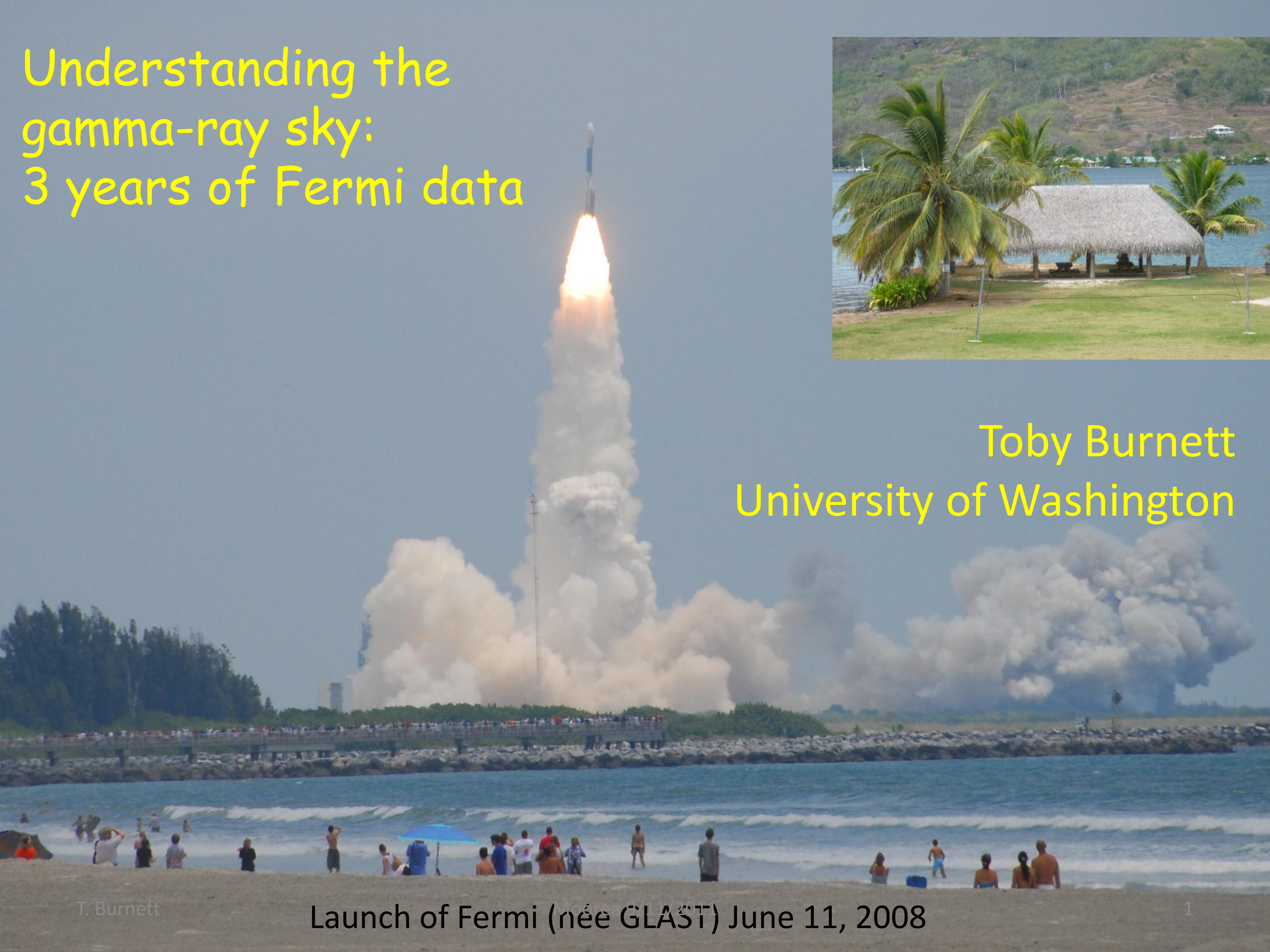
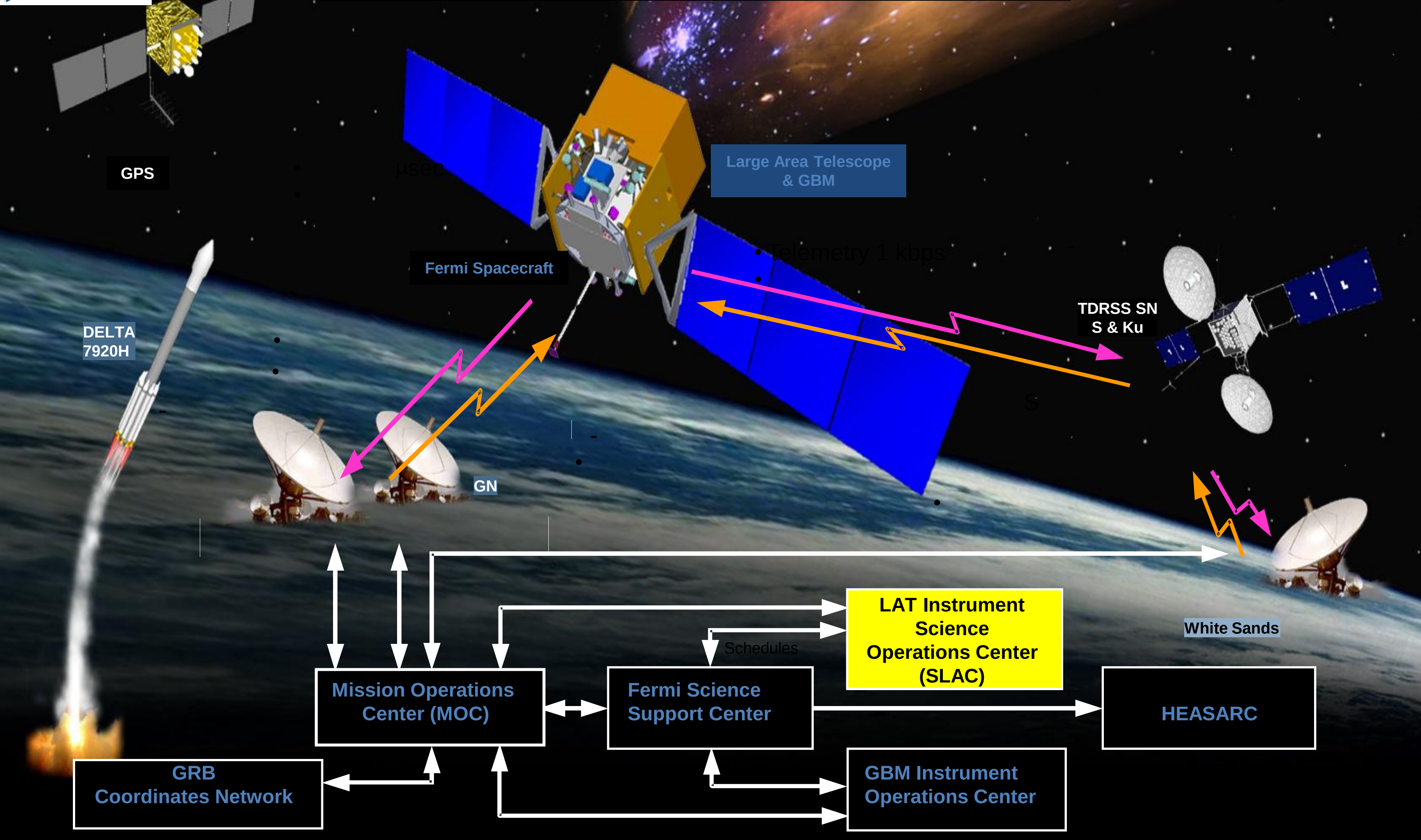
Understanding the gamma-ray sky: 3 years of Fermi data



Toby Burnett
University of Washington

Launch of Fermi (née GLAST) June 11, 2008

Fermi MISSION ELEMENTS



Observation modes

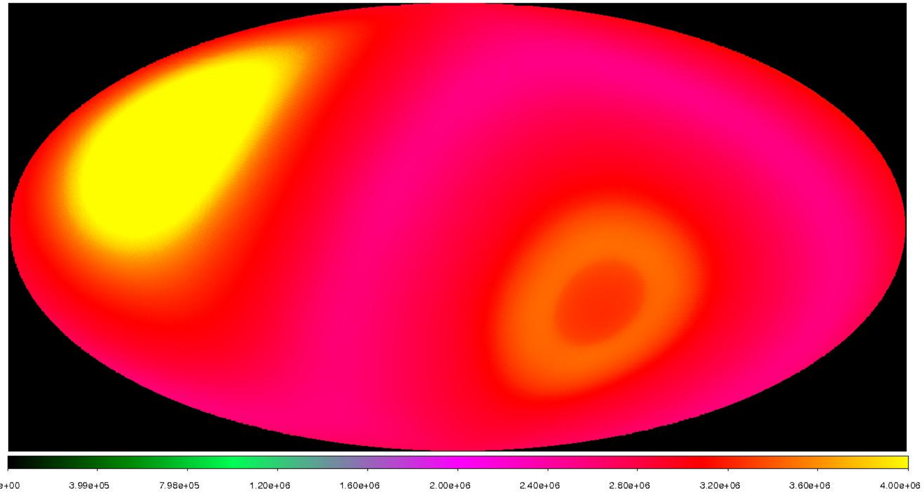
Pointing (traditional telescope)

- Continuous stare, if not obscured
- Otherwise:
  - Follow Earth limb (CGRO strategy)
  - Slew to a secondary point
  - Survey mode
- Recent targets
  - Nadir, to detect TGF events
  - Crab, during flare
  - GC: MW campaign

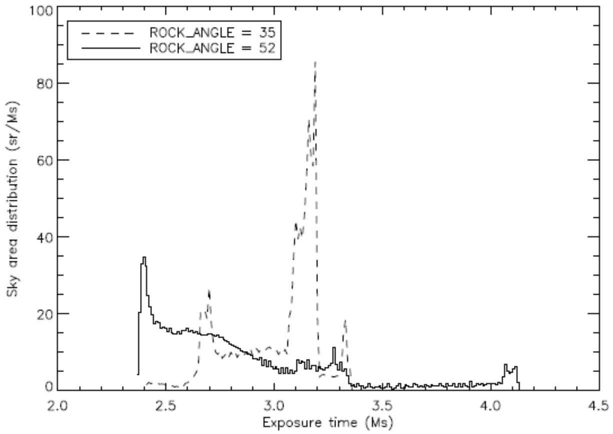
Survey mode – our standard

- Look away from Earth, but rock toward poles to equalize north/south
- Full sky coverage every 3 hours.

2FGL survey mode exposure



Maximum deviation 30%
Note that south pole is less due to South Atlantic Anomaly



Fermi-LAT collaboration

United States
- California State University at Sonoma
- University of California at Santa Cruz - Santa Cruz Institute of Particle Physics
- Goddard Space Flight Center – Laboratory for High Energy Astrophysics
- Naval Research Laboratory
- Ohio State University
- Stanford University (SLAC and HEPL/Physics)
- **University of Washington**

France
- IN2P3, CEA/Saclay

Italy
- INFN, ASI

Japanese GLAST Collaboration
- Hiroshima University
- ISAS/JAXA, RIKEN
- Tokyo Inst of Technology

Spain
- ICREA and Inst de Ciencies de l'Espi

Swedish GLAST Collaboration
- Kalmar University
- Royal Institute of Technology (KTH)
- Stockholm University

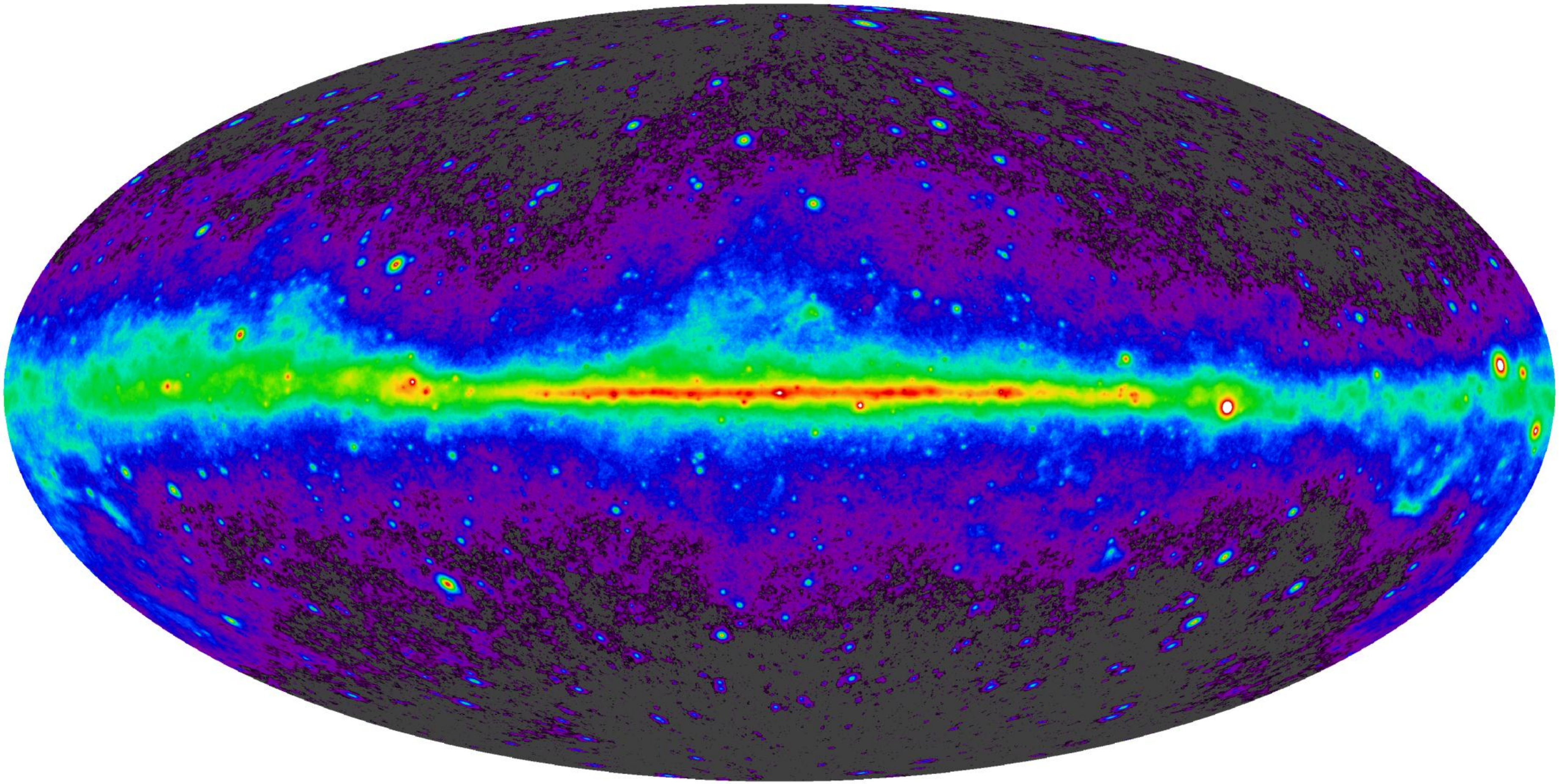
PI: Peter Michelson (Stanford & SLAC)

~270 Members (including ~90 Affiliated Scientists, plus 37 Postdocs, and 48 Graduate Students)

