# NEWS

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

***WP4: Fermi-LAT data analysis***

*Melissa Pesce-Rollins*

*Annual General Meeting, Pisa, November 4-5, 2019*

***Web site: risenews.df.unipi.it***

European Commission

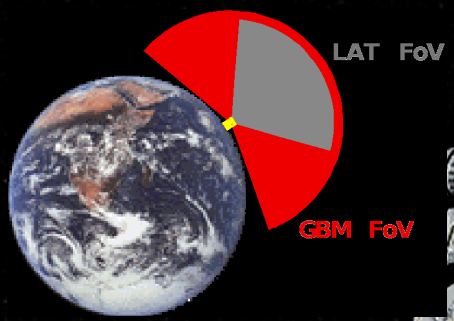
# The *Fermi* Space Telescope

## Gamma-ray Burst Monitor (GBM)

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

## The Large Area Telescope (LAT)

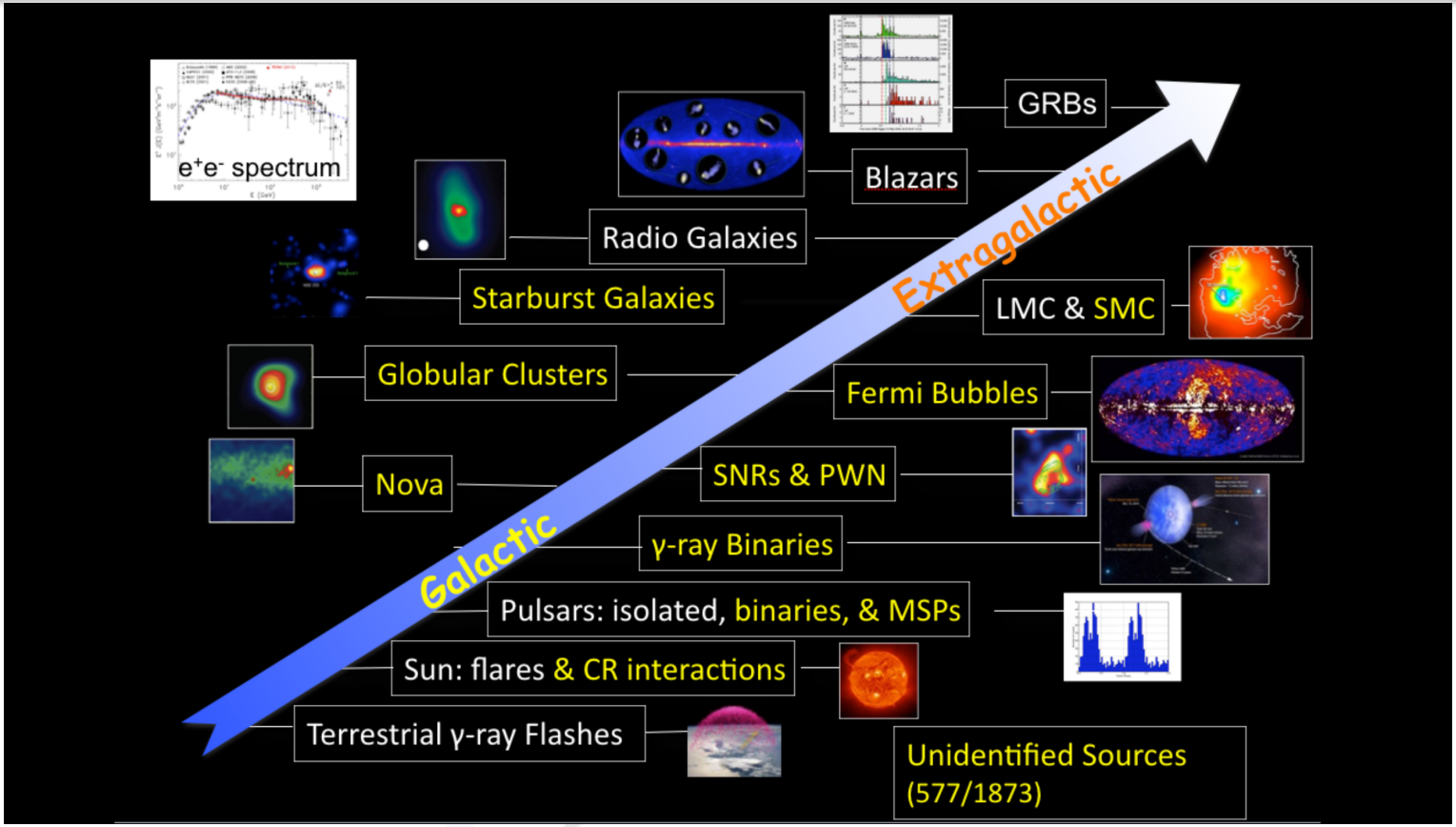
- Pair conversion telescope
- Energy range: 20 MeV–> 300 GeV
- Large field of view ($\approx$ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours




## 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 4$^{th}$ Fermi Gamma-ray Catalog

- WP4 team has actively participated in the catalog effort
- The 4$^{th}$ Fermi Gamma-ray Catalog (4FGL) released on Feb 25$^{th}$
- 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?

