Búsqueda de axiones mediante observaciones gamma de AGNs distantes

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Photon/axion oscillations

- Axions were postulated to solve the CP problem in the 70s.
- Good Dark Matter candidates (axions with masses ≈ μeV-meV 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

$$\begin{cases} \Delta_B = \dfrac{B_t}{2M} \simeq 1.7 \times 10^{-21} M_{11} B_{\rm mG}\ {\rm cm}^{-1}, \\[2ex] \Delta_{\rm osc}^2 \simeq \underbrace{(\Delta_{\rm CM} + \Delta_{\rm pl} - \Delta_a)}^{}{}^2 + 4\Delta_B^2, \end{cases}$$

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

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

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

- For an efficient conversion:

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

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

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

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:

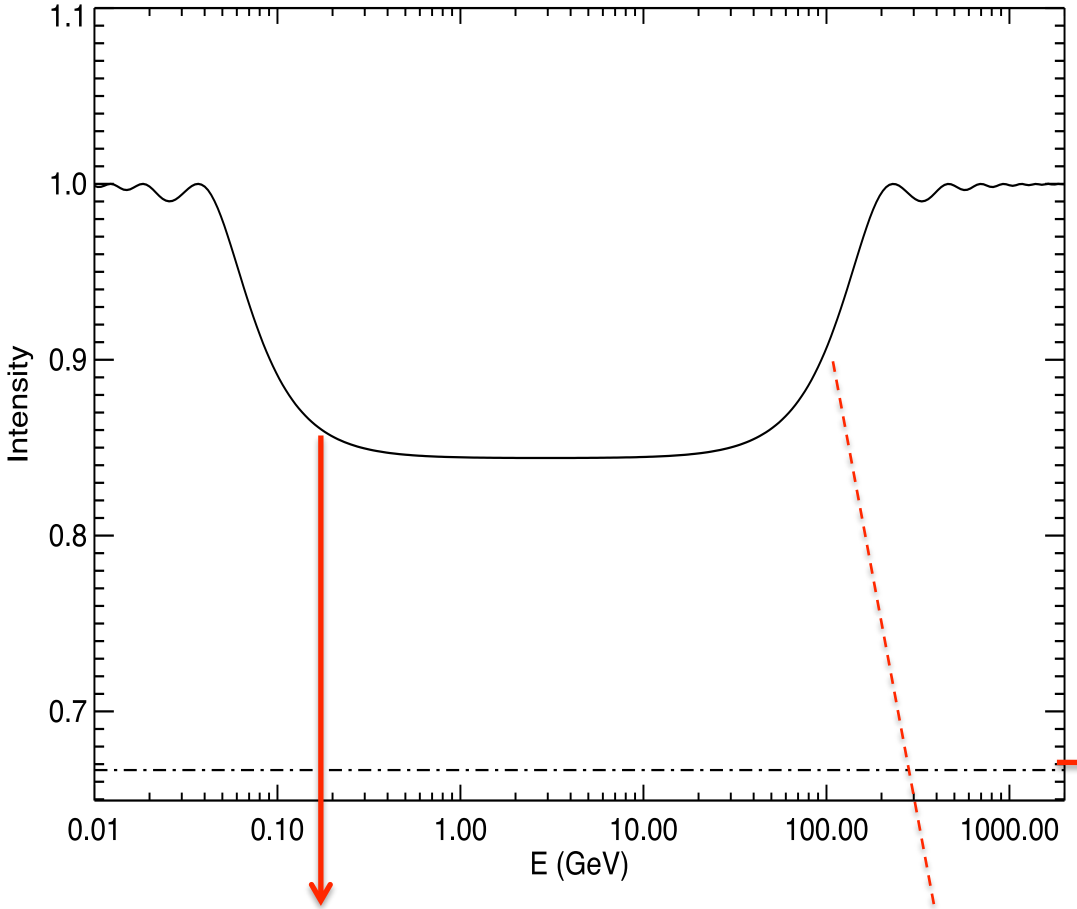
$E_{max} = 9.3 \cdot 10^{20} \cdot B_G \cdot s_{pc}$ eV (**Hillas criterion**)

