Milagro:
A TeV All Sky Monitor

Brenda Dingus
(Los Alamos National Lab)
for the Milagro Collaboration

Detectors in Gamma-Ray Astrophysics

High Sensitivity
HESS, MAGIC, CANGAROO, VERITAS

Large Effective Area

Excellent Background Rejection (>99%)

Low Duty Cycle/Small Aperture

High Resolution Energy Spectra

Studies of known sources

Surveys of limited regions of sky

Low Energy Threshold
EGRET/GLAST

Space-based (small area)

"Background Free"

Large Duty Cycle/Large Aperture

Sky Survey (<10 GeV)

AGN Physics

Transients (GRBs) <100 GeV

Large Aperture/High Duty Cycle
Milagro, Tibet, ARGO, HAWC?

Moderate Area/Large Area (HAWC)

Good Background Rejection

Large Duty Cycle/Large Aperture

Unbiased Sky Survey

Extended sources

Transients (GRB's)

Solar physics/space weather

Milagro Gamma Ray Observatory @ 8600' altitude near Los Alamos, NM

R.Atkins,[1,2] W. Benbow,[3,4] D. Berley,[5] E. Blaufuss[5], D.G. Coyne,[3] T. DeYoung,[3,5] B.L. Dingus,[6] D.E. Dorfan,[3] R.W. Ellsworth,[7] L. Fleysher,[8] R.Fleysher[8], M.M. Gonzalez,[1] J.A. Goodman[5], E. Hays[5], C.M. Hoffman,[6] L.A. Kelly,[3] C.P. Lansdell,[5] J.T. Linnemann,[9] J.E. McEnery,[1,10] A.I. Mincer,[8] M.F. Morales,[3,11] P. Nemethy,[8] D. Noyes,[5] J.M. Ryan,[12] F.W. Samuelson,[6] P.M. Saz Parkinson,[3] A. Shoup,[13] G. Sinnis,[6] A.J. Smith,[5] G.W. Sullivan,[5] D.A. Williams,[3] M.E. Wilson,[1] X.W. Xu[6] and G.B. Yodh[13]

1. Department of Physics, University of Wisconsin
2. Current Address: Department of Physics, University of Utah
3. Santa Crux Institute for Particle Physics, University of California, Santa Cruz
4. Current address: Max-Plank-Institute fur Kernphysik
5. Deoartment of Physics, University of Maryland
6. Los Alamos National Laboratory
7. Department of Physics and Astronomy, George Mason University
8. Department of Physics, New York University
9. Department of Physics and Astronomy, Michigan State University
10. Current address: NASA Goddard Space Flight Center
11. Current address: Massachusetts Institute of Technology
12. Department of Physics, University of New Hampshire
13. Department of Physics and Astronomy, University of California, Irvine

Los Alamos NATIONAL LABORATORY

UC SANTA CRUZ

UNIVERSITY OF MARYLAND

MICHIGAN STATE UNIVERSITY

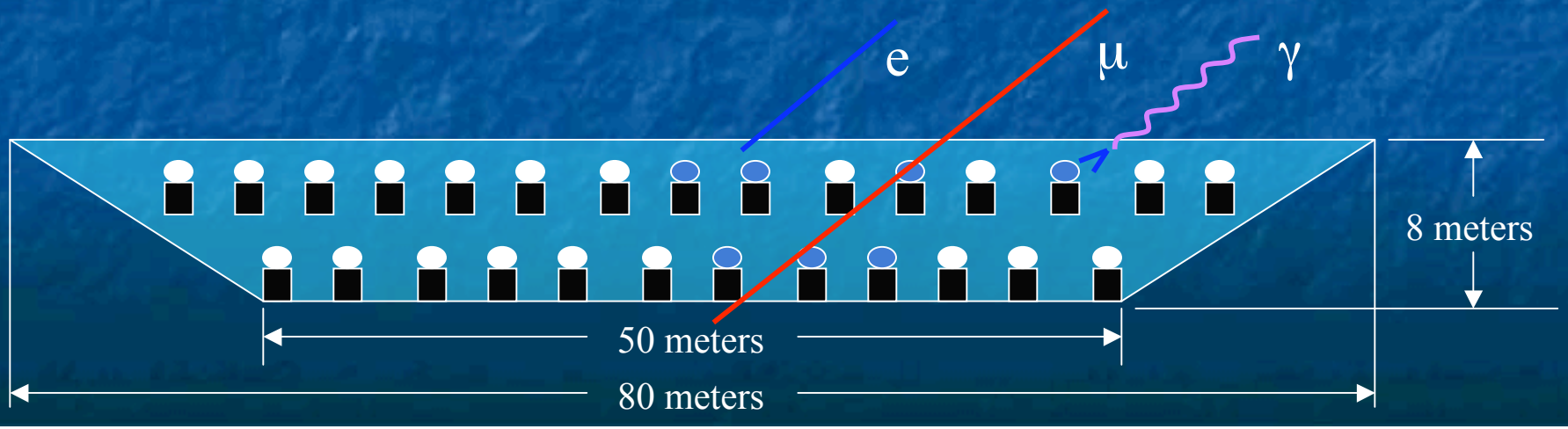
UCIrvine University of California, Irvine

