Diffuse TeV emission from the Cygnus region

References:
"Discovery of TeV gamma-ray emission from the Cygnus region of the Galaxy"
Abdo et al., astro-ph/0611691
"Dissecting the Cygnus region with TeV gamma rays and neutrinos"
Beacom & Kistler, astro-ph/0701751

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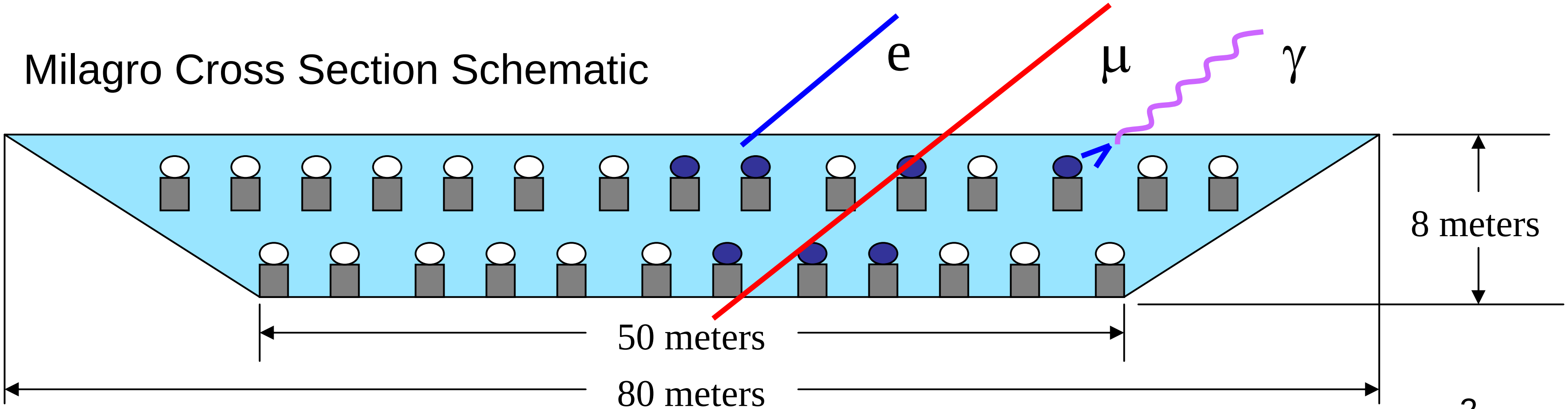
ICRR CANGAROO group Internal seminar, February 1, 2007

Milagro

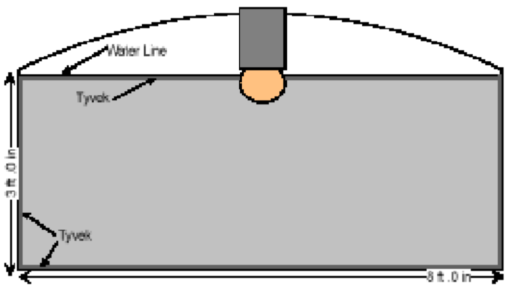
- A Water Cherenkov detector.
- Reconstruct shower direction to 0.3-0.7^{o} from the timing shower front.
- Reject background by detecting penetrating component of hadronic showers
- Field of view is ~2 sr
- Duty factor ~95%
- Trigger rate ~1700 Hz (6 Mbytes/sec)

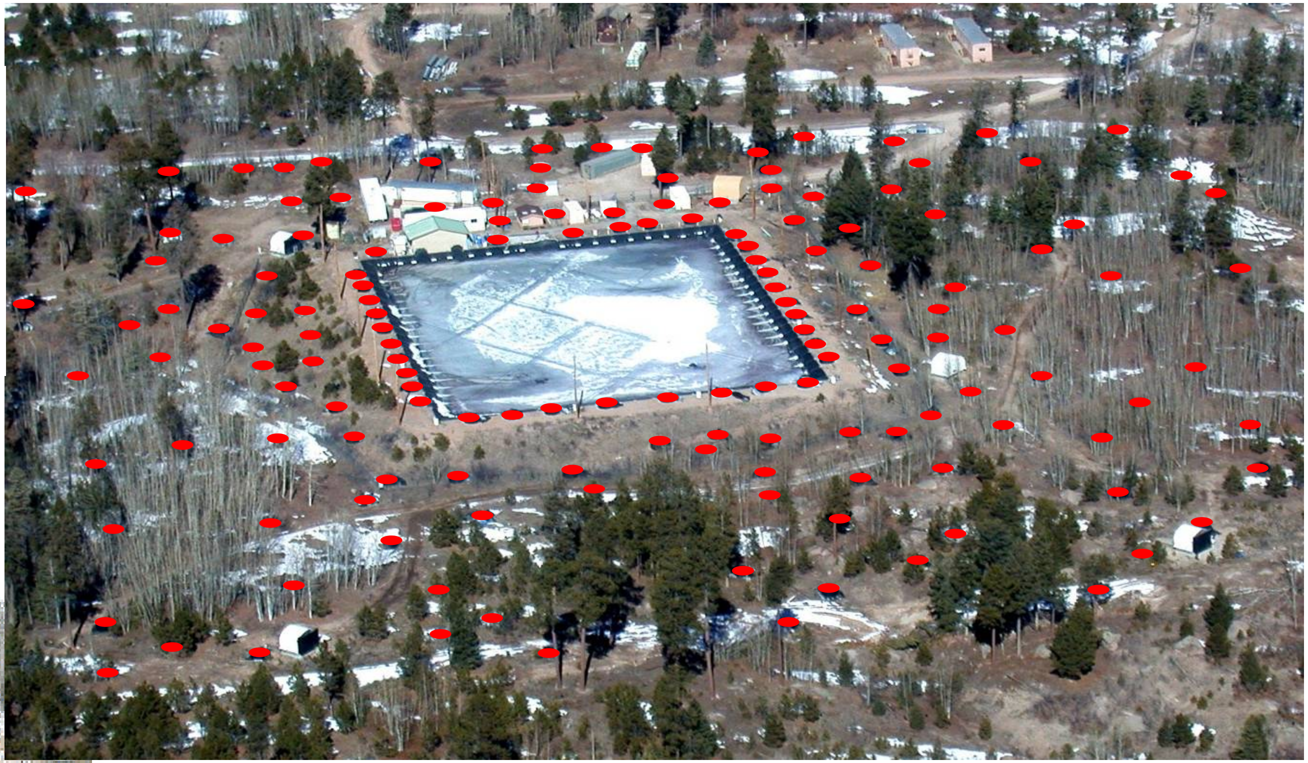
Los Alamos, NM, 2650m a.s.l.

Milagro Cross Section Schematic



Milagro with outriggers





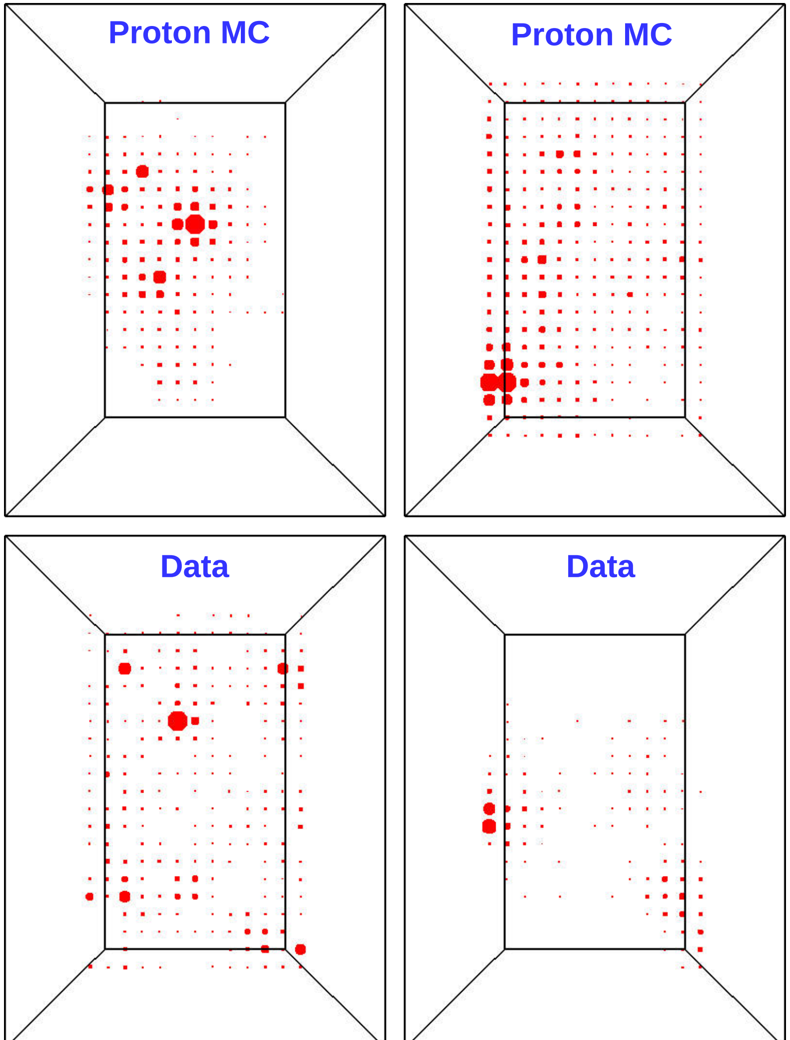
175 Outrigger tanks (Tyvek lined – water filled)
2.4m diameter, 1m deep
34,000 m^2 enclosed area
Completed in May 2003

