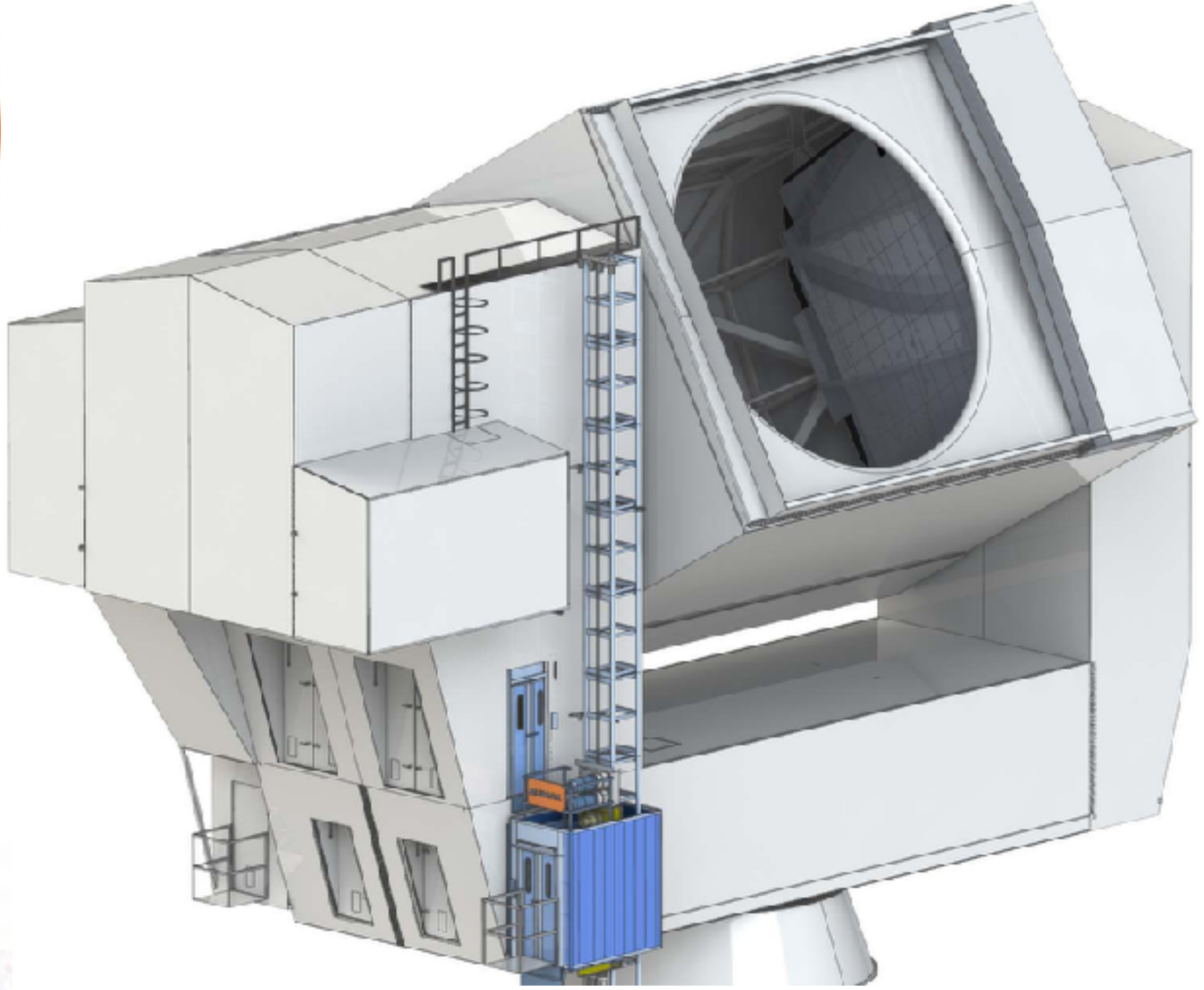



The South Pole Observatory

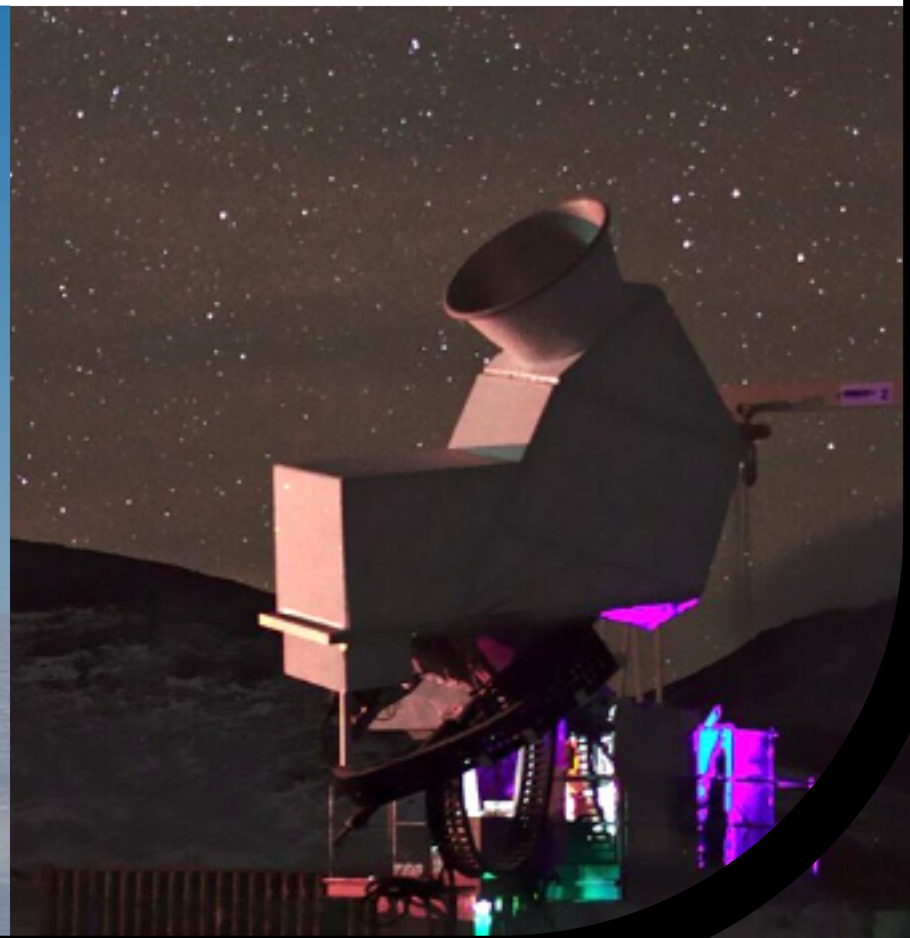



SIMONS OBSERVATORY



CCAT-p


