Constraining ALPs with CMB Polarization Birefringence

Matteo Galaverni *Specola Vaticana (Vatican Observatory), INAF/OAS Bologna & INFN Bologna*

Cosmic Birefringence in CMB anisotropies

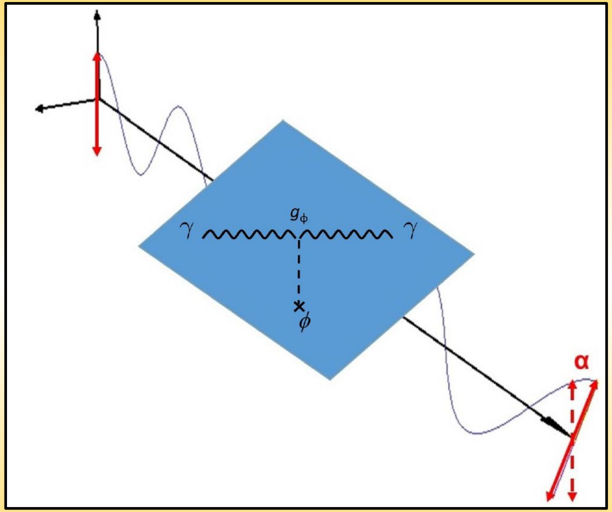
- **Redshift independent** approximation;
- Current constraints for **isotropic cosmic birefringence**;
- **Time/redshift evolution** of the pseudoscalar field;
- Constraints for axion-like acting as - **Early Dark Energy (EDE)**
  - **Dark Energy (DE)**
  - **Dark Matter (DM)**

- Conclusions

In collaboration with **Fabio Finelli** and **Daniela Paoletti** *(INAF/OAS Bologna)*
Email: matteo.galaverni@gmail.com

Cosmological pseudoscalar field

Photon propagation in a **time dependent background of pseudoscalar particles**.



Cosmological pseudoscalar field ϕ (axion-like particle):

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

$$\ddot{\phi} + 3H\dot{\phi} - \frac{dV}{d\phi} = 0,$$

Rotation of the polarization plane α (single photon)

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

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

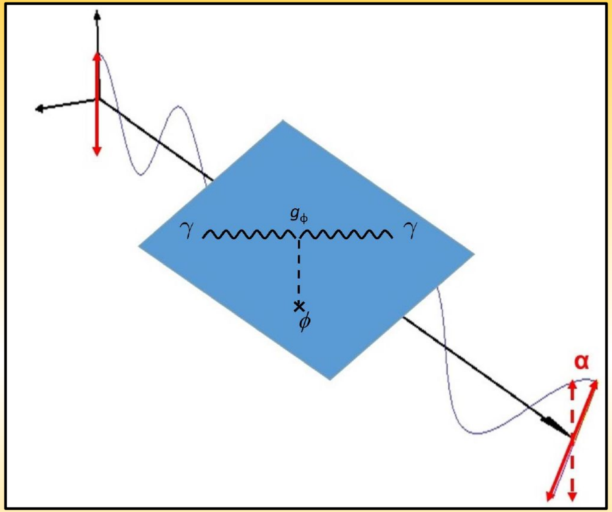
1990: first constraint on cosmic birefringence

Cosmological birefringence was first constrained looking at polarized **Radio Galaxies.**

Perpendicularity is expected between:

- **the position angle of the radio axis** and
- **the position angle of linear radio polarization in distant RG**

→ it is possible to **constrain the rotation of the plane of polarization** for radiation traveling over cosmic distances.



PHYSICAL REVIEW D VOLUME 41, NUMBER 4 15 FEBRUARY 1990

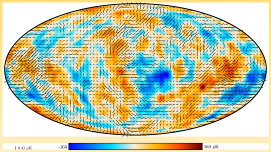
Limits on a Lorentz- and parity-violating modification of electrodynamics

Sean M. Carroll and George B. Field
Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

Roman Jackiw*
Department of Physics, Columbia University, New York, New York 10027
(Received 5 September 1989)

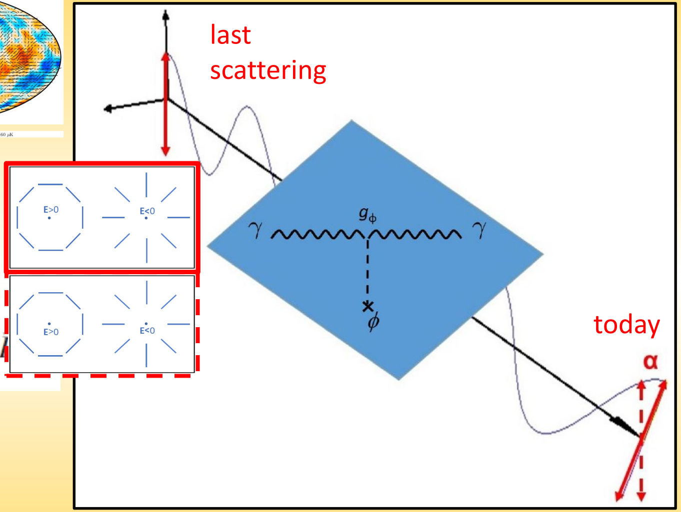
$\Delta\phi \leq 6.0°$ (at the 95% confidence level) at $z = 0.4$

Cosmological pseudoscalar field and CMB polarization



Planck 2018 **map of the polarized CMB anisotropies**

$$\mathcal{L} \supset -\frac{g_\phi}{4}\phi F_{\mu\nu}$$



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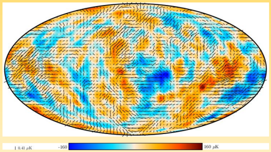

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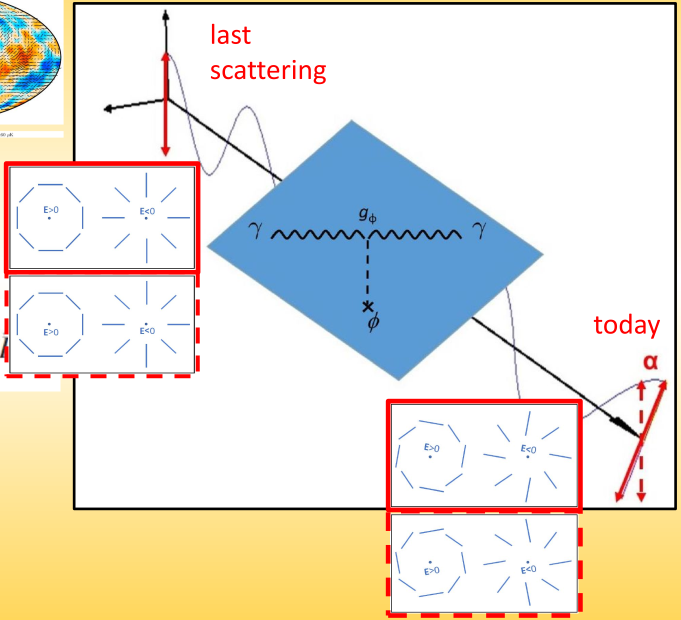

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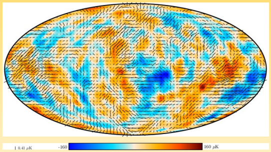

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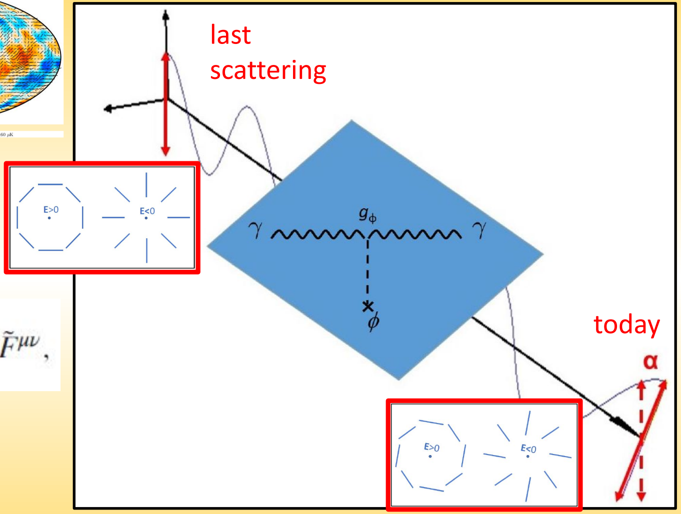
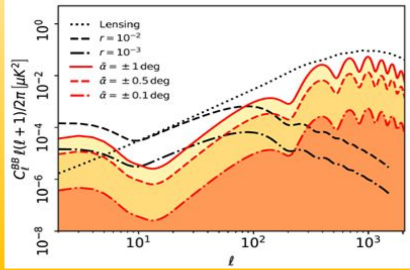


birefringence induced B modes



CMB power spectra at recombination (last scattering):

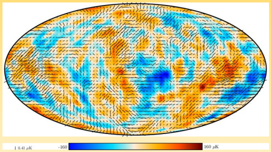
$$C_\ell^{TT,\mathrm{rec}},\ C_\ell^{TE,\mathrm{rec}},\ C_\ell^{EE,\mathrm{rec}},\ C_\ell^{BB,\mathrm{rec}}$$

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

Observed CMB power spectra (assuming ***z* indep.** rot. angle):

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

Cosmological pseudoscalar field and CMB polarization



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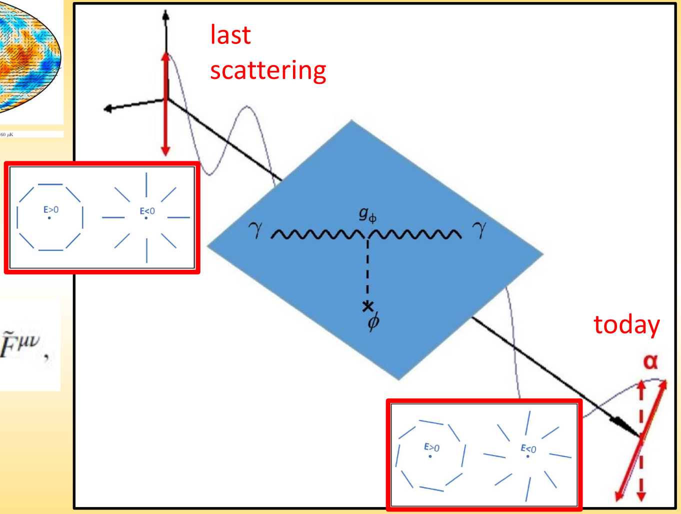

