

# **Study of indirect detection of Axion-Like-Particles with the Fermi-LAT instrument and Imaging Atmospheric Cherenkov Telescopes**

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and

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## **1 – Axion-Like-Particle phenomenology**

**Oscillation photon-ALP in astrophysical-sources**

**Oscillation photon-ALP in the Intergalactic medium**

## **2 – Signatures of ALPs in spectra of gamma-ray sources**

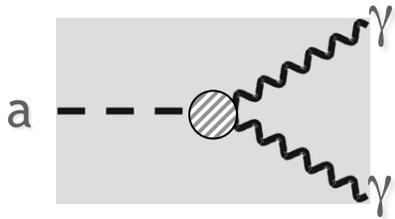
## **3 - Prescription for Indirect detection of ALPs with Fermi and IACTs**

## **4 - Conclusions**

# 1 - Axion-Like-Particle phenomenology

## Coupling with photons

Axions are expected from the Peccei-Quinn mechanism, which is the preferred mechanism to solve the CP-problem in QCD



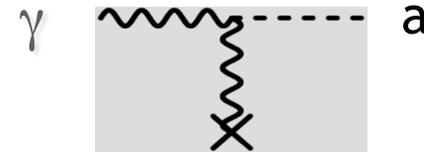
Two-photon coupling:

$$g_{a\gamma} \sim k m_a$$

Axion-like particles (ALPs) are light particles with a two-photon coupling  $g_{a\gamma}$  with no specific relation with  $m_a$ . ALPs arise in theories with extra dimensions, string-inspired models, etc., but can be discussed in a phenomenological way

## Solar and stellar ALPs

ALPs produced in stars, e.g. Primakoff production



- Search for solar ALPs (CAST)

$$g_{a\gamma} < 9 \times 10^{-11} \text{ GeV}^{-1}$$

## Photon-ALP oscillation

In an external magnetic field, there is a mixing between ALPs and the photon polarization component along the field direction.

**Important consequences for  
γ-ray astronomy**

# 1 - Axion-Like-Particle phenomenology

For a photon propagating in a domain of size  $s$  with uniform field  $B$  polarized along its direction, a neutrino-like oscillation probability formula holds

$$P_{osc} = \sin^2(2\theta) \sin^2 \left[ \frac{g_{a\gamma} B s}{2} \sqrt{1 + \left( \frac{K}{E} \right)^2} \right]$$
$$\sin^2(2\theta) = \frac{1}{1 + (K/E)^2} \quad K = \frac{m^2}{2g_{a\gamma} B}$$

Large phases (=large conversions)  $15 g_{11} B_G s_{pc} \geq 1$   $g_{11} = g_{a\gamma} / 10^{-11} \text{ GeV}^{-1}$

$B_G s_{pc}$  also determines maximum energy ( $E_{max}$ ) to which sources can confine and accelerate cosmic rays; “Hillas criterion”  $E_{max} \sim 9 \times 10^{20} \text{ eV } B_G s_{pc}$

Since cosmic rays have been detected up to energies of  $3 \times 10^{20} \text{ eV}$ , sources with  $B_G s_{pc} \geq 0.3$  MUST exist.

**$g_{11} \gtrsim 0.1$  can be probed in “hillas sources”**

# 1 - Axion-Like-Particle phenomenology

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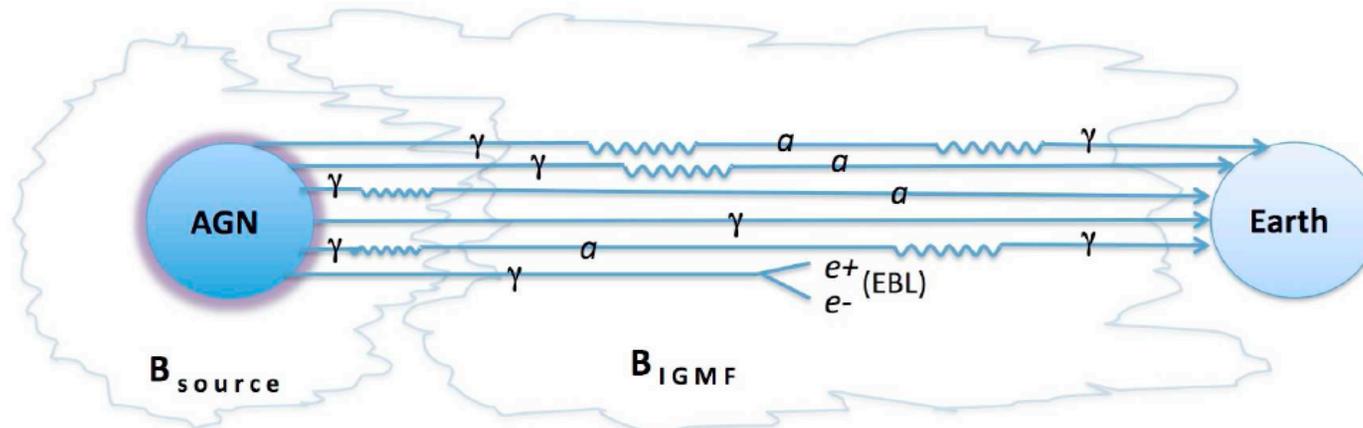
Large phases (=large conversions)  $15 g_{11} B_G s_{pc} \geq 1$   $g_{11} = g_{a\gamma} / 10^{-11} \text{ GeV}^{-1}$

*In the Intergalactic Magnetic field (IGMF)  $B_G \leq 1 \text{ nG}$ . Photon-ALP oscillation can only occur if sources located far away:  $s_{pc} \geq 10^8 - 10^9 \text{ pc}$*

**$g_{11} > \sim 0.1$  can be probed with Gpc sources (if  $B_{IGMF} \sim 1 \text{ nG}$ )**

**AGNs are good laboratories to look for ALPs**

## 2 – Signatures of ALPs in spectra of gamma-ray sources



The concept of photon-ALP oscillation is not new. Several authors worked on that in the past: Sikivie 1983, Raffelt 1988, Csaki et al 2003 ...