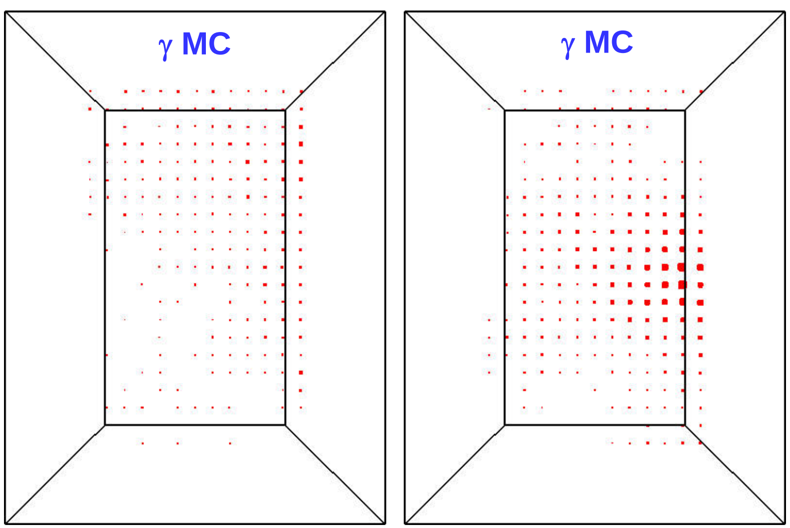
Angular resolution: 0.5deg (with outriggers) / 0.75deg (without)

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



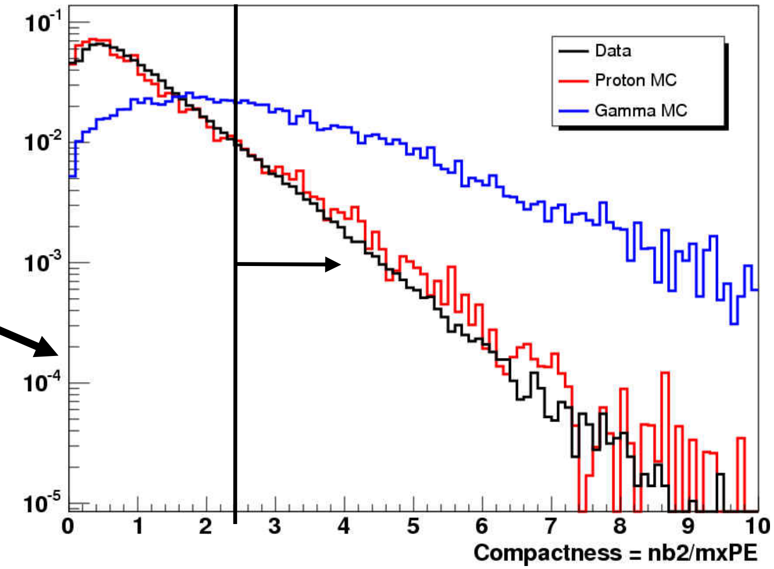


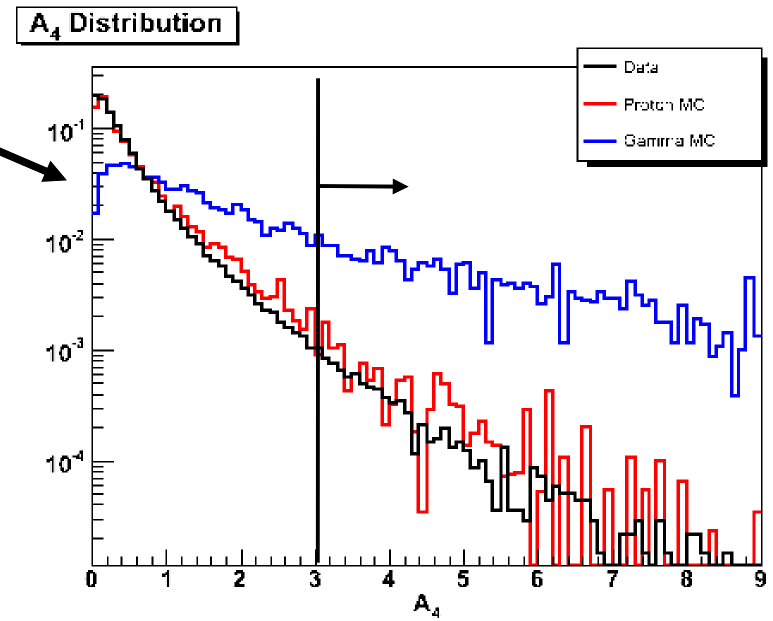
Background rejection (cont'd)

- Parameterize "clumpiness" of the bottom layer hits
  - Compactness $C = \dfrac{nb2}{mxPE}$
    - Require C > 2.5
    - 50% gammas & 10% hadrons
    - Sensitivity improved by 1.6

$$A_4 = \frac{\left(fTop + fOut\right) * nFit}{mxPE}$$

- Require $A_4 > 3.0$
- 20% gammas & 1% hadrons
- Sensitivity further improved by 1.4



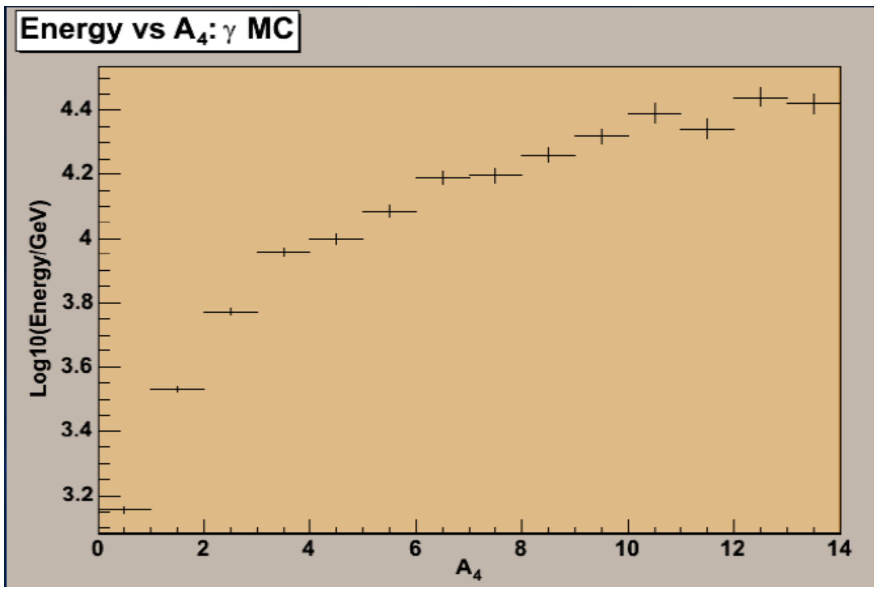


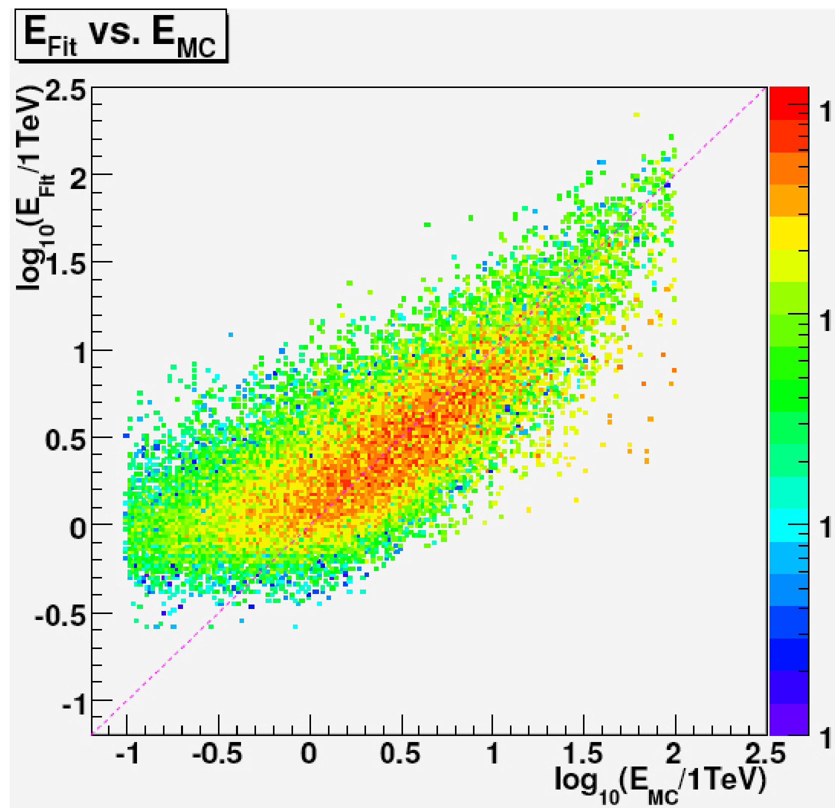
mxPE:	maximum # PEs in bottom layer PMT
nb2:	# bottom layer PMTs with 2 PEs or more
fTop:	# fraction of hit PMTs in Top layer
fOut:	# fraction of hit PMTs in Outriggers
nFit:	# PMTs used in the angle reconstruction

