Axion-like particles in the high energy universe

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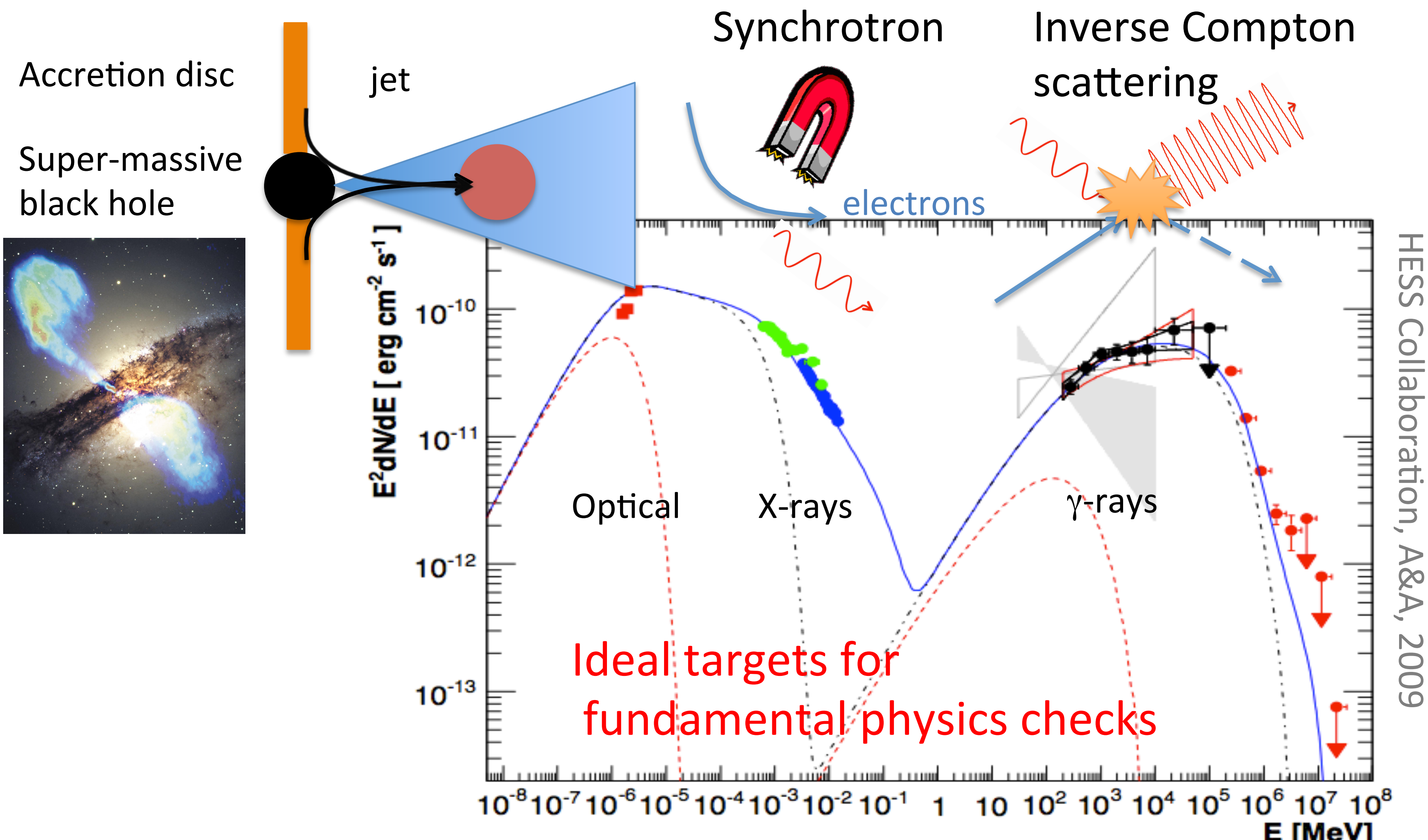
The high energy universe

- Charged particles are accelerated (producing cosmic-rays)
- Example : Active Galactic Nuclei (AGN)