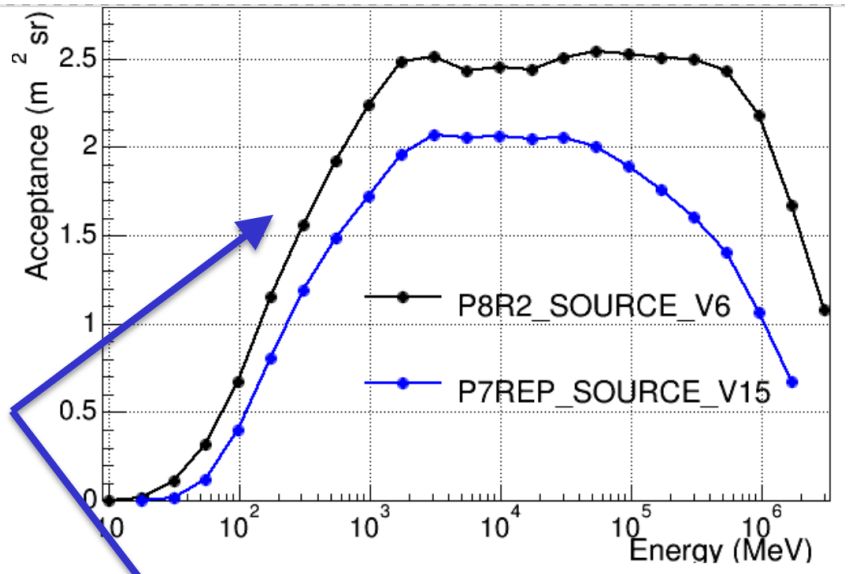
**3FGL: *838 citations* *(NASA ADS)***

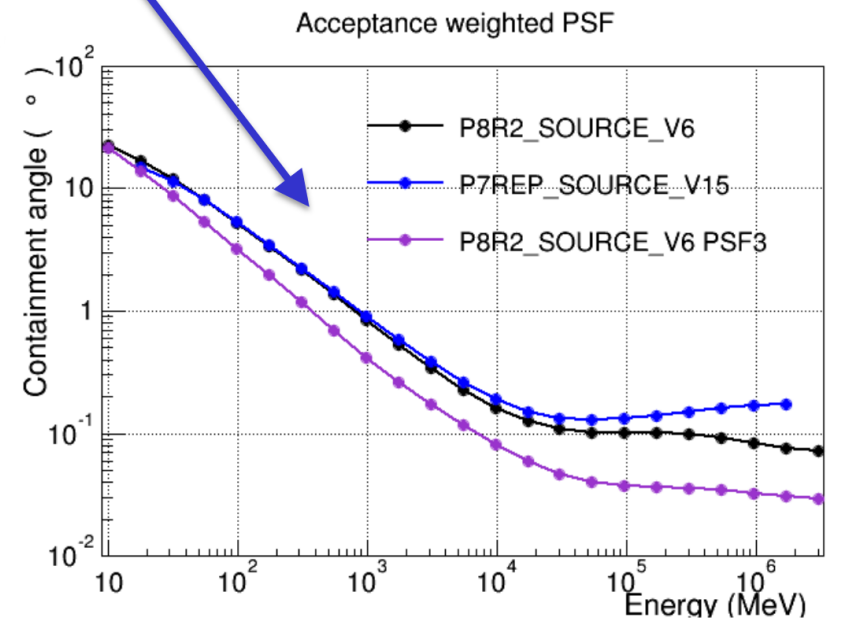
- **Predictions/optimization of future observatories: LHAASO, CTA, SKA…**
- **Sky model for data analysis**
- **Reference for studies on:**
  - **individual sources**
  - **source populations**
  - **MW analyses**
- **Source samples to investigate**
  - **Extragalactic Background Light**
  - **Extragalactic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

# The 4$^{th}$ *Fermi* Gamma-Ray Source List

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

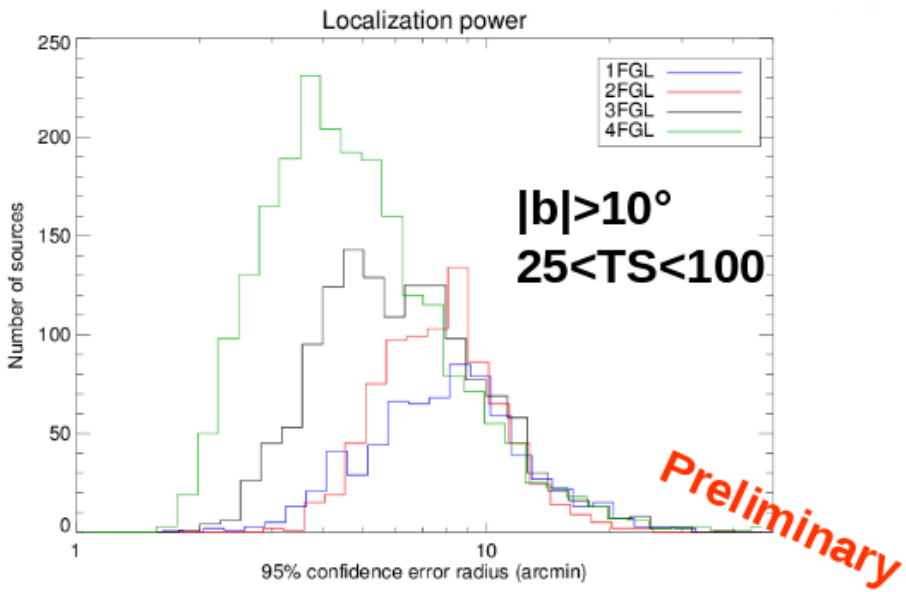
- Follow-up unassociated sources
- Deeper and better data/calibration
  - 3FGL was based on Pass7
  - 4FGL will use Pass8
- Update underlying interstellar emission model
- Look for variable sources
  - Provide yearly and bimonthly light curves
- WP4 objective complete by the end of 2019



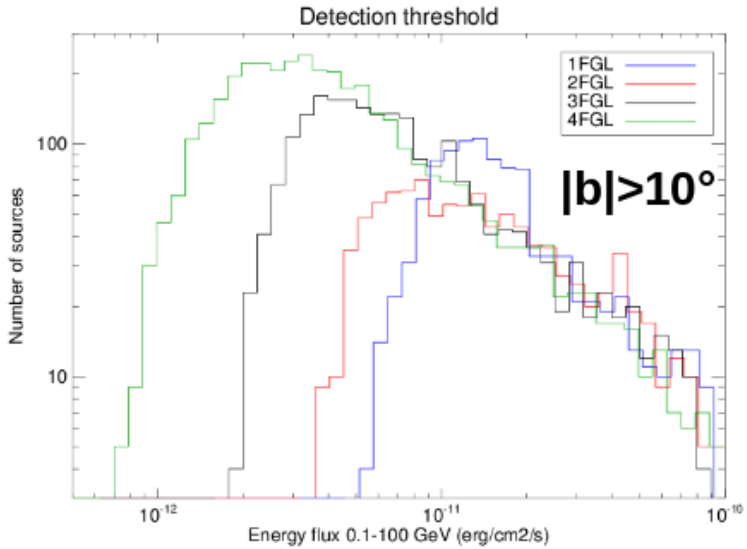



# Source characterization

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)



