# Windows on the TeV Sky: Milagro and HAWC

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Physics Department Seminar
Southern Methodist University
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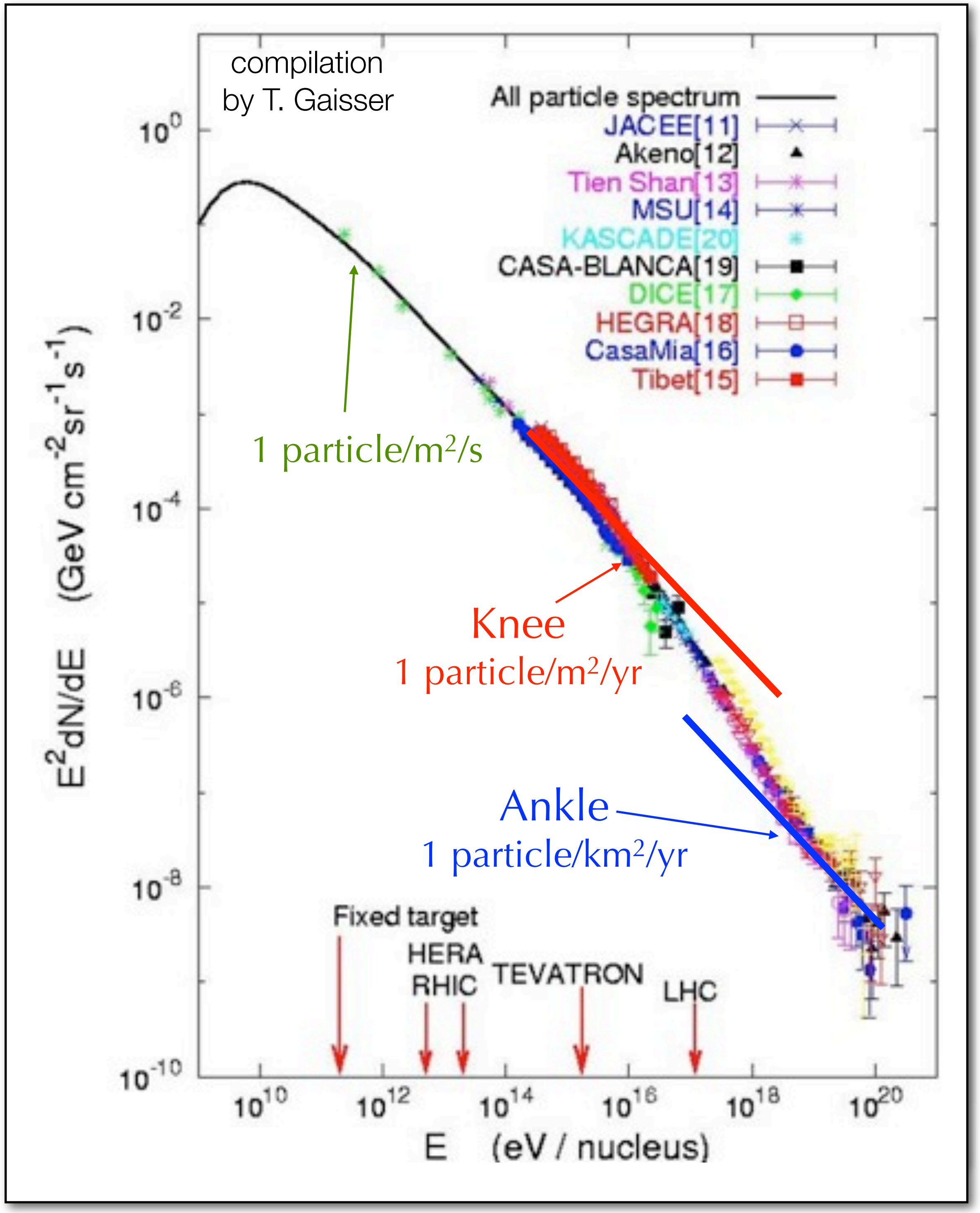
# Outline

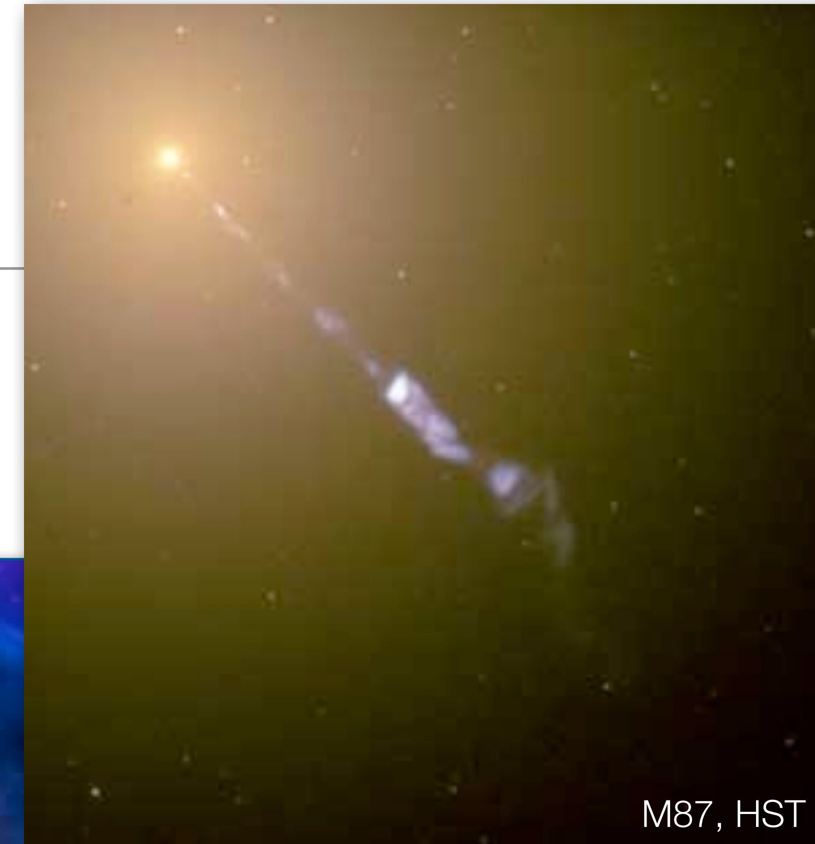
- Very High Energy Astrophysics & the Sources of Cosmic Rays
- Results from Milagro
  - Survey of the Galactic Plane
  - The Geminga pulsar
  - Diffuse Galactic emission
  - Cosmic ray anisotropy
- The High Altitude Water Cherenkov (HAWC) Observatory
  - Capabilities
  - Status

# Cosmic Rays and the High Energy Universe

- Radiation of cosmic origin first established in 1912
  - Hess carries electroscopes to 5000 m altitude (!) in a balloon
- What are they?
  - Charged particles, so they don't point back to their sources
  - Clues from spectrum, composition
- Where do they come from?
- How are they accelerated?
- Can we learn new physics by understanding their sources?

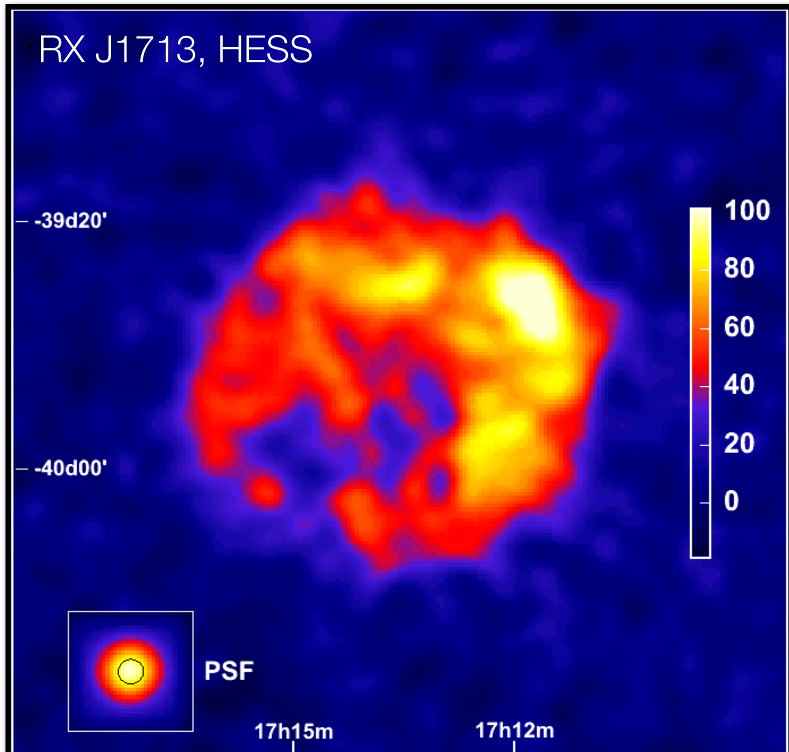


# Astrophysical Accelerators

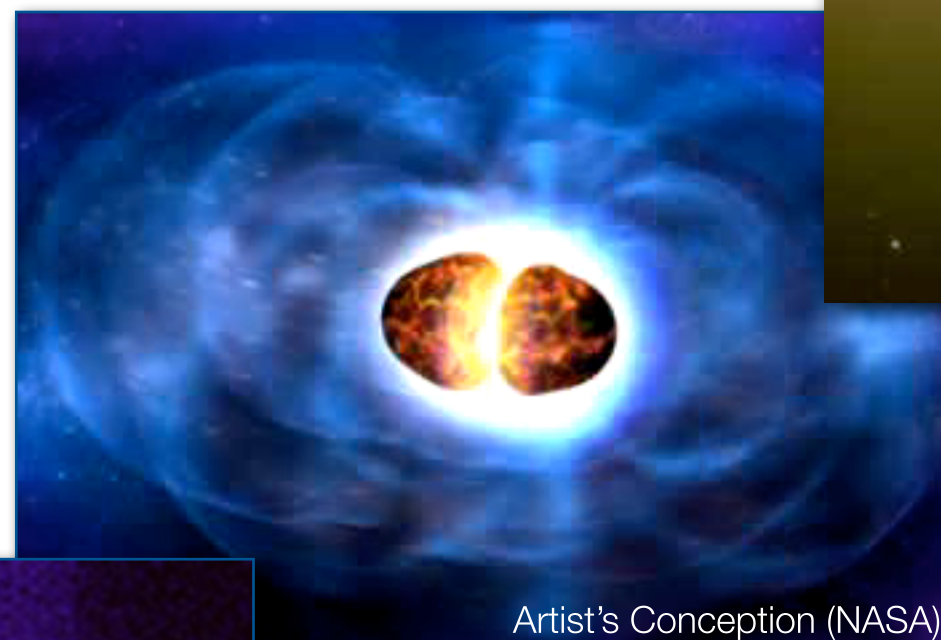


M87, HST

AGN

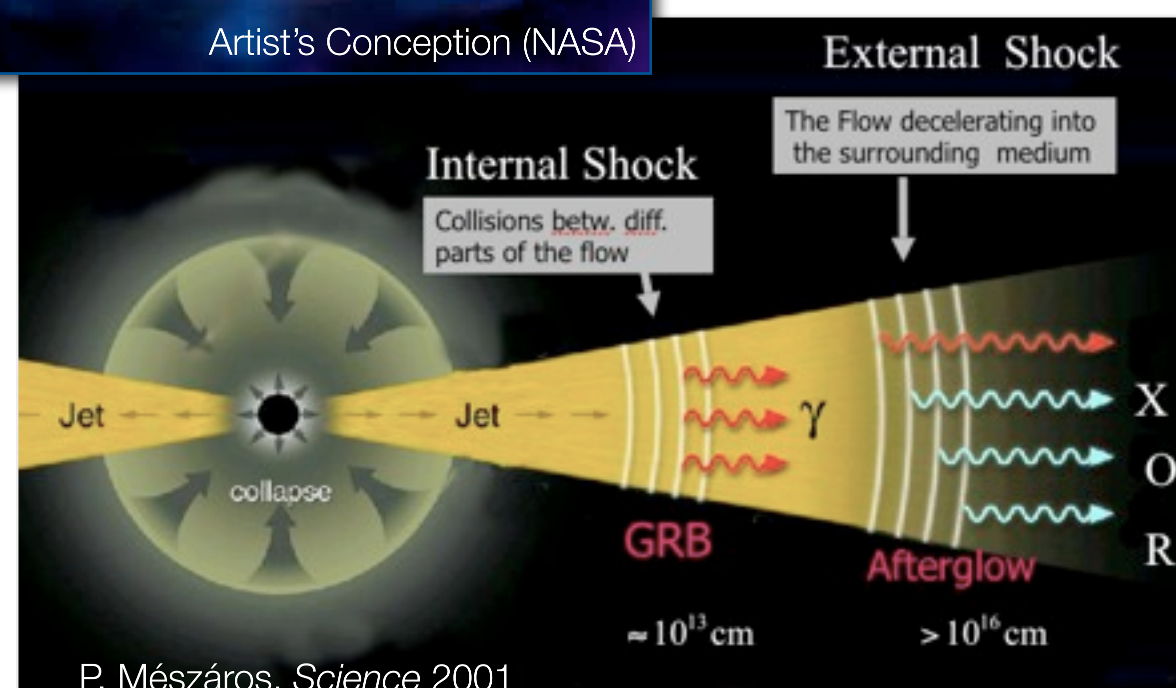



RX J1713, HESS



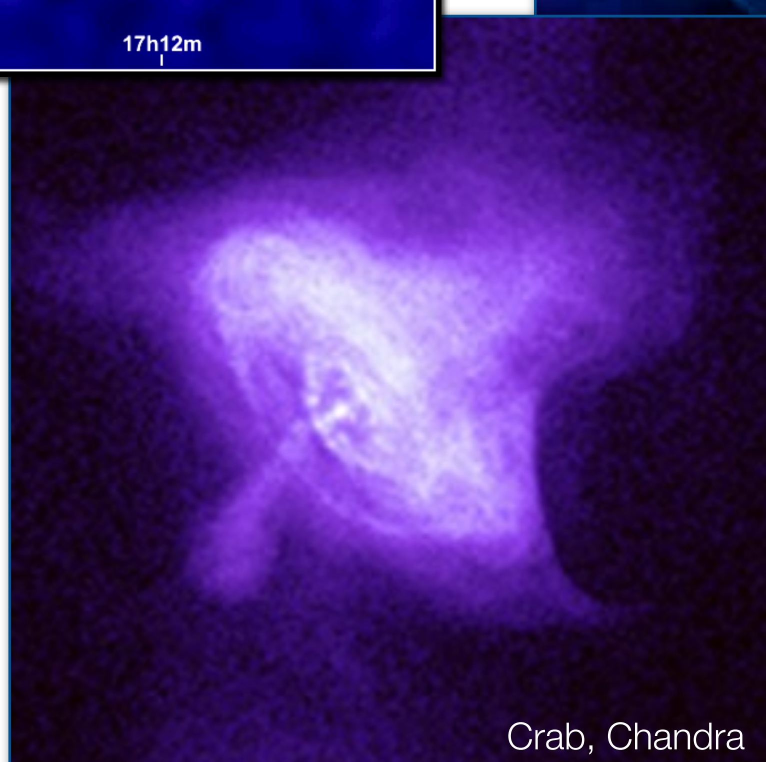
Artist's Conception (NASA)

GRBs




P. Mészáros, *Science* 2001

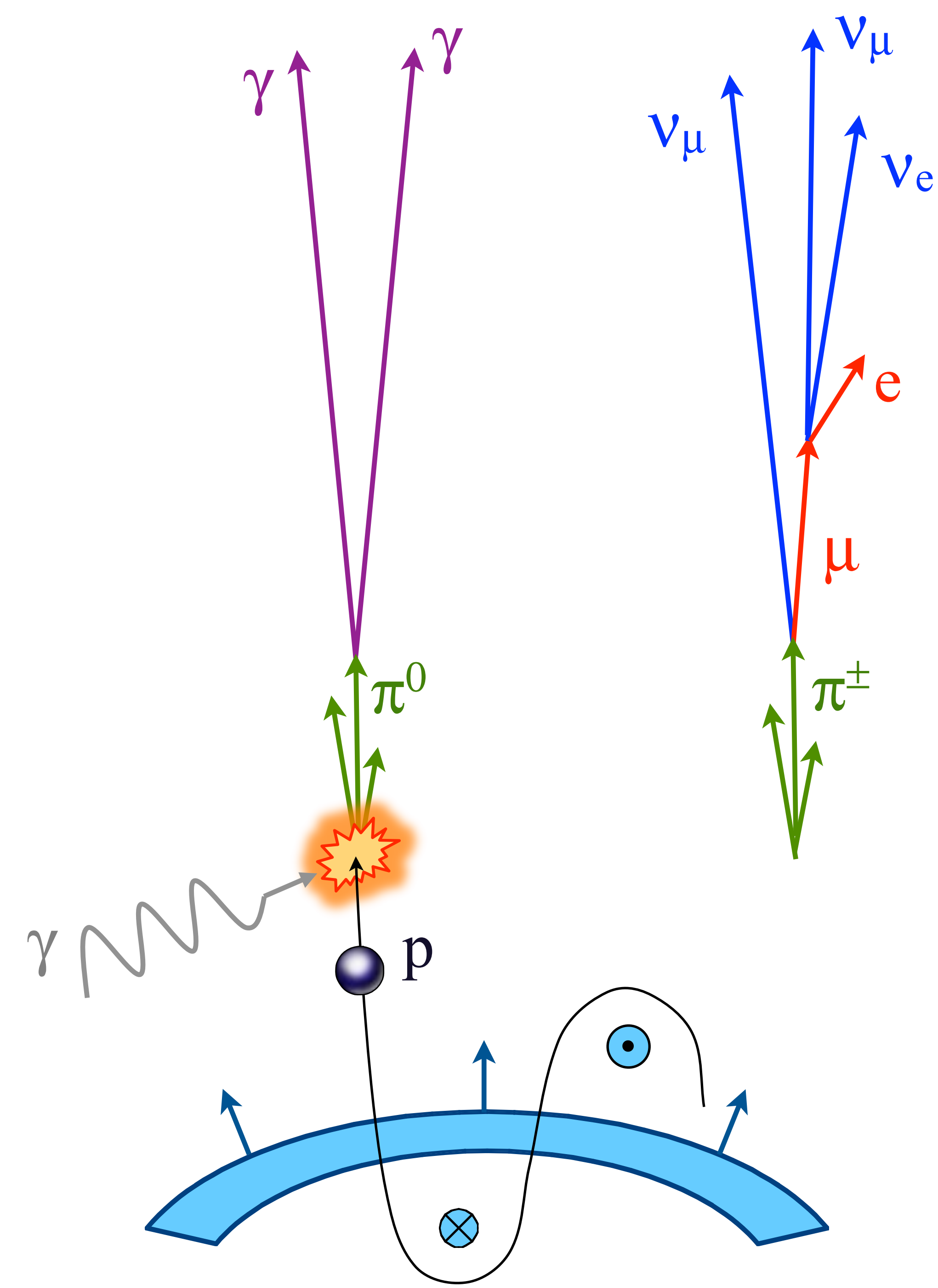
SNRs & PWN



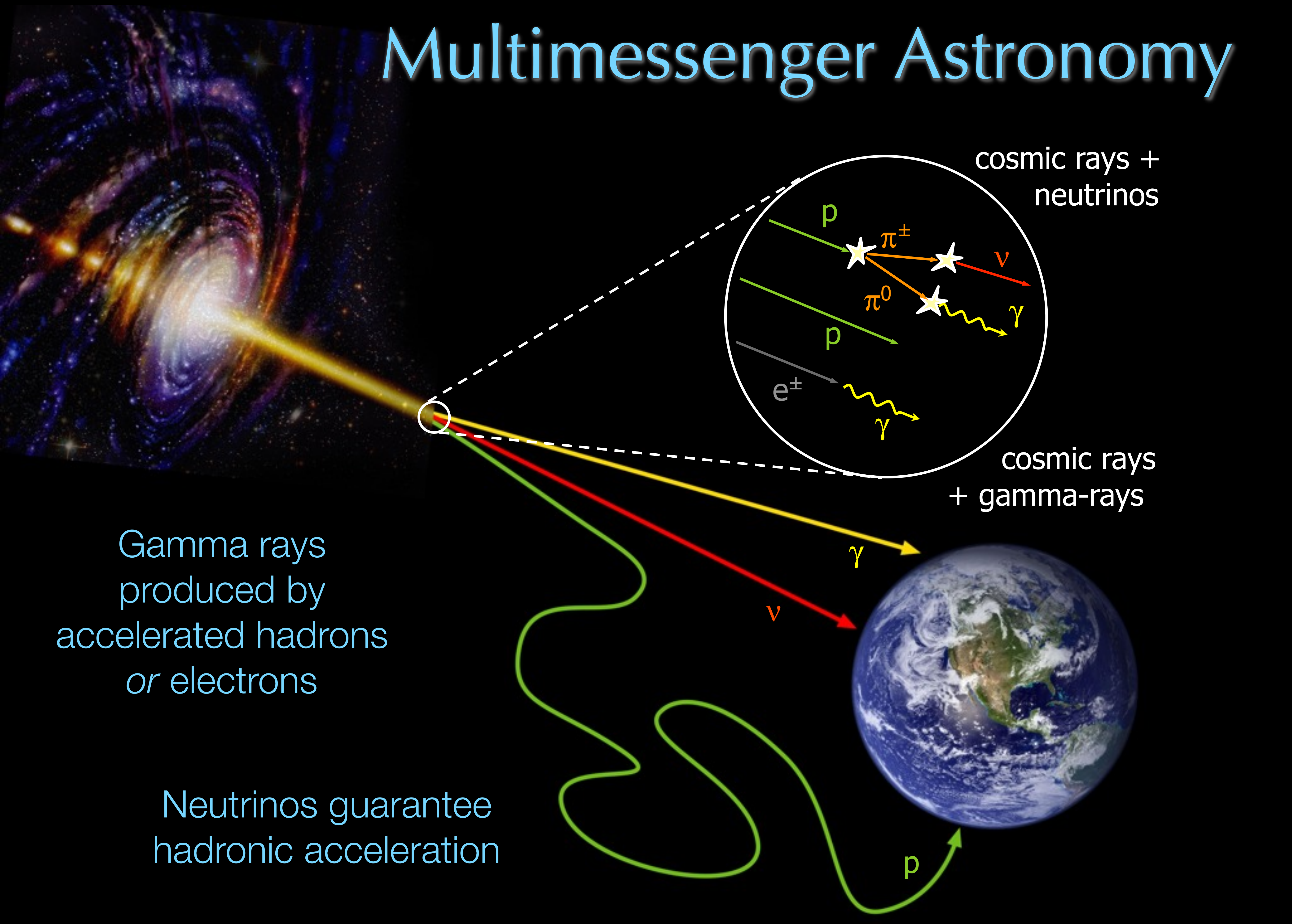
Crab, Chandra

# Neutrinos, Gamma Rays, & Cosmic Rays

- Cosmic ray trajectories scrambled by magnetic fields – need a proxy
- Accelerated cosmic rays are likely to interact with matter or radiation fields
  - Neutrinos via decay of $\pi^{\pm}$, $K^{\pm}$
  - Gamma ray production from neutral $\pi$, $K$
- Secondaries have $\mathcal{O}(10\%)$ of the cosmic ray's energy



