ENERGY ANISOTROPIES OF PROTON-LIKE ULTRA-HIGH ENERGY COSMIC RAYS

Jon Paul Lundquist

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THE UNIVERSITY OF UTAH

INTRODUCTION

PART ONE

- Overview of Ultra-high Energy Cosmic Rays (UHECR)
  - Sources and propagation
  - Previous Results
    - Anisotropy
    - Energy Spectrum
    - Composition
  - Extensive Air Showers
  - Telescope Array Project and UHECR Detection

PART TWO

- Anisotropy Studies
  - ~~Kernel Density Estimation Hotspot Analysis~~ (not enough time)
  - Energy Spectrum Anisotropy
  - Energy-Distance Correlation
  - Hot/Coldspot Summary Analysis

PART THREE

- Composition Study
  - Pattern Recognition Analysis
  - Composition
    - L-test and the Shift plot

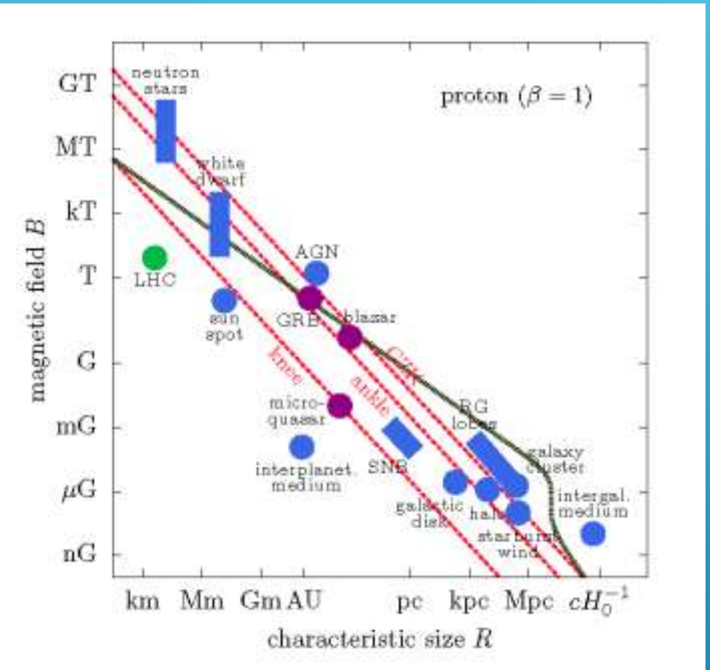
GOALS

- Remove model dependencies – assumptions and parameters – whenever possible.
  - Requires the development of new statistical methods.
- Anisotropy – magnetic deflection as a signature of a source instead of a confounding variable
- Combine UHECR energy, anisotropy, and composition into one picture.

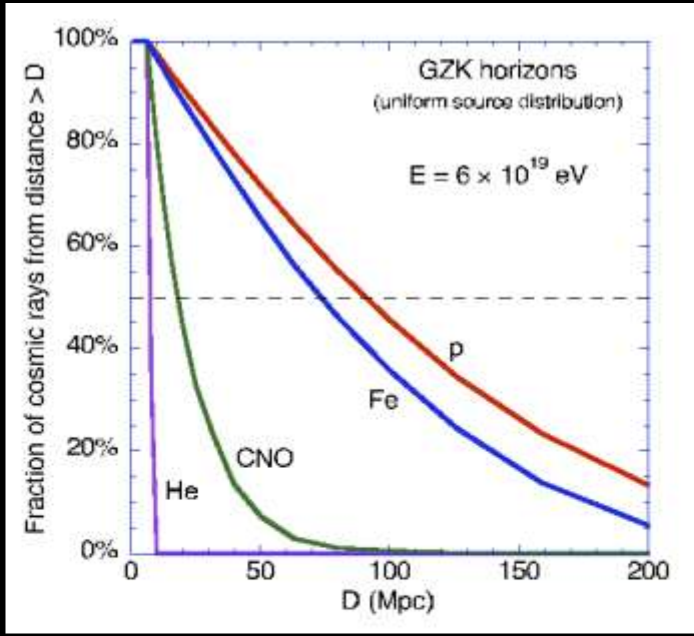
PART ONE
OVERVIEW OF ULTRA-HIGH ENERGY COSMIC RAYS

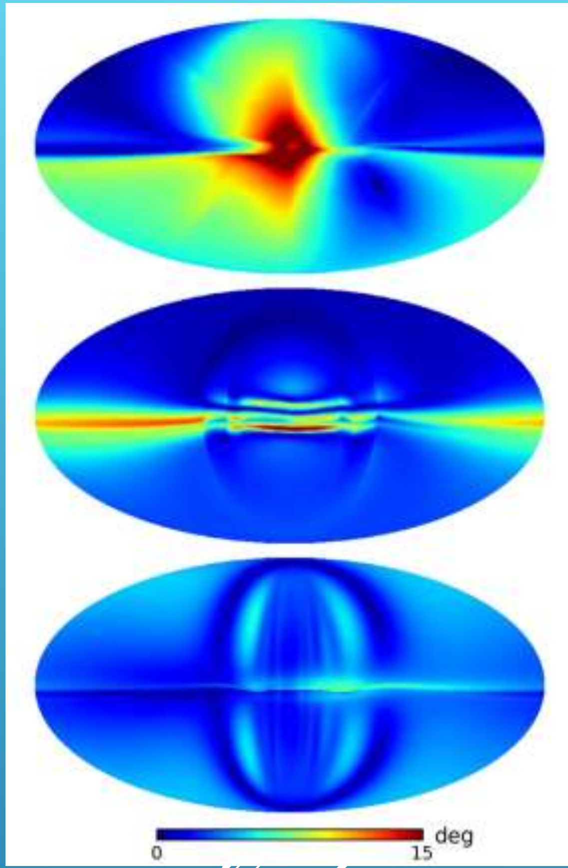
SOURCES AND PROPAGATION

SOURCES



?
Intergalactic EM Field
(1-10 nG)?





Larmor radius energy limitation

$$E < \frac{E_{max}}{10^{18}\ eV} \cong \frac{1}{2}\beta \cdot Z \cdot \frac{B}{\mu G} \cdot \frac{L}{kpc}$$

Relates: energy, sources, composition

$$\delta = \frac{S}{R_{Larmor}} = 0.5^{\circ} Z \frac{L}{kpc} \frac{B}{\mu G} \frac{10^{20}}{E}$$

Greisen–Zatsepin–Kuzmin limit
Cosmic Microwave Background

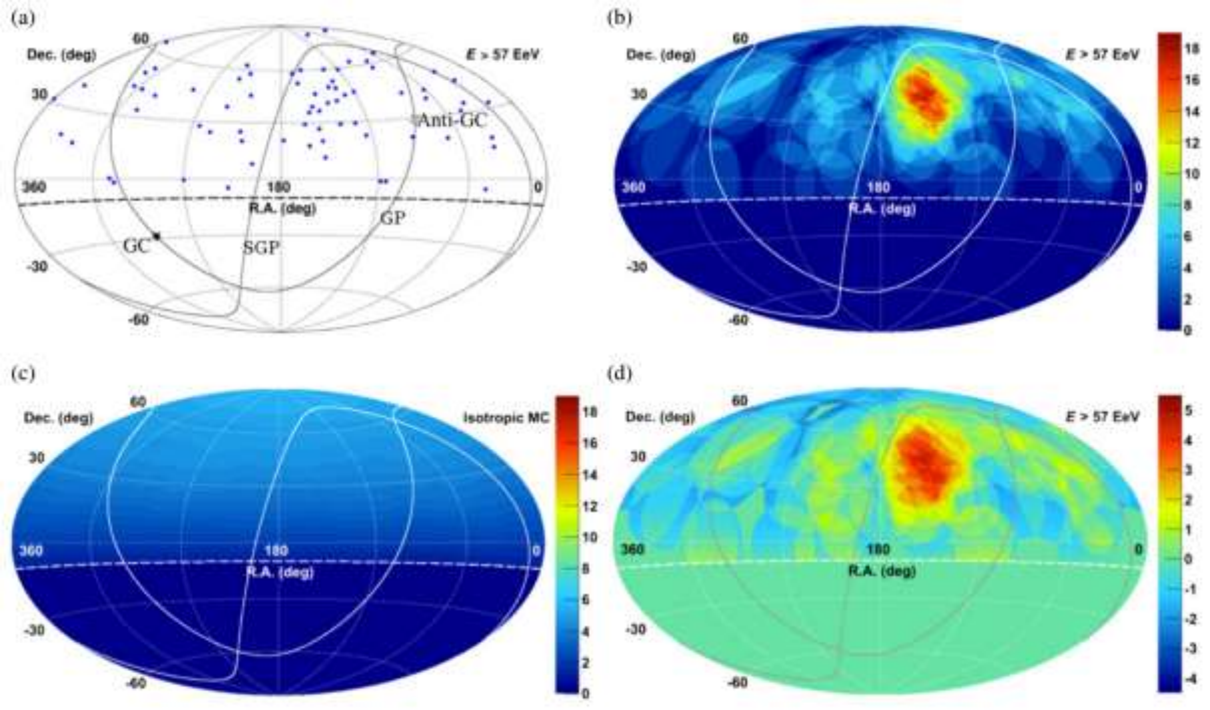
$$p + \gamma_{CMB} \longrightarrow \Delta^{+}(1232MeV) \longrightarrow p + \pi^{0}$$
$$\longrightarrow n + \pi^{+} (\longrightarrow p + \nu + \pi^{+})$$

Total Deflection
$<\delta> \approx \sim 10^{\circ}$ -- $\delta \lesssim 50^{\circ}$ for E = 10^{20}

Intragalactic EM Field

PREVIOUS RESULTS - ANISOTROPY

TA Hotspot

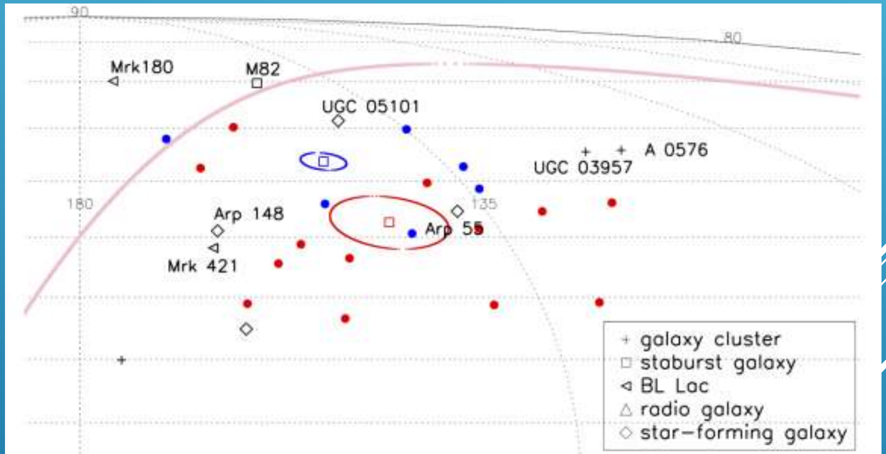


3.4σ significance of the anisotropy observation

Hotspot near the supergalactic plane:

Ursa Major cluster (20 Mpc from Earth)
Coma cluster (90 Mpc)
Virgo cluster (20 Mpc)

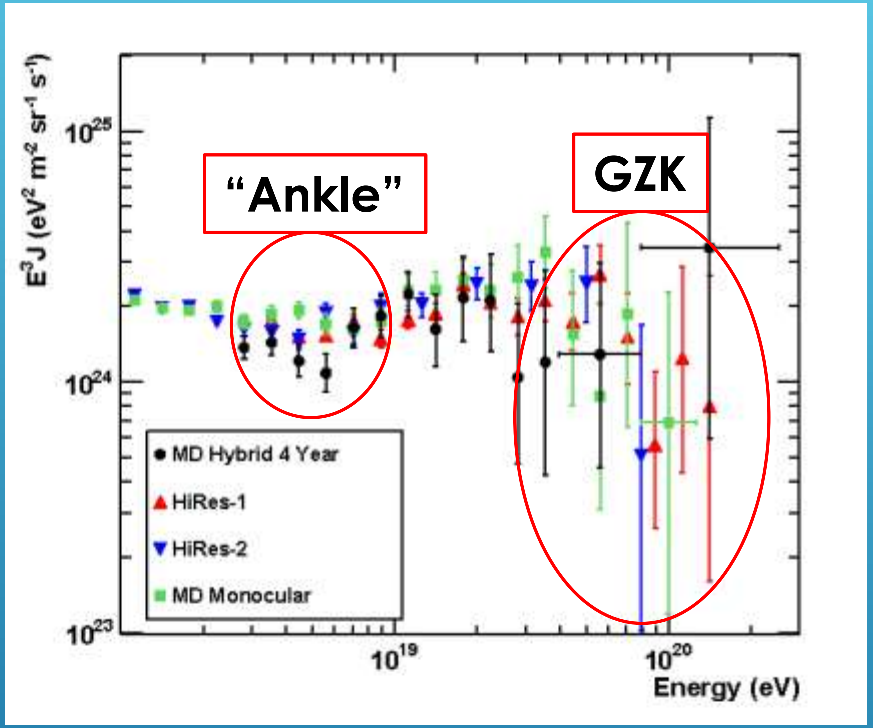
The angular distance to the supergalactic plane is ∼17∘.

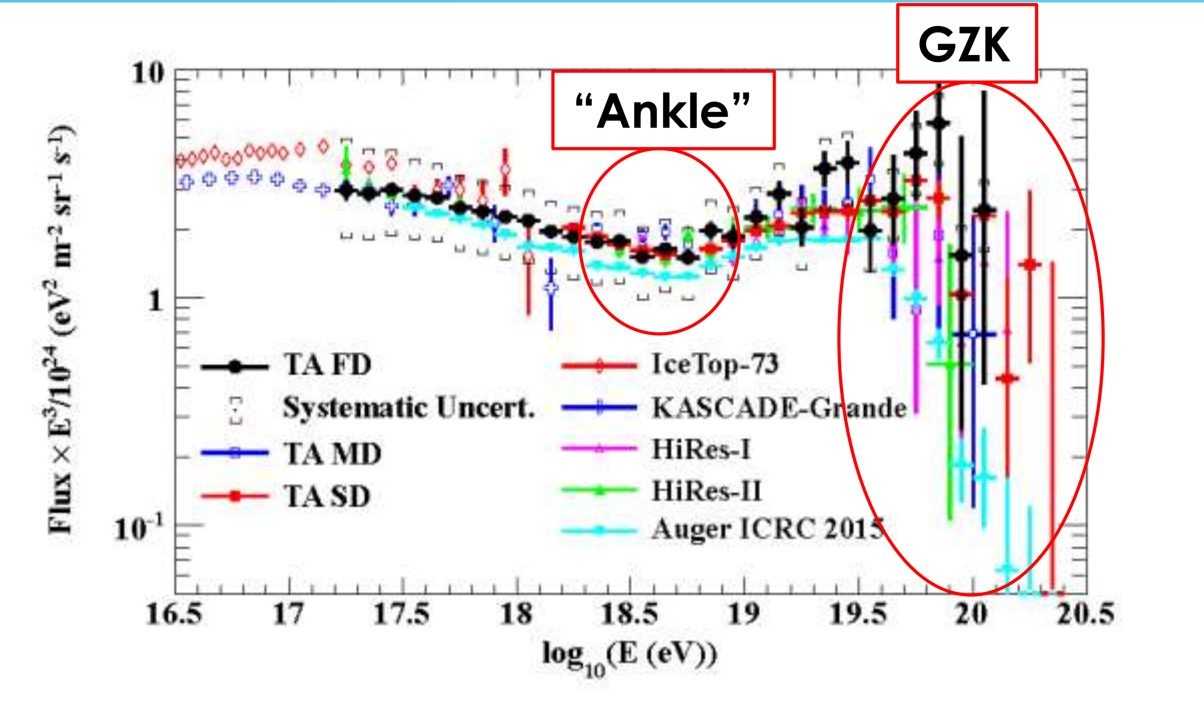


"A Monte Carlo Bayesian Search for the Plausible Source of the Telescope Array Hotspot" He, H.N. et al.

FIG. 2: The 19 events at the hotspot in the equatorial coordinates are denoted by filled circles (*red:* $E < 75$EeV; *blue:* $E > 75$EeV). Reconstructed positions of shifted sources for two groups of the hotspot events are denoted by the open squares; the errors are shown by ellipses of the corresponding color.

PREVIOUS RESULTS – ENERGY SPECTRUM



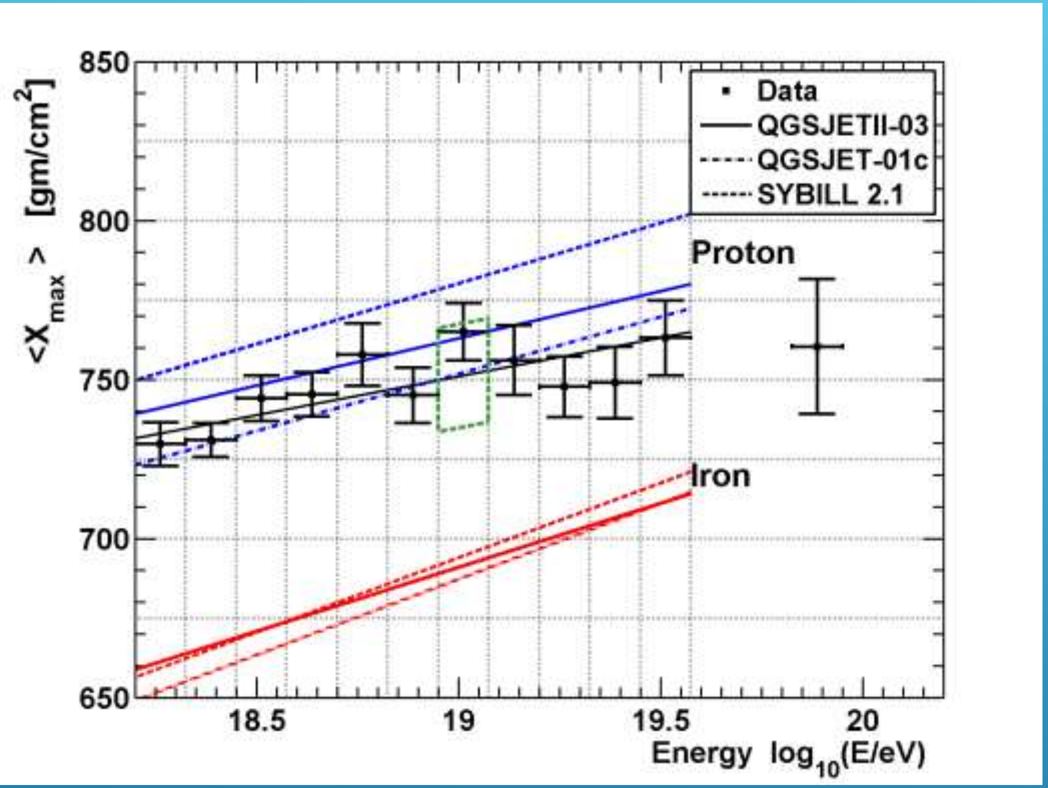


Good Agreement Between TA Detectors

Good Agreement Between Experiments

"Ankle" is approximately the end of galactic sources

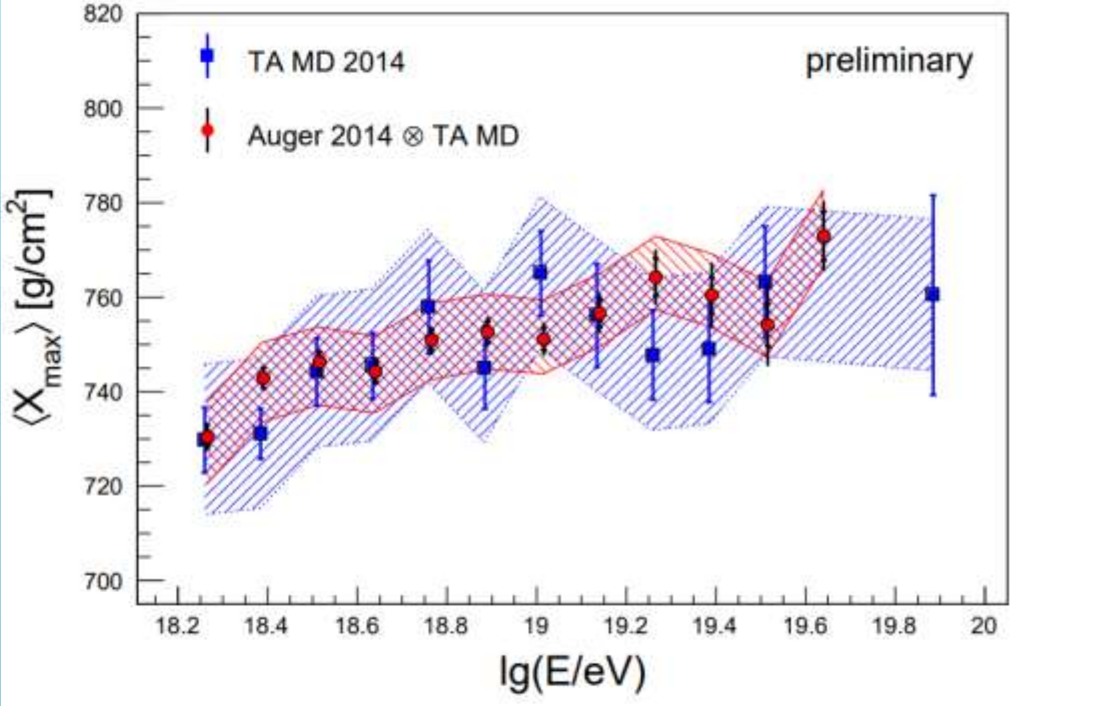
PREVIOUS RESULTS - COMPOSITION



Published 5 year data result from this thesis work

- proton-dominant *depending on model*

Compared to PAO

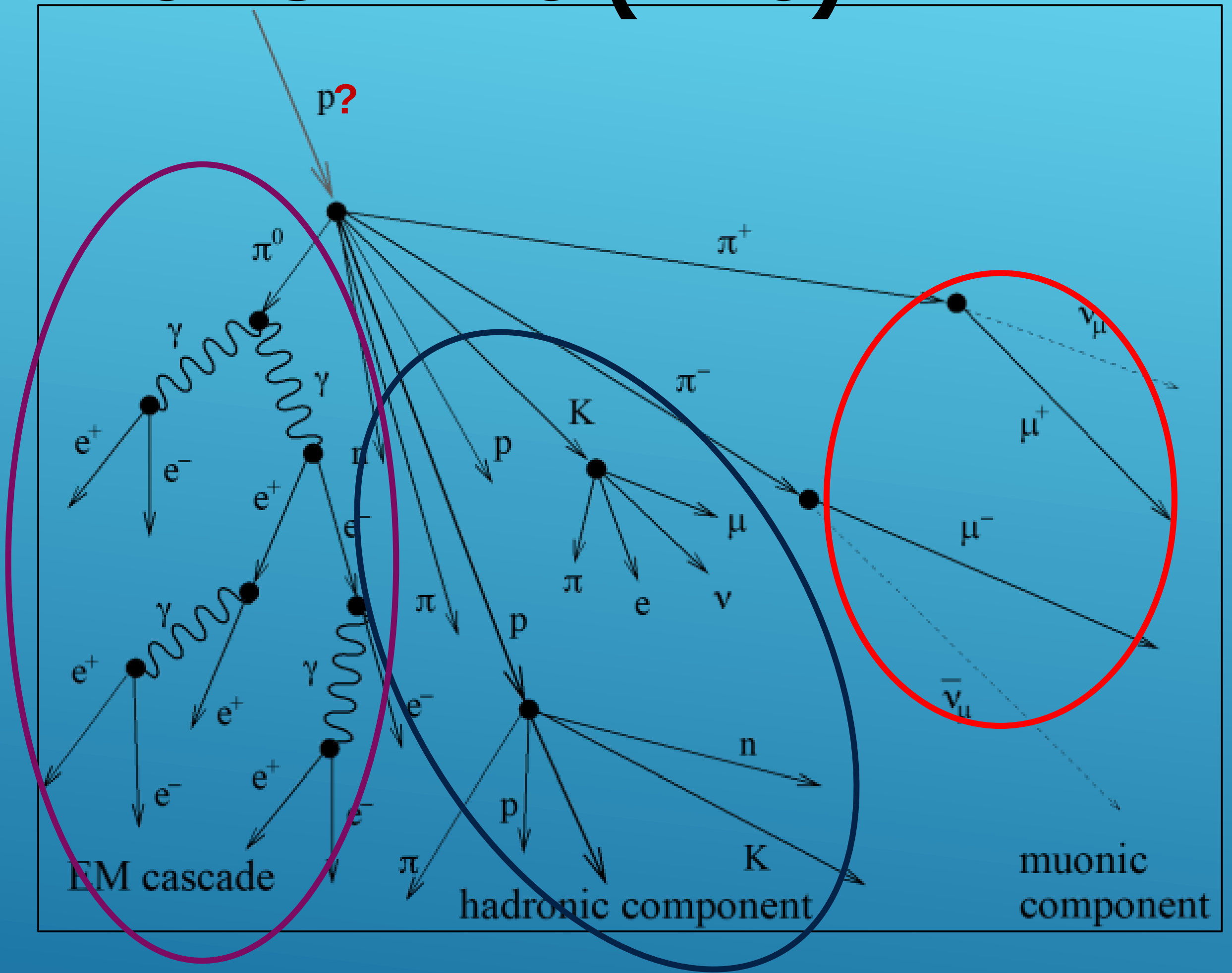


- PAO reports heavier at higher energies
  - Data of TA and PAO agree

- *Result of different simulations or North/South anisotropy?*

EXTENSIVE AIR SHOWERS (EAS)

UHECR studied indirectly using extensive air shower



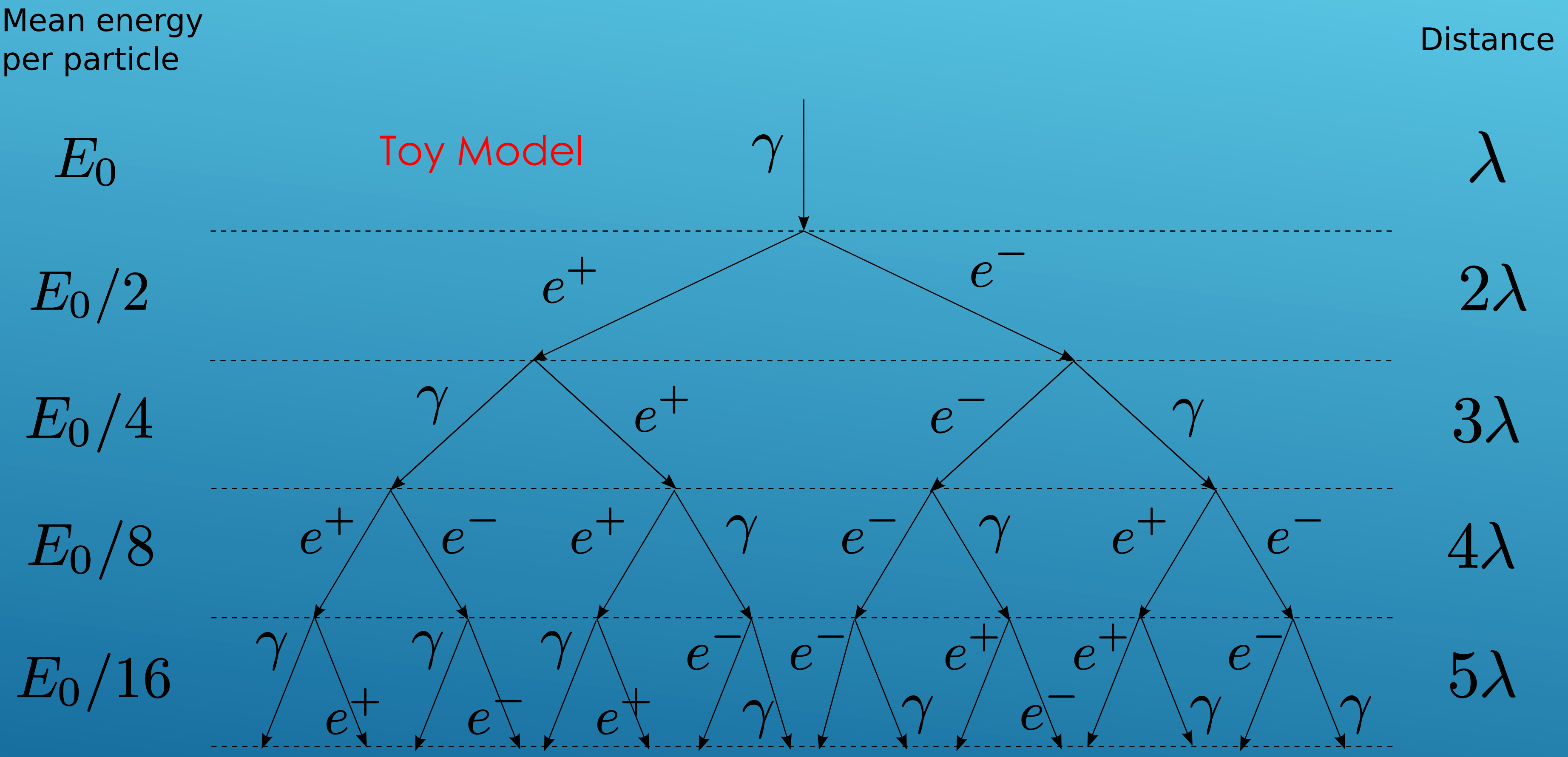
EM Cascade is the largest contribution.

- Muons created early in shower -- charged Pion decays.
- Muons and neutrinos are "missing energy"

- Collisions result in Pions, Kaons (~8%), and Nucleons (~4-5%)
- 1/3 of the Pions (π^0) decay into two photons and contribute to EM cascade in each generation.
- Kaons contribute ~8% to EM cascade in later generations.

