Isotropic birefringence from cosmological pseudoscalar fields

SPECOLA VATICANA

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INAF/OAS Bologna, Via Gobetti 101, I-40129 Bologna, Italy

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

INFN Istituto Nazionale di Fisica Nucleare

- **Isotropic 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 **Dark Matter (DM) and Dark Energy (DE).**

- **Constraints on Cosmic Birefringence from astrophysical polarization data**

- **Conclusions.**

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4th International FLAG Workshop:
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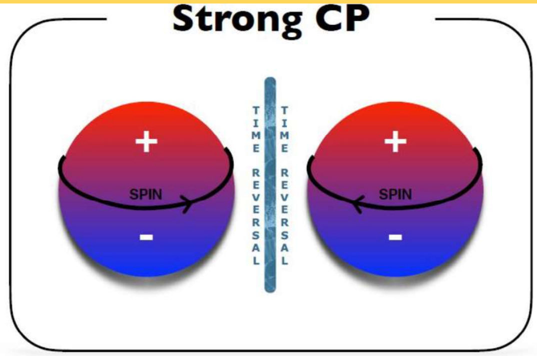
In collaboration with **Fabio Finelli** and **Daniela Paoletti** *(INAF/OAS Bologna)*
Email: matteo.galaverni@gmail.com

Axions and Axion-Like ParticleS (ALPS)

Axions were first invoked to **<u>solve the strong CP problem of QCD</u>** *[R. Peccei and H.Quinn, PRL 38 (1977)]*.

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)



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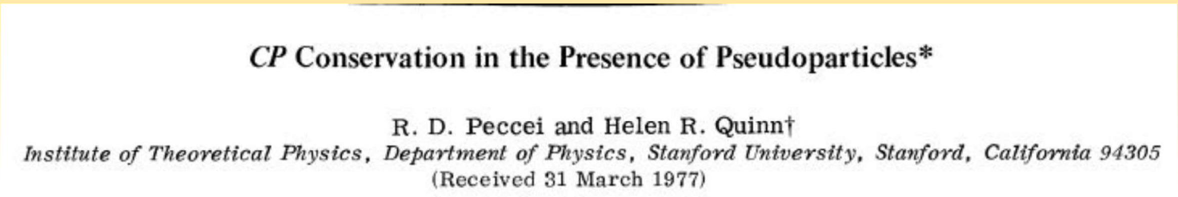

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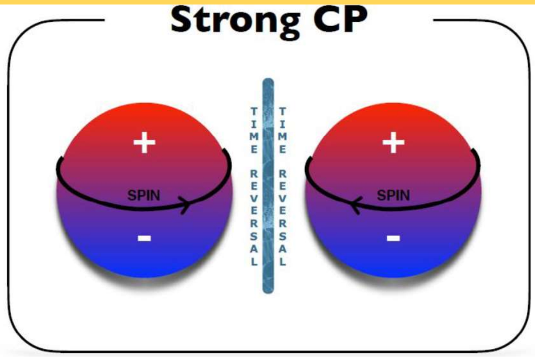


Axions **acquire an effective mass** due to their coupling with gluons. Because of the mixing with pions, axions share not only their mass, but also their **coupling to photons**, nucleons, [leptons].

Pseudoscalars are considered also <u>good candidates for cold dark matter</u>.

Coupling between pseudoscalars and photons

The **coupling with photons** play a key role for most of the searches

$$\mathcal{L}_{\phi\gamma} = g_\phi \mathbf{E}\cdot\mathbf{B}\phi = -\frac{g_\phi}{4} F_{\mu\nu}\tilde{F}^{\mu\nu}\phi$$

where:

$$F^{\mu\nu} = \nabla^\mu A^\nu - \nabla^\nu A^\mu = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & B_z & -B_y \\ E_y & -B_z & 0 & B_x \\ E_z & B_y & -B_x & 0 \end{pmatrix}$$

$$\widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma} = \begin{pmatrix} 0 & B_x & B_y & B_z \\ -B_x & 0 & -E_z & E_y \\ -B_y & E_z & 0 & -E_x \\ -B_z & -E_y & E_x & 0 \end{pmatrix}$$

$$F^2 \equiv F_{\mu\nu}F^{\mu\nu} = 2\left(\mathbf{B}\cdot\mathbf{B} - \mathbf{E}\cdot\mathbf{E}\right)$$

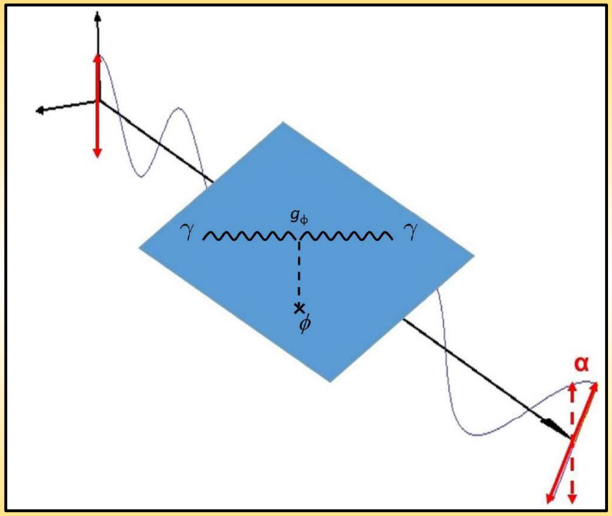
This is a **scalar**: invariant under parity transformation.

$$F\widetilde{F} \equiv F_{\mu\nu}\widetilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}$$

This is a **pseudoscalar**: changes sign under parity transformation.

Cosmological pseudoscalar field

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



Cosmological pseudoscalar field ϕ (axion-like particle):

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

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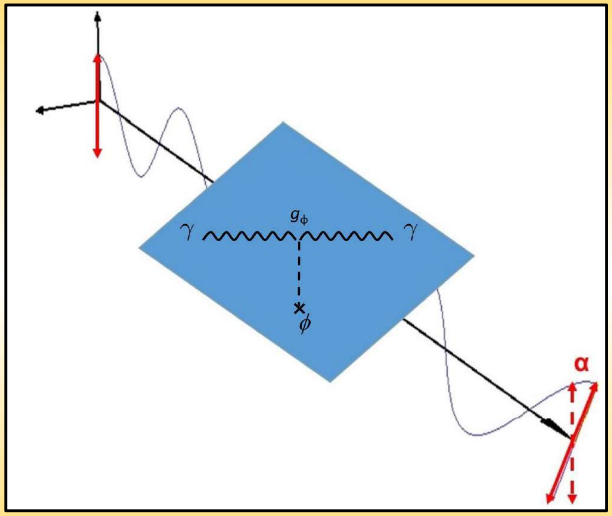

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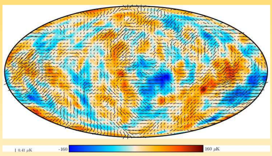
$$\ddot{\phi} + 3H\dot{\phi} - \frac{dV}{d\phi} = 0,$$

Rotation of the polarization plane α (single photon)