# Multimessenger Astronomy

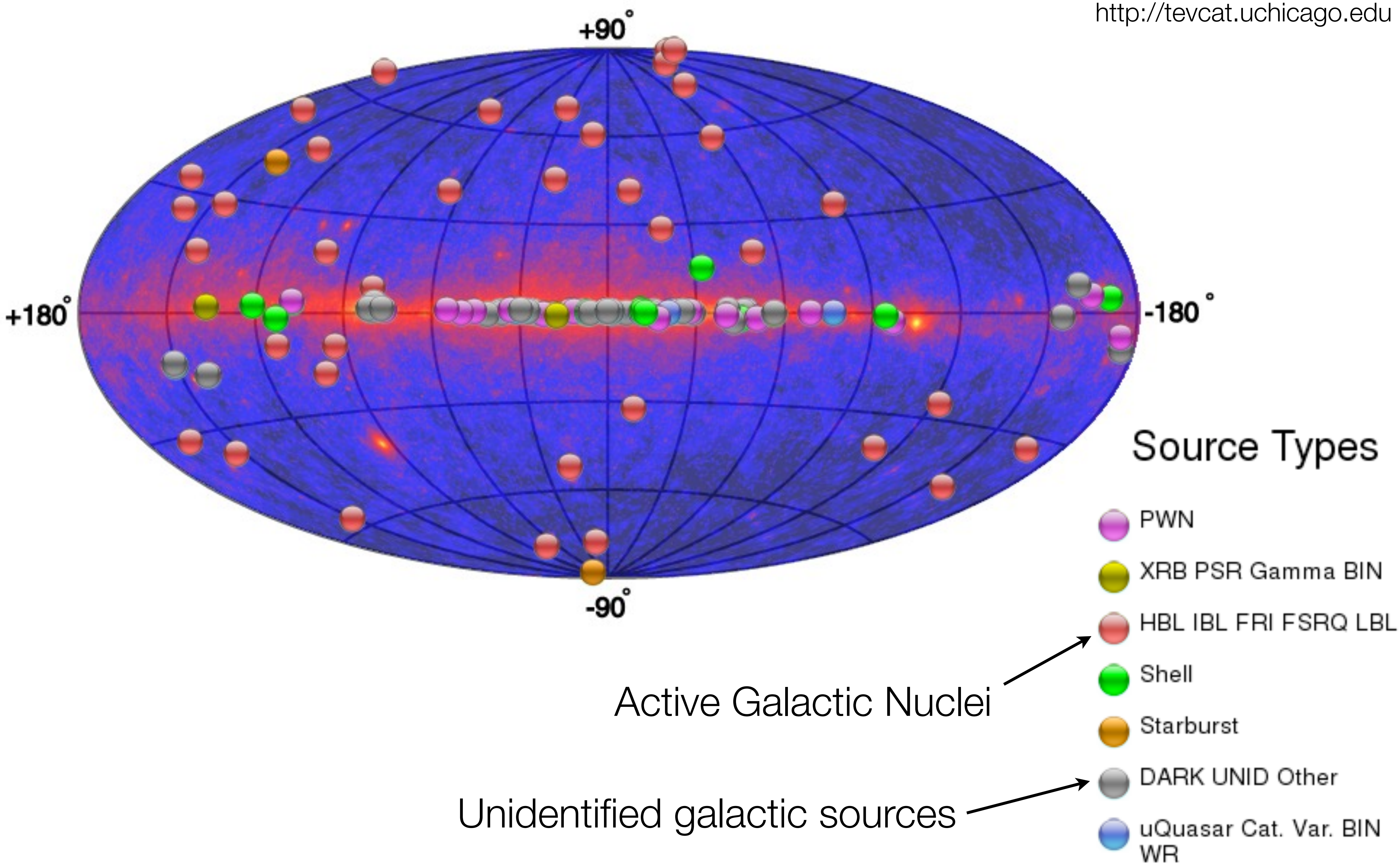



Gamma rays produced by accelerated hadrons *or* electrons

Neutrinos guarantee hadronic acceleration

# The Gamma Ray Sky (2010)

http://tevcat.uchicago.edu




Active Galactic Nuclei

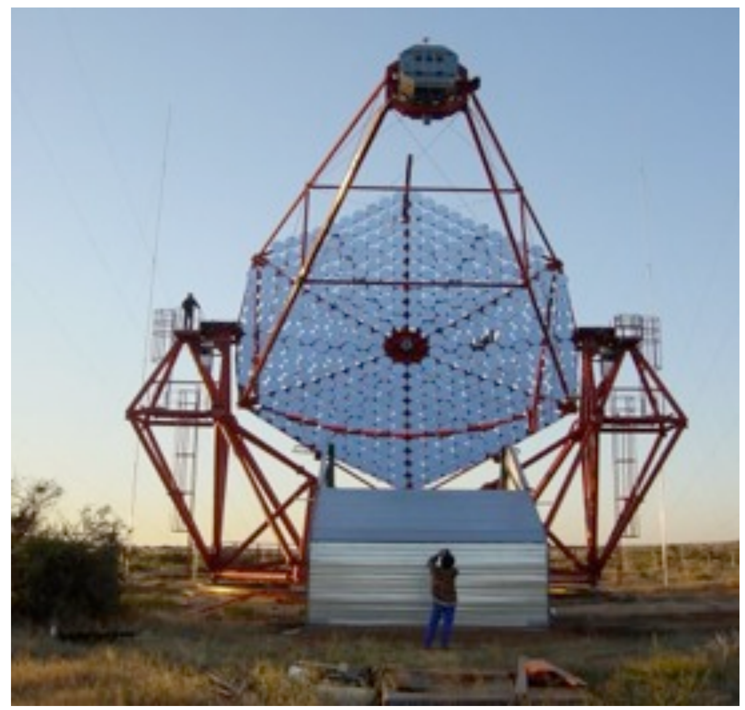
Unidentified galactic sources

# Gamma Ray Telescopes

**Low Energy Threshold**
EGRET, Fermi

Optimal energy ~ 1 GeV
Area ~ 1 $m^2$
"Background Free" (>>99%)
Angular resolution ~ 0.5°
Energy resolution ~ 10%
85% duty cycle / ~2.7 sr aperture

**High Sensitivity**
HESS, VERITAS, MAGIC



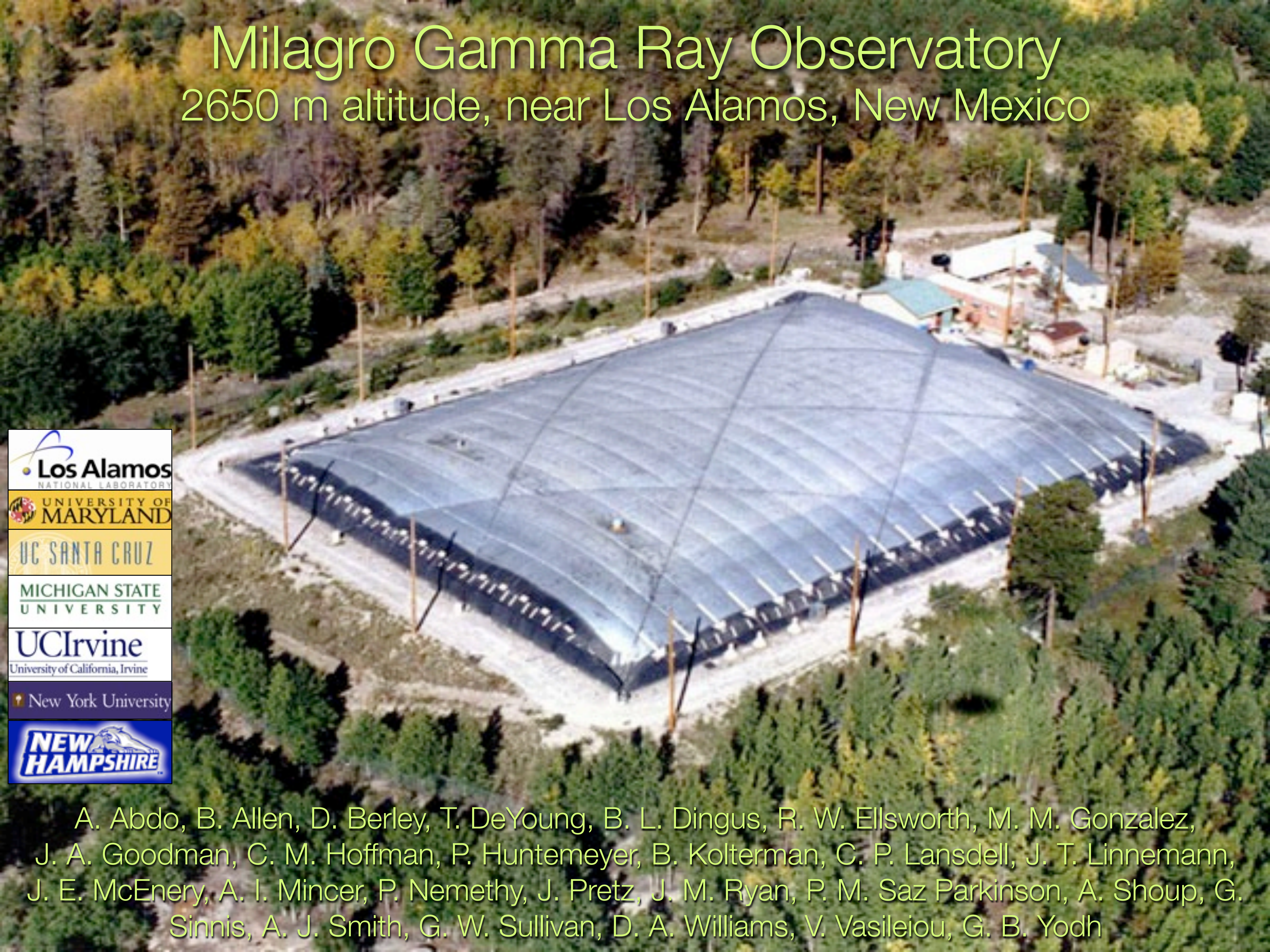
Optimal energy ~ 1 TeV
Effective area ~ $10^4$ $m^2$
Background rejection ~ 99%
Angular resolution ~ 0.05°
Energy Resolution ~ 15%
10% duty cycle / ~0.003 sr aperture

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

Optimal energy ~ 20 TeV
Effective area ~ $10^4$ $m^2$
Background rejection ~ 95%
Angular resolution ~ 0.7°
Energy resolution ~ 50%
95% duty cycle / ~1.8 sr aperture

# Milagro Gamma Ray Observatory

## 2650 m altitude, near Los Alamos, New Mexico

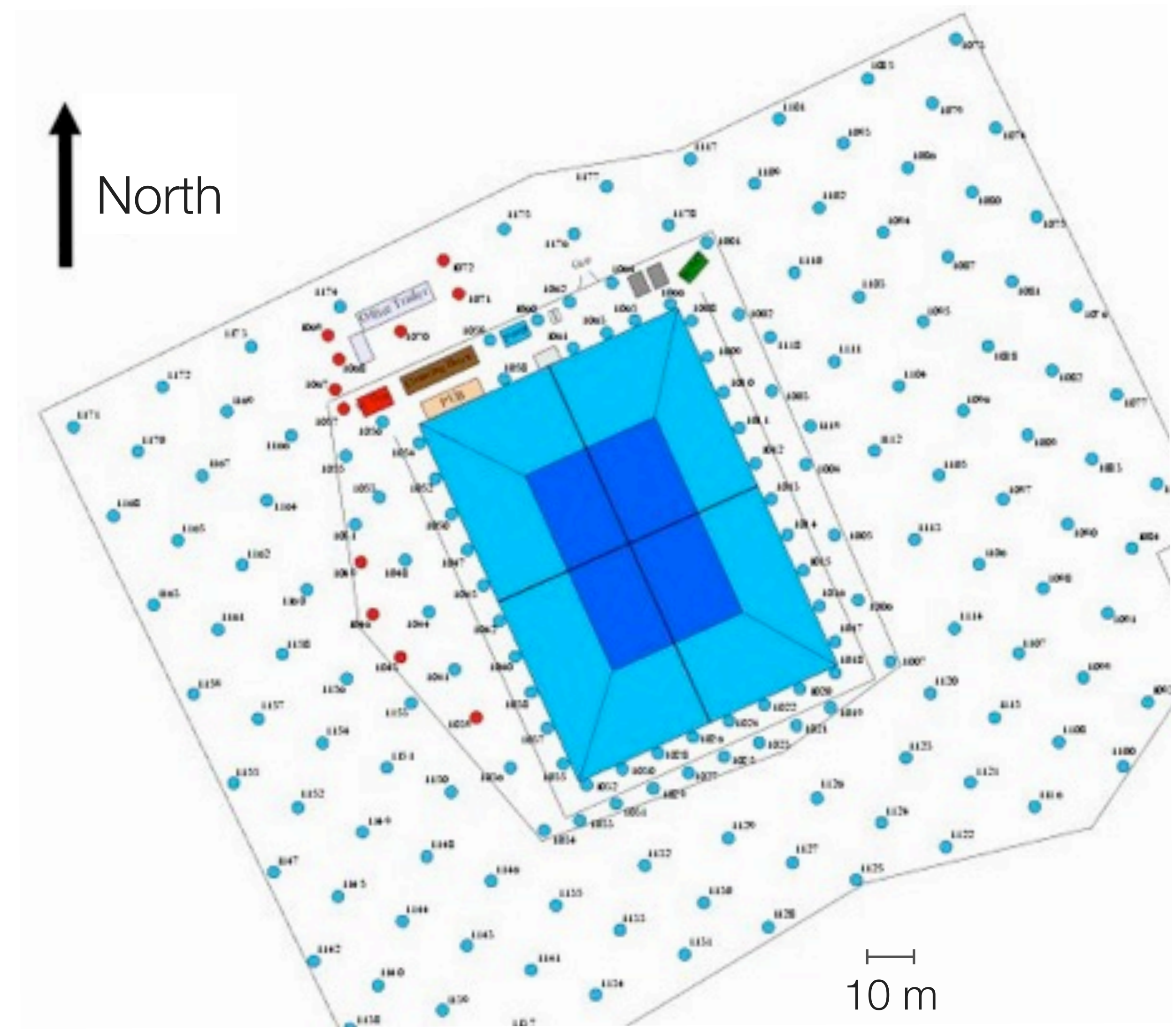


Los Alamos National Laboratory
University of Maryland
UC Santa Cruz
Michigan State University
UCIrvine University of California, Irvine
New York University
New Hampshire

A. Abdo, B. Allen, D. Berley, 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

# The Milagro Observatory

- 2650 m above sea level
- 898 photomultipliers
  - 450 in top layer of pond
  - 273 in bottom layer of pond
  - 175 outrigger tanks
- 3600 m$^2$ pond, operational Jan. 2001



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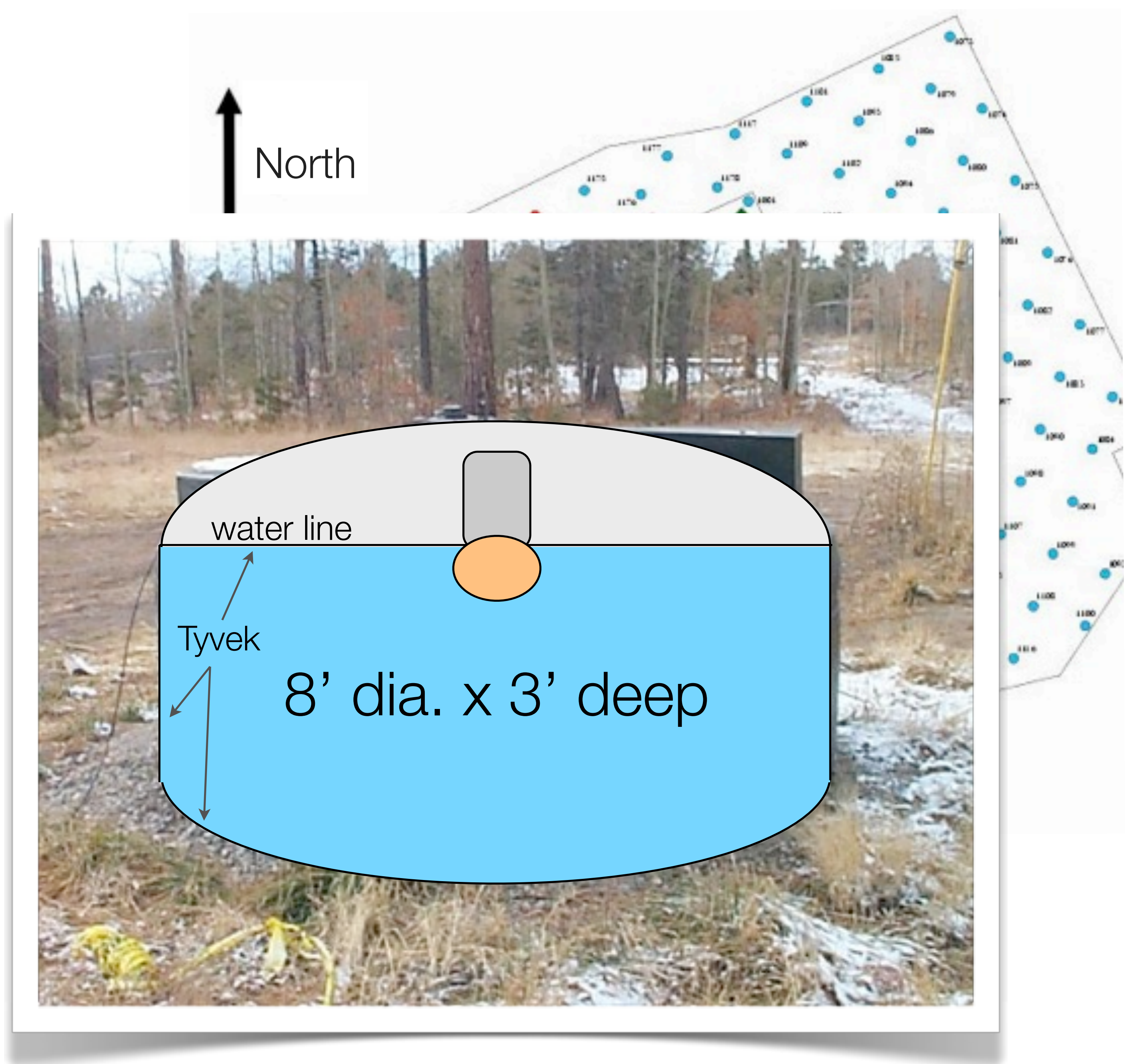
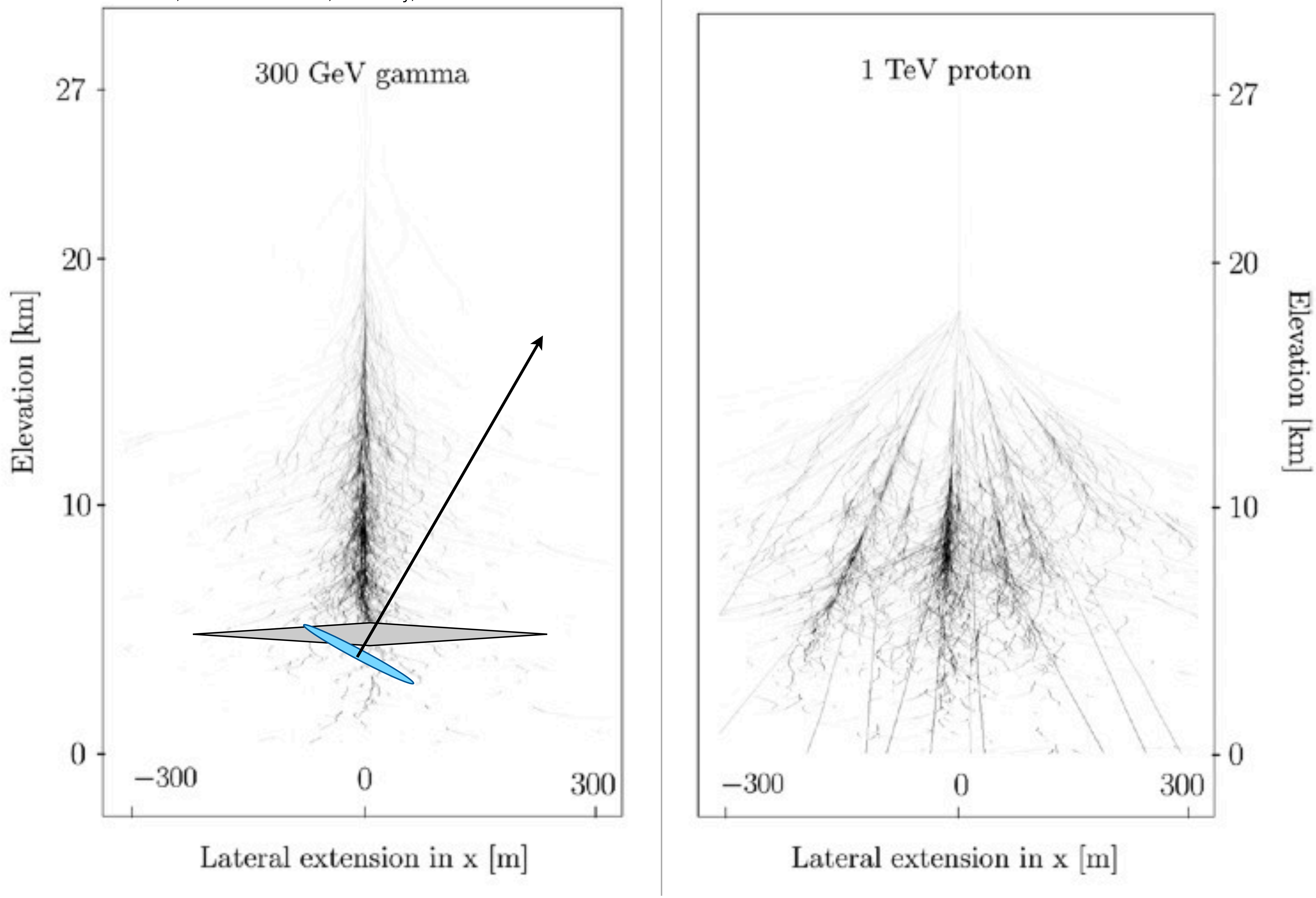
- 3600 m$^2$ pond, operational Jan. 2001
- 34,000 m$^2$ outrigger array, fully operational June 2004