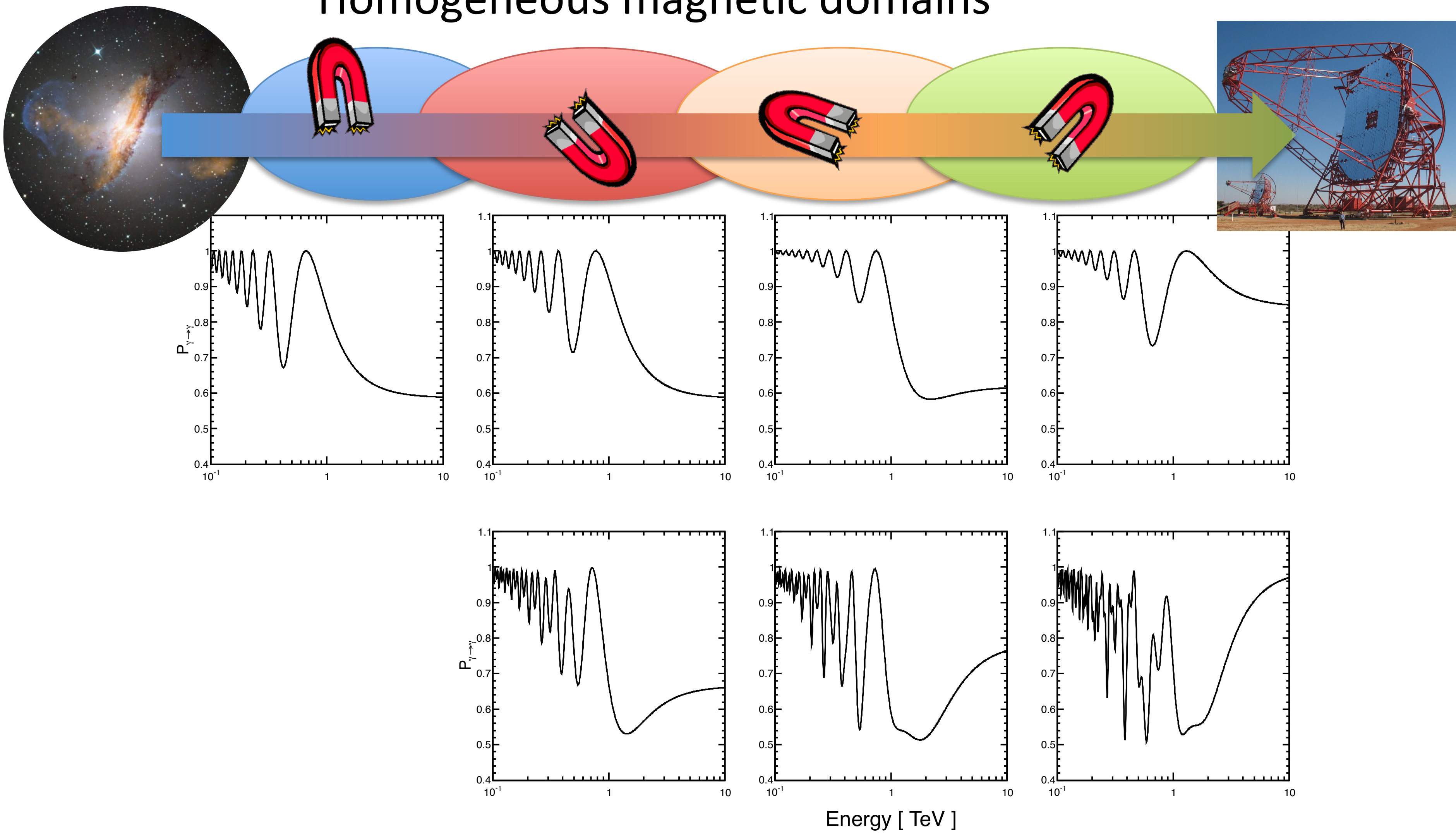
Search for ALPs

- γ/ALPs conversion in turbulent astrophysical magnetic fields
- Search with H.E.S.S. at TeV energies
- Search with Chandra in X-rays

ALPs phenomenology in turbulent magnetic field

- Magnetic fields in astrophysics usually turbulent

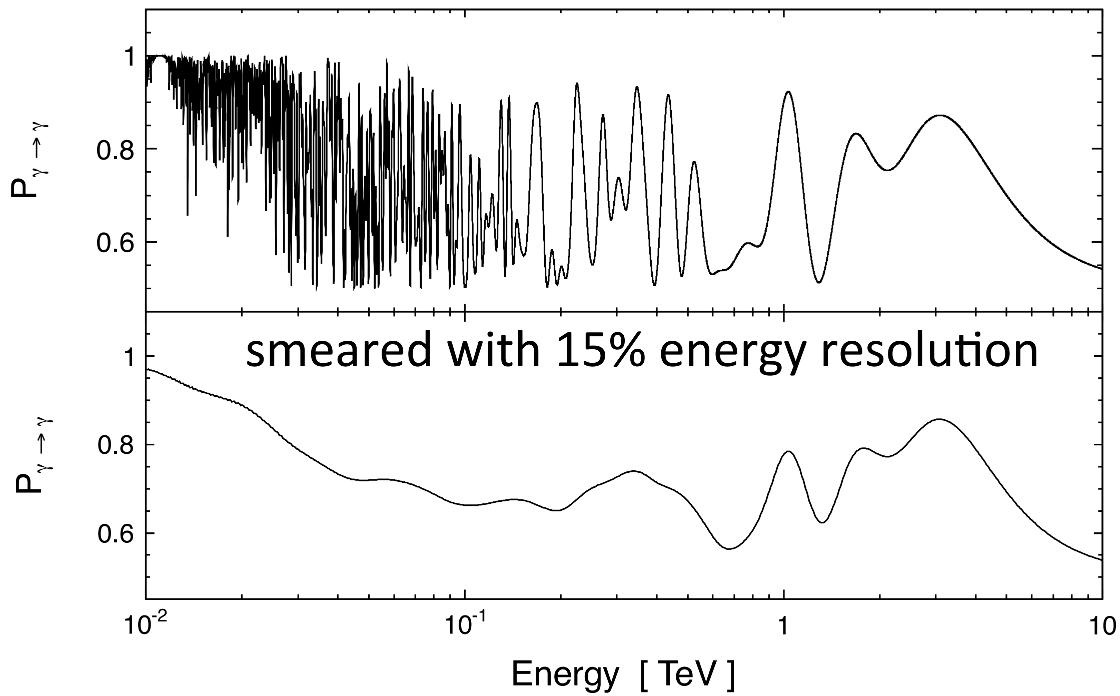
Homogeneous magnetic domains



ALPs phenomenology in turbulent magnetic field

- Strong spectral irregularities around threshold of coupling
- Unpolarized beam : described with density matrix.

typical signal for conversion in a turbulent magnetic field



See Wouters & Brun, PRD, 2012

- Amplitude of irregularities driven by $g_{\gamma a}$
- Position in energy driven by m
- Signature detectable in TeV spectra

Choice of the source

- Brightest AGN observed by H.E.S.S. : PKS 2155-304
- Strong flare in July 2006: ~ 7 Crab flux above 200 GeV

  ⇨ Large statistics: accurate spectrum and sensitivity to irregularities

- Galaxy cluster observed around PKS 2155-304

  ⇨ Magnetic field in the cluster

- Redshift $z = 0.116$

  ⇨ Magnetic field in intergalactic medium

Modeling of magnetic fields

- Magnetic fields in galaxy clusters
  - Measurement by Faraday rotation
  - B > 1 μG
  - Kolmogorov power spectrum on scales up to 10 kpc

- PKS 2155-304 cluster
  - Size of the cluster : 370 kpc
  - No measurement of B and turbulence power spectrum
  - Assumes B = 1 μG, Kolmogorov power spectrum on scales $1 \rightarrow 10$ kpc
  - Conservative description

- Intergalactic magnetic field
  - 10^{-16} G $< B < 10^{-9}$ G
  - Assumes turbulence on one scale, 1 Mpc

PKS 2155-304 observations with H.E.S.S.