Spectral determination

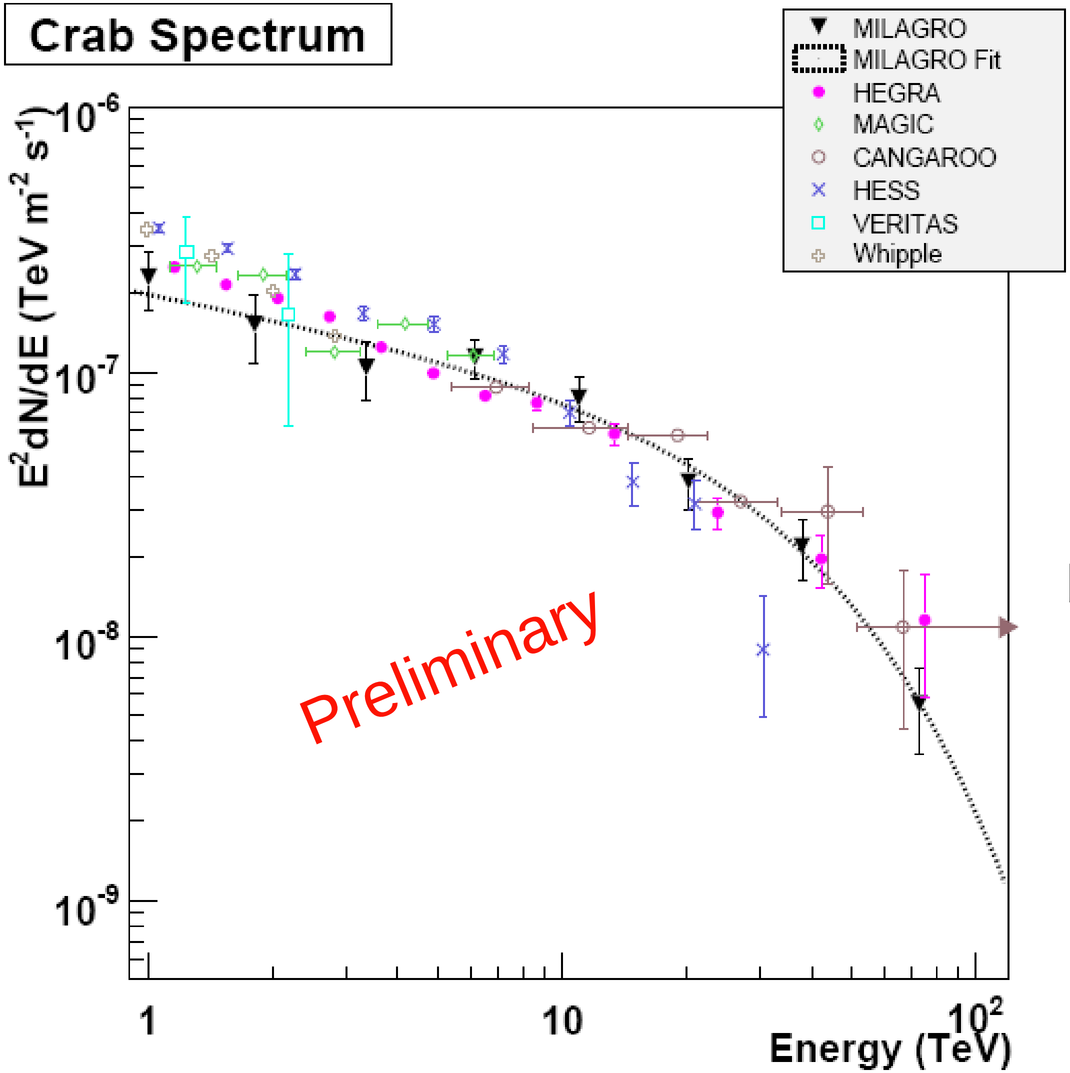
A_4 is related to energy
2-20 TeV useful range

Parameterization of events





Crab spectrum



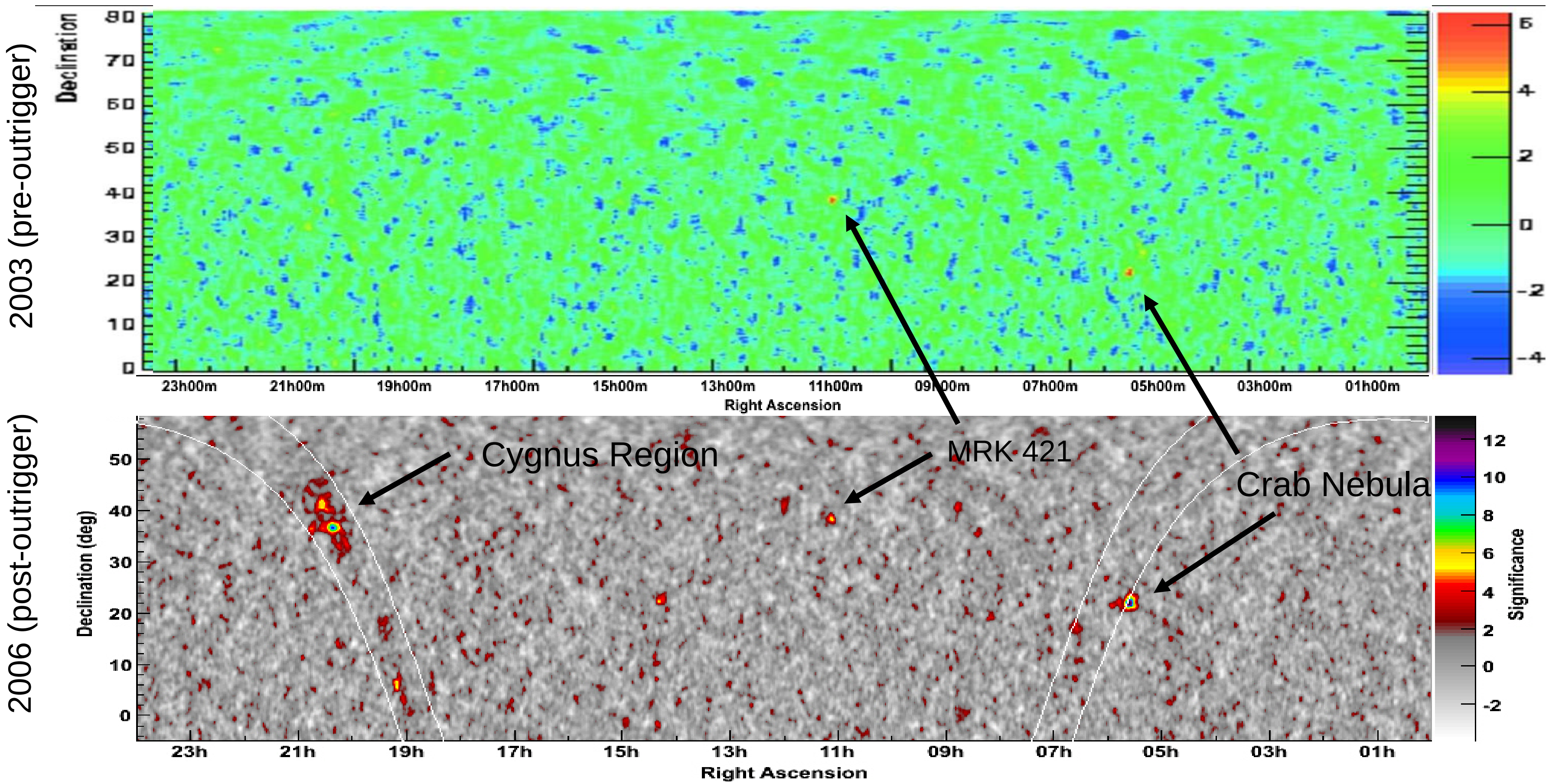
Exponential cut off energy is E_c = 31.0 TeV (w/large error bars)

