1st General Meeting of COST Action
COSMIC WISPers (CA21106)
Bari - September 5-8, 2023

Birefringence in CMB anisotropies due to cosmological pseudoscalar fields

Vatican Observatory

Matteo Galaverni

Based on a work with:
Fabio Finelli and **Daniela Paoletti** (INAF/OAS Bologna & INFN Bologna)
Phys.Rev.D **107** (2023) 8, 083529 (arXiv 2301.07971 [astro-ph.CO])

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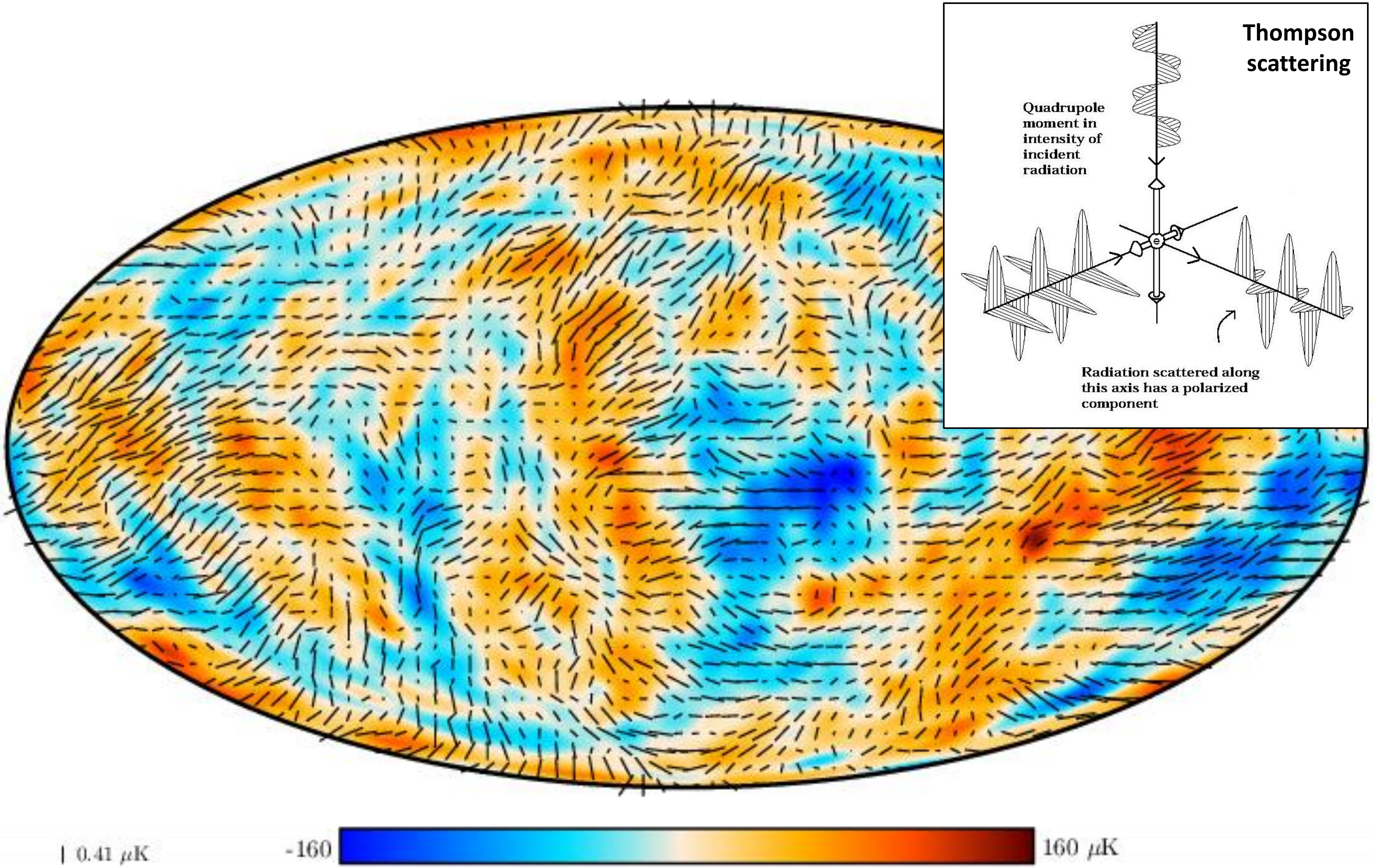
Plan of the talk

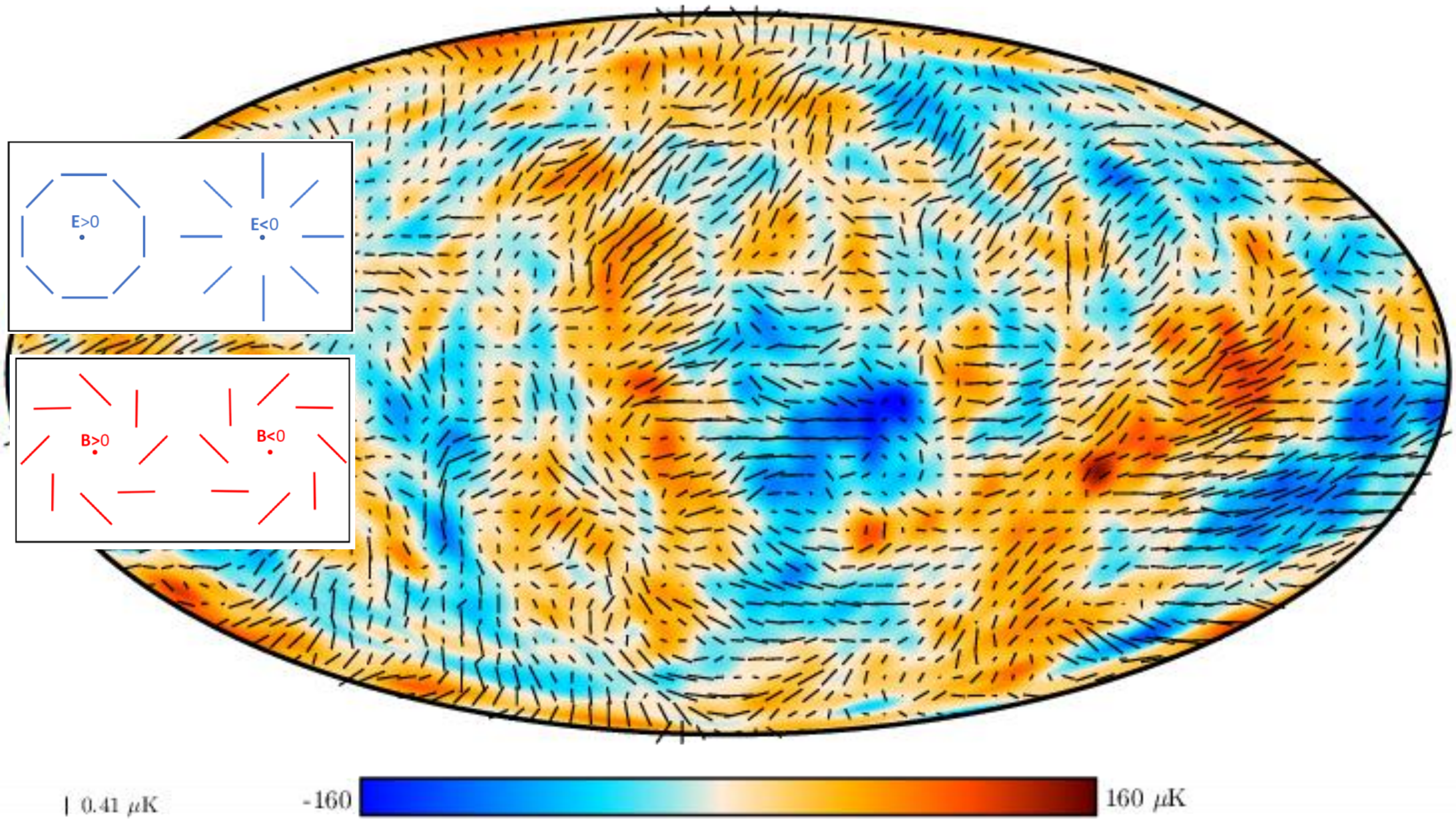
- **CMB polarization anisotropies** & **cosmic birefringence**;
- **Redshift/time evolution** of cosmic birefringence and CMB;
- Cosmological pseudoscalar field: **Early Dark Energy (EDE)**, **Quintessence (DE) or axion-like Dark Matter (DM)**;
- **Conclusions**.

CMB polarization anisotropies



[2018 Planck map of the polarized CMB anisotropies]

CMB polarization anisotropies



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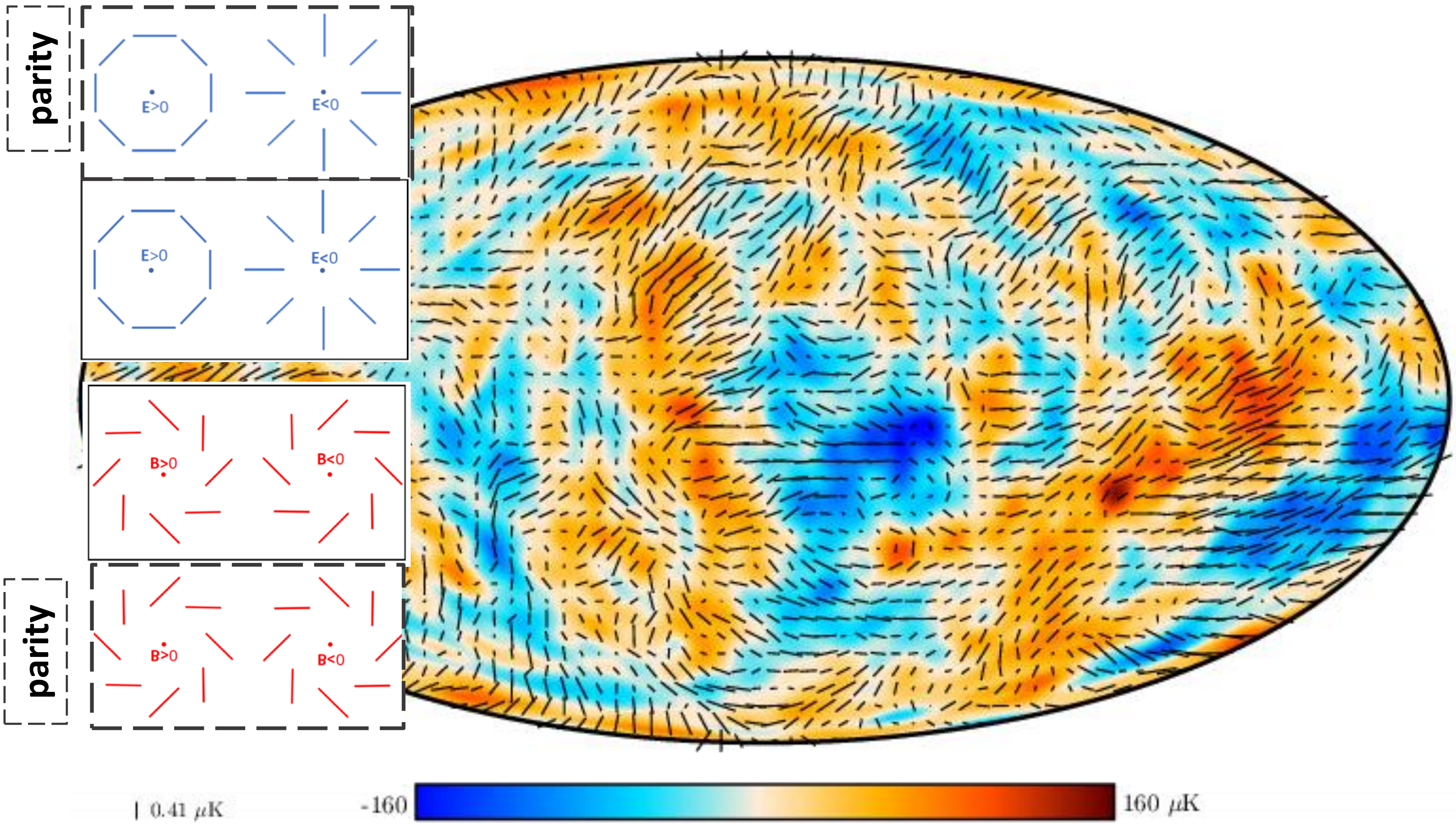
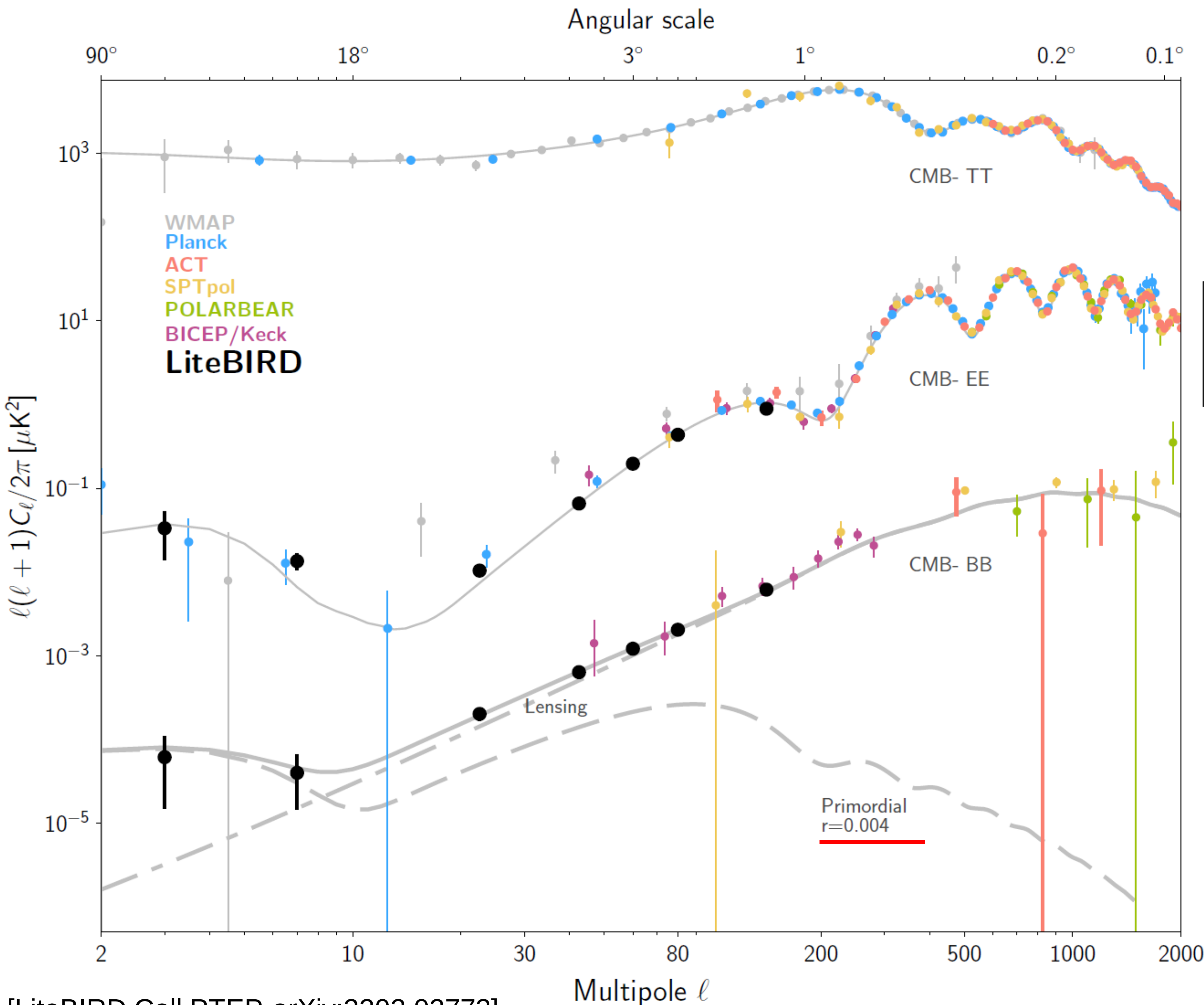
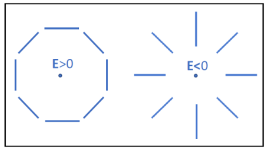


