# Axions and CMB spectral distortions in cosmic magnetic field

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**Damian Ejlli**,
"Axion production and CMB spectral distortion in cosmological tangled magnetic field," arXiv:1504.00157

**Damian Ejlli**,
"Bounds on QCD axion mass and primordial magnetic field from CMB $\mu$-distortion," Phys. Rev. D **90** (2014) 123527

**Damian Ejlli and Alexander D. Dolgov**,
"CMB constraints on mass and coupling constant of light pseudoscalar particles," Phys. Rev. D **90** (2014) 063514

# Table of contents

# CMB spectral distortions

- The COBE/FIRAS experiment showed that CMB has almost a perfect blackbody spectrum with temperature $T = 2.725 \pm 0.001$ K.
- COBE/FIRAS did not detect any spectral distortion of the CMB at all!
- However, the standard model of cosmology predicts distortions in the spectrum from processes which heat, cool, scatter and create CMB photons, throughout most of the history of the Universe.
- Most of processes that might create CMB spectral distortions are in general connected with new physics.
- However, there are also processes that create spectral distortions that are connected with very well known physics.

# CMB spectral distortions

- Spectral distortions are very small but fortunately significant progress in technology in the last two decades an improvement of 2 to 3 orders of magnitude over COBE/FIRAS.
- Proposed space mission with improved sensitivity with respect to COBE include: PIXIE, PRISM, CoRE, LiteBIRD.
- PIXIE will be able to make absolute measurements as well as measure anisotropies with an angular resolution of 2.6 degree.
- CoRE and LiteBIRD will be able to measure only the frequency dependent anisotropies with high sensitivity and have proposed angular resolutions of $\sim 5'$ and $\sim 30'$ respectively.

# CMB spectral distortions

- Mechanisms that might produce spectral distortions by injecting energy and photons in the plasma include: evaporating primordial black holes, decaying of relic particles, dark matter annihilation, tangled cosmological magnetic fields.
- However, there are also processes that tend to erase any spectral distortion that might be created in the CMB and attempt to restore the full thermal equilibrium, *thermalization*.
- Energy release or absorption in the early Universe can lead to distortions of the Planckian spectrum (**Sunyaev and Zel'dovich 1970, Illirianov and Sunyaev 1973**)
- numerical and analytical approaches for solution of the photon kinetic equation for small spectral distortions were done by (**Danese and De Zotti '77, '82, Burigana, Danese and De Zotti 1991, Hu and Silk 1996, Burigana and Salvaterra 2003, Chubla and Sunyaev 2012**)

# $y$ distortion

- When CMB photons pass through a gas of hot electrons $T_\gamma \ll T_e$, its spectrum it is slightly distorted due to Compton (**Sunyaev and Zel'dovich 1969**) ($x = \nu/T$)

$$\frac{\partial n_\gamma}{\partial y} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(n_\gamma + n_\gamma^2 + \frac{T}{T_e}\frac{\partial n_\gamma}{\partial x}\right), \quad y(z) = \int_0^z dz \frac{\sigma_T n_e T}{m_e H(1+z)}$$

- $y$ distortion is formed for redshift values of $z \leq 1.5 \times 10^4$ with photon occupation number ($y \ll 1$)

$$n_\gamma = y\frac{xe^x}{(e^x-1)^2}\left[x\left(\frac{e^x+1}{e^x-1}\right) - 4\right]$$

- The Sunyeav-Zel'dovich effect has been observed by several instruments including Planck, ACT and SPT in the direction of many clusters of galaxies

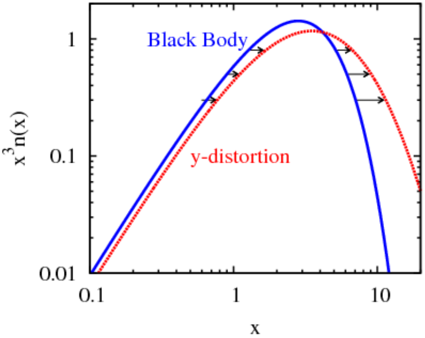



Figure : CMB intensity $I \propto x^3 n_\gamma(x)$ vs. dimensioneless frequency $x$ for $y$ type distortion

# $\mu$ distortion

- Compton scattering when efficient can restore the BE distribution of distorted CMB with $|\mu| \neq 0$
- Inelastic processes lead to a decrease of $|\mu|$ and restore complete equilibrium for $z \geq 2 \times 10^6$ **Khatri and Sunyaev 2013**
- For $2 \times 10^5 \lesssim z \lesssim 2 \times 10^6$, energy release or absorption would eventually create the BE distribution of CMB with $|\mu| \neq 0$
- Most of mechanisms of spectral distortions, generate very small $\mu \ll 1$
- For small chemical potential $\mu \ll 1$ the photon occupation number is

$$n_\gamma = \frac{\mu e^x}{(e^x - 1)^2} \left[ \frac{x}{2.19} - 1 \right]$$

- The chemical potential can be either positive or negative depending on the energy release or absorption.