Notes in the paper

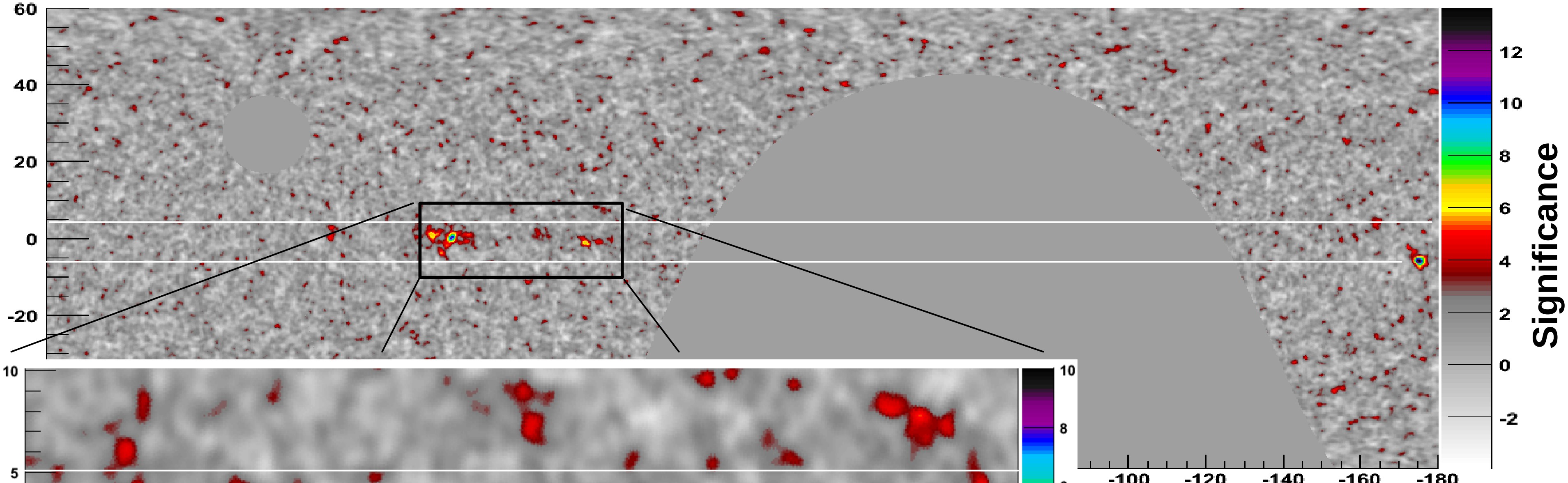
The dependence of the derived source flux on the spectrum is minimized when it is quoted at the median detected energy, which is ~12 TeV for typical gamma-ray power law spectra and the weighted analysis using A_4. A change in the assumed source differential photon spectral index from -2.4 to -2.8 changes the quoted flux at 12 TeV by < 10%.

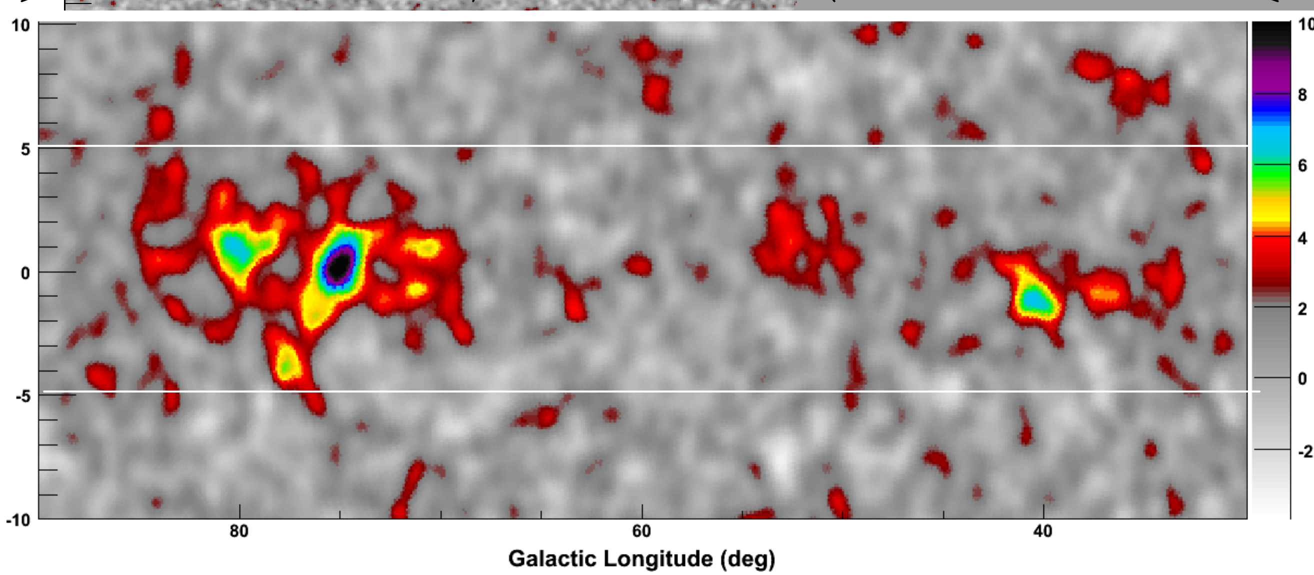
However, the Milagro trigger rate as determined from simulations of protons and helium using the flux from direct measurements (Haino *et al.* 2004 & Asakimori *et al.*1998) is underpredicted, so a <u>systematic error of 30%</u> is given to the gamma-ray fluxes quoted here.

Milagro sky survey



The Galactic plane





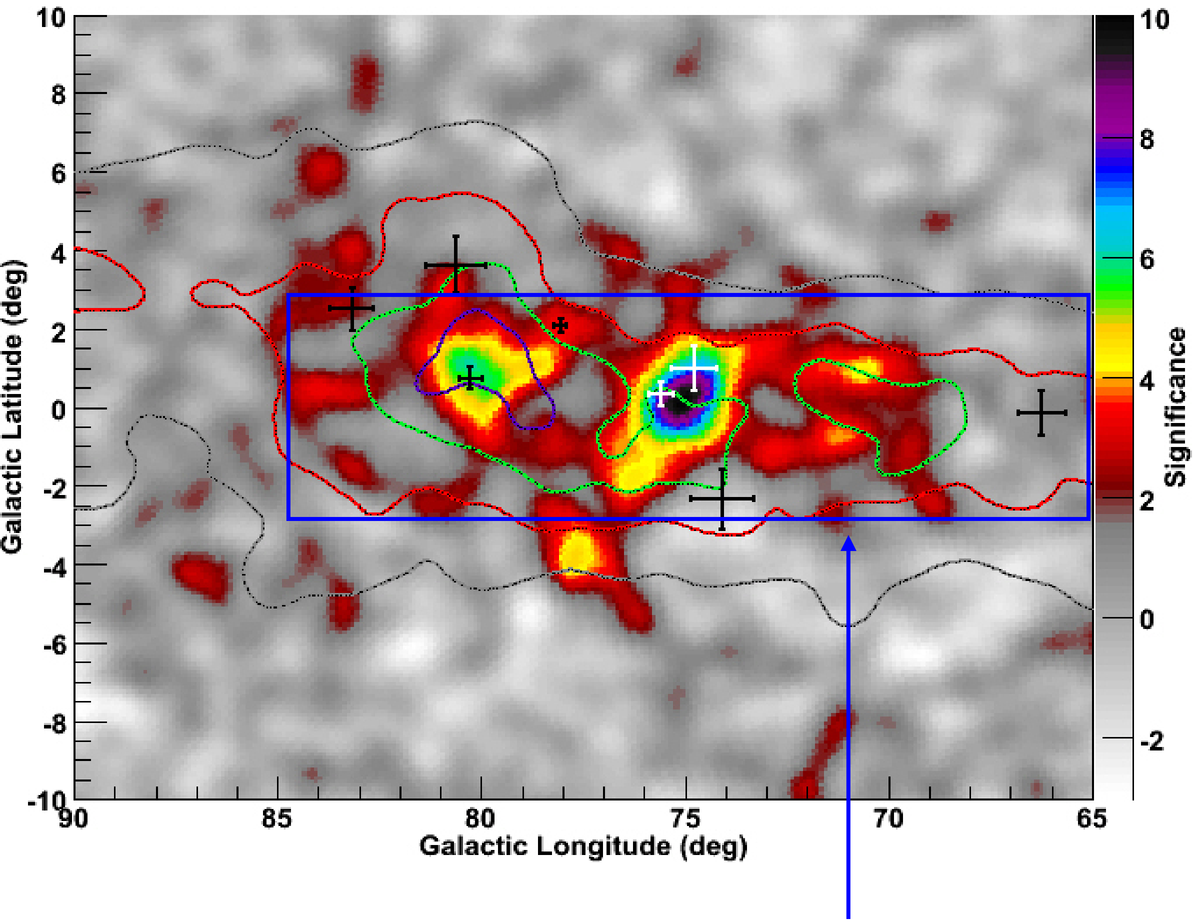
GP diffuse excess clearly visible from l=25° to l=90°

Cygnus Region shows extended excess

$F_{Cygnus} \sim 2 \times F_{crab}$

120 square degrees
l (65,85), b (-3,3)

The Cygnus region



- Contours are GALPROP pion model
- Crosses are EGRET (unidentified) sources
- TeV/matter correlation good
  Chance noncorrelation **1.5×10^{-6}**
- Brightest TeV Region
  - **MGRO J2019+37**
  - ~0.5 Crab @ 12 TeV
  - Extent = 0.32 ± 0.12 deg.
  - Coincident with 2 EGRET sources (unID)
    - PWN G75.2 + 0.1
    - Blazar (B2013+370)
  - *Energy Analysis in progress*

