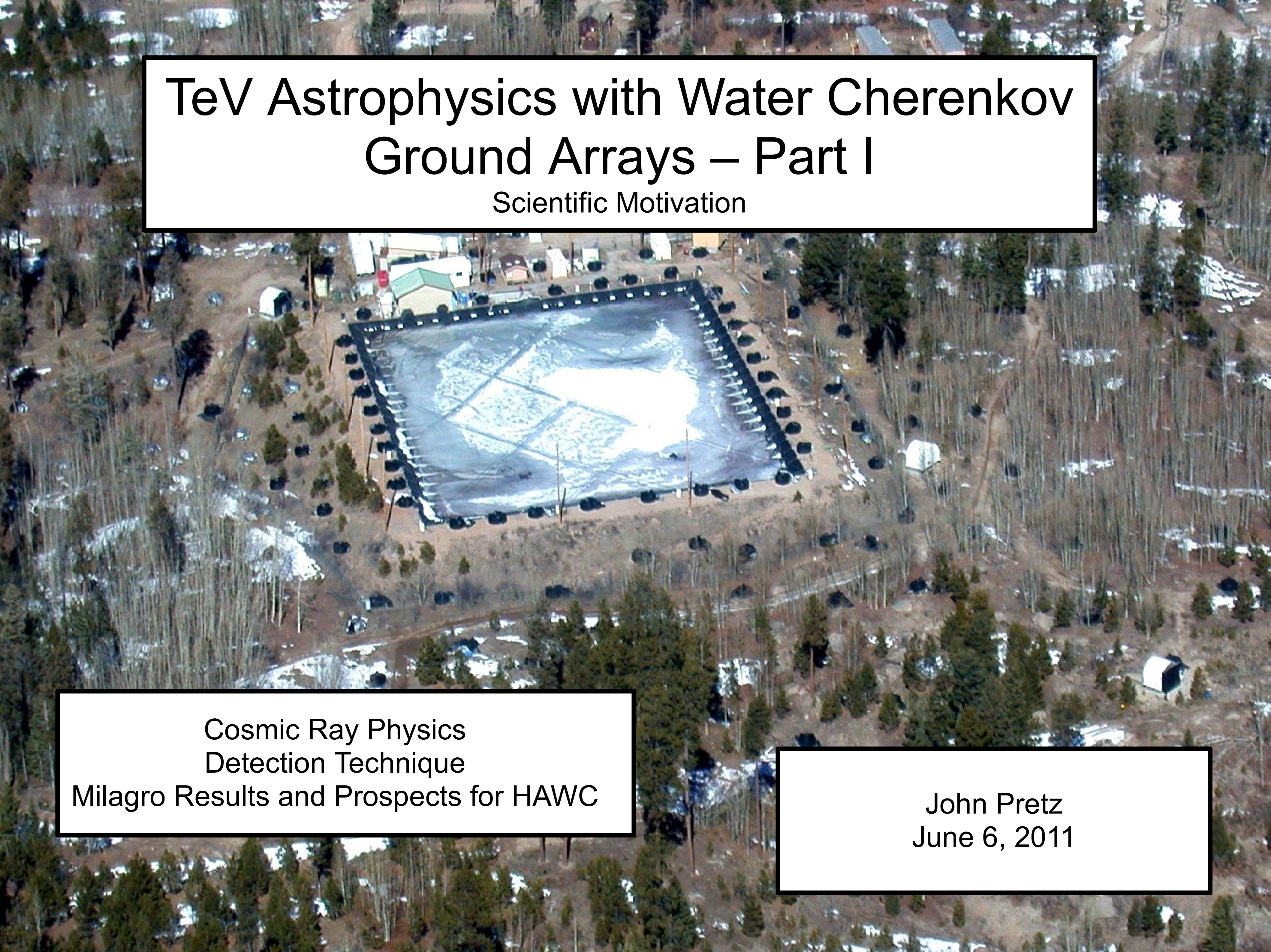


TeV Astrophysics with Water Cherenkov Ground Arrays – Part I

Scientific Motivation

Cosmic Ray Physics
Detection Technique
Milagro Results and Prospects for HAWC

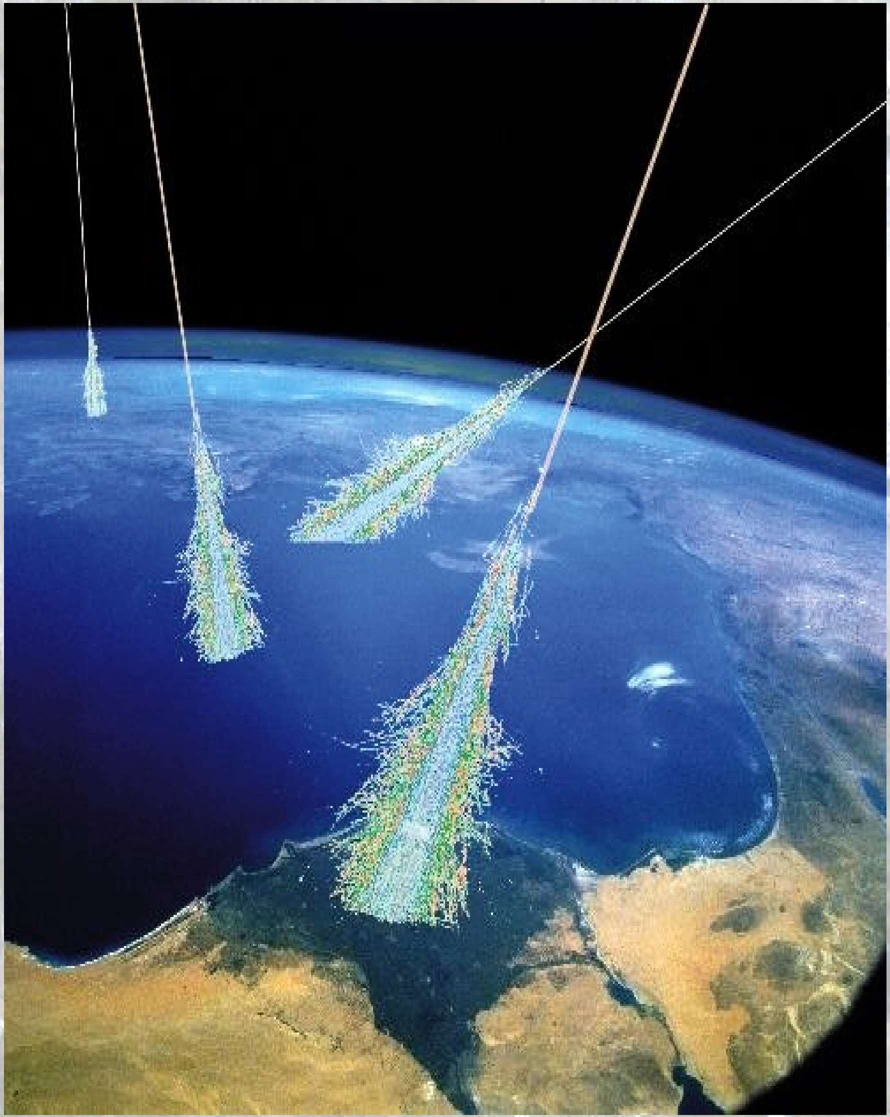
John Pretz
June 6, 2011

Cosmic Rays

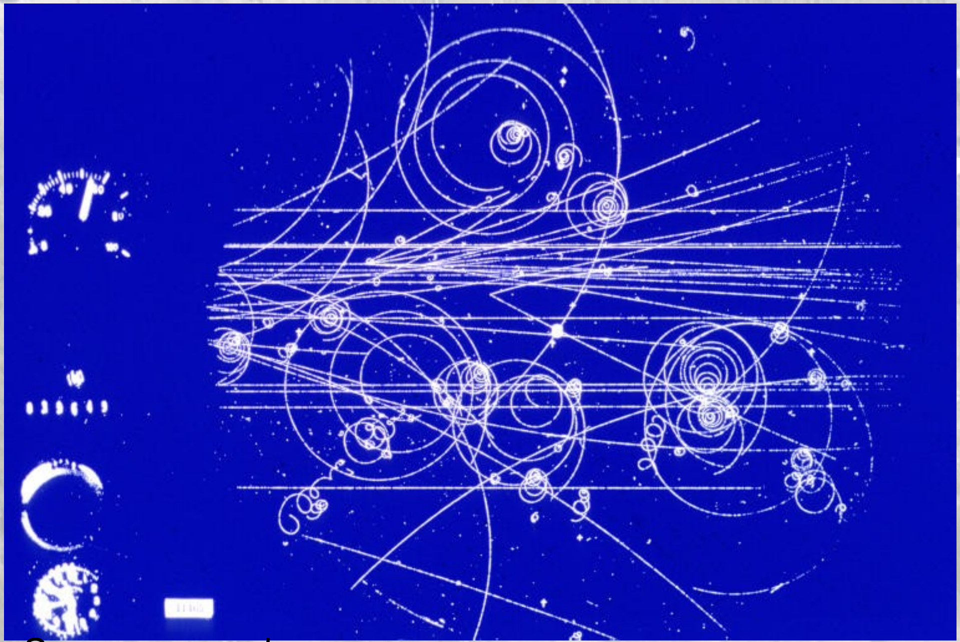
- Discovered by Victor Hess in 1912 (Nobel Prize in 1936)
- Increase in radiation at high altitudes
- Radiation is cosmic in origin
- Became clear later that we were seeing secondaries from nuclear primaries.

Cosmic Rays

- Cosmic ray nuclei interact to produce large air showers
- Mess of π^0,$\pi^\pm$, $K^\pm$,γ, ν, $e^\pm$,$\mu^\pm$
- Detected with ground-based arrays or viewing the light from the shower development directly
- We don't know where they are coming from.
- Particle physics born in cosmic ray air showers.

