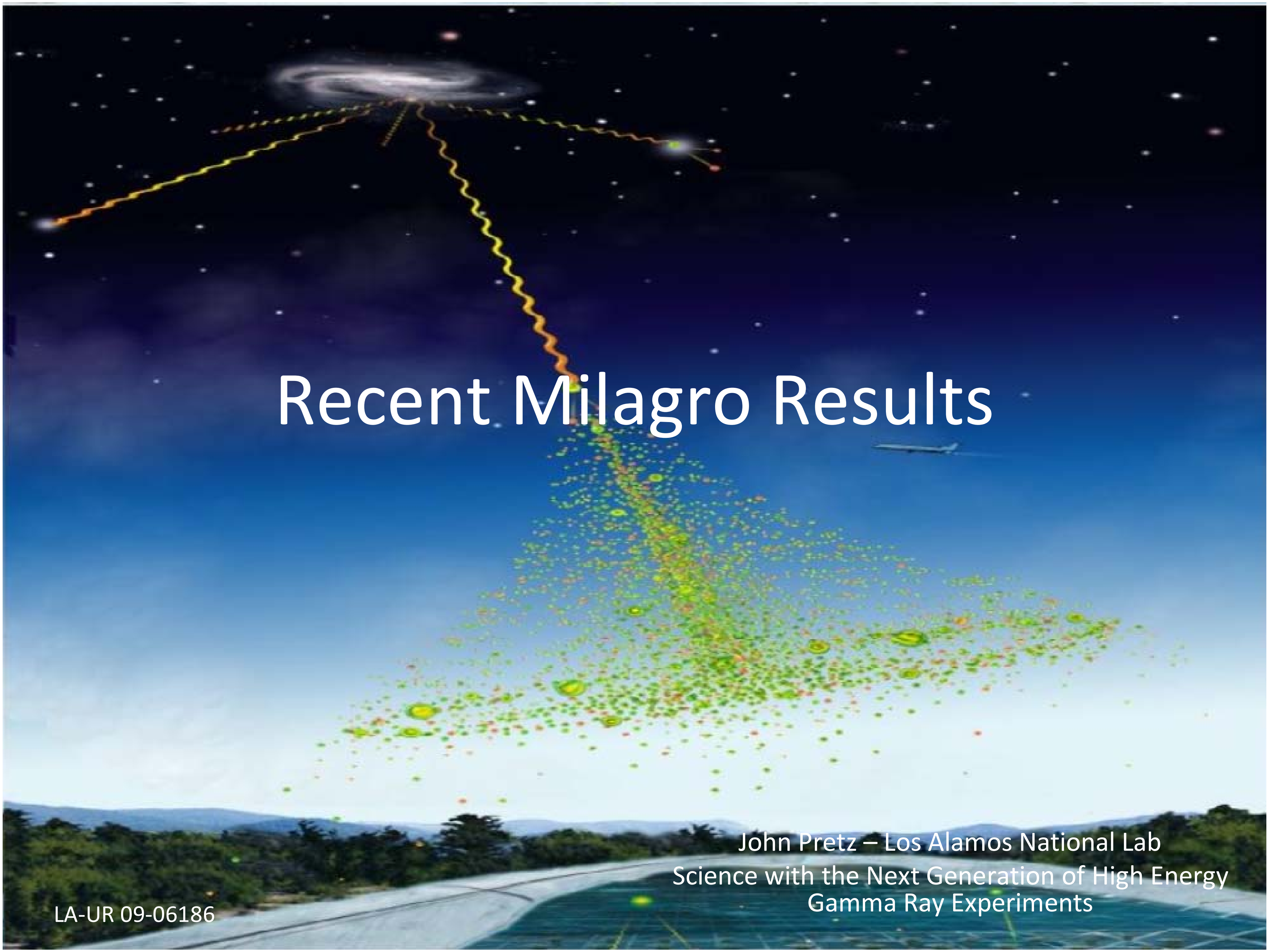


Recent Milagro Results

John Pretz – Los Alamos National Lab

Science with the Next Generation of High Energy Gamma Ray Experiments

LA-UR 09-06186

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

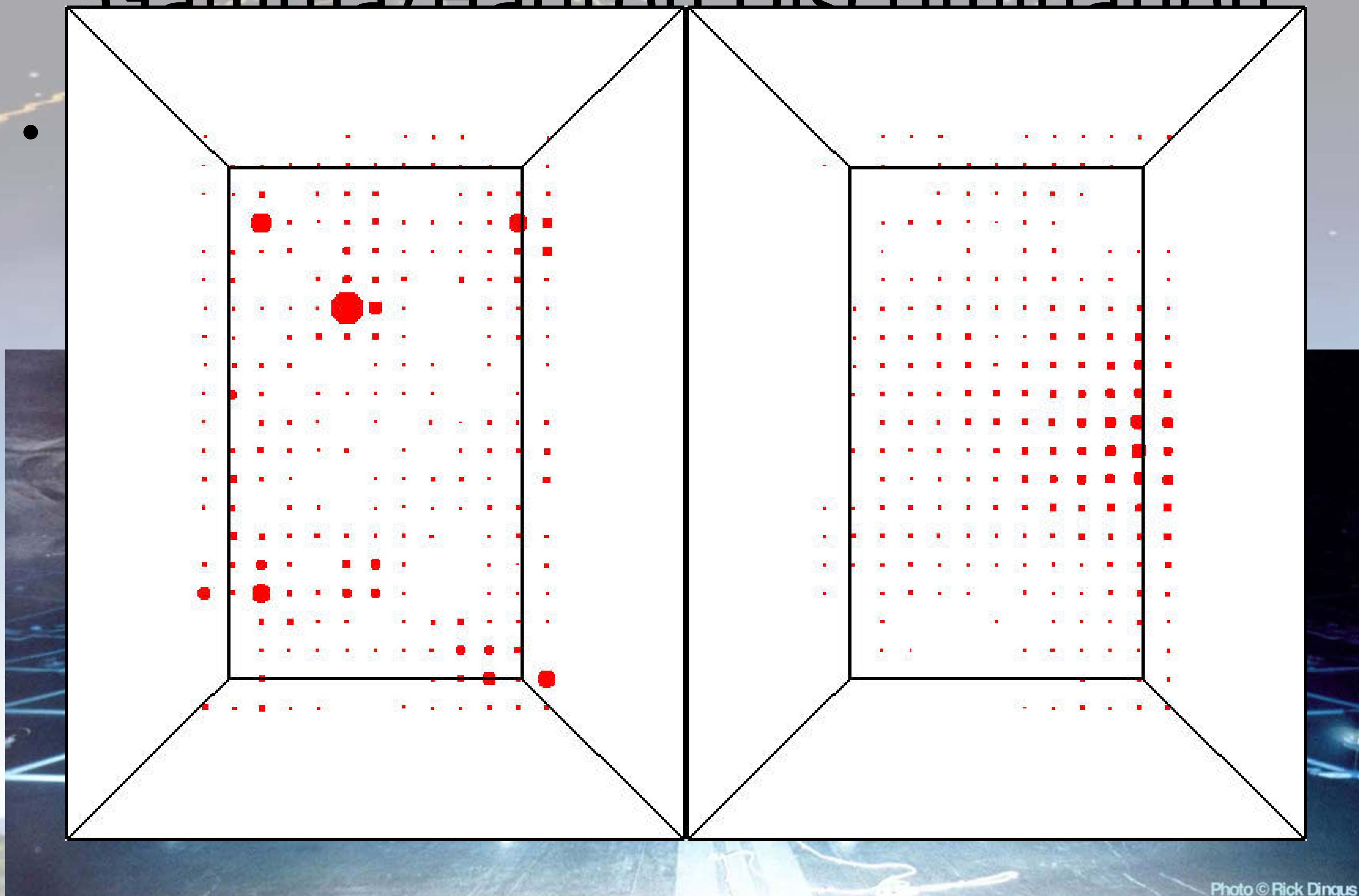
Milagro Detector

- 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.

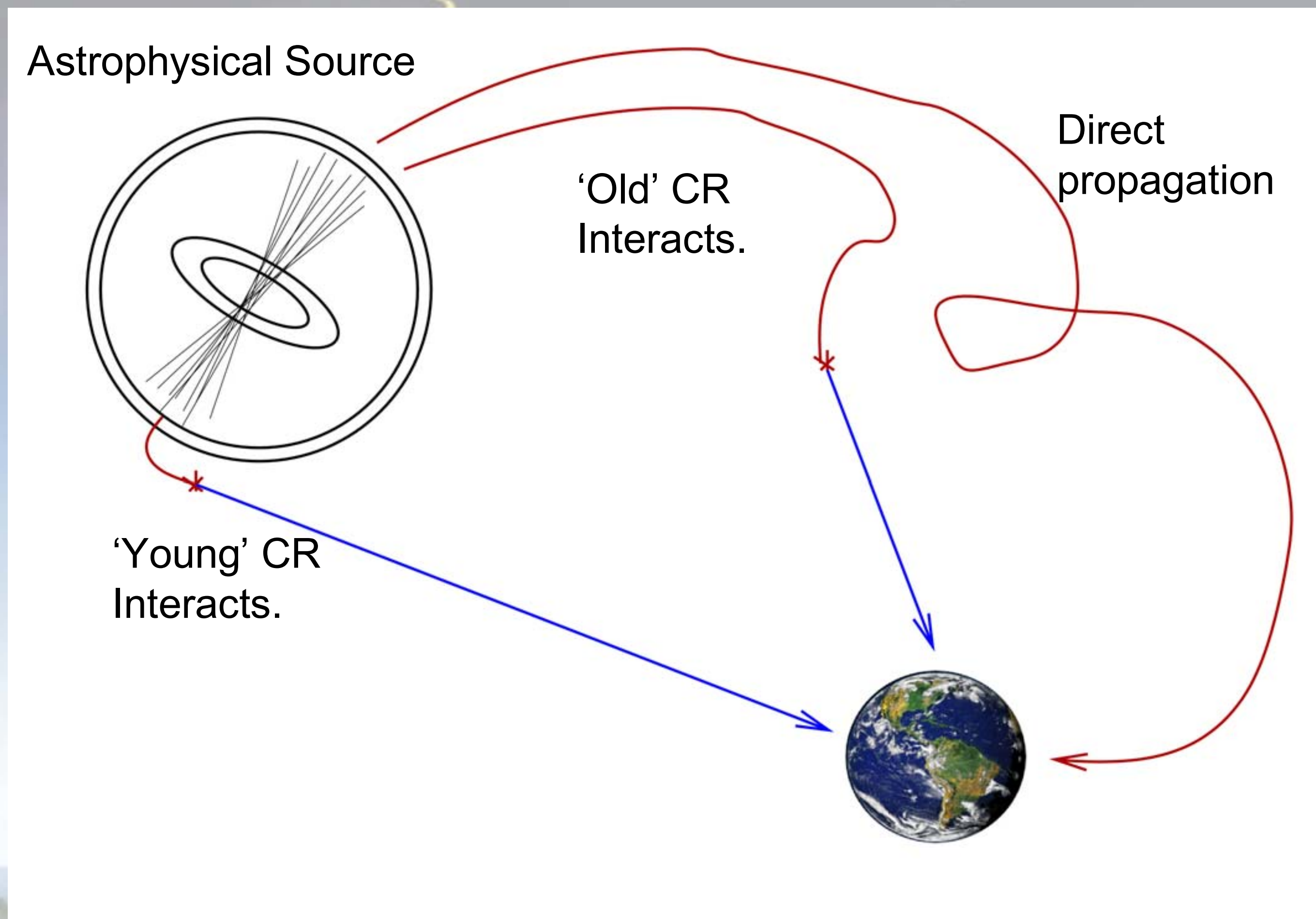
Gamma/Hadron Discrimination

- Penetrating component of Hadronic air showers illuminates the bottom layer.

