# Surveying the TeV Sky: Milagro and HAWC

Tyce DeYoung
Department of Physics
Penn State University

CHIPP Workshop on Astroparticle Physics
École Polytechnique Fédérale de Lausanne
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# Outline

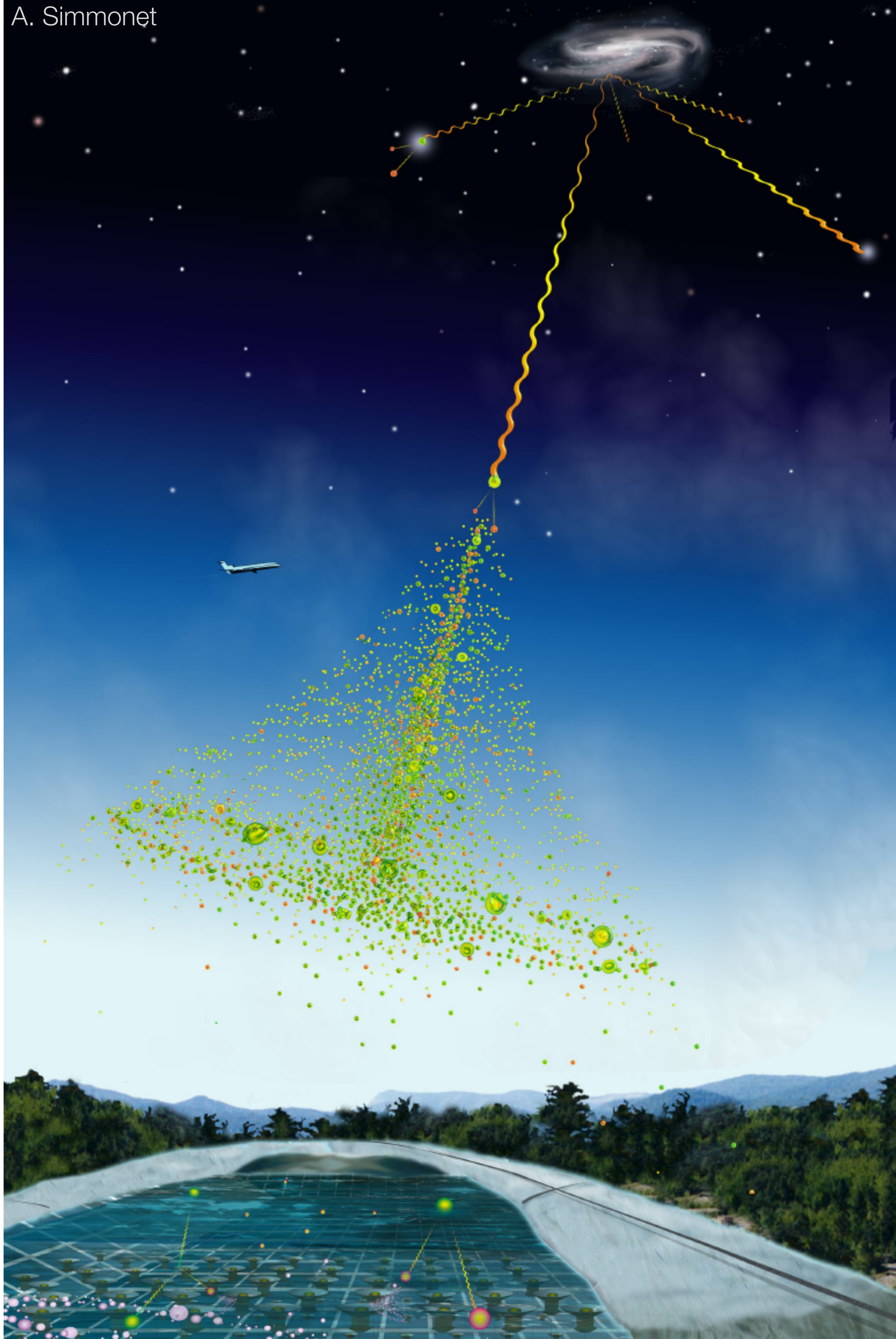
- The Milagro Observatory
- Summary of Milagro Results
  - Galactic Plane Survey
  - Small-scale Cosmic Ray Anisotropy
  - Fermi Bright Source List Follow-Up
- High Altitude Water Cherenkov (HAWC) Observatory
  - Design
  - Sensitivity
  - Status

# Milagro Gamma Ray Observatory

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


A. Abdo, B. Allen, D. Berley, G. Christopher, T. DeYoung, B. L. Dingus, R. W. Ellsworth, M. M. González, J. A. Goodman, C. M. Hoffman, P. Hüntemeyer, 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

# Milagro: An EAS TeV Gamma Observatory



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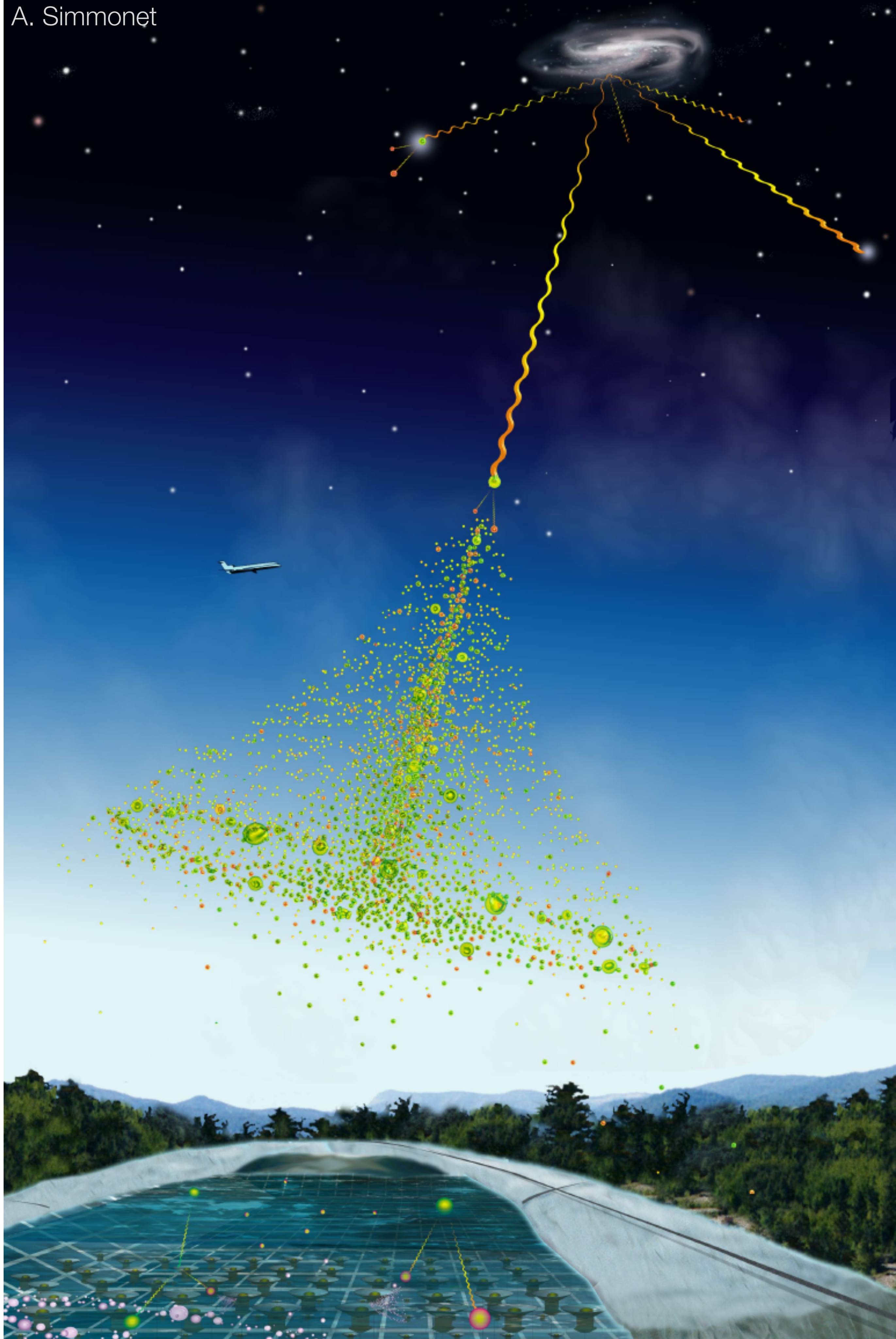

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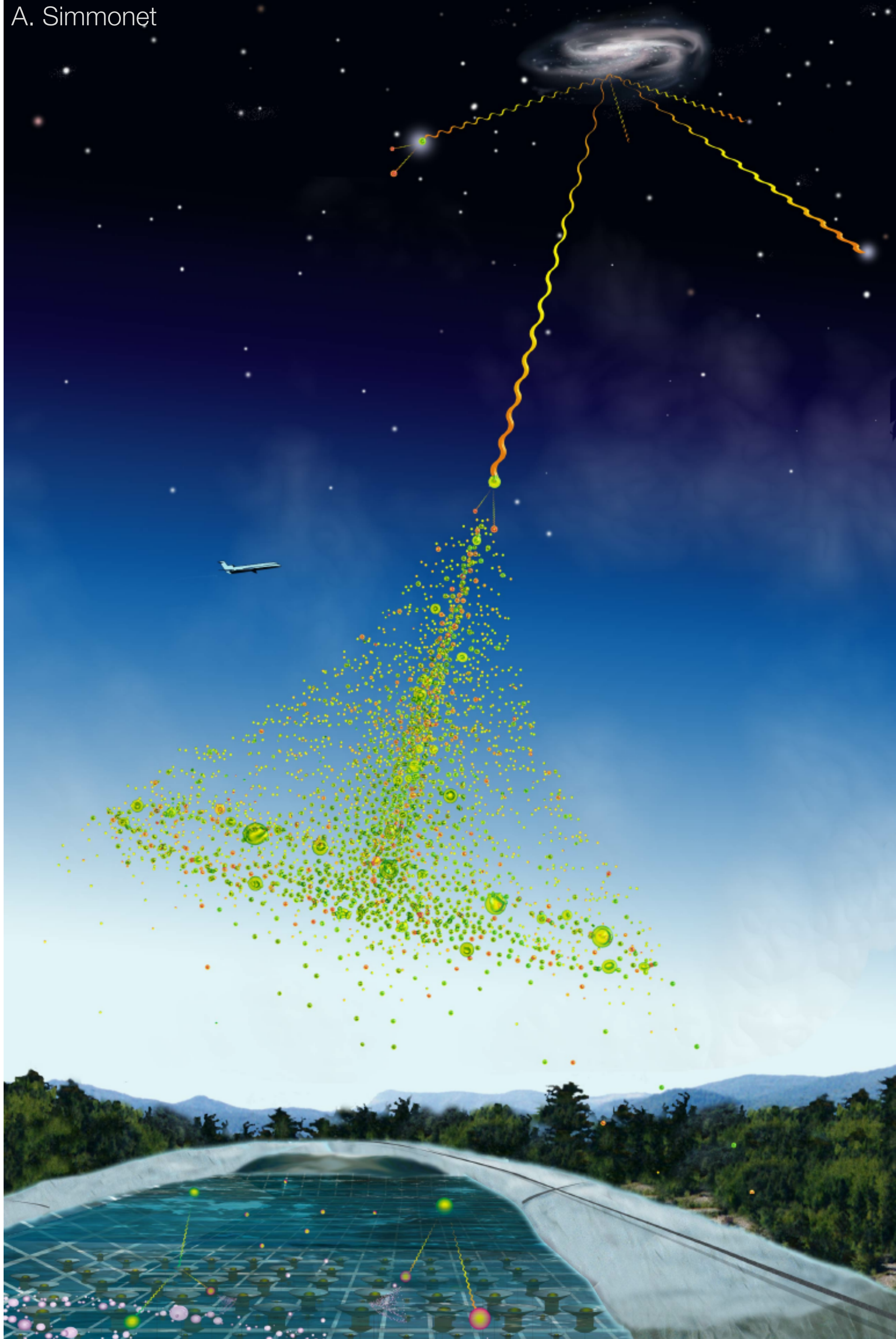

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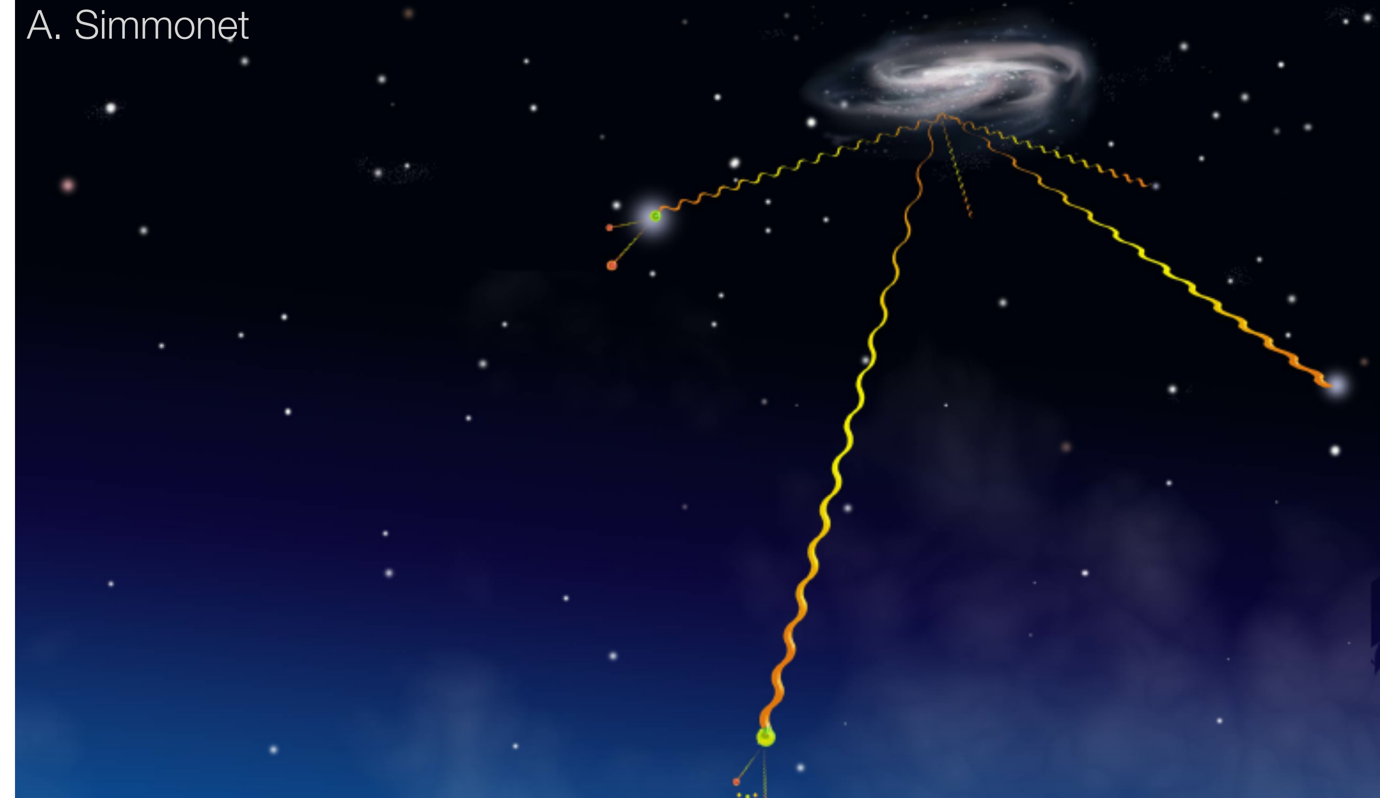


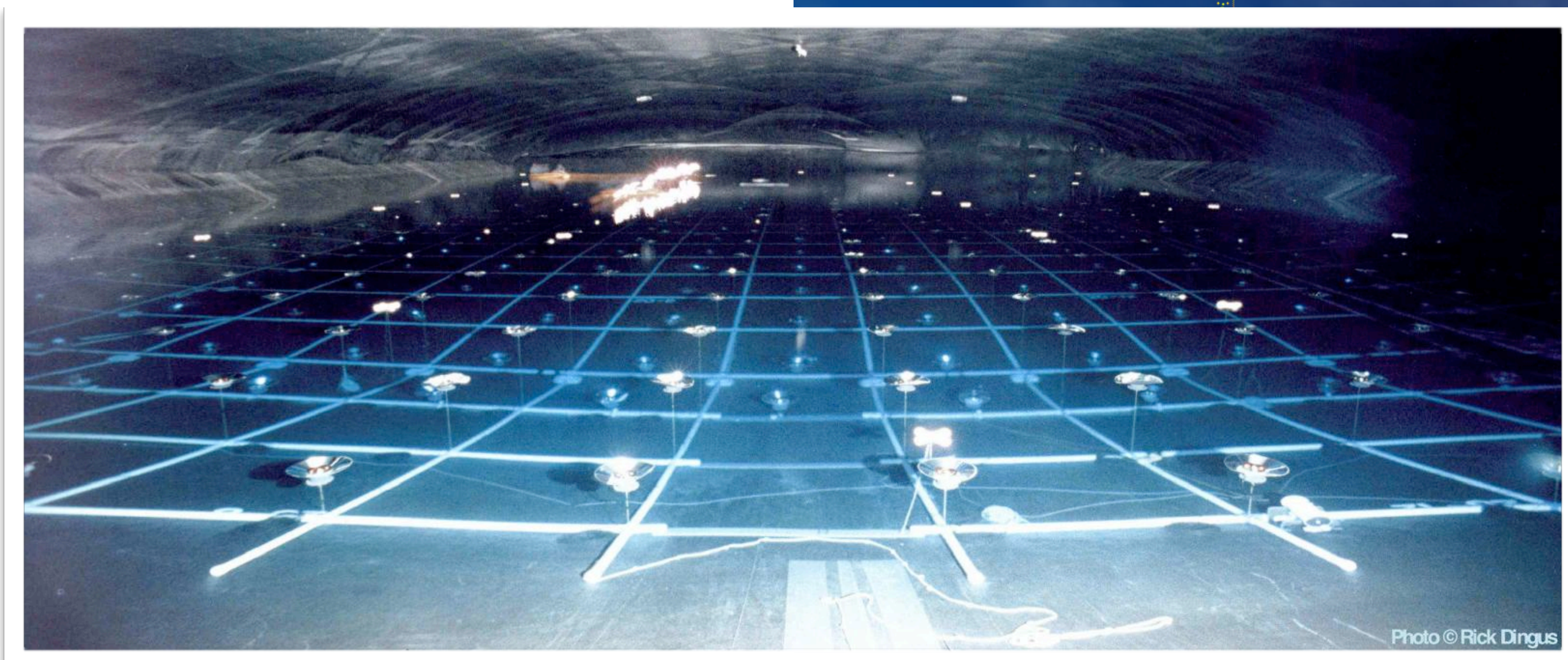


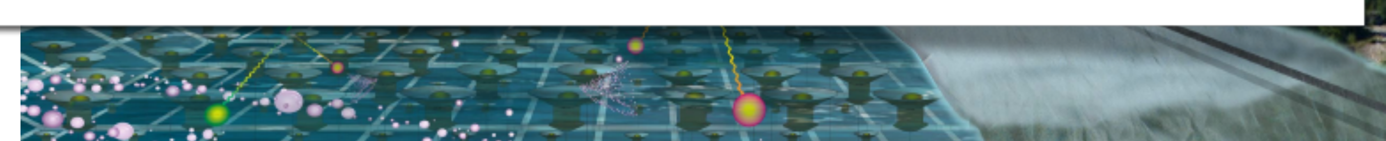

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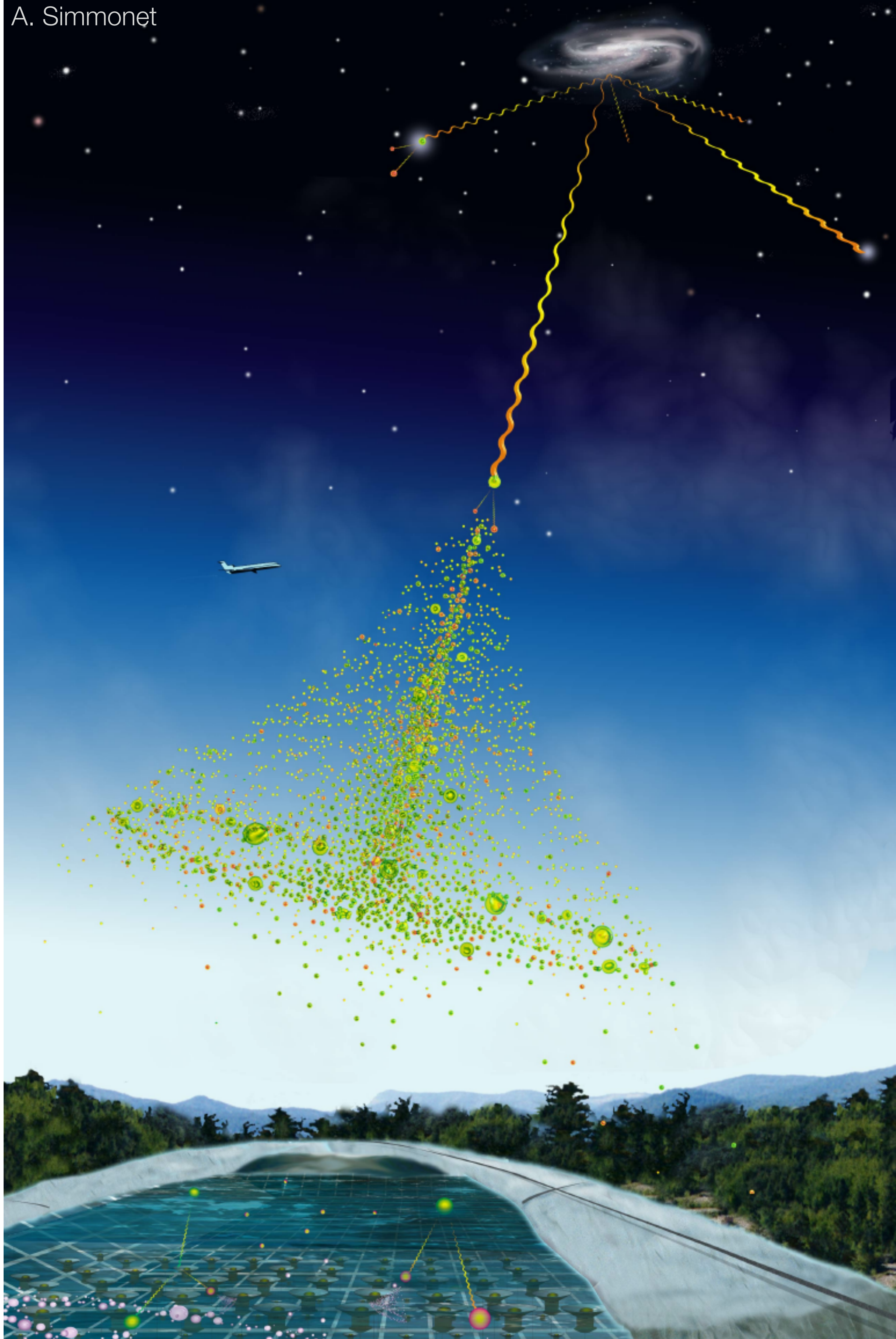