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

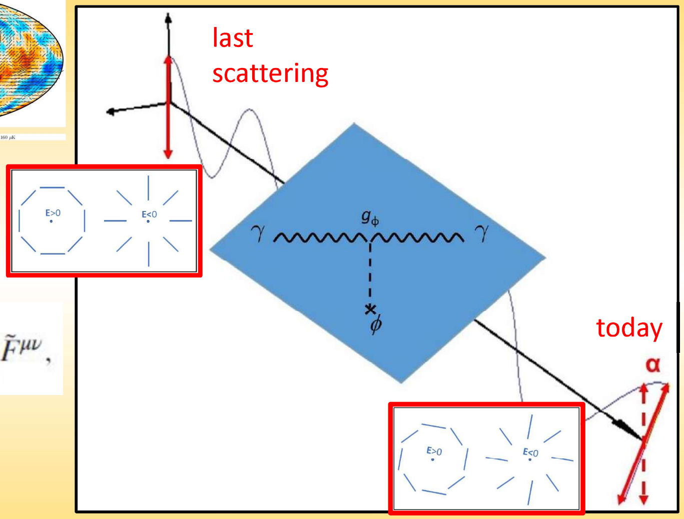
Carrol, Field and Jackiw [PRD 1990], Harari and Sikivie [Phys. Lett. B 1992],…

Cosmological pseudoscalar field and CMB polarization



Planck 2018 map of the polarized CMB anisotropies

$$\mathcal{L} \supset -\frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu},$$



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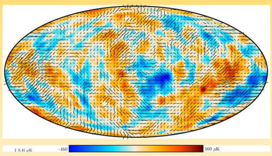

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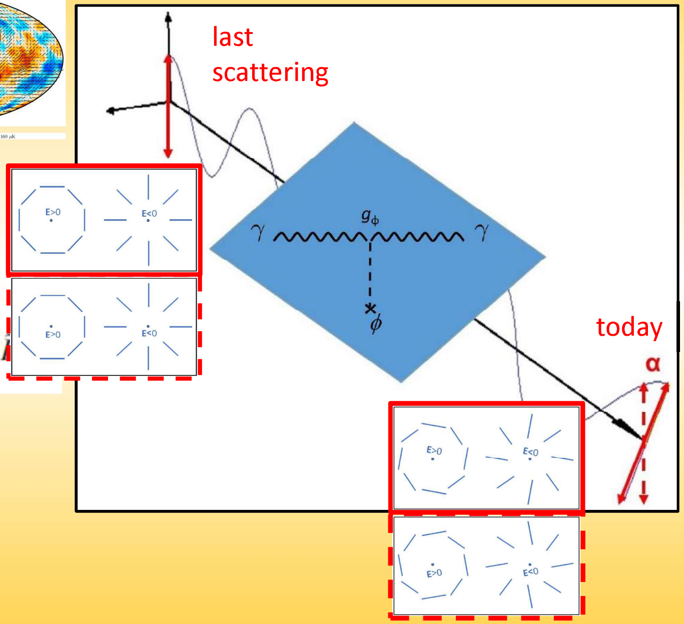

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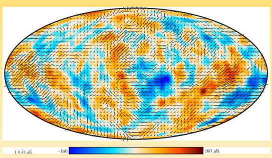

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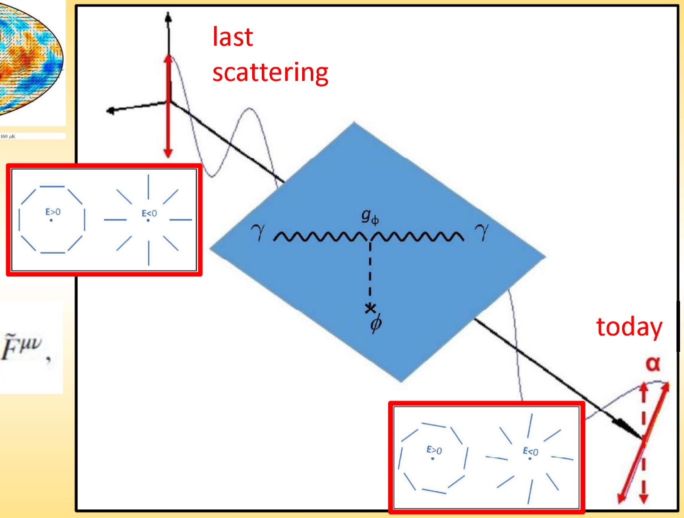
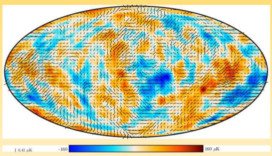


CMB power spectra at <u>recombination (last scattering)</u>:

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

Cosmological pseudoscalar field and CMB polarization



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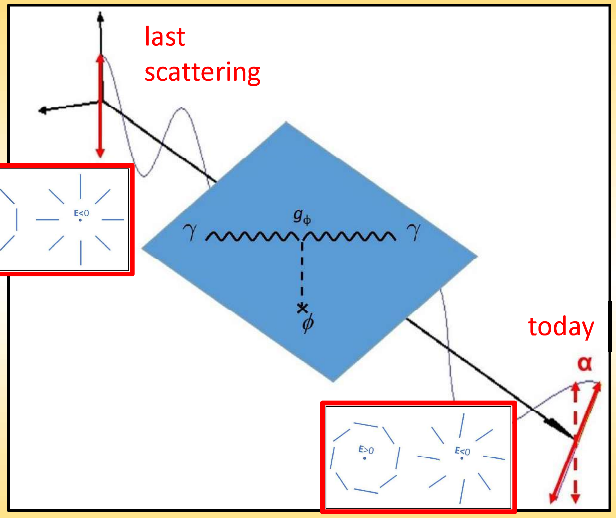
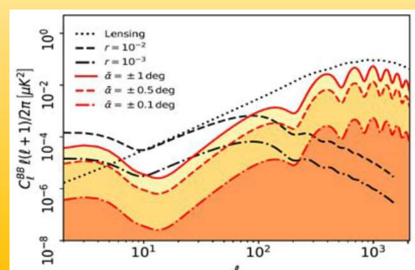


birefringenge induced B modes



CMB power spectra at <u>recombination (last scattering)</u>:

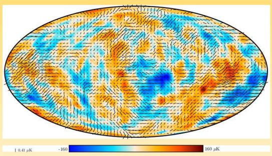
$$C_\ell^{TT,\mathrm{rec}}, C_\ell^{TE,\mathrm{rec}}, C_\ell^{EE,\mathrm{rec}}, C_\ell^{BB,\mathrm{rec}}$$

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

<u>Observed</u> CMB power spectra (assuming ***z*** **indep.** rot. angle):

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

Cosmological pseudoscalar field and CMB polarization



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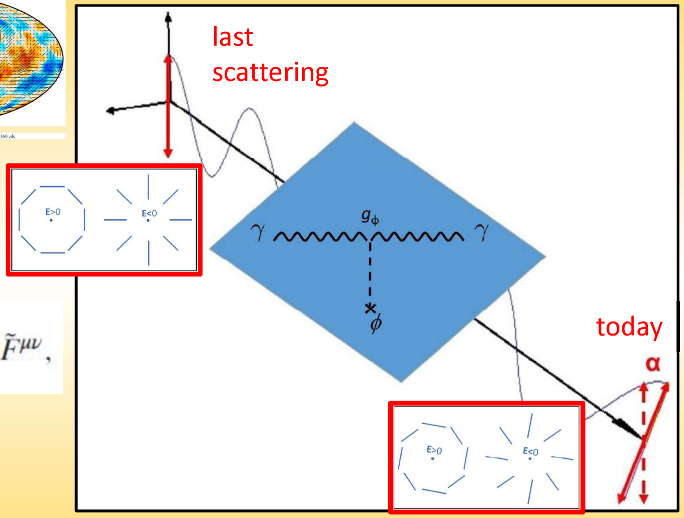