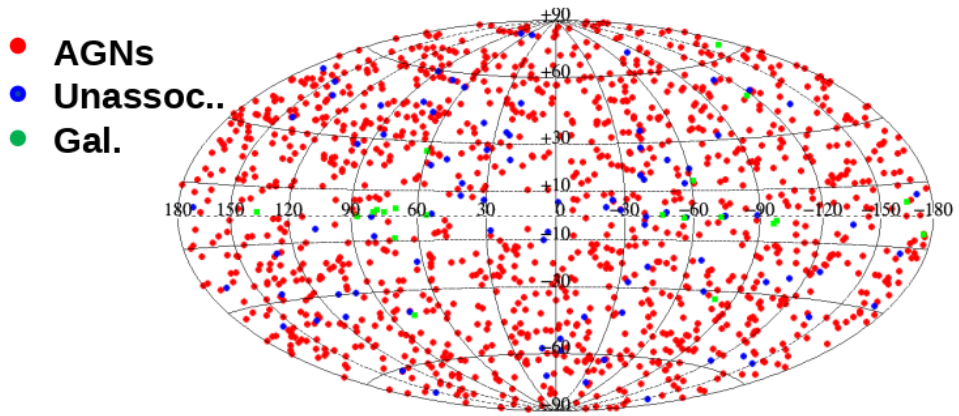
# Source variability

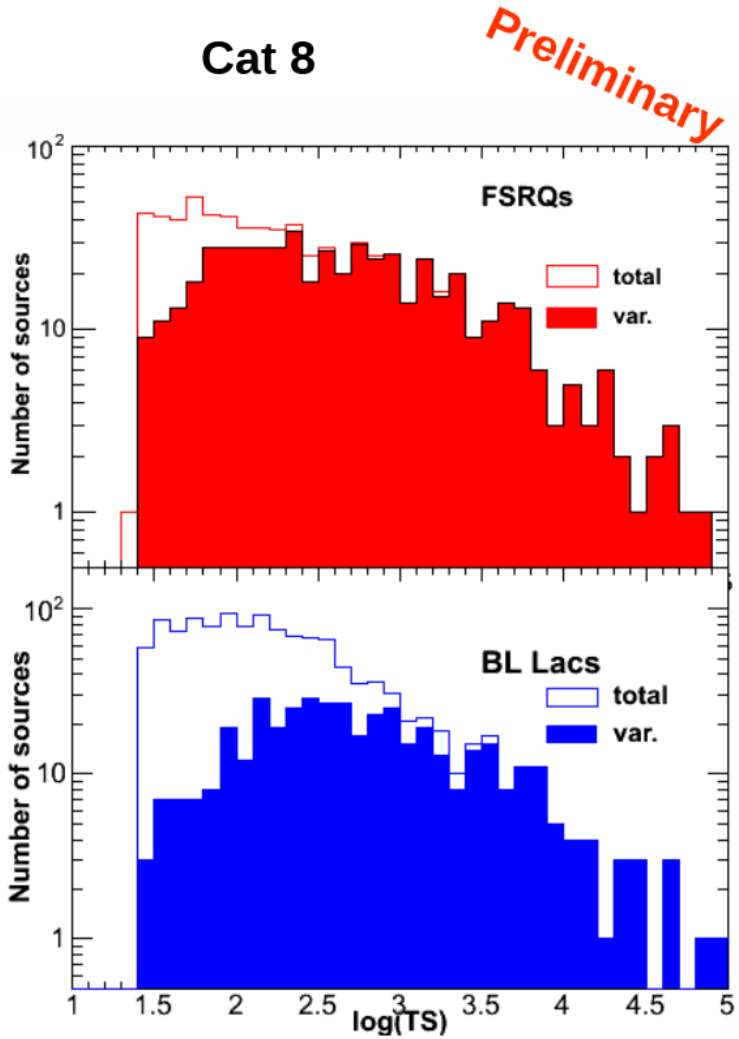
**Two sets of lightcurves created for 4FGL:**

