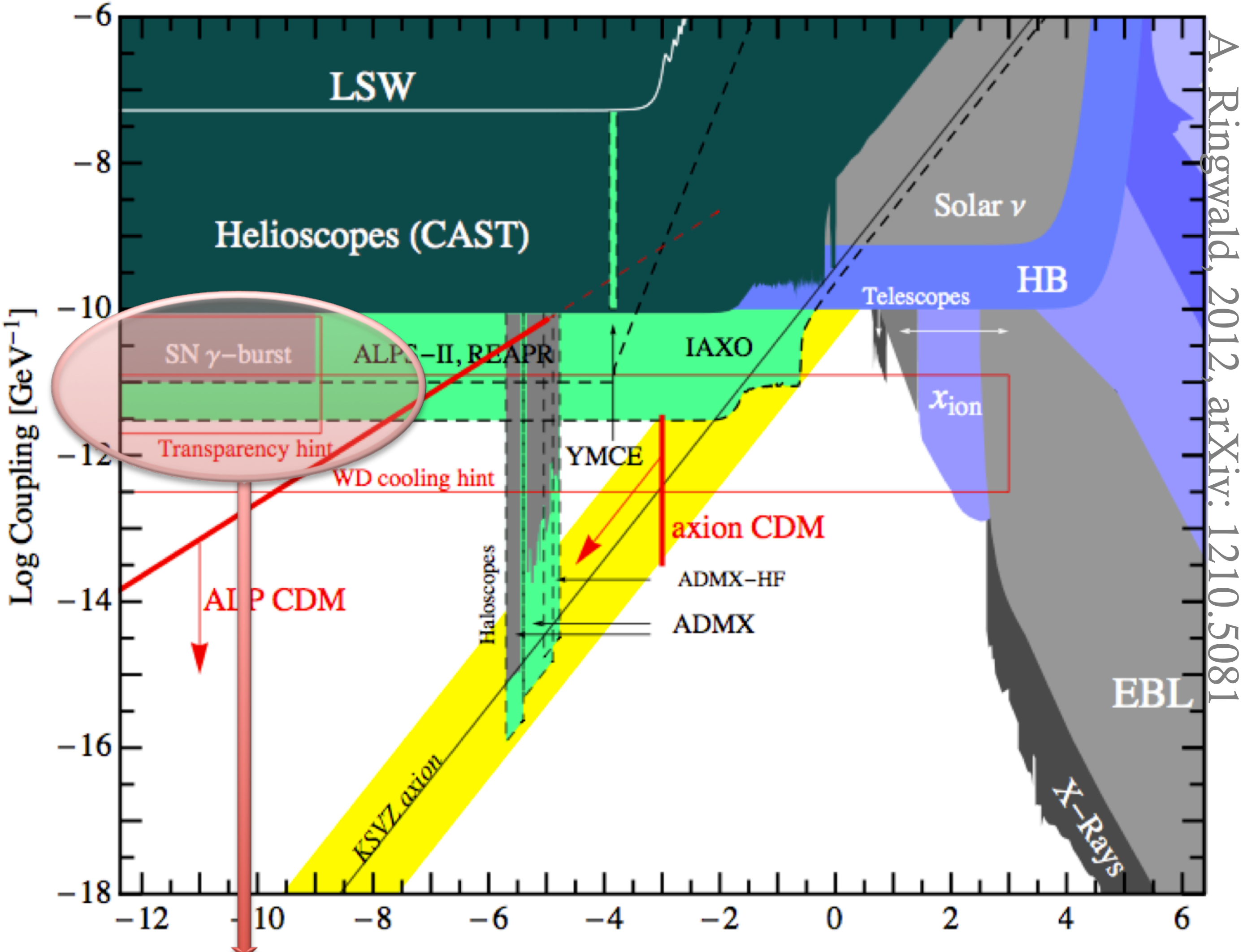
Axion-like particles in the high energy universe

Denis Wouters

Which ALPs ?



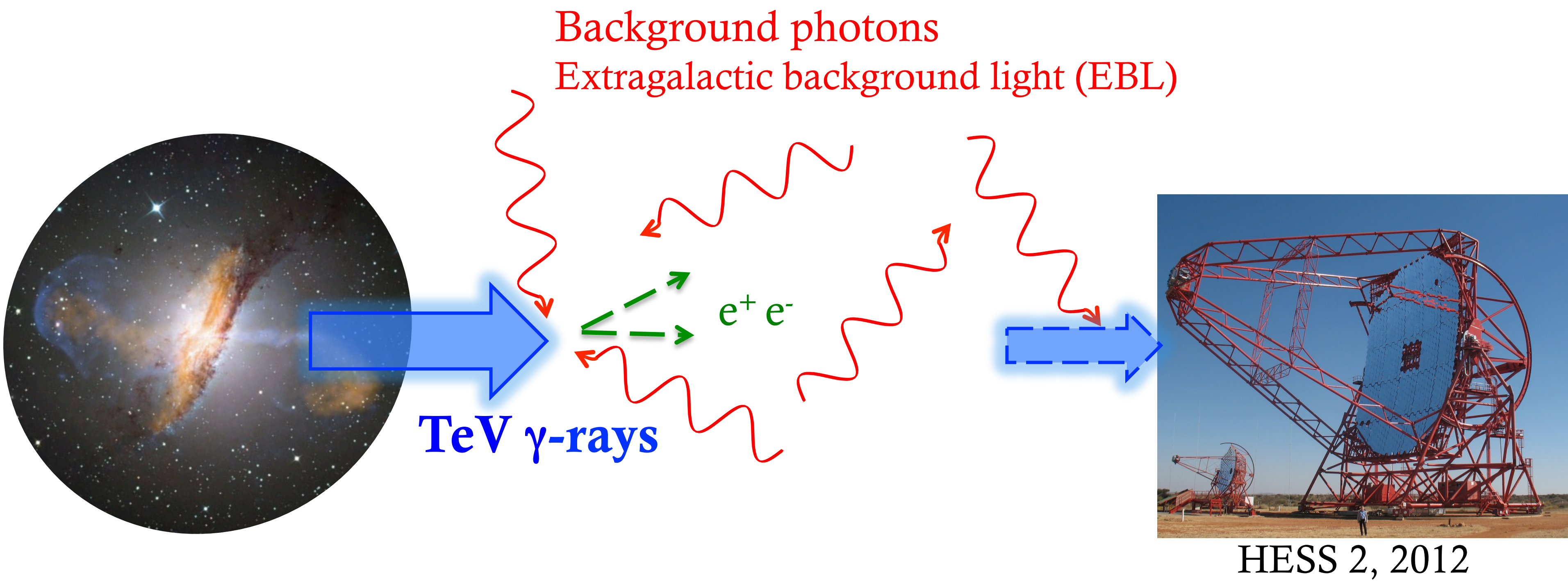
Low mass ALPs

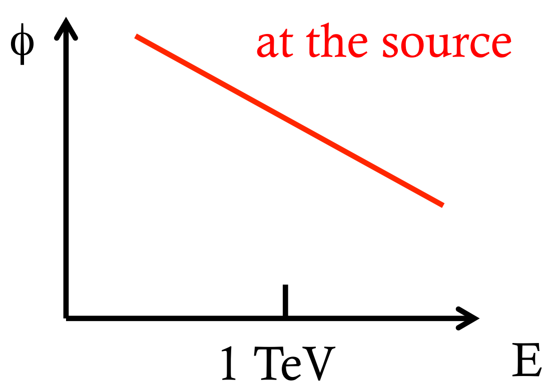
« Transparency hint »

