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Axion-like particles and high energy astrophysics

PHOTON 2019

Frascati , 3-7 June 2019

Outline

- Axion-like particles
- Active Galactic Nuclei
- Galaxy Clusters
- Extragalactic space
- Milky Way and total effect
- Main sequence and evolved stars
- Conclusions

Axion-like particles

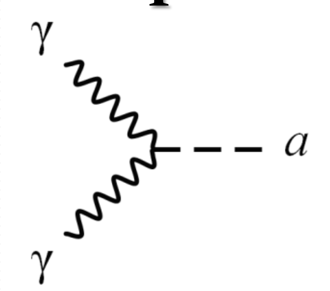
Axions and axion-like particles

- QCD nonperturbative effects produce **CP violation** in the strong sector measured by the angle θ
- **BUT** experimentally, $|\theta| < 10^{-10}$ → fine tuning needed
- Proposed solution → new symmetry $U(1)_{PQ}$ for the Lagrangian
- Symmetry broken → new particle: the **axion**
- Axion mass and coupling are *related*
- Axion-like particles have same properties but their mass m_a and two-photon coupling $g_{a\gamma\gamma}$ are *unrelated*

Axion-like particles (ALPs)

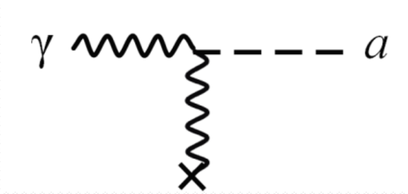
- Predicted by String Theory
- Very light particles ($m_a < 10^{-8}$ eV)
- Spin 0
- Interaction with two photons (coupling $g_{a\gamma\gamma}$)
- Interactions with other particles discarded
- Possible candidate for dark matter (see F. Giacchino talk next 6th June)

Two photons

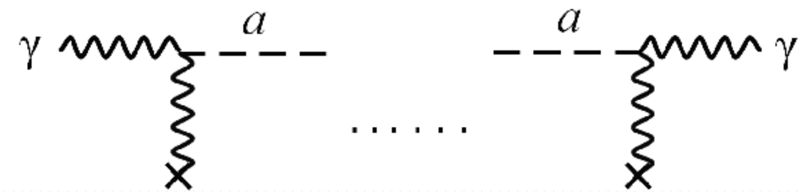


$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\,\mathbf{E}\cdot\mathbf{B}\,a$$

In an external B field



Photon-ALP oscillations



ALPs in astrophysical contest

- Photon/ALP beam in the very-high energy (VHE, 100 GeV – 100 TeV) band
- VHE photons absorbed when interacting with low energy photons present in several environments ($\gamma_{VHE} + \gamma_{soft} \rightarrow e^+ + e^-$)
- ALPs are not absorbed
- Photon-ALP oscillations increase medium transparency
- More photons detectable by Earth observatories at TeV energy
- **IMPLICATIONS** for:
  - Spectra of Active Galactic Nuclei (AGN)
  - Propagation of photon/ALP beam in AGN jets, galaxy clusters, extragalactic space, Milky Way
  - Transparency of the Universe
  - Emission from main sequence and evolved stars

ALP limits

- Lack of detection of ALPs from the Sun[1] and stellar evolution[2]

  $g_{a\gamma\gamma} < 0.66 \cdot 10^{-10}$ GeV^{-1} for $m_a < 0.02$ eV

- Unobserved spectral alterations induced by ALPs in the Perseus clusters[3]

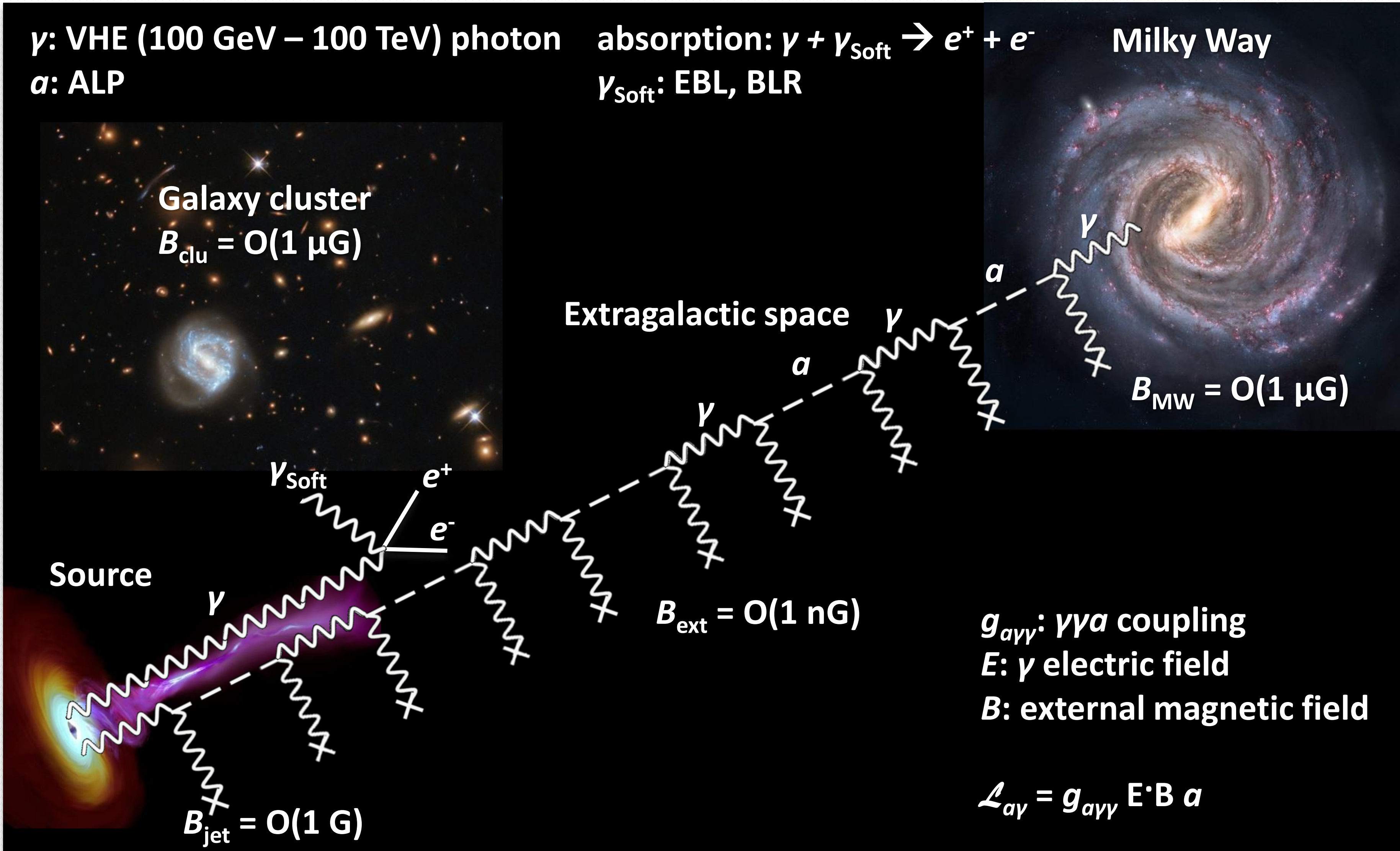
  $g_{a\gamma\gamma} < 5 \cdot 10^{-12}$ GeV^{-1} for $5 \cdot 10^{-10} < m_a < 5 \cdot 10^{-9}$ eV

- *Lack of detection of gamma rays from supernova SN1987A[4]

  $g_{a\gamma\gamma} < 5.3 \cdot 10^{-12}$ GeV^{-1} for $m_a < 4.4 \cdot 10^{-10}$ eV

[1] Anastassopoulos et al. 2017
[2] Ayala et al. 2014
[3] Ajello et al. 2016
[4] Payez et al. 2015

