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Redshift evolution of cosmic birefringence in CMB anisotropies

SPECOLA VATICANA

Vatican Observatory

INAF
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NATIONAL INSTITUTE FOR ASTROPHYSICS

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Based on a work with:
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Photon coupling with pseudoscalar fields

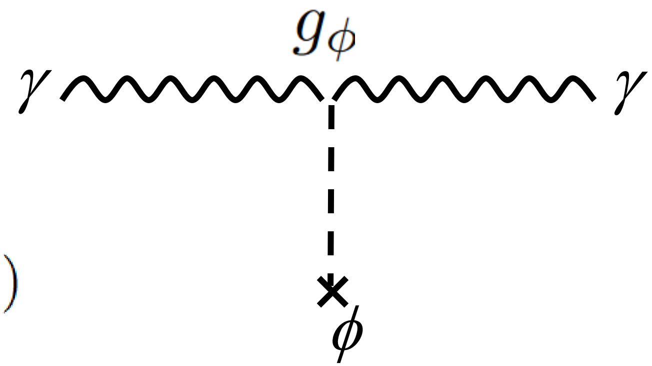
Coupling with photons plays a key role in the search for pseudoscalar particles:

$$\mathcal{L} \supset g_\phi \phi \mathbf{E} \cdot \mathbf{B} = -\frac{g_\phi}{4} \phi F_{\mu\nu} \widetilde{F}^{\mu\nu} \,,$$

- *Astrophysical constraints* (e.g. additional energy loss channel for stars);
- *Light shining through walls experiments*: produce and immediately detect the axions with the help of a photon laser beam (e.g. ALPS);
- The *haloscope* (e.g. ADMX) and *helioscope* (e.g. CAST, [Baby-]IAXO) methods proposed by P. Sikivie [PRL 1983];
- […]
- Photon propagation in a time dependent background of pseudoscalar particles: ***cosmological birefringence*.**

Cosmological birefringence

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.

$V(\phi)$

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

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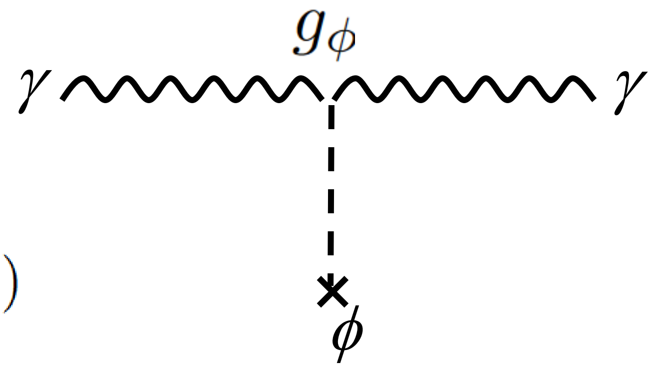

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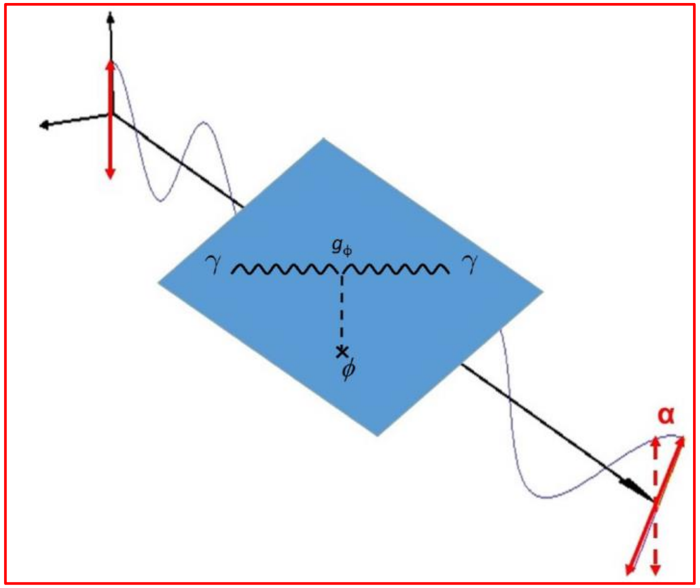
$$\boxed{\alpha(x) = \frac{g_\phi}{2}\left[\phi(x) - \phi(x_{\mathrm{em}})\right] \ ,}$$

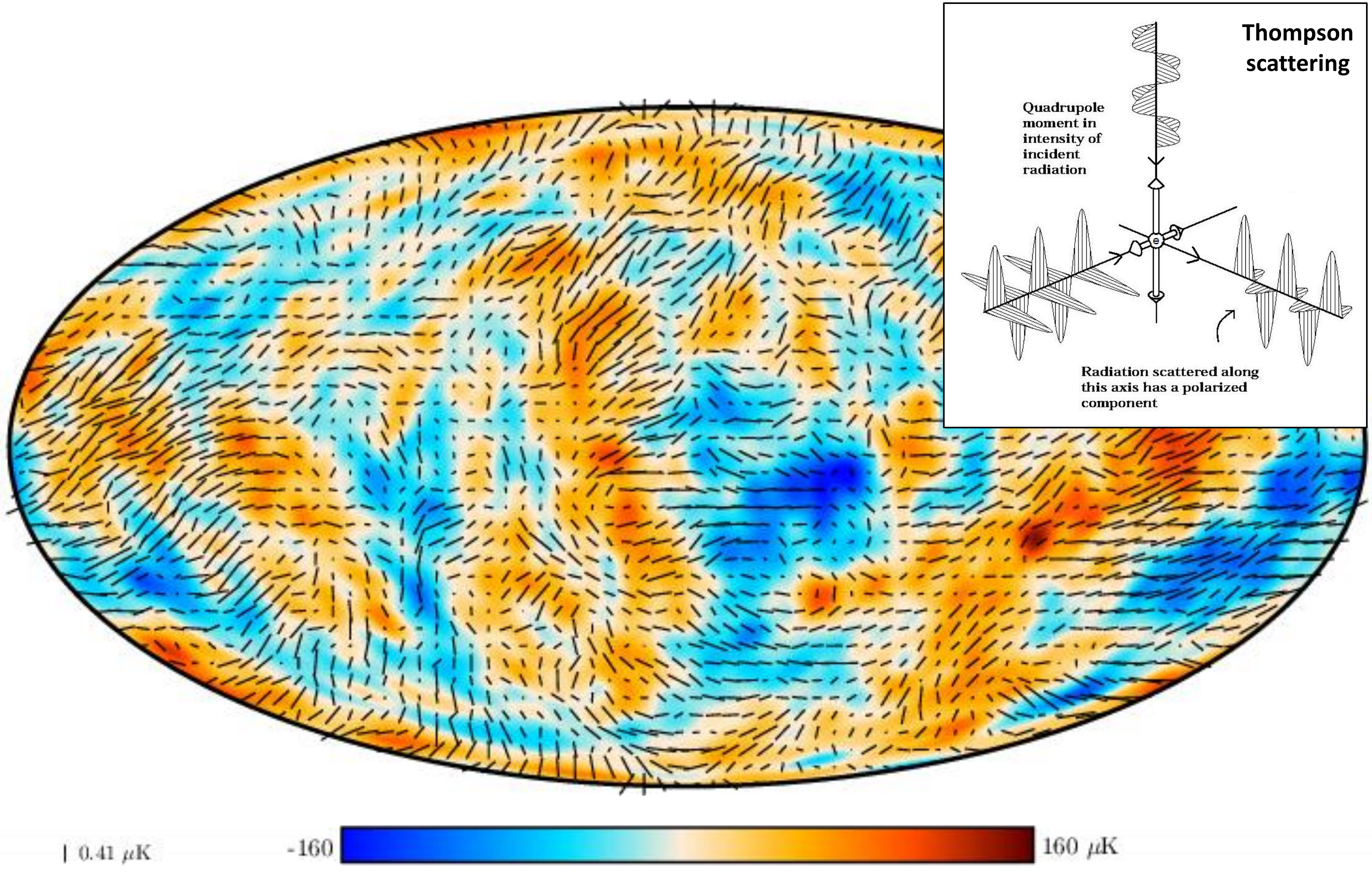
rotation of the polarization plane

(single photon)



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

CMB polarization anisotropies



[2018 Planck map of the polarized CMB anisotropies]

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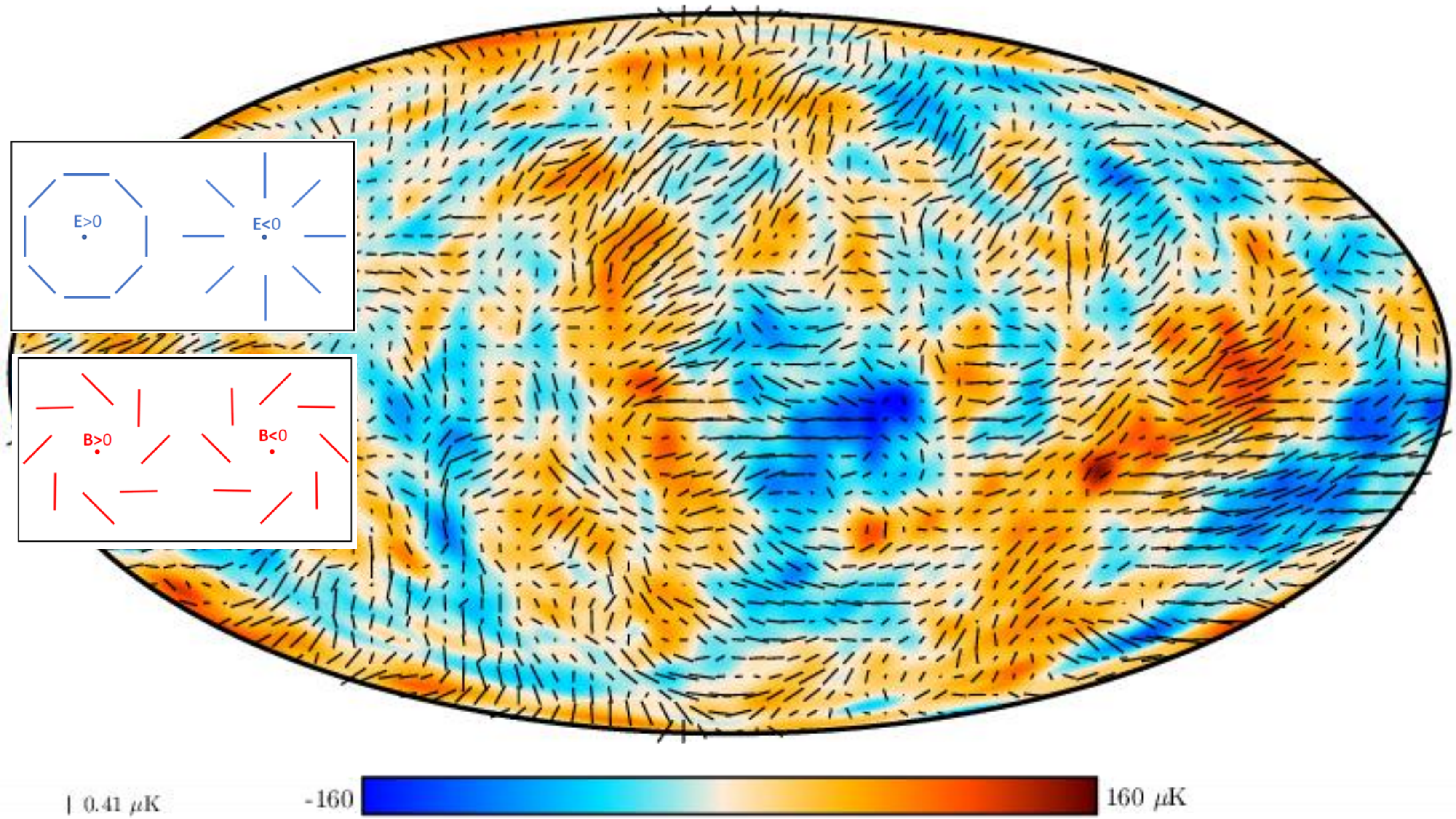