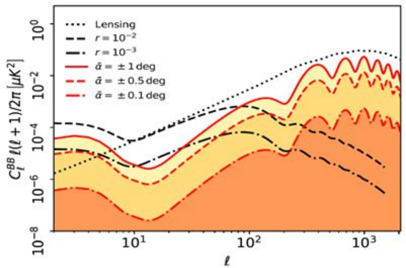

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$$\begin{aligned}
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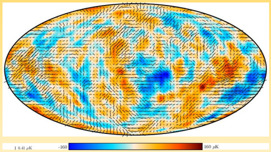
C_\ell^{BB,\mathrm{obs}} &= C_\ell^{BB,\mathrm{rec}}\cos^2(2\bar{\alpha}) + C_\ell^{EE,\mathrm{rec}}\sin^2(2\bar{\alpha})
\end{aligned}$$

$$\begin{aligned}
C_\ell^{TB,\mathrm{obs}} &= C_\ell^{TE,\mathrm{rec}}\sin(2\bar{\alpha}) \\
C_\ell^{EB,\mathrm{obs}} &= \frac{1}{2}\left(C_\ell^{EE,\mathrm{rec}} - C_\ell^{BB,\mathrm{rec}}\right)\sin(4\bar{\alpha})
\end{aligned}$$

parity ODD

Cosmological pseudoscalar field and CMB polarization



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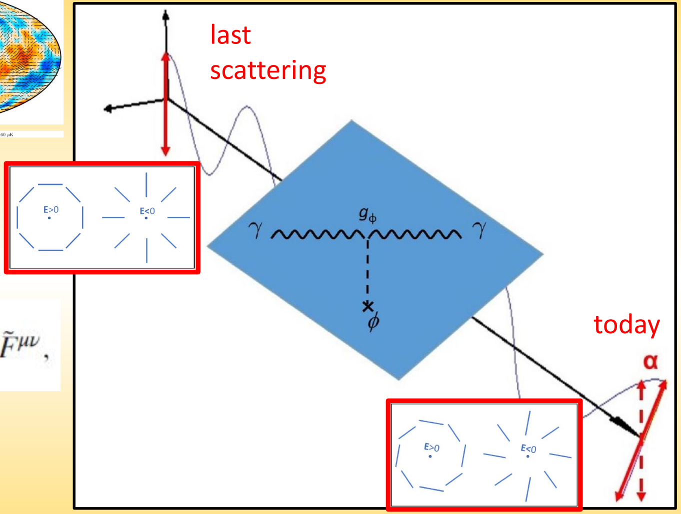
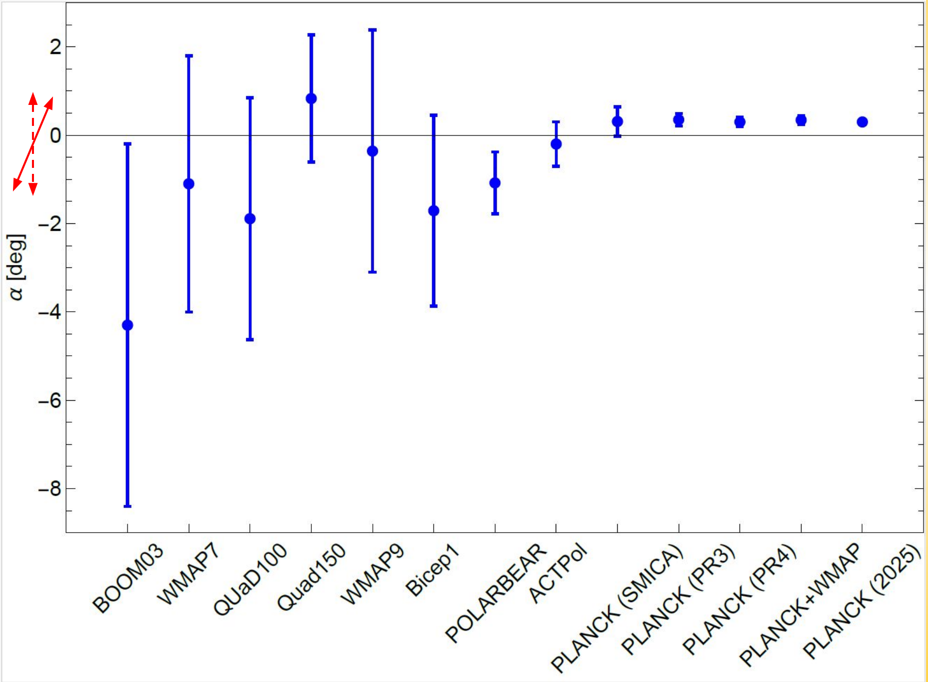
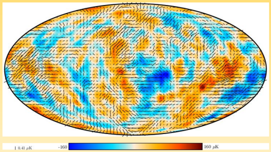




Isotropic cosmic birefringence from CMB experiments with 1σ errors (statistical and systematic uncertainties summed linearly)
[Planck XLIX. Parity-violation constraints from polarization data (2016) *+updates*]

Cosmological pseudoscalar field and CMB polarization



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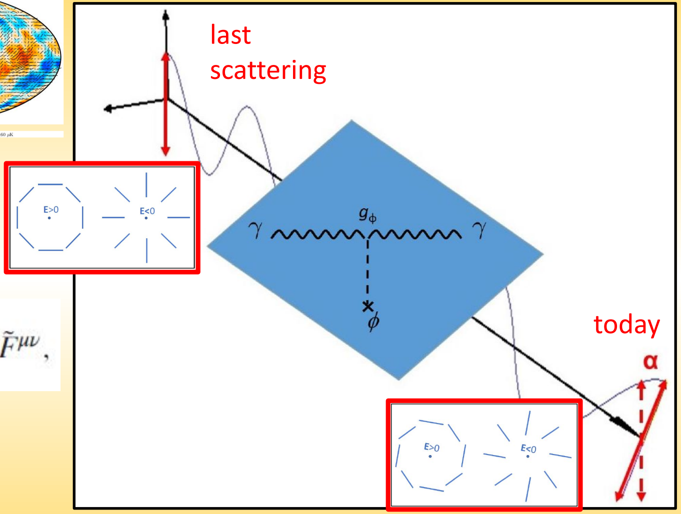

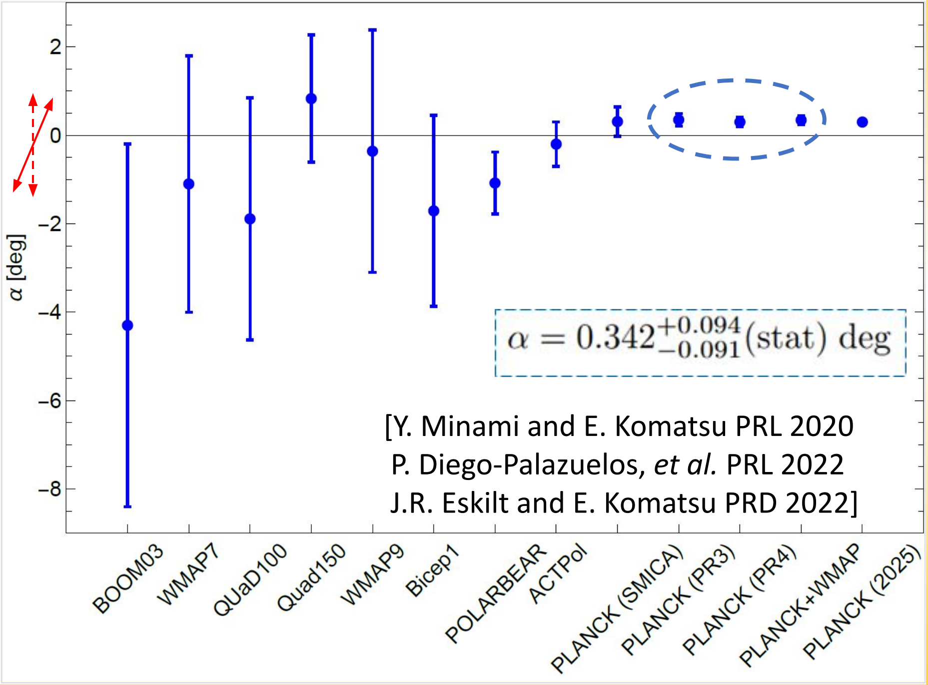

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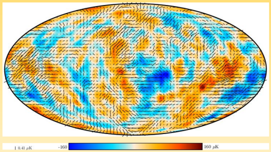

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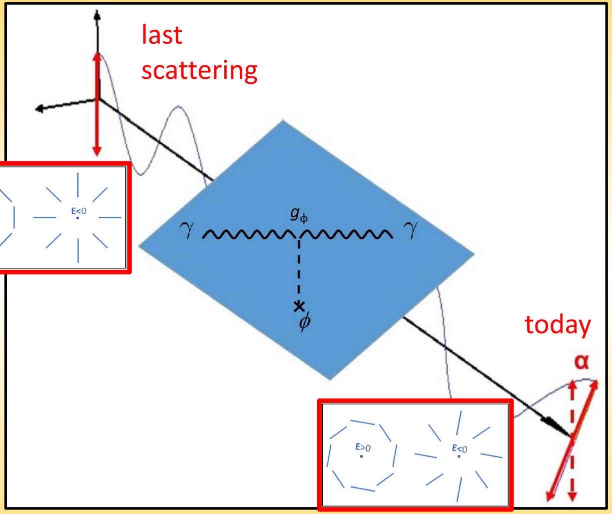

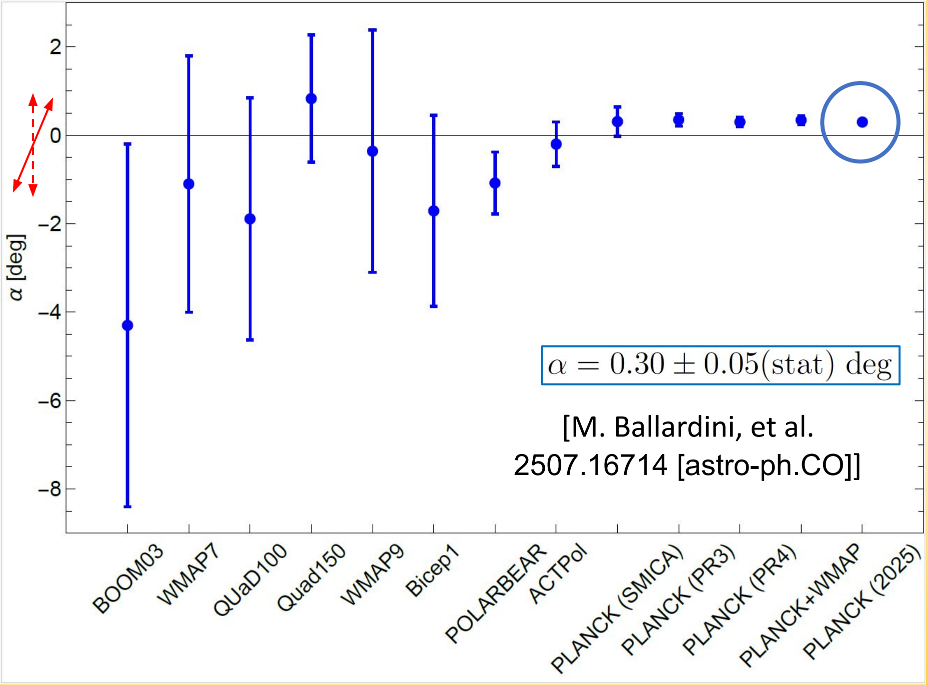

Isotropic cosmic birefringence from CMB experiments with 1σ errors (statistical and systematic uncertainties summed linearly)
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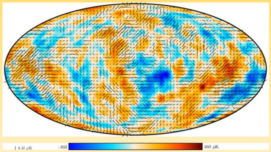
Time/redshift dependent pseudoscalar field



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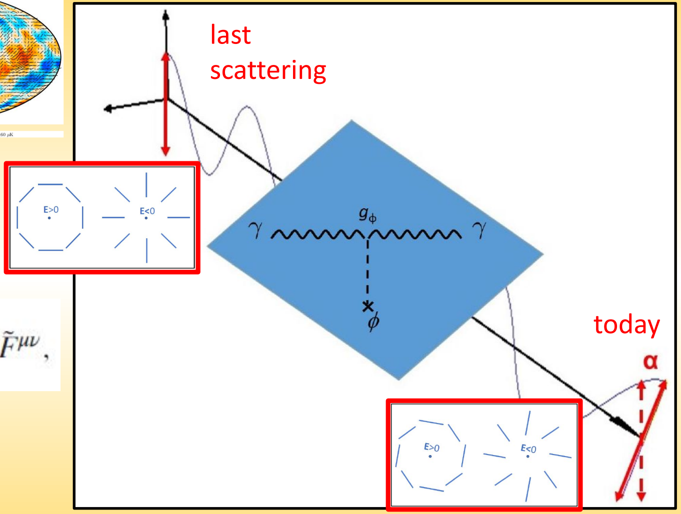
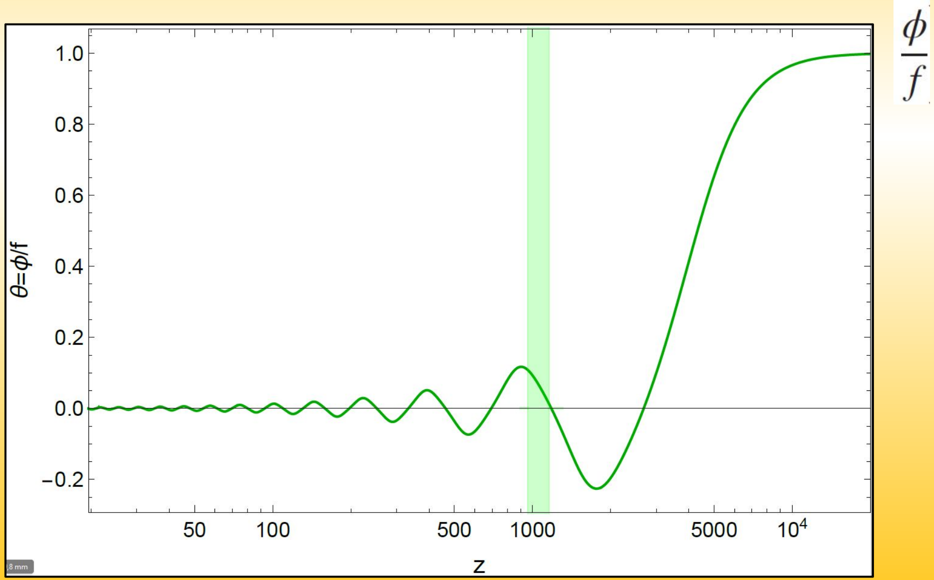


$$V(\phi) = \Lambda^4\left(1 - \cos\frac{\phi}{f}\right)^n,$$

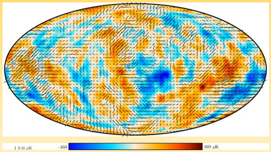
[n=2, Λ= 0.417 eV, f= 0.05 M_{pl}, $(\phi/f)_{in}$=1, $(\dot{\phi}/f)_{in}$=0]

