# THE AXION CHALLENGE IN GAMMA-RAYS: A BLUEPRINT OF THE BEST SEARCH STRATEGY

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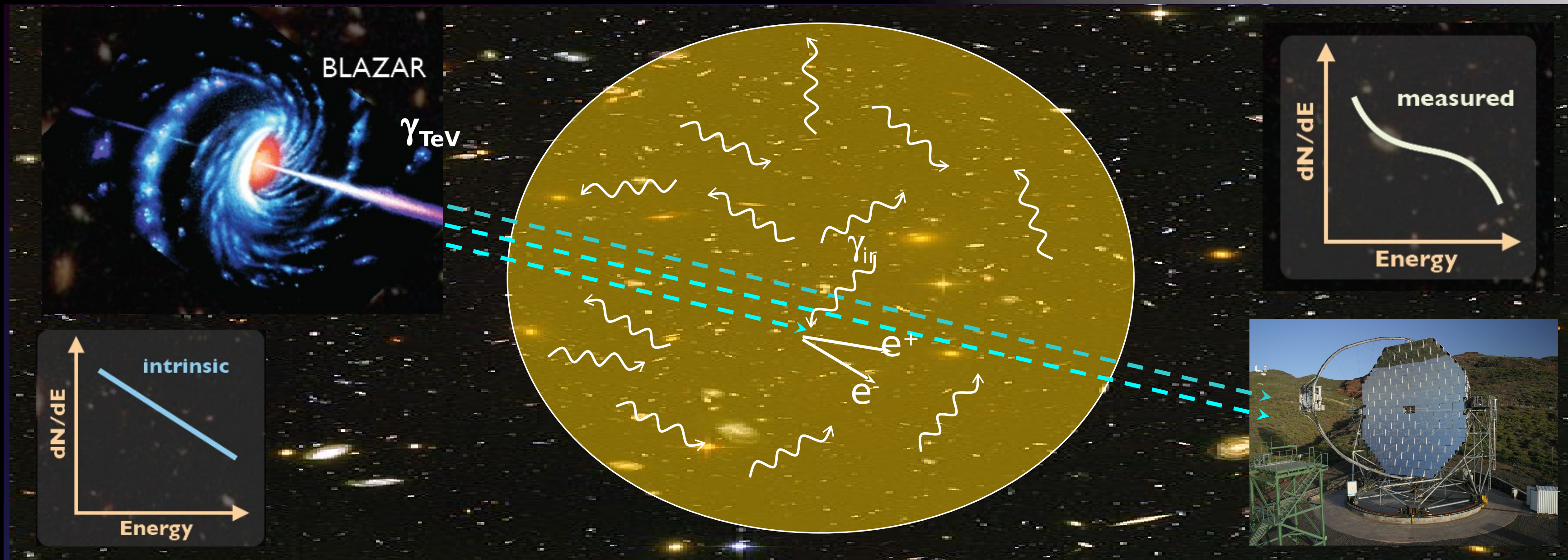
# Intergalactic absorption of VHE photons




*Credit: Mazin & Raue*

Around the TeV region:

$$\lambda \approx 1.24\left(\frac{E}{1TeV}\right)\mu m$$

Infrared/optical background photons:

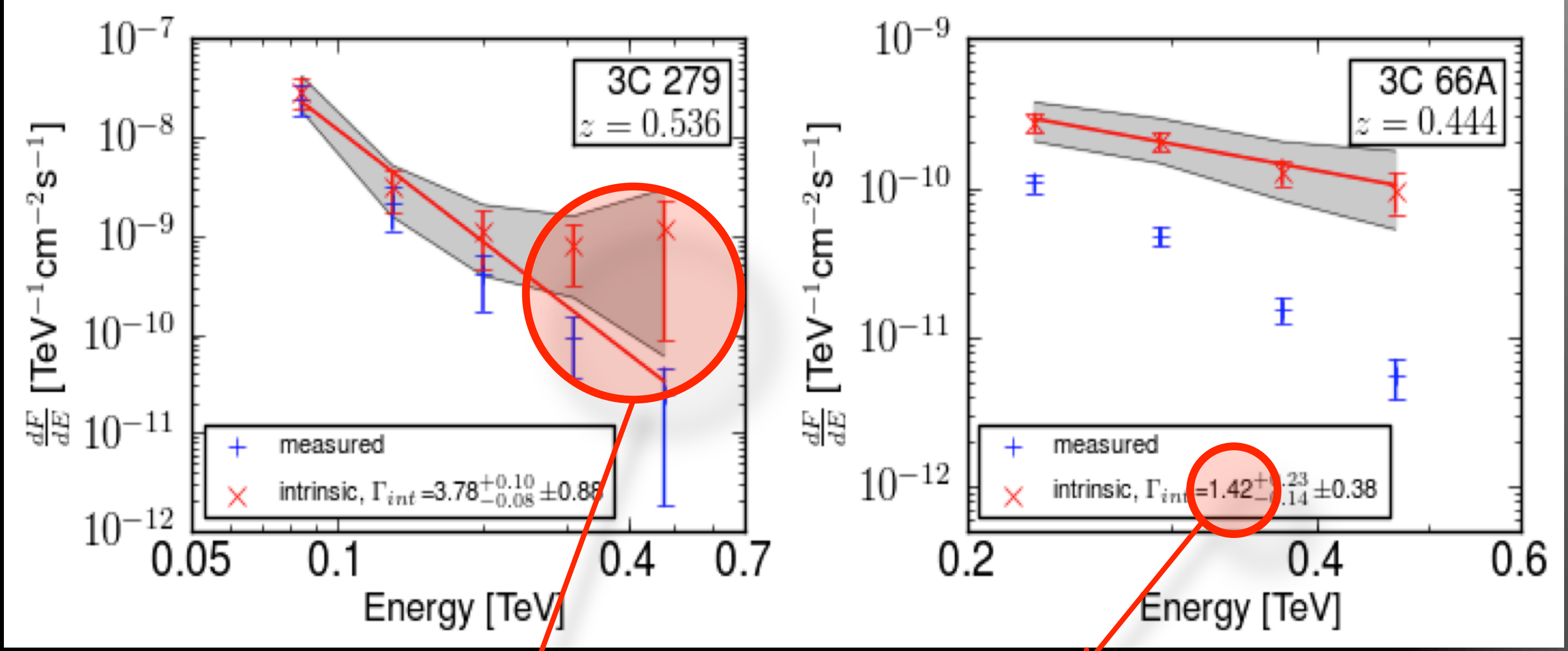
***Extragalactic Background Light (EBL)***

For a source at redshift 0.5 and 0.5 TeV, attenuation ~2 orders of magnitude!!

# Hints for new physics?

- Recent gamma observations might already pose substantial challenges to the conventional models to explain the observed source spectra and/or EBL density.
  - More high energy photons than expected: pile-up problem.
  - Very hard intrinsic spectrum, difficult to explain with conventional EBL models and physics.