New York University

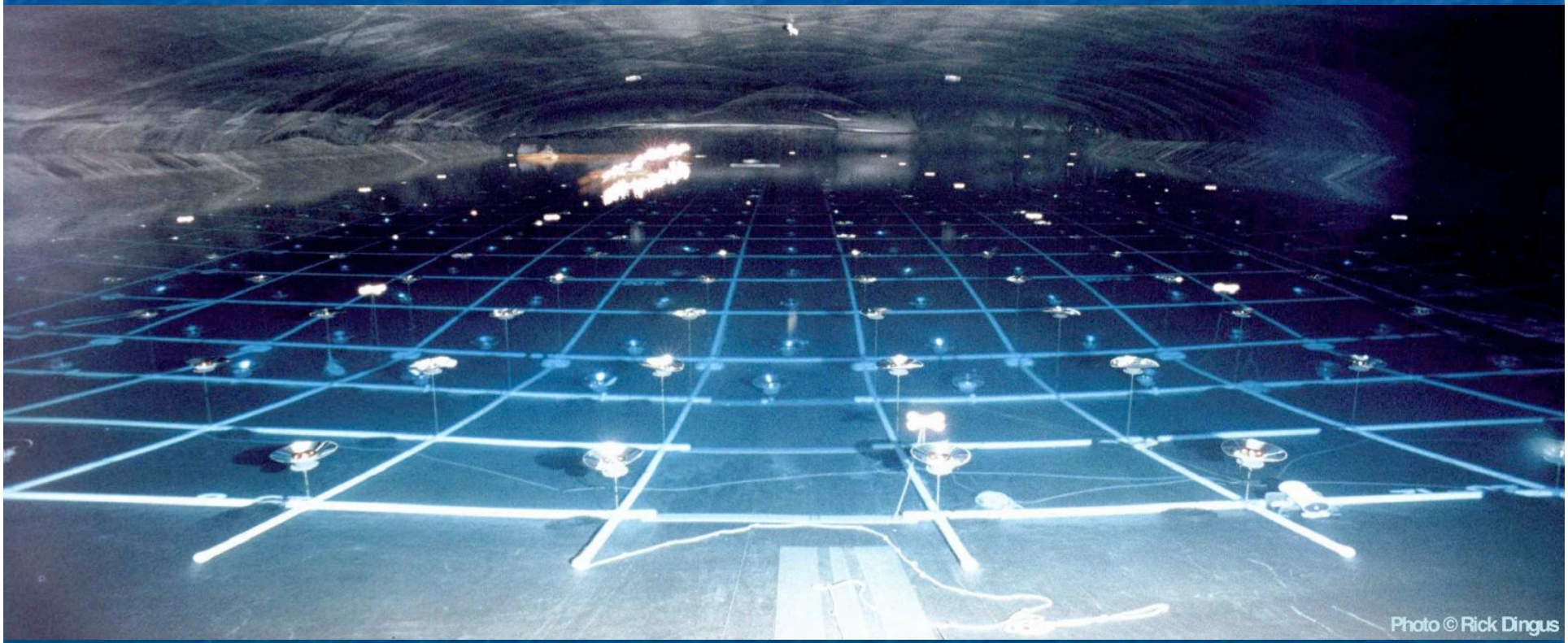
NEW HAMPSHIRE

How Does Milagro Work?

- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 6m pond containing filtered water.
- Reconstruct shower direction to ~ 0.5 degrees from the time different photodetectors are hit.
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays
- Field of view is ~2 sr (± 45 degrees) and the average duty factor is >90%

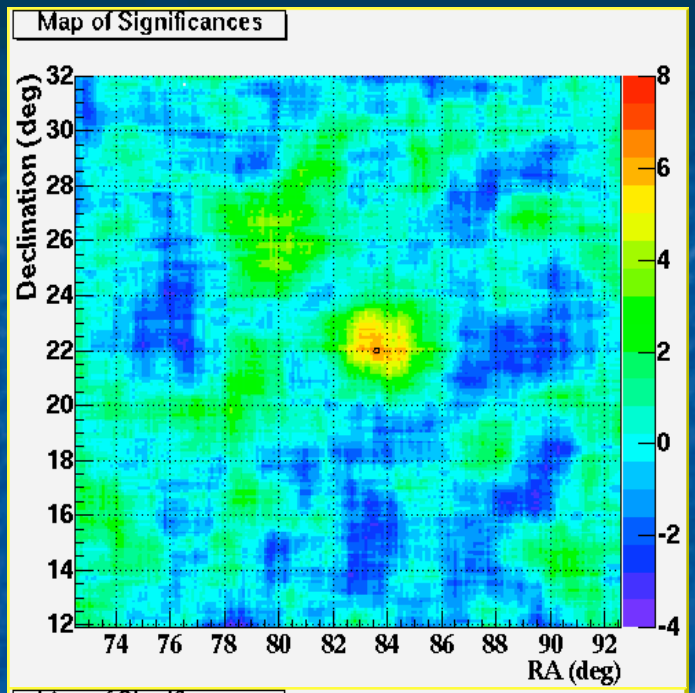


Inside the Milagro Detector

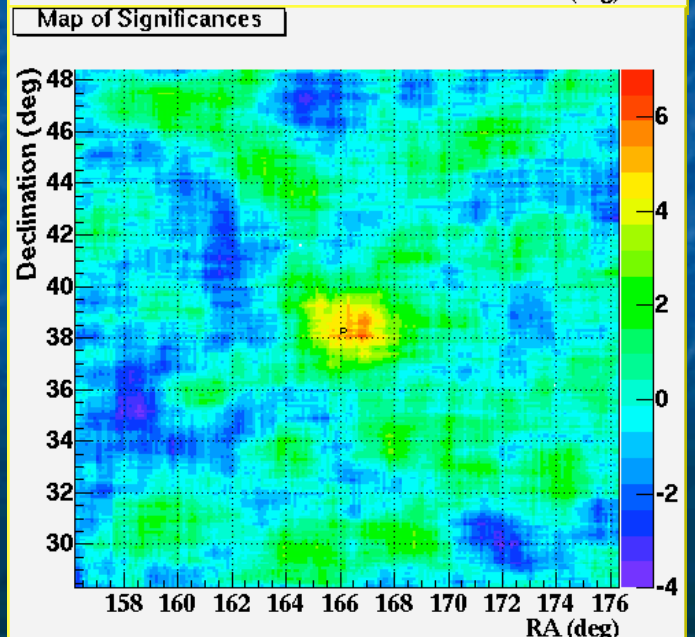


Observation of the Crab and Mrk 421

Crab Nebula



Mrk 421

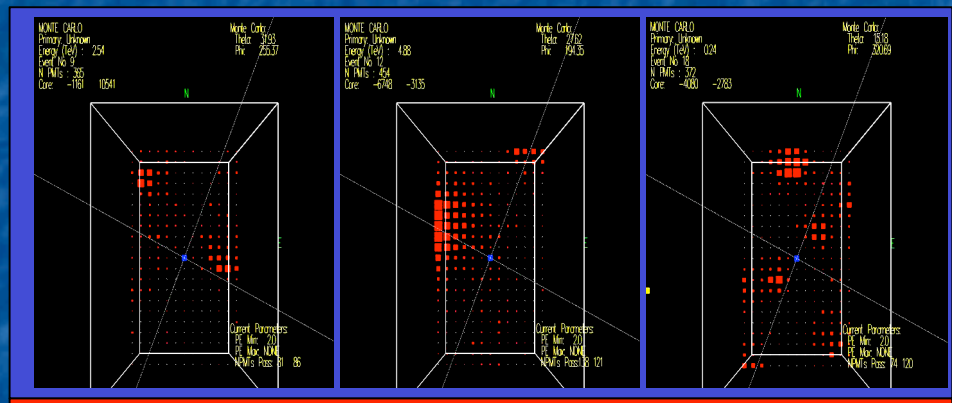


- Flux Consistent with Air Cerenkov Observations
- Median γ-ray Energy 2-3 TeV
- Angular Point Spread Function $\sigma \sim 0.5^{\circ}$

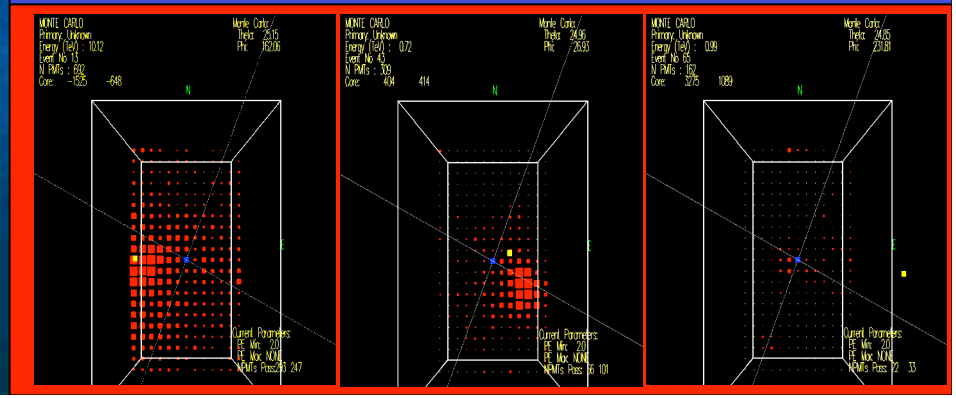
γ / Hadron Separation

(reject 90% p & keep 50% γ)

