Results from Milagro and Prospects for HAWC

John Pretz (Los Alamos National Lab)

Stefan Westerhoff (University of Wisconsin-Madison)

ICHEP 2010

Paris, July 22 - 28, 2010

Milagro Collaboration

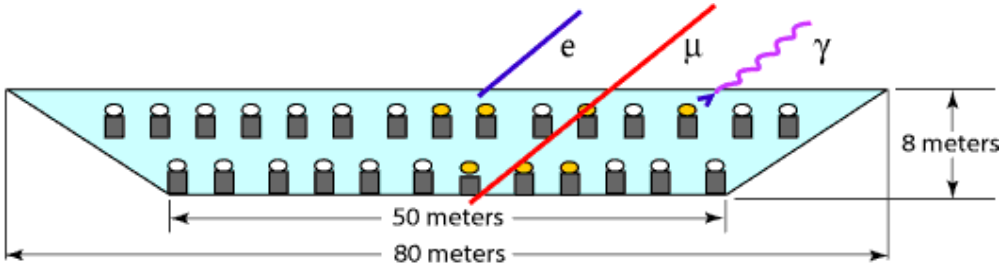
A. Abdo, B. Allen, D. Berley, G. Christopher, T. DeYoung, B.L. Dingus, R.W. Ellsworth, M.M. Gonzalez, J.A. Goodman, C.M. Hoffman, P. Huntemeyer, B. Kolterman, C.P. Lansdell, J.T. Linnemann, J.E. McEnery, A.I. Mincer, P. Nemethy, J. Pretz, J.M. Ryan, P.M. Saz Parkinson, A. Shoup, G. Sinnis, A.J. Smith,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

The Milagro Detector

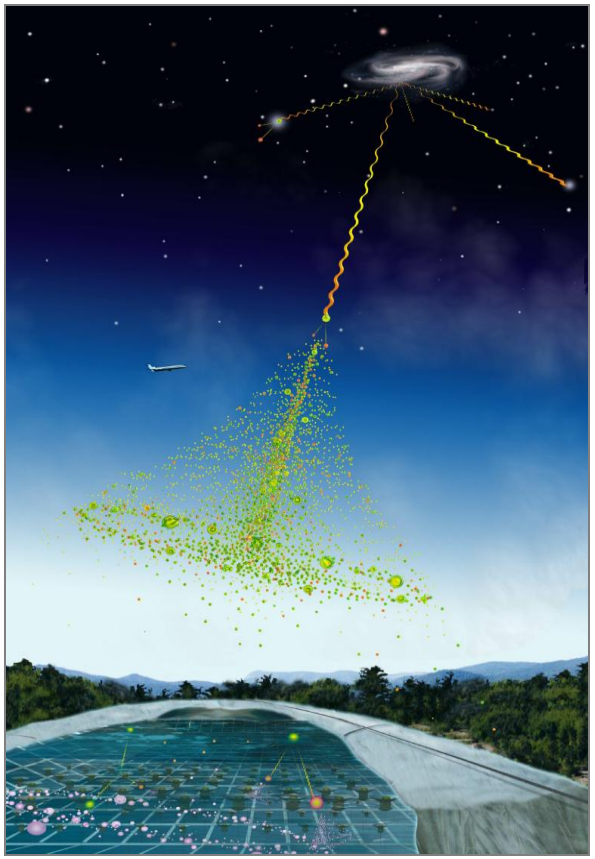
- First generation water Cherenkov detector for gamma rays and cosmic rays at TeV energies with…
  - … large field of view.
  - … 100% duty cycle.
- Location: Jemez Mountains (near Los Alamos) at 2630 m altitude, 36º N.
- Detector:
  - 60m × 80m water-filled pond with light-tight cover and 723 8'' photomultiplier tubes.
  - Sparse 200m × 200m array of 175 outrigger tanks (with one photomultiplier each) surrounding the pond.

Detection Principle



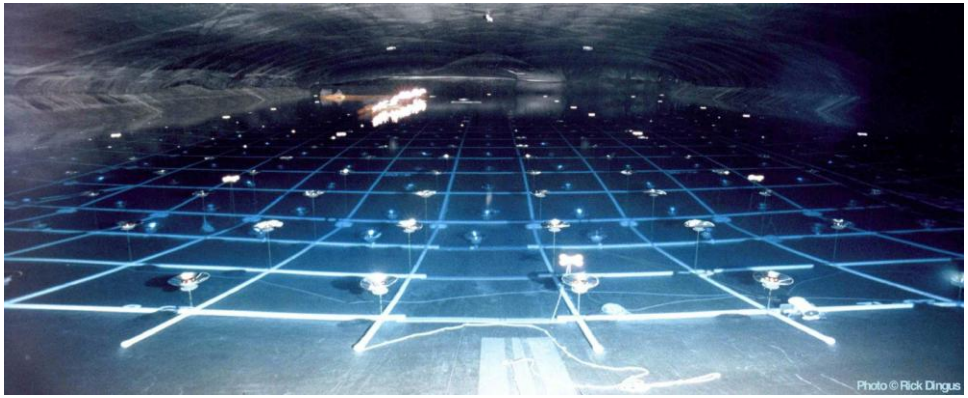
- **Pond is instrumented with two layers of photomultipliers (PMTs):**
  - **Air shower layer: 450 PMTs at 1.4m depth**
    ⇒ accurate measurements of air shower particle arrival times, used for arrival direction reconstruction and triggering.
  - **Muon layer: 273 PMTs at 6m depth**
    ⇒ detection of penetrating muons and hadrons, used for rejection of cosmic ray background.

- **Outrigger array (added in 2003) ⇒ improvement of angular resolution, providing longer lever arm for event reconstruction.**



Gamma Ray Detectors

	Gamma Ray Energy	Field of View (sr)	Point Spread Function	Sensitivity (erg/cm^2/sec)
Fermi	**0.1 GeV**	**4 □**	**0.04º**	**$1 \cdot 10^{-12}$**
Veritas / HESS	**0.2 TeV**	**0.002**	**0.05º**	**$0.2 \cdot 10^{-12}$**
Milagro	**20 TeV**	**2 □**	**0.7º**	**$2 \cdot 10^{-12}$**

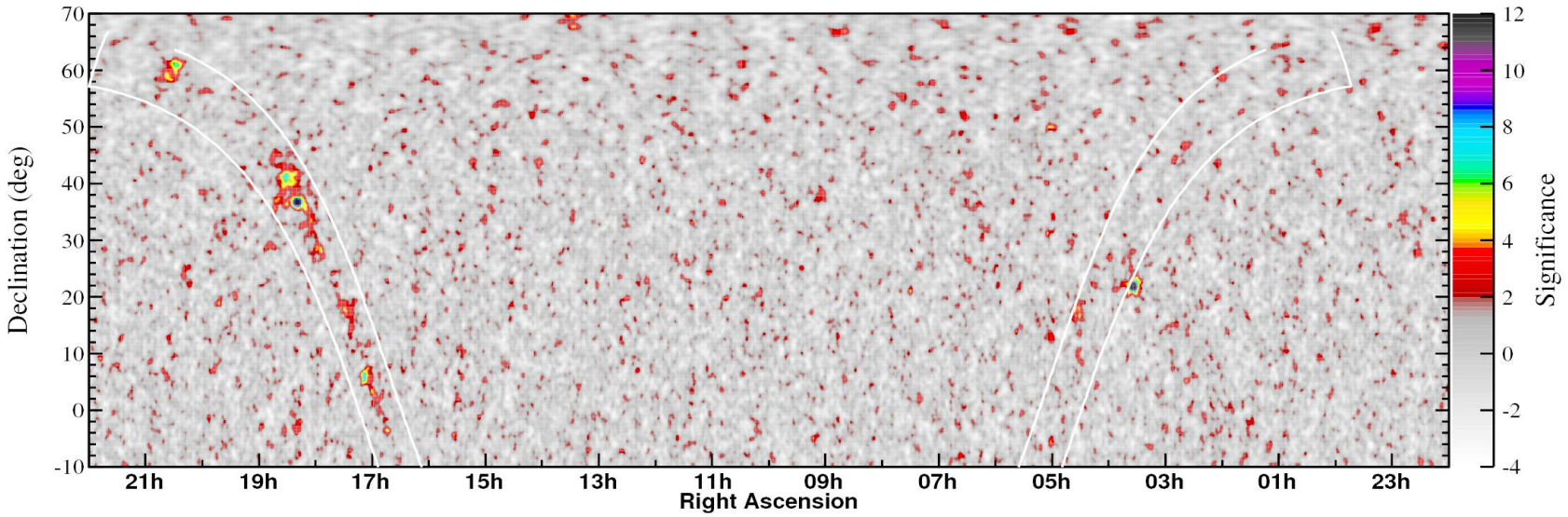


Summary of Main Discoveries

- **Multi-TeV emission from 5 Galactic sources associated with Fermi pulsars (in addition to the Crab), evidence for multi-TeV emission from 8 additional Galactic Fermi sources.**
  - » *Astrophys. J. 700 (2009) L127*
- **Diffuse TeV emission from the Galactic plane.**
  - » *Astrophys. J. 688 (2008) 1078*
- **TeV Gamma Ray Survey of the Galactic plane.**
  - » *Astrophys. J. 664 (2007) L91*
- **Large-scale anisotropy of cosmic ray directions.**
  - » *Astrophys. J. 698 (2009) 2121*
- **Discovery of localized regions of excess cosmic rays.**
  - » *Phys. Rev. Lett. 101 (2008) 221101*