[Domínguez et al. 2011]

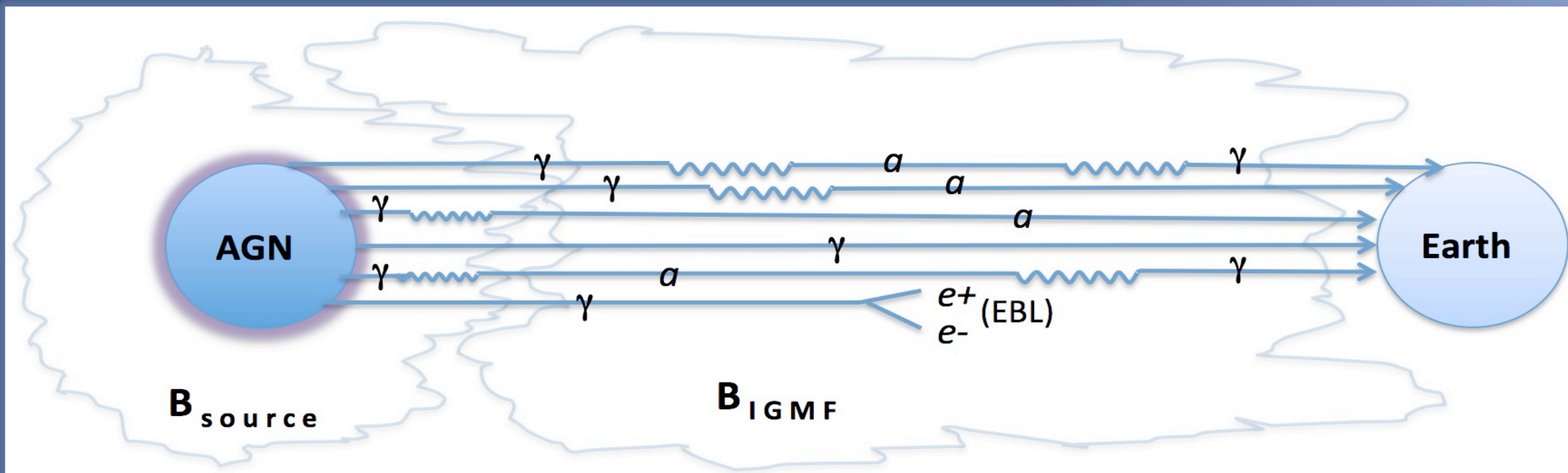



**PILE-UP!**

Modeling of AGN emission mechanisms typically assume **spectral index >1.5**

# Photon/axion conversions in gamma-rays

- Axions (pseudoscalar boson) were postulated to solve the strong-CP problem in the 70s.
- Good Dark Matter candidates
- It is possible to generalize to an axion-like particle (ALP), where mass and coupling are not related.
- ALPs are expected to convert into photons (and viceversa) in the presence of magnetic fields:




[MASC, Paneque, Bloom, Prada and Domínguez, 2009]

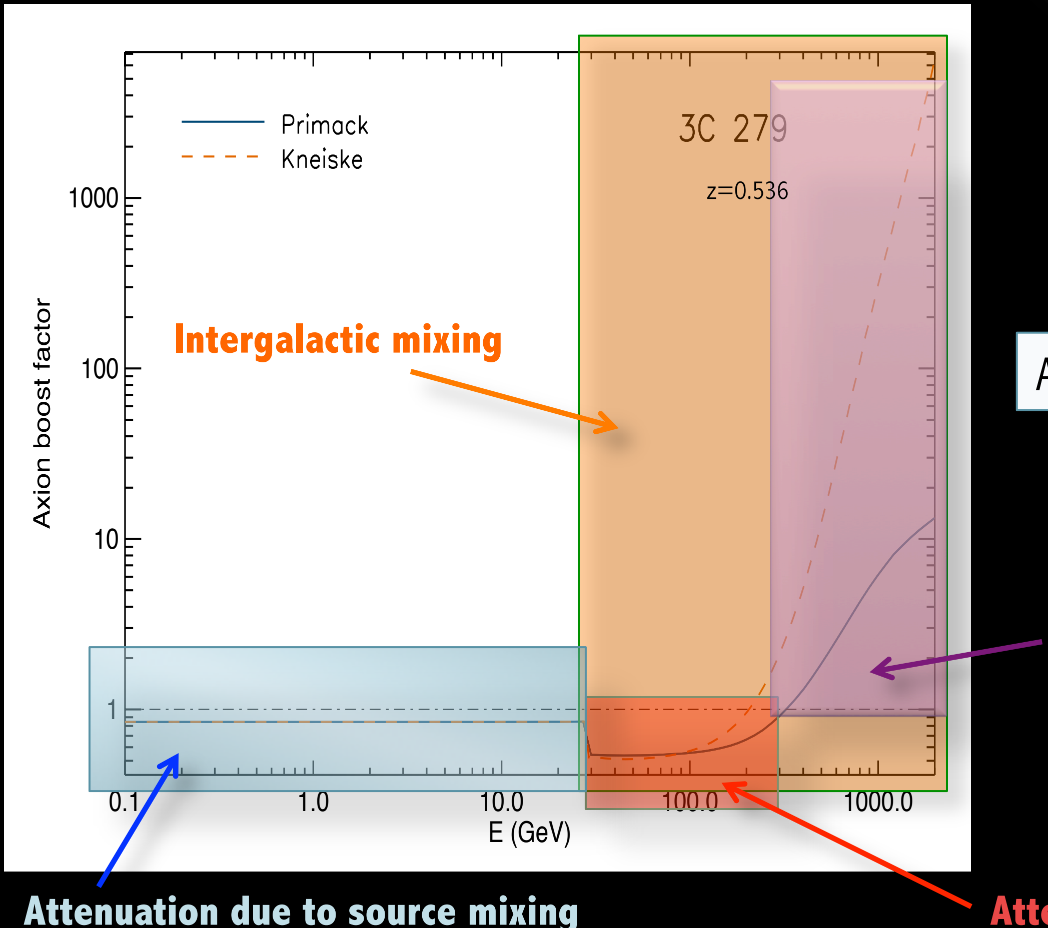
AGNs located at cosmological distances will be affected by:

A. Source mixing (Hooper & Serpico 07): flux attenuation
B. IGM mixing (De Angelis+07): flux attenuation and/or enhancement.

$$E_{crit}(GeV) \equiv \frac{m_{\mu eV}^2 \ M_{11}}{0.4 \ B_G}$$

Gamma-ray energy range ➡ ultralight ALPs.

# Axion boosts




Axion boost =(Flux w axions) / (Flux w/o axions)

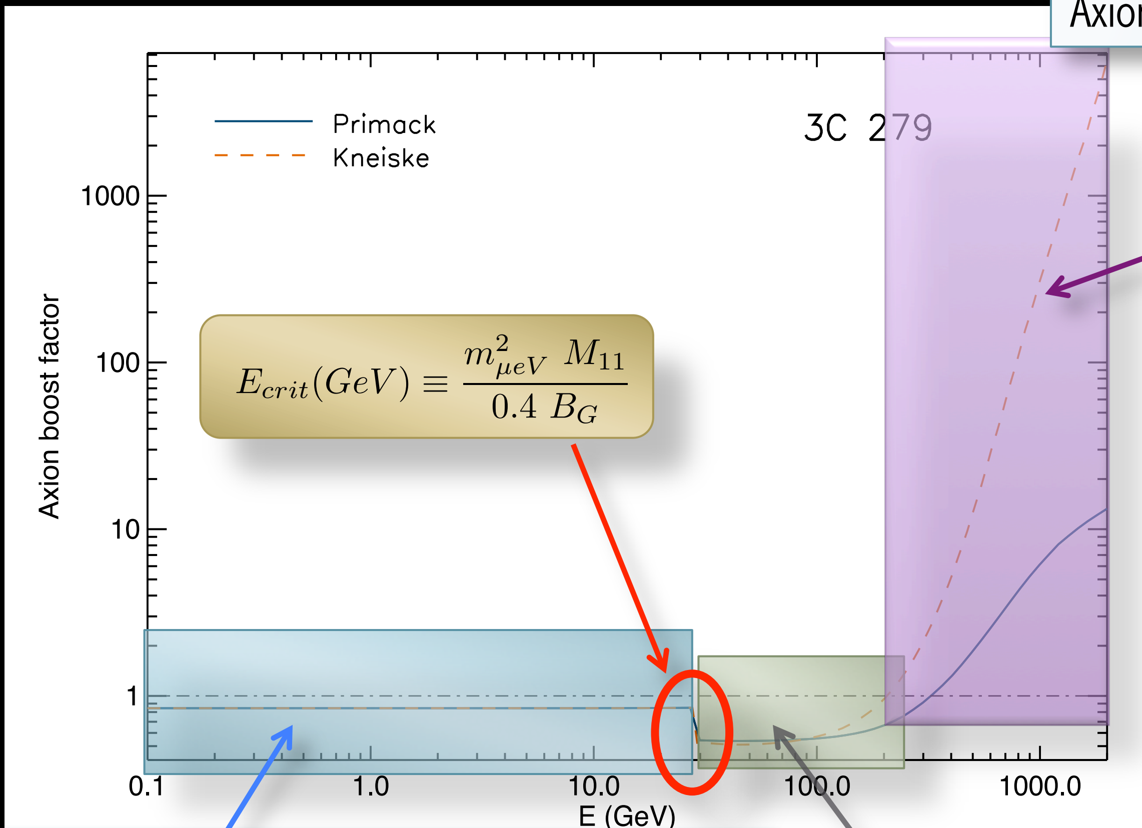
- ✓ Larger axion boosts for distant sources.
- ✓ The more attenuating the EBL, the larger the axion boosts.