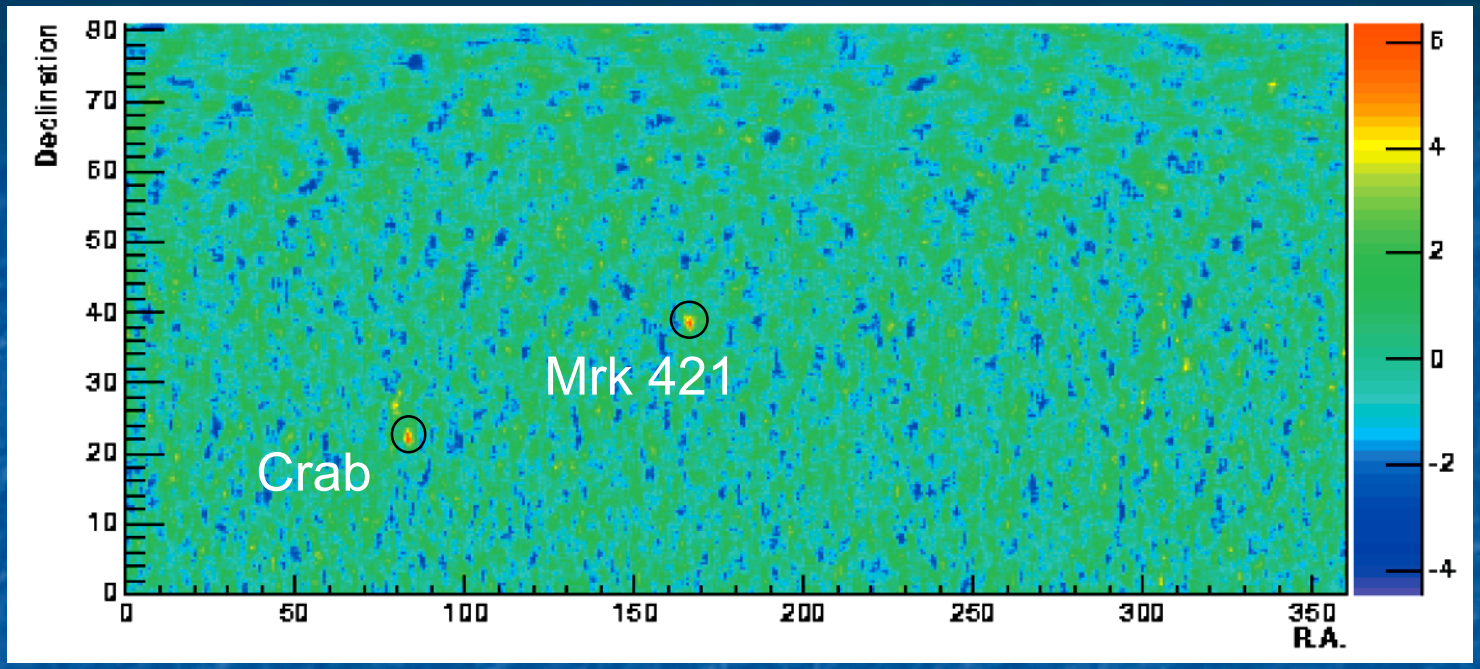
P



γ



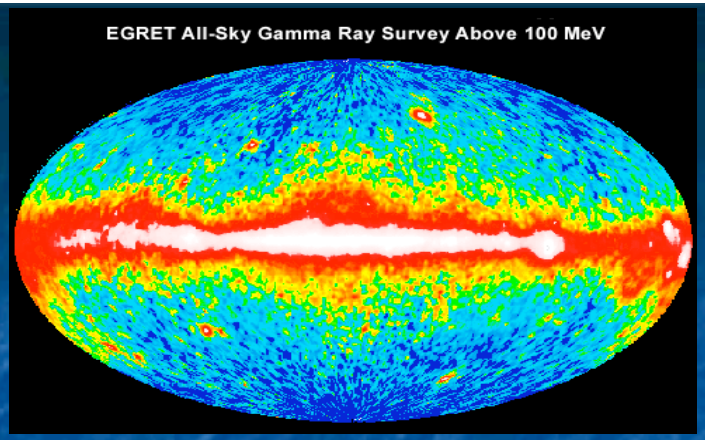
Milagro All Sky Point Source Survey



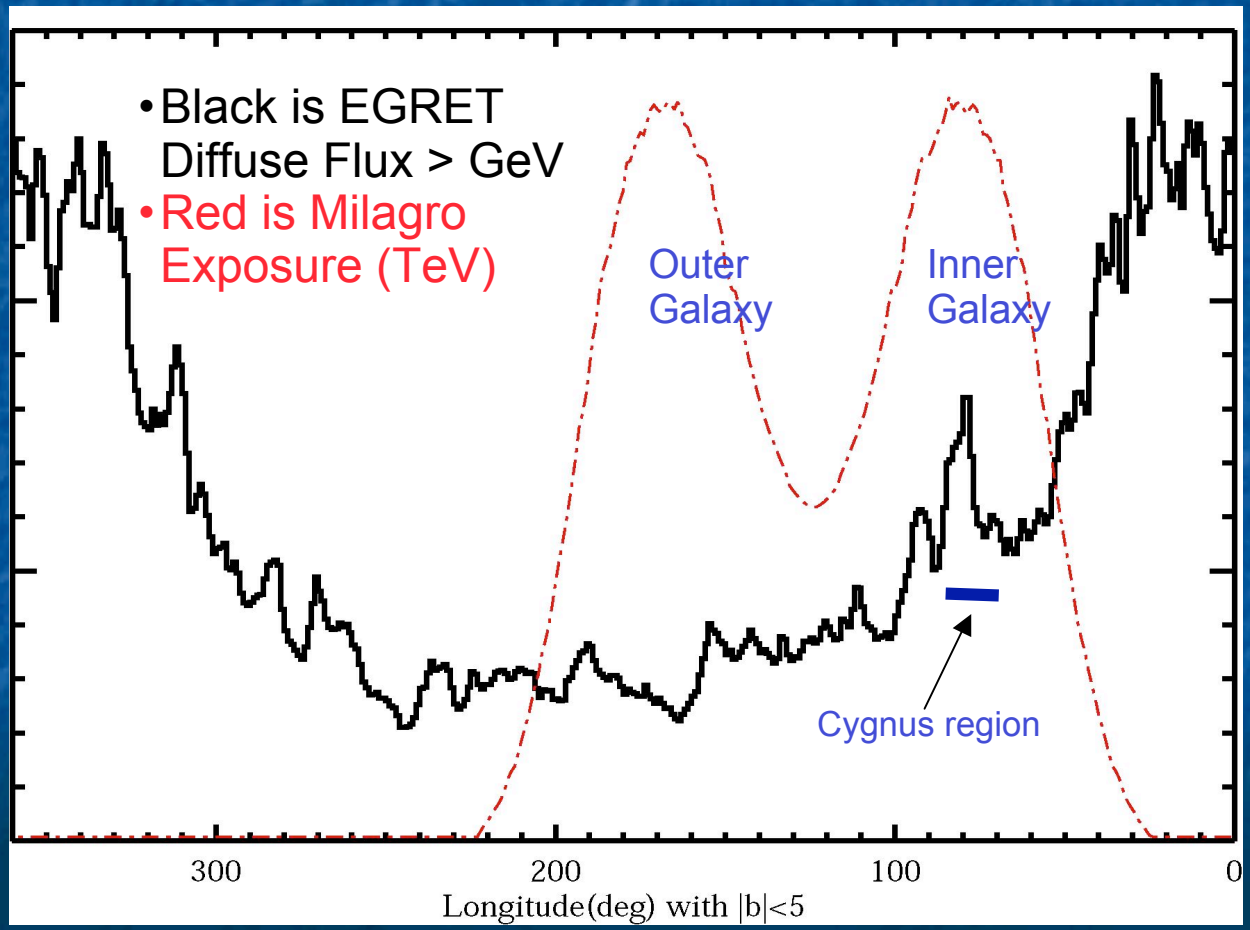
- 3/9 of these most significant regions overlap with 4/18 of Tibet AS most significant regions
- P ~ 1 e -4
- Walker, G. et al. ApJ Lett 2004