# Bringing all together: US-led CMB Stage IV Late 2020s (~$600M)

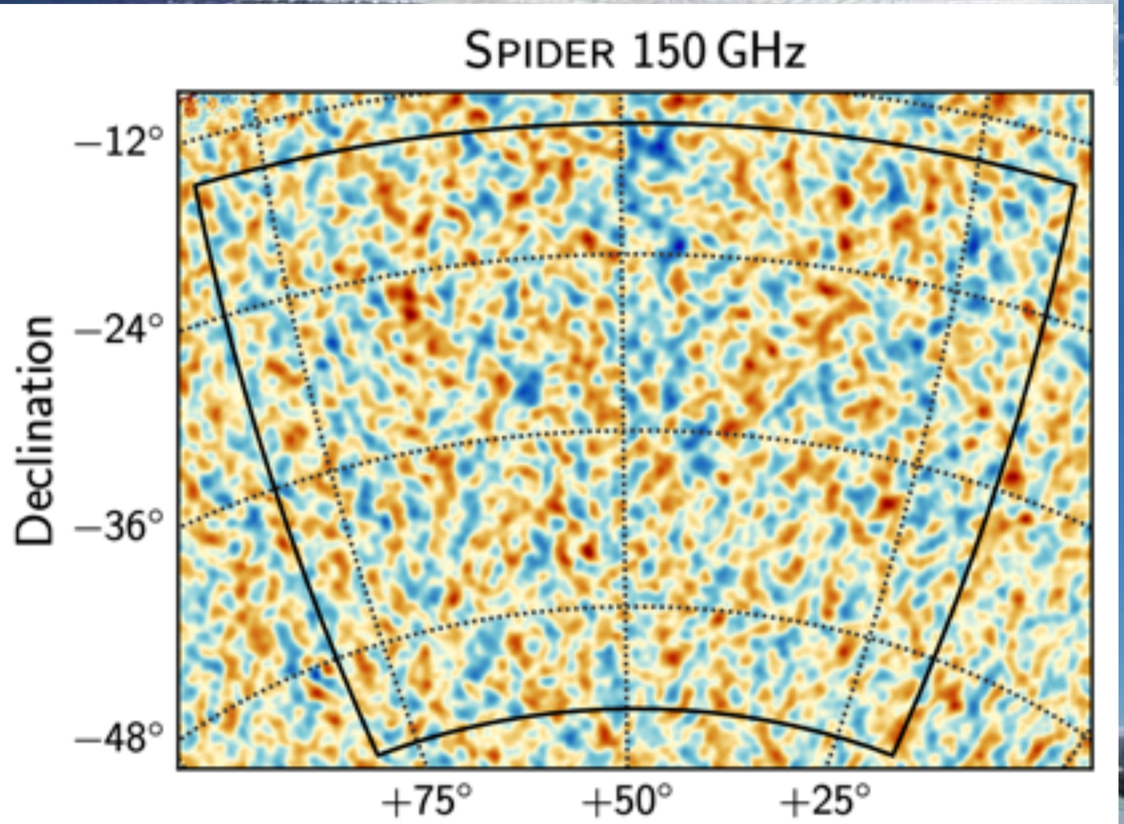


# Balloons!

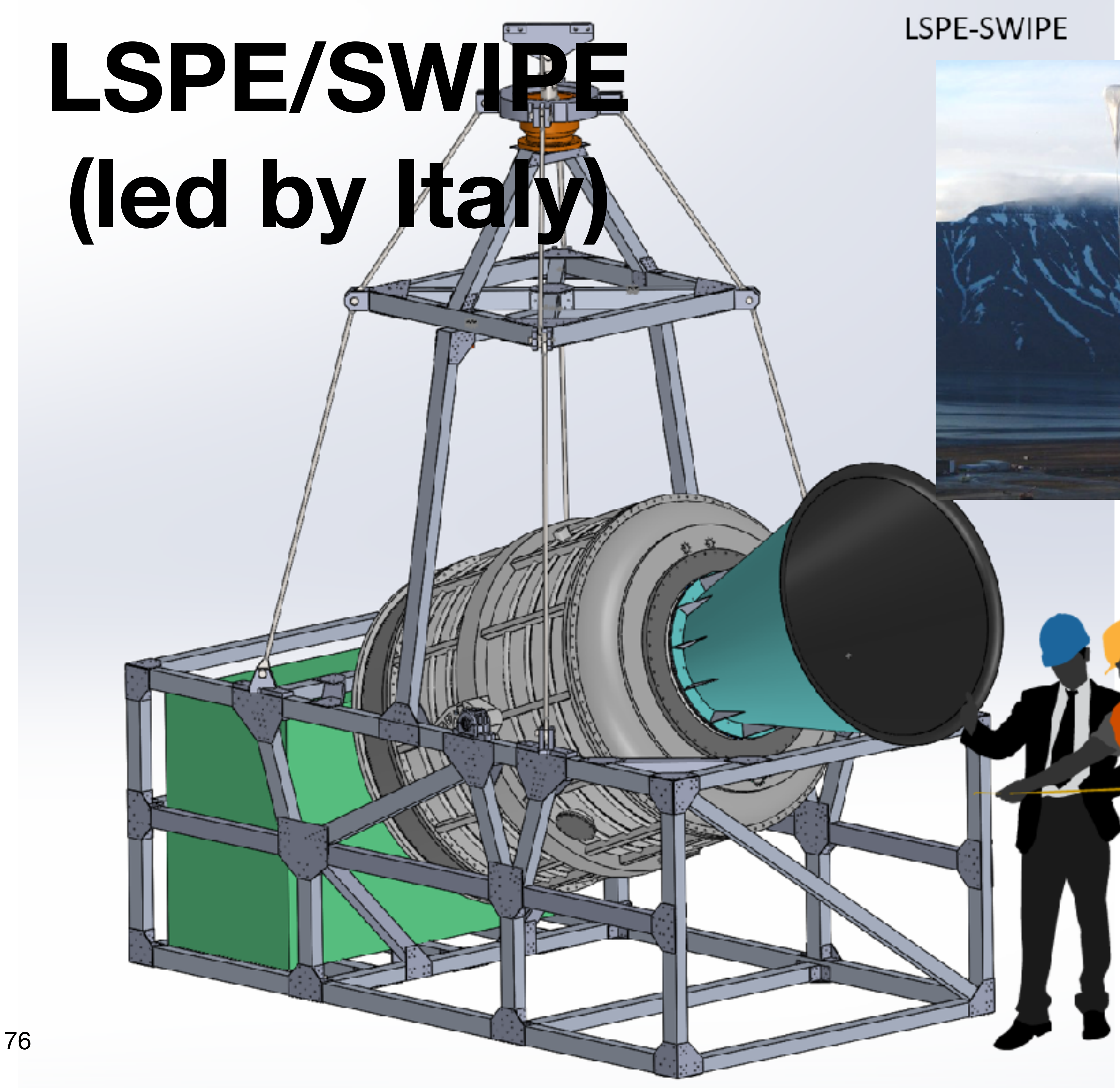
## “Almost space”

