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# Axion-like particles and polarization

*Hands on the Extreme Universe with High Energy Gamma Rays*

**Sexten, 19 July 2021**

# Outline

- Axions and axion-like particles
- Part I: Spectral effects
  - Active Galactic Nuclei
  - Galaxy Clusters
  - Extragalactic space
  - Milky Way and total effect
  - Pulsars
  - Final remarks
- Part II: Polarization effects
  - Galaxy Clusters
  - Blazars
  - Final remarks
- Conclusions

# Axions and axion-like particles

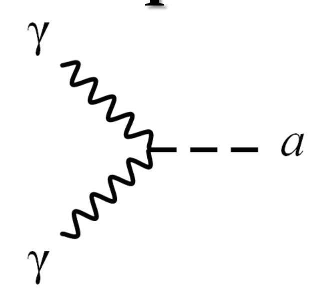
# Axions and axion-like particles

- QCD nonperturbative effects produce **CP violation** in the strong sector measured by the angle $\theta$
- **BUT** experimentally, $|\theta| < 10^{-10}$ → fine tuning needed → **Strong CP problem**
- Proposed solution → new Peccei-Quinn symmetry $U(1)_{PQ}$ for the Lagrangian
- Symmetry broken → new particle: the **axion**
- Axion mass and axion-two-photon coupling are *related*
- Axions interact with fermions and gluons
- 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)

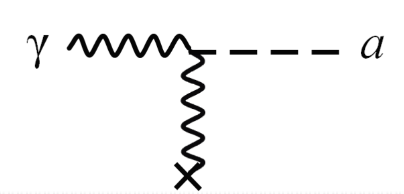
- Predicted by String Theory
- Very light particles ($m_a < 10^{-8}$ eV)
- Spin 0
- **Interaction with** two **photons** (coupling $g_{a\gamma\gamma}$)
- Interactions with other particles negligible
- Possible candidate for dark matter
- **Induce the *change of the polarization state* of photons**

**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

- 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 in the energy band $E >> m_a$
- For $E$ < 10 GeV → negligible photon absorption due to EBL, BLR, …
  - **Photon-ALP interaction** produces effective **photon absorption**
- For $E$ > 10 GeV → photons absorbed by EBL, BLR, …
  - **Photon-ALP oscillations increase medium transparency**
- **IMPLICATIONS** for:
  - Spectra of Active Galactic Nuclei (AGN) → **HINT** at **ALP existence**
  - Propagation of photon/ALP beam in AGN jets, galaxy clusters, extragalactic space, Milky Way → **HINT** at **ALP existence**
  - Transparency of the Universe
  - Photon polarization

# ALP limits

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

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

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

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

- Unobserved ALP-induced spectral modifications on photons from AGN in or behind galaxy clusters, see e.g. [4,5]

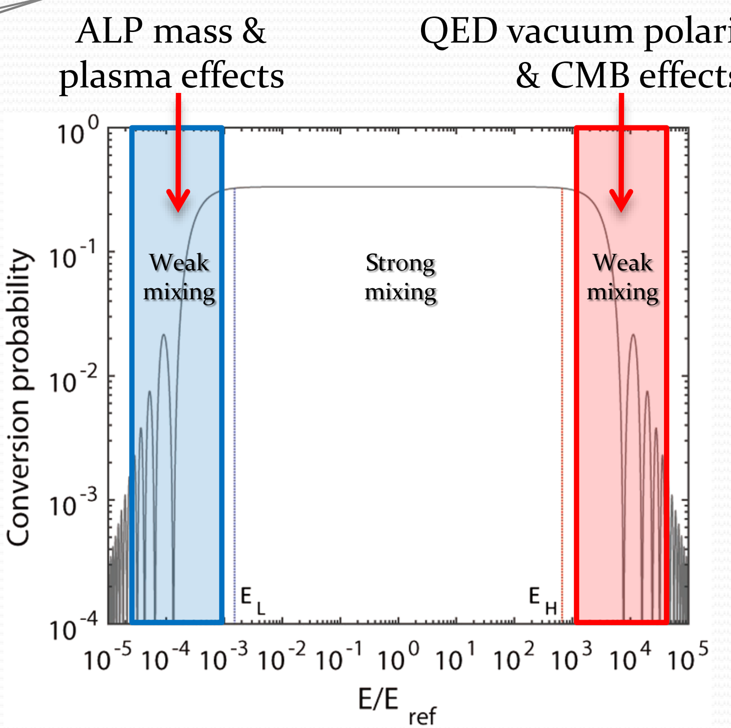
  $g_{a\gamma\gamma} < O(10^{-12})$ GeV$^{-1}$ for $m_a < O(10^{-12})$ eV

- *Lack of detection of gamma rays from supernova SN1987A [6]

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

# ALP-induced irregularities




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

**BLUE AREA:**

- Spectral/polarization effects investigated in:

  The CTA Consortium, JCAP 02, 048 (2021) [arXiv: 2010.01349].

  G. Galanti, arXiv:2202.11675.; G. Galanti, M. Roncadelli, F. Tavecchio, arXiv:2202.12286.
- No/low EBL absorption

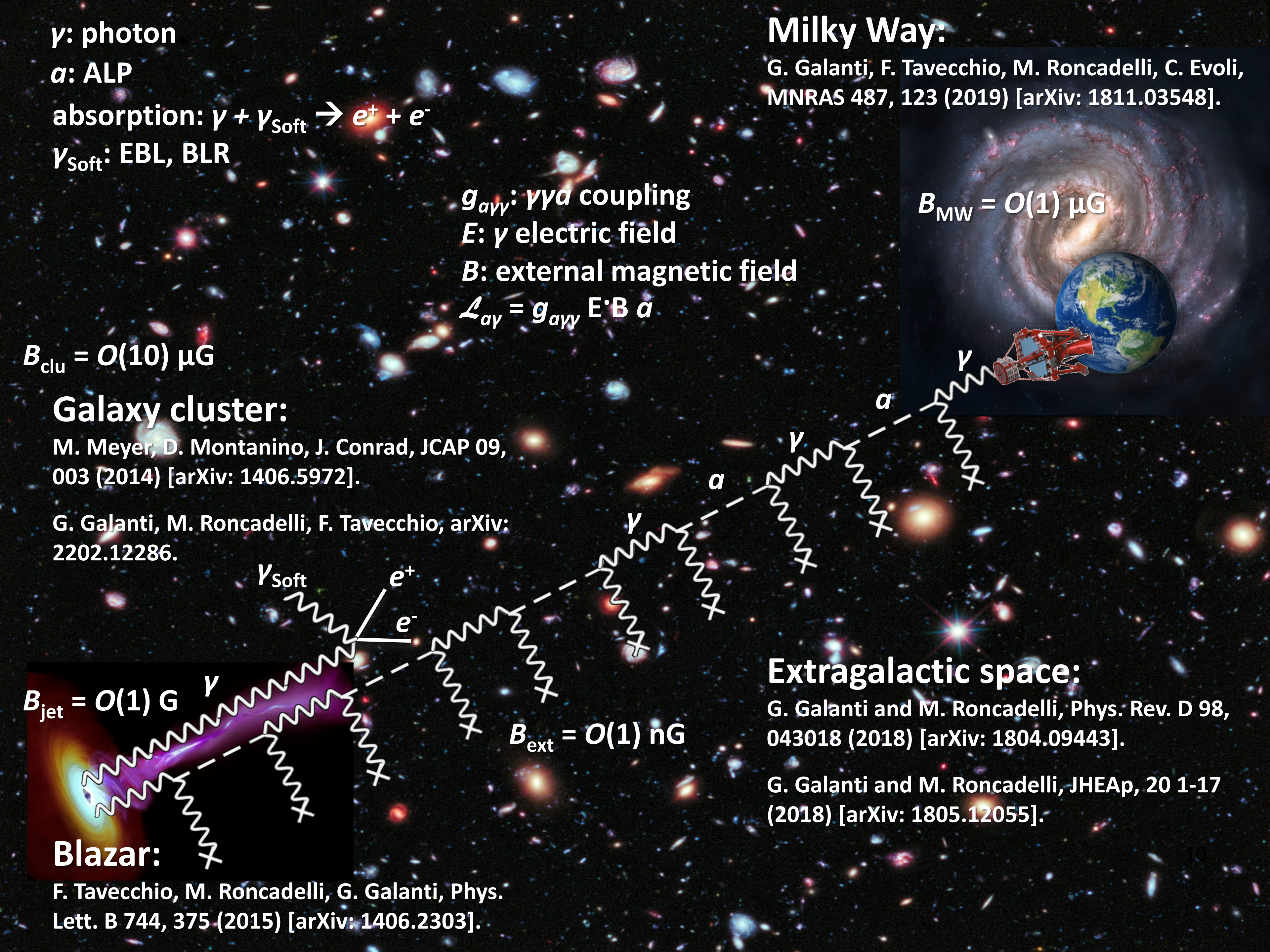
**RED AREA:**

- Spectral effects investigated in:

  G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019) [arXiv: 1811.03548].

  G. Galanti, F. Tavecchio, M. Landoni, MNRAS 491, 5268 (2020) [arXiv:1911.09056].
- Higher EBL absorption

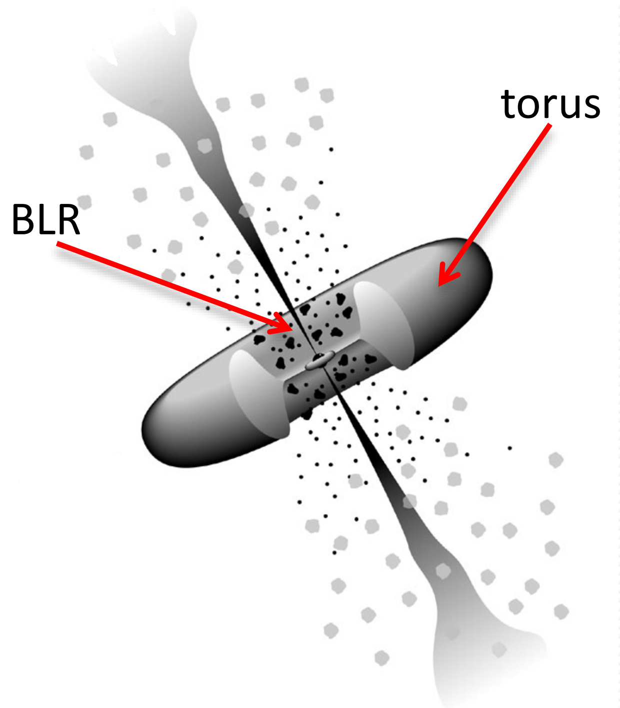
# Part I: Spectral effects


γ: photon
a: ALP
absorption: $\gamma + \gamma_{Soft} \rightarrow e^+ + e^-$
$\gamma_{Soft}$: EBL, BLR
$g_{a\gamma\gamma}$: $\gamma\gamma a$ coupling
E: γ electric field
B: external magnetic field
$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, E \cdot B\, a$
Milky Way:
G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, MNRAS 487, 123 (2019) [arXiv: 1811.03548].
$B_{MW} = O(1)$ μG
$B_{clu} = O(10)$ μG
Galaxy cluster:
M. Meyer, D. Montanino, J. Conrad, JCAP 09, 003 (2014) [arXiv: 1406.5972].
G. Galanti, M. Roncadelli, F. Tavecchio, arXiv: 2202.12286.
$\gamma_{Soft}$
$e^+$
$e^-$
γ
a
$B_{jet} = O(1)$ G
$B_{ext} = O(1)$ nG
Extragalactic space:
G. Galanti and M. Roncadelli, Phys. Rev. D 98, 043018 (2018) [arXiv: 1804.09443].
G. Galanti and M. Roncadelli, JHEAp, 20 1-17 (2018) [arXiv: 1805.12055].
Blazar:
F. Tavecchio, M. Roncadelli, G. Galanti, Phys. Lett. B 744, 375 (2015) [arXiv: 1406.2303].

# Active Galactic Nuclei

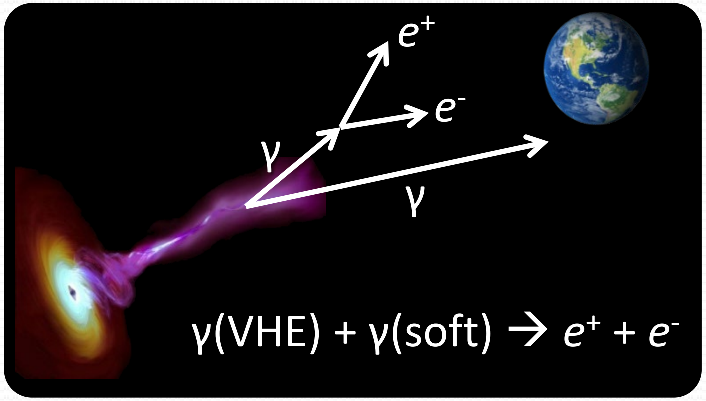
# Active Galactic Nuclei (AGN)

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



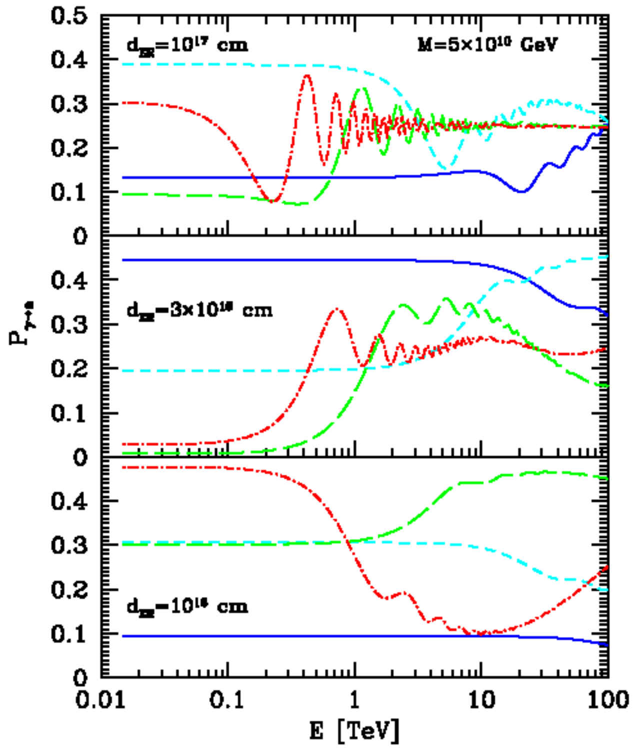

**BL Lacs**:
- No broad line region (BLR)
- No dusty torus
- Absorption due to the extragalactic background light (EBL) for $E > 100$ GeV

