SEARCH FOR AXION-LIKE PARTICLE SIGNATURES IN FERMI LARGE AREA TELESCOPE DATA

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Partikel dagarna
Uppsala
1 December, 2015
**AXIONS & AXION LIKE PARTICLES**

- **Axions**: by-product of solution of strong CP problem in QCD
- **Axion-like particles**: generalization, arise in string theories
- Couple to photons in external magnetic fields
- **DM candidate** if produced non-thermally

**ONE OBSERVABLE:**
SPECTRAL IRREGULARITIES AT CRITICAL ENERGY
[WOUTERS & BRUN 2012; ÖSTMAN & MÖRTSELL 2005]

\[ E_{\text{crit}} \propto \frac{|m_a^2 - \omega_{\text{plasma}}^2|}{g_{a\gamma} B} \]

IN FERMI-LAT ENERGY RANGE FOR MASSES \( \lesssim 100 \text{ neV} \)

Radio galaxy **NGC 1275**, bright Fermi and MAGIC source [e.g. Abdo et al. 2009]

In the center of **cool-core Perseus cluster**

Rotation measures: central B field \(\sim 25\mu G\), morphology on larger scales \(\sim 100\) kpc **unknown** [Taylor et al. 2006]

\(B \gtrsim 2\mu G\) from non-observation of \(\gamma\) rays in Perseus cluster [Aleksić et al. 2012, 2014]

**ONE OBSERVABLE:**

Spectral irregularities at critical energy 
[Wouters & Brun 2012; Östman & Mörtvell 2005]

\[
E_{\text{crit}} \propto \frac{|m_a^2 - \omega_{\text{plasma}}^2|}{g_{a\gamma} B}
\]

**IN FERMI-LAT ENERGY RANGE FOR MASSES \(\lesssim 100\) neV**
- Considered $B$ fields: Perseus cluster & Milky Way
- Cluster field: gaussian turbulence & follows electron density
- Turbulence: assumed the same as in A2199 [given in Vacca et al. 2012]
- Conservative estimate of central $B$ field: 10 $\mu$G [Aleksić et al. 2012]
### THE FERMI LAT

<table>
<thead>
<tr>
<th><strong>Energy range</strong></th>
<th>30 MeV - over 300 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Effective Area ($E &gt; 1$ GeV)</strong></td>
<td>$\sim 1\ m^2$</td>
</tr>
<tr>
<td><strong>Point spread function (PSF)</strong></td>
<td>$\sim 0.8^\circ$ at 1 GeV</td>
</tr>
<tr>
<td><strong>Field of view</strong></td>
<td>2.4 sr</td>
</tr>
<tr>
<td><strong>Orbital period</strong></td>
<td>91 minutes</td>
</tr>
<tr>
<td><strong>Altitude</strong></td>
<td>565 km</td>
</tr>
</tbody>
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- **Public data**, available within 12 hours; surveys **full sky every 3 hours**
- **New Pass 8** released for the public this year
- Improves effective area, PSF, …
- Now possible to **split data** corresponding to quality of energy reconstruction
- Joint analysis for these 4 **EDISP event types**
• **6 years** of **Pass 8** Source data

• Split into analysis **EDISP event types**

• Method: **log-likelihood ratio test** for no-ALP and ALP hypothesis

• Use **bin-by-bin likelihood curves**, similar to dSph analysis [Ackermann et al. 2014, 2015]

• Hypothesis test **calibrated with Monte-Carlo simulations**

**ALP HYPOTHESIS:**

\[ P_{\gamma \gamma}(E, m_a, g_{a\gamma}, B)F(E) \]

Photon. surv. prob. Intrinsic spectrum
EXPECTED LIMITS AND DETECTION SENSITIVITY FROM SIMULATIONS

EXPECTED 95% CONFIDENCE LIMITS FROM 400 SIMULATIONS W/O AN ALP SIGNAL

ALP parameters we could detect
ALP HYPOTHESIS NOT PREFERRED, DERIVE 95% CONFIDENCE LIMITS
"Hole": irregularities fluctuate rapidly over whole energy range, washed out.

NO ALP OBSERVED: SETTING LIMITS

ALP HYPOTHESIS NOT PREFERRED, DERIVE 95% CONFIDENCE LIMITS
• Strongest **limits** to date between \(0.5 \lesssim m_a \lesssim 20\) neV

• **Comparable** with sensitivity of future laboratory experiments in that mass range

• Strongly constrains possibility that ALPs explain \(\gamma\)-ray transparency
SYSTEMATIC CHECKS

- **B-field modeling:**
  - Kolmogorov turbulence: Power-law index of turbulence $q$
  - Central magnetic field $\sigma_B$
  - Maximal spatial extent of $B$ field $r_{\text{max}}$
  - Increasing $\sigma_B$ increases excluded area of parameter space by 43%

- **Energy dispersion:**
  - Artificially broadened with 5%, 10%, 20%
  - Reduces excluded parameter space up to 25%
SUMMARY & CONCLUSIONS

- We have **searched for spectral irregularities** induced by **photon-ALP oscillations** in the spectrum of **NGC 1275**

- We **do not find any indications** for ALPs and set the strongest **bounds** to date between $0.5 \lesssim m_a \lesssim 20$ neV

- In this mass range, the limits are **comparable to the sensitivity of future laboratory experiments**

- Together with other limits, the possibility that **ALPs could explain a reduced $\gamma$-ray opacity** of the Universe is now **strongly constrained**

- Systematic effects with strongest impact on limits: Modeling the **magnetic field and the energy dispersion**

- Better handle on magnetic field with future **SKA all-sky rotation measure survey** [Gaensler et al. 2004; Bonafede et al. 2015]
BACK UP
Events in PASS 8 can be split into sub classes (event types) according to quality of energy reconstruction.

