Probing Axions through Tomography of Anisotropic Cosmic Birefringence

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Progress on Old and New Themes on Cosmology 2023

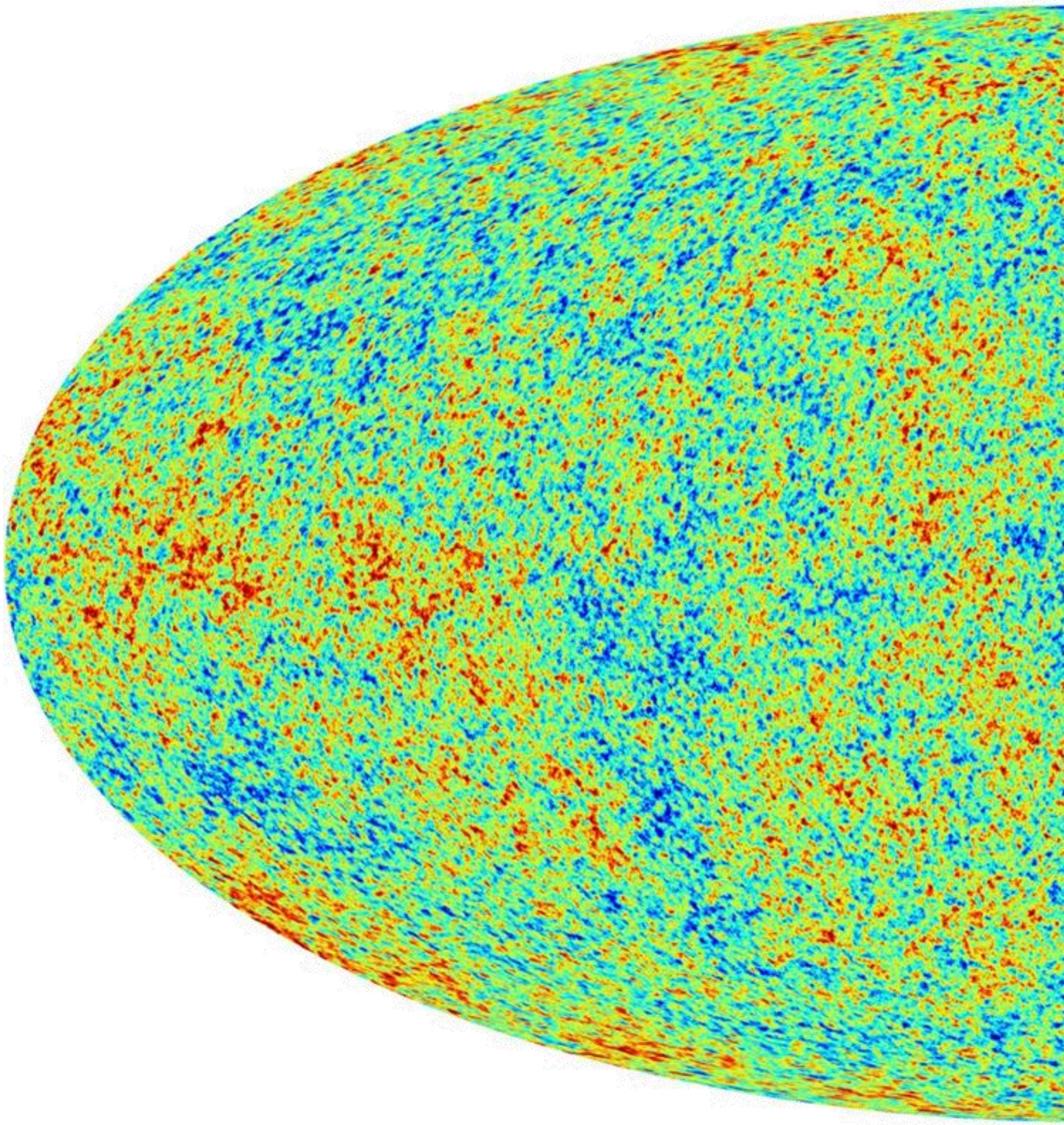
INTRODUCTION

- The **Cosmic Microwave Background** (CMB) is electromagnetic radiation which is remnant from an early stage of the Universe.

- CMB is polarized at the level of a few μK in E-modes and B-modes. CMB polarization arise naturally from Thomson scattering, and in particular the B-modes are generated by gravitational lensing of E-modes and by gravitational waves produced during inflation.

- B-modes and E-modes polarizations are uncorrelated, since any cross-correlation between them would be **parity-violating**. In analogy with electrostatics, they transform in the opposite way under spatial inversion.

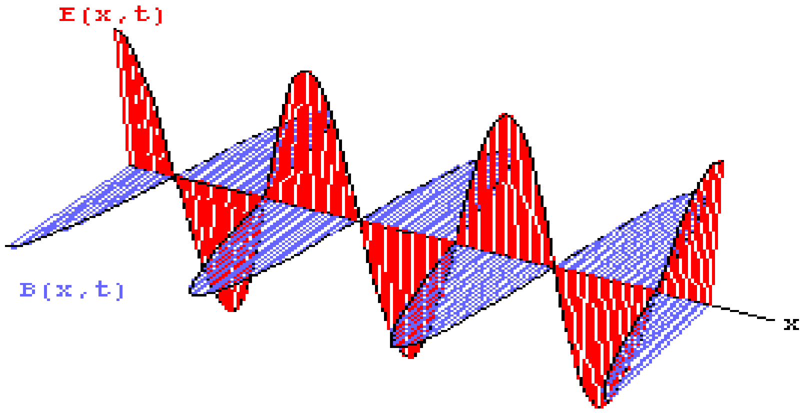
- CMB can be seen as a very efficient natural «laboratory» for investigating deviations from the standard Maxwell theory.



Modified Electromagnetism

Maxwell Electromagnetic Theory

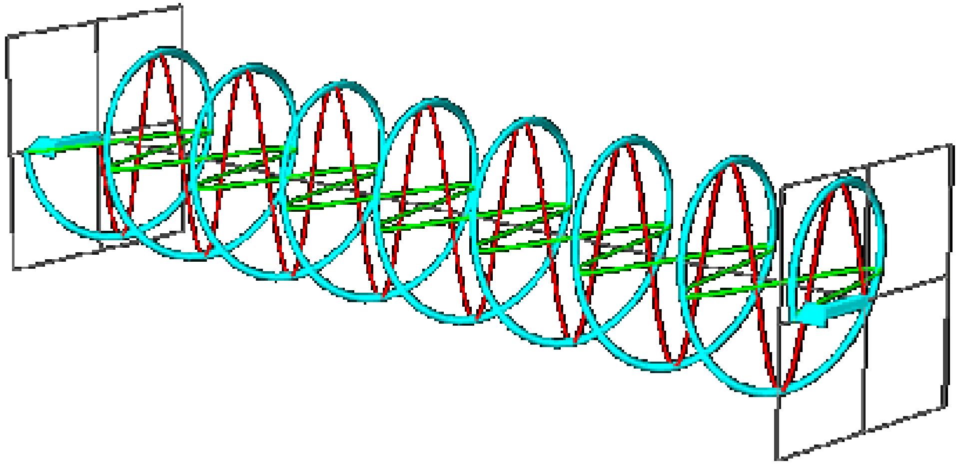
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$



$F_{\mu\nu} \equiv \nabla_\mu A_\nu - \nabla_\nu A_\mu$ Maxwell Field Tensor

Chern-Simons Modification of Electromagnetism

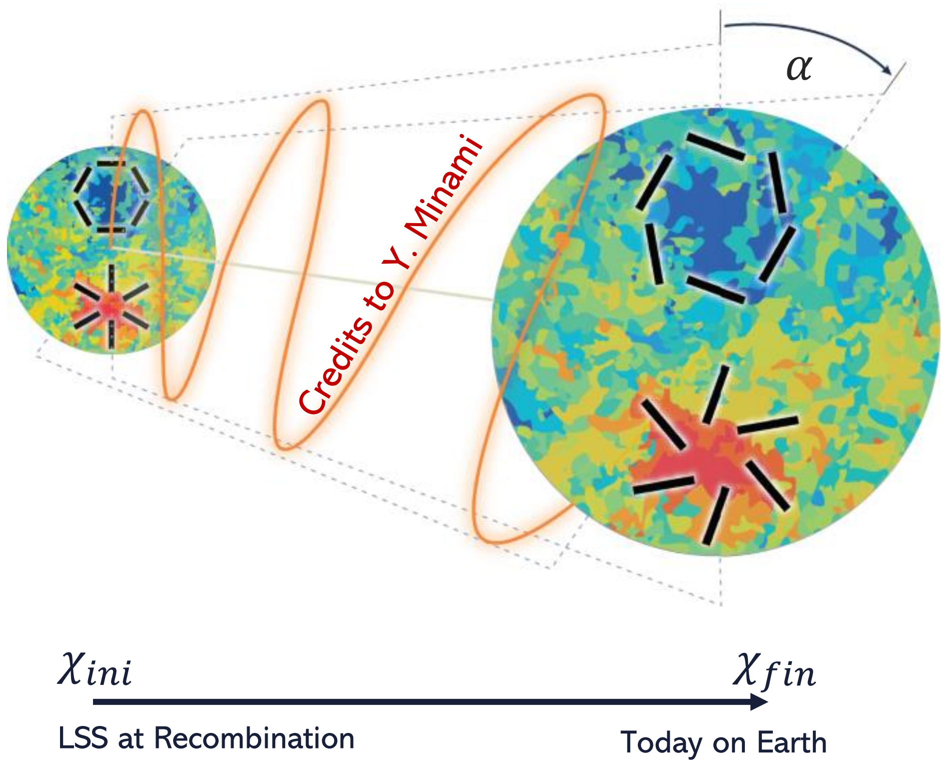
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{4f} \chi F_{\mu\nu} \tilde{F}^{\mu\nu}$$ |Carroll+1990