HEITLER MODEL

Radiation length, λ (36.5 g/cm^2 in air), is about the same for pair production and Bremsstrahlung radiation.



n= X/λ

$N = 2^n$

$E_n = \frac{E_0}{A} \cdot 2^{-n}$

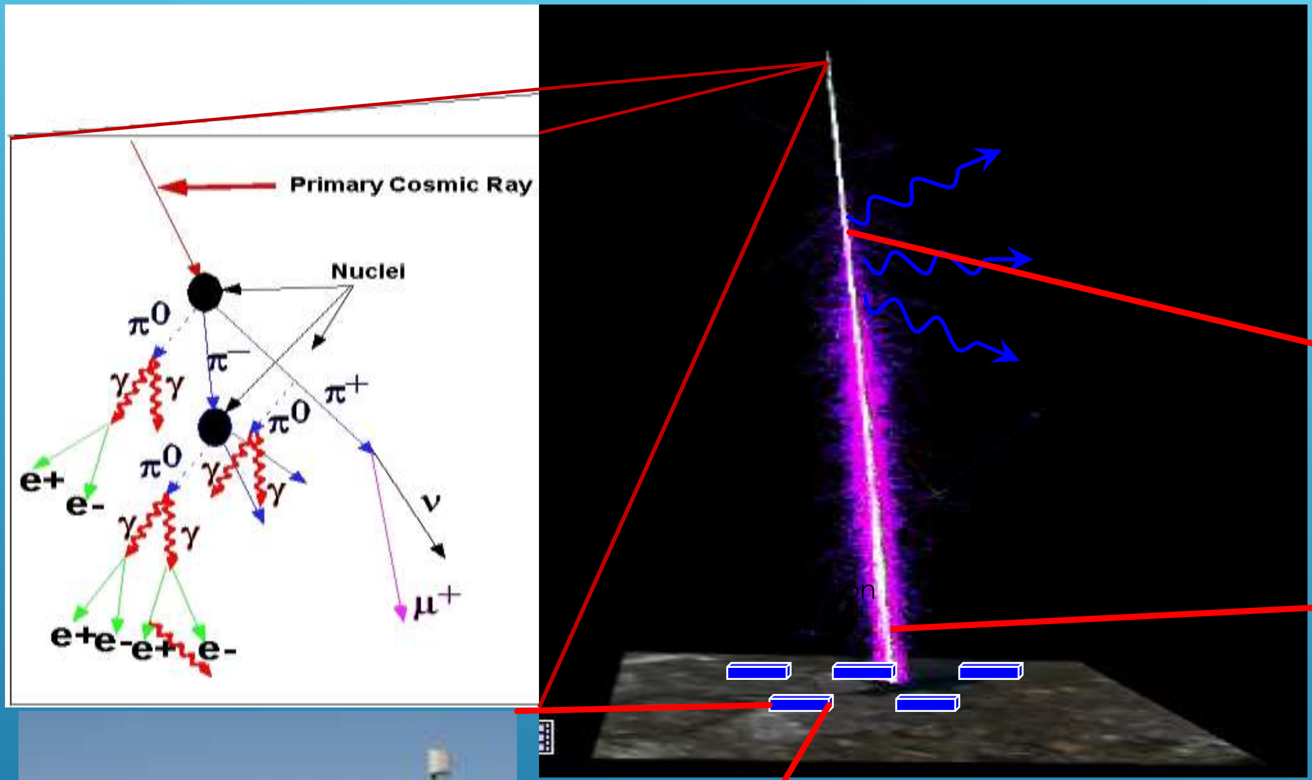
$N_{max} = \frac{E_0}{E_c}$

$X_{max} = \lambda \frac{\ln \frac{E_0}{AE_c}}{\ln 2}$

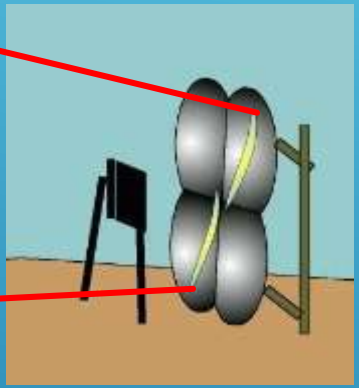
Measure of composition

X_{max}: shower depth with maximum particles.
The shower then decreases in size due to ionization losses.

INDIRECT DETECTION



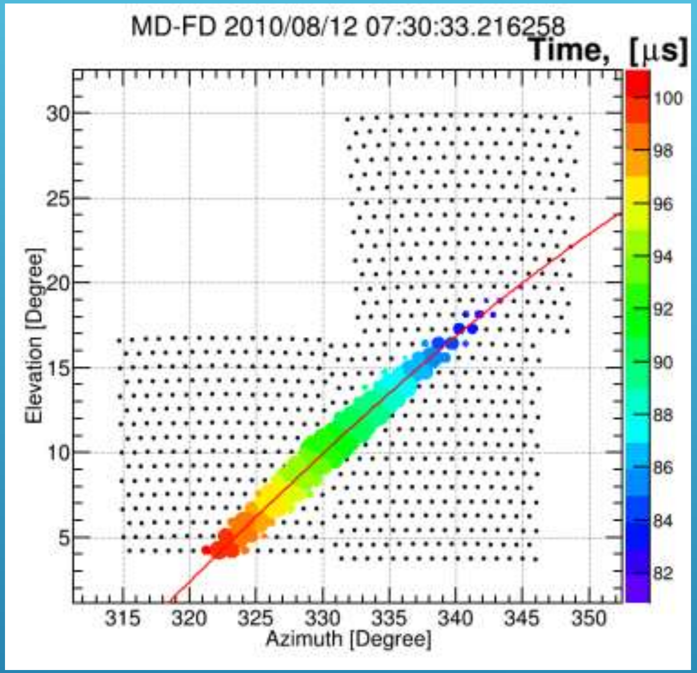
- Fluorescence from charged particle excitation of nitrogen.

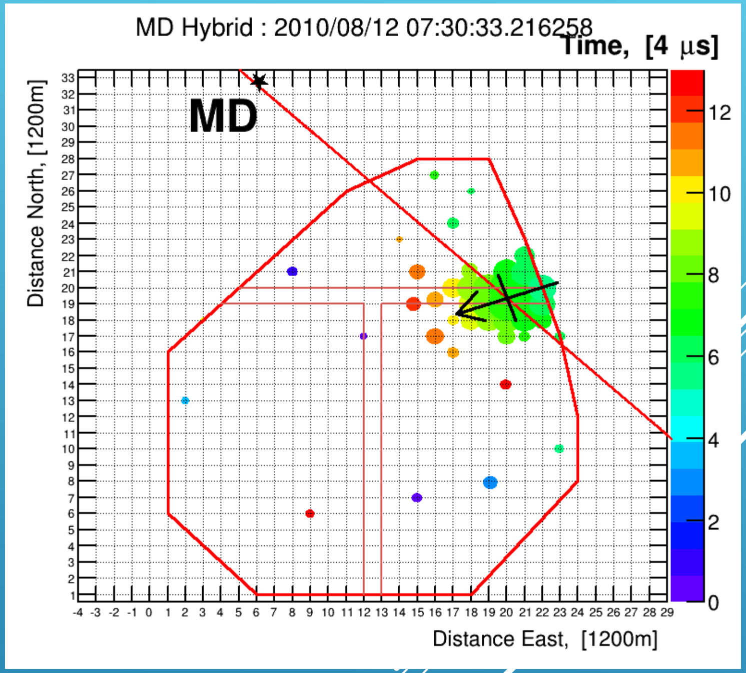


- Charged particles activate scintillator plastic. Picked up by photomultiplier tubes.

SIMULATION, DETECTION, RECONSTRUCTION

Reconstructions used from previous works





CORSIKA Simulated Air Shower 10^{15} eV $45°$ inclination

Red – $e^{+/-}$, γ

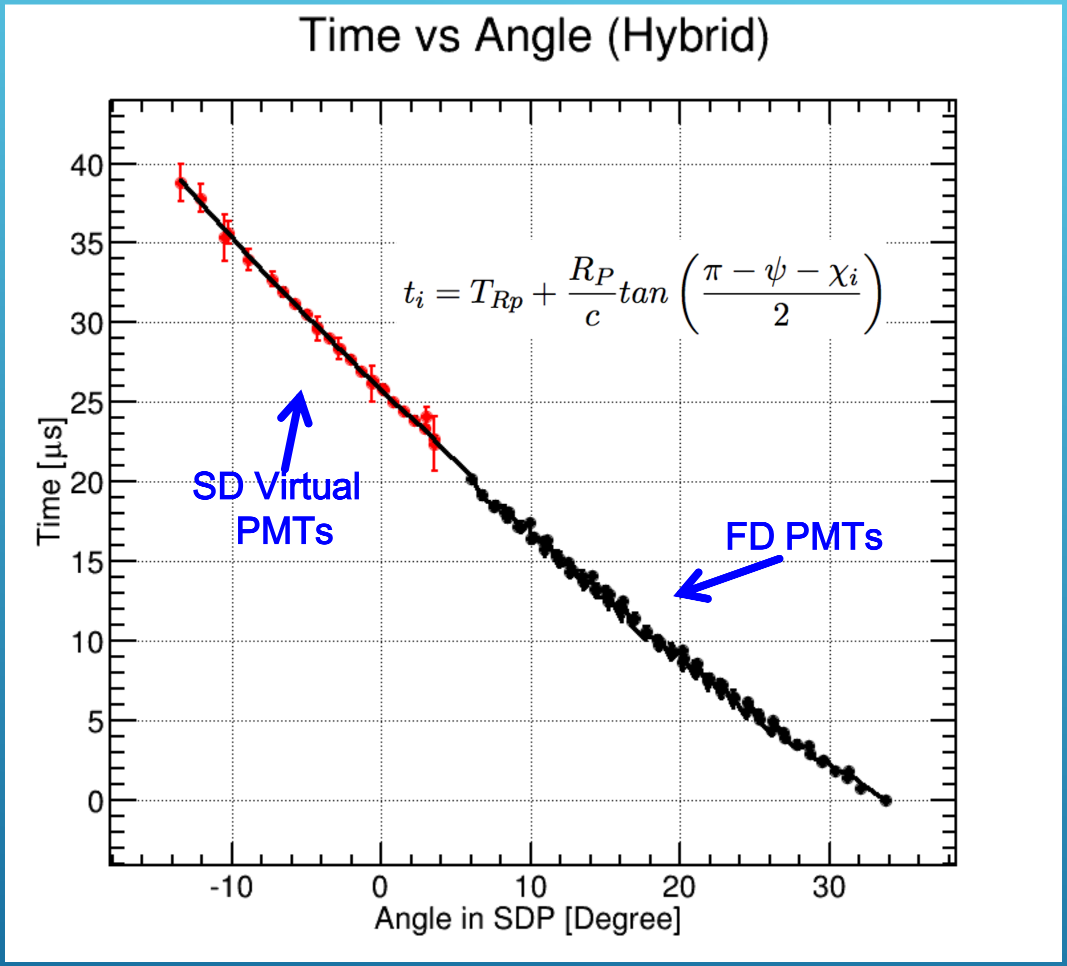
Green – $\mu^{+/-}$

Blue – Hadrons ($\pi^{0/+/-}$, $K^{0/+/-}$, p, n)

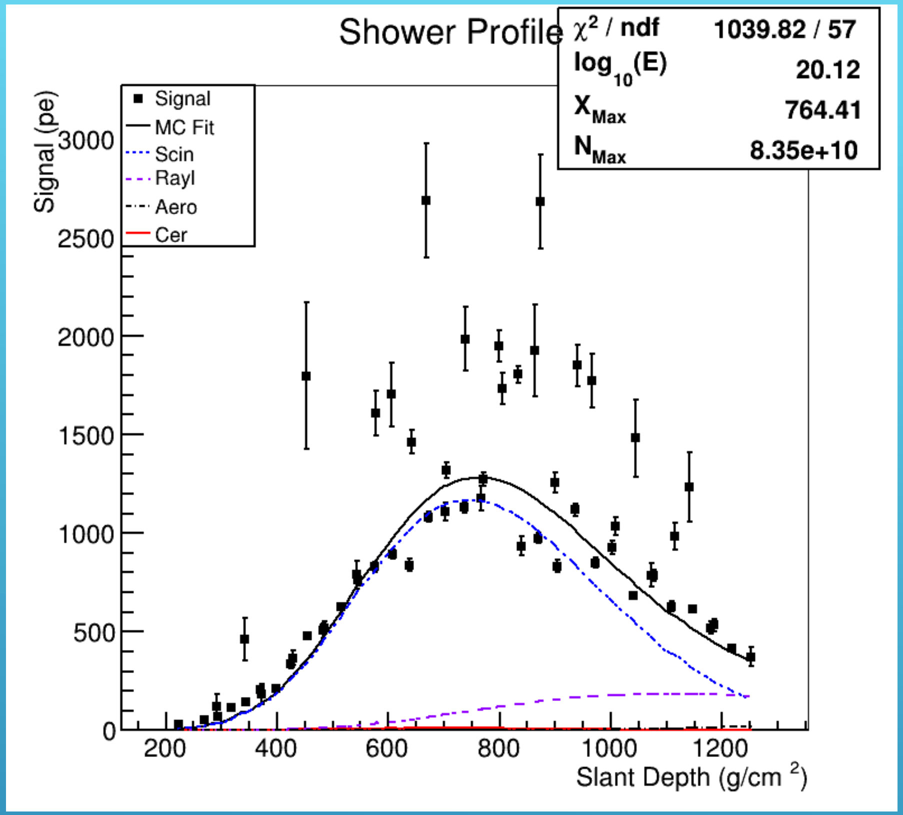
Fluorescence Detector

Surface Detector

RECONSTRUCTION



Viewing angle converted to slant depth using atmospheric profile



Fit to GH profile and search for the reconstructed Monte Carlo event that matches the data

$$N(X) = N_{\max}\left(\frac{X - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max} - X_0}{\lambda}} \exp\left(\frac{X_{\max} - X}{\lambda}\right)$$

Take energy from MC event which minimizes

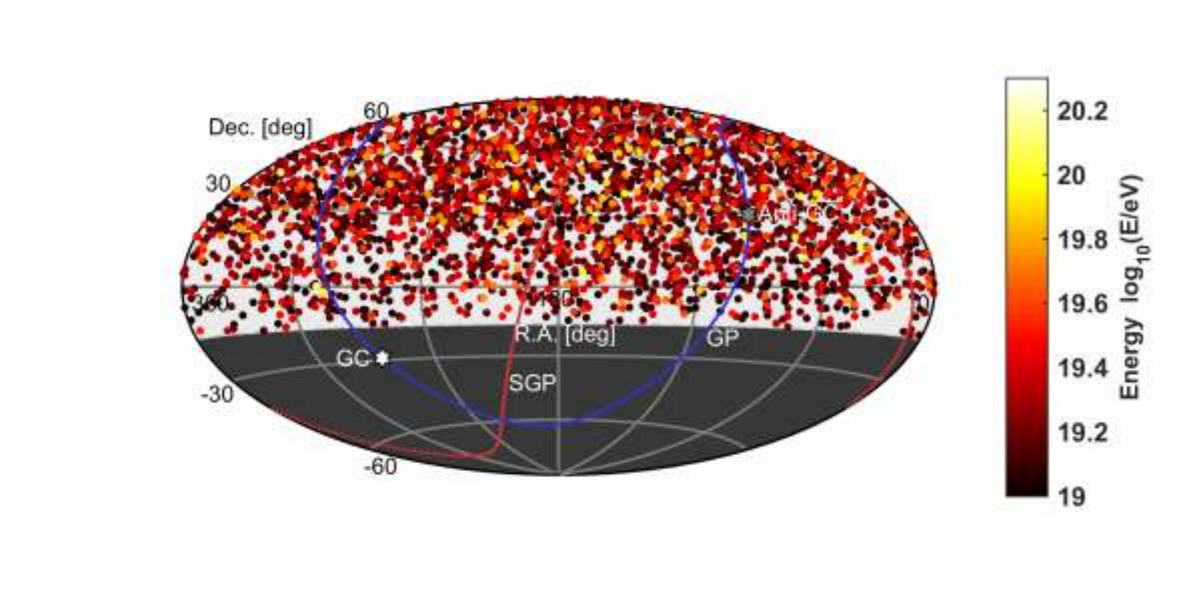
$$\chi^2_{Profile} = \sum_i \frac{1}{\sigma_i^2}\left(S_i^{(m)} - S_i^{(p)}\right)^2$$

S_i are measured and predicted tube signals

PART TWO
ANISOTROPY STUDIES

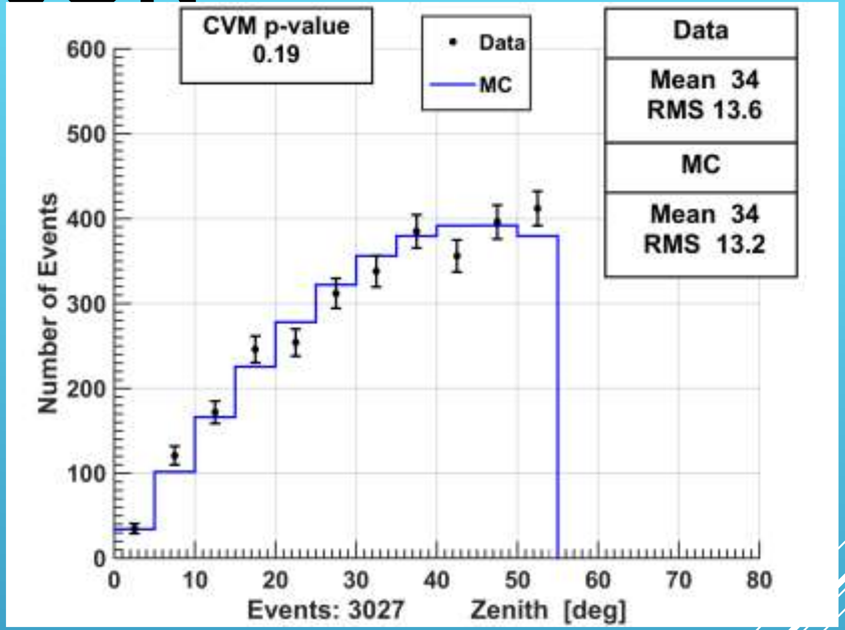
DATA SUMMARY

- **Data:**
- **7 years surface detector data** *(from ICRC hotspot).*
  # Detector. ≥ 4, Zenith angle < 55°, Pointing Error < 10°
  - **Additional cuts** (due to lower energy):
    - **Pointing direction error < 5°, boundary > 1.2 km , Lateral fit χ^2 < 10**
  - ***E* $\geq 10^{19.0}$ *eV - 3027 events***

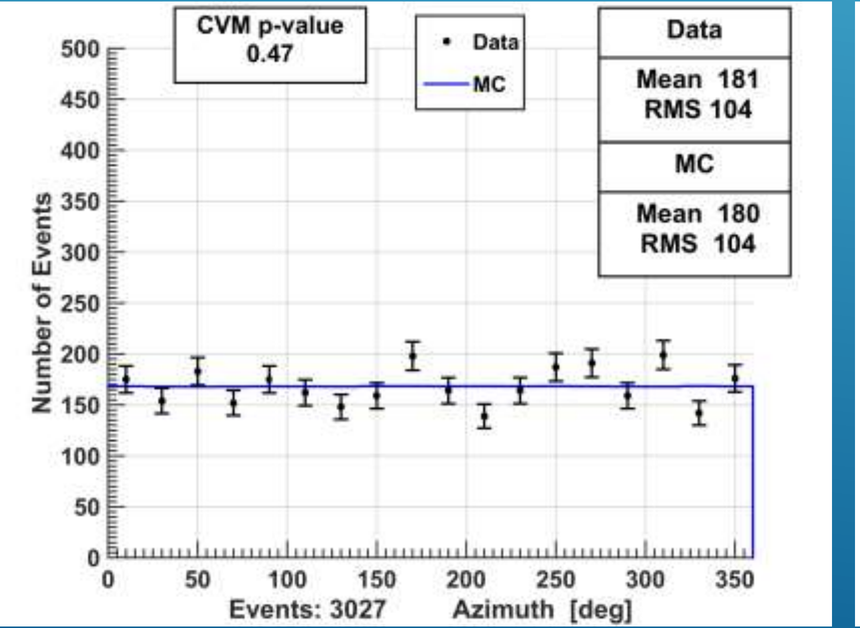


ISOTROPIC MONTE-CARLO COMPARISON

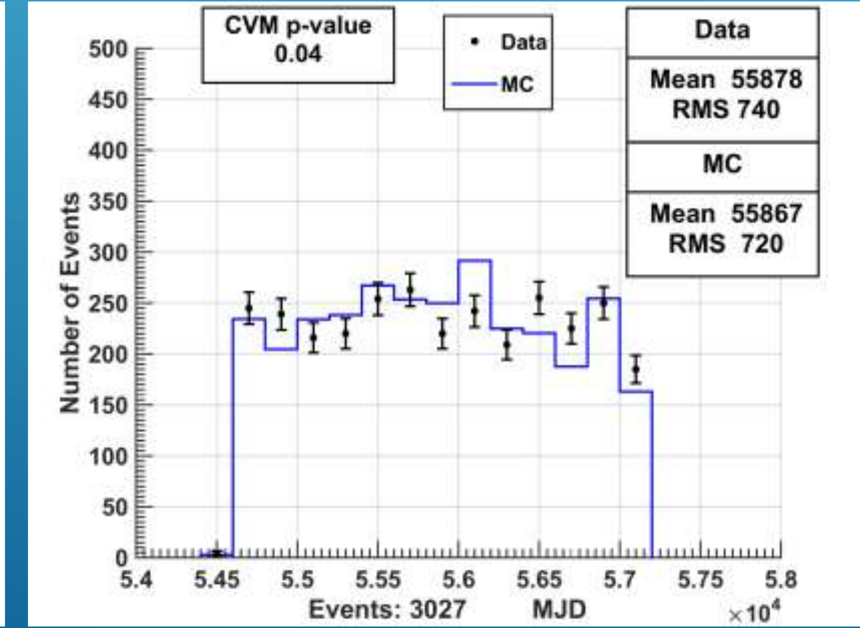
- Sin(θ)*cos(θ) – Zenith distribution from detector geometry
- Flat Azimuthul angle distribution.
- On-time simulated – sampling 250,000 event times (E > 17.7 EeV).
- Energy sampled from reconstructed HiRes spectrum.



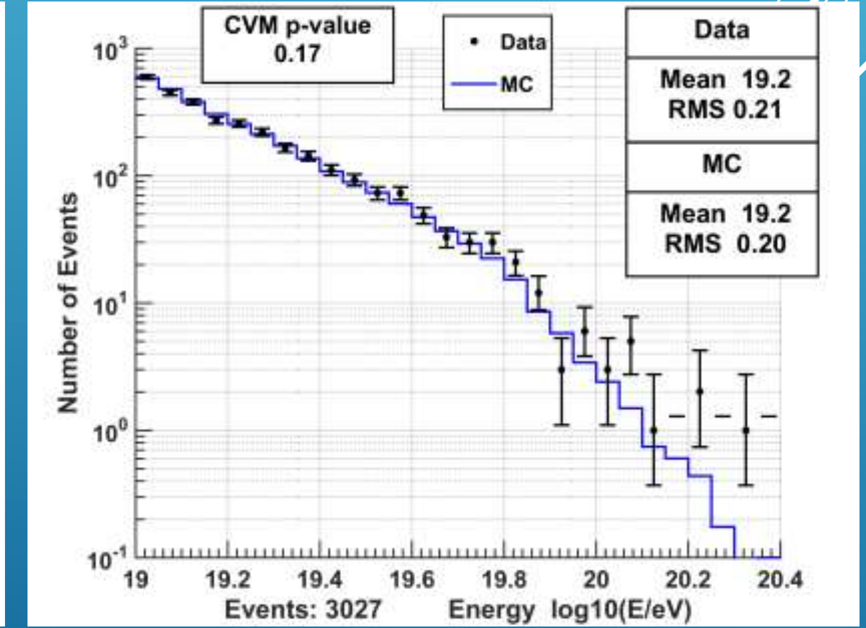
(E > 20 EeV, p = 0.48)



Uniform Azimuth



Time taken from data



Reconstructed HiRes Spectrum

ENERGY SPECTRUM ANISOTROPY

Is there a location on the sky which has a significantly different overall spectrum? Signature of sources, magnetic deflection or both.

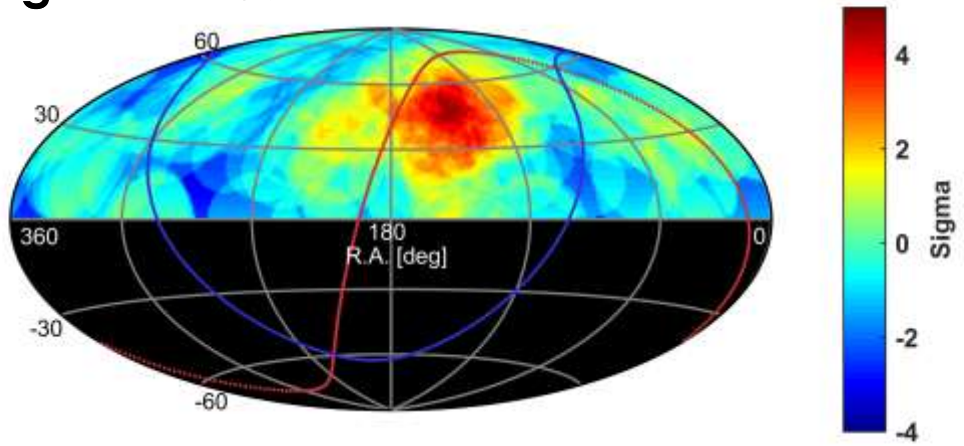
7-YEAR DATA HOTSPOT RESULT

Period : 2008 May – 2015 May

Cuts:
- # of used detectors ≥ 4
- Zenith angle < 55°
- Pointing Error < 10°
- Energy Threshold ≥ 57EeV

Resulting Data: 109 events

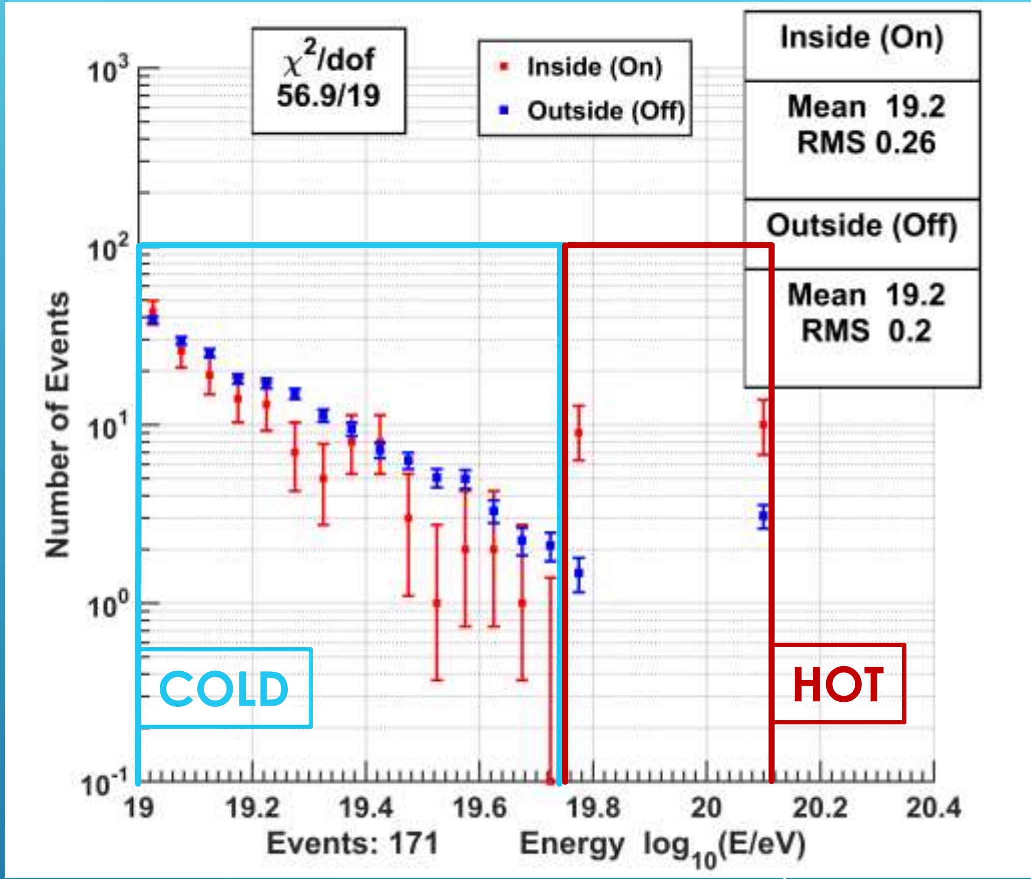
20° binning



3.4σ post-trial significance

Max. significance 5.1σ
148.5° R.A, 44.5° Dec.
(17° from SGP)

Tighter Cuts, 20° bin



Energy distribution shows an overall deficit of events

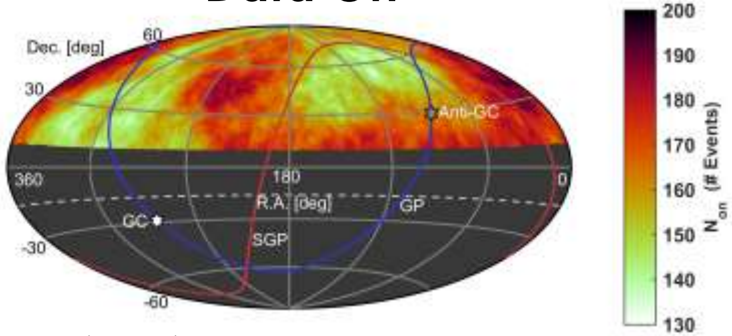
METHOD

ESTIMATED BACKGROUND – EQUAL EXPOSURE

- Likelihood and χ^2 tests are sample size biased
  - Need to control statistics
- Equal exposure binning samples the sky equally.
  - "On" exposure such that bin size average = 15°, 20°, 25°, 30°

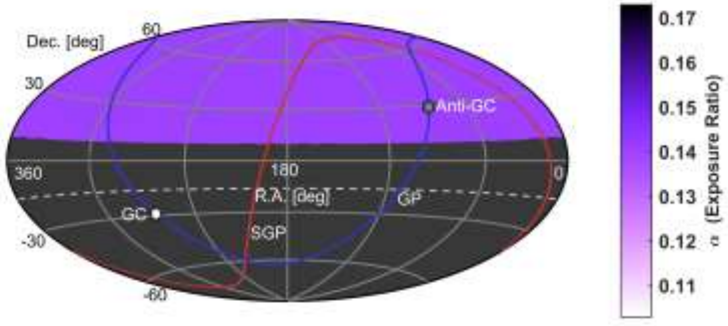
- $\alpha = N_{on}^{MC} / N_{off}^{MC}$ = constant

Data On



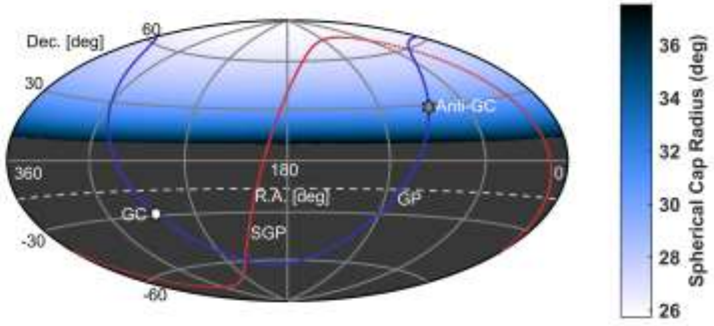
$\langle N_{on} \rangle = 163 \;\; RMS\ 12$

MC α



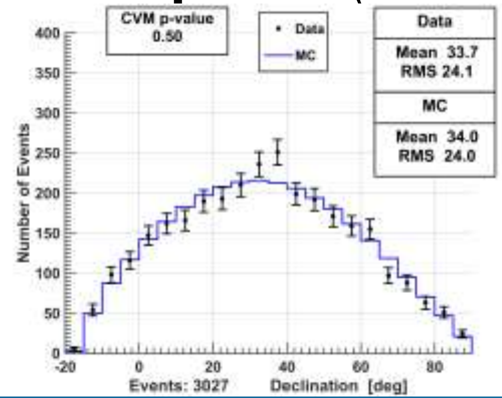
$\langle \boldsymbol{\alpha} \rangle = 0.14028 \;\; RMS\ 9e-05$

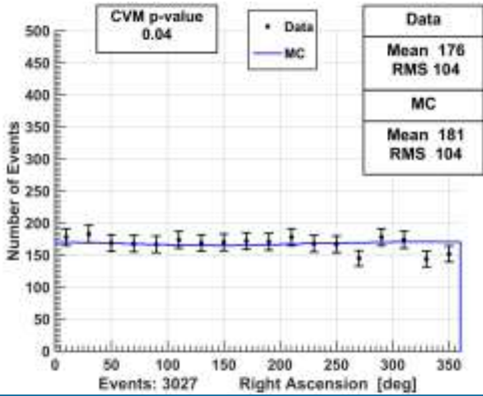
Bin Sizes α = 14.03%



$\langle Radius \rangle = 30 \;\; RMS\ 3$

- 30° <bin>, E ≥ $10^{19.2}$ eV



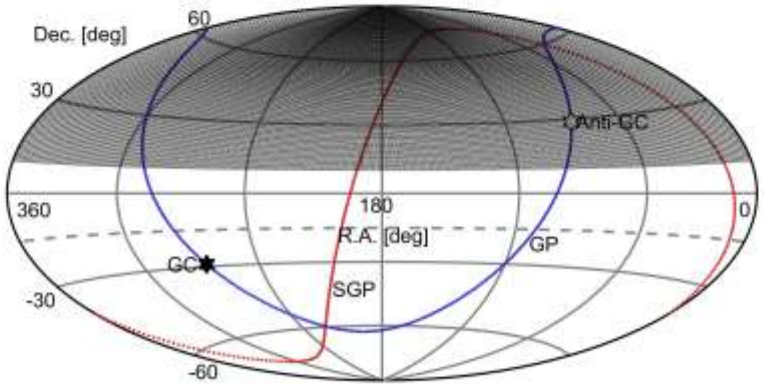


- Maximum pre-trial significance for mean bin size of 30°
- Energy threshold scanned - $10^{19.0}$, $10^{19.1}$, $10^{19.2}$, $10^{19.3}$ eV.

