8th Patras workshop, 2012

Light Pseudo-scalar particles and γ-ray source spectra

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based on the work:

arXiv:1205.6428

Phys. Rev. D, 2012

Irregularity in gamma ray source spectra as a signature of axionlike particles

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Outline:

- Motivations: the opacity effect
  « How transparent is the universe » ?

- Axion Like Particles (ALPs) phenomenology

- Average Behavior in turbulent magnetic fields

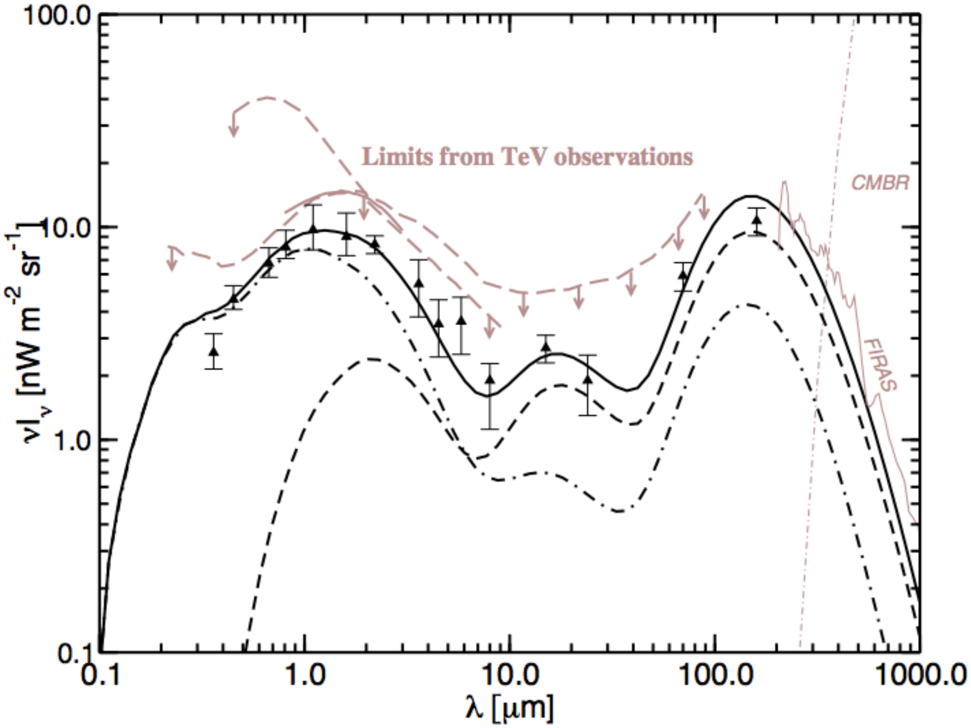
Originality of this work:

- Single source behavior in turbulent magnetic fields
- Spectral signature for single source observation
- Prospects for constraints

The opacity effect (1):

Extragalactic Background Light (EBL):

- 2 components: IR and UV peak
- Light from stars since beginning of the universe (UV peak)
- Absorbed by dust and reemitted (IR peak)



from Kneiske and Dole, A&A (2010), 515.

- Difficult measurements (zodiacal light)
- Uncertainty between models

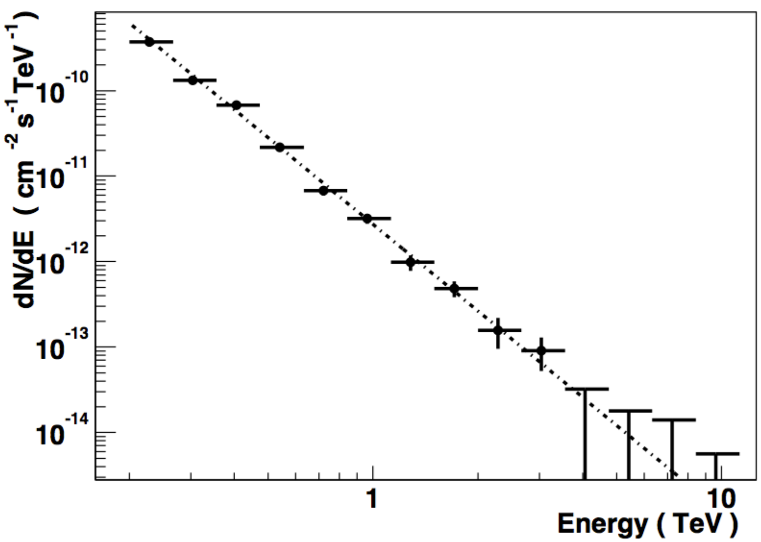
The opacity effect (2):

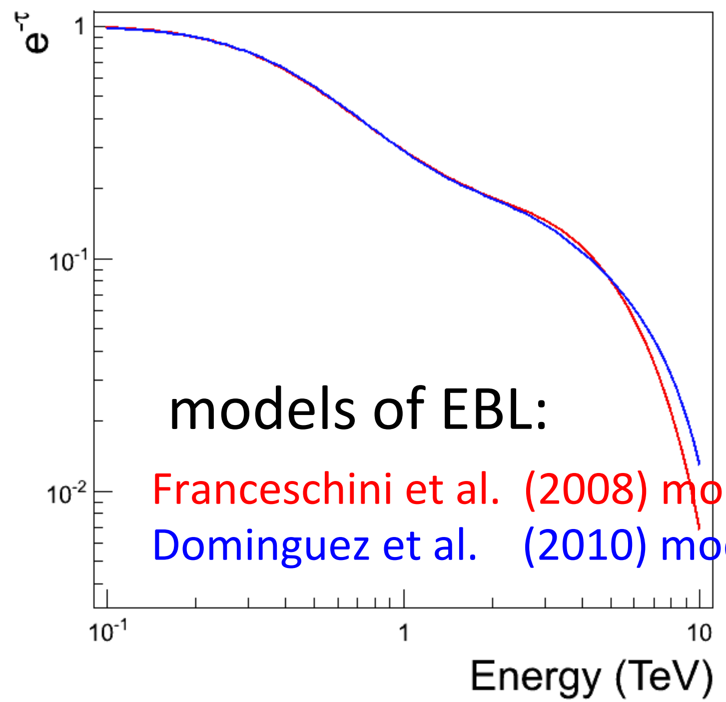
VHE γ-ray absorbed on EBL:

$$\gamma + \gamma_{EBL} \rightarrow e^+ + e^-$$

Spectrum and attenuation
for PKS 2155-304 (z = 0.116)

from H.E.S.S. Collaboration, A&A, 2004





- The universe becomes opaque at very high energies
- Imprint of absorption in γ-ray spectra (*Biteau et al., Gamma 2012 symposium*)