Present measurements + expected sensitivity for LiteBIRD

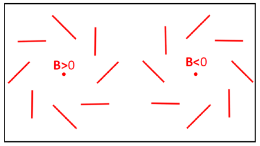
Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection"



TT



EE



BB

[LiteBIRD Coll PTEP-arXiv:2202.02773]

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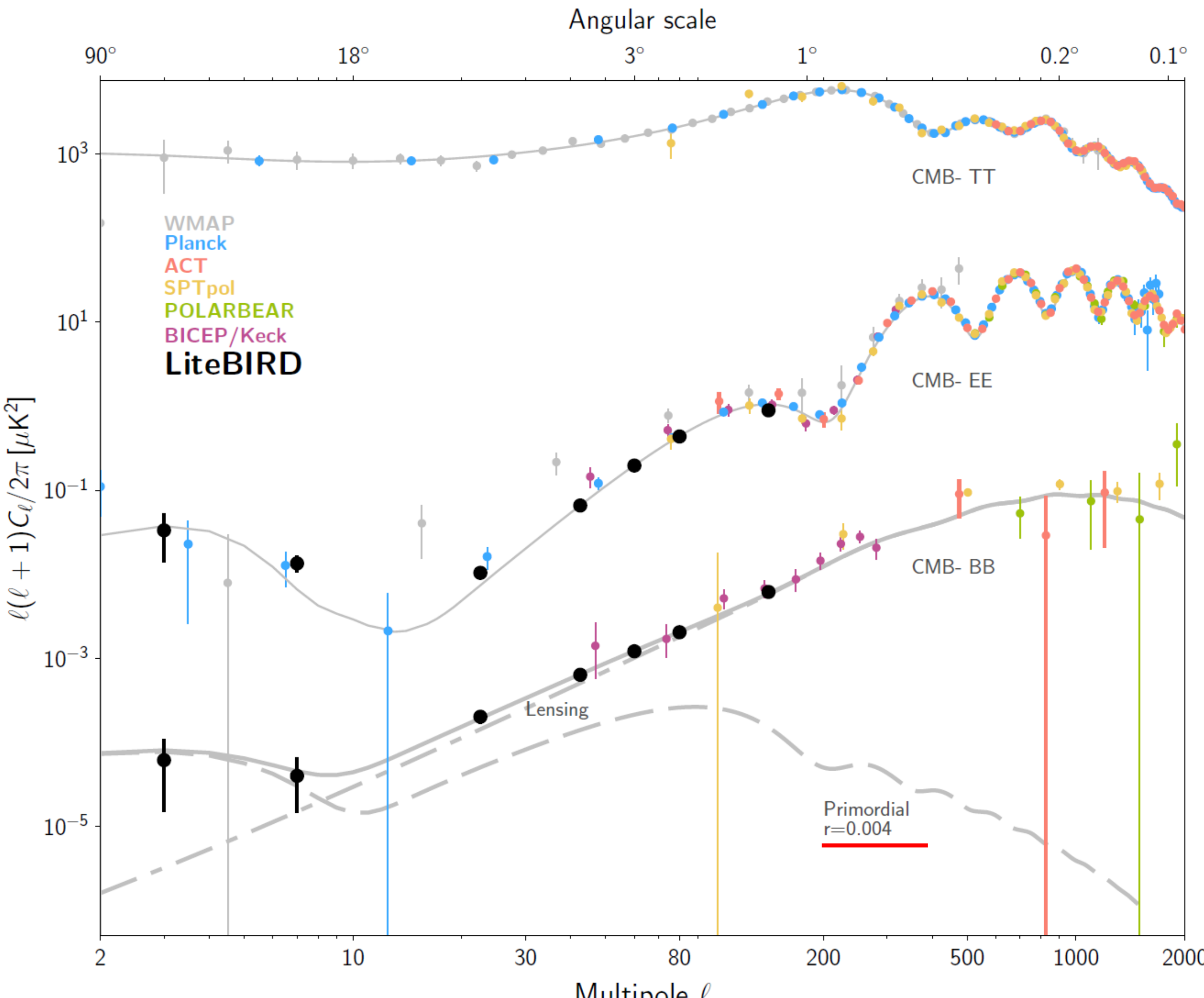

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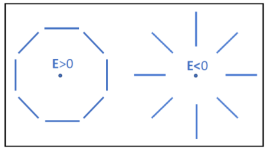

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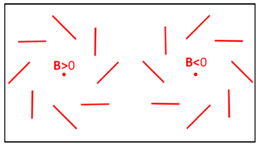
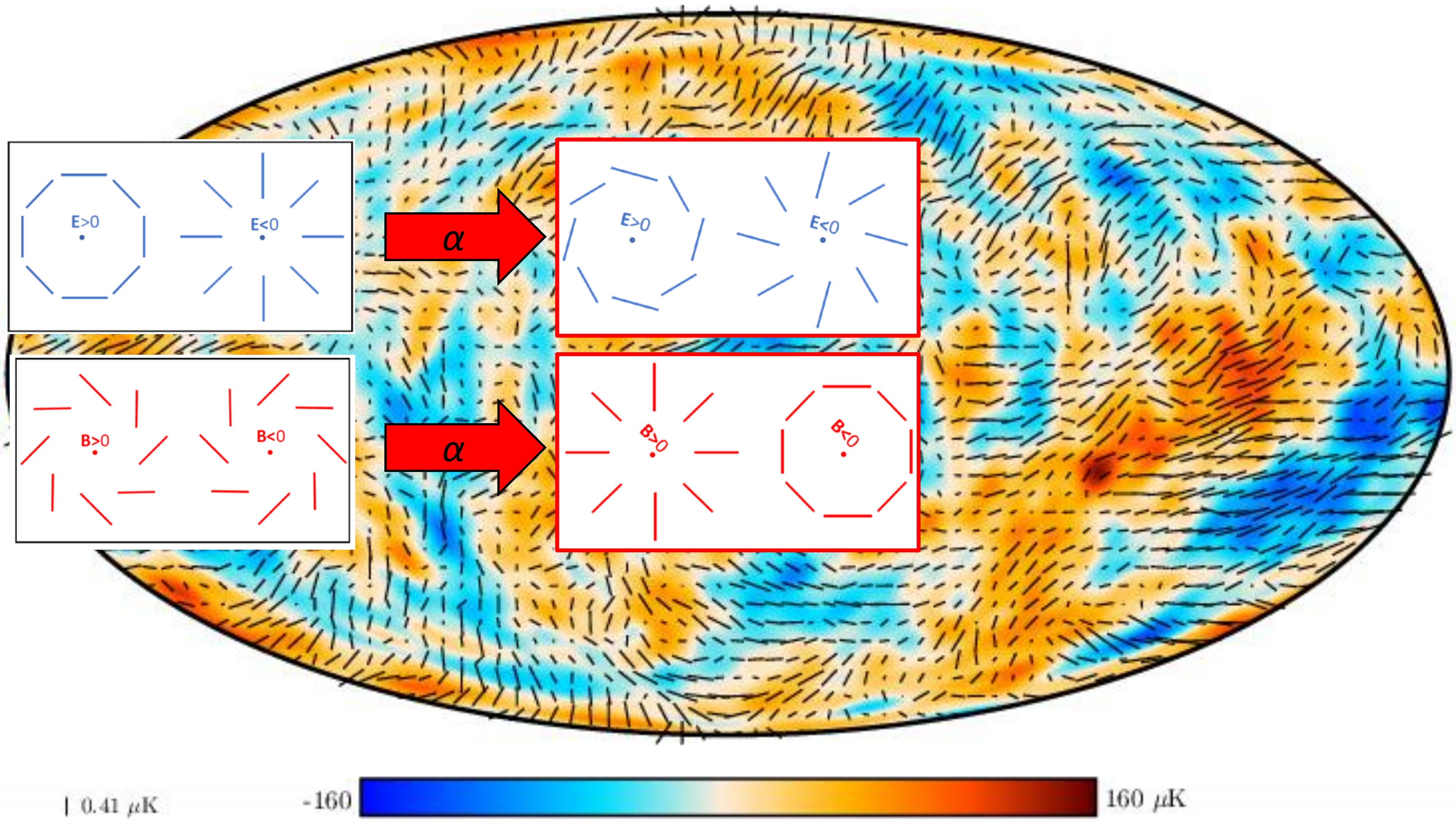


BB

Potential sources of B mode:

- Gravitational lensing;
- Inflationary gravitational w.;
- Primordial magnetic fields;
- Cosmic strings and other topological defects;
- Cosmic birefringence: coupling of CMB photons with a pseudoscalar field; …

Cosmic Birefringence



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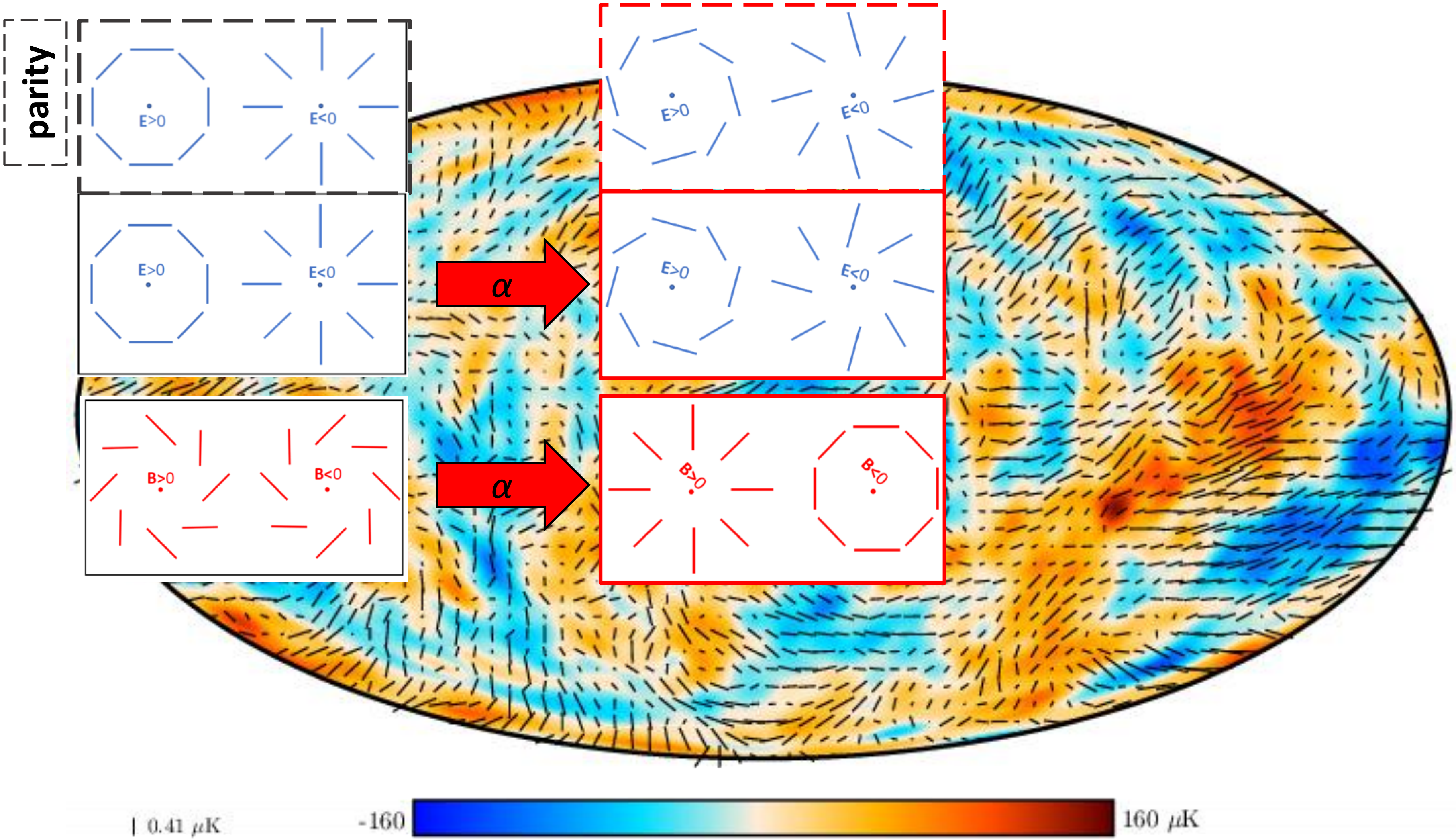

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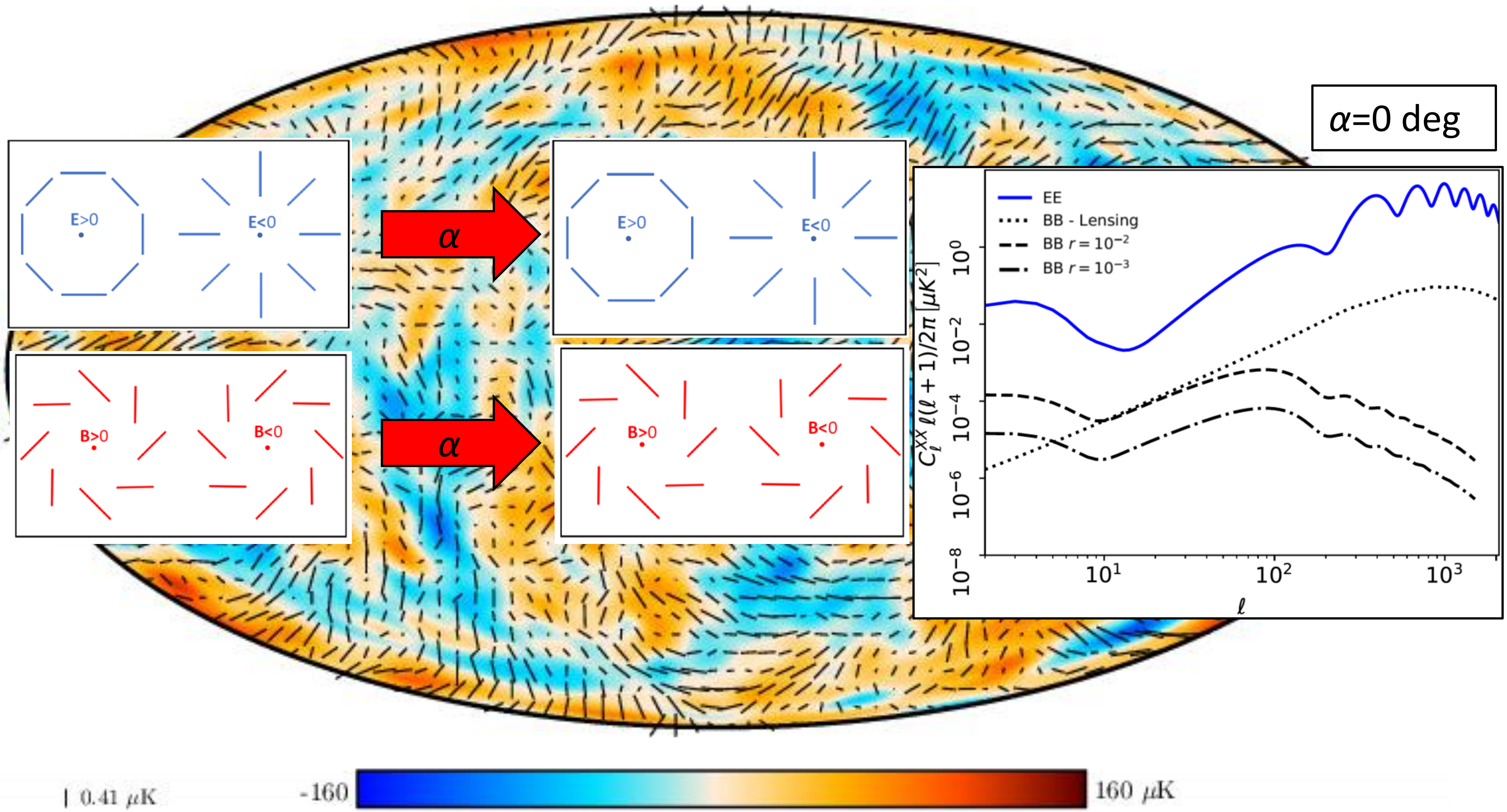