$\tilde{F}^{\mu\nu} \equiv \epsilon^{\mu\nu\varrho\sigma} F_{\varrho\sigma}/2$ Hodge Dual Tensor

A phenomenological consequence of the extra-coupling (λ/f) between photons and a new field χ is **birefringence**, i.e. the in-vacuo rotation of the polarization plane during the electromagnetic waves' propagation. |Komatsu2022

Cosmic Birefringence



The birefringence angle is related to the field χ via

$$\boxed{\alpha = \frac{\lambda}{2f}[\chi_{fin} - \chi_{ini}]}$$

| Li+2008

The linear polarization of CMB radiation is described by the following combination of Stokes parameters:

$$[Q \pm iU](\hat{n}) = -\sum_{\ell m}(E_{\ell m} \pm iB_{\ell m})\,{}_{\pm 2}Y_{\ell m}\,(\hat{n})$$

that behaves as a spin-2 field. The Chern-Simons modifications of Maxwell theory induces a rotation of the polarization plane by an angle α, the **birefringence angle**, so that the Stokes parameters are rotated too:

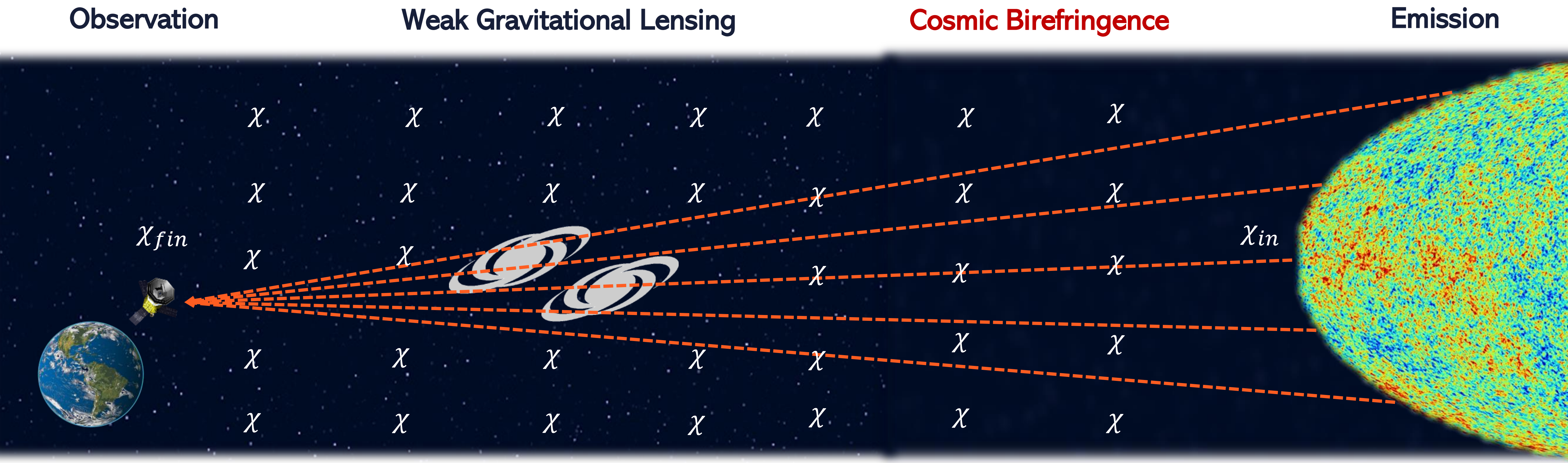
$$[Q \pm iU] \longrightarrow [Q \pm iU]e^{\pm 2i\alpha}$$

| Liu+2006

Investigating **Cosmic Birefringence** (CB) can help us in unveiling the nature of the field χ, which could be e.g.:

- early dark energy in the form of a Nambu-Goldstone boson; | Capparelli+2020
- dark matter in form of an ultra-light axion. | Liu+2017

The Birefringence Mechanism



$$[Q \pm iU]\left(\hat{n} + \vec{\nabla}_{\hat{n}}\Phi\right)e^{\pm 2i\alpha(\hat{n})} \longleftarrow [Q \pm iU](\hat{n})e^{\pm 2i\alpha(\hat{n})} \longleftarrow [Q \pm iU](\hat{n})$$

ΛCDM

0 1000

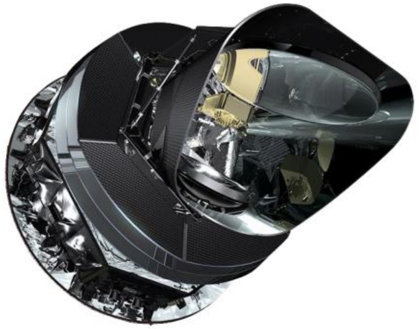
Redshift z

Observational Constraints on Isotropic CB

Cosmic birefringence impacts on the CMB observations producing a mixing of E and B polarization modes which is otherwise null in the standard scenario. |Lue+1999

ΛCDM		+ Cosmic Birefringence
C_ℓ^{TT}	$\longrightarrow$	C_ℓ^{TT}
C_ℓ^{EE}	$\longrightarrow$	$C_\ell^{EE}\cos(2\alpha_0)^2 + C_\ell^{BB}\sin(2\alpha_0)^2$
C_ℓ^{TE}	$\longrightarrow$	$C_\ell^{TE}\cos(2\alpha_0)$
C_ℓ^{BB}	$\longrightarrow$	$C_\ell^{BB}\cos(2\alpha_0)^2 + C_\ell^{EE}\sin(2\alpha_0)^2$
$0 = \{ C_\ell^{TB}$	$\longrightarrow$	$C_\ell^{TE}\sin(2\alpha_0)$
C_ℓ^{EB}	$\longrightarrow$	$\frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\alpha_0)$

If the rotation angle is isotropic in sky, $\alpha(\hat{n}) = \alpha_0$, then we talk about **isotropic birefringence**, which is currently constrained by measurements of CMB polarized data.



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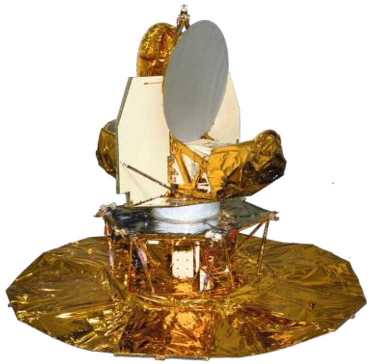


|Minami+2020 |Diego-Palazuelos+2022 |Eskilt+2022

PR3 $[68\%\ \mathrm{C.L.}]$	**PR4** $[68\%\ \mathrm{C.L.}]$	***Planck* + WMAP** $[68\%\ \mathrm{C.L.}]$
$\alpha_0 = (0.35 \pm 0.14)^\circ$	$\alpha_0 = (0.30 \pm 0.11)^\circ$	$\alpha_0 = 0.342^{\circ}{}^{+0.094^\circ}_{-0.091^\circ}$

$\alpha_0 = 0$ **excluded at** $(99.2 - 99.987)\%\ \mathrm{C.L.}!$

ANISOTROPIC BIREFRINGENCE

- Inhomegeneites $\delta\chi$ of the field χ at the last scattering surface (LSS) can induce anisotropies $\delta\alpha$ in the angle α.

$$\chi = \chi_0 + \delta\chi \longrightarrow \alpha = \alpha_0 + \delta\alpha(\hat{n})$$