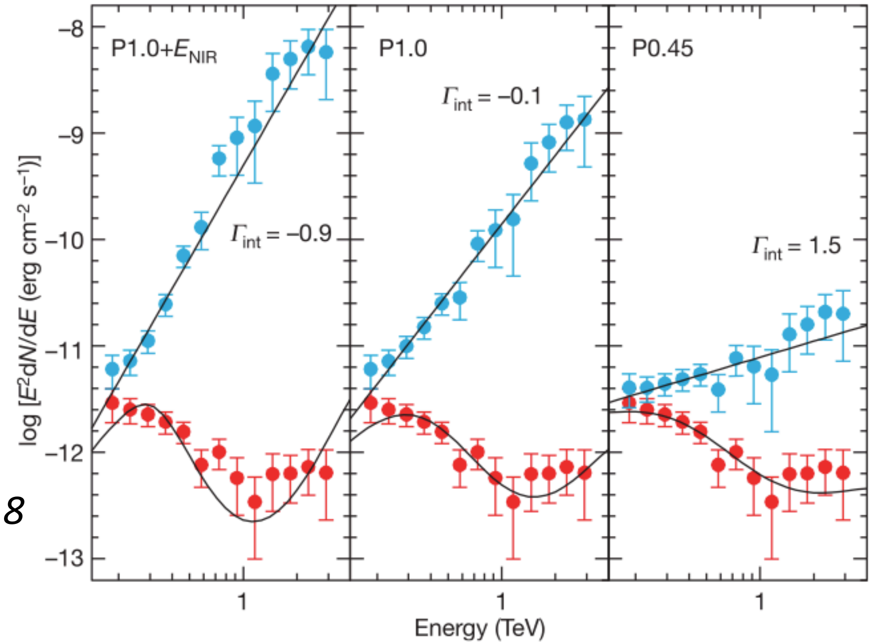
The opacity effect (3):

- 2006: H.E.S.S. observation of 2 AGNs at z = 0.165 and 0.186

Hard observed spectra

Intrinsic spectra not compatible with emission models ($\Gamma_{int} < 1.5$)

H.E.S.S. Collaboration, Nature (2006), 440, 1018



- 2008: MAGIC observation of 3C279 at z = 0.536

MAGIC Collaboration, Science (2008), 320, 1752

- 2012: H.E.S.S. observation of KUV 00311-1938 at z = 0.61

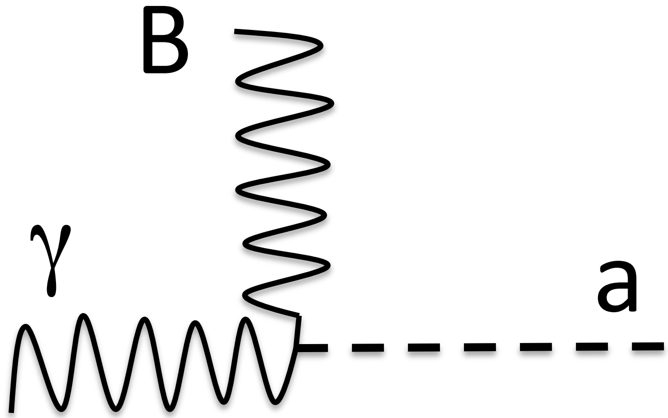
Becherini et al., Gamma 2012 symposium

The universe is more transparent than expected!

- Indication for a pair-production anomaly (see talk M. Meyer)

Phenomenology (1):

Axion – Photon coupling in a magnetic field:



Efficient coupling for $E > E_{\mathrm{thr}} = \frac{m_{\mathrm{a}}^2}{2gB}$

with $g_{a\gamma} = 8.10^{-11}$ GeV^{-1} (CAST upper limit) *CAST Collaboration, PRL, 2011*

B	m_a	E_{thr}
1 nG	1 neV	300 GeV
100 mG	10 μeV	300 GeV

Phenomenology (2):

- Equations of motion:

$$(E - i\partial_z + \mathcal{M}) \begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} = 0$$

- Mixing matrix $\mathcal{M} = \begin{pmatrix} \Delta_{11} - i\Delta_{\rm abs} & \Delta_{12} & \Delta_{\rm B}\cos\phi \\ \Delta_{21} & \Delta_{11} - i\Delta_{\rm abs} & \Delta_{\rm B}\sin\phi \\ \Delta_{\rm B}\cos\phi & \Delta_{\rm B}\sin\phi & \Delta_{\rm a} \end{pmatrix}$

ALP mass term $\Delta_a = -\frac{m_a^2}{2E}$

Photon – ALP coupling $\Delta_B = \frac{gB\sin\theta}{2}$

Two geometrical angles θ and ϕ

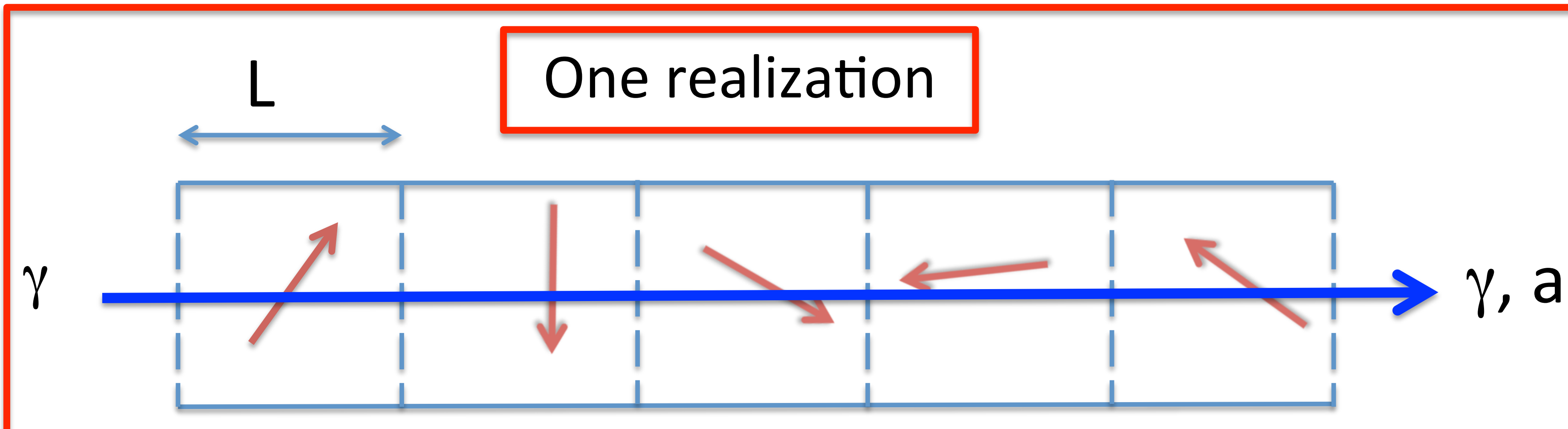
- Absorption of γ on background photons (EBL):