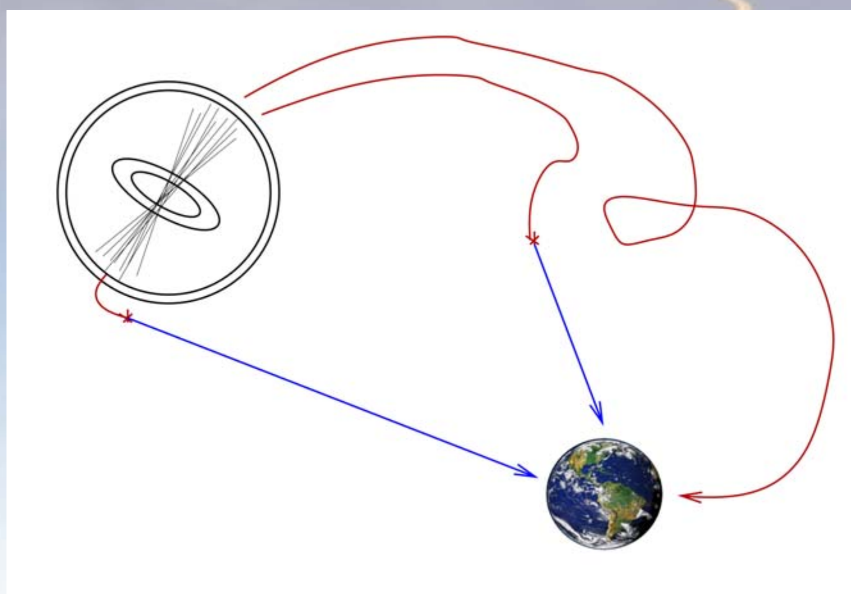
Gamma/Hadron Discrimination



The Cosmic Ray Picture

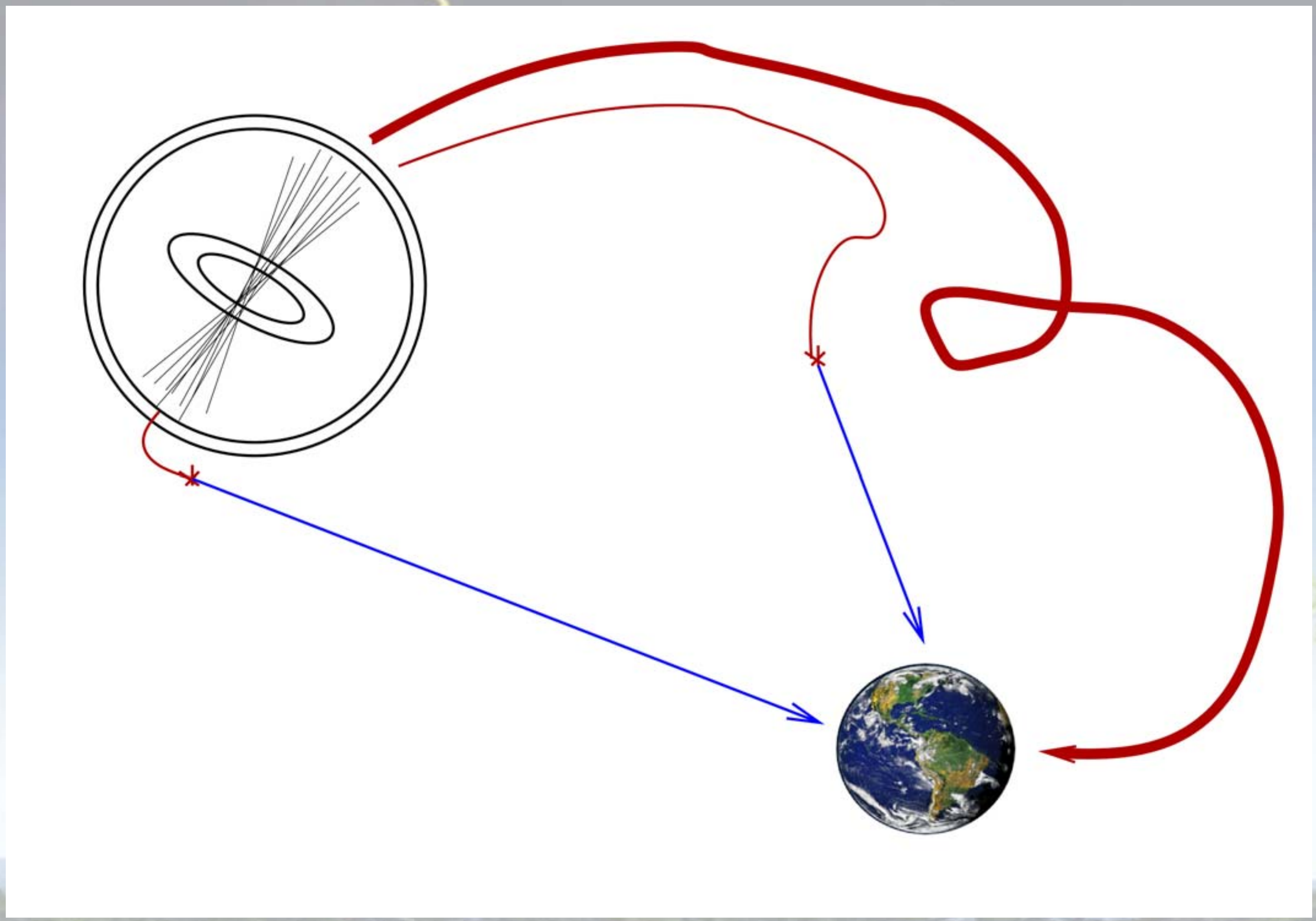


Open Questions

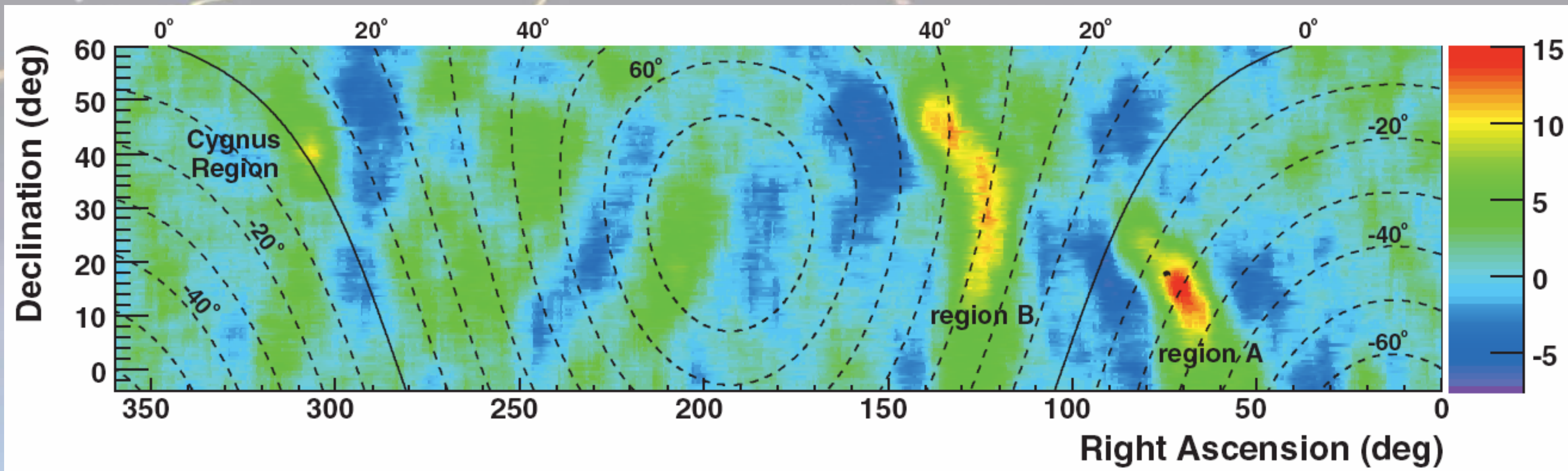


- What are sources of cosmic rays?
- How do the accelerators work?
- What is the source of the TeV Galactic diffuse emission?
- Is there a nearby source of cosmic rays?

