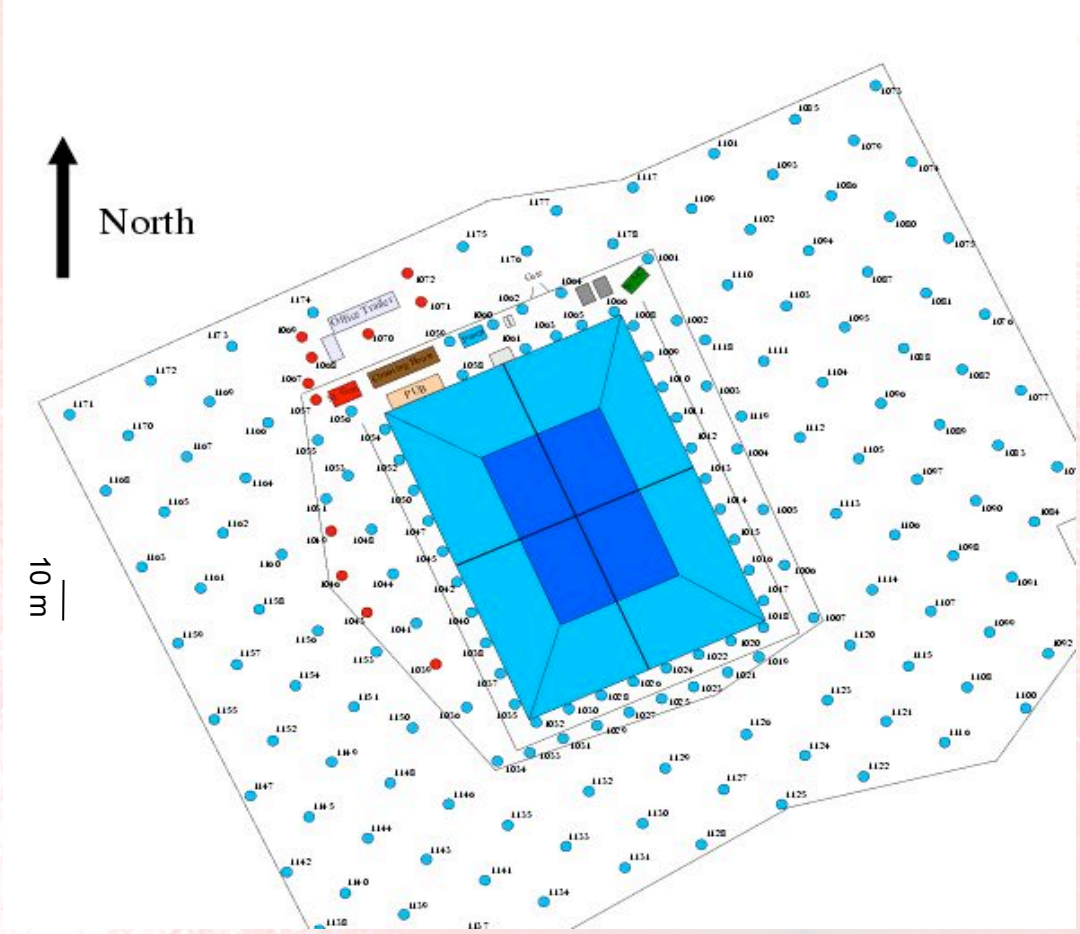
Spectrum and Morphology of Milagro Sources

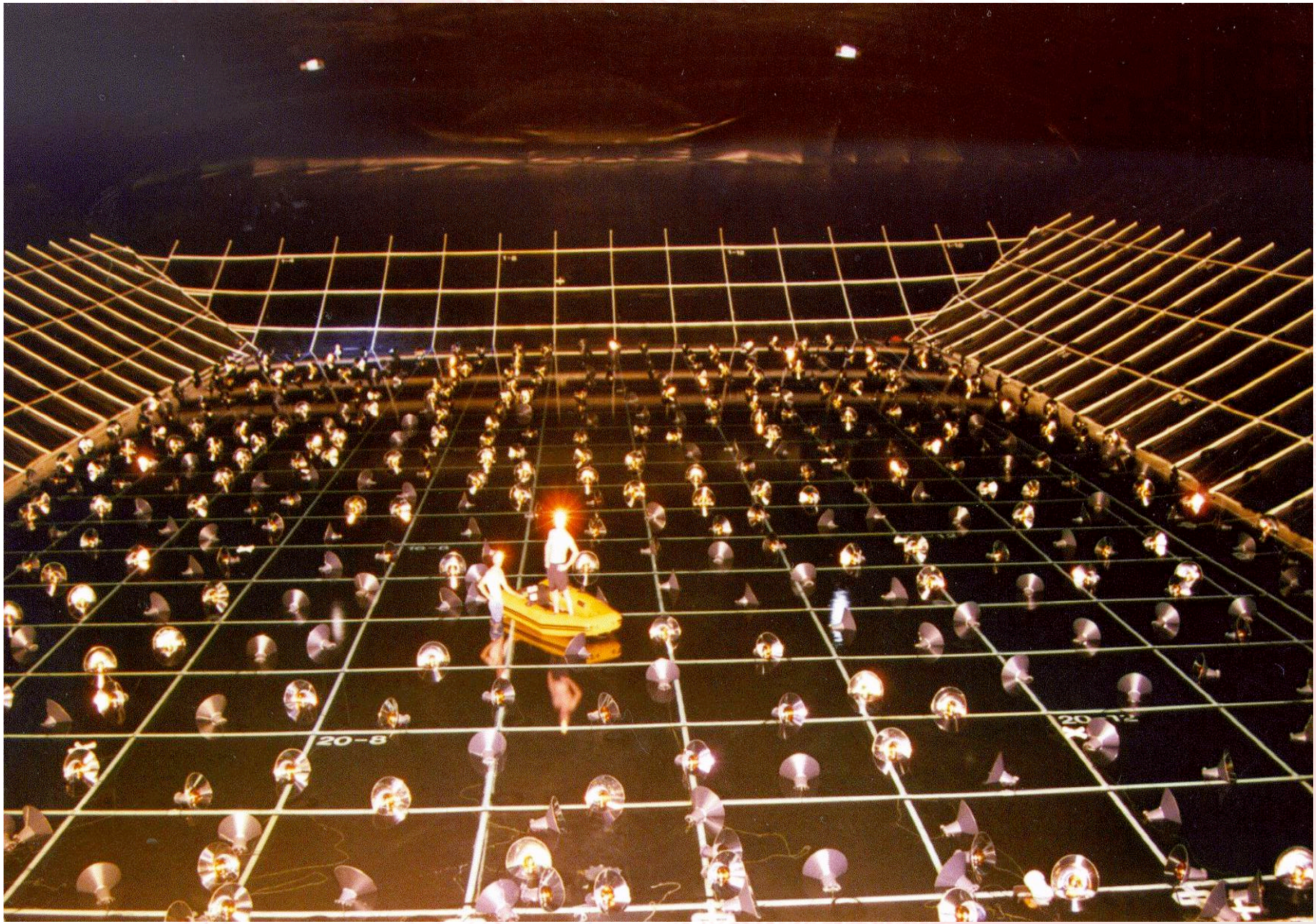
Aspen Summer Workshop, June 13 – June 27, 2010

Andrew Smith
University of Maryland

Milagro Detector

- Water Cherenkov Detector
- 2640m (8640') elevation
- 898 photomultiplier tubes
  - 450 in top layer in pond
  - 273 in bottom layer in pond
  - 175 water tank outriggers
- Pond Area is 3600 m^2
  - Operational in January 2001
- Outrigger Array area is ~ 30000 m^2
  - Operational in June 2004
- Shutdown June 2008
- 10x the data rate as Tibet.




20-8

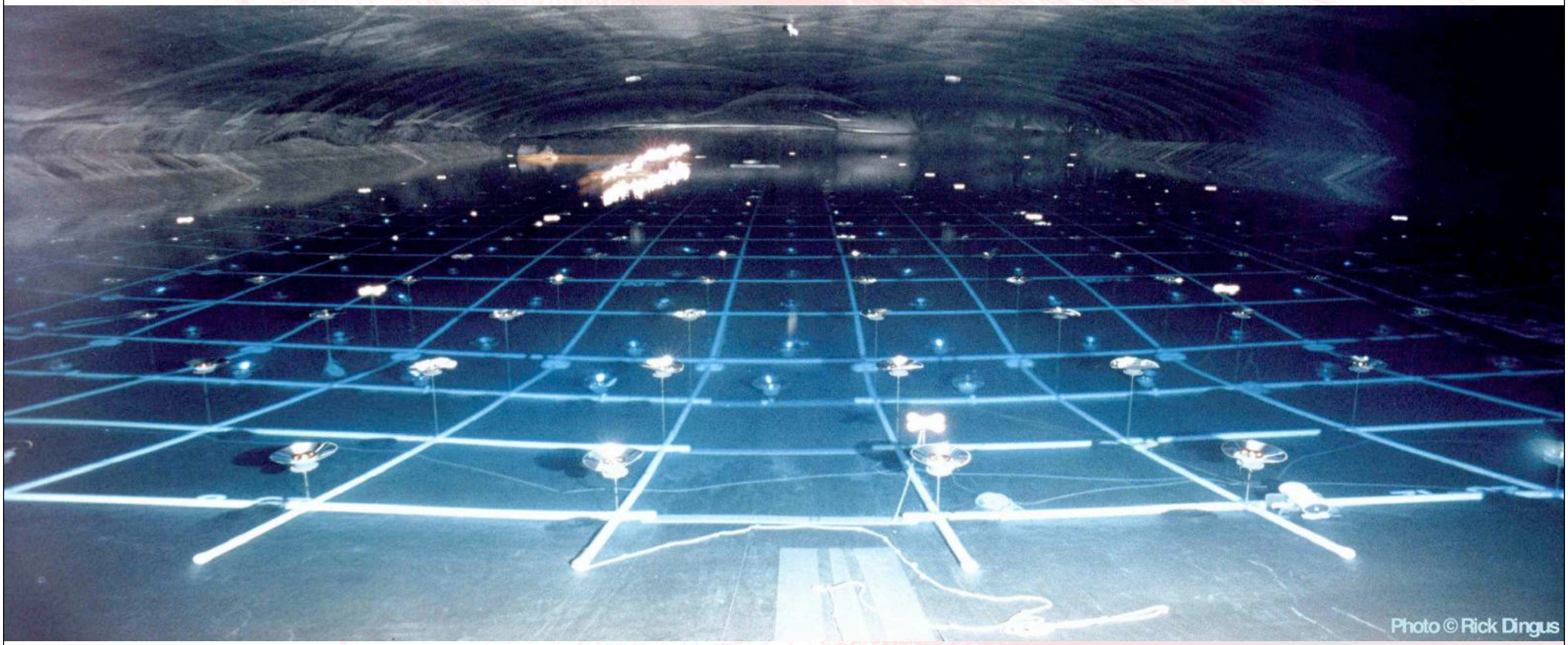
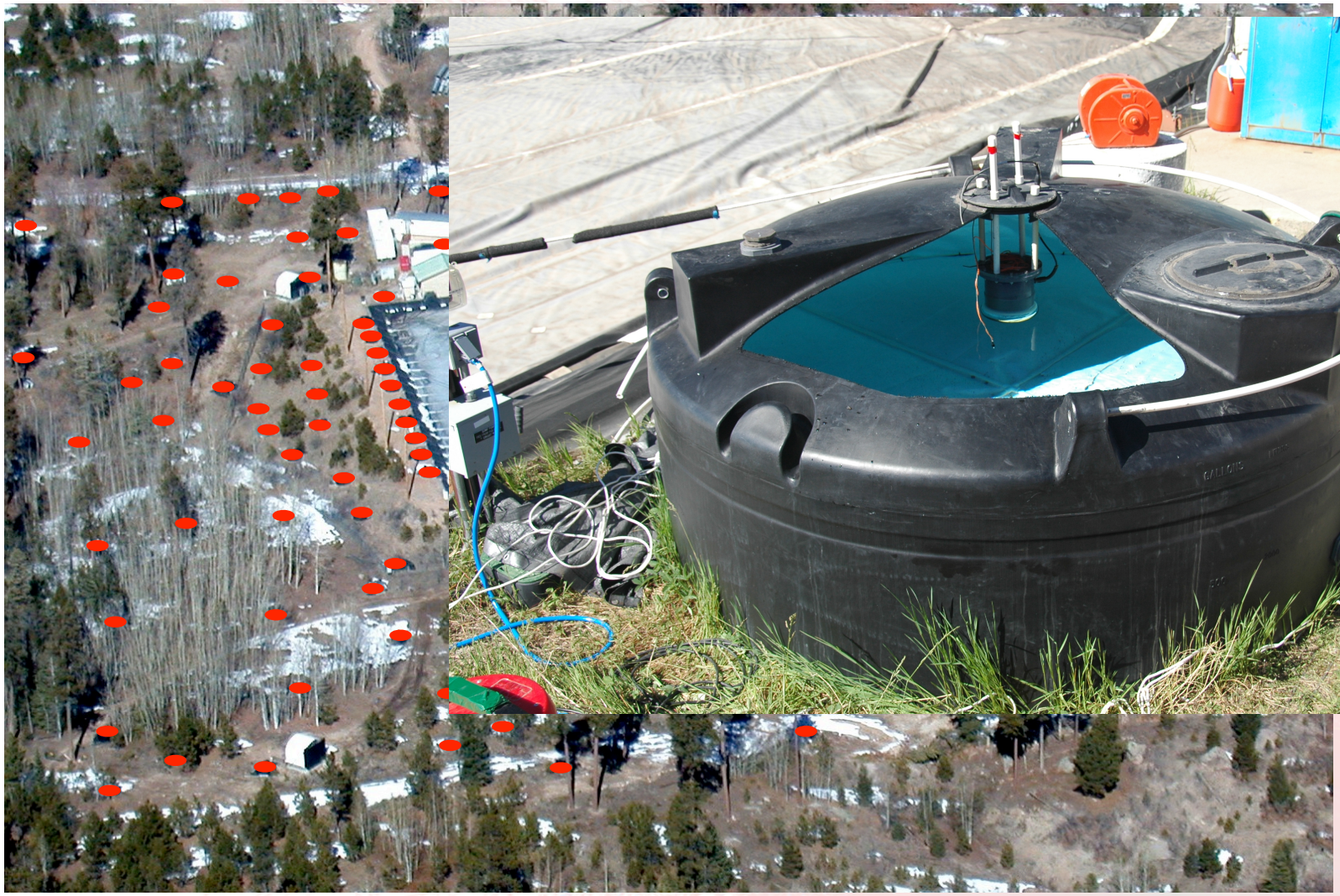
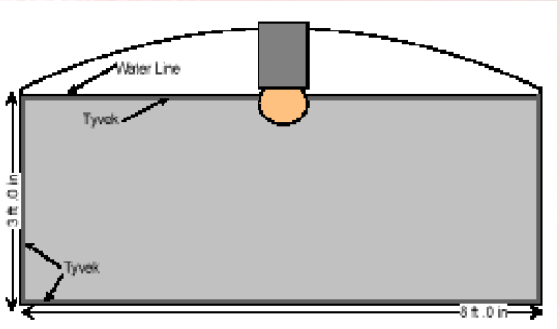