$$\Delta_{\rm abs} = \frac{\tau}{2L}$$

τ from *Kneiske and Dole, A&A (2010), 515.*

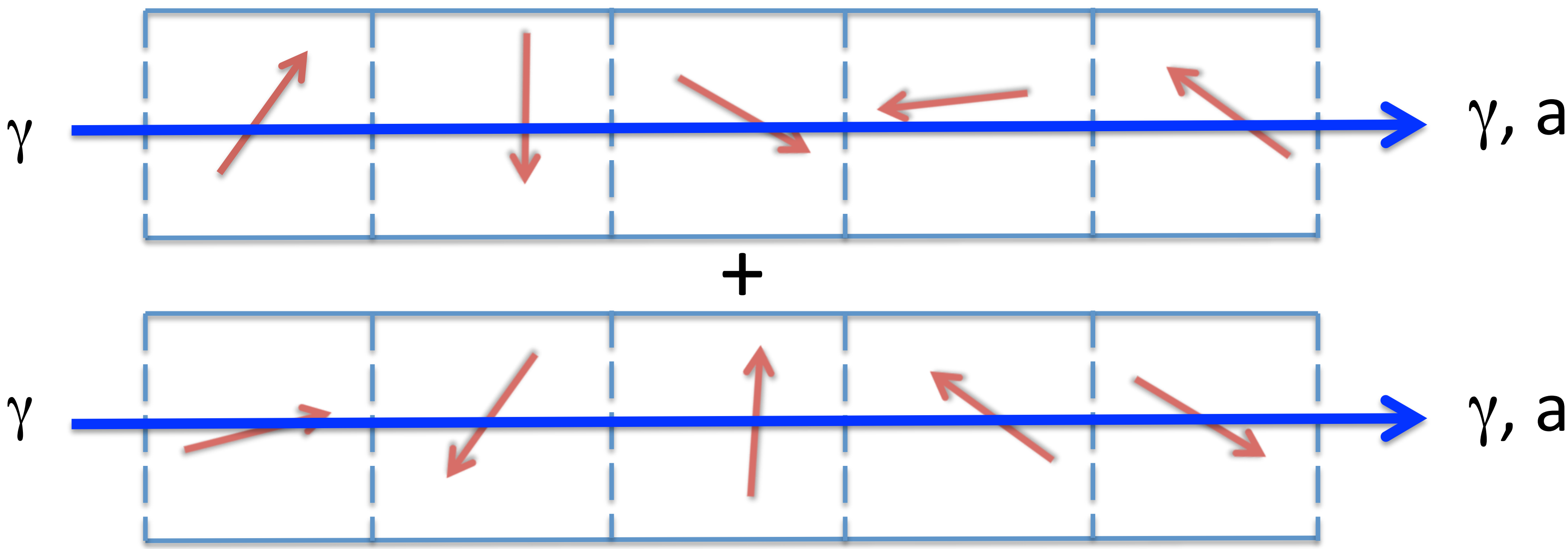
The Inter-Galactic Magnetic Field (IGMF):

- no measurements
- constraints: 10^{-16} G < B < 10^{-9} G
- turbulent: divide beam path in coherent domains
  - Typical size of domains: coherence length L ~ 1 Mpc
  - Equal field strength between domains
  - Different orientation for B per domain
  - Can also be described by Kolmogorov-like turbulence



Averaged behavior (1):

Averaging over many realizations:



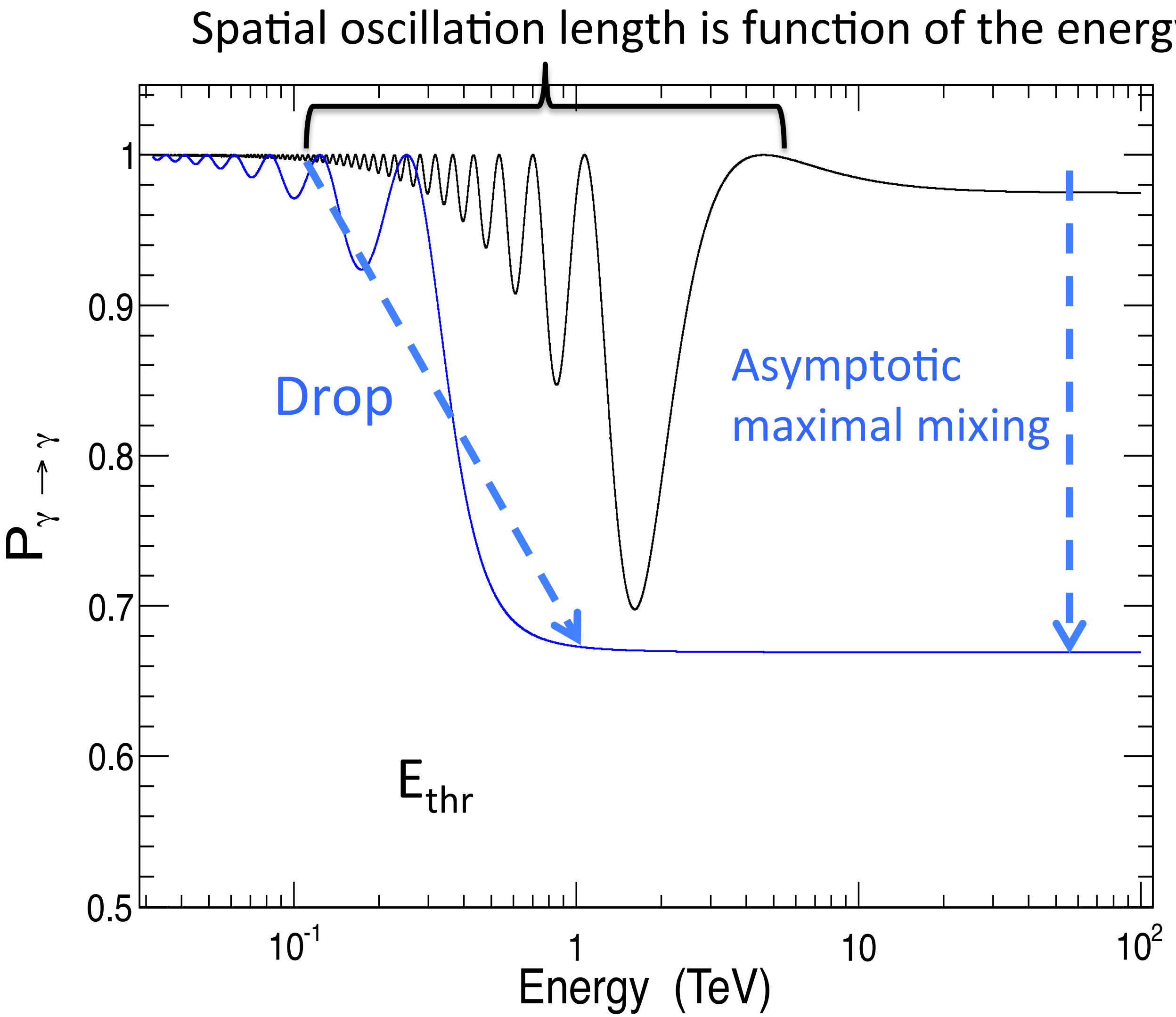
$$+ \ \ldots = \quad P_{\gamma\to a} = \frac{1}{3}\left(1 - e^{-3NP_{\gamma\to a}(1\ \mathrm{Domain})}\right)$$

