NEWS

NEw WindowS on the universe and technological advancements from trilateral EU-US-Japan collaboration

WP4: Fermi-LAT data analysis

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MidTerm Review, Pisa, March 4-5, 2019

Web site: risenews.df.unipi.it

European Commission

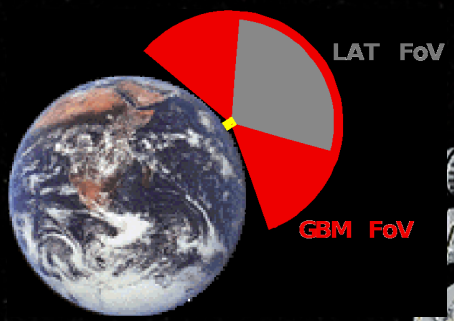
The *Fermi* Space Telescope

Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors
- Energy range: 8 keV–40 MeV

The Large Area Telescope (LAT)

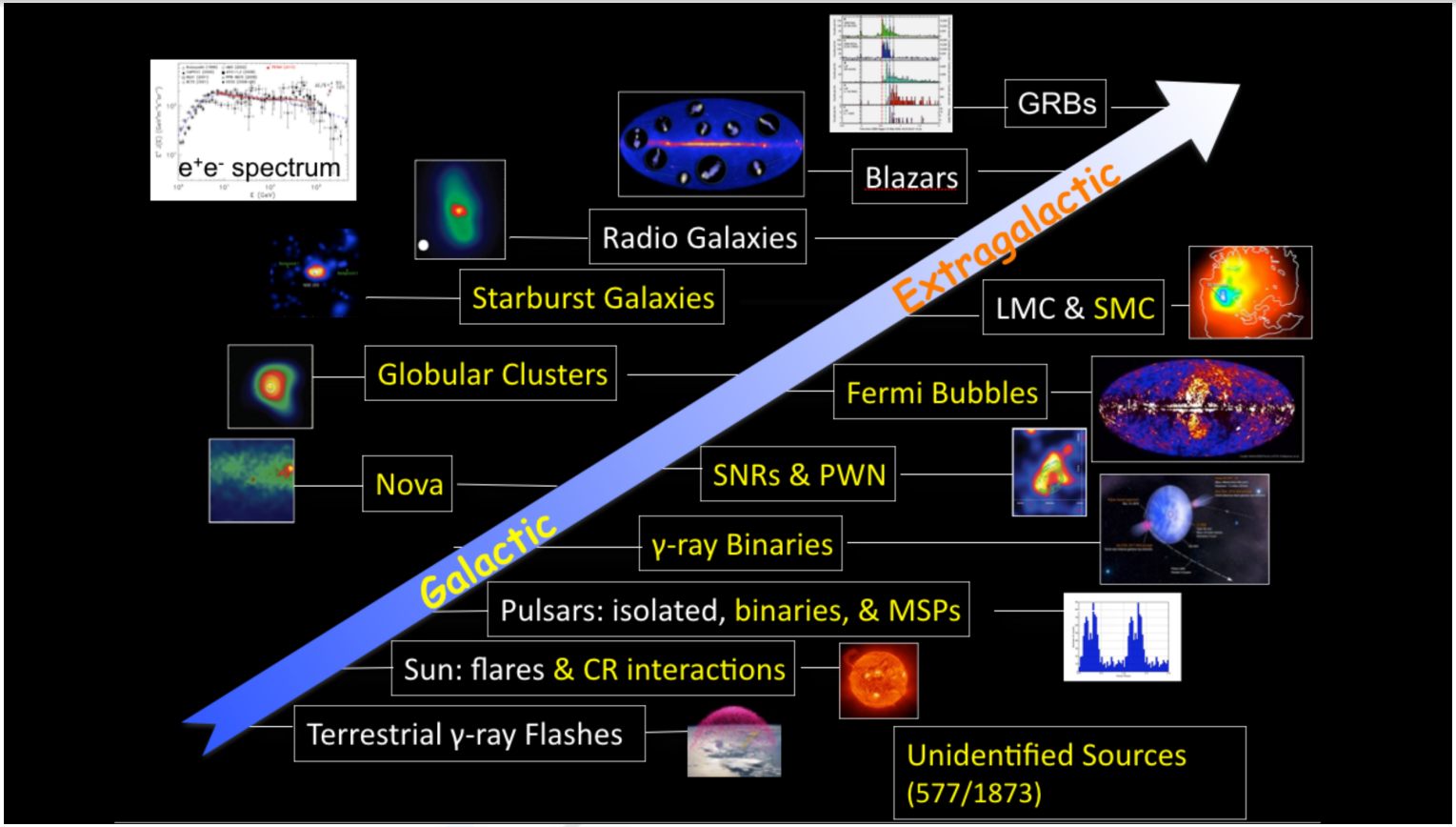
- Pair conversion telescope
- Energy range: 20 MeV–> 300 GeV
- Large field of view ($\approx$ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours



LAT key features

- Good energy resolution (<15% for E>100 MeV)
- Good point spread function (<1° for E>1 GeV)
- Large effective area (~8000 cm^2 on-axis for E>1 GeV)

Fermi-LAT SCIENCE MENU



WP4: Focus on four topics

- *Fermi*-LAT source catalog (4FGL)
- WIMP dark matter searches
- Cosmic-Ray Electron science
- Electromagnetic counterparts to gravitational wave events

The 4th Fermi Gamma-ray Catalog

- WP4 team has actively participated in the catalog effort
- The 4th Fermi Gamma-ray Catalog (4FGL) released on Feb 25th
- The 4FGL comprises 5457 sources
  - With a ~66% association rate

Catalog	Energy Range (GeV)	Data Interval (m)	Sources	Unasso-ciated	Event Selection	Release Date
0FGL	0.2-100	3	205	37 (18%)	P6V1 DIFFUSE	Feb. 2009
1FGL	0.1-100	11	1451	630 (43%)	P6V3 DIFFUSE	Feb. 2010
2FGL	0.1-100	24	1873	649 (35%)	P7V6 SOURCE	Aug. 2011
3FGL	0.1-300	48	3033	992 (33%)	P7V15 SOURCE	Jan. 2015
4FGL	0.05-1000	96	~5500	~1800(33%)	P8 SOURCE	End of 2018
1FHL	10-500	36	511	65 (13%)	P7V6 CLEAN	Jun. 2013
2FHL	50-2000	80	360	48 (14%)	P8 SOURCE	Aug. 2015
3FHL	10-2000	84	1556	176 (11%)	P8 SOURCE	Mar. 2017

What are catalogs good for?

