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Extreme BL Lacs as a probe of axion-like particles

eXtreme19

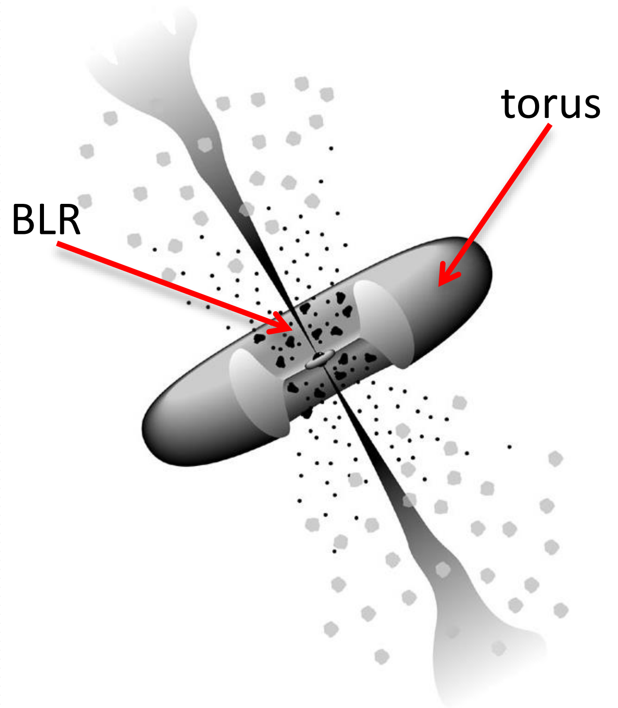
22-25 January 2019

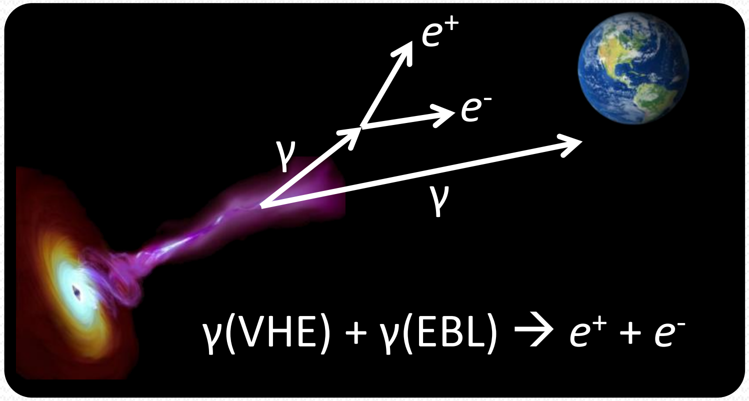
Blazars

γ-ray absorption in blazars

BL Lacs:

- No broad line region (BLR)
- No dusty torus
- Absorption due to the extragalactic background light (EBL) for $E > 100$ GeV





BL Lacs

- Is there a way to prevent (partially) photon absorption due to the EBL in the TeV energy band?

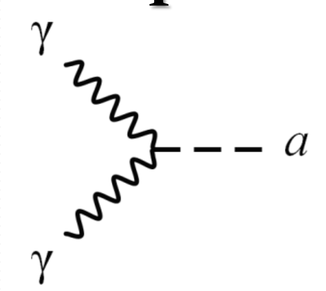
- **YES**: through photon–axion-like particle interactions

Axion-like particles (ALPs)

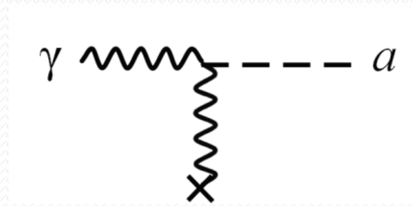
Axion-like particles (ALPs)

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

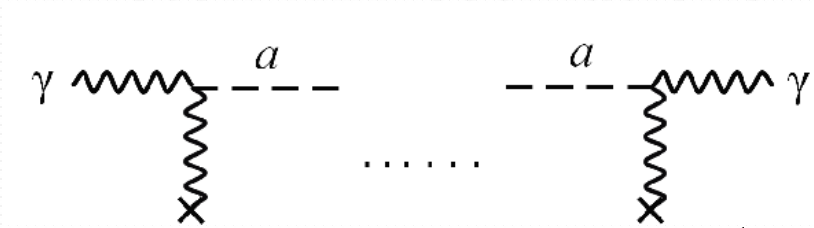
Two photons



In an external B field



Photon-ALP oscillations



ALPs in astrophysical contest (1)

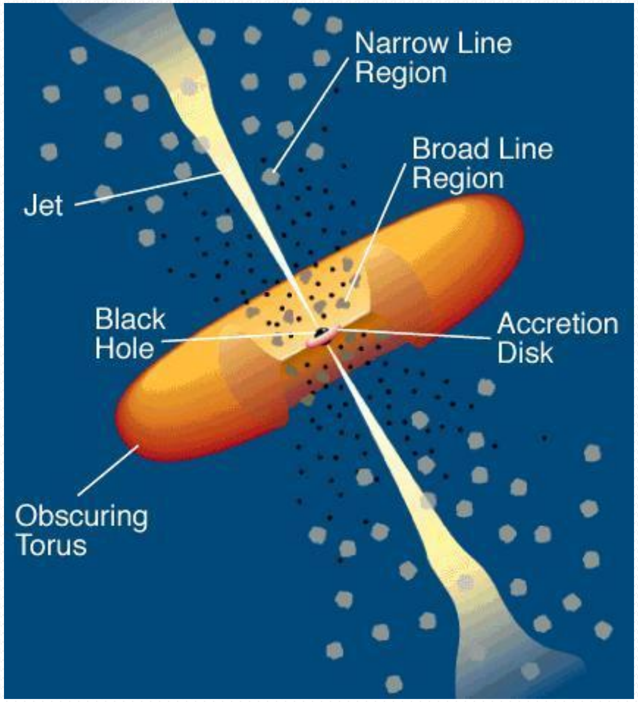
Extragalactic Background Light (EBL)

- EBL absorbs very-high energy (VHE, 100 GeV – 100 TeV) photons
- ALPs are not absorbed
- Photons are not absorbed when are converted to ALPs
- Photon-ALP oscillations increase Universe transparency
- More photons detectable by Earth observatories at TeV energy

ALPs in astrophysical contest (2)

