SEARCHES FOR AXIONLIKE PARTICLES WITH THE FERMI LARGE AREA TELESCOPE

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AXIONS AND AXION-LIKE PARTICLES

- QCD: has CP violating term with strength $\theta$, measurement: $|\theta| < 10$

- Introduce symmetry, $\theta$ is a dynamical field, relaxes to zero in potential

- Symmetry broken at scale $f_a \Rightarrow$ new particle: the axion! (similar to Higgs mechanism)

- Axion mass $m_a \sim f_a^{-1}$

- Oscillations around minimum: act like cold dark matter

- Axion-like particles (ALPs):
  - arise in similar way, also dark-matter candidate
  - plethora of ALPs predicted in string theory (axiverse) and other standard model extensions

- ALP mass independent of $f_a$

[Peccei & Quinn 77; Wilczek 78; Weinberg 78; Preskill et al. 83; Abbott & Sikivie 83; Witten 84; e.g. Arvanitaki et al. 09; Cicoli et al. 12; Arias et al. 2012]
DETECTING AXIONS/ALPs WITH GAMMA RAYS

\[ \mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} E B a \]

\[ g_{a\gamma} = \frac{\alpha}{2\pi} \frac{1}{f_a} \mathcal{N} \]

See, e.g., Fermi-LAT constraints for decaying relativistic axions produced in neutron stars [Berenji, Gaskins, MM 2016]
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DETECTING GAMMA RAYS WITH THE FERMI LAT

- **Survey mode:** observes **full sky every 3 hours**
- **Public data**, available within 12 hours

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>20 MeV - over 300 GeV</td>
</tr>
<tr>
<td>Effective Area (E &gt; 1 GeV)</td>
<td>~ 1 m²</td>
</tr>
<tr>
<td>Point spread function (PSF)</td>
<td>~ 0.8° @ 1 GeV</td>
</tr>
<tr>
<td>Energy resolution ΔE/E</td>
<td>5% - 15% @ 10 GeV</td>
</tr>
<tr>
<td>Field of view</td>
<td>2.4 sr</td>
</tr>
<tr>
<td>Orbital period</td>
<td>91 minutes</td>
</tr>
<tr>
<td>Altitude</td>
<td>565 km</td>
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</tbody>
</table>
PHOTON-ALP MIXING IN GALAXY CLUSTER & MILKY WAY

[Credit: SLAC National Accelerator Laboratory/Chris Smith]

SEARCH FOR IRREGULARITIES WITH FERMI LAT FROM NGC 1275

- Radio galaxy NGC 1275, bright *Fermi* source [e.g. Abdo et al. 2009]
- In the center of *cool-core* Perseus cluster
- Rotation measures: central $B$ field $\sim 25 \mu G$ [Taylor+ 2006]
- $B \approx 2 \mu G$ from non-observation of $\gamma$ rays [Aleksic et al. 2012]

[Ajello et al. 2016]
MODELING PHOTON-ALP CONVERSIONS IN PERSEUS CLUSTER

- Considered $B$ fields: Perseus cluster & Milky Way
- Conservative estimate of central $B$ field: 10 $\mu$G [Aleksić et al. 2012]
- Includes EBL absorption

$P_{\gamma\gamma}(E, m_a, g_{a\gamma}, B)$

[Ajello et al. 2016]
FERMI-LAT DATA ANALYSIS

- 6 years of Pass 8 Source data
- Split into analysis EDISP event types
- Method: log-likelihood ratio test for no-ALP and ALP hypothesis
- Hypothesis test calibrated with Monte-Carlo simulations

[Andello et al. 2016]
NO ALP OBSERVED: CONSTRAINTS
FIT WITH ALPs NOT PREFERRED

[Figure showing a plot with axes labeled $g_{\alpha\gamma}$ (10^{-11} GeV^{-1}) and $m_\alpha$ (neV).]

[Ajello et al. 2016]
AXIONLIKE PARTICLES FROM
CORE COLLAPSE SUPERNOVAE

• ALPs would be produced in a core-collapse SN explosion via Primakoff process

• Could convert into gamma-rays in Galactic magnetic field

• Non-observation of signal from SN1987A with Gamma-Ray Spectrometer on Solar Maximum Mission satellite still strongest bounds for ALPs with masses $m_a \lesssim 1\text{neV}$ [Payez et al. 2015]
ALPs produced in SN core within ~10 s after explosion and escape core ➔ short burst

Spectrum has thermal-like shape, peaks at ~50 MeV

Gamma rays would arrive co-incident with SN neutrinos (provides time tag)

Better gamma-ray sensitivity and large FoV of Fermi LAT promise unparalleled sensitivity for ALPs in case of a Galactic core-collapse SN within Fermi-LAT lifetime and FoV
• Use **Galactic Center** as target

• Estimate number of background counts from data:
  • From one exposure of the Galactic Center (~1500s)
  • Energy Range: **50-500 MeV**
  • Within **68% PSF** (~ 11 degrees @ 50 MeV)
  • Use **20s time bins** (full explosion time)

