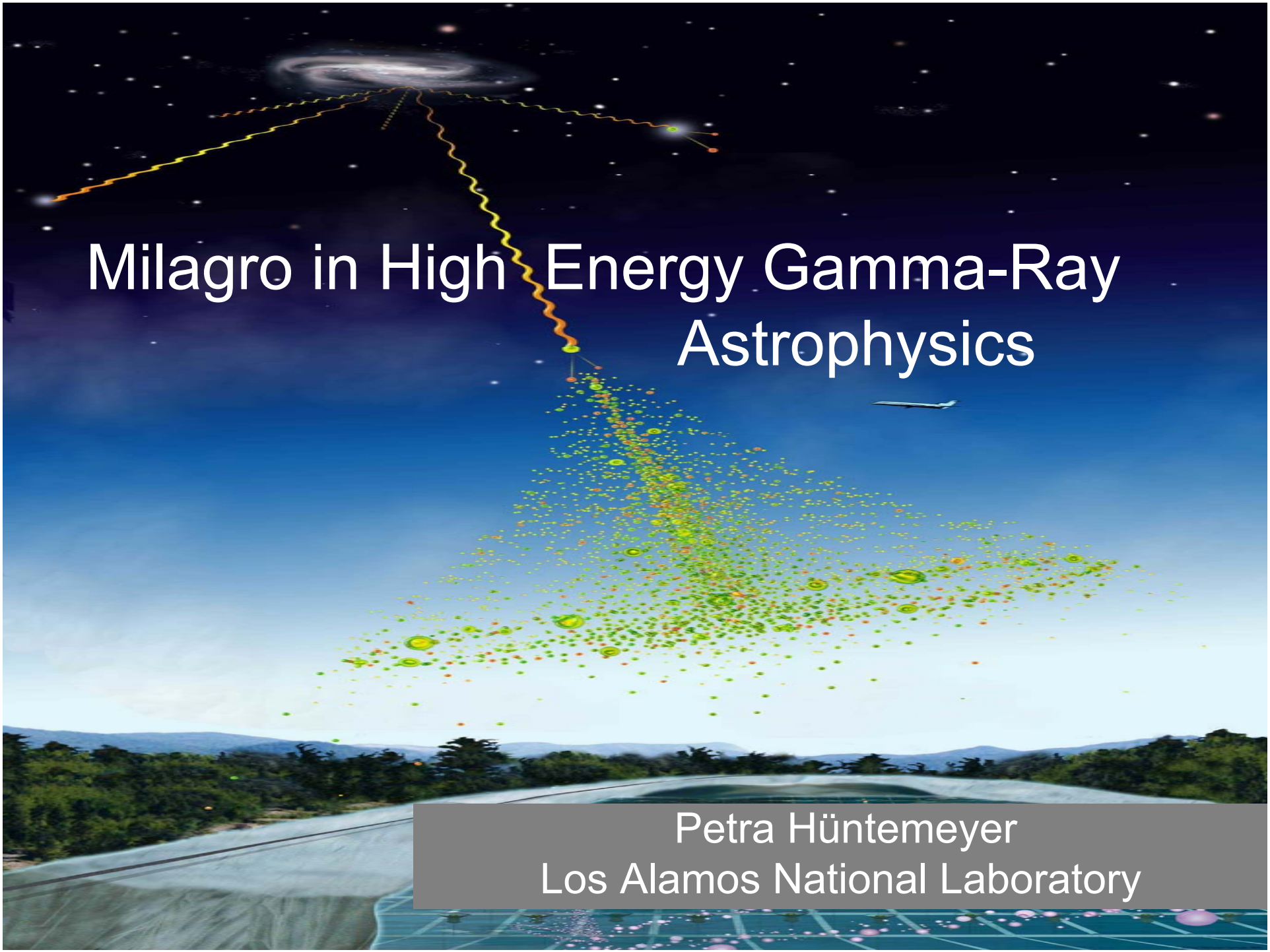
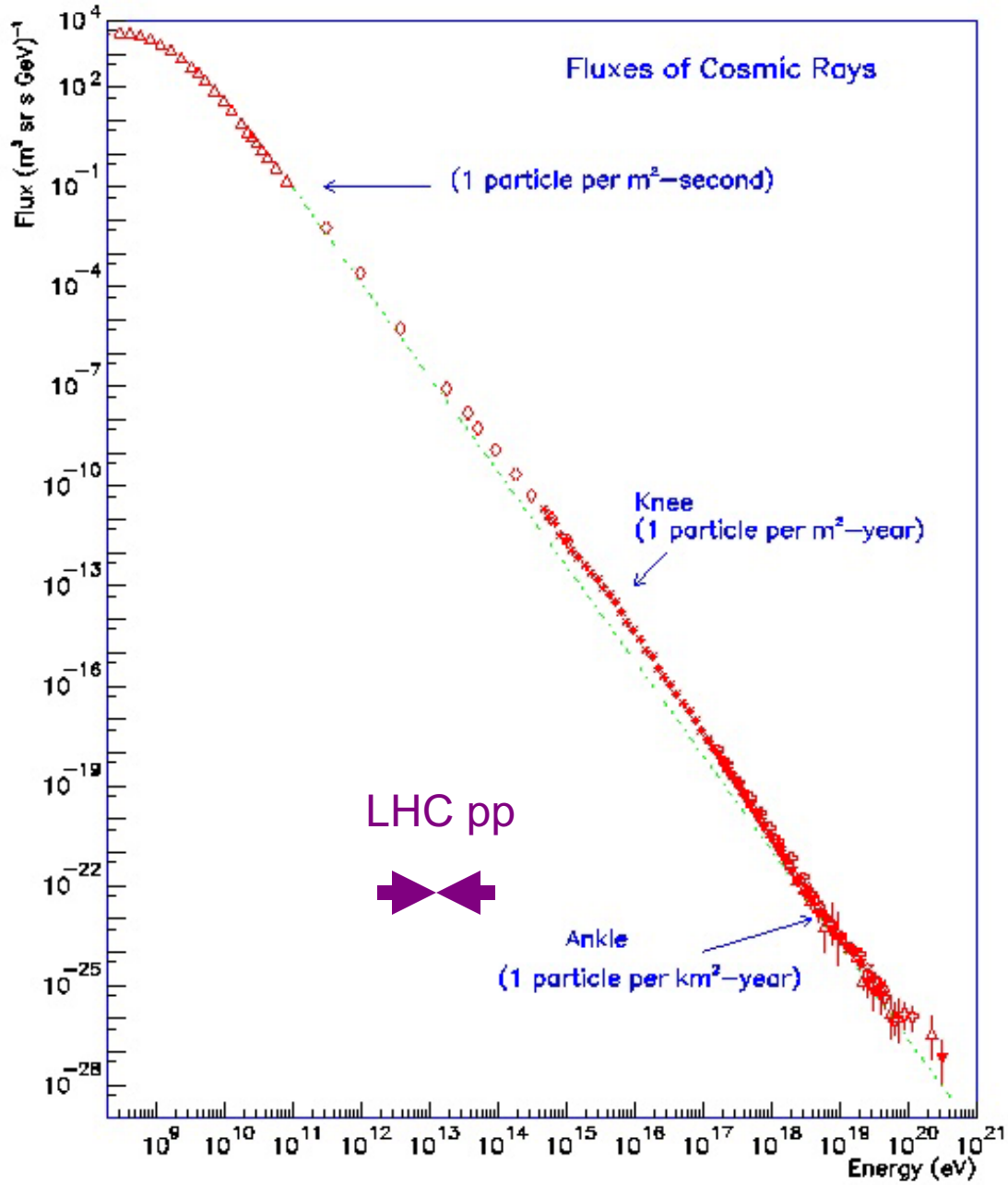


Milagro in High Energy Gamma-Ray Astrophysics

Petra Hüntemeyer
Los Alamos National Laboratory

An Introduction to High Energy Particle Astrophysics

The Cosmic Ray Spectrum

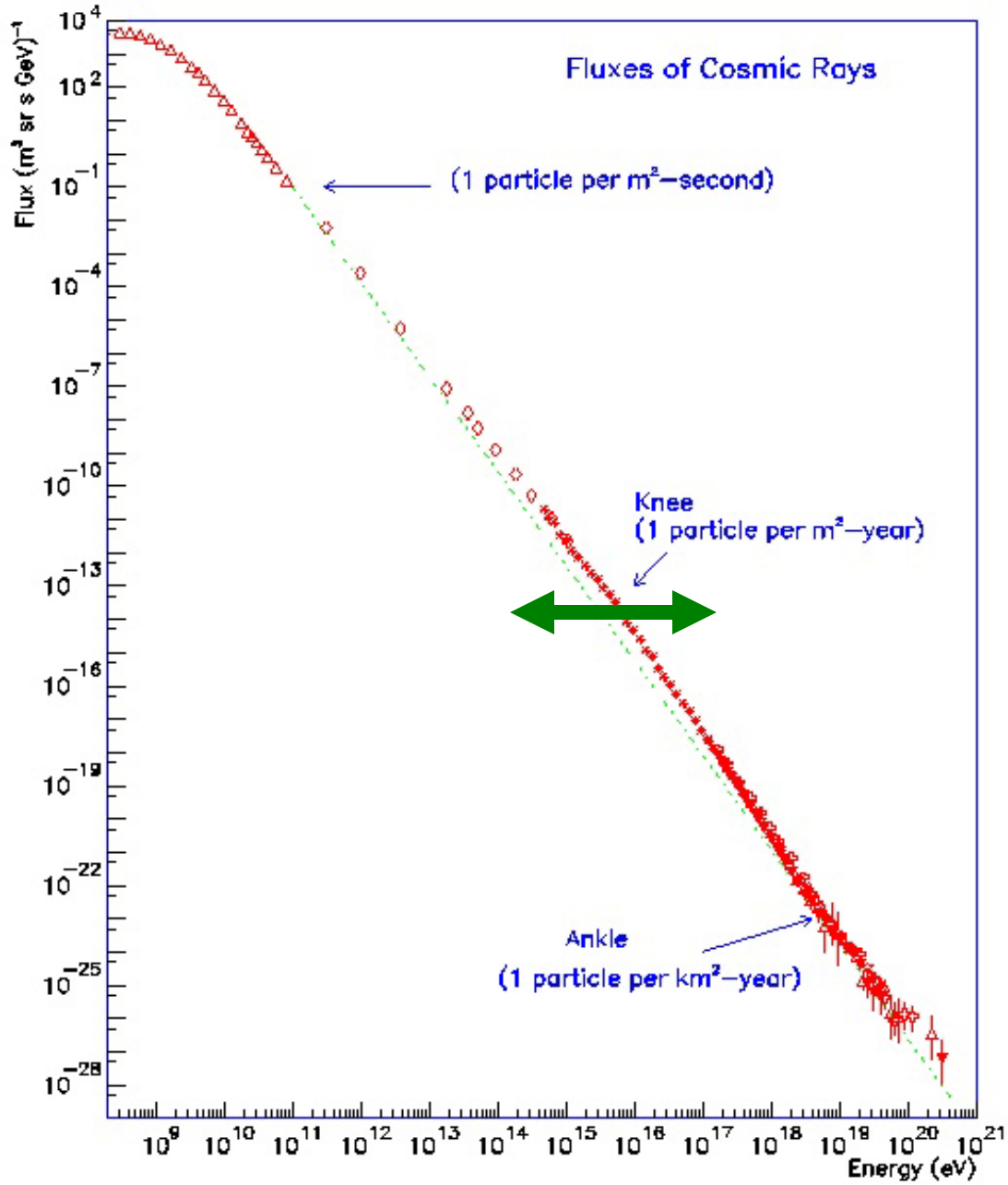


Petra Hüntemeyer
BNL Seminar, November 2007

An Introduction to High Energy Particle Astrophysics

What are Cosmic Rays?

e.g. around the knee:
- proton
- helium
- carbon
- silicon
- iron
- electrons
- gamma rays (<0.1%)

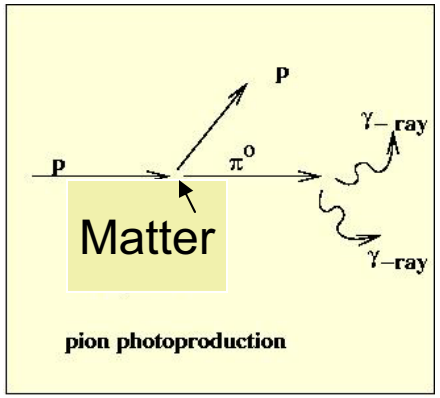


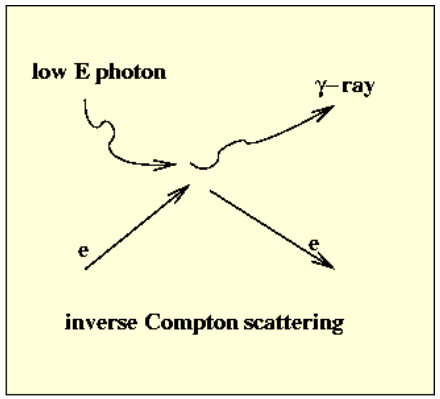
High Energy Particle Astrophysics Questions

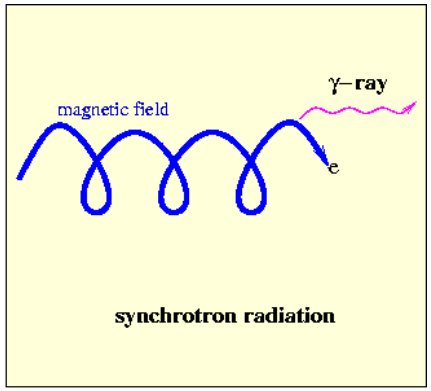
- What is the origin of cosmic rays?
  - Are the accelerators of hadrons different from electrons?
  - How high in energy can galactic sources produce particles?
  - What extragalactic sources can accelerate particles to even higher energies?
- How do astrophysical sources accelerate particles?
  - What is the role of the extreme magnetic and gravitational fields surrounding black holes and neutron stars?
  - How are particles accelerated within relativistic jets?
  - What interactions cause these particles to lose their energy?
- What constraints can we place on fundamental physics?
  - What is the dark matter?
  - What are the tightest constraints on Lorentz invariance?
  - Are there primordial black holes?

