

# Detection of TeV Gamma-Rays from Extended Sources with Milagro

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The Milagro gamma-ray observatory employs a water Cherenkov detector to observe extensive air showers produced by high-energy particles impacting in the Earth's atmosphere. A 4800 m<sup>2</sup> pond instrumented with 723 8" PMTs detects Cherenkov light produced by secondary air-shower particles. An array of 175 4000 liter water tanks surrounding the central pond detector was recently added, extending the physical area of the Milagro observatory to 40,000 m<sup>2</sup> and substantially increasing the sensitivity of the detector. Because of its wide field of view and high duty cycle, Milagro is ideal for monitoring the northern sky almost continuously (>90% duty cycle) in the 100 GeV to 100 TeV energy range. Here we discuss the first detection of TeV gamma-rays from the inner Galactic plane region. We also report the detection of an extended TeV source coincident with the EGRET source 3EG J0520+2556, as well as the observation of extended TeV emission from the Cygnus region of the Galactic plane.

## 1. THE MILAGRO OBSERVATORY

Milagro is a TeV gamma-ray detector which uses the water Cherenkov technique to detect extensive air-showers produced by very high energy (VHE, > 100 GeV) gamma rays as they interact with the Earth's atmosphere. Milagro is located in the Jemez Mountains of northern New Mexico, at an altitude of 2630 m, has a field of view of  $\sim 2$  sr and a duty cycle greater than 90%. The effective area of Milagro is a function of zenith angle and ranges from  $\sim 10$  m<sup>2</sup> at 100 GeV to  $\sim 10^5$  m<sup>2</sup> at 10 TeV. A sparse array of 175 4000 liter water tanks, each containing an individual PMT, was recently added. These additional detectors, known as "outriggers" (Figure 1), extend the physical area of Milagro to 40,000 m<sup>2</sup>, substantially increasing the sensitivity of the instrument and lowering the energy threshold. The angular resolution is approximately 0.75 degrees without the outriggers and 0.45 degrees with them.

## 2. THE ALL-SKY SEARCH

A full survey of the northern hemisphere (declination of 1.1–80°) for point sources was carried out [Atkins et al. 2004]. Figure 2 shows the map of the northern hemisphere in TeV gamma rays for the Milagro data set between 15 December 2000 and 25 November 2003. Table I lists all point sources with



Figure 1: One of 175 outriggers (recently added to Milagro).

an excess greater than  $4\sigma$ . The last column represents the 95% confidence upper limit on the flux, in units of the Crab. The Crab and Mkn 421 are both clearly visible in the map, and are listed in the sixth and seventh row, respectively, of Table I. A square bin of 2.1° in declination ( $\delta$ ) and  $[2.1/\cos(\delta)]^\circ$  in right ascension was used in this analysis. To detect other possible sources of VHE emission it is necessary to survey the sky at many different timescales and at many different bin sizes. In addition to searching for steady point sources of TeV gamma rays, Milagro has searched for short bursts of TeV gamma rays [Atkins et al. 2004], for TeV emission from the direction of satellite detected GRBs [Saz Parkinson et al. 2004], and for extended sources of TeV emission [Smith et al. 2004], as we summarize in this paper.

## 3. THE GALACTIC PLANE

Diffuse emission from the Galactic plane is the dominant source in the gamma-ray sky [Hunter et al.

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\*R. Atkins, W. Benbow, D. Berley, E. Blaufuss, D. G. Coyne, T. DeYoung, B. L. Dingus, D. E. Dorfan, R. W. Ellsworth, L. Fleysher, R. Fleysher, M. M. Gonzalez, J. A. Goodman, T. J. Haines, E. Hays, C. M. Hoffman, L. A. Kelley, C. P. Lansdell, J. T. Linnemann, J. E. McEnery, A. I. Minner, M. F. Morales, P. Nemethy, D. Noyes, J. M. Ryan, F. W. Samuelson, P. M. Saz Parkinson, A. Shoup, G. Sinis, A. J. Smith, G. W. Sullivan, D. A. Williams, M. E. Wilson, X. W. Xu and G. B. Yodh

