Milagro TeV Galactic Unidentified Sources

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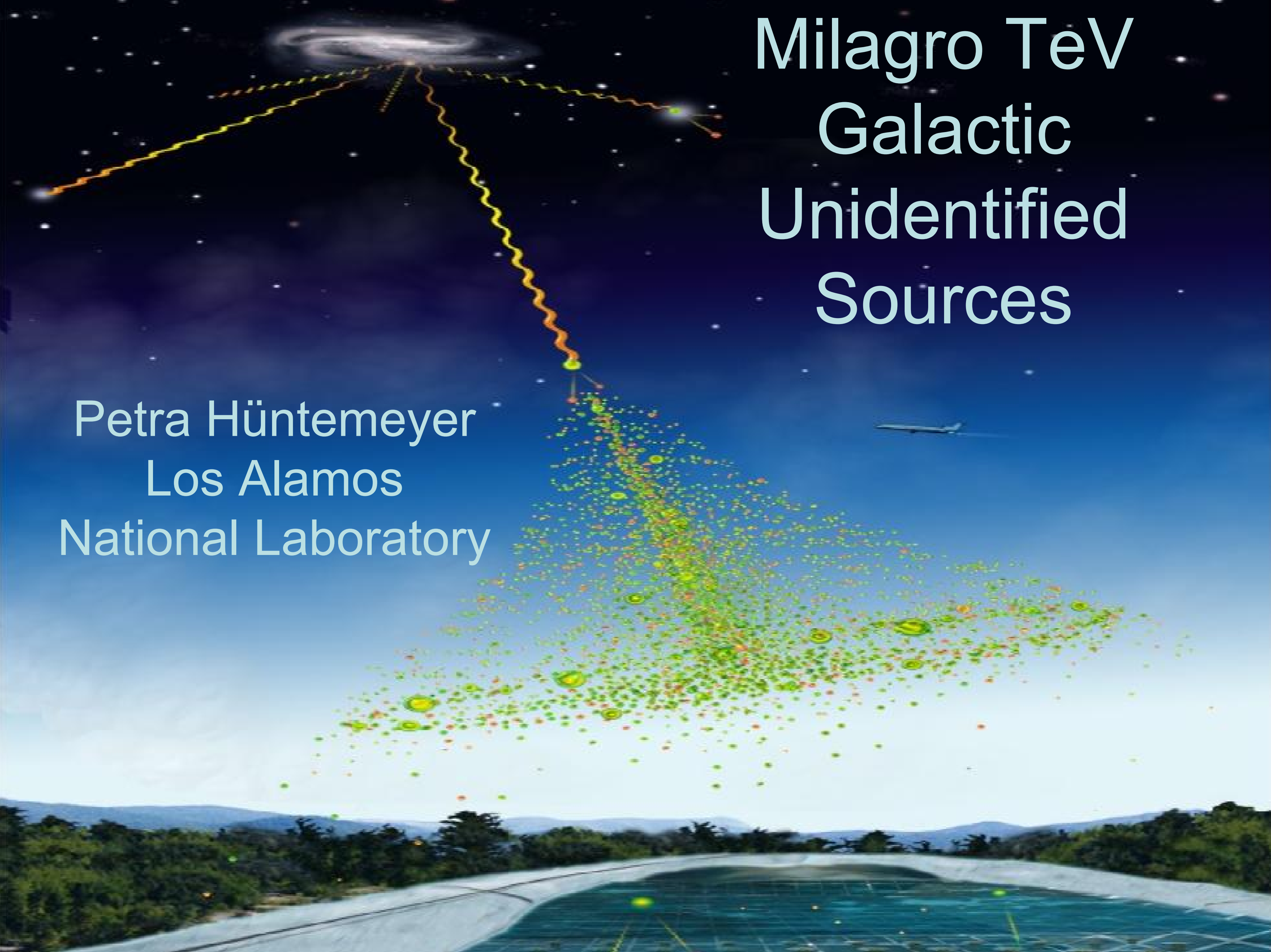
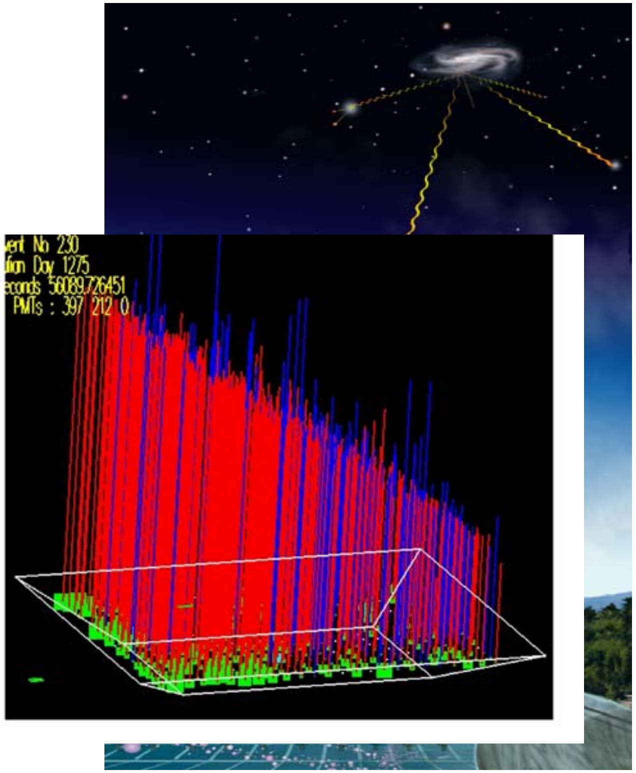


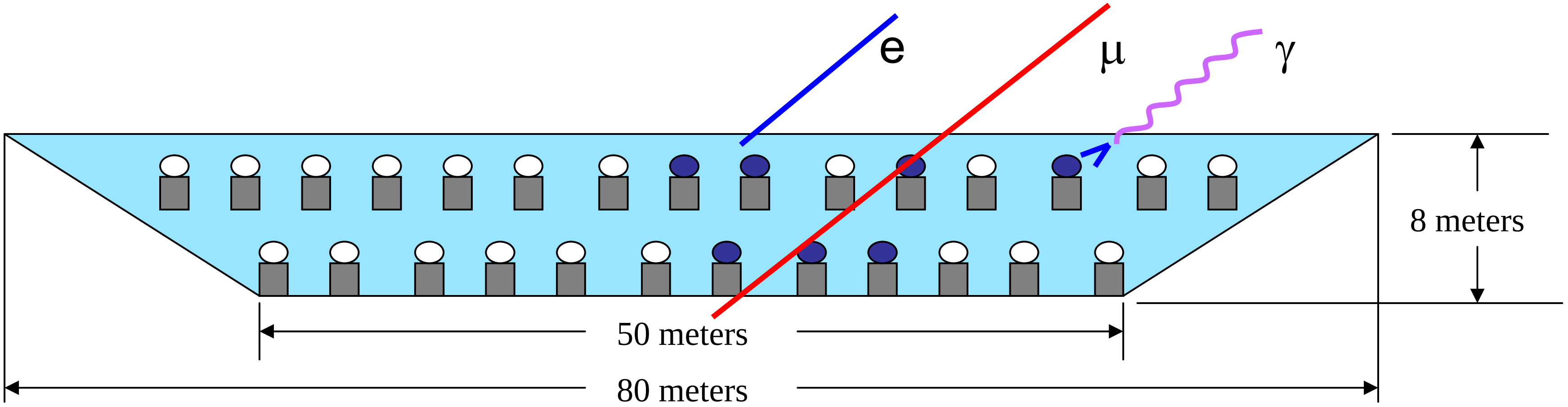
Milagro Gamma Ray Observatory @ 8600' altitude near Los Alamos, NM

A. Abdo, B. Allen, D. Berley, T. DeYoung,B.L. Dingus, R.W. Ellsworth, M.M. Gonzalez, J.A. Goodman, C.M. Hoffman,P. Huntemeyer, B. Kolterman, C.P. Lansdell, J.T. Linnemann, J.E. McEnery, A.I. Mincer, P. Nemethy, J. Pretz, J.M. Ryan, P.M. Saz Parkinson, A. Shoup, G. Sinnis, A.J. Smith, G.W. Sullivan, D.A. Williams, V. Vasileiou, G.B. Yodh

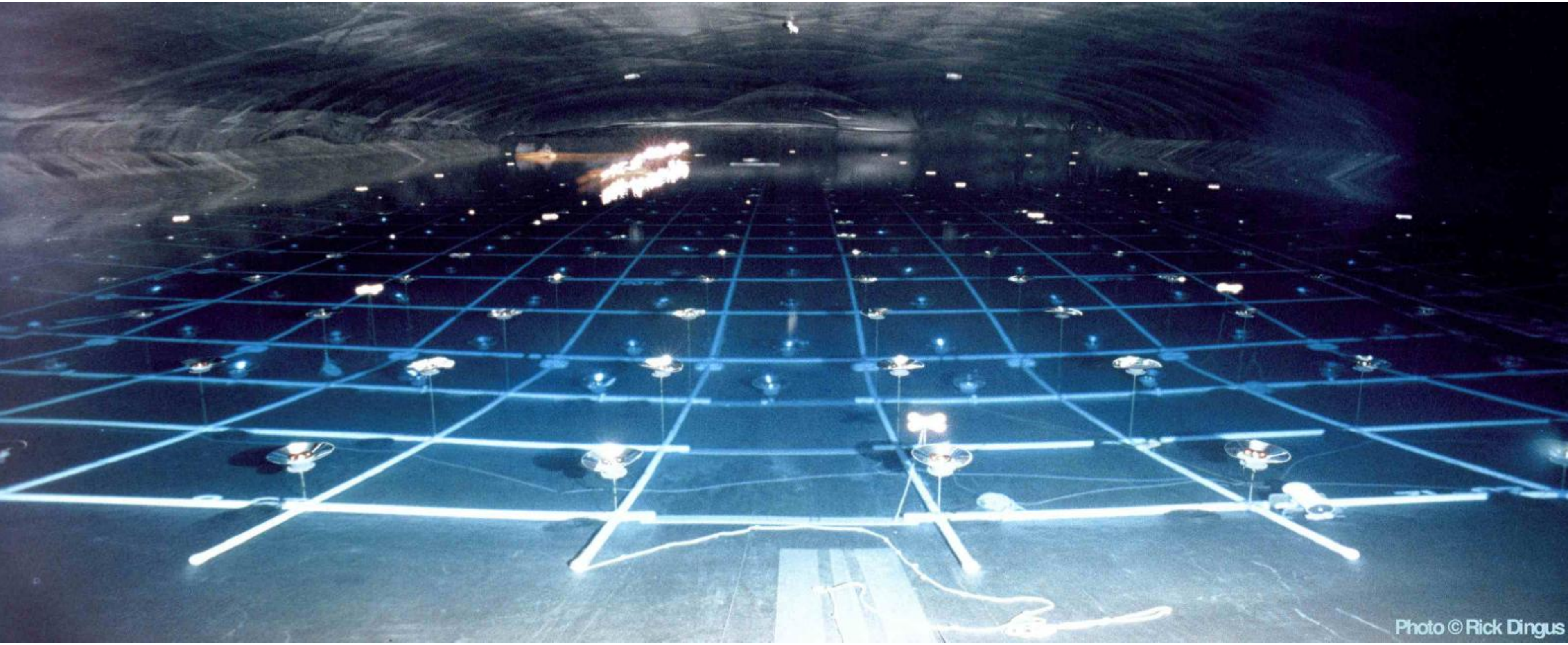
The Instrument: Milagro



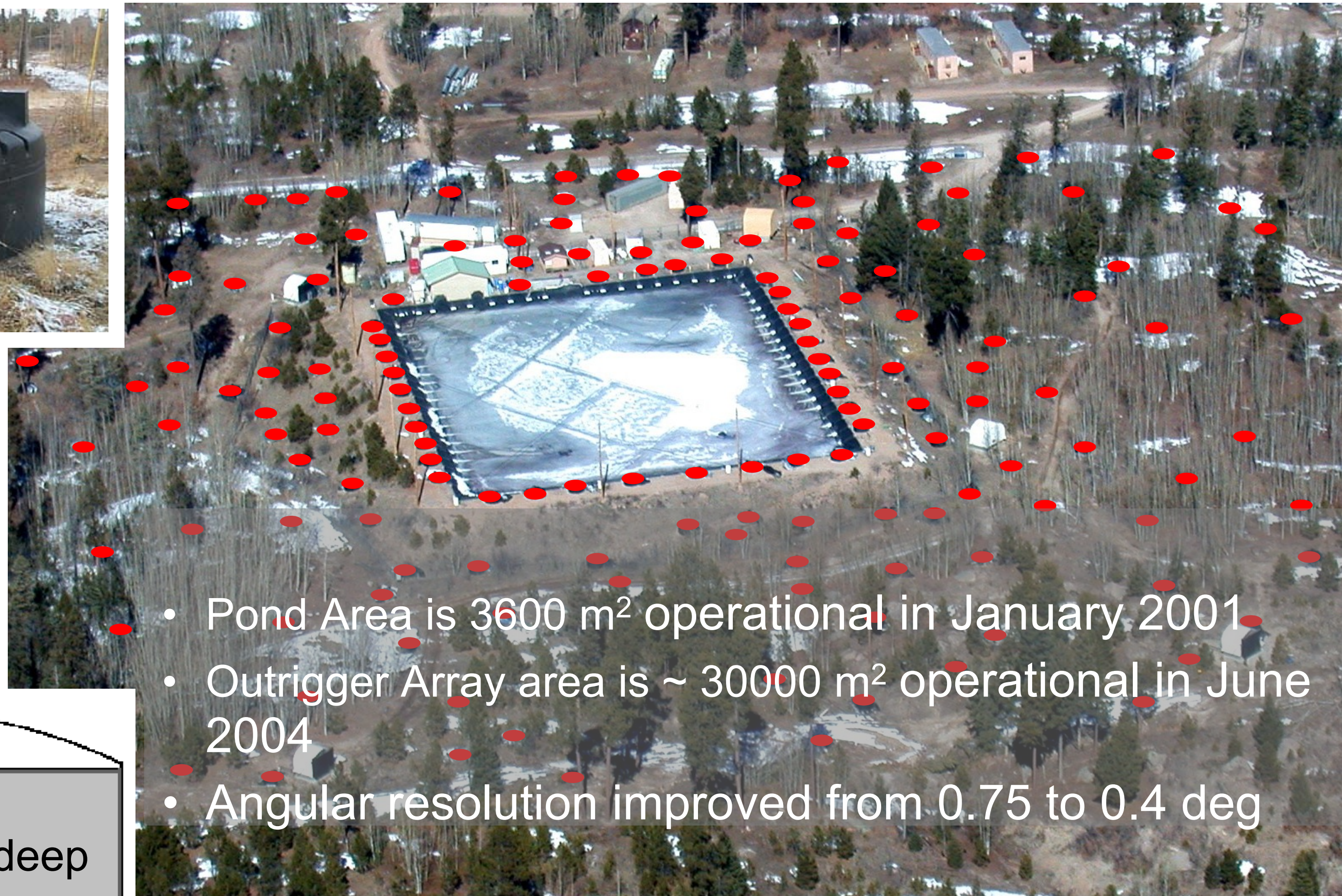
- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water
- Field of view is ~2 sr and the average duty factor is >90%
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Reconstruct shower direction to ~0.75° from the time different PMTs are hit



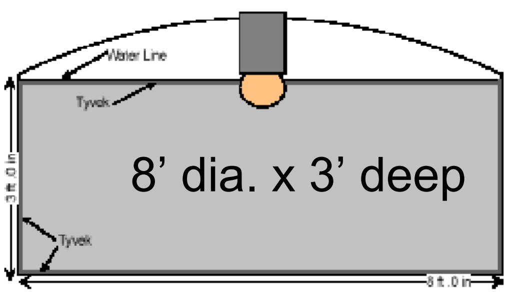
Inside the Milagro Detector



Array of 175 Outriggers



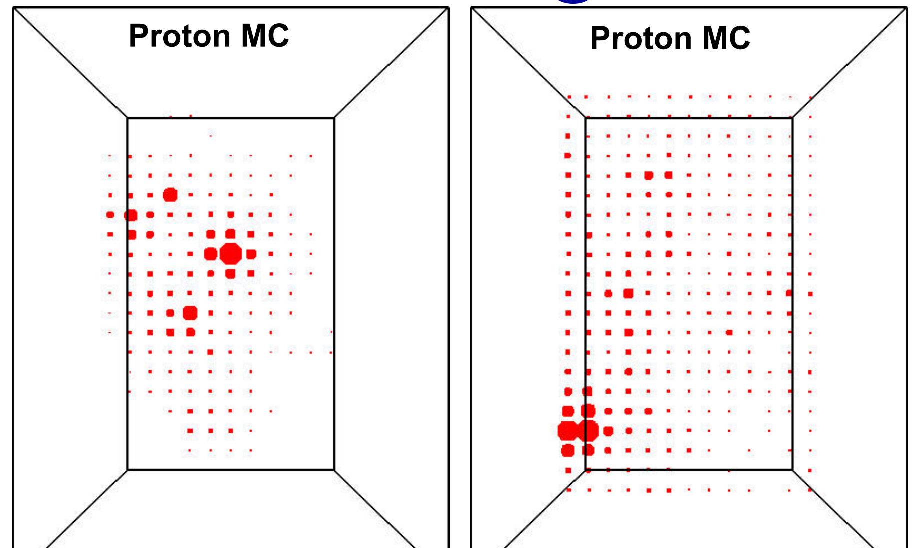
- Pond Area is 3600 m^2 operational in January 2001
- Outrigger Array area is ~ 30000 m^2 operational in June 2004
- Angular resolution improved from 0.75 to 0.4 deg