Time/redshift dependence of the pseudoscalar field (e.g. acting as **Early Dark Energy** - EDE)



NOW **LAST SCATT.**

Cosmological pseudoscalar field and CMB polarization



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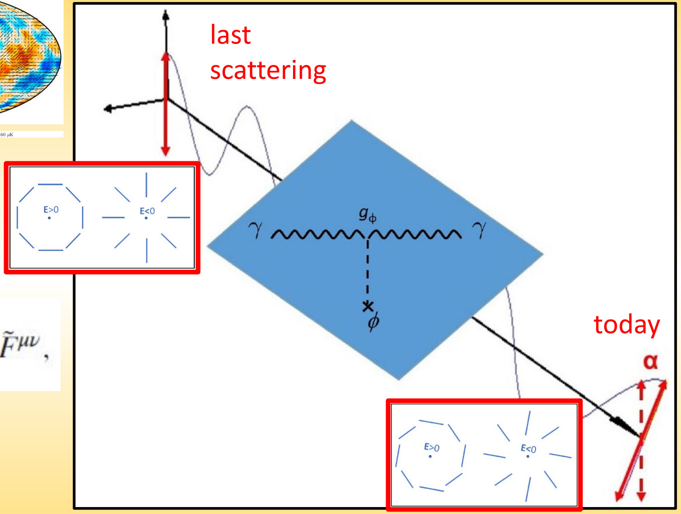
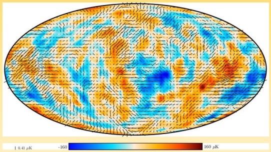


Boltzmann equation for linear polarization **with cosmic birefringence** (Liu, Lee and Ng [PRL 2006], Finelli and Galaverni [PRD 2009]):

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

Cosmological pseudoscalar field and CMB polarization



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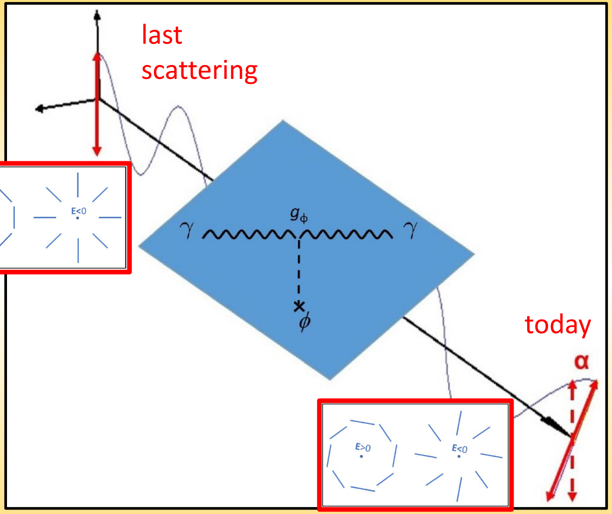

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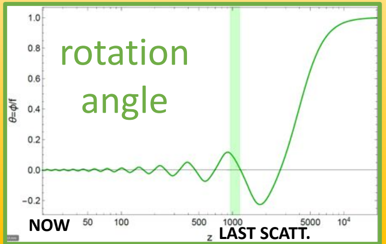
Following the line-of-sight strategy [Seljak and Zaldarriaga (1996)], the source terms for the scalar perturbations are:

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

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



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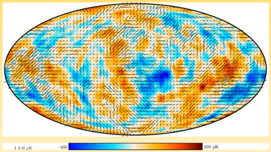

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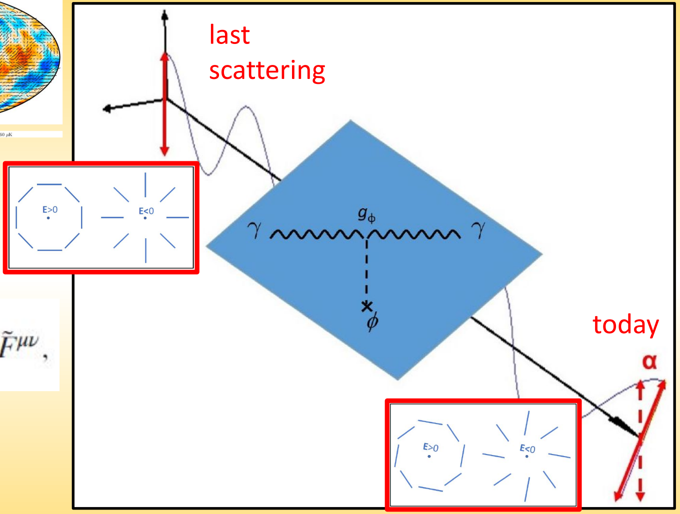

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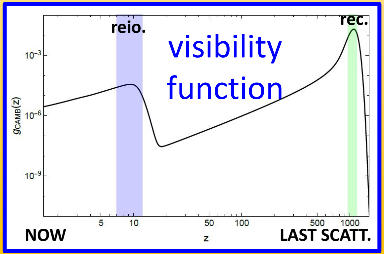
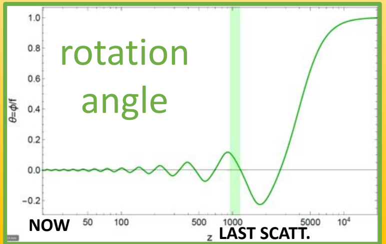
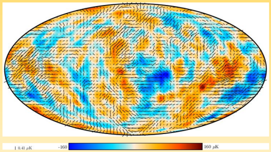




Cosmological pseudoscalar field acting as EDE



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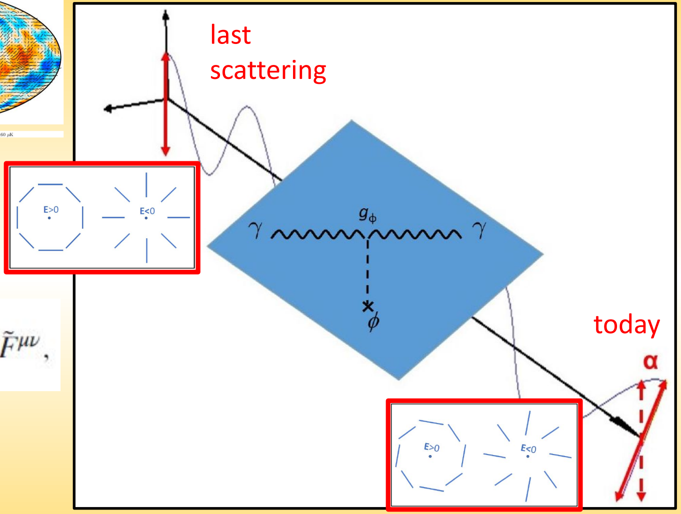
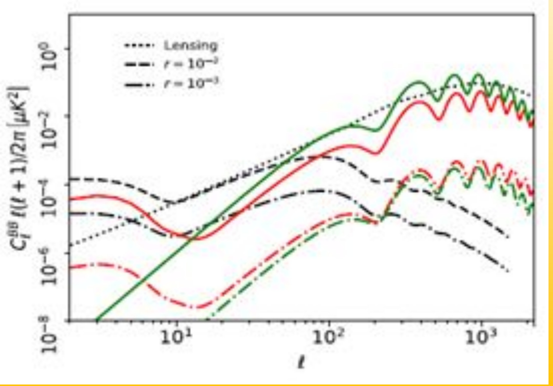


The **redshift dependence** of the pseudoscalar field induces a **nontrivial multipole dependence of the cosmological birefringence effect in the CMB power spectra:**

- Axionlike as **Early Dark Energy**

$$C_{ll}^{BB}$$

different multipole dependence!



BB induced by **EDE** g_ϕ=8.17 x 10^{-18} GeV^{-}

BB induced by a const. rot *α*=1 deg

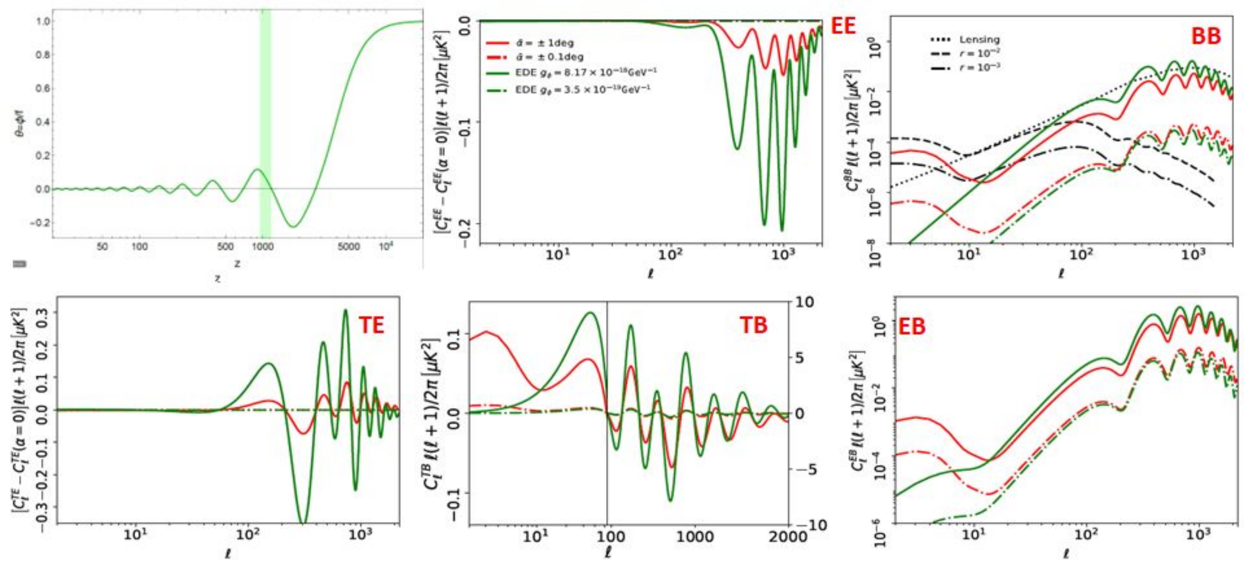
BB induced by a const. rot *α*=0.1 deg

BB induced by **EDE** g_ϕ=3.5 x 10^{-19} GeV^{-1}

Constraints for a LiteBIRD-like mission for EDE

For **Early Dark Energy** we consider the potential:
and assume n=2, Λ= 0.417 eV, f= 0.05 M_{pl}, $(\phi/f)_{in}$=1, $(\dot{\phi}/f)_{in}$=0

