Outline

- WCD 2 -
  - Cosmic Ray Background
  - Large and small scale anisotropy
  - Energy Reconstruction
  - Gamma-Ray Data

Cosmic Ray Discovery

- Physikalische Zeitschrift: “The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above.”

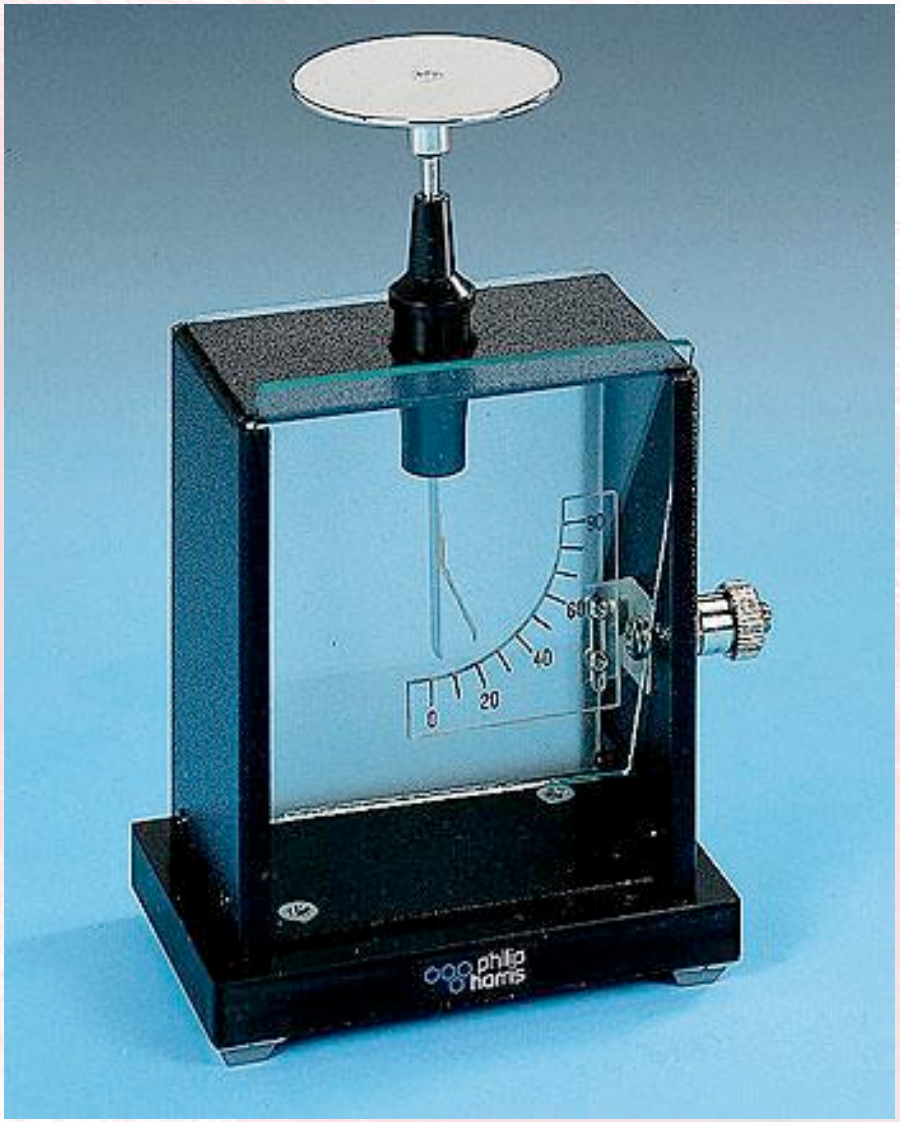
Victor Franz Hess

Elevation	Rate
Ground	12
1km	10
2 km	12
3.5 km	15
5 km	27

V. F. Hess. Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten. Physikalische Zeitschrift, 13:1084-1091, November 1912.

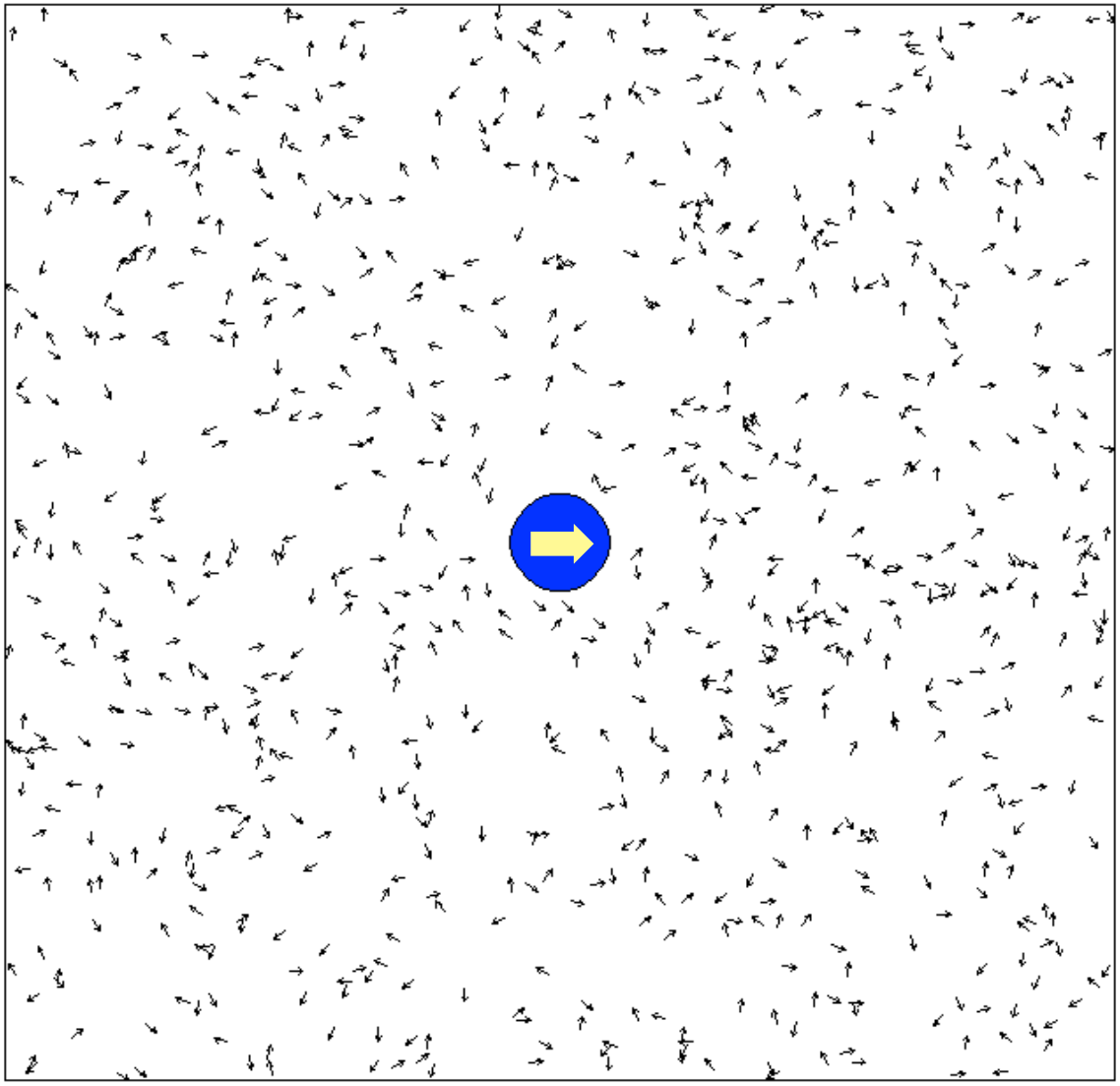
Electroscope

- Charged gold leaf spontaneously discharges due to ionizing radiation.
- Invented in 1787 by Abraham Bennet.



Compton-Getting Effect

The motion of the earth through a cosmic-ray 'aether' creates a forward-backward anisotropy in the direction of motion

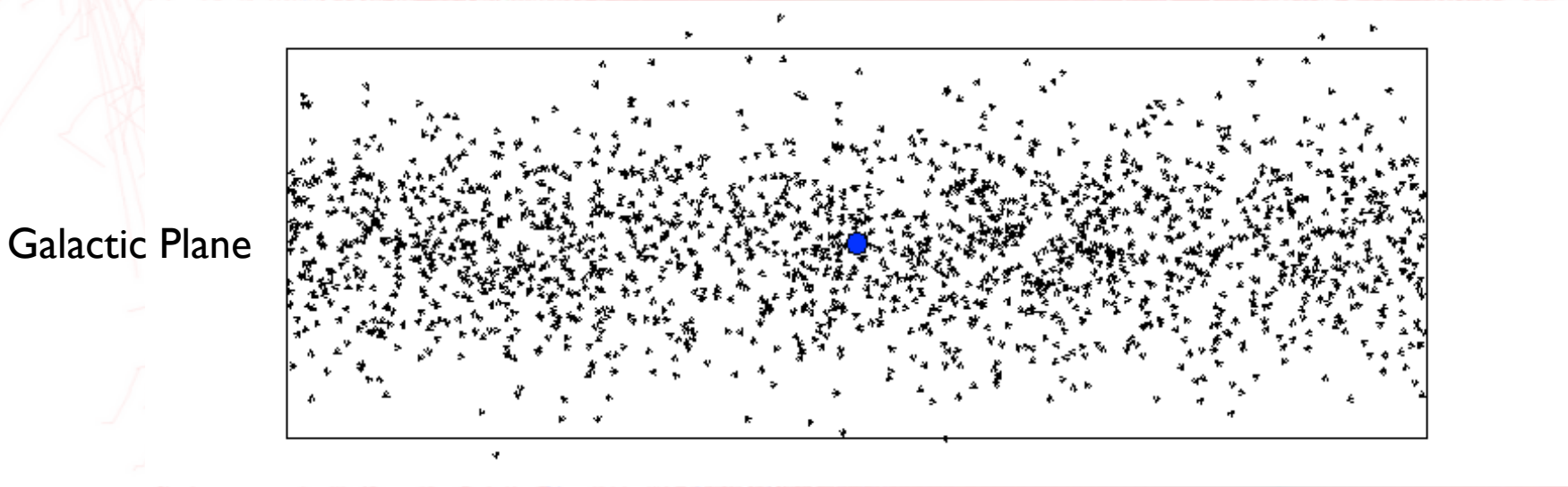


If CR's stationary w.r.t galactic rotation, a large anisotropy should be visible (~1%).

Phys Rev Vol 47, No11 (1935)

Other sources of anisotropy

- Diffusion from the galactic plane (higher matter density) into the galactic halo (lower matter density).

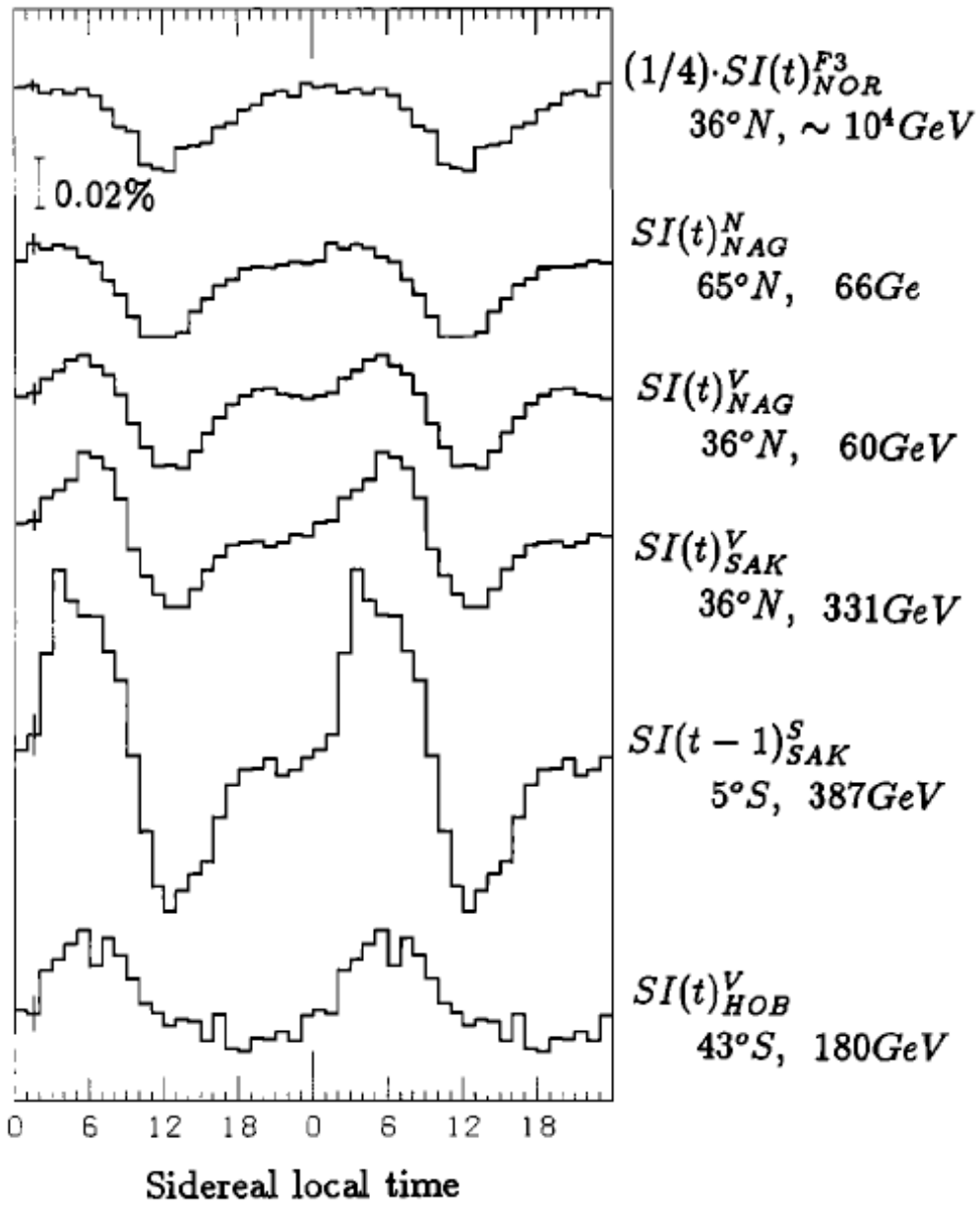


- Local CR sources.

Early detection of Anisotropy

Sidereal counting rates for various experiments

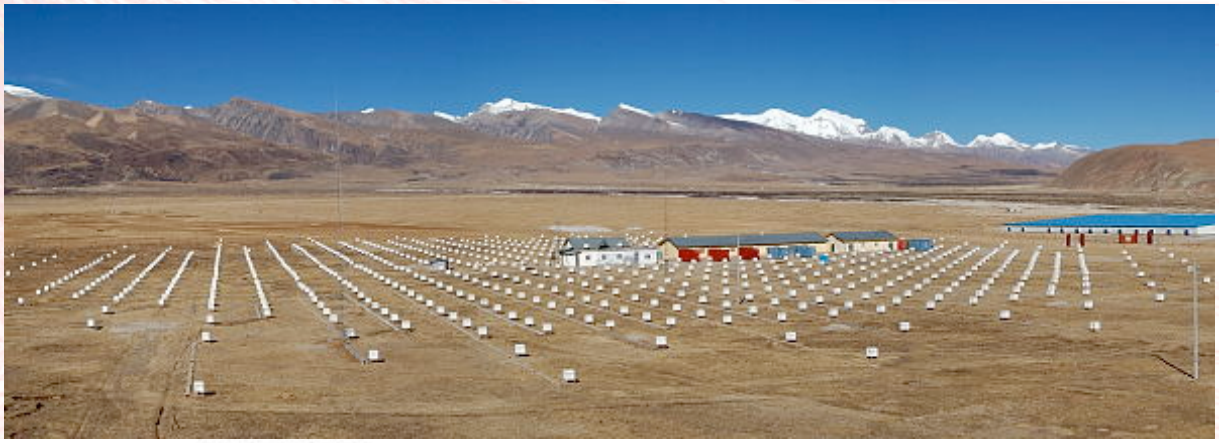
Anisotropy ~few parts in 1000 observed.