Involving Gamma-ray astronomy (among others):

Hooper&Serpico 2007: photon-ALP in source (1)

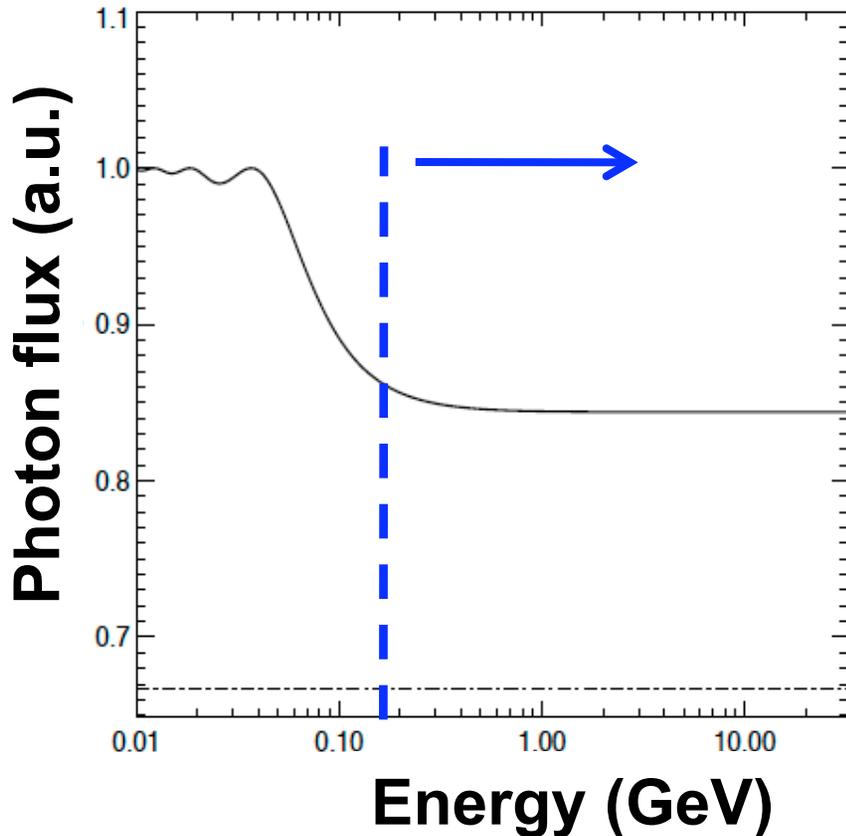
Angelis et al 2007 : photon-ALP in IGMF (2)

**This work:** [\*Phys. Rev. D 79,123511 \(2009\)\*](#)

*We concentrated on the study of the signatures produced by effects (1) and (2) combined, as well as defining a strategy to search for those effects with current gamma-ray instruments*

## 2 – Signatures of ALPs in spectra of gamma-ray sources

Oscillation photon-ALP in the AGN source and vicinity



**Attenuation of photon flux above a given “Critical Energy” (K)**

$$K \text{ (GeV)} = \frac{m^2}{2g_{\gamma}B} = \frac{m_{\mu\text{eV}}^2}{0.4g_{11}B_G}$$

$$m_{\mu\text{eV}} = 1$$

$$g_{11} = 8.8 \text{ (CAST limit)}$$

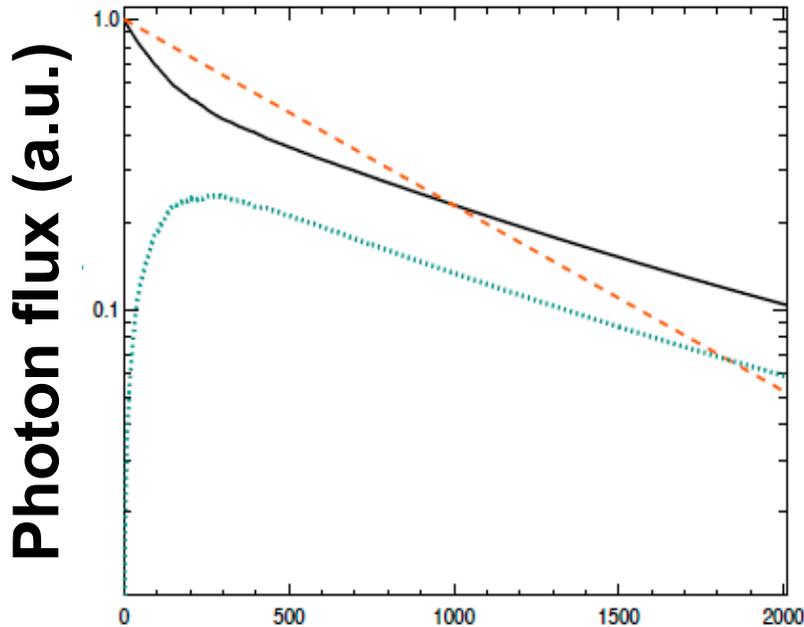
$$B_G = 1.5$$

$$\rightarrow \mathbf{K = 0.19 \text{ GeV}}$$

## 2 – Signatures of ALPs in spectra of gamma-ray sources

Oscillation photon-ALP in the IGMF ( $E_{ph} \gg K$ )

$E=500$  GeV



Distance to the source (Mpc)