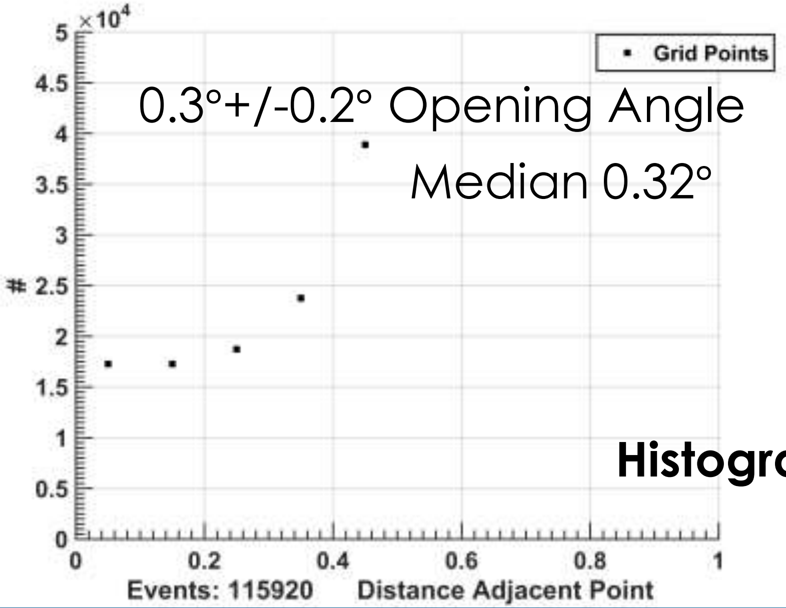
OVERSAMPLING GRID

*N. A. Teanby (2006) "An icosahedron-based method for even binning of globally distributed remote sensing data" COMPUTERS & GEOSCIENCES, 32 (9), 1442-1450.

0.5°x0.5° in RA and Decl.



Changing sampling -- declination bias

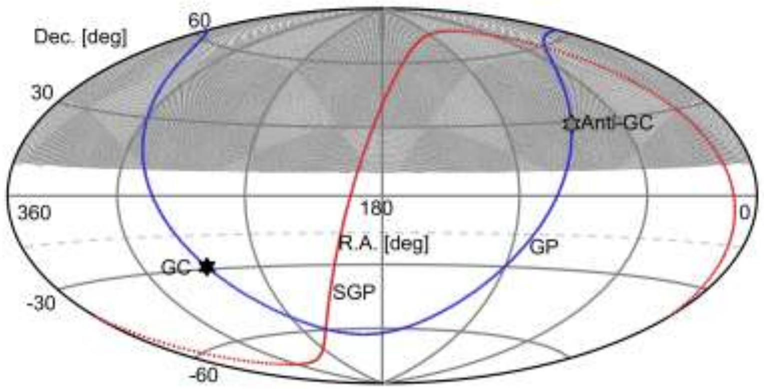


0.3°+/-0.2° Opening Angle

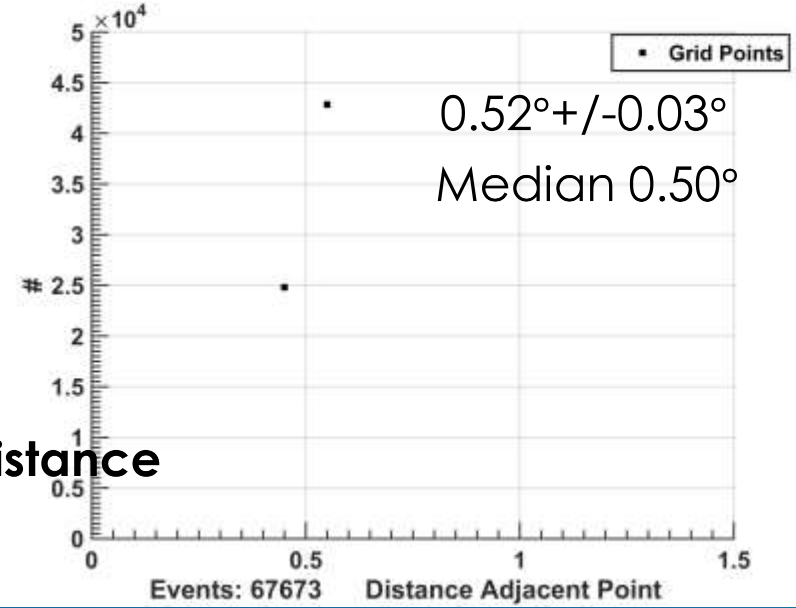
Median 0.32°

Used here

0.5°x0.5° in Opening Angle*



Sky is sampled equally



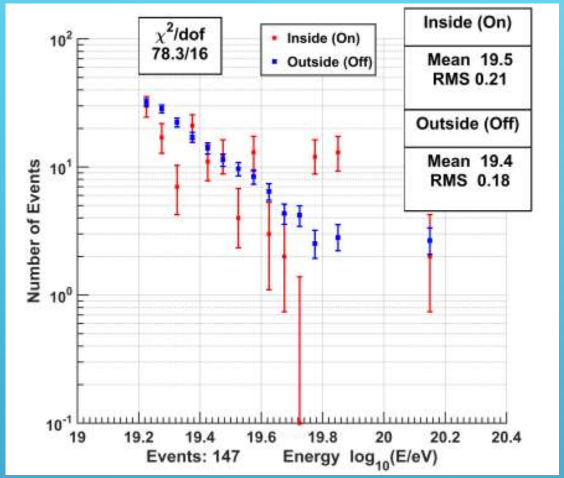
0.52°+/-0.03°

Median 0.50°

Histograms of closest grid distance

POISSON LIKELIHOOD GOODNESS-OF-FIT

- Compare energy distribution "On" (inside) to "Off" (outside)
  - "Off" Normalized to N_{bg} (expectation)
  - Energy bins of 0.05 $log_{10}(E/eV)$
    - Less than mean energy resolution



$$\chi_k^2 \simeq 2n_{on} \log \frac{n_{on}}{n_{bg}} + n_{bg} - n_{on}$$

$$\sum n_k^{bg} = N_{bg} = \alpha N_{off}^{data}$$

- N_{off} Normalized to expectation

- n_{on} # data in bin
- n_{bg} expectation
- Degrees of freedom:
  - # bins
  - +1 for fluctuating background
  - +1 for variable number of bins

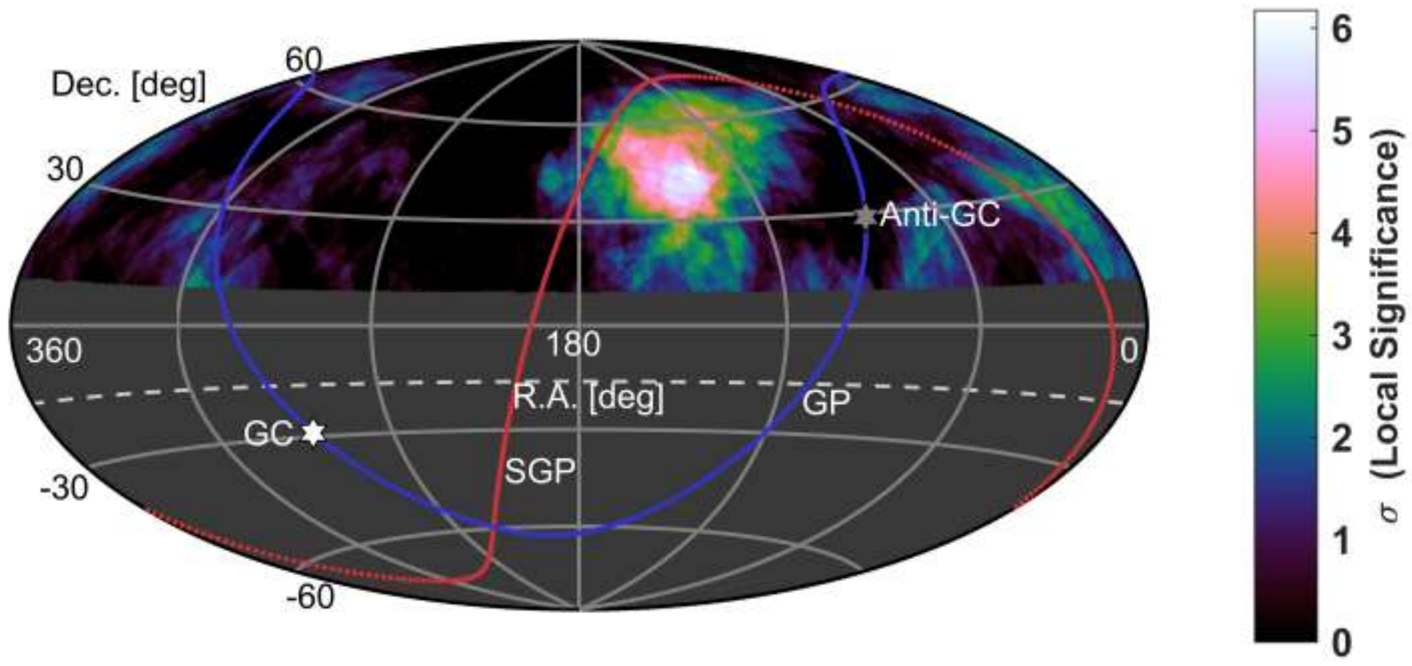
Test Used Previously by T.A. In:
Study of Ultra-High Energy Cosmic Ray Composition Using Telescope Array's Middle Drum Detector and Surface Array in Hybrid Mode, Astroparticle Phys. **64**, 49 (2014).

- Good reference http://www.fysik.su.se/~conrad/James/james.5.gof.pdf or *Particle Data Group book*

RESULT

ENERGY SPECTRUM ANISOTROPY – 30° <BIN>

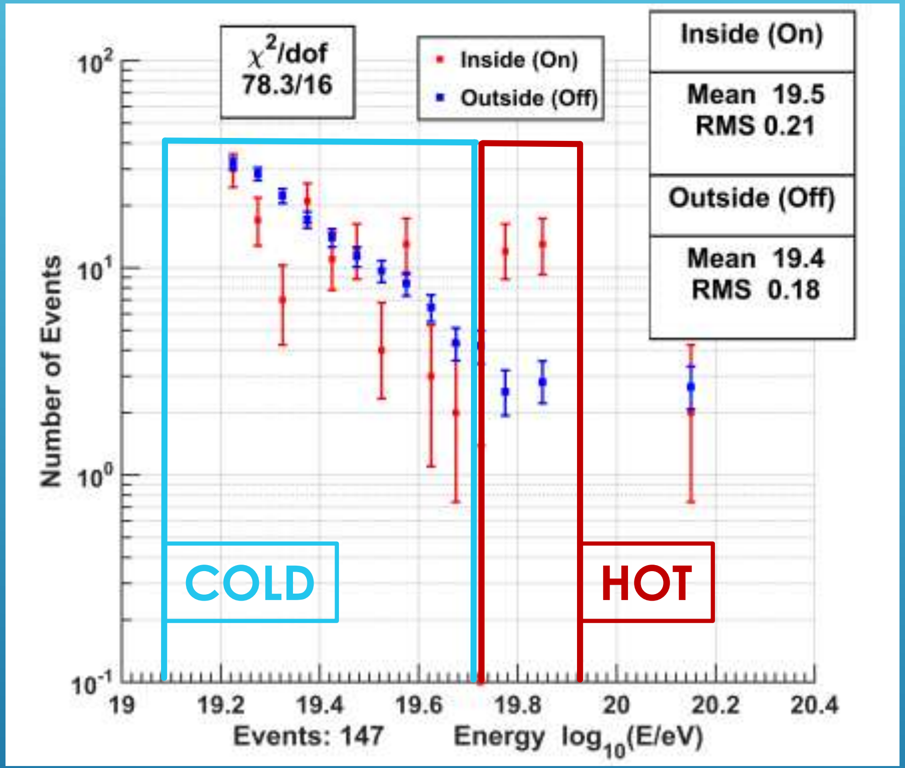
- σ deviation — "On" data compared to "Off" data

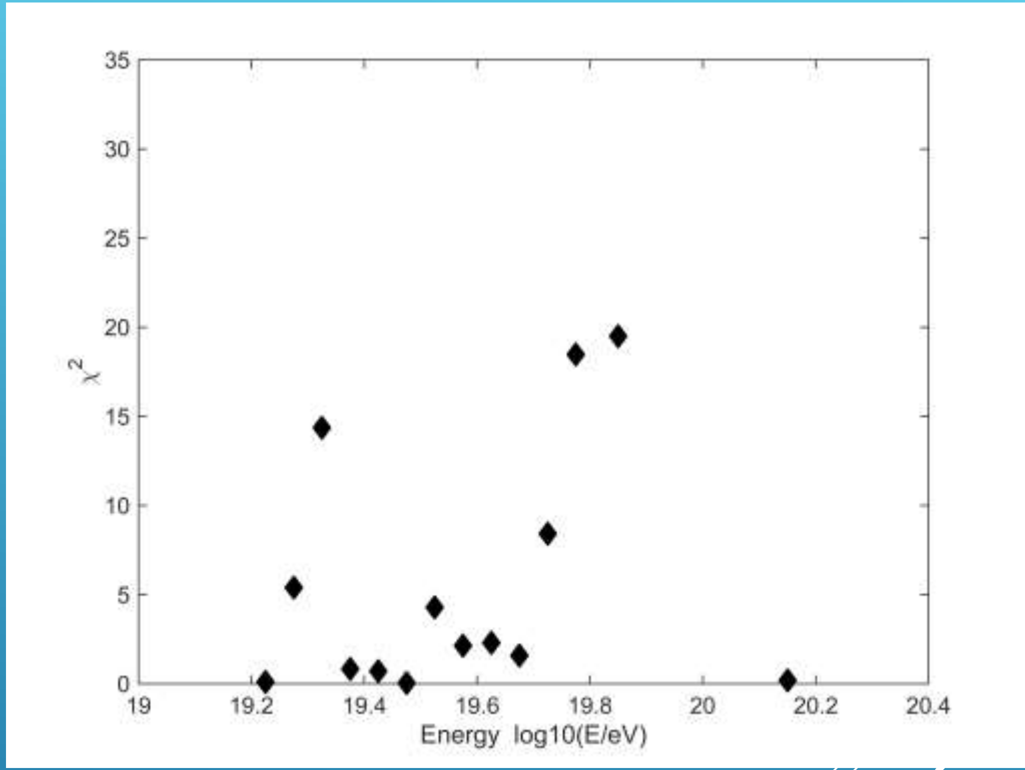


30° <bin>, E ≥ $10^{19.2}$ eV

- **Maximum: 6.17σ**
- **138.8° R.A., 44.8° Decl.**
- **Bin size: 28.43°**
- **# Events: 147**
- **6.8° from "hotspot"**

ENERGY COMPARISON – MAX. LOCAL SIGMA





- Max. local σ (6.17) location — 138.8° R.A., 44.8° Decl.

- 28.43° radius cap bin
- E ≥ $10^{19.2}$ eV
- Expected Background: N_{bg} = 166.2

Bin Chi Squares

$$\chi_k^2 \simeq 2n_{on}\log\frac{n_{on}}{n_{bg}} + n_{bg} - n_{on}$$

GLOBAL SIGNIFICANCE

- Count simulations with $\sigma \geq 6.17$

- *MC TEST Penalties*
  - *Bin scan - 15°, 20°, 25°, 30°* average bin sizes
    - *Not enough events inside bins less than 15°*
    - *Not enough events outside bins greater than 30°*

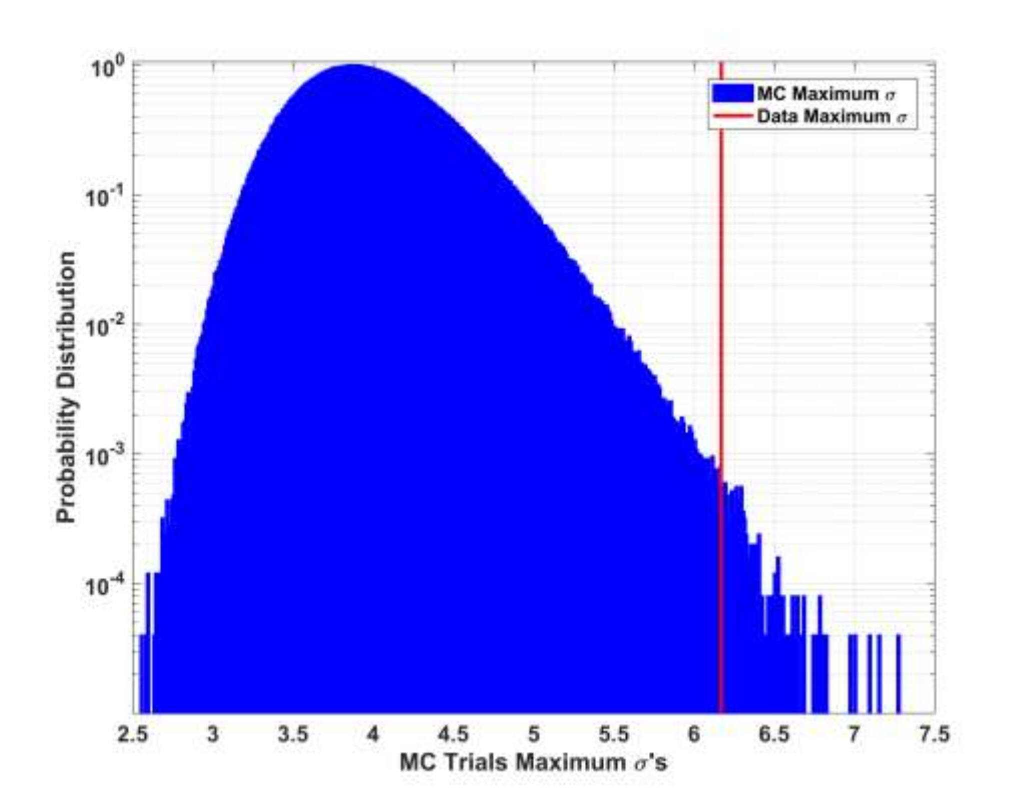
  - Energy threshold scan - $10^{19.0}$, $10^{19.1}$, $10^{19.2}$, $10^{19.3}$ eV.
    - *Not enough events for cuts > $10^{19.3}$ eV*

- Max. σ of 4*4 = 16 is counted as 1 MC.

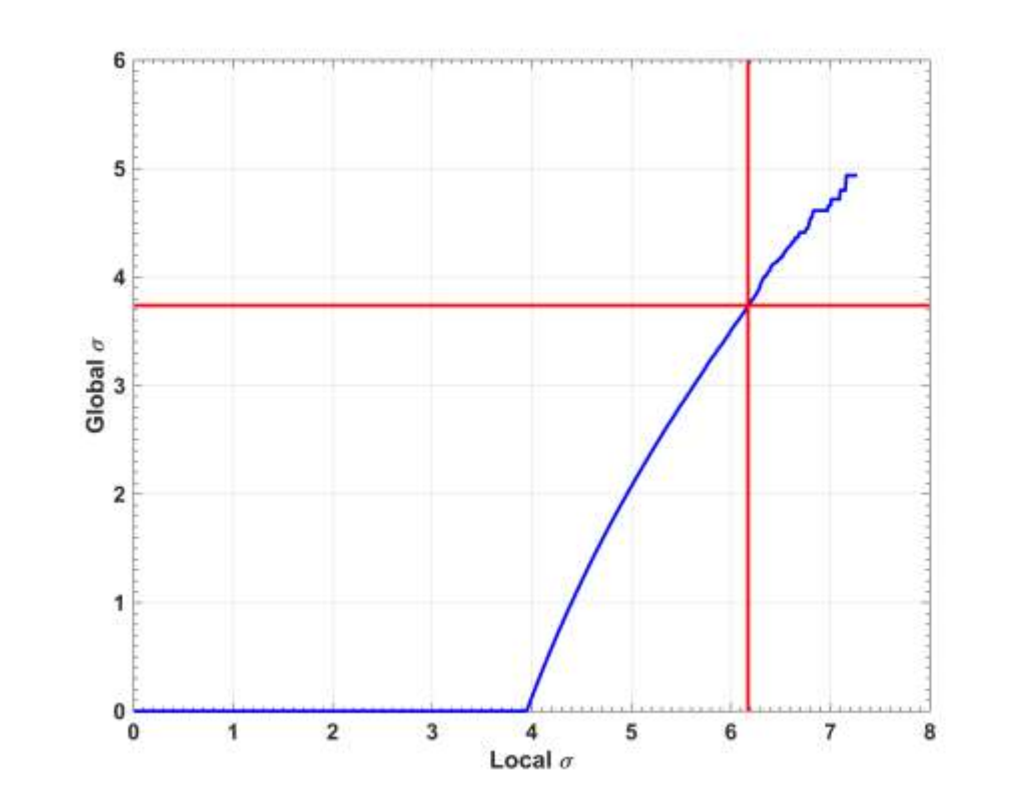
Result: from 2,500,000 sets of 16 maps 232 passed for $3.74\sigma_{global}$

***One sided probability with 16 times scan penalty**

SPECTRUM ANISOTROPY – GLOBAL SIGNIFICANCE

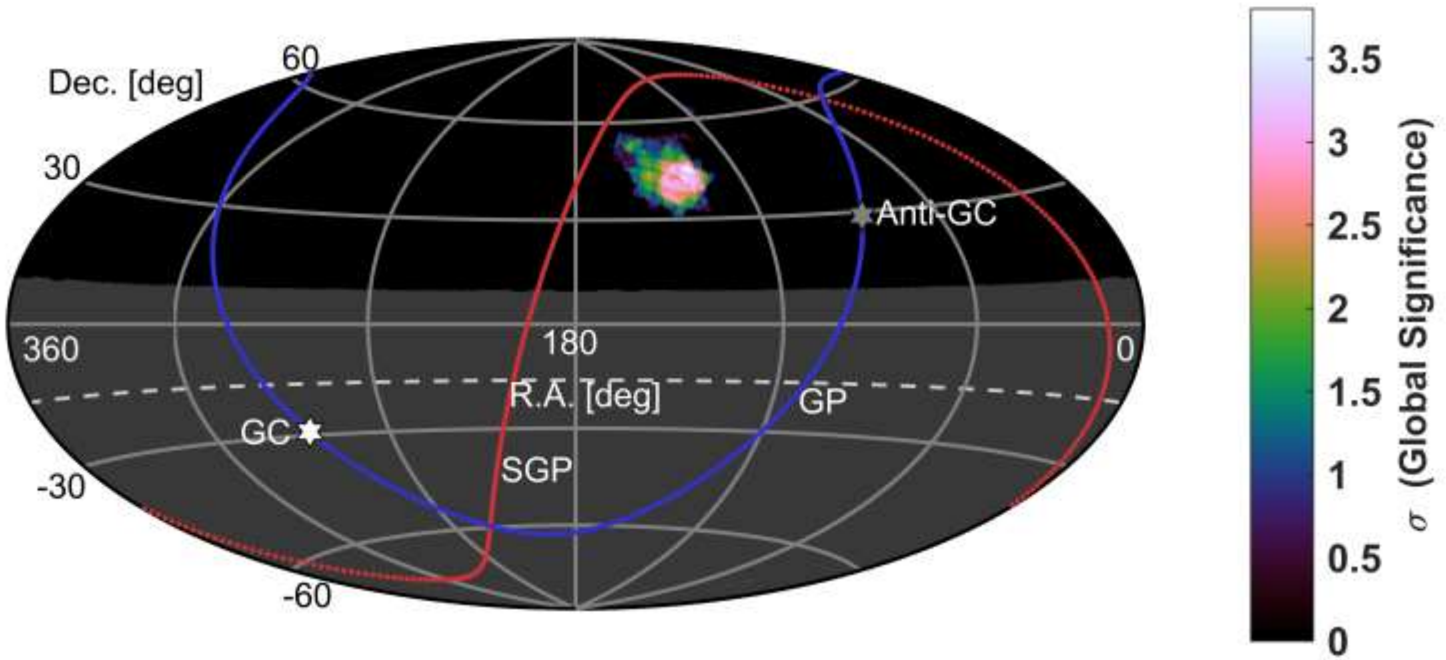


MC trials maximum distribution



Local sigma to Global post-trial sigma

SPECTRUM ANISOTROPY – GLOBAL SIGNIFICANCE



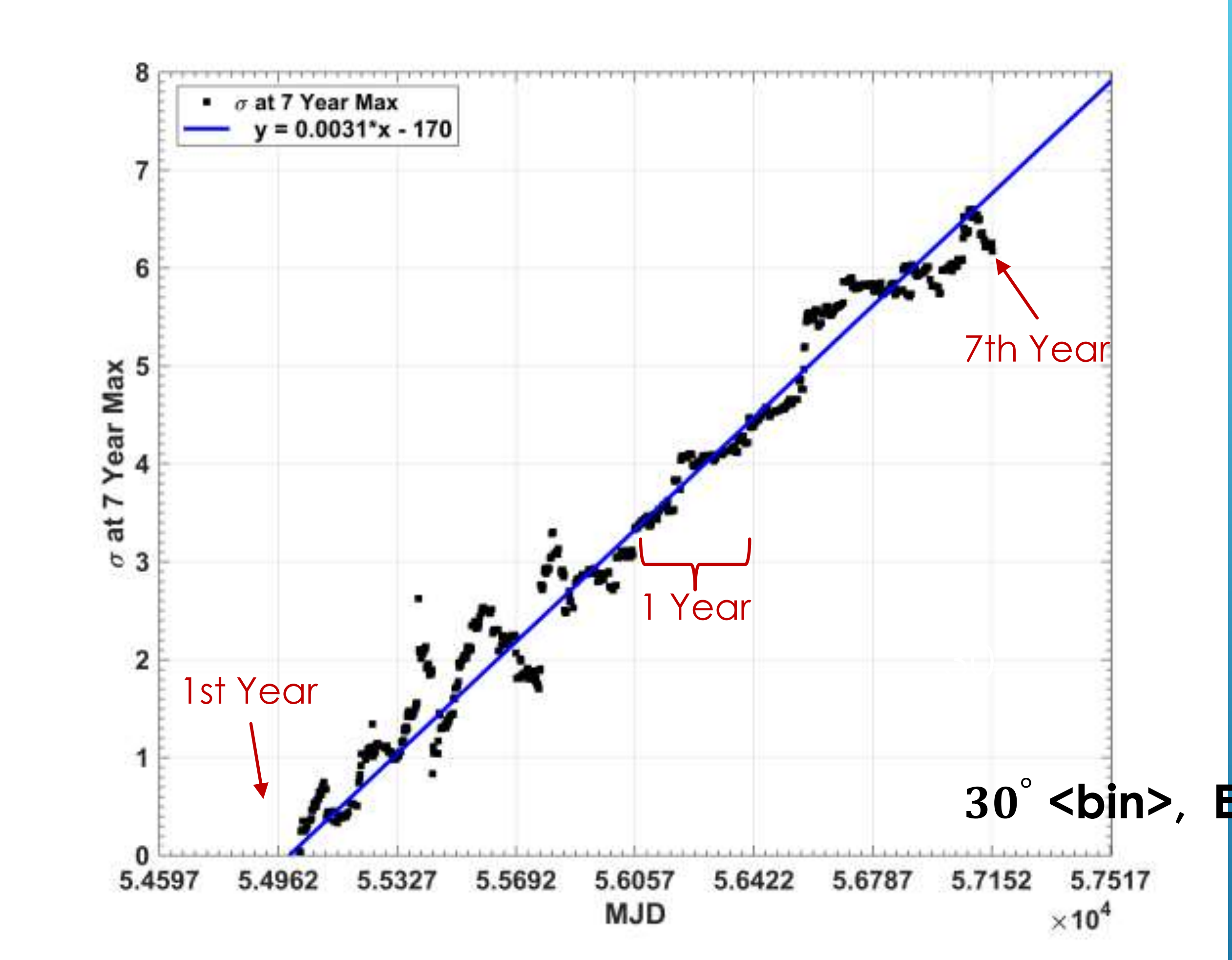
30° <bin>, $E \geq 10^{19.2}$ eV

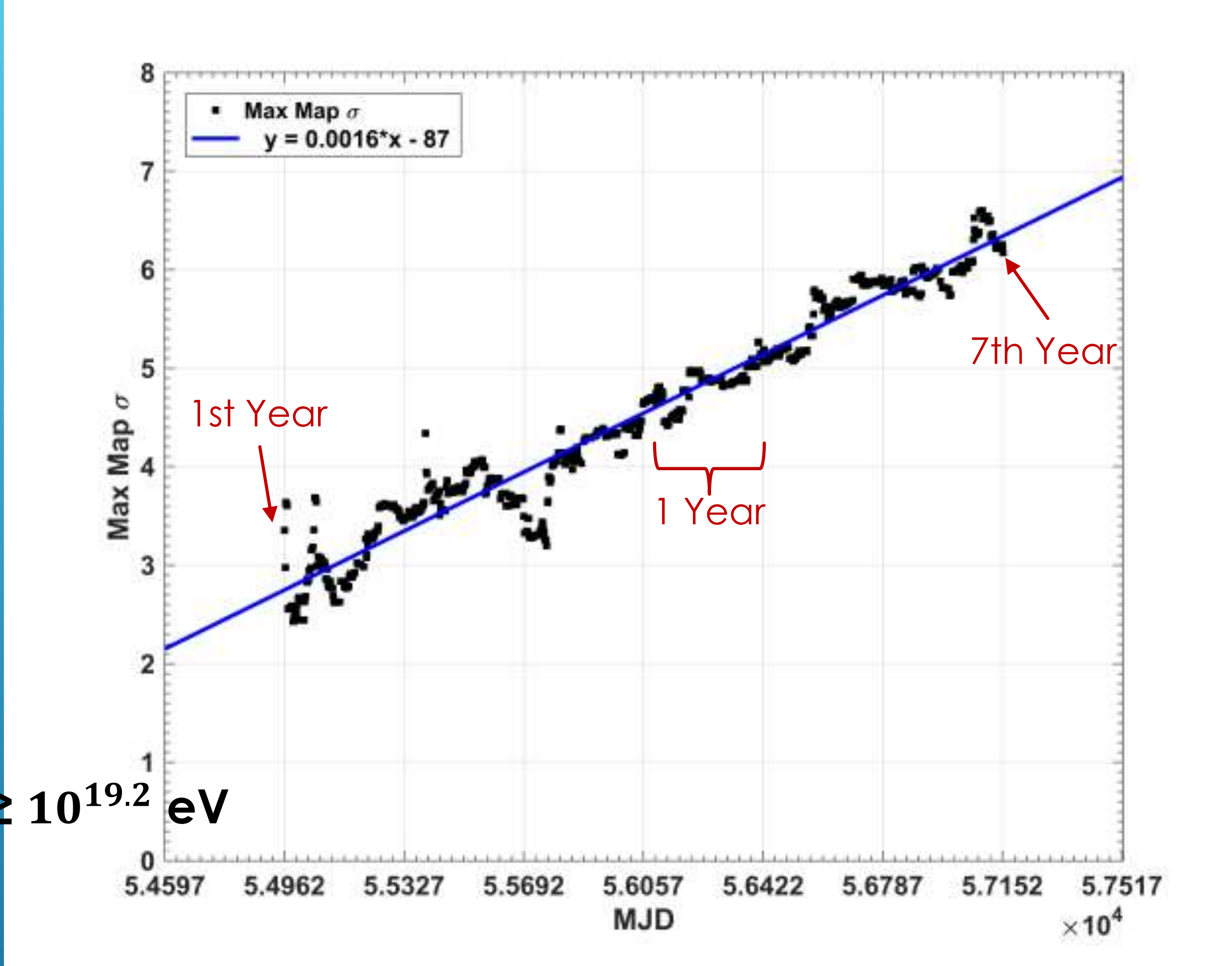
- 138.8° R.A., 44.8° Decl.
- Local sigma: 6.17σ
- Global sigma: 3.74σ