Grossman et al. (2002) Phy. Lett. B

Maximal mixing of 1/3 for $N^*P_{\gamma\text{->}a}$(1Domain) -> ∞

Averaged behavior (2):

« Drop in spectra »   at threshold of coupling



Coherent B field

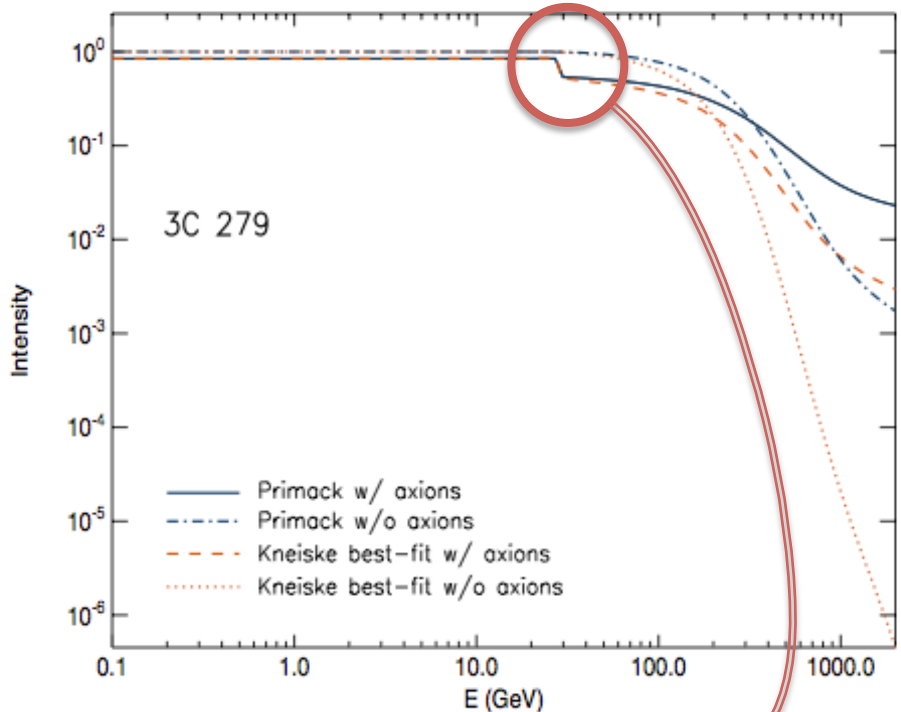
B = 1 nG
$g_{a\gamma}$ = 8 10^{-11} GeV^{-1}
m_a = 2 neV
s = 10 Mpc

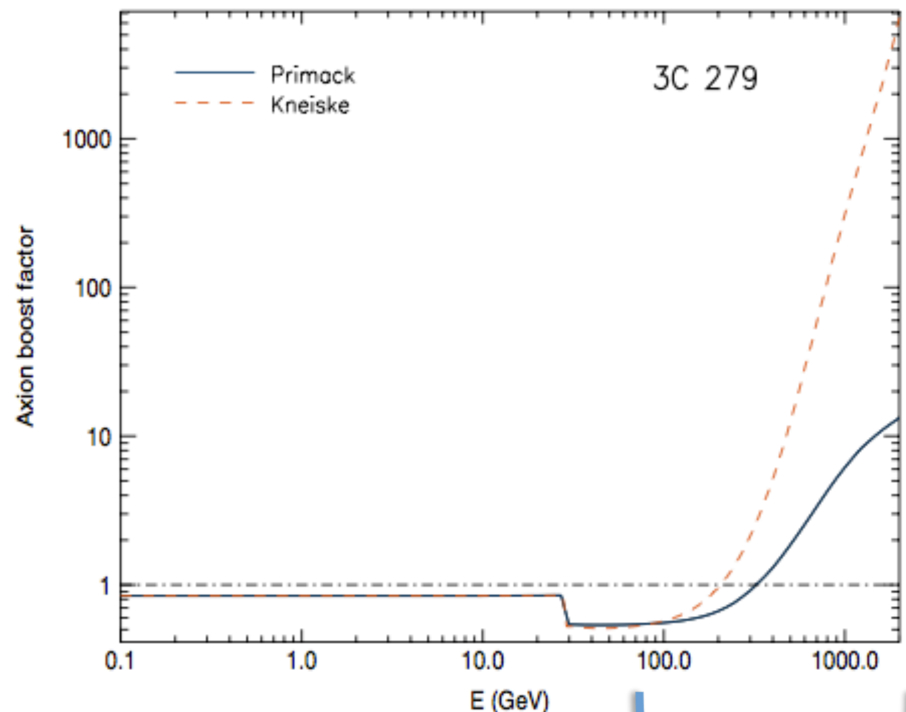
Turbulent B field with 10 domains

Averaged behavior (3):

