Theoretical and Computational Models for Axion Searches with Neutron Stars with the Fermi LAT

Fermi-LAT Collaboration Meeting: CERN/LAT Combined Session

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Overview

- We present constraints on the nature of axions and axion-like particles (ALPs) by analyzing gamma-ray data from neutron stars using the Fermi Large Area Telescope.
- In addition to axions solving the strong CP problem of particle physics, axions and ALPs are also possible dark matter candidates.
- We derive a phenomenological model for the gamma ray spectrum arising from axion decays.
- By analyzing a sample of 4 nearby neutron stars, we do not find evidence for an axion or ALP signal, thus we obtain a combined 95% confidence level upper limit on the axion mass of 7.9×10^{-2} eV, and an lower limit on f_a of 7.6×10^{7} GeV.

Introduction

- Axions are a theoretically well-motivated particle: to solve the strong CP problem, to be a possible dark matter candidate
- Many different astrophysical studies have studied the axion such as photon to axion conversion from sources such as type Ia SNe, EBL

- Axions satisfy the following relation between the axion mass m_a and the decay constant f_a:

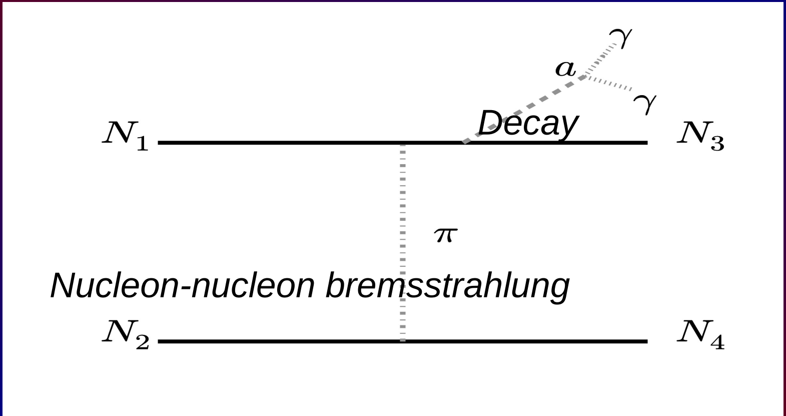
$$m_a \simeq 6\ \mu\text{eV} \left(\frac{f_a}{10^{12}\ \text{GeV}} \right)^{-1}$$

- It is possible to relax this condition, and investigate axion-like particles (ALPs)

Axions from Neutron Stars

- We consider a different mechanism here
- We set bounds on m_a by considering radiative decays from axions produced by nucleon-nucleon bremsstrahlung
  - In neutron stars, primarily neutrons scattering off of neutrons $nn \rightarrow nna$
- Here, for the first time, we use Fermi LAT observations of neutron stars to search for signatures of axions and ALPs

Depiction of the process



Axion production

- Axions are generated by nucleon-nucleon bremsstrahlung in neutron stars in a timescale Δt
- Axions decay into photons with a given width $\Gamma_{a\gamma\gamma}$

$$\Gamma_{a\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi} = 1.1 \times 10^{-24} \mathrm{s}^{-1} (m_a / 1 \text{ eV})^5$$

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$$E \frac{d\Phi}{dE} = 2 \frac{d\epsilon_a}{d\omega} \delta(E - \omega/2) \frac{V_{NS} \Delta t \Gamma_{a\gamma\gamma}}{4\pi d^2}.$$

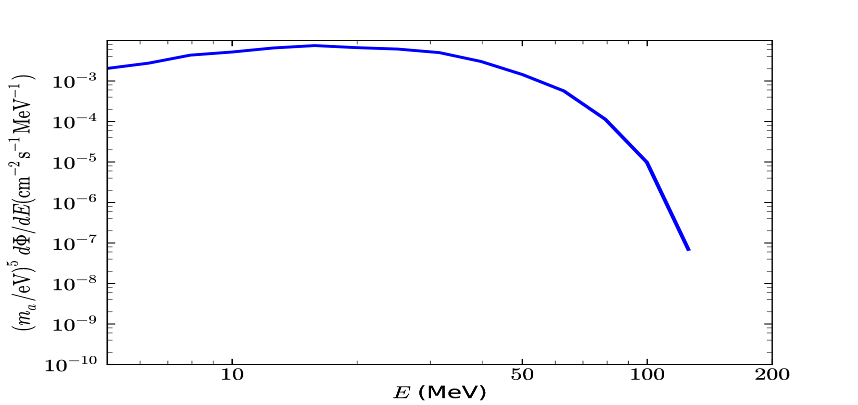
Model Spectrum

- We have derived the following form for the spectrum

$$E\frac{d\Phi}{dE} = 1.8 \times 10^{-2} \left(\frac{m_a}{\text{eV}}\right)^5 \left(\frac{\Delta t}{23.2\ \text{s}}\right) \left(\frac{100\ \text{pc}}{d}\right)^2 \left(\frac{2E}{100\ \text{MeV}}\right)^4 \left(\frac{S_\sigma(2E)}{10^7\ \text{MeV}^2}\right)\ \text{cm}^{-2}\text{s}^{-1}.$$