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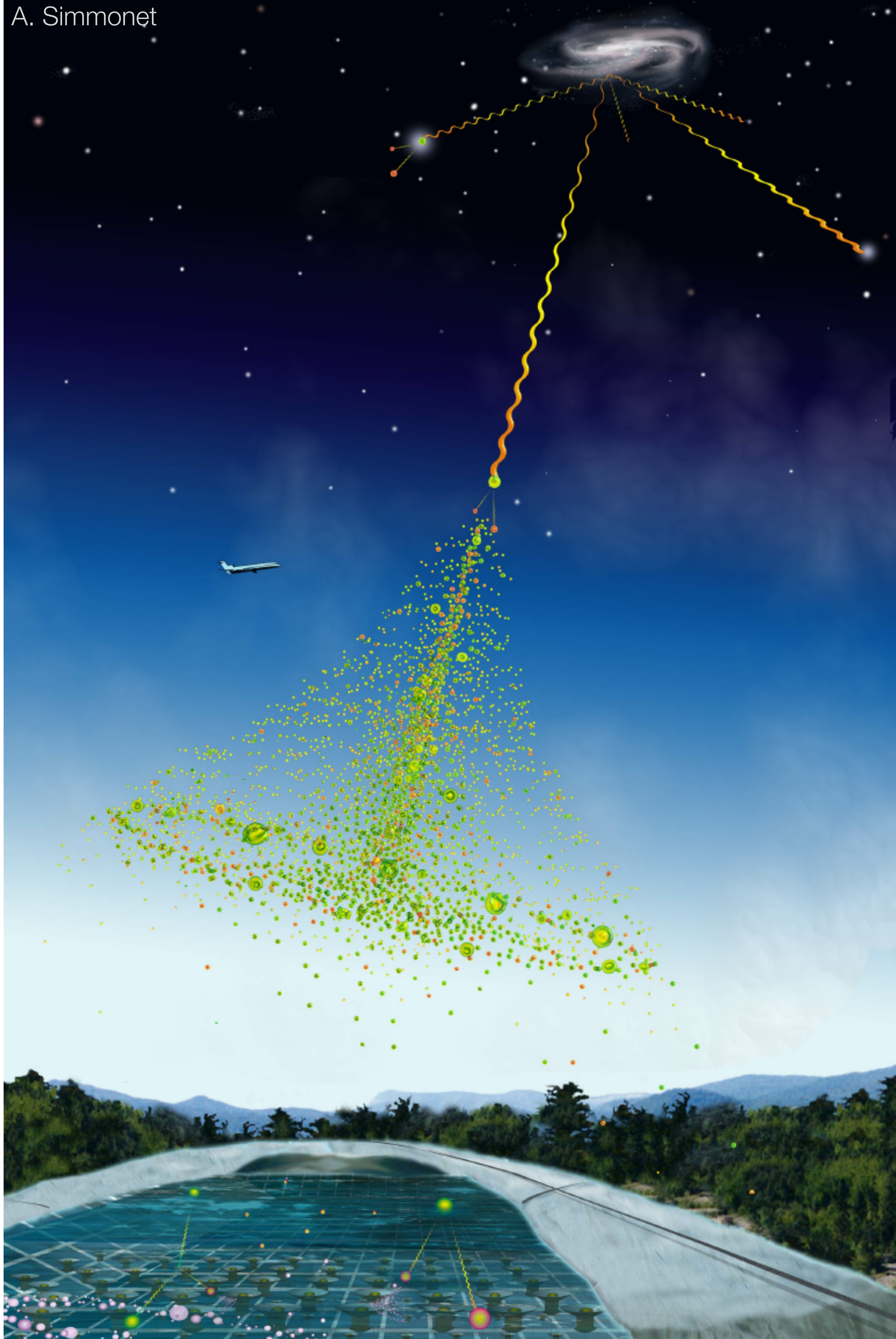

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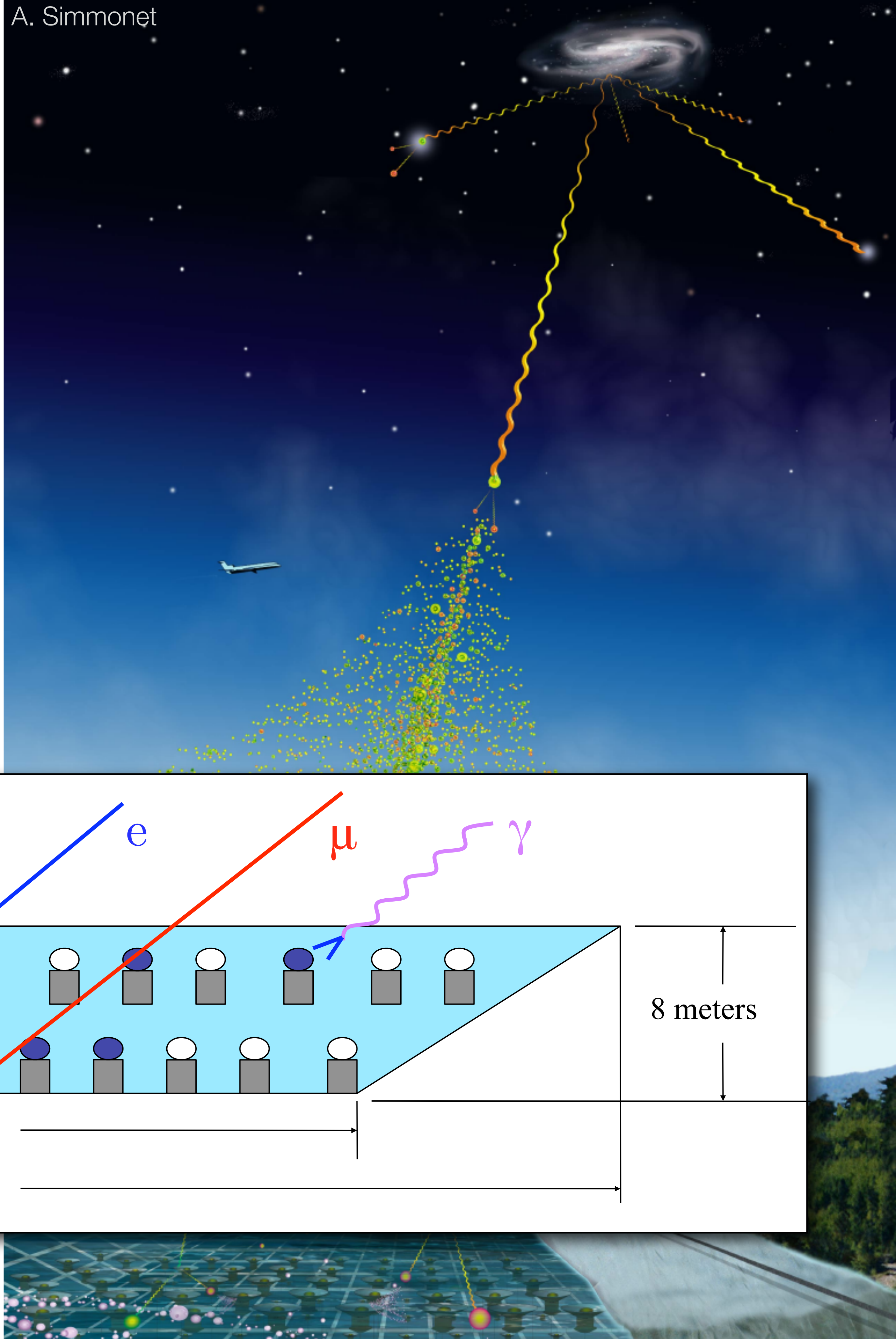


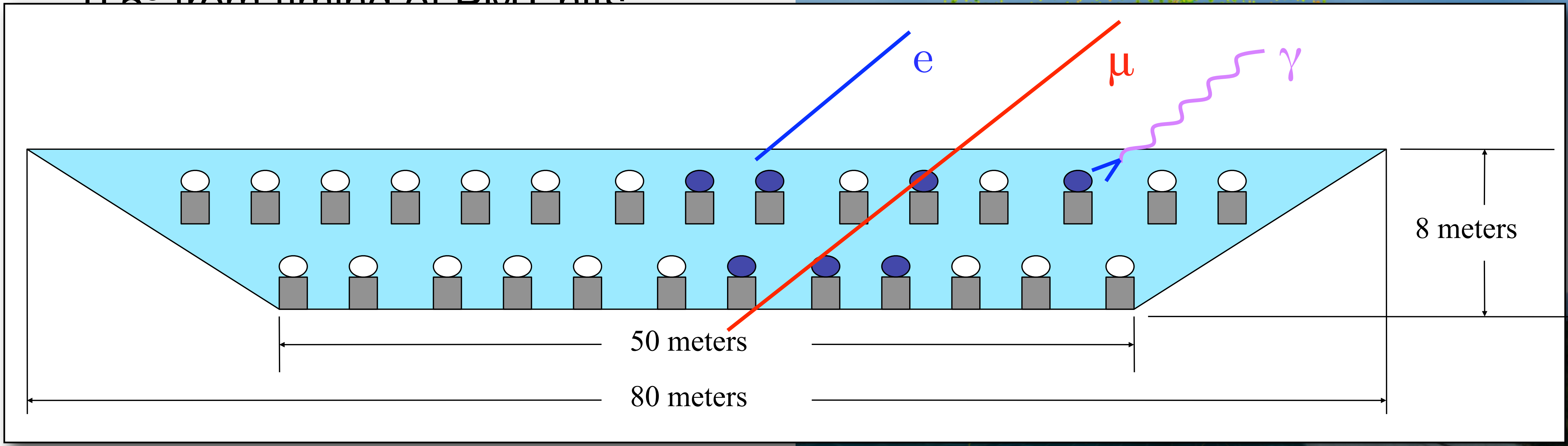

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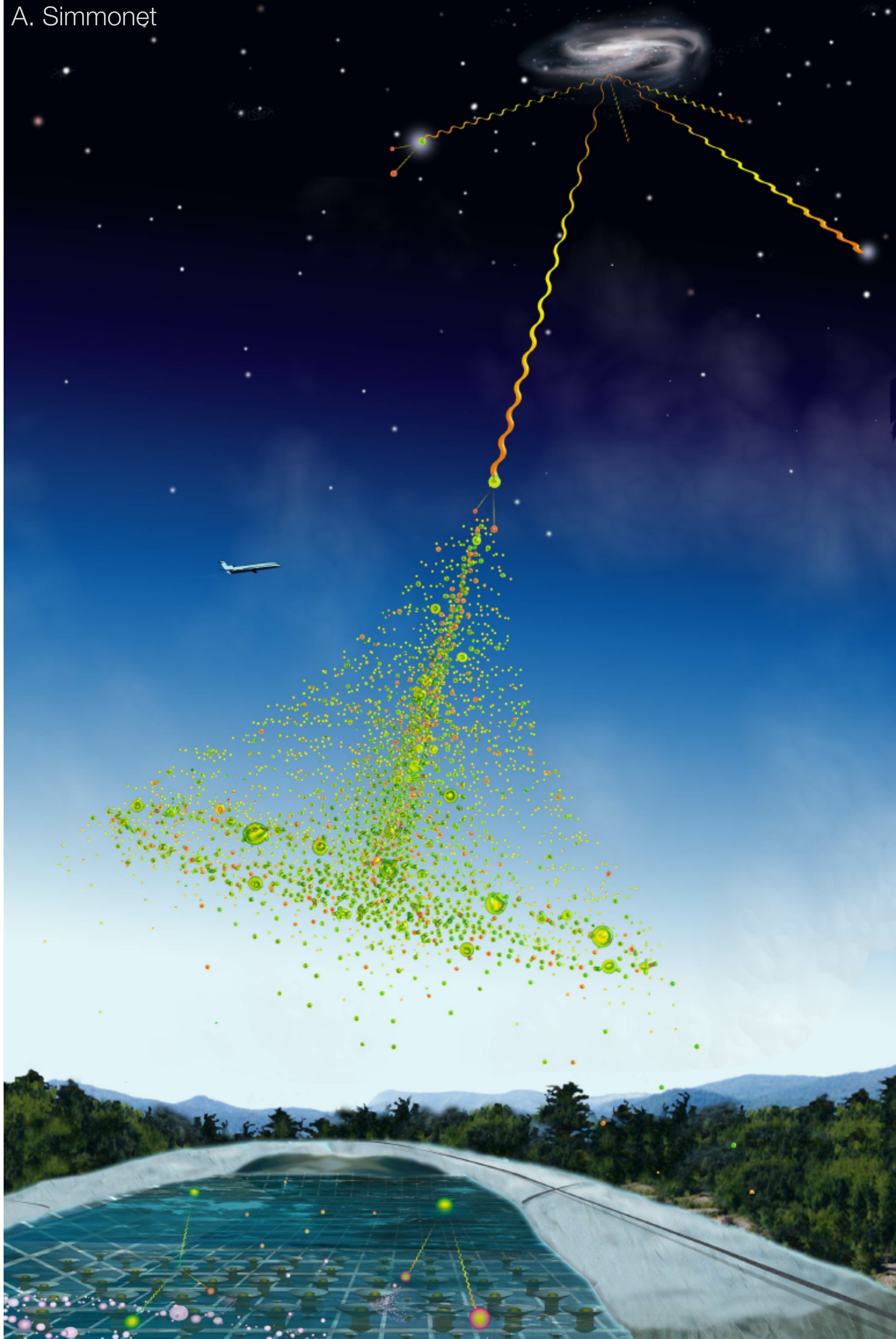
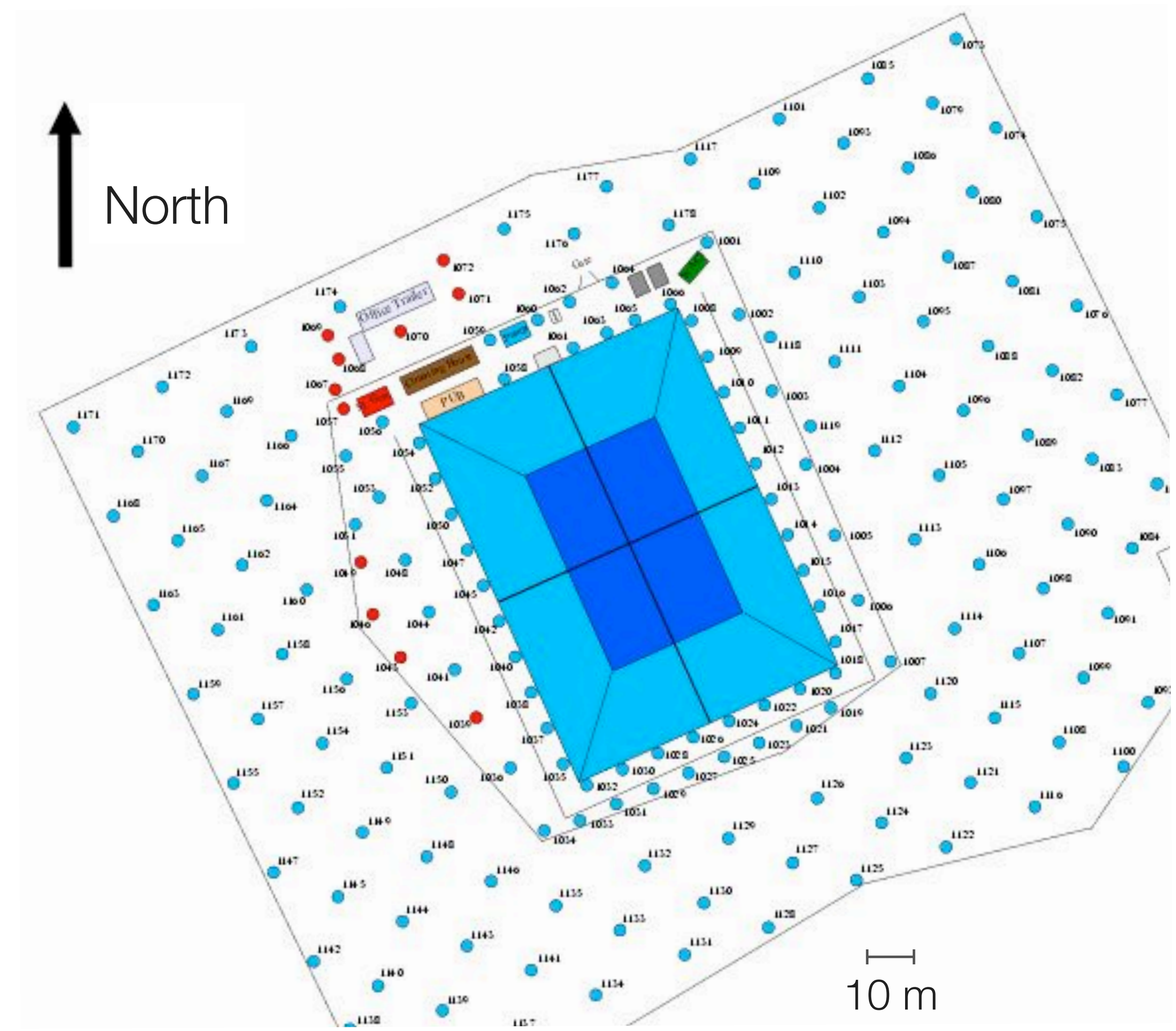
- Field of view ~2 sr, typical duty factor >95%



# 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
- 3,600 m$^2$ pond, operational January 2001
- 34,000 m$^2$ outrigger array, fully operational June 2004
- Decommissioned in June 2008



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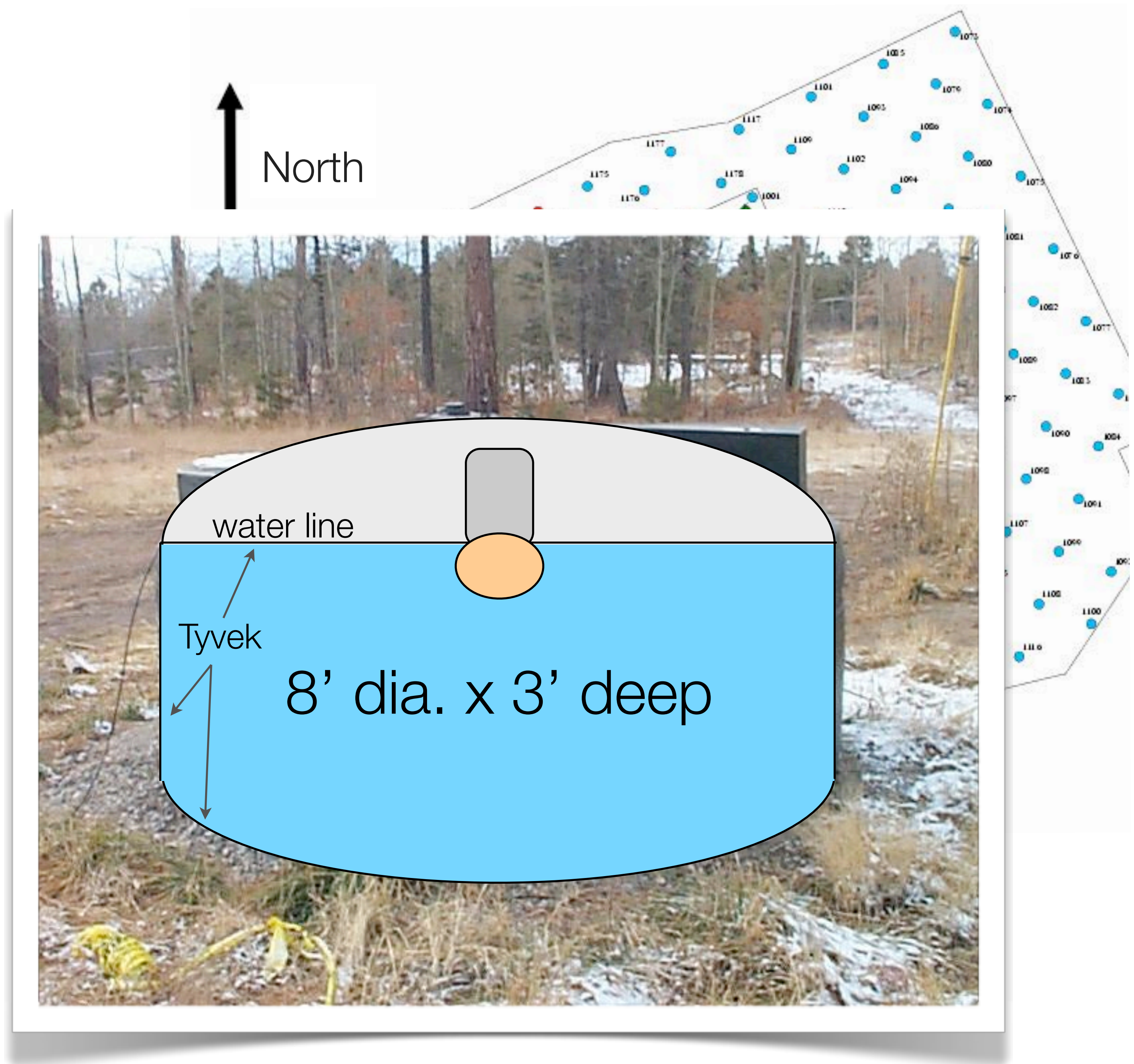

# Milagro Energy Response

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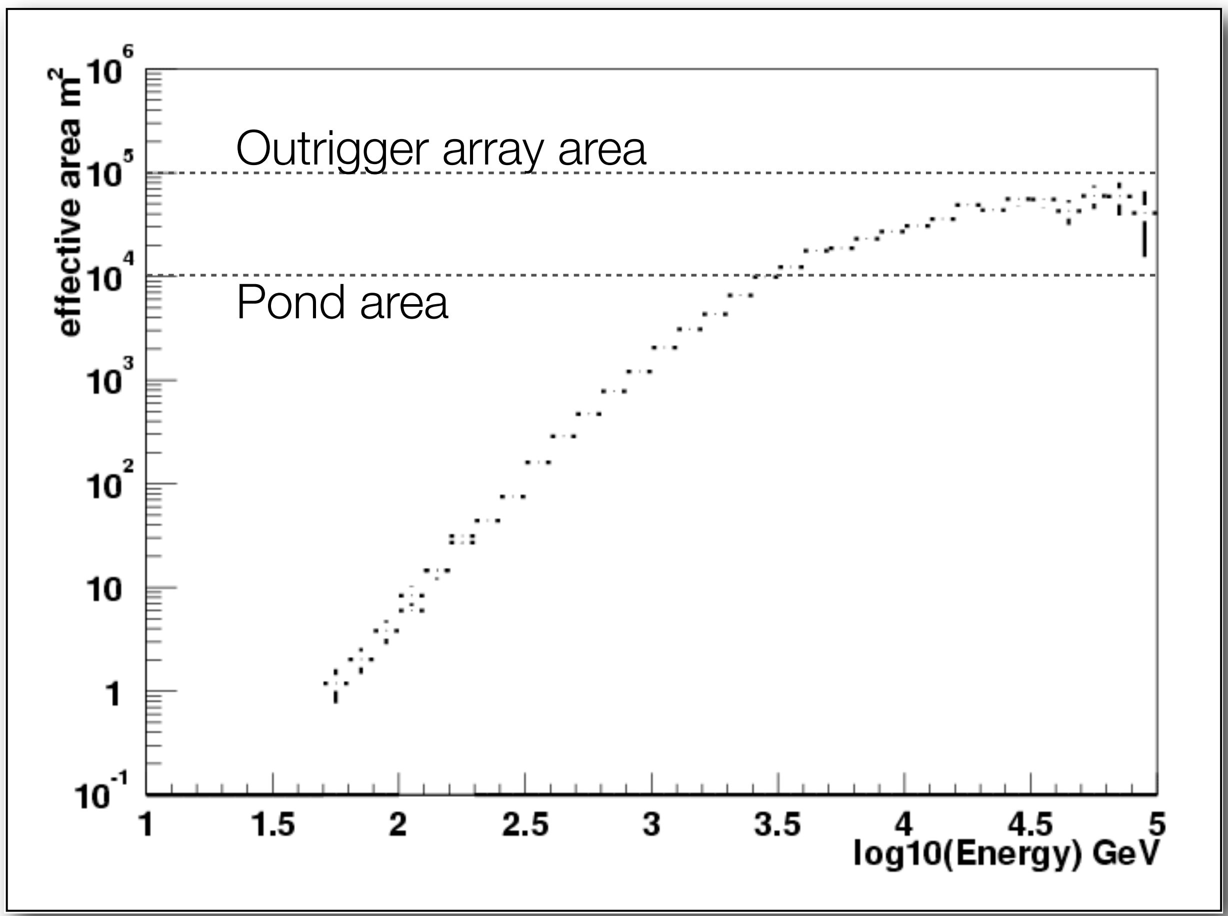