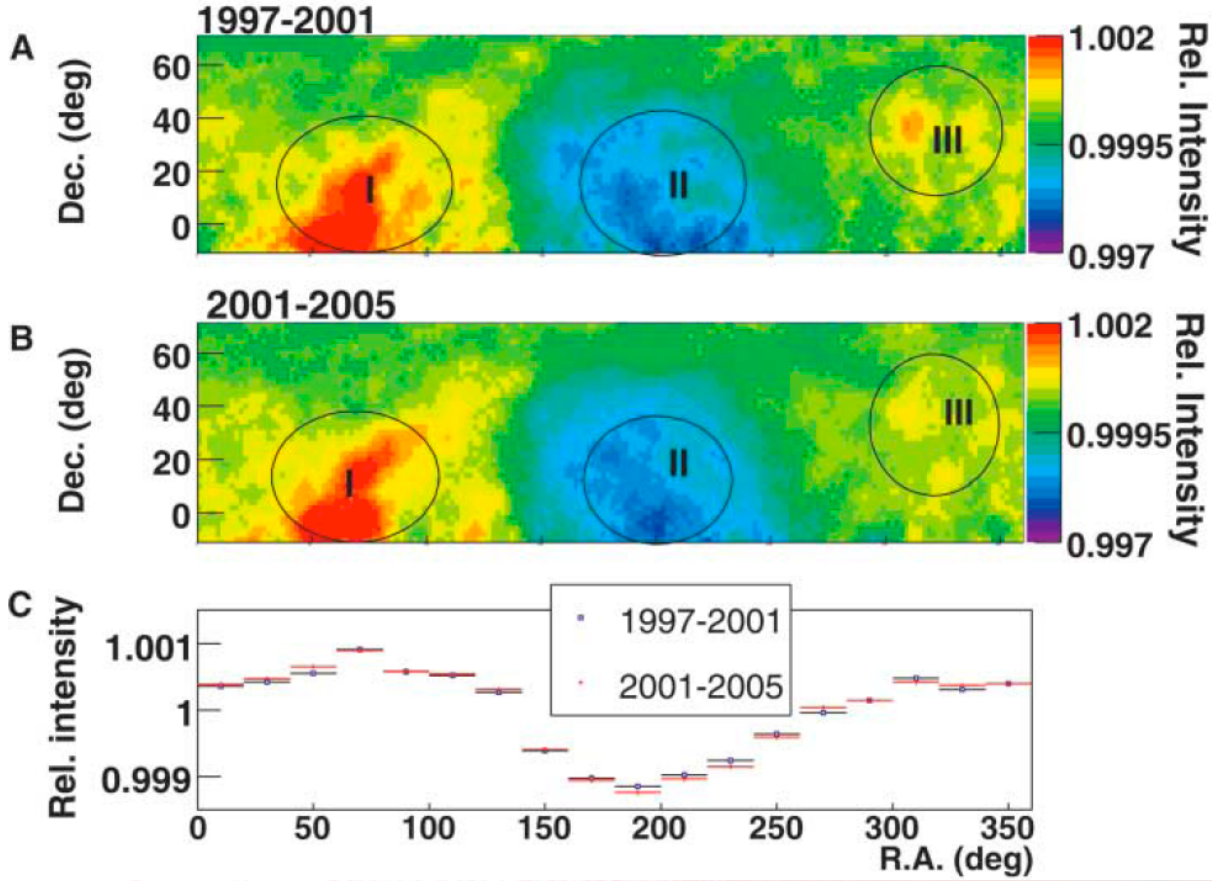


Nagashima, K., K. Fujimoto, and R. M. Jacklyn (1998) J.Geophys. Res., 103(A8), 17,429–17,440.

Tibet Air Shower Array

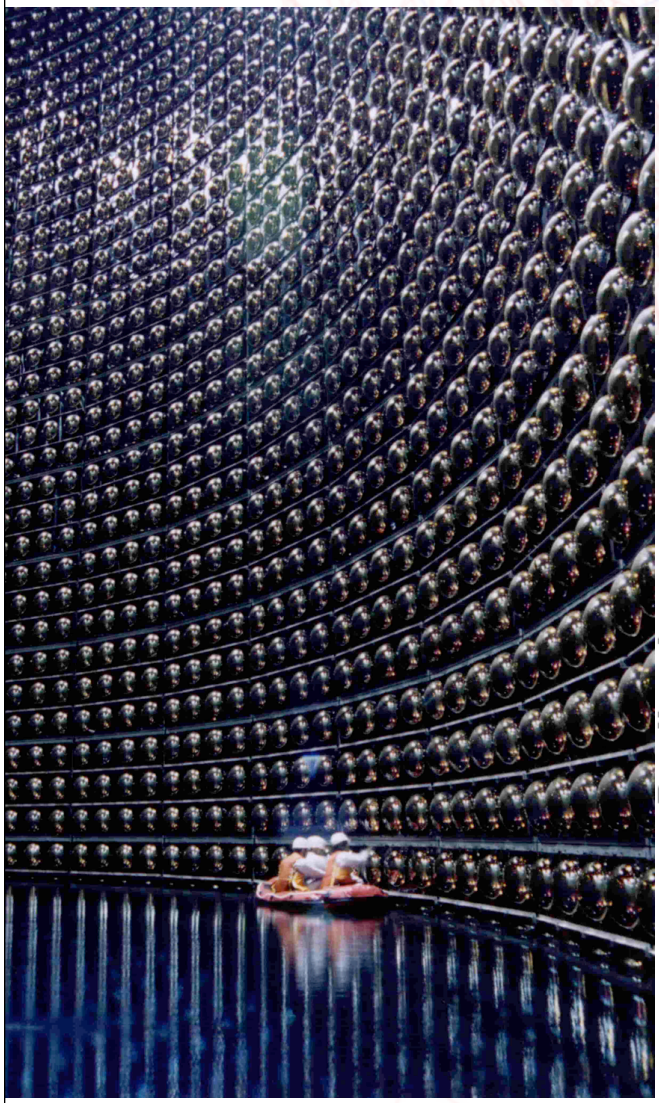
2006-
High statistics examination of anisotropy with a surface detector



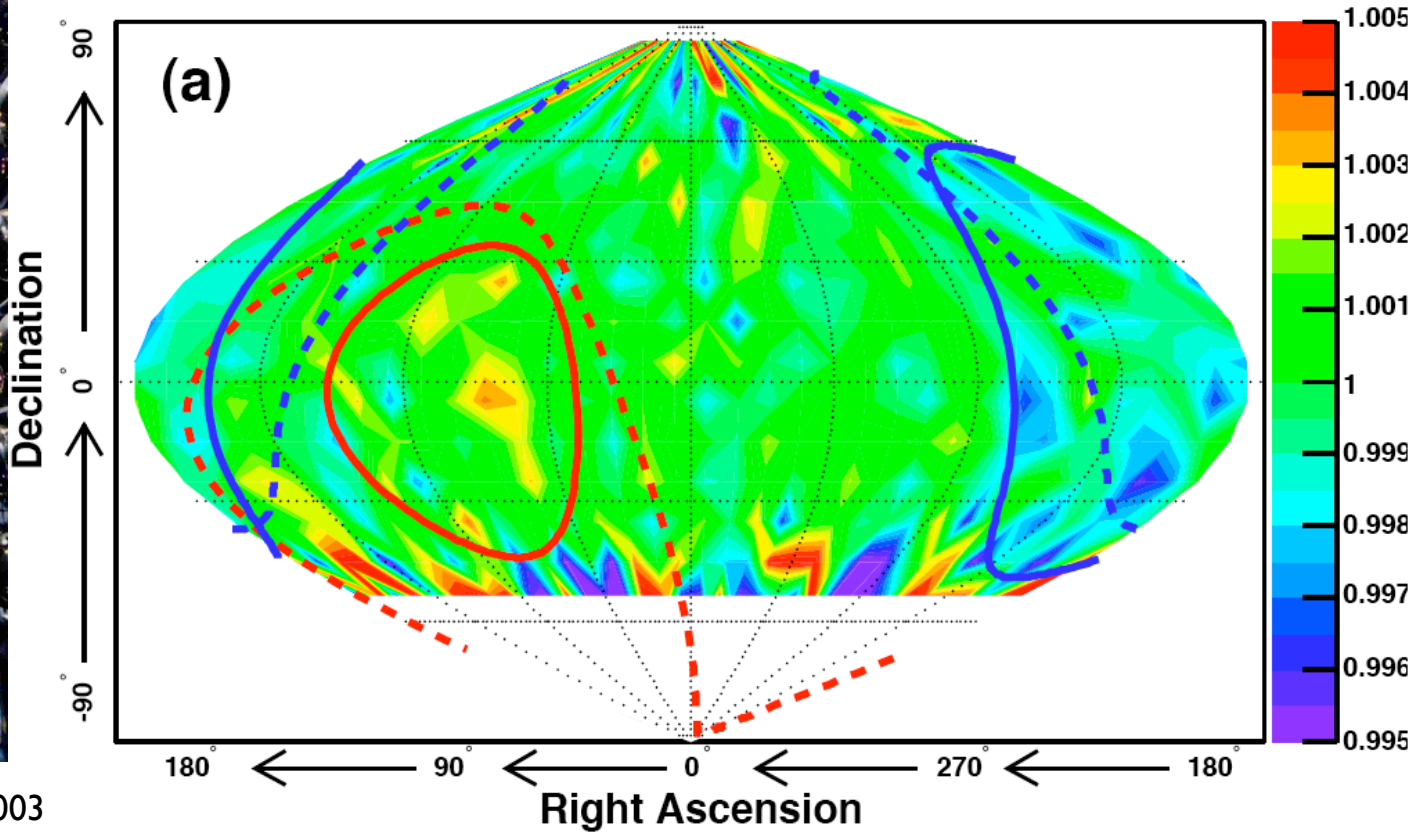


M. Amenomori, *et al.* *Science* ***314***, *439 (2006)*

Super-K neutrino detector



Observe neutrino secondaries from CR air showers



Guillian et al,Phys.Rev. D75 (2007) 062003

2 Approaches to CR anisotropy

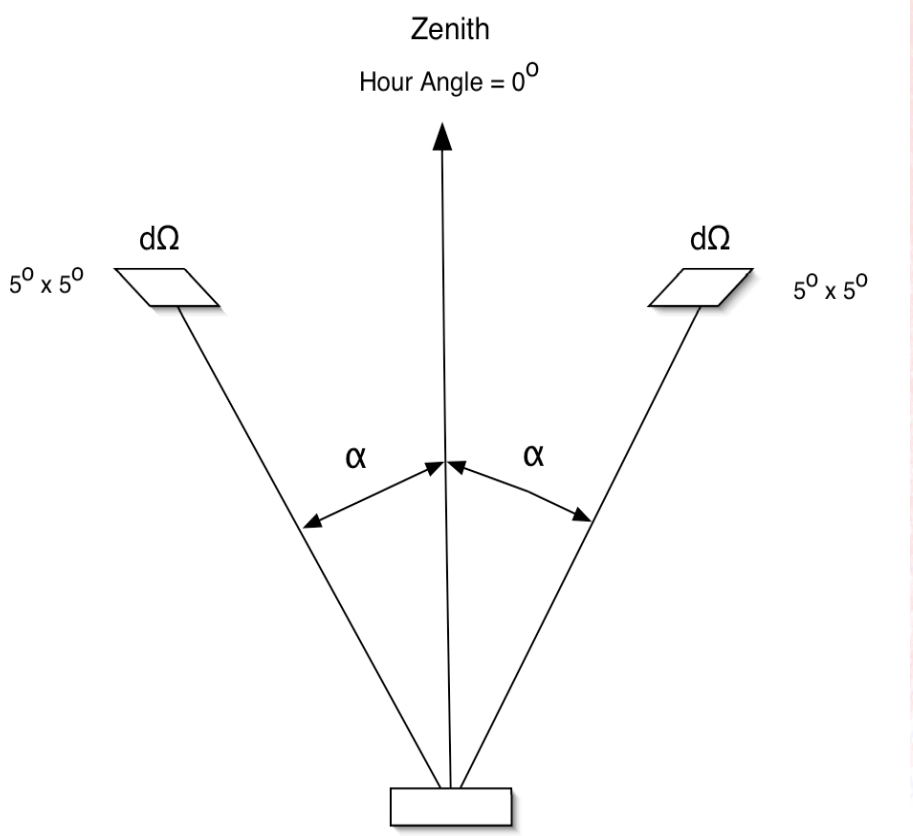
1) Forward backward asymmetry method to study "large scale anisotropy".

Derive shape of large scale features.

2) "Direct Integration" background subtraction to study "intermediate scale anisotropy".

Background derived from vicinity of source. High pass filter.

Search for Large scale anisotropy



Systematic effects can be large

Day/night variation

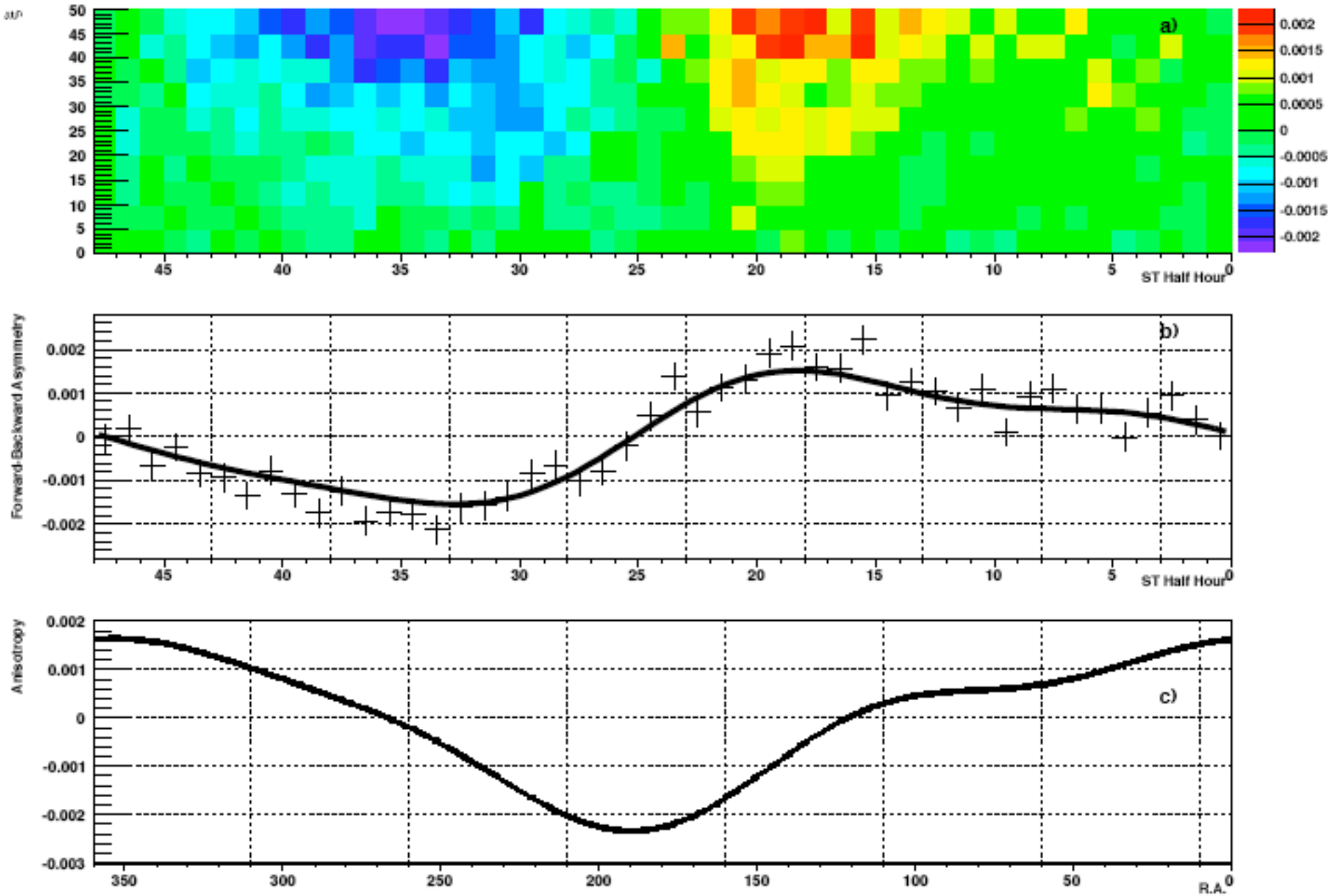
Seasonal variation

Forward-backward asymmetry technique

Declination strips (5 degrees)

$$FBAsymmetry(\theta,\alpha) = \frac{R(\theta+\alpha) - R(\theta-\alpha)}{R(\theta+\alpha) + R(\theta-\alpha)}$$

7 years of data
95 billion events in sample
6 TeV median proton energy

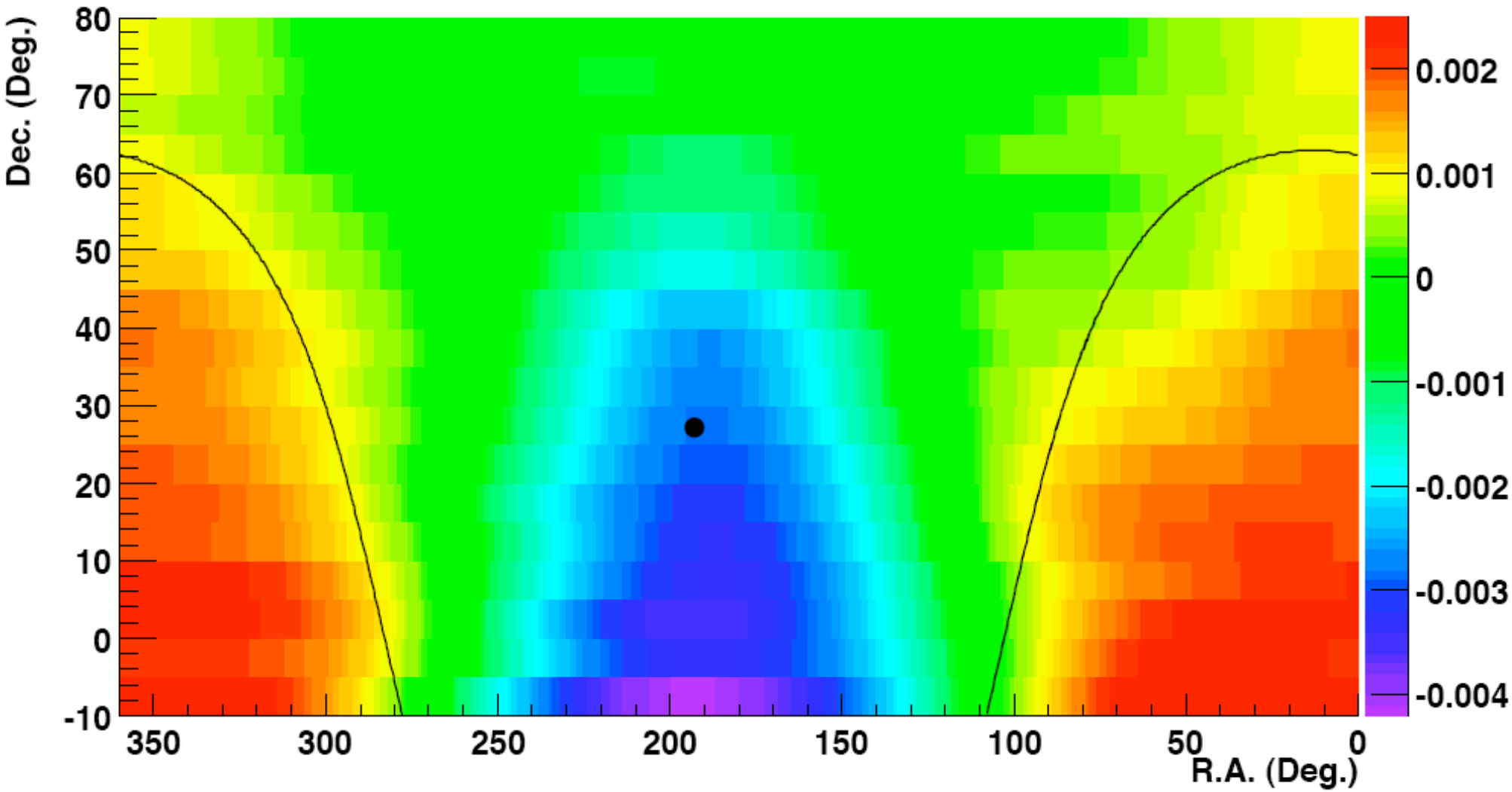

a)
ST Half Hour
b)
Forward-Backward Asymmetry
ST Half Hour
c)
Anisotropy
R.A.