Flux @ 12.5 TeV= $E^2\, dN/dE = (4.18 \pm 0.52_{stat} \pm 1.26_{sys}) \times 10^{-10}$ TeV $cm^{-2}\ s^{-1}$ <u>sr</u>$^{-1}$
(excluding new source & assuming $E^{-2.6}$)
~3.5 Crab in 180 sq. degree region

MGRO J2019+37

- Position: (α,δ)=(304.83 ± 0.14 ± 0.3, 36.83 ± 0.08 ± 0.25)deg
- Source size: 0.32 ±0.12 deg (high energy events [0.35deg ang.res.] only)
- *Flux:* $E^2 dN/dE$=(3.49 ± 0.47 ± 1.05)×10^{-12} TeV $cm^{-2}s^{-1}$ at the median detected energy of 12TeV (assuming $E^{-2.6}$)

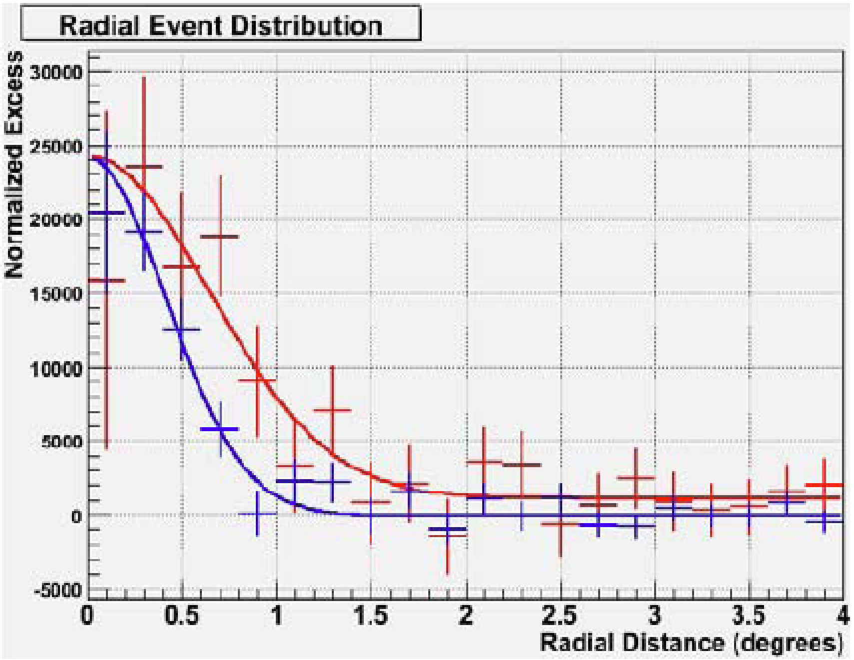
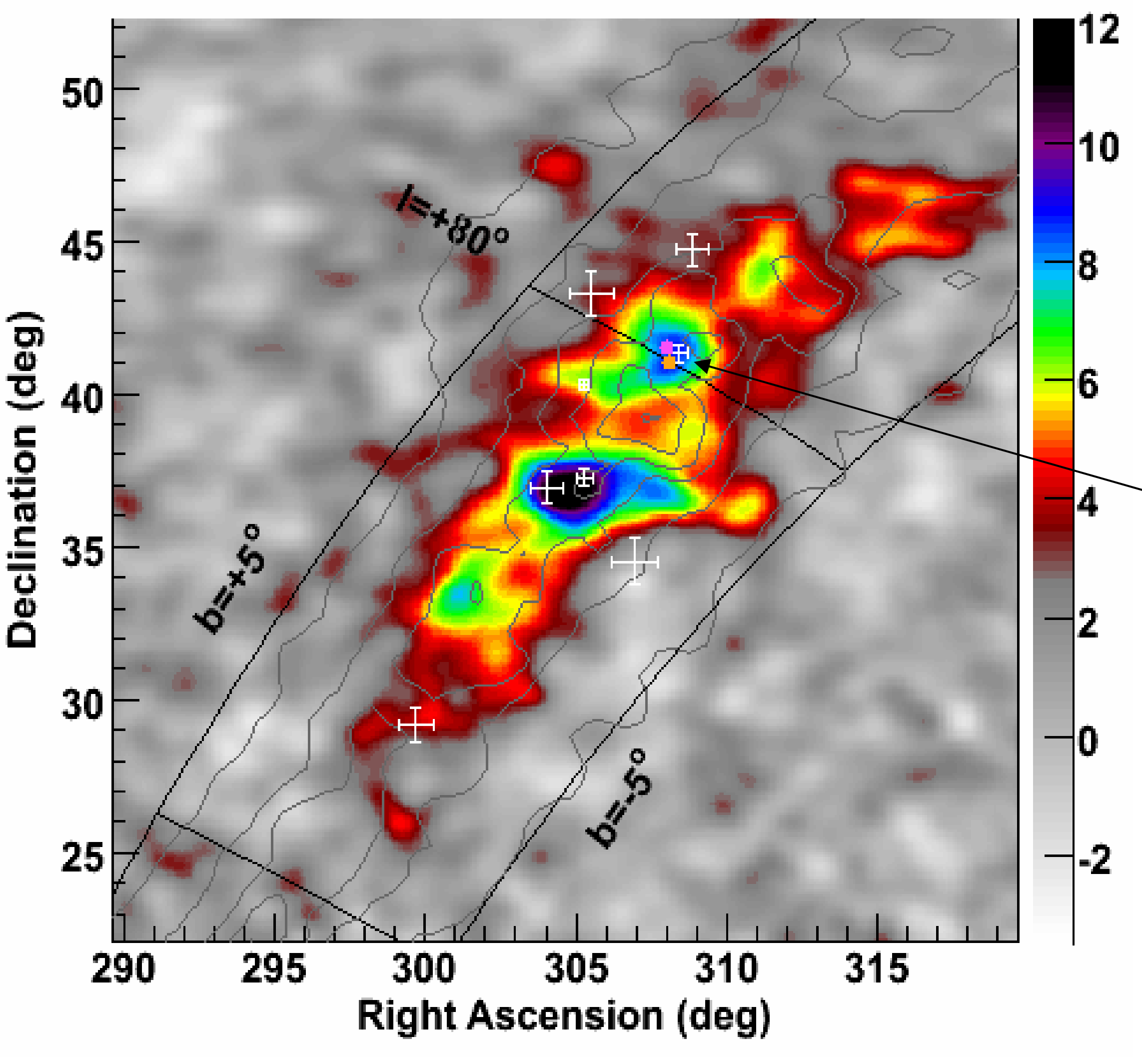


Figure 4 Radial profile of events from the direction of the Crab (blue) and from MGRO J2019+37 (red). Only events with large number of photomultiplier tube hits and outrigger information are shown due to their better angular resolution.

