AXIONS IN GAMMA-RAYS: A BLUEPRINT OF THE BEST SEARCH STRATEGY

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[PHYSICAL REVIEW D 79, 123511 (2009)]

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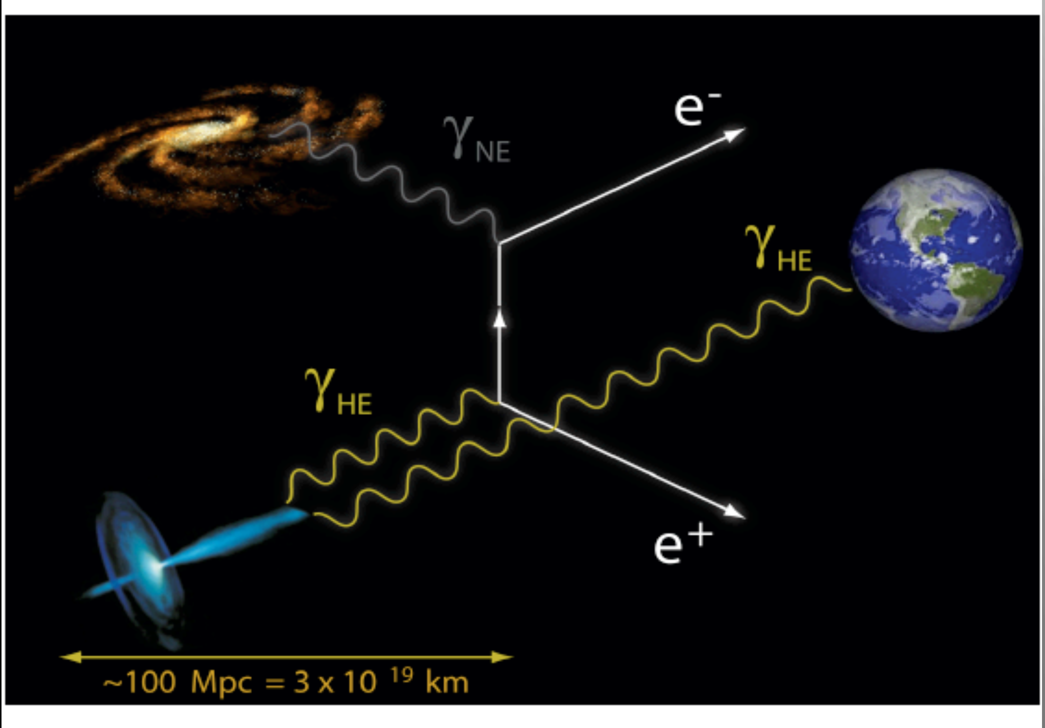
Intergalactic absorption of VHE photons

QED pair creation processes is the dominant process for the cosmological absorption of gamma-rays:

$$\gamma + \gamma_{background} \longrightarrow e^{+} + e^{-}$$



Around the TeV region:

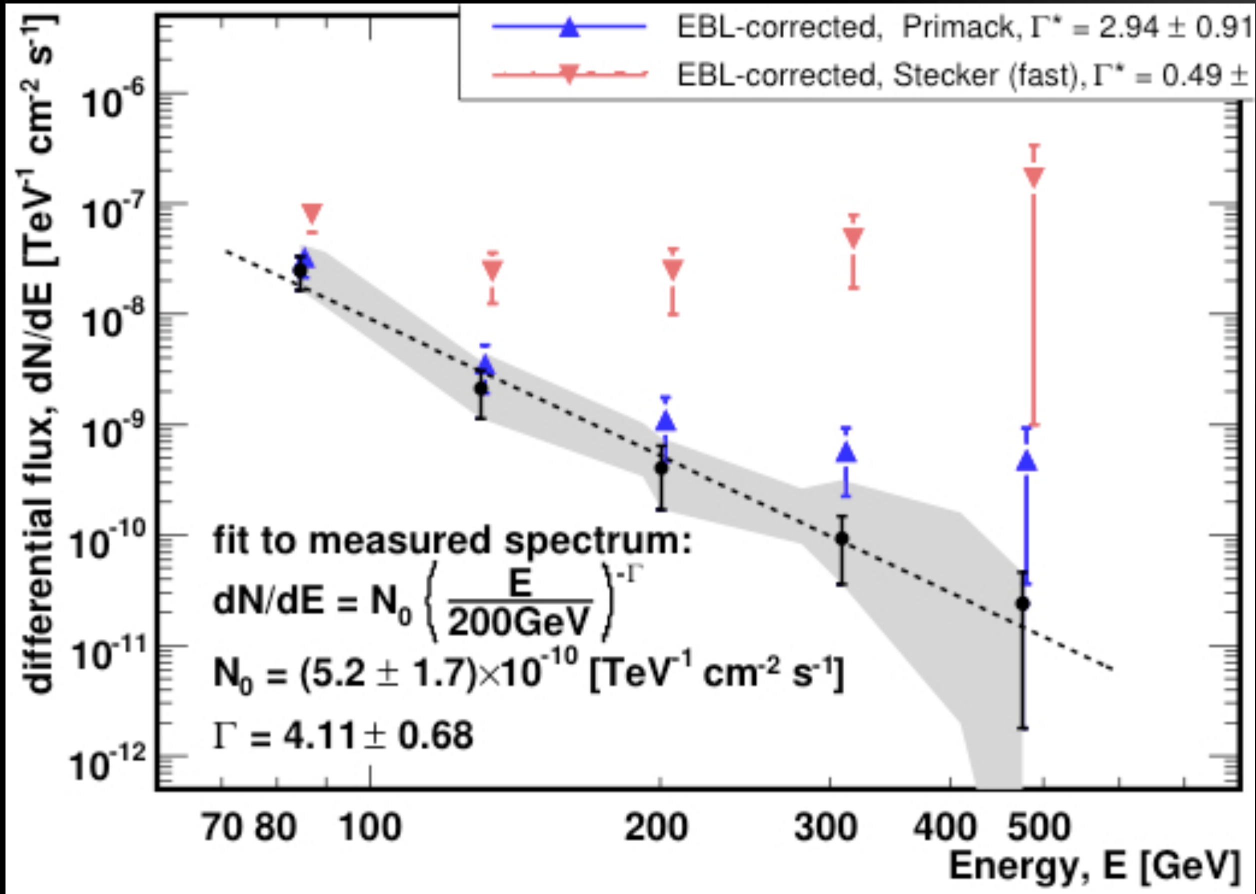
$$\varepsilon \approx 0.5\left(\frac{1TeV}{E}\right)eV$$