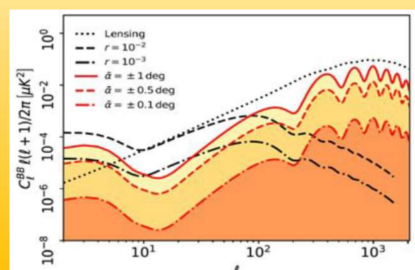

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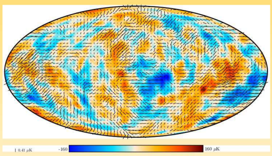
<u>Observed</u> CMB power spectra (assuming ***z*** **indep.** rot. angle):

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

Cosmological pseudoscalar field and CMB polarization



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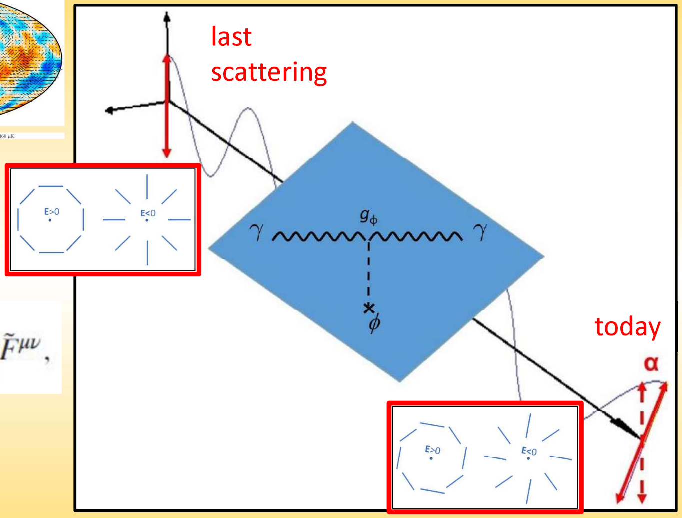

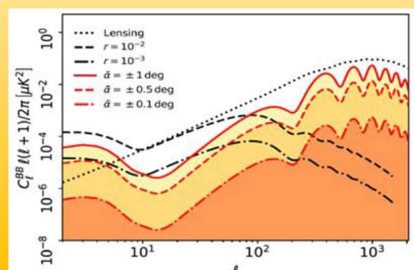

CMB power spectra at recombination (last scattering):

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

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

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

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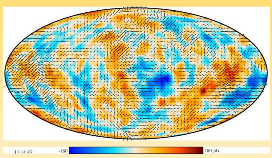
$$C_\ell^{BB,\mathrm{obs}} = C_\ell^{BB,\mathrm{rec}}\cos^2(2\bar{\alpha}) + C_\ell^{EE,\mathrm{rec}}\sin^2(2\bar{\alpha})$$

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

parity ODD

Cosmological pseudoscalar field and CMB polarization



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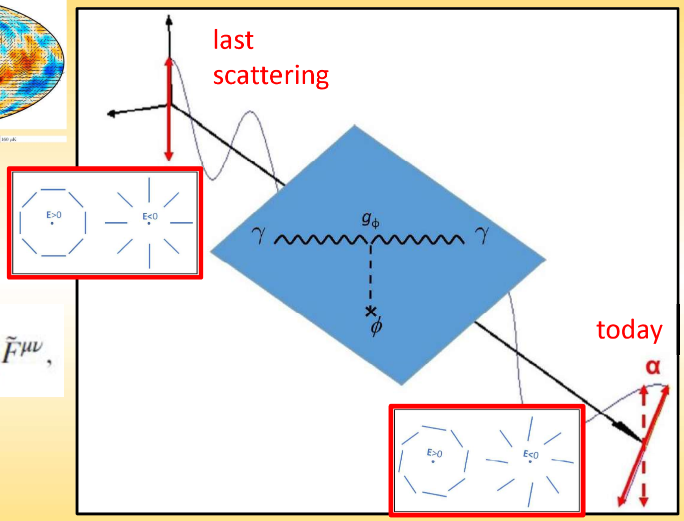
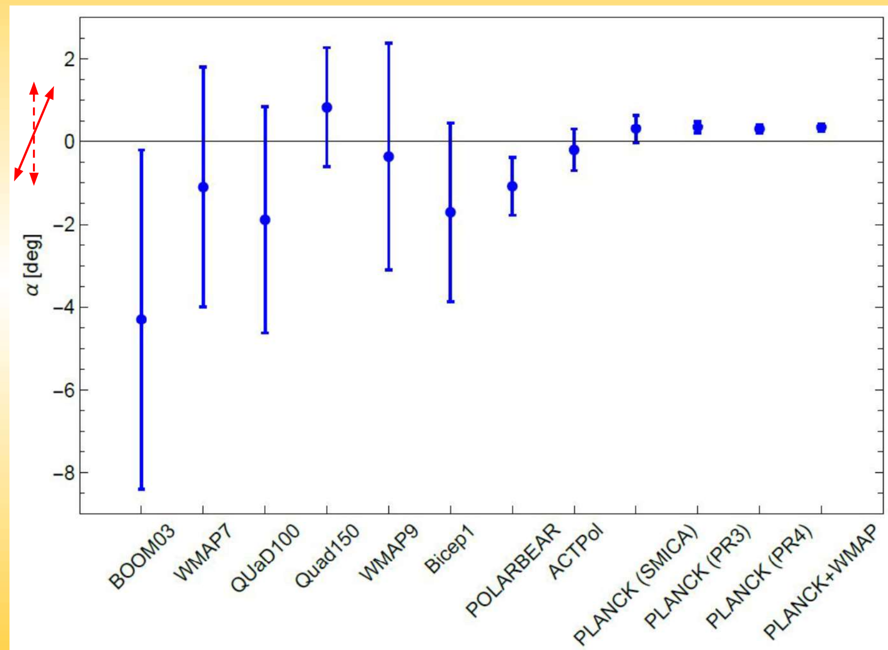
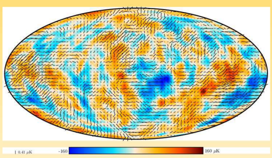




Isotropic cosmic birefringence from CMB experiments with 1σ errors (statistical and systematic uncertainties summed linearly)

[Planck XLIX. Parity-violation constraints from polarization data (2016) *+updates*]

Cosmological pseudoscalar field and CMB polarization



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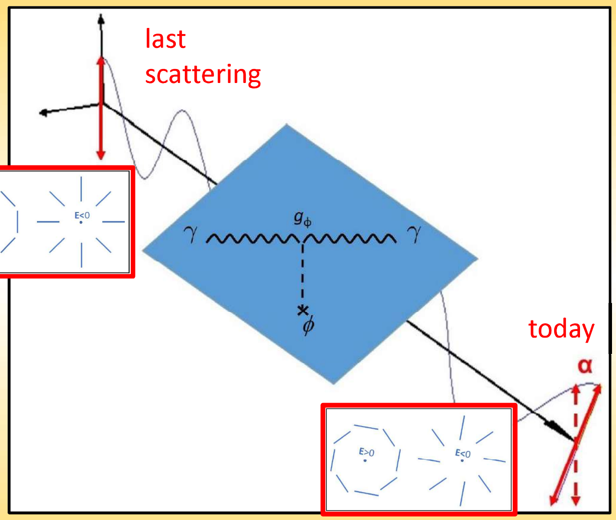