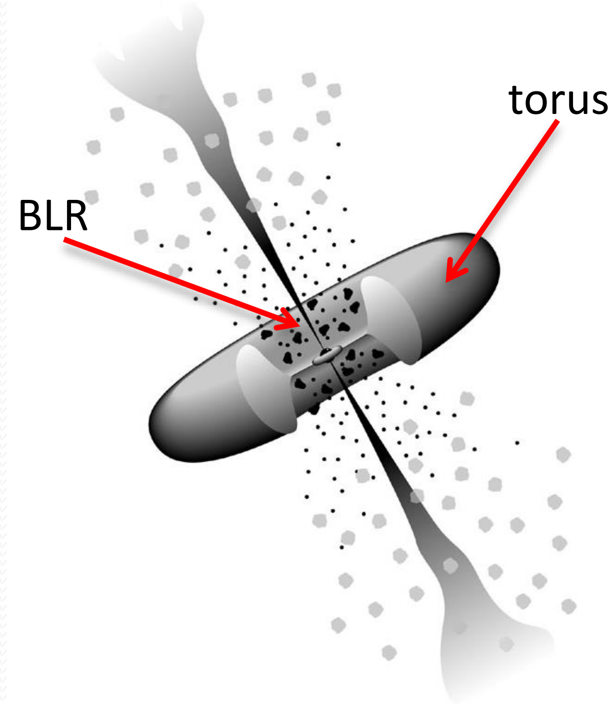
Photon-ALP propagation



Active Galactic Nuclei

Active Galactic Nuclei (AGN)

- Super massive black holes ($10^6 - 10^9 M_\odot$)
- Accretion disk
- Two collimated jets
- Photons produced at the jet base

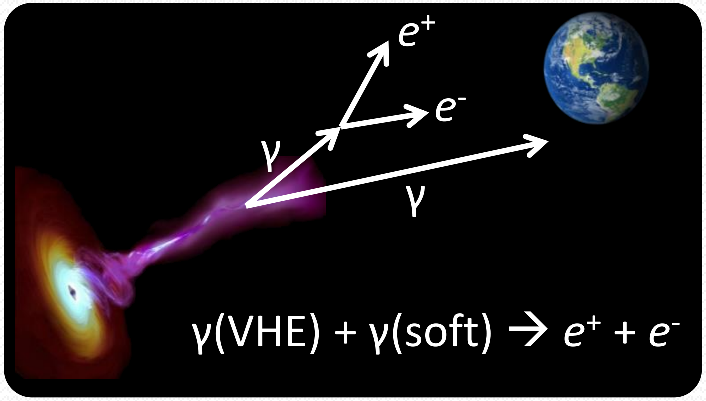


BL Lacs:

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

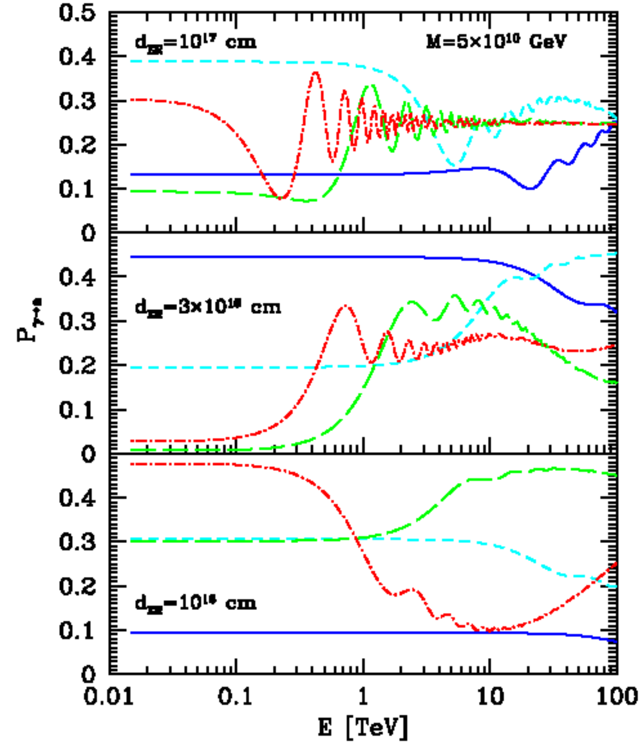
Flat spectrum radio quasars (FSRQs):

- Absorption due to the BLR for $E > 20$ GeV
- Absorption due to the dusty torus for $E > 300$ GeV
- Absorption due to the EBL for $E > 100$ GeV



ALPs in BL Lacs

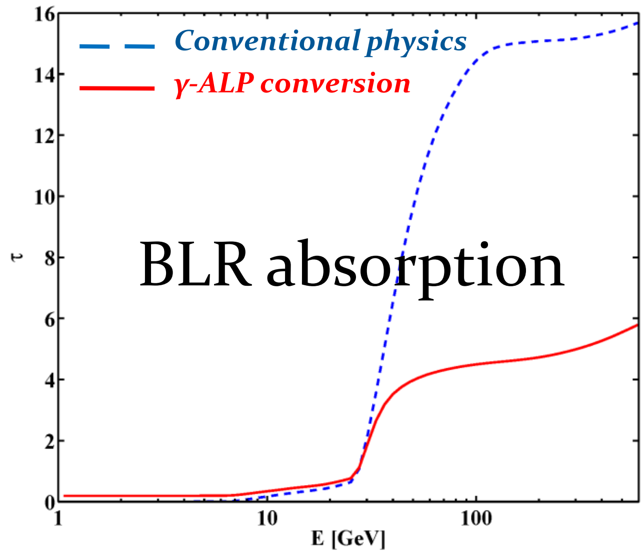
- Photons produced at $d_{\mathrm{VHE}} = 10^{16}$ cm from the centre
- $B_{\mathrm{jet}} = 0.1 - 1$ G and scales as 1/distance
- Electron density $n_e = 5 \cdot 10^4$ cm^{-3} and scales as 1/distance^2
- Lorentz factor $\Gamma = 15$
- Photon-ALP conversion inside B_{jet}
- Amount of photons/ALPs produced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

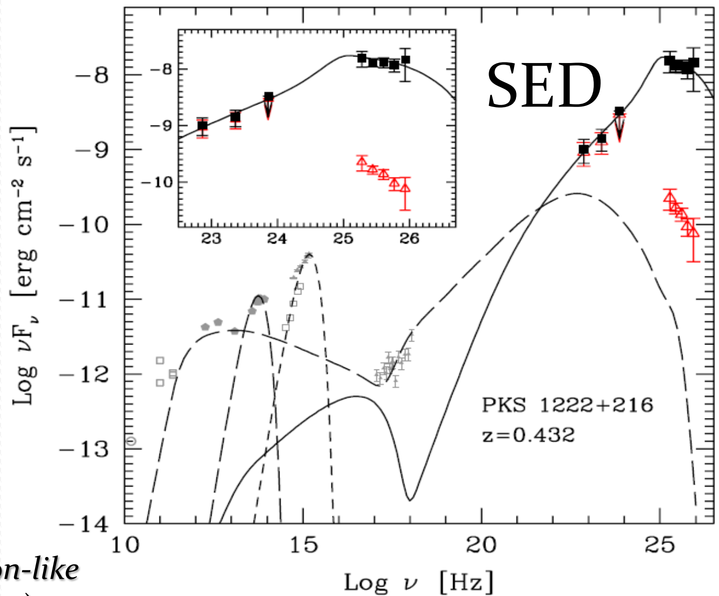


F. Tavecchio, M. Roncadelli and G. Galanti, *Photons to axion-like particles conversion in Active Galactic Nuclei*, Phys. Lett. B 744, 375 (arXiv: 1406.2303) (2015).

ALPs in FSRQs

- High BLR absorption → no photons with $E > 20$ GeV **BUT**
- Photons observed up to 400 GeV
- **Why?** Photon/ALP conversions?
- $B_{\text{jet}} = 0.2$ G and scales as 1/distance
- $g_{a\gamma\gamma} = 10^{-11}$ GeV^{-1}, $m_a < O(10^{-10}$ eV$)$
- BLR $n_{e,\text{BLR}} = 10^{10}$ cm^{-3}, $T = 10^4$ K
- Photon-ALP conversion before the BLR – reconversion outside BLR
- BLR absorption **REDUCED**
- Physically motivated flux (SED)





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).