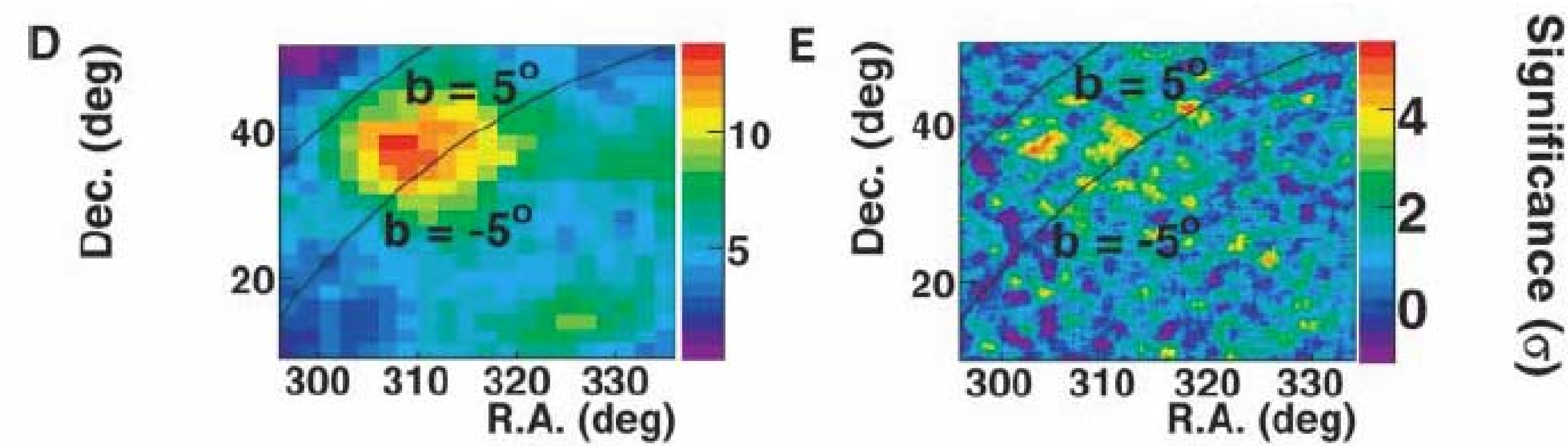
Cygnus region



TeV J2032+4130 / Cyg X-3

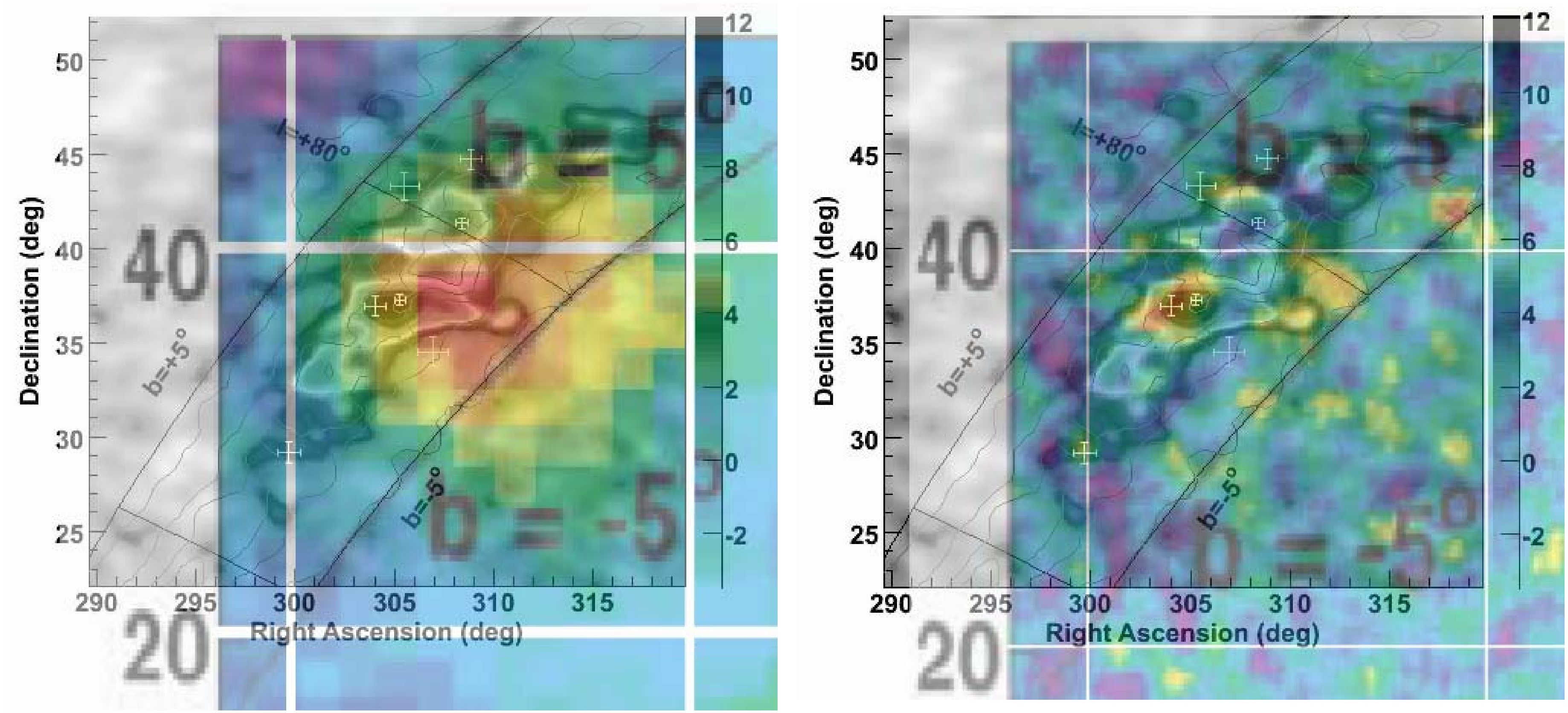
Tibet: Amenomori et al., Science 314, 439 (2006)

Cygnus region: Tibet



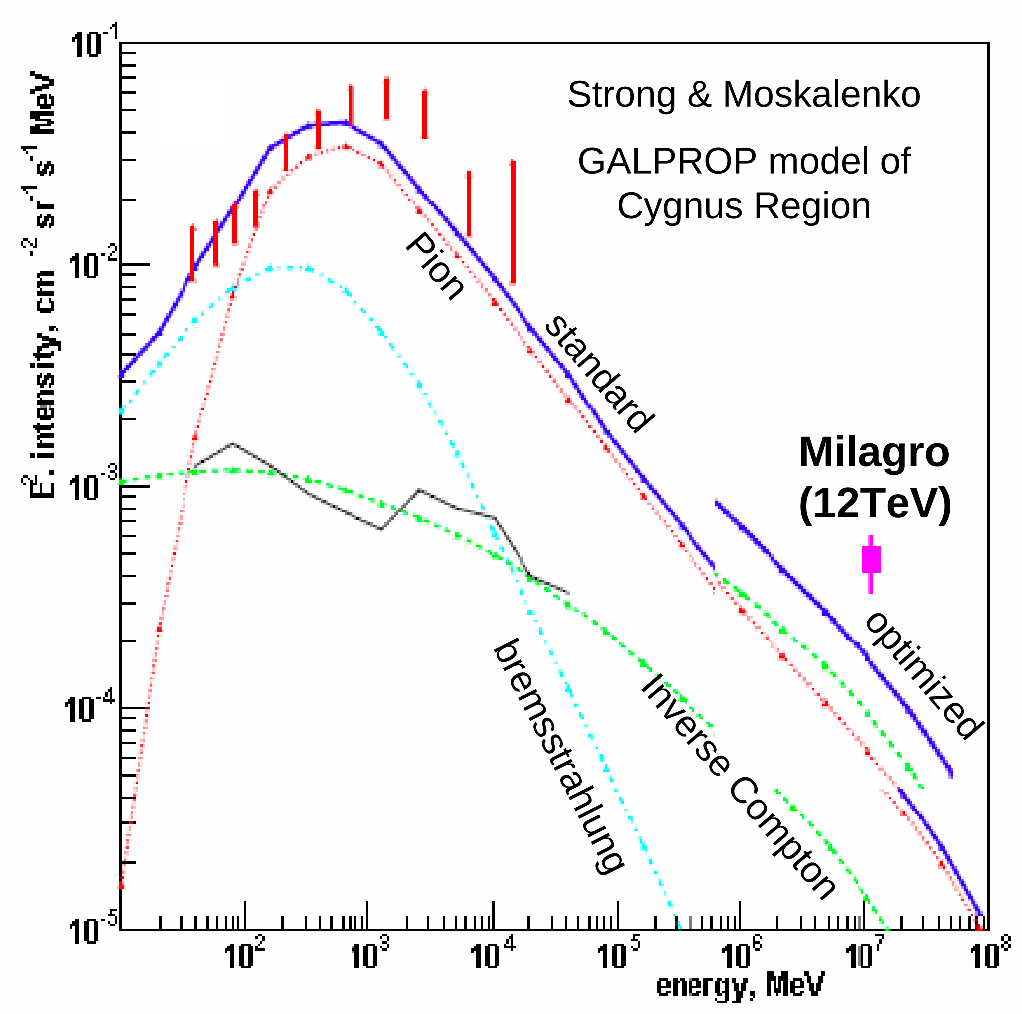
(D) and (E) show significance maps of the Cygnus region [pixels in radius of 0.9° and sampled over a square grid of side width 0.25° for (E)] for data from 1997 to 2005. The vertical color bin widths are 0.69 SD and 0.42 SD for significance in (D) and (E), respectively. Two thin curves in (D) and (E) stand for the Galactic parallel b=±5°. Small-scale anisotropies (E) superposed onto the large-scale anisotropy hint at the extended gamma-ray emission.

Cygnus region: Milagro & Tibet



MILAGRO: A. Abdo, Santa Fe Workshop, May 2006
Tibet: Amenomori et al., Science 314, 439 (2006)

Cygnus region: diffuse gamma-rays



- Strong & Moskalenko optimized model
  - Increase π^0 and IC component throughout Galaxy
  - Milagro 2-6x above prediction (optimized-standard models)
  - Unresolved sources?
  - Cosmic-ray accelerators?