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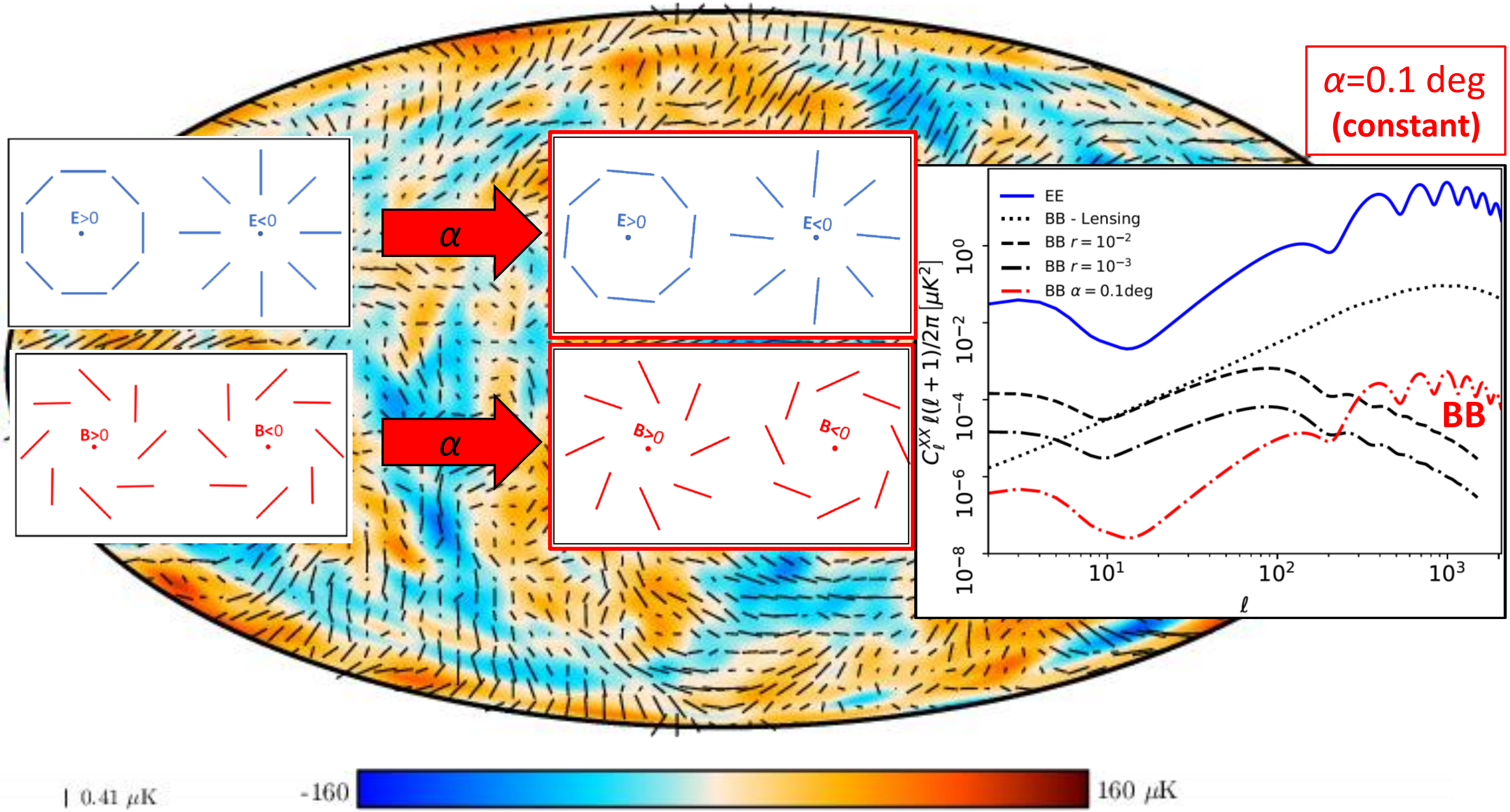

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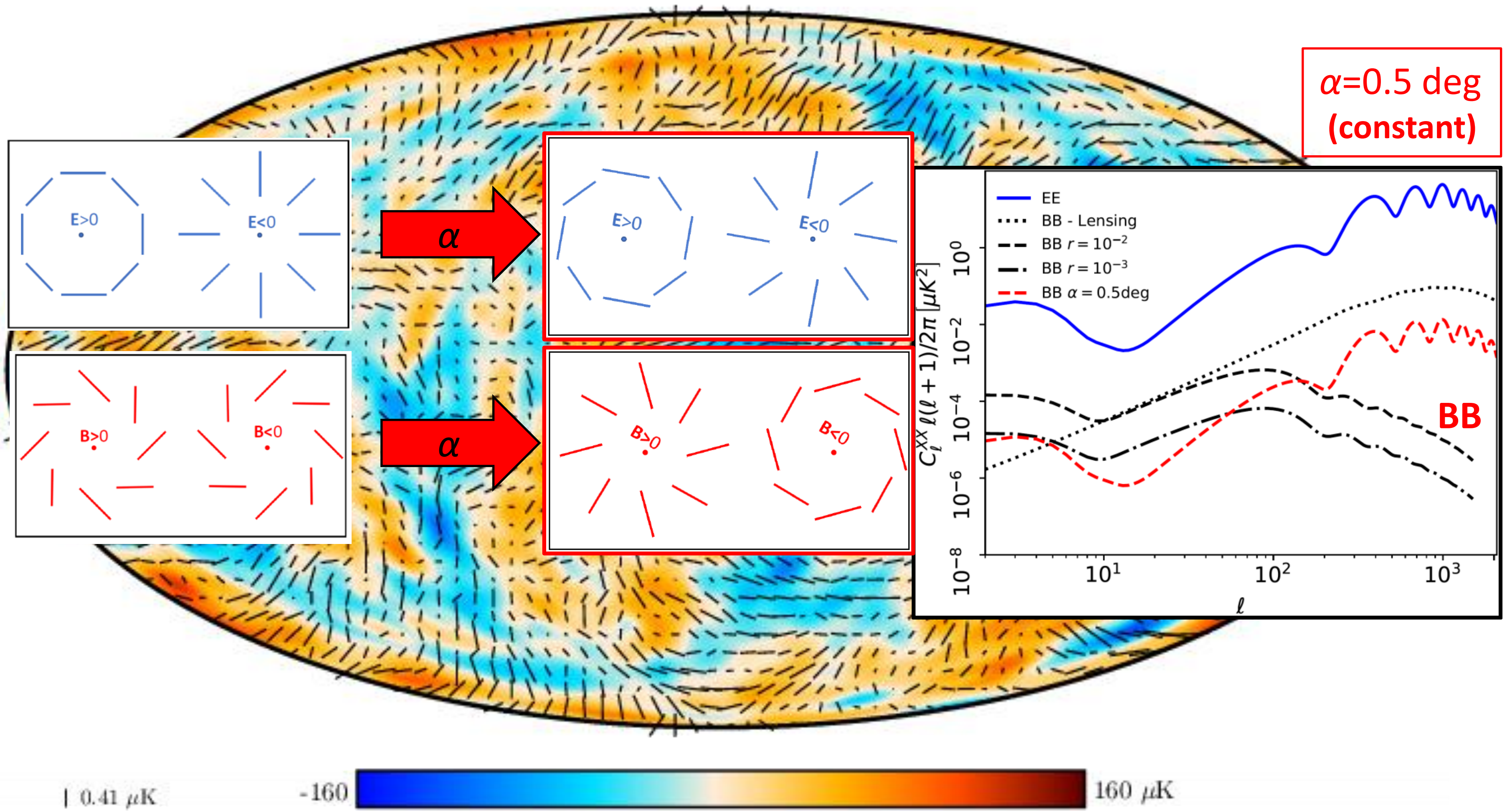

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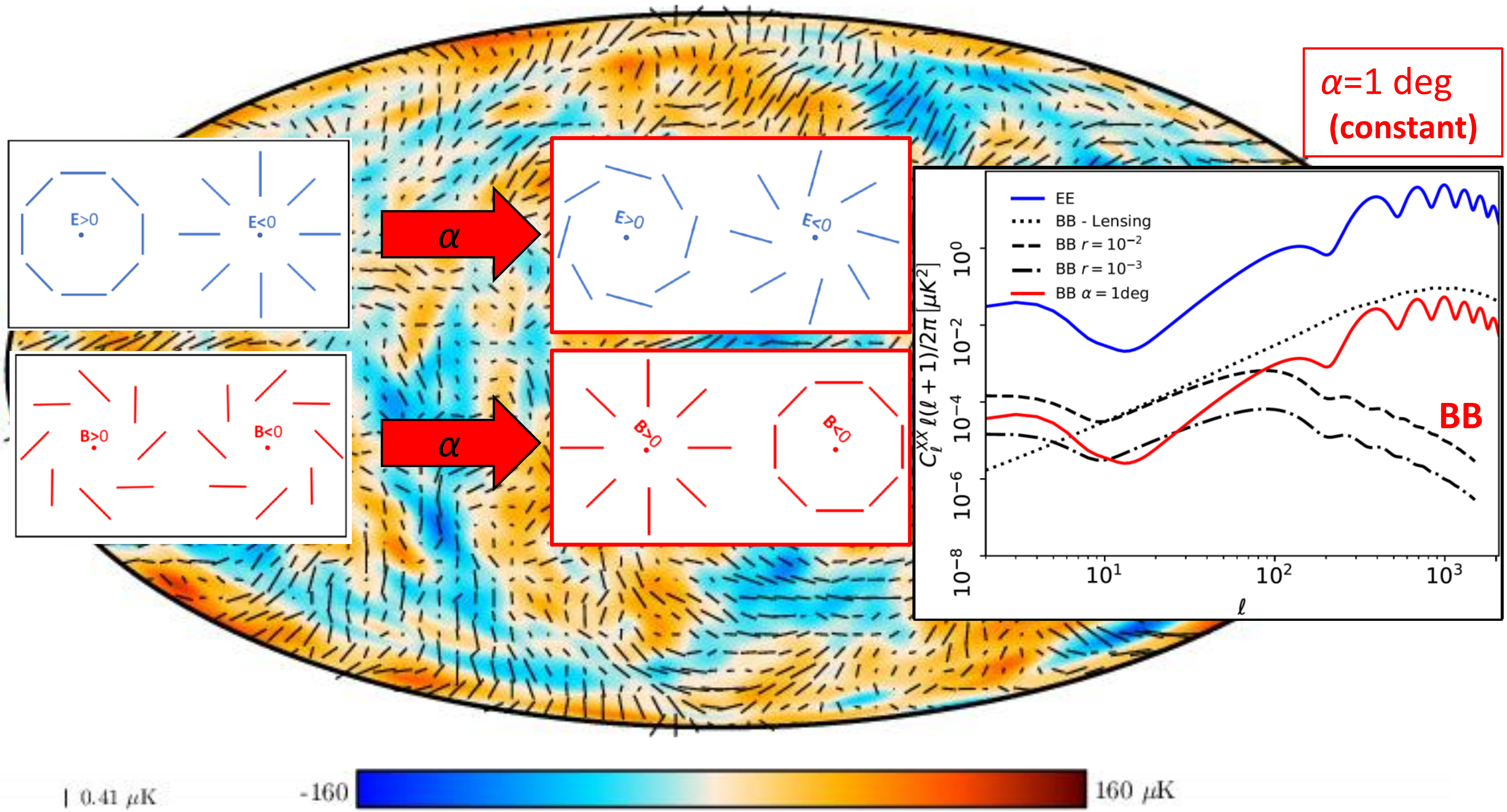


α [deg]: *isotropic* and *constant in redshift*

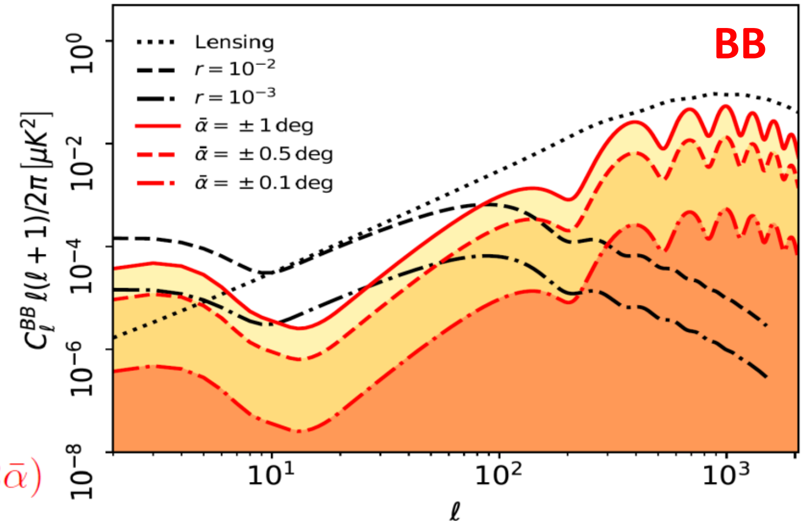
For a **cosmological birefringence**:

-***isotropic***

-***constant in redshift***

→only "total rotation" is important:

$$\bar{\alpha} \equiv \alpha(\eta_{\rm rec}) - \alpha(\eta_0) = \frac{g_\phi}{2}\left[\phi(\eta_{\rm rec}) - \phi(\eta_0)\right]$$



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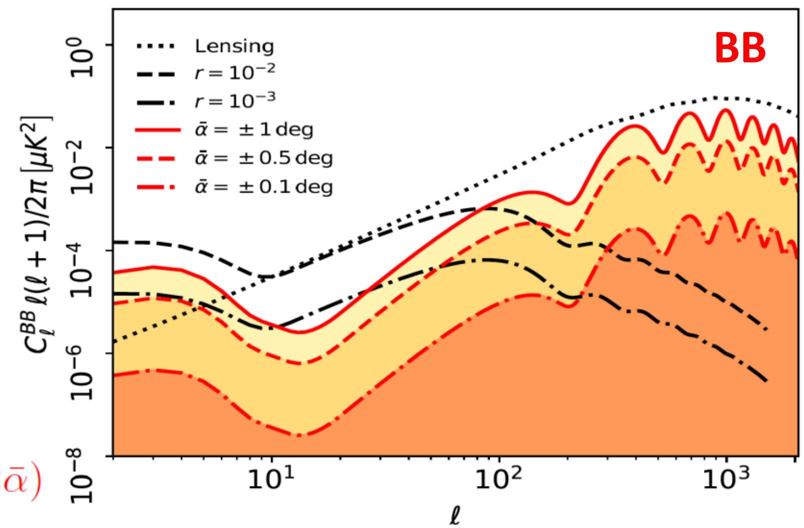