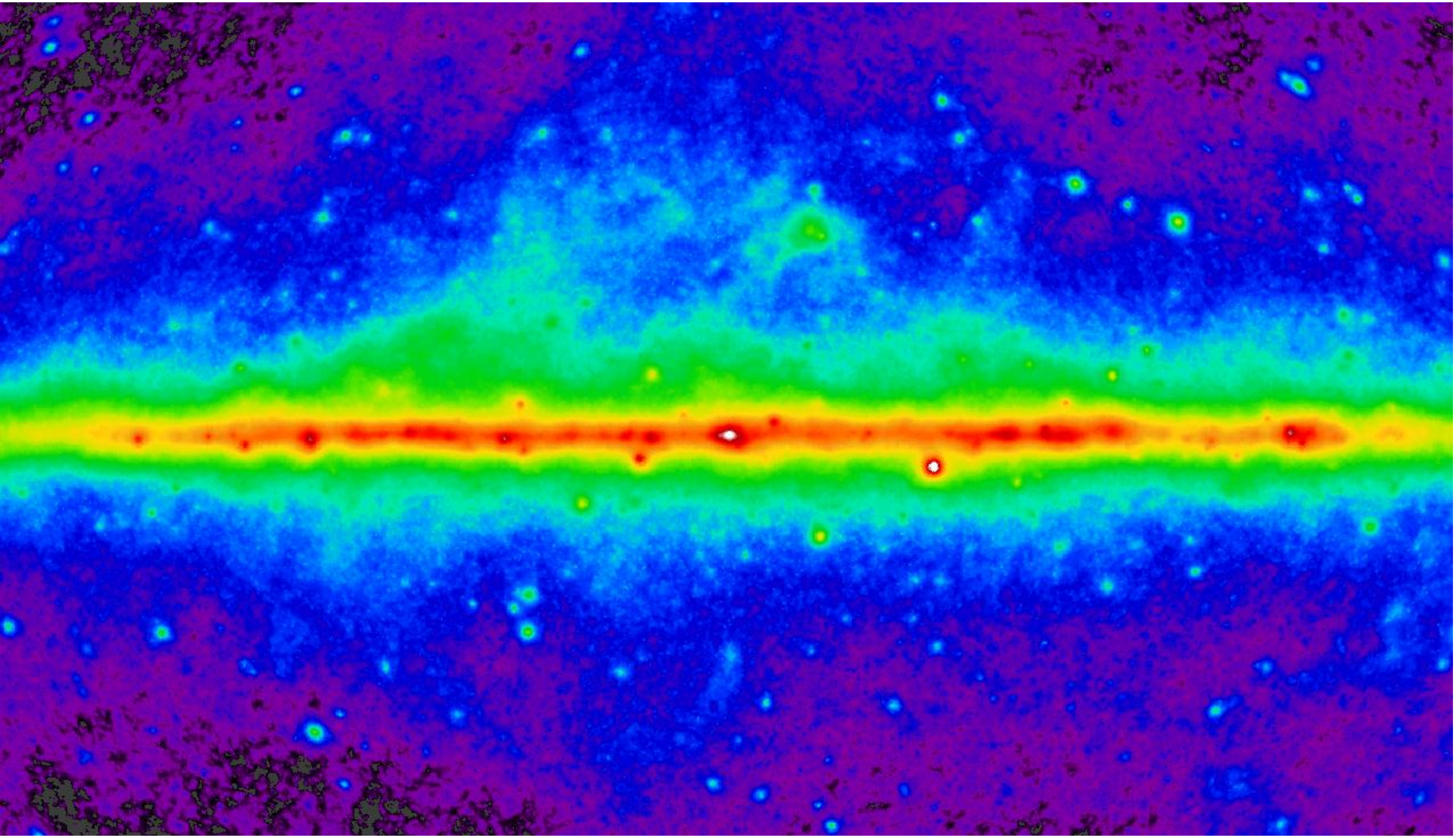
Cooperation between NASA and DOE, with key international contributions from France, Italy, Japan and Sweden.

Managed at Stanford Linear Accelerator Center (SLAC).

2-years of LAT data



Zoom in on Galactic center



A pause from gamma rays: Fermi can measure *electrons* and *positrons* too! (but cannot distinguish them)

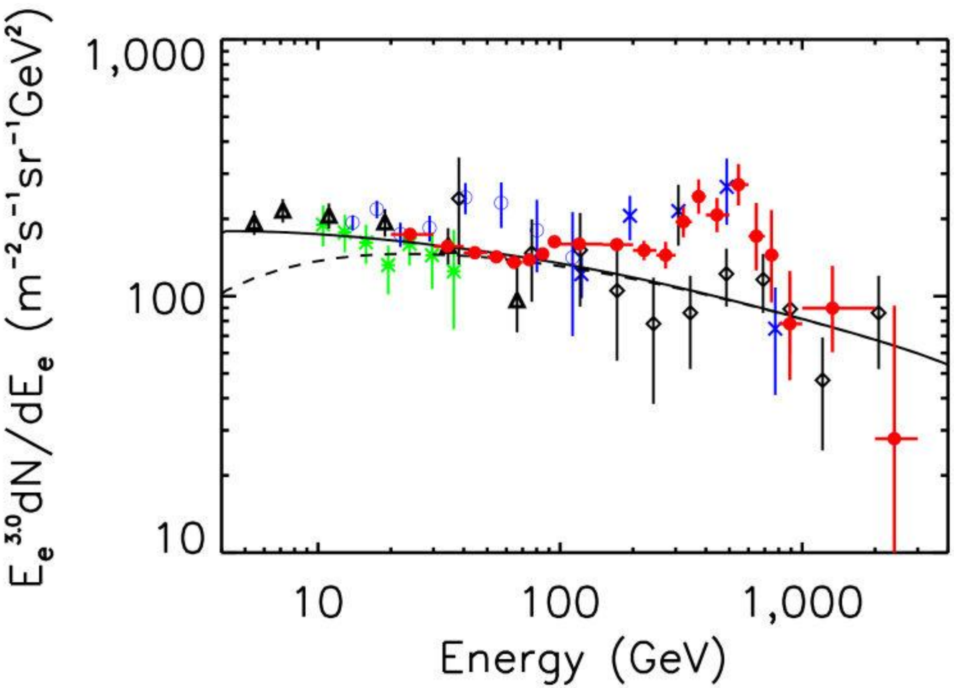
(these data are also not public)

Fermi Gamma-ray Space Telescope

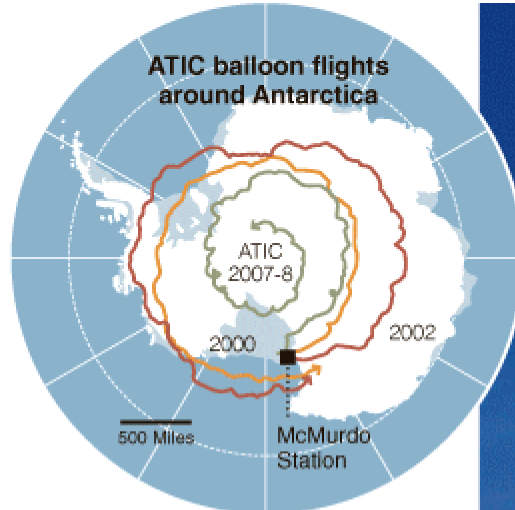
ATIC: "A Whisper, Perhaps, From the Universe's Dark Side"*

November 25, 2008

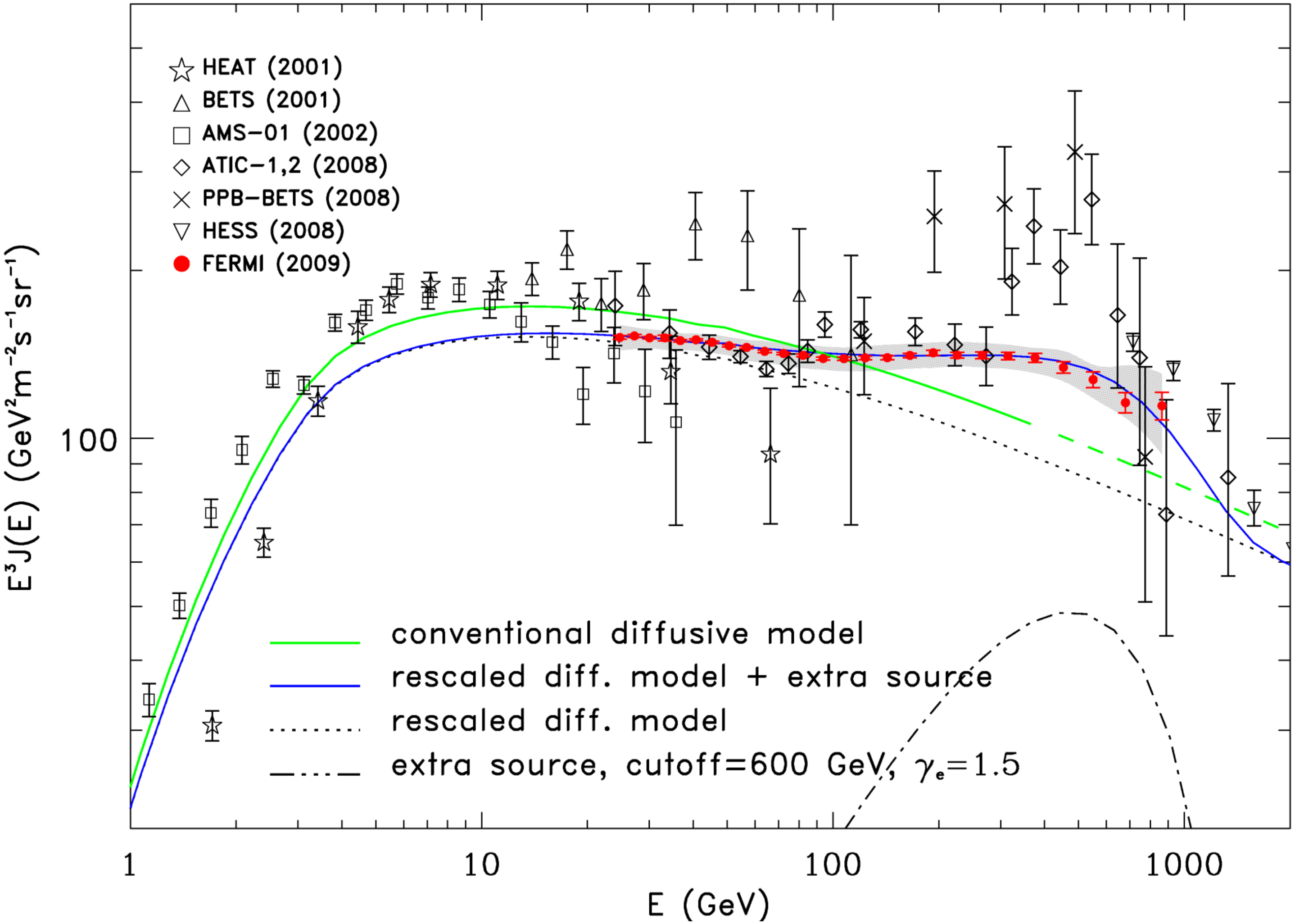
*NY Times headline Nov 25, 2008



● ATIC 1+2, ✱ Alpha Magnetic Spectrometer,
△ HEAT magnetic spectrometer, ○ BETS,
× PPB-BETS, ◇ Emulsion chambers



Fermi can measure electrons, too!

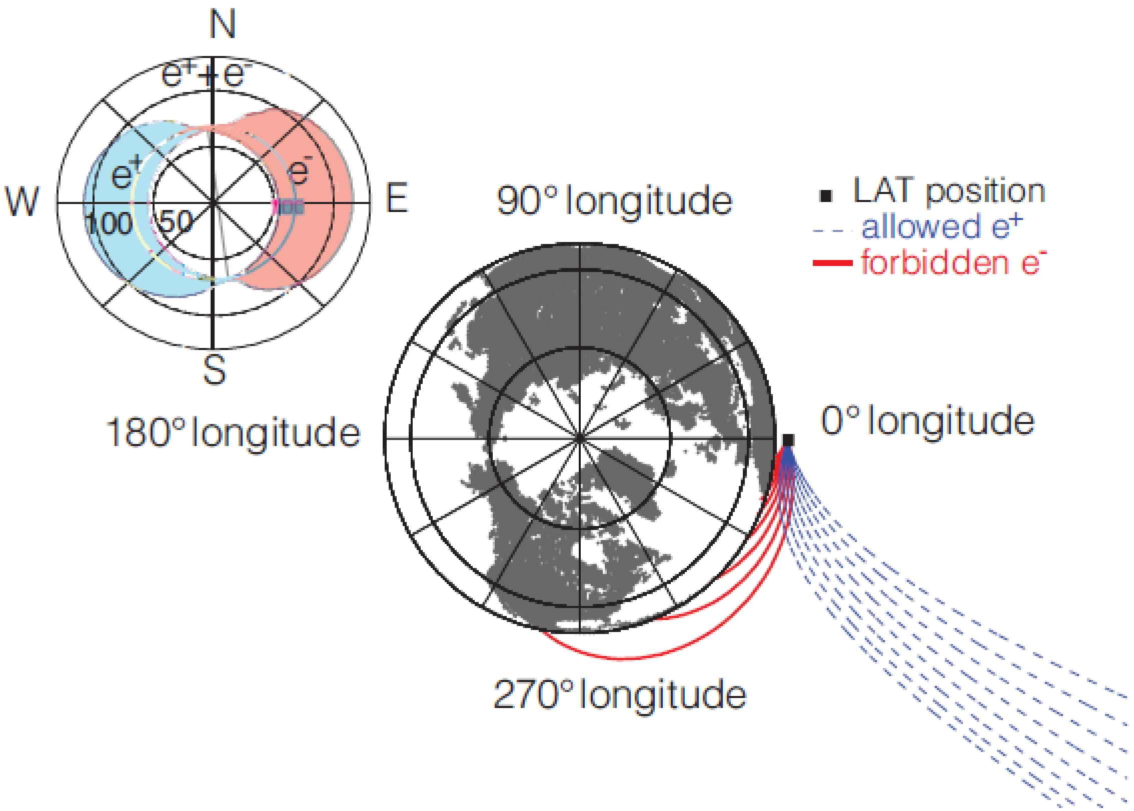


Our paper "Measurement of the Cosmic Ray e^{+}+e^{-} Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope" (05/2009 has 266 citations.

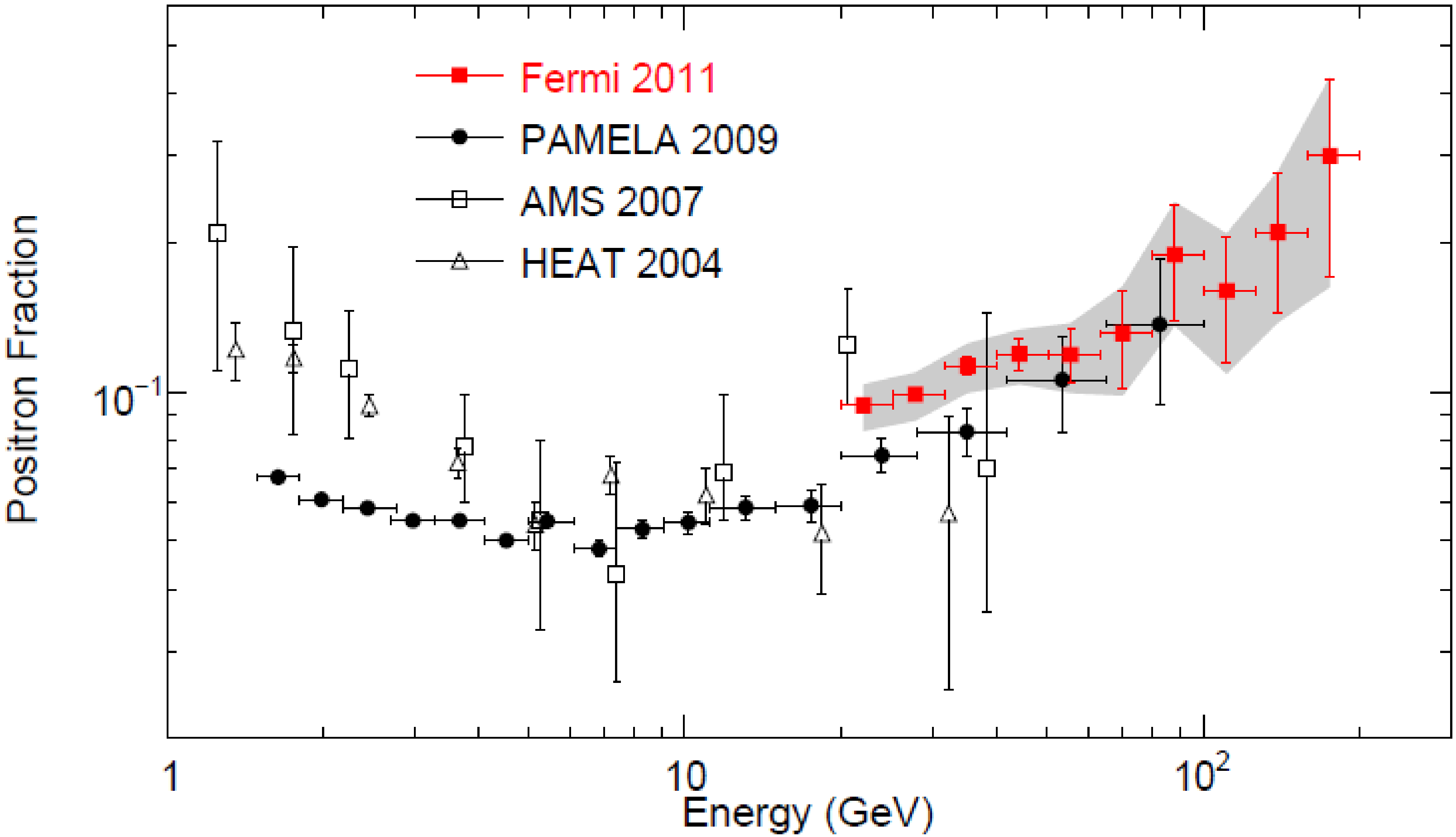
New result: positron asymmetry!