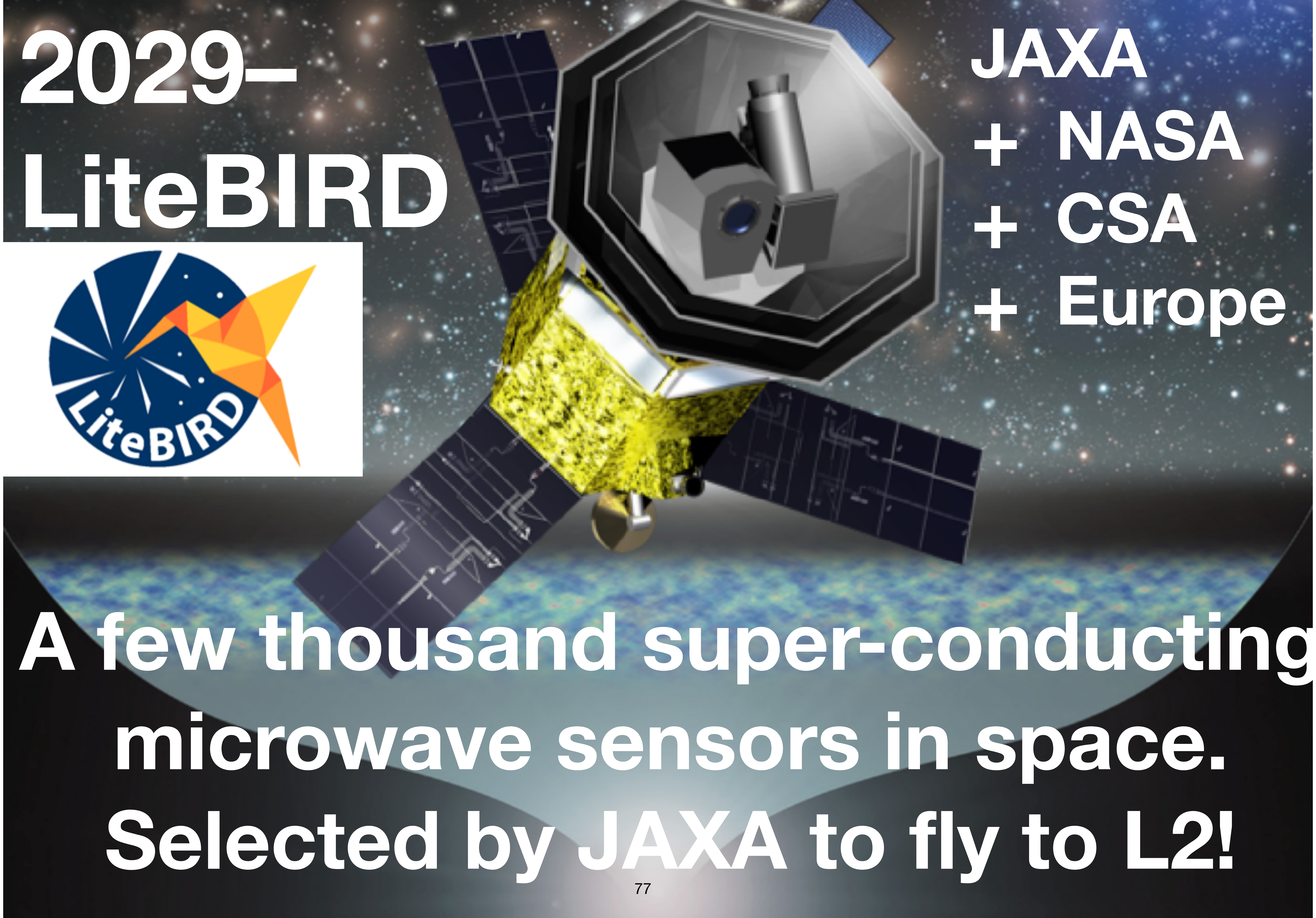
**SPIDER**
**(led by USA)**

*First B-mode result:*
*arXiv:2103.13334*




**LSPE/SWIPE**
**(led by Italy)**



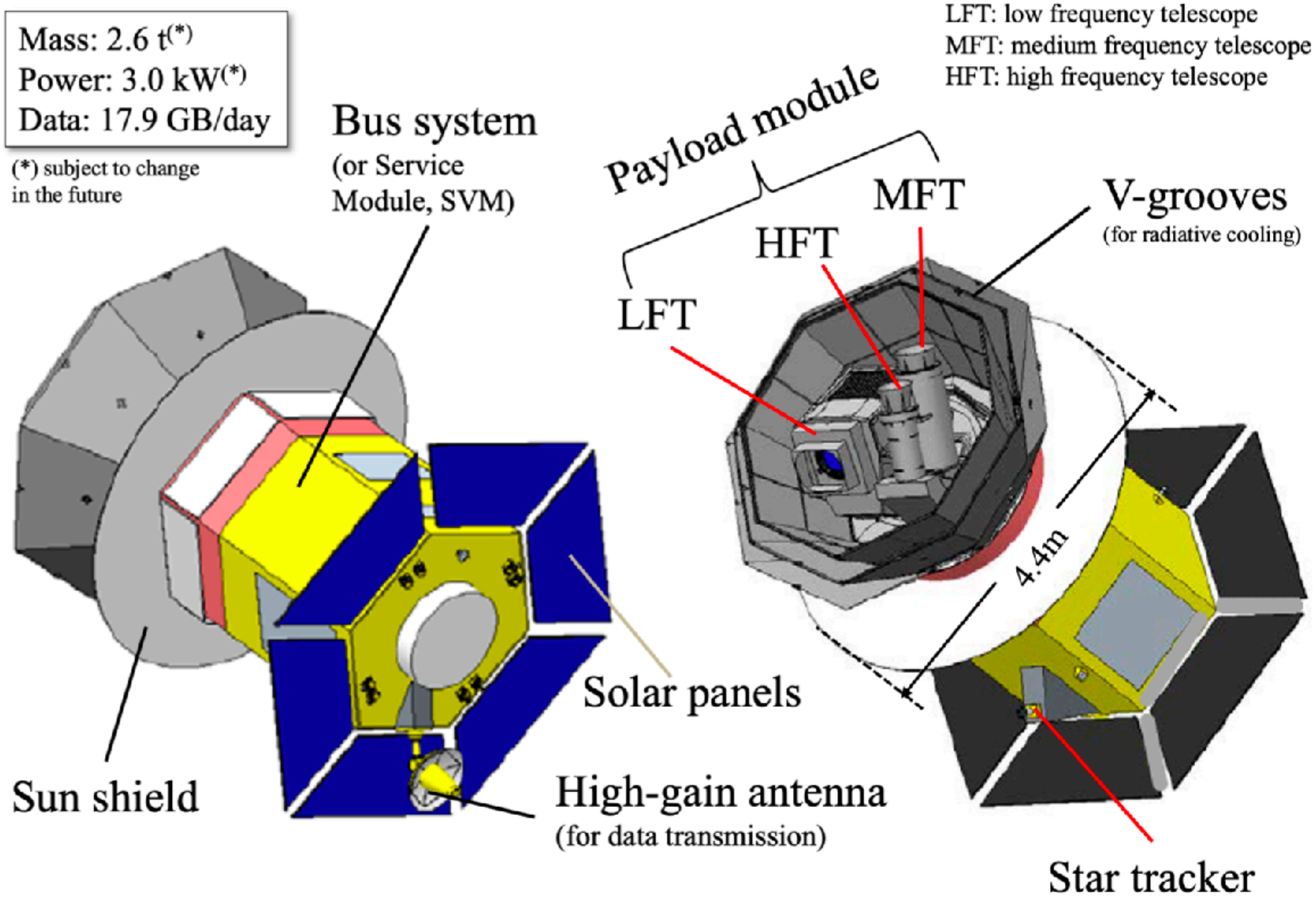
# 2029–
# LiteBIRD

JAXA
\+ NASA
\+ CSA
\+ Europe