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

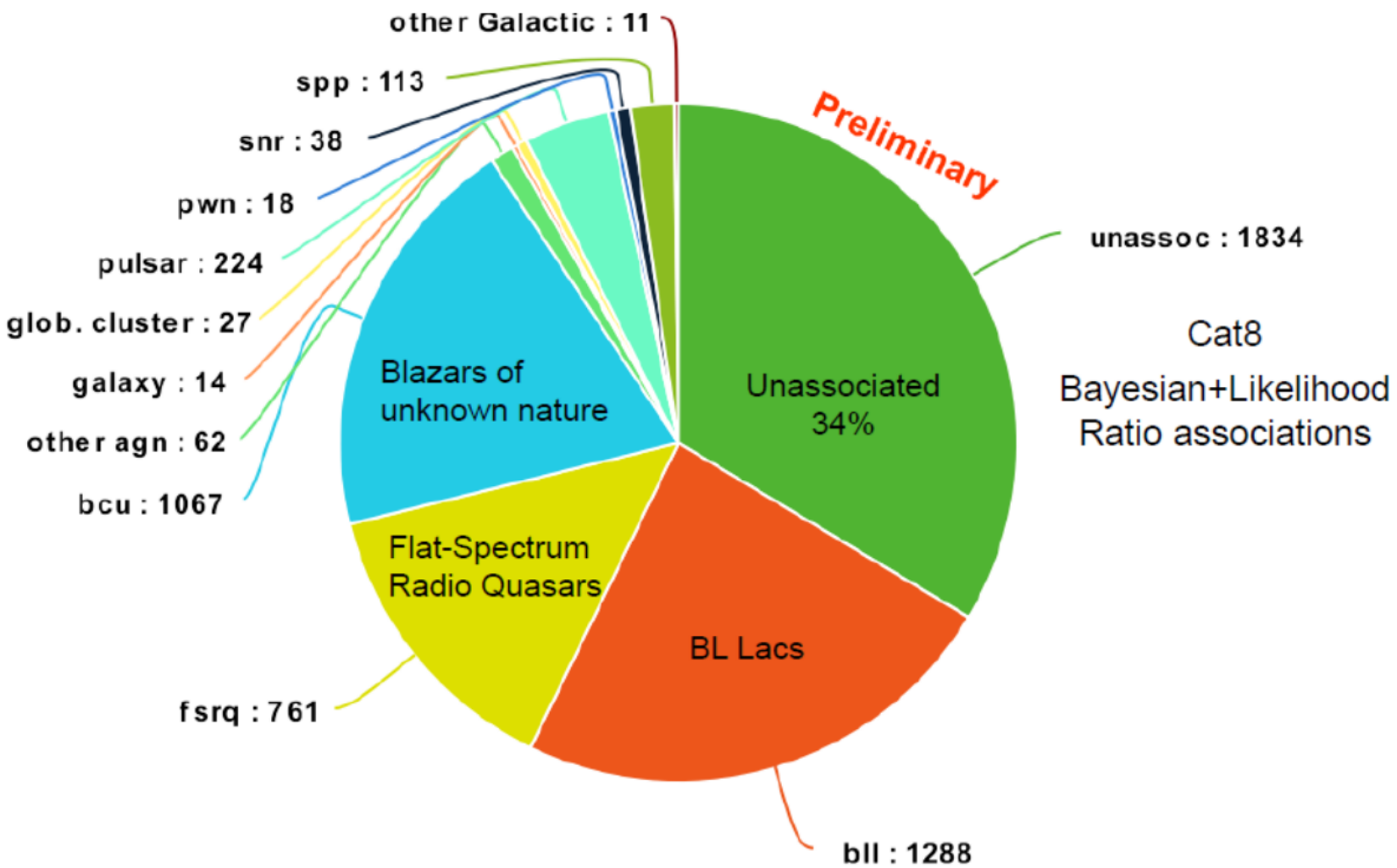
  **Ex: exercise on Cat8**

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



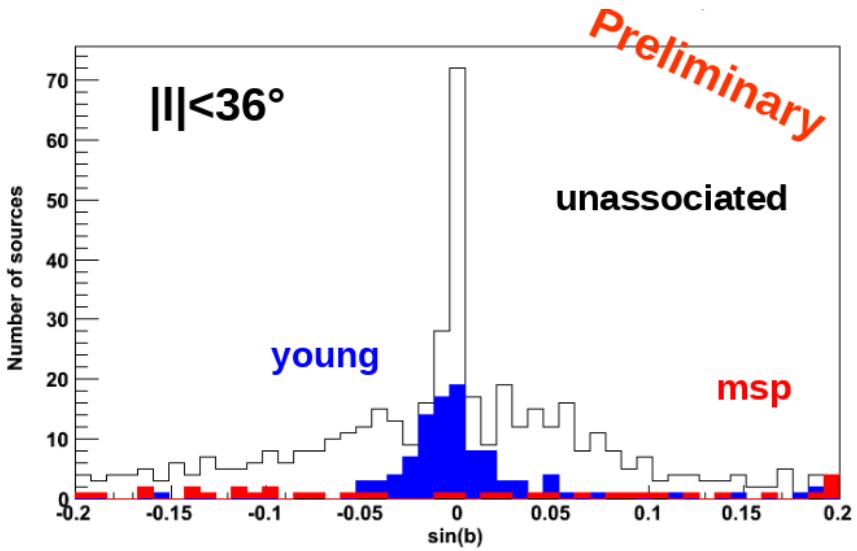



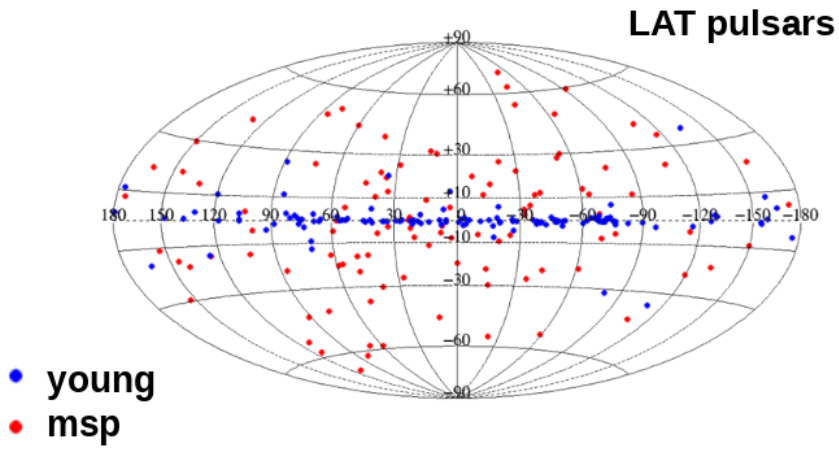
# Association summary



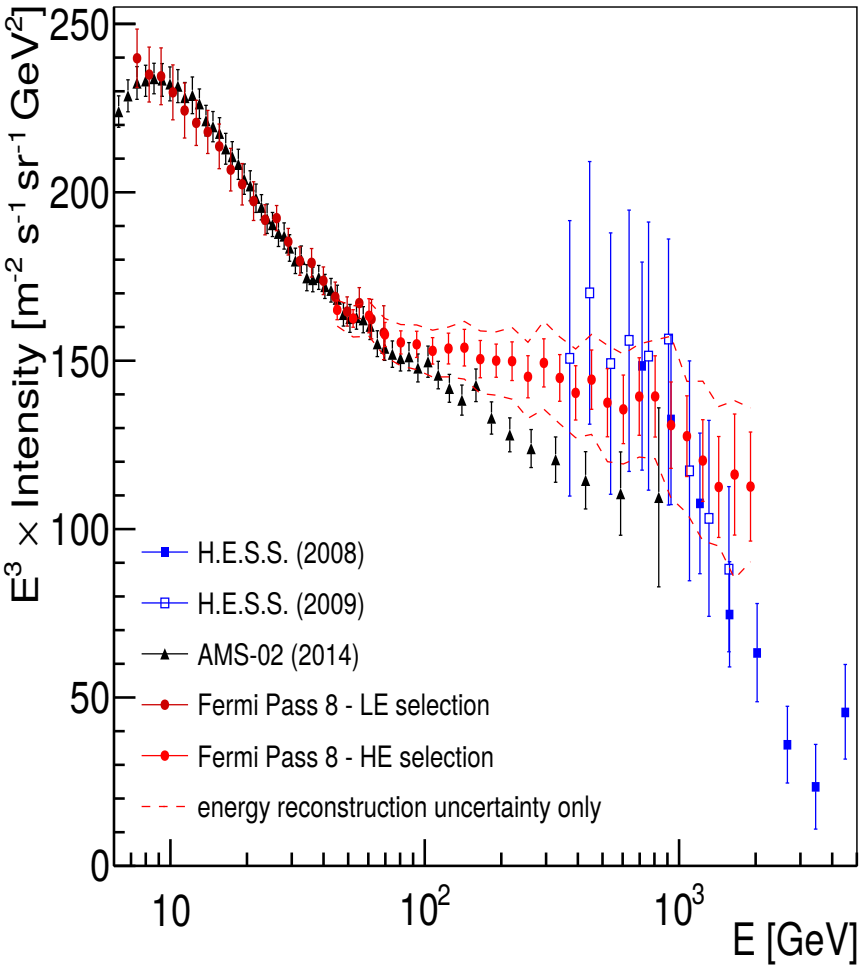
# Features of Galactic unassociated

- 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



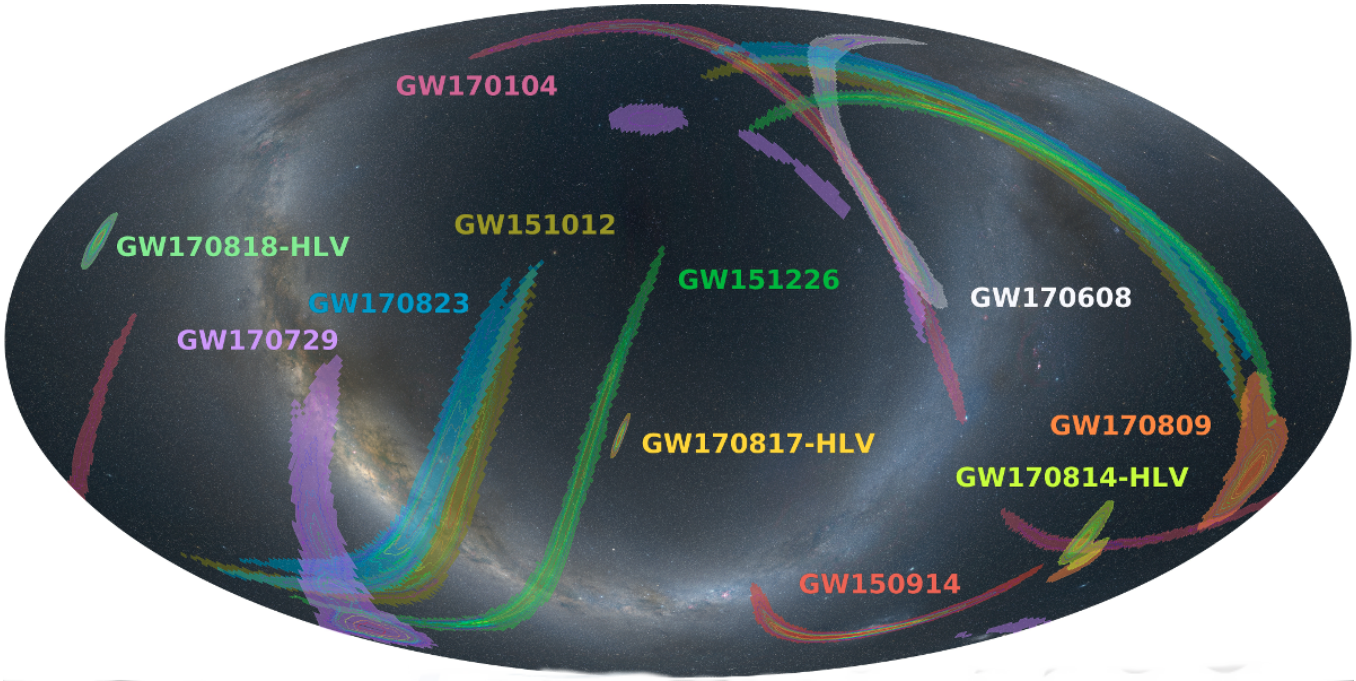
# Cosmic-Ray Electron (CRE) science




Phys. Rev. D 95, 082007

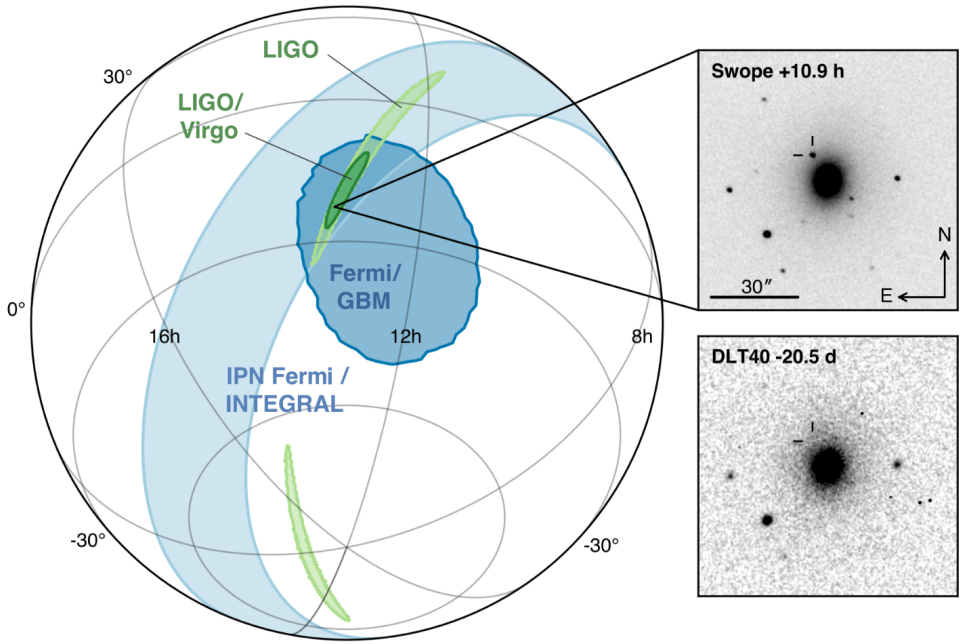
- Cosmic-ray $e^+ + e^-$ spectrum from 7 GeV to 2 TeV measured by *Fermi*-LAT
  - First space-based instrument to explore the region above 1 TeV