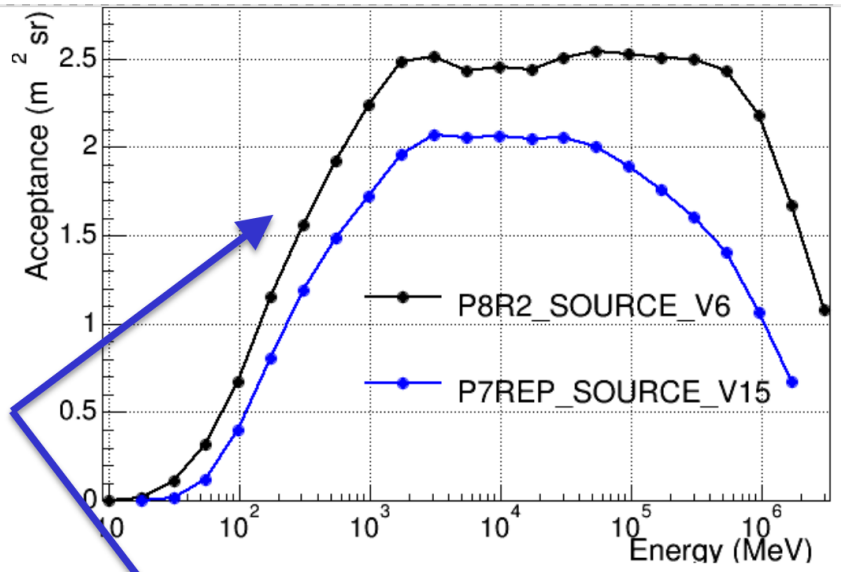
3FGL: *838 citations* *(NASA ADS)*

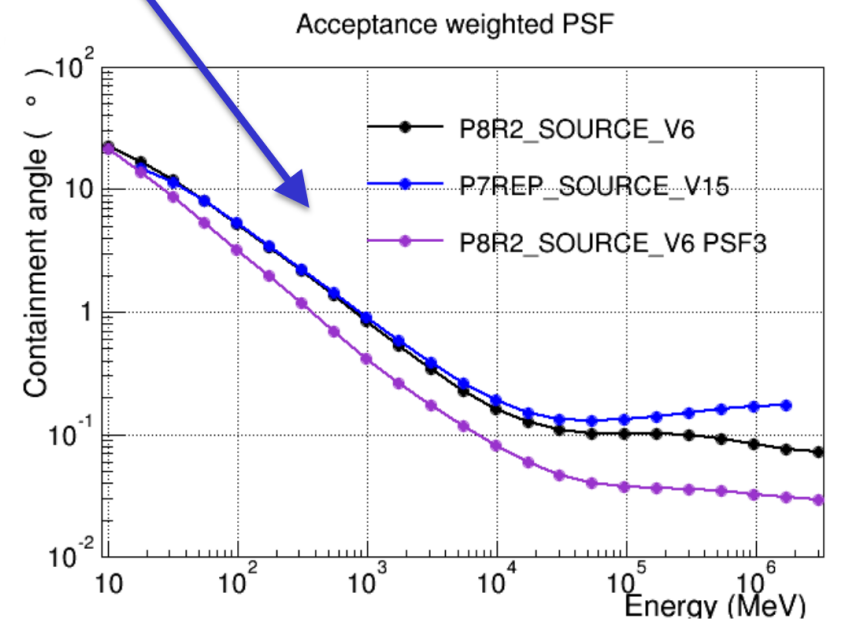
- **Predictions/optimization of future observatories: LHAASO, CTA, SKA…**
- **Sky model for data analysis**
- **Reference for studies on:**
  - **individual sources**
  - **source populations**
  - **MW analyses**
- **Source samples to investigate**
  - **Extragalactic Background Light**
  - **Extragalactic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

The 4th *Fermi* Gamma-Ray Source List

WP4 team has worked on the 4th *Fermi* Gamma-Ray Source List (4FGL)

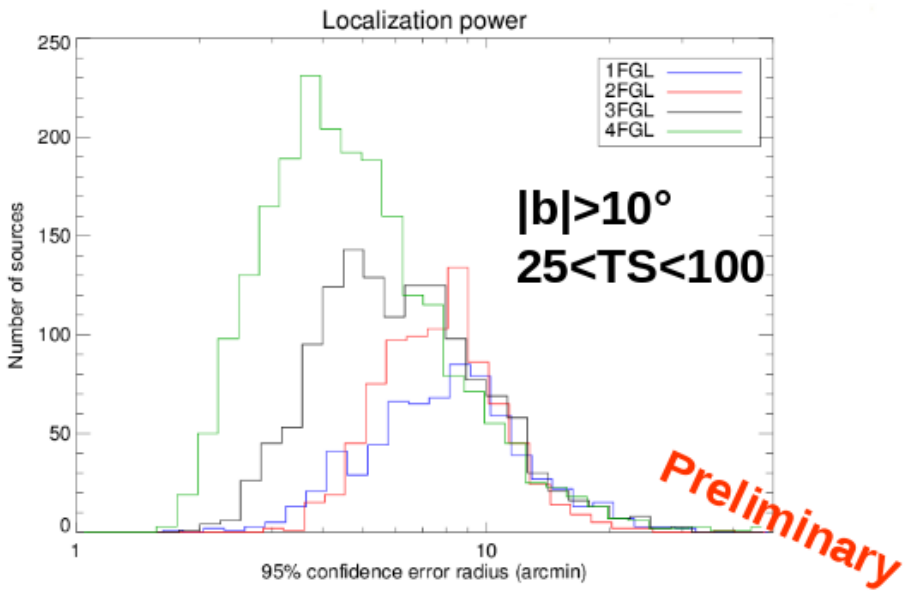
- Follow-up unassociated sources
- Deeper and better data/calibration
  - 3FGL was based on Pass7
  - 4FGL will use Pass8
- Update underlying interstellar emission model
- Look for variable sources
  - Provide yearly and bimonthly light curves
- WP4 objective complete by the end of 2019



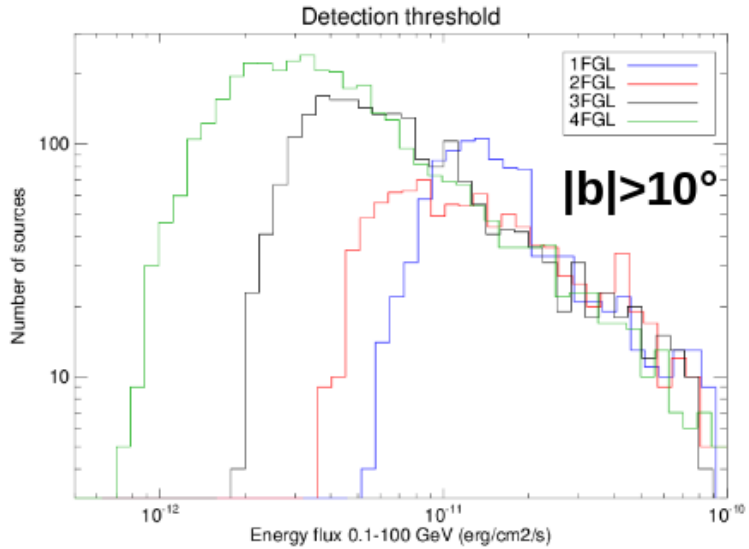


Source characterization

Improved localization (important for association)
Median error radius at 25<TS<100
4.4 arcmin



Detection theshold for extragalactic sources: energy flux ~2.10^{-12} erg $cm^{-2}s^{-1}$ (depends slightly on spectral shape)