[Sánchez-Conde+09]

# Observational strategies with Fermi and IACTs



Axion boost =(Flux w axions) / (Flux w/o axions)




**IACTs observations**

Look for systematic intensity **enhancements** at energies where the EBL is important.

**Distant (z > 0.2) sources** at the highest possible energies (>1 TeV), to push EBL models to the extreme.

**Source and EBL model dependent,** but very important enhancement expected in some cases.

**Fermi/LAT**

Look for intensity **drops** in the residuals ("best-model"-data).

**Source model dependent.**

Powerful, relatively **near** AGNs.

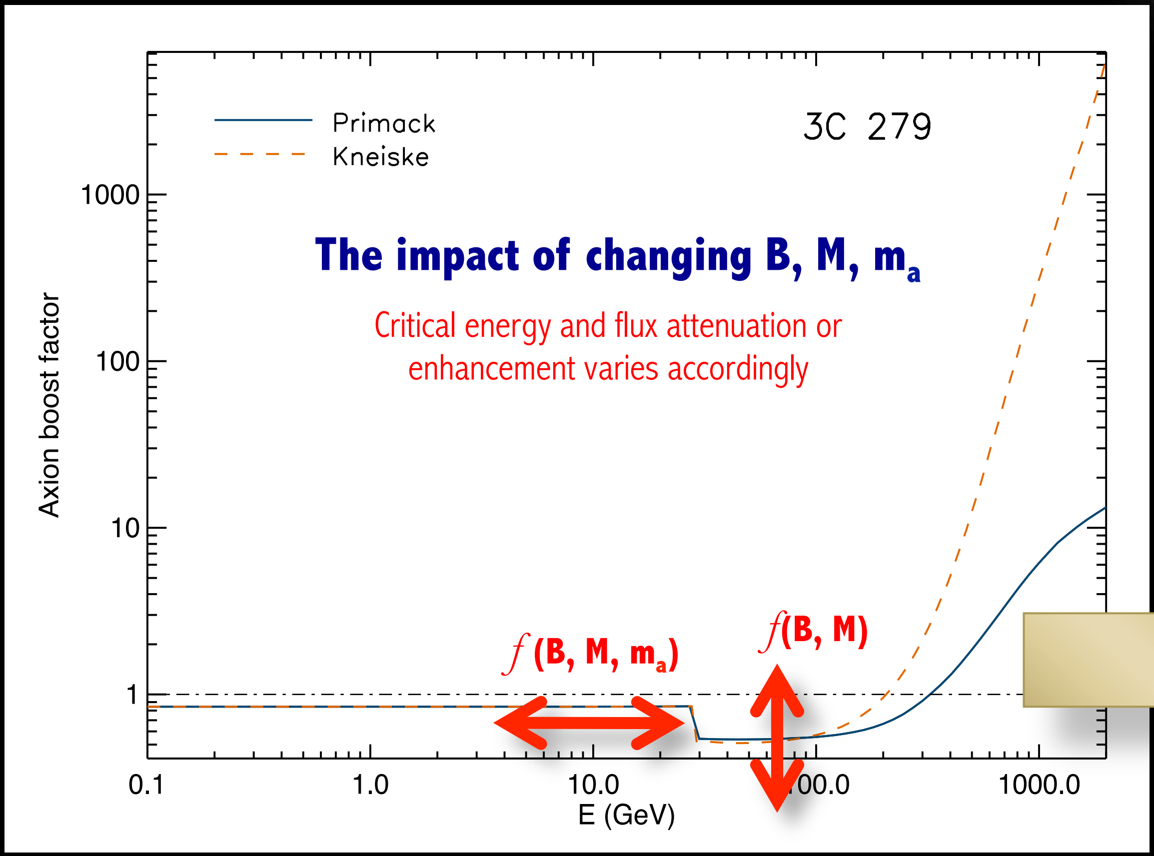
**Fermi/LAT and/or IACTs**

Look for intensity **drops** in the residuals.

Only depends on the IGMF and axion properties (mass and coupling constant).

**Independent of the sources -> CLEAR signature!**

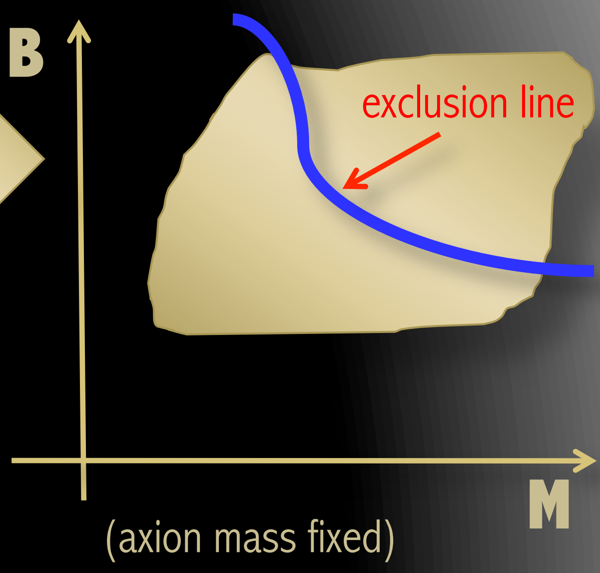
# $E_{crit}$ -based search strategy




$$E_{crit} \propto \frac{m_a^2 \cdot M_{11}}{B_G}$$

$$mixing \propto B_G \cdot M_{11}$$

1. Search of the systematic drop at the same (critical) energy
2. Stacking analysis using different sources and observational periods
3. In parallel, performance simulations.
4. Detection? If not, constrains on the parameter space



# ALPs and the PILE-UP problem

More high energy photons than expected at the highest energies: deviation from a power-law?