MGRO J2019+37 field

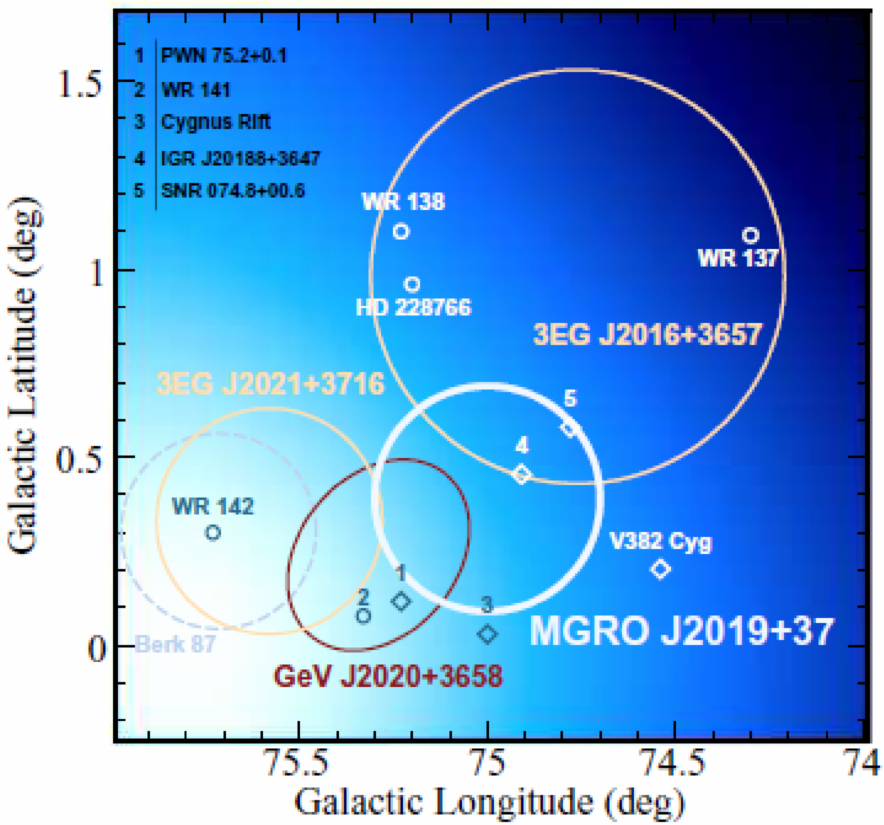


FIG. 1: The field near MGRO J2019+37. Shown are 3EG Catalog sources, a GeV Catalog source, and potential counterparts to the gamma-ray sources. These sources are overlaid upon diffuse GeV emission observed by EGRET (white most intense). For details, please see the caption of Fig. 2.

- 2 EGRET unIDs
  - 3EG J2016+3657 (blazar?)
  - 2EG J2021+3716
- GeV J2020+3658 (PWN 75.2+0.1?)
- 5 Wolf-Rayet stars
- 1 Massive eclipsing binary V382 Cyg
- 2 SNRs
  - 074.8+00.6 (just an H II region?)
  - 074.9+01.2 (12kpc!)
- IGR J20188+3647 (only in 17-30keV)
- Cygnus rift (molecular cloud complex)

$$r \approx 5\left(\frac{\theta}{0.3^\circ}\right)\left(\frac{D}{1\,\mathrm{kpc}}\right)\mathrm{pc}$$

Beacom & Kistler, astro-ph/0701751

Cygnus region

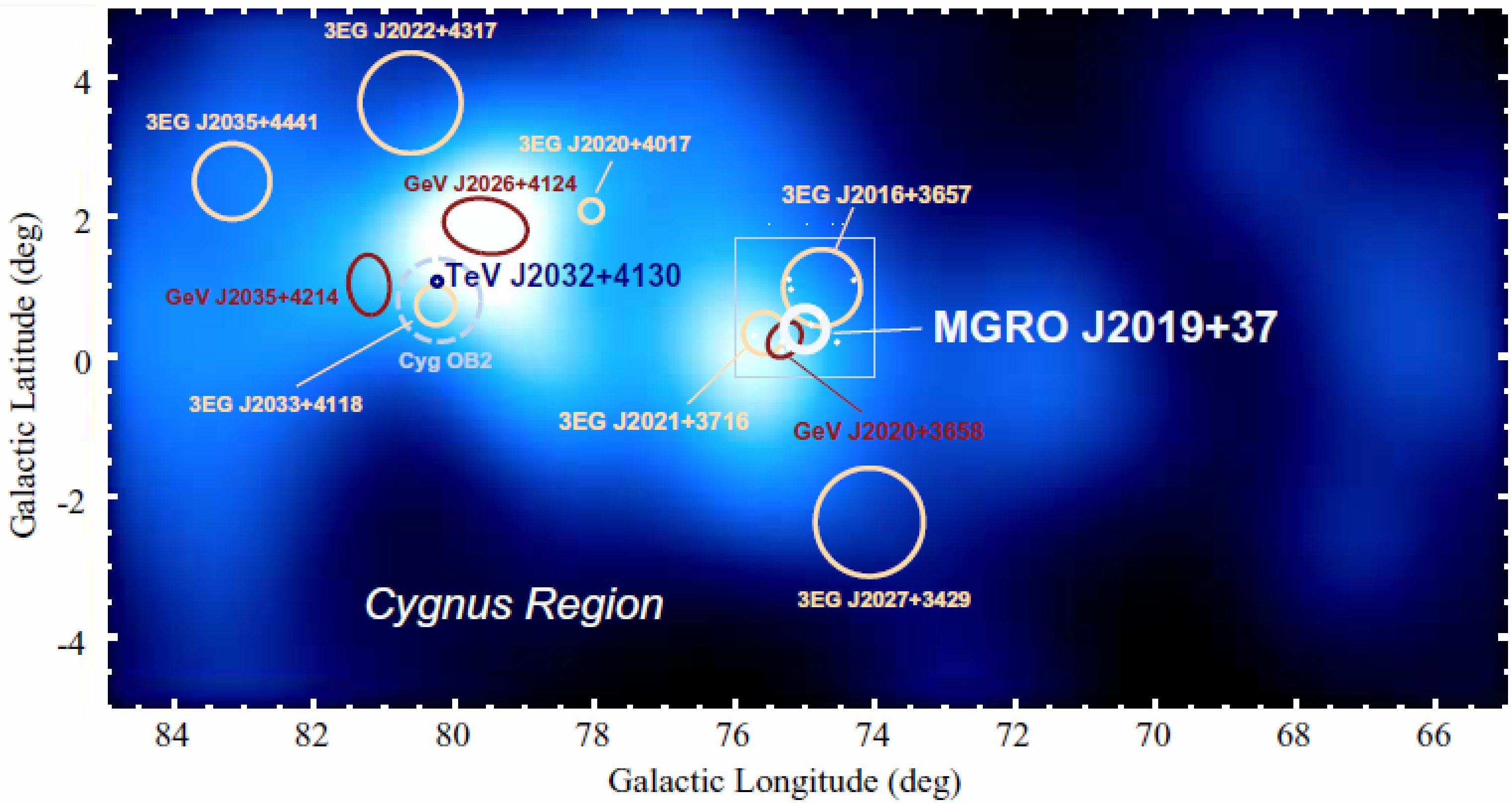


FIG. 2: Gamma-ray sources and diffuse GeV emission in the Cygnus region. Shown are the sources discovered by Milagro (MGRO J2019+37) and HEGRA (TeV J2032+4130), along with their approximate (1σ) error circles. The fitted extent of the Milagro source is comparable to the circle shown. Also shown are nearby Third EGRET (3EG) (compiled from >100 MeV gamma rays) and GeV (>1 GeV gamma rays) catalog sources (all at 95% confidence); as well as gamma-ray source candidates (points), the Cyg OB2 core (dashed circle), and the region of Fig. 1 (box). EGRET 4 – 10 GeV (point-source subtracted) diffuse emission (smoothed and scaled linearly from $\sim 1-10\times10^{-6}$ cm^{-2} s^{-1} sr^{-1}, with white most intense) is also displayed.

Spectral consideration

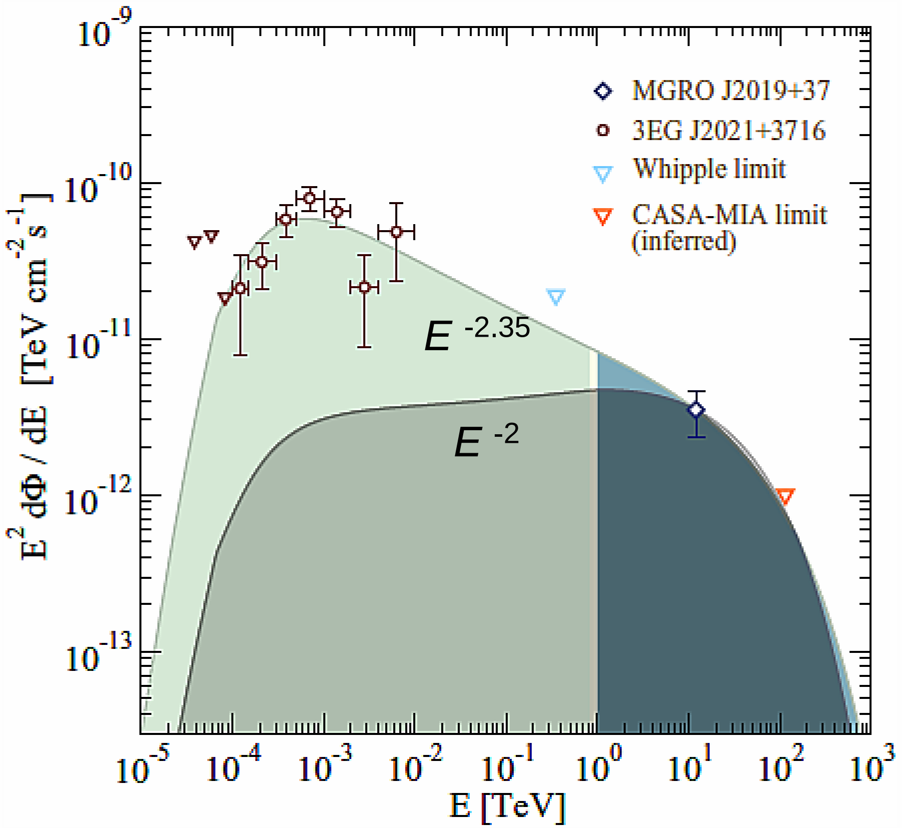


FIG. 3: Data and possible hadronic spectra for MGRO J2019+37. Shown are the Milagro measurement at 12 TeV (diamond), the EGRET spectrum for 3EG J2021+3716 (circles), the upper limit from Whipple (0.3 TeV), and our inferred upper limit from CASA-MIA (115 TeV). Also shown are hadronic fits to the data, assuming $E_p^{-2.35}$ (upper) and E_p^{-2} (lower) source proton spectra. The region above 1 TeV is of greatest interest to neutrino astronomy.