Use Earth's
magnetic field

arXiv:1109.0521

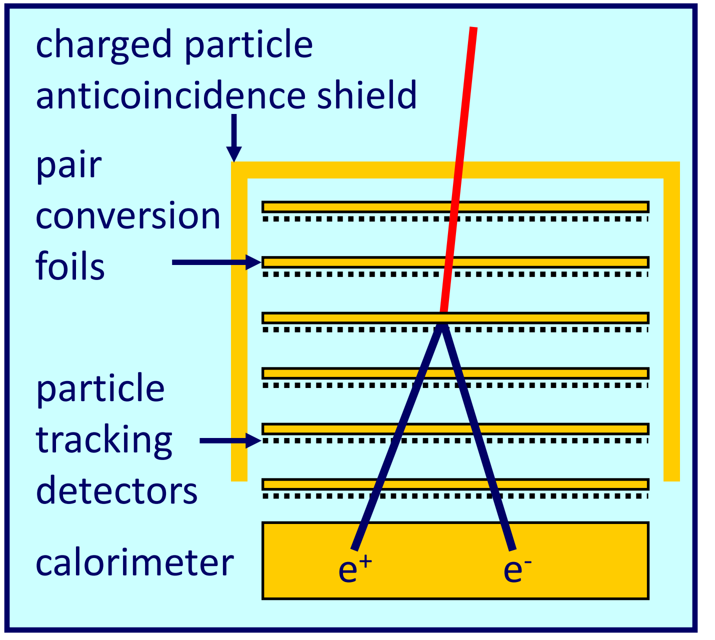


Asymmetry confirms PAMELA

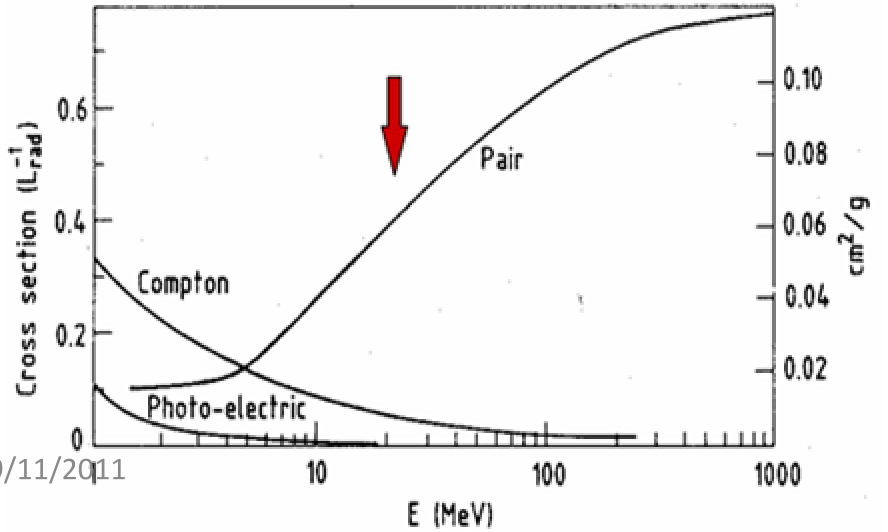


Detecting gamma-rays: Pair conversion detector design & requirements

- Anticoincidence shield:
  - required by very high flux of cosmic rays relative to gammas (~10^4)
  - Must be very efficient
  - Segmented to reduce self-veto
- Conversion foil (W):
  - High Z
  - thick for efficiency
  - *But*: thin for good PSF, due to multiple scattering
- Tracking (Si strips in Fermi)
  - Good efficiency, coverage
  - Small pitch
- Calorimeter (CsI in Fermi)
  - Thick to contain shower
  - *But*: Thin to reduce mass for launch
  - Segmented for shower pattern recognition



Photon cross sections in Pb



Also:

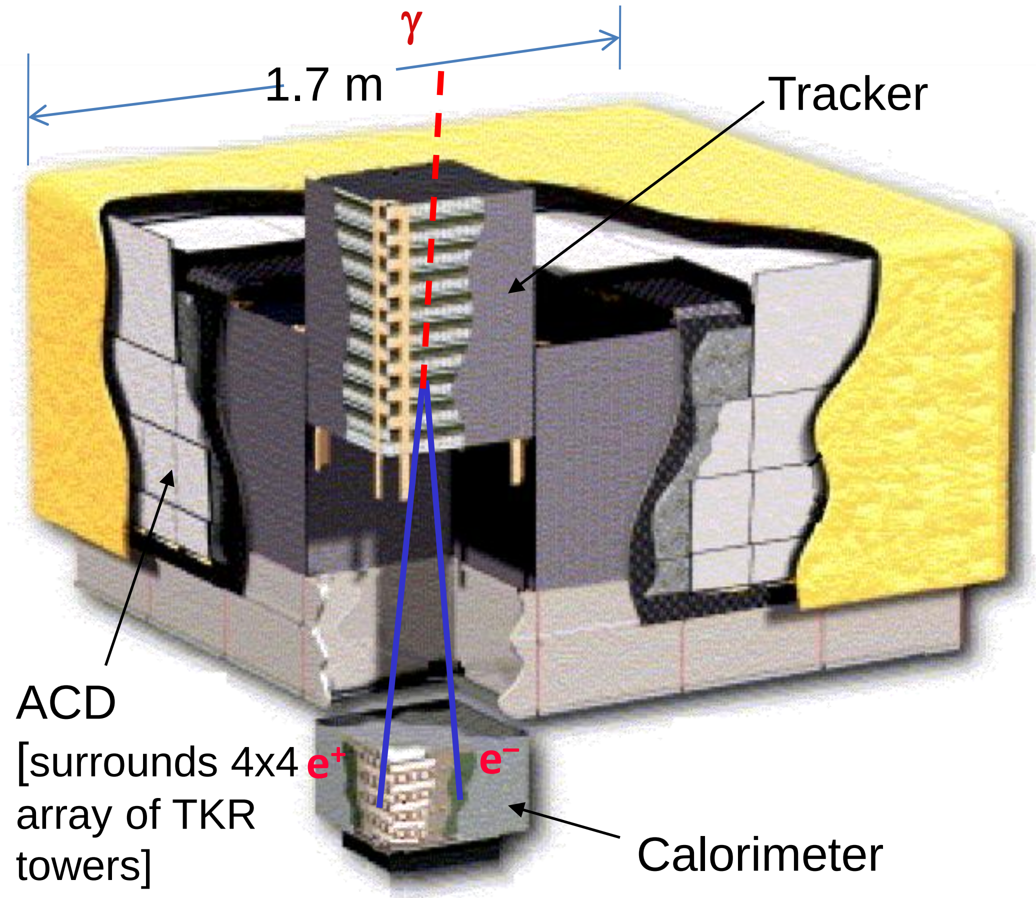
- Trigger system
- Data acquisition
- Onboard analysis

Spacecraft:

- Power
- communication
- Orientation, control, info
- Downlink

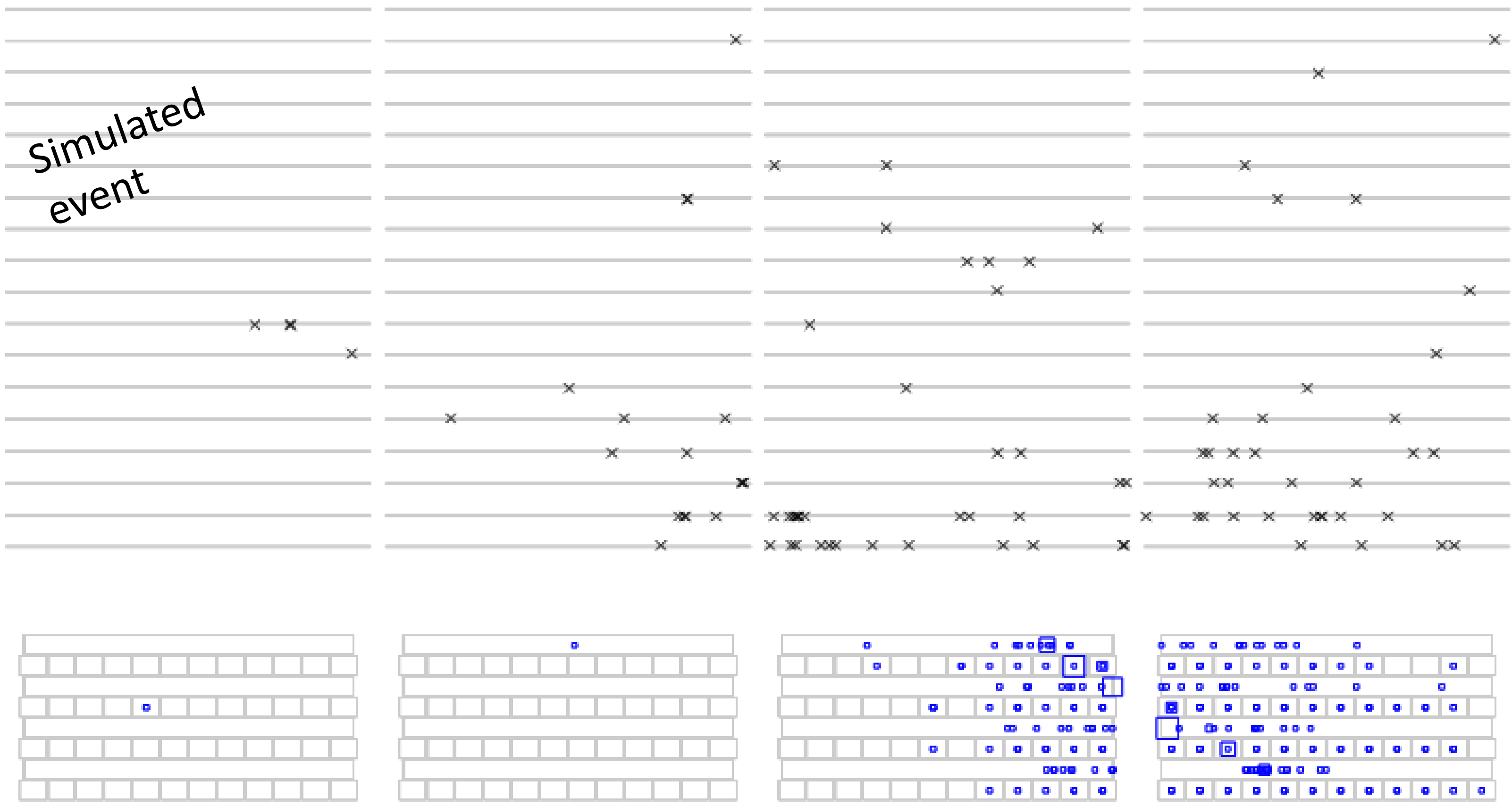
Overview of the LAT

- Precision Si-strip Tracker (TKR)
  18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.
- Hodoscopic CsI Calorimeter(CAL)
  1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.
- Segmented Anticoincidence Detector (ACD)
  89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.
- Electronics System Includes flexible, robust hardware trigger and software filters.



Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

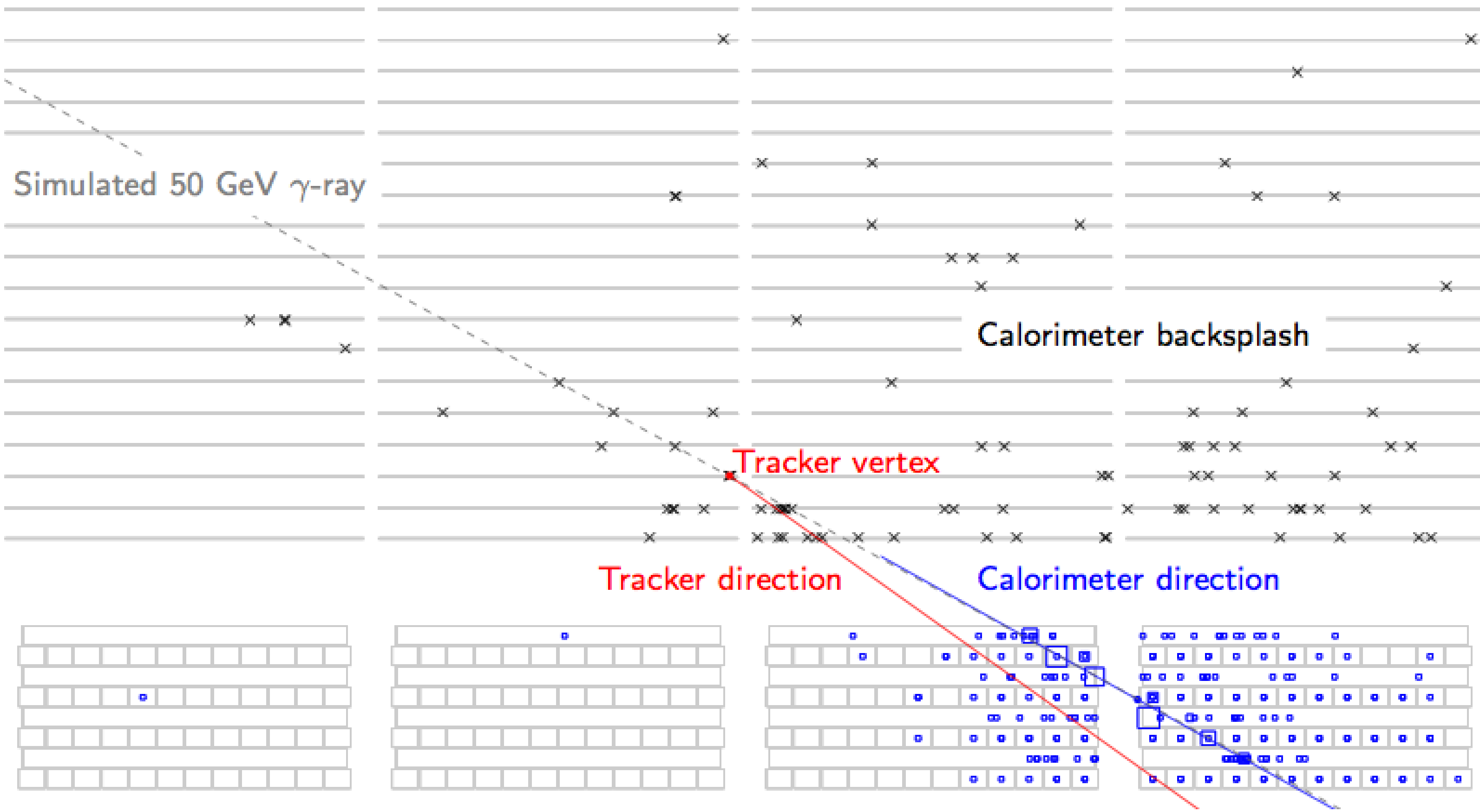
Real events can be messy!