★ **Working hypothesis:**

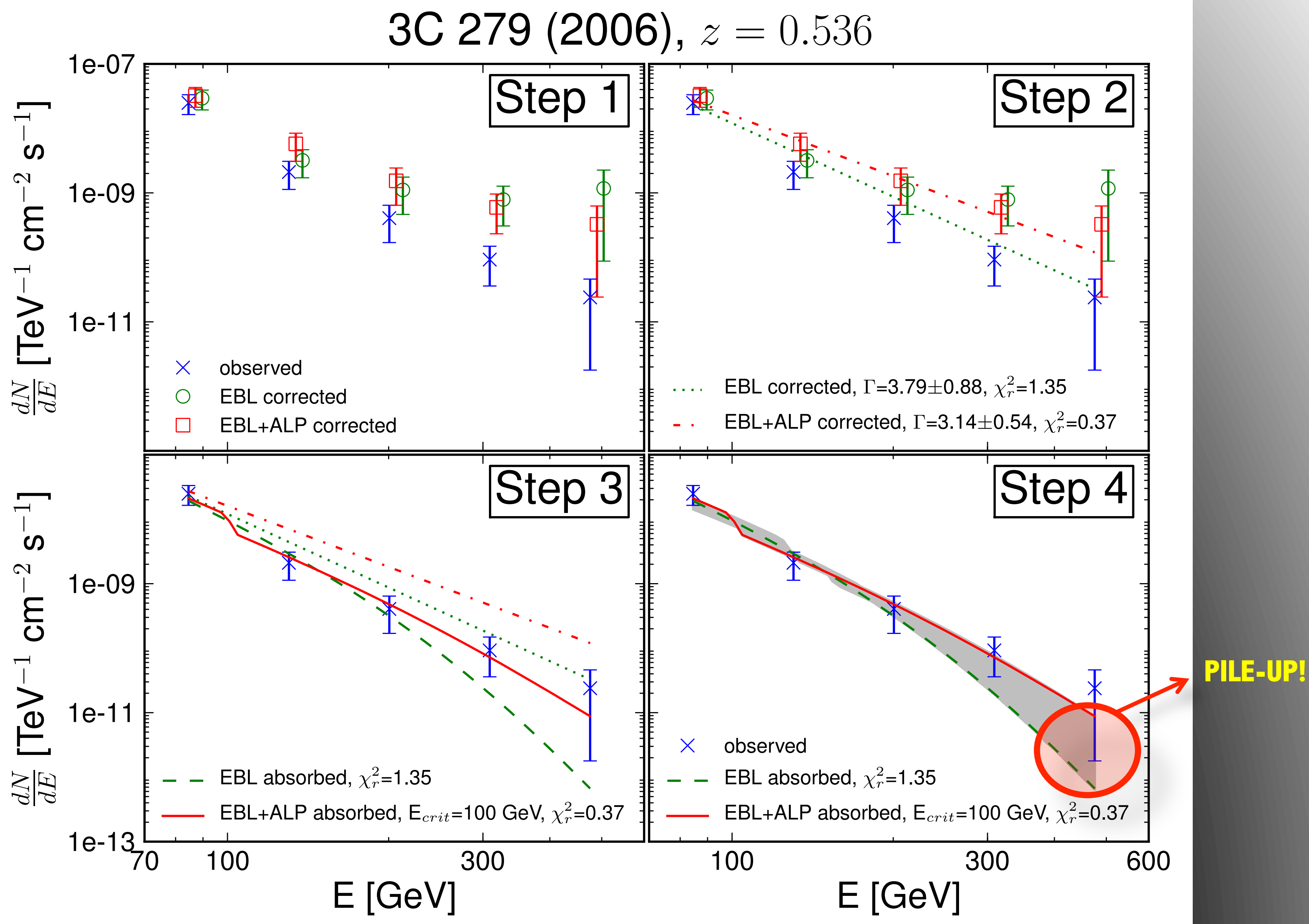
1) Intrinsic spectra of AGNs are well-described by power laws.

2) $M_{11}$ has an optimistic value but still within experimental limits.

3) $E_{crit}$ for the intergalactic mixing is within the energy range of present IACTs.

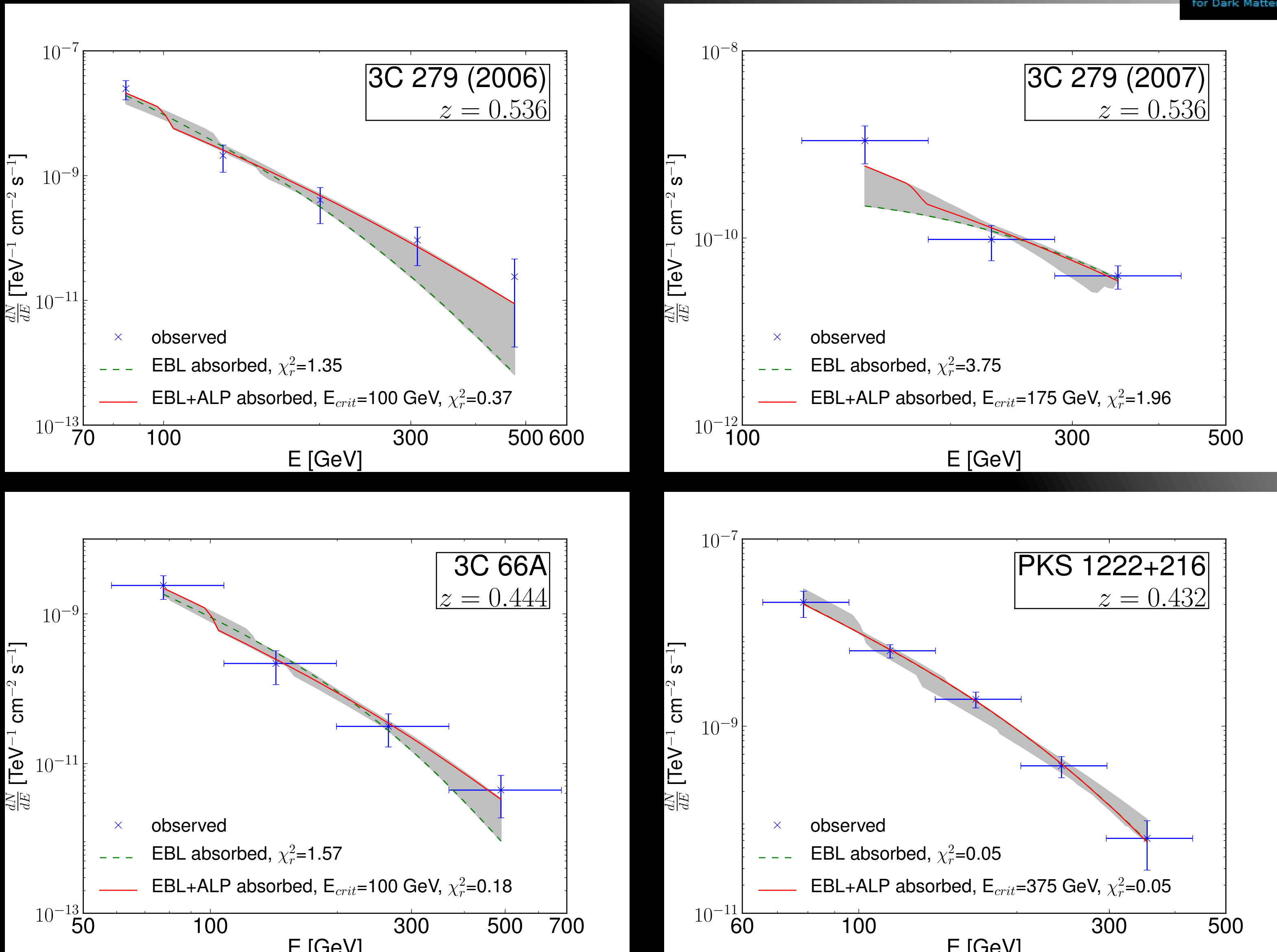
4) The EBL is well described by the Dominguez+11 EBL model.

Source modeling using multi-wavelength SSC fits available in the literature.




[Domínguez, MASC & Prada, submitted]

MULTIDARK
Multimessenger Approach for Dark Matter Detection

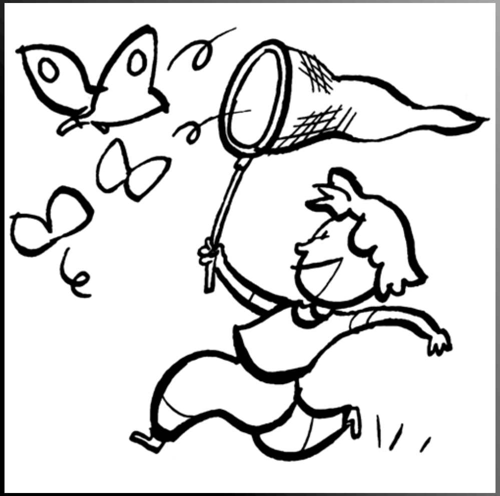



- Similar critical energies, i.e. similar ALP and IGMF properties

MULTIDARK
Multimessenger Approach for Dark Matter Detection

# MultiDarkians hunting axions

(high and low!)