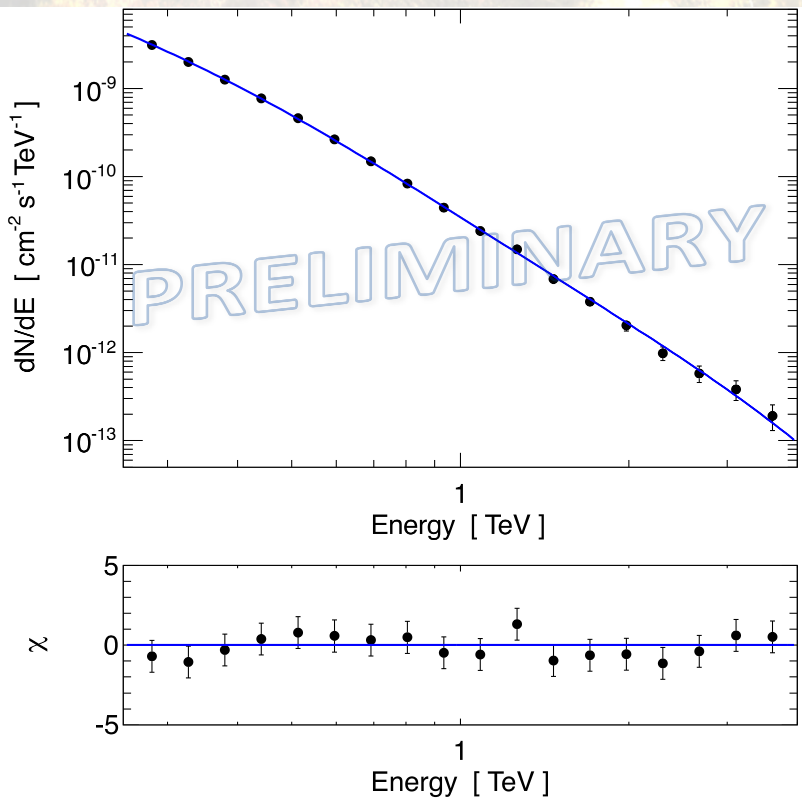
- Observations with 4 telescopes
- Dataset from 2006 flare: background free
- Energy resolution ~ 15%, threshold of 250 GeV
- 45505 reconstructed γ-rays

Unfolded spectrum:

Well –modeled with
log-parabola with EBL absorption
(from Franceschini et al. 2008, A&A)

$$\frac{\mathrm{d}N}{\mathrm{d}E} \propto \left(\frac{E}{1\mathrm{TeV}}\right)^{-\alpha-\beta\log E/1\mathrm{TeV}} e^{-\tau_{\gamma\gamma}(E)}$$

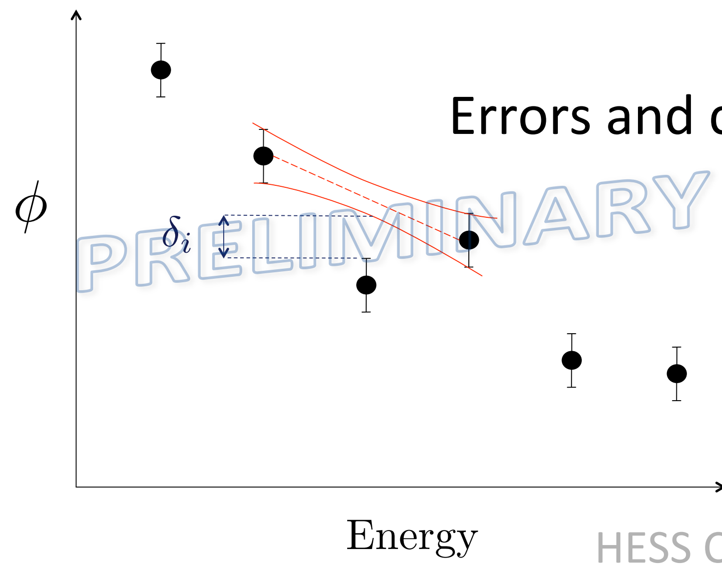
- $\alpha = 3.18 \pm 0.03$
- $\beta = 0.32 \pm 0.02$
- F(E > 200 GeV) = $8.38 \pm 0.43\ 10^{-10}$ cm^{-2}s^{-1}



HESS Collab, in prep.

Method for the constraints (1)

- Intrinsic spectral shape unknown
- Estimate irregularities in spectrum without spectral shape assumption:



Errors and correlation accounted

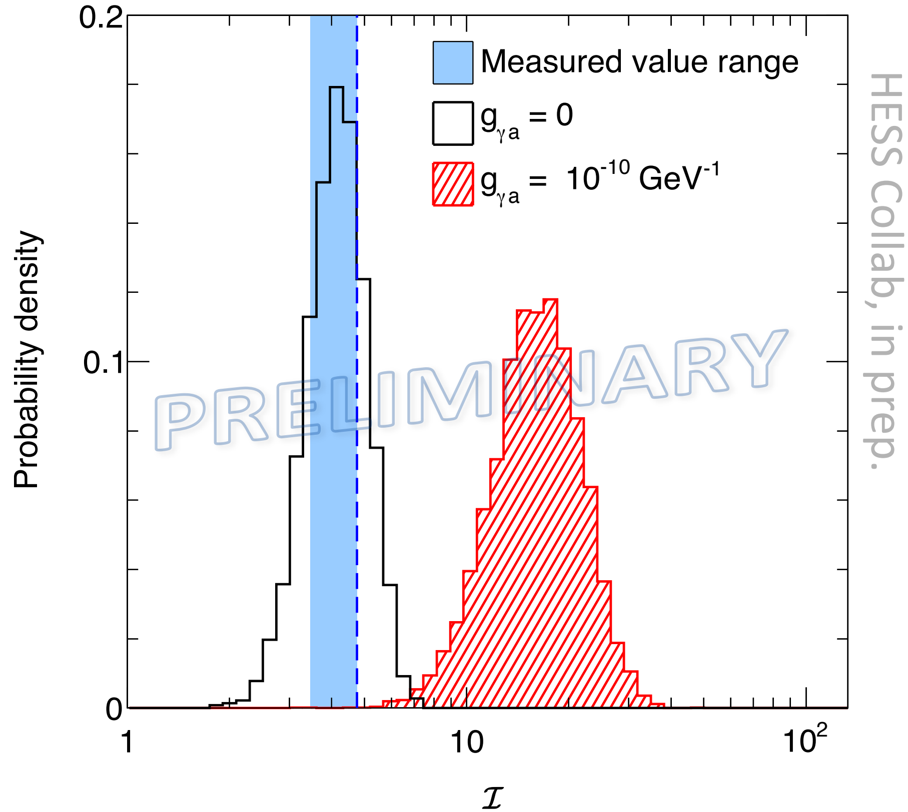
$$\mathcal{I} = \sum \delta_i^2$$

HESS Collab, in prep.

- Look for anomalous deviations in triplet of successive bins
- Estimator of irregularities in spectrum
- Assumption: intrinsic spectrum log-linear on scales of 3 bins

Method for the constraints (2)

- Exclusion on a statistical basis:



- Measured value slightly depends on the binning

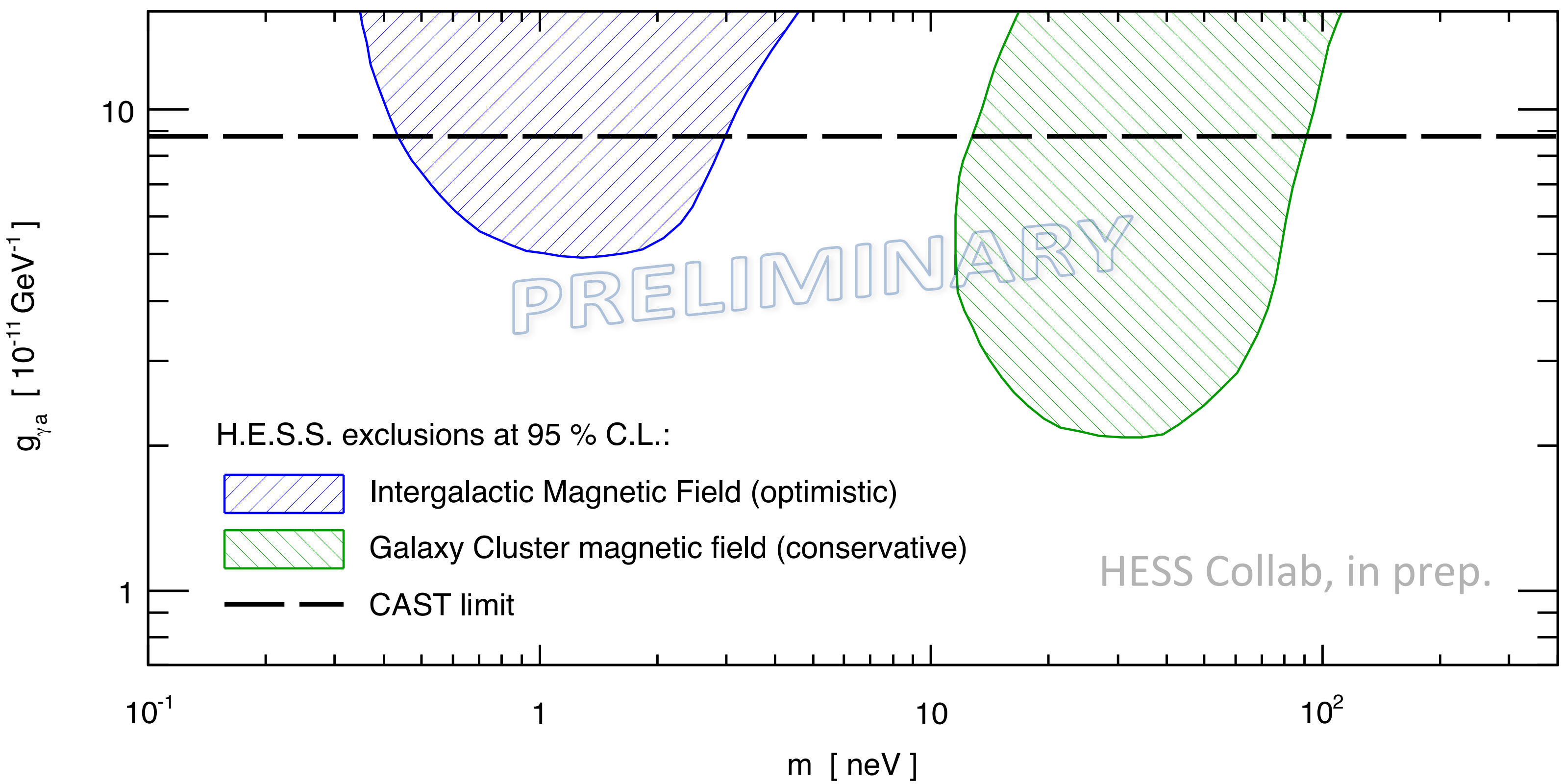
→ Estimate fluctuations with different bin sizes, take upper value

Constraints (2)

- Constraints on $g_{\gamma a}$ and m with:

L → size of conversion domain
s → coherence length

	B	L	L/s
Cluster magnetic field	1 μG	370 kpc	37
IGMF	1 nG	478 Mpc	505



Constraints on very low mass ALPs

- Uses electron plasma term

$$\mathcal{M} = \begin{pmatrix} -\frac{\omega_{\rm pl}^2}{2E} & \frac{g_{\gamma a}B}{2} \\ \frac{g_{\gamma a}B}{2} & -\frac{m_{\rm a}^2}{2E} \end{pmatrix}$$

