Rotation of Linear Polarization Plane from Cosmological Pseudoscalar Fields

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based on a work with:
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Overview

- Pseudoscalar – photon coupling.
- Main effects on CMB polarization.
- Modified Einstein – Boltzmann equations for a time dependent linear polarization rotation angle.
- Fixed **DM** (or **DE**) model:

-full linear polarization angular power spectra;
-comparison with constant rotation angle approximation.

Work based on:

-F. Finelli and MG, "*Rotation of Linear Polarization Plane and Circular Polarization from Cosmological Pseudoscalar Fields* ", arXiv:0802.4210 [astro-ph], *accepted in Phys. Rev. D.*

-F. Finelli and MG, *"CMB Cosmological Birefringence and Ultralight Pseudo Nambu-Goldstone Bosons", in preparation*.

Pseudoscalar – photon coupling

Pseudoscalar fields are invoked to solve the **strong CP-problem of QCD** [R. Peccei and H.Quinn PRL **38** (1977)]

$$\mathcal{L}_{\mathrm{QCD}} = \mathcal{L}_{\mathrm{PERT}} + \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi + \frac{g^2}{32\pi^2}\frac{\phi}{f_a}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

They are also good candidates for cold dark matter (misalignment axion production).

Pseudoscalar particles **interact with ordinary matter**:
photons, nucleons, [electrons].

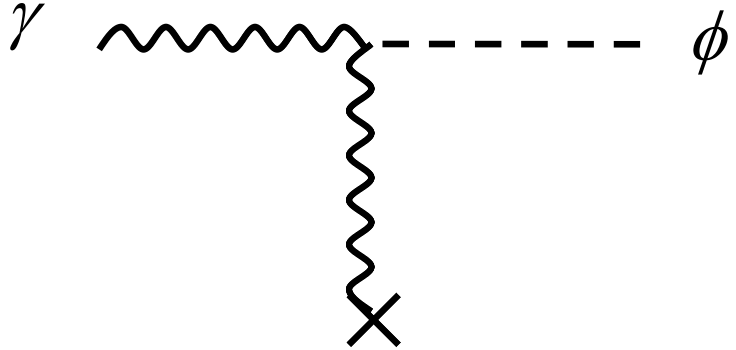
The **coupling with photons** play a key role for most of the searches:

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

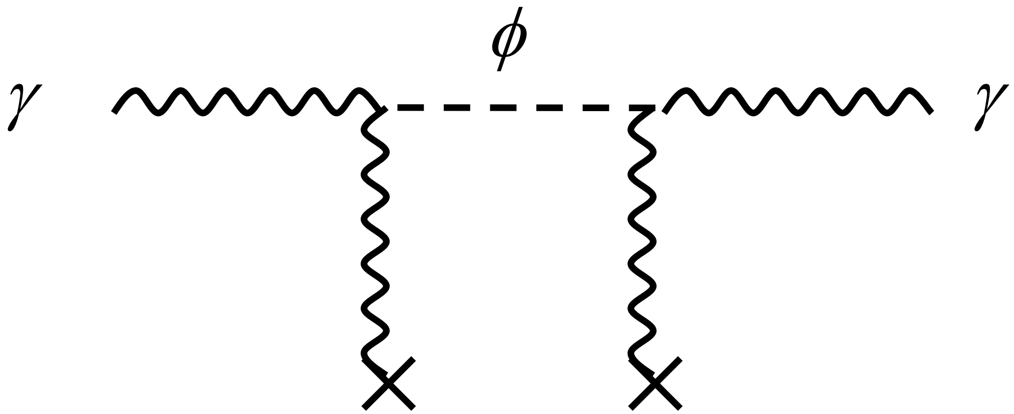
where: $F^{\mu\nu} \equiv \nabla^\mu A^\nu - \nabla^\nu A^\mu \quad \text{and} \quad \tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$

Pseudoscalar – photon coupling

Most of this searches make use of the ***Primakoff effect***, by which pseudo-scalars convert into photons in presence of an external electromagnetic field.

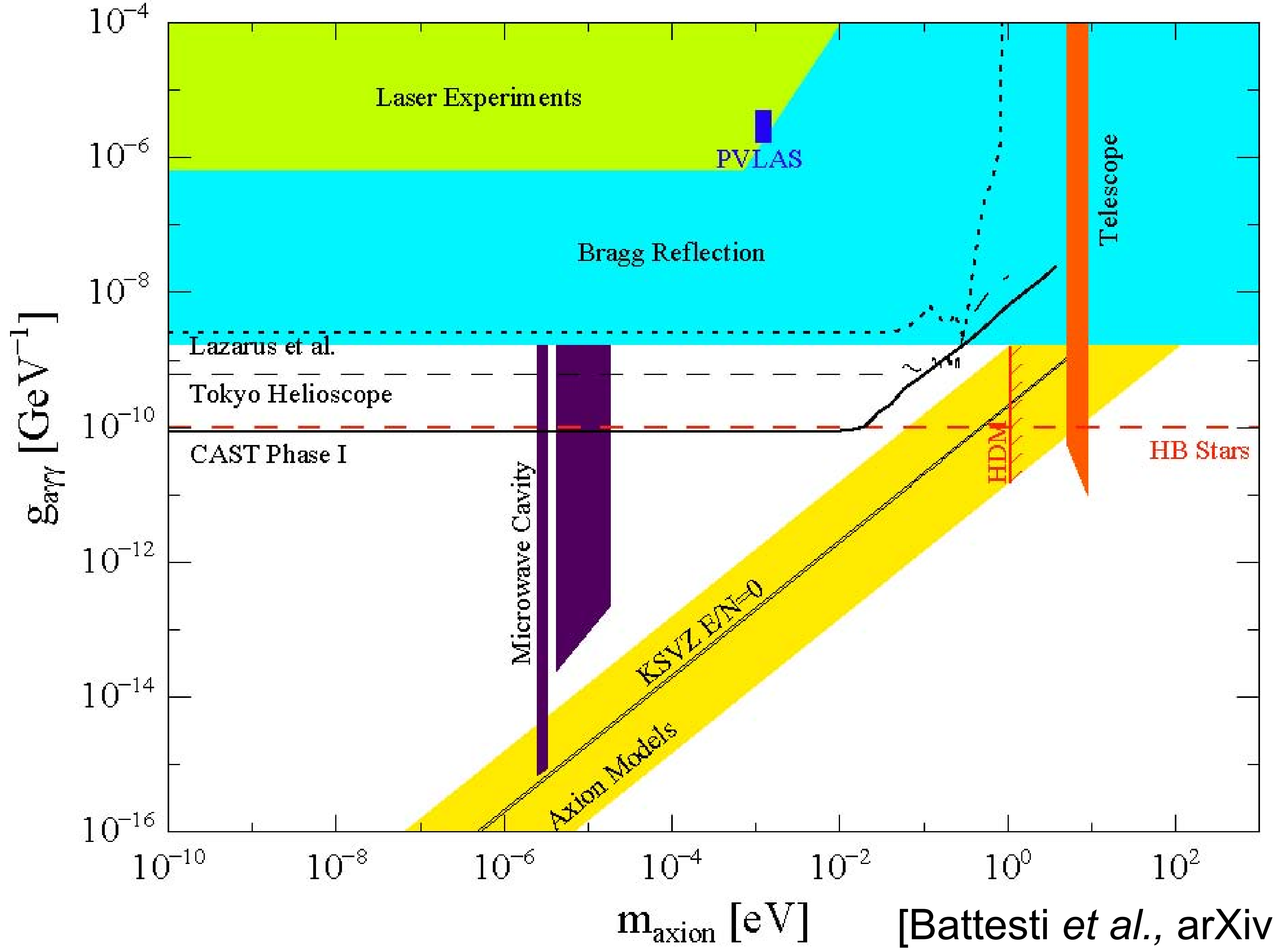


- Dichroism in laser experiments
- Solar axions (e.g. CAST)



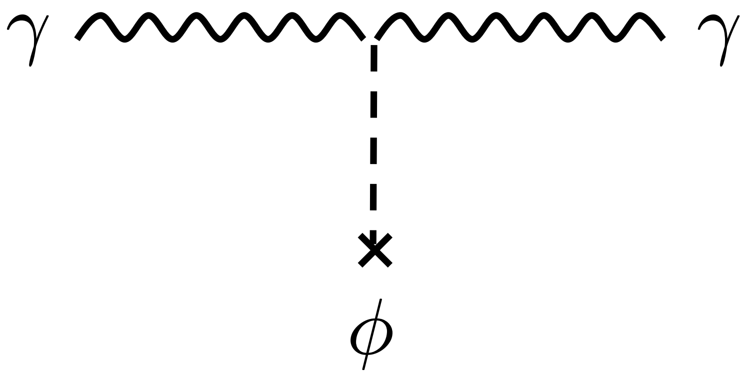
- Birefringence in laser experiments
- Light shining through walls experiments

Current Constraints



[Battesti *et al.*, arXiv:0705.0615]

Cosmological background



Photon propagation in a **time dependent background** of pseudoscalar particles acting as **DM** (e.g. axion-like particles) or **DE** (e.g. ultralight pseudo Nambu-Goldstone bosons)

We want to evaluate the effect on CMB polarization of a coupling of this kind between **pseudoscalar field** and **photon**, improving the estimate obtained by D.Harari and P. Sikivie in 1992 [Phys. Lett. B **289** 67] for linear polarization:

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

Pseudoscalar – photon coupling

- Assume a spatially flat Roberson-Walker universe:

$$ds^2 = -dt^2 + a^2(t)d\boldsymbol{x}^2 = a^2(\eta)\left[-d\eta^2 + d\boldsymbol{x}^2\right]$$

- Neglect the spatial variations of the pseudoscalar field:

$$\phi = \phi(\eta)$$

ϕ is homogeneous throughout our universe (inflation occurs after the PQ-symmetry breaking): PQ scale is much higher than $10^{11\div12}$ GeV, case motivated by anthropic considerations [Linde, Phys. Lett. B **201** (1988), M. Tegmark, A. Aguirre, M. Rees, F. Wilczek Phys. Rev. D **73** (2006), M.P. Hertzberg, M. Tegmark, F. Wilczek Phys. Rev. D **78** (2008)]

For a plane wave propagating along z-axis, the equation for Fourier transform of the vector potential (in the Coulomb Gauge $\nabla \cdot \boldsymbol{A} = 0$) :

$$\tilde{A}''_+(\eta,k) + \left[k^2 + \underline{g_\phi k \frac{d\phi}{d\eta}}\right]\tilde{A}_+(\eta,k) = 0$$

$$\tilde{A}''_-(\eta,k) + \left[k^2 - \underline{g_\phi k \frac{d\phi}{d\eta}}\right]\tilde{A}_-(\eta,k) = 0$$

