PHOTON-AXION OSCILLATIONS WITH ELMAG

(www.tuhogar.com)

Jonas Tjemsland

PhD candidate
Supervisor: Michael Kachelrieß
Norwegian University of Science and Technology

TOOLS 2021

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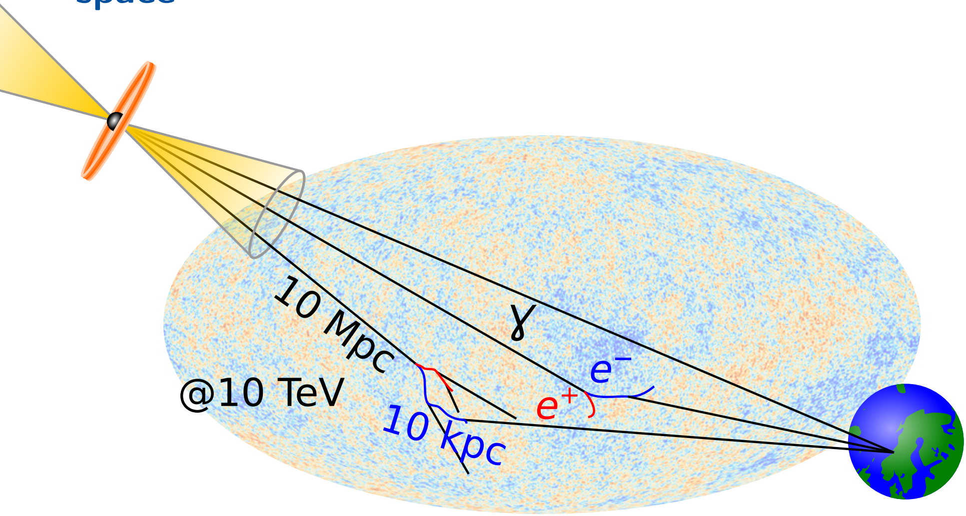
Summary

Electromagnetic cascades in extragalactic space



ELMAG [1106.5508, 1909.09210]

Monte Carlo simulation tool for electromagnetic cascades of high-energy photons and electrons

- $\gamma + \gamma_{\mathrm{EBL}} = e^+ + e^-$ (pair production [$E \lesssim 10^{15}$ eV])
- $e^\pm + \gamma_{\mathrm{EBL}} = e^\pm + \gamma$ (inverse Compton scattering)
- Photon-axion oscillations in a magnetic field ($a \leftrightarrow \gamma$)

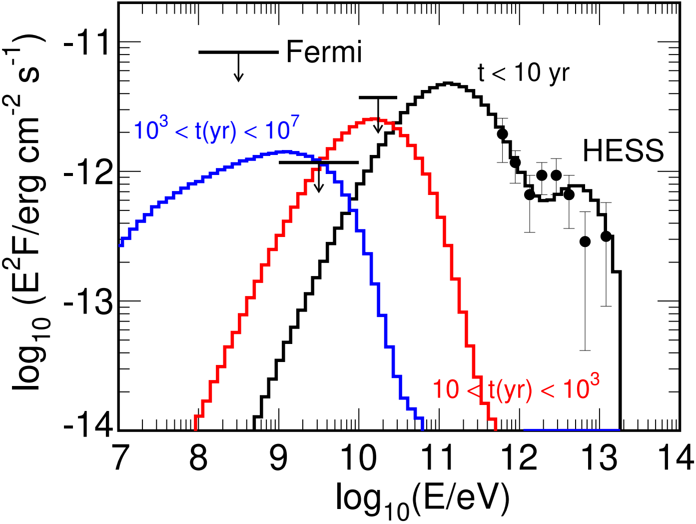
Features:

- Deflection in magnetic fields
- Adiabatic energy losses
- Synchrotron losses
- Plasma instabilities
- Detector properties
- ...

Results:

- Energy spectrum
- Observation angle
- Time delay
- Two-dimensional source images

Example: Spectrum of blazar 1ES 0029+200



[1106.5508]

The strong CP problem and axions

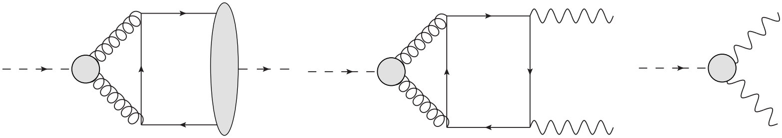
$$\mathcal{L}_{\rm SM} \supset \frac{\vartheta g^2}{8\pi^2} G\tilde{G}, \quad \vartheta \in [0, 2\pi)$$

- Measurements of the neutron dipole moment $\Rightarrow |\vartheta| \lesssim 10^{-10}$
- Fine tuning: Why not $\vartheta = \mathcal{O}(1)$?!
- The Peccei-Quinn solution:

  (Peccei, Quinn 1977, Wilczek 1978; Weinberg 1978)

  Make ϑ dynamically relax to 0 by introducting an U(1) chiral symmetry spontaneously broken at an energy f_a

$\Rightarrow$ Axions, $\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - \frac{g^2}{16\pi^2}\frac{a}{f_a} G\tilde{G}$