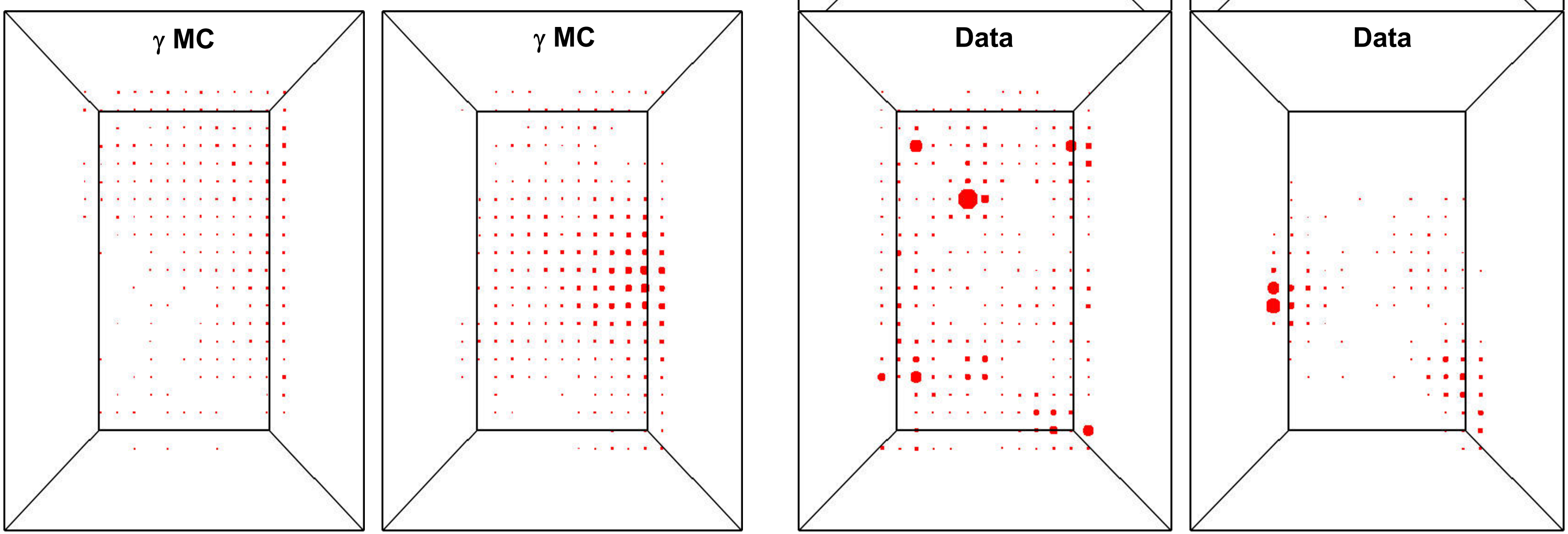


Background Rejection in Milagro

Hadronic showers contain penetrating component: μ's & hadrons

- Cosmic-ray showers lead to clumpier bottom layer hit distributions
- Gamma-ray showers give smooth hit distributions

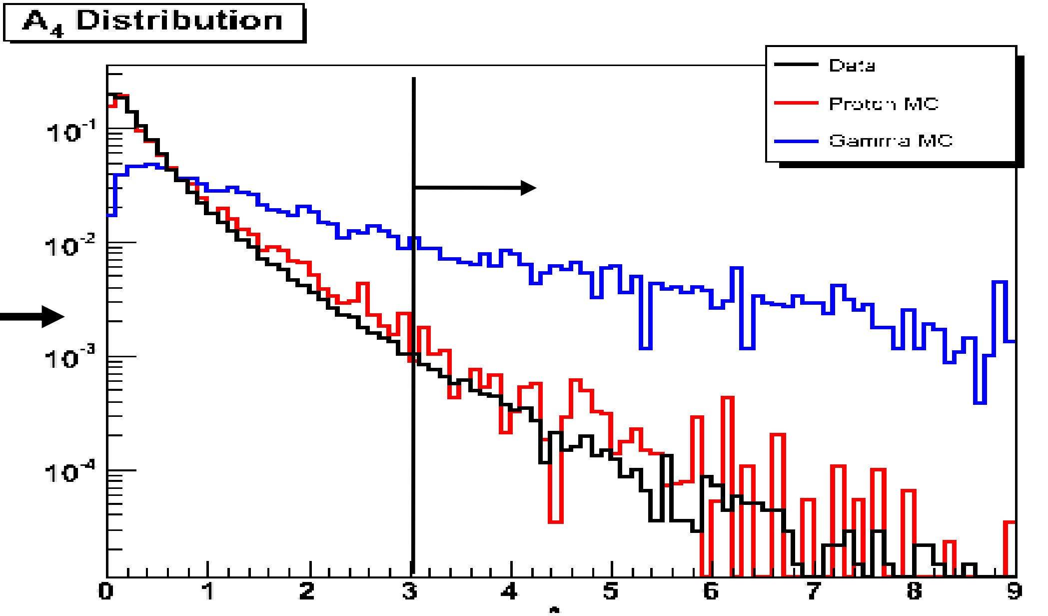




Milagro Background Rejection (Cont'd)

Background Rejection Parameter

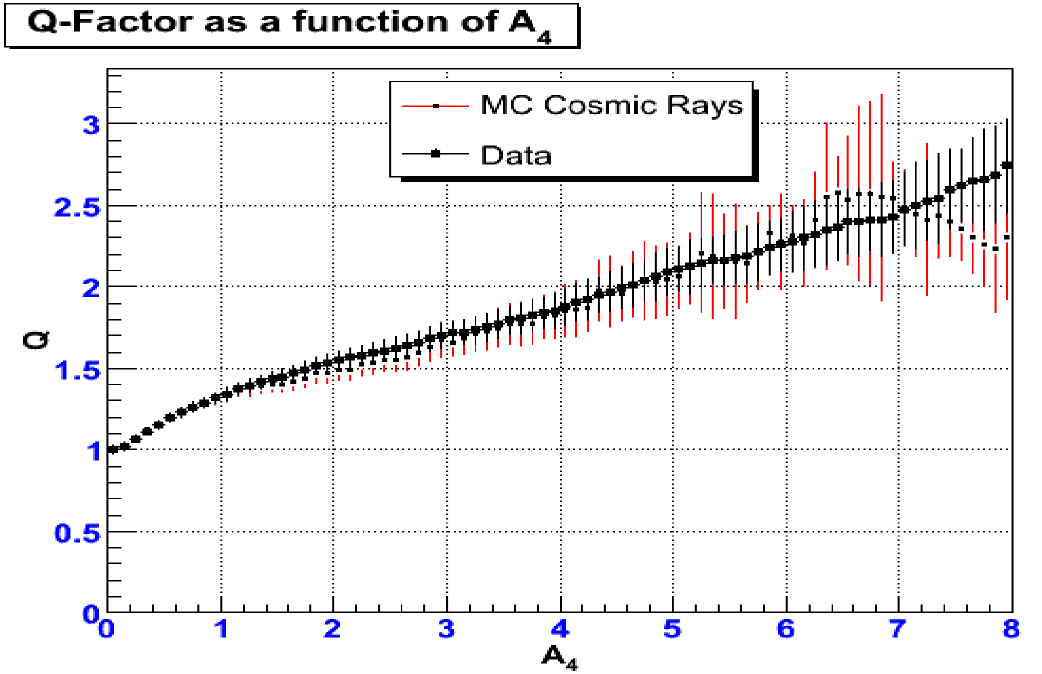
$$A_4 = \frac{(fTop + fOut) * nFit}{mxPE}$$

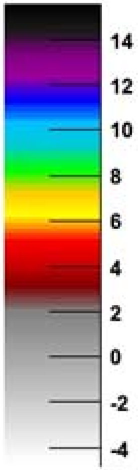


mxPE:	maximum # PEs in bottom layer PMT
fTop:	fraction of hit PMTs in Top layer
fOut:	fraction of hit PMTs in Outriggers
nFit:	# PMTs used in the angle reconstruction

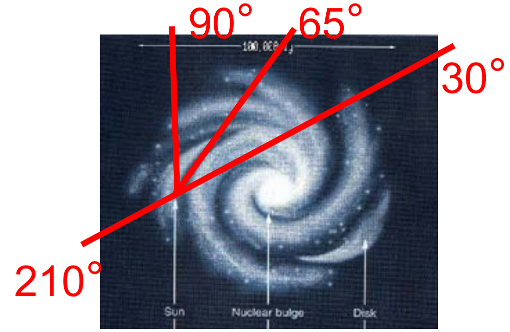
S/B increases with increasing A_4 so analysis weights events by S/B as determined by the A_4 value of the event

Improves sensitivity by ~2x



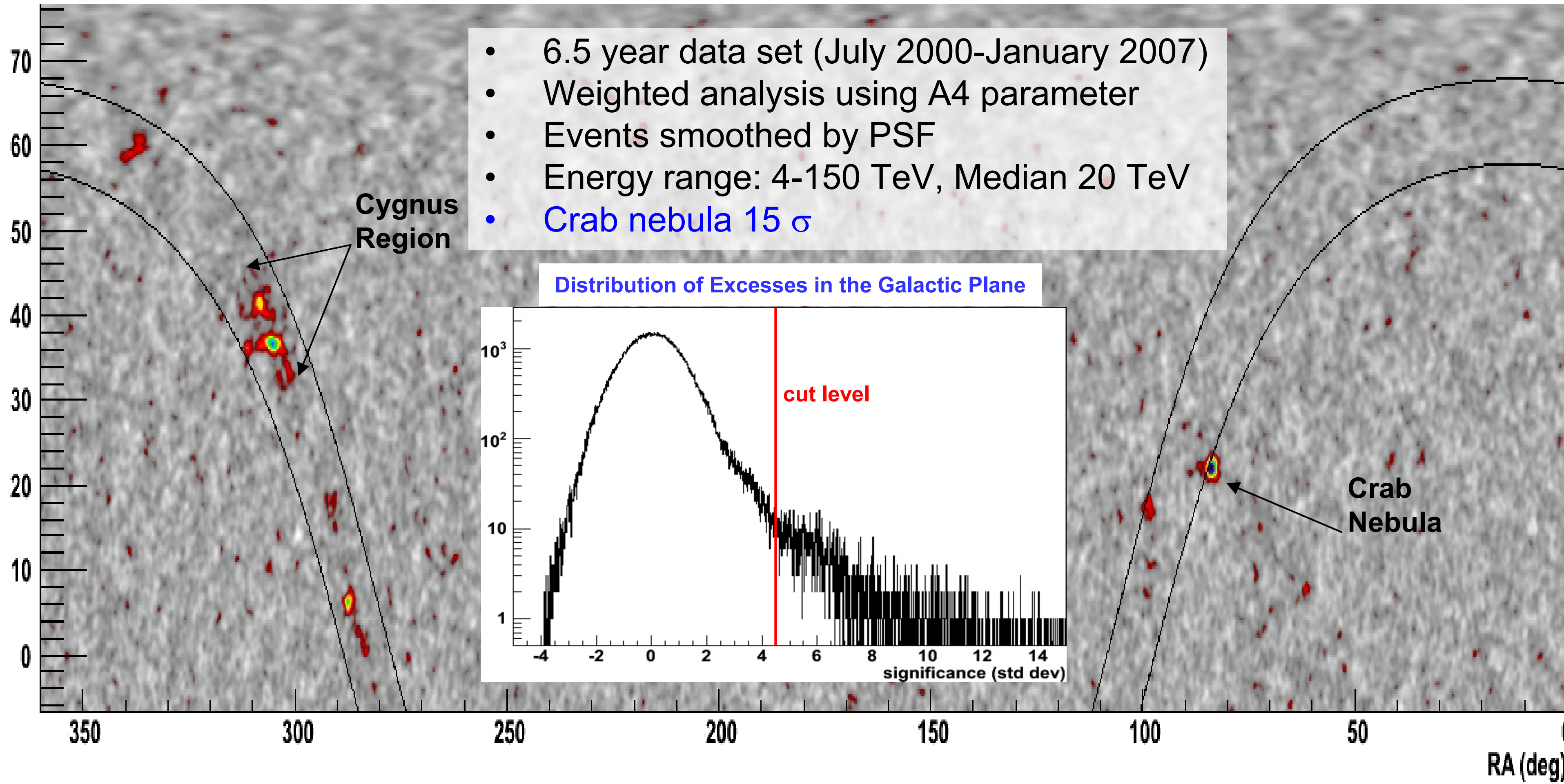


Milagro Survey

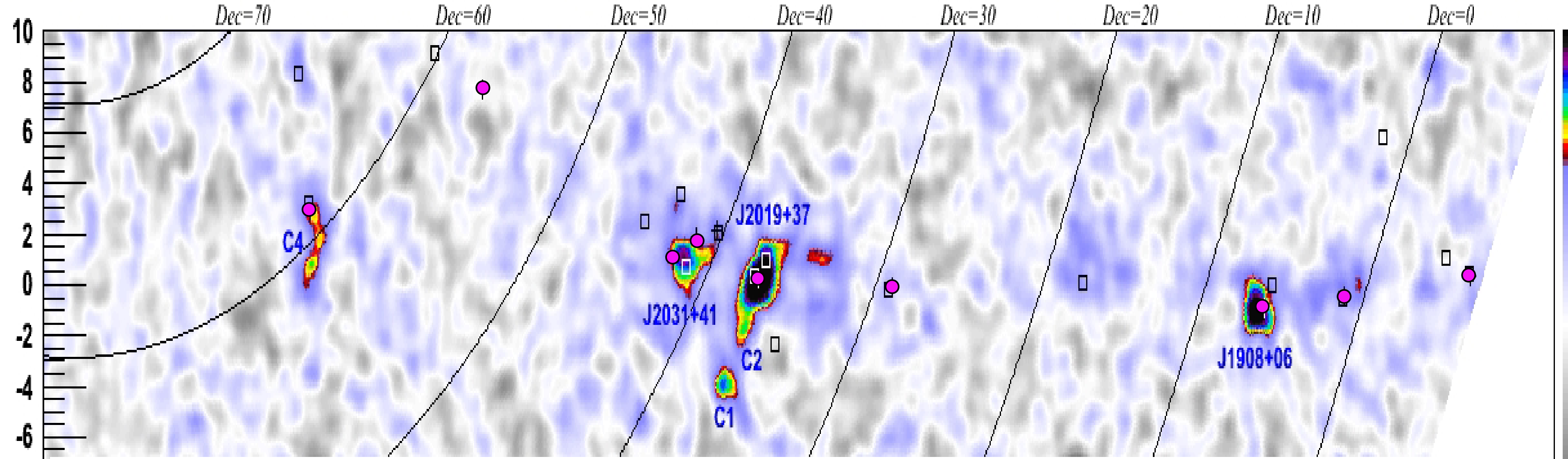


Milagro sees the Galactic plane from longitude ~30° to ~220°

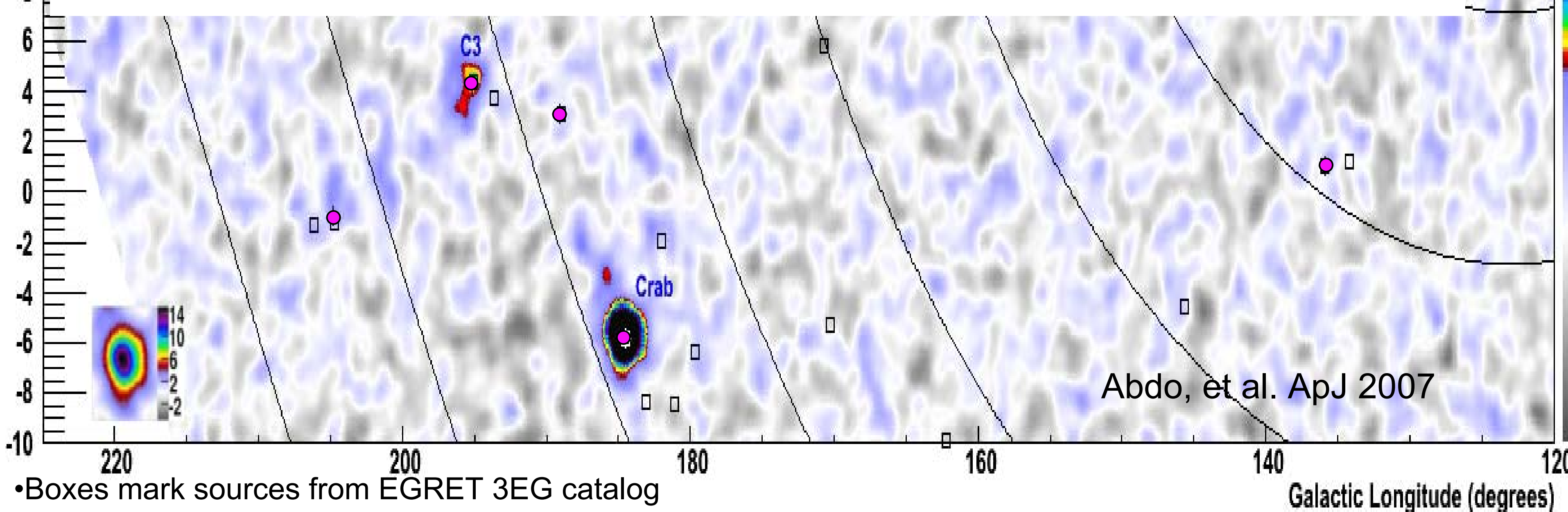
- 6.5 year data set (July 2000-January 2007)
- Weighted analysis using A4 parameter
- Events smoothed by PSF
- Energy range: 4-150 TeV, Median 20 TeV
- Crab nebula 15 σ