Infrared/optical background photons:

Extragalactic Background Light (EBL)

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

AGN spectra and the EBL



[MAGIC Collaboration, Albert et al. 2008]

3C 279

- ✓ Flat spectrum radio quasar
- ✓ z=0.54
- ✓ The most distant AGN in gamma-rays (>100 GeV)
- ✓ Push EBL models already to the limit!

- ✓ Modeling of AGN emission mechanisms typically assume spectral index >1.5

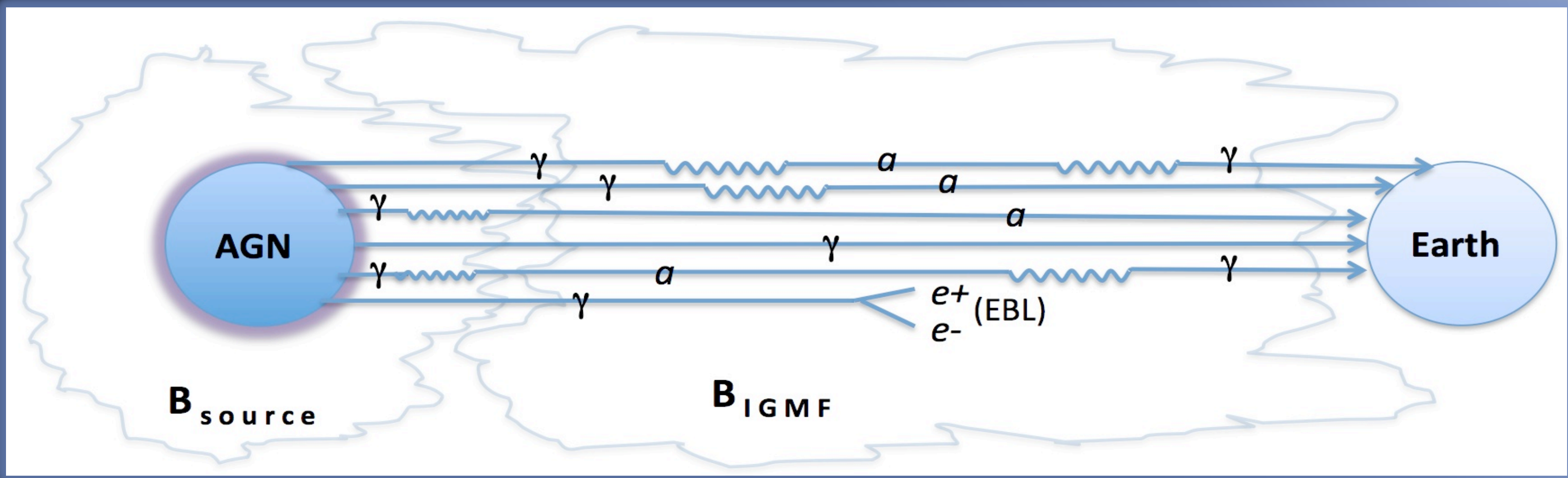
Hints for new physics?

- 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 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 (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 (pseudoscalar boson) were postulated to solve the strong-CP problem in the 70s.
- Good Dark Matter candidates
- They are expected to oscillate into photons (and viceversa) in the presence of magnetic fields:



(Sánchez-Conde+, PRD 09)

AGNs located at cosmological distances will be affected by both mixing in the source (e.g. Hooper & Serpico 07) and in the IGMF (De Angelis+07):