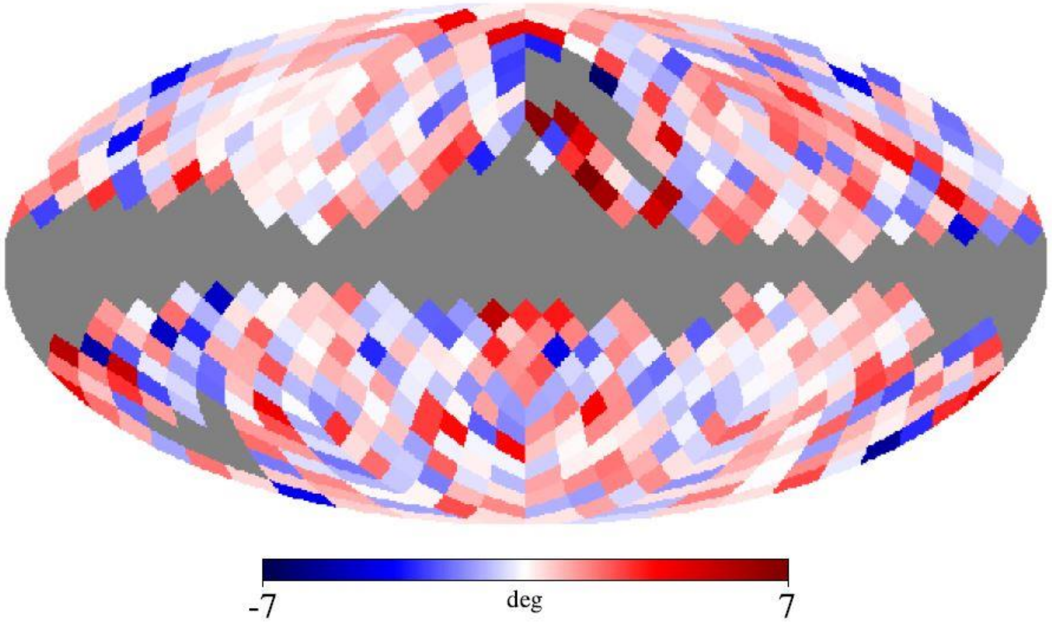
- It is possible to expand the **anisotropic cosmic birefringence** angle on the sky.

$$\delta\alpha(\hat{n}) = \sum_{\ell m} \alpha_{\ell m} Y_{\ell m}(\hat{n})$$

- In literature, the angular power spectra involving the anisotropic CB and its cross-correlation with CMB have been computed, and they are constrained by observations.

Planck PR3
| Bortolami+2022

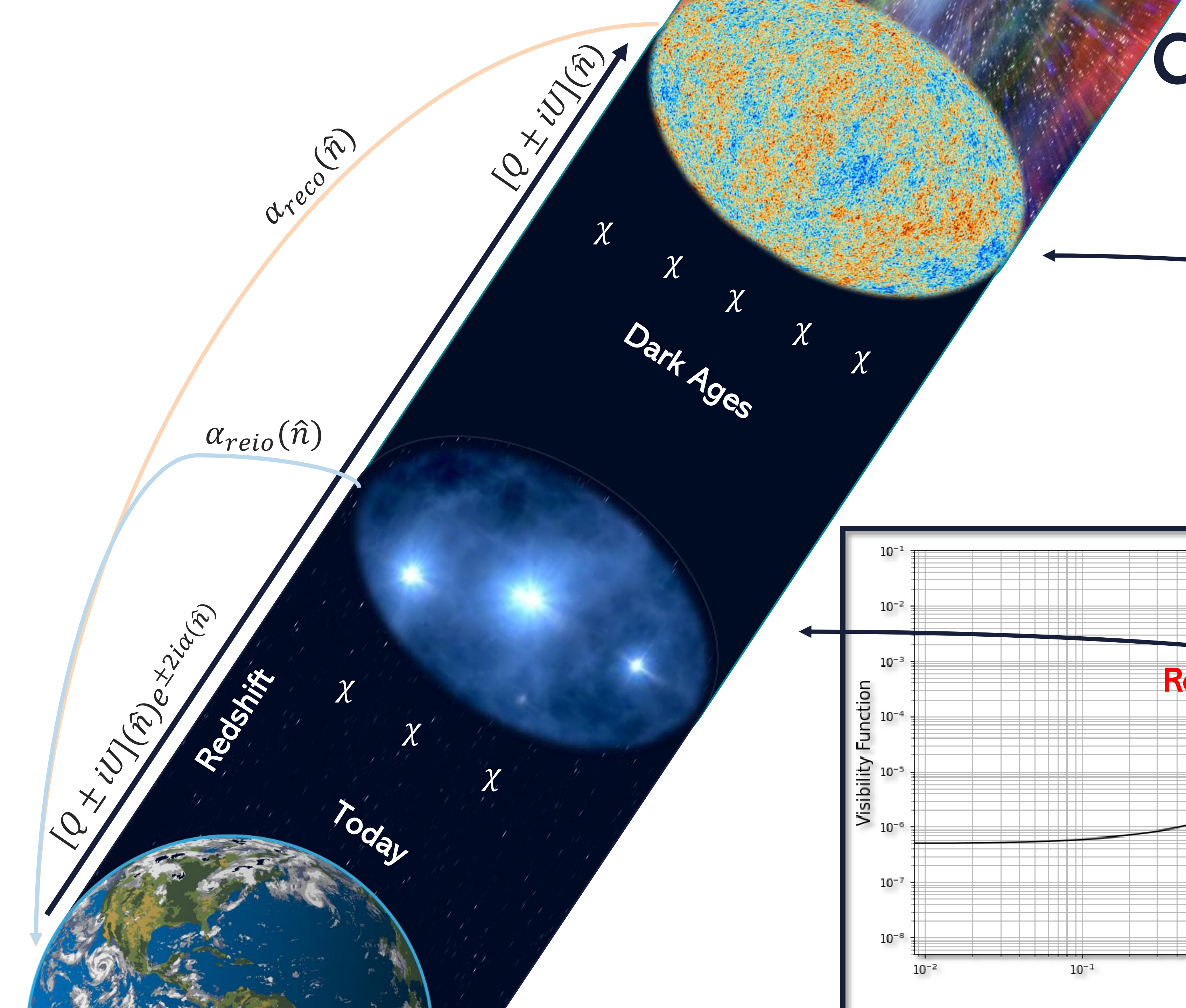
$$\begin{cases} \dfrac{\ell(\ell+1)C_\ell^{\alpha\alpha}}{2\pi} < 0.007\ \mathrm{deg}^2 \\ \dfrac{\ell(\ell+1)C_\ell^{\alpha T}}{2\pi} = (-1.827 \pm 0.953)\ \mu\mathrm{K}\cdot\mathrm{deg} \\ \dfrac{\ell(\ell+1)C_\ell^{\alpha E}}{2\pi} = (-3.5 \pm 6.0)\ \mathrm{nK}\cdot\mathrm{deg} \\ \dfrac{\ell(\ell+1)C_\ell^{\alpha B}}{2\pi} = (-2.4 \pm 4.0)\ \mathrm{nK}\cdot\mathrm{deg} \end{cases}$$

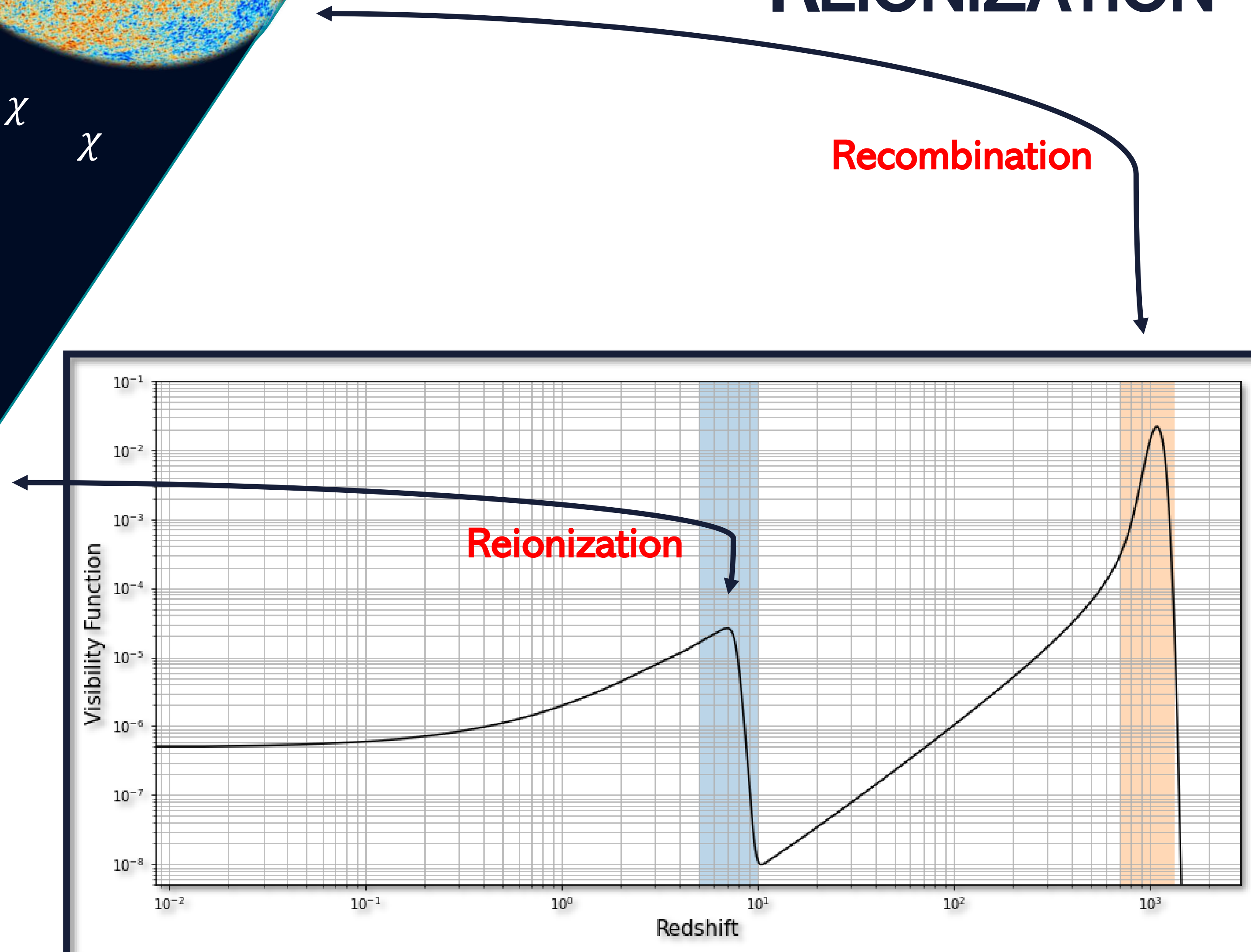


CB angle maps from PR3 for the **Commander** component separation method.