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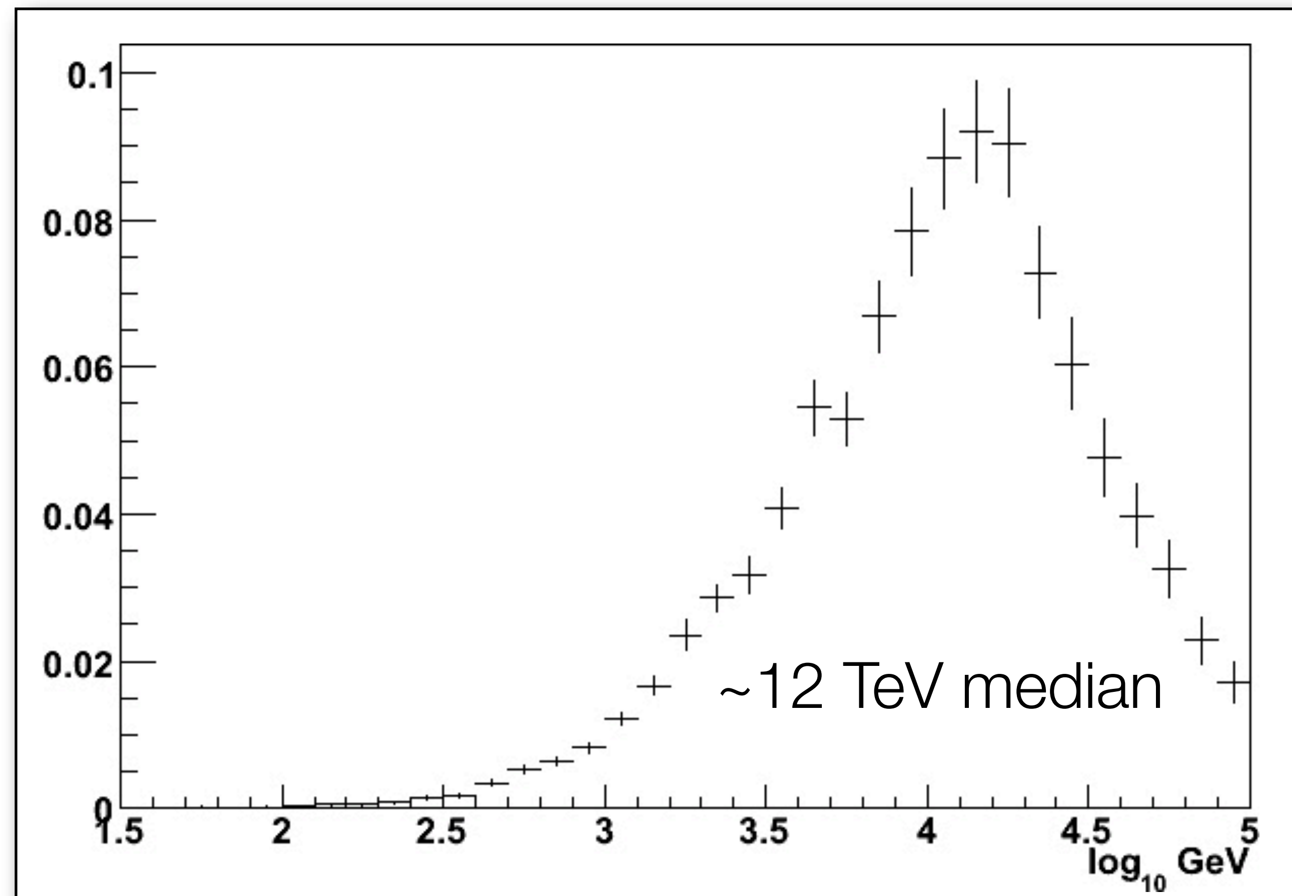

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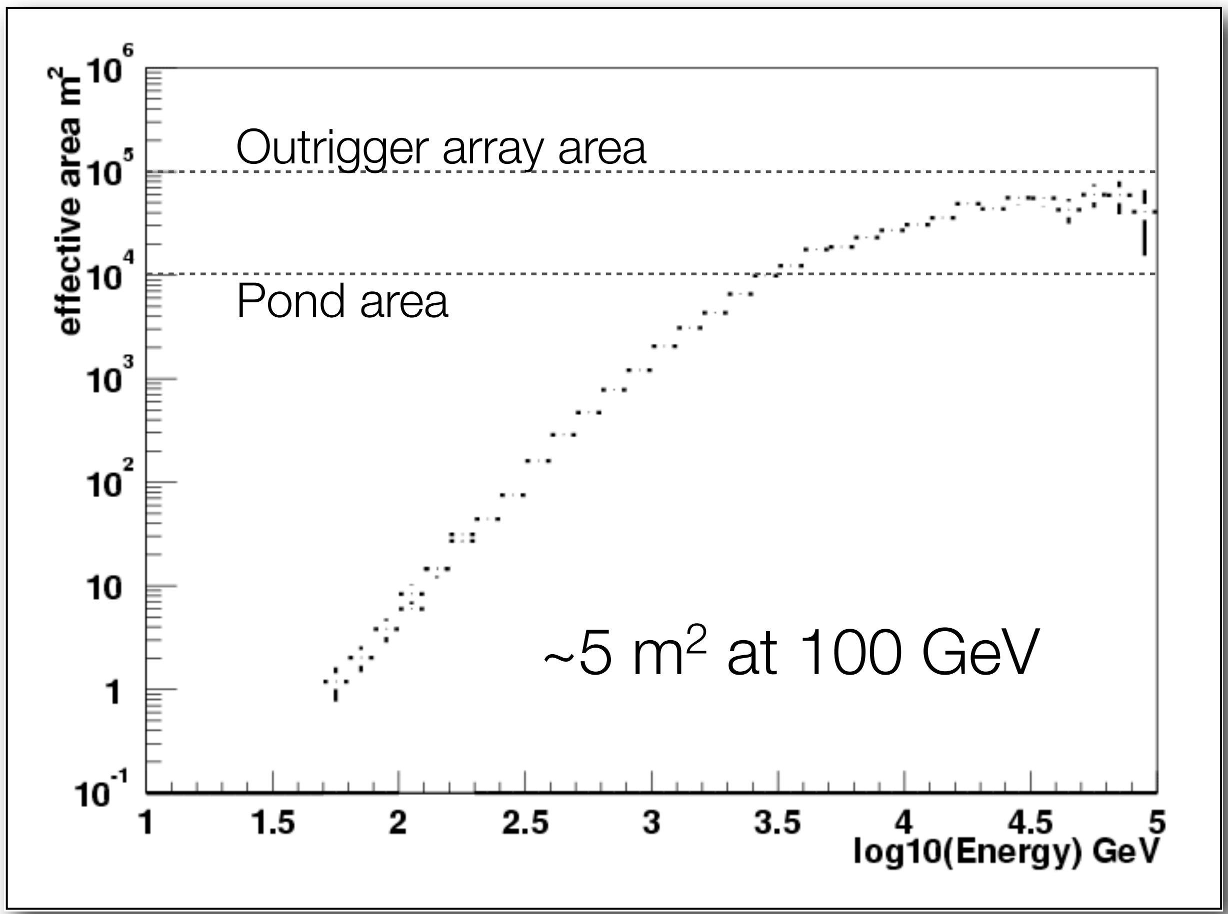


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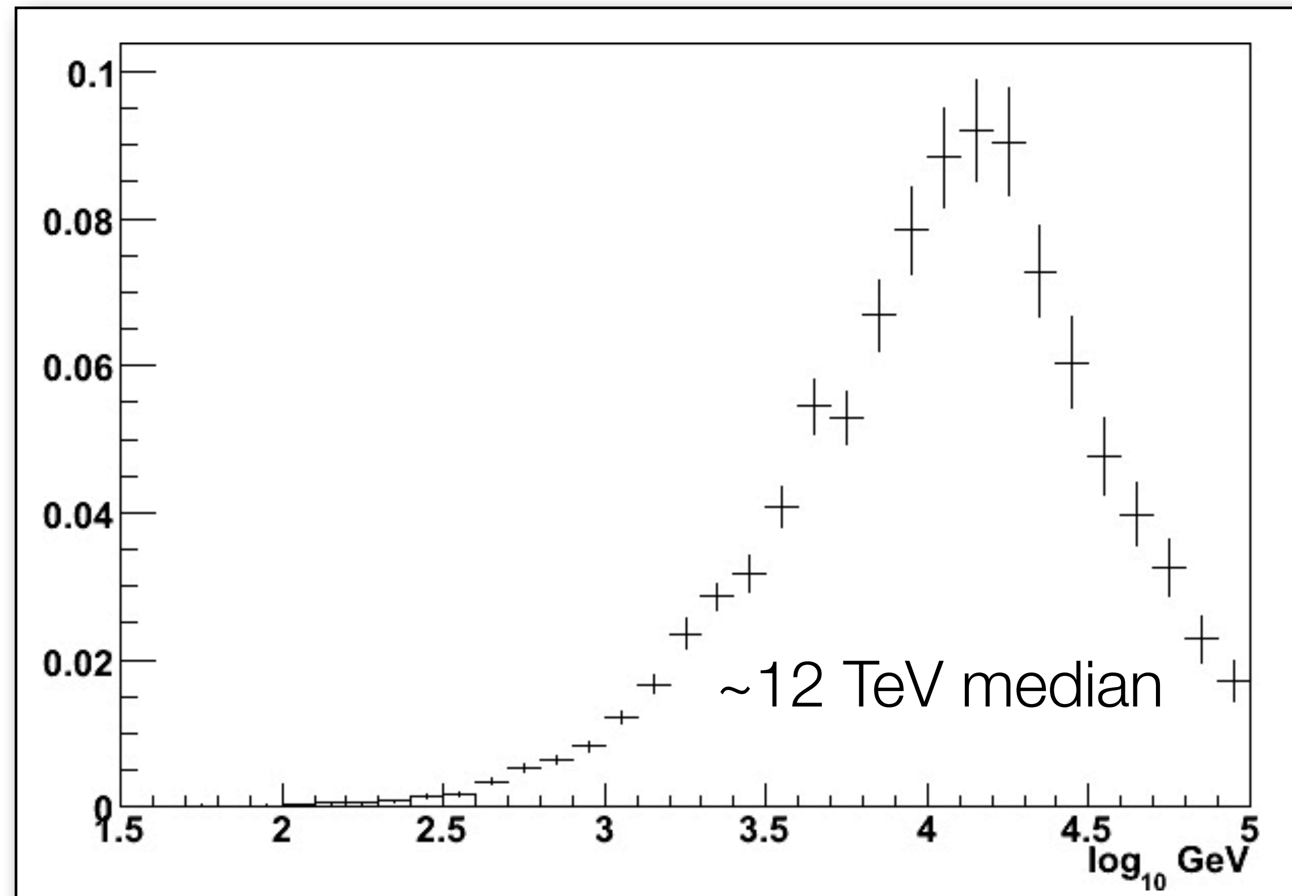

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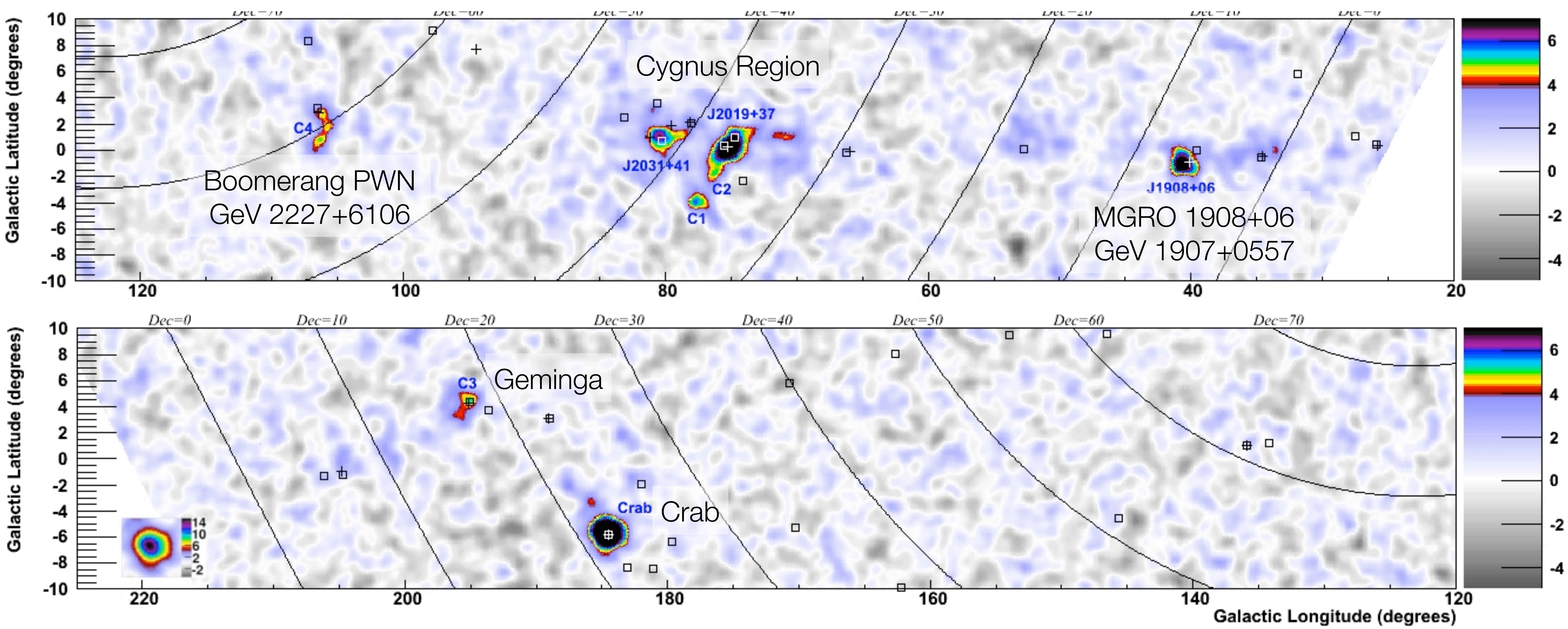


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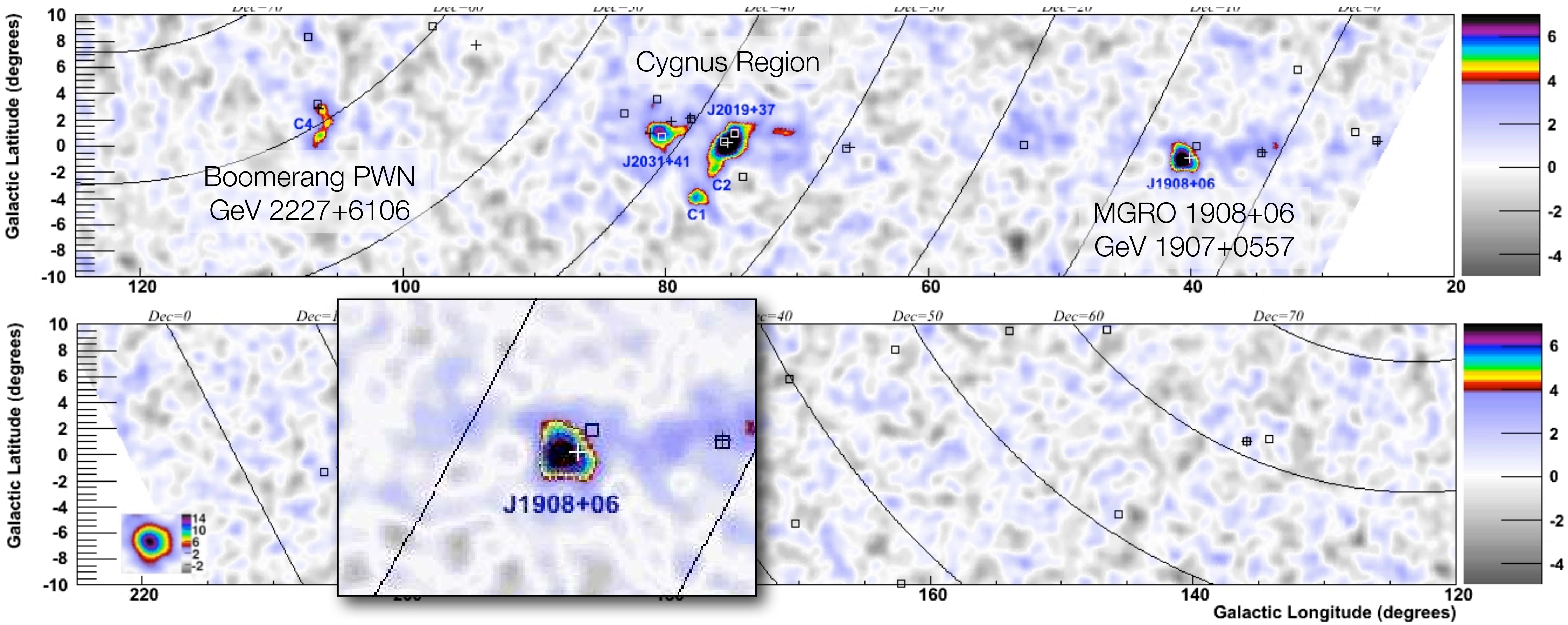


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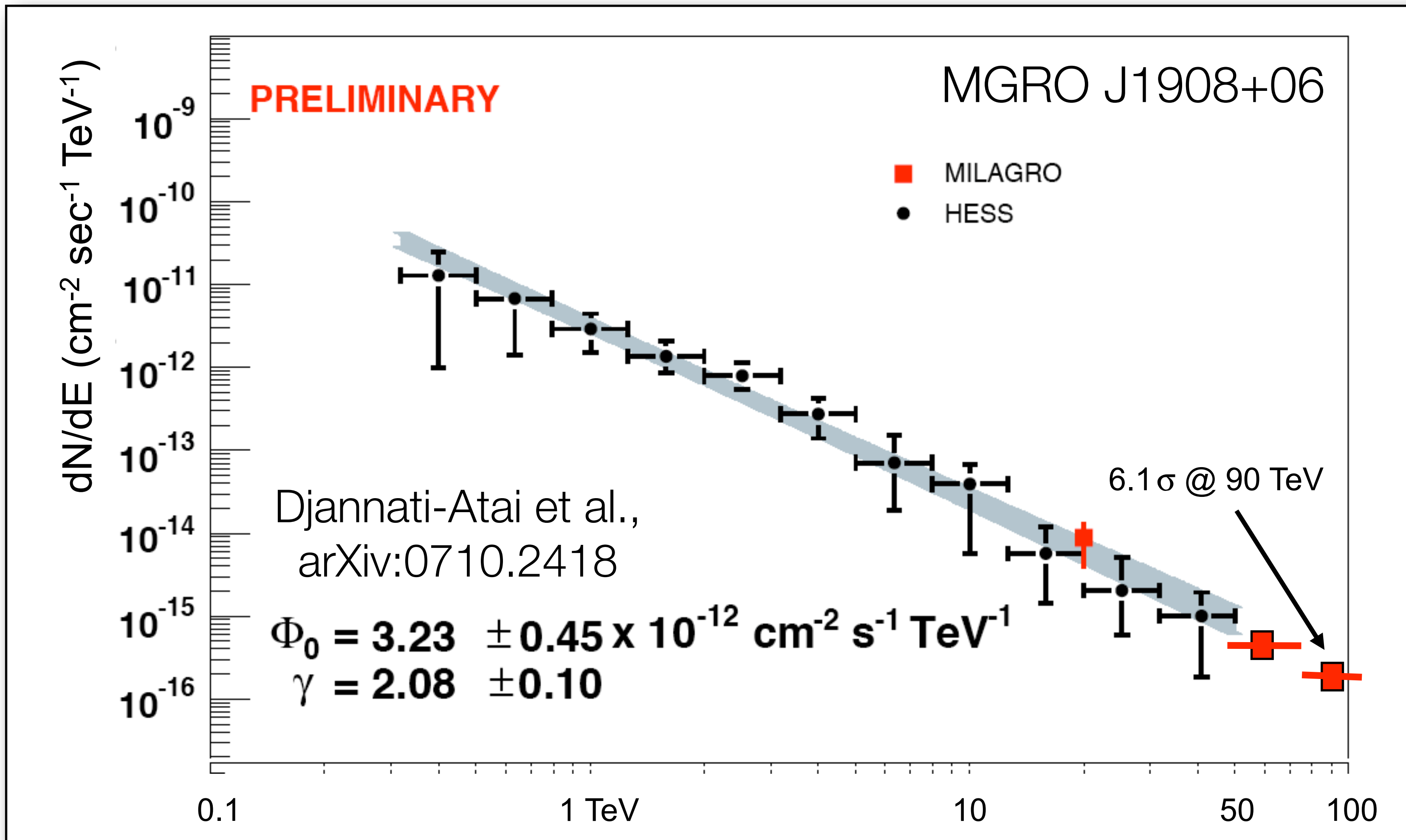
# A Galactic PeVatron?