Data Set

- **8 Years of Livetime from 2000 – 2008.**
- **Events weighted according to the likelihood that they are due to gamma rays utilizing muon-layer PMT information.**
- **Background estimated from nearby right ascension bins within a declination bin (accounts for changing rate of background).**

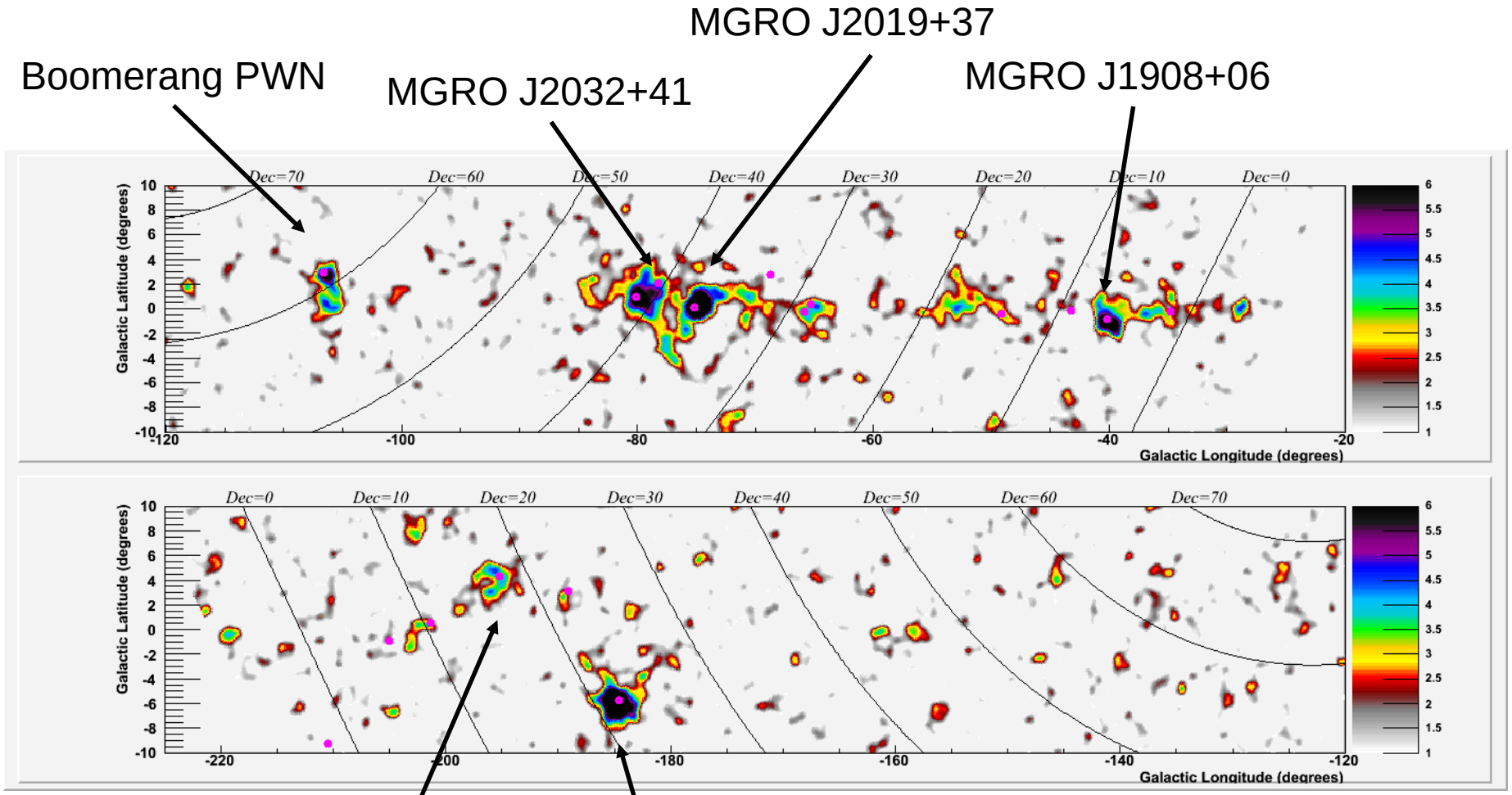


Results

- **With its large field of view and long observation time…**
  - **… Milagro is the most sensitive instrument for the study of large, low surface brightness sources (such as diffuse gamma radiation).**
  - **… Milagro can survey large regions of the sky, for example the Galactic plane.**

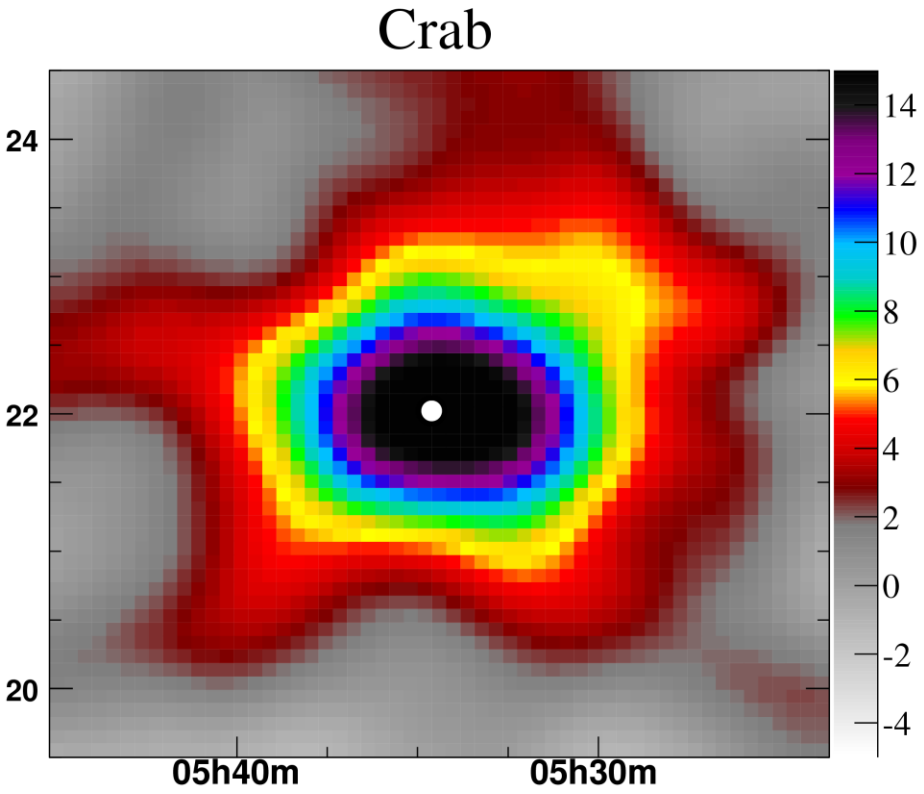
- ***Recent Results:***
  - **Survey of Galactic plane (longitude $\in$ [30º, 200º], latitude $\in$ [-10º, 10º]) at a median energy of ~ 20 TeV:**
  - **Search for diffuse gamma ray emission:**
    - **Arises from the interaction of cosmic ray particles with matter and radiation in the Galaxy and potentially and may provide clues on the origin of Galactic cosmic rays.**
  - **Comparison of Milagro skymap with Fermi Bright Source List:**
    - **What type of sources produces TeV gamma rays?**