Galaxy clusters

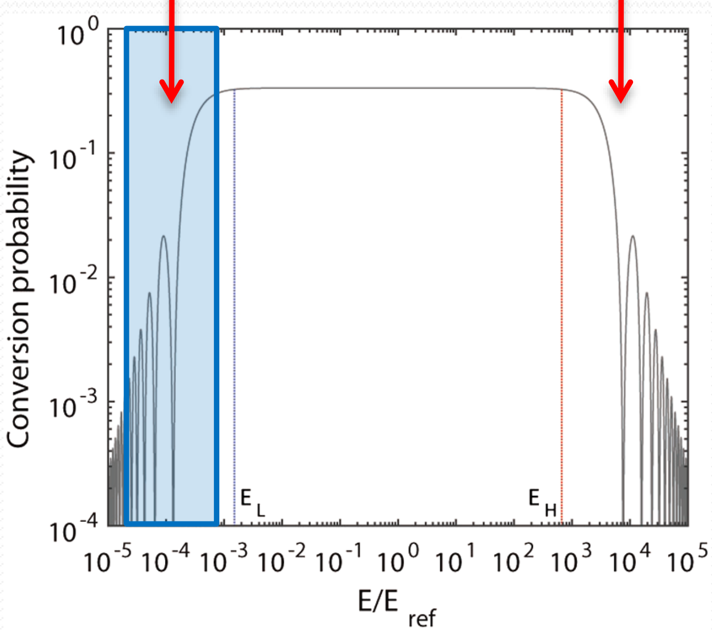
ALP irregularities in galaxy clusters?

- Perseus cluster[1]
- NGC 1275 (central galaxy) → bright gamma-ray emitter
- Cluster central magnetic field $B_{clu,0} = 10\ \mu G$
- $B_{clu} \geq 2\ \mu G$
- Turbulent B_{clu} profile
- Photon/ALP beam propagation in the Perseus B_{clu} and Milky Way B_{MW} magnetic fields
- Extragalactic magnetic field B_{ext} not considered
- EBL absorption (but negligible, redshift $z \approx 0.02$)

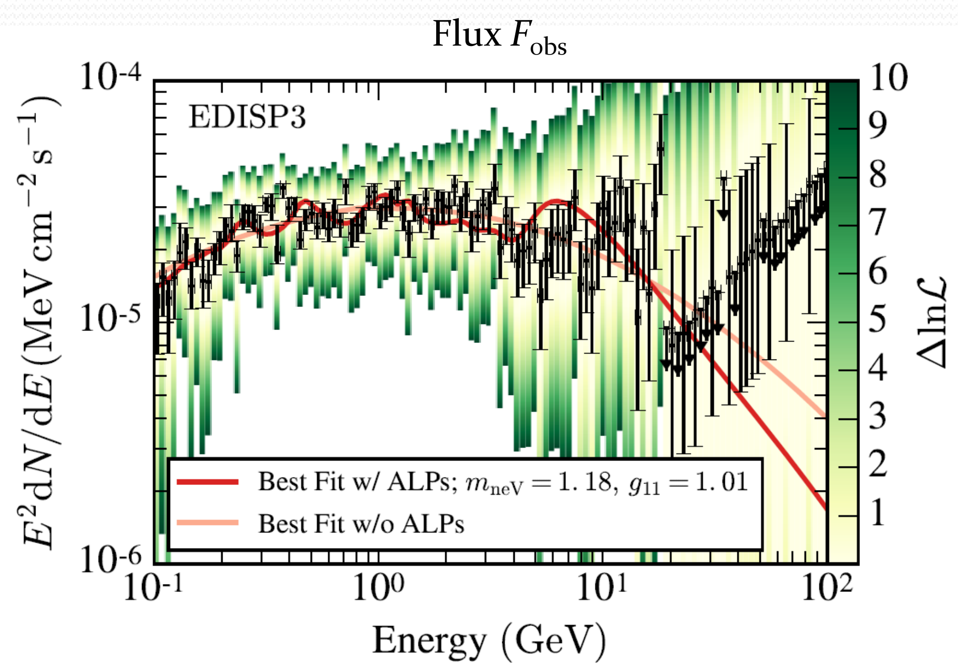
Ajello et al. 2016

[1] Similar strategy adopted in Abramowski et al. 2013

ALP irregularities in galaxy clusters? (2)



- Photon-ALP conversion probability $P_{\gamma \to a}(E, m_a, g_{a\gamma\gamma}, B_{clu})$
- Highlighted zone predicts spectral irregularities in observational data
- Constraints on $g_{a\gamma\gamma}$ and m_a



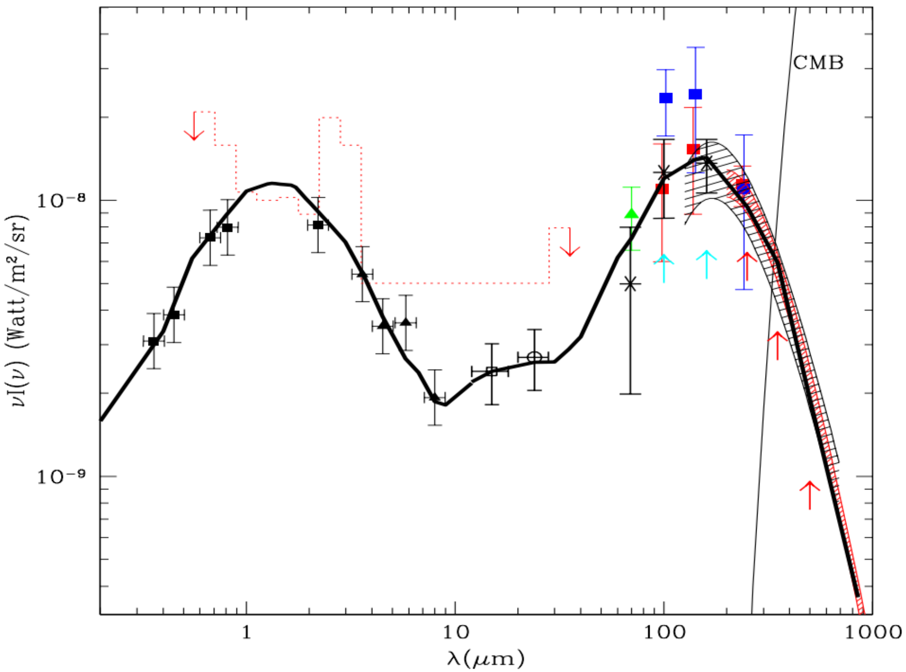
- Flux $F_{obs} = P_{\gamma \to \gamma}(m_a, g_{a\gamma\gamma})\, F_{em}$
- Statistically → **no preference** for photon-ALP conversion to fit data
- $g_{a\gamma\gamma} < 5 \cdot 10^{-12}$ GeV^{-1} for $5 \cdot 10^{-10} < m_a < 5 \cdot 10^{-9}$ eV

Ajello et al. 2016

Extragalactic space

Extragalactic Background Light (EBL)