**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

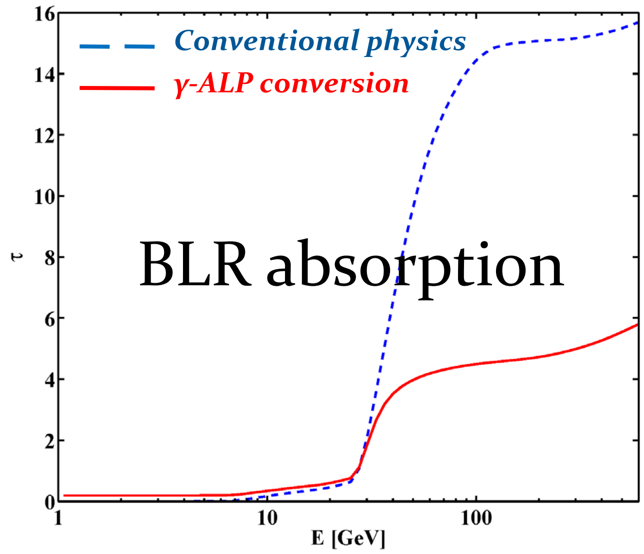
- Photons produced at $d_{\mathrm{VHE}} = 10^{16}$ cm from the centre
- $B_{\mathrm{jet}} = 0.1 - 1$ G and scales as 1/distance
- Electron density $n_e = 5 \times 10^4\ \mathrm{cm}^{-3}$ and scales as 1/distance$^2$
- Lorentz factor $\Gamma = 15$
- Photon-ALP conversion inside $B_{\mathrm{jet}}$
- $m_a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

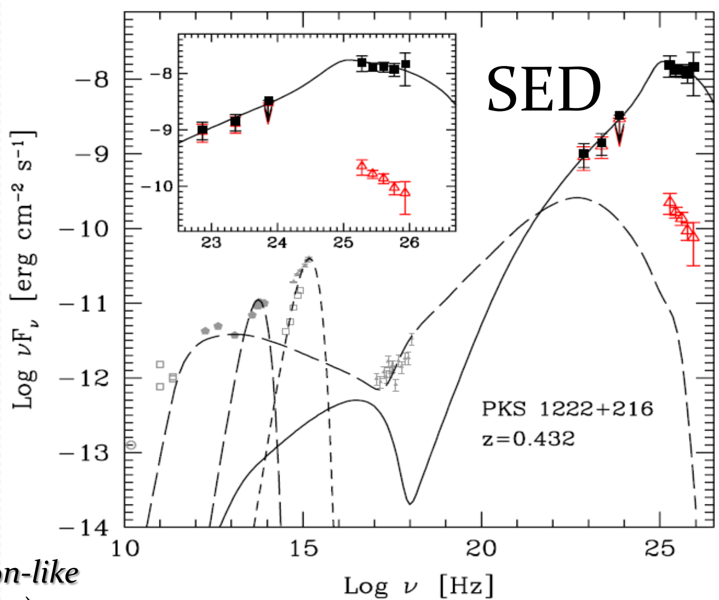



F. Tavecchio, M. Roncadelli and G. Galanti, *Photons to axion-like particles conversion in Active Galactic Nuclei*, Phys. Lett. B 744, 375 (arXiv: 1406.2303) (2015).

# ALPs in FSRQs

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




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 $B_{clu,0} = O(10)$ μG
- $B_{clu} \geq 2$ μG
- 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 $z \approx 0.02$)

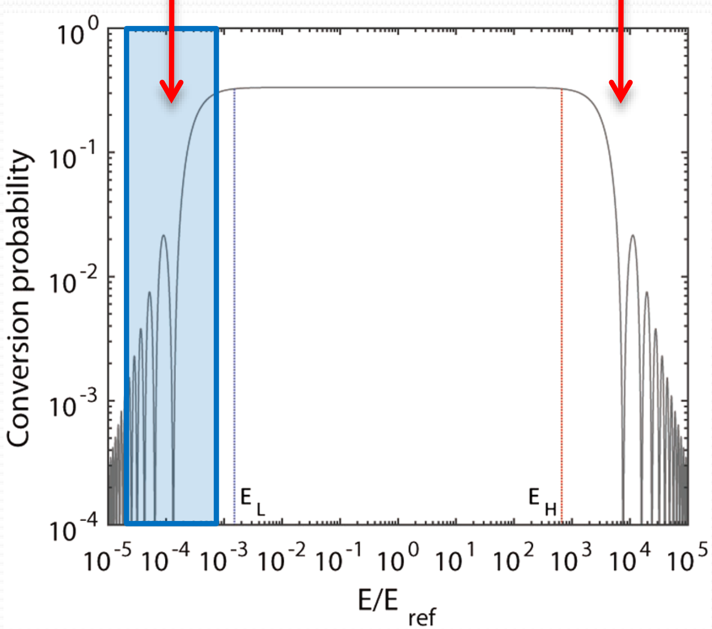
Ajello et al. 2016

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

# ALP irregularities in galaxy clusters? (2)

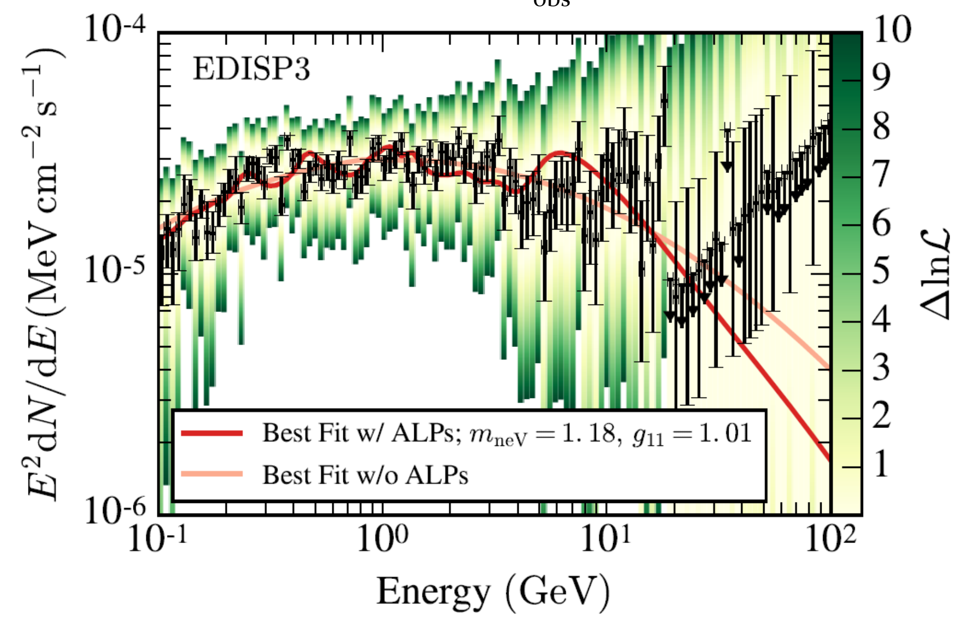
ALP mass & plasma effect

QED vacuum polarization & CMB effects




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

Flux $F_{obs}$



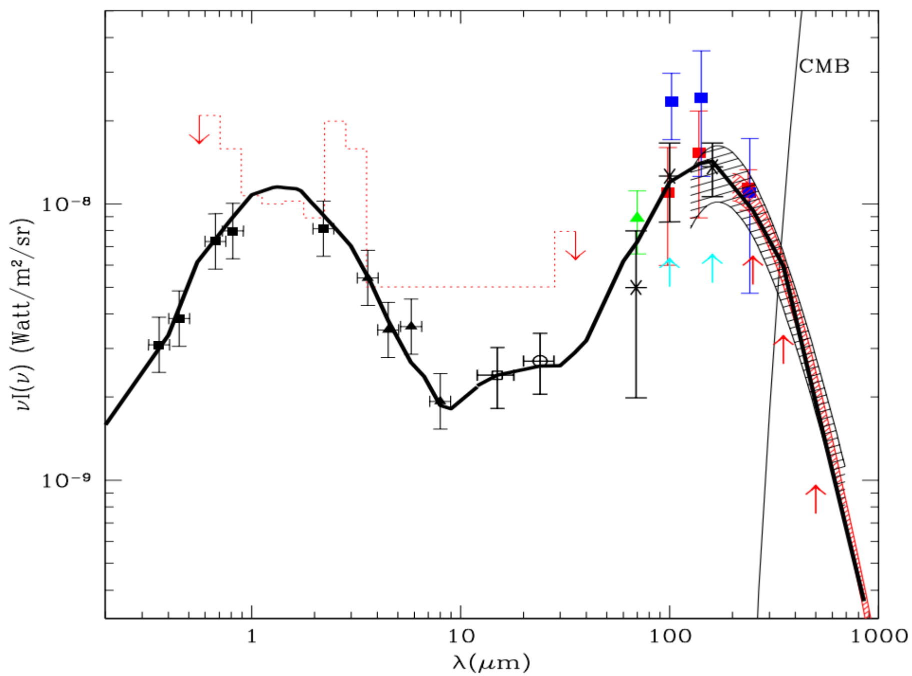

- Flux $F_{obs} = P_{\gamma\rightarrow\gamma}(m_a, g_{a\gamma\gamma})\ F_{em}$
- Statistically → **no preference** for photon-ALP conversion to fit data
- $g_{a\gamma\gamma} < 5 \times 10^{-12}$ GeV$^{-1}$ for $5 \times 10^{-10} < m_a < 5 \times 10^{-9}$ eV

Ajello et al. 2016

# Extragalactic space

# Extragalactic Background Light (EBL)

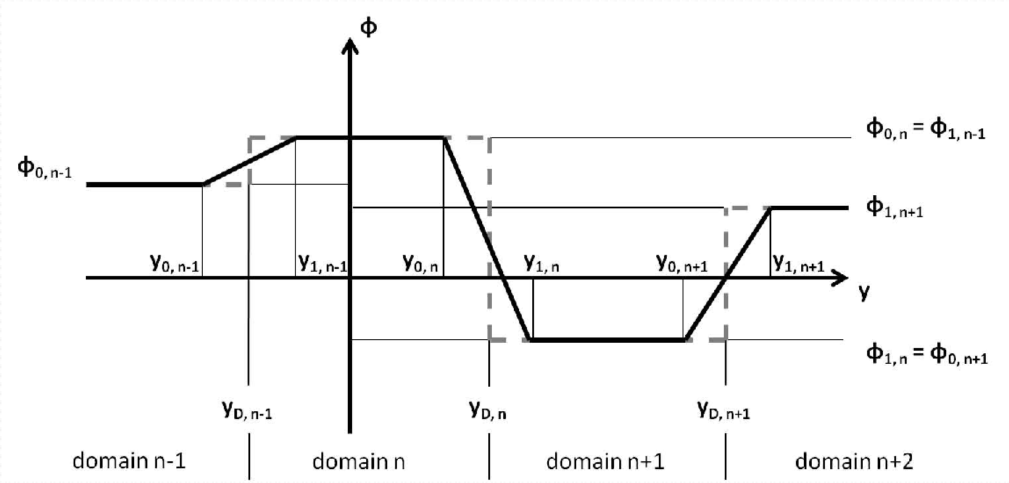
- Direct product of the ***stellar radiation*** and ***light absorbed and reradiated*** by the ***dust*** during the whole cosmic evolution
- From FIR to UV (0.005 eV – 5 eV)
- **VHE photon absorption:** $\gamma_{VHE} + \gamma_{EBL} \rightarrow e^{+} + e^{-}$
- VHE photon **flux dimming**




Franceschini & Rodighiero 2017

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

# Domain-like magnetic fields



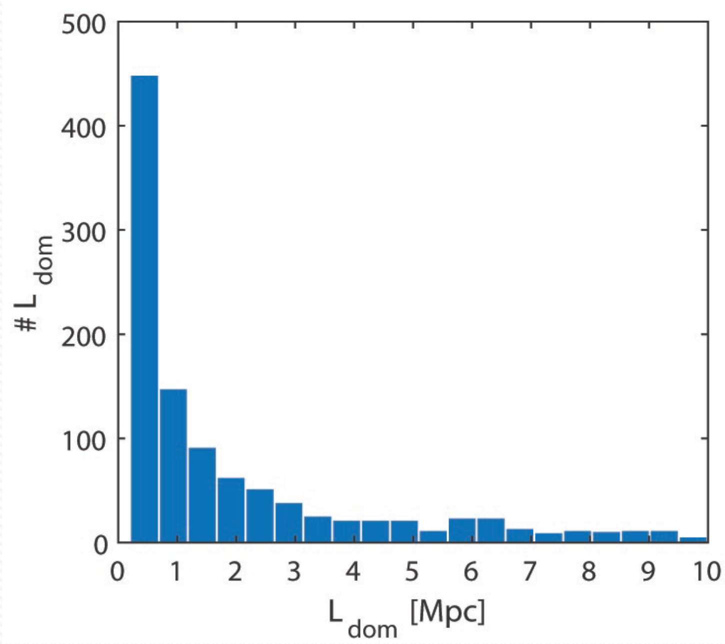

- **Norm ||B||** is **constant in each domain** of length $L_{\mathrm{dom}}$
- **B** orientation **angle ϕ varies** from a domain to the following
- **Old** sharp **model** with **discontinuous transitions**

- **New model** for astrophysical magnetic fields **B**
- **Domain-like** model **but** now **with continuous components** of **B**
- Useful for: extragalactic space, spiral and elliptical galaxies, radio lobes
- $L_{\mathrm{dom}}$ and ϕ are **random variables**

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).