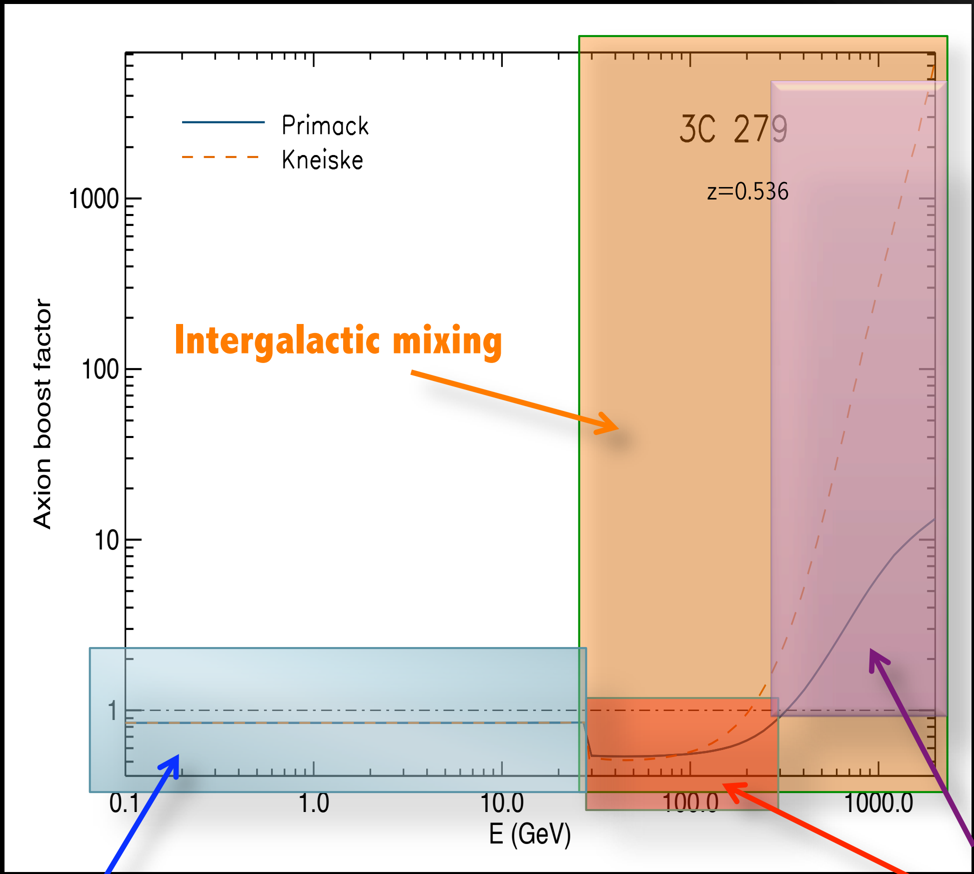
A. Source mixing: flux attenuation
B. IGM mixing: flux attenuation and/or enhancement

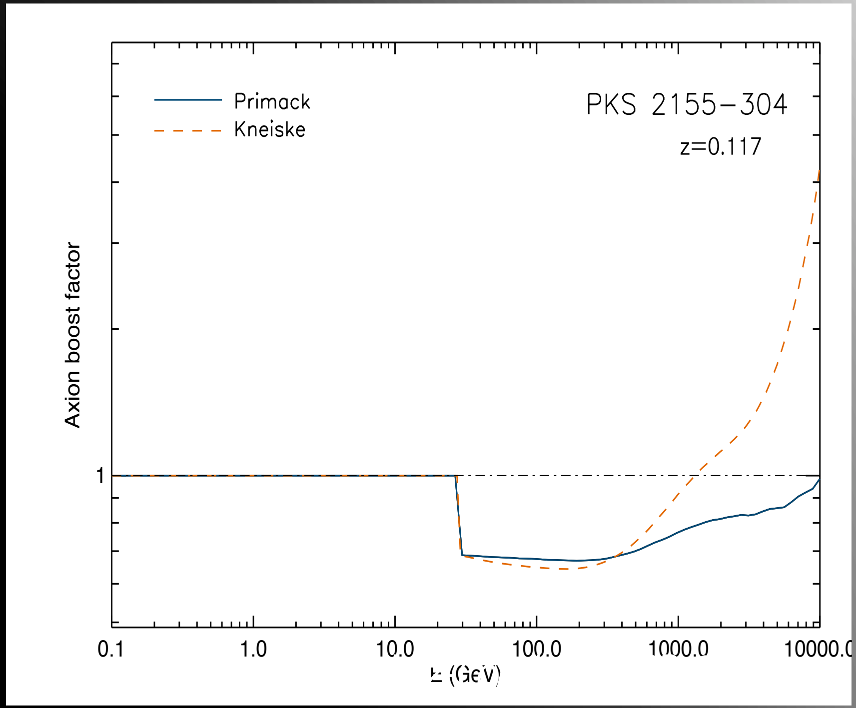
$$E_{crit}(GeV) \equiv \frac{m^2_{\mu eV}\ M_{11}}{0.4\ B_G}$$

In order to observe both effects in the gamma-ray band, we need ultralight axions.