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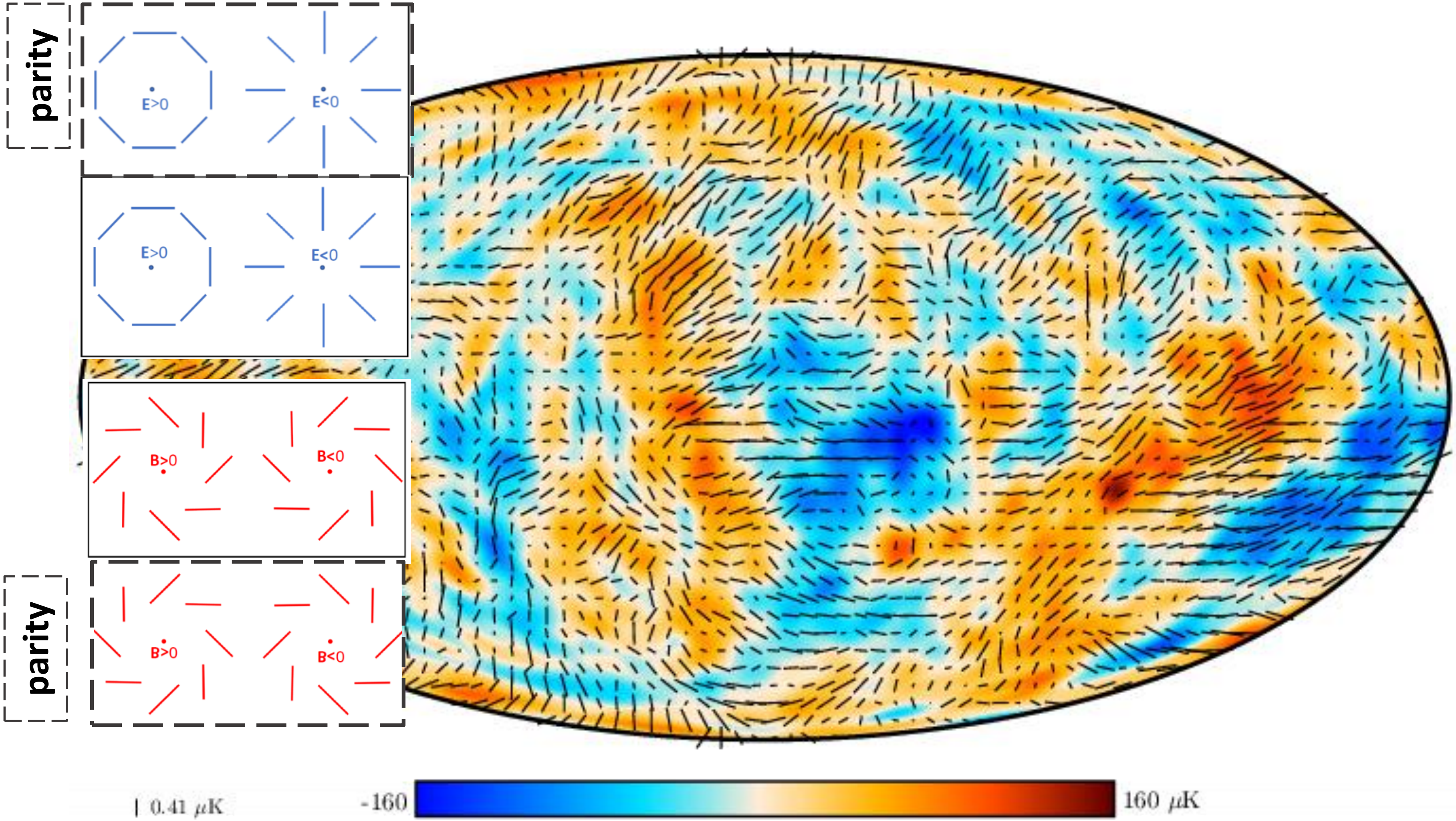

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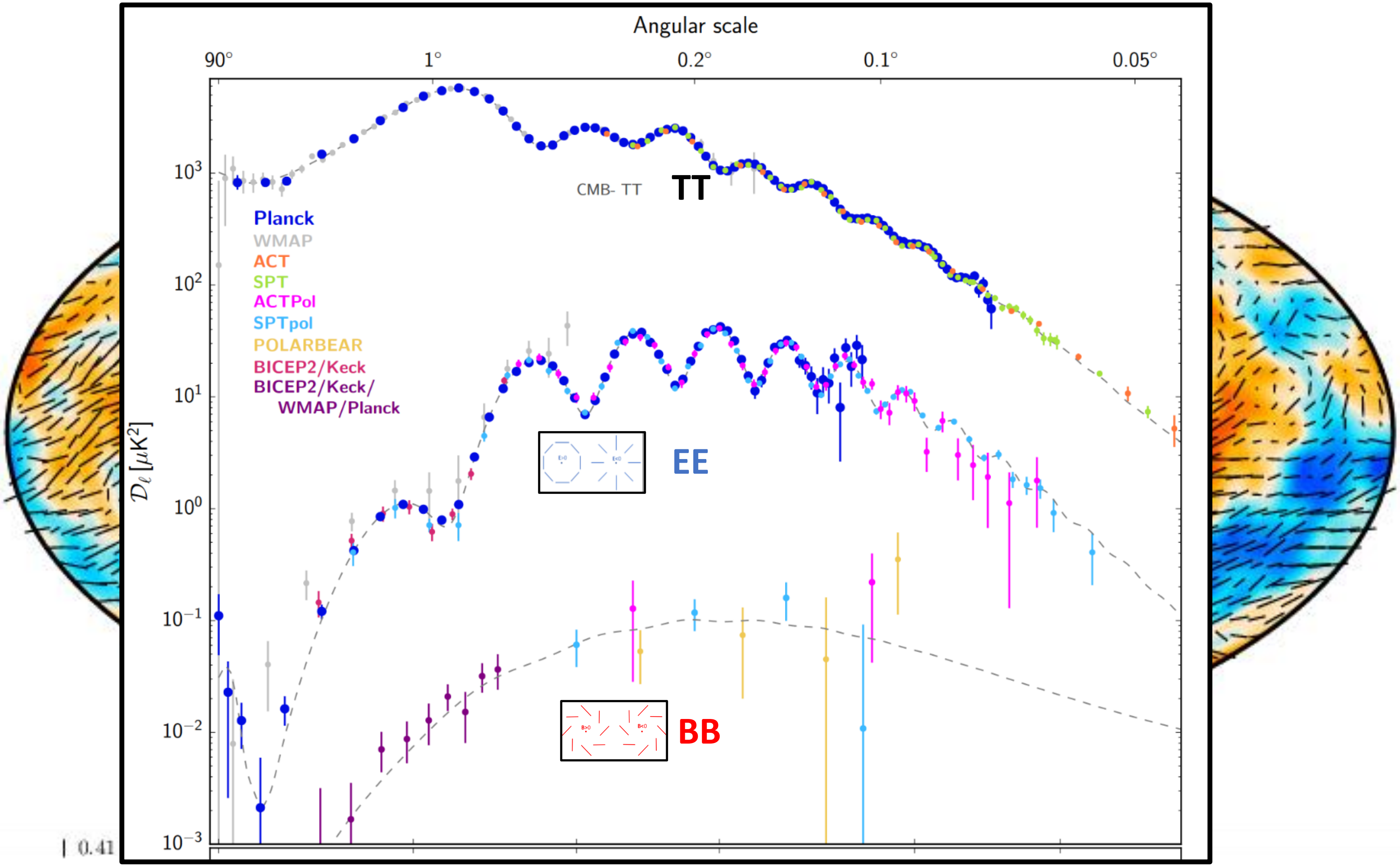

[Planck 2018 results I, A&A 641, A1 (2020)]

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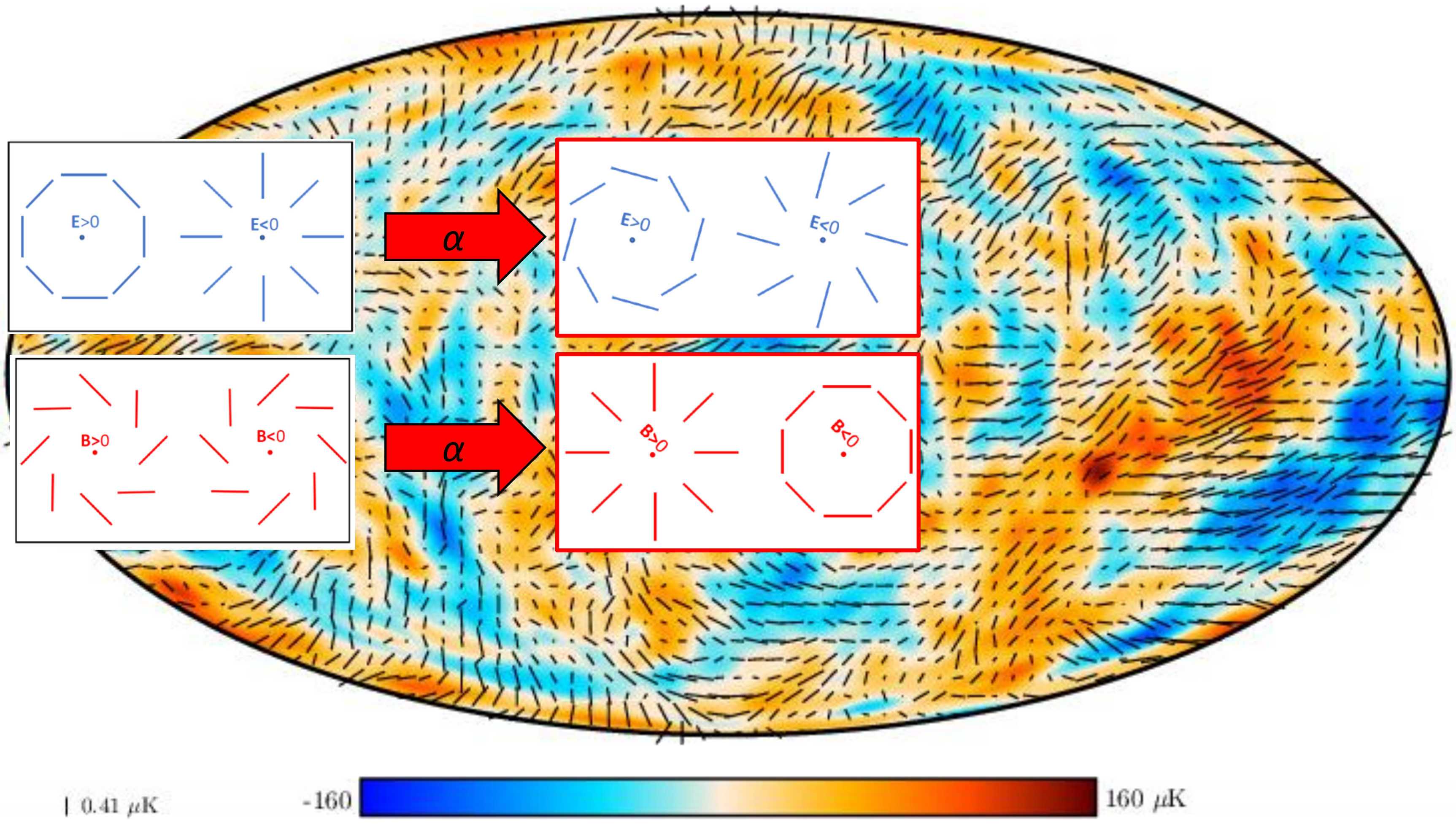