Analysis goals:

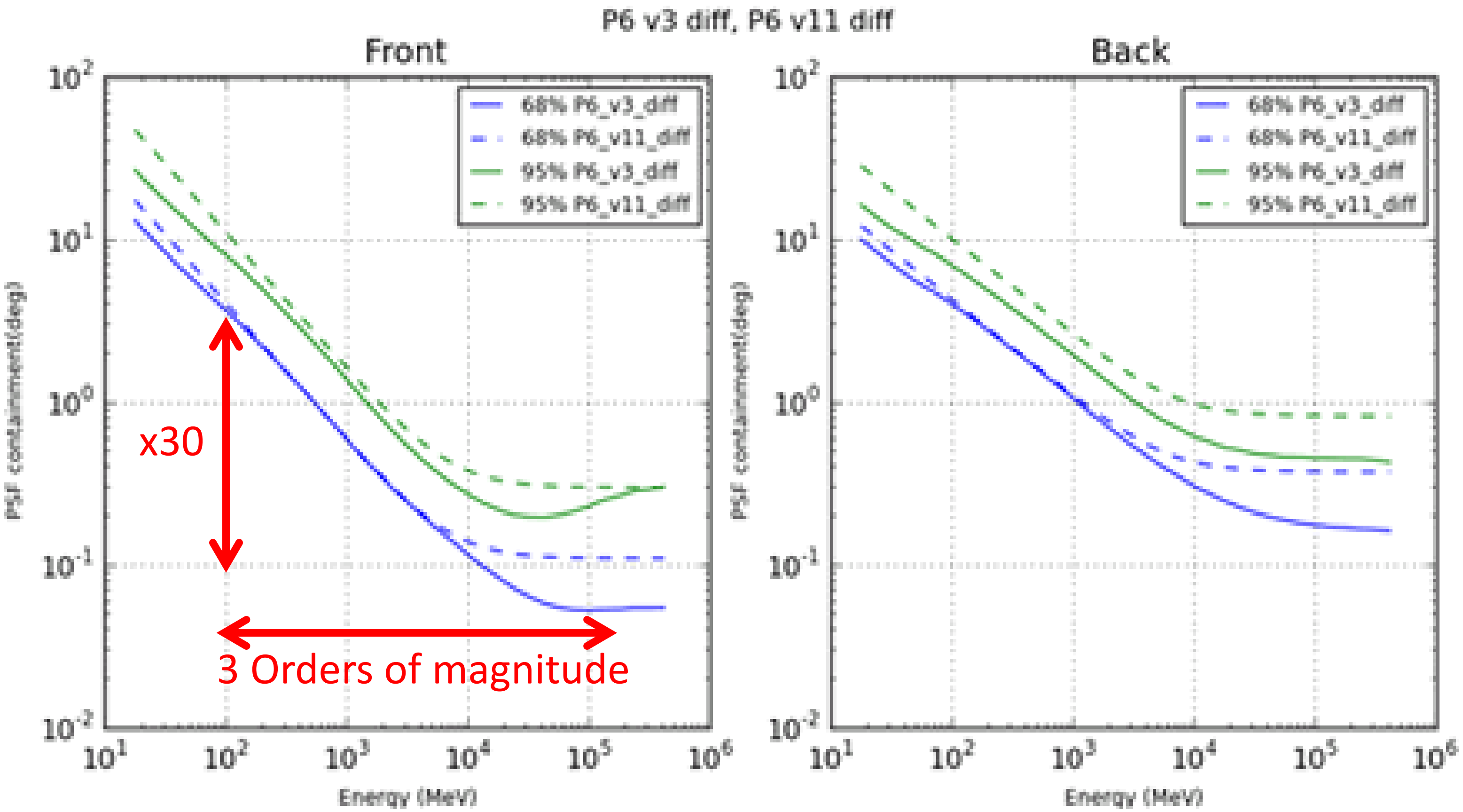
- measure incoming direction and energy
- Identify particle

Real events can be messy!



Actually, two detectors: 'Front' and 'Back'

Our angular resolution, or PSF



Dashed line is a measurement using the data. Current public representation is wrong by x2 at high energies.
This misunderstanding played a role in at least two external "discoveries"

The Gamma-ray data set is (partly) public

Many independent analyses

Fermi Gamma-ray Space Telescope

Did Hooper and Goodenough discover DM in our data?

"When I look at this data, it lines up perfectly," he says. "It quacks like a duck."

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Published online 19 October 2009 | Nature | doi:10.1038/news.2009.1018

News

Bright light hints at a dark centre to the Galaxy

Mysterious matter may be colliding at the Milky Way's core.

Geoff Brumfiel

Researchers are once again proposing that an orbiting telescope may have seen evidence for dark matter — the undetected material that is believed to permeate the Universe.

Flashes of radiation from the heart of the Milky Way could be a hint of dark matter.

NASA/JPL-Caltech

The Fermi Gamma Ray Space Telescope has captured flashes of high-energy γ-ray light that might come from dark matter, according to Lisa Goodenough of New York University in New York City and Dan Hooper at the Fermi National Accelerator Laboratory in Batavia, Illinois. In a paper posted on the arXiv pre-print server[1], the duo suggests that flashes seen at the Milky Way's core could be caused by the collision of dark-matter particles with their antiparticles. "We were really shocked just how well a simple dark matter model accommodated this data," says Hooper.

Fermi Gamma-ray Space Telescope

SPACE DAILY

your portal to space

And did Ando and Kusenko discover “primordial magnetic fields” by detecting halos around AGN’s that we missed?

TIME ✦ SPACE

Primordial Magnetic Fields Discovered Across The Universe

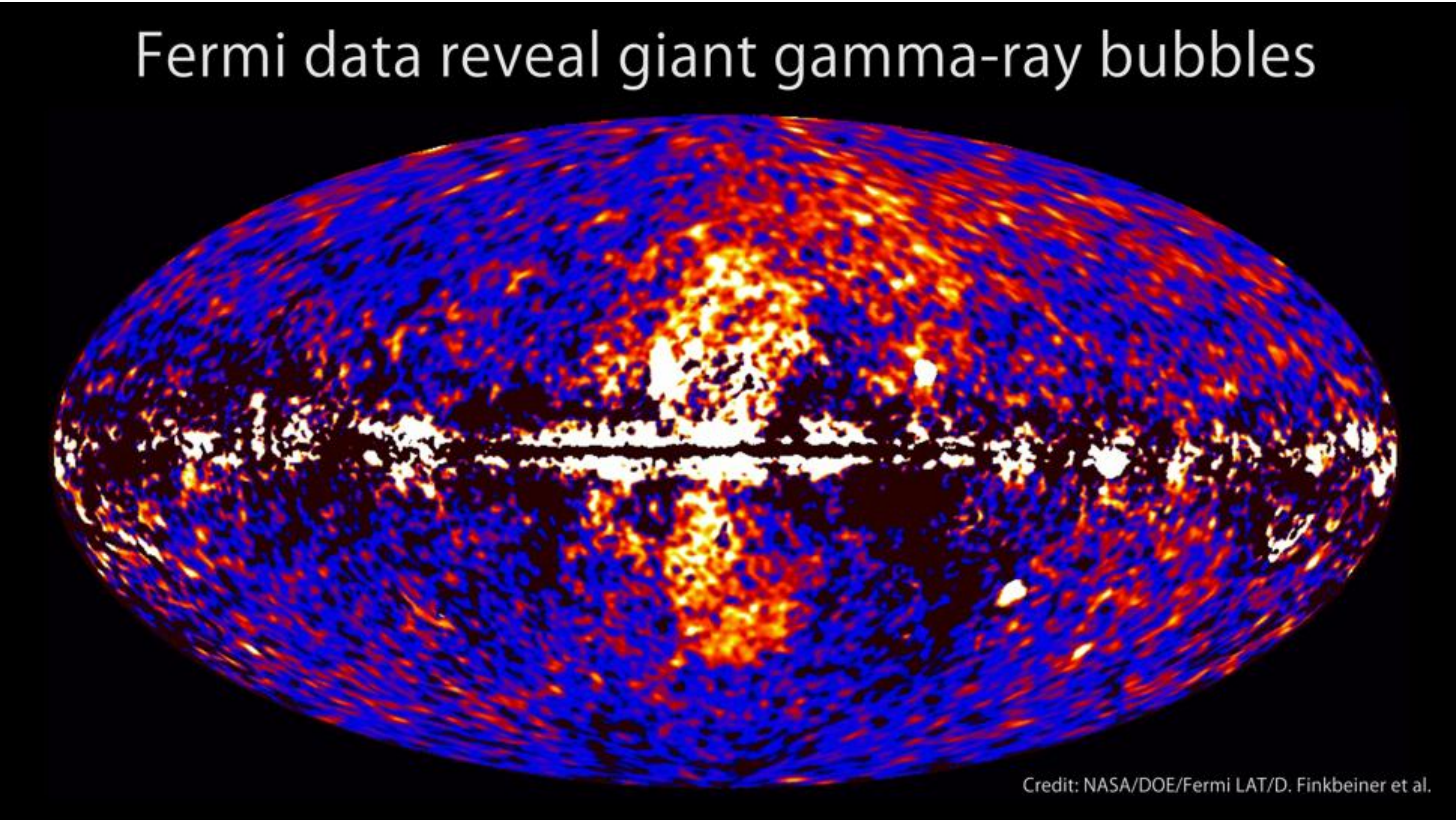
by Staff Writers
Los Angeles CA (SPX) Sep 23, 2010

Scientists from the California Institute of Technology and UCLA have discovered evidence of "universal ubiquitous magnetic fields" that have permeated deep space between galaxies since the time of the Big Bang.

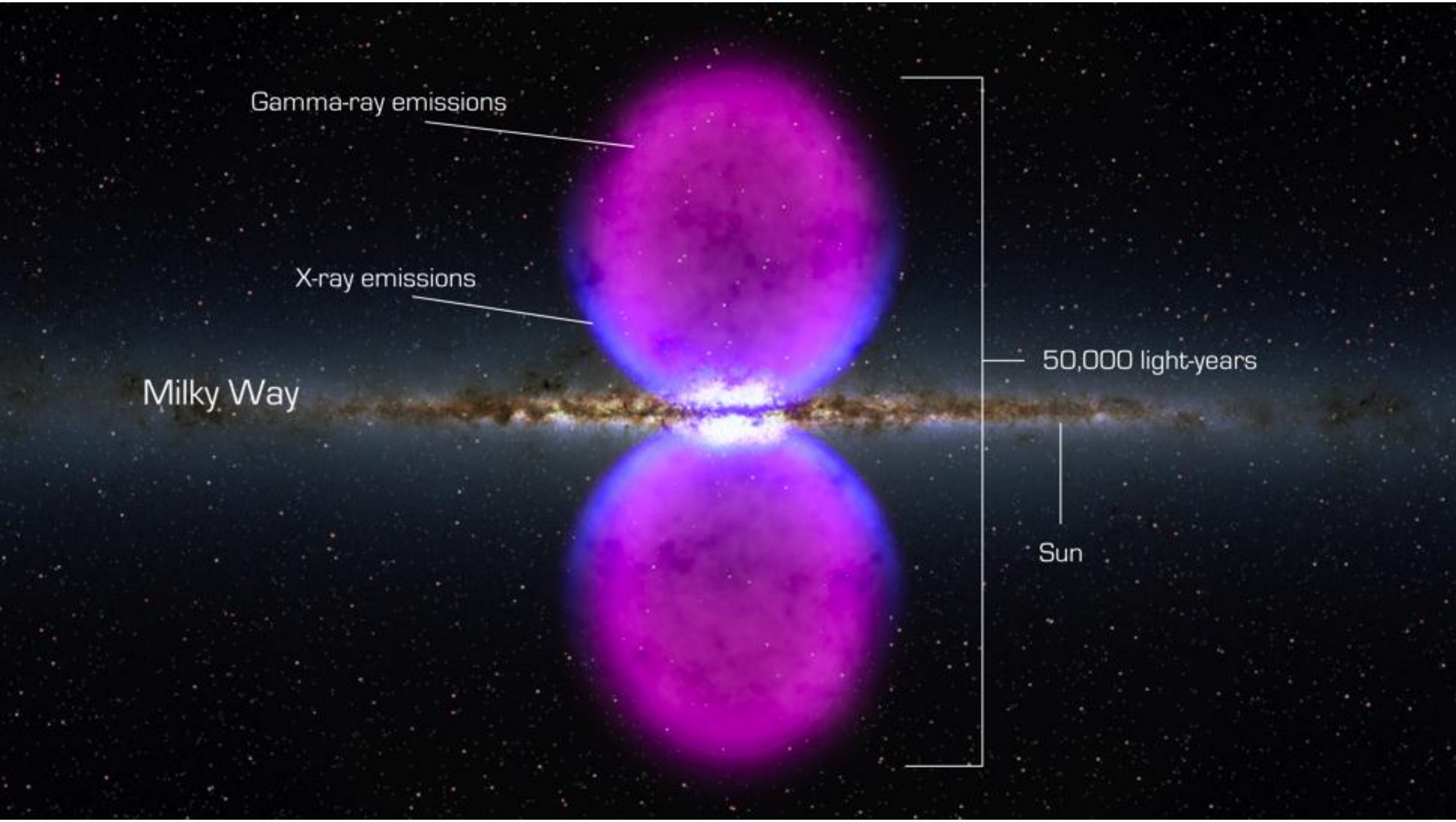
An artist's conception of an "active galactic nucleus" courtesy of NASA. In some galaxies, the nucleus, or central core, produces more radiation than the entire rest of the galaxy. (Credit: NASA)

Caltech physicist Shin'ichiro Ando and Alexander Kusenko, a professor of physics and astronomy at UCLA, report the discovery in a paper to be published in an upcoming issue of Astrophysical Journal Letters; the research is currently available online.

