

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$S_B = \frac{k_B 4\pi G}{\hbar c} M^2$$

$$\Psi(x) = \frac{1}{\sqrt{K_0}} (A_+ e^{ix} + A_- e^{iwx}) \quad x < 0$$

$$\sigma = \frac{24\pi^3 L^2}{T^2 c^2 (1-e^2)}$$

**Giorgio GALANTI**

$$K_i = \sqrt{2mE/\hbar^2}$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$H = \frac{P^2}{2m} + V(r)$$

$$Re[\Psi(x)] \quad S = \frac{1}{2k} \int R \sqrt{-g} d^4x$$

$$INAF - IASF-MI$$

$$P = -i\hbar\nabla$$



$$L = \Gamma \left\{ \frac{1}{\beta} F_{IJ} F^{IJ} - i \lambda [D_I \lambda] \right\}$$

$$H|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$$

$$\delta(k_1+k_2)$$

# Axion-like particle effects in high-energy astrophysics

$$I = \int e^{-\alpha x^2/2} dx = \sqrt{\frac{2\pi}{\alpha}}$$

$$E^2 = P^2 c^2 + m^2 c^4$$

$$E^2 = (pc)^2 + (mc^2)^2$$

$$r = \frac{\theta}{2\pi} + \frac{4\pi}{9^2}$$

$$k^2$$

$$P = \hbar k = \frac{\hbar \omega}{c} = \frac{\hbar}{\lambda}$$

18<sup>th</sup> Patras Workshop on

Axions, WIMPs and WISPs

$$A_{ij} = \frac{8\pi\hbar v^3}{c^5} B_{ij}$$

$$S_{fi} = \langle S_f | S_i \rangle$$

$$S = \frac{1}{2} \int d^4x \left( R + \frac{R^2}{6M^2} \right)$$

$$\Omega_m = 1.0$$

$$\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [\hat{A}, \hat{H}] \rangle + \left\langle \frac{\partial \hat{A}}{\partial t} \right\rangle$$

$$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2} \sum_{n=1}^N \frac{1}{m_n} \nabla_n^2 \psi + V\psi$$

$$\frac{d}{dt} \psi = e^{-i\omega t} V(X_{t,r}) dr_\Theta(X,s) \frac{\partial \omega}{\partial X} d\omega$$

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$Rijeka, 4 July 2023$$

# Outline

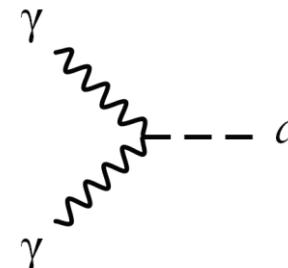
- Axion-like particles
- Part I: Spectral effects
  - Active Galactic Nuclei
  - Extragalactic space
  - Milky Way and total effect
  - Final remarks
- Part II: Polarization effects
  - Galaxy Clusters
  - Blazars
  - Final remarks
- GRB 221009A
- Conclusions

# Axion-like particles

# Axion-like Particles (ALPs)

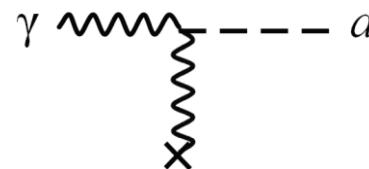
- Predicted by String Theory
- Very light particles ( $m_a < 10^{-8}$  eV)
- Spin 0
- **Interaction with two photons** (coupling  $g_{a\gamma\gamma}$ )
- Subdominant interactions with other particles
- Possible candidate for dark matter
- Induce the **change of the polarization state of photons**

## Two photons

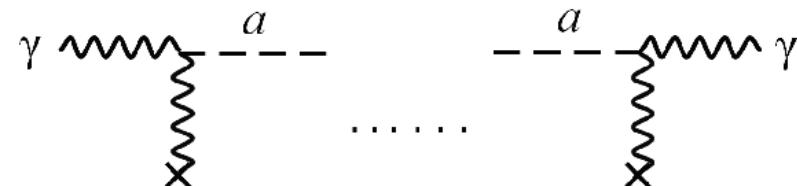


$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} a$$

## In an external B field



## Photon-ALP oscillations



# ALPs in astrophysical contest

- ALPs very **elusive** in laboratory experiments (low coupling) → **astrophysical environment** is the **best opportunity** to study ALPs and ALP effects (*for free*)
- Photon/ALP beam with  $E \gg m_a$
- For  $E < 10$  GeV → negligible photon absorption due to EBL
  - **Photon-ALP interaction** produces effective **photon absorption**
- For  $E > 10$  GeV → photons absorbed by EBL ( $\gamma\gamma \rightarrow e^+e^-$ ), **ALPs** are **not absorbed**
  - **Photon-ALP oscillations increase medium transparency**
- **HINTS** at ALP existence:
  - Explain how flat spectrum radio quasars (FSRQs) can emit up to 400 GeV  
F. Tavecchio, M. Roncadelli, G. Galanti and G. Bonnoli, Phys. Rev. D, 86, 085036 (2012) [arXiv: 1202.6529].
  - Solve the anomalous redshift dependence of blazar spectra  
G. Galanti, M. Roncadelli, A. De Angelis, G. F. Bignami, MNRAS 493, 1553 (2020) [arXiv: 1503.04436].
  - GRB 221009A?  
G. Galanti, L. Nava, M. Roncadelli and F. Tavecchio, arXiv:2210.05659.

# ALP limits

- Lack of detection of ALPs from the Sun [1] and stellar evolution [2]  
$$g_{a\gamma\gamma} < 0.66 \times 10^{-10} \text{ GeV}^{-1} \text{ for } m_a < 0.02 \text{ eV}$$
- Unobserved spectral alterations induced by ALPs in the Perseus clusters [3]  
$$g_{a\gamma\gamma} < 5 \times 10^{-12} \text{ GeV}^{-1} \text{ for } 5 \times 10^{-10} < m_a < 5 \times 10^{-9} \text{ eV}$$
- Unobserved ALP-induced spectral modifications on photons from AGN in or behind galaxy clusters, see e.g. [4,5]  
$$g_{a\gamma\gamma} < O(10^{-12}) \text{ GeV}^{-1} \text{ for } m_a < O(10^{-12}) \text{ eV}$$
- Lack of detection of gamma rays from supernova SN1987A [6]  
$$g_{a\gamma\gamma} < 5.3 \times 10^{-12} \text{ GeV}^{-1} \text{ for } m_a < 4.4 \times 10^{-10} \text{ eV}$$
- Polarization measurement of the emission from magnetic white dwarfs [7]  
$$g_{a\gamma\gamma} < 5.4 \times 10^{-12} \text{ GeV}^{-1} \text{ for } m_a < 3 \times 10^{-7} \text{ eV}$$

[1] Anastassopoulos et al. 2017

[2] Ayala et al. 2014

[3] Ajello et al. 2016

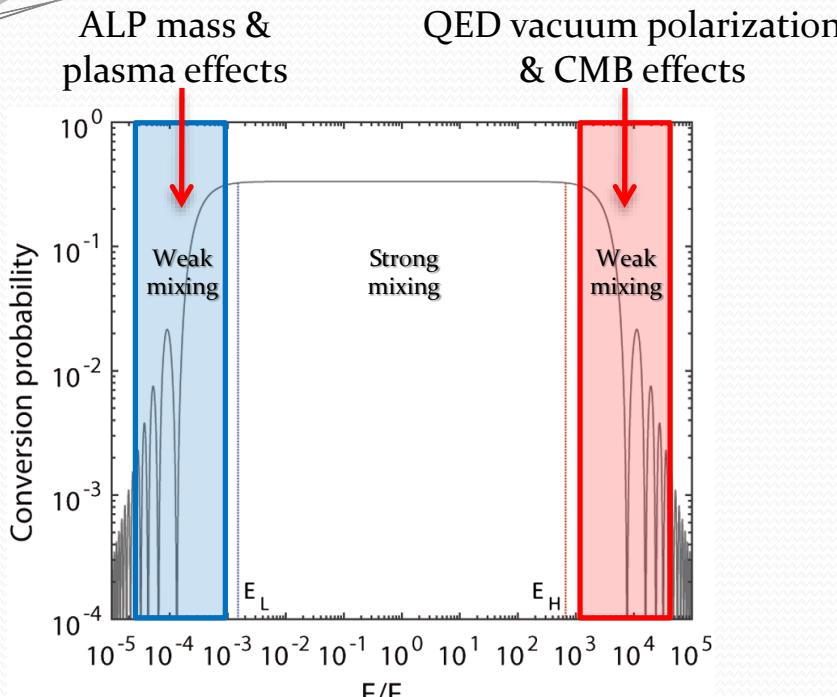
[4] Conlon et al. 2017

[5] Sisk-Reynés et al. 2022

[6] Payez et al. 2015

[7] Dessert et al. 2022

# ALP-induced irregularities



## BLUE AREA:

- Spectral effects investigated in:

D. Wouters, P. Brun, Phys. Rev. D 86, 043005 (2012).

Fermi-LAT Collaboration, Phys. Rev. Lett. 116, 161101 (2016).

CTA Consortium, JCAP 02, 048 (2021).

- Polarization effects studied in:

G. Galanti, Phys. Rev. D 107, 043006 (2023).

G. Galanti, M. Roncadelli, F. Tavecchio, E. Costa, Phys. Rev. D 107, 103007 (2023).

- Photon-ALP conversion probability  $P_{\gamma \rightarrow a}(E, m_a, g_{a\gamma\gamma}, B)$
- Highlighted zones predict **spectral irregularities and polarization effects** in observational data
- Constraints on  $g_{a\gamma\gamma}$  and  $m_a$  but the firmest is  $g_{a\gamma\gamma} < 6.6 \times 10^{-11} \text{ GeV}^{-1}$  for  $m_a < 0.02 \text{ eV}$  (CAST collaboration, 2017)

## RED AREA:

- Spectral effects investigated in:

G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019).