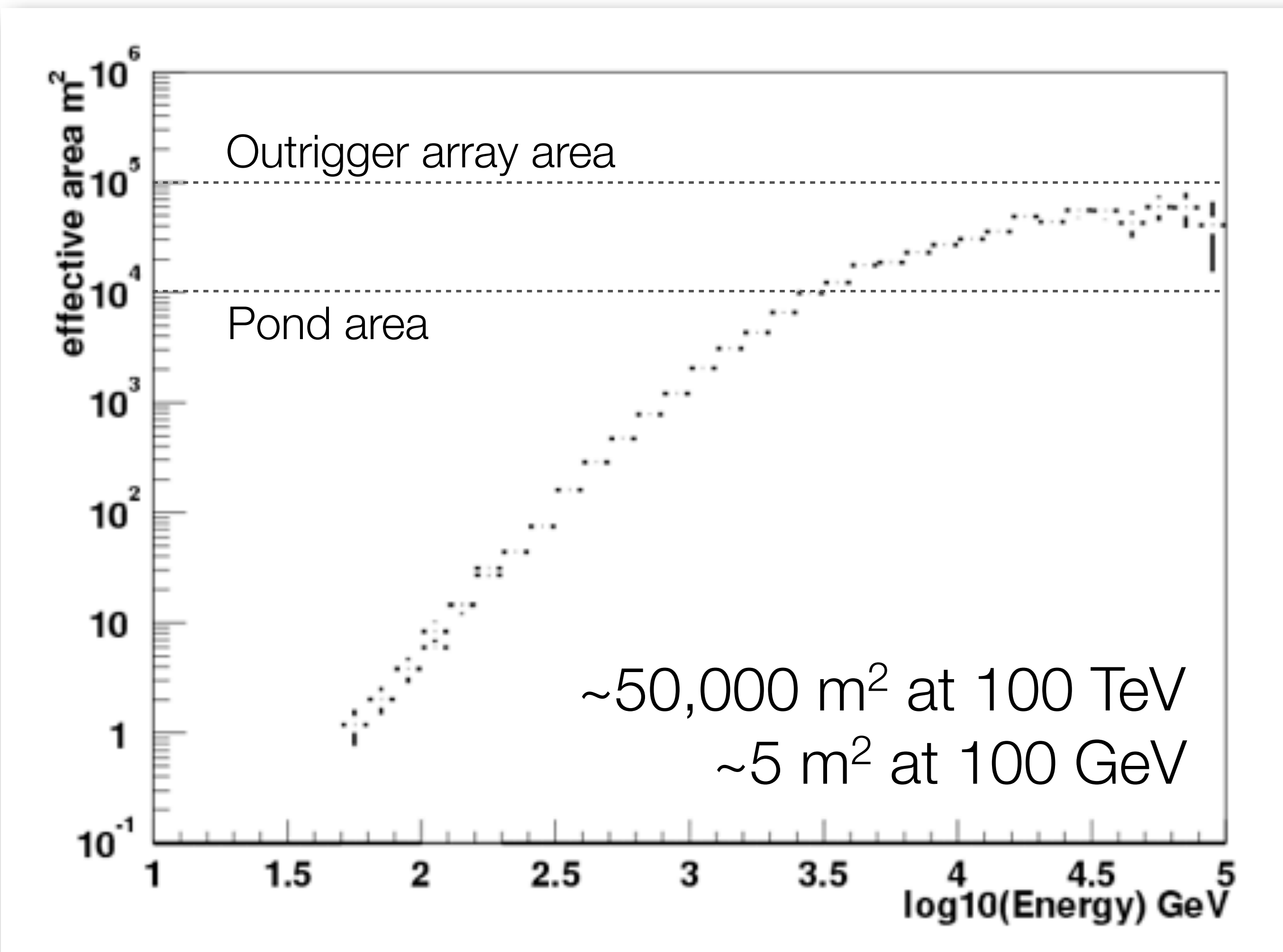
S. Funk, from Aharonian, Buckley, Kifune & Sinnis 2008



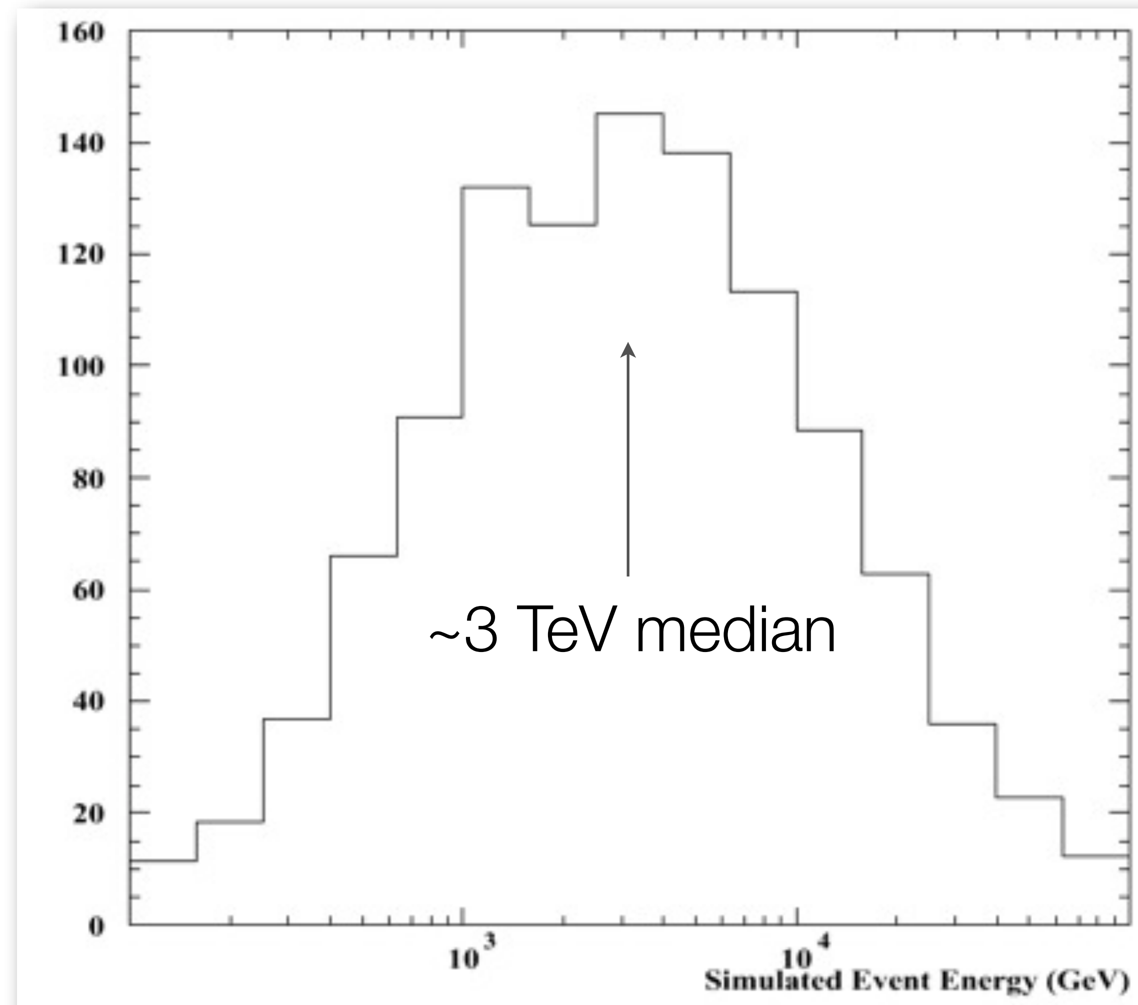

Need to separate gamma rays from cosmic ray background

# Milagro Capabilities

## Effective Area

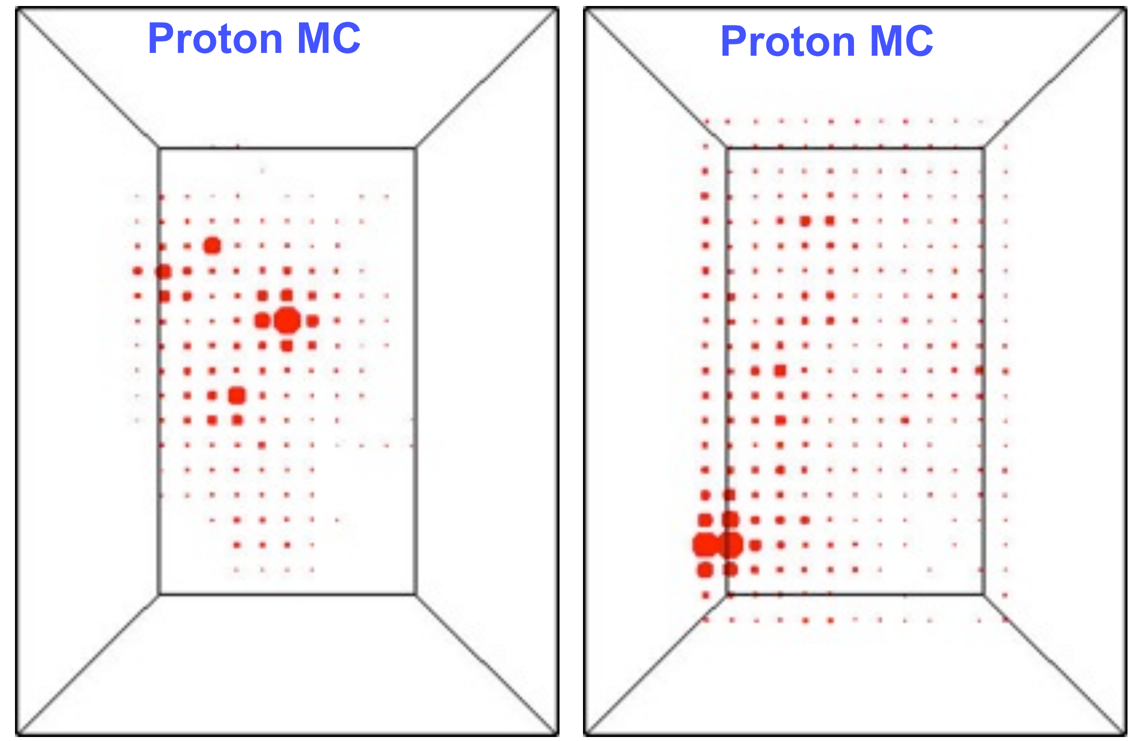


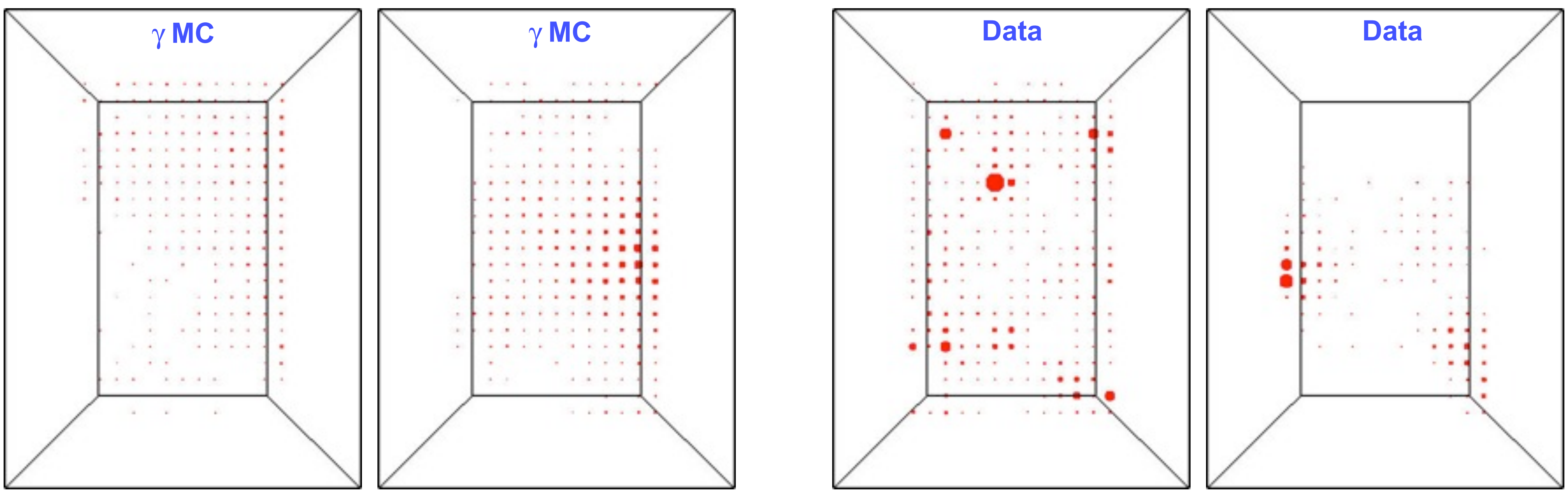

## Energy Response (Crab)



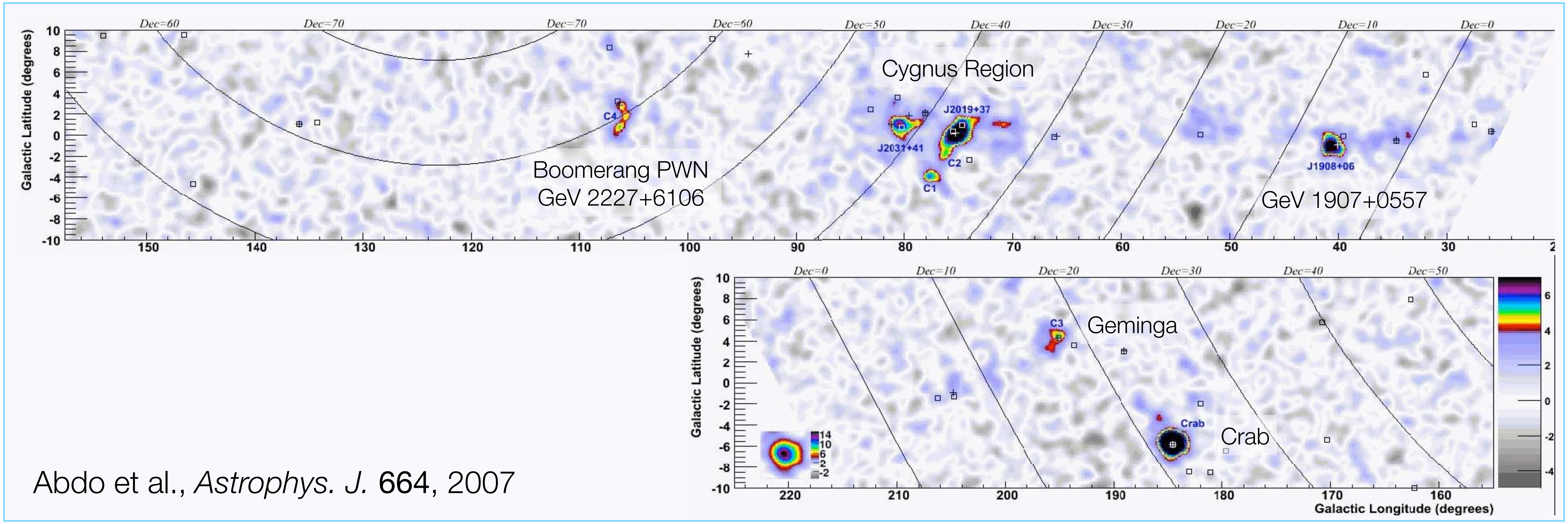
# Background Rejection in Milagro

- Need to separate gamma rays from much more numerous cosmic rays
  - Cosmic-ray induced air showers contain penetrating μ’s & hadrons
  - Cosmic-ray showers lead to clumpier distribution of particles than smooth gamma rays



# Milagro TeV Survey of the Galactic Plane




Abdo et al., *Astrophys. J.* 664, 2007

- Observations with Milagro wide-field TeV telescope, 2000–06
  - 4 detected sources, additional 3-4 candidates (<5σ post-trials)
  - 5/7 have EGRET GeV counterparts (13 sources in the region, $p$=3x10$^{-6}$)
  - Significant diffuse emission in the Cygnus region

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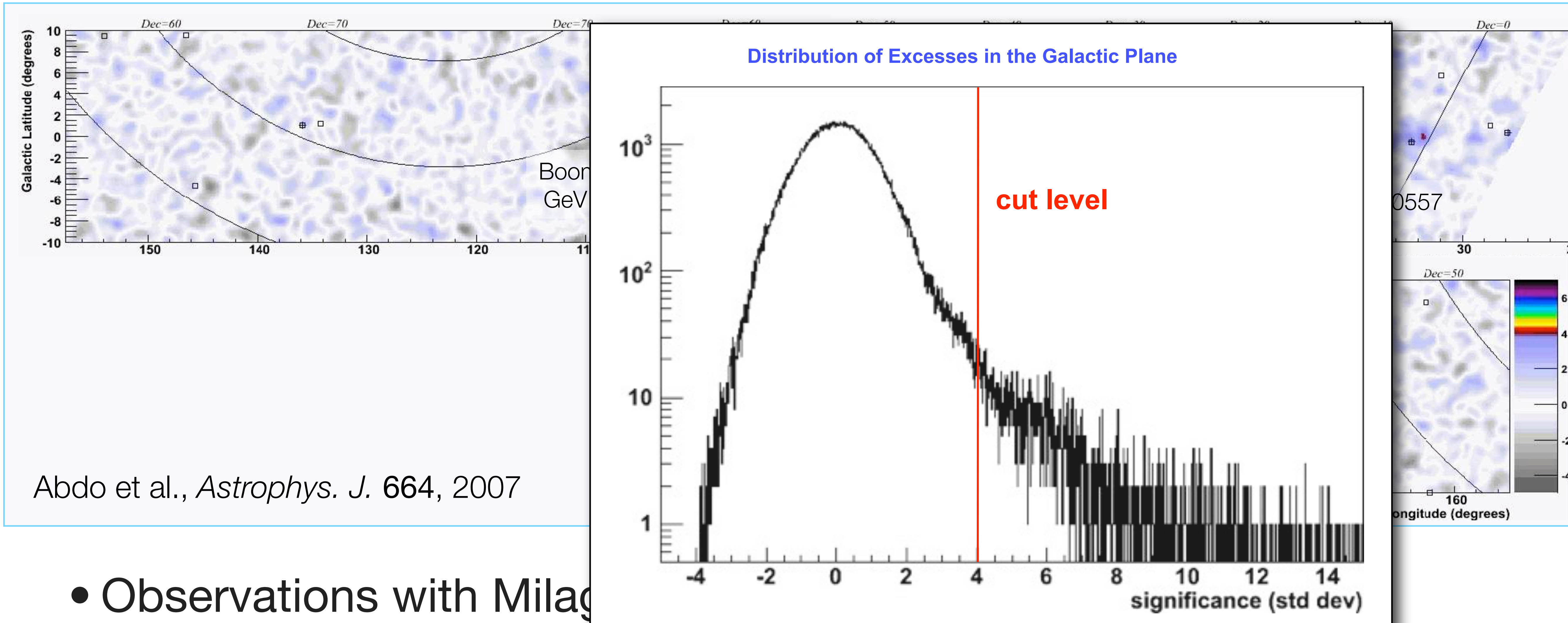