Photo © Rick Dingus




Water Line
Tyvek
3 ft .0 in
Tyvek
8 ft .0 in

Milagro Collaboration

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

Los Alamos NATIONAL LABORATORY

UC SANTA CRUZ

UNIVERSITY OF MARYLAND

MICHIGAN STATE UNIVERSITY

UCIrvine University of California, Irvine

New York University

NEW HAMPSHIRE

Trigger: ~60 PMTs hit within 180ns window

Event Rate ~1700 Hz with 8% dead time. Due almost entirely to CR p(70%) He(25%) C,O, Ne, Mg,Si,Fe(5%)

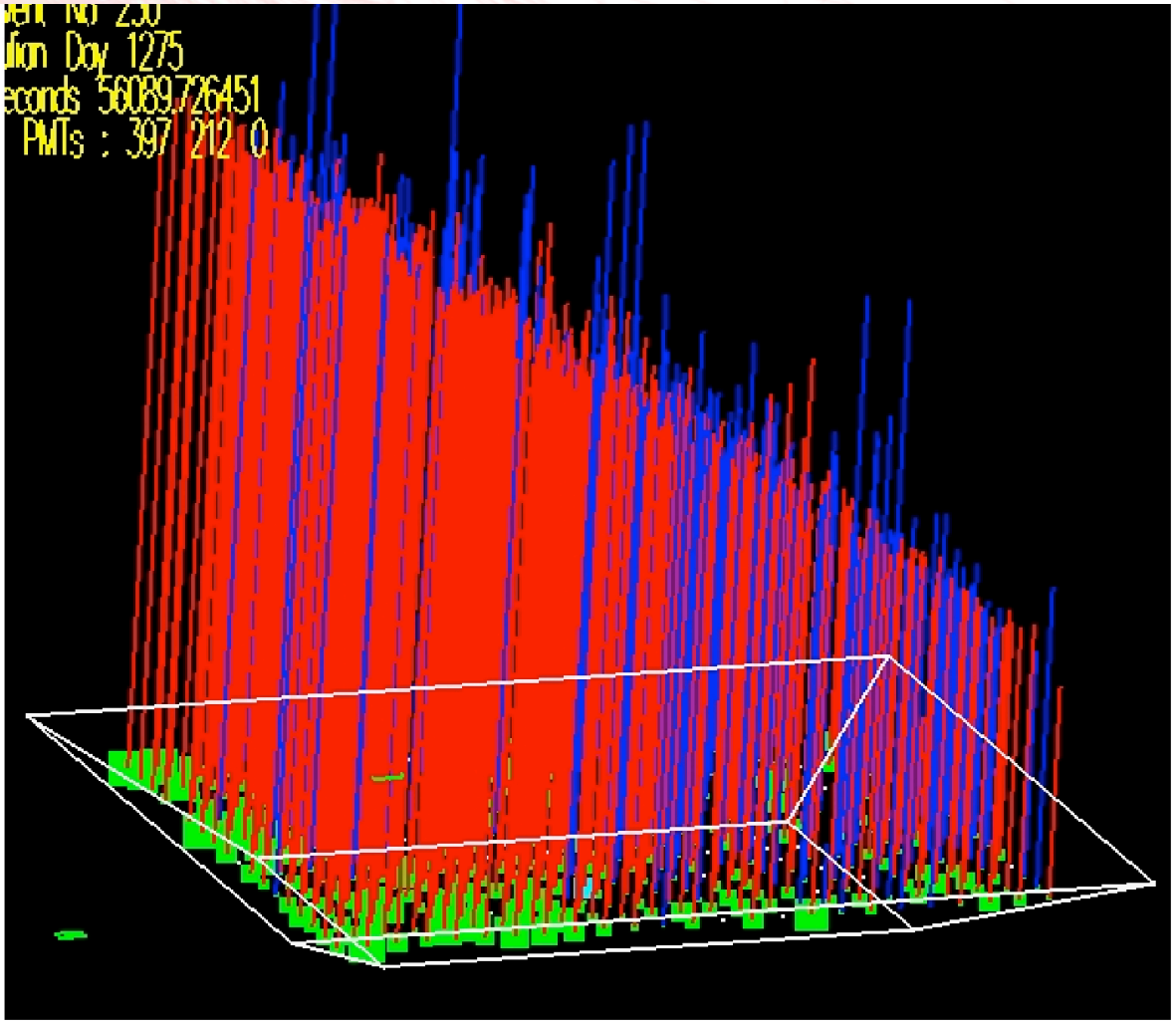
Operational for 7 years, 4 years with outrigger array.

>90% on-time

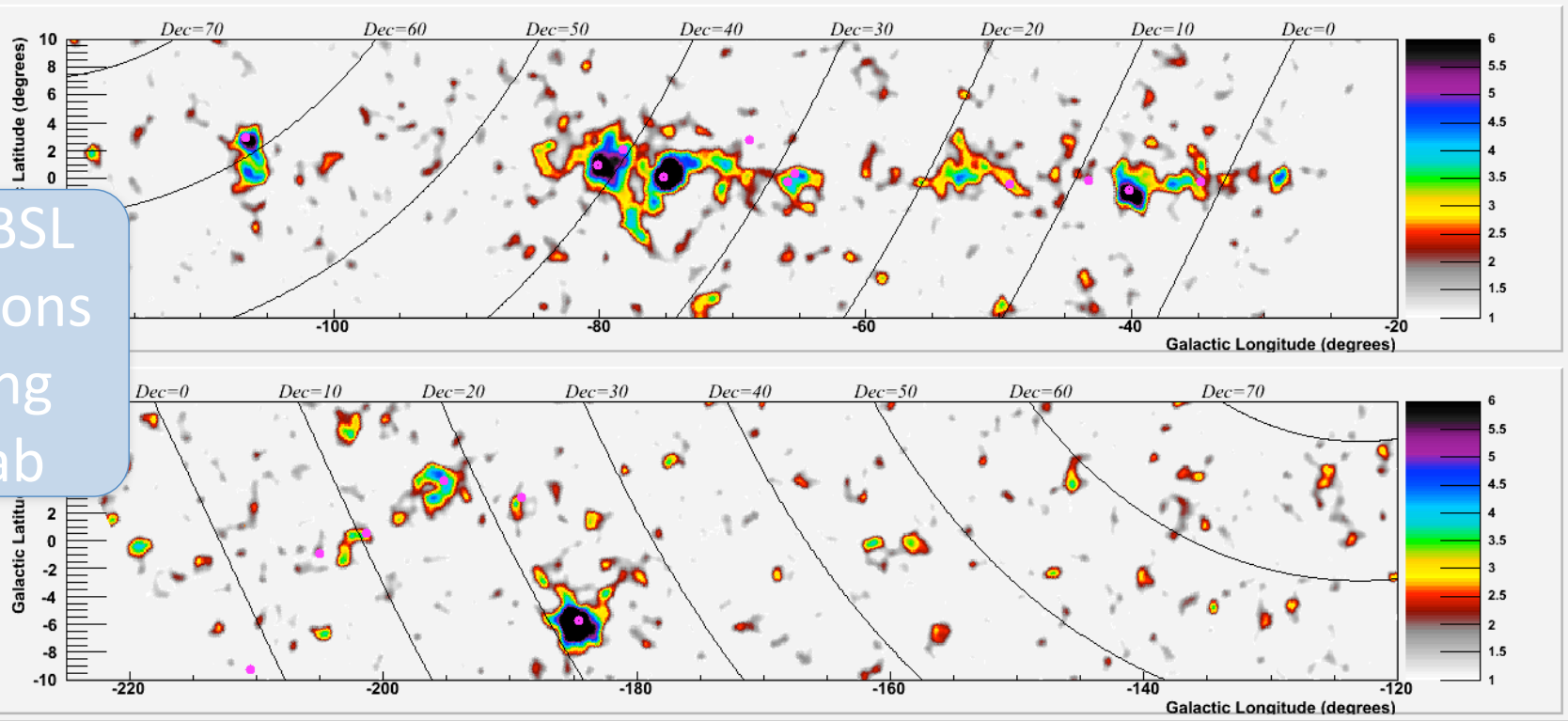
Online reconstruction only, "raw" data not recorded.