Milagro Survey of the Galactic Plane



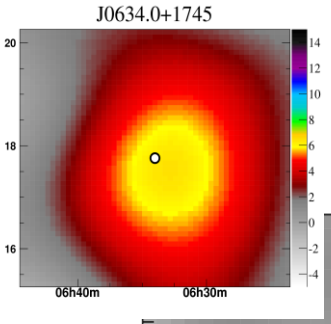
The Crab

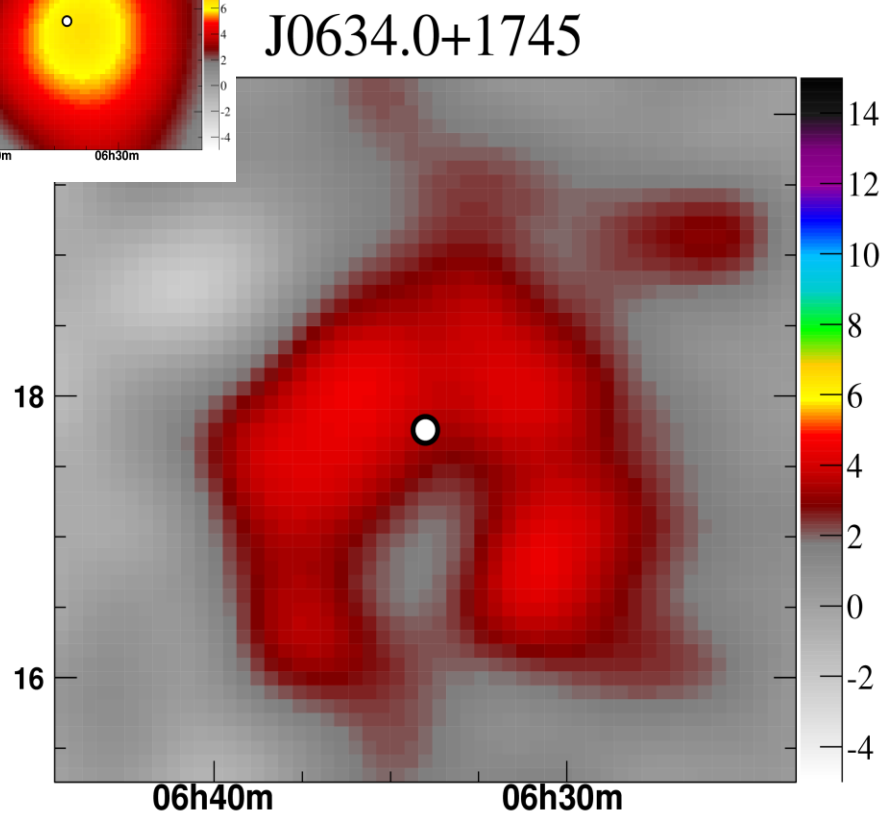
- ***Crab:***
  - **Standard candle in TeV astronomy. TeV emission discovered by the Whipple Air Cherenkov Telescope.**
  - **Young pulsar, resulting from supernova in 1054 AD.**
  - **Pulsed emission at lower energies. Steady at TeV.**
  - **17.2σ at pulsar location.**
  - **A calibration source for Milagro and HAWC.**



Geminga

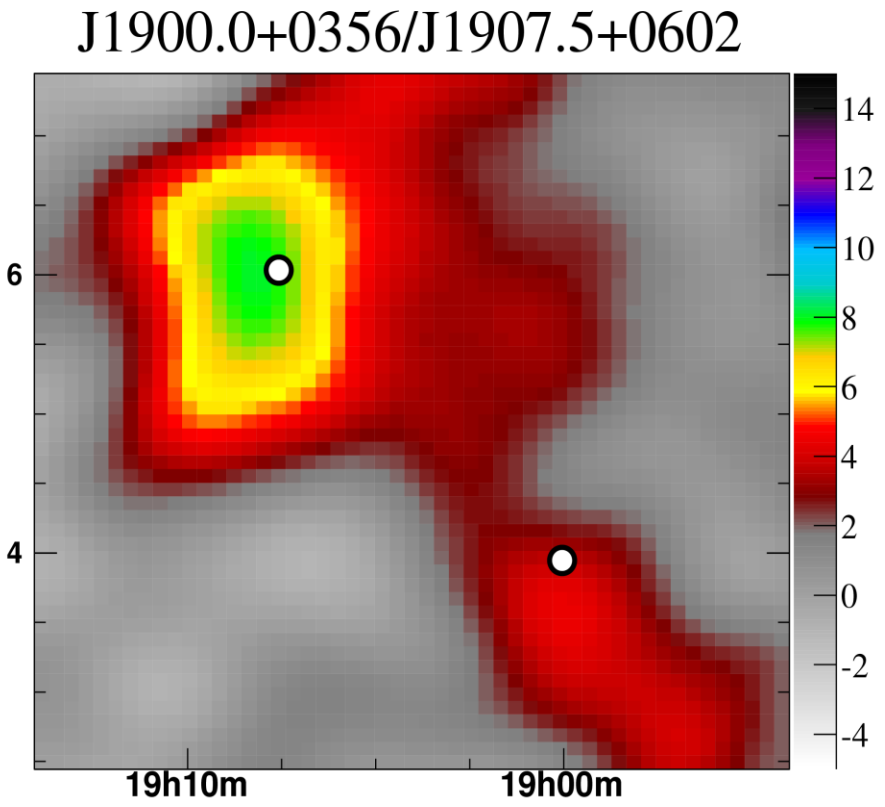
- *Geminga:*
  - Associated with Fermi pulsar 0FGL J0634.0+745, the Geminga pulsar.
  - 3.5σ at the location of Geminga.
  - 6.3σ when assuming a 1° extended source.
  - Fitted 1.1º extent, consistent with air Cherenkov telescope observations of more distant Pulsar Wind Nebula.





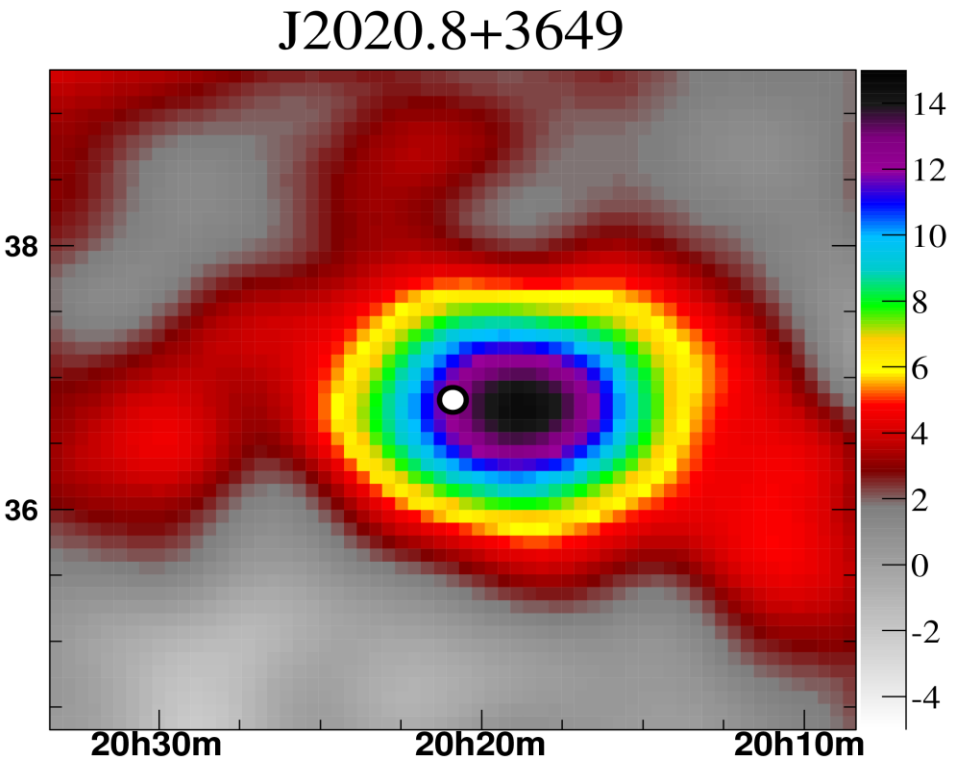
MGRO J1908+06

- ***MGRO J1908+06:***
  - **Associated with Fermi 0FGL J2020.8+3649, a new pulsar discovered by Fermi-LAT.**
  - **7.4σ at Fermi pulsar location, 8.1σ at local maximum.**
  - **Verified by HESS and Veritas.**
  - **Identified as a young pulsar by AGILE.**
  - **Extended by 0.21° in HESS data.**



MGRO J2019+37

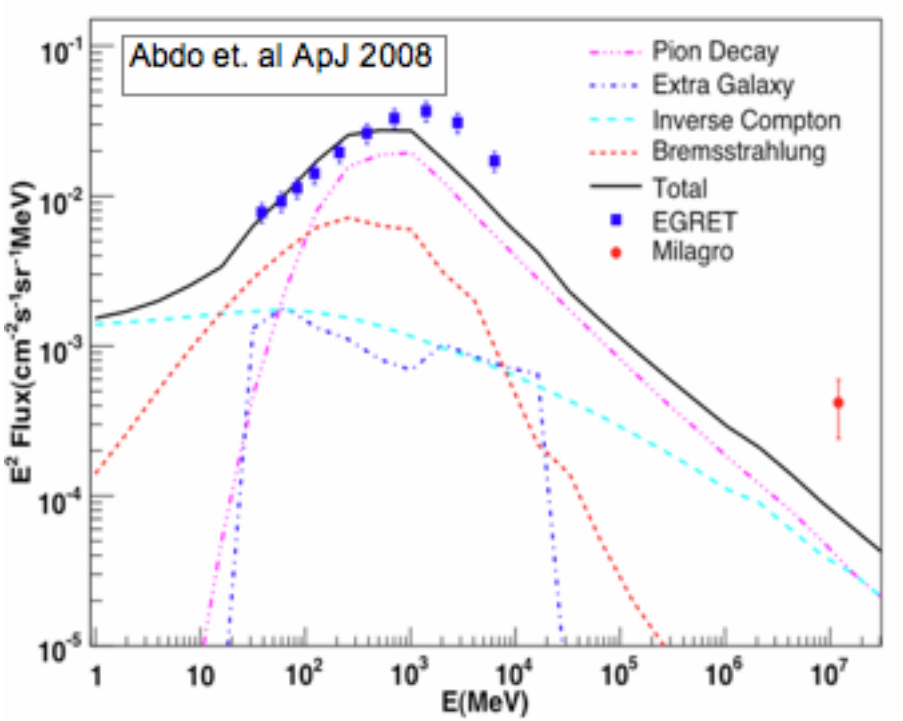
- ***MGRO J2019+37:***
  - **In the Cygnus region of the Galaxy.**
  - **Near Fermi source 0FGL J2020.8+3649.**
  - **Most significant Milagro source after the Crab (12.4σ at peak).**
  - **Identified as a young pulsar by AGILE.**
  - **Milagro peak is separated from pulsar by 0.3° with a 1σ error of 0.1°.**