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



E_{crit}= 0.19 GeV
(B=1.5 G; m_{axion}=1μeV)

Effect of the Cotton-Mouton term

Maximum theoretical
attenuation = 1/3

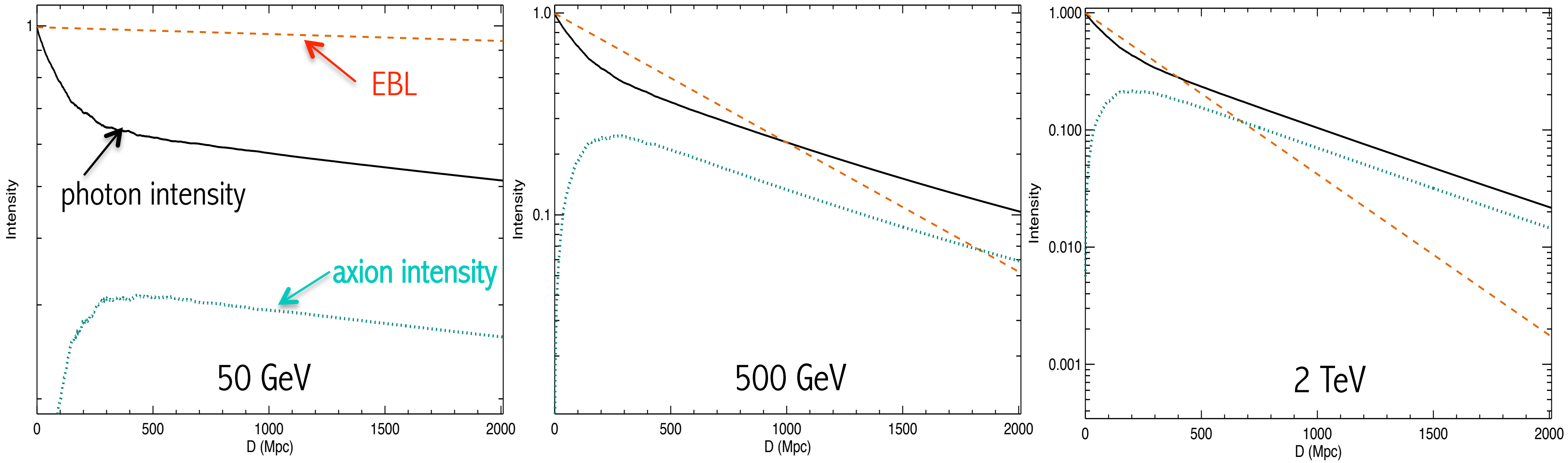
The main effect is an **ATTENUATION** of the photon flux above the critical energy:

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

For typical AGN numbers, the effect is present in **gamma-rays below axion masses ≈ 10^{-6} eV**

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.

