γ-ray catalogs and unidentified sources

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LAT collaboration

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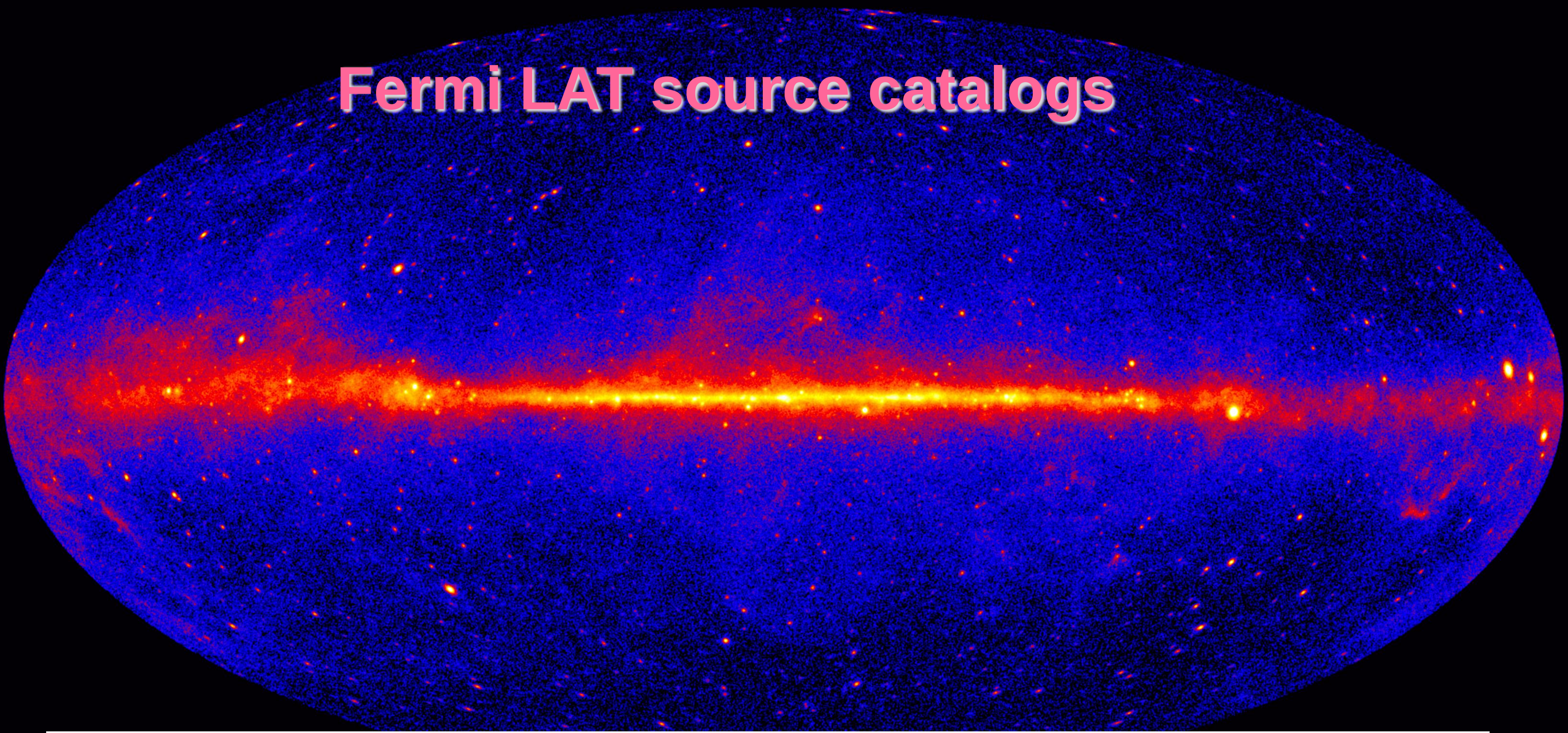
Fermi LAT source catalogs



Concentrate on **persistent** sources (not GRBs, novae)

- 0/1/2/3FGL: full energy range (> 100 MeV)
- 1/2/3FHL: high-energy only (> 10 / 50 GeV)
- Dedicated catalogs: AGN (0/1/2/3LAC), PSR (1/2PC), SNR

Each generation has used **improved data/calibration**: P6 → P7 → P7Rep → P8

The main LAT source catalog: 3FGL

Acero et al 2015, ApJS **218**, 23: **4 years** of Front/Back **P7Rep** data > 100 MeV

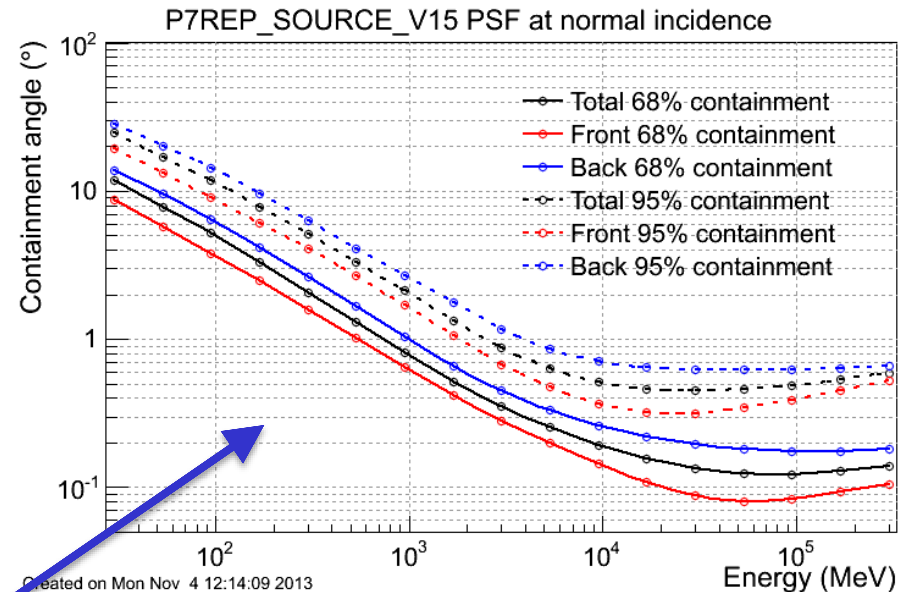
3D maximum likelihood (x,y,E) over RoIs paving the sky.

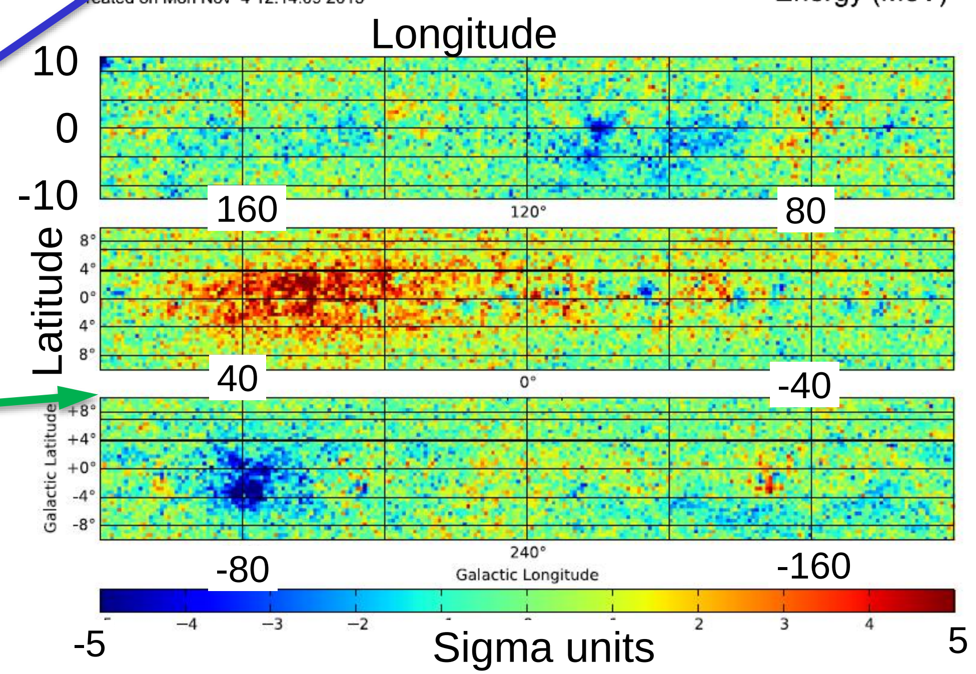
Point sources on top of isotropic, interstellar model and individual extended sources