LOCATIONS OF ALL REGIONS WITH AN EXCESS GREATER THAN 4 σ

R.A.	Decl.	ON	OFF	Excess	σ	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[a]	22.0	2.17188e+06	2.16222e+06	9665	6.3	NA
166.5[b]	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



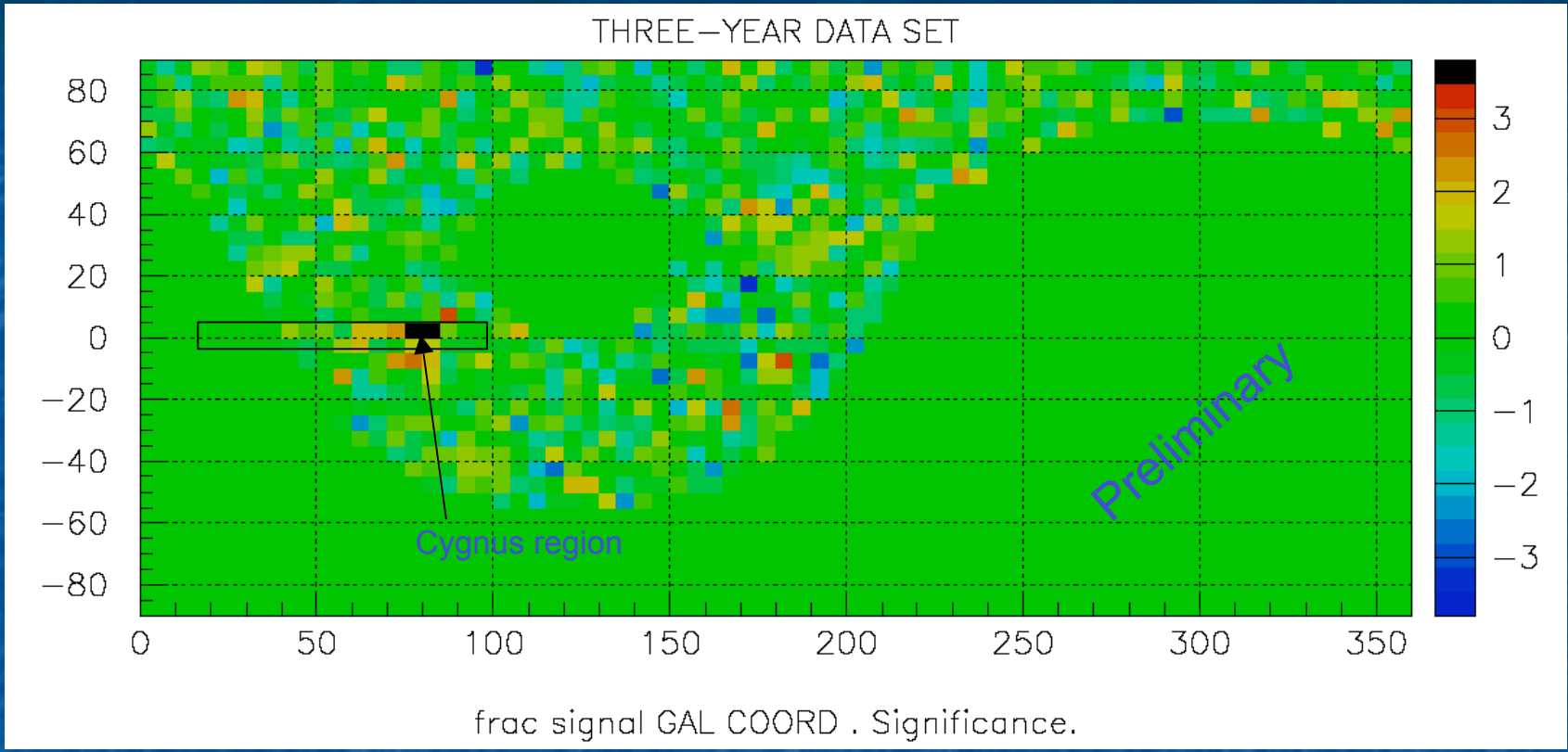
Milagro Observation of the Galactic Plane



Select Region of Galactic plane which is optimized for detection of the diffuse emission predicted by EGRET measurements.

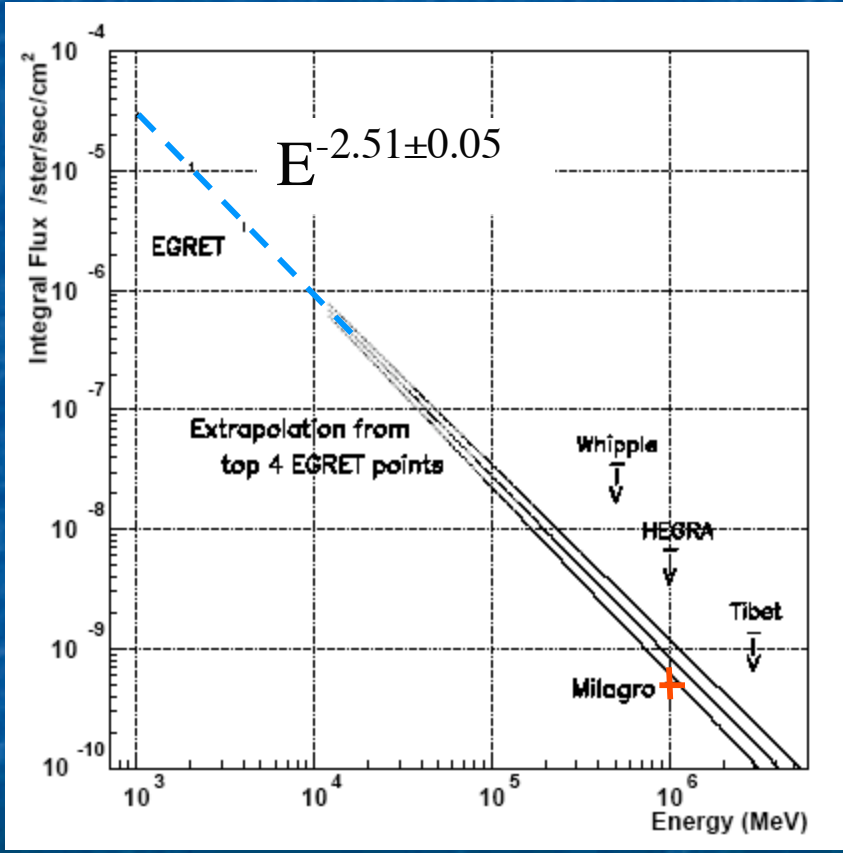
Inner Galaxy bin
l = [20,100]
b = [-5,5]