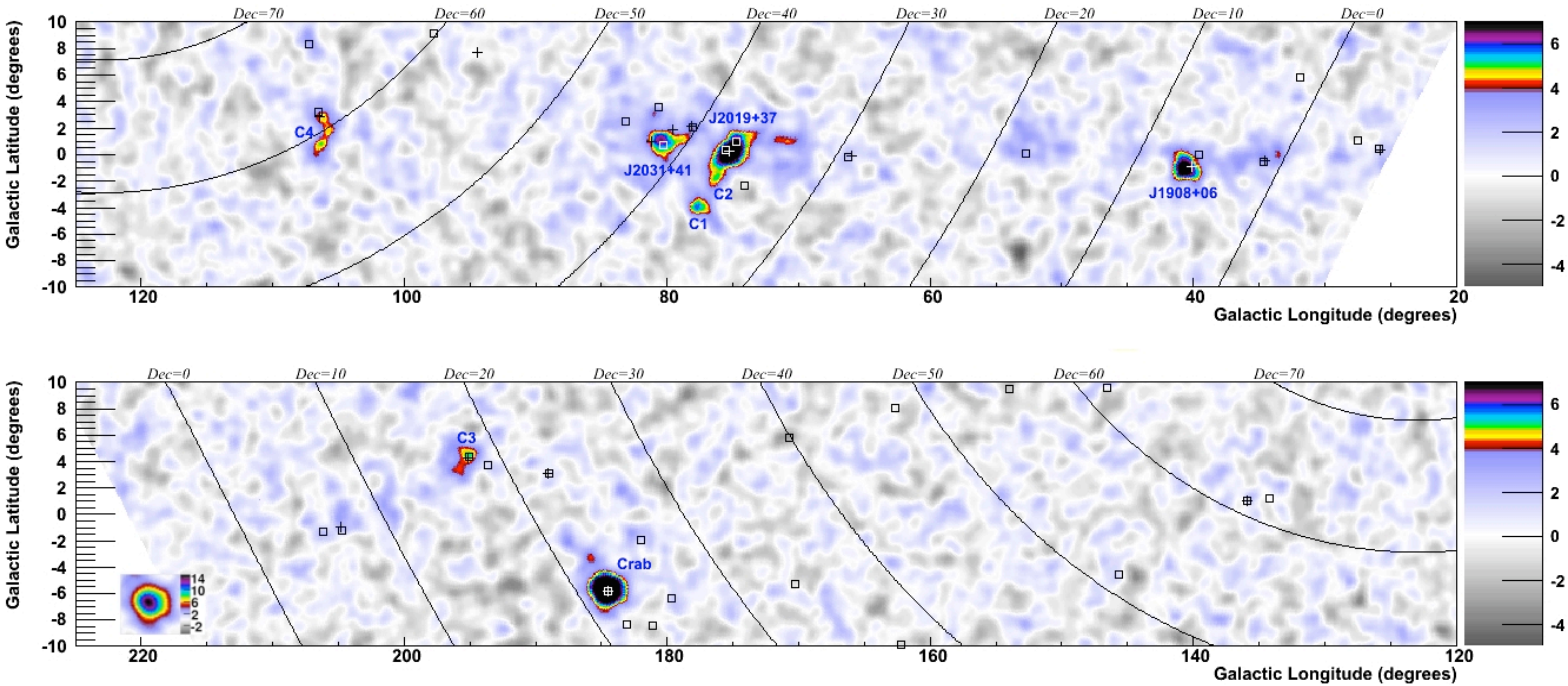



$E_\gamma \sim E_h/10$

for stochastic acceleration and photopion production

- Background cuts correlated with gamma ray energy
  - Evolution of significance with harder cuts can be used as a crude spectral measurement (improvements underway)
  - Spectrum appears to extend to nearly 100 TeV – nearly the knee

# TeV Diffuse Emission from the Galactic Plane




- Galactic plane survey, with 8 detected sources/candidates subtracted

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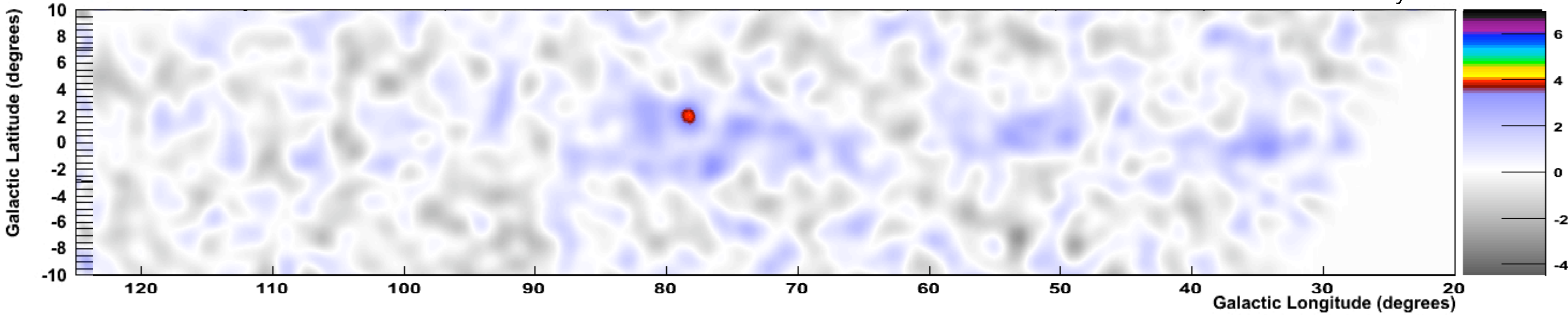


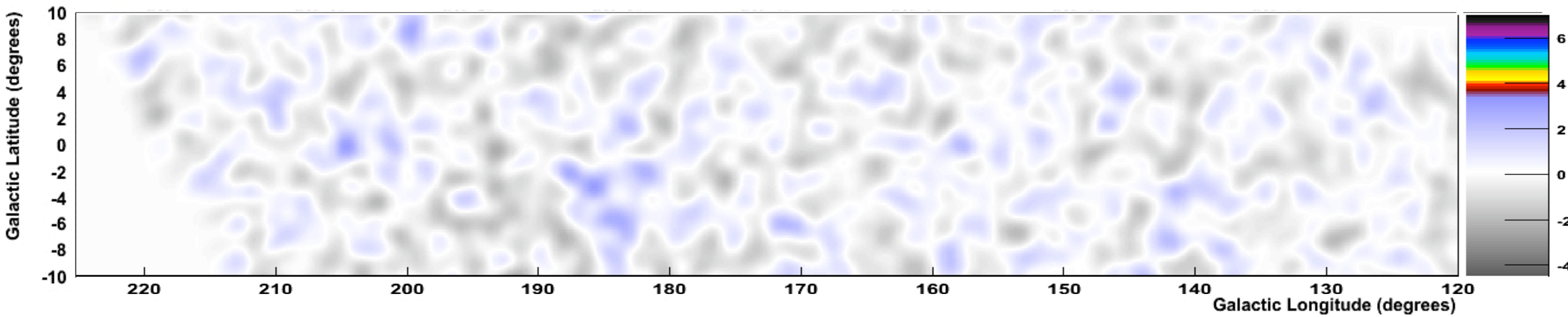


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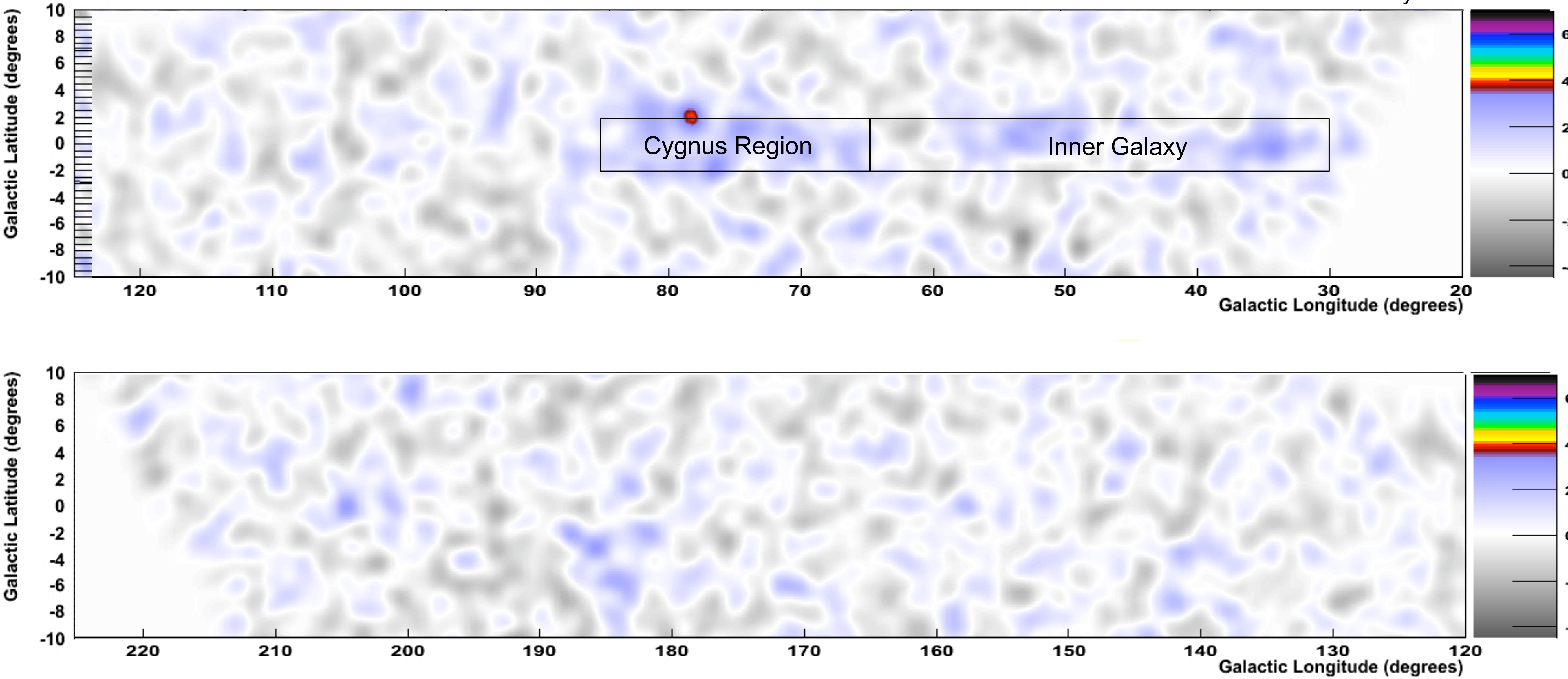


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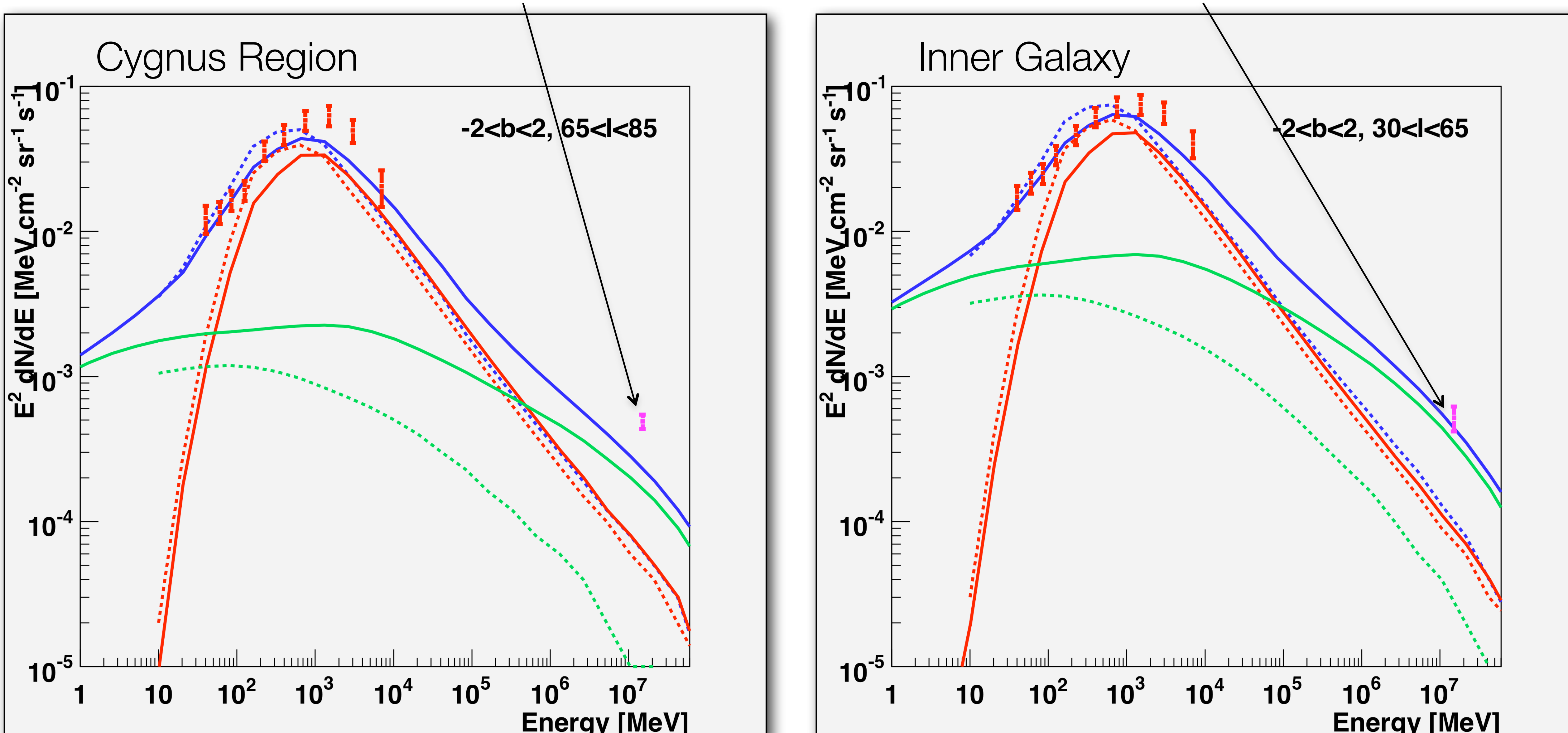
# TeV Diffuse Excess

8 times the conventional flux

4.7 times the conventional flux




Total GALPROP Prediction
Pion Decay
Electron Inverse Compton

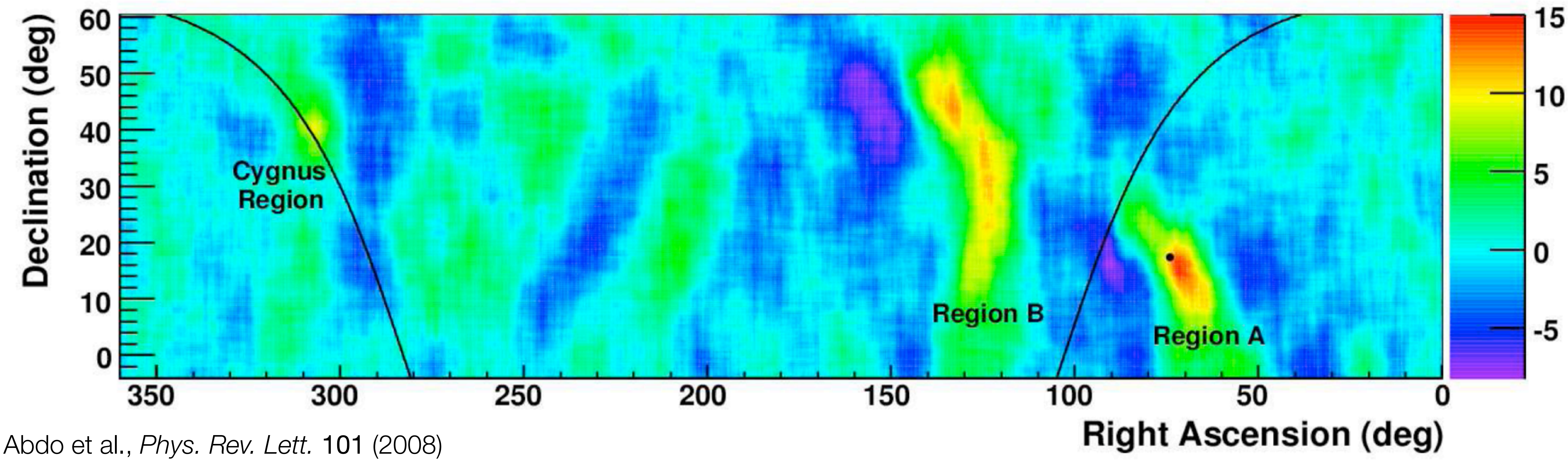
Optimized GALPROP
Conventional GALPROP

Strong et al., *Ap. J.* 613 (2004)
Strong et al., *A&A* 422 (2004)

# Possible Explanations for the TeV Diffuse Excess

- Unresolved Gamma Ray Sources
  - Extrapolating the HESS source population can explain a substantial portion of the TeV excess (Casanova & Dingus, *Astropart. Phys.* 2008)
- Young Cosmic Rays Interacting with Matter
  - Harder spectrum than observed locally because near their sources
  - Cf. HESS observations along Galactic Center (Aharonian et al., *Nature* 2006)
- Dark Matter
  - E.g., new TeV scale physics leads to high dark matter-hadron scattering cross section (Masip & Mastromatteo, arXiv:0904.0921)

# Small-Scale Cosmic Ray Anisotropy

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- Significant (>12σ) anisotropy in the arrival direction of cosmic rays
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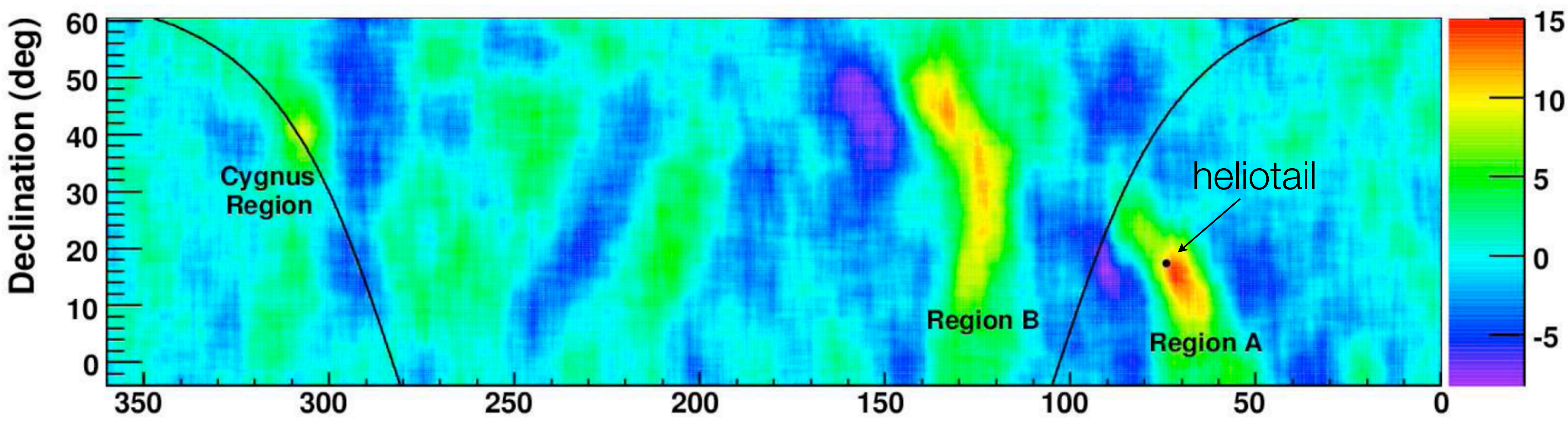


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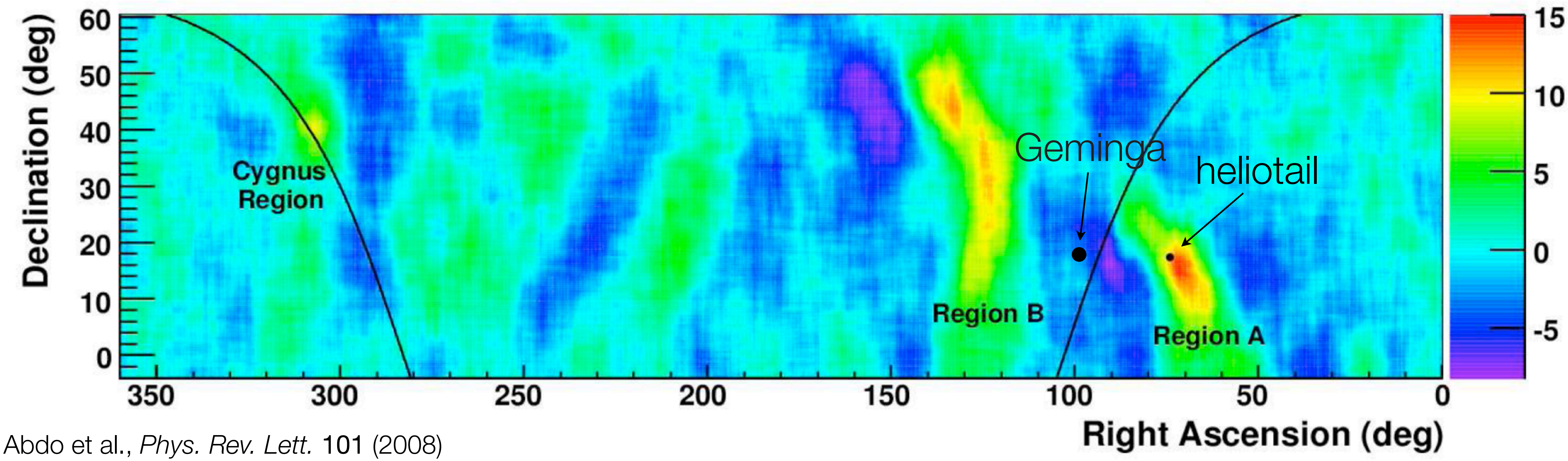


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# Attempts to Explain Small-Scale Anisotropy

- Compatible observations by Tibet – unlikely to be expt'l error
- Heliotail: not at these energies
- Related to Geminga pulsar?
  - 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)
    - But then cosmic rays should have passed us by within ~$10^4$ years!
- IceCube working on a similar map of the southern sky – Vela?

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- Heliota
- Relate
  - Puls … Bubble(?)
  - Diffu … ght
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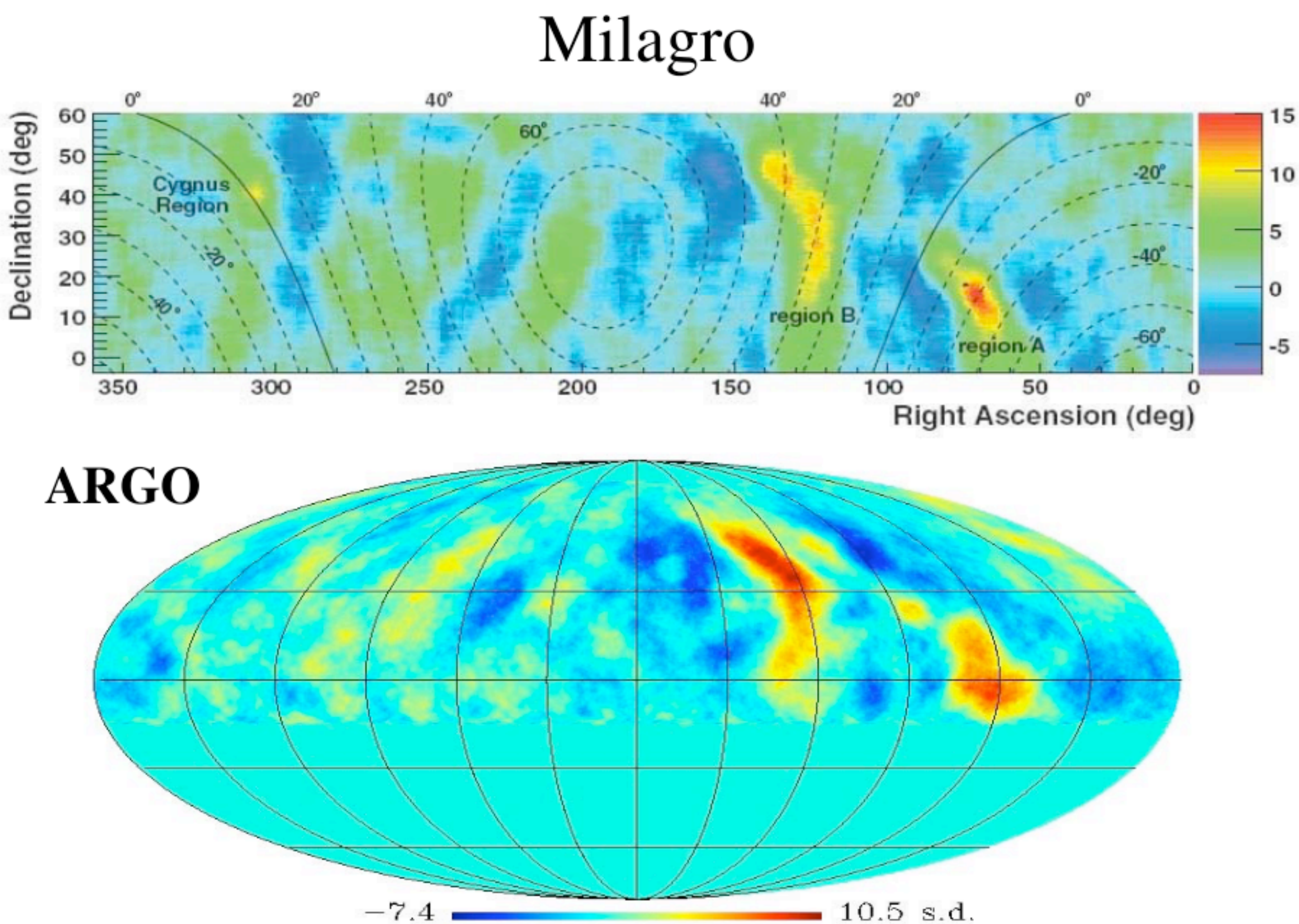
  - Free
    - B … ars!
- IceCub … a?