Cosmic Ray Anisotropy



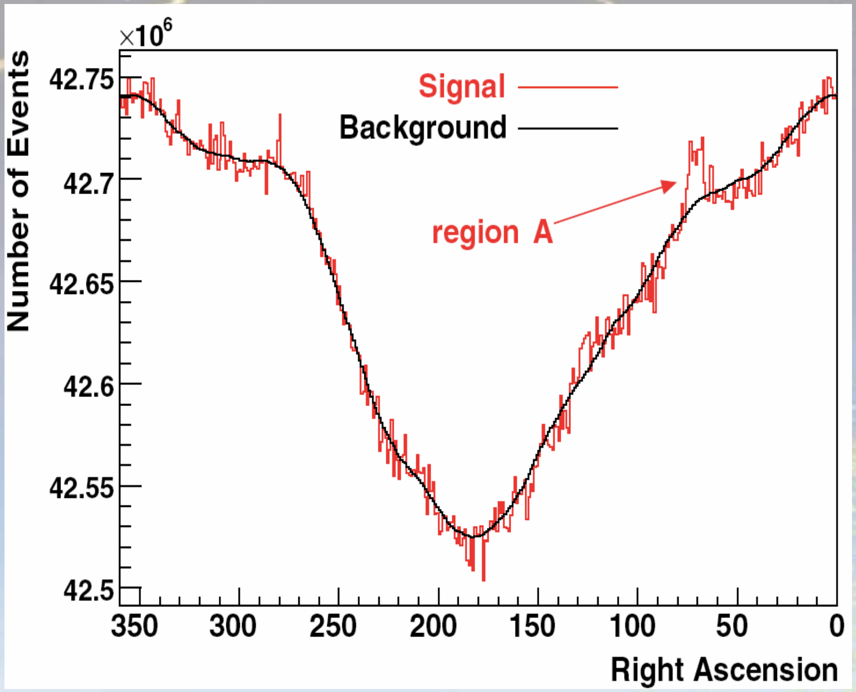
Milagro Cosmic Ray Observations

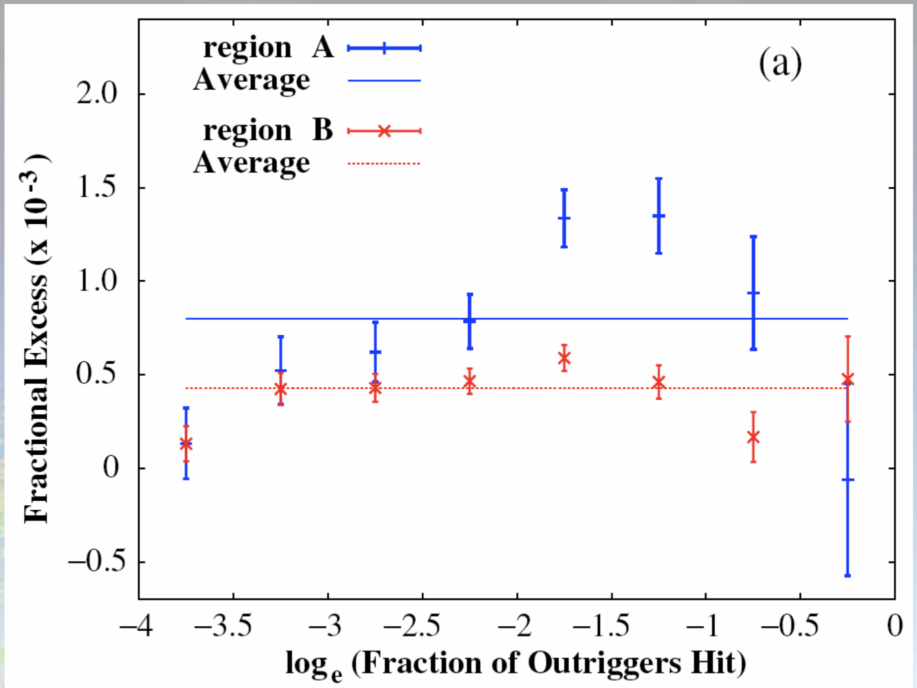


- No weighting or cutting. Map dominated by cosmic rays.
- Background subtraction serves as a high-pass filter.
- 10o smoothing looks for largeish features.
- Two regions of excess 15.0σ and 12.7σ. Fractional excess of 6×10^{-4} (4×10^{-4}) for region A(B).
- Seen also by Tibet ASγ and ARGO-YBJ

PRL **101**, 221101 (2008)

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)

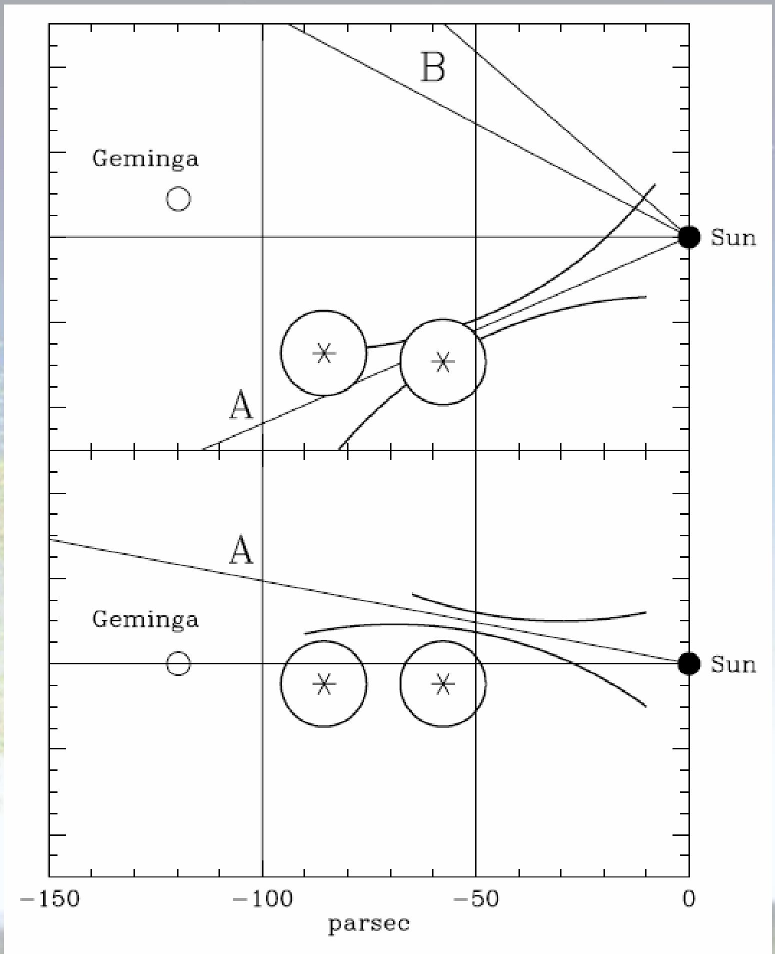
What are these features?

- 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)

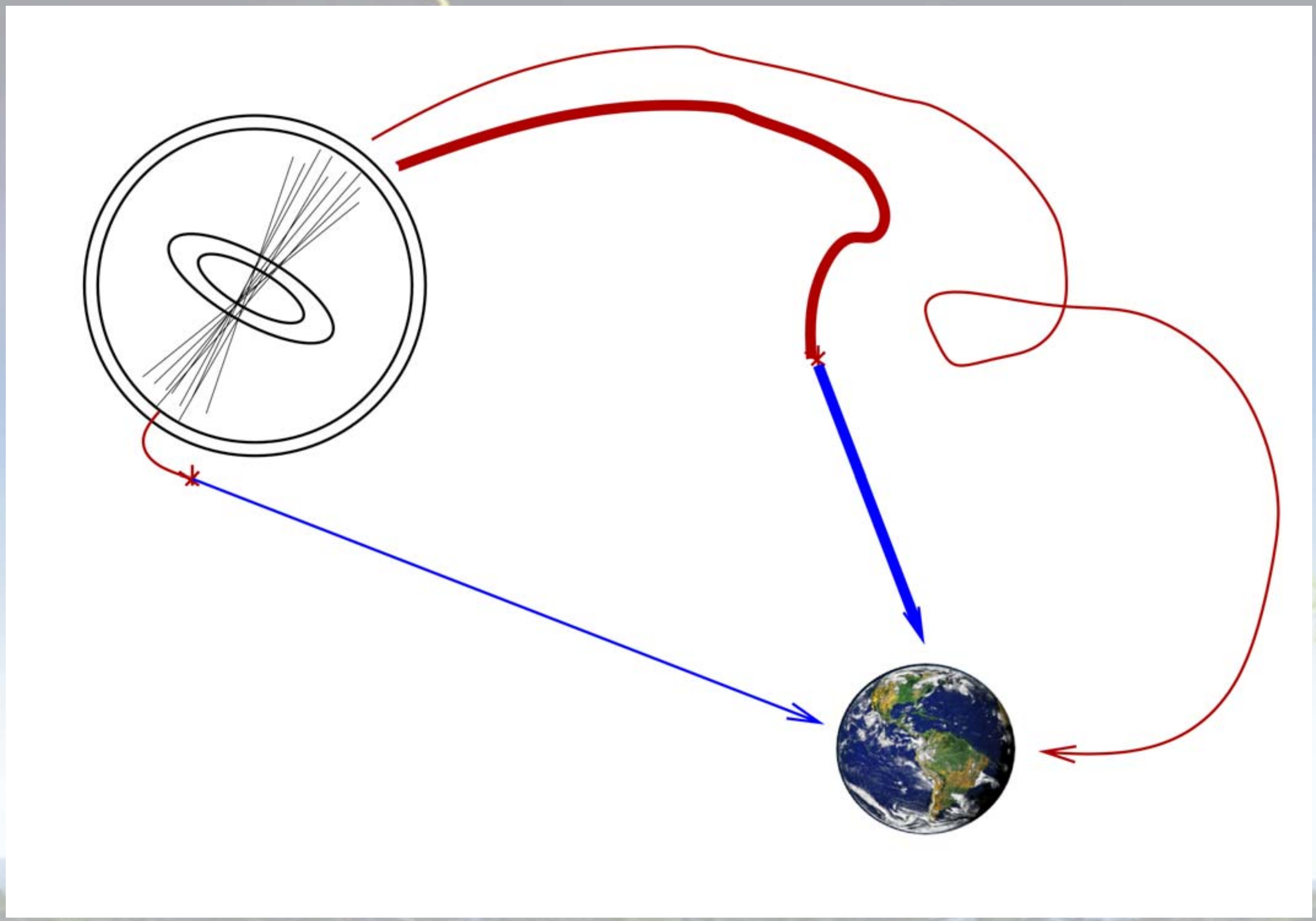
Potential Nearby Cosmic-Ray Accelerator

- Considered plausible by those who've considered it
- Requires non-standard cosmic-ray diffusion and a nearby source (Geminga supernova? As little as 90 pc away.)
- Some coherent magnetic structure connecting us to the source.
- Need to understand cosmic-ray propagation better.

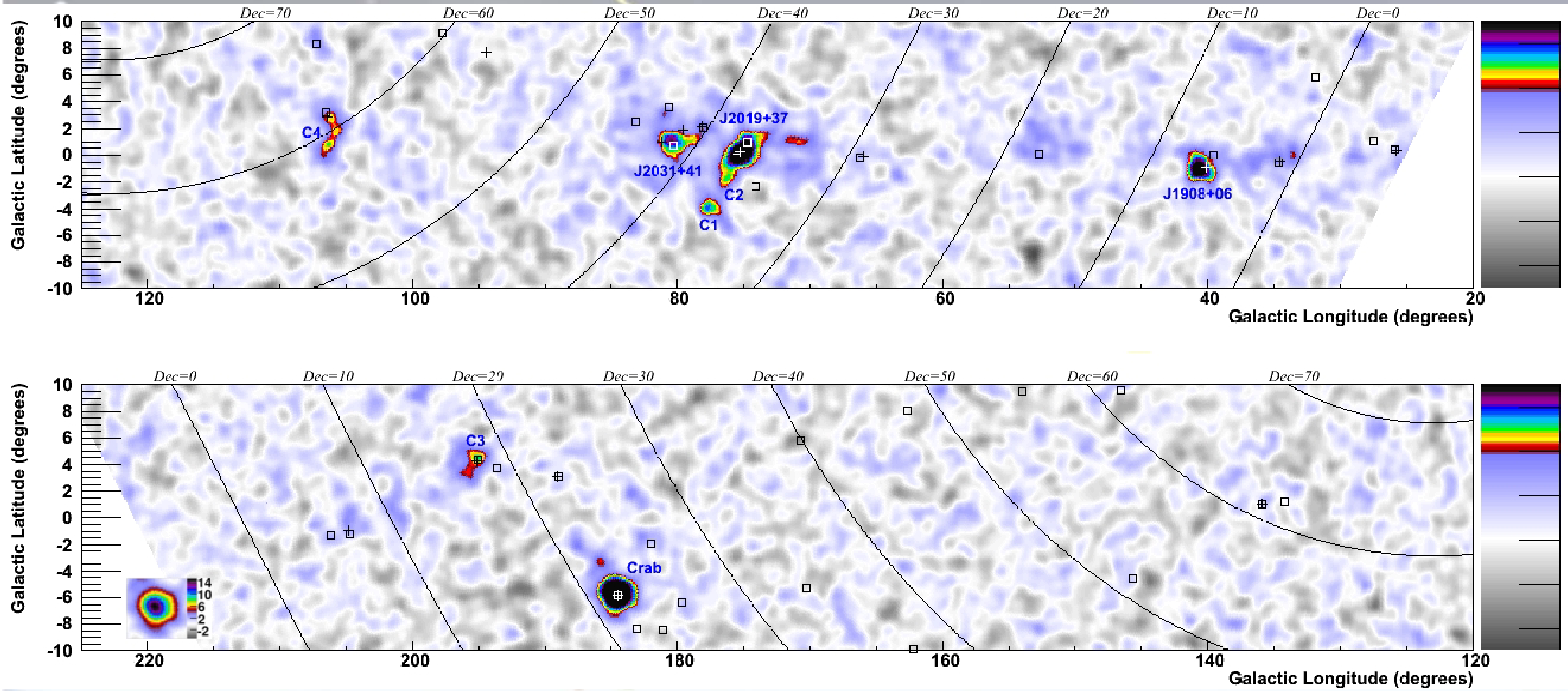


From: Salvati and Sacco. A&A 485, 527-529 (2008)