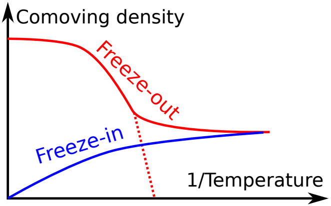
Axionic dark matter

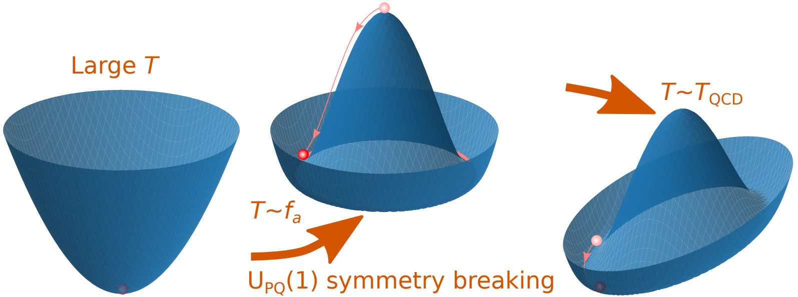
- Very light, $m_a \lesssim \mathrm{eV}$

⇒ Thermal production gives hot dark matter...

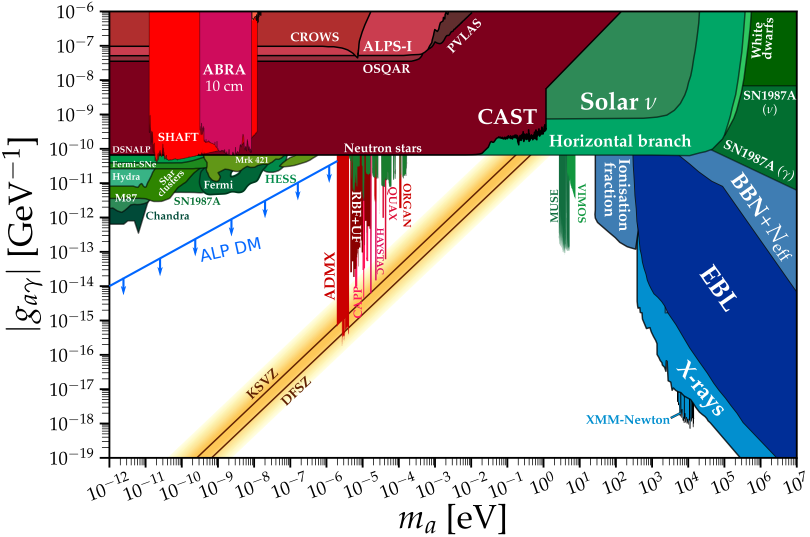
- Misalignment mechanism
  (Preskill, Wise, Wilczek 1983, ++)

→ The axion field oscillates coherently and looses energy by producing physical axions





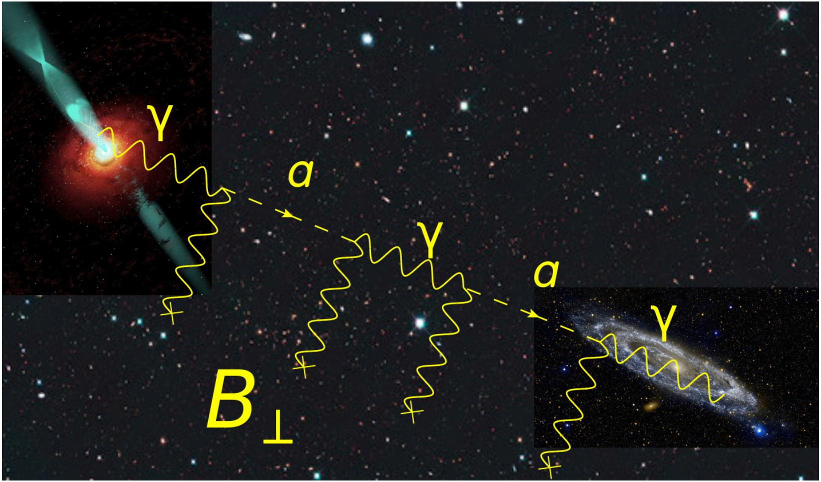
The ALP parameter space



(adapted from [10.5281/zenodo.3932430])

Photon-axion oscillations in TeV astrophysics

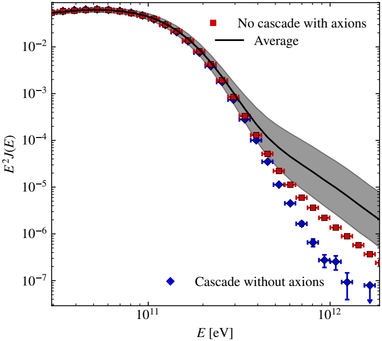
Based on [2111.08303]



