The First Catalog of Fermi-LAT sources below 100 MeV

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on behalf of the Fermi-LAT collaboration

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The First Catalog of Fermi-LAT sources below 100 MeV (1FLE)

1. Introduction about Fermi-LAT and motivation of 1FLE

1. MC analysis
   1. Data selection
   2. PGWave parameter optimization
   3. Flux reconstruction

3. Results
   1. Comparison with the 3FGL catalog
   2. 1FLE blazars
   3. Sensitivity 1FLE

4. Summary
Fermi-LAT Instrument

Fermi-LAT
- Launch date: June 11, 2008
- Energy range: 20 MeV – 300 GeV
- General catalogs(*): 1FGL, 2FGL, 3FGL


No catalogs between 30 and 100 MeV!

Principe G. – 1FLE – Fermi Symposium 2018
Missing MeV Sources?

There exists a population of very energetic sources having hard X-ray emission but no detected emission by Fermi LAT.

FSRQ TXS 0552+398
Vaidhe et. al. in prep.

Harding et. al.(2017)
Fermi Low Energy Catalog

We are interested in studying the Fermi-LAT data between 30 and 100 MeV since they were not covered in the previous Fermi-LAT Catalogs. To detect the sources and estimate their flux we want to use PGWave, a background-independent method already used in the Fermi-LAT catalog pipeline to find candidate sources.

LAT 8.7 years 30-100 MeV counts map
Why are there no Catalogs in the 30-100 MeV band?

1) Angular resolution gets worse

2) Effective area gets smaller

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Principe G. – 1FLE – Fermi Symposium 2018
3) Difficulty in creating an accurate model for the diffuse emission

These reasons make the 30-100 MeV band one of the most complicated energy range!
PGWave Parameter optimization

PGWave uses the 2-dim “Mexican Hat” wavelet. (Damiani et.al. 1997)

<table>
<thead>
<tr>
<th>PGWave parameters</th>
<th>30 – 100 MeV</th>
<th>100 – 300 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel dim.</td>
<td>0°.458</td>
<td>0°.458</td>
</tr>
<tr>
<td>N° sigma for the stat. confidence</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>MH Wavelet Transform scale</td>
<td>1°.4 – 1°.8</td>
<td>0°.9 - 1°.8</td>
</tr>
<tr>
<td>Min. number of connected pixels</td>
<td>5 - 6</td>
<td>7 - 6</td>
</tr>
<tr>
<td>Min. distance between sources</td>
<td>1°.8 – 2°.7</td>
<td>1°.8 - 2°.7</td>
</tr>
</tbody>
</table>

Based on simulations

False Positives:
- 5 in 30-100 MeV
- 17 in 100-300 MeV
Syst. and Stat. Uncertainty of PS Localization

Using 10 realizations
Random PS maps

30 -100 MeV

Syst. Unc ≈ 0°. 25

We optimize the position given by PGWave using a parabolic fit in 5x5 pixel grid around the maximum.
Flux Determination

Flux Reconstruction with PGWave; Principe & Malyshev 2017, arXiv:1610.01351v2

energy flux / ln(Emax/Emin)

30 – 100 MeV

Flux Reconstruction with PGWave; Principe & Malyshev 2017, arXiv:1610.01351v2
Fermi-LAT sources below 100 MeV

**Association:**
- Based on a positional coincidence
- Tolerance radius 1°.5
- Flux ordering

<table>
<thead>
<tr>
<th>Results</th>
<th>PS (counts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3FGL (grey points)</td>
<td>3034</td>
</tr>
<tr>
<td>PGWave 30-100 MeV</td>
<td>198</td>
</tr>
<tr>
<td>Associated</td>
<td>187</td>
</tr>
</tbody>
</table>
1FLE and 3FGL Catalog comparison

**3FGL**
(3033 sources)

- **AGN**: 58%
- **Other Galactic**: 5%
- **Unassoc. Unclassif.**: 14%
- **PSR**: 6%
- **Unassoc**: 31%

**1FLE**
(198 sources)

- **AGN**: 75%
- **Unassoc. Unclassif.**: 14%
- **PSR**: 6%
- **Other Galactic**: 5%
- **Unassoc**: 31%
Comparison of the blazars in 1FLE and in 3FGL(3LAC), 3FHL and TeVCat.