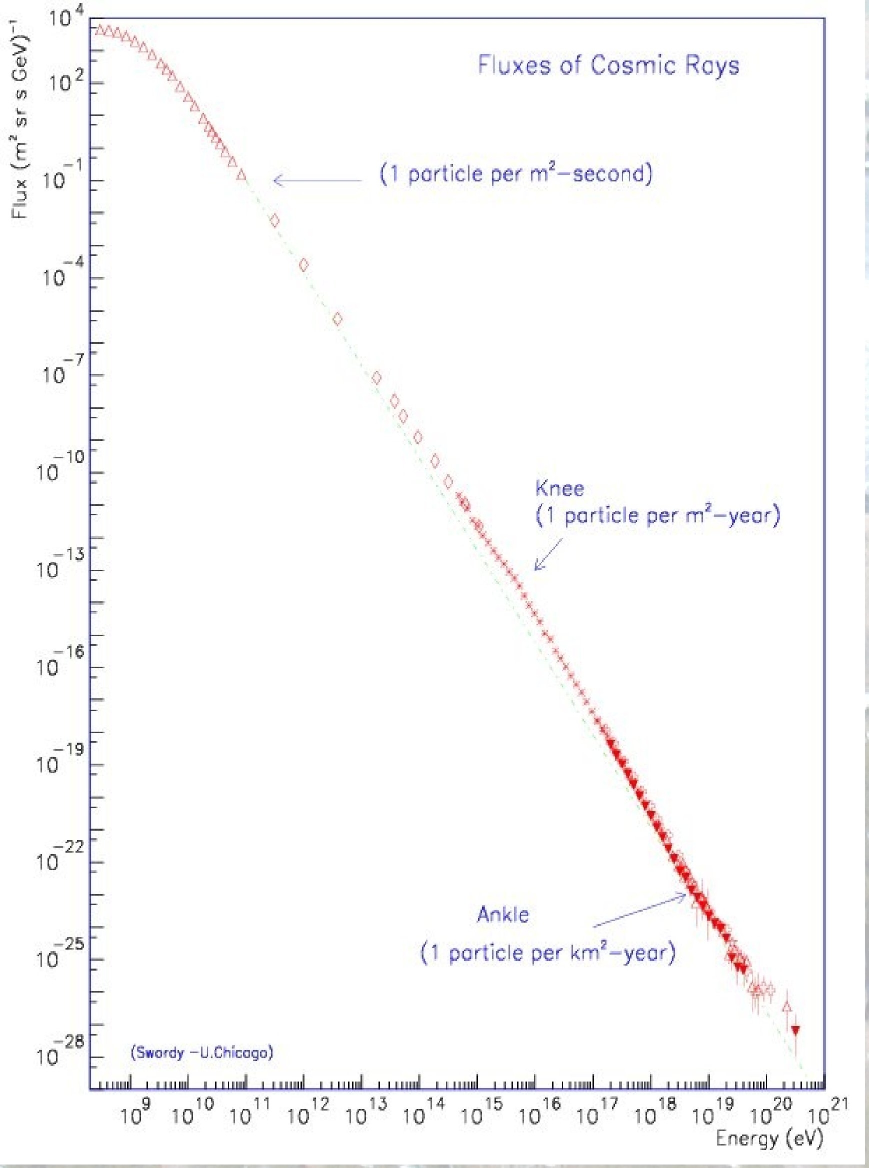


Source: nasa.gov



Source: cern.ch

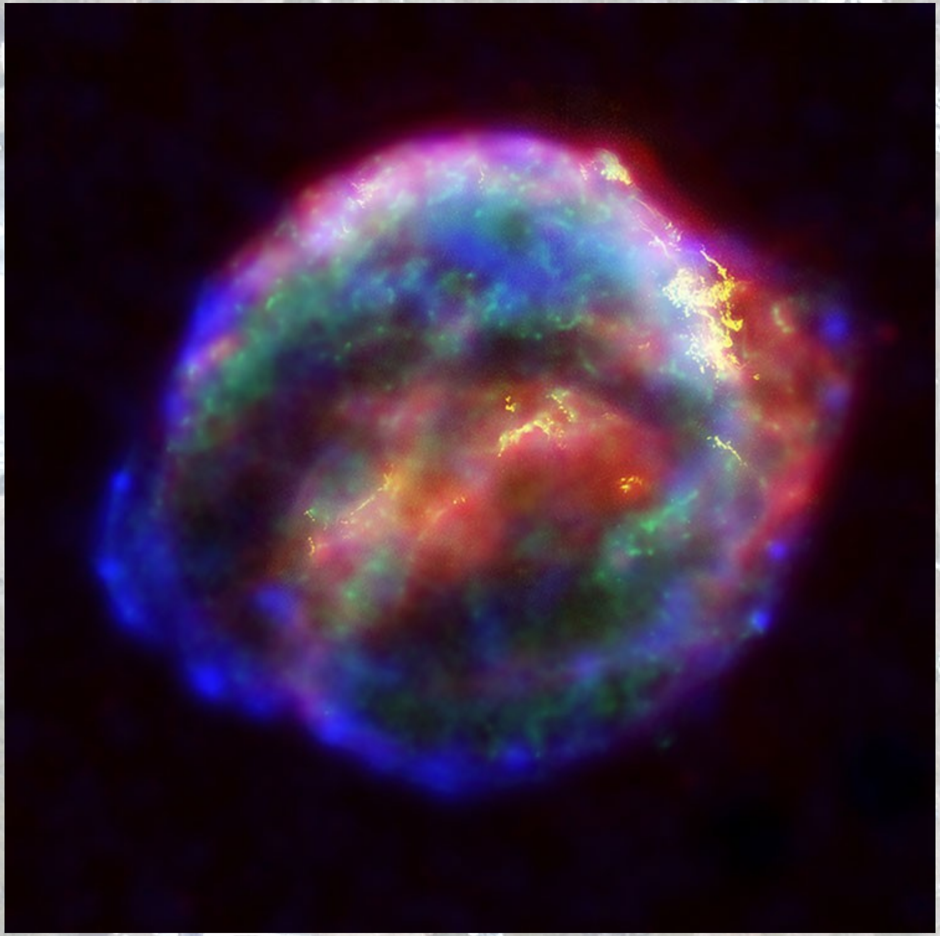
Cosmic Ray Knowns and Known Unknowns



- Very nearly isotropic.
- Energy spectrum ~$E^{-2.7}$
- Huge range of fluxes and energies
- Highest energy > 10^{20} eV
- Low-energy composition matches solar system abundances (with important differences)
- 'Ankle' is apparent transition to extra-galactic cosmic rays.
- Energy density comparable to energy density in photons.
- Consistent model for galactic CR of acceleration in supernova shocks.

Acceleration Mechanism?

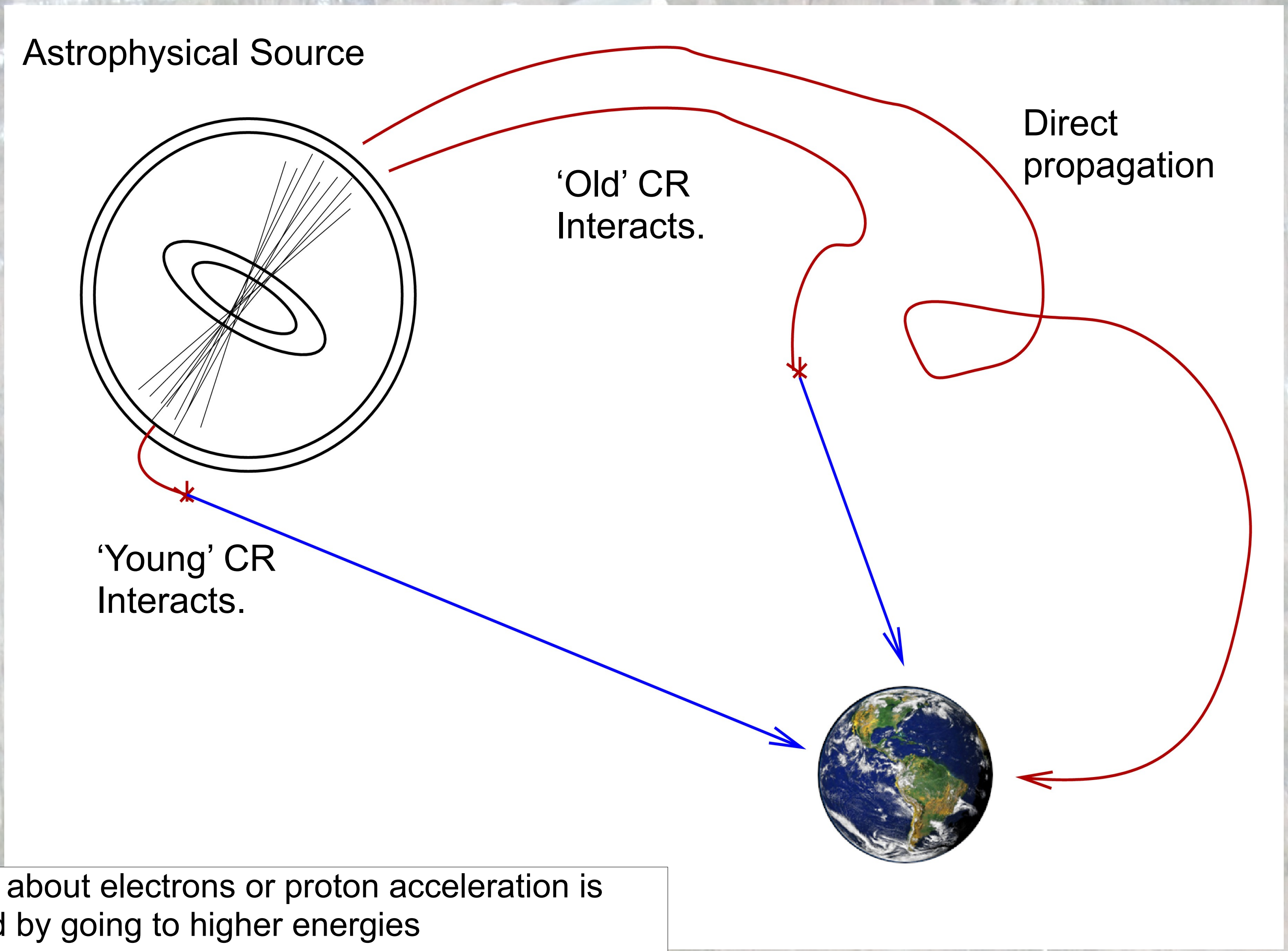
- Fermi Acceleration at shock fronts.
- Particles ping-pong back and forth across the shock gaining energy at each crossing.
- Requires accelerated particles to be contained.
- Predicts universal E^{-2} energy spectrum



SN1604 in X-Ray (Chandra X-Ray Telescope)

Big Picture of Cosmic Radiation

and the role of gamma rays....

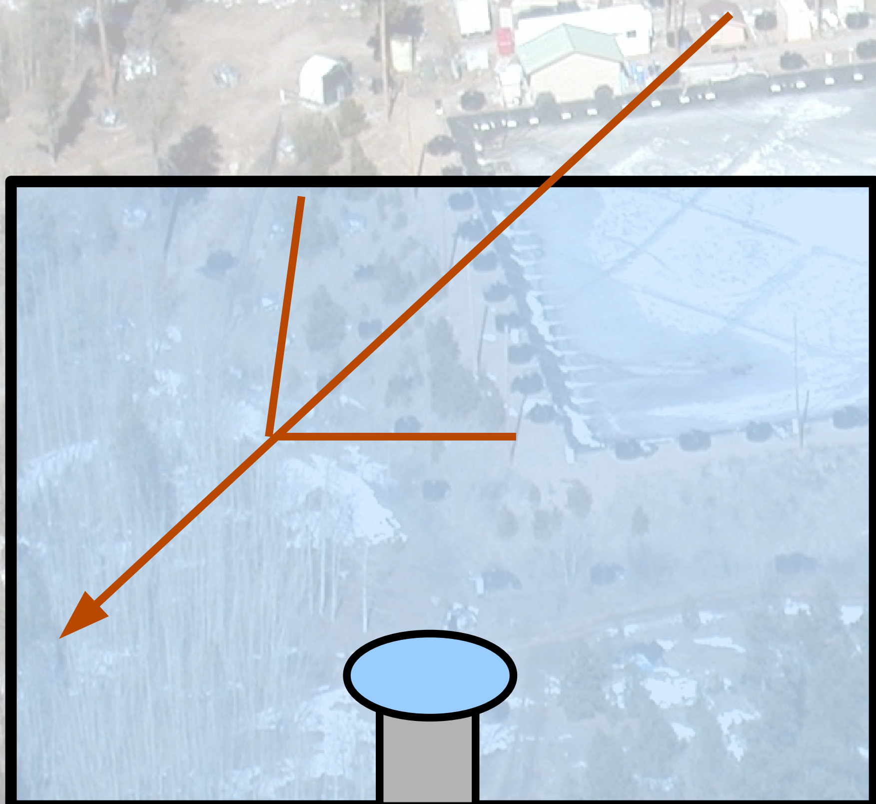


- Ambiguity about electrons or proton acceleration is addressed by going to higher energies
  - ~100 TeV is less ambiguous

To Summarize

- Cosmic rays are out there and we do not know where they are coming from.
- Sites of cosmic ray acceleration should be sites of gamma ray (and neutrino) production.
- Looking for multi-TeV gamma rays as a signature of cosmic ray acceleration.