- Universe is more transparent with ALPs

(Sanchez-Conde et al. 2009) *PRD (2009), 79*



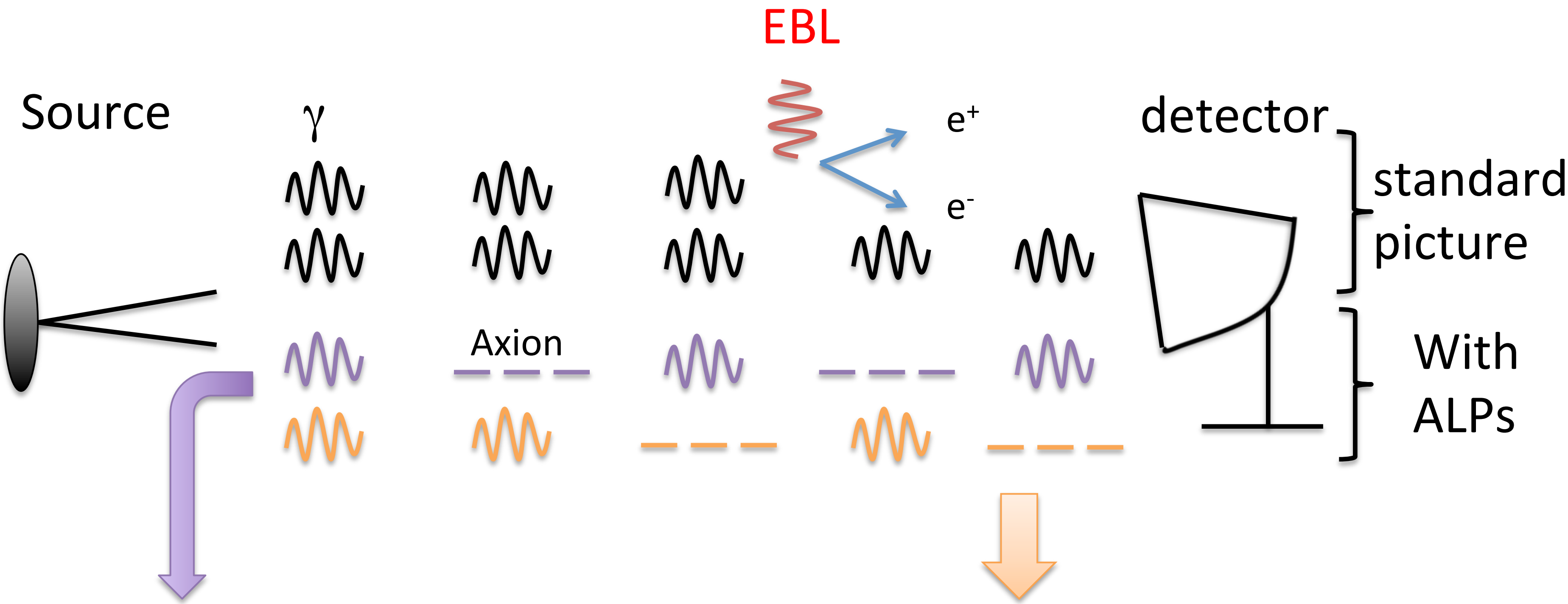


Averaged behavior:

- Drop
- Enhancement at Very High Energies (VHE)

Not realistic for one single source

ALPs and the opacity effect (1):

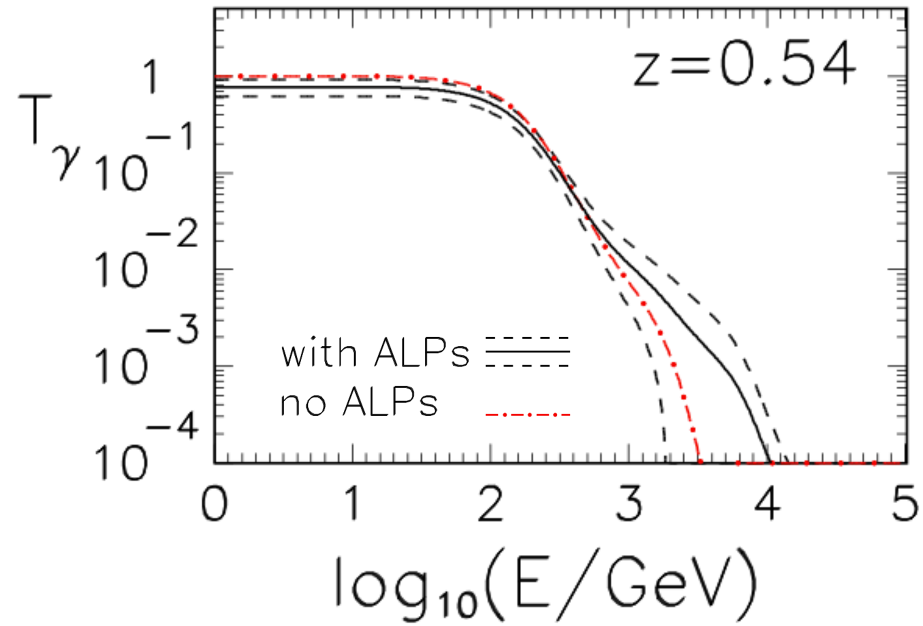


- Enhancement of the flux … or further attenuation!

ALPs and the opacity effect (2):

Mirizzi et Montanino (2009):
enhancement or attenuation, depends on the realization of the magnetic field

from A. Mirizzi and D. Montanino, JCAP 12, 4 (2009)