<u>Hadronic scenario</u>

dF/dE = $E^{-2.35}$exp(-E/E^{cut})
E^{cut}=1000 TeV

$$\rightarrow E \approx 5\times10^{50}\left(\frac{1\mathrm{cm}^{-3}}{n_H}\right)\left(\frac{D}{1\,\mathrm{kpc}}\right)^2 \mathrm{erg}$$

If a few kpc, this is the order of the total explosion energy of a SN.

dF/dE = E^{-2}exp(-E/E^{cut})
E^{cut}= 500 TeV

Neutrino emission

- Neutrino emission from *p-p* interaction
  $\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_\mu \bar{\nu}_e \nu_\mu$
  $\pi^- \to \mu^- \bar{\nu}_\mu \to e^- \nu_\mu \bar{\nu}_e \bar{\nu}_\mu$
- $\nu_e : \nu_\mu : \nu_\tau = 1:2:0 \to 1:1:1$ by oscillation
- Typical ν energy ~ ½ of π^0 gamma-ray

- $d\Phi_\nu / dE_\nu = (1/2)^{\Gamma-1} \phi_\gamma E_\nu^{-\Gamma} = \phi_\nu E_\nu^{-\Gamma}$ (for each ν)

- $d\Phi_\gamma / dE_\gamma = A_\gamma E_\gamma^{-\beta} \exp[-(E_\gamma / E_\gamma^{cut})^{1/2}]$
  where β=2.2, E_γ^{cut}=45TeV for $E_p^{-2.35}$,
  β=1.9, E_γ^{cut}=20TeV for E_p^{-2}

Neutrino-induced muon spectrum

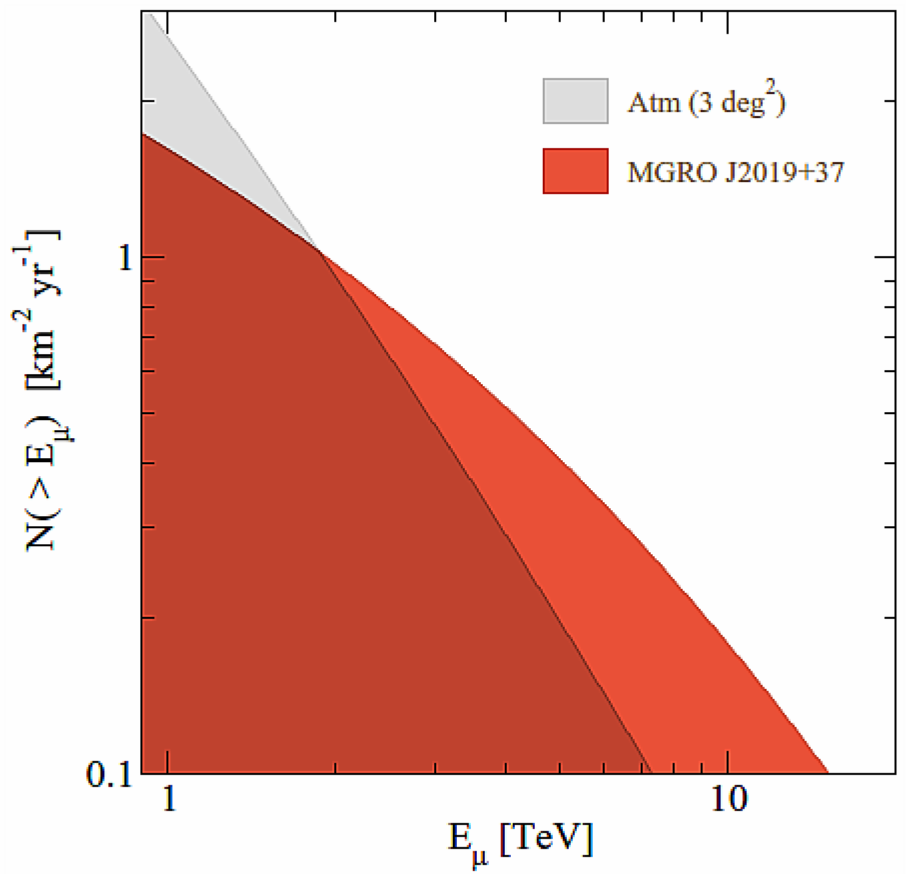


FIG. 4: Integrated $(\nu_\mu + \bar{\nu}_\mu)$-induced muon rates from MGRO J2019+37 above a given muon energy within IceCube for one year. These rates result from an $E_p^{-2.35}$ source proton spectrum (see Fig. 3). The E_p^{-2} fit yields a nearly identical result. The shaded region shows the expected atmospheric background in a 3 deg^2 bin.

$\nu_\mu + p \rightarrow \mu^+ + X$

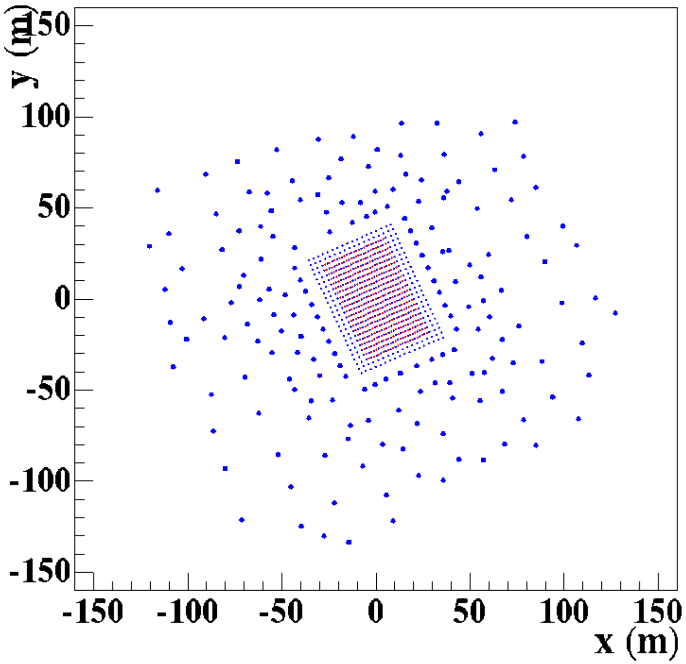
$E_\mu > 1$ TeV

Detectable by IceCube? – marginal!

3deg^2 bin – cannot resolve!

HAWC

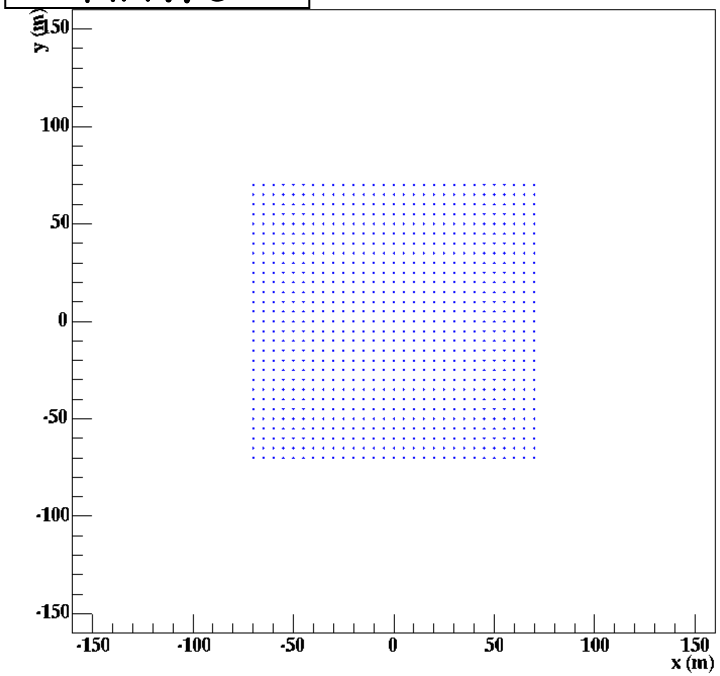
Milagro



Milagro:
450 PMT (25x18) shallow (1.4m) layer
273 PMT (19x13) deep (5.5m) layer
175 PMT outriggers

Instrumented Area:	~40,000m^2
PMT spacing:	2.8m
Total Area:	3500m^2
μ det Area:	2200m^2

HAWC



HAWC:
900 PMTs (30x30)
5.0m spacing
Single layer with 4m depth

Instrumented Area:	22,500m^2
PMT spacing:	5.0m
Total Area:	22,500m^2
μ det Area:	22,500m^2

Mexico?
2010?