- $(2E)^4\ S_\sigma(E)$ depends on the nuclear process
- Δt depends on the timescale for axion emission in the nuclear medium
- The SED depends on axion mass to the 5th power
- We do not consider axion to photon conversions, as it can be shown that it is a negligible effect in the vicinity of neutron stars

Spectral Energy Distribution



For source **J0108-1431**

The normalization depends on m_a^5

Table of Sources Analyzed

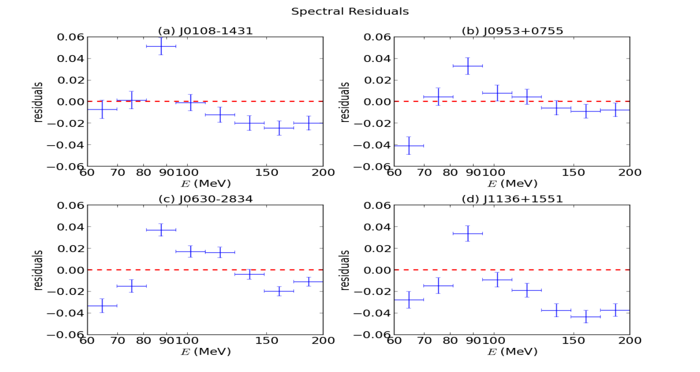
- Criteria on neutron star sources:
  - d < .4 kpc
  - |b| > 15°
  - No 2FGL sources closer than 1.5° away

Source Name	RA (°)	Dec.(°)	ℓ (°)	b (°)	d (kpc)	Age (Myr)	B_{surf} (G)
J0108-1431	17.035	-14.351	140.93	-76.82	$0.240^{+0.124}_{-0.061}$	166	2.52×10^{11}
J0953+0755	148.289	7.927	228.91	43.7	$0.262^{+0.005}_{-0.005}$	17.5	2.44×10^{11}
J0630-2834	97.706	-28.579	236.95	-16.76	$0.332^{+0.052}_{-0.040}$	2.77	3.01×10^{12}
J1136+1551	174.014	15.851	241.90	69.20	$0.36^{+0.019}_{-0.019}$	5.04	2.13×10^{12}

Data Analysis

- 5 year dataset from the Fermi-LAT (MET 239557417– 397323817)
- 20° ROI around each of the 4 selected NS
- Select front events
- IRF: P7REP_SOURCE_V15::FRONT
- We modeled background point sources according to the 2FGL catalog.
- Use the diffuse models: gll_iem_v05.fits and iso_source_front_v05.txt
- Unbinned analysis, no energy dispersion
- Extract upper limits using pyLikelihood; use composite likelihood to combine the limits from the different ROIs

Spectral Residuals



Spectral residuals over the ROI, as a function of energy, according to (counts-model)/model, for the sources (a) J0108-1431 (b) J0953+0755 (c) J0630-2834 (d) J1136+1551.

Systematic Uncertainties

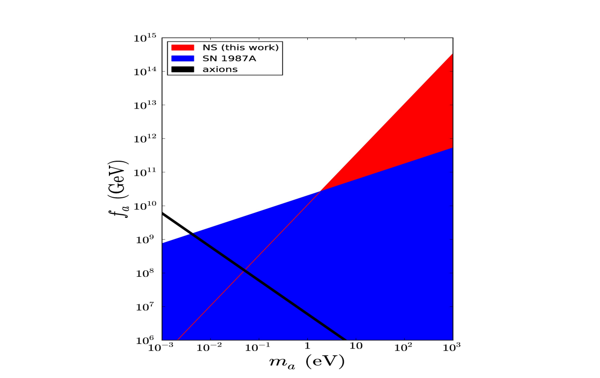
- Neutron Star Distance uncertainties
  - Uncertainties propagated into the limits (as high as 103%)
- Uncertainty in the flux measurements
  - Estimated to be 20% at these energies due to the IRF that we use
- Uncertainty in the diffuse flux
  - Since residuals are of order 5%, 5% of the diffuse flux within a 1 PSF radius (in each ROI) is added to the flux limit
- Systematic uncertainty from theoretical model estimated at 42%.