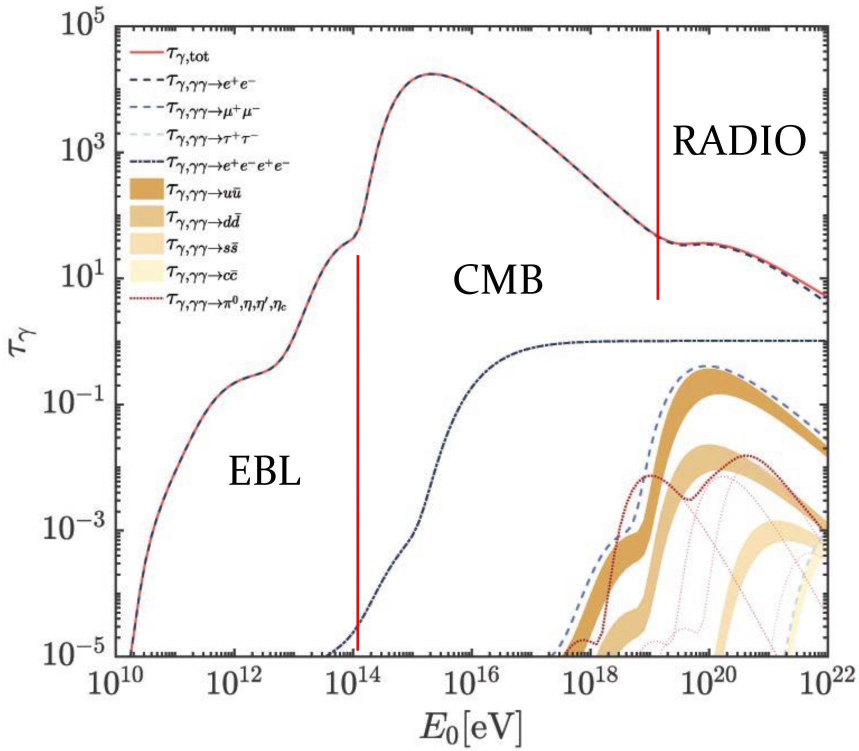
- Direct product of the ***stellar radiation*** and ***light absorbed and reradiated*** by the ***dust*** during the whole cosmic evolution
- From FIR to UV (0.005 eV – 5 eV)
- VHE photon absorption:
  $\gamma_{VHE} + \gamma_{EBL} \rightarrow e^{+} + e^{-}$
- VHE photon flux dimming



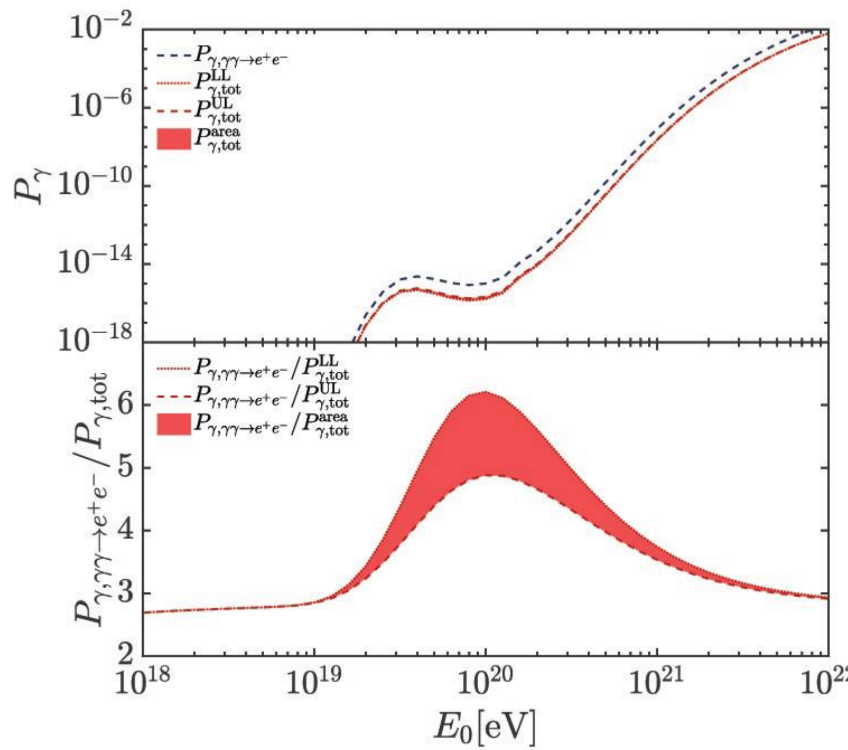
Franceschini & Rodighiero 2017

e.g. Dominguez et al. 2011
Gilmore et al. 2012
Franceschini & Rodighiero 2017

Extragalactic transparency



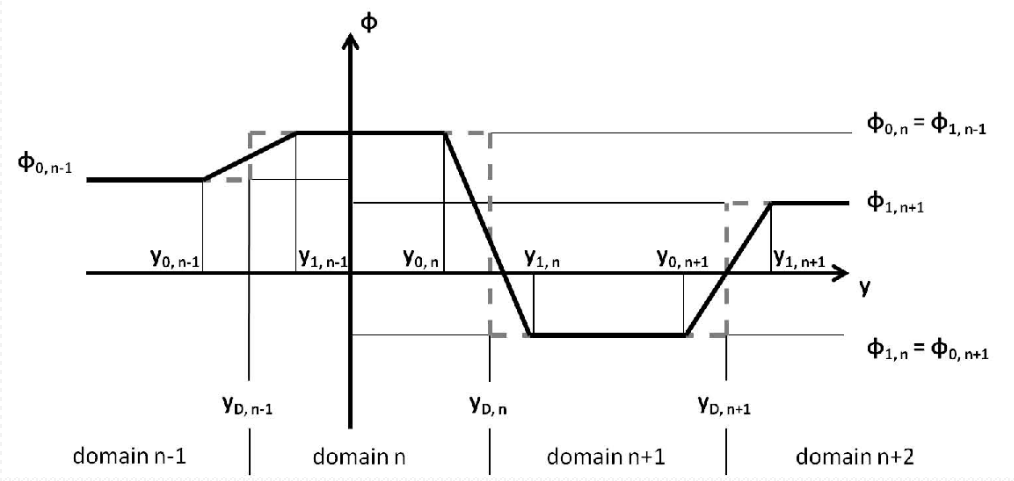
- Optical depth τ_γ due to:
  $\gamma_{VHE} + \gamma_{soft} \rightarrow e^+ + e^-$ (dominant)
- Survival probability:
  $P_\gamma = \exp(-\tau_\gamma)$



- Inclusion of double pair production, **other fermion pairs**, **single meson** production
- P_γ reduced for photons $E_0 > 10^{18}$ eV

G. Galanti, F. Tavecchio, F. Piccinini, M. Roncadelli, *Revisiting γγ absortpion for UHE photons with ll and qq production*, (arXiv: 1905.13713) (2019).

Domain-like magnetic fields



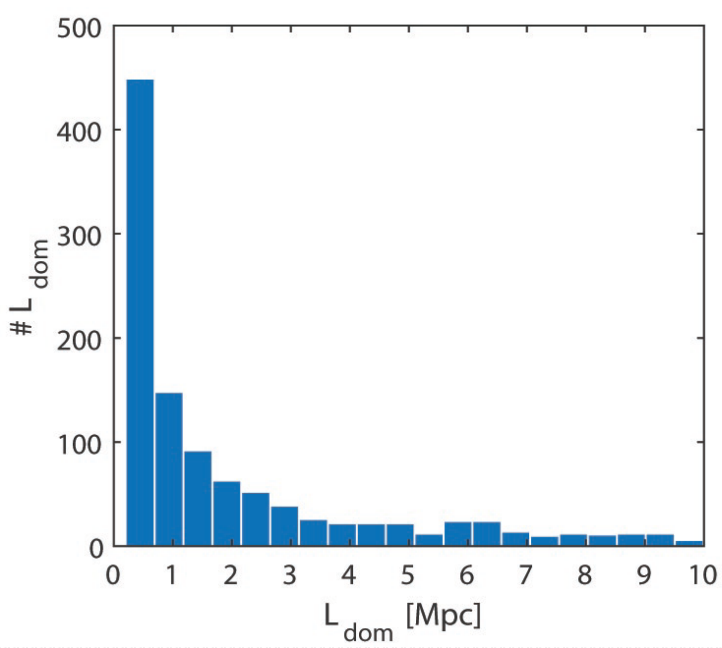
- $||\mathbf{B}||$ = const in domain of length L_{dom}
- ϕ: **B** orientation angle in the transverse direction
- Sharp transition → discontinuities

- 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

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).