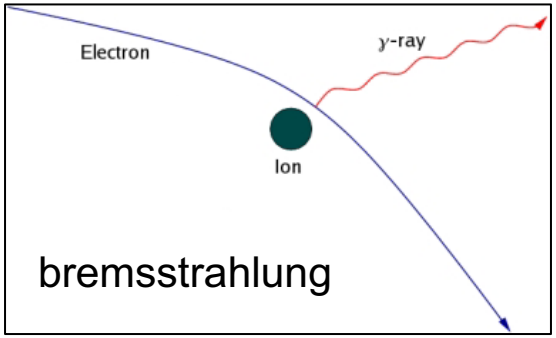
How do γ-rays answer these questions?

- γ-rays are produced by cosmic-ray interactions in their sources
  - The highest energy particles produce highest energy γ-rays







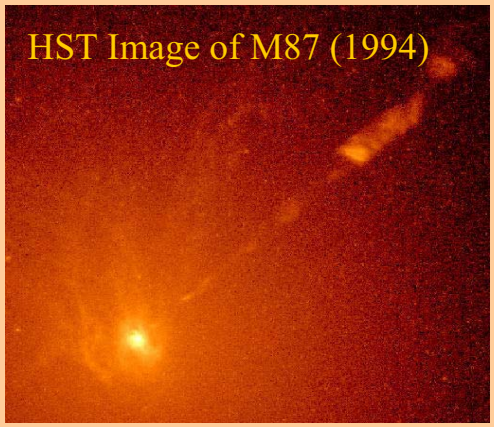


How do γ-rays answer these questions?

- γ-rays are produced by cosmic-ray interactions in their sources
  - The highest energy particles produce highest energy γ-rays
- Several classes of astrophysical objects produce γ-rays
  - But γ-ray fluxes within classes is not predictable

How do γ-rays answer these questions?

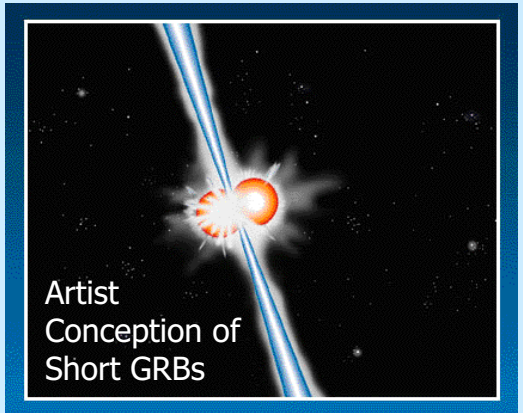
Black Hole producing relativistic jet of particles



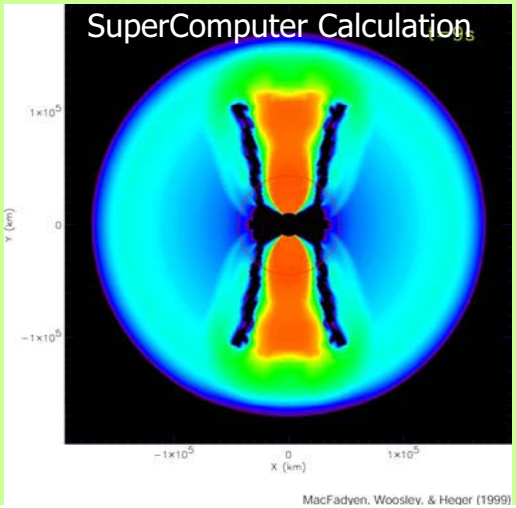
Spinning Neutron Star powering a relativistic wind

TeV image of Vela Jr. Supernova Remnant

Binary Neutron Star Coalescing



Massive Star Collapsing into a Black Hole

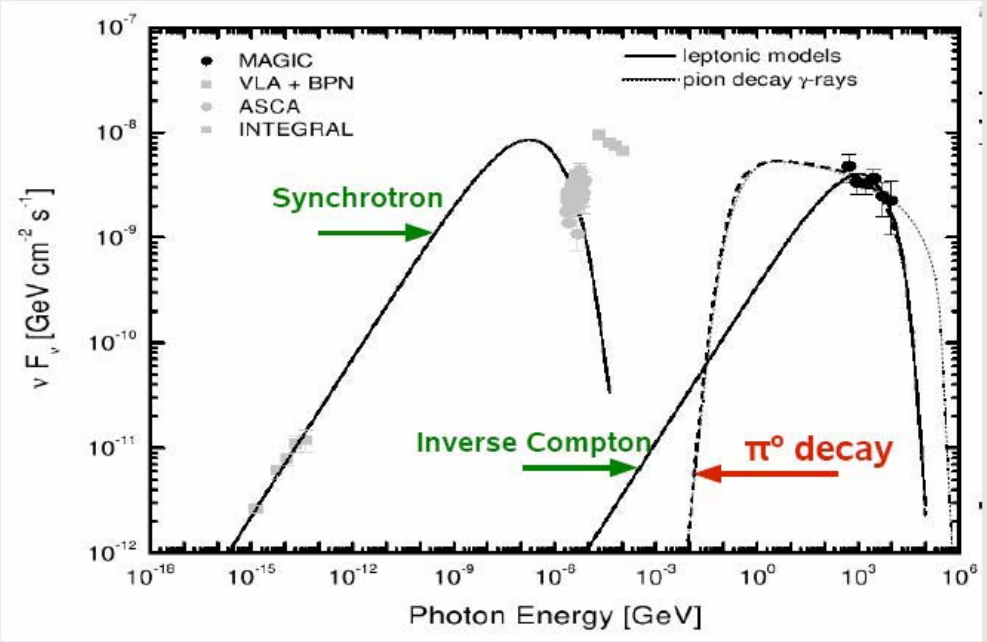


How do γ-rays answer these questions?

- γ-rays are produced by cosmic-ray interactions in their sources
  - The highest energy particles produce highest energy γ-rays
- Several classes of astrophysical objects produce γ-rays
  - But γ-ray fluxes within classes is not predictable
- Hadronic vs leptonic interactions
  - Produce different energy spectra and γ-ray time variability

How do γ-rays answer these questions?

Leptonic or Hadronic ?

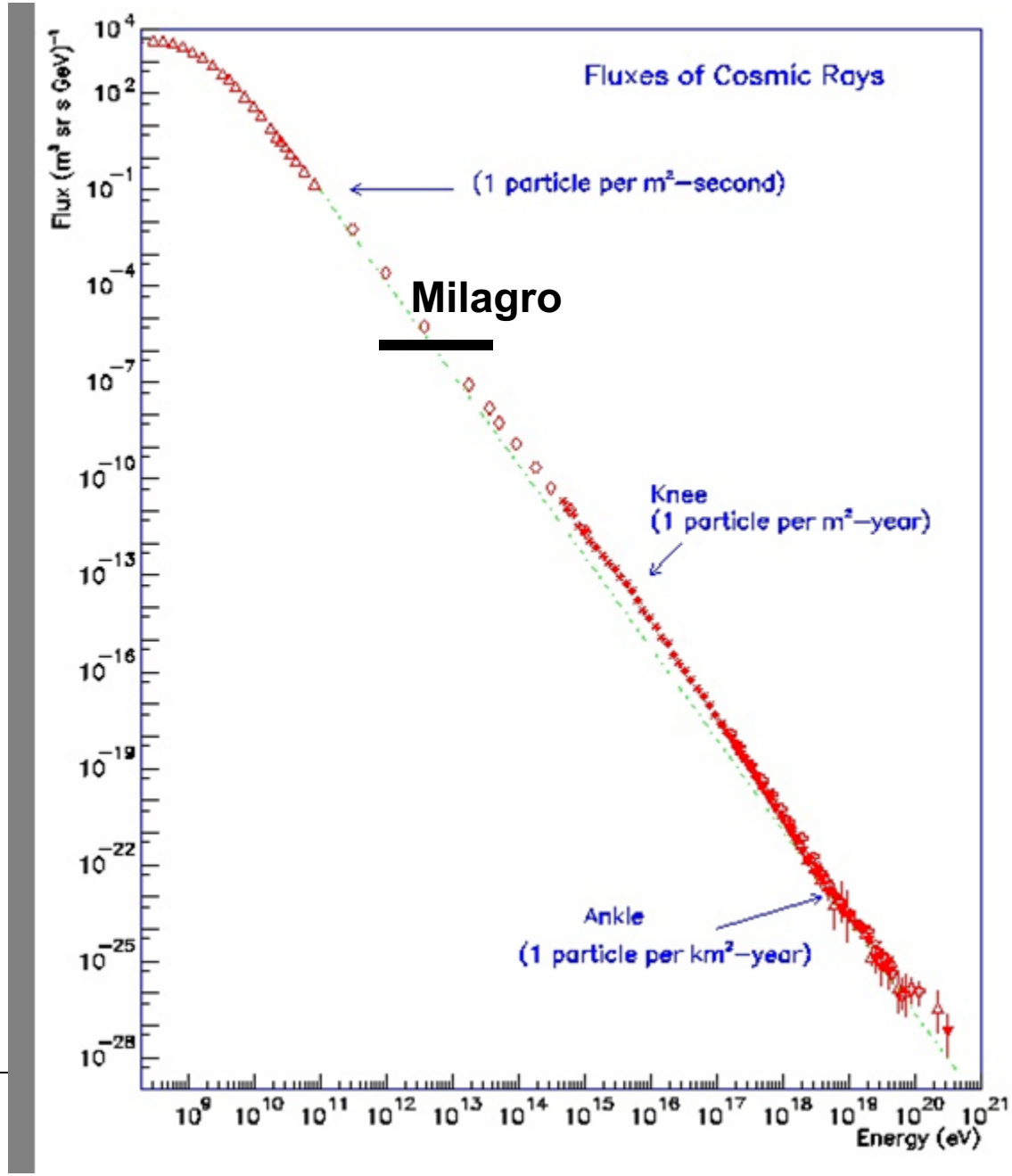


HESS J1813-178 both models fit !

How do γ-rays answer these questions?