Diffuse TeV Excess

- *Study of the Cygnus region:*
  - **Even after excluding MGRO J2019+37, the TeV gamma ray flux from the Cygnus region exceeds that predicted from models of cosmic ray production and propagation.**
  - **Flux is 8 times higher than conventional GALPROP predictions.**

- **Excess could be due to unresolved gamma ray sources or hard-spectrum cosmic ray or electron accelerators.**

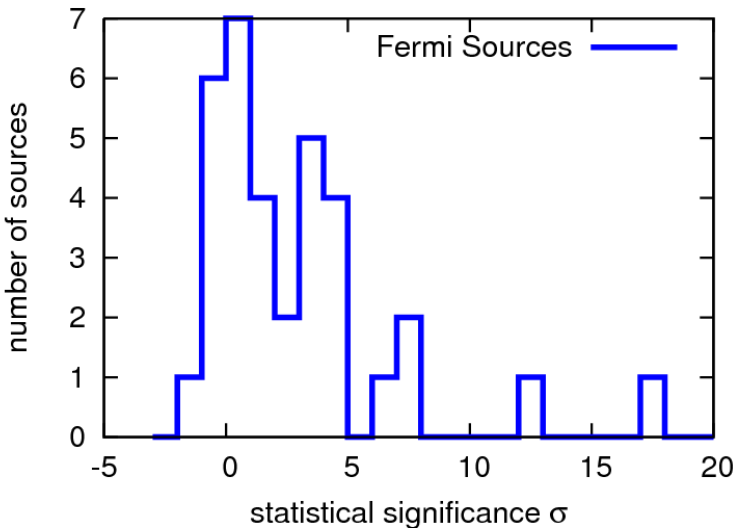


Fermi-LAT Bright Source List

- **A better understanding of Milagro Galactic TeV sources comes from a study of the Fermi Bright Source List.**

- **34 out of 205 Fermi BSL objects are possibly Galactic and in Milagro's field of view:**
  - **16 pulsars, 1 X-ray binary, 5 SNRs, 12 unknown.**

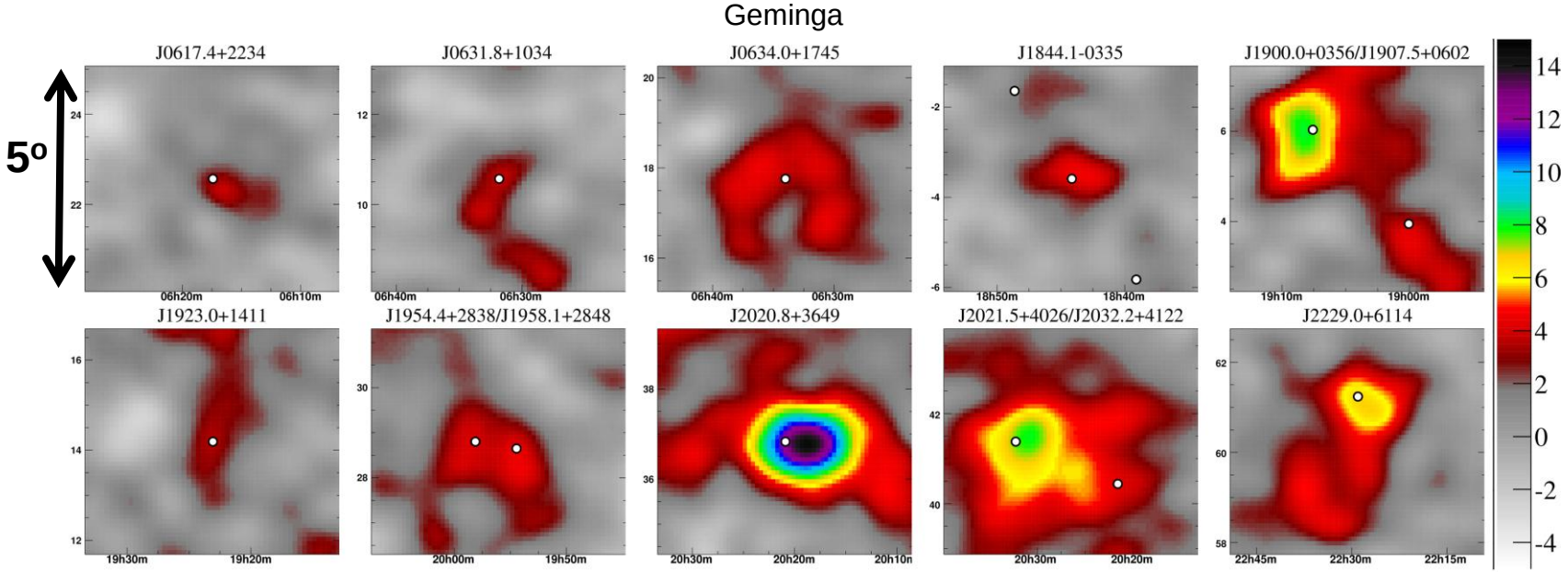
- ***Results of search in full Milagro data set:***
  - **14/34 are observed at 3σ or more in Milagro data.**
  - **Probability of a single 3σ detection in 34 trials is only 4%.**
  - **6/14 have been reported by Milagro before.**
  - **9/14 are pulsars (all 6 previous Milagro sources are now associated with pulsars).**
  - **3/14 are SNRs.**



Associations with Fermi Bright Source List

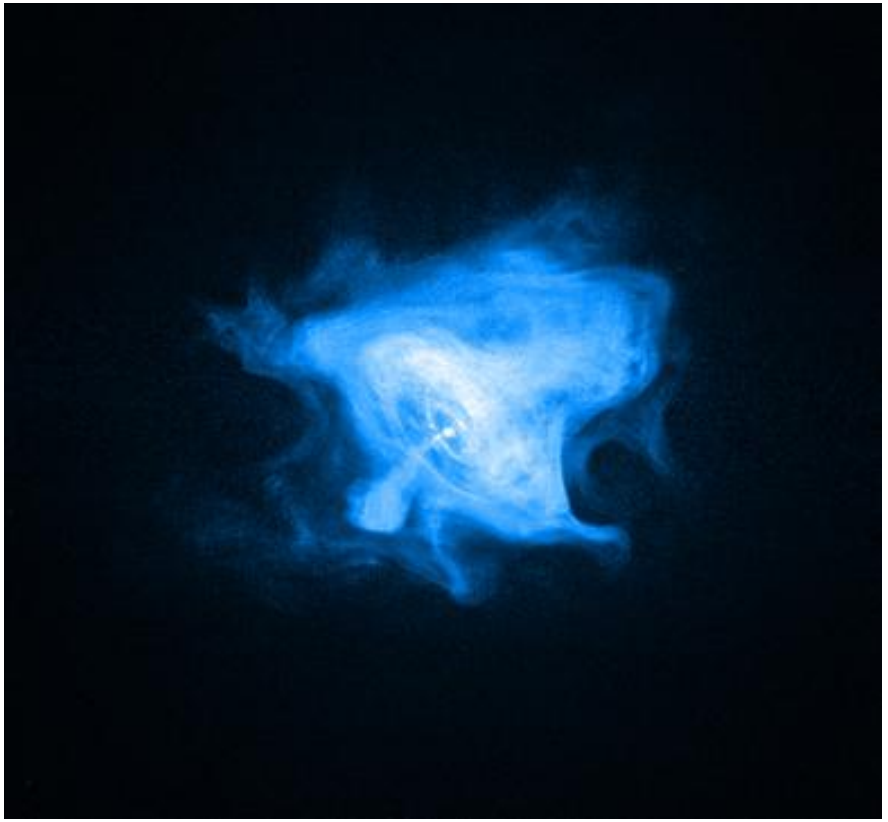
- **All high-significance sources are identified with Fermi pulsars. 'Most' of the low-significance sources are true TeV detections, but cannot be claimed individually.**

- **Strong evidence for multi-TeV emission associated with Galactic LAT BSL sources "as a class."**



Pulsar Wind Nebula

- ***Emerging picture:***
  - **The typical Galactic multi-TeV source is a Pulsar Wind Nebula (PWN) associated with an MeV to GeV pulsar.**
  - **‘Wind’ driven by electrons from the central pulsar.**
  - **Shocks where 'wind' meets ISM give additional electron acceleration.**
  - **Gamma-rays are from electron inverse-Compton of local photons.**



Chandra X-ray image of the Crab

The Next Step: HAWC

- **Lesson from analysis of Fermi BSL with Milagro: there are potentially many TeV gamma ray sources right below the Milagro detection threshold.**