Axion boosts

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

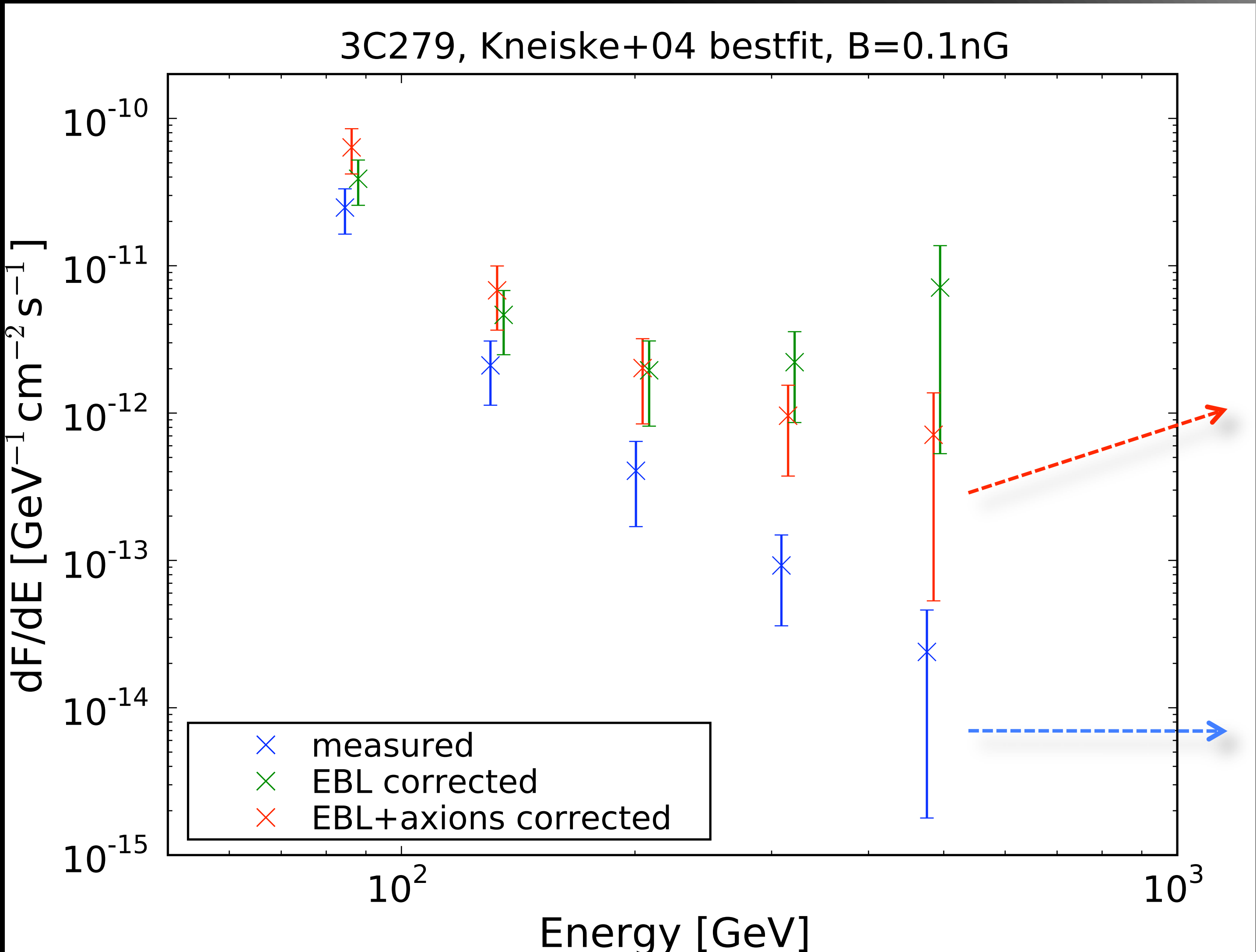




- ✓ Larger axion boosts for distant sources.
- ✓ The more attenuating the EBL, the larger the axion boosts.

(Sánchez-Conde+, PRD 09)

Axions are our friends



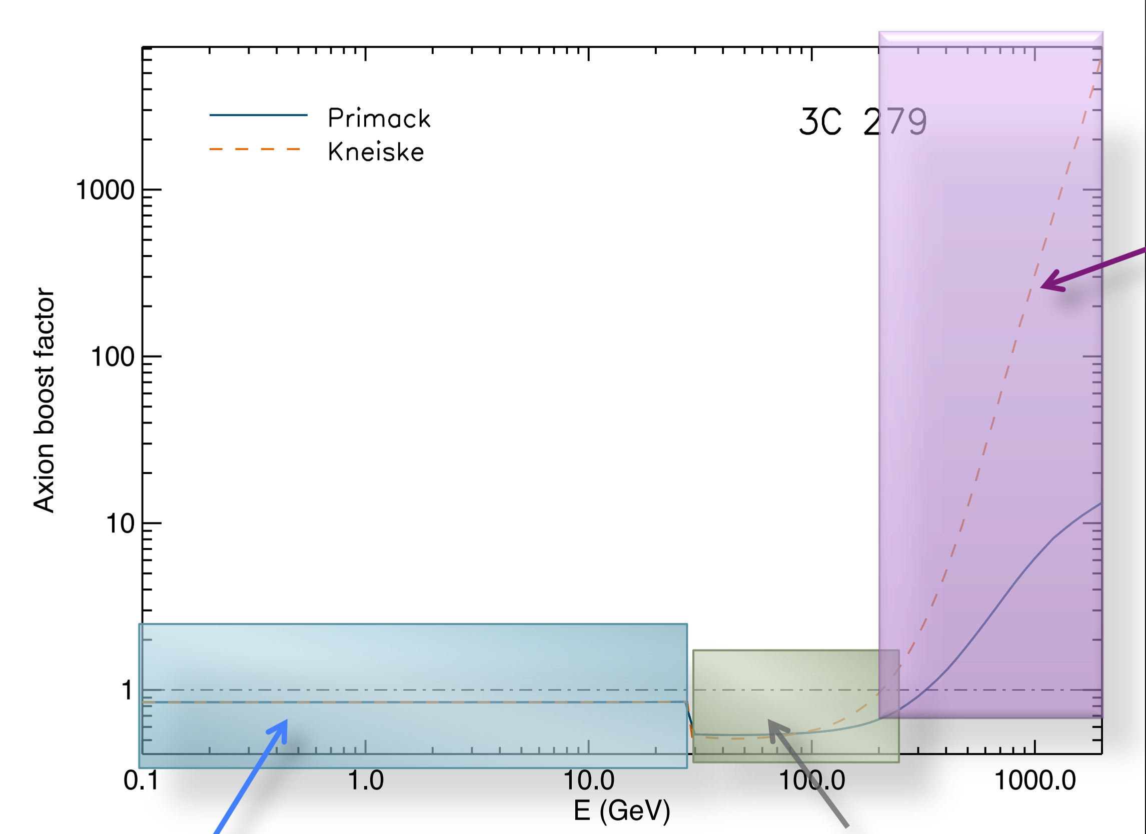
Softer intrinsic spectrum with axions

We can observe the spectrum up to higher energies with axions

(Sánchez-Conde & Dominguez, in prep.)

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

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!

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 $\mathbf{m_{axion}} \approx \mathbf{10^{-10}}$ **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 **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.