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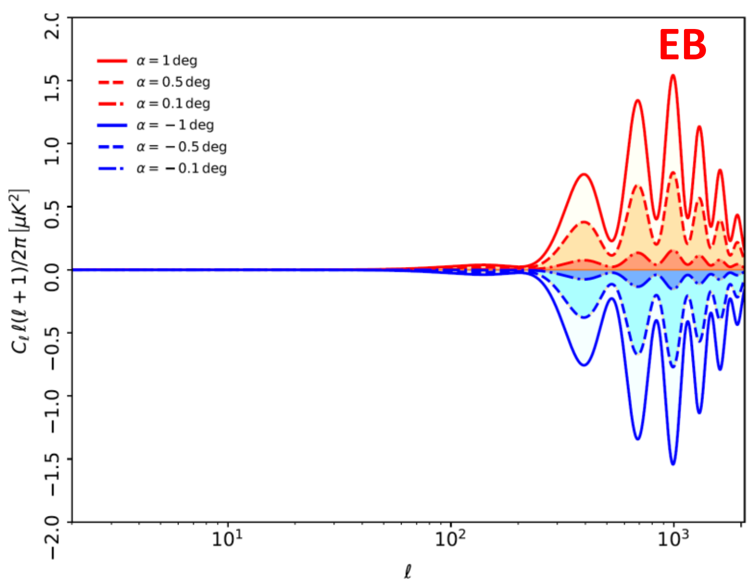
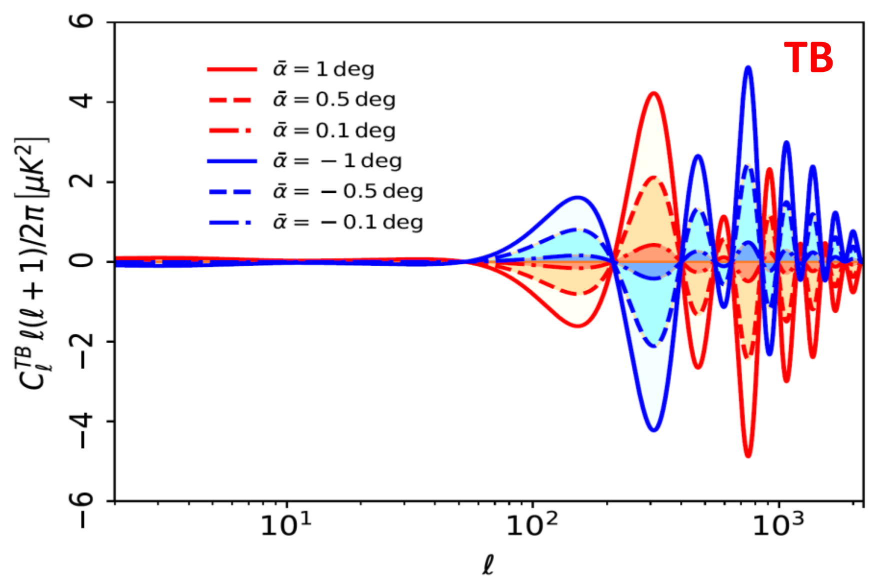
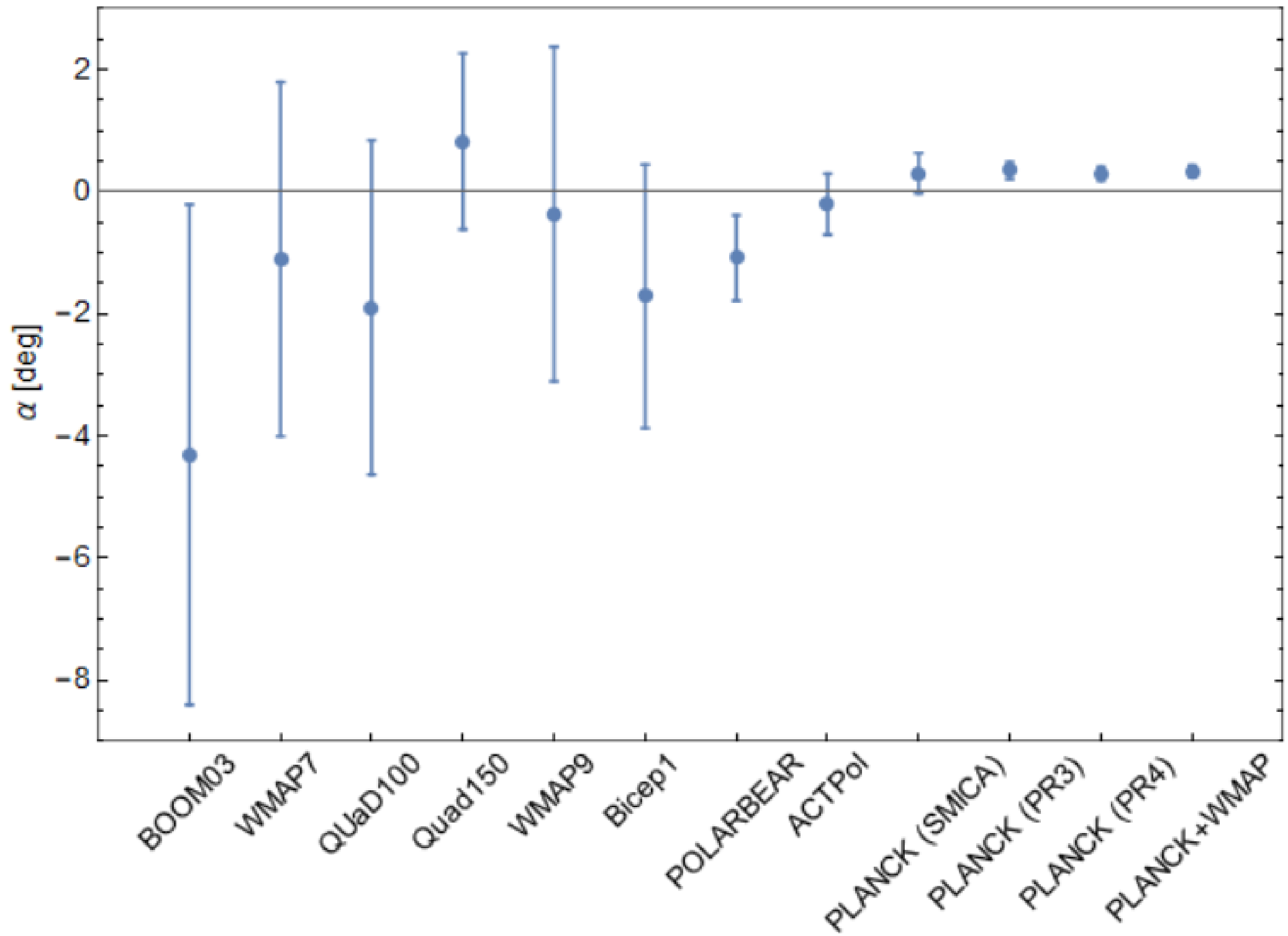
$$C_\ell^{TB,\rm obs} = C_\ell^{TE,\rm rec}\sin^2(2\bar{\alpha})$$





Constraints for α (*isotropic* and *constant in z*)



CMB polarization experiments constraints on isotropic cosmological birefringence as reviewed in Kaufman *et al.* (2016), Planck (2016), Greco *et al.* (2023), Williams (2023).

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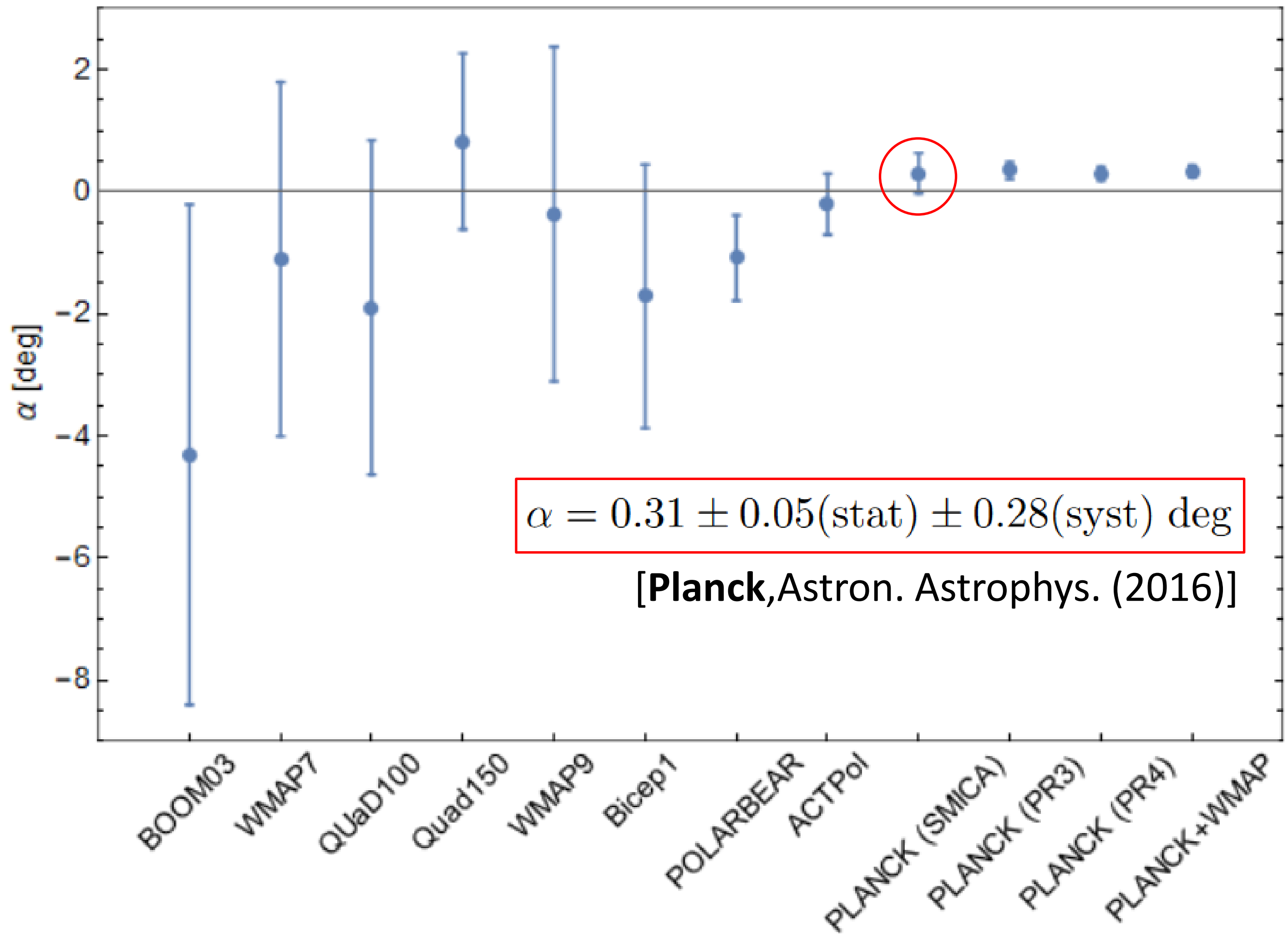

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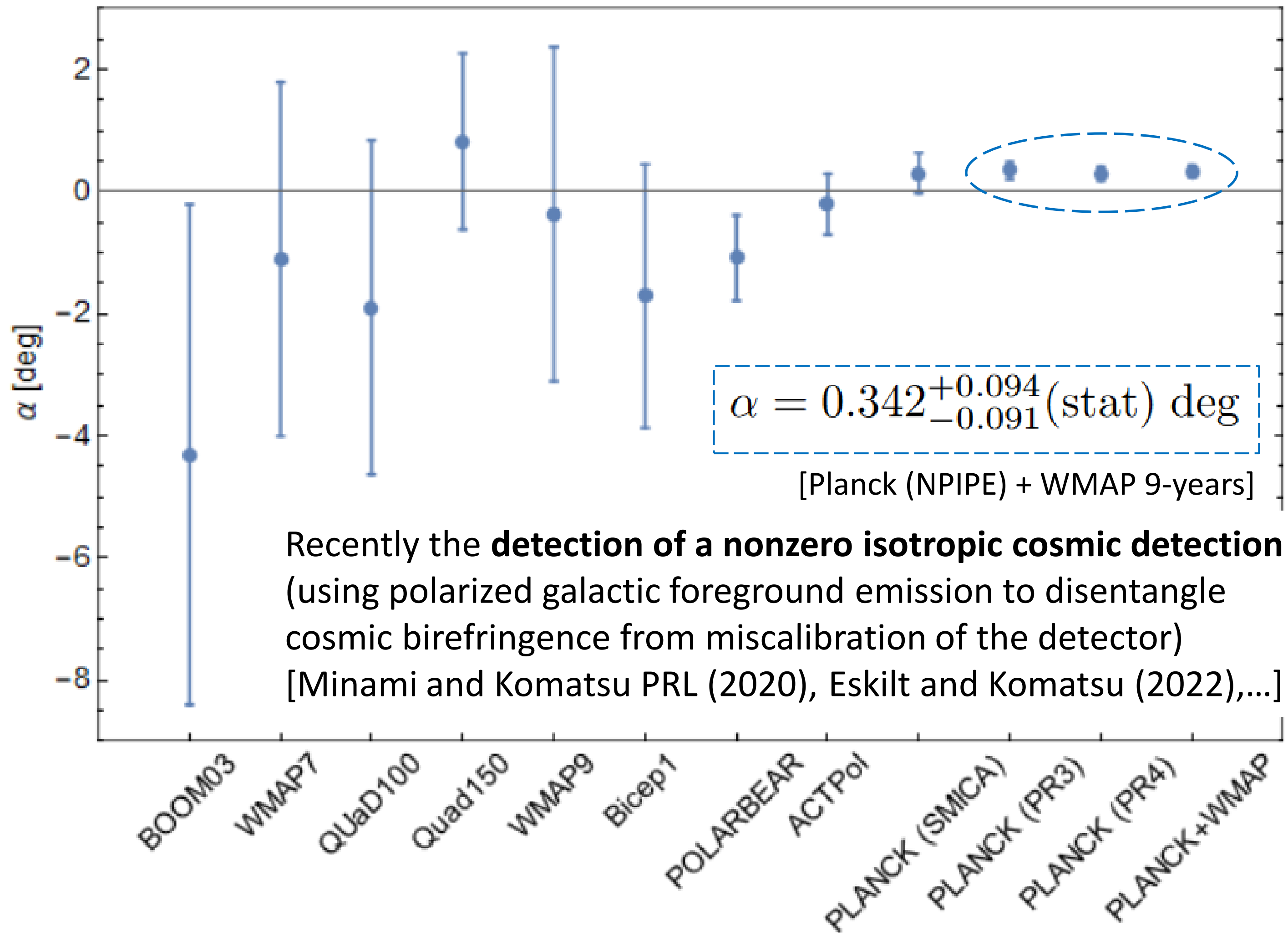

$$\alpha = 0.342^{+0.094}_{-0.091}\,(\text{stat})\ \text{deg}$$

[Planck (NPIPE) + WMAP 9-years]

Recently the **detection of a nonzero isotropic cosmic detection was claimed** (using polarized galactic foreground emission to disentangle cosmic birefringence from miscalibration of the detector) [Minami and Komatsu PRL (2020), Eskilt and Komatsu (2022),…]

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α [deg]: *isotropic* and ***z dependent***

Boltzmann equation for linear polarization **with cosmic birefringence** (Liu, Lee and Ng [PRL 2006], Finelli and Galaverni [PRD 2009]):

$$\Delta'_{Q\pm iU}(k,\eta) + ik\mu\Delta_{Q\pm iU}(k,\eta) = -n_e\sigma_T a(\eta)\left[\Delta_{Q\pm iU}(k,\eta) + \sum_m \sqrt{\frac{6\pi}{5}}\,{}_{\pm2}Y_2^m S_P^{(m)}(k,\eta)\right] \mp i2\alpha'(\eta)\Delta_{Q\pm iU}(k,\eta)$$

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we follow the **line-of-sight** strategy [Seljak and Zaldarriaga (1996)]

$$C_\ell^{EE/BB/EB} = (4\pi)^2 \frac{9\,(\ell+2)!}{16\,(\ell-2)!}\int k^2 dk\,\left[\Delta_{E/B/E}(k,\eta_0)\Delta_{E/B/B}(k,\eta_0)\right]$$

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$$\Delta_E(k,\eta_0) = \int_0^{\eta_0} d\eta\, g(\eta) S_P^{(0)}(k,\eta)\frac{j_\ell(k\eta_0 - k\eta)}{(k\eta_0 - k\eta)^2}\boxed{\cos 2\left[\alpha(\eta) - \alpha(\eta_0)\right]}$$