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4. Mattia Fornasa (IAA/CSIC & MultiDark fellow)
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6. Ji Haeng Huh (IFT UAM/CSIC)
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8. Abelardo Moralejo (IFAE)
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10. María Ángeles Pérez García (USAL)
11. Francisco Prada (IAA/CSIC)
12. Oriol Pujolas (IFAE)
13. Miguel A. Sánchez-Conde (IAC)
14. Konstancja Satalecka (UCM-GAE & MultiDark fellow)
15. Fabio Zandanel (IAA/CSIC)

# ALP search already ongoing in MultiDark

1. Two strategies are being explored:
   - Systematic intensity enhancements at the highest possible energies.
   - Intensity drops at the same critical energy for all sources.

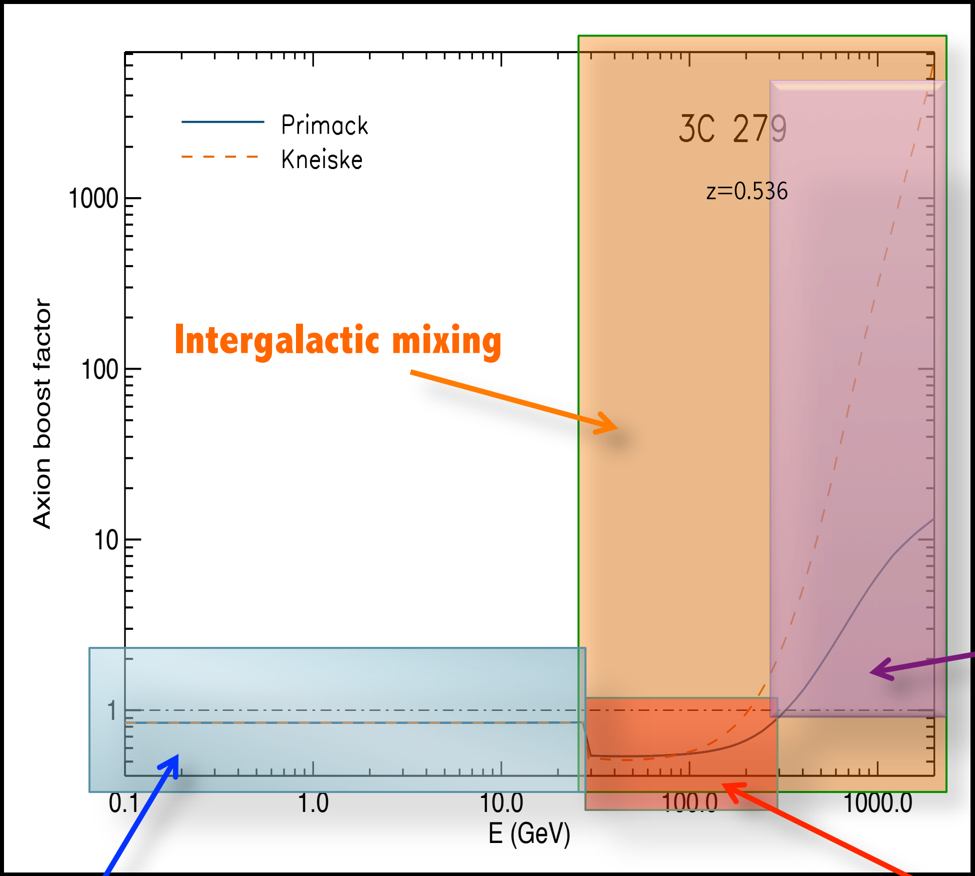
2. Study of MAGIC and CTA capabilities using performance simulations.

3. A Fermi-MultiDark proposal is under negotiation for a joint effort with Fermi guys.

# BACKUP

## Additional material

# Axion boosts




Axion boost =(Flux w axions) / (Flux w/o axions)

**Enhancement due to intergalactic mixing**

**Attenuation due to source mixing**

**Attenuation due to intergalactic mixing**

- ✓ Larger axion boosts for distant sources.
- ✓ The more attenuating the EBL, the larger the axion boosts.

[Sánchez-Conde+09]

# Hints for new physics?

- Recent gamma observations might already pose substantial challenges to the conventional models to explain the observed source spectra and/or EBL density.
  - The VERITAS Collaboration recently claimed a detection above 0.1 TeV coming from 3C66A ($z=0.444$). EBL-corrected spectrum harder than 1.5 (Acciari+09).
  - TeV photons coming from 3C 66A? (Neshpor+98; Stepanyan+02). Difficult to explain with conventional EBL models and physics.
  - The lower limit on the EBL at 3.6 $\mu$m was recently revised upwards by a factor ~2, suggesting a more opaque universe (Levenson+08).
  - Some sources at $z = 0.1 - 0.2$ seem to have harder intrinsic energy spectra than previously anticipated (Krennrich+08).

- While it is still possible to explain the above points with conventional physics (EBL, very hard spectrum), the axion/photon oscillation would naturally explain these puzzles:
  - More high energy photons than expected.
  - Softer intrinsic spectrum when including axions.

# Photon/axion oscillations

- Axions were postulated to solve the strong CP problem in the 70s.
- Good Dark Matter candidates (axions with masses ≈ meV-μeV could account for the total Dark Matter content).
- They are expected to oscillate into photons (and viceversa) in the presence of magnetic fields:

$$\boxed{P_0 = (\Delta_B s)^2 \frac{\sin^2(\Delta_{\rm osc} s/2)}{(\Delta_{\rm osc} s/2)^2}.}$$

with

$$\left\{\begin{array}{l} \Delta_B = \dfrac{B_t}{2M} \simeq 1.7 \times 10^{-21} M_{11} B_{\rm mG} \ {\rm cm}^{-1}, \\ \Delta_{\rm osc}^2 \simeq (\Delta_{\rm CM} + \Delta_{\rm pl} - \Delta_a)^2 + 4\Delta_B^2, \end{array}\right.$$

Photon/axion oscillations are the main vehicle used at present in axion searches (ADMX, CAST…).

Some astrophysical environments fulfill the mixing requirements

**AGNs, IGMFs**

$$\frac{15 \cdot B_G \cdot s_{pc}}{M_{11}} \geq 1$$

$M_{11} \geq 0.114$ GeV (CAST limit)

- $M_{11}$: coupling constant inverse ($g_{\alpha\gamma}/10^{11}$ GeV)
- $B_G$: magnetic field (G)
- $s_{pc}$: size region (pc)

# Photon/axion oscillations

$$\boxed{P_0 = (\Delta_B s)^2 \frac{\sin^2(\Delta_{\rm osc} s/2)}{(\Delta_{\rm osc} s/2)^2}.}$$

with

$$\Delta_B = \frac{B_t}{2M} \simeq 1.7 \times 10^{-21} M_{11} B_{\rm mG}\ {\rm cm}^{-1},$$

$$\Delta_{\rm osc}^2 \simeq (\Delta_{\rm CM} + \Delta_{\rm pl} - \Delta_a)^2 + 4\Delta_B^2,$$

$$\Delta_a = \frac{m_a^2}{2E_\gamma} \simeq 2.5 \times 10^{-20} m_{a,\mu{\rm eV}}^2 \left(\frac{\rm TeV}{E_\gamma}\right)\ {\rm cm}^{-1}$$

$$\Delta_{\rm pl} = \frac{w_{\rm pl}^2}{2E} \simeq 3.5 \times 10^{-20} \left(\frac{n_e}{10^3\ {\rm cm}^{-3}}\right)\left(\frac{\rm TeV}{E_\gamma}\right)\ {\rm cm}^{-1}$$

$$\Delta_{\rm CM} = -\frac{\alpha}{45\pi}\left(\frac{B_t}{B_{\rm cr}}\right)^2 E_\gamma \simeq -1.3 \times 10^{-21} B_{\rm mG}^2 \left(\frac{E_\gamma}{\rm TeV}\right)\ {\rm cm}^{-1}$$

$$\frac{15 \cdot B_G \cdot s_{pc}}{M_{11}} \geq 1$$

- $M_{11}$: coupling constant inverse ($g_{\alpha\gamma}/10^{11}$ GeV)
- $B_G$: magnetic field (G)
- $s_{pc}$: size region (pc)

# Mixing in astrophysical environments

- Some astrophysical environments fulfill the mixing requirements:

$$\frac{15 \cdot B_G \cdot s_{pc}}{M_{11}} \geq 1$$

$M_{11} \geq 0.114$ GeV (CAST limit)

Astrophysical sources with $B_G \cdot s_{pc} \geq 0.01$ will be valid.