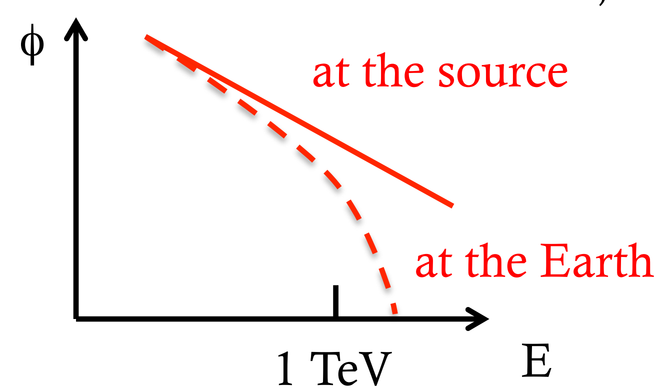
Transparency hint?

Gould & Schréder, 1967, Phys. Rev.
Stecker, de Jager, Salamon, 1992, ApJ Lett.

- Universe opaque at very high energies (VHE, E ~ 1 TeV)





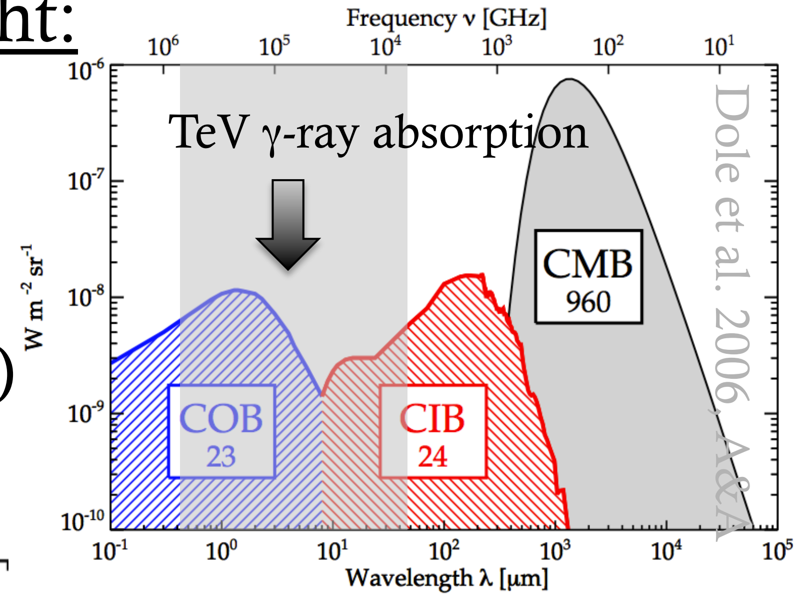


The Extragalactic Background Light:

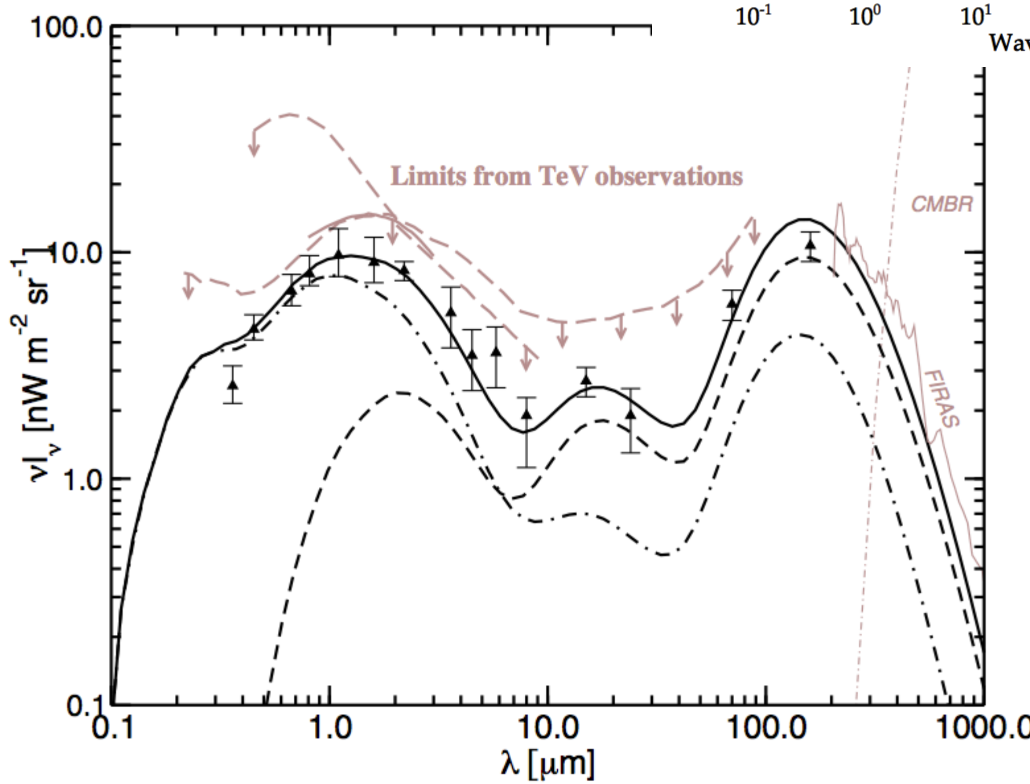
- Optical background (COB)
- hard to measure

(foreground emission from Milky Way)

