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Bridging the gap - Fermi-LAT sources at 20-200 MeV

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The under-explored MeV band has an extremely rich scientific potential. Awaiting an all-sky MeV mission, it is now the prime time to take full advantage of the capabilities of the Fermi Large Area Telescope to explore this regime. With more than 12 years of the best available dataset (Pass8), we have developed an all-sky analysis to build a sensitive catalog of sources from 20 to 200 MeV. This work will allow us to cover the SED peak of the most luminous gamma-ray blazars, fundamental to understand their nature, and possibly discover a whole new population of MeV sources. Importantly, this program will start bridging the gap between the MeV and GeV energy bands, strongly supporting the scientific case for a future all-sky MeV mission and enhancing the legacy of the Fermi mission. In this talk I will highlight the scientific potential of this project. I will also discuss the difference with respect to the first catalog of low-energy sources (1FLE, Principe et al. 2018).

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1. Introduction

The last decade has seen an incredible improvement in the sensitivity of both hard X- and γ-ray telescopes. This advance has led to the detection of hundreds of both Galactic and extra-galactic sources which show a rising hard X-ray spectrum (photon index, $\Gamma_X < 1.5$) and falling γ-ray one ($\Gamma_\gamma > 2$), hence likely peaking in the MeV band [1–6].

For example, the most powerful and distant blazars are brightest in the MeV band [e.g., 7]. Found even beyond $z = 5$ [e.g. 8], in general they harbor extremely massive black holes ($M_{\rm BH} \gtrsim 10^9 M_\odot$). Since their emission is highly beamed, the detection of a single source implies the existence of $2\Gamma^2$ (i.e., ~ 450 for a typical bulk Lorentz factor, $\Gamma \sim 15$, [9]) quasars with similar properties, at the same z, with jets pointed somewhere else. In other words, the discovery of each new blazar hosting a billion solar mass black hole allows us to constrain the size of the parent population and to quantify the supermassive black hole space density at high-z. Importantly, following blazar evolution studies, [9] compared the supermassive black hole number density of radio-quiet (i.e. without jets) sources versus radio-loud (i.e. with jets). The authors found that while the density of radio-quiet AGNs peaks around $z \sim 2$ (when the universe was ~ 3.5 billion years old), the radio-loud one peaks much earlier, around $z \sim 4$ (when the universe was only ~ 1.5 billion years old, see Figure 1 left panel). This fact challenges our understanding of black hole growth and evolution in the early universe and might point to a connection between jet activity and fast accretion. Detecting these sources in large numbers will take us a step closer to understanding the formation of supermassive black holes in the early universe [9, 10].

Similarly, the poorly understood physics of pulsars can be unveiled by studying these sources in the MeV band [11]. For instance, the *Fermi*-Large Area Telescope (LAT) has detected 271 pulsars, but only ~ 40 are detected at high-significance ($> 5\sigma$) < 300 MeV and only 4 at $50 - 100$ MeV [12]. The number of pulsars seen at soft γ-rays (< 50 MeV) therefore remains less than 20 [see 13]. The soft γ-pulsars are found to have high spin values, they are young and very energetic with respect to other detected *Fermi*-LAT pulsars. At the hard X-rays they usually display a hard power-law spectral index and reach maximum luminosities typically in the MeV range, implying a peak around 0.1-1 MeV. While some of these 'MeV pulsars' are found to be radio-loud, for the majority of them neither radio nor GeV emission has been detected. PSR B1509-58 is an example of an 'MeV pulsar' that has been detected by the LAT. With a soft γ-ray spectrum and a very hard X-ray one (see Figure 1, right panel, [13, 14]), it was also detected by COMPTEL which unveiled its MeV peak. The high-energy emission of these pulsars can be explained by synchrotron radiation of pairs in the magnetic field. However, the location of production of such pairs is still highly debated [see, e.g. 11]. Only measurement of the SED peaks for a number of these 'MeV pulsars' can allow us to test different models, understand the location of particle production and pinpoint the physical processes powering them.

The proposed analysis presented in this talk is aimed to develop, for the first time using an all-sky likelihood analysis, a point source catalog in the 20–200 MeV range, bridging the gap between traditional LAT catalogs and the MeV energy regime. Creating a new census of the MeV sky is fundamental because it would both enable us to (i) explore the SED peak of known sources (e.g., high-redshift blazars, pulsars, high mass binaries); (ii) detect for the first time sources that, lacking a dedicated low-energy analysis, could have been missed by other LAT catalogs; and (iii)