  - High-energy cutoff excluded up to 1.8 TeV at 95% CL
- Thanks to large amount of statistics we can now perform anisotropy searches to help constrain existence 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



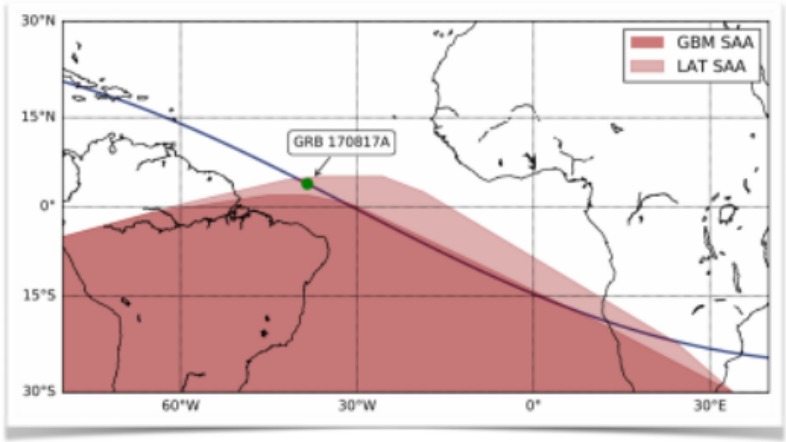

- **September 14, 2015: first observation of gravitational waves, originating from a pair of merging black holes using the Advanced LIGO detectors.**
- **To date, 6 GW events announced by the LIGO/VIRGO Collaboration (LVC):**
  - **5 BH- BH: GW150914, LVT151012, GW151226,GW170104, GW170814;**
  - **1 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)

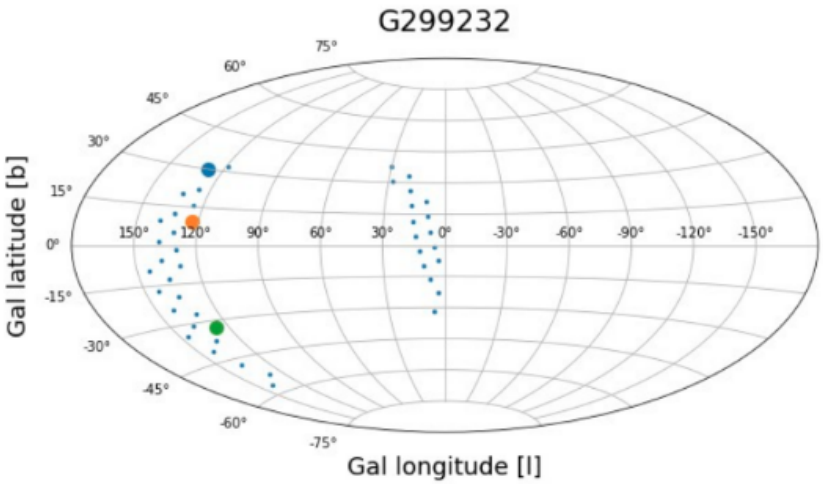
# EM follow-up to gravitational wave events