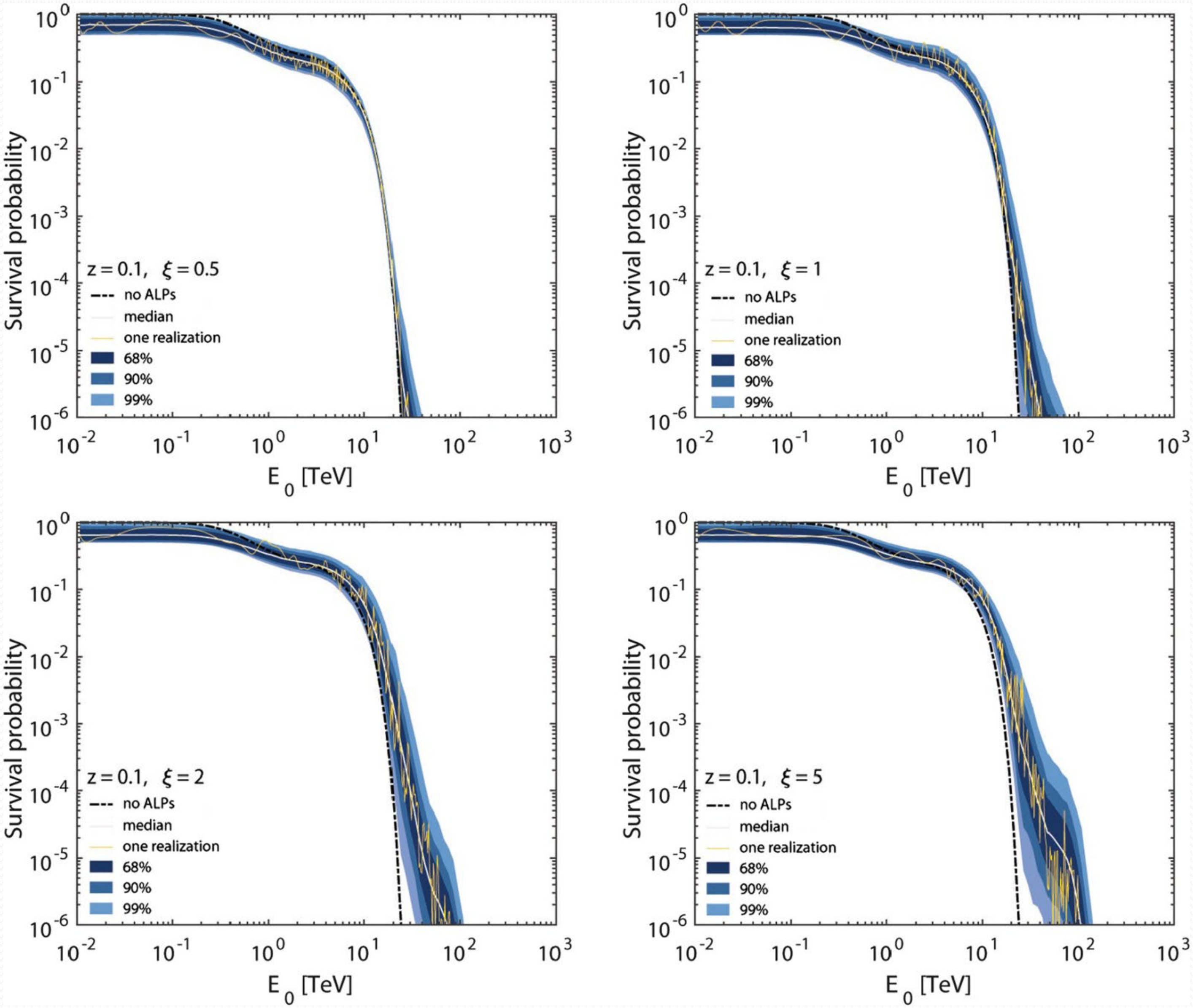
# Propagation in the extragalactic space

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



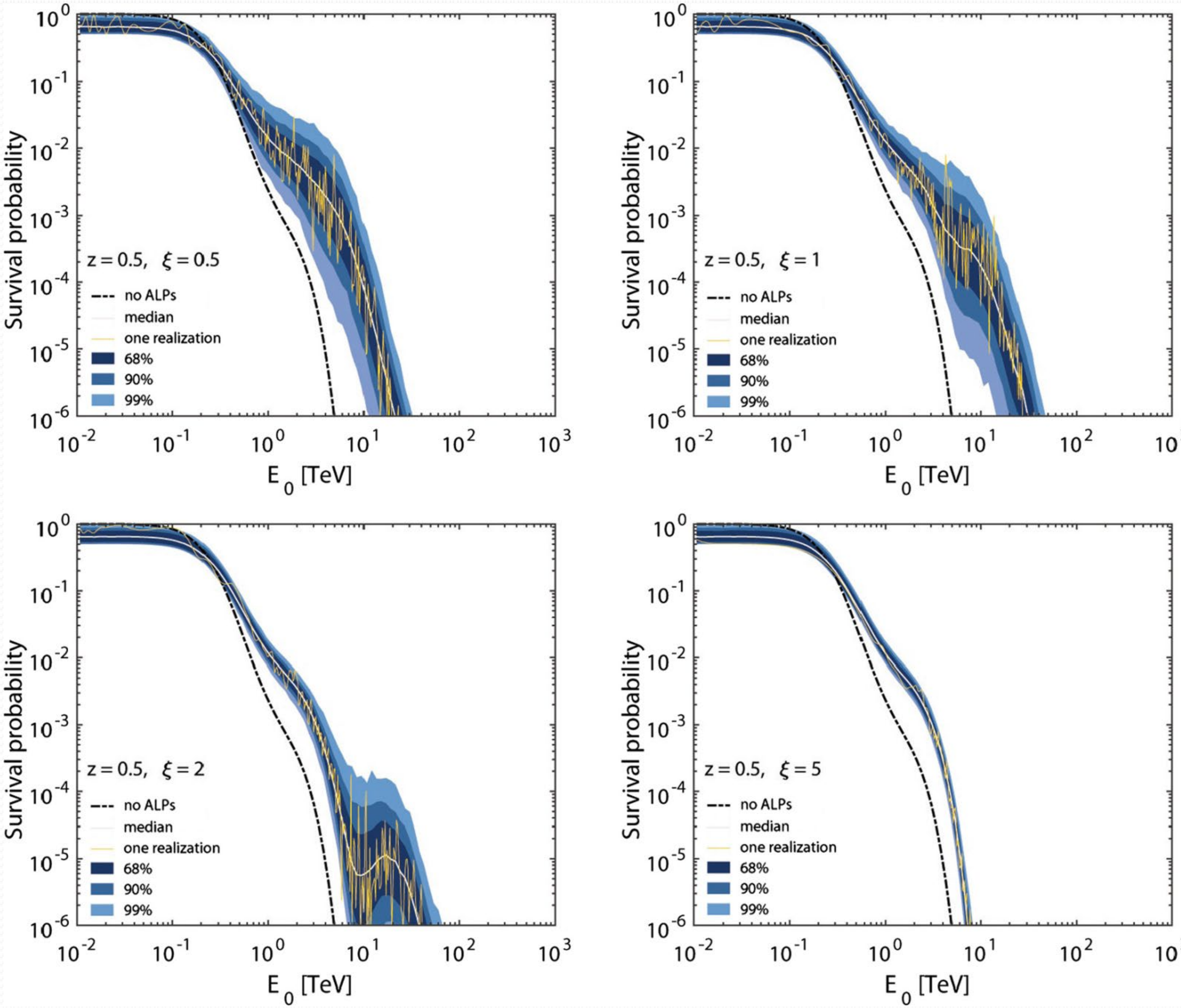

G. Galanti, M. Roncadelli, *Extragalactic photon–axion-like particle oscillations up to 1000 TeV*, JHEAp, 20 1-17 (arXiv: 1805.12055) (2018).

# 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).

# 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 → **power law**

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

- Observed spectrum → **power law**

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

- Emitted – observed spectrum relation

$$\Phi_{\rm obs}(E_0, z) = P_{\gamma \to \gamma}(E_0, z)\, \Phi_{\rm em}\big(E_0(1+z)\big)$$

- We **deabsorb** the **observed spectrum**:
  - if no ALPs → EBL absorption only
  - **with ALPs** → EBL absorption and photon-ALP oscillations

G. Galanti, M. Roncadelli, A. De Angelis, G. F. Bignami, *Hint at an axion-like particle from the redshift depencence of blazar spectra*, Mon. Not. R. Astron. Soc. 493, 1553 (arXiv: 1503.04436) (2020).

# Anomalous z dependence of Blazars (2)

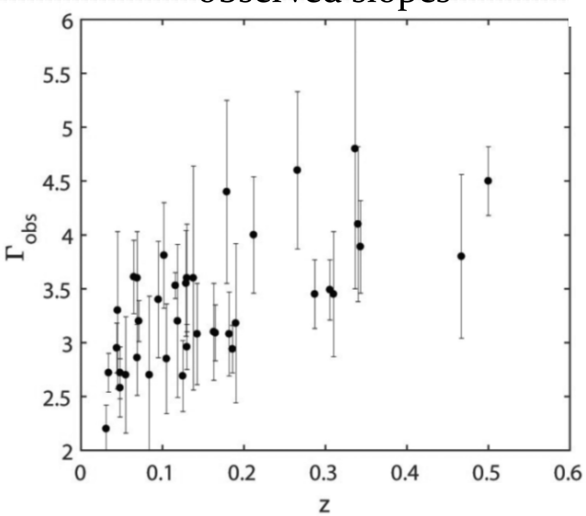
**Conventional Physics (CP):**

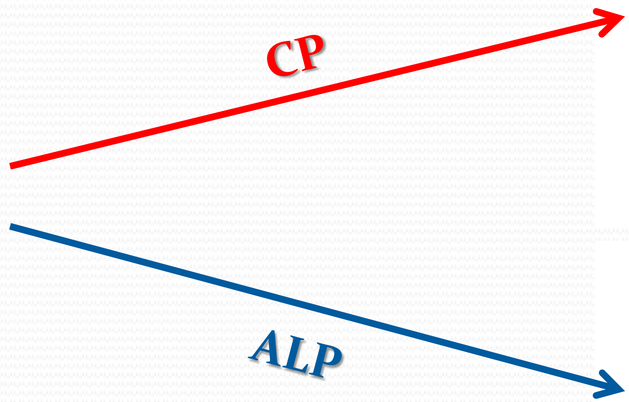
- Anomalous redshift dependence of blazar spectra

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

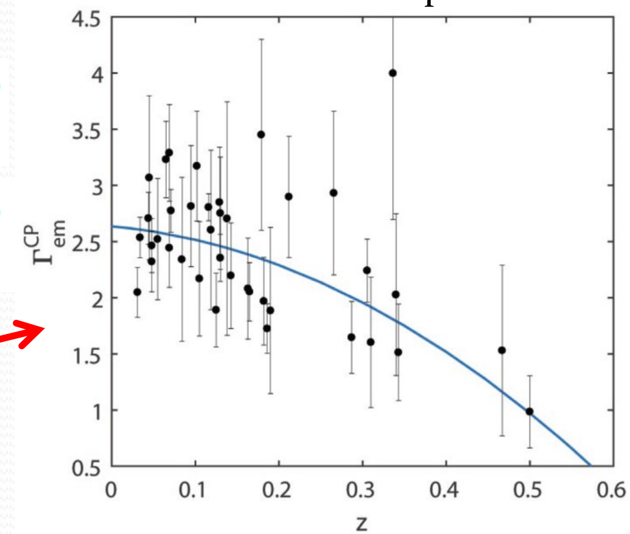
$$\Phi^{\mathrm{CP,BF}}_{\mathrm{em}}(E_0(1+z)) = K^{\mathrm{CP}}_{\mathrm{em}}(z) \left(\frac{E_0(1+z)}{E_{0,*}}\right)^{-\Gamma^{\mathrm{CP}}_{\mathrm{em}}(z)}$$

observed slopes




emitted slopes

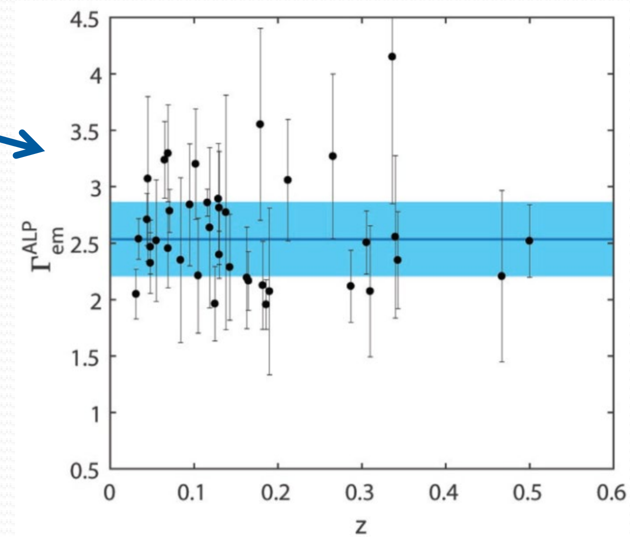



**With ALPs:**

$$\Phi^{\mathrm{ALP}}_{\mathrm{em}}(E_0(1+z)) = \left(P^{\mathrm{ALP}}_{\gamma\to\gamma}(E_0,z)\right)^{-1} K_{\mathrm{obs}}(z) \left(\frac{E_0}{E_{0,*}}\right)^{-\Gamma_{\mathrm{obs}}(z)}$$

- Anomaly **SOLVED**

$$\Phi^{\mathrm{ALP,BF}}_{\mathrm{em}}(E_0(1+z)) = K^{\mathrm{ALP}}_{\mathrm{em}}(z) \left(\frac{E_0(1+z)}{E_{0,*}}\right)^{-\Gamma^{\mathrm{ALP}}_{\mathrm{em}}(z)}$$




***See also Alberto Franceschini's talk on Thursday***

G. Galanti, M. Roncadelli, A. De Angelis, G. F. Bignami, *Hint at an axion-like particle from the redshift depencence of blazar spectra*, Mon. Not. R. Astron. Soc. 493, 1553 (arXiv: 1503.04436) (2020).

# Propagation in the extragalactic space (2)

- 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

- **Second hint** for **ALP existence** coming from the solution of the anomalous redshift dependence of blazar spectra


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).

G. Galanti, M. Roncadelli, A. De Angelis, G. F. Bignami, *Hint at an axion-like particle from the redshift depencence of blazar spectra*, Mon. Not. R. Astron. Soc. 493, 1553 (arXiv: 1503.04436) (2020).