Adiabatic solution

It is possible to search a solution in this form:

$$\tilde{A}_s = \frac{1}{\sqrt{2\omega_s}} e^{\pm i \int \omega_s d\eta} \quad \text{where:} \quad \omega_s(\eta) = k\sqrt{1 \pm \frac{g_\phi}{k}\phi'} \equiv k\sqrt{1 \pm \Delta(\eta)}$$

It is a good *approximation* of the solution when: $\frac{3\omega_s'^2}{4\omega_s^4} \ll 1 \quad \text{and} \quad \frac{\omega_s''}{2\omega_s^3} \ll 1\,.$

If also $\Delta(\eta) \ll 1$:

$$\begin{aligned} \tilde{A}_\pm &\simeq \frac{1}{\sqrt{2k\left(1 \pm \Delta/4\right)}} \exp\left[\pm ik\left(\eta \pm \frac{1}{2}\int \Delta(\eta) d\eta\right)\right] \\ &= \frac{1}{\sqrt{2k\left(1 \pm \underline{g_\phi \phi' k/4}\right)}} \exp\left[\pm i\left(\underline{k\eta \pm g_\phi \phi/2}\right)\right]\,. \end{aligned}$$

Adiabatic solution

The two main effects on the propagation of the wave are:

• a k-independent shift between the two polarized waves, which corresponds to **rotation of the plane of linear polarization** of an angle:

$$\theta(\eta) = \frac{g_\phi}{2}\left[\phi(\eta) - \phi(\eta_{\rm rec})\right]$$

• production of a certain **degree of circular polarization** (dependent on k):

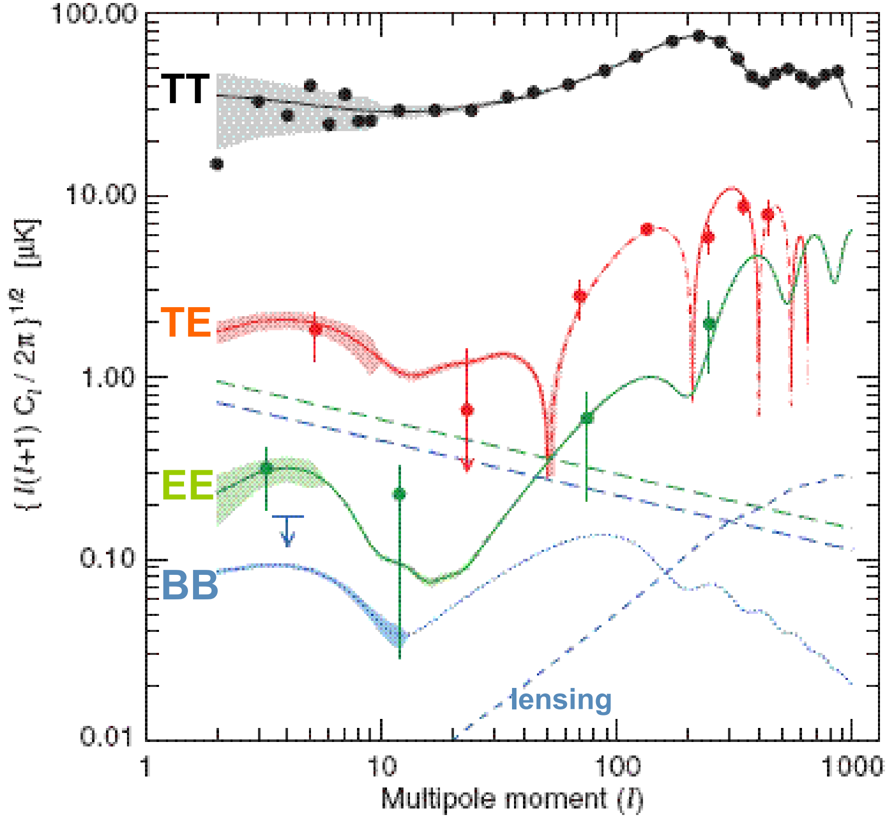
$$\tilde{\Pi}_V(\eta) \equiv \frac{V}{T} = \frac{\left|\tilde{A}'_+\right|^2 - \left|\tilde{A}'_-\right|^2}{\left|\tilde{A}'_+\right|^2 + \left|\tilde{A}'_-\right|^2} \simeq \frac{\Delta(\eta)}{2} = \frac{g\phi'(\eta)}{2k}$$

CMB Polarization

•Linear polarization of CMB was **predicted** soon after CMB discovery in 1968 by Martin Rees [Rees, ApJ 153 1968] (Thomson scattering of anisotropic radiation at last scattering give rise to linear polarization).

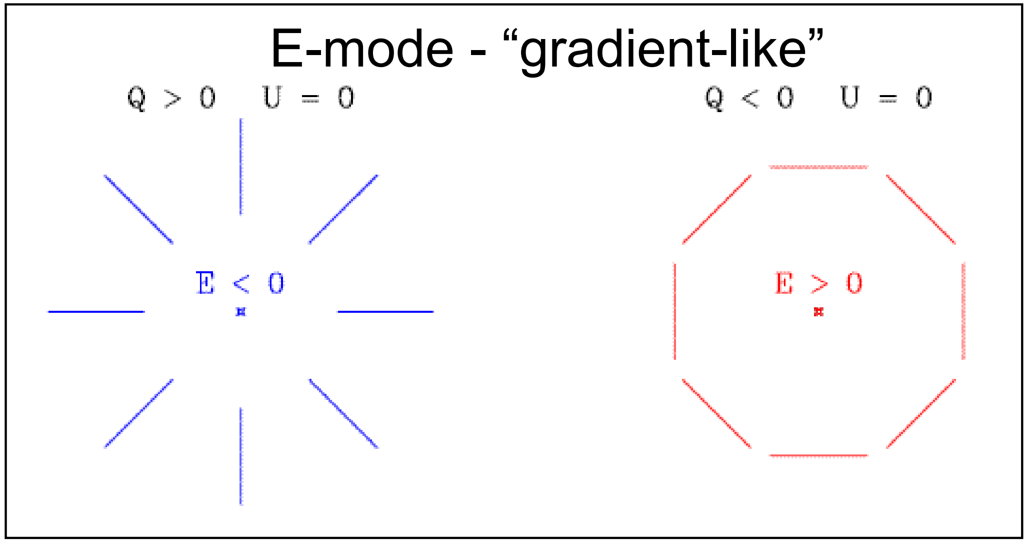
•The first **detection** of CMB polarization was made by the Degree Angular Scale Interferometer (DASI, Kovac *et al.*, Nature 420, 2002).

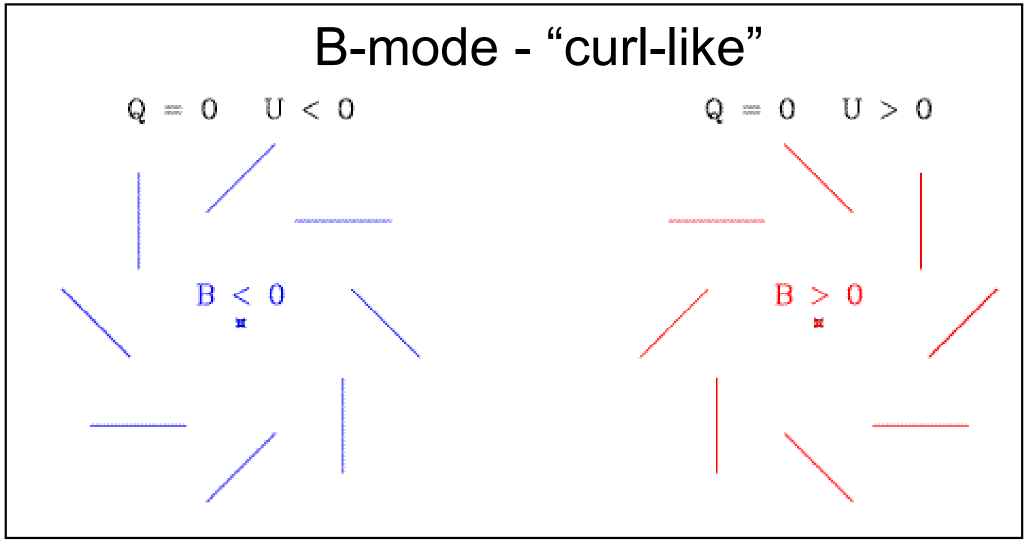
•First **full-sky polarization map** released from WMAP in 2006.



Plot of signal for TT, TE, EE, BB for the best fit model.
[Page *et al.*, 2006]

E and *B* linear polarization





[Zaldarriaga, astro-ph/0305272]

Potential sources of B polarization:

•*Cosmological gravitational waves* (tensor perturbation of the metric)

•*Gravitational lensing* of E-mode polarization

•*Faraday Rotation* of E-mode polarization (magnetic fields)

• Coupling of CMB photons with a *pseudoscalar field* (e.g. axion). …

Polarization Boltzmann equation

One of the main effects of coupling between photons and pseudoscalar fields is **cosmological birefringence**:

$$\theta(\eta) = \frac{g_\phi}{2}\left[\phi(\eta) - \phi(\eta_{\rm rec})\right]$$

Including the time dependent rotation angle contribution in the Boltzmann equation for polarization [Liu *et al*., PRL 97, 161303 (2006)] :

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

Polarization Boltzmann equation

Following the line of sight strategy for scalar perturbations, we have an additional term in polarization sources:

$$\begin{aligned}
\Delta_T(k,\eta) &= \int_0^{\eta_0} d\eta\, g(\eta) S_T(k,\eta) j_\ell(k\eta_0 - k\eta)\,, \\
\Delta_E(k,\eta) &= \int_0^{\eta_0} d\eta\, g(\eta) S_P^{(0)}(k,\eta) \frac{j_\ell(k\eta_0 - k\eta)}{(k\eta_0 - k\eta)^2} \cos\left[2\theta(\eta)\right]\,, \\
\Delta_B(k,\eta) &= \int_0^{\eta_0} d\eta\, g(\eta) S_P^{(0)}(k,\eta) \frac{j_\ell(k\eta_0 - k\eta)}{(k\eta_0 - k\eta)^2} \sin\left[2\theta(\eta)\right].
\end{aligned}$$

If θ is constant in time the new terms exit from the time integrals and:

$$\begin{aligned}
\Delta_E &= \Delta_E(\theta = 0) \cos(2\bar{\theta})\,, \\
\Delta_B &= \Delta_E(\theta = 0) \sin(2\bar{\theta})\,.
\end{aligned}$$

Constant rotation angle

In the constant rotation angle approximation new polarization power spectra are given by [A. Lue, L. Wang, M. Kamionkowski PRL **83**, 1506 (1999)]:

$$
\begin{aligned}
C_\ell^{EE,obs} &= C_\ell^{EE}\cos^2(2\bar\theta)\,, \\
C_\ell^{BB,obs} &= C_\ell^{EE}\sin^2(2\bar\theta)\,, \\
C_\ell^{EB,obs} &= \frac{1}{2}C_\ell^{EE}\sin(4\bar\theta)\,, \\
C_\ell^{TE,obs} &= C_\ell^{TE}\cos(2\bar\theta)\,, \\
C_\ell^{TB,obs} &= C_\ell^{TE}\sin(2\bar\theta)\,.
\end{aligned}
$$

Where C_l^{XY} are the primordial power spectra produced by scalar fluctuations in absence of parity violation, while $C_l^{XY,obs}$ are what we would observe in the presence of anfor an isotropic, k-independent **rotation** θ of the plane of liner polarization.