Sky Map of CR large scale anisotropy

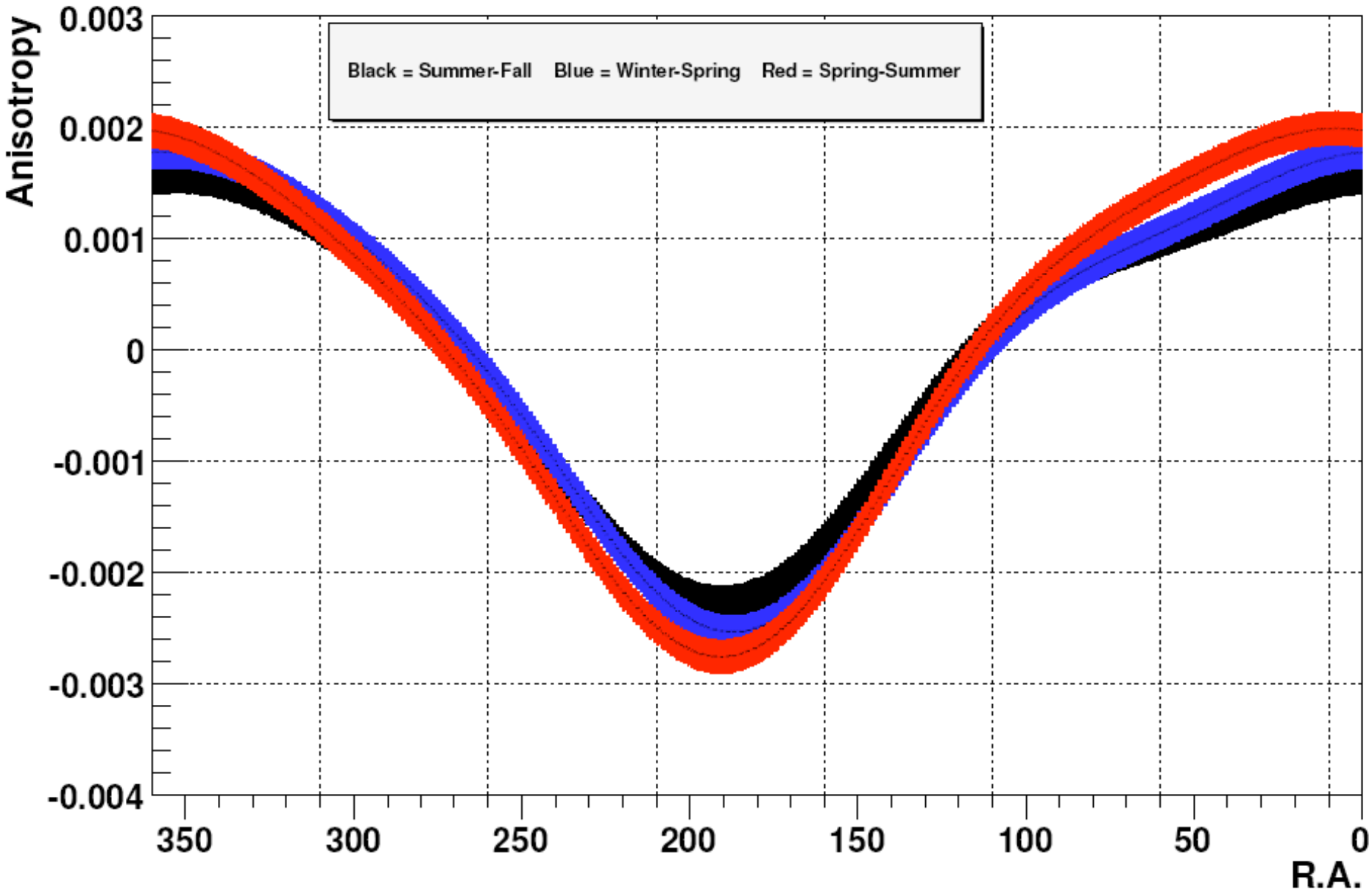
(Declination strips are not correlated)

Range of variation ~5×10^{-3}

consistent with Tibet results



Seasonal Variation



Background Estimation

Background estimation confined to local declination strip.

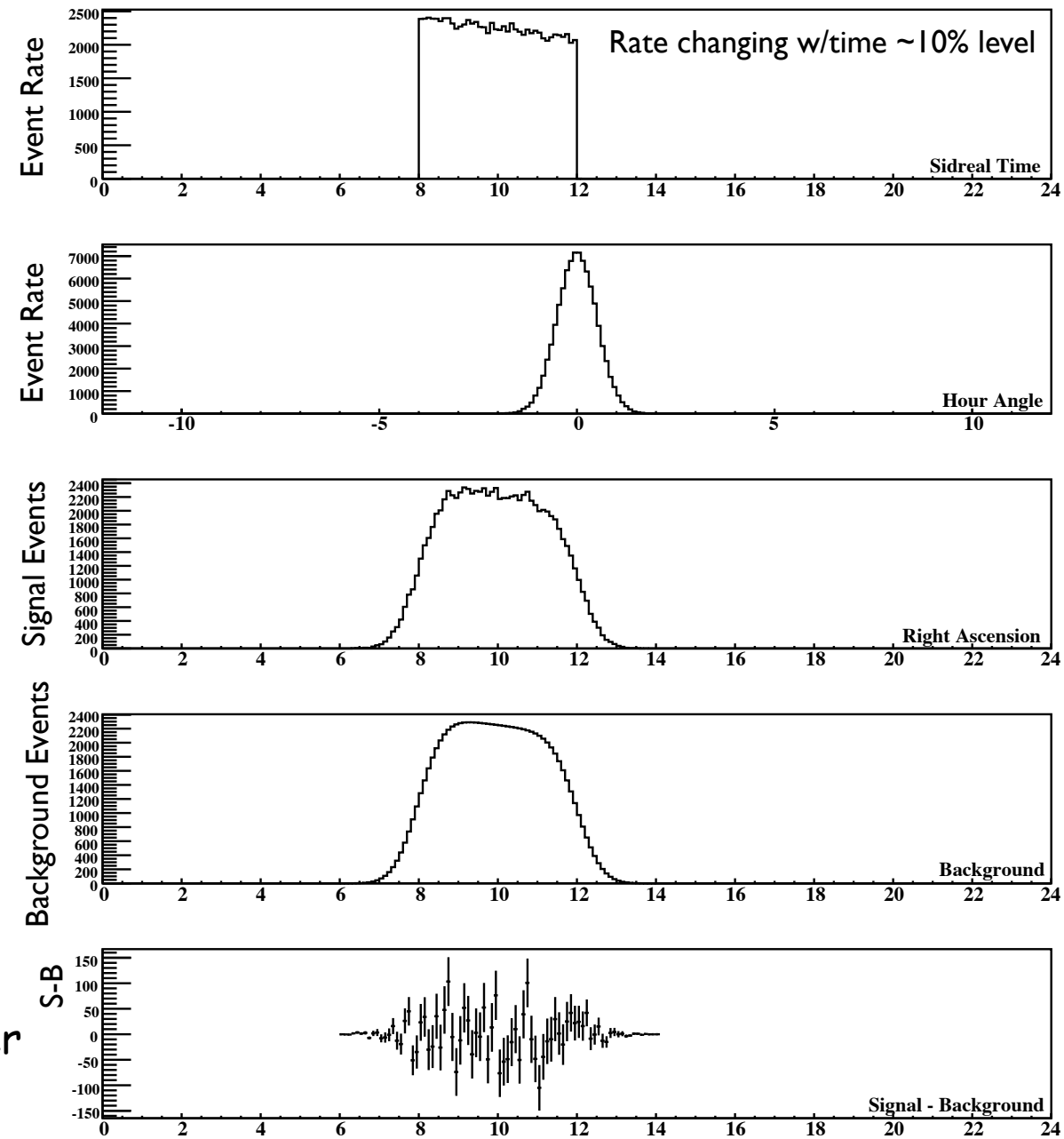
Method used to estimate background for gamma-ray source analysis.

Assume: Local coordinate distribution is stable on short time scale.

Need not assume that the rate is constant in time.

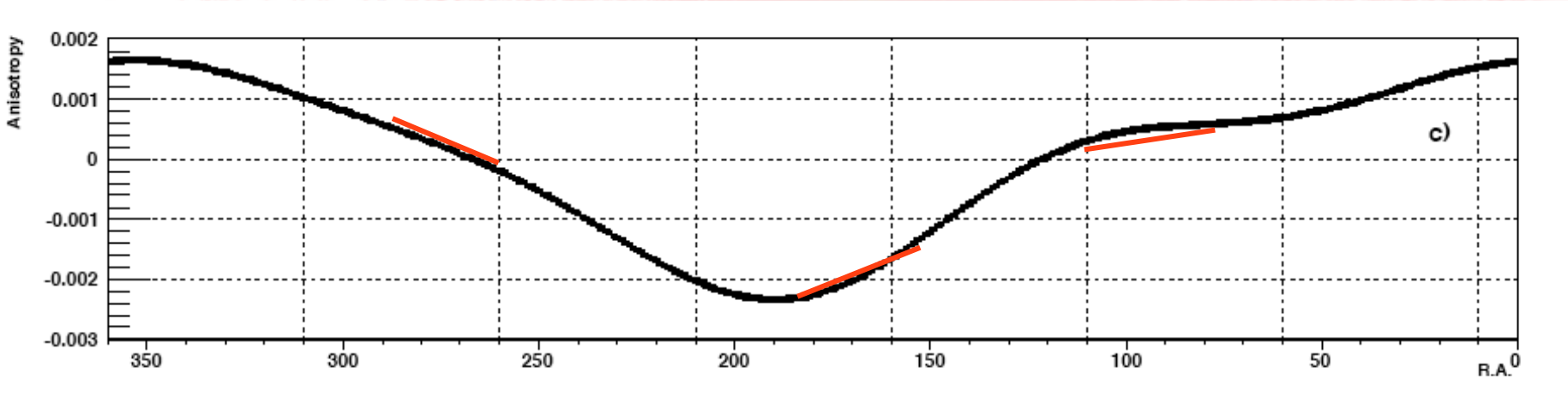
Integration time is 30° (2hr)

Effectively this is a High-Pass filter



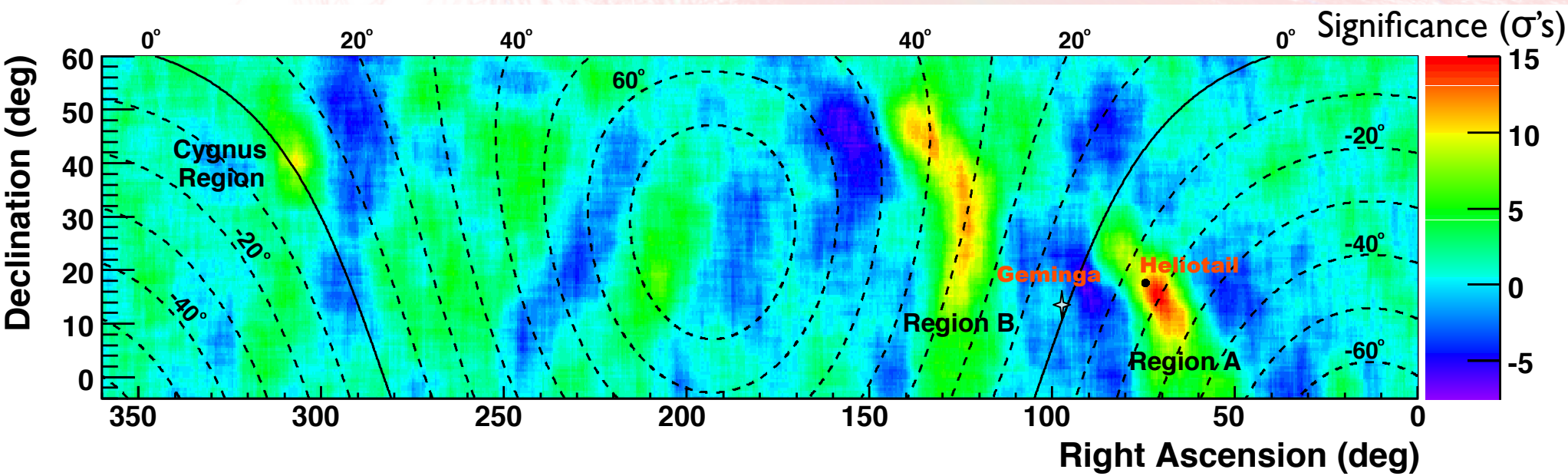
Suppression of large scale features

2hr background interval



- Anisotropy on the 5-10 degree scale.
- Peak excess ~7 x 10^{-4} (much smaller than the LSA)

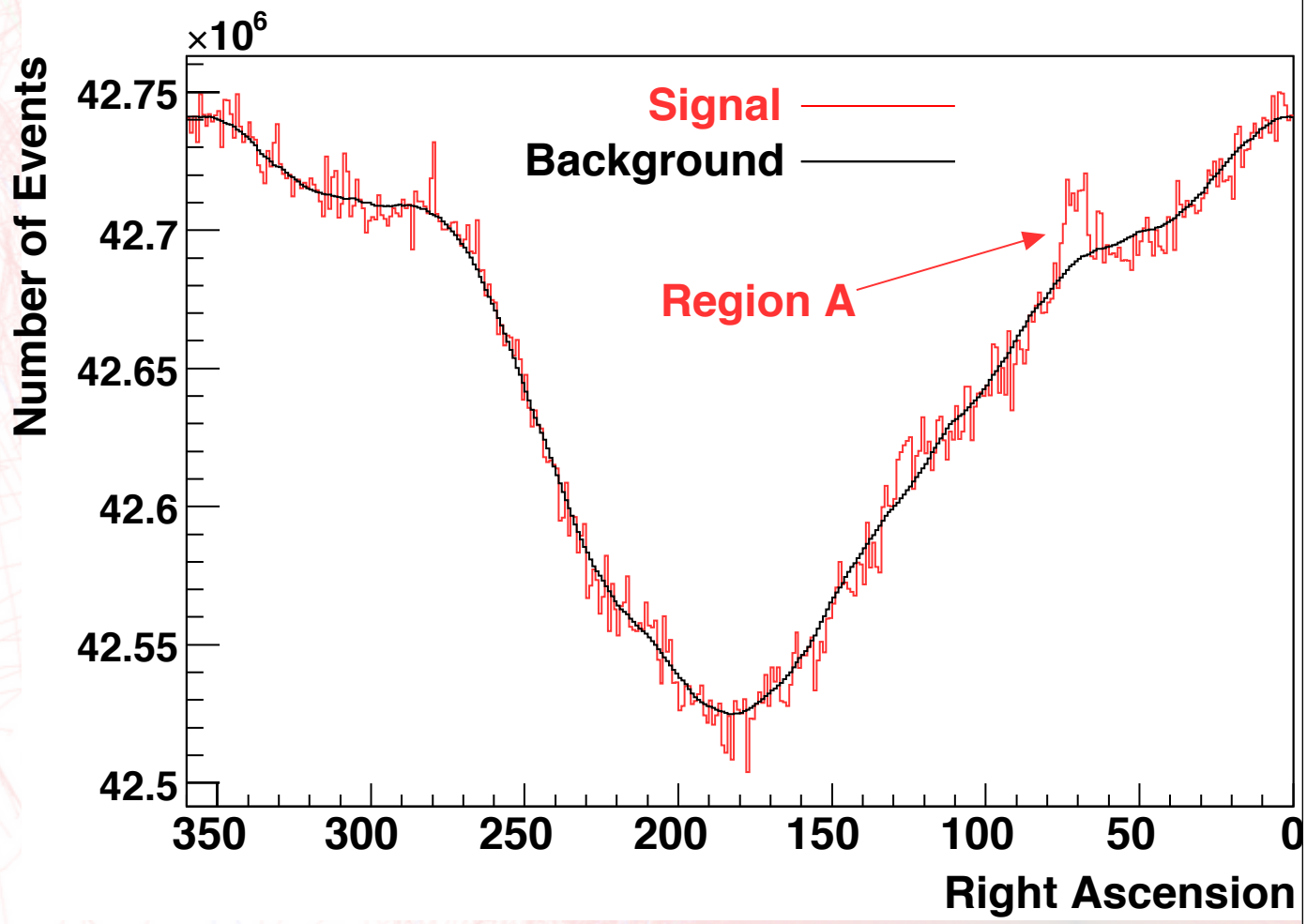
- Explanations are difficult because the gyro-radius of a 10 TeV proton in a 1 μG field is 0.01 parsecs=2000 AU



No Background Subtraction

RA strip for Dec range 10°-20

Large scale structure due to exposure variation + LSA



- Milagro can separate gamma-ray and hadron induced events through the presence of large depositions in the bottom layer.