Blazars

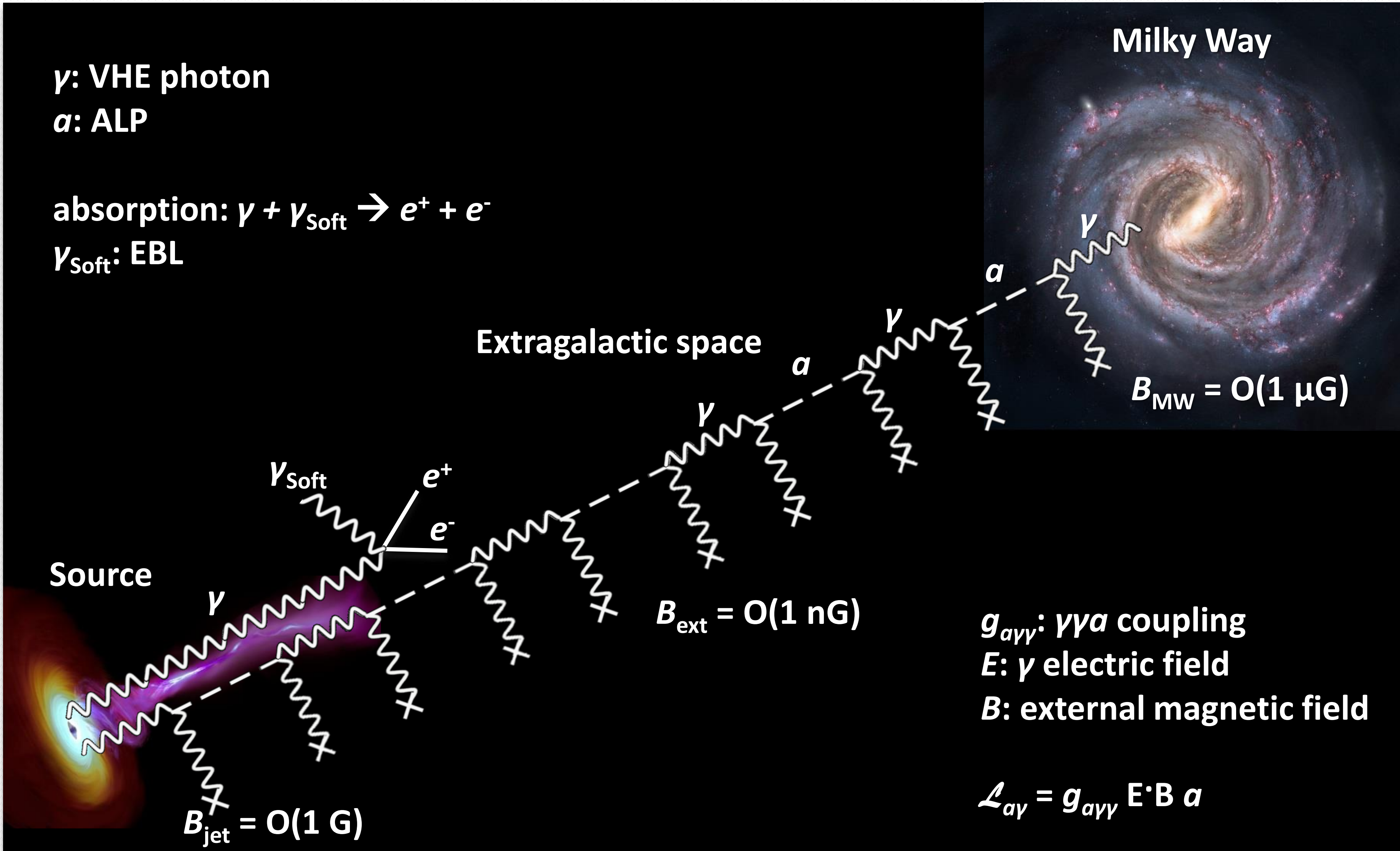
- Active galactic nuclei (AGN) divided between flat spectrum radio quasars (FSRQs) and BL Lacs
- Photons produced at the jet base
- VHE photons absorbed by the broad line region (BLR) present in FSRQs
- Photon-ALP oscillations modify blazar emission
  - In FSRQs they increase BLR transparency (similar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



C. M. Urry & P. Padovani, 1995

NOW: we concentrate on BL Lacs → no BLR, only EBL absorption. ALP contribution?

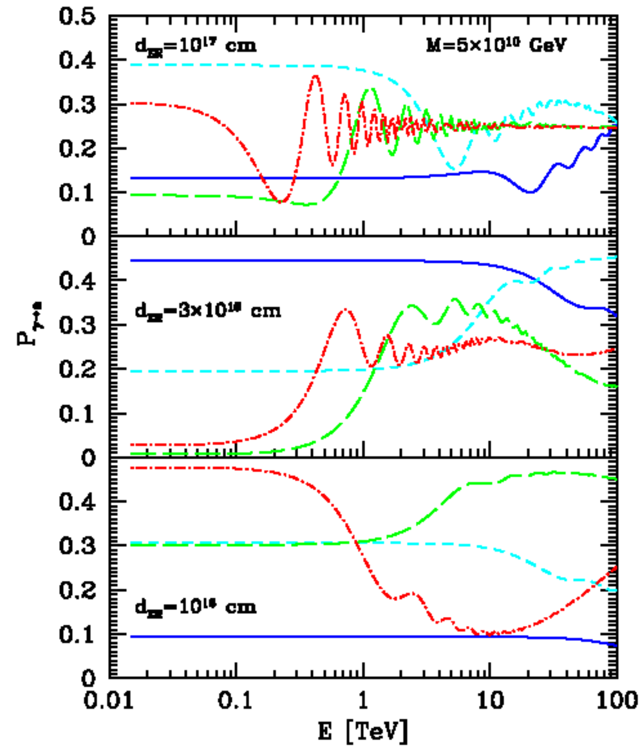
Photon-ALP propagation



Extragalactic photon/ALP oscillations

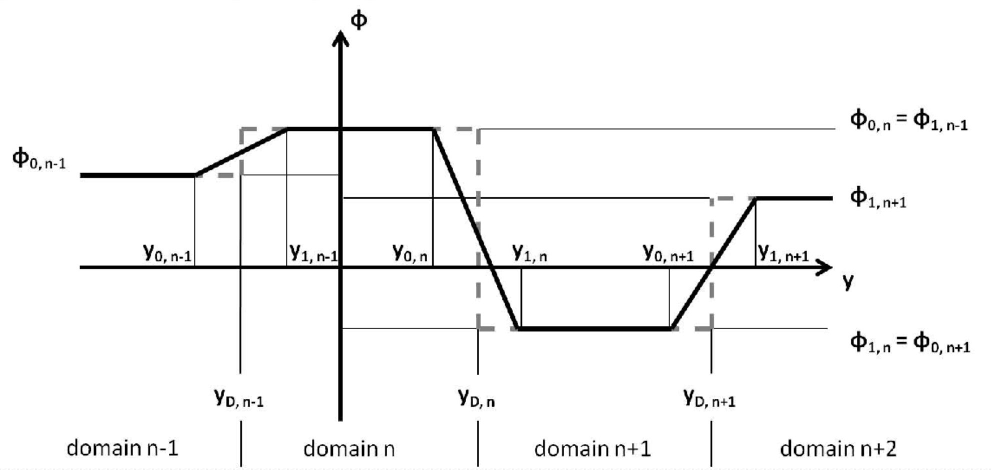
Propagation in the BL Lac jet

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



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).