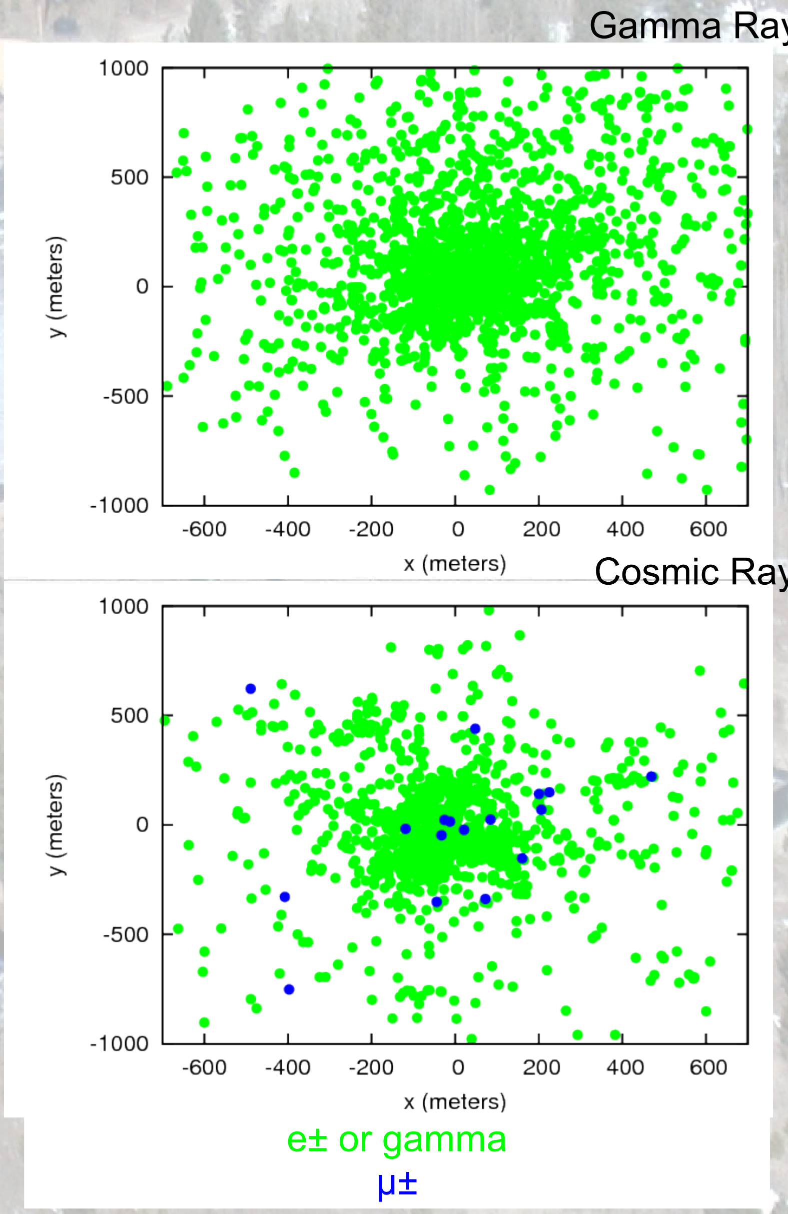
Water Cherenkov Detection of (gamma ray and cosmic ray) Air Showers



- Instrument a volume of water with Photo-Multiplier Tubes
- Detect Cherenkov light from high-energy particle passage through the water.
- Technique used by Super Kamiokande, IceCube, SNO to name a few.
- Why Water?
  - Clear Cherenkov medium.
  - Inexpensive and abundant.
- Instrument a large flat area to see air showers.
- Reconstruct primary particle direction from PMT timing

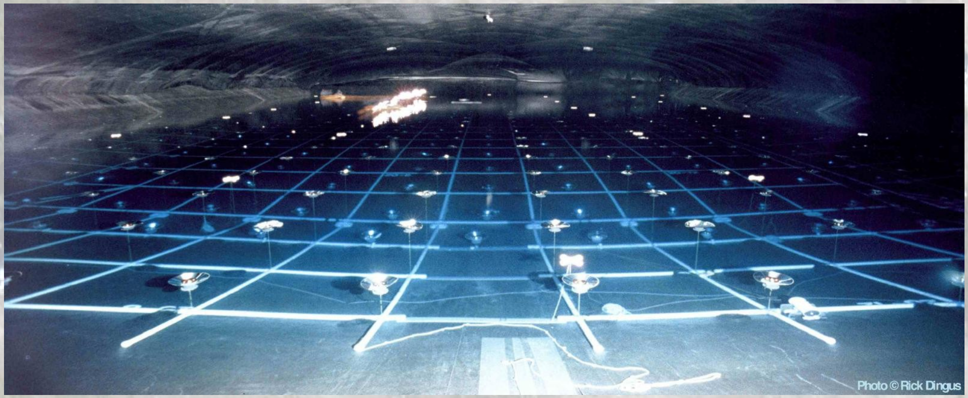
Gamma Ray vs Cosmic Ray Air Shower

- Gamma-ray events are pure electro-magnetic processes.
  - Pair-production, Bremsstrahlung, Compton scattering are dominant processes
  - Pure e±, gamma particles (mostly)
- Cosmic-ray events produce hadronic air showers
  - π±, K± result in μ at ground level
  - Clumpy distribution on the ground from jets in the shower.



Gamma Ray Detectors

	Gamma ray Energy	Field of View (sr)	Point Spread Function	Sensitivity (ergs/cm**2/sec)
Fermi	0.1 GeV	4π	0.04^{o}	$1x10^{-12}$
Veritas / HESS	0.2 TeV	0.002	0.05^{o}	$0.2x10^{-12}$
Milagro	20 TeV	2π	0.7^{o}	$2x10^{\wedge -12}$



Milagro Collaboration

A. Abdo, B. Allen, D. Berley, G. Christopher, 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

Los Alamos NATIONAL LABORATORY

UC SANTA CRUZ

UNIVERSITY OF MARYLAND

MICHIGAN STATE UNIVERSITY

UCIrvine University of California, Irvine

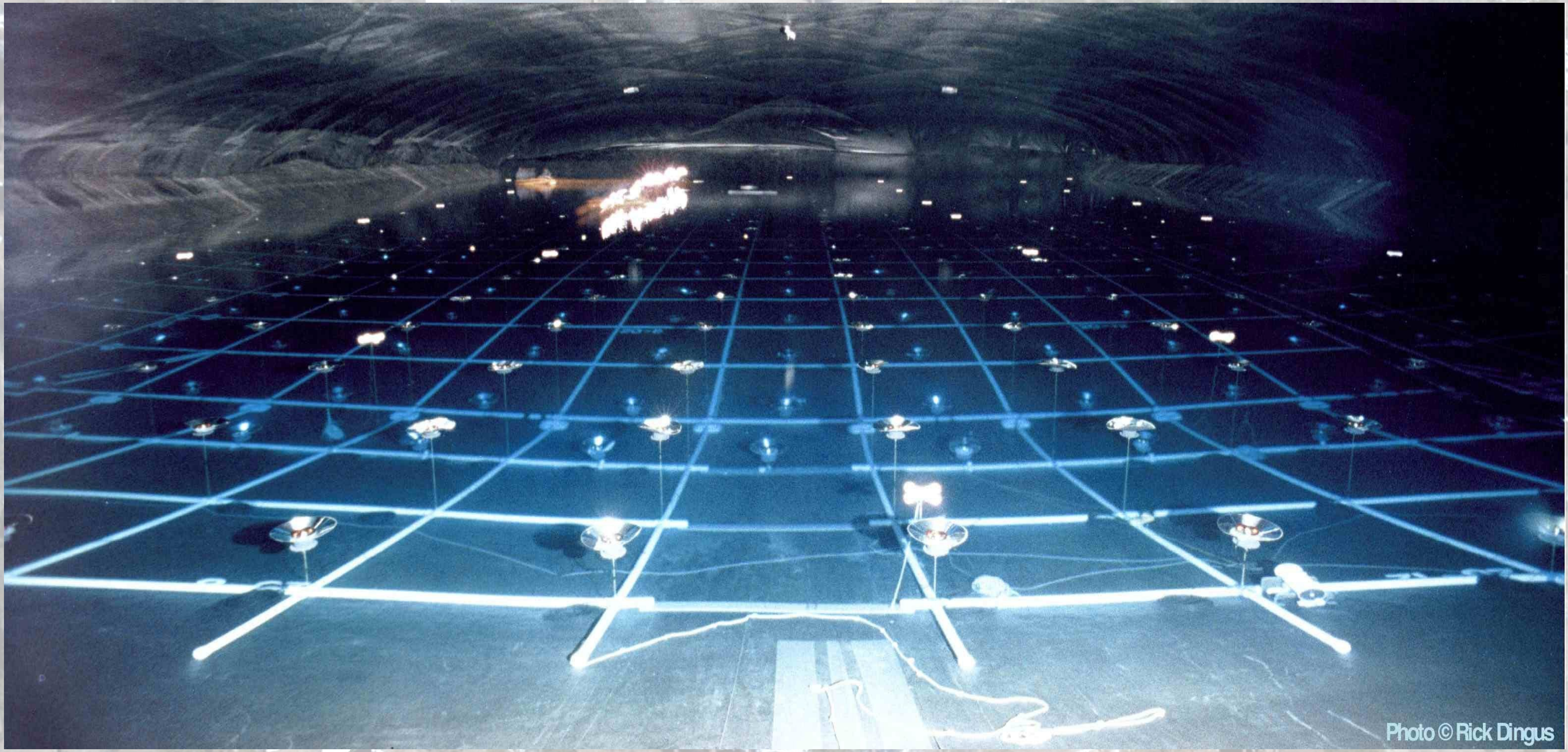
New York University

NEW HAMPSHIRE

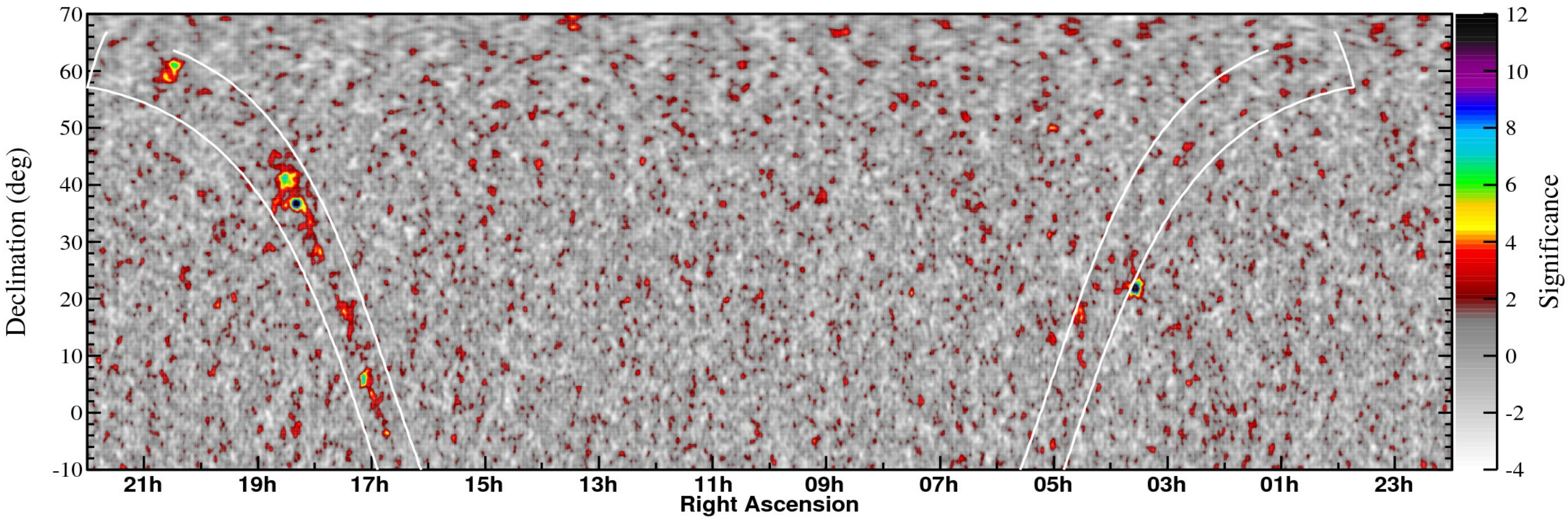
Milagro Detector

- Central Water Pond (80x60 meter)
  - 450 PMTs under 1.5 m water
  - 273 PMTs under 6 m water
- Outriggers
  - 2.4 meter diameter
  - 1.4 meter tall
  - 175 PMTs in outrigger tanks
- Water Cherenkov Detector
- 2600 meters altitude
- 4000 m^2 pond / 40000 m^2 outrigger coverage
- 1700 Hz Trigger Rate
- 0.4^{o} – 1.0^{o} angular resolution
- Sensitivity 100 GeV – 100 TeV Median energy 10 – 40 TeV (depending on cuts, weights etc)
- Operated from 2000-2008.