Table of Upper Limits

	J0108-1431	J0953+0755	J0630-2834	J1136+1551	Combined
95% CL u.l. for m_a (10^{-2} eV)	9.1	9.4	10.2	10.9	7.9
95% CL u.l. on the flux (10^{-9} cm^{-2} s^{-1})	4.03	7.40	4.82	8.52	-

Table of 95% Confidence Level upper limits on m_a and the flux, for the various sources taken individually, as well as the combined limit. The flux and mass upper limits have been corrected for systematic uncertainties, including those from neutron star model parameters. In addition, the limits on m_a account forthe uncertainties on the neutron star distances.

Limits on ALPs



Exclusion plot for the (m_a , f_a) parameter space for ALPs at 95% CL.

NS describes the region derived from this work,
SN 1987A describes the region derived from Fermi LAT analysis of SN 1987A remnant.

Conclusion

- We have developed a model that allows setting limits on axions using gamma ray measurements with Fermi LAT
- We set constraints on axions and ALPs, and compare with the literature values
- We performed checks on the systematic uncertainties
- This work has been submitted to *Phys Rev D*

  and will be posted on the arXiv shortly.

Constraints on Axions from Spatially Extended gamma-ray Emission from Neutron Stars

January 2016

Abstract

Axions are hypothetical particles proposed to solve the strong CP problem in QCD and may constitute a significant fraction of the dark matter in the Universe. Axions are expected to be produced in neutron stars and subsequently decay, producing gamma-rays detectable by the Fermi Large Area Telescope (Fermi-LAT). Considering that light axions may travel a long range before they decay into gamma rays, neutron stars may appear as a spatially-extended source of gamma rays. We extend our previous search for gamma rays from axions, based on a point source model, to consider the neutron star as an extended source of gamma rays.

Introduction

1. Extended gamma-ray sources have been extensively studied with Fermi (Lande et al. [2012])
   1.1 pulsar wind nebulae(Slane et al. [2010])
   1.2 supernova remnants.
   1.3 dark matter in galaxies(Abazajian and Kaplinghat [2012])
2. Photons produced by axion decays may also create extended gamma-ray sources.
   2.1 Decays that occur at a distance from supernova remnants. (Giannotti et al. [2011]).
   2.2 **Decays from axions produced in neutron stars.**

Neutron Stars as Extended Sources of Axions

1. Point-source emission from axions has previously been considered, with Fermi analysis of point sources (PRD **93** 4)(Berenji et al. [2016]).
   1.1 axions produced via nuclear bremsstrahlung and then decay
2. Axion decay lifetime expected to produce extended gamma-ray emission
   2.1 extended source analysis might be more sensitive than point-source analysis

- The theoretical lower bound on axion decays from supernova energy-loss arguments has been placed at ~ 10 meV(Raffelt [1996]).
- The 100 meV to 1 meV range has been mentioned as a promising region for future axion searches(Raffelt et al. [2011]; Redondo et al. [2012]).
- The possibility of diffuse emission from axions produced by $NN-$bremsstrahlung in supernova cores has been theorized to yield axion mass limits in the meV range(Raffelt et al. [2011]).
- We hope to set limits, and perhaps provide even more restrictive constraints, from considering extended axion emission from neutron stars.

Astrophysical Model

We developed an astrophysical model to derive an energy flux from axions emitted from neutron stars, which subsequently decay to photons in [Berenji et al. (2016)]. The energy flux is related to the axion emissivity from nucleon-nucleon bremsstrahlung, as well as the timescale of axion emission from the nuclear medium, which both depend on the axion mass.

$$E\frac{d\Phi}{dE} = 2\frac{d\epsilon_a}{d\omega}\delta(E-\omega/2)\frac{V_{NS}\Delta t\Gamma_{a\gamma\gamma}}{4\pi d^2}. \tag{1}$$

ω is the energy of emitted axions, and $S_\sigma(\omega)$ is the spin-structure function, which accounts for the energy and momentum transfer and includes the spins of the nucleons. This phenomenologically accounts for the nucleon-nucleon bremmstrahlung process as a nucleon-nucleon scattering. V_{NS} is the volume of the neutron star, and d is the distance to the neutron star. We model the timescale of axion emission from a neutron star as the mean time Δt between successive axion emissions in the nuclear medium. It is shown that $\Delta t \simeq 23.2$ s.

The function $\omega^4 S_\sigma(\omega)$, which we use in our extended analysis, is shown in Figure 1. For the purpose of this investigation, this function has been fit to a analytic functional form.