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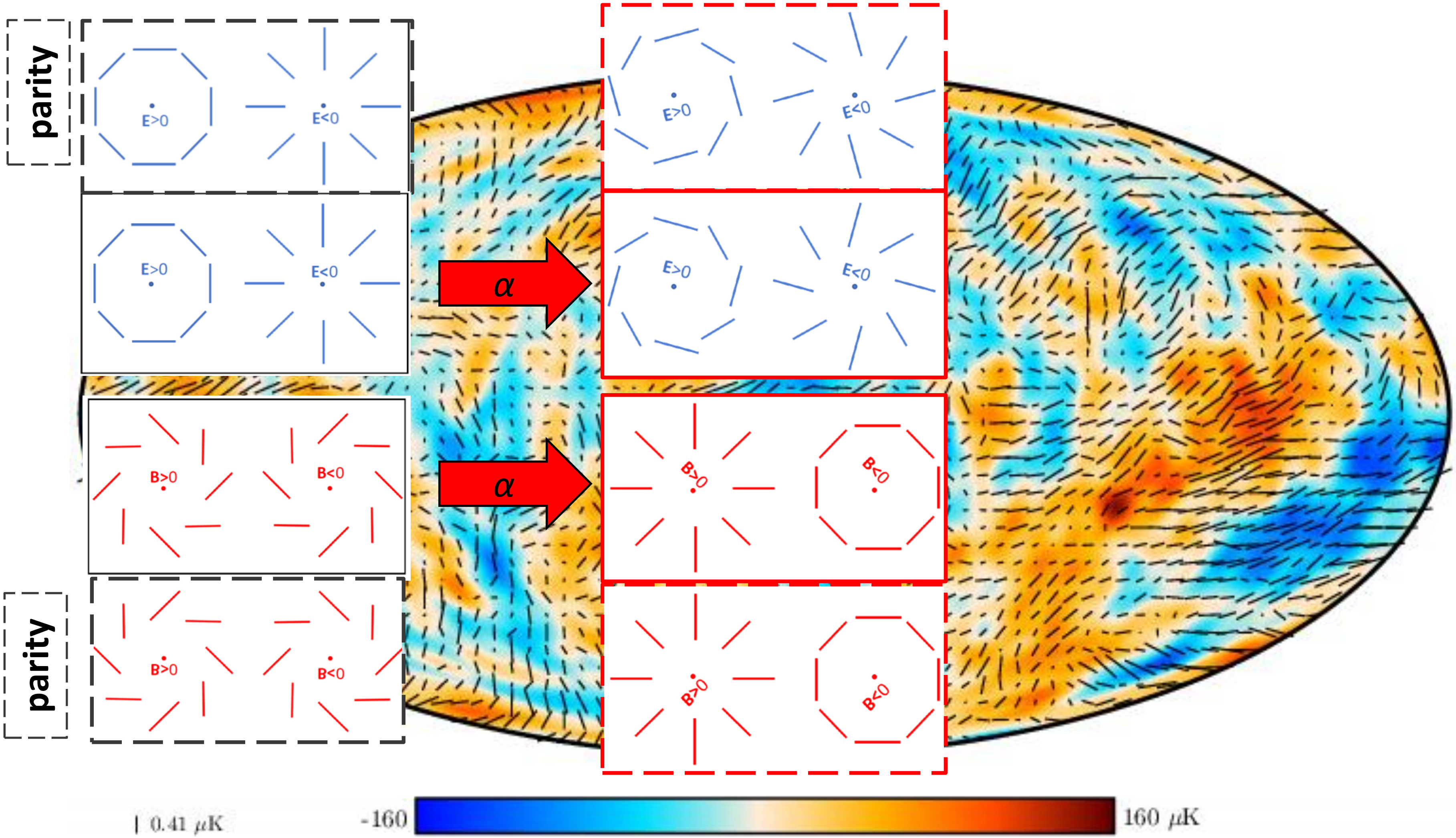

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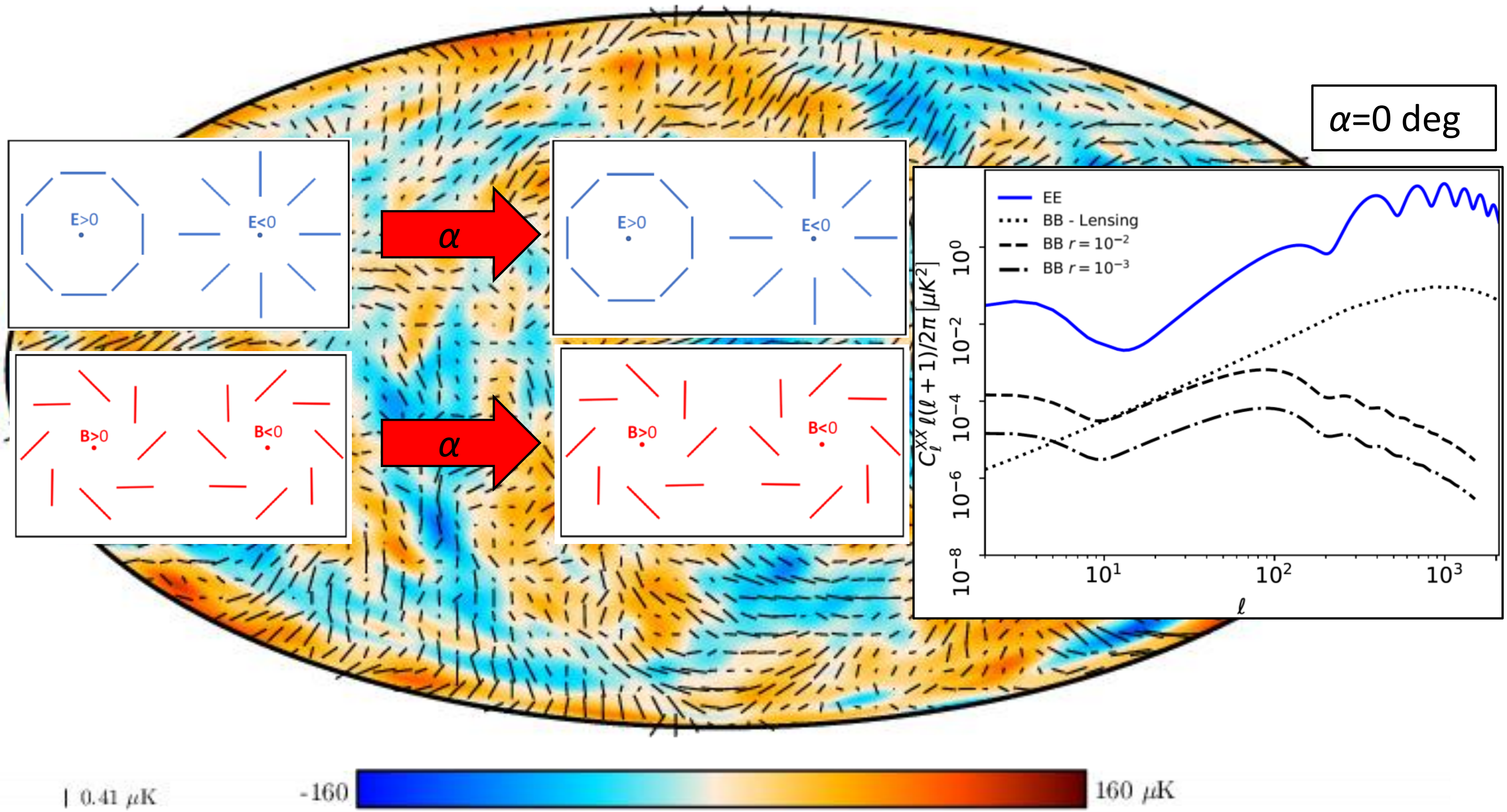

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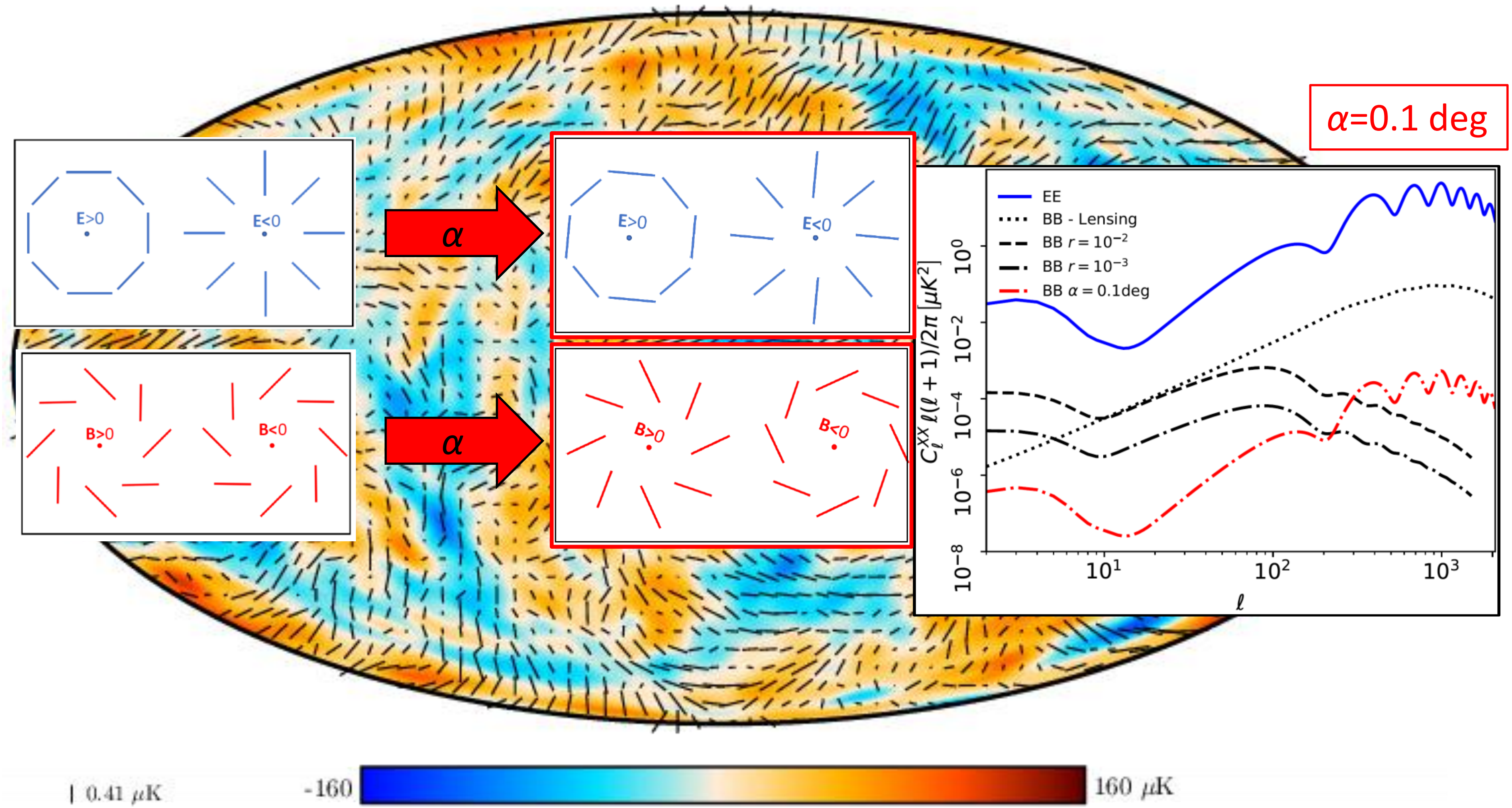

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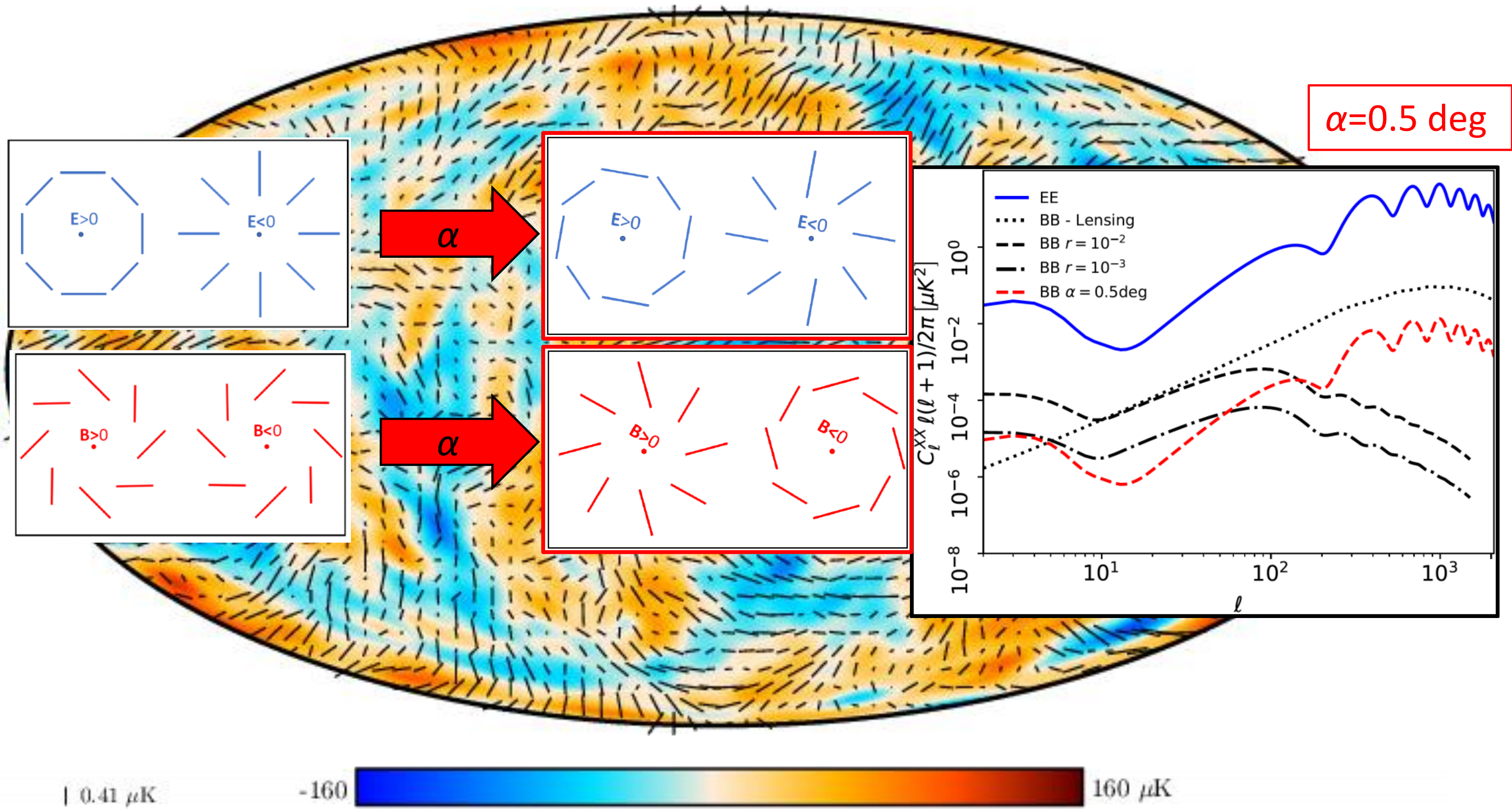