Our Nearest Non-blazar AGN

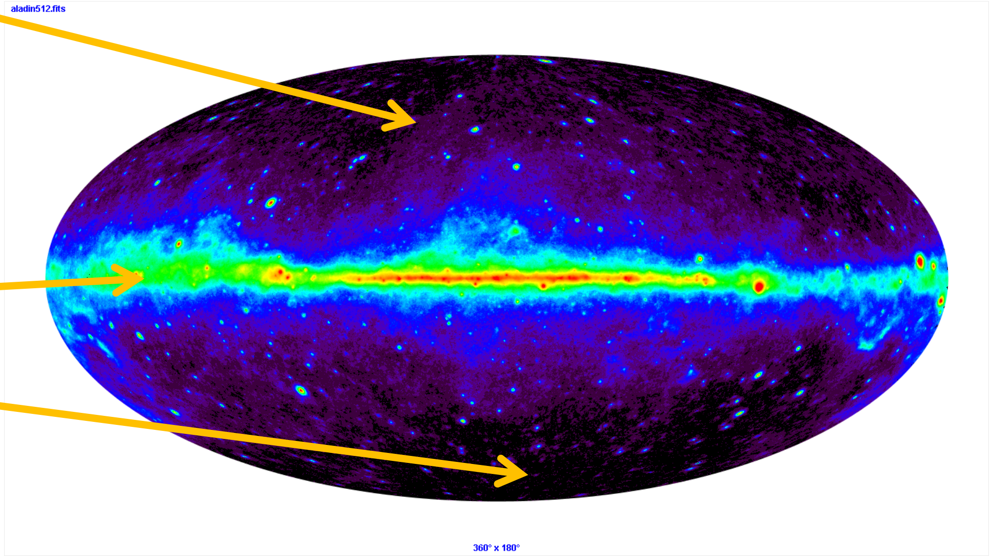


Our Nearest Non-blazar AGN



Goal: account for *every* photon

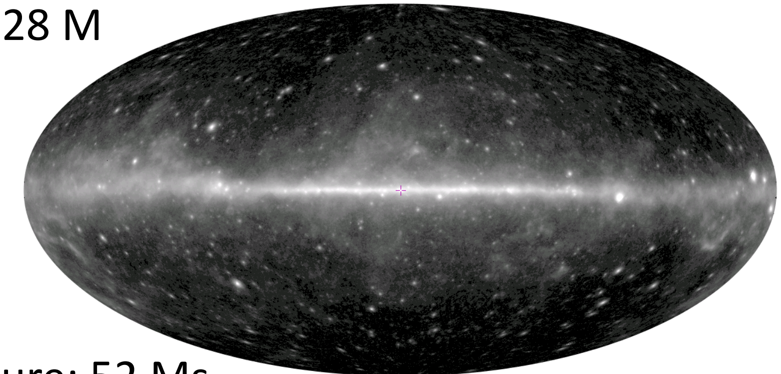
- ~Steady Sources of photons
  - Point sources
    - Pulsars, including binaries
    - Galaxies, mostly AGN
      - AGN probes B, photons
    - Unknown
  - Galactic diffuse
  - Isotropic diffuse
    - Unresolved point sources
    - Proton background
    - Unknown
- Transients
  - GRB
  - Nova



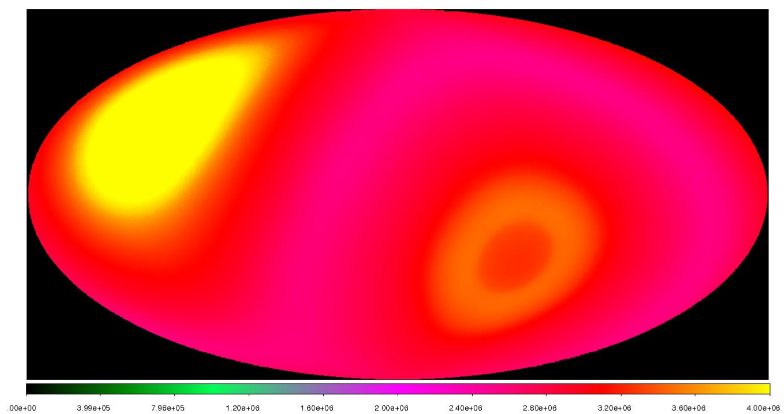
Making the 2FGL catalog

Understanding the sky: extract a list of sources for the 2FGL catalog

Data: 28 M



Exposure: 52 Ms



Two years (excluding 3 GRBs)
"Pass7 processing"

[1FGL: 11 months]

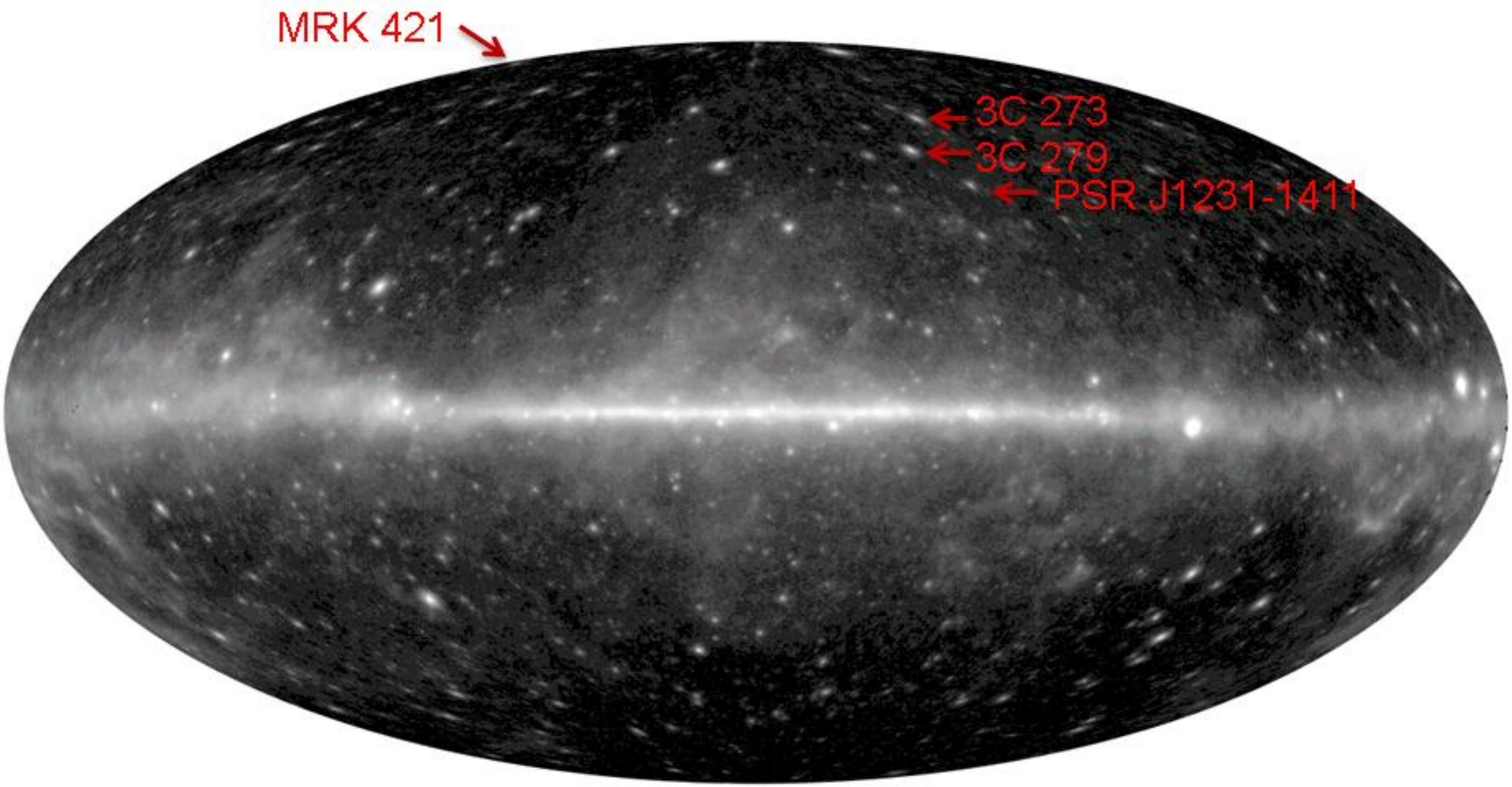
2FGL Table

1873 entries
[1FGL: 1451]

	Source_Name	NickName	RAJ2000	DEJ2000	
1	2FGL J0000.9-0748	P72Y0002	0.233711	-7.8155	88
2	2FGL J0001.7-4159	P72Y0005	0.438849	-41.9965	334
3	2FGL J0002.7+6220	P72Y0008	0.679812	62.3396	117
4	2FGL J0004.2+2208	P72Y0013	1.05569	22.1365	108
5	2FGL J0004.7-4736	P72Y0015	1.18021	-47.6116	323
6	2FGL J0006.1+3821	P72Y0016	1.52516	38.3502	113
7	2FGL J0007.0+7303	PSRJ0007+7303	1.77352	73.0545	119
8	2FGL J0007.7+6825	P72Y0024	1.92505	68.4232	118
9	2FGL J0007.8+4713	P72Y0025	1.97432	47.2298	115
10	2FGL J0008.7-2344	P72Y0027	2.19605	-23.7363	49
11	2FGL J0009.0+0632	P72Y0028	2.26231	6.54235	104
12	2FGL J0009.1+5030	P72Y0030	2.2914	50.5062	116
13	2FGL J0009.9-3206	P72Y0031	2.48449	-32.1118	1
14	2FGL J0010.5+6556	P72Y0034	2.64068	65.9339	118
15	2FGL J0011.3+0054	P72Y0036	2.82765	0.903578	102
16	2FGL J0012.9-3954	P72Y0040	3.24638	-39.9005	332
17	2FGL J0013.8+1907	P72Y0043	3.46375	19.126	110
18	2FGL J0014.3-0509	P72Y0045	3.58116	-5.15295	99
19	2FGL J0017.4-0018	P72Y0054	4.364	-0.302	104
20	2FGL J0017.6-0510	P72Y0055	4.40364	-5.18249	101
21	2FGL J0018.5+2945	P72Y0057	4.63305	29.7602	114
22	2FGL J0018.8-8154	P72Y0058	4.71587	-81.9027	304
23	2FGL J0019.4-5645	P72Y0059	4.85732	-56.7558	311
24	2FGL J0021.6-2551	P72Y0063	5.41178	-25.852	42
25	2FGL J0022.2-1853	P72Y0064	5.55909	-18.8884	82
26	2FGL J0022.3-5141	P72Y0065	5.59589	-51.6913	313
27	2FGL J0022.5+0607	P72Y0066	5.64299	6.12368	110
28	2FGL J0023.2+4454	P72Y0068	5.81783	44.9046	117
29	2FGL J0023.5+0924	P72Y0069	5.89215	9.40666	111
30	2FGL J0023.9-7204	P72Y0070	5.98558	-72.0825	305
31	2FGL J0024.5+0346	P72Y0073	6.14599	3.78296	110
32	2FGL J0029.2-7043	P72Y0082	7.30062	-70.7255	305
33	2FGL J0030.2-4223	P72Y0085	7.57263	-42.3863	317
34	2FGL J0030.4+0450	PSRJ0030+0451	7.60105	4.83868	113
35	2FGL J0031.0+0724	P72Y0090	7.775	7.414	114
36	2FGL J0032.7-5521	P72Y0094	8.17868	-55.3563	308
37	2FGL J0033.5-1921	P72Y0096	8.39111	-19.357	94
38	2FGL J0034.4-0534	PSRJ0034-0534	8.61312	-5.58218	111
39	2FGL J0035.2+1515	P72Y0098	8.80866	15.2583	117
40	2FGL J0035.8+5951	P72Y0099	8.96431	59.8537	120
41	2FGL J0037.8+1238	P72Y0101	9.47307	12.6449	117
42	2FGL J0038.1+0015	P72Y0102	9.54151	0.264987	115
43	2FGL J0038.3-2457	P72Y0103	9.5827	-24.9632	68
44	2FGL J0038.7-2215	P72Y0104	9.6918	-22.2522	91
45	2FGL J0038.8+6259	P72Y0106	9.72048	62.9967	121
46	2FGL J0039.1+4331	P72Y0108	9.78034	43.5271	120
47	2FGL J0042.5+4114	P72Y0112	10.633	41.245	121
48	2FGL J0043.7+3426	P72Y0116	10.9409	34.4394	121
49	2FGL J0044.7-3702	P72Y0118	11.1951	-37.0404	310
50	2FGL J0045.3+2127	P72Y0120	11.3351	21.4524	121
51	2FGL J0045.5+1218	P72Y0121	11.3964	12.3121	120
52	2FGL J0046.7-8416	P72Y0123	11.6926	-84.27	303

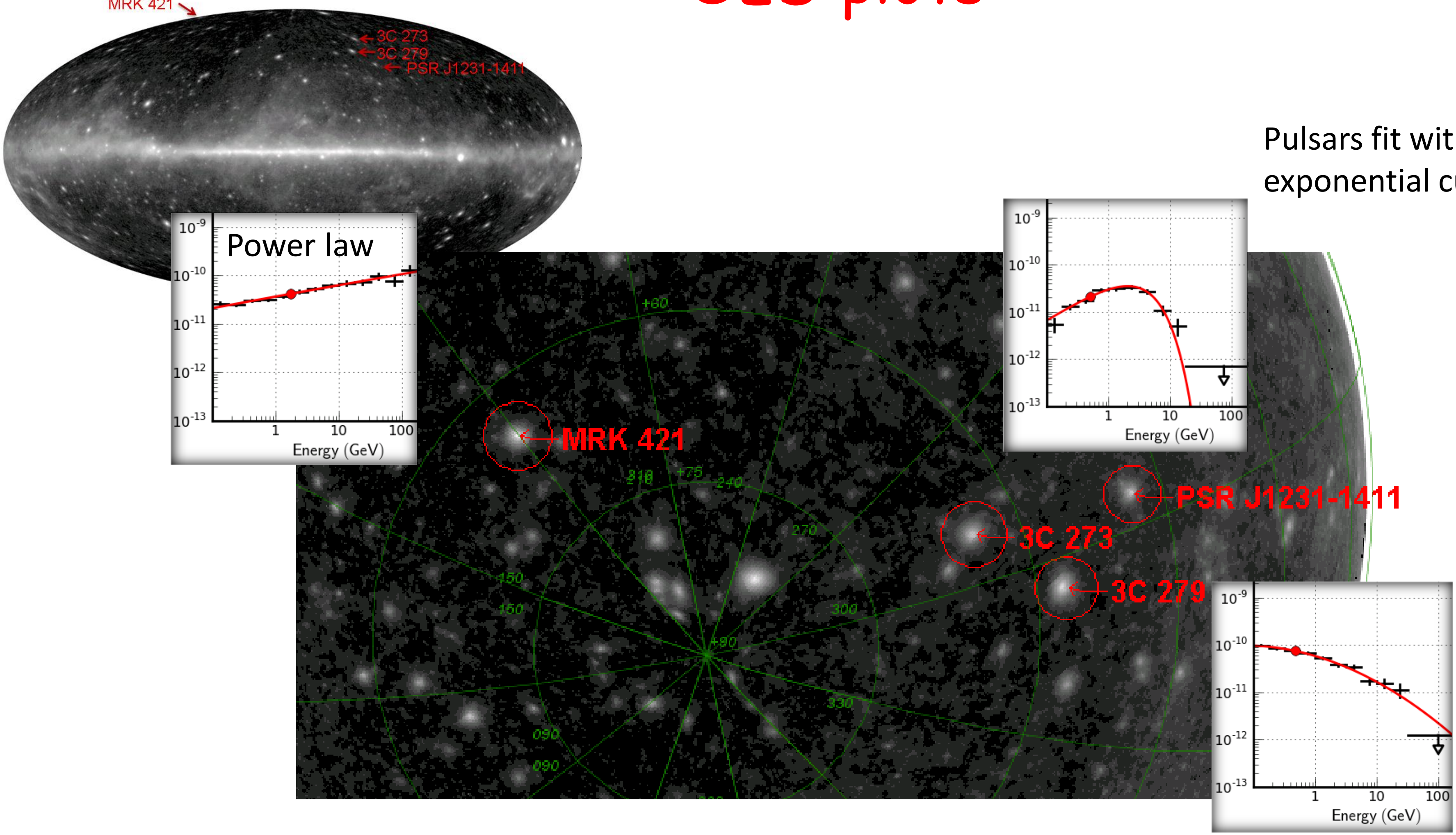
+ Light curves,
SED plots,
associations

Bright sources at high latitudes are easy



Strong source high latitude example: SED plots

Pulsars fit with exponential cutoff

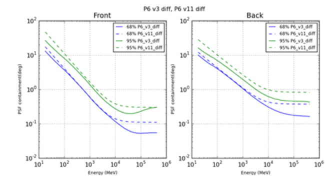


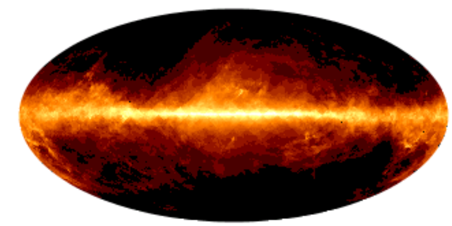
Use log parabola if better fit

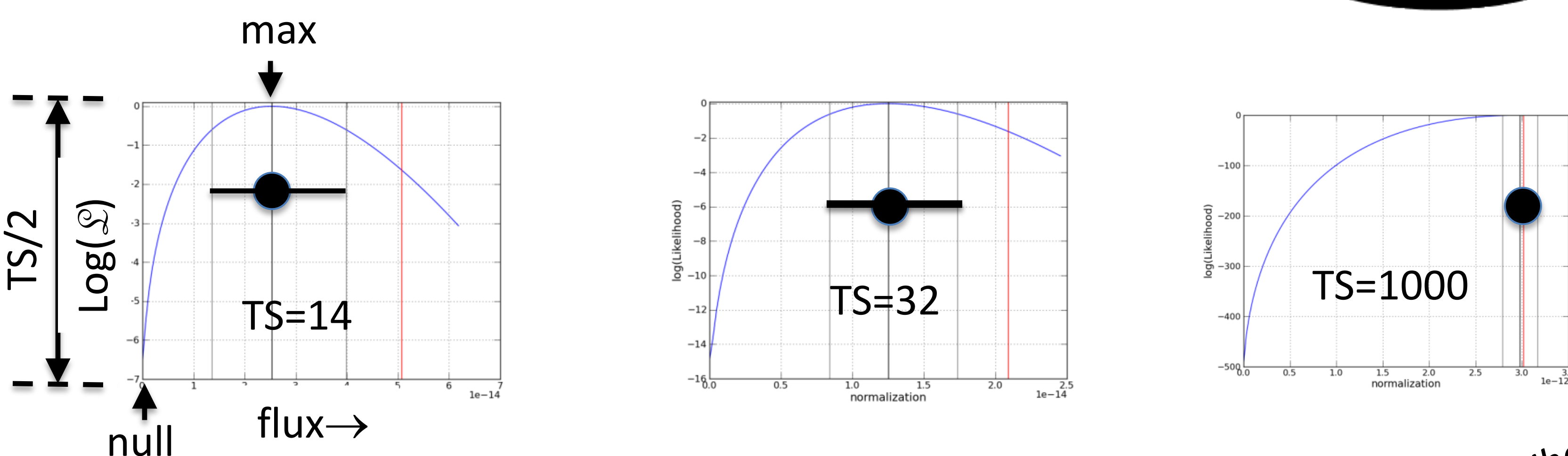
Circles are 3°, 100 MeV PSF ('front' section) (varies by a factor of 30 with energy!)

