SIGNATURES OF ALP OSCILLATIONS IN AGN SPECTRA

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Context and assumptions

In 2015 Raffelt *et al.* pointed out that at energies $E \gtrsim 15\,\mathrm{TeV}$ photon dispersion on the CMB becomes the leading effect in photon-ALP oscillations. Hence, in view of the new generation of VHE detectors like CTA, HAWC, GAMMA-400, LHAASO, TAIGA-HiSCORE e HERD it is compelling to take such an effect into account.

This is however a non-trivial task. So far, the extragalactic magnetic field $\mathbf{B}_{\rm ext}$ has been modeled as a network of nearly equal domains – of linear size $\mathcal{O}(1\,\mathrm{Mpc})$ – wherein $\mathbf{B}_{\rm ext}$ has almost the same strength but its direction changes *discontinuously* from one domain to the next.

In the absence of that effect $\lambda_{\rm osc} \gg \mathcal{O}(1\,{\rm Mpc})$, and so the discontinuity of $\mathbf{B}_{\rm ext}$ becomes irrelevant, since only a tiny part of one oscillation is affected by $\mathbf{B}_{\rm ext}$ in a single domain, and the coherence is lost.

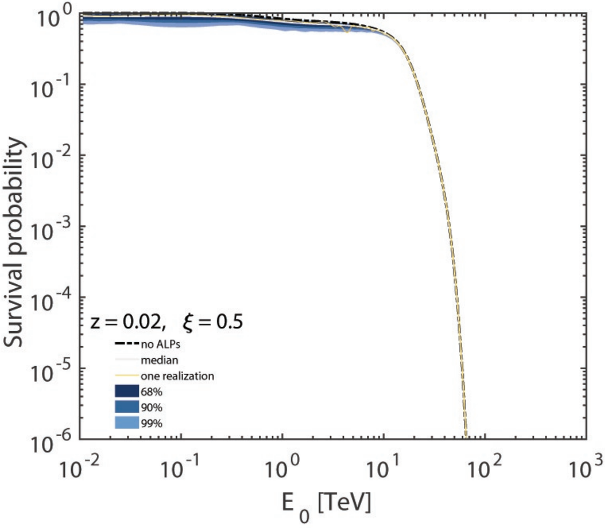
Things change drastically for $E \simeq 40\,{\rm TeV}$ since then $\lambda_{\rm osc} \simeq \mathcal{O}(1\,{\rm Mpc})$, and $\lambda_{\rm osc}$ *decreases* as E *increases*. Now a whole oscillation – and even more oscillations – probe a whole single domain, thereby feeling the discontinuity: this makes the whole scenario *physically meaningless*.

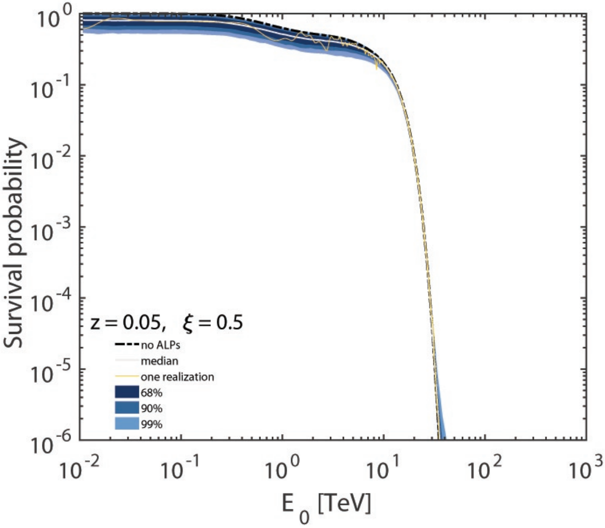
Therefore it look mandatory to smooth out the change of direction of $\mathbf{B}_{\rm ext}$ from one domain to the next. The drawback is that the beam propagation equation become very difficult to solve.