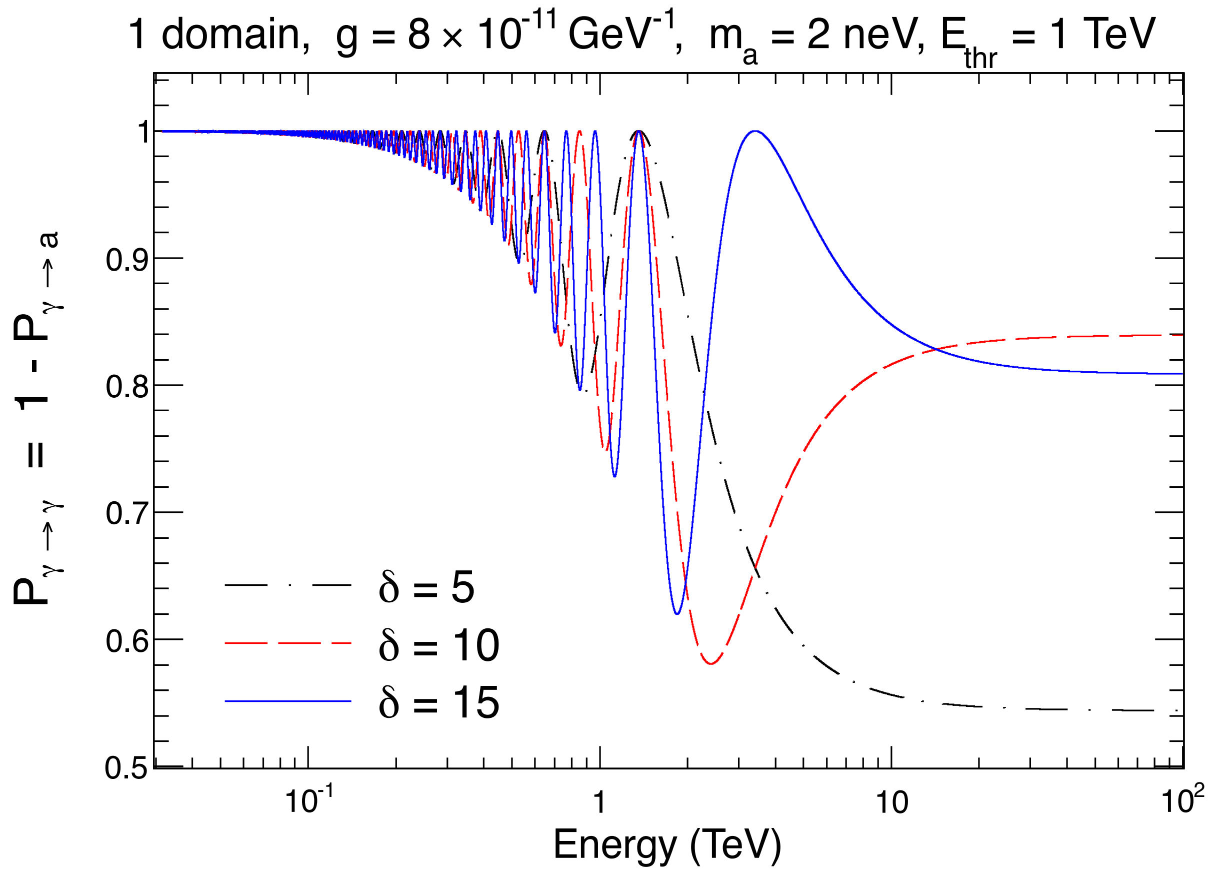


➡ First study of the dependence on the random realizations

Spectral signature for single source observations?

Behavior for one realization:

- One domain transfer function: Spectral Oscillation pattern



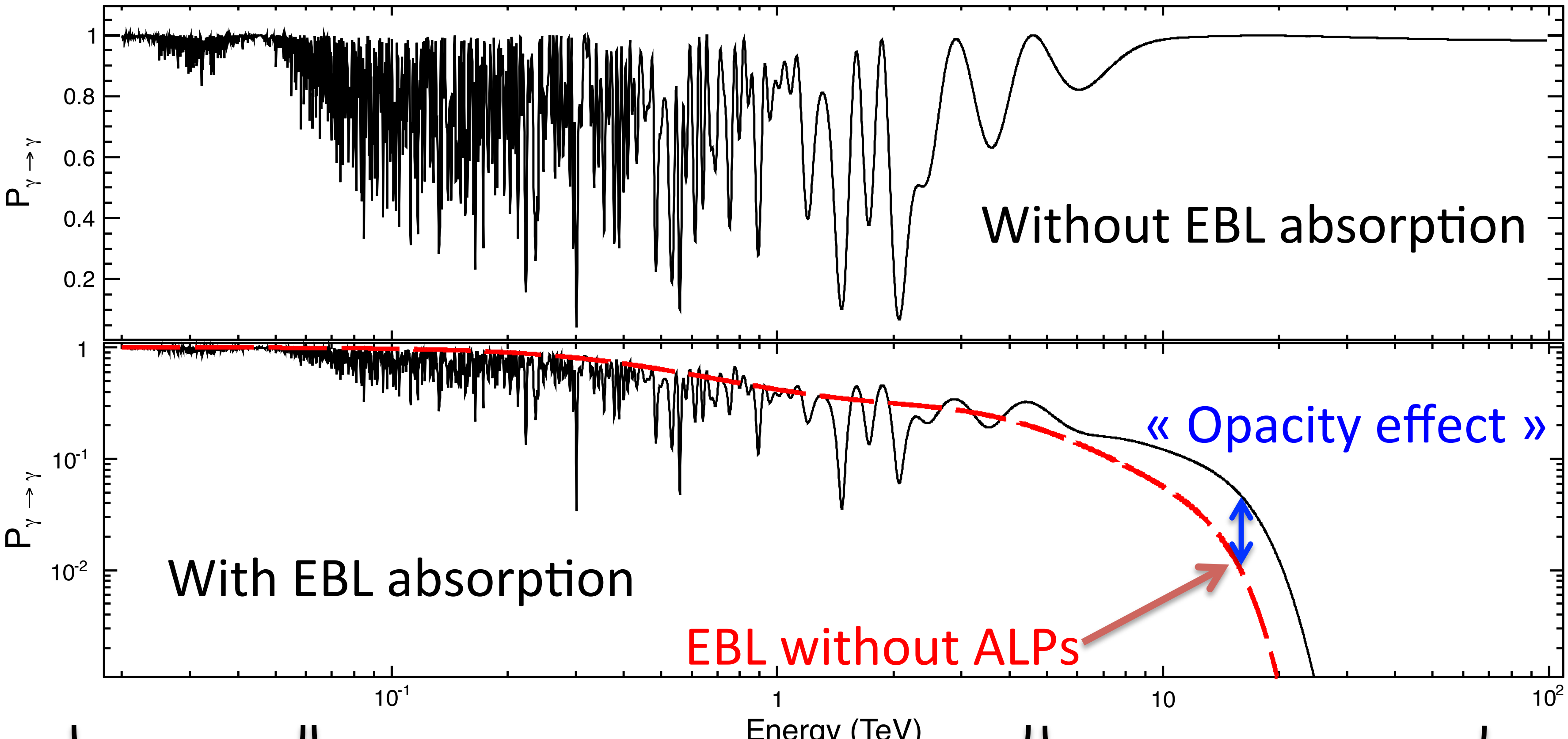
- Global transfer function = Π individual transfer functions

➡ Spectral oscillations interfere

Spectrum for one random realization:

Conversion in Inter-Galactic Magnetic Field:

- Source at redshift 0.1
- $g = 8\ 10^{-11}\ \text{GeV}^{-1}$, $m_a = 2$ neV, B = 1 nG , L = 1 Mpc



Smooth - Noisy - Smooth behavior

Experimental simulation (1):