Each event type has ~same number of events per bin.
• **Extract likelihood** for expected counts in every energy bin → **independent of assumed spectrum** [similar to dSph dark matter analysis, e.g. Ackermann et al. 2014, 2015]

• **Joint likelihood fit** over EDISP event types $i$ using bin-by-bin likelihood

• **Number of expected counts** in reconstructed energy bin $k'$ and event type $i$:

$$
\mu_{ik'} = \sum_k D^i_{kk'} \int_{E_k}^{E_k+\Delta E_k} dE \, P_{\gamma\gamma} \, F(E) \, \mathcal{E}^i(E)
$$

- $D^i_{kk'}$: Energy dispersion
- $P_{\gamma\gamma}$: Photon survival prob.
- $F(E)$: Intrinsic spectrum
- $\mathcal{E}^i(E)$: Exposure ($A_{\text{eff}} \times $ obs. time)

[Diagram showing logarithmic parabola log($E^2 dN/dE$) vs. log($E$)]
METHOD

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![P8R2_SOURCE_V6 acceptance graph](image)
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- **Energy dispersion**
- **Photon survival prob.**
- **Intrinsic spectrum**
- **Exposure** ($A_{\text{eff}} \times \text{obs. time}$)
SEARCHING FOR AN ALP SIGNAL WITH A LOG-LIKELIHOOD RATIO TEST

Joint likelihood $\forall$ event types $i$ and reconstructed energy bins $k'$:

$$\mathcal{L}(\mu, \theta|D) = \prod_{i,k'} \mathcal{L}(\mu_{ik'}(m_a, g_{a\gamma}, B), \theta_i|D_{ik'})$$

Test null hypothesis (no ALP, $\mu_0$) with likelihood ratio test:

$$TS = -2 \ln \left( \frac{\mathcal{L}(\mu_0, \hat{\theta}|D)}{\mathcal{L}(\hat{\mu}_{95}, \hat{\theta}|D)} \right)$$

Threshold $TS$ value for which we could claim ALP detection derived from fit to Monte Carlo simulations (Asymptotic theorems not applicable)

$$TS_{thr} (3\sigma) = 33.1$$
[Mathematical expression: \[ \text{null distribution from MC} \]

\[ j\text{-th Monte Carlo realization: } \text{TS}_j = -2 \ln \left( \frac{\mathcal{L} (\mu_0, \hat{\theta} | D_j)}{\mathcal{L} (\hat{\mu}_{95}, \hat{\theta} | D_j)} \right) \]
DERIVING LIMITS ON ALP PARAMETERS

• Calculate likelihood ratio between best fit and ALP parameter:

\[
\lambda(m_a, g_{a\gamma}) = -2 \ln \left( \frac{\mathcal{L}(\mu_{95}(m_a, g_{a\gamma}), \hat{\theta}|D)}{\mathcal{L}(\hat{\mu}_{95}, \hat{\theta}|D)} \right)
\]

• If \( \lambda > \lambda_{\text{thr}} \): ALP parameter excluded

• Ansatz: derive \( \lambda_{\text{thr}} \) from null distribution and check coverage

• From null distribution: \( \lambda_{\text{thr}} = 22.8 \) for 95% confidence

• Ansatz yields over coverage where irregularities are strongest \( \Rightarrow \) conservative limits
• Assuming **flat prior** for B-field realizations

• Assuming **logarithmic flat priors** on ALP parameters

• Posterior sorted by decreasing likelihood

• Bayesian limits give **under coverage**
THE “HOLE” FEATURE

Preliminary
EXAMPLE FOR EXCLUDED ALP PARAMETERS

[Graph showing excluded ALP parameters with a cross indicating a region of interest.]

- $g_{\alpha\gamma} (10^{-11} \text{ GeV}^{-1})$
- $m_\alpha (\text{neV})$

Inset 1: Photon survival probability vs. energy (GeV)

Inset 2: $E^2 dN/dE (\text{MeV cm}^{-2} \text{ s}^{-1})$ vs. energy (GeV)

Legend:
- $m_\alpha = 1.18$
- $g_{\alpha\gamma} = 1.01$
- EDISP $\times$ 1.70
- EDISP $\times$ 1.88
- EDISP $\times$ 2.08
- EDISP $\times$ 2.30
- median
- one realization
- EBL attenuation only

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EXAMPLE FOR EXCLUDED ALP PARAMETERS

![Graph showing excluded ALP parameters](image)

- $g_{\alpha\gamma} = 10^{-11}$ GeV$^{-1}$
- $m_\alpha$ (neV)
- $E_{\text{crit}} = 100$ GeV
- Photon survival probability
- Energy (GeV)
- $E_\gamma^2 \cdot dN/dE^\gamma$ (MeV cm$^{-2}$ s$^{-1}$)
- Energy (GeV)

Legend:
- EDISP3
- Best Fit w/ ALPs: $m_{\alpha,\gamma} = 3.96$, $g_{\alpha\gamma} = 1.01$
- Best Fit w/o ALPs

Preliminary