Probing Axions through Tomography of Anisotropic Cosmic Birefringence

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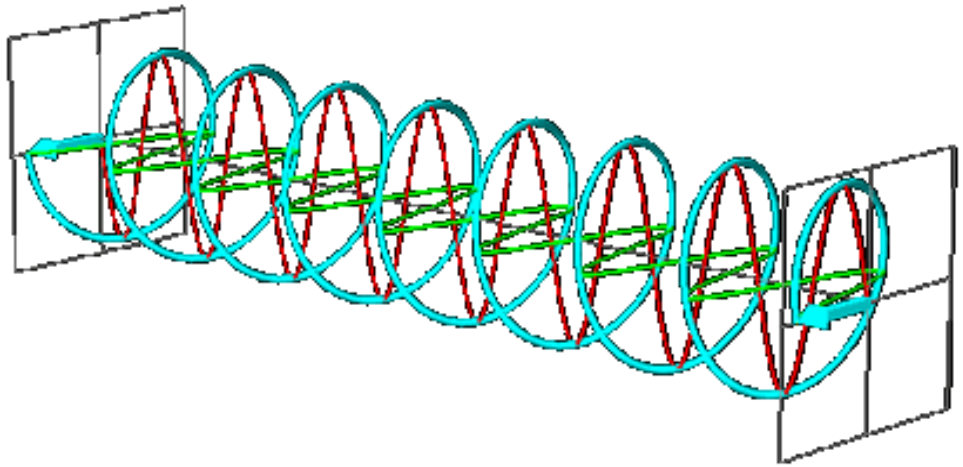
Modified Electromagnetism

Maxwell Electromagnetic Theory

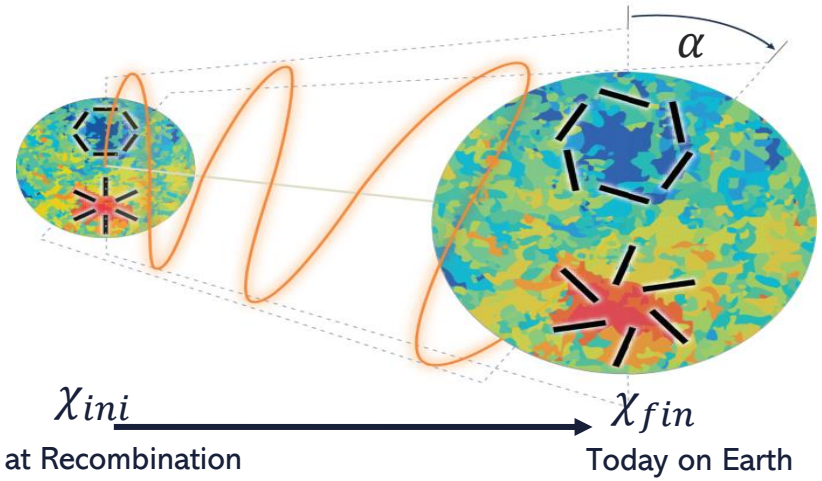
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$



$F_{\mu\nu} \equiv \nabla_\mu A_\nu - \nabla_\nu A_\mu$ 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