Other observational constraints are provided e.g. by former Planck analysis, ACTPol and SPTpol | Gruppuso+2020 | Namikawa+202 | Bianchini+2020

COSMIC BIREFRINGENCE FROM REIONIZATION



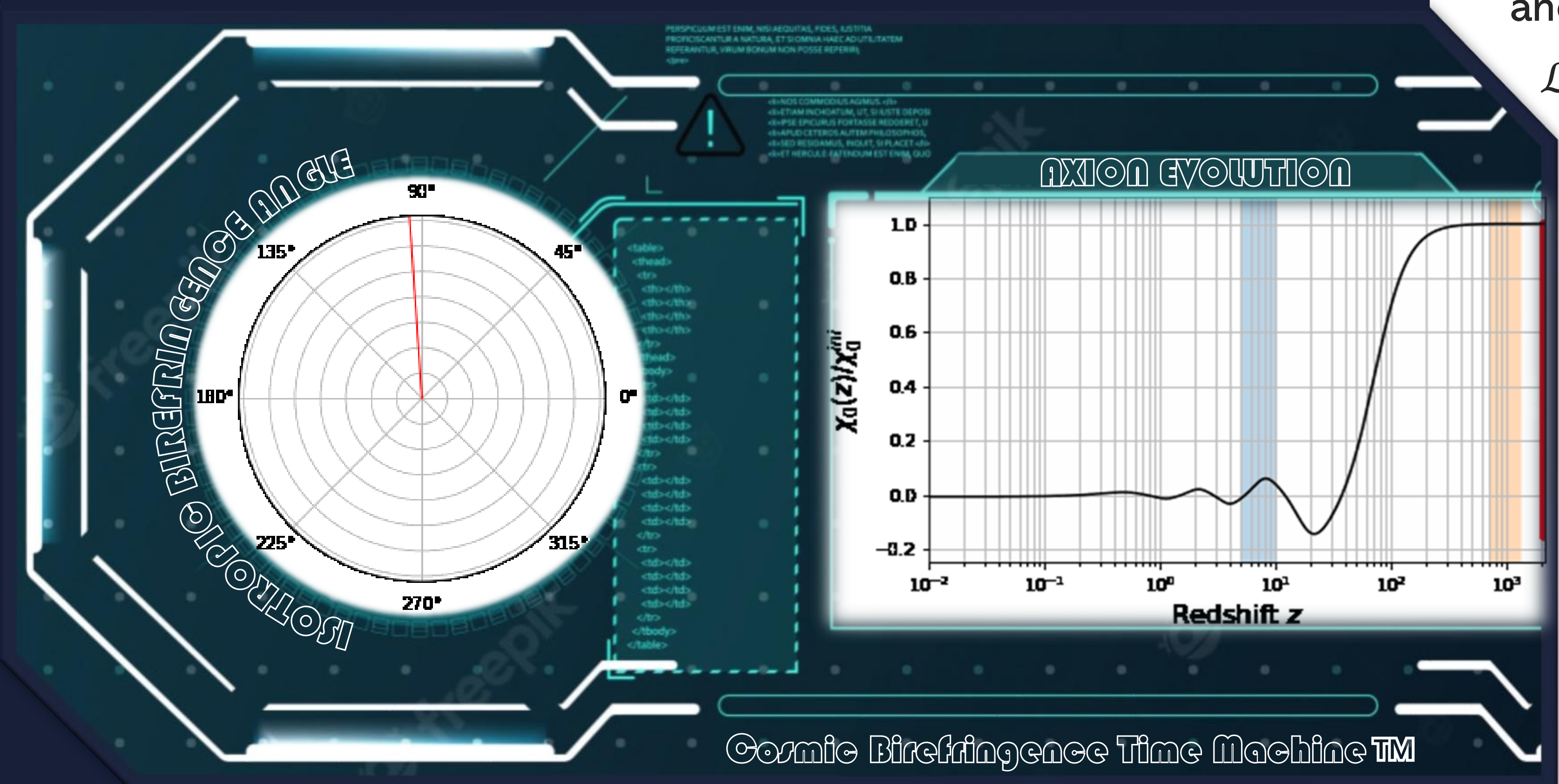


Tomography of Cosmic Birefringence

To get information about the axion-like field χ, a **tomographic** approach can be adopted:

- one tracks the time-evolution of the background field χ_0 to study the isotropic angle α_0:

$$\mathcal{L}_\chi = -\frac{1}{2} g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - V(\chi) - \frac{\lambda}{4f}\chi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



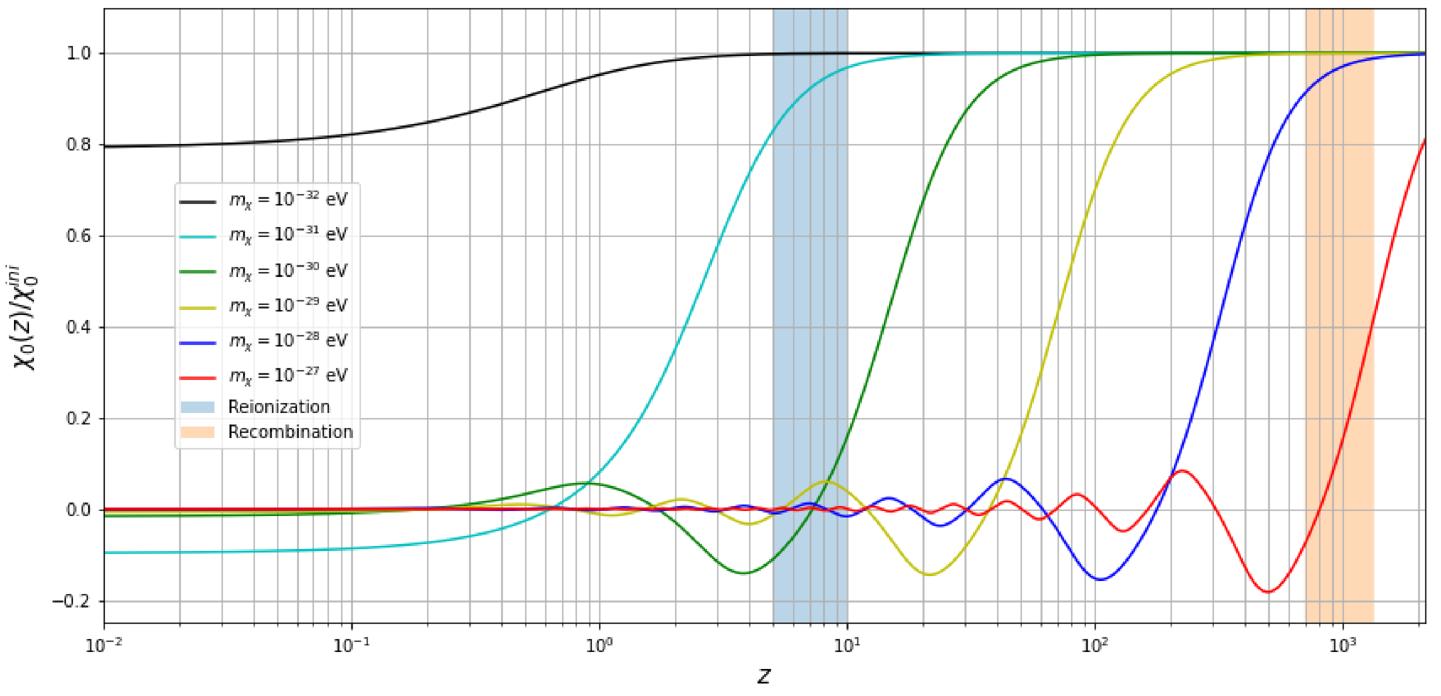
- the axion parameters (its potential and the coupling with photons) strongly affect the isotropic angle from recombination and reionization;
- hence, we can use birefringence as a sort of **time machine!** | Sherwin+2021
- In arXiv:2211.06380 we extend this treatment to the anisotropic counterpart.