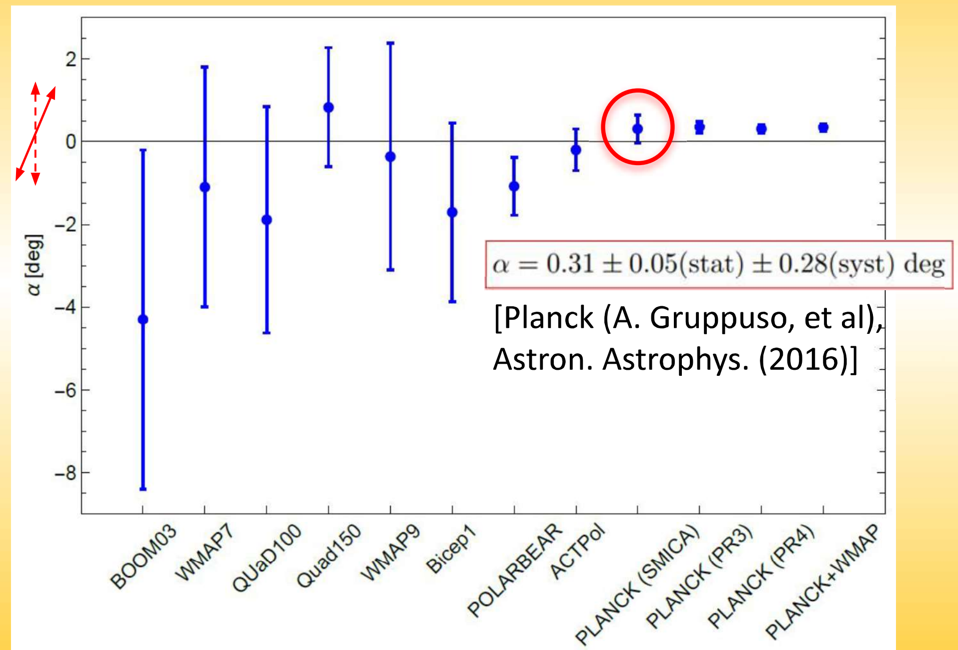

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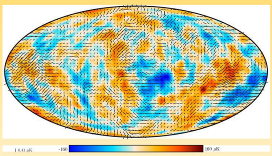

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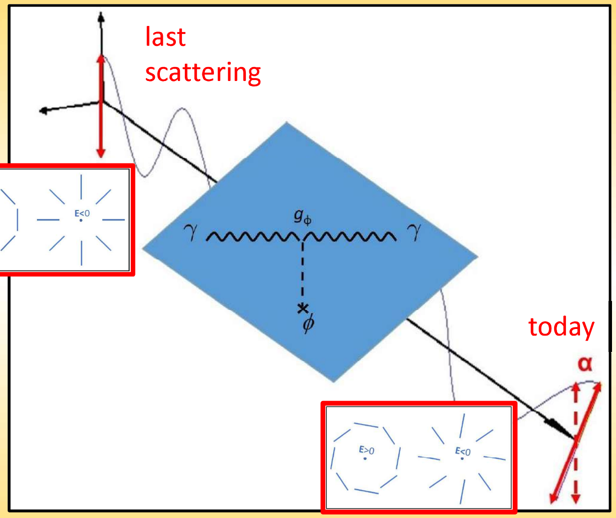

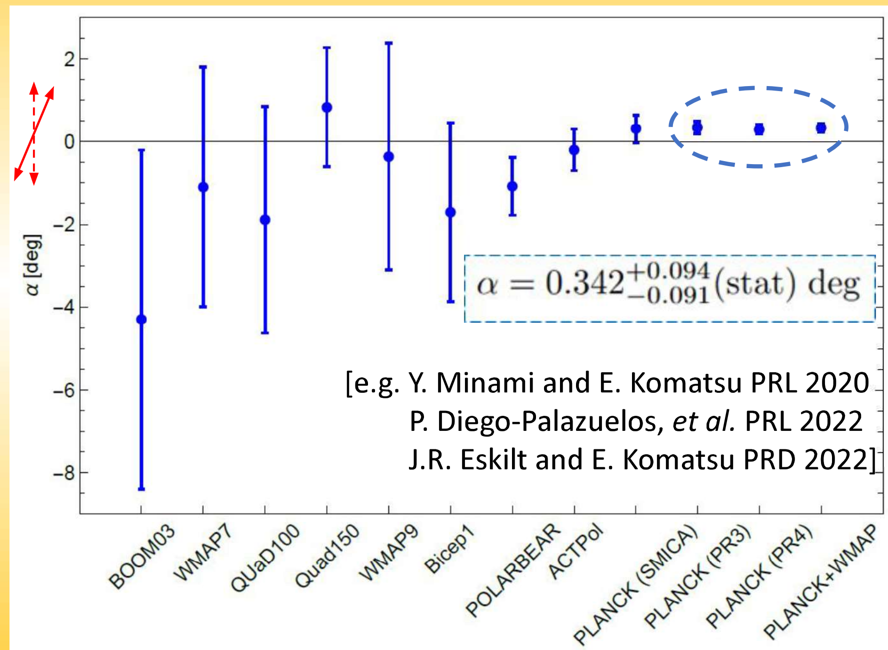

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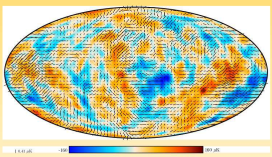

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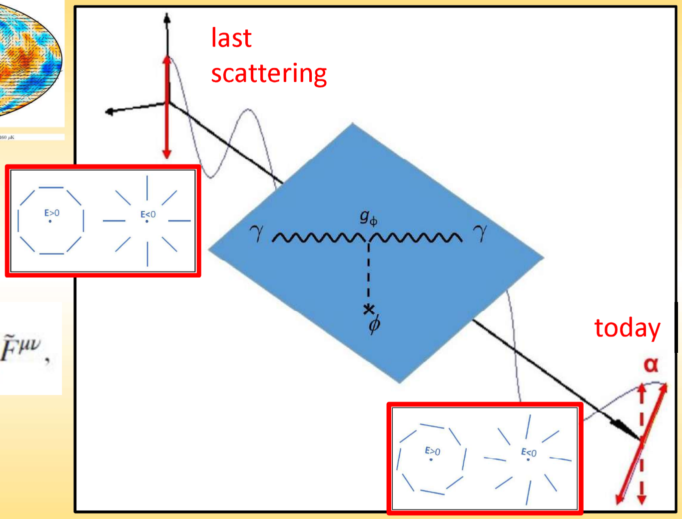
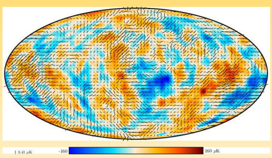


Boltzmann equation for linear polarization **with cosmic birefringence** (Liu, Lee and Ng [PRL 2006], Finelli and Galaverni [PRD 2009]):

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

Cosmological pseudoscalar field and CMB polarization



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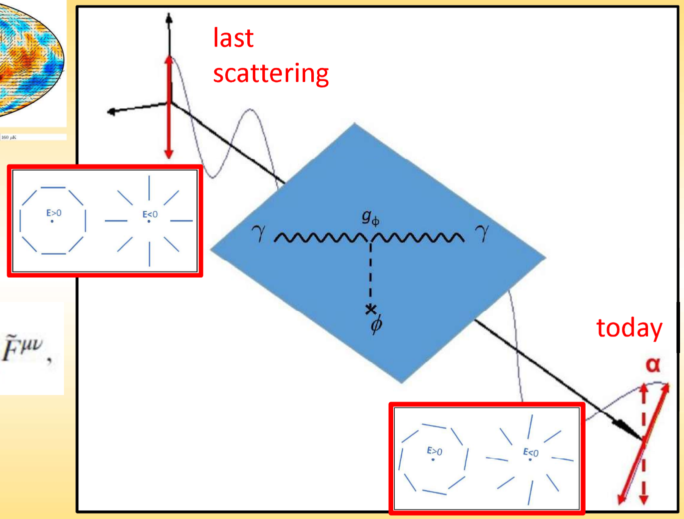