Diffuse Gamma-ray Emission

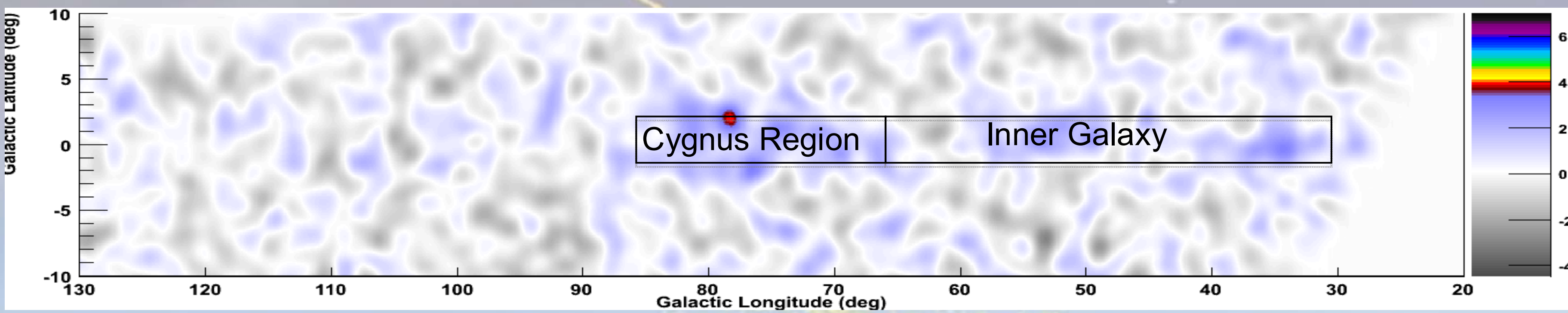


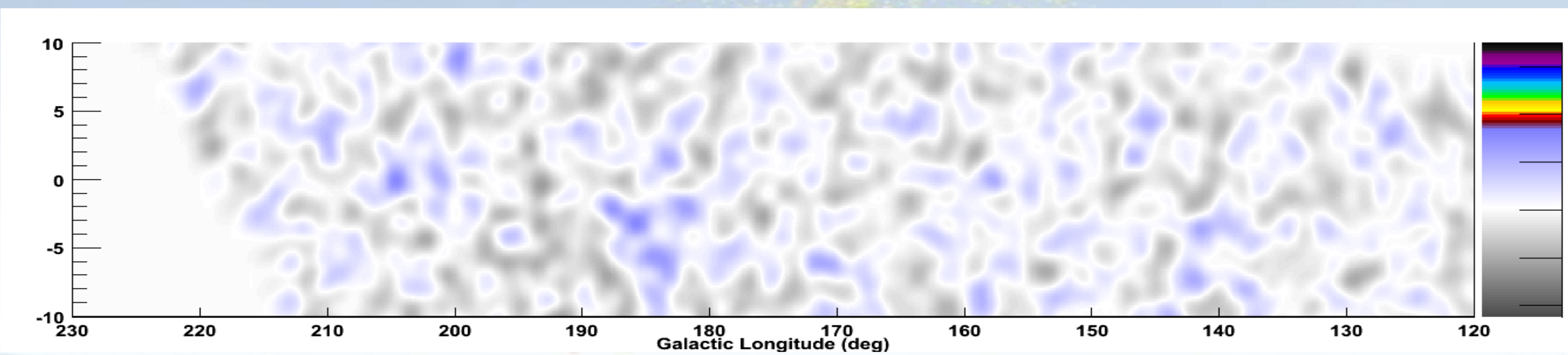
Milagro Galactic Plane



Abdo et al. ApJL **664**. 91-94. (2007)

TeV Diffuse Emission from the Galactic Plane with Milagro (Abdo et al. 2008)