• **Expected number of background counts**: ~3.3

• Compare against number of **expected counts from SN explosion**

• Use statistical test for low-count regime [Feldman & Cousins 1998]

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**Energy range**
50-500 MeV

**Event Class / IRF**
P8R2_TRANSIENT020_V6

**Zenith Angle**
< 80°

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde; submitted; arXiv:1609.02350]
- Integrated over explosion time (~20s)
- Integrated over energy, 50-500 MeV
- Folded with Fermi-LAT instrumental response function
- Expected number of counts $\sim g_{\alpha\gamma}^4$
- Little dependence on progenitor mass

Assuming 4 background counts in one 20s time bin:
Exclude ALP models predicting more than 6.4 counts at 95% confidence

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde; submitted; arXiv:1609:02350]
CONSTRAINTS & SENSITIVITIES

- CAST
- ALP DM
- ADMX
- IAXO
- ALPS II
- SN1987A γ-ray burst
- Globular clusters

$g_{\nu\gamma}$ (GeV$^{-1}$)

$m_\alpha$ (eV)

$\mathcal{M}_\alpha (\mathcal{E}_\Lambda)$
• Fermi-LAT limits strongest 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
Fermi-LAT has best sensitivity for ALPs with $m_a < 10$ neV from a Galactic core-collapse SN.

Core collapse SN rate: ~2–3% per year, Fermi LAT observes ~20% of the sky at any time.

If Fermi lasts for 15 years ~ 3% chance to catch at least one such event.
SUMMARY & CONCLUSIONS

- Axions and ALPs arise in various extensions of the Standard Model
- Well motivated dark-matter candidates
- 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 γ-ray opacity of the Universe is now strongly constrained
- Fermi-LAT observation of galactic core collapse SN would yield strong bounds on ALP parameters, would probe dark-matter parameter space
BACK-UP SLIDES
Coherent oscillations = dark matter axions

Oscillations should start at latest by matter-radiation equality, so that ALP mass is stable

Oscillation frequency $\omega = m_a$

Energy density: $\rho_{aDM} \sim \frac{1}{2} (75 \text{ MeV})^4 \theta_0^2$

Energy density:

$$\begin{align*}
\dot{\theta} + 3H \dot{\theta} + m_a^2(t) \theta &= 0 \\
\theta(t) &= \theta_0 \cos(m_a t)
\end{align*}$$

$$\frac{g_{a\gamma}}{\text{GeV}^{-1}} \lesssim 2.2 \times 10^{-12} \frac{\alpha}{2\pi} \theta_1 \mathcal{N} \sqrt{\frac{m_a}{\text{eV}}} \frac{\Omega_{DM}}{\Omega_a}$$

[e.g. Arias et al. 2012]
TIME INTEGRATED EXPECTED ALP / $\gamma$-RAY FLUX

- Integrated over SN explosion time (20s for 18 solar masses, 10s for 10 solar mass progenitor)

\[
\frac{d\dot{N}_a}{dE} = g_{a\gamma}^2 C \left( \frac{E}{E_0} \right) \beta e^{-(\beta+1)E/E_0}
\]

Galactic center, $d = 8.5$ kpc, $g_{11} = 0.10$

[Collaboration with Giannotti & Mirizzi, see also Payez et al. 2015]
SYSTEMATIC CHECKS

✓ Different progenitor masses

✓ Different Galactic magnetic field models (largest effect)

✓ Different sources (less background compared to GC)

✓ Different time intervals

✓ Analysis repeated with different time binning of 30 and 60s

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GC</th>
<th>Betelgeuse</th>
<th>M31</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.A. (°)</td>
<td>266.42</td>
<td>88.79</td>
<td>10.63</td>
</tr>
<tr>
<td>Dec. (°)</td>
<td>-28.99</td>
<td>7.41</td>
<td>41.30</td>
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<tr>
<td>Distance (kpc)</td>
<td>8.5</td>
<td>0.197</td>
<td>778</td>
</tr>
<tr>
<td>(t_0) (MJD)</td>
<td>57,231.582</td>
<td>57,231.284</td>
<td>57,231.144</td>
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<tr>
<td>(\Delta t) (s)</td>
<td>1581</td>
<td>1519</td>
<td>1079</td>
</tr>
<tr>
<td>(\langle r_{68}\rangle) (°)</td>
<td>10.92</td>
<td>9.73</td>
<td>10.37</td>
</tr>
<tr>
<td>(\hat{b})</td>
<td>3.32</td>
<td>1.11</td>
<td>0.94</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>0.014</td>
<td>0.014</td>
<td>0.030</td>
</tr>
<tr>
<td>(\mu_{UL})</td>
<td>6.43</td>
<td>5.61</td>
<td>4.19</td>
</tr>
</tbody>
</table>
1. **Step through expected counts** $\mu$

2. **For each value** $\mu$: calculate **log likelihood ratio** (LLR) for a range of observed counts $N_{ON}$