- Various models, uncertainties



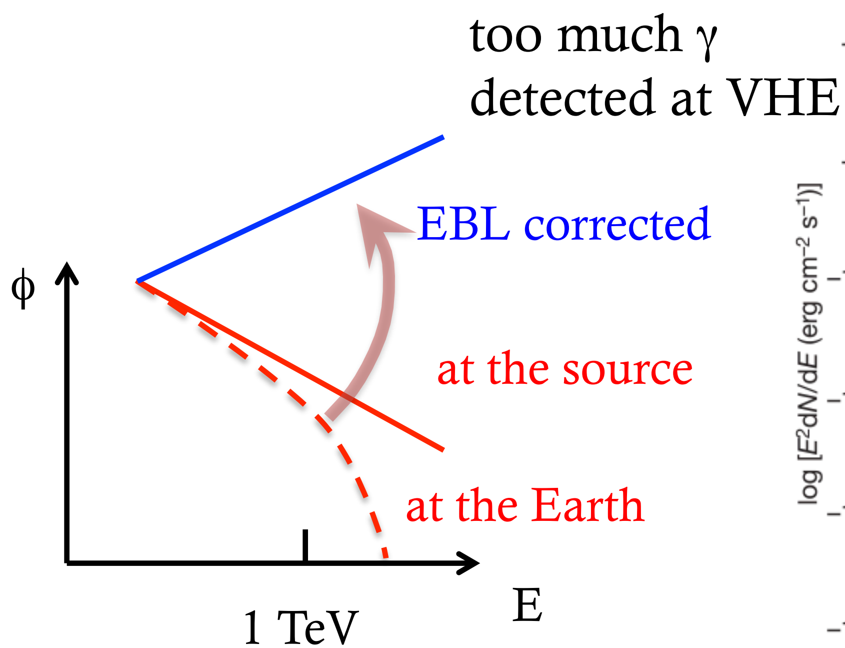
Dole et al. 2006, A&A

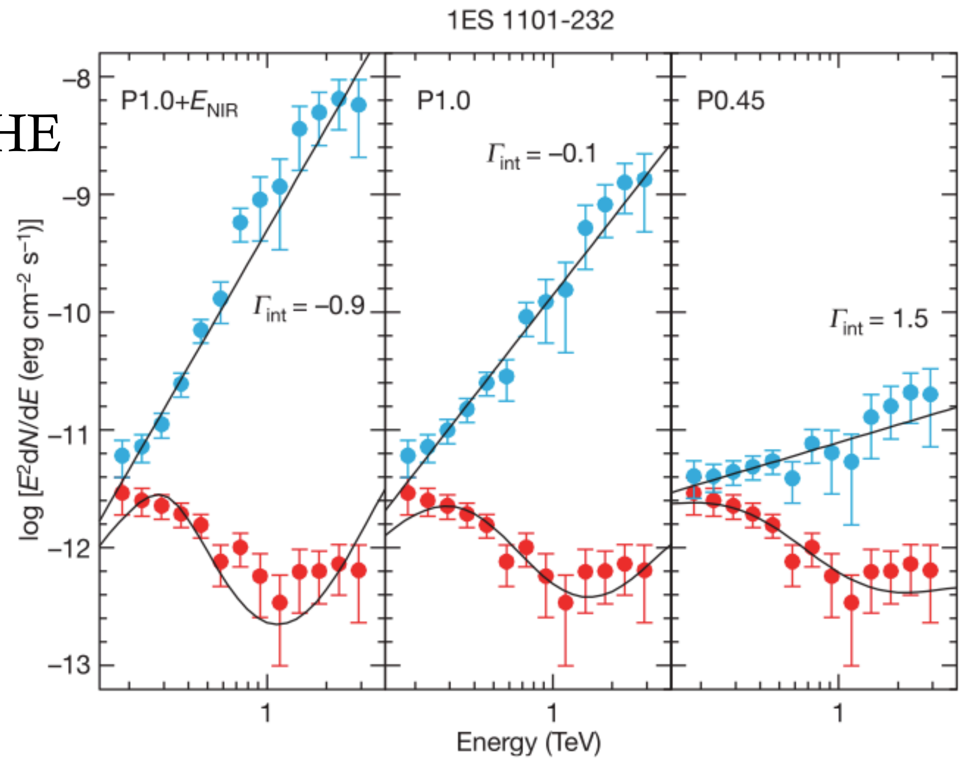


Kneiske & Dole, 2010, A&A

Universe too transparent?

- 2006: H.E.S.S. observations of 2 sources at z = 0.165, 0.186





HESS Collaboration, 2006, Nature

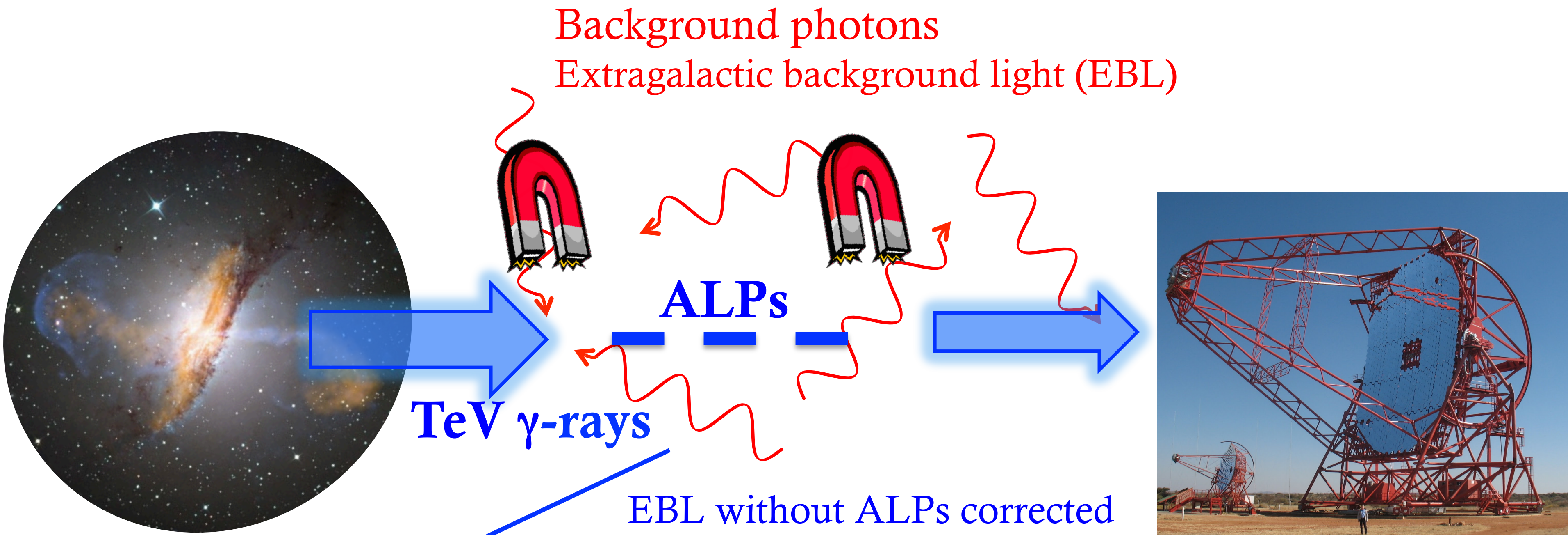
- 2008: MAGIC observation of 3C279 at z = 0.536