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



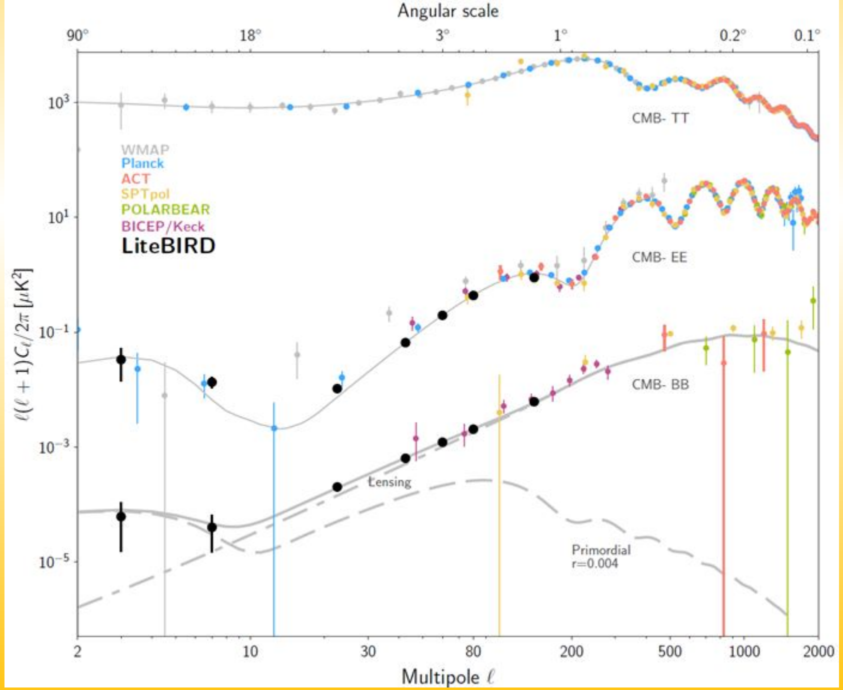
An **axion-like field acting as Early Dark Energy (EDE)** could produce a signal similar to the detection of **α = 0.35 deg** [Minami and Komatsu, PRL2020] if:

$\mathbf{g_\phi = 1.65 \times 10^{-18}\ GeV^{-1}}$

Constraints for a LiteBIRD-like mission

Present measurements + expected sensitivity for LiteBIRD

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



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

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

Constraints for a LiteBIRD-like mission

The **noise power spectra** are obtained by considering an **inverse-variance weighted sum of the noise sensitivity** convolved with a Gaussian beam window function for each frequency channel ν:

$$N_\ell^{XX} = \left[\sum_\nu \frac{1}{N_{l\nu}^{XX}} \right]^{-1}$$

with:

$$N_{l\nu}^{XX} = \Delta_{X\nu}^2 \exp\left[l(l+1) \frac{\theta_{\mathrm{FWHM}\nu}^2}{8 \ln 2} \right]$$

ν [GHz]	$\theta_{\mathrm{FWHM}\nu}$ [arcmin]	$\Delta_{T\nu}$ [μK arcmin]	$\Delta_{P\nu}$ [μK arcmin]
78	39	9.56	13.5
89	35	8.27	11.7
100	29	6.50	9.2
119	25	5.37	7.6
140	23	4.17	5.9
166	21	4.60	6.5
195	20	4.10	5.8

The **full width half maximum** and the **detector noise levels** for different frequency channels for LiteBIRD-like mission. [M. Hazumi, et al. J. Low Temp. Phys.(2019); Paoletti and Finelli, JCAP (2019)].

Constraints for a LiteBIRD-like mission

Following Xia *et al.* [Astron. Astrophys. 2008] we introduce an **effective χ^2** containing also **parity odd correlators** (see J. Q. Xia, *et al.* A&A (2008); M.G., F. Finelli, and D. Paoletti PRD2023 for more details):

$$\chi^2_{\rm eff} = \sum_\ell (2\ell+1)\, f_{\rm sky} \left(\frac{A}{|\bar{C}|} + \ln \frac{|\bar{C}|}{|\hat{C}|} - 3 \right) ,$$

where f_{sky} denotes the observed sky fraction, we define A and the determinant of the theoretical (observed) covariance matrix as follows:

$$\begin{aligned} A = {} & \hat{C}_\ell^{TT}(\bar{C}_\ell^{EE}\bar{C}_\ell^{BB} - (\bar{C}_\ell^{EB})^2) + \hat{C}_\ell^{TE}(\bar{C}_\ell^{TB}\bar{C}_\ell^{EB} - \bar{C}_\ell^{TE}\bar{C}_\ell^{BB}) + \hat{C}_\ell^{TB}(\bar{C}_\ell^{TE}\bar{C}_\ell^{EB} - \bar{C}_\ell^{TB}\bar{C}_\ell^{EE}) \\ & + \hat{C}_\ell^{TE}(\bar{C}_\ell^{TB}\bar{C}_\ell^{EB} - \bar{C}_\ell^{TE}\bar{C}_\ell^{BB}) + \hat{C}_\ell^{EE}(\bar{C}_\ell^{TT}\bar{C}_\ell^{BB} - (\bar{C}_\ell^{TB})^2) + \hat{C}_\ell^{EB}(\bar{C}_\ell^{TE}\bar{C}_\ell^{TB} - \bar{C}_\ell^{TT}\bar{C}_\ell^{EB}) \\ & + \hat{C}_\ell^{TB}(\bar{C}_\ell^{TE}\bar{C}_\ell^{EB} - \bar{C}_\ell^{EE}\bar{C}_\ell^{TB}) + \hat{C}_\ell^{EB}(\bar{C}_\ell^{TE}\bar{C}_\ell^{TB} - \bar{C}_\ell^{TT}\bar{C}_\ell^{EB}) + \hat{C}_\ell^{BB}(\bar{C}_\ell^{TT}\bar{C}_\ell^{EE} - (\bar{C}_\ell^{TE})^2), \end{aligned}$$

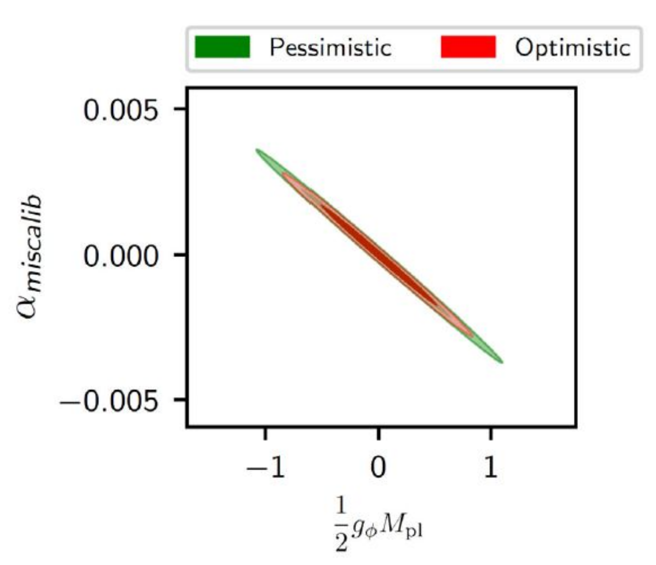
$$|\bar{C}| = \bar{C}_\ell^{TT}\bar{C}_\ell^{EE}\bar{C}_\ell^{BB} + 2\bar{C}_\ell^{TE}\bar{C}_\ell^{TB}\bar{C}_\ell^{EB} - \bar{C}_\ell^{TT}\left(\bar{C}_\ell^{EB}\right)^2 - \bar{C}_\ell^{EE}\left(\bar{C}_\ell^{TB}\right)^2 - \bar{C}_\ell^{BB}\left(\bar{C}_\ell^{TE}\right)^2 ,$$

$$|\hat{C}| = \hat{C}_\ell^{TT}\hat{C}_\ell^{EE}\hat{C}_\ell^{BB} + 2\hat{C}_\ell^{TE}\hat{C}_\ell^{TB}\hat{C}_\ell^{EB} - \hat{C}_\ell^{TT}\left(\hat{C}_\ell^{EB}\right)^2 - \hat{C}_\ell^{EE}\left(\hat{C}_\ell^{TB}\right)^2 - \hat{C}_\ell^{BB}\left(\hat{C}_\ell^{TE}\right)^2 .$$

Constraints for a LiteBIRD-like mission for EDE

For the EDE case we perform *few exploratory runs* exploring the standard s**ix cosmological parameters** of ΛCDM ($\Omega_C h^2$, $\Omega_B h^2$, θ, τ, n_s, A_s)
+ **birefringence parameter space**
+ time indep. rotation of the spectra (**miscalibration**)
using the Markov chain Monte Carlo code `cosmomc`.

[M.G., F. Finelli, and D. Paoletti PRD2023]



$$|g_\phi| \lesssim 5.7 \times 10^{-19} \mathrm{GeV}^{-1} \text{ at } 2\sigma$$

$$|g_\phi| \lesssim 6.7 \times 10^{-19} \mathrm{GeV}^{-1} \text{ at } 2\sigma$$

We consider two cases:
-*optimistic*: width of the prior 0.1 deg= 6 arcmin;
-*pessimistic*: width of the prior 0.2 deg= 12 arcmin.

There is still a correlation between the miscalibration angle and the coupling constant, but the degeneracy as would be neglecting the redshift dependendence is broken.

Cosmological pseudoscalar field acting as DE

The for a pseudoscalar acting as **Dark Energy** (DE) we consider the potential:

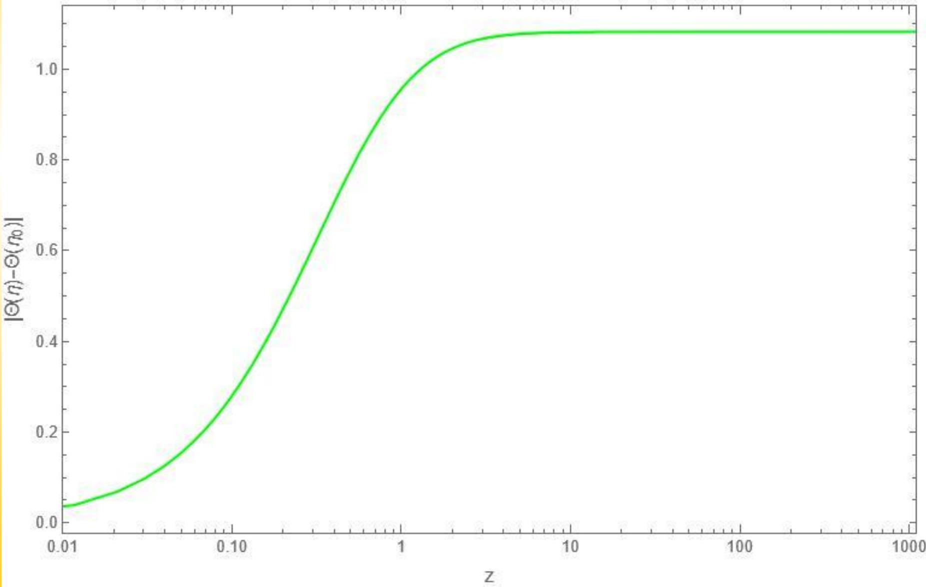
$$V(\phi) = M^4 \left(1 + \cos\frac{\phi}{f}\right)$$

The evolution of ϕ is determined by the following system of equations (here $x = \ln t/t_i$):

$$\frac{d\Theta}{dx^2} + \left(\frac{3}{a}\frac{da}{dx} - 1\right)\frac{d\Theta}{dx} - t_i^2 e^{2x}\frac{M^4}{f^2}\sin\Theta = 0,$$

$$\frac{da}{dx} = t_i e^x H_i a\left[\Omega_{\mathrm{RAD,i}}\left(\frac{a_i}{a}\right)^4 + \Omega_{\mathrm{MAT,i}}\left(\frac{a_i}{a}\right)^3 + \frac{1}{6}\frac{f^2}{H_i^2 M_{\mathrm{pl}}^2 t_i^2}e^{-2x}\left(\frac{d\Theta}{dx}\right)^2 + \frac{1}{3}\frac{M^4}{H_i^2 M_{\mathrm{pl}}^2}(1+\cos\Theta)\right]^{1/2}.$$

Assuming M=1.95 x 10^{-3} eV, f= 0.25 M_{pl}, $(\phi/f)_{in}$=0.25, $(\dot{\phi}/f)_{in}$=0 (m_{eff}= 5x10^{-33} eV) we obtain this kind of **redshift dependence** for the pseudoscalar field acting as **DE**