Rough estimate of radius: 1659 grid points σ>0.7. sqrt((1659*0.5)/pi) ≈15°

INTEGRAL DAY SIGNIFICANCE

- Blue line is linear fit





30° <bin>, $E \geq 10^{19.2}$ eV

- σ_{local} at 7 year max location — +1 σ/year
  - Linear correlation 0.989

- Maximum σ_{local} on map
- Linear correlation 0.976

POSSIBLE CAUSES

- Possible source:
  - M82 starburst galaxy most likely source
    - "A Monte Carlo Bayesian Search for the Plausible Source of the Telescope Array Hotspot" https://arxiv.org/abs/1411.5273
    - "Ultra-high-energy-cosmic-ray hotspots from tidal disruption events" https://arxiv.org/abs/1512.04959

- Possible magnetic field:
  - Supergalactic magnetic sheet increases post-GZK flux (E > 50 EeV) and deflects (E < 50 EeV)
    - "The supergalactic structure and the origin of the highest energy cosmic rays" https://arxiv.org/abs/astro-ph/9709250
    - "Cosmic Magnetic Fields in Large Scale Filaments and Sheets" https://arxiv.org/pdf/1512.04959v2.pdf

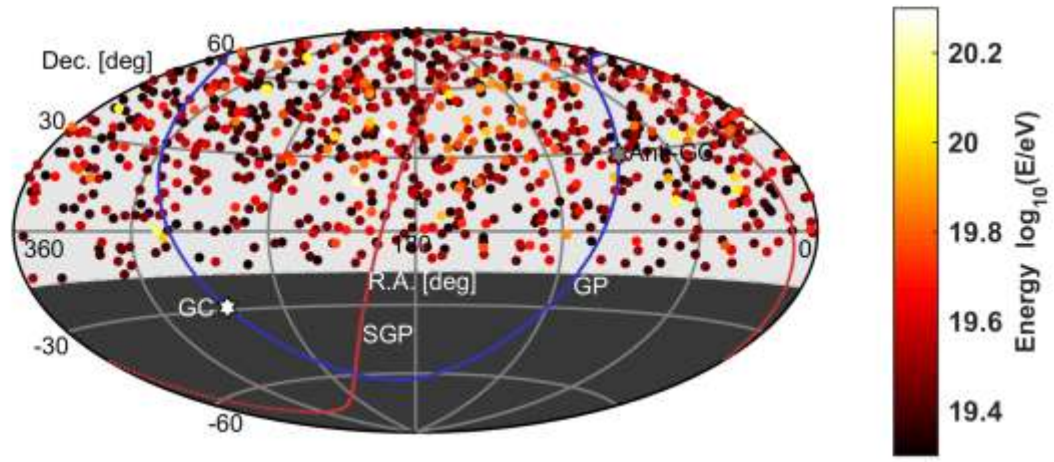
ENERGY SPECTRUM ANISOTROPY CONCLUSION

- There is a **3.74σ** Energy Spectrum Anisotropy ($E \geq 10^{19.2}$ eV) at 138.8° R.A., 44.8° Decl.
    - Deficit at low energies and excess at high energies
    - It has been increasing in significance every year.
- Evidence of magnetic deflection of UHECR

ENERGY-DISTANCE CORRELATION

Is there a direct signature of magnetic deflection?

GOAL



E ≥ *20 EeV*

- **Anisotropy search with fewest assumptions**
  - **Magnetic fields deflect low energy more than high energy.**
  - **Single dominant source**
- **No assumptions for:**
  - source distribution
  - event composition
  - magnetic field configurations.

SOME PREVIOUS STUDIES

Most similar to this analysis

- ***Search for signatures of magnetically-induced alignment in the arrival directions measured by the Pierre Auger Observatory*** **Astroparticle Phys. Vol 35, Issue 6, Jan. 2012, 354-361**
    - **Parameters:**
        - ***20 EeV threshold – USED IN THIS ANALYSIS***
        - ***Lots of other parameters*****:**
            - **Linear correlations with inverse energy**
            - **directional with limit on transverse spread**
            - **20 deg. distance limit**
            - **one event E>45 EeV required**
            - **limit on minimum correlation**
            - **There are a number of other hidden parameters as well…**

"…there is no significant evidence for the existence of correlated multiplets in the present data set."

https://arxiv.org/pdf/1111.2472v1.pdf

SOME PREVIOUS STUDIES

- ***Search for patterns by combining cosmic-ray energy and arrival directions at the Pierre Auger Observatory***
  Aab, A., et al. European Physical Journal C (2015) 75: 269.

  - **Parameters:**
    - **5 EeV cut**
    - ***Lots of other parameters*:**
      - **Number of iterations**
      - **Cone size**
      - **60 EeV events as center of cones.**

"…using observables sensitive to patterns characteristic for deflections in cosmic magnetic fields. No such patterns have been found within this analysis."

https://arxiv.org/pdf/1410.0515v4.pdf

METHOD

ENERGY-DISTANCE RANKED CORRELATION

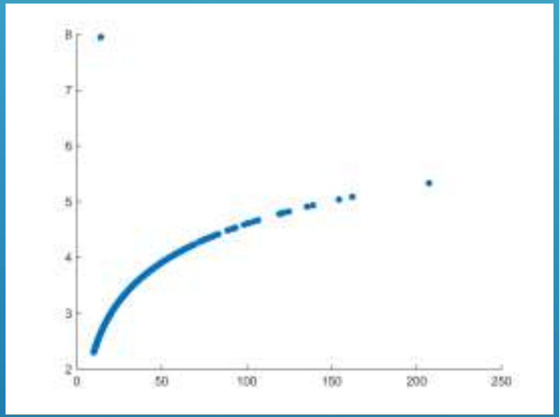
B is a test point

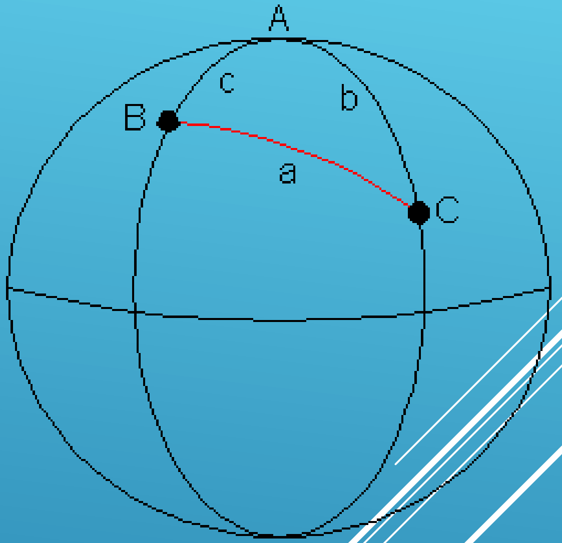
C is an event with Energy >= B

a is the Opening Angle

For each event (i) Kendall's τ correlation $F_i[E_j(E_j > E_i), \theta_{ij}(E_j > E_i)]$

$$\tau = \frac{(\text{number of concordant pairs}) - (\text{number of discordant pairs})}{\frac{1}{2}n(n-1)}.$$

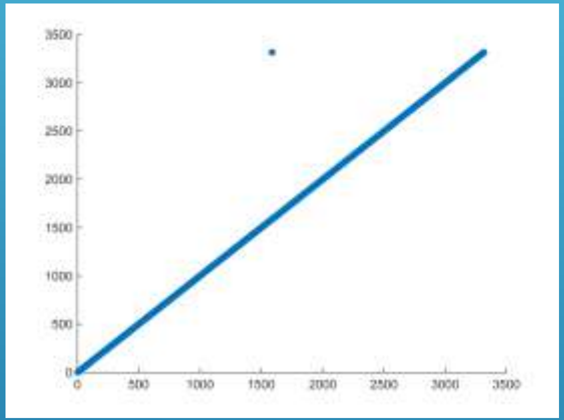




$$\Delta\sigma = \arccos(\mathbf{n}_1 \cdot \mathbf{n}_2)$$

Robust against outliers

Linear Corr: 0.903
Outlier decreases corr: ~0.02



Rank Corr: 0.9994
Outlier decreases corr: 0.0006

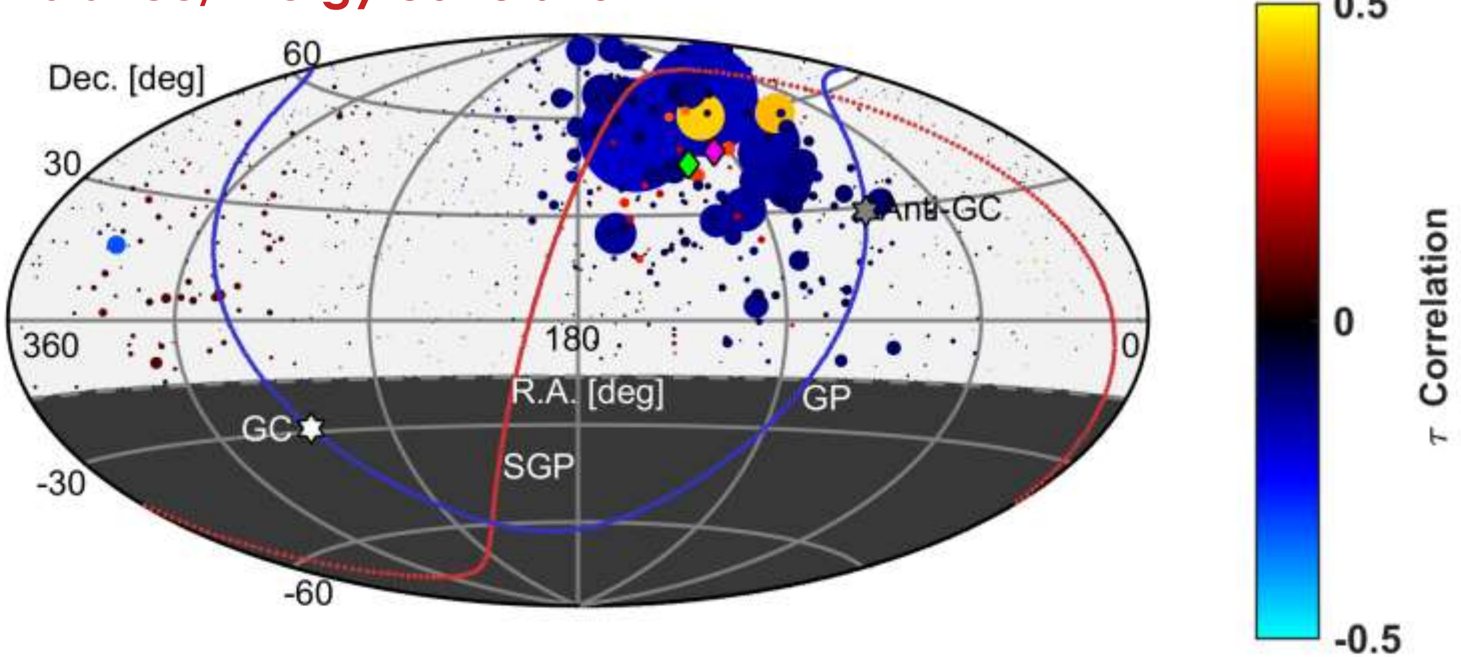
- **No binning**
- **Each event becomes a test point. Test parameters (location and energy cut) decided by the data. Removes free parameters.**

RESULT

DATA RESULT

- Each test point (i) calculate Kendall's τ correlation $F_i[E_j(E_j > E_i), \theta_{ij}(E_j > E_i)]$
  - Negative Correlation: Energy *Increases (decreases)* → Angle *decreases (increases)*
  - Positive Correlation: Energy *Increases (decreases)* → Angle *Increases (decreases)*

- Size proportional to 1/p-value
- Color is Distance/Energy correlation

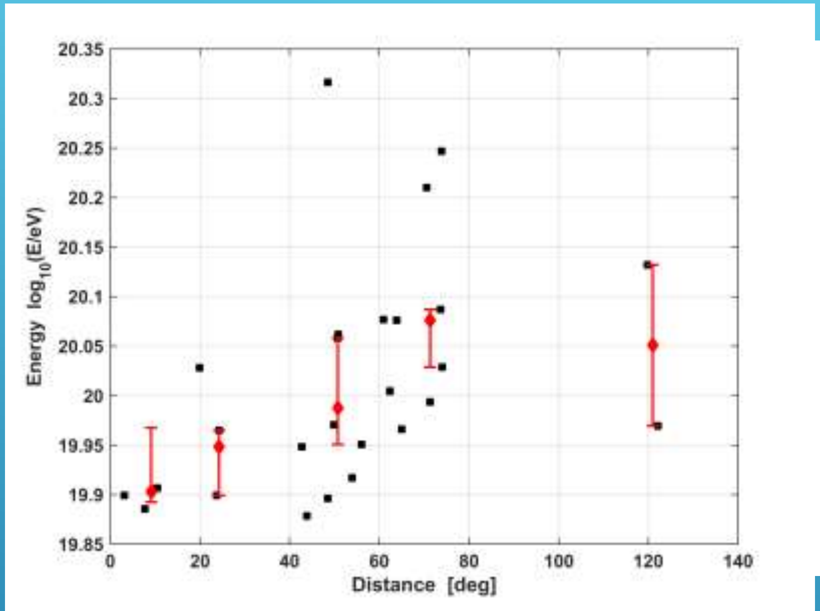


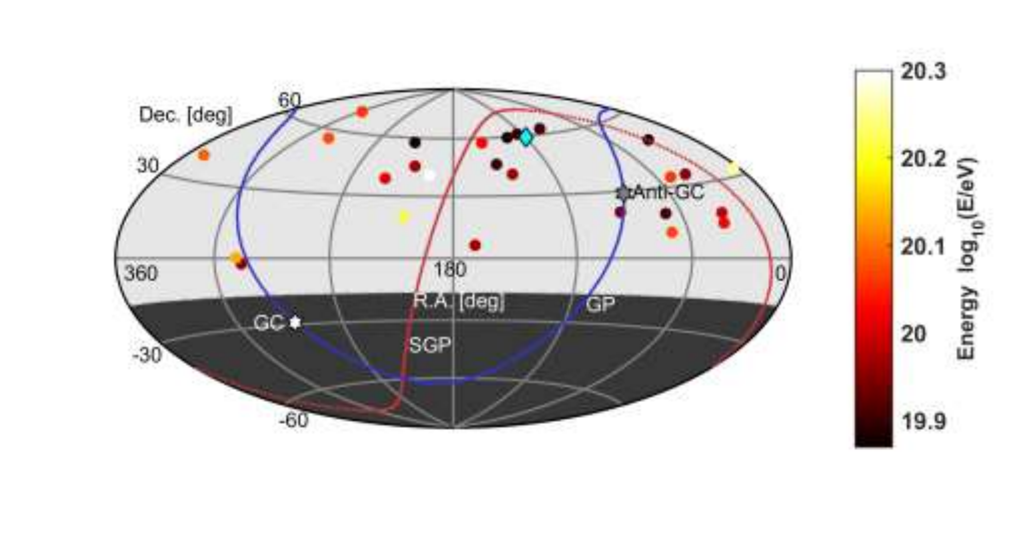
*Each Test Point sample size is different

Events with
E ≥ *20 EeV*

- Spectrum Anisotropy center: 138.8° R.A., 44.8° Dec.
- Correlation Weighted (1/p) Average: 126.2° R.A. , 48.4° Dec.

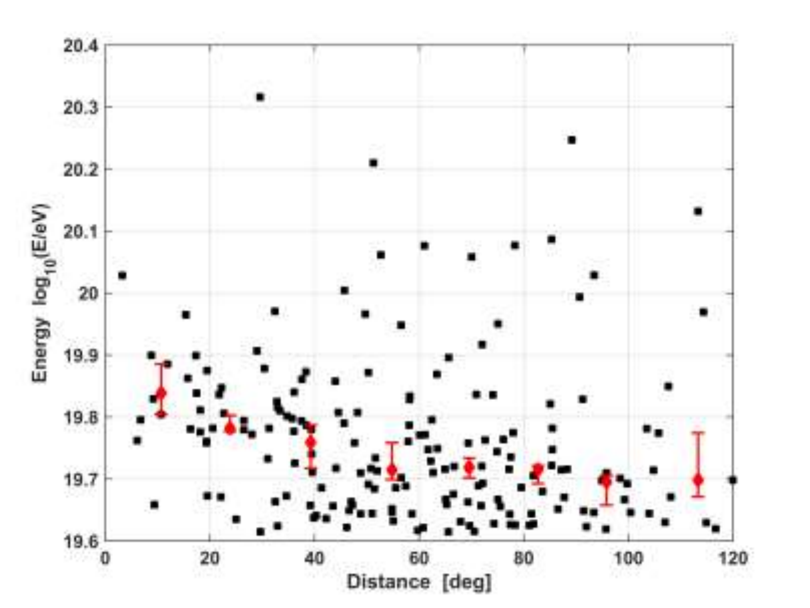
2 MOST SIGNIFICANT POINTS

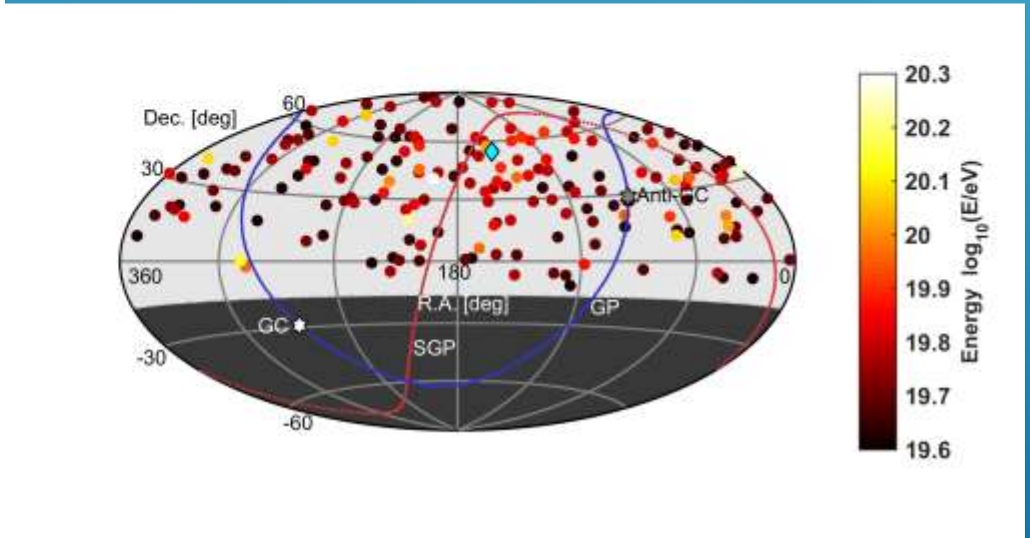




R.A. 119.6, Dec. 59.2
E ≥ 75.0 EeV

tau	p-val	σ-local	σ-global
0.452	0.000927	2.9	2.46





R.A. 154.6, Dec 54.6
E ≥ 41.2 EeV

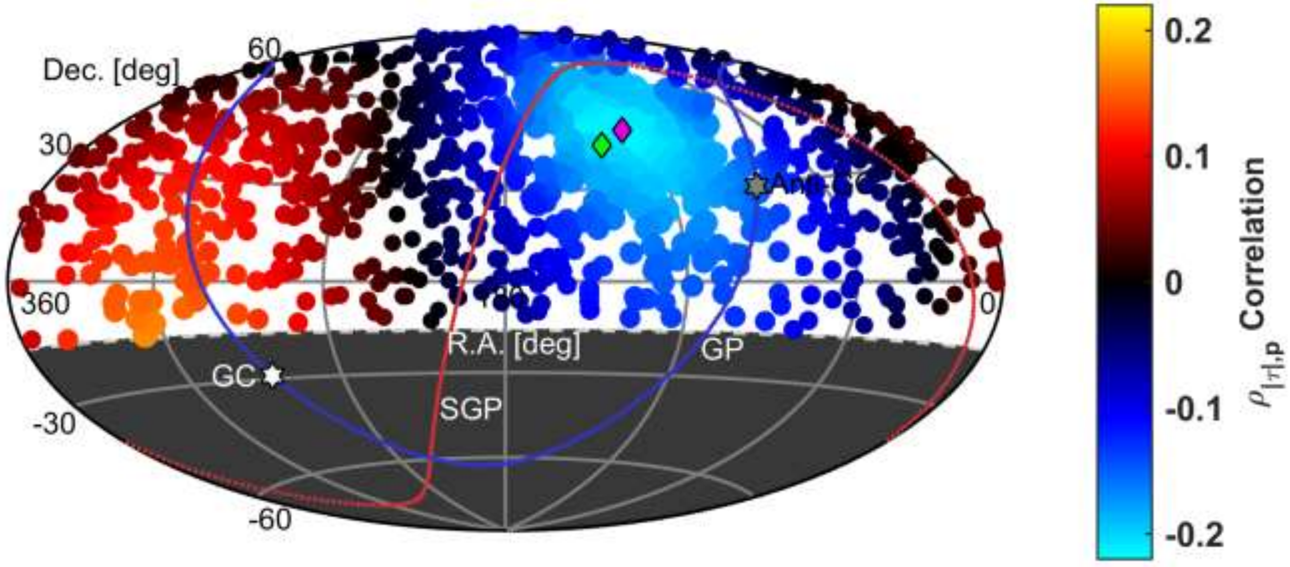
tau	p-val	σ-local	σ-global
-0.188	0.000167	3.4	2.33

Localization of Effect with Unbinned Data

- For each *test point* (i) PARTIAL LINEAR correlation of all *test points* $|\tau|'s$ - $F_i[|\tau_j|, \theta_{ij}]$
  - Account for differing sample size by controlling for p-value

- Negative Correlation: Correlations decrease from that point. *A "source."*
- Positive Correlation: Correlations increase from that point.

- Size proportional to 1/p, Color is $\rho_{|\tau|,p}$



Correlation of correlations assumes single source

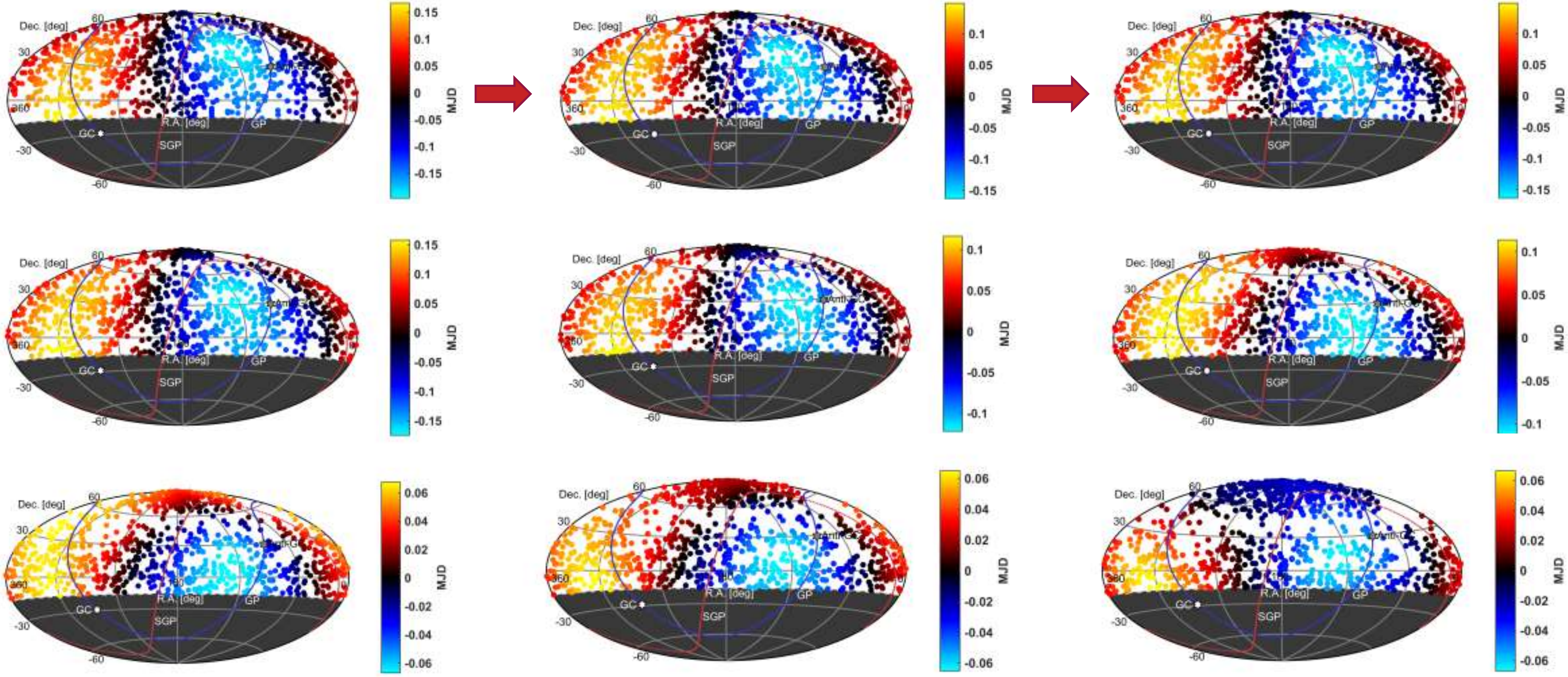
- Circular Mean Weighted by τ's 1/p
  - 126.2° R.A. , 48.4° Dec.

- Maximum $|\rho_{|\tau|,p}|$:
- 125.9° R.A., 49.7° Dec.

*Each test point sample size is the same

NOT A MEASURE OF DENSITY

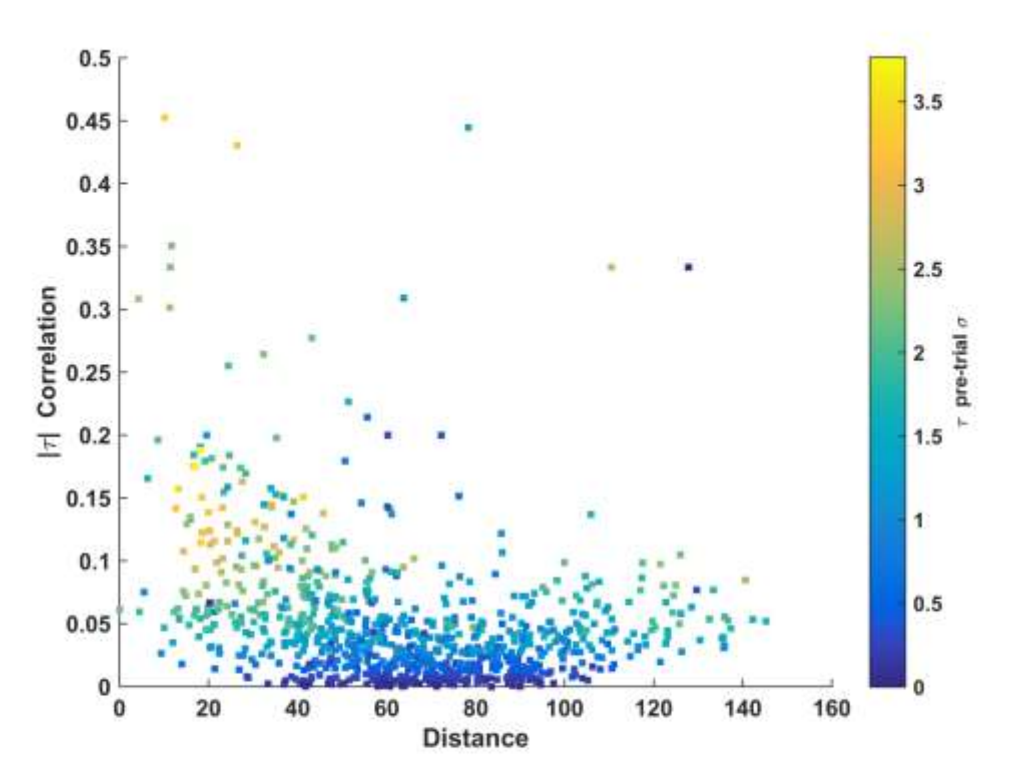
- Data declination is subtracted and folded up toward top of FOV to see how location is tracked
  - Steps of -5 deg. Left to right, top to bottom.