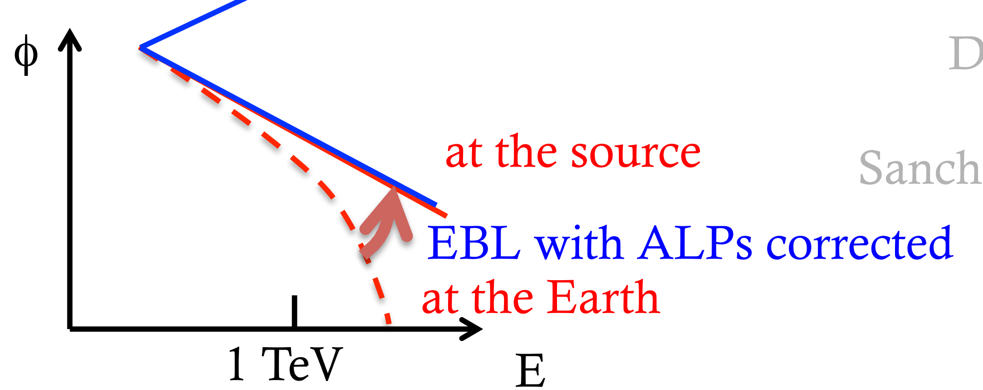
MAGIC Collaboration, 2008, Science

The universe is more transparent than expected!

ALPs can explain this effect:

- γ-ALP oscillations in intergalactic magnetic field (IGMF)
- ALPs not absorbed by EBL





De Angelis et al. 2007, PRD
Simet et al. 2008, PRD
Sanchez Conde et al. 2009, PRD

γ-ALP mixing:

$$\begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix}$$

- Two photon polarization states, one ALP state
- Optical depth of photons on the EBL
- No plasma correction, Faraday rotation, Birefringence

Mixing matrix:

Projection on polarization axis

$$\begin{pmatrix} -i\frac{\tau}{2s} & 0 & \frac{gB}{2}\sin\theta\cos\phi \\ 0 & -i\frac{\tau}{2s} & \frac{gB}{2}\sin\theta\sin\phi \\ \frac{gB}{2}\sin\theta\cos\phi & \frac{gB}{2}\sin\theta\sin\phi & -\frac{m^2}{2E} \end{pmatrix}$$

EBL absorption

γ-ALP coupling with transverse component of B

ALP mass

Csaki et al. 2005, JCAP

Coherent magnetic field:

- Magnetic field: Uniform orientation and strength
- Turn-off EBL absorption (for the moment)
- Conversion in domain of size s:

δ

$$P_{\gamma\to a} = \frac{1}{2} \frac{1}{1+\frac{E_c^2}{E^2}} \sin^2\left(\boxed{\frac{gBs\sin\theta}{2}}\sqrt{1+\frac{E_c^2}{E^2}}\right)$$

- Effect is energy dependent. Critical energy $E_c = \frac{m^2}{2gB\sin\theta}$
  - E << E_c : No conversion
  - E ~E_c : spatial oscillations, energy dependent
  - E >> E_c : spatial oscillations, energy independent

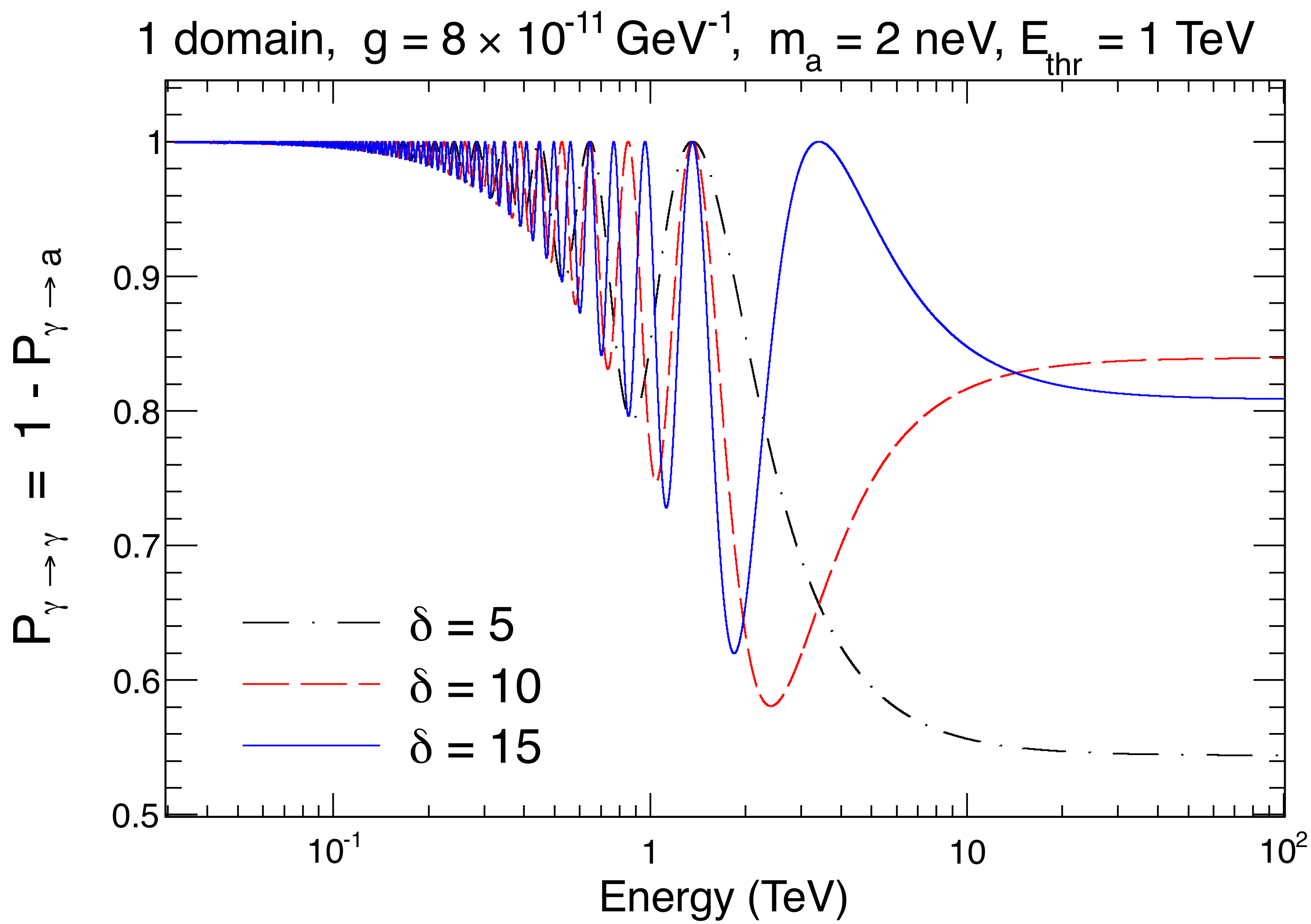
Hochmuth & Sigl, 2007, PRD

- δ : strength of the coupling ⇔ Hillas criterion (max. Bs)