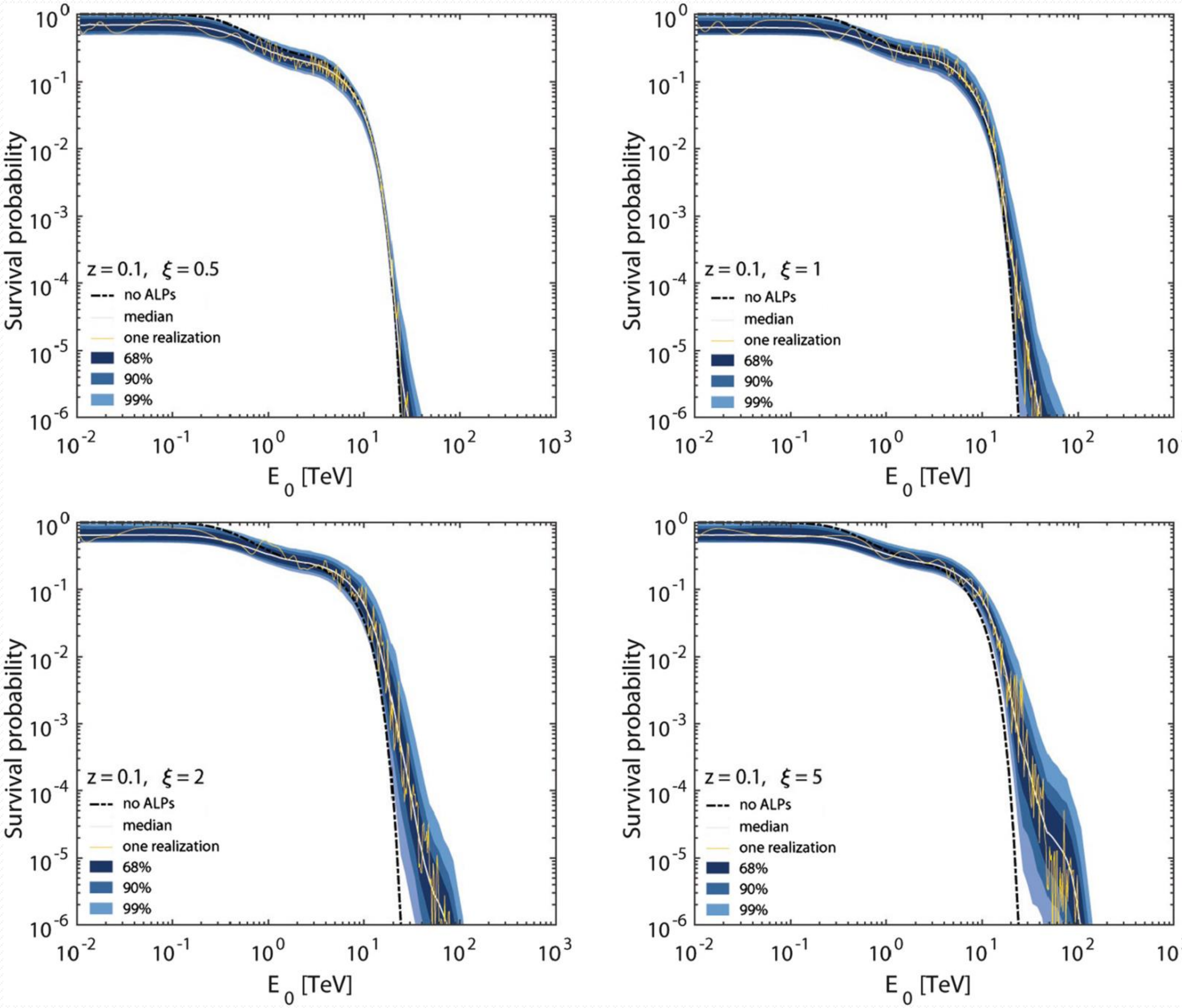
Propagation in the extragalactic space

- Extragalactic magnetic field B_{ext} = O(1 nG)
- L_{dom} with distribution $L_{dom}^{-1.2}$, $\langle L_{dom} \rangle$ = 2 Mpc
- Last data on EBL
- CMB photon dispersion considered ($\propto E$)
- $\xi = (B_{T,ext}/\text{nG})\cdot(g_{a\gamma\gamma} \cdot 10^{11}\ \text{GeV}) = 0.5 - 5$
- $m_a < O(10^{-10}\ \text{eV})$
- Redshift z = 0.02 – 2



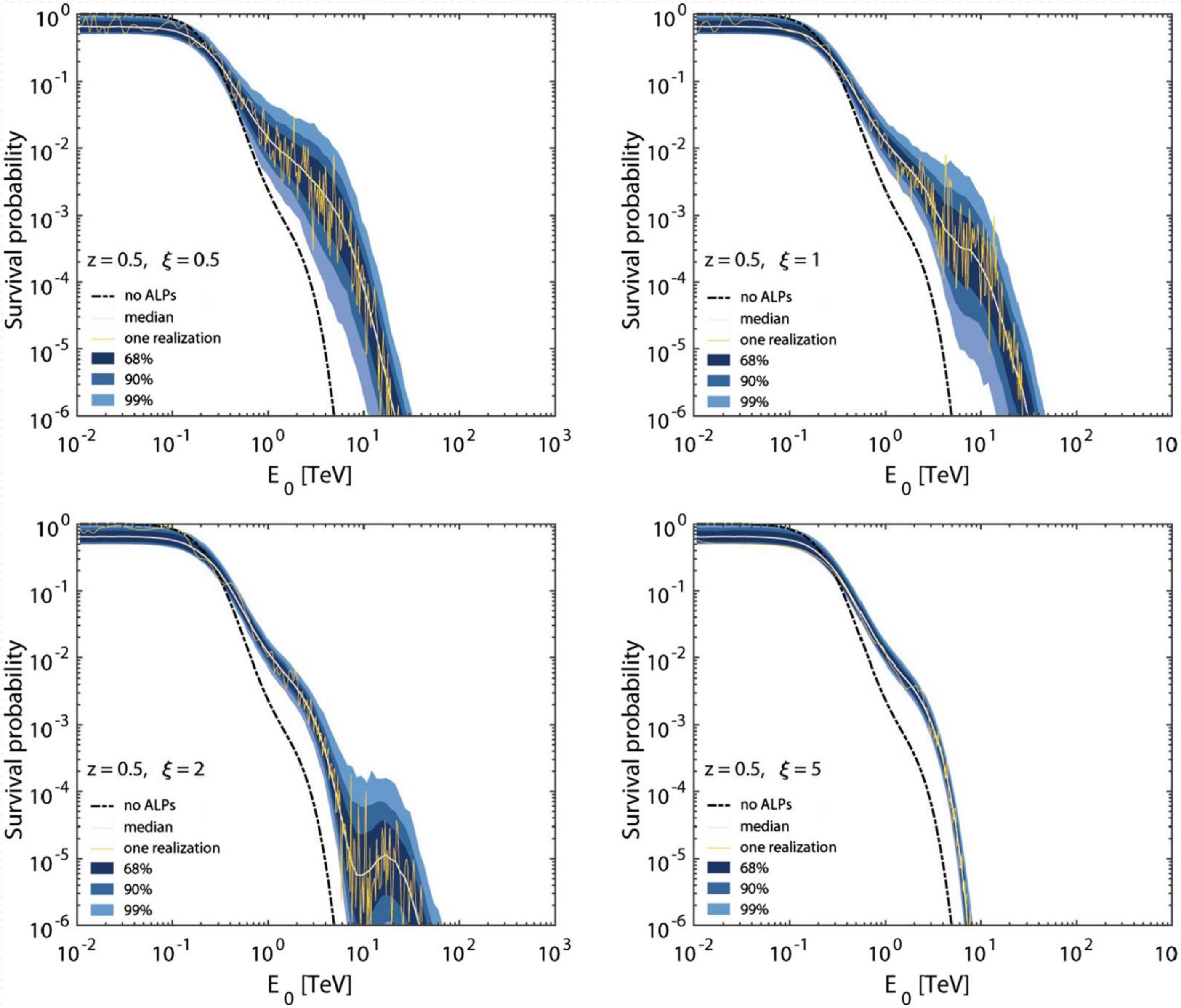
G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

Redshift 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).