**A few thousand super-conducting microwave sensors in space.**
**Selected by JAXA to fly to L2!**

# LiteBIRD: 3 telescopes to cover wide frequencies

## LFT/MFT/HFT to cover 34 to 448 GHz



Credit: ESA

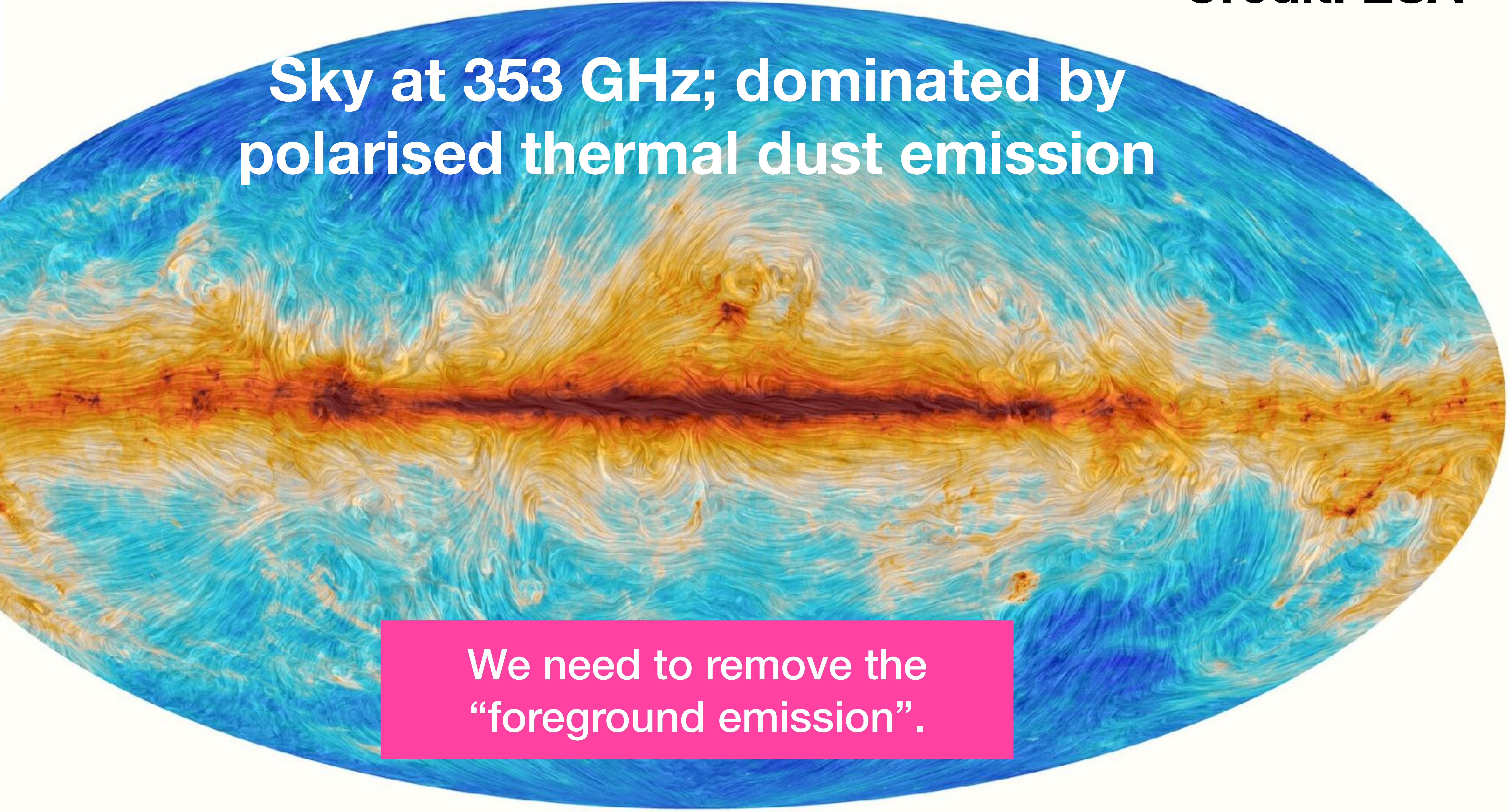
# Why need a wide frequency coverage?