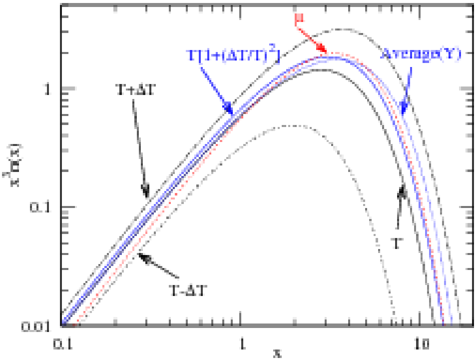



Figure : $I_\nu$ vs. $x$ for CMB $\mu$ distortion (red line). The spectrum of two blackbodies with different temperature is also shown, *Sunyaev and Khatri 2013*

# CMB spectral distortions

- Current limits on the CMB spectral distortions from COBE/FIRAS are $\mu < 5 \times 10^{-5}$ and $y < 9 \times 10^{-4}$
- future space missions that have better sensitivity than COBE/FIRAS include PRISM and PIXIE
- these space missions, among other studies, would in principle detect spectral distortions with parameters of the order $\mu \simeq 10^{-8}$ and $y \simeq 10^{-8}$

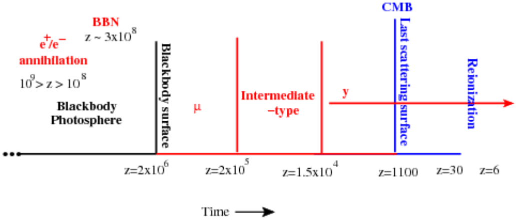



Figure : *Khatri and Sunyeav 2012*

# Large scale magnetic field

- Magnetic fields seems to be everywhere in the Universe. They are present in our solar system, in stars (**Donati and Landstreet 2009**), in the Milky way (**Wielebinski 2005**), in low and high redshift galaxies and galaxy clusters (**Kronberg 1994, Beck 2012**), in superclusters (**Xu et al. 2006**) and in voids of LSS (**Neronov and Vovk 2010**).
- Magnetic field strength in galaxies is of the order of few to ten $\mu$G independently on the redshift (**Kronberg et al.1992**) while in clusters is of the order of $\mu$G (**Ferretti et al. 2012**).
- Magnetic fields in astronomical objects from stars to galaxy clusters, are thought to be produced by amplification of pre-existing weaker magnetic fields via different types of dynamo and via flux-conserving compression during gravitational collapse accompanying structure formation.

- The dynamo and compression amplification mechanisms can act only if a non-zero magnetic field is present. This seed field for the amplification might be tiny, but it has to be generated by a different mechanism, which pre-dates the structure formation epoch or operates at the on set of structure formation.
- Two main models have been proposed: either it is produced in the early universe prior to the epoch of LSS or it is produced during gravitational collapse at the start of LSS.
- The existing data on magnetic fields in galaxies and galaxy clusters cannot provide direct constraints on the properties and origin of the seed fields.
- The only potential opportunity for understanding the nature of the initial seed fields is to search for places in the Universe where these fields might exist in their original form, namely in the intergalactic medium (IGM), more precisely, the voids of LSS.

# Homogeneous magnetic field

- The first studies on homogeneous cosmological magnetic field were done by (**Y. Zeldovich 1965 and K. Thorne 1967**)
- Such fields may permeate all universe with a scale up to the horizon scale $H_0^{-1} \simeq 10^{28}$ cm.
- For a homogeneous magnetic field directed along the z axis, the metric has the form (Bianchi type IX metric)

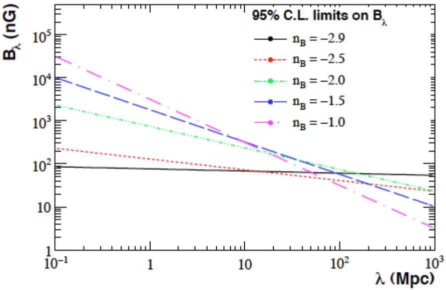
$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2) - b^2(t)dz^2$$