$B_G \cdot s_{pc}$ also determines the Emax to which sources can accelerate cosmic rays:

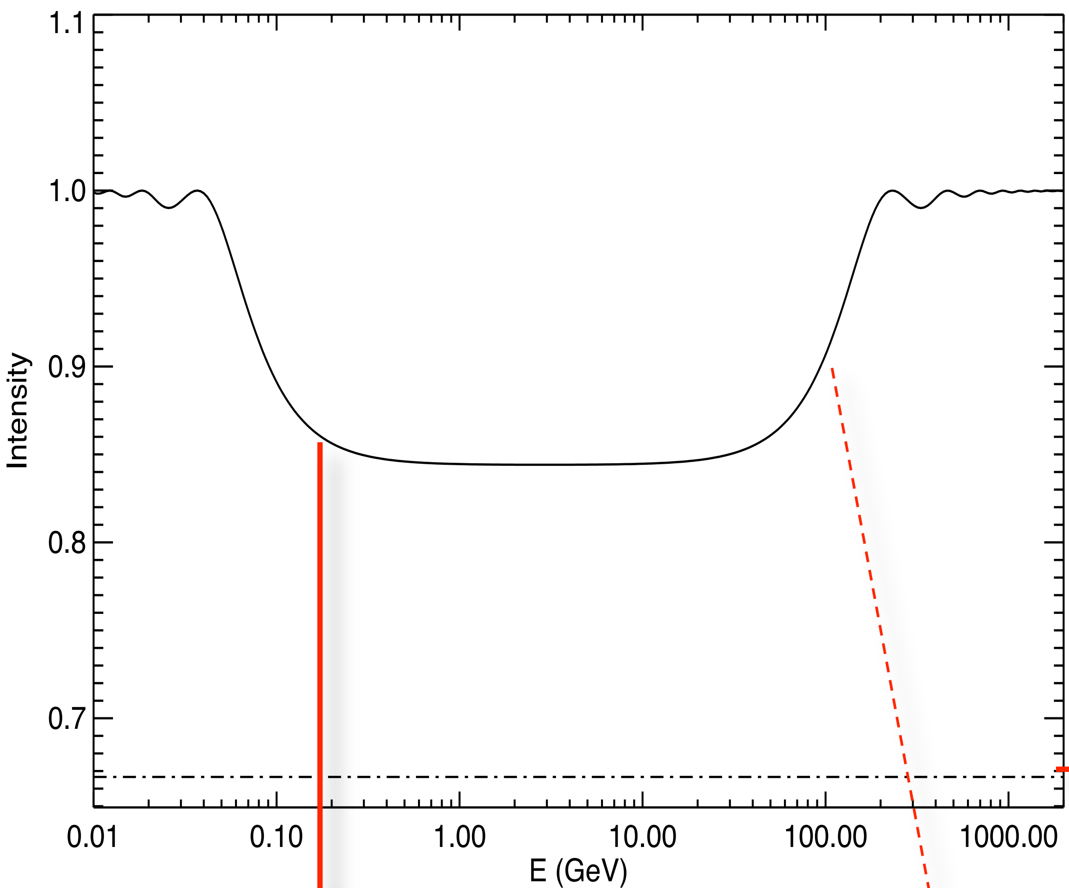
$E_{max} = 9.3 \cdot 10^{20} \cdot B_G \cdot s_{pc}$ eV (**Hillas criterion)**

We observe cosmic rays up to $3 \cdot 10^{20}$ eV -> $B_G \cdot s_{pc}$ up to 0.3 must exist!

In **IGMFs**, $B_G \approx 10^{-9}$ -> Mixing also possible for cosmological distances ($s_{pc} \geq 10^8$)

- Important implications for astronomical observations (AGNs, pulsars, GRBs…).

# Mixing in the source




The main effect is an **ATTENUATION** of the photon flux above the critical energy:

$$E_{crit}(GeV) \equiv \frac{m^2_{\mu eV}\; M_{11}}{0.4\; B_G}$$

For typical A[redacted] the effect is present in **gamma-ra**[redacted]**on masses ≈ $10^{-6}$ eV**

Ma[redacted]

att[redacted]

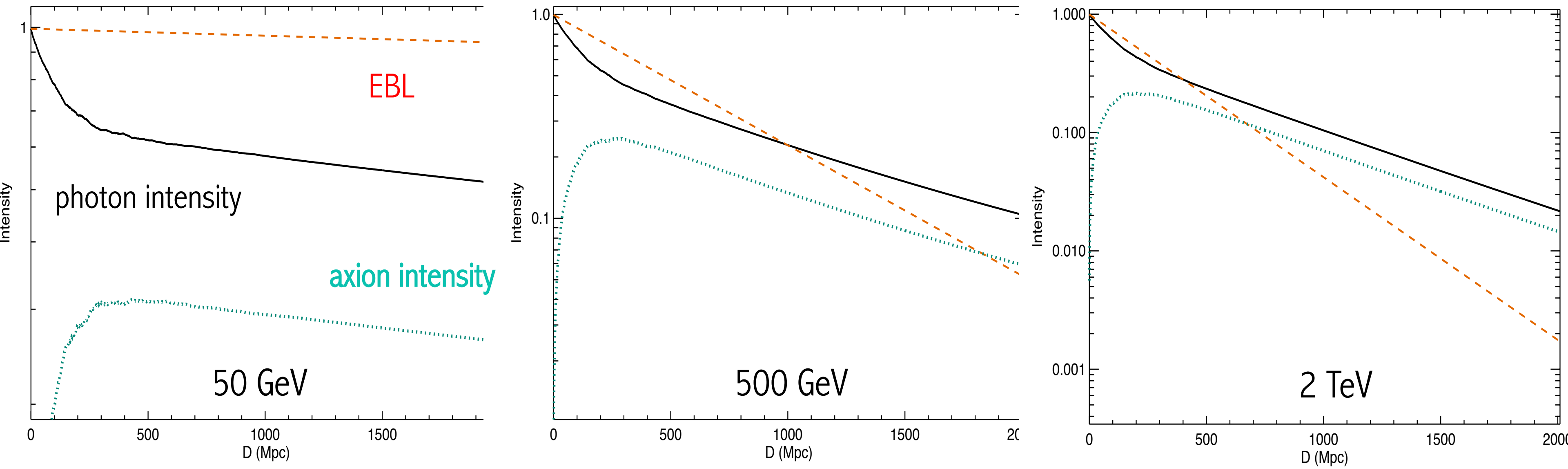
# Variation of source attenuation with the size domain

TABLE I: Maximum attenuations due to photon/axion oscillations in the source obtained for different sizes of the region where the magnetic field is confined ("B region") and different lengths for the coherent domains. Only length domains smaller than the size of the **B** region are possible. The **B** field strength used is 1.5 G (see Table II). The photon flux intensity without ALPs was normalized to 1. In bold face, is the attenuation given by our fiducial model.

| B region (pc) | Length domains (pc) | | | |
|---|---|---|---|---|
| | $3\times10^{-4}$ | $3\times10^{-3}$ | 0.03 | 0.3 |
| 0.3 | 0.84 | 0.67 | 0.67 | 0.75 |
| 0.03 | 0.98 | **0.84** | 0.77 | - |
| $3\times10^{-3}$ | 0.99 | 0.98 | - | - |

# Mixing in the IGMF

- We compute the photon/axion mixing in N coherent domains with equal size and random B orientation.
- The **EBL** introduces an additional absorption. The more attenuating the EBL, the more important the mixing in the final intensity.




