

**1 Scientific rationale** The Large Area Telescope (LAT) on board the Gamma-Ray Space Telescope (*Fermi*) has been operating since 2008 producing the most detailed and precise maps of the  $\gamma$ -ray sky ever in the energy range 0.05 – 2000 GeV. The region toward the Galactic plane is the brightest direction in *Fermi*-LAT maps.  $\gamma$  rays from this line of sight (l.o.s.) are mainly due to the Interstellar Emission (IE). This is also the direction of the sky with the highest concentration of detected sources with about 70% higher density of sources with respect to the direction outside the Galactic plane ( $|b| > 20^\circ$ ).

In the preliminary LAT 8-year Point Source List (FL8Y)<sup>1</sup>, derived in the 0.1-1000 GeV energy range, among the 2593 sources detected at  $|b| < 20^\circ$  about one half are unassociated sources. The FL8Y contains 218 pulsars (PSR) most of which are located within a few kpc from the Solar System. These PSR belong to the disk population that follows the spiral arms of our Galaxy [1]. The properties of Galactic PSR emitting  $\gamma$  rays, such as their luminosity function and spatial distribution, are poorly known due to detection biases and because the identification of a *Fermi* source as a PSR through the detection of pulsation in  $\gamma$  rays is a challenging task. The number of PSR in *Fermi*-LAT catalogs might be much greater because many of them could be listed among unassociated sources due to the lack of detection of pulsation. Indeed, using the same relative numbers of FL8Y PSR and blazars, among the unassociated sources detected at  $|b| < 20^\circ$  around 220 should be PSR.

In the last seven years many groups analyzing *Fermi*-LAT data and using the predictions from a variety of IE models (IEM) and point source catalogs have reported the detection of an excess at GeV energies and  $20^\circ$  around the Galactic center (GC) (see e.g. [2] and references therein). This excess is well modeled with a spherically symmetric generalized Navarro-Frenk-White (NFW) density profile with index 1.25 and its energy spectrum is peaked at a few GeV. Recently, evidence of the existence of an unresolved population of sources in the inner  $20^\circ$  of the Galaxy with a total flux and spatial distribution consistent with the GC excess has been published by [3, 4]. These faint sources have been interpreted as a Galactic bulge population of PSR and the brightest exemplars of this population should have been already detected in *Fermi*-LAT catalogs [5]. The results from Refs. [3, 4] and the Spectral Energy Distribution (SED) of PSR make a Galactic bulge population of PSR one of the best motivated interpretation of this excess.

We propose to use the large amount of data collected by *Fermi* after almost 10 years of operation and the huge improvement in energy and spatial resolution brought by Pass 8 [6] to extract from sources detected in the entire sky PSR candidates selected through criteria based on their SED. **We will use these candidates to infer for the first time the spatial distribution and luminosity function of the disk and bulge PSR population from *Fermi*-LAT data. Our list of PSR candidates will be used in radio followup search of pulsation bringing the  $\gamma$ -ray pulsar population to increase significantly in the next few years. We will be able also to test the PSR interpretation of the GC excess and provide the sensitivity of the LAT to detect sources from the Galactic bulge.**

**2 Data Selection and Analysis Details** We plan to use ten years of Pass 8 data in an energy range  $E = [0.3, 500]$  GeV. Since we are interested in detecting the emission from point sources, we will consider P8R2\_SOURCE\_V6 instrument response functions.

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<sup>1</sup><https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/>

We are going to employ the Fermipy python package<sup>2</sup> that automates the analysis with *Fermi* Science Tools and that provides a set of high-level tools for performing  $\gamma$ -ray analysis such as computing SED of a source, generating Test Statistic ( $TS$ )<sup>3</sup> map for a region of interest, finding new source candidates, localizing a source or fitting its spatial extension.

We will search for PSR candidates using the following steps. We subdivide the sky in Regions of Interest (ROI) each of them  $12^\circ \times 12^\circ$  wide. We will include in each ROI the IEM and isotropic template<sup>4</sup> and all FL8Y sources. Since we will use more data than the FL8Y, we find new sources detected with a  $TS > 16$ . We then make a fit to the ROI with these new seeds and we calculate SED parameters of all sources. We plan to employ the Likelihood Weights method encoded in the *Fermi* Science Tools in order to include in our analysis the uncertainties due to the modeling of the IE. The Galactic plane is dominated by this emission mechanism so it is of central importance to use these tools.