# Milky Way
# and total effect

# Propagation in the Milky Way and total effect

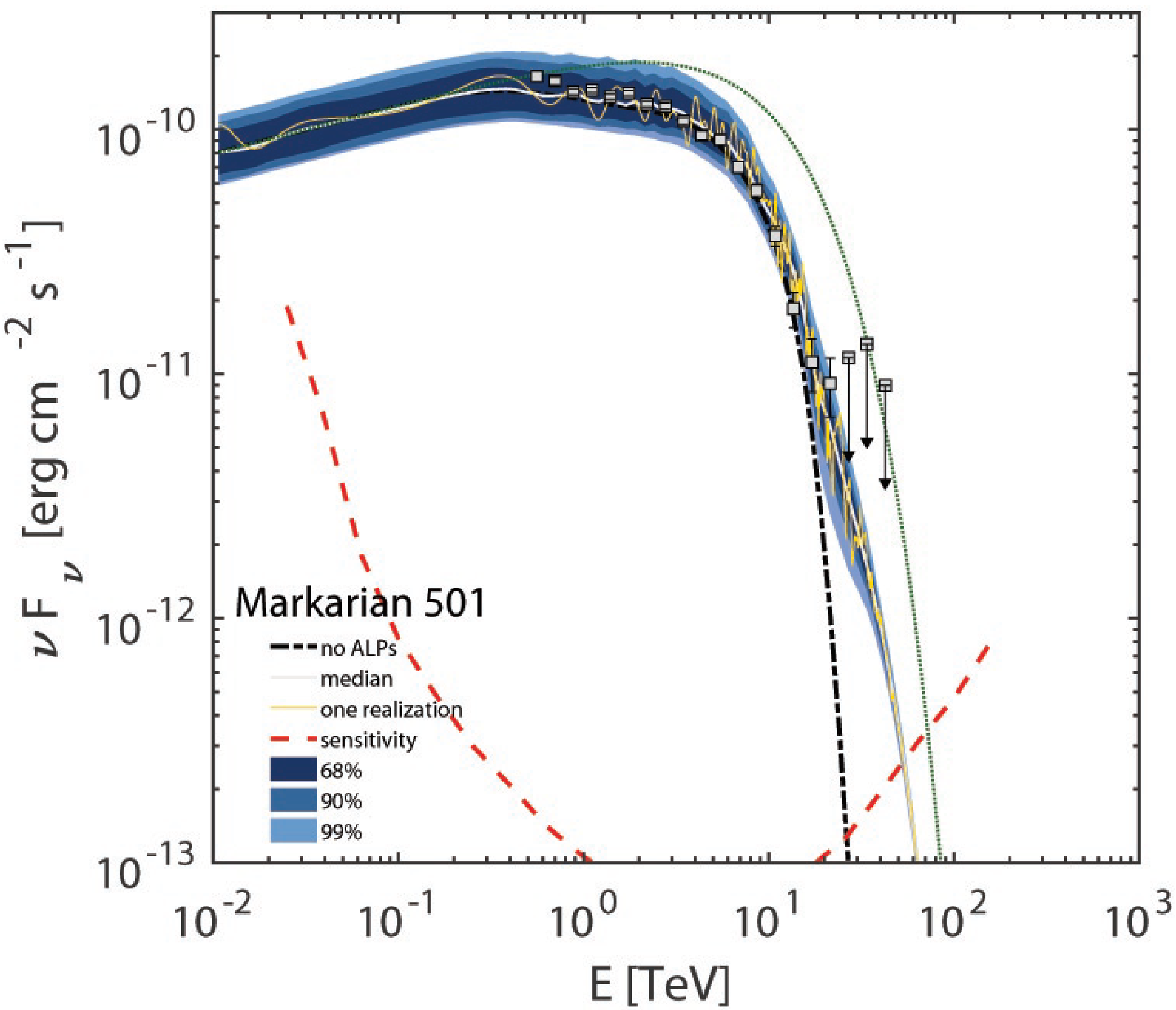
- Important only the **regular component** of the Milky Way magnetic field $B_{\rm MW}$
- $B_{\rm MW}$ = 5 μG, coherence length $l_{\rm coh}$ = 10 kpc
- But **detailed sky maps** of $B_{\rm MW}$ exist (Jansson & Farrar 2012)

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

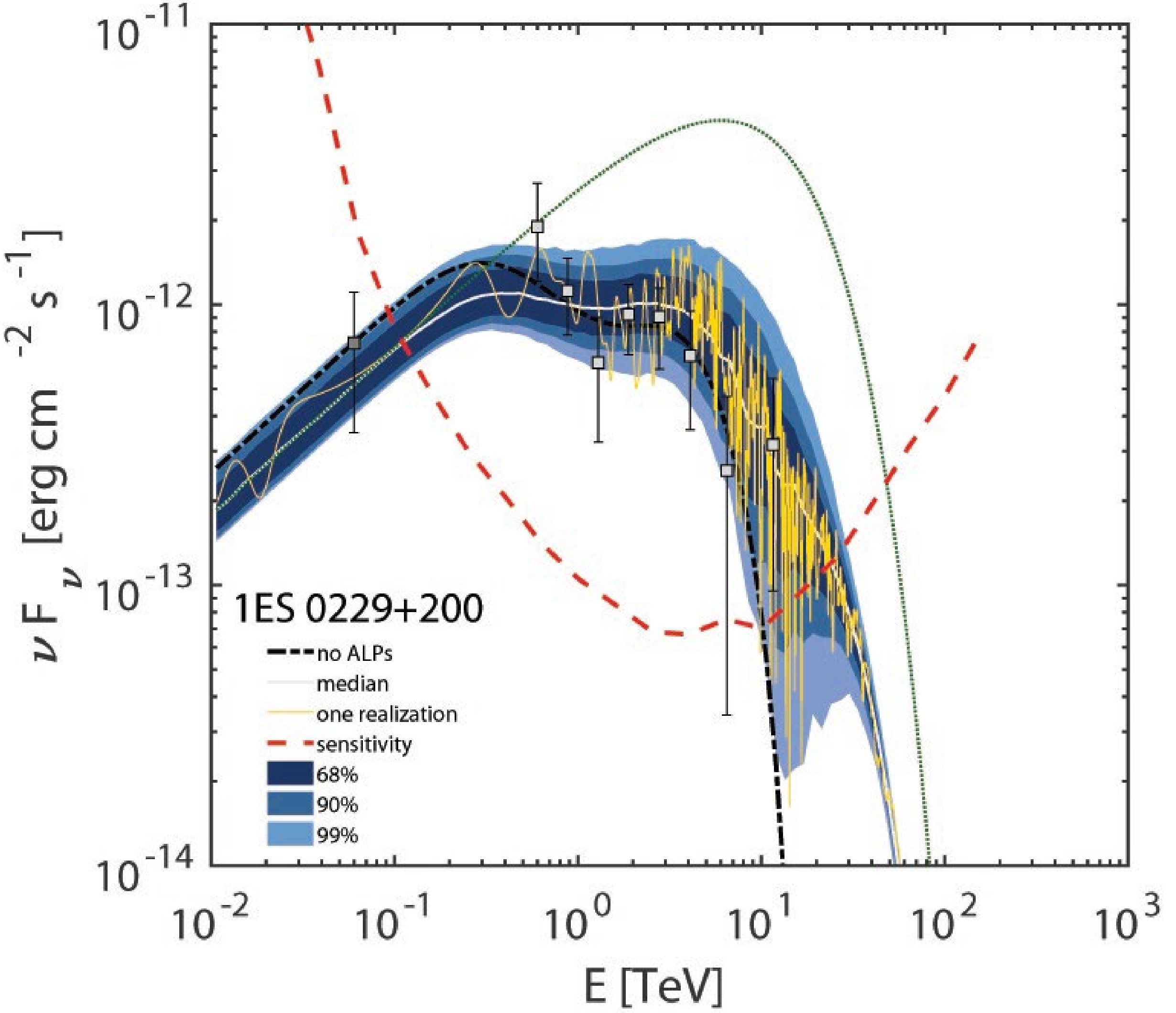
DATA from HEGRA (Aharonian et al. 2001)




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).

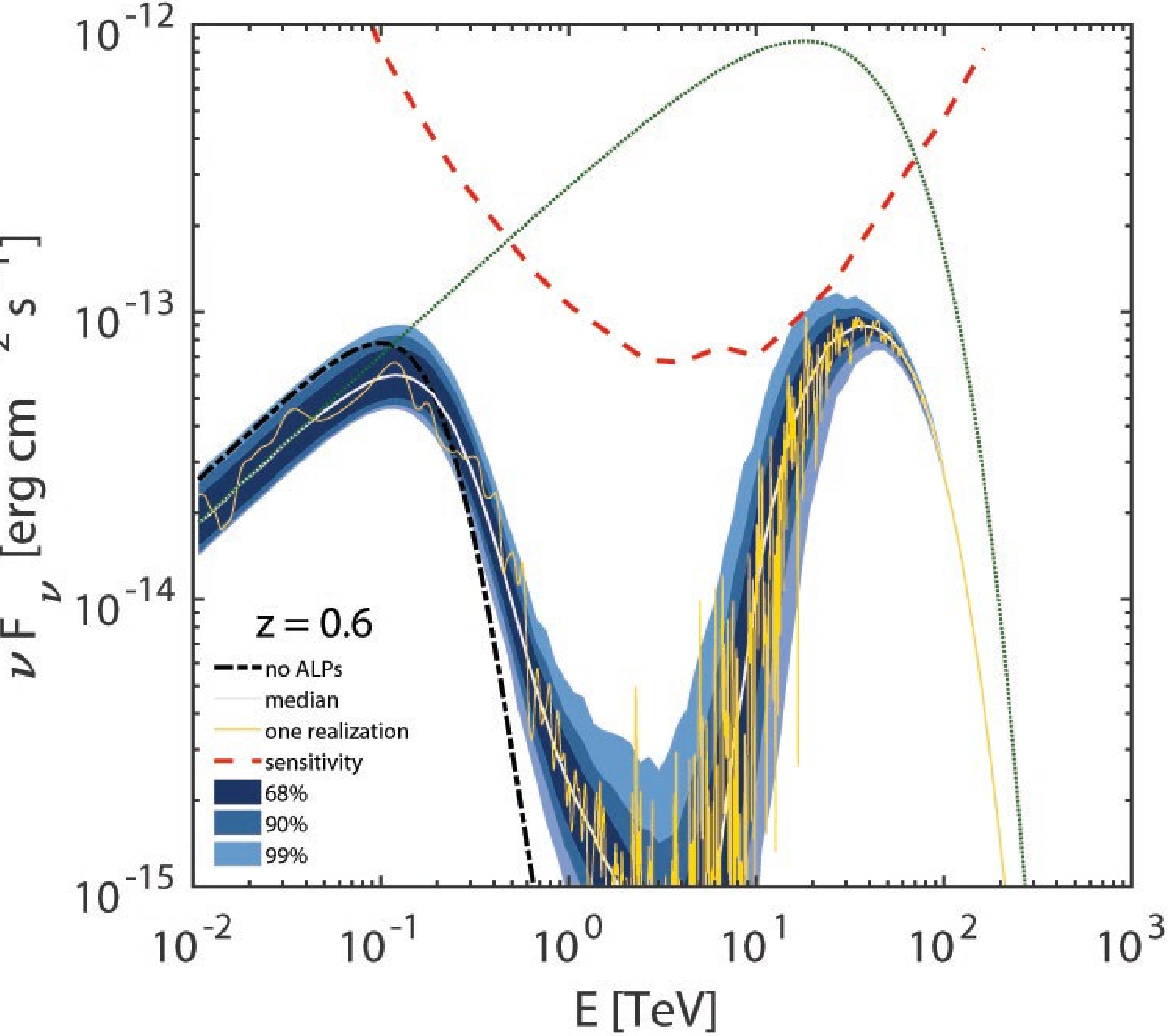
# 1ES 0229+200

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)

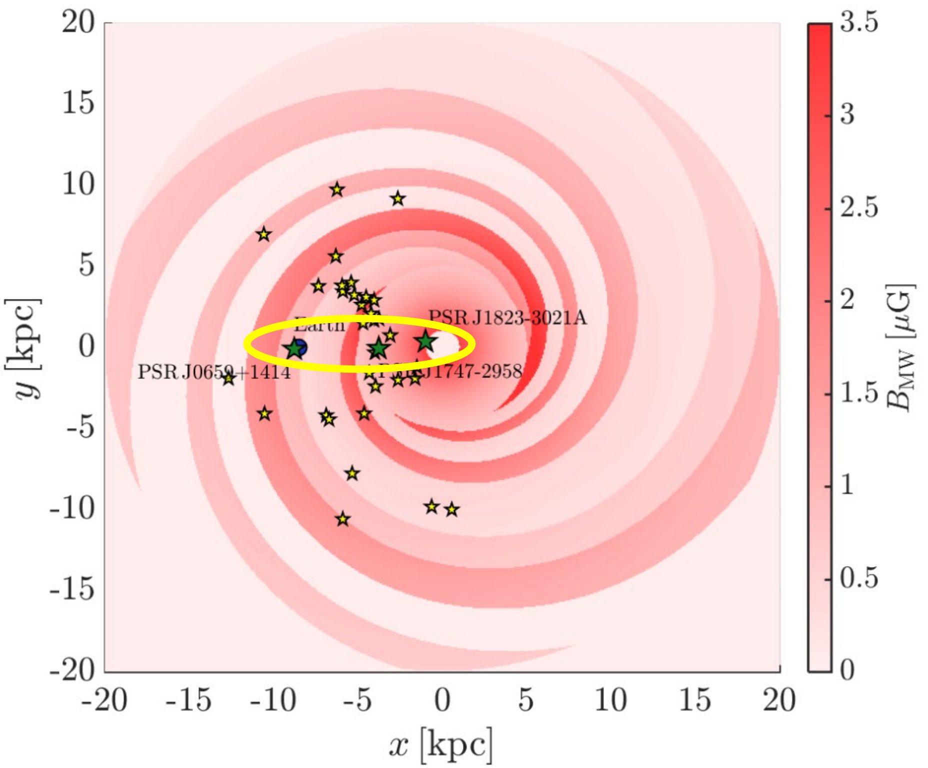
- **Conventional physics hardly explains the highest energy point** in the spectra of Markarian 501 and of 1ES 0229+200
- **photon/ALP oscillations** are instead **successful**
- As the energy increases photon/ALP oscillation effect is more and more evident
- photon/ALP oscillations generate features in BL Lacs: (i) **oscillatory** behavior in blazar spectra and (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

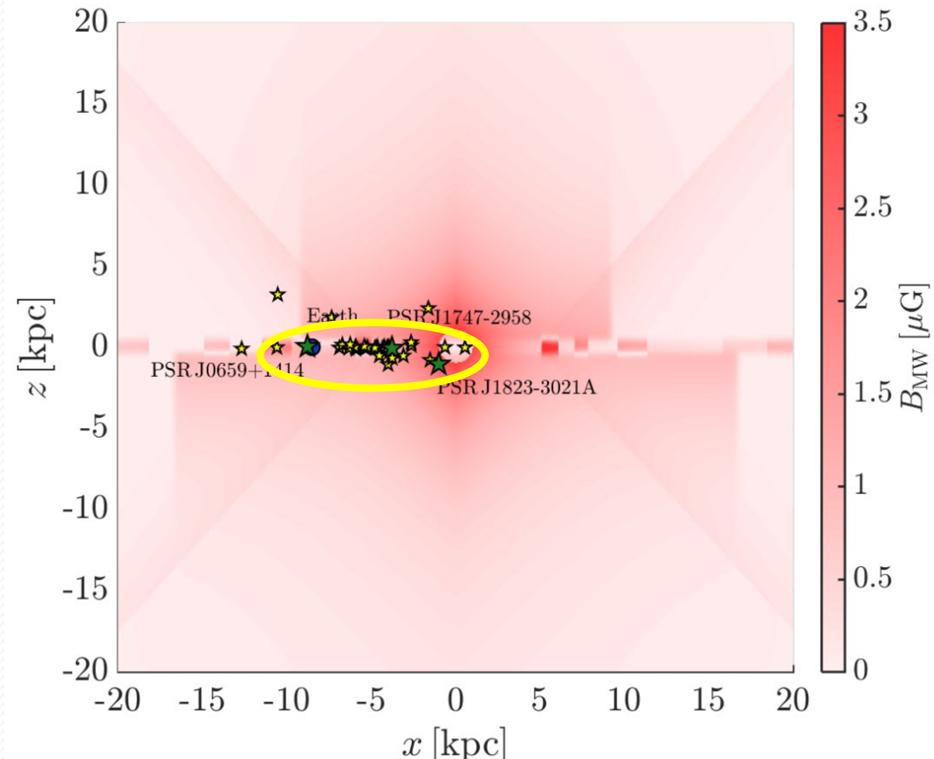
G. Galanti, F. Tavecchio, M. Roncadelli, C. Evoli, *Photon-ALP oscillations from a blazar to us up to 1000 TeV*, Mon. Not. R. Astron. Soc. 487, 123 (arXiv: 1811.03548) (2019).

