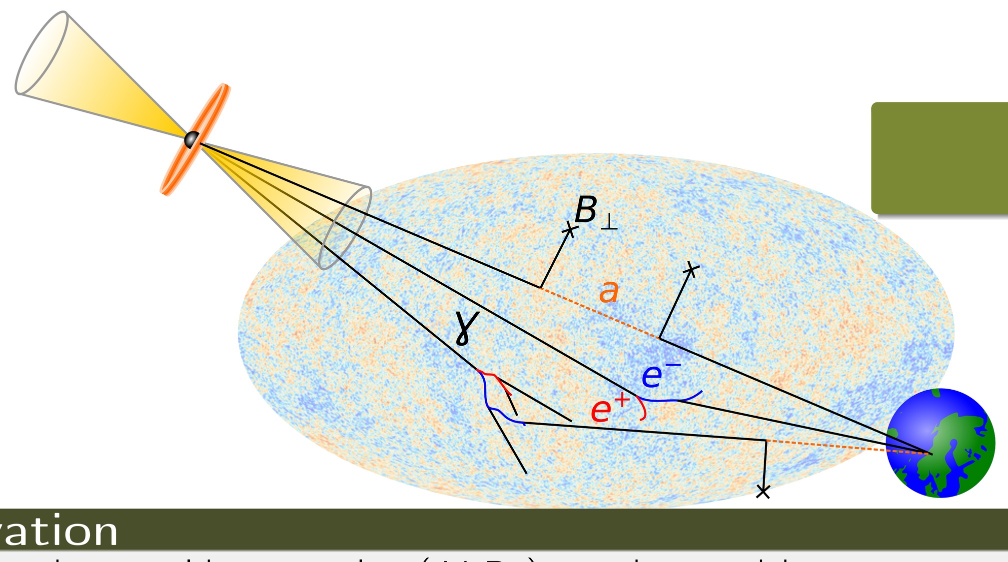

Photon-ALP oscillations at TeV energies

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Motivation

Axions and axion-like particles (ALPs) can be used by a creative physicist to explain many of the unsolved mysteries in physics, including e.g. the nature of dark matter, the strong CP problem, the $g-2$ anomaly, inflation and dark energy. Due to the characteristic two-photon–ALP coupling, astrophysical photons will mix with ALPs when they propagate through external magnetic fields. Thus, one can search for axionis and ALPs by searching for the charactersitc imprints that the oscillations leave on high energy photon spectra.

The Monte Carlo program ELMAG

ELMAG [1] is a standard tool for modelling the propagation of gamma-rays in the Universe in a Monte Carlo framework. The tool was made to simulate the electromagnetic cascade that arises when high energy gamma-rays undergo pair production upon interacting with the extragalactic background light (EBL), $\gamma + \gamma_{\rm EBL} \to e^+ + e^-$.

We have now implemented photon-ALP oscillations into ELMAG, allowing us to include properly the interplay of cascading and oscillations.