Hooper & Serpico, 2007, PRL

Coherent magnetic field:

- Example for different values of δ:

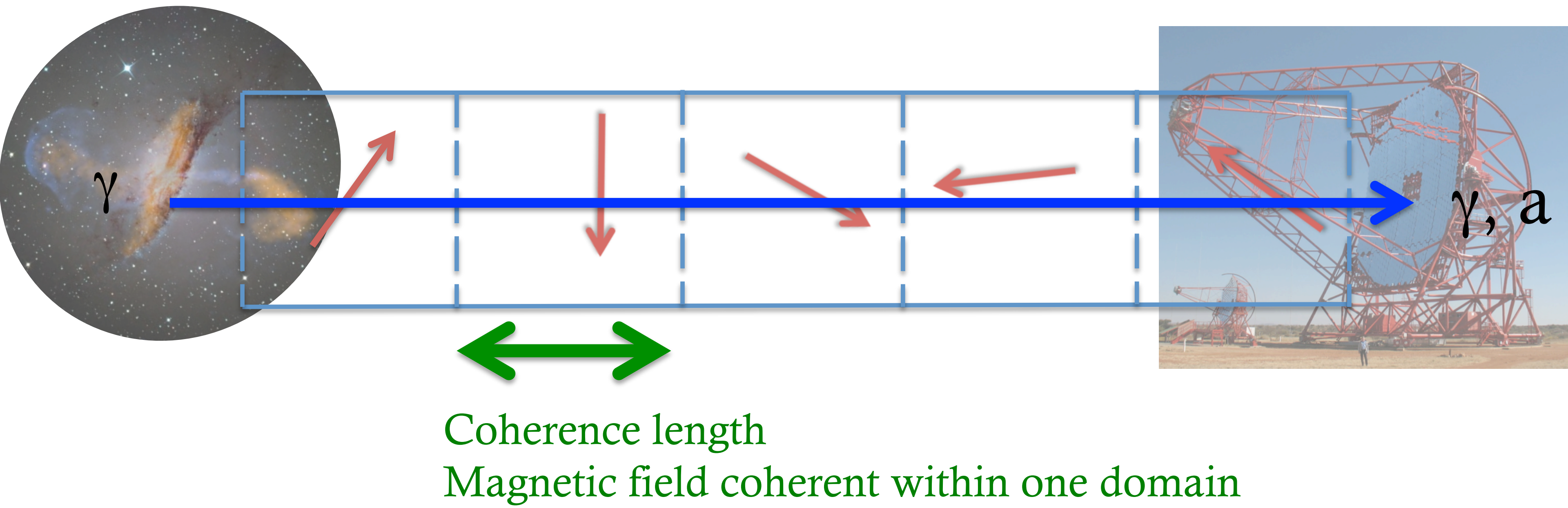


Wouters & Brun, 2012, PRD

- Unpredictable attenuation at high energies

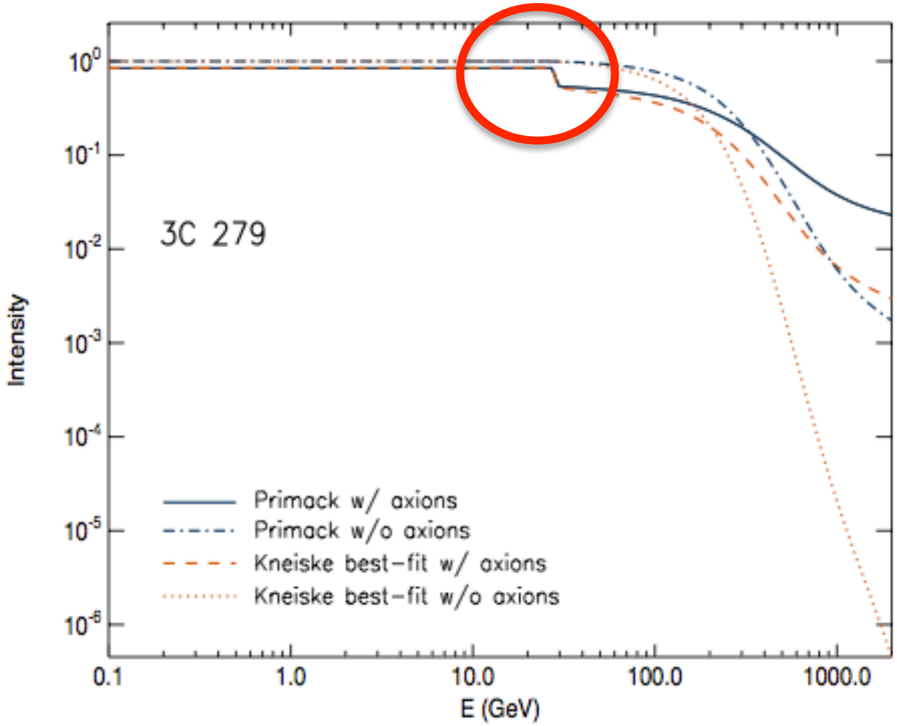
Astrophysical magnetic fields:

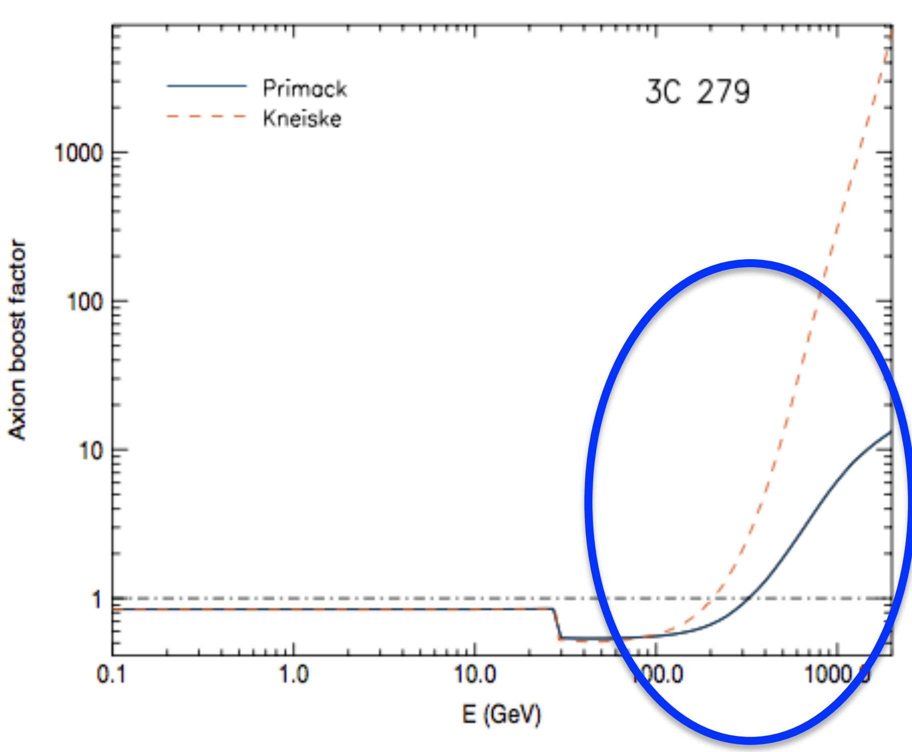
- Various magnetic fields:
  - Milky-way
  - Intergalactic Magnetic Field (IGMF)
  - Cluster of galaxies
- Not coherent: turbulence
- Naive representation of the turbulence:



Averaged behavior:

- Behavior for average over all possible realizations of B
- Two effects in the spectrum:
  - Drop of 1/3 at E_c
  - Boost at high energies due to non-EBL absorption of ALPs



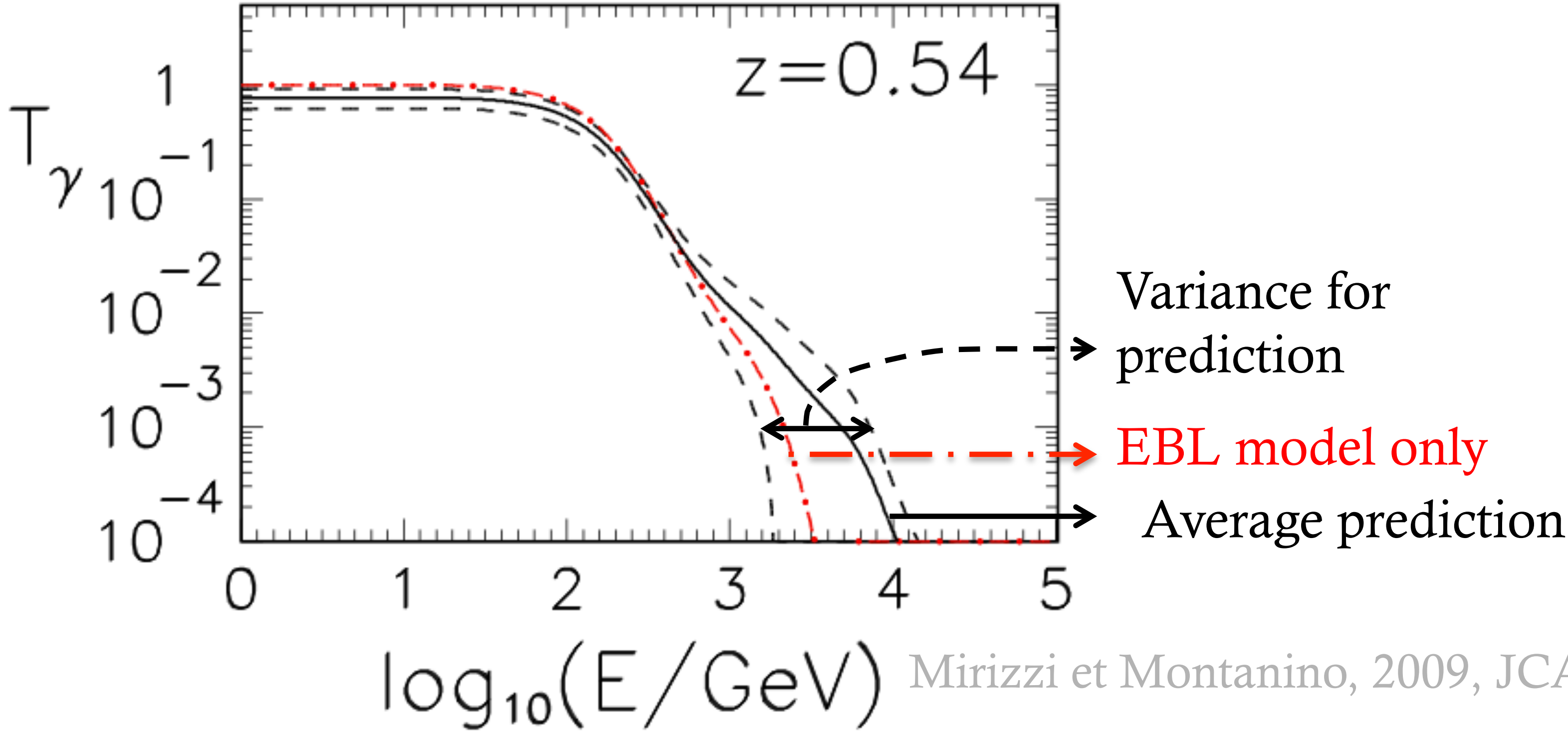


Sanchez Conde et al. 2009, PRD

For one realization:

- Average behavior ➡ Average over many sources
- Not available at TeV energies: ~ 10 sources.
- ALP mixing random process: variance of the prediction?

universe can be more transparent or more opaque!