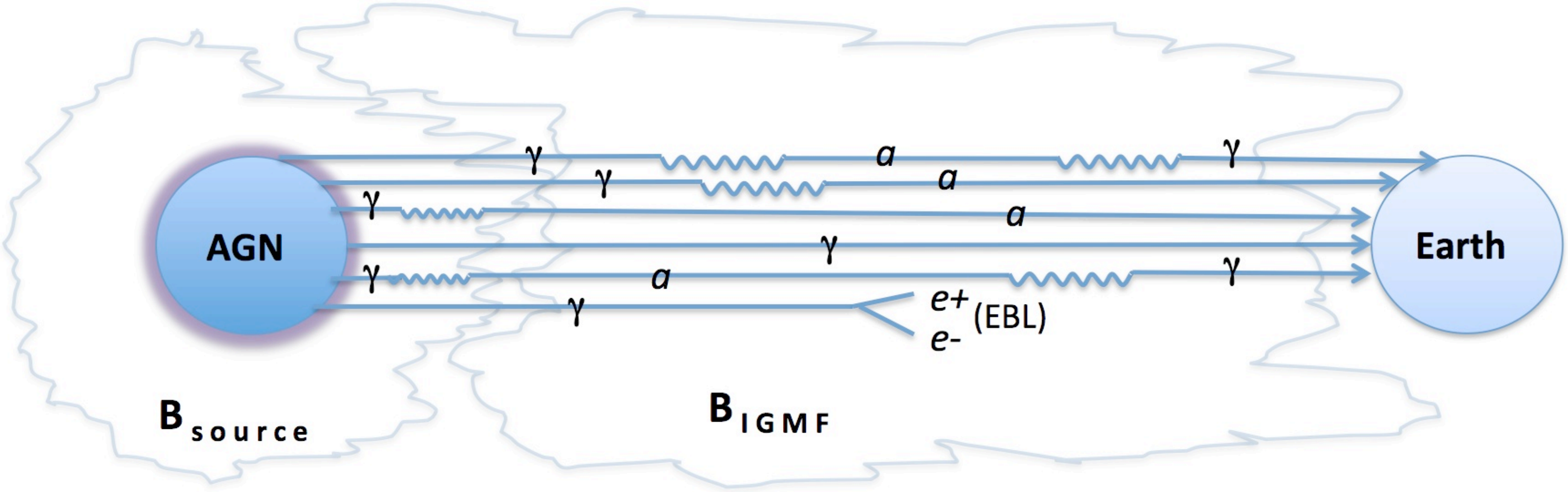


$B=1$ nG; $M_{11}=0.7$ GeV; $D=2$ Gpc, $L_{dom}=1$ Mpc; Primack EBL model

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**

Source and intergalactic mixing working together



- AGNs located at cosmological distances will be affected by both mixing in the source and in the IGMF.
- In order to observe both effects in the gamma-ray band, we need ultralight axions.

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	3×10^{-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)	1.14×10^{10}	1.14×10^{10}
	ALP mass (eV)	10^{-10}	10^{-10}