- Region A:

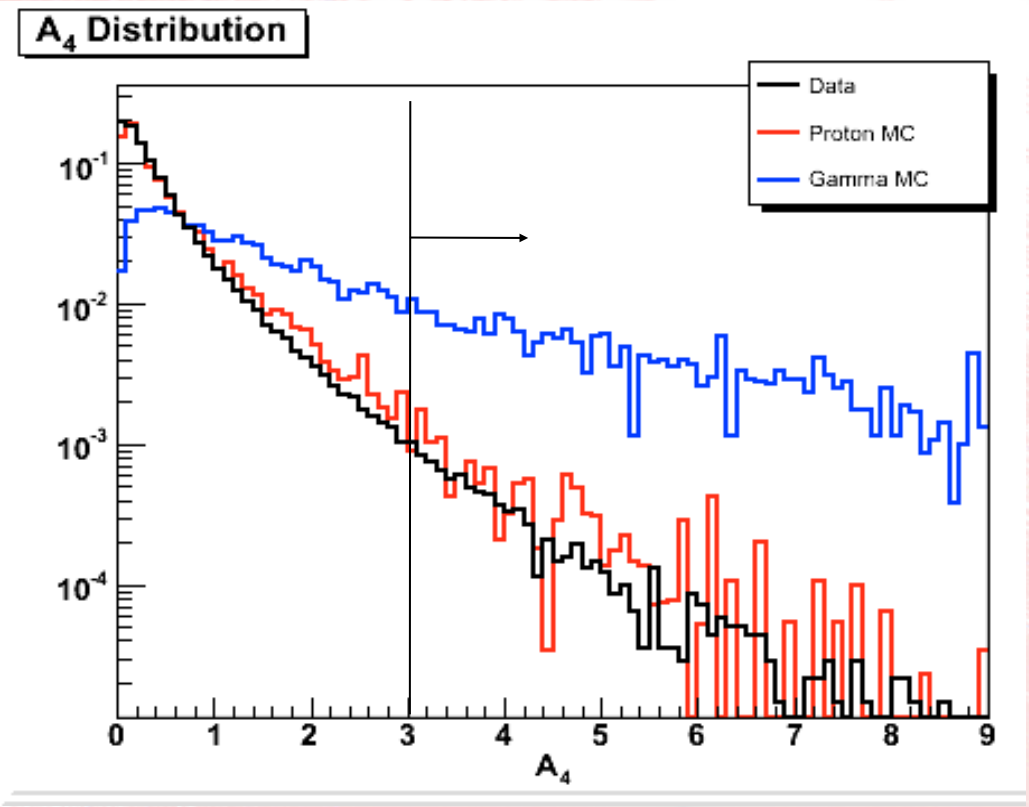
  χ^2(hadron) = 10.3/16 dof

  χ^2(gamma) = 124.0/16 dof

- Region B:

  χ^2(hadron) = 19.0/16 dof

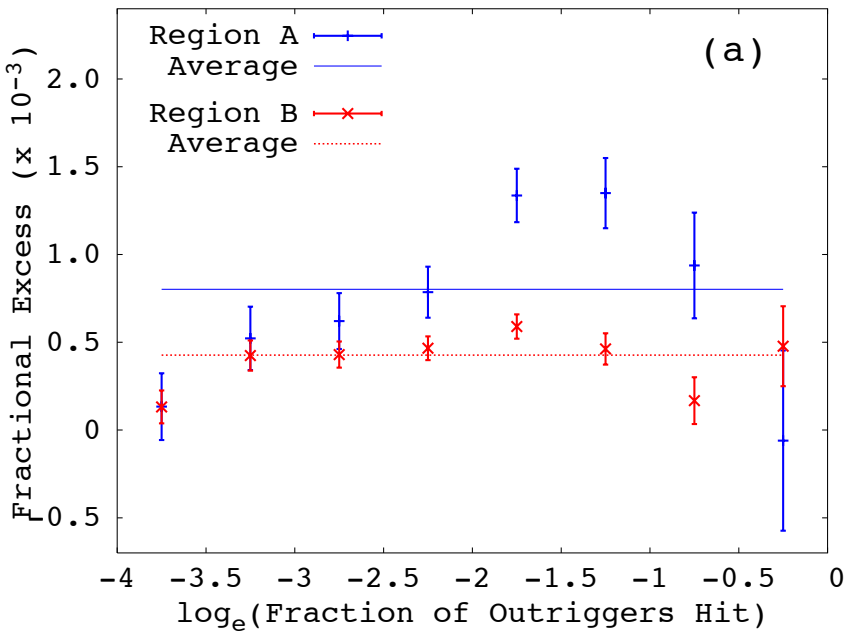
  χ^2(gamma) = 84.8/16 dof

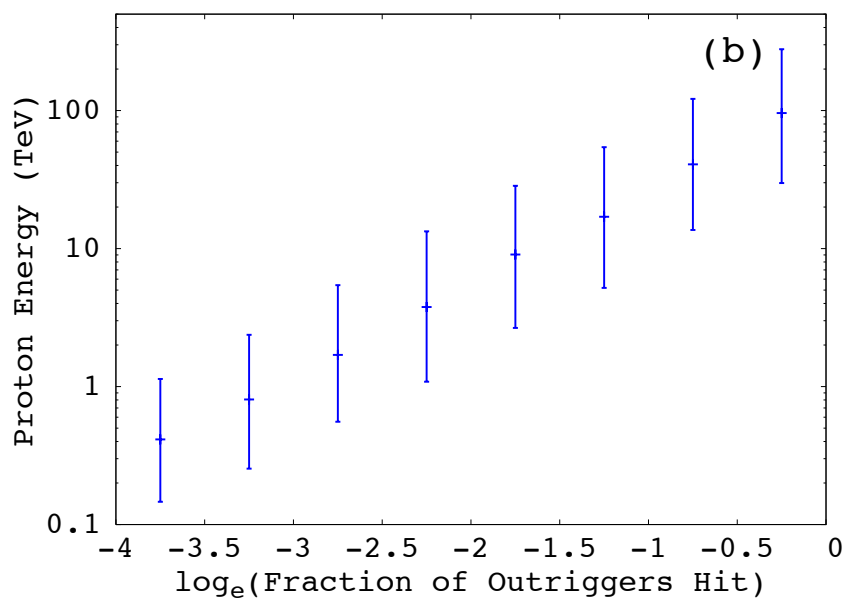


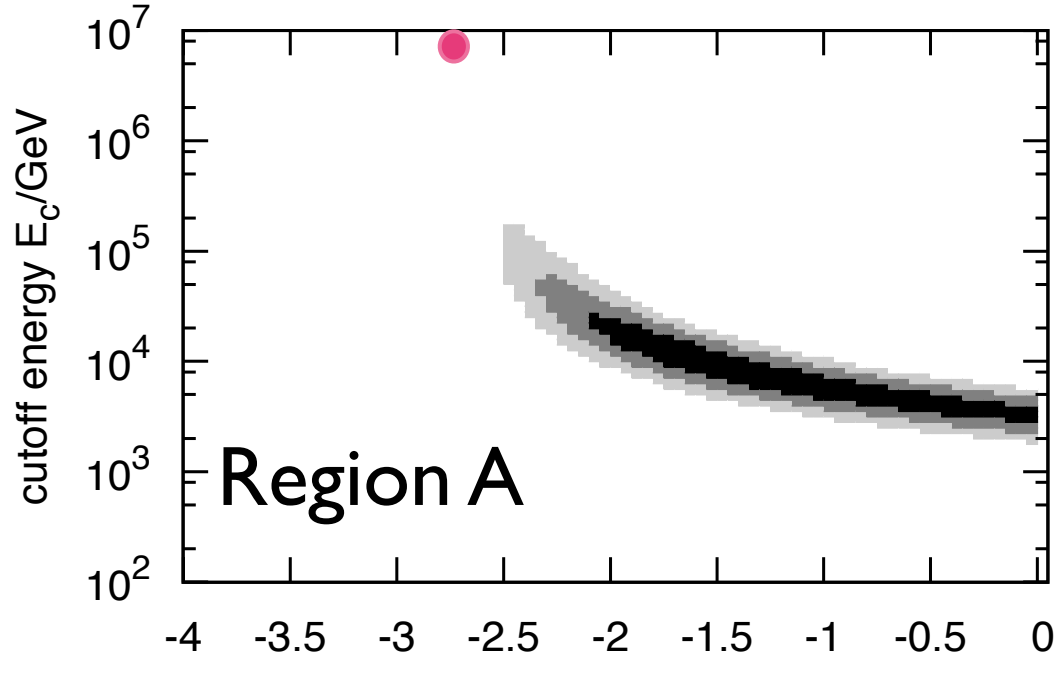
$$A_4 = \frac{(fTop + fOut) * nFit}{mxPE}$$

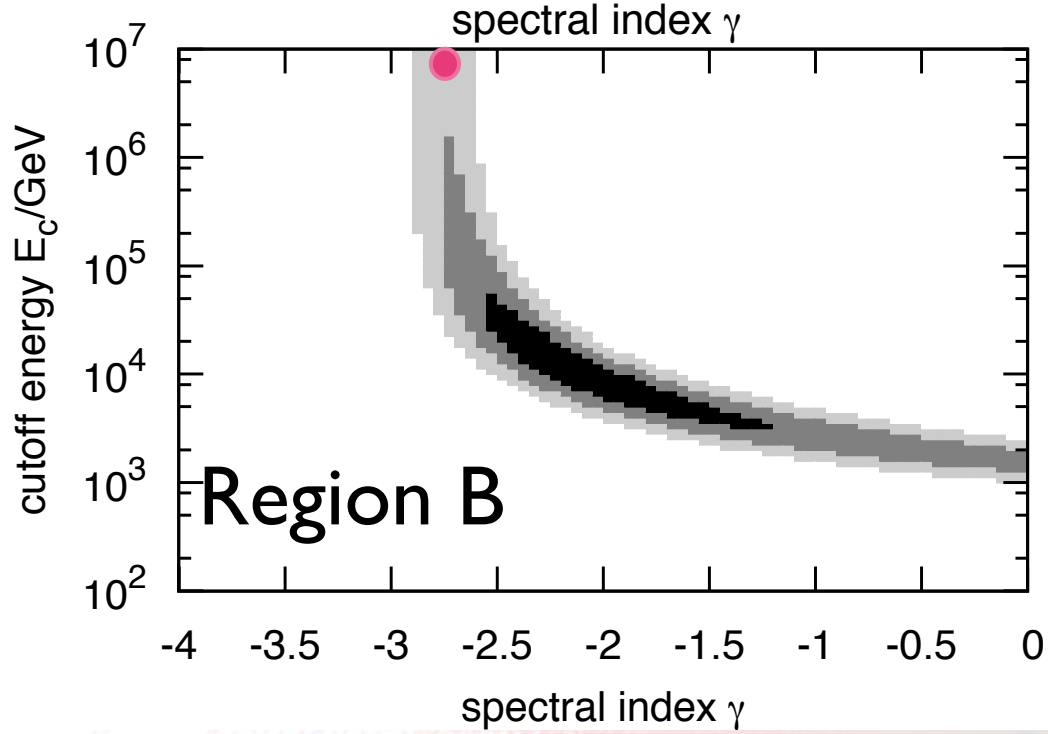
mxPE:	maximum # PEs in bottom layer PMT
fTop:	fraction of hit PMTs in Top layer
fOut:	fraction of hit PMTs in Outriggers
nFit:	# PMTs used in the angle reconstruction

Spectral fit to excess

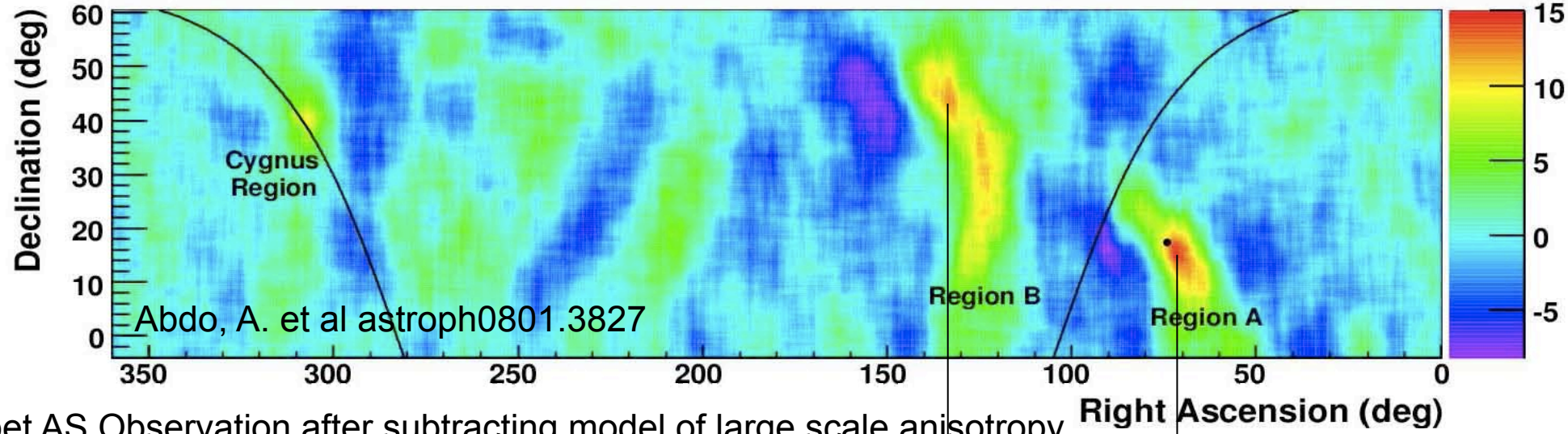




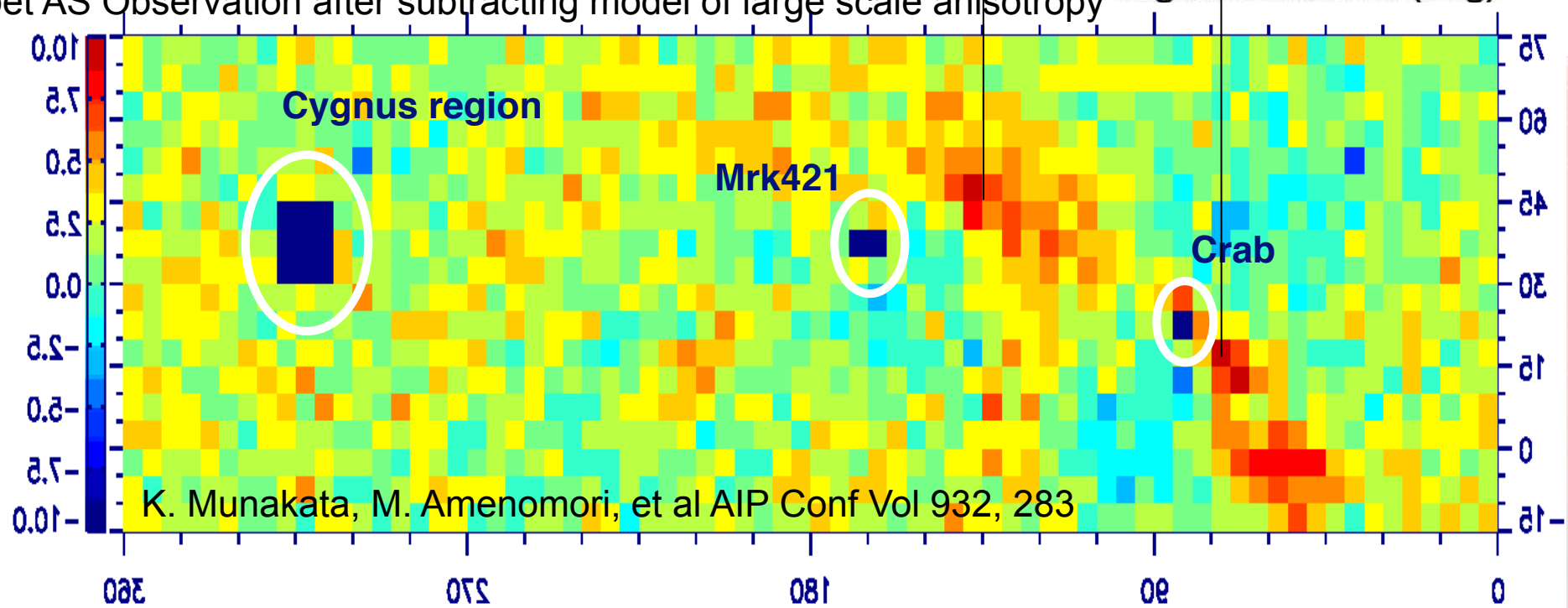




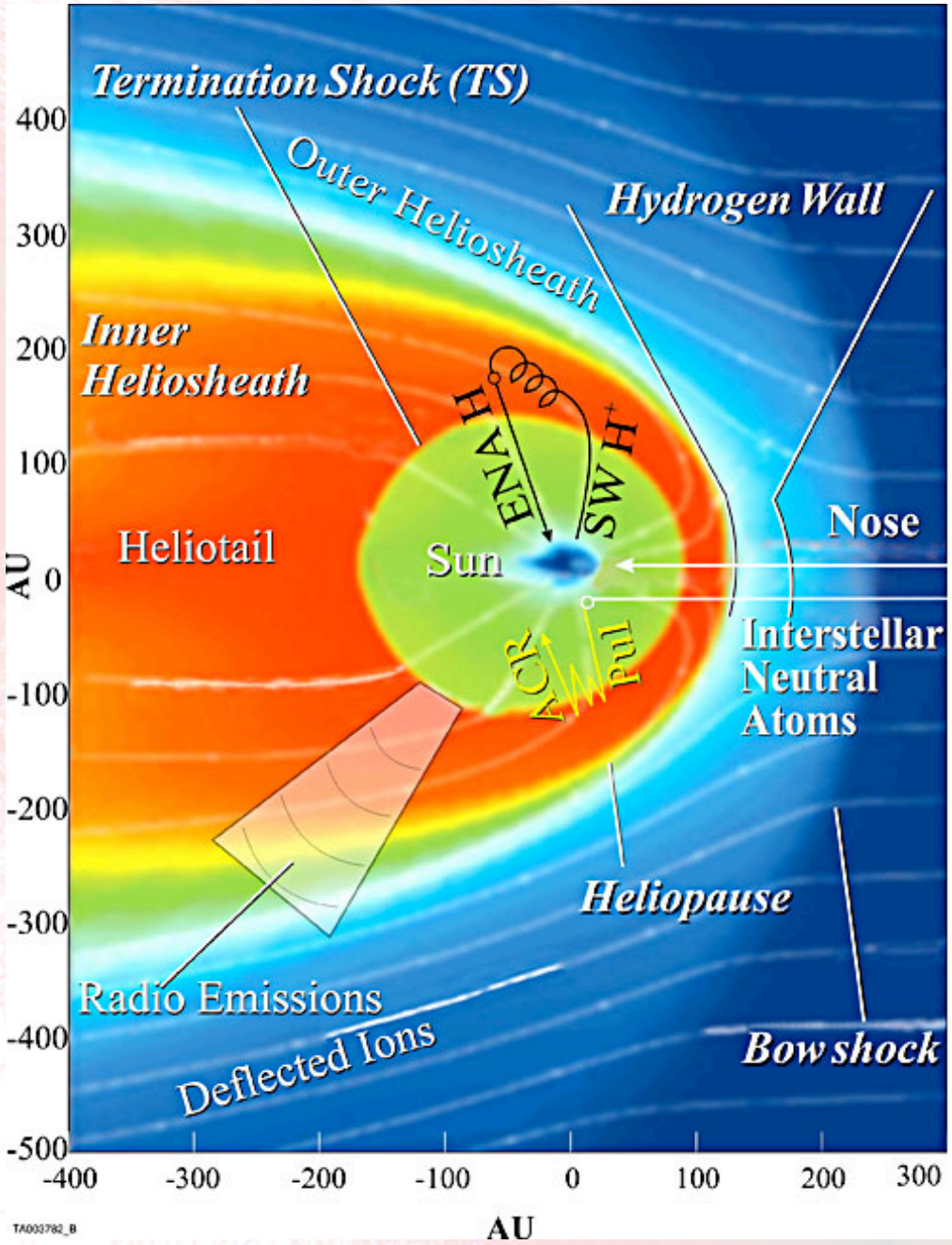
Milagro Observation using Background Calculation over 2 hour (30° in RA) intervals