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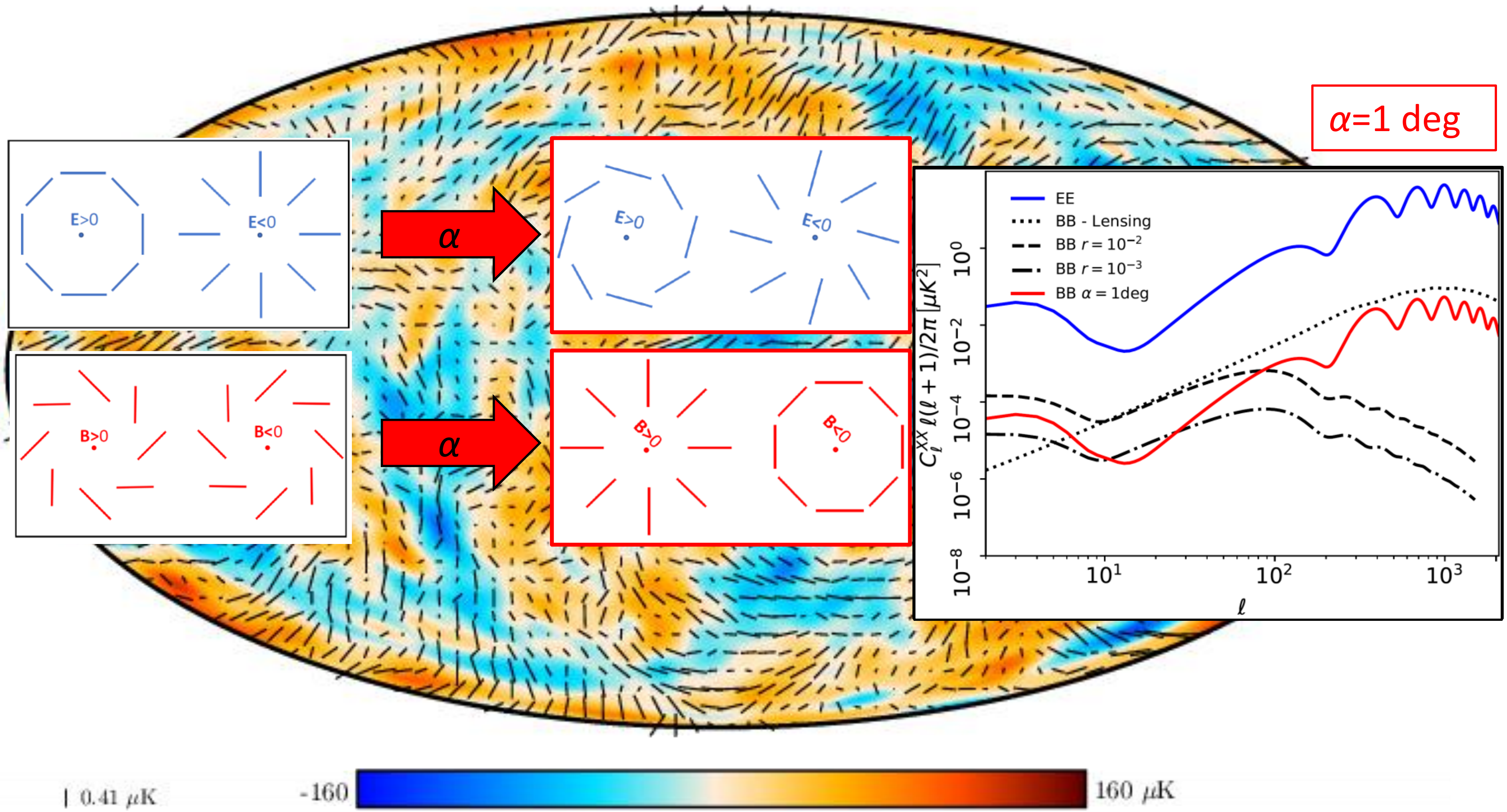


α [deg]: *isotropic* and *constant in z*

For a **cosmological birefringence**:

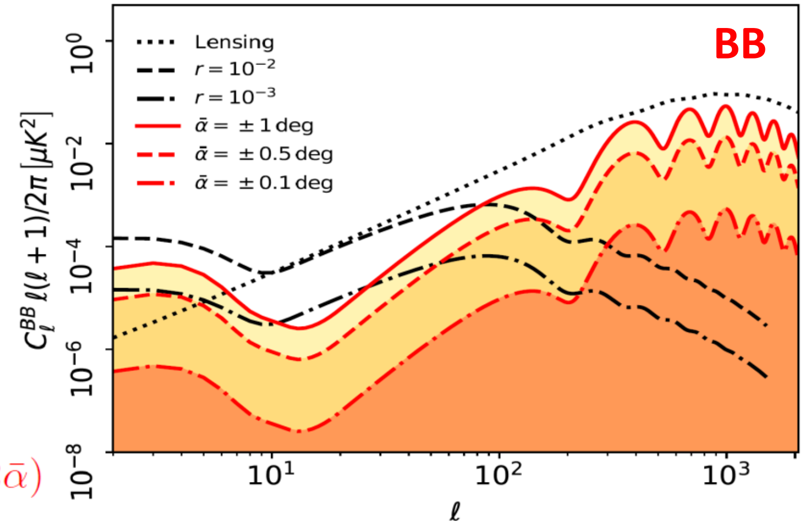
-***isotropic***

-***constant*** in *z*

→only "total rotation" is important:

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

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



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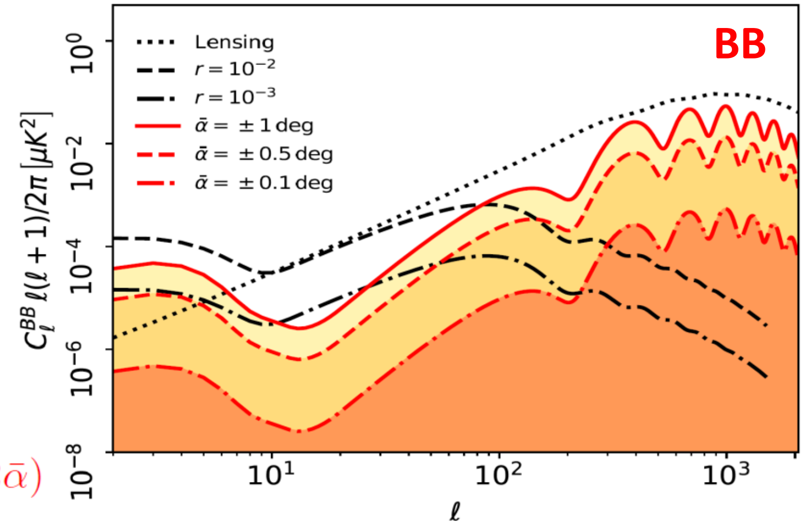

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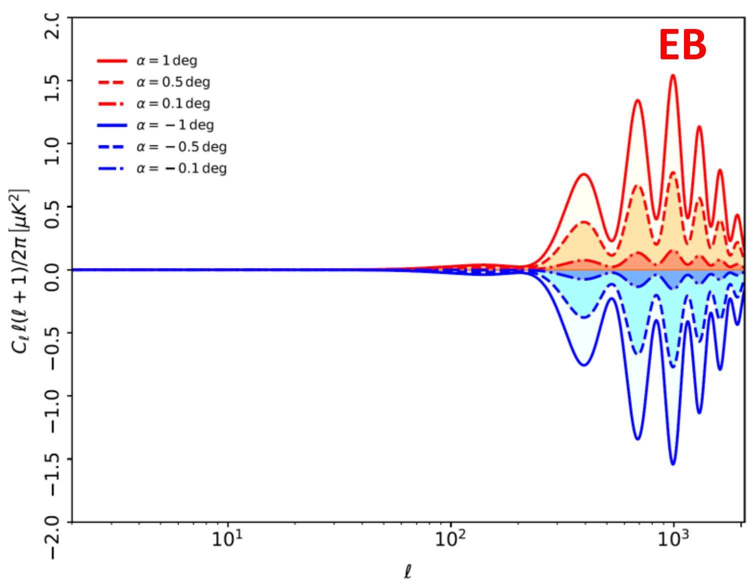
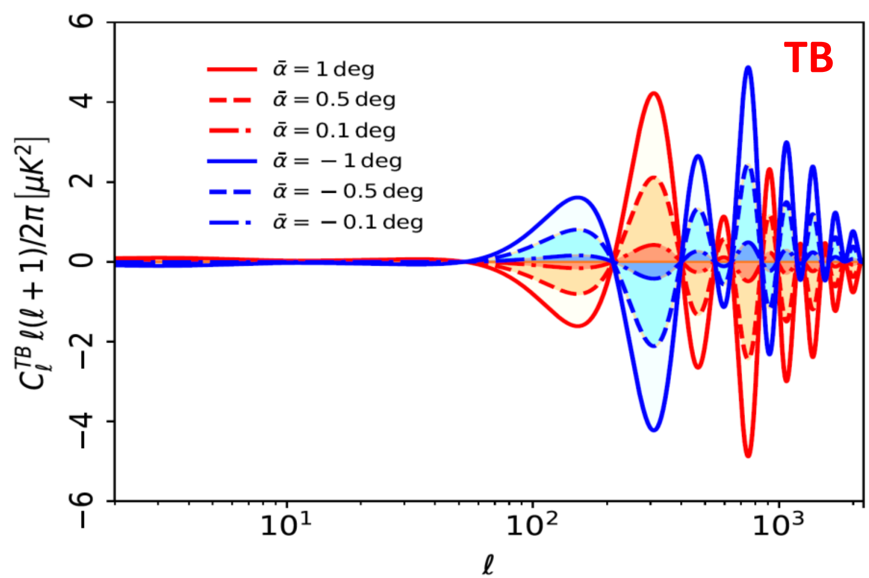
$$C_\ell^{EB,\rm obs} = \frac{1}{2}\left(C_\ell^{EE,\rm rec} - C_\ell^{BB,\rm rec}\right)\sin(4\bar{\alpha})$$