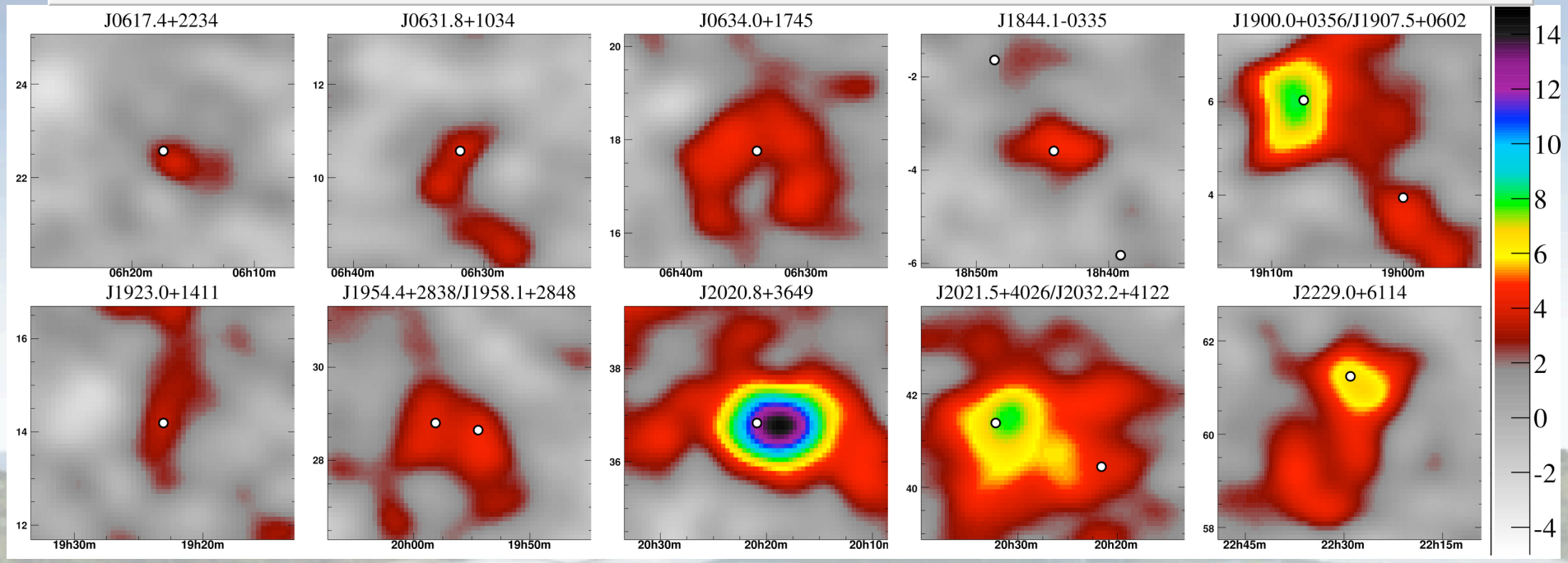
Angular resolution <1°

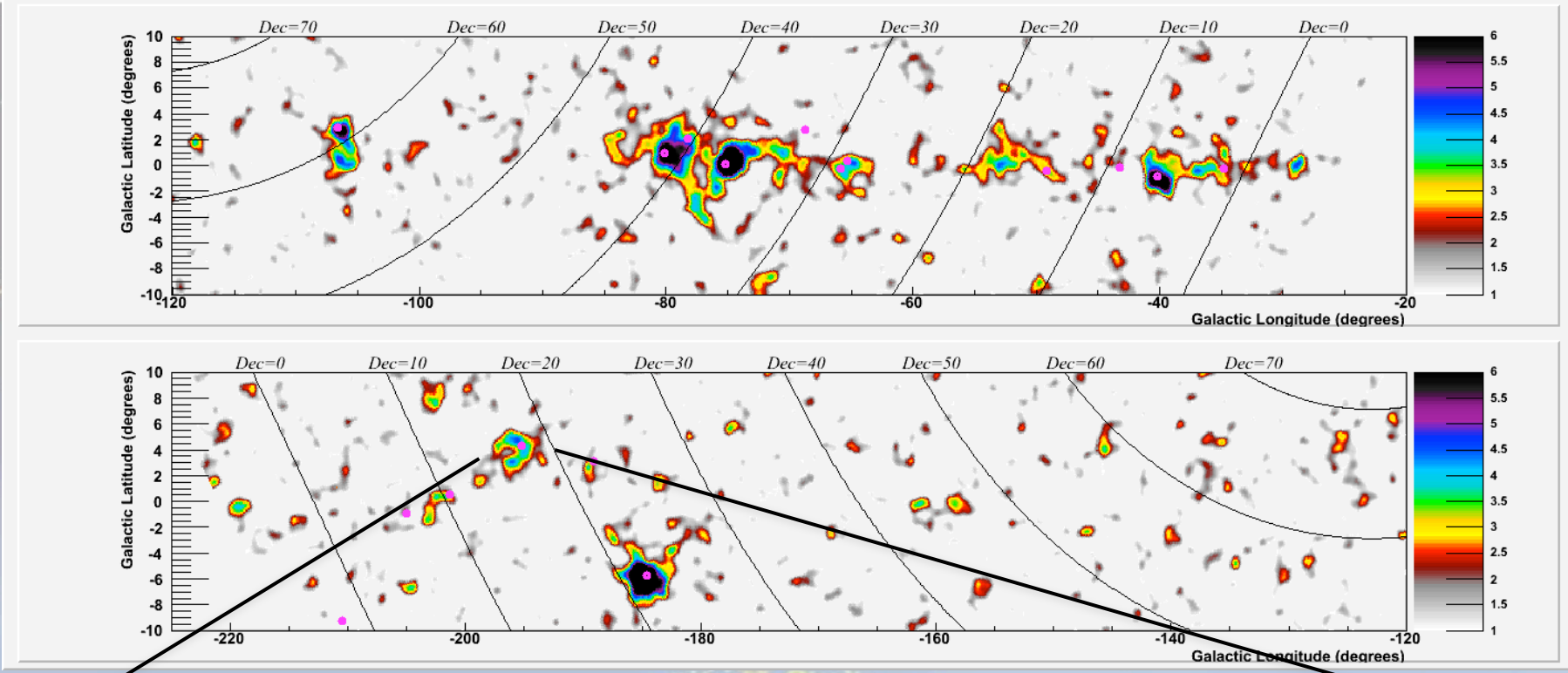
>300 x 10^9 events logged.

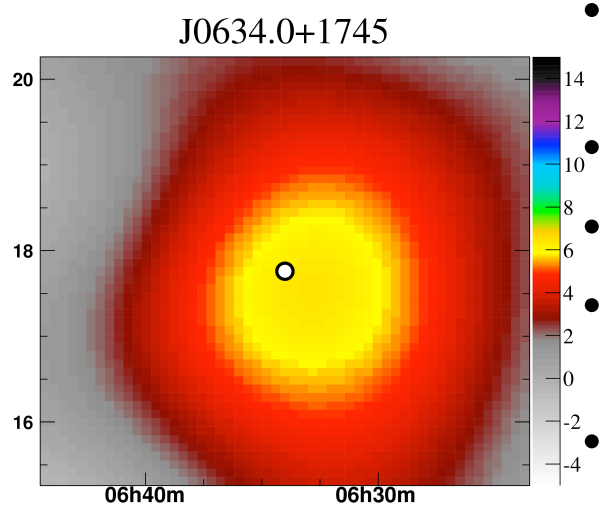


14 TeV BSL associations including the Crab

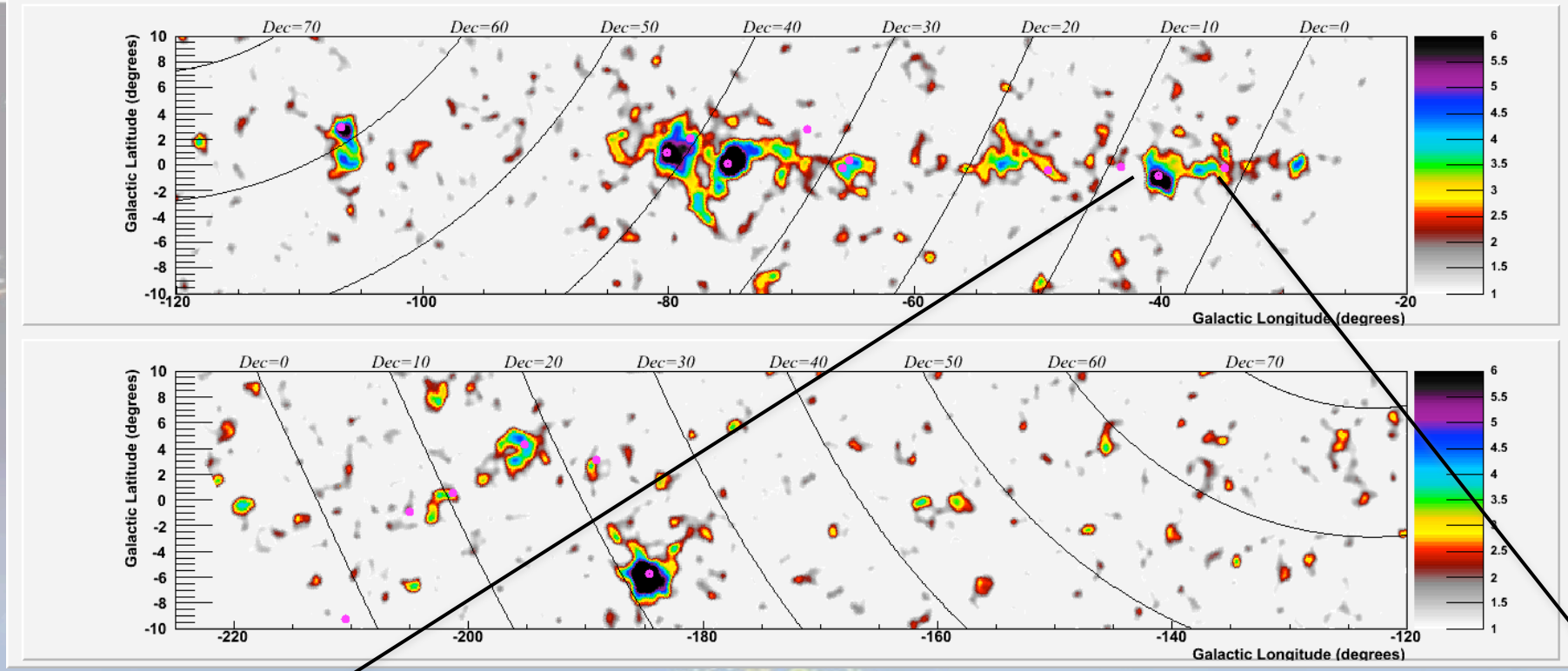


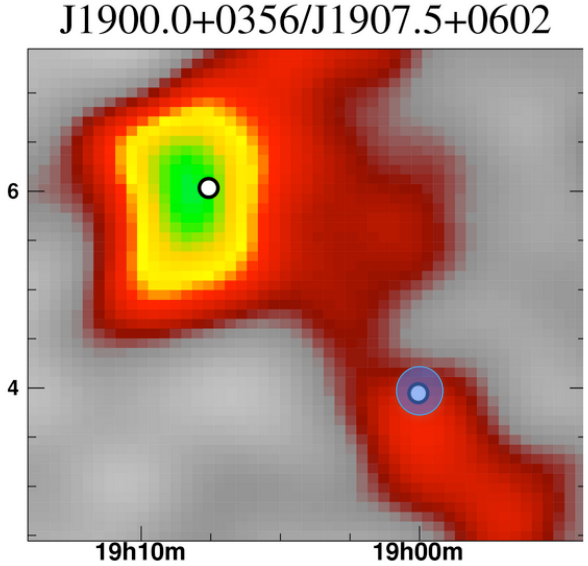




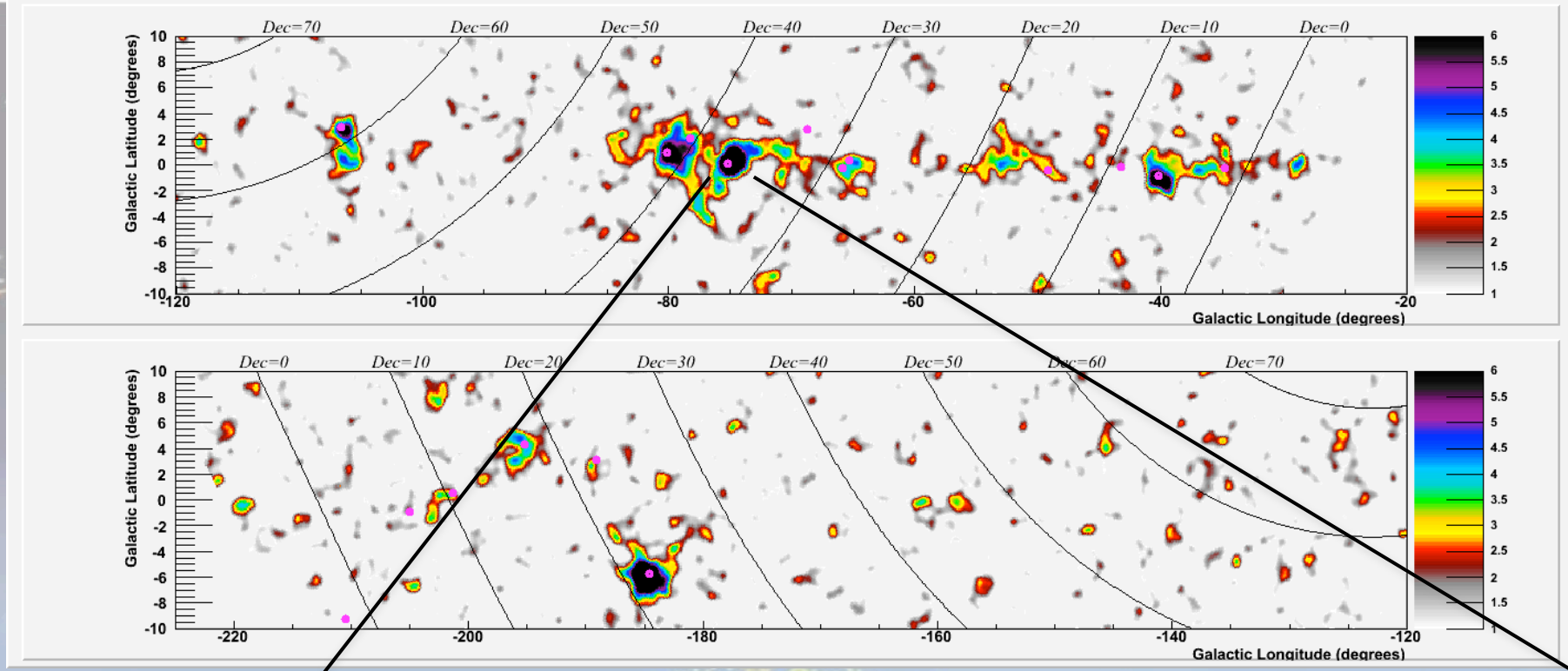


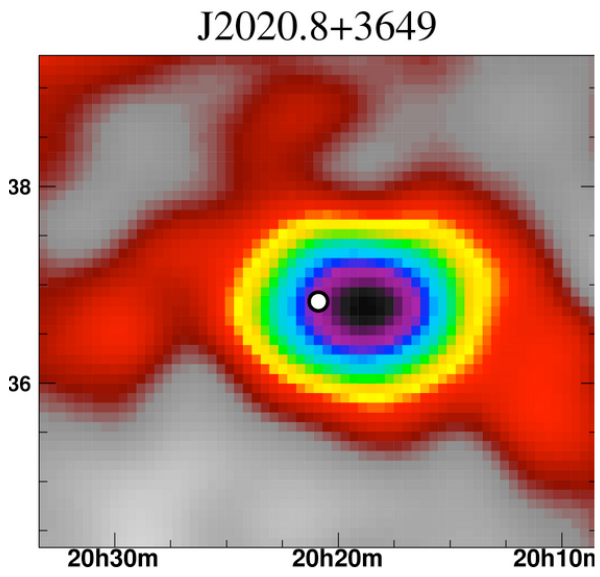
- Most Significant northern Fermi source
- Old (300 kyr) and nearby (169 pc)
- 3.5σ at the location of Geminga
- 6.3σ when assuming 1° extended source
- Fitted FWHM 2.6° extent, consistent with IACT observations of more distant PWN