Catalog reports position, significance, association, basic SED and light curve

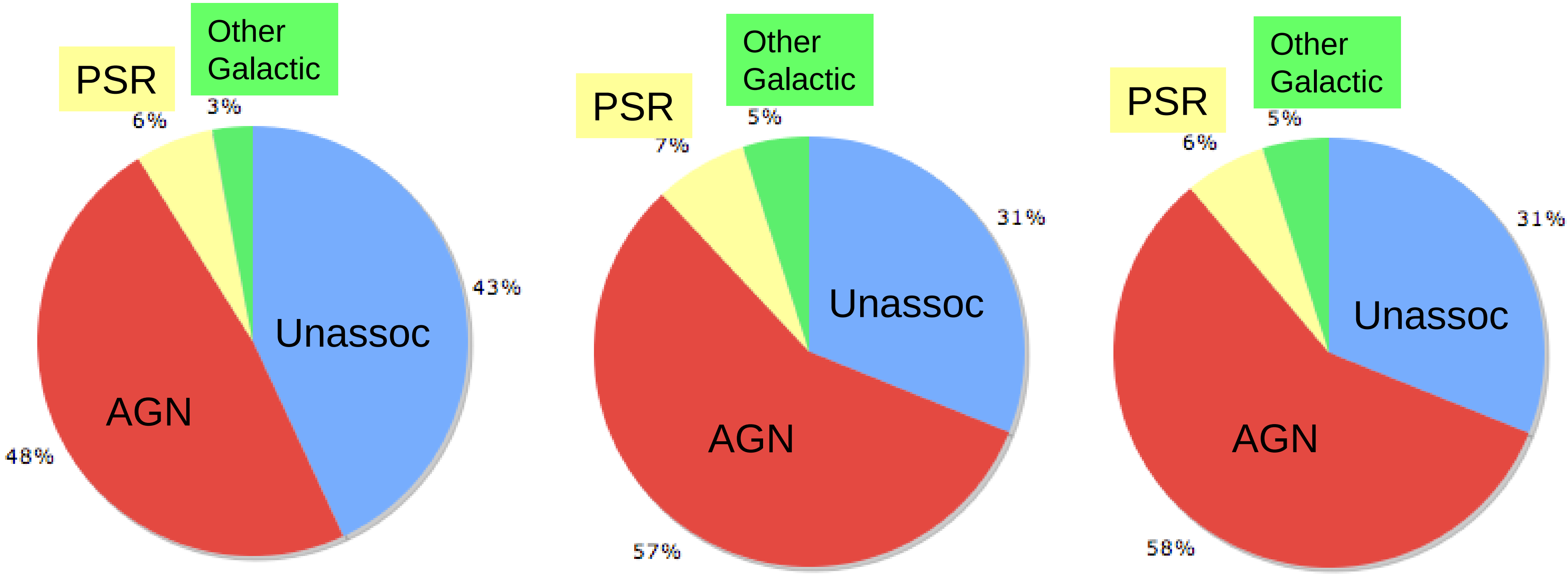
Confusion is strong at low energy (average angular separation is 2.2° outside Galactic plane)

Interstellar emission model (Acero et al 2016, ApJS **223**, 26) is not perfect. **Residuals** are small (2 – 3%) but impact sources at the same level as statistical errors over the whole Galactic plane.





Source association



1FGL (1451 sources)

2FGL (1873 sources)

3FGL (3033 sources)

Numbers as written in the original paper (have gone down since then)

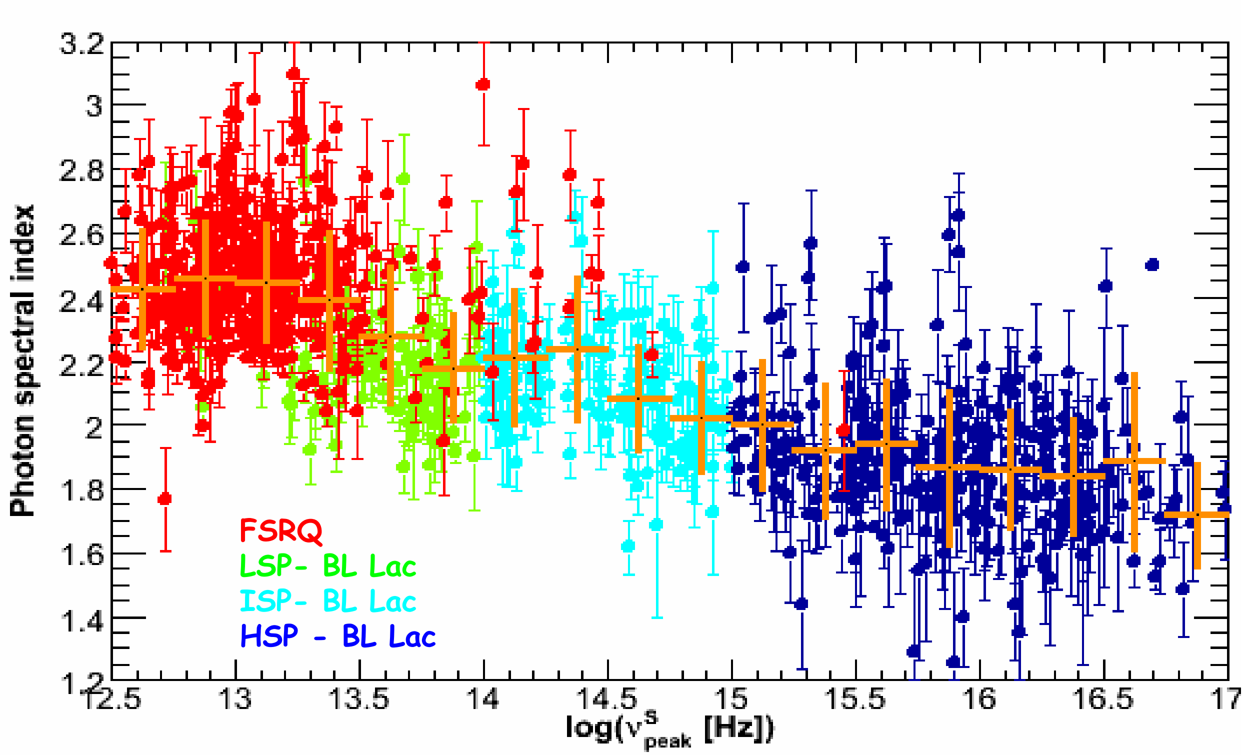
Similar fraction of associated sources in 3FGL as in 2FGL, thanks to ongoing effort on deepening counterpart catalogs

Main source types

3LAC (Ackermann et al 2015, ApJ **810**, 14): 1591 **AGN** from 3FGL

Nearly flux-limited sample in terms of **energy flux** over full band

Follows nicely **blazar sequence**, from luminous faraway FSRQs to less luminous nearby HSP BL Lacs



Pulsars (2PC: Abdo et al 2013, ApJS **208**, 17); now 205 detected (93 MSPs)

SNRs (Acero et al 2016, ApJS **224**, 8): 30 detections of radio SNRs

Beyond 3FGL

Look at unassociated sources

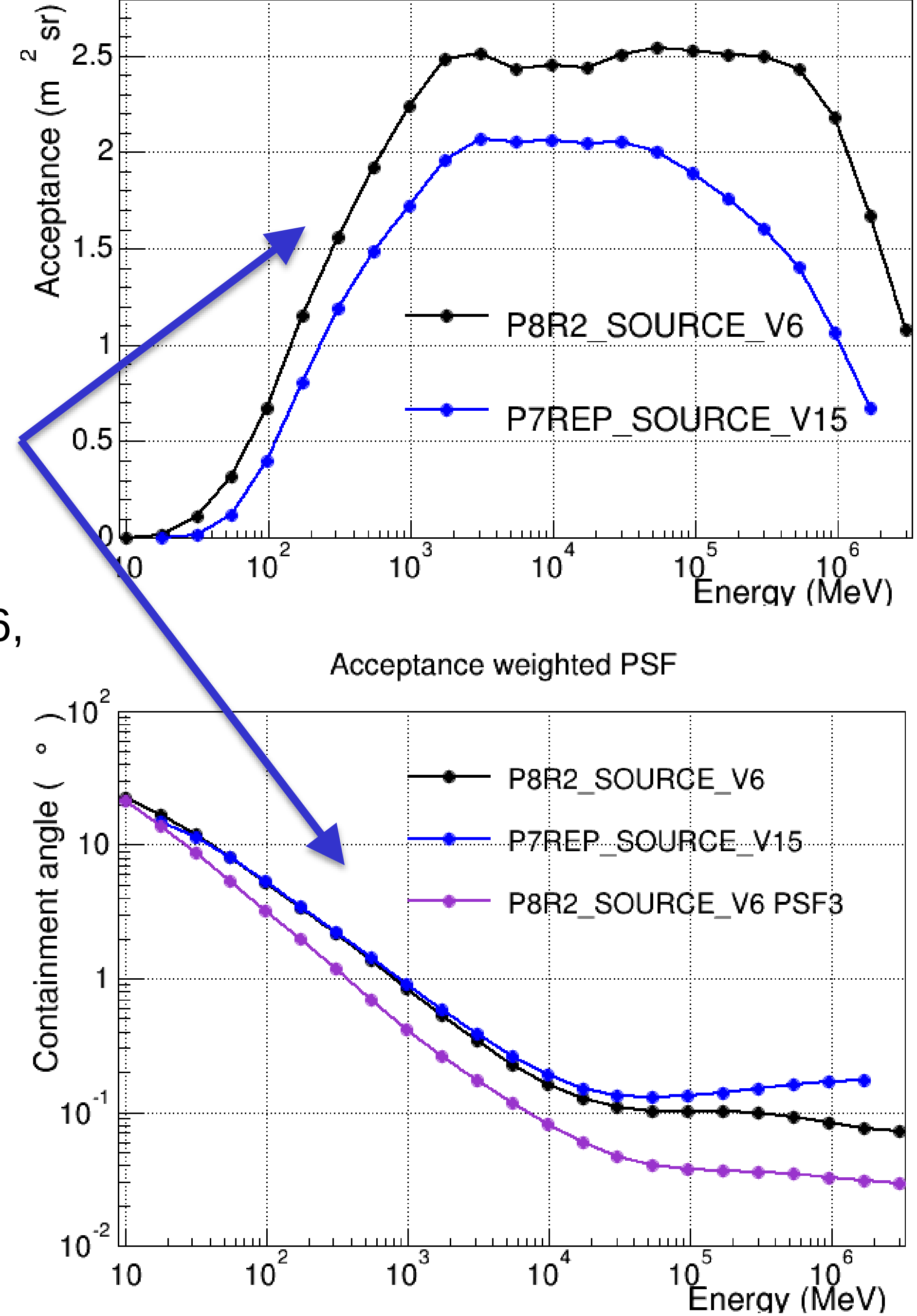
Deeper and better data/calibration (**Pass8**)