- The energy momentum of EM field is anisotropic with positive pressure along x-axis (deceleration) and negative pressure along y-axis (acceleration)
- The induced temperature anisotropy is ($\alpha = \dot{a}/a, \beta = \dot{b}/b$) and $\sigma = \alpha - \beta$

$$(T_x - T_z)/T_{rec} \simeq -(1/2) \int_{t_{rec}}^{t_0} \sigma d(lnt)$$

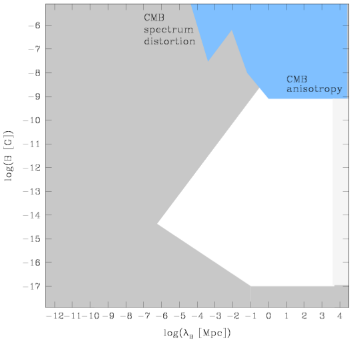
# Tangled magnetic field

- Several models predict magnetic field spectra with no homogeneous term, inhomogeneous (tangled) magnetic field.
- From CMB angular anisotropy, $B_\lambda \lesssim 3 \cdot 10^{-9}$ G on length scale $\lambda_B \sim$ Mpc (**Paoletti and Finelli '12**)
- Faraday rotation of the CMB polarization, $B_\lambda \lesssim 10^{-8} - 10^{-6}$ G for $\lambda_B \sim 10^3$ Mpc (**Kahniashvili et al. '09**)



# Tangled magnetic field

- Limits on homogeneous and inhomogeneous (tangled) magnetic field from CMB anisotropy and spectral distortions



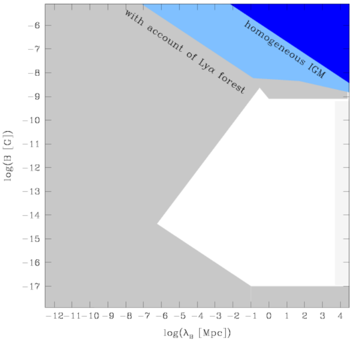




Figure : Limits on $B$ and $\lambda_B$( *Durrer and Neronov 2013*)

# Eq. of motion for photon-pseudoscalar mixing

- The Lagrangian density of photons+pseudoscalars and their interaction is

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\alpha^2}{90 m_e^4}\left[(F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4}(\tilde{F}_{\mu\nu}F^{\mu\nu})^2\right] + \frac{1}{2}\left(\partial_\mu\phi\partial^\mu\phi - m_\phi^2\phi^2\right) - \frac{g_{\phi\gamma}}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}\phi,$$

- the classical equations of motion in the WKB regime are $(\lambda_p \ll \lambda_B)$

$$\left[(\omega + i\partial_{\mathbf{x}})\mathbf{I} + \begin{bmatrix} m_+ & 0 & 0 \\ 0 & m_\times & m_{\phi\gamma} \\ 0 & m_{\phi\gamma} & m \end{bmatrix}\right]\begin{bmatrix} A_+ \\ A_\times \\ \phi \end{bmatrix} = 0\,,$$

where $m_+ = \omega(n-1)_+$, $m_\times = \omega(n-1)_\times$, $m_{\phi\gamma} = g_{\phi\gamma}B_T/2$, $m = -m_\phi^2/2\omega$

# Mixing angle and transition probability

- the diagonalized matrix $\mathcal{M}'$ has the entries

$$\mathcal{M}' = \begin{bmatrix} m'_1 & 0 \\ 0 & m'_2 \end{bmatrix} \qquad m'_{1,2} = \frac{m_\lambda}{2} \pm \frac{m_\lambda}{2\cos\theta}$$

- the mixing angle reads ($m_{\phi\gamma} = g_{\phi\gamma} B_T/2$)

$$\frac{1}{2}\tan(2\theta) = \frac{m_{\phi\gamma}}{m'_2}$$

- the probability for a photon with polarization state $A_+$ to transform into a pseudoscalar $\phi$ after traveling a distance $z$ is

$$P_{\phi\gamma} = |\langle\phi(z)|A_+(0)\rangle|^2 = \sin^2(2\theta)\sin^2(m_{\phi\gamma} z/2)$$

# Eq. of motions for the density operator: photon-axion

- the wave function approximation is not accurate on describing the oscillation process in the case when the oscillation length is greater than the mean free path, $l_{osc} \gg l_{free}$
- the system becomes open and total Hamiltonian is not hermitian.
- when there is a loss of coherence a density matrix description is needed
- We need to write equations of motions in the FRW metric

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\mathrm{d}x_i\mathrm{d}x_j$$

- in the FRW metric the density operator equation reads

$$HT\frac{d\rho}{dT} = i[M, \rho] - \{\Gamma, (\rho - \rho_{eq})\}$$

# Eq. of motion for photon-pseudoscalar mixing

- Both photons and ALPs interact with medium and photons have stronger interactions with it
- equations of density operator are complicated!