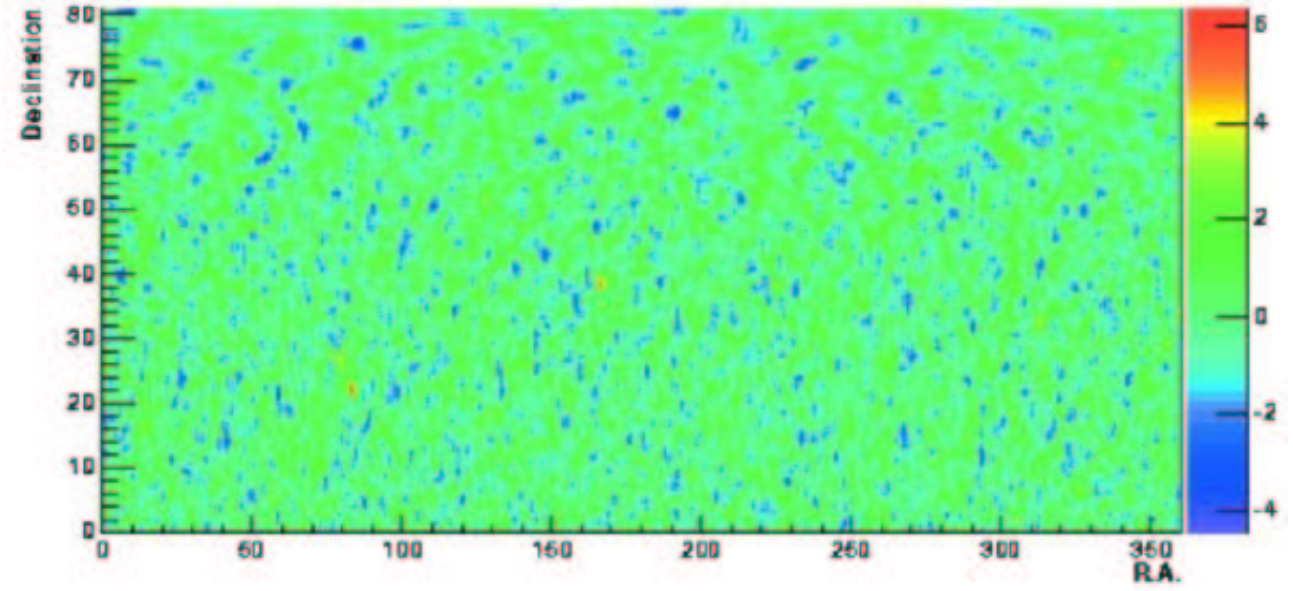


Figure 2: Northern hemisphere as seen in TeV gamma rays. At each point, the excess is summed over a  $2.1$  by  $[2.1/\cos(\delta)]^\circ$  bin, and the significance of the excess in standard deviations is shown by the color scale (Figure from Atkins et al. [2004]).

Table I Locations of All Regions with an Excess Greater than  $4\sigma$

R.A.	Decl.	ON	OFF	Excess	$\sigma$	UL
0.3	34.3	3.12308e+06	3.11456e+06	8623	4.7	0.84
37.8	6.7	7.02166e+05	6.98667e+05	3498	4.0	1.8
43.6	4.8	5.85952e+05	5.82716e+05	3236	4.1	2.0
49.1	22.5	2.21431e+06	2.20813e+06	6175	4.0	0.87
79.9	26.8	2.57841e+06	2.57025e+06	8161	4.9	0.97
83.6	22.0	2.17188e+06	2.16222e+06	9665	6.3	NA
166.5	38.6	3.23552e+06	3.22467e+06	10850	5.8	NA
306.6	38.9	3.25329e+06	3.24531e+06	7983	4.2	0.78
313.0	32.2	3.08380e+06	3.07548e+06	8320	4.5	0.85
339.1	72.5	6.63534e+05	6.59727e+05	3807	4.2	3.02
356.4	29.5	2.98656e+06	2.97910e+06	7455	4.1	0.84

1997]. Most of the diffuse VHE emission from the Galactic plane is thought to be produced by the interaction of cosmic-ray hadrons with the interstellar matter. The flux measured by EGRET below 1 GeV fits models well, but that measured between 1 and 40 GeV is significantly larger than what is predicted by most models. One possible explanation for this enhanced emission is the inverse-Compton scattering of cosmic-ray electrons [Porter & Protheroe 1997]. If this turns out to be the dominant source of diffuse gamma-ray emission from the Galactic plane, then the flux at TeV energies could be an order of magnitude higher than previously thought. Figure 3 shows the