Parameter space of photon-ALP oscillation

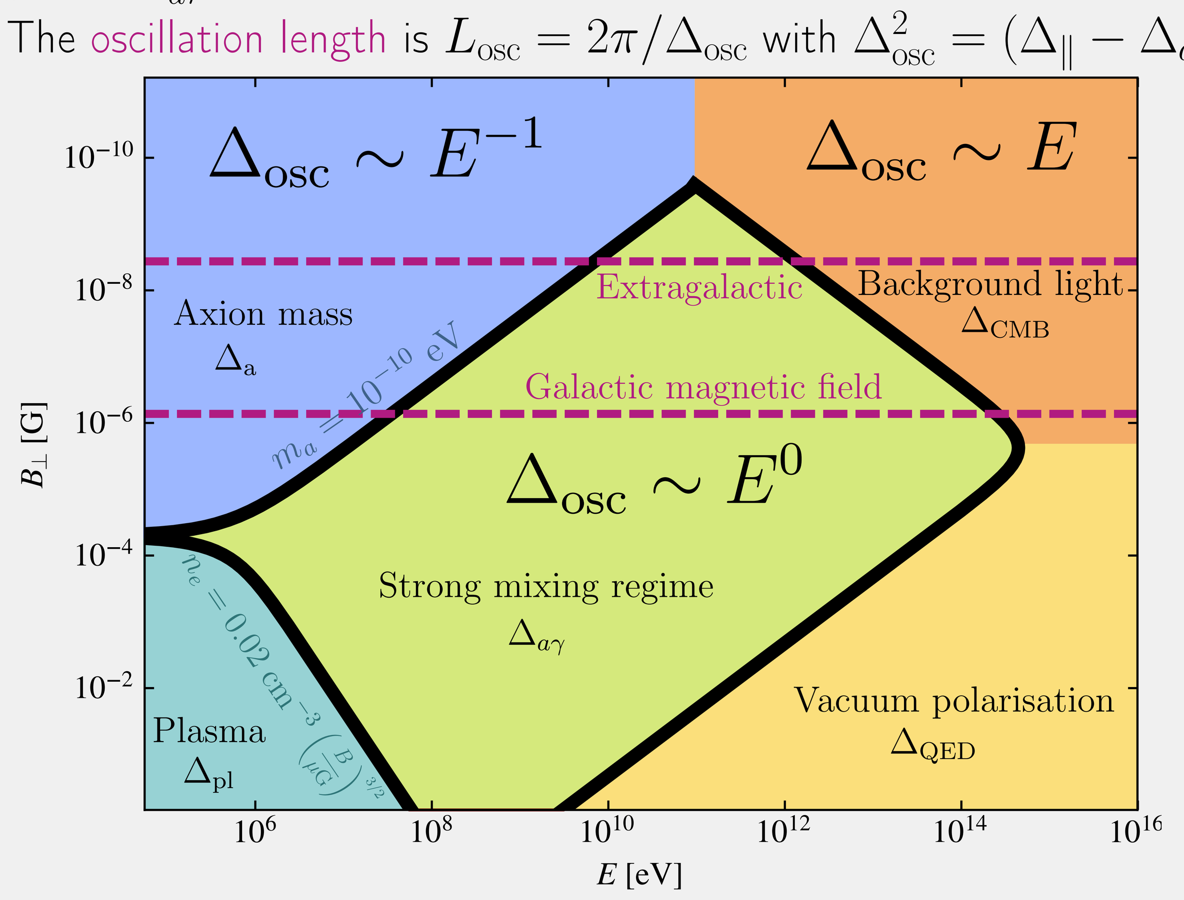
Photon-ALP oscillations can physically be described as a mixing between two mass-eigenstates, similar to neutrino oscillations. An energy dependence of the oscillation length is induced by the variation of the refractive index of the photon.

The photon-ALP oscillations at high energies can described by the equation of motion

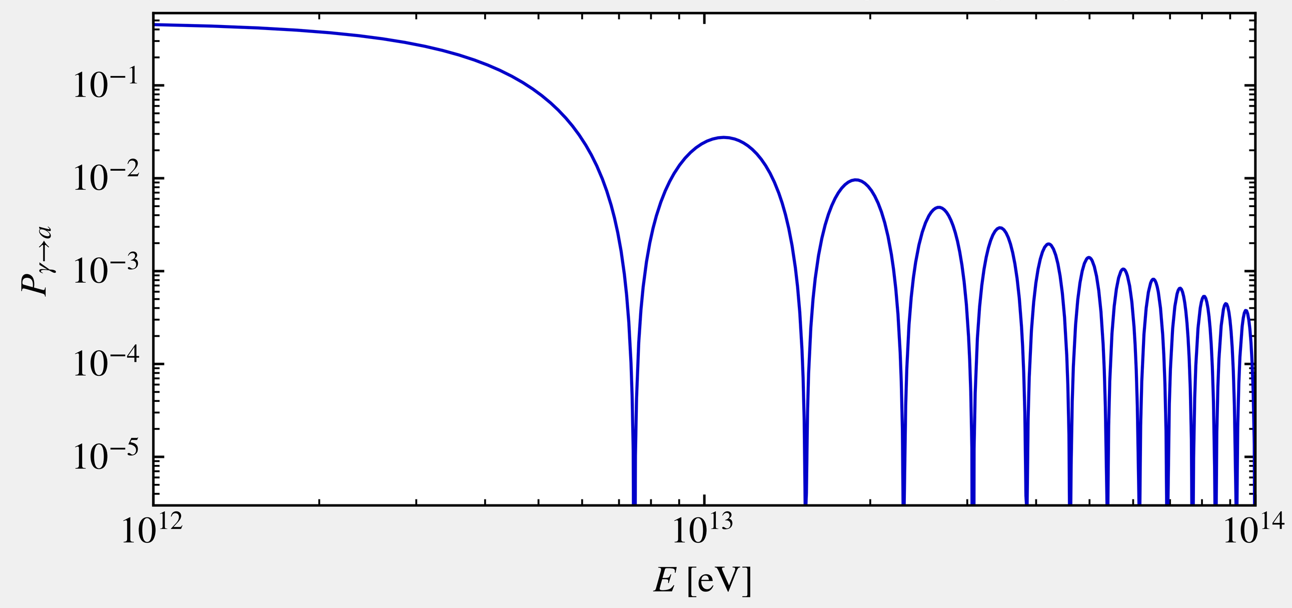
$$(E + \mathcal{M} - \mathrm{i}\partial_z)\,\phi(z) = 0, \qquad M = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}, \qquad (1)$$