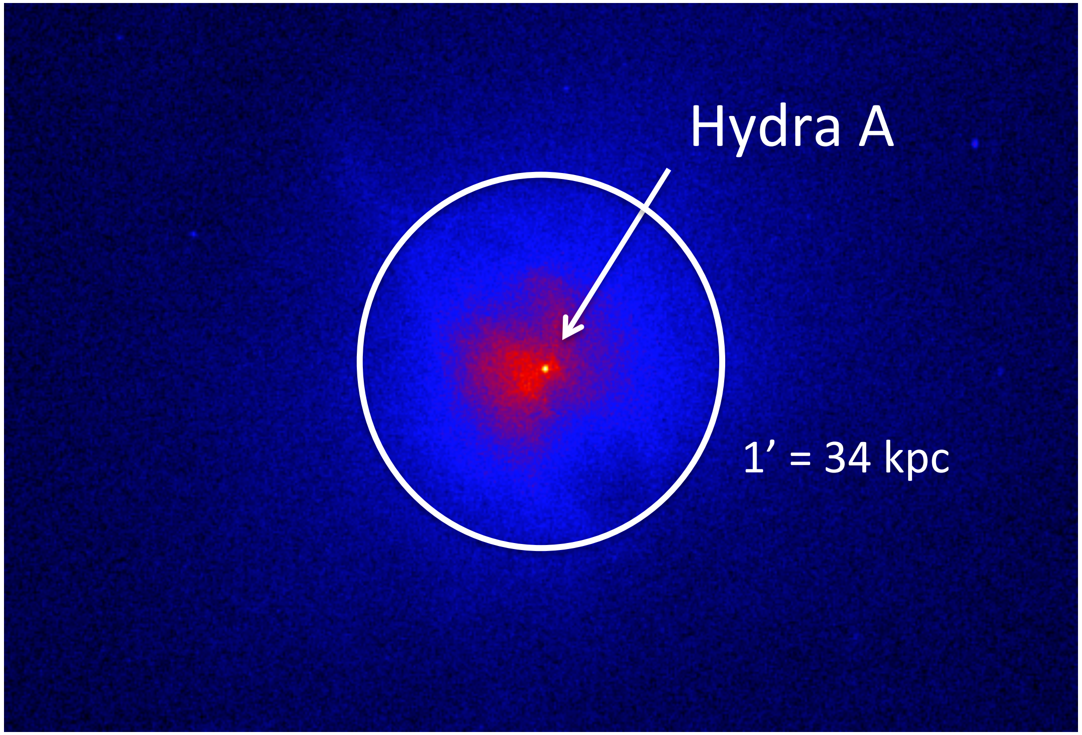
- When $\omega_{\rm pl} \gg m_{\rm a}$ $\qquad E_c = \frac{\omega_{\rm pl}^2}{2 g_{\gamma a} B}$

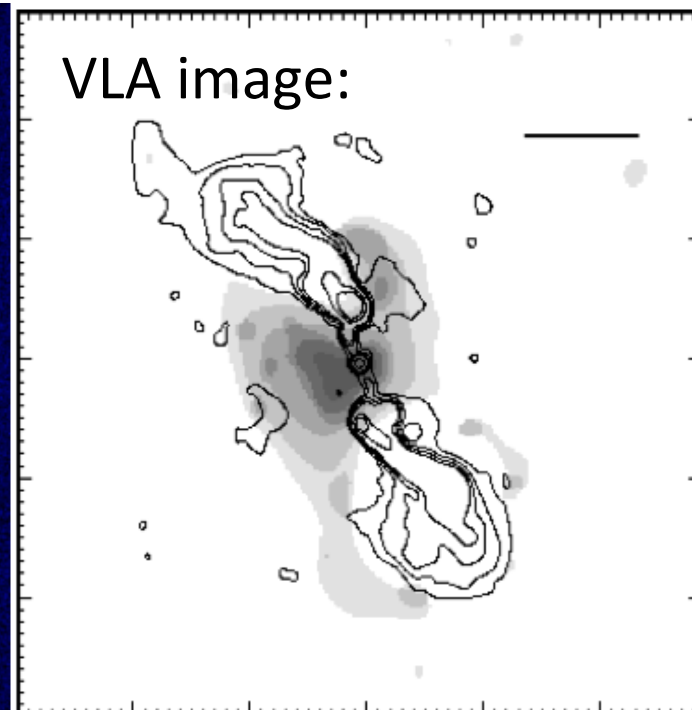
- For typical electron densities in galaxy clusters:
  - $\omega_{pl} \sim 10^{-11}$ eV
  - $E_c \sim$ a few keV

⇒ X-ray observations

Hydra A galaxy cluster

- Chandra observations of Hydra A galaxy cluster (0.5-10 keV)





- Bright X-ray point-like source

Mc Namara et al, 2000, ApJ

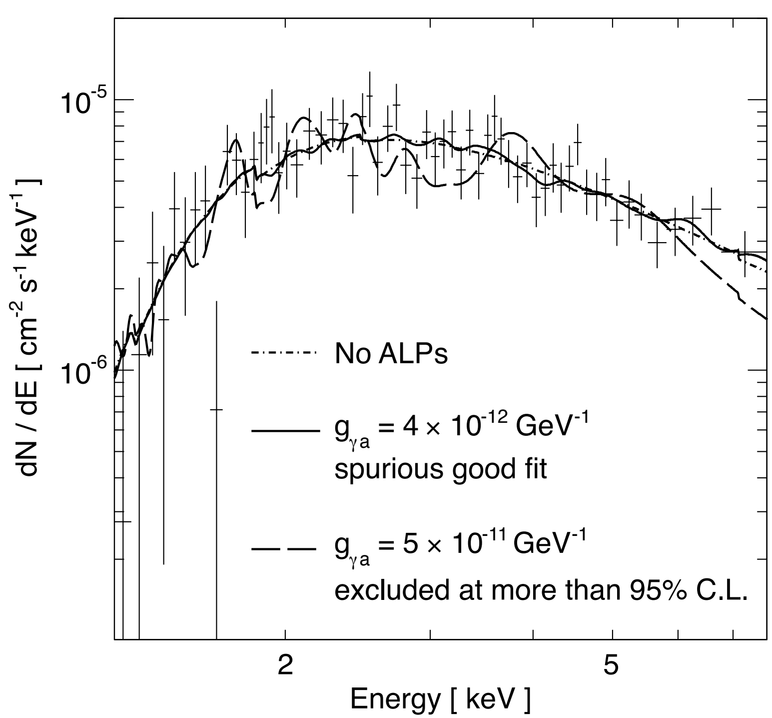
- Magnetic field profile and electron density from Faraday rotation maps

