The latest *Fermi*-LAT catalogs and SKA prospects for high energy studies

Marcello Giroletti  
Filippo D’Ammando  
Monica Orienti  
Giacomo Principe  
on behalf of the *Fermi*-LAT collaboration  

INAF Istituto di Radioastronomia  

*Bologna, The II National Workshop on SKA science and Technology, 3-5 Dec 2018*
What are LAT catalogs good for?

• Predictions/optimisation of future observatories: CTA, SKA, LHAASO, ...
• Sky model for data analysis
• Reference for studies on:
  – individual sources
  – source populations
  – MW analyses
• Source samples to investigate
  – Extragalactic Background Light
  – Extragalactic Diffuse Gamma-ray Background
• Exploration of new classes: stars, galaxy clusters...
• Nature of unassociated sources via follow-up observations
• Classification of unassociated sources

1+2+3FGL
2774 citations
(NASA ADS)
### Fermi-LAT general catalogs

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Energy Range (GeV)</th>
<th>Data Interval (months)</th>
<th>Sources</th>
<th>Unassociated</th>
<th>Release Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>0FGL</td>
<td>0.2-100</td>
<td>3</td>
<td>205</td>
<td>37 (18%)</td>
<td>Feb. 2009</td>
</tr>
<tr>
<td>1FGL</td>
<td>0.1-100</td>
<td>11</td>
<td>1451</td>
<td>630 (43%)</td>
<td>Feb. 2010</td>
</tr>
<tr>
<td>2FGL</td>
<td>0.1-100</td>
<td>24</td>
<td>1873</td>
<td>649 (35%)</td>
<td>Aug. 2011</td>
</tr>
<tr>
<td>3FGL</td>
<td>0.1-300</td>
<td>48</td>
<td>3033</td>
<td>992 (33%)</td>
<td>Jan. 2015</td>
</tr>
<tr>
<td>4FGL</td>
<td>0.05-1000</td>
<td>96</td>
<td>~5500</td>
<td>~1800 (33%)</td>
<td>Early 2019</td>
</tr>
<tr>
<td>1FHL</td>
<td>10-500</td>
<td>36</td>
<td>511</td>
<td>65 (13%)</td>
<td>Jun. 2013</td>
</tr>
<tr>
<td>2FHL</td>
<td>50-2000</td>
<td>80</td>
<td>360</td>
<td>48 (14%)</td>
<td>Aug. 2015</td>
</tr>
<tr>
<td>3FHL</td>
<td>10-2000</td>
<td>84</td>
<td>1556</td>
<td>176 (11%)</td>
<td>Mar. 2017</td>
</tr>
<tr>
<td>1FLE</td>
<td>0.03-0.1</td>
<td>104</td>
<td>198</td>
<td>28 (14%)</td>
<td>Oct. 2018</td>
</tr>
</tbody>
</table>

Each “FGL” catalogue is accompanied by a sibling “LAC” catalogue of gamma-ray active galactic nuclei.

---

Principe et al. (2018)
FL8Y

- Preliminary LAT 8-year Point Source List, 5523 sources, released early January 2018
  - it was meant to help in writing 2018 NASA Fermi Guest Investigator proposals.
  - it will be similar to 4FGL in many aspects (data+analysis procedure) but 4FGL will use an updated diffuse emission model
- Caveats
  - The FL8Y list is meant to provide researchers analysing Fermi data with an updated description of the gamma-ray sky with respect to 3FGL. It contains nearly 2500 new sources which can be used as a starting point for new works. It can also be used for modelling the source background in a region of interest.
  - Being a courtesy effort, FL8Y is neither published nor posted on the arXiv. We request the community users to refrain from publishing works (in particular population studies) using directly material from FL8Y, and wait for the future 4FGL catalog that will supersede FL8Y.
FL8Y characterisation

Improved localisation (important for association):
median error radius (at 25<TS<100) 4.4 arcmin

Detection threshold for extragalactic sources:
energy flux \( \sim 2.10^{-12} \text{ erg cm}^{-2}\text{s}^{-1} \)
(depends slightly on spectral shape)
Bayesian method (general), J. Knödlseder (following Mattox et al. 1997)

- true association: offset determined by position uncertainty (Rayleigh distribution)
- false association: offset determined by counterpart local density
- Prior via Monte-Carlo

\[ N_{false} = \sum_{p_{ik} \geq P_{thr}} (1 - p_{ik}) \]

\[ P_{thr} = 0.8 \]

\[ N_{assoc} = \sum_{p_{ik} \geq P_{thr}} 1 \]

- New features: provide low-confidence \((P>0.1)\) associations

Likelihood-ratio method (AGNs), ASDC (following de Ruiter 1977)

- Similar to Bayesian-method, false associations from density of objects brighter than considered candidate.
  + inspection of SEDs for « blazarness ».
- Can handle large surveys: NVSS, SUMSS, ROSAT
- Overlap between Bayesian and LR methods for AGNs \(~75\%)
## Association summary