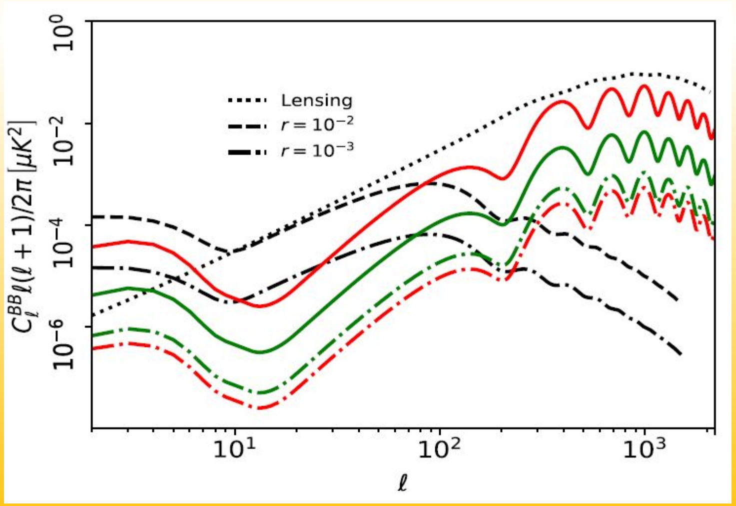
NOW **LAST SCATT.**

Cosmological pseudoscalar field acting as DE

The **redshift dependence** of the pseudoscalar field induces a **nontrivial multipole dependence of the cosmological birefringence effect in the CMB power spectra:**

- Axionlike as **Dark Energy** [$M=1.95 \times 10^{-3}$ eV, $f= 0.25\ M_{pl}$, $(\phi/f)_{in}=0.25$, $(\dot{\phi}/f)_{in}=0$]

C_{ll}^{BB}



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

BB induced by a const. rot α=1 deg

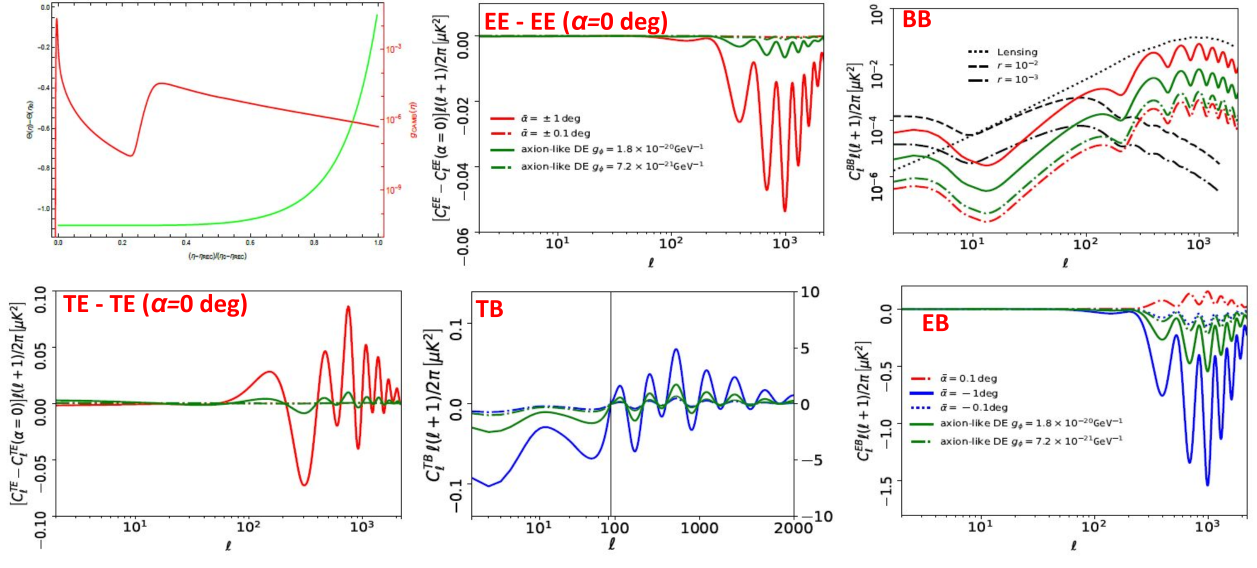
BB induced by a const. rot α=0.1 deg

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

Constraints for a LiteBIRD-like mission for DE

For axion-like Dark Energy we consider the potential:
and assume $M=1.95 \times 10^{-3}$ eV, $f= 0.25\, M_{pl}$, $(\phi/f)_{in}=0.25$, $(\dot{\phi}/f)_{in}=0$

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



An **axion-like field acting as Dark Energy (DE)** could produce a signal similar to the detection of **α = 0.35 deg** [Minami and Komatsu, PRL2020] if:

$\mathbf{g_\phi = 1.80 \times 10^{-20}\ GeV^{-1}}$

The bound that a LiteBIRD like experiment could put on the pseudoscalar-photon coupling is of the order:

$\mathbf{g_\phi = 9.0 \times 10^{-22}\ GeV^{-1}}$

Cosmological pseudoscalar field acting as DM

The for a pseudoscalar acting as **Dark Matter** (DM) we consider the potential:

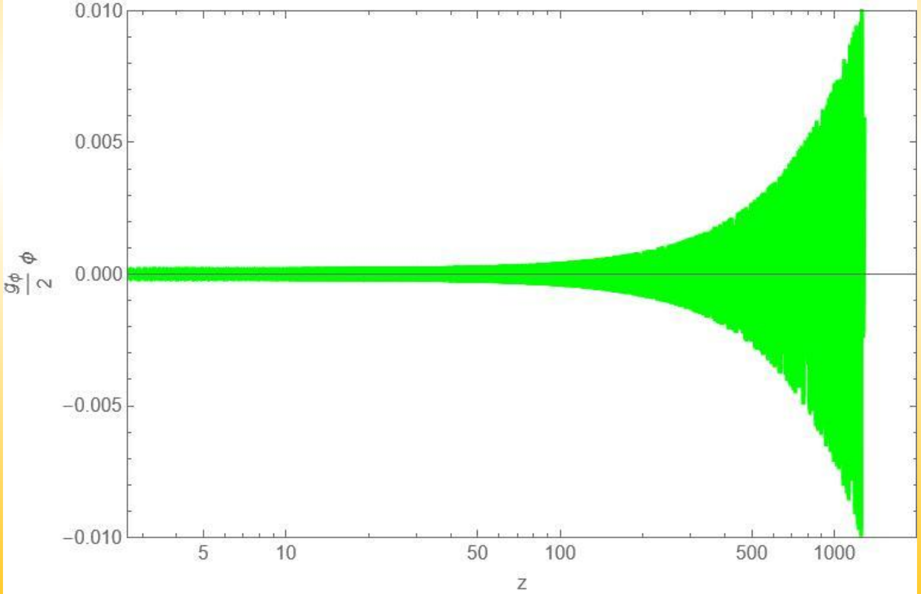
$$V(\phi) = m^2 f^2 \left(1 - \cos\frac{\phi N}{f}\right) \simeq \frac{1}{2} m^2 \phi^2 \,,$$

The **background field** evolves according to:

$$\phi(t) = \sqrt{6\Omega_{\rm MAT}} \frac{H_0 M_{\rm pl}}{m a^{3/2}(t)} \times \sin\left[mt\sqrt{1 - (1-\Omega_{\rm MAT})\left(\frac{3H_0}{2m}\right)^2}\right],$$

We consider this kind of **redshift dependence**
for the pseudoscalar field acting as **Dark Matter** (DM):

[$N=1$, $m= 10^{-22}$ eV, $(\phi/f)_{in}=1$, $(\dot{\phi}/f)_{in}=0$]

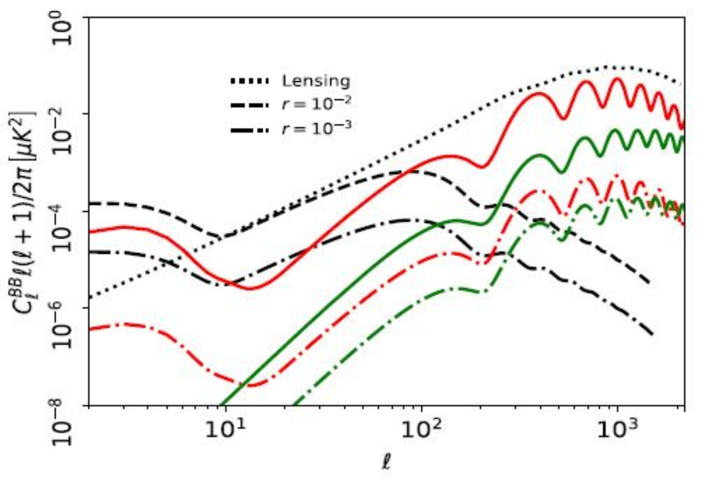


NOW **LAST SCATT.**

Cosmological pseudoscalar field acting as DM

The **redshift dependence** of the pseudoscalar field induces a
nontrivial multipole dependence of the cosmological birefringence effect in the CMB power spectra which breaks its degeneracy with a miscalibration angle (when CB is treated as redshift independent).

- Axionlike as **Dark Matter** [m= 10^{-22} eV, $(\phi/f)_{in}$=1, $(\dot{\phi}/f)_{in}$=0]



BB induced by a const. rot α=1 deg

BB induced by **DM** $g_\phi = 10^{-14}$ GeV^{-1}

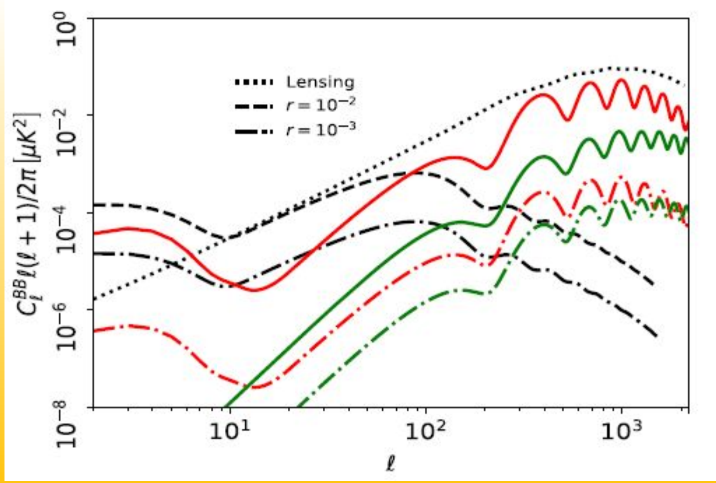
BB induced by a const. rot α=0.1 deg

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

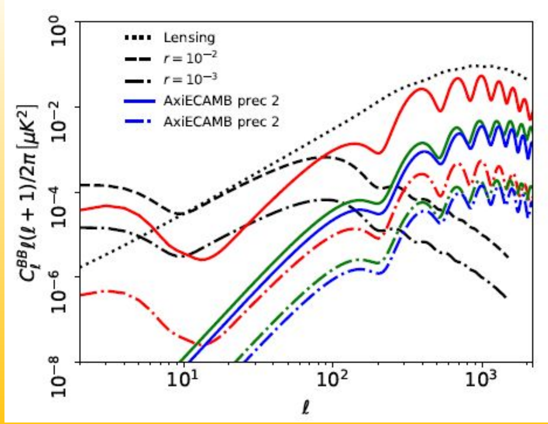
Cosmological pseudoscalar field acting as DM

The **redshift dependence** of the pseudoscalar field induces a
nontrivial multipole dependence of the cosmological birefringence effect in the CMB power spectra which breaks its degeneracy with a miscalibration angle (when CB is treated as redshift independent).