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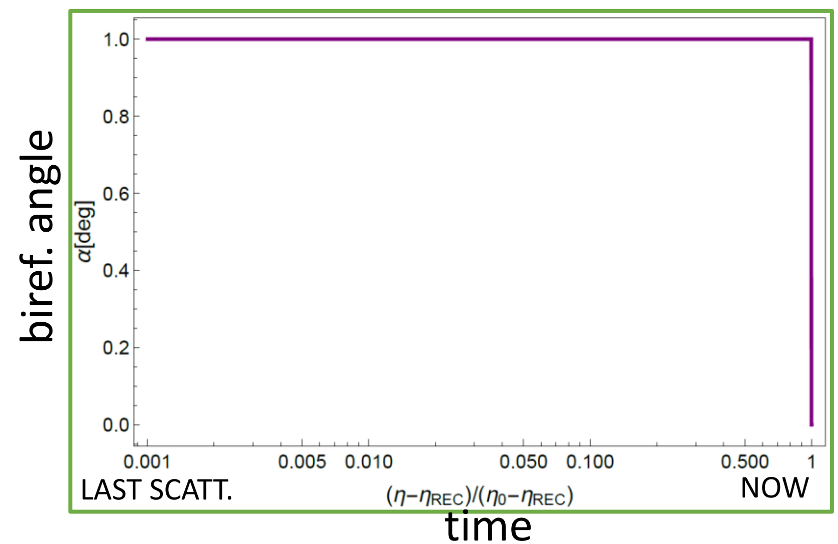

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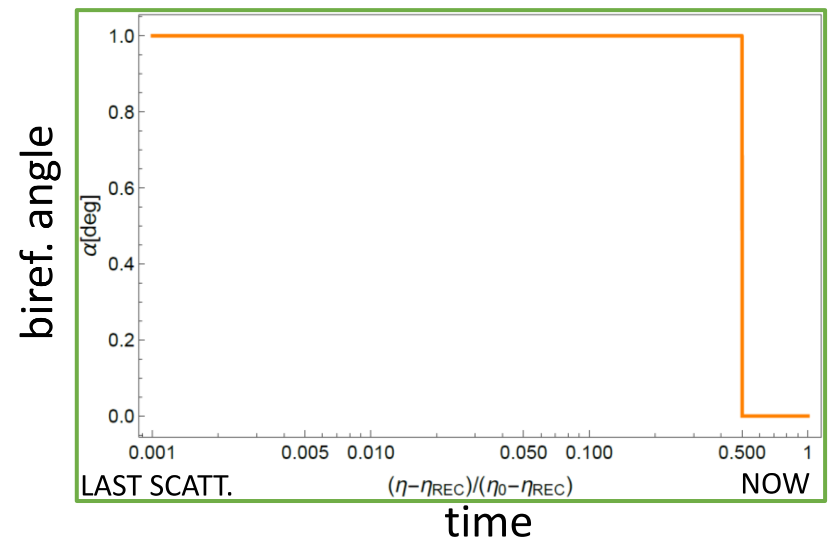

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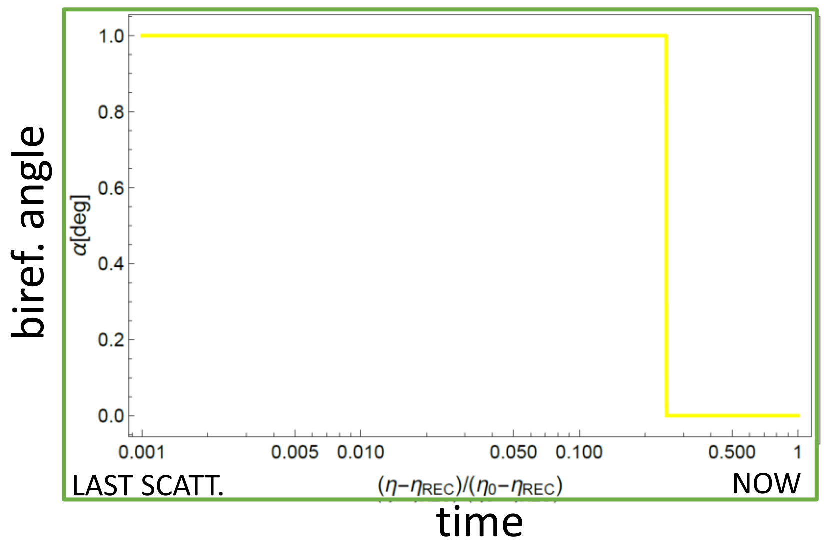

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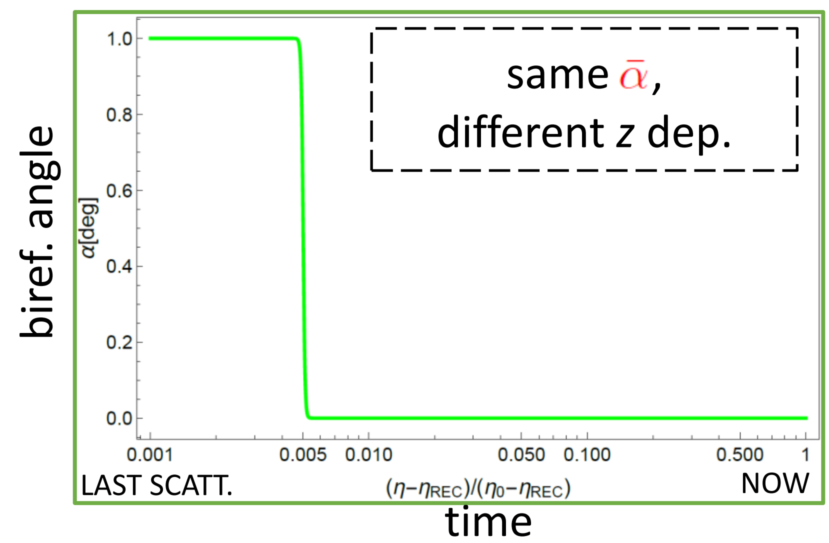

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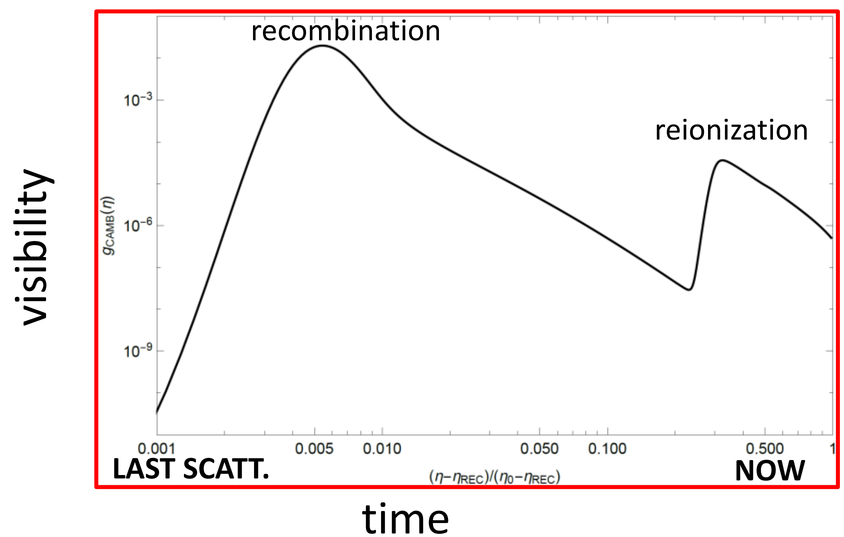

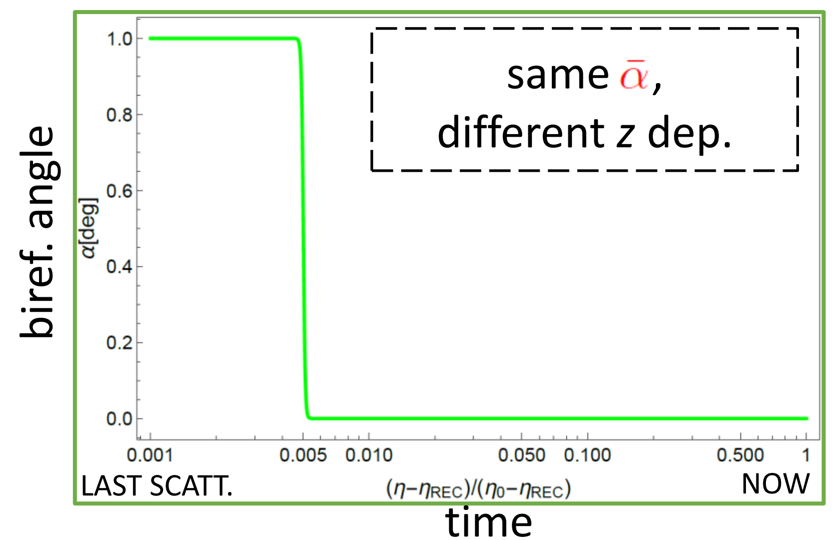

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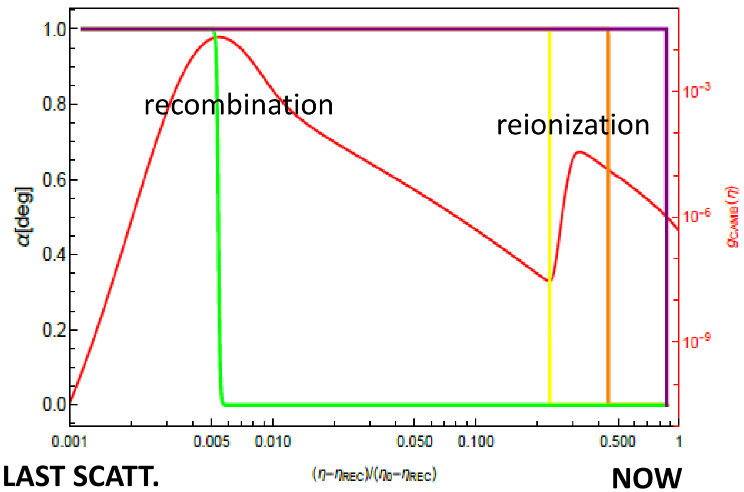
- same $\bar{\alpha}$ =1 deg
- but linear polarization rotation happens at different epochs!



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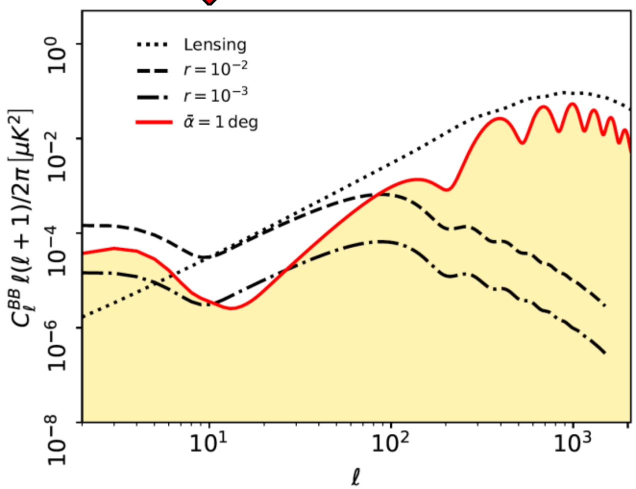

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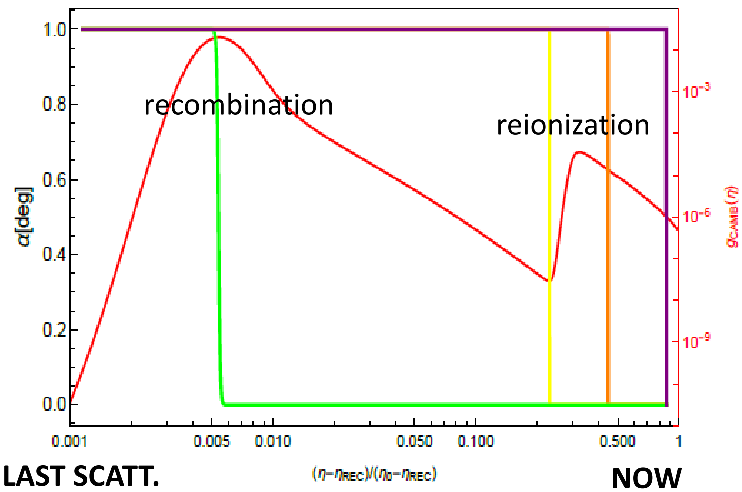

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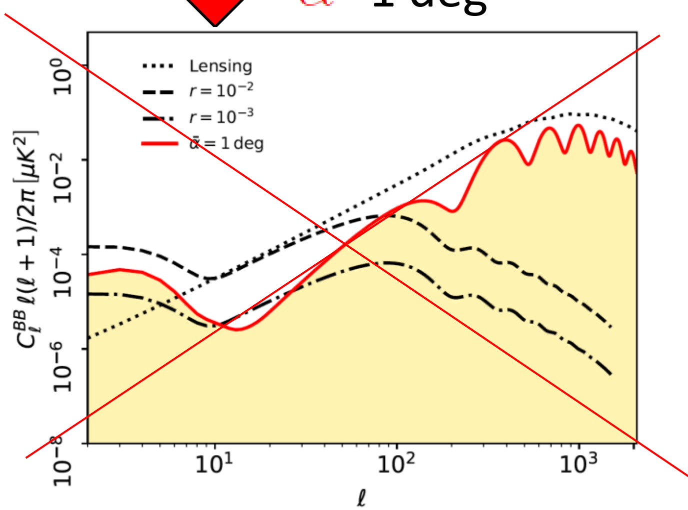
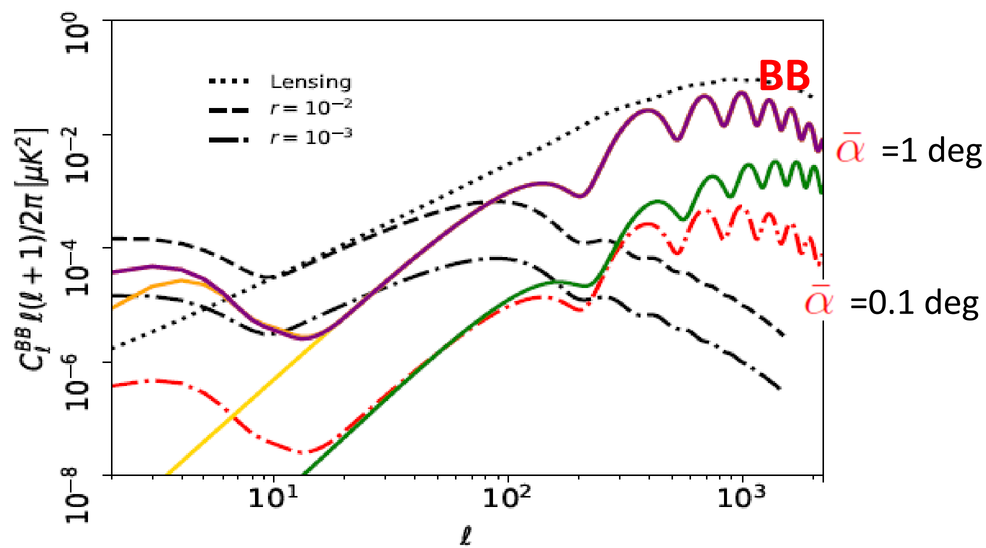


Integrating the Boltzmann equation along the line-of-sight:



~~$C_\ell^{BB,\mathrm{obs}} = C_\ell^{EE,\mathrm{rec}} \sin^2(2\bar{\alpha})$~~

(in agreement only if $\bar{\alpha}$ is constant from last scattering to today)

[see also Nakatsuka, Namikawa and Komatsu PRD 2022]