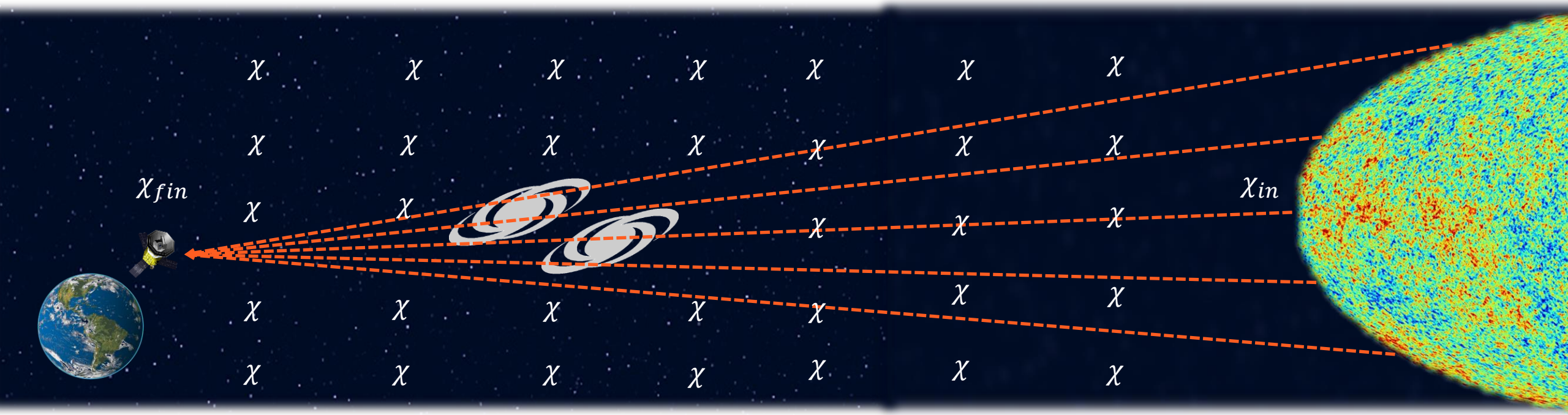


$\tilde{F}^{\mu\nu} \equiv \epsilon^{\mu\nu\varrho\sigma} F_{\varrho\sigma}/2$ Hodge Dual Tensor

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

The Birefringence Mechanism

Observation | Weak Gravitational Lensing | Cosmic Birefringence | Emission



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

ΛCDM

0 → 1000

Redshift z

ANISOTROPIC BIREFRINGENCE

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

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

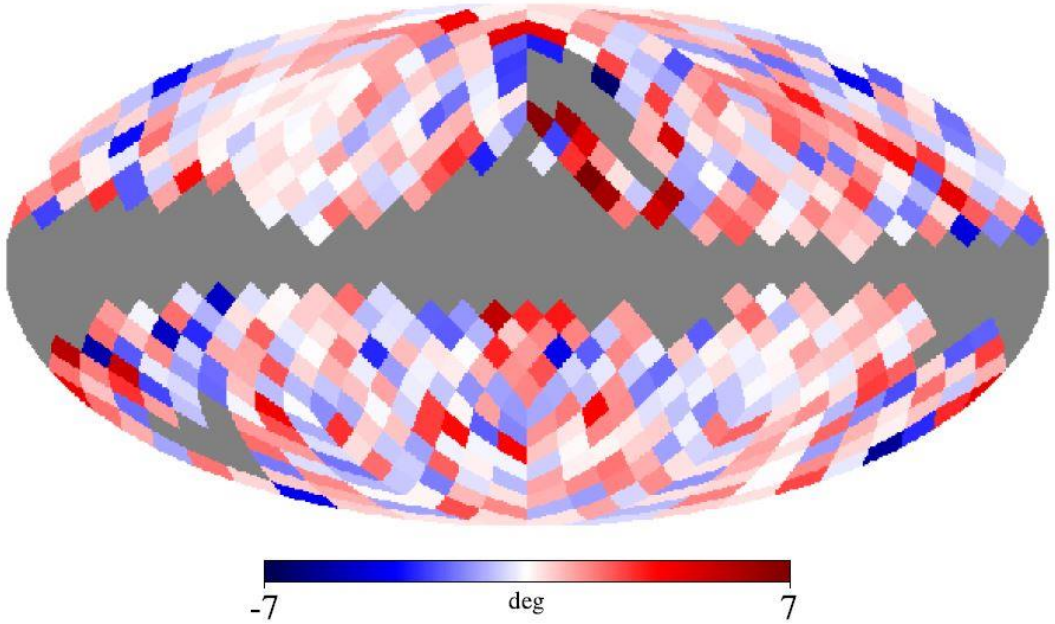
- In literature, the angular power spectra involving the anisotropic CB and its cross-correlation with CMB have been computed, and they are constrained by observations.