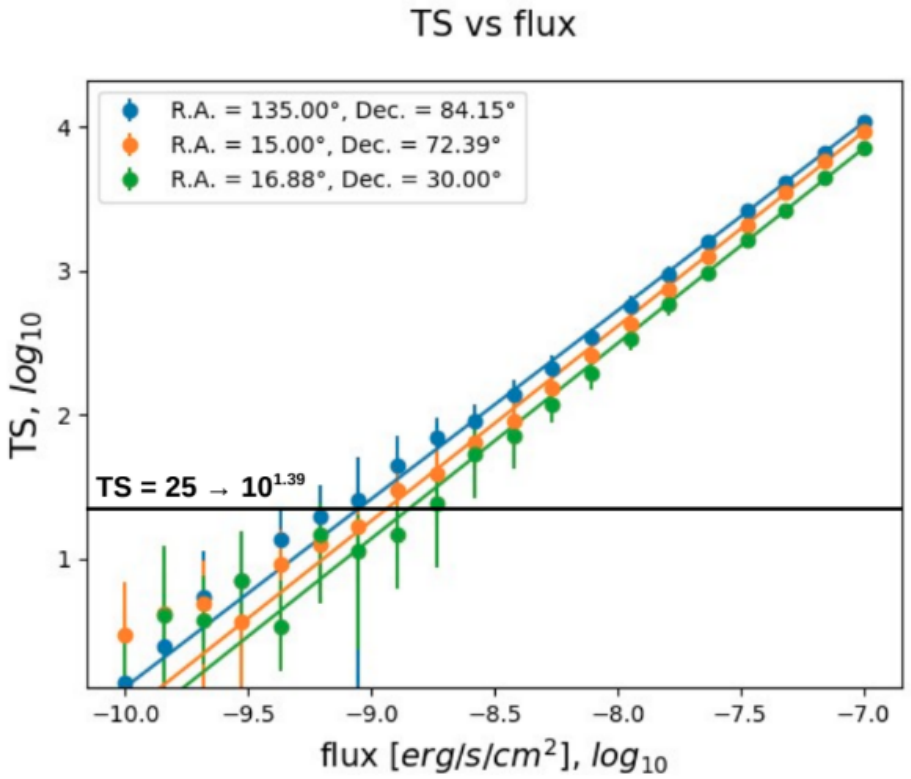

- Large contribution from WP4 team in setting up pipeline to automatically perform dedicated analyses to search for electromagnetic counterparts to gravitational wave events in Fermi-LAT data
  - The pipeline is triggered by the arrival of a LIGO/Virgo Gamma-ray Coordinates Network (GCN)
- Team has also worked on sensitivity studies to improve estimates on flux upper limits
- WP4 objective more than 60% complete

# EM follow-up to gravitational wave events: Sensitivity studies

For each pixel of the grid:

- TS is an **increasing function** of the GRB flux;
- error bars: TS is averaged over the seeds;
- **flux so that the GRB is detected with TS = 25**.




3 different positions on the grid.

Check:

- the sensitivity decreases near the galactic disk → consistent with higher galactic background.

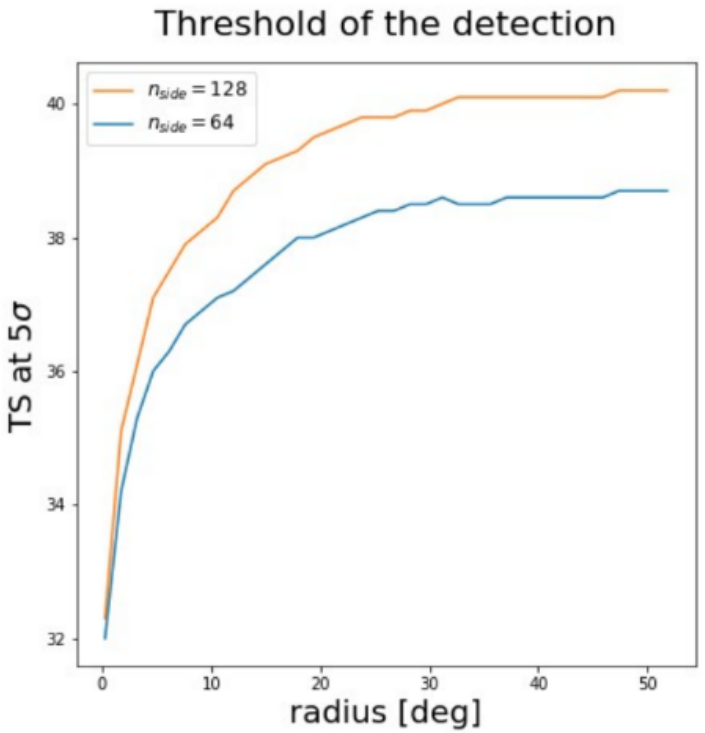
# EM follow-up to gravitational wave events: Trial Factors

Threshold of the detection $TS_{thr}$:

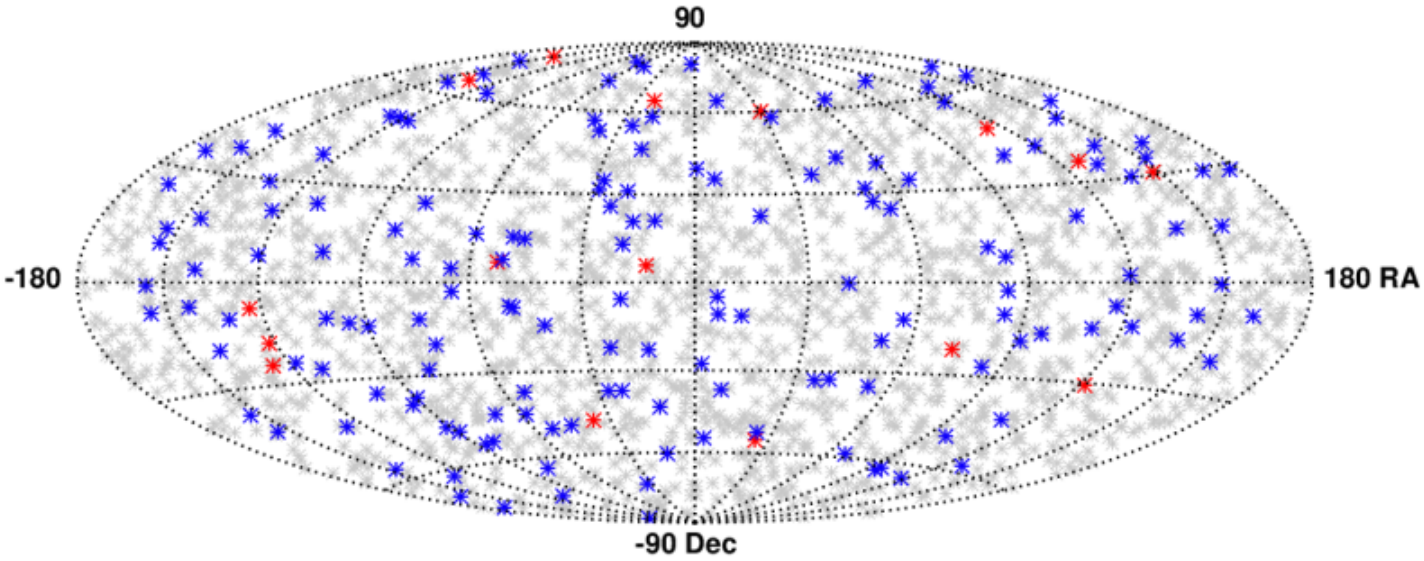
- $TS_{thr}$ scales with the dimension of the area (both $n_{side}$);
- curve **steep for small areas**:
  → $TS_{thr}$ increases quickly;
- **limit the search to small areas** in order to have the lowest $TS_{thr}$ :

  → determine a quantitative criterion to define the optimal region of the search;

  → in case of non-detection, increase the area.