G. Galanti, F. Tavecchio, M. Landoni, MNRAS 491, 5268 (2020).

- Polarization effects studied in:

G. Galanti, Phys. Rev. D 107, 043006 (2023).

# Part I: Spectral effects

$\gamma$ : photon

$a$ : ALP

absorption:  $\gamma + \gamma_{\text{Soft}} \rightarrow e^+ + e^-$

$\gamma_{\text{Soft}}$ : EBL, BLR

$$B_{\text{clu}} = O(10) \mu\text{G}$$

## Galaxy cluster:

M. Meyer, D. Montanino, J. Conrad, JCAP 09, 003 (2014).

G. Galanti, M. Roncadelli, F. Tavecchio, E. Costa, Phys. Rev. D 107, 103007 (2023).

$$B_{\text{jet}} = O(1-10^4) \text{ G}$$

## Source:

F. Tavecchio, M. Roncadelli, G. Galanti, Phys. Lett. B 744, 375 (2015).

G. Galanti, L. Nava, M. Roncadelli, F. Tavecchio, arXiv: 2210.05659.

## Milky Way:

D. Horns, L. Maccione, M. Meyer et al., Phys. Rev. D, 86, 075024 (2012).

G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019).

$$B_{\text{MW}} = O(1) \mu\text{G}$$



$g_{a\gamma\gamma}$ :  $\gamma\gamma a$  coupling

$E$ :  $\gamma$  electric field

$B$ : external magnetic field

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

## Extragalactic space:

A. Mirizzi and D. Montanino, JCAP 12, 004 (2009).

G. Galanti and M. Roncadelli, Phys. Rev. D 98, 043018 (2018).

G. Galanti and M. Roncadelli, JHEAp, 20 1-17 (2018).

# Active Galactic Nuclei

# Active Galactic Nuclei (AGN)

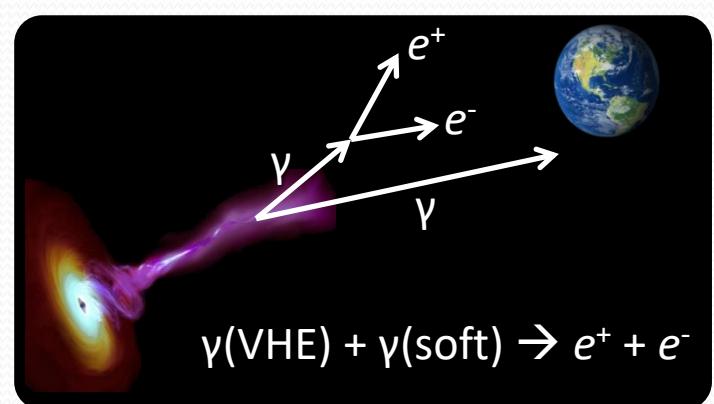
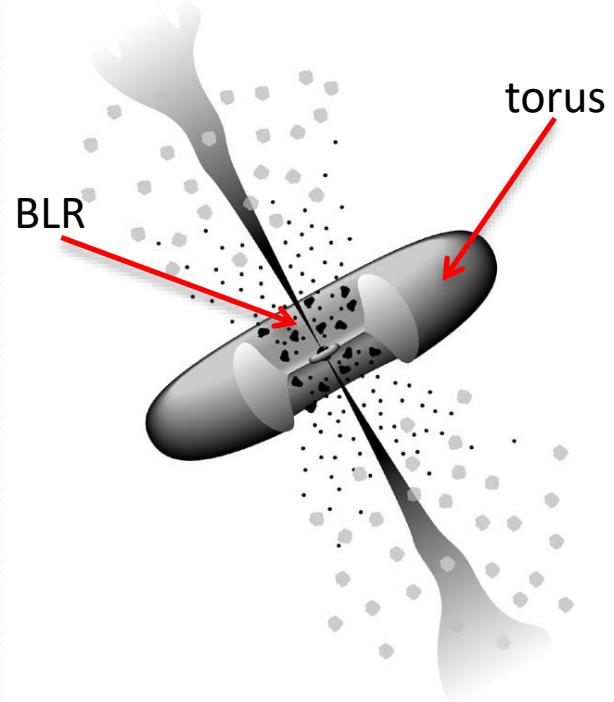
- Super massive black holes ( $10^6 - 10^9 M_\odot$ )
- Accretion disk
- Two collimated jets
- Photons produced at the jet base

## BL Lacs:

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

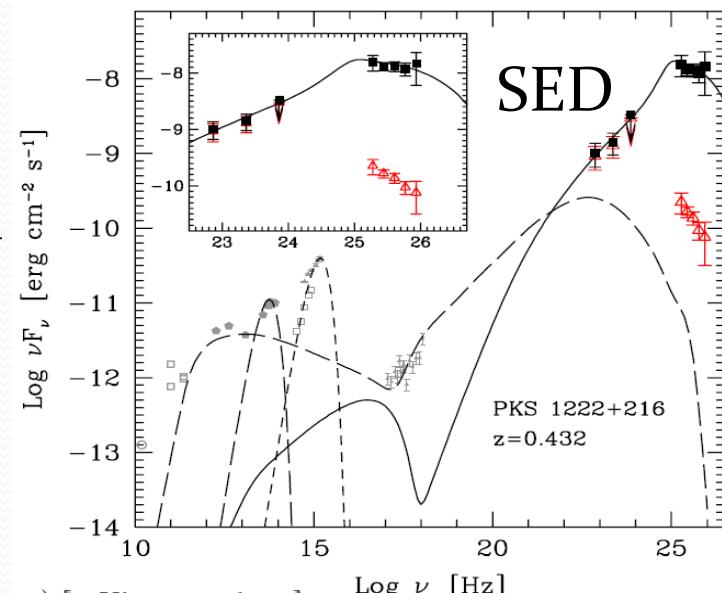
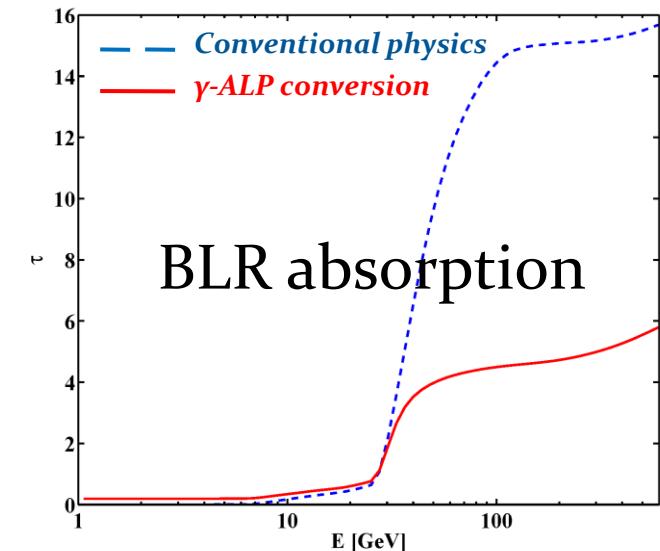
## Flat spectrum radio quasars (FSRQs):

- 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 FSRQs

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



# Extragalactic space

# Extragalactic Space

## TWO MAIN INGREDIENTS:

- **Extragalactic Background Light (EBL)** [1,2,3,4]
  - VHE photon absorption:  $\gamma_{\text{VHE}} + \gamma_{\text{EBL}} \rightarrow e^+ + e^-$
  - VHE photon flux dimming
- **Extragalactic magnetic field**  $B_{\text{ext}}$ 
  - Domain-like structure [5]
  - Limits:  $10^{-7} \text{ nG} < B_{\text{ext}} < 1.7 \text{ nG}$  on the scale  $O(1) \text{ Mpc}$  [6]
  - $B_{\text{ext}} = O(1) \text{ nG}$  on the scale  $O(1) \text{ Mpc}$  favored [7,8]

e.g. [1] Domínguez et al. 2011

[2] Gilmore et al. 2012

[3] Franceschini & Rodighiero 2017

[4] Saldana-Lopez et al. 2021

[5] Galanti & Roncadelli 2018

[6] Pshirkov et al. 2016

[7] Rees & Setti 1968

[8] Kronberg et al. 1999

# Anomalous z dependence of Blazars

- We consider all BL Lacs with strong VHE spectrum:

- In flare
- $E > 100$  GeV
- redshift up to  $z = 0.6$

- Emitted spectra  $\rightarrow$  power law

$$\Phi_{\text{em}}(E) = \hat{K}_{\text{em}} E^{-\Gamma_{\text{em}}}$$

- Observed spectrum  $\rightarrow$  power law

$$\Phi_{\text{obs}}(E_0, z) = \hat{K}_{\text{obs}}(z) E_0^{-\Gamma_{\text{obs}}(z)}$$

- Emitted – observed spectrum relation

$$\Phi_{\text{obs}}(E_0, z) = P_{\gamma \rightarrow \gamma}(E_0, z) \Phi_{\text{em}}(E_0(1+z))$$

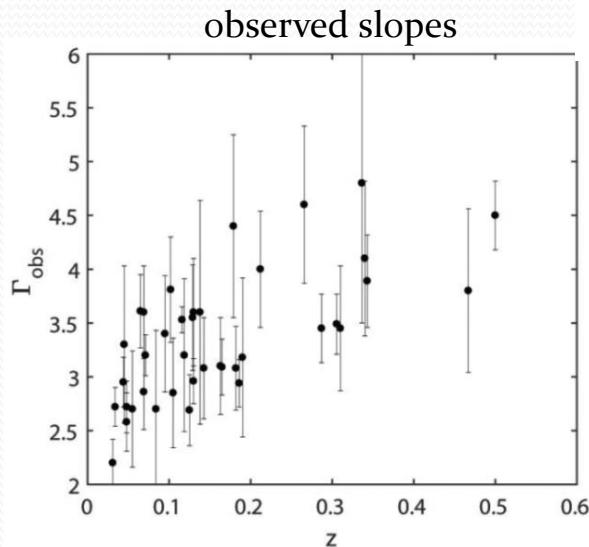
- We deabsorb the observed spectrum:

- if no ALPs  $\rightarrow$  EBL absorption only
- with ALPs  $\rightarrow$  EBL absorption and photon-ALP oscillations

# Anomalous z dependence of Blazars (2)

## Conventional Physics (CP):

- Anomalous redshift dependence of blazar spectra



$$\Phi_{\text{em}}^{\text{CP}}(E_0(1+z)) = e^{\tau_{\gamma}^{\text{FR}}(E_0, z)} K_{\text{obs}}(z) \left( \frac{E_0}{E_{0,*}} \right)^{-\Gamma_{\text{obs}}(z)}$$

$$\Phi_{\text{em}}^{\text{CP,BF}}(E_0(1+z)) = K_{\text{em}}^{\text{CP}}(z) \left( \frac{E_0(1+z)}{E_{0,*}} \right)^{-\Gamma_{\text{em}}^{\text{CP}}(z)}$$