- **The water Cherenkov technique is working, but we need a detector that is more sensitive than Milagro. Possible ways to improve sensitivity:**
  - **Move to higher altitude to decrease the energy threshold.**
  - **Improve optical isolation.**
  - **Increase detector area.**

High
Altitude
Water
Cherenkov

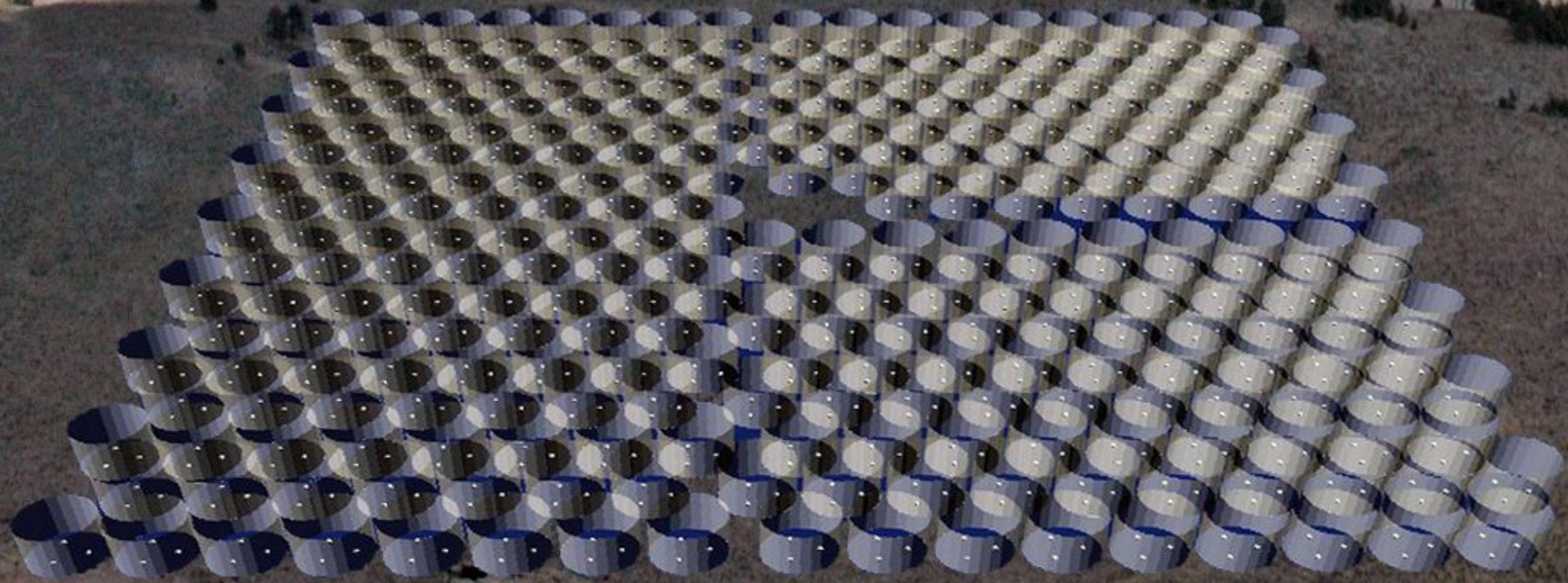
The HAWC Detector

- 4100 meter site at Sierra Negra, Mexico (~19º N), near the Large Millimeter Telescope.
- Recycled Milagro photomultipliers and electronics.
- 160m × 160m area.
- 300 water tanks:
  - 7.3m diameter.
  - 4.0m water above photomultipliers.
  - 3 upward-facing 8'' photomultipliers on the bottom of each tank.

- Overall 15 × sensitivity improvement over Milagro.
- HAWC can detect sources 225 × faster ⇒ 1 Crab per day.

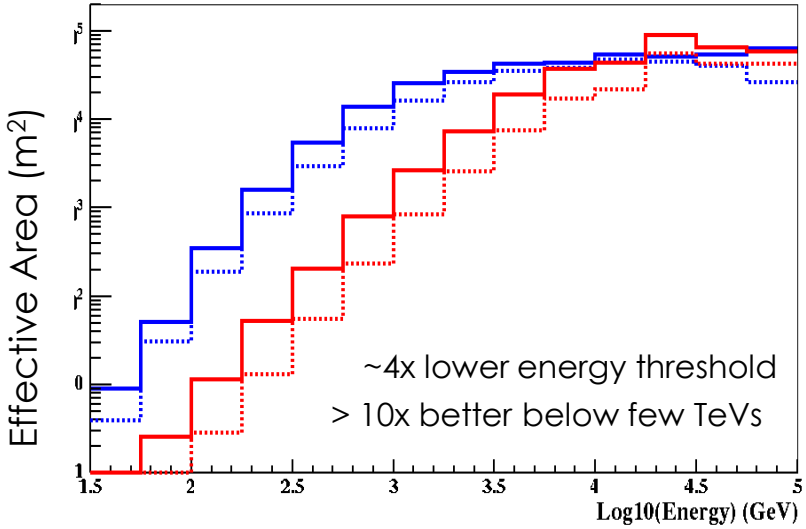
HAWC Design

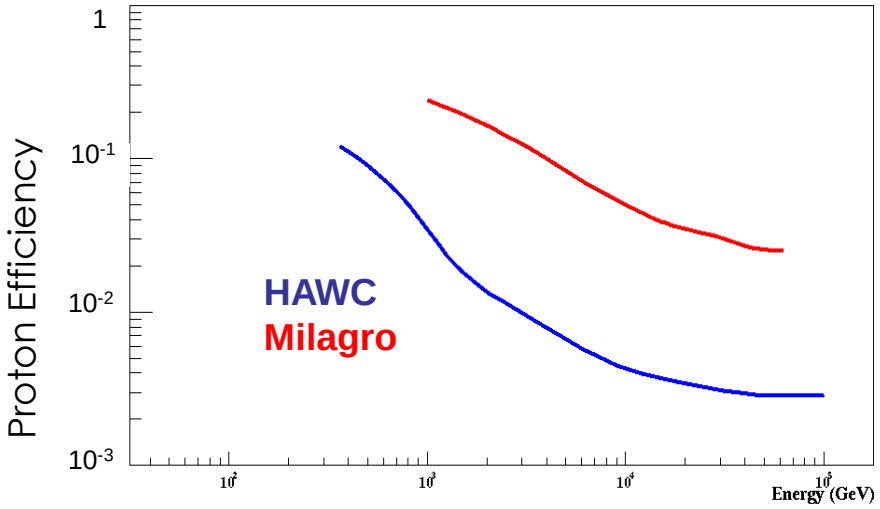
300 - 7.2m diameter steel tanks with 3 PMTs

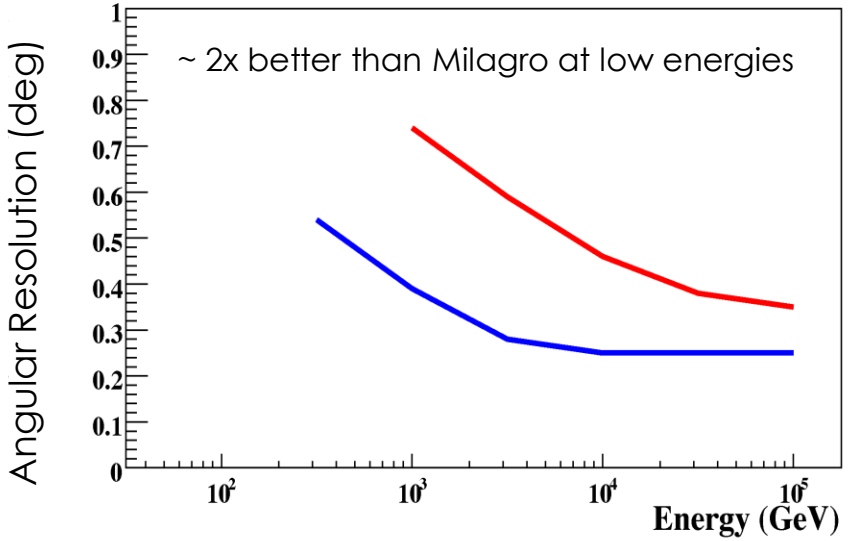


HAWC versus Milagro

- **Increased altitude gives increased effective area at 50 - 100 GeV and better angular resolution.**
- **Large muon-sensitive area improves gamma/hadron discrimination.**