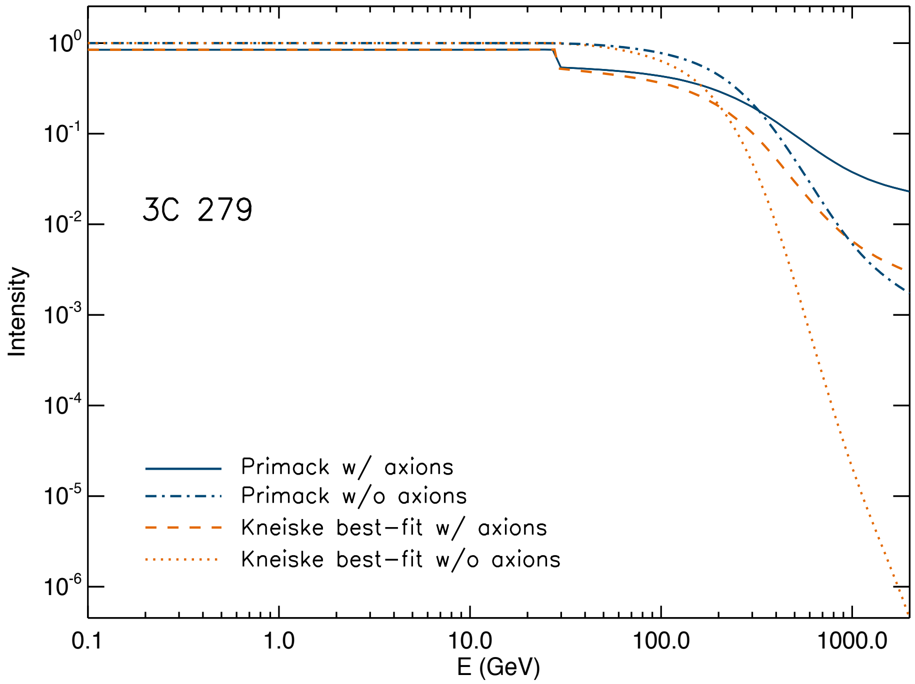
$E_{crit,source}(3C) = 4.6$ eV

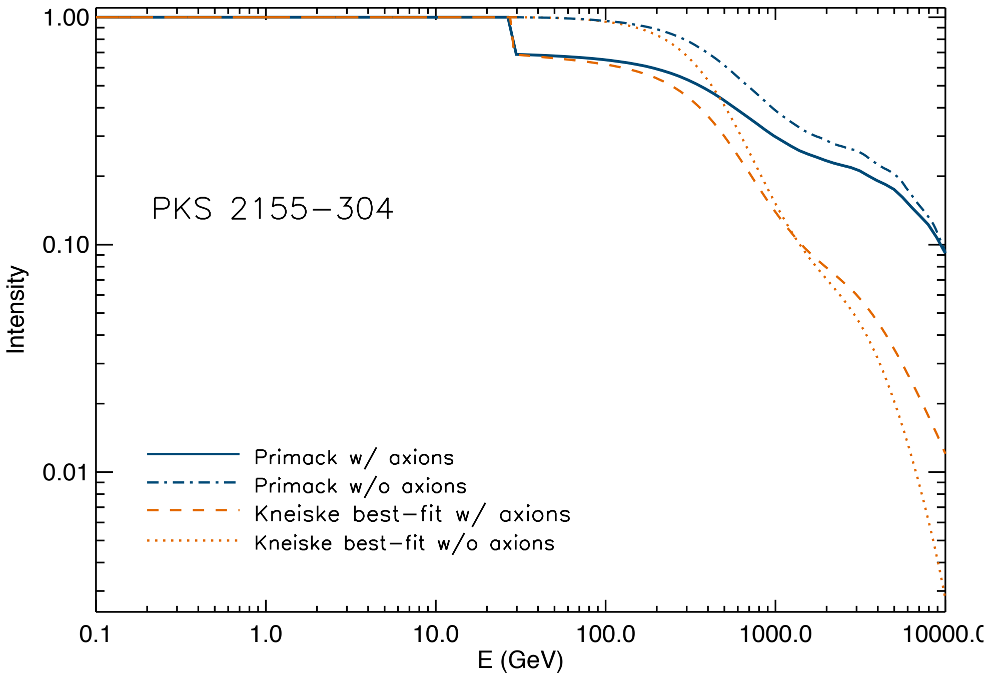
$E_{crit,source}(PKS) = 69$ eV

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

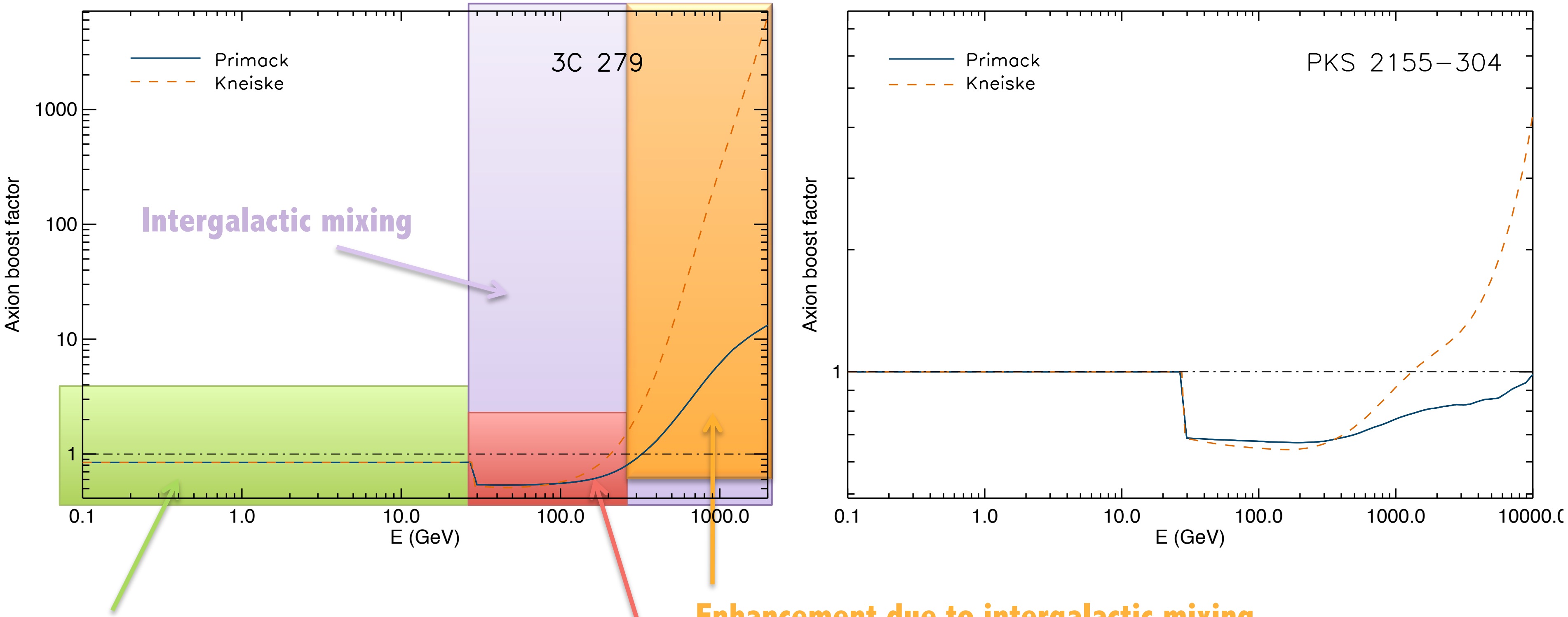