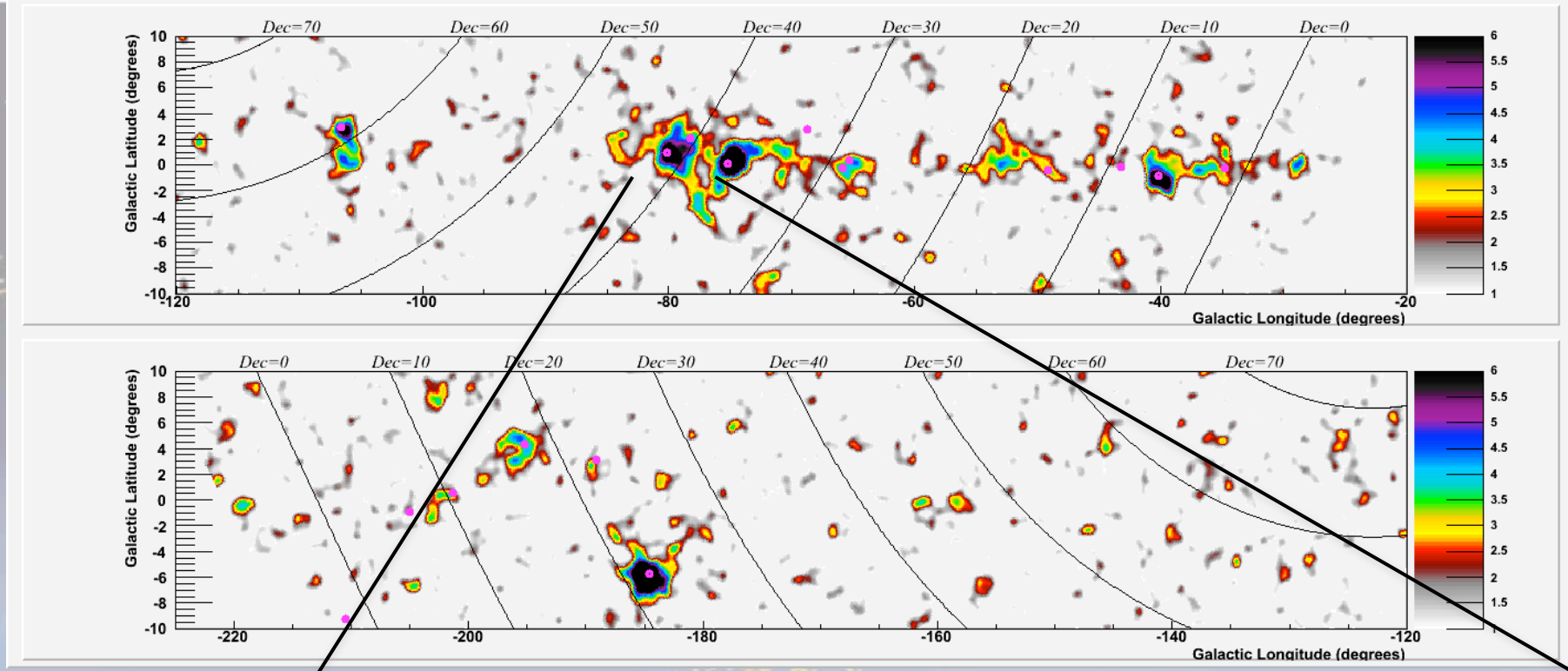
- Associated with MGRO J1908+06, discovered by Milagro and confirmed by HESS and VERITAS (left)
- J1900..0+0356 has no know association (right)
- Milagro detects an excess of 7.4σ and 3.6σ respectively at the location of the Fermi sources.
- VERITAS detection and spectrum



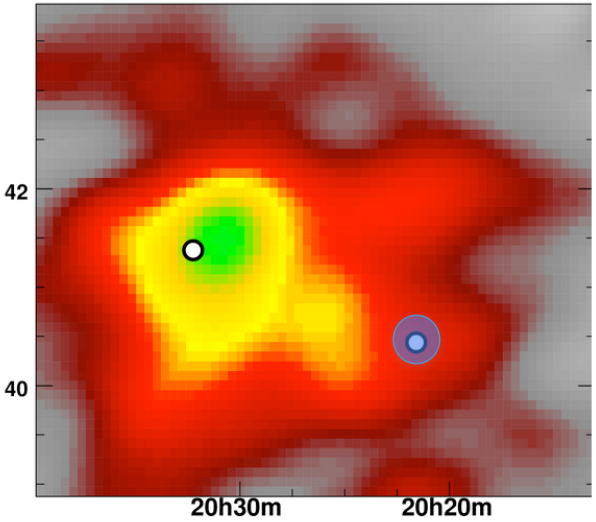


- BSL source associated with previously reported MGRO J2019+37
- Most significant source in the Milagro data set apart from the crab.
- Young pulsar (17.2kyr) discovered by AGILE
- Milagro detects a 12.4σ excess at the position of the Fermi source
- ~2 sigma broader than point source

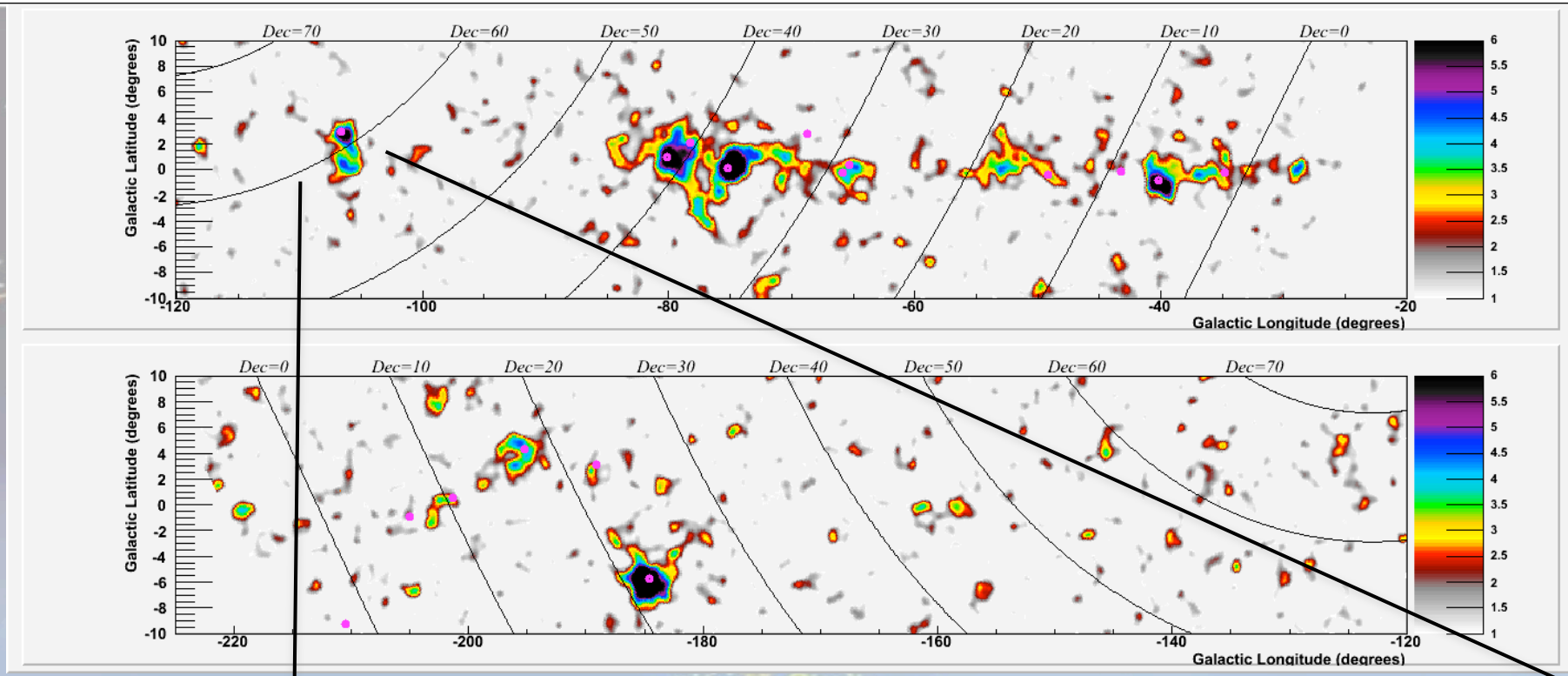
Abdo et al. ApJL (accepted)
arXiv:0904.1018

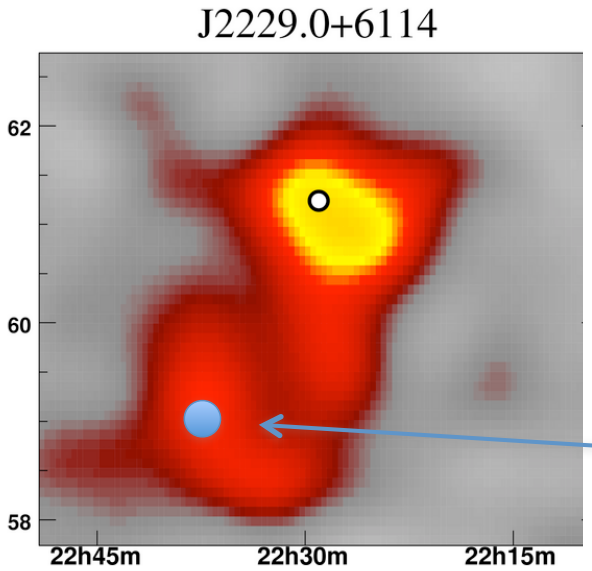


J2021.5+4026/J2032.2+4122



- J2021.5+4026 LAT discovered pulsar associated with gamma-Cygni SNR.
- J2032.2+4122 is a LAT discovered pulsar associated with HEGRA, Milagro and MAGIC TeV detections.
- Milagro observers excesses of 4.2σ and 7.6σ respectively at the positions of the Fermi sources.