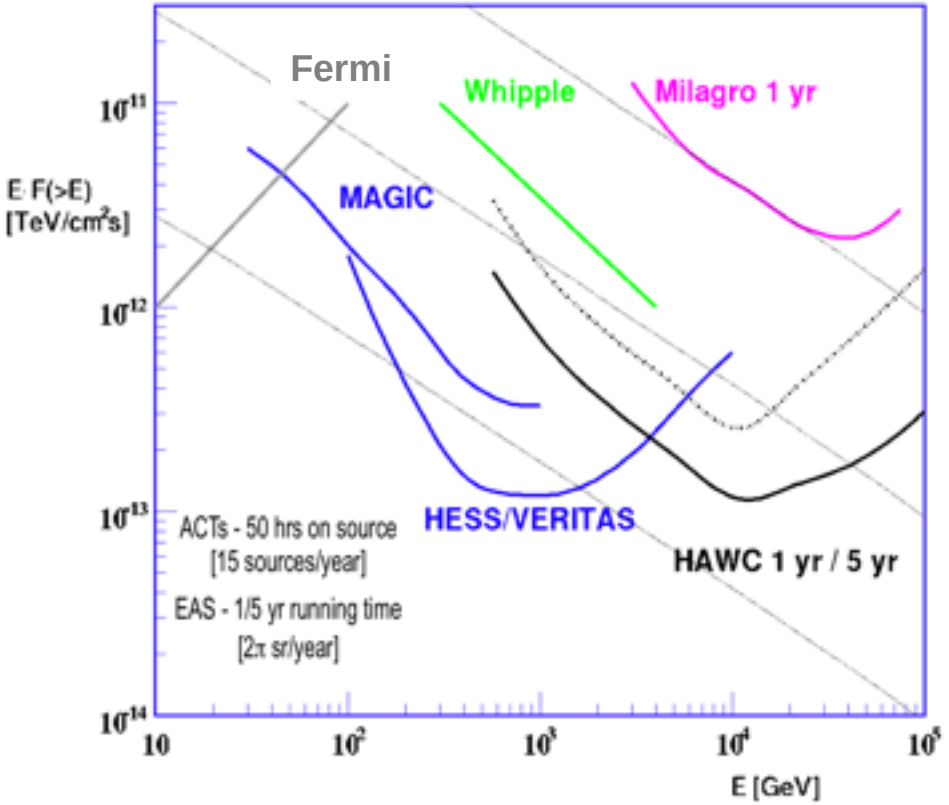






HAWC Science

- **Goal: get started quickly to have maximum time overlap with Fermi.**
- ***Studies:***
  - **Galactic sources up to 100 TeV.**
  - **Extended sources and Galactic plane.**
  - **Continuous operation allows search for transients (AGN flares, GRBs).**
  - **Study of cosmic ray anisotropy.**
  - **Unbiased sky survey allows for discovery potential.**




July 2010
HAWC30 mid-2011

The HAWC Collaboration

University of Maryland
Jordan Goodman, Andrew Smith, Greg Sullivan

Los Alamos National Laboratory
Gus Sinnis, Brenda Dingus, John Pretz

University of Utah
Dave Kieda, Wayne Springer

Univ. of California, Irvine
Gaurang Yodh

Michigan State University
Jim Linnemann, Kirsten Tollefson

George Mason University
Robert Ellsworth

University of New Hampshire
James Ryan

Pennsylvania State University
Tyce DeYoung, Patrick Toale, Kathryne Sparks

University of New Mexico
John Matthews, William Miller

Michigan Technological University
Petra Hüntemeyer, Brian Fick

NASA/Goddard Space Flight Center
Julie McEnery, Vlasios Vasileiou

Georgia Institute of Technology
Ignacio Taboada, Andreas Tepe

University of Wisconsin-Madison
Teresa Montaruli, Stefan Westerhoff, Segev BenZvi, Juan A. Aguilar

Harvey Mudd College
Richard Haskill, Ann Esin, Pat Little and Greg Lyzenga

Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
Alberto Carramiñana, Eduardo Mendoza, Luis Carrasco, William Wall, Daniel Rosa, Guillermo Tenorio Tagle, Sergey Silich

Universidad Nacional Autónoma de México (UNAM), Instituto de Astronomía:
Octavio Valenzuela, Vladimir Avila-Reese, Marco Martos, Maria Magdalena Gonzalez, Sergio Mendoza, Dany Page, William Lee, Hector Hernández, Deborah Dultzin, Erika Benitez

Universidad Nacional Autónoma de México (UNAM), Instituto de Física
Arturo Menchaca, Rubén Alfaro, Varlen Grabski, Andres Sandoval, Ernesto Belmont. Arnulfo Matinez-Davalos

Universidad Nacional Autónoma de México (UNAM), Instituto de Ciencias Nucleares
Lukas Nellen, G. Medina-Tanco, Juan Carlos D'Olivo

Universidad Nacional Autónoma de México (UNAM), Instituto de Geofísica
José Valdés Galicia, Alejandro Lara, Rogelio Caballero

Benemérita Universidad Autónoma de Puebla
Humberto Salazar, Arturo Fernández, Caupatitzio Ramirez, Oscar Martínez, Eduardo Moreno, Lorenzo Diaz, Alfonso Rosado

Universidad Autónoma de Chiapas
Cesar Álvarez, Eli Santos Rodriguez, Omar Pedraza

Universidad de Guadalajara
Eduardo de la Fuente

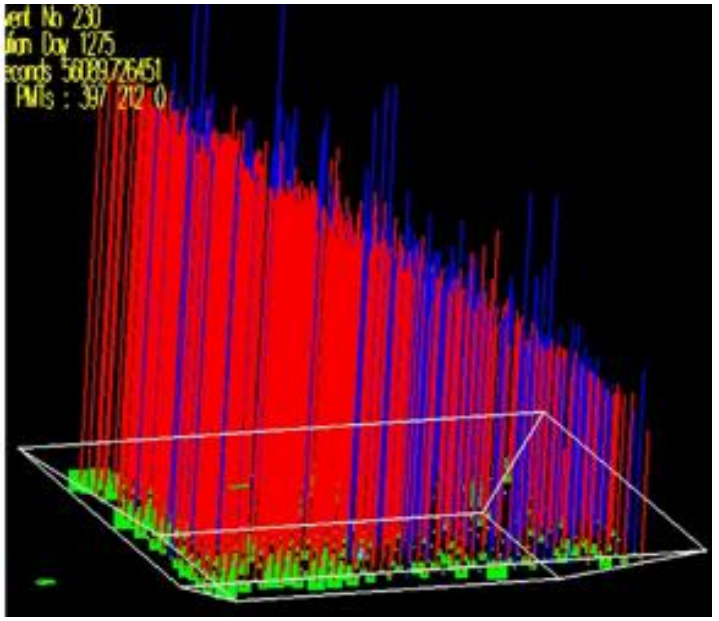
Universidad Michoacana de San Nicolás de Hidalgo
Luis Villaseñor, Umberto Cotti, Ibrahim Torres, Juan Carlos Arteaga Velazquez

Centro de Investigación y de Estudios Avanzados
Arnulfo Zepeda

Universidad de Guanajuato
David Delepine, Gerardo Moreno, Edgar Casimiro Linares, Marco Reyes, Luis Ureña, Mauro Napsuciale, Victor Migenes