Distribution of Excesses in the Galactic Plane



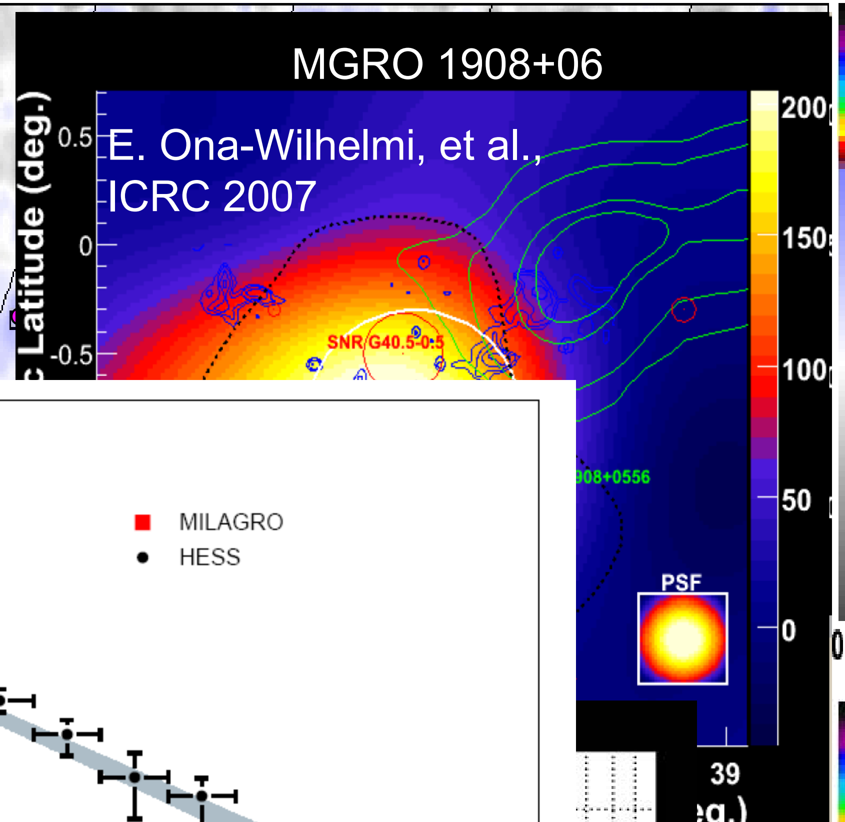
- Milagro has discovered 3 new sources & 4 candidate sources in the Galaxy.
- 5/7 of these TeV sources have GeV counterparts (only 13 GeV counterparts in this region - excluding Crab)
  - Probability = 3×10^{-6}

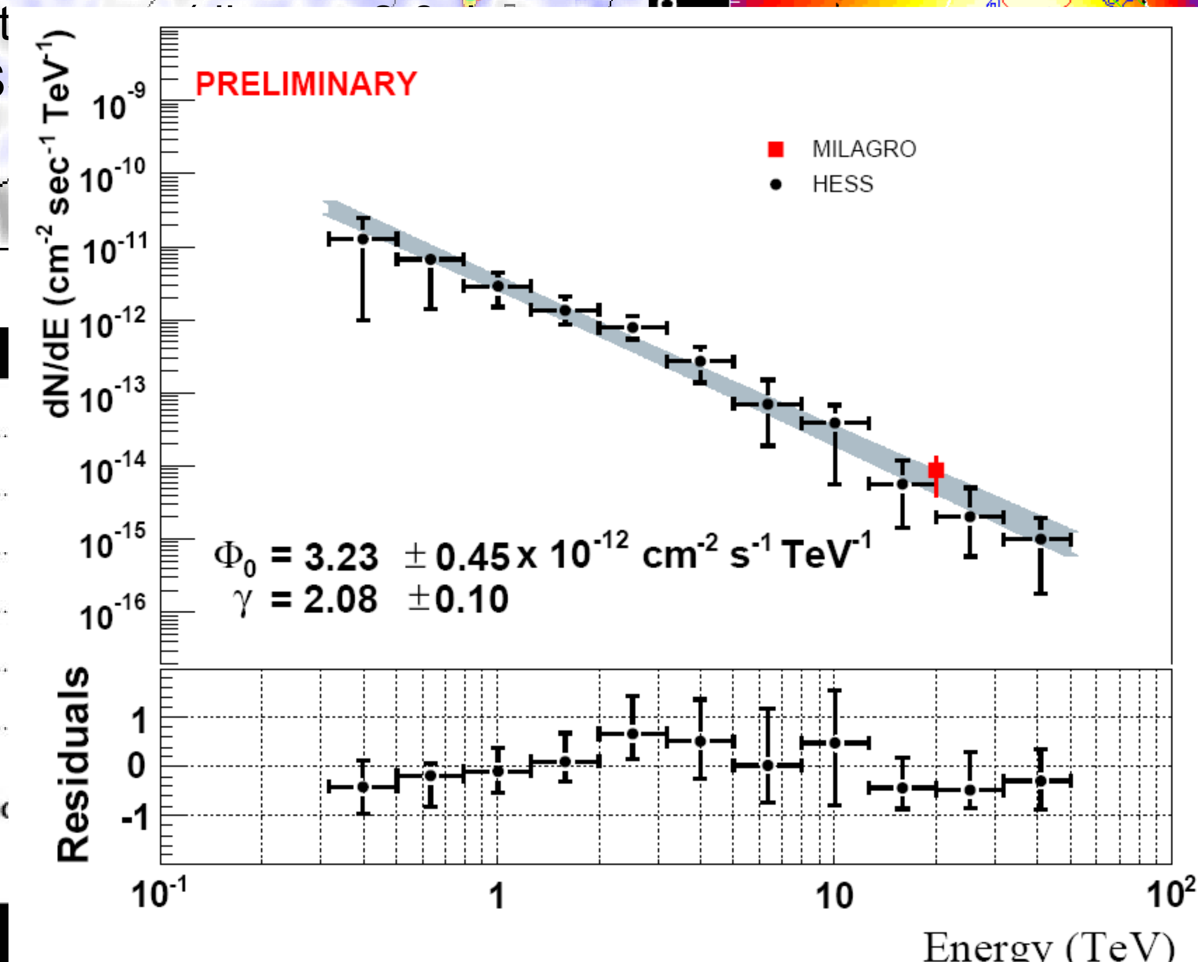


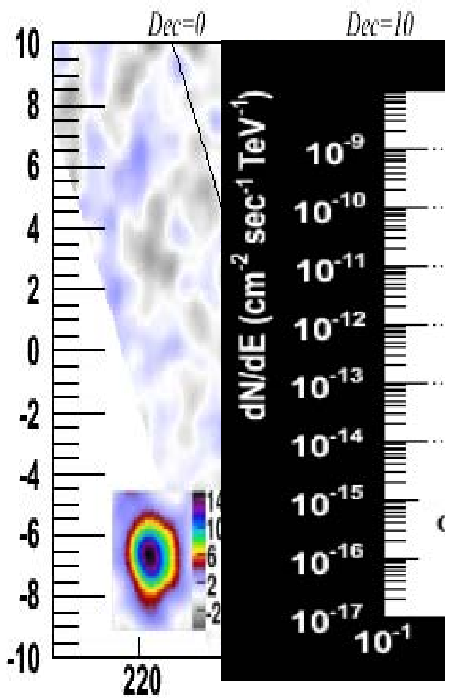
•Boxes mark sources from EGRET 3EG catalog

Dec=70 Dec=60 Dec=50 Dec=40 Dec=30 Dec=20 Dec=10 Dec=0

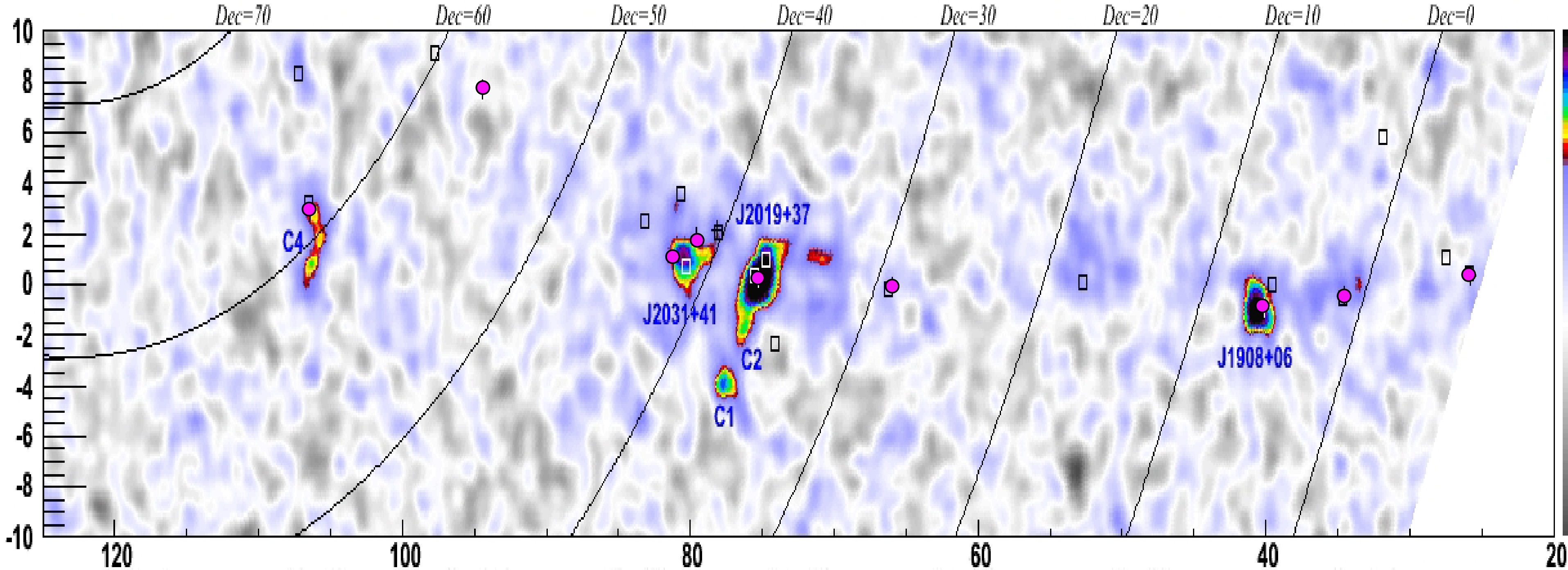
- 80% of the Crab flux
- 87 hr observation by HEGRA upper limit of 2.6% of the Crab flux (700 GeV)
- could be both extended and point … HES …

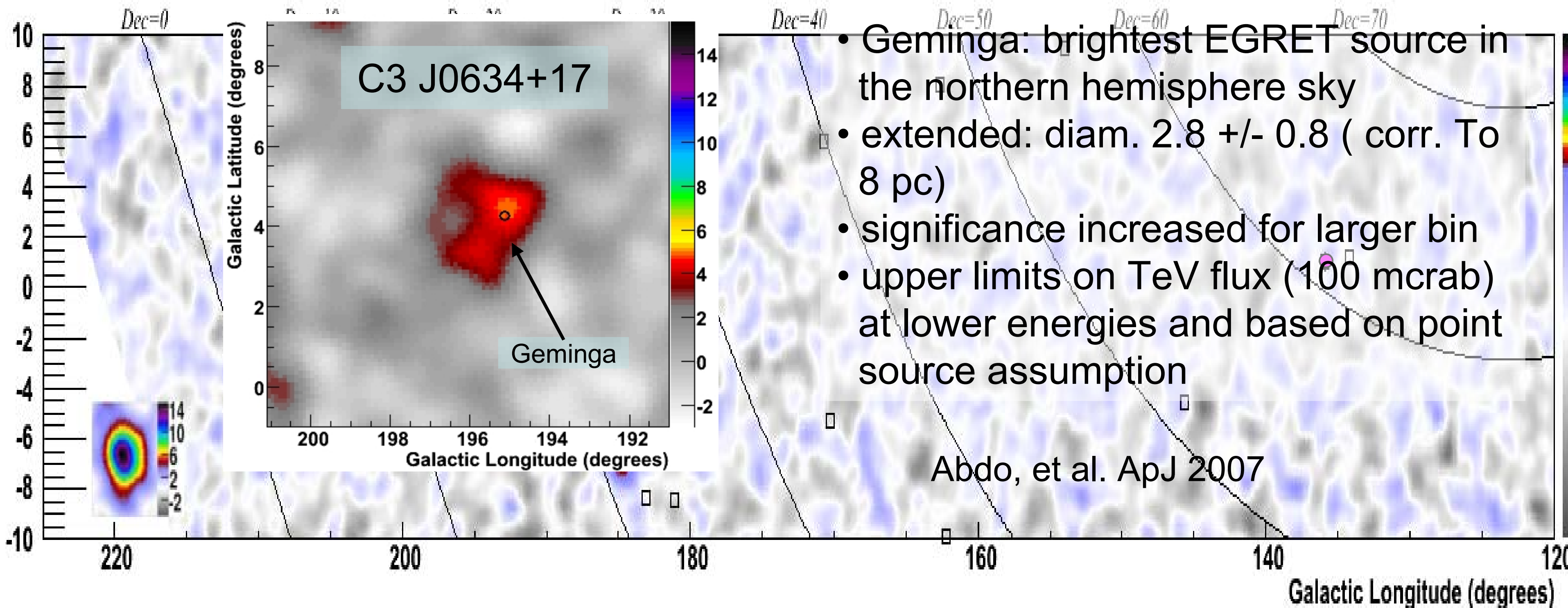






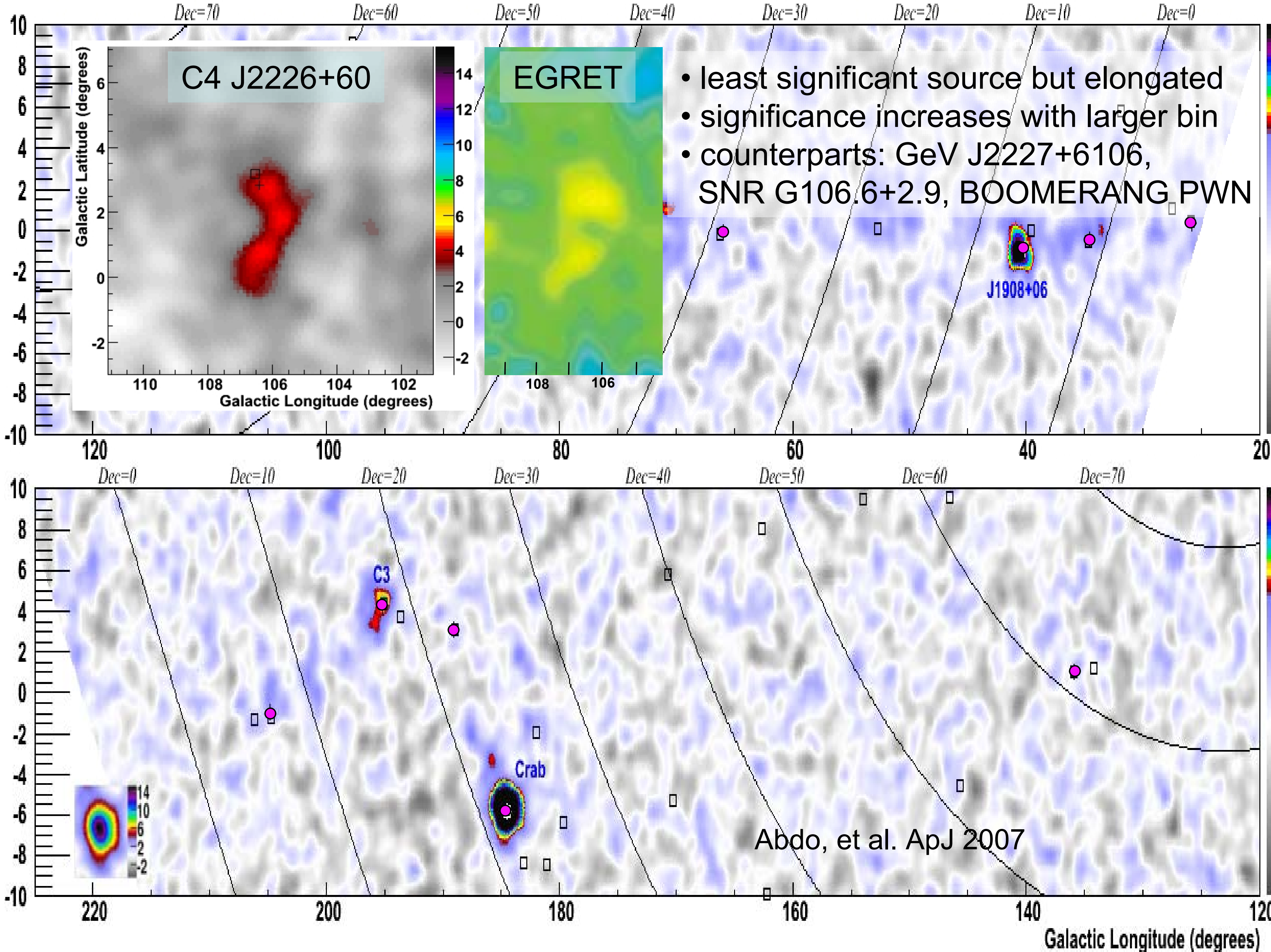
Galactic Longitude (degrees)