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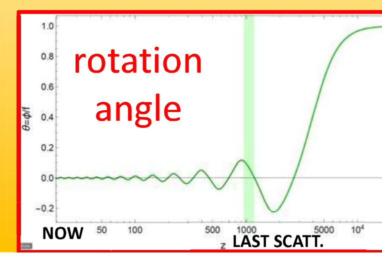
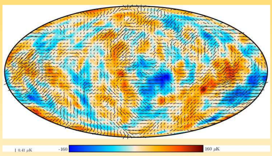
Following the line-of-sight strategy [Seljak and Zaldarriaga (1996)], the source terms for the scalar perturbations are:

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

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



Cosmological pseudoscalar field and CMB polarization



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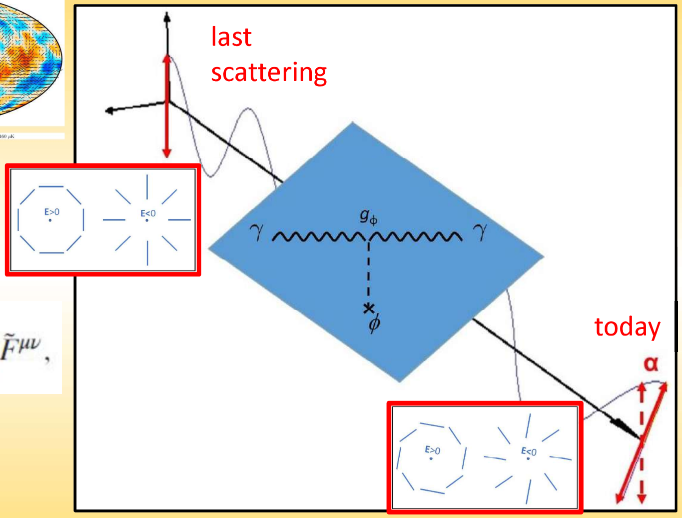

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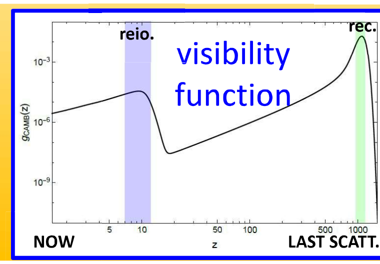

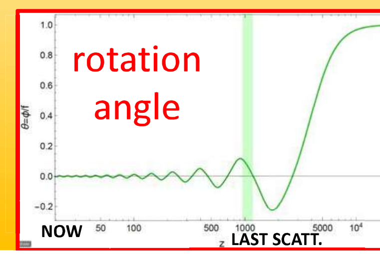

Cosmological pseudoscalar field acting as DM

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**
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We consider this kind of **redshift dependence**
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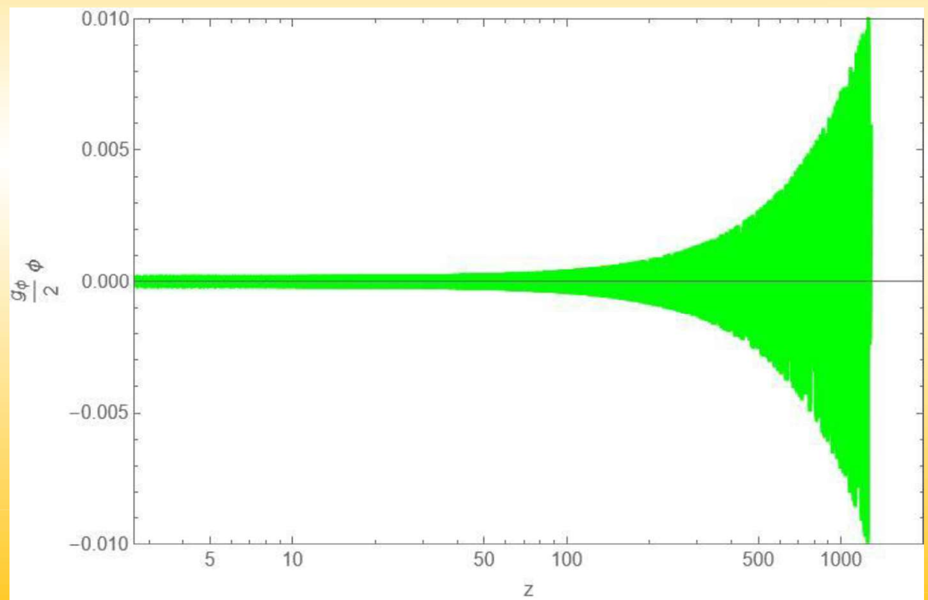
[N=1, m= 10^{-22} eV, $(\phi/f)_{in}$=1, $(\dot{\phi}/f)_{in}$=0]

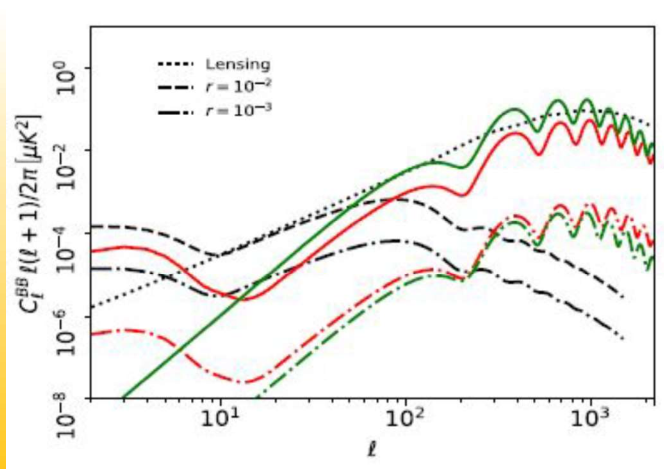


NOW **LAST SCATT.**

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



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

BB induced by a const. rot α=1 deg

BB induced by a const. rot α=0.1 deg

BB induced by **DM** $g_\phi = 2 \times 10^{-15}$ GeV^{-1}

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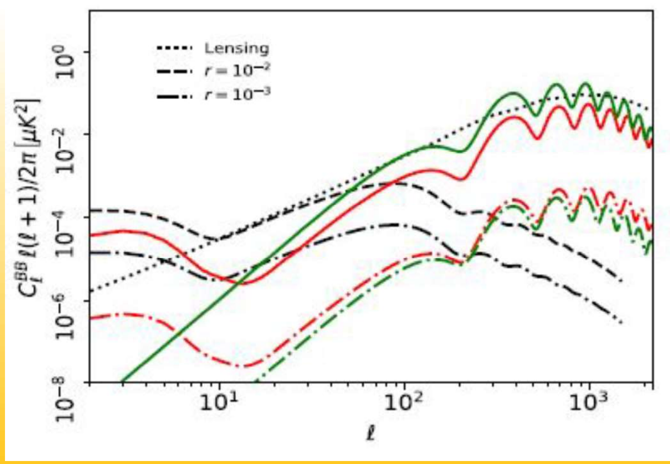

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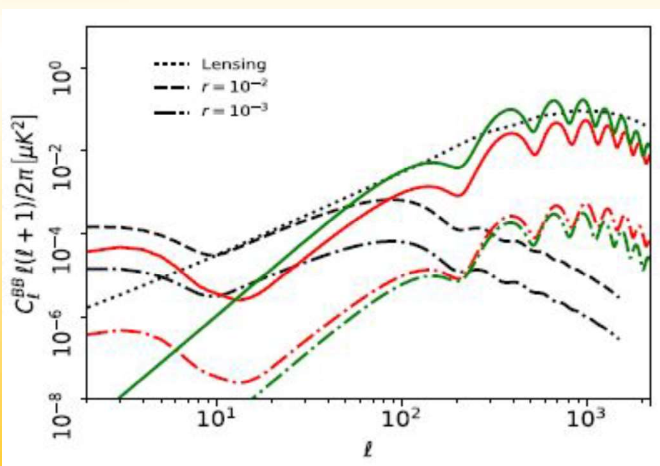
different multipole dependence!