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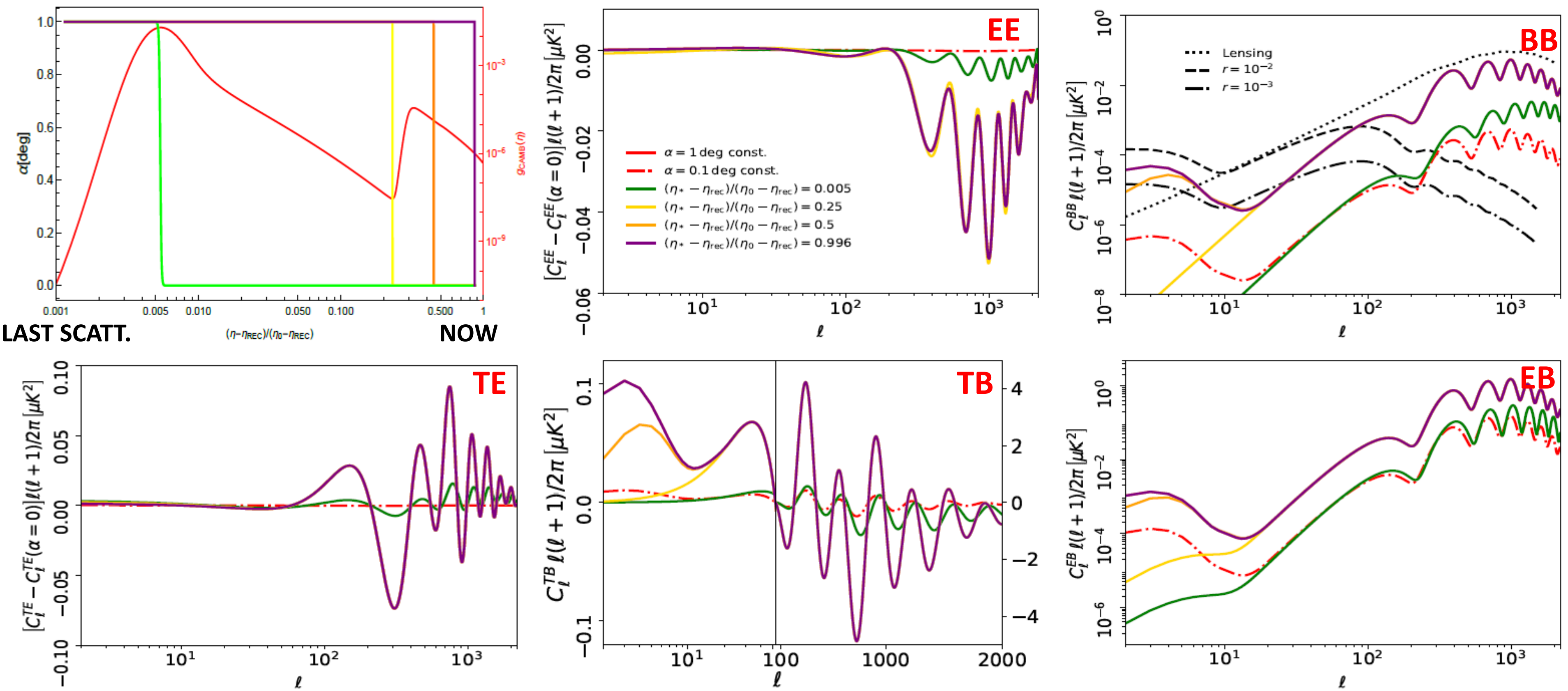


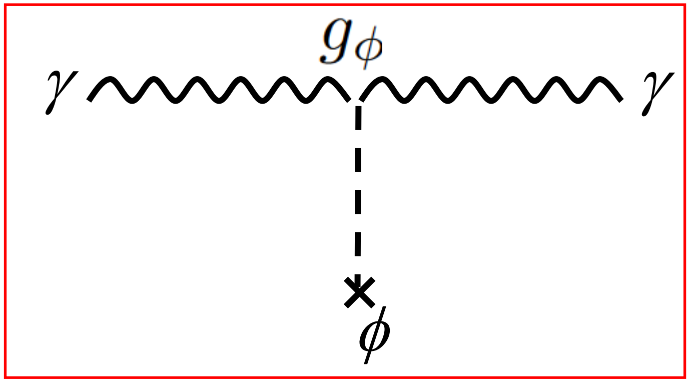
Cosmological pseudoscalar field

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi) - \boxed{\frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}},$$

Cosmological **pseudoscalar field ϕ** acting as:

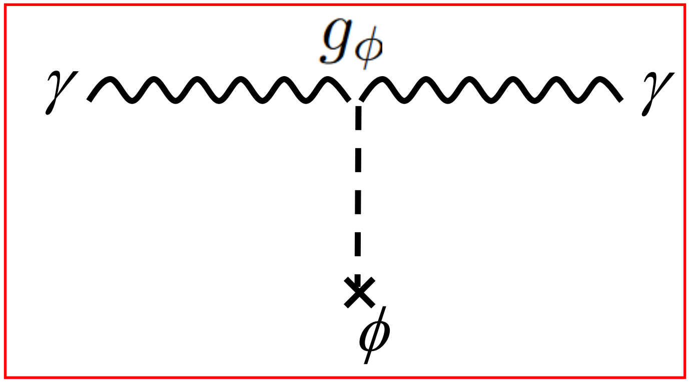
- **Dark Matter** (e.g. axion-like particles);
- **Dark Energy** (e.g. ultralight pseudo Nambu-Goldstone bosons);
- **Early Dark Energy**.

} $V(\phi)$



Cosmological pseudoscalar field

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - V(\phi) - \boxed{\frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}},$$



Cosmological **pseudoscalar field ϕ** acting as:

- **Dark Matter** (e.g. axion-like particles);
- **Dark Energy** (e.g. ultralight pseudo Nambu-Goldstone bosons);
- **Early Dark Energy**.

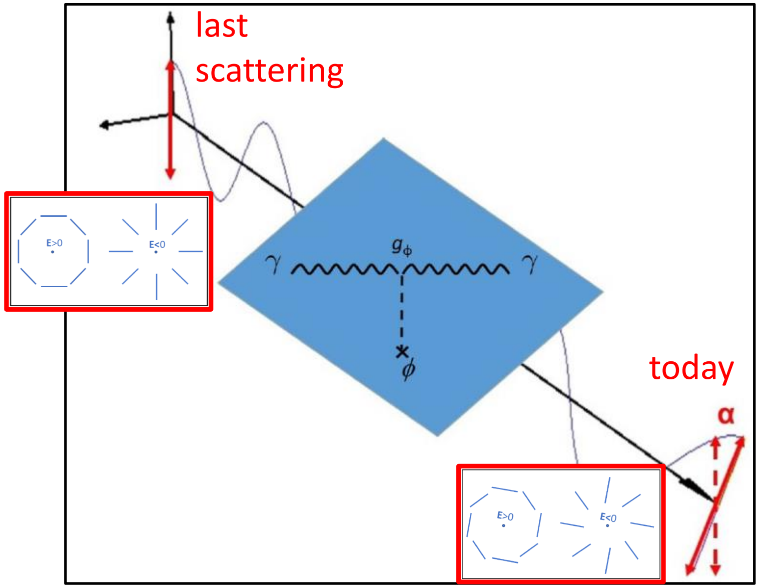
} $V(\phi)$

$$\boxed{\alpha(x) = \frac{g_\phi}{2}\left[\phi(x) - \phi(x_{\rm em})\right],}$$

rotation of the polarization plane

(single photon)

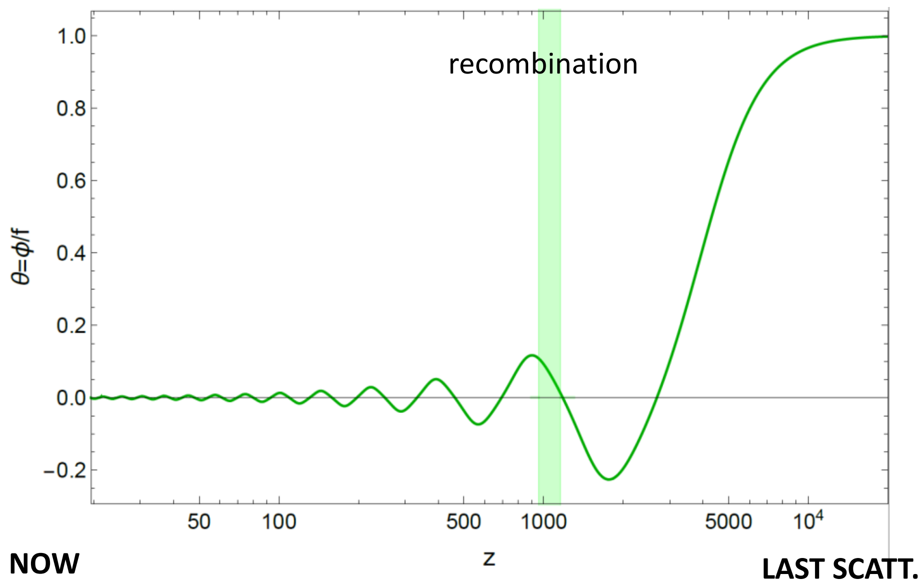
Carrol, Field and Jackiw [PRD 1990],
Harari and Sikivie [Phys. Lett. B 1992],...



Early Dark Energy

$$V(\phi) = \Lambda^4 \left(1 - \cos\frac{\phi}{f}\right)^n$$

[fixed:
n=2, Λ=0.417 eV, f=0.05 M_{pl},
$(\phi/f)_{in}$=1 and $(\dot{\phi}/f)_{in}$=0]



Early Dark Energy

$$V(\phi) = \Lambda^4 \left(1 - \cos\frac{\phi}{f}\right)^n$$

[fixed:
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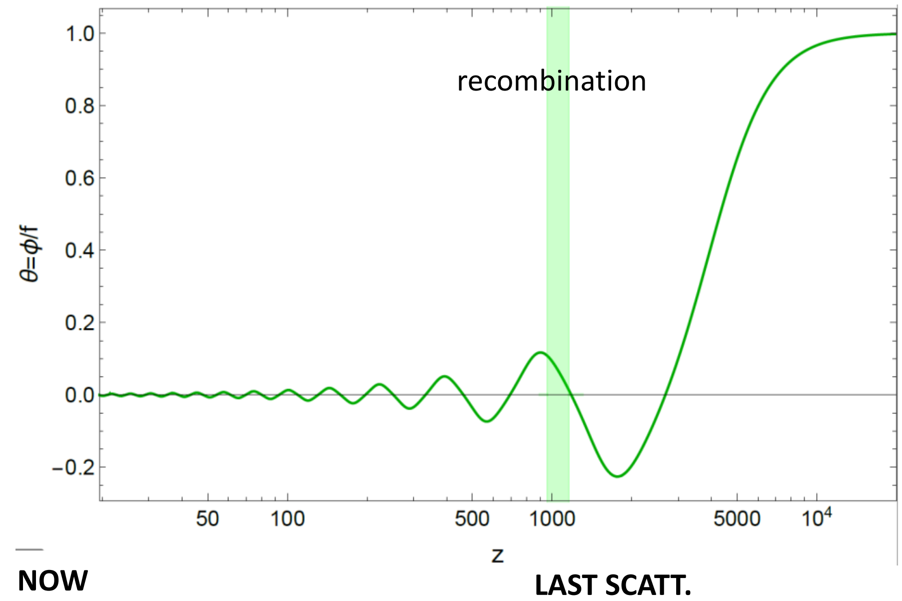
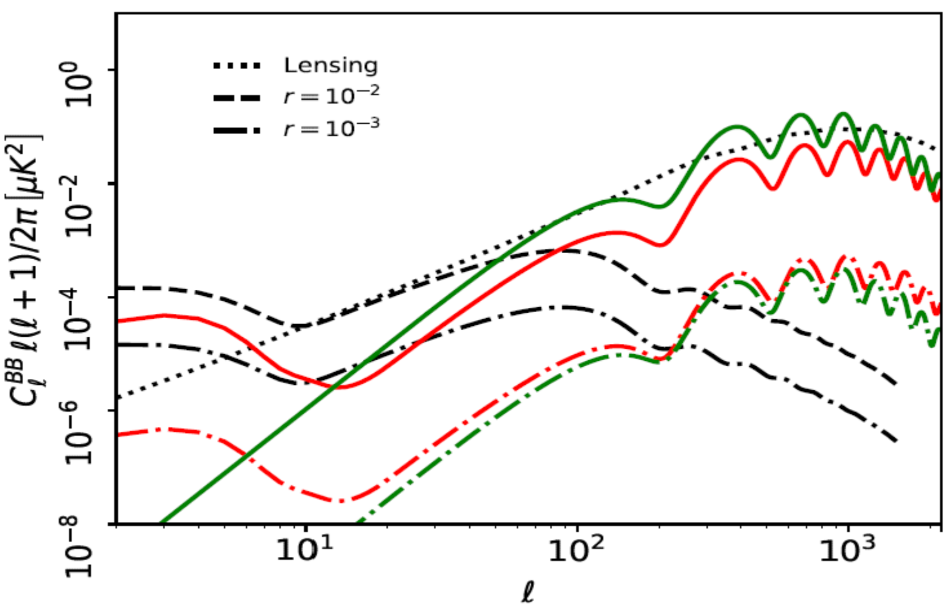




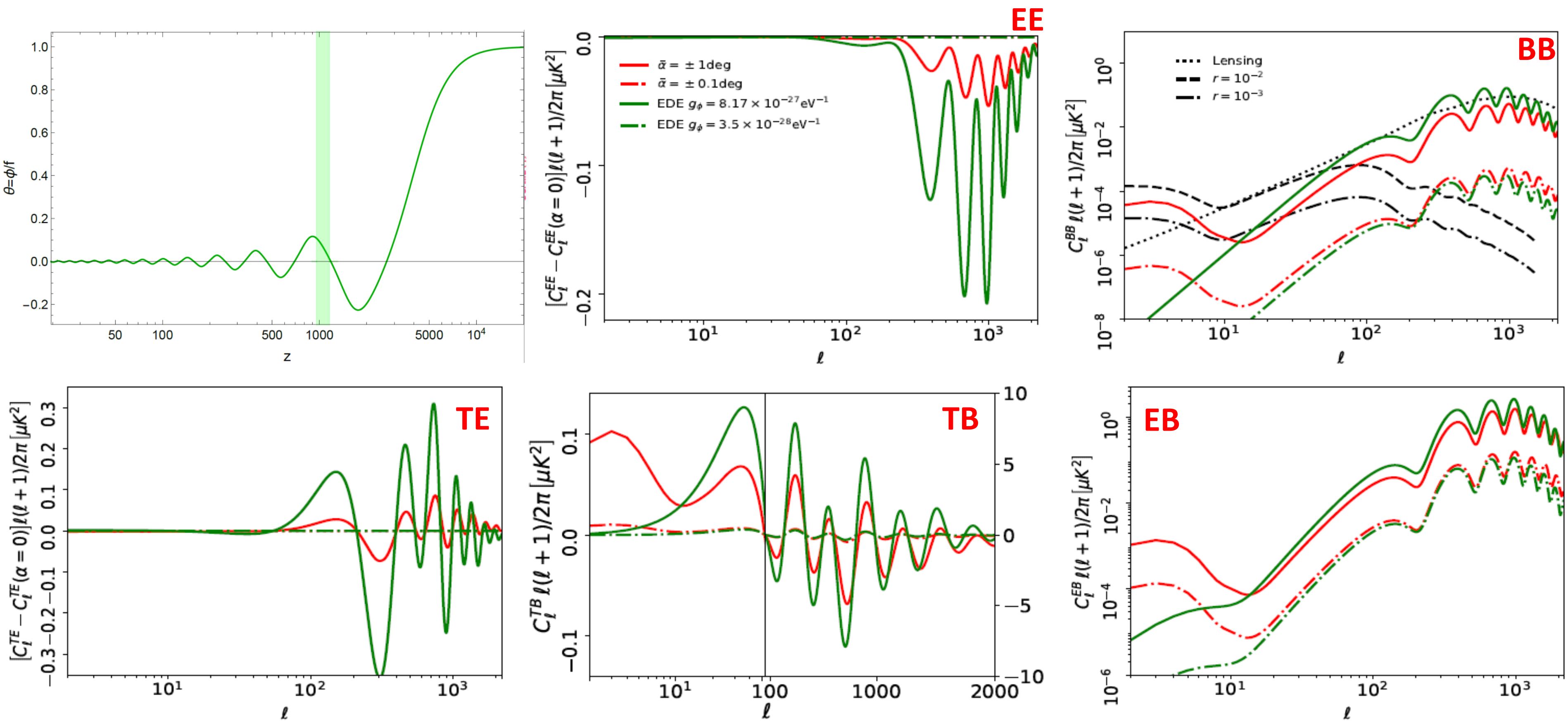
BB induced by **EDE** $g_\phi=8.17 \times 10^{-18}$ GeV^{-1}