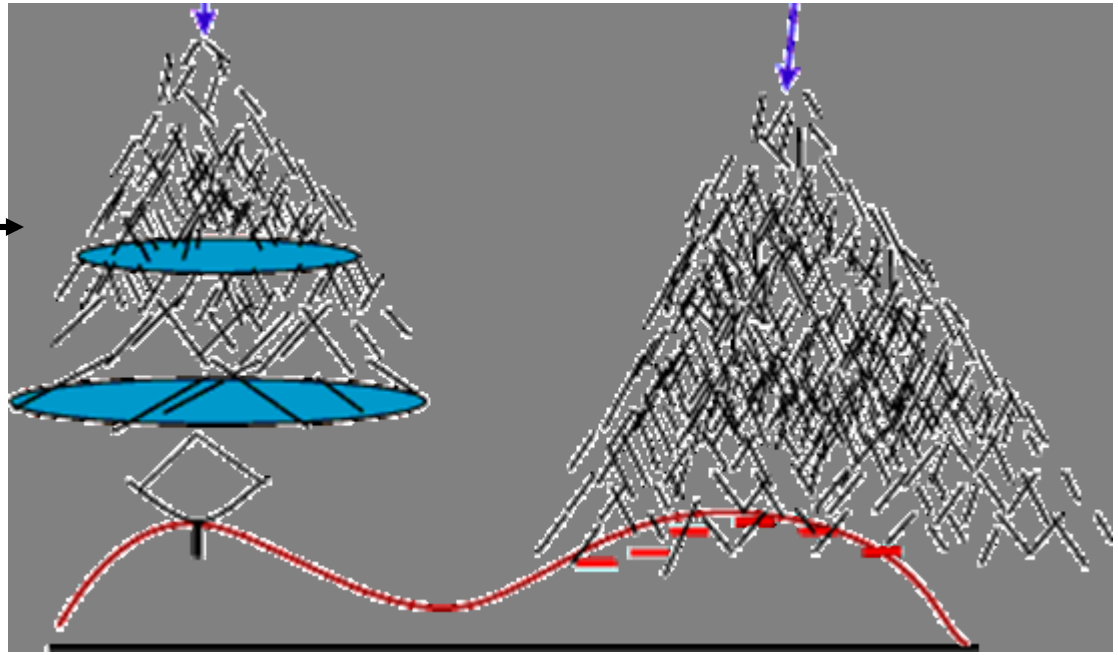
- γ-rays are produced by cosmic-ray interactions in their sources
  - The highest energy particles produce highest energy γ-rays
- Several classes of astrophysical objects produce γ-rays
  - But γ-ray fluxes within classes is not predictable
- Hadronic vs leptonic interactions
  - Produce different energy spectra and γ-ray time variability
- Goals of γ-ray observations
  - Detect many sources of many different classes
  - Observe highest energies and most rapid variability
  - Compare γ-ray images, spectra, and variability with those from other wavelengths

How are γ-Rays detected?



How are γ-Rays detected? Ground-Based Techniques:

EAS
Extensive Air Showers



ACT
Air Cherenkov Telescope

EAS Array

Complementarity of TeV Gamma-Ray Detectors

Imaging Air Cherenkov Telescopes

Energy Range .05-50 TeV
Area > 10^4 m^2
Background Rejection > 99%
Angular Resolution 0.05°
Energy Resolution ~15%
Aperture 0.003 sr
Duty Cycle 10%

High Resolution Energy Spectra
Precision Study of Known Sources
Source Location & Morphology
Deep Surveys of Limited Regions of Sky

Extensive Air Shower Arrays

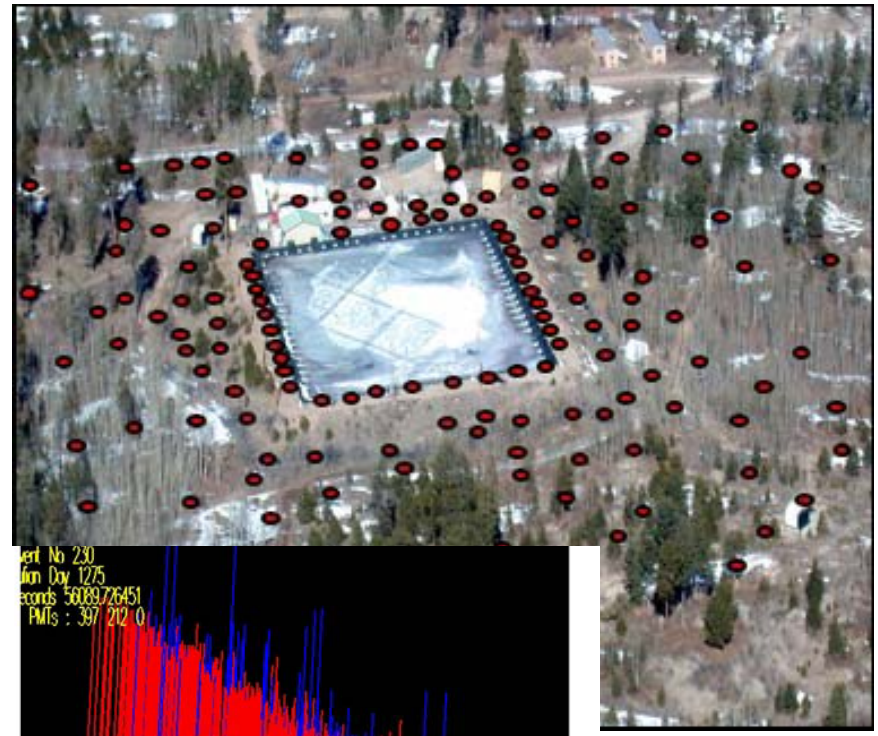
Energy Range 0.1-100 TeV
Area > 10^4 m^2
Background Rejection > 95%
Angular Resolution 0.3° - 0.7°
Energy Resolution ~50%
Aperture > 2 sr
Duty Cycle > 90%

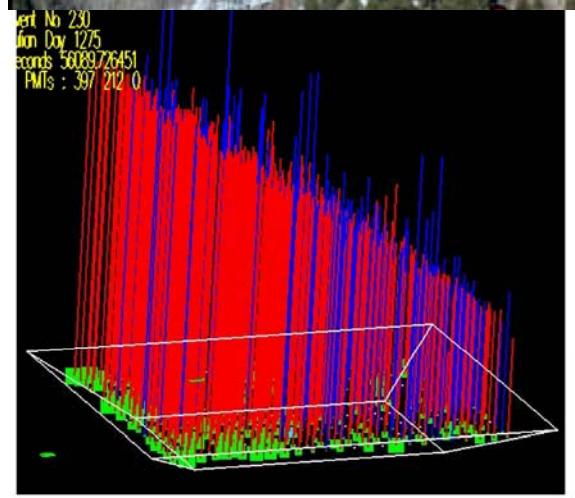
Unbiased Complete Sky Survey
Extended Sources
Transient Objects (GRB's)

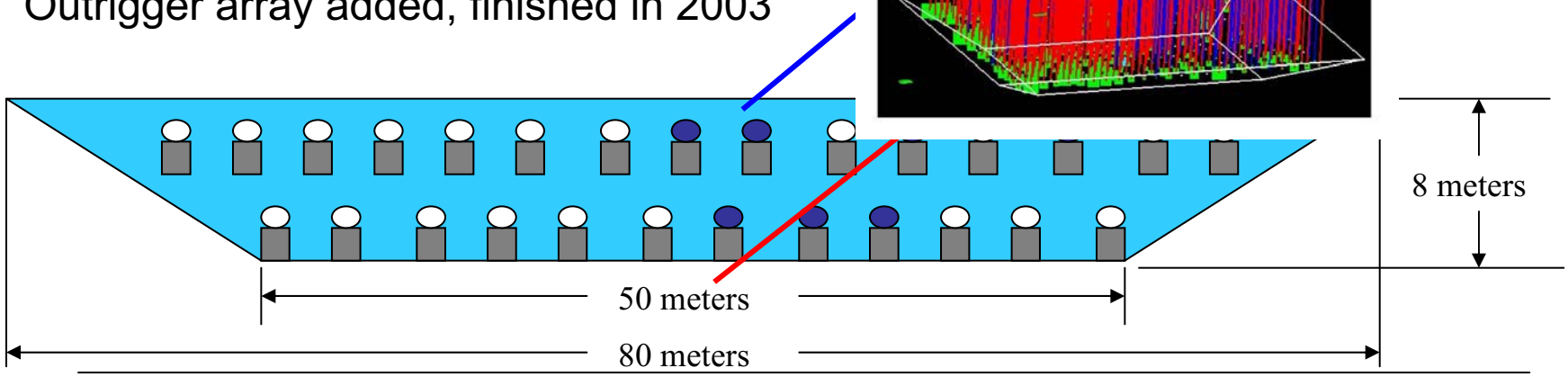
Complementarity of TeV Gamma-Ray Detectors

The Milagro Detector

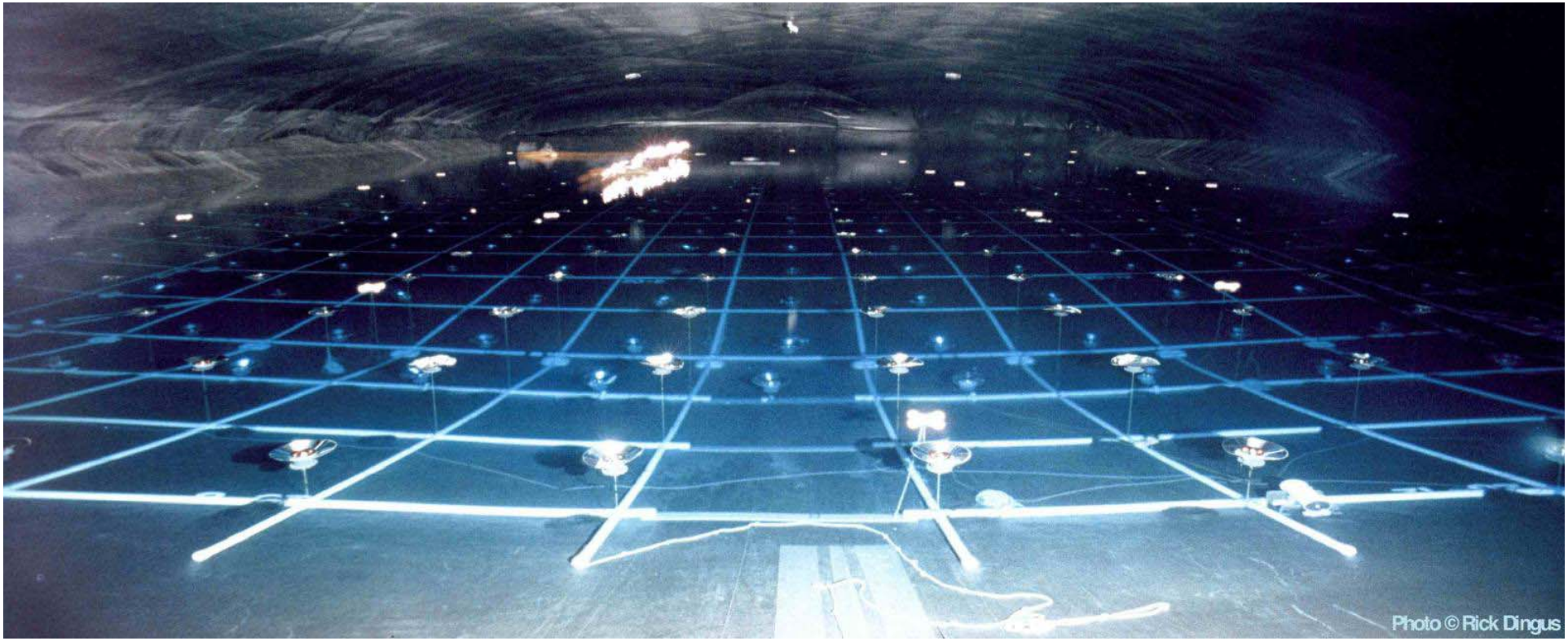
- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water
- Reconstruct shower direction to ~0.5° from the time different PMTs are hit
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Field of view is ~2 sr and the average duty factor is >90%
- Outrigger array added, finished in 2003