Because we are supposing that $E \gg m_{\rm alp}$, the beam propagation equation has a Schrödinger-like form, with $t \to y$ ($y =$ propagation direction). So, for a linear smoothing we have been able to solve such an equation by a clever use of the Laplace transform, thereby getting an analytic exact result in a single domain. Moreover, the beam propagation is *formally* equivalent to a 3 level non-relativistic unstable (because of EBL absorption) quantum system! Hence, by iteration one gets the whole beam behaviour. Note that the angles of $\mathbf{B}_{\rm ext}$ with a fixed direction are random variables, and so the same is true for the paths followed by the beam.

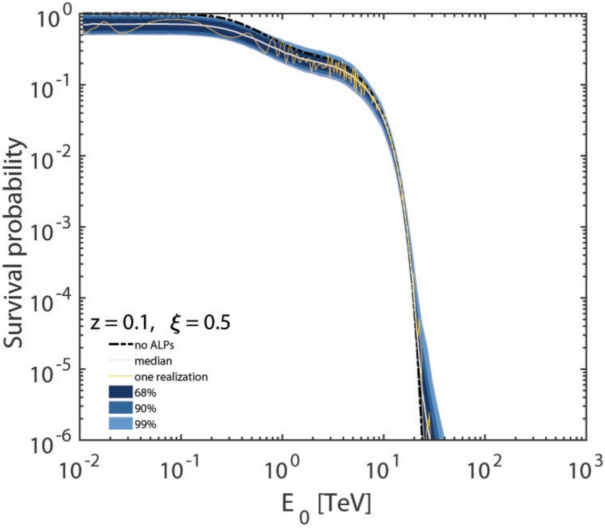
- The CAST upper bound on the ALP 2 photon coupling is $g_{a\gamma\gamma} < 0.66 \cdot 10^{-10}\,{\rm GeV}^{-1}$.
- The upper bound on the strength of $\mathbf{B}_{\rm ext}$ is $B_{\rm ext} < 1.7\,{\rm nG}$.
- Defining $\xi \equiv \left(\frac{B_{\rm ext}}{\rm nG}\right)\left(g_{a\gamma\gamma}\,10^{11}\,{\rm GeV}\right)$, we get $\xi < 9.20$.
- In order to stay in the *strong mixing regime* for $100\,{\rm GeV} \lesssim E \lesssim 15\,{\rm TeV}$ we must have $m_{\rm alp} \lesssim 10^{-10}\,{\rm eV}$, assuming $g_{\ \gamma\gamma} < 10^{-10}\,{\rm eV}$: OK with all constraints.

Results

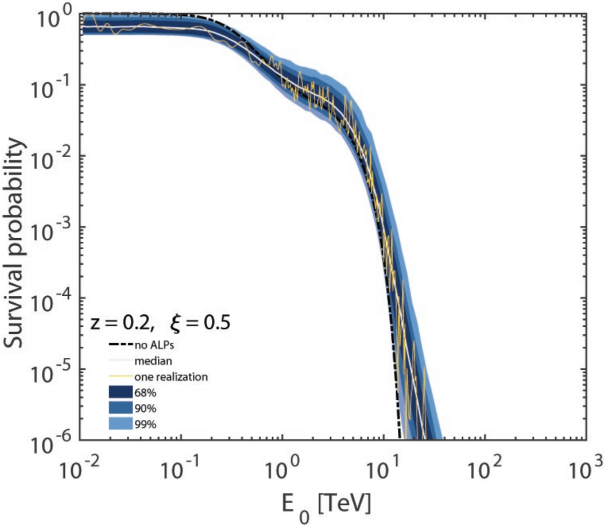

z = 0.02, ξ = 0.5
no ALPs
median
one realization
68%
90%
99%
Survival probability
E 0 [TeV]
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-2
10^-1
10^0
10^1
10^2
10^3