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

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

***Planck* PR3** | Bortolami+2022

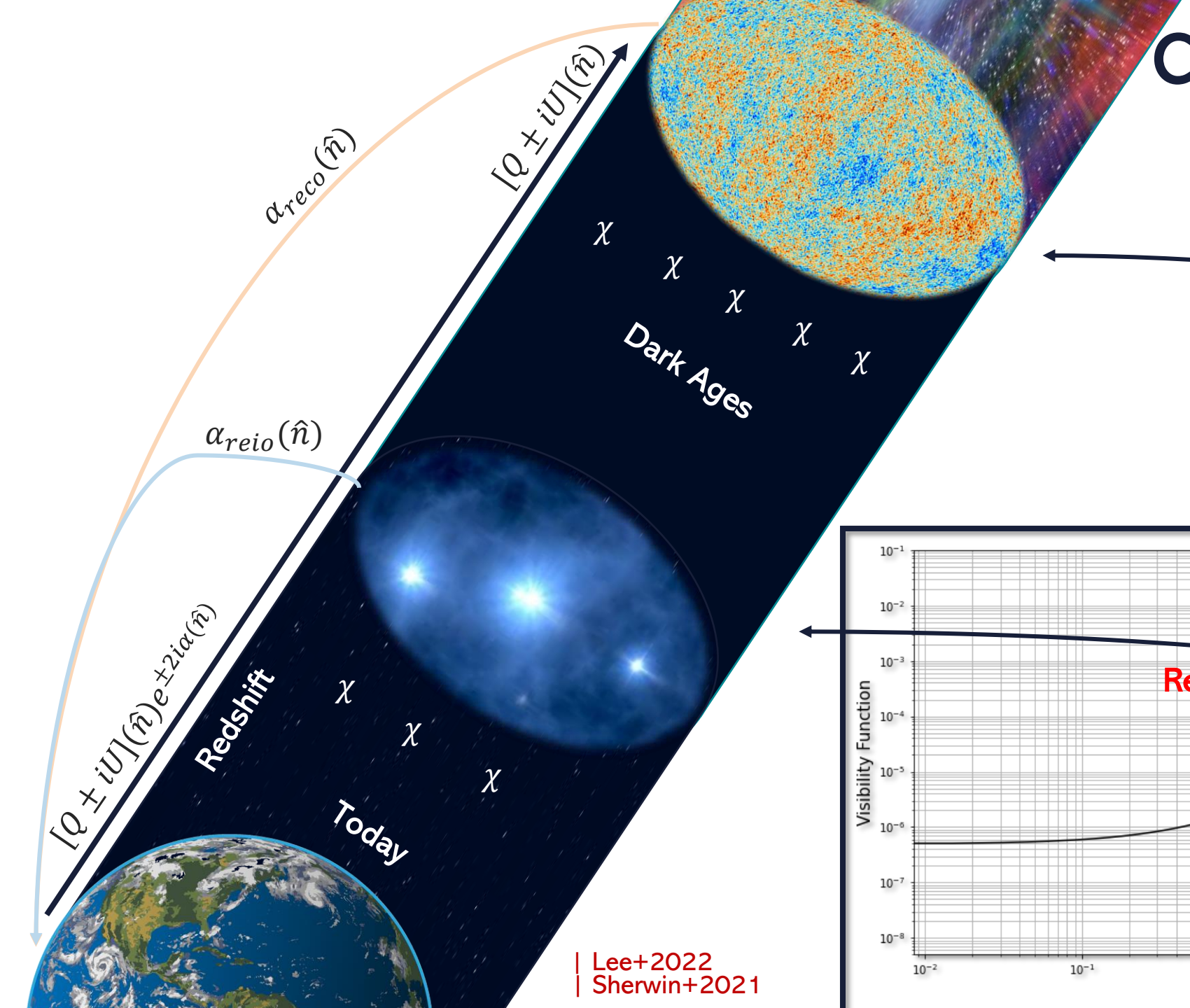
$$\begin{cases} \dfrac{\ell(\ell+1)C_\ell^{\alpha\alpha}}{2\pi} < 0.007\ \mathrm{deg}^2 \\ \dfrac{\ell(\ell+1)C_\ell^{\alpha T}}{2\pi} = (-1.827 \pm 0.953)\ \mu\mathrm{K}\cdot\mathrm{deg} \\ \dfrac{\ell(\ell+1)C_\ell^{\alpha E}}{2\pi} = (-3.5 \pm 6.0)\ \mathrm{nK}\cdot\mathrm{deg} \\ \dfrac{\ell(\ell+1)C_\ell^{\alpha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