**Photon flux without ALPs (flux attenuation due to EBL )**

**Photon flux with ALPs (flux variations due to EBL+ALPs)**

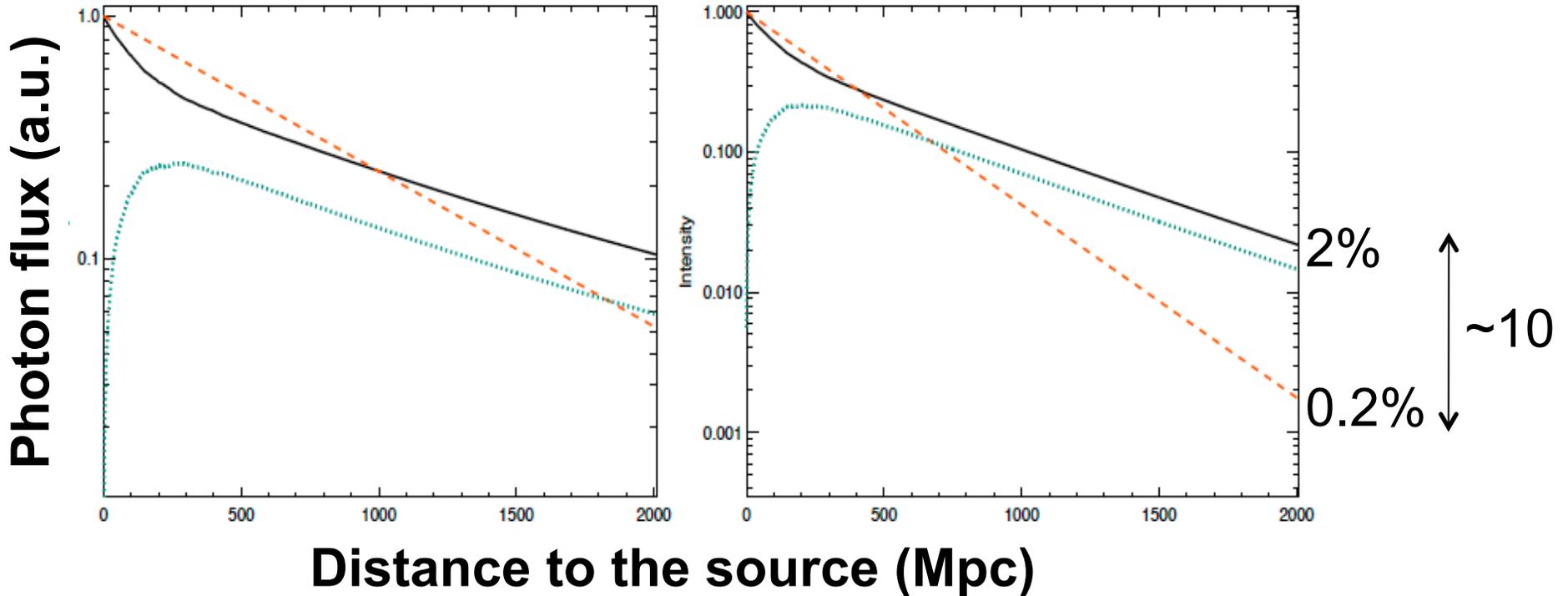
**ALP flux (assuming initial flux is zero)**

## 2 – Signatures of ALPs in spectra of gamma-ray sources

Oscillation photon-ALP in the IGMF ( $E_{ph} \gg K$ )