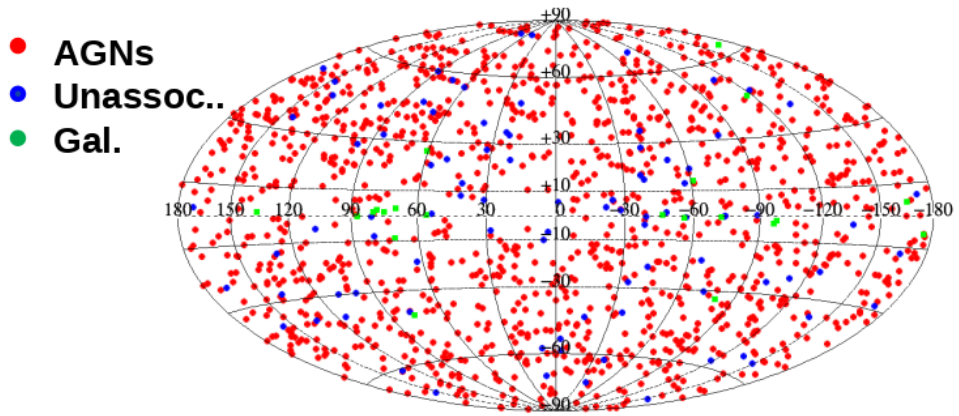
Source variability

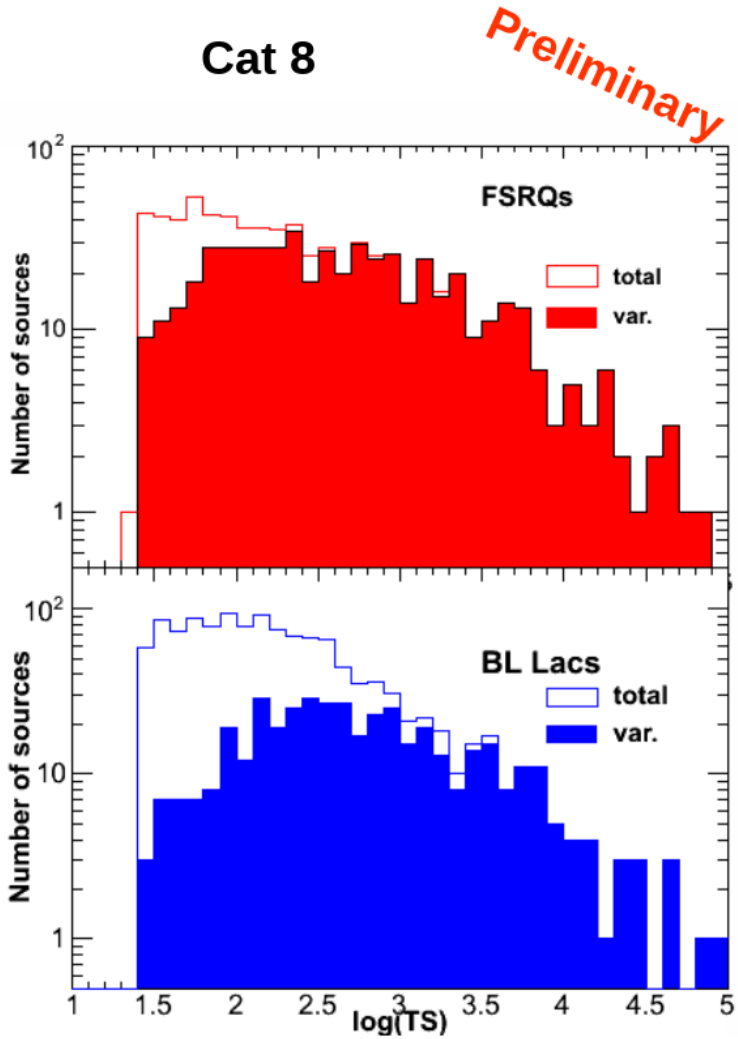
Two sets of lightcurves created for 4FGL:

- **Yearly light curves (8 points)**
  - **variability index (χ^2 with 7 d.o.f., 99% confidence limit: 18.48)**