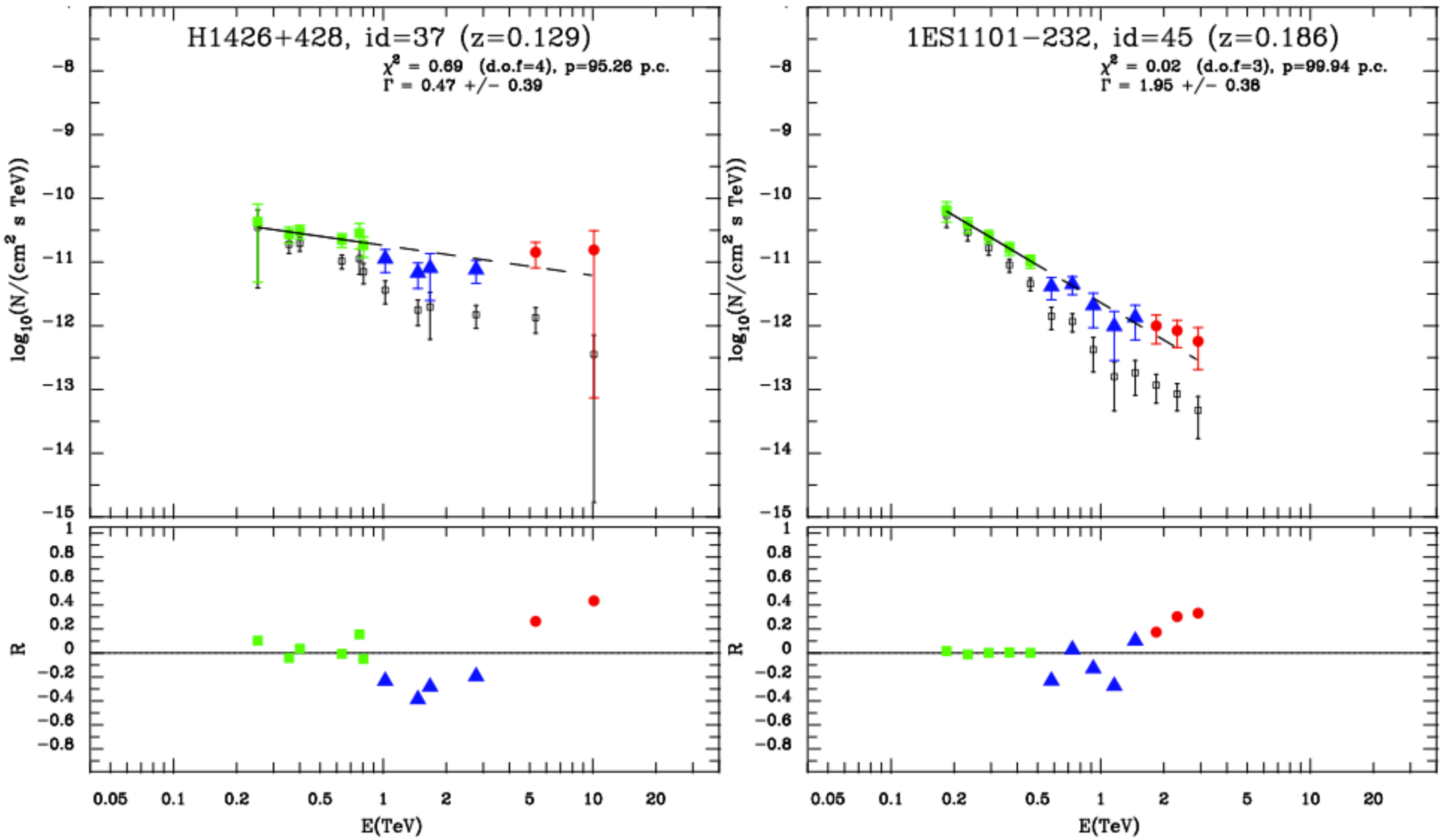


Mirizzi et Montanino, 2009, JCAP

- Large population studies required for average

Population studies:

- Look for anomaly in spectra of extragalactic sources
- 2012: 24 extragalactic sources discovered

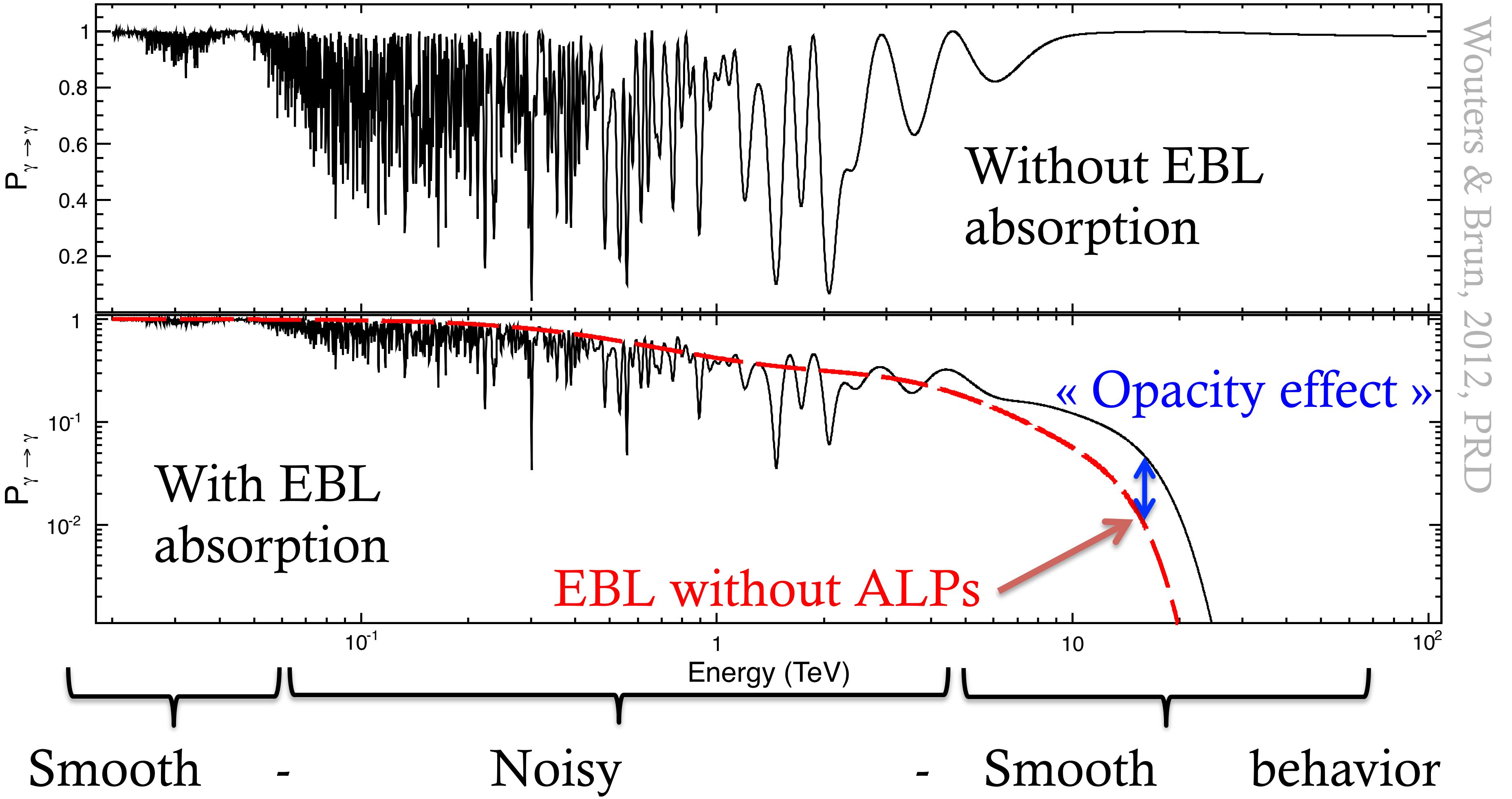


Horns & Meyer, 2012, JCAP

- Claim for unexpected boost at VHE (4.2σ effect)
- Not enough sources… prospect for CTA