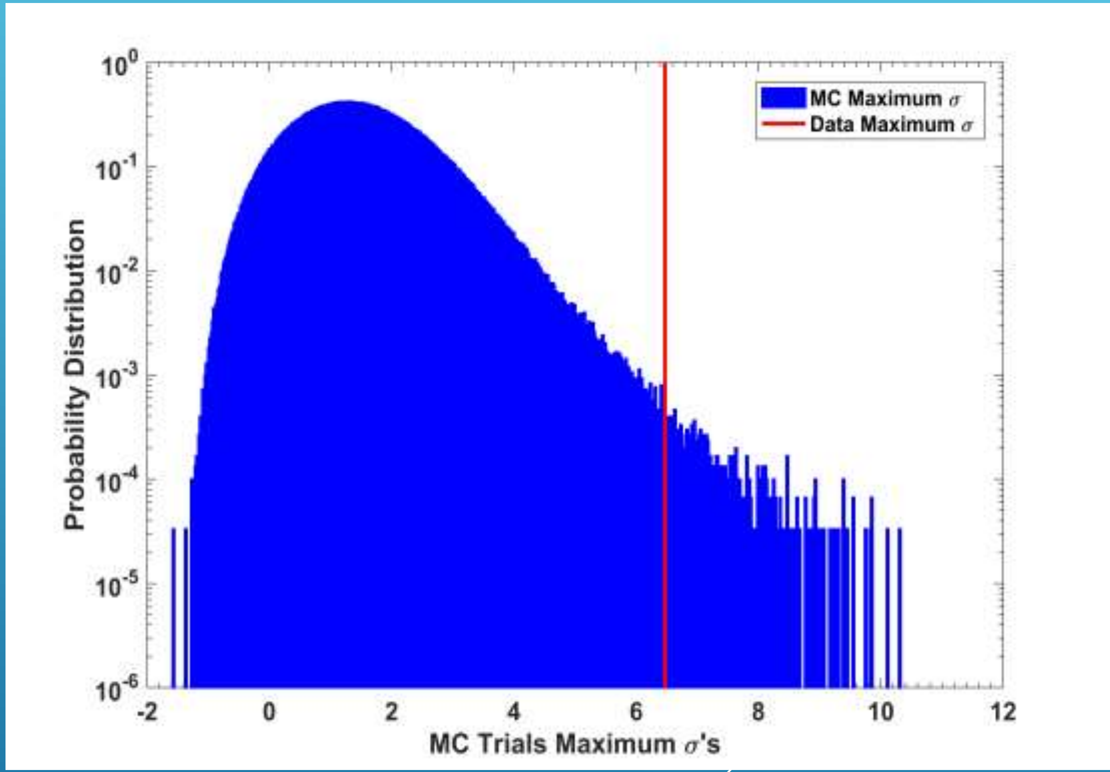


CORRELATION ANISOTROPY SIGNIFICANCE TEST

Single parameter search in MC – use $\sigma_{\rho_{|\tau|,p}}$

- $\sigma_{\rho_{|\tau|,p}}$ = 6.47σ $\rho_{|\tau|,p}$= -0.22
- 125.9° R.A., 49.7° Dec. – 9.4° from *Energy Spectrum Anisotropy* maximum



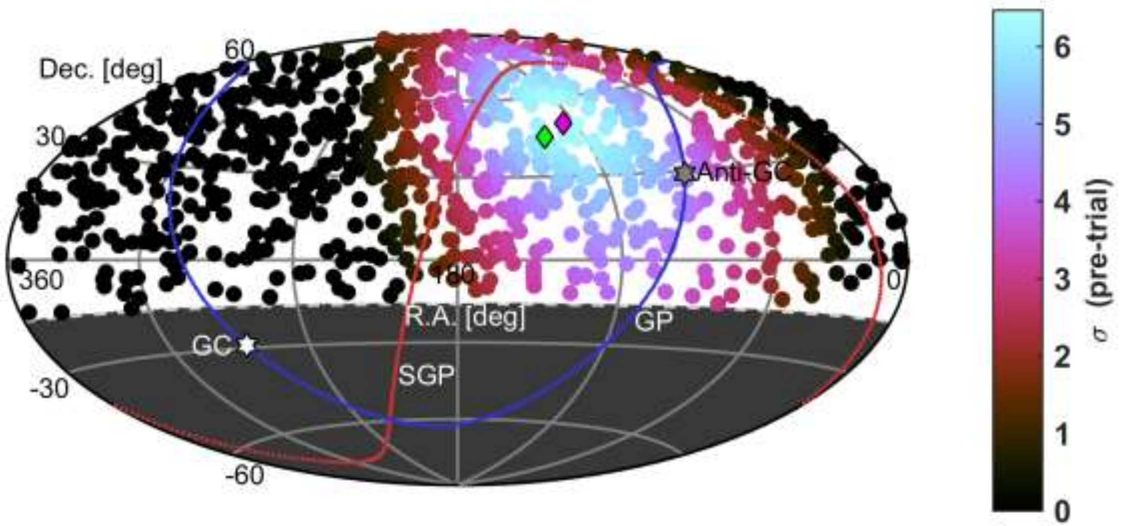


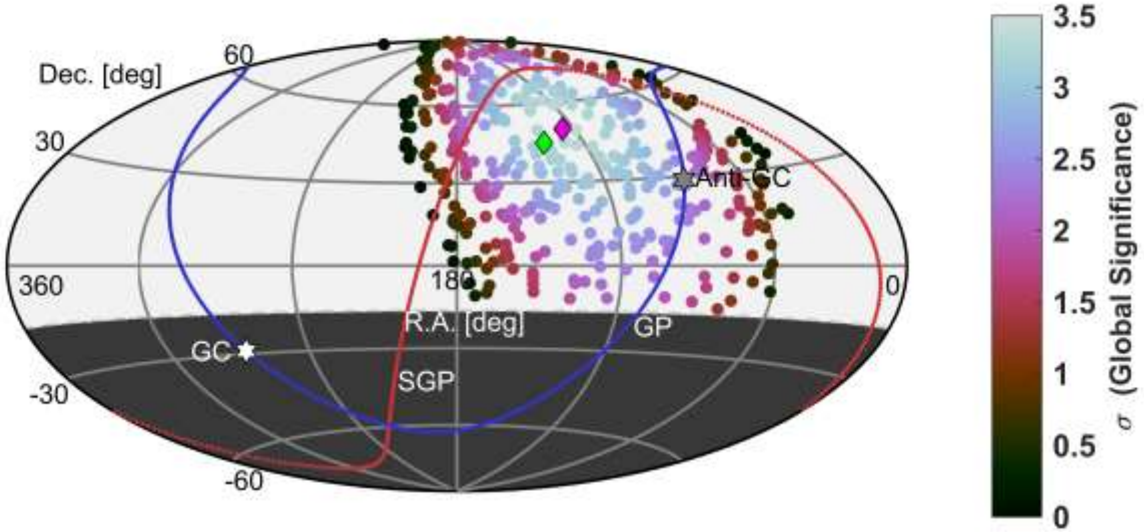
Count MC (or energy scrambled data) with $\sigma \geq \sigma_{data}$ for $\rho_{|\tau|,p}<0$

Result: 556 (or 521) counts out of 1,500,000 - that's 3.37σ

CORRELATION ANISOTROPY SIGNIFICANCE TEST

Pre-trial significance | **Post-trial significance (zeros removed)**



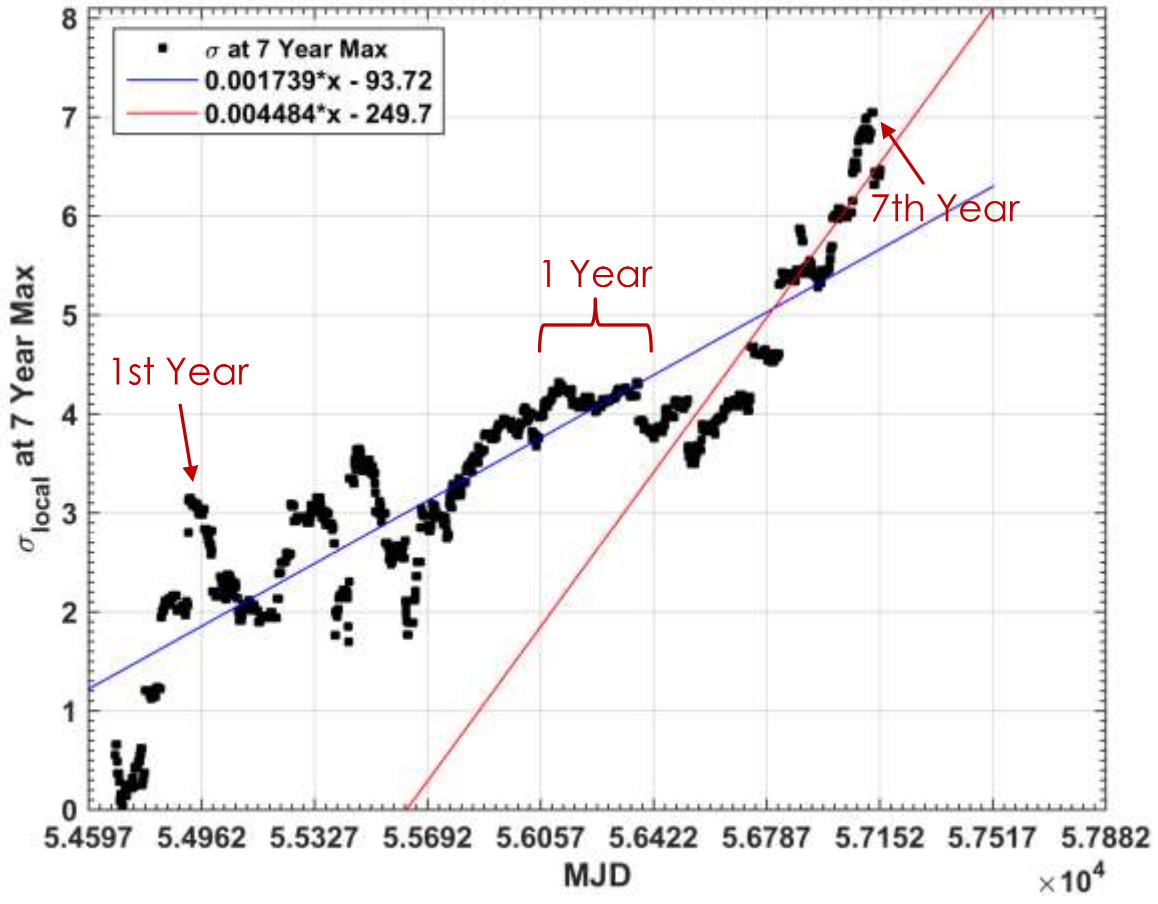


Count MC (or energy scrambled data) with $\sigma \geq \sigma_{data}$ for $\rho_{|\tau|,p}$<0

Result: 556 (or 521) counts out of 1,500,000 - that's 3.37σ

INTEGRAL DAY SIGNIFICANCE

8 year estimate ~$4\sigma_{global}$



- σ_{local} at 7 year max location — +1 σ/year
  - Linear correlation 0.910 (0.944 after 5th year)

- Maximum σ_{local} on map
- Linear correlation 0.905 (0.935 after 5th year)

ENERGY-DISTANCE CORRELATION CONCLUSION

- There is a 3.37σ Energy/Distance Correlation Anisotropy ($E \geq 10^{19.3}$ eV) located at 125.9° R.A., 49.7° Dec.
  - It has increased in significance 6 out of 7 years.

- Direct evidence of magnetic deflection of UHECR

COMBINED MEASURE OF ENERGY SPECTRUM ANISOTROPY AND ENERGY/POSITION CORRELATION

- **Energy Spectrum Anisotropy significance: 3.74σ**
- **Energy-Distance Correlation Anisotropy significance: 3.37σ**
- ***Stouffer's Method combined significance: 5.03σ***

NEXT UP:

- **Hot/Coldspot Anisotropy (a result of Spectrum AND Position Correlation): 5.4σ**

HOT/COLDSPOT SUMMARY ANALYSIS

Is there a direct signature of magnetic deflection?

METHOD

LI-MA SIGNIFICANCE

- Compare N events "On" (inside) to expectation – How significant is the excess or deficit?
- Derived by Poisson likelihood ratio and approximation to χ^2 (like the Poisson Likelihood GOF)

$$S = sign(N_{on} - N_{bg})\sqrt{2}\left\{N_{on}\, ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right] + N_{off}\, ln\left[(1+\alpha)\left(\frac{N_{off}}{N_{on}+N_{off}}\right)\right]\right\}^{1/2}$$

- N_{on} = # data in bin
- N_{off} = # data outside bin
- α = ratio of N_{on} / N_{off} for simulated isotropy

- N_{bg} expectation

$$N_{bg} = \alpha N_{off}^{data}$$

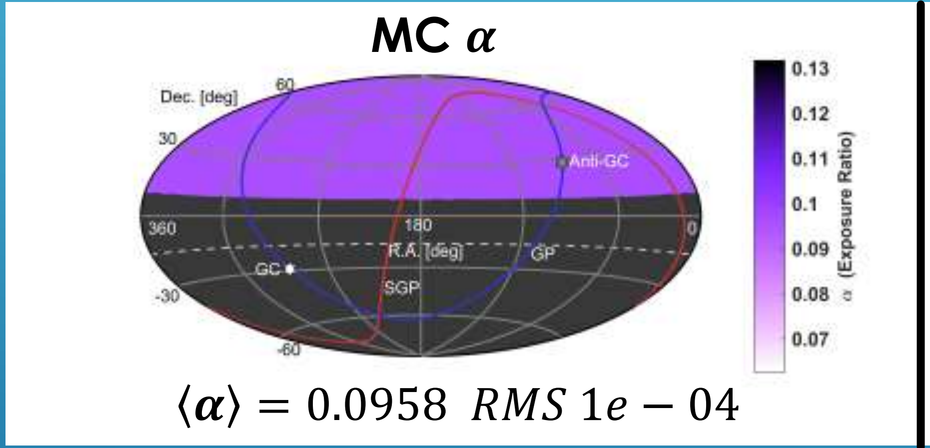
- N_{off} Normalized by exposure ratio

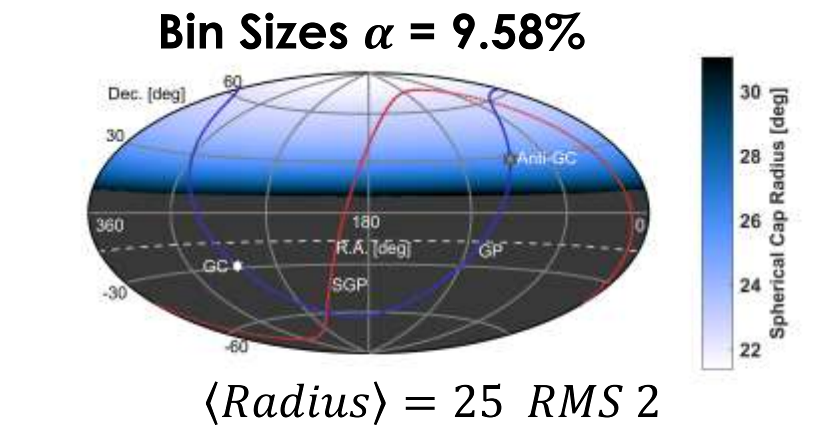
Test Used Previously by T.A. In:
INDICATIONS OF INTERMEDIATE-SCALE ANISOTROPY OF COSMIC RAYS WITH ENERGY GREATER THAN 57 EeV IN THE NORTHERN SKY MEASURED WITH THE SURFACE DETECTOR OF THE TELESCOPE ARRAY EXPERIMENT

ESTIMATED BACKGROUND – EQUAL EXPOSURE

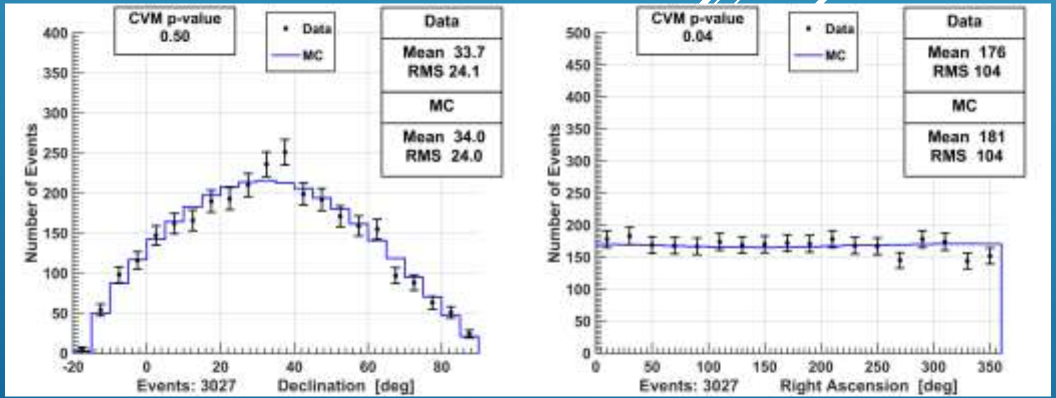
- Equal exposure binning samples the sky equally.
  - "On" exposure such that bin size average = 15°, 20°, 25°, 30°
- Maximum Li-Ma significance for mean bin size of 25°

- $\alpha = N_{on}^{MC}/N_{off}^{MC}$ = constant





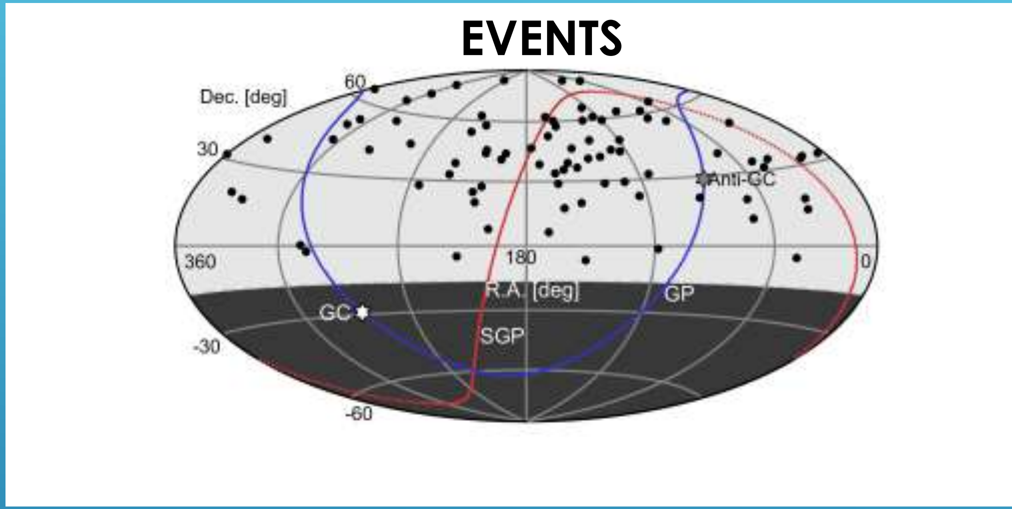
25° <bin>

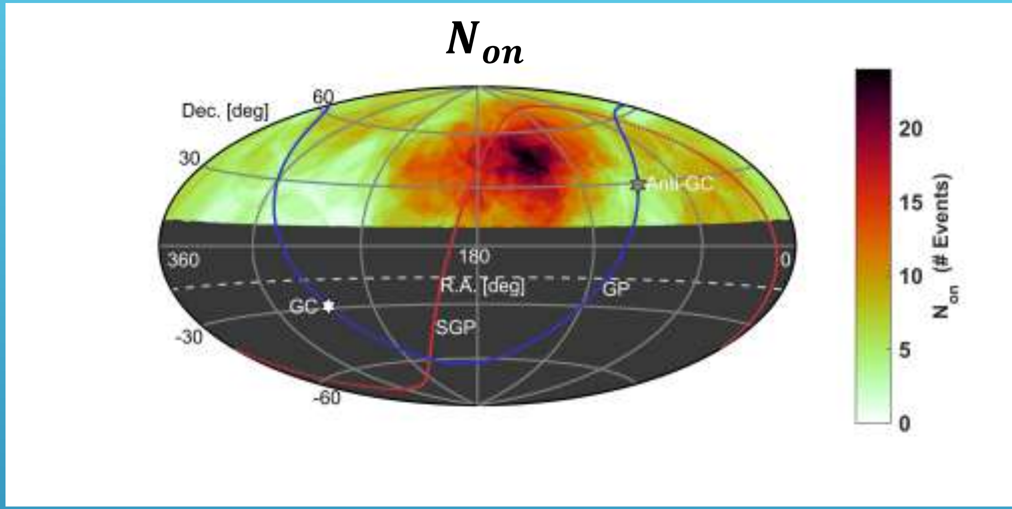


RESULT

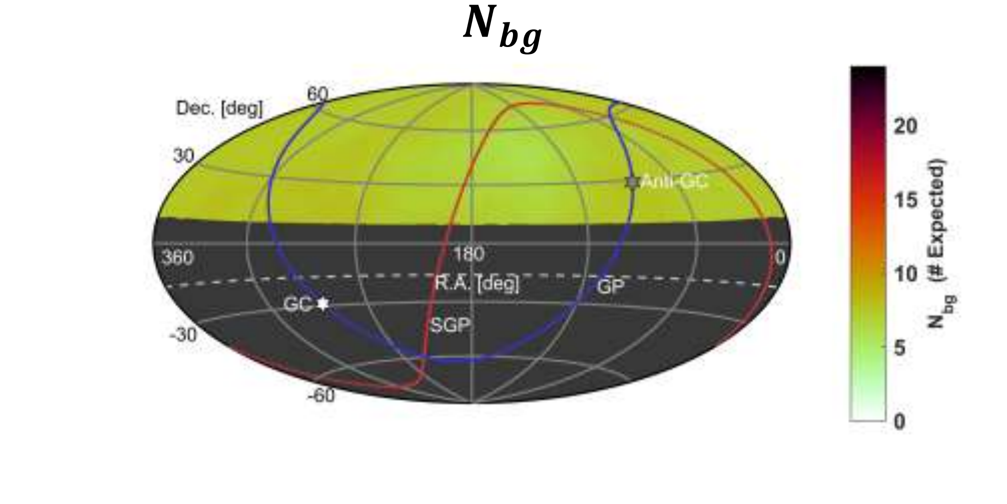
TWO ENERGY BIN LI-MA STATISTICS

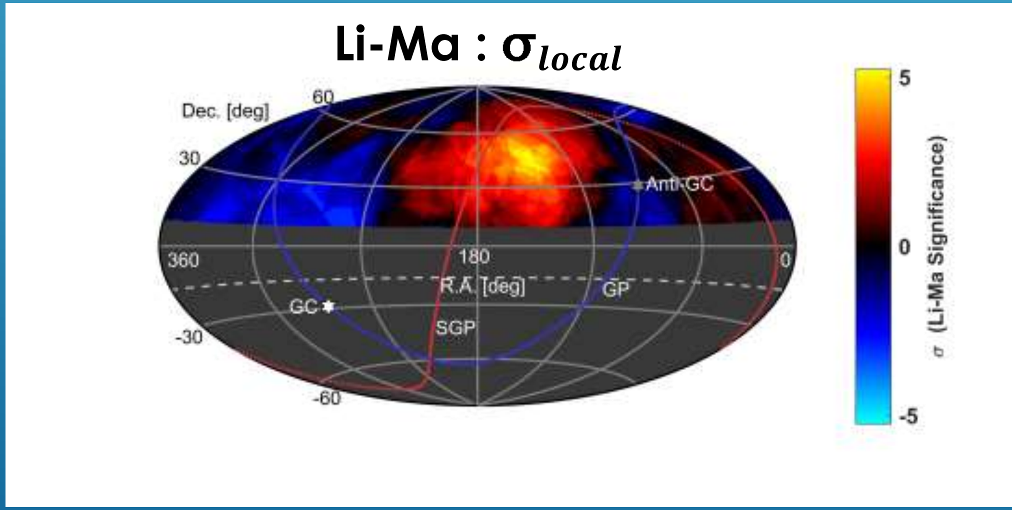
Data: E ≥ 57 EeV ($10^{19.75}$) – a priori choice from previous studies





\# Events in 25 <bin>



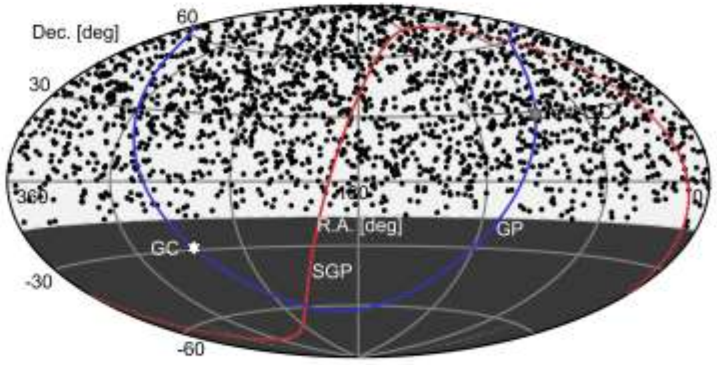


Pre-trial significance

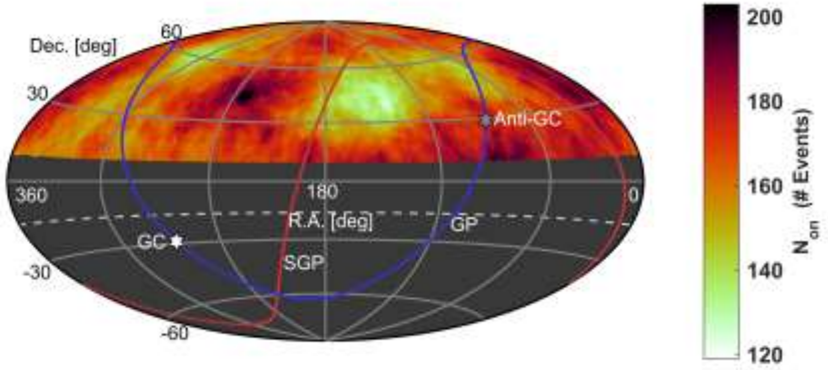
TWO ENERGY BIN LI-MA STATISTICS

Data: $10^{19.1} \leq E \leq 10^{19.75}$

EVENTS

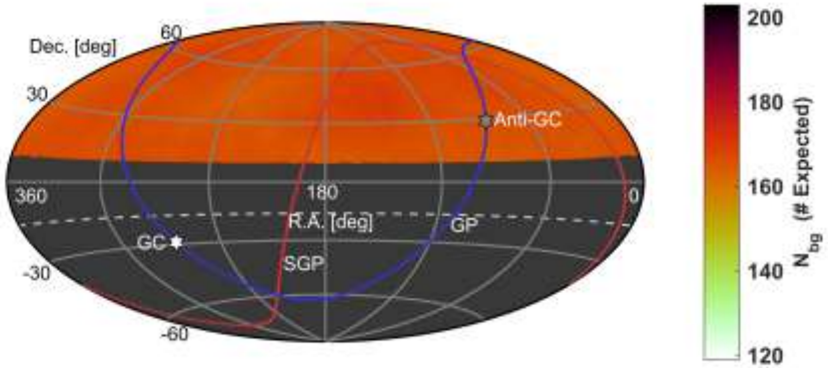


N_{on}

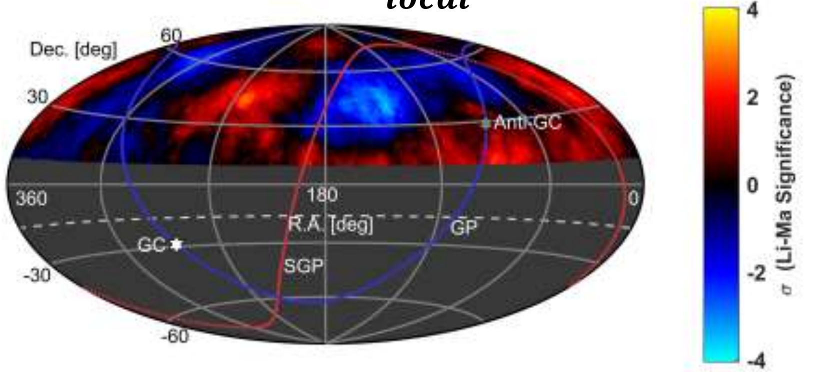


\# Events in 25 <bin>

N_{bg}



Li-Ma : σ_{local}

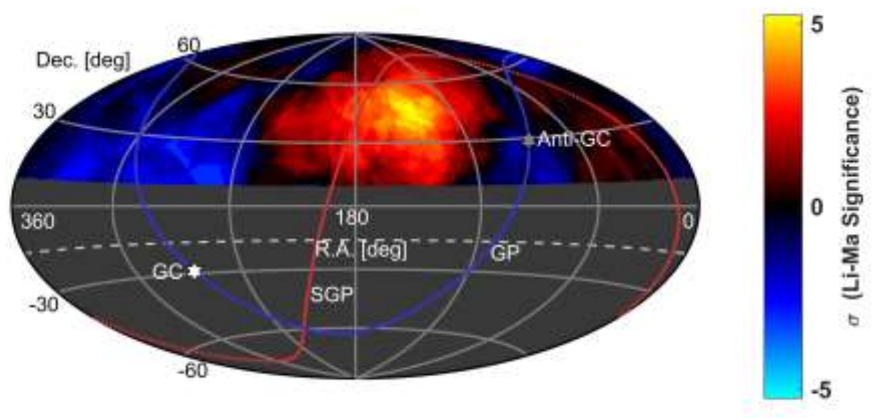


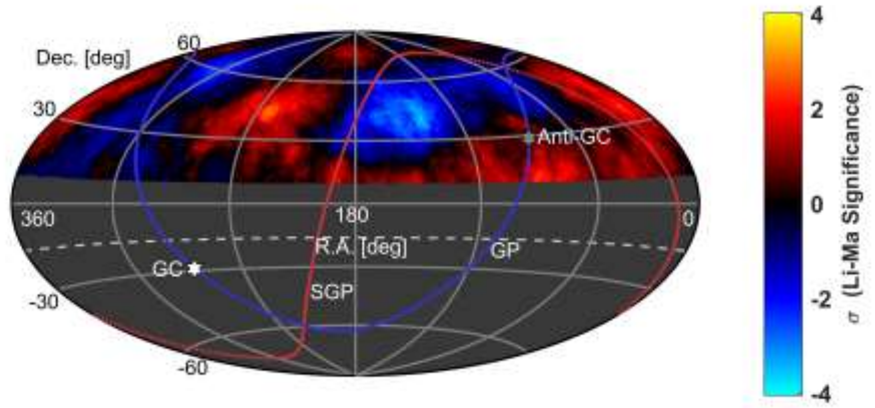
Pre-trial significance

- Energy threshold scanned- $10^{19.0}$, $10^{19.1}$, $10^{19.2}$, $10^{19.3}$ eV.