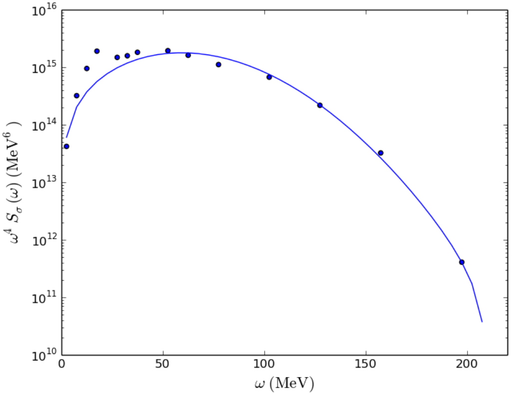


Figure 1: The function $\omega^4 S_\sigma(\omega)$, which has been fit to analytic functional form.

Extended Emission of Axions and Axionlike Particles from Neutron Stars

Axions decay with finite width $\Gamma_{a\gamma\gamma} = 1.1 \times 10^{-24}\ \mathrm{s}^{-1} \left(\frac{m_a}{1\mathrm{eV}}\right)^5$; the probability that ALPs decay from the point of emission from the neutron star increases with distance from the source. In other words, the survival probability decreases with angular distance from the neutron star. The gamma rays arising from the ALP decay would render the neutron star as an extended source in gamma rays. The probability P of an axion of surviving depends on its distance r from the neutron star source.

$$P(r) = P_0 \exp\left(-\frac{\Gamma_{a\gamma\gamma}}{\beta\gamma c} r\right) \tag{2}$$

We may convolve the function $P(r)$ with the function $1/r^2$, which describes the spatial density distribution of axions, to obtain $f(r;\gamma)$.

$$f(r;\gamma) = P(r;\gamma) \star 1/r^2 \tag{3}$$

The energy and spatial dependence of the flux may be factorized.

$$\frac{d\Phi}{dEd\Omega} = \frac{1}{2\pi}\frac{dP_r(\theta; m_a, \omega)}{d\cos\theta}\frac{d\Phi_0}{dE} \tag{4}$$

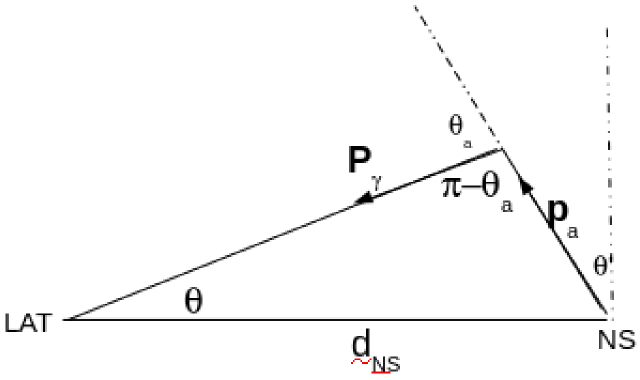


Figure 2: The geometry of the axion decay into photon. The NS-LAT line defines the focal plane. The axion is emitted on a radial path with a colatitude of θ'. The decay photon is emitted at an angle θ_a, and the θ is a measure of the extension of the source.

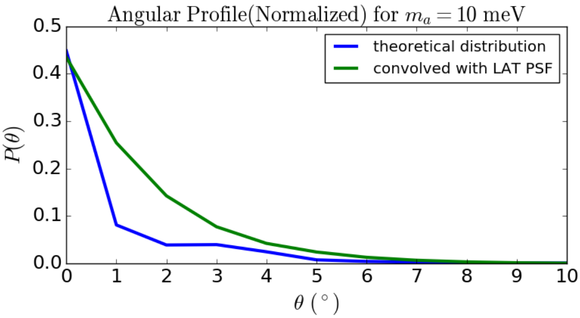


Figure 3: Theoretical angular profile of 10 meV axions, non-convolved and convolved with the PSF of the LAT

- Compare the theoretical angular distribution, within the angular spread of 0.90°, with the angular distribution convolved with the LAT PSF at 60 MeV of $\sim 6^\circ$.

In Figure 3, we plot the angular distributions for $P(\theta)$, as derived from the Monte Carlo simulation.
We may determine the $\gamma-$ray energy from

$$E_\gamma = \frac{1}{2} m\gamma(1 + \beta\cos(\theta_a)) \tag{5}$$

We determine the spectral energy distribution from modifying equation 7, by considering instead of the distance of the neutron star, the distance from the LAT at which the decay vertex occurred.

$$r' = \sqrt{r^2 + d^2 - 2rd\sin\theta'} \tag{6}$$

This corresponds to angular acceptance of 11.5°, which is reasonable considering that the LAT has geometrical acceptance of 2.4 sr.