- Axionlike as **Dark Matter** [m= 10^{-22} eV, $(\phi/f)_{in}=1$, $(\dot{\phi}/f)_{in}=0$]



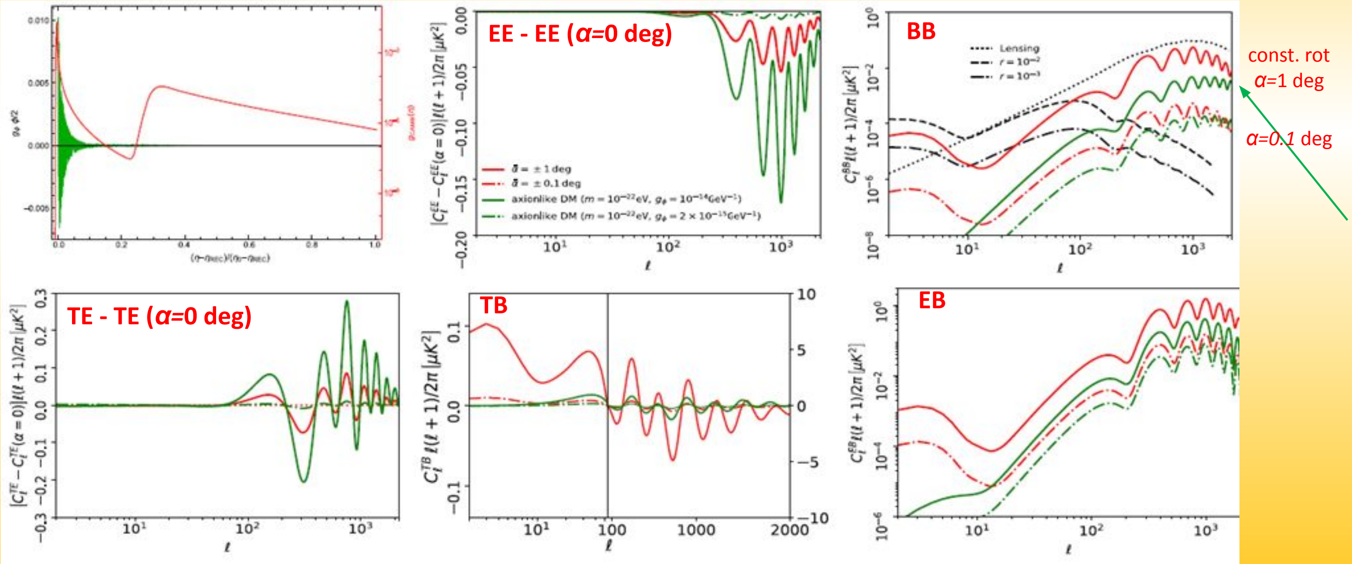
AxiECAMB (Axion Effective-method in CAMB)
[Liu, W. Hu and D. Grin, arXiv:2412.15192 [astro-ph.CO]]]



Constraints for Dark Matter

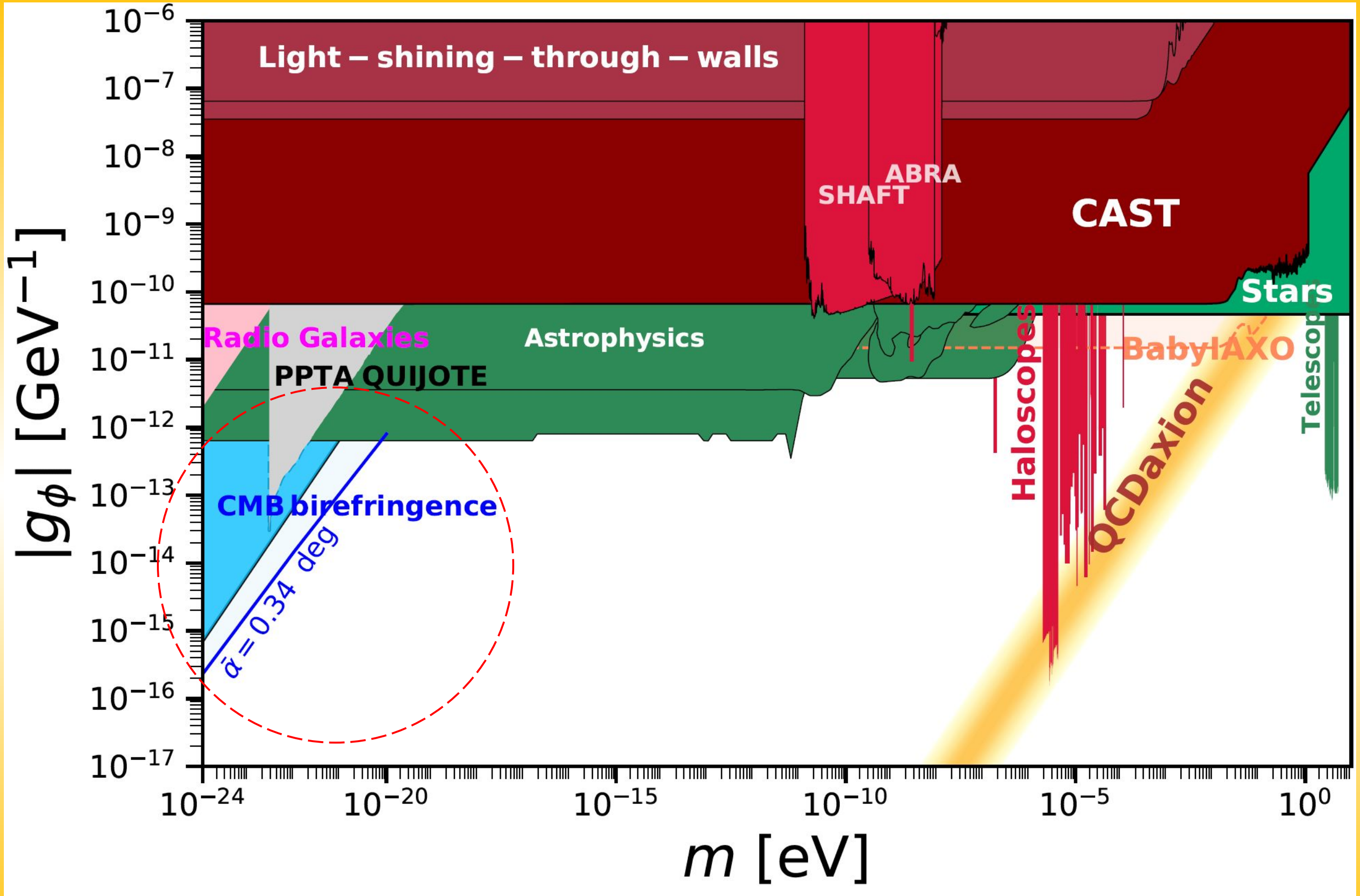
For axion-like Dark Matter we consider the potential:
and assume N=1, m= 10^{-22} eV, $(\phi/f)_{in}$=1, $(\dot{\phi}/f)_{in}$=0

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



An **axion-like field acting as Dark Matter (DM)** could produce a signal similar to the detection of **α = 0.35 deg** [Minami and Komatsu, PRL 2020] if:

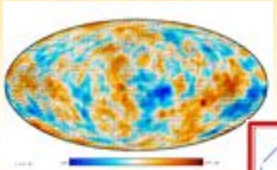
g_ϕ = 1.37 x 10^{-14} GeV^{-1}



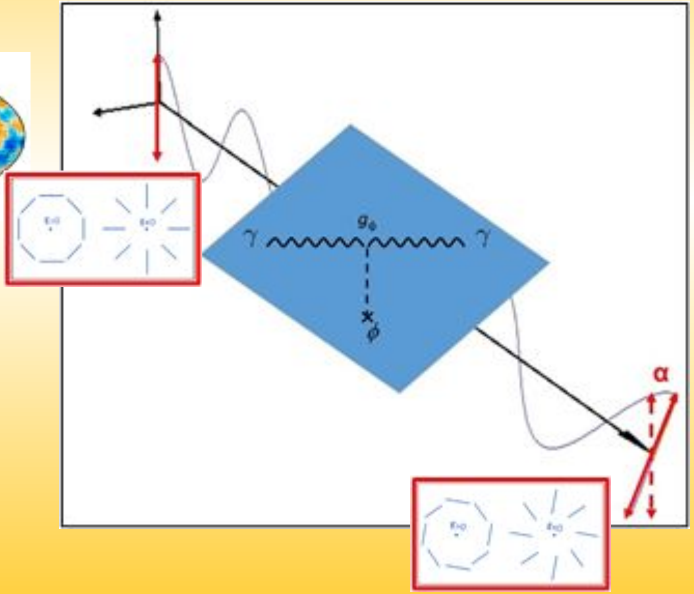
[M.G., F. Finelli, and D. Paoletti PRD2023 - plot created with the *AxionLimits* code https://cajohare.github.io/AxionLimits/]

Conclusions

We studied the imprints of an **isotropic redshift/time dependent cosmological pseudoscalar field** on CMB polarization power spectra



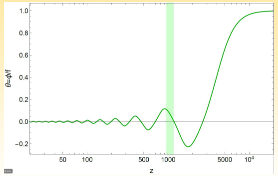
Planck 2018 map of the polarized CMB anisotropies

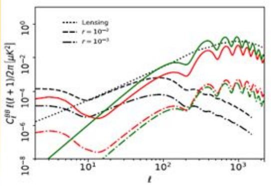


z dependent rotation angle

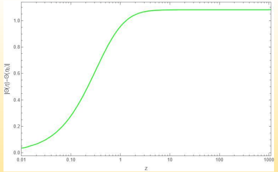
$C_\ell^{BB} \ldots C_\ell^{EE}, C_\ell^{TE}, C_\ell^{TB}, C_\ell^{EB}$

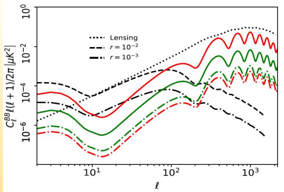
EDE



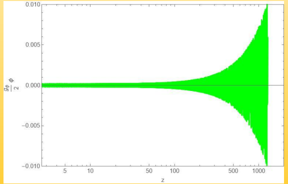


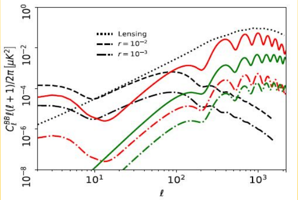
DE





DM





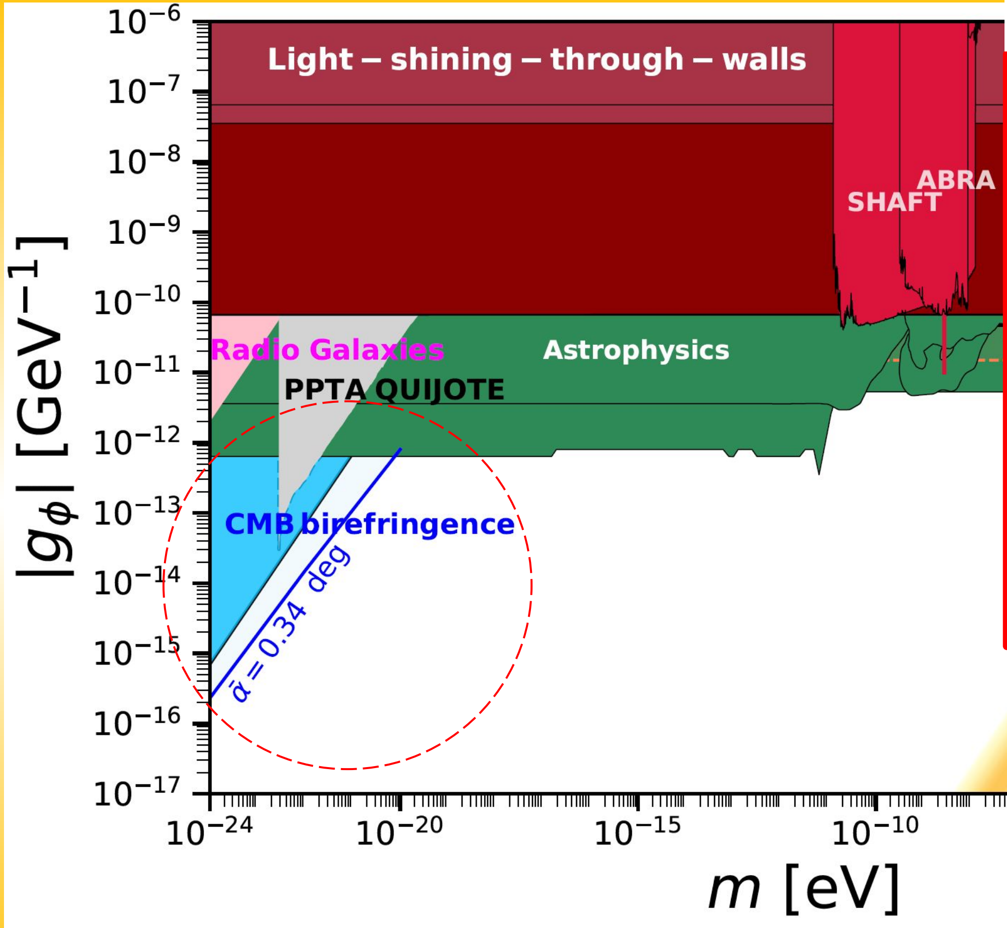
Conclusions

- We studied the imprints of an **isotropic redshift/time dependent cosmological pseudoscalar field** on CMB polarization power spectra
$\longrightarrow$ **redshift/time evolution of the birefringence angle** has important **effects on CMB polarization power spectra**
  - not only total rotation is important, but also **when** the rotation occurs;
  - **different theoretical motivated redshift dependencies** of the pseudoscalar field (EDE, DM, DE) produce **different multipole dependence** for the spectra;
$\longrightarrow$ Constraints for different behaviours of the pseudoscalar field (EDE, DE, DM)