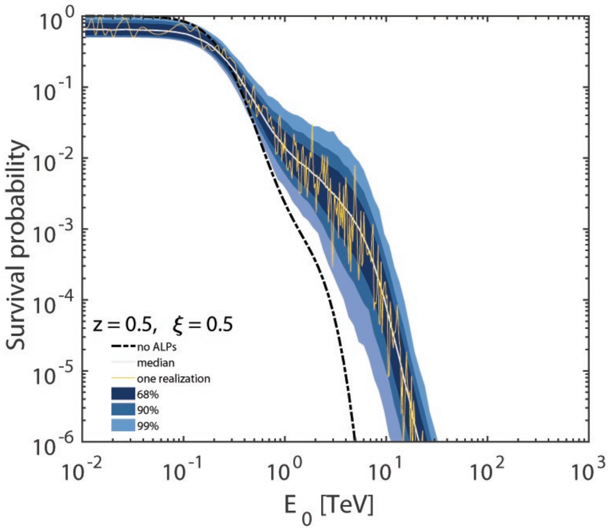
Survival probability
E 0 [TeV]
z = 0.05, ξ = 0.5
no ALPs
median
one realization
68%
90%
99%



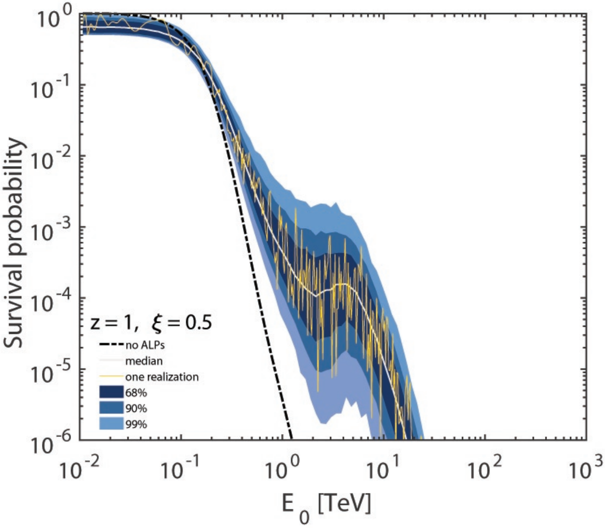
Survival probability
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
E_0 [TeV]
$z = 0.1, \quad \xi = 0.5$
no ALPs
median
one realization
68%
90%
99%



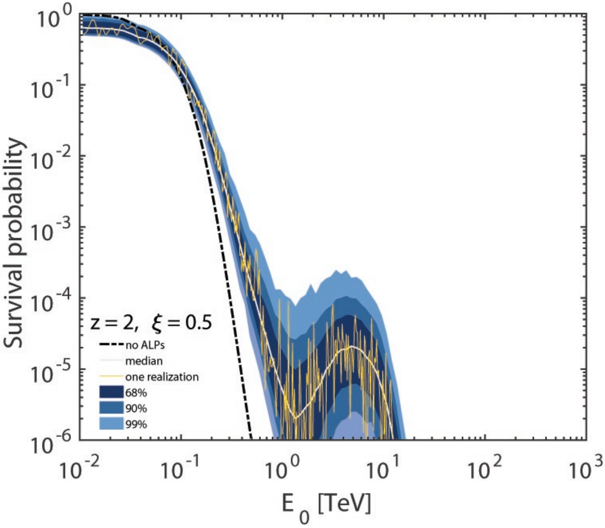
Survival probability
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$z = 0.2, \quad \xi = 0.5$
no ALPs
median
one realization
68%
90%
99%
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
E_0 [TeV]



Survival probability
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$z = 0.5, \quad \xi = 0.5$
no ALPs
median
one realization
68%
90%
99%
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
E_0 [TeV]



Survival probability
E 0 [TeV]
z = 1, ξ = 0.5
no ALPs
median
one realization
68%
90%
99%



Survival probability
E 0 [TeV]
z = 2, ξ = 0.5
no ALPs
median
one realization
68%
90%
99%