Abdo et al., *Astrophys. J.* 664, 2007

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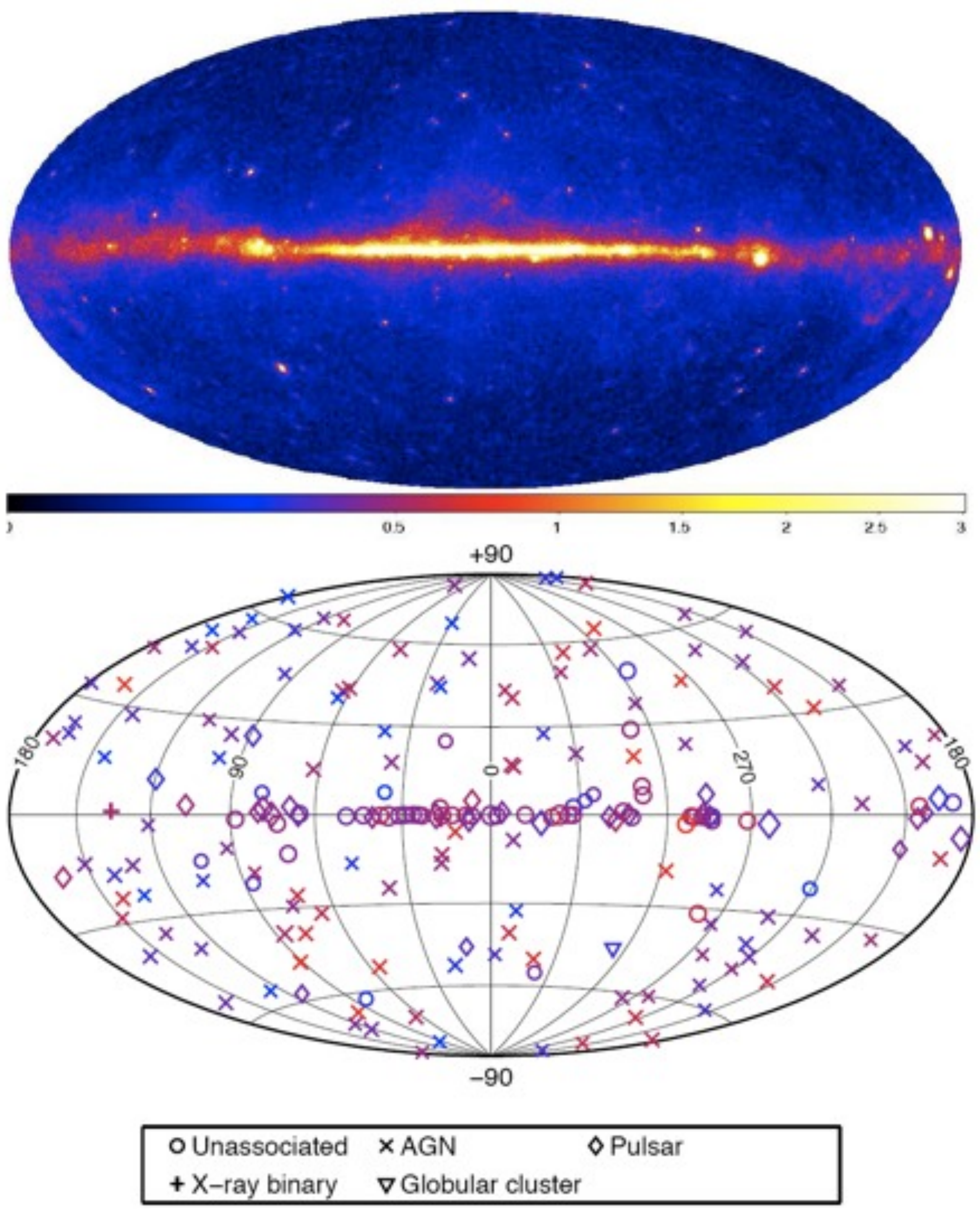
# Fermi-LAT Bright Source List

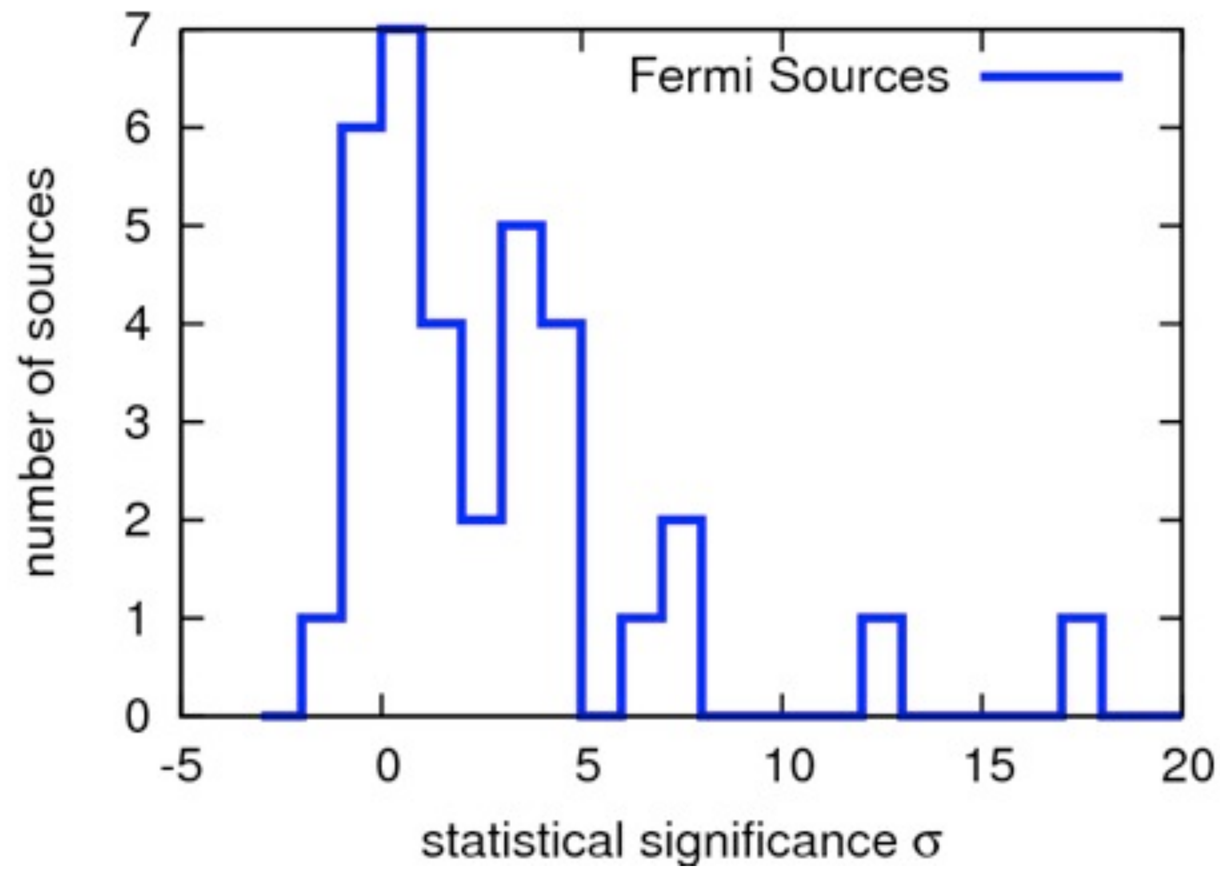



- 205 sources >10σ in 3 months
  - Deeper exposure than the complete EGRET data set
- Sensitivity from 100 MeV to hundreds of GeV
  - Blazars, pulsars identified by their variability
  - Several new gamma ray pulsars (identified first by GeV pulsation)
- Angular resolution <0.1° at highest energies

# Milagro Observations of Fermi BSL Objects

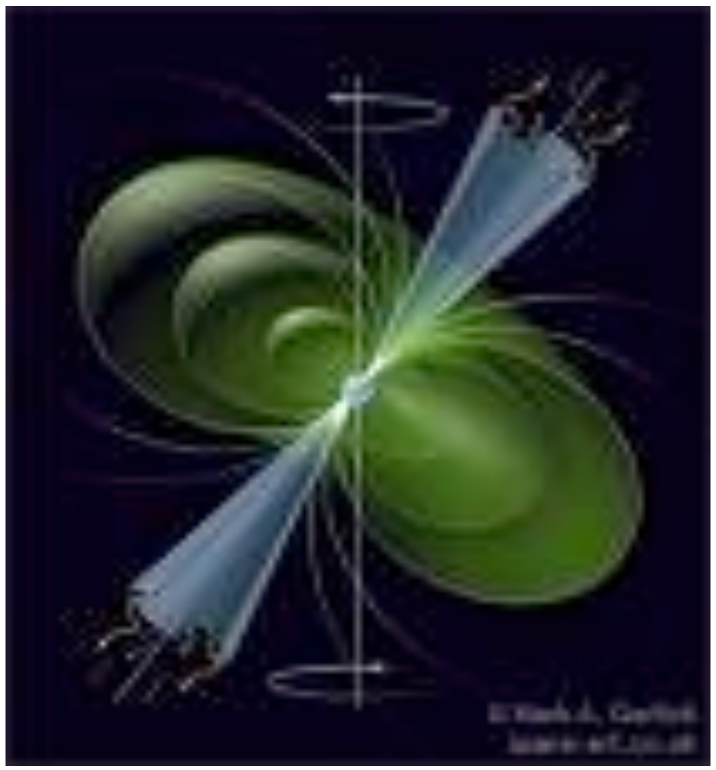
Abdo et al., *Astrophys. J. Lett.* **700**, 2009

- 34 of 205 BSL sources are definitely or possibly Galactic and in Milagro's field of view
  - 16 pulsars, 1 XRB, 5 SNRs, 12 unknown (poss. extragalactic)
- 14 of the 34 are observed at $>3\sigma$ in Milagro data set
  - 6 of 14 are previous Milagro sources
  - 9 of 14 are pulsars (incl. all 6 previously reported), 3 are SNRs
  - 6 of 14 not previously reported at TeV energies



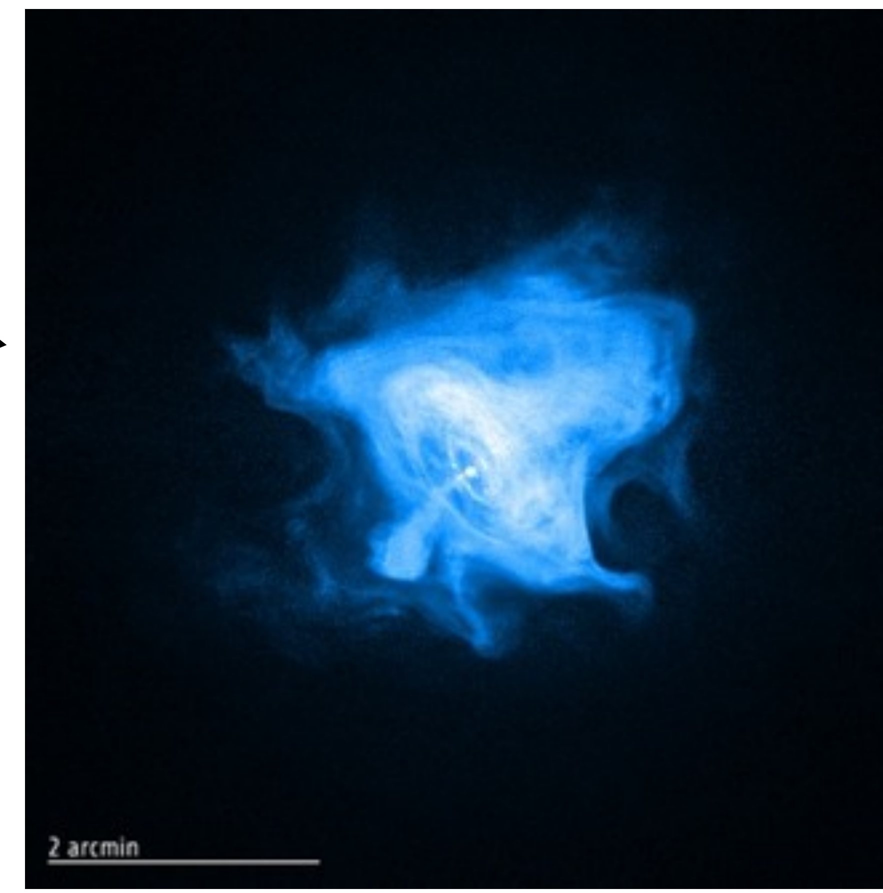

- Probability of even a single $3\sigma$ detection in 34 trials is 4.4%

# Gamma Ray Pulsars and Pulsar Wind Nebulae



Rapidly spinning neutron star with magnetic dipole of ~$10^{12\text{-}13}$ Gauss, GeV emission is due to particle flows in the strong electromagnetic fields

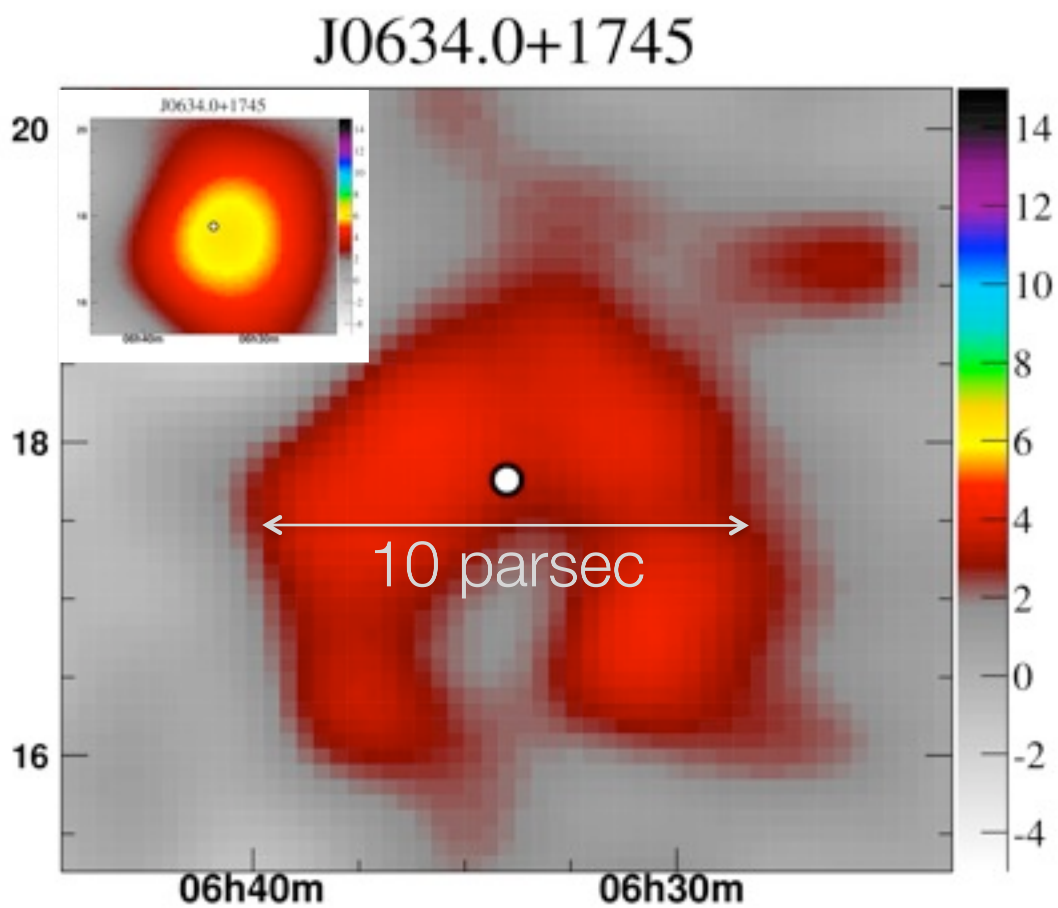
TeV Emission is produced by particles further accelerated in the shock interacting with the ambient medium.