BB induced by a const. rot α=1 deg

BB induced by a const. rot α=0.1 deg

BB induced by **EDE** $g_\phi=3.5 \times 10^{-19}$ GeV^{-1}

Early Dark Energy



Constraints for a LiteBIRD-like mission for EDE

The parity violating nature of the interaction generates **nonzero parity odd correlators (TB and EB)**, therefore we consider the **full theoretical covariance matrix**:

$$\bar{\mathbf{C}}_l = \begin{pmatrix} \bar{C}_\ell^{TT} & \bar{C}_\ell^{TE} & \bar{C}_\ell^{TB} \\ \bar{C}_\ell^{TE} & \bar{C}_\ell^{EE} & \bar{C}_\ell^{EB} \\ \bar{C}_\ell^{TB} & \bar{C}_\ell^{EB} & \bar{C}_\ell^{BB} \end{pmatrix}$$

Following Xia *et al.* [Astron. Astrophys. 2008] we introduce the effective χ^2

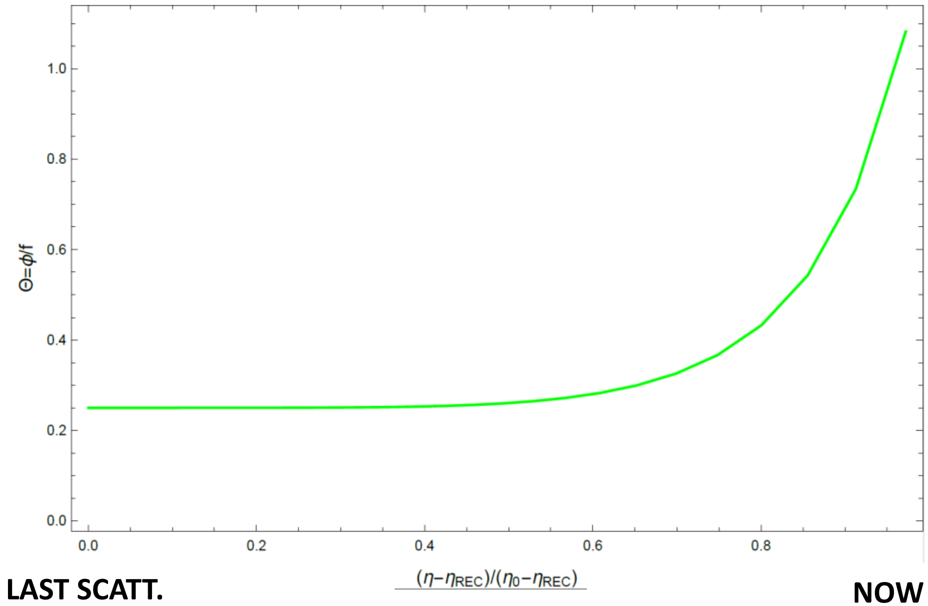
For Early Dark Energy:

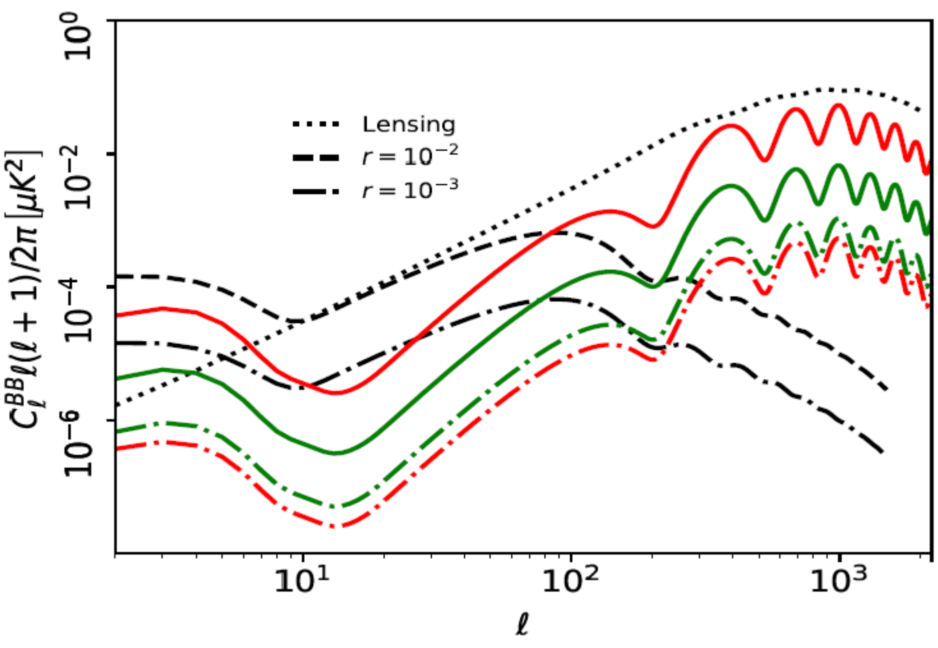
$\bar{C}_\ell$ theoretical (EDE) $+N_\ell$	$\hat{C}_\ell$ observed $+N_\ell$	$\chi^2_{\rm eff}$
$C_\ell(g_\phi = 1.65 \times 10^{-18}\,\mathtt{GeV}^{-1})$	$C_\ell(\bar{\alpha} = 0.35\,\deg)$	67.3
$C_\ell(g_\phi = 6.0 \times 10^{-20}\,\mathtt{GeV}^{-1})$	$C_\ell(\alpha = 0\,\deg)$	10.5

Axion-like Dark Energy

$$V(\phi) = M^4\left(1+\cos\frac{\phi}{f}\right)$$

assuming:
$M = 1.95 \times 10^{-3}$ eV, $f = 0.25\, M_{pl}$,
$(\phi/f)_{in} = 0.25$ and $(\dot{\phi}/f)_{in} = 0$





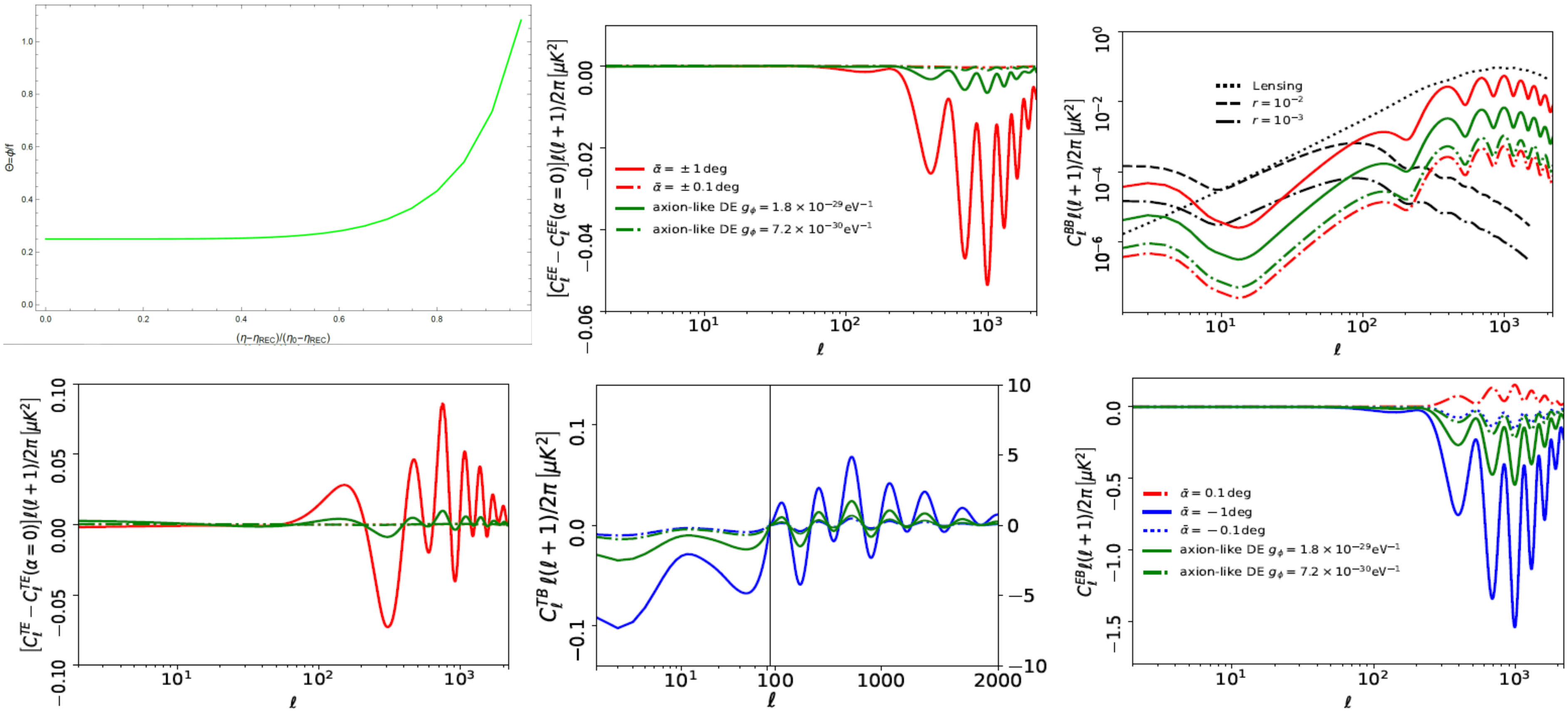
BB induced by a const. rot α=1 deg

BB induced by **DE** $g_\phi = 1.8 \times 10^{-20}$ GeV^{-1}

BB induced by **DE** $g_\phi = 7.2 \times 10^{-21}$ GeV^{-1}

BB induced by a const. rot α=0.1 deg

Constraints for a LiteBIRD-like mission for DE



$\bar{C}_\ell$ theoretical (DE) $+N_\ell$	$\hat{C}_\ell$ observed $+N_\ell$	$\chi^2_{\rm eff}$
$C_\ell(g_\phi = 1.8\times 10^{-20}\,\texttt{GeV}^{-1})$	$C_\ell(\bar{\alpha} = -0.35\,\text{deg})$	0.30
$C_\ell(g_\phi = 1.8\times 10^{-20}\,\texttt{GeV}^{-1})$	$C_\ell(\alpha = 0\,\text{deg})$	3.78×10^3
$C_\ell(g_\phi = 9.0\times 10^{-22}\,\texttt{GeV}^{-1})$	$C_\ell(\alpha = 0\,\text{deg})$	9.4

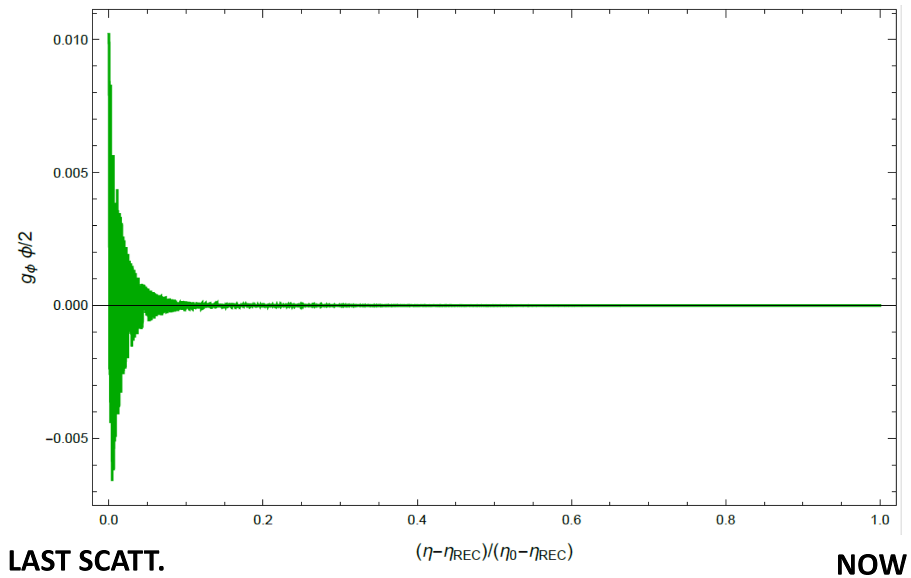
Axion-like Dark Matter

$$V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi}{f}\right) ,$$

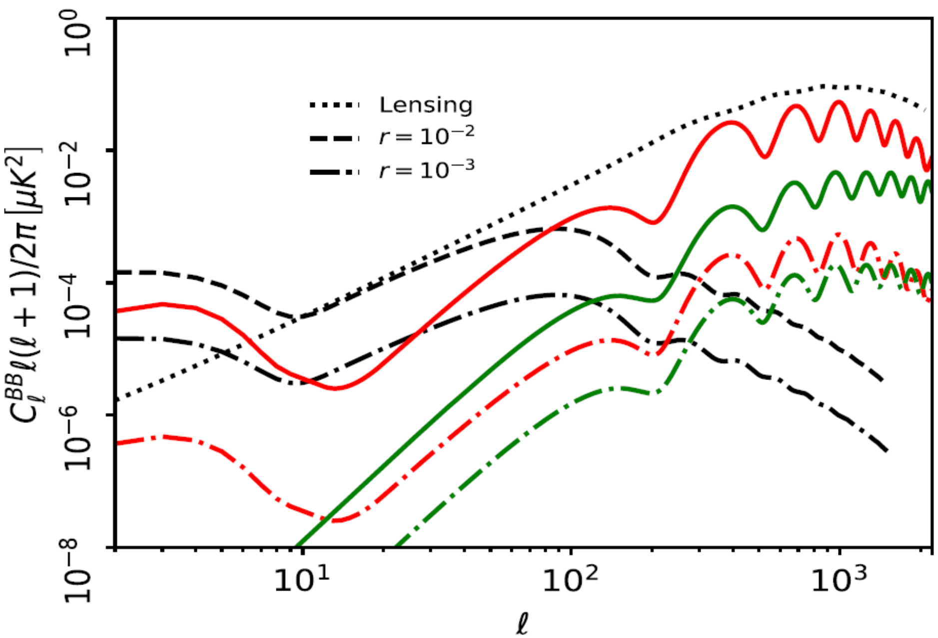
assuming:

m=10^{-22} eV and

g_ϕ = 10^{-14} GeV^{-1} (g_ϕ =2 x 10^{-15} GeV^{-1})