Kuchar & Ensslin, 2011, A&A

- Thermal component of hot electrons (3 keV)

Method for the constraints (1)

- X-ray spectrum well fitted by absorbed power-law
- Likelihood of measured data for a given model



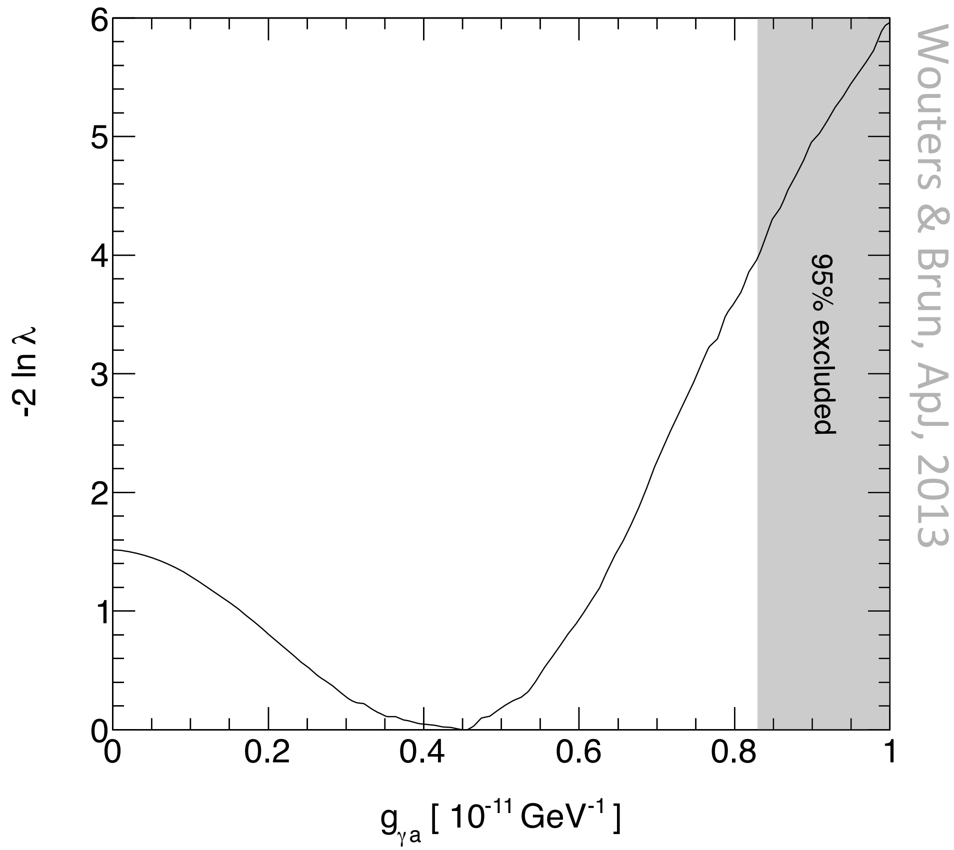
Wouters & Brun, ApJ, 2013

- Log-Likelihood ratio test with nuisance parameters (unknown configuration of B field)

$$\lambda(g_{\gamma a}) = \frac{\sup_{\theta} \mathcal{L}(g_{\gamma a}, \theta)}{\sup_{g_{\gamma a}, \theta} \mathcal{L}(g_{\gamma a}, \theta)}$$

Method for the constraints (2)

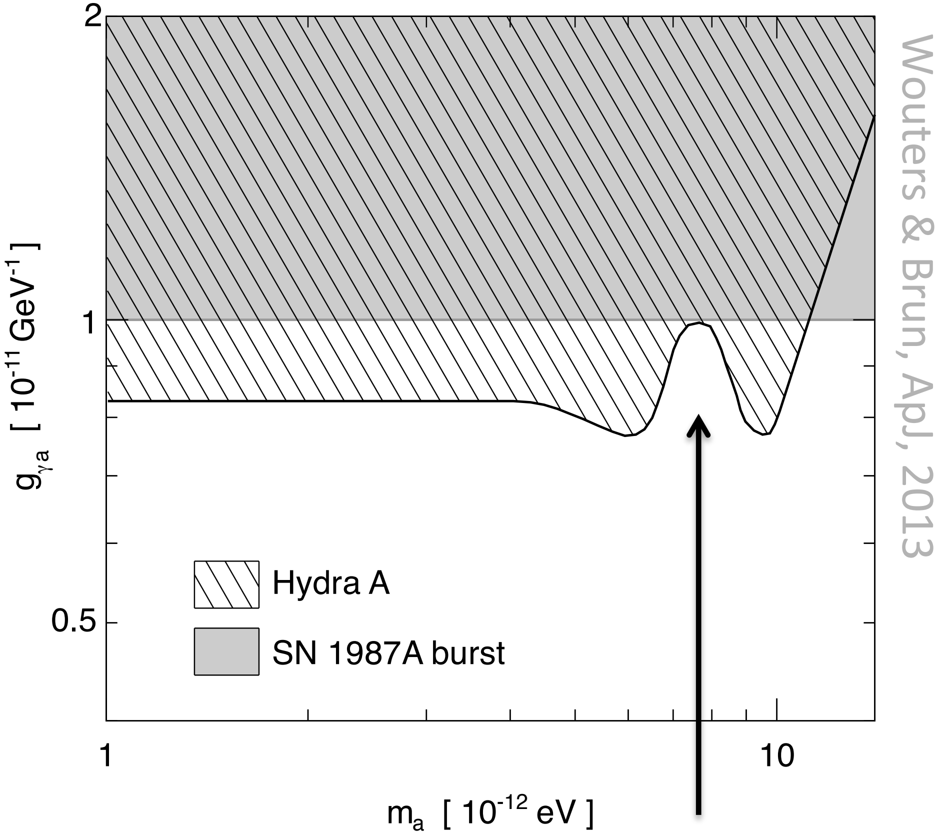
- Log-likelihood profile for $m_a = 0$



- Excludes $g_{\gamma a} > 0.83 * 10^{-11} GeV^{-1}$ at 95% C.L.
- Expected best fit (not physical) for $g_{\gamma a} = 0.4 * 10^{-11} GeV^{-1}$ (1.2 σ)