*B=1 nG; $M_{11}$=0.7 GeV; D=2 Gpc, $L_{dom}$=1 Mpc; Primack EBL model*

The effect can be an **ATTENUATION** or an **ENHANCEMENT** of the photon flux, depending on distance, B field and EBL model considered.

The effect will be present in the gamma-ray band for **axion masses ≈ $10^{-10}$ eV**

# IGMF mixing equations

$$\begin{pmatrix}\gamma_x\\ \gamma_z\\ a\end{pmatrix} = \mathrm{e}^{iEy}\left[T_0\,\mathrm{e}^{\lambda_0 y} + T_1\,\mathrm{e}^{\lambda_1 y} + T_2\,\mathrm{e}^{\lambda_2 y}\right]\begin{pmatrix}\gamma_x\\ \gamma_z\\ a\end{pmatrix}_0$$

$$\begin{aligned}
\lambda_0 &\equiv -\frac{1}{2\;\lambda_\gamma},\\
\lambda_1 &\equiv -\frac{1}{4\lambda_\gamma}\;\left[1+\sqrt{1-4\;\delta^2}\right]\\
\lambda_2 &\equiv -\frac{1}{4\;\lambda_\gamma}\;\left[1-\sqrt{1-4\;\delta^2}\right]
\end{aligned}$$

No plasma term
No CM term
Only $\Delta_B$

$$\delta \equiv \frac{B\,\lambda_\gamma}{M}$$

$$T_0 \equiv \begin{pmatrix} \sin^2\theta & -\cos\theta\sin\theta & 0\\ -\cos\theta\sin\theta & \cos^2\theta & 0\\ 0 & 0 & 0\end{pmatrix} \qquad T_1 \equiv \begin{pmatrix} \frac{1+\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\cos^2\theta & \frac{1+\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\cos\theta\sin\theta & -\frac{\delta}{\sqrt{1-4\,\delta^2}}\cos\theta\\ \frac{1+\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\cos\theta\sin\theta & \frac{1+\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\sin^2\theta & -\frac{\delta}{\sqrt{1-4\,\delta^2}}\sin\theta\\ \frac{\delta}{\sqrt{1-4\,\delta^2}}\cos\theta & \frac{\delta}{\sqrt{1-4\,\delta^2}}\sin\theta & -\frac{1-\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\end{pmatrix}$$

$$T_2 \equiv \begin{pmatrix} -\frac{1-\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\cos^2\theta & -\frac{1-\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\cos\theta\sin\theta & \frac{\delta}{\sqrt{1-4\,\delta^2}}\cos\theta\\ -\frac{1-\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\cos\theta\sin\theta & -\frac{1-\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\sin^2\theta & \frac{\delta}{\sqrt{1-4\,\delta^2}}\sin\theta\\ -\frac{\delta}{\sqrt{1-4\,\delta^2}}\cos\theta & -\frac{\delta}{\sqrt{1-4\,\delta^2}}\sin\theta & \frac{1+\sqrt{1-4\,\delta^2}}{2\,\sqrt{1-4\,\delta^2}}\end{pmatrix}$$

# Two examples: 3C279 and PKS 2155-304

| | Parameter | 3C 279 | PKS 2155-304 |
|---|---|---|---|
| Source parameters | B (G) | 1.5 | 0.1 |
| | $e_d$ ($cm^{-3}$) | 25 | 160 |
| | L domains (pc) | 0.003 | $3 \times 10^{-4}$ |
| | B region (pc) | 0.03 | 0.003 |
| Intergalactic parameters | z | 0.536 | 0.117 |
| | $e_{d,int}$ ($cm^{-3}$) | $10^{-7}$ | $10^{-7}$ |
| | $B_{int}$ (nG) | 0.1 | 0.1 |
| | L domains (Mpc) | 1 | 1 |
| ALP parameters | M (GeV) | $1.14 \times 10^{10}$ | $1.14 \times 10^{10}$ |
| | ALP mass (eV) | $10^{-10}$ | $10^{-10}$ |

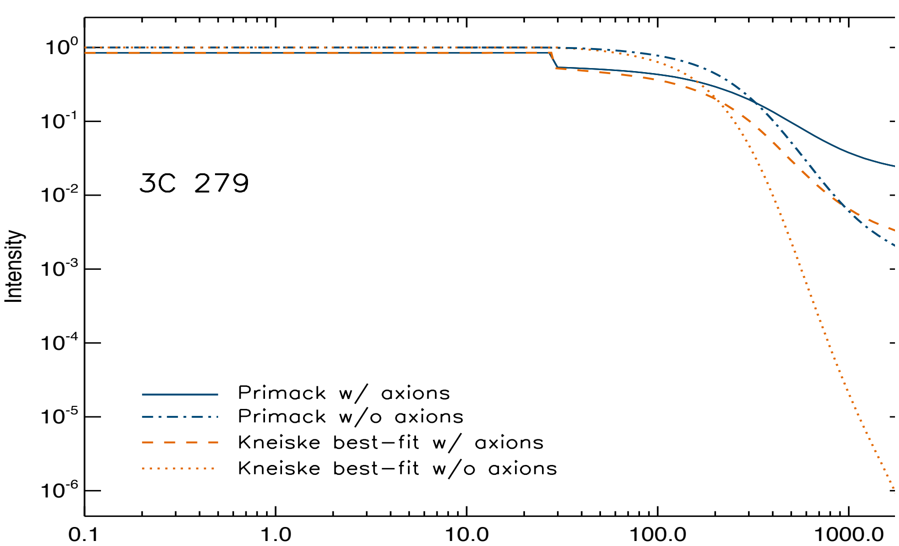
$E_{crit,source}(3C) = 4.6$ eV

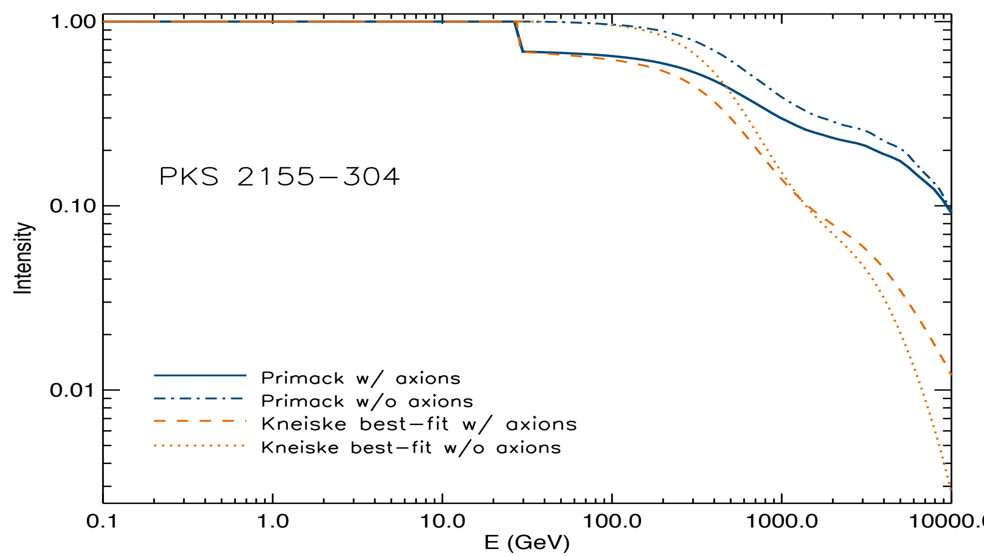
$E_{crit,source}(PKS) = 69$ eV

$E_{crit,interg} = 28.5$ GeV (**both**)