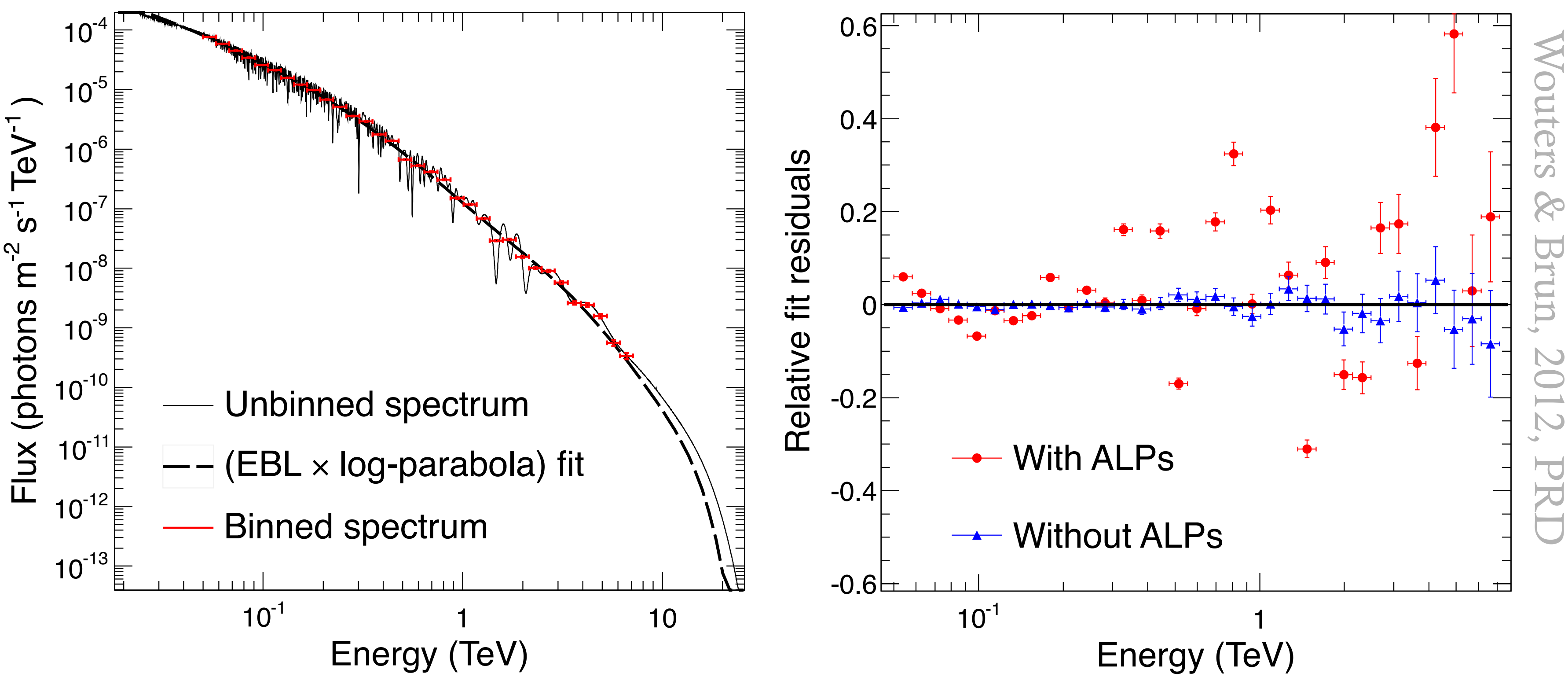
Signature for single source:

- Boost at VHE not valid for observations of one source
- Behavior around critical energy?
  - Source at redshift 0.1
  - $g = 8\ 10^{-11}\ GeV^{-1}$, $m_a = 2$ neV, B = 1 nG , L = 1 Mpc



Signature for single source:

- Turbulence of magnetic field ➡ irregularities in spectrum
- Irregularities around critical energy
- Can be detected by Cherenkov telescopes

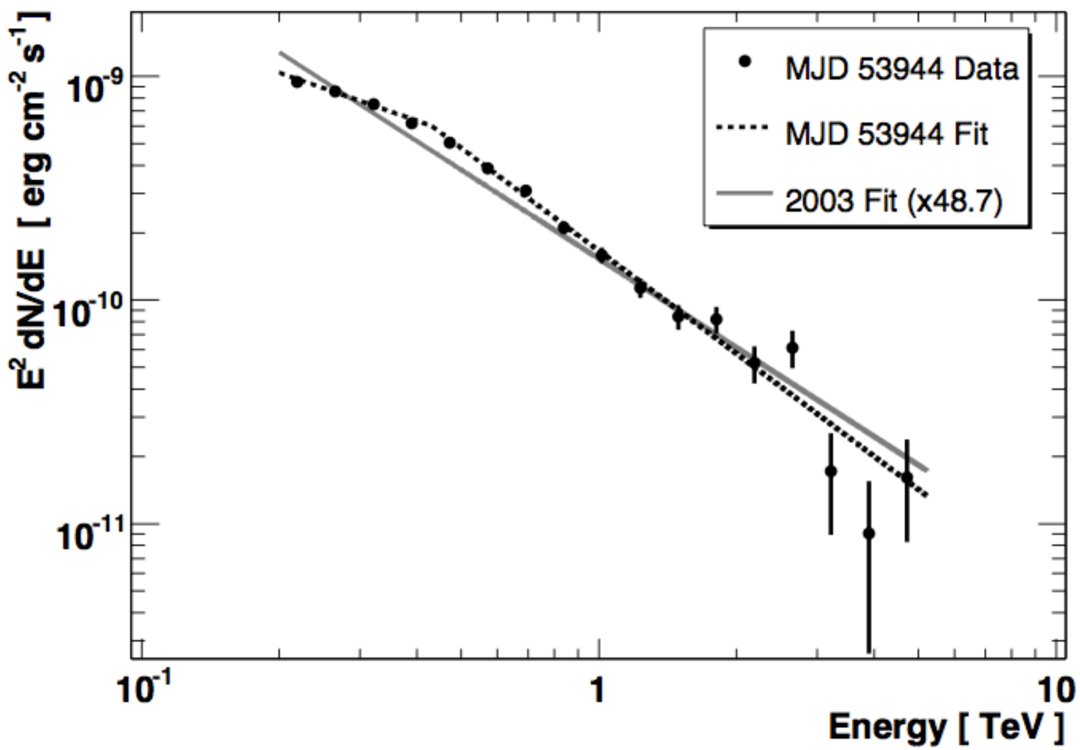


- Proposed for quasars observations in optical

Application to HESS:

- Look for irregularities in spectrum of one bright source

- Brightest extragalactic source: PKS 2155-304
- Redshift z = 0.116 (d = 478 Mpc)
- Big flare in July 2006, ~50*base flux



H.E.S.S. Collaboration, 2007, ApJ Lett.

Conclusion:

- ALPs relevant for γ−ray astronomy at very low mass (< μeV)

- Unexpected transparency of the universe:
  - Anomaly weakens with recent EBL models
  - can be explained by ALPs
  - can be explained by other exotic models
  - cannot be used to put constraints on ALP models

- Irregularities at critical energy:
  - independent from « transparency hint »
  - signature for potential detection
  - can be used to put constraints with HESS