Inside the Milagro Detector

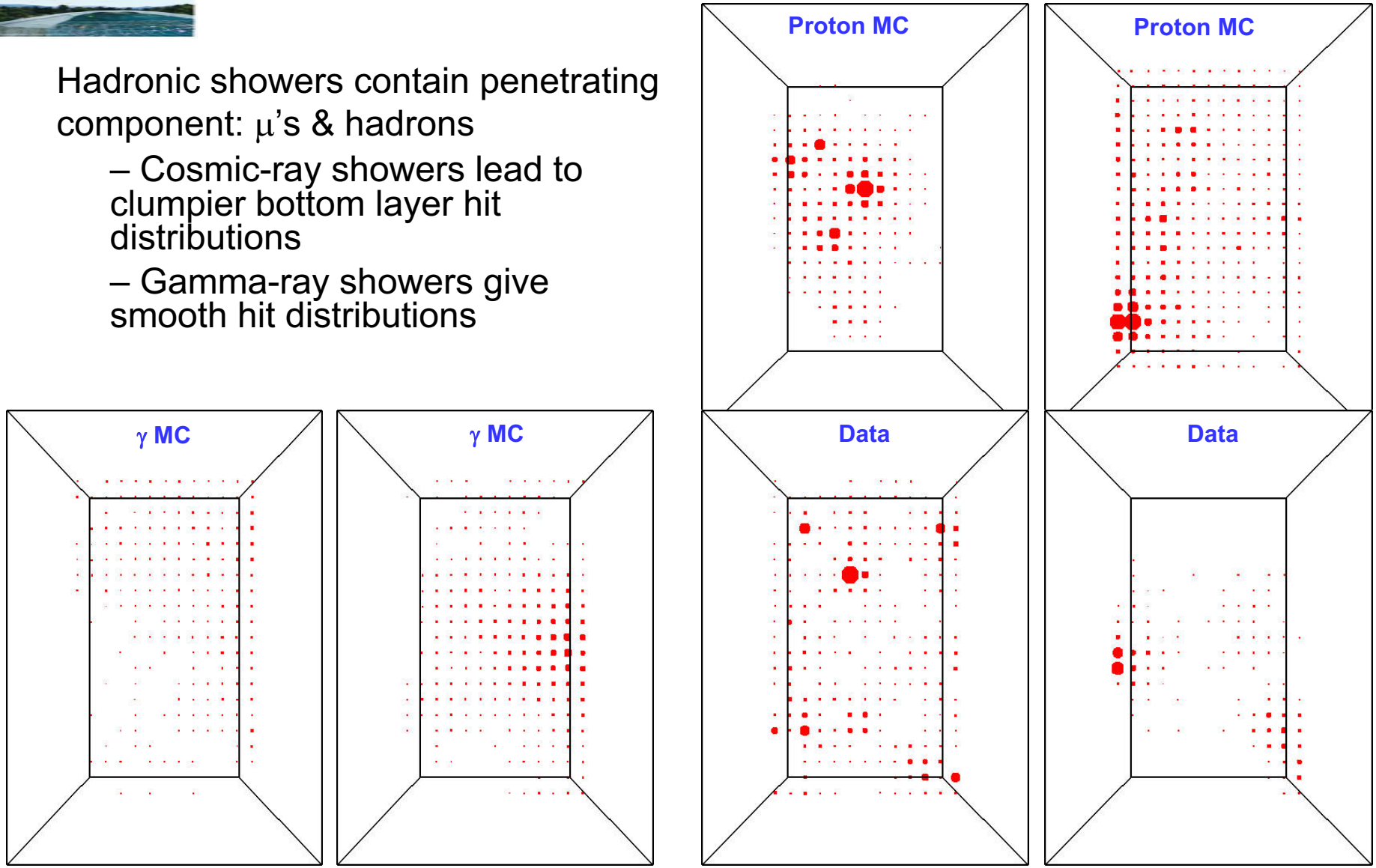


728 PMTs of 8" dia. in a pond of ~4000 m^2 x ~8 m deep and
176 PMTs in ~6 m^2 tanks spread over ~10^5 m^2

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

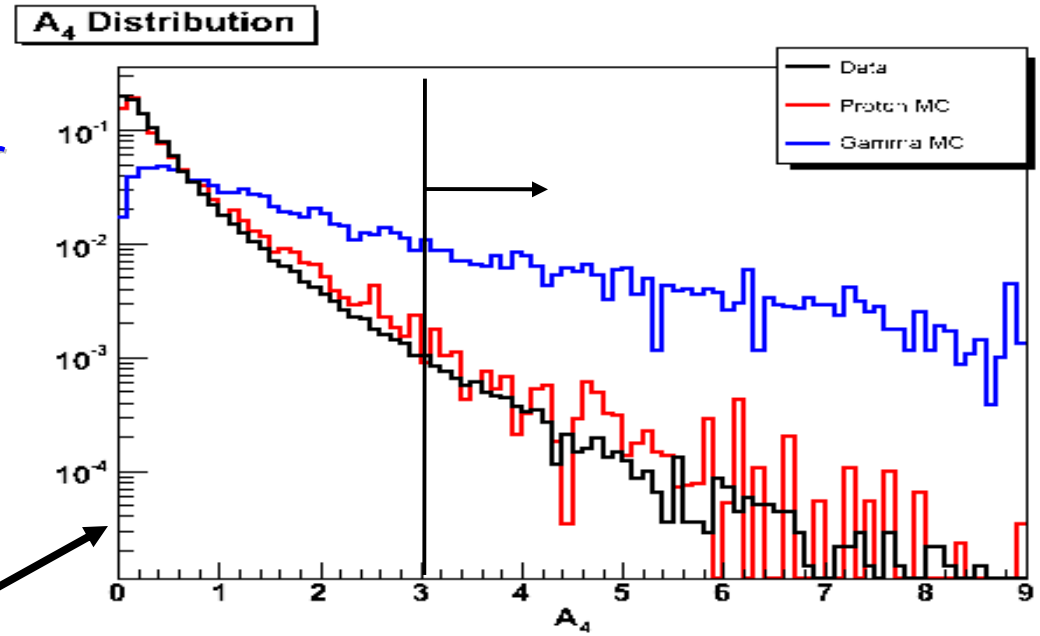


Background Rejection (Cont'd)