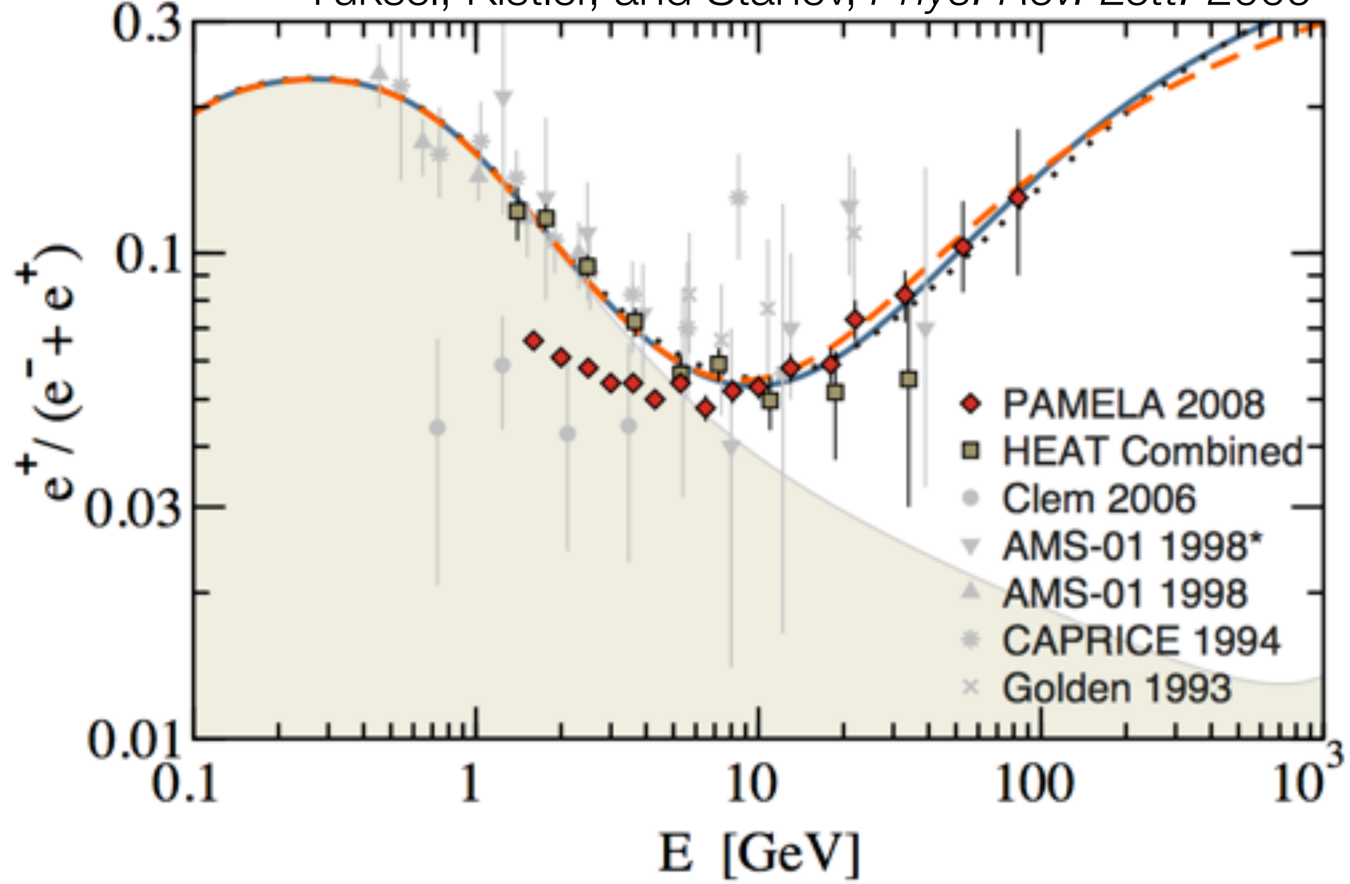

- GeV emission broadly beamed compared to other wavebands

- GeV pulsars frequently (generally?) produce TeV PWN

# Geminga as a Local Positron Source




Yüksel, Kistler, and Stanev, *Phys. Rev. Lett.* 2009

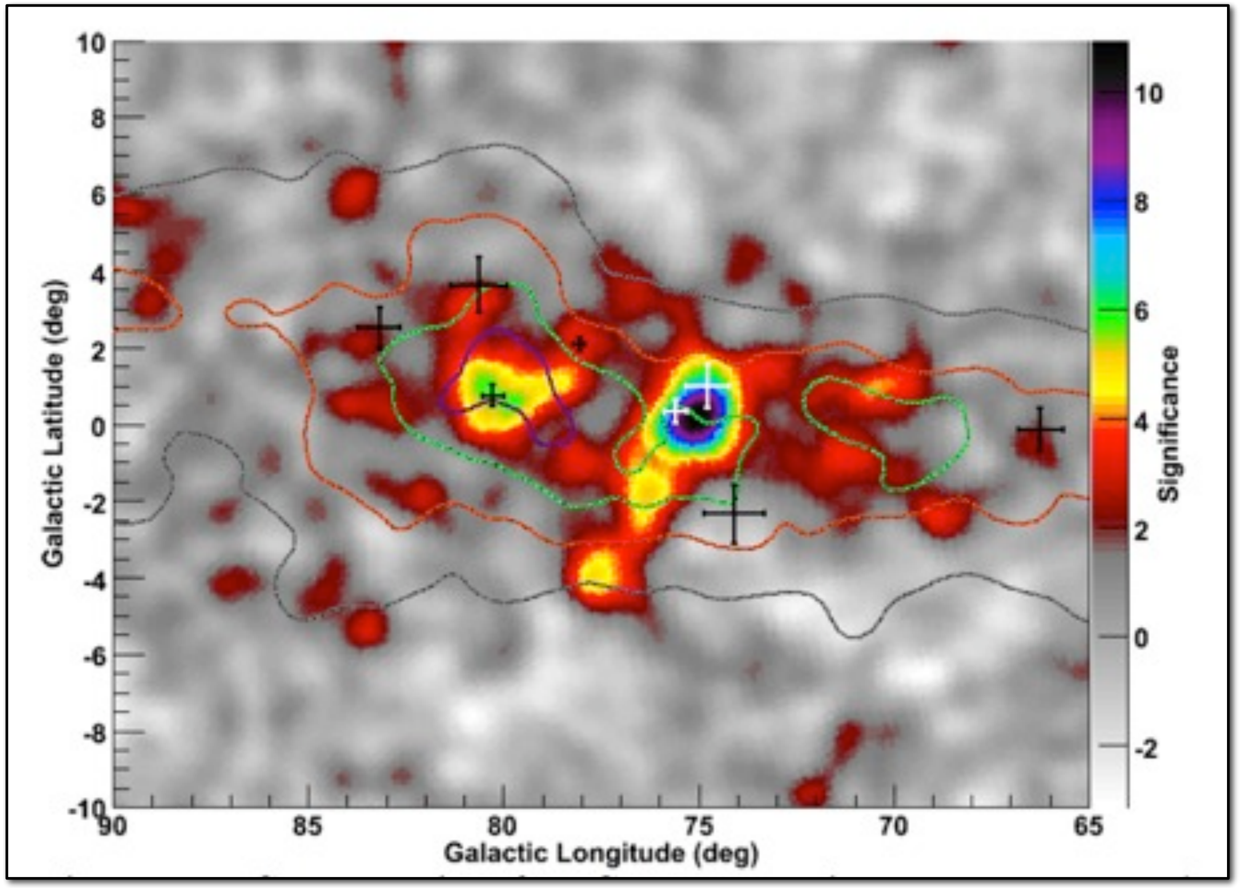


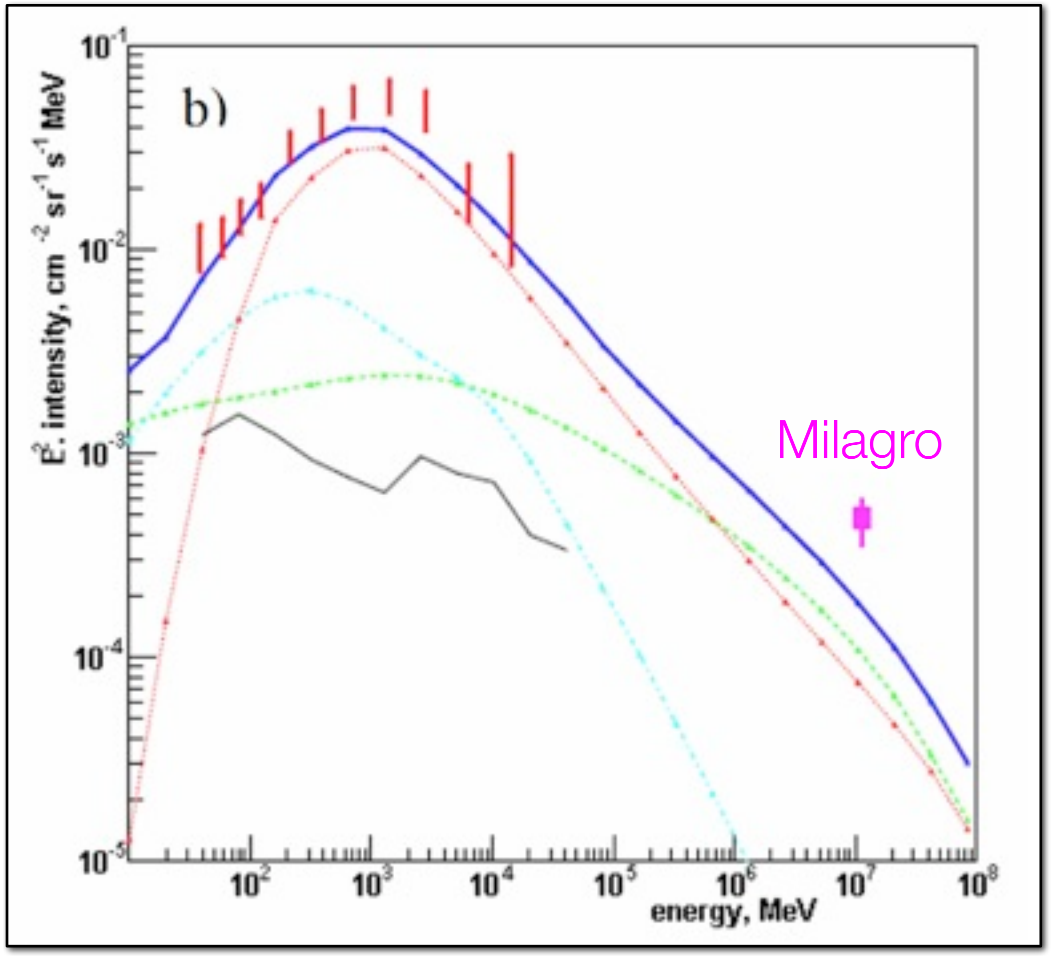

- Milagro detects an extended VHE gamma ray PWN centered on the Geminga pulsar
- PAMELA's positron excess (sometimes explained as evidence of dark matter) can be well fit given Milagro's flux from Geminga

# The TeV Diffuse Excess

Abdo et al., *Astrophys. J.* 2007

- Milagro observations of Cygnus arm of the galaxy
  - Point sources plus diffuse emission (cosmic rays on dust)
  - Level of diffuse emission suggests higher CR density, harder spectrum, unresolved sources, dark matter?

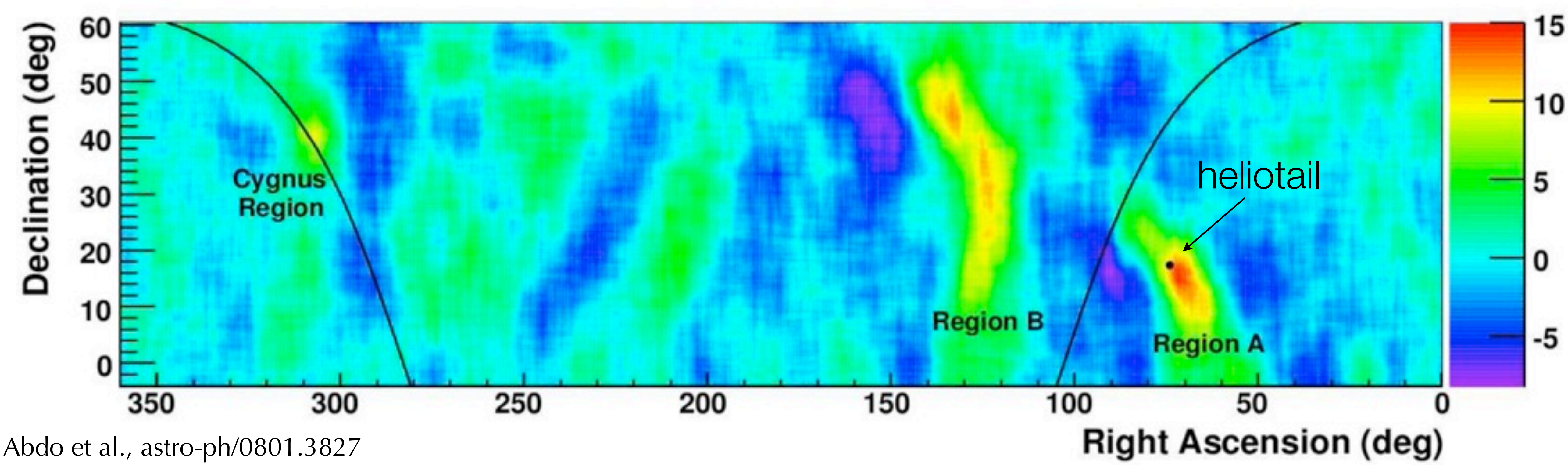


# Cosmic Ray Anisotropy

Abdo et al., *Phys. Rev. Lett.* **101**, 2008

- Significant (>12σ) anisotropy in the arrival direction of cosmic rays at energies ~10 TeV
  - Cosmic ray deficit ~5x10$^{-4}$ on ~10° scale
  - Gyroradius in 2μG ≈ 0.005 parsecs; neutron decay length 0.1 parsec



Abdo et al., astro-ph/0801.3827

# Attempts to Explain Cosmic Ray Anisotropy

Drury & Aharonian, *Astropart. Phys.* **29**, 420
Salvati & Sacco, *Astron. Astrophys.* **485**, 527

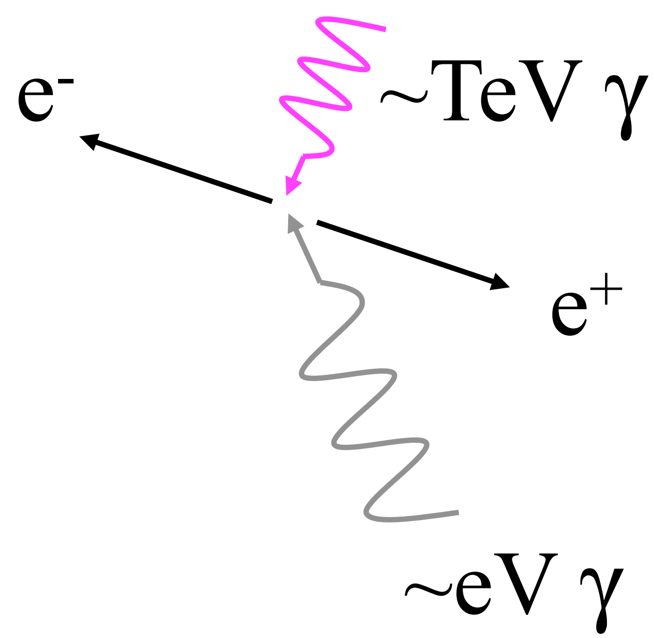
- Compatible observations by Tibet, ARGO
- Heliotail: unlikely to affect cosmic rays at these energies
- Related to Geminga?
  - Pulsar at a distance of ~150 pc, 3.4 x $10^5$ yr old, related to Local Bubble(?)
  - Diffusion of cosmic rays from Geminga – time & distance about right
    - How can it produce such a narrow feature on the sky?
  - Free streaming cosmic rays from Geminga (magnetic highway)
    - Cosmic rays should have passed us by within ~$10^4$ years!
- IceCube sees consistent structure in the southern sky (Vela?)

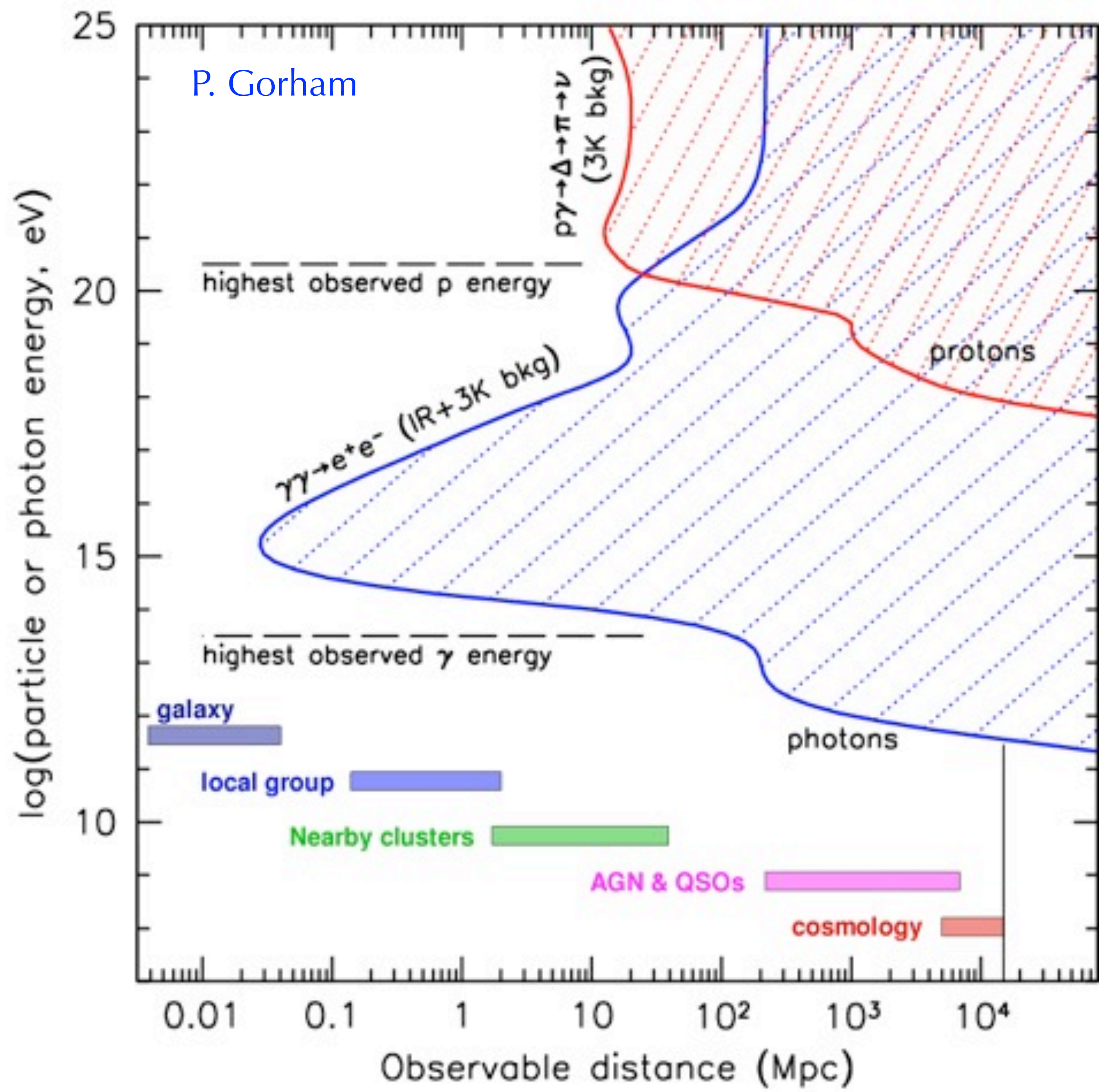
# Extragalactic Accelerators of Cosmic Rays

- At high energies, the cosmic rays are universally believed to come from sources outside the Galaxy
- Are Gamma Ray Bursts or Active Galactic Nuclei the sources of the cosmic rays?
  - Does GRB emission extend to very high energies? (Observed up to 10's of GeV)
  - What produces the observed TeV emission from AGN?
  - Are hadrons being accelerated, or is the gamma emission purely electromagnetic?
- Energy budgets are tough: easier to build models without hadrons
  - But we know the cosmic rays are produced *somewhere!*

# Extragalactic VHE Astronomy: EBL Absorption

- Attenuation via pair production on low energy background photons
  - IR background above few 100 GeV
  - CMB above ~10 TeV




- Cosmological interest in measuring the IR background

# From Milagro to HAWC

- The High Altitude Water Cherenkov Observatory
- Redeploy Milagro at Volcán Sierra Negra, México
  - Increase altitude from 2650 m to 4100 m
  - Increase area from 3,600 $m^2$ (pond) to 22,000 $m^2$
  - Segment the Cherenkov medium: separate tanks instead of a single pond
  - Better angular resolution and background rejection, lower energy threshold
- Achieve 10-15 x sensitivity of Milagro
  - Detect Crab at $5\sigma$ in 6 hours instead of 3 months
- Cost: ~$15M (construction + contingency)

# The HAWC Collaboration

## USA

- University of Maryland
- Los Alamos National Laboratory
- University of California, Irvine
- University of California, Santa Cruz
- Colorado State University
- George Mason University
- Georgia Institute of Technology
- Goddard Space Flight Center
- Harvey Mudd College
- Michigan State University
- Michigan Technological University
- University of New Hampshire
- University of New Mexico
- Pennsylvania State University
- University of Utah
- University of Wisconsin, Madison

## México

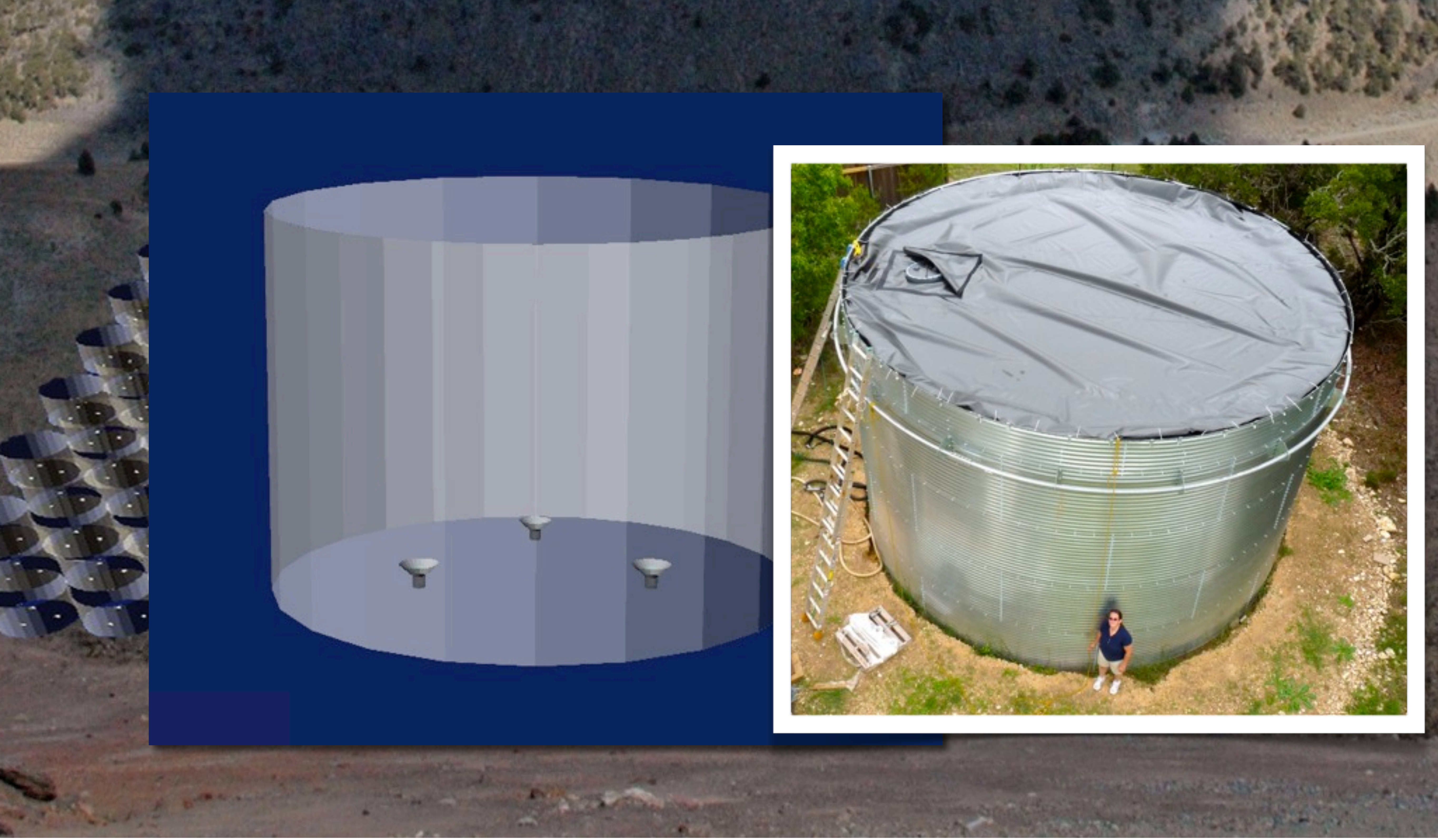
- Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
- Universidad Nacional Autónoma de México (UNAM)
- Universidad Autónoma de Chiapas
- Universidad de Guadalajara
- Universidad de Guanajuato
- Universidad Michoacana de San Nicolás de Hidalgo
- Centro de Investigación y Estúdios Avanzados (CINVESTAV)
- Benemérita Universidad de Puebla

# The HAWC Collaboration

- Pennsylvania State University
- Benemérita Universidad de Puebla

HAWC

Pico de Orizaba, altitude 4100 m, latitude 18º 59’ N
Two hours drive from Puebla, four from México City
Site of Large Millimeter Telescope (infrastructure exists)



# Design

300 water Cherenkov detectors, 7.3 m diameter x 4.5 m tall
200,000 liters water with 3 upward looking 8” PMTs per tank
~20,000 $m^2$ area, >60% active Cherenkov volume

