

National Aeronautics and Space Administration



Fermi

Gamma-ray Space Telescope

www.nasa.gov/fermi



Analysis Coordinators' Report

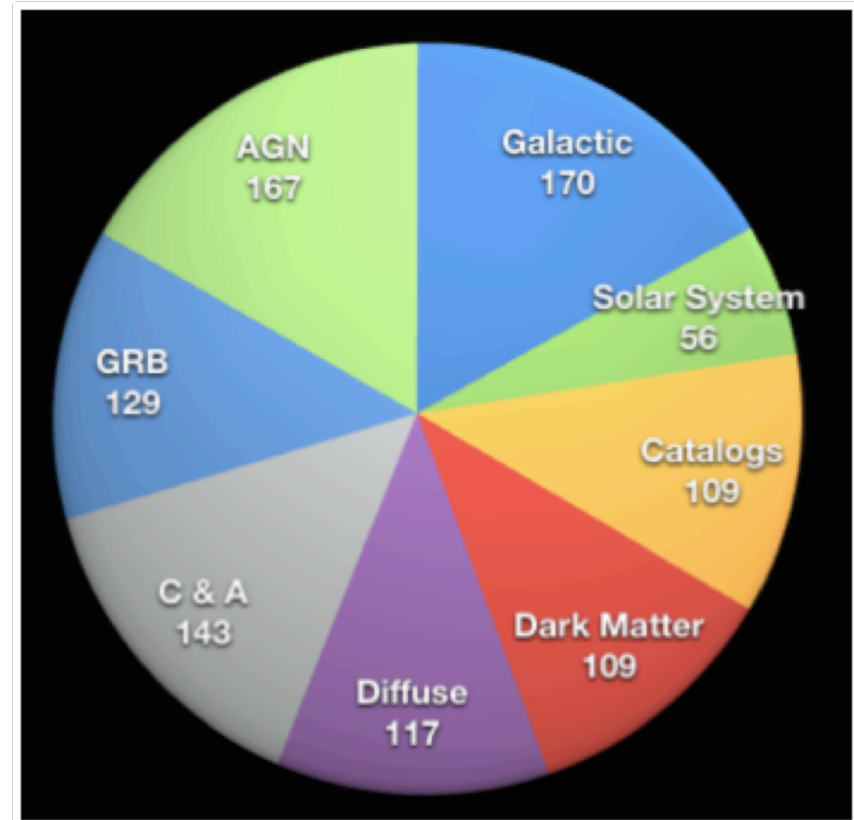
N. Omodei, S. Digel & G. Tosti

Outline

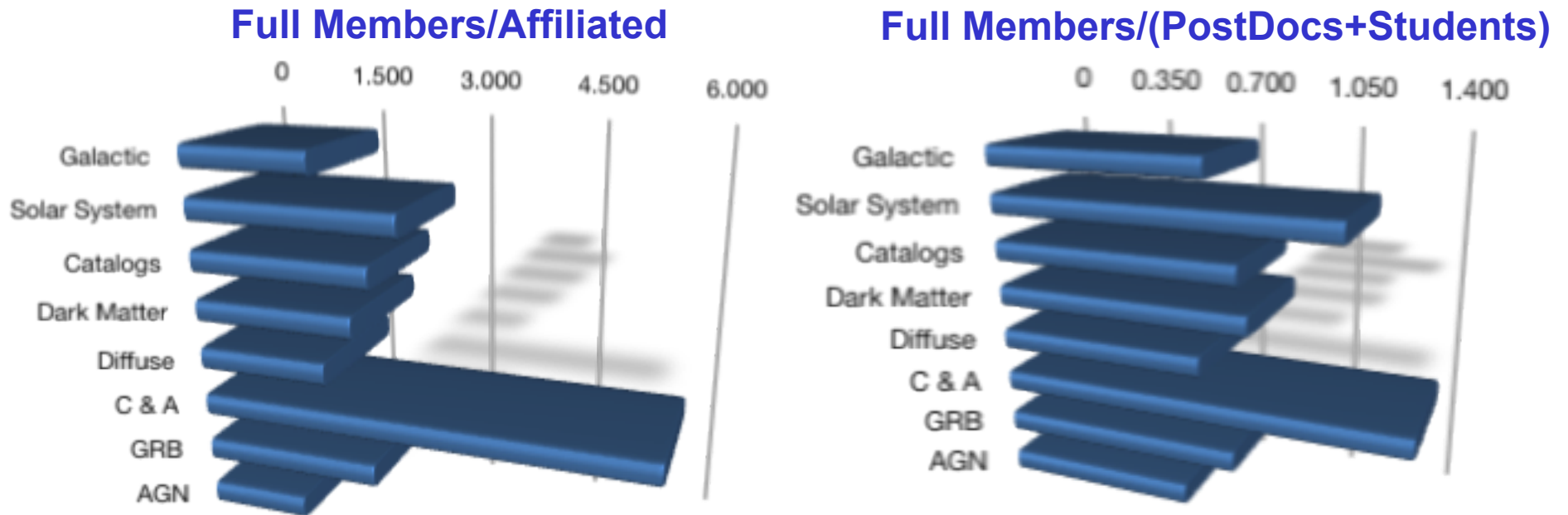
- **Scientific organization of the collaboration**
- **Collaboration service work**
- **Status of publications**
- **First-year catalogs**
- **Dark matter searches**
- **Year 2 timeline**

Science Working Group Membership

- From the database: 448 collaboration members
- Full members (118), Affiliated(103), Postdoc (93) and Students (134)
- On average each member is subscribed to 2.23 science groups, making the number of Science group members exactly 1000

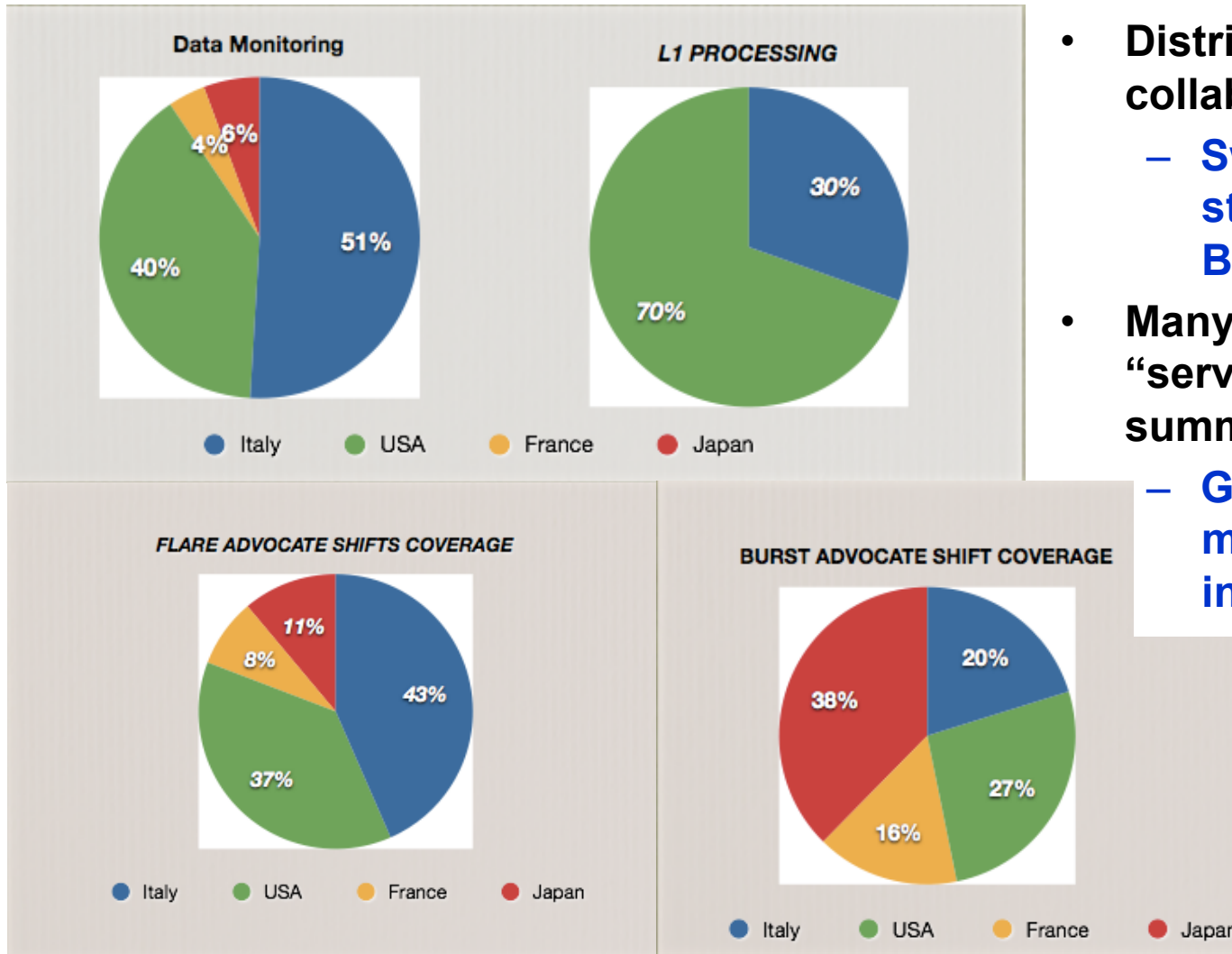


Two Derived Quantities



- **Full Members/Affiliated:** people working mainly for Fermi
- **Full Members/(PostDoc+Students):** “age” of the Science Groups

Collaboration Service Work



- **Distribution across the collaboration**
 - Sweden recently started covering some Burst Advocate shifts
- **Many other classes of “service works” are not summarized here**
 - Generation of MC, maintenance of the infrastructure,...)

Publications by the Collaboration

As of March 9,
2010

Category I and II papers in refereed journals

| Journal | Published | Accepted | Total |
|--|-------------|----------|-----------|
| Astronomy and Astrophysics | 0/1 | 1 | 2 |
| Astroparticle Physics | 1/2 | - | 3 |
| Astrophysical Journal | 26/2 | 3 | 31 |
| Astrophysical Journal Letters | 12/0 | 1 | 13 |
| Astrophysical Journal Supplement | 1/0 | 1 | 2 |
| Journal of Cosmology and Astroparticle Physics | 0/2 | - | 2 |
| Nature | 2/0 | - | 2 |
| Physical Review D | 1/0 | - | 1 |
| Physical Review Letters | 3/0 | 1 | 4 |
| Science | 7/0 | - | 7 |
| Total | 53/7 | 7 | 67 |

Papers submitted to journals: 13 (not yet accepted for
Near submission: 3 publication)

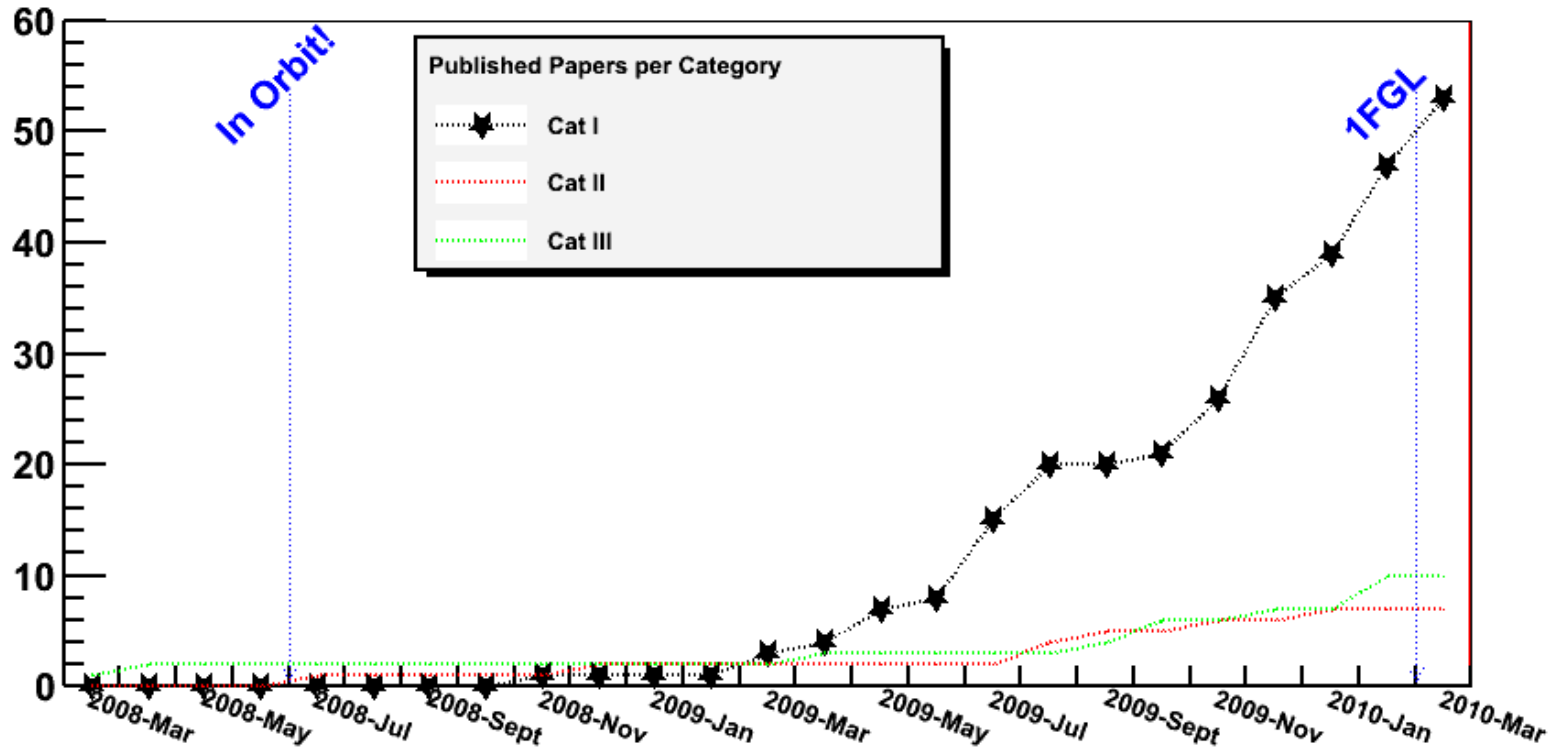
Cat I/Cat II

Rapid publications

Astronomer's telegrams (ATel): **67**

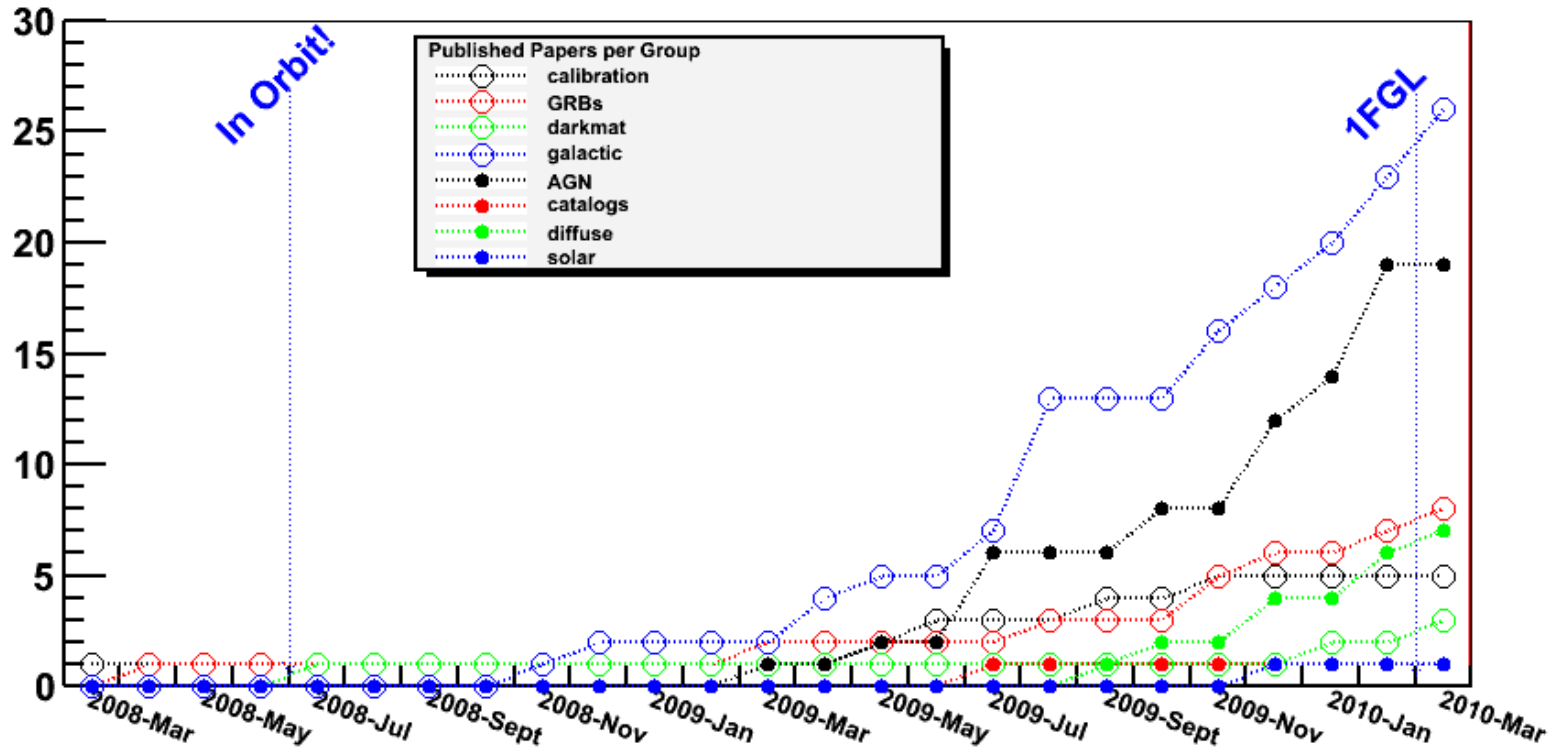
GCN Circulars: **22**

Papers Published



- Cumulative number of published papers, from March 2008

Papers Published by Group



- Cumulative number of published papers, from March 2008

- **Paper citations for 2009 (from ADS) – 5 of the top 50**
 - **CR electrons (#8)**
 - **LAT instrument paper (#14)**
 - **Bright Source List (#20)**
 - **LAT Bright AGN Sample (#35)**
 - **GRB 080916C (#43)**

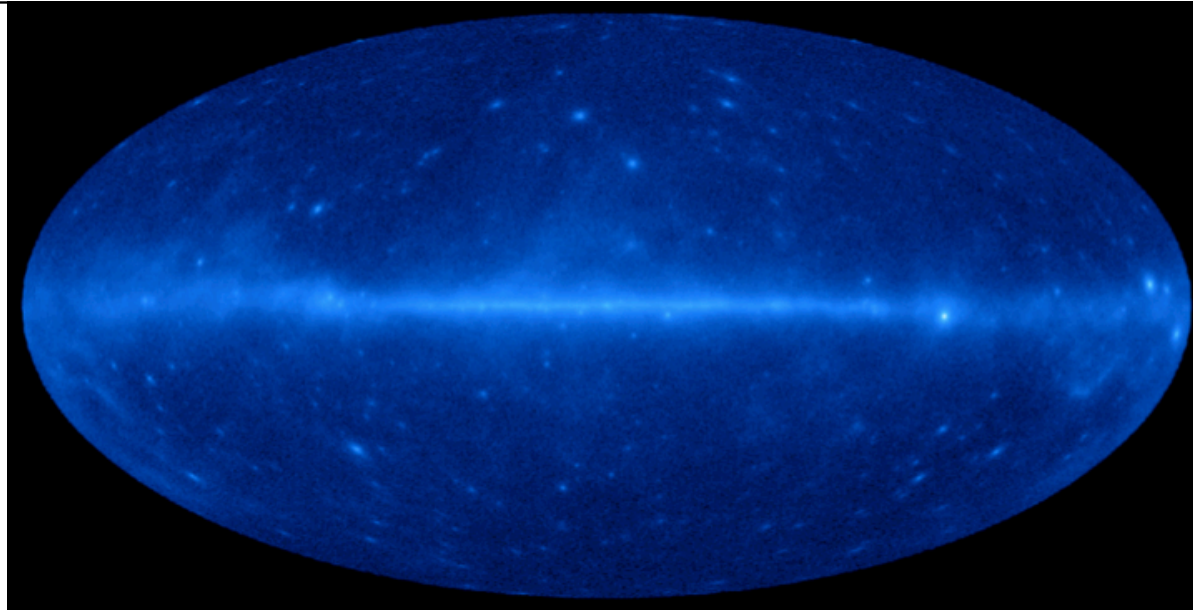
Catalogs of LAT Sources

- **Two Goals for LAT Catalogs:**
- **Find new populations**
 - **Pre-LAT confirmed populations were blazars and rotation-powered pulsars**
 - **Discovery potential among associated (or not) sources**
- **Population studies**
 - **For established populations numbers of members become usefully large**
 - **Measurables: positions, fluxes, spectral shapes, light curves (more later)**
- **The combination of quality and quantity of the LAT data is unprecedented for high-energy gamma-ray astronomy**

First-Year LAT Catalogs

- **1FGL: First Fermi Gamma-ray LAT**
 - ApJS, submitted, arXiv:1002.2280
 - Succeeding the Bright Source List 0FGL (Abdo et al. 2009) based on 3 months of data
- **1LAC: First LAT AGN Catalog**
 - ApJS, submitted, arXiv:1002.0150
 - Succeeding LBS (Abdo et al. 2009) based on 3 months' data
- **LAT Pulsar Catalog**
 - ApJS, in press, arXiv:0910.1608
 - Spectral analysis is based on 6 months of data

1FGL Analysis Inputs



>1 GeV
log scaling

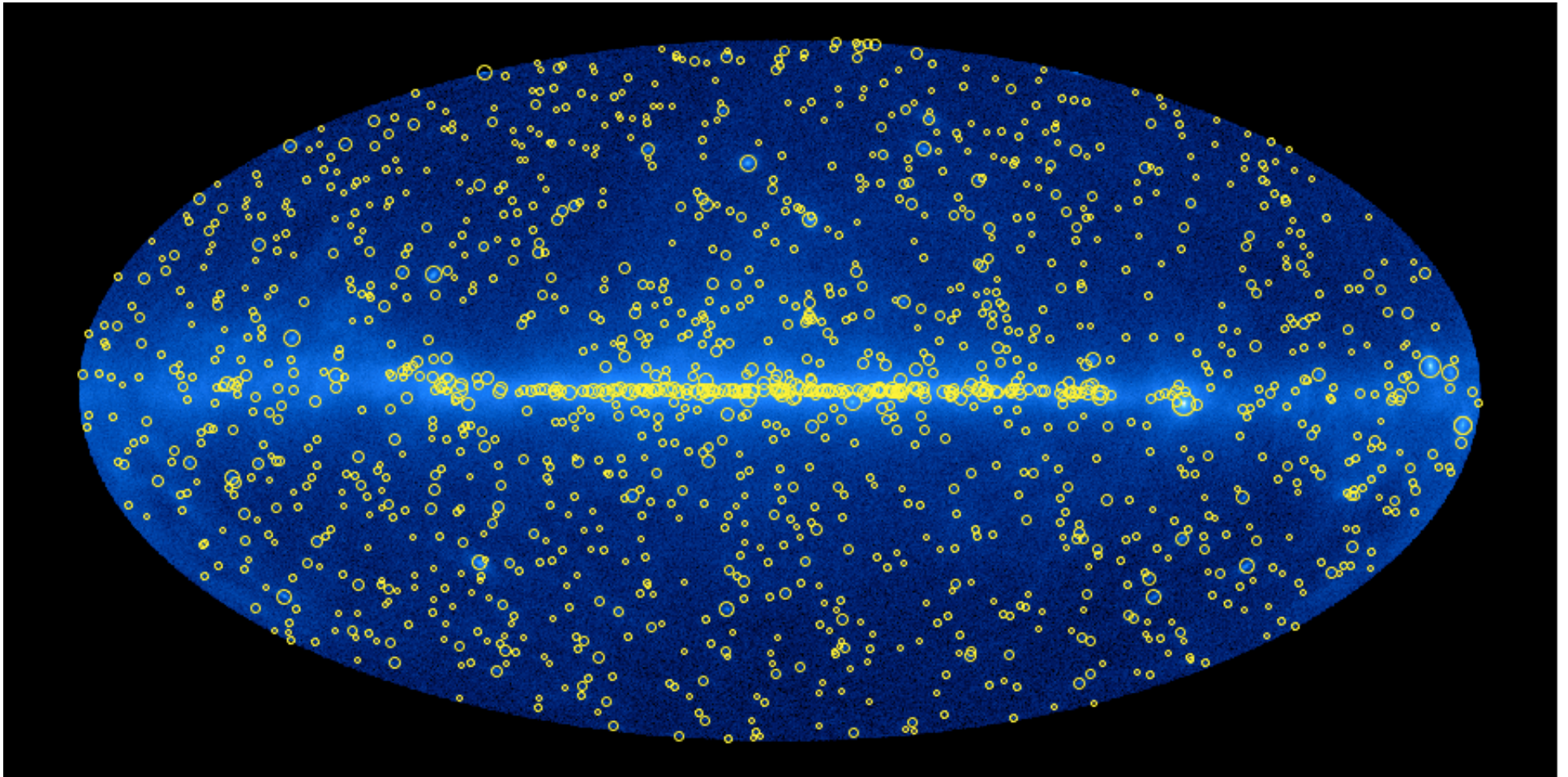
- **11 months of data 100 MeV to 100 GeV, 23.3 Ms live time**
- **10.6 M events over the whole sky (Pass 6 Diffuse class γ -rays)**
 - **Raw data are essentially pure cosmic rays (~ 2.5 kHz)**
 - **Diffuse-class γ -rays (>100 MeV) ~ 0.5 Hz**
- **First in-flight instrument response functions (taking into account pile-up effects) – Pass 6 v3**
- **Very uniform exposure (factor 1.25 between north and south)**

1FGL Analysis

- **Based on the LAT Science Tools* with a lot of supporting machinery: the fundamental analysis is maximum likelihood**
 - **Fit a model of the sky (sources + diffuse emission) to the data and thereby derive information like source significances, locations, fluxes, spectra**
- **Evaluation and optimization of the likelihood function is time-consuming and in particular general likelihood analysis is not efficient for searching for sources**
 - **We employed a variety of source-detection algorithms and used other inputs to provide additional ‘seeds’**
 - **And used a simplified likelihood function to optimize the positions of the sources**
- **Limitations: non-homogenous catalog (not that it could be otherwise) – in particular it is more incomplete for soft sources; dependence on model for the Galactic diffuse emission**

* Public release available from Fermi Science Support Center:
<http://fermi.gsfc.nasa.gov/ssc/> Fermi LAT IFC Meeting, Paris, 19 March 2010

The Fermi LAT 1FGL Source Catalog



1451 sources (4.1σ significance threshold); symbol size encodes >1 GeV flux

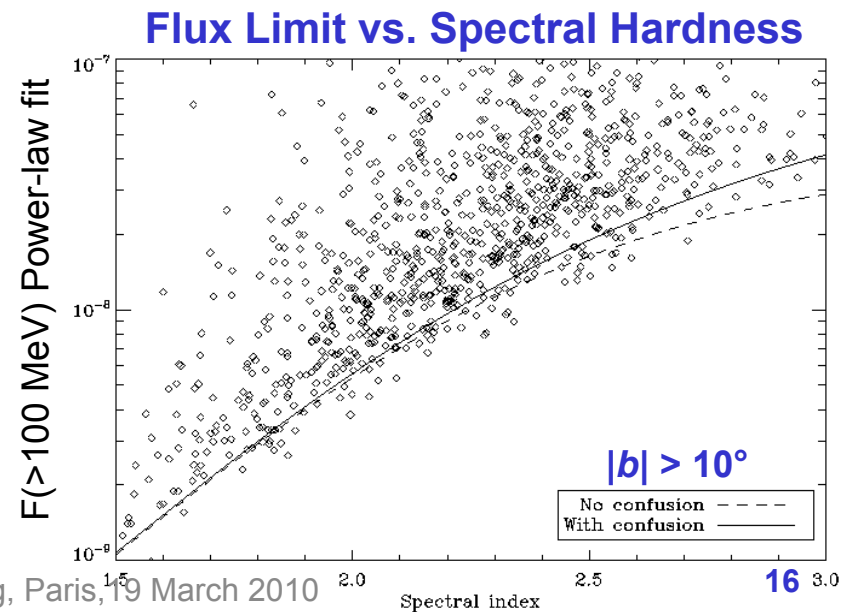
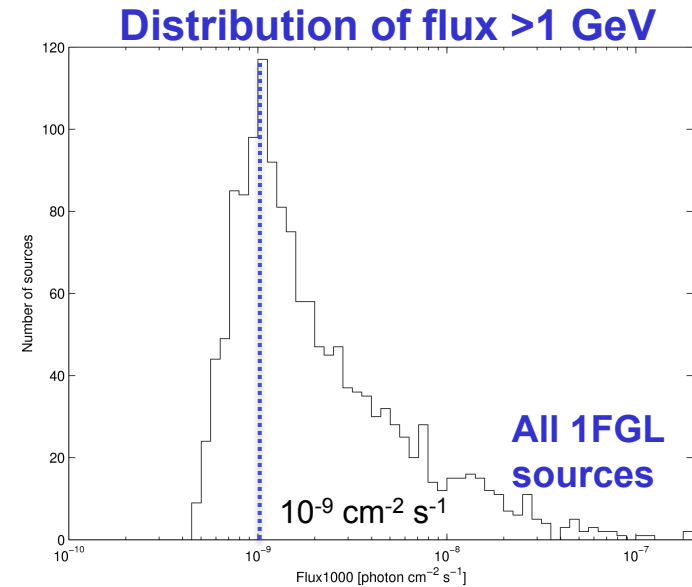
1FGL catalog entries

- **Source coordinates and error ellipse at 95% confidence**
 - **Detection based on integrated data (not on flares)**
 - **Precise localization**
- **Source significance (threshold significance 4.1σ)**
- **Quality flags: sensitivity to diffuse model, confusion, error ellipse not well defined, etc.**
- **Average flux in 5 energy bands 0.1 – 0.3 – 1 – 3 – 10 – 100 GeV, plus spectral index, pivot energy, and differential flux for single power-law fit, curvature index**
- **Flux per month, variability index**
- **Association with external catalogs**

1FGL Catalog is available from the Fermi Science Support Center <http://fermi.gsfc.nasa.gov/ssc>

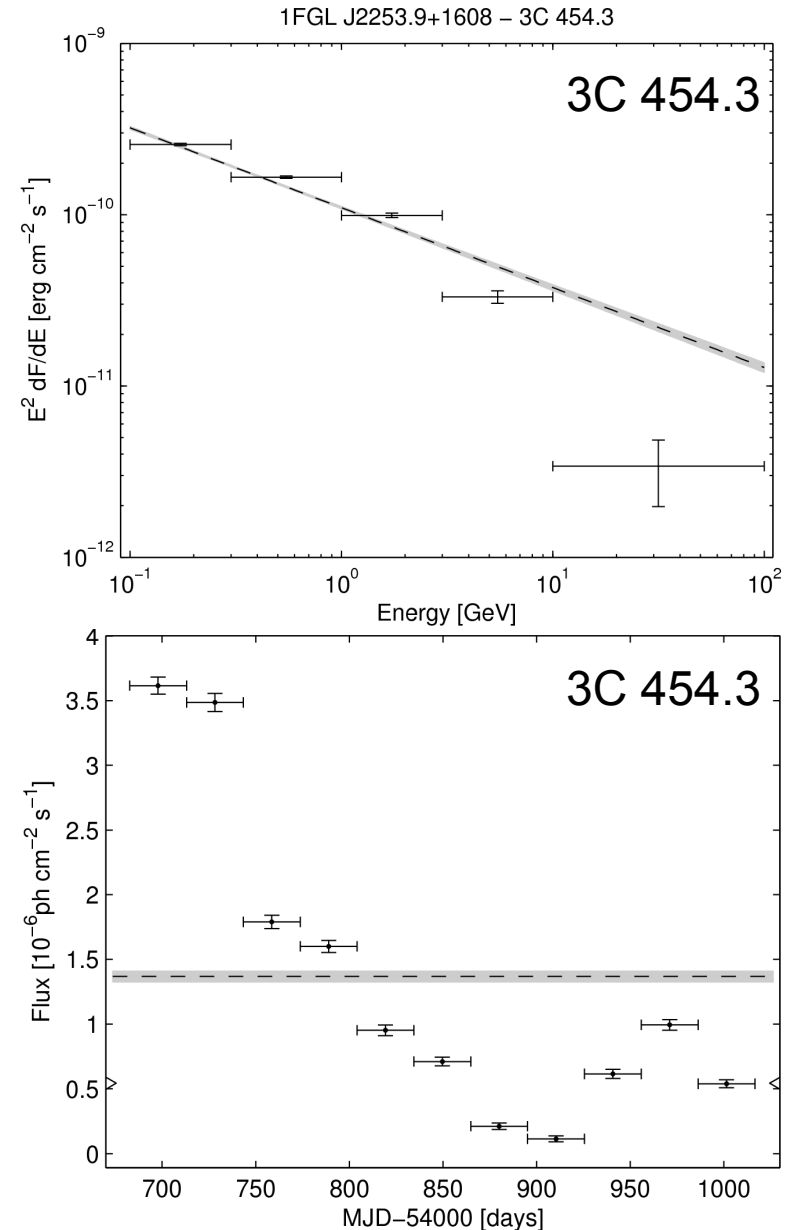
Sensitivity of the 1FGL Catalog

- The flux limit is not well defined – depends on source spectra and diffuse background intensity
- Analytical approximation for high-latitude sky works well
 - Lower envelope is from energy dependence of the PSF width
 - Confusion (overlapping PSFs) reduces sensitivity for the softer sources
 - N.B. Spectra are only *approximately* power-law
- Flux limits at low latitudes are factors of ~few greater



Source Spectra and Variability

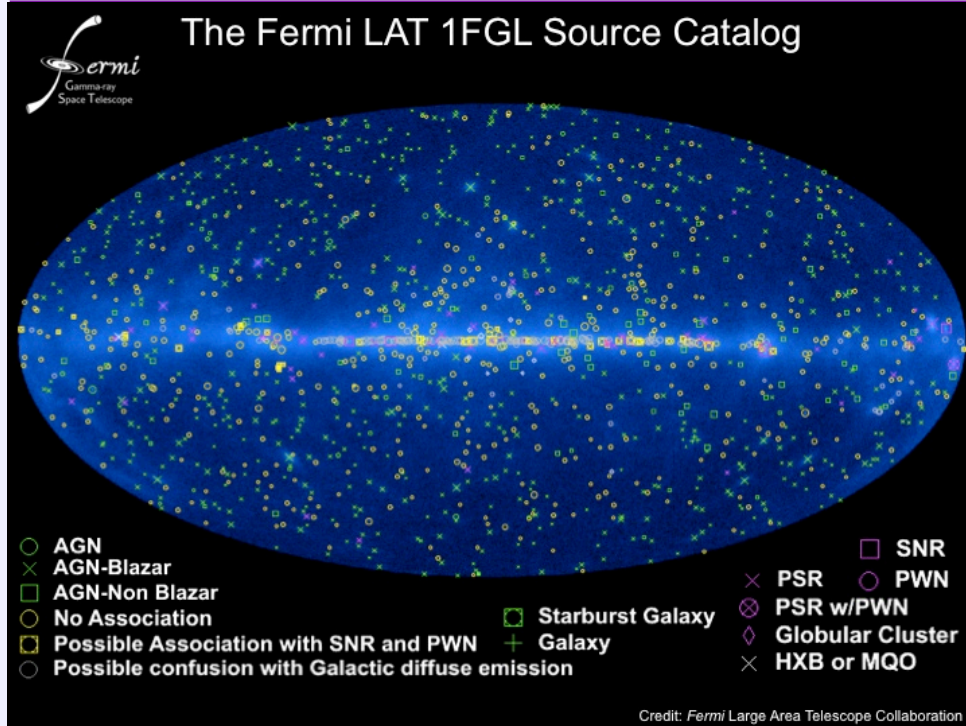
- Evaluated fluxes in 5 bands from 100 MeV to 100 GeV
 - Curvature index: χ^2 against power-law hypothesis
- Built light curves of all sources on one-month time scales
 - Pulsars are stable within 3%; bright blazars are very clearly variable
 - Variability index: χ^2 against constant hypothesis
 - 241 variable sources at 99% confidence



Astronomy Picture of the Day

Discover the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by a professional astronomer.

2010 March 18



Fermi Catalogs the Gamma-ray Sky
 Credit: NASA, DOE, International Fermi LAT Collaboration

Explanation: What shines in the gamma-ray sky? The most complete answer yet to that question is offered by the Fermi Gamma-ray Space Telescope's [first all-sky catalog](#). Fermi's sources of cosmic gamma-rays feature nature's most energetic particle accelerators, ultimately producing 100 MeV to 100 GeV photons, photons with more than 50 million to 50 billion times the energy of visible light. Distilled from 11 months of sky survey data using Fermi's Large Area Telescope (LAT), the 1,451 cataloged sources include energetic star burst galaxies and active galactic nuclei (AGN) far beyond the Milky Way. But within our own galaxy are many pulsars (PSR) and pulsar wind nebulae (PWN), supernova remnants (SNR), x-ray binary stars (HXB) and micro-quasars (MQO). Fermi's all sky map is shown centered on the Milky Way with the diffuse gamma-ray emission from the Galactic plane running horizontally through the frame. To locate the cataloged gamma-ray sources, just slide your cursor over the map. For now, 630 of the sources cataloged at gamma-ray energies remain otherwise unidentified, not associated with sources detected at lower energies.

- AGN
- × AGN-Blazar
- AGN-Non Blazar
- No Association
- ◻ Possible Association
- Possible confusion

- SNR
- PSR
- PWN
- ⊗ PSR w/PWN
- ◇ Globular Cluster
- × HXB or MQO

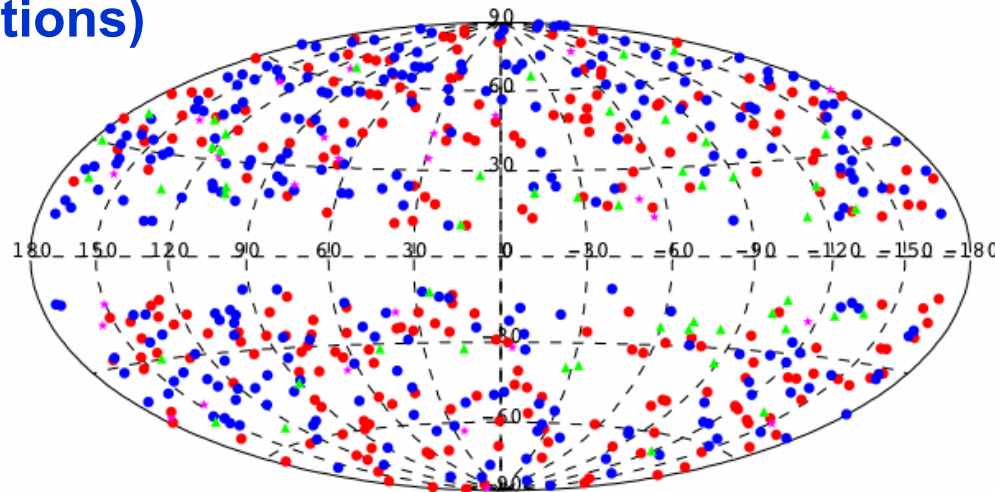
* Astronomy Picture of the Day

1FGL Highlights

- **1451 sources** above 4.1σ significance threshold
- Typical 95% error radius is **10'**. Absolute accuracy is $<1'$
- **241 sources** show evidence of **variability**
- About half the sources are **associated** positionally, mostly with **blazars (~600) and pulsars (~60)**
- **Other classes** of sources exist in small numbers (XRB, PWN, SNR, starbursts, globular clusters, radio galaxies, narrow-line Seyferts)
- Uncertainties due to the diffuse model, particularly in the **Galactic ridge**, should be kept in mind for low-latitude and local cloud studies
- The Catalog is an **analysis product** but also a **useful input** for many other studies with LAT data

First LAT AGN Catalog (1LAC)

- Based on 1FGL sources associated with AGN
- 1LAC sample is for $|b| > 10^\circ$ & includes lower-confidence associations (down to $P = 0.5$)
 - 671 1FGL sources: 300 BL Lacs, 296 FSRQs, 41 AGNs of other types, 72 of unknown type (some multiple associations)



FSRQ
BL Lacs
Radio galaxies
AGNs unknown type

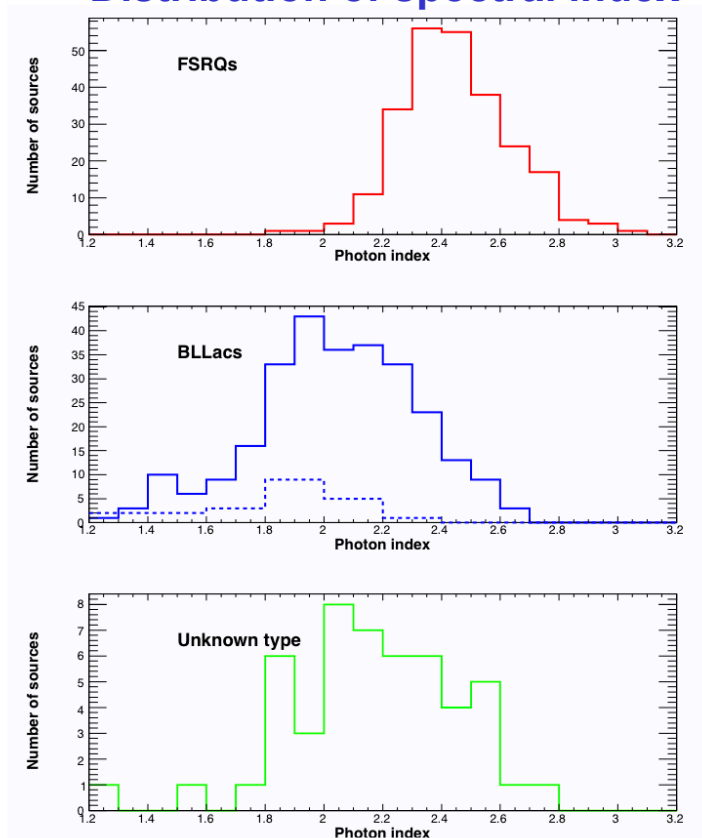
'Clean' subsample:
 $P > 0.8$, singly assoc.

- 1LAC paper also lists 51 low-latitude associations and 104 high-latitude 'affiliations' (plausible associations for which quantitative probabilities could not be defined)

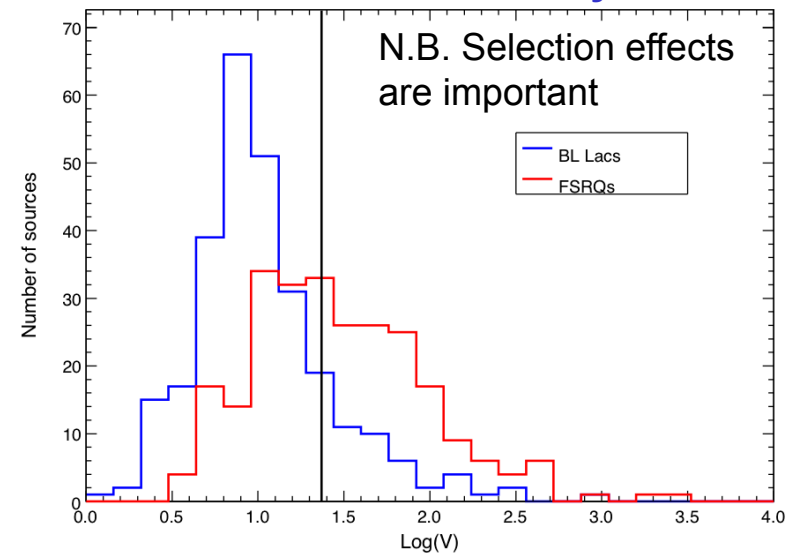
More on 1LAC

- Extensive studies of gamma-ray properties by source class,

e.g. **Distribution of spectral index**



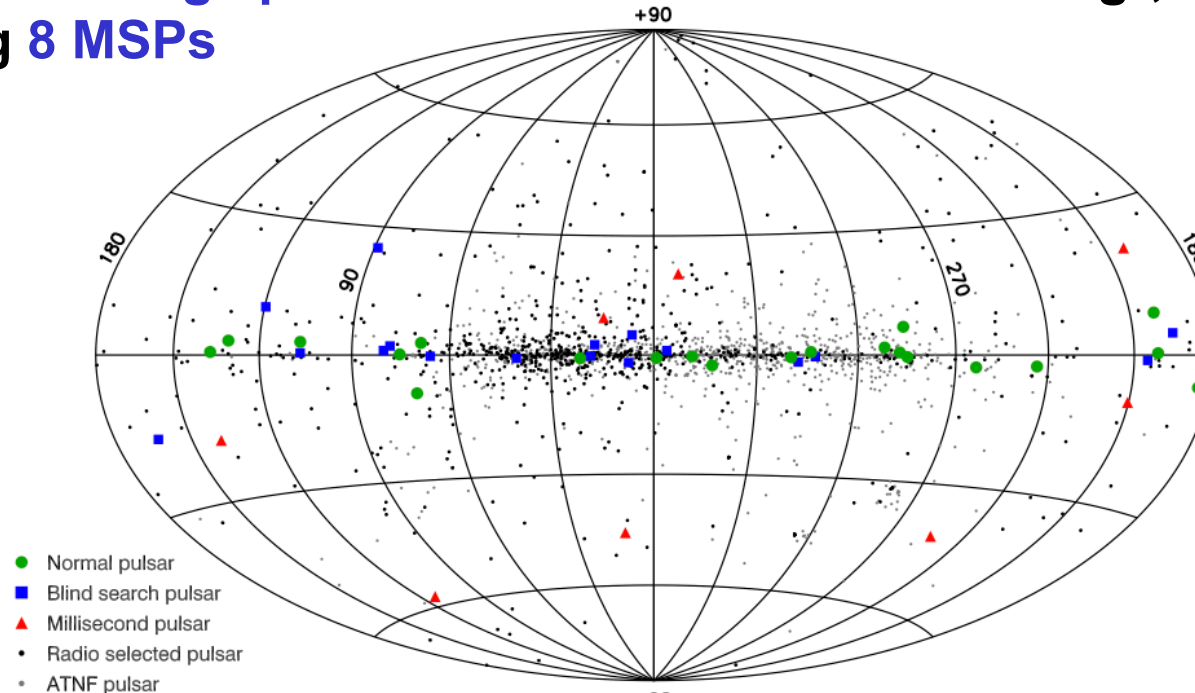
Distribution of variability index



- 1LAC paper also includes **archival radio continuum fluxes**, **redshifts**, and examines **GeV/TeV correlations**

LAT Pulsar Catalog

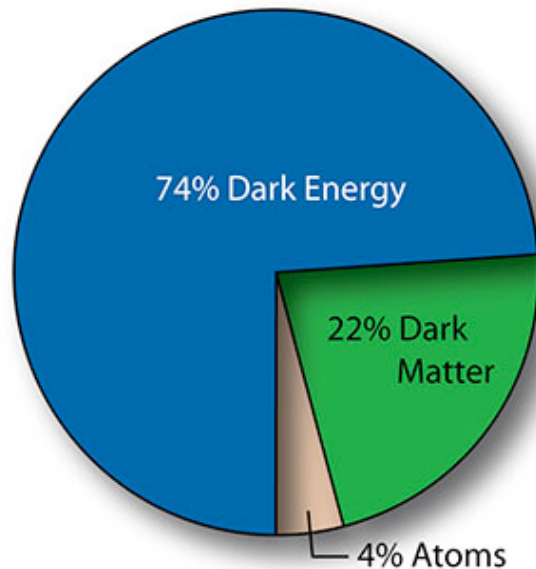
- Comprehensive, uniform presentation of **46** pulsars detected by the LAT using the **first 6 months** of LAT data
- Of the 46, **16** resulted from **blind searches**, and **24** were **discovered using ephemerides** from radio monitoring*, including **8 MSPs**



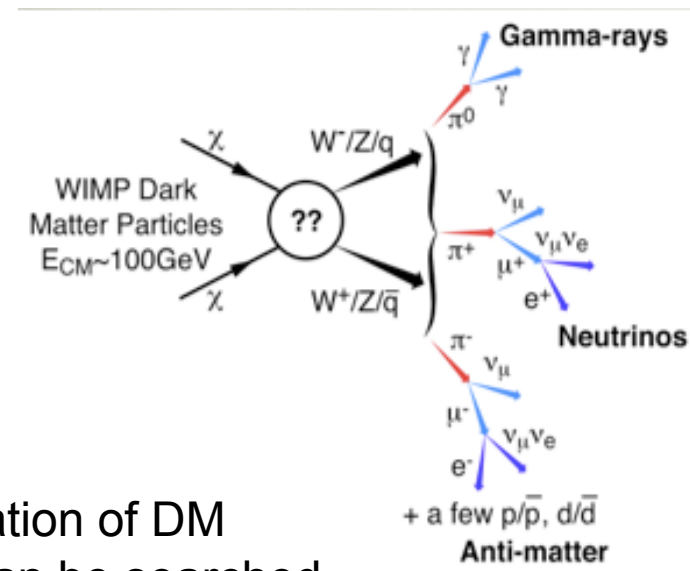
- **Light curves (with tabulated peak phases), spectral fits, log N-log S**

Searches for Dark Matter

- Searches for signals from DM annihilation or decay are a principal science driver of the Fermi mission
- Sensitivity depends on **long integration times** as well as **detailed understanding of the LAT** and **detailed knowledge of the astrophysical foregrounds**



Decay or annihilation of DM particles signal can be searched for in gamma-rays (and electrons)



Many places to look!

Galactic Center

Good statistics but source confusion/diffuse background

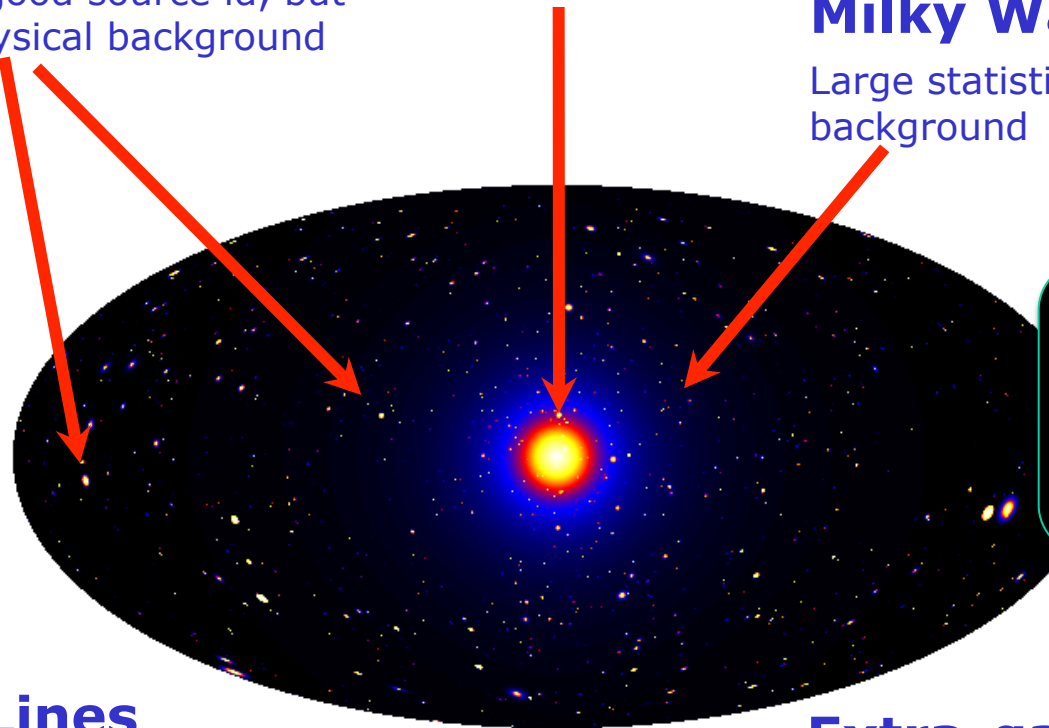
Satellites & Clusters

Low background and good source id, but low statistics, astrophysical background

Milky Way Halo

Large statistics but diffuse background

All-sky map of simulated gamma ray signal from DM annihilation (Baltz 2006)



Dark Matter sources can also produce features in the local Cosmic Ray Electron spectrum

Spectral Lines

No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR

Extra-galactic

Large statistics, but astrophysics, galactic diffuse background

Many places to look!

Galactic Center

Good statistics but source confusion/diffuse background

Satellites & Clusters

“Observations of Milky Way Dwarf Spheroidal galaxies with the Fermi-LAT detector and constraints on Dark Matter models” (ApJ 2010)

“Direct constraints on minimal supersymmetry from Fermi-LAT observations of the dwarf galaxy Segue 1” (JCAP 2010)

“Constraints on Dark Matter Annihilation in Clusters of Galaxies with the Fermi Large Area Telescope” (JCAP submitted)

Milky Way Halo

Large statistics but diffuse background

Dark Matter sources can also produce features in the local Cosmic Ray Electron spectrum

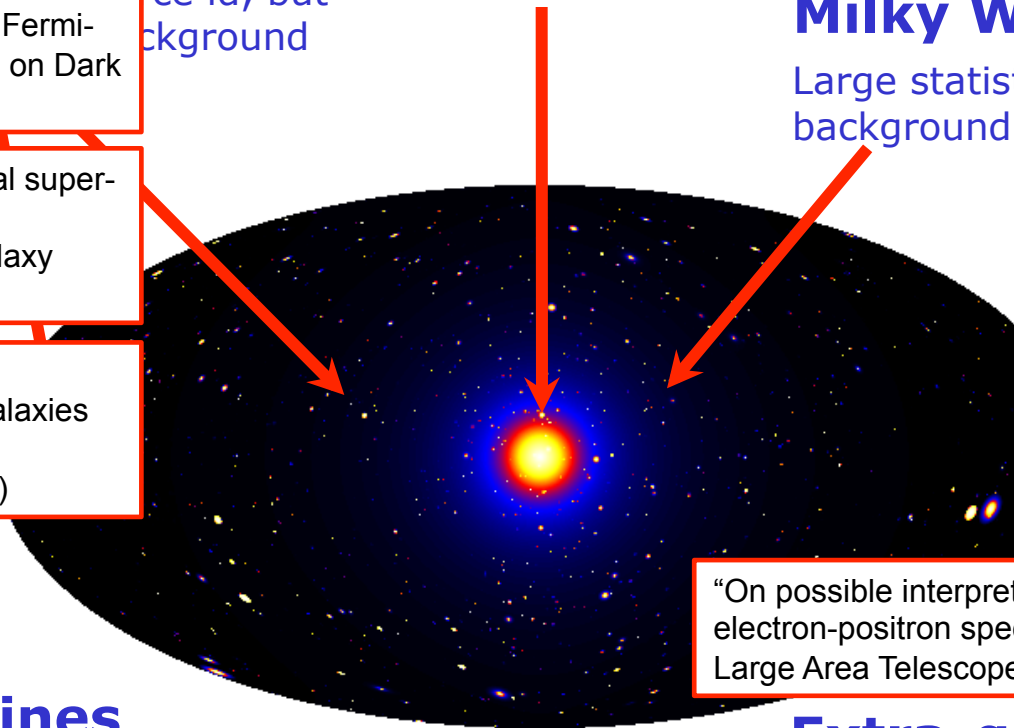
“On possible interpretations of the high energy electron-positron spectrum measured by the Fermi Large Area Telescope” (Astropart. Phys 2009)

Spectral Lines

“Fermi LAT Search for Photon Lines from 30 to 200 GeV and Dark Matter Implications” (PRL 2010)

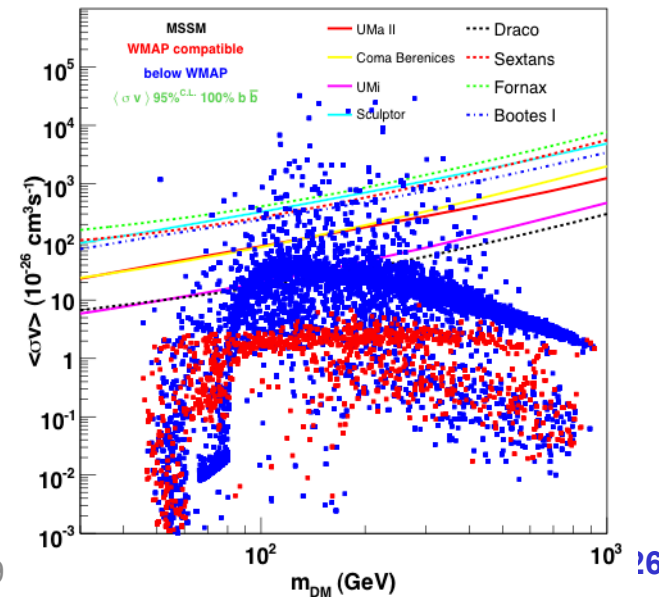
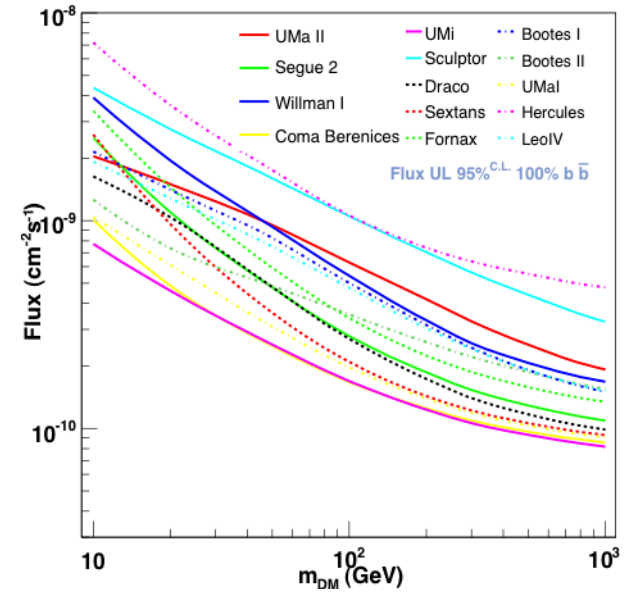
Extra-galactic

“Constraints on Cosmological Dark Matter Annihilation from the Fermi-LAT Isotropic Diffuse Gamma-Ray Measurement” (submitted to JCAP)



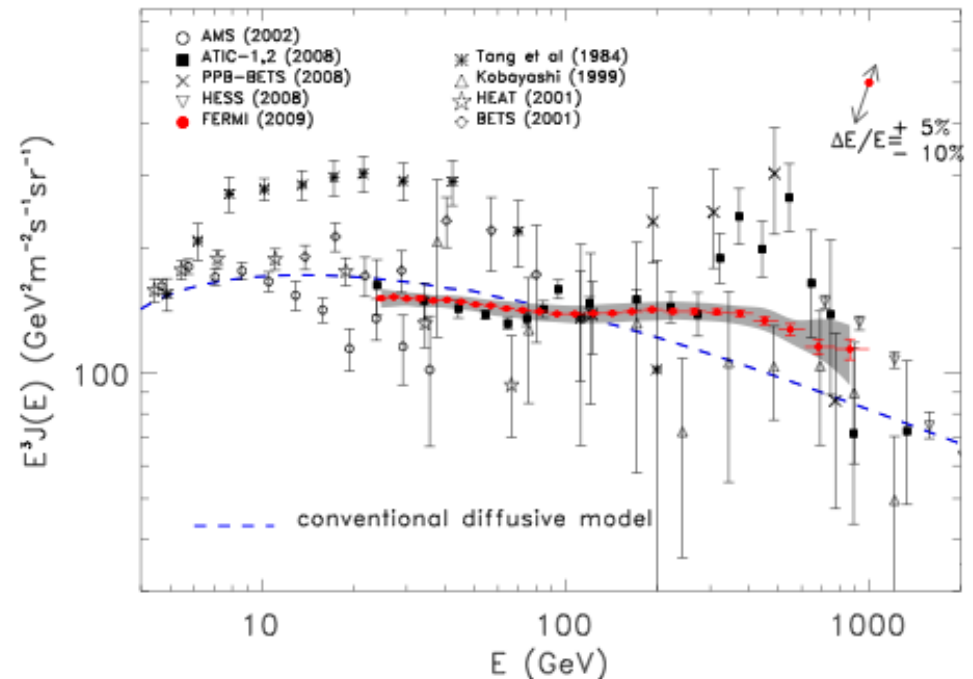
Example from Study of Dwarf Spheroidals

- Flux upper limits for an assumed final state (here $b\bar{b}$) and DM particle mass can be related to cross section limits for that channel
- Here the limits for different dwarf spheroidals span a large range owing to differences in J (los integral of square of mass density) and brightness of diffuse background

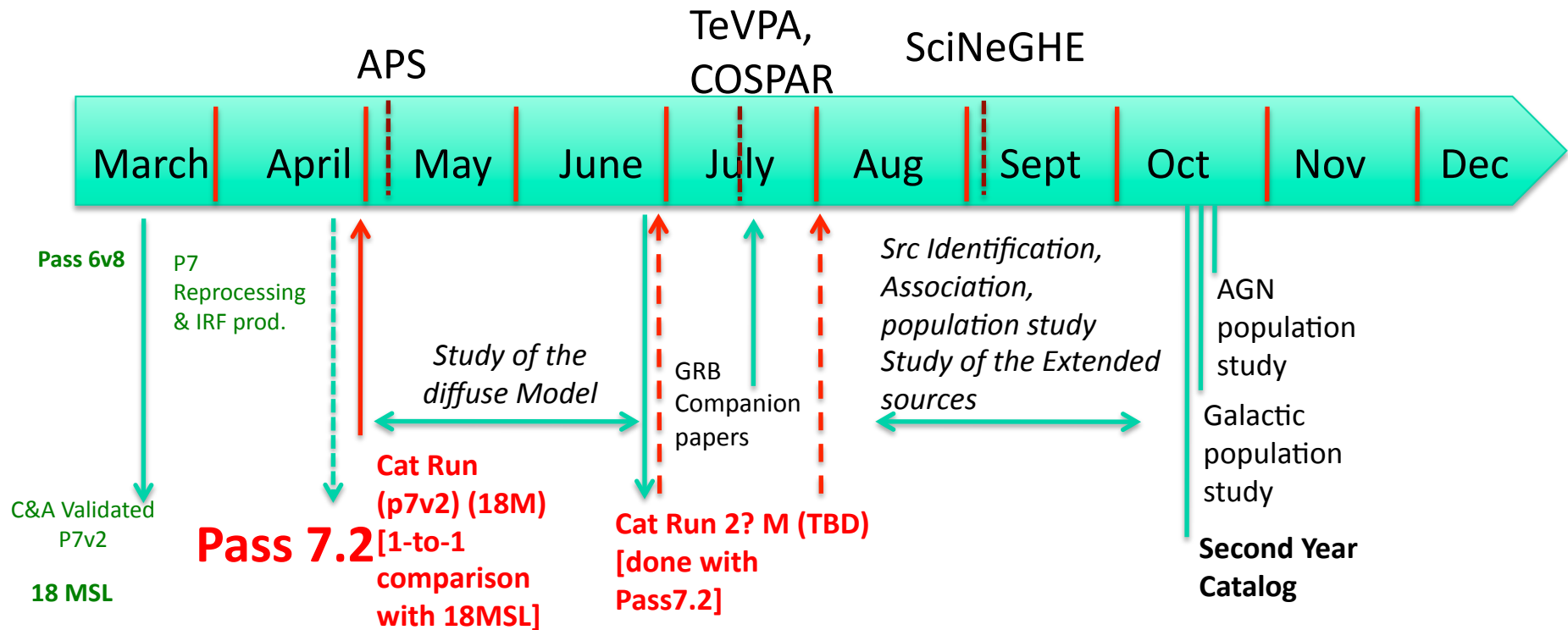


On Cosmic-Ray Electrons

- The acceptance and livetime of the LAT are vast relative to cosmic-ray experiments
 - The data acquisition system accepts all events that deposit more than 20 GeV
 - A dedicated analysis for classifying electrons and evaluating the LAT response was developed
- The LAT spectrum of CR electrons (+ positrons) has some structure but does not have the prominent bump reported by ATIC (which prompted DM interpretations)
- This is by far our most cited paper (268); follow-up works extending the spectrum to lower energies and evaluating the isotropy are far along



Science Timeline for Year 2

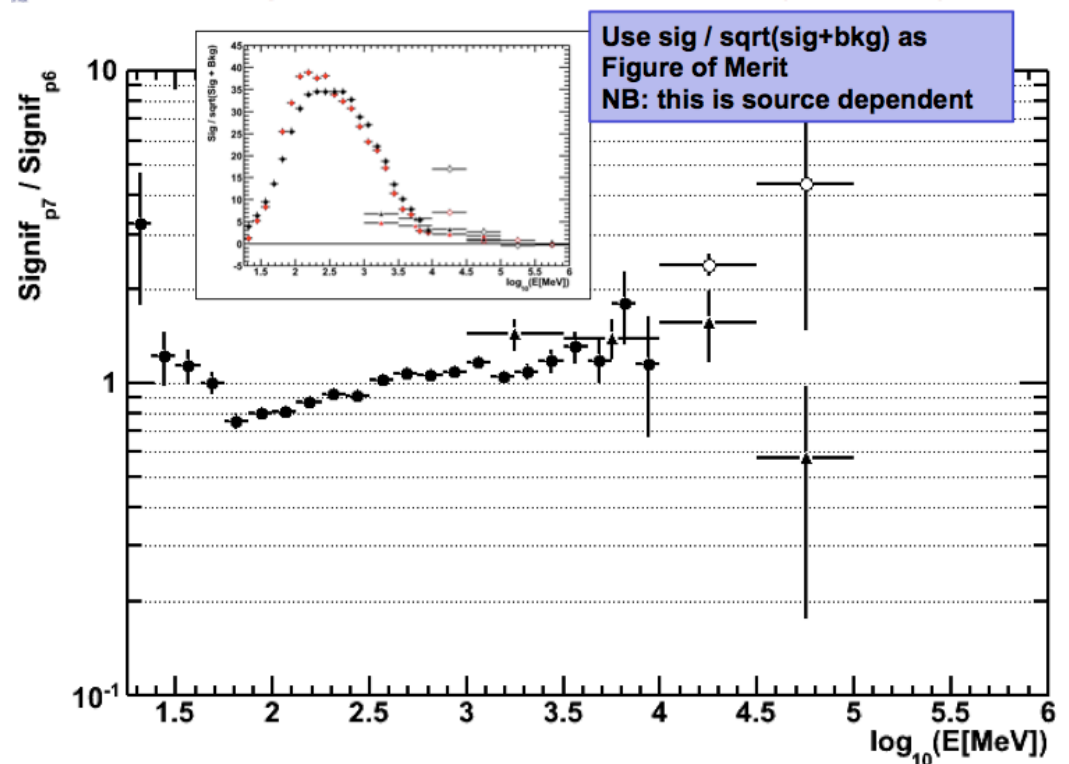


- **Some milestones are common for all of the science working groups**
 - **Pass 7.2 adoption (validation analyses, generation of IRFs, re-evaluation of high-energy PSF in flight data, Pass 7 reprocessing**
 - **18M, 2FGL Catalog runs**
 - **Diffuse emission model (gll_iem_v03)**

Pass 7: Moving Toward a New Classification

- Pass 7 represents the new standard of Fermi LAT analysis
- Significant increase of the effective area <100 MeV and at high energy relative to Pass 6 for the standard classes
- New event classes are also available in Pass 7
 - E.g., S3, ExtraDiffuse
- Looking ahead: Pass 8 is being developed (starting with fundamental improvements in tracking and energy assignment by taking into account ‘ghosts’ at the reconstruction level)
- A meeting on Pass 8 is planned in Pisa later this spring

Sensitivity relative to Pass 6



Snapshot of the Science Working Groups

~Now During Year 2

| Catalog | 6M, BSL | 1FGL | 18MSL Identif. Unid | 2FGL |
|------------------|---------------------|---|---|--------------------|
| C&A | P6V1 | P6V3 | P6V8 | PASS7 |
| DIFFUSE | !GeVExcess | <i>gll_iem_v02.fit</i> | “Reconciliation” with GALPROP Galactic Center | New model? |
| AGN | LBS | 1LAC AGN Population Galaxy Clusters | EBL study | AGN related |
| Galactic | Blind Search MSP | Pulsar Catalog | Galactic Center | Populations |
| GRB | Bright GRBs | Bright GRBs | UL paper LAT GRB Catalog | |
| DM&NP | | DM Galaxy Clusters Lines, Dwarfs | Galactic Center | New UL’s? |
| Solar | Steady Sun, Moon | Steady Sun, Moon | Steady Sun, Moon | First Solar Flare? |

Conclusions

- **Organizationally, the 8 collaboration science working groups are inter-connected via **common needs, cross-group membership, and collaboration service work*****
- **The collaboration has been effective in publishing papers, including a number of “high-impact” and catalog works, and the rate of publication has not plateaued**
- **Year 2 science is building on the advances during Year 1**

*** Dedicated coordination at the working group lead level – for conference contributions, proposal preparation, plots for release, standards for high-level analysis – has also helped to make the collaboration cohesive**



Backup slides

Population Protocol Results

Table 8. Results from Application of the Population Protocol

| Test Population | N_p | b | C | CP | P | (CP < P)? | CL |
|----------------------------------|-------|-------|-----|-----------------------|----------------------|-----------|-----------|
| Galactic Populations | | | | | | | |
| Pulsars | 215 | 1.440 | 30 | 5.3×10^{-29} | 1.0×10^{-9} | yes | > 99.999% |
| Millisecond Pulsars | 23 | 0.050 | 7 | 1.5×10^{-13} | 1.0×10^{-8} | yes | 99.89% |
| EGRET SNRs | 23 | 1.590 | 13 | 1.5×10^{-8} | 1.0×10^{-8} | no | ... |
| TeV SNRs | 4 | 0.920 | 3 | 6.6×10^{-2} | 9.9×10^{-7} | no | ... |
| Magnetars | 13 | 0.120 | 0 | ... | 9.9×10^{-7} | ... | ... |
| WR-binaries | 41 | 0.260 | 0 | ... | 9.9×10^{-7} | ... | ... |
| MQ/ γ -ray bin. | 17 | 0.140 | 3 | 4.1×10^{-4} | 9.9×10^{-7} | no | ... |
| Binary pulsars | 10 | 0.040 | 0 | ... | 9.9×10^{-7} | ... | ... |
| Globular clusters | 29 | 0.240 | 4 | 1.1×10^{-4} | 9.9×10^{-7} | no | ... |
| Extragalactic Populations | | | | | | | |
| Blazars | 215 | 0.480 | 61 | 0.0 | 1.0×10^{-9} | yes | > 99.999% |
| Misaligned jet sources | 53 | 0.150 | 5 | 5.5×10^{-7} | 9.9×10^{-7} | yes | 99.25% |
| Starbursts | 15 | 0.050 | 4 | 2.5×10^{-7} | 9.9×10^{-7} | yes | 97.89% |
| Galaxy clusters | 48 | 0.150 | 0 | ... | 9.9×10^{-7} | ... | ... |
| Dwarf spheriodals | 18 | 0.070 | 0 | ... | 9.9×10^{-7} | ... | ... |

Source Associations in 1FGL

Table 6. LAT 1FGL Source Classes

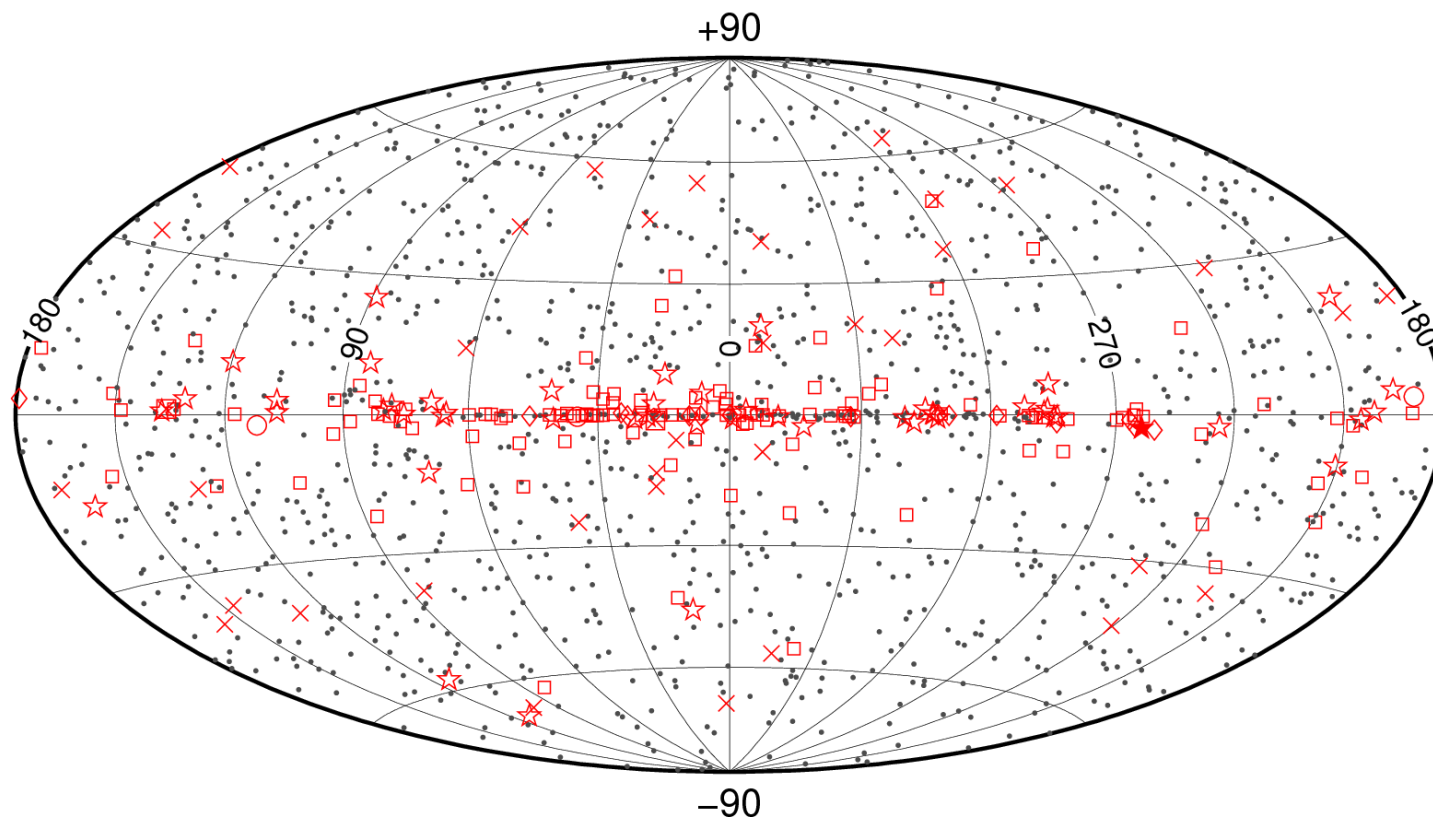
| Description | Designator | Number Assoc. (ID) |
|---|------------|--------------------|
| Pulsar, X-ray or radio, identified by pulsations | psr (PSR) | 7 (56) |
| Pulsar, radio quiet (LAT PSR, <i>subset of above</i>) | PSR | 24 |
| Pulsar wind nebula | pwn (PWN) | 2 (3) |
| Supernova remnant | † (SNR) | 41 (3) |
| Globular Cluster | glc (GLC) | 8 (0) |
| Micro-quasar object: X-ray binary (black hole or neutron star) with radio jet | mqq (MQO) | 0 (1) |
| Other X-ray binary | hxb (HXB) | 0 (2) |
| BL Lac type of blazar | bzb (BZB) | 295 (0) |
| FSRQ type of blazar | bzq (BZQ) | 274 (4) |
| Non-blazar active galaxy | agn (AGN) | 28 (0) |
| Active galaxy of uncertain type | agu (AGU) | 92 (0) |
| Normal galaxy | gal (GAL) | 6 (0) |
| Starburst galaxy | sbg (SBG) | 2 (0) |
| Unassociated | | 630 * |



Note. — The designation ‘†’ indicates potential association with SNR or PWN (see Table 7). Designations shown in capital letters are firm identifications; lower case letters indicate associations. In the case of AGN, many of the associations have high confidence (Abdo et al. 2010). Among the pulsars, those with names beginning with LAT were discovered with the LAT. For the normal galaxy class, 5 of the associations are with the Large Magellanic Cloud. In the FITS version of the 1FGL catalog, the † designator is replaced with ‘spp’; see Appendix D.