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

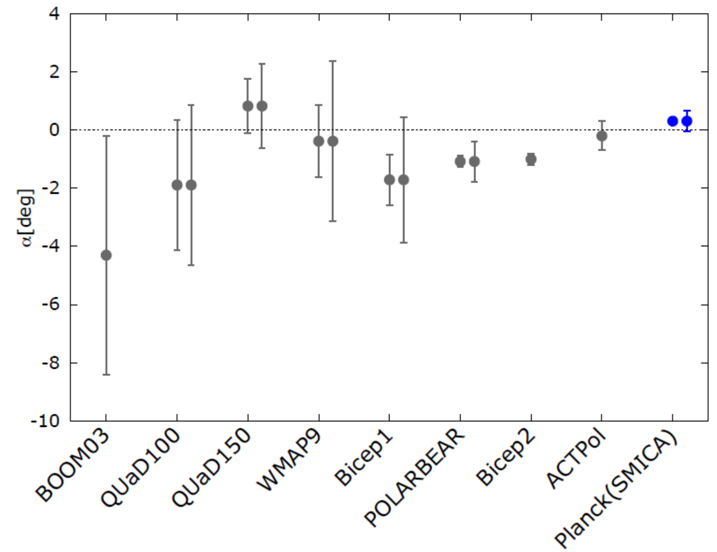




Constraints for α (*isotropic* and *constant in z*)

Several CMB polarization experiments provide **constraints on the cosmological birefringence angle α**
[**Planck**],Astron. Astrophys.(2016):

$$\alpha = 0.31 \pm 0.05(\mathrm{stat}) \pm 0.28(\mathrm{syst})\ \mathrm{deg}$$



Future experiments

“LiteBIRD-like”: 6’ = 0.1 deg [see arXiv:2202.02773]

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),…]:

$$\alpha = 0.342^{+0.094}_{-0.091}(\mathrm{stat})\ \mathrm{deg}$$ [Planck (NPIPE) + WMAP 9-years]

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]):

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

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

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

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

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

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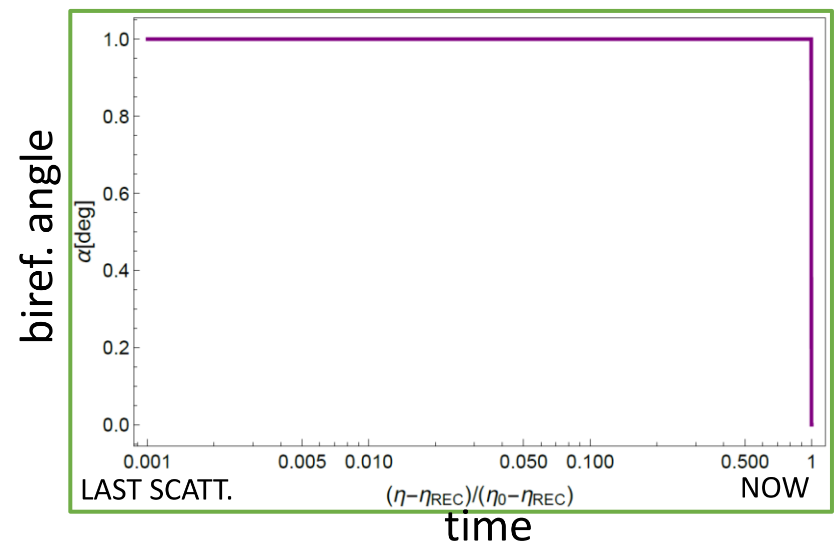

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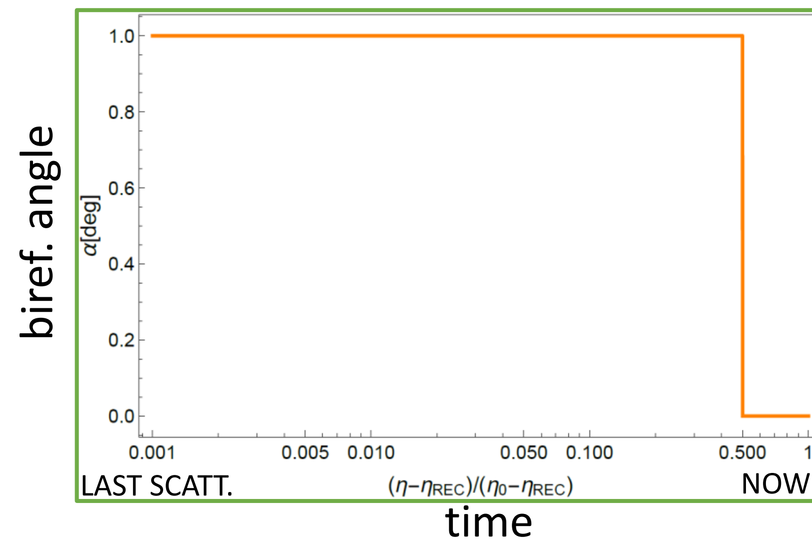

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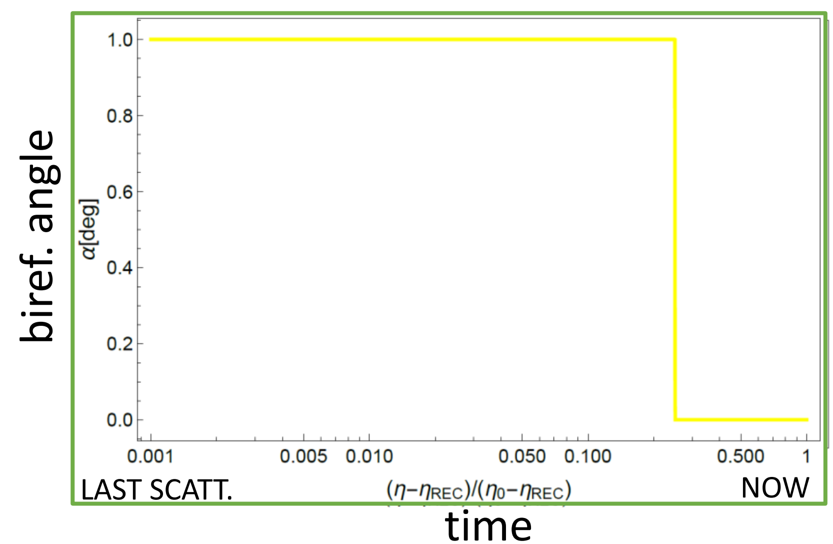

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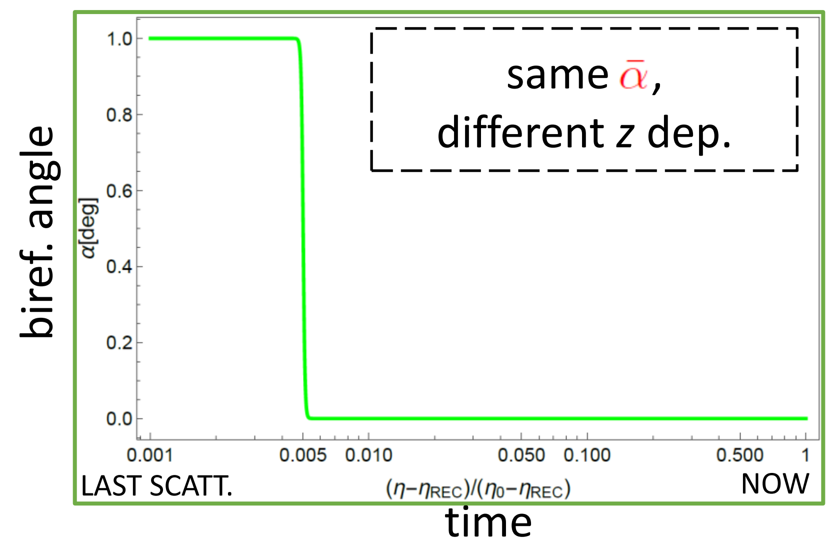

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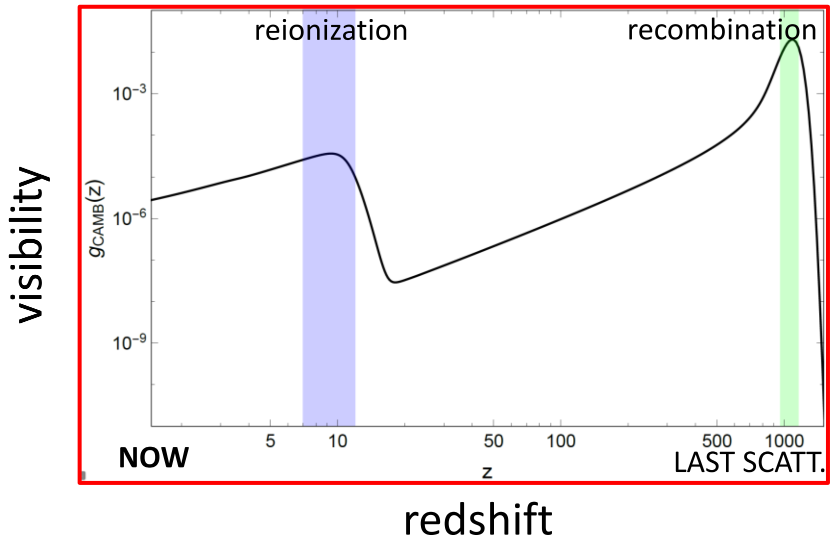

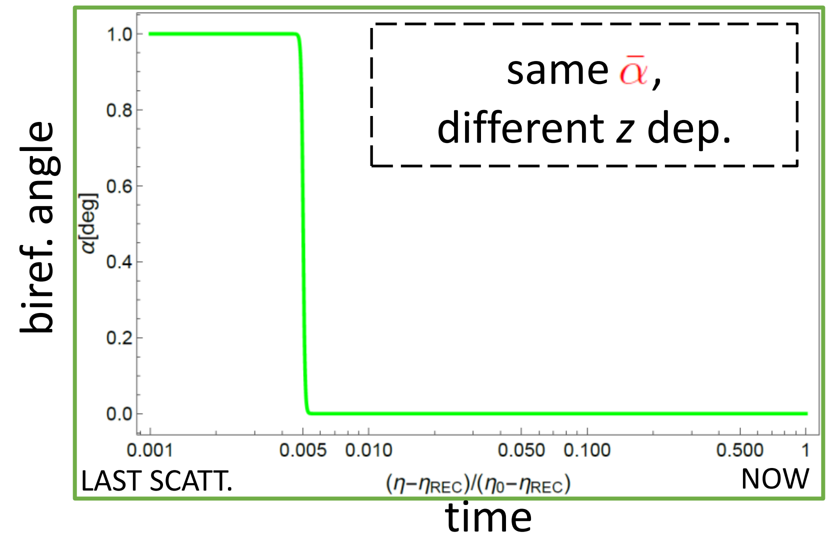

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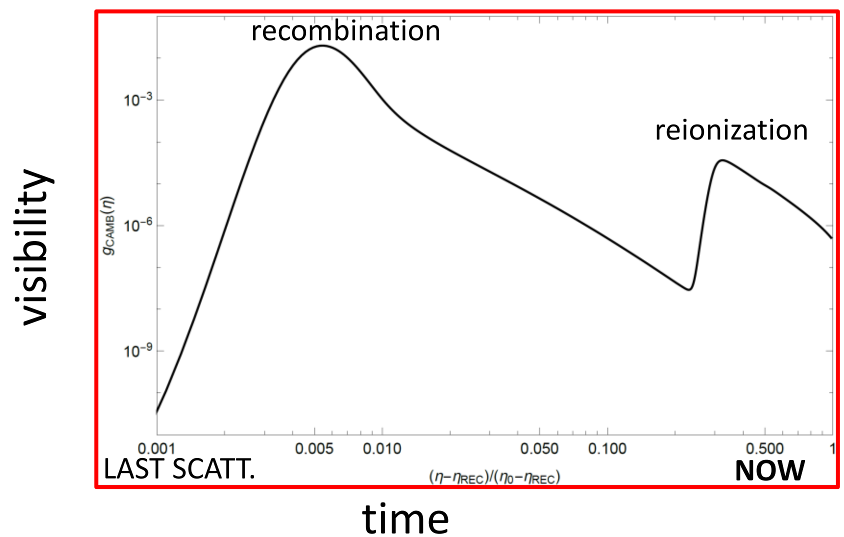