$$
\begin{aligned}
\rho_\gamma' &= \frac{2m_{\phi\gamma} I + \Gamma_\gamma \left(\rho_\gamma - \rho_{\rm eq}^\gamma\right)}{HT}, \\
\rho_\phi' &= \frac{-2m_{\phi\gamma} I + \Gamma_\phi (\rho_\phi - \rho_{\rm eq}^\phi)}{HT}, \\
R' &= \frac{-(m_\times - m_a) I + (\Gamma_\gamma + \Gamma_\phi) R/2}{HT}, \\
I' &= \frac{(m_\times - m_a) R + (\Gamma_\gamma + \Gamma_\phi) I/2 + m_{\phi\gamma}(\rho_\phi - \rho_\gamma)}{HT},
\end{aligned}
$$

- the system of equations is highly stiff! very difficult to solve numerically!

# Hydrogen ionization history

- For $T > 4226$ K hydrogen is completely ionized
- The solution for $X_e(T)$ for $T < 4226$ K is valid until the period of re-ionization of the Universe.
- Universe re-ionization epoch is the most mysterious in the whole its evolution
- Re-ionization started at $z \sim 20$ and was completed at $z \sim 7$ **Dunkley et al (WMAP Collaboration) '09**

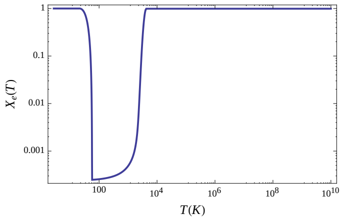



Figure : Ionization fraction *Ejlli and Dolgov 2013*

# Steady state approximation

- Even in the case of photon-pseudoscalar mixing $l_{\rm osc} \ll H^{-1}$, $I' \simeq R' \simeq 0$ where $I' \simeq 0$ and $R' \simeq 0$
- a closed system of diff. equation is obtained here

$$
\begin{aligned}
\rho'_\gamma &= \frac{1}{HT}\left[\Gamma_\gamma(\rho_\gamma - \rho_\gamma^{eq}) + \frac{4\Gamma m^2_{\phi\gamma}}{4\Delta m^2 + \Gamma^2}(\rho_\gamma - \rho_\phi)\right], \\
\rho'_\phi &= \frac{1}{HT}\left[\Gamma_\phi(\rho_\phi - \rho_\phi^{eq}) - \frac{4\Gamma m^2_{\phi\gamma}}{4\Delta m^2 + \Gamma^2}(\rho_\gamma - \rho_\phi)\right].
\end{aligned}
$$

where $\Delta m = m_\times - m_a$

- the initial conditions are $\rho_\phi(T_i) = 0$ and $\rho_\gamma(T_i) = \rho_\gamma^{eq}$.

## How to limit the ALP parameter space?

- We do not know which is the mass $m_{\phi\gamma}$ and coupling constant $g_{\phi\gamma}$. In the case of ALPs they are unrelated while in the case of QCD axion there is a linear relationship between the two.
- we can use limits on $\mu$ and $\delta T/T$ to constrain the ALP parameter space (**Ejlli and Dolgov 2014**)
- for small chemical potential $\mu$ we can bound the ALP production probability

$$P_\phi \simeq \mu \frac{e^x}{e^x - 1}, \qquad x = \omega/T$$

- at post recombination we require that the CMB photon deficit in the direction perpendicular to the external magnetic field relative with CMB photons propagating along field direction should be comparable with temperature anisotropy