CAST limit

ultralight axions





Axion boosts



Intergalactic mixing

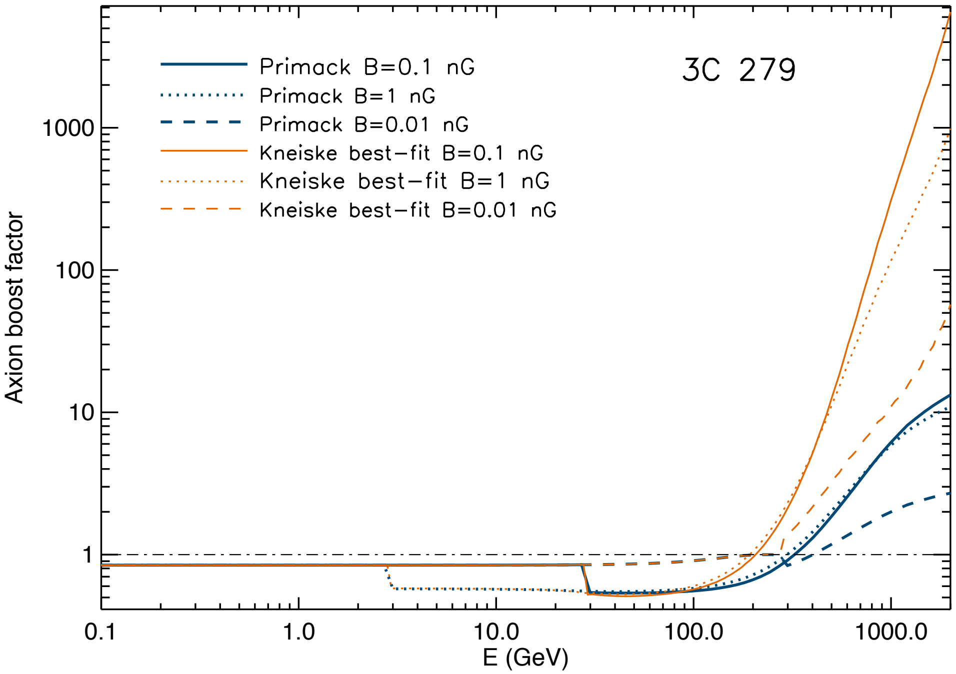
Attenuation due to source mixing

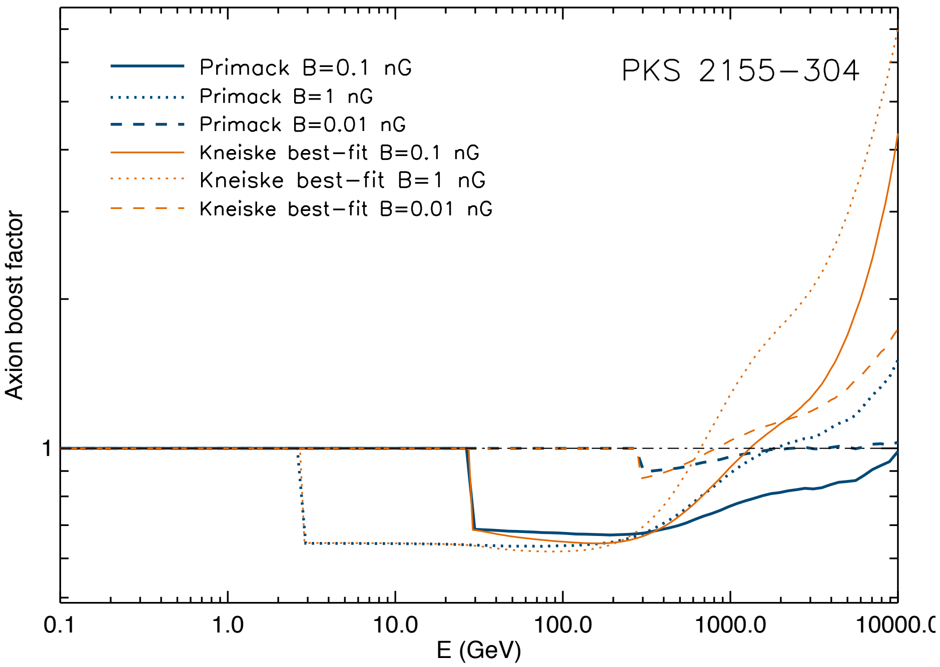
Enhancement due to intergalactic mixing

Attenuation due to intergalactic mixing

- Larger axion boosts for distant sources.
- The more attenuating the EBL, the larger the axion boosts.
- Same critical energies for different objects -> clear signature for detection!