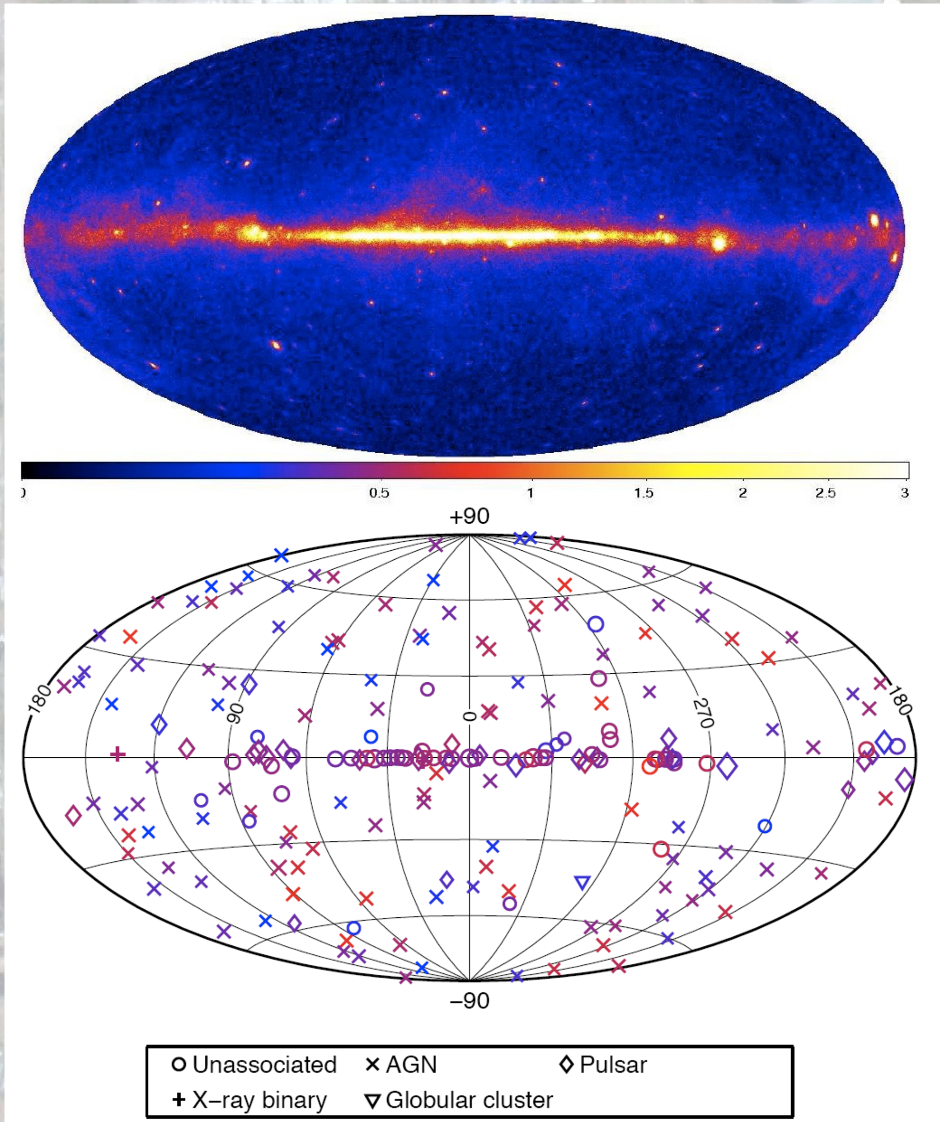
Inside the Pond



Milagro Results



Fermi-LAT Bright Source List

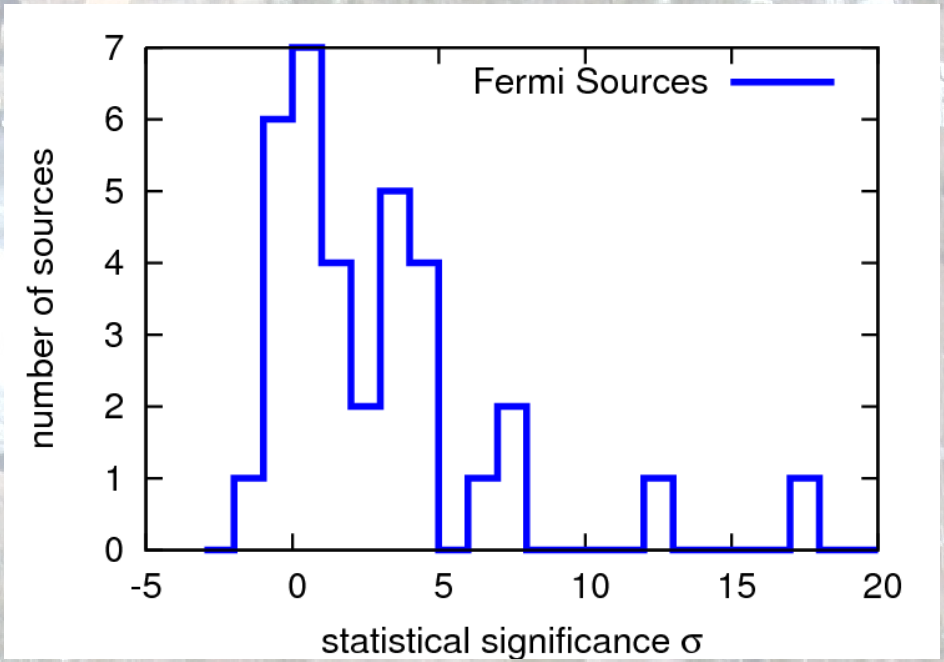


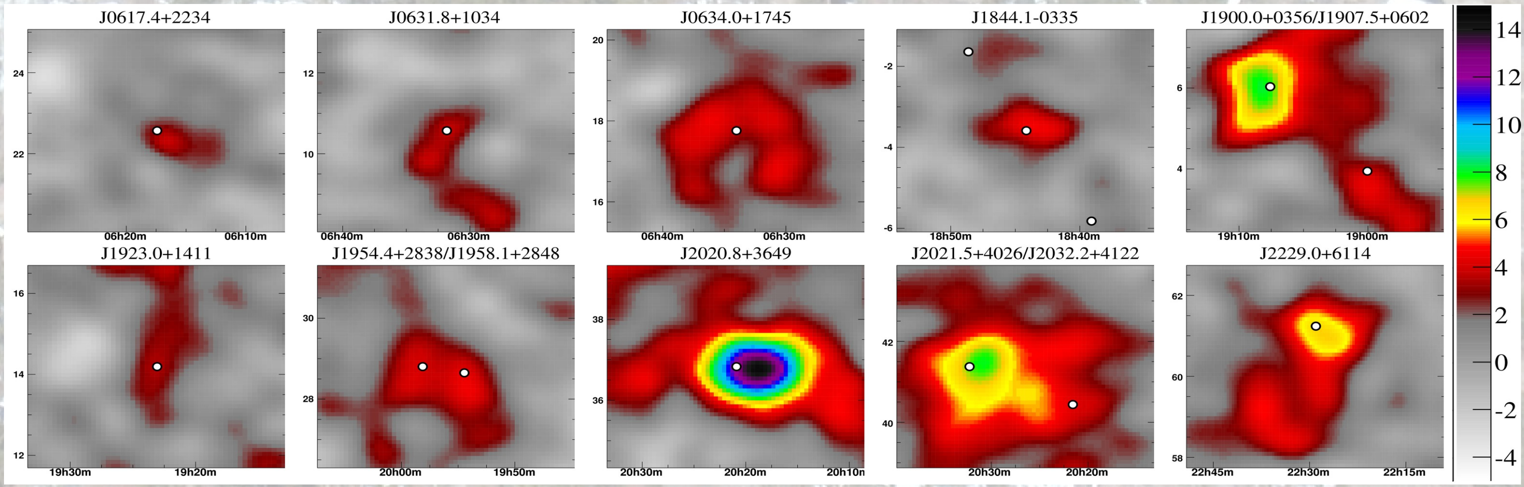
- Sensitivity from 100 MeV to hundreds of GeV
- 205 10σ sources in 3 months of data
- Blazars, pulsars identified by their variability.
- Several new pulsars (pulsations discovered in the GeV first)
- Deeper survey than entire EGRET dataset
- Angular resolution < 0.1^{o} at the higher energies

Abdo et al. arXiv:0902.1340

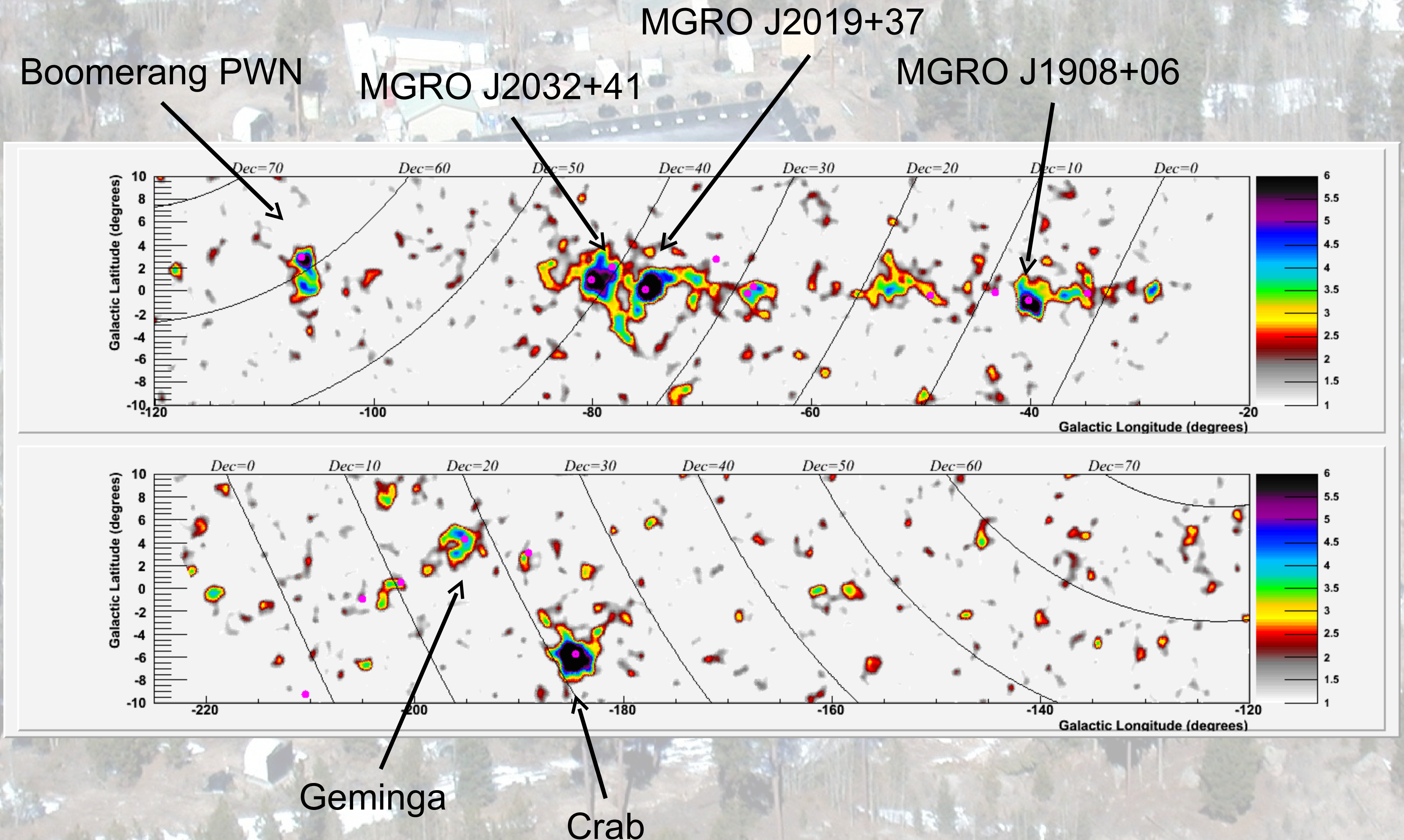
Milagro Search for TeV emission from Galactic sources

- 34 / 205 BSL sources are possibly Galactic and in Milagro's field of view ($\delta > -5^o$)
  - 16 pulsars
  - 1 x-ray binary
  - 5 SNR
  - 12 unknown
- 14/34 are observed at 3σ or more in Milagro data
- Probability of a single 3σ detection in 34 trials is only 4%
- 6/14 have been reported by Milagro before
- 9/14 are pulsars (all 6 previous Milagro sources are now associated with pulsars)
- 3/14 are SNR