New propagation model inside domain-like B fields

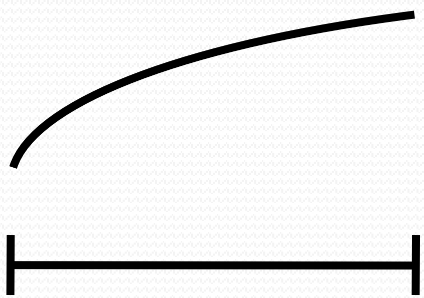


ϕ: B orientation angle in the transverse direction

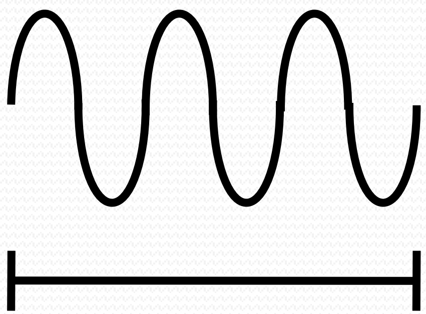
- New model for astrophysical magnetic fields B
- Useful for: extragalactic space, spiral and elliptical galaxies, radio lobes
- Domain-like model but now with continuous components of B (old model → discontinuities)
- Magnetic domain lengths $L_{\rm dom}$ are random variables with some distribution
- Full analytical solution in the new "smooth" model: DLSME (Domain-Like SMooth-Edges) model

G. Galanti, M. Roncadelli, *Behavior of axion-like particles in smoothed out domain-like magnetic fields*, Phys. Rev. D 98, 043018 (arXiv: 1804.09443) (2018).

New propagation model inside domain-like B fields (2)



$l_{\mathrm{osc}} > L_{\mathrm{dom}}$



$l_{\mathrm{osc}} < L_{\mathrm{dom}}$

- l_{osc}: photon/ALP beam oscillation length
- If $l_{\mathrm{osc}} > L_{\mathrm{dom}}$ photon/ALP beam insensitive to B structure – old discontinuous model can be used
- If $l_{\mathrm{osc}} < L_{\mathrm{dom}}$ photon/ALP beam sees the B structure – old discontinuous model is unphysical

G. Galanti, M. Roncadelli, *Behavior of axion-like particles in smoothed out domain-like magnetic fields*, Phys. Rev. D 98, 043018 (arXiv: 1804.09443) (2018).

New propagation model inside domain-like B fields (3)

- By taking $g_{a\gamma\gamma} = 10^{-11}$ GeV^{-1}

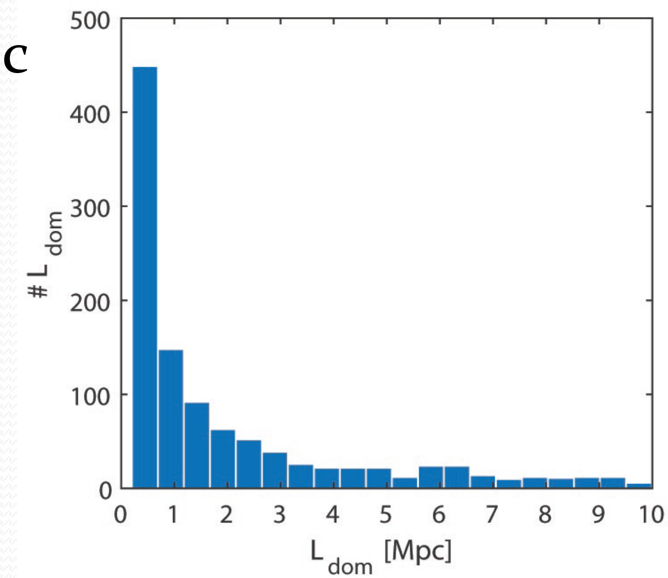
Astronomical object	B/μG	$L_{\rm dom}/$kpc	Min $\mathcal{E}/$MeV such that $l_{\rm osc} \gtrsim L_{\rm dom}$	Max $\mathcal{E}/$TeV such that $l_{\rm osc} \gtrsim L_{\rm dom}$
Radio lobes	10	10	1.36	690
Spiral galaxies	7	10	1.30	1350
Starburst galaxies	50	10	DLSME model always needed	DLSME model always needed
Elliptical galaxies	5	0.15	$1.88 \cdot 10^{-2}$	$1.5 \cdot 10^{5}$

- By taking:
  - $\langle L_{\rm dom} \rangle = 2$ Mpc
  - $B = O(1\ \text{nG})$
- In extragalactic space: new model necessary for $E > 40$ TeV

G. Galanti, M. Roncadelli, *Behavior of axion-like particles in smoothed out domain-like magnetic fields*, Phys. Rev. D 98, 043018 (arXiv: 1804.09443) (2018).