Redshift 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).

Propagation in the extragalactic space (2)

- E > 15 TeV CMB photon dispersion is dominant
- For E > 40 TeV only the new continuous B_{ext} model gives physical results about the photon survival probability
- If 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, *Behavior of axion-like particles in smoothed out domain-like magnetic fields*, Phys. Rev. D 98, 043018 (arXiv: 1804.09443) (2018).
G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

Milky Way
and total effect

Propagation in the Milky Way and total effect

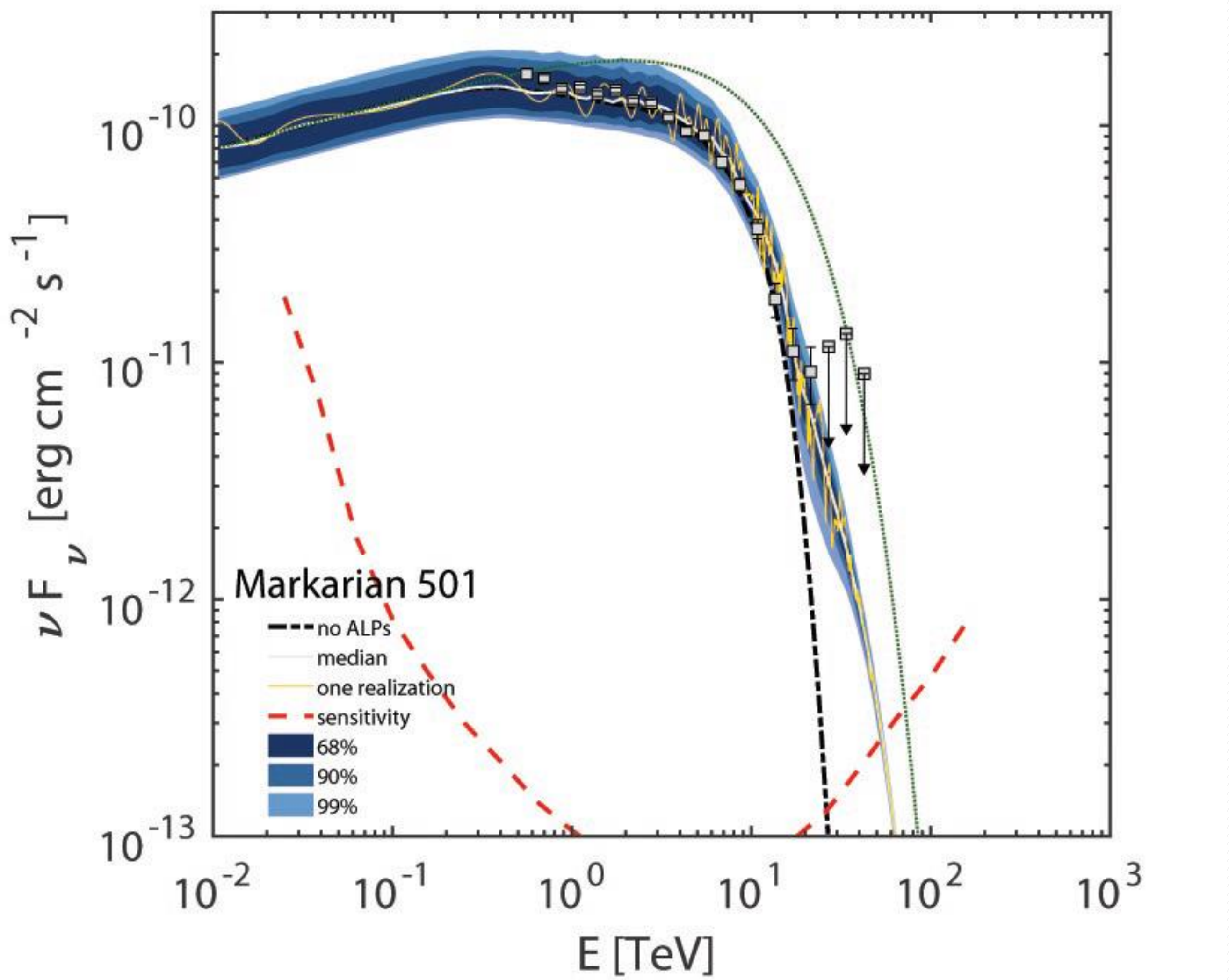
- Important only the regular component of the Milky Way magnetic field B_{MW}
- $B_{\mathrm{MW}} = 5$ μG, coherence length $l_{\mathrm{coh}} = 10$ kpc
- But detailed sky maps of B_{MW} exist

- 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
- $g_{a\gamma\gamma} = 10^{-11}$ GeV^{-1}, $m_a = 10^{-10}$ eV
- $d_{\mathrm{VHE}} = 3 \cdot 10^{16}$ cm, $n_e = 5 \cdot 10^4$ cm^{-3}
- $\Gamma = 15$

G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, Mon. Not. R. Astron. Soc. 487, 123 (arXiv: 1811.03548) (2019).

Markarian 501

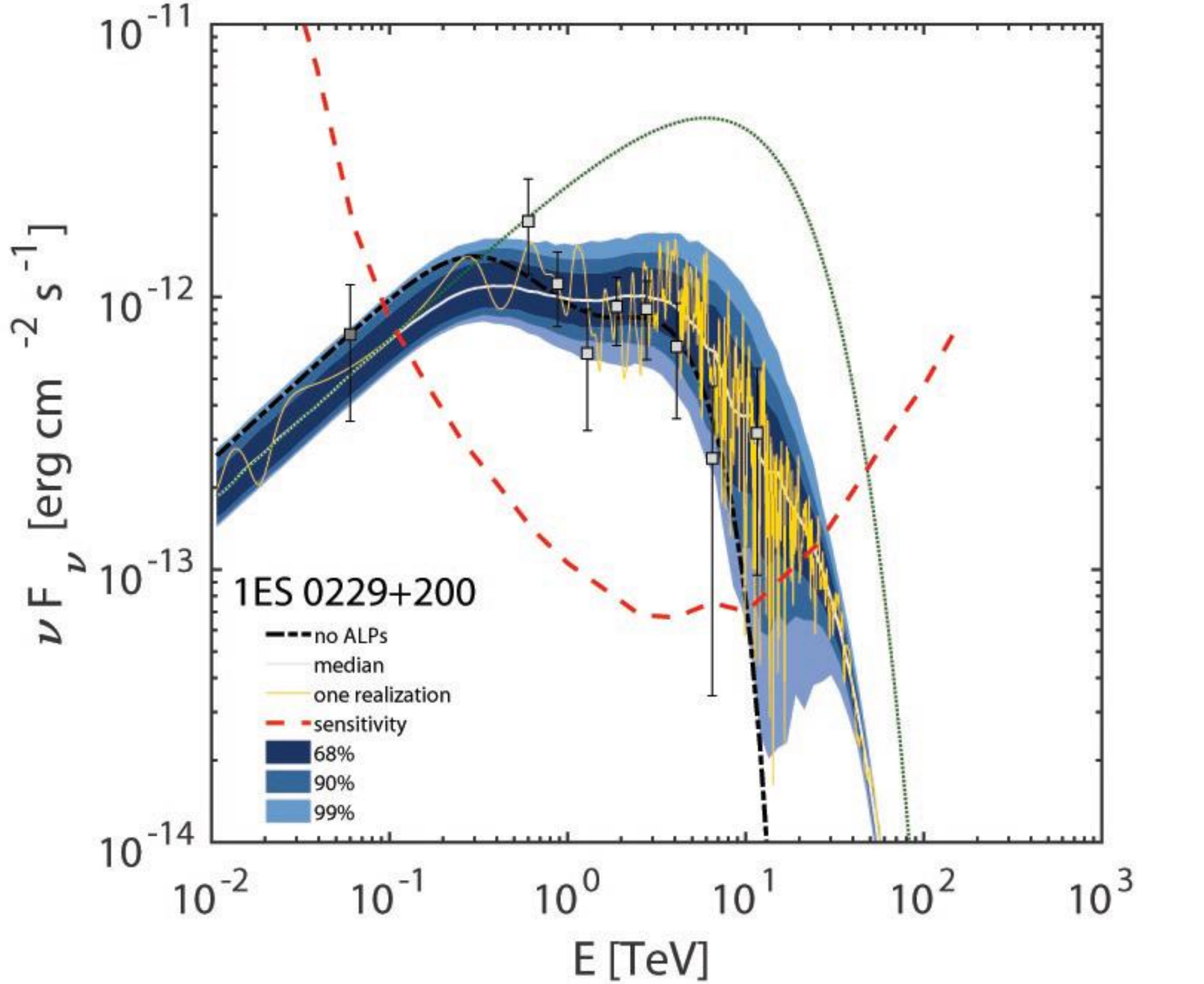
DATA from HEGRA (Aharonian et al. 2001)