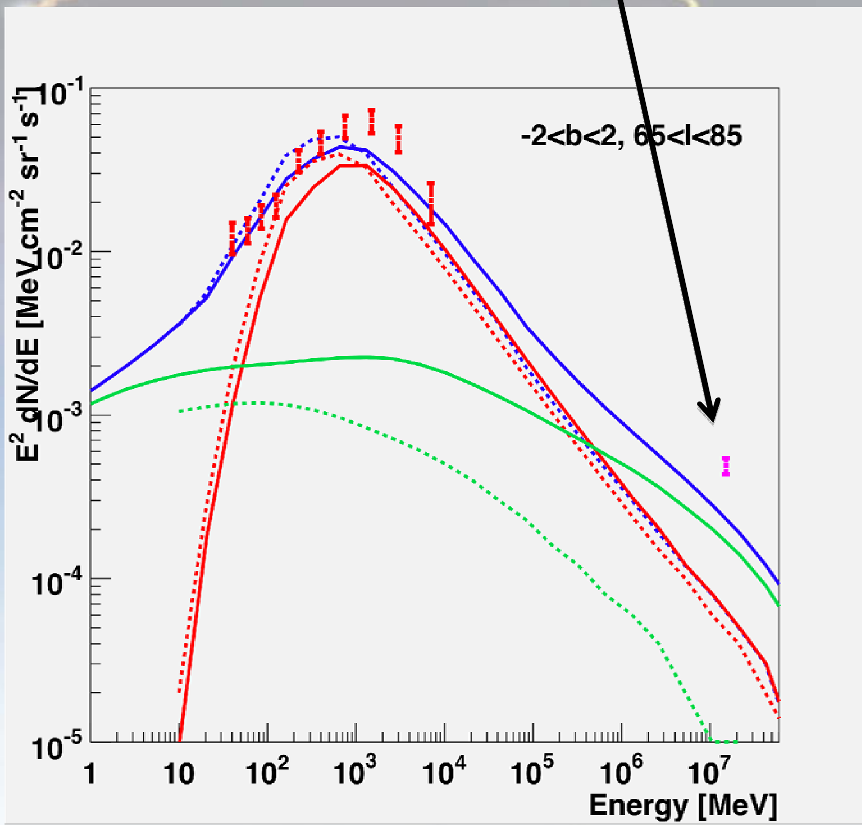


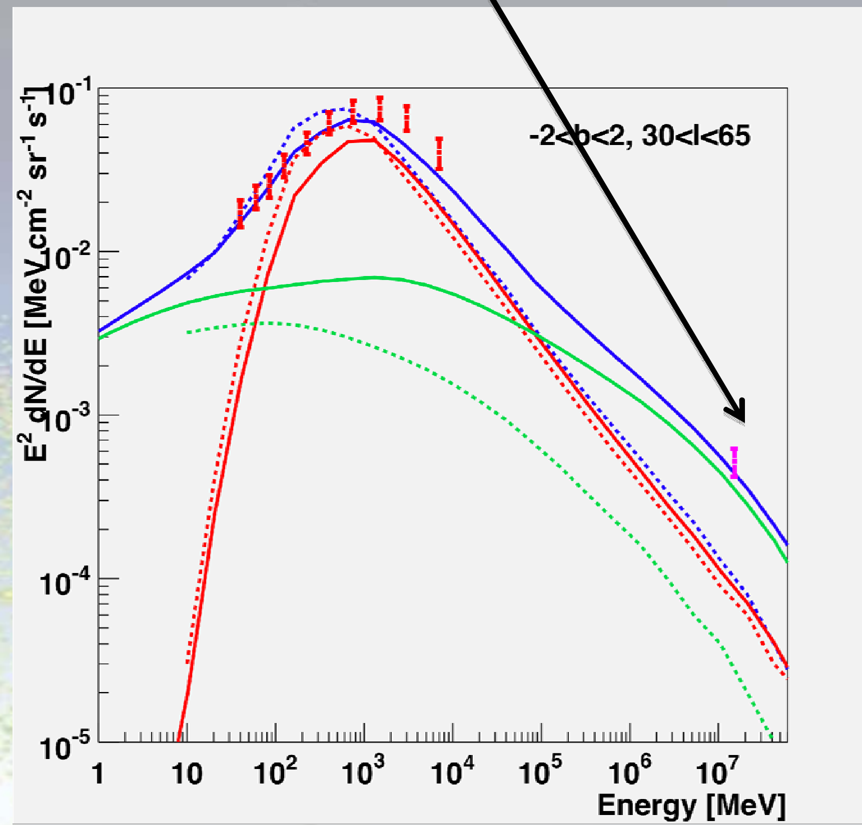
Petra Huentemeyer

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

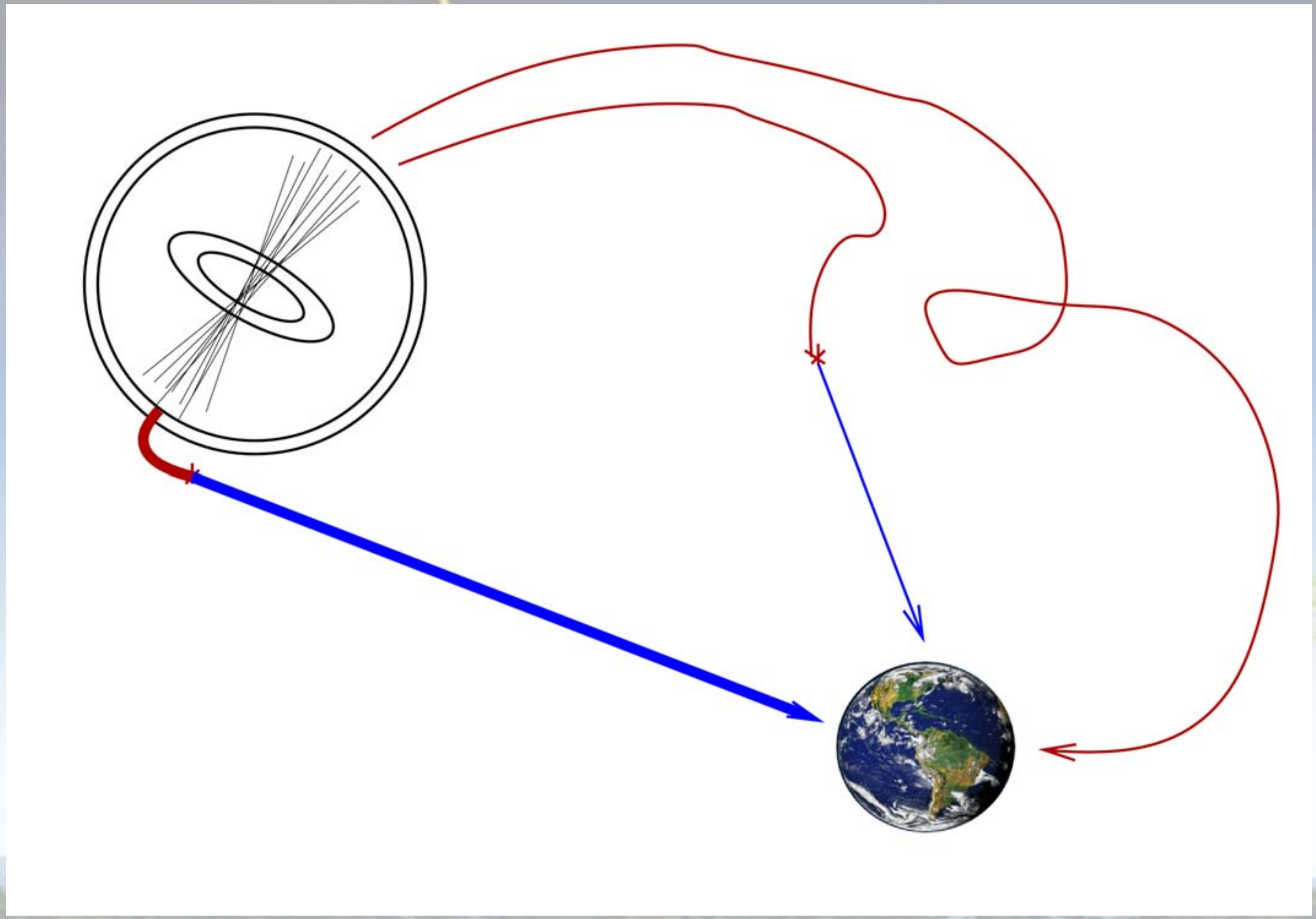
Strong et al., ApJ **613**, 962 (2004)
Strong et al., A&A **422**, L47 (2004)

Petra Huentemeyer

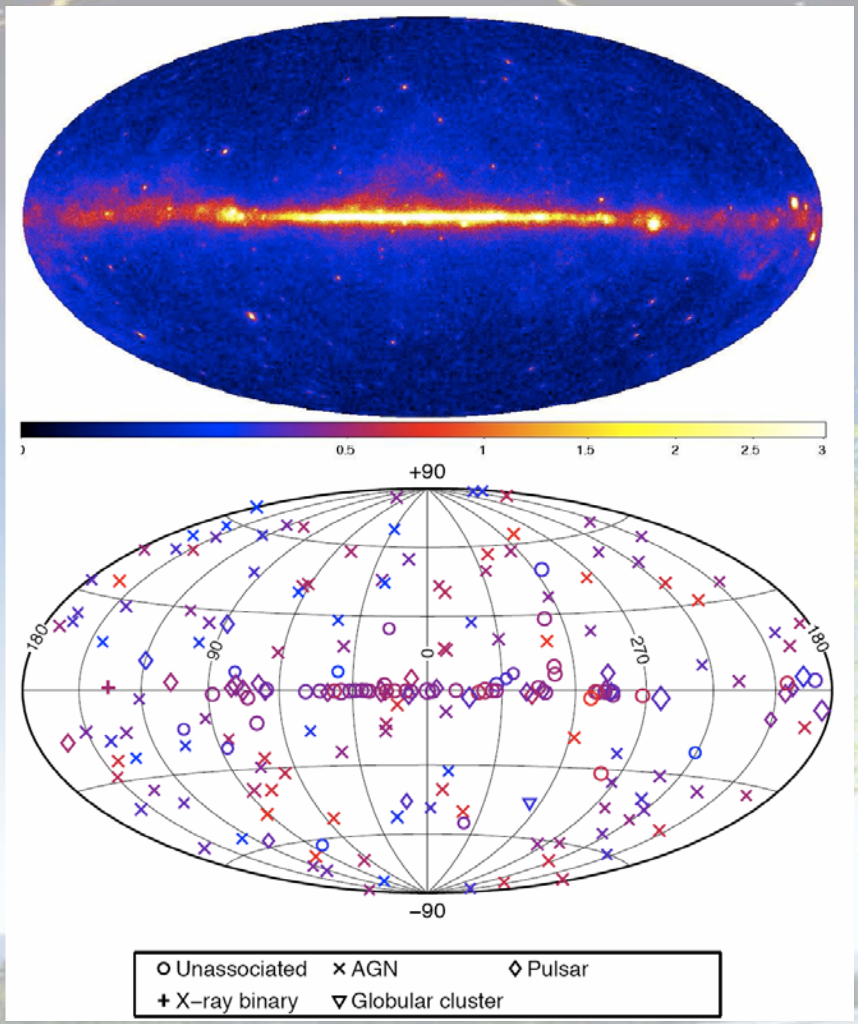
TeV Diffuse Emission Excess

- 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)