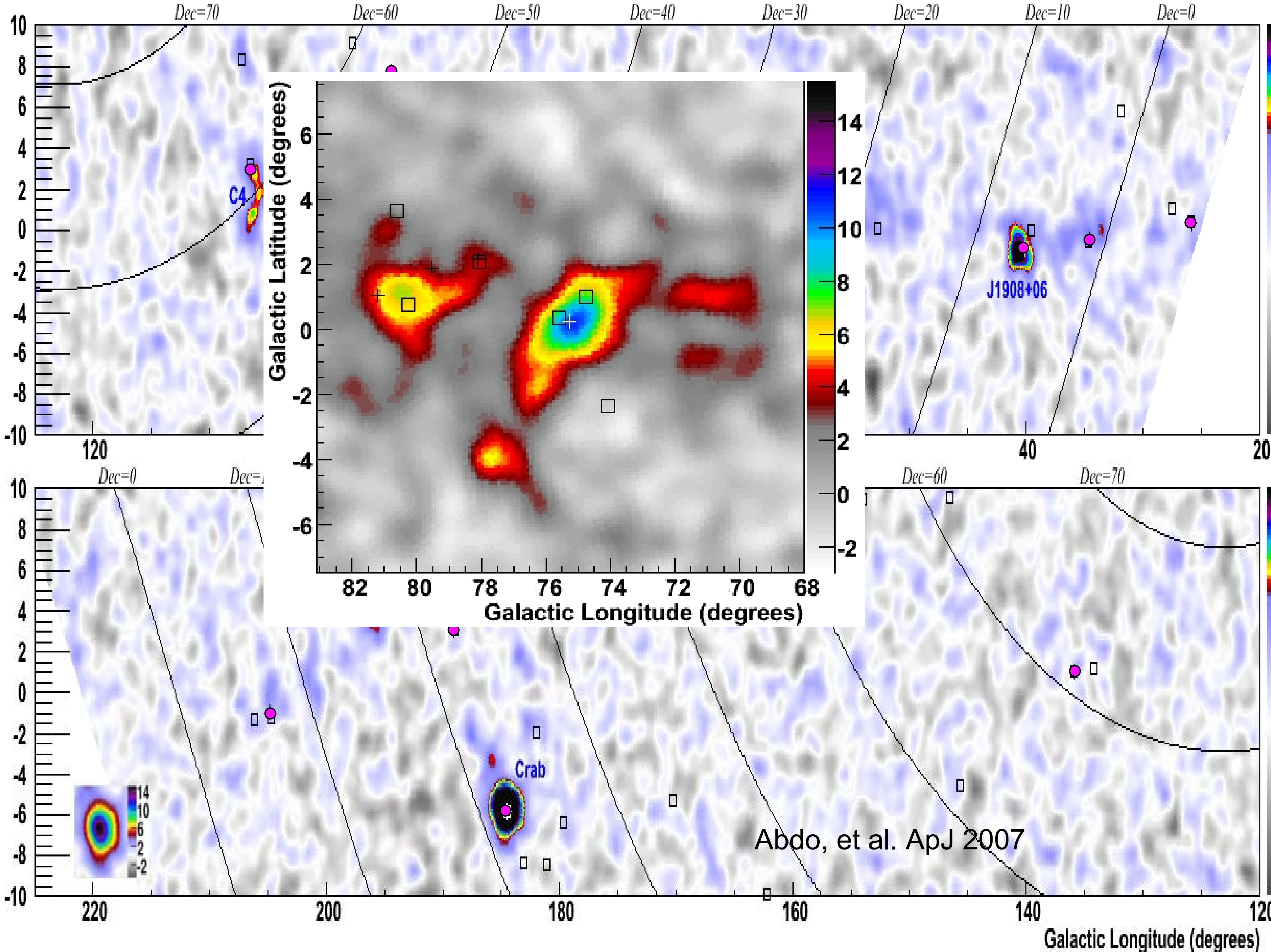




- Geminga: brightest EGRET source in the northern hemisphere sky
- extended: diam. 2.8 +/- 0.8 (corr. To 8 pc)
- significance increased for larger bin
- upper limits on TeV flux (100 mcrab) at lower energies and based on point source assumption

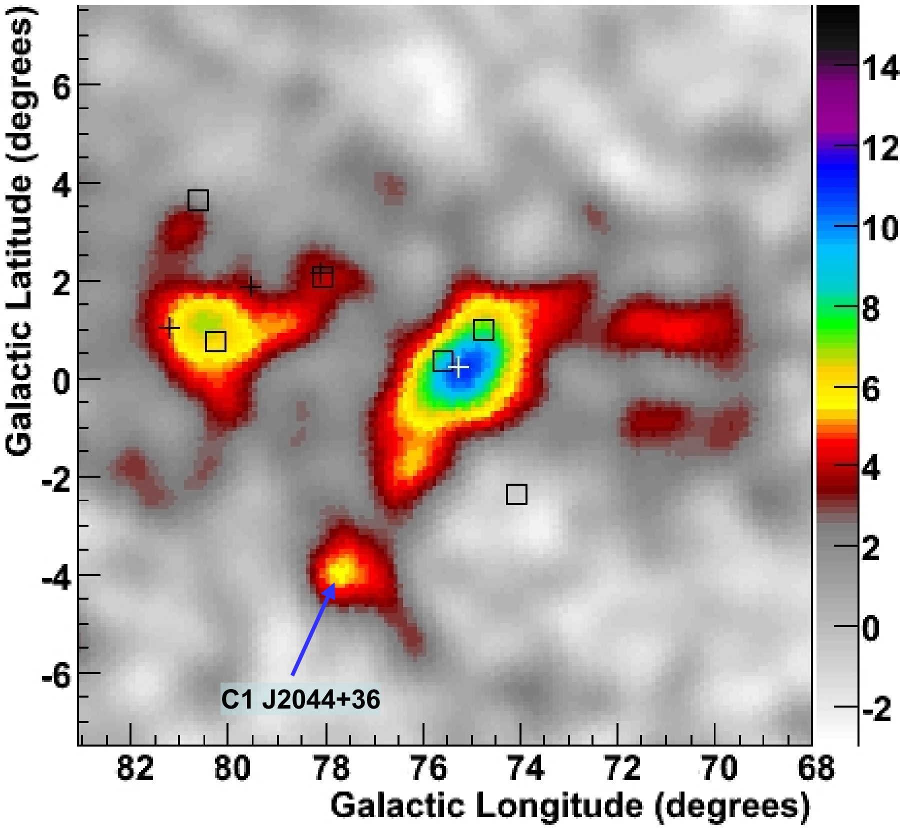
Abdo, et al. ApJ 2007


C4 J2226+60
EGRET
• least significant source but elongated
• significance increases with larger bin
• counterparts: GeV J2227+6106,
SNR G106.6+2.9, BOOMERANG PWN
Galactic Latitude (degrees)
Galactic Longitude (degrees)
J1908+06
C3
Crab
Abdo, et al. ApJ 2007
Dec=0
Dec=10
Dec=20
Dec=30
Dec=40
Dec=50
Dec=60
Dec=70



Dec=70
Dec=60
Dec=50
Dec=40
Dec=30
Dec=20
Dec=10
Dec=0
C4
J1908+06
Galactic Latitude (degrees)
Galactic Longitude (degrees)
Dec=0
Dec=60
Dec=70
Crab
Abdo, et al. ApJ 2007
Galactic Longitude (degrees)

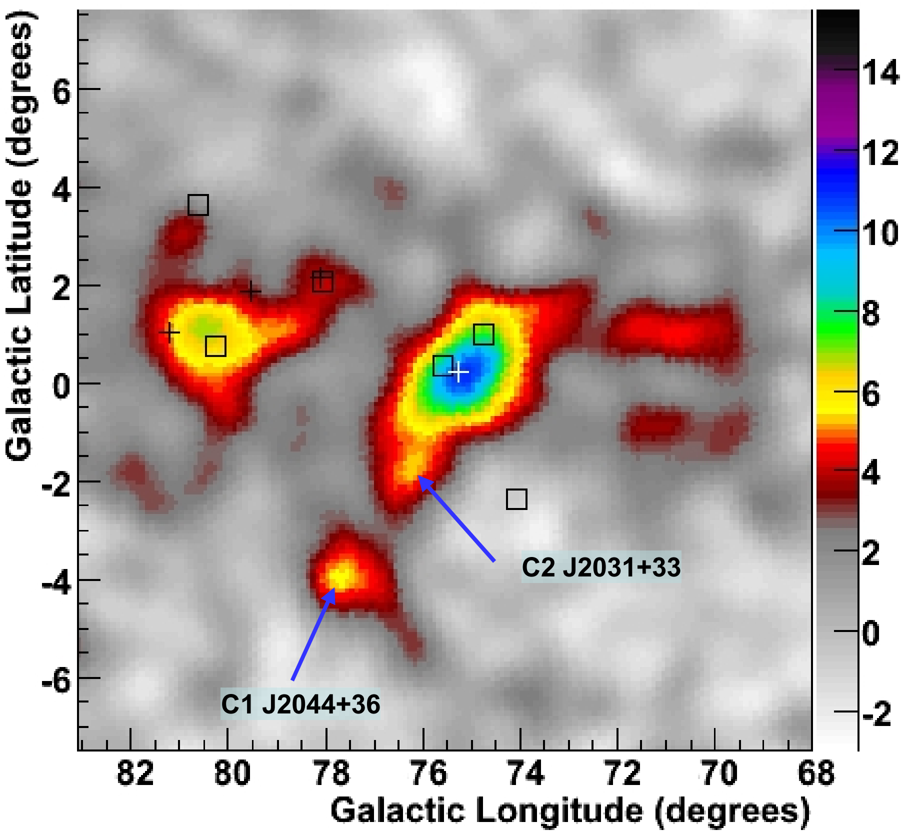
The Cygnus Region



- C1 J2044+36: 5.8σ pre-trials
  - no counterparts
  - < 2.0°

Abdo, et al. ApJ 2007

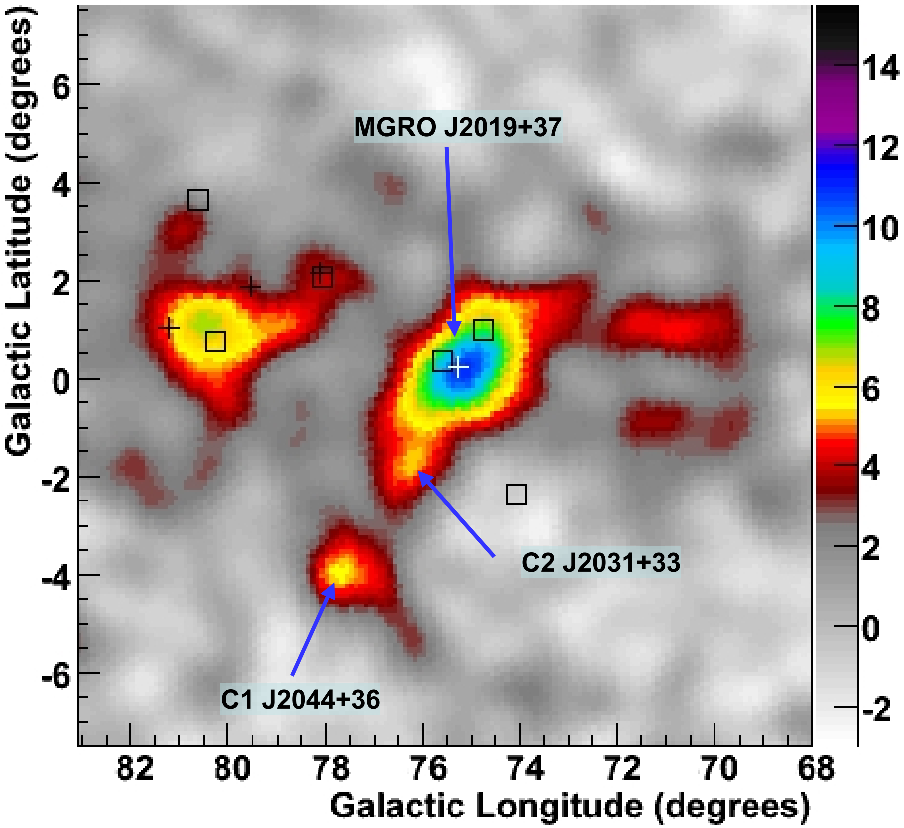
The Cygnus Region



- C1 J2044+36: 5.8σ pre-trials
  - no counterparts
  - < 2.0°
- C2 J2031+33: 5.1σ pre-trials
  - no counterparts
  - possible extension of MGRO J2019+37
  - possible fluctuation of MGRO J2019 tail & diffuse emission & background

Abdo, et al. ApJ 2007

The Cygnus Region

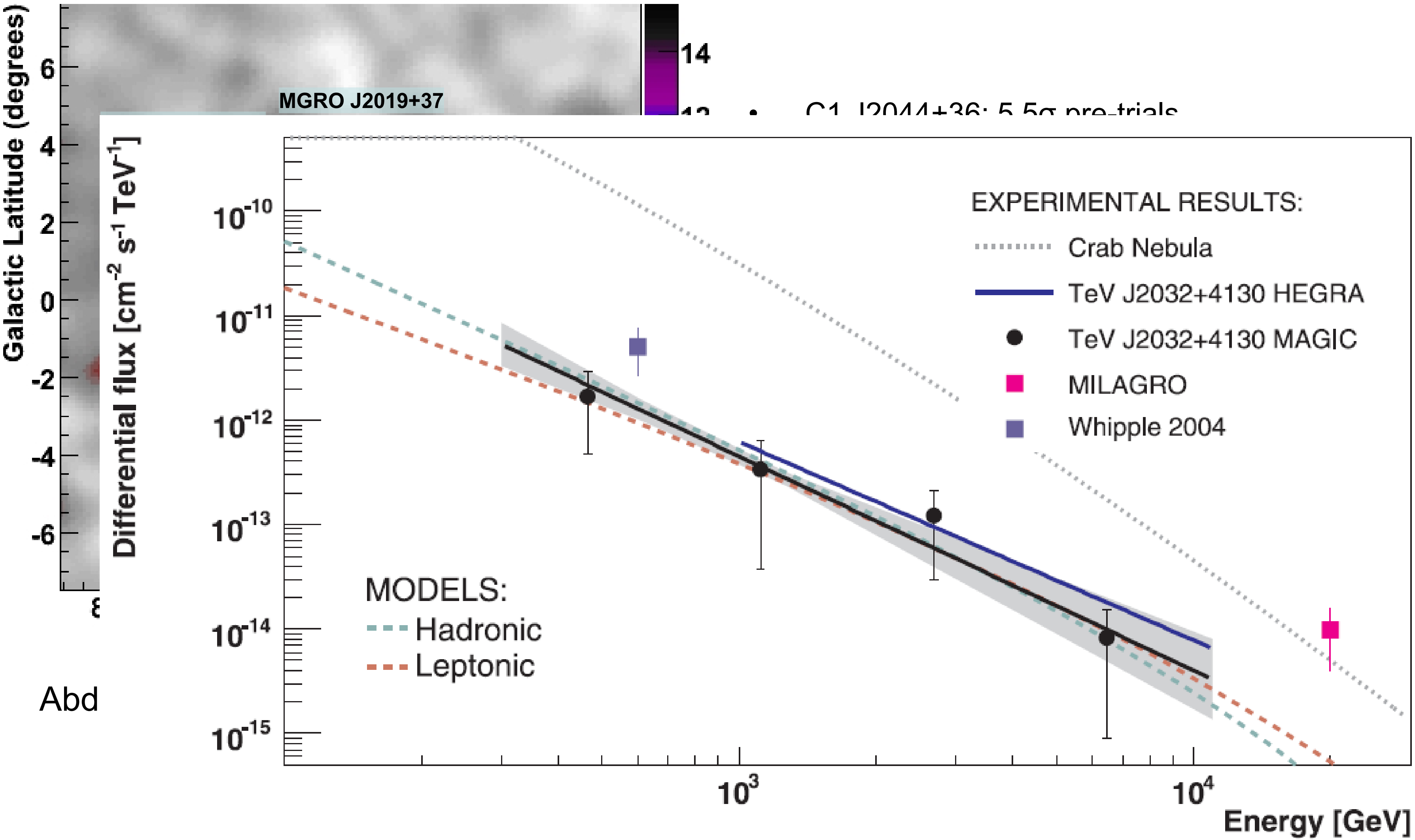


- C1 J2044+36: 5.8σ pre-trials
  - no counterparts
  - < 2.0°
- C2 J2031+33: 5.1σ pre-trials
  - no counterparts
  - possible extension of MGRO J2019+37
  - possible fluctuation of MGRO J2019 tail & diffuse emission & background