CP

ALP

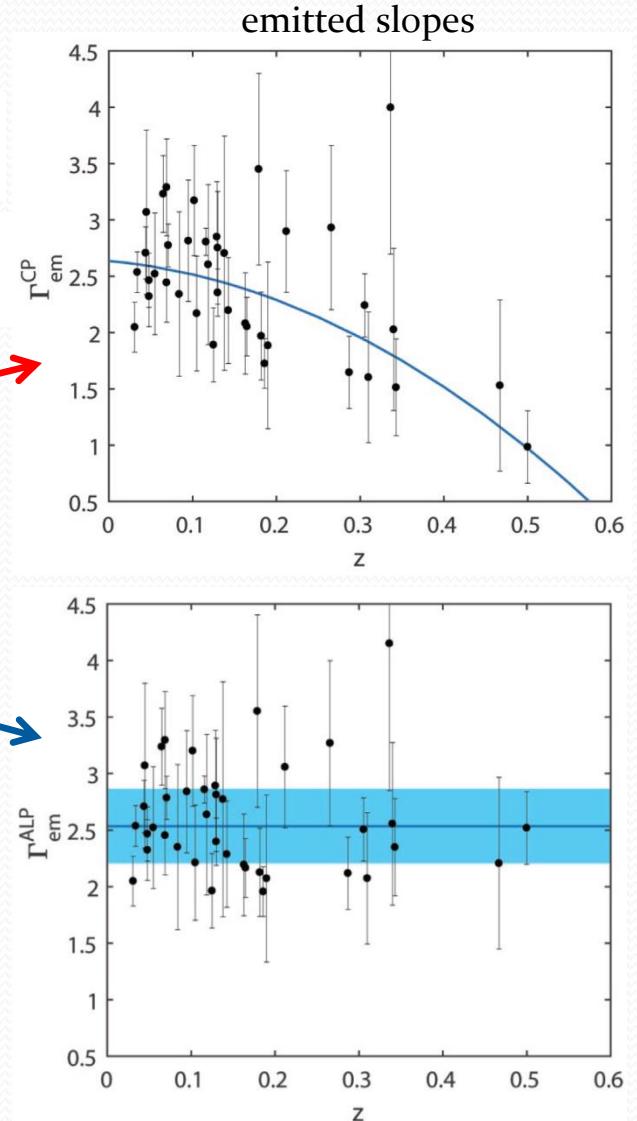
## With ALPs:

- Anomaly **SOLVED**

$$\Phi_{\text{em}}^{\text{ALP}}(E_0(1+z)) = \left( P_{\gamma \rightarrow \gamma}^{\text{ALP}}(E_0, z) \right)^{-1} K_{\text{obs}}(z) \left( \frac{E_0}{E_{0,*}} \right)^{-\Gamma_{\text{obs}}(z)}$$

$$\Phi_{\text{em}}^{\text{ALP,BF}}(E_0(1+z)) = K_{\text{em}}^{\text{ALP}}(z) \left( \frac{E_0(1+z)}{E_{0,*}} \right)^{-\Gamma_{\text{em}}^{\text{ALP}}(z)}$$

## Second hint at ALP existence



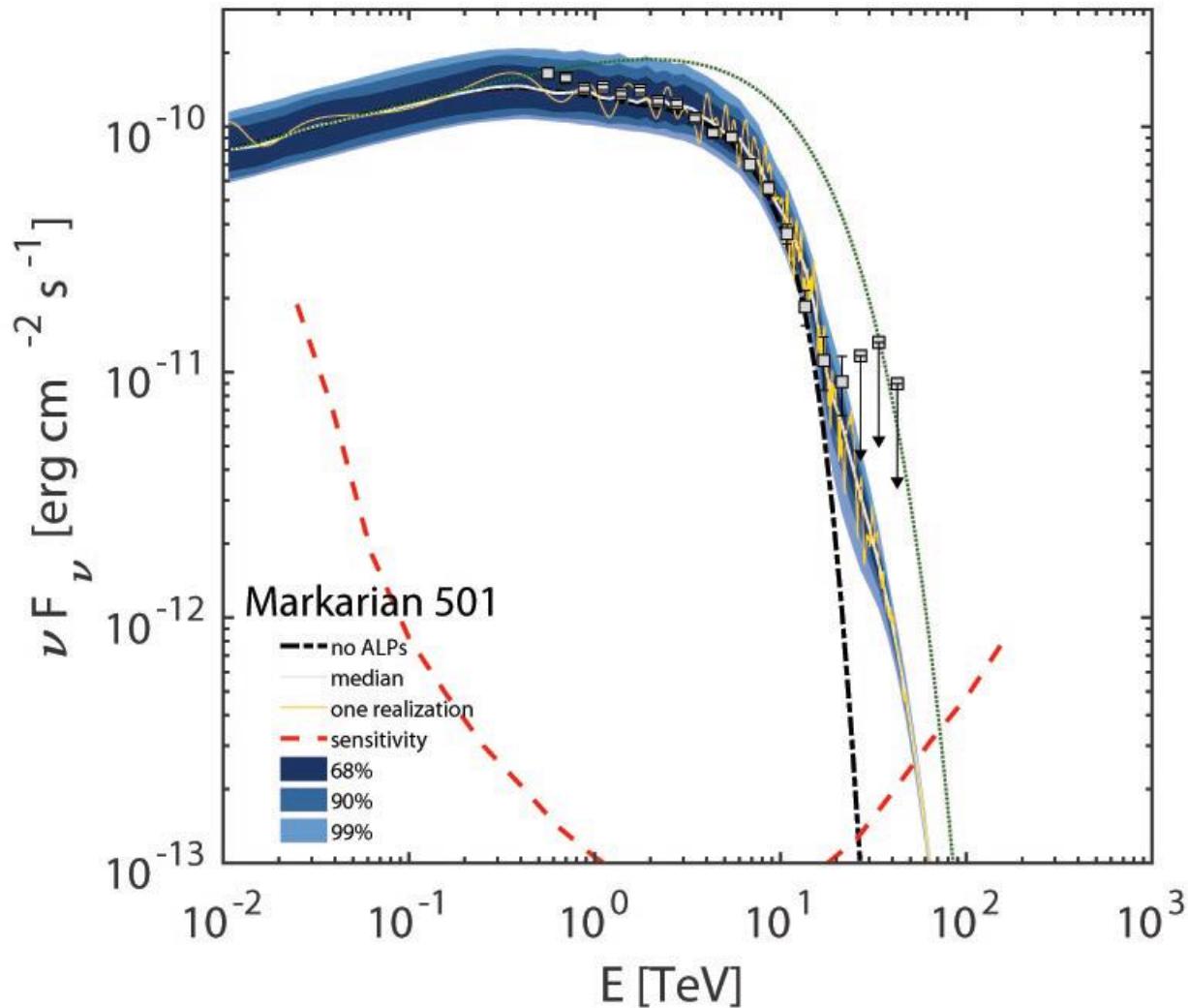
# Milky Way and total effect

# Propagation in the Milky Way and total effect

- **Regular component** of the Milky Way magnetic field  $B_{\text{MW}} \rightarrow$  most important
  - $B_{\text{MW}} = 5 \mu\text{G}$ , coherence length  $l_{\text{coh}} = 10 \text{ kpc}$
- But **detailed sky maps** of  $B_{\text{MW}}$  exist (Jansson & Farrar 2012a,b)
- **Combination of photon/ALP propagation** in  $B_{\text{jet}}, B_{\text{ext}}, B_{\text{MW}}$
- Exponentially truncated spectra
  - $B_{\text{jet}} = 0.5 \text{ G}, B_{\text{ext}} = 1 \text{ nG}$
  - $g_{a\gamma\gamma} = 10^{-11} \text{ GeV}^{-1}, m_a = 10^{-10} \text{ eV}$
  - $d_{\text{VHE}} = 3 \times 10^{16} \text{ cm}, n_e = 5 \times 10^4 \text{ cm}^{-3}$
  - $\Gamma = 15$

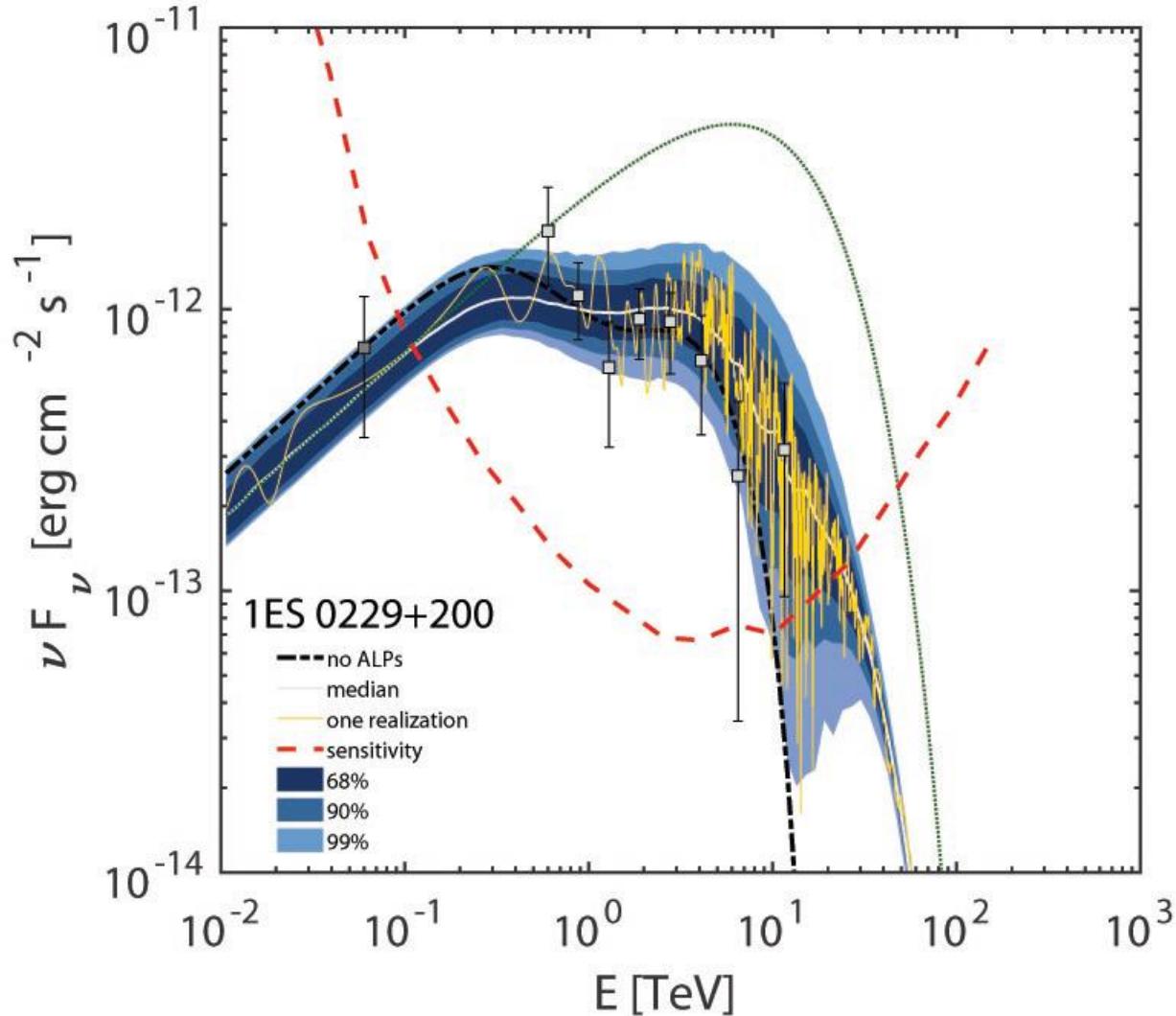
# Markarian 501

DATA from HEGRA (Aharonian et al. 2001)