Constraints

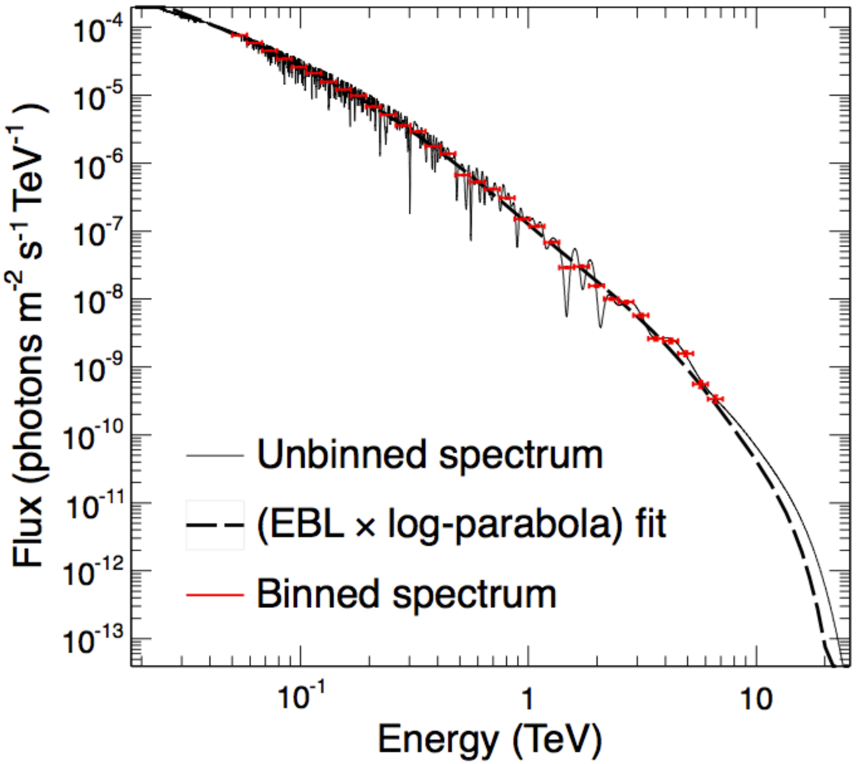
- Constraints in ($g_{\gamma a}$, m) plane



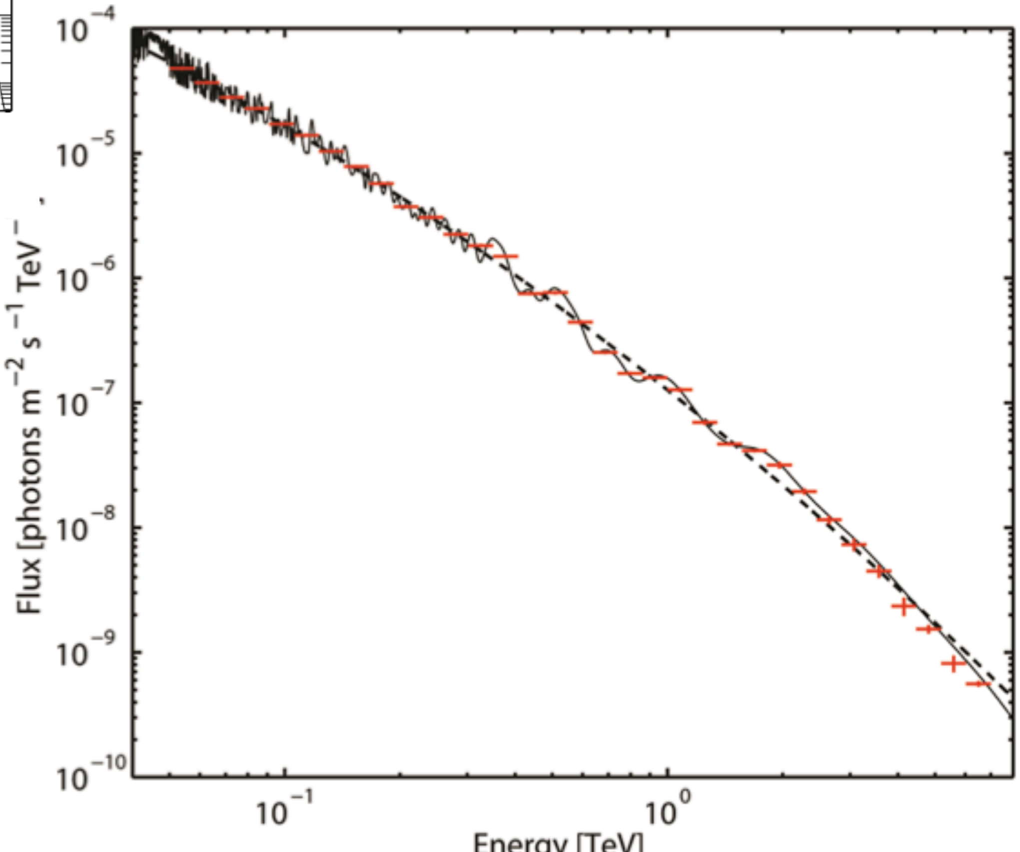
- Improve the constraint with : $m_a = \omega_{pl}$
  - Better statistic
  - More accurate determination of the magnetic field profile