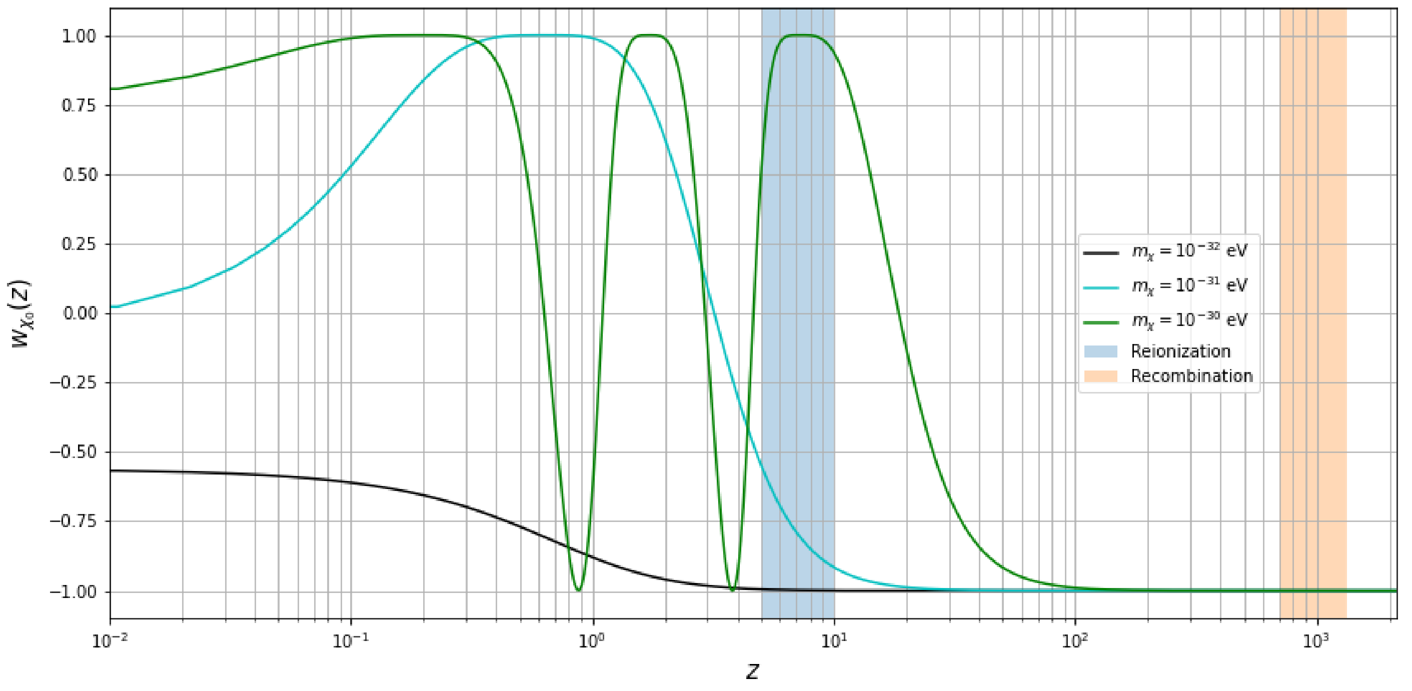
Background Evolution

The background physics can be treated as a Cauchy problem: | Nakatsuka+2022

$$\begin{cases} \chi_0'' + 2\mathcal{H}\chi_0' + a^2 \dfrac{\mathrm{d}V}{\mathrm{d}\chi_0} = 0 \\ \chi_0(\tau_{ini}) = m_{Pl} \\ \chi_0'(\tau_{ini}) = 0 \end{cases}$$

How much the two birefringence angles (from recombination and reionization) differ from each other depends on the field's evolution.





We have specified our treatment for a quintessence field playing the role of **early dark energy** (EDE)

POTENTIAL $$V(\chi_0) = m_\chi^2 M_{Pl}^2 \left[1 - \cos\left(\frac{\chi_0}{M_{Pl}}\right)\right]^2$$

EQ. OF STATE $$w_{\chi_0} = \frac{\chi_0'^2 - 2a^2V(\chi_0)}{\chi_0'^2 + 2a^2V(\chi_0)}$$

ANISOTROPIC SIGNAL

The **anisotropic birefringence angle** is proportional to the field fluctuations (x being "reco" or "reio"):

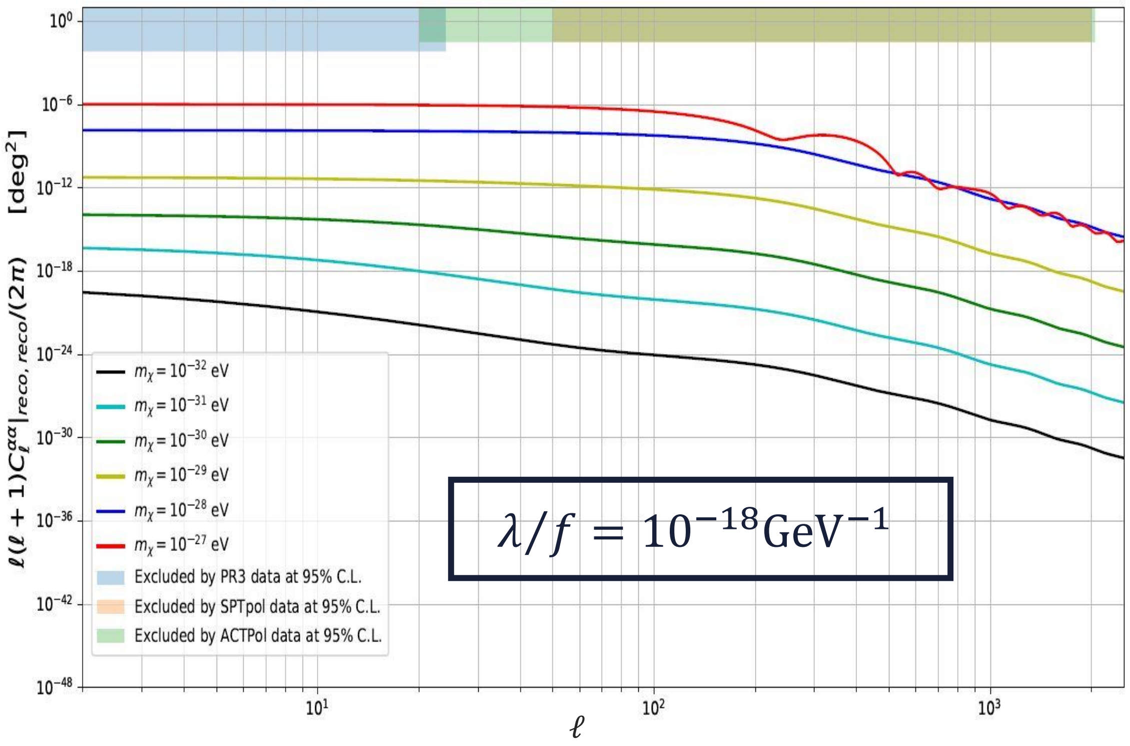
$$\delta\alpha_x(\hat{n}) = -\frac{\lambda}{2f}\delta\chi[\tau_x, (\tau_x - \tau_0)\hat{n}]$$

We have solved the perturbed equation of motion in the **Newtonian gauge** for **adiabatic initial conditions**, by modifying the Boltzmann Code **CLASS** |Lesgourgues+2011

$$\delta\chi'' + 2\mathcal{H}\delta\chi' + a^2\left(k^2 + \frac{d^2V}{d\chi_0^2}\right)\delta\chi =$$
$$= \chi_0'(3\Phi' + \Psi') - 2a^2\frac{dV}{d\chi_0}\Psi$$

We have computed angular power spectra of $\delta\alpha$ with the other scalar-sourced CMB anisotropies:

$$C_\ell^{\alpha\alpha}|_x = 4\pi\int\frac{dk}{k}\mathcal{P}_\mathcal{R}(k)\Delta^2_{\alpha,\ell}(k,\tau_x)$$
$$C_\ell^{\alpha T}|_x = 4\pi\int\frac{dk}{k}\mathcal{P}_\mathcal{R}(k)\Delta_{\alpha,\ell}(k,\tau_x)\,\Delta_{T,\ell}(k,\tau_x)$$
$$C_\ell^{\alpha E}|_x = 4\pi\int\frac{dk}{k}\mathcal{P}_\mathcal{R}(k)\Delta_{\alpha,\ell}(k,\tau_x)\,\Delta_{E,\ell}(k,\tau_x)$$