Tibet AS Observation after subtracting model of large scale anisotropy



Helio-Tail


Termination Shock (TS)
Outer Heliosheath
Hydrogen Wall
Inner Heliosheath
Heliotail
Sun
ENA H
SW H+
Nose
Interstellar Neutral Atoms
ACR
Pul
Heliopause
Radio Emissions
Deflected Ions
Bow shock
400
300
200
100
0
-100
-200
-300
-400
-500
AU
-400
-300
-200
-100
0
100
200
300
AU
TA003782_B

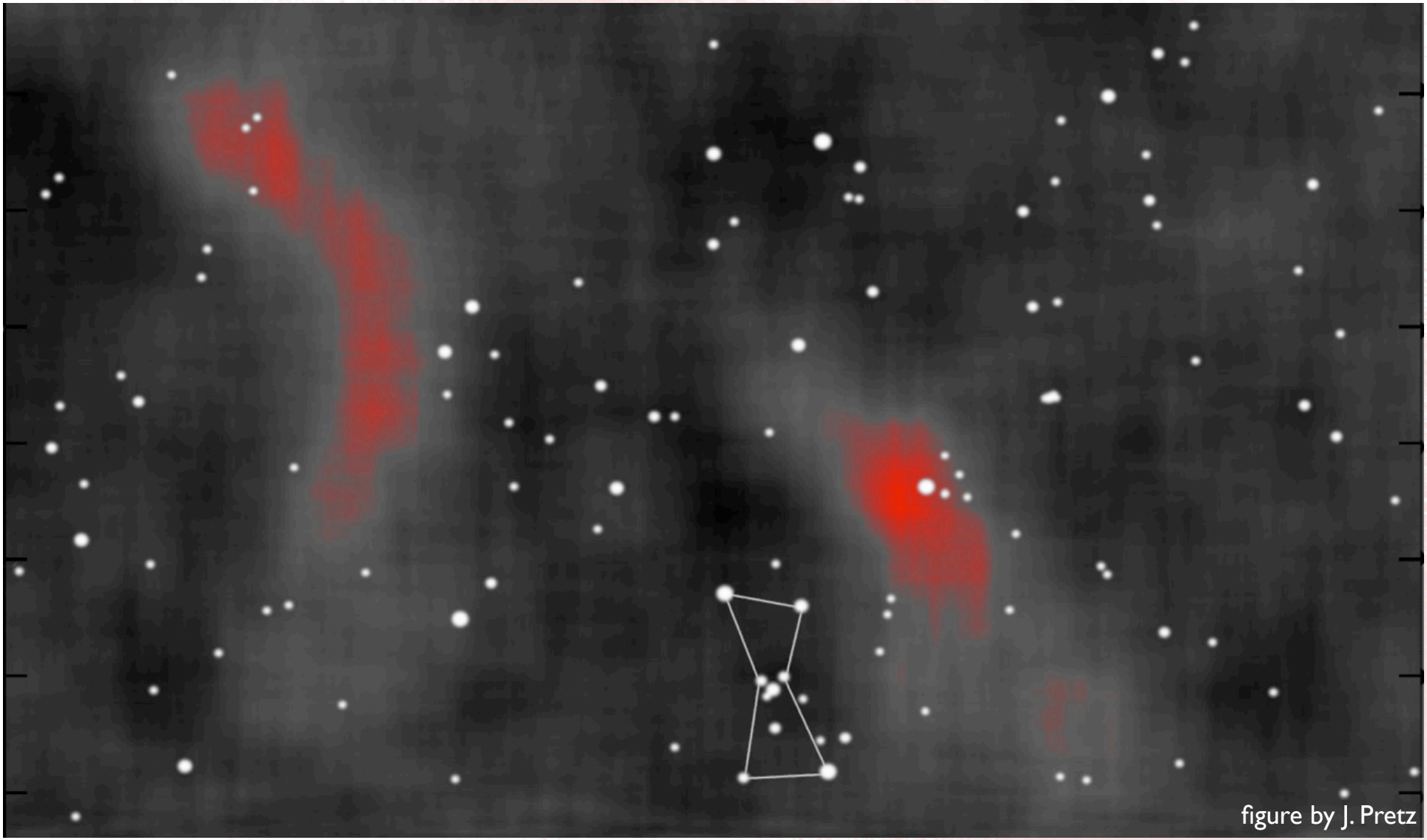
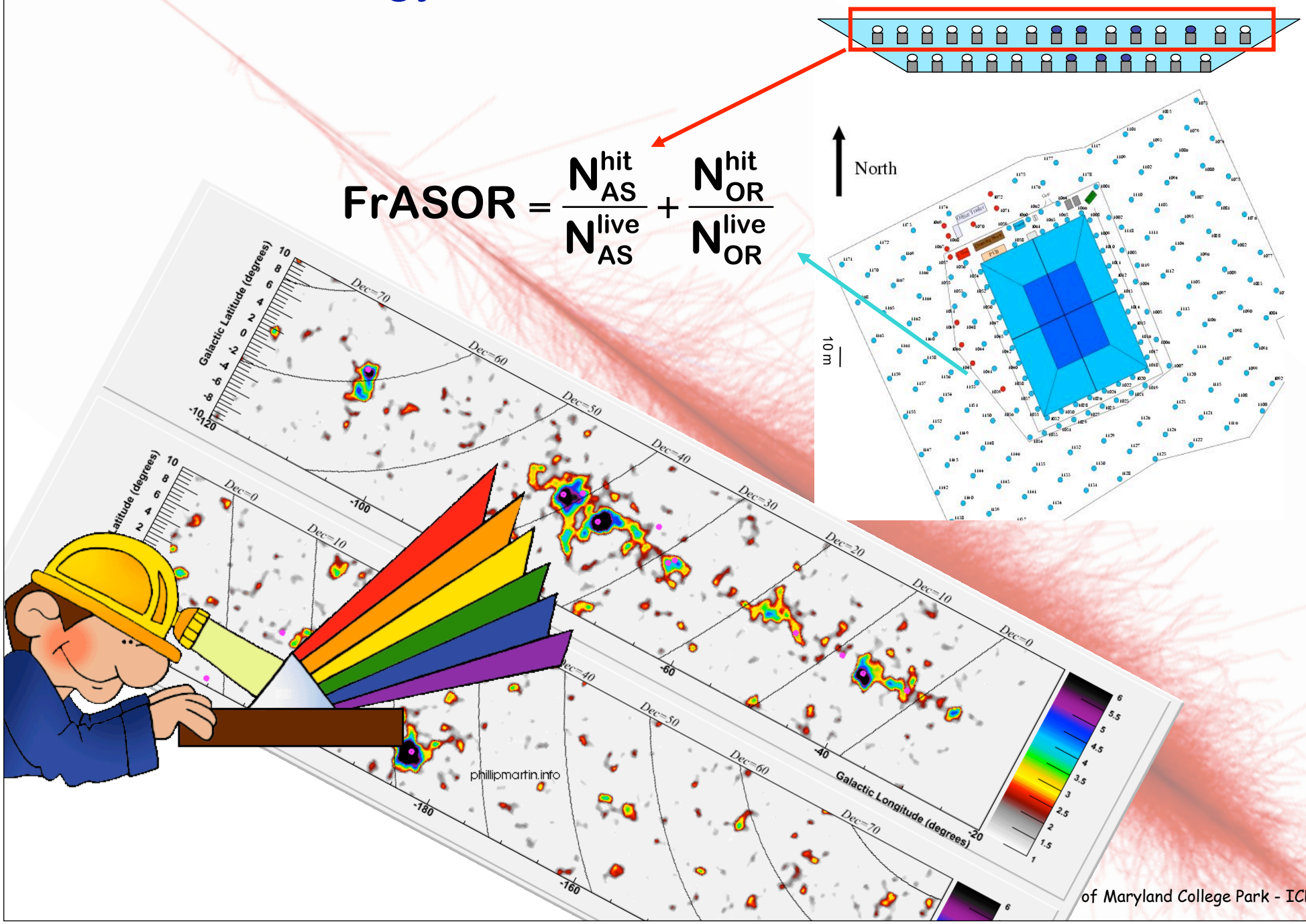


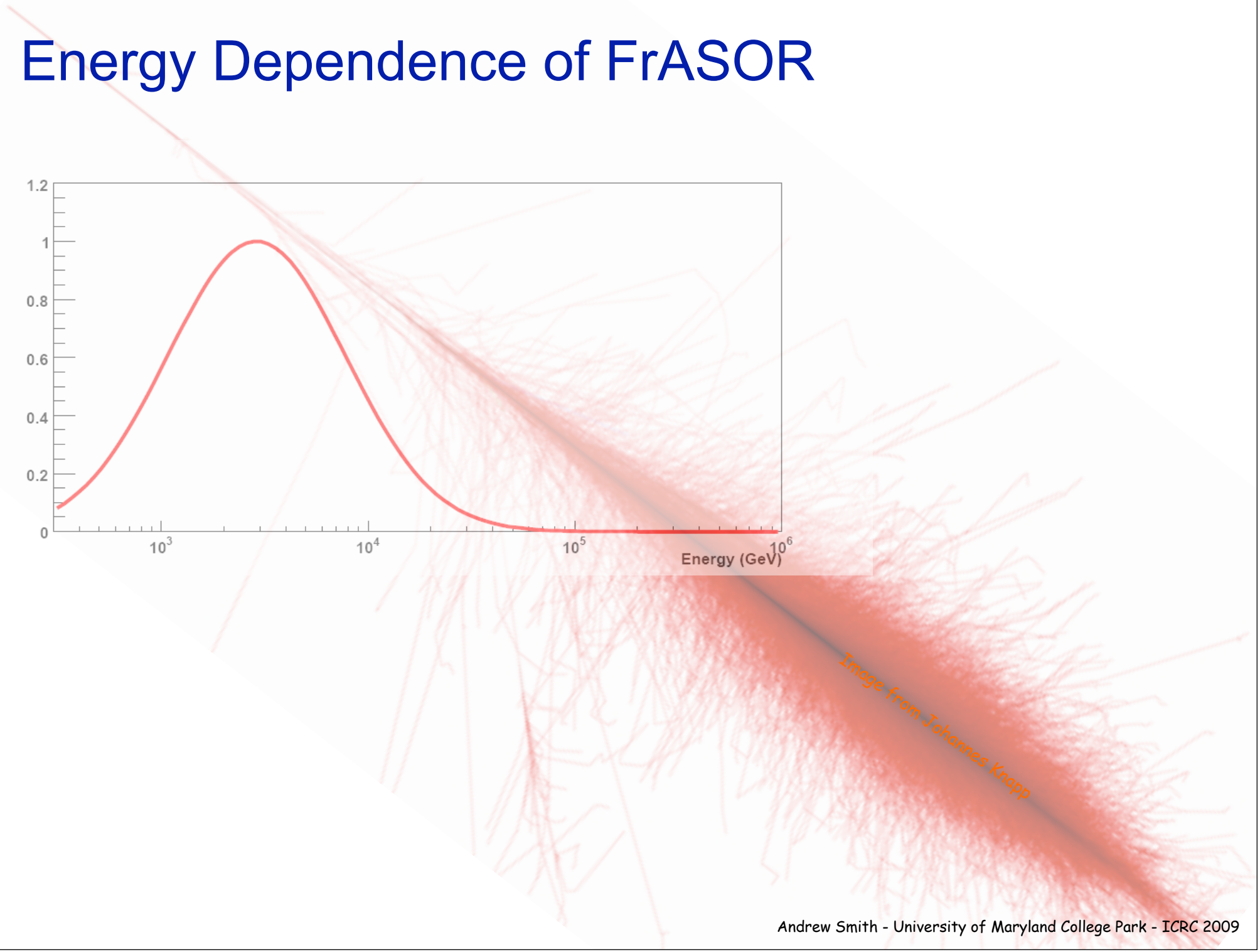
figure by J. Pretz

Energy Parameter

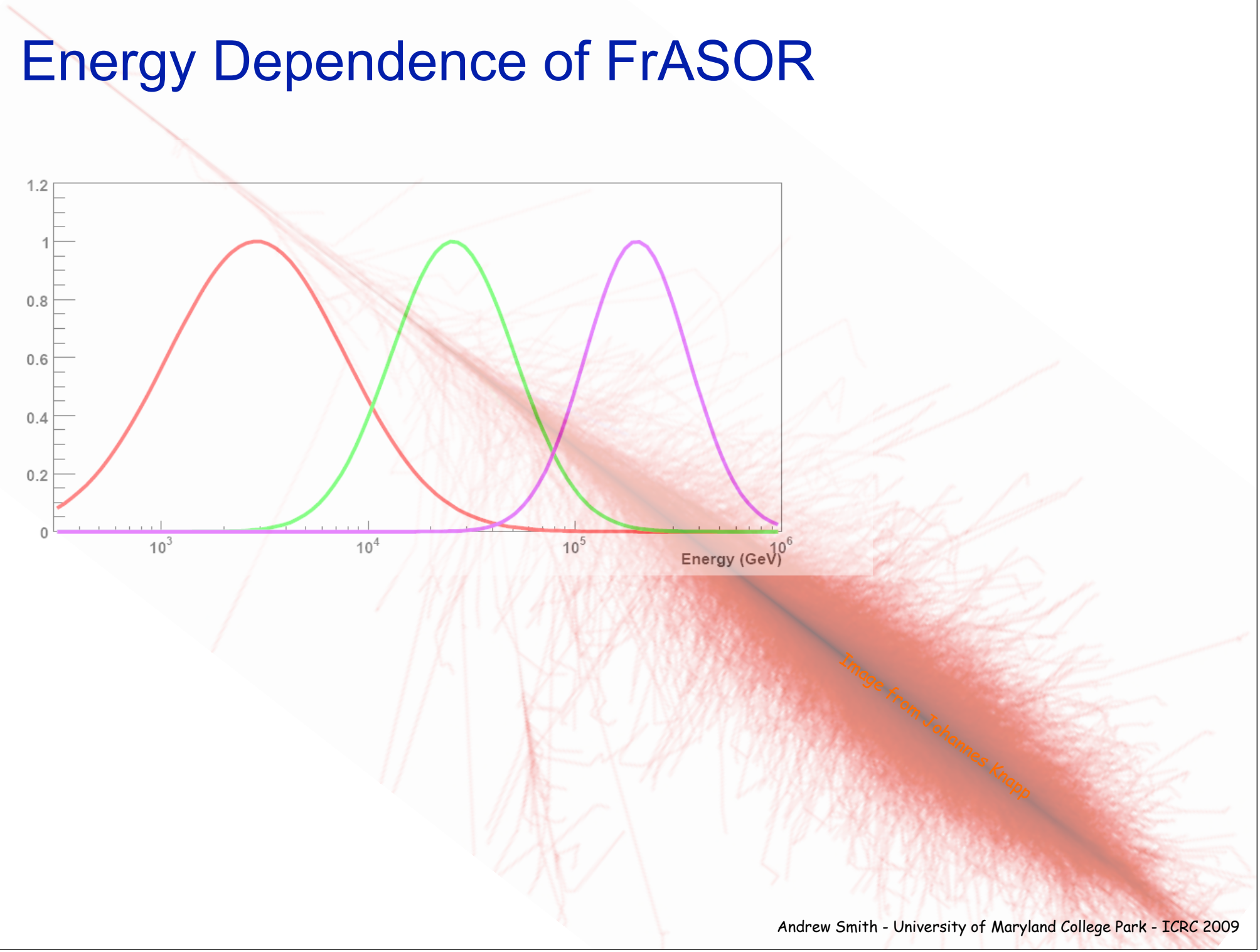
$$\mathbf{FrASOR} = \frac{N_{AS}^{hit}}{N_{AS}^{live}} + \frac{N_{OR}^{hit}}{N_{OR}^{live}}$$