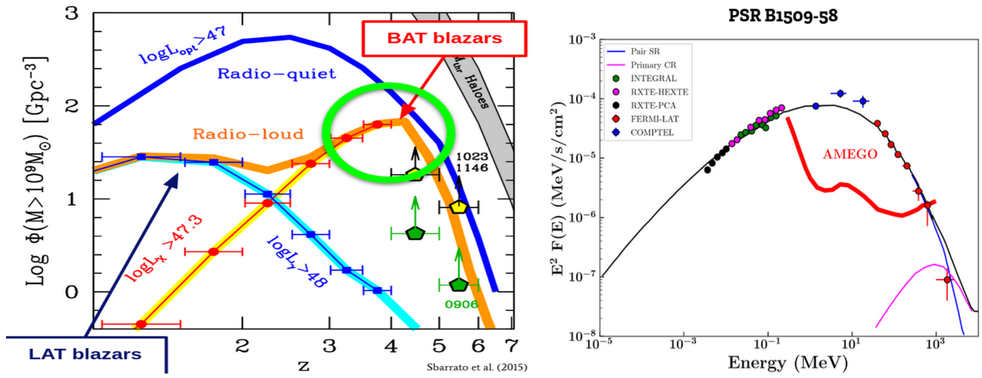


Figure 1: Left: supermassive black hole space density plot, adapted from [9]. Radio-loud sources peak at $z \sim 4-5$, indicating a connection between a jetted phase of the AGN and the fast supermassive black hole growth. **Right:** high-energy SED of PSR B1509-58, adapted from [11].

provide a 'map' of the MeV sky in preparation for future MeV missions.

2. The Past

Since the last light of the COMPTEL [15] instrument onboard the Compton Gamma-Ray Observatory, the MeV sky has yet to be explored with good sensitivity. This mission left us with a MeV catalog comprising 63 objects that emit between 0.75 and 30 MeV (see Figure 2, left panel, [16, 17]). Among the 32 steady sources detected by COMPTEL, about 1/2 are blazars. Another 1/2 are sources of Galactic origin, such as pulsars, pulsar wind nebulae, and supernova remnants. Lacking an all-sky MeV instrument, the only chance we have to explore the MeV regime is to take advantage of the *Fermi*-LAT low-energy threshold, which allows for the detection of photons down to 20 MeV. The majority (>80 %) of the 5065 sources reported in the 4FGL-DR2 catalog [1, 12] has a power-law spectral index >2. It is thus clear that most LAT-detected γ-ray sources emit most of their energy in the MeV rather than the GeV band. Moreover, the 4FGL-DR2 contains 520 sources detected at a significance level $> 5\sigma$ in the 50-300 MeV energy range. Among those, the majority (86%) are blazars, 10% are sources of Galactic origin (pulsars, PWNe, etc.) and few remain unclassified. Only a dedicated analysis in this energy band would enable the detection and precise determination of the spectral properties of these sources and possibly discover more low-energy sources.

Previous work exploiting the LAT capabilities [18] looked for sources between 30 − 100 MeV using 8.7 years of LAT data and produced the first low-energy catalog of the LAT (1FLE). Their analysis employed a wavelet algorithm (PGWave) and detected 198 sources at $\geq 3\,\sigma$. The authors did not use any diffuse emission model to avoid dependence on the imperfections of these models. Of the detected sources, the majority are associated with blazars, 10% are of Galactic origin and there is also a fraction of $\sim$ 5% which does not have any association with the 3FGL [19], hence could potentially be the seed for a new source class to be revealed in the MeV range.

3. Analysis and Challenges

We will use 13 years of LAT data to detect sources in the 20−200 MeV energy band. The detection algorithm is based on a tested implementation of the binned likelihood method, and has

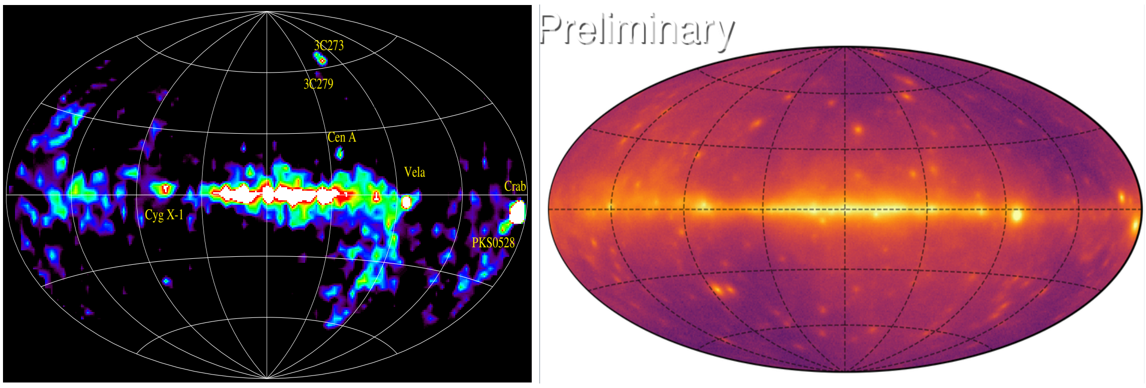


Figure 2: Left: all-sky 1-30 MeV COMPTEL intensity map [15]. A few of the brightest sources are identified, such as powerful blazars (e.g. 3C 273 and 3C 279) and pulsars (e.g. Vela and Crab). **Right:** preliminary all-sky counts map of PSF3 events between 20−200 MeV using 12 years of LAT data.

the potential to complement and improve over the results of the 1FLE.