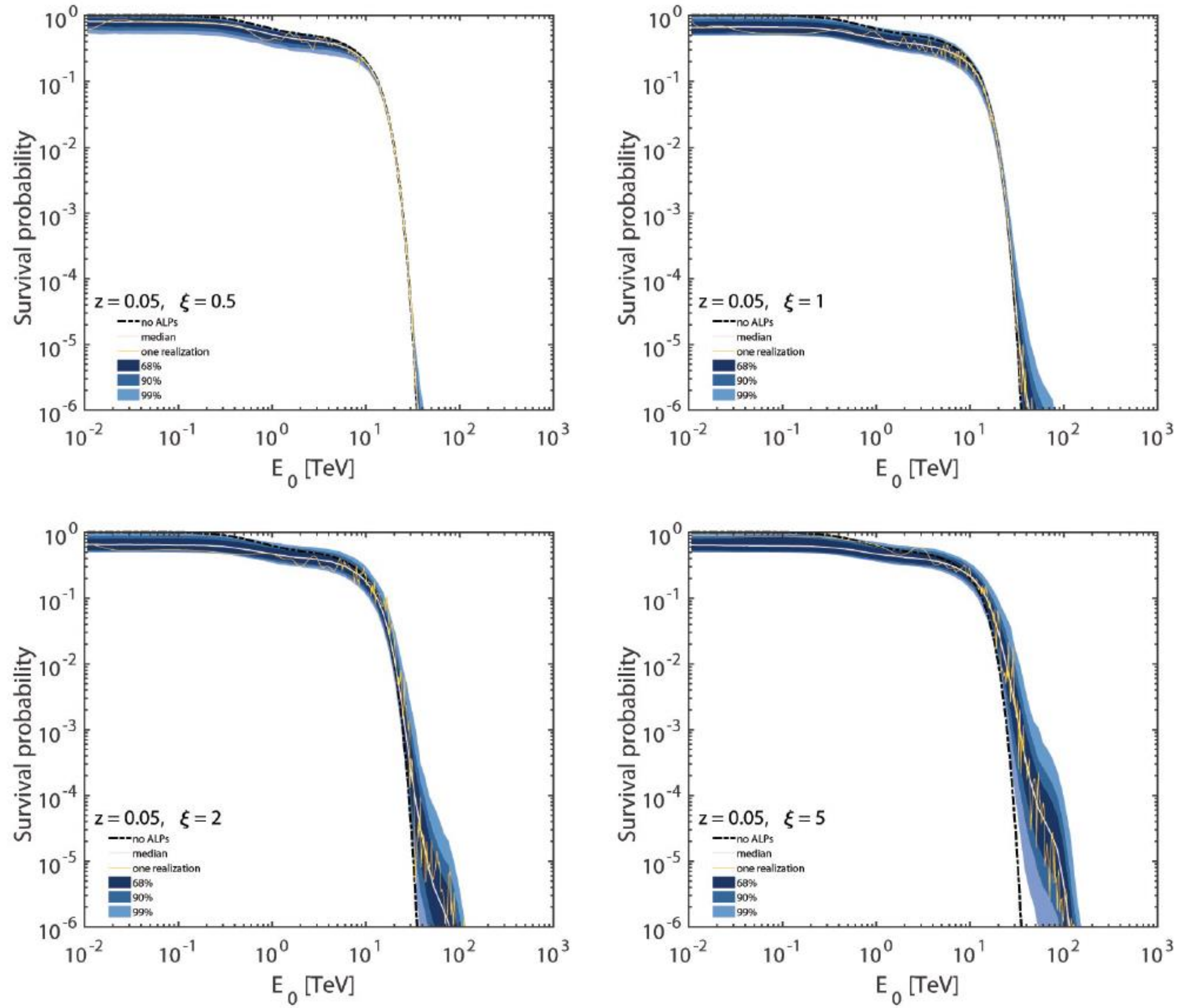
Propagation in the extragalactic space

- Extragalactic magnetic field B_{ext}
- L_{dom} with distribution $L_{\mathrm{dom}}^{-1.2}$, $\langle L_{\mathrm{dom}} \rangle = 2$ Mpc
- Last data on EBL
- CMB photon dispersion considered ($\propto E$)
- $\xi = (B_{\mathrm{T,ext}}/\mathrm{nG}) \cdot (g_{a\gamma\gamma} \cdot 10^{11}\ \mathrm{GeV}) = 0.5 - 5$
- Redshift $z = 0.02 - 2$



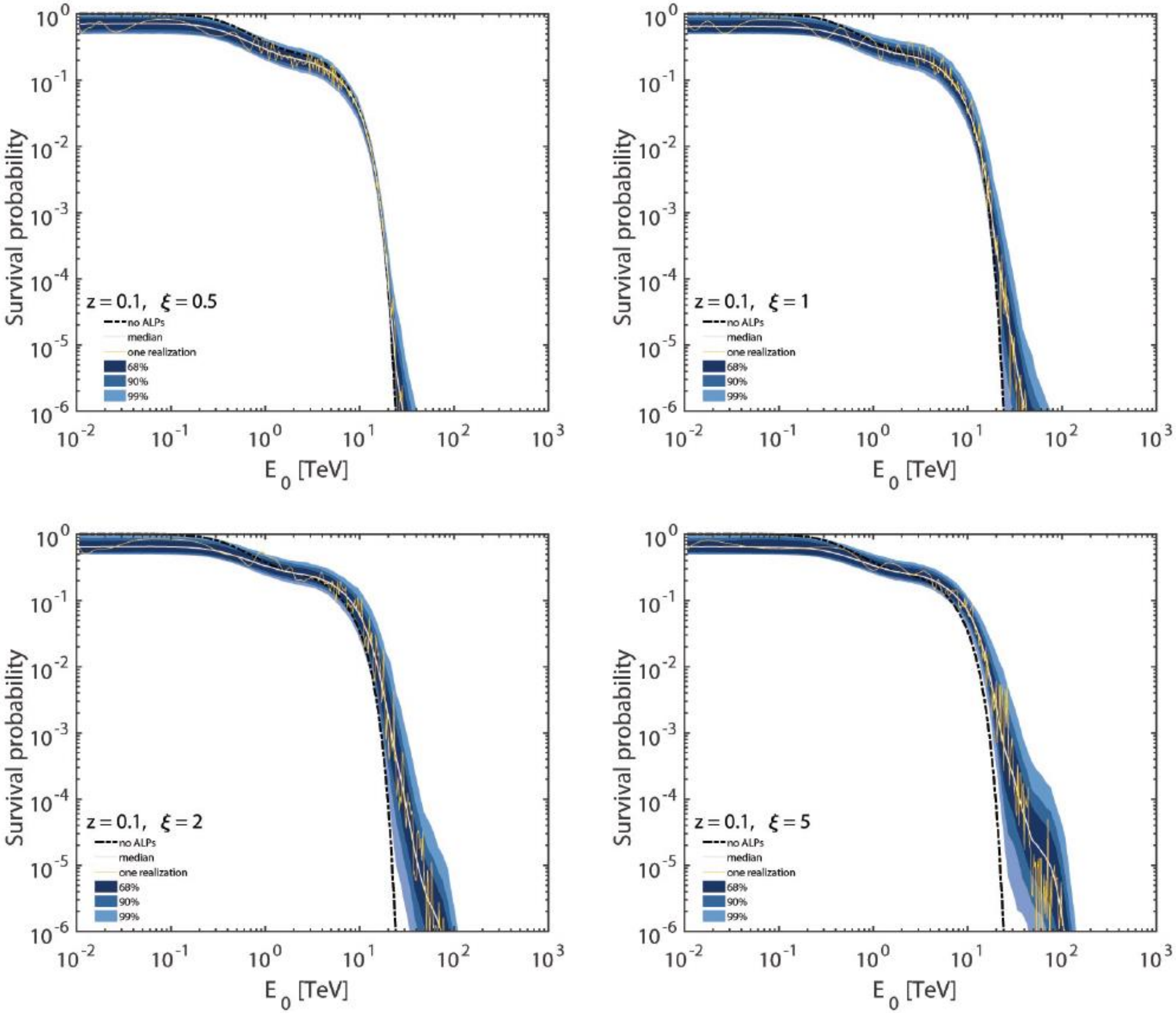
G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