3. **Sum up poisson likelihoods** for $N_{ON}$ sorted by LLR until you reach desired confidence level

$$TS = -2 \ln \left( \frac{L(\mu, \hat{b}(\mu); \alpha|N_{ON}, n)}{L(\hat{\mu}, \hat{b}; \alpha|N_{ON}, n)} \right)$$

**Off counts:** $n = \sum_i n_i$

**Exposure ratios:** $\alpha = \left( \sum_i \epsilon_i \right)^{-1}$

**Maximum likelihood estimators:**
- $\hat{b} = \alpha n$
- $\hat{\mu} = N_{ON} - \alpha n$

[Feldman & Cousins 1998; Rolke et al. 2005]
PHOTON-ALP CONVERSION IN GALACTIC MAGNETIC FIELD

- Mixing in **coherent** component of B field
- **Position of SN** will determine $\gamma$-ray yield
- Two state-of-the-art models implemented

\[ g_{\alpha\gamma} = 5 \times 10^{-11} \text{ GeV}^{-1} \]

pure ALP beam propagating through entire Milky Way

[Jansson & Farrar 2012 model]
UNDERSTANDING THE LIMITS

IRREGULARITIES MOVE INTO THE FERMI-LAT ENERGY RANGE

AMPLITUDE OF IRREGULARITIES BECOMES TOO SMALL

IRREGULARITIES MOVE OUT OF THE FERMI-LAT ENERGY RANGE

[Ajello et al. 2016]
LAST OSCILLATION (BROAD) AT 1 GEV, BUT NOT AS PRONOUNCED ANYMORE, OVERALL SPREAD DECREASES

"QUENCHING" AT HIGH COUPLINGS DUE TO GMF

IRREGULARITIES OVER ENTIRE ENERGY RANGE

[Ajello et al. 2016]
UNDERSTANDING THE LIMITS

[Ajello et al. 2016]

LAST OSCILLATION (BROAD) AT 1 GEV, BUT NOT AS PRONOUNCED ANYMORE, OVERALL SPREAD DECREASES

INCREASING COUPLING:
1. ENERGY RANGE OF IRREGULARITIES DECREASES
2. SPREAD BETWEEN B FIELD REALIZATION DECREASES (GAL FIELD)

IRREGULARITIES OVER ENTIRE ENERGY RANGE
COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

BEST FIT — NOT PREFERRED

$E^2 dN/dE$ (MeV cm$^{-2}$ s$^{-1}$)

$E_{\text{neV}} = 44.61$, $g_{11} = 4.76$

Summed fit, $\ln \mathcal{L} = -199.48$

Summed fit w/o ALP, $\ln \mathcal{L} = -203.92$

max. $\mathcal{L}$ per bin

[Ajello et al. 2016]
Comparing excluded ALP parameters with best fit.

Excluded at > 95% C.L.

$E^2 \frac{dN}{dE}$ (MeV cm$^{-2}$ s$^{-1}$)

- $m_{\text{neV}} = 1.18$, $g_{11} = 1.01$
- Summed fit, $\ln \mathcal{L} = -261.65$
- Summed fit w/o ALP, $\ln \mathcal{L} = -203.92$
- Max. $\mathcal{L}$ per bin

[Reference: Ajello et al. 2016]
COMPARING EXCLUDED ALP PARAMETERS WITH BEST FIT

EXCLUDED AT 95% C.L.

$E^2 \frac{dN}{dE}$ (MeV cm$^{-2}$ s$^{-1}$)

$m_{\text{neV}} = 3.96, \quad g_{11} = 1.01$

- Red: Summed fit, $\ln \mathcal{L} = -214.43$
- Blue: Summed fit w/o ALP, $\ln \mathcal{L} = -203.92$
- Max. $\mathcal{L}$ per bin

[Ajello et al. 2016]
**SYSTEMATIC UNCERTAINTIES**

- **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%

[Ajello et al. 2016]
Null distribution from MC

What is the TS value for which we can claim evidence for ALPS?

- Non-linear behaviour of ALP effect, scales with photon-ALP coupling, ALP mass, and magnetic field

- Testing 228 values of ALP mass and photon-ALP coupling introduces trial factor

⇒ Derive null distribution from simulations

- For \( i \)-th B-field realization and \( j \)-th pseudo experiment the null distribution is formed by the test statistic

\[
TS_{ij} = -2 \ln \left( \frac{\mathcal{L}(\mu_0, \hat{\theta} | D_j)}{\mathcal{L}(\hat{\mu}_i, \hat{\theta} | D_j)} \right)
\]

[Ajello et al. 2016]
What is the TS value for which we can claim evidence for ALPS?

[Image of histogram and cumulative distribution function (CDF) plot with annotations: Non-cen. $\chi^2$, d.o.f. = 10.09, $s = 2.51$, $N_{PE} = 400$.]

[Reference: Ajello et al. 2016]
SEARCHING FOR AN ALP SIGNAL
WITH 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)

\[
TS_{\text{thr}} (3\sigma) = 33.1
\]

[Ajello et al. 2016]