The higher fraction of FSRQs is expected in 1FLE since they typically have softer spectra than BL Lacs.
1FLE Blazars – Redshift distributions

60% LSP BL Lacs in 1FLE, compared to 25% in 3LAC. LSP – Low-synchrotron peaked blazar.

<table>
<thead>
<tr>
<th>Blazar class</th>
<th>1FLE</th>
<th>3LAC</th>
<th>KS test p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>All blazars</td>
<td>1.06 ± 0.06</td>
<td>0.84 ± 0.02</td>
<td>8.1 × 10⁻⁶</td>
</tr>
<tr>
<td>FSRQ</td>
<td>1.22 ± 0.06</td>
<td>1.21 ± 0.03</td>
<td>0.964</td>
</tr>
<tr>
<td>BL Lac</td>
<td>0.59 ± 0.09</td>
<td>0.41 ± 0.02</td>
<td>0.018</td>
</tr>
<tr>
<td>Other blazars</td>
<td>0.55 ± 0.17</td>
<td>0.33 ± 0.04</td>
<td>0.124</td>
</tr>
</tbody>
</table>
Spectral Energy Distributions

Two examples of SED.

SED 1FLE J0633+1746 - Geminga

SED 1FLE J1256-0545 - 3C279
1FLE AGN flares

<table>
<thead>
<tr>
<th>Source Name</th>
<th>GLON (deg)</th>
<th>GLAT (deg)</th>
<th>1FLE $\nu F_{\nu}$ (100-100 MeV) $10^{-12}$ erg cm$^{-2}$ s$^{-1}$</th>
<th>3FGL $\nu F_{\nu}$ (100-300 MeV) $10^{-12}$ erg cm$^{-2}$ s$^{-1}$</th>
<th>Flare comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1FLE J0424-0042</td>
<td>194.8</td>
<td>-32.6</td>
<td>$5.49 \pm 2.19$</td>
<td>$18.79 \pm 1.17$</td>
<td>flare in 3FGL</td>
</tr>
<tr>
<td>1FLE J0443-0024</td>
<td>197.5</td>
<td>-28.2</td>
<td>$6.26 \pm 2.50$</td>
<td>$19.72 \pm 0.86$</td>
<td>flare in 3FGL</td>
</tr>
<tr>
<td>1FLE J1224+2118</td>
<td>255.5</td>
<td>81.6</td>
<td>$49.77 \pm 14.79$</td>
<td>$83.52 \pm 1.12$</td>
<td>flare in 3FGL</td>
</tr>
<tr>
<td>1FLE J1227+0218</td>
<td>289.1</td>
<td>64.6</td>
<td>$37.46 \pm 10.63$</td>
<td>$87.53 \pm 1.41$</td>
<td>flare in 3FGL</td>
</tr>
<tr>
<td>1FLE J1332-0518</td>
<td>321.6</td>
<td>56.0</td>
<td>$11.93 \pm 3.39$</td>
<td>$26.22 \pm 1.93$</td>
<td>flare in 3FGL</td>
</tr>
<tr>
<td>1FLE J1503+1033</td>
<td>11.3</td>
<td>54.8</td>
<td>$3.60 \pm 1.02$</td>
<td>$6.73 \pm 1.19$</td>
<td>flare in 3FGL</td>
</tr>
<tr>
<td>1FLE J2231+1132</td>
<td>77.1</td>
<td>-38.6</td>
<td>$74.32 \pm 22.09$</td>
<td>$29.34 \pm 1.03$</td>
<td>flare after 3FGL</td>
</tr>
</tbody>
</table>

Table 5. 1FLE sources with a flare during the 3FGL observation time (flare in 3FGL) or after the 3FGL observation time (flare after 3FGL).
In red, the **1FLE total sensitivity** (95% detection efficiency at $|b| > 10^\circ$), while in black the **1FLE statistical sensitivity** determined as the flux corresponding to the 5$\sigma$ significance of PGWave.
Summary