# Pulsars

# Photon-ALP conversion in the Galaxy

- **Galactic magnetic field** $B_{MW}$ (Jansson & Farrar 2012) is **important**
- **Select pulsars with distance > 4 kpc** for sizable ALP effects
- Focus on pulsars from **Fermi** catalog (50 MeV – 200 GeV)
- Spectra modified by ALPs ($g_{a\gamma\gamma} = 0.5 \times 10^{-10}$ GeV$^{-1}$; $m_a = 2 \times 10^{-8}$ eV)



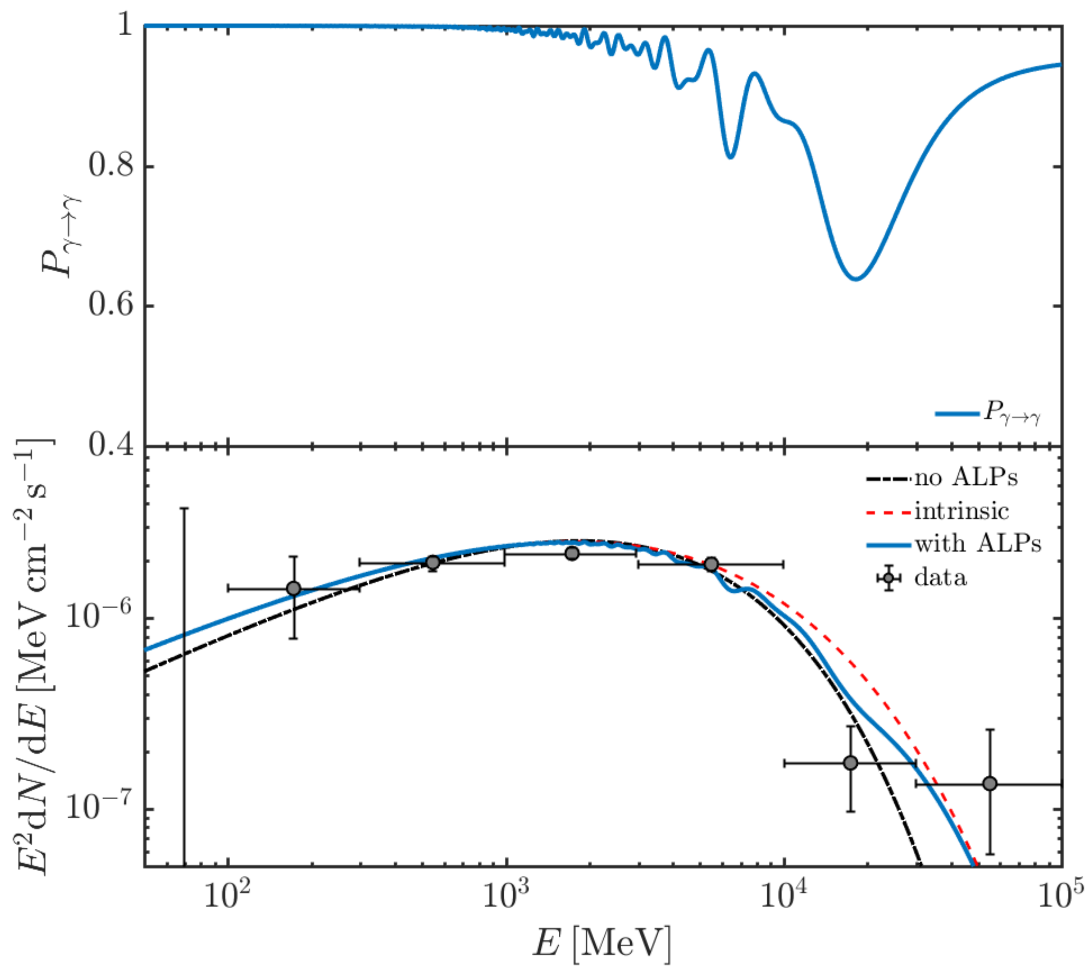

G. Galanti, P. Caraveo, in preparation.

# Photon-ALP conversion in the Galaxy (2)

- **Distance is the key parameter**
- **Power law super exponential cutoff** fit $N \exp[\Gamma \ln(E/E_0) - (E/E_{cut})^b]$ applied to *emitted* spectra (modified by $P_{\gamma \to \gamma}$)
- Comparison with pulsars similar to those considered but at *different distances* (similar *emitted* spectra are expected)
- **Hint on the presence of ALPs** if:
  - Comparing similar pulsars at different distances should yield different spectral shapes as a function of distance
  - **farther pulsars should have spectra more modified than closer ones**
- Without such correlation → hint against ALPs

G. Galanti, P. Caraveo, in preparation.

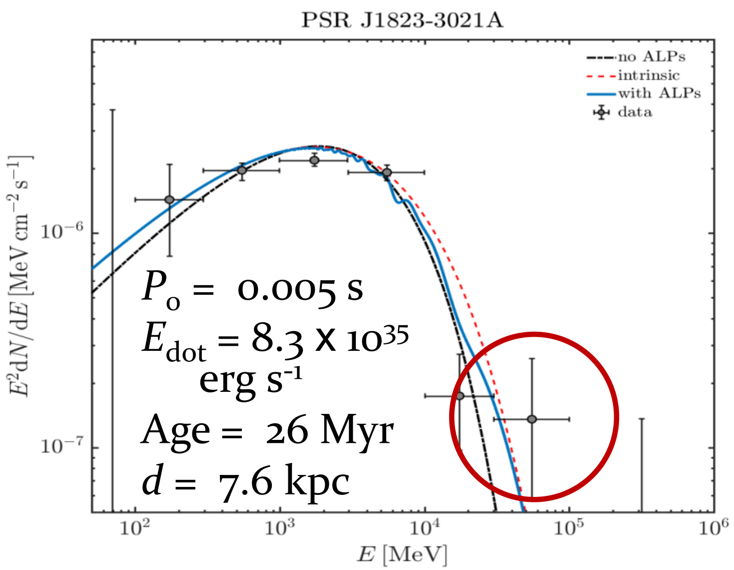
# PSR J1823-3021A

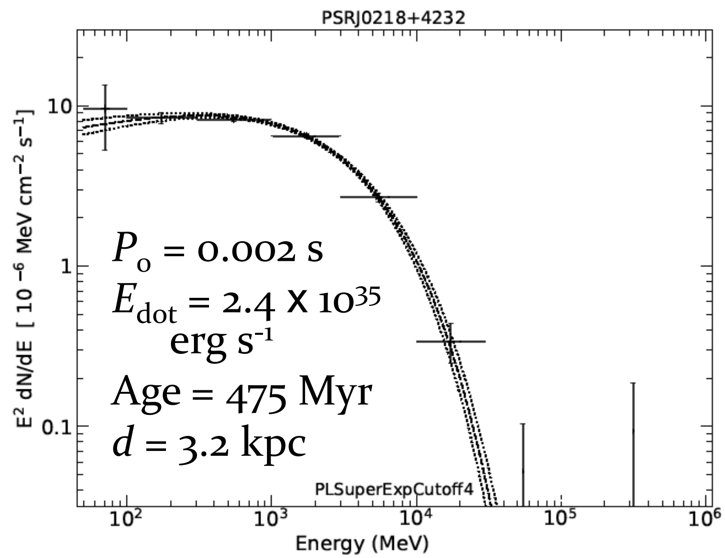


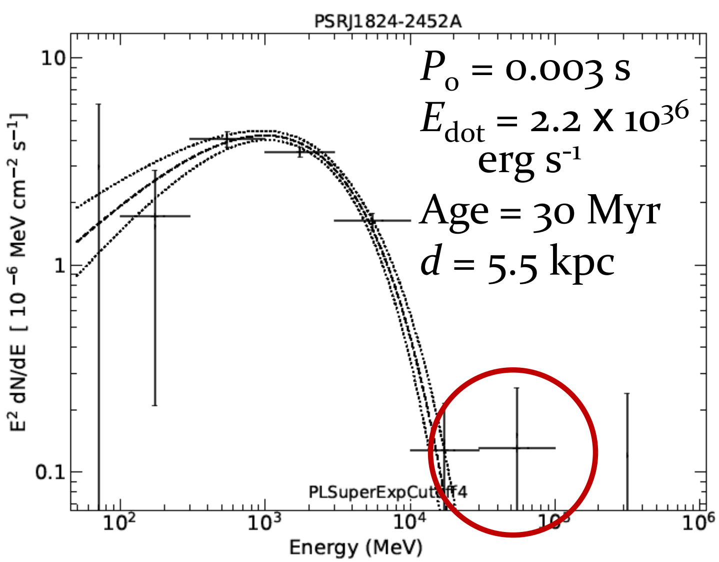

G. Galanti, P. Caraveo, in preparation.

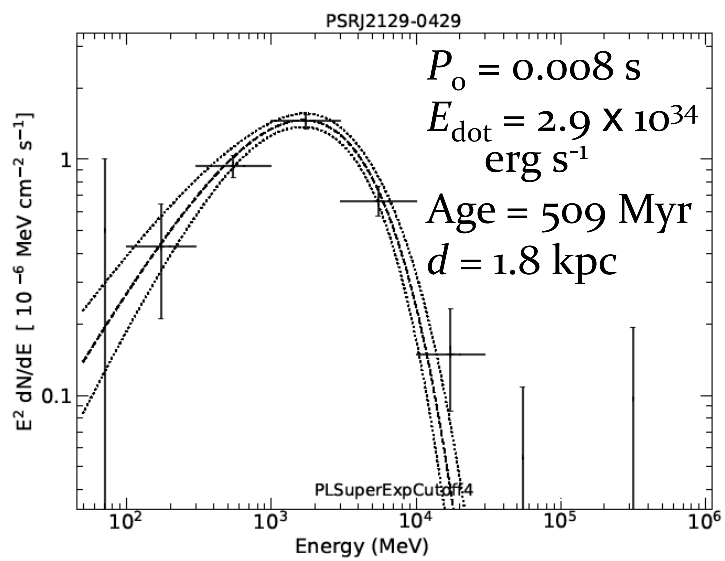
- ALP effects for $E > 1$ GeV
- Tentative new heuristic fit "with ALPs" resulting in
  - $\Gamma = 1.33$
  - $E_{cut} = 1100.8$ MeV
  - $b = 0.53$
- Small increase of $\Gamma$, small decrease of $E_{cut}$ and $b$

# PSR J1823-3021A




G. Galanti, P. Caraveo, in preparation.

# Photon-ALP conversion in the Galaxy (3)

- **In the GeV energy range what matters for photon-ALP conversion is the *transverse* component of $B_{\rm MW}$ only**
- **Best pulsars for ALP studies: distant, in the Galactic plane, towards the centre**
- Possible improvement of the spectral fits (to be confirmed with a more ROBUST analysis)
- Possible existence of ALP hint from the behavior of pulsar with similar properties but at different distances (to be investigated further)
- Possible constraints on ALP parameter space ($g_{a\gamma\gamma}$, $m_a$)

G. Galanti, P. Caraveo, in preparation.

# 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 and ASTRI
- Possible additional information from **pulsars**
- Many of previous effects with the same model parameters ($g_{a\gamma\gamma}$, $m_a$) → possible ***ALP existence***??
- Astrophysical new data from observatories like the CTA, ASTRI 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 $\rho = |\psi\rangle\langle\psi|$ ($\psi$ → photon-ALP state vector)

- Stokes parameters $I$, $Q$, $U$, $V$ → 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:

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

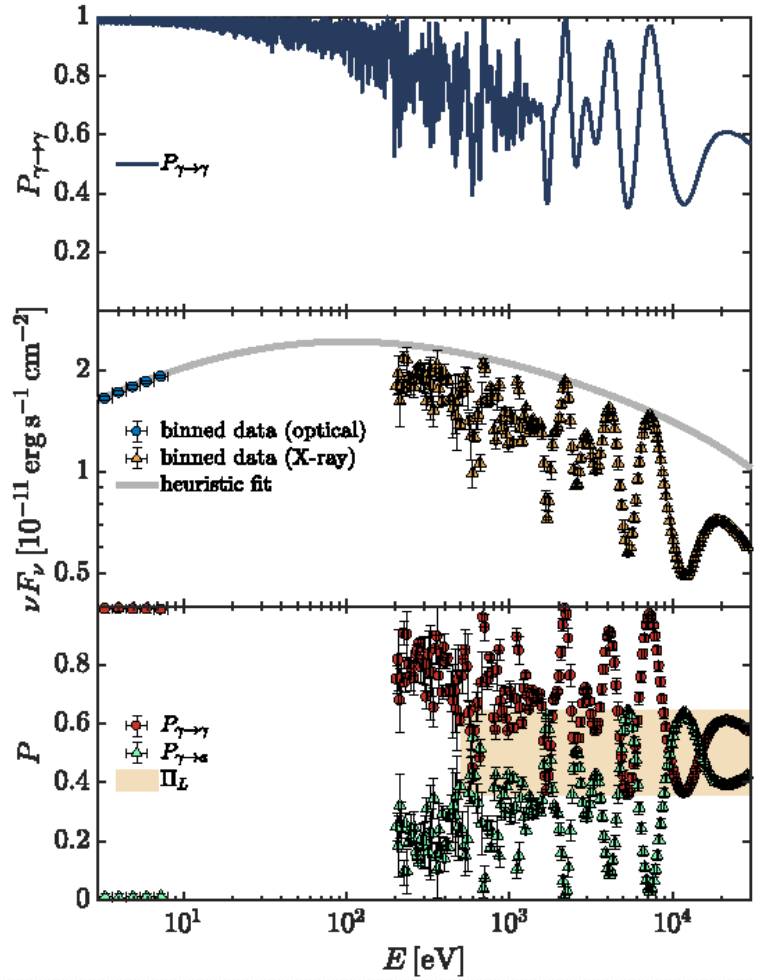
- Polarization angle:

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

# ALPs measure **initial** photon polarization

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

Photon emission from a blazar




G. Galanti, Phys. Rev D 105, 083022 (2022) [arXiv: 2202.10315].

# Galaxy Clusters

# Photon-ALP beam from a galaxy cluster

**GALAXY CLUSTER**

- Diffuse emission in the cluster central region ($r_{\rm core}$ ~ 100 kpc)
  - X-ray: Bremsstrahlung, initial $\Pi_{L,0} = 0$ (Felten+1966)
  - High-energy (HE) range: e.g. synchrotron (turbulent $B$), $\Pi_{L,0} = 0$ (Timokhin+2004)
- Electron number density $n_{e,\rm clu}$ → (double) *beta model* (Hudson+2010)
- Magnetic field $B_{\rm clu} = O(10)$ μG, Kolmogorov-type turbulence, profile $\propto (n_{e,\rm clu}/n_{e,\rm clu,0})^{\eta_{\rm clu}}$, where $n_{e,\rm clu,0}$ is the central $n_{e,\rm clu}$ and $\eta_{\rm clu} \sim 0.75$ (Meyer+2014)