$$P_\phi(x) \lesssim \delta T/T$$

# Limits from COBE and sensitivity for PIXIE/PRISM

Tighter limits comes from ALPs hitting the resonance

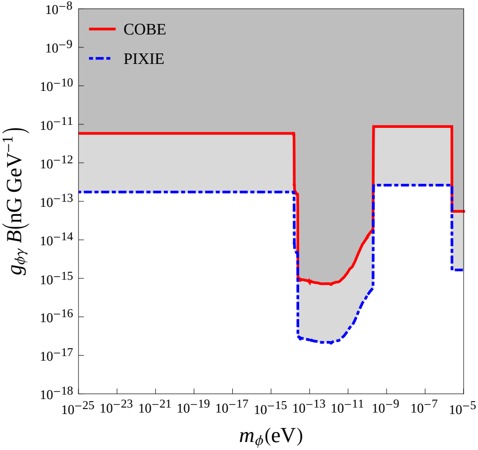


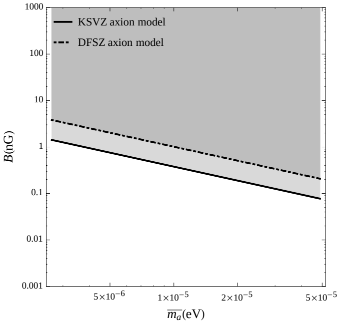

Figure : Ejlli and Dolgov 2013

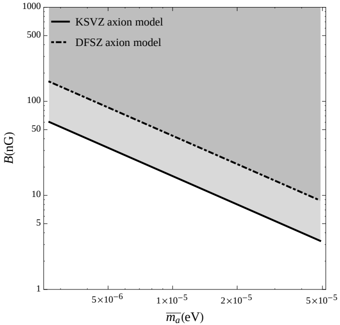
# What about the QCD axion?

- The QCD axion is phenomenologically different from ALPs
- extensions of the standard model (KSVZ and DSFZ axions models), in principle relate both $m_a$ and $g_{a\gamma}$
- in the KSVZ and DSFZ axions models, the number of independent parameters is two ($B$ and $m_a$)
- we can use CMB limits on $\mu$ to constrain both $B$ and $m_a$ for homogeneous and tangled magnetic field (**D. Ejlli 2014 and 2015**)
- moreover we can predict the mass range of axions which could be find by of PIXIE/PRISM

# Limits on the QCD axion mass from homogeneous $B$

- left COBE limits on $B - m_a$ and on the right, expected sensitivity for PIXIE/PRISM
- if $m_a \simeq 5 \times 10^{-5}$ eV, the limit on $B \lesssim 3.2$ nG
- if $B \sim 1 - 3$ nG, PIXIE/PRISM could detect axions with mass $m_a \simeq 2 - 3\mu$ eV (*D. Ejlli 2014*)



# Limits on the strength of tangled $B$

- If the magnetic field is tangled it would dissipate energy and generate spectral distortions prior to recombination.
- Also axions would generate spectral distortions as well. Which one would win?

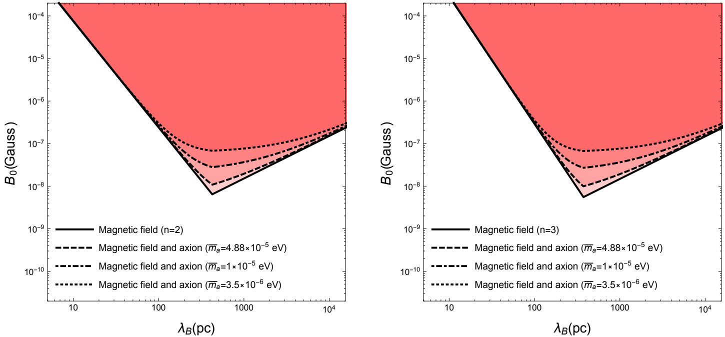



Figure : *DFSZ axion model, Ejlli 2015*

# Limits on the strength of tangled $B$

- Magnetic field with negative power index is in general generated by noncasual mechanism such as inflation.

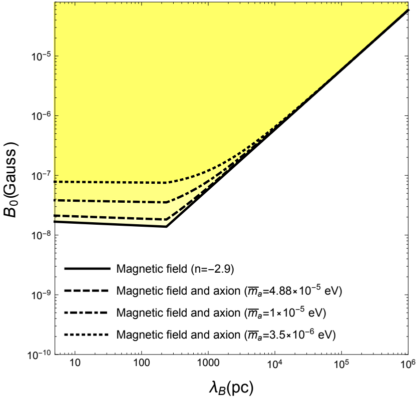



Figure : *DFSZ axion model, Ejlli 2015*

# Conclusions

- CMB turn out again to be one of the most important ways that we have to test fundamental physics
- It can couple to large scale magnetic field and oscillate into low mass bosons (axions and pseudo-scalars particles)
- the oscillation probability depends essentially on $g_{a\gamma}$ for axions and $g_{\phi\gamma}, m_\phi$ for pseudo-scalars
- Axions and ALPs are extremely important for the SM, its extension and string theory. However, we don't know $g_{\phi\gamma}, m_\phi$
- CMB spectral distortions gives stringent bounds on $g_{\phi\gamma}, m_\phi$ for light pseudo-scalars $10^{-25}$ eV$\lesssim m_\phi \lesssim 10^{-5}$ eV
- axions in the mass range $m_a \simeq 2 - 3\mu$ eV could be indirectly detected by PIXIE/PRISM
- Very stringent limits on the large scale scale homogeneous magnetic field in comparison with other methods. In case of tangled fields the limits are in general weaker!