Milagro Galactic Plane Detection



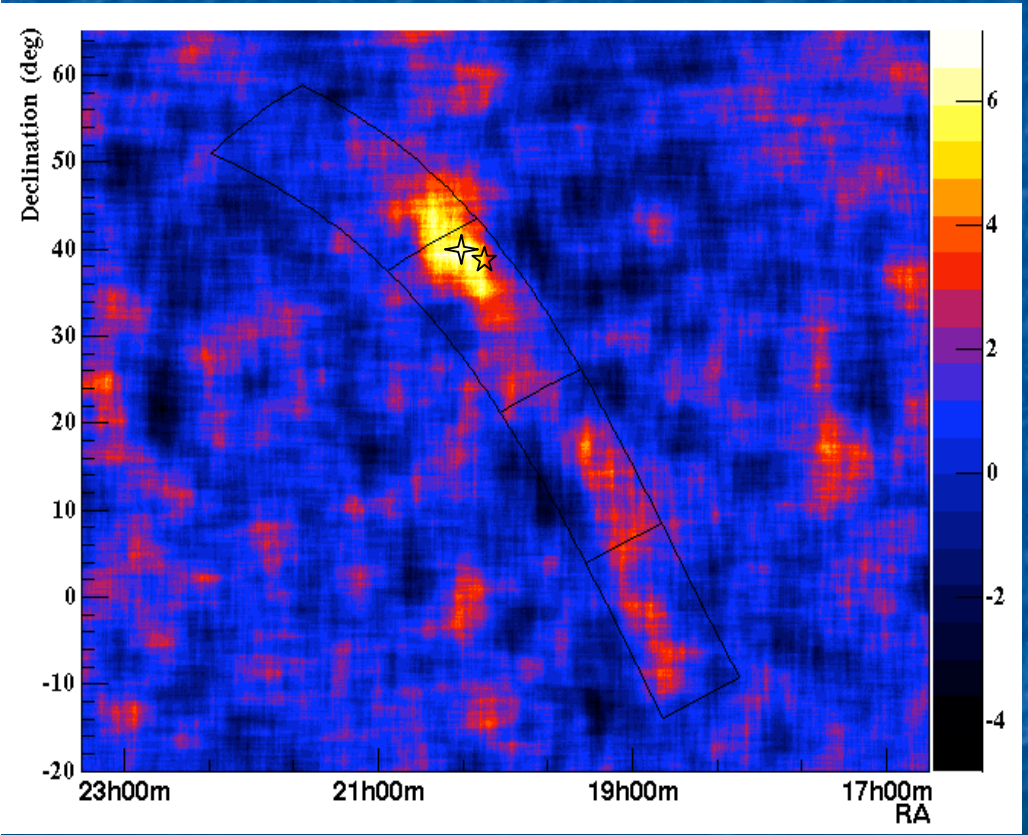
- **4.9 σ excess for the "inner galaxy"**
- **Flux fraction (4.9±1.7) x 10^{-5} of CR**
- **This is the first detection of the galactic plane at these energies (~TeV)**
- **Difficult analysis due to large angular region & small fractional excess**

Galactic Plane Flux Measurement



- Demonstrates the strength of EAS detectors in finding diffuse and extended sources
  - Due to good "inherent" background rejection
  - Angular resolution unimportant
  - Large observation time
  - Large field of view
- Milagro flux measurement is ~1/10 of previous upper limits
- Milagro flux is consistent with extrapolation of EGRET spectrum as well as an $E^{-2.7}$ spectrum which is predicted for cosmic-ray interactions with Galactic matter

Extended Sources



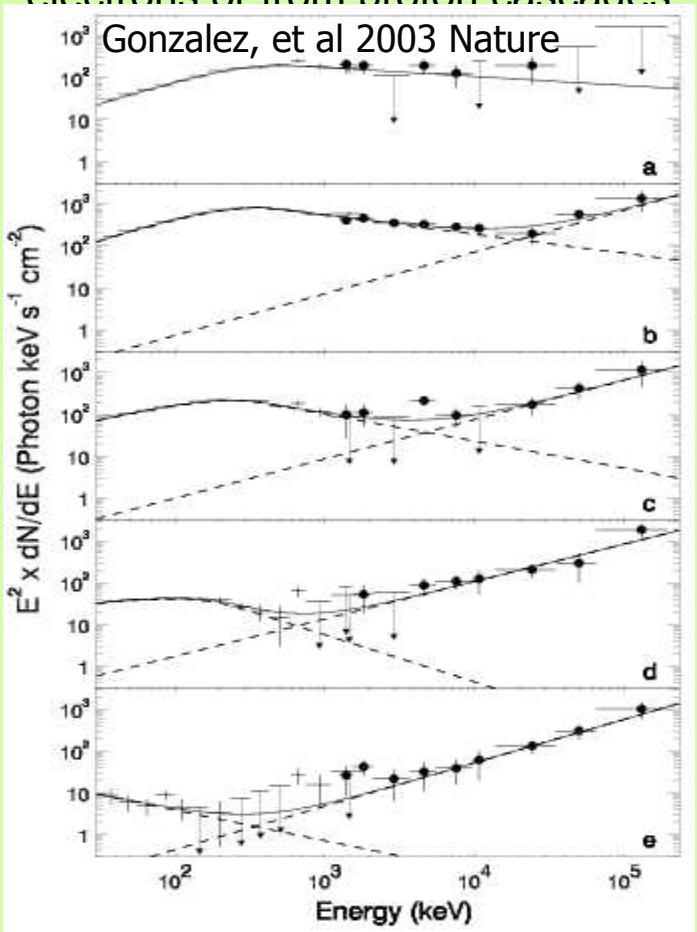
- Search Northern sky for large sources
- ~6 degree source in Cygnus region of Galaxy
  - EGRET observed as brightest region in Northern hemisphere
- ~3 degree source near the Crab
  - Coincident with an EGRET unID