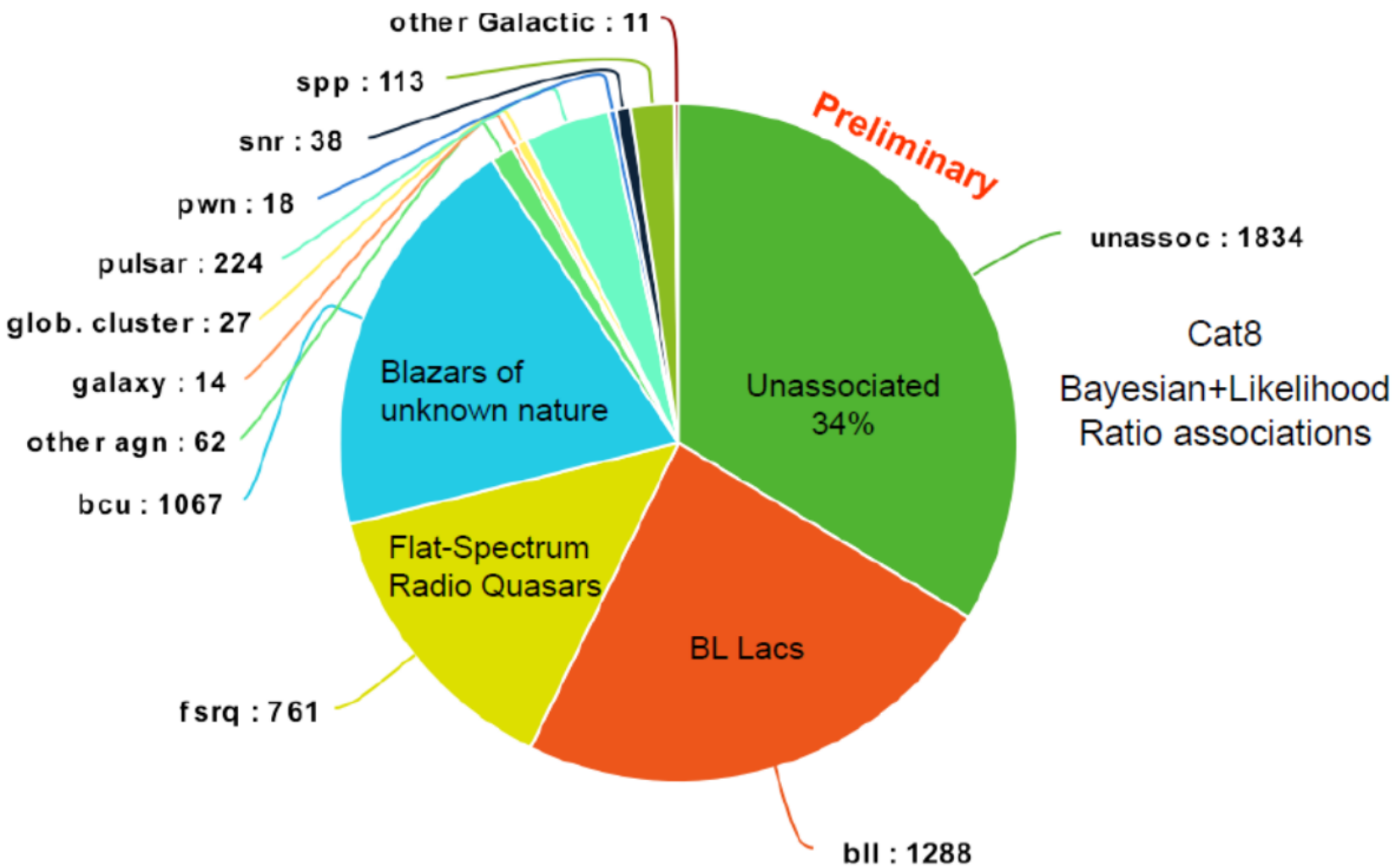
  Ex: exercise on Cat8

  1380 variables sources, 1267 AGNs, 21 Gal., 92 unassociated
  - **fractional variability**
- **Bimonthy light curves (48 points)**



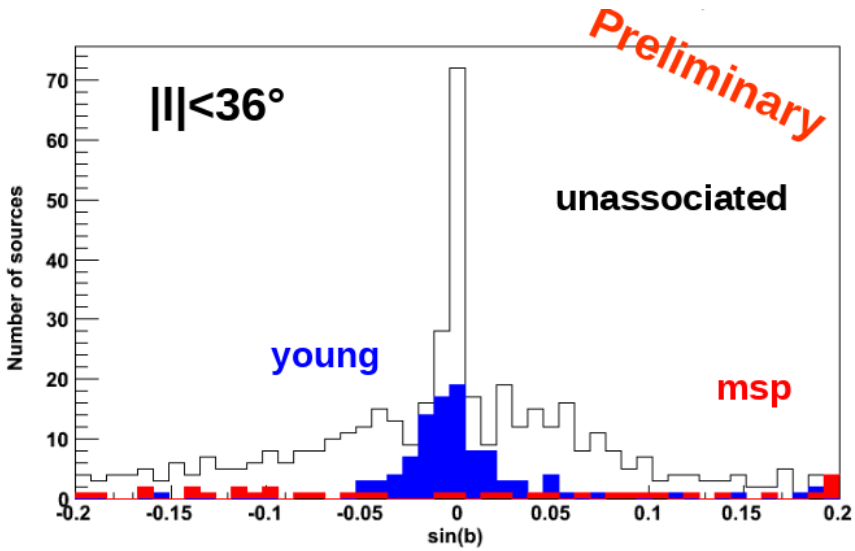


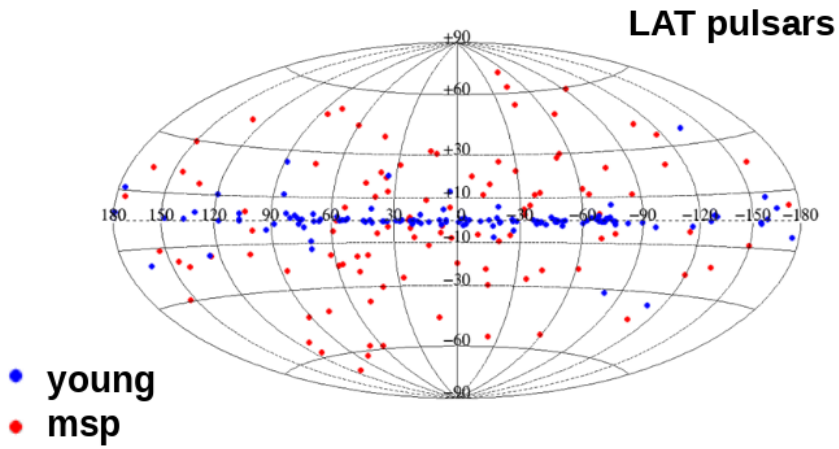
Association summary



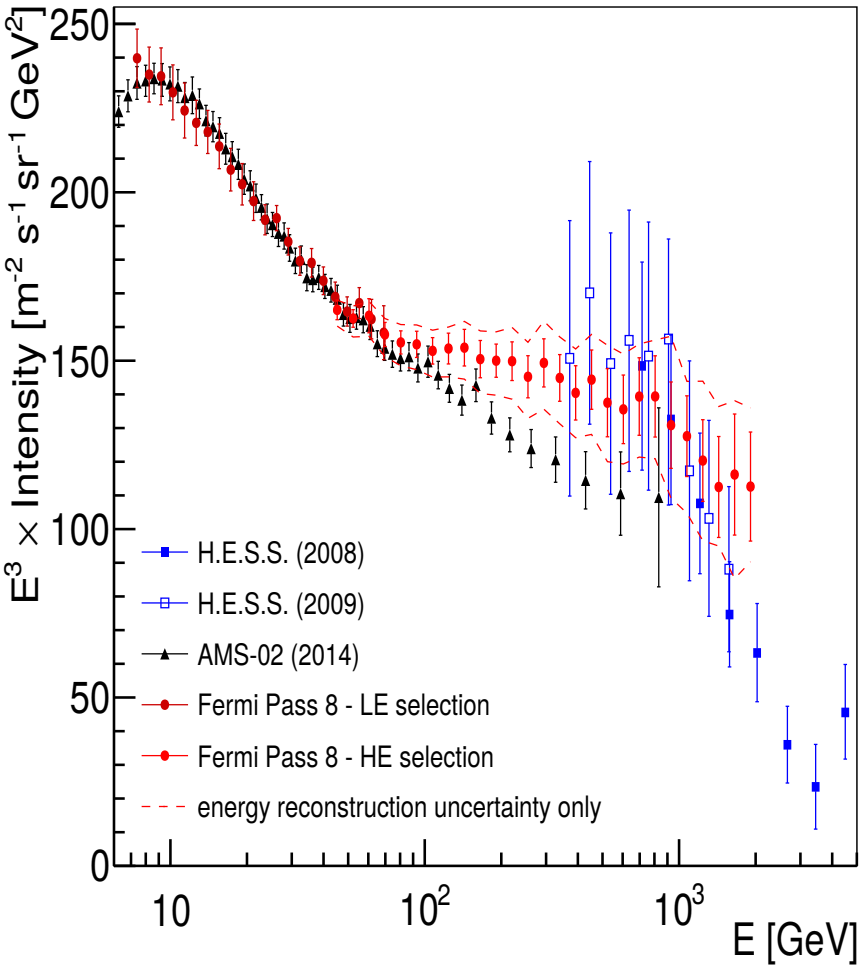
Features of Galactic unassociated

- 229 unassociated sources located at |l|<36° and 2°< |b| <7°
- Galactic origin → pulsars?
- Spectral hardness (median index Γ=2.5) compatible with young pulsars (Γ=2.4) but not with MSP (Γ=2.2)
- Latitude dispersion compatible with that of >10^6 yr ATNF pulsars. Gamma-ray death line makes this possibility unlikely.
- No convincing evidence for other classes: LMXB, Be stars, O stars, X-ray stars, eclipsing binaries…
- Still there with new diffuse emission model but could still be related to missing diffuse component