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

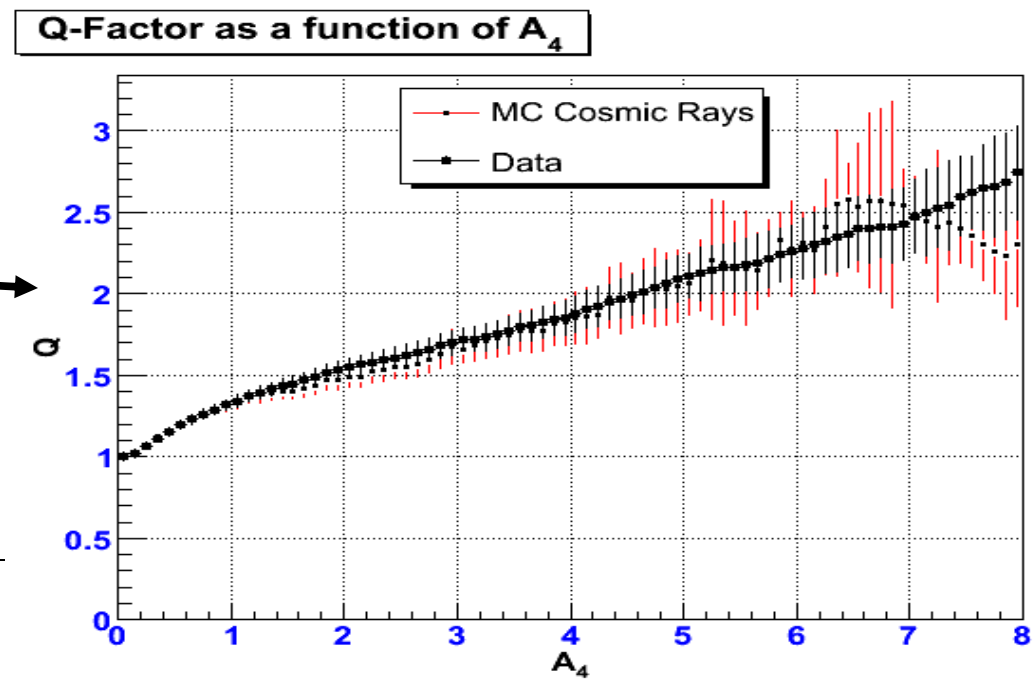


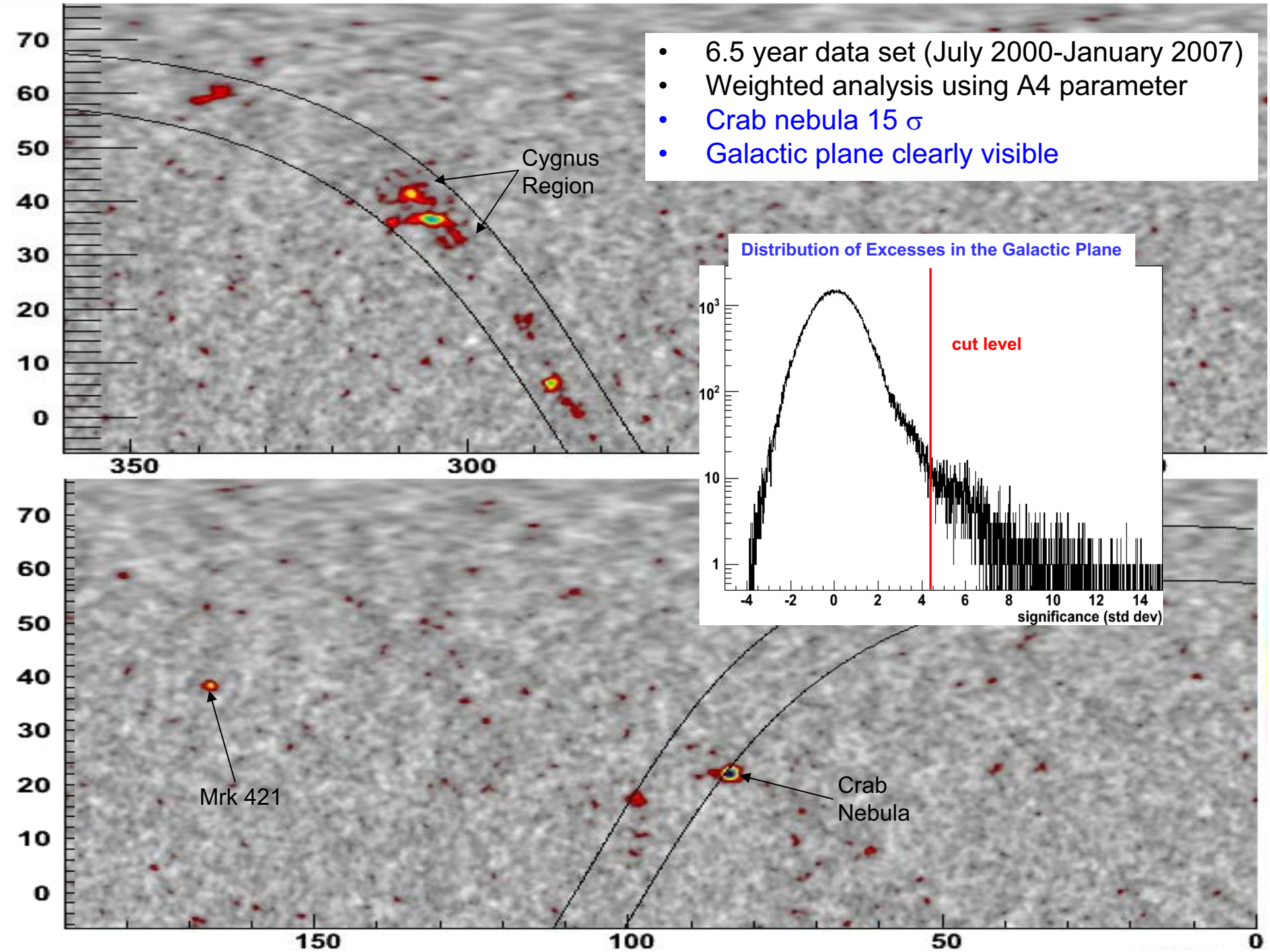
$A_4 > 3$ rejects 99% of Hadrons

retains 18% of Gammas

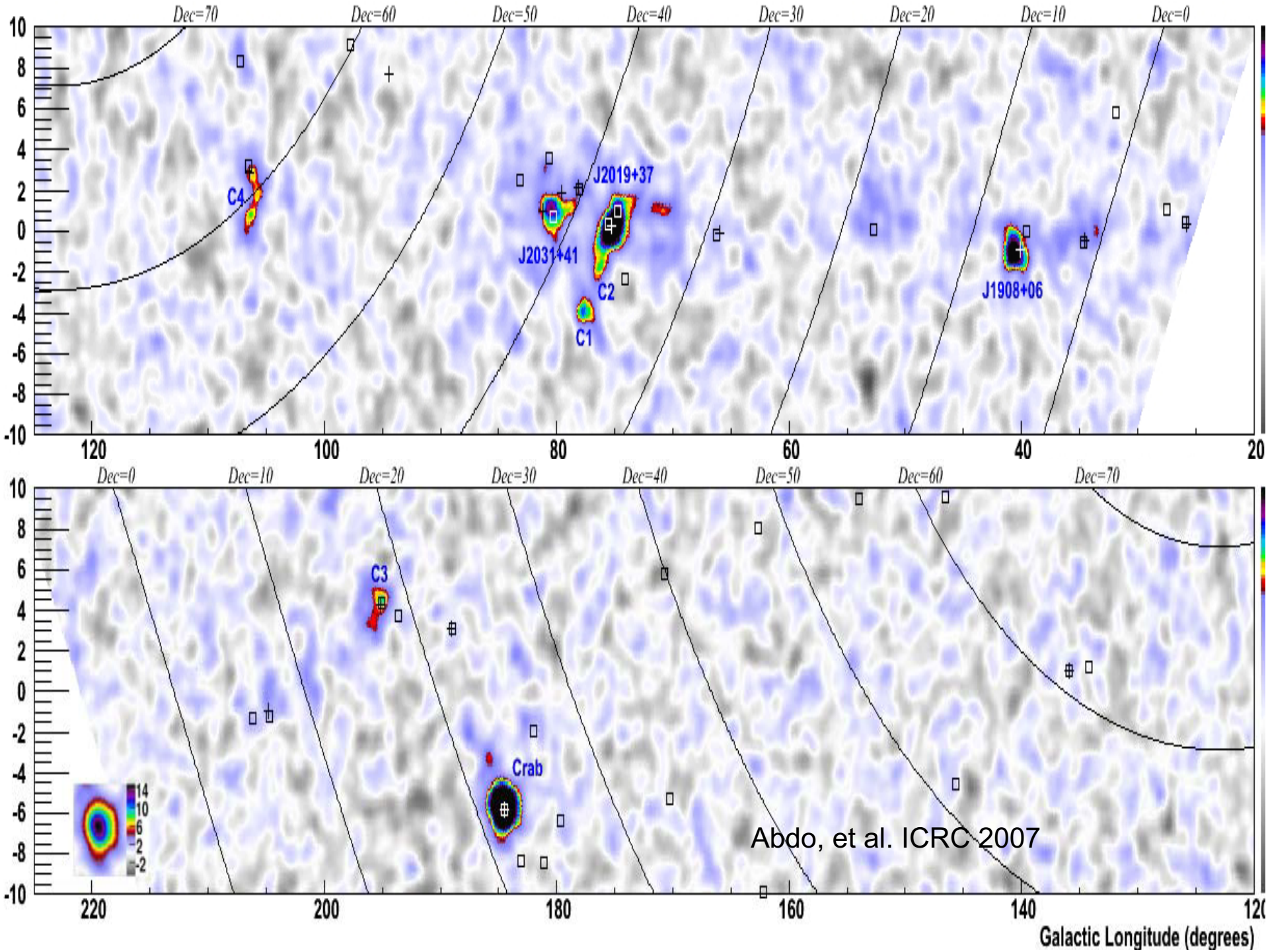
S/B increases with increasing A_4

$$Q = \frac{\varepsilon_\gamma}{\sqrt{\varepsilon_{bkg}}}$$

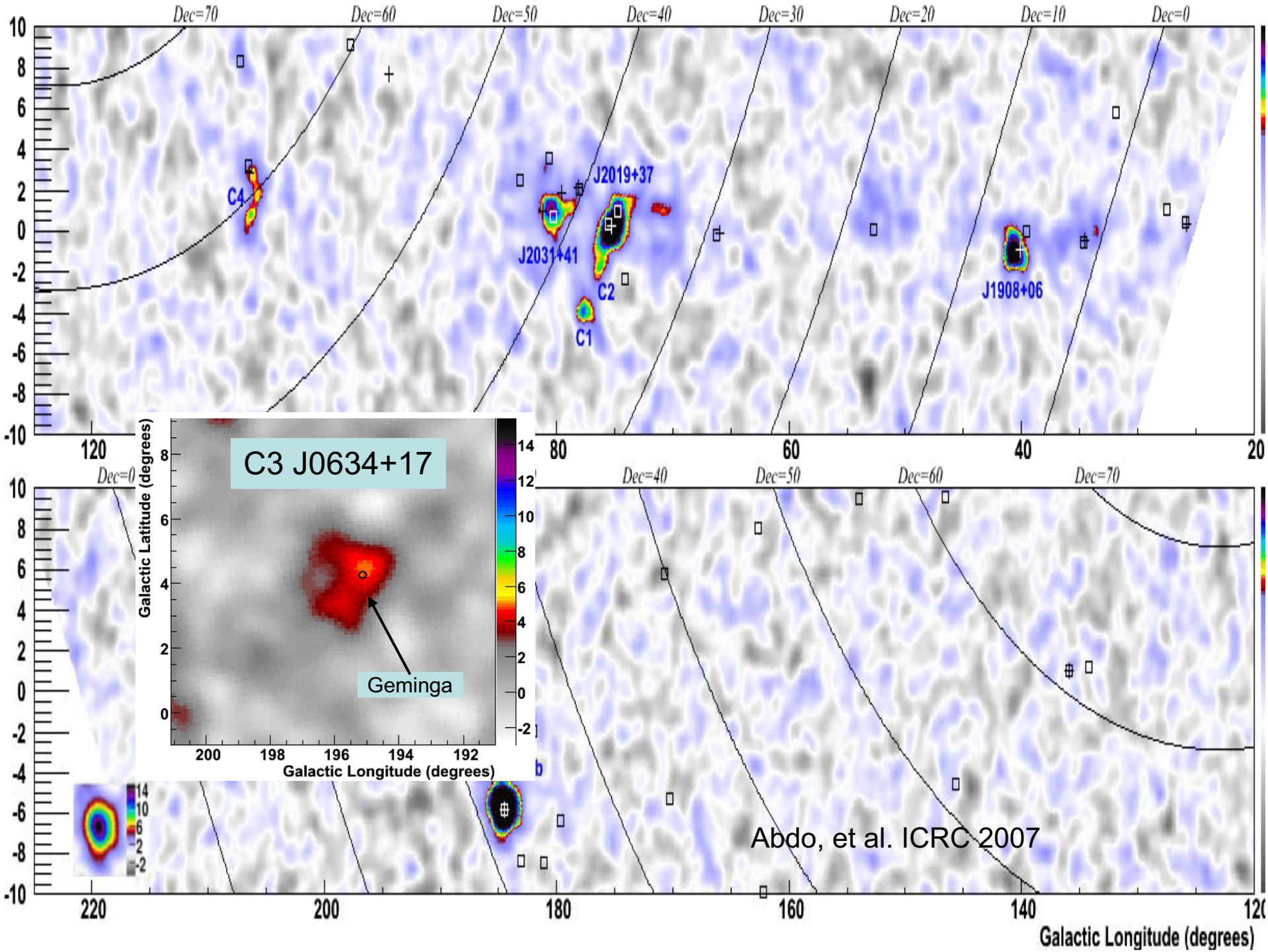




- 6.5 year data set (July 2000-January 2007)
- Weighted analysis using A4 parameter
- Crab nebula 15 σ
- Galactic plane clearly visible



Abdo, et al. ICRC 2007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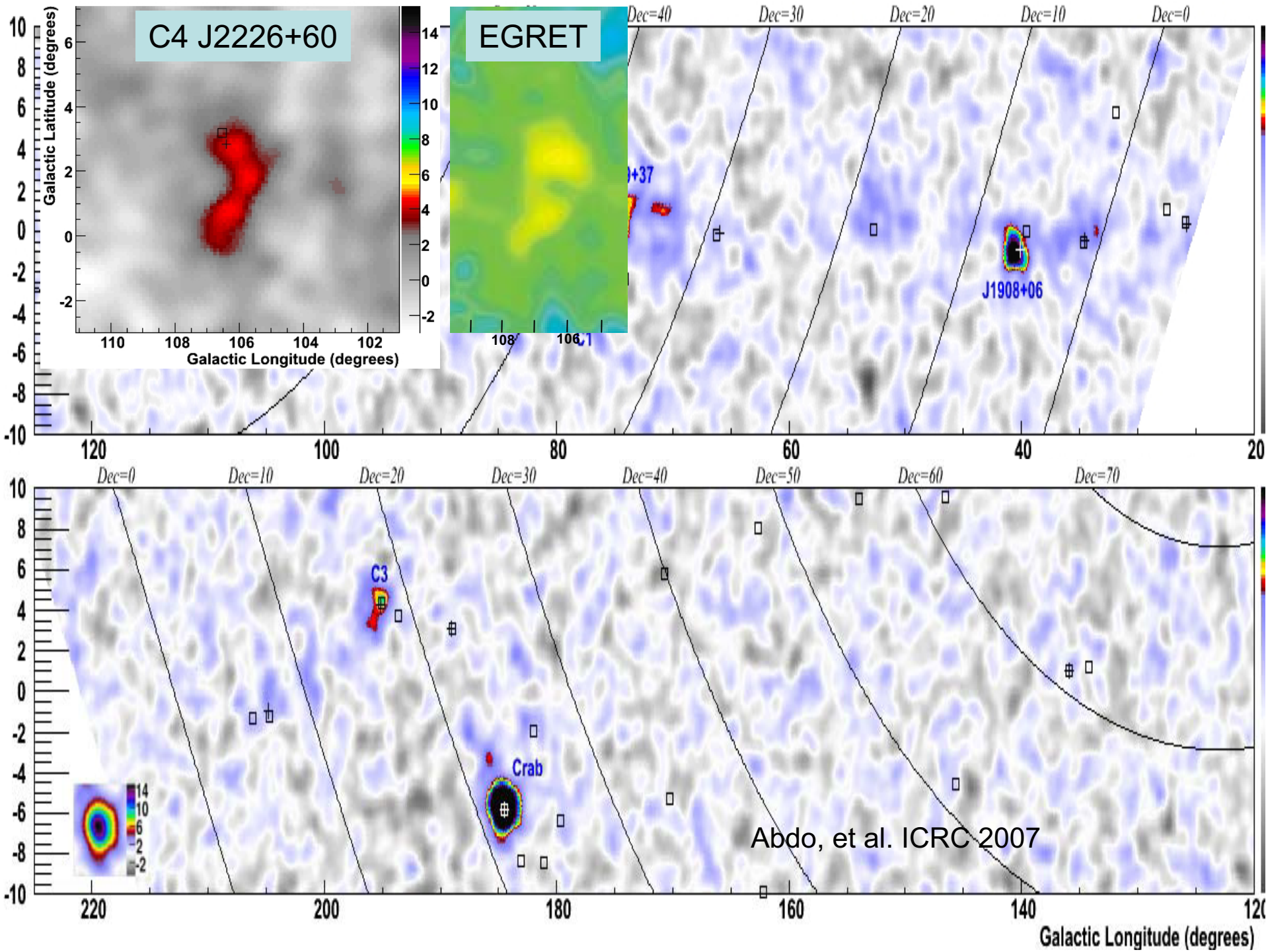
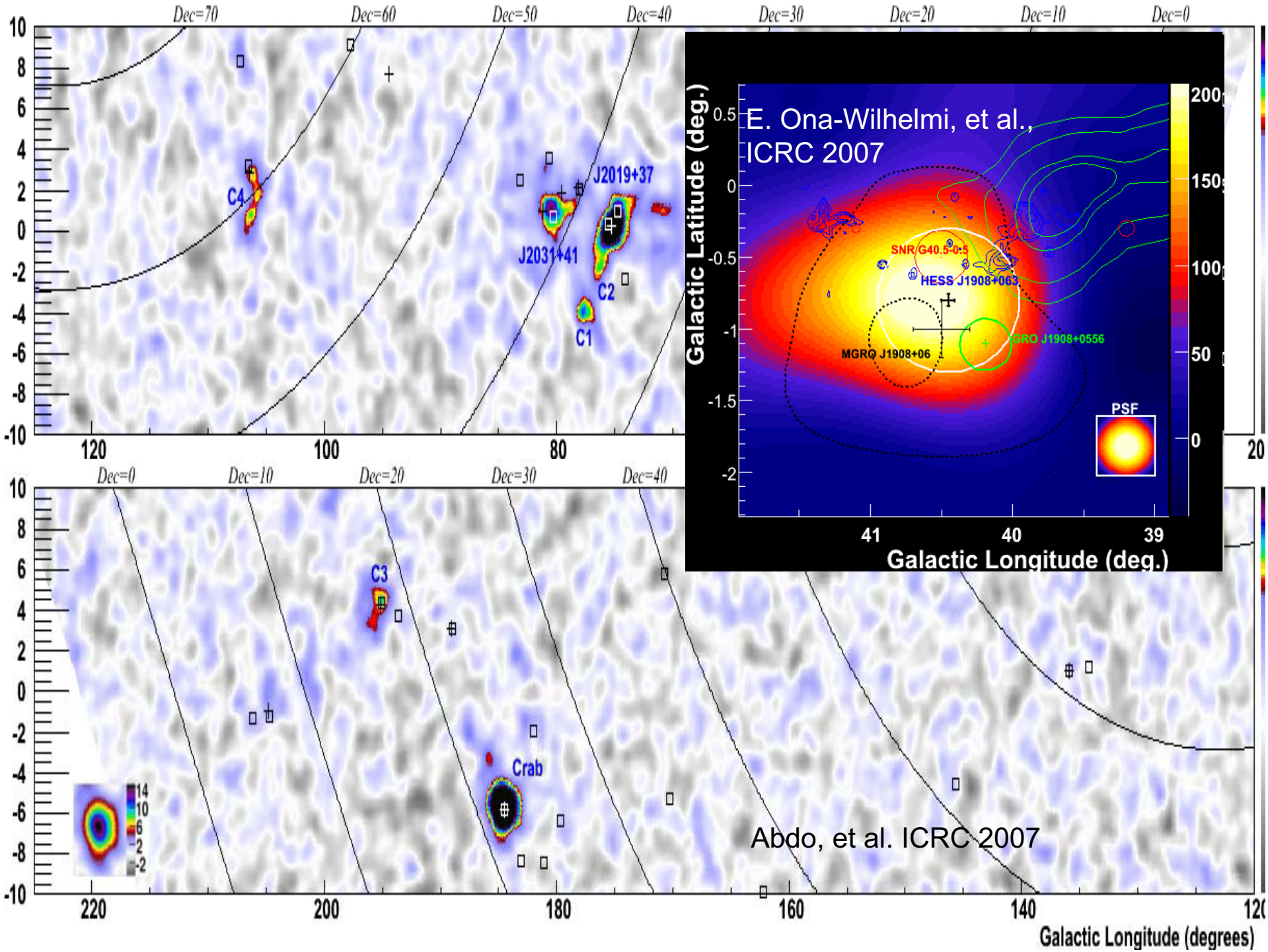
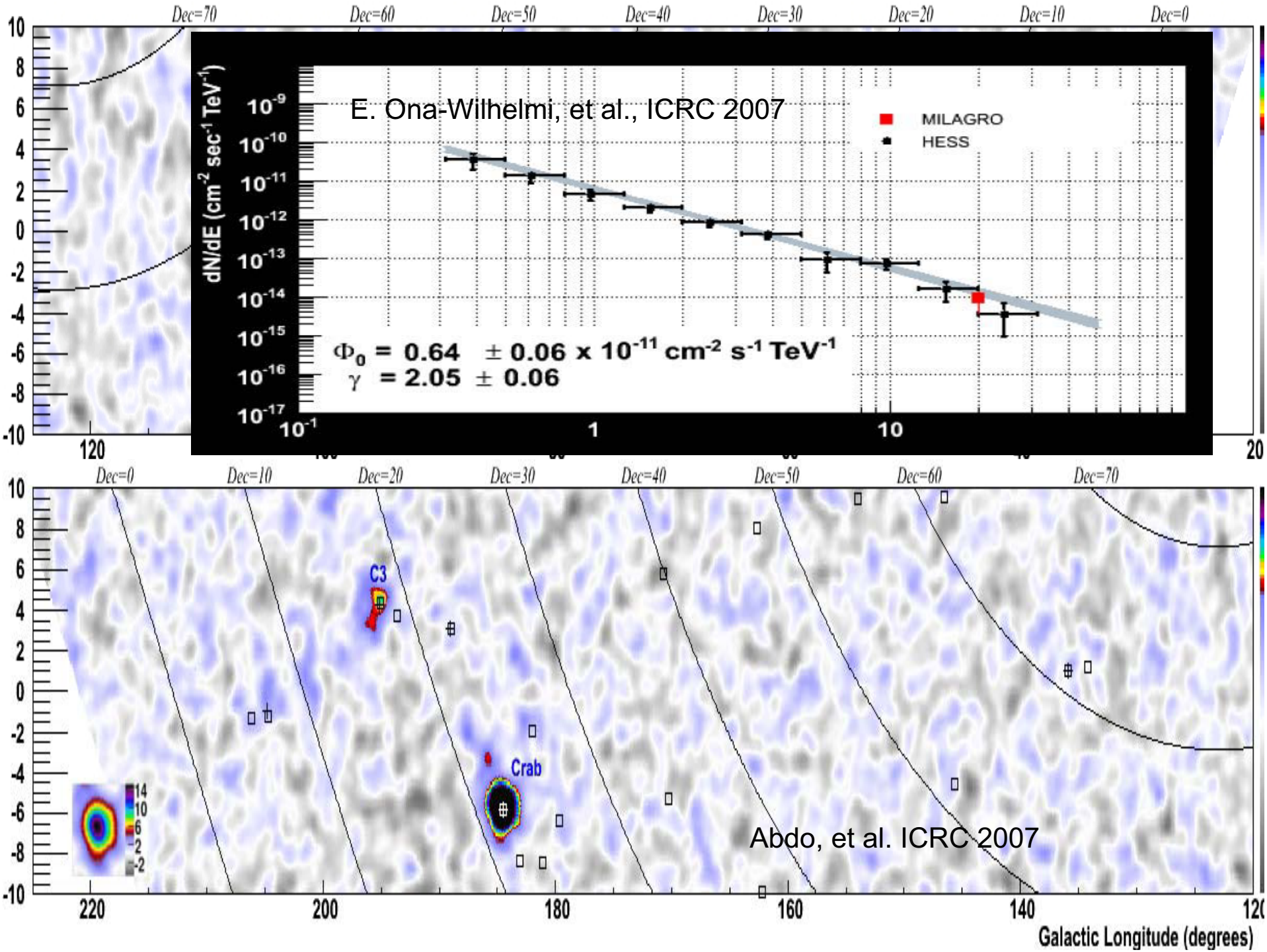
Dec=60
Dec=50
Dec=40
Dec=30
Dec=20
Dec=10
Dec=0
C4
J2019+37
J2031+41
C2
C1
J1908+06
C3 J0634+17
Geminga
Galactic Latitude (degrees)
Galactic Longitude (degrees)
Abdo, et al. ICRC 2007
Galactic Longitude (degrees)