**EXTRAGALACTIC SPACE**

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

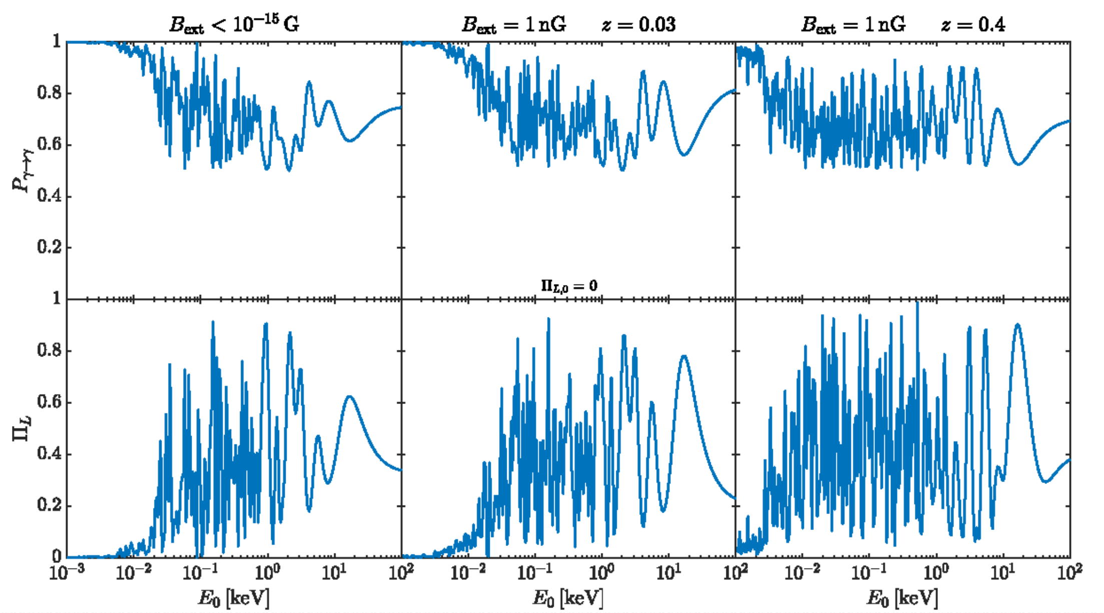
**MILKY WAY**

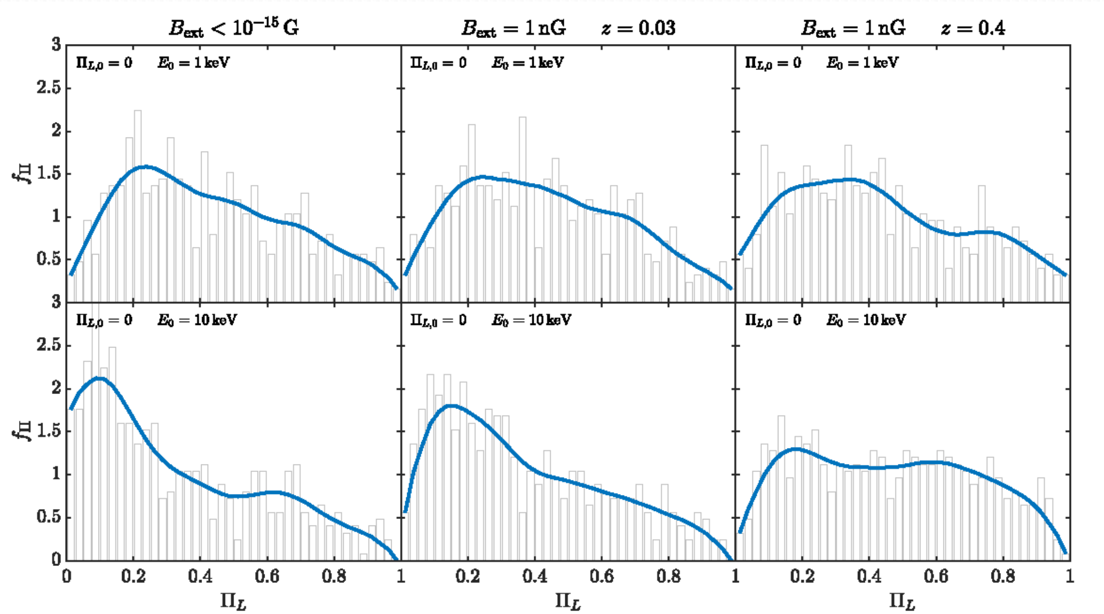
- $B_{\rm MW}$ map by Jansson & Farrar (Jansson & Farrar, 2012a,b)

**PHOTON-ALP BEAM PROPAGATION**

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

# Galaxy cluster – general



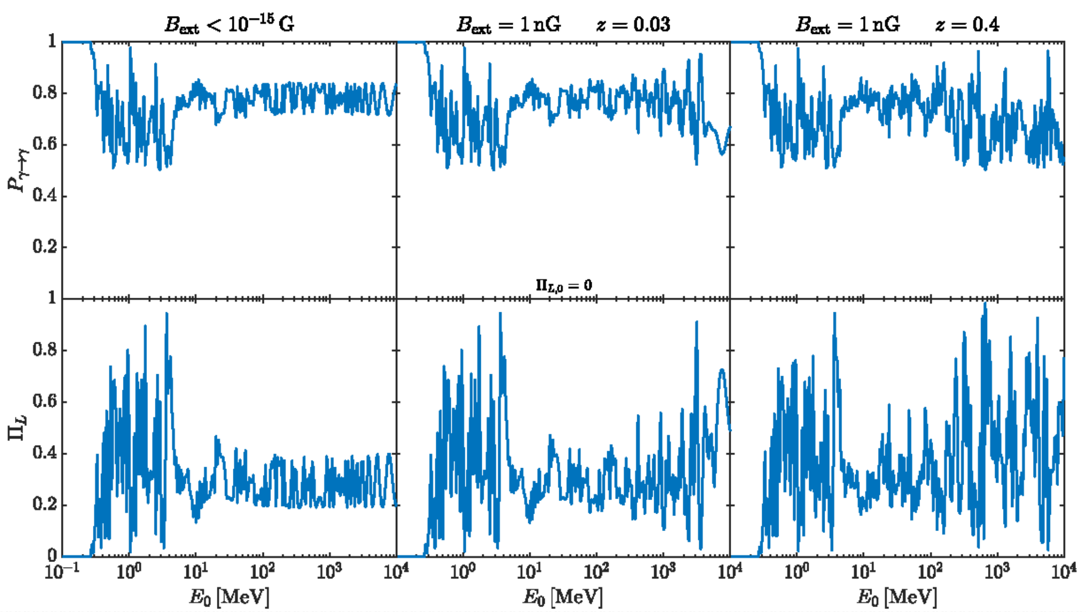



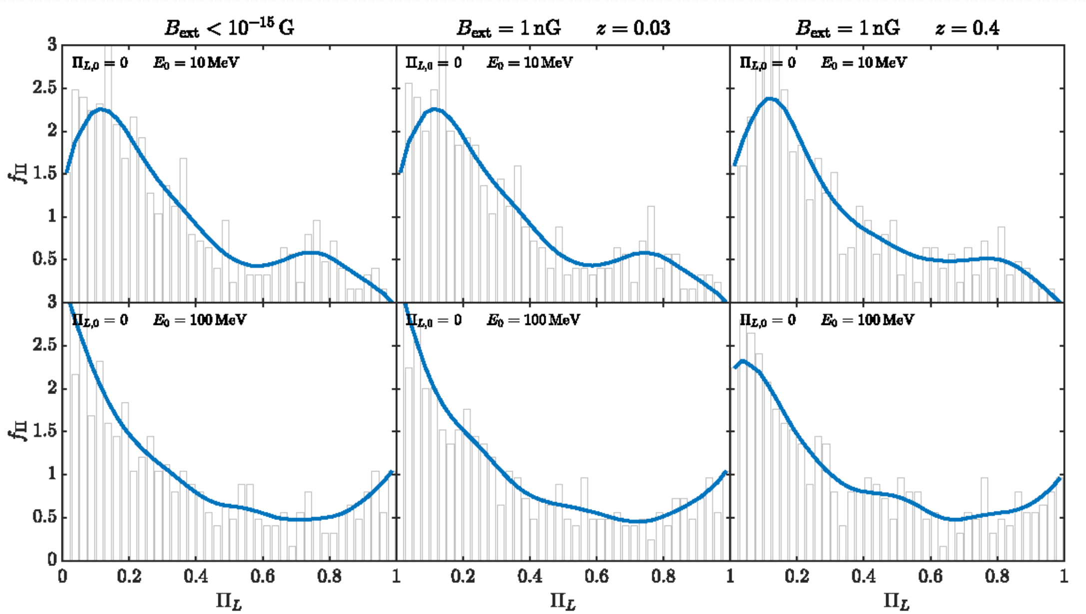

**X-ray band:**

- **Initial** $\Pi_{L,0} = 0$
- $g_{a\gamma\gamma} = 0.5 \times 10^{-11}$ GeV$^{-1}$
- $m_a < 10^{-14}$ eV
- $n_{e,clu,0} = 0.5 \times 10^{-2}$ cm$^{-3}$ (non cool core)
- Most probable **final** $\Pi_L > 0.1$

G. Galanti, arXiv: 2202.11675.

# Galaxy cluster – general




## HE band:

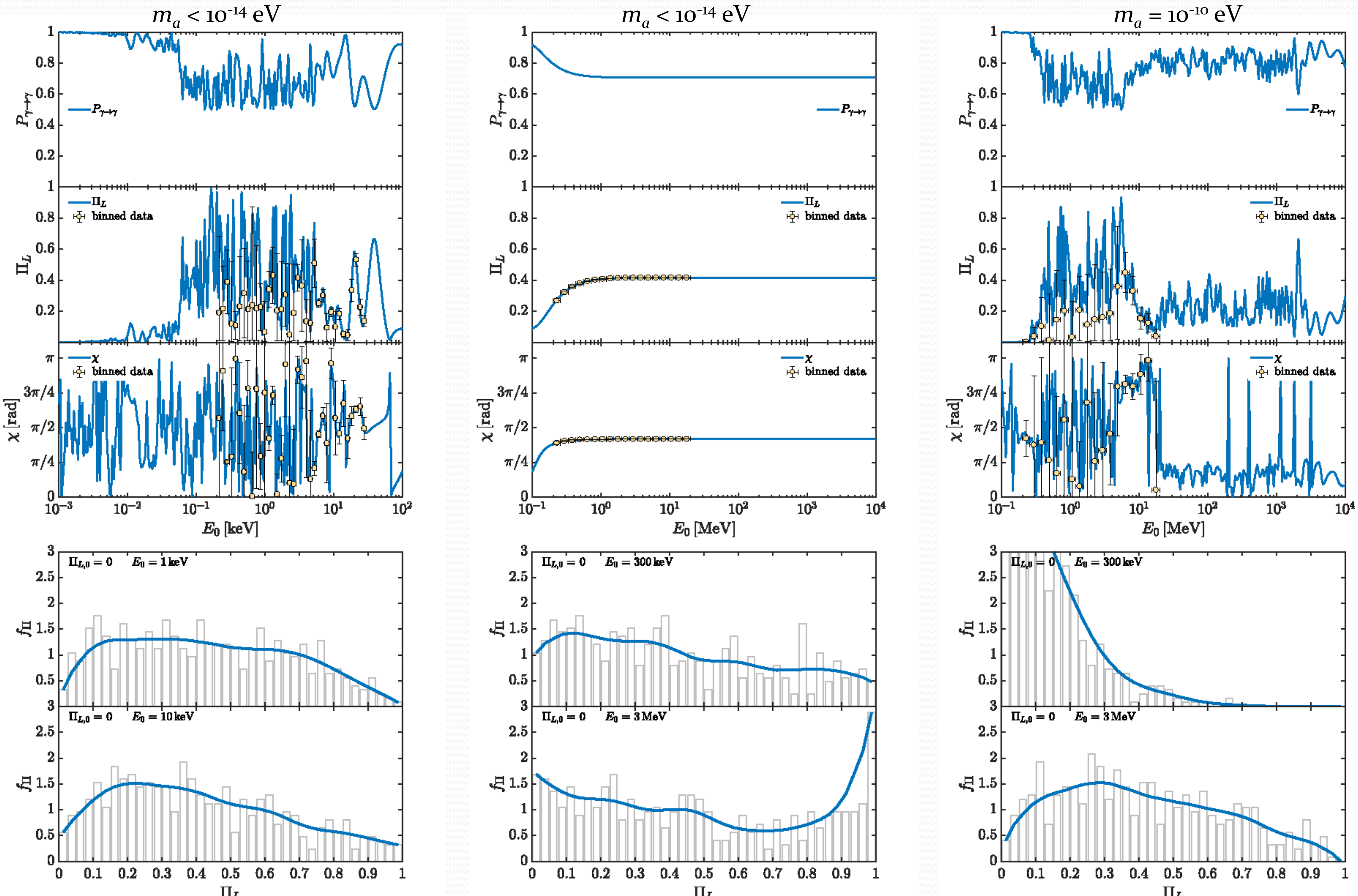
- **Initial** $\Pi_{L,0} = 0$
- $g_{a\gamma\gamma} = 0.5 \times 10^{-11}$ GeV$^{-1}$
- $m_a = 10^{-10}$ eV
- $n_{e,clu,0} = 0.5 \times 10^{-2}$ cm$^{-3}$ (non cool core)
- Most probable **final** $\Pi_L > 0.1$ (10 MeV), $\Pi_L < 0.2$ (100 MeV)

G. Galanti, arXiv: 2202.11675.

# Galaxy cluster – Perseus

Models of $n_{e,\mathrm{clu}}$ and $B_{\mathrm{clu}}$: Churazov+2003; Bonafede+2010