- MGRO J2019+37: 10.4σ
  - Extended source 1.1° ± 0.5° (top hat dia.)
  - Possible Counterparts
    - GeV J2020+3658, PWN G75.2+0.1

Abdo, et al. ApJ 2007

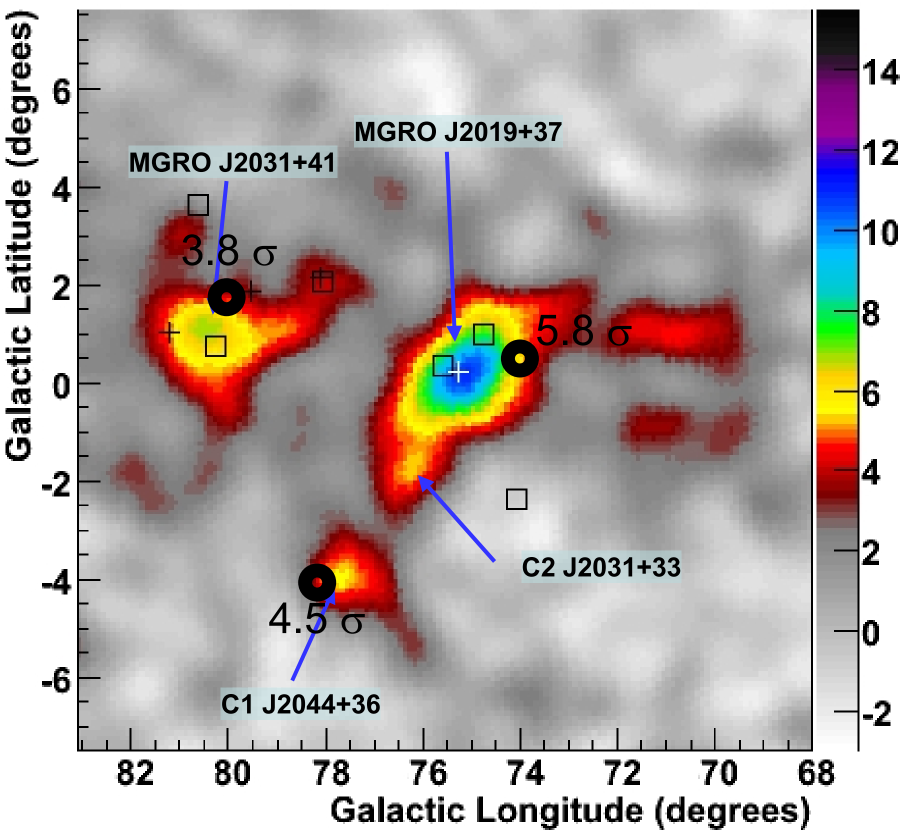
The Cygnus Region



• C1 J2044+36: 5.5σ pre-trials

Abd

The Cygnus Region



Abdo, et al. ApJ 2007

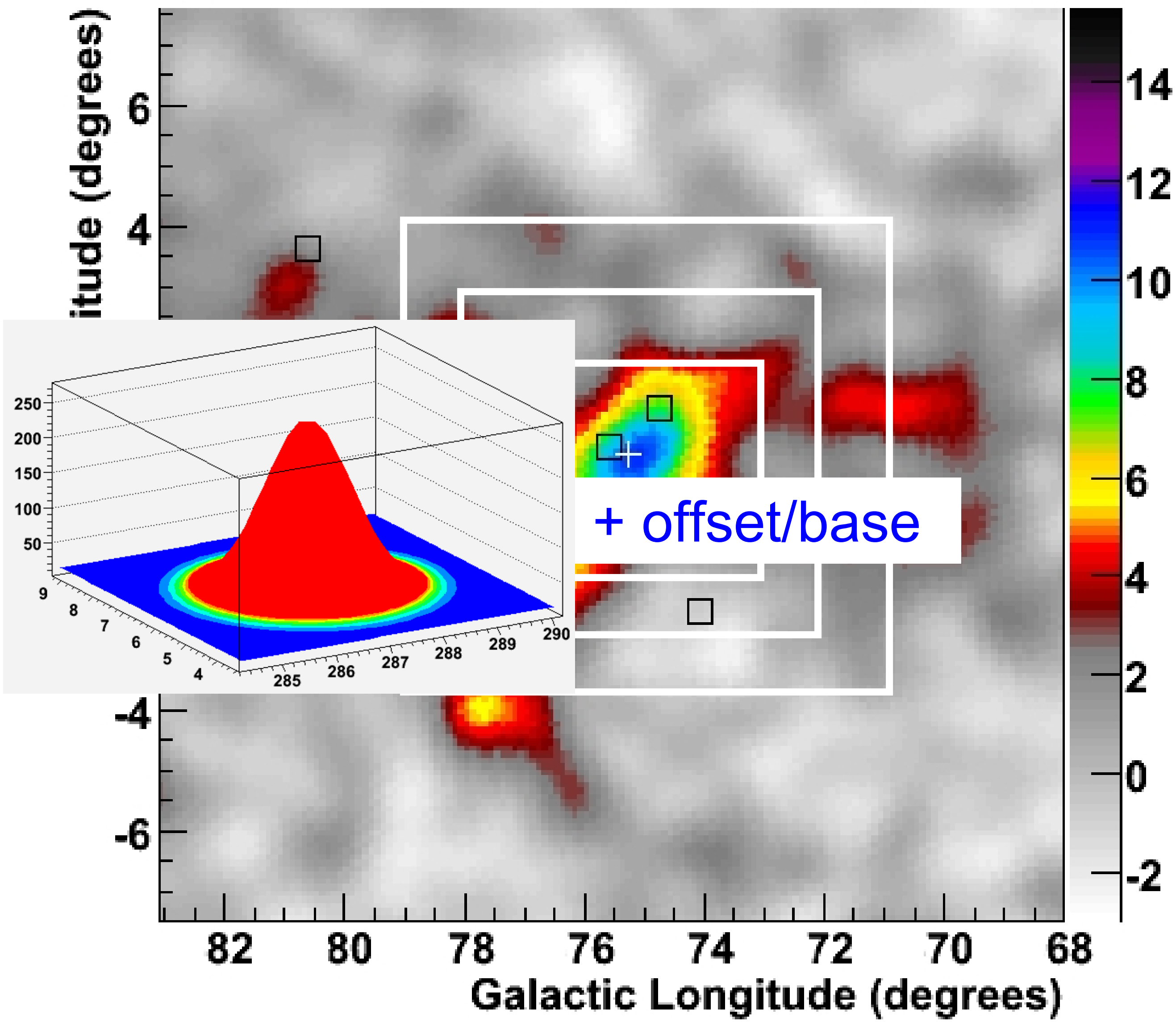
Wang, et al. ICRC 2007

Tibet ASγ preliminary detections of 3 Milagro sources

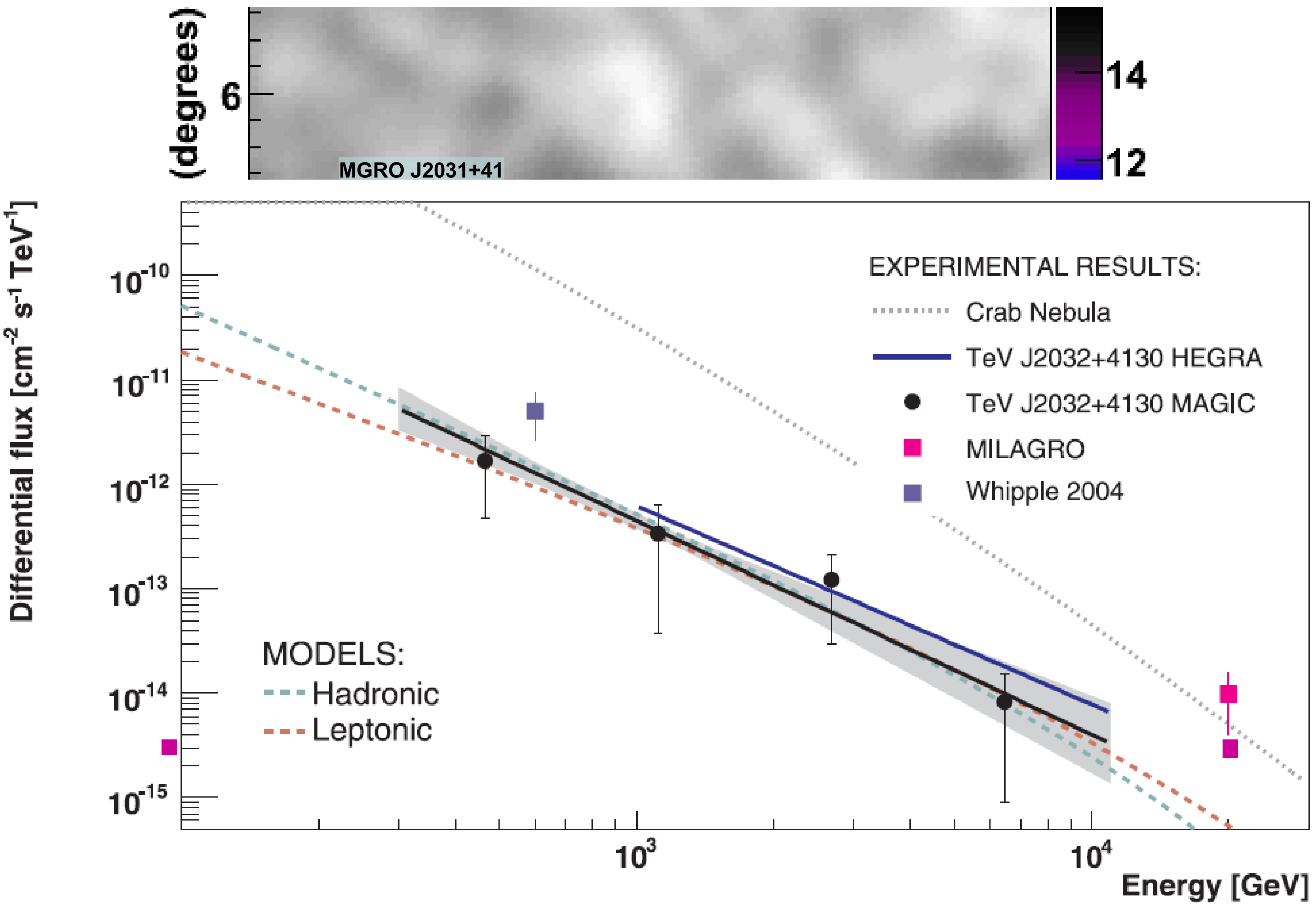
- C1 J2044+36: 5.5σ pre-trials
  - no counterparts
  - < 2.0o
- C2 J2031+33: 5.3σ pre-trials
  - no counterparts
  - possible extension of MGRO J2019+37
  - possible fluctuation of MGRO J2019 tail & diffuse emission & background

- MGRO J2019+37: 10.9σ
  - Extended source 1.1o ± 0.5o (top hat dia.)
  - Possible Counterparts
    - GeV J2020+3658, PWN G75.2+0.1
- MGRO J2031+41: 6.6σ (54.9σ post-trials)
  - Possible Counterparts:
    - 3EG J2033+4118, GEV J2035+4214
    - TEV J2032+413 (⅓ of Milagro flux)
  - $3.0^{o} \pm 0.9^{o}$ (top hat dia.)