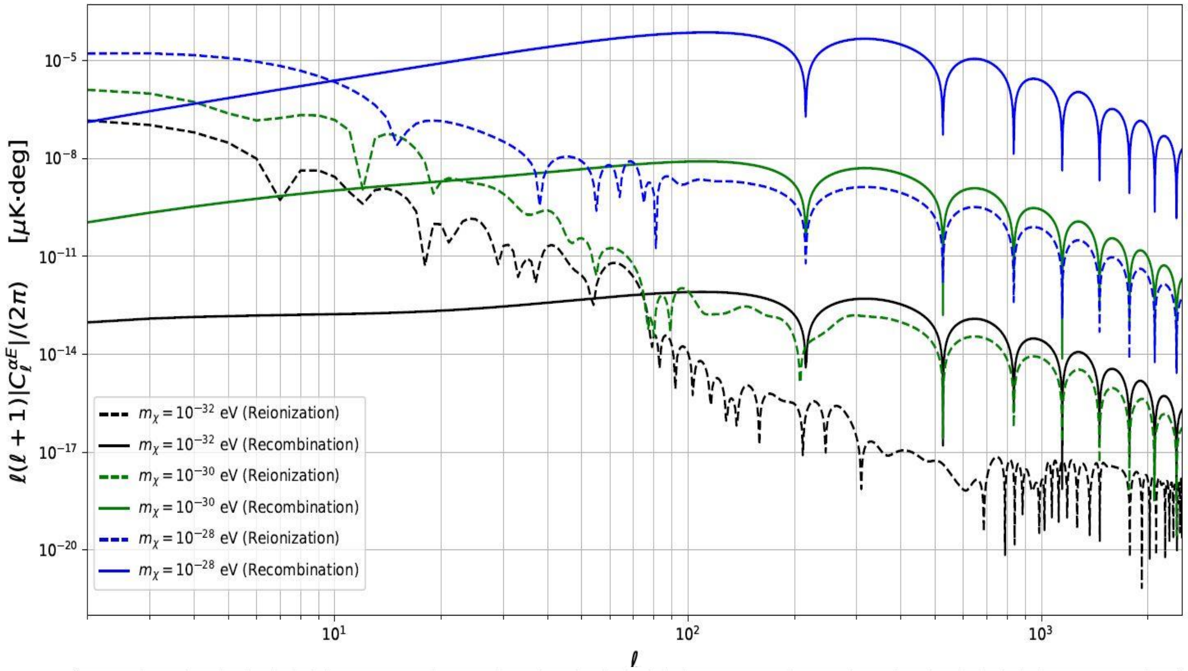
Example: plot of $\ell(\ell+1)C_{\ell,\,\mathrm{reco}}^{\alpha\alpha}/2\pi$ in units of $[\mathrm{deg}^2]$ for different values of the axion mass, compared with observational constraints.

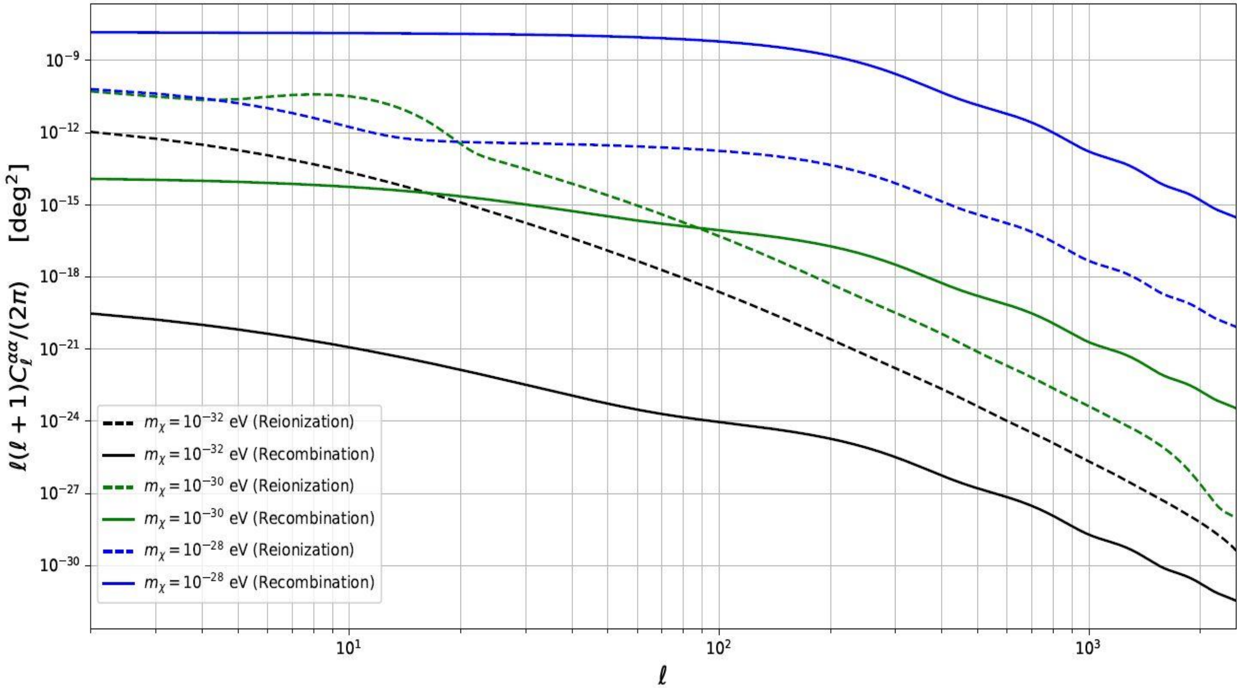
Tomographic Analysis

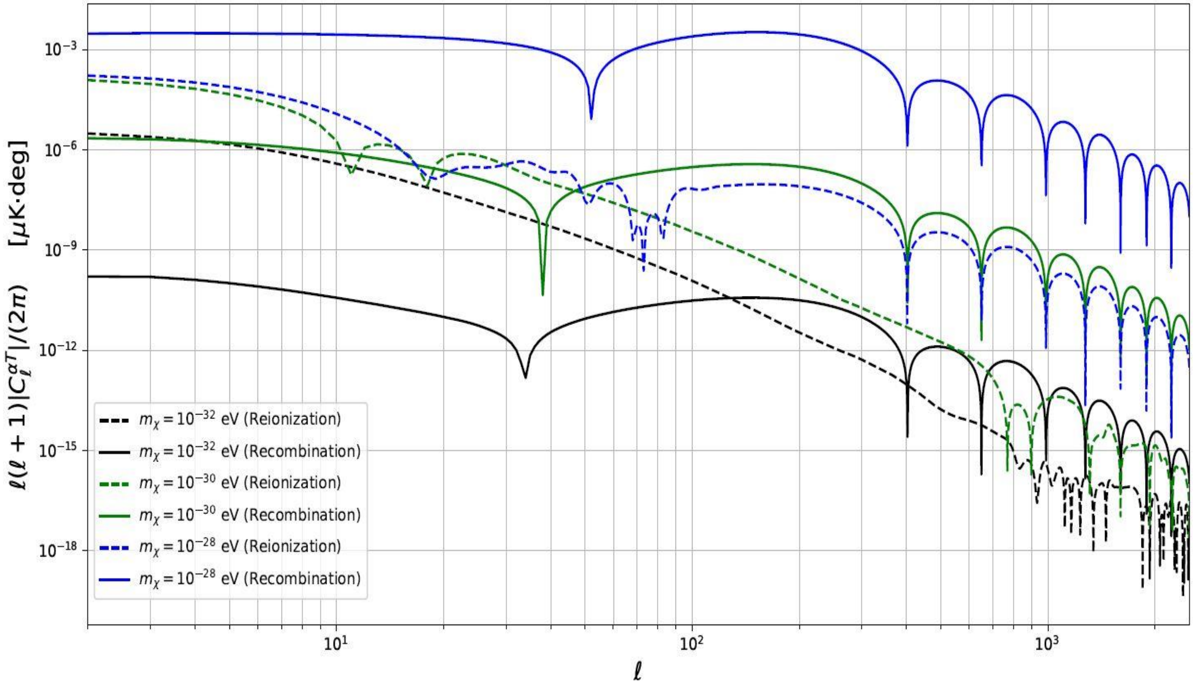
By performing a tomographic analysis of ACB we have found something extremely interesting:

I. larger the axion-like field mass is, larger the spectra's amplitudes are;

II. for a sufficiently light axion, the reionization signal can be larger than that from recombination at large scales.







Impact on CMB Observables

Both the component of cosmic birefringence (isotropic and anisotropic) from both the sources (recombination and reionization) contribute to inducing an overall modification of the CMB power spectra:

$$
\begin{aligned}
C^{EE}_{\ell,\mathrm{rot}}\big|_{xz} = {} & \left(1 - 2V_\alpha\big|_{xx} - 2V_\alpha\big|_{zz}\right)\left[C^{EE}_\ell\big|_{xz}\cos(2\alpha_{0,x})\cos(2\alpha_{0,z}) + C^{BB}_\ell\big|_{xz}\sin(2\alpha_{0,x})\sin(2\alpha_{0,z})\right] \\
& + \frac{2}{2\ell+1}\sum_{L_1L_2} I^{2,-2,0}_{\ell L_1 L_2}\Big(C^{\alpha\alpha}_{L_2}\big|_{xz} I^{2,-2,0}_{\ell L_1 L_2}\Big\{C^{EE}_{L_1}\big|_{xz}\left[\cos(2\alpha_{0,x}-2\alpha_{0,z}) - (-1)^{\ell+L_1+L_2}\cos(2\alpha_{0,x}+2\alpha_{0,z})\right] \\
& + C^{BB}_{L_1}\big|_{xz}\left[\cos(2\alpha_{0,x}-2\alpha_{0,z}) + (-1)^{\ell+L_1+L_2}\cos(2\alpha_{0,x}+2\alpha_{0,z})\right]\Big\} \\
& + C^{\alpha E}_{L_1}\big|_{xz} C^{\alpha E}_{L_2}\big|_{zx} I^{2,0,-2}_{\ell L_1 L_2}\left[\cos(2\alpha_{0,x}-2\alpha_{0,z}) - (-1)^{\ell+L_1+L_2}\cos(2\alpha_{0,x}+2\alpha_{0,z})\right]\Big),
\end{aligned}
$$