The impact of changing B





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

Detection prospects for Fermi and IACTs

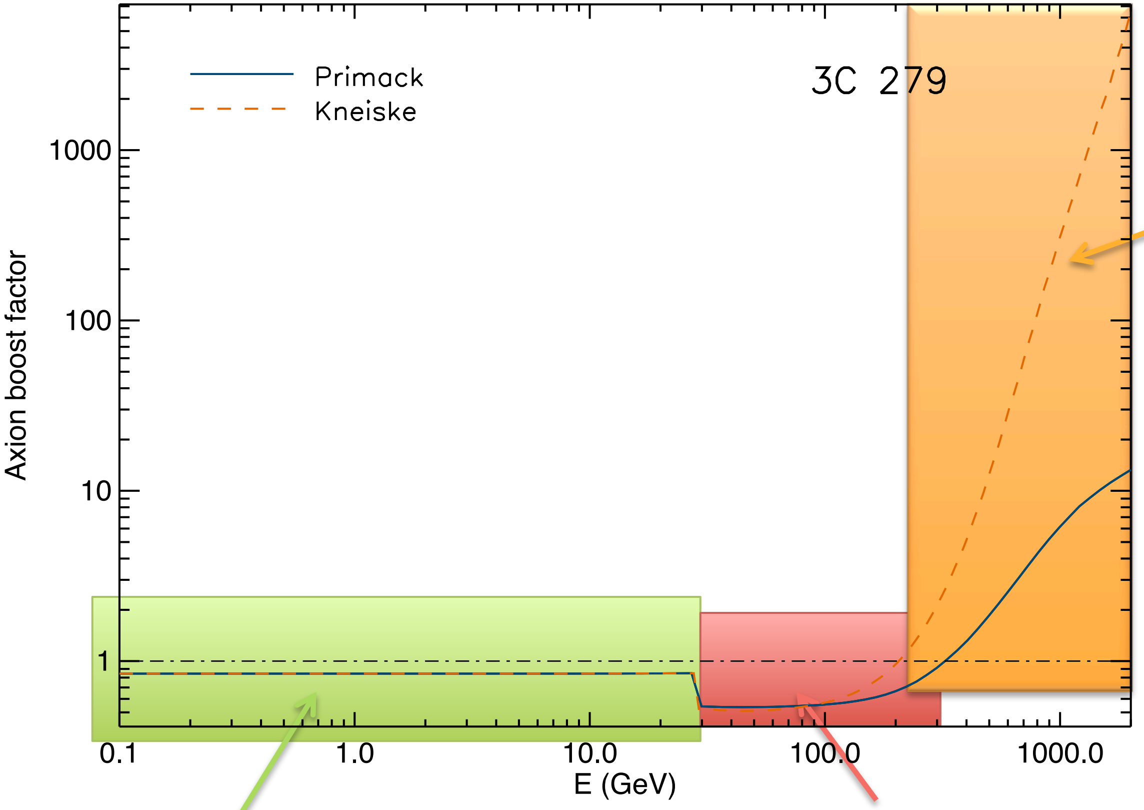
- If we accurately knew the intrinsic spectrum of the sources and/or the density of the EBL, we should be able to observationally detect axion signatures or to exclude some portions of the parameter space.

- We lack this knowledge… Detection challenging but still possible!

- Before going to axions:
  - Observe several AGNs located at different redshifts, as well as the same AGN undergoing different flaring states, from radio to TeV.
  - Try to describe the observational data with “conventional” theoretical models for the AGN emission and for the EBL.

- If these “conventional” models for the source emission and EBL fail (important residuals for the best-fit model), then the axion scenario should be explored.

Observational strategy with Fermi and IACTs



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 and/or IACTs
Look for intensity **drops** in the residuals ("best-model"-data).
Source model dependent.
Powerful, relatively **near** AGNs.