BACKUP

Additional material

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:

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

with

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

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

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

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

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

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

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

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

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

- 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:

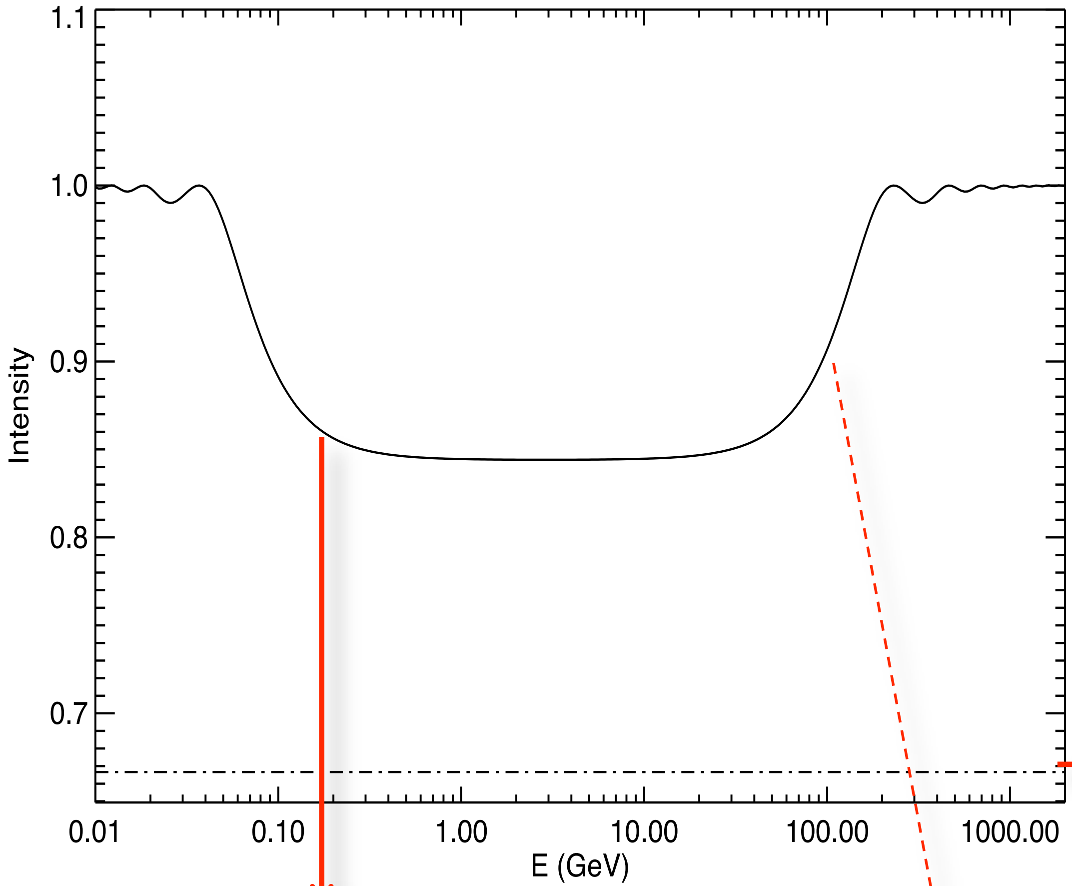
$E_{max} = 9.3 \cdot 10^{20} \cdot B_G \cdot s_{pc}$ eV (**Hillas criterion**)

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



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

Effect of the Cotton-Mouton term

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

Maximum theoretical attenuation = 1/3

Variation of source attenuation with the size domain

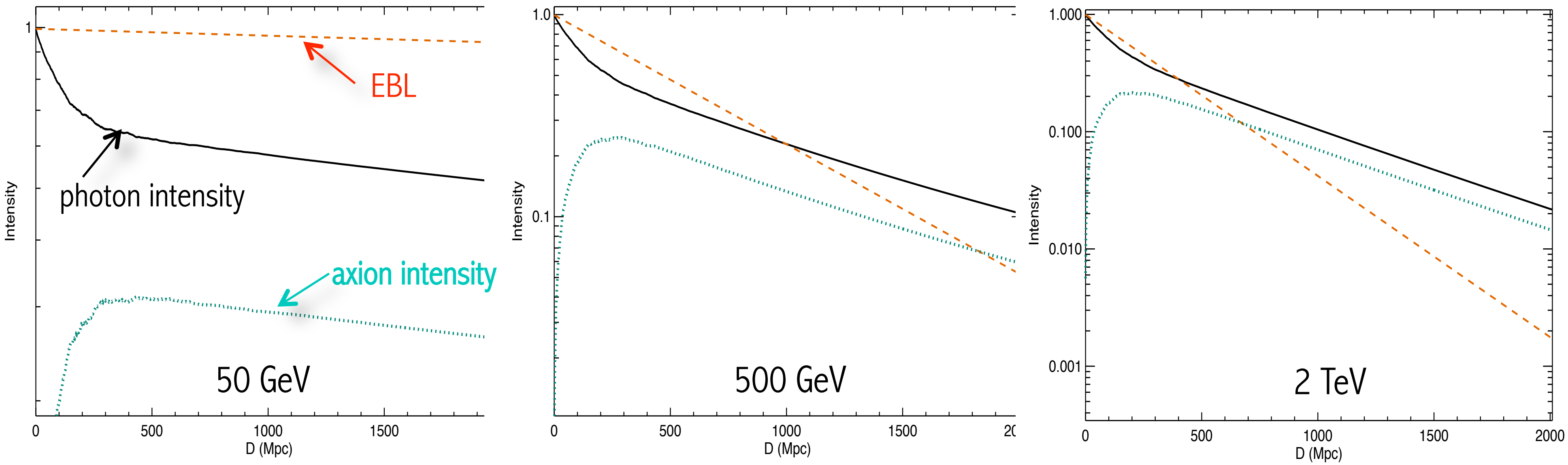
TABLE I: Maximum attenuations due to photon/axion oscillations in the source obtained for different sizes of the region where the magnetic field is confined ("B region") and different lengths for the coherent domains. Only length domains smaller than the size of the **B** region are possible. The **B** 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)			
	3×10^{-4}	3×10^{-3}	0.03	0.3
0.3	0.84	0.67	0.67	0.75
0.03	0.98	**0.84**	0.77	-
3×10^{-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