EGRET observations of the Galactic plane. The top panel shows the all-sky map, in Galactic coordinates, produced by EGRET, clearly showing the Galactic plane. The bottom panel shows the EGRET diffuse GeV flux (in black) along with the Milagro exposure (in red), indicating that the Milagro observation region is optimized for the detection of the diffuse emission predicted by the EGRET measurements. Using 36 months of data, from 19 July 2000 to 18 July 2003, we looked at the inner (40-100 degrees) and outer (140-220 degrees) regions of the Galaxy [Fleysher et al. 2004]. While the outer Galaxy shows no significant excess, the inner Galaxy shows a 5 sigma excess [Fleysher et al. 2004]. Figure 4 shows the profile in latitude for the longitude band (40 to 100 degrees) of the inner Galactic region (left panel) and the profile in longitude for the latitude band (-5 to 5 degrees) of the inner Galactic region (right panel), where the enhancement can be seen just north of the equator. Figure 5 shows the significance map of the Galaxy. The region of the inner Galaxy shows an enhancement along and just north of the Galactic equator. This is the same region where EGRET detected the strongest signal in the 100 MeV energy range. The 5 sigma excess is seen by summing the entire inner Galaxy with a  $\pm 5$  degree latitude band, as was suggested by the EGRET results. We note that the Milagro observation of the Galactic plane remains significant even when the region around the Cygnus Arm is excluded. This constitutes the first detection of the Galactic plane at TeV energies.

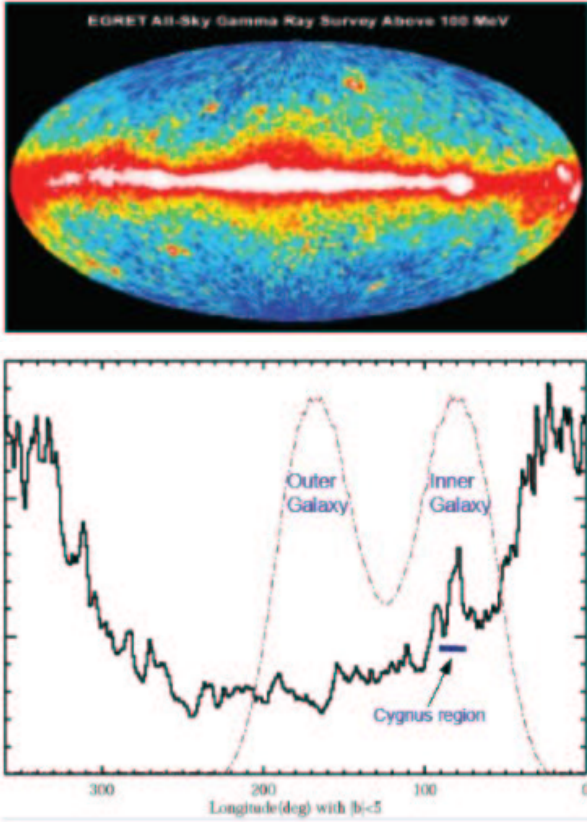


Figure 3: **Top** – EGRET all-sky map showing Galactic plane emission above 100 MeV. **Bottom** – EGRET diffuse GeV flux (in black) along with the Milagro exposure (in red).

## 4. EXTENDED SOURCES

A search for extended emission was carried out for the Milagro data collected between 17 August 2000 and 5 May 2004 [Smith et al. 2004]. A set of standard cuts has been developed by the Milagro collaboration and validated by observations of the Crab [Atkins et al. 2003] and Mkn 421 [Atkins et al. 2004]. Events with 20 or more PMT hits used by the angle fitter ( $N_{FIT} \geq 20$ ) are kept (this rejects about 20% of events which have poor fits). In addition, we cut on a parameter known as “compactness” [Atkins et al. 2004] ( $X_2 \geq 2.5$ ) to retain 50% of the gammas while removing more than 90% of the background protons. The excess at each position is determined by counting the number of events in a particular bin and subtracting the estimated background. The background is computed from data collected at the same local detector coordinates, but at a different time, ensuring the celestial angles of the background event sample do not overlap with the source position under consideration. The method of Li & Ma [1983] is used to compute the significance of each excess. While the optimal

square bin for detection of point sources with Milagro is 2.1 degrees on each side [Atkins et al. 2004], to look for diffuse sources, the standard Milagro sky maps were searched using a range of bin sizes from 2.1 to 5.9 degrees in steps of 0.2. 20 separate searches were performed on the same maps, though the results are highly correlated. Monte Carlo simulations were used to compute the post-trials probability for each source candidate.