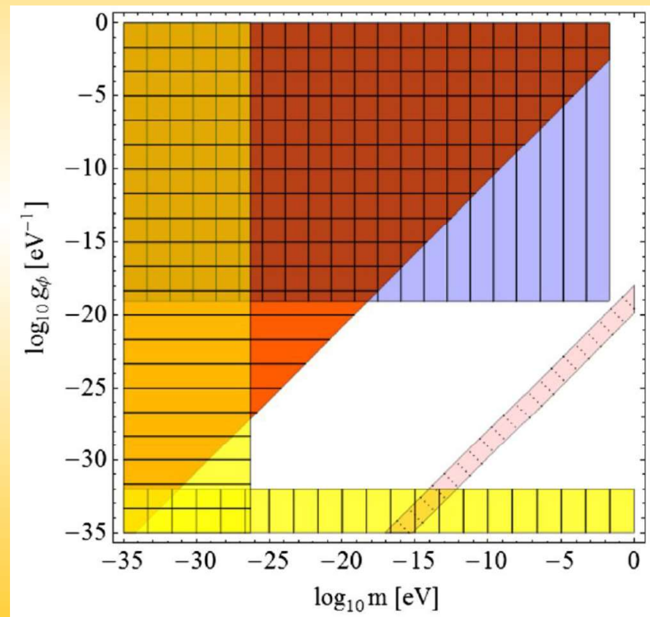
Cosmological pseudoscalar field acting as DM

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

- Axionlike as **Dark Matter**

C_{ll}^{BB}





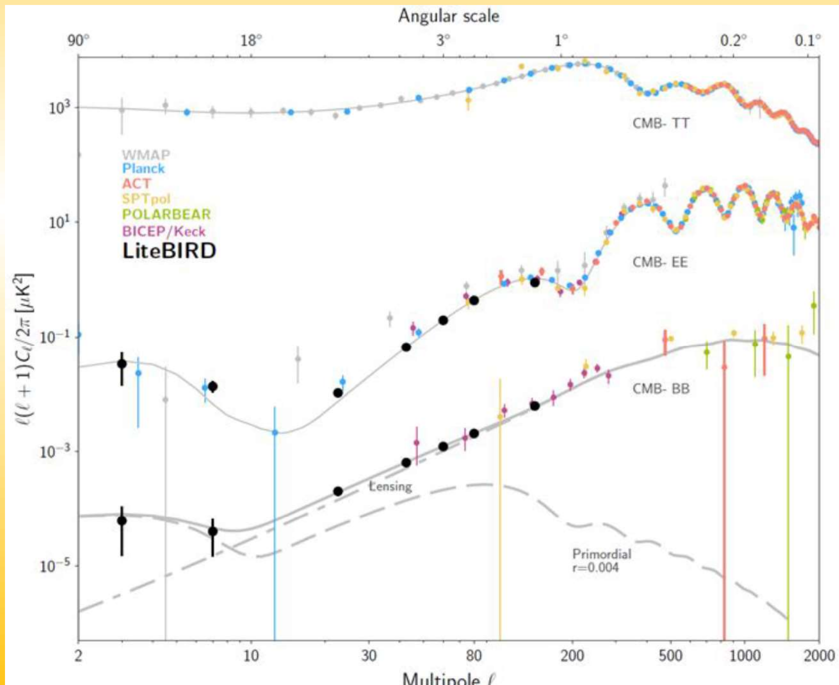
[Finelli and Galaverni, PRD 2009]

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

Constraints for a LiteBIRD-like mission

Present measurements + expected sensitivity for **LiteBIRD**

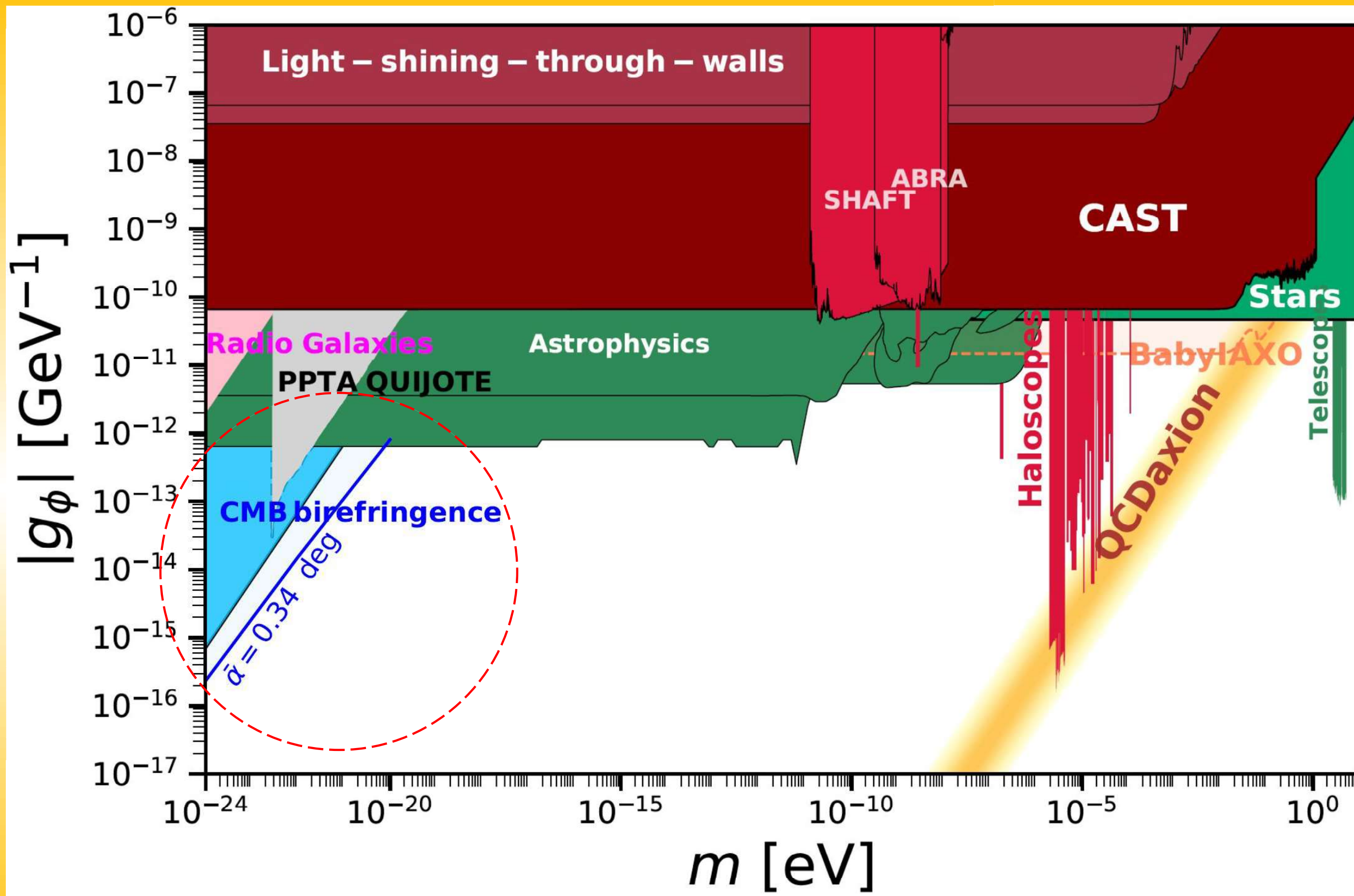
"Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection"