C4 J2226+60
EGRET
Galactic Latitude (degrees)
Galactic Longitude (degrees)
J1908+06
C3
Crab
Dec=0
Dec=10
Dec=20
Dec=30
Dec=40
Dec=50
Dec=60
Dec=70
Abdo, et al. ICRC 2007
Galactic Longitude (degrees)


Dec=70
Dec=60
Dec=50
Dec=40
Dec=30
Dec=20
Dec=10
Dec=0
C4
J2019+37
J2031+41
C2
C1
C3
Crab
Galactic Longitude (degrees)
E. Ona-Wilhelmi, et al., ICRC 2007
Galactic Latitude (deg.)
Galactic Longitude (deg.)
SNR G40.5-0.5
HESS J1908+063
MGRO J1908+06
GRO J1908+0556
PSF
Abdo, et al. ICRC 2007


E. Ona-Wilhelmi, et al., ICRC 2007
MILAGRO
HESS
dN/dE (cm^{-2} sec^{-1} TeV^{-1})
Φ_0 = 0.64 ± 0.06 x 10^{-11} cm^{-2} s^{-1} TeV^{-1}
γ = 2.05 ± 0.06
C3
Crab
Abdo, et al. ICRC 2007
Galactic Longitude (degrees)

Dec=70
Dec=60
Dec=50
Dec=40
Dec=30
Dec=20
Dec=10
Dec=0
Applications Actions
Fri Aug 3, 2:19 PM
H.E.S.S. Source of the Month - Mozilla Firefox
File Edit View Go Bookmarks Tools Help
http://www.mpi-hd.mpg.de/hfm/HESS/public/som/current.htm
Go
Distros
Milagro Project
HiRes: High Resolution...
ISMD 2007 Berkeley
NASA ADS: ADS Hom...
Link Everything Online
Welcome to Gmail
The ROOT System Ho...
Milinda: Main Page
PAW to ROOT convers...
H.E.S.S. Source of the Month
Each month a TeV gamma ray source investigated with the H.E.S.S. telescopes is featured
Index | Previous | Next | H.E.S.S. Home
August 2007: Confirming MGRO 1908+06
Galactic Latitude (deg)
Galactic Longitude (deg)
Significance
TeV gamma-ray image of the Inner Galaxy from Milagro (A. Abdo, Ph.D. Thesis, 2007, and A. Abdo et al., 2007). MGRO 1908+06 is the source at about 40 degr. longitude. The complex of sources at 70-80 degr. longitude coincides with the Cygnus region.
Recently, the Milagro collaboration, operating a ground-based air shower detector based on the water Cherenkov technique, announced the detection of several new sources of very-high-energy gamma rays in the Galactic Plane (A. Abdo et al., 2007). Compared to Cherenkov telescopes, Milagro has a higher energy threshold - the median energy of detected events is about 20 TeV - and a reduced angular resolution of about 1 degr. Located in the northern hemisphere, Milagro coverage of the Galactic Plane extends from about 30 degr. longitude towards higher longitudes. Four sources are detected at sufficient significance, the Crab Nebula and the new sources MGRO 2019+37, MGRO 1908+06 and MGRO 2031+41. Of these, MGO 1908+06, with a flux of 80% of the Crab flux and a diameter of up to 2.6 degr., is within the field of view of the H.E.S.S. Galactic Plane Survey, at a longitude around 40 degr.
Fig. 1 shows the H.E.S.S. sky map of the corresponding region, based on 10 h of data. Confirming the Milagro result, a gamma-ray source is detected with up to 9 sigma significance. The H.E.S.S. source is located at l=40.45 degr. and b=-0.80 degr., consistent with the Milagro position of l=40.4 degr. and b=-1.0 degr., with an error radius of 0.24 degr. The rms size of the H.E.S.S. source is about 0.2 degr. The energy spectrum measured by H.E.S.S. is shown in Fig. 2; the source exhibits a rather flat spectrum with a spectral index of 2.1. The spectrum measured with H.E.S.S agrees well with the Milagro data point at 20 TeV. The nature of the source is unclear; it coincides within errors with the (also unidentified) EGRET GeV source GRO J1908+0556 / GEV J1907+0557 (Lamb and Macomb 1997, Reimer et al. 1997) and with the shell-type supernova remnant G40.5-0.5 (Fig. 3), which is however smaller than the TeV source.
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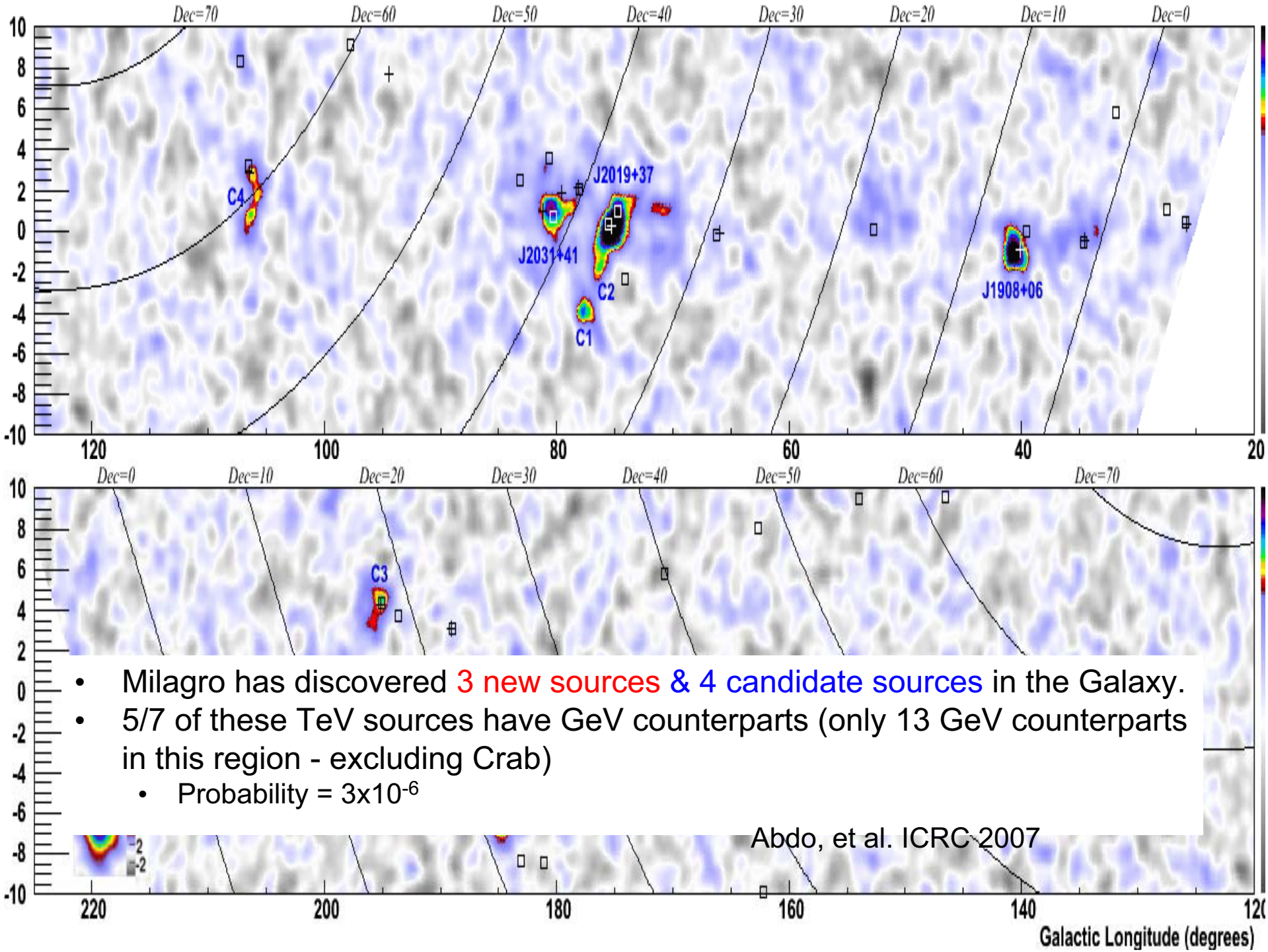
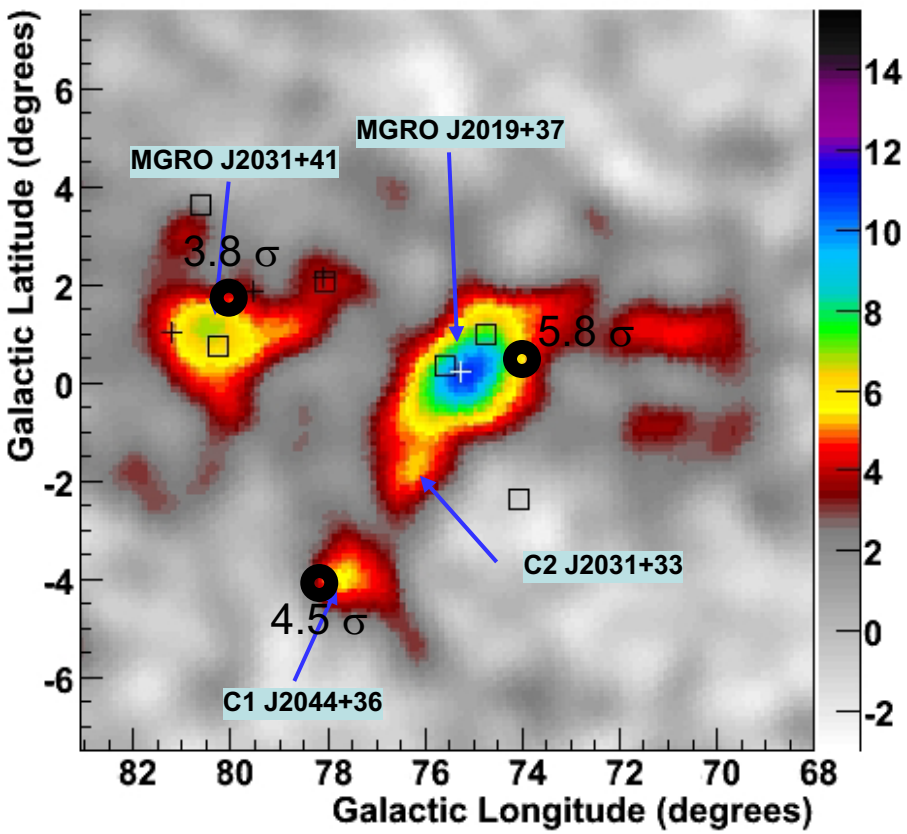
Downloads
H.E.S.S. Source of the M
[Terminal]
Abdo, et al. ICRC 2007
Galactic Longitude (degrees)