S. Vernetto, ARGO-YBJ, RICAP 09

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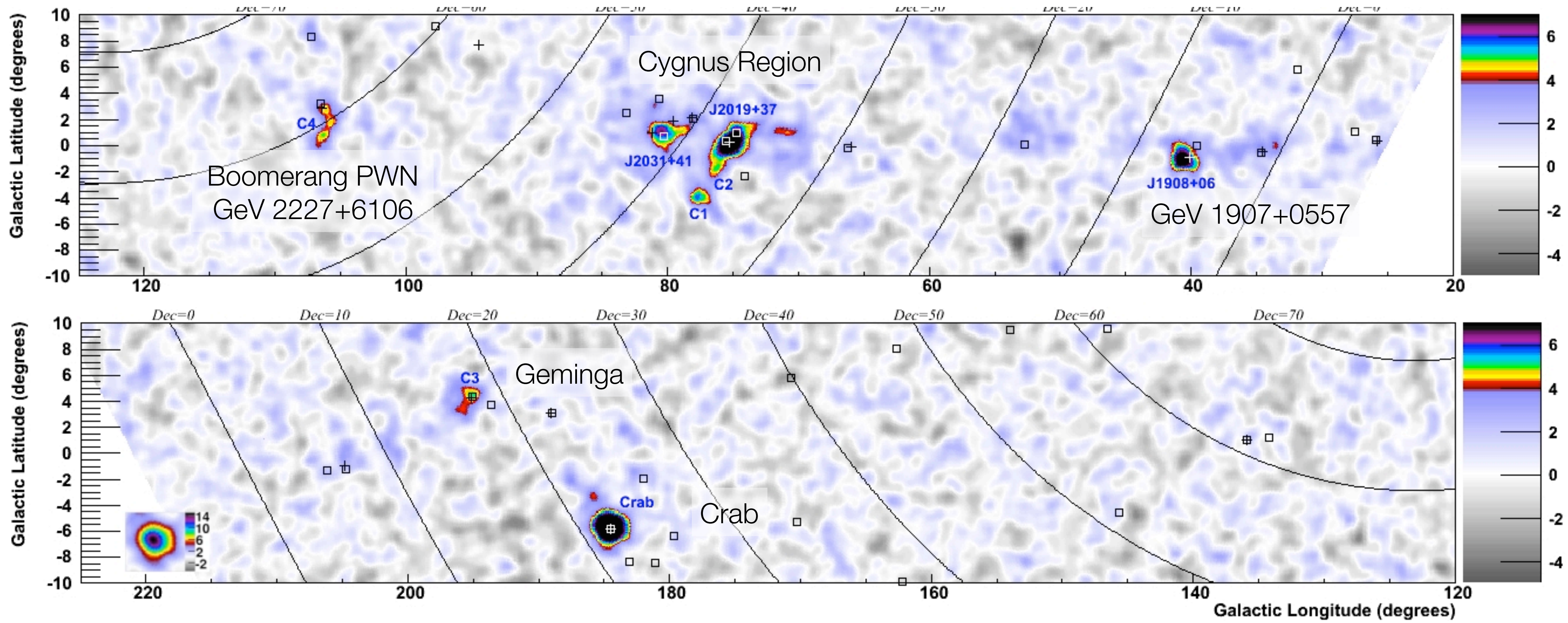


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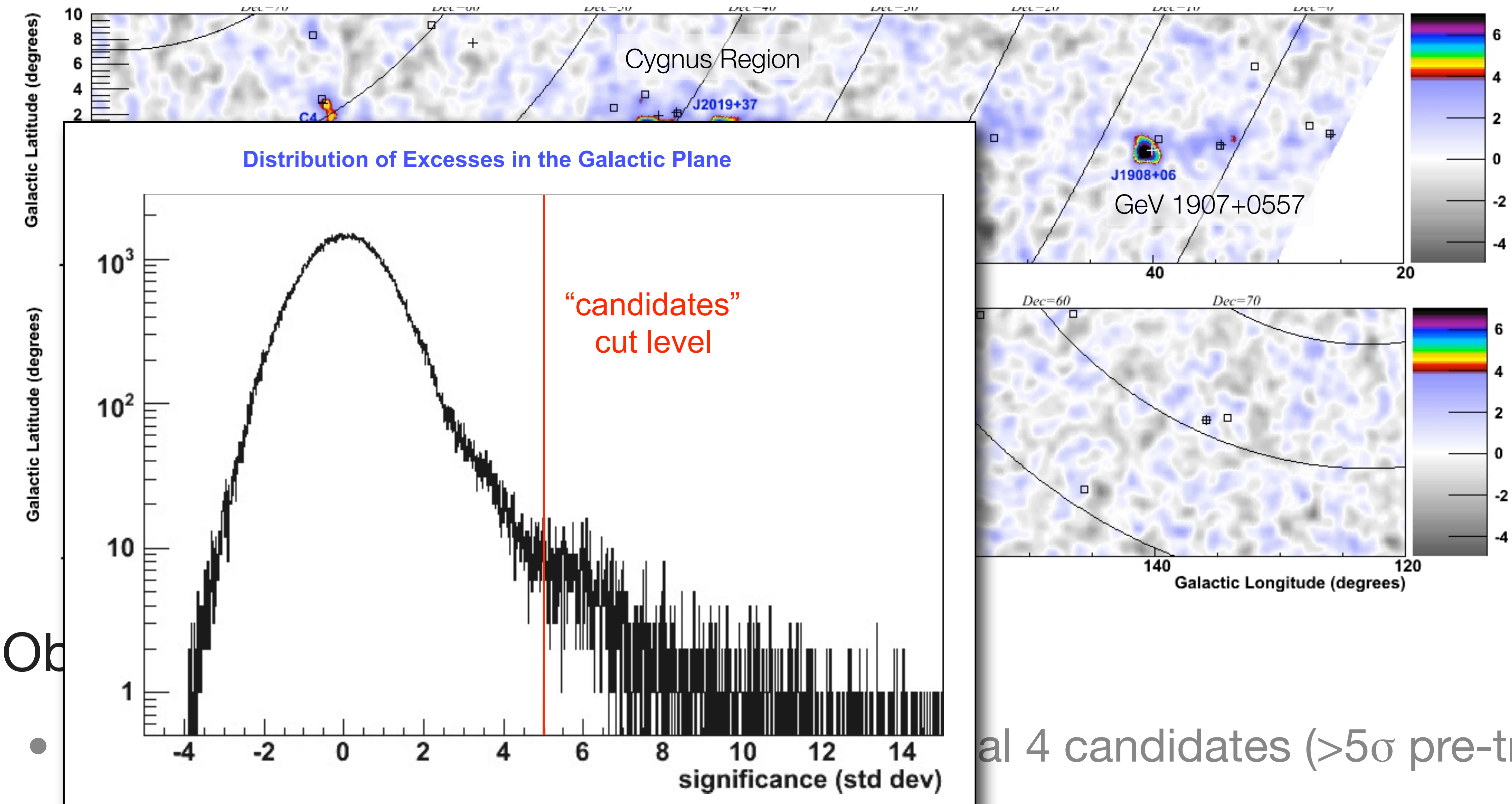


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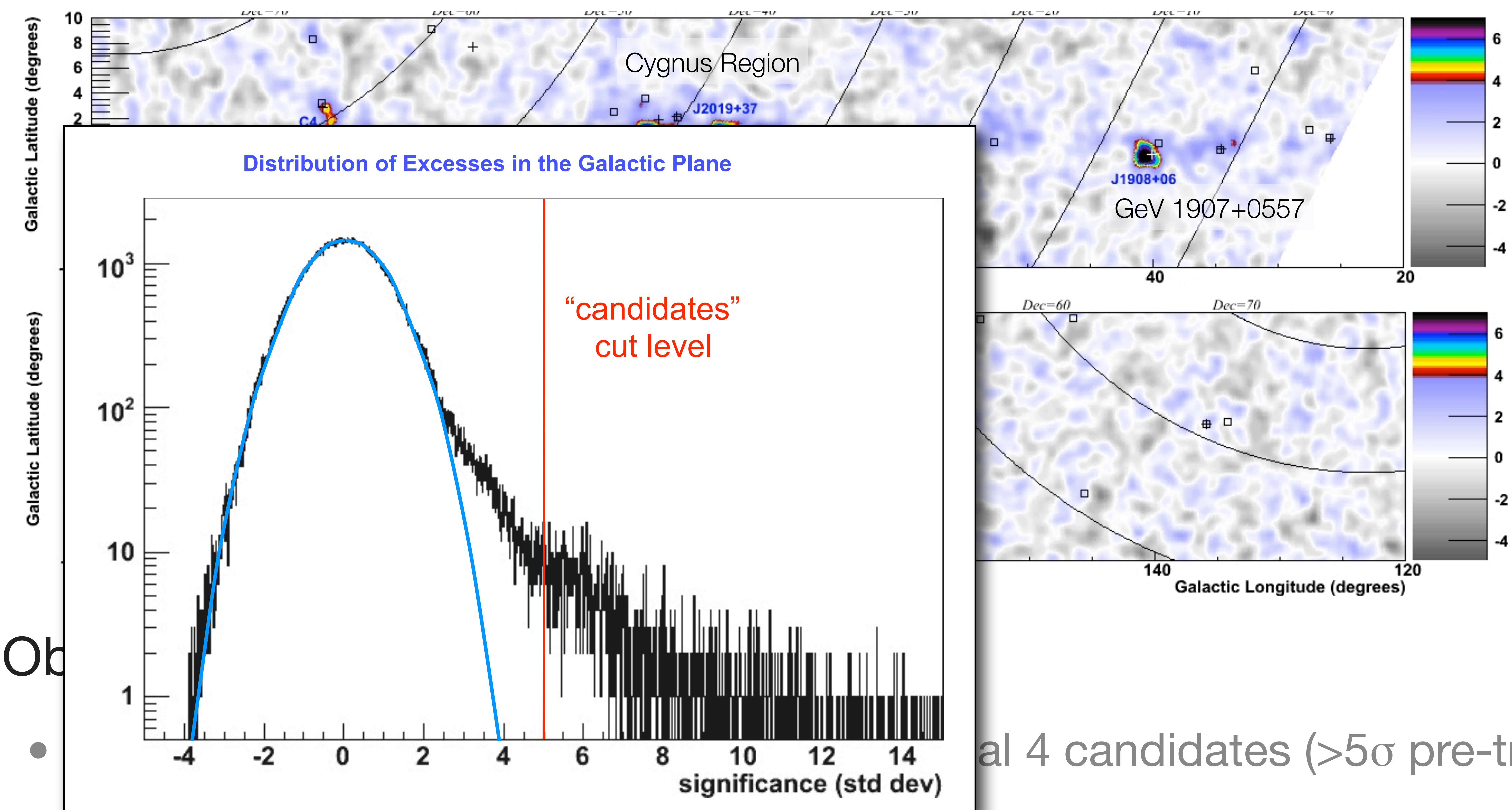


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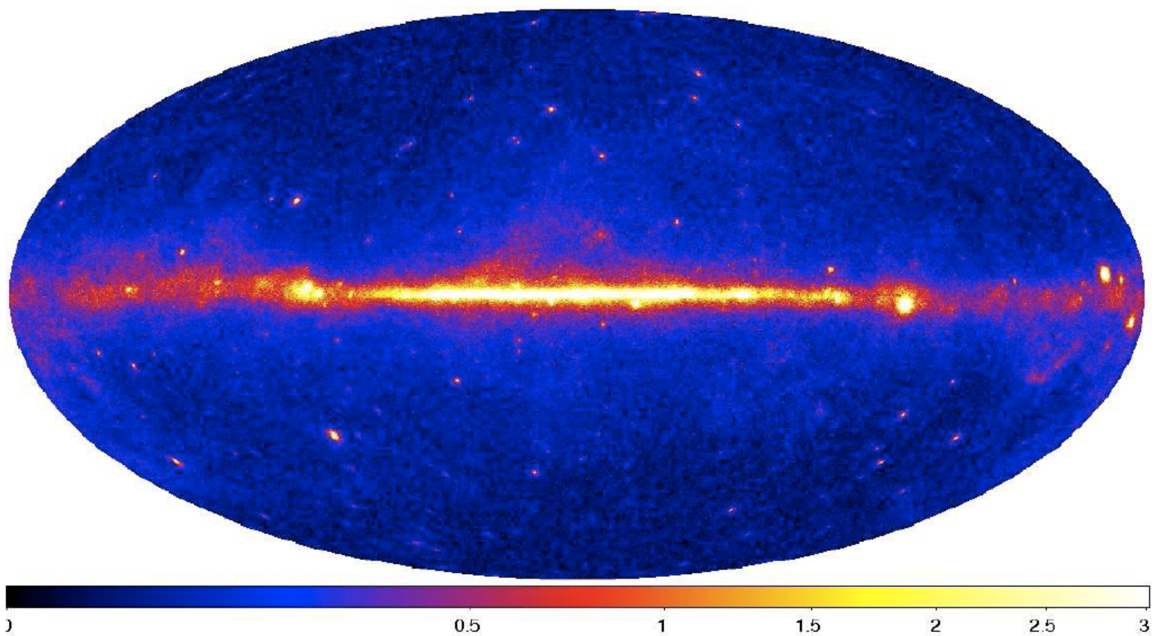
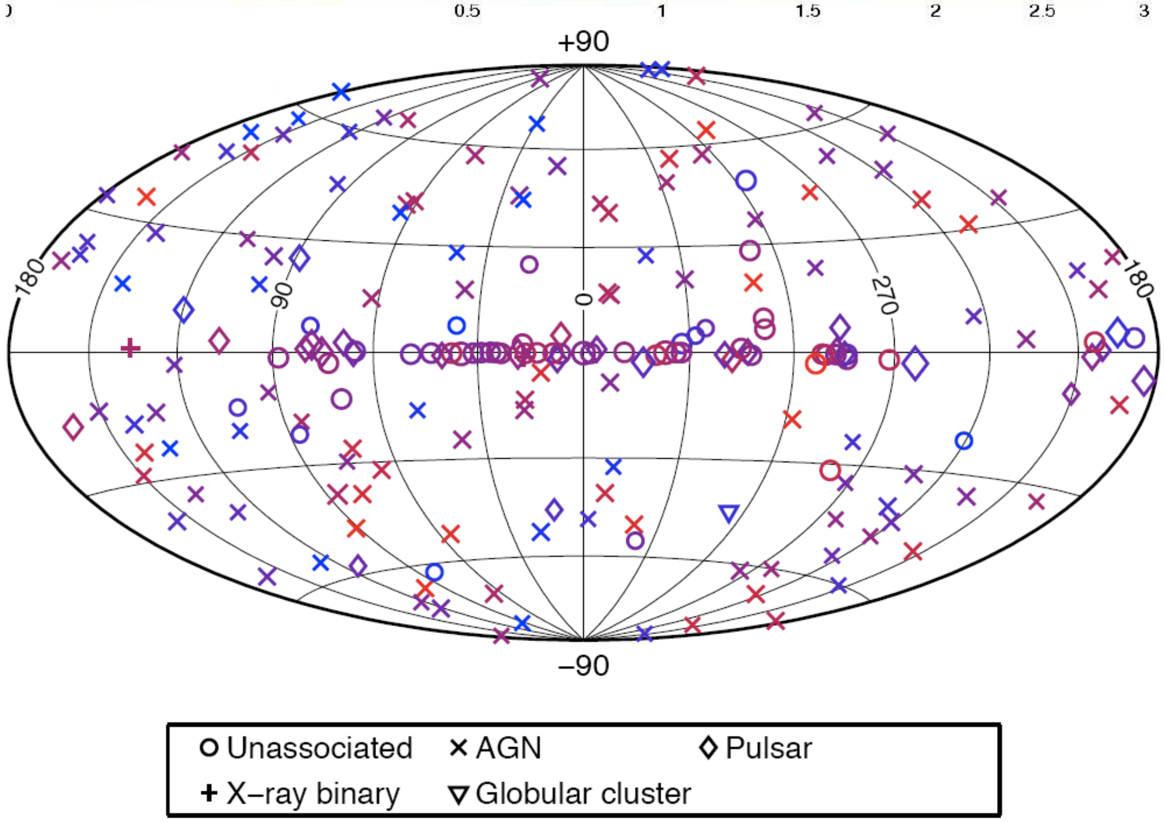
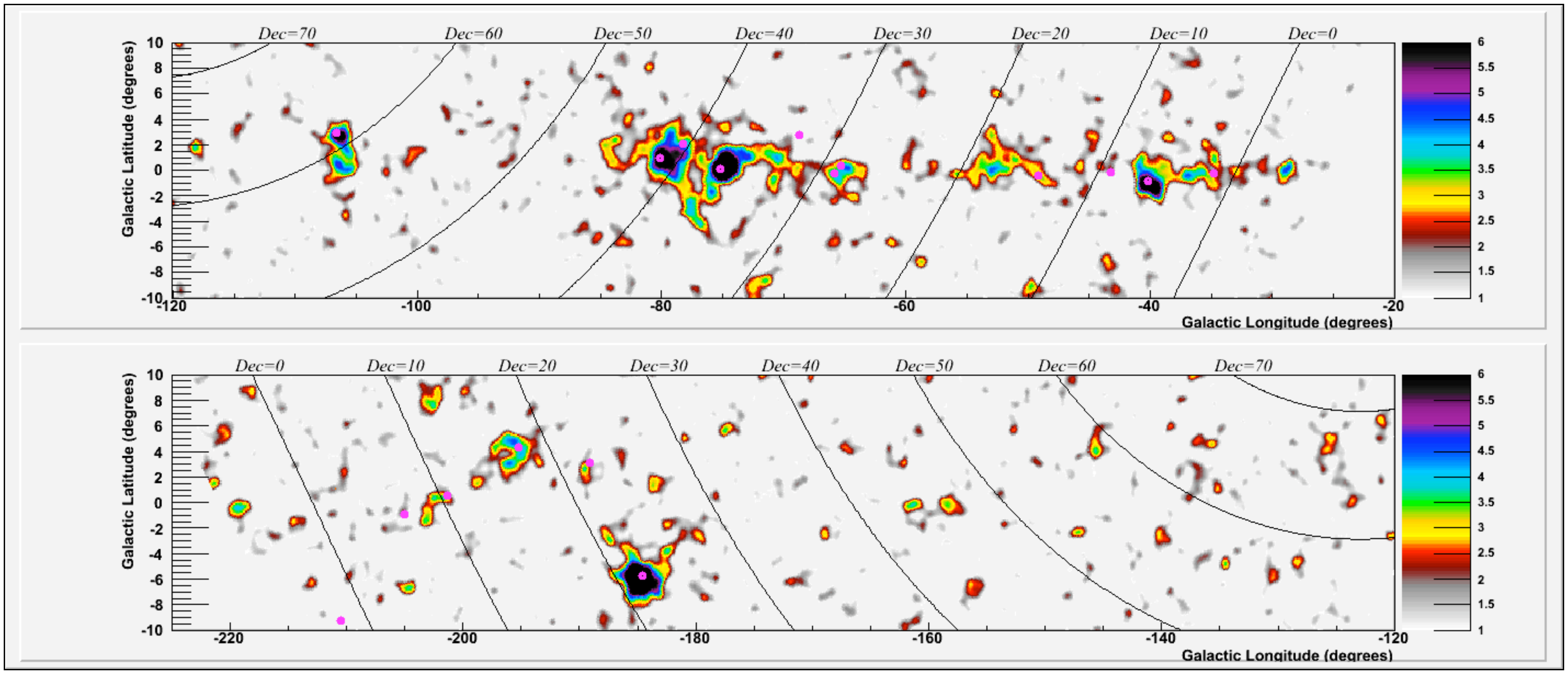
# Fermi-LAT Bright Source List




- 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

# Updated Galactic Plane Analysis




Full data set included

- Additional 1.5 years of data

New energy estimator ("frasor")

- Used in significance weighting

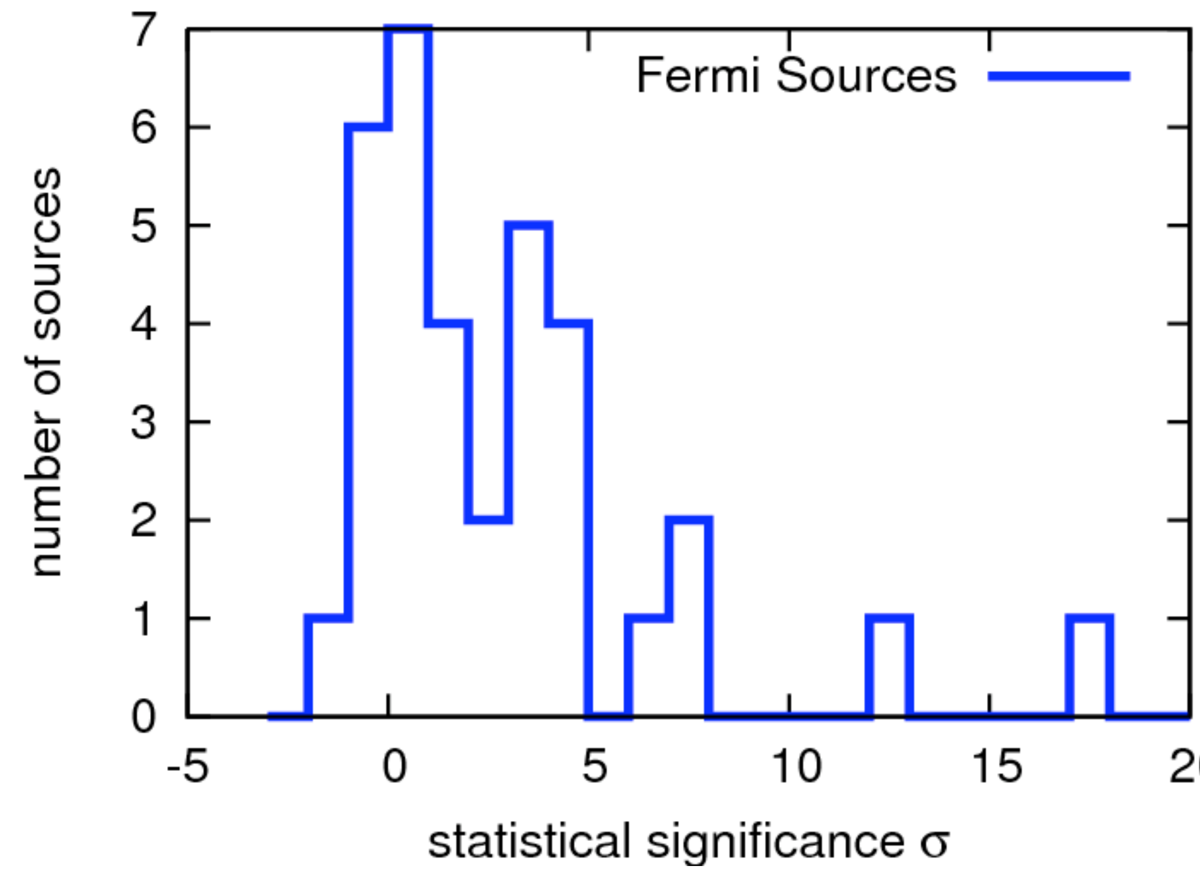
15-25% cumulative increase in sensitivity