Temperature (smoothed) + Polarisation

ESA's Planck

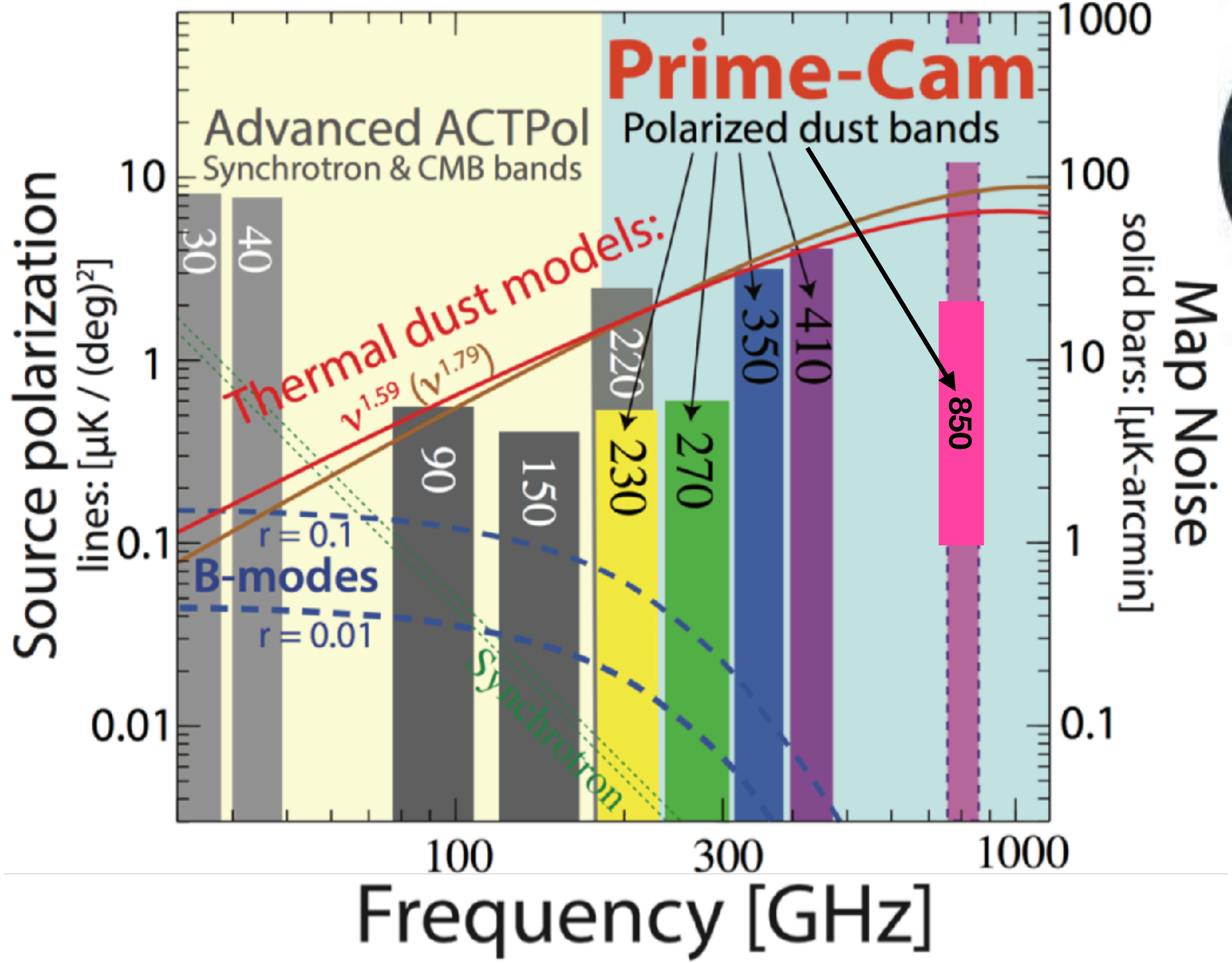
**Credit: ESA**

# Sky at 353 GHz; dominated by polarised thermal dust emission



We need to remove the "foreground emission".

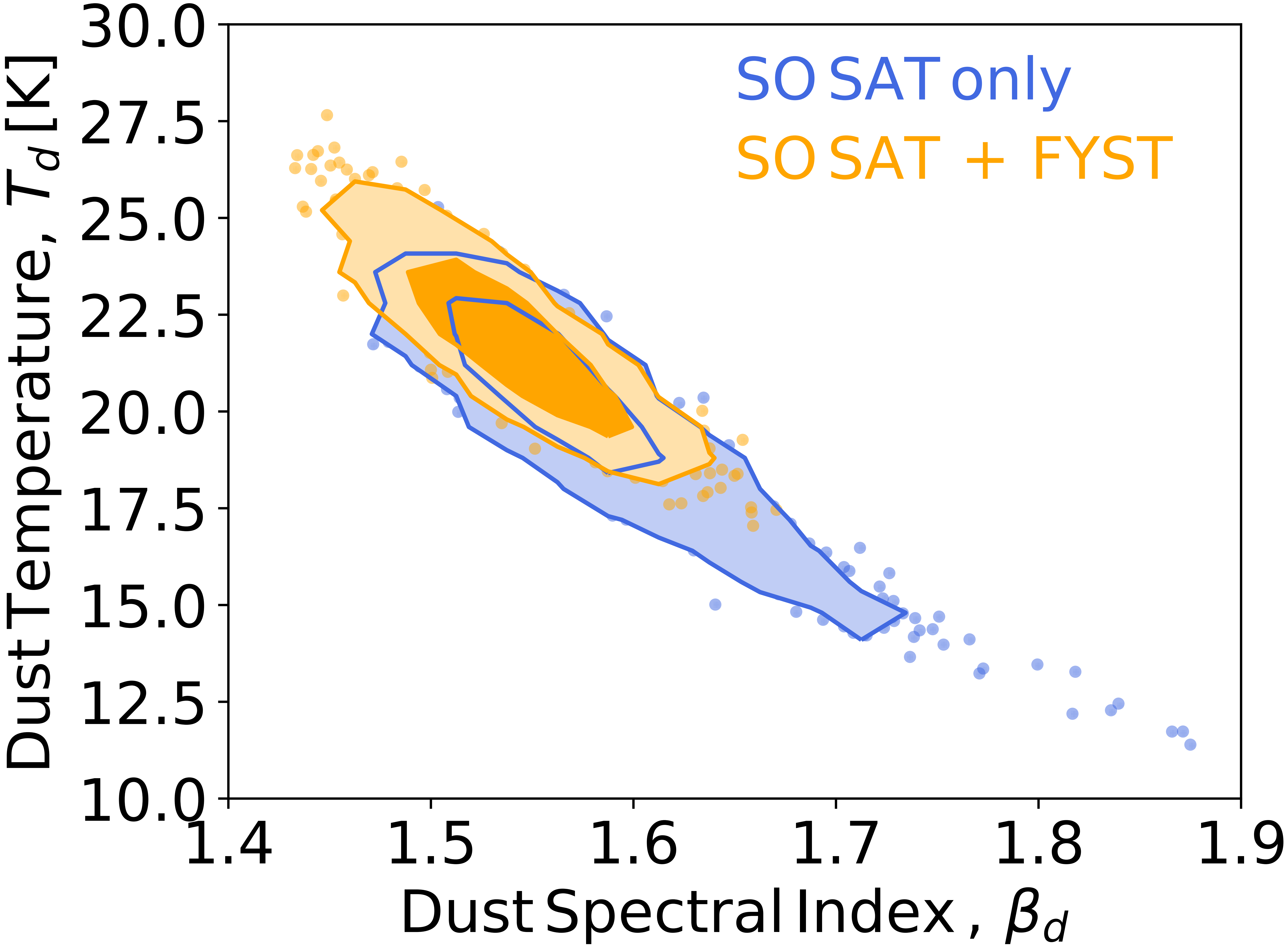
Directions of the magnetic field inferred from polarisation of the thermal dust emission in the Milky Way


Prime-Cam
Polarized dust bands
Advanced ACTPol
Synchrotron & CMB bands
Thermal dust models:
ν1.59 (ν1.79)
30
40
90
150
220
230
270
350
410
850
r = 0.1
B-modes
r = 0.01
Synchrotron
Source polarization
lines: [μK / (deg)²]
Map Noise
solid bars: [μK-arcmin]
Frequency [GHz]
100
300
1000
10
1
0.1
0.01
1000
100
10
1
0.1