# 1ES 0229+200

DATA from Fermi/LAT (Vovk et al. 2012) from HESS (Aharonian et al. 2007)



# 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 (ii) photon excess at high energy (> 10 TeV)
- These features can be detected by new observatories like the Cherenkov Telescope Array (CTA), ASTRI, LHAASO

# Final remarks

# Remarks – ALP spectral effects

**ALP-photon interactions have deep astrophysical impact:**

- Modification of AGN spectra
  - In FSRQs ALPs explain why emission above 20 GeV: **First HINT**
  - In BL Lacs ALPs predict observable peculiar features
- **Increase of the Universe transparency**
  - Solve BL Lac spectra redshift dependence: **Second HINT**
- **Blazar spectral features** detectable by the CTA, ASTRI, LHAASO
- Many of previous effects with the same model parameters ( $g_{a\gamma\gamma}$ ,  $m_a$ ) → possible **ALP existence??**
- Astrophysical new data from observatories like CTA, ASTRI, LHAASO, Fermi, IAXO and laboratory experiments like ALPS II can **shed light**

# Part II: Polarization effects

# Photon polarization

- Photon-ALP beam described by the polarization density matrix  $\rho = |\psi\rangle\langle\psi|$  ( $\psi \rightarrow$  photon-ALP state vector)
- Stokes parameters  $I, Q, U, V \rightarrow$  photonic part of  $\rho$  and denoted by  $\rho_\gamma$ :

$$\rho_\gamma = \frac{1}{2} \begin{pmatrix} I + Q & U - iV \\ U + iV & I - Q \end{pmatrix}$$

- Photon degree of linear polarization:

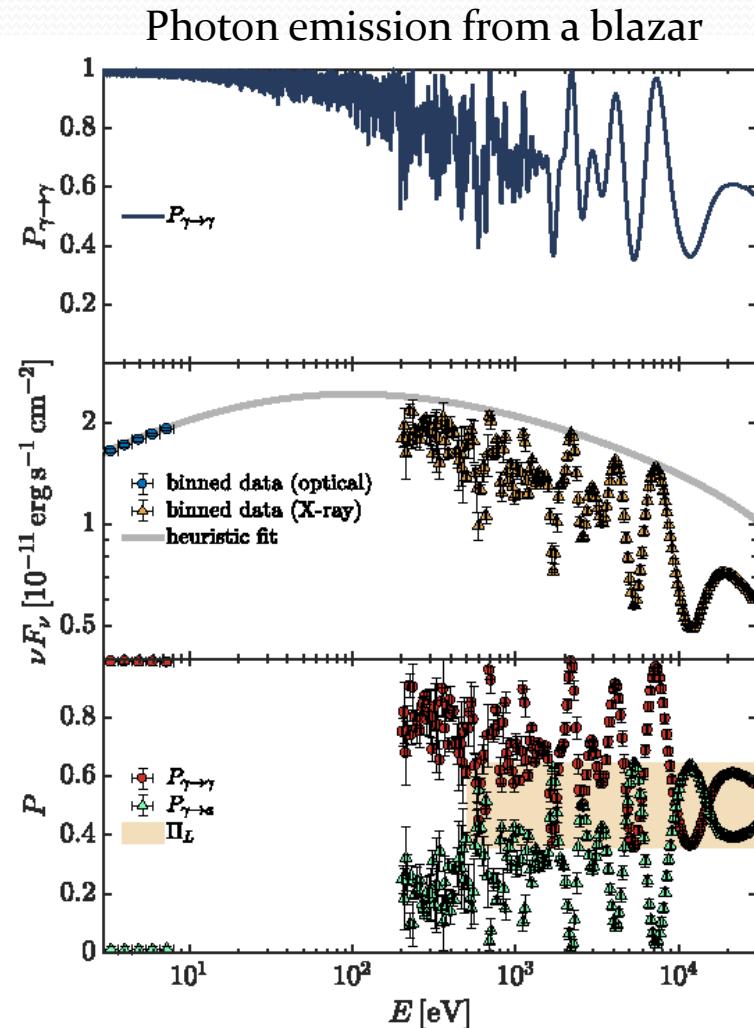
$$\Pi_L \equiv \frac{(Q^2 + U^2)^{1/2}}{I} = \frac{[(\rho_{11} - \rho_{22})^2 + (\rho_{12} + \rho_{21})^2]^{1/2}}{\rho_{11} + \rho_{22}}$$

- Polarization angle:

$$\chi \equiv \frac{1}{2} \text{atan} \left( \frac{U}{Q} \right) = \frac{1}{2} \text{atan} \left( \frac{\rho_{12} + \rho_{21}}{\rho_{11} - \rho_{22}} \right)$$

# ALPs measure **initial** photon polarization

- Photon conversion probability  $P_{\gamma \rightarrow a}$
- Photon survival probability  $P_{\gamma \rightarrow \gamma}$
- **Initial** degree of linear polarization  $\Pi_L$
- Theorems state (hypothesis of no  $\gamma\gamma$  absorption for photons):
  - $P_{\gamma \rightarrow a} \leq (1 + \Pi_L)/2$
  - $P_{\gamma \rightarrow \gamma} \geq (1 - \Pi_L)/2$
  - $\Pi_L$  = **measure of the overlap** between the values of  $P_{\gamma \rightarrow a}$  and  $P_{\gamma \rightarrow \gamma}$
- In the presence of ALPs:
  - $\Pi_L$  **can be extracted from flux measurements!!!**



# Galaxy Clusters

# Photon-ALP beam from a galaxy cluster

## GALAXY CLUSTER

- Diffuse emission in the cluster central region ( $r_{\text{core}} \sim 100$  kpc)
  - X-ray: Bremsstrahlung, initial  $\Pi_{L,0} = 0$  ([Mitchell+1979](#))
  - High-energy (HE) range:  $\pi^0$  decay, inverse Compton,  $\Pi_{L,0} = 0$  ([Lei+1997](#); [Giomi+2017](#))
- Electron number density  $n_{e,\text{clu}} \rightarrow$  (double) *beta model* ([Hudson+2010](#))
- Magnetic field  $B_{\text{clu}} = O(10)$   $\mu\text{G}$ , Kolmogorov-type turbulence, profile  $\propto (n_{e,\text{clu}}/n_{e,\text{clu},0})^{\eta_{\text{clu}}}$ , where  $n_{e,\text{clu},0}$  is the central  $n_{e,\text{clu}}$  and  $\eta_{\text{clu}} \sim 0.75$  ([Meyer+2014](#))

## EXTRAGALACTIC SPACE

- $10^{-7}$  nG  $< B_{\text{ext}} < 1.7$  nG with coherence  $O(1)$  Mpc ([Pshirkov+2016](#))
- $B_{\text{ext}} \sim 1$  nG with coherence  $O(1)$  Mpc favored ([Rees & Setti, 1968](#); [Kronberg+1999](#))
- Domain-like model ([Galanti & Roncadelli, 2018](#))