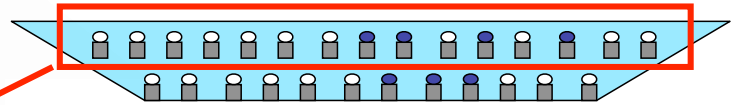


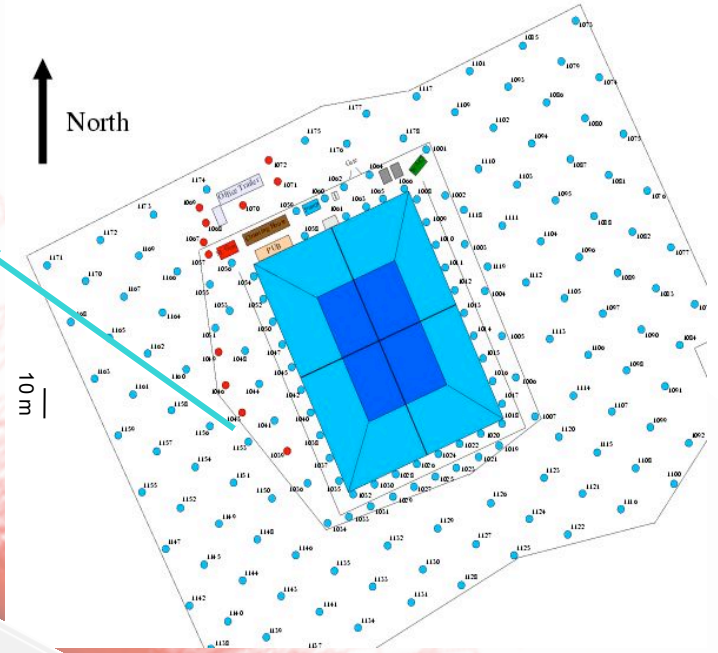
- "Boomerang" PWN
- Associated with radio pulsar J2229+6114
- Milagro detects a 6.6σ excess at the location of the Fermi source.
- Noted excess was very extended (4 deg)
- New Fermi pulsar (Science last Summer) located in the southern 'tail' with 4.7σ in Milagro data.
- VERITAS source

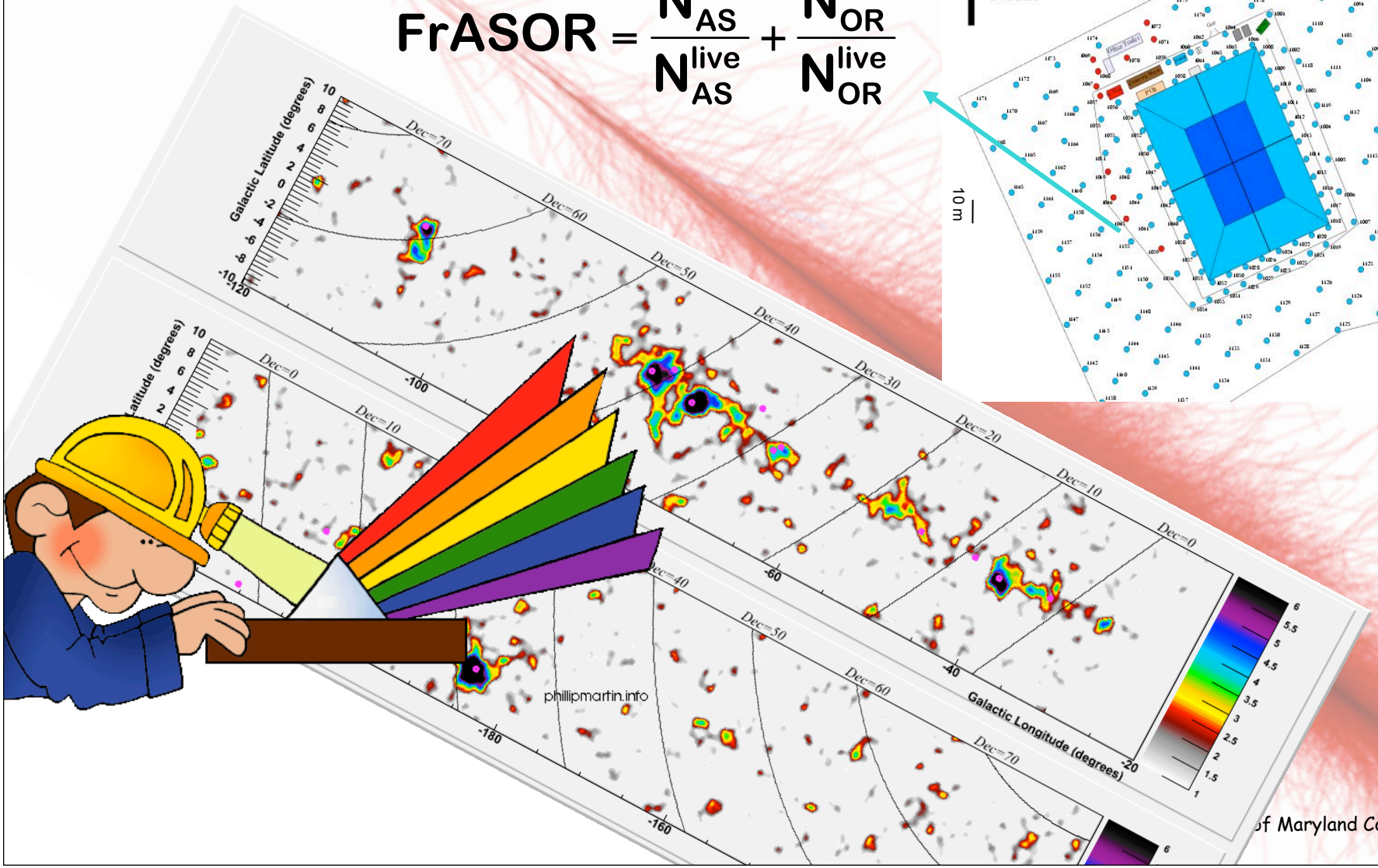
Abdo et al. ApJL (accepted)
arXiv:0904.1018

Introduction of Energy Parameter

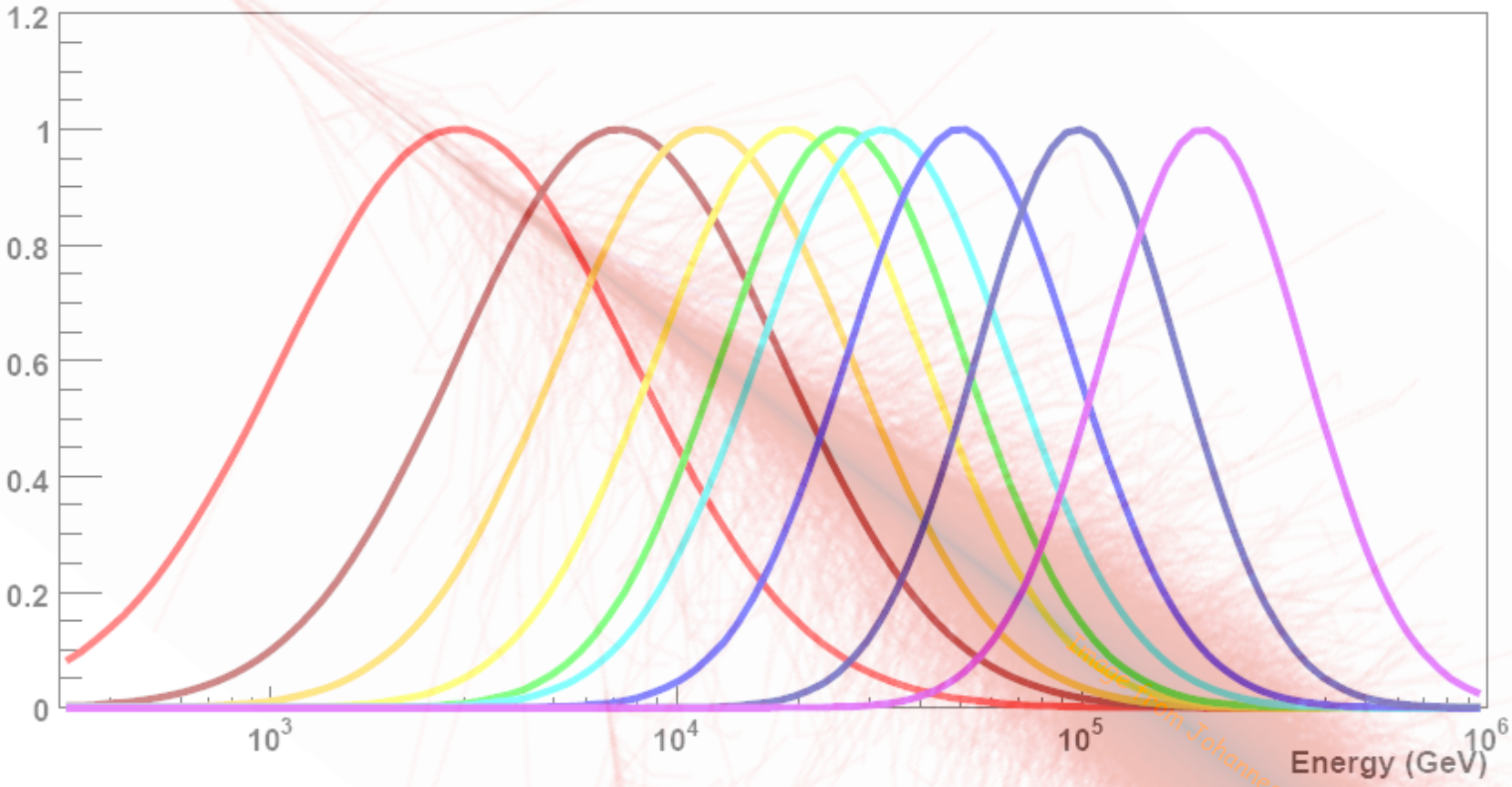
$$\mathrm{FrASOR} = \frac{N_{AS}^{hit}}{N_{AS}^{live}} + \frac{N_{OR}^{hit}}{N_{OR}^{live}}$$







Energy Dependence of FrASOR

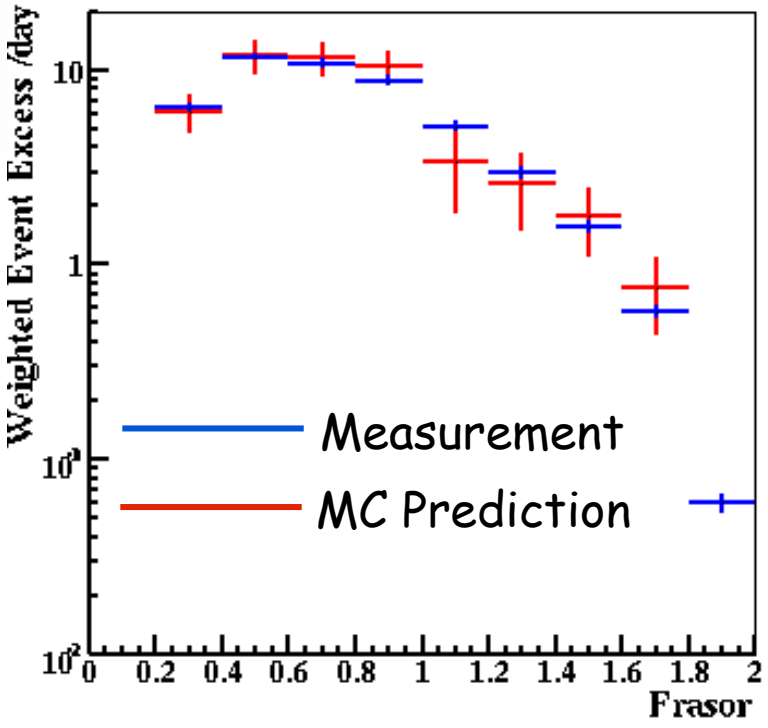


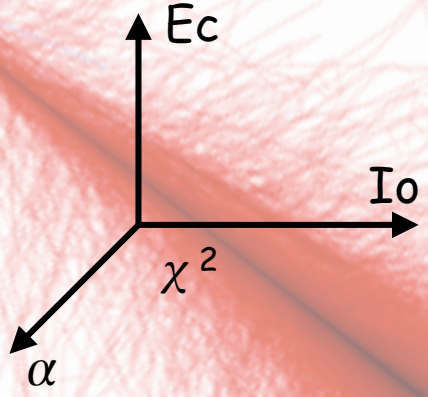
Fitting Procedure

$$\text{Flux} = \text{Io}(E/\text{TeV})^{-\alpha} e^{-(E/Ec)}$$

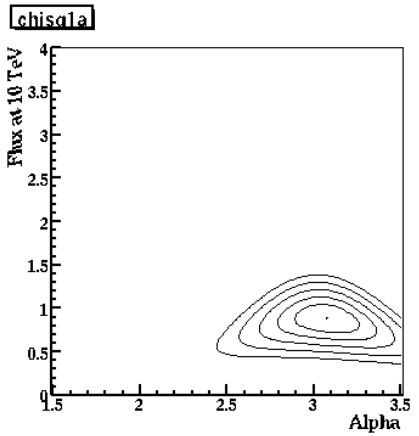
Perform fit in 'Frasor' space, not energy space.