### 4.1. 3EG J0520+2556

The most significant candidate found in our search of extended sources had a pre-trials significance of 5.9 sigma, located at RA=79.8 degrees and Dec=26.0 degrees and was identified using a 2.9 degree bin size. The probability of observing an excess this significant at any point in the sky at any bin size is 0.8%. Figure 6 (left panel) shows the map of significances around the source, which is located  $\sim 5.5$  degrees from the Crab. This candidate was first reported in 2002 [Sinnis et al. 2002]. The cumulative significance using only data since it was first reported is  $3.7\sigma$ . The right panel of Figure 6 shows the accumulation of significance with time, indicating that the excess increases at a constant rate and shows no periods of significant flaring. This candidate is coincident with the EGRET unidentified source 3EG J0520+2556 (See Figure 7).

### 4.2. The Cygnus Arm

The second extended source candidate is coincident with the region known as the Cygnus Arm, a spiral arm within our Galaxy that extends radially away from observers on Earth. This region is known to be a dense region of gas and dust and was observed by EGRET as the brightest source of GeV gamma rays in the northern sky, with a diffuse GeV emission comparable to the Galactic bulge. Like the emission from the Galactic plane region, VHE emission from the Cygnus Arm is thought to originate mainly from interactions of cosmic rays with the interstellar gas and dust. A 5.5 sigma excess was detected using a 5.9 degree bin, at RA=308 degrees and Dec=42 degrees. The probability of observing an excess this significant at any point in the sky at any bin size is 2.0%. Figure 8 shows the significance of the region of the sky containing the Cygnus arm, showing also the Galactic plane from  $l=20$  degrees to  $l=100$  degrees and  $b=\pm 5$  degrees superimposed on the plot. The excess observed by Milagro is inconsistent with a point source and the number of events coming from the entire  $5.9^\circ$  bin is approximately twice that of the Crab. Like in the case of 3EG J0520+2556, the accumulation of the excess is steady, and no evidence for flaring is observed. While this is an extremely bright region, making it



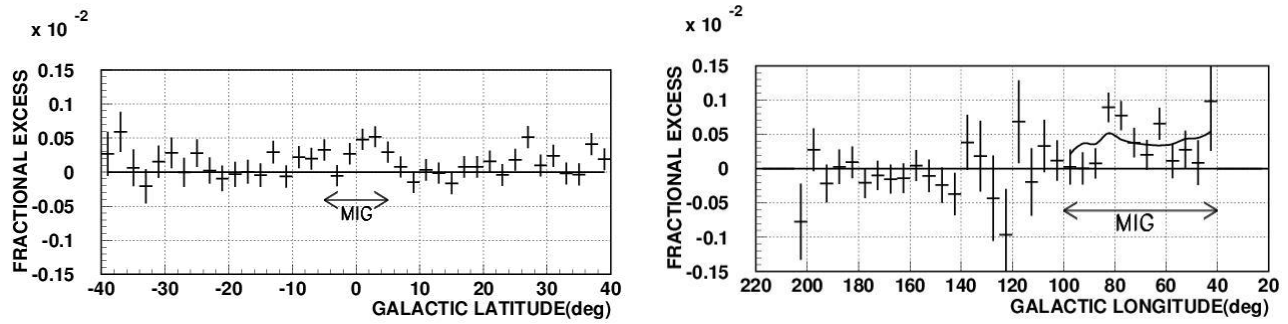


Figure 4: **Left** – Profile of the fractional excess as a function of Galactic latitude ( for a Galactic longitude between 40 and 100 degrees). **Right** – Profile of the fractional excess as a function of Galactic longitude (for a Galactic latitude between -5 and 5 degrees). The EGRET longitudinal source shape is superposed. (Figures from Atkins et al. [2005])