E=500 GeV

E=2 TeV



**Photon flux without ALPs (flux attenuation due to EBL )**

**Photon flux with ALPs (flux variations due to EBL+ALPs)**

**ALP flux (assuming initial flux is zero)**

## 2 – Signatures of ALPs in spectra of gamma-ray sources

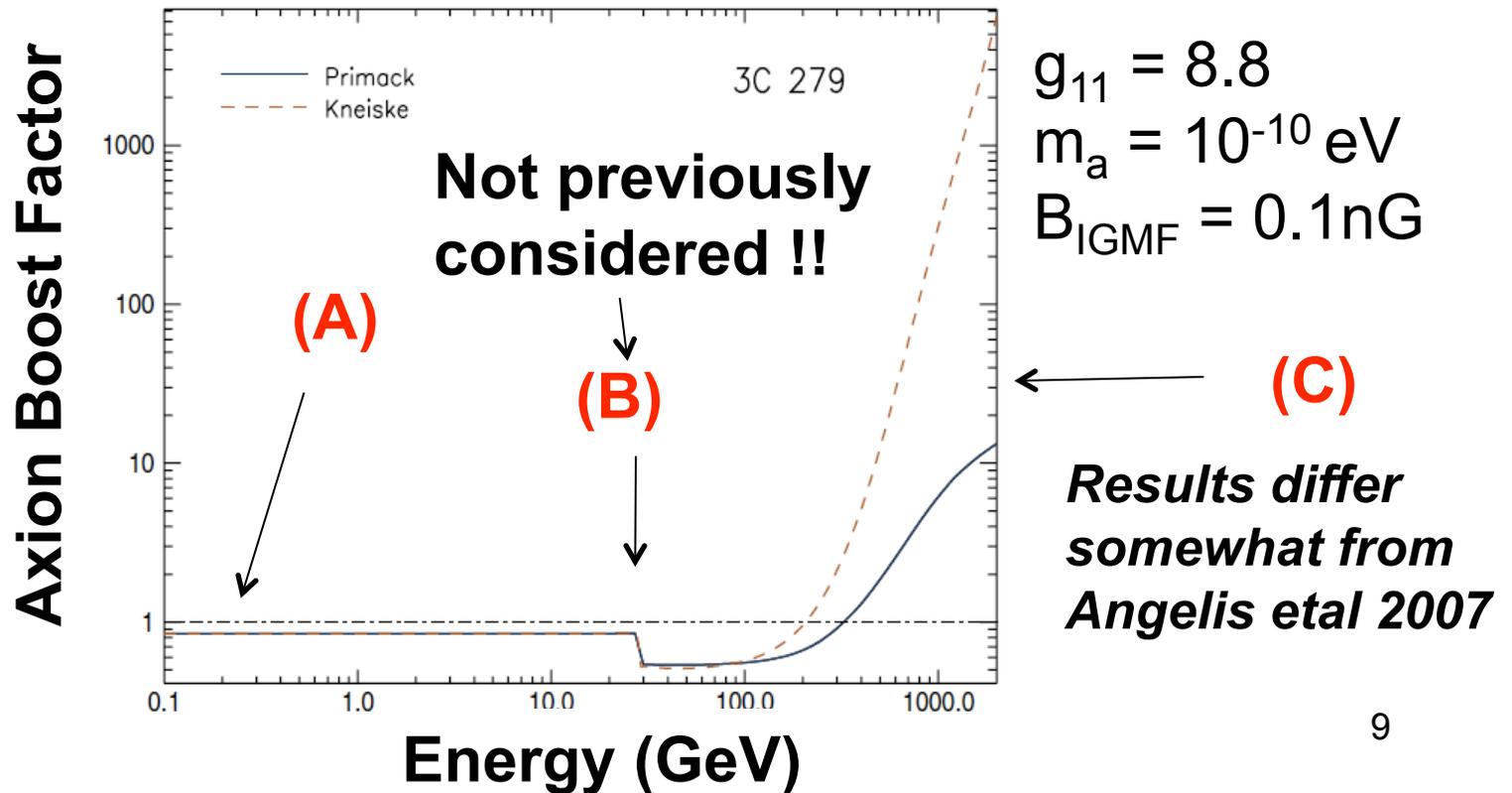
AGN source at 2 Gpc (3c279: *bright gamma-ray source*)

A - Attenuation due to photon-ALP oscillation in source

B – Attenuation due to photon-ALP in IGMF

C – Enhancement due to reconversion ALP-photon at energies affected by EBL photon attenuation

**AxionBoostFactor = Photon Flux (with ALPs) / Photon Flux (without ALPs)**



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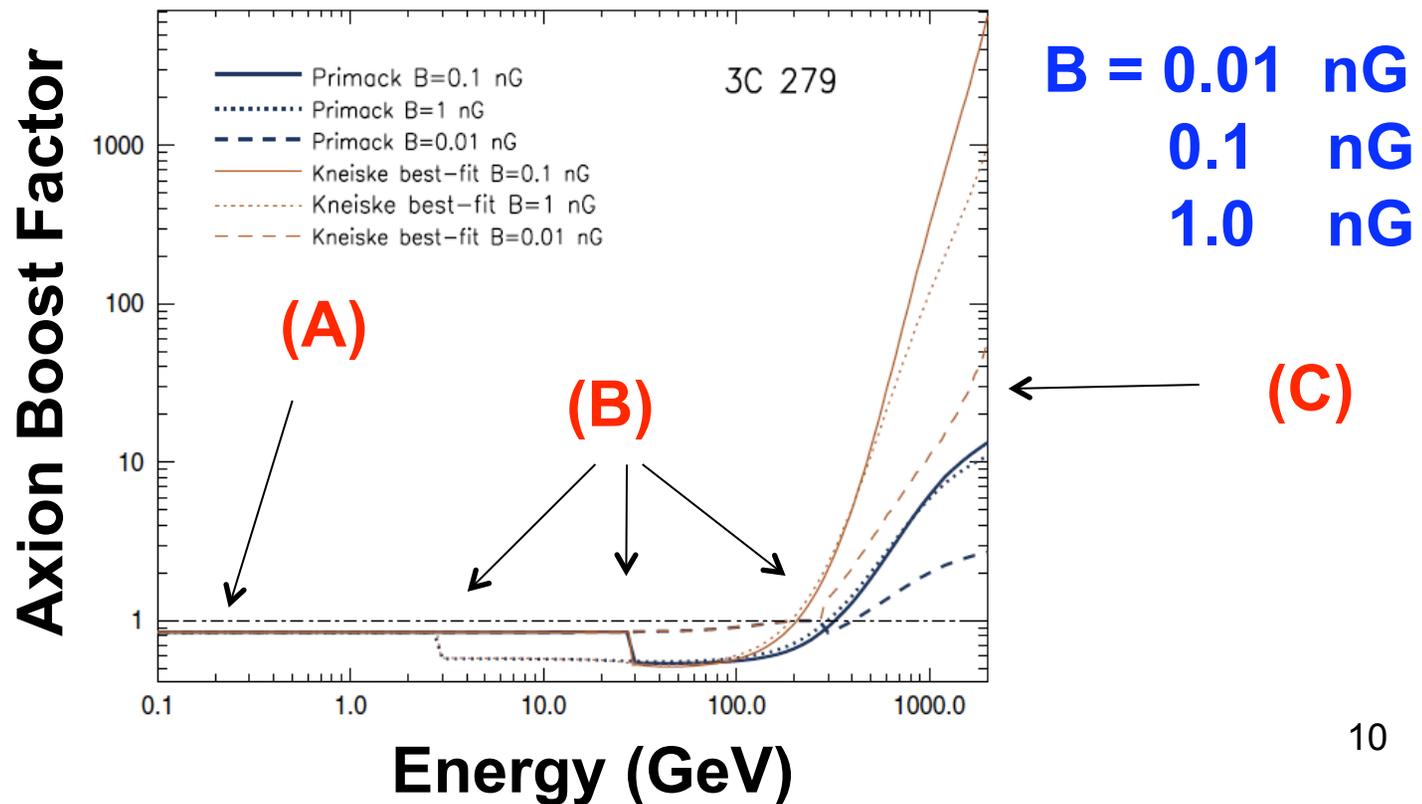
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### 3 - Indirect detection of ALPs with Fermi and IACTs

If one knew intrinsic source spectrum,  $B_{\text{IGMF}}$  and EBL density, ALPs could be detected in a wide range of the unexplored parameter space, or to exclude relevant portions of it.