Remarks about source fitting

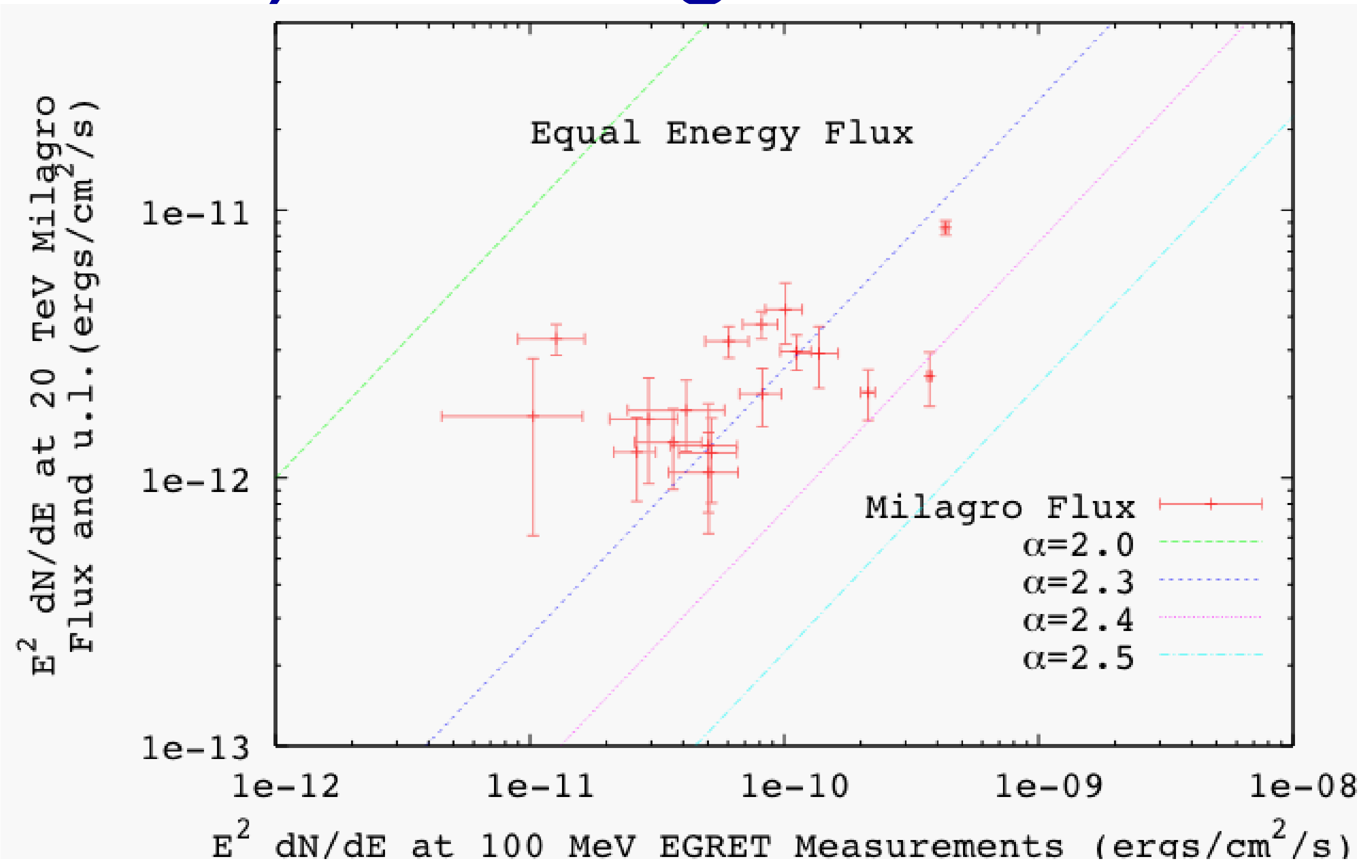


Remarks about source fitting

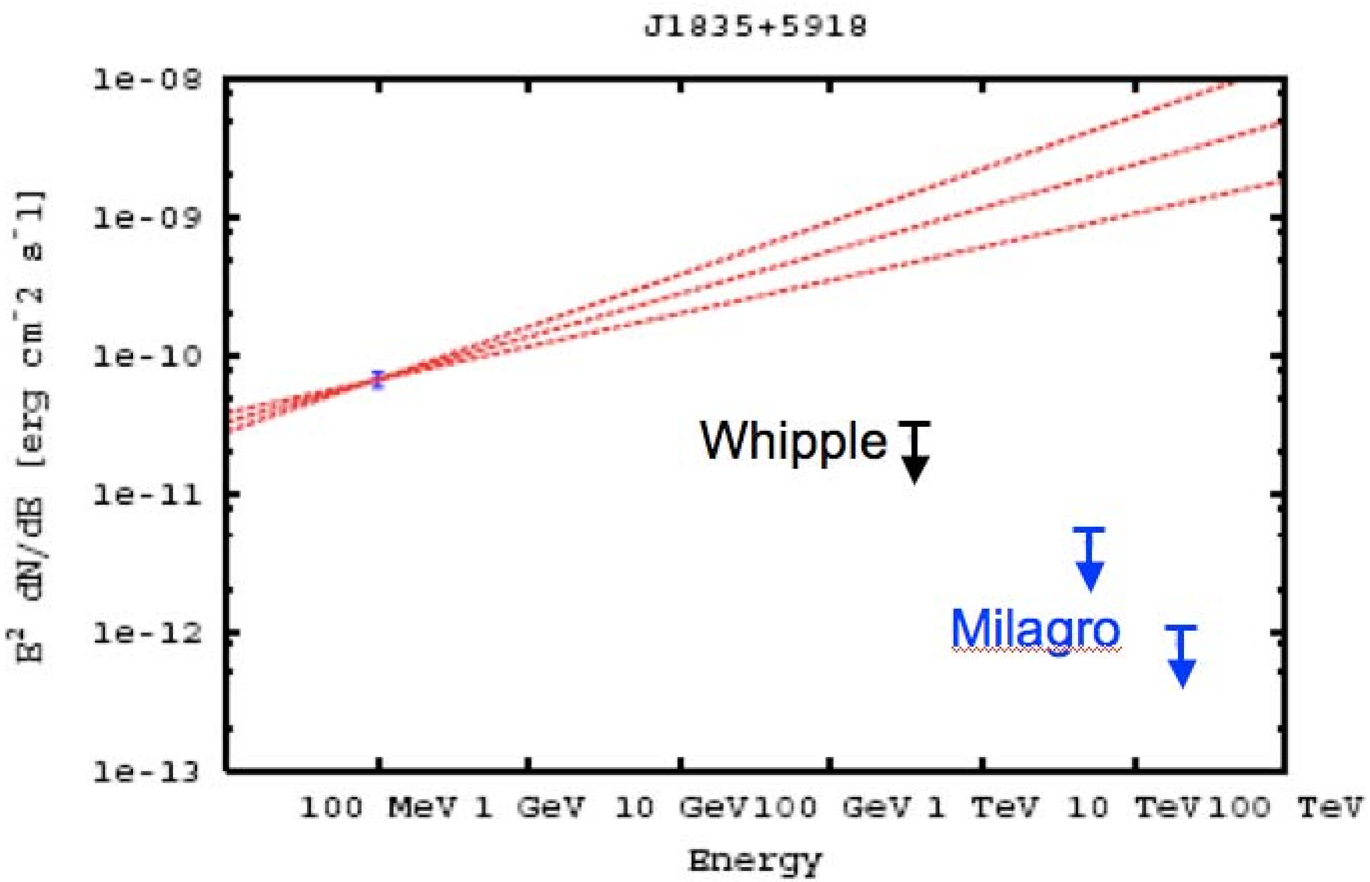


129 EGRET sources (>100 MeV) in Milagro fov

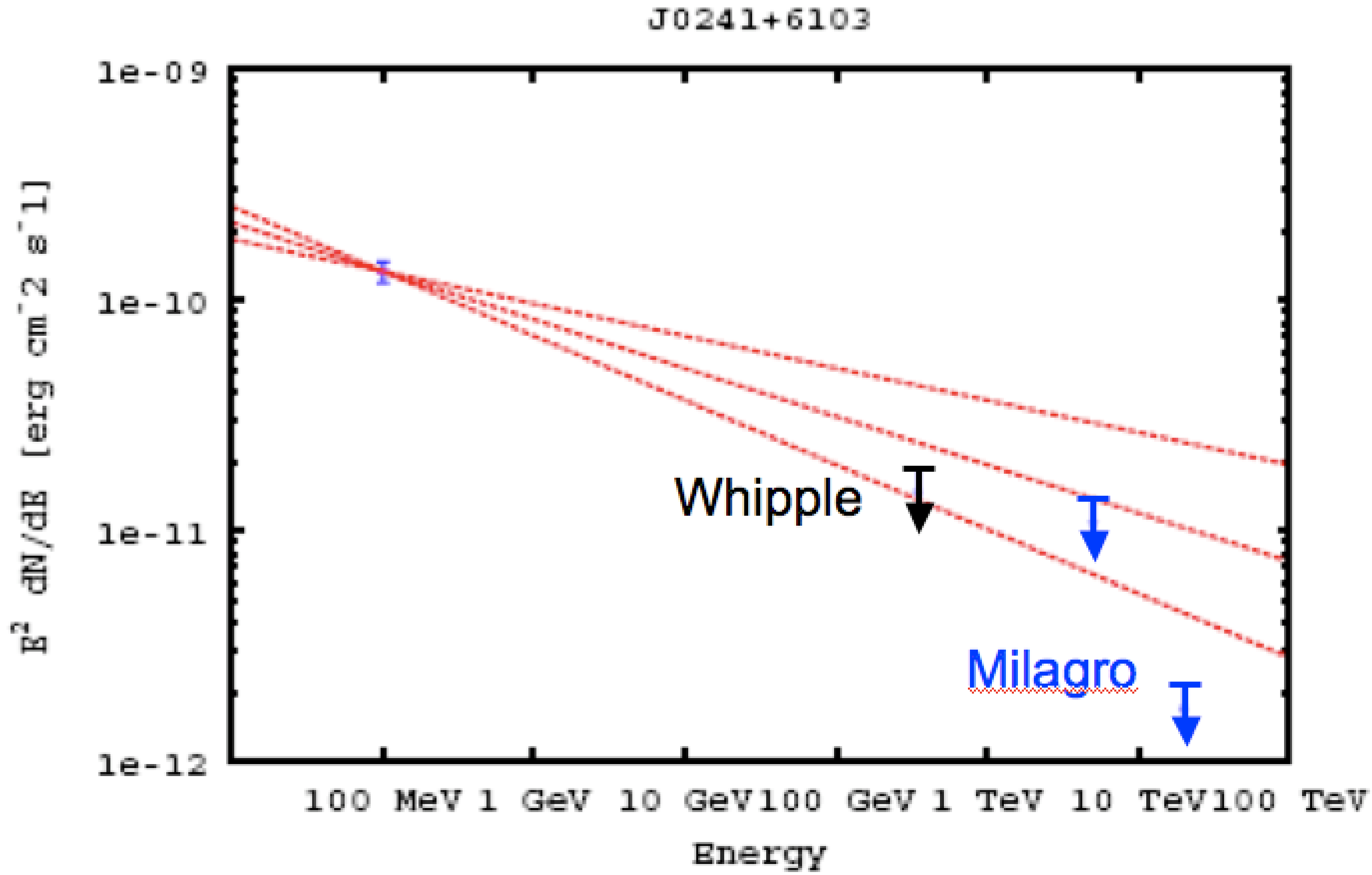
- 20 of the EGRET sources are > 2 sigma in Milagro map



Flat Spectrum EGRET sources break



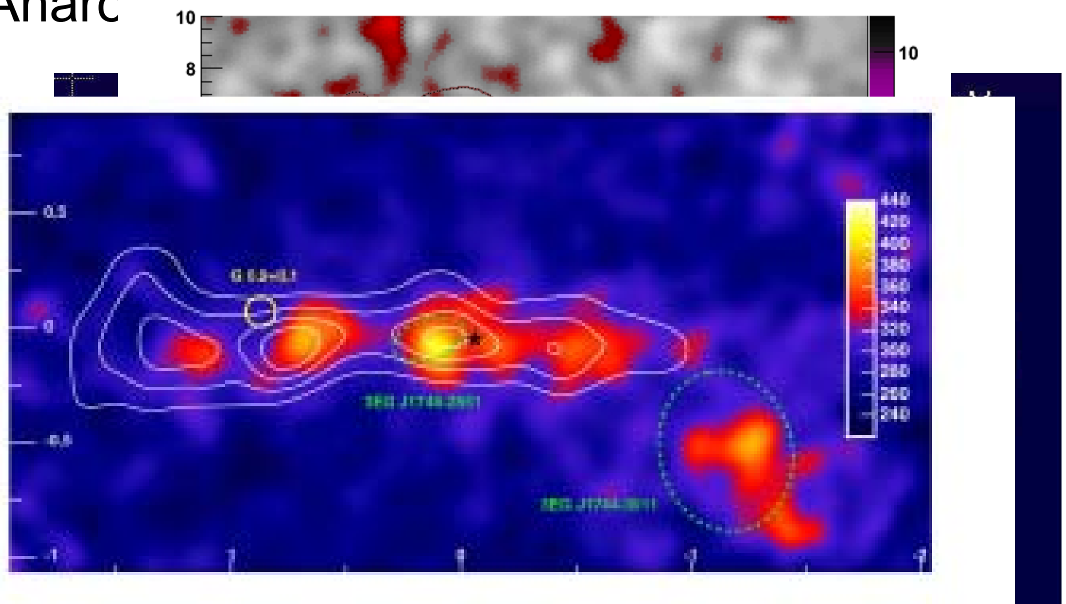
Some Steeper Spectrum Sources also break



TeV Diffuse Emission from the Galactic Plane

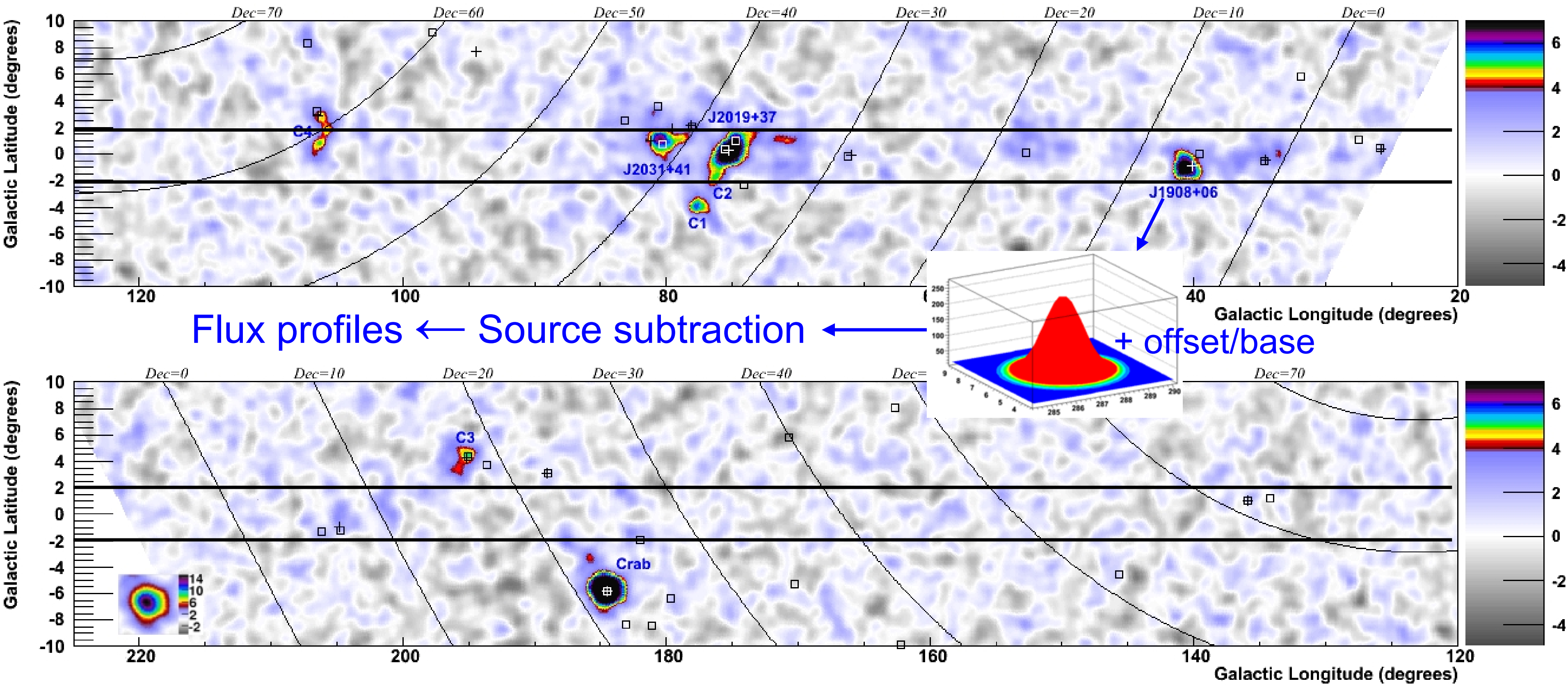
Previous measurements

- **EGRET:** EGRET observations to 20 GeV indicate a **"GeV excess"**, harder ɣ-ray spectrum than predicted on the basis of local cosmic-ray spectrum and intensity measurements (Hunter et al. 1997)
- **Milagro:** >3.5 TeV, 40<l<100 → indication of **"TeV excess"**; @ 12 TeV, Cygnus region → 3 to 7 times higher then cosmic-propgation model GALPROP (Atkins et al. 2005, Abdo et al. 2007)
- **HESS :** Galactic Center Ridge, diffuse emission correlated with giant molecular clouds, al… by a factor 3-9 above 1 TeV (Aharc…