- Crab 15σ → 17.2σ
- Median energy 20 TeV → 35 TeV for unbroken crablike spectrum

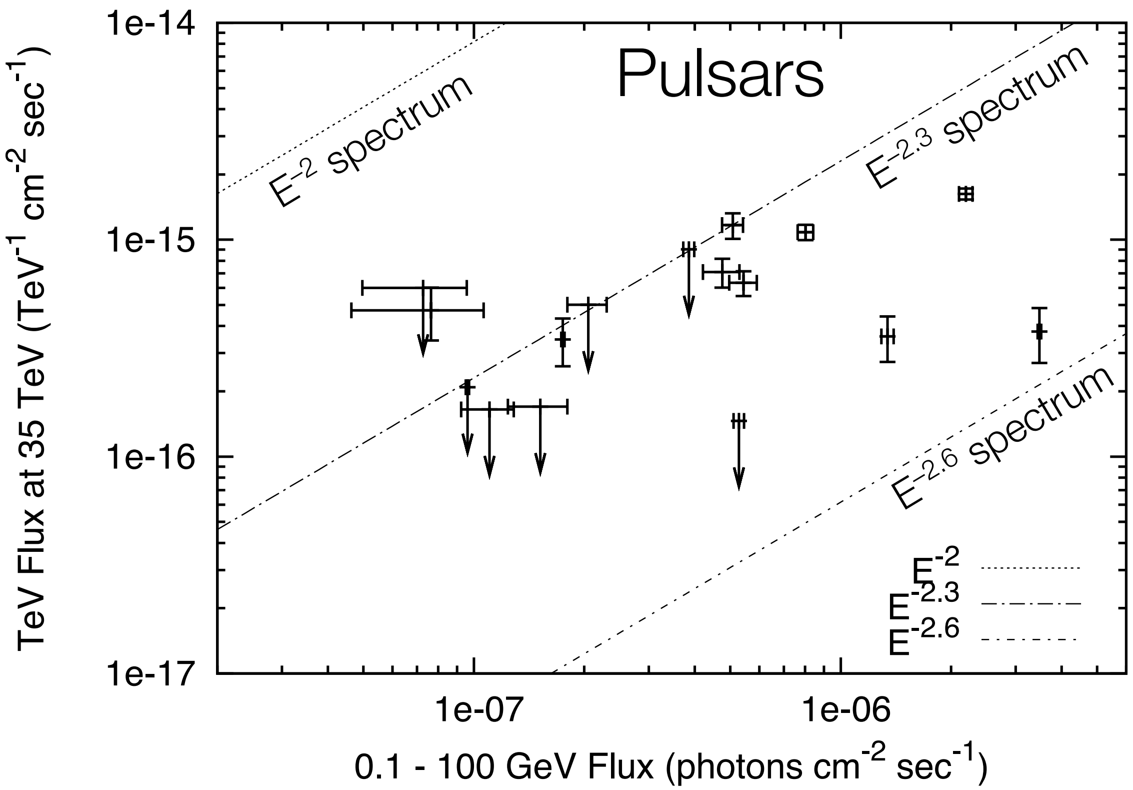
# Milagro Observations of Fermi BSL Objects

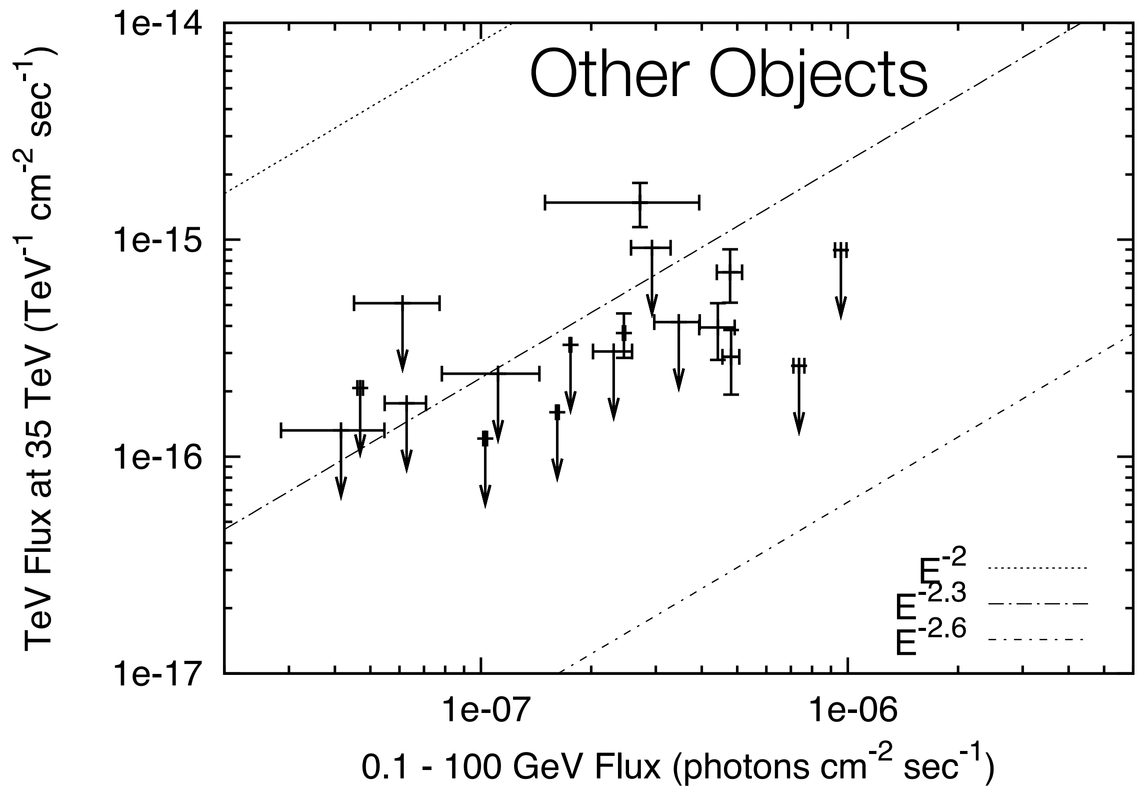
- 34 of 205 BSL sources are definitely or possibly Galactic and in Milagro's field of view
    - 16 pulsars, 1 XRB, 5 SNRs, 12 unknown (poss. extragalactic)
- 14 of the 34 are observed at >3σ in Milagro data set
    - 6 of 14 are previous Milagro sources
    - 9 of 14 are pulsars (incl. all 6 previously reported), 3 are SNRs
    - 6 of 14 not previously reported at TeV energies
- Probability of even a single 3σ detection in 34 trials is 4.4%

Abdo et al., arXiv:0904.1018



# GeV-TeV Comparisons




- Milagro's strongest sources are probably PWN
- TeV emission appears commonly associated with MeV-GeV pulsars
- Spectrum needed to connect GeV to TeV is $E^{-2.3}$ or softer
  - TeV flux is quoted at 35 TeV assuming unbroken crablike spectrum

# Outline

- The Milagro Observatory
- Summary of Milagro Results
  - Galactic Plane Survey
  - Small-scale Cosmic Ray Anisotropy
  - Fermi Bright Source List Follow-Up
- High Altitude Water Cherenkov (HAWC) Observatory
  - Design
  - Sensitivity
  - Status

# From Milagro to HAWC

- 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 20,000 $m^2$
  - Segment the Cherenkov medium: separate tanks instead of a single pond
- Achieve 10-15 x sensitivity of Milagro
  - Detect Crab at 5σ in 6 hours instead of 3 months
- Hardware cost: $8.5M
  - Mostly tanks, water – technically straightforward

# The HAWC Collaboration

## USA

- Los Alamos National Laboratory
- University of Maryland
- University of California – Irvine
- Georgia Institute of Technology
- NASA Goddard Space Flight Ctr.
- Michigan State University
- Michigan Technological University
- University of New Hampshire
- University of New Mexico
- Pennsylvania State University
- University of Utah
- University of Wisconsin

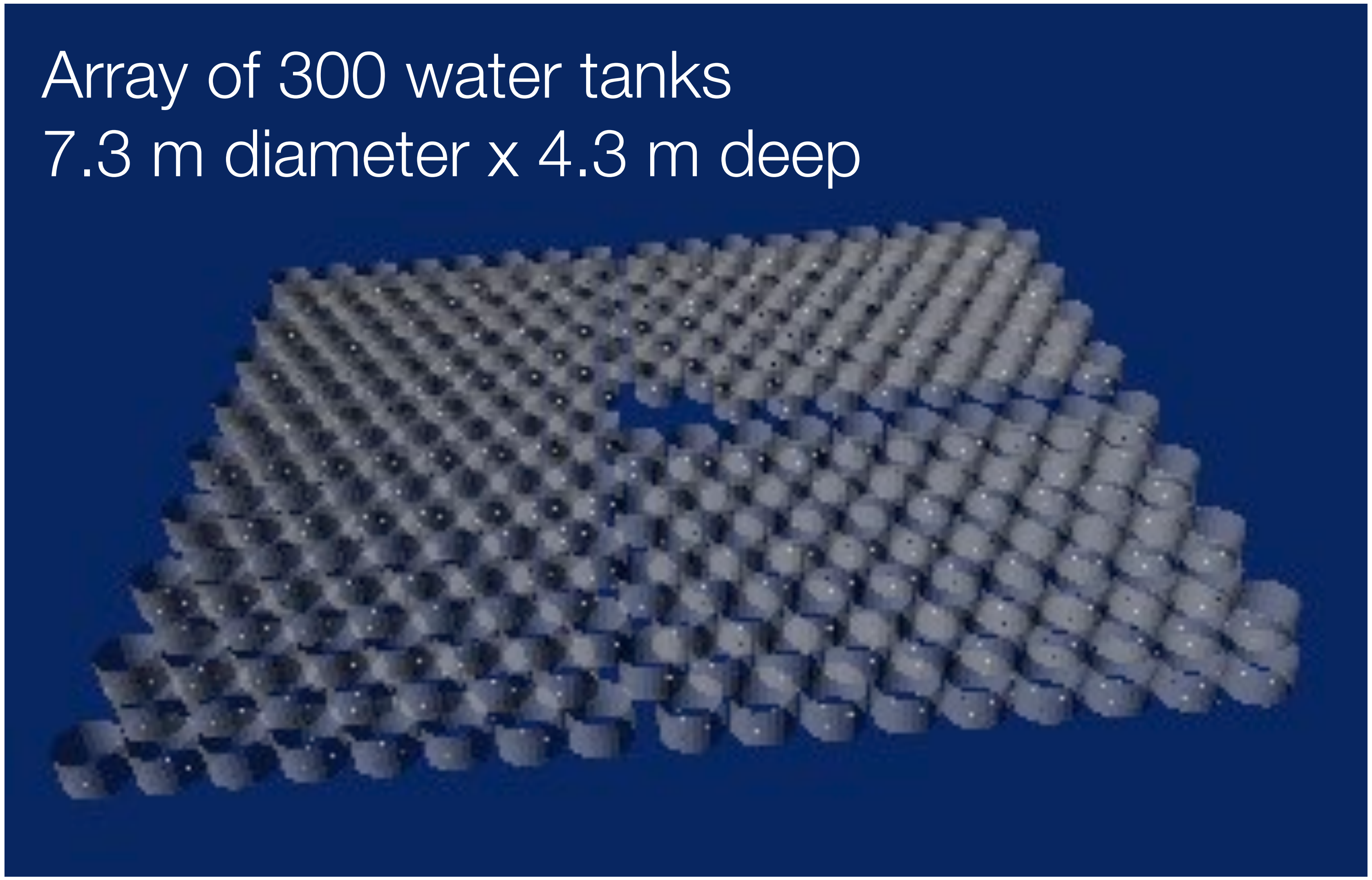
## México

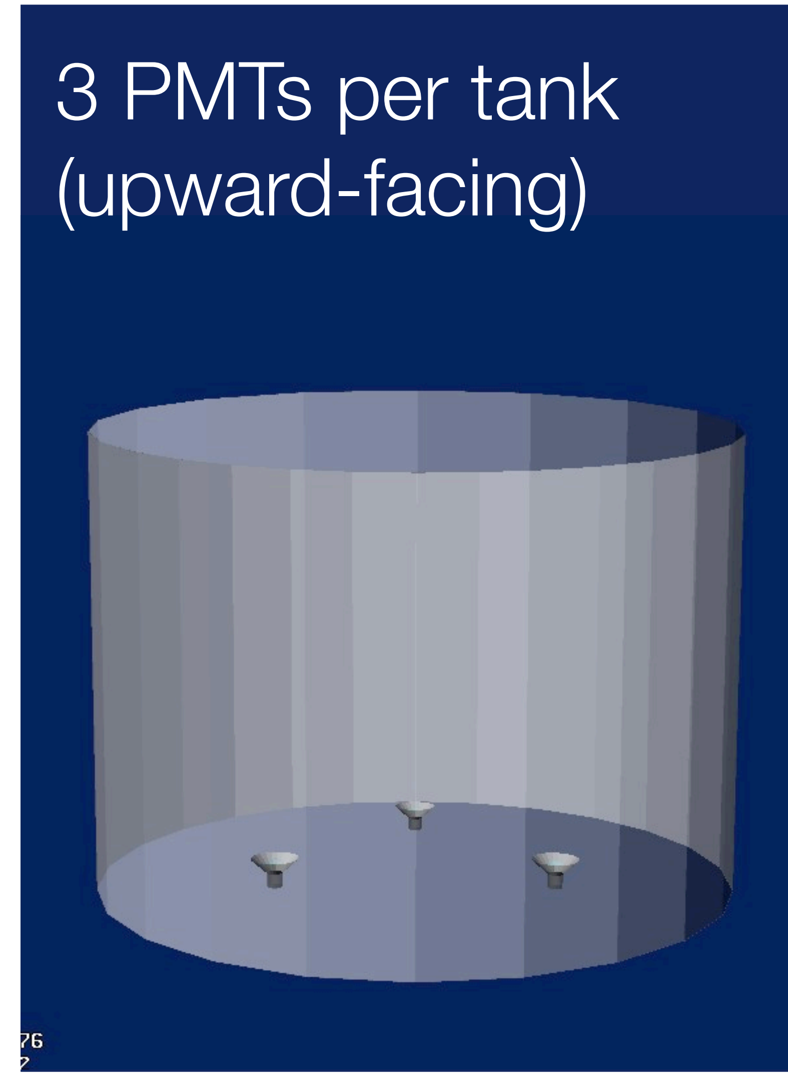
- Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE)
- Universidad Nacional Autónoma de México (UNAM)
- Universidad de Guanajuato
- Universidad Michoacana de San Nicolás de Hidalgo
- Centro de Investigación y Estúdios Avanzados del Instituto Politécnico Nacional (CINVESTAV)
- Benemérita Universidad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

# HAWC Design



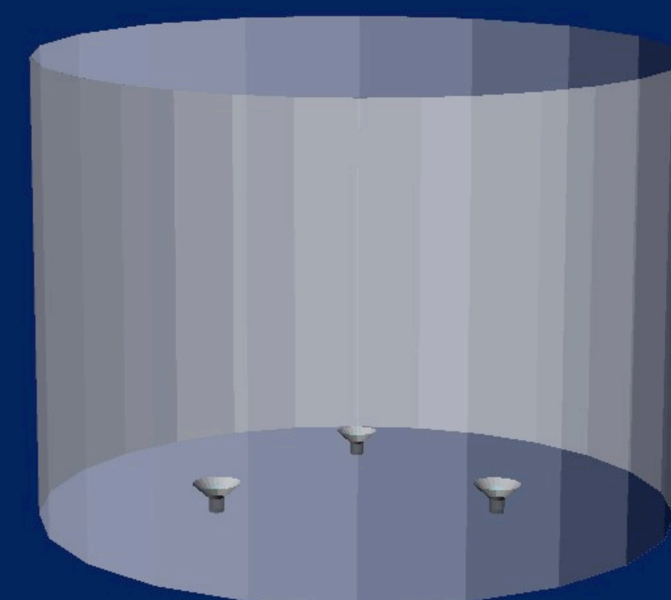

~20,000 m$^2$ instrumented area, >60% active Cherenkov volume

EM particles stop in top ~1 m of tank → uniform response per MeV
Muons pass near PMTs → high amplitude signals

# HAWC Design

Array of 300 water tanks
7.3 m diameter x 4.3 m deep

3 PMTs per tank
(upward-facing)



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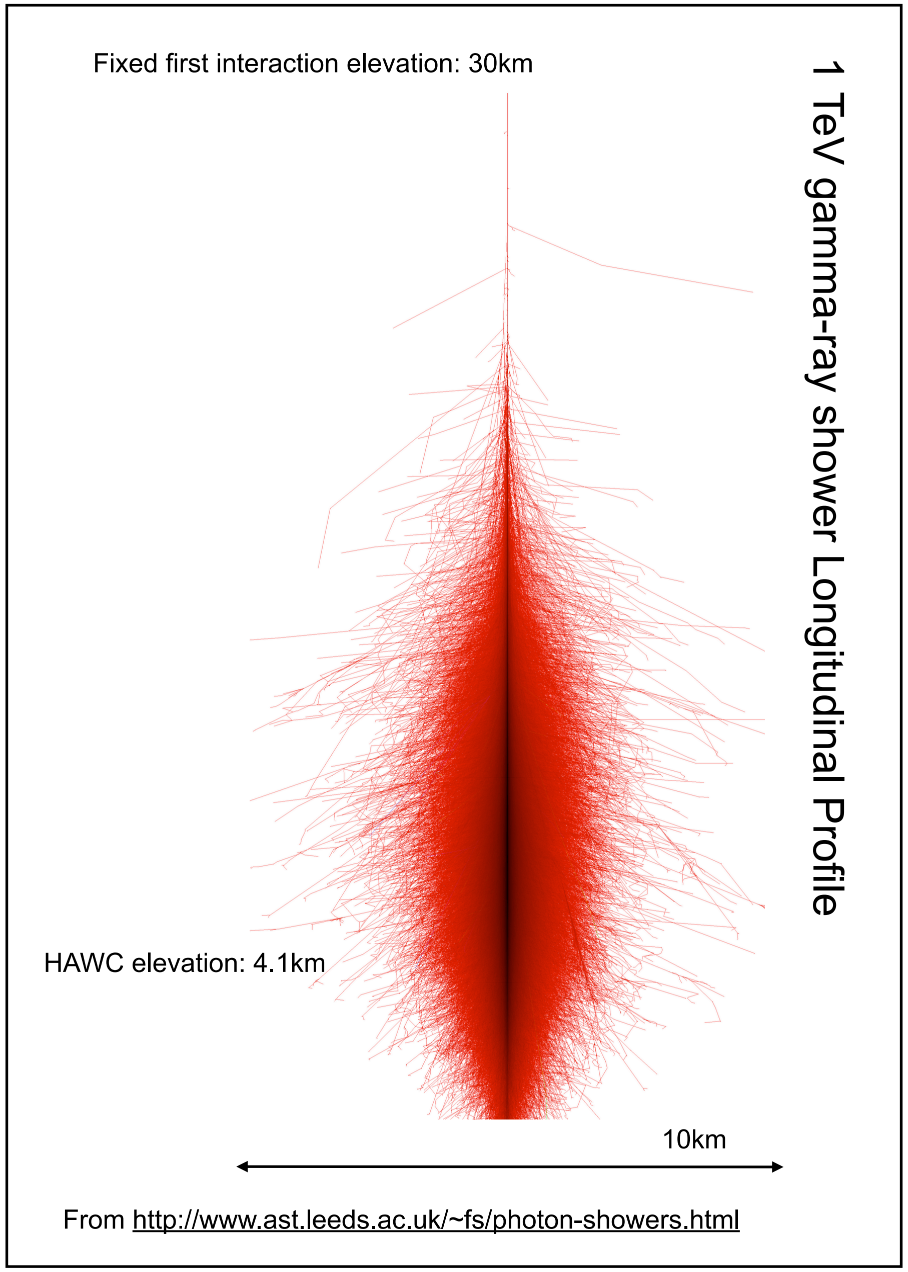
# Energy Threshold and Effective Area

- EAS detectors are tail-catching calorimeters
- Universal shape to energy
  - Probability distribution for first interaction, plus exponential attenuation past shower max