Start with highest energies (360 sources in 2FHL at E > 50 GeV: Ackermann et al 2016, ApJS **222**, 5)

Go down to initial FHL energy range (> 10 GeV): 3FHL

Look for variable sources

Confront full energy range (> 100 MeV): 4FGL



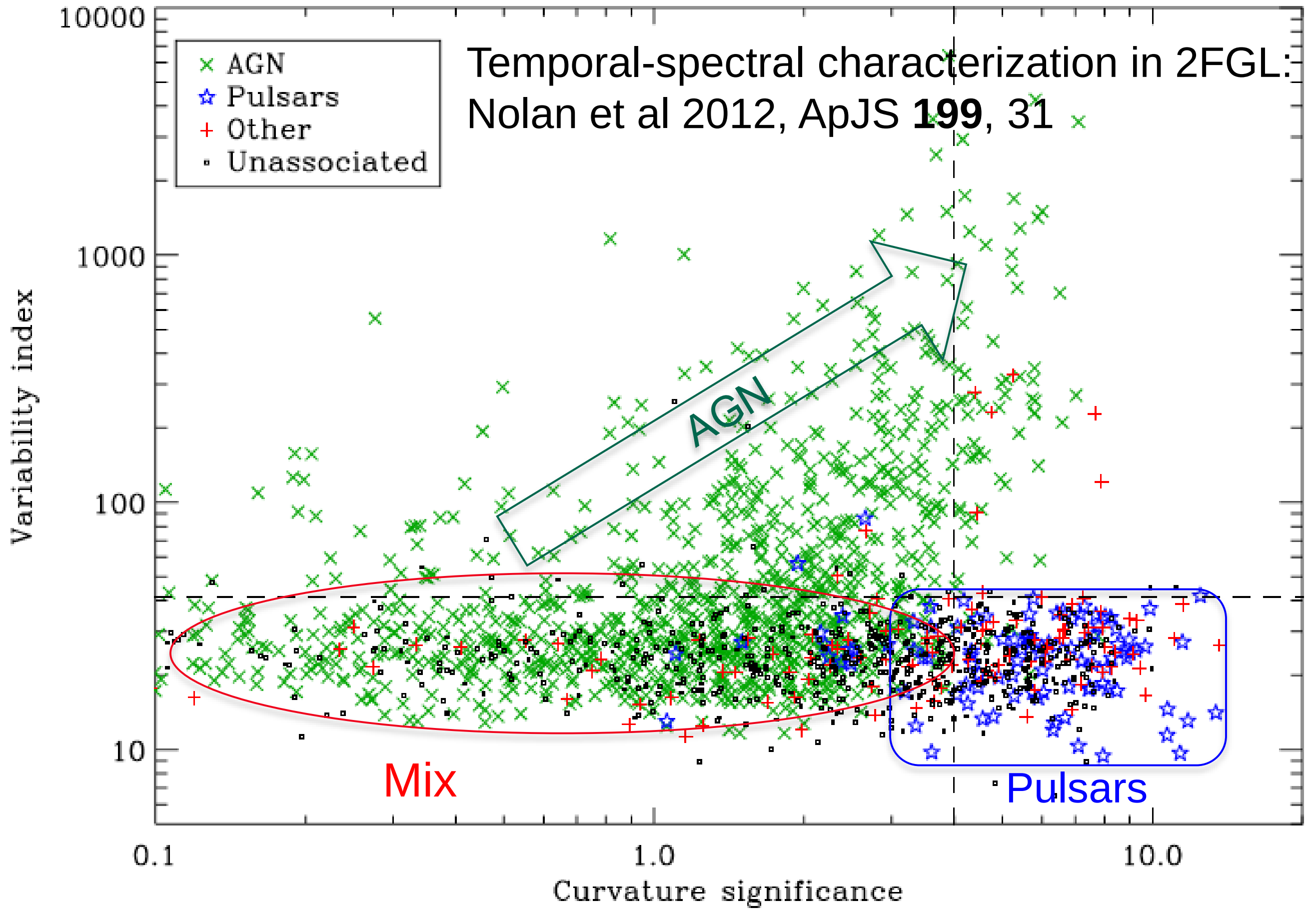
Statistical assessment of UNIDs

Concentrate MW efforts on what is most promising

Use all γ–ray information (particularly variability, spectral curvature) to feed **classification algorithms**, learning from known associations

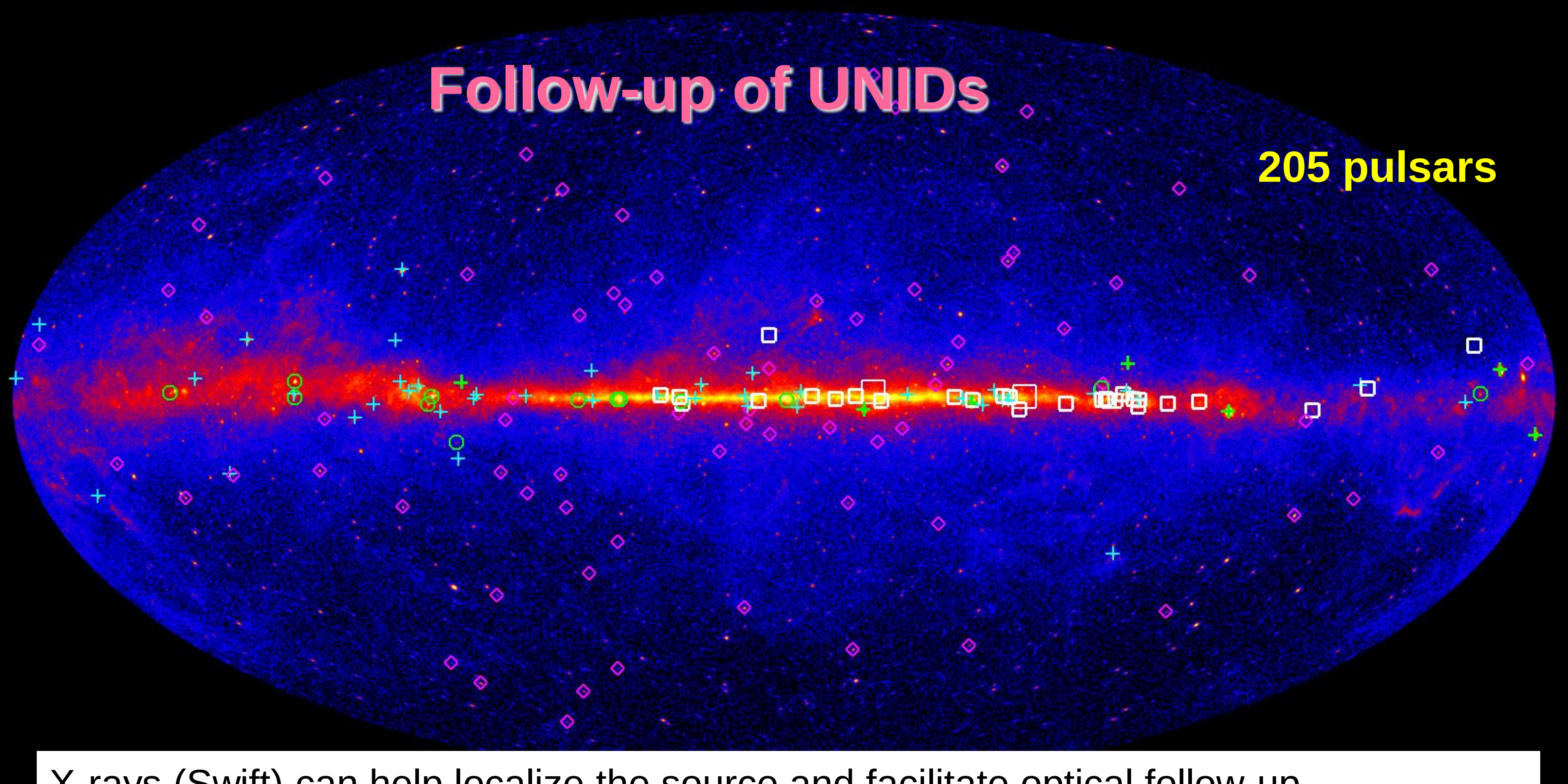
Logistic regression, classification trees, random forest