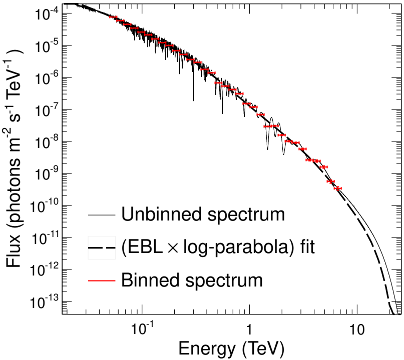
Divergence free Gaussian turbulent field, Kolmogorov spectrum,
$B \sim \mathrm{nG}$, $L_{\mathrm{coh}} \sim \mathrm{Mpc}$, $g_{a\gamma} \sim 10^{-20}\ \mathrm{eV}^{-1}$

Observational consequences

Increased opacity of the Universe



"Irregularities" in photon spectra



(Adapted from [1205.6428])

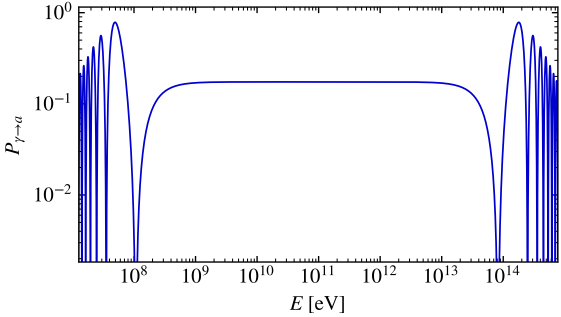
Photon-axion oscillations

Oscillation due to a mass difference of two mass eigenstates

$$\Rightarrow P_{\gamma\to a} = |\langle a|\Psi(t)\rangle|^2 = \sin^2(2\vartheta)\sin\left(\frac{L}{2E}\left(m_1^2 - m_2^2\right)\right)$$

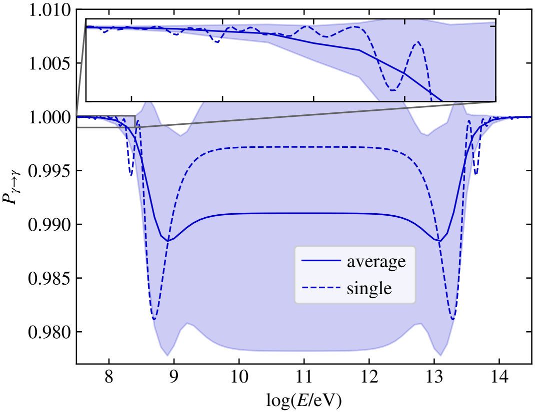
$$\Delta_{\rm osc}^2 = (\Delta_\gamma - \Delta_a)^2 + 4\Delta_{a\gamma}^2; \qquad \Delta_{a\gamma} = \frac{g_{a\gamma}B_\perp}{2}$$

$$\Delta_\gamma = \Delta_\gamma^{\rm CMB} + \Delta_\gamma^{\rm QED} + \Delta_\gamma^{\rm pl}$$



Energy dependence in a turbulent field

$$\left(-\mathrm{i}\frac{\partial}{\partial z} + E + \mathcal{M}\right)\begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0; \qquad \mathcal{M} = \mathcal{M}(B_\perp, E)$$



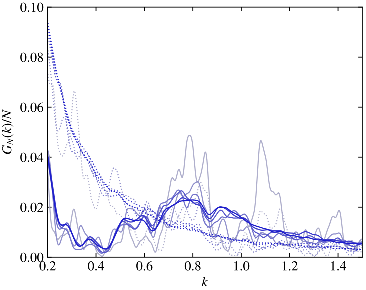
A direct detection of axion wiggles

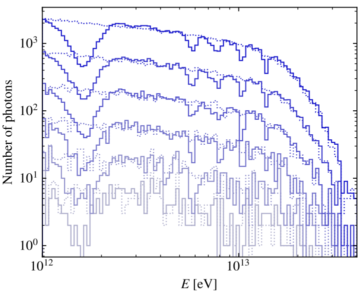
- **Idea:** Use the energy dependence of the wiggles as observable

$$G(k) = \left| \int_{\eta_{\min}}^{\eta_{\max}} \mathrm{d}\eta\, q(\eta) \mathrm{e}^{\mathrm{i}\eta k} \right|^2 \approx \left| \frac{1}{N} \sum_{\text{events}} \exp\{\mathrm{i}\eta k\} \right|^2$$

- Observables:
  - Peak in $G(k)$ for $\eta \sim E$ at "low" energies
  - Peak in $G(k)$ for $\eta \sim E^{-1}$ at "high" energies
  - No systematic signal otherwise
- The signal can be used to infer information about the magnetic field

Example: detecting axion wiggles





Title: `ELMAG 3.03` [1106.5508, 1909.09210]

Webpage: `http://elmag.sourceforge.net`

Language: Fortran 90

Usage: Monte Carlo simulation of electromagnetic cascades on the extragalactic background light in magnetic fields.

Photon-axion oscillations with `ELMAG`

- Solves the photon-axion equation of motion in a Monte Carlo treatment of an electromagnetic cascade
- Includes cascade photons
- Can easily consider polarisation effects and any magnetic field configuration
- Axion wiggles can be detected using the discrete power spectrum

Will be made public in a future release of `ELMAG`.