Spectral Energy Distribution

Thus, we obtain for the extended-emission model (contrast with point-source model)

$$E\frac{d\Phi}{dE} = 1.8\times10^{-2}\left(\frac{m_a}{\mathrm{eV}}\right)^5\left(\frac{\Delta t}{23.2\ \mathrm{s}}\right)\left(\frac{100\ \mathrm{pc}}{r'}\right)^2\left(\frac{2E}{100\ \mathrm{MeV}}\right)^4\left(\frac{S_\sigma(2E)}{10^7\ \mathrm{MeV}^2}\right)\ \mathrm{cm}^{-2}\mathrm{s}^{-1}. \tag{7}$$

Spatial Templates

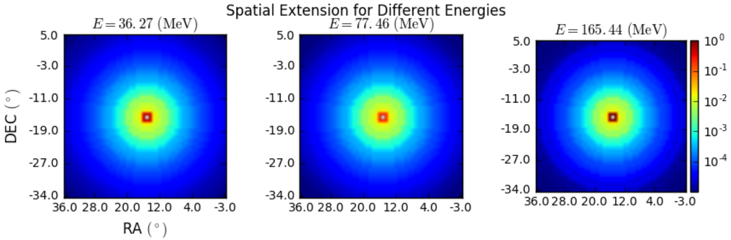


Figure 4: Spatial distribution maps of expected gamma-rays around neutron star J0108-1431 for 10 meV

We generate a "MapCubeFunction," a FITS-formatted file with a spatial map at the following 7 log-spaced gamma ray energies: 24.81, 36.27, 53.00, 77.46, 113.20, 165.44, 241.78 MeV.

Spectral Model

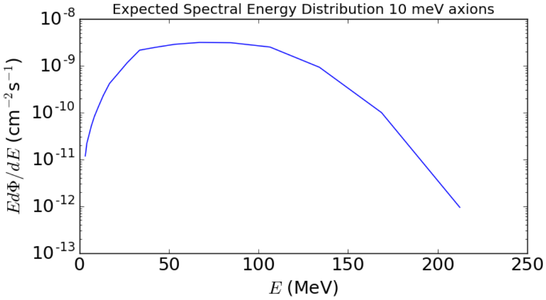


Figure 5: Spectrum for extended emission of axions from neutron star J0108-1431, $m_a = 10\text{meV}$

Projected Limits

Using this spectral model and the extended emission profile, we project sensitivity to upper limits on m_a as low as 10 meV, based on our previous limits from neutron star J0108-1431 of 64 meV. We take into account the extended profile and the increased sensitivity of the model. The 95% confidence level upper limits on m_a are determined by likelihood-based methods. The test statistic for detection significance would be determined by

$$\mathrm{TS} = -2 \ln(L_0/L)$$

Sensitivity Plot

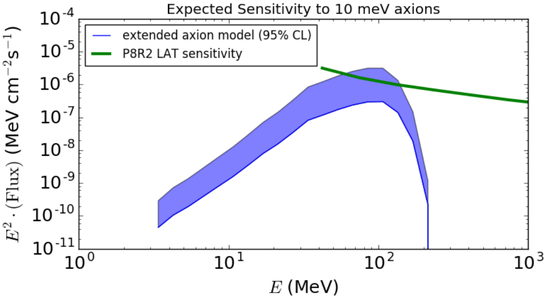


Figure 6: The projected flux sensitivity to axions of m_a=10 meV, shown as a 95% CL region, compared to the projected sensitivity of the LAT (green). Based on a 10-year Fermi-LAT sensitivity projection for Pass 8 instrument response functions Wood et al. [2016]

Projected Limits

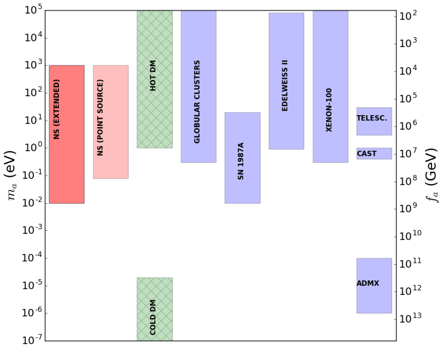


Figure 7: Comparison of exclusion ranges compared with the possible range of masses presented in this article. Exclusion regions for axions and ALPs: the proposed limits (red) from the theoretical models with Fermi-LAT observations of neutron stars, point source model and projected limits from the extended model, compared with previous astrophysical limits.

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