z = 0.05



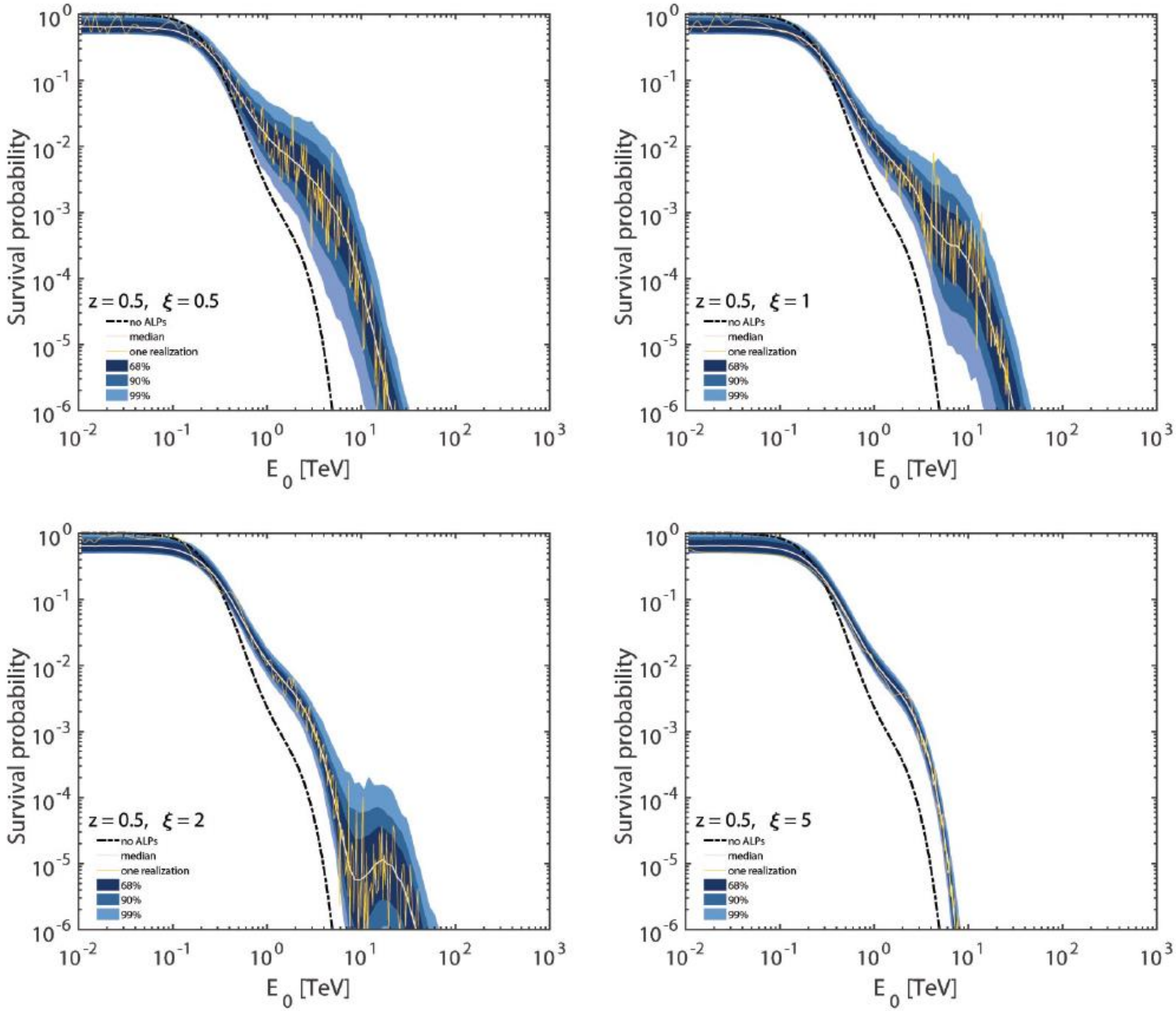
G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

z = 0.1



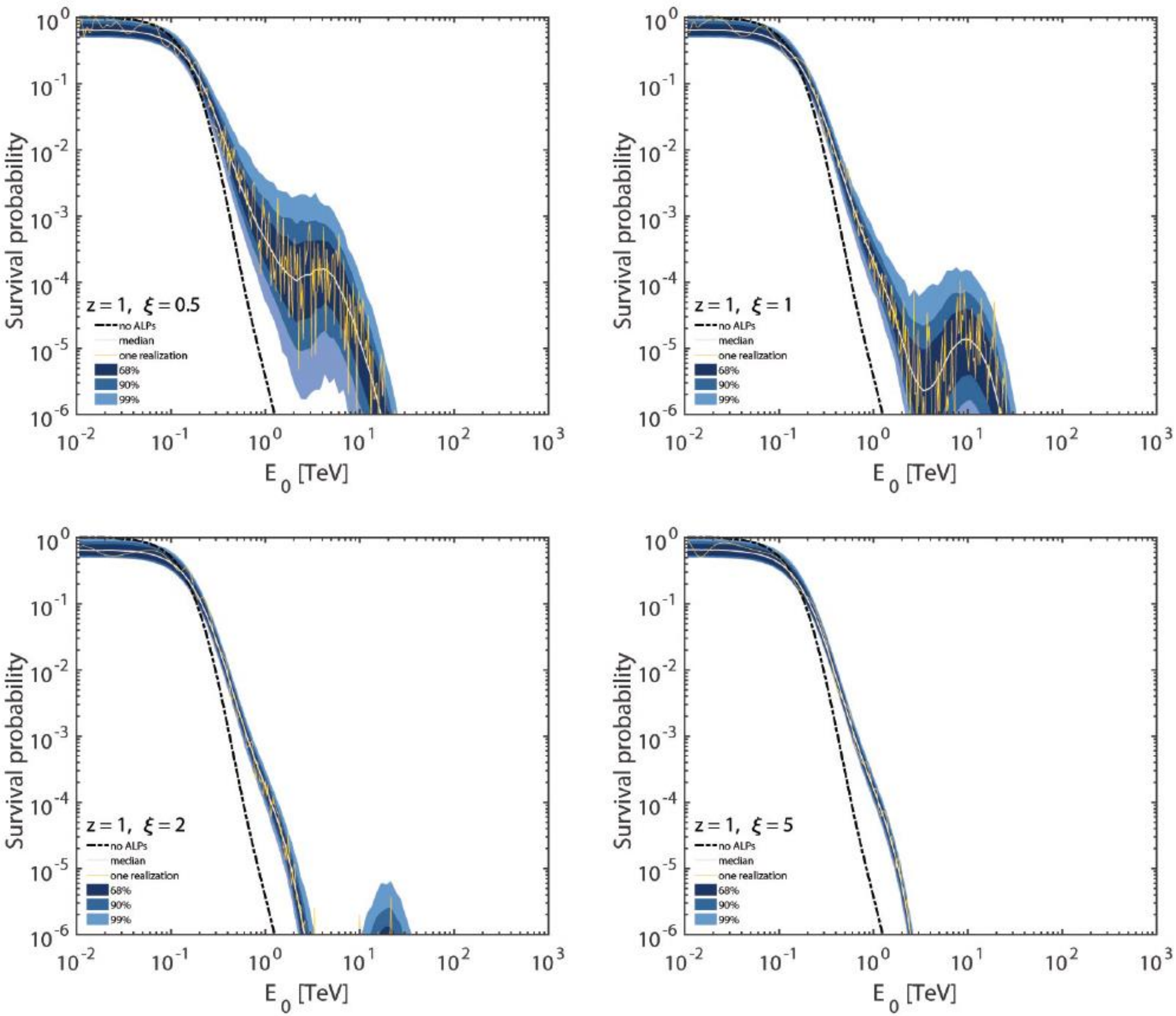
G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