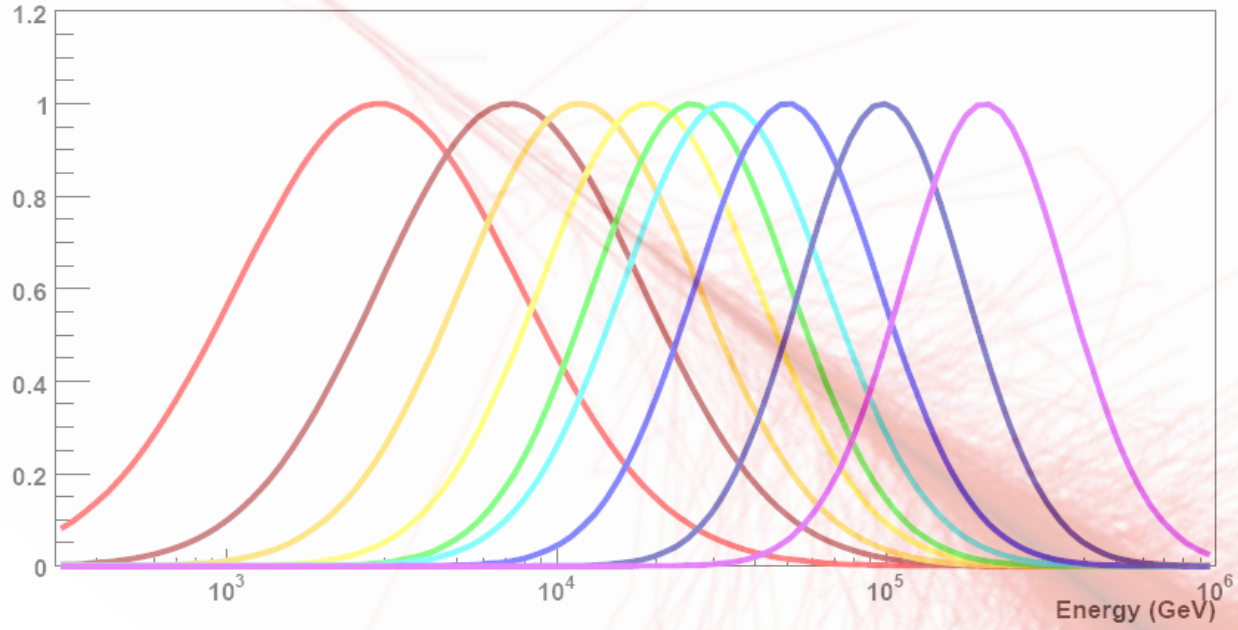
Energy Dependence of FrASOR

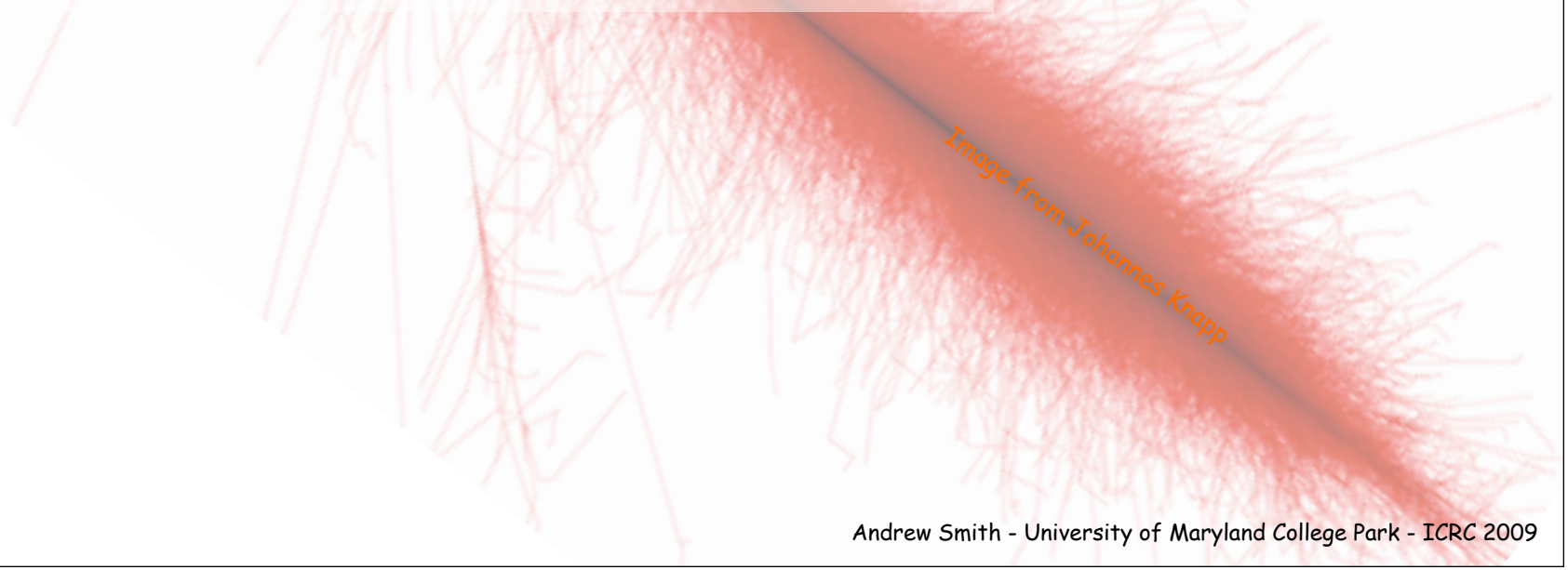


Energy Dependence of FrASOR



Energy Dependence of FrASOR





About the data....

- Milagro collected data from 2000 to 2008
- Outrigger array was completed in 2004.
- Addition of outriggers: 2x sensitivity increase
- Data is divided into 9 operational 'epochs'.
- Each epoch is simulated independently.
- Epochs 7,8,9 used in energy analysis.
- Data used in energy fits: September 2005 - March 2008.

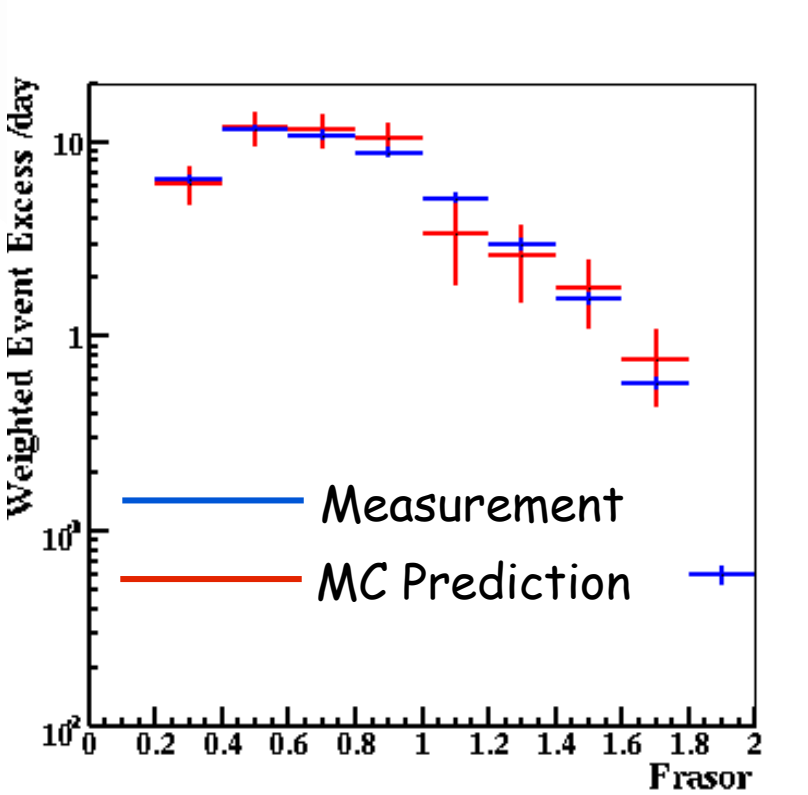
Image from Johannes Knapp

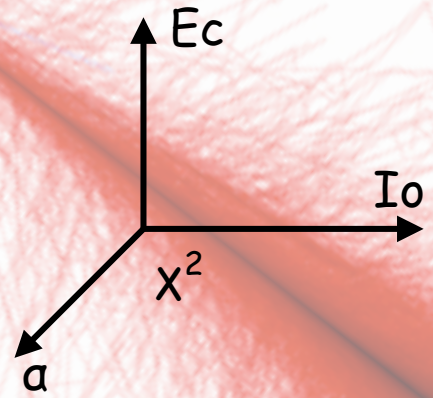
Fitting Procedure

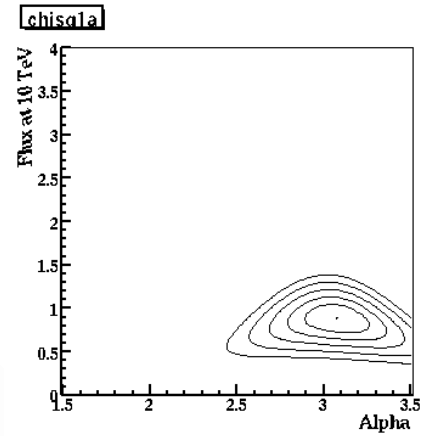
$$\text{Flux} = Io(E/TeV)^{-a}e^{-(E/Ec)}$$

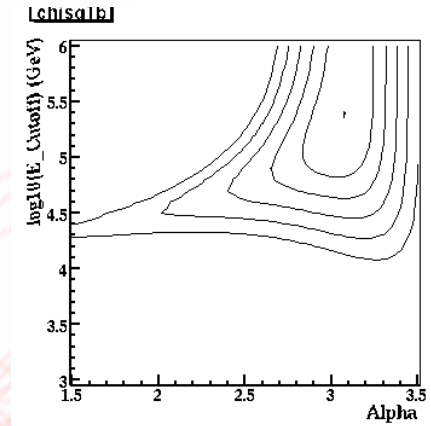
Perform fit in 'Frasor' space, not energy space.

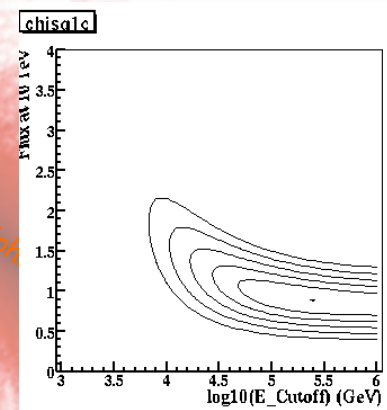
Minimize $\chi^2(Io,a,Ec) = \sum (Fr(Io,a,Ec) - Fr^{measured})^2/\sigma^2$