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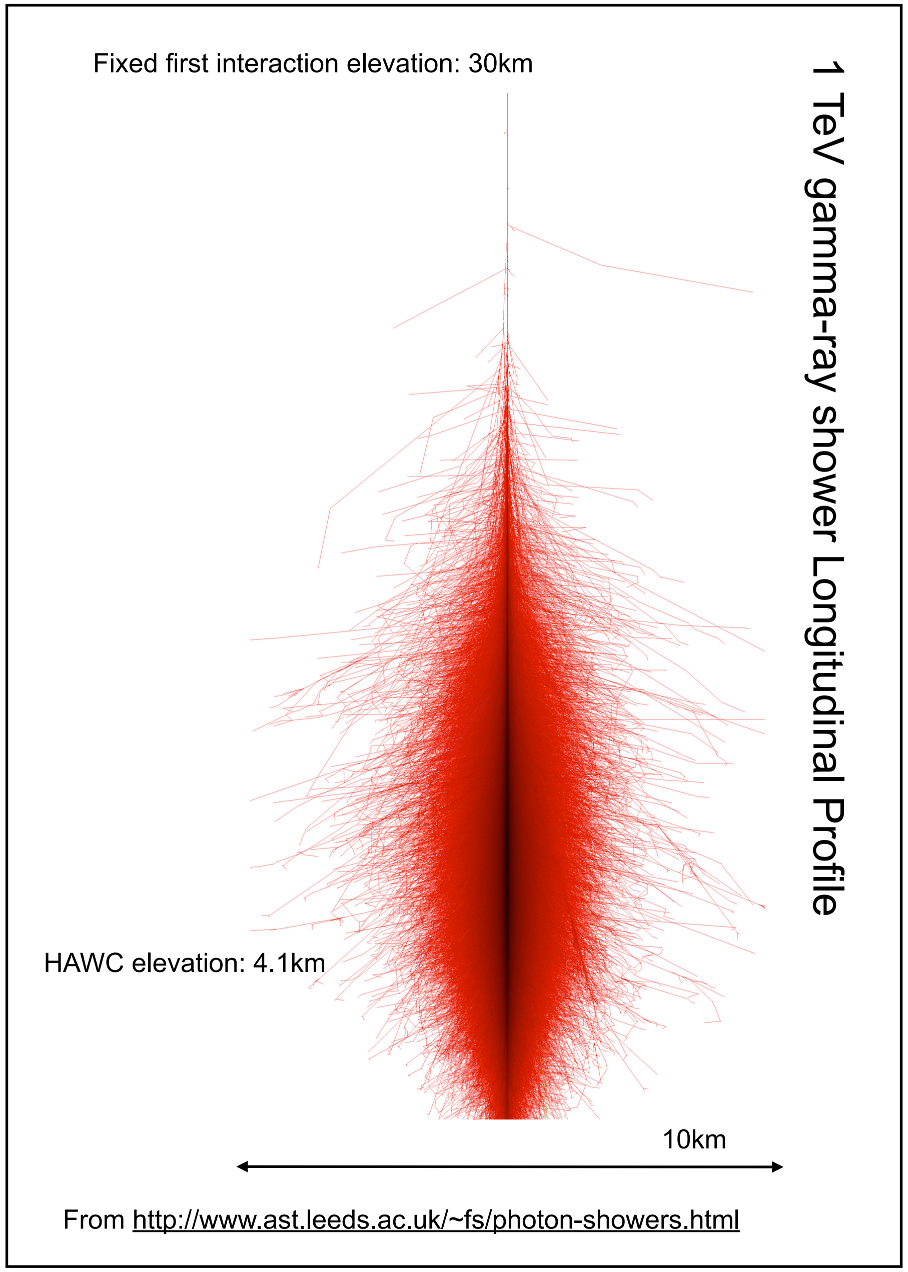
  - Higher altitude = lower threshold



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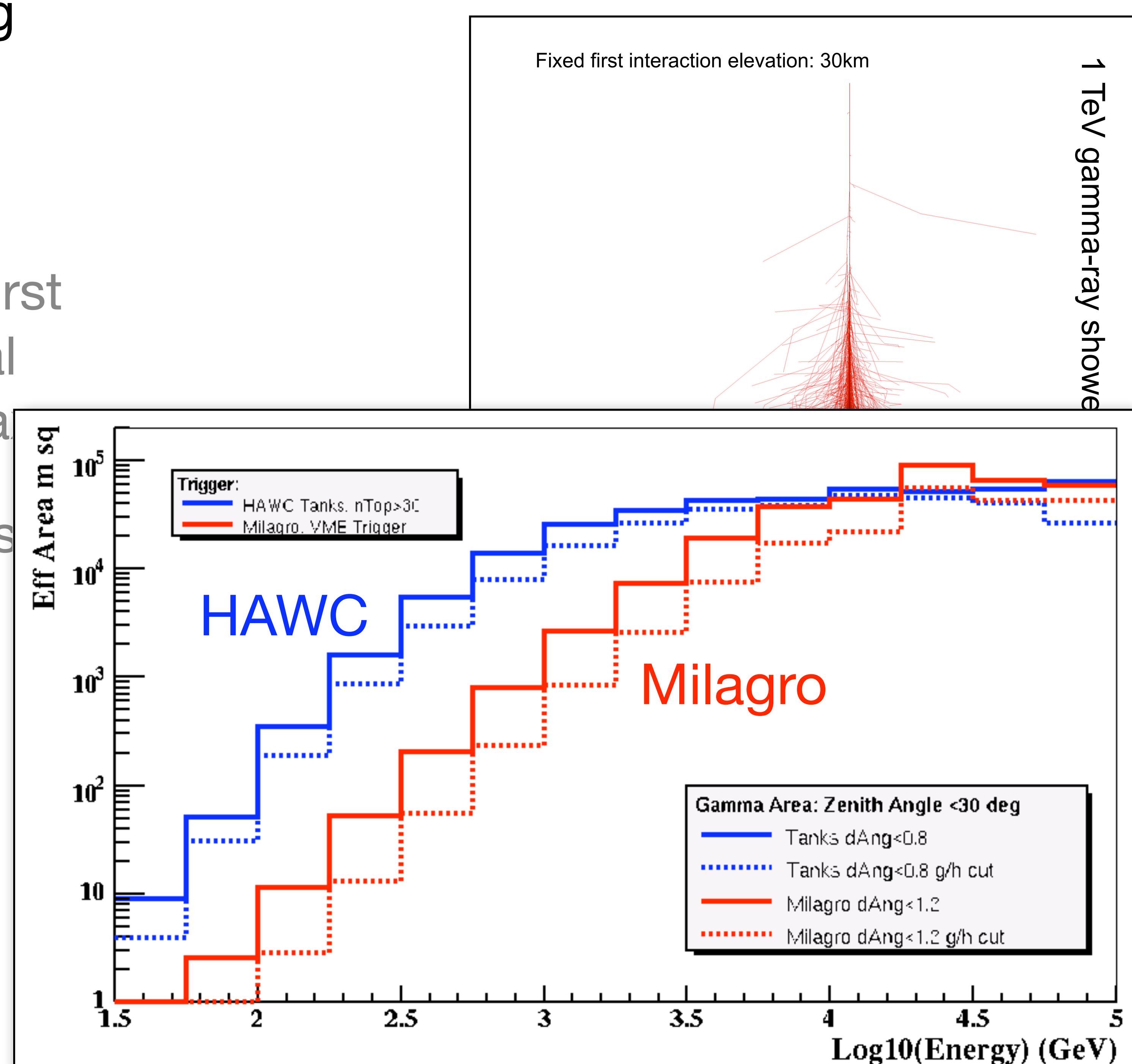

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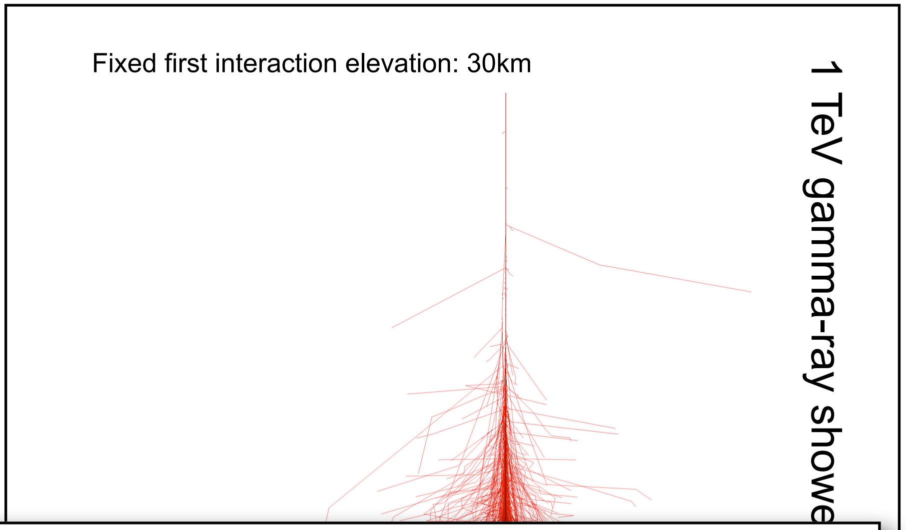
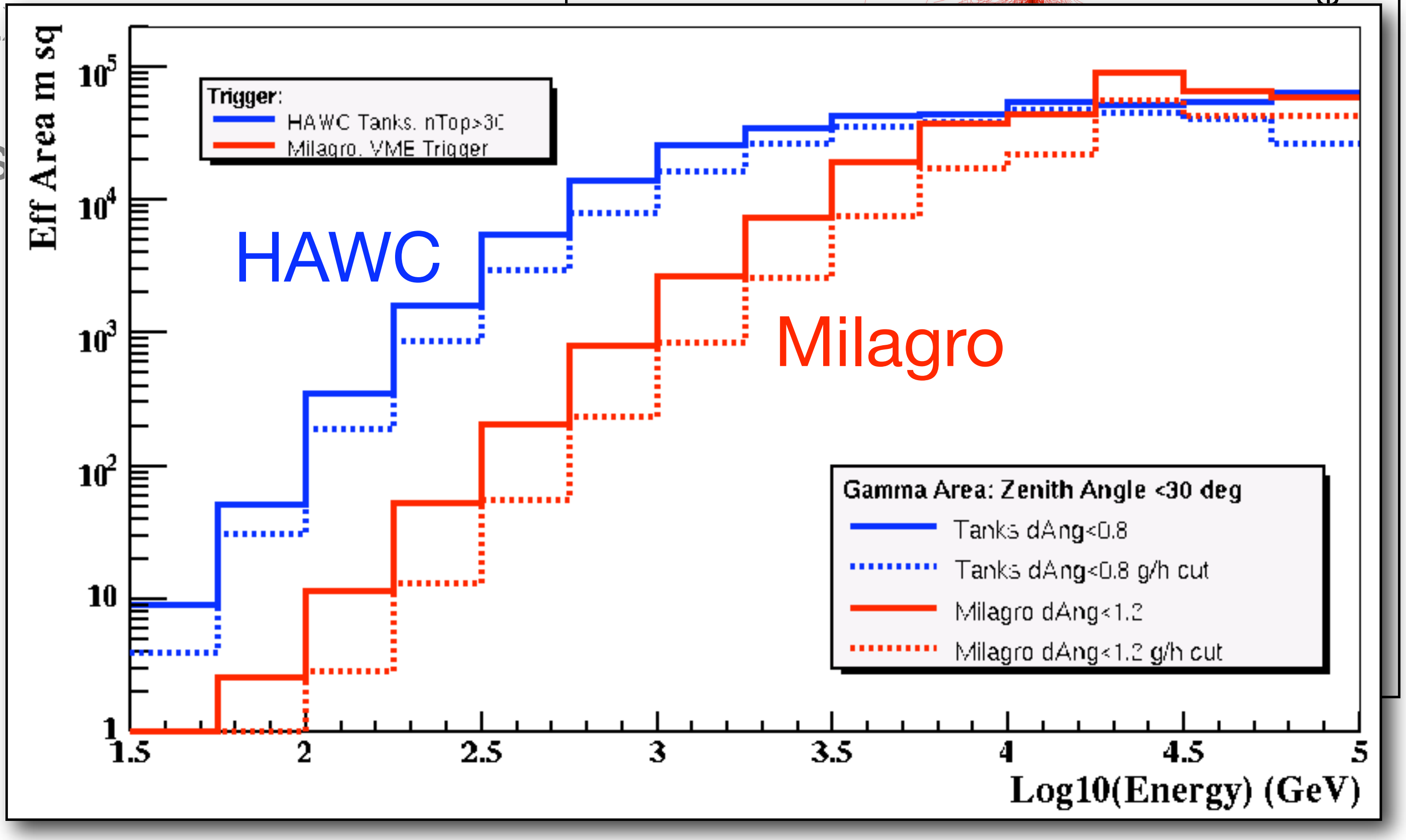
- HAWC fully efficient above ~2 TeV



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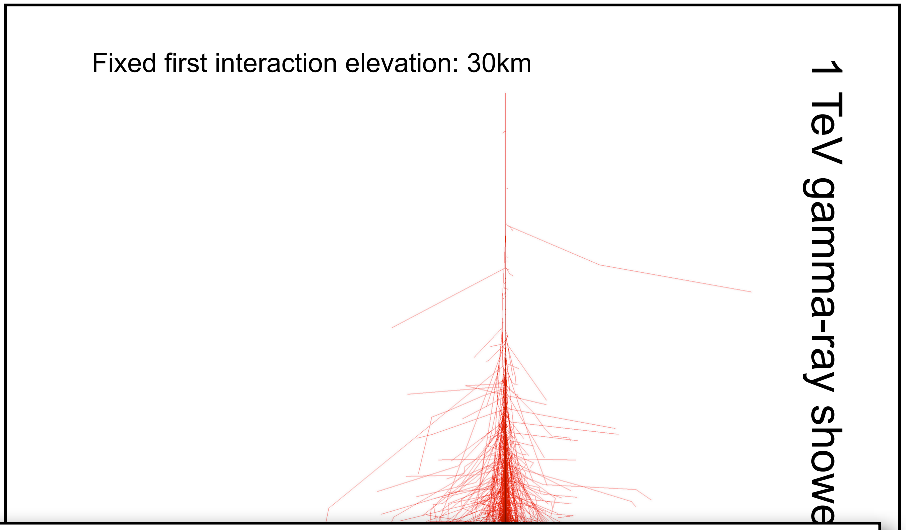
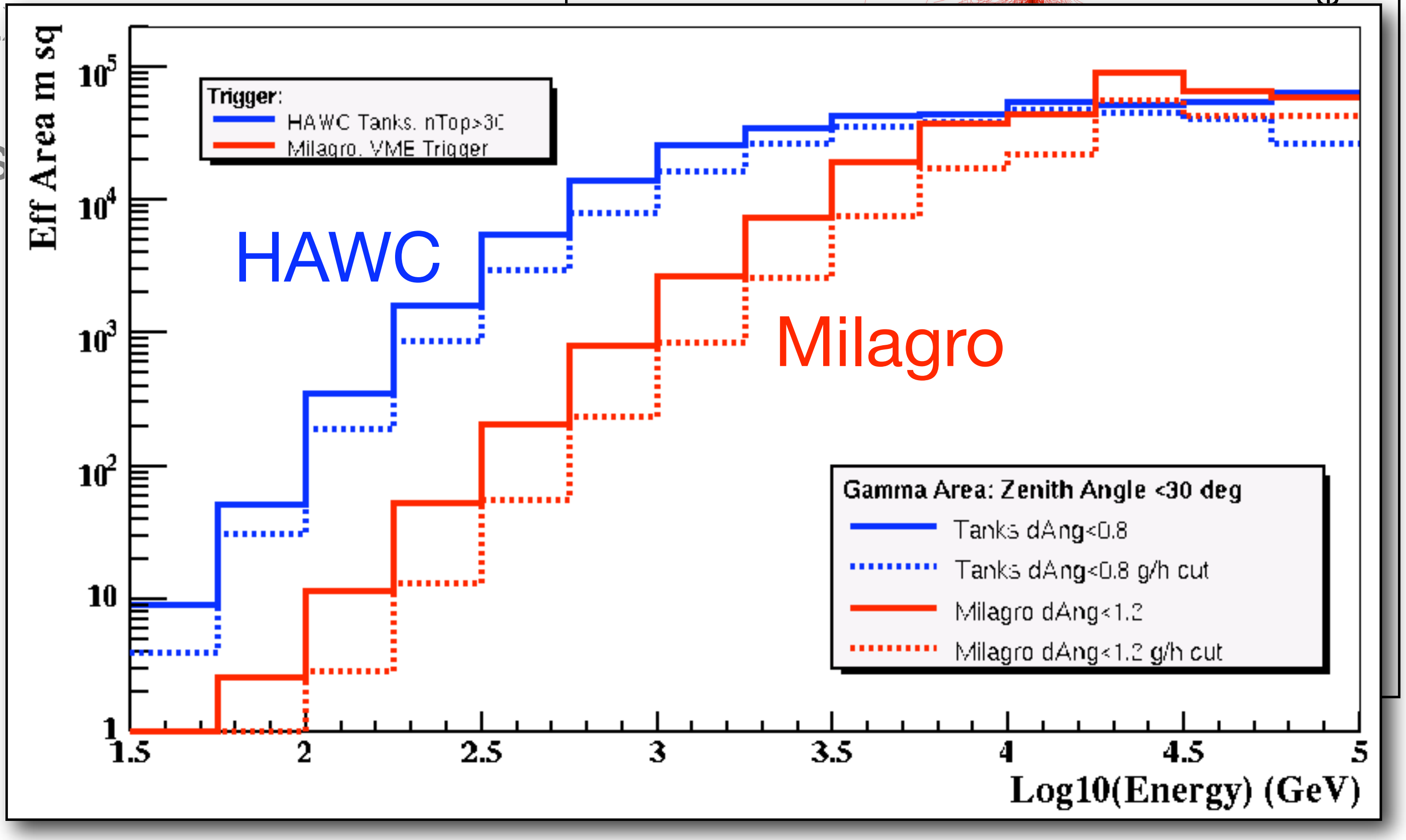
- HAWC fully efficient above ~2 TeV
- Still ~100 m$^2$ area at 100 GeV



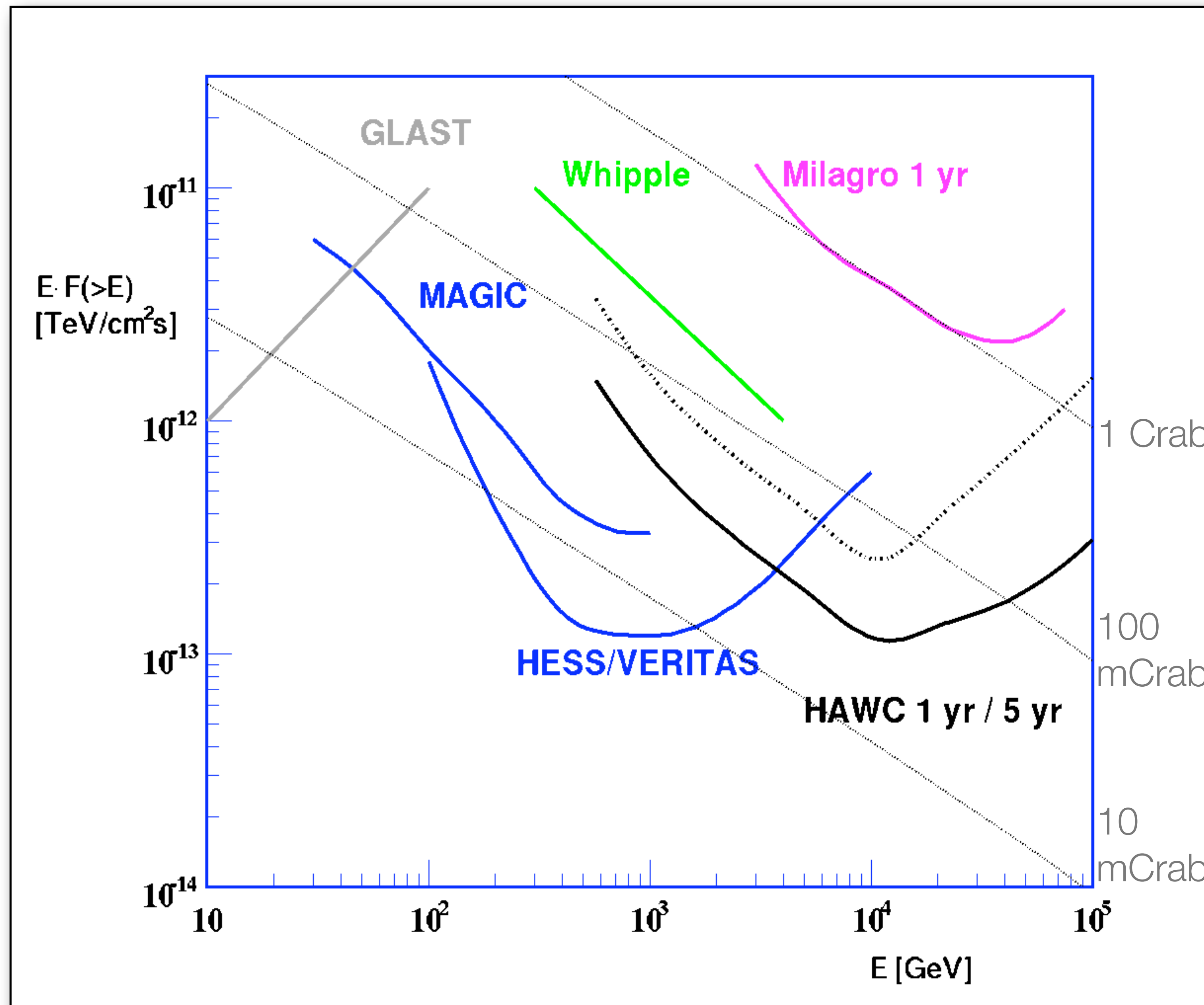



# Sensitivity to Crab-like Point Sources

- 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

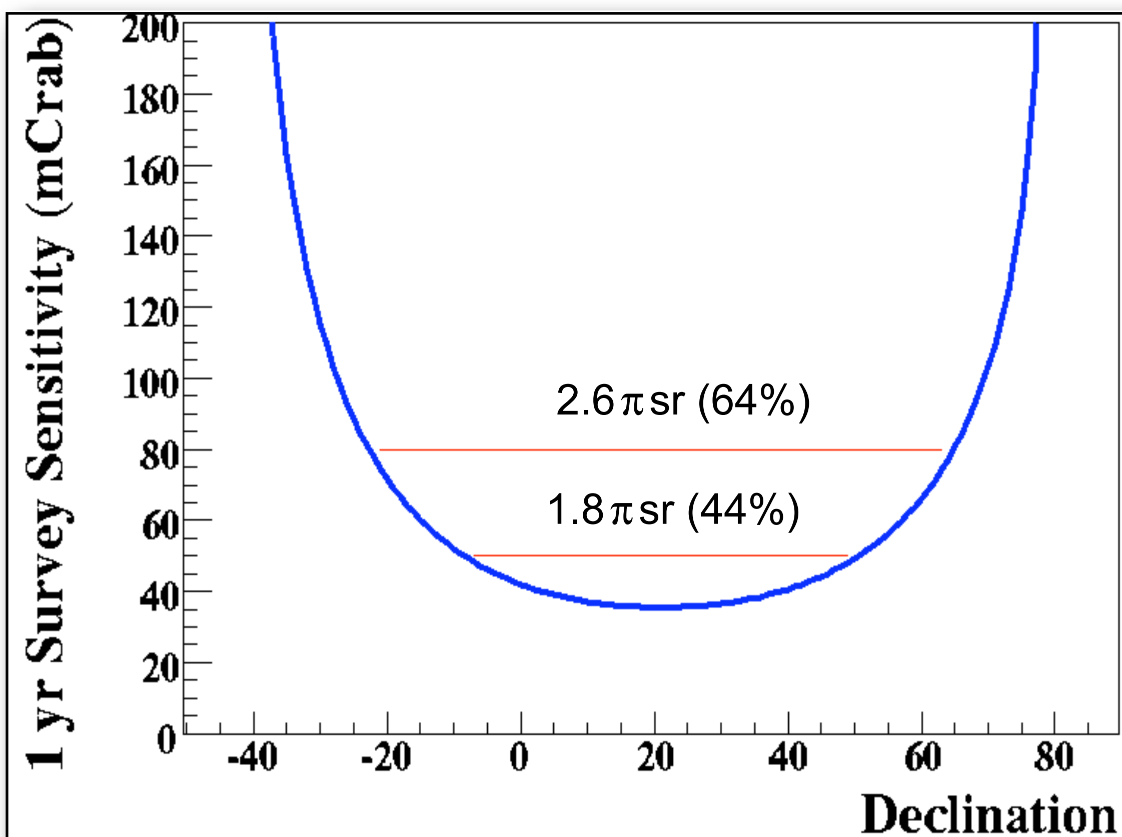
- 10-15x Milagro sensitivity
  - Lower energy threshold
  - Better angular resolution
  - Better rejection of cosmic rays