# HAWC Detectors

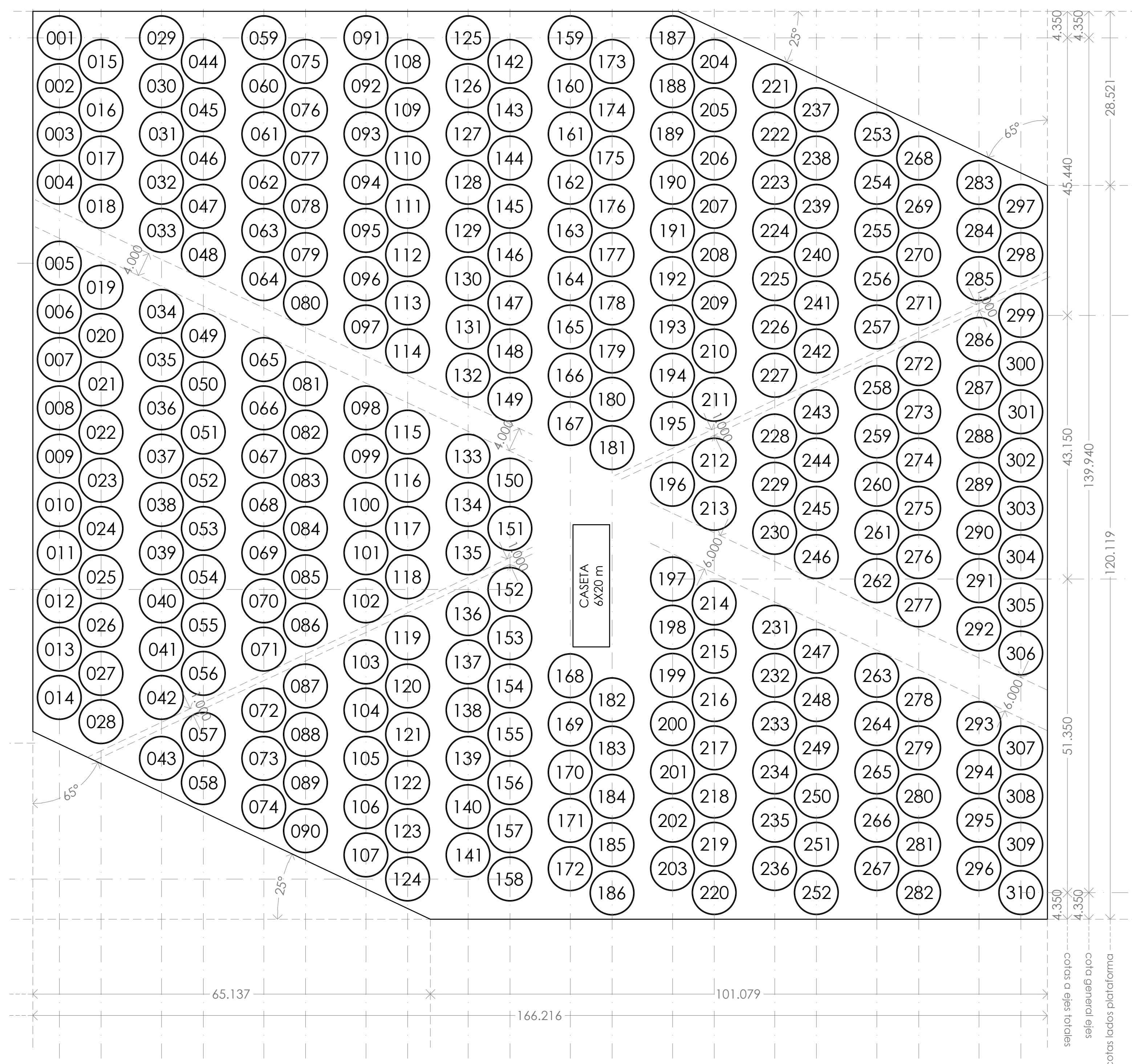
- Steel cylinders with liners, assembled in place
  - Light-tight, black plastic bladder to hold water
  - Ultra-pure filtered and demineralized water
  - 3 upward looking PMTs with <1 ns time resolution
- 900 8” Hamamatsu PMTs and most electronics re-used from Milagro

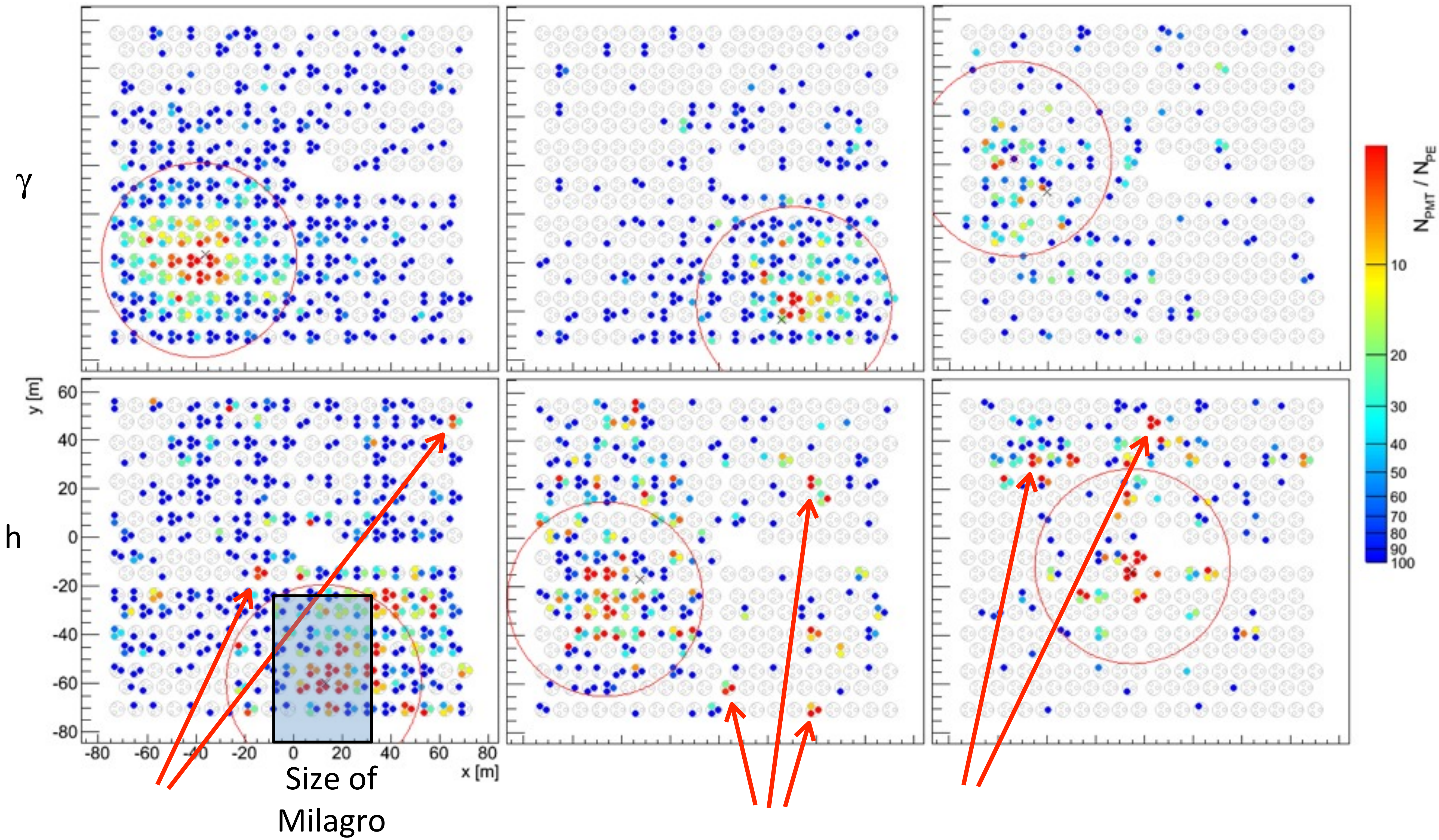
# HAWC Detectors

from Milagro

# HAWC Construction Schedule

- VAMOS
  - Verification Assessment Measuring Observatory Subsystems (6 months)
- HAWC-30
  - Implementation of all subsystems (1 year)
- HAWC-100
  - Science operations with 2 times Milagro’s sensitivity (18 months)
- HAWC-300
  - Full detector (18 months)





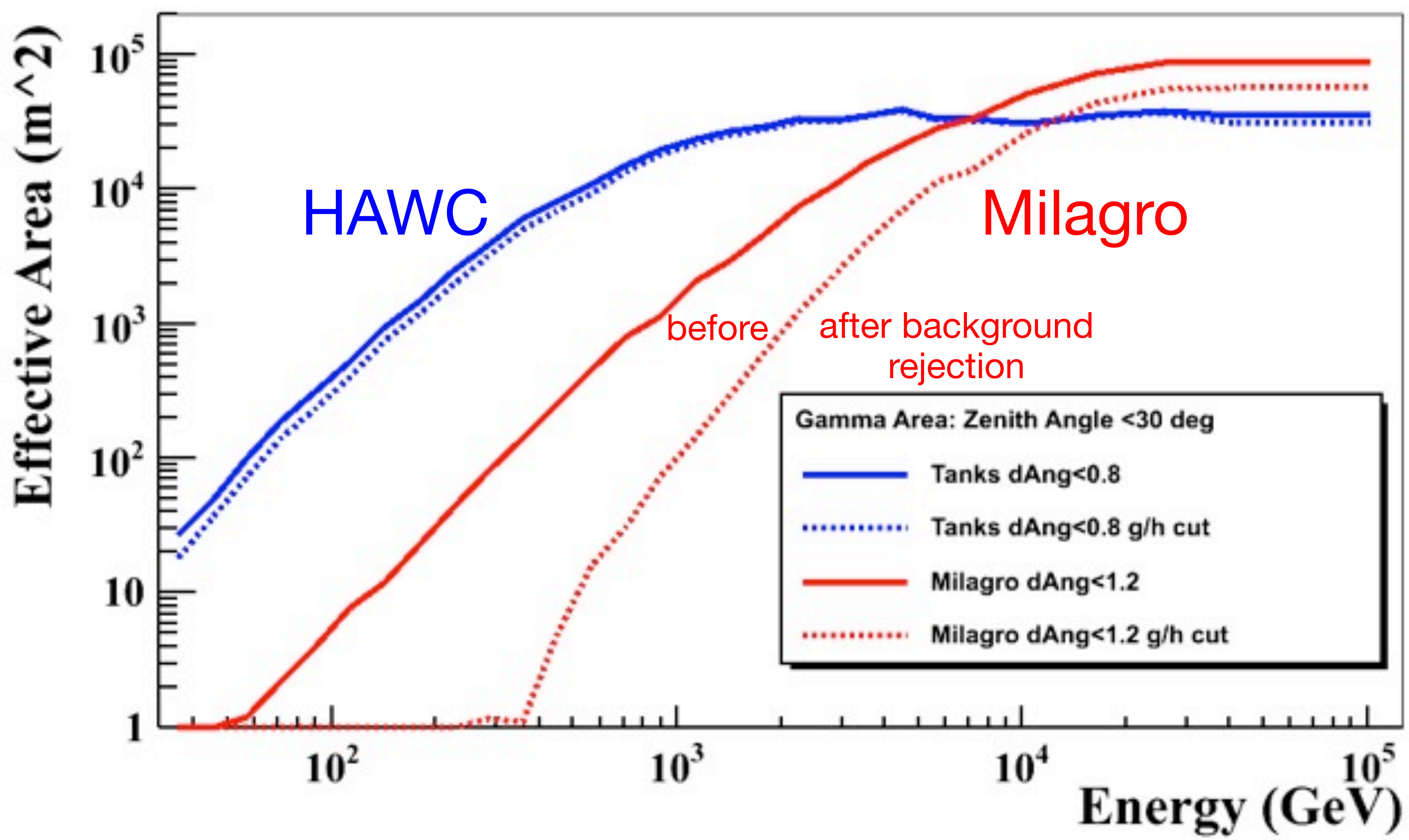

# Background Rejection

Cosmic ray showers are clumpier than gamma rays

Algorithm looks for high-amplitude hits more than 40 m from the reconstructed core location

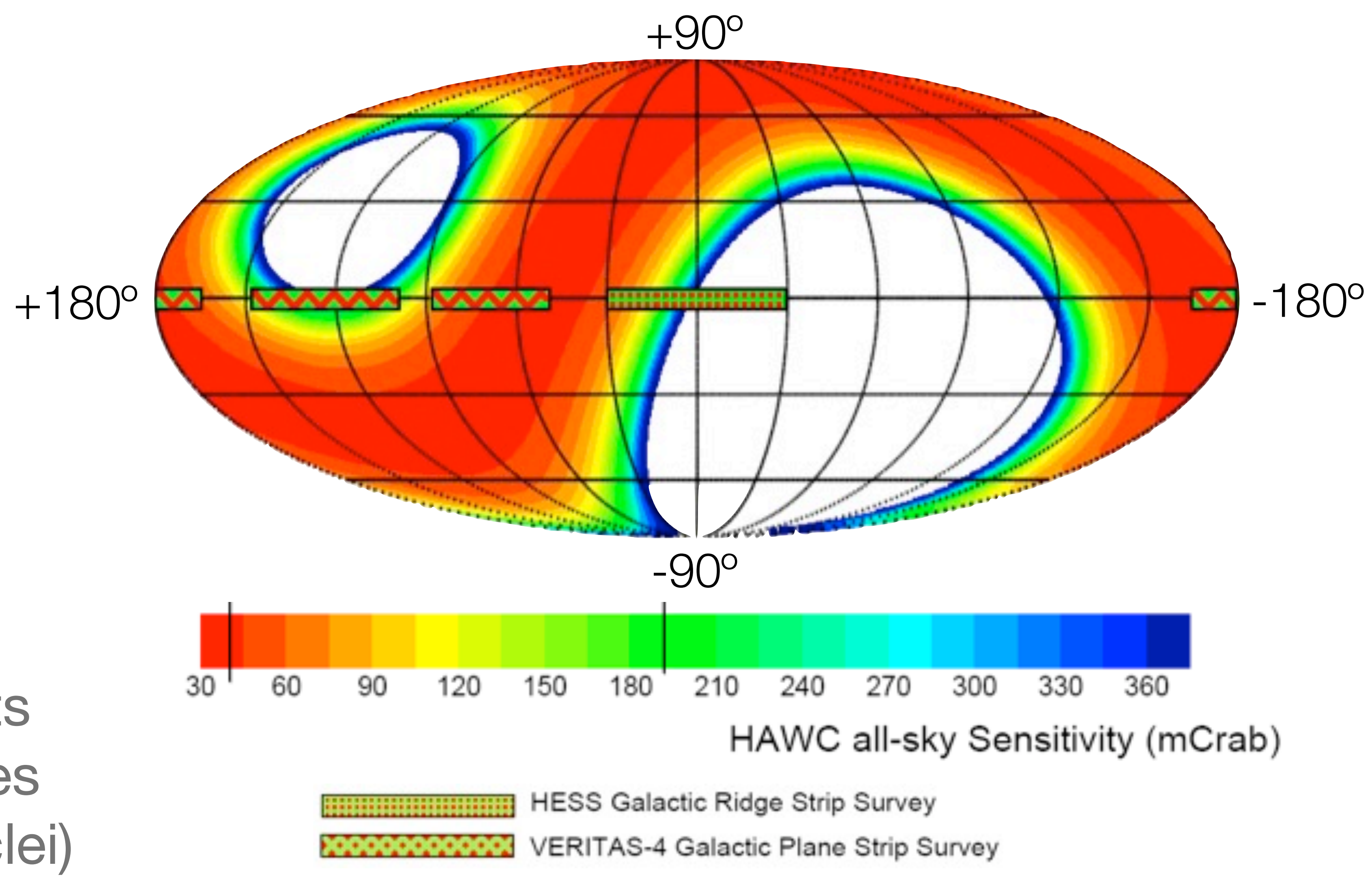
# Energy Threshold and Effective Area

- Higher altitude leads to a lower energy threshold
  - Stochastics of shower development lead to very soft threshold
- HAWC will be fully efficient above ~2 TeV
  - Still >100 $m^2$ effective area at 100 GeV
- Improvements even more significant after hadron cuts



# Monitoring the Sky with HAWC

- Wide field of view provides several advantages
  - Survey of a large fraction of the sky (look for the unknown)
  - Measure the highest energy emission from astronomical objects
  - Observe larger objects (nearby supernova remnants & pulsar wind nebulae, Galactic disk)
  - Observe transient events (gamma ray bursts, flares from active galactic nuclei)



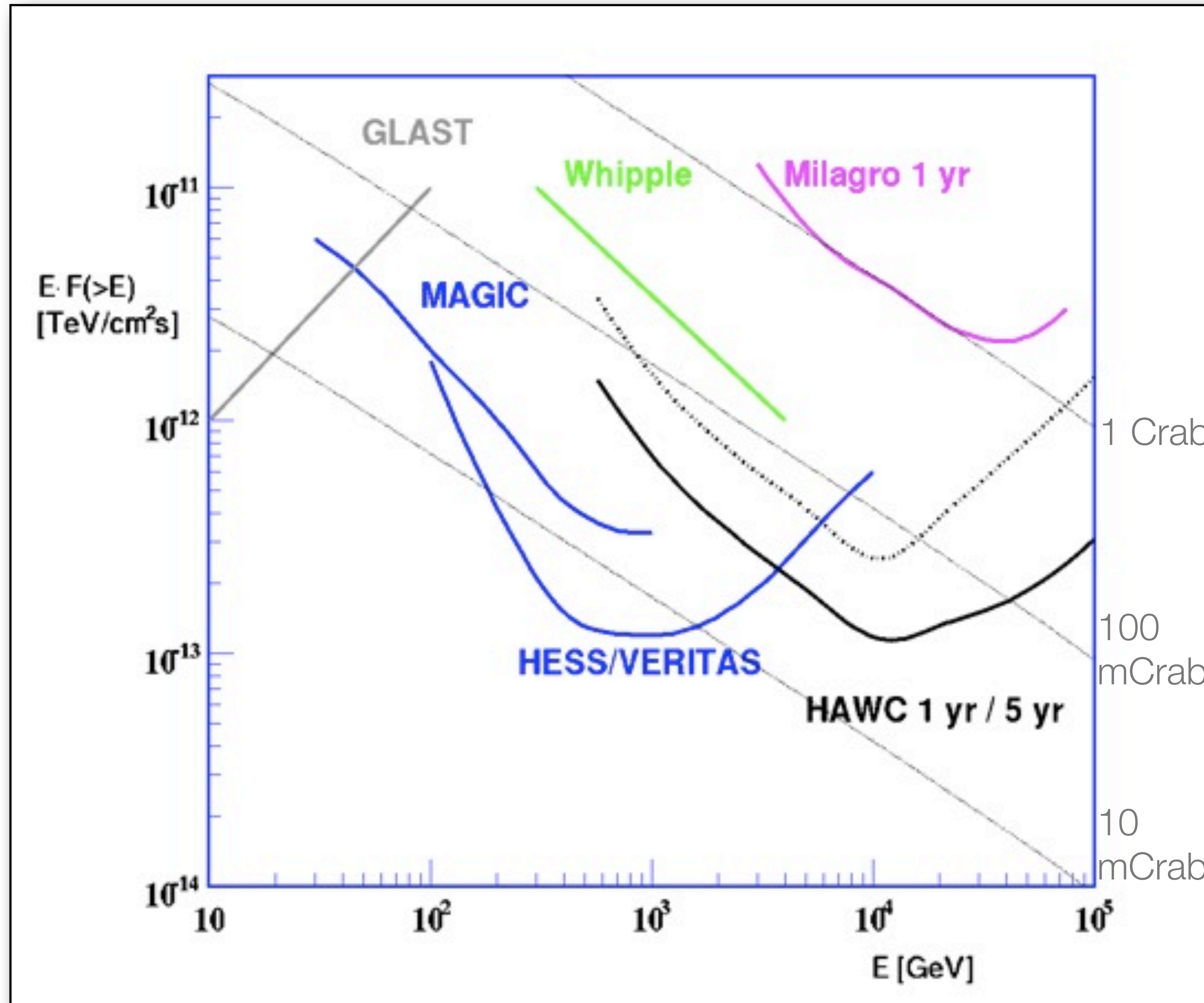
# Sensitivity to Crab-like Point Sources

- Long integration times lead to excellent sensitivity at highest energies (> few TeV)
- 5σ sensitivity to:

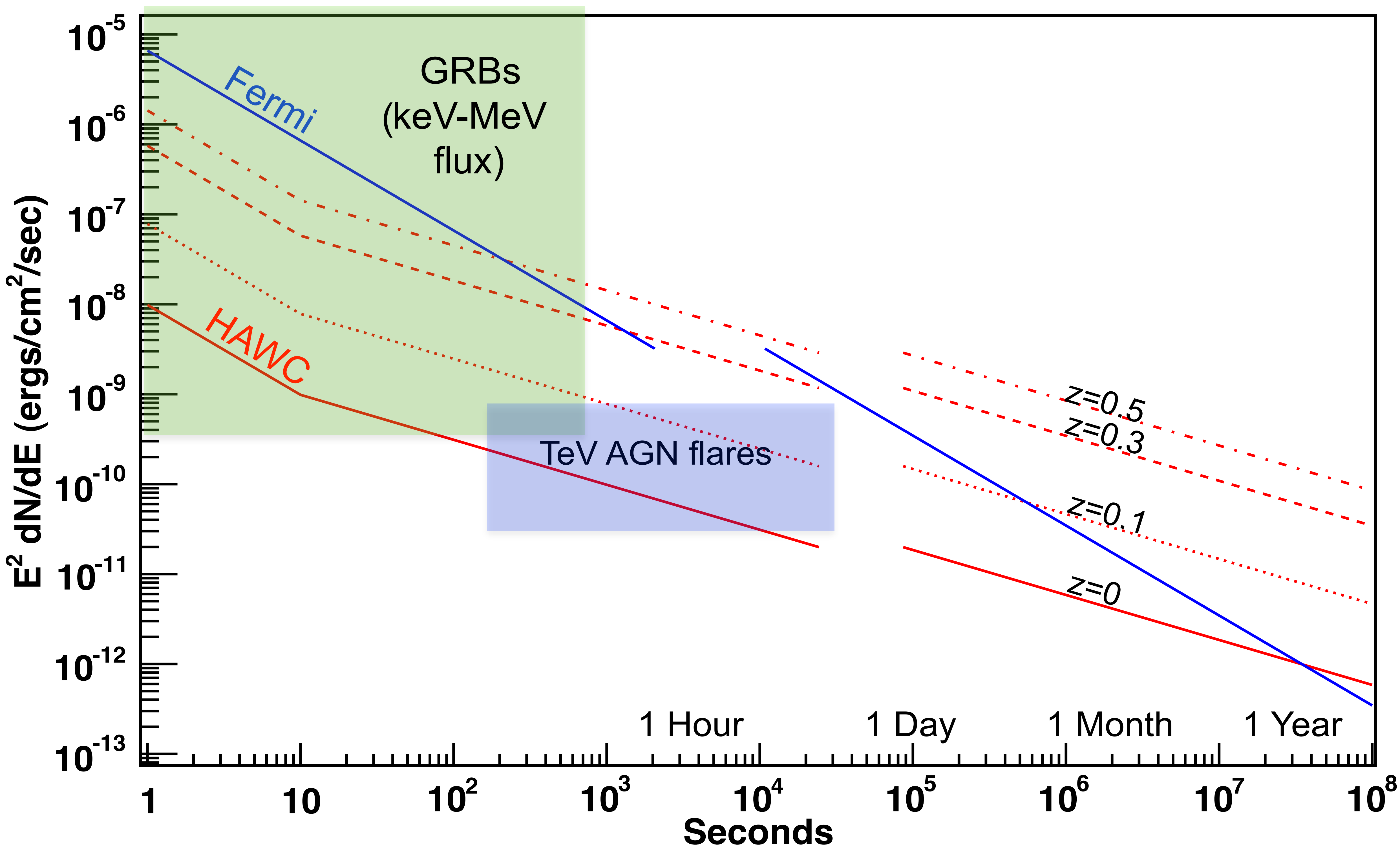
  10 Crab in 3 minutes

  1 Crab in 5 hr (1 transit)

  0.1 Crab in ⅓ year
- 10-15x Milagro sensitivity
  - Lower energy threshold
  - Better angular resolution
  - Better rejection of cosmic rays



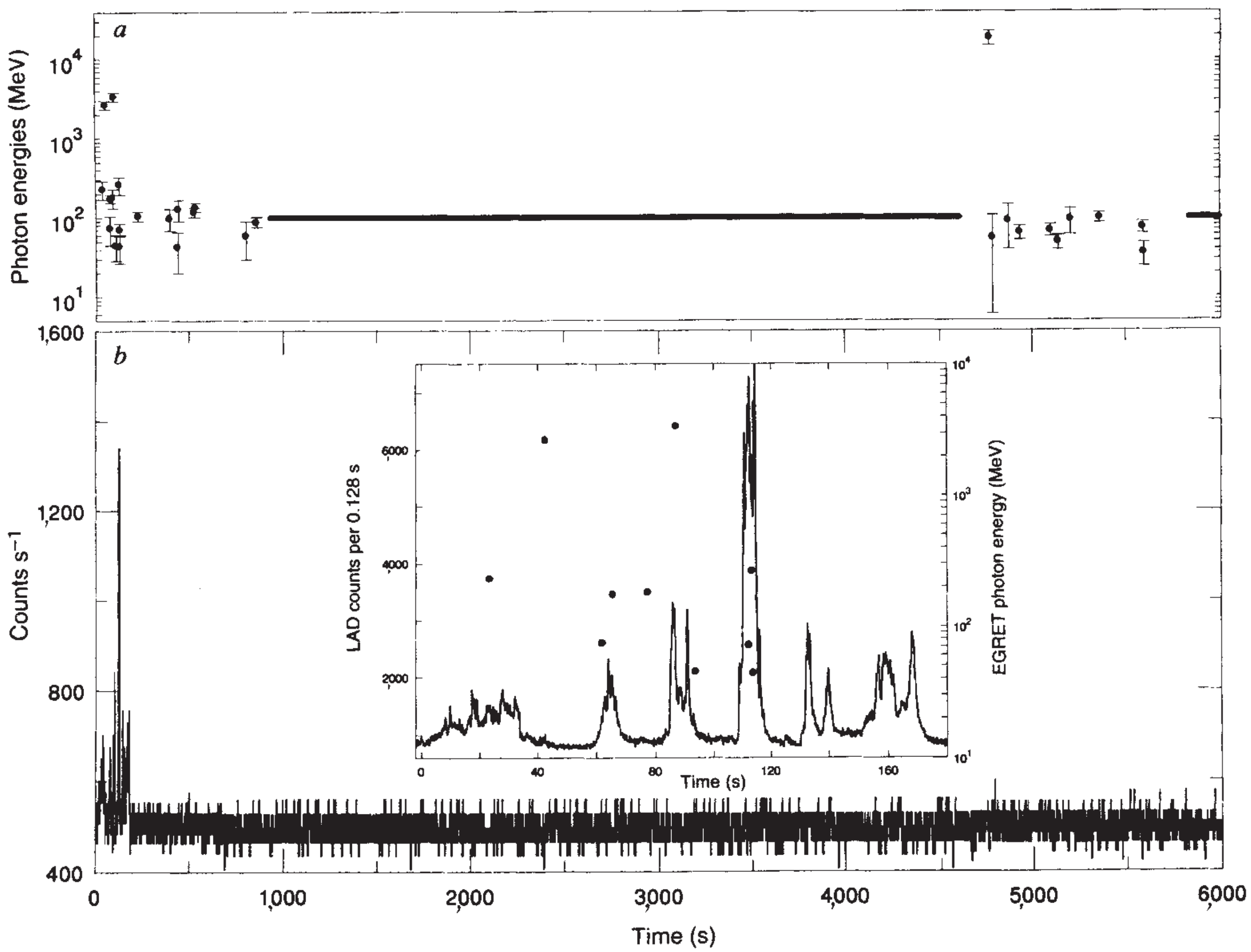

50 hr observation time assumed for IACTs, HAWC source transit 15° off zenith



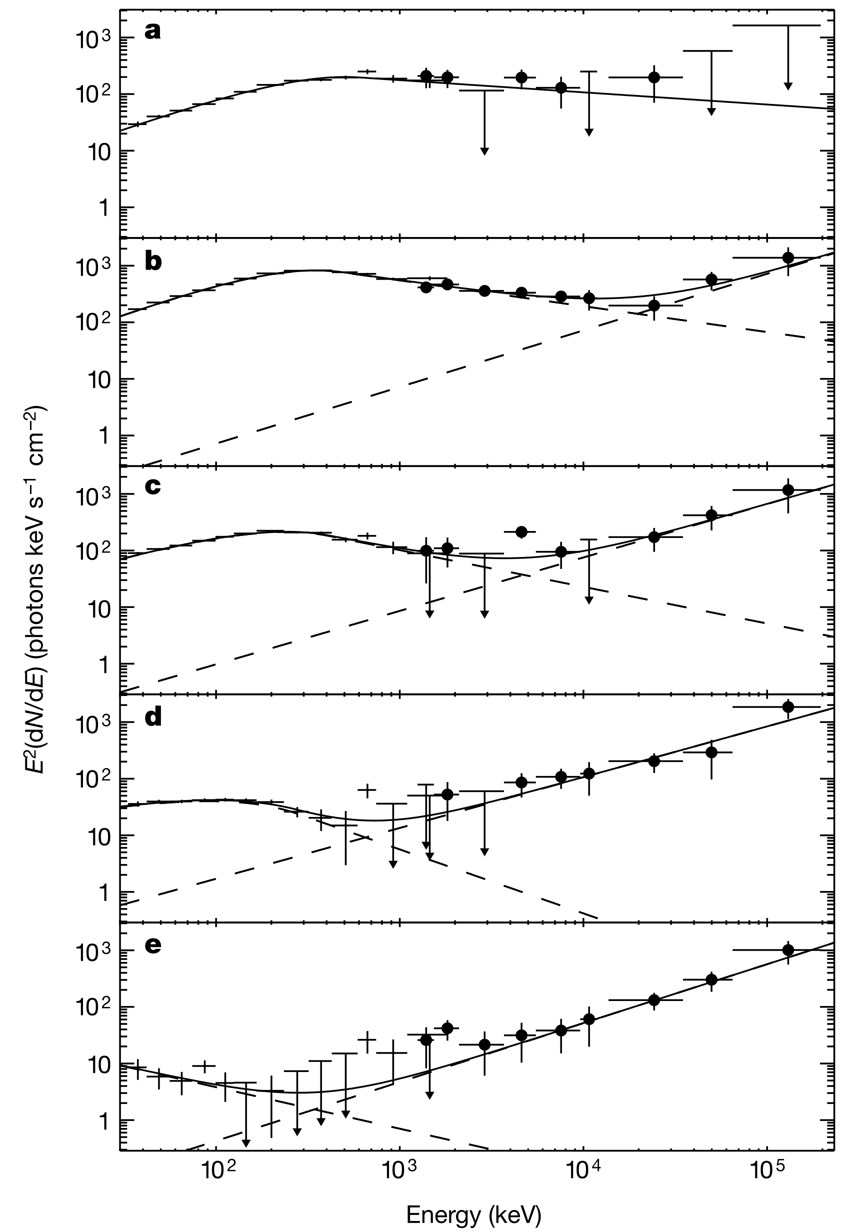

# Transient Sensitivity

Assumed $E^{-2}$ emission spectrum
Full HAWC simulation
Fermi-LAT assumed 0.8 $m^2$ effective area, no background

# Gamma Ray Bursts: A High Energy Component?




EGRET: Hurley et al., Nature 1994




EGRET: González et al., Nature 2003

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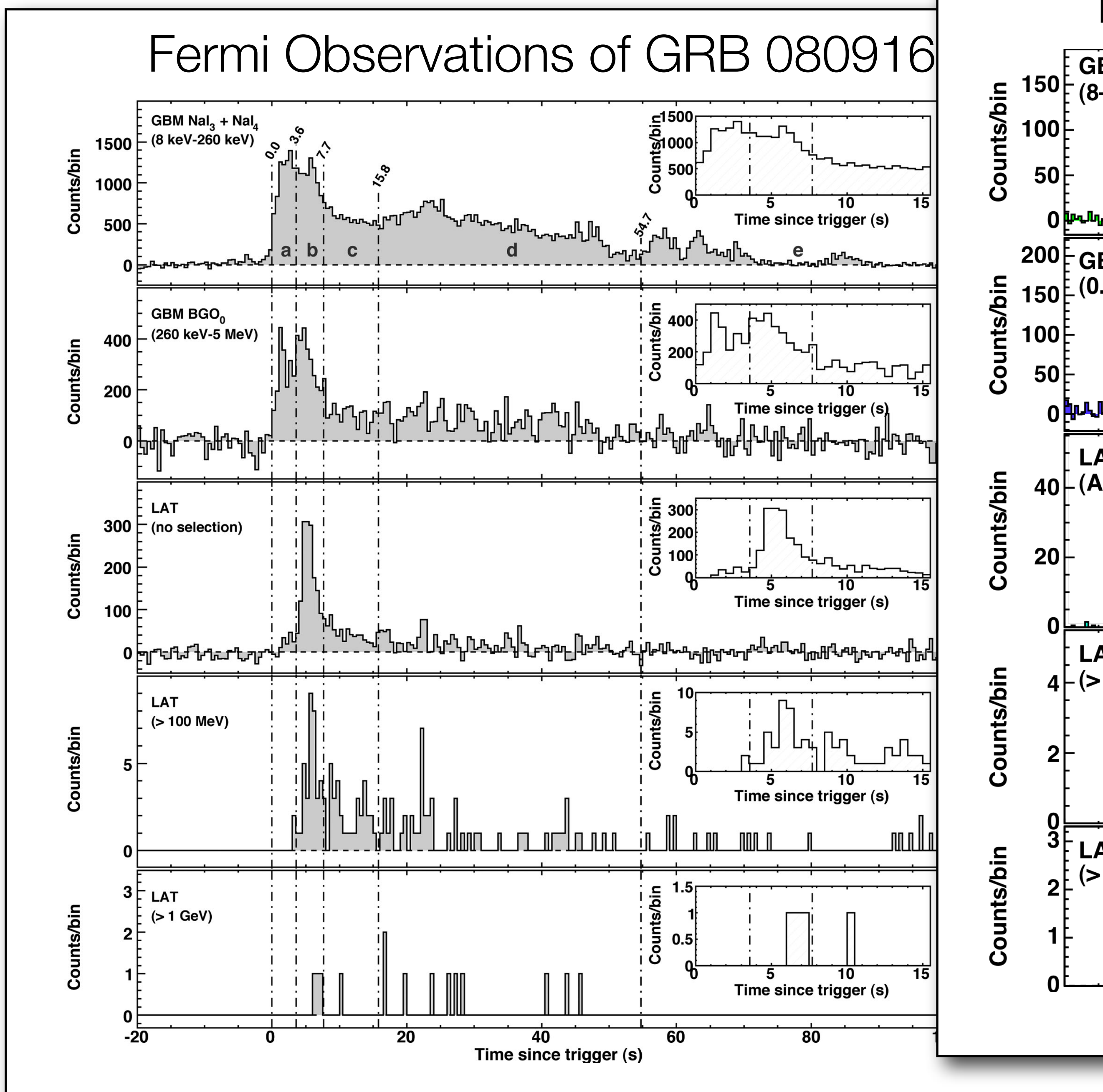
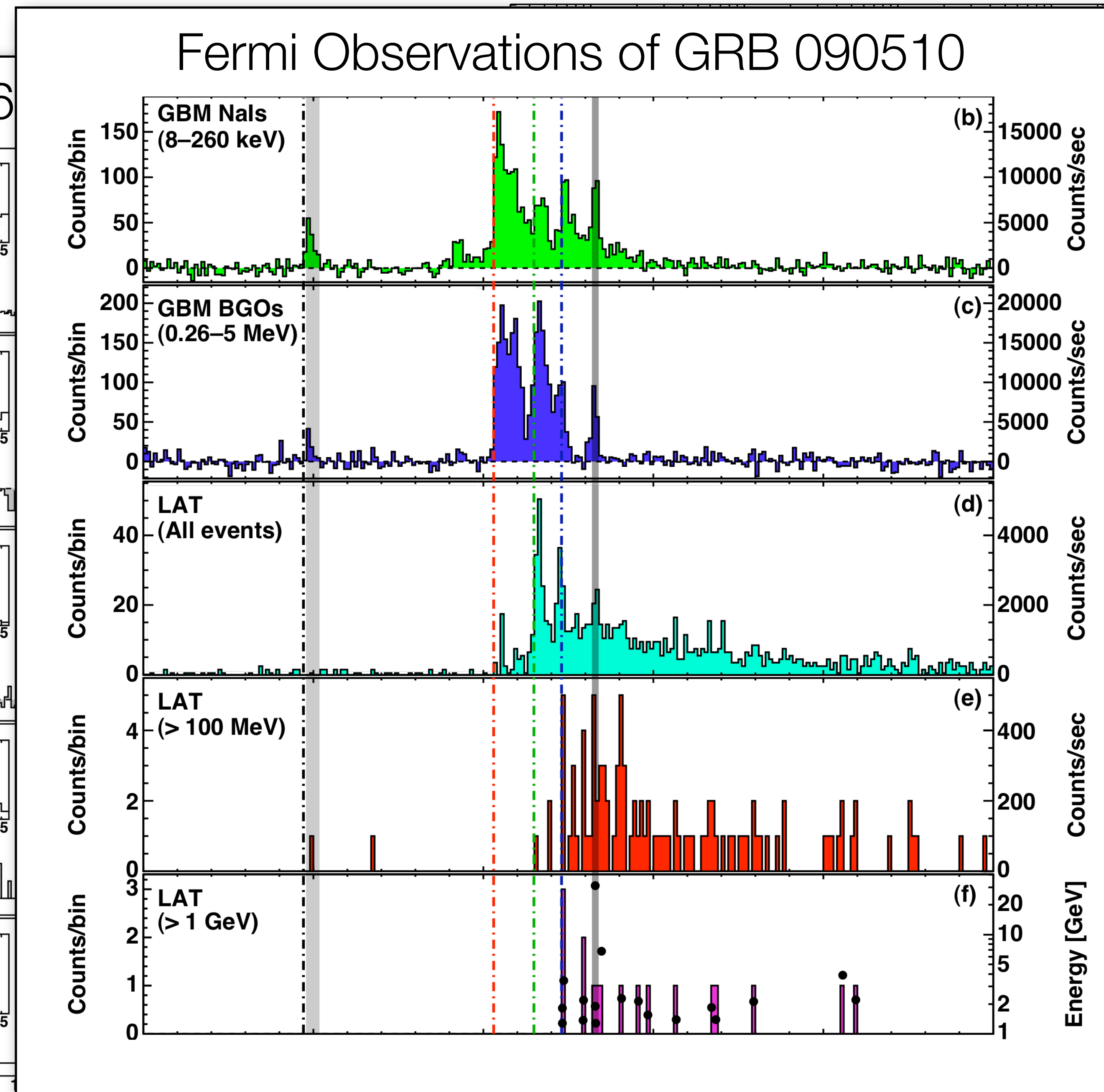
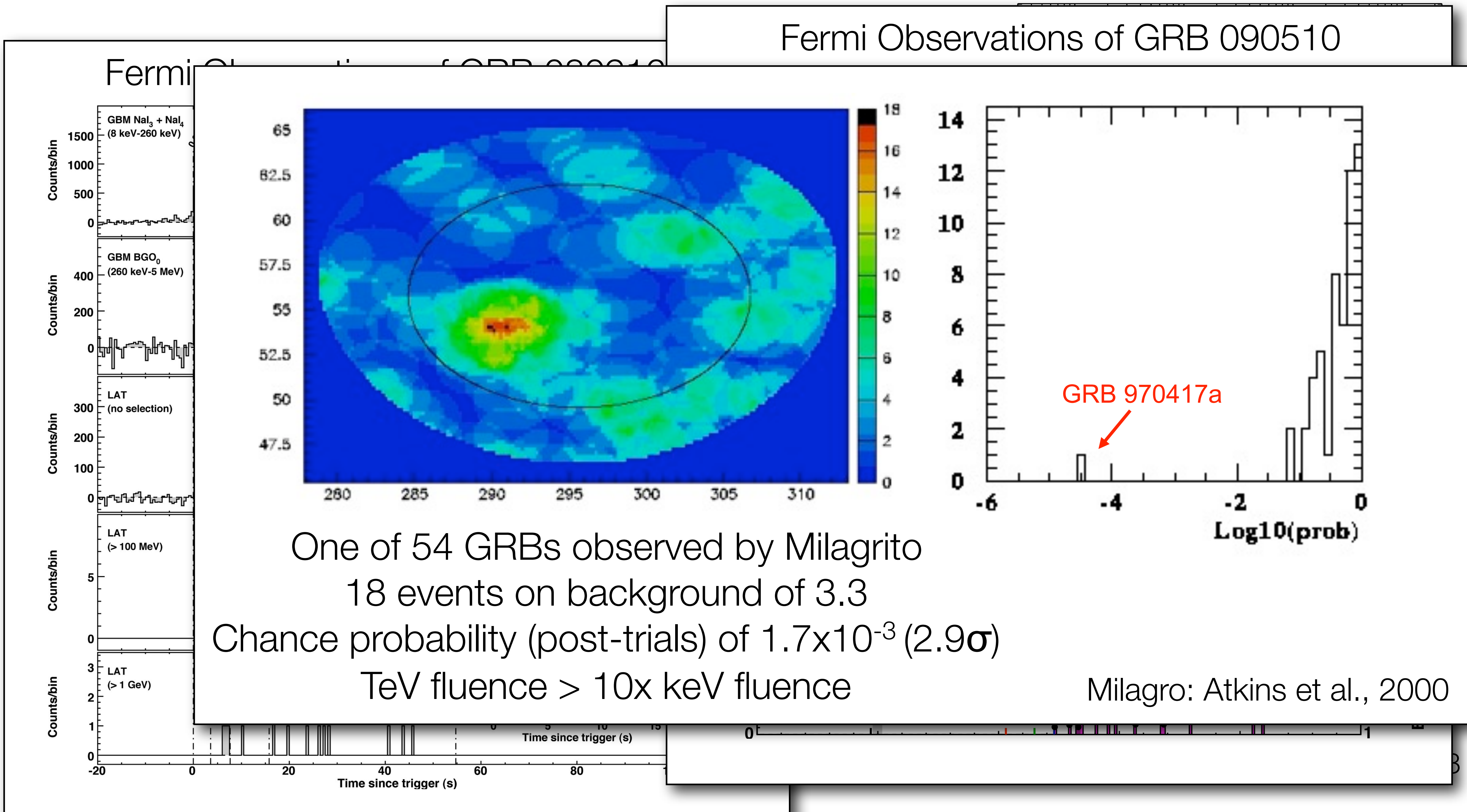