Discrete Gamma-Ray Sources



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

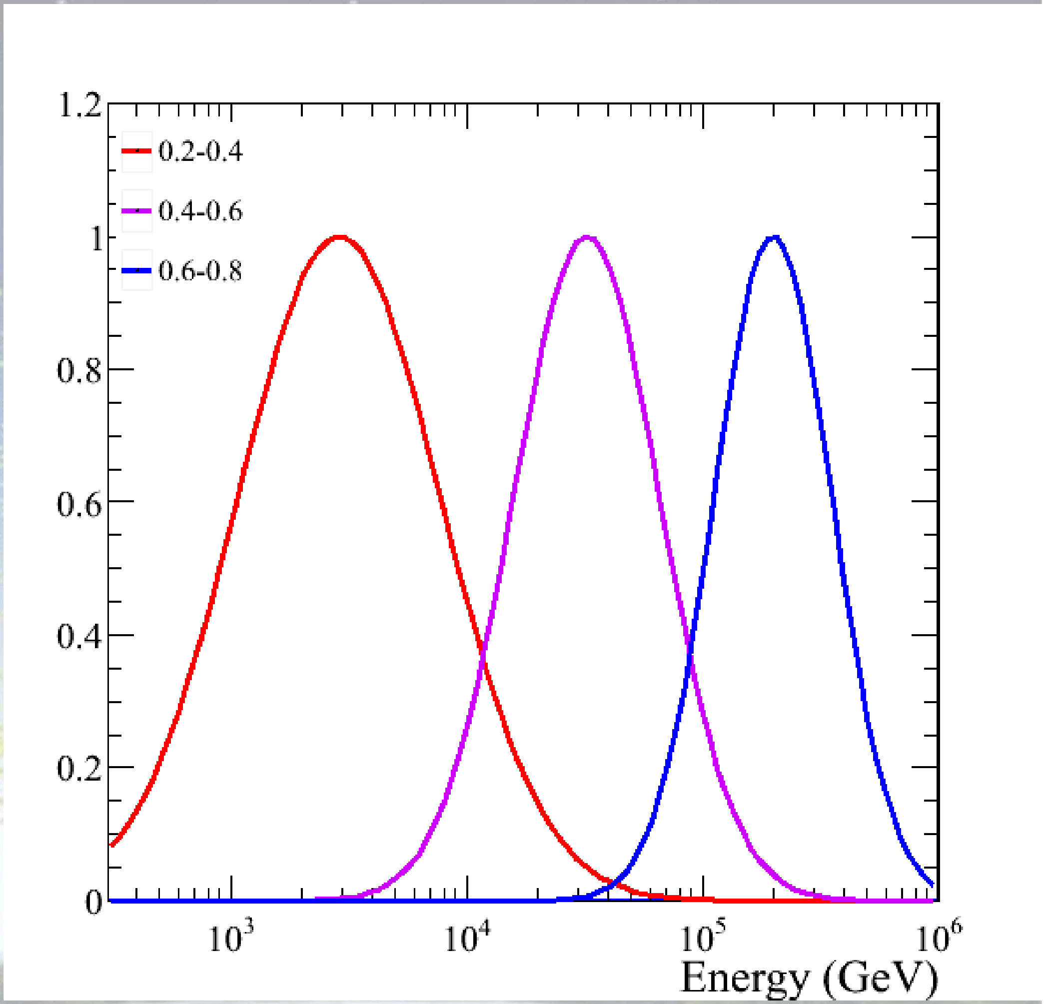
Abdo et al. arXiv:0902.1340

Next Generation of Analysis - Energy

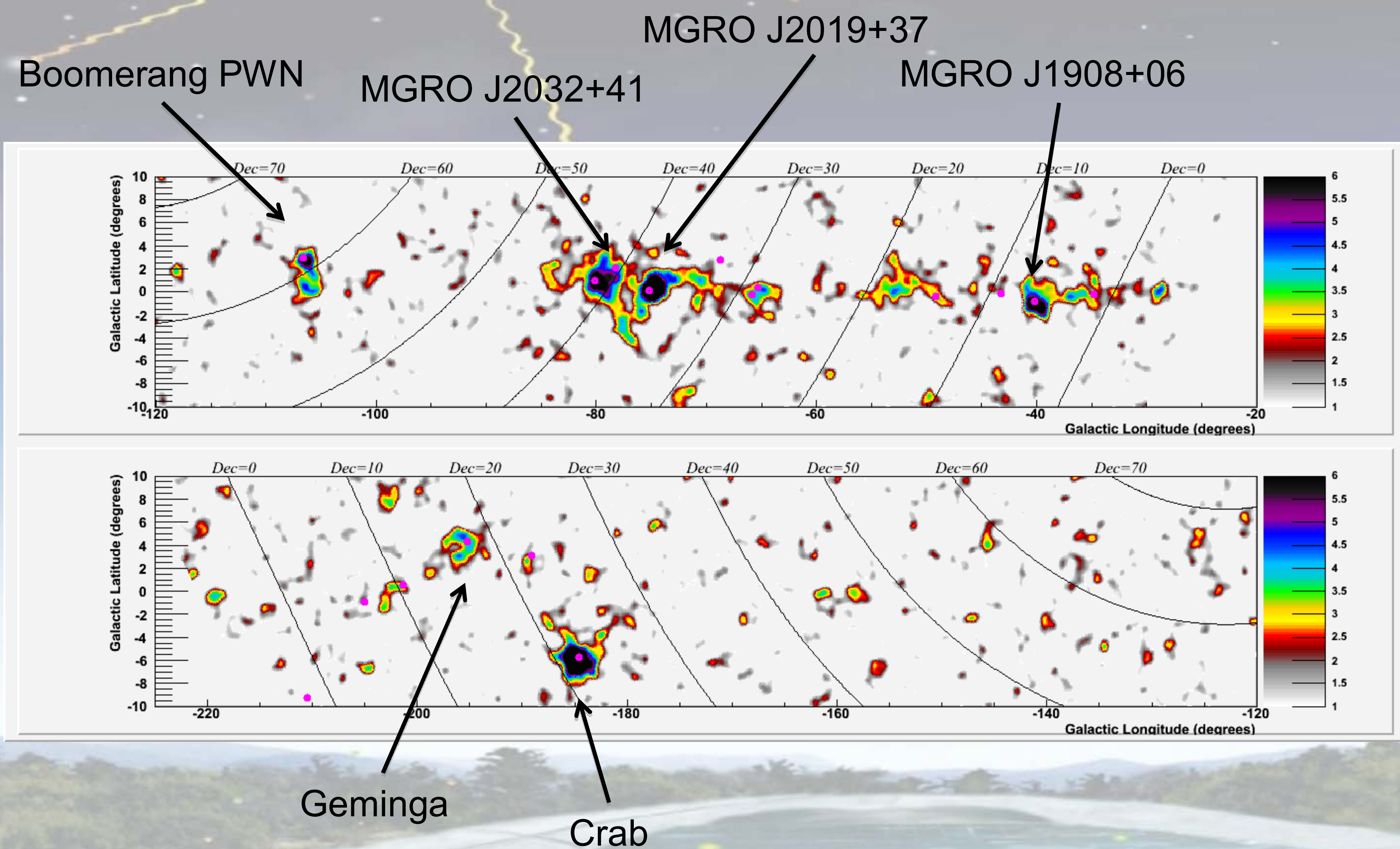
- Frasor variable F tracks energy

$$F = \frac{N_{AS}}{Live_{AS}} + \frac{N_{OR}}{Live_{OR}}$$

  - Optimize weighting separately in each F bin.
  - Excess in each F bin fit to MC to generate energy spectrum
- 1.5 years more data
- Crab 15.0σ -> 17.2σ
- 15% - 25% cumulative increase in sensitivity
- Median energy 20 -> 35 TeV

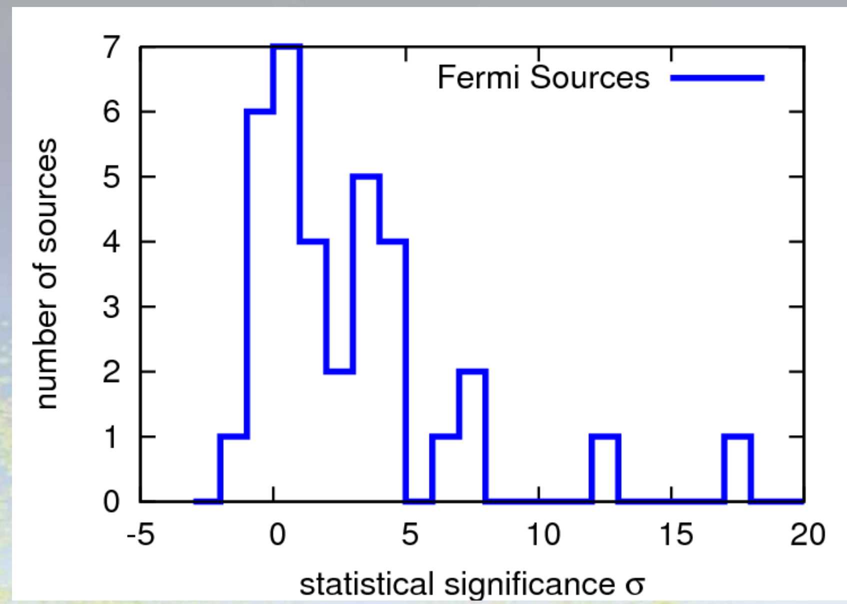


Survey of the Galactic Plane



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



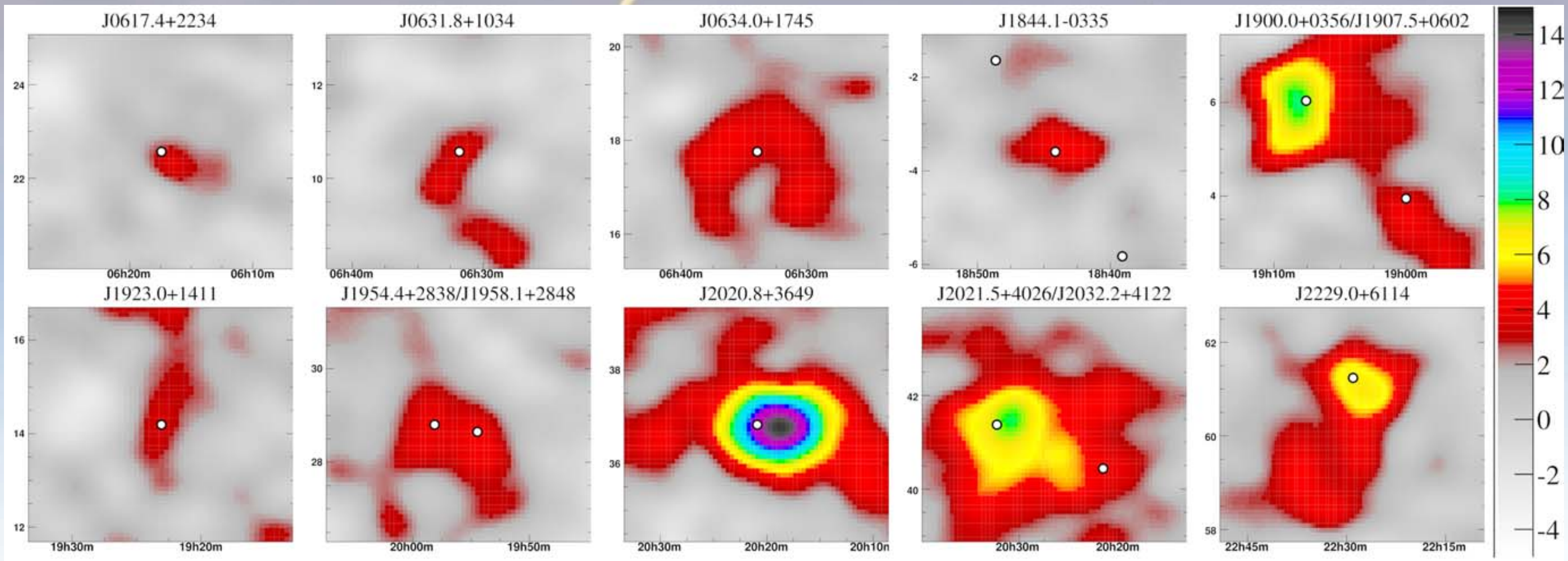
- 'Most' of the 3σ sources are true TeV detections, but cannot be claimed individually
- All of these will be observable with 3 months of HAWC data

Abdo et al. ApJL **700** (2009) L127-131

Name (0FGL)	type	RA (deg)	DEC (deg)	l (deg)	b (deg)	Flux ($\times 10^{-17}$ TeV^{-1} sec^{-1} cm^{-2})	Signif. (σ's)	TeV assoc.
J0007.4+7303	PSR	1.85	73.06	119.69	10.47	< 90.4	2.6	
J0030.3+0450	PSR	7.60	4.85	113.11	-57.62	< 20.9	-1.7	
J0240.3+6113	HXB	40.09	61.23	135.66	1.07	< 26.2	0.7	LSI +61 303
J0357.5+3205	PSR	59.39	32.08	162.71	-16.06	< 16.5	-0.1	
J0534.6+2201	PSR	83.65	22.02	184.56	-5.76	162.6 ± 9.4	17.2	Crab
J0613.9-0202	PSR	93.48	-2.05	210.47	-9.27	< 60.0	-0.0	
J0617.4+2234	SNR[a]	94.36	22.57	189.08	3.07	28.8 ± 9.5	3.0	IC443
J0631.8+1034	PSR	97.95	10.57	201.30	0.51	47.2 ± 12.9	3.7	
J0633.5+0634	PSR	98.39	6.58	205.04	-0.96	< 50.2	1.4	
J0634.0+1745	PSR	98.50	17.76	195.16	4.29	37.7 ± 10.7	3.5	MGRO C3 Geminga
J0643.2+0858		100.82	8.98	204.01	2.29	< 30.5	0.3	
J1653.4-0200		253.35	-2.01	16.55	24.96	< 51.0	-0.5	
J1830.3+0617		277.58	6.29	36.16	7.54	< 32.8	0.2	
J1836.2+5924	PSR	279.06	59.41	88.86	25.00	< 14.6	-0.9	
J1844.1-0335		281.04	-3.59	28.91	-0.02	148.4 ± 34.2	4.3	
J1848.6-0138		282.16	-1.64	31.15	-0.12	< 91.7	1.7	
J1855.9+0126	SNR[a]	283.99	1.44	34.72	-0.35	< 89.5	2.2	
J1900.0+0356		285.01	3.95	37.42	-0.11	70.7 ± 19.5	3.6	
J1907.5+0602	PSR	286.89	6.03	40.14	-0.82	116.7 ± 15.8	7.4	MGRO J1908+06 HESS J1908+063
J1911.0+0905	SNR[a]	287.76	9.09	43.25	-0.18	< 41.7	1.5	
J1923.0+1411	SNR[a]	290.77	14.19	49.13	-0.40	39.4 ± 11.5	3.4	HESS J1923+141
J1953.2+3249	PSR	298.32	32.82	68.75	2.73	< 17.0	0.0	
J1954.4+2838	SNR[a]	298.61	28.65	65.30	0.38	37.1 ± 8.6	4.3	
J1958.1+2848	PSR	299.53	28.80	65.85	-0.23	34.7 ± 8.6	4.0	
J2001.0+4352		300.27	43.87	79.05	7.12	< 12.1	-0.9	
J2020.8+3649	PSR	305.22	36.83	75.18	0.13	108.3 ± 8.7	12.4	MGRO J2019+37
J2021.5+4026	PSR	305.40	40.44	78.23	2.07	35.8 ± 8.5	4.2	
J2027.5+3334		306.88	33.57	73.30	-2.85	< 16.0	-0.2	
J2032.2+4122	PSR	308.06	41.38	80.16	0.98	63.3 ± 8.3	7.6	TEV 2032+41 MGRO J2031+41
J2055.5+2540		313.89	25.67	70.66	-12.47	< 17.6	-0.0	
J2110.8+4608		317.70	46.14	88.26	-1.35	< 24.1	1.1	
J2214.8+3002		333.70	30.05	86.91	-21.66	< 20.7	0.6	
J2229.0+6114	PSR	337.26	61.24	106.64	2.96	70.9 ± 10.8	6.6	MGRO C4
J2302.9+4443		345.75	44.72	103.44	-14.00	< 13.2	-0.6	