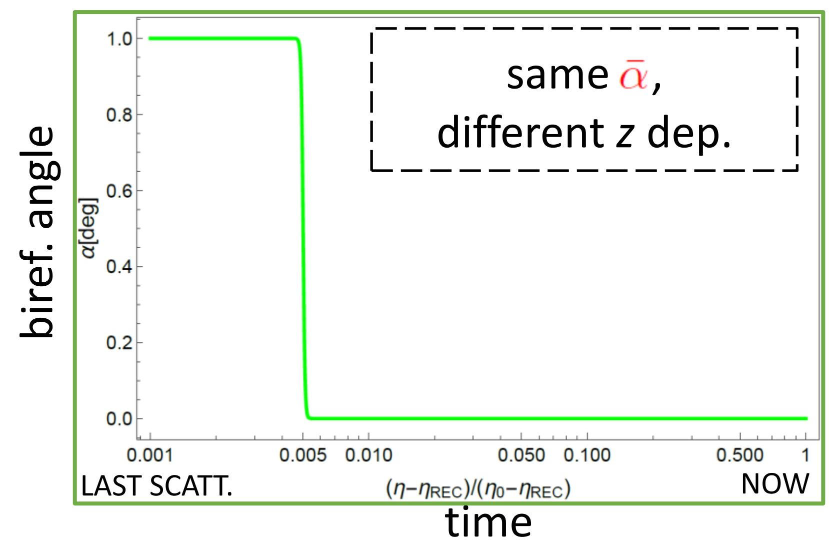

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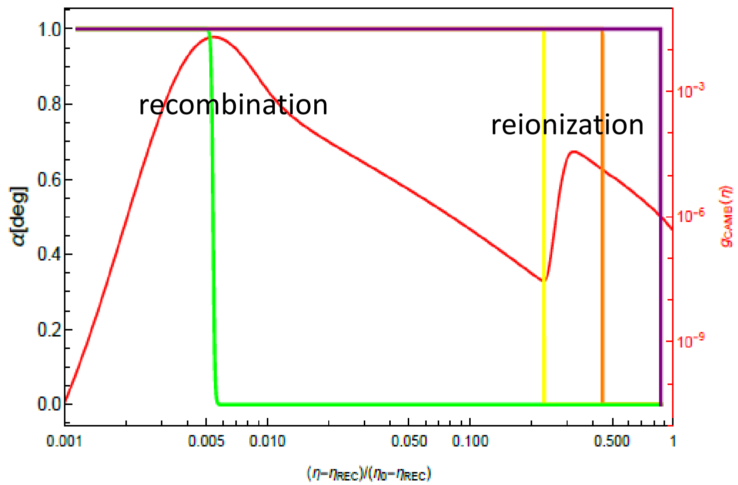
- same $\bar{\alpha}$ =1 deg
- but linear polarization rotation happens at different epochs!



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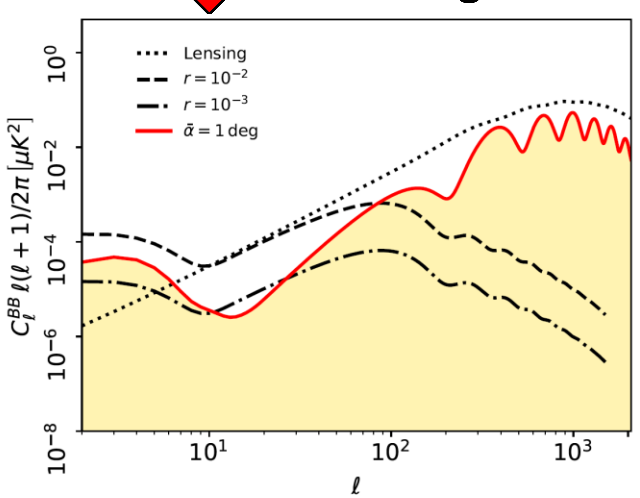

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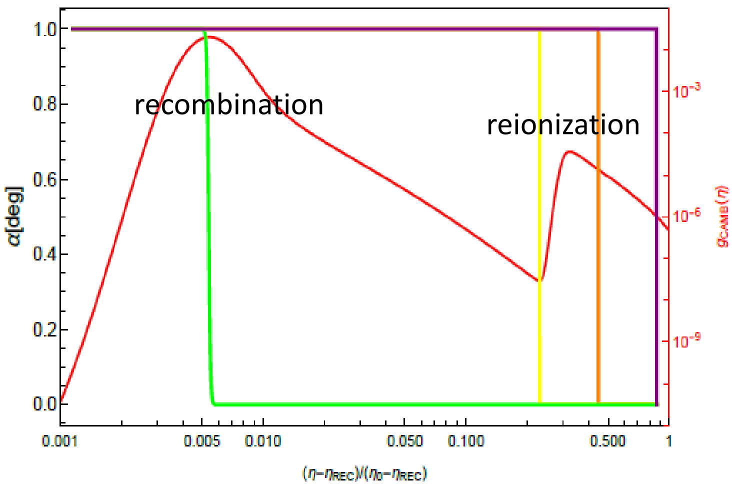
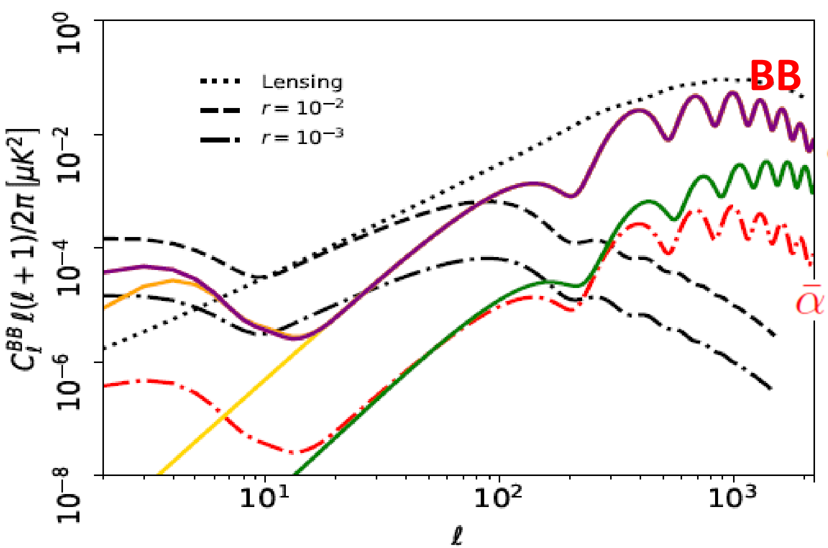
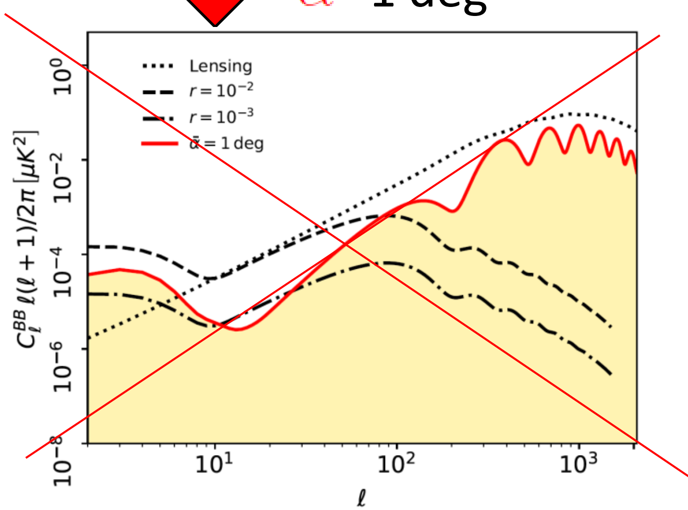


Integrating the Boltzmann equation along the line-of-sight:



$\bar{\alpha}$ =1 deg



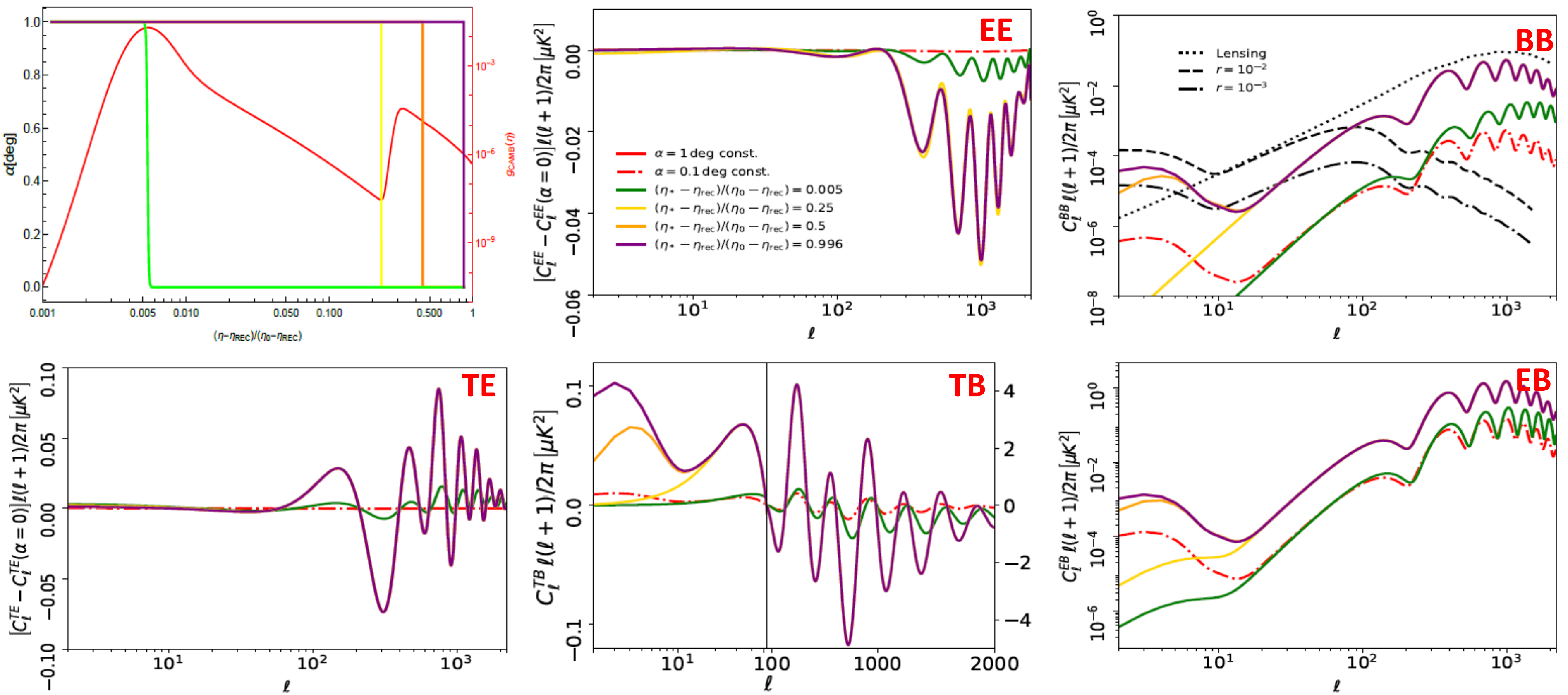
$$\cancel{C_\ell^{BB,\mathrm{obs}} = C_\ell^{EE,\mathrm{rec}}\sin^2(2\bar{\alpha})}$$

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

[see also Nakatsuka, Namikawa and Komatsu PRD 2022]

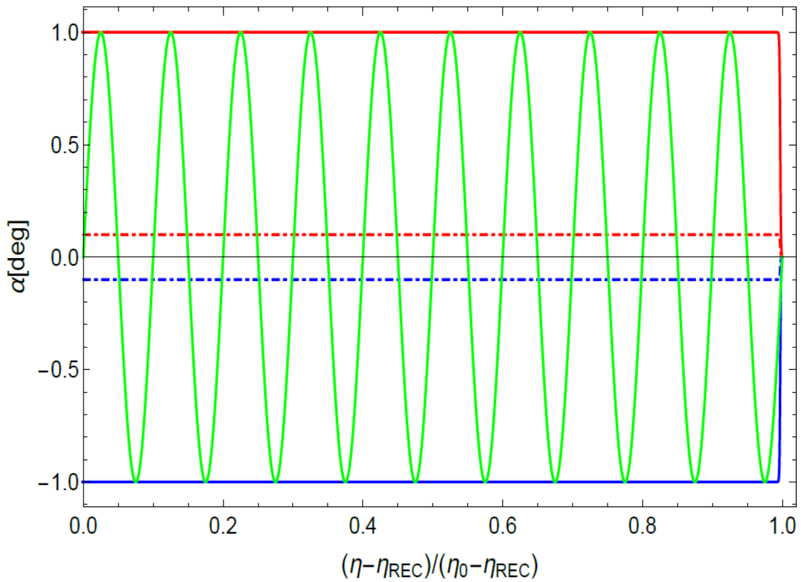
α [deg]: *isotropic* and ***z dependent***

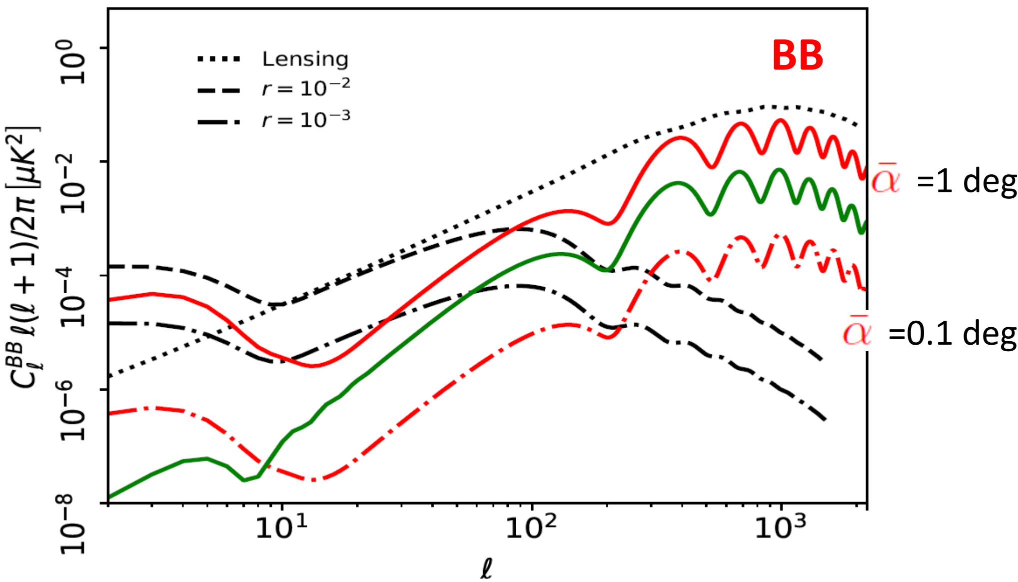
- same $\bar{\alpha}$ =1 deg
- but linear polarization rotation happens at different epochs!