- 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}

Abdo, et al. ICRC 2007

The Cygnus Region



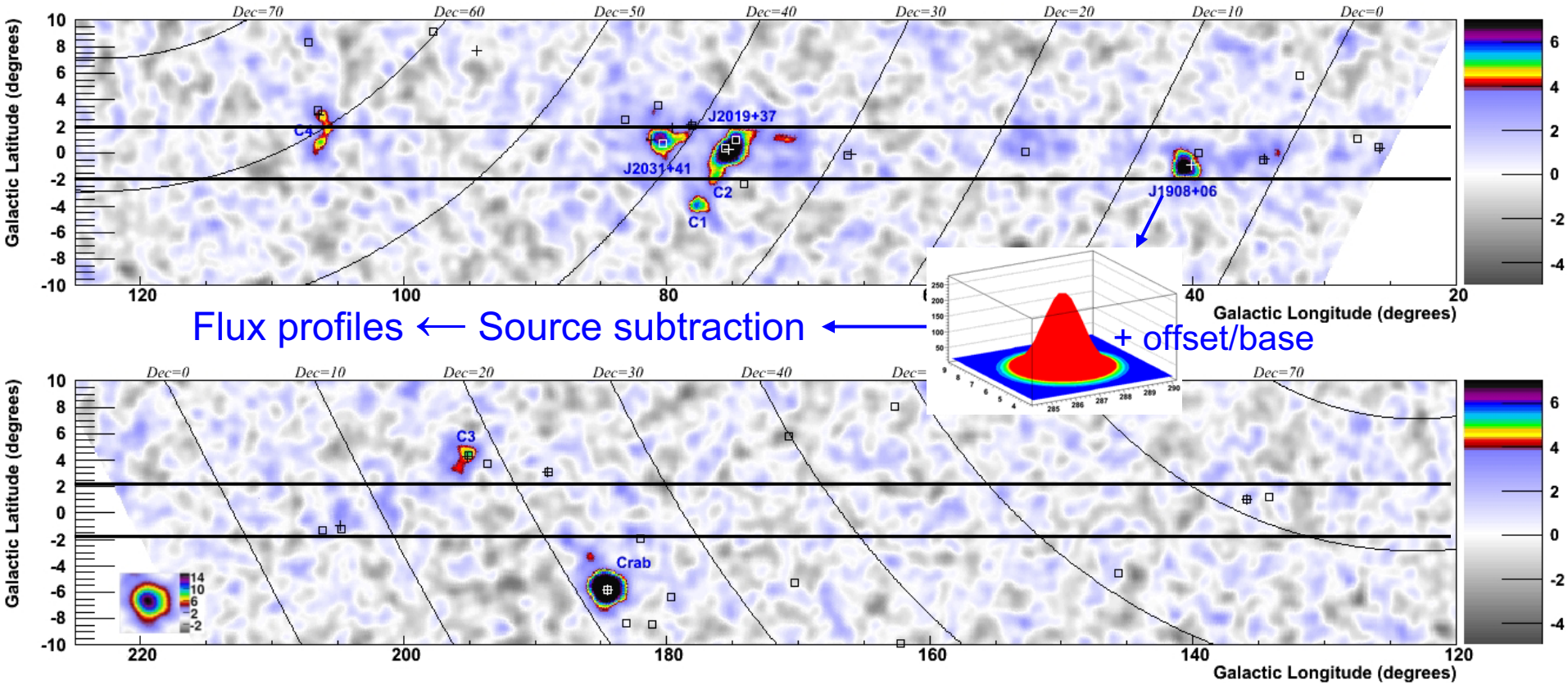
Abdo, et al. ICRC 2007

Wang, et al. ICRC 2007

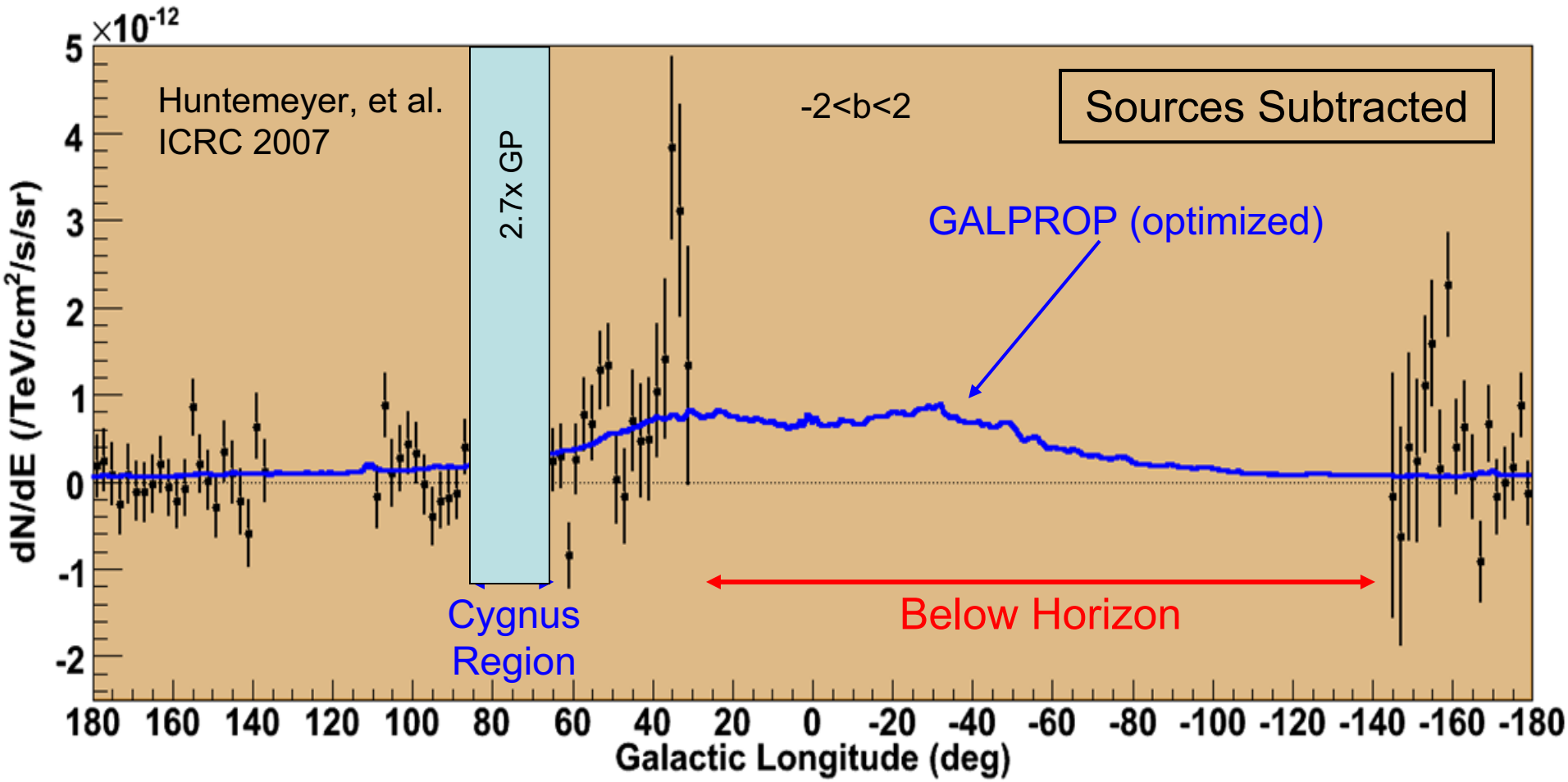
- MGRO J2019+37: 10.9σ
  - Extended source 1.1° ± 0.5° (top hat dia.)
  - Possible Counterparts
    - GeV J2020+3658, PWN G75.2+0.1
- MGRO J2031+41: 6.9σ (5.0σ post-trials)
  - Possible Counterparts:
    - 3EG J2033+4118, GEV J2035+4214
    - TEV J2032+413 (⅓ of Milagro flux)
  - 3.0° ± 0.9° (top hat dia.)
- C1 J2044+36: 5.5σ pre-trials
  - no counterparts
  - < 2.0°
- C2 J2031+33: 5.3σ pre-trials
  - no counterparts
  - possible extension of MGRO J2019+37
  - possible fluctuation of MGRO J2019 tail & diffuse emission & background
- Tibet ASγ preliminary detections of 3 sources

Diffuse Emission Calculation

- Diffuse emission expected from cosmic ray interactions with matter and radiation
- Gamma rays probe cosmic rays outside the near Earth environment