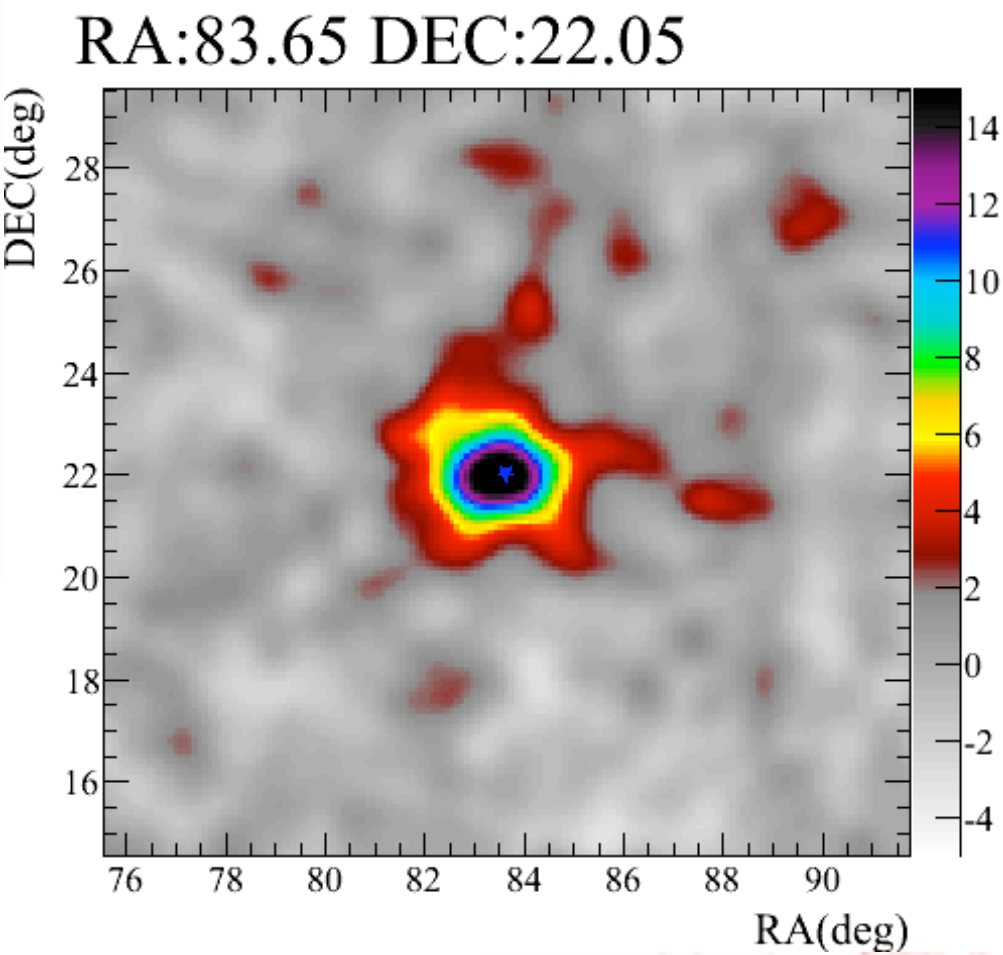


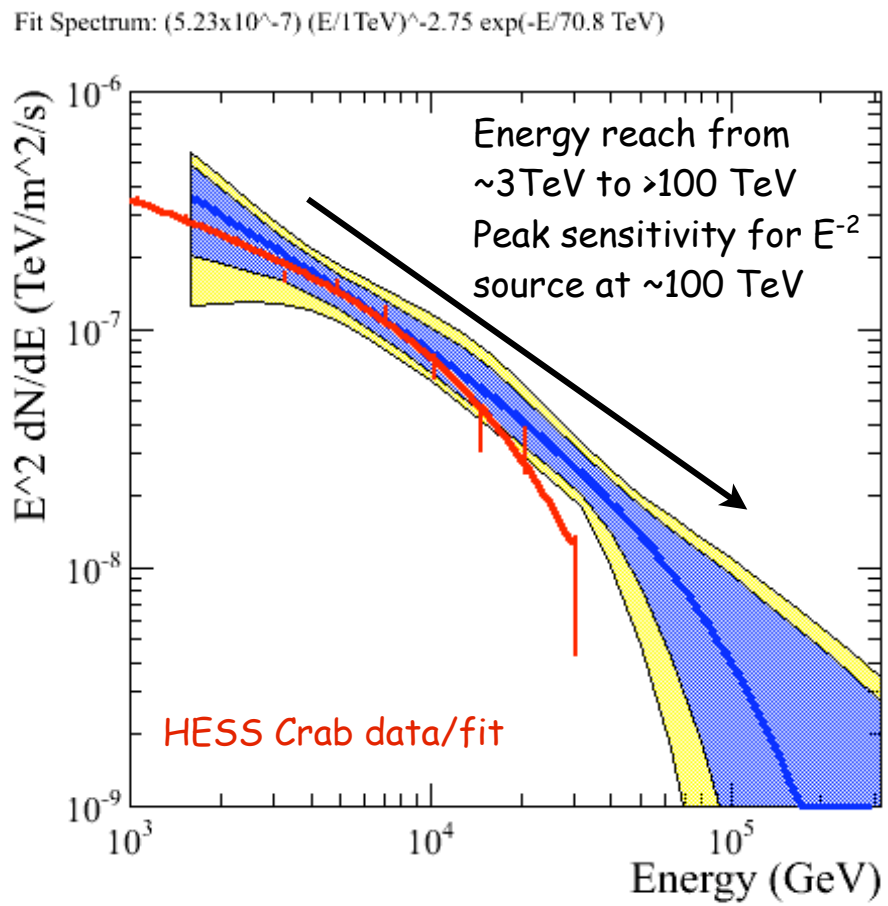




Method tested with fits to the hadronic background spectrum

Spectrum of the Crab



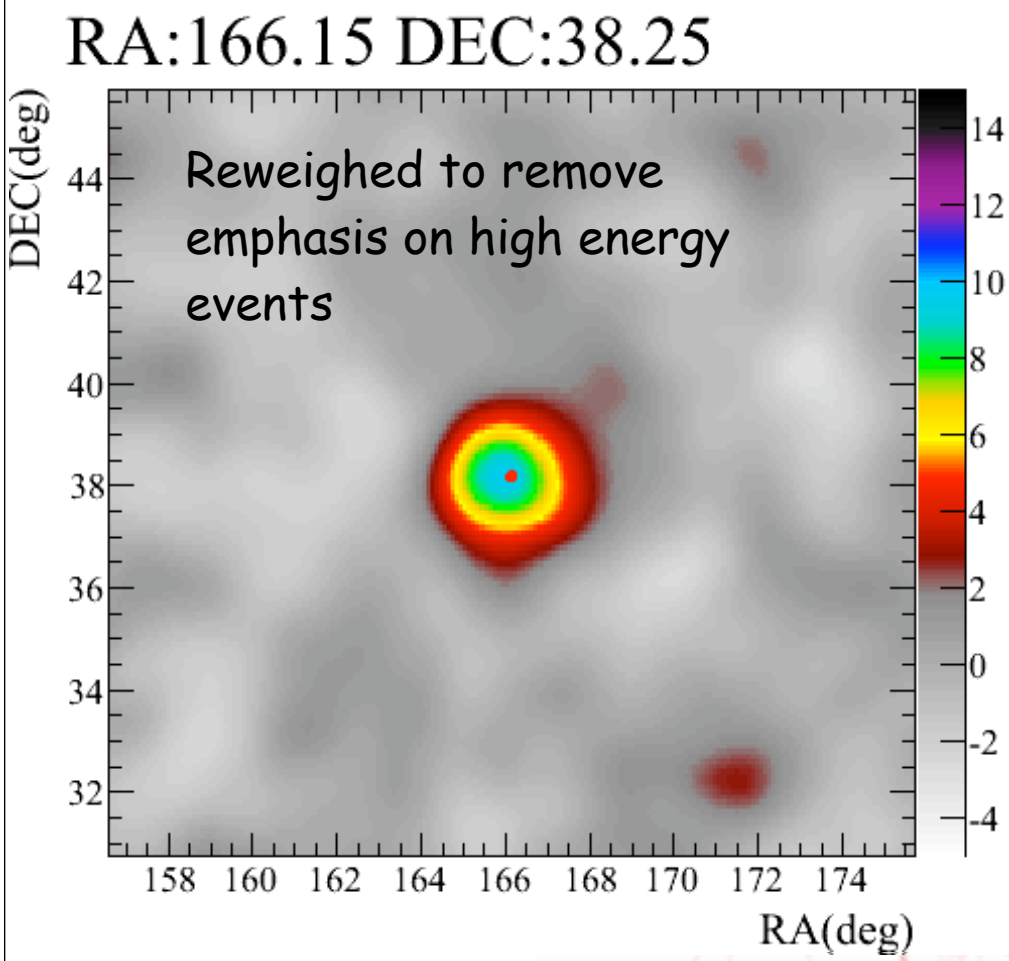


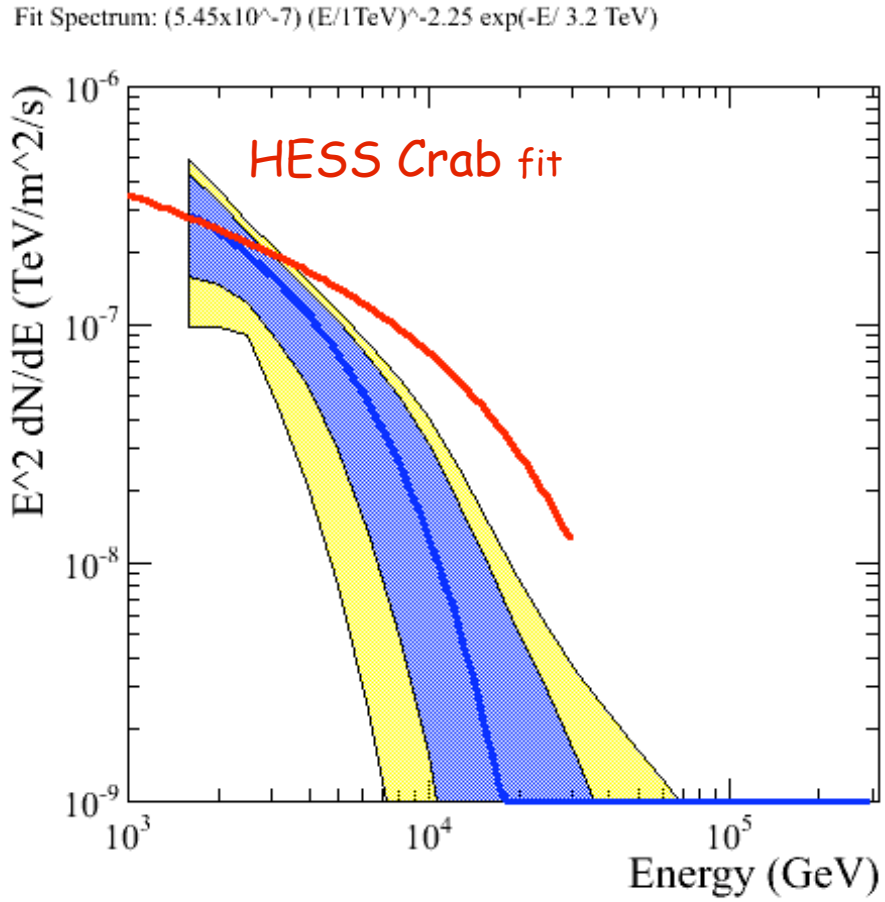
Fit Results: (no cutoff)
Io = 6.6 [5.0,8.0]x 10^{-7} /s/m^2/TeV
a = 2.95 [2.85,3.03]
χ^2 = 28.3 (25 dof)

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

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

Mrk 421

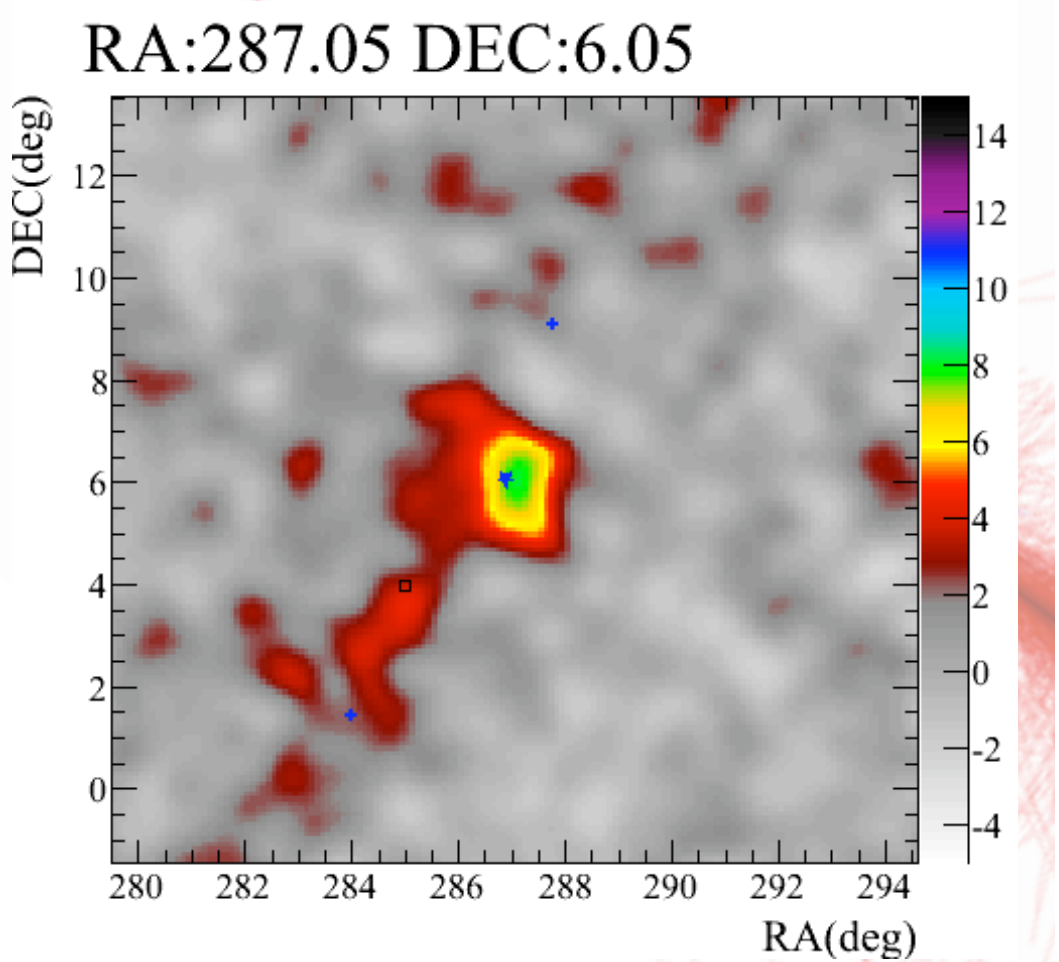


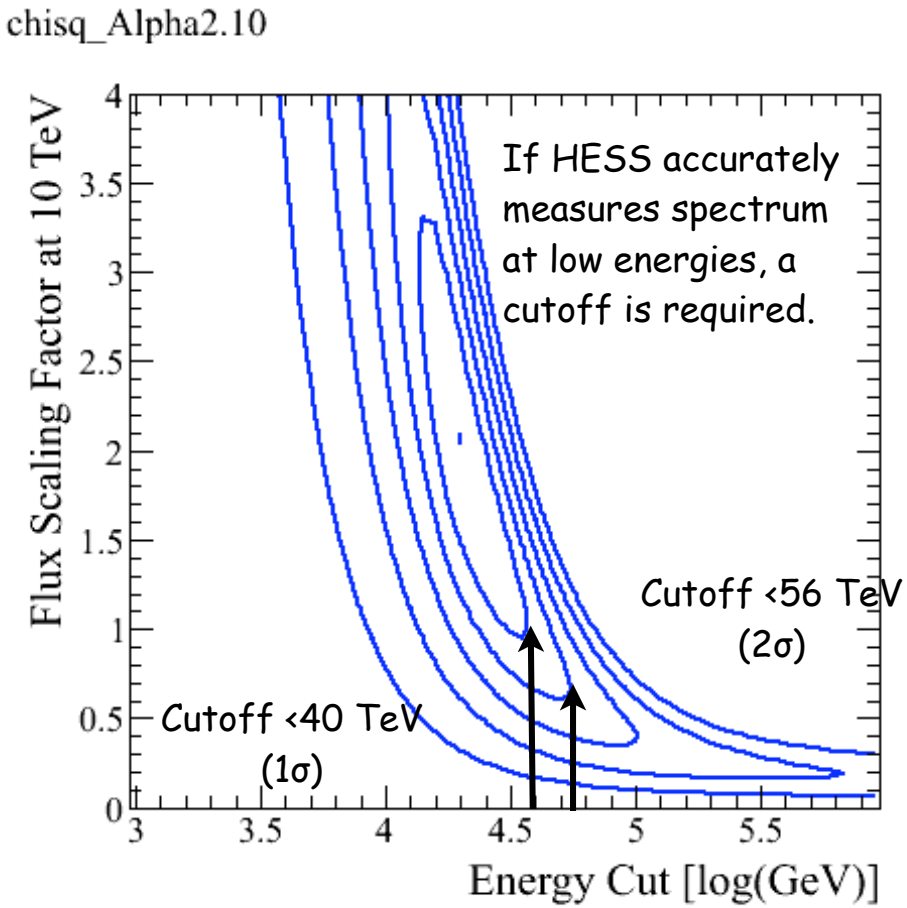


Fit Results: (3-parameter)
Io = 5.2 [1.9,14.0] x 10^{-7} /s/m^2/TeV
α = 1.90 [1.50,3.5]
Ec = 2.5 [1.4,20]
χ^2 = 33.5 (24 DOF)

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



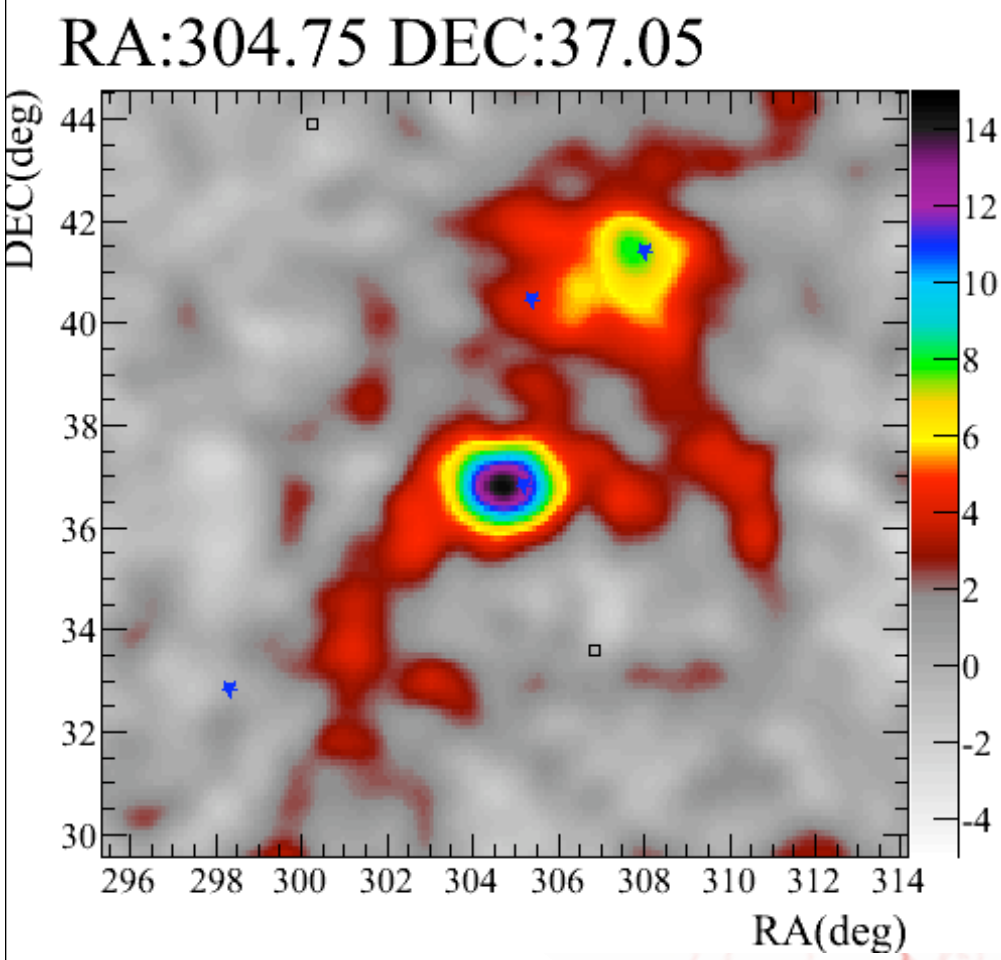


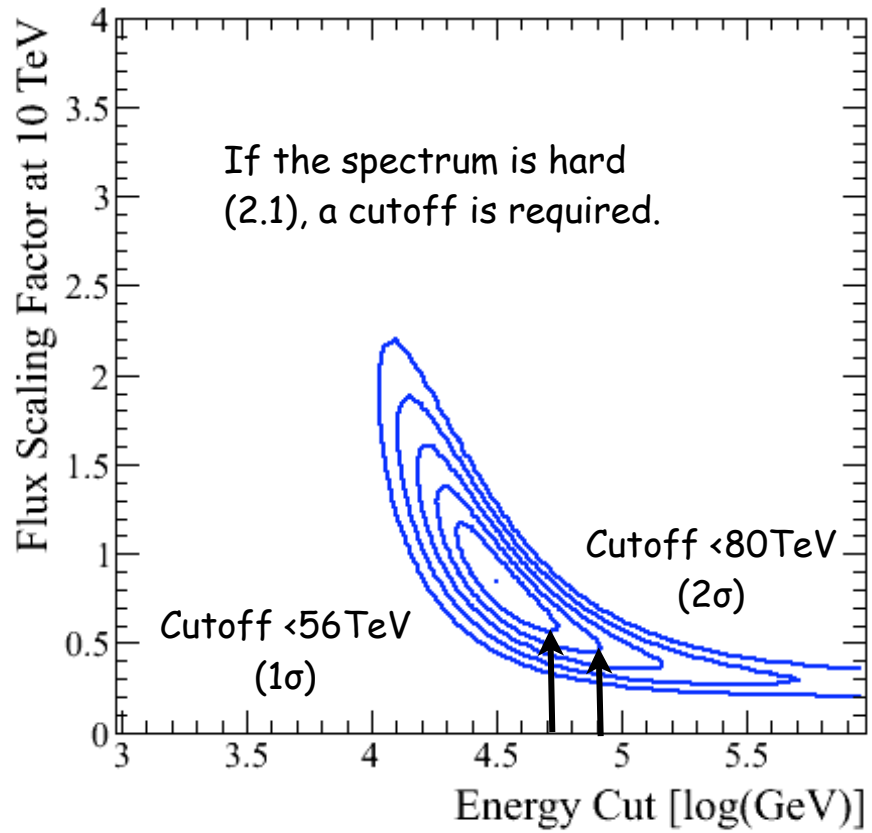
Fit Results: (no cutoff)
Io = 6.6 [3.4,12.1] x 10^{-7} /s/m^2/TeV
α = 3.00 [2.8,3.2]
χ^2 = 29.3 (25 DOF)

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)