z = 0.5



G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

z = 1



G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

Propagation in the extragalactic space (2)

- E > 40 TeV CMB photon dispersion makes $l_{osc} < L_{dom}$
- For E > 40 TeV only the new continuous B_{ext} model gives physical results about the photon survival probability
  - Low z and low ξ → low survival probability (expected)
  - Low z and high ξ → high survival probability (expected)
  - High z and low ξ → high survival probability (why?)
  - High z and high ξ → low survival probability (why?)
- Photon-ALP conversion too efficient → many photons (reconverted back from ALPs) are absorbed by the EBL
- Universe transparency still increased by photon-ALP oscillations even in the presence of CMB photon dispersion

G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

Propagation in the Milky Way and total effect

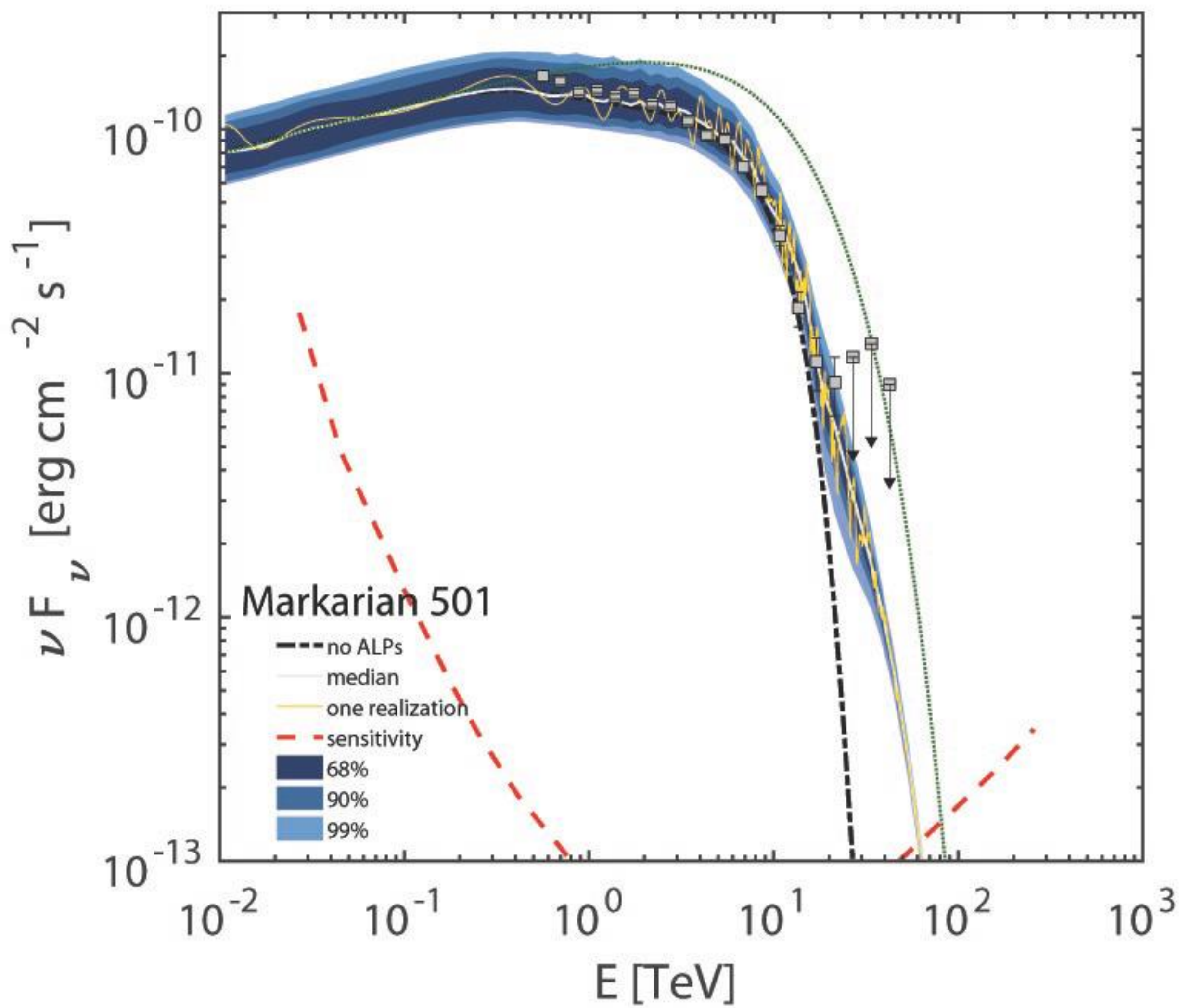
- Important only the regular component of the Milky Way magnetic field B_{MW}
- $B_{\mathrm{MW}} = 5\ \mu\mathrm{G}$, coherence length $l_{\mathrm{coh}} = 10$ kpc
- But detailed sky maps of B_{MW} exist

- Combination of photon/ALP propagation in B_{jet}, B_{ext}, B_{MW}
- Exponentially truncated spectra
- $B_{\mathrm{jet}} = 0.5$ G, $B_{\mathrm{ext}} = 1$ nG
- $g_{a\gamma\gamma} = 10^{-11}\ \mathrm{GeV}^{-1}$, $m_a = 10^{-10}$ eV
- $d_{\mathrm{VHE}} = 3 \cdot 10^{16}$ cm, $n_e = 5 \cdot 10^4\ \mathrm{cm}^{-3}$
- $\Gamma = 15$

G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, submitted.