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



| Lee+2022
| Sherwin+2021

ANISOTROPIC SIGNAL

The **anisotropic birefringence angle** is proportional to the field fluctuations (x being "reco" or "reio") | Greco+2022

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

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:

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

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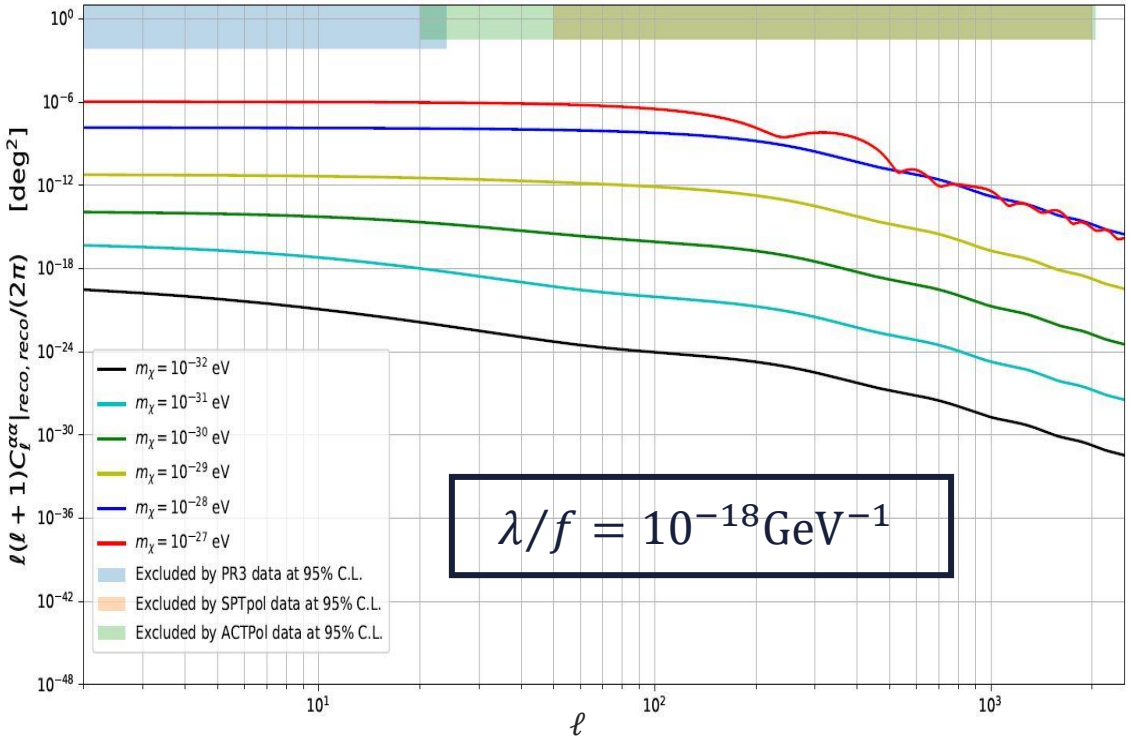