Measuring point source properties: maximize likelihood

- Model of the sky must account for *all* photons
  - PSF
  - Aeff
  - Galactic, isotropic diffuse including CR
  - 1/8 degree grid, pixels centered on plane
  - Earth limb
- An important issue: how to measure significance?
  Test Statistic: $TS=-2\log(L_{fit}/L_{null})$



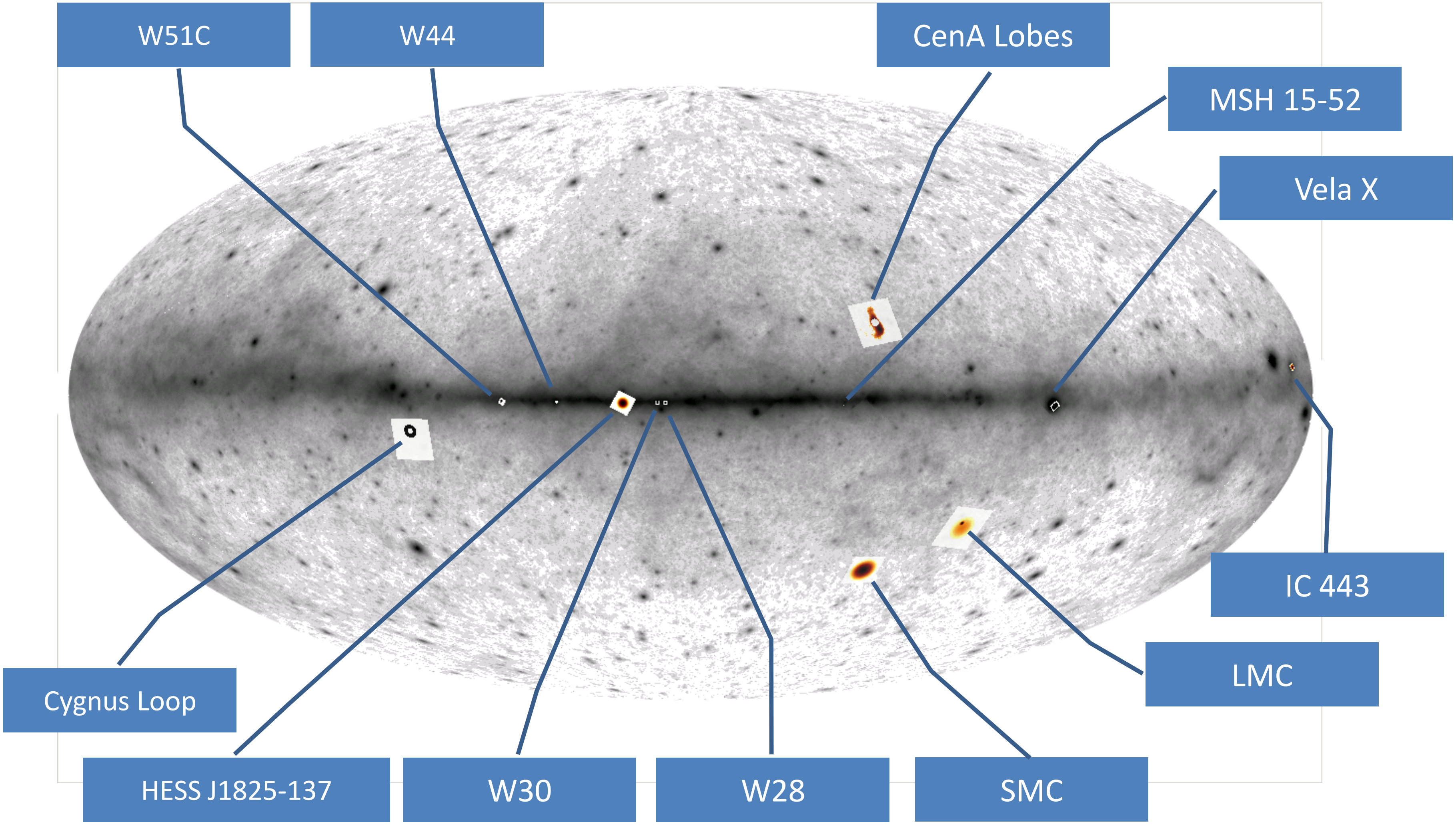




- We conservatively choose only sources with TS>25.

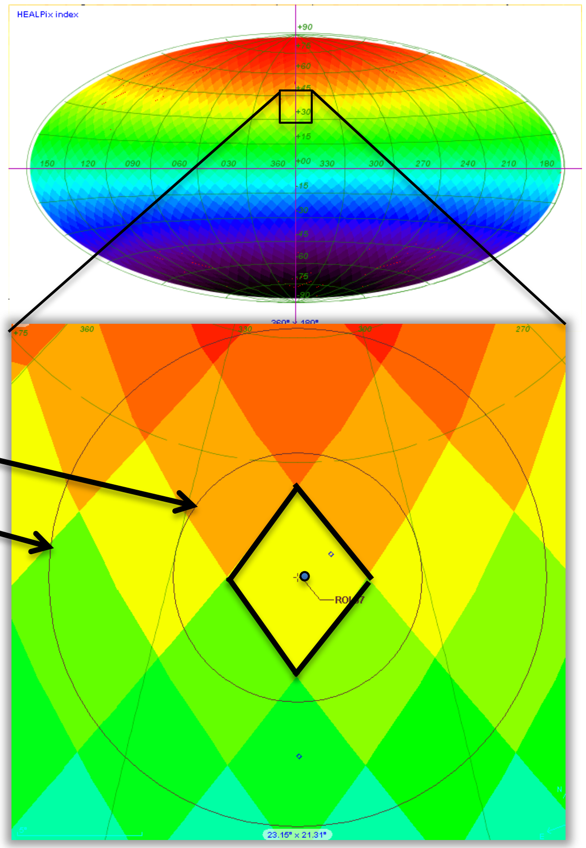
Likelihood caveat from Bernard!

Extended source templates



Details about the sky model

- Tessellate sky using HEALPix: 1728 regions
- Each ~5° square pixel defines:
  - Center of circular regions for:
    - data (5 deg)
    - sources (10 deg)
  - sources inside are varied; those outside fixed to results of previous iteration
  - Note ~x3 overlap of data: not independent
- Diffuse component normalizations free
- Iteration procedure:
  - Each region fit (full likelihood maximized) independently
  - Each fit remeasures point source positions: Apply updates between cycles.
  - Check changes in log(L): iterate until none changes by more than 10 (8-10 iterations required)

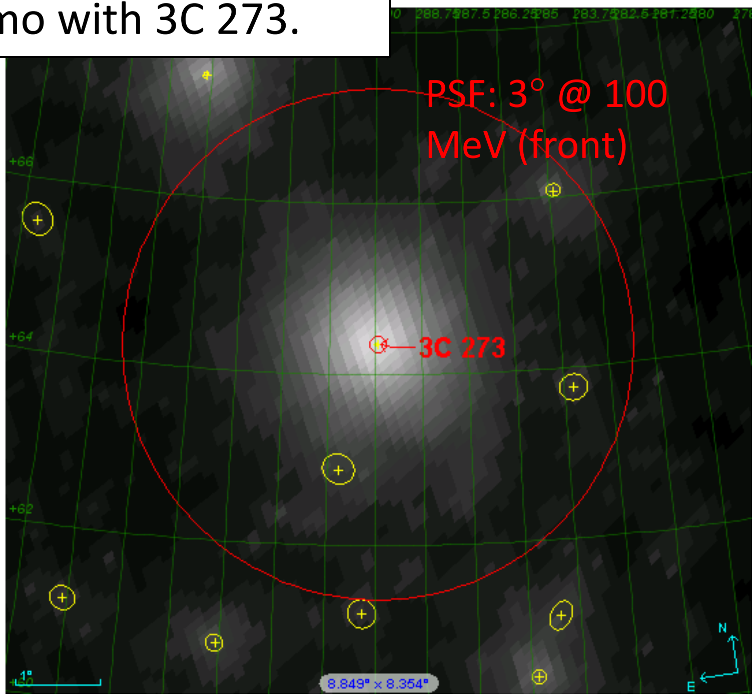


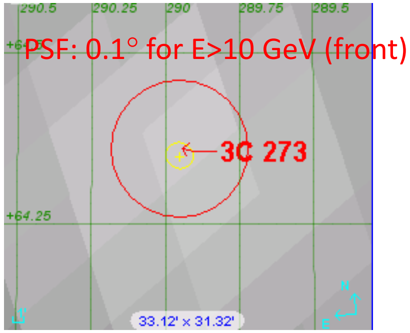
Colors: HEALPix index

Localization

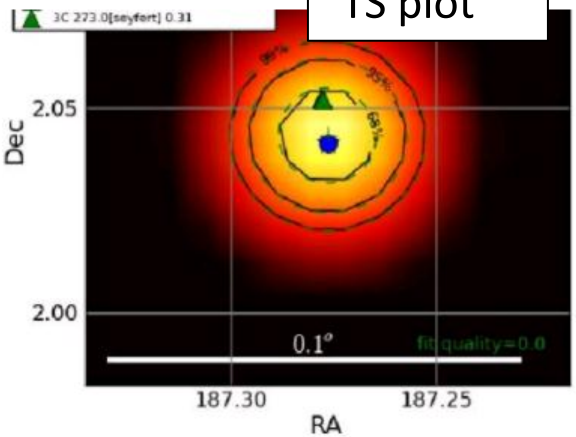
Basic principle: the likelihood function, as a function of the position of a source, is an estimator of the position, with the curvature defining the resolution.

Demo with 3C 273.





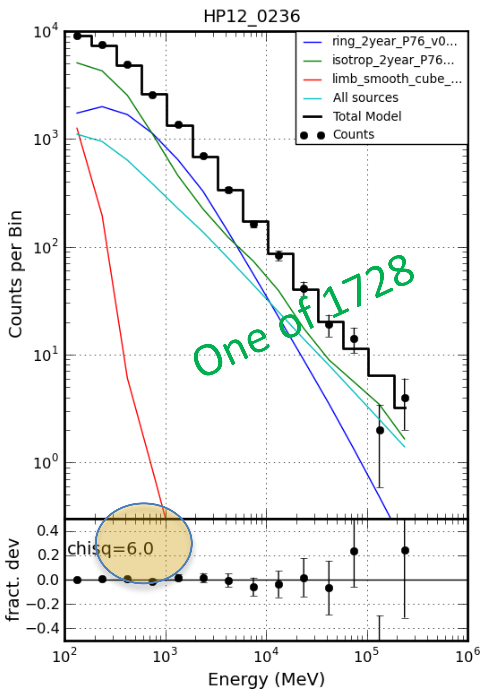
'TS plot'



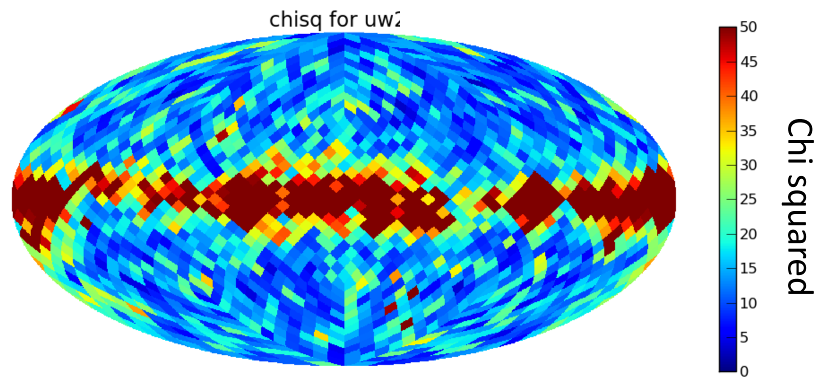
Error ellipse defined by 95% contour (2.45σ).
Plot shows contours, and results of fit to quadratic surface

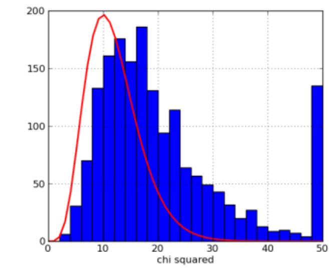
Stage I Summary

Consistency mostly good

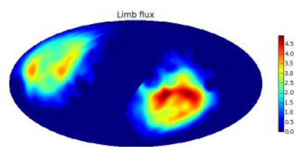


Example consistency check:
all photons in 5° radius circle
(Approx. 12 d.o.f.)