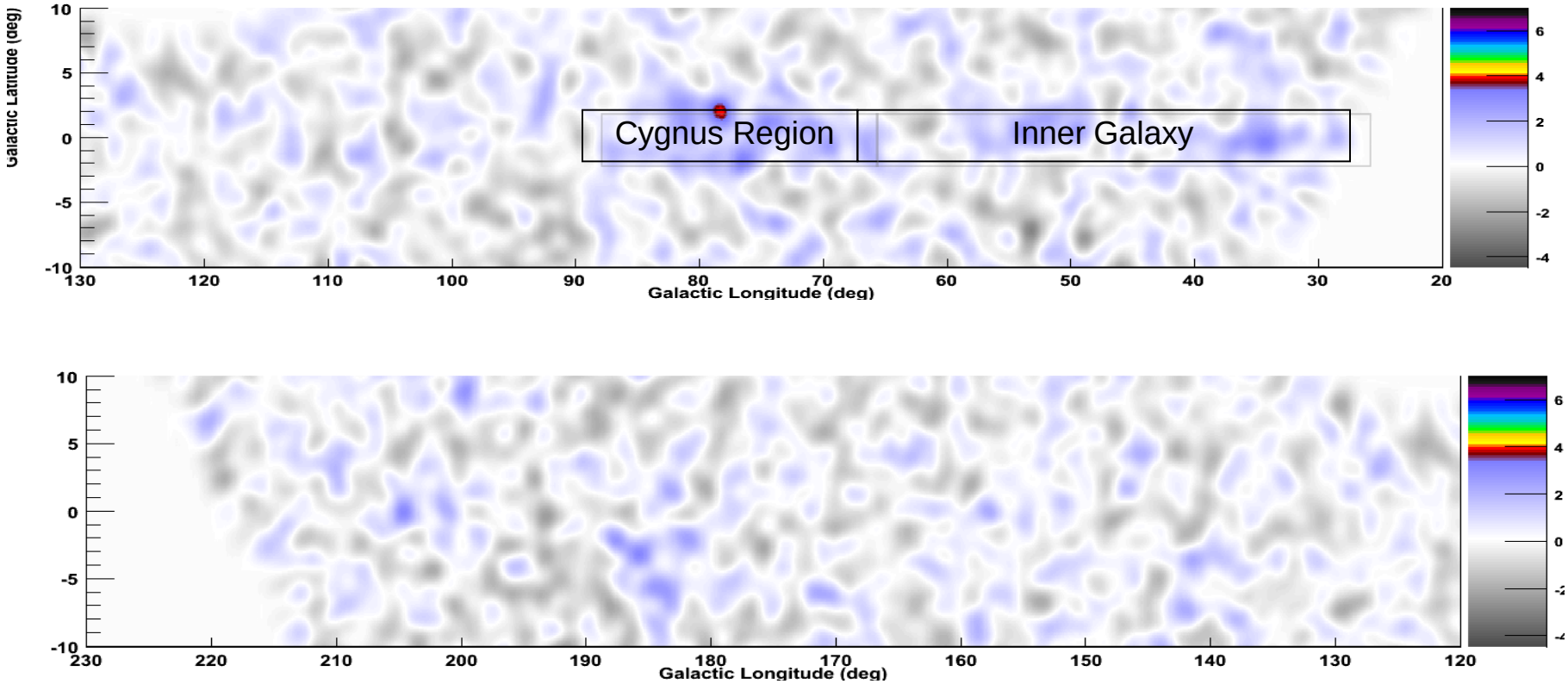
Backup Slides

The Milagro Detector



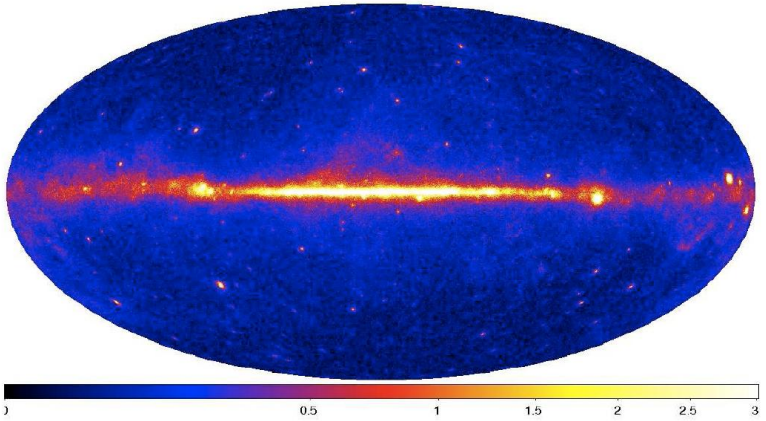
- 1700 Hz trigger rate.
- 0.4 º– 1.0° angular resolution.
- Energy range 100 GeV – 100 TeV, median energy 10 – 40 TeV (depending on cuts, weights etc).
- Outriggers:
  - 2.4 meter diameter.
  - 1.4 meter tall.
  - 175 PMTs in outrigger tanks.

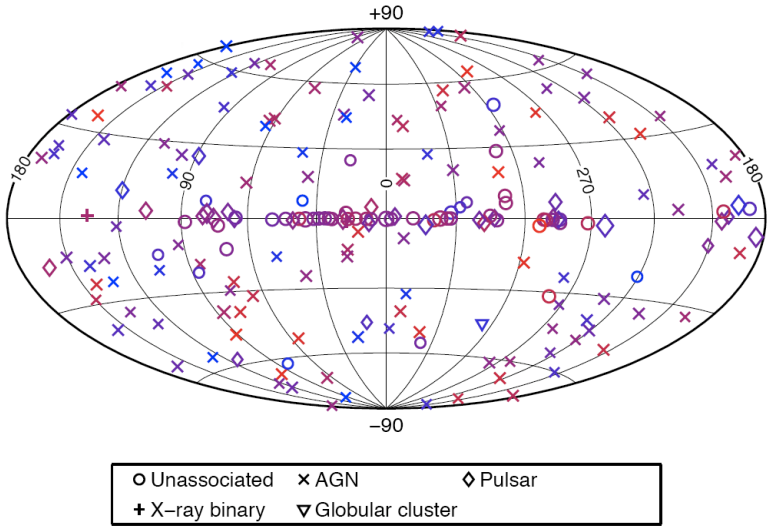
TeV Diffuse Emission from the Galactic Plane



Fermi-LAT
Bright Source List

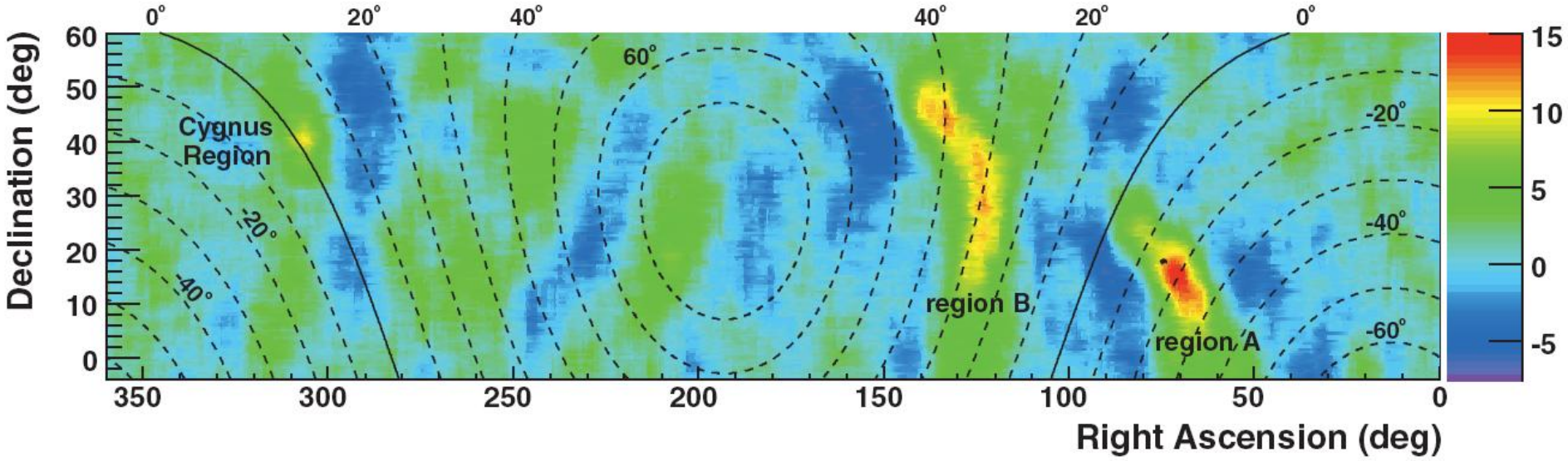
- **Sensitivity from 100 MeV to hundreds of GeV.**
- **205 sources > 10σ in 3 months of data.**
- **Blazars, pulsars identified by their variability. Several new pulsars (pulsations discovered in the GeV first).**
- **Deeper survey than entire EGRET dataset.**
- **Angular resolution < 0.1° at the higher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