Finally for each source detected with  $TS > 25$  we will test a Power-law (PL) and Power-law with an exponential cutoff (PLE) shape for their SED<sup>5</sup>. From a fit to the ROI with a PL and PLE SED we will derive the likelihood value for the PL ( $\mathcal{L}_{\text{PL}}$ ) and PLE shapes ( $\mathcal{L}_{\text{PLE}}$ ) and we calculate for each source the  $TS$  for a curved spectrum defined as:  $TS_{\text{curv}}^{\text{PLE}} = 2 \cdot (\log \mathcal{L}_{\text{PLE}} - \log \mathcal{L}_{\text{PL}})$ . This parameter represents the preference to fit the SED of a source with a PLE with respect to a PL. We have already applied this pipeline in [7] where we derived a catalog of sources detected in the inner  $40^\circ \times 40^\circ$  region of the Galaxy. We have demonstrated in that paper our capability to perform the proposed analysis.

**The goal of this part of the analysis will be to have for each source the  $TS$  for curvature ( $TS_{\text{curv}}^{\text{PLE}}$ ), the photon index ( $\Gamma$ ) and energy cutoff ( $E_{\text{cut}}$ ) in the case of PLE SED. These parameters will be used to select PSR-like sources among our list of detected sources.**

**3 Energy Spectrum of Pulsars and Blazars** In the FL8Y catalog blazars are the most numerous source population with about 85% of all the associated sources. The SED of 90% of blazars in the FL8Y are modeled with a PL function while blazars with a significant curvature (only about 10% of the entire population) are modeled with a Log-Parabola (LP). On the other hand of the PSR reported in FL8Y, about 80% are parametrized with a PLE because they have a significant curvature and  $E_{\text{cut}}$  at a few GeV. Thus, the shape of the energy spectrum is a promising observable that can be used to separate PSR from blazars.

In [7] we used the 3FGL catalog to find SED-based criteria to select efficiently PSR candidates among unassociated sources. We considered 7.5 years of LAT data and the analysis explained in the previous section to test the PLE versus the PL shape on blazars and PSR detected in the 3FGL with the goal of finding for each source the  $TS_{\text{curv}}^{\text{PLE}}$ ,  $\Gamma$  and  $E_{\text{cut}}$ . We present the result of this analysis in the left panel of Fig 1 where we show the values of  $\Gamma$  and  $\log_{10}(E_{\text{cut}})$  for blazars and PSR (divided into young and Millisecond PSR) detected with  $TS_{\text{curv}}^{\text{PLE}} > 9$ . Only 9% of blazars have  $TS_{\text{curv}}^{\text{PLE}} > 9$  and among them only 12 have  $\Gamma < 2.0$  and  $\log_{10}(E_{\text{cut}}) < 4$ , thus less than 1% of the entire blazar population in the 3FGL catalog.

<sup>2</sup>See <http://fermipy.readthedocs.io/en/latest/>

<sup>3</sup>The  $TS$  is defined as twice the difference in log-likelihood between the null hypothesis (i.e., no source present) and the test hypothesis:  $TS = 2 \log \mathcal{L}_{\text{test}} - \log \mathcal{L}_{\text{null}}$

<sup>4</sup>For descriptions of these templates see <http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html>

<sup>5</sup>see <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/source.models.html> for a description of the spectral models implemented in the ST