where $\Delta_{\perp/\parallel} = (n_{\perp/\parallel} - 1)E = \Delta_{\rm QED} + \Delta_{\rm CMB} - \Delta_{\rm plasma}$, $\Delta_{a\gamma} = g_{a\gamma}B_\perp/2$ and $\Delta_a = -m_a^2/2E$.

The oscillation length is $L_{\rm osc} = 2\pi/\Delta_{\rm osc}$ with $\Delta_{\rm osc}^2 = (\Delta_\parallel - \Delta_a)^2 + 4\Delta_{a\gamma}^2$



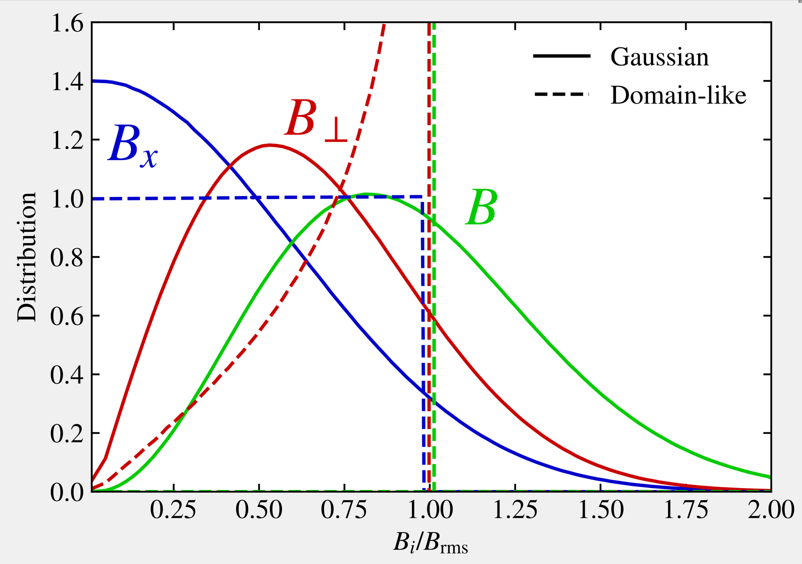
The energy dependence of the oscillation length leads to oscillatory features in the photon survival probability, which are strongest *close* to the strong mixing regime.



Magnetic field

We simulate the extragalactic magnetic field as a Gaussian turbulent field with a Kolmogorov spectrum with a coherence length L_c and $B_{\rm rms} = 5\times10^{-9}$ G.

For comparison, we consider also a simple domain-like field in which the magnetic field is split into patches of size L_c of homogeneous magnetic field with a random direction.



Detecting axions with CTA

The Cherenkov Telescope Array (CTA) is expected to have a great sensitivity for photons with energies between 10^{11} and 10^{14} eV, which means that it will be sensitive to ALP wiggles induced by a magnetic field of strength $10^{-11}\,\mathrm{G} \lesssim Bg_{a\gamma}/10^{-20}\,\mathrm{eV} \lesssim 10^{-8}\,\mathrm{G}$.