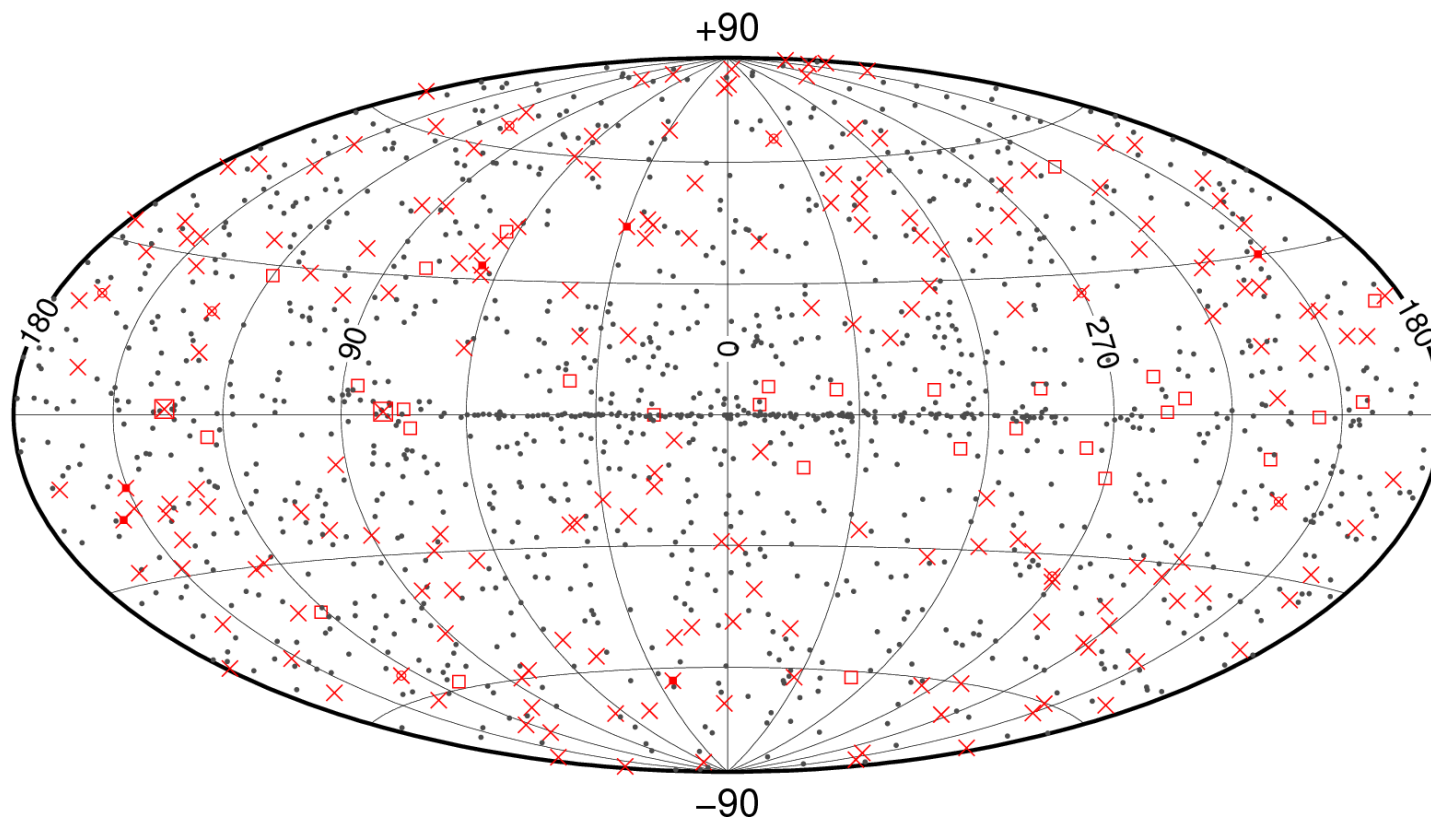
* Lower-confidence AGN associations and ‘affiliations’ are listed in 1LAC

Sources with Large 'Curvature Index'



| | | |
|-----------------|-----------------|--------------------|
| □ Unassociated | × AGN – blazar | × AGN – unknown |
| ◇ Potential SNR | * Starburst Gal | × AGN – non blazar |
| ☆ Pulsar | ★ Pulsar w/PWN | + Galaxy |
| ○ SNR | ⊠ XRB or MQO | △ Globular cluster |

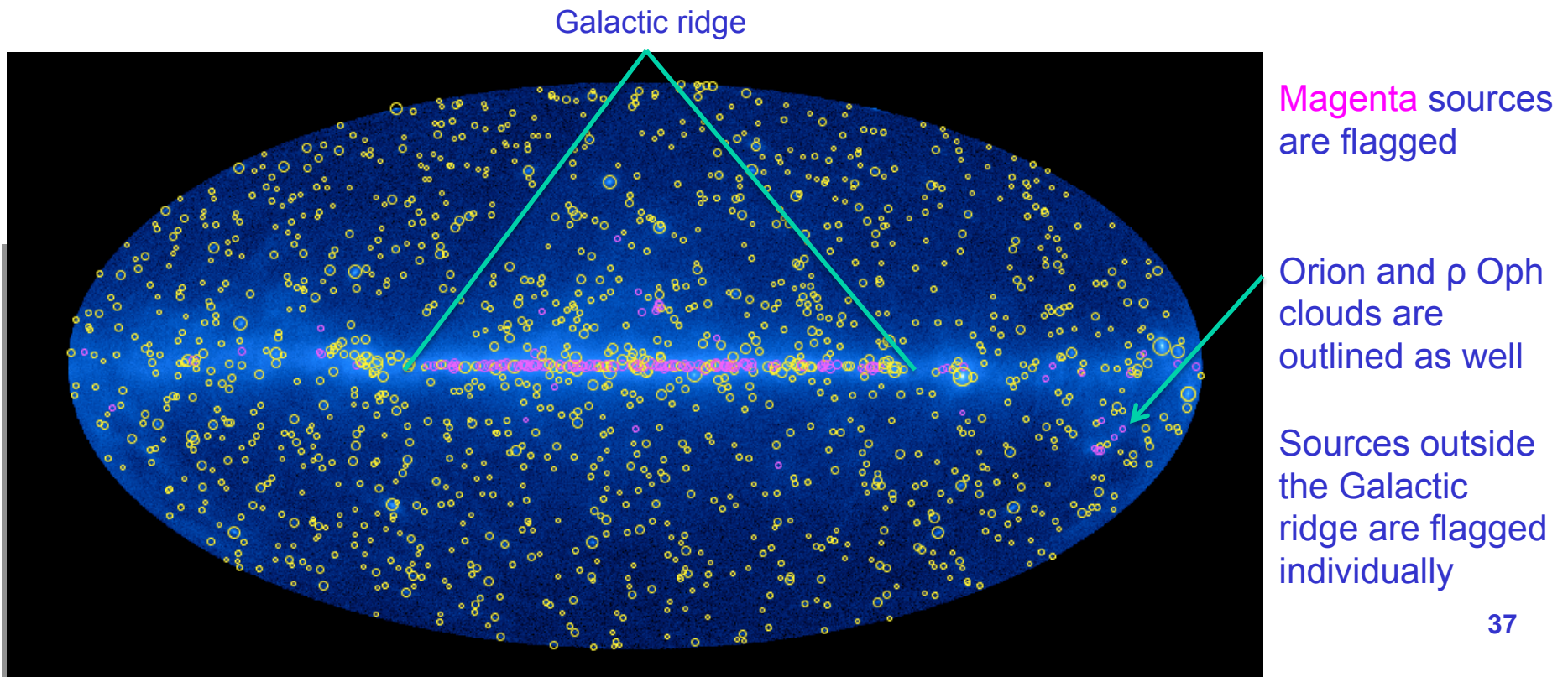
Sources with Large Variability Index



| | | |
|-----------------|-----------------|--------------------|
| □ Unassociated | × AGN – blazar | × AGN – unknown |
| ◇ Potential SNR | * Starburst Gal | × AGN – non blazar |
| ☆ Pulsar | ★ Pulsar w/PWN | + Galaxy |
| ○ SNR | ⊠ XRB or MQO | △ Globular cluster |

1FGL Quality Flags

- In the Galactic ridge and toward prominent interstellar clouds, source density is high, sources are not bright above the background <3 GeV, and the Galactic diffuse model has uncertainties on small scales
 - 161 sources (all unidentified) have ‘c’ designation, cautioning against relying on them without detailed analysis
- 10 0FGL sources in the ridge are not associated with 1FGL sources (moved or were replaced with a combination of sources in 1FGL)



Source Populations and Source Association

- Both **Population protocol** and **Source-by-source association**
- For **Population protocol**: before launch we defined representative (physically motivated) members of each of a number of source classes, and a simple definition of source association, and the budget for association probabilities
 - Has some challenges in application – needing to guess correctly about representative members of classes in terms of detectability; separability of populations (a 1FGL source lining up with a representative SNR could be LAT pulsar)
- The **Source association*** is like calibrated cross correlation between catalogs – the goal being quantitative probabilities of association and to controlled false association rate
 - For 1FGL we adopted $P = 0.8$ threshold

* Association \neq Identification (which requires, e.g., correlated variability, finite angular extent)

C&A current and future activities

- **“Pass 7.2”, the new classification**
 - **“Retraining” of the analysis, based on Monte Carlo with overlay**
 - **New Classification of the events, defining new classes for analysis**
 - **Big improvements expected, less background contamination**
- **Further off: “Pass 8”**
 - **This is a long time project**
 - **Rewrite partially the reconstruction, considering overlays events**
- **Improvement of the Monte Carlo**
- **New Background model, based on observation**