✧ Tibet hotspot

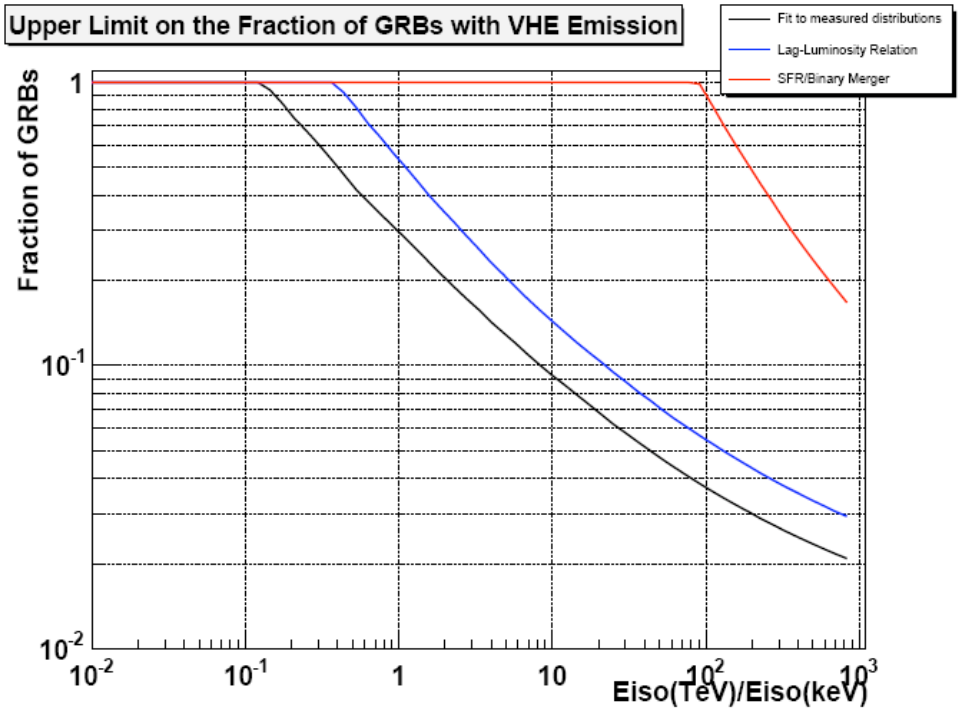
☆ Milagro point source hotspot

Searches for New Classes of TeV emitters: Gamma-Ray Bursts

- Higher energy γ-ray component has been observed up to 100MeV.
- TeV emission is predicted from Inverse Compton scattering of electrons or from proton cascades



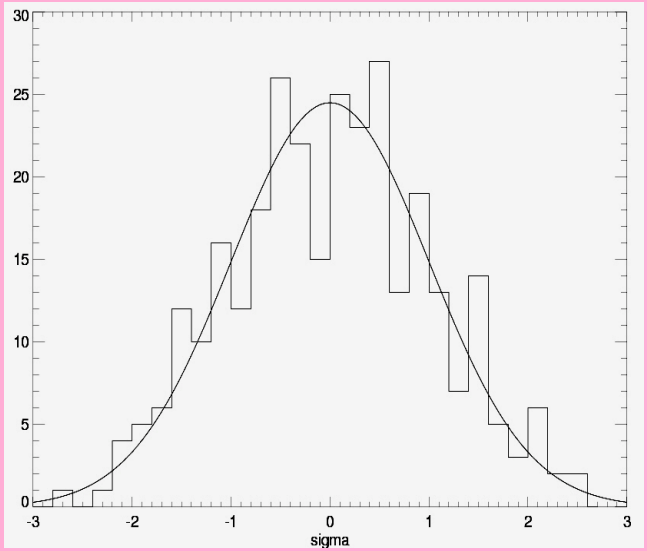
- Milagro data is searched promptly (<4 sec) for transient sources of duration 0.25 msec to >2 hours with no significant detections.
- Milagro upper limits constrain TeV emission, but depend on GRB redshift distribution.
- SWIFT satellite provides GRBs (many with redshift) at rate of ~15/yr in Milagro's f.o.v.



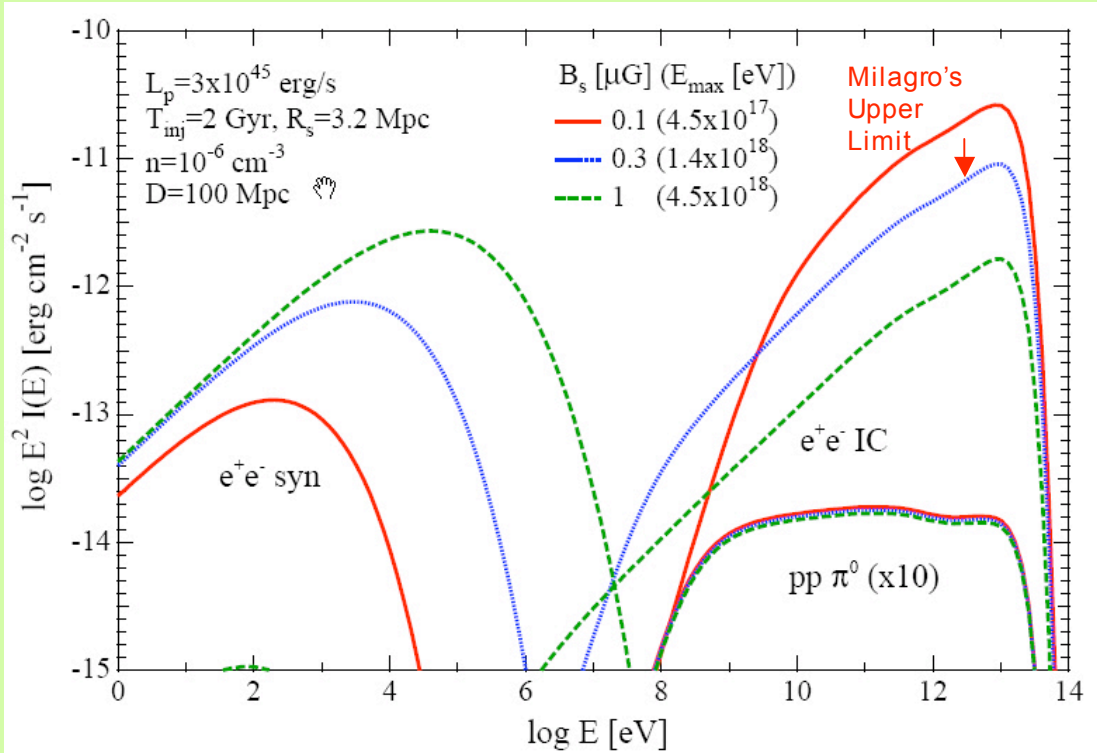
Searches for New Classes of TeV emitters: Galaxy Clusters

- Protons can be accelerated in accretion shocks to >10^{18} eV, and then cascade to produce TeV γ-rays from π^0 decay and Inverse Compton scattering of secondary electrons.
- Emission is predicted to be extended by a few degrees which is well matched to Milagro's point spread function of ~0.5 degrees.