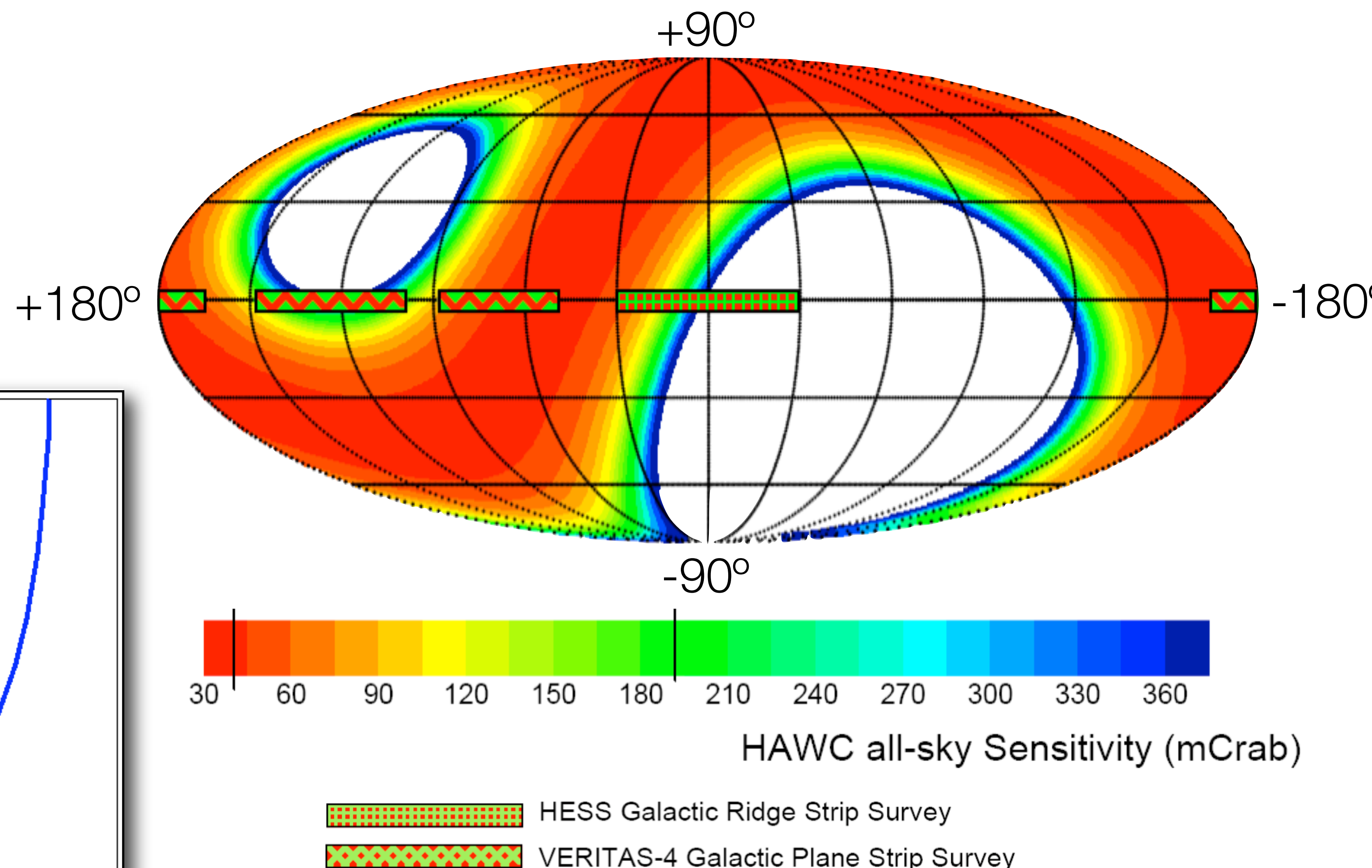



50 hr observation time assumed for IACTs,
HAWC source transit 15° off zenith

# TeV Sky Survey

- Wide field of view, limited by atmospheric depth
  - 45° from zenith (Milagro standard analysis)
  - 50 mCrab survey in 1 yr over 44% of the sky

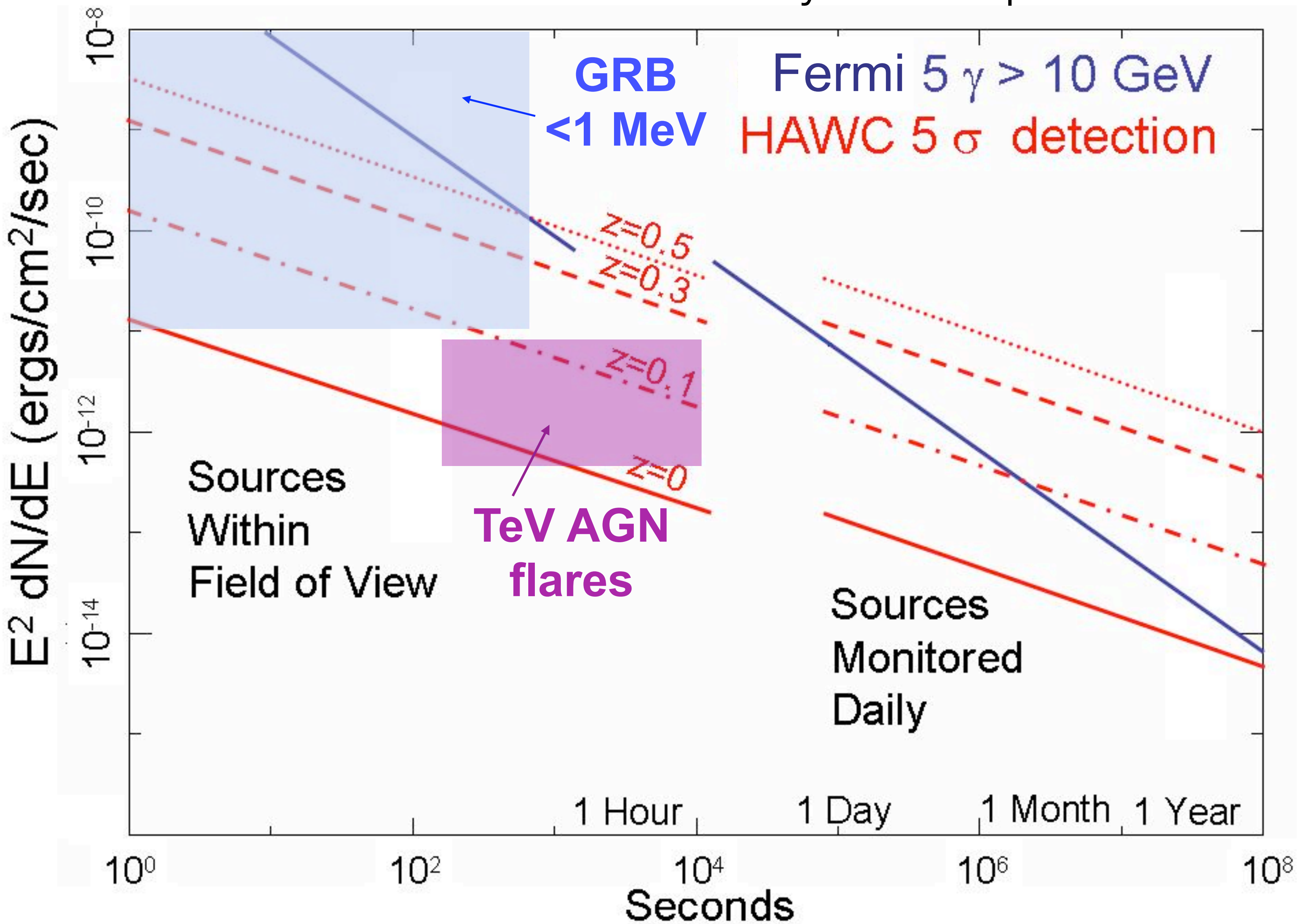


# Extragalactic Transients with HAWC

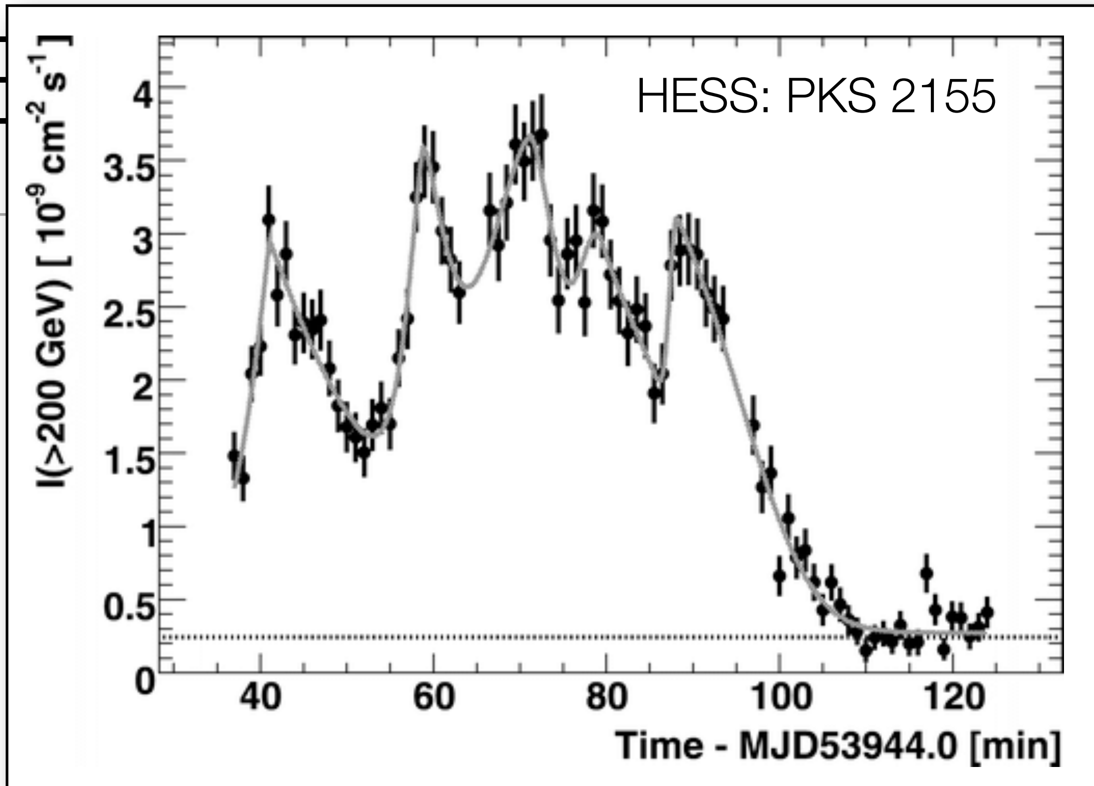
- GRBs
  - Sensitive to high energy component of prompt emission
- AGN flares
  - E.g. PKS 2155-304 (z=0.117) flare to 50-100x quiescent flux for ~1 hour, with $dN/dE \sim E^{-3.5}$
  - Such a flare would give 6σ in HAWC

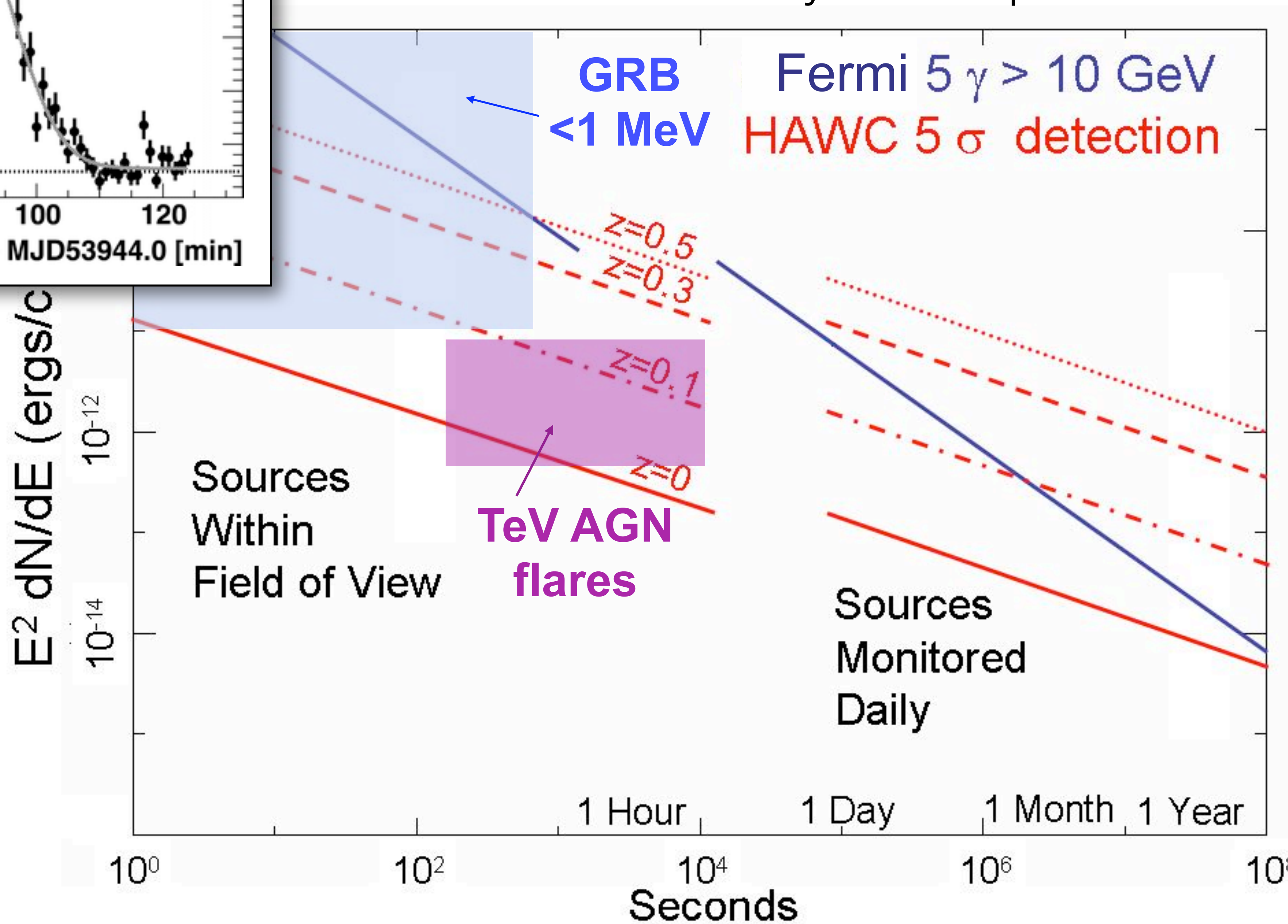
Fermi and HAWC Sensitivity to $E^{-2}$ spectra



# E with HAWC

- mi and HAWC Sensitivity to $E^{-2}$ spectra

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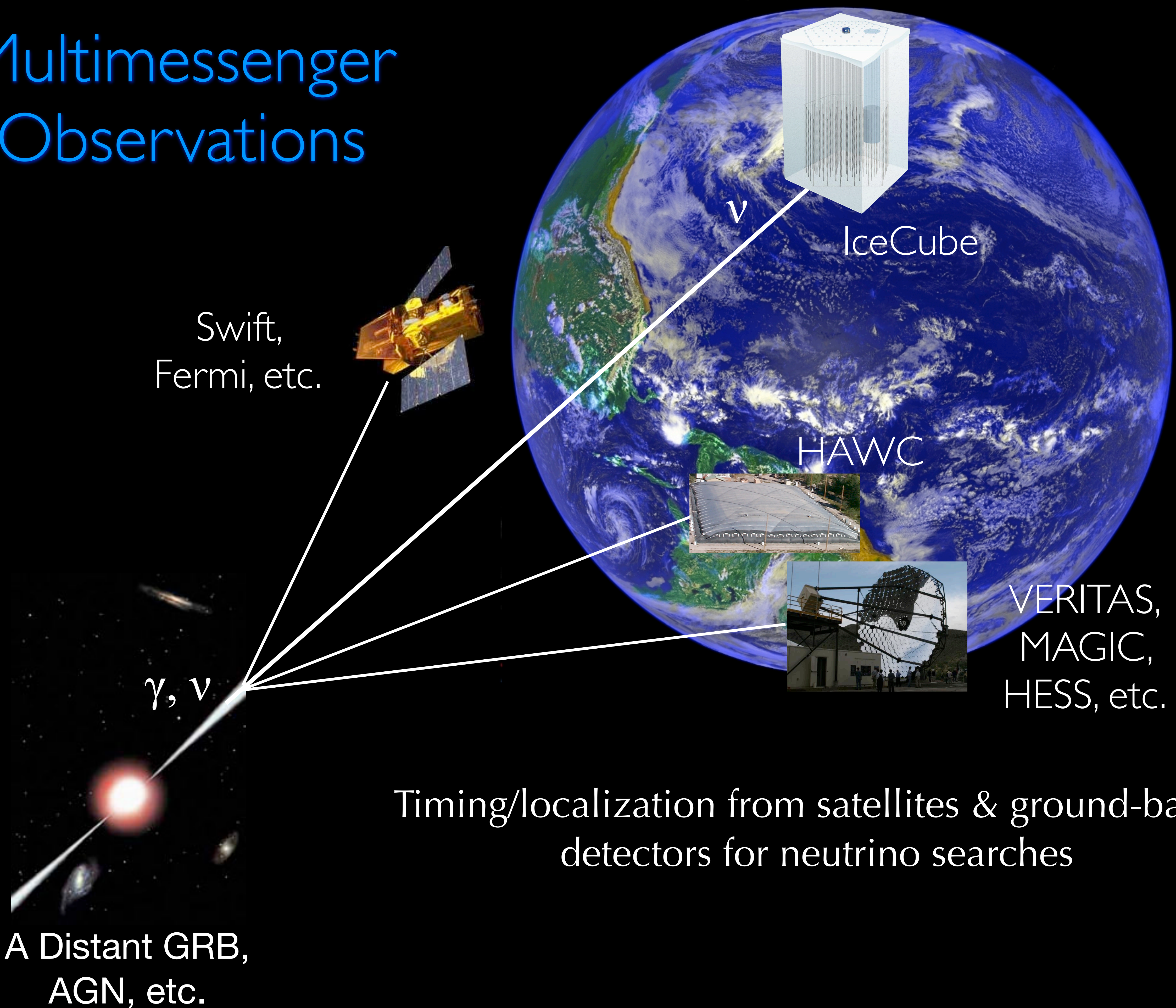
# Multimessenger Observations



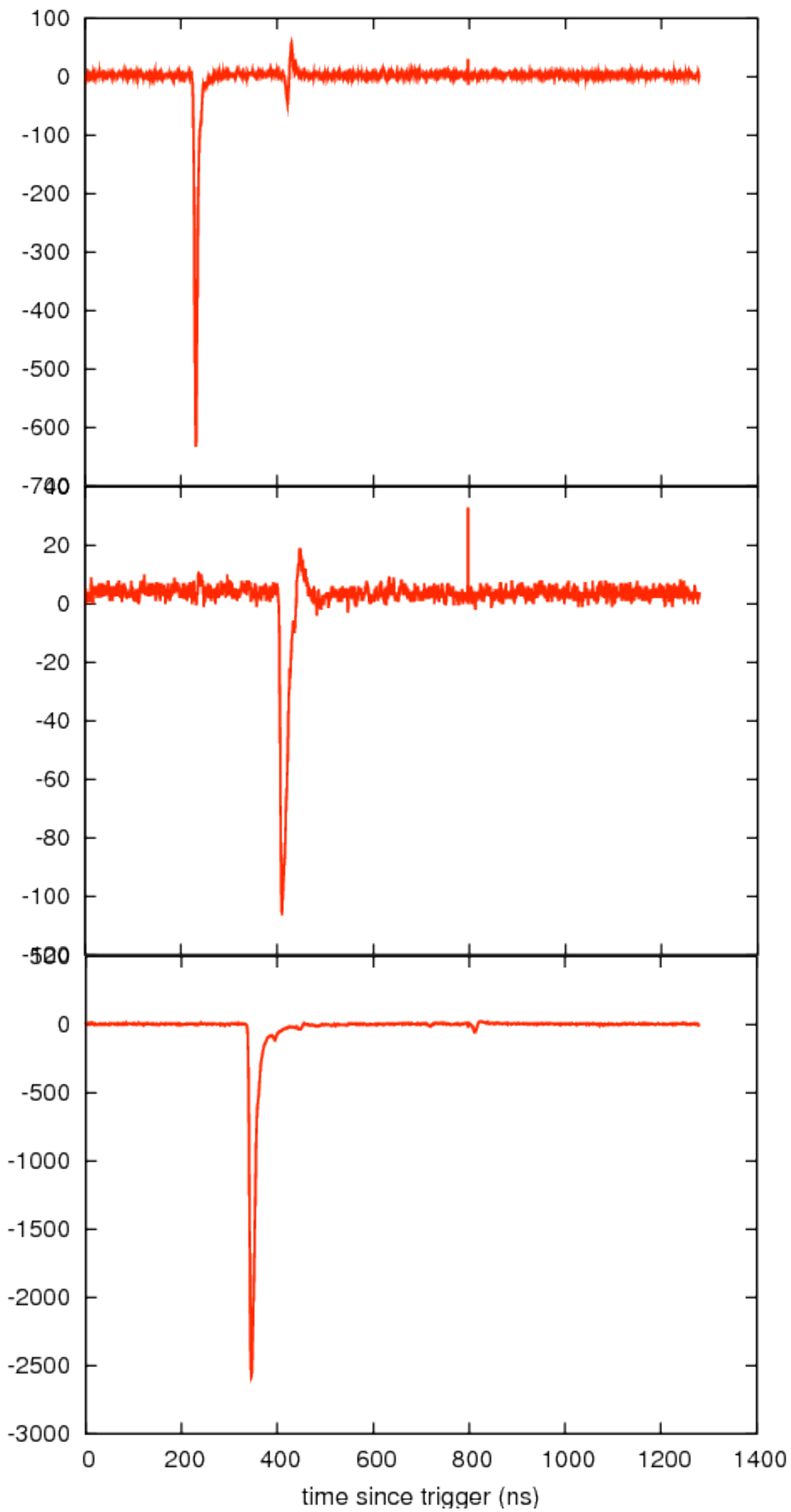

Timing/localization from satellites & ground-based detectors for neutrino searches

# Status of HAWC

- October 2007: NSF proposal submitted for full HAWC array
  - December 2007: NSF panel review states that "There is a strong case for HAWC as a wide field of view survey instrument at the TeV scale."
  - Proposal under evaluation at NSF
- January 2008: Major Research Instrumentation (MRI) proposal funded at a level of $1.2M (NSF + match) in August 2008
  - ProtoHAWC plus evaluation of tank technologies
  - Site preparation underway with funding from Mexican institutions (INAOE)
- NSF PASAG review underway
  - Operation of 100 tank array (⅓ of HAWC) possible by summer, 2011


ProtoHAWC Test Array

3 plastic tanks (3 m diameter) in place and recording air showers at the summit of Sierra Negra (LMT site)




First light with protoHAWC!

# Conclusions

- Milagro has demonstrated the success of the water Cherenkov technique
  - TeV survey of the Galactic plane
  - Diffuse TeV emission from Galactic plane
  - Cosmic ray anisotropy
  - High energy measurements of Fermi BSL objects
- Future improvements with HAWC
  - Evolution of Milagro design: size, altitude, optical isolation
  - 10-15x sensitivity of Milagro
  - Complement to Fermi, Swift, VERITAS, HESS, IceCube, CTA/AGIS, Auger