## MILKY WAY

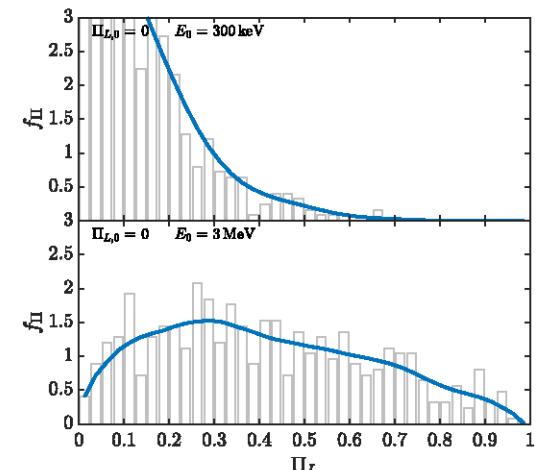
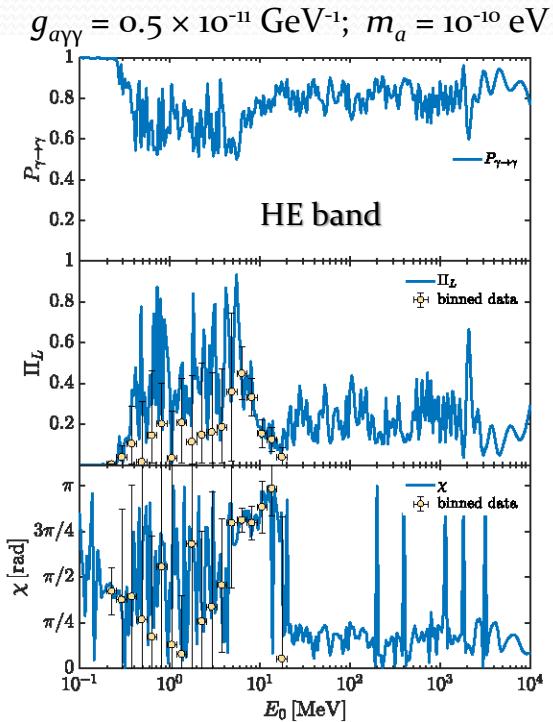
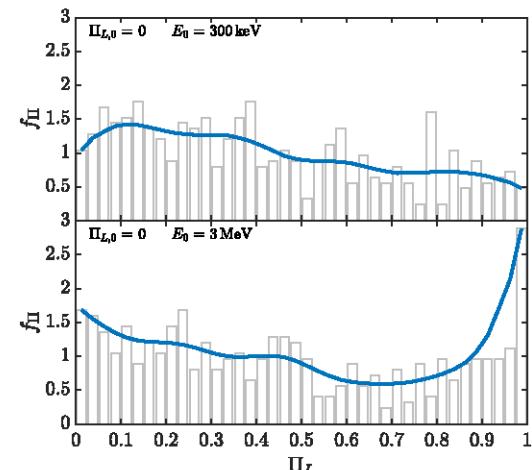
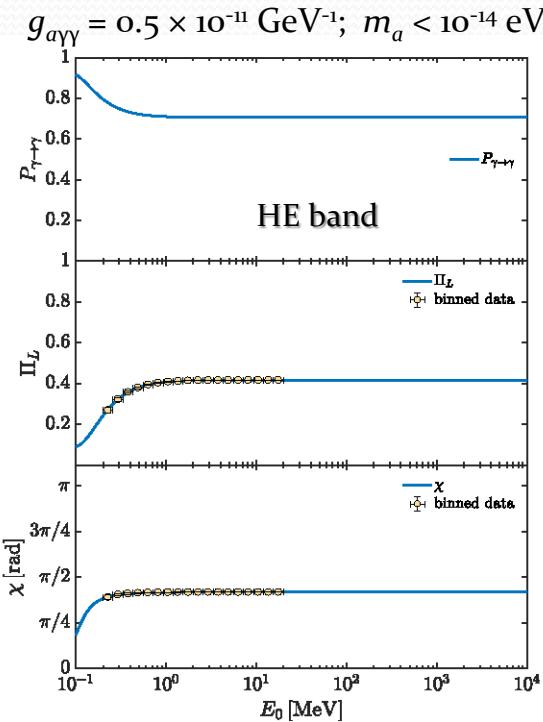
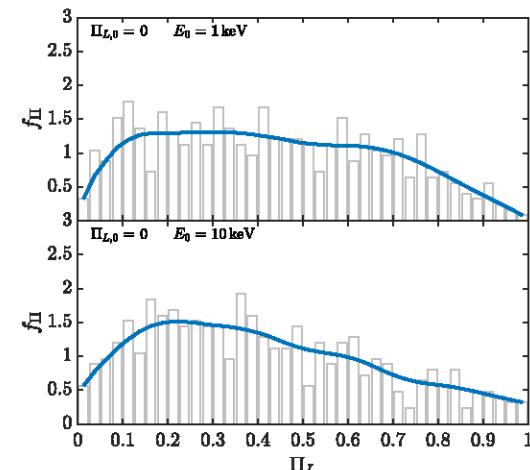
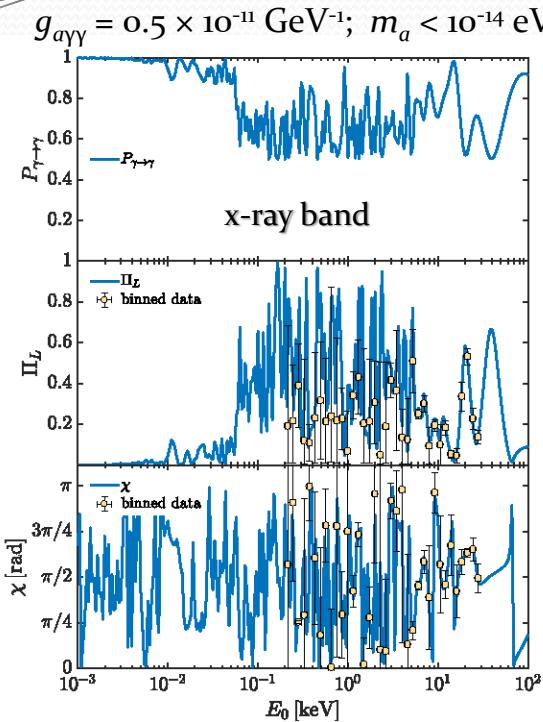
- $B_{\text{MW}}$  map by Jansson & Farrar ([Jansson & Farrar, 2012a,b](#))

## PHOTON-ALP BEAM PROPAGATION

- **Stochastic process**  $\rightarrow$  exact expression of  $B_{\text{clu}}, B_{\text{ext}}$  unknown
- $\rightarrow$  Several realizations of the propagation process  $\rightarrow \Pi_L$  **probability density**

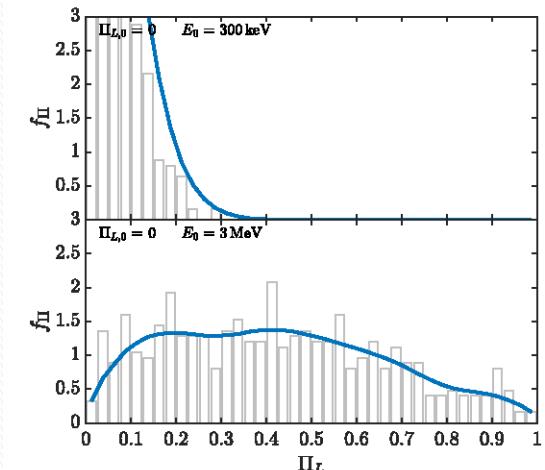
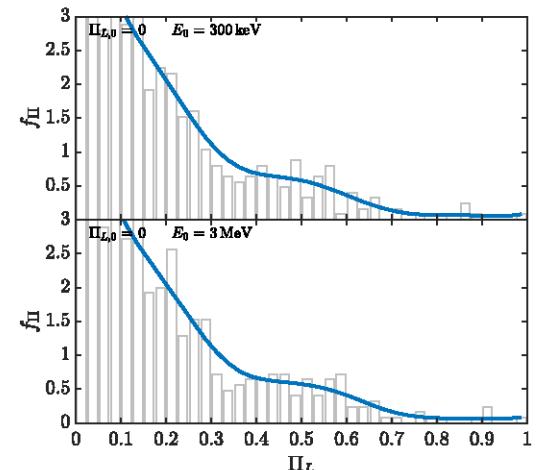
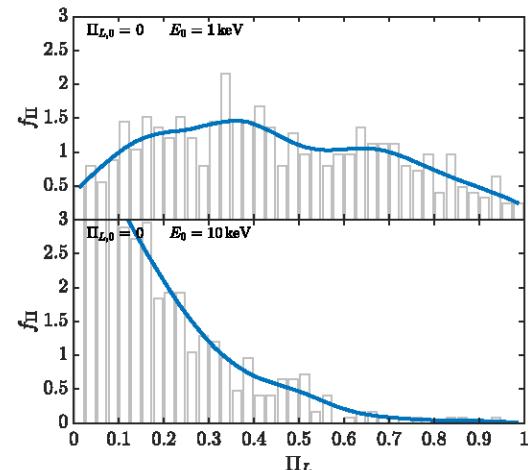
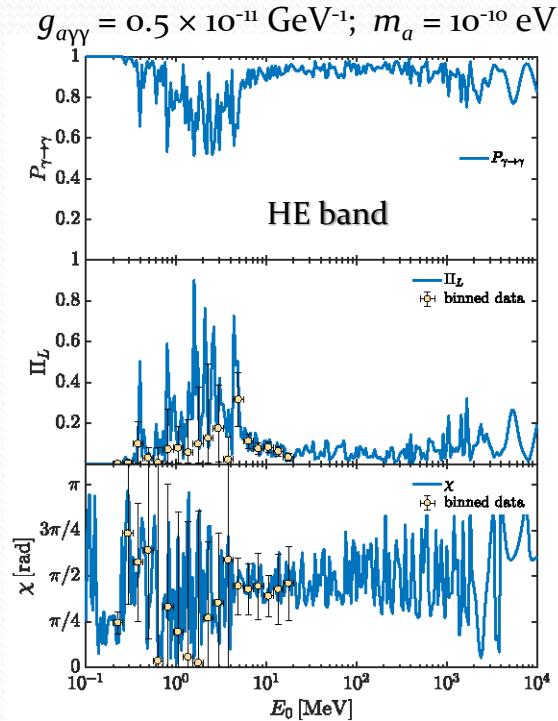
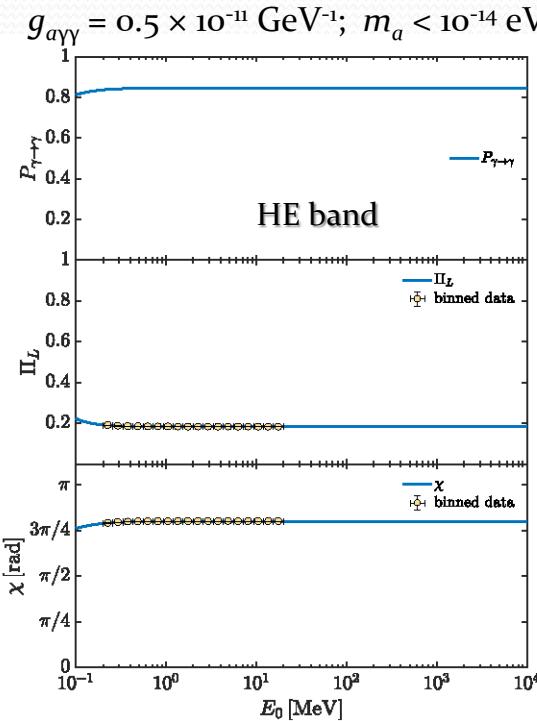
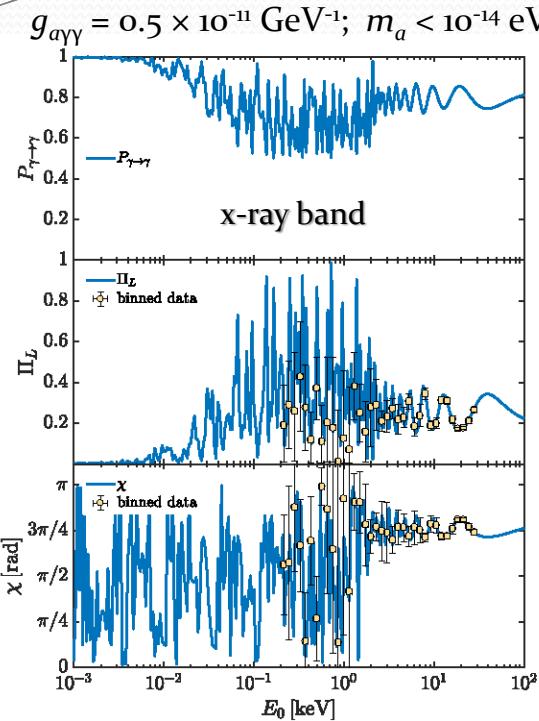
# Galaxy cluster – Perseus