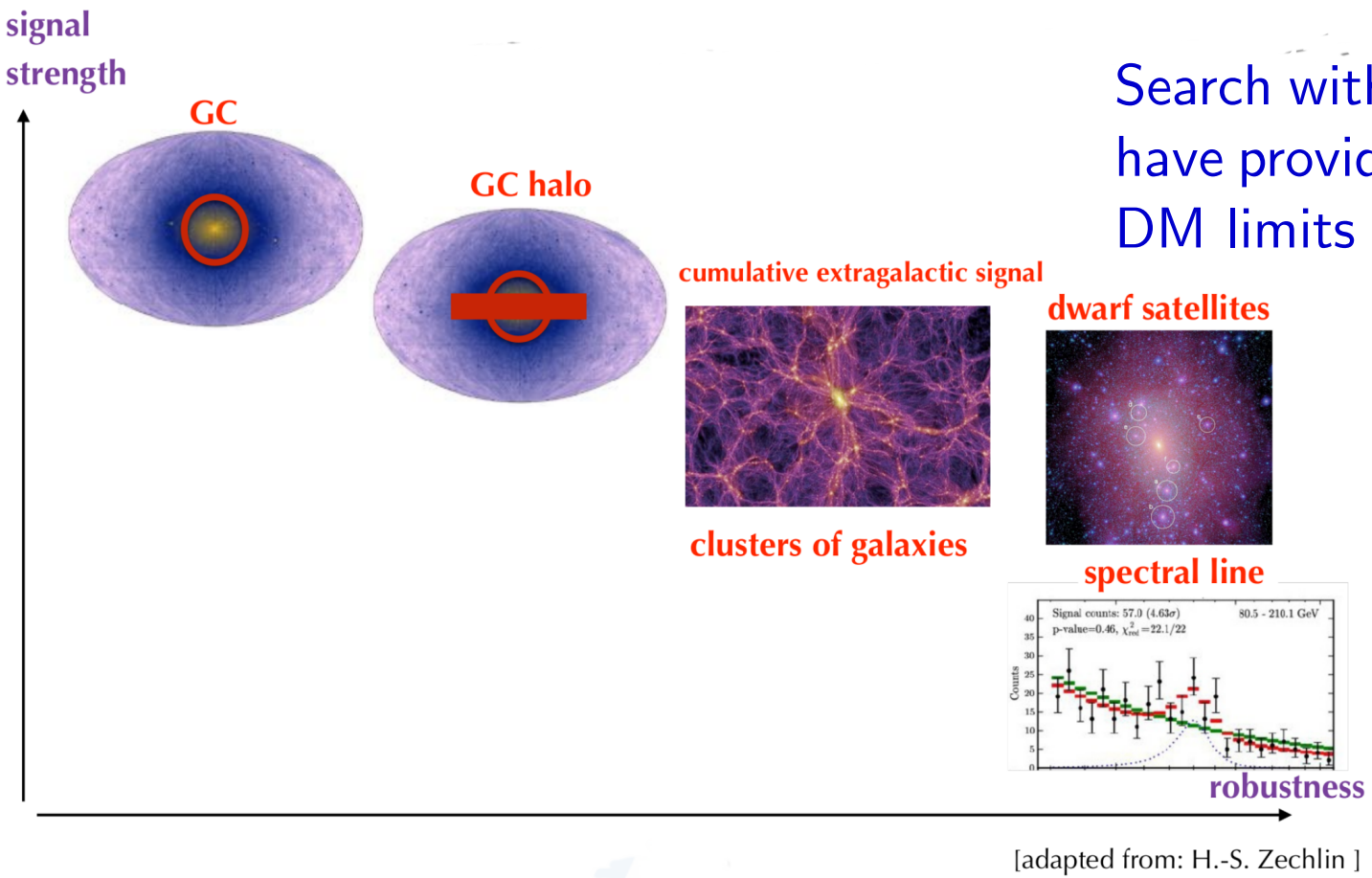


# The LAT 2$^{nd}$ GRB catalog




- The LAT 2$^{nd}$ 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
  - Work performed during WP4 secondments to Tokyo University

# 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 is contributing in the development of the analysis framework
  - Applying to new targets such as the dwarf galaxies found by DES

# WP4 use of Secondments

Completed

- INFN: 6.5 months
- OCK: 11 months
- KTH: 1 month
- Dalarna: 1 month
- HOG: 0.1 month
- Total: 19.6 months

Planned in 2020

- INFN: 3.5 months
- OCK: 3 months
- KTH: 3 months
- Total: 9.5 months

**Objectives**

- Variability studies in blazars
- 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
- Working on Fermi-LAT analysis for DM detection
  - Developing and testing new analysis techniques

# 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 in Feb 2019 and planned for publication by the end of the year
- 4.2 is more than 60% complete
  - pipeline is running smoothly for O3 of LIGO/Virgo
  - $\sim$ 2 months of secondments used in summer of 2019 to work on completing the pipeline and the related analysis tools
- 4.3 work started