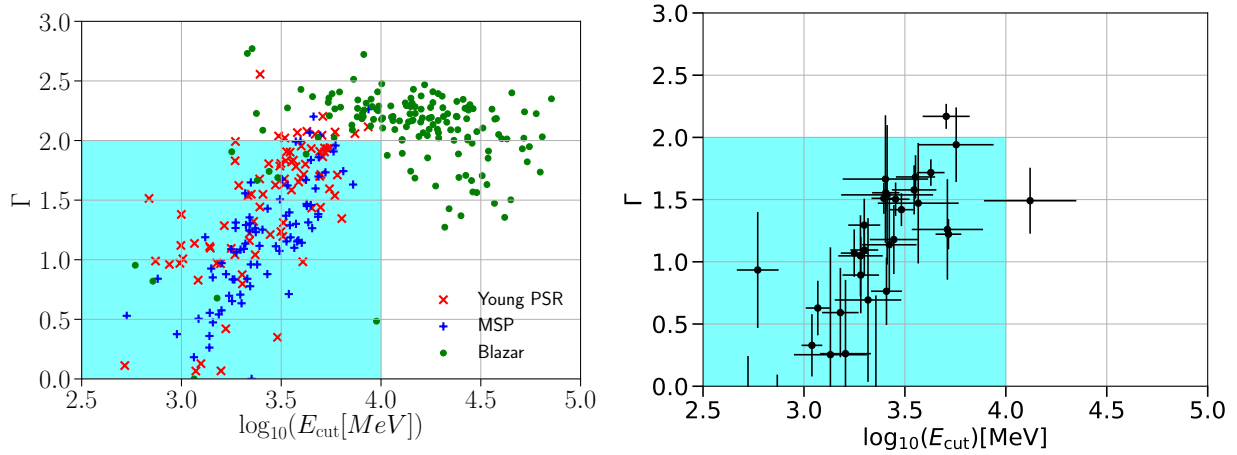


Figure 1: Left panel:  $\Gamma$  and  $\log_{10}(E_{\text{cut}}[\text{MeV}])$  of 3FGL PSR (MSP are shown as blue points and young PSR as black points) and of blazars in the 3FGL with  $TS_{\text{curv}}^{\text{PLE}} > 9$  (red points). Right panel: same as in the left panel but for new  $\gamma$ -ray PSR in the FL8Y catalog.

On the other hand about 88% of PSR have  $TS_{\text{curv}}^{\text{PLE}} > 9$  and 80% are in this region of the PLE parameters (displayed in the figure with a cyan band). The average photon index and energy cutoff is  $\Gamma = 1.48 \pm 0.45$  and  $\log_{10}(E_{\text{cut}}[\text{MeV}]) = 3.46 \pm 0.25$  for young PSR and  $\Gamma = 1.20 \pm 0.49$  and  $\log_{10}(E_{\text{cut}}[\text{MeV}]) = 3.42 \pm 0.22$  for MSP. Young and MSP have thus the same energy cutoff and MSP have slightly harder indexes. **We found with 3FGL sources that the selection criteria  $TS_{\text{curv}}^{\text{PLE}} > 9$  and  $\Gamma < 2.0$  and  $\log_{10}(E_{\text{cut}}) < 4$  are very efficient to disentangle a PSR from a blazar. We plan to refine these criteria using PSR and blazars of the FL8Y and 10 years of LAT data. We will use this SED-based selection to find PSR candidates among the sources detected in our analysis.**

**4 Feasibility** We show here the feasibility of our method applying it to the most updated list of 218  $\gamma$ -ray PSR in FL8Y catalog. In particular we consider among this sample new  $\gamma$ -ray PSR with respect to the 3FGL. This selects 51 new PSR among which 26 are unassociated 3FGL sources and 25 are new sources. We thus apply our analysis to 100 months of LAT data finding for each PSR:  $TS_{\text{curv}}^{\text{PLE}}$ ,  $\Gamma$  and  $\log_{10}(E_{\text{cut}})$  as done before for blazars and 3FGL PSR. In the right panel of Fig. 1 we show the photon index and energy cutoff that we derive. 38 PSR over 51 have  $TS_{\text{curv}}^{\text{PLE}} > 9$  and only 2 of them has SED parameters that are not compatible with our criteria ( $TS_{\text{curv}}^{\text{PLE}} > 9$  and  $\Gamma < 2.0$  and  $\log_{10}(E_{\text{cut}}) < 4$ ). **Our method thus works very efficiently also with new  $\gamma$ -ray PSR recently discovered.**

In [7] we applied the proposed analysis in the inner  $40^\circ \times 40^\circ$  region of the Galaxy finding 66 sources either unassociated in the 3FGL or that are new sources and that satisfy our SED-like criteria. These sources are therefore very promising PSR candidates. Indeed, two of the pulsars recently discovered with *Fermi*-LAT data in [8] and that are close to the region of interest analyzed in [7] satisfy our SED-like criteria. These sources are associated in the 3FGL with 3FGL J1650.3-4600 and 3FGL J1624.2-4041 and they have  $TS_{\text{curv}}^{\text{PLE}} > 100$  and 140,  $\Gamma = 1.15$  and 1.27 and  $E_{\text{cut}} = 2.6$  and 2.2 GeV, respectively.