COMBINED LI-MA STATISTICS

High Energy HOTSPOT



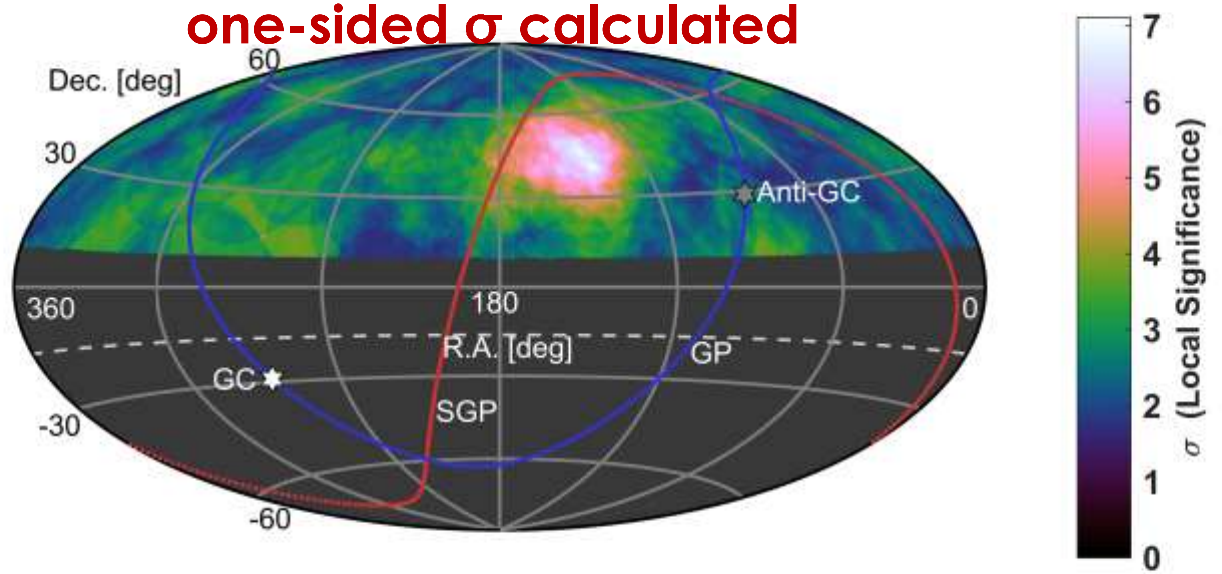


Low Energy COLDSPOT

- Maximum σ_{local} =7.11 at 142° R.A., 40° Dec.
  - 5° from Energy Spectrum Anisotropy
  - 16 degrees from supergalactic plane

Combined σ: two-sided test probabilities multiplied

one-sided σ calculated



Cap with maximum joint significance (p-values multiplied)
HOT excess = 5.24 σ_{local} and COLD deficit = -4.03 σ_{local}

EVIDENCE OF CAUSAL CONNECTION

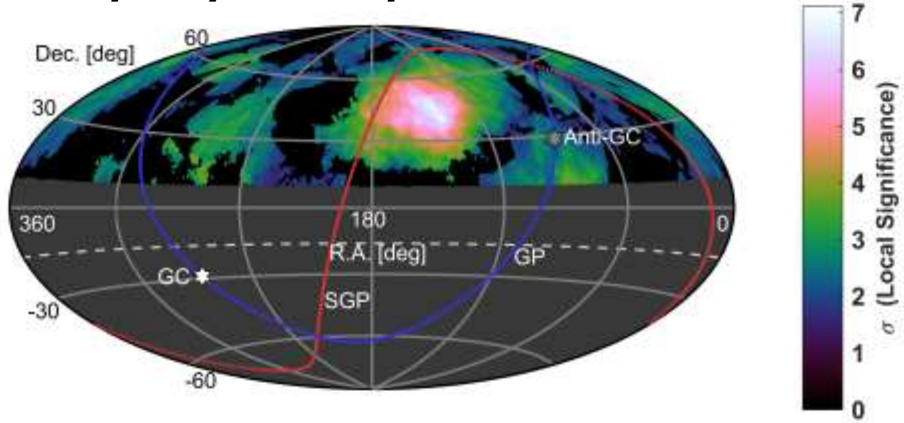
Evidence for physical cause resulting in an excess at same point as deficit

- **Energy-Distance Correlation Anisotropy is direct evidence.**
- **Measured independently the Hotspot and Coldspot have the same size ~25°**

SUPERGALACTIC PLANE SHIFT

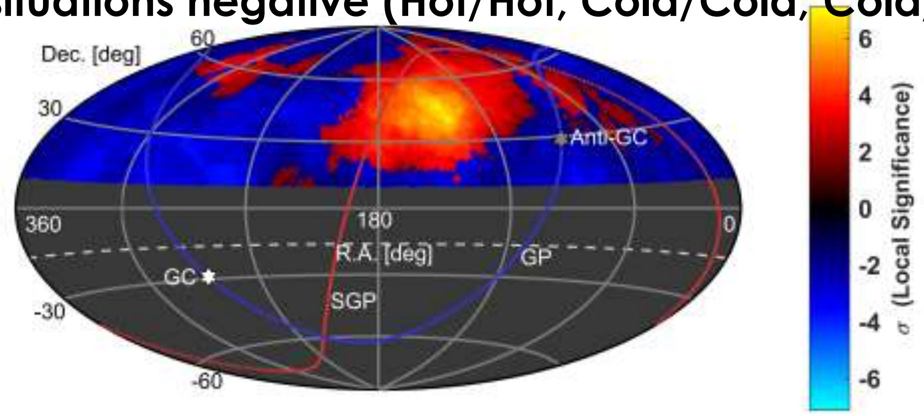
Supergalactic magnetic sheet increase flux of post-GZK particles(E>50 EeV) and deflects (E<50 EeV) – suggested by (Biermann, Kang, Ryu)[1, 2]

Event Density Asymmetry – Hot/Cold and Cold/Hot

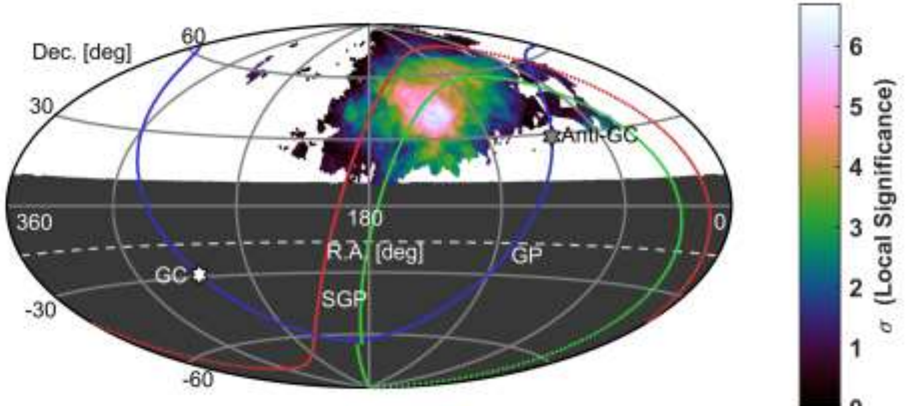


Test for post-trial significance

Hot/Cold positive
All other situations negative (Hot/Hot, Cold/Cold, Cold/Hot)



Looks like supergalactic plane



Sky positions where there is hot/cold behavior
30° <bin>

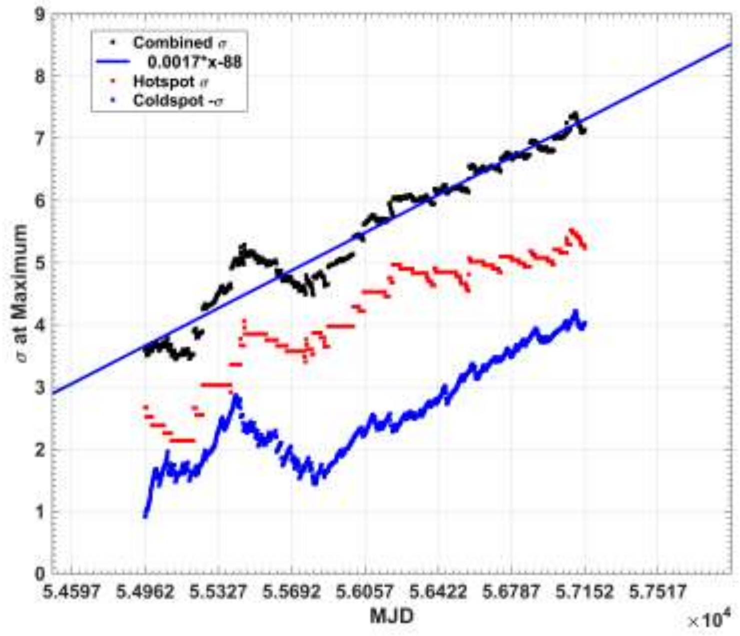
Green line is linear in SG weighted by energy anisotropy σ^2 of Hot/Coldspot points.

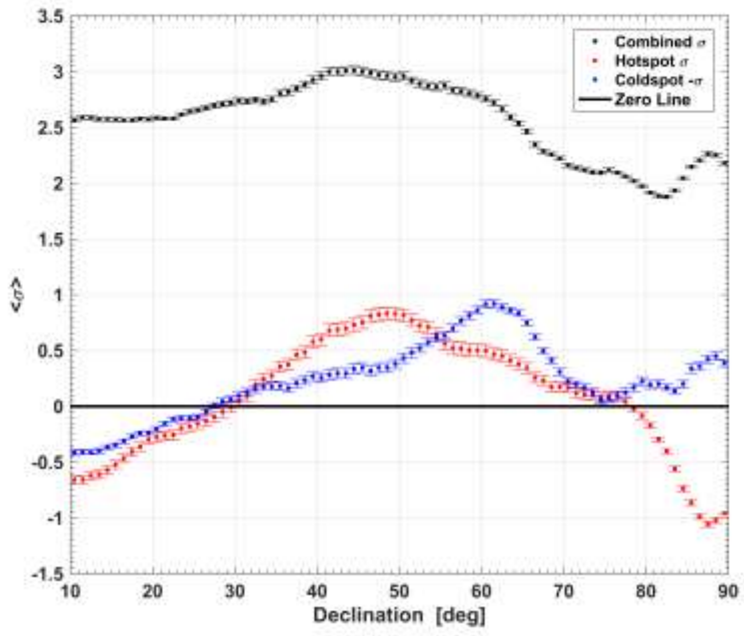
Result is SGP shifted -16°

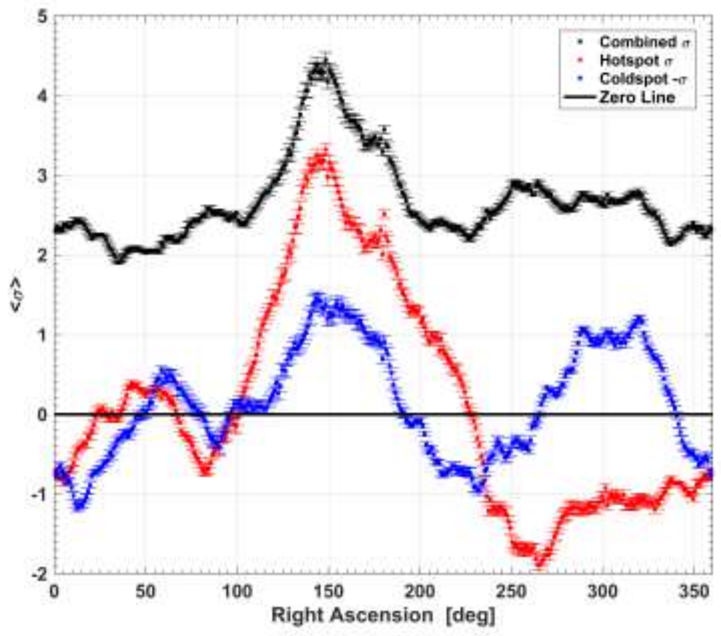
TWO ENERGY BIN CORRELATIONS

These analyses can be done due to equal opening angle grid

Li-Ma σ_{local} for Combined, Low Energy Bin, and High Energy bin







Correlated in time (Integral day data σ_{local} at max. point)

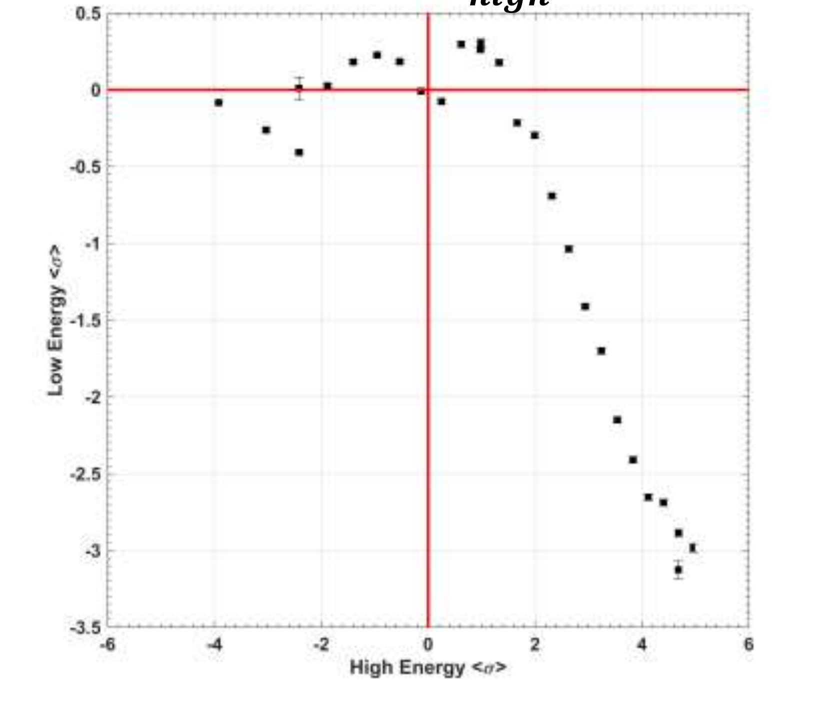
Correlated in Declination (1° Dec. bins average σ_{local})

Correlated in Right Ascension (1° Dec. bins average σ_{local})

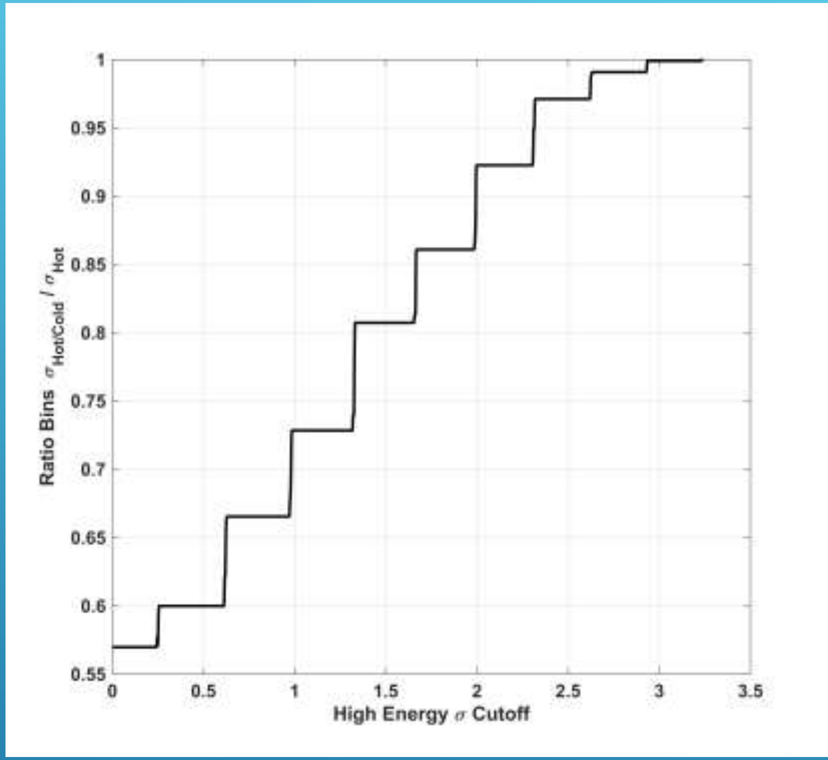
TWO ENERGY BIN CORRELATIONS

Li-Ma σ_{local} for Low Energy Bin, and High Energy bin

Linear Correlation σ_{high} >0 : -0.625



Excesses directly correlated with deficits (average of grid points within 0.1 σ_{high} bins)



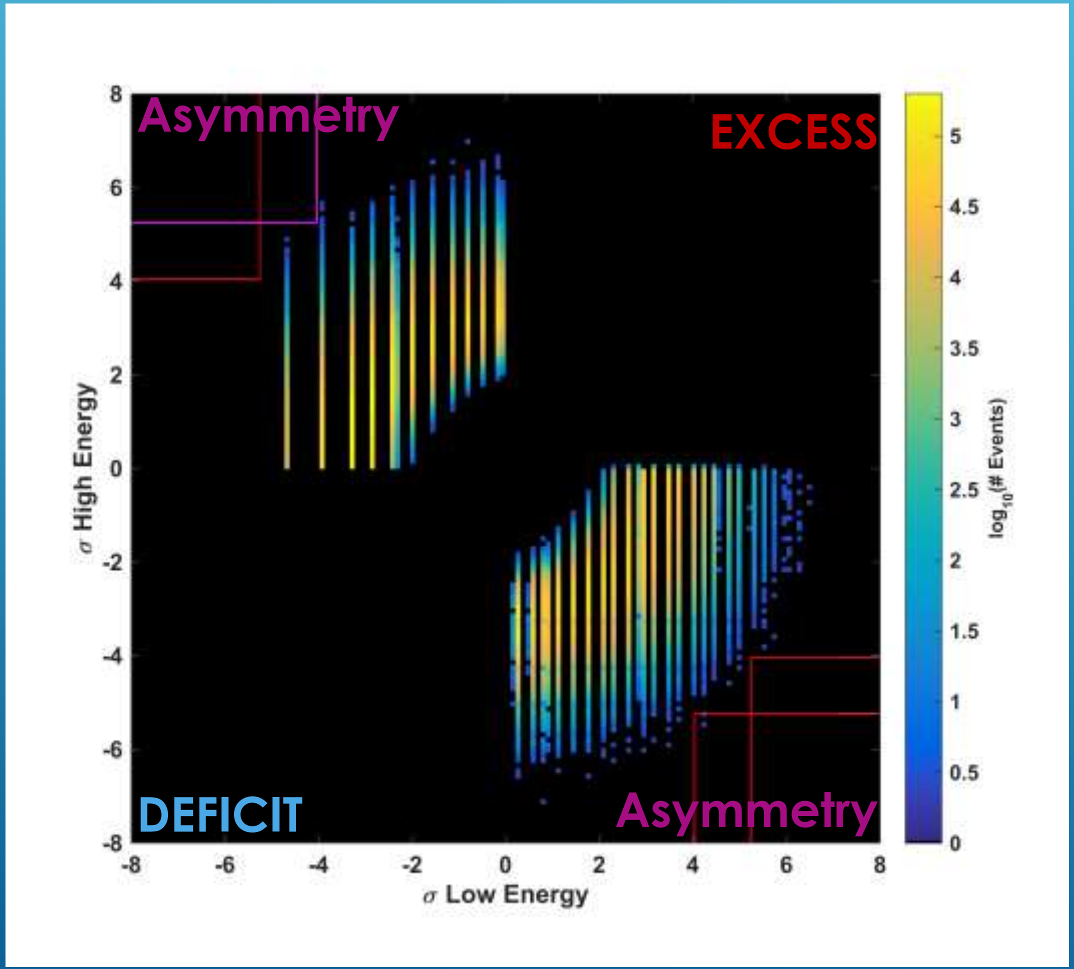
 # Grid points with Hot/Coldspot divided by # Hotspot Versus high energy bin σ_{high} cutoff (100% of grid points with σ_{high} > 3.24 are a Hot/Coldspot)

EVENT DENSITY ASYMMETRY SIGNIFICANCE

EVENT DENSITY ASYMMETRY SIGNIFICANCE

- Testing MC trials for combined significance underestimates significance
  - Maxima with excess/deficit in both bins are not signatures of magnetic deflection
- Significance of MC is found from separate energy bin σ thresholds.

MC sets outside of four bounds pass the test



MC Sets scanned same bin sizes and energy thresholds as data

- 3 isotropic MC have equal or greater event density asymmetry out of 16 * 87.89 million
- 5.4 σ significance

COMBINED MEASURE OF ENERGY SPECTRUM ANISOTROPY AND ENERGY/POSITION CORRELATION

- **Energy Spectrum Anisotropy significance: 3.74σ (parameters scanned and accounted for)**
- **Energy-Distance Correlation Anisotropy significance: 3.37σ (parameters not scanned)**
  - ***Stouffer's Method combined significance: 5.03σ***
- **Hot/Coldspot Anisotropy (a result of Spectrum AND Position Correlation): 5.4σ**

CONCLUSION

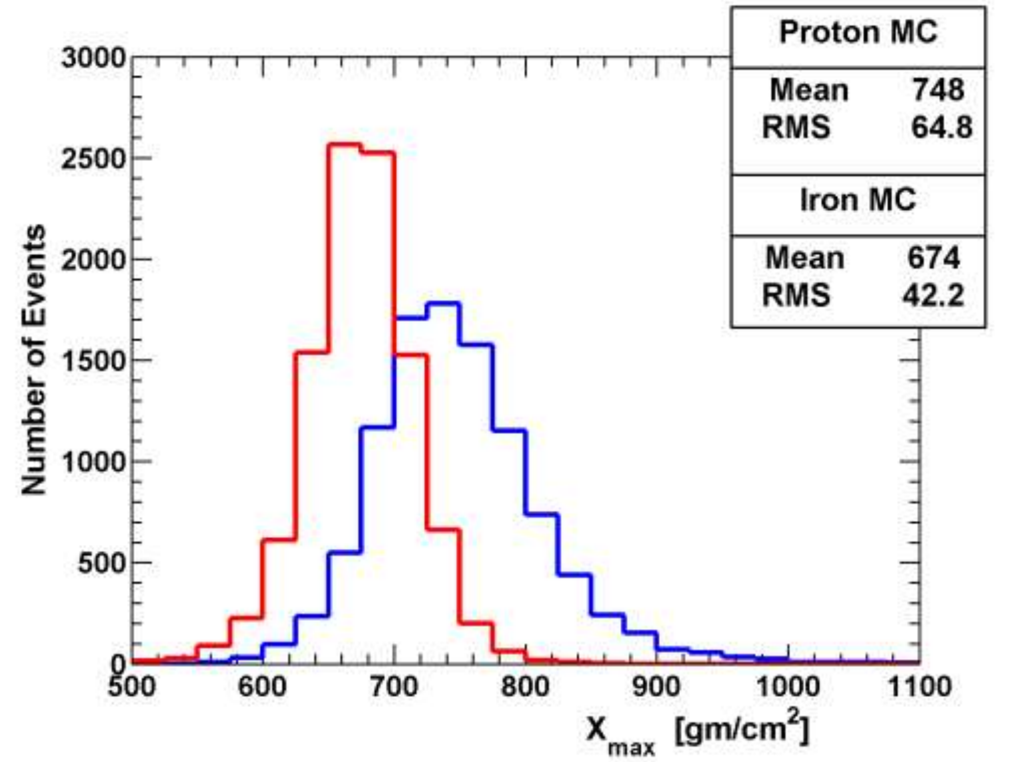
- Hot/Coldspot Event Density Asymmetry (energy-position correlation)
  - **Post-trial σ = 5.4**

- **The previously reported Hotspot is correlated with a deficit of low energy events. This *observation* is suggestive of magnetic deflection.**

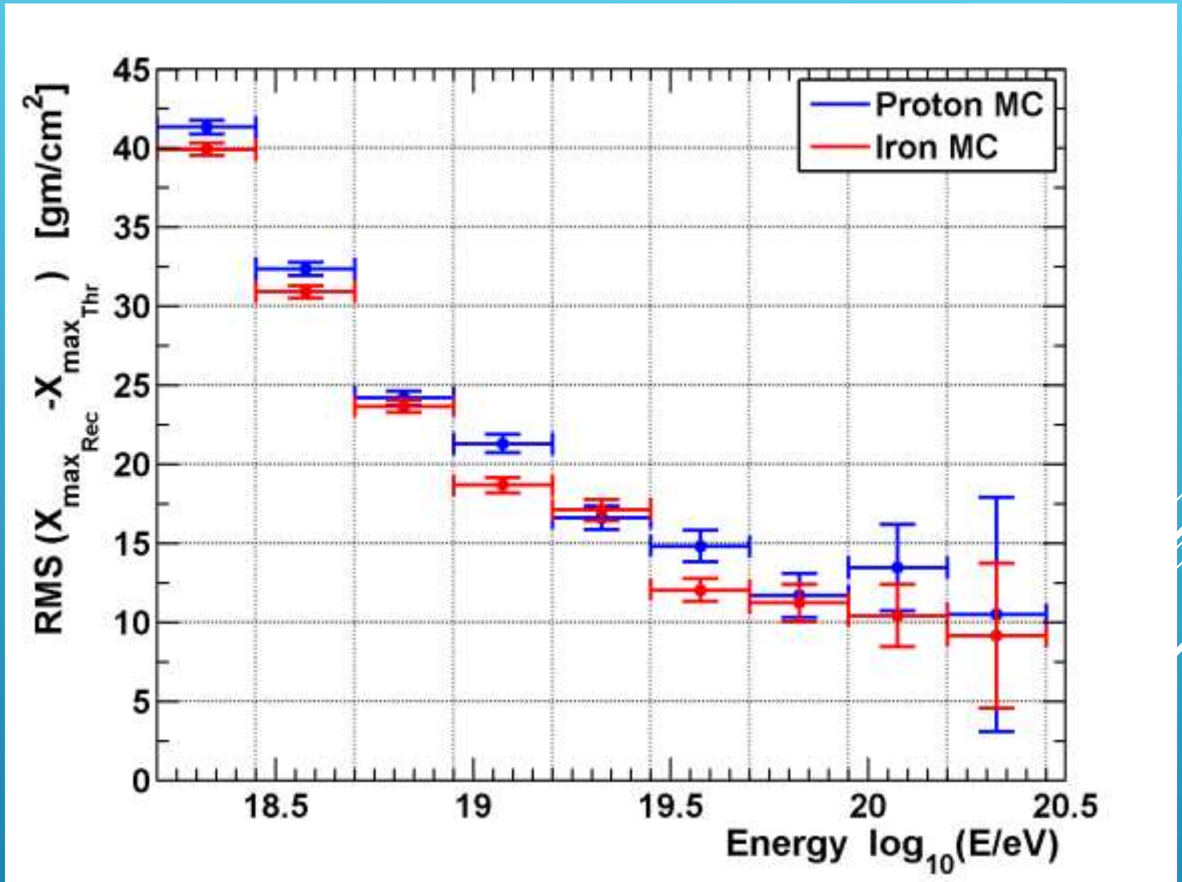
PART TWO
COMPOSITION STUDY

PATTERN RECOGNITION ANALYSIS
&
QUALITY FACTOR ANALYSIS

XMAX RESOLUTION – ENERGY DEPENDENCE

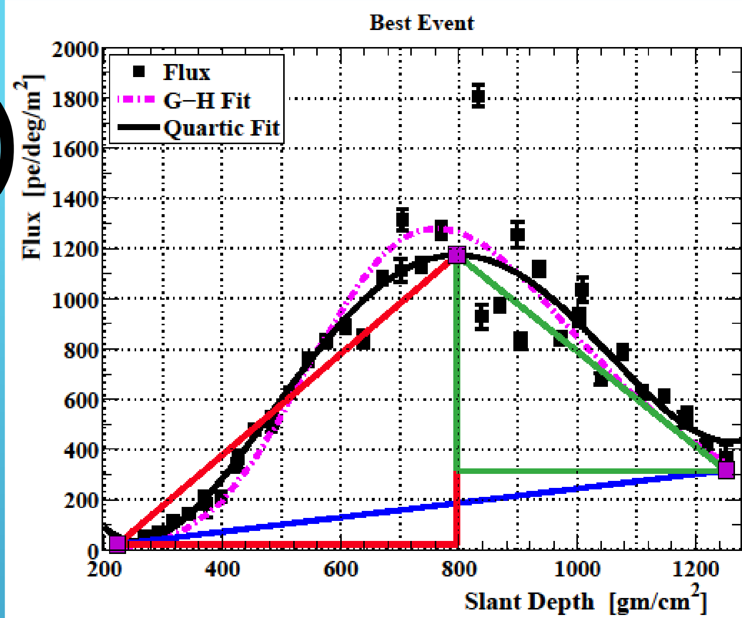


- Protons deeper and wider than iron.
  Xmax (peak) gives composition information



- Energy dependence of resolution is important if there is a change in composition

PATTERN RECOGNITION ANALYSIS (PRA)



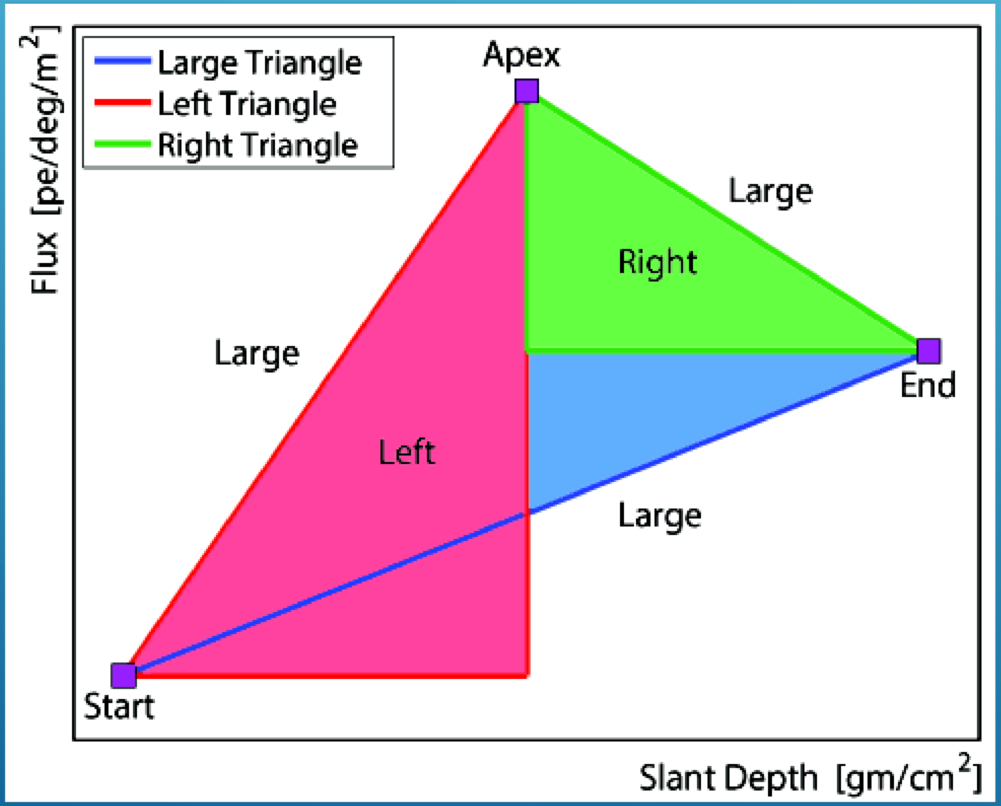
- No model needed to see increase and decrease in signal
- Fit shower profiles to triangles
  - Extract features from triangles. Describes shape of event. (Length of sides, angles, etc.)

- Brains are good at pattern recognition: use them to create *training set* of known good and bad events.

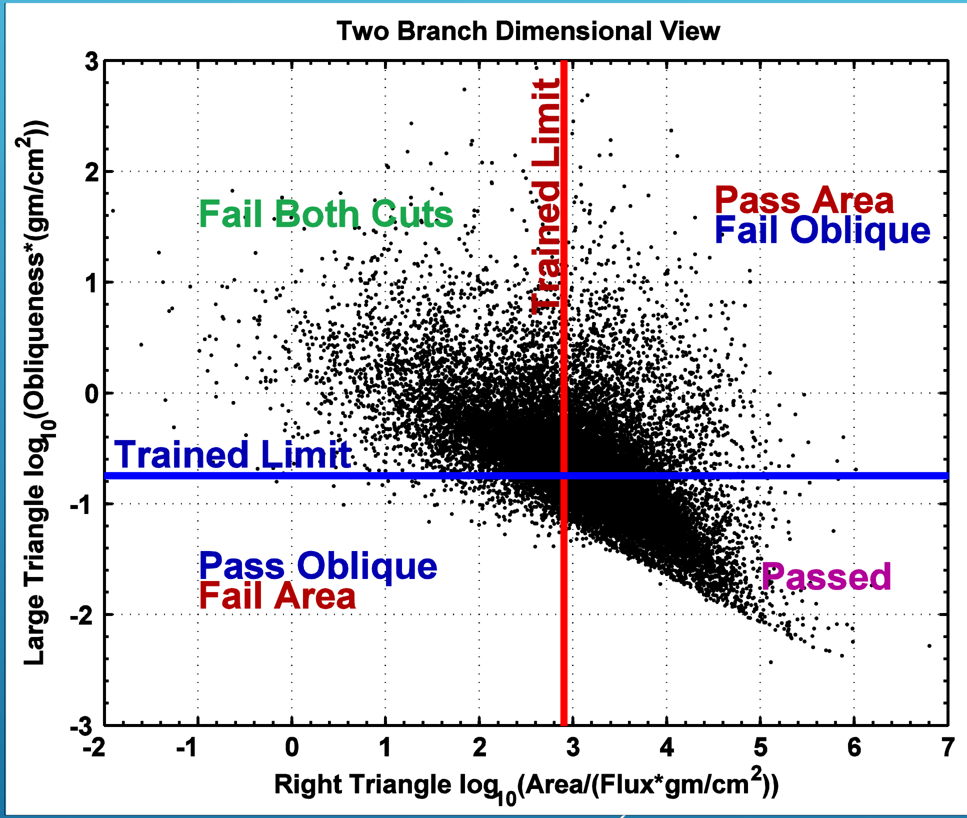
- Training set is used to find useful features, and cut values, for a yes/no determination.
  - The result agrees with the human observers on the 97.2% to 99.6% percent level.