Difficulty: Training sample (brighter) has smaller error bars than most UNIDs



Particularly used to single out **PSR candidates** (minority) against **AGN**

eg Saz-Parkinson et al 2016 (ApJ **820**, 8): rather surprising conclusion that hundreds of unassociated 3FGL sources might be pulsars



X-rays (Swift) can help localize the source and facilitate optical follow-up

AGN: optical/IR colors, spectroscopy: 39 blazars found on top of LAT UNIDs

Pulsars: radio searches and pure γ timing: > 20 PSR found on top of 3FGL UNIDs

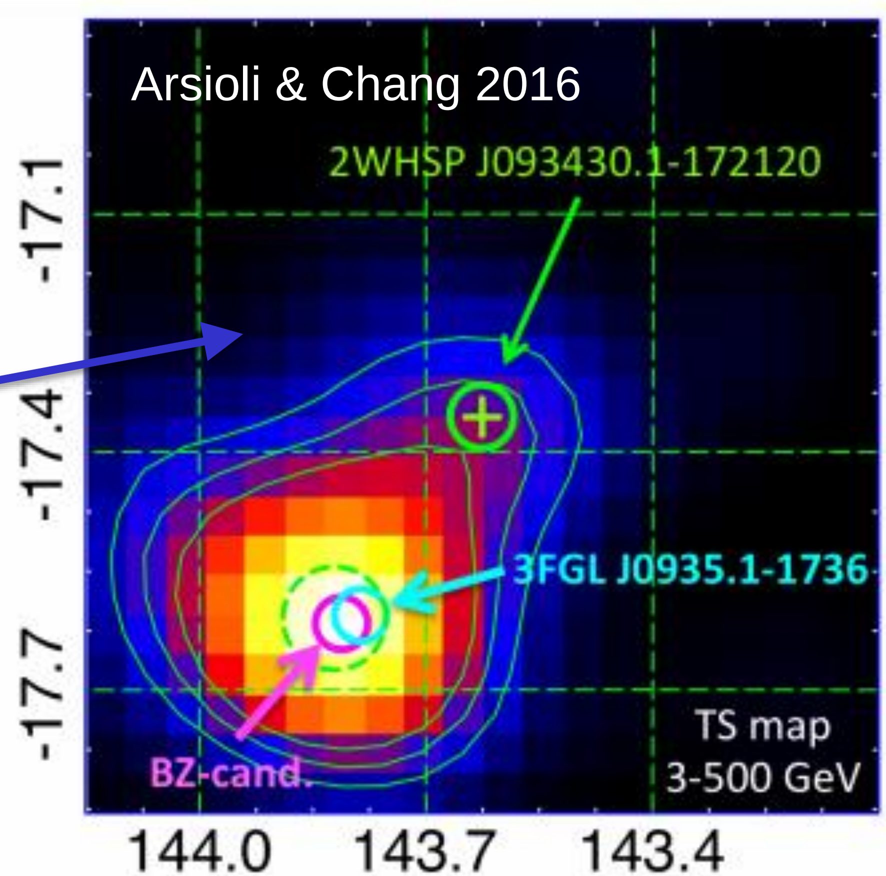
Binaries: search for hour/day periods: 1 more since 3FGL (in LMC)

clusters of UNIDs in Galactic plane → **extended** sources; 25 in 3FGL, about 50 now

Starting from counterparts

Look for signal in LAT data corresponding to particular source classes

- **PSRs**: phase-folding on radio ephemeris
- **SNRs**: Green's radio catalog
- **Blazars**: check potential confusion between soft FSRQ and hard better localized BL Lac; look for rare subclasses
- **Magnetars**: none found yet, too much confusion
- **Galaxy clusters**: none found yet
- **Dwarf MW satellites:** for dark matter, none found yet)



Looking for variable sources

Fermi All-sky Variability Analysis (Giomi et al, EWASS 2016)

387 **weekly** time bins

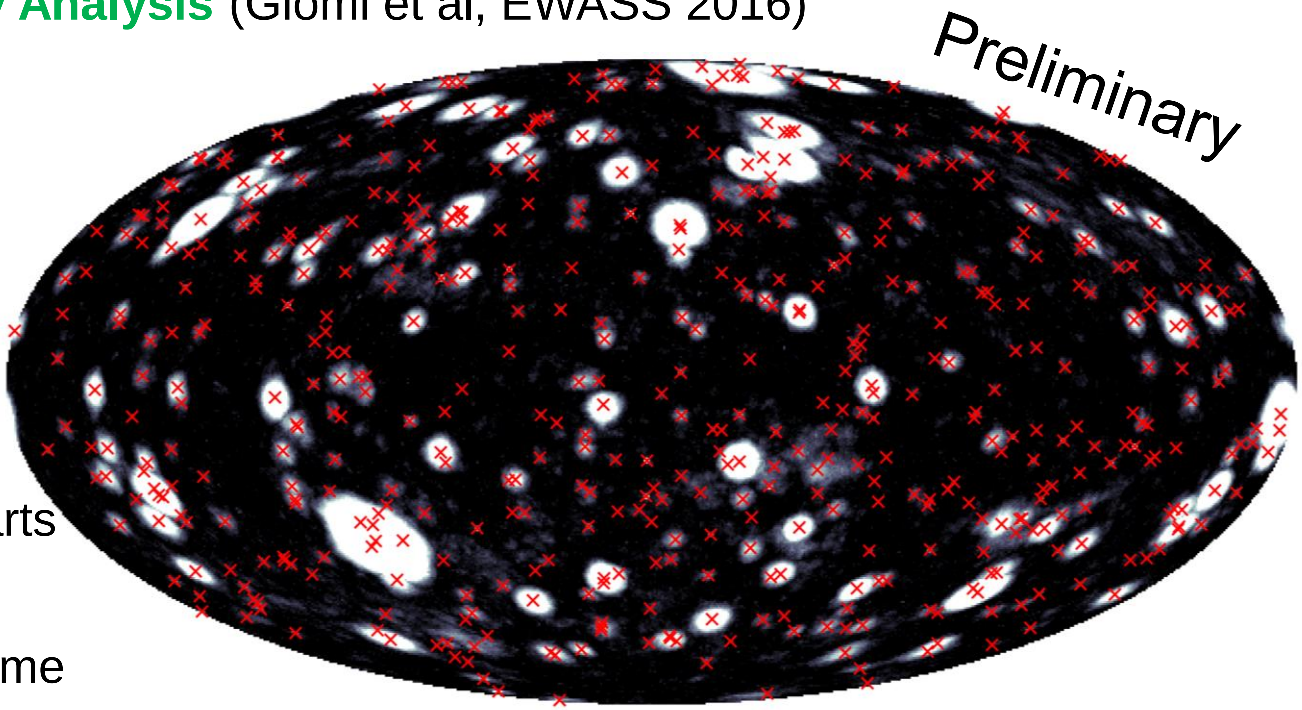
Aperture photometry + likelihood localization