CCAT-p

# FYST measures dusty parameters

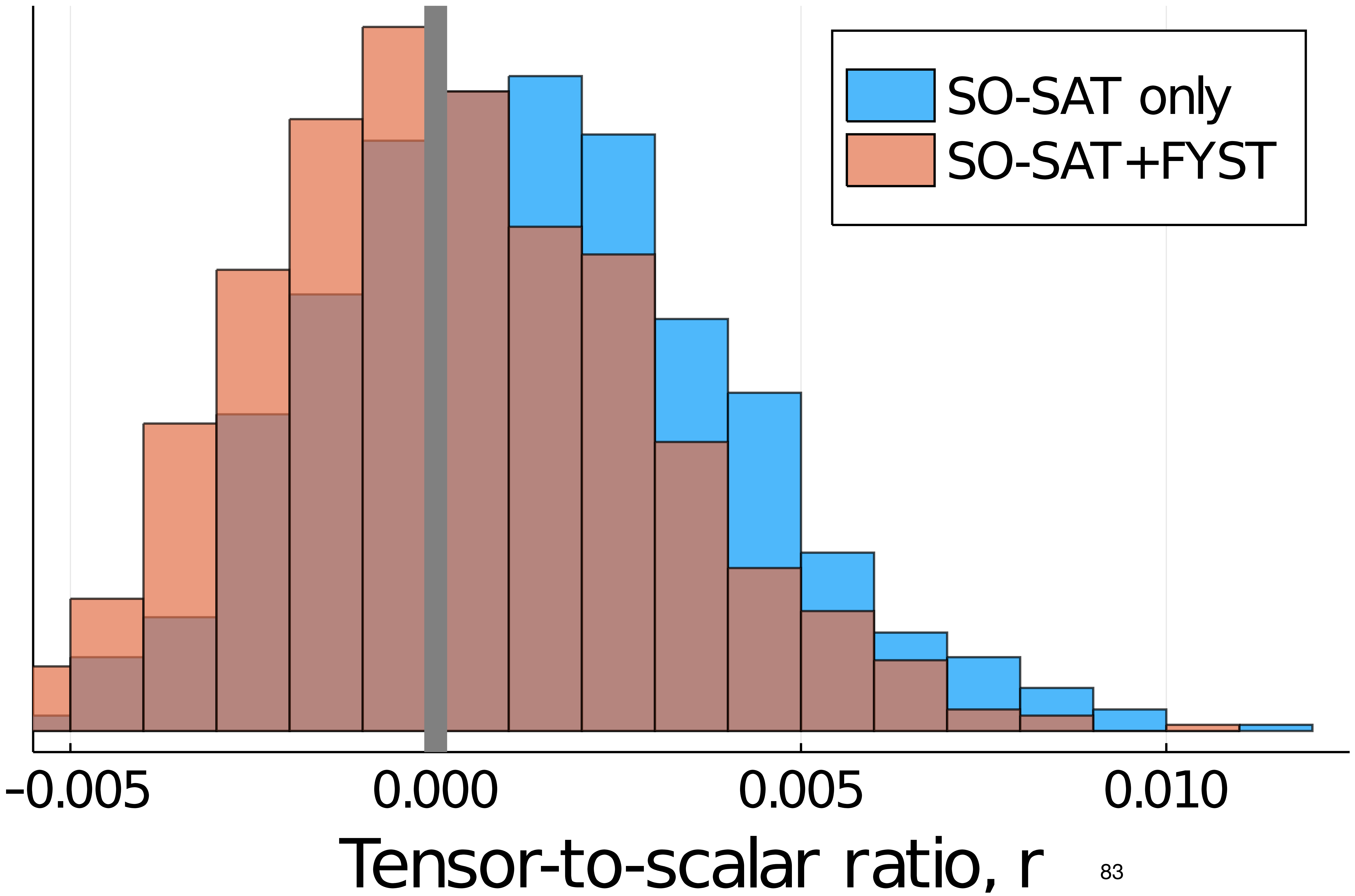
## Fig. 6 of FYST/CCAT-prime Science Paper (2107.10364)




- SO-SAT cannot break degeneracy between βd and Td.
  - The constraints are dominated by the prior.
- FYST/Prime-Cam can determine these parameters much more accurately.

# FYST aids determination of the tensor-to-scalar ratio parameter

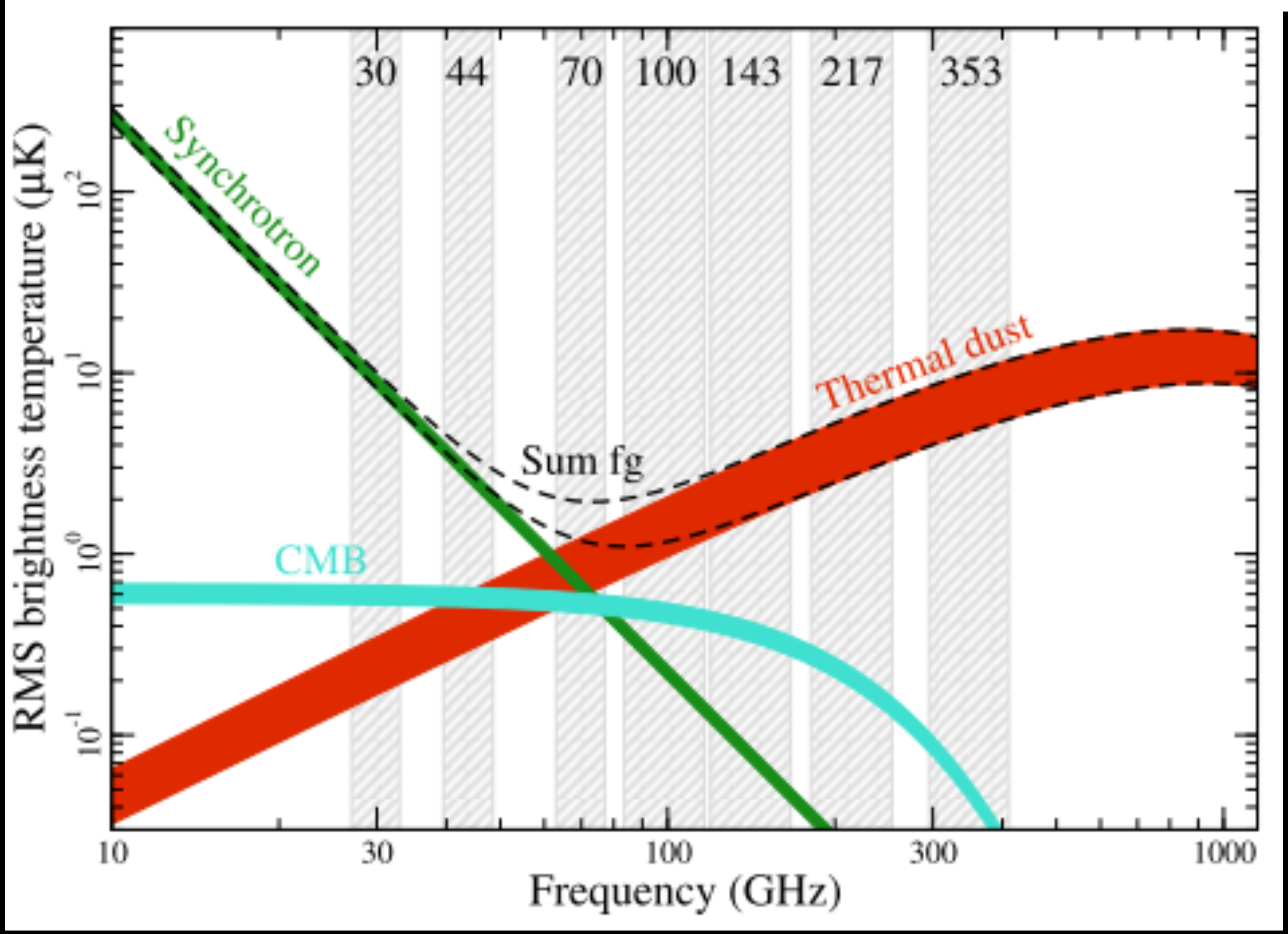
## Fig. 7 of FYST/CCAT-prime Science Paper (2107.10364)