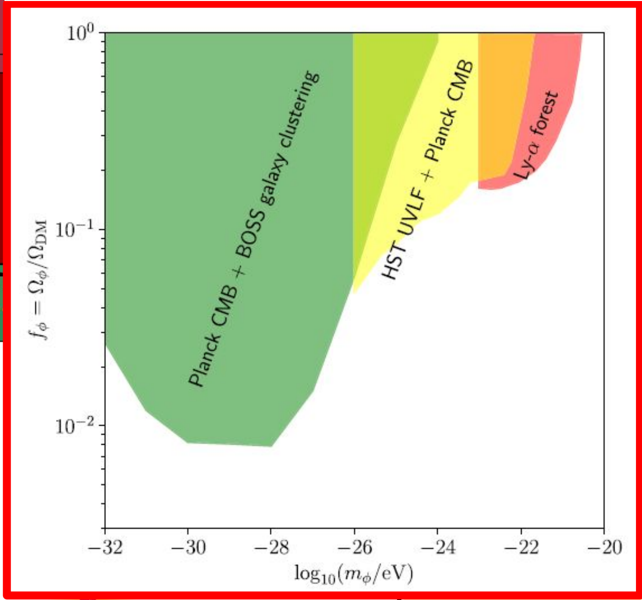
Future work:

- Beyond isotropic redshift dependence: **add the effects due inhomogeneities** (CMB anisotropic birefringence).

BACKUP SLIDES

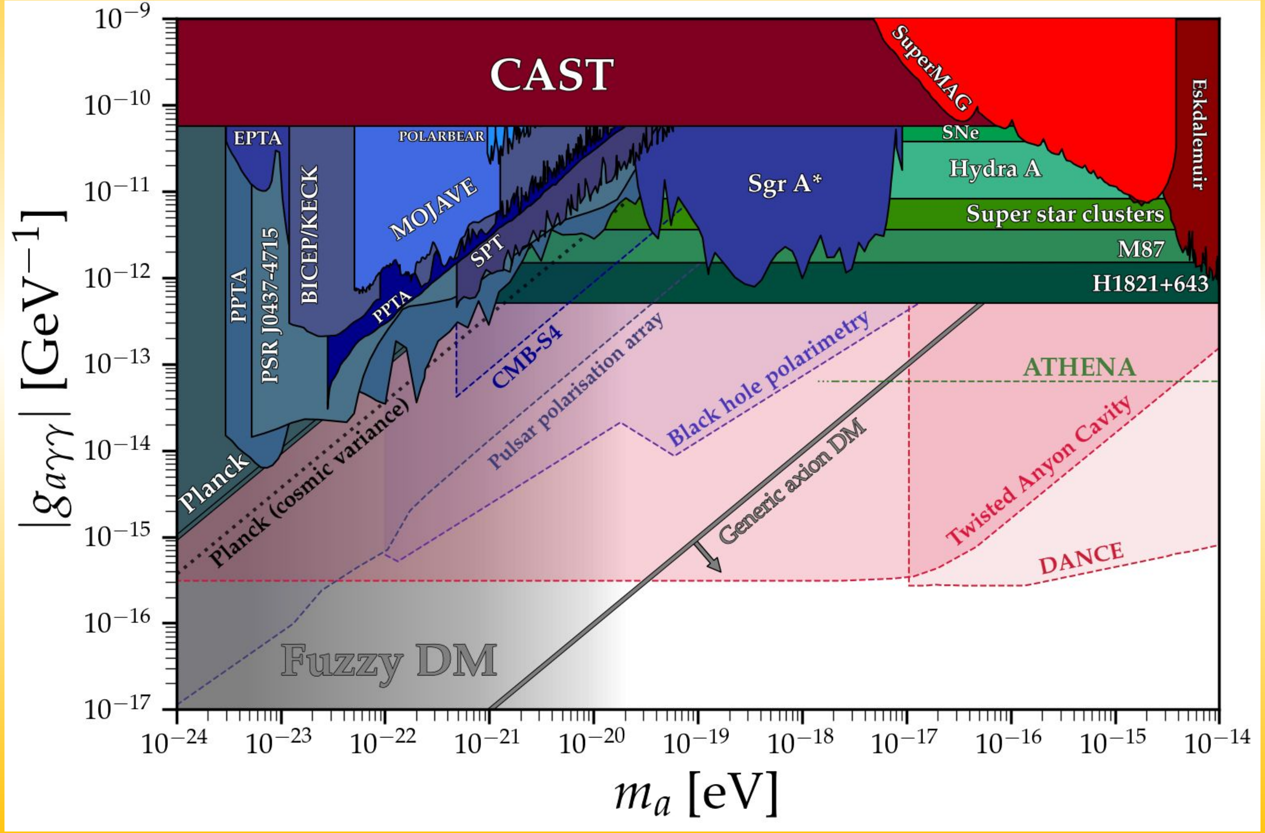


Bounds on the mass and fraction of ADM
[Zhang, Ferreira, Obata, Namikawa - PRD 2024]



[M.G., F. Finelli, and D. Paoletti PRD2023 - plot created with the *AxionLimits* code https://cajohare.github.io/AxionLimits/]

AxionPhoton Ultralight with Projections



[*AxionLimits* - https://cajohare.github.io/AxionLimits/]

Cosmological pseudoscalar field acting as DM

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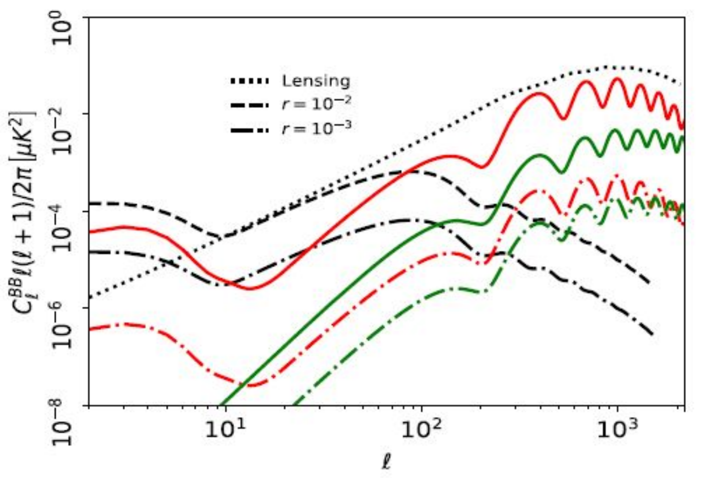
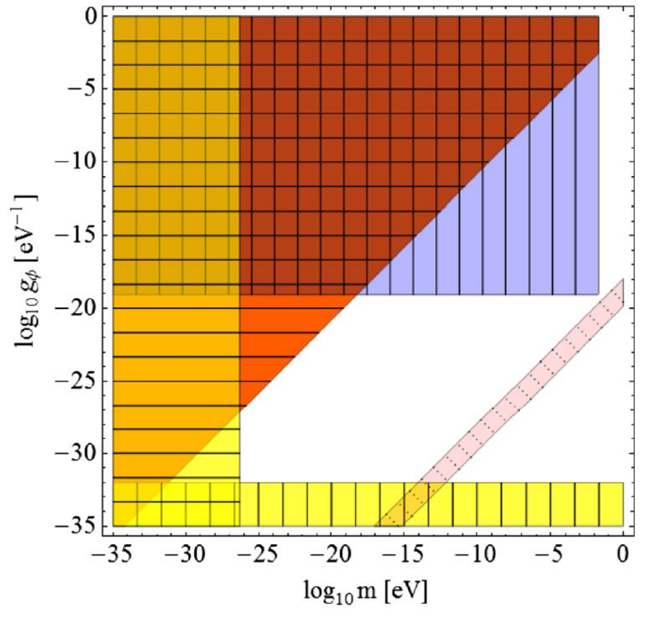
C_{ll}^{BB}





[Finelli and Galaverni, PRD 2009]

Excluded regions by CERN Axion Solar Telescope (2007) (blue), **CMB birefringence> 10 deg (red region with horizontal lines).**

Constraints from other astrophysical polarized sources

Cosmological birefringence bounds not only from **CMB**
but also from **other astrophysical sources** at different wavelengths (radio, optical, X and ɣ)
and distances:

– **Cosmic Microwave Background**;
– **Distant UV Radio Galaxies;**
– **Radio Sources;**
– **Crab Nebula.**

Table 1 Current constraints on the cosmological birefringence angle α coming from a variety of astrophysical and cosmological observations; for each dataset we report the typical redshift and the effective energy

Dataset	z	E (eV)	$\alpha \pm \Delta\alpha$ (deg)	Reference
CMB	1090	2.2×10^{-4}	-0.36 ± 1.9	Hinshaw et al. (2013)
UV RG	2.62	2.5	0.7 ± 2.1	di Serego Alighieri et al. (2010)
Radio sources	0.47	3.4×10^{-5}	1.6 ± 1.8	Leahy (1997)
Crab Nebula	4.5×10^{-7}	2.3×10^{5}	1 ± 11	Maccione et al. (2008)

The Astrophysical Journal, 715:33–38, 2010 May 20 doi:10.1088/0004-637X/715/1/33

LIMITS ON COSMOLOGICAL BIREFRINGENCE FROM THE ULTRAVIOLET POLARIZATION OF DISTANT RADIO GALAXIES

Sperello di Serego Alighieri[1], Fabio Finelli[2,3], and Matteo Galaverni[2]
[1] INAF-Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy
[2] INAF-IASF Bologna, Via Gobetti 101, I-40129 Bologna, Italy
Received 2009 December 18; accepted 2010 March 24; published 2010 April 23

Comment on the Measurement of Cosmological Birefringence

J. P. Leahy
University of Manchester, NRAL, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, England

PHYSICAL REVIEW D 78, 103003 (2008)

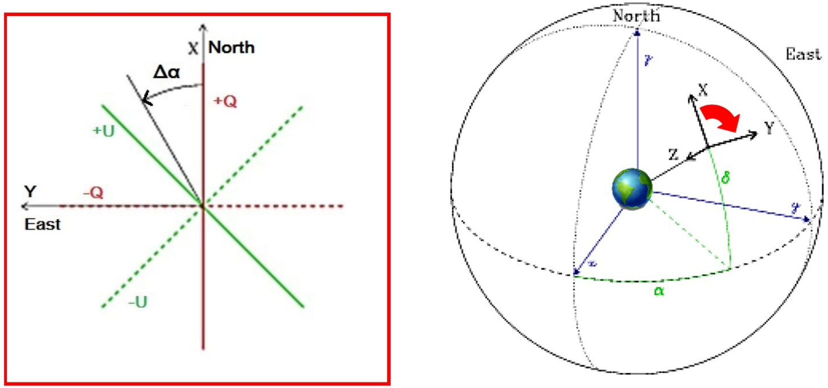
γ-ray polarization constraints on Planck scale violations of special relativity

Luca Maccione, Stefano Liberati, and Annalisa Celotti
SISSA/ISAS, via Beirut 2-4, 34014, Trieste, and INFN, Sezione di Trieste, via Valerio, 2, 34127 Trieste, Italy
John G. Kirk
Max-Planck-Institut für Kernphysik, Saupfercheckweg, 1, D-69117, Heidelberg, Germany
Pietro Ubertini
IASF-INAF, via Fosso del Cavaliere 100, Roma, Italy
(Received 31 August 2008; published 5 November 2008)

Constraints from other astrophysical polarized sources

IAU/IEEE

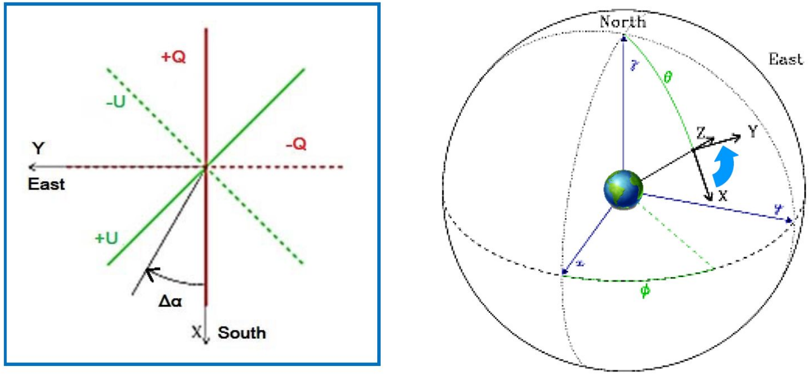
Looking ***toward*** the source…



…polarization angle Δα increases **anti-clockwise**.