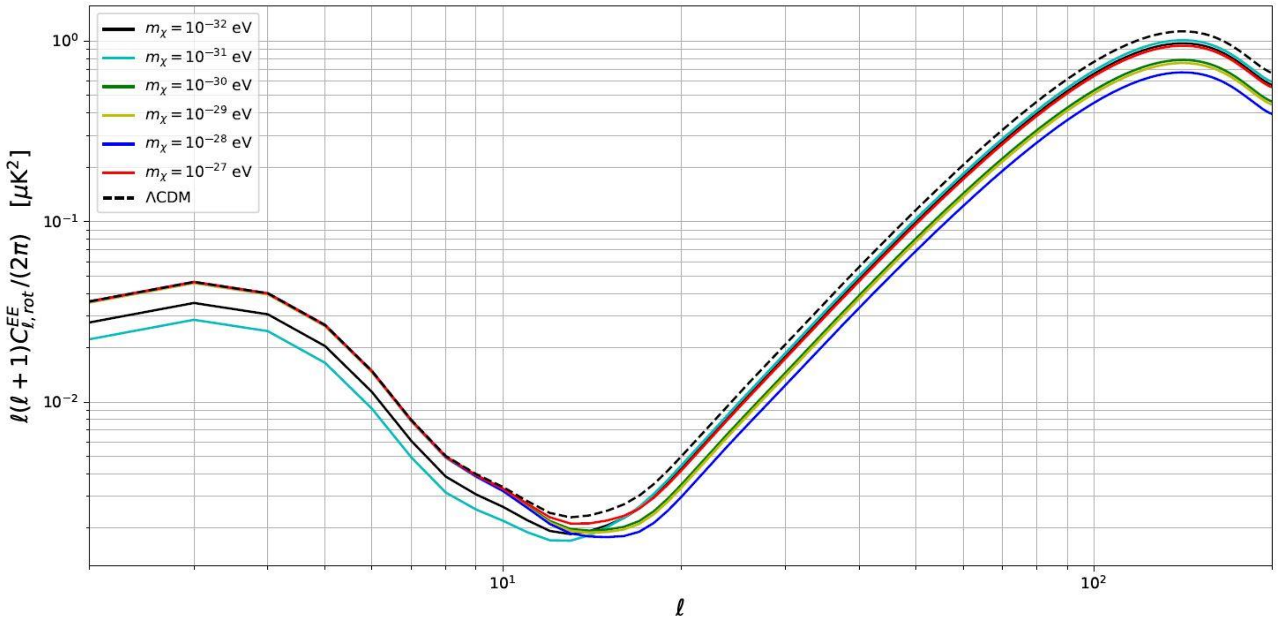
$$
\begin{aligned}
C^{BB}_{\ell,\mathrm{rot}}\big|_{xz} = {} & \left(1 - 2V_\alpha\big|_{xx} - 2V_\alpha\big|_{zz}\right)\left[C^{BB}_\ell\big|_{xz}\cos(2\alpha_{0,x})\cos(2\alpha_{0,z}) + C^{EE}_\ell\big|_{xz}\sin(2\alpha_{0,x})\sin(2\alpha_{0,z})\right] \\
& + \frac{2}{2\ell+1}\sum_{L_1L_2} I^{2,-2,0}_{\ell L_1 L_2}\Big(C^{\alpha\alpha}_{L_2}\big|_{xz} I^{2,-2,0}_{\ell L_1 L_2}\Big\{C^{EE}_{L_1}\big|_{xz}\left[\cos(2\alpha_{0,x}-2\alpha_{0,z}) + (-1)^{\ell+L_1+L_2}\cos(2\alpha_{0,x}+2\alpha_{0,z})\right] \\
& + C^{BB}_{L_1}\big|_{xz}\left[\cos(2\alpha_{0,x}-2\alpha_{0,z}) - (-1)^{\ell+L_1+L_2}\cos(2\alpha_{0,x}+2\alpha_{0,z})\right]\Big\} \\
& + C^{\alpha E}_{L_1}\big|_{xz} C^{\alpha E}_{L_2}\big|_{zx} I^{2,0,-2}_{\ell L_1 L_2}\left[\cos(2\alpha_{0,x}-2\alpha_{0,z}) + (-1)^{\ell+L_1+L_2}\cos(2\alpha_{0,x}+2\alpha_{0,z})\right]\Big),
\end{aligned}
$$

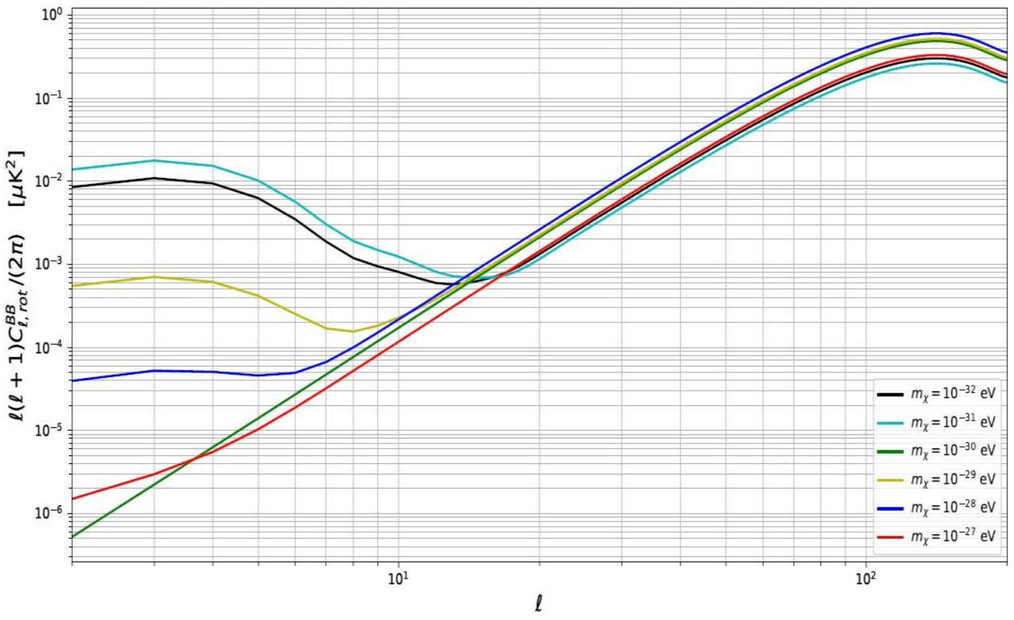
$$
\begin{aligned}
C^{EB}_{\ell,\mathrm{rot}}\big|_{xz} = {} & \left(1 - 2V_\alpha\big|_{xx} - 2V_\alpha\big|_{zz}\right)\left[C^{EE}_\ell\big|_{xz}\cos(2\alpha_{0,x})\sin(2\alpha_{0,z}) - C^{BB}_\ell\big|_{xz}\sin(2\alpha_{0,x})\cos(2\alpha_{0,z})\right] \\
& + \frac{2}{2\ell+1}\sum_{L_1L_2} I^{2,-2,0}_{\ell L_1 L_2}\Big(C^{\alpha\alpha}_{L_2}\big|_{xz} I^{2,-2,0}_{\ell L_1 L_2}\Big\{C^{BB}_{L_1}\big|_{xz}\left[\sin(2\alpha_{0,x}-2\alpha_{0,z}) - (-1)^{\ell+L_1+L_2}\sin(2\alpha_{0,x}+2\alpha_{0,z})\right] \\
& - C^{EE}_{L_1}\big|_{xz}\left[\sin(2\alpha_{0,x}-2\alpha_{0,z}) + (-1)^{\ell+L_1+L_2}\sin(2\alpha_{0,x}+2\alpha_{0,z})\right]\Big\} \\
& - C^{\alpha E}_{L_1}\big|_{xz} C^{\alpha E}_{L_2}\big|_{zx} I^{2,0,-2}_{\ell L_1 L_2}\left[\sin(2\alpha_{0,x}-2\alpha_{0,z}) - (-1)^{\ell+L_1+L_2}\sin(2\alpha_{0,x}+2\alpha_{0,z})\right]\Big),
\end{aligned}
$$