G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, Mon. Not. R. Astron. Soc. 487, 123 (arXiv: 1811.03548) (2019).

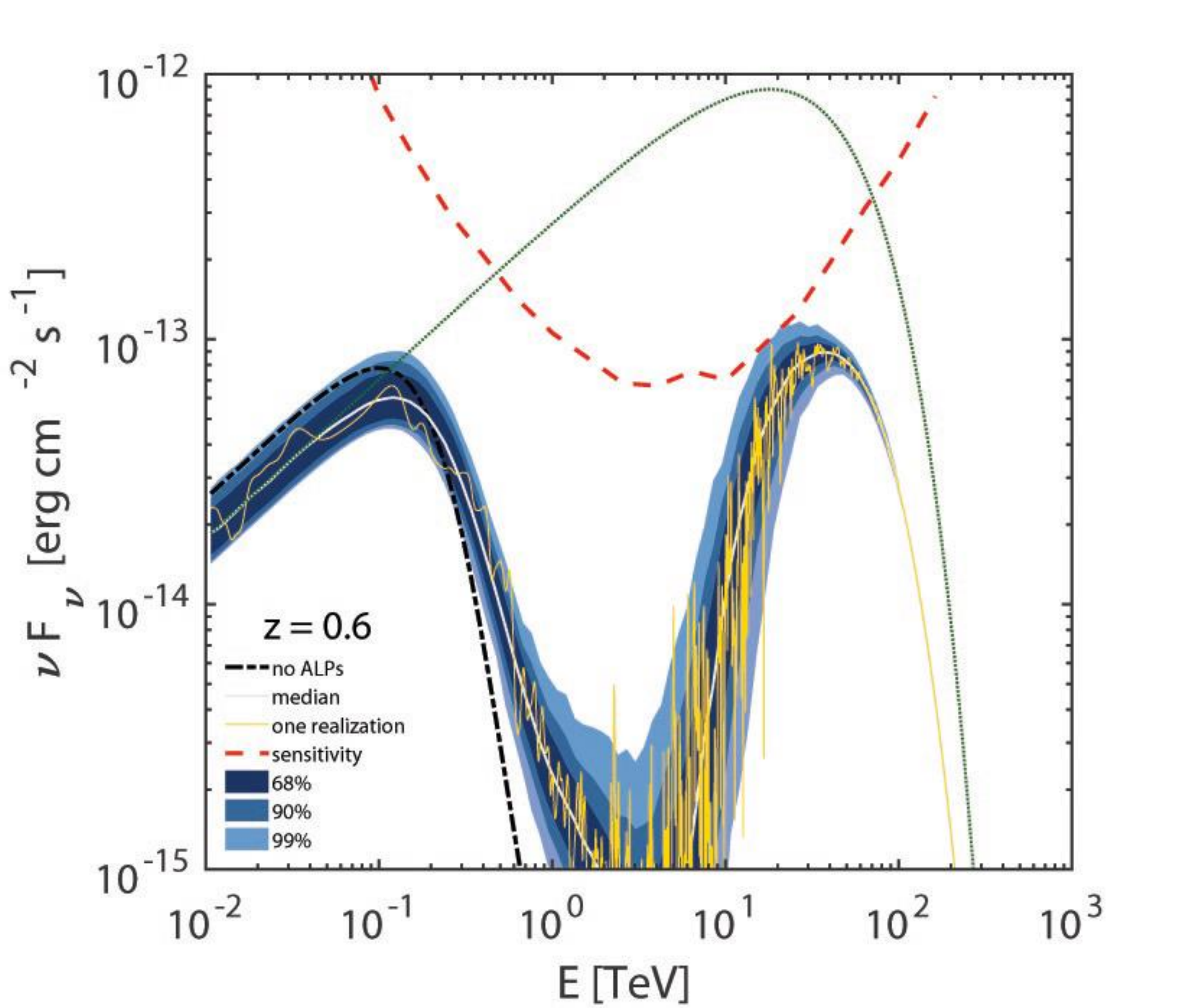
1ES 0229+200

DATA from Fermi/LAT (Vovk et al. 2012) 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*, Mon. Not. R. Astron. Soc. 487, 123 (arXiv: 1811.03548) (2019).

BL Lac at redshift z = 0.6



G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, Mon. Not. R. Astron. Soc. 487, 123 (arXiv: 1811.03548) (2019).

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 features in BL Lacs: (i) **oscillatory** behavior in blazar spectra and a (ii) photon **excess** at high energy (> 10 TeV)

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

G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, Mon. Not. R. Astron. Soc. 487, 123 (arXiv: 1811.03548) (2019).

Main sequence and evolved stars

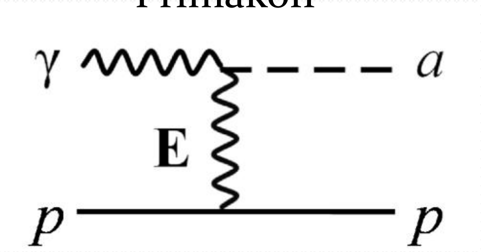
ALPs from Sun and stellar evolution

CAST EXPERIMENT:

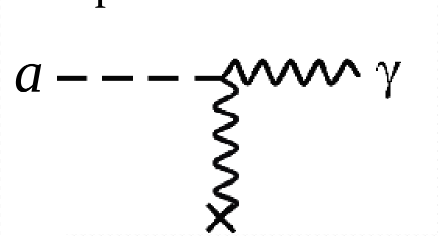
- ALPs produced in the Sun by Primakoff scattering: $p + \gamma \rightarrow p + a$ ($p \rightarrow$ protons or charged particles)
- ALPs reconverted back to photons inside the B-field of a magnet at LHC ($\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\ \mathbf{E}\cdot\mathbf{B}\ a$)
- **NO DETECTION** $\rightarrow g_{a\gamma\gamma} < 0.66 \cdot 10^{-10}$ GeV^{-1} for $m_a < 0.02$ eV

Anastassopoulos et al. 2017

Primakoff



ALP to photon reconversion



GLOBULAR CLUSTERS:

- ALPs produced in stars by Primakoff scattering $\rightarrow$ source of stellar **cooling** (ALPs escape from the stellar core since $g_{a\gamma\gamma}$ very low)
- Modification in the stellar evolution as a function of $g_{a\gamma\gamma}$ and m_a
- From observational data $\rightarrow$ **bounds** on ALP parameters: $g_{a\gamma\gamma} < 0.66 \cdot 10^{-10}$ GeV^{-1}

Ayala et al. 2014

ALPs from supernovae?