α [deg]: *isotropic* and ***oscillating***

- $\bar{\alpha}$ = 0 deg
- linear polarization angle oscillates between +1 deg and -1 deg





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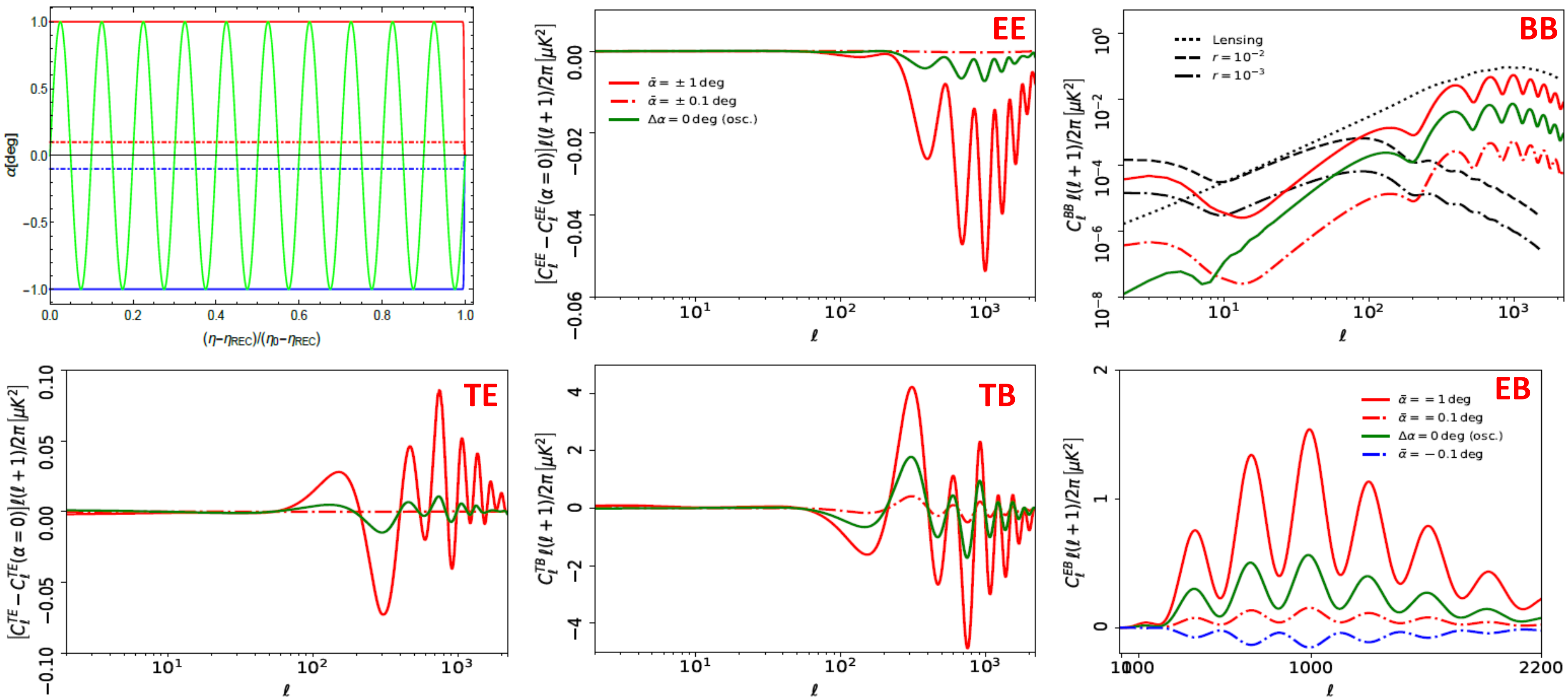
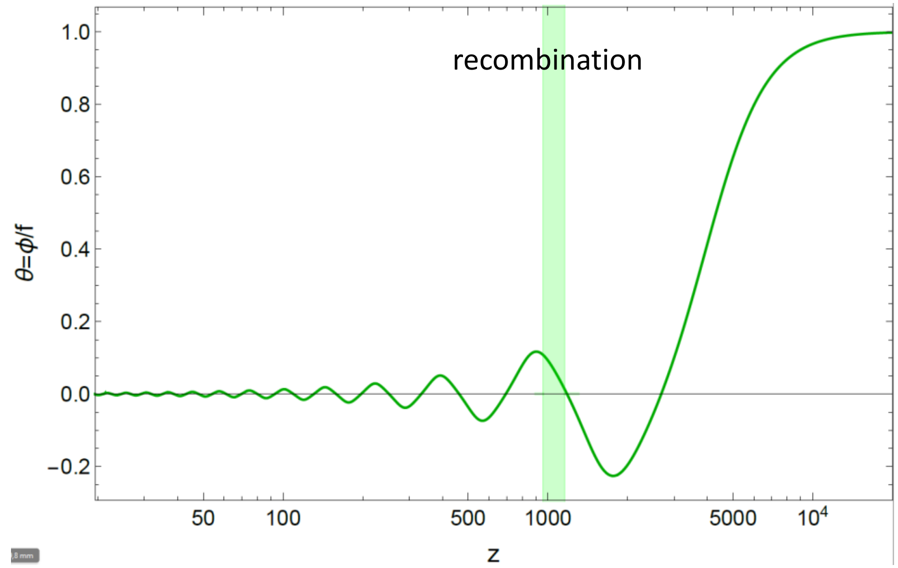


Early Dark Energy

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

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



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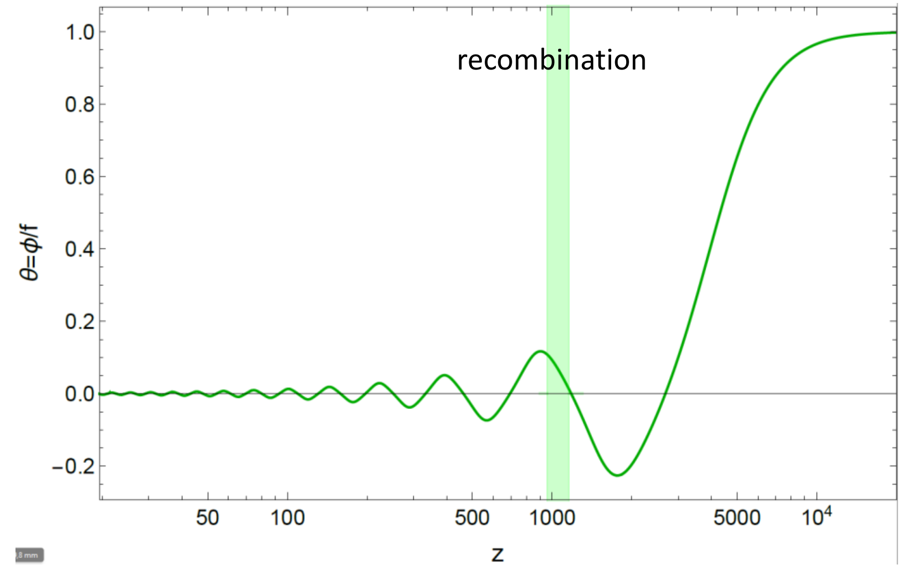
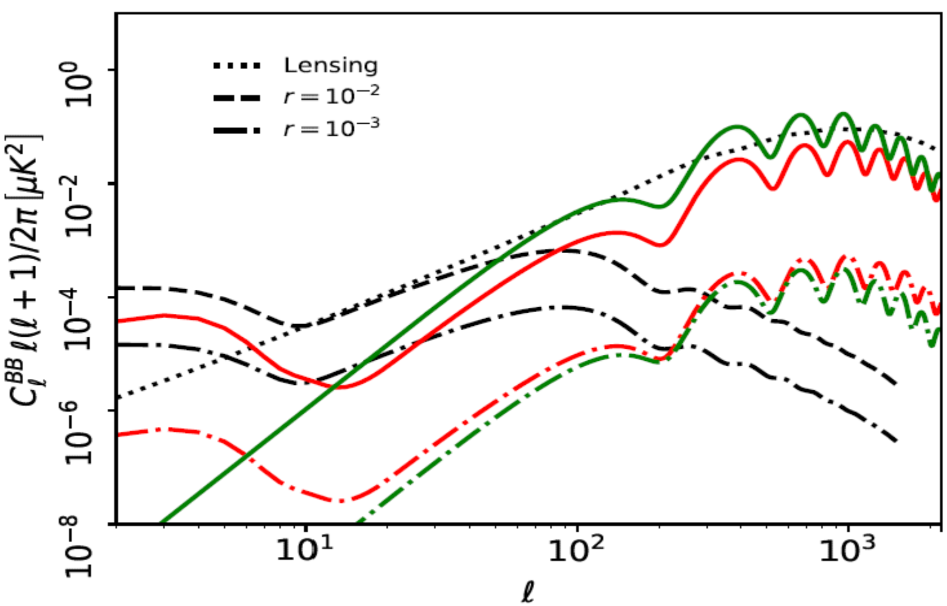