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

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

No plasma term
No CM term
Only Δ_B → $\delta \equiv \frac{B\,\lambda_\gamma}{M}$

$$T_0 \equiv \begin{pmatrix} \sin^2\theta & -\cos\theta\sin\theta & 0\\ -\cos\theta\sin\theta & \cos^2\theta & 0\\ 0 & 0 & 0\end{pmatrix}$$

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

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

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	3×10^{-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}

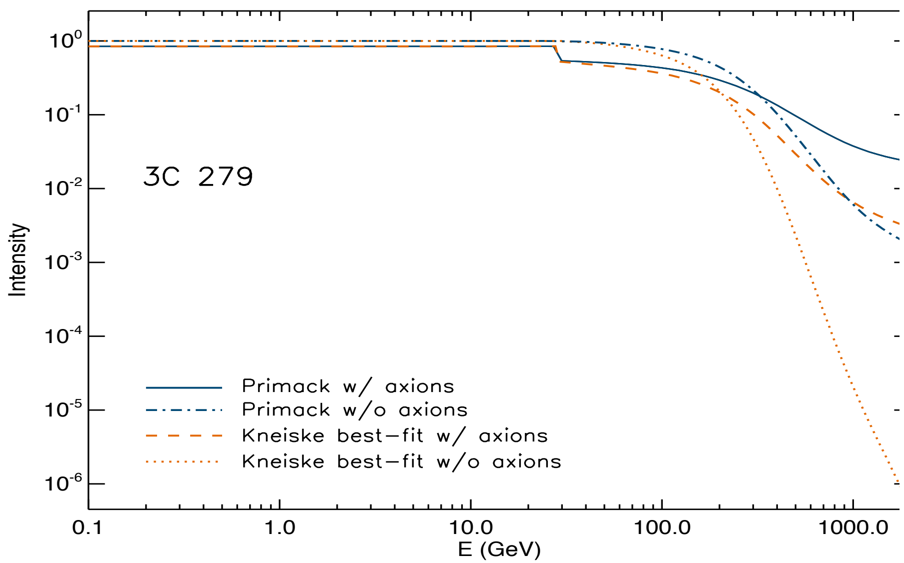
$E_{crit,source}$(3C) = 4.6 eV

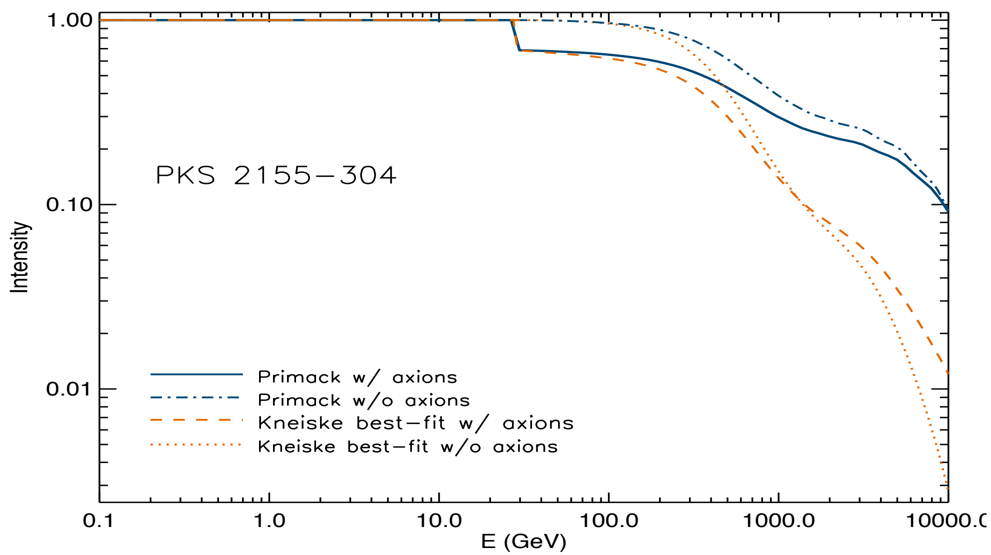
$E_{crit,source}$(PKS) = 69 eV