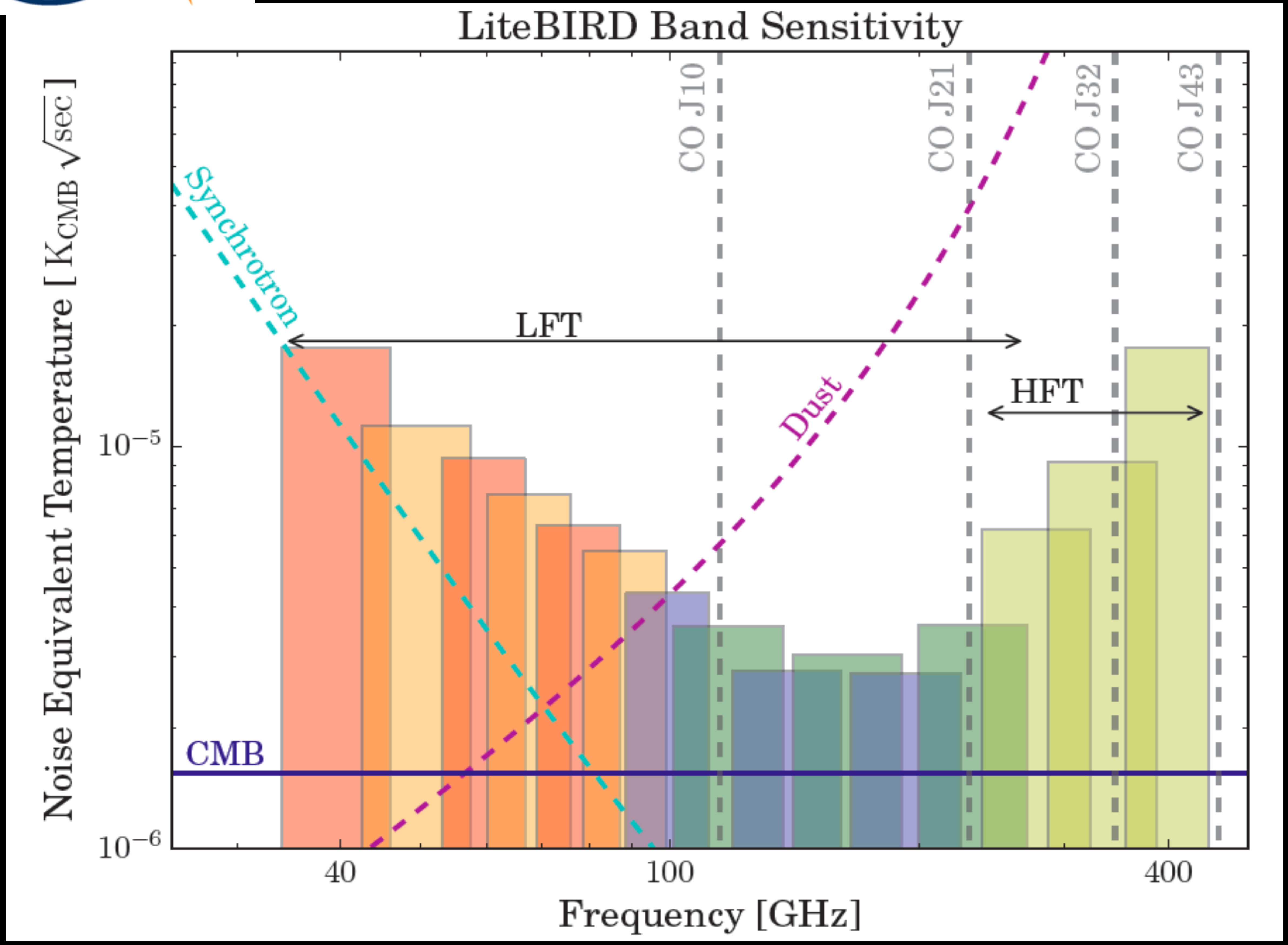

- SO-SAT only
  - r = (1.30 ± 2.76) x $10^{-3}$
  - With 1500 realisations, the error on the mean is $7 \times 10^{-5}$. A significant bias is detected, in agreement with the SO forecast paper.
- FYST+SO-SAT
  - r = (0.19 ± 2.73) x $10^{-3}$
  - The bias is largely gone!

# Foreground Removal

*Slide courtesy Toki Suzuki (Berkeley)*




Polarized galactic emission (Planck X)