Constraints on the rotation angle

- analyzing a subset of **WMAP3 and BOOMERANG data**
  [B. Feng, *et al.,* PRL **96** 221302 (2006)]

$$-13.7\,\mathrm{deg} < \bar{\theta} < 1.9\,\mathrm{deg}\ \ (2\sigma)$$

- analyzing **WMAP three years polarization data**
  [P.Cabella, *et al.,* PRD **76** 123014 (2007)]

$$-8.5\,\mathrm{deg} < \bar{\theta} < 3.5\,\mathrm{deg}\ \ (2\sigma)$$

- analyzing **WMAP five years polarization data**
  [E. Komatsu, *et al*., arXiv:0803.0547]

$$-5.9\,\mathrm{deg} < \bar{\theta} < 2.4\,\mathrm{deg}\ \ (2\sigma)$$

- analyzing **QUaD** experiment second and third season observations
  [QUaD Collaboration, arXiv:0811.0618]

$$-1.2\,\mathrm{deg} < \bar{\theta} < 3.9\,\mathrm{deg}\ \ (2\sigma)$$

Cosine-type potential

Assuming that dark matter is given by **massive pseudoscalar particles** (e.g. axions), we consider the potential:

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

the evolution of *Φ* is given by the equation:

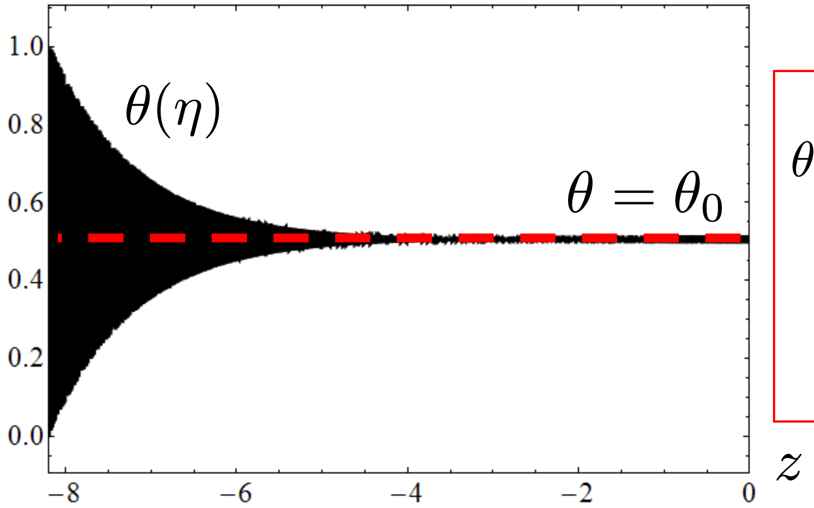
$$\ddot{\phi} + 3H\dot{\phi} + m^2(T)\phi = 0$$

If $m \ll 3H$ the solution simply is: $\phi \simeq \phi_i$

If $m > 3H$ the field begins to oscillate and the solution, in a matter dominated universe ($\dot{a}/a = 2/3t$), is:

$$\phi(t) \overset{m_\phi t \gg 1}{\simeq} \frac{\phi_0}{mt} \sin(mt)$$

Cosine-type potential

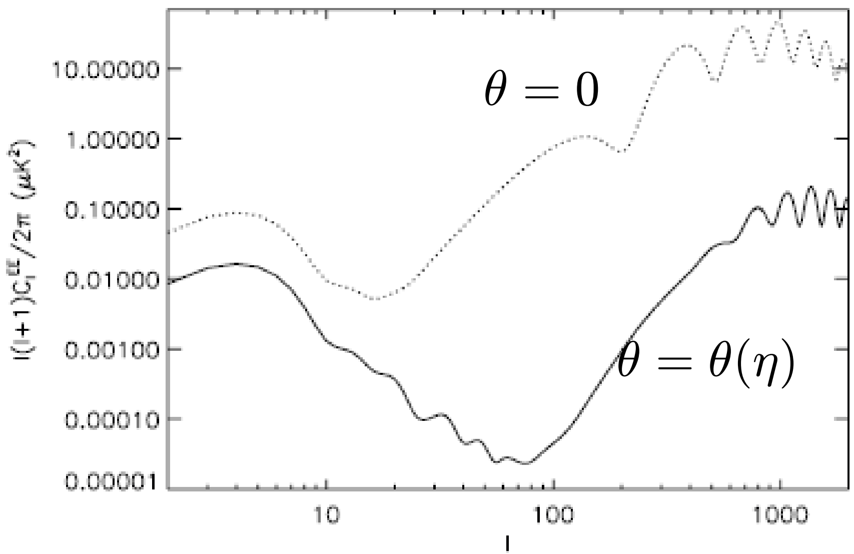


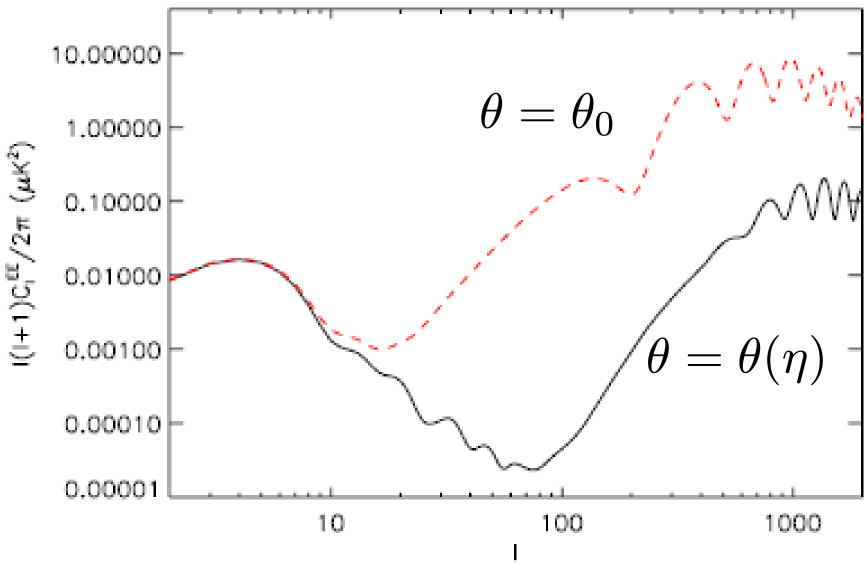
$$\theta(\eta) = \sqrt{\frac{3}{\pi}}\frac{g_\phi M_{\rm pl}}{2m\eta_0}\left\{\left(\frac{\eta_0}{\eta}\right)^3 \sin\left[m\frac{\eta_0}{3}\left(\frac{\eta}{\eta_0}\right)^3\right] - \left(\frac{\eta_0}{\eta_{\rm rec}}\right)^3 \sin\left[m\frac{\eta_0}{3}\left(\frac{\eta_{\rm rec}}{\eta_0}\right)^3\right]\right\}$$