<table>
<thead>
<tr>
<th>Class</th>
<th>3FGL</th>
<th>FL8Y (E&gt;50 MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>3034</td>
<td>5457</td>
</tr>
<tr>
<td>Pulsar*</td>
<td>143+24</td>
<td>210+14 (+34%)</td>
</tr>
<tr>
<td>PWN</td>
<td>11</td>
<td>18 (+63%)</td>
</tr>
<tr>
<td>SNR</td>
<td>23</td>
<td>38 (+65%)</td>
</tr>
<tr>
<td>HMB</td>
<td>3</td>
<td>6 (+100%)</td>
</tr>
<tr>
<td>SPP†</td>
<td>49</td>
<td>113 (+122%)</td>
</tr>
<tr>
<td>Glob. Cluster</td>
<td>15</td>
<td>27 (+80%)</td>
</tr>
<tr>
<td>AGN</td>
<td>1751</td>
<td>3184 (+81%)</td>
</tr>
<tr>
<td>Associated</td>
<td>2041</td>
<td>3621 (+77%)</td>
</tr>
</tbody>
</table>

### Pie Chart

- **Unassociated**: 34%
- **BL Lacs**: 1288
- **Flat-Spectrum Radio Quasars**: 1067
- **Galaxy**: 14
- **Other AGN**: 62
- **Global Cluster**: 27
- **PWN**: 18
- **SPP**: 113
- **Other Galactic**: 11

### Associations

- **Cat8 Bayesian+Likelihood Ratio associations**: 1834
- **Unassoc**: 1834
Towards 4LAC

Bayesian- +LR- method associations in Cat8
2750 sources $|b|>10^\circ$ (3LAC: 1591 sources)
• number of FSRQs: 714 (+53%)
• number of BLLs: 1223 (+92%)
• number of BCUs: 759 (+68%)
3184 sources (all sky)
9 NLSy1 (4 new), 34 radio galaxies, 16 other AGNs
1422 sources in BZCAT
69 TeV sources

8% deficit in the Southern hemisphere
1628 redshifts in Cat8

- several new $z > 3$ FSRQs
- maximum redshift $z = 3.9$
- 468/1233 (38%) BL Lacs have no measured redshifts
Photon-index distributions

- Little overlap between FSRQs and BL Lacs, limit at $\Gamma=2.2$
- New FSRQs notably softer than 3LAC ones
  - $<\Gamma>=2.60$ vs. 2.46
- New BL Lacs notably softer than 3LAC ones
  - $<\Gamma>=2.19$ vs. 2.04
- BCUs index distribution straddling the two classes and extending beyond 2.6. New BCUs softer than 3LAC ones
  - $<\Gamma>=2.32$ vs. 2.11
The *Fermi* view of the radio-gamma ray connection

- All associated gamma-ray sources are radio emitters
- Specific radio properties are a defining characteristic of blazars
  - flat radio spectrum at all frequencies (work with SKA precursors/pathfinders)
    - Massaro+13, Giroletti+16, Mooney+18
  - compactness/strong core dominance
  - superluminal motion in parsec scale jets
  - variability
- Large scatter and flux density limits prevent simple linear fit - questions:
  - can we improve our understanding of this correlation to finally constrain physics (in blazars, and not only - eg EGRB)?
  - what about UGS (~30% of total, ie many 100’s)

- Moderately strong, extremely significant
  - correlation coefficient: $r=0.47$
  - chance probability $<10^{-7}$

NB only two unassociated sources above this flux

Characterizing UGS

• most UGS have relatively low gamma-ray flux
  – positional uncertainty is larger
  – low $F_{\gamma}$ sources have higher spatial density
    • it gets nearly impossible to associate counterparts only on the basis of pure spatial coincidence
• yet, these sources could be very important, eg low $F_{\gamma}$ could stem from
  – low luminosity
    • and large $V_{\text{peak}}$: extreme accelerators
    • and low $V_{\text{peak}}$: blazar sequence outliers
  – or high distance
    • early blazars: constraints on massive BH formation history
  – and if they are not blazars, it could even be more fun!
• need VLBI to filter out extended emission!
SKA prospects

• The final Fermi catalog will likely be one magnitude deeper than 1LAC
  – not only longer exposure but also better characterisation of detector, diffuse model, etc.
  – weakest known 3LAC blazar is 4.2 mJy, unassociated ones are probably fainter
  – sub-mJy sources can certainly be expected
• Radio catalogs will not only need to be deeper but also more physically informative
  – multi-λ, multi-epoch, polarisation sensitive
  – high frequency bands desirable to get closer to gamma-ray emission region
• Even more intriguing when very high energy gamma rays are considered
  – the radio-gamma connection breaks down if we consider the hard source Fermi catalogues
  – CTA will come online, too!

Lico et al. (2017)
1. Radio and gamma rays, despite being the most distant parts of the EM spectrum, are connected in many important astrophysical contexts
   - jets, pulsars, SNe, SNR, ...

2. Large improvements are happening/going to happen in both bands
   - with *Fermi*, SKA, and its pathfinders/precursors
   - and the Cherenkov Telescope Array (CTA)

3. We should organize operations in order to maximize scientific return
   - improving also connection with UHECRs studies