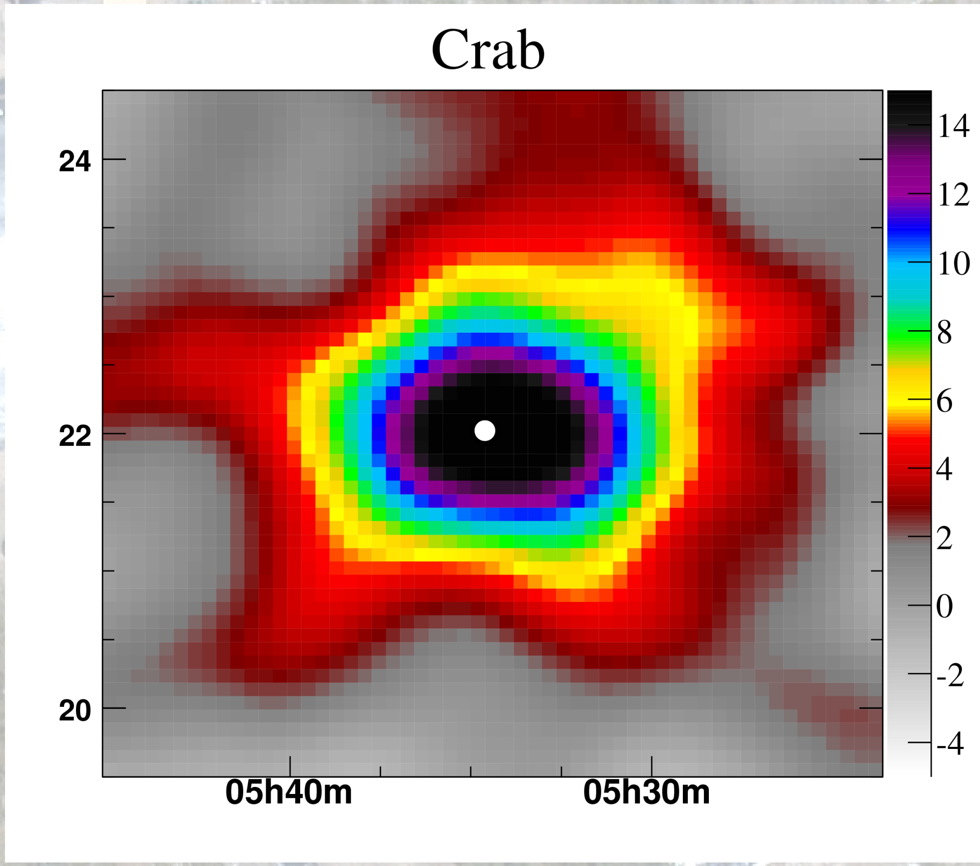


Milagro Survey of the Galactic Plane



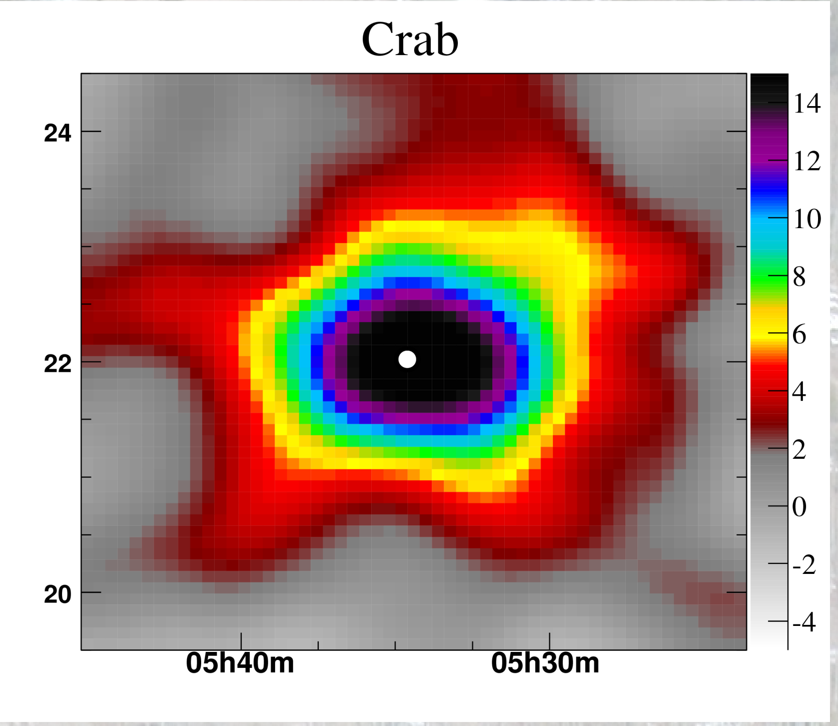
Crab

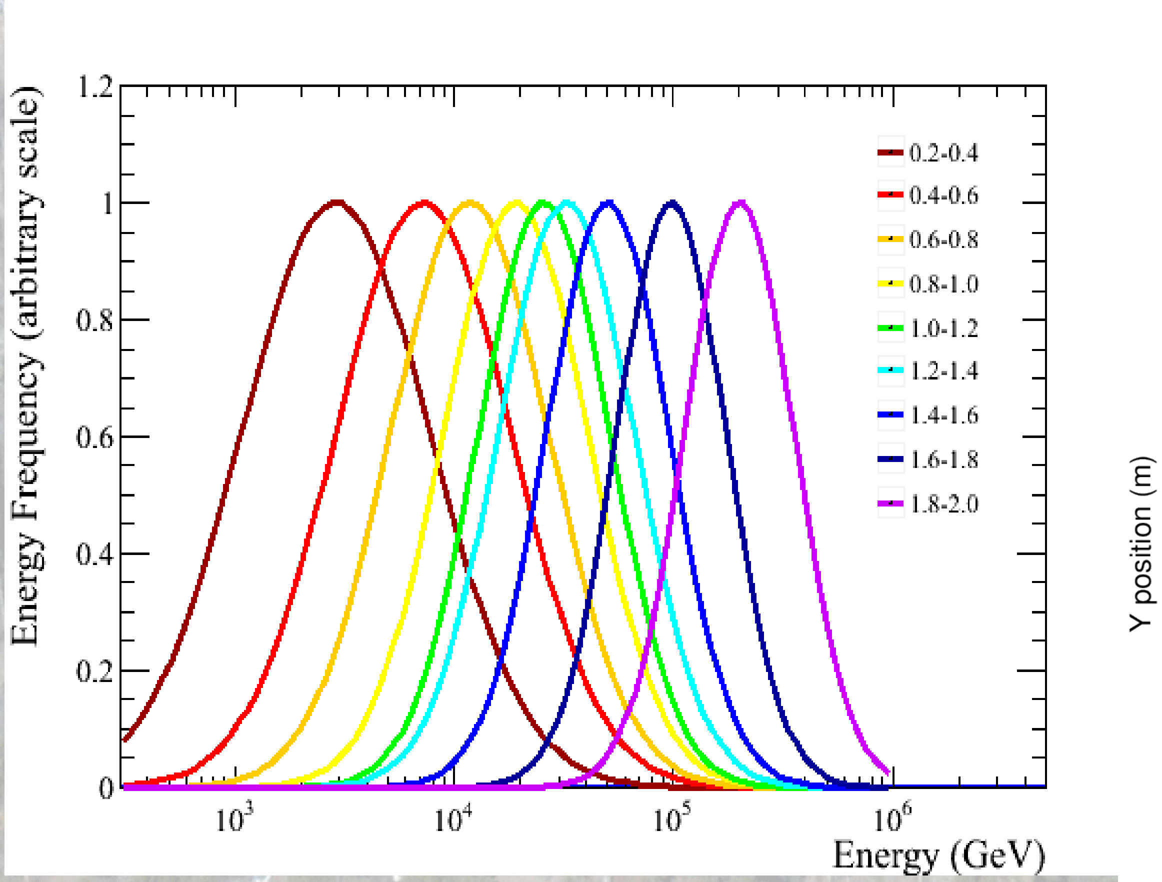
- Standard candle in TeV astronomy. TeV emission discovered by Whipple.
- Young pulsar, resulting from supernova in 1054 CE.
- Pulsed emission at lower energies. Steady at TeV.
- 17.2σ at pulsar location.
- A calibration source for Milagro and HAWC.