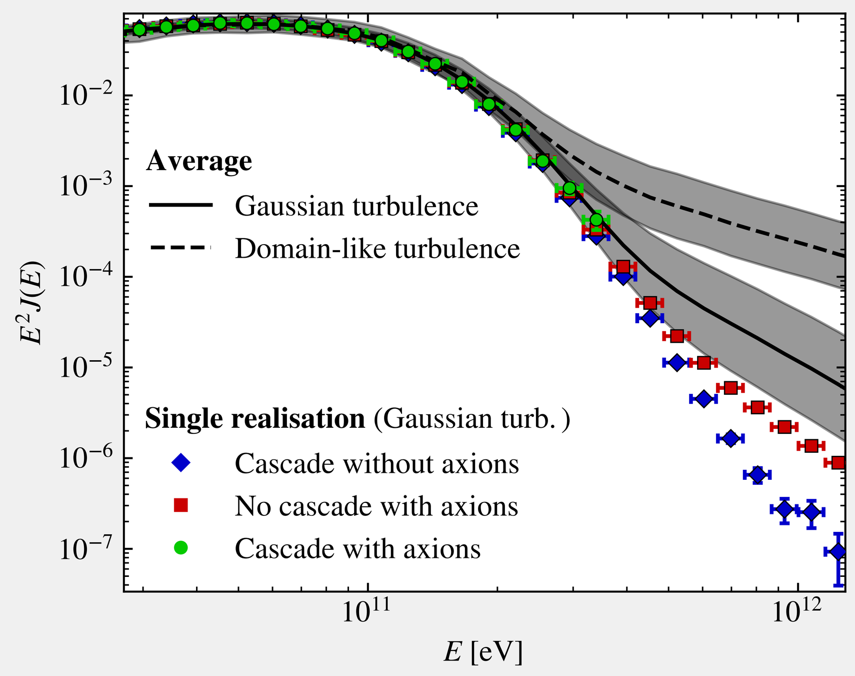
At the same time, the attenuation of photons due to interactions with the extragalactic background light becomes significant above TeV energies.

Increased mean free path length

At energies $E_\gamma \gtrsim \mathrm{TeV}$, photons will undergo pair production upon interacting with the extragalactic background light (EBL), leading to a strong attenuation of the photon spectrum. Since ALPs do not interact with the EBL, photon-ALP oscillations will lead to an increased mean free path length of the photon.

The figure shows how a production spectrum $\mathrm{d}N/\mathrm{d}E \propto E^{-1.2}$ at redshift $z = 0.1$ is affected by the attenuation and photon-ALP oscillations.

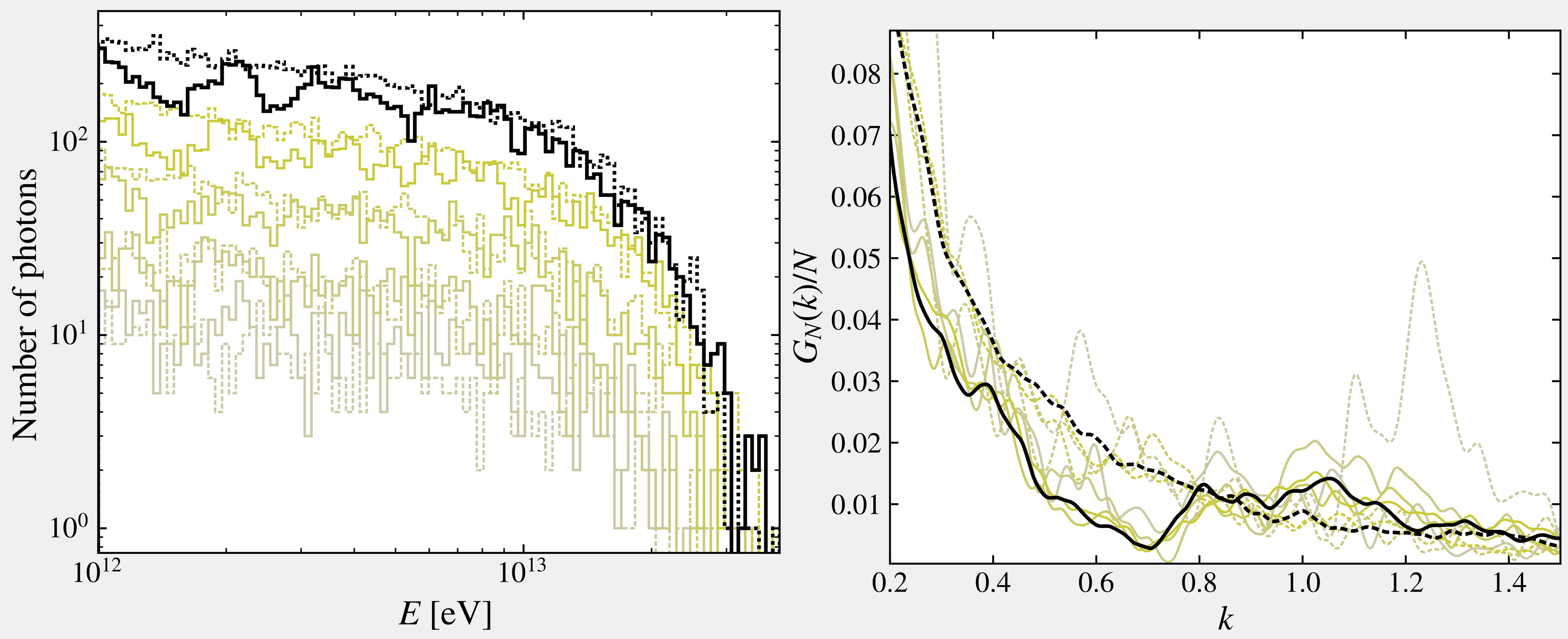
The effect depends strongly on the considered magnetic field configuration.