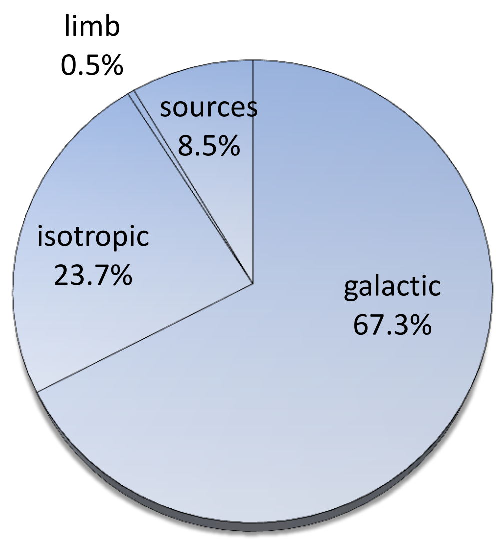


Limb distribution



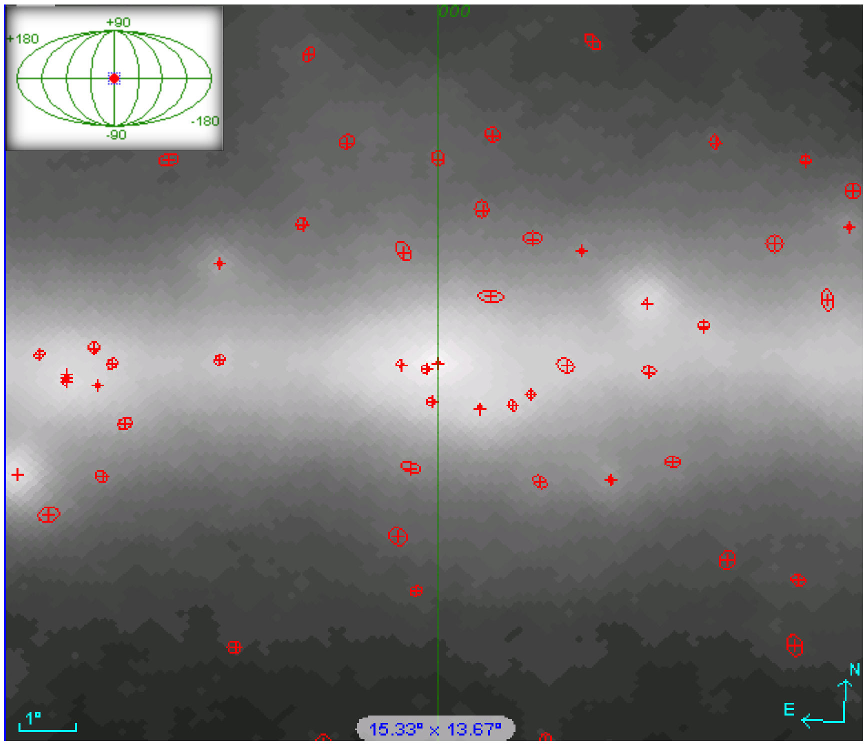
Free parameters	
Type	**Number**
Spectra	7603
Diffuse normalization	3456
Location (2 per TS>16 source)	5096

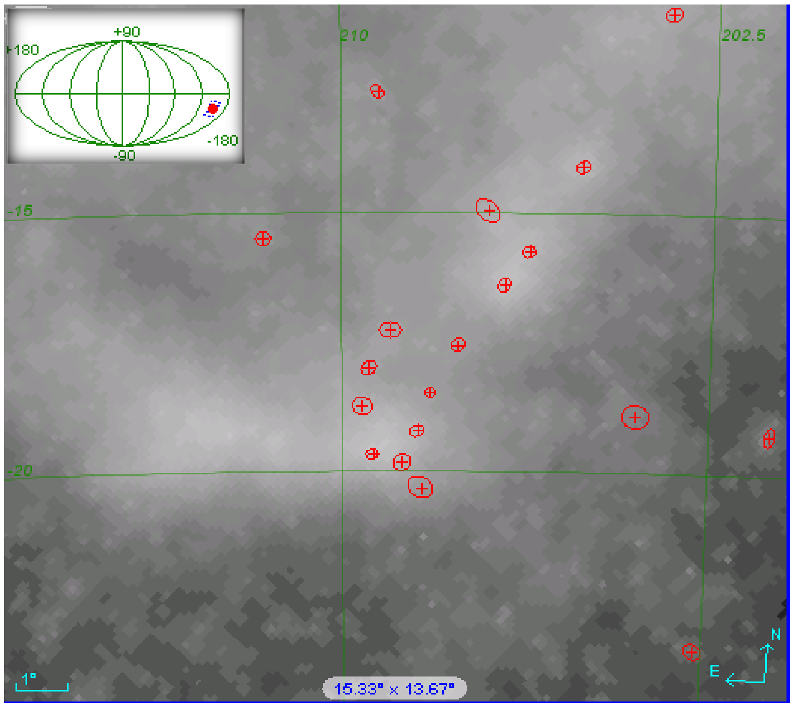
Contributions for all energies, full sky



It is not all so rosy…

Most sources apparently associated with diffuse structures probably result from inadequate representation of the diffuse



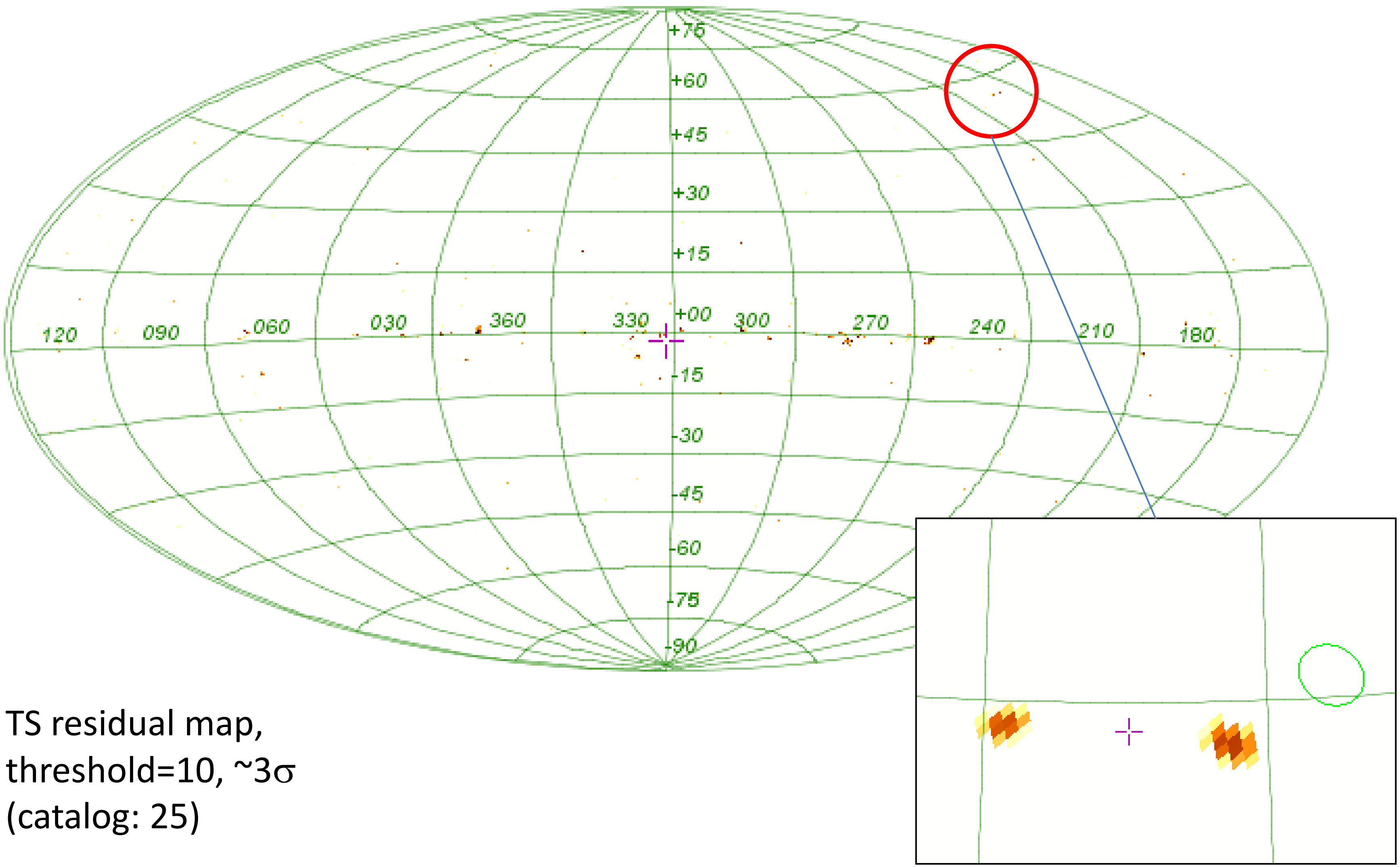


Galactic center is complicated!

Orion molecular cloud:

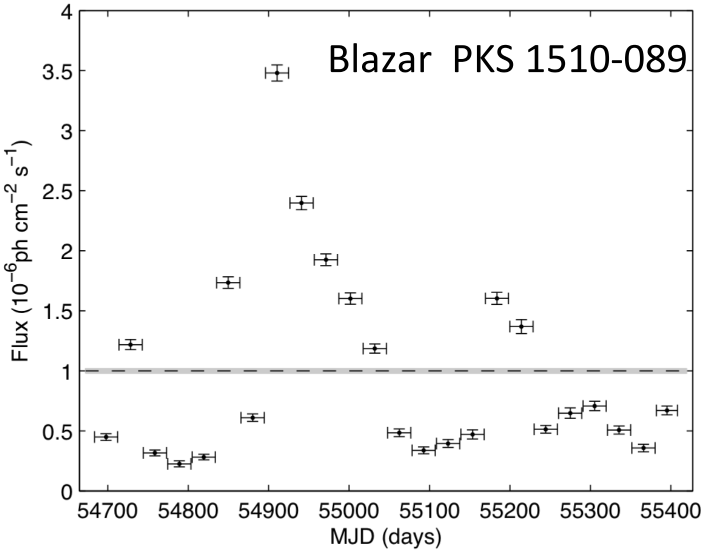
Sources: TS>10 seeds for 2FGL

Sources: did we miss any?



TS residual map, threshold=10, ~3σ (catalog: 25)

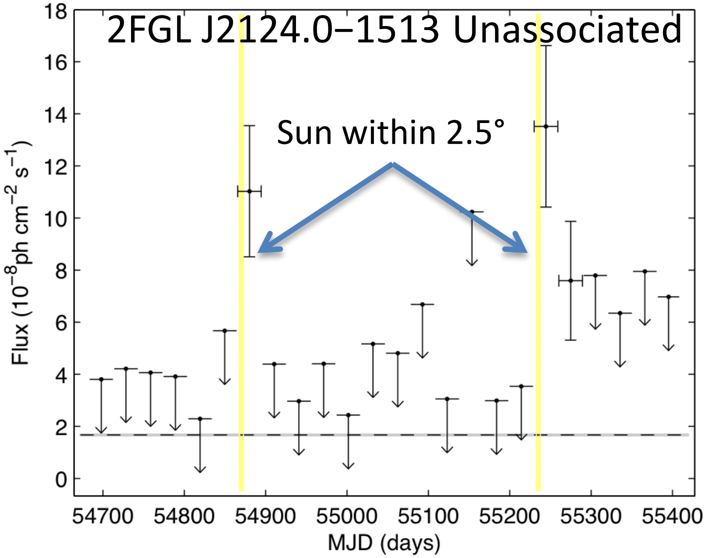
Variability analysis

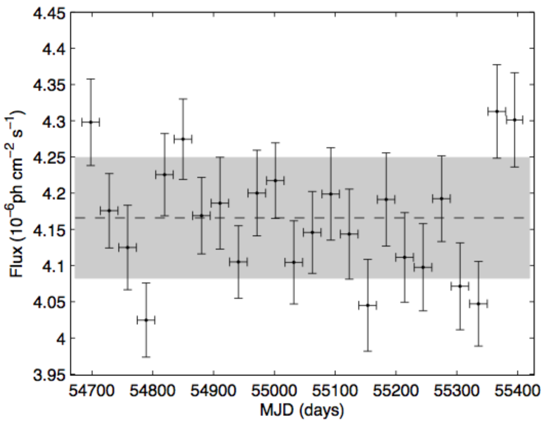


variability index is based on 24 ~monthly flux measurements.

likelihood ratio of observed values to the null, constant hypothesis

A total of 458 sources were found to be variable with high confidence.