$m = 10^{-22}\ {\rm eV}\,, \quad g_\phi = 10^{-20}\ {\rm eV}^{-1}$

$\theta_0 \sim 0.506\ {\rm rad}$

EE

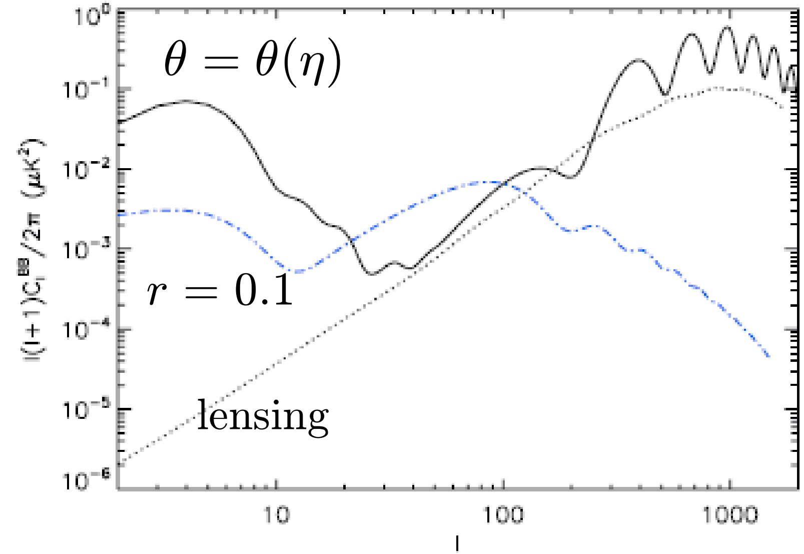


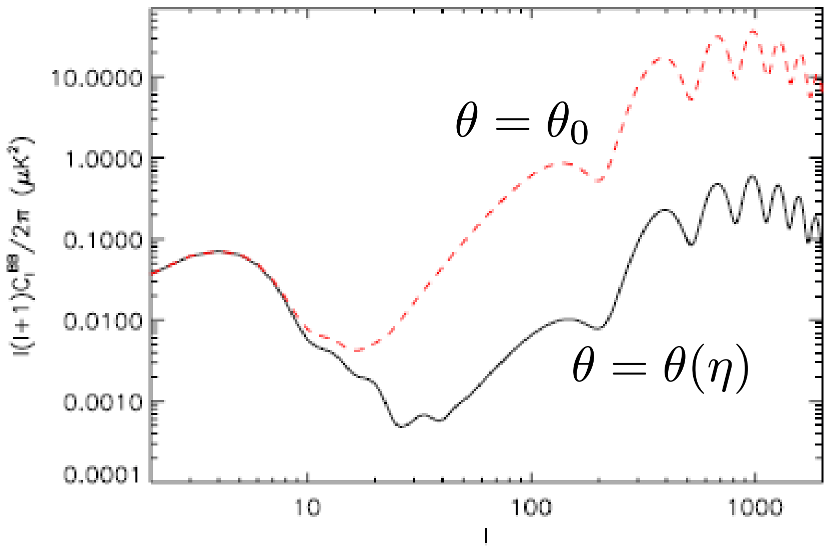


Cosine-type potential

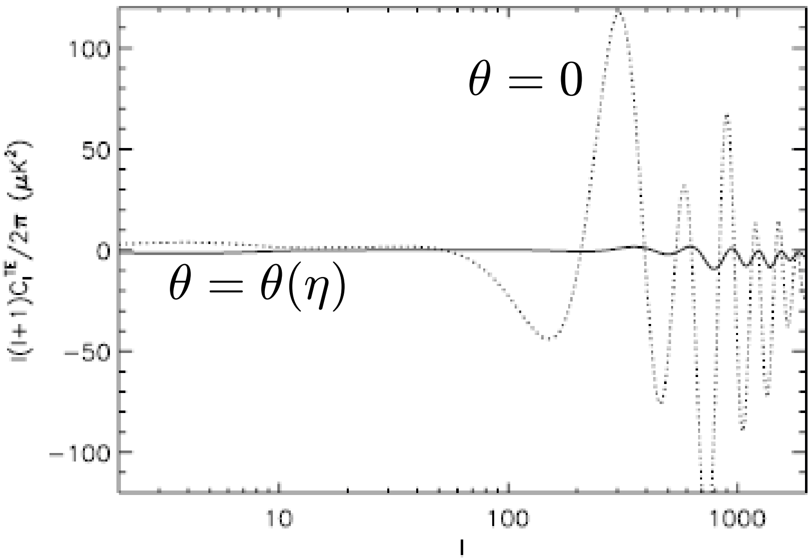
BB

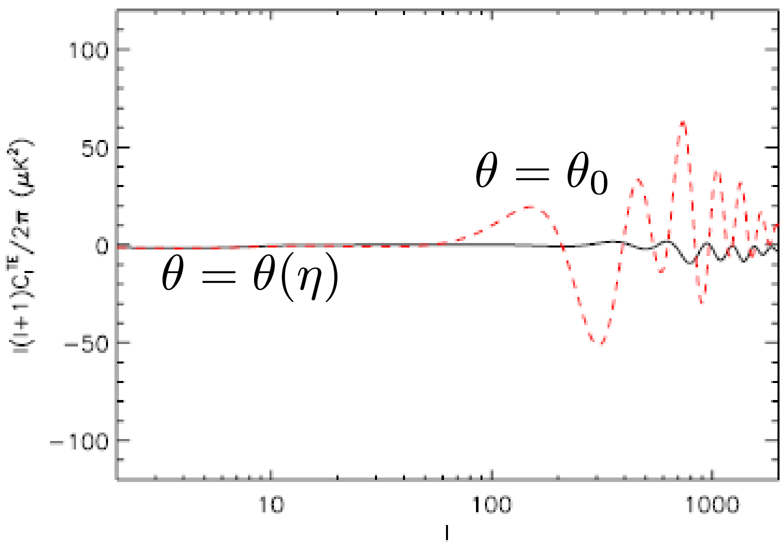
$\theta_0 \sim 0.506$ rad





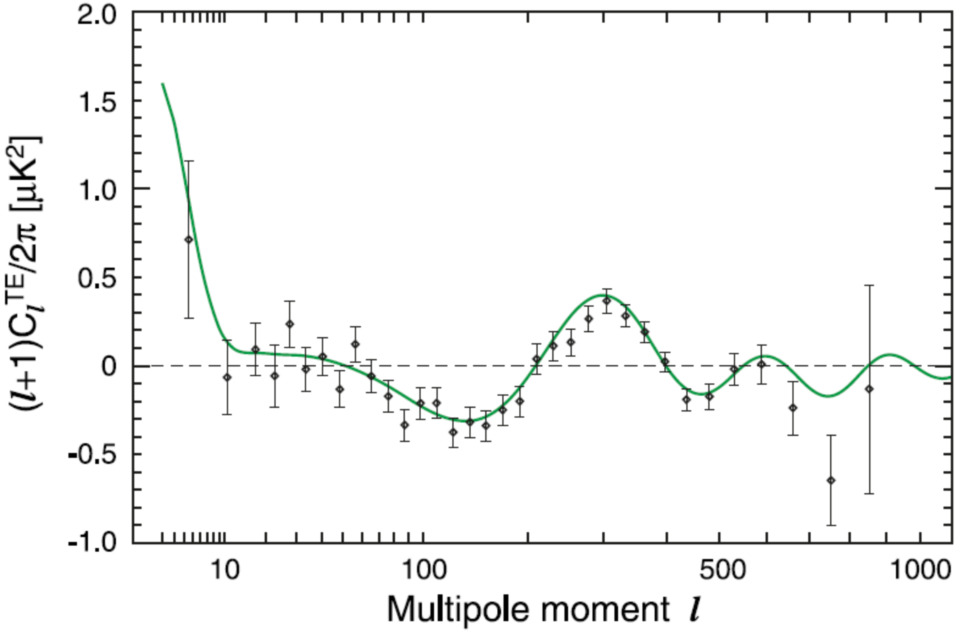
TE



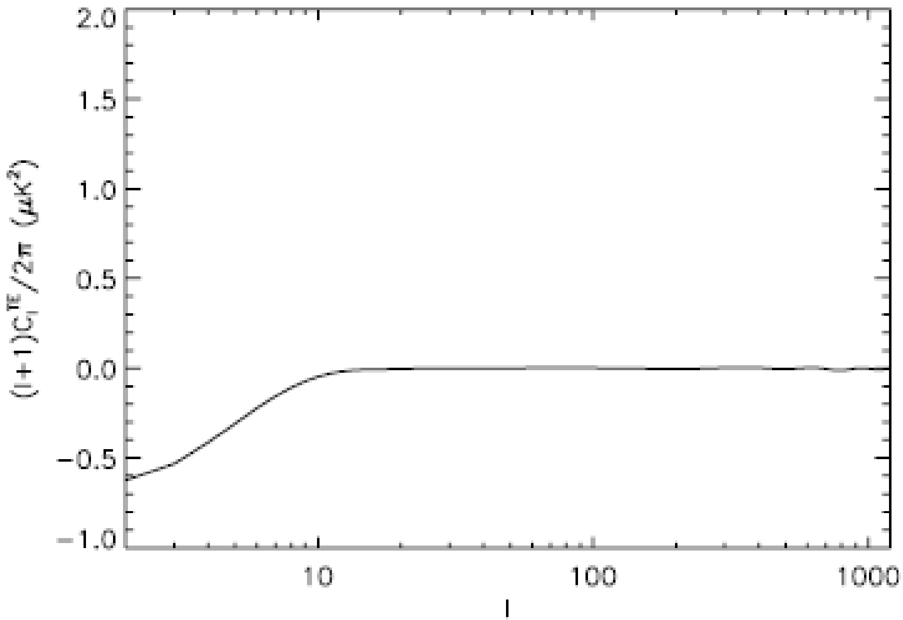


WMAP 2008 - TE

Cosine-type potential *[note vertical axis]*



WMAP collaboration
[**arXiv:0803.0593**]



Cosine-type potential with:

$$m = 10^{-22}\ \mathrm{eV}\,, \quad g_\phi = 10^{-20}\ \mathrm{eV}^{-1}$$

Parity odd correlators

In absence of parity-violating interactions, the ensemble of fluctuations is statistically parity symmetric and therefore the parity odd correlators have to vanish.
In this case photons interact with pseudoscalars:

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

therefore also parity-odd correlators should be considered:

$$C_l^{TT} \stackrel{P}{\longmapsto} C_l^{TT}$$

$$C_l^{TE} \stackrel{P}{\longmapsto} C_l^{TE} \qquad C_l^{EE} \stackrel{P}{\longmapsto} C_l^{EE}$$

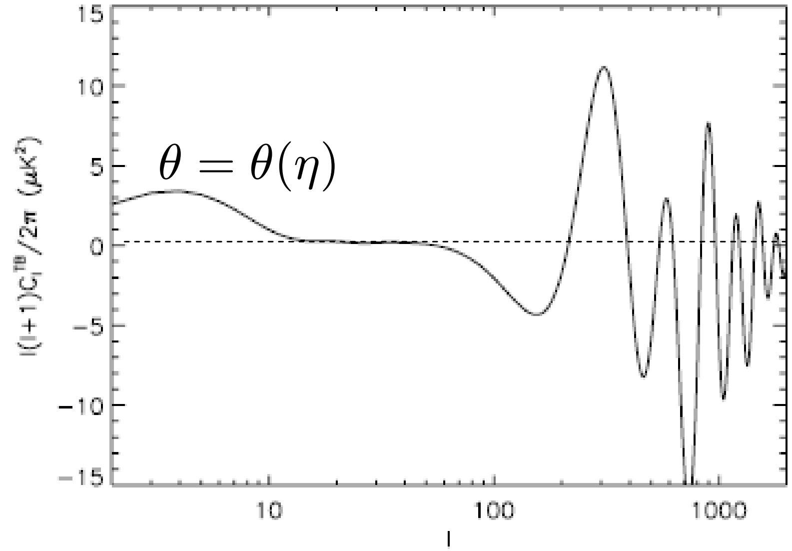
$$\boxed{C_l^{TB} \stackrel{P}{\longmapsto} -C_l^{TB} \qquad C_l^{EB} \stackrel{P}{\longmapsto} -C_l^{EB}} \qquad C_l^{BB} \stackrel{P}{\longmapsto} C_l^{BB}$$