4548 significant flares

519 flaring sources

441 have clear counterparts (89% AGN), 78 don’t

On-line at GSFC in real time

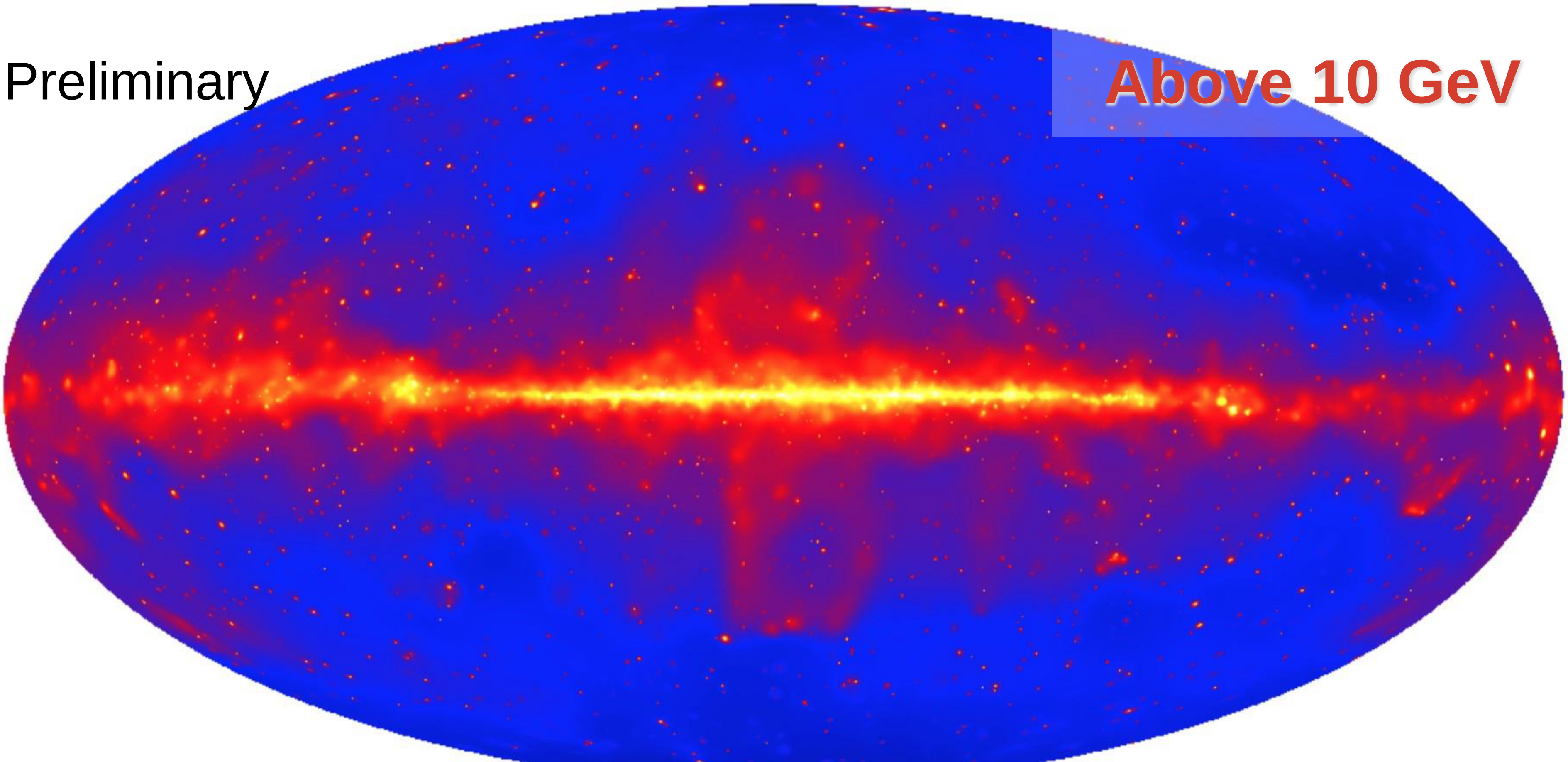


Monthly time bins (Burnett et al, Fermi symposium 2015)

PGWave/TSmap source search, likelihood analysis

Simulations to quantify spurious detections

Associations with blazar catalogs



Much simpler analysis

Many fewer events (700,000)

Galactic diffuse emission not as dominant, except in Ridge

Fermi bubbles

3FHL (7 years)

> 1500 sources

Dominguez et al,
TeVPA 2016

3FHL improvements

Pass 8, 3D likelihood using PSF types

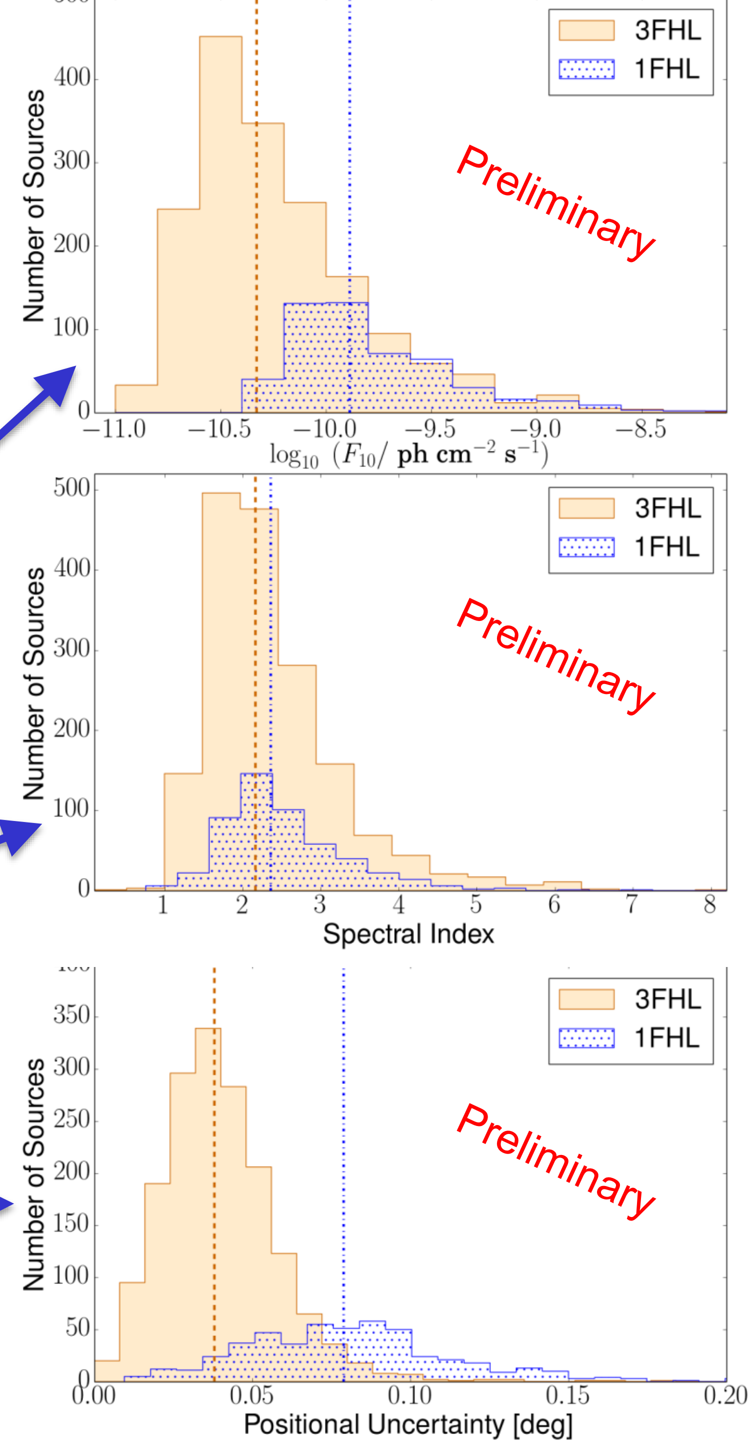
7 years of data

45 extended sources

74% blazars, 7% Galactic, 19% unassoc

3FHL vs 1FHL

- ✓ Three times more sources
- ✓ > 2.5 deeper in **flux**
- ✓ Similar **spectral index**
- ✓ > twice better **localization**; median R95 is 2.34 arcmin