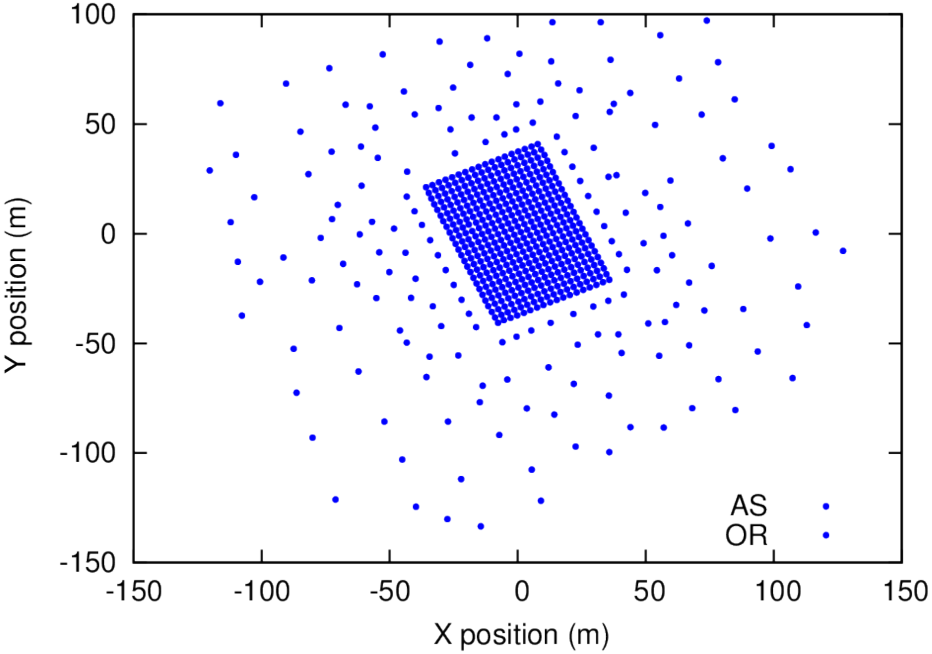


Spectral Fitting

$$\mathcal{F} = \frac{N_{AS}}{N_{AS}^{live}} + \frac{N_{OR}}{N_{OR}^{live}}$$



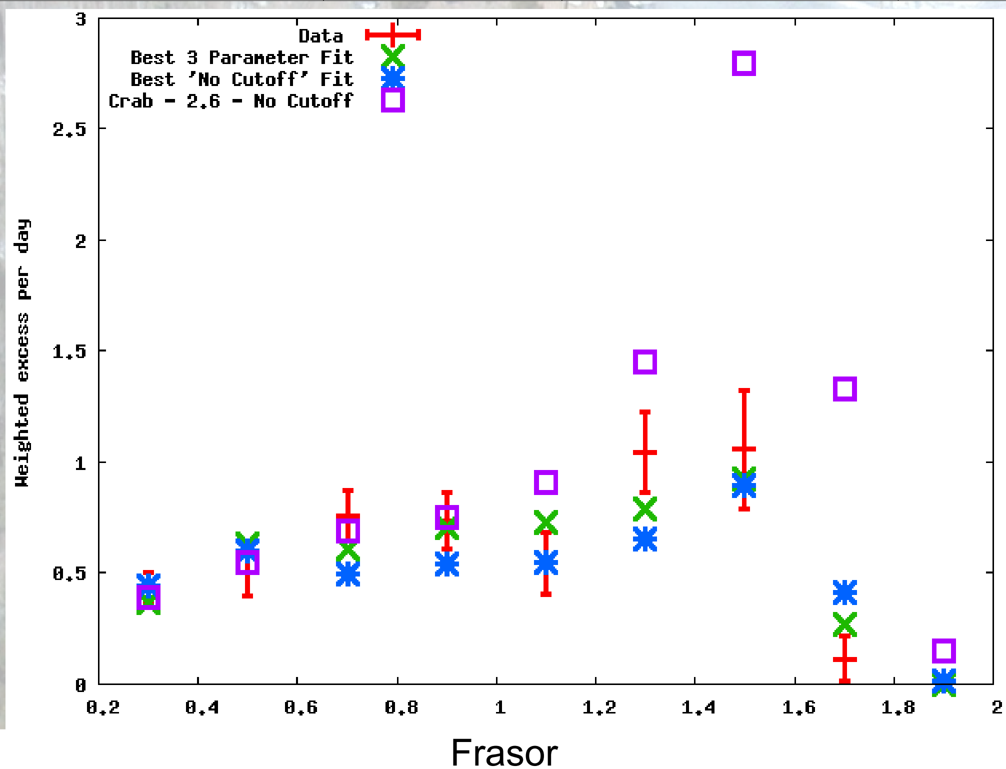


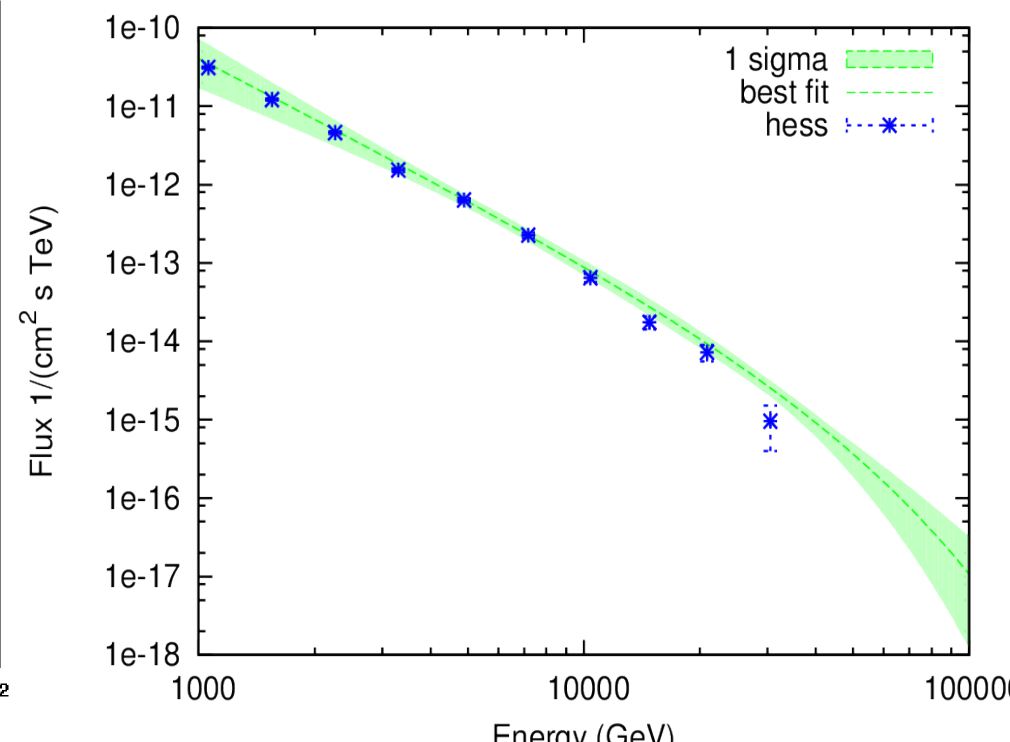


Spectrum of the Crab

$$\frac{dN}{dE}(I_o, \alpha, E_{\text{cut}}) = I_o\left(\frac{E}{10TeV}\right)^{-\alpha} \exp\left(\frac{-E}{E_{\text{cut}}}\right)$$

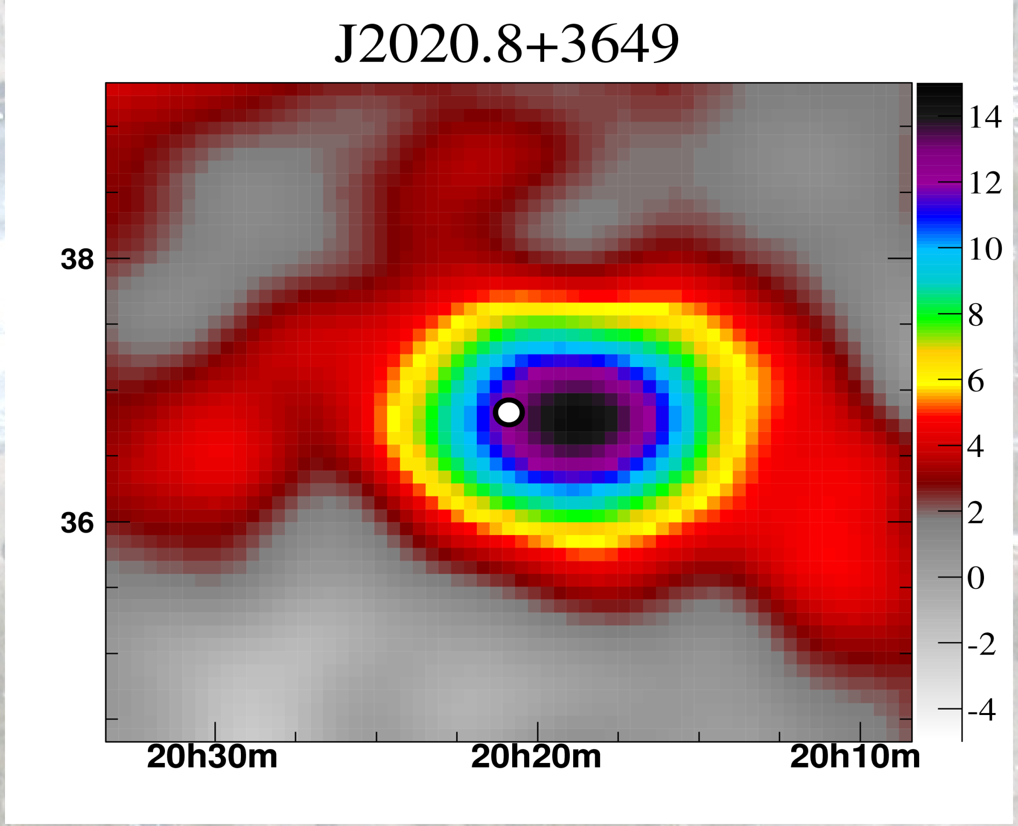
Fit	Index	Cutoff	Flux (Crab @ 10 TeV)	Chisq	Prob.
3 Parameter	2.52	10**4.45	1.55	10.8/6	9.4%
No Cutoff	3.10	inf	0.8	21.6/7	0.3%
2.6 @ low energy	2.6 (fixed)	10**4.5	1.45	10.9/6	9.1%





MGRO J2019+37

- Near Fermi source 0FGL J2020.8+3649
- Most significant source for Milagro after the Crab. 12.4σ at peak
- Identified as a young pulsar by AGILE.
- Milagro peak is separated from pulsar by 0.3° with a 1σ error of 0.1.
- In the Cygnus region being surveyed by Veritas.

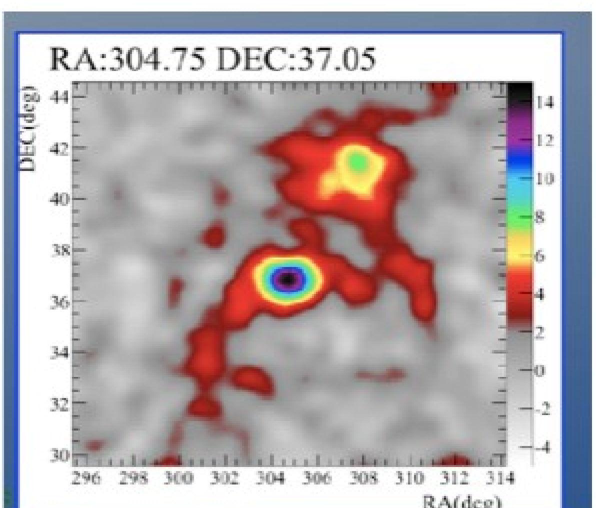


MGRO 2019+37

- Poster at FERMI Symposium 2011
- VERITAS observed Cyg OB1 between May 2010 and December 2010 for 75 hours
- Results above 650 GeV:

VER Source	θ_{int}	Excess events	S pre-trial	S post-trial
J2016+372	0.09°	60.2	6.2σ	6.1σ
TeV Cyg OB1 complex	0.23°	230	8.3σ	7.4σ

Table 1. Emission detected above > 5σ post-trial



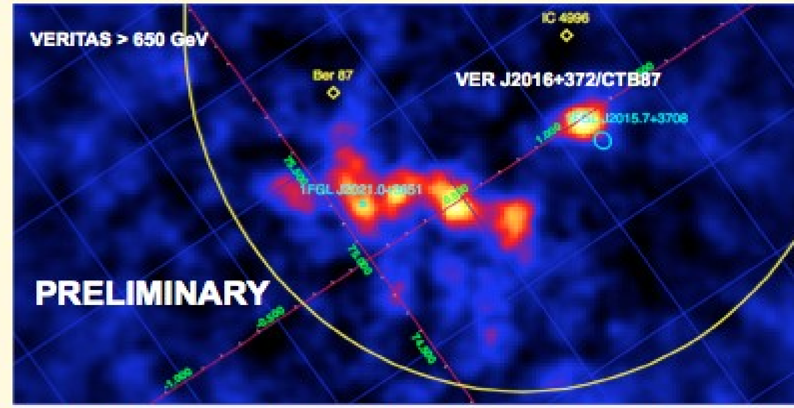
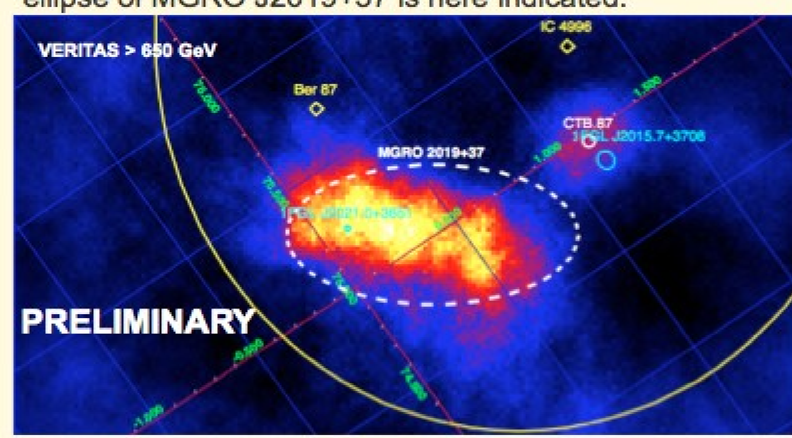


Fig 1. Excess-counts sky map towards the Cyg OB1 region (big yellow circle) above 650 GeV obtained with VERITAS. We used θ_{int}=0.09°(see text). Significant excesses post-trials are evident (see text). The positions of Ber 87 and IC4996 (young stellar clusters associated with Cyg OB1), are indicated, along with those of 1FGL sources in the region.

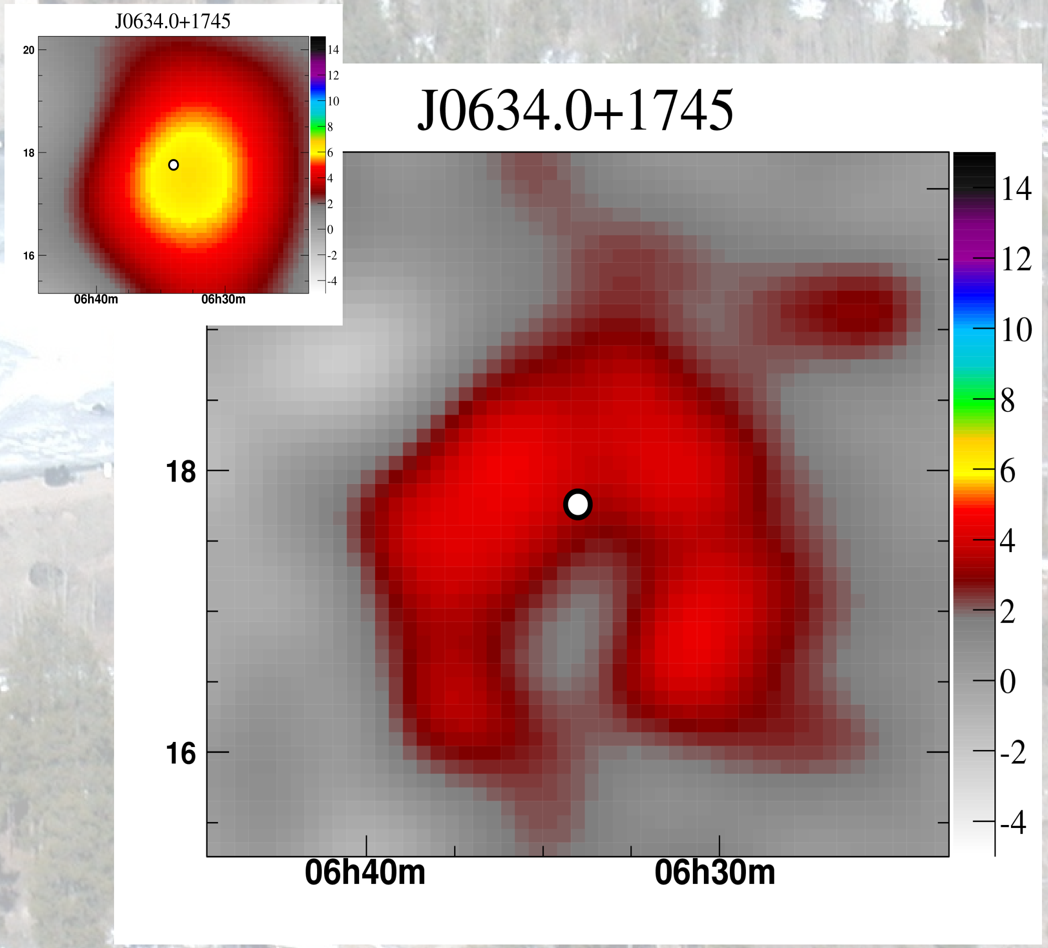
Fig 2. Same as above using an integration radius θ_{int}=0.23° to look for extended emission. The best-fit ellipse of MGRO J2019+37 is here indicated.