Simulation:
1. We optimize the PGWave parameters to maximize detection rate and minimize the false positives.
2. We optimize the reconstructed position with a parabolic fit.
4. Flux Reconstruction:
   • We reconstruct the flux using the WT peak
   • We estimate the Stat. and Syst. Unc. for flux reconstruction

Results:
1. We analyze 8.7 years of data between 30-100 MeV: we found 198 PS, 187 have an association in 3FGL and 11 have no association (no significant evidence of new sources).
2. We compare the 1FLE AGNs with other gamma ray catalogs (3LAC, 3FHL, TeVCat).
3. We create the spectral energy distributions for the 1FLE PS.
4. We estimate the sensitivity of the 1FLE catalog.

Recently accepted by A&A and posted on arXiv

Thanks for your attention
PGWave: a Wavelet Transform Method

PGWave is a method, based on Wavelet Transforms (WTs) [1], to detect sources in astronomical images obtained with photon-counting detectors, such as X-ray or gamma-ray images.

1. The WT of a 2-dim image \( f(x,y) \) is defined as:

\[
w(x, y, a) = \int \int g\left(\frac{x - x'}{a}, \frac{y - y'}{a}\right)f(x', y')dx' dy'
\]

where \( g(x/a, y/a) \) is the generating wavelet, \( x \) and \( y \) are the pixel coordinates, and \( a \) is the scale parameter.

2. PGWave uses the 2-dim “Mexican Hat” wavelet:

\[
g\left(\frac{x}{a}, \frac{y}{a}\right) = g\left(\frac{r}{a}\right) = \left(2 - \frac{r^2}{a^2}\right)e^{-r^2/2a^2} \quad (r^2 = x^2 + y^2)
\]

3. The peak of the WT for a source with Gaussian shape (\( N_{\text{src}} \) total counts and width \( \sigma_{\text{src}} \)) is:

\[
w_{\text{peak}}(a) = \frac{2N_{\text{src}}}{(1 + \sigma_{\text{src}}^2/a^2)^2}
\]

PSF Class Selection
Random PS maps
Analysis Procedure

**Analysis procedure:**
1. **Gtbin**: we use 12 ROIs of the dimensions of 180° x 90° (LON, LAT)
2. **PGWave**: we perform PGWave and create a dictionary
3. **Restrict area**: we eliminate the seeds that are close to the boarder
4. **Merge seeds**: we merge the seeds in the overlapped regions (we perform the previous steps 1-4 are performed also for the diffuse maps)
5. **Eliminate diffuse**: we eliminate the seeds that match with those from the diffuse
6. **Comparison**: we compare the resulting sources with the 3FGL
7. **Flux determination**: we determine the flux using the WT peak of PGWave
## Data Selection

<table>
<thead>
<tr>
<th>Data Selection</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRFs</td>
<td>P8R2_SOURCE_v6</td>
</tr>
<tr>
<td>PSF Classes</td>
<td>PSF3</td>
</tr>
<tr>
<td>Time Interval</td>
<td>8.7 years</td>
</tr>
<tr>
<td>Energy Range</td>
<td>[30-100 MeV] [100-300 MeV]</td>
</tr>
<tr>
<td>Zenith angle</td>
<td>90°</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>0.458°</td>
</tr>
</tbody>
</table>
Since PGWave returns the positions of the center of the pixel (in which the WT has a maximum), we optimize the reconstruction of the position using a parabolic fit in 5x5 pixel grid around the maximum.

Tolerance radius (1°.5): 98% of the reconstructed sources are localized at less than 1°.5 from the input position.
Syst. and Stat. Uncertainty of PS Localization

We used 10 realizations of the MC maps with random positioned PS for studying the systematic and statistical error in the localization ([30-100 MeV], {100-300 MeV].