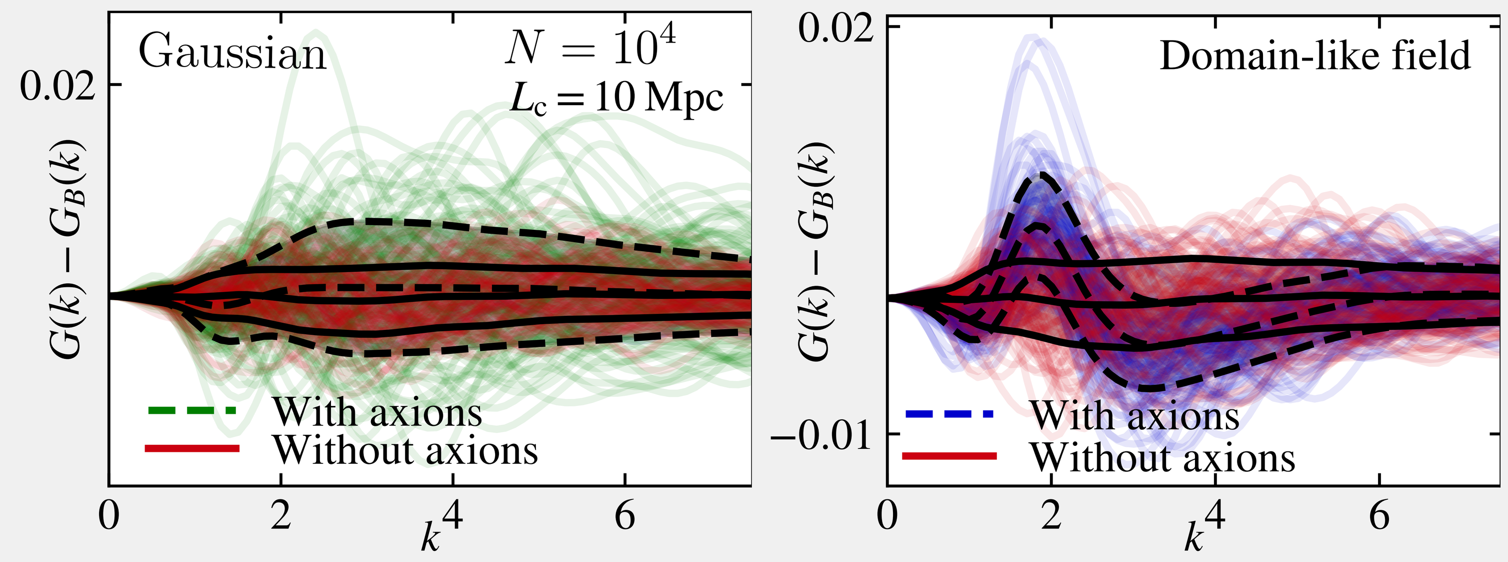
ALP Wiggles

Since the photon-ALP oscillations lead to wiggles in the photon spectra with a characteristic energy dependence ($\eta \sim E^{-1}$ at low energies and $\eta \sim E$ at high energies), one can extract the information using the discrete power spectrum

$$G_N(k) = \left| \int_{\eta_{\rm min}}^{\eta_{\rm max}} \mathrm{d}\eta\, q(\eta)\mathrm{e}^{\mathrm{i}\eta k} \right|^2 = \left| \frac{1}{N} \sum_{\rm events} \mathrm{e}^{\mathrm{i}\eta k} \right|^2 . \qquad (2)$$