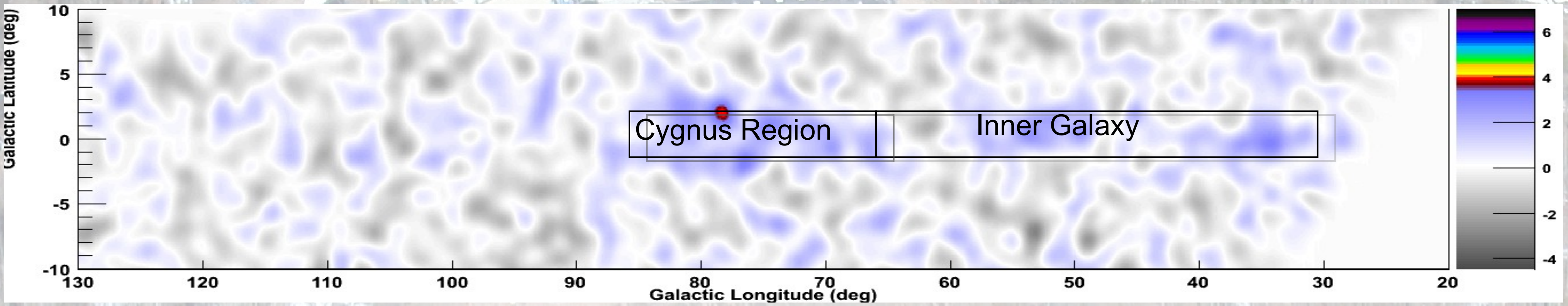
VERITAS Collaboration

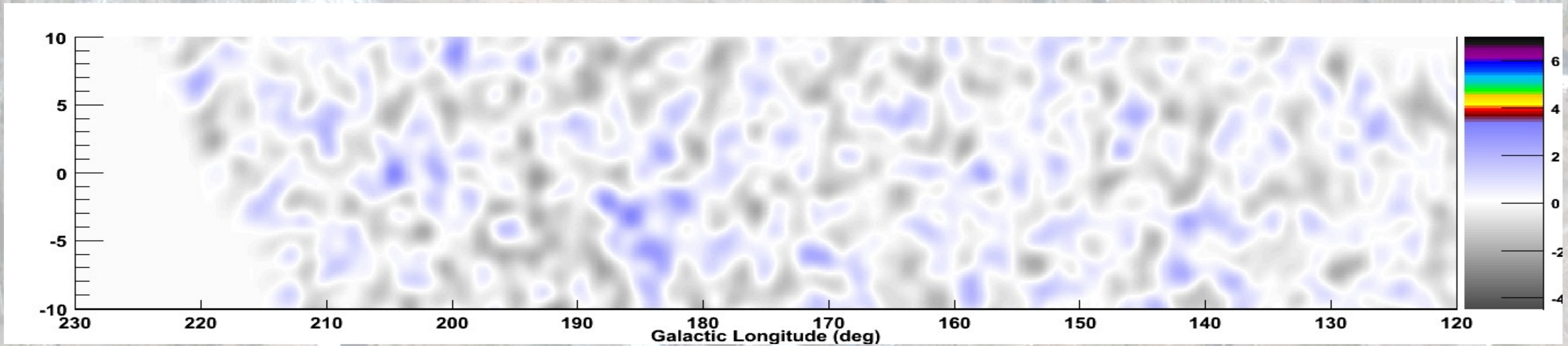
Geminga

- Associated with Fermi pulsar 0FGL J0634.0+745, the Geminga pulsar.
- 3.5σ at the location of Geminga.
- 6.3σ when assuming a 1° extended source.
- Fitted 1.1° extent, consistent with IACT observations of more distant PWN.
- Nearby. May be responsible for PAMELA excesses.



TeV Diffuse Emission from the Galactic Plane with Milagro

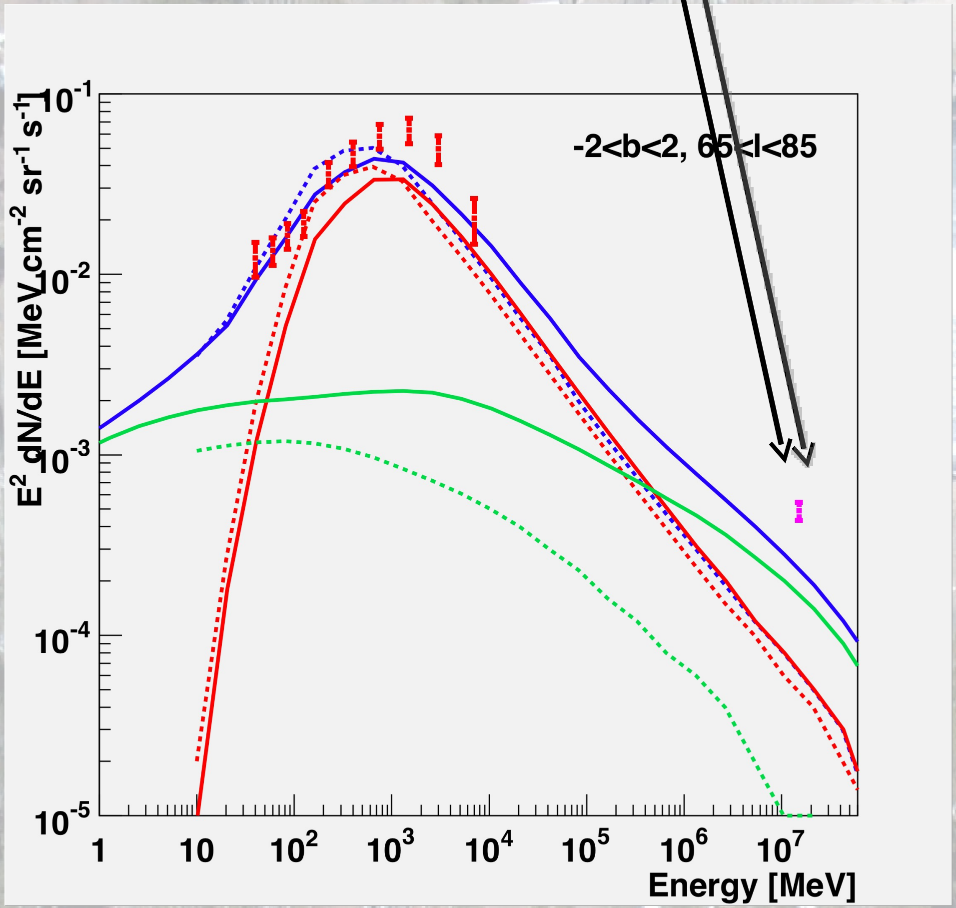


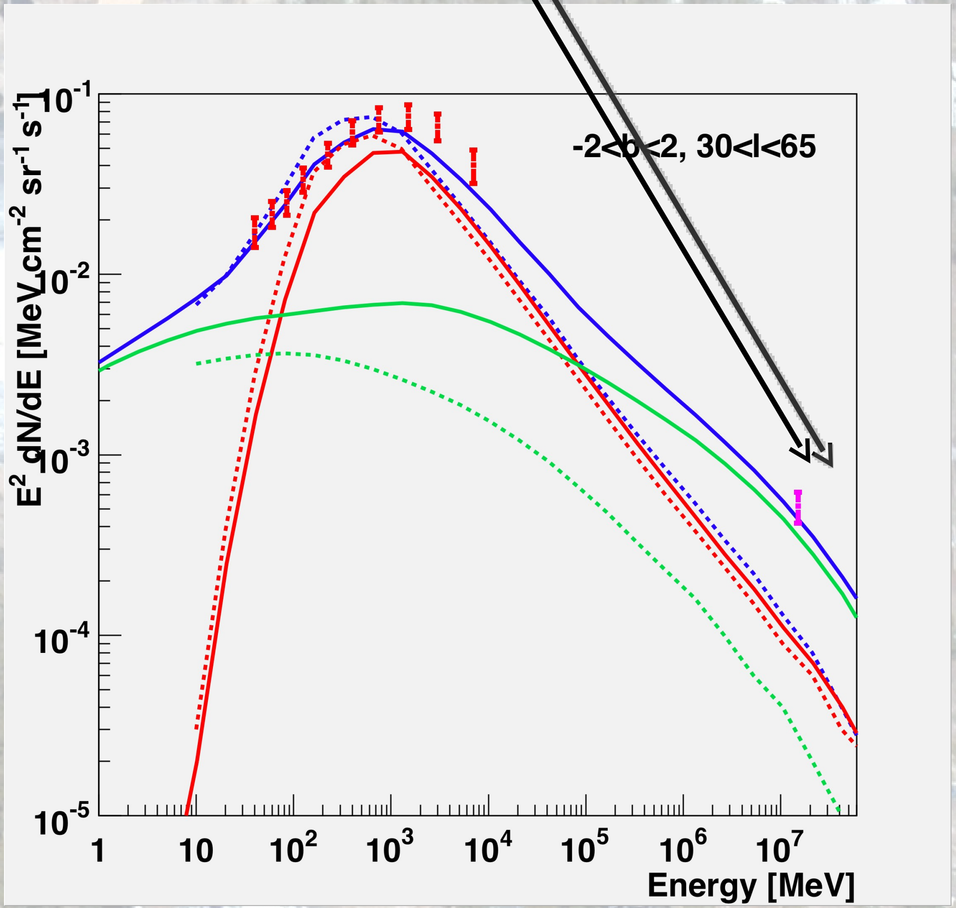


Inner Galaxy and Cygnus Region Compared to Galprop

8 times the conventional flux

4.7 times the conventional flux





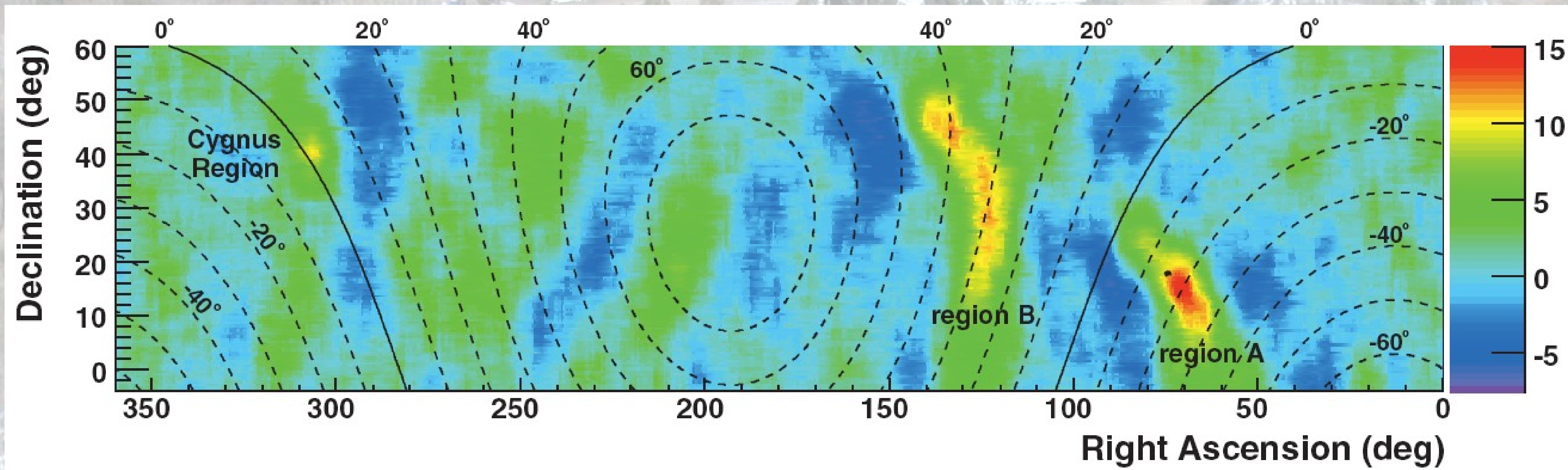
Total Galprop Prediction
Pion Decay
Electron Inverse Compton