BINARY PRA

- Example of cut on two features extracted from triangles. (These two cut the most events)
  - Obliqueness: perimeter/area of the large triangle.
  - Right triangle area: 1/2*Slantdepth*Flux of the triangle sides.



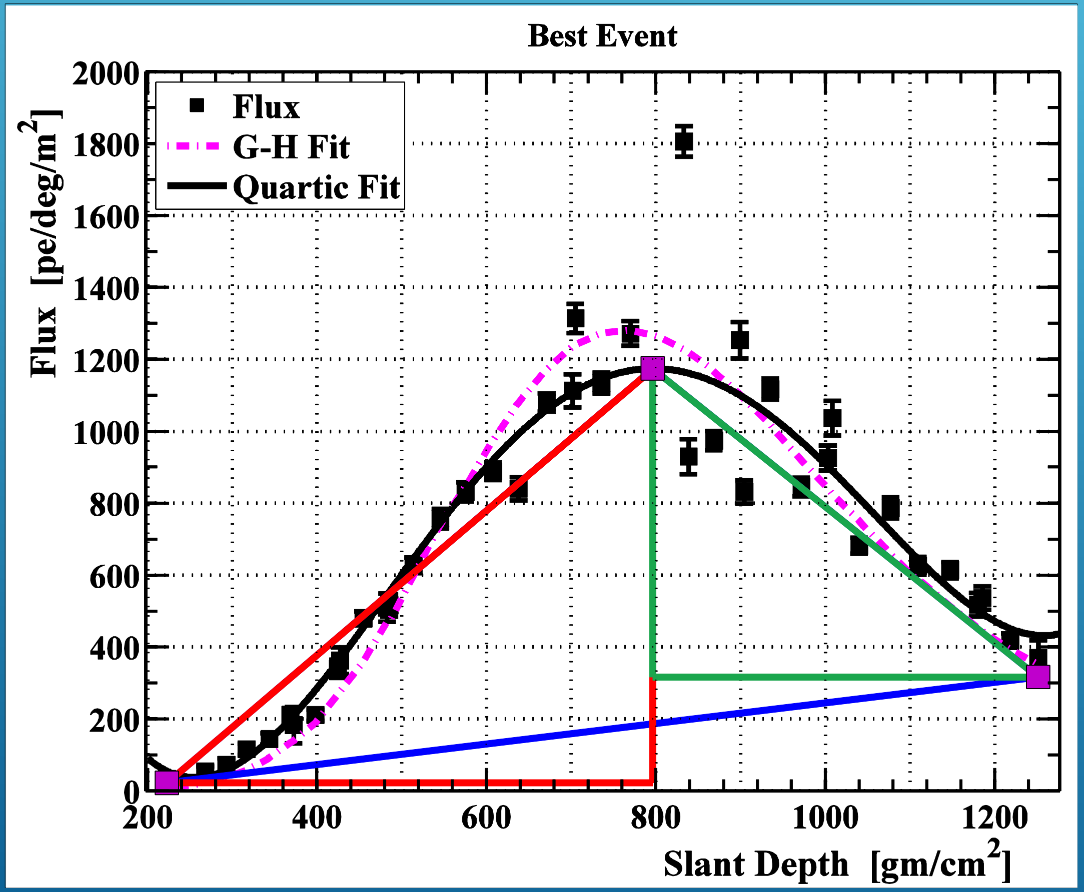
Triangle Labels



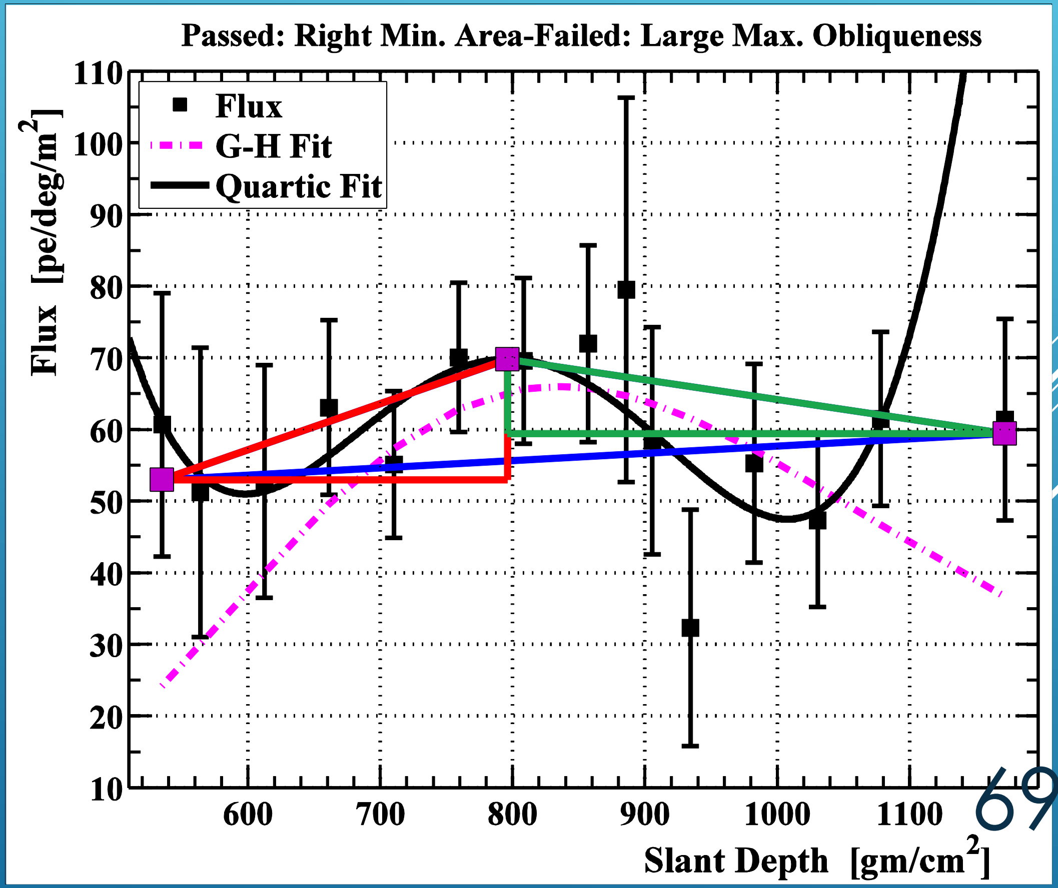
2d view of two cuts

BINARY PRA

- PRA determines whether an event has an acceptable profile and returns a binary yes/no answer.



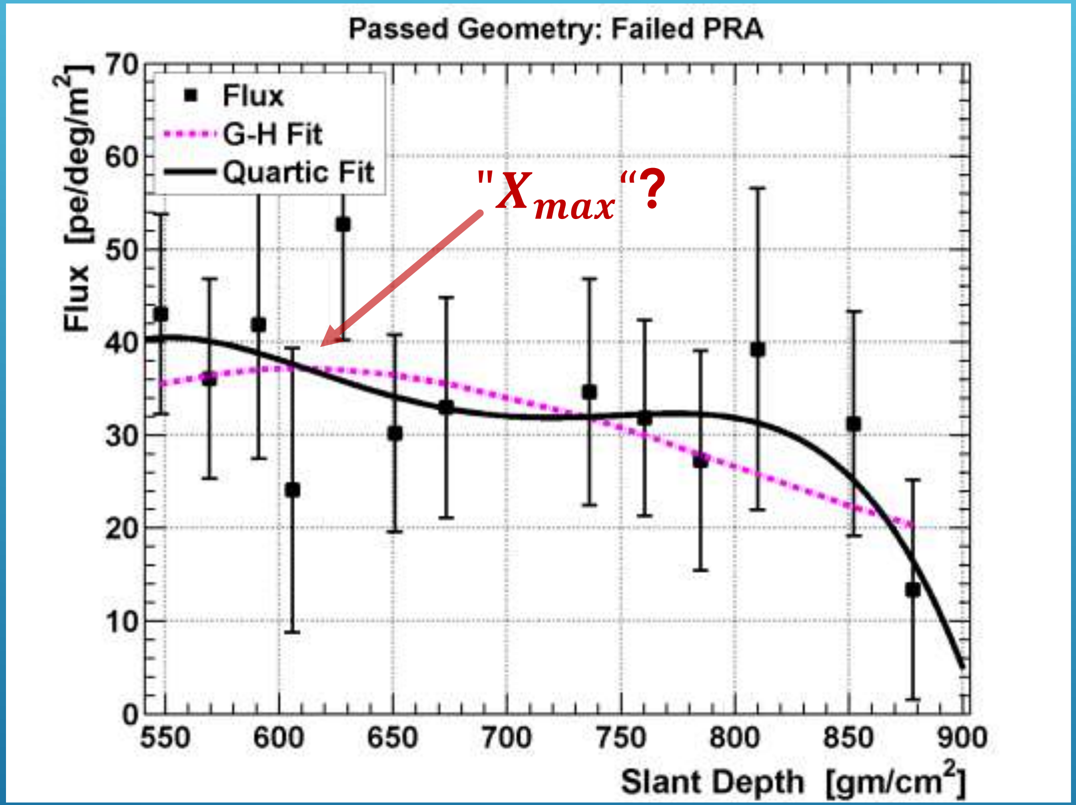
Good (1)

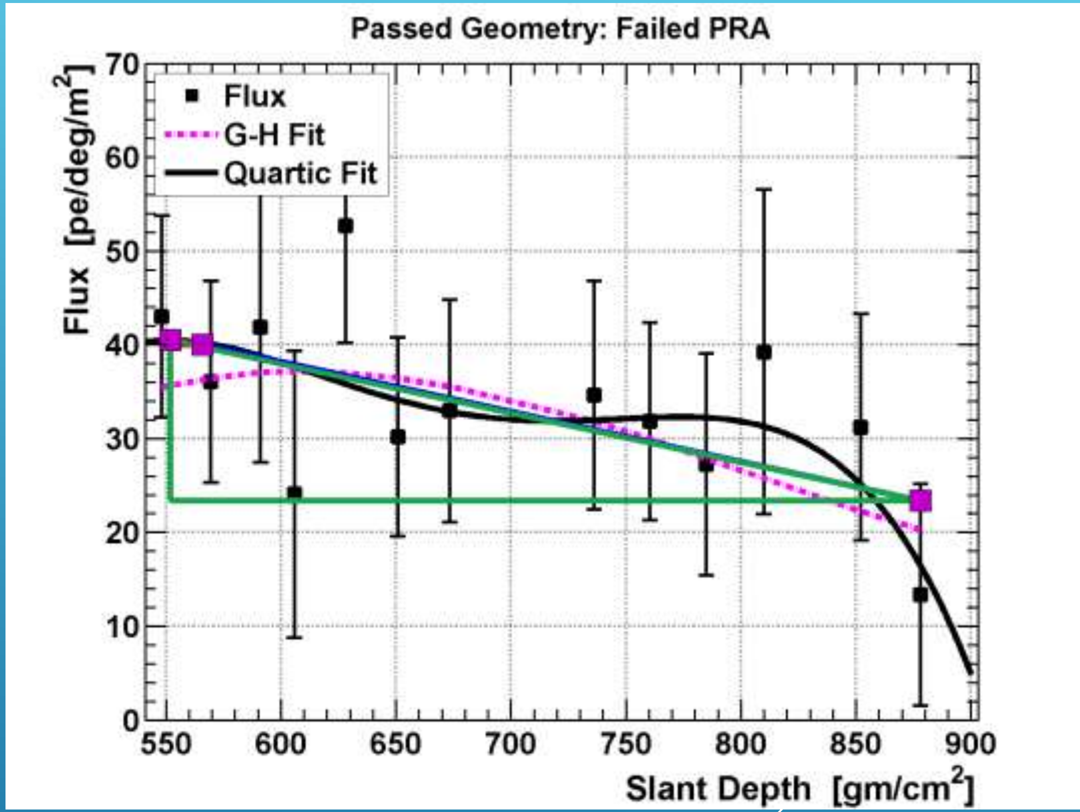


Bad (0)

FAILED PRA – PASSED GEOMETRY CUTS

Discrepancy is ~2 times the separation between means of Iron and proton primaries.

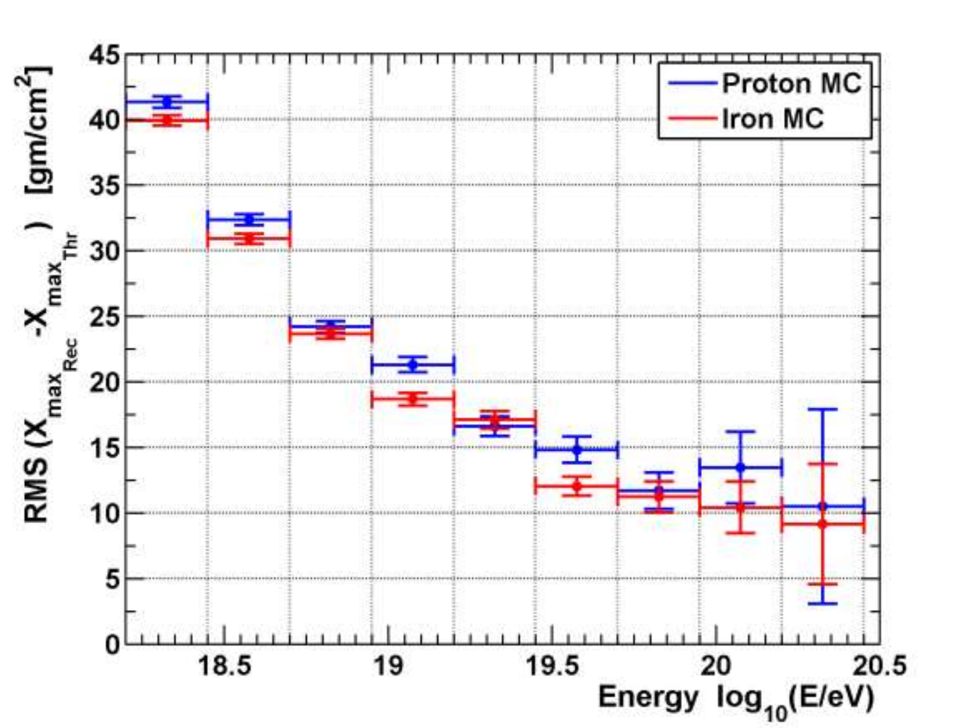




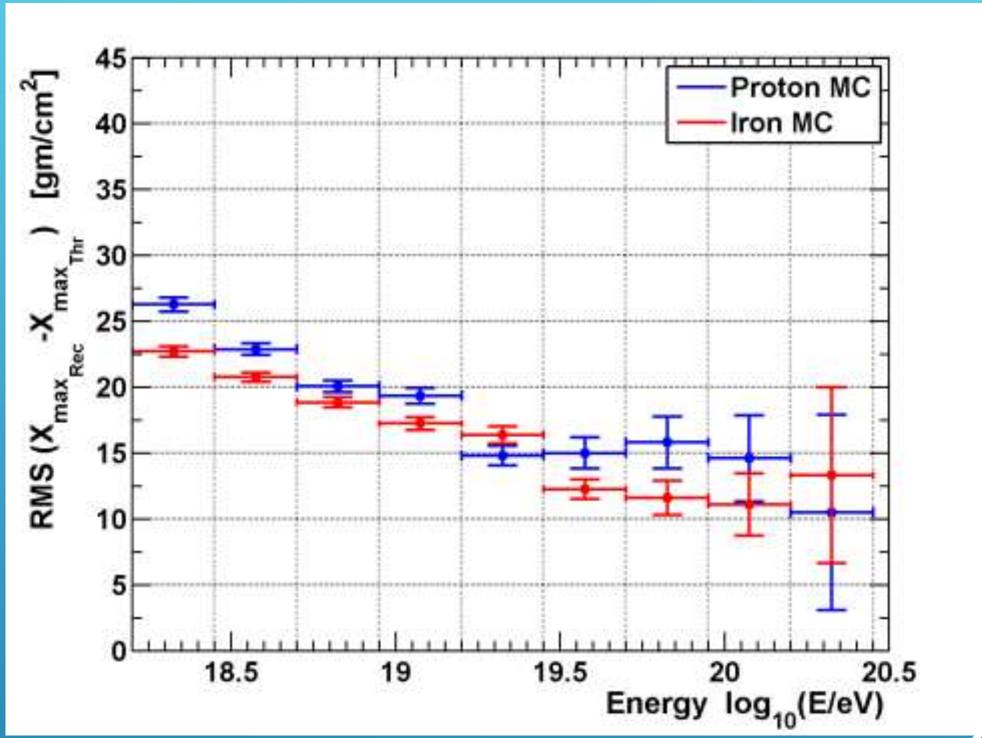
$$X_{max_{Reconstructed}} - X_{max_{Thrown}} = -130 \frac{gm}{cm^2}$$

$E = 10^{18.3} eV, \theta = 40.2\ deg, R_P = 17\ m$, SD/FD Core Diff = 511, Boundary Dist. = 2883 m, Tracklength = 13.4

PRA RESOLUTION IMPROVEMENT



Tight Geometry Cuts



Loose Geometry Cuts and PRA

Composition Results Published in: R. U. Abbasi, et al., Study of Ultra-High Energy Cosmic Ray composition using Telescope Arrays Middle Drum detector and surface array in hybrid mode, Astropart. Phys. 64 (2014) 49–62. arXiv:1408.1726

Also used for:

- R. U. Abbasi, et al., Measurement of the proton-air cross section with Telescope Arrays Middle Drum detector and surface array in hybrid mode, Phys.Rev. D92 (3) (2015) 032007. arXiv:1505.01860
- T. Stroman, Y. Tameda, Telescope Array measurement of UHECR composition from stereoscopic fluorescence detection, PoS ICRC2015 (2016) 361.

BINARY PRA TO QUALITY FACTOR ANALYSIS (QFA)

- A good start. How do you make it better? **MORE EVENTS**
  - Maybe, we can lower our standards (or make the computer smarter than us) without compromising resolutions, resolution slopes, and biases.

- Instead of a yes/no answer a scale of event quality.

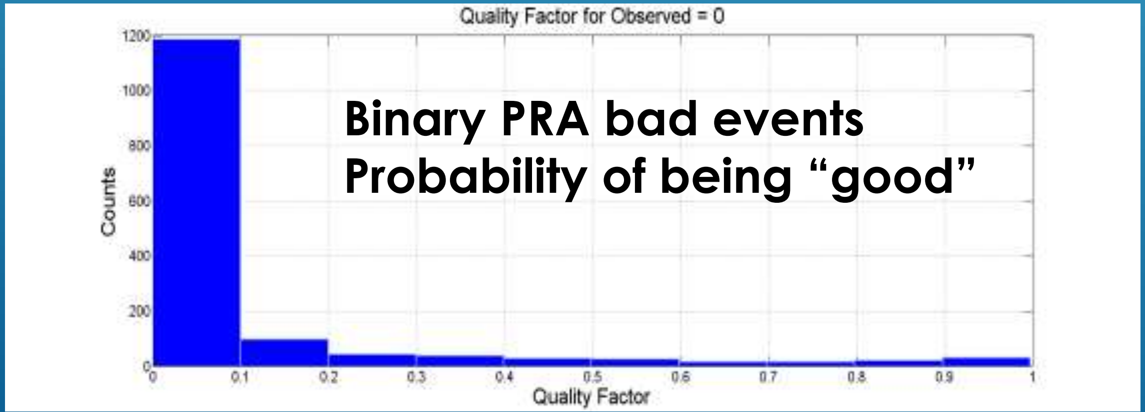
LOGISTIC REGRESSION

Finds weights, β_j, for prediction from features

$$min_\beta\, J(\beta) = \sum_{j=1}^{N}\left[y_j \log p(\vec{x_j}) + (1 - y_j)\log(1 - p(\vec{x_j}))\right]$$

$$p_j(\vec{x_j}) = \frac{1}{1 + e^{-(\beta_0 + \vec{\beta}\cdot\vec{x_j})}}$$

y_j *(Binary PRA)* (1 or 0) and $\vec{x}_j$ vector of triangle feature values for that event.



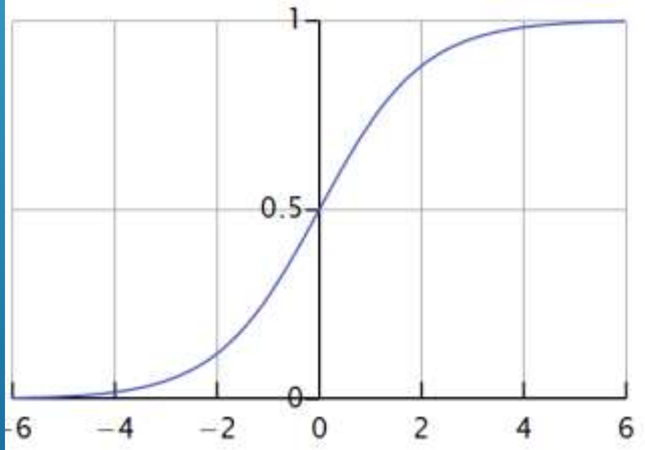
LOGISTIC REGRESSION

$$t_j = \beta_0 + \sum_{i}^{10} \beta_i \cdot x_{ji}$$

Found weights β_i

Result is $p_j(t_j)$ the *probability* that the vector $\vec{x}_j$ comes from an event that is a 'success'

$$p_j(t_j) = \frac{1}{1 + e^{-(t_j)}}$$



Logistic Function maps the range (-inf, inf) to [0,1]

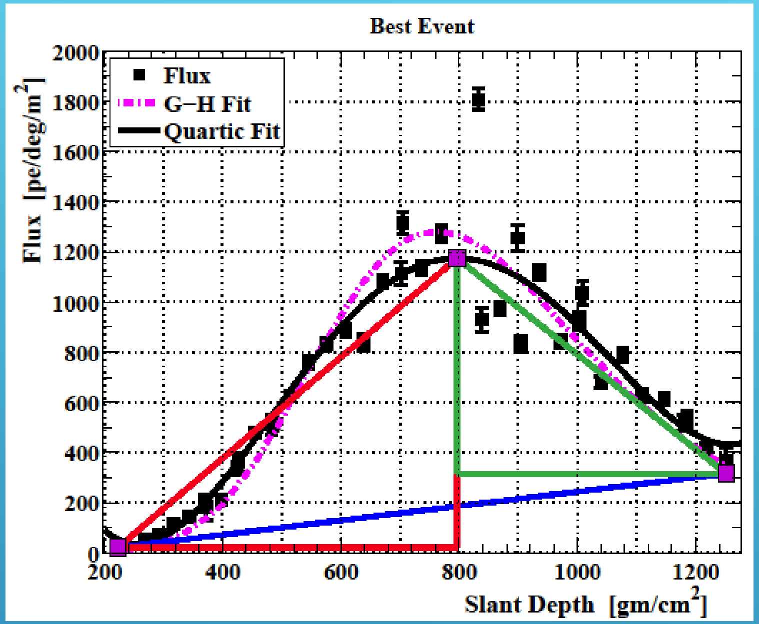
EXAMPLE EVENT

Triangle Attributes $\vec{x}_j$

1. Apex highest point = 1
2. Bins before apex = 0.315
3. Cubic term = 0.021
4. Max. Sig. Diff. = 2.471
5. Midsize length = 3.271
6. Signal Mean = 3.524
7. Norm. Missing =-1.721
8. Apex angle/Hyp. =-1.665
9. Left Oblique. =-3.292
10. Large under right =-0.179

Fitted Weights β_j

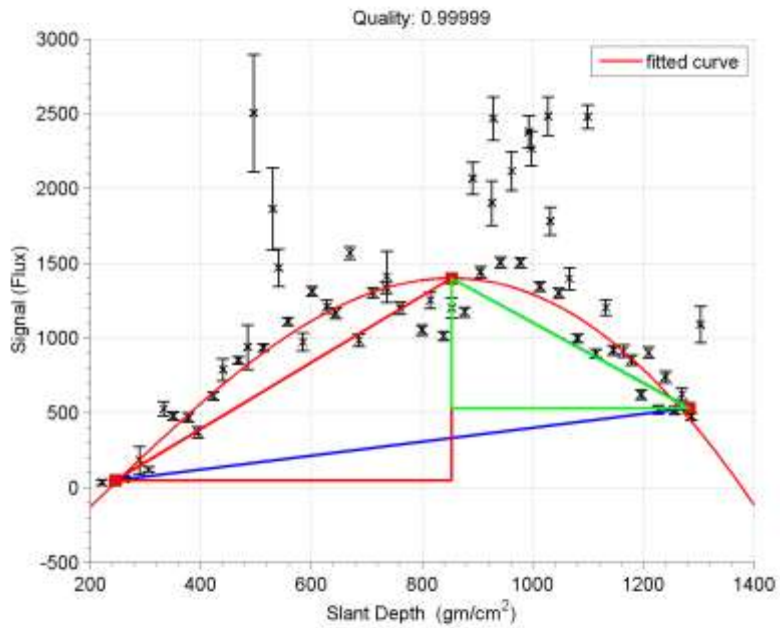
0. -7.969
1. 3.474
2. 7.456
3. 42.286
4. 0.570
5. -0.054
6. 0.391
7. -0.242
8. 0.632
9. -3.351
10. 2.068

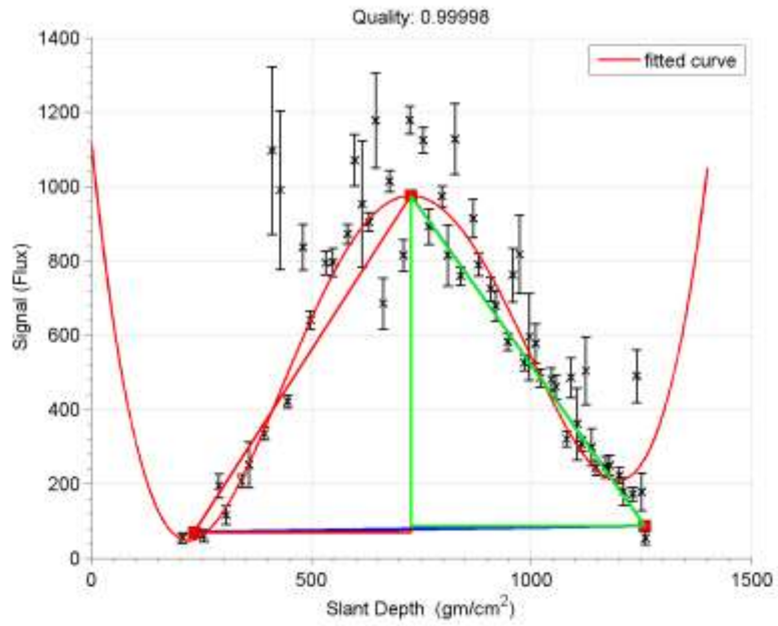


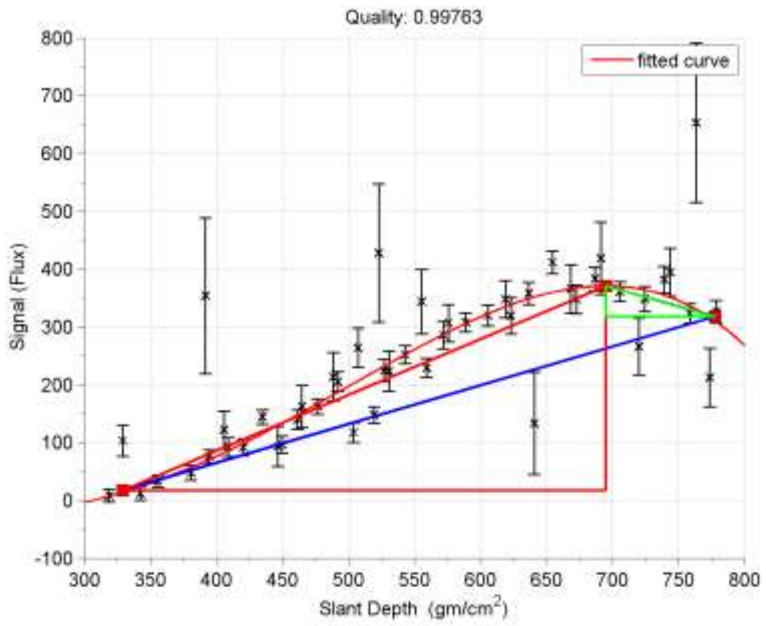
- Highest energy event in data set.
- Has 5th highest quality factor at 0.99999

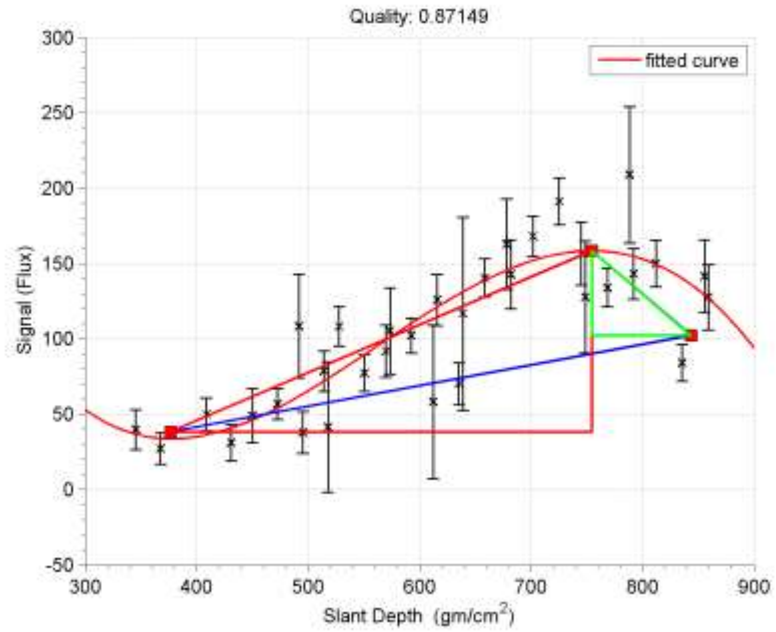
$$t_j = \beta_0 + \sum_{i}^{10} \beta_i \cdot x_{ji} = 11.391$$

$$p_j(\vec{x_j}) = \frac{1}{1 + e^{-(11.391)}} = 0.99999$$


Quality: 0.99999
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)


Quality: 0.99998
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)


Quality: 0.99763
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)