Models of  $n_{e,\text{clu}}$  and  $B_{\text{clu}}$ : Churazov+2003;  
Bonafede+2010  
 $B_{\text{clu},0} = 16 \mu\text{G}$ ;  $\Pi_{L,0} = 0$



# Galaxy cluster – Coma

Models of  $n_{e,\text{clu}}$  and  $B_{\text{clu}}$ : Briel+1992;  
Bonafede+2010  
 $B_{\text{clu},0} = 4.7 \mu\text{G}$ ;  $\Pi_{L,0} = 0$



# Galaxy cluster – Results

## X-ray band:

- Only  $m_a < 10^{-14}$  eV for sizable conversion (weak mixing)
  - $m_a < 10^{-14}$  eV disfavored but not excluded by ALP limits (e.g. Conlon+2017; Reynolds+2020; Sisk-Reynés+2022)
  - **Possible signal** of new physics (ALPs) since **final**  $\Pi_L > 0.1$
  - **Perseus better target** than Coma

## HE band:

- $m_a < 10^{-14}$  eV → strong mixing
  - **Possible strong signal** from Perseus:  $\Pi_L > 0.8$  at and above 3 MeV
  - **Perseus better target** than Coma
- $m_a = 10^{-10}$  eV → weak mixing
  - **Possible signal**:  $\Pi_L > 0.2$  at 3 MeV
  - Similar behavior from Perseus and Coma

# Blazars

# Photon-ALP beam from a blazar

## BLAZAR (BL Lac) JET

- Emission at the jet base [ $O(10^{16}-10^{17})$  cm from the centre]
  - X-ray: electron synchrotron, initial  $\Pi_{L,o} \sim 0.3$  ([Zhang+2014](#))
  - High-energy (HE) range:
    - **Leptonic model** (more likely): inverse Compton, initial  $\Pi_{L,o} = 0$  ([Maraschi+1992](#))
    - **Hadronic model**: e.g. proton synchrotron, initial  $\Pi_{L,o} = 0.4 - 0.6$  ([Mannheim, 1993a,b](#))
- Electron number density  $n_{e,\text{jet}} \propto y^{-2}$ , central  $n_{e,\text{jet},o} = 5 \times 10^4 \text{ cm}^{-3}$  ([Tavecchio+2010](#))
- Magnetic field  $B_{\text{jet}} \propto y^{-1}$  with central value  $B_{\text{jet},o}$  ([Begelman+1984](#))
  - $B_{\text{jet},o} = O(0.1-1)$  G (leptonic model)
  - $B_{\text{jet},o} = O(20)$  G (hadronic model)

## HOST GALAXY

- Domain-like model
- $B_{\text{host}} = 5 \mu\text{G}$  with coherence 150 pc ([Moss & Shukurov, 1996](#))

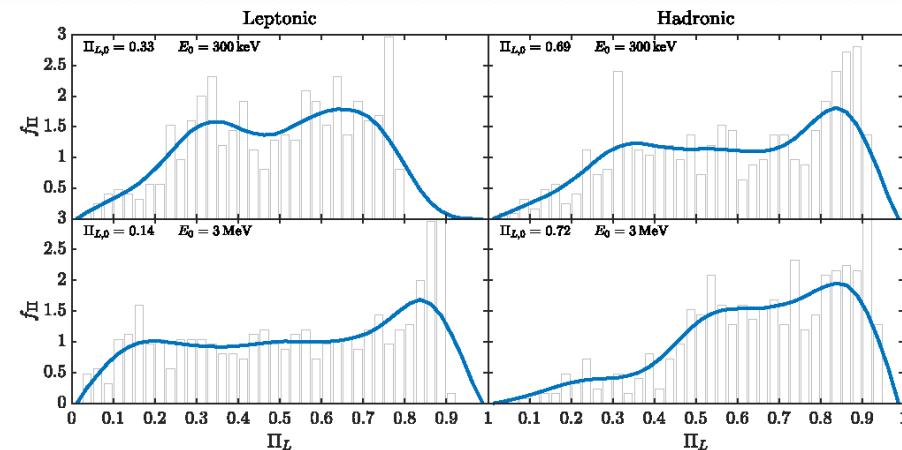
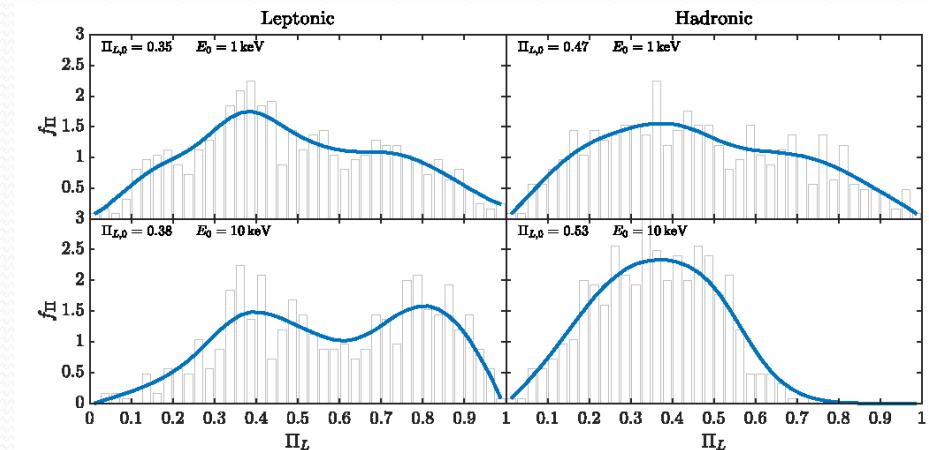
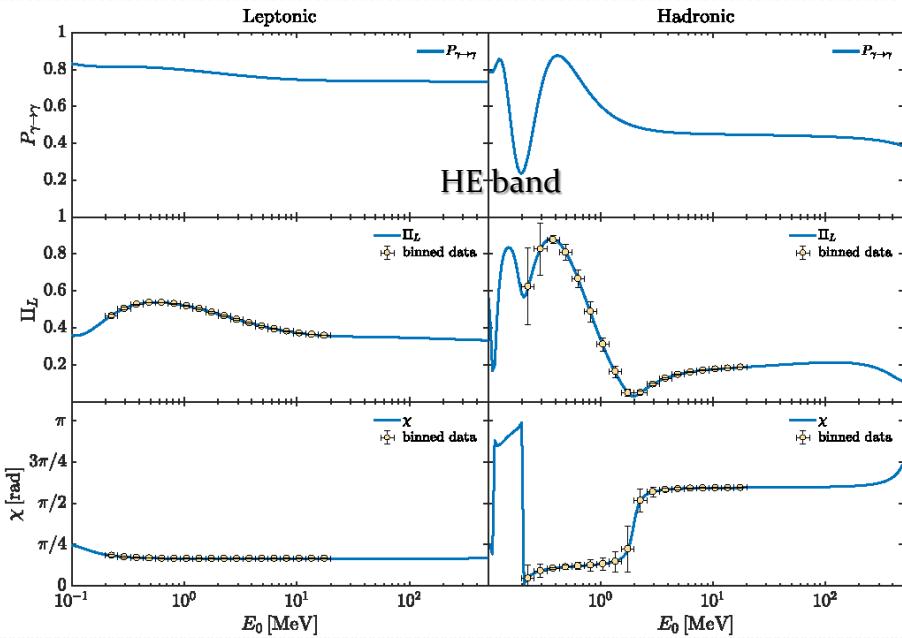
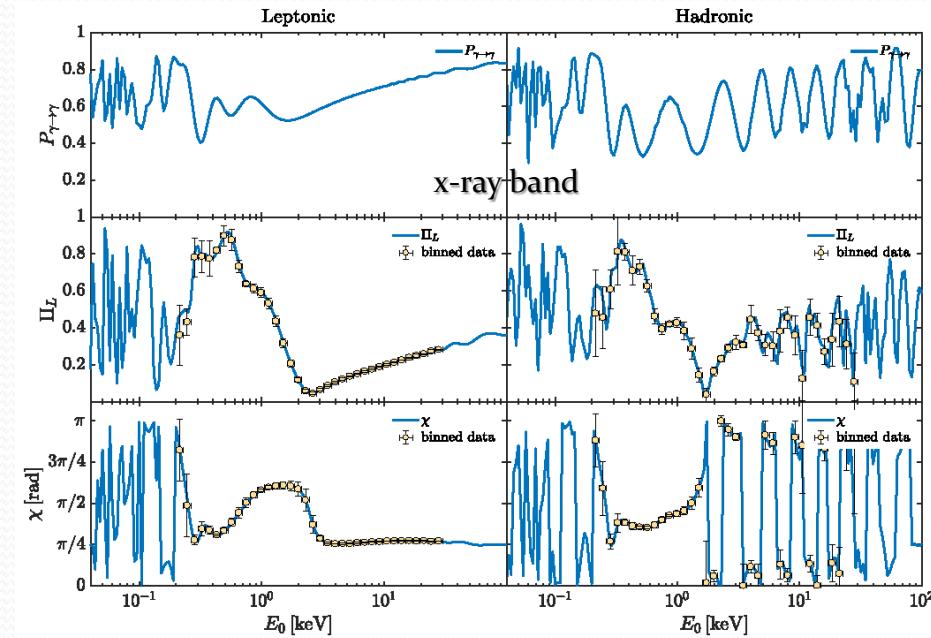
## GALAXY CLUSTER – EXTRAGALACTIC SPACE – MILKY WAY