Optimized GALPROP
Conventional GALPROP

Strong et al., ApJ **613**, 962 (2004)
Strong et al., A&A **422**, L47 (2004)

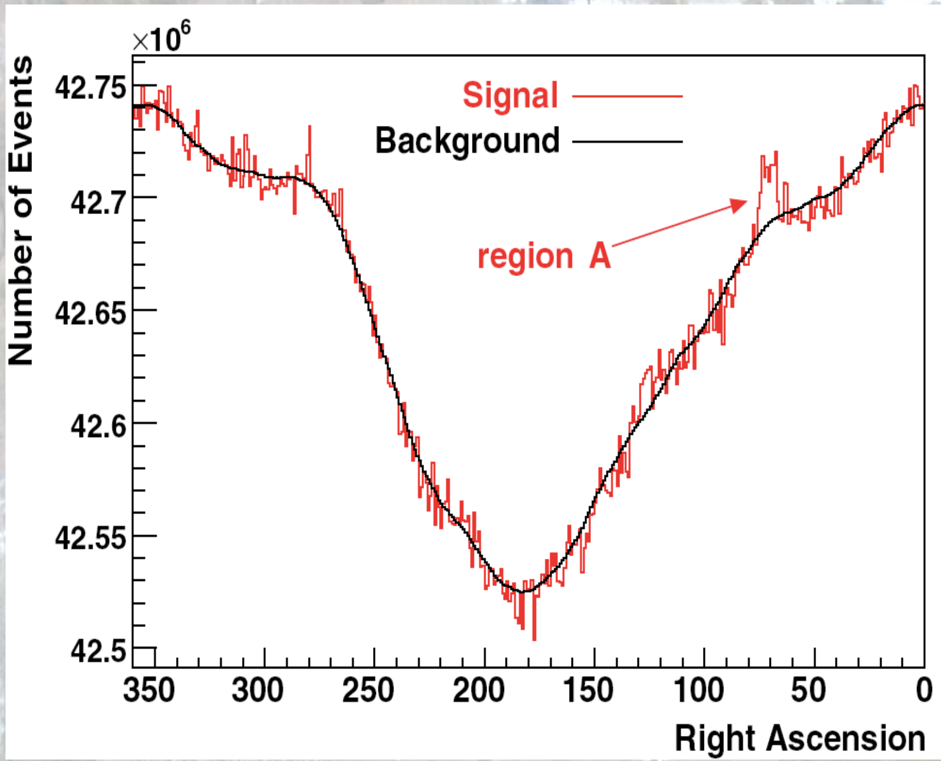
Petra Huentemeyer

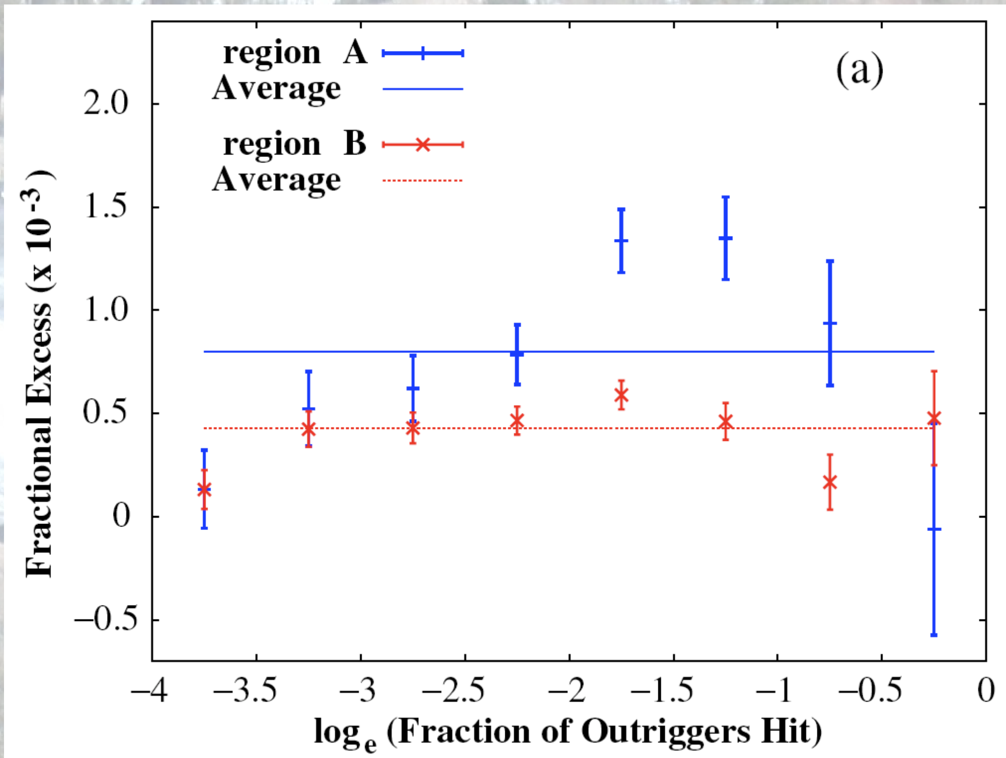
Milagro Cosmic Ray Observations



- No weighting or cutting. Map dominated by cosmic rays.
- Background subtraction serves as a high-pass filter.
- 10o smoothing looks for largeish features.
- Two regions of excess 15.0σ and 12.7σ. Fractional excess of 6×10^{-4} (4×10^{-4}) for region A(B).
- Seen also by Tibet ASγ

Milagro Cosmic Ray Observations





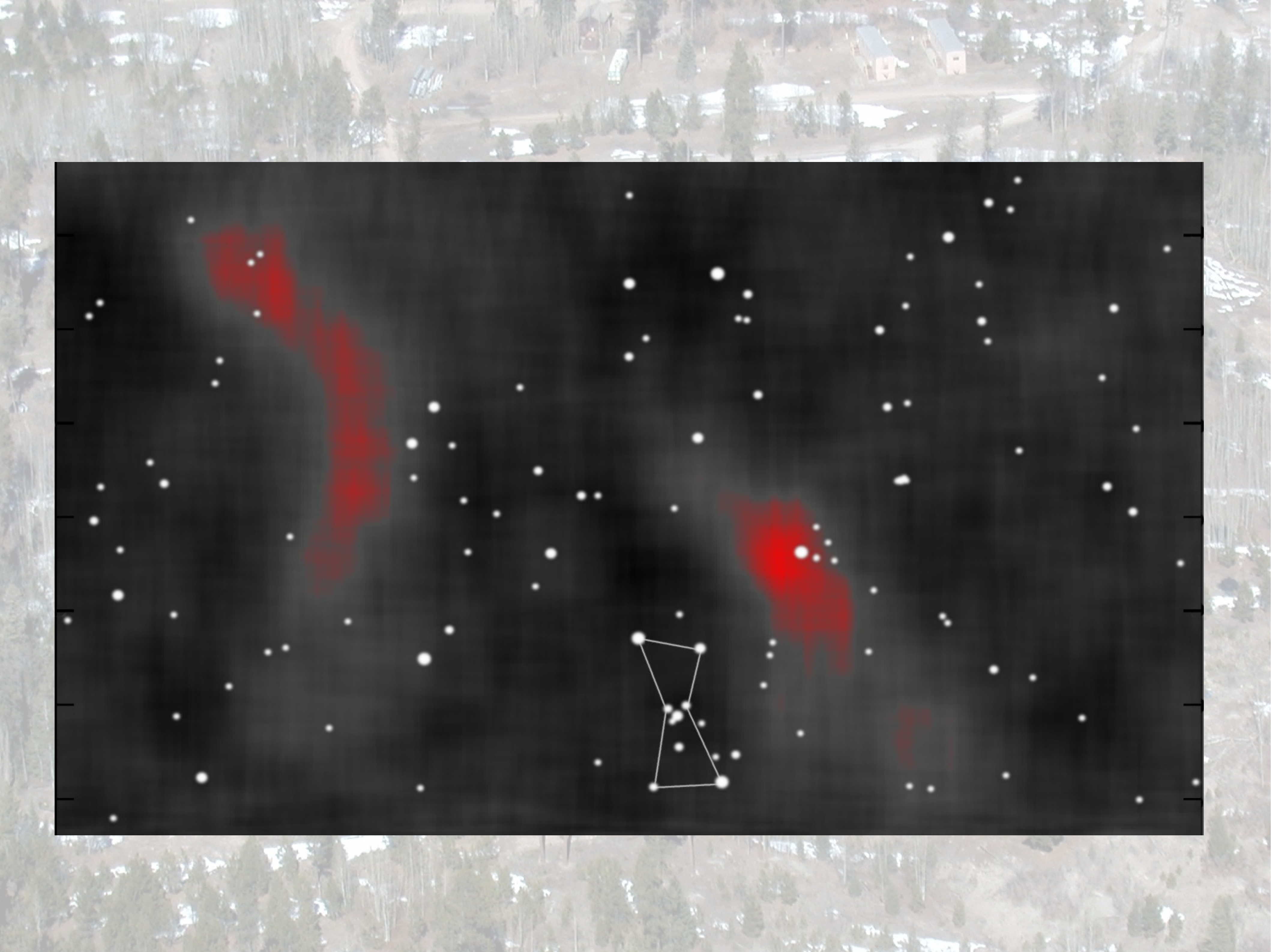
- Gamma-ray origin excluded to high confidence. Cosmic-ray hypothesis fits well.
- Appear harder than background cosmic-rays with a cutoff at ~10 TeV.

PRL **101**, 221101 (2008)

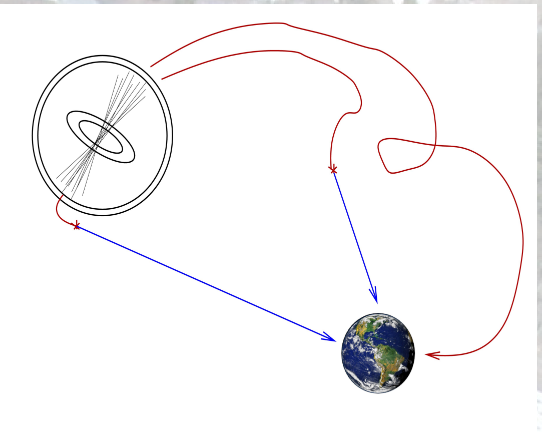
What are these features?

- Heliospheric?
  - Considered by Salvati and Sacco and found not likely.
- Neutron production in clump of ISM matter gathred at the heliotail.
  - Rejected by Drury and Aharonian
- Nearby Source
  - Gyroradius of 10 TeV proton is in >1μG <0.01 pc.
  - 10 TeV neutron will live for 0.1 pc
- An effect resulting from the summation of sources near Earth?

Salvati and Sacco. A&A 485, 527-529 (2008)
Drury and Aharonian. Astropart. Phys. 29 420-423 (2008)



Milagro's view of the Galactic Plane



- Unbiased survey of the entire Galactic plane in TeV gamma rays.
- All high-significance sources are identified with Fermi pulsars. Probably TeV PWN.
  - TeV association with MeV-GeV pulsars is quite common.
- Galactic plane excess is unexplained.
  - Unresolved Sources
    - Extrapolating HESS source population model can account for a substantial fraction of the excess (Casanova & Dingus. Astropart. Phys. 2008.)
  - Unmodeled 'young' cosmic rays interacting near their sources
    - For instance, HESS observation of emission along the Galactic Center Ridge (Aharonian et al. Nature. 2006.)
  - Dark Matter
    - Upscattered cosmic rays due to high dark-matter/hadron cross section using new TeV physics. (Masip & Mastromatteo arXiv:0904.0921)
- Curious cosmic ray anisotropy lacks explanation
- Many more sources at the edge of Milagro's sensitivity

Conclusions

- Studies of gamma-rays probe the acceleration mechanisms of high-energy cosmic rays (electrons and hadrons).
- Milagro's measurements identified several new TeV sources as well as anomalously high emission from the Galactic plane.
- Strength of water-Cherenkov is unbiased survey.
  - GRBs and AGN are a target for HAWC