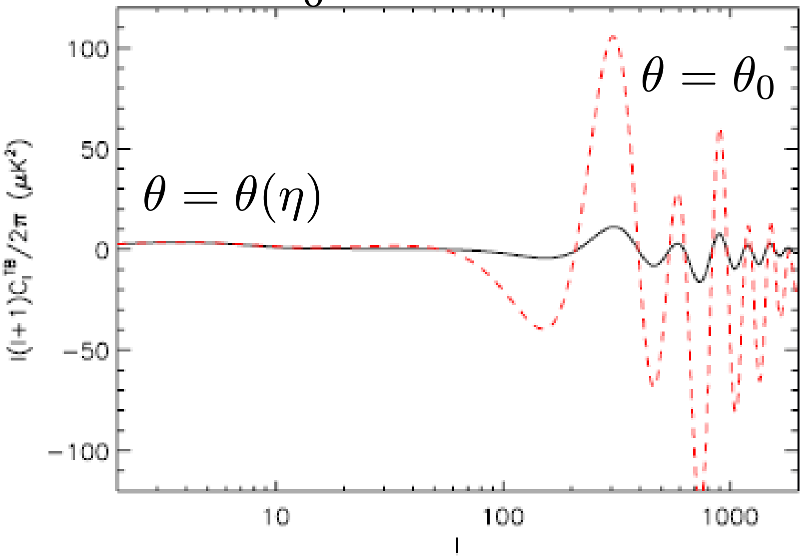
$$\left[C_l^{TV} \stackrel{P}{\longmapsto} -C_l^{TV} \qquad C_l^{EV} \stackrel{P}{\longmapsto} -C_l^{EV} \qquad C_l^{BV} \stackrel{P}{\longmapsto} C_l^{BV} \qquad C_l^{VV} \stackrel{P}{\longmapsto} C_l^{VV}\right]$$

Cosine-type potential

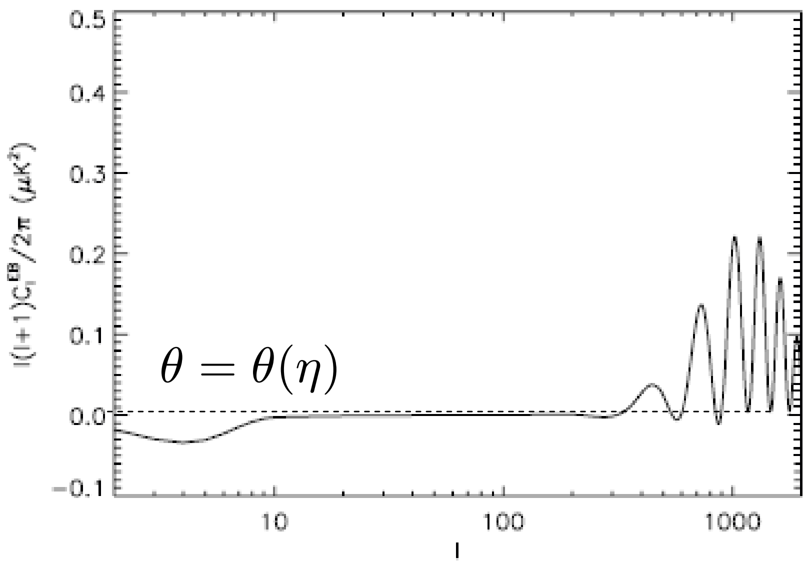
$\theta_0 \sim 0.506$ rad

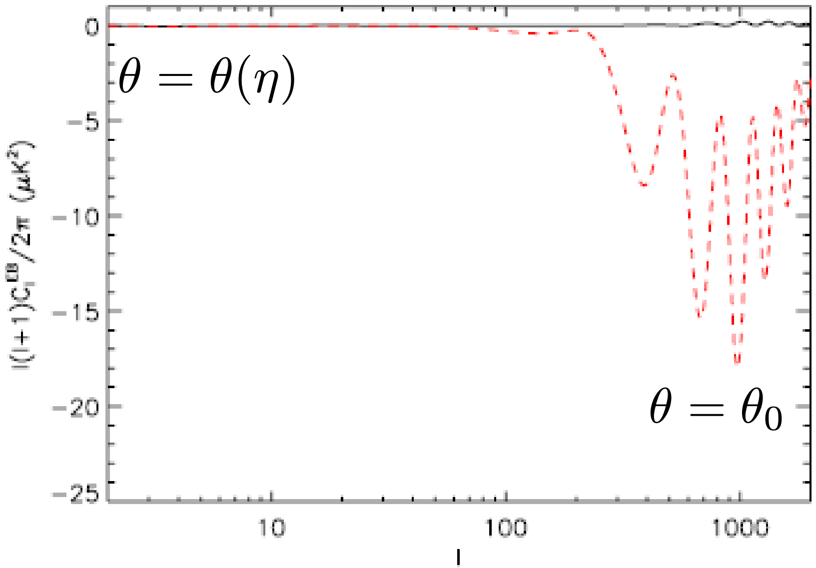
TB





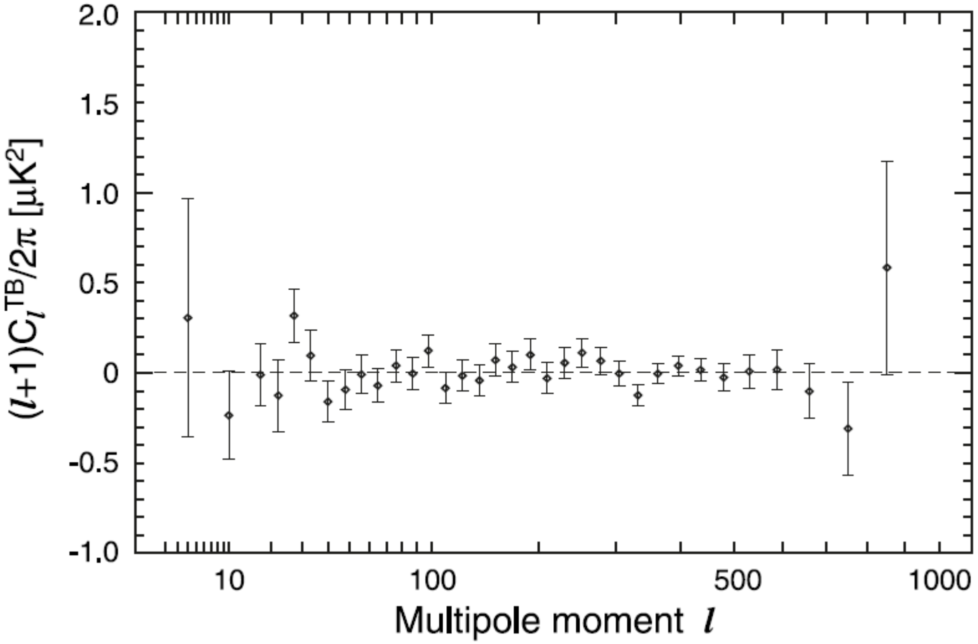
EB





WMAP 2008 - TB

Cosine-type potential *[note vertical axis]*



WMAP collaboration
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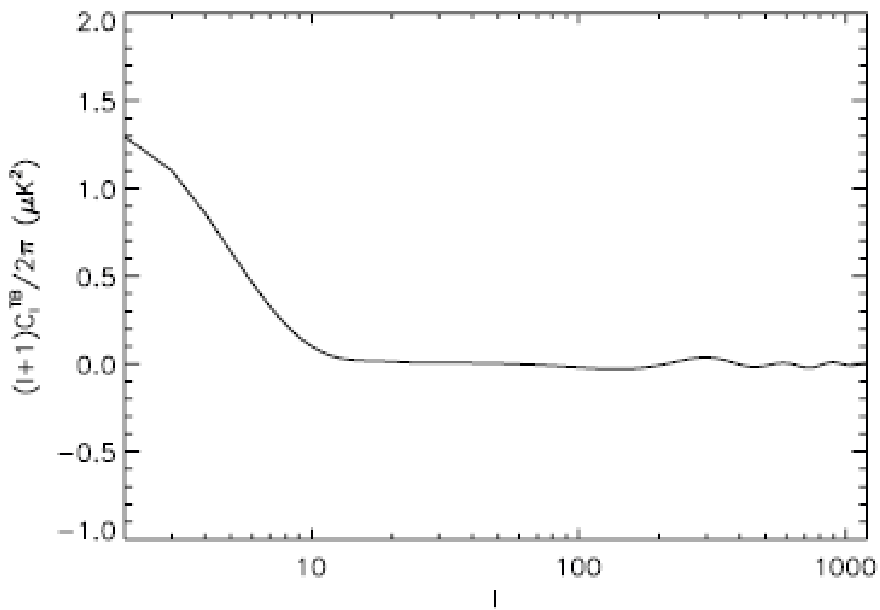


Cosine-type potential with:

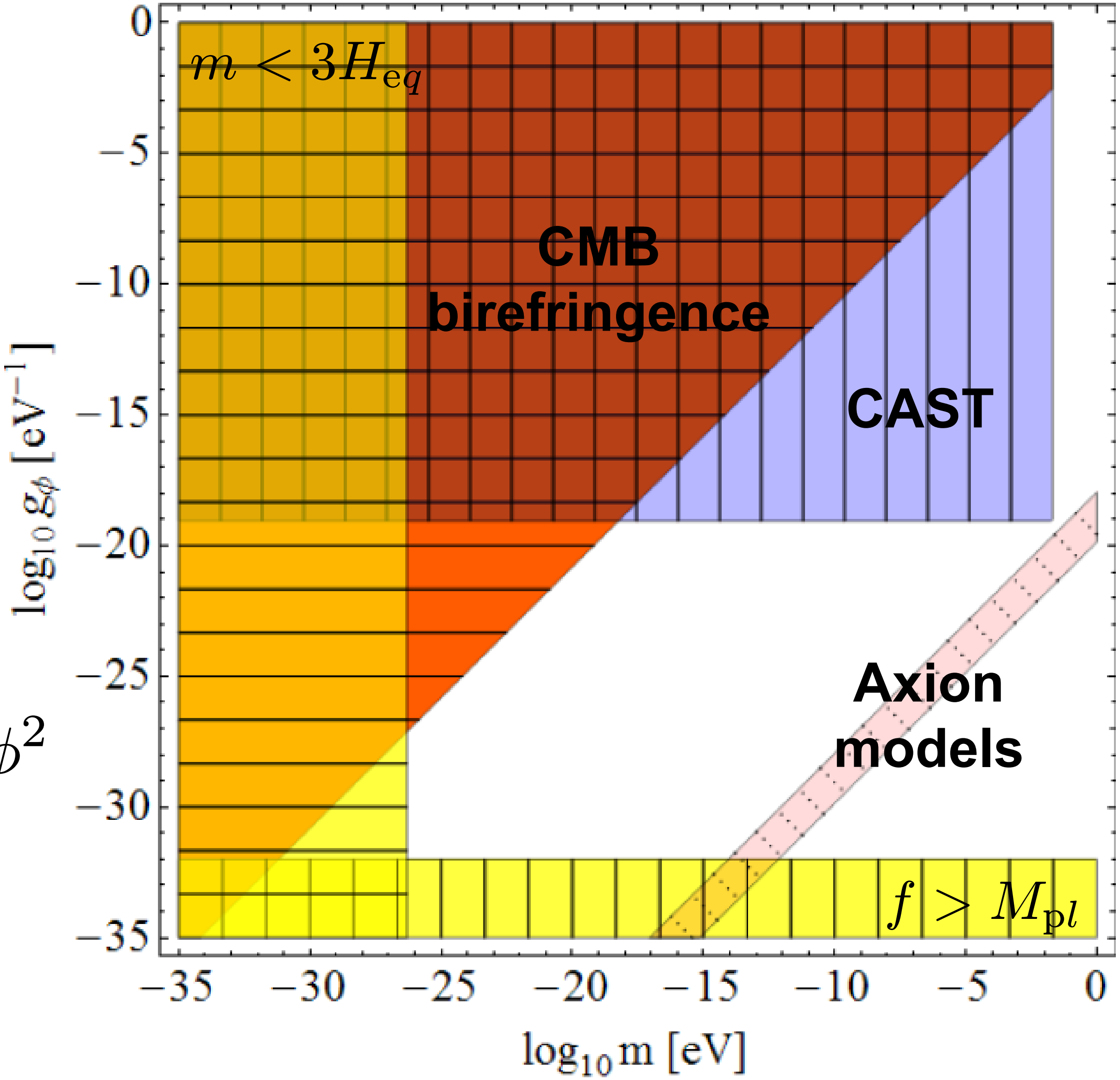
$m = 10^{-22}\ \mathrm{eV}\,,\quad g_\phi = 10^{-20}\ \mathrm{eV}^{-1}$