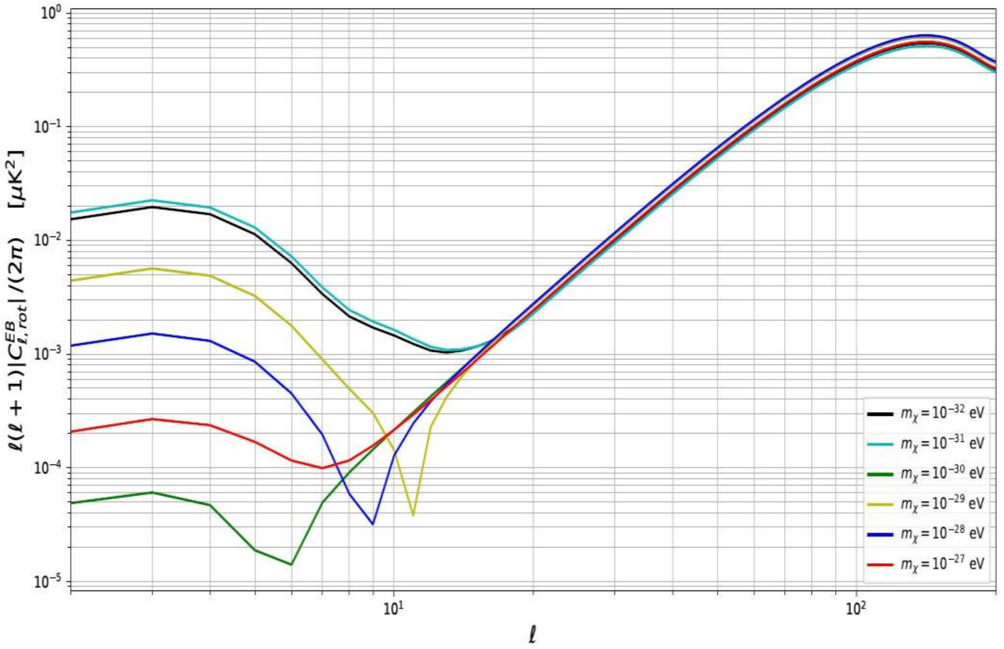
In arXiv:2211.06380, we have derived the formulas here listed, that completely generalize the standard expression that can be found in literature (e.g. |Li+2008)

Therefore, it is now possible to use tomography of anisotropic cosmic birefringence for constraining (e.g.) EDE models!

Impact on CMB Observables

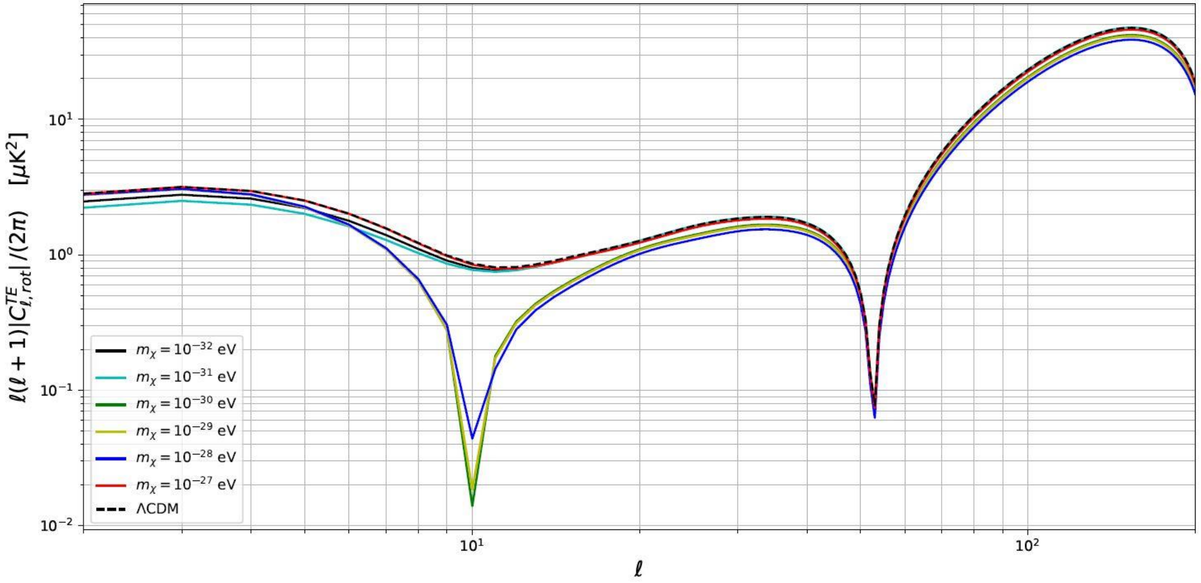






Unlensed angular power spectra of CMB polarization with E and B polarization modes (tensor-to-scalar ratio set equal to zero), affected by isotropic and anisotropic cosmic birefringence, from recombination and reionization

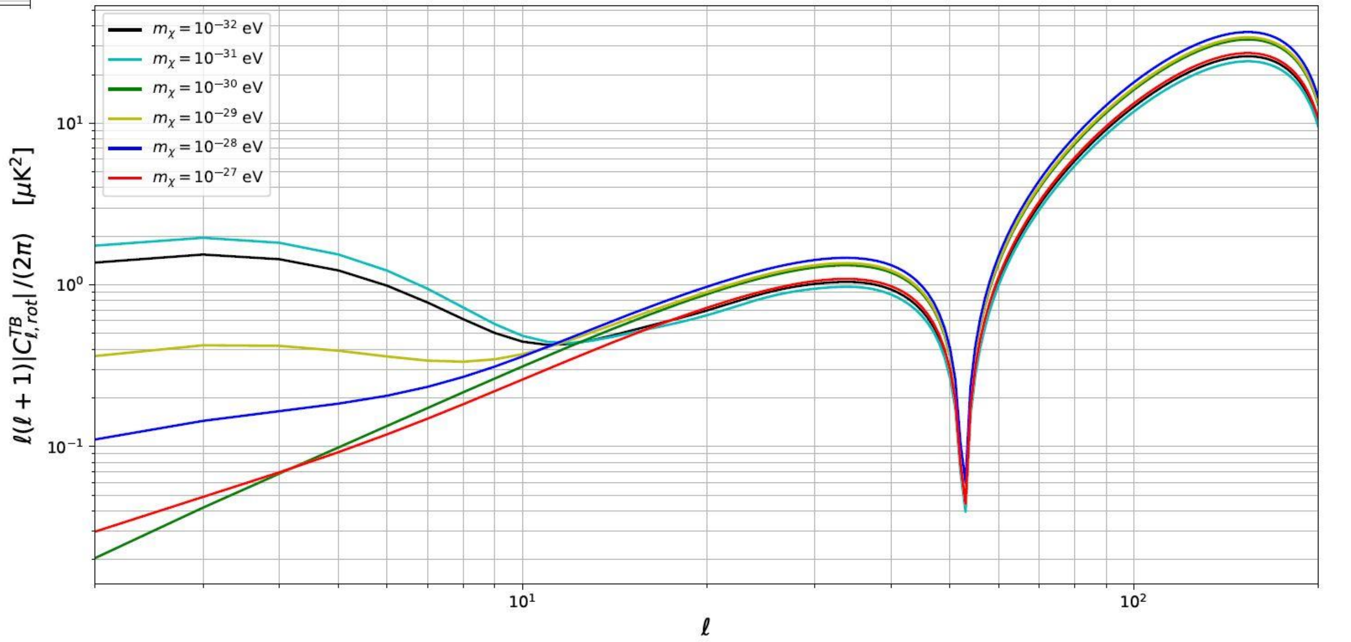
Impact on CMB Observables



Unlensed cross-correlation of CMB polarization (E and B modes) with temperature anisotropies T (tensor-to-scalar ratio set equal to zero), affected by isotropic and anisotropic cosmic birefringence, from recombination and reionization

$$C^{TE}_{\ell,\mathrm{rot}}\big|_{xz} = \left(1-2V_\alpha\big|_{zz}\right)\cos(2\alpha_{0,z})C^{TE}_{\ell}\big|_{xz},$$

$$C^{TB}_{\ell,\mathrm{rot}}\big|_{xz} = \left(1-2V_\alpha\big|_{zz}\right)\sin(2\alpha_{0,z})C^{TB}_{\ell}\big|_{xz},$$



Conclusions and Future Prospects

We have considered a well-motivated parity-violating extension of electromagnetism which induces the phenomenon of cosmic birefringence, and we have computed the angular power spectra involving the anisotropic angle, $C_\ell^{\alpha\alpha}$, $C_\ell^{\alpha T}$ and $C_\ell^{\alpha E}$:

- we have performed a tomographic treatment of anisotropic cosmic birefringence, finding that the reionization signal can encode relevant information for the underlying axion physics;
- our approach has been able to make manifest unique features of the birefringence anisotropies with respect to the purely isotropic case: we have shown that, although a large axion mass prevents the possibility to have isotropic cosmic birefringence, this behavior is not mimicked by the anisotropic counterpart;
- we found that for low multipoles and for sufficiently small values of the axion mass, the reionization contribution to anisotropic cosmic birefringence is higher with respect to the recombination one, a future development of our research could be trying to use the signal coming from reionization encoded in ACB as a probe of the axion parameters;

Thank you for your attention!