Milagro's search for TeV emission from 307 clusters with z<0.1. This ensemble of sources shows no significant excess.

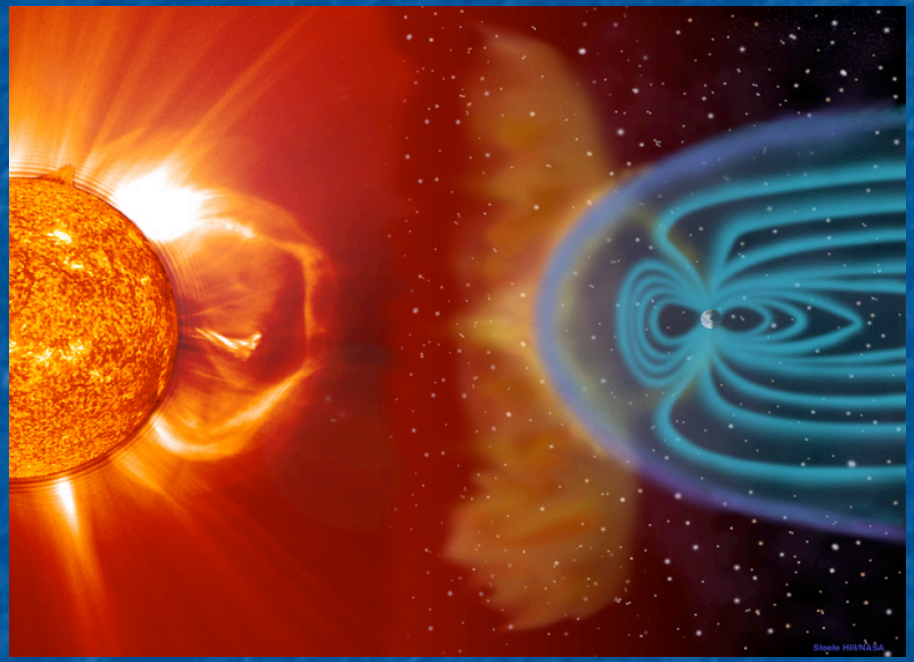


Coma Cluster is massive, nearby cluster. Model for Coma (S. Inoue, F. A. Aharonian, & N. Sugiyama, astro-ph/ 0505398) is shown with the Milagro upper limit

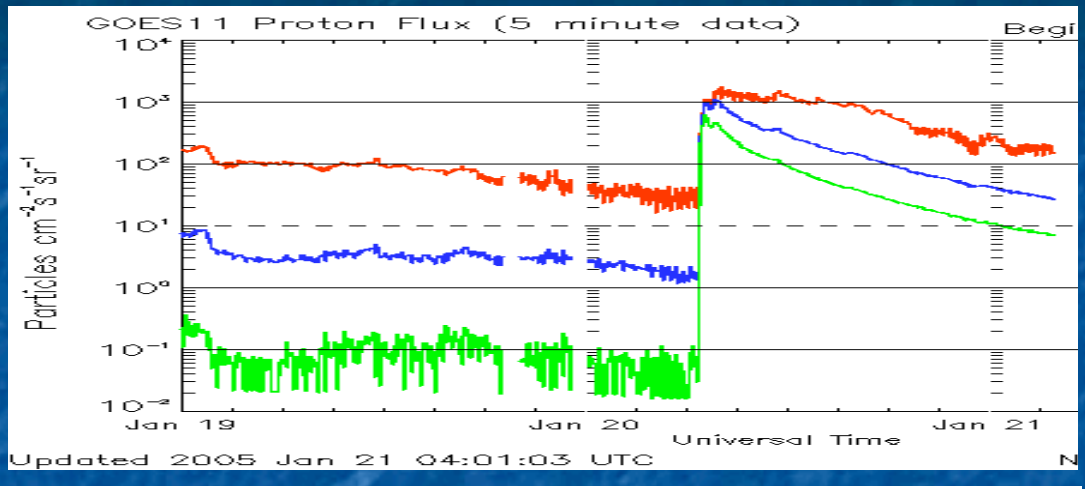


Solar Physics

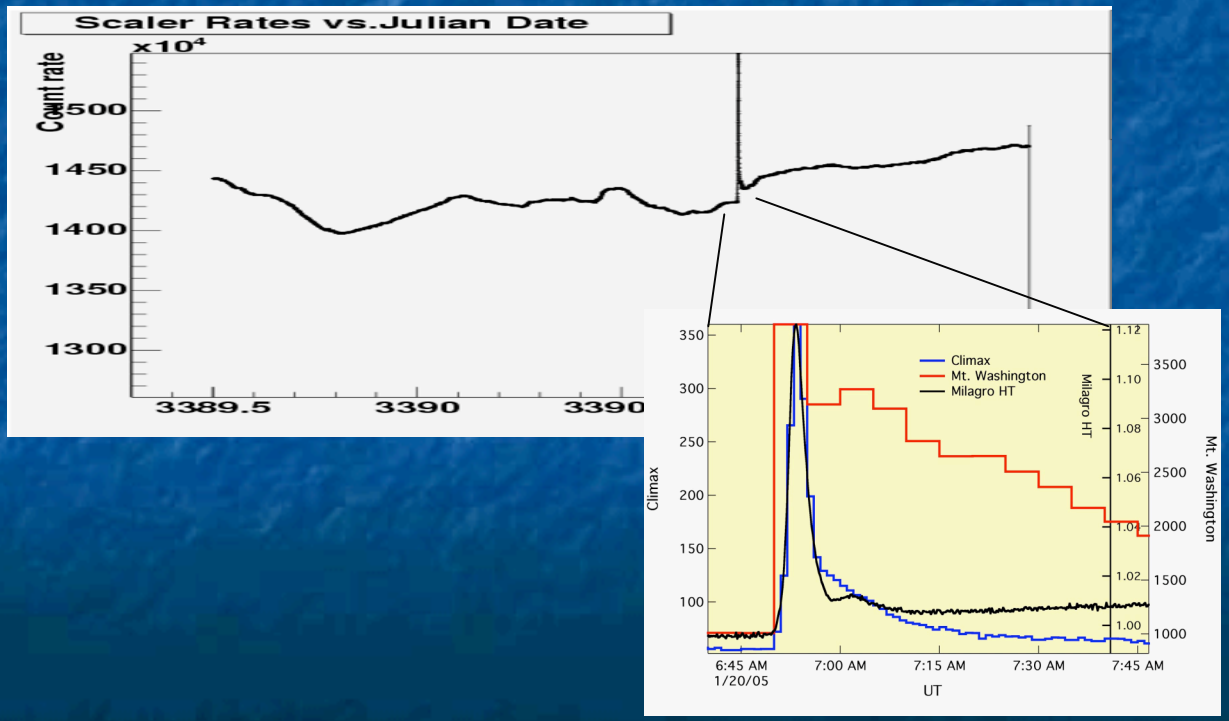
- Coronal mass ejections are an ideal laboratory to study particle acceleration in the cosmos
- By monitoring the singles rates in all PMTs we are sensitive to “low”-energy particles (>10 GeV)
- Milagro has detected 4 events from the Sun with >10 GeV particles



