Constraints on Axion-Like Particles from H.E.S.S. observations of PKS 2155-304

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Axion-like particles

• 1977: U(1) Peccei-Quinn symmetry
  Possible explanation for strong CP problem
• particle associated to the breaking of the symmetry: Axion
• Coupling with two photons:

\[ a - g_{\gamma a} - \gamma \]

Axions: \( g_{\gamma a} \propto m \)

• Axion-like particles (ALPs): \( g_{\gamma a} \) and \( m \) unrelated but same phenomenology
• Possible explanation for dark matter (for specific \( m, g_{\gamma a} \))
• CAST (solar ALPs): \( g_{\gamma a} < 8 \times 10^{-11} \text{ GeV}^{-1} \) for \( m < 0.01 \text{ eV} \)
Axion-like particles in astrophysics

- $\gamma$/ALP oscillations in external magnetic field
  \[ E_\gamma > \frac{m_a^2}{2 g_{a\gamma} B} \]

- Possibly modify opacity of the universe to TeV $\gamma$-rays

Sanchez Conde et al. 2009, PRD
Horns et al. 2012, PRD
De Angelis et al. 2007, PRD
Simet et al. 2008, PRD
...
Phenomenology in turbulent magnetic field

- Magnetic fields in astrophysics usually turbulent
- ALPs $\Rightarrow$ Strong irregularities in energy spectra around

\[ E_c = \frac{m^2}{2 g_{\gamma a} B} \]

\[ B = 1 \, \text{nG} \]
\[ \text{Coherence length } s = 1 \, \text{Mpc} \]
\[ g_{\gamma a} = 8 \times 10^{-11} \, \text{GeV}^{-1} \]
\[ m = 2 \, \text{neV} \]

$\Rightarrow E_c = 1 \, \text{TeV}$

- 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: $\sim 7$ 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
  - \( B > 1 \, \mu G \)
  - 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 \( B = 1 \, \mu G \), Kolmogorov power spectrum on scales 1→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 \(\sim 15\%\), threshold of 250 GeV
- 45505 reconstructed \(\gamma\)-rays

**Unfolded spectrum:**

Well –modeled with log-parabola with EBL absorption

(from Franceschini et al. 2008, A&A)

\[
\frac{dN}{dE} \propto \left( \frac{E}{1\text{ TeV}} \right)^{-\alpha - \beta \log E/1\text{ TeV}} e^{-\tau_{\gamma\gamma}(E)}
\]

- \(\alpha = 3.18 \pm 0.03\)
- \(\beta = 0.32 \pm 0.02\)
- \(F( E > 200 \text{ GeV}) = 8.38 \pm 0.43 \times 10^{-10} \text{ cm}^{-2}\text{s}^{-1}\)
Method for the constraints (1)

- Intrinsic spectral shape unknown
- Estimate irregularities in spectrum without spectral shape assumption:
  \[ I = \sum \delta_i^2 \]
  
- 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)

- Template of irregularities depends on exact magnetic field structure (unknown)
- Simulations of spectra for given \((m, g_{\gamma a})\) with various magnetic field structure, in same observation conditions
- Spectral shape: fitted on data * ALP irregularity template
- Reconstruction with same analysis chain

\[ \text{P.D.F. of the irregularity estimator for given } (m, g_{\gamma a}) \]

- Compare with estimator value measured on data
Method for the constraints (3)

- Exclusion on a statistical basis:

- Measured value slightly depends on the binning

  Estimate fluctuations with different bin sizes, take upper value
Constraints (1)

- Constraints expressed in parameters making them independent of B and L (size of conversion domain)

\[ \epsilon = \frac{m}{\sqrt{B}} \]

\[ \Gamma = \frac{g_{\gamma a} BL}{2\sqrt{L/s}} \]

H.E.S.S. exclusions at 95% C.L.

Galaxy cluster Magnetic Field

Intergalactic Magnetic Field
• Translation to $g_{\gamma a}$ and $m$ with:

$$L \rightarrow \text{size of conversion domain}$$

$$s \rightarrow \text{coherence length}$$

<table>
<thead>
<tr>
<th>Constraints</th>
<th>$B$ [µG]</th>
<th>$L$ [kpc]</th>
<th>$L/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster magnetic field</td>
<td>1</td>
<td>370</td>
<td>37</td>
</tr>
<tr>
<td>IGMF</td>
<td>1</td>
<td>478</td>
<td>505</td>
</tr>
</tbody>
</table>

H.E.S.S. exclusions at 95 % C.L.:

- Intergalactic Magnetic Field (optimistic)
- Galaxy Cluster magnetic field (conservative)
- CAST limit
Conclusion

• ALPs usually considered in $\gamma$-ray astronomy for «transparency hint»

• ALPs signature: irregularities in $\gamma$-ray spectra

• Mixing considered for:
  – Galaxy cluster magnetic field (conservative)
  – Intergalactic magnetic field (optimistic)

• Constraints in limited mass range

• First exclusion from TeV $\gamma$-ray astronomy