HEALPix

Looking ***toward*** the source…



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Constraints from astrophysical polarized sources

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Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Cosmological birefringence constraints from CMB and astrophysical polarization data

M. Galaverni,[a] G. Gubitosi,[b,c] F. Paci[d] and F. Finelli[e,f]

[M.G, G. Gubitosi, F. Paci, F. Finelli JCAP (2015) arXiv:1411.6287 [astro-ph.CO]]
[M.G, *Astrophys.Space Sci.Proc.* 51 (2018)]

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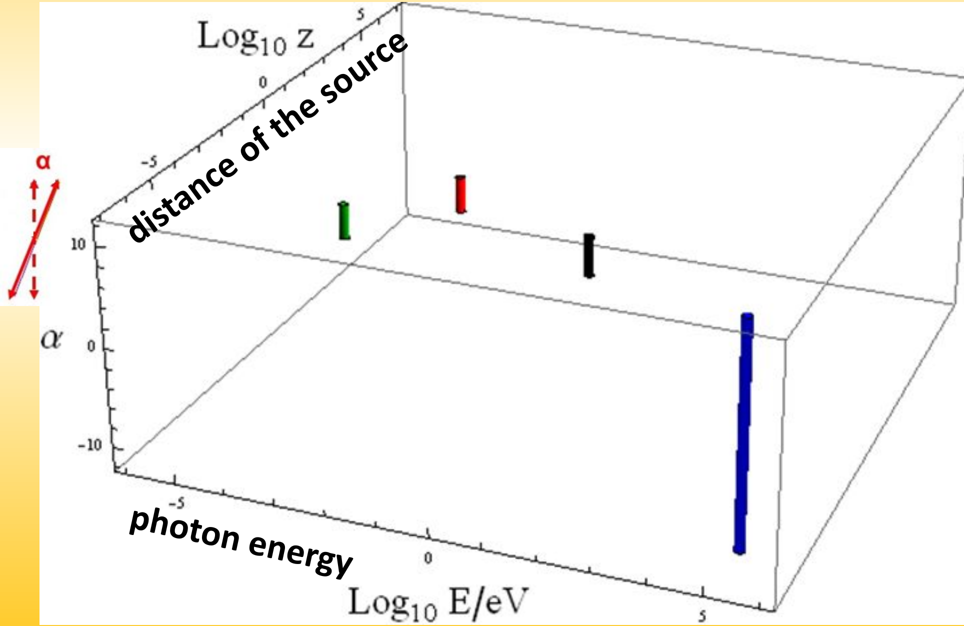

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Energy (and distance) dependent birefringence effects

We constrain different theoretical models predicting birefringence, each one characterized by a different energy dependence.

1. Energy-independent

e.g. coupling with a cosmological **pseudoscalar** field or **Chern-Simons** theory:

$$\mathcal{L}_{PS} = -\frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathcal{L}_{CS} = -\frac{1}{4}p_\mu A_\nu \tilde{F}^{\mu\nu}$$

Rotation angle can be written as a function of the source redshift ($z_\star$):

$$\alpha(z_\star) = -\frac{1}{2}p_0 \int_0^{z_\star} \frac{1}{(1+z)H(z)}dz$$

2. Linear energy dependence can be due to '**Weyl**' interaction;

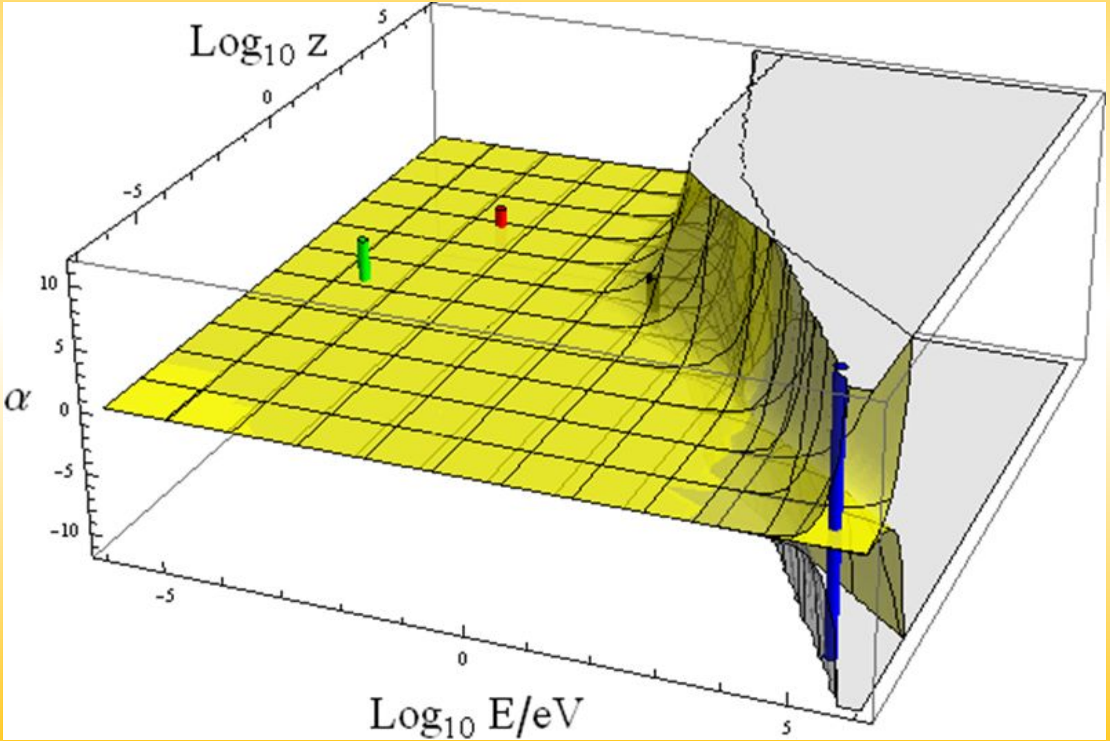
$$\alpha(z_\star, E) = 8\pi\Psi_0 E \int_0^{z_\star} \frac{1}{H(z)}dz$$

3.Quadratic energy dependence of birefringence angle might be traced back to **Quantum Gravity** Planck-scale effects:

$$\alpha(z_\star, E) = \frac{\xi}{M_P}E^2 \int_0^{z_\star} \frac{1+z}{H(z)}dz$$

[M.G. *et al.*, JCAP (2015) arXiv:1411.6287 [astro-ph.CO]]

Energy (and distance) dependent birefringence effects

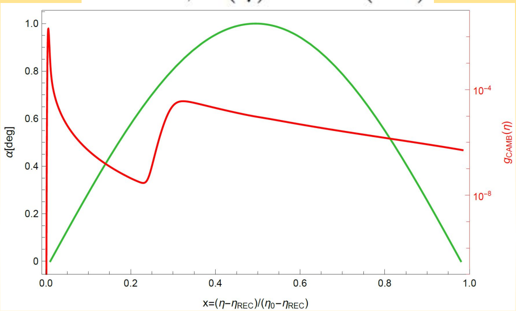


Energy dependence	Best constraint from:
independent	**CMB**
linear	**Radio Galaxies**
quadratic	**Crab Nebula**

Beyond the redshift independent approximation

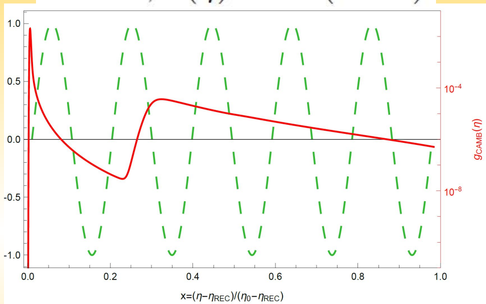
Birefringence effects on power spectra can be present even if $\bar{\alpha} \equiv \alpha(\eta_{\rm rec}) - \alpha(\eta_0) = 0$

$\bar{\alpha} = 0\,, \alpha(\eta) = \sin(\pi x)$



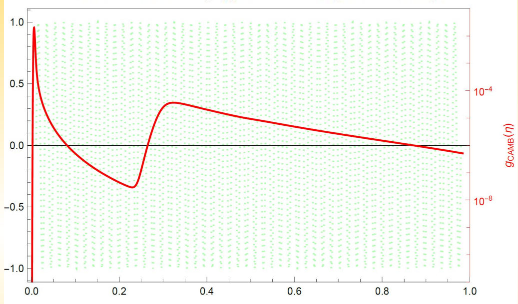
LAST SCATT. NOW

$\bar{\alpha} = 0\,, \alpha(\eta) = \sin(10\pi x)$



LAST SCATT. NOW

$\bar{\alpha} = 0\,, \alpha(\eta) = \sin(100\pi x)$

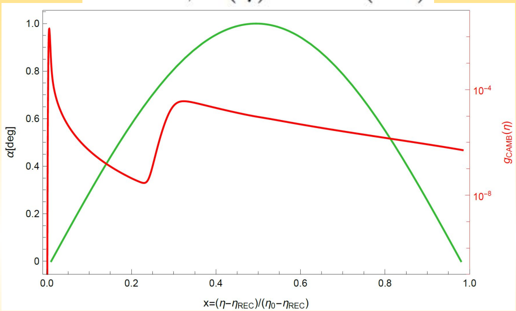


LAST SCATT. NOW

Beyond the redshift independent approximation

Birefringence effects on power spectra can be present even if $\bar{\alpha} \equiv \alpha(\eta_{\rm rec}) - \alpha(\eta_0) = 0$

$\bar{\alpha} = 0\,, \alpha(\eta) = \sin(\pi x)$



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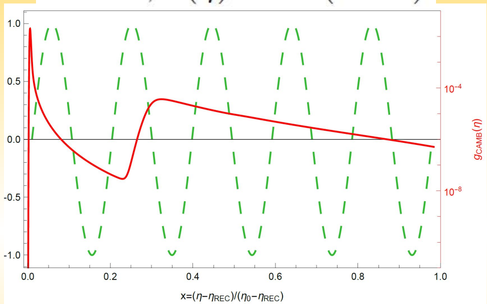
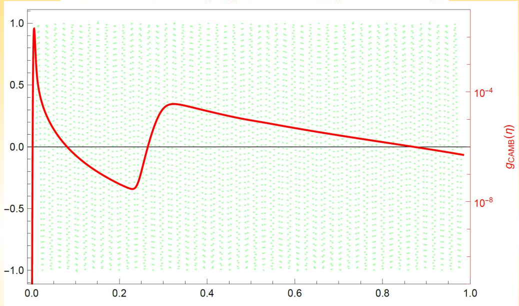
$\bar{\alpha} = 0\,, \alpha(\eta) = \sin(10\pi x)$



LAST SCATT. NOW

$\bar{\alpha} = 0\,, \alpha(\eta) = \sin(100\pi x)$



LAST SCATT. NOW