LAST SCATT. **NOW**



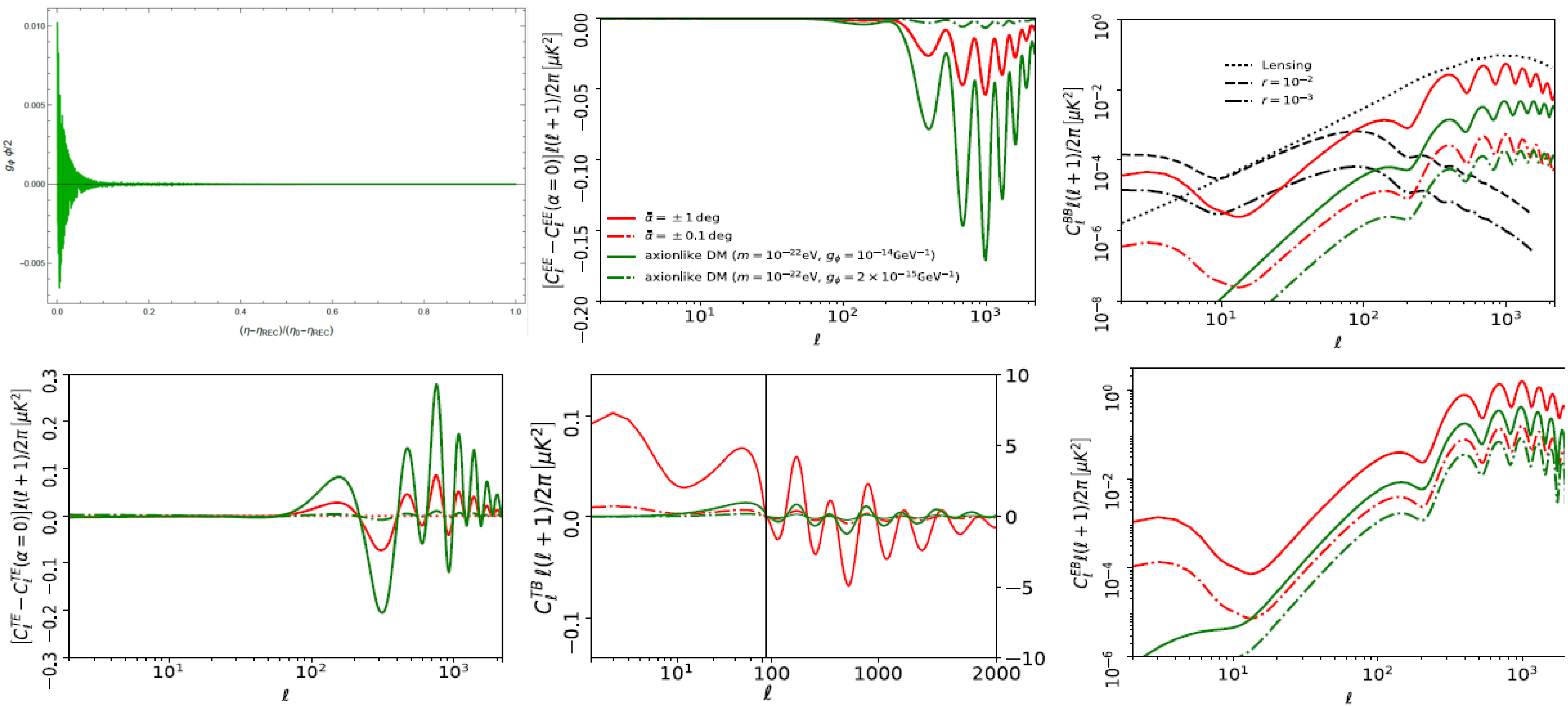
BB induced by a const. rot α=1 deg

BB induced by **DM** g_ϕ= 10^{-14} GeV^{-1}

BB induced by **DM** g_ϕ=2 x 10^{-15} GeV^{-1}

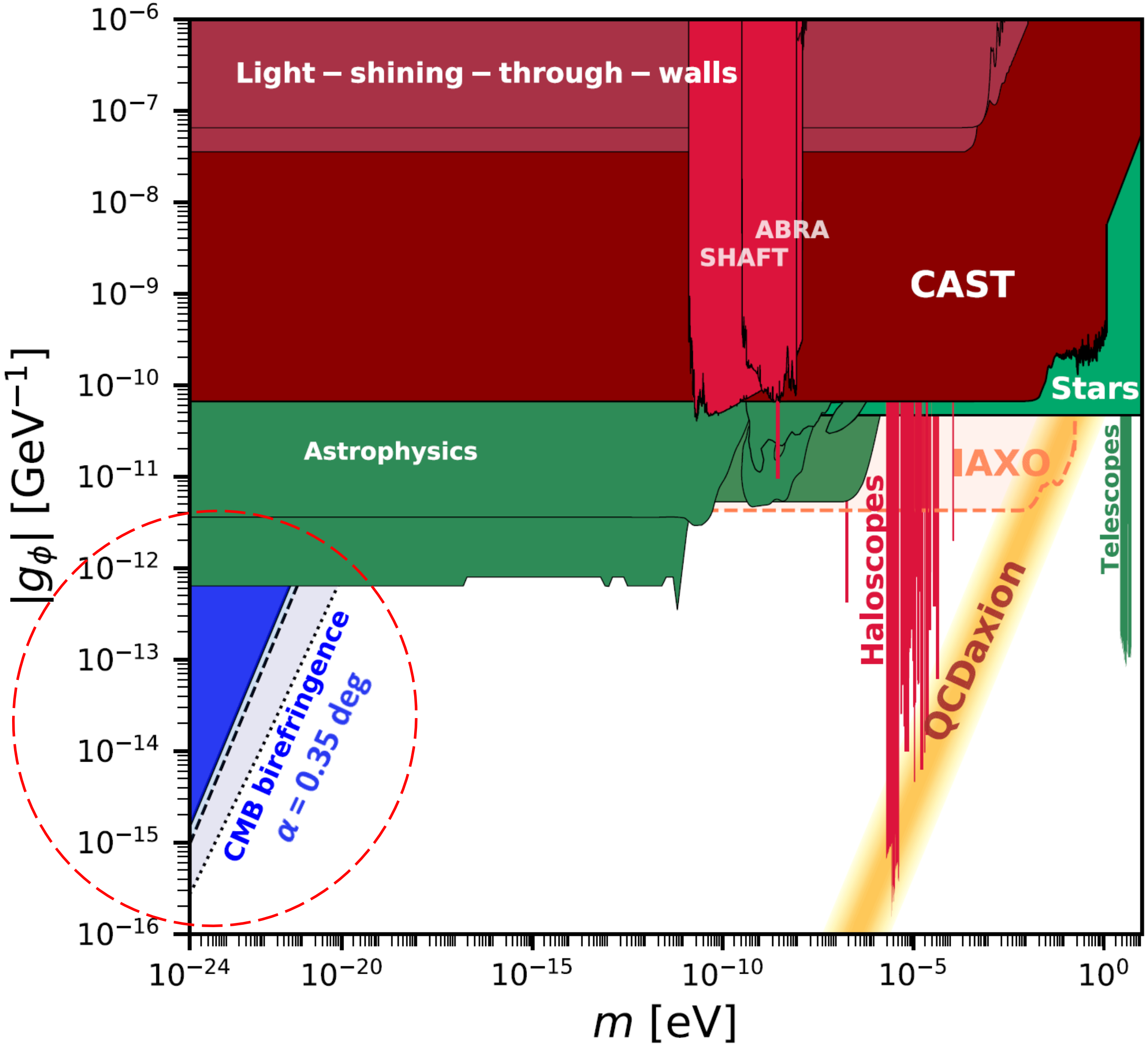
BB induced by a const. rot α=0.1 deg

Constraints for a LiteBIRD-like mission for DM



$\bar{C}_\ell$ theoretical (DM) $+N_\ell$	$\hat{C}_\ell$ observed $+N_\ell$	χ^2_{eff}
$C_\ell(g_\phi = 1.37\times10^{-14}\,\mathtt{GeV}^{-1})$	$C_\ell(\bar{\alpha}=0.35\,\mathrm{deg})$	69.8
$C_\ell(g_\phi = 8.1\times10^{-16}\,\mathtt{GeV}^{-1})$	$C_\ell(\alpha=0\,\mathrm{deg})$	10.4

Constraints for axion-like DM



[M.G., F. Finelli and D. Paoletti Phys.Rev.D 107 (2023) 8, 083529;
plot created with **AxionLimits** code]

Conclusions

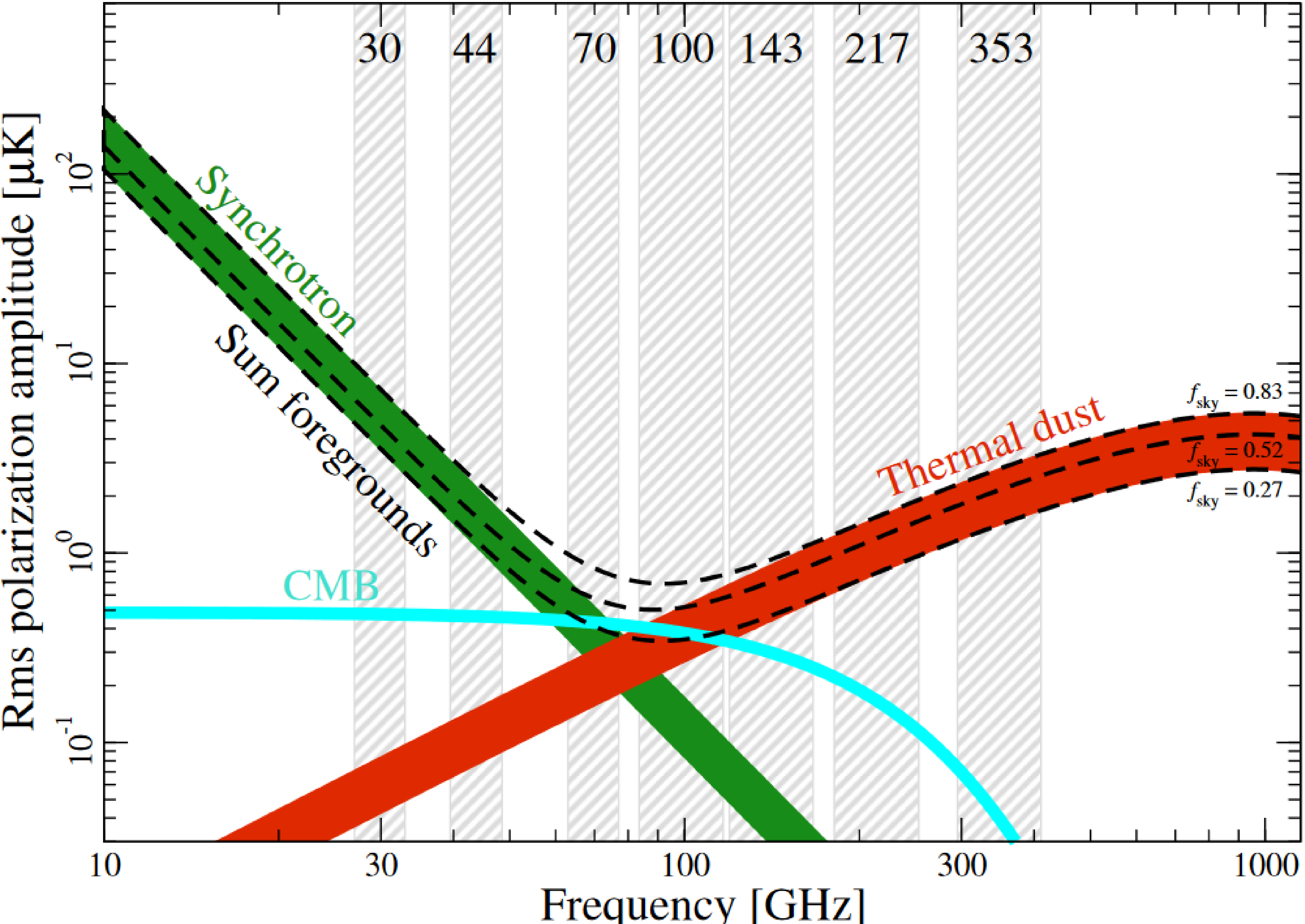
We studied the imprints of an **isotropic redshift-dependent pseudoscalar field** on CMB polarization power spectra for phenomenological and physical motivated models.

→**Redshift evolution of the birefringence angle**
has important **effects on CMB polarization power spectra**:

- not only $\bar{\alpha} \equiv \alpha(\eta_{\rm rec}) - \alpha(\eta_0)$ is important ,
  but also **when** the rotation occurs;
- **different theoretical motivated redshift dependencies** of the pseudoscalar field (EDE, DE, DM) produce **different multipole dependence** for the CMB polarization power spectra;
- **isotropic birefringence -** and not only anisotropic one - can produce **different multipole dependencies** of the power spectra, this can be used to break the degeneracy with the miscalibration angle of the detector.

For more details see:

Redshift evolution of cosmic birefringence in CMB anisotropies
M.G., F. Finelli and **D. Paoletti**
Phys.Rev.D **107** (2023) 8, 083529 (arXiv 2301.07971 [astro-ph.CO])



[Planck 2018 - https://www.cosmos.esa.int/web/planck/picture-gallery]

Cosmic Birefringence from the *Planck* Data Release 4

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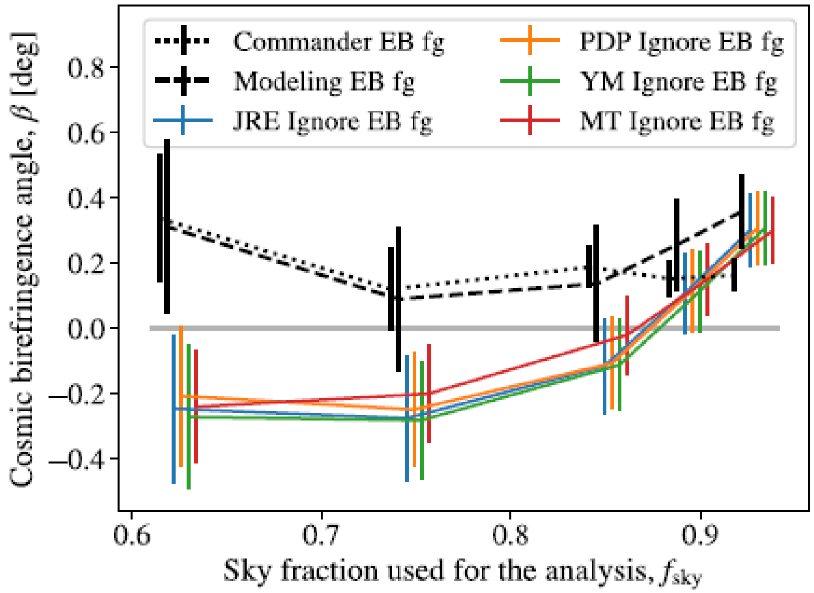

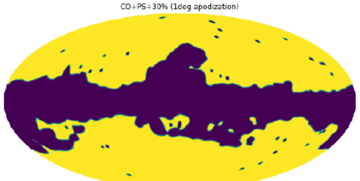

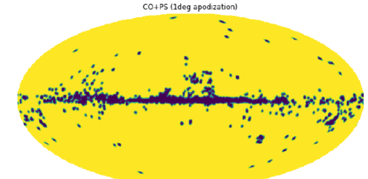

FIG. 1. Constraints on β for various values of $f_{\rm sky}$ with and without accounting for the foreground EB correlations. For the former, the dashed and dotted lines show corrections using the filament model [Eq. (2)] and the COMMANDER sky model, respectively. For the latter, the results of four pipelines (JRE, PDP, YM, MT) are shown.

α [deg]: *isotropic* and ***z dependent***

Boltzmann equation for linear polarization **with cosmic birefringence** (Liu, Lee and Ng [PRL 2006], Finelli and Galaverni [PRD 2009]):

$$\Delta'_{Q\pm iU}(k,\eta) + ik\mu\Delta_{Q\pm iU}(k,\eta) = -n_e\sigma_T a(\eta)\left[\Delta_{Q\pm iU}(k,\eta) + \sum_m \sqrt{\frac{6\pi}{5}}\,{}_{\pm 2}Y_2^m S_P^{(m)}(k,\eta)\right] \mp i2\alpha'(\eta)\Delta_{Q\pm iU}(k,\eta)$$

we follow the **line-of-sight** strategy [Seljak and Zaldarriaga (1996)]

$$C_\ell^{EE/BB/EB} = (4\pi)^2 \frac{9\,(\ell+2)!}{16\,(\ell-2)!}\int k^2 dk\,\left[\Delta_{E/B/E}(k,\eta_0)\Delta_{E/B/B}(k,\eta_0)\right]$$

where the **source terms for scalar perturbations** are modified:

$$\Delta_E(k,\eta_0) = \int_0^{\eta_0} d\eta\, g(\eta) S_P^{(0)}(k,\eta)\frac{j_\ell(k\eta_0 - k\eta)}{(k\eta_0-k\eta)^2}\cos 2\left[\alpha(\eta)-\alpha(\eta_0)\right]$$

$$\Delta_B(k,\eta_0) = \int_0^{\eta_0} d\eta\, g(\eta) S_P^{(0)}(k,\eta)\frac{j_\ell(k\eta_0 - k\eta)}{(k\eta_0-k\eta)^2}\sin 2\left[\alpha(\eta)-\alpha(\eta_0)\right]$$