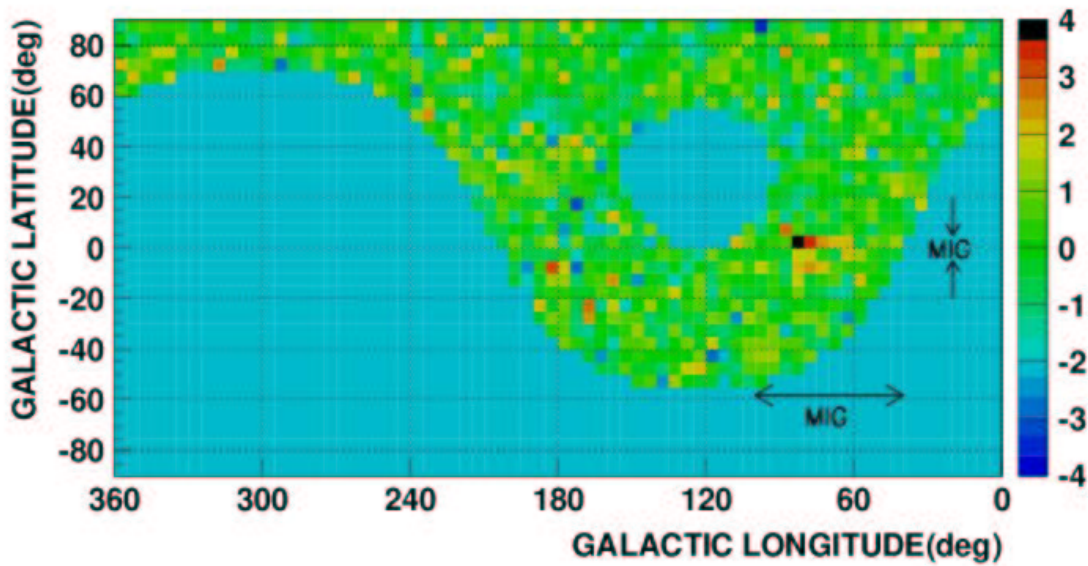


Figure 5: Map in Galactic coordinates of Milagro significances in  $5^\circ$  by  $5^\circ$  bins. The light area has no Milagro exposure (Figure from Atkins et al. [2005]).

the hottest spot in the Galactic plane, it is not surprising that it has not been detected yet by any of the Atmospheric Cerenkov Telescopes, given the diffuse nature of the source, and the limited field of view of such telescopes.

## 5. CONCLUSION

Milagro has detected three previously unknown diffuse sources of TeV gamma rays. Milagro has reported the first observation of diffuse TeV emission from the Galactic plane. In addition to this, two other diffuse sources have been detected. The first, coincident with 3EG J0520+2556, and the second coincident with the Cygnus Arm, at 5.9 and 5.5 sigma respectively. When all trials of the all-sky search are con-

sidered, the probabilities of these excesses being due to background fluctuations are 0.8% and 2.0% respectively. The source coincident with 3EG J0520+2556 was previously reported by Milagro as a “hot spot”.

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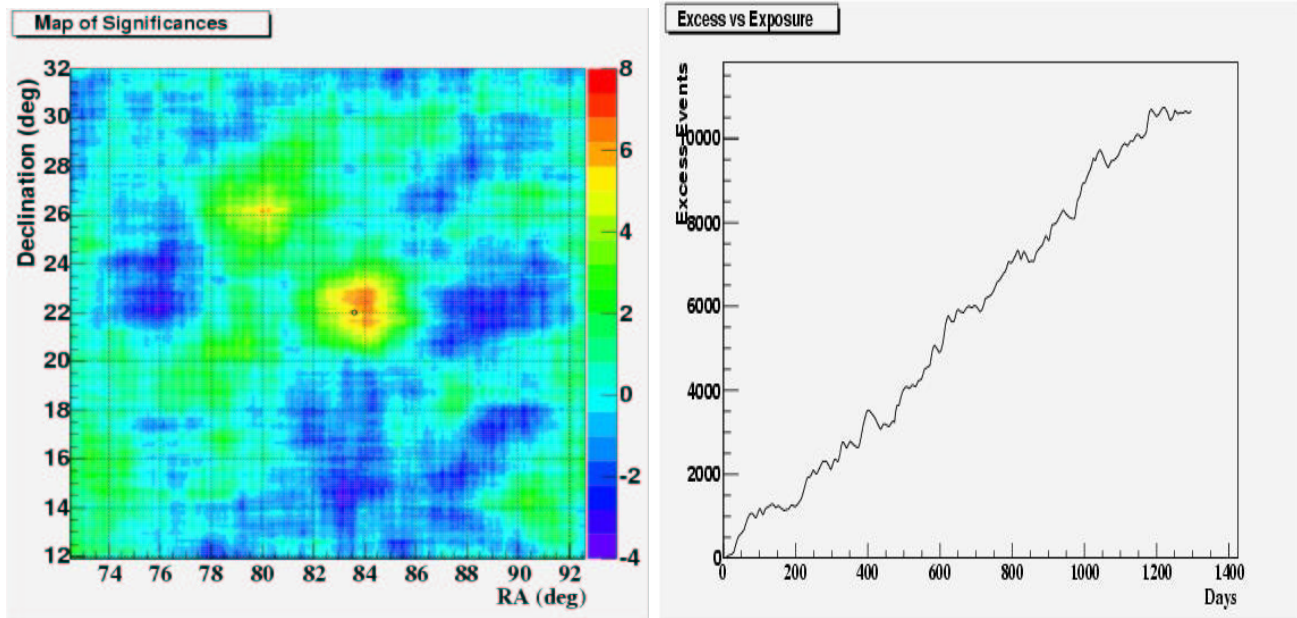