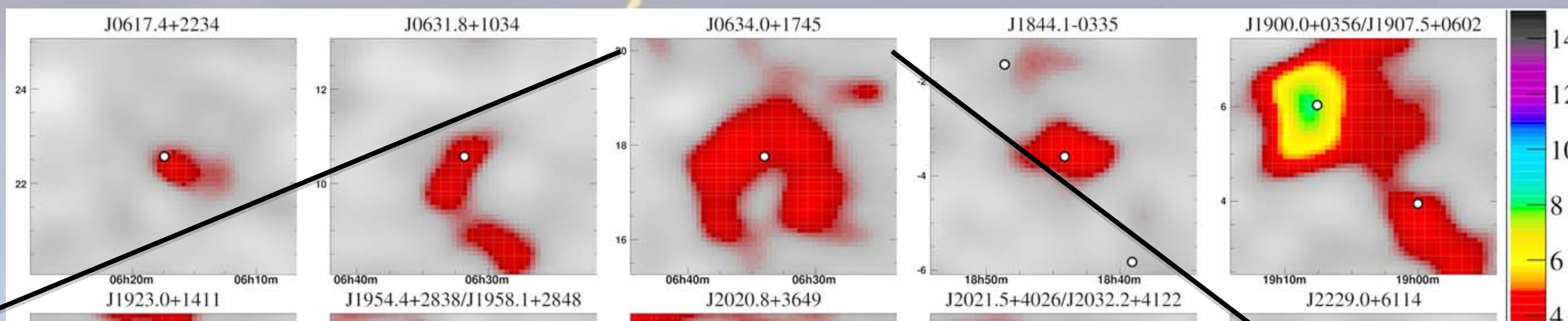
Abdo et al. ApJL **700** (2009) L127-131

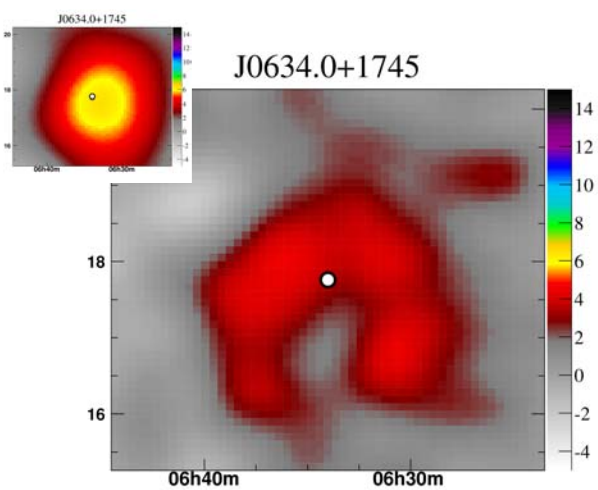
The 3σ Locations



Abdo et al. ApJL **700** (2009) L127-131

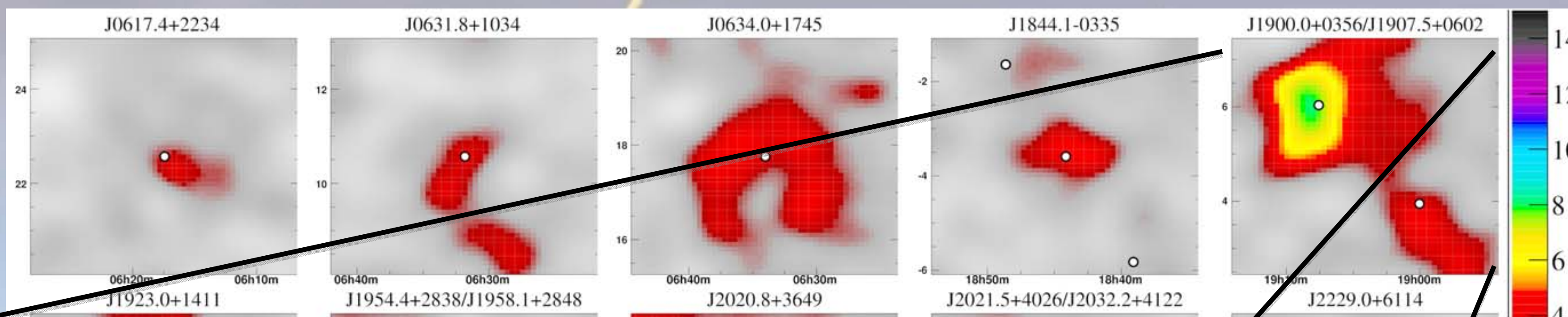
The 3σ Locations

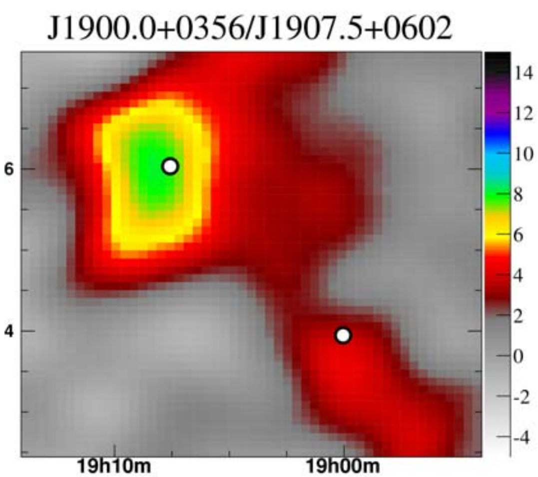




- Most Significant source in BSL
- Old (300 kyr) and nearby (169 pc)
- 3.5σ at the location of Geminga
- 6.3σ when assuming 1° extended source
- Fitted 1.1° extent, consistent with IACT observations of more distant PWN

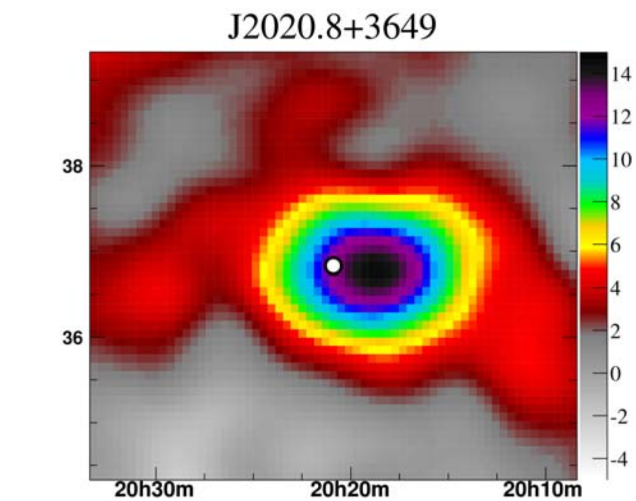
The 3σ Locations



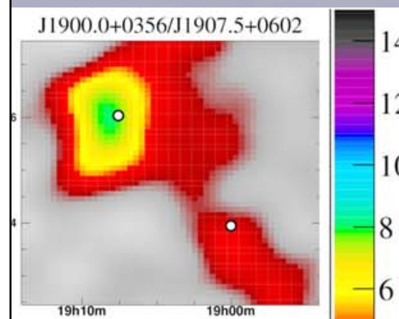


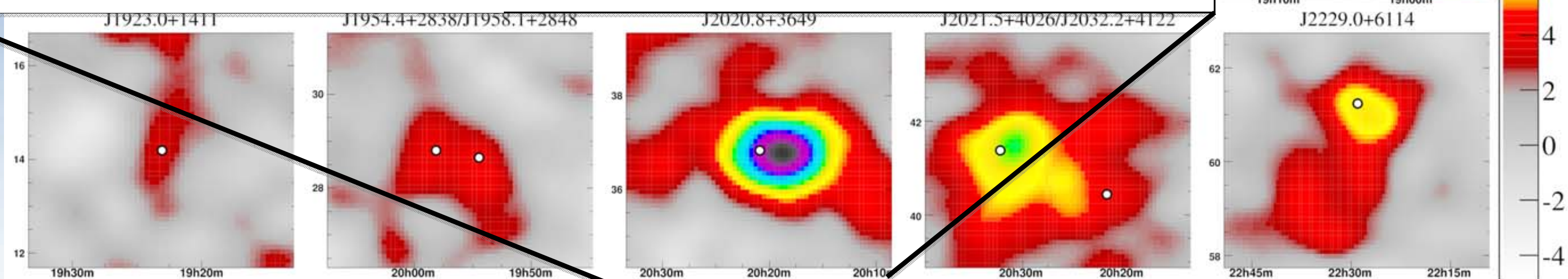
- 7.4σ at pulsar location. 8.1σ at local maximum.
- Pulsar discovered by the LAT.
- Verified by HESS and Veritas.
- Extended by 0.21° in HESS data

The 3σ Locations

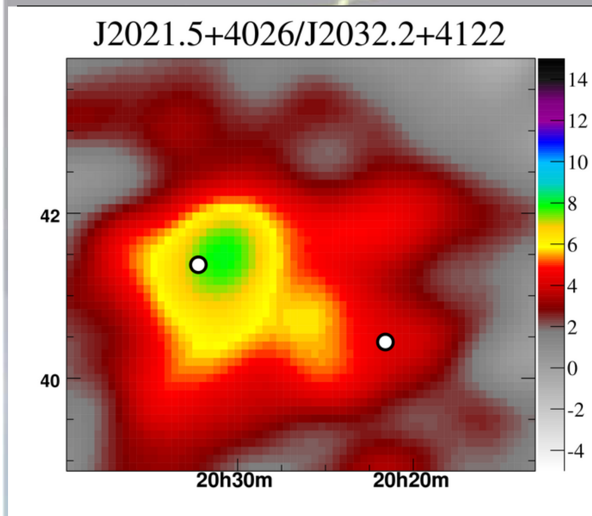


- Most significant source for Milagro after the Crab. 12.4σ at the pulsar location. 14.5σ at peak.
- Identified as a young pulsar by AGILE.
- Milagro peak is separated from pulsar by 0.3° with a 1σ error of 0.1°.
- In the Cygnus region being surveyed by Veritas.