Photon coupling with pseudoscalar fields

Oscillating behaviour:

axion-like particles

$$\mathcal{L} = -\frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \frac{1}{2}m^2\phi^2 - \frac{g_\phi}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Ultralight pseudo Nambu-Goldstone bosons

In 1995 Frieman *et al.* [PRL **75**, 2077] proposed a quintessence model based on a pseudoscalar field.

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Cosmology with Ultralight Pseudo Nambu-Goldstone Bosons

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(Received 17 May 1995)

We explore the cosmological implications of an ultralight pseudo Nambu-Goldstone boson. With global spontaneous symmetry breaking scale $f \simeq 10^{18}$ GeV and explicit breaking scale comparable to Mikheyev-Smirnov-Wolfenstein neutrino masses, $M \sim 10^{-3}$ eV, such a field, which acquires a mass $m_\phi \sim M^2/f \sim H_0$, would currently dominate the energy density of the Universe. The field acts as an effective cosmological constant before relaxing into a condensate of nonrelativistic bosons. Such a model can reconcile dynamical estimates of the density parameter, $\Omega_m \sim 0.2$, with a spatially flat universe, yielding $H_0 t_0 \simeq 1$ consistent with limits from gravitational lens statistics.

Ultralight pseudo Nambu-Goldstone bosons

In 1995 Frieman *et al.* [PRL **75**, 2077] proposed a quintessence model based on a pseudoscalar field.

This model is still in agreement with observations and can be probed by future experiment reaching stage 4 of DETF methodology (Planck CMB measurements, future SNIa surveys, baryon acoustic oscillations, and weak gravitational lensing). This analysis can be improved considering also birefringence of CMB polarization:

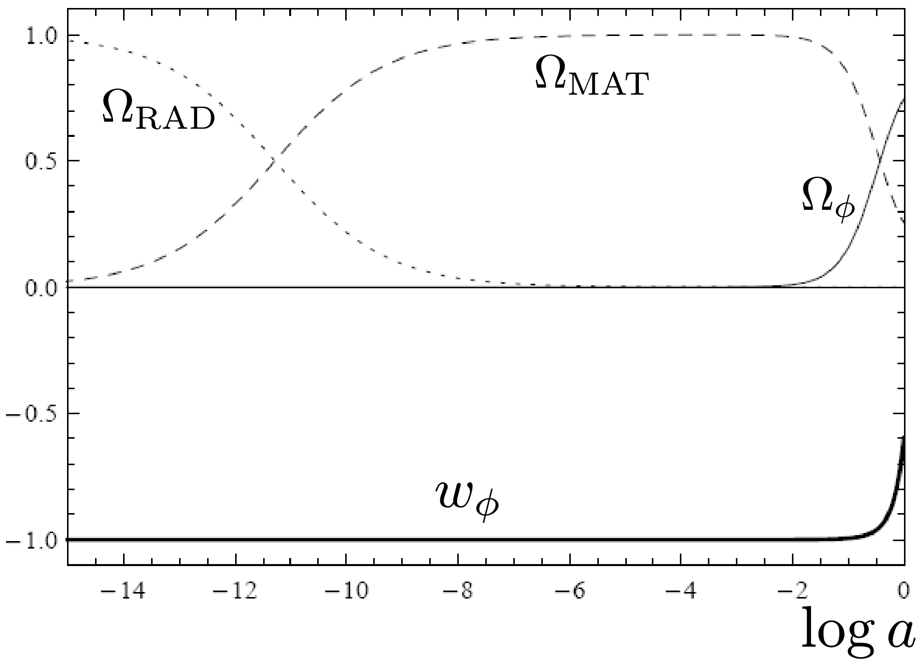
$$\begin{aligned} \mathcal{L}_\phi &= -\frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - M^4\left(1+\cos\frac{\phi}{f}\right) \\ \mathcal{L}_{\phi\gamma} &= -\frac{1}{4f}\phi F^{\mu\nu}\tilde{F}_{\mu\nu} \end{aligned}$$

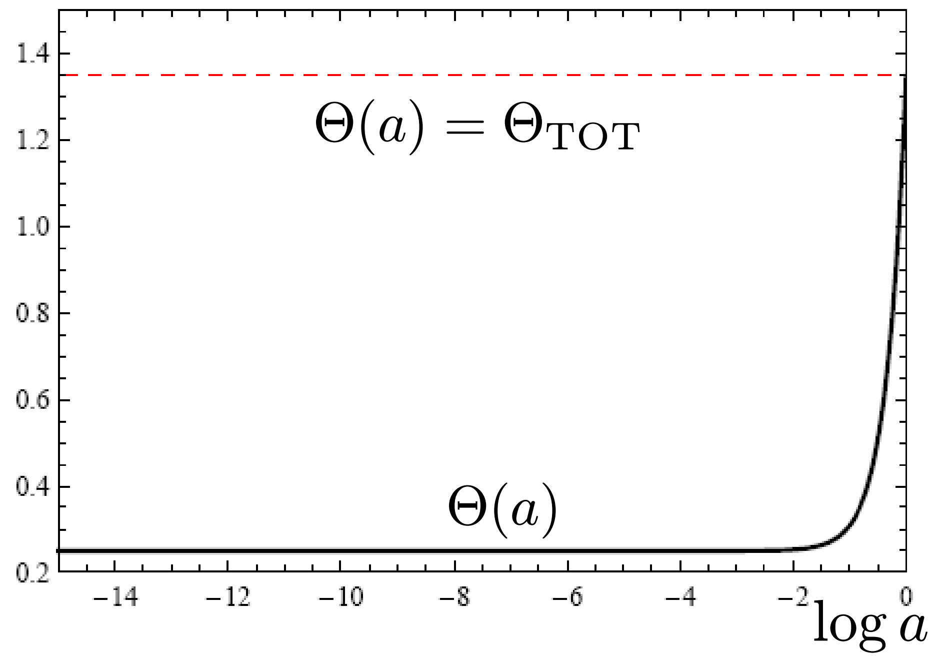
where: $M \sim 10^{-3}\ \mathrm{eV}$ and $f \lesssim M_{\rm pl}/\sqrt{8\pi}$

Ultralight pseudo Nambu-Goldstone bosons

Fixed $M = 8.8 \times 10^{-4}\ \mathrm{eV}\,,\ f = 0.3\frac{M_{\rm pl}}{\sqrt{8\pi}}\,,\ \Theta_i \equiv \frac{\phi}{f} = 0.25\,,\ \dot{\Theta}_i = 0$

the pseudoscalar field mimes the behaviour of the cosmological constant:

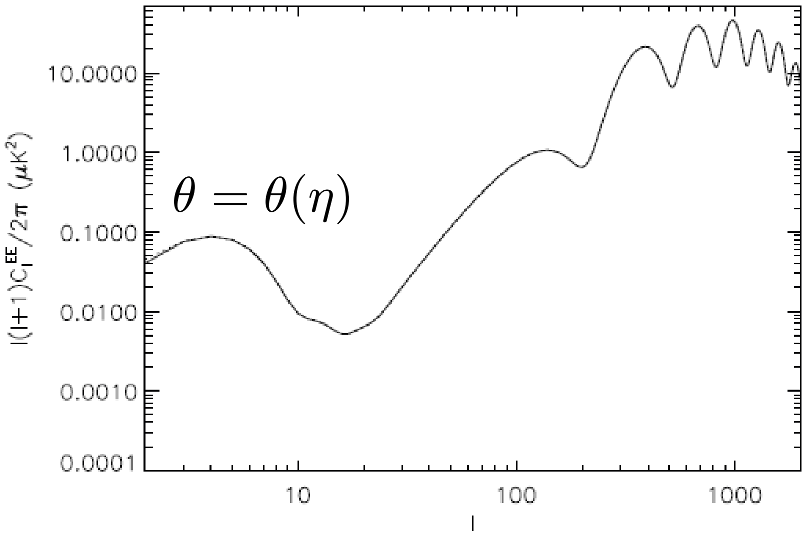


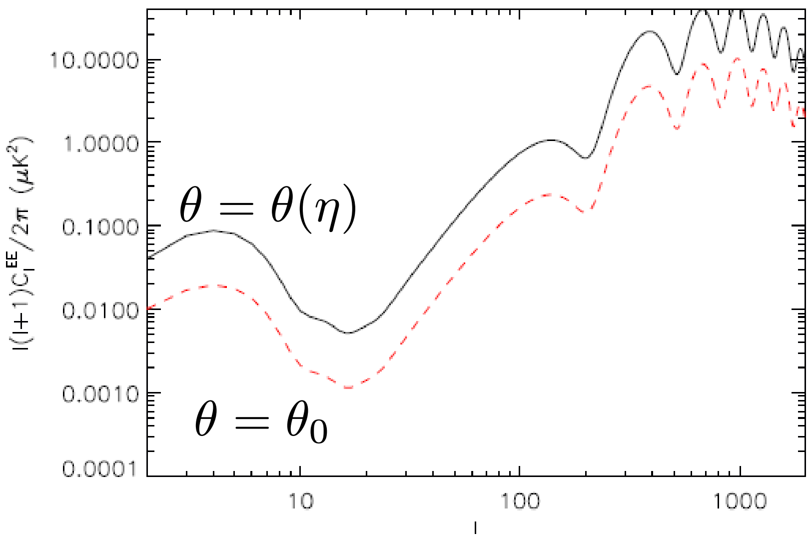


Ultralight pseudo Nambu-Goldstone bosons

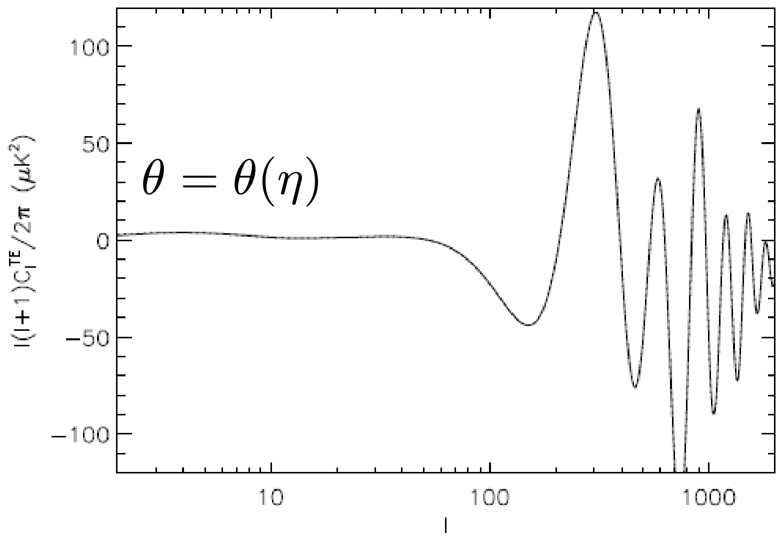
$\theta_0 \sim 0.54$ rad

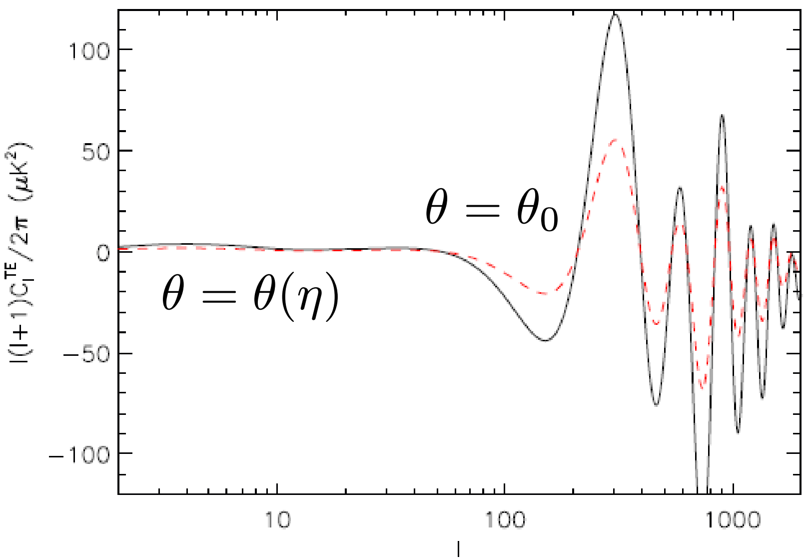
EE





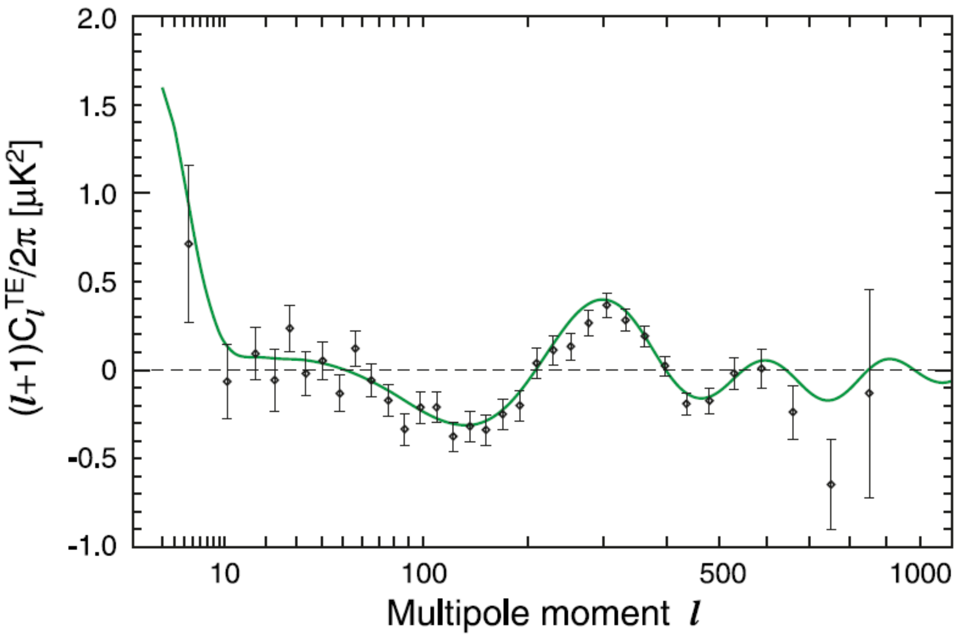
TE



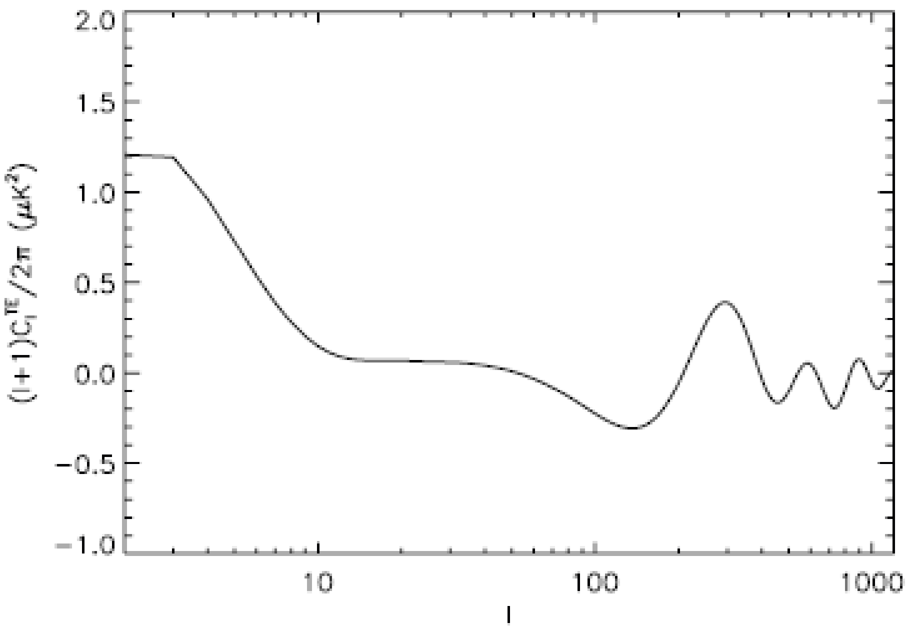


WMAP 2008 - TE

Ultralight pseudo Nambu-Goldstone bosons *[note vertical axis]*



WMAP collaboration
[arXiv:0803.0593]



Fixed:

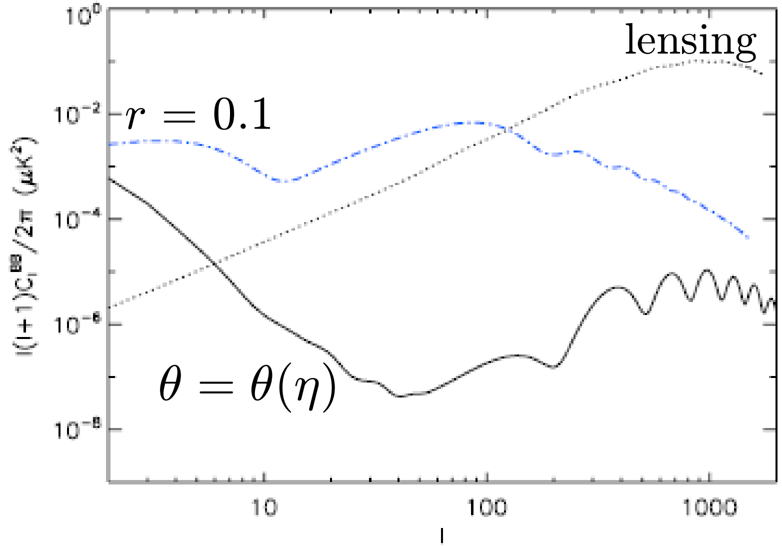
$$M = 8.8 \times 10^{-4}\ \mathrm{eV}\,,\ f = 0.3\frac{M_{\rm pl}}{\sqrt{8\pi}}\,,$$

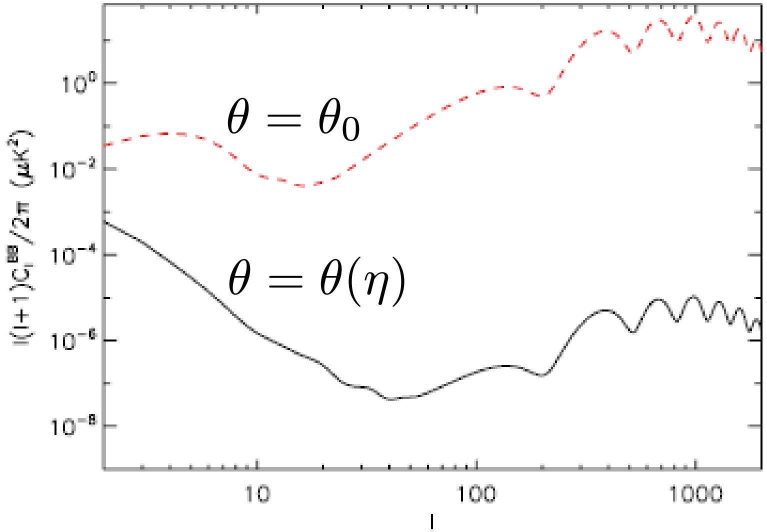
$$\Theta_i \equiv \frac{\phi}{f} = 0.25\,,\ \dot{\Theta}_i = 0$$