X7-Class Solar flare Jan. 20, 2005



GOES proton data
- >10 MeV
- >50 MeV
- >100 MeV

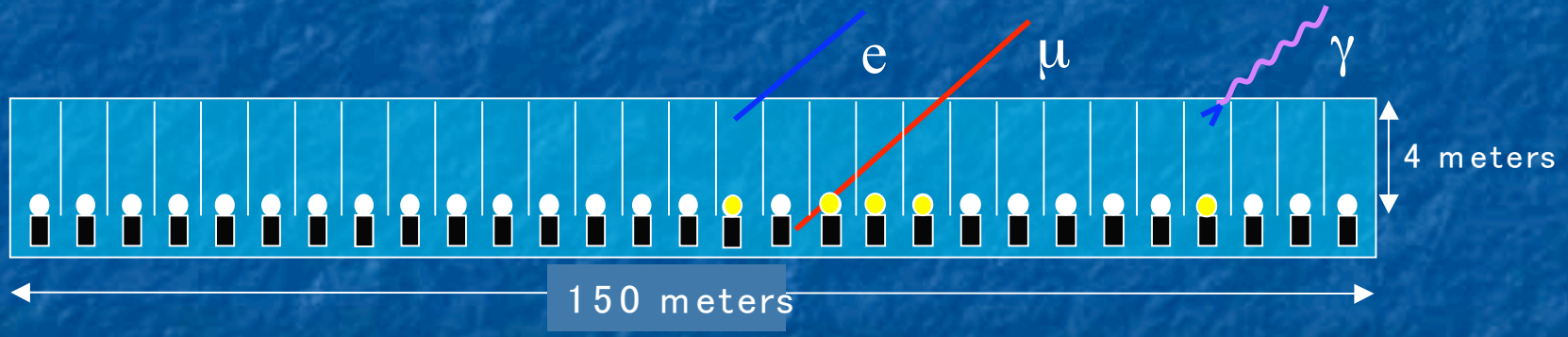


Milagro scaler data
- > 10 GeV protons
- ~1 min rise-time
- ~5 min duration

Neutron Monitors
- Traditional GLE detectors
- 1 min. time resolution

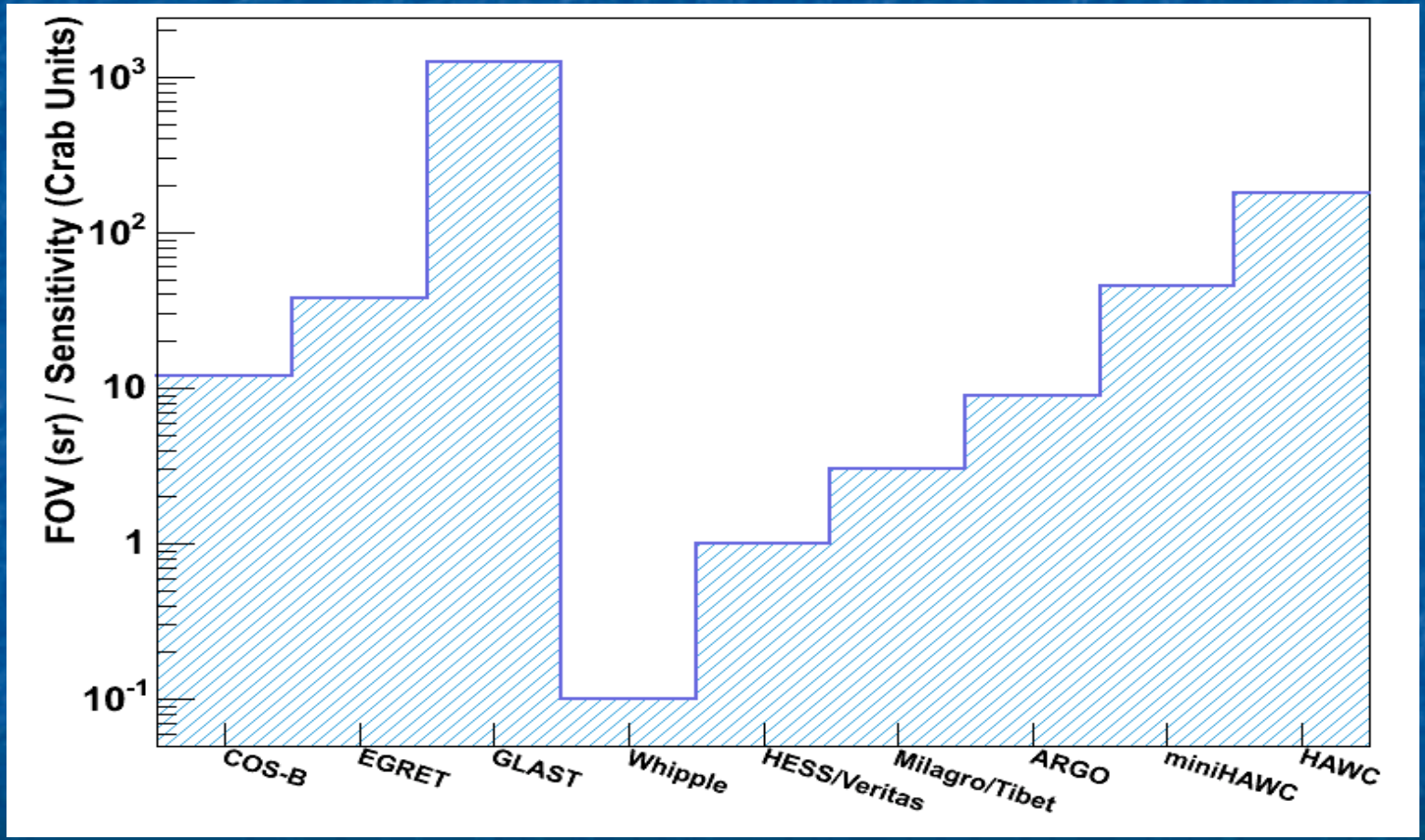
What's Next?
miniHAWC (High Altitude Water Cherenkov)

- Reuse Milagro's 900 PMTs and DAQ system
- Build pond at extreme altitude (Tibet 4300m or Chile 5200m)
- Incorporate new design
  - Optical isolation between PMTs
  - Larger PMT spacing (5 m vs 3 m in Milagro)
  - Deeper PMT depth (in only one layer)



- ~$2-3 M for complete detector
- ~15x sensitivity of Milagro
  Crab Nebula at 4 σ in 1 day
  60 mCrab at 5 σ in 1 year on entire sky

Survey Sensitivity



Conclusions

- Milagro is a new technique using water Cherenkov that is capable of surveying the TeV sky
- Milagro has discovered TeV emission from extended sources
- Milagro has placed constraints on the TeV emission from various classes of sources
- Milagro has proven to be useful detector of solar energetic particles and Forbush decreases
- Milagro (1st generation water Cherenkov detector) sensitivity can improved by 15 times with modest cost (2nd generation)
- Large Field of View, High Duty Cycle, TeV observatories complement Air Cherenkov Telescopes providing different, yet in many cases, supporting information.