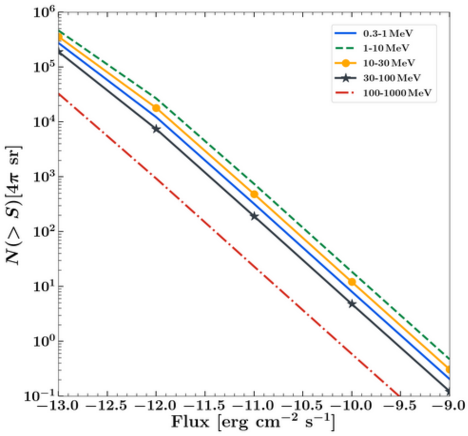
Since systematics highly dominate the considered energy range, the analysis has been designed to take them into account and minimize them. Because the LAT angular resolution worsens dramatically with energy[1], only point spread function (PSF) events that belong to the quartile of the best position reconstruction (PSF3) will be selected [18]. In 12 years of exposure, there are more than 35 million PSF3 events with energy in the 20−200 MeV range. These are contained in the all-sky map shown in Figure 2 (right panel). For comparison, the left panel shows the all-sky map as observed by COMPTEL. Many point-like sources can be seen by eye, indicating that many more will be detected by a dedicated analysis.

We will rely on the Galactic and isotropic diffuse templates[2] derived for the analysis of the 4FGL. To test the reliability of the sources against systematic uncertainties of the Galactic diffuse emission, we will use alternative Galactic diffuse templates, as is the standard practice [1]. We will also perform end-to-end Monte Carlo simulations to assess the systematics of our analysis. The simulations will contain: the Galactic diffuse emission and isotropic models; the Sun and Moon templates; the templates for spatially extended sources provided in the 4FGL[3]; and, importantly, the Earth's limb model [19]. Indeed, the spectrum of this component will have to be modeled down to 20 MeV, becoming a possible source of systematic uncertainty, and generating spurious sources.

4. Prospects of Detection

The prospects of detection in the MeV band are bright. In fact, using luminosity function studies of the MeV blazar population (Marcotulli et al. in prep.), we can derive the expected source count distribution (i.e. number of sources as function of flux) of these sources at different MeV energy bands (see Figure 3, left panel). In the 20-200 MeV band, taking the average LAT sensitivity ($S \sim 2 \times 10^{-12}$ erg cm^{-2} s^{-1}), one would expect to detect >1000 blazars. Therefore constructing a sensitive analysis in this energy range would enable us to produce a catalog that could (i) unveil the

[1] https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm
[2] gll_iem_v07.fits and iso_P8R3_SOURCE_V2_PSF3_v1.txt
[3] See 'Extended Source Template Archive'.



MISSION	Sensitivity	N(>S) [4π sr]
Fermi-LAT	~2x10^{-12} erg cm^{-2} s^{-1} (20-200 MeV, 10 years)	~1500
AMEGO	~4x10^{-12} erg cm^{-2} s^{-1} (1-10 MeV in 5 years)	~2400
AMEGO-X	~1.6x10^{-11} erg cm^{-2} s^{-1} (>100 MeV in 2 years)	~300
COSI-SMEX	~3x10^{-11} erg cm^{-2} s^{-1} (1-3 MeV in 2 year)	~60

Preliminary

Figure 3: Left: predicted source count distribution of MeV blazars in different MeV energy bands (Marcotulli et al. in preparation). **Right:** blazar counts to be detected by *Fermi*-LAT and proposed MeV missions based on the predicted sensitivities (Marcotulli et al. in prep).

bulk of this source class and (ii) be used as a map for proposed MeV missions (such as AMEGO [20]) which are expected to detect hundreds to thousands MeV blazars (see Figure 3, right panel).

5. Summary

We are developing a new analysis to detect sources in the 20-200 MeV range using 13 years of *Fermi*-LAT data. This would enable us to explore the SED peak of known sources (e.g., high-redshift blazars, pulsars, high mass binaries) and possibly detect for the first time sources that could have been missed by other LAT catalogs. Furthermore, such catalog would provide a map of the MeV sky in preparation for future MeV missions (e.g. AMEGO[4][20] or COSI[5]).

6. Acknowledgments

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