# Gamma Ray Bursts: A High Energy Component?




One of 54 GRBs observed by Milagrito

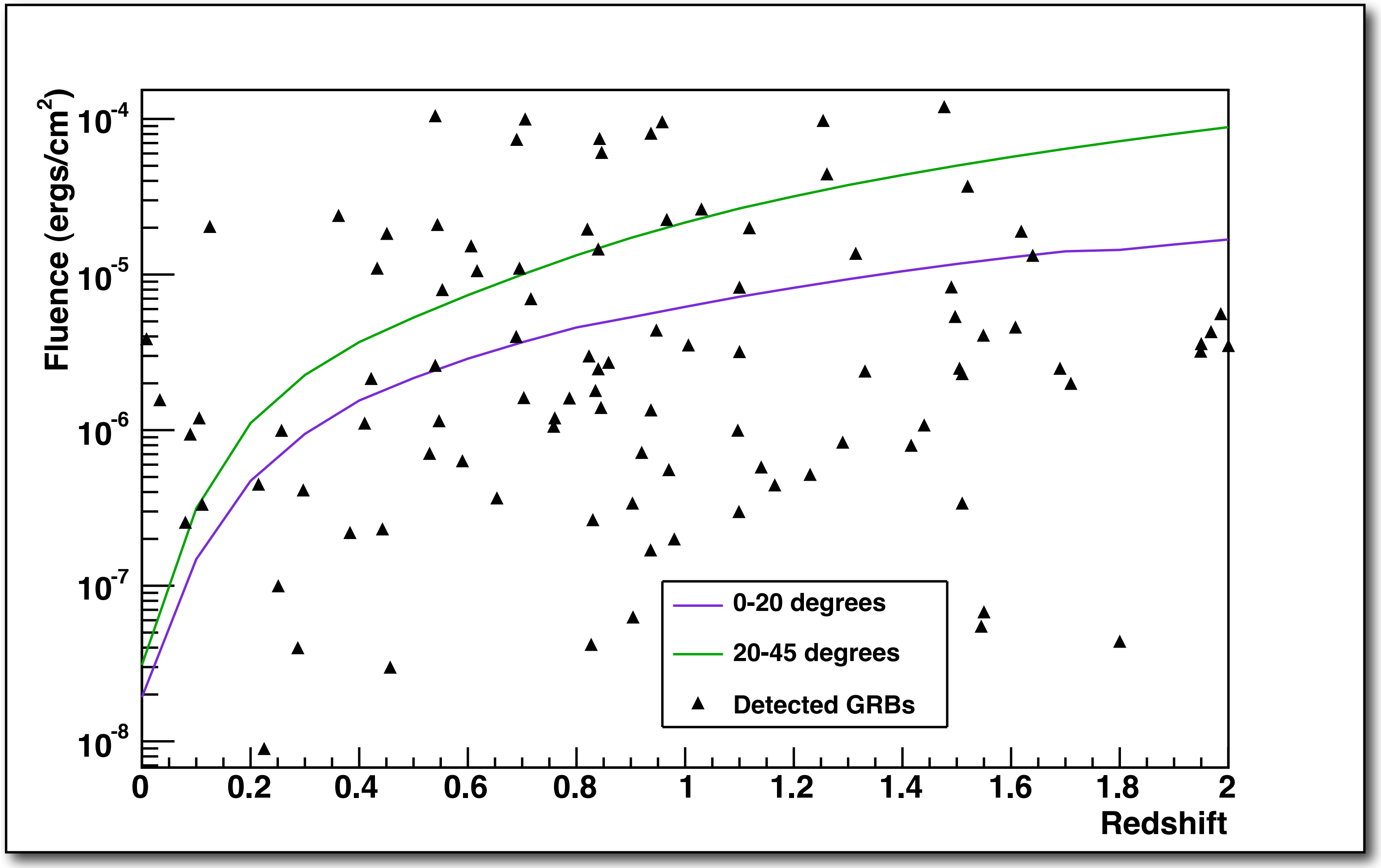
18 events on background of 3.3

Chance probability (post-trials) of $1.7\times10^{-3}$ ($2.9\sigma$)

TeV fluence > 10x keV fluence

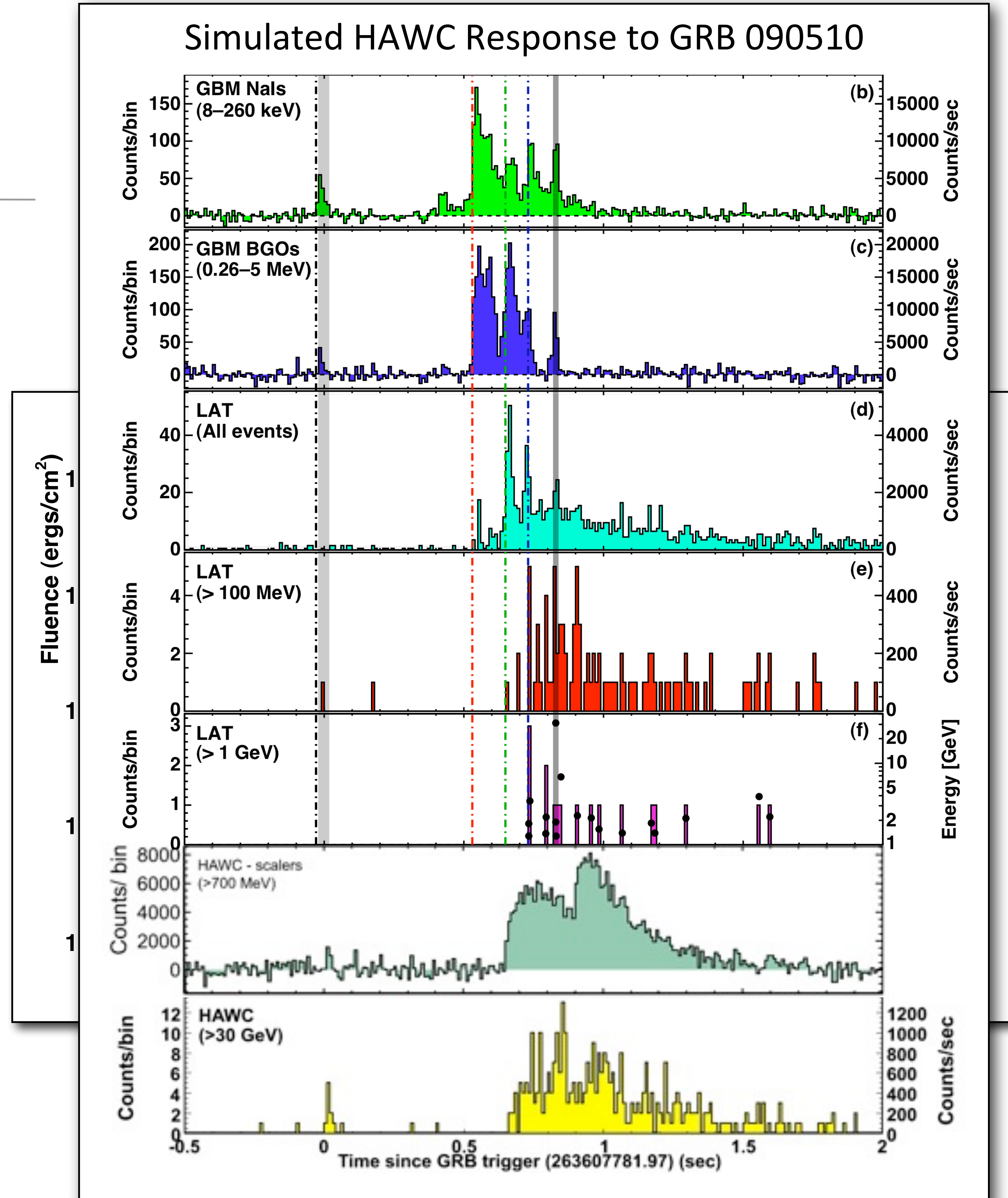
Milagro: Atkins et al., 2000

# Sensitivity to Gamma Ray Bursts



# Sensitivity to Gamma Ray Bursts

- Fermi observation of GRB 090510 (z = 0.9) in GBM and LAT
- Simulated HAWC light curve assuming extension of spectrum with LAT index
    - EBL absorption included
    - Cosmic ray background included
- ~200 events expected above 30 GeV
- Detection (5σ) by HAWC if emission extended to 50 GeV



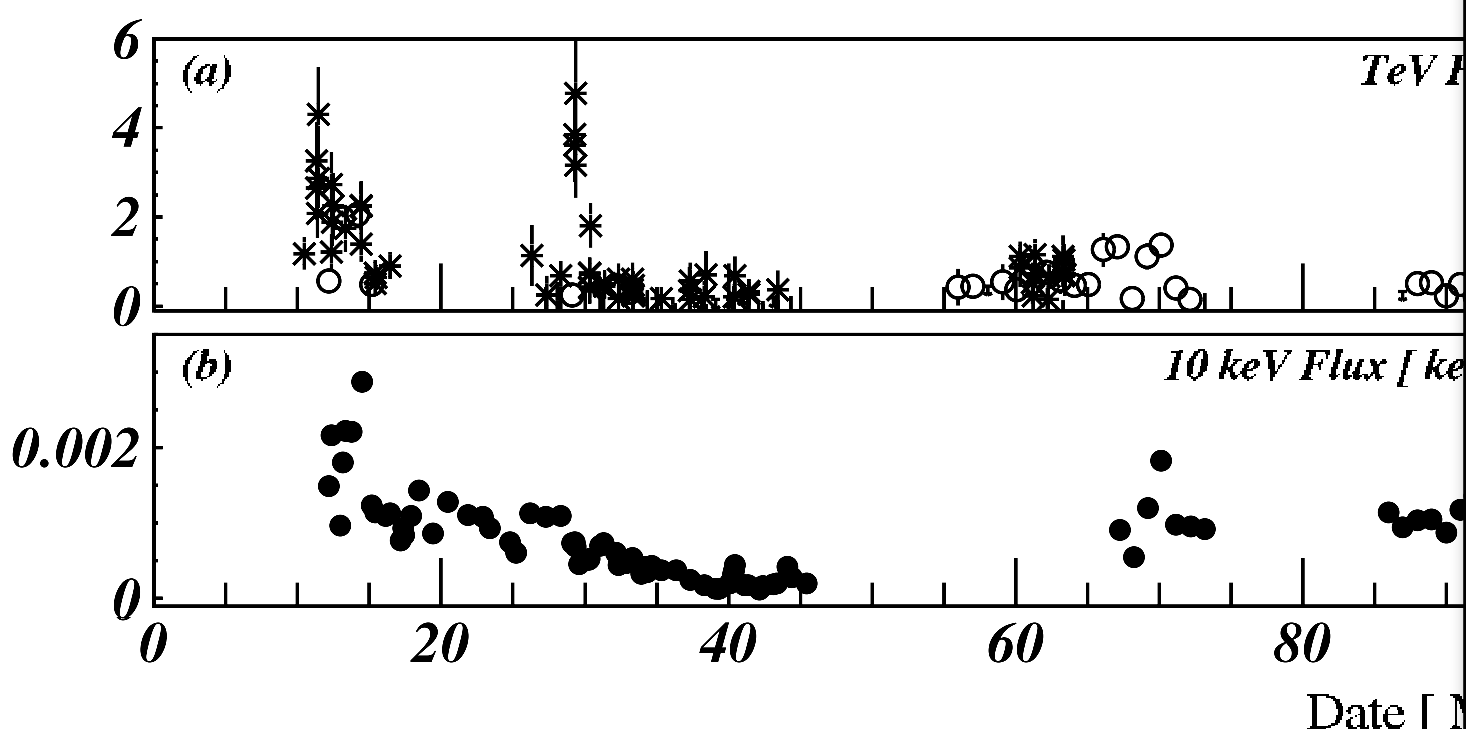
# Active Galactic Nuclei

- TeV gamma ray emission has been observed from 25 AGN
  - Mainly HBLs (23)
  - Also M87, Cen A, 2 FSRQs, 3 LBLs, and 2 IBLs
- AGN are highly variable in the TeV band
  - Somewhat difficult to observe due to low duty cycle, small FoV of IACTs
  - Variability time scales ranging from months to minutes
- Auger claim of correlation with AGN catalog suggests hadronic acceleration taking place
  - But may just be a proxy for local matter distribution, and correlation has not been supported by most recent data
  - Recent composition measurements somewhat in conflict – suggest Fe

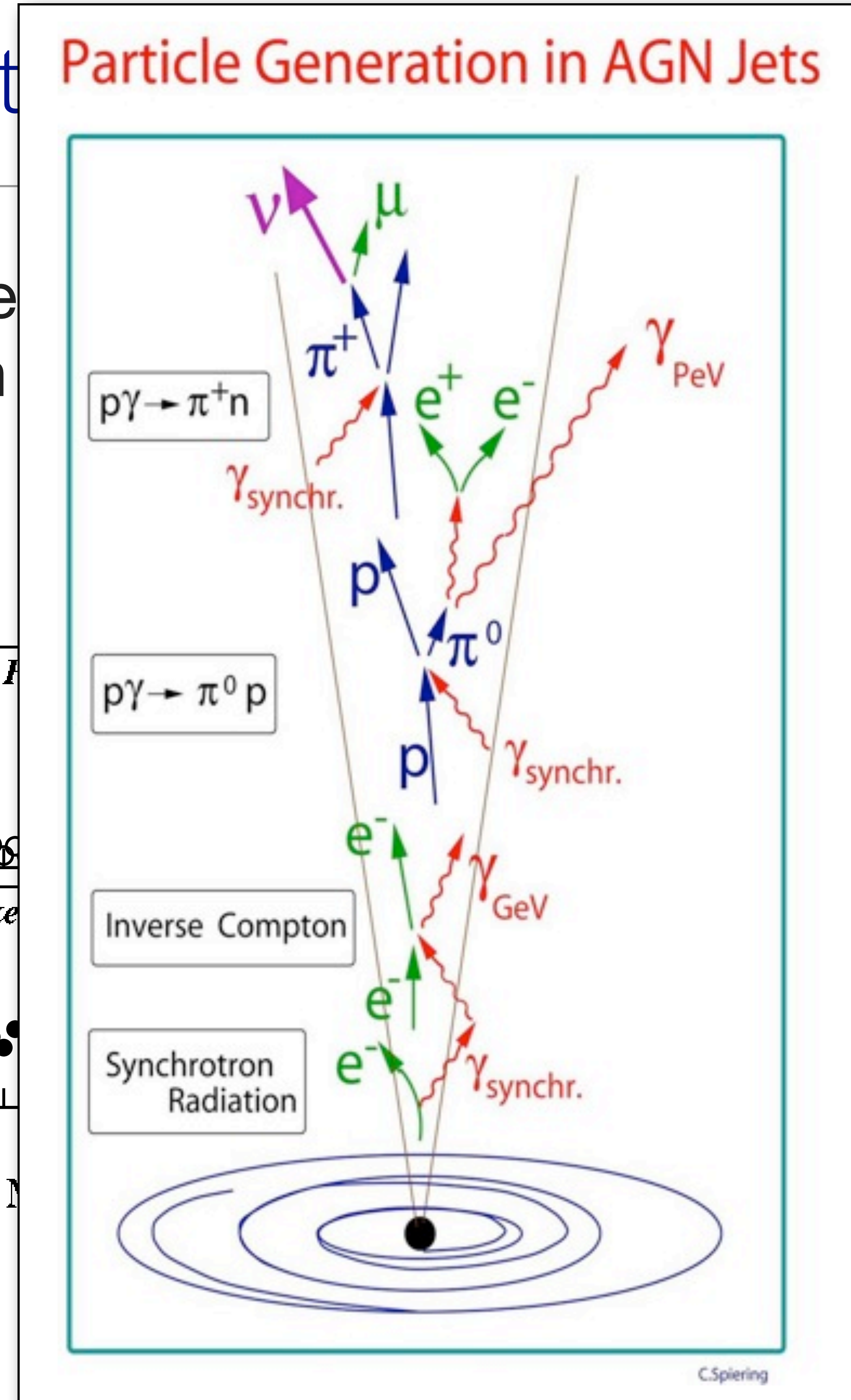
# AGN: "Orphan" Flares Suggest

- In some cases, TeV gamma ray flares are observed without correlated increases in X-ray flux: "orphan flares"

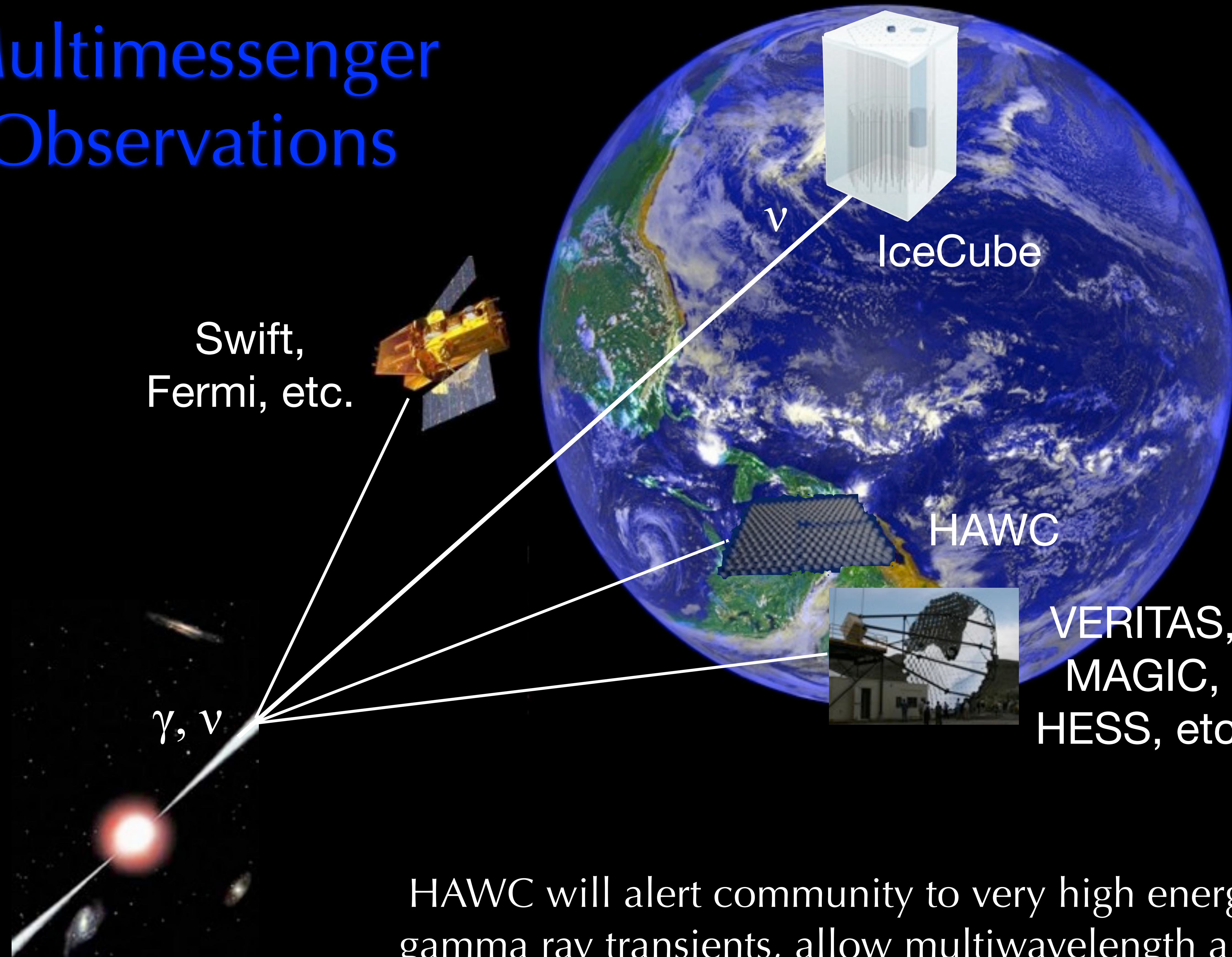
1ES 1959+650




Krawczynski et al., 2004



# Multimessenger Observations




HAWC will alert community to very high energy gamma ray transients, allow multiwavelength and multimessenger observations of these objects

# Open Questions: Extragalactic Sources

- Are Gamma Ray Bursts the sources of the cosmic rays?
    - Does GRB emission extend to very high energies?
- Are Active Galactic Nuclei the sources of the cosmic rays?
    - What particle dynamics are responsible the observed TeV emission?
    - What is the time-dependent spectral behavior?
    - What are the orphan flares?  Are they common?
- Can we use these sources to probe fundamental physics?
    - Ultra-long baselines, very high energies
    - Cosmological absorption measurements, searches for violation of Lorentz invariance, axions, etc.

# Summary

- Exciting period in very high energy astrophysics!
- Milagro demonstrated success of the water Cherenkov technique
  - Excess diffuse TeV emission from Galactic plane
  - Seven new Galactic TeV sources
  - TeV emission from Geminga may explain PAMELA positron excess
  - Strange anisotropy in ~10 TeV cosmic rays
- Future improvements with HAWC
  - Evolution of Milagro design: size, altitude, optical isolation
  - 10-15x sensitivity of Milagro
  - VHE alerts will facilitate multiwavelength/multimessenger observations

# Summary

- Future improvements with HAWC
  - Evolution of Milagro design: size, altitude, optical isolation
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