Figure 6: **Left** – Milagro significance map, showing the Crab in the center and the TeV source coincident with EGRET source 3EG J0520+2556 to the left. **Right** – Accumulated significance on TeV 0520+2556 as a function of time (Figure from Smith et al. [2004]).

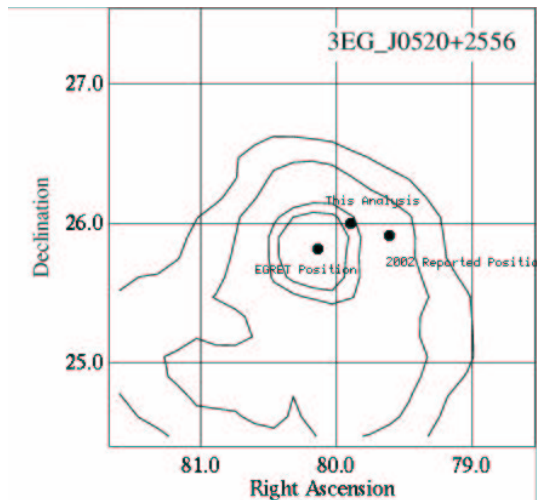


Figure 7: EGRET Source Location and contours. We include the position reported by Milagro in 2002 [Sinnis et al. 2002], as well as the current location of maximum significance (Figure from Smith et al. [2004]).

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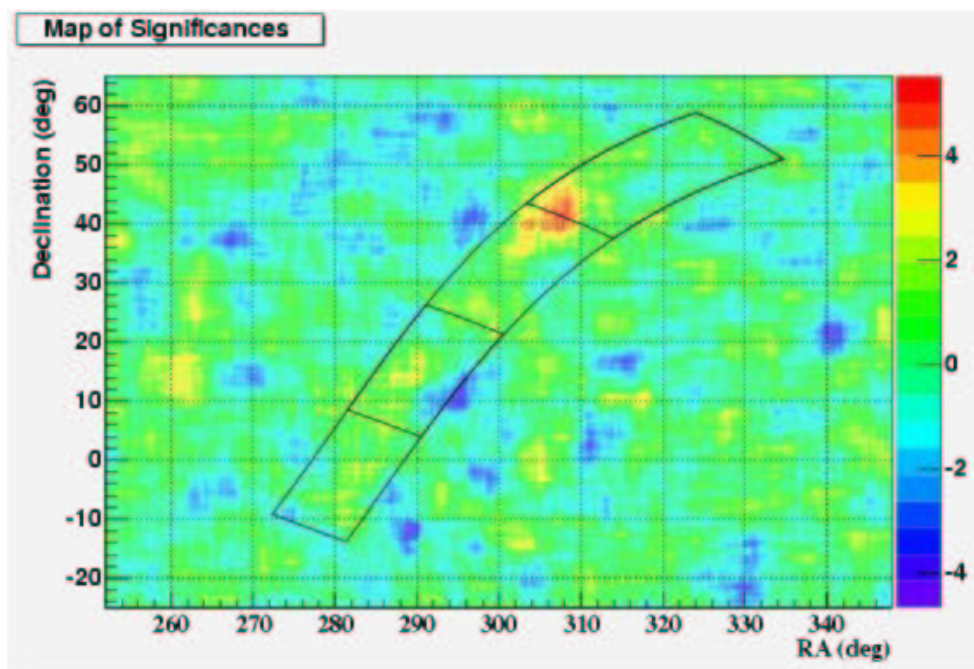


Figure 8: Milagro significance map, showing a clear excess in the Cygnus region. Also shown is the Galactic plane region from a latitude of 20 degrees to 100 degrees and longitude of -5 to 5 degrees (Figure from Smith et al. [2004]).