Quality: 0.87149
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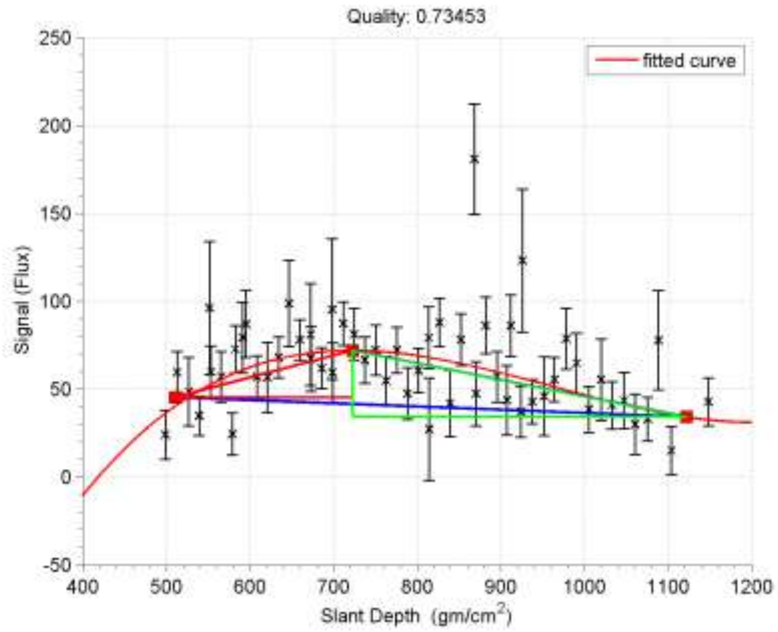
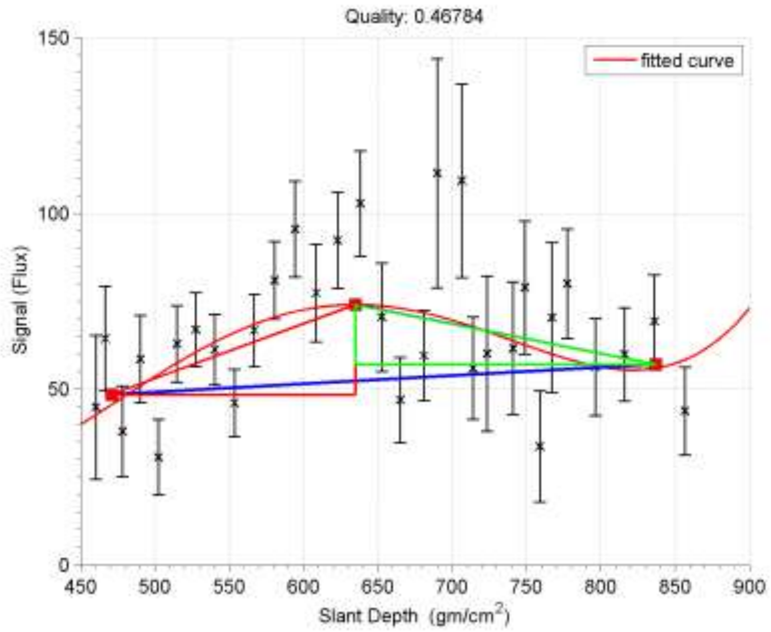
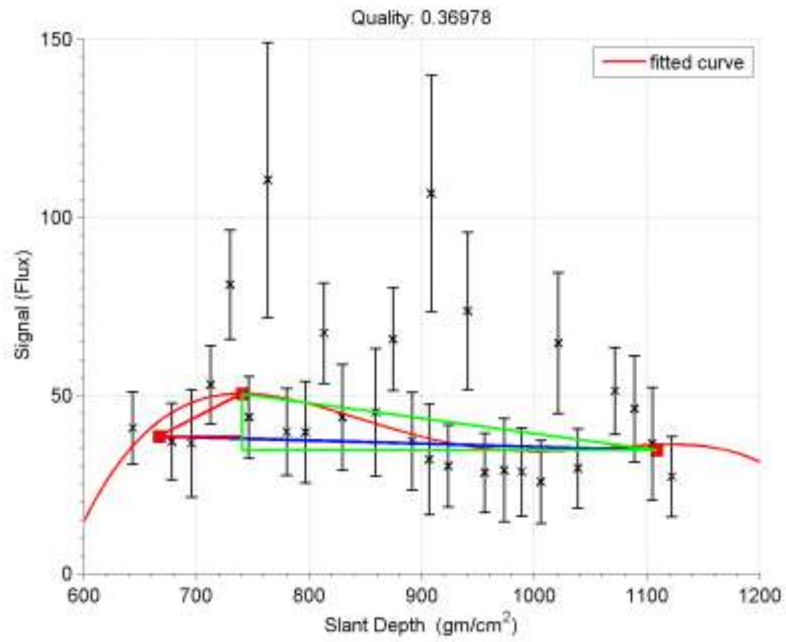
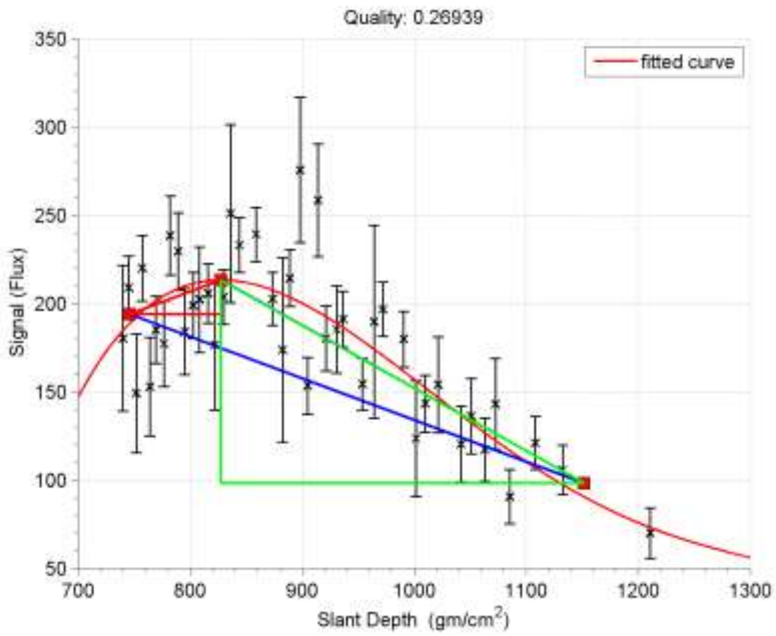
Signal (Flux)
Slant Depth (gm/cm^2)


Quality: 0.73453
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)


Quality: 0.46784
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)


Quality: 0.36978
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)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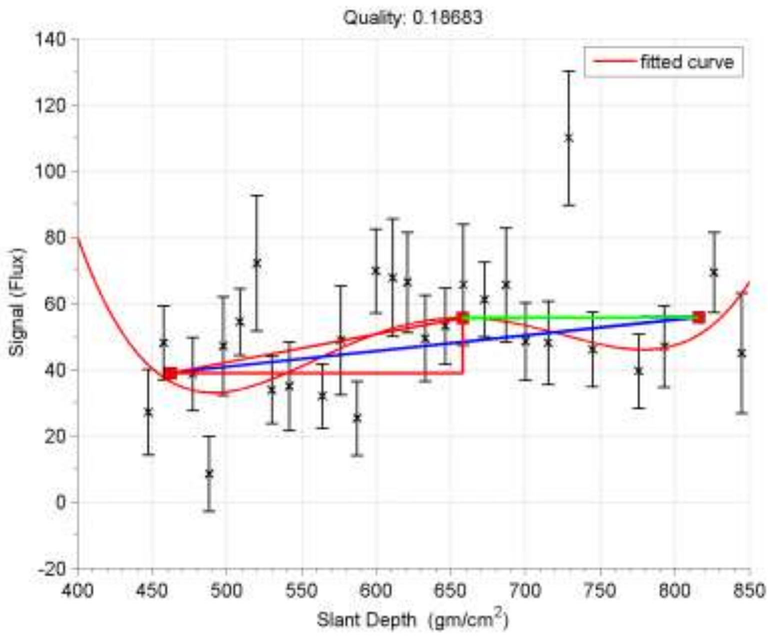
Signal (Flux)
Slant Depth (gm/cm^2)


Quality: 0.18683
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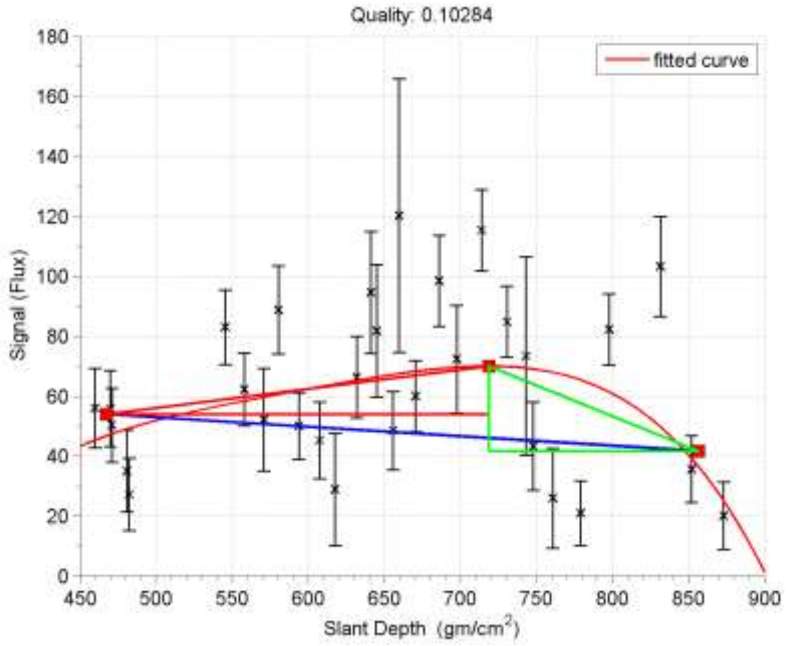
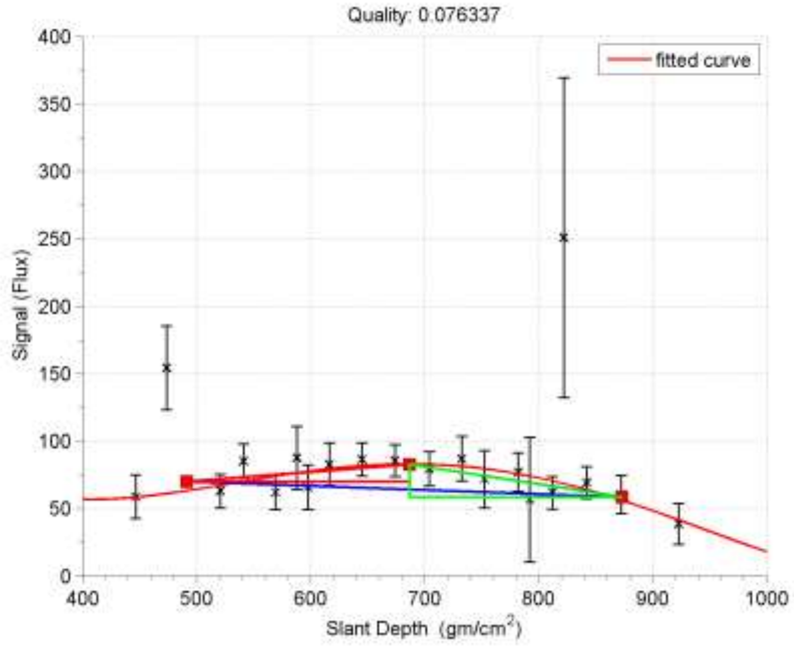
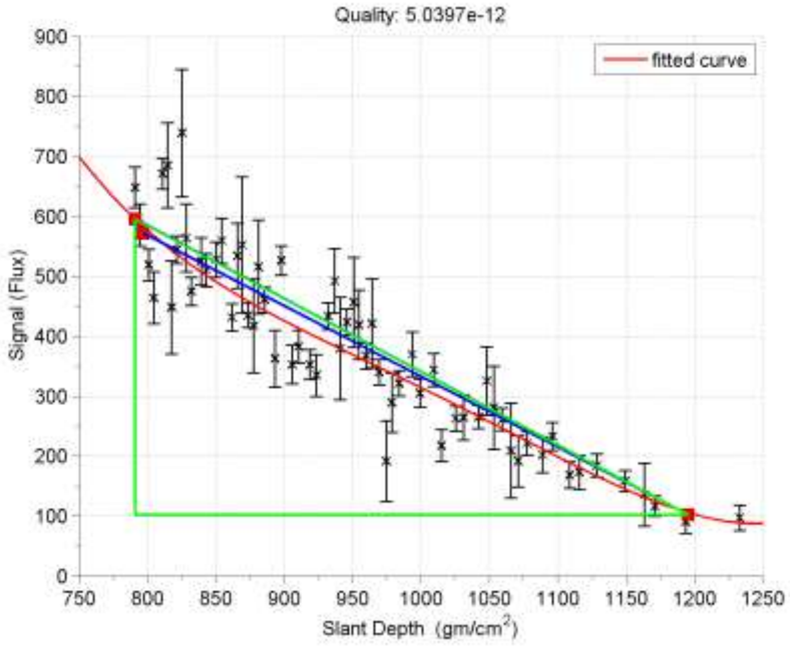
Signal (Flux)
Slant Depth (gm/cm^2)

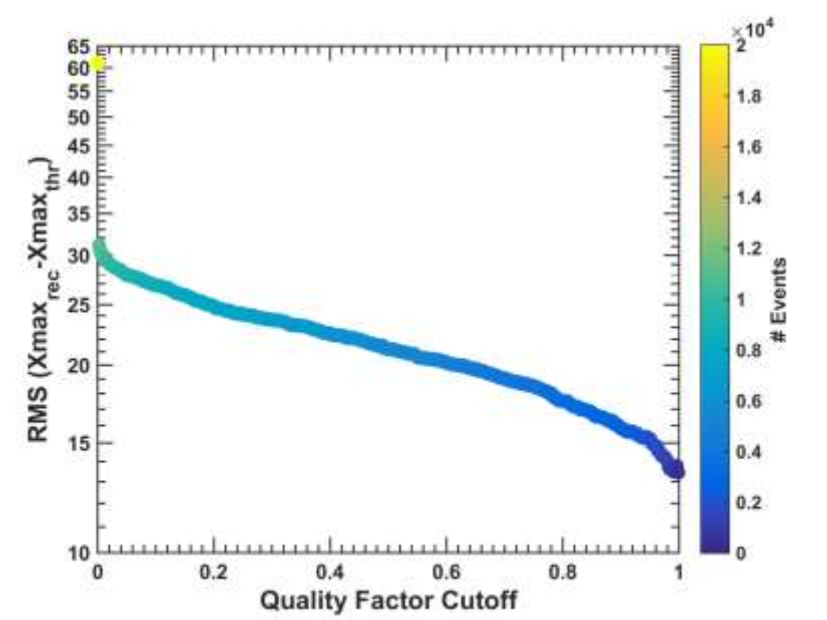

Quality: 0.10284
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)


Quality: 0.076337
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)

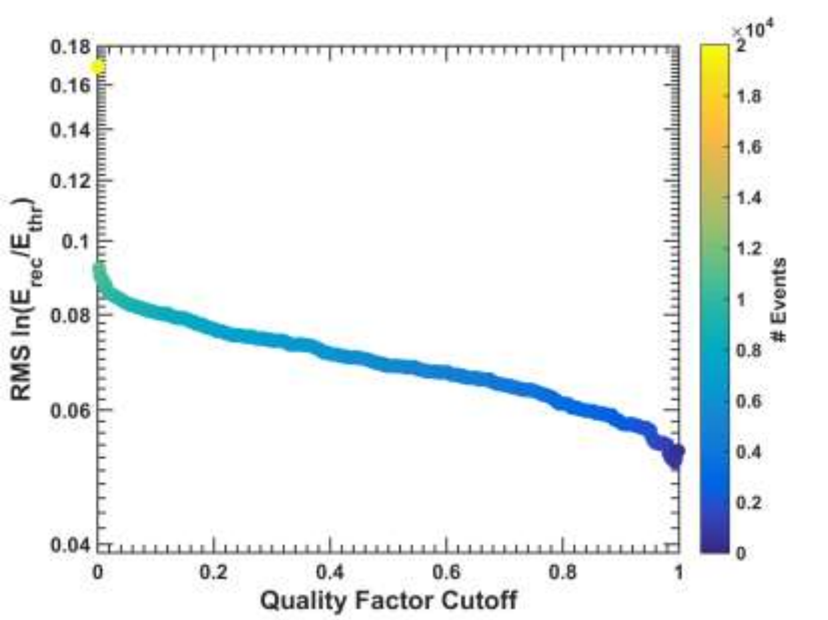

Quality: 5.0397e-12
fitted curve
Signal (Flux)
Slant Depth (gm/cm^2)

RESOLUTION CORRELATIONS WITH QUALITY FACTOR

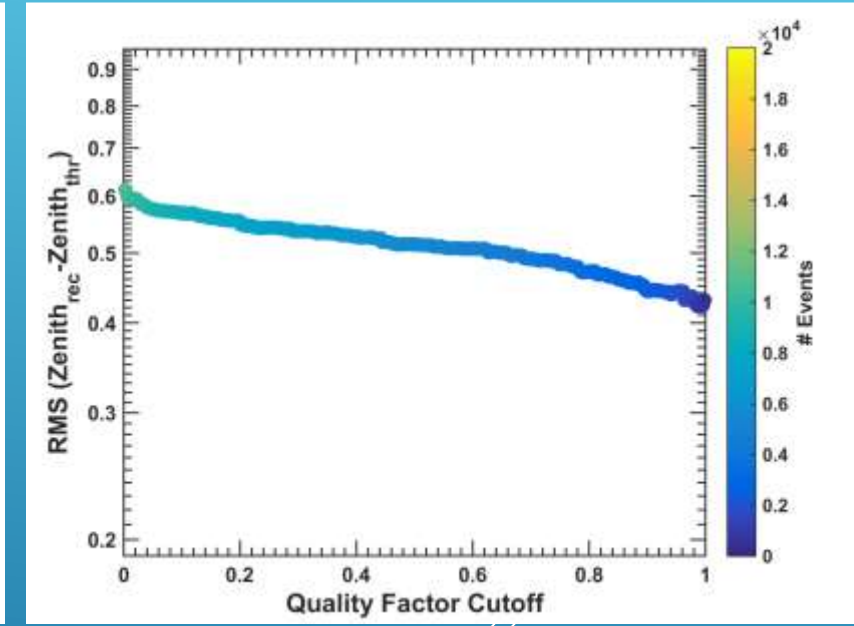
RMS of difference between thrown and reconstructed values for proton MC



Xmax



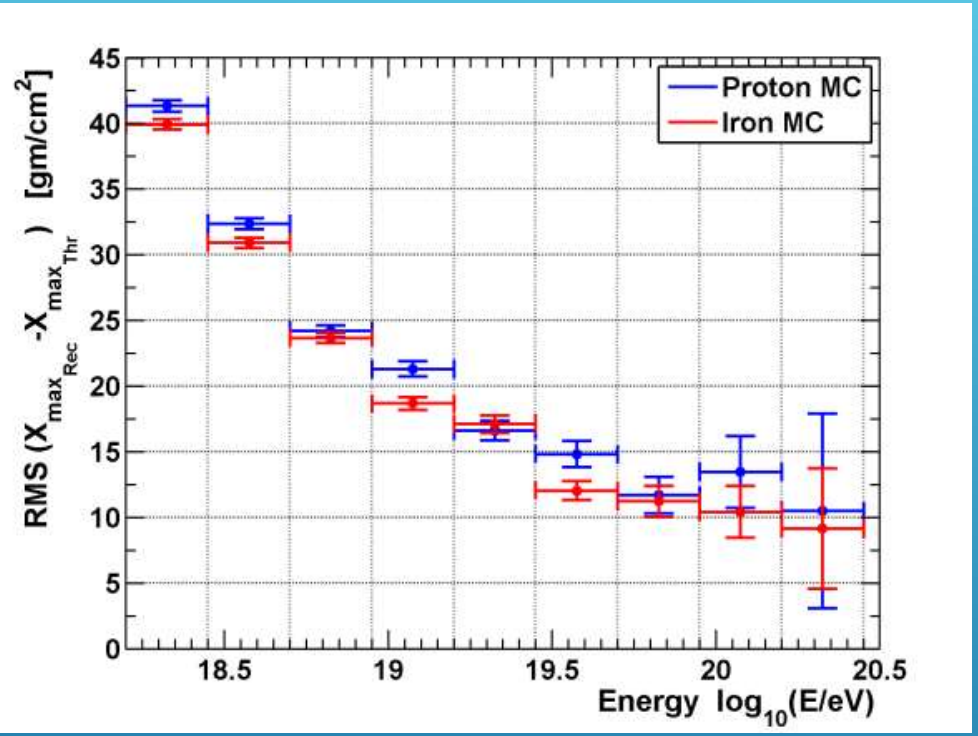
Energy



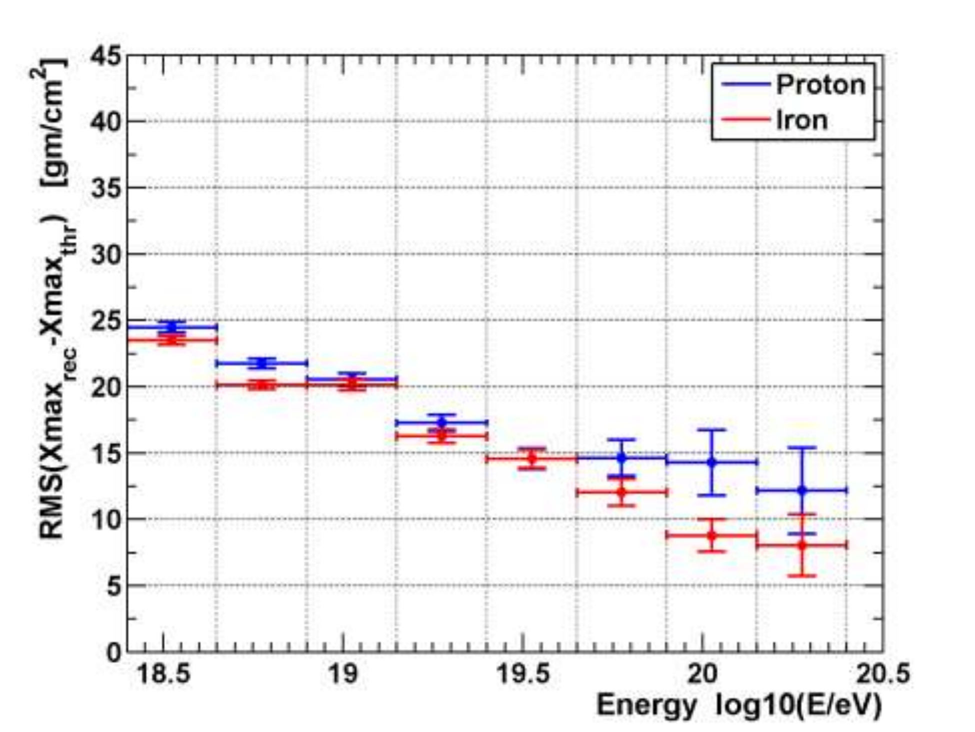
Zenith Angle

*Very loose geometry cuts

QFA RESOLUTION IMPROVEMENT



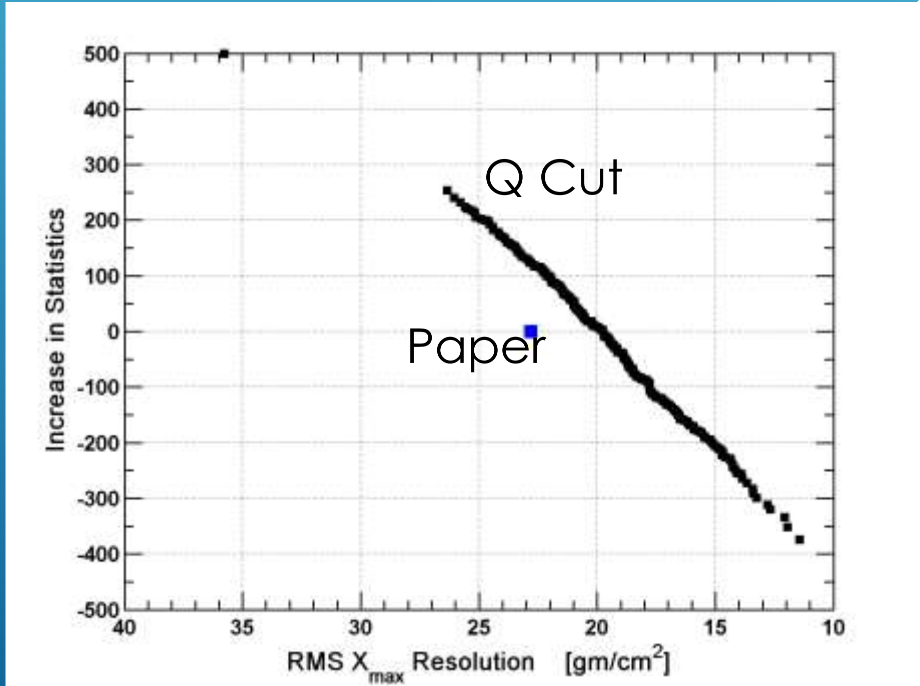
Tight Geometry Cuts



Loose Geometry Cuts and PRA

QFA CONCLUSION

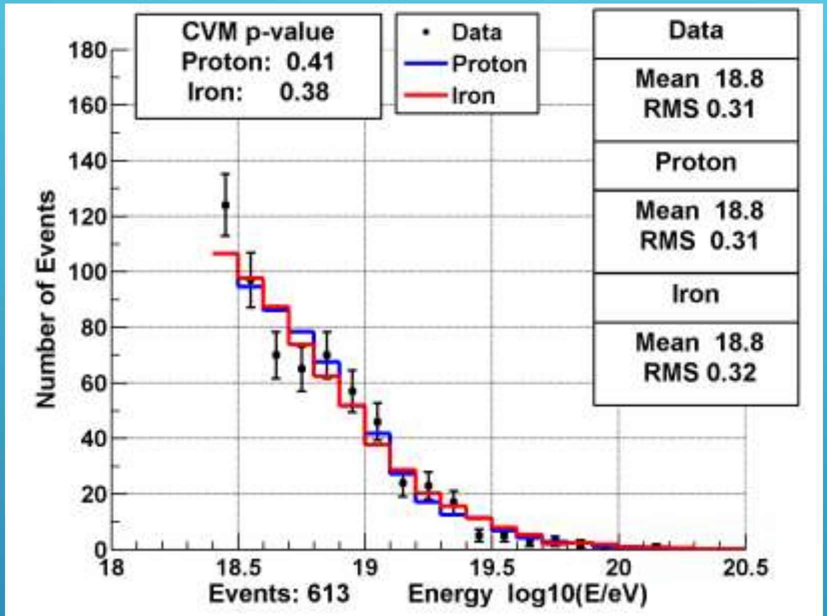
- Quality Factor describes how well events are seen by the FD
- Fairly linear correlation between Quality and RMS resolutions (and biases).
- Setting a QF threshold instead Binary PRA improves statistics.

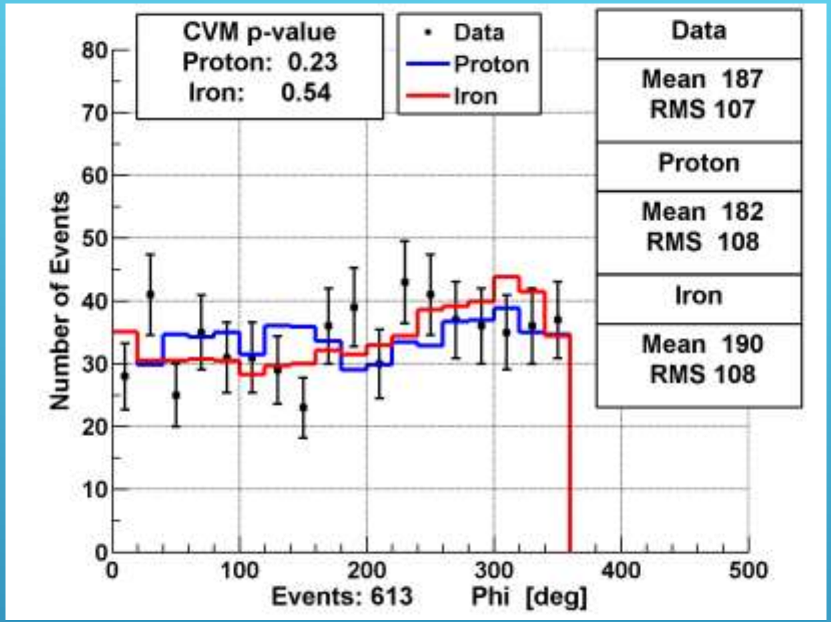


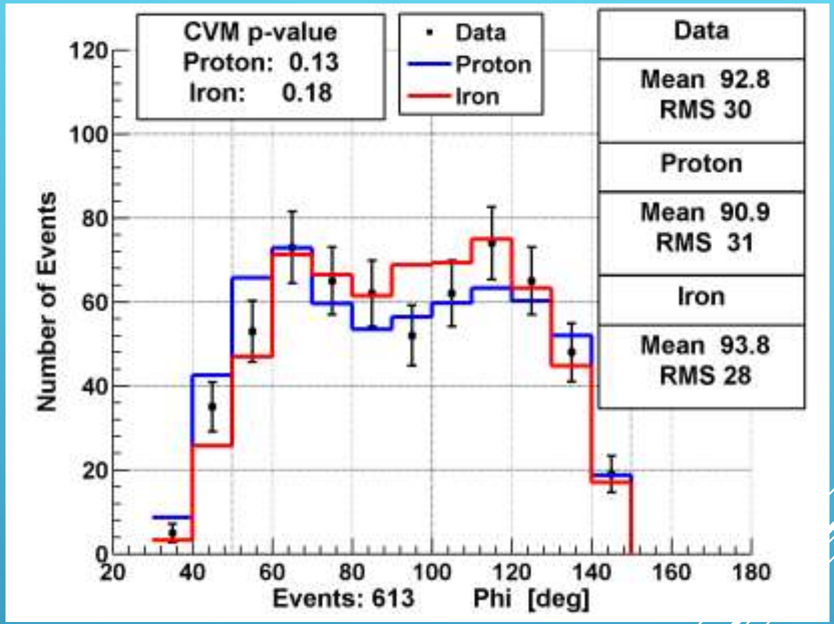
7 YEAR GDAS(3-HOUR) DATA 4 YEAR QGSJETII-03 **FLOATED X0 = -60, LAMBDA = 70**

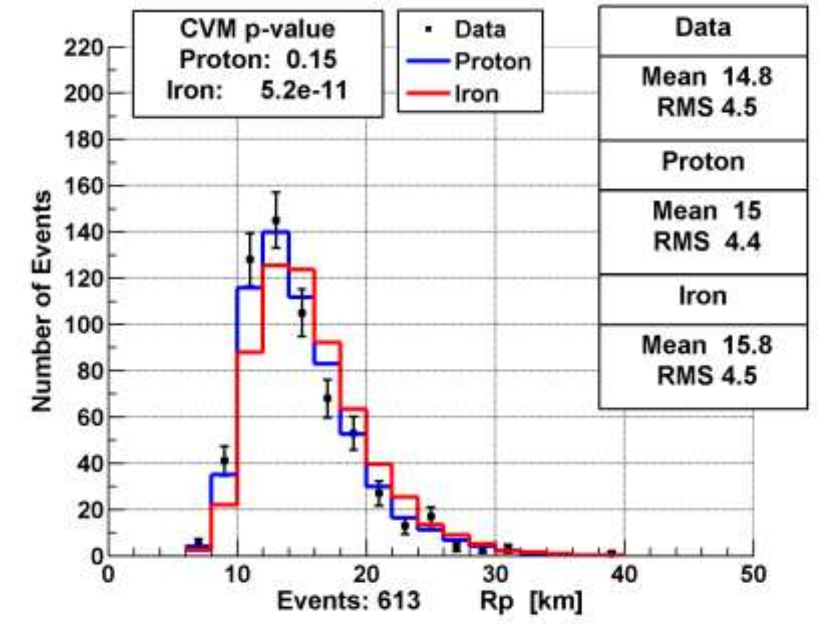
Quality Factor > 0.2 (for ~22 gm/cm^2 resolution), Energy > 18.4, Boundary Dist. > -500 m SD/FD Core Difference < 1600 m, Zenith < 58, Geometry Fit Chi^2/DOF < 5, and Xmax Bracketed.