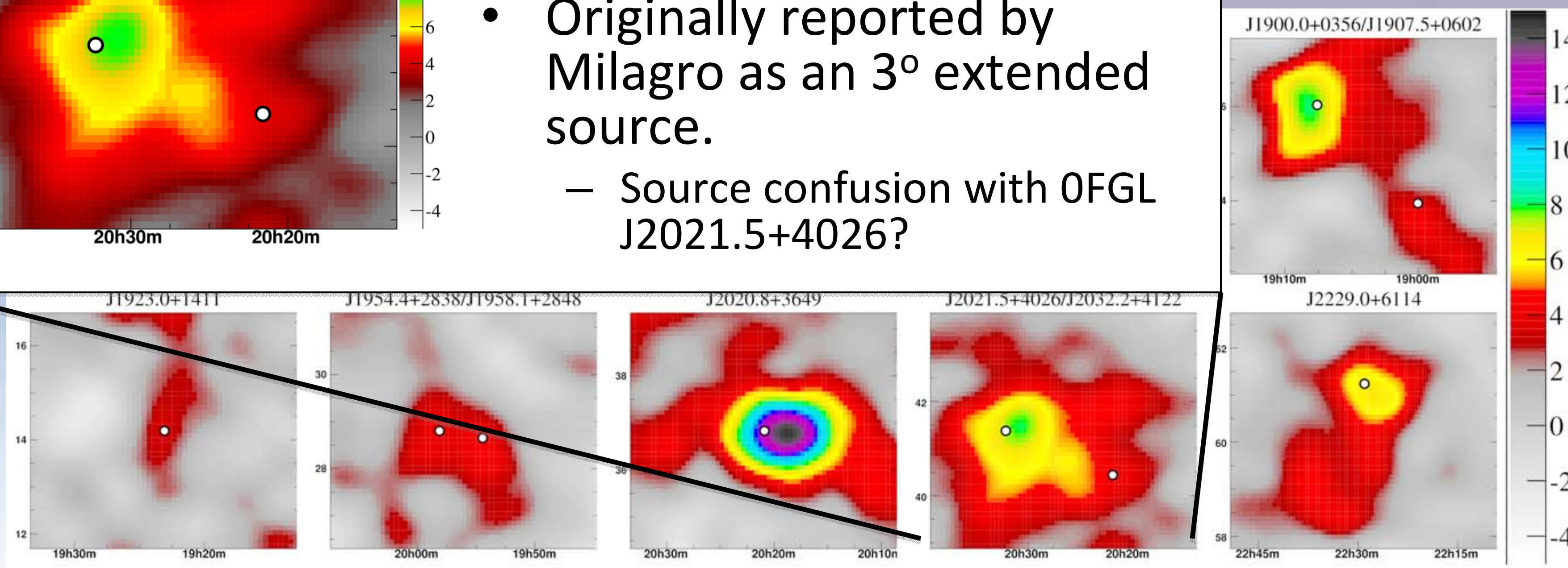




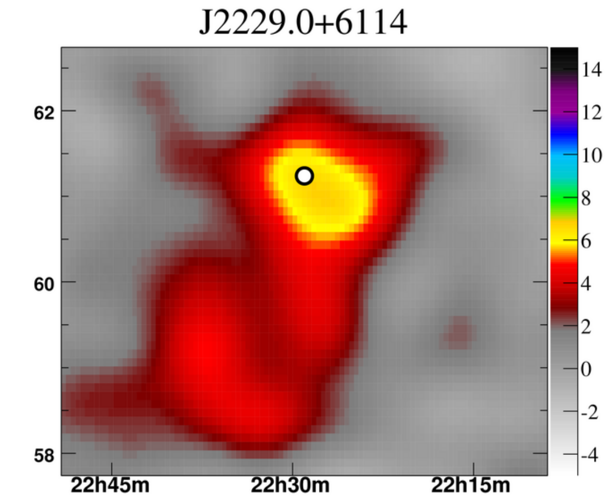
The 3σ Locations



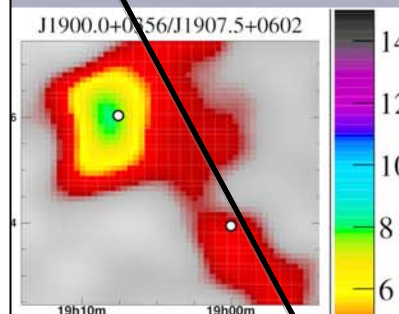
- Associated with LAT-identified pulsar
- Originally reported by Milagro as an 3° extended source.
  - Source confusion with 0FGL J2021.5+4026?

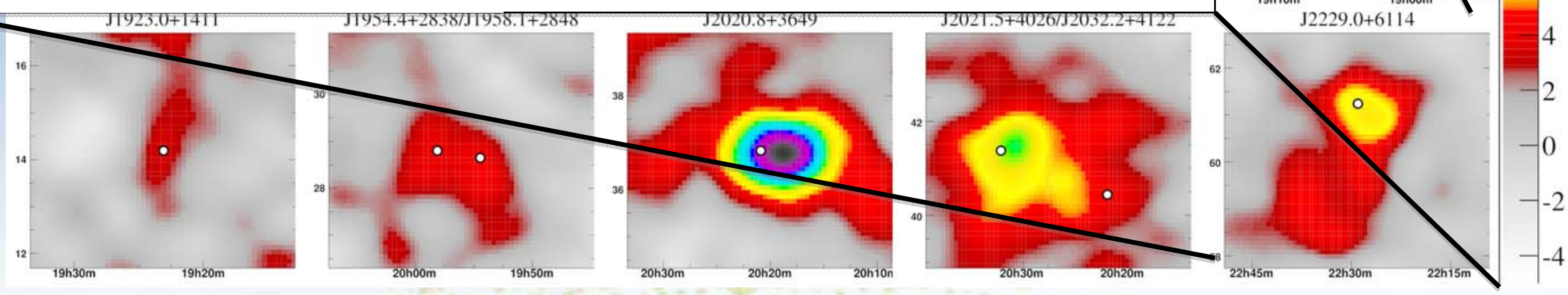


The 3σ Locations

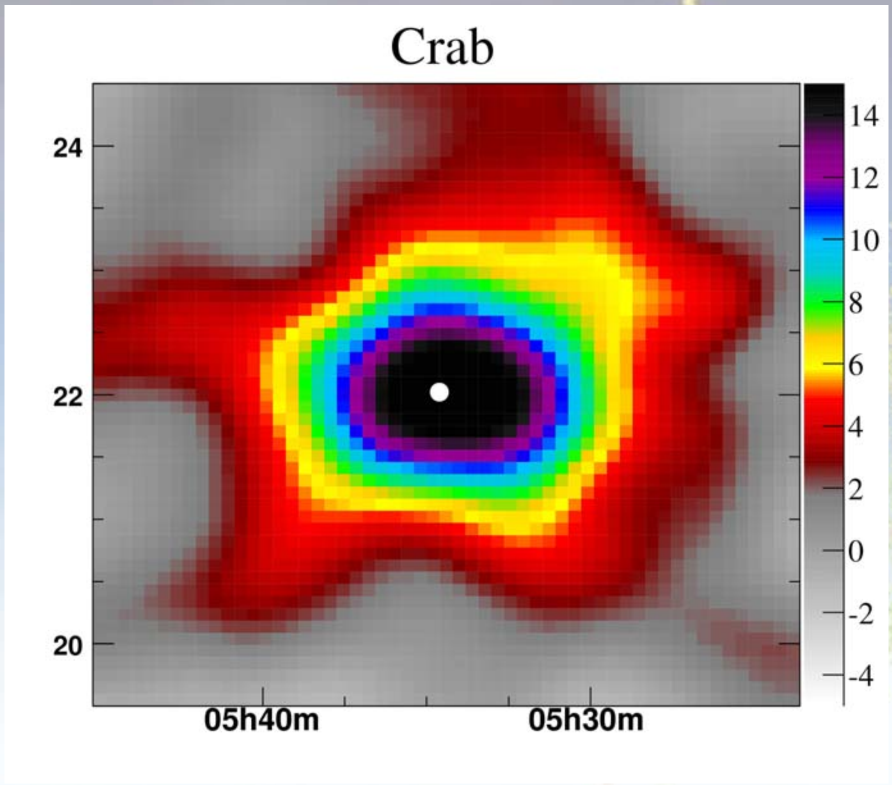


- Boomerang PWN
- 6.6σ at the pulsar location 6.8σ.
- Associated with radio pulsar J2229+6114
- Extended source or additional source to the south.





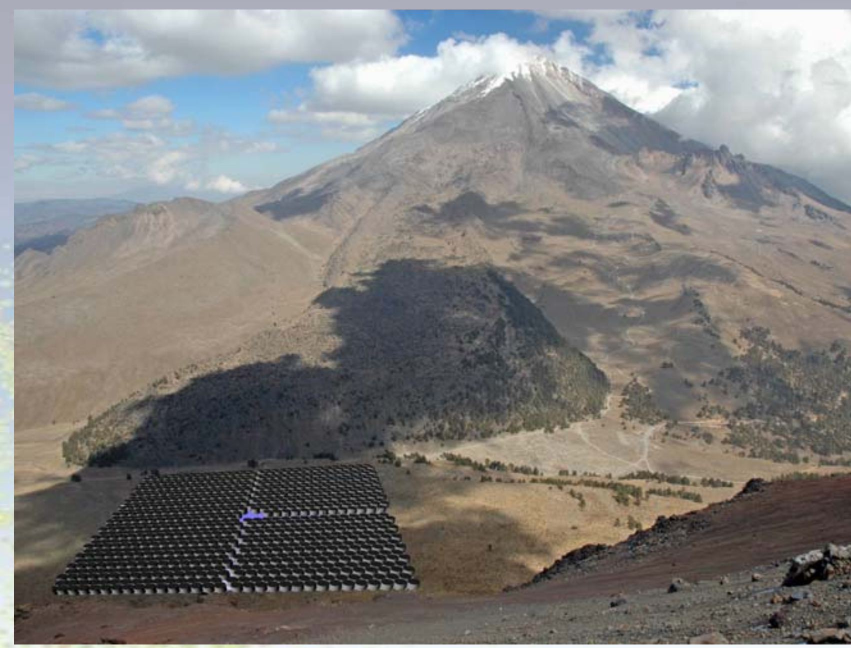
Milagro Gamma-Ray Sources



- Milagro's strongest sources are very likely TeV PWN. Typical TeV source is a PWN.
- TeV emission is quite commonly associated with MeV-GeV Pulsars.
- Spectrum to connect Milagro measurements to Fermi measurements are universally softer than 2.3.

High Altitude Water Cherenkov detector (HAWC)

- Move Milagro PMTs to high-altitude site at Sierra Negra, Mexico
- One layer representing 10x the area of Milagro's bottom layer
- Tanks can distinguish muons from EMS particles.
  - Better gamma/hadron separation.
- Overall 15x sensitivity improvement over Milagro.
- See sources 225x faster.
  - See 1 Crab every day.



High Altitude Water Cherenkov detector (HAWC)

- Move Milagro PMTs to high-altitude site at Sierra Negra, Mexico

See Andy Smith's Talk Tomorrow

  from EMS particles.
  - Better gamma/hadron separation.
- Overall 15x sensitivity improvement over Milagro.
- See sources 225x faster.
  - See 1 Crab every day.

Conclusions

- Milagro decommissioned in June 2008 and analysis of final dataset is underway.
  - Exhibits the need for an all-sky survey instrument.
- Cosmic-rays:
  - Localized anisotropy seen at $\sim 5\times10^{-4}$ level.
  - No compelling explanation yet. Most inspiring idea is that we are seeing cosmic rays from Geminga.
  - Need better understanding of Galactic magnetic fields.
- Gamma-rays:
  - List of sources and potential TeV emitters is growing. Appear to be mostly TeV PWN associated with MeV-GeV pulsars.
  - High-confidence TeV detection from Geminga and Boomerang PWN
  - How much Galactic Diffuse emission is explainable this way is an open question. Remaining Fermi data will help.
- HAWC
  - 15x increase in Milagro sensitivity
  - Engineering progressing with $850k MRI
  - “Shovel Ready”