Lacking this knowledge, the detection of ALP signatures becomes challenging, *but not impossible*. In order to tackle the problem, we propose the following strategy:

- 1 – Improve knowledge on the baseline AGN gamma-ray emission models  
New IACTs and Fermi play an important role
- 2 – Signatures of the type (A): look for intensity drops in the residuals [“best-model”–data] in powerful, relatively nearby AGN. **Source model dependent !!**  
The search can be performed with both IACTs and Fermi

### 3 - Indirect detection of ALPs with Fermi and IACTs

3 – Signatures of type (B): look for systematic intensity deficits in the residuals [“best-model”-data] of distant sources.

**Location of Energy with flux drop depends ONLY on  $B_{\text{IGMF}}$  and ALP properties: **Source model independent !!! CLEAR signature****

Stacking analysis should improve sensitivity to detect this signature.

Fermi/LAT AGN data is the suitable instrument for this search:

→ Thousands of distant AGN sources detected over large dynamic range

4 - A signature specific for the effect (C) would be revealed by systematic enhancements in the residuals [“best-model”-data] at the highest energies ( $E > 300$  GeV). **Source AND EBL model dependent. But effects can be LARGE (x10 or x100)**

Search can only be done with AGN detected by IACTs ( $E > 0.3$  TeV)

Fermi/LAT data important to constrain Source/EBL models

### 3 - Indirect detection of ALPs with Fermi and IACTs

**Recent TeV observations might pose some challenges to the current understanding of TeV blazars and EBL density (*too many High E  $\gamma$ ?*):**

1 – EBL-corrected spectrum of 3c66A ( $z=0.444$ ) has a photon index harder than 1.5 ( $1.1\pm 0.4$ ): Acciari et al 2009 (VERITAS collab.)

2- Claimed detection of TeV gammas from 3c66A with Crimean Astroph. Obs. (GT48): Neshpor 1998 and Stepanyan 2002. Current EBL models are not compatible with detection of TeV photons from such large distance.

*Those signals could have come from nearby radio galaxy 3c66B ( $z=0.02$ ) which was also detected above TeV with MAGIC (Aliu et al 2009). This source is 0.1 deg away from 3c66A and thus location of source is barely consistent with 3c66A.*

3 – Several distant ( $z=0.1-0.2$ ) TeV sources appear to be harder than expected (spectral index  $< 1.5$ ): Krennrich et al 2008

4 – Lower limit on EBL at  $3.6 \mu\text{m}$  revised upwards by factor  $\sim 2$   
Levenson et al 2008. This suggests stronger EBL absorption than used so far

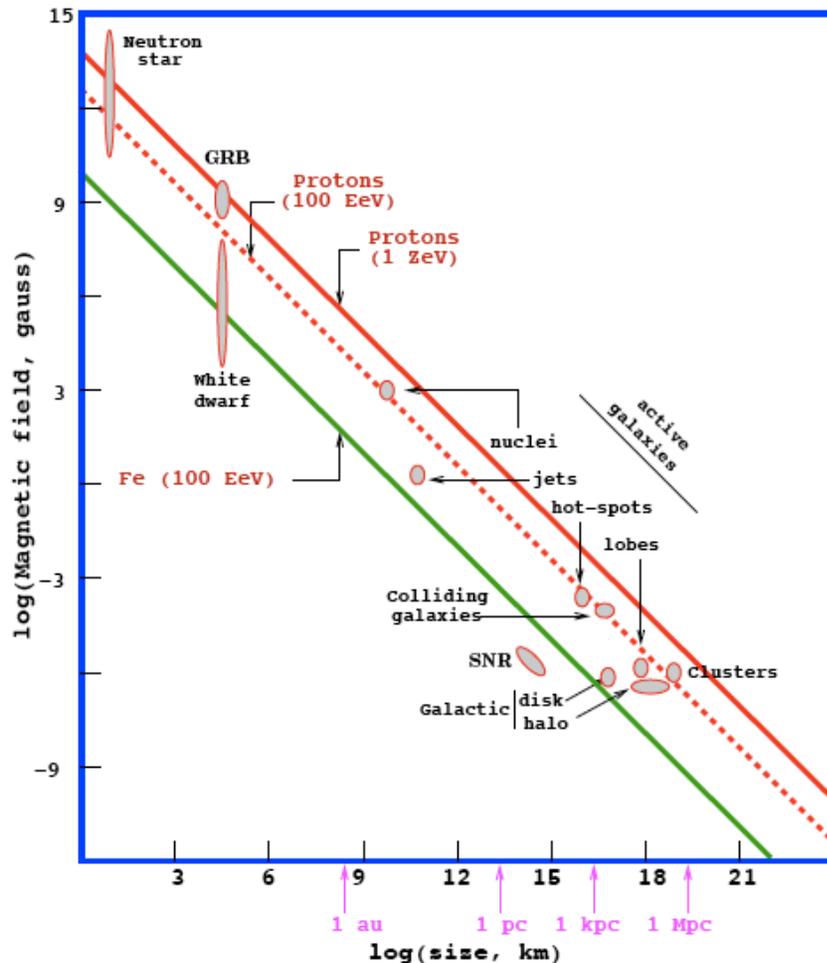
**Photon-ALP oscillation in IGMF could easily explain the “excess” of high energy photons observed in distant sources**