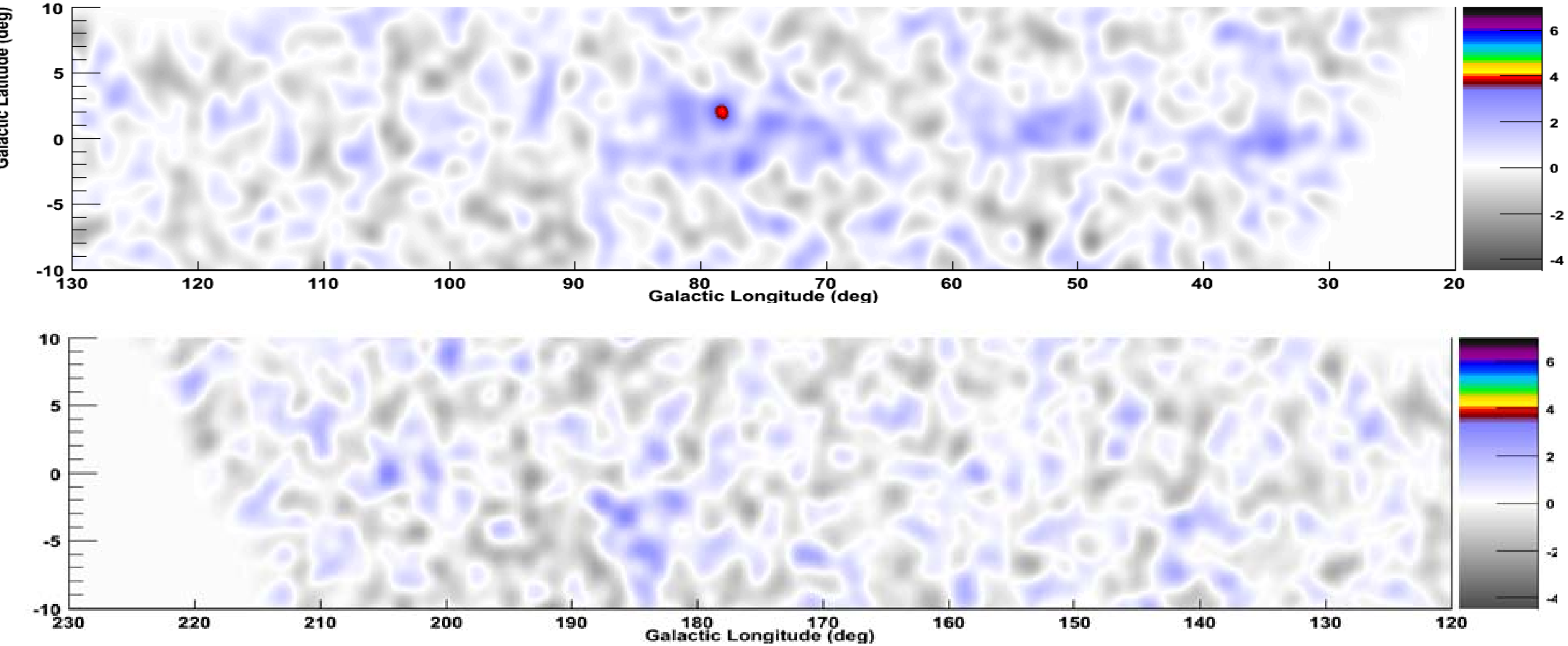
Diffuse Emission

A4 -weighted sky map



Diffuse Emission

The Diffuse Galactic Plane



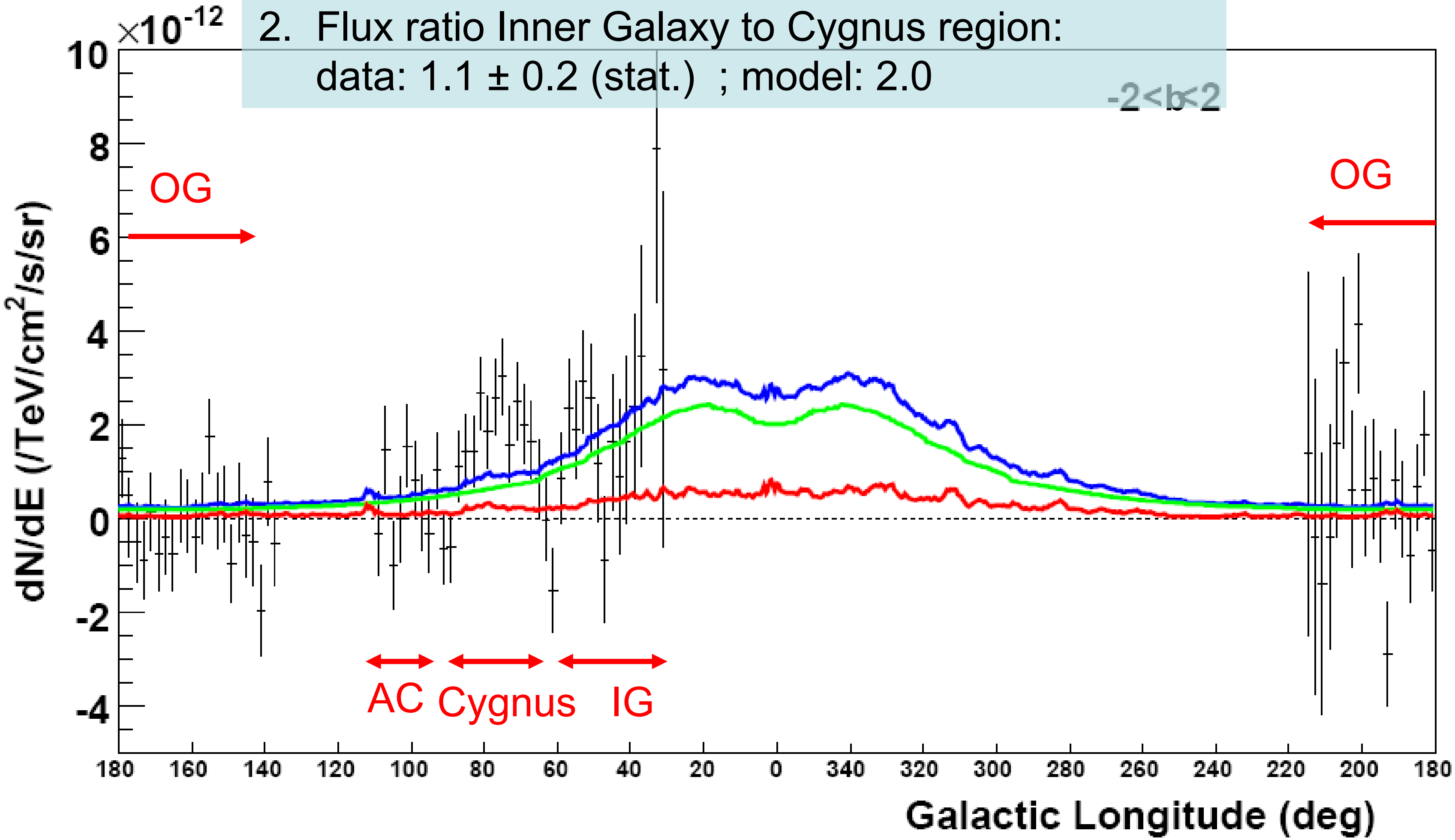
TeV Diffuse Emission from the Galactic Plane with Milagro

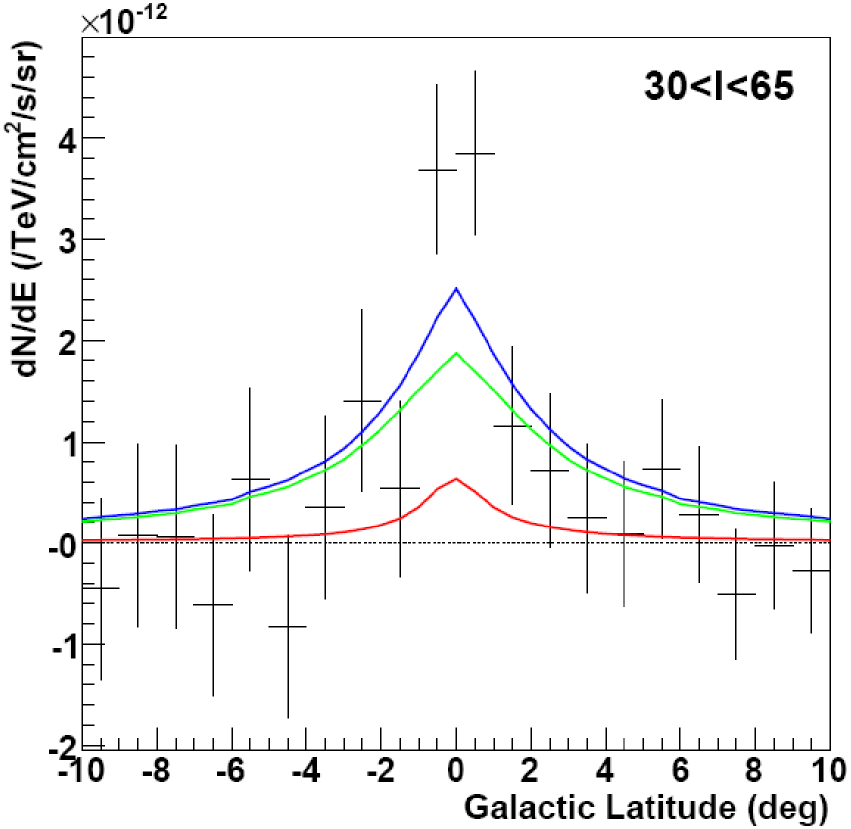
Comparison with model predictions

- Compare flux and longitudinal and latitudinal emission profiles to model predictions
- We used GALPROP for the comparison (Strong et al. 2004)
- GALPROP is a model calculating cosmic-ray propagation numerically
- Emissivities are calculated based on propagated CR spectra and gas and radiation densities in the Galaxy
- two versions: “conventional” → reproduces local CR measurements; “optimized” → tuned to match EGRET data

Flux Profiles: I Galactic Longitude

1. Cygnus region: Flux observation exceeds model predictions by a factor of two
2. Flux ratio Inner Galaxy to Cygnus region: data: 1.1 ± 0.2 (stat.) ; model: 2.0

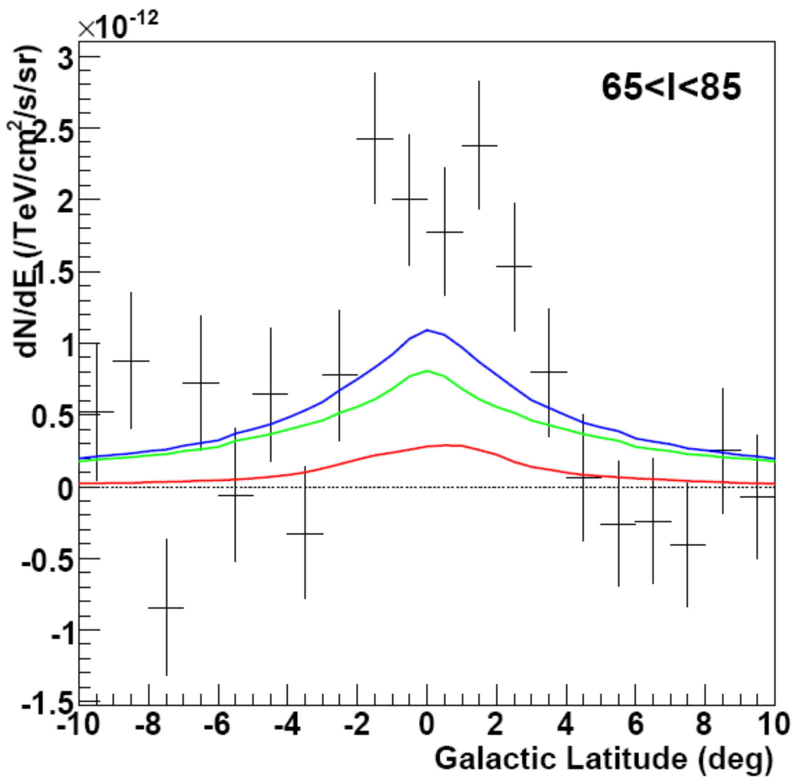




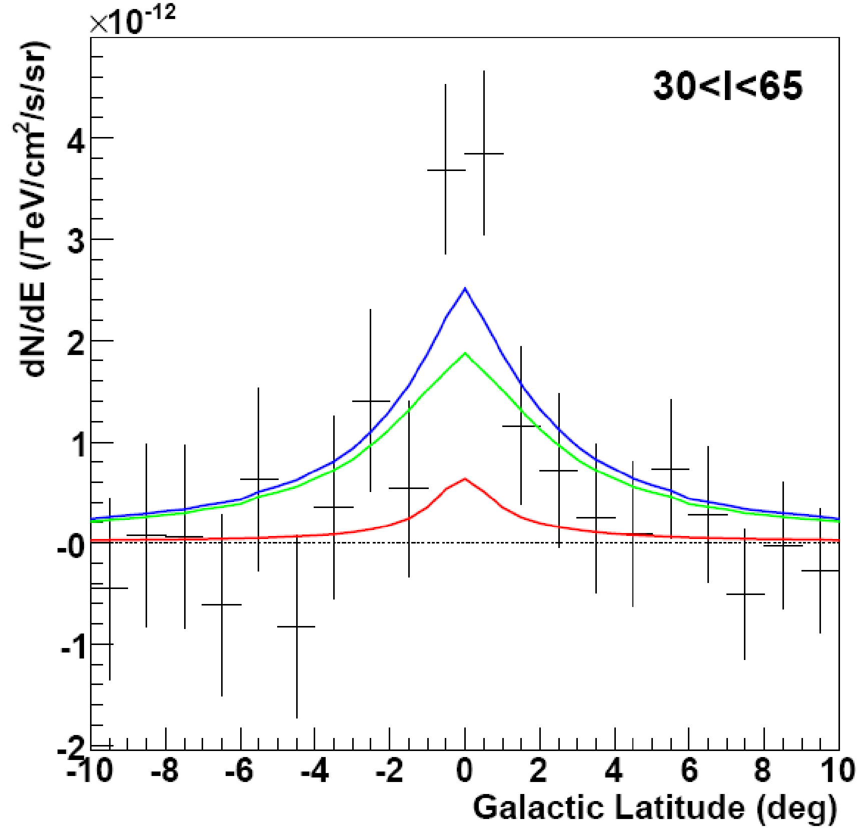
Flux Profiles: II Galactic Latitude

The Model:

- Inverse Compton target photons extend to higher latitudes
- Pion decay due to interactions with matter at low latitudes
- Inverse Compton flux increases towards inner Galaxy



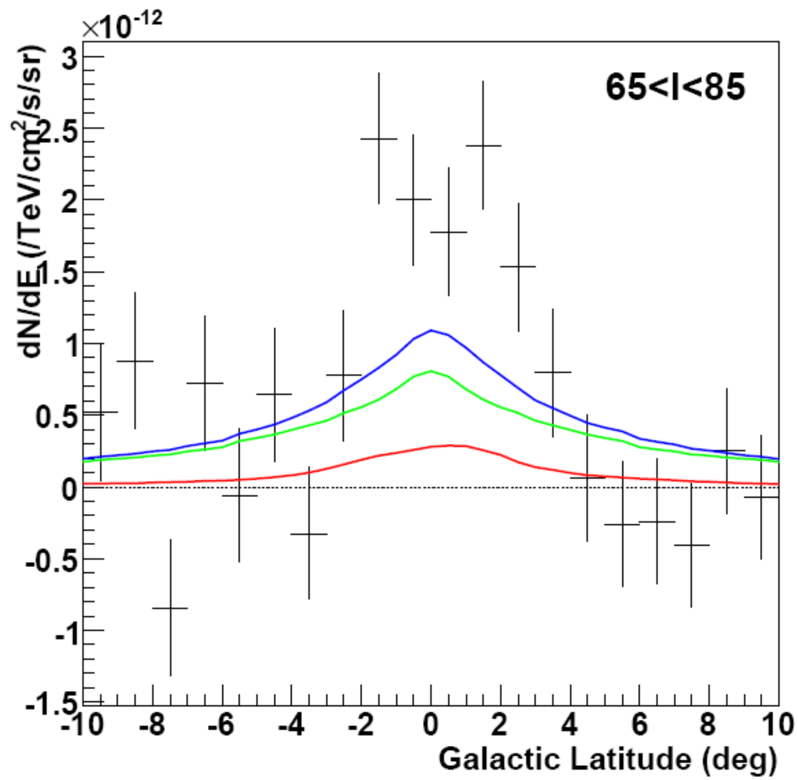
Flux Profiles: II Galactic Latitude

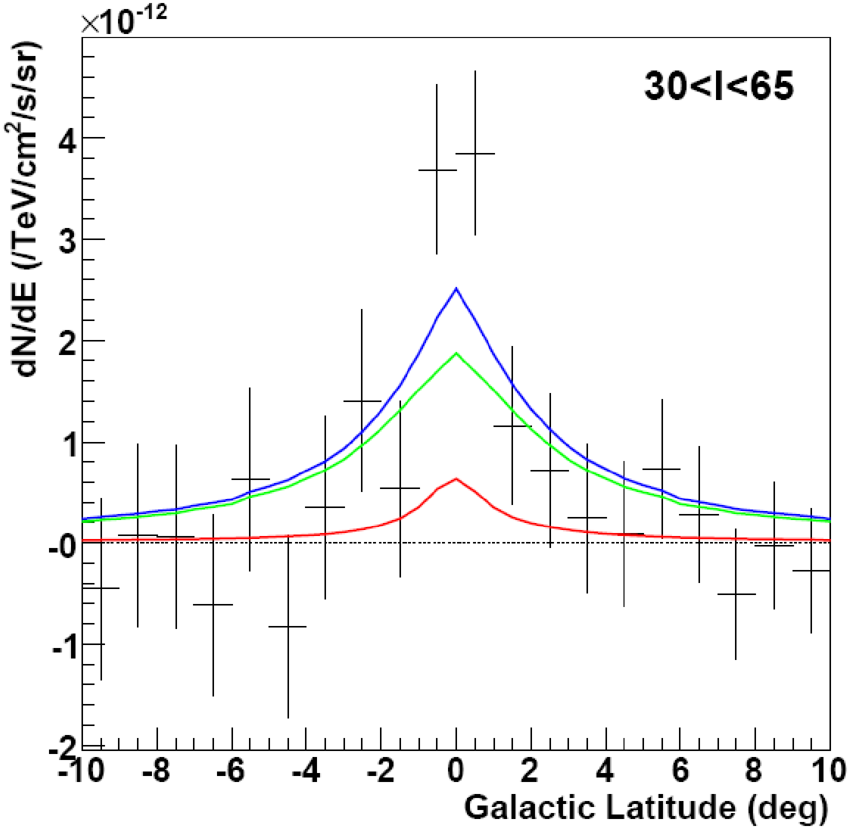


Compare the shape:

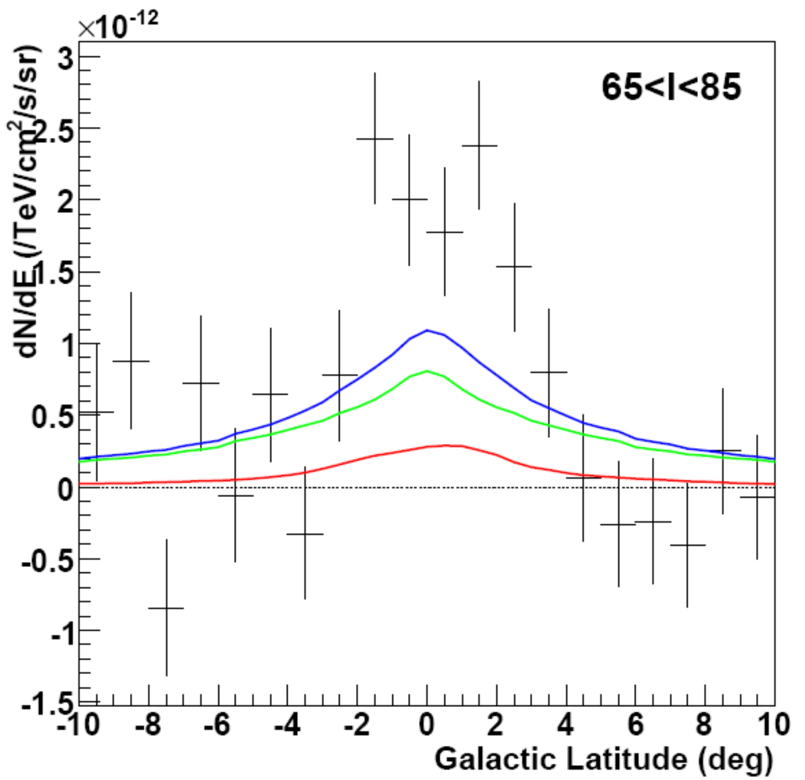
One test: perform Gaussian fit and compare FWHM