Markarian 501

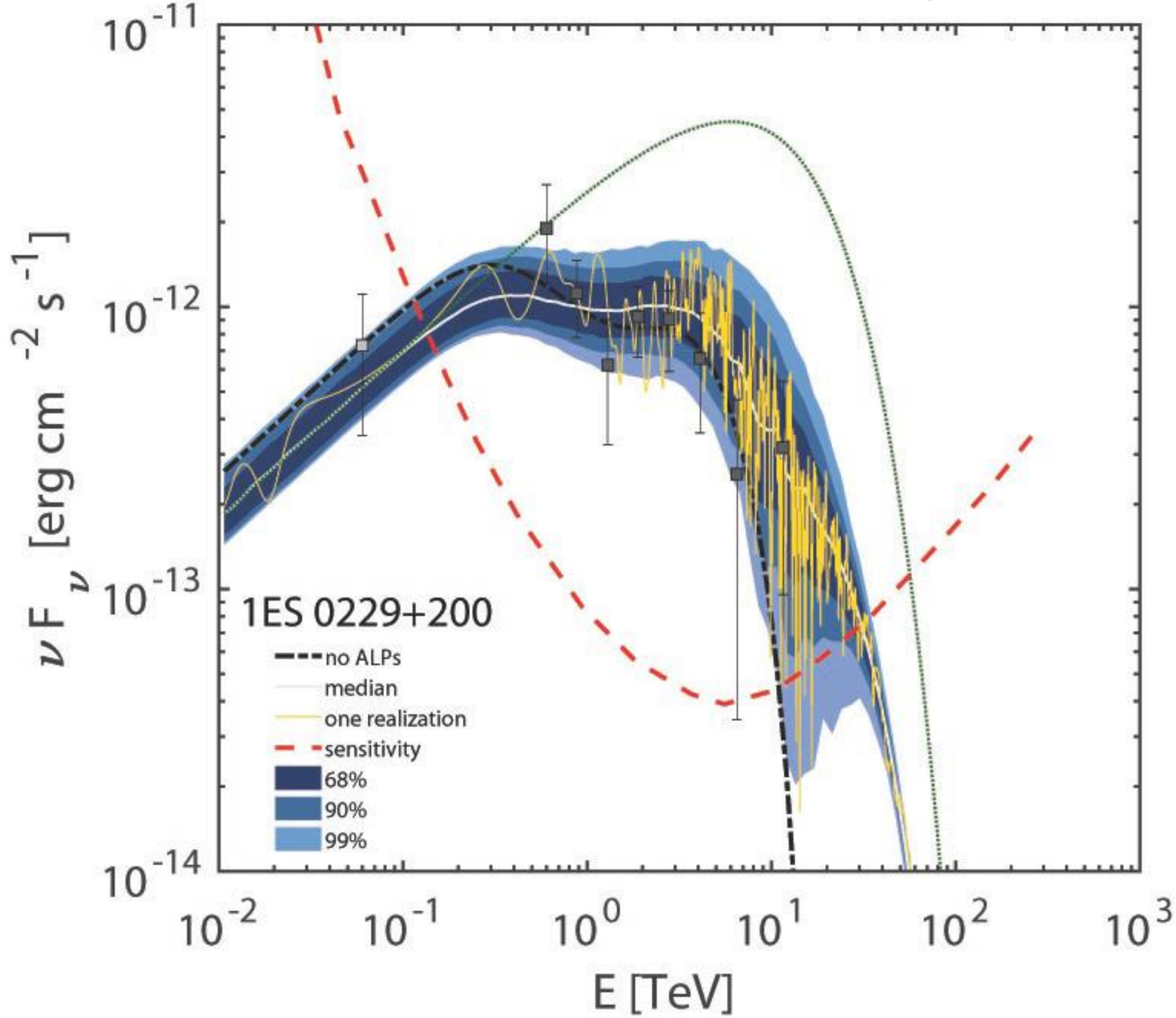
DATA from HEGRA (Aharonian et al. 2001)



G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, submitted.