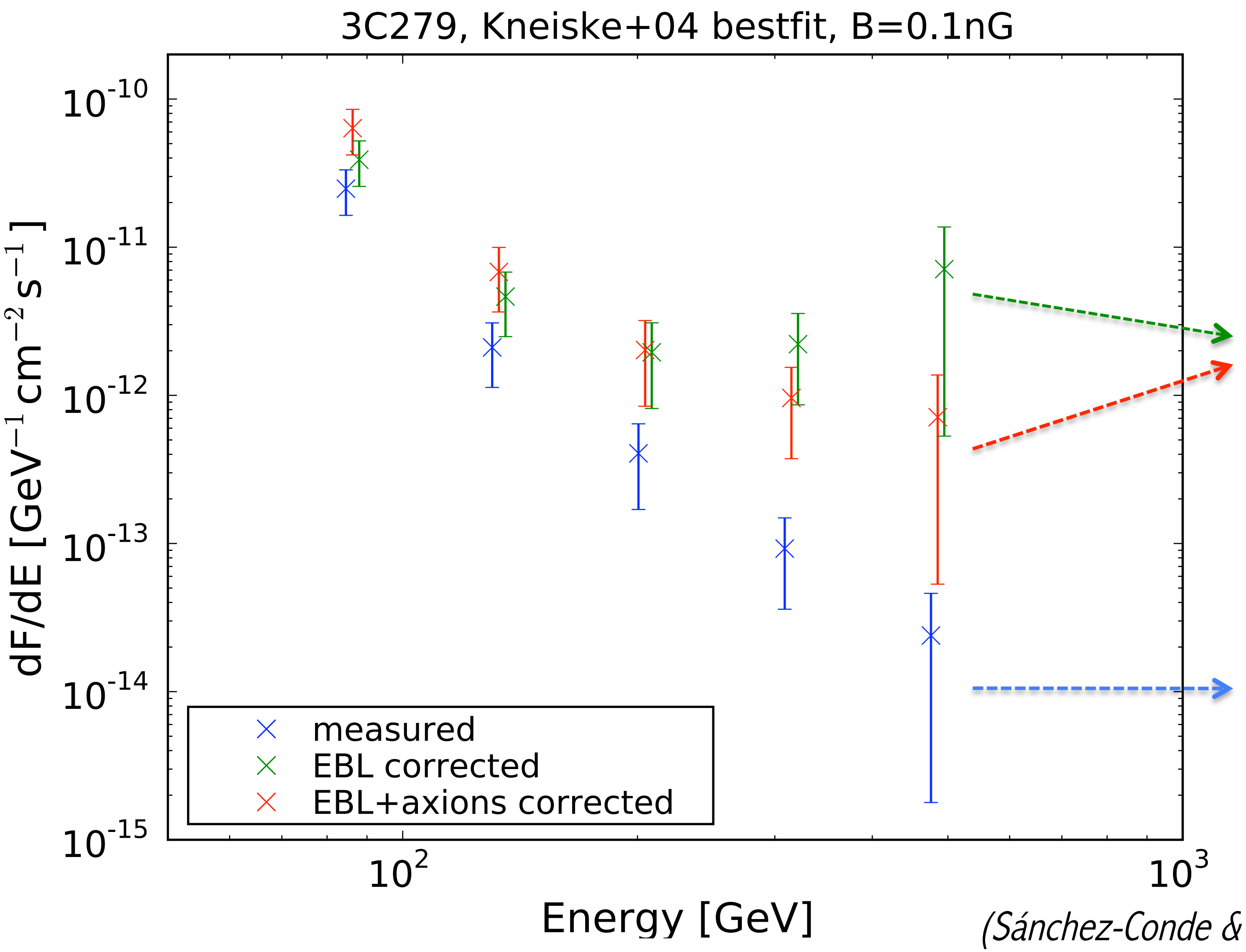
Fermi/LAT and/or IACTs
Look for intensity **drops** in the residuals.
Only depends on the IGMF and axion properties (mass and coupling constant).
Independent of the sources -> CLEAR signature!

Are we detecting axions already?

- 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 μm 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, the axion/photon oscillation would naturally explain these puzzles:
  - More high energy photons than expected.
  - Softer intrinsic spectrum when including axions.

Axions are our friends



Softer intrinsic spectrum with axions

We can observe the spectrum up to higher energies with axions

(Sánchez-Conde & Domínguez, in prep.)

[3C279 data points from the MAGIC Collaboration, Albert et al. 2008]

CONCLUSIONS

- If axions exist, they could **distort the spectra** of astrophysical sources importantly.
- If photon/axion mixing in the IGMFs, then also mixing in the source.
  For $\mathbf{m_{axion} \approx 10^{-10}}$ **eV -> gamma** ray energy range.
- Photon/axion mixing in both the source and the IGM are expected to be at work over several decades in energy -> **joint effort of Fermi and current IACTs** needed.
  - Fermi/LAT instrument expected to play a key role, since it will detect thousands of AGNs (up to z~5), at energies where the EBL is not important.
  - IACTs specially important at higher energies (>300 GeV), where the EBL is present.
- Main **problem**: 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.