# Conclusions

- Existence of ALPs can produce substantial distortions in the spectra of AGN sources
- Signatures are difficult to identify due to lack of knowledge of AGN sources and their environment
- Indirect identification of ALPs would benefit from better understanding of conventional physics (AGN and EBL). Moving in that direction. *Operation of Fermi is boosting our experimental capability for understanding AGNs*
- IACTs and specially Fermi (*thousands of distant AGNs characterized over a large dynamic range*) can become key players in the indirect search for ALPs

# Backup

# Hillas diagram

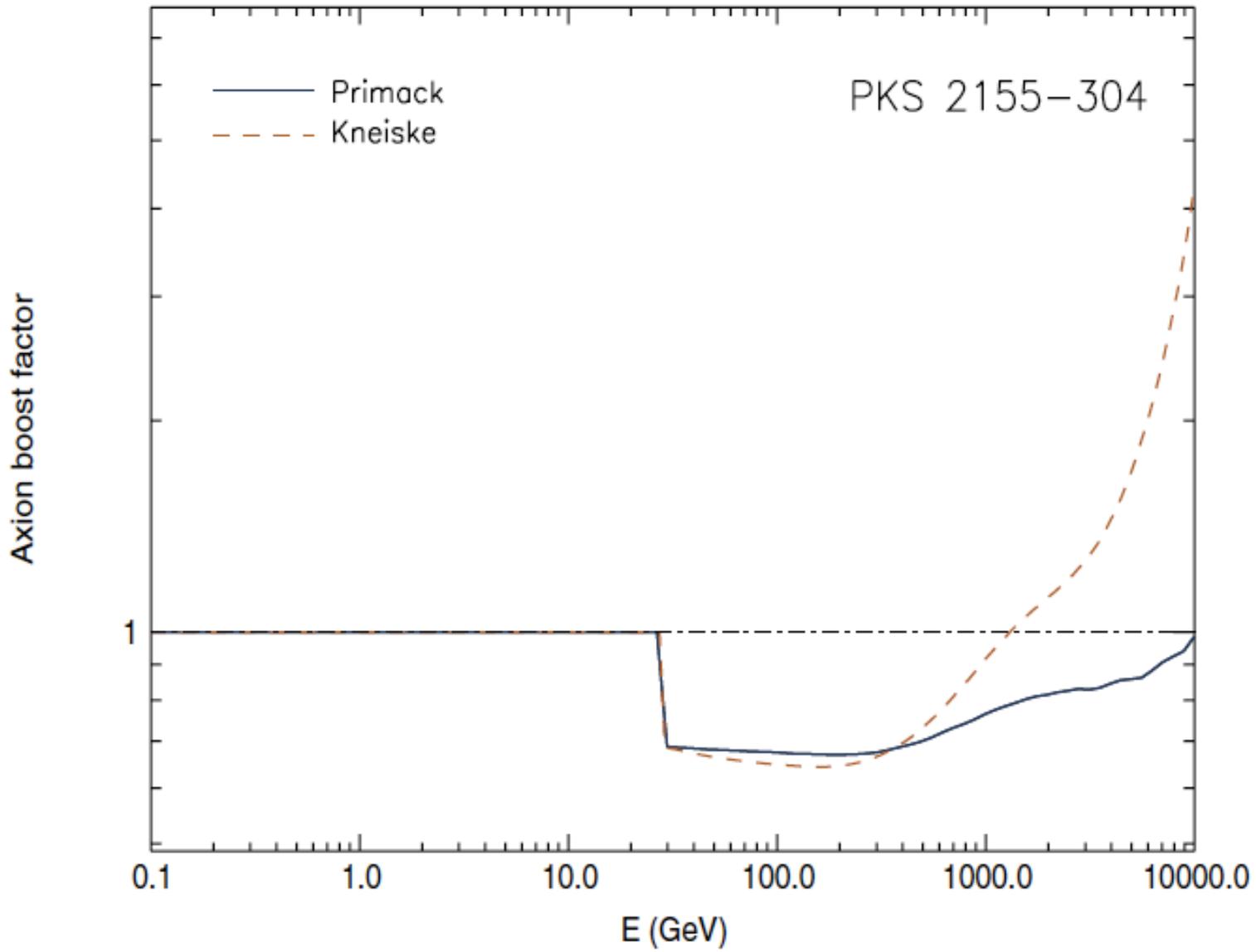


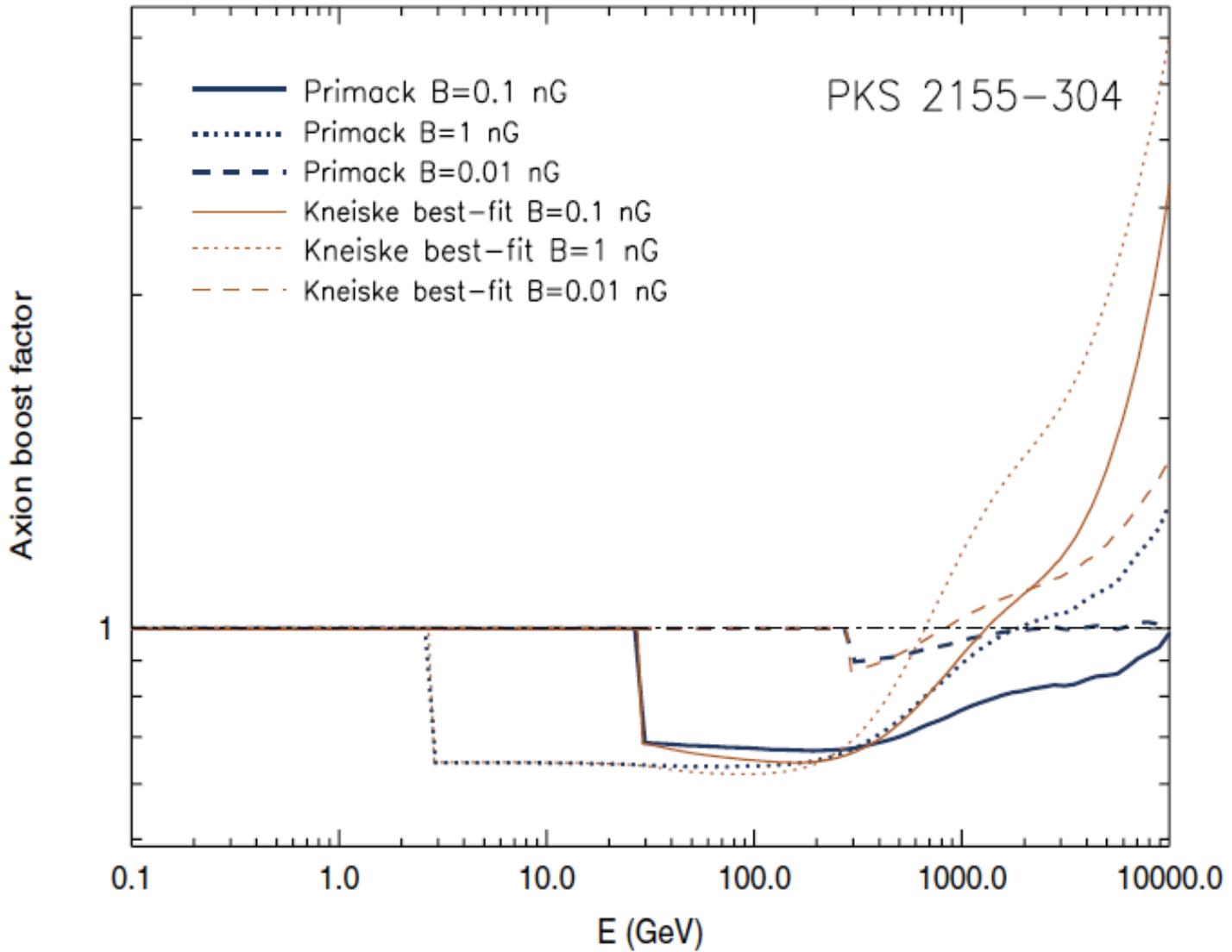
Several possible sources.

The compact ones are not favoured because high electron density will make E characteristic be too high for gamma rays

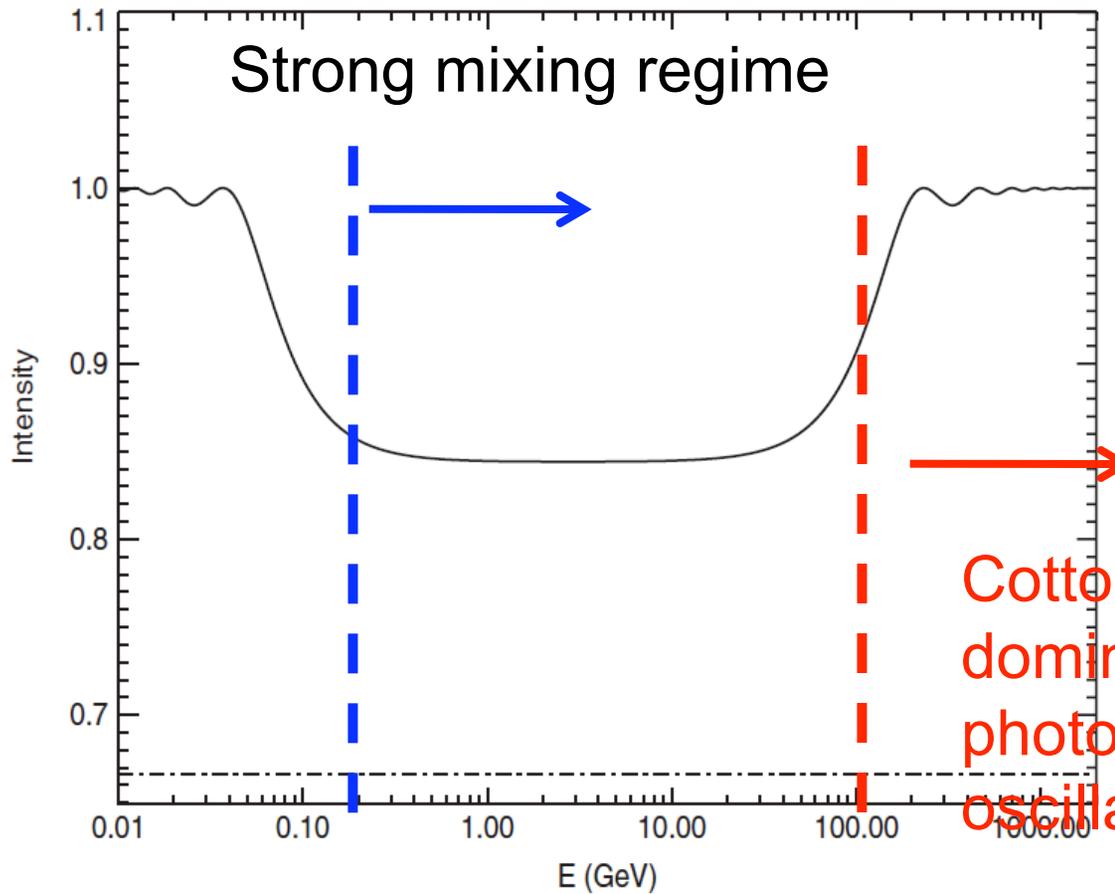
AGNs have been recently appointed as sources of UHECRs by Auger (recent AUGER data seems to disfavour that)

Good candidate, but not the only one !!