- Like before

# Blazar – OJ 287

$\Pi_{L,o}$ : Zhang & Böttcher, 2013

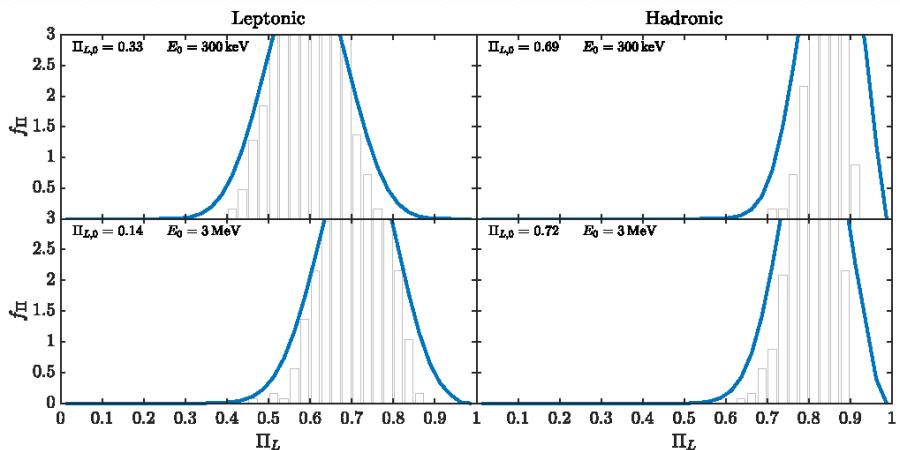
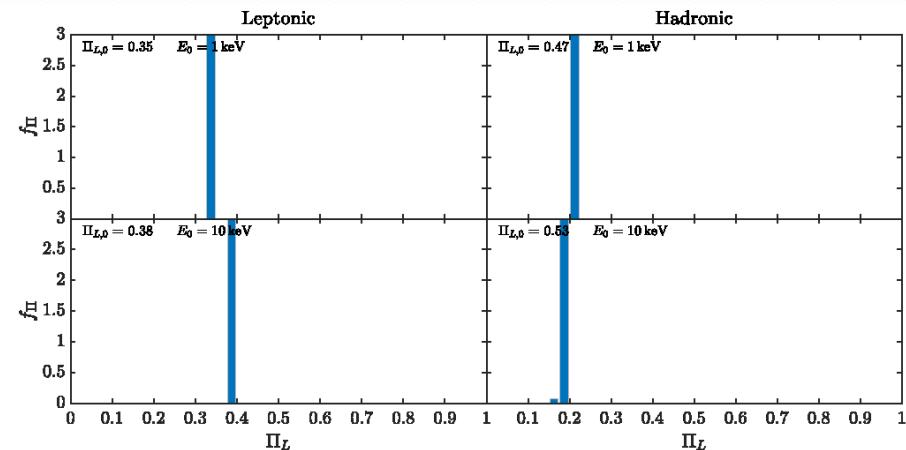
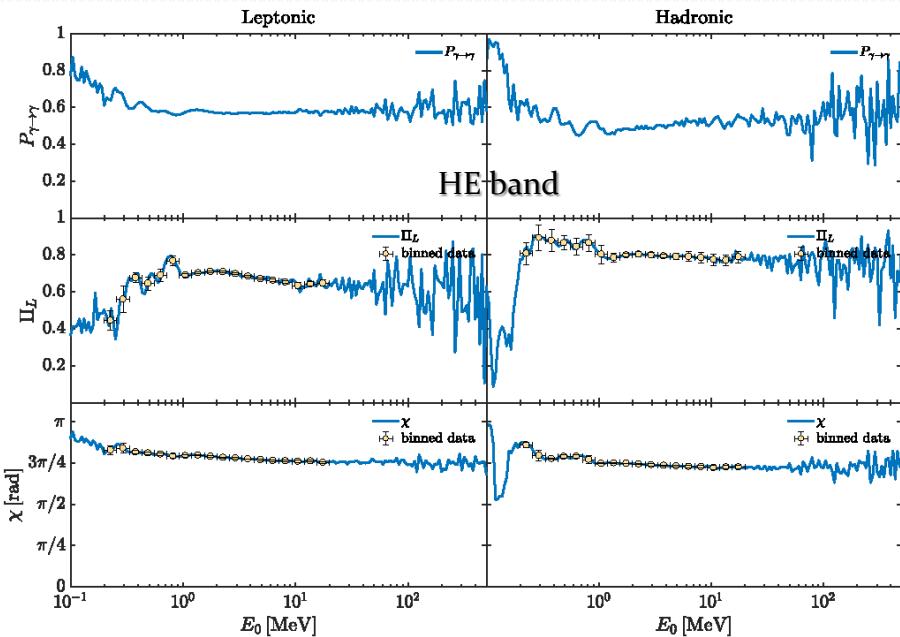
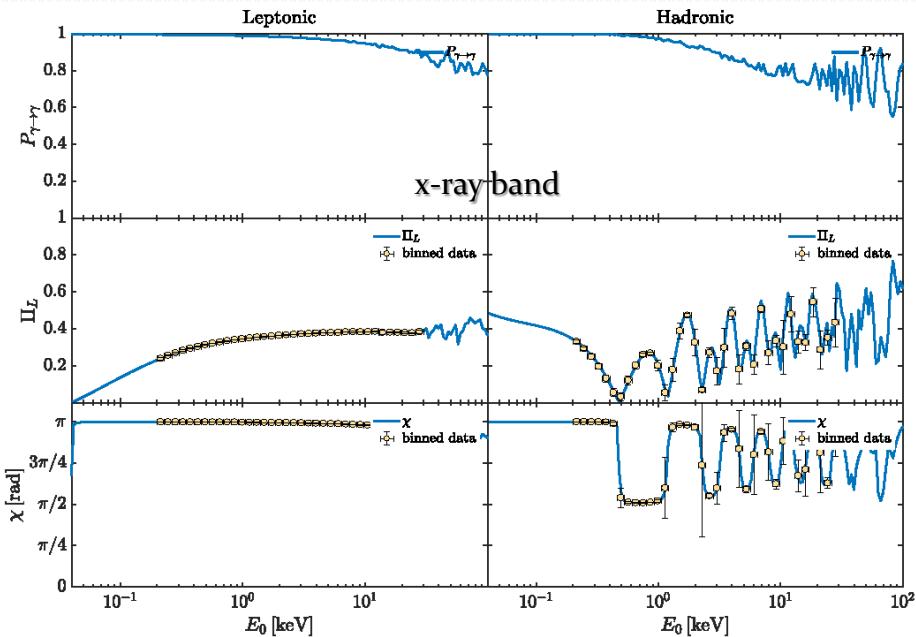
$$g_{a\gamma\gamma} = 0.5 \times 10^{-11} \text{ GeV}^{-1}; m_a < 10^{-14} \text{ eV}$$



# Blazar – OJ 287

$\Pi_{L,o}$ : Zhang & Böttcher, 2013

$$g_{a\gamma\gamma} = 0.5 \times 10^{-11} \text{ GeV}^{-1}; m_a = 10^{-10} \text{ eV}$$



# Blazar – Results

## X-ray band:

- $m_a < 10^{-14}$  eV → weak mixing
  - $m_a < 10^{-14}$  eV disfavored but not excluded by ALP limits (e.g. Conlon+2017; Reynolds+2020; Sisk-Reynés+2022)
  - Broadening of the initial  $\Pi_{L,o}$
- $m_a = 10^{-10}$  eV → weak mixing (conversion only in *hadronic* models)
  - High value of  $B_{\text{jet},o} \sim 20$  G is mandatory to have ALP effects
  - Possible signal: **dimming** of the initial  $\Pi_{L,o} \sim 0.5$

## HE band:

- $m_a < 10^{-14}$  eV → strong mixing
  - **Possible strong signal:**  $0.3 < \Pi_L < 0.8$  at and above 3 MeV
- $m_a = 10^{-10}$  eV → weak mixing
  - **Possible strong signal:**  $\Pi_L > 0.5$  for  $E > (1\text{-}10)$  MeV

# Final remarks

# Remarks – ALP polarization effects

- Photon-ALP interaction transforms flux-measuring observatories into **polarimeters**
  - The **only** method to measure **initial** (emitted) photon polarization
  - Extended energy band (no photon absorption,  $E < 100$  GeV for  $z < 0.5$ )
- Photon-ALP interaction produces measurable modifications to **final** photon polarization
  - In the X-ray band (detectable by IXPE)
  - In the HE band (detectable by COSI, e-ASTROGAM and AMEGO)
- Possible **additional hints** at ALP existence (two hints coming from spectral measurements)
  - Signal of final  $\Pi_L > 0$  from clusters *robust* in favor of ALPs since  $\Pi_{L,o} = 0$
  - For blazars final  $\Pi_L > 0.5$  explained also by *hadronic* emission model



**GRB 221009A**

# GRB 221009A

- Extremely luminous Gamma Ray Burst (GRB) at  $z = 0.151$
- Observed by:
  - Fermi-GBM, Fermi-LAT, Swift
  - LHAASO at  $E \simeq 18$  TeV within 2000 s after the initial burst
  - Carpet-2 at  $E \simeq 251$  TeV at 4536 s after Fermi-GBM trigger

BUT **strong EBL absorption** for  $E \gtrsim 14$  TeV at  $z = 0.151$  in Conventional Physics (CP)

EBL	15 TeV		18 TeV		100 TeV		251 TeV	
	$\tau_{\text{CP}}$	$P_{\text{CP}}$	$\tau_{\text{CP}}$	$P_{\text{CP}}$	$\tau_{\text{CP}}$	$P_{\text{CP}}$	$\tau_{\text{CP}}$	$P_{\text{CP}}$
D	12.7	$3 \times 10^{-6}$	19.4	$4 \times 10^{-9}$	350	$2 \times 10^{-152}$	9654	$\sim 0$
G	9.4	$8 \times 10^{-5}$	13.1	$2 \times 10^{-6}$	246	$2 \times 10^{-107}$	9502	$\sim 0$
FR	10.1	$4 \times 10^{-5}$	14.1	$7 \times 10^{-7}$	333	$2 \times 10^{-145}$	15411	$\sim 0$
SL	12.8	$3 \times 10^{-6}$	18.3	$10^{-8}$	220	$3 \times 10^{-96}$	>9251	$\sim 0$

$\tau_{\text{CP}} \rightarrow$  optical depth;  $P_{\text{CP}} \rightarrow$  photon survival probability