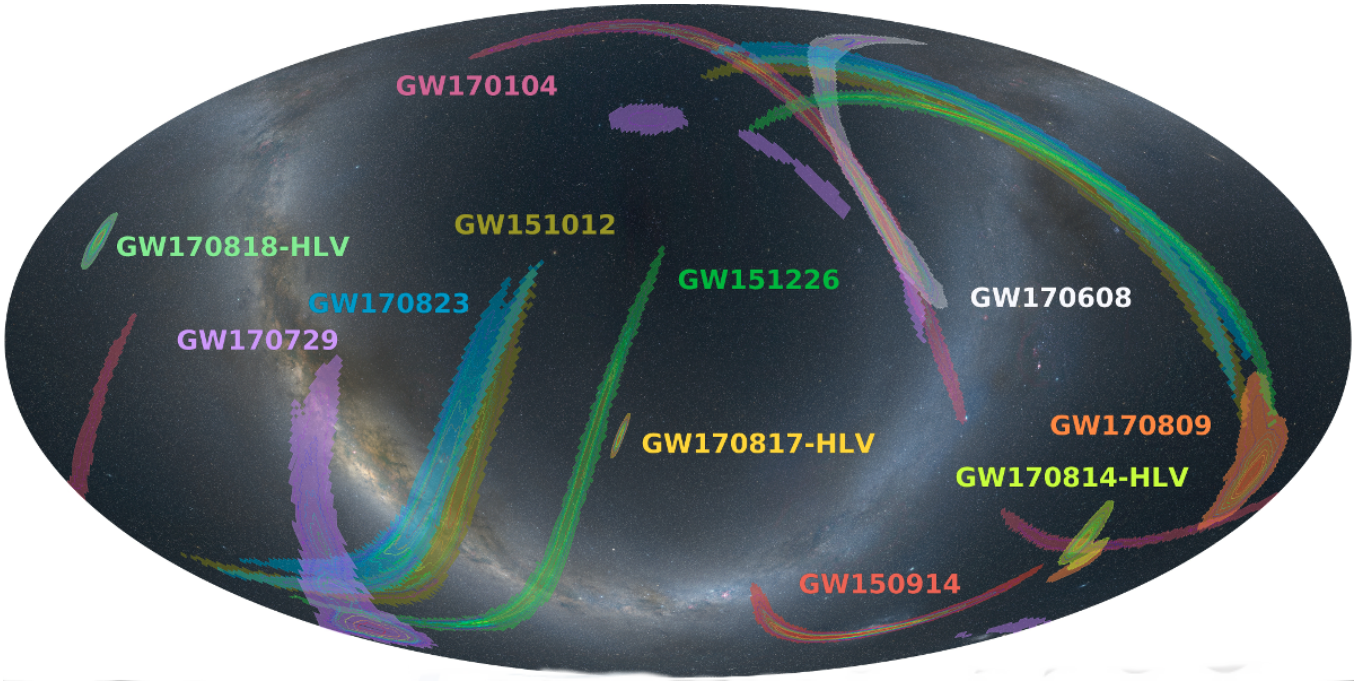
Cosmic-Ray Electron (CRE) science



Phys. Rev. D 95, 082007

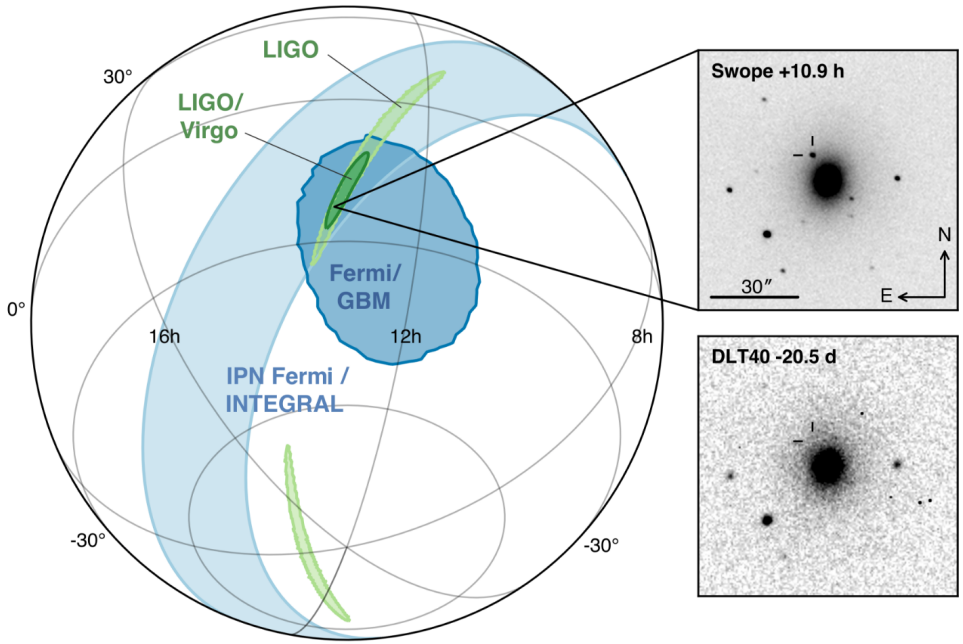
- Cosmic-ray $e^+ + e^-$ spectrum from 7 GeV to 2 TeV measured by *Fermi*-LAT
  - First space-based instrument to explore the region above 1 TeV
  - High-energy cutoff excluded up to 1.8 TeV at 95% CL
- Thanks to large amount of statistics we can now perform anisotropy searches to help constrain existence of local CRE sources
- WP4 team has contributed in the effort of the spectral and anisotropy studies of the CRE with *Fermi*-LAT
- WP4 objective completed

Following up on LIGO events



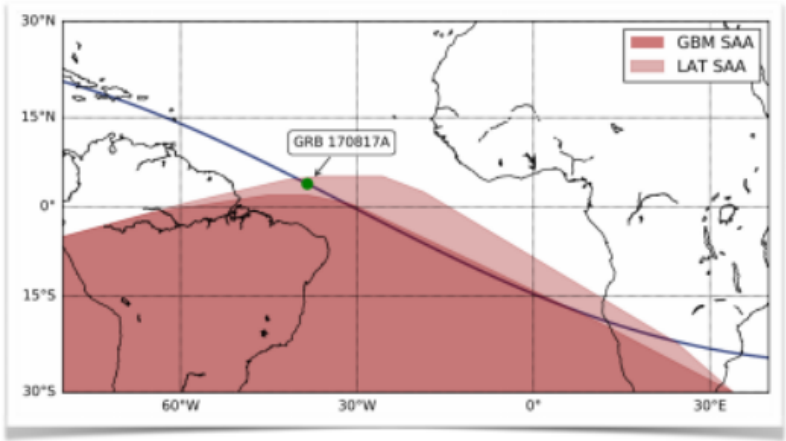
- **September 14, 2015: first observation of gravitational waves, originating from a pair of merging black holes using the Advanced LIGO detectors.**
- **To date, 6 GW events announced by the LIGO/VIRGO Collaboration (LVC):**
  - **5 BH- BH: GW150914, LVT151012, GW151226,GW170104, GW170814;**
  - **1 NS-NS: GW170817;**
- **BH-BH mergers are not expected to produce EM radiation.**
- **NS-NS: predicted (and confirmed) to have EM radiation.**