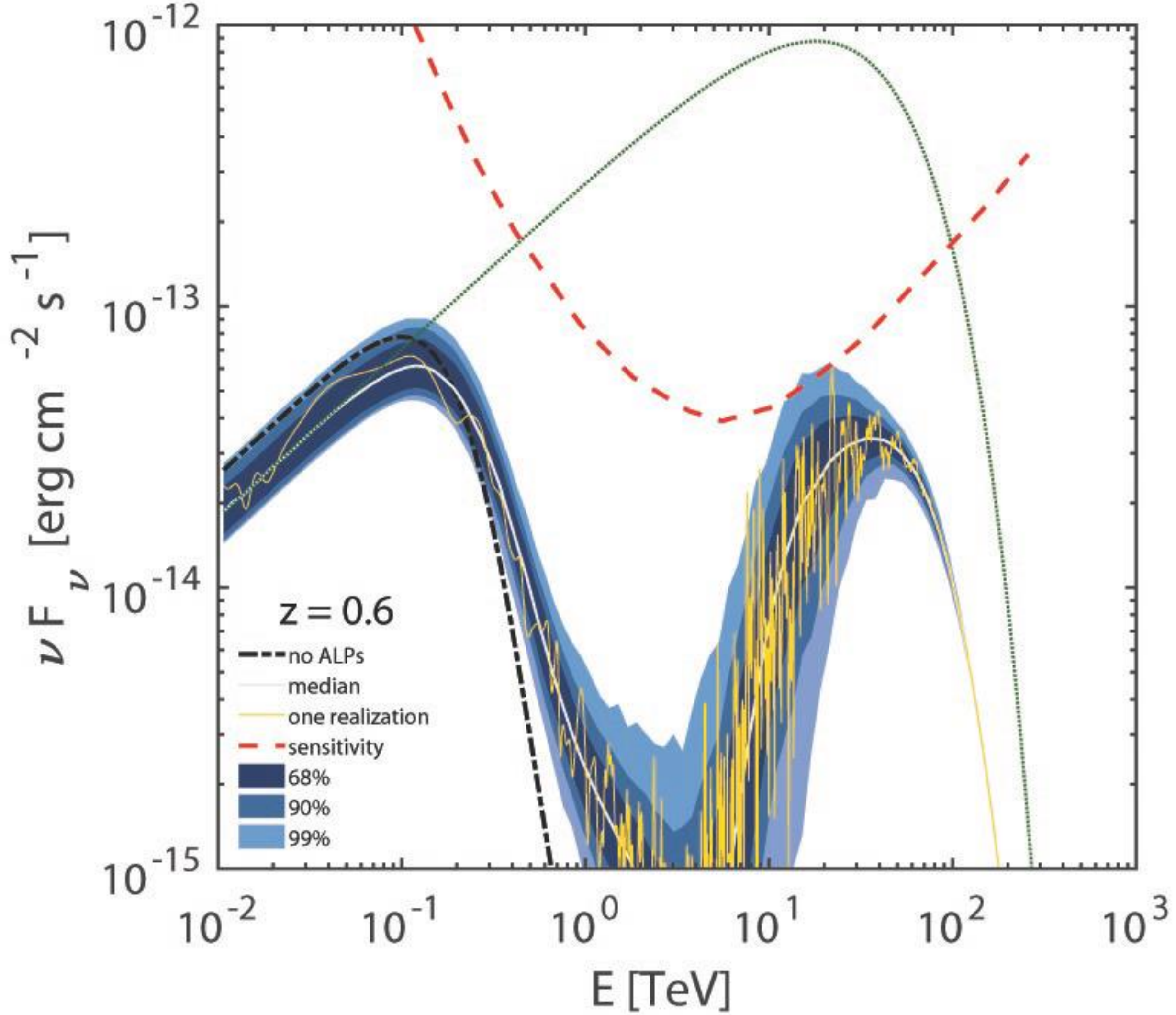
1ES 0229+200

DATA from HESS (Aharonian et al. 2007)



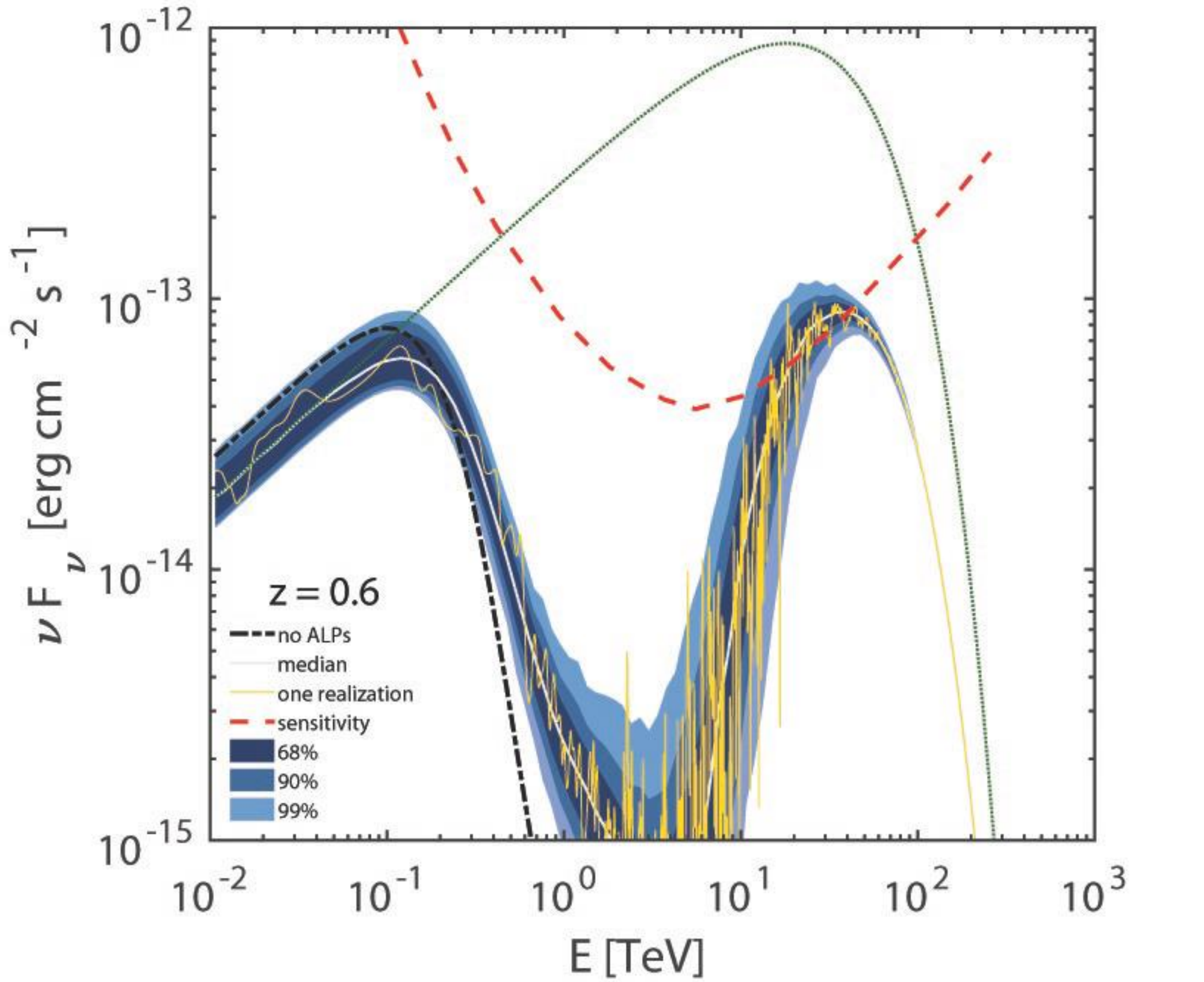
G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, submitted.

z = 0.6 – pole direction



G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, submitted.

z = 0.6 – plane direction



G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, submitted.

Propagation in the Milky Way and total effect (2)

- Conventional physics hardly explains the highest energy point in the spectra of Markarian 501 and of 1ES 0229+200

- photon/ALP oscillations are instead successful

- As the energy increases photon/ALP oscillation effect is more and more evident

- photon/ALP oscillations generate an observable **oscillatory** behavior in observed blazar spectra (induced by CMB photon dispersion) and a photon **excess** at high energy (> 10 TeV)

- These features can be detected by the planned new observatories like the Cherenkov Telescope Array (CTA)

G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, submitted.

Conclusions

- Photon-ALP oscillations increase Universe transparency to VHE photons even with CMB photon dispersion
- Photon-ALP oscillations increase BLR transparency to photons with $E > 20$ GeV explaining observed FSRQ emission
- They predict observable **excess** of VHE photons with $E > 10$ TeV from BL Lacs even at $z = 0.6$
- They predict an observable **oscillatory** behavior in observed blazar spectra
- Everything with the same photon-ALP model parameters: m_a, $g_{a\gamma\gamma}$

Perspectives

BL Lac spectra

- **Oscillations** in the low part of the VHE band and/or photon **excess** at ~30 TeV at high redshift can be detected by the planned new observatories like the Cherenkov Telescope Array (CTA)

- We are performing dedicated **simulations** in order to test in BL Lac spectra the **detectability** of both energy oscillations and/or photon excess (CTA and ASTRI mini-array)

Thank you