Summary

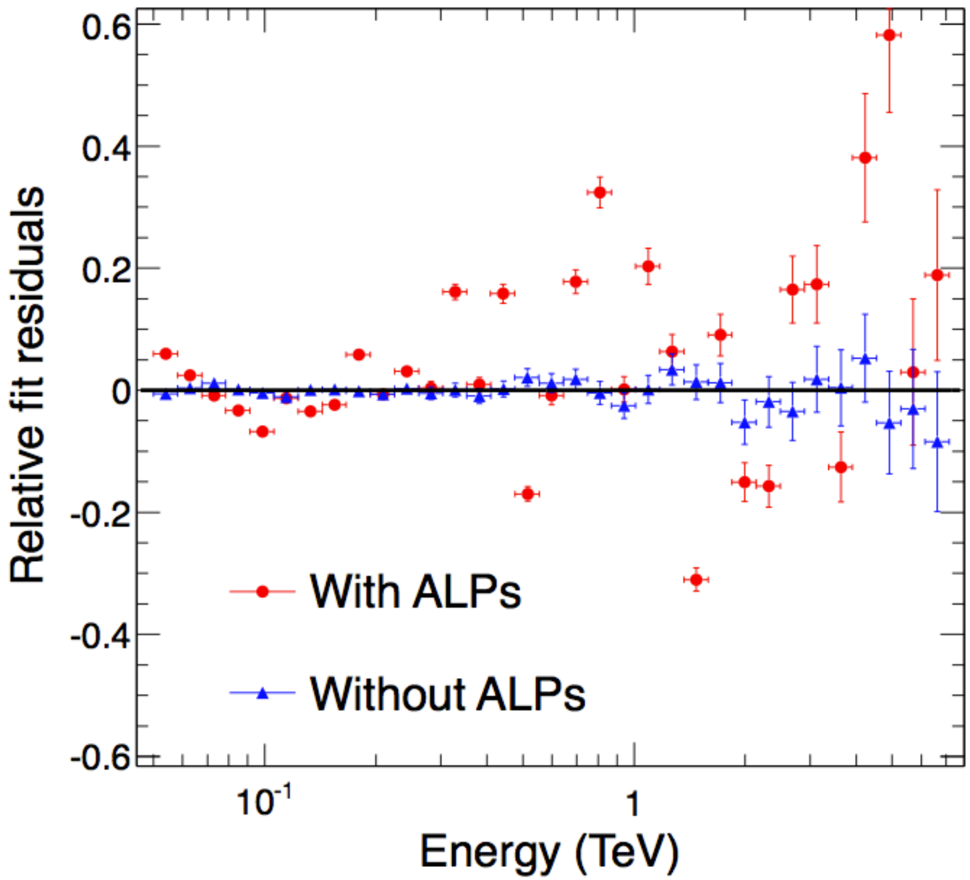
- Very-high energy γ-ray data in agreement with EBL models
- New Observable for search for ALPs in astrophysics
  - Spectral irregularities from turbulent magnetic fields
- Constraints on neV mass ALPs from TeV observations
- Constraints on $m < 10^{-11}$ eV ALPs from X-ray observations



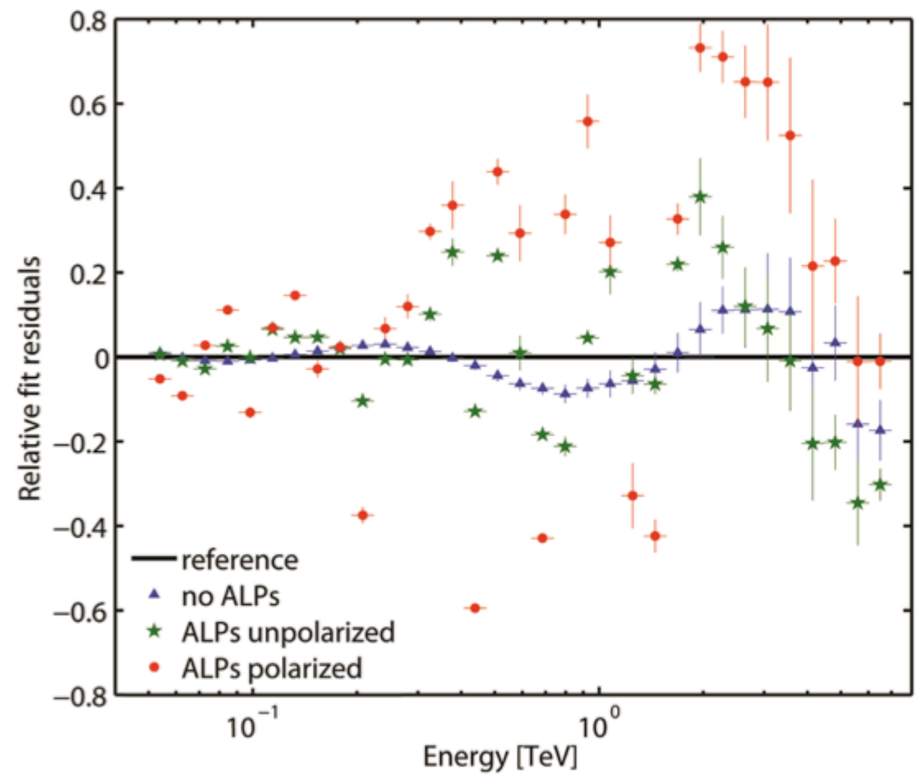
Flux (photons m^{-2} s^{-1} TeV^{-1})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
Unbinned spectrum
(EBL × log-parabola) fit
Binned spectrum
10^{-1}
1
10
Energy (TeV)



Flux [photons m^{-2} s^{-1} TeV^{-}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-1}
10^{0}
Energy [TeV]



0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Relative fit residuals
With ALPs
Without ALPs
10^-1
1
Energy (TeV)



0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
Relative fit residuals
reference
no ALPs
ALPs unpolarized
ALPs polarized
10^−1
10^0
Energy [TeV]