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



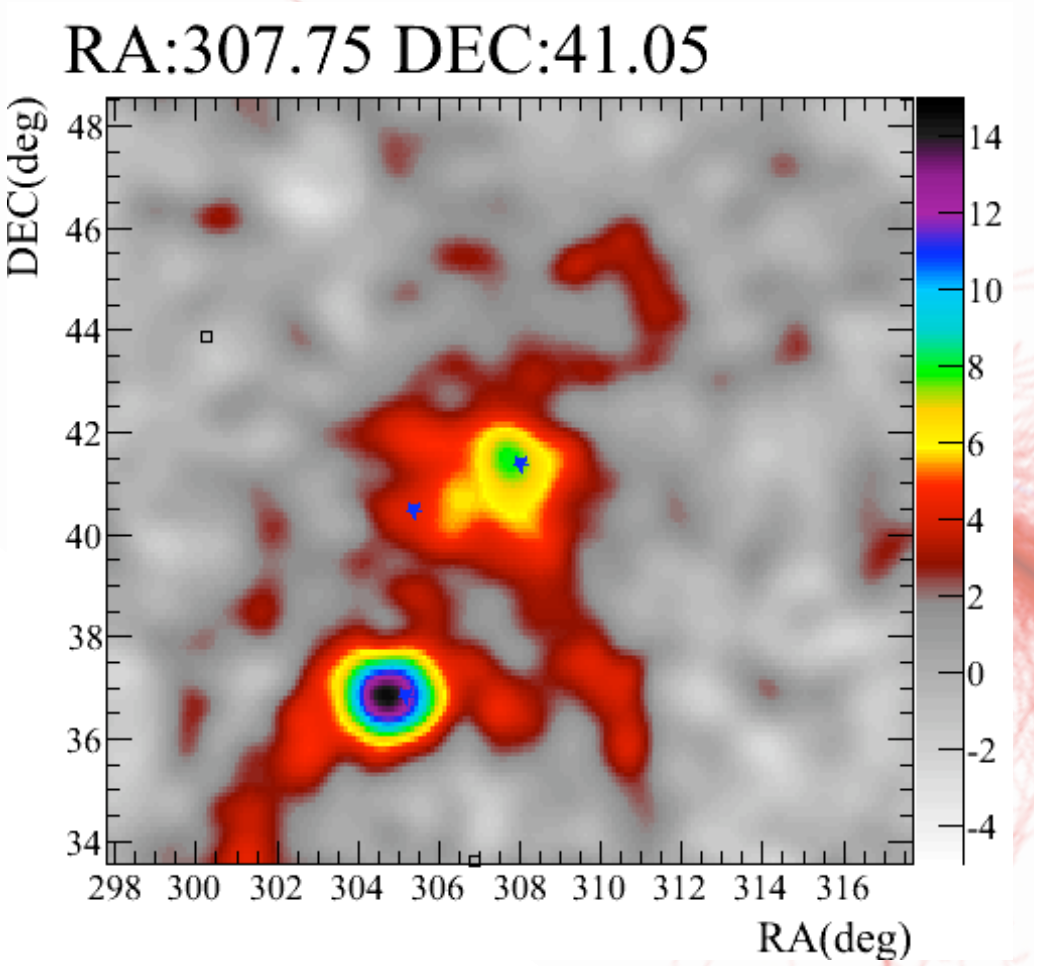


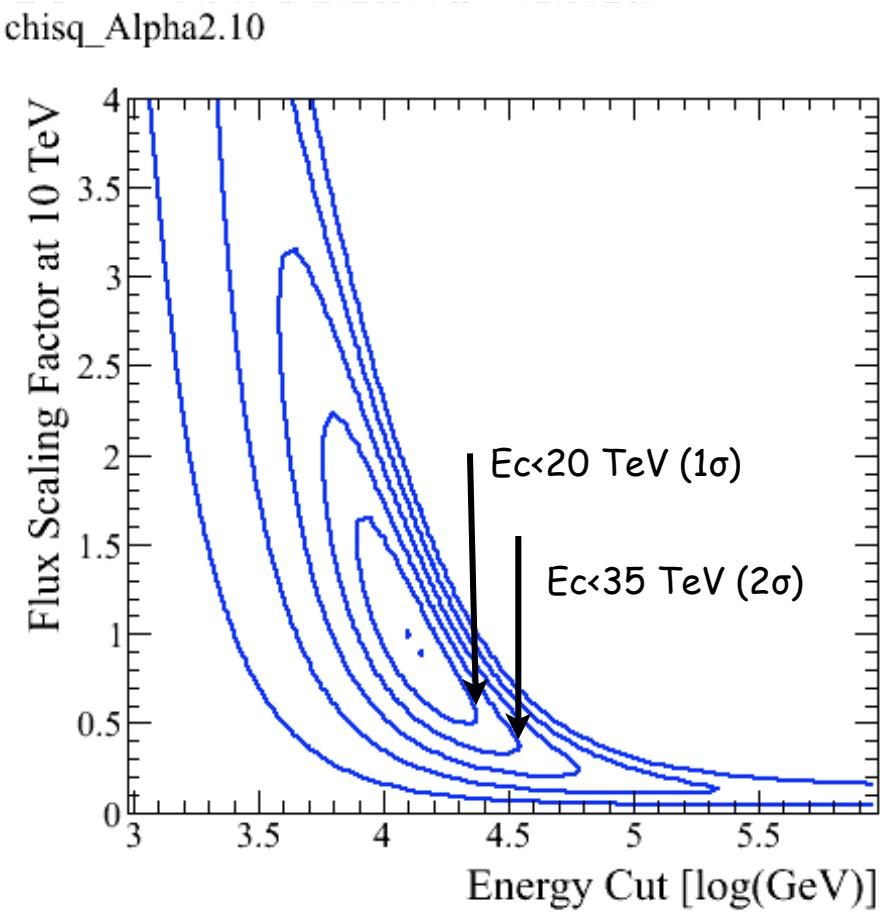
Fit Results: (no cutoff)
Io = 1.74 [1.10-2.50] x 10^{-7} /s/m^2/TeV
α = 2.62 [2.50-2.75]
χ^2 = 31.7 (25 DOF)

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



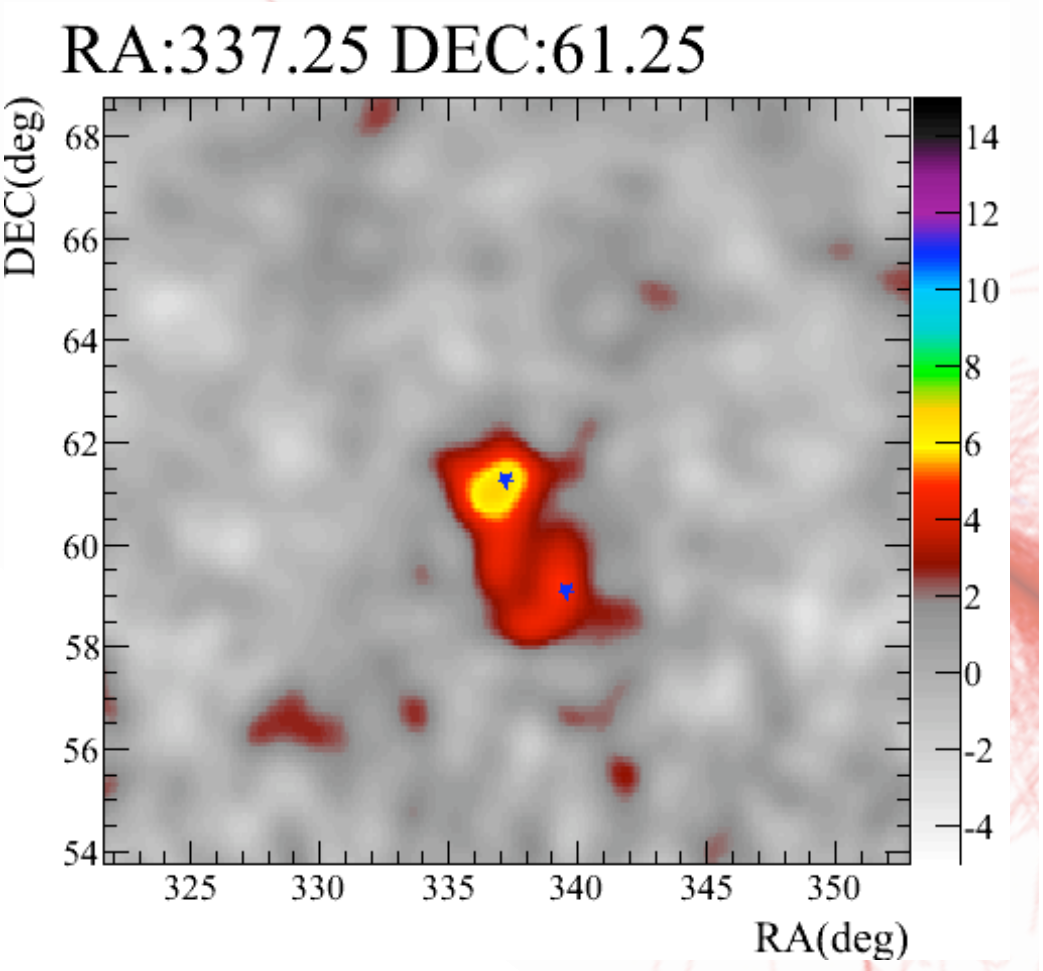


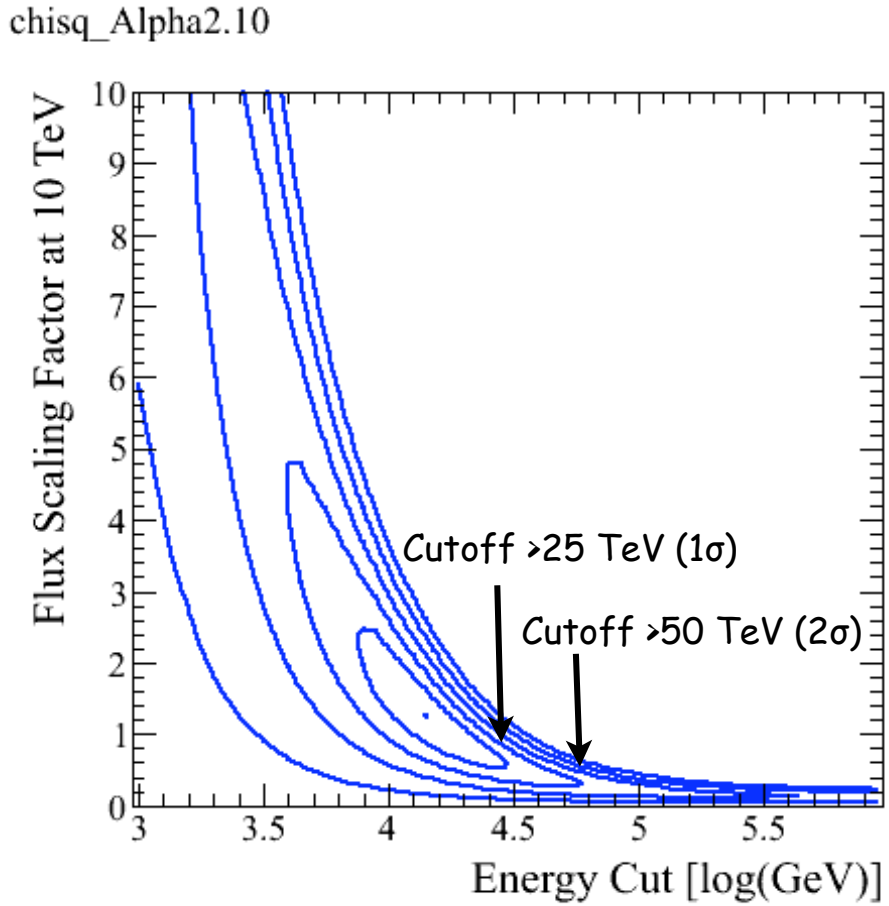
Fit Results: (no cutoff)
Io = 2.6 [1.3,3.6] x 10^{-7} /s/m^2/TeV
α = 3.02 [2.80,3.20]
χ^2 = 24.2 (25 DOF)

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



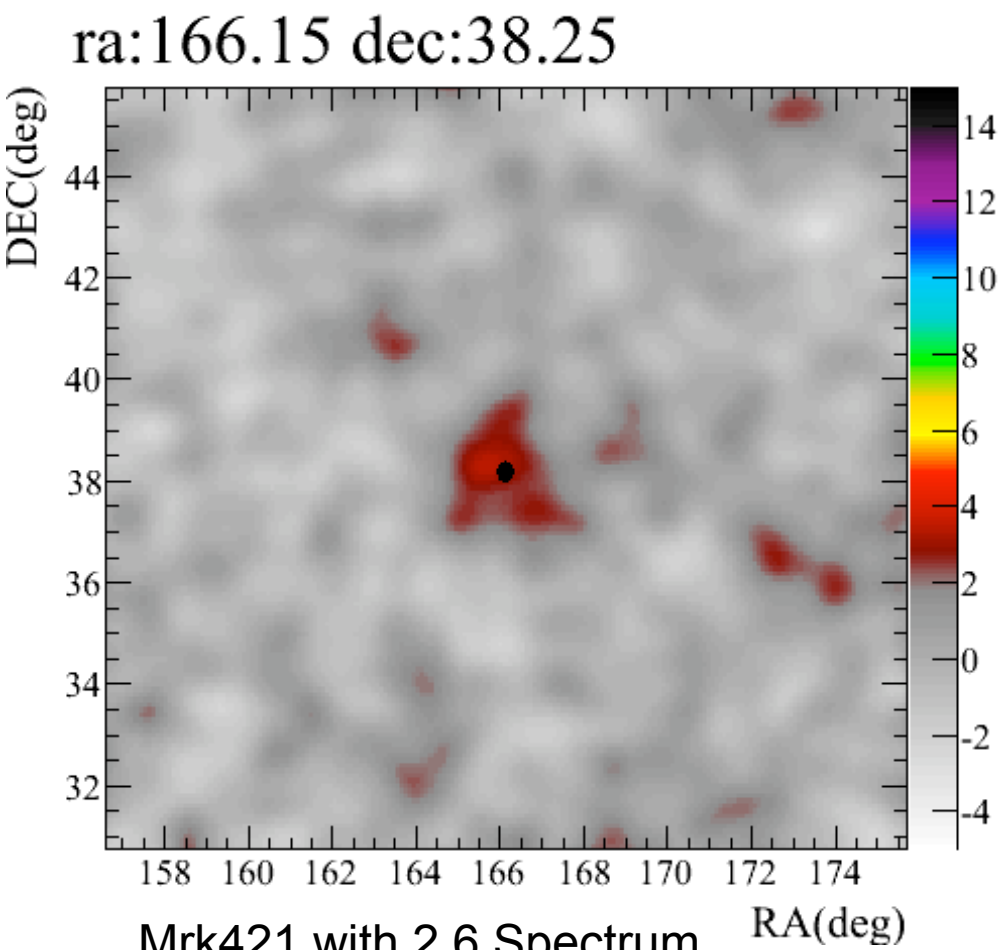


Fit Results: (no cutoff)
Io = 4.0 [1.7,7.1] x 10^{-7} /s/m^2/TeV
α = 3.10 [2.83,3.38]
χ^2 = 14.4 (25 DOF)

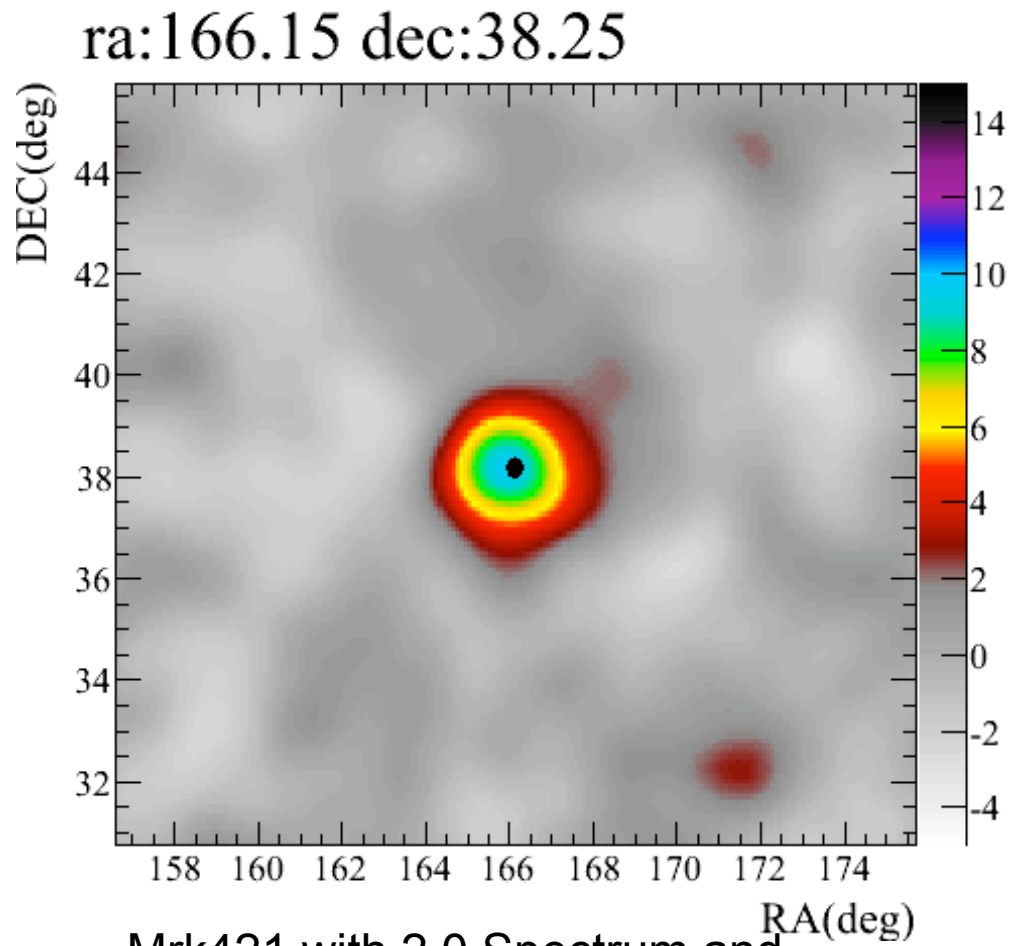
Fit Results: (3-parameter)
Io = 2.68 (0.18,7.72) x 10^{-7} /s/m^2/TeV
α = 2.70 (1.50,3.42)
Γ= 45 (6,inf) TeV
χ^2 = 13.9 (24 DOF)

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)

Benefit of Adjusting Spectral Hypothesis Example: Active Galaxy Markarian 421



Mrk421 with 2.6 Spectrum Hypothesis



Mrk421 with 2.0 Spectrum and 5TeV Cutoff Hypothesis