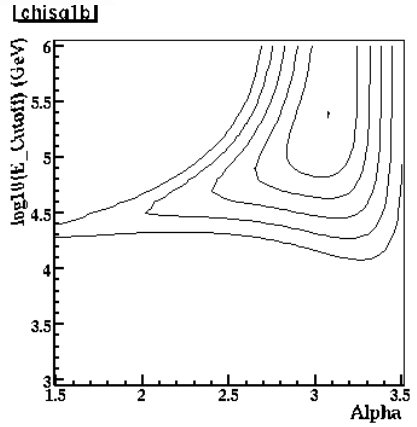
Minimize $\chi^2(\text{Io}, \alpha, \text{Ec}) = \sum (\text{Fr}(\text{Io}, \alpha, \text{Ec}) - \text{Fr}^{\text{measured}})^2 / \sigma^2$

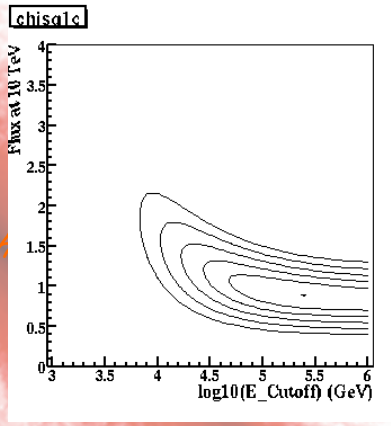




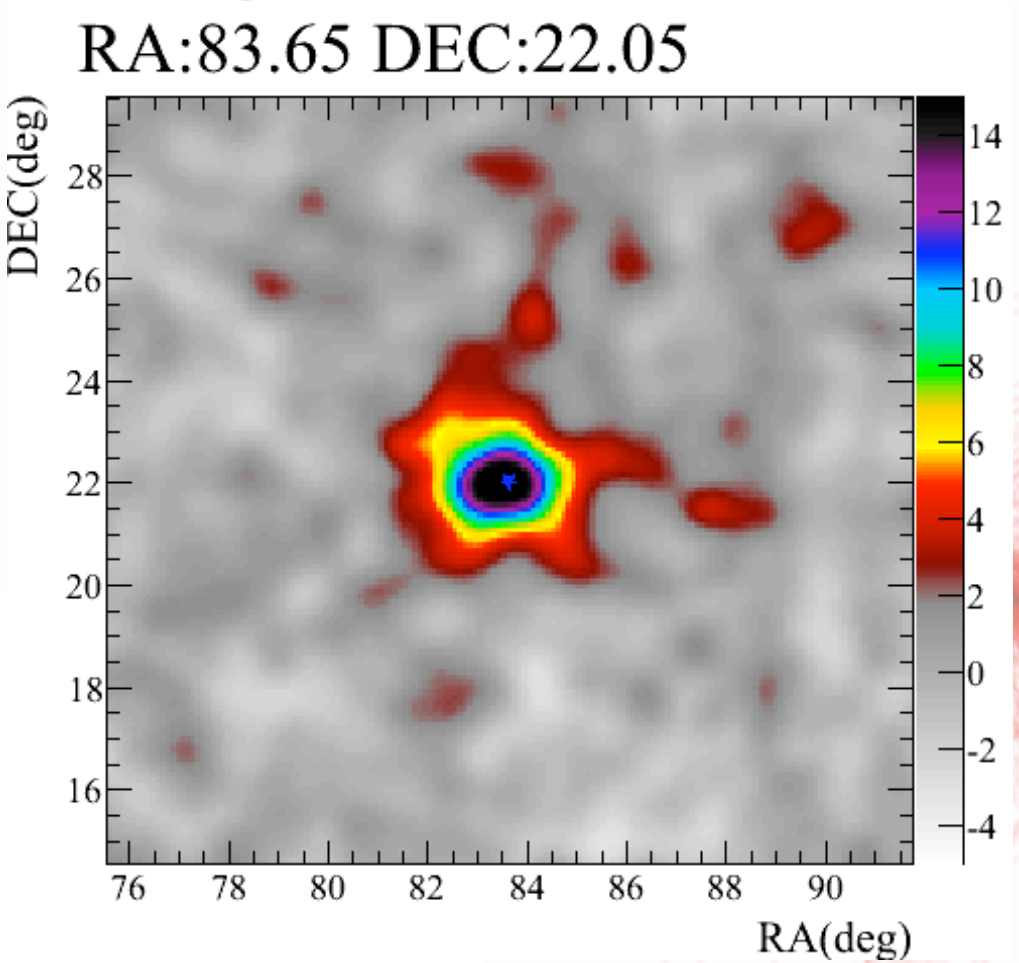
Method extensively tested with fits to the hadronic background spectrum

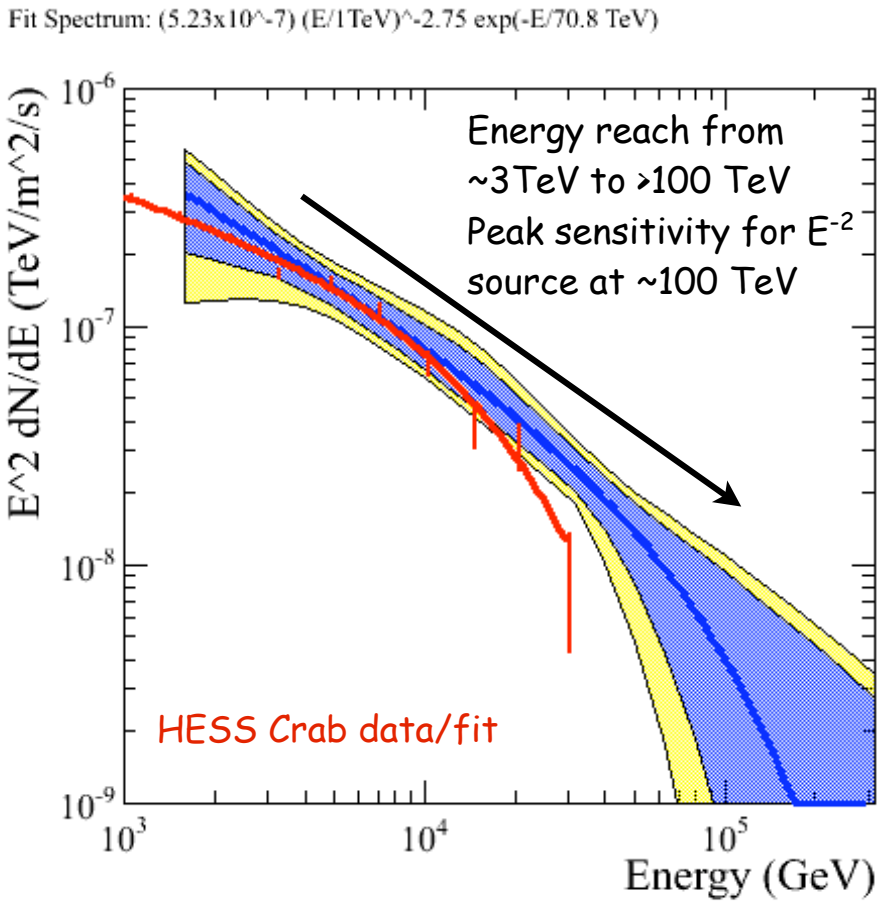






Spectrum of the Crab





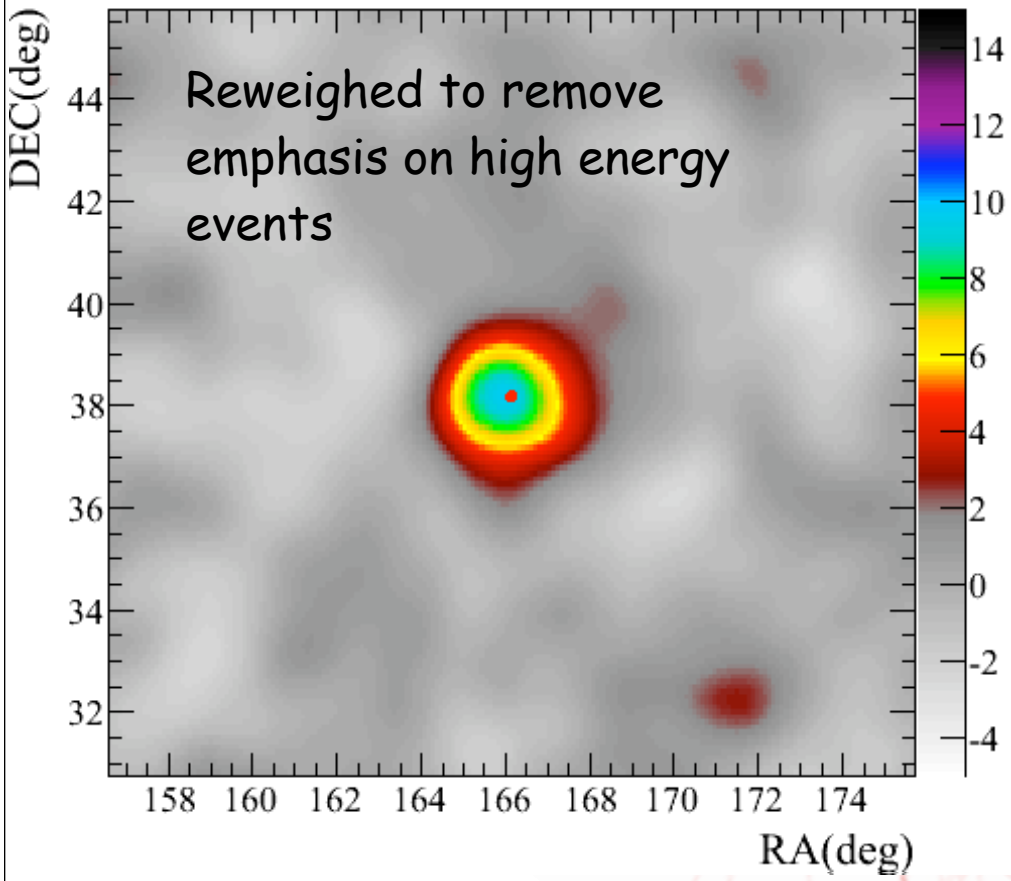
Fit Results: (no cutoff)
Io = 6.6 [5.0,8.0]x 10^{-7} /s/m^2/TeV
α = 2.95 [2.85,3.03]
χ^2 = 28.3 (25 dof)

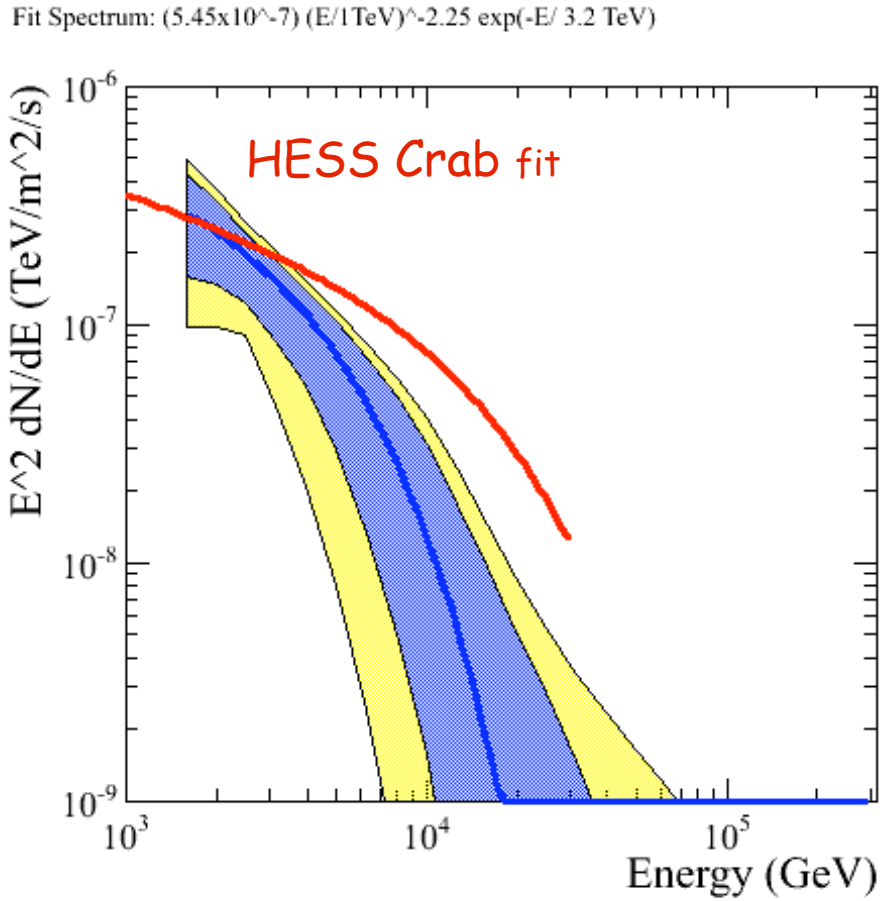
Softer than IACT spectra (α_{IACT} ~2.6)

Fit Results: (3-parameter)
Io = 5.2 [2.0,8.0] x 10^{-7} /s/m^2/TeV
α = 2.75 [2.22,3.03]
Γ = 71 [22,inf]
χ^2 = 27.1 (24 DOF)

Mrk 421

RA:166.15 DEC:38.25





Fit Results: (3-parameter)

Io = 5.2 [1.9,14.0] x 10^{-7} /s/m^2/TeV

α = 1.90 [1.50,3.5]

Ec = 2.5 [1.4,20]

χ^2 = 33.5 (24 DOF)