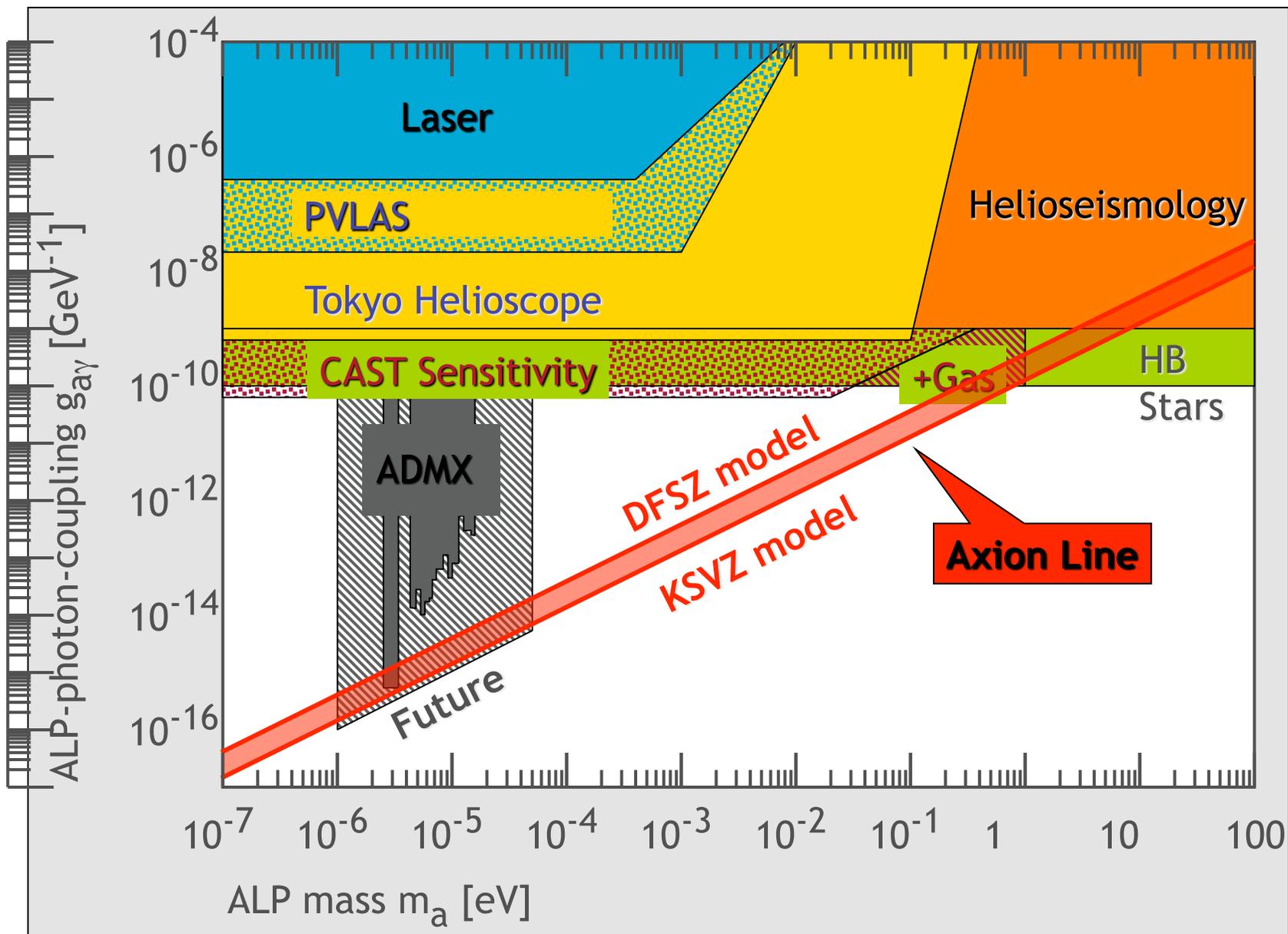
# Oscillation photon-ALP in the AGN source and vicinity



**Attenuation of photon flux above a given “Critical Energy” (K)**

$$K \text{ (GeV)} = \frac{m^2}{2g_{a\gamma}B} = \frac{m_{\mu eV}^2}{0.4g_{11}B_G}$$

Cotton-Mouton term dominates at the highest photon energies, precluding oscillation photon-axion



$B$ region (pc)	Length domains (pc)			
	$3 \times 10^{-4}$	$3 \times 10^{-3}$	0.03	0.3
0.3	0.84	0.67	0.67	0.75
0.03	0.98	<b>0.84</b>	0.77	...
$3 \times 10^{-3}$	0.99	0.98	...	...

	Parameter	3C 279	PKS 2155-304
Source parameters	$B$ (G)	1.5	0.1
	$e_d$ ( $\text{cm}^{-3}$ )	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
	$e_{d,\text{int}}$ ( $\text{cm}^{-3}$ )	$10^{-7}$	$10^{-7}$
	$B_{\text{int}}$ (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)	$10^{-10}$	$10^{-10}$