Extragalactic photon–axion-like particle oscillations up to 1000 TeV

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Axion-like particles (ALPs) are very light, neutral, pseudo-scalar bosons which are supposed to interact with two photons. They can give rise to very interesting astrophysical effects taking place in the very-high energy band and above (10 GeV – 1000 TeV) when an external magnetic field is present. So far, the extragalactic magnetic field B_{ext} has been generally modeled as a domain-like network with 'sharp edges': all domains have the same size L_{dom} and B_{ext} has the same strength, but the direction of B_{ext} changes randomly and abruptly from one domain to the next. While this model has repeatedly been used so far, it is a mathematical idealization wherein the components of B_{ext} are discontinuous across the edges. Still, it gives correct results under the unstated assumption that the photon-ALP oscillation length l_{osc} is much larger than L_{dom}. However, for the new generation of γ-ray observatories like CTA, HAWC, GAMMA-400, LHAASO and TAIGA-HiSCORE things are different: photon dispersion on the CMB implies $l_{osc} < L_{dom}$, which occurs just above the TeV scale. In such a situation the above model breaks down and must be replaced by one in which B_{ext} is continuous across the edges. We describe such a new model and apply it to a sample of mock blazars at different z and at energy E up to 1000 TeV. We analyze the propagation of the photon-ALP beam generated as pure photons at the jet base of a BL Lac, we study the photon-ALP oscillations during its path up to us while crossing the BL Lac magnetic field, the extragalactic magnetic field which we describe by means of our new model and the Milky Way magnetic field.

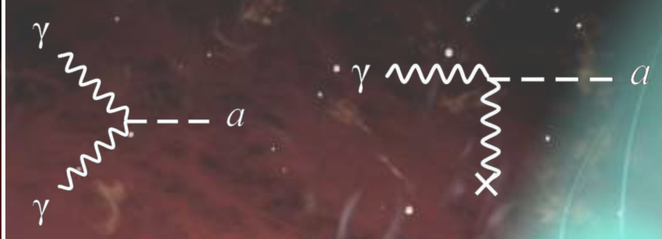
Axion-like particles (ALPs)

Properties

- Predicted by String Theory
- Very light particles ($m_a < 10^{-8}$ eV)
- Spin 0
- Interaction with two photons (coupling $g_{a\gamma\gamma} = 1/M$)
- Interactions with other particles discarded

ALP interactions

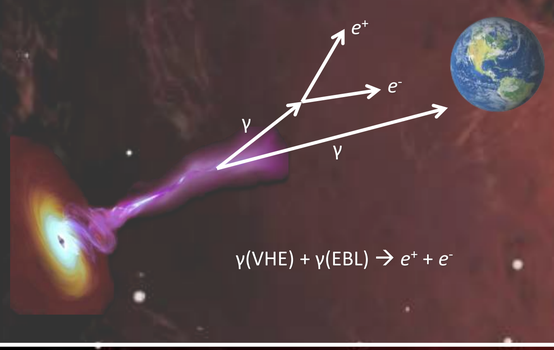
- Two photons
- In an external B field



Photon-ALP oscillations inside a B field

ALPs in astrophysical contest

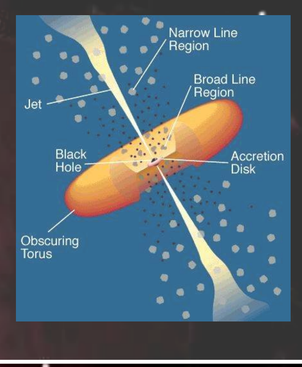
Extragalactic background light (EBL)



- EBL absorbs VHE photons
- ALPs are not absorbed
- Photons are not absorbed when are ALPs
- Photon-ALP oscillations reduce the optical depth
- More photons detectable by Earth observatories at TeV energy

Blazars

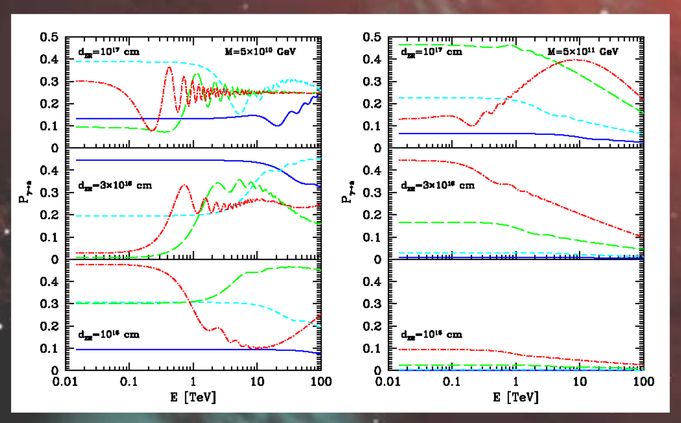
- Active galactic nuclei (AGN) divided into flat spectrum radio quasars (FSRQs) and BL Lacs
- Photons produced at the jet base
- VHE photons absorbed by the broad line region (BLR) present in FSRQs
- Photon-ALP oscillations modify blazar emission
- In FSRQs they reduce BLR optical depth (similarly to EBL)
- They explain FSRQ emission above 20 GeV [1]