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

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

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



[plot created with the *AxionLimits* code https://cajohare.github.io/AxionLimits/]

Cosmological pseudoscalar field acting as DE

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

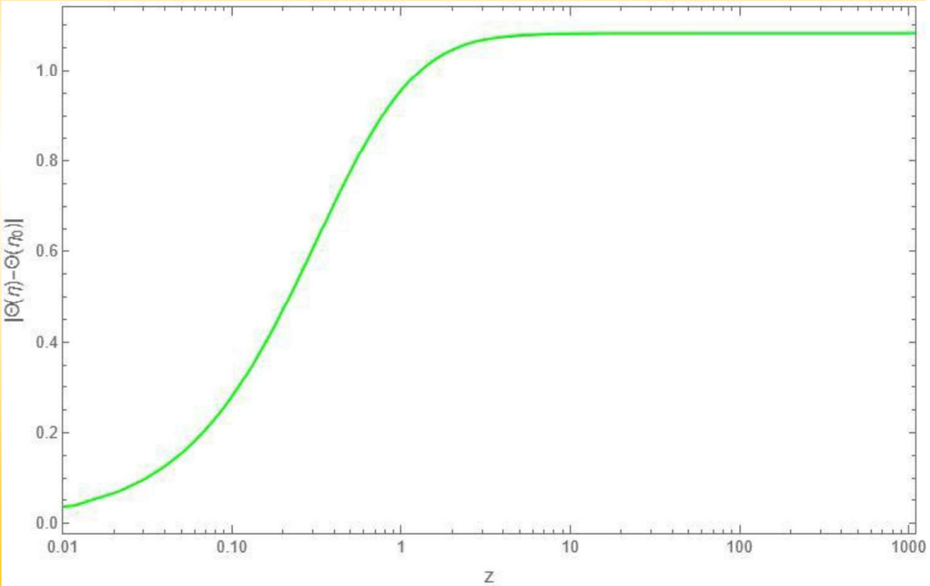
$$V(\phi) = M^4\left(1 + \cos\frac{\phi}{f}\right)$$

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**



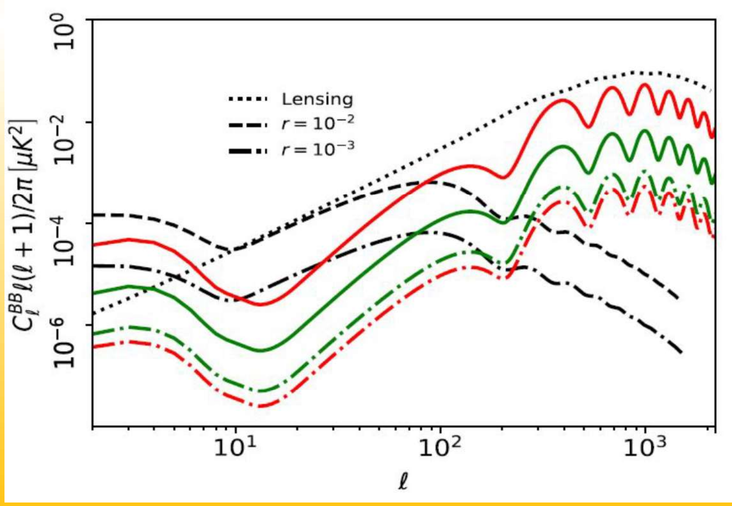
NOW **LAST SCATT.**

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 x 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_ϕ =1.8 x 10^{-20} GeV^{-1}

BB induced by a const. rot α=1 deg

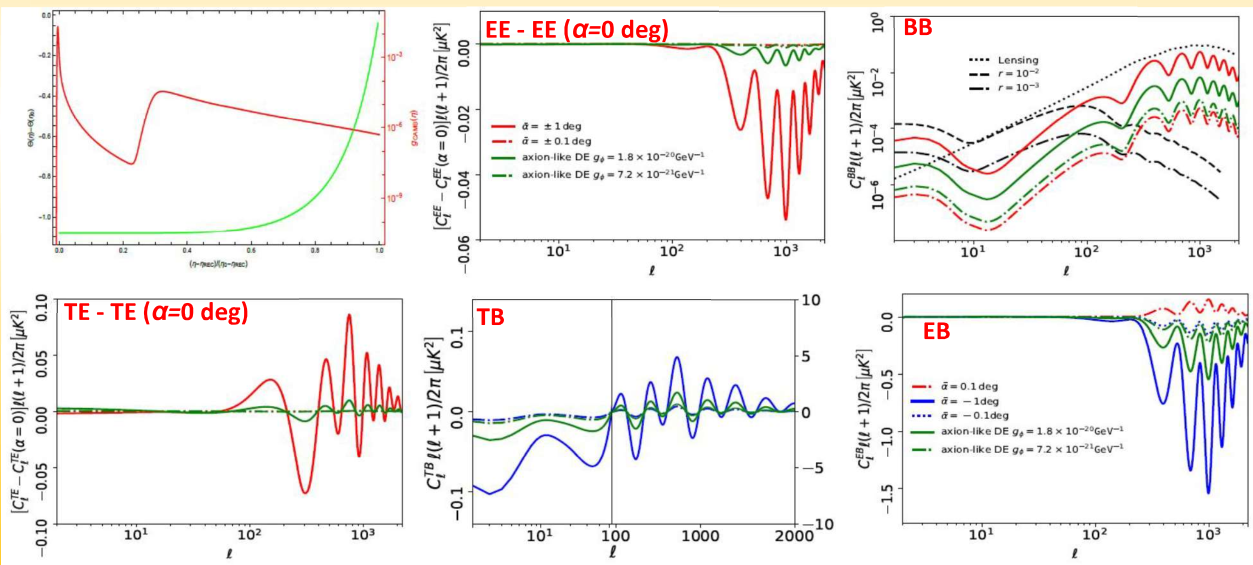
BB induced by a const. rot α=0.1 deg

BB induced by **DE** g_ϕ= 7.2 x 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 x 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:

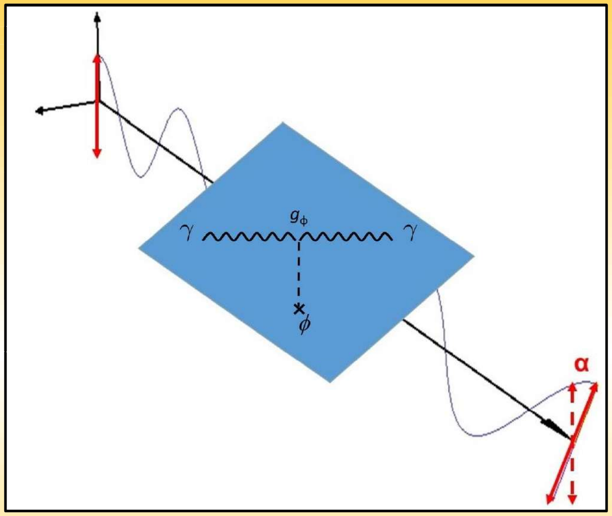
g_ϕ = 1.80 x 10^{-20} GeV^{-1}

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

g_ϕ = 9.0 x 10^{-22} GeV^{-1}

Constraints from 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:



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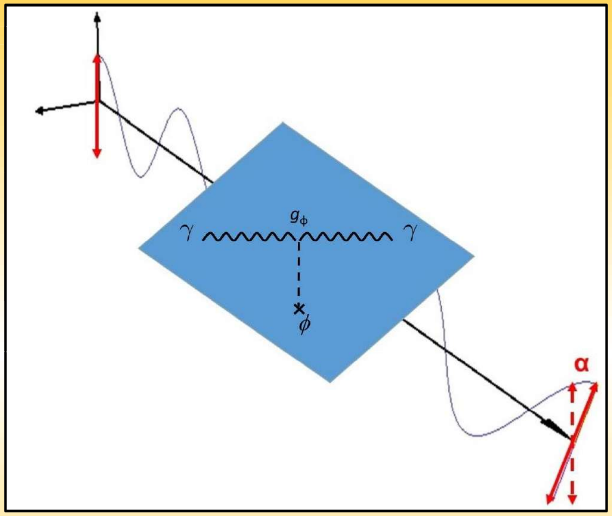

PHYSICAL REVIEW D VOLUME 41, NUMBER 4 15 FEBRUARY 1990

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 $z = 0.4$

Constraints from astrophysical polarized sources

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

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Cosmological birefringence constraints from CMB and astrophysical polarization data

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[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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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)

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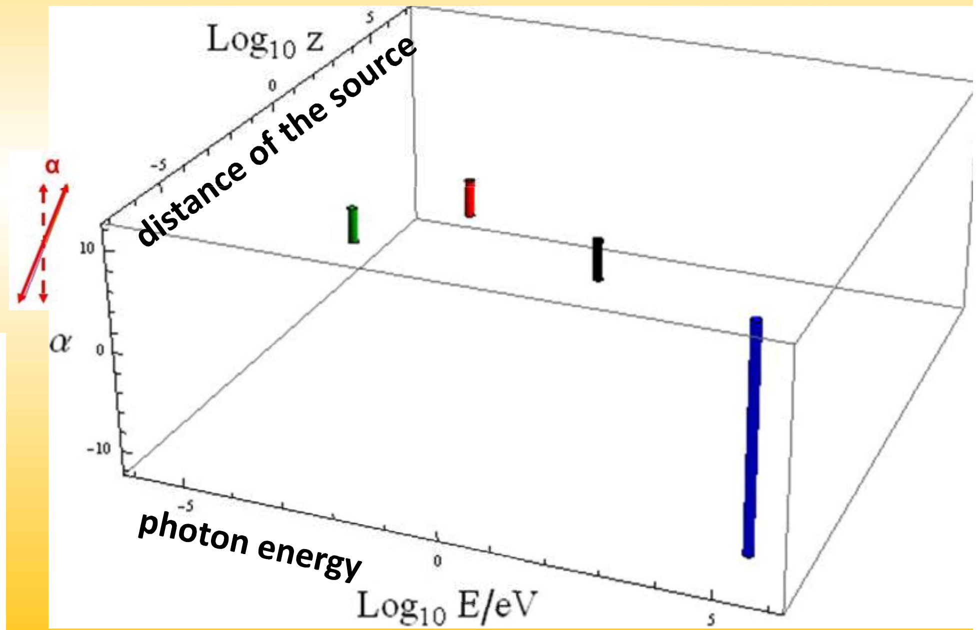


Energy (and distance) dependent birefringence effects

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:

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

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;

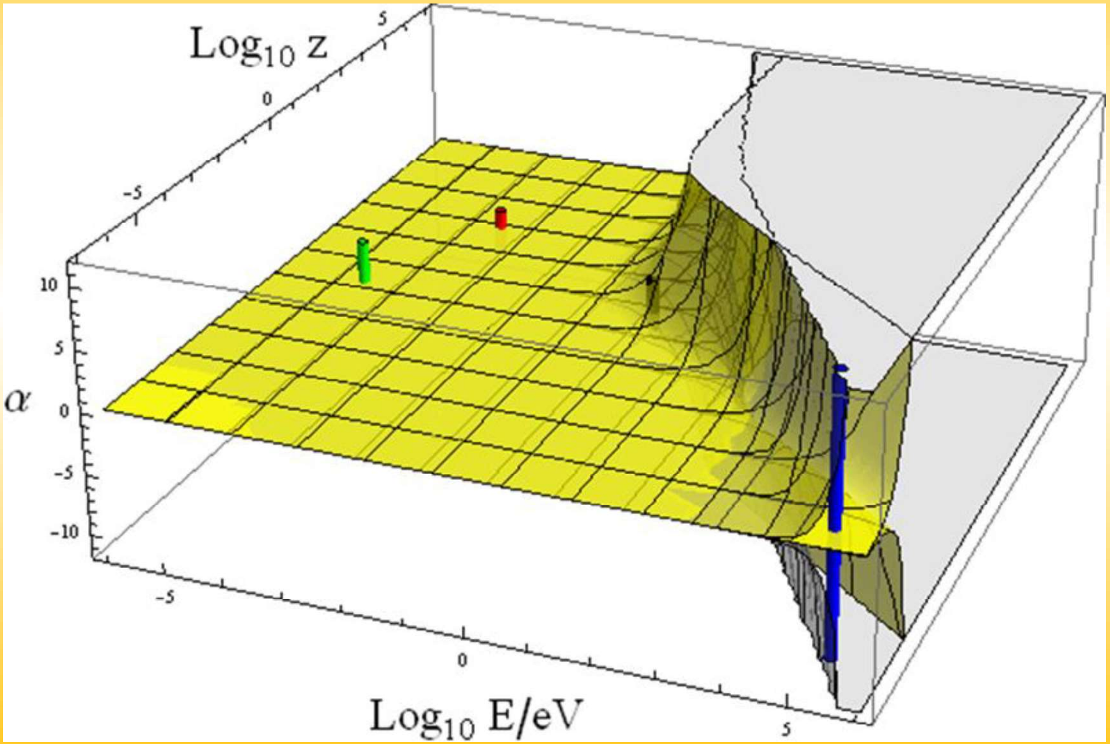
$$\alpha(z_\star, E) = 8\pi\Psi_0 E \int_0^{z_\star} \frac{1}{H(z)}dz$$

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**

Conclusions

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

  → **redshift/time evolution of the birefringence angle** has important **effects on CMB polarization power spectra** [Finelli & M.G., PRD 2009 - arXiv:0802.4210 [astro-ph]]

  - not only total rotation is important, but also **when** the rotation occurs;

  - **different theoretical motivated redshift dependencies** of the pseudoscalar field (es. DM and DE) produce **different multipole dependence** for the spectra;

  → Constraints for different behaviours of the pseudoscalar field (DM and DE)

  [M.G., F. Finelli and D. Paoletti, PRD 2023 - arXiv:2301.07971 [astro-ph.CO]]

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Future:

- Beyond isotropic redshift dependence: **add the effects due inhomogeneities**