GW170817/GRB170817A



- On August 17, 2017 LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars
- The first time that a cosmic event has been viewed in both gravitational waves and light

- The LAT in the SAA at the time of the GBM trigger
- GRB 170817A in field of view after 1ks
- Set upper limit (0.1-1 GeV) of $<4.5\times10^{-10}$erg cm^{-2}s^{-1}



Pipeline for EM follow-up to GW events

General strategy for Fermi-LAT searches at high-energy:

- Automated full sky searches of transients
- Specific searches in the LIGO contours
- Specific followups of detected counterparts

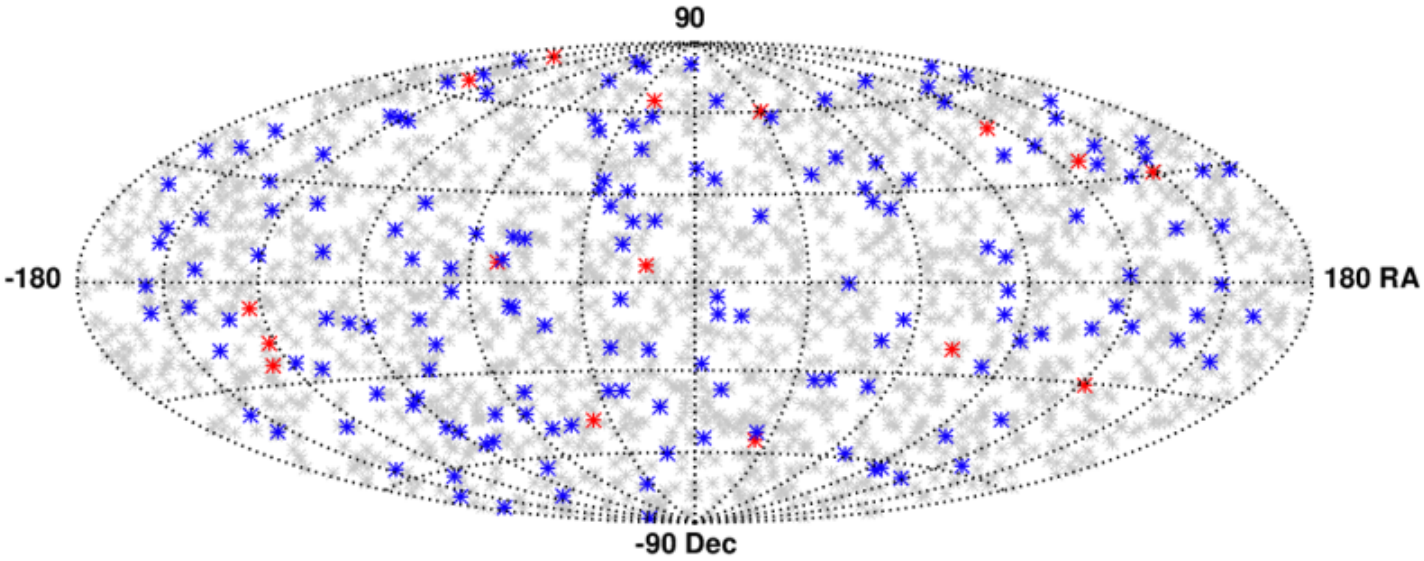
Cumulative coverage of the map as a function of time

- In all cases we reached 100% of the coverage within 8 ks
- Different pixels of the map enter and exit at different times
- We set up three different analysis: fixed time window, adaptive time window and LLE (at low energy)
- see: Ackermann et al. 2016 (GW150915), Racusin et al. 2017 (GW151226, LVT151012), Goldstein at al. 2017 (GW170114), Vianello et al. 2017 (Methods)

EM follow-up to gravitational wave events

- Large contribution from WP4 team in setting up pipeline to automatically perform dedicated analyses to search for electromagnetic counterparts to gravitational wave events in Fermi-LAT data
  - The pipeline is triggered by the arrival of a LIGO/Virgo Gamma-ray Coordinates Network (GCN)
- Team has also worked on sensitivity studies to improve estimates on flux upper limits
- WP4 objective ∼50% complete

The LAT 2nd GRB catalog



- The LAT 2nd GRB catalog is finalized
- The catalog contains 186 GRBs, and is the most complete analysis of high-energy emission from GRBs to date
- WP4 team searched for LAT counterparts to over 4000 low-energy triggers
  - Imperative for the GW follow-up work
  - See Axelsson's talk this afternoon

WP4 use of Secondments

Completed

- INFN: 3 months
- OCK: 3.8 months
- KTH: 1 month
- HOG: 0.1 month
- Total: 7.9 months

Planned in 2019

- INFN: 4.5 months
- OCK: 4 months
- KTH: 4 months
- HOG: 1.5 months
- Total: 14 months

Objectives

- Variability studies in blazars
  - Important for the 4FGL
- Sensitivity studies for the likelihood analysis of GW pipeline
- Work on the 2^{nd} Fermi-LAT GRB catalog
  - Important for the GW follow-up pipeline
  - More on this later today

Summary

Deliverables

- 4.1 Analysis package 4^{th} Fermi Gamma-ray source List (4FGL)
- 4.2 Automatic pipeline for gamma-ray follow-up of gravitational wave triggers
- 4.3 Fermi Data Legacy Archive