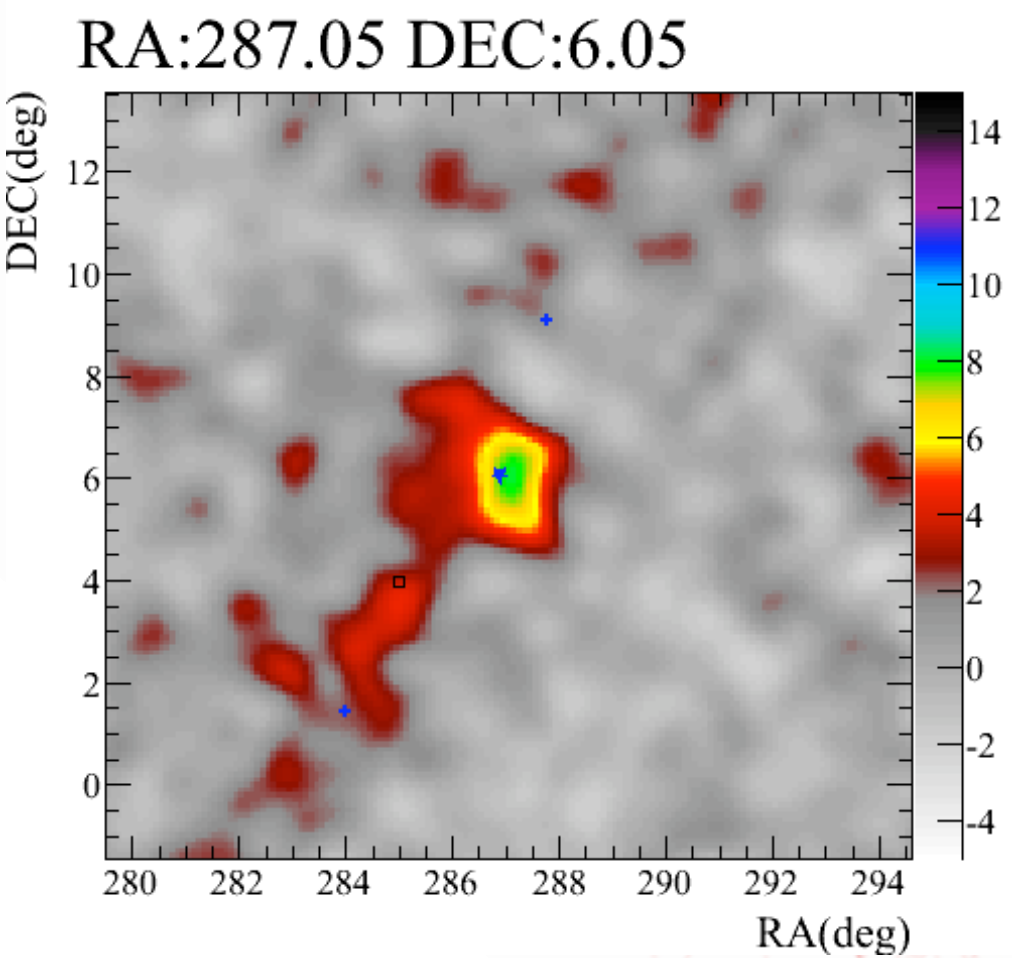
Fit Results: Fix spectral index at 2.1 (2-parameter)

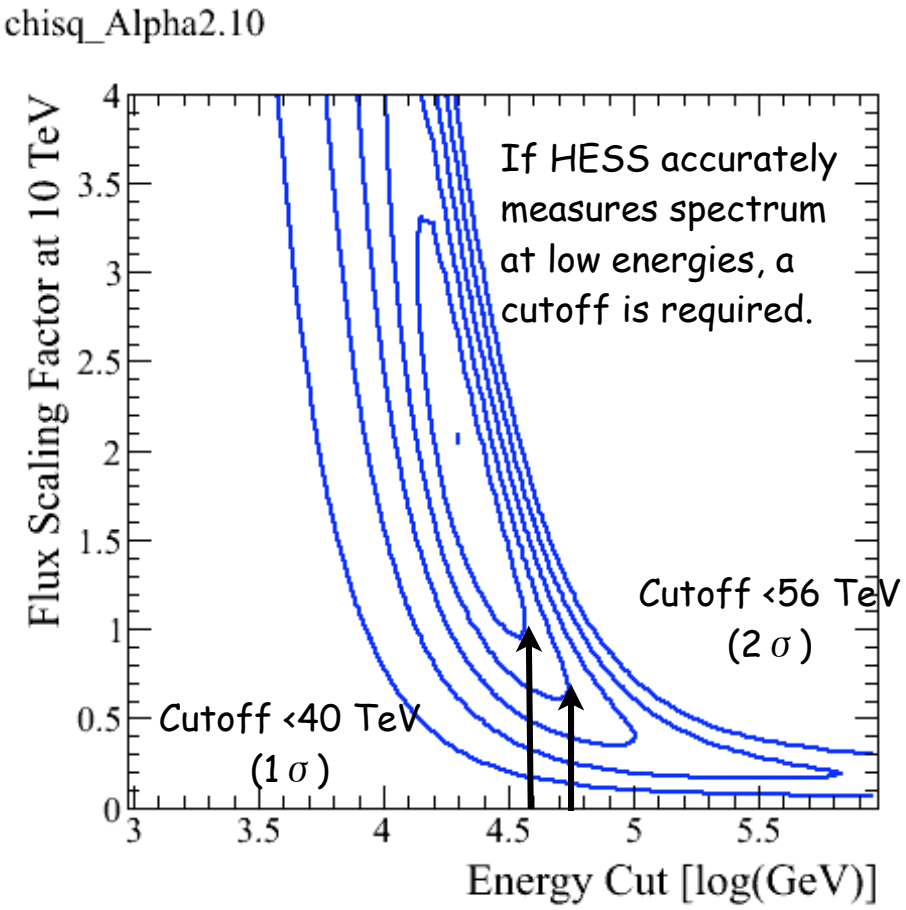
Io = 5.4 [3.0,10.1]x 10^{-7} /s/m^2/TeV

Ec = 2.8 [1.8,4.0] TeV

χ^2 = 28.3 (25 dof)

MGRO J1908+06





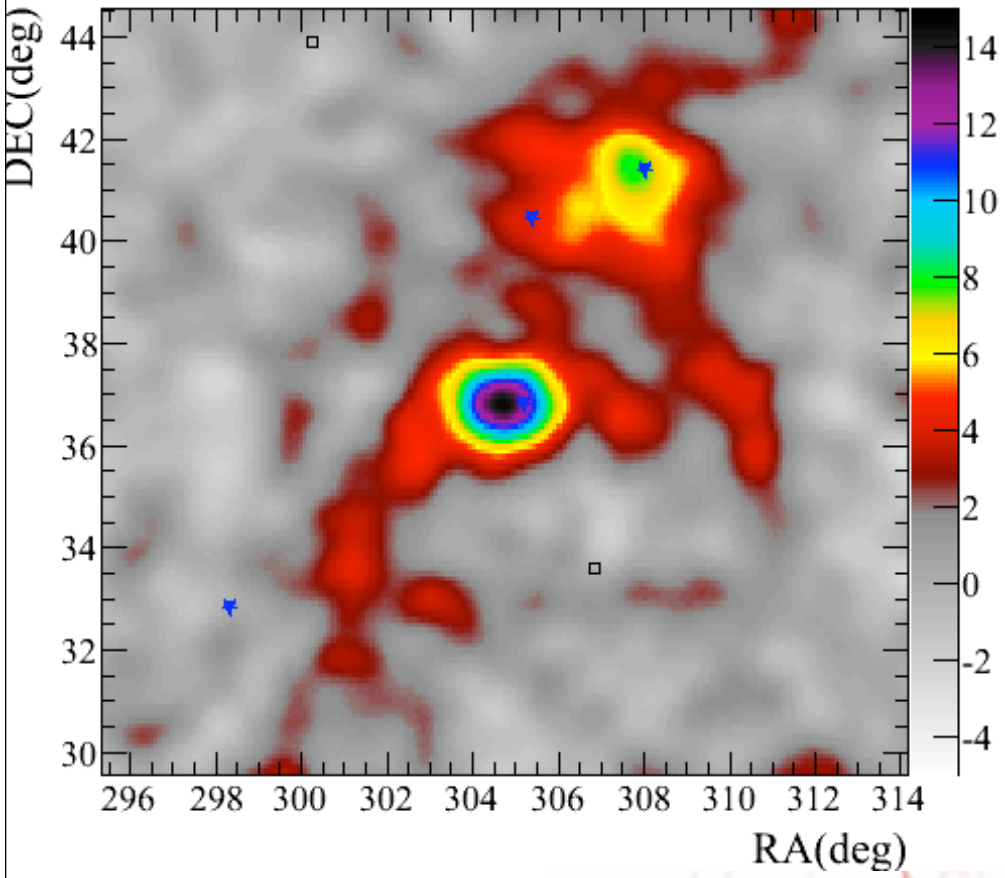
Fit Results: (no cutoff)
Io = 6.6 [3.4,12.1] x 10^{-7} /s/m^2/TeV
α = 3.00 [2.8,3.2]
χ^2 = 29.3 (25 DOF)

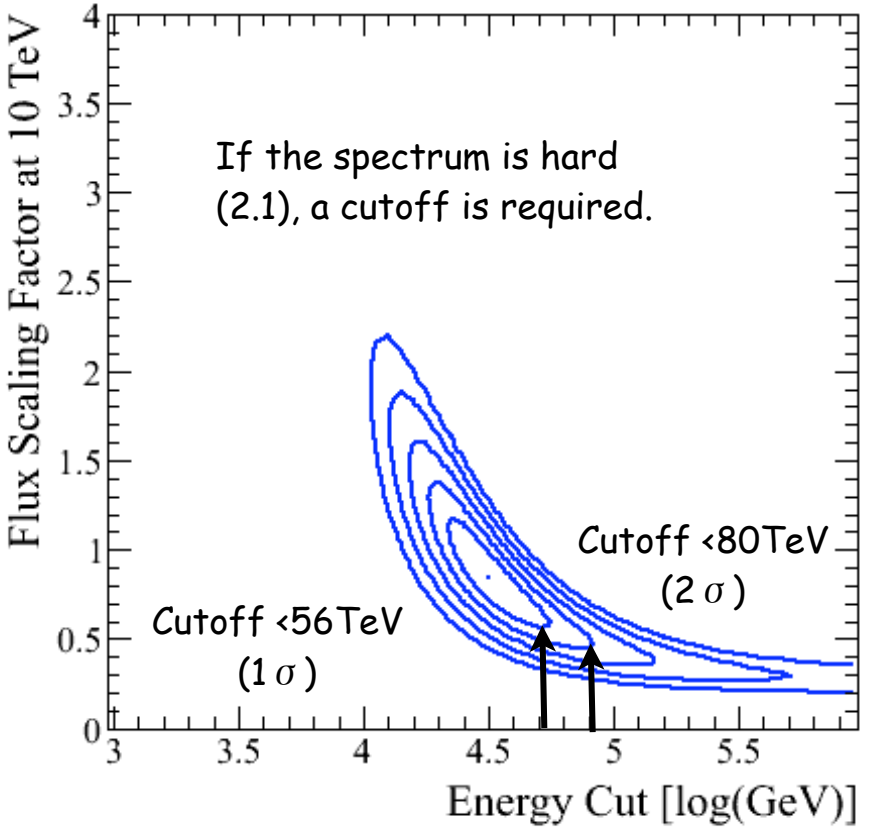
Fit Results: (3-parameter)
Io = 0.62 [0.29,4.9] x 10^{-7} /s/m^2/TeV
α = 1.50 [1.50,2.65]
Ec= 14 [10,50] TeV
χ^2 = 22.1 (24 DOF)

Fit Results: (hold α=2.1)
Io = 2.1 [1.1,3.1] x 10^{-7} /s/m^2/TeV
Ec = 14 [10,40] TeV
χ^2 = 23.3 (25 DOF)