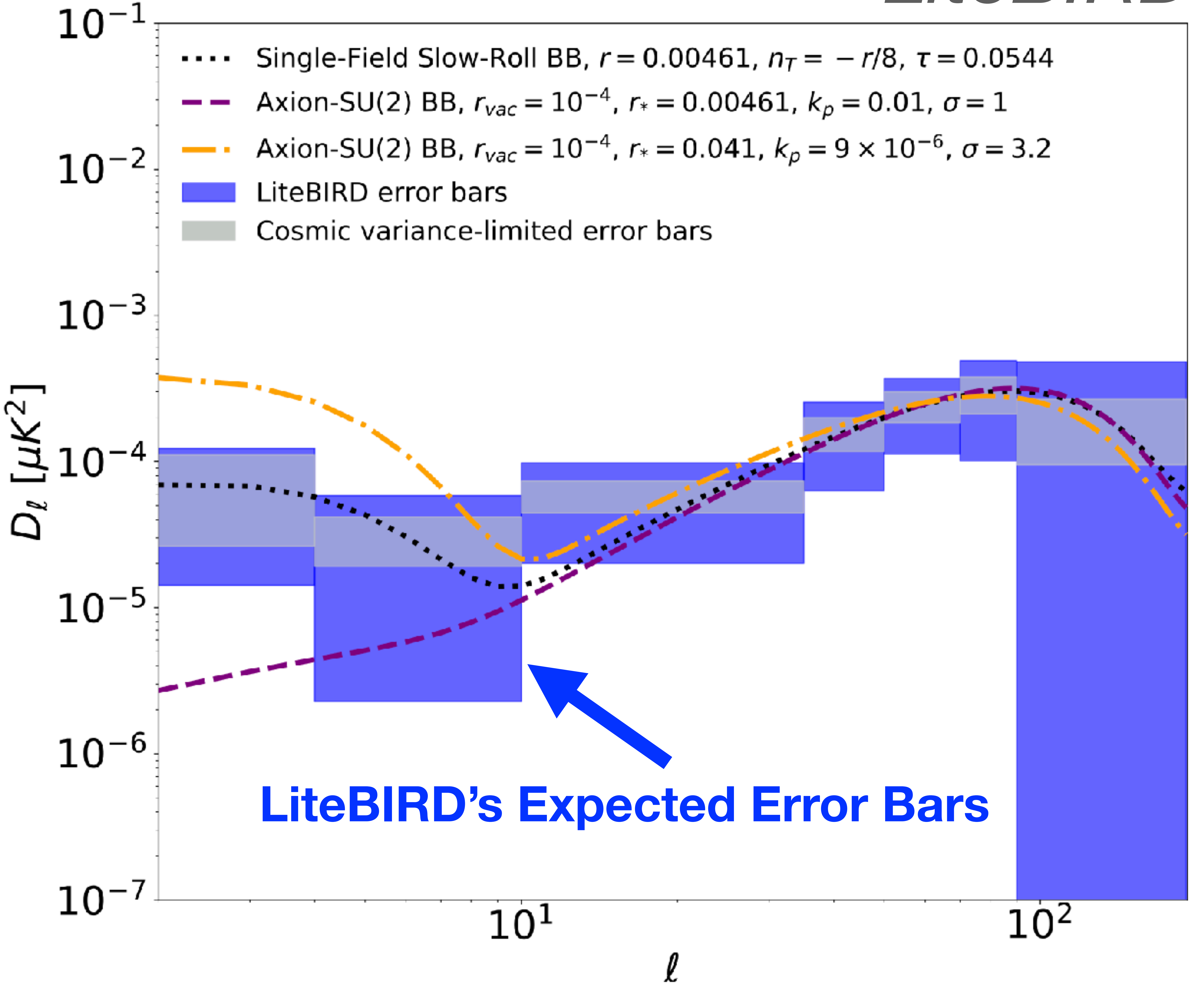



LiteBIRD: 15 frequency bands

- Polarized foregrounds
  - Synchrotron radiation and thermal emission from inter-galactic dust
  - Characterize and remove foregrounds

# B-mode Power Spectrum

*LiteBIRD Collaboration*



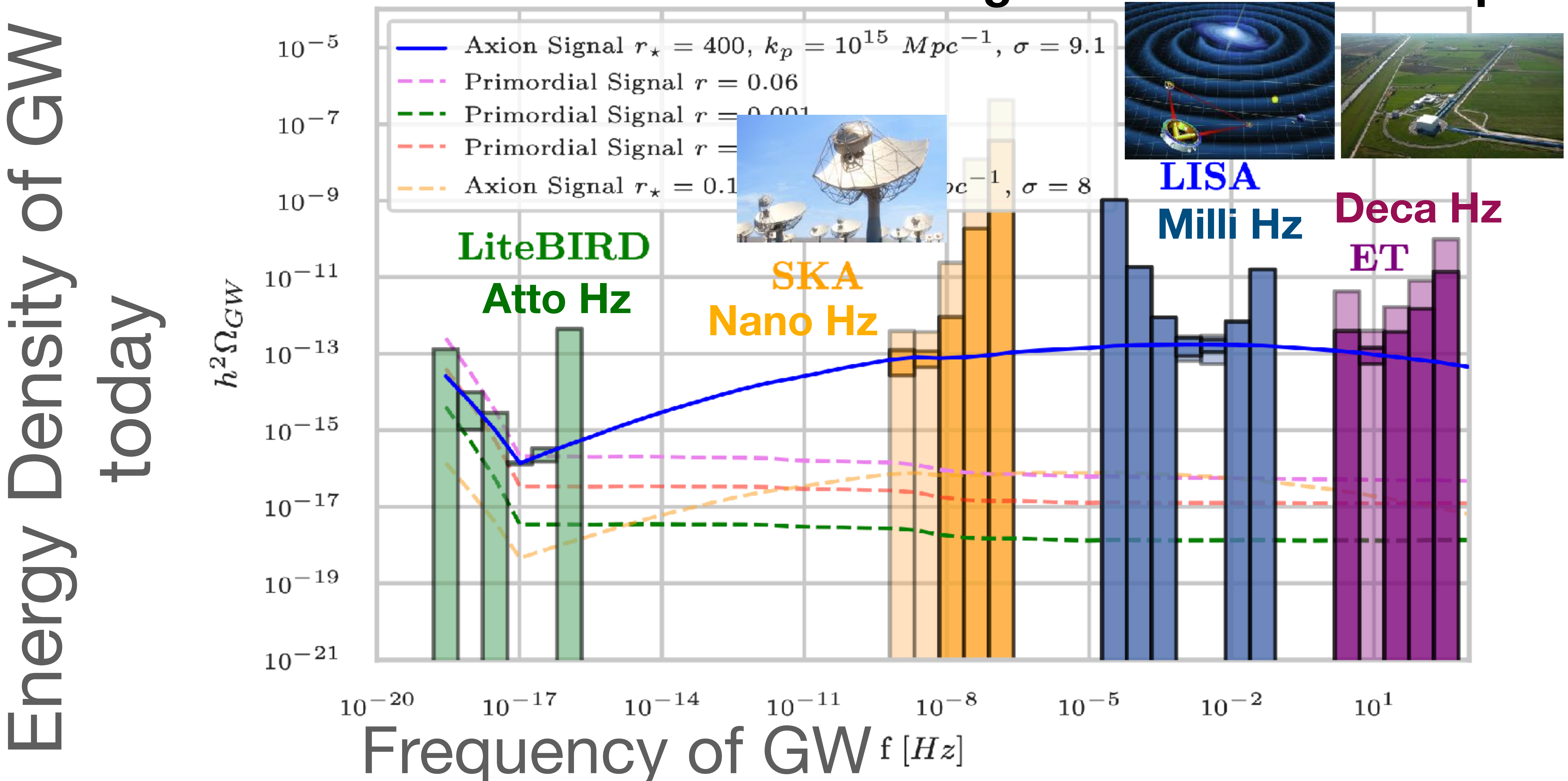

LiteBIRD Collaboration
Tensor-to-Scalar Ratio (r)
0.1
0.03
0.01
0.003
0.001
3×10^-4
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
1.00
Primordial Tilt (n_s)
LiteBIRD
LiteBIRD/Planck
BK18/Planck
m^2φ^2 47< N_* < 57
μ^3φ 47< N_* < 57
μ^{10/3}φ^{2/3} 47< N_* < 57
R^2 42< N_* < 52
Poincaré disks
Higgs N_* = 57
exact scale-invariance
LiteBIRD's Expected Constraints
(If we find a signal!)


Tensor–to–Scalar Ratio (r)
0.1
0.03
0.01
0.003
0.001
3×10^-4
M = 5 M_P
M = M_P
LiteBIRD's Expected Constraints
(If we do not find a signal…)
LiteBIRD
LiteBIRD/Planck
BK18/Planck
V_0 tanh^2(φ/2M)
φ^p 47< N_* < 57
R^2 43< N_* < 53
Higgs N_* = 57
exact scale-invariance
0.955
0.960
0.965
0.970
0.975
0.980
0.985
0.990
0.995
1.00
Primordial Tilt (n_s)

Campeti, EK, Poletti, Baccigalupi (2021)

# But let’s recall again: not just CMB!

**We can measure it across 21 orders of magnitude in the GW frequency**



# Conclusion: Part II

## Towards finding primordial gravitational waves from inflation

- Discovery of the primordial gravitational wave with the wavelength of billions of light years gives **definitive evidence for inflation.**
- Hoping to find the first evidence from ground-based and balloon-borne experiments within the next 10 years.
  - **CCAT-prime/FYST** will **aid** search for primordial gravitational waves by measuring dust contamination better.
- Then, the definitive measurement will come from **LiteBIRD** in early 2030s.