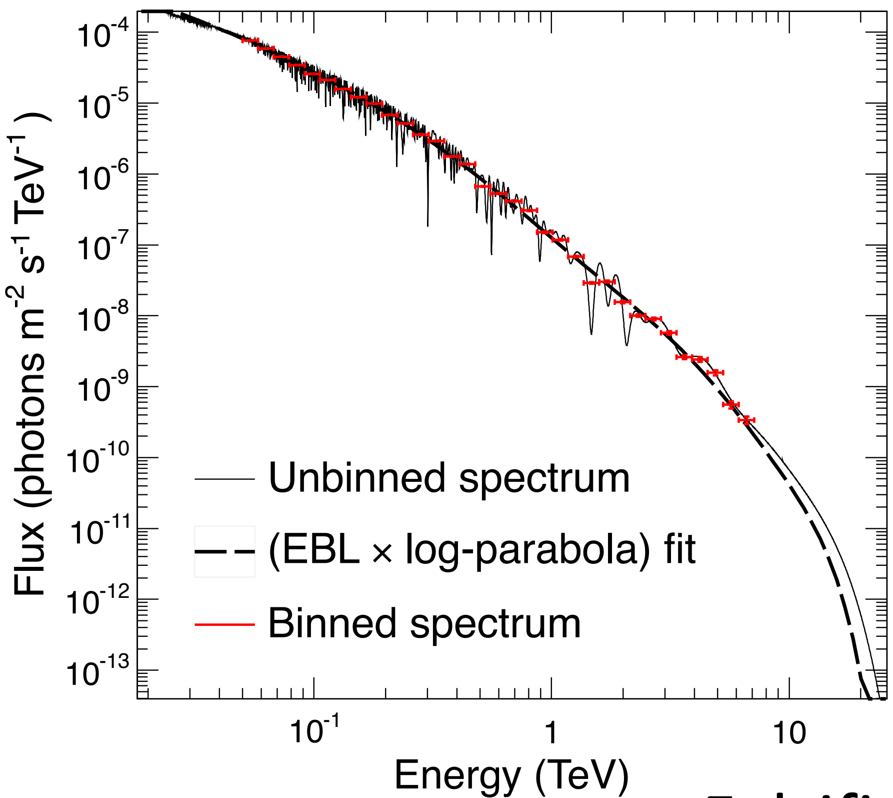
- TeV γ-ray astronomy: ground based Cherenkov telescopes.
- Effective area ~ 10^5 m^2 between 100 GeV and 10 TeV
- Energy resolution ~ 15%
- Angular resolution ~ 0.1 deg
- Typical sources: Pulsars Nebulae, Supernovae remnants…(galactic) and Active Galactic Nuclei (extra-galactic)

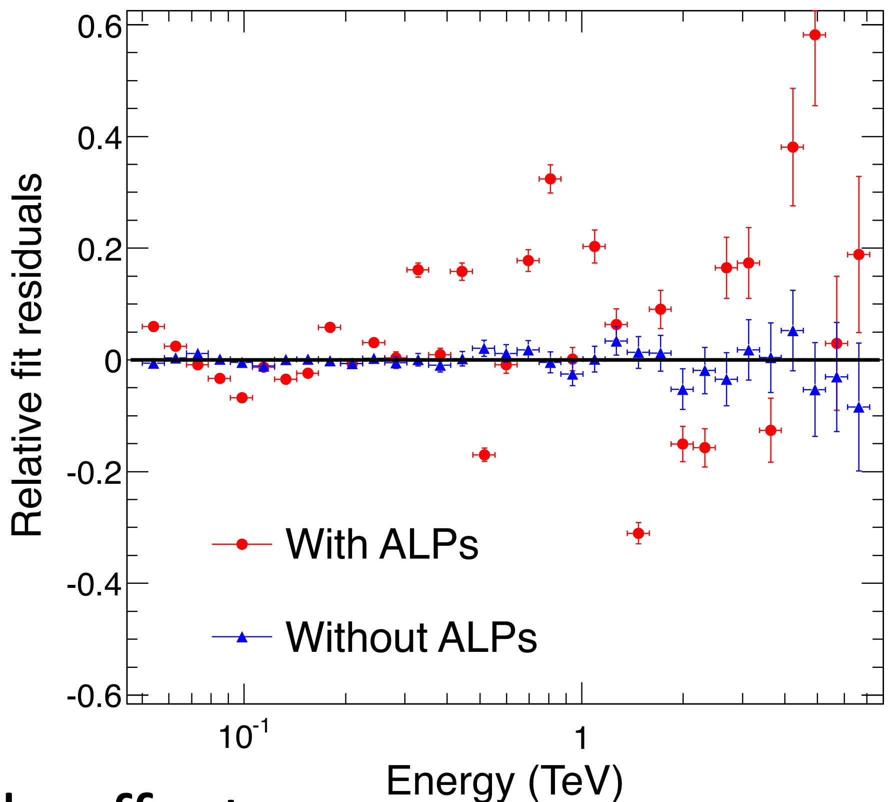
Picture of 2 H.E.S.S. telescopes

Experimental simulation (2):

- Intrinsic source spectrum: log-parabola
- Observed spectrum: log-parabola*EBL*ALP factor
- Fit of binned observed spectrum with log-parabola*EBL

→ Residuals





Falsifiable effect

The spectral signature:

- Alternation of smooth-noisy-smooth behavior in energy

- Variance of fit residuals ± statistical variance over 5000 random realizations of the magnetic field

Constant size domains turbulence

Model	Variance of the fit residuals
No ALP	0.04 ± 0.01
$g = 10^{-11}$, $m = 0.35$	0.11 ± 0.04
$g = 8 \times 10^{-11}$, $m = 1$	0.20 ± 0.05

Kolmogorov-like turbulence

Model	Variance of the fit residuals
$g = 10^{-11}$, $m = 0.35$	0.18 ± 0.05
$g = 8 \times 10^{-11}$, $m = 1$	0.42 ± 0.14

⇨ variance ↗ when gB ↗

Summary and outlooks (1):

Averaged Behavior with ALPs:

- Drop in spectrum
- Universe more transparent

Single source behavior with ALPs:

- Smooth-Noisy-Smooth spectrum
- Universe not necessarily more transparent

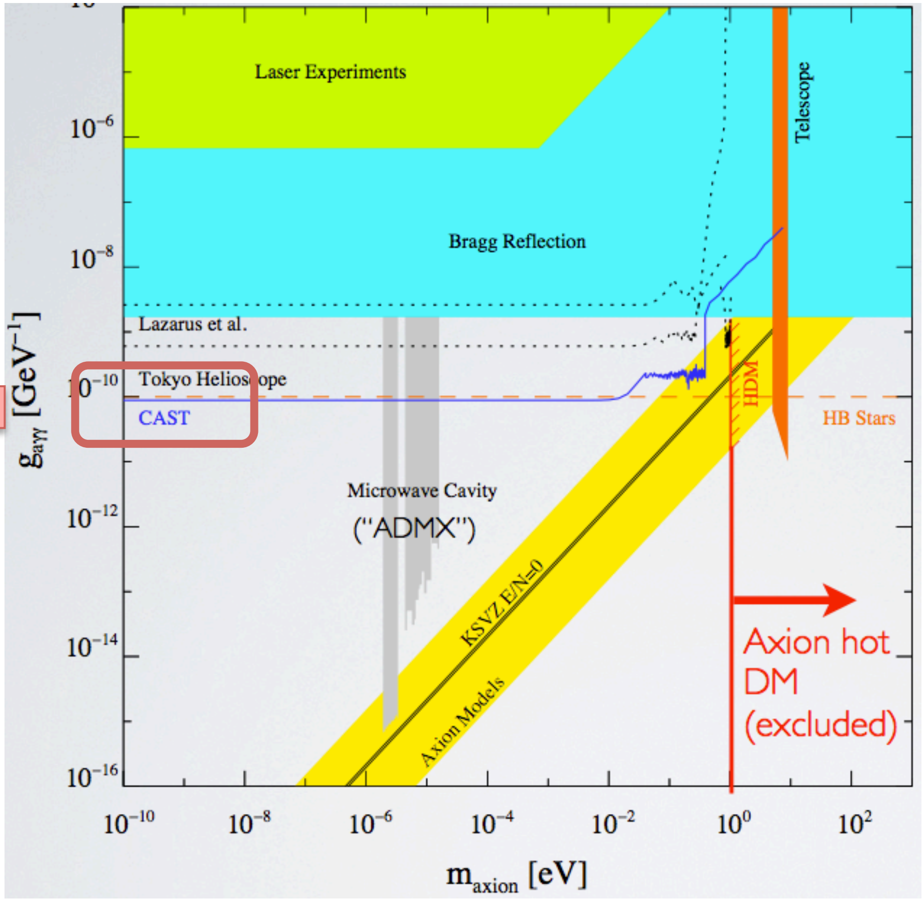
Prospects for detection:

- If anomalously noisy spectrum: take more data
- Deviant bins should strengthen if ALPs are involved
- Look at VHE for smoothness

Summary and outlooks (2):

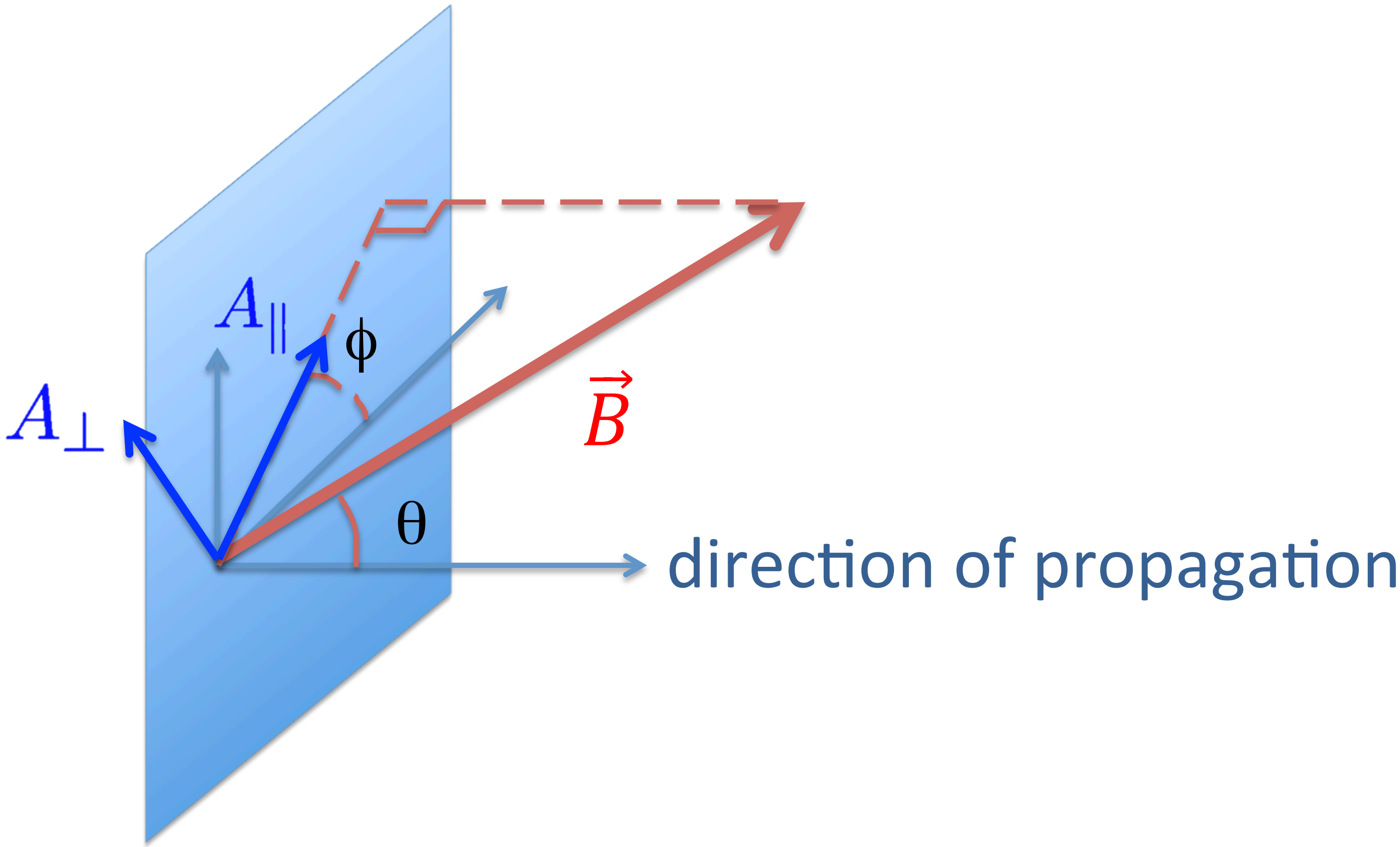
- Prospects for constraints:
  - Pick one source with good statistic
  - Turbulent magnetic field (inside the source or IGMF)
  - Estimate the level of noise and compare with MC

γ-ray astronomy accessible



from Battesti et al. (2007):
« Axion searches in the past, at present and in the near future »

Coupling and photon polarization:



- Transverse component of B couples: angle θ
- Photon: Parallel to B polarization couples: angle ϕ