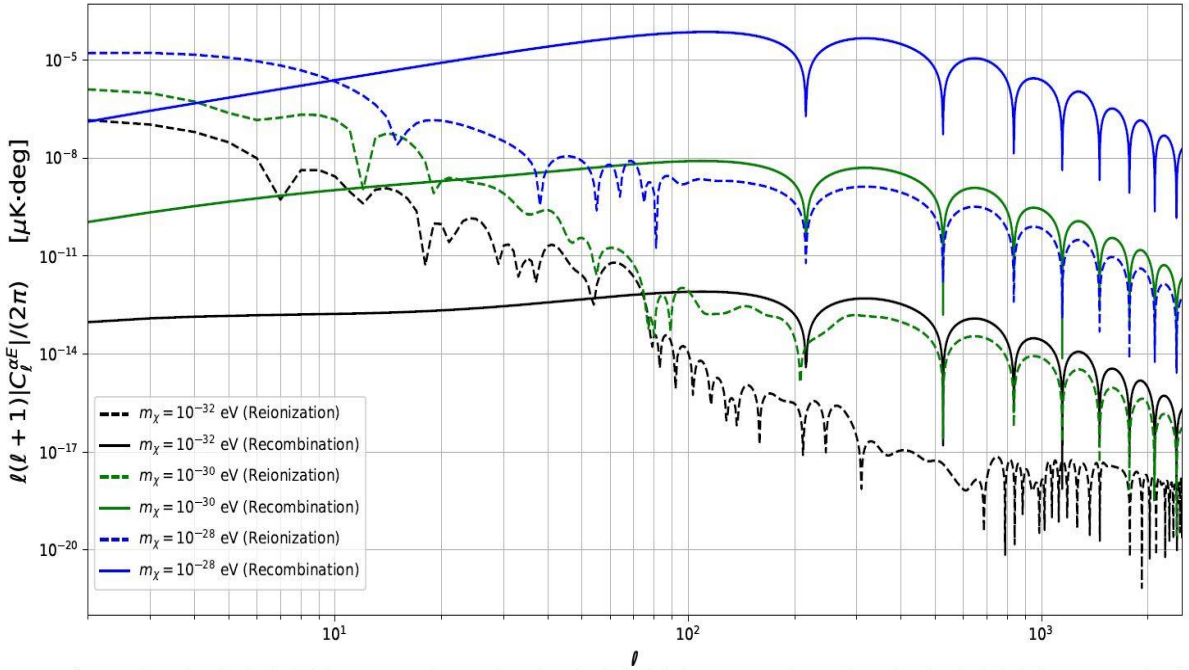
Example: plot of $\ell(\ell+1)C^{\alpha\alpha}_{\ell,\,\mathrm{reco}}/2\pi$ in units of $[\mathrm{deg}^2]$ for different values of the axion mass, compared with observational constraints.