**Statistical:**
for each reconstructed PS \((K)\) we compute the mean and the standard deviation (sigma) of the position of the seeds from the different realizations, with the mean position \(X_{\text{mean}}\) where \(n\) is the number of PGWave seeds associated at this reconstructed PS (input PS). Our statistical Unc. is the mean of all the single sigma\(_k\) of each reconstructed PS

\[
\sigma = \sqrt{\frac{\sum (X_{PGW_i} - X_{PGW_{\text{mean}}})^2}{n}}
\]

\[
\sigma_k = \frac{\sigma}{\sqrt{n - 1}}
\]

Total Deviation in the Position (Systematic)
We compute the difference between the mean position for the seeds of the same reconstructed PS and the position of the input PS:

\[
\Delta_k = X_{PGW_{\text{mean}}} - X_{IN}
\]

Then for all the reconstructed PS

\[
\sigma_{DEV} = \sqrt{\frac{\sum \Delta_k^2}{k}}
\]
To derive the Syst. Unc. of the Flux Reconstruction, we divide the sources in bins of WT peak, then we estimate the mean distance, inside each bin, between the Input MC Flux and the PGWave best fit. (Stat. Unc. given by PGWave)

Relative Stat. and Syst. Unc of Flux estimation
30 – 100 MeV
Flux Determination

$\nu F_{\nu} \text{ (erg cm}^{-2}\text{s}^{-1})$

$100 - 300 \text{ MeV}$
## 1FLE sources characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>Associated Designator</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar</td>
<td>psr</td>
<td>12</td>
</tr>
<tr>
<td>Pulsar wind nebula</td>
<td>pwn</td>
<td>2</td>
</tr>
<tr>
<td>Supernova remnant</td>
<td>snr</td>
<td>2</td>
</tr>
<tr>
<td>Supernova remnant / Pulsar wind nebula</td>
<td>spp</td>
<td>5</td>
</tr>
<tr>
<td>High mass binary</td>
<td>hmb</td>
<td>1</td>
</tr>
<tr>
<td>BL Lac type of blazar</td>
<td>bll</td>
<td>31</td>
</tr>
<tr>
<td>Flat spectrum radio quasar type of blazar</td>
<td>fsrq</td>
<td>98</td>
</tr>
<tr>
<td>Narrow-line seyfert 1</td>
<td>nlsyl</td>
<td>1</td>
</tr>
<tr>
<td>Radio galaxy</td>
<td>rdg</td>
<td>3</td>
</tr>
<tr>
<td>Steep spectrum radio quasar</td>
<td>ssrq</td>
<td>1</td>
</tr>
<tr>
<td>Normal galaxy (or part)</td>
<td>gal</td>
<td>1</td>
</tr>
<tr>
<td>Blazar candidate of uncertain type</td>
<td>bcu</td>
<td>13</td>
</tr>
<tr>
<td>Unclassified</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Unassociated</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td><strong>Total in the 1FLE</strong></td>
<td></td>
<td><strong>198</strong></td>
</tr>
</tbody>
</table>

Source classes of the 1FLE sources determined using the 3FGL associations.  
Little evidence that the 11 sources with no 3FGL association are actually new sources.
### 1FLE sources not associated to the 3FGL