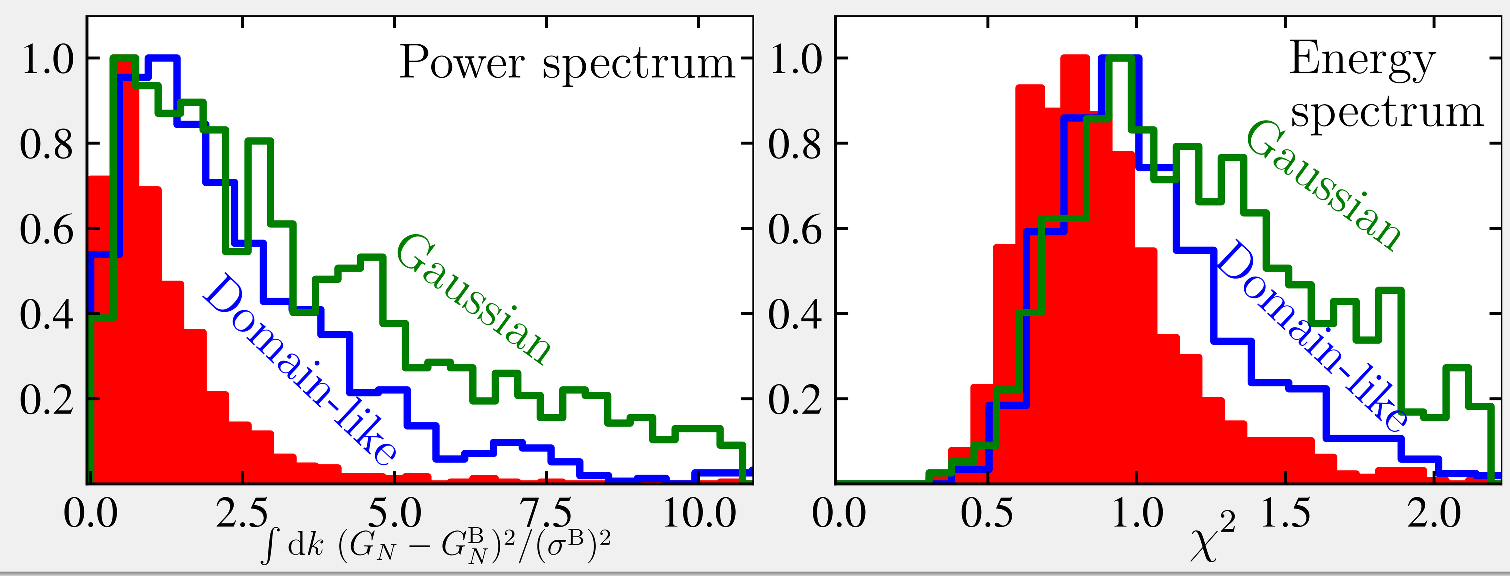


We isolate the signal from the ALP wiggles by subtracting a background energy spectrum found by performing a MLE fit using the function $f(E) \propto E^{-b}\mathrm{e}^{-\tau(E)}$ with $\tau(E) = \alpha\mathrm{e}^{\beta\log^3 E - \gamma\log^2 E + \delta\log E}$.



The domain-like field fail to describe the cosmic variance of the magnetic field, which gives rise to a clear average peak in the power spectrum. The Gaussian turbulent field shows no clear signal on average, but a large variance in single realisations.

The use of the discrete power spectrum increases the experimental sensitivity for ALP wiggles compared to a standard χ^2 test.



Conclusions

- At TeV energies, photon-ALP oscillation will lead to two features in photon spectra: (1) an apparent increase in the opacity of the Universe and (2) characteristic wiggles.
- Since we know the energy dependence of the wiggles, we can directly search for them by using the discrete power spectrum.
- CTA will be ideal to search for photon-ALP oscillations in the extragalactic space.
- Results obtained using a simplified model for the turbulent magnetic field should be interpreted with care.

Further readings

Most of the material presented here is discussed in more detail in:

[1] M. Kachelriess and J. Tjemsland, JCAP **01** (2022) no.01, 025 [arXiv:2111.08303]
[2] M. Kachelriess and J. Tjemsland, PoS **CompTools2021** (2021), 002
[3] M. Kachelriess, S. Ostapchenko and R. Tomas, Comput. Phys. Commun. **183** (2012), 1036-1043 [arXiv:1106.5508]

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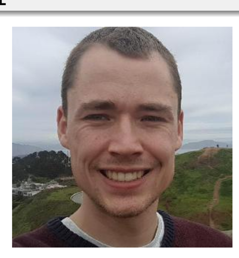

Questions?

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