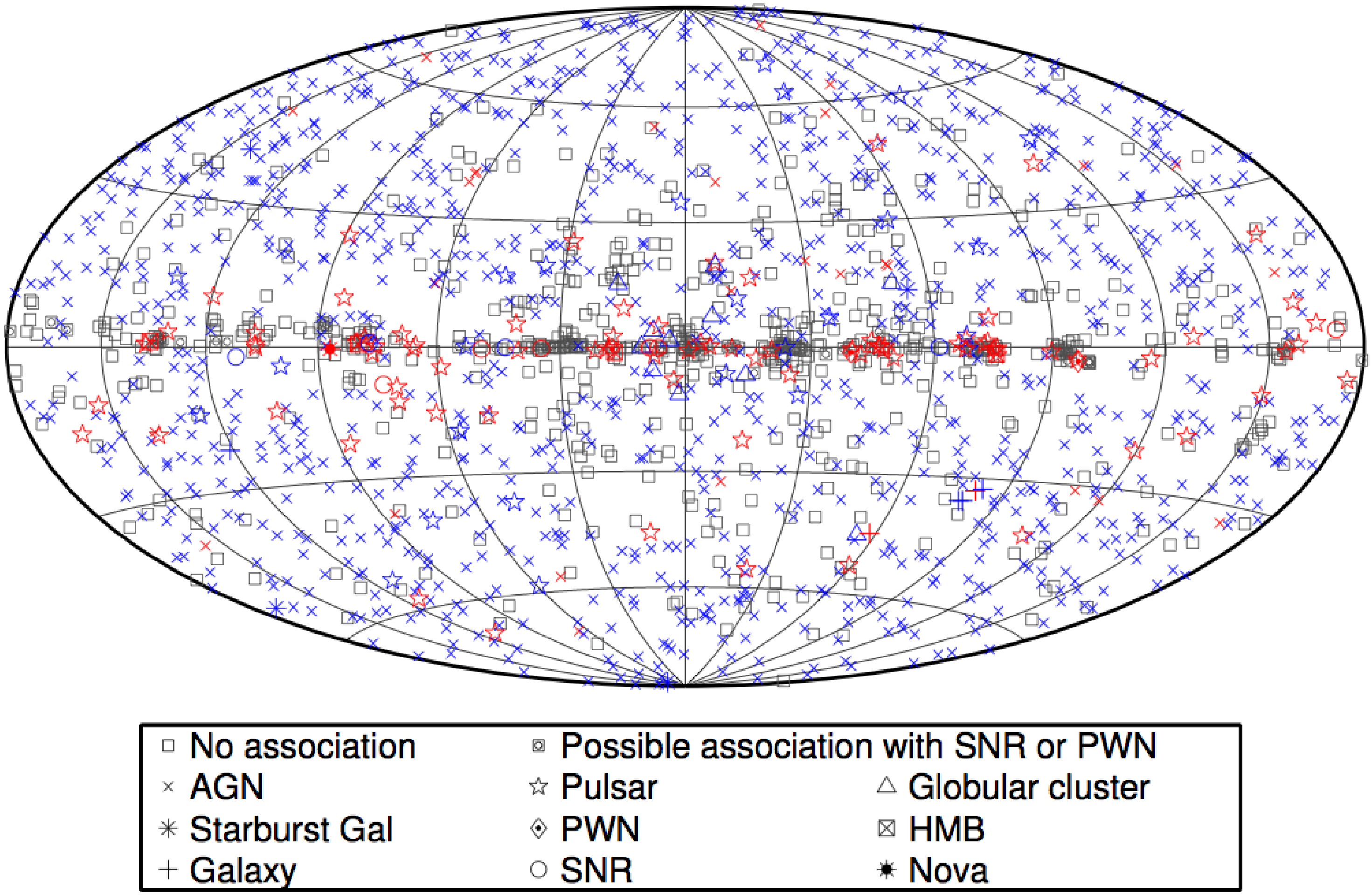




2FGL Associations

Red symbols: Identified sources

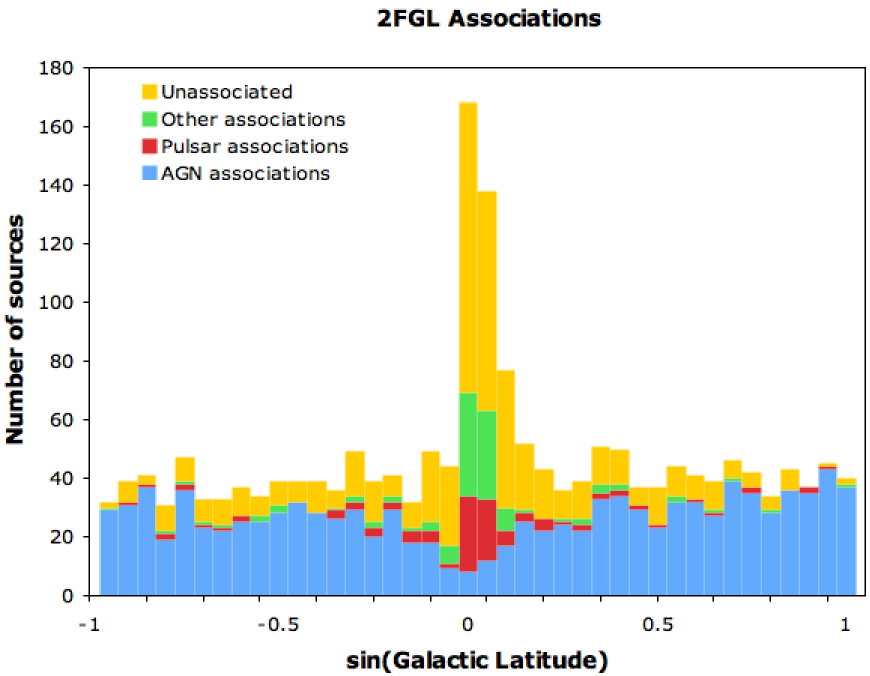
Blue symbols: Associated sources

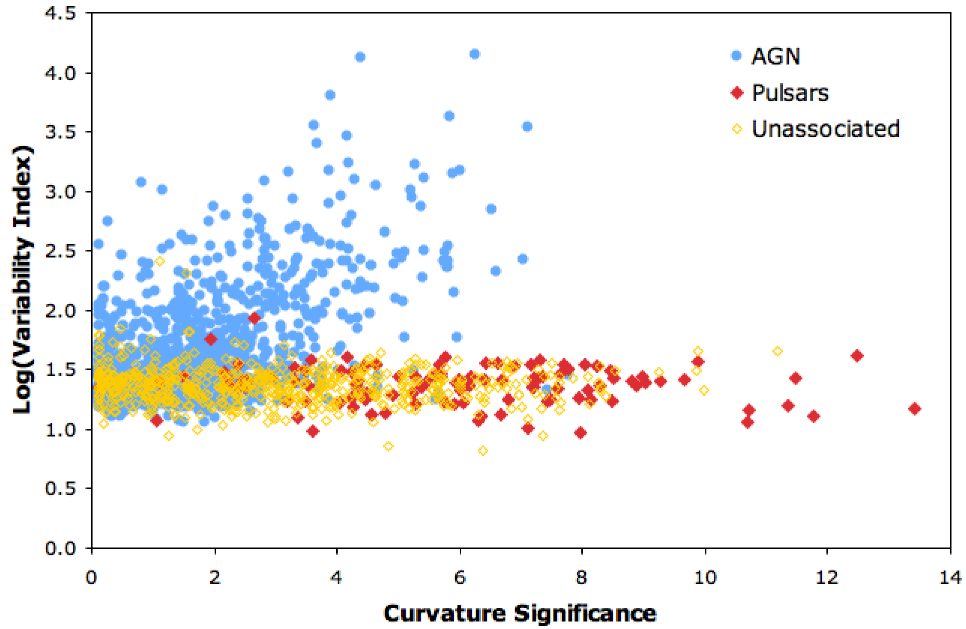


Classifications

CLASS	Identified	Associated
Pulsar, identified by pulsations	83	-
Pulsar, no pulsations seen in LAT yet	-	25
Pulsar wind nebula	3	0
Supernova remnant	6	4
Supernova remnant / Pulsar wind nebula	-	58
Globular cluster	0	11
High-mass binary	4	0
Nova	1	0
BL Lac type of blazar	7	428
FSRQ type of blazar	17	353
Non-blazar active galaxy	1	10
Radio galaxy	2	10
Seyfert galaxy	1	5
Active galaxy of uncertain type	0	257
Normal galaxy (or part)	2	4
Starburst galaxy	0	4
Class uncertain	-	1
Unassociated	**-**	**576**
Total	**127**	**1746**

Properties of the unassociated

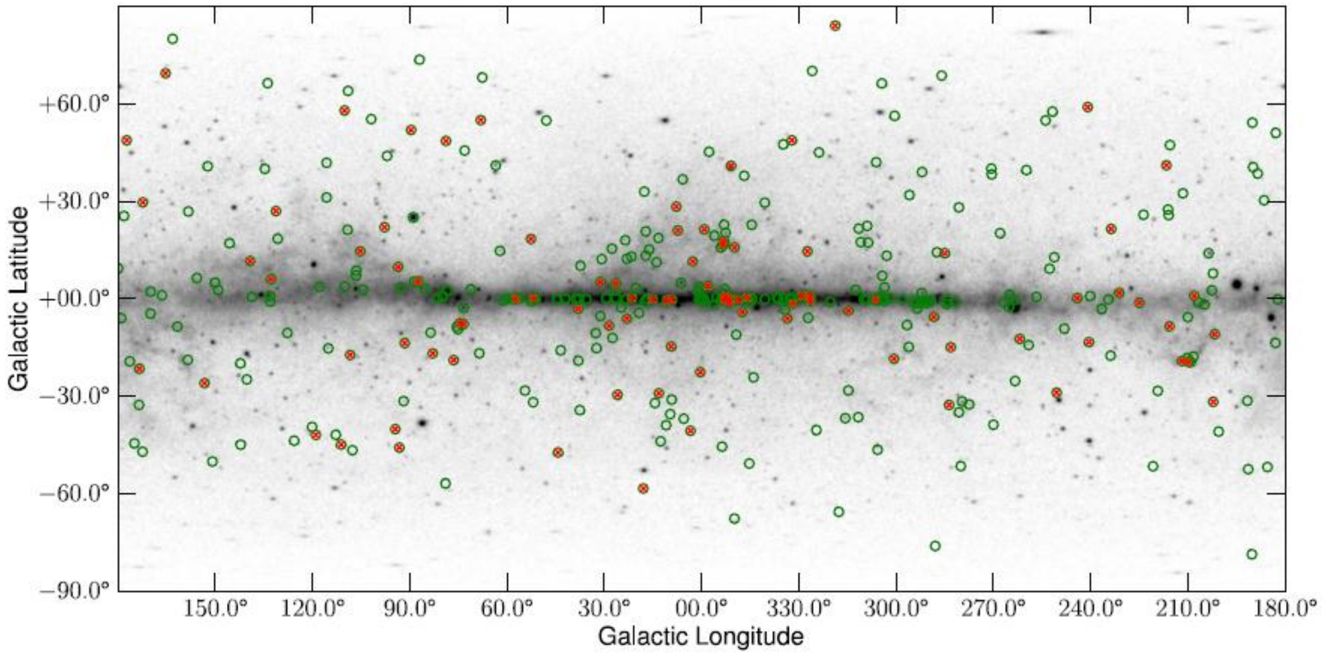




Additional details

- Why are so many 1FGL sources (352 out of 1499) not included in 2FGL??

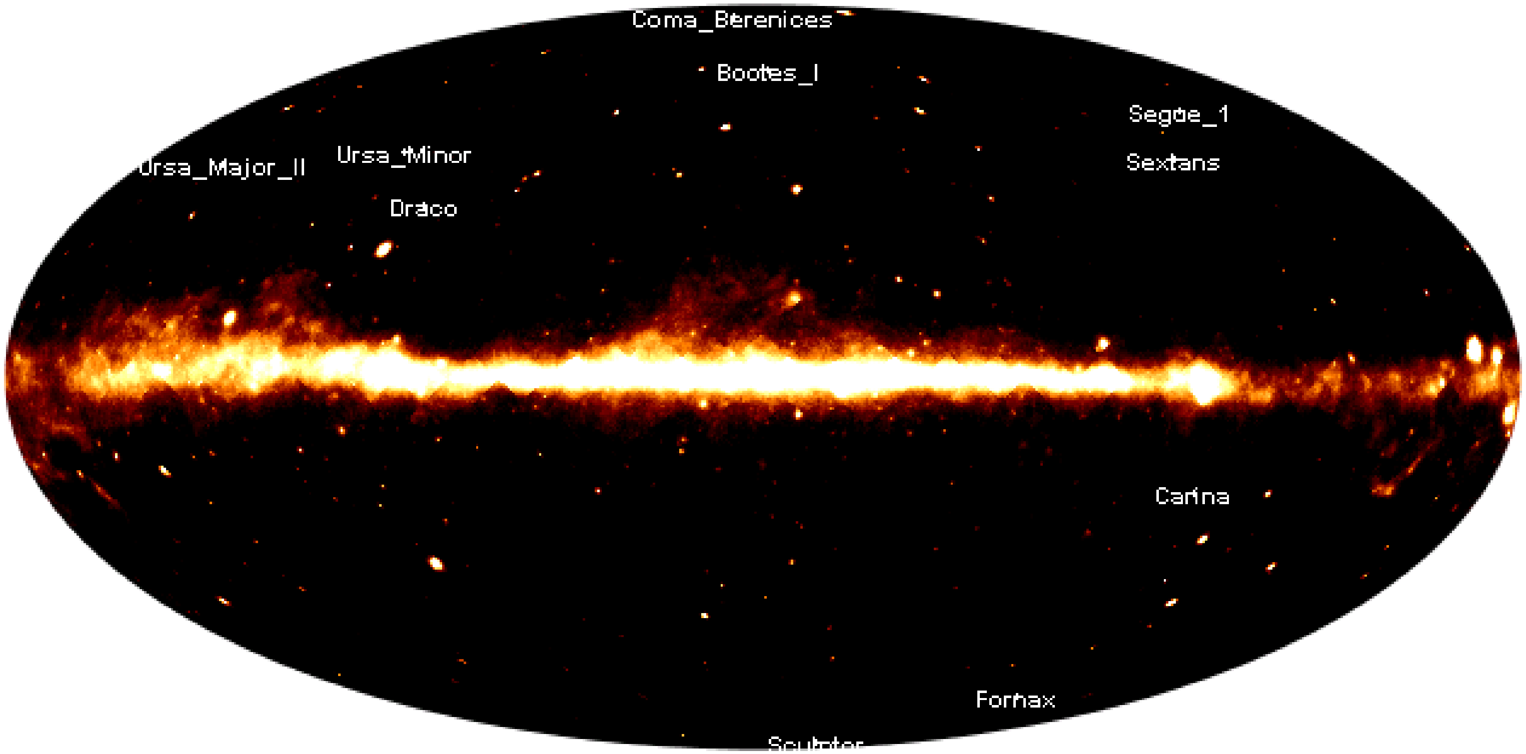
Green circles



Detailed analysis, ~10 pages, 8 figures focusing on different procedures narrows down to 89 'non-confirmed'

Some potential sources that we don't find are important!

- Milky Way satellite analysis



WIMP annihilation from Dwarf spherioidals

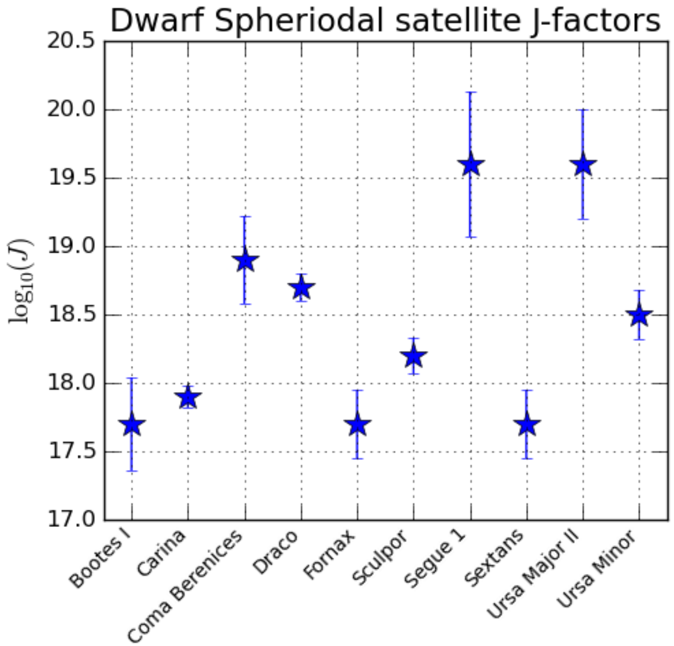
$$\phi_{WIMP}(E,\psi) = J(\psi) \times \Phi^{PP}(E)$$

Particle physics:

$$\Phi^{PP}(E) = \frac{1}{2}\frac{<\sigma_{ann} v>}{4\pi m^2_{WIMP}} \sum_f \frac{dN_f}{dE} B_f$$

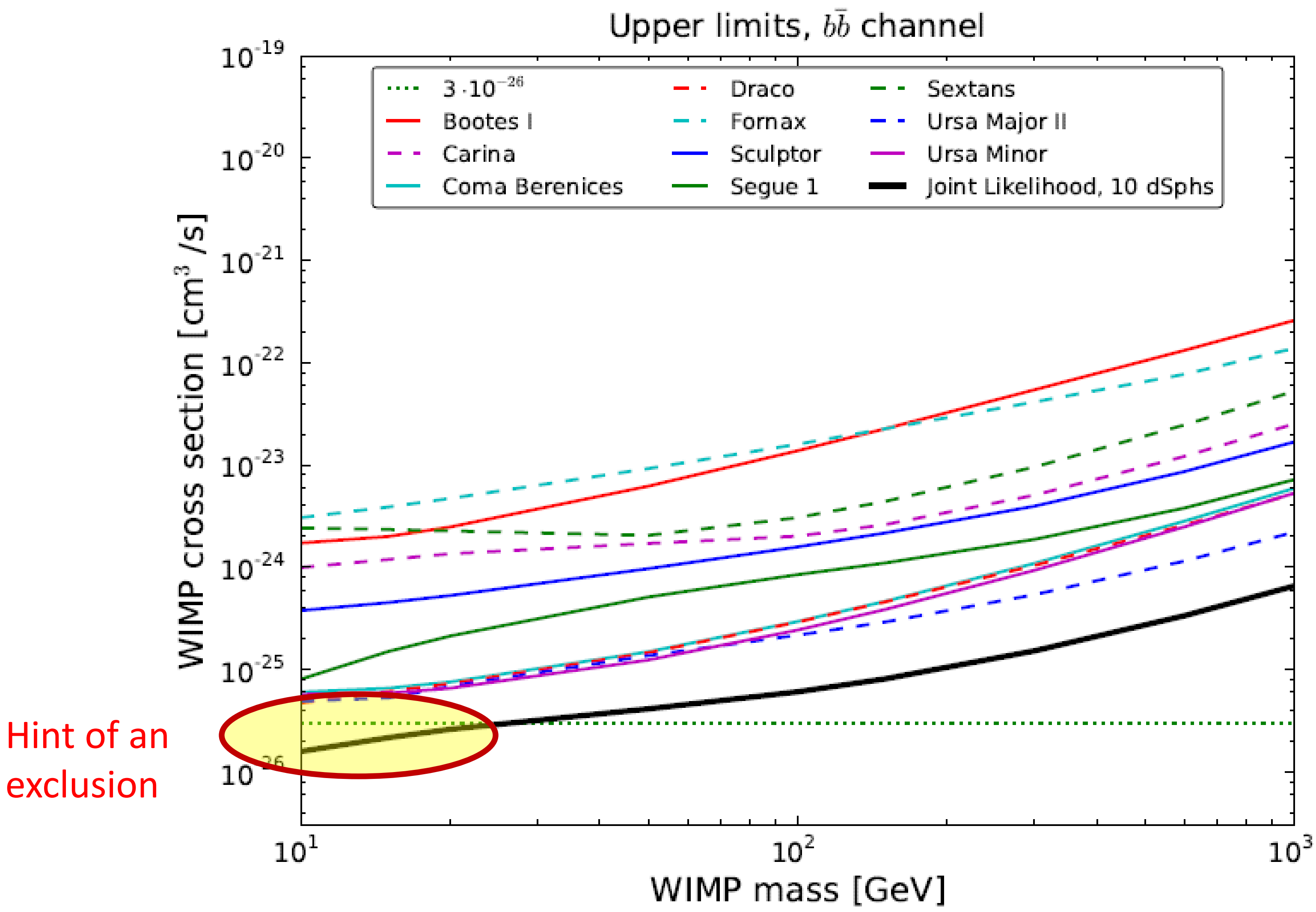
Astrophysics:

$$J(\psi) = \int_{l.o.s.} dl(\psi)\rho^2(l(\psi))$$



Uncertainties matter!

The result



Upper limits, $b\bar{b}$ channel
$3 \cdot 10^{-26}$
Bootes I
Carina
Coma Berenices
Draco
Fornax
Sculptor
Segue 1
Sextans
Ursa Major II
Ursa Minor
Joint Likelihood, 10 dSphs
WIMP cross section [cm^3 /s]
WIMP mass [GeV]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{1}
10^{2}
10^{3}
Hint of an exclusion

No time to cover

- Pulsars – up to 100 now, many MSPs, breakthroughs in blind detection
- AGNS
- GRBs
- The nova
- Diffuse analysis: do unresolved sources account for it?

Summary

- Many discoveries
- But: After three years, we are still trying to understand both the performance of the detector, and subtleties in the sky!
- Dark matter still the holy grail ☺