Status of the deliverables

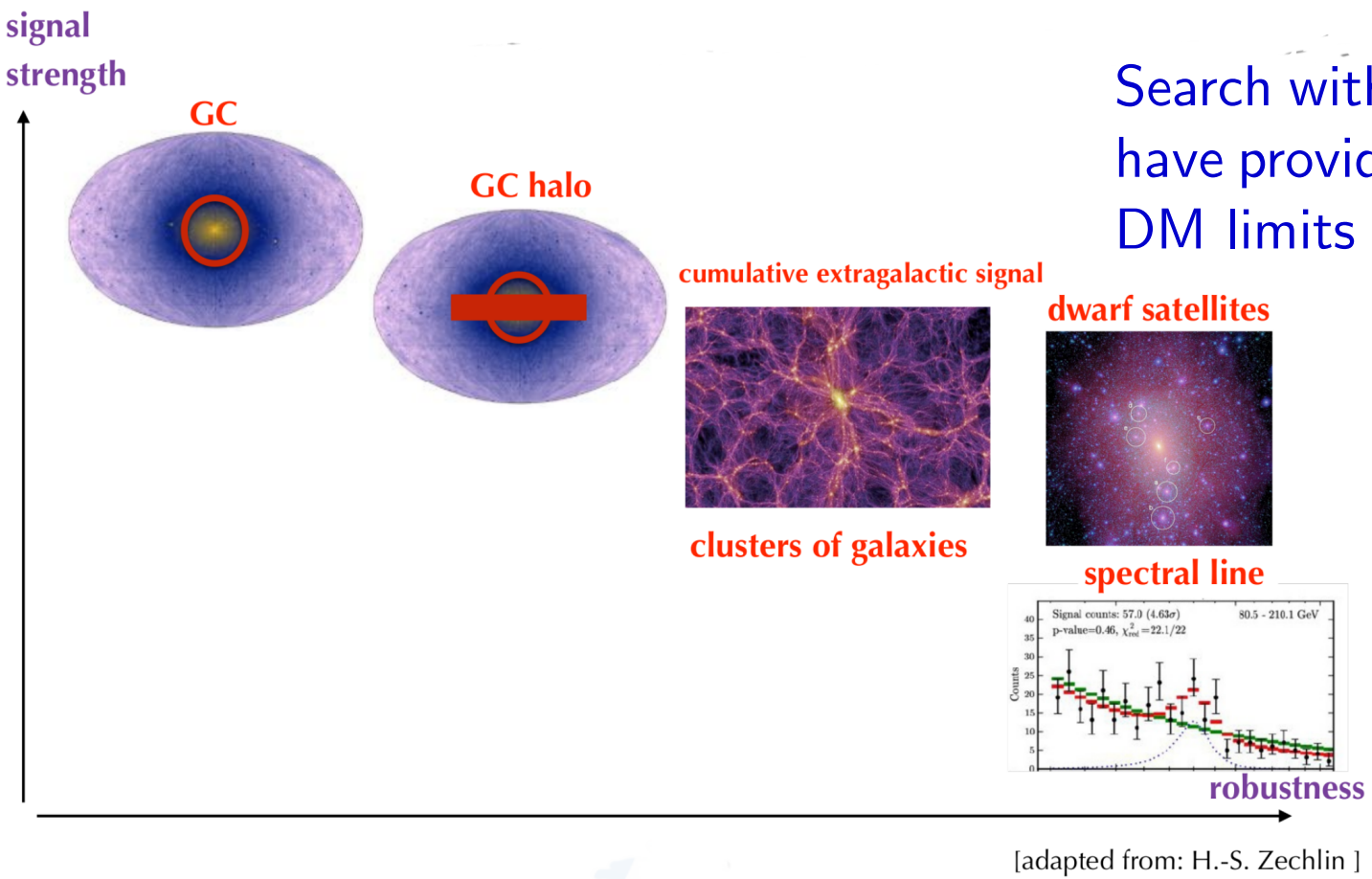
- 4.1 is nearing completion with the 4FGL posted to archive last week and planned for publication by the end of the year
- 4.2 is more than 50% complete
  - pipeline ready for O3 of LIGO/Virgo
  - >4 months of secondments are planned for 2019 to work on completing the pipeline and the related analysis tools
- 4.3 is still work in progress

Spare slides

The LAT signal searches

- The custom signal searches implemented for the follow-up of EM to GW events, fixed time and adaptive time windows
- The fixed time window search:
  - Search over a set of fixed time windows around the LIGO trigger
  - For each time window, select all pixels that were observable by the LAT within the LIGO localization map
  - Perform un-binned likelihood in an 8° radius RoI
- Adaptive time window search
  - Optimize the time window for the analysis based on when the pixel becomes observable by the LAT
  - For each pixel select only the interval that contains the GW trigger time, or the one immediately after
  - Perform un-binned likelihood analysis for each pixel
- We also have several standard automatic signal searches up and running since launch
  - automatically run both of the custom analysis every time we receive a LIGO/VIRGO GCN

WIMP DARK MATTER SEARCHES



Search with dwarf satellites have provided the strongest DM limits to date!

[adapted from: H.-S. Zechlin]

- *Fermi*-LAT team has performed several dark matter searches over a wide range of astrophysical targets
- WP4 team will contribute in the development of the analysis framework
  - Applying to new targets such as the dwarf galaxies found by DES

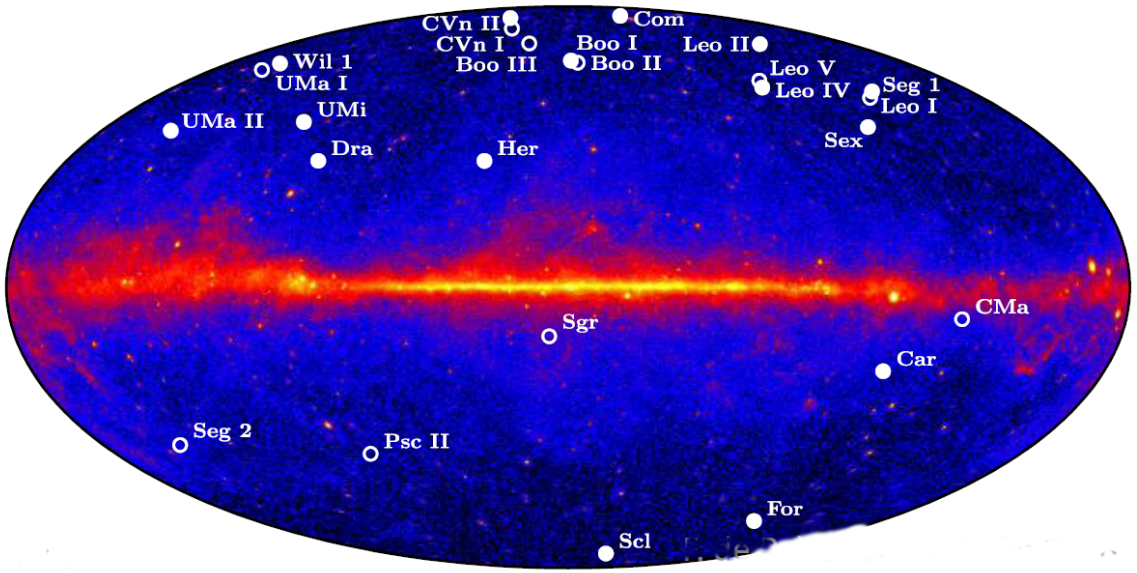
Dark matter pipeline

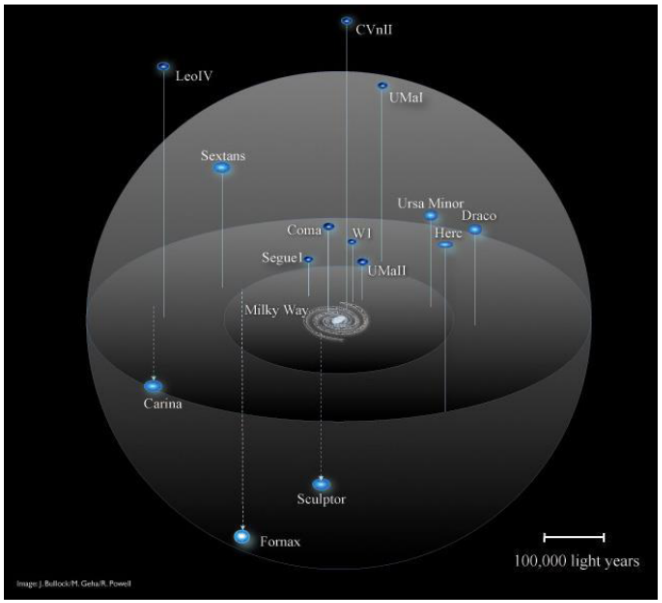
WP4 team has contributed to the dark matter pipeline effort:

- Almost ten years of Fermi-LAT data has been analyzed and combined searches for DM from the LMC, SMC, M31, M33 and dSphs have been performed
  - No significant emission from DM has been found
- Future steps of the analysis
  - add to the target list clusters and the Galactic center
- Plan to publish a paper with the analysis, including likelihood profiles for individual targets and for the combined searches
- Results can be used by the community to test their particular DM models
- Results presented at the 8^{th} International Fermi Symposium
- WP4 objective still in progress

Dark matter searches in dSph Galaxies

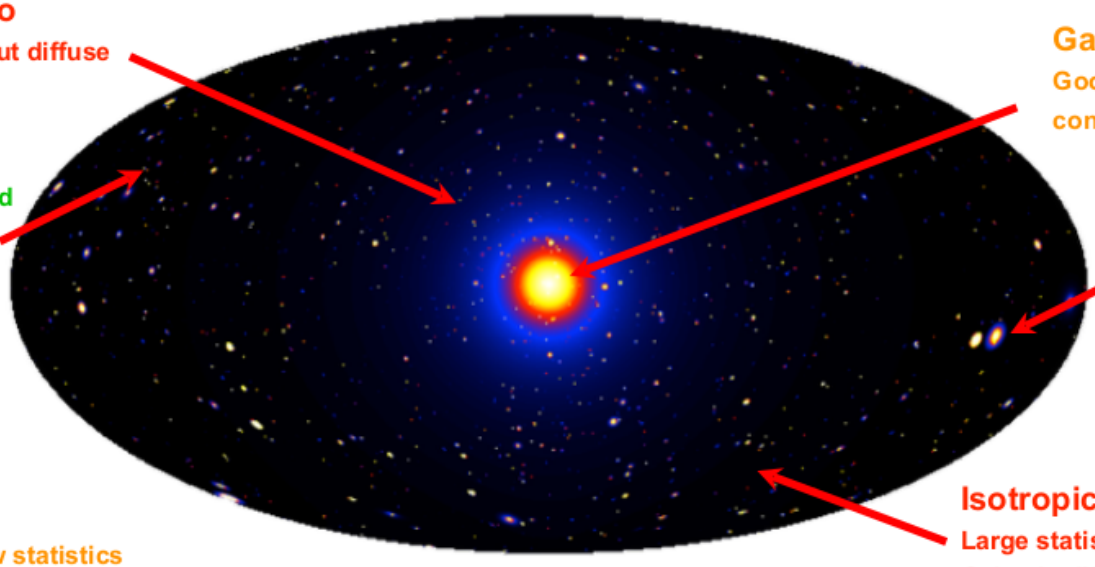
- dSph Galaxies are the cleanest target for DM searches:
  - DM-dominated (1000:1)
  - 10s to 1000s of stars
    - Mostly old stars
    - Few gamma-ray emitters (pulsars, SNRs)
    - Little gas content
  - often high latitude ➔ low diffuse background
  - nearby (<250 kpc)
  - many! (50+) ➔ allows for joint analyses





Dark matter pipeline

- **DMcat project**: perform a combined search for Dark Matter (DM) from multiple targets.
- We plan to release the results in a format that can be used by the community to perform their own DM searches.



Milky Way Halo
Large statistics, but diffuse background

Satellite galaxies
Low background and good source id, but low statistics

Galactic Center
Good statistics, but source confusion/diffuse background

Nearby Galaxies
Good statistics, diffuse background

Unassociated sources

Galaxy Clusters
Low background, but low statistics

Isotropic contributions
Large statistics, but astrophysics, Galactic diffuse background

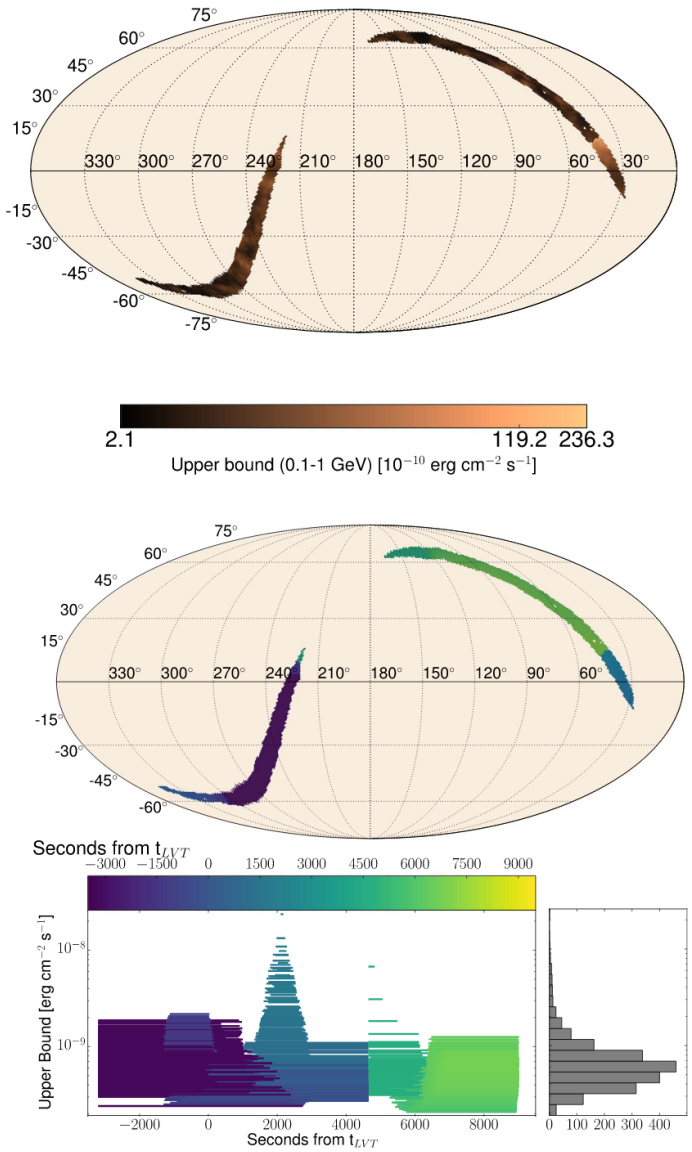
Targets already implemented

Targets will be considered in the future

Targets we will probably not consider

Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

EM follow-up to gravitational wave events



Racusin et al. 2017, ApJ, 835, 1

- *Fermi*-LAT is continuously observing the entire sky
- Covering localization probability maps of gravitational wave events within hours of their detections
- In the case of a detection of an EM counterpart, the LAT could substantially reduce the localization uncertainty
- Facilitating follow-ups at other wavelengths
- Six papers published so far