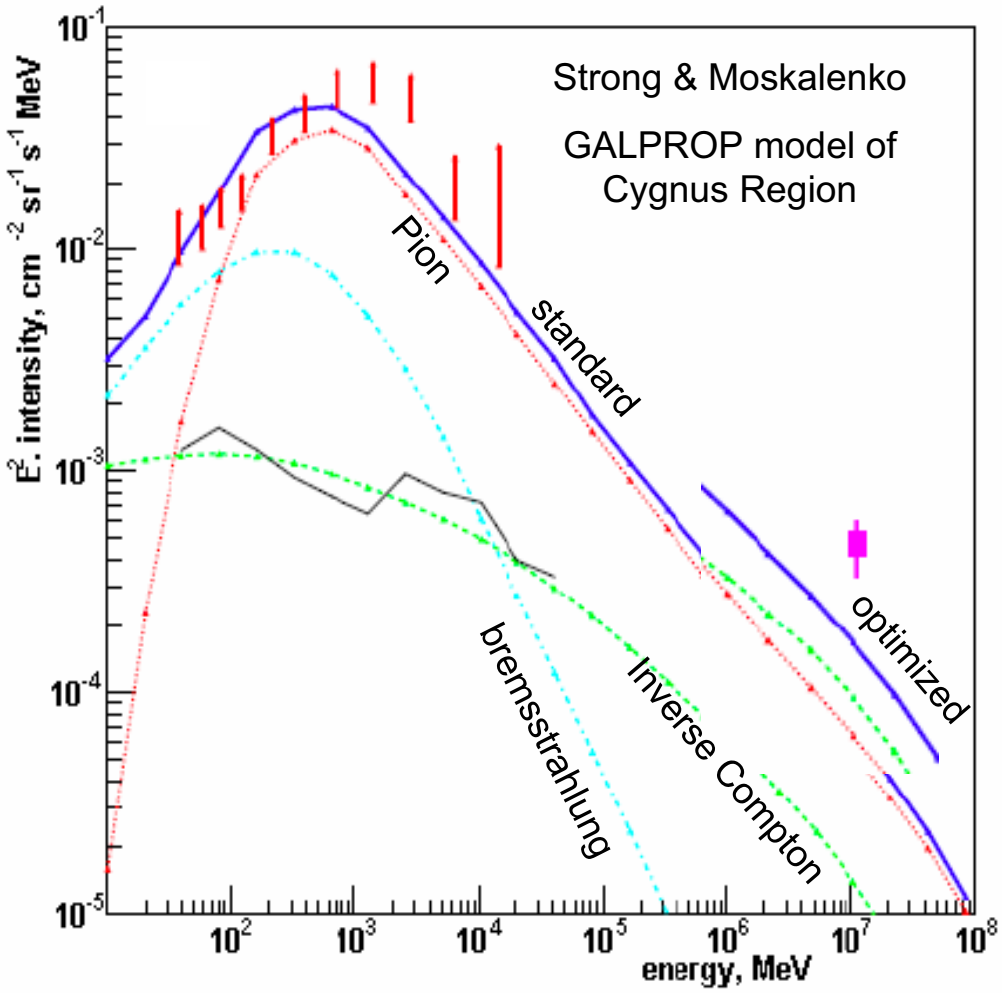
TeV Galactic Diffuse Emission



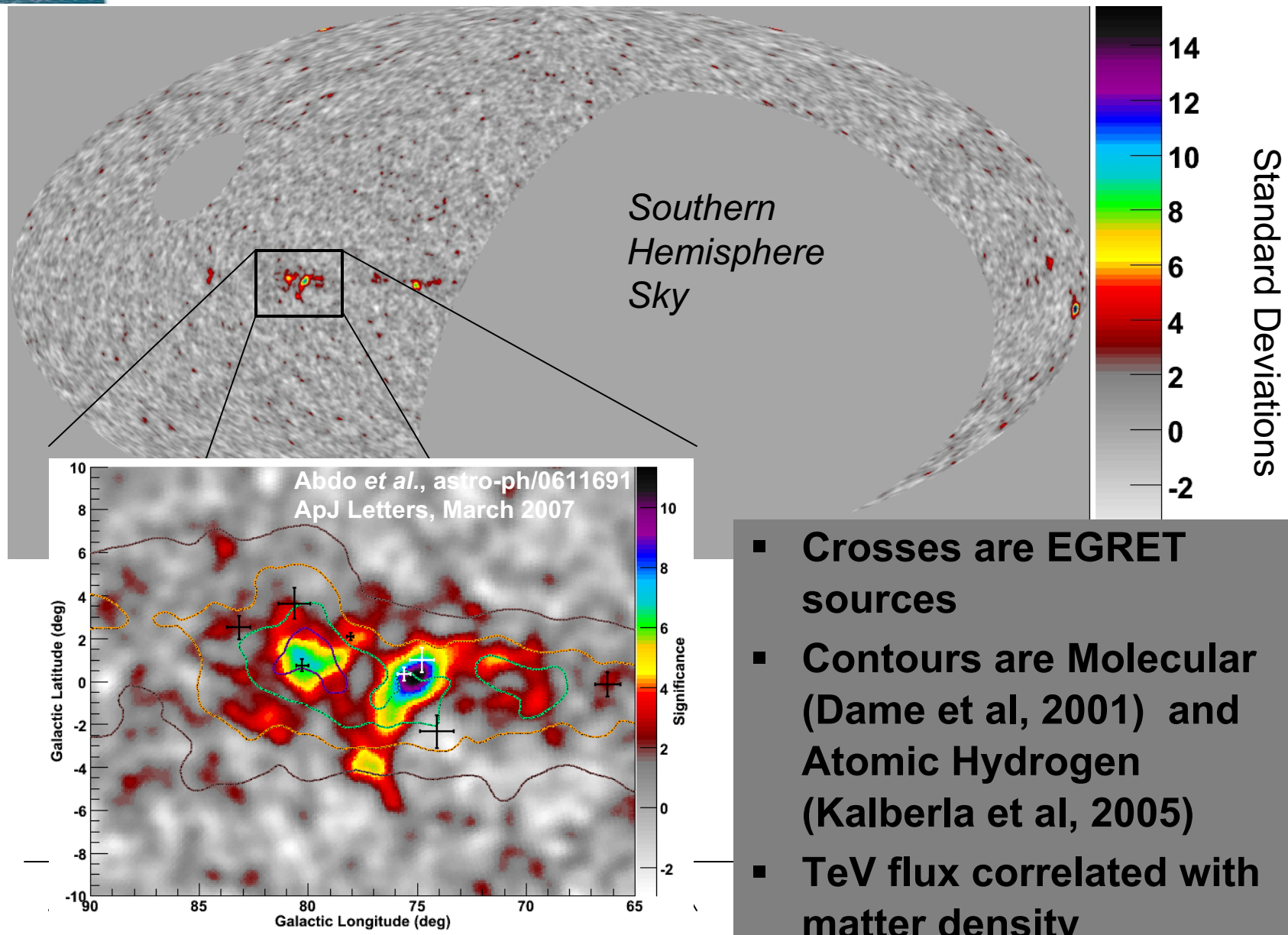
- What is GLAPROP? What does optimized mean?

Diffuse Emission from Cygnus Region

- Not only Milagro's TeV flux exceeds predictions
- GeV gamma ray fluxes (EGRET) also exceed predictions based on local cosmic ray flux
- GALPROP (Strong & Moskalenko) model
  - "optimized": Fit to EGRET
  - Increase π^0 and IC component throughout Galaxy
  - Milagro flux ~2.5*x* prediction
  - Possible explanations:
    - Hard spectrum cosmic ray sources?
    - Unresolved point sources?



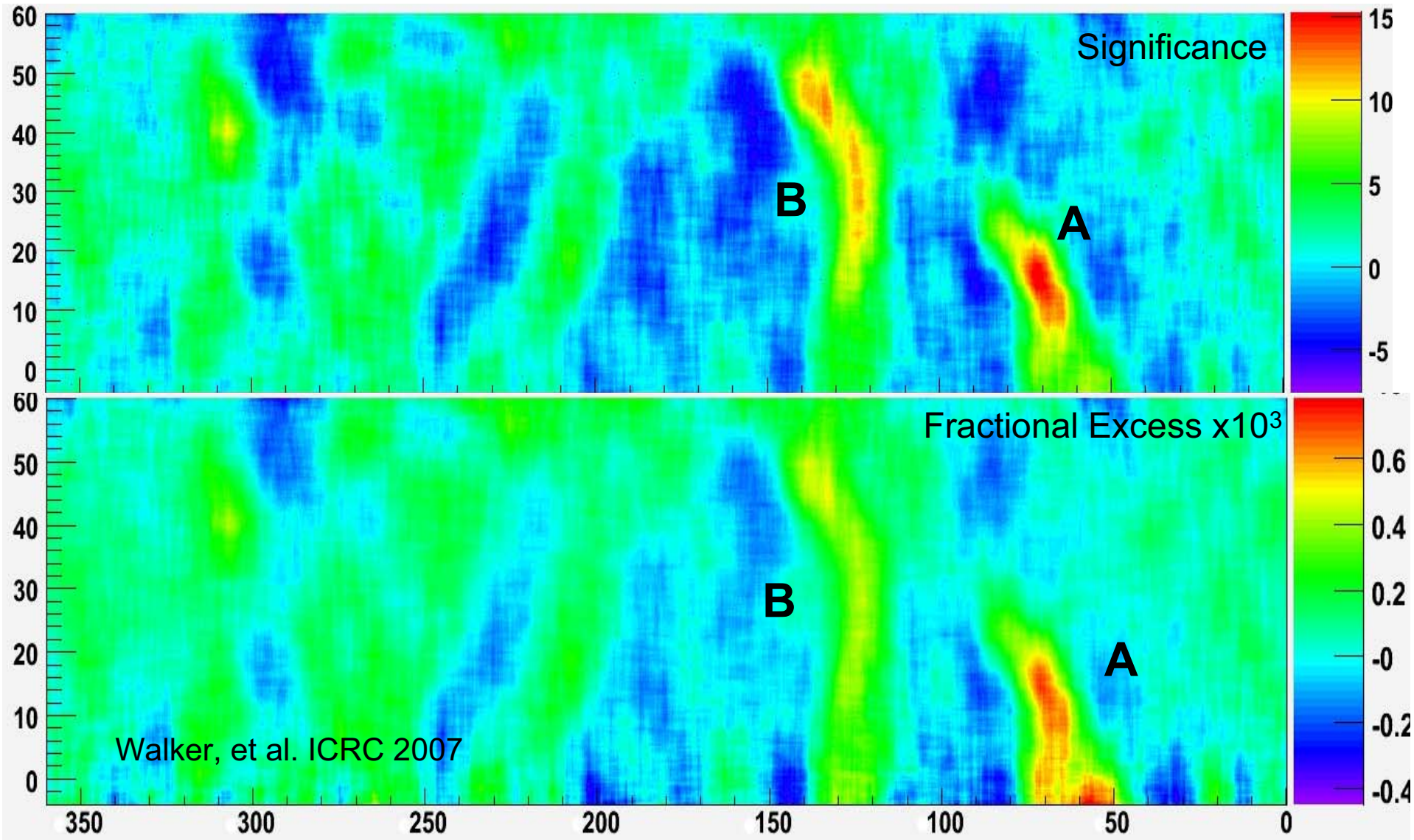
The Cygnus Region



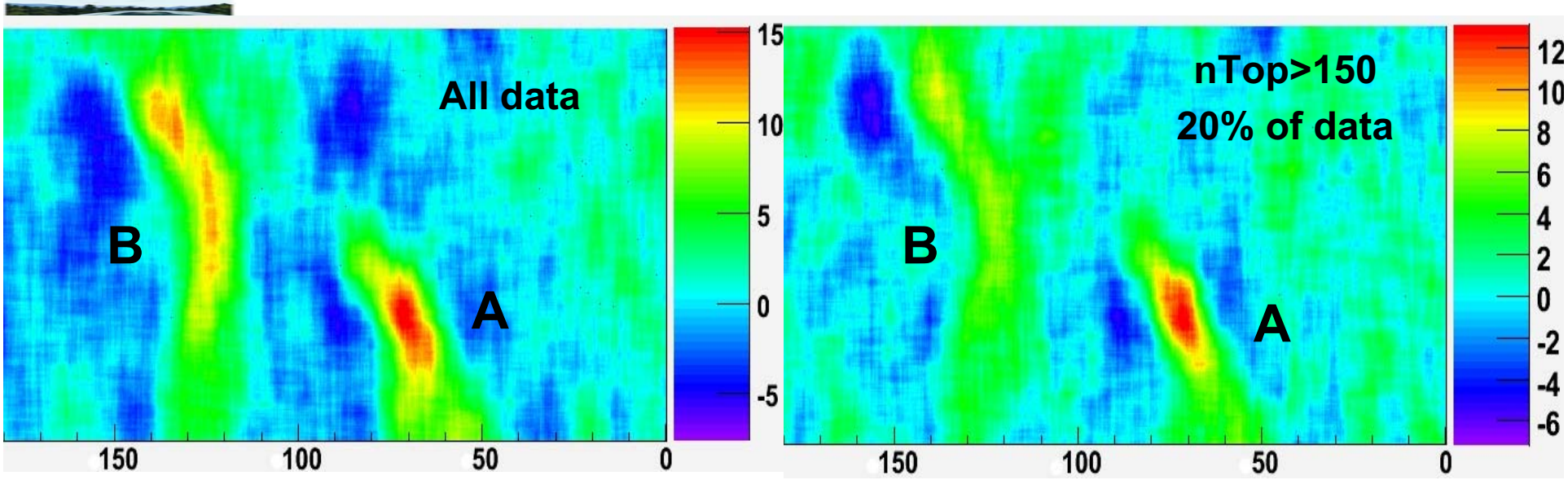
- **Crosses are EGRET sources**
- **Contours are Molecular (Dame et al, 2001) and Atomic Hydrogen (Kalberla et al, 2005)**
- **TeV flux correlated with matter density**

0°

Another Analysis: Anisotropy of TeV Sky



Anisotropy: What is it?



- Signal (A) disappears when cosmic-ray rejection applied
- Signal (A) maintains significance when threshold raised
  - Expected 7 σ observed 13 σ
- Anisotropy due to hard (<2.6) spectrum cosmic rays

Walker, et al. ICRC 2007