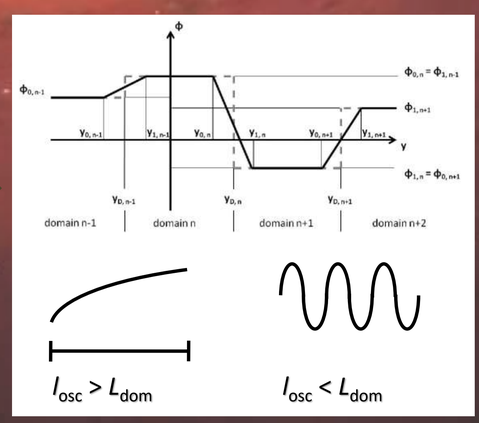
Extragalactic photon-ALP oscillations

Propagation in the BL Lac jet [2]

- Photons produced at $d_{VHE} = 10^{16}$ cm from the centre
- $B_{jet} = 0.1 – 1$ G and goes like 1/distance
- Electron density $n_e = 5 \cdot 10^4$ cm^{-3} and goes like 1/distance^2
- Lorentz factor $\Gamma = 15$
- Photon-ALP conversion inside B_{jet}
- Amount of photons/ALPs produced strongly depends on the values of d_{VHE}, B_{jet}, $g_{a\gamma\gamma}$

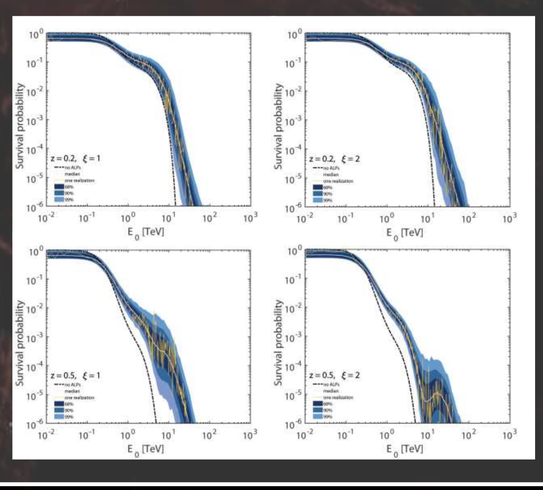


New model for propagation inside domain-like B fields [3]



- New model for astrophysical magnetic fields B
- Useful for: extragalactic space, spiral and elliptical galaxies, radio lobes
- Domain-like model but now with continuous components of B (old model → discontinuities)
- Magnetic domain lengths L_{dom} are random variables with some distribution
- l_{osc}: photon/ALP oscillation length
- If $l_{osc} > L_{dom}$ photon/ALP beam insensible to B structure – old discontinuous model can be used
- If $l_{osc} < L_{dom}$ photon/ALP beam sees the B structure – old discontinuous model is unphysical

Propagation in the extragalactic space [4]



- Extragalactic magnetic field B_{ext}
- L_{dom} with distribution $L_{dom}^{-1.2}$
- For $E > 40$ TeV CMB photon dispersion makes $l_{osc} < L_{dom}$
- Photon/ALP beam becomes sensible to the B_{ext} shape
- For $E > 40$ TeV only the new continuous B_{ext} model gives physical results about the photon survival probability
- Last data on EBL
- $\xi = (B_{T,ext}/\text{nG}) \cdot (g_{a\gamma\gamma} \cdot 10^{11}\ \text{GeV}) = 0.5 – 5$
- Redshift $z = 0.02 – 2$

For the future

- As the energy increases photon/ALP oscillations differ more and more from conventional physics
- photon/ALP oscillations generate an observable oscillatory behavior in observed blazar spectra
- These features can in principle be detected by the planned new observatories like the Cherenkov Telescope Array (CTA)
- Dedicated simulations for CTA about blazar spectra – Stay tuned!

[1] F. Tavecchio, M. Roncadelli, G. Galanti and G. Bonnoli, *Evidence for an axion-like particle from PKS 1222 + 216?*, Phys. Rev. D 86, 085036 (arXiv: 1202.6529) (2012).
[2] F. Tavecchio, M. Roncadelli and G. Galanti, *Photons to axion-like particles conversion in Active Galactic Nuclei*, Phys. Lett. B 744, 375 (arXiv: 1406.2303) (2015).
[3] G. Galanti and M. Roncadelli, *Behavior of axion-like particles in smoothed out domain-like magnetic fields*, (arXiv: 1804.09443).
[4] G. Galanti and M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, (arXiv: 1805.12055).