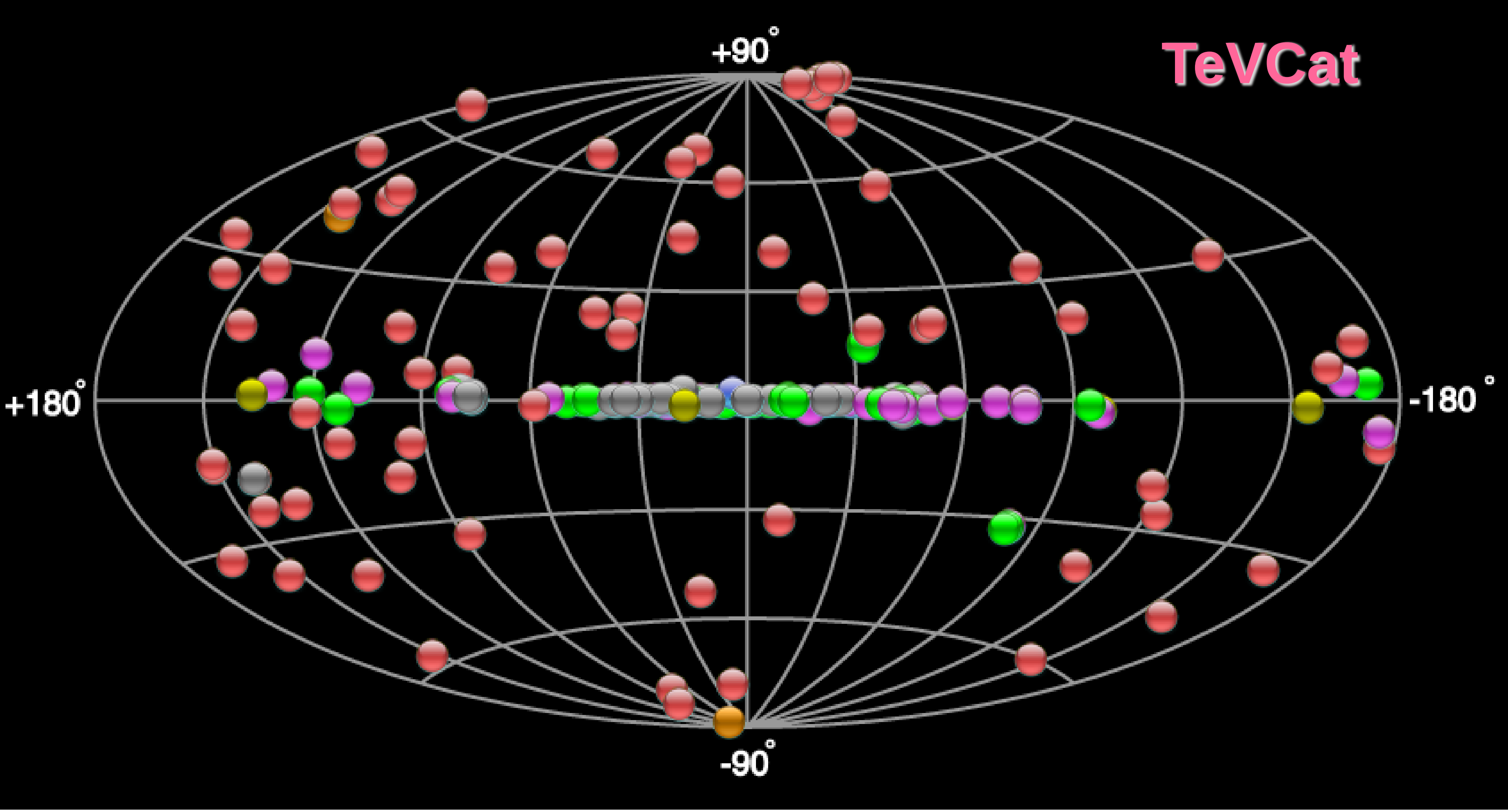


Longer term: 4FGL

- ✓ Update underlying **interstellar emission model**
- ✓ Use PSF event types (as in 3FHL)
- ✓ Keep only **best PSF event types below 1 GeV** to fight confusion and Earth limb contamination
- ✓ Use **logLikelihood weights** to limit statistical precision of the diffuse signal under the PSF to its systematic uncertainty (in order to derive reasonable significances and errors)
- ✓ Try extracting SED point **below 100 MeV** using PSF3; this requires handling energy dispersion
- ✓ Updated catalogs for Bayesian and likelihood ratio **associations**

Probably based on 8 years of data

Aim at releasing 4FGL end 2017

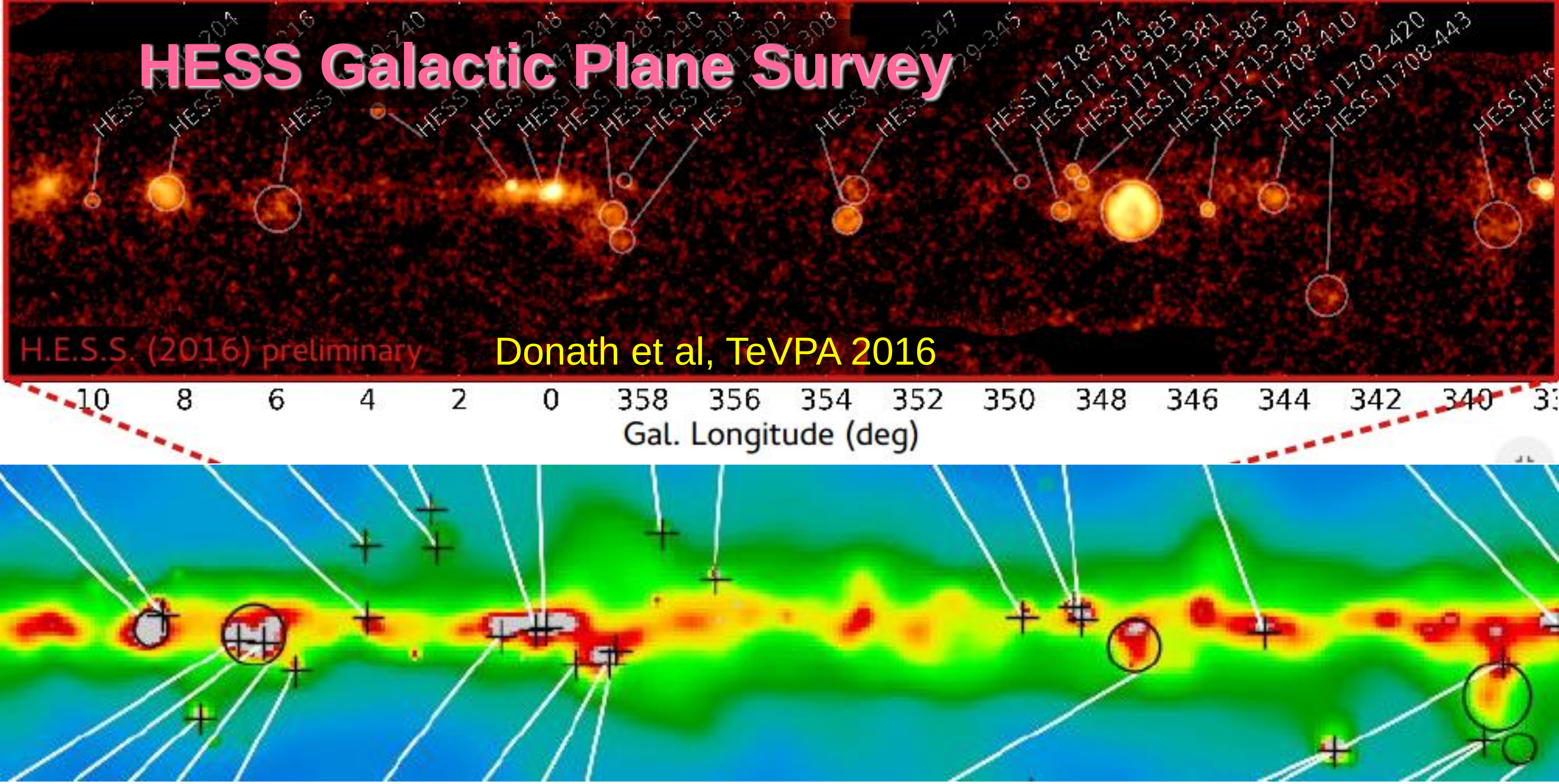


178 entries in TeVCat (http://tevcat.uchicago.edu/), 67 extragalactic

Sparse sky coverage (but HAWC is filling this gap) except in Gal plane

AGN best **detected with Fermi** (soft sources due to EBL attenuation)
but best **studied in TeV** (larger count rate)