- ALPs produced via Primakoff process in core-collapse supernova (protoneutron star phase)
- Reconverted back to photons inside the Milky Way magnetic field
- Photons from ALP reconversions supposed to be observed in coincidence with observation of neutrinos from SN1987A
- **NO DETECTION** → strong bound on ALPs: $g_{a\gamma\gamma} < 5.3 \cdot 10^{-12}$ GeV^{-1} for $m_a < 4.4 \cdot 10^{-10}$ eV

Payez et al. 2015

- **BUT** model oversimplified:
  - Strong interactions not considered
  - Strong magnetic field $B = 10^{12} - 10^{16}$ G not considered (too strong B may reduce ALP production – *QED effects*)
  - Calculation almost performed as in the vacuum (instead the medium at twice the nuclear saturation density and at $T \approx 40$ MeV)
- Derived **bound cannot be** assumed as fully **solid**

Conclusions

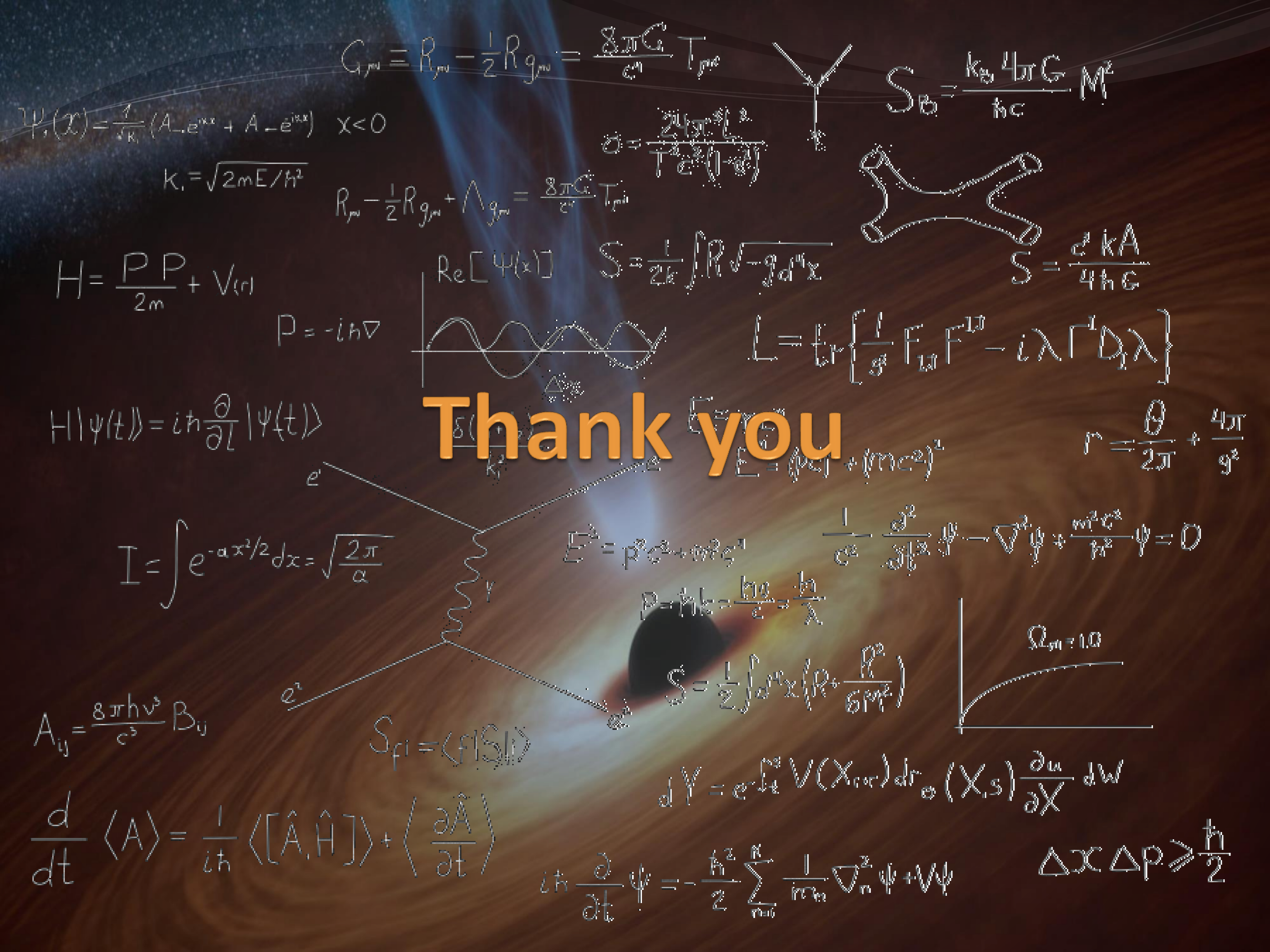
Other ALP studies

- Spectral irregularities of point sources in galaxy clusters in the X-ray energy band (Berg et al. 2016; Marsh et al. 2017; Conlon et al. 2017) – similar to same studies in the VHE band
- Spectral distortions of the continuum thermal emission ($T \sim$ 2 – 8 keV) of galaxy clusters (Conlon et al. 2016)
- Unexpected spectral line at 3.5 keV – dark matter decay into ALP and conversion to photons? (Jaeckel et al. 2014; Lee et al. 2014; Cicoli et al. 2014)
- In the VHE band AGN spectral indices better described with ALPs (De Angelis, Galanti & Roncadelli 2011; Horns & Meyer 2012; Rubtsov & Troitsky 2014; Galanti et al. 2015) but other possibility: EM cascades (Essey & Kusenko 2012) and other statistical analyses (Sanchez et al. 2013; Biteau & Williams 2015; Domìnguez & Ajello 2015)
- Search for diffuse flux of photon from ALP concomitant with neutrino production in extragalactic space (Vogel, Laha & Meyer 2017)

Conclusions

ALP-photon interactions have deep astrophysical impact:

- Modification of AGN spectra
  - In FSRQs ALPs explain why emission above 20 GeV
  - In BL Lacs ALPs predict observable peculiar features
- Production of spectral irregularities in galaxy clusters
- Increase of the Universe transparency
- Modification of stellar evolution
- Consequences in different energy bands (X- to gamma-rays)
- Many of previous effects with the same model parameters ($g_{a\gamma\gamma}$, m_a) → possible first *ALP existence* hints??
- Astrophysical new data from observatories like the CTA and ASTRI, IAXO and laboratory experiments like ALPS II can shed light



Thank you

$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$S_B = \frac{k_B 4\pi G}{\hbar c} M^2$
$k_1 = \sqrt{2mE/\hbar^2}$
$x<0$
$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$H = \frac{P P}{2m} + V(r)$
$S = \frac{1}{2k} \int R \sqrt{-g}\, d^4x$
$S = \frac{c^3 kA}{4\hbar G}$
$P = -i\hbar\nabla$
$Re[\Psi(x)]$
$H|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$
$E = mc^2$
$E^2 = (pc)^2 + (mc^2)^2$
$I = \int e^{-\alpha x^2/2} dx = \sqrt{\frac{2\pi}{\alpha}}$
$E^2 = p^2c^2 + m^2c^4$
$\frac{1}{c^2}\frac{\partial^2}{\partial t^2}\psi - \nabla^2\psi + \frac{m^2c^2}{\hbar^2}\psi = 0$
$p = \hbar k = \frac{h\nu}{c} = \frac{h}{\lambda}$
$A_{ij} = \frac{8\pi h\nu^3}{c^3} B_{ij}$
$S_{fi} = \langle f|S|i\rangle$
$\frac{d}{dt}\langle A\rangle = \frac{1}{i\hbar}\langle[\hat{A},\hat{H}]\rangle + \left\langle\frac{\partial\hat{A}}{\partial t}\right\rangle$
$\Delta x \Delta p \geq \frac{\hbar}{2}$