Ultralight pseudo Nambu-Goldstone bosons

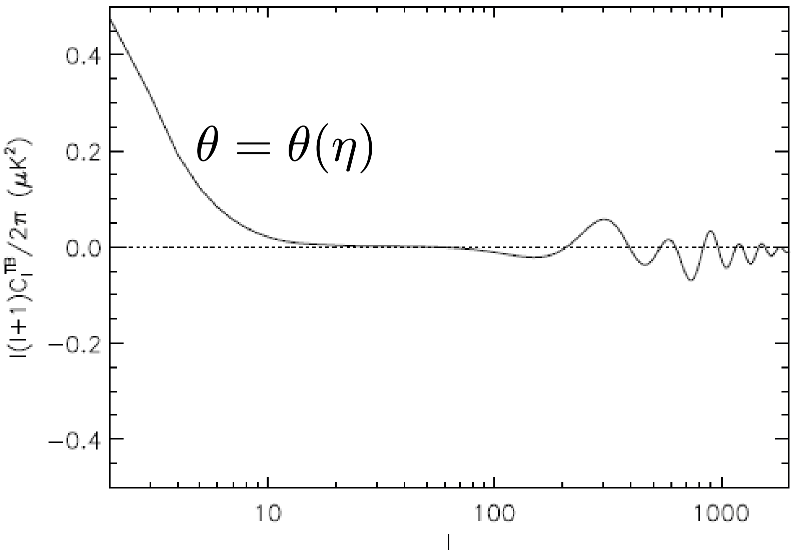
BB

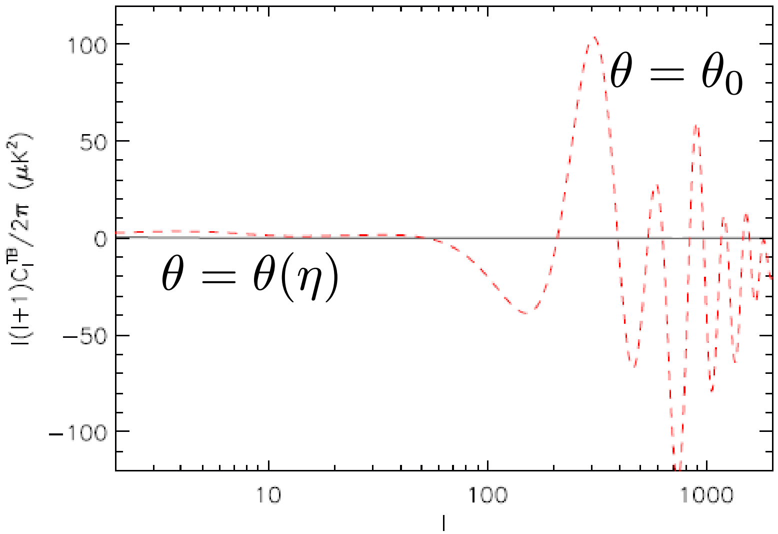
$\theta_0 \sim 0.54$ rad





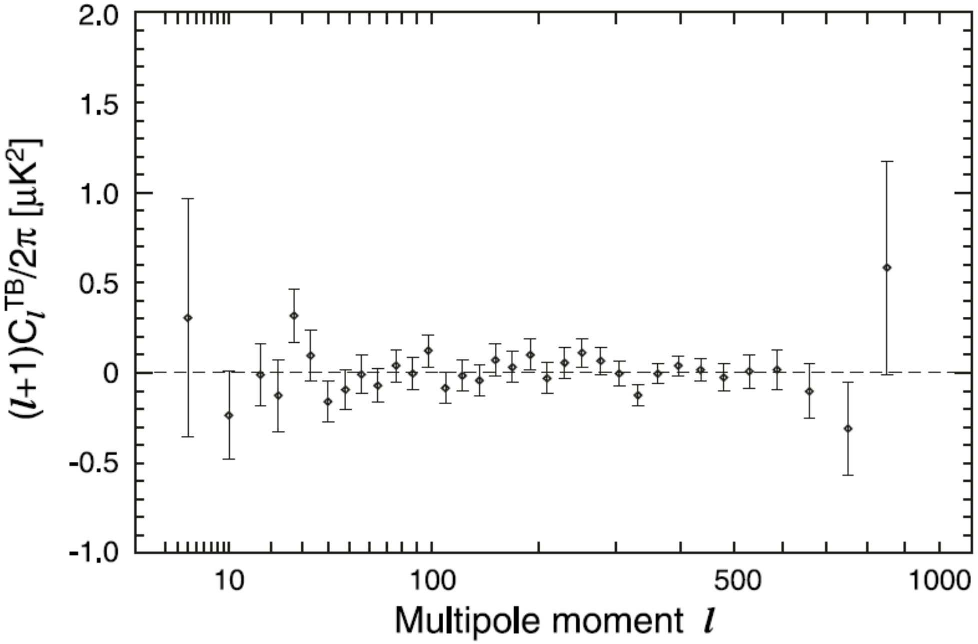
TB



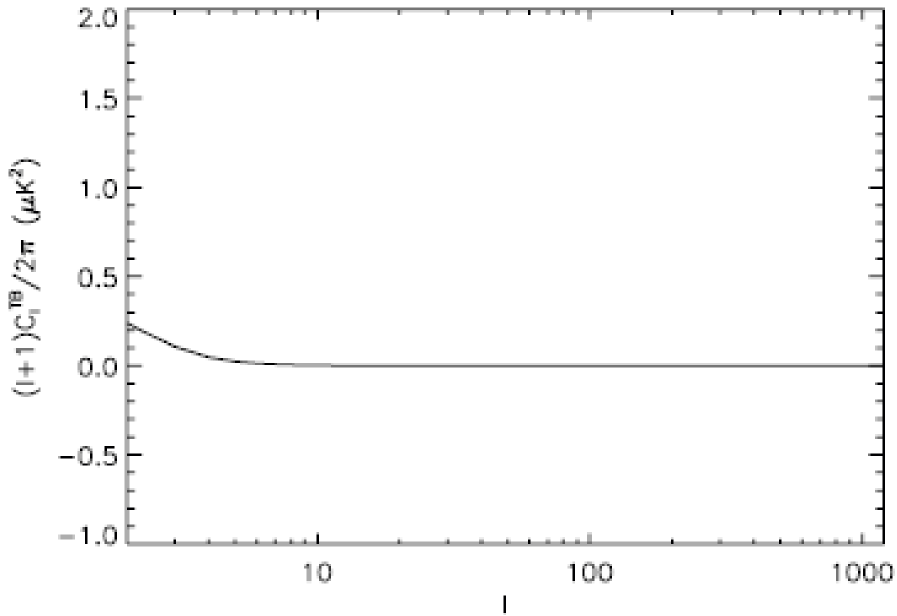


WMAP 2008 - TB

Ultralight pseudo Nambu-Goldstone bosons *[note vertical axis]*



WMAP collaboration
[**arXiv:0803.0593**]



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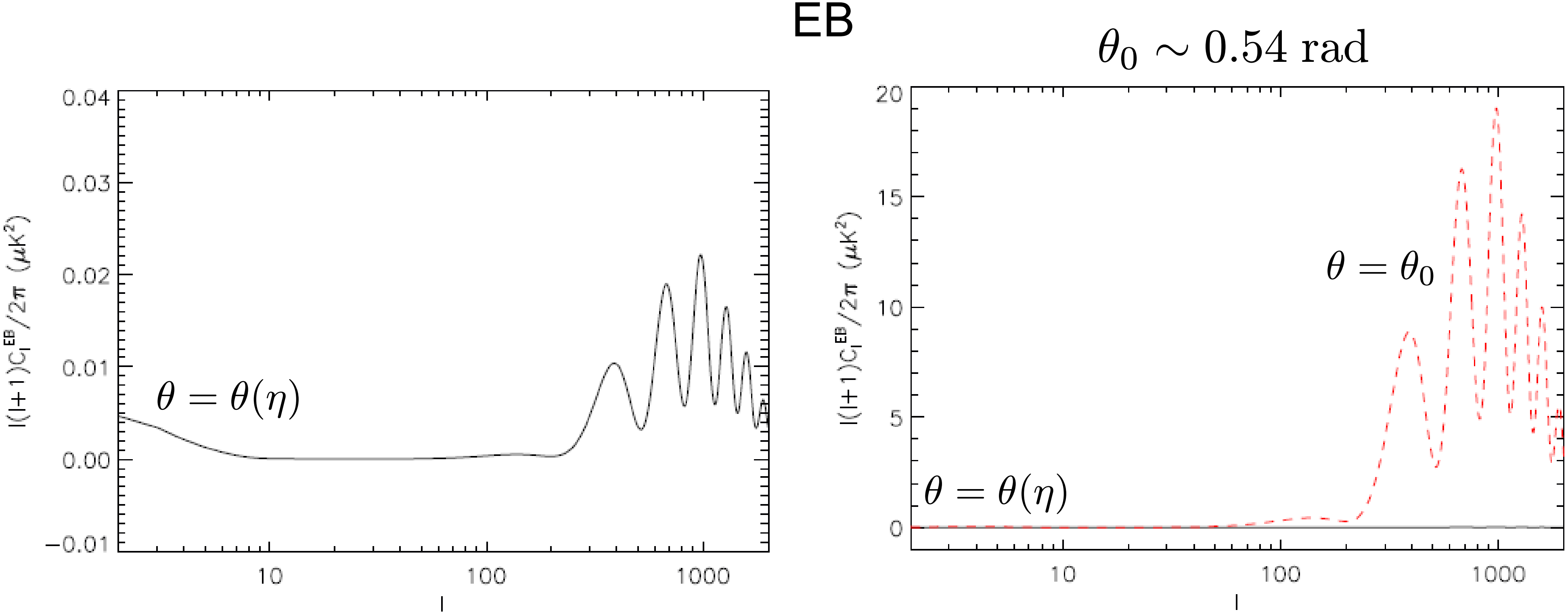
Ultralight pseudo Nambu-Goldstone bosons

EB



Conclusions & Developments

We discuss the effects of coupling between pseudoscalar fields and photons on Cosmic Microwave Background Polarization:

•how the public code CAMB can be modified in order to take into account the rotation of the linear polarization plane by a cosmological pseudoscalar field acting as dark matter from last scattering surface to nowadays.

•Polarization power spectra strongly depend on the kinematics of the pseudoscalar field.

CMB birefringence constraints are complementary to experiments and astroparticle observations