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

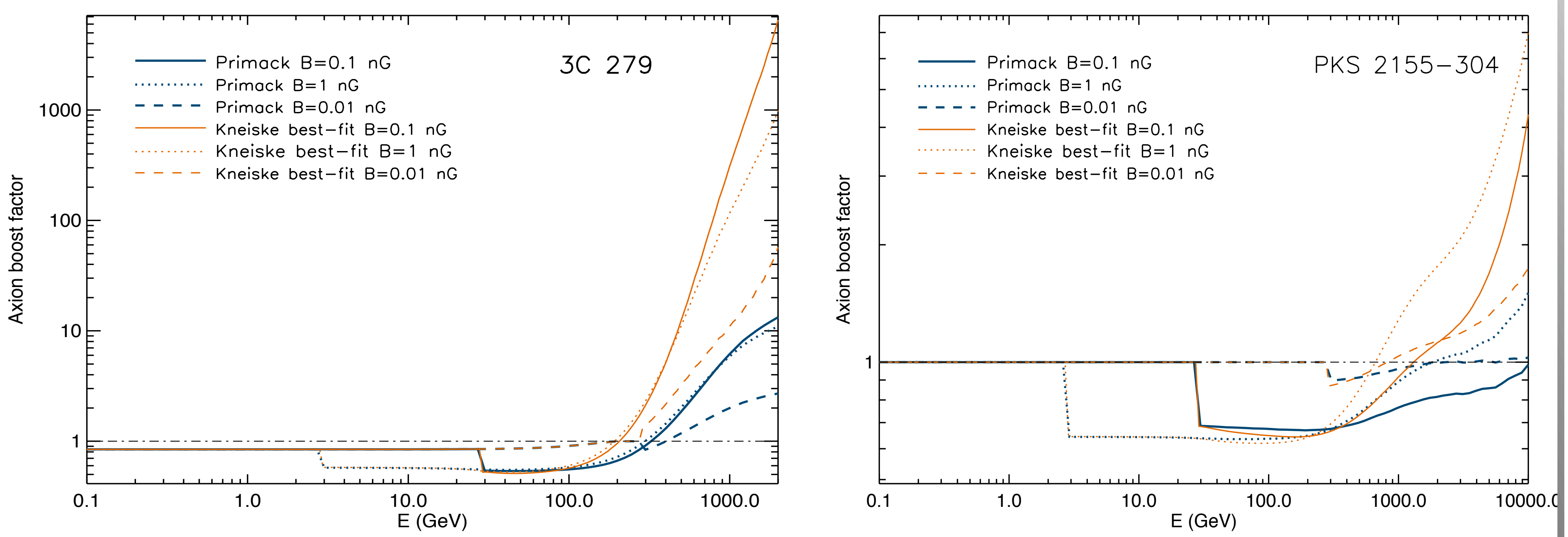
CAST limit

ultralight axions



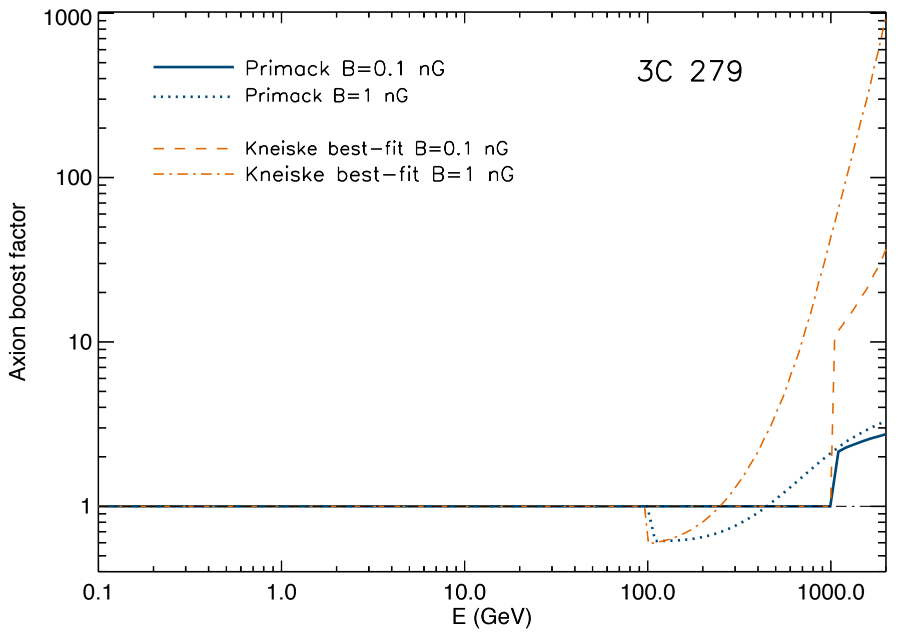


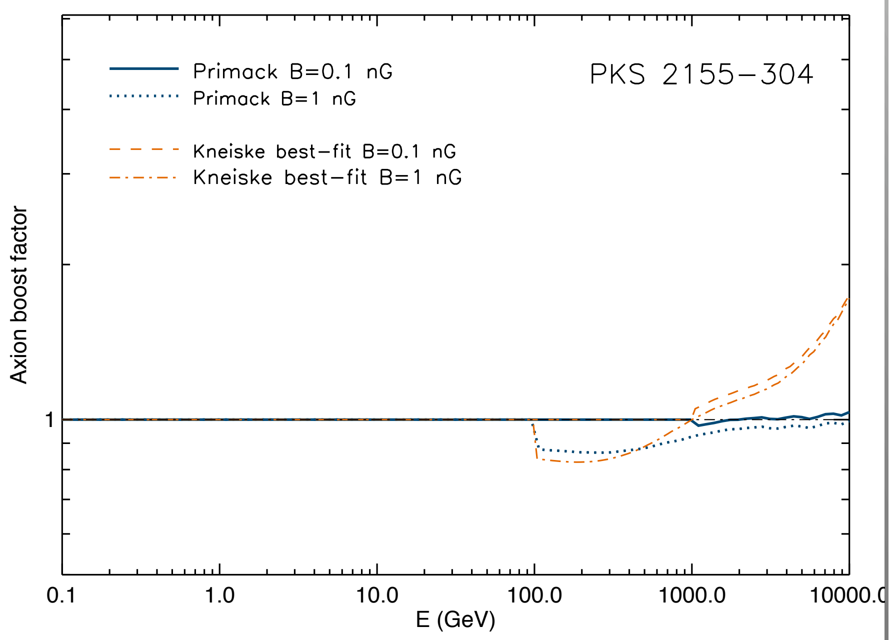
The impact of changing B



- 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





Detection prospects for Fermi and IACTs

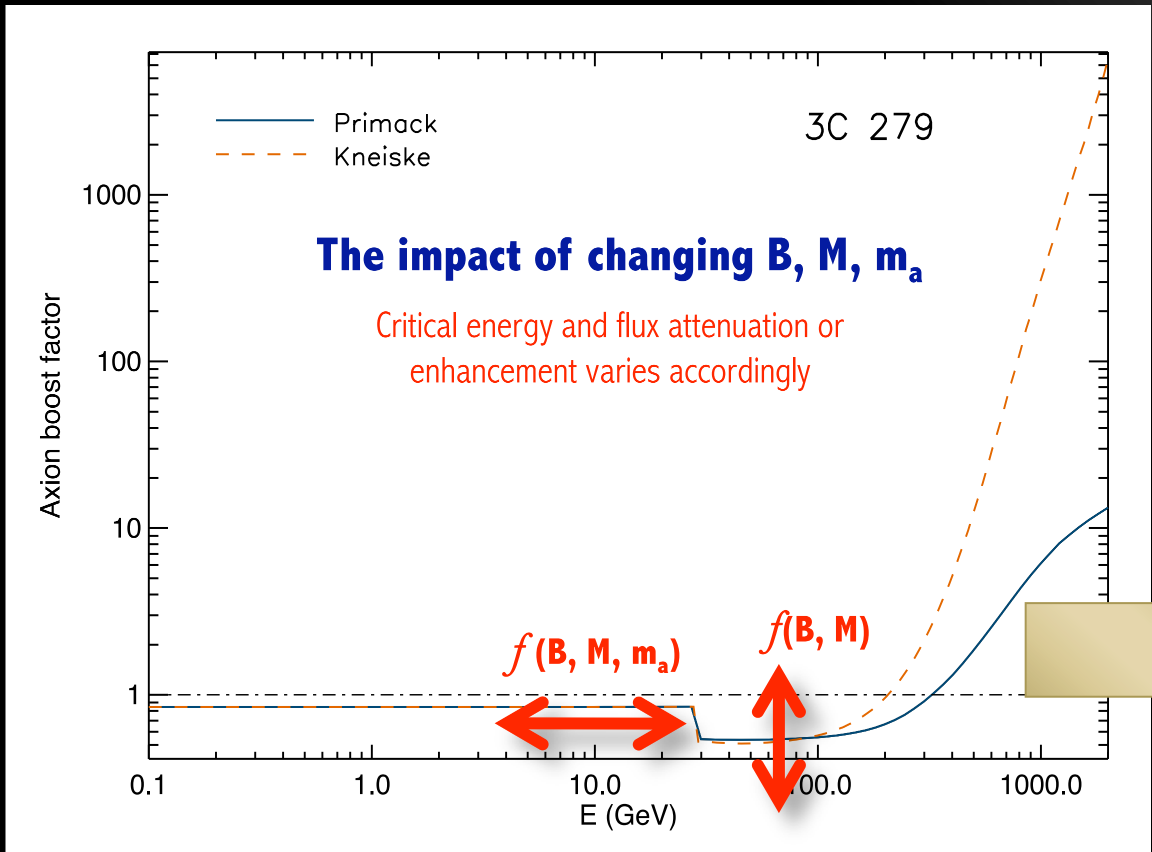
- If we accurately knew the intrinsic spectrum of the sources and/or the density of the EBL, we should be able to observationally detect axion signatures or to exclude some portions of the parameter space.

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

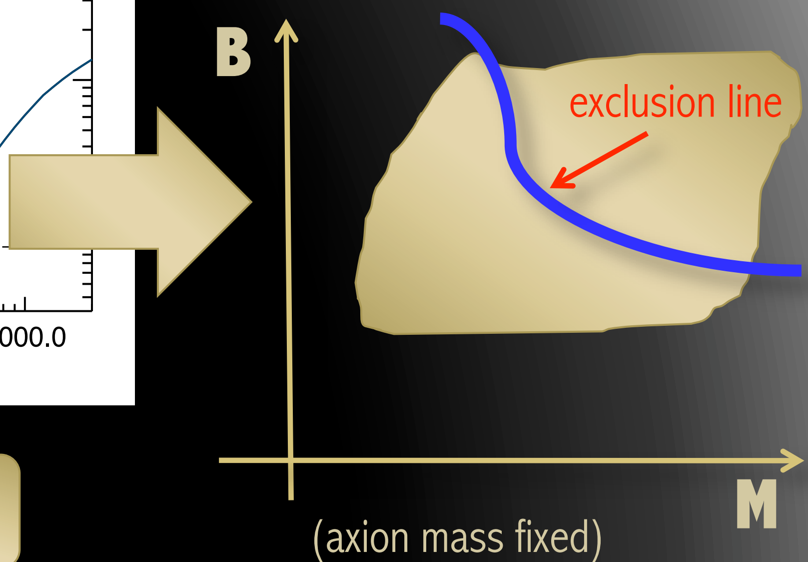
- Before going to axions:
  - Observe several AGNs located at different redshifts, as well as the same AGN undergoing different flaring states, from radio to TeV.
  - Try to describe the observational data with "conventional" theoretical models for the AGN emission and for the EBL.

- 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.

Constraints on B field and axion parameters



1. Search of e.g. the systematic drop at the SAME energy
2. Stacking analysis using different sources and periods
3. In parallel, simulations
4. Detection? If not, constrains on the parameter space



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

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