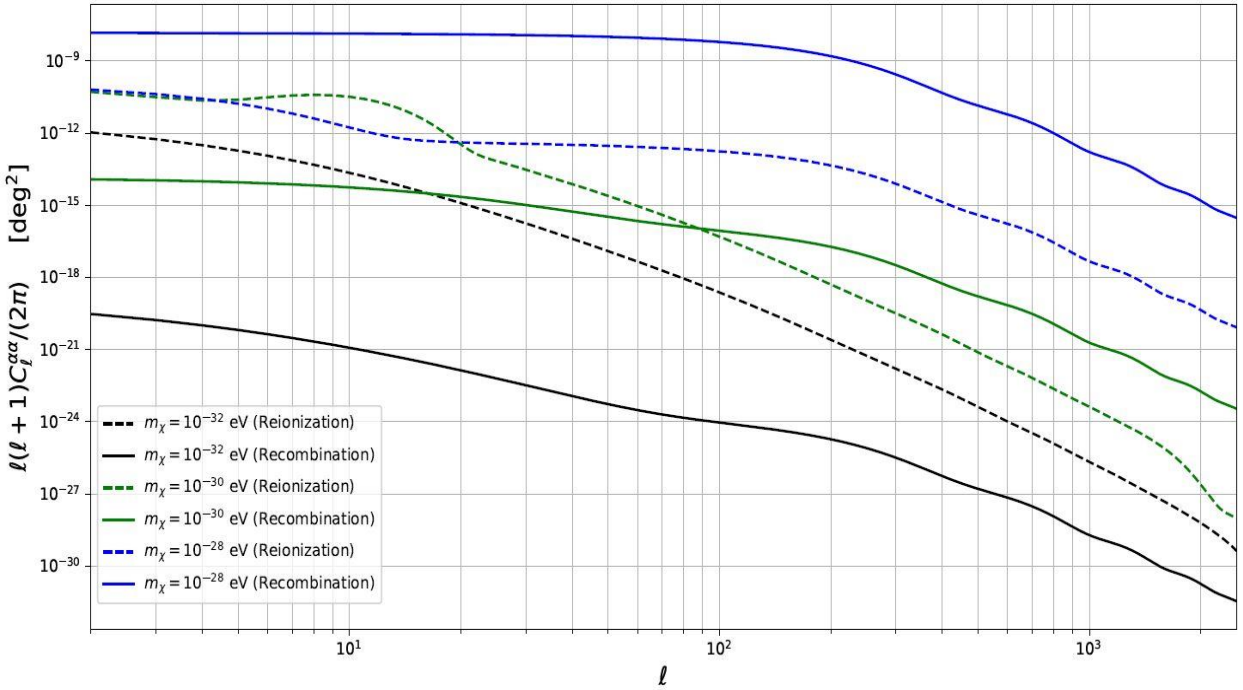
TOMOGRAPHIC ANALYSIS

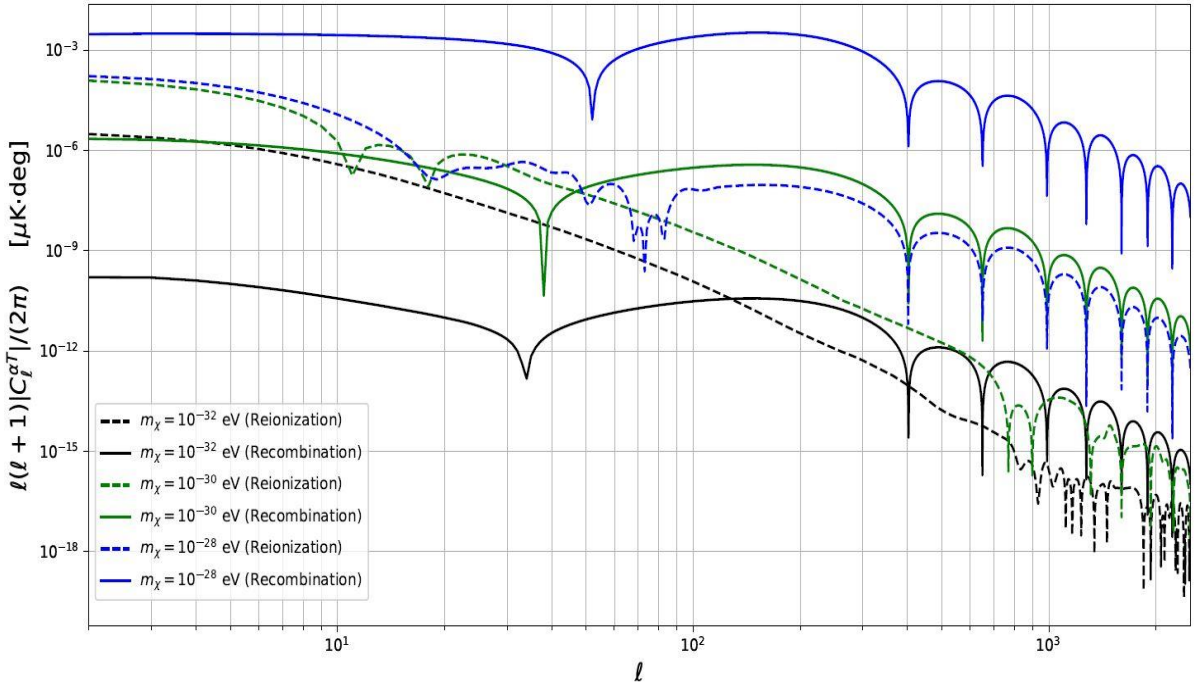
By performing a tomographic analysis of ACB we have found something extremely interesting:

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.







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!