MGRO J2019+37/ 0FGL J2020.8+3649

RA:304.75 DEC:37.05



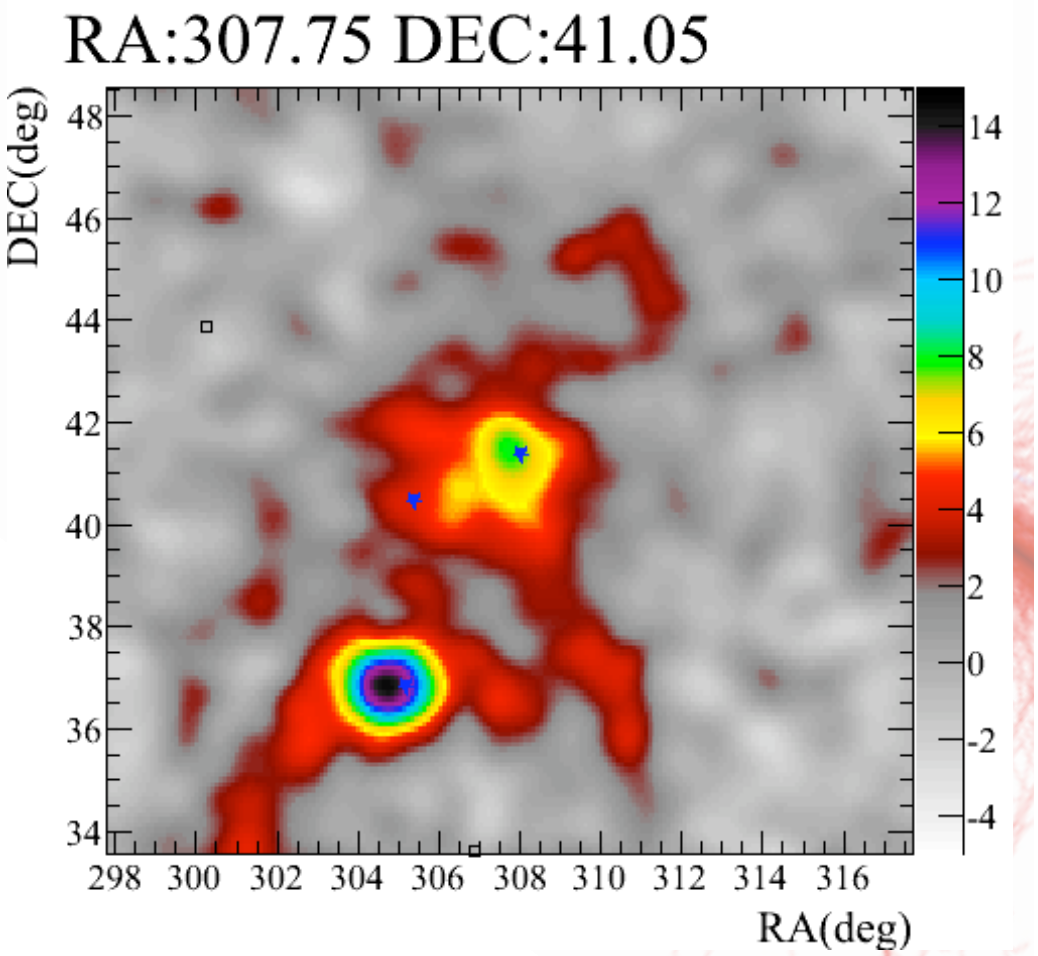


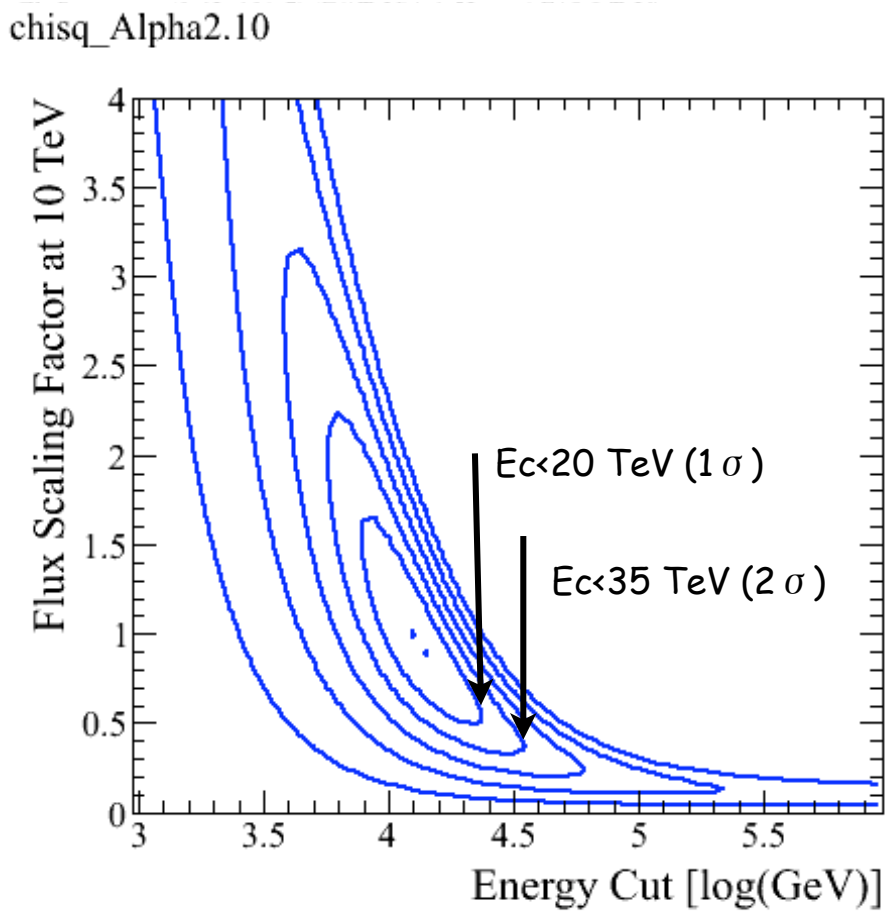
Fit Results: (no cutoff)
Io = 1.74 [1.10-2.50] x 10^{-7} /s/m^2/TeV
α = 2.62 [2.50-2.75]
χ^2 = 31.7 (25 DOF)

Fit Results: (3-parameter)
Io = 0.54 [0.20,1.82] x 10^{-7} /s/m^2/TeV
α = 1.83 [1.50,2.55]
Ec = 22 [12,177] TeV
χ^2 = 26.9 (24 DOF)

Fit Results: (hold α =2.1)
Io = 0.87 [0.64,1.1] x 10^{-7} /s/m^2/TeV
Ec = 31 (25,44) TeV
χ^2 = 27.3 (25 DOF)

MGRO J2031+41/TeV 2032+41



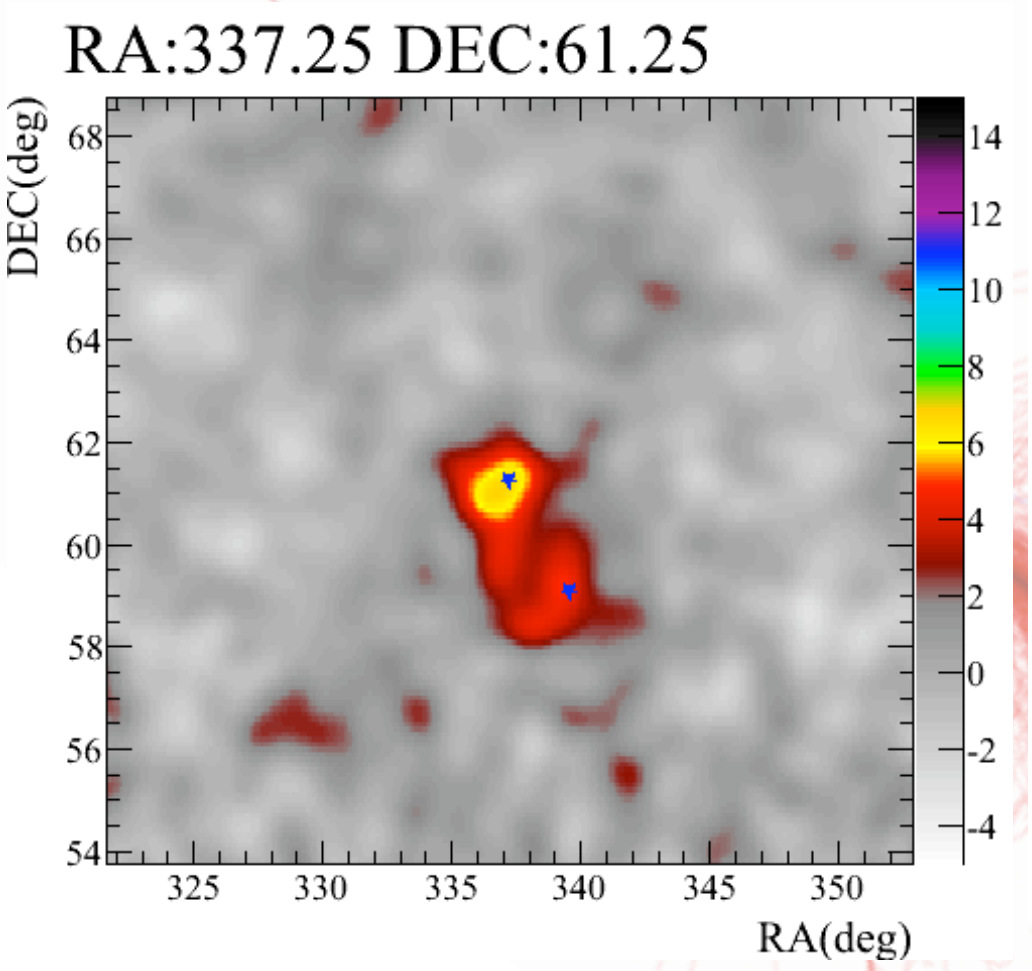


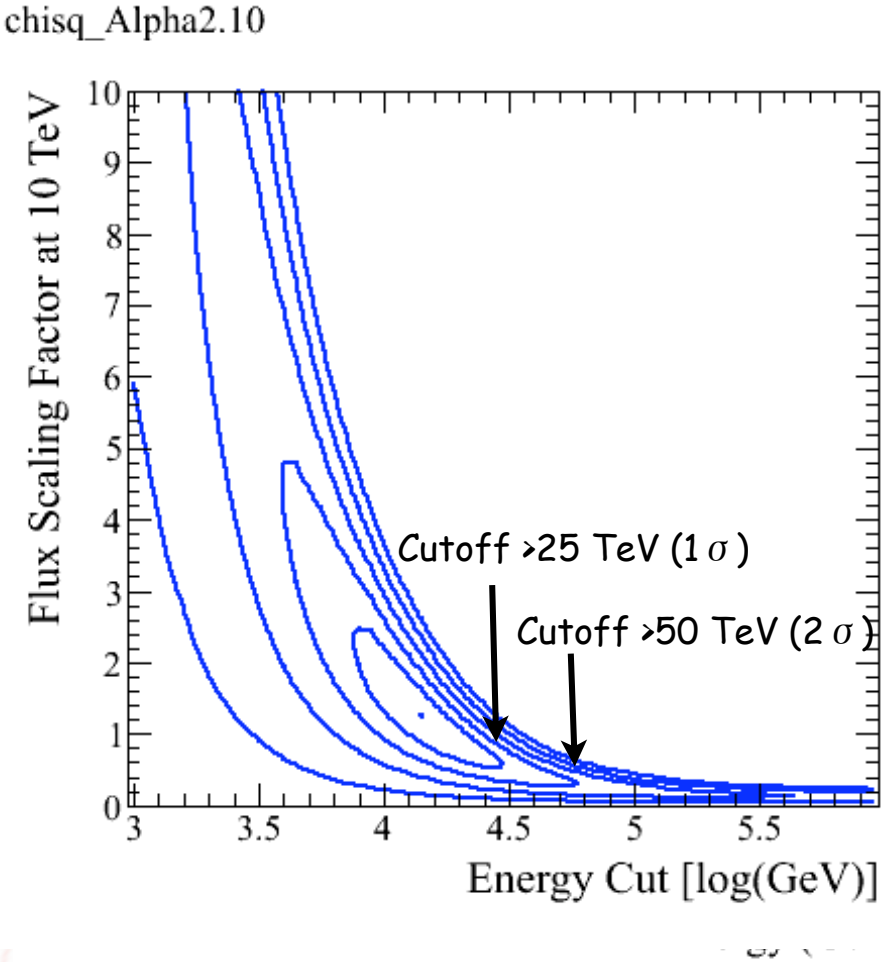
Fit Results: (no cutoff)
Io = 2.6 [1.3,3.6] x 10^{-7} /s/m^2/TeV
α = 3.02 [2.80,3.20]
χ^2 = 24.2 (25 DOF)

Fit Results: (3-parameter)
Io = 0.42 (0.20,2.40) x 10^{-7} /s/m^2/TeV
α = 1.53 [1.50,2.83]
Ec= 9 [5.6,56] TeV
χ^2 = 18.6 (24 DOF)

Fit Results: (hold α=2.1)
Io = 0.92 [0.58,1.50] x 10^{-7} /s/m^2/TeV
Ec= 14 (9,20) TeV
χ^2 = 18.6 (25 DOF)

Boomerang - MGRO J2229+61,0FGL J2229+6114





Fit Results: (no cutoff)
Io = 4.0 [1.7,7.1] x 10^{-7} /s/m^2/TeV
α = 3.10 [2.83,3.38]
χ^2 = 14.4 (25 DOF)

Fit Results: (3-parameter)
Io = 2.68 (0.18,7.72) x 10^{-7} /s/m^2/TeV
α = 2.70 (1.50,3.42)
Γ = 45 (6,inf) TeV
χ^2 = 13.9 (24 DOF)

Fit Results: (hold α=2.1)
Io = 1.28 [0.55,2.50] x 10^{-7} /s/m^2/TeV
Ec= 14 (8,25) TeV
χ^2 = 18.6 (25 DOF)