D  $\rightarrow$  EBL model by Domínguez et al., 2011

G  $\rightarrow$  EBL model by Gilmore et al. 2012

FR  $\rightarrow$  EBL model by Franceschini & Rodighiero 2017

SL  $\rightarrow$  EBL model by Saldana-Lopez et al. 2021

## QUESTION:

*How can we have detected this GRB at  $E \simeq 18$  TeV, 251 TeV?*



## ANSWER:

with **axion-like particles (ALPs) !!!**

# ALP detection from GRB 221009A?

- **Photon-ALP mixing**

- $\mathcal{L}_{\text{ALP}} = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} a$
- $g_{a\gamma\gamma} = 5 \times 10^{-12} \text{ GeV}^{-1}$
- $m_a = O(10^{-10}) \text{ eV}$

- **Lorentz Invariance Violation (LIV)**

- $E_{\text{LIV, } n=1} = 3 \times 10^{29} \text{ eV}$
- $E_{\text{LIV, } n=2} = 5 \times 10^{21} \text{ eV}$

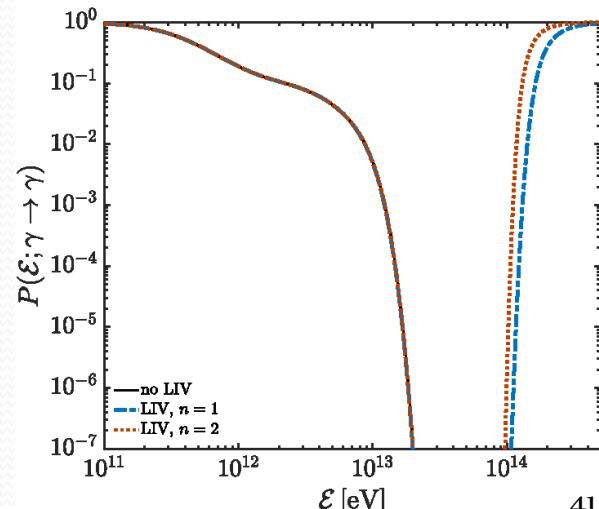
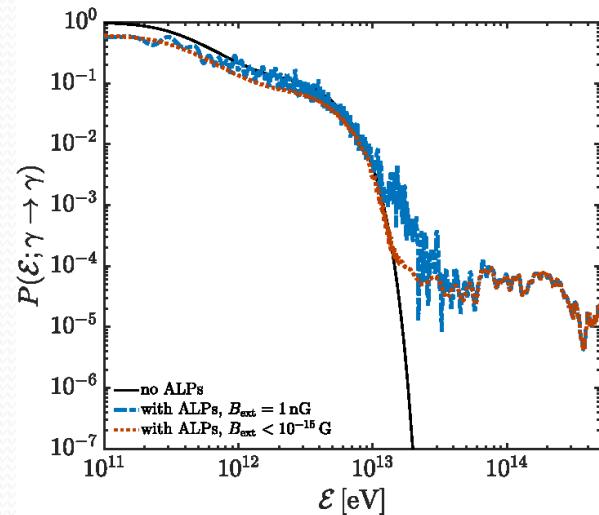
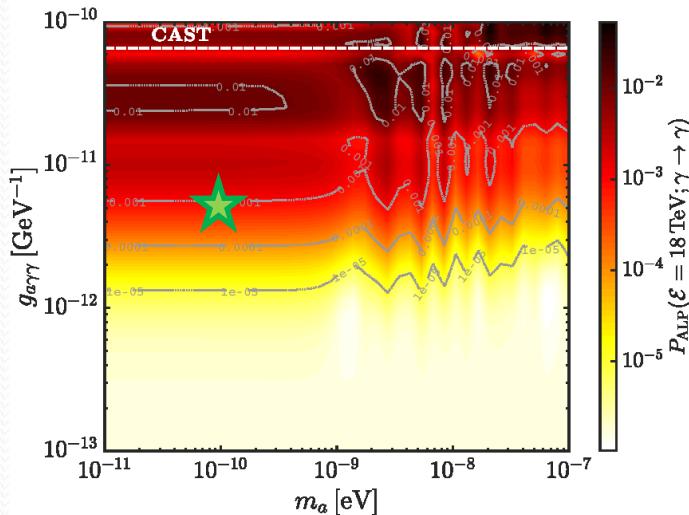
- Photon-ALP mixing in all the possible crossed magnetic fields [source (negligible effect), host, extragalactic space\*, Milky Way]

- $E = 18 \text{ TeV} \rightarrow P_{\text{ALP}}(\gamma \rightarrow \gamma) \simeq 9 \times 10^{-4}$
- $E = 251 \text{ TeV} \rightarrow P_{\text{ALP}}(\gamma \rightarrow \gamma) \simeq 5 \times 10^{-5}$
- **ALPs can explain both observations**
- **LIV very good at 251 TeV, fails at 18 TeV**
- Possible **ALP indirect detection**??

G. Galanti, L. Nava, M. Roncadelli and F. Tavecchio, arXiv:2210.05659

Other ALP models: A. Baktash, D. Horns and M. Meyer, arXiv:2210.07172

P. Carenza and M.C.D. Marsh, arXiv:2211.02010



# Conclusions

# DO ALPs EXIST?

- We have hints from astrophysical spectra
- We expect additional hints from photon polarization
- GRB 221009A??

## FINAL ANSWER:

- Within few years
- **Confirmed or disproved:**
  - From new data by ASTRI, CTA, LHAASO
  - Possible polarization data from IXPE, COSI, e-ASTROGAM
  - From laboratory experiments such as ALPSII

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$S_B = \frac{k_B 4\pi G}{\hbar c} M^2$$

$$\Psi(x) = \frac{1}{\sqrt{K_0}}(A_+ e^{ixx} + A_- e^{-ixx}) \quad x < 0$$

$$\sigma = \frac{24\pi^3 L^2}{T^2 c^2 (1-e^2)}$$

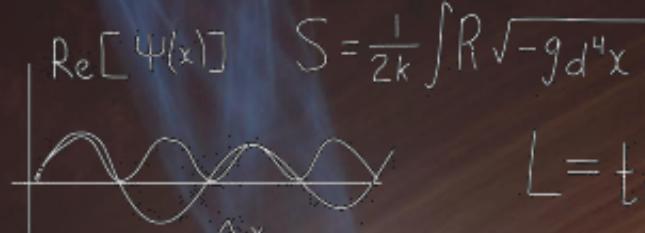
$$K_i = \sqrt{2mE/\hbar^2}$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$



$$H = \frac{P^2}{2m} + V(r)$$

$$P = -i\hbar\nabla$$



# Thank you

$$H|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$$

e'

$$I = \int e^{-\alpha x^2/2} dx = \sqrt{\frac{2\pi}{\alpha}}$$

$$A_{ij} = \frac{8\pi\hbar v^3}{c^3} B_{ij}$$

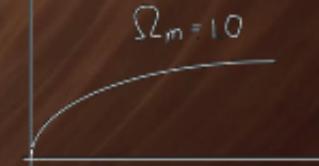
$$\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [\hat{A}, \hat{H}] \rangle + \left\langle \frac{\partial \hat{A}}{\partial t} \right\rangle$$

$$S_{fl} = \langle f(S) \rangle$$

$$E^2 = P^2 c^2 + m^2 c^4 \quad \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \Psi - \nabla^2 \Psi + \frac{m^2 c^2}{\hbar^2} \Psi = 0$$

$$P = \hbar k = \frac{\hbar a}{c} = \frac{\hbar}{\lambda}$$

$$S = \frac{1}{2} \int d^4x \left( R + \frac{R^2}{6M^2} \right)$$



$$dV = e^{\int_t^s V(X_{\tau,r}) d\Gamma_\Theta(X,s)} \frac{\partial u}{\partial X} dW$$

$$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2} \sum_{n=1}^N \frac{1}{m_n} \nabla_n^2 \psi + V\psi$$

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$S_B = \frac{k_B 4\pi G}{\hbar c} M^2$$

$$\Psi(x) = \frac{1}{\sqrt{K_0}}(A_+ e^{ix} + A_- e^{-ix}) \quad x < 0$$

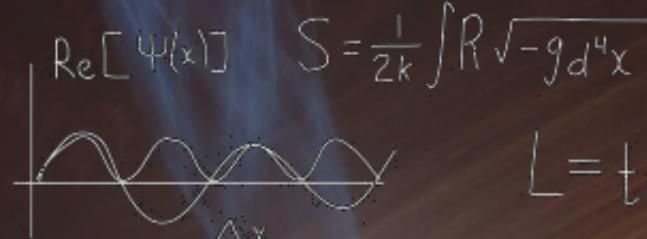
$$\sigma = \frac{24\pi^3 L^2}{T^2 c^2 (1-e^2)}$$

$$K_i = \sqrt{2mE/\hbar^2}$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$$H = \frac{P^2}{2m} + V(r)$$

$$P = -i\hbar\nabla$$



$$H|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$$

$$\frac{\delta(k_1+k_2)}{k_1^2}$$

$$E = mc^2$$

$$E^2 = (pc)^2 + (mc^2)^2$$

$$r = \frac{\theta}{2\pi} + \frac{4\pi}{9^2}$$

$$I = \int e^{-\alpha x^2/2} dx = \sqrt{\frac{2\pi}{\alpha}}$$

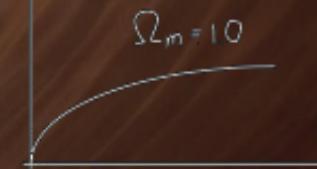
$$E^2 = p^2 c^2 + m^2 c^4$$

$$\frac{1}{c^2} \frac{\partial^2}{\partial t^2} \psi - \nabla^2 \psi + \frac{m^2 c^2}{\hbar^2} \psi = 0$$

$$A_{ij} = \frac{8\pi\hbar v^3}{c^3} B_{ij}$$

$$S_{fi} = \langle f | S_i | i \rangle$$

$$S = \frac{1}{2} \int d^4x \left( R + \frac{R^2}{6M^2} \right)$$



$$\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [\hat{A}, \hat{H}] \rangle + \left\langle \frac{\partial \hat{A}}{\partial t} \right\rangle$$

$$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2} \sum_{n=1}^N \frac{1}{m_n} \nabla_n^2 \psi + V\psi$$

$$dV = e^{\int_t^s V(X_{\tau,r}) d\tau} \epsilon_{\Theta}(X,s) \frac{\partial \omega}{\partial X} d\omega$$

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$