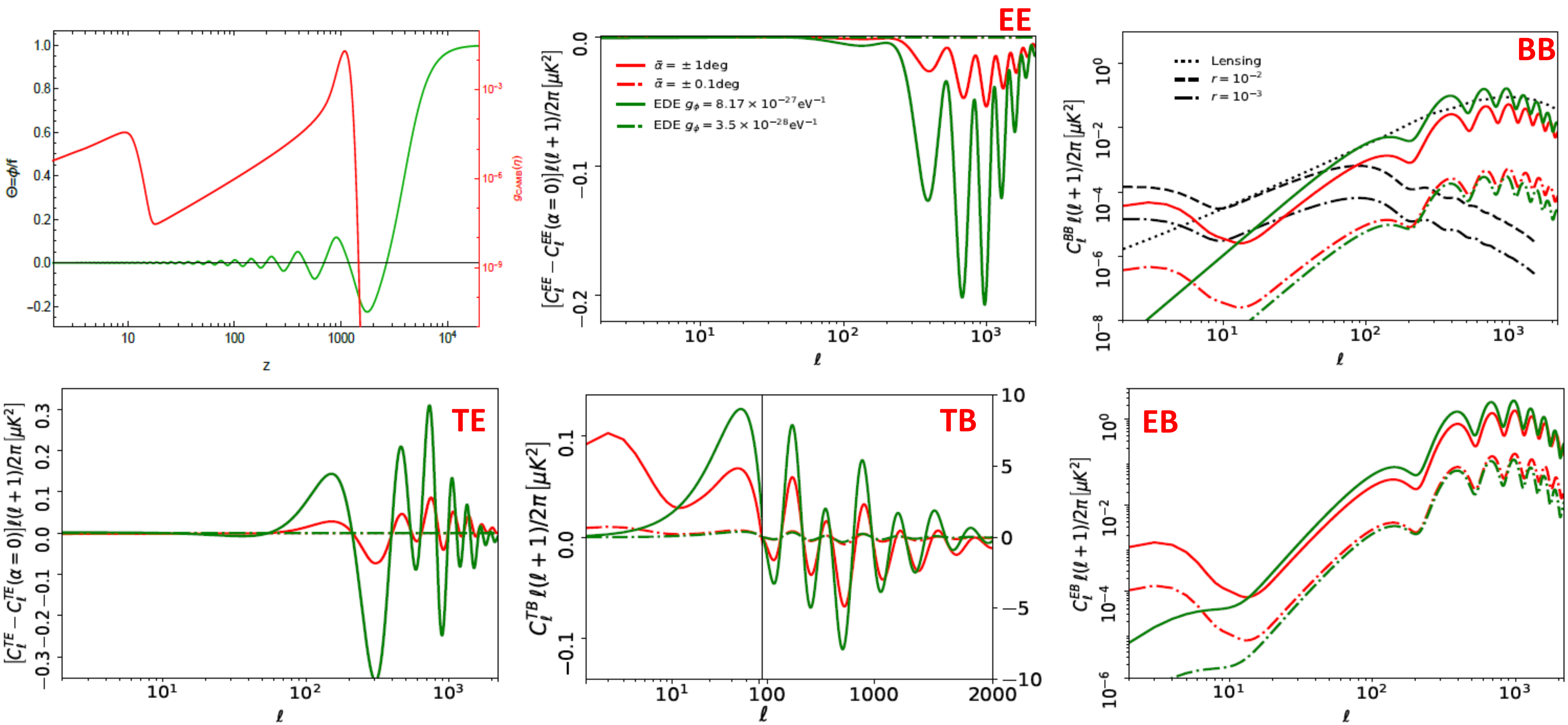
BB power spectra for different values of the coupling constant g_ϕ

EDE $g_\phi = 8.17 \times 10^{-27}\mathrm{eV}^{-1}$

EDE $g_\phi = 3.5 \times 10^{-28}\mathrm{eV}^{-1}$

$$\mathcal{L} \supset g_\phi \phi \mathbf{E}\cdot\mathbf{B} = -\frac{g_\phi}{4}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu}\,,$$

Early Dark Energy



Constraints for a LiteBIRD-like mission

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

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

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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 $+N_\ell$	$\chi^2_{\rm eff}$ (see Eq. $\boxed{39}$)
$C_\ell(g_\phi = 8.17 \times 10^{-27}\mathtt{eV}^{-1})$	$C_\ell(\alpha = 0\,\mathrm{deg})$	1.10×10^5
$C_\ell(g_\phi = 1.51 \times 10^{-27}\mathtt{eV}^{-1})$	$C_\ell(\alpha = 0\,\mathrm{deg})$	3.81×10^3
$C_\ell(g_\phi = 4.35 \times 10^{-28}\mathtt{eV}^{-1})$	$C_\ell(\alpha = 0\,\mathrm{deg})$	3.21×10^2
$C_\ell(g_\phi = 3.5 \times 10^{-28}\mathtt{eV}^{-1})$	$C_\ell(\alpha = 0\,\mathrm{deg})$	2.09×10^2
$C_\ell(g_\phi = 7 \times 10^{-28}\mathtt{eV}^{-1})$	$C_\ell(\bar{\alpha} = 0.165\,\mathrm{deg})$	8.65

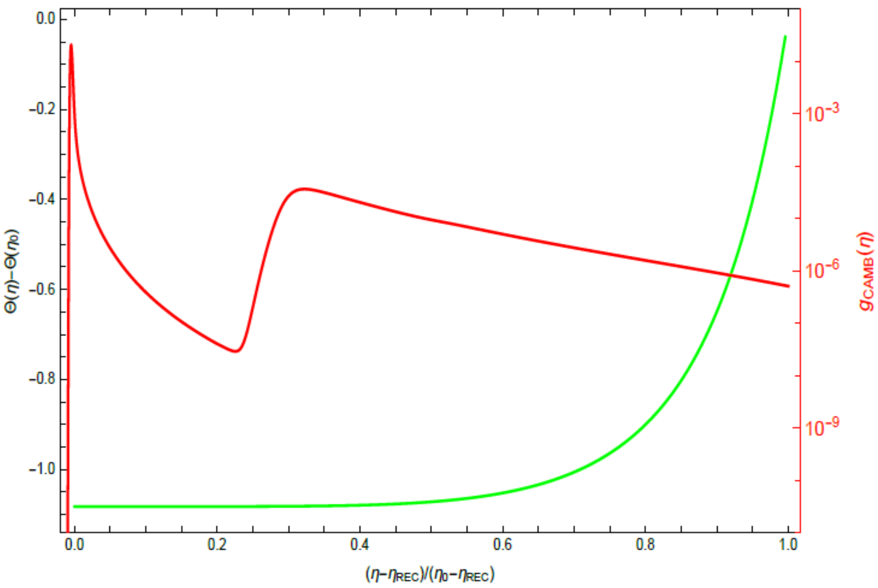
[Competitive with other constraints on this model:

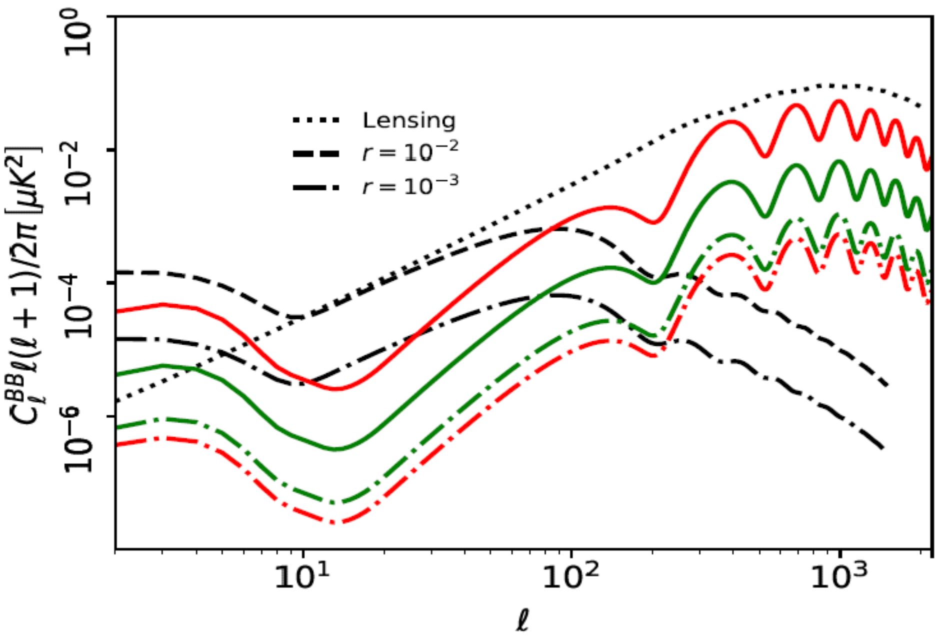
$10^{-19}\mathtt{GeV}^{-1} \lesssim g_\phi \lesssim 10^{-16}\mathtt{GeV}^{-1}$ (see Fujita *et al.* PRD 2021)]

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 $(\dot{\phi}/f)_{in} = 0$



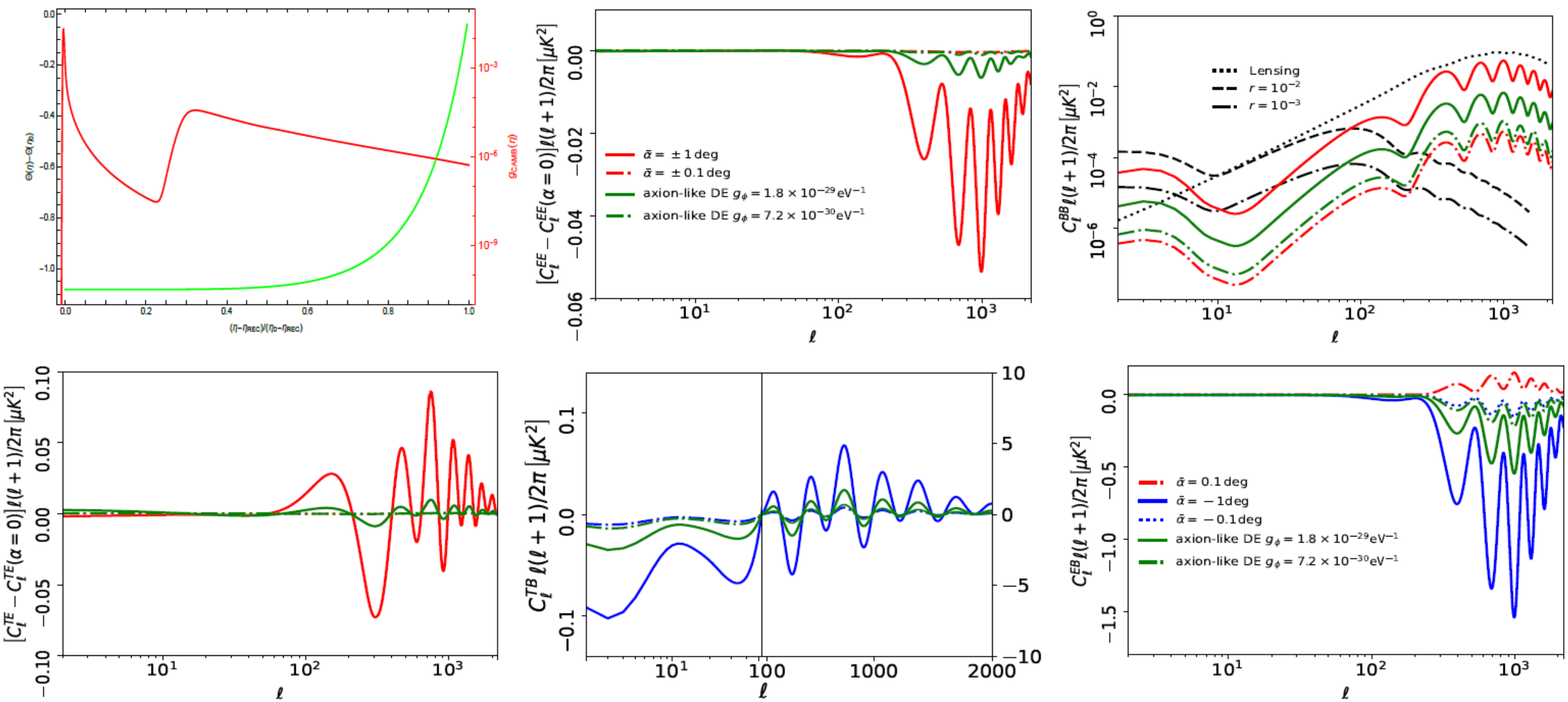


BB power spectra for different values of the coupling constant g_ϕ

axion-like DE $g_\phi = 1.8 \times 10^{-29}\mathrm{eV}^{-1}$

axion-like DE $g_\phi = 7.2 \times 10^{-30}\mathrm{eV}^{-1}$

Axion-like Dark Energy



$\bar{C}_\ell$ theoretical (DE) $+N_\ell$	$\hat{C}_\ell$ observed $+N_\ell$	χ^2_{eff} (see Eq. 39)
$C_\ell(g_\phi = 1.8 \times 10^{-29}\,\mathrm{eV}^{-1})$	$C_\ell(\alpha = 0\,\mathrm{deg})$	3.78×10^3
$C_\ell(g_\phi = 5.2 \times 10^{-30}\,\mathrm{eV}^{-1})$	$C_\ell(\alpha = 0\,\mathrm{deg})$	3.15×10^2
$C_\ell(g_\phi = 7.2 \times 10^{-30}\,\mathrm{eV}^{-1})$	$C_\ell(\alpha = 0\,\mathrm{deg})$	6.04×10^2
$C_\ell(g_\phi = 5.0 \times 10^{-28}\,\mathrm{eV}^{-1})$	$C_\ell(\bar{\alpha} = -9.8\,\mathrm{deg})$	5.5

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;
- even if $\bar{\alpha}$=0 some effects can be present in the power spectra;
- **different theoretical motivated redshift dependencies** of the pseudoscalar field (EDE, DE,…) 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,** e-Print: 2207.xxxxx