$B_{\mathrm{clu,0}} = 16\ \mu\mathrm{G}$

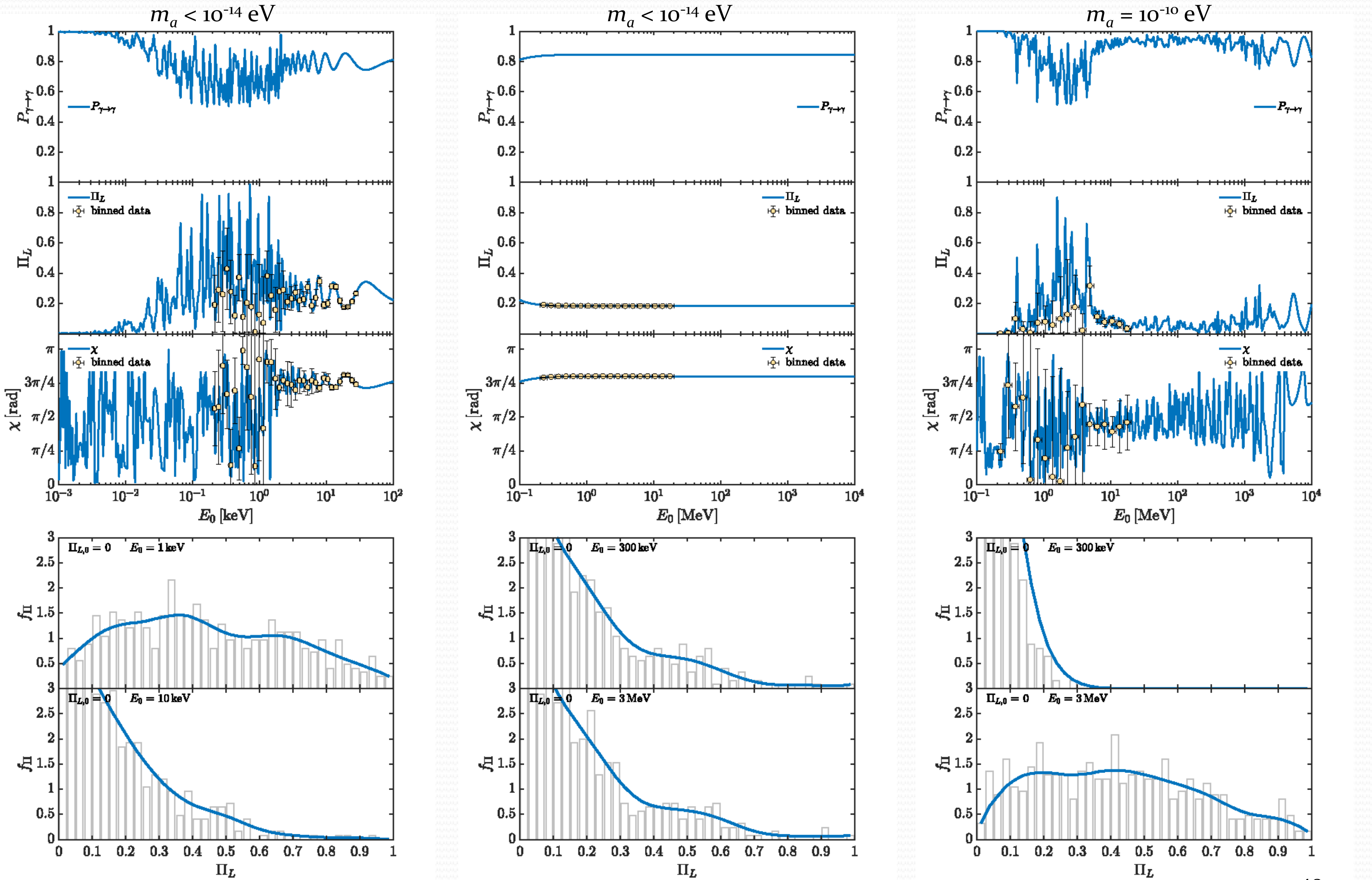



G. Galanti, M. Roncadelli, F. Tavecchio, arXiv: 2202.12286.

# Galaxy cluster – Coma

Models of $n_{e,\mathrm{clu}}$ and $B_{\mathrm{clu}}$: Briel+1992; Bonafede+2010

$B_{\mathrm{clu,0}} = 4.7\ \mu\mathrm{G}$




G. Galanti, M. Roncadelli, F. Tavecchio, arXiv: 2202.12286.

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

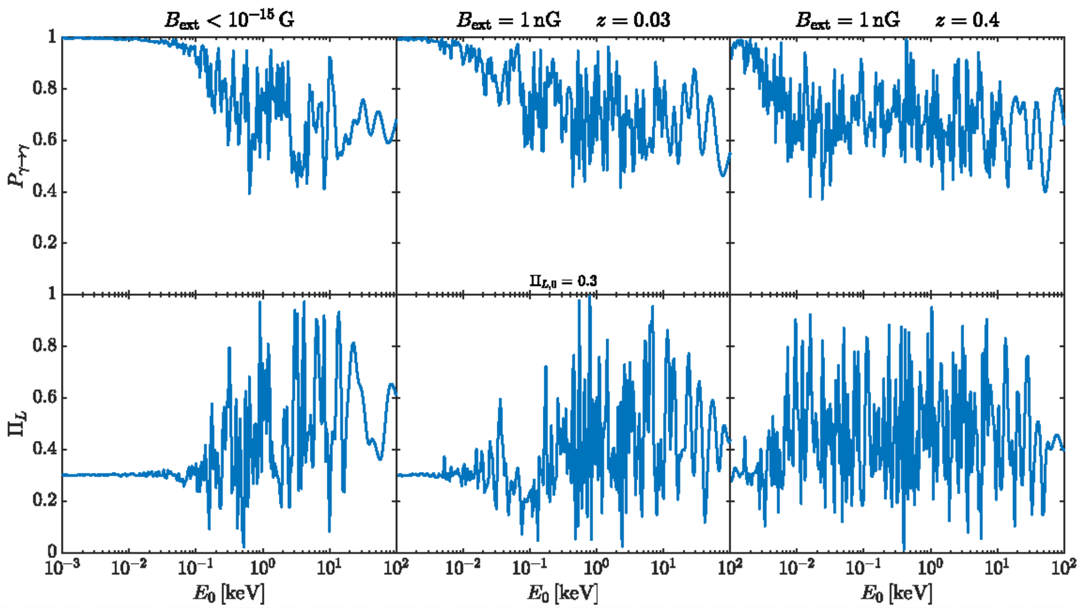
**HOST GALAXY**

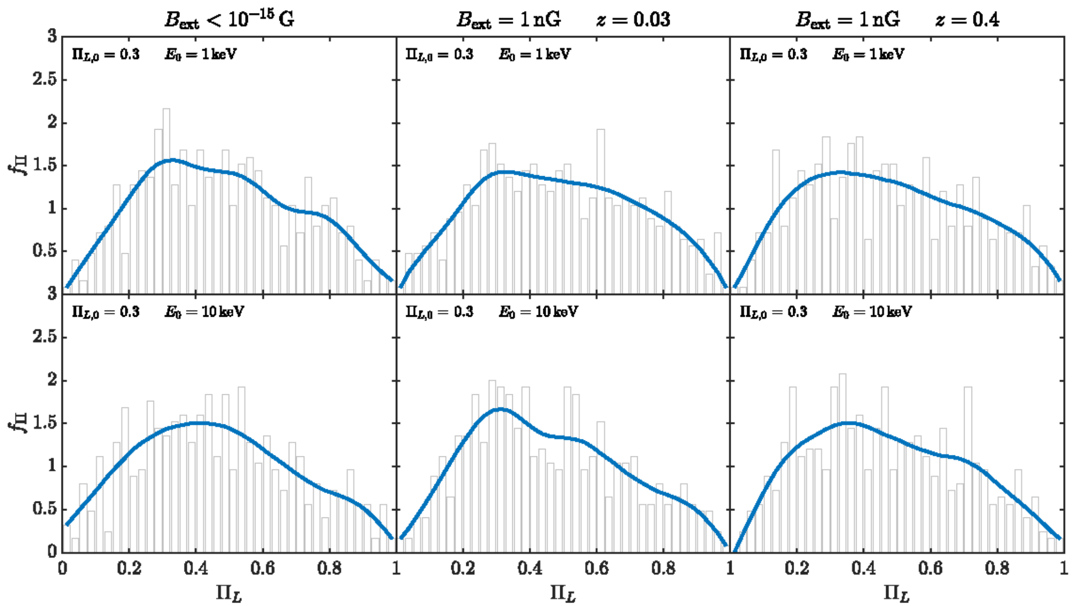
- Domain-like model
- $B_{\mathrm{host}} = 5$ μG with coherence 150 pc (Moss & Shukurov, 1996)

**GALAXY CLUSTER – EXTRAGALACTIC SPACE – MILKY WAY**

- Like before

# Blazar (leptonic) – general



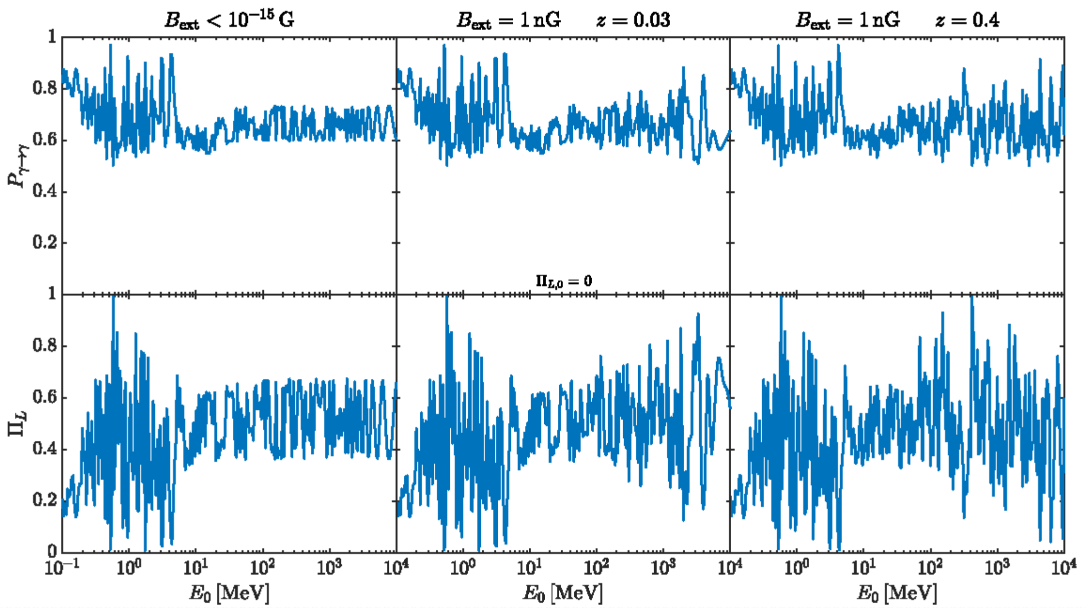



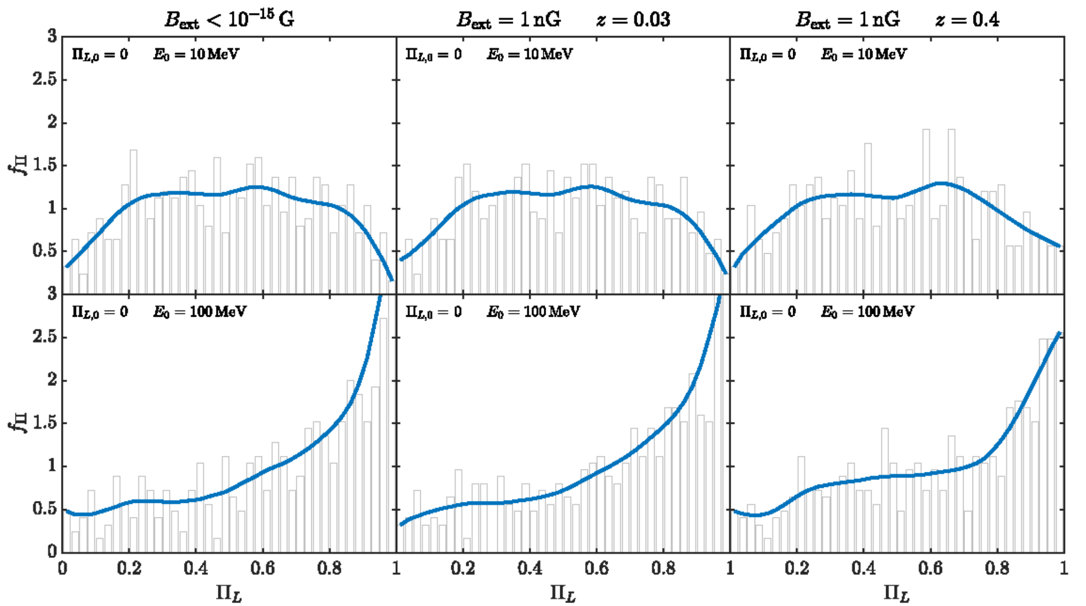

**X-ray band:**

- **Initial** $\Pi_{L,0} = 0.3$
- $g_{a\gamma\gamma} = 0.5 \times 10^{-11}$ GeV$^{-1}$
- $m_a < 10^{-14}$ eV
- $n_{e,clu,0} = 5 \times 10^{-2}$ cm$^{-3}$ (cool core)
- Most probable **final** $\Pi_L$ = 0.3 with broadening

G. Galanti, arXiv: 2202.11675.

# Blazar (leptonic) – general




## HE band:

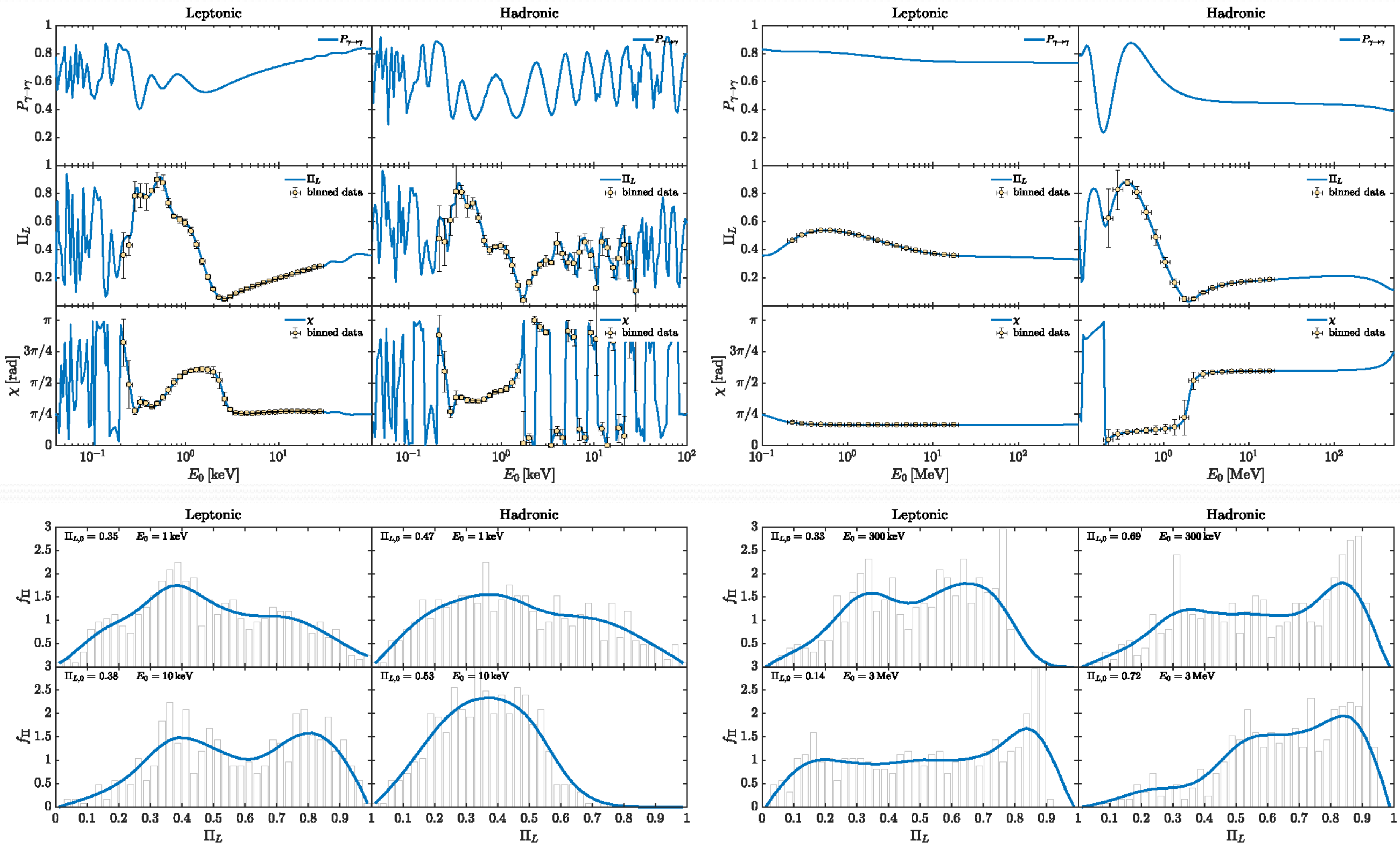
- **Initial** $\Pi_{L,0} = 0$
- $g_{a\gamma\gamma} = 0.5 \times 10^{-11}$ GeV$^{-1}$
- $m_a = 10^{-10}$ eV
- $n_{e,clu,0} = 5 \times 10^{-2}$ cm$^{-3}$ (cool core)
- Most probable **final** $\Pi_L > 0.2$ (10 MeV), $\Pi_L > 0.8$ (100 MeV)