# 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 $8^\circ$ 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

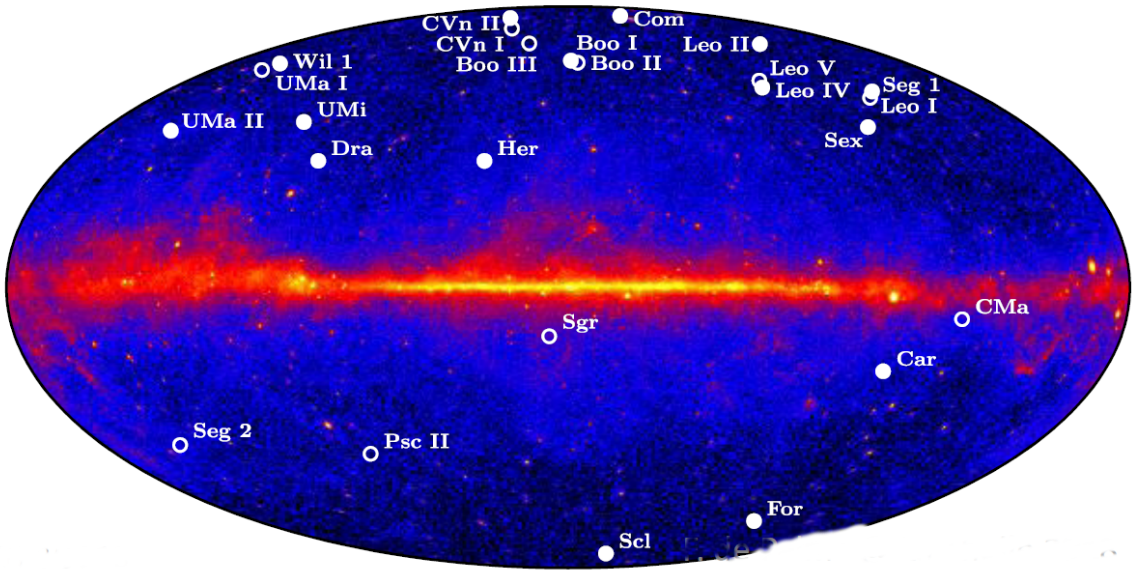
# Dark matter pipeline

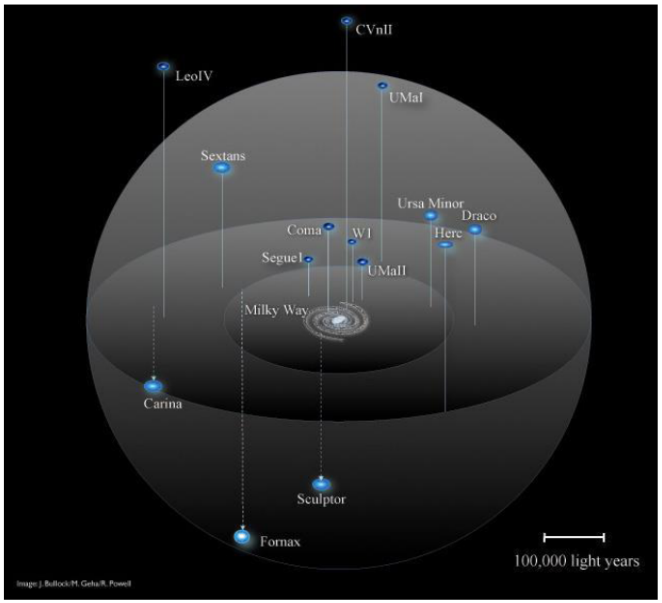
WP4 team has contributed to the dark matter pipeline effort:

- 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 nearly completed

# Dark matter searches in dSph Galaxies

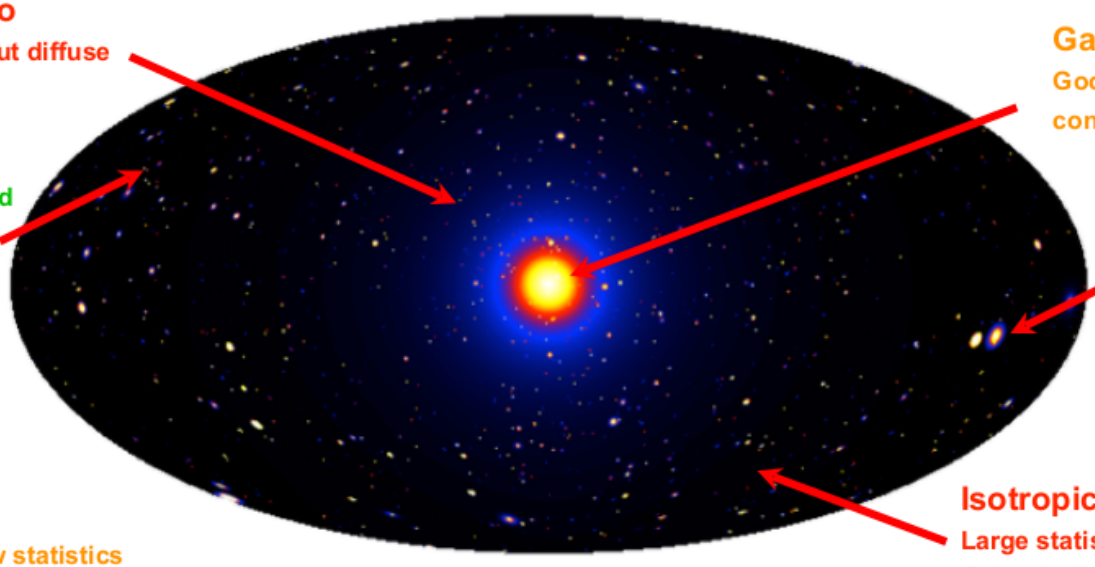
- dSph Galaxies are the cleanest target for DM searches:
  - DM-dominated (1000:1)
  - 10s to 1000s of stars
    - Mostly old stars
    - Few gamma-ray emitters (pulsars, SNRs)
    - Little gas content
  - often high latitude ➔ low diffuse background
  - nearby (<250 kpc)
  - many! (50+) ➔ allows for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

**Unassociated sources**

**Galaxy Clusters**
Low background, but low statistics

**Galactic Center**
Good statistics, but source confusion/diffuse background

**Nearby Galaxies**
Good statistics, diffuse background

**Isotropic contributions**
Large statistics, but astrophysics, Galactic diffuse background

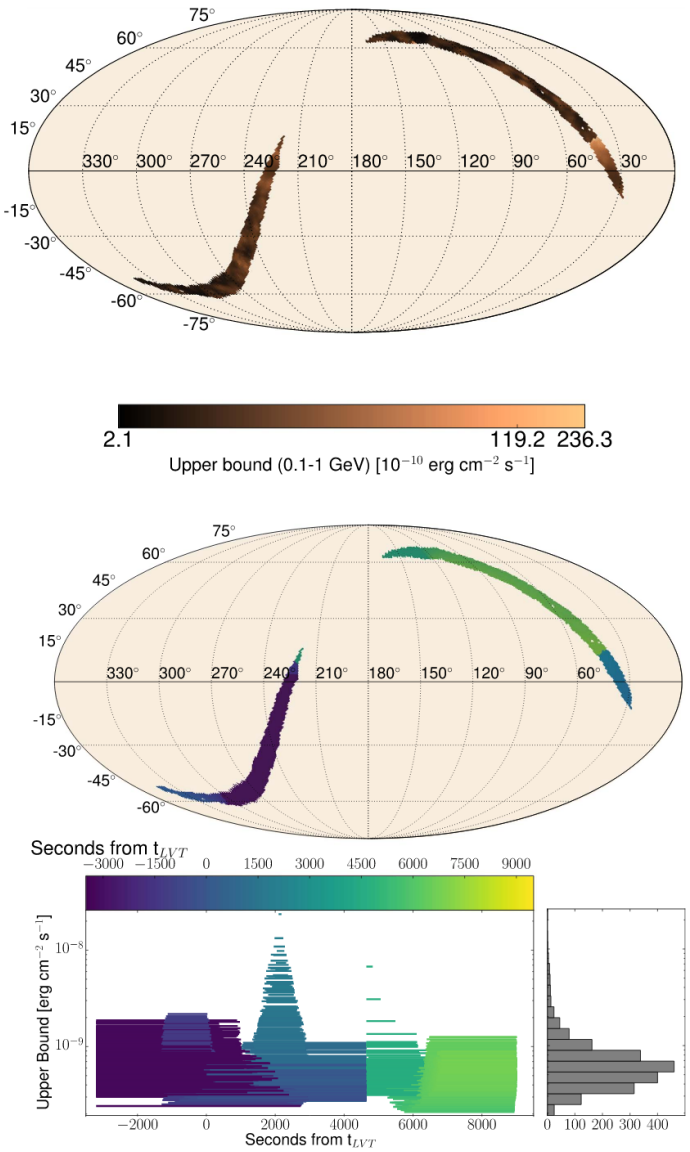
**Targets already implemented**

**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