	Data	GALPROP
Inner Galaxy:	2.1±0.7	4.1
Cygnus:	4.7±0.5	6.9





Flux Profiles: II Galactic Latitude



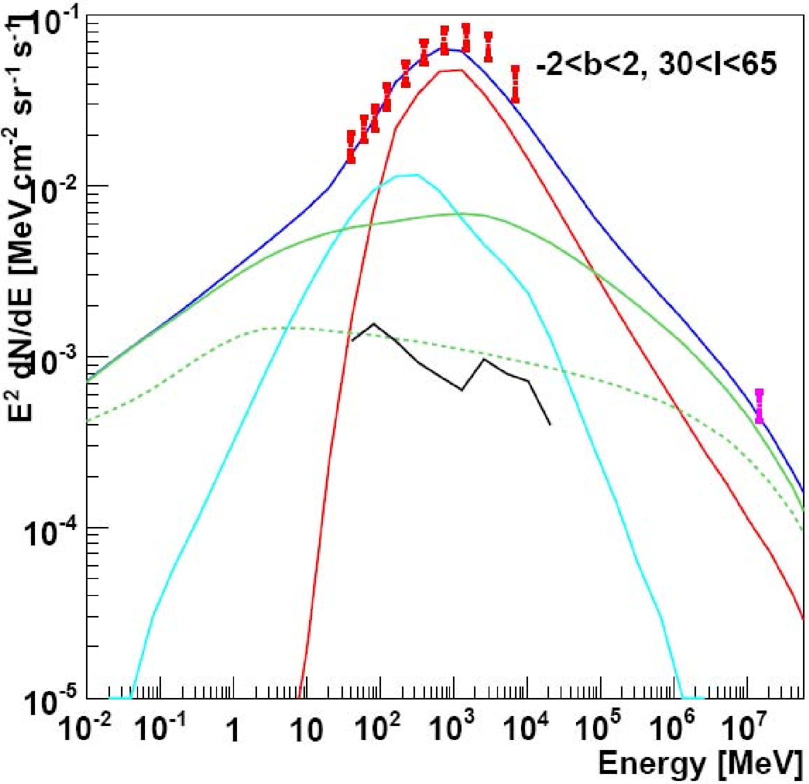
Compare the shape:

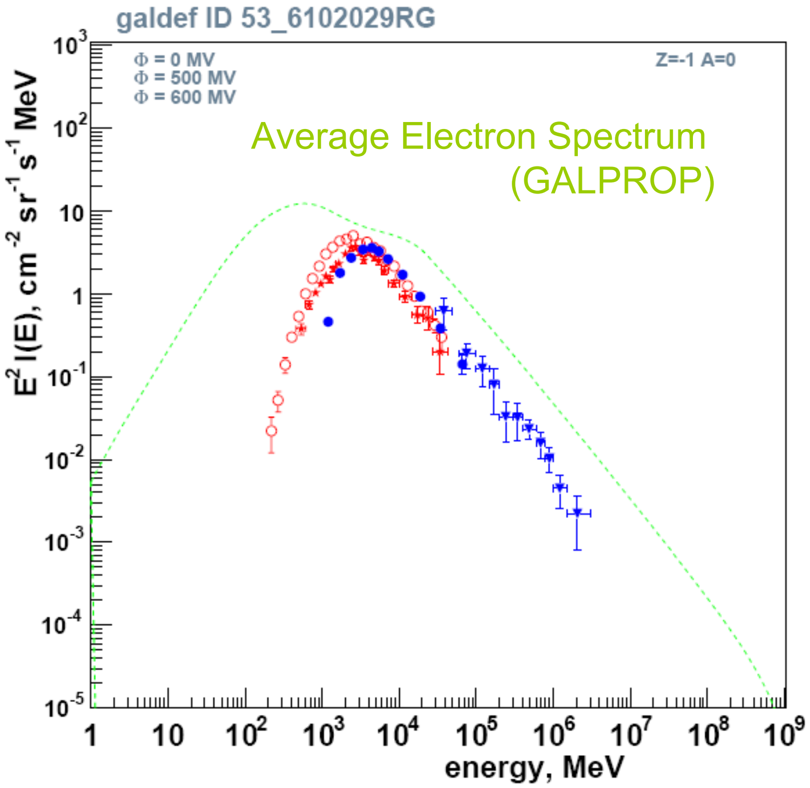
Better test: perform a χ^2 fit of 2 components predicted by GALPROP to data

	Prob.
Inner Galaxy:	5.7×10^{-1}
Cygnus:	1.1×10^{-4}

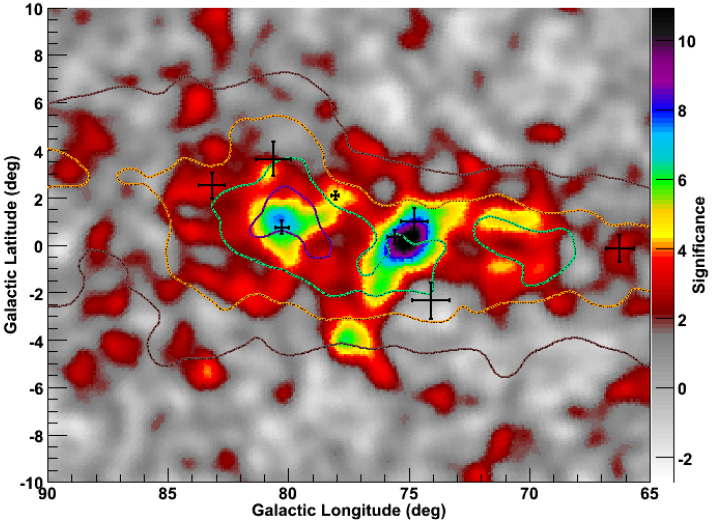
Best fit in Cygnus: Increase pion contribution by a factor of ~7

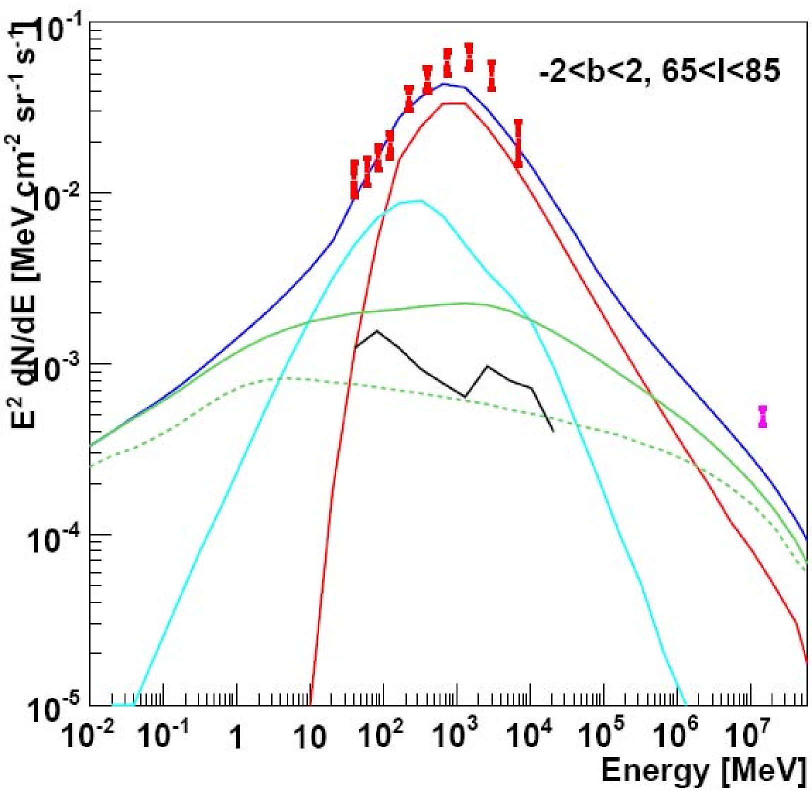
Spectrum Inner Galaxy





Spectrum
Cygnus Region



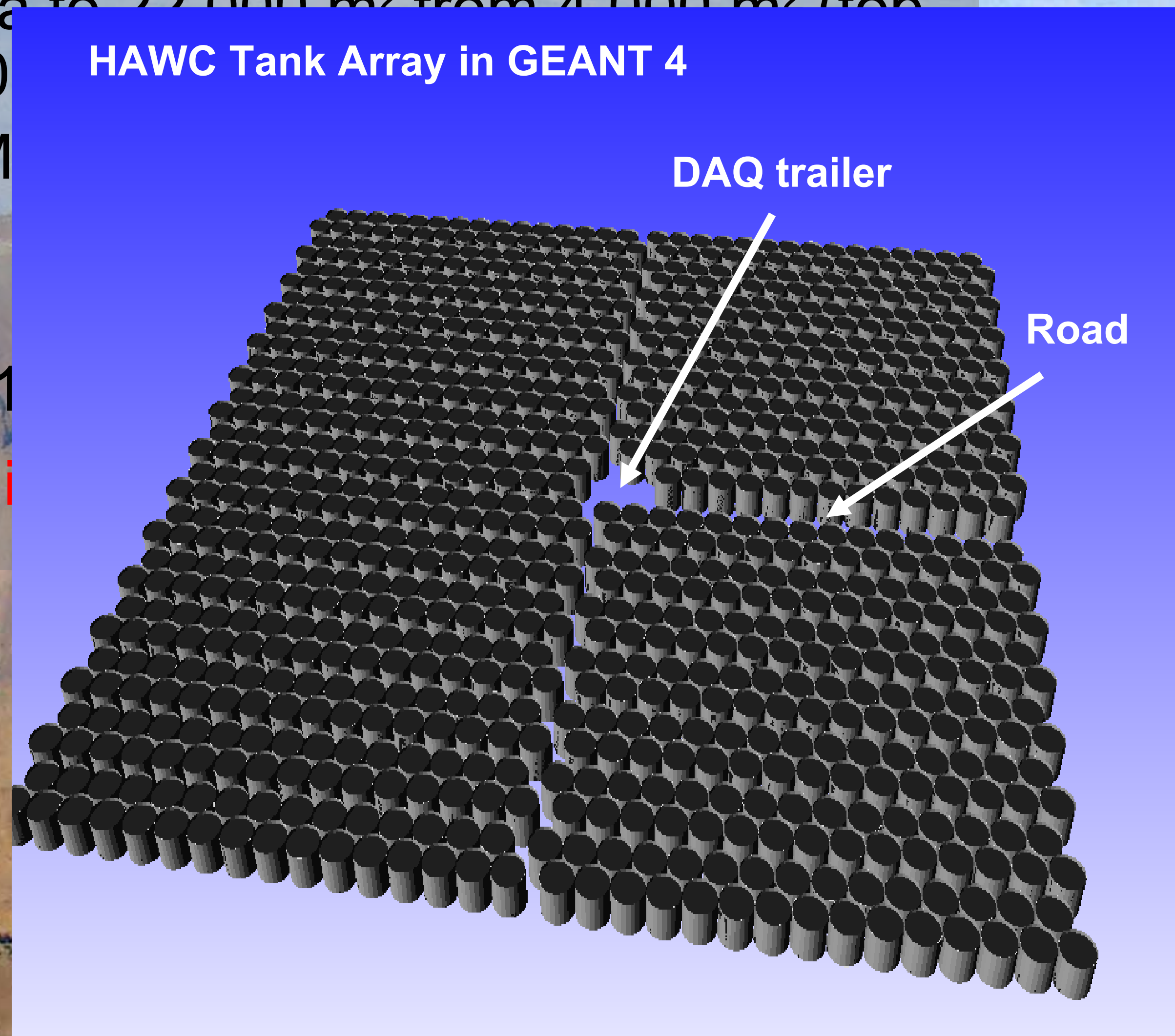


- region of intense star formation activity
- Cygnus OB2, VLA SNR detection, XMM extended x-ray source observation, TeV 2032+4130, MGRO J2031+41
- GALPROP:
  again dominant IC contribution,
  but measured profile agrees better with pion prediction of GALPROP
- remaining excess can be explained with a only a few strong young proton accelerators, where the protons interact with clouds at only 100 pc distance from the source (estimation based on
  Gabici & Ahahronian et al. 2007)

The future: HAWC

- Increase Altitude to 4100 m from 2650 m
- Increase Area to 22,000 m^2 from 4,000 m^2 (top layer) or 2,20
- Reuse 900 M electronics
- Cost $7.4M
- HAWC 10 – 1

Detect Crab i



HAWC Collaboration

USA:

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University of Utah Dave Kieda
University of New Mexico John Matthews
Michigan State University Jim Linnemann
Pennsylvania State University Ty DeYoung
NASA/Goddard Space Flight Center Julie McEnery
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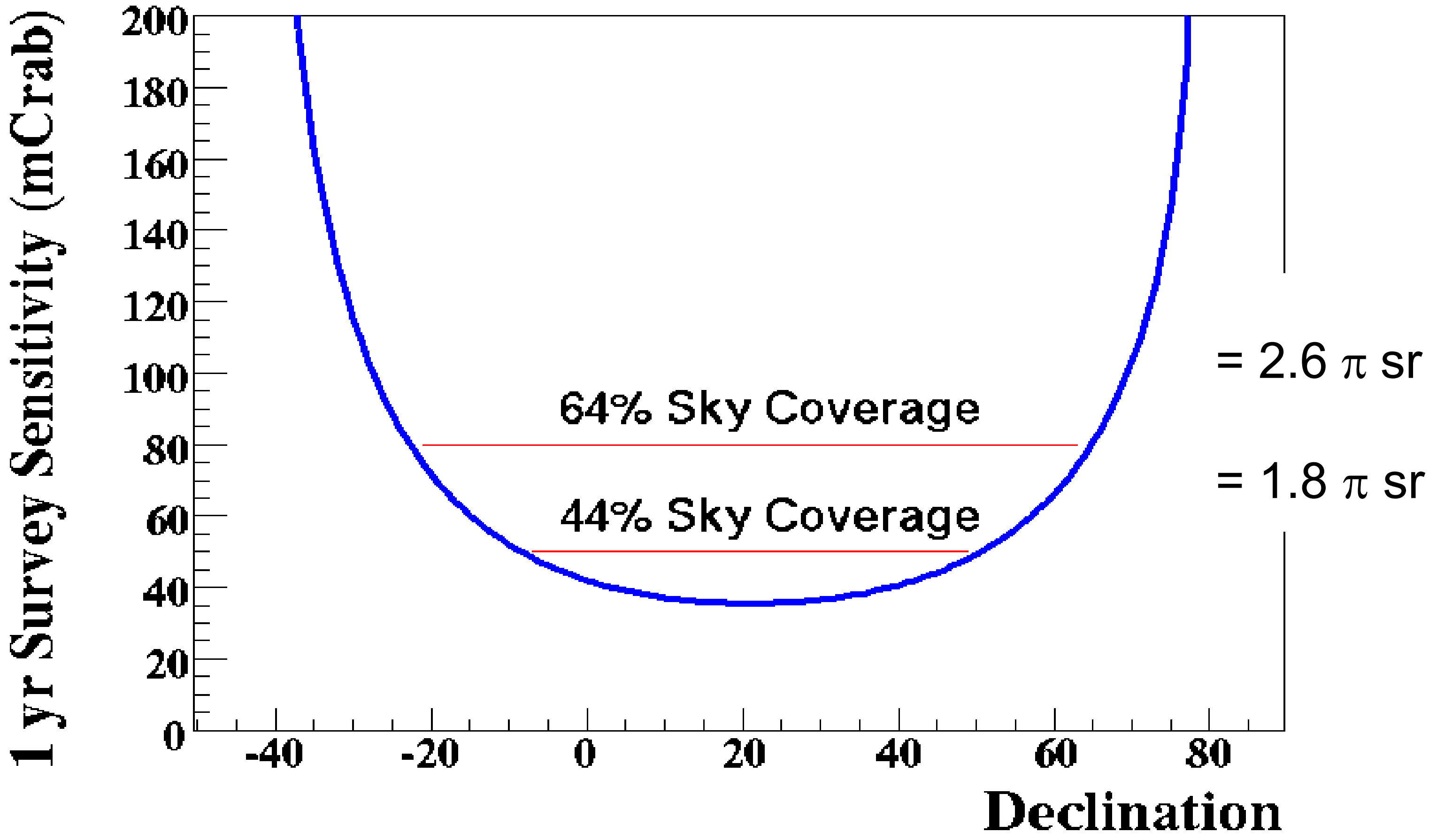
Instituto de Física: Arturo Menchaca, Rubén Alfaro, Andres Sandoval, Ernesto Belmont
Instituto de Ciencias Nucleares: Lukas Nellen, G. Medina-Tanco
Instituto de Geofísica: José Valdés Galicia, Alejandro Lara
Benemérita Universidad Autónoma de Puebla
Humberto Salazar, Oscar Martínez, Cesar Álvarez, Arturo Fernández
Universidad Michoacana de San Nicolás de Hidalgo Luis Villaseñor
CINVESTAV Arnulfo Zepeda
Universidad de Guanajuato
David Delepine, Gerardo Moreno, Marco Reyes, Luis Ureña, Victor Migenes

HAWC's Field of View



Conclusion

- Milagro GP survey:
  - 8 sources, 7 new
  - 4 high significance and 2 low significance coincide with EGRET GeV sources
  - 4 of these six sources appear extended
  - Connecting spectrum between EGRET GeV and Milagro TeV: -2.3 (except Geminga)
  - Four assiociated with PWN, 1 SNR
  - Diffuse emission excess in Cygnus: a few young accelerators
  - Need to be careful when disentangle diffuse and source emission