G. Galanti, arXiv: 2202.11675.

# Blazar – OJ 287 (preliminary)

$\Pi_{L,0}$: Zhang & Böttcher, 2013

$m_a < 10^{-14}$ eV

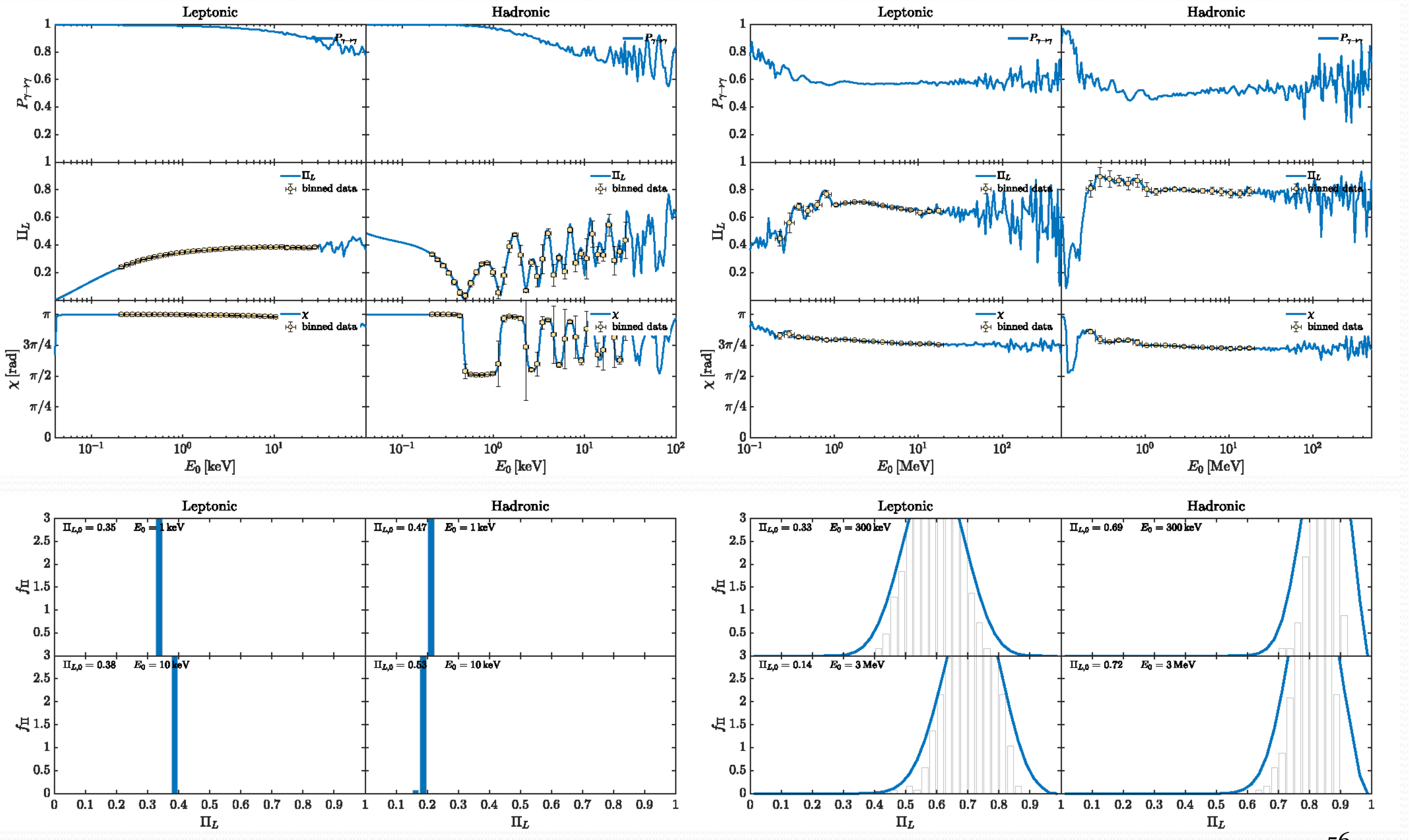



G. Galanti, M. Roncadelli, F. Tavecchio, in preparation.

# Blazar – OJ 287 (preliminary)

$\Pi_{L,0}$: Zhang & Böttcher, 2013

$m_a = 10^{-10}$ eV




G. Galanti, M. Roncadelli, F. Tavecchio, in preparation.

# 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 $\Pi_{L,0}$
- $m_a = 10^{-10}$ eV → weak mixing (conversion only in hadronic models)
  - High vale of $B_{\rm jet,0}$ ~ 20 G is mandatory to have ALP effects
  - Possible signal: **dimming** of the initial $\Pi_{L,0}$ ~ 0.5 **[preliminary]**

**HE band:**

- $m_a < 10^{-14}$ eV → strong mixing
  - **Possible strong signal**: $0.4 < \Pi_L < 0.8$ at and above 3 MeV
- $m_a = 10^{-10}$ eV → weak mixing
  - **Possible strong signal**: $\Pi_L > 0.5$ for $E >$ (1-10) 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, Polstar)
  - In the HE band (detectable by COSI, e-ASTROGAM and AMEGO)

- Possible **additional hints** for ALP existence (two hints coming from spectral measurements)
  - Signal of final $\Pi_L > 0$ from clusters robust in favor of ALPs since $\Pi_{L,0} = 0$
  - For blazars final $\Pi_L > 0.5$ explained also by hadronic emission model

# Conclusions

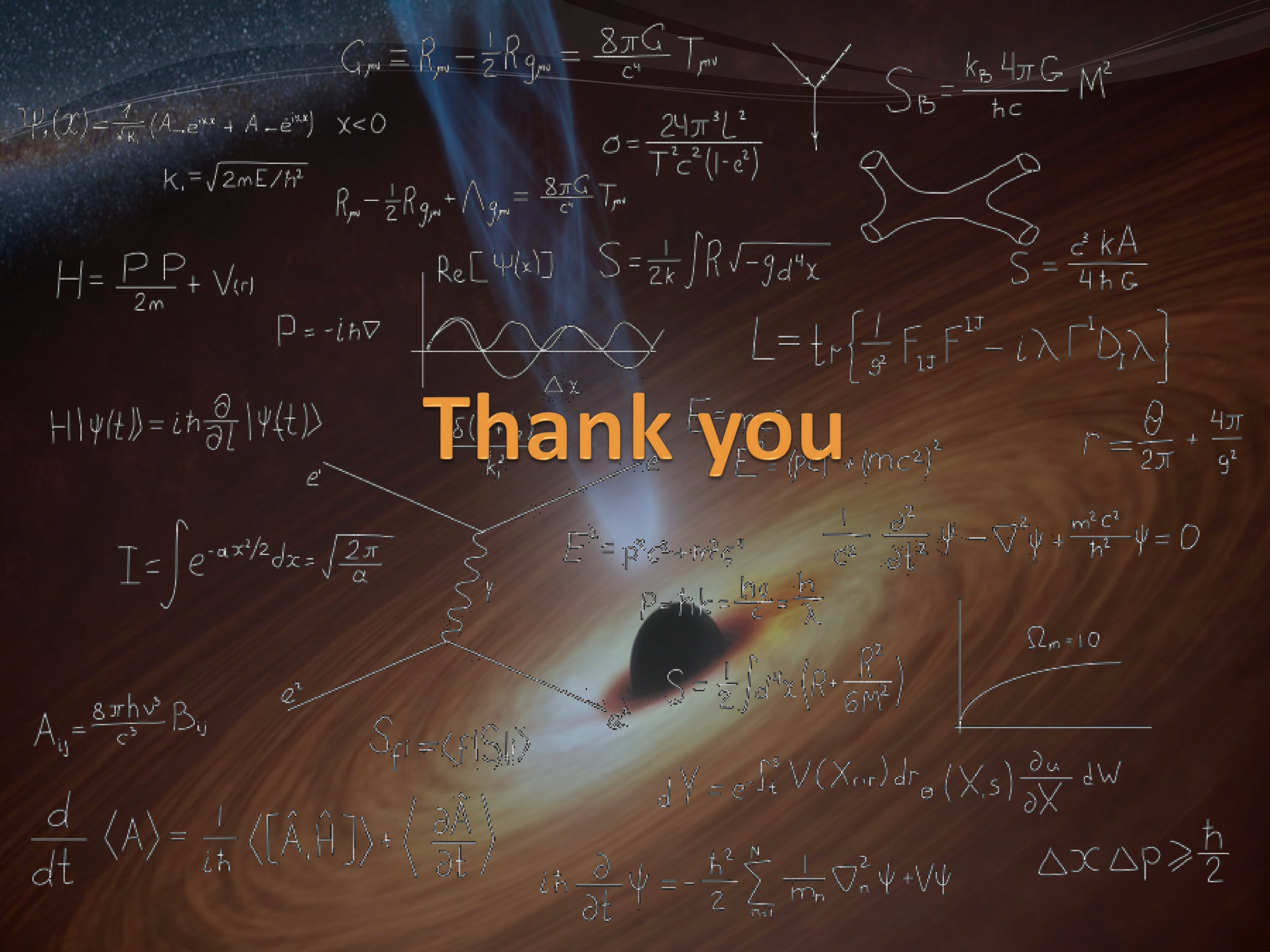
# DO ALPs EXIST?

- We have hints from astrophysical spectra
- We expect additional hints from photon polarization

# FINAL ANSWER:

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

# Thank you



$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$S_B = \frac{k_B 4\pi G}{\hbar c} M^2$
$x<0$
$k_1 = \sqrt{2mE/\hbar^2}$
$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$H = \frac{P P}{2m} + V(r)$
$\mathrm{Re}[\Psi(x)]$
$S = \frac{1}{2k} \int R \sqrt{-g} d^4x$
$S = \frac{c^3 kA}{4\hbar G}$
$P = -i\hbar\nabla$
$\Delta x$
$H|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$
$E = mc^2$
$E^2 = (pc)^2 + (mc^2)^2$
$r = \frac{\theta}{2\pi} + \frac{4\pi}{g^2}$
$I = \int e^{-ax^2/2} dx = \sqrt{\frac{2\pi}{a}}$
$\Omega_m = 1.0$
$A_{ij} = \frac{8\pi h \nu^3}{c^3} B_{ij}$
$S_{fi} = \langle f|S|i\rangle$
$\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [\hat{A}, \hat{H}] \rangle + \left\langle \frac{\partial \hat{A}}{\partial t} \right\rangle$
$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2} \sum_{n=1}^{N} \frac{1}{m_n} \nabla_n^2 \psi + V\psi$
$\Delta x \Delta p \geq \frac{\hbar}{2}$

# Additional content

# Main sequence and evolved stars

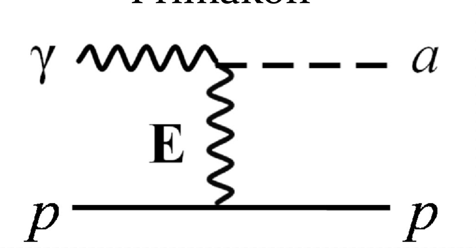
# ALPs from Sun and stellar evolution

**CAST EXPERIMENT:**

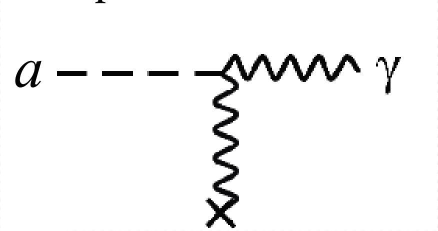
- ALPs produced in the Sun by Primakoff scattering: $p + \gamma \rightarrow p + a$ ($p \rightarrow$ protons or charged particles)
- ALPs reconverted back to photons inside the *B*-field of a magnet at LHC ($\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$)
- **NO DETECTION** $\rightarrow g_{a\gamma\gamma} < 0.66 \times 10^{-10}$ 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: $g_{a\gamma\gamma} < 0.66 \times 10^{-10}$ 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:
  $g_{a\gamma\gamma} < 5.3 \times 10^{-12}$ GeV$^{-1}$ for $m_a < 4.4 \times 10^{-10}$ 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**

$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$S_B = \frac{k_B 4\pi G}{\hbar c} M^2$
$x<0$
$\sigma = \frac{24\pi^3 L^2}{T^2 c^2 (1-e^2)}$
$k_1 = \sqrt{2mE/\hbar^2}$
$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$H = \frac{P P}{2m} + V(r)$
$\mathrm{Re}[\psi(x)]$
$S = \frac{1}{2k} \int R \sqrt{-g}\, d^4x$
$S = \frac{c^3 kA}{4 \hbar G}$
$P = -i\hbar \nabla$
$\Delta x$
$H|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle$
$\frac{\delta(k_1 + k_2)}{k_1^2}$
$E = mc^2$
$E^2 = (pc)^2 + (mc^2)^2$
$r = \frac{\theta}{2\pi} + \frac{4\pi}{g^2}$
$I = \int e^{-ax^2/2} dx = \sqrt{\frac{2\pi}{a}}$
$\gamma$
$\Omega_m = 1.0$
$A_{ij} = \frac{8\pi h \nu^3}{c^3} B_{ij}$
$S_{fi} = \langle f|S|i\rangle$
$\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [\hat{A}, \hat{H}] \rangle + \left\langle \frac{\partial \hat{A}}{\partial t} \right\rangle$
$\Delta x \Delta p \geq \frac{\hbar}{2}$
$i\hbar \frac{\partial}{\partial t} \psi = -\frac{\hbar^2}{2} \sum_{n=1}^{N} \frac{1}{m_n} \nabla_n^2 \psi + V\psi$