<table>
<thead>
<tr>
<th>Source Name</th>
<th>GLON (deg)</th>
<th>GLAT (deg)</th>
<th>Err_pos (deg)</th>
<th>Signif. (σ)</th>
<th>$#(30-100\text{ MeV}) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$</th>
<th>$#(100-300\text{ MeV}) \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1FLE J2206+ 7040</td>
<td>110.02</td>
<td>12.06</td>
<td>0.25</td>
<td>4.38</td>
<td>$23.75 \pm 7.16$</td>
<td>$0.0 \pm 0.0$</td>
<td>Diffuse</td>
</tr>
<tr>
<td>1FLE J0330+ 3304</td>
<td>157.42</td>
<td>-18.94</td>
<td>0.25</td>
<td>9.87</td>
<td>$23.56 \pm 7.10$</td>
<td>$0.0 \pm 0.0$</td>
<td>3FGL sources</td>
</tr>
<tr>
<td>1FLE J0422+ 5243</td>
<td>151.75</td>
<td>2.07</td>
<td>0.25</td>
<td>7.00</td>
<td>$22.73 \pm 6.85$</td>
<td>$0.0 \pm 0.0$</td>
<td>Gal. plane</td>
</tr>
<tr>
<td>1FLE J0647-0345</td>
<td>215.89</td>
<td>-2.48</td>
<td>0.25</td>
<td>7.75</td>
<td>$17.71 \pm 5.34$</td>
<td>$0.0 \pm 0.0$</td>
<td>Gal. plane</td>
</tr>
<tr>
<td>1FLE J0655-1106</td>
<td>223.33</td>
<td>-4.08</td>
<td>0.25</td>
<td>4.01</td>
<td>$14.93 \pm 4.94$</td>
<td>$4.07 \pm 1.63$</td>
<td>Gal. plane</td>
</tr>
<tr>
<td>1FLE J0522+ 3734</td>
<td>170.17</td>
<td>0.68</td>
<td>0.25</td>
<td>5.00</td>
<td>$13.66 \pm 4.52$</td>
<td>$0.0 \pm 0.0$</td>
<td>Gal. plane</td>
</tr>
<tr>
<td>1FLE J0637-0110</td>
<td>212.35</td>
<td>-3.72</td>
<td>0.25</td>
<td>4.80</td>
<td>$10.88 \pm 3.6$</td>
<td>$0.0 \pm 0.0$</td>
<td>Gal. plane</td>
</tr>
<tr>
<td>1FLE J1033+ 1601</td>
<td>224.87</td>
<td>56.14</td>
<td>0.25</td>
<td>3.65</td>
<td>$10.30 \pm 3.41$</td>
<td>$0.0 \pm 0.0$</td>
<td>$\sigma &lt; 4$</td>
</tr>
<tr>
<td>1FLE J2158-5424</td>
<td>339.89</td>
<td>-48.37</td>
<td>0.25</td>
<td>3.99</td>
<td>$8.51 \pm 2.82$</td>
<td>$0.0 \pm 0.0$</td>
<td>$\sigma &lt; 4$</td>
</tr>
<tr>
<td>1FLE J1203-2504</td>
<td>289.40</td>
<td>36.53</td>
<td>0.25</td>
<td>4.07</td>
<td>$8.39 \pm 2.77$</td>
<td>$0.0 \pm 0.0$</td>
<td>3FGL sources</td>
</tr>
<tr>
<td>1FLE J1030-3133</td>
<td>270.81</td>
<td>22.38</td>
<td>0.25</td>
<td>3.43</td>
<td>$7.11 \pm 2.35$</td>
<td>$0.0 \pm 0.0$</td>
<td>$\sigma &lt; 4$</td>
</tr>
</tbody>
</table>

**Gal. Plane:** inside the galactic plane $|b|<10^\circ$ where the diffuse emission has several structures.

**Diffuse:** particular regions where the diffuse emission has some bright features.

**3FGL sources:** due to the large PSF if there are two or more 3FGL sources close each other, they could form a single structure and PGWave does not distinguish the different sources but returns a seed in the middle.
Fermi blazar sequence

Using the 3LAC blazars

Ghisellini et al. 2017

Using the 3LAC blazars

FSRQs

BL Lacs

All

Ghisellini et al. 2017

Log $L_{\text{AC}}$ [erg s$^{-1}$]

Redshift $z$

Log $\nu L_{\nu}$ [erg s$^{-1}$]

Log $\nu$ [rest frame]
The COMPTEL and EGRET sensitivities are given for the typical observation time accumulated during 9 years. The Fermi-LAT sensitivity is for a high Galactic latitude source in 10 years of observation in survey mode. e-ASTROGAM sensitivity for an effective exposure of 1 year and for a source at high Galactic latitude.
One of the reasons for the lack of new sources is the lower sensitivity of the Fermi-LAT at low energies due to small effective area and angular resolution.

**Two consequences of non-observation of new sources** in 1FLE:
1. No sufficiently bright flaring sources (not in 3FGL) after 3FGL time interval
2. No very bright sources with a very soft spectrum, e.g. cutoff around 100 MeV
Outlook – eASTROGAM

De Angelis et. al. 2017