**5 Efficiency and Maximum Likelihood Analysis** We propose to employ the analysis explained above to find PSR-like sources in the entire sky. We will bin these detected

PSR-like sources in longitude ( $l$ ), latitude ( $b$ ) and energy flux ( $S$ ):  $N^{\text{real}}(l, b, S)$ . We plan then to infer the efficiency for the detection of PSR-like sources:  $\omega(l, b, S)$ . This will be derived simulating PSRs with different luminosities and positions in the Galaxy and using the analysis pipeline explained in this proposal to find sources detected with  $TS_{\text{curv}}^{\text{PLE}} > 9$  and  $\Gamma < 2.0$  and  $\log_{10}(E_{\text{cut}}) < 4$ . Given the number of simulated ( $N^{\text{true}}$ ) and detected ( $N^{\text{det}}$ ) PSRs for each  $l$ ,  $b$  and  $S$  bin, the efficiency is given by:  $\omega(l, b, S) = N^{\text{det}}/N^{\text{true}}$ . We will then model the number of expected PSRs from the disk and the bulge  $N_{\text{PSR}}$ . For the disk component we will start considering the spatial distribution given in [9] while for the bulge population we will use  $dN/dV \propto r^\alpha$  where  $r$  is the radial distance from the GC [10]. The parameters of the spatial distribution of disk and bulge PSR will be free to vary in the fit. For the luminosity of PSR we will employ a luminosity function given by a PL or a broken PL with different slopes for the disk and bulge PSR populations. The number of disk ( $N_{\text{disk}}$ ) and bulge PSR ( $N_{\text{bulge}}$ ) will be also free parameters. Given the number of PSR in our model as a function of the parameters reported above ( $\vec{\lambda}$ ) we will calculate the number of PSR candidates detected in each pixel and energy flux bin as:  $N_{\text{PSR}}(l, b, S) = N_{\text{PSR}}(\vec{\lambda}) \times \omega(l, b, S)$ . We will then employ a Maximum Likelihood Analysis (MLA) with Poisson statistics from which, comparing the number of PSR candidates from the model and from PSR candidates detected in the real sky, we will derive the best fit parameters for spatial distribution and luminosity function of the disk and bulge PSR population. **This analysis will enable us to use for the first time LAT data to derive precisely the spatial distribution and luminosity function of the two PSR populations.**

**6 Plans and Schedule** Our plan is to run our analysis **in the entire sky** to find PSR-like sources (detected with  $TS_{\text{curv}}^{\text{PLE}} > 9$  and  $\Gamma < 2.0$  and  $\log_{10}(E_{\text{cut}}) < 4$ ). We will employ the new FL8Y catalog of sources and 10 years of *Fermi*-LAT data. Then we will derive the efficiency of the LAT to detect PSR-like sources and we will employ a MLA to provide predictions for the number of PSRs in the disk and in the bulge and to find their spatial distribution and luminosity function. This result will enable us to state conclusively if the GC excess is given by a Galactic bulge PSR population. Finally, since we demonstrated that our criteria is very efficient in selecting PSR-like sources we are confident that we will provide PSR candidates list that could be used as targets of future radio follow for the search of radio pulsation. This will increase significantly the number of  $\gamma$ -ray PSRs detected by the LAT in the next few years.

**Budget:** Given the substantial data analysis effort, we request one year funding to support for the PI ( $\sim 30\%$ ), for two conferences per year and publication charges. Including overheads we request a budget of 55k\$. Co-Is Di Mauro and Charles, will be directly in charge of the analysis, while co-Is Digel and Wood will provide both technical and the scientific input.

## References

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