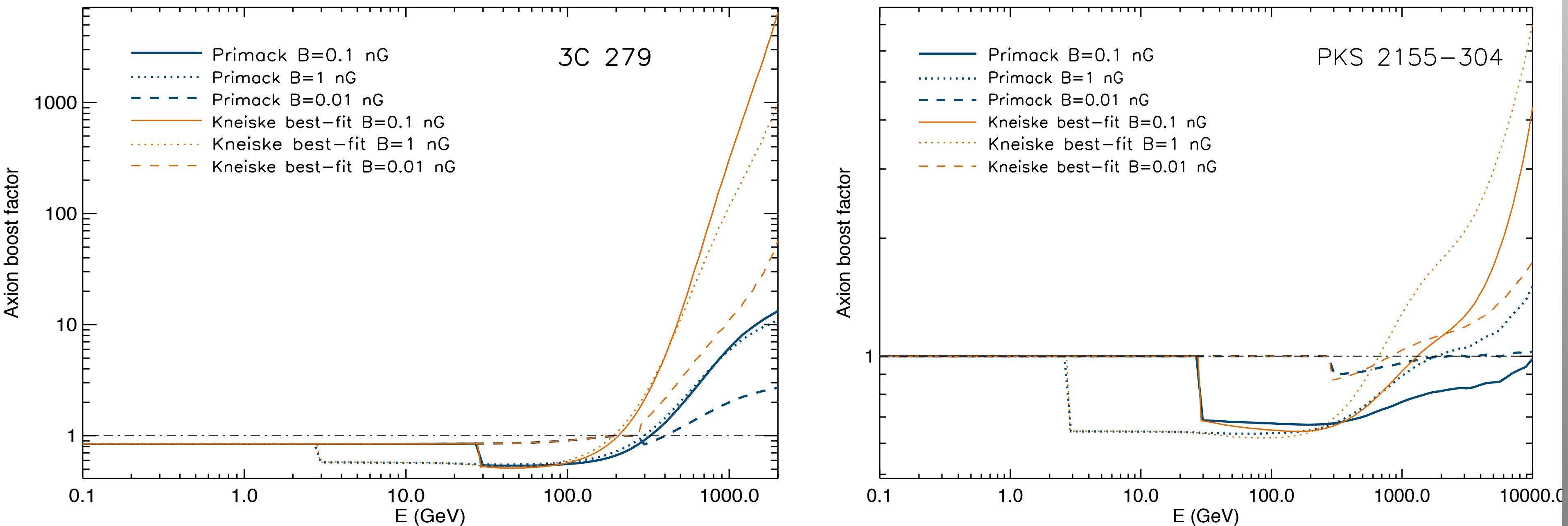
CAST limit

ultralight axions



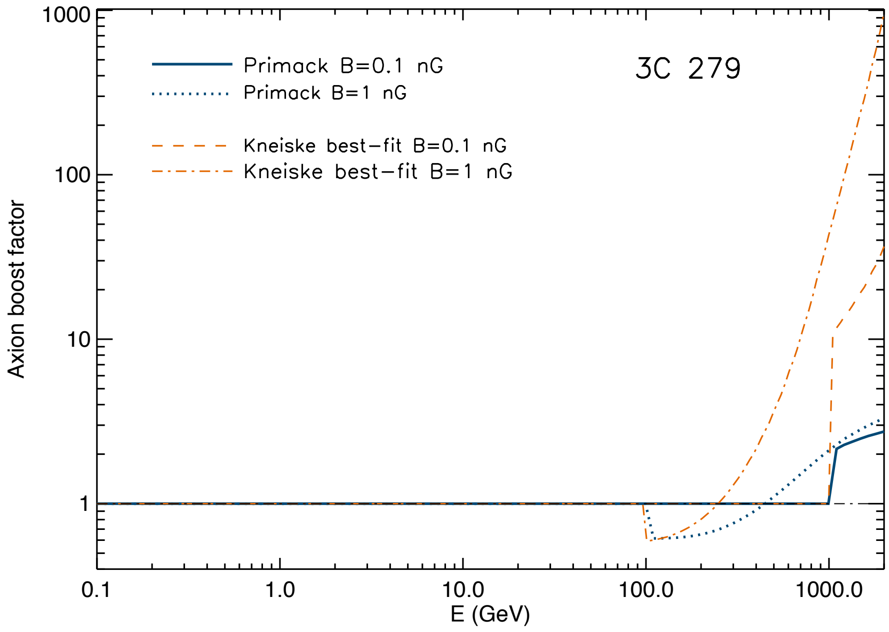



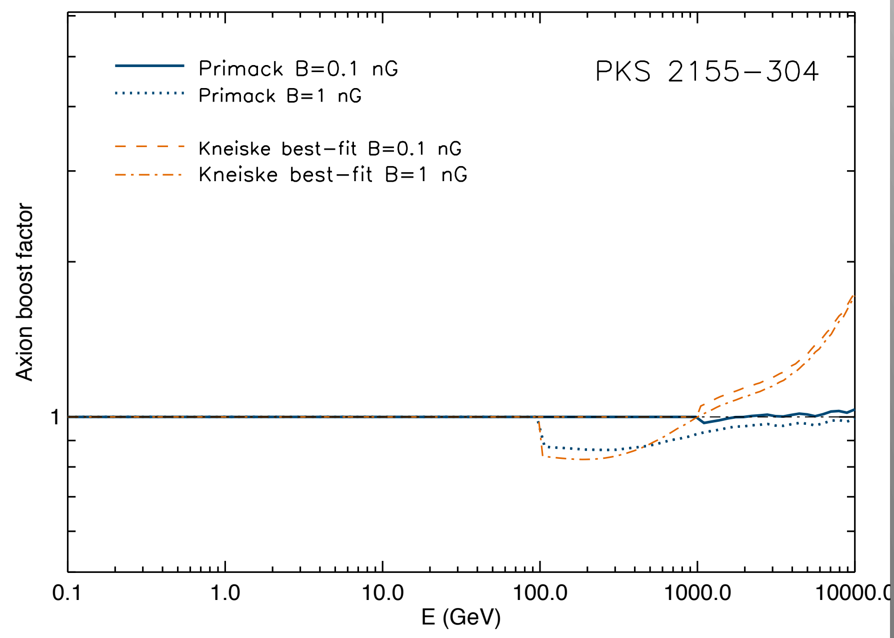
# The impact of changing B




- The critical energy varies accordingly.
- **For distant sources, weaker intergalactic B fields could lead to higher axion boosts**.

# M=4e11 GeV
# i.e. SN1987A coupling constant



# Future of ALP searches in $\gamma$-rays

- If axions exist, they could **distort the spectra** of astrophysical sources importantly.
- If there is mixing in the IGMFs, then also mixing in the source. **If $m_{axion} \approx 10^{-10}$ eV -> $\gamma$-rays**.
- The effect is expected to be present over several decades in energy -> **joint effort of Fermi and current IACTs** needed.
- **Detailed observations of AGNs** at different redshifts and different flaring states could be used to identify the signature of an effective photon/axion mixing.
- Main **caveats**: the effect of photon/axion oscillations could be attributed to conventional physics in the source and/or propagation of the gamma-rays towards the Earth.
- However, **detailed observations of AGNs** at different redshifts and different flaring states could be used to identify the signature of an effective photon/axion mixing.