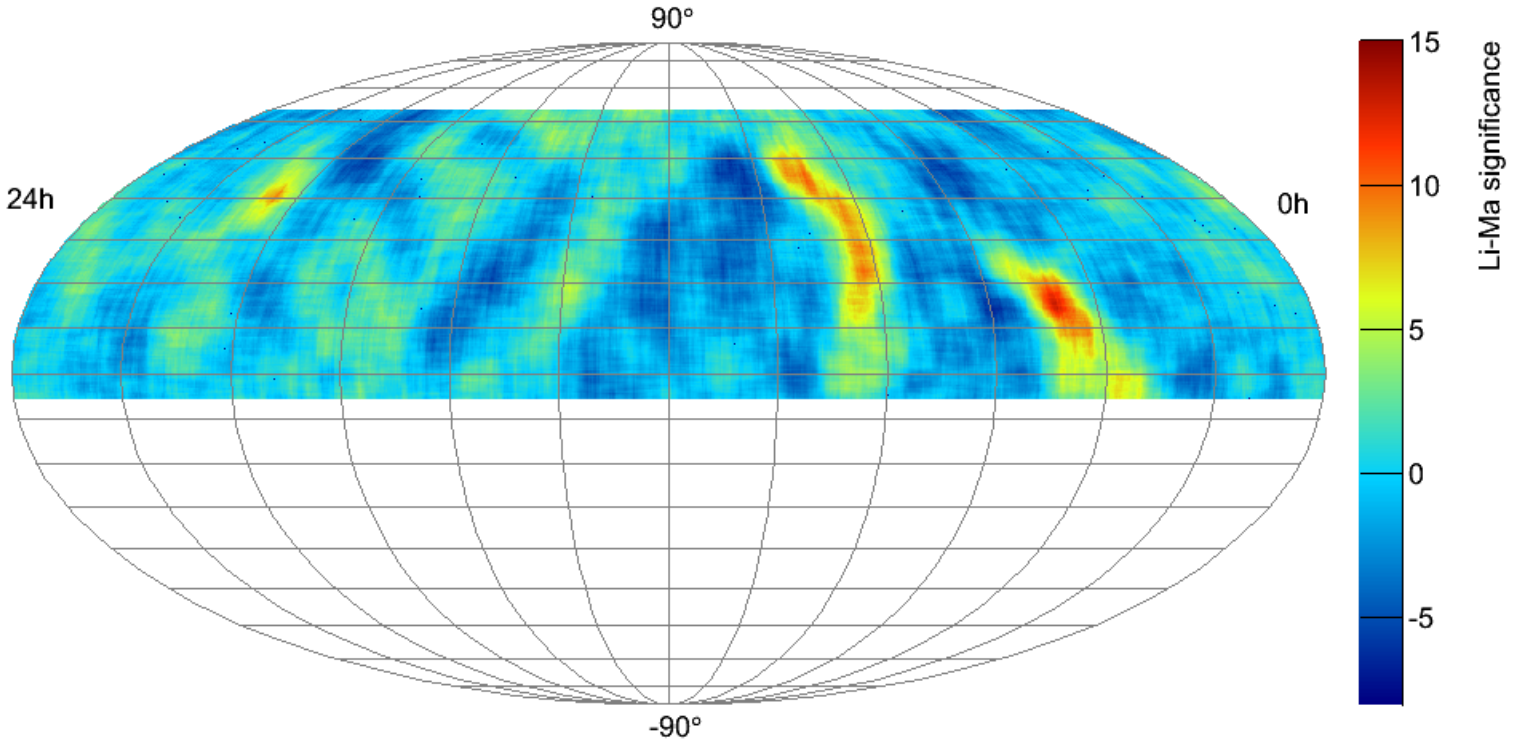
Milagro Cosmic Ray Observations

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

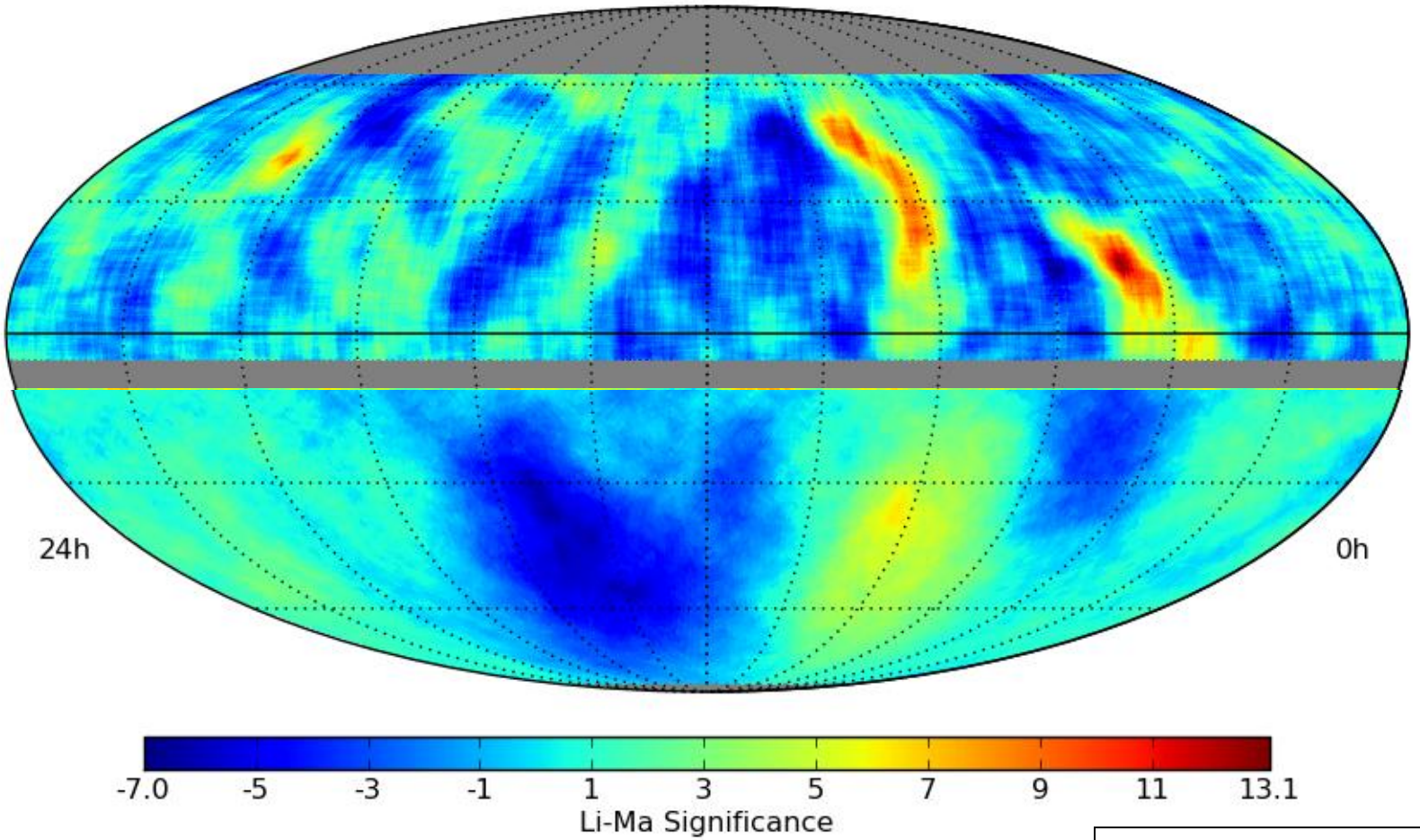


Milagro Cosmic Ray Observations

- **Milagro also observes two localized regions with flux excess of significance > 10 σ in the total data set of 2.2×10^{11} events recorded over 7 years. The "hot" regions have fractional excesses of order several times 10^{-4} relative to the background.**

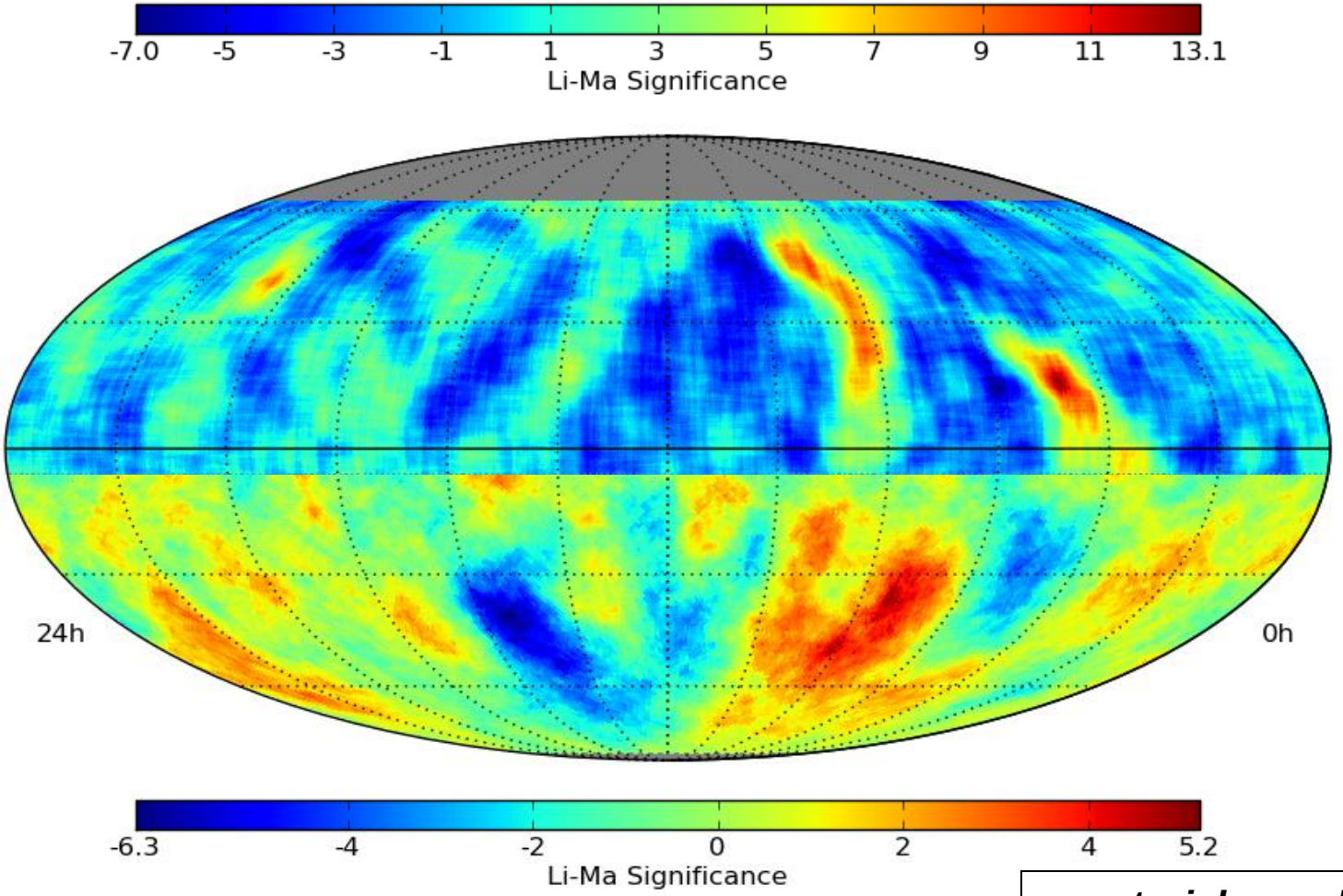


IceCube and Milagro



equatorial coordinates

IceCube and Milagro



equatorial coordinates