HESS Galactic Plane Survey



3FHL (preliminary, > 10 GeV) Dominguez et al, TeVPA 2016

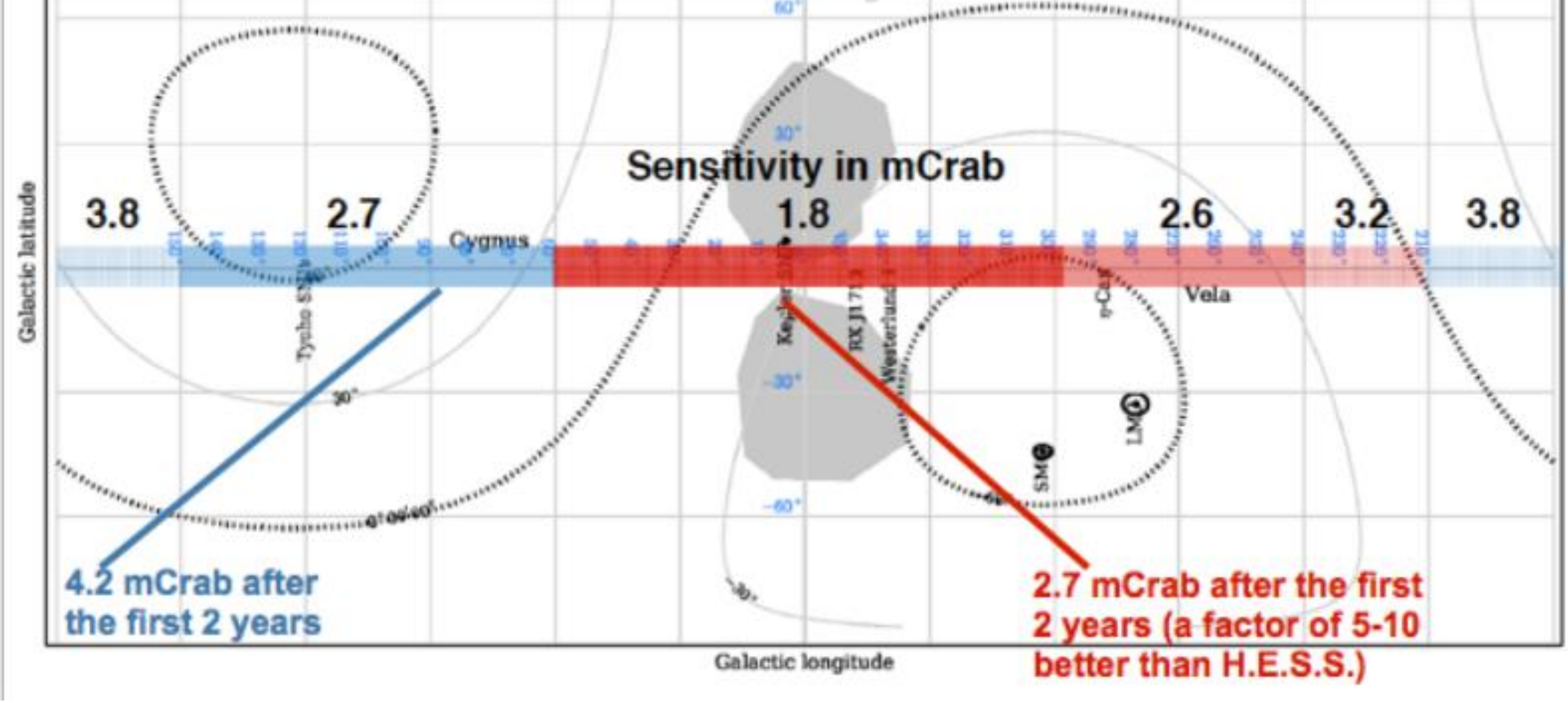
Better resolution and higher stats in HESS Galactic Plane Survey

Most sources **extended**, 60% do not have one obvious MW counterpart

PWN brighter at TeV energies, old SNRs brighter at GeV energies

CTA Galactic Plane Survey

Vercellone et al, Gamma 2016



Better angular resolution than HESS (~ 3 arcmin)

Combines North and South sites, deeper in inner Galaxy

Point-source detection limit around 3 mCrab

Expect 300 – 500 sources, mainly PWNe and SNRs

Superposition of extended sources will be a difficulty

Conclusions

- **Fermi LAT** is a very rich data set
- Main catalog (3FGL) is starting to get out of date
- Finding **counterparts** to UNIDs
- Ongoing routine search for variable sources on daily (flare advocates, ATels) and weekly (FAVA) time scales
- Updated **high-energy catalogs** (> 50 GeV, then > 10 GeV)
- Full 4FGL still more than one year away
- **TeV** catalog not as rich, but growing fast
- TeV particularly valuable in **Galactic plane** where Fermi LAT is limited by confusion and diffuse emission
- **CTA** will find hundreds of sources in the plane

Backup slides

Weighted logLikelihood for *Fermi*

The problem:

- Fermi-LAT data is dominated by imperfectly known diffuse emission
- Point spread function 1° or worse below 1 GeV
- Large counts ➔ systematics dominated at low energy

The proposed solution:

Weighted logLikelihood: $\mathbf{wlog}\mathscr{L} = \sum_i w_i\,(n_i \log M_i - M_i)$

w_i reduces the weight of systematics-dominated areas/energies

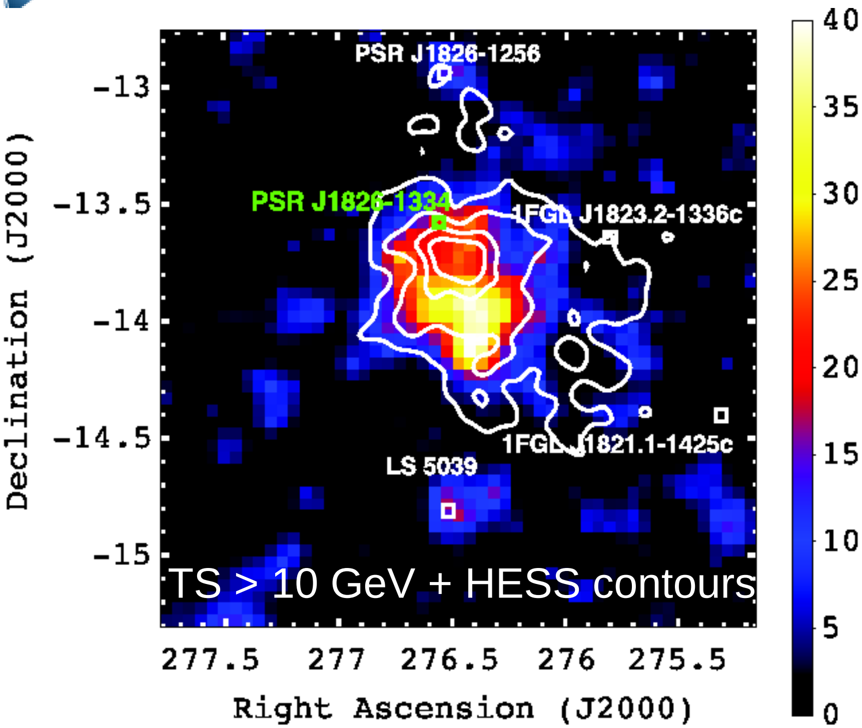
The difficulty: How to define the weights in a proper way

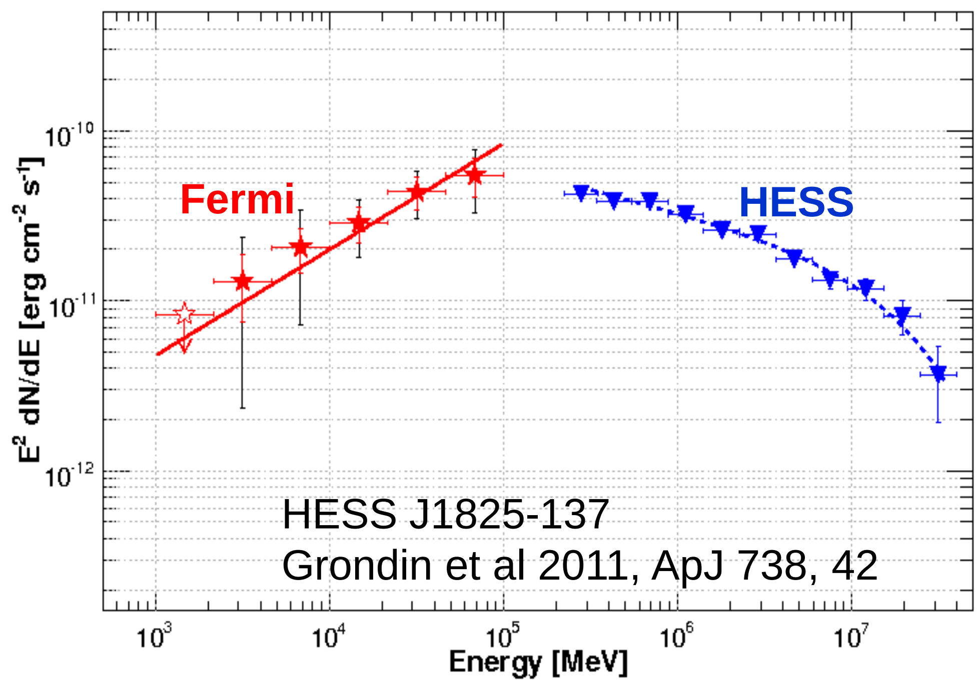
$w_i = \sigma_i^2 / (\sigma_i^2 + \varepsilon^2 B_i^2) = 1 / (1 + \varepsilon^2 B_i)$ where ε = 2 – 3 %

$$B_i = \mathrm{N}(\mathbf{r}_i, E_i) = \int_{E_i}^{E_{\max}} S(\mathbf{r}_i, E)\,dE \text{ and } S(\mathbf{r}, E) = \frac{dB}{dE}(\mathbf{r}, E) \otimes \frac{P(\mathbf{r}, E)}{P(0, E)} \approx \frac{dB}{dE}\,\pi R_{68}^2(E)$$

J. Ballet & T. Burnett, SCMA 2016

Pulsar Wind Nebulae





Special case when the pulsar itself was not detected by Fermi

PWN normally harder to detect on top of bright pulsar, but possible with phase selection or spatial information

30 TeV PWN detected at 10 GeV (Acero et al 2013, ApJ **773**, 77)

PWN remain much easier to detect at TeV than GeV energies

Main help from Fermi in pulsar itself for interpretation (power input)

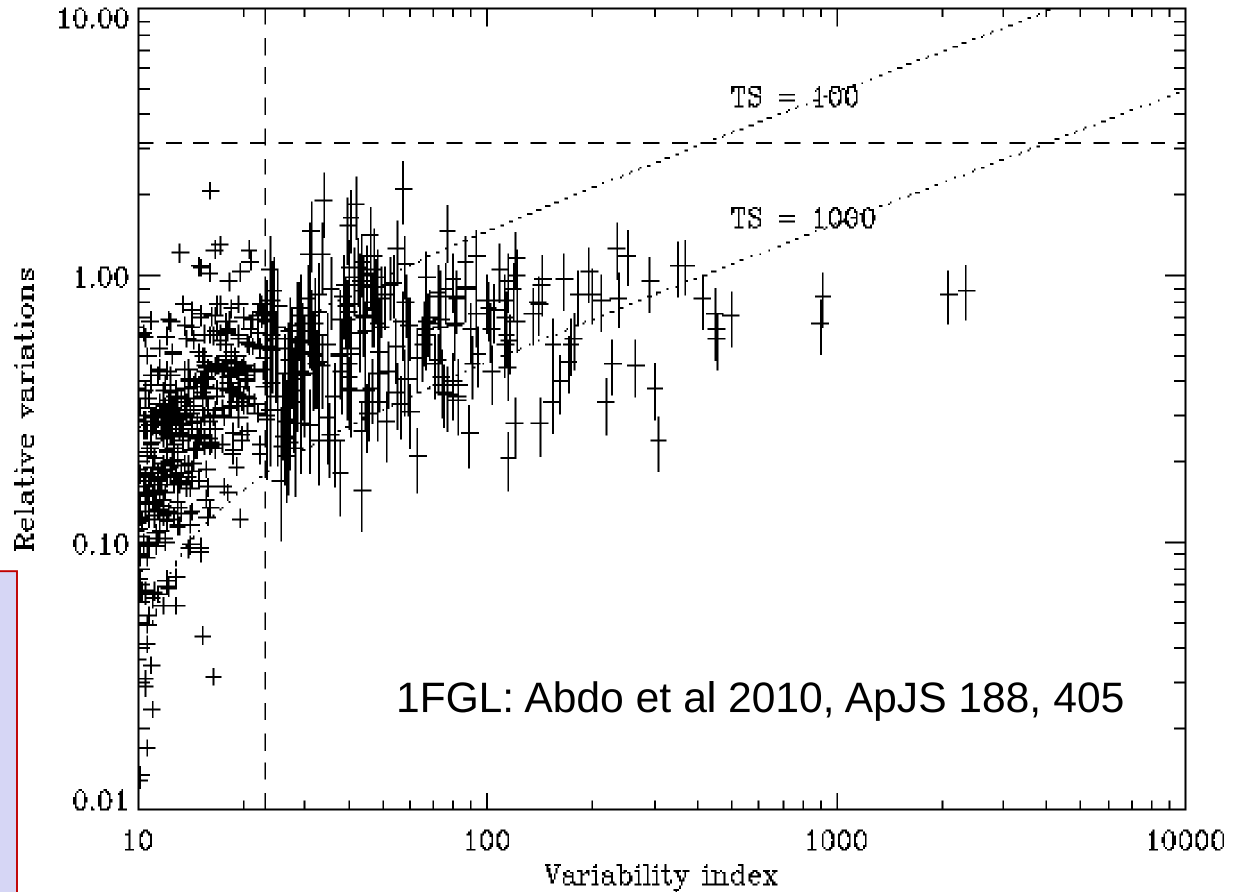
AGN: variability

When variability is detected, **large relative variations**

Fermi can characterize variability on **long time scales** but short time scales not reachable for most sources

TeV instruments can characterize short term (but not long term) variability

GeV and TeV observations are very complementary for statistical studies



1FGL: Abdo et al 2010, ApJS 188, 405

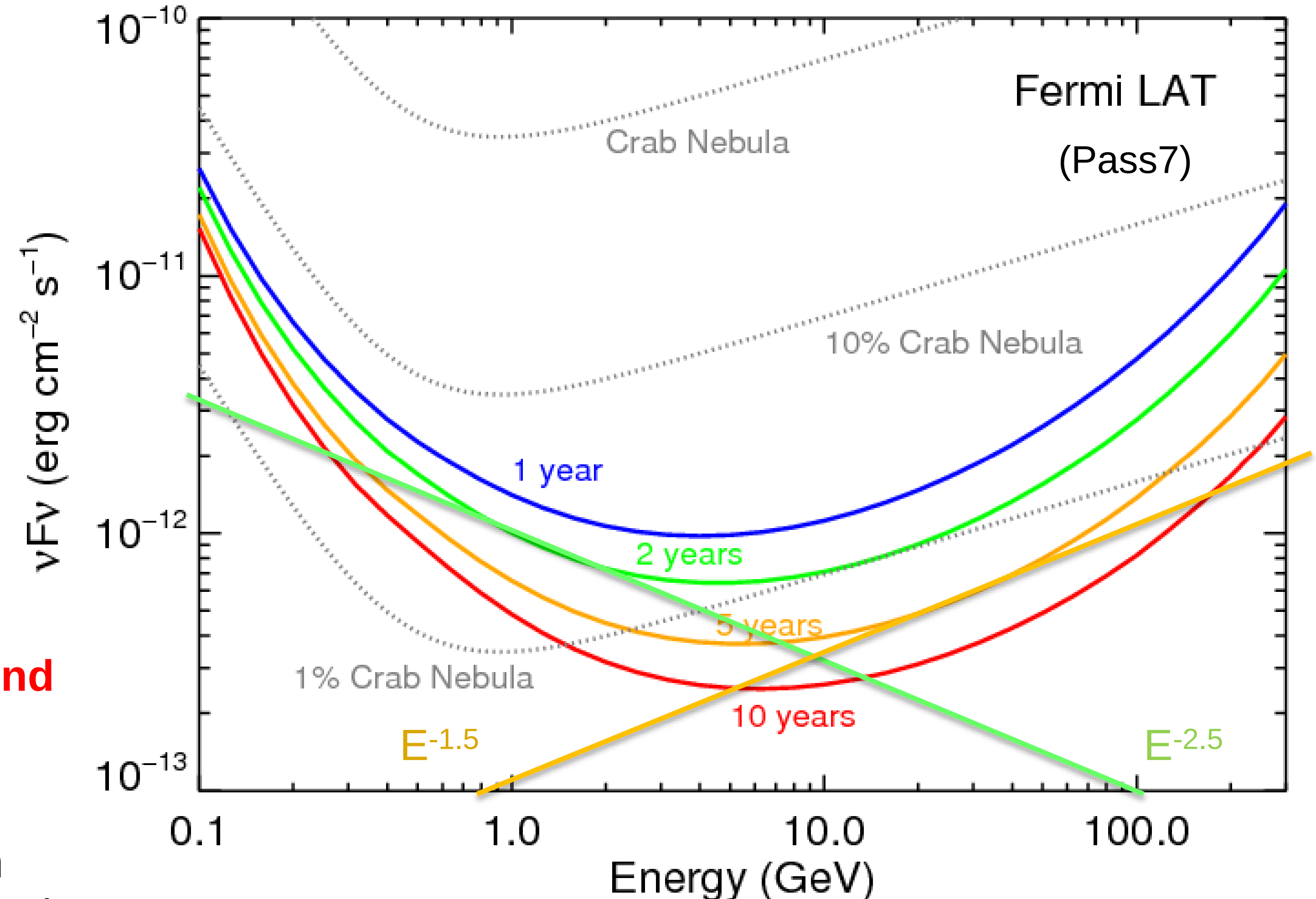
Power-law detection threshold

Fermi Gamma-ray Space Telescope

P7Source_V6

Rocking angle 50°

|Latitude| > 10°



Soft sources limited by:

- Knowledge of **diffuse background** (5% precision)
- **Source density** (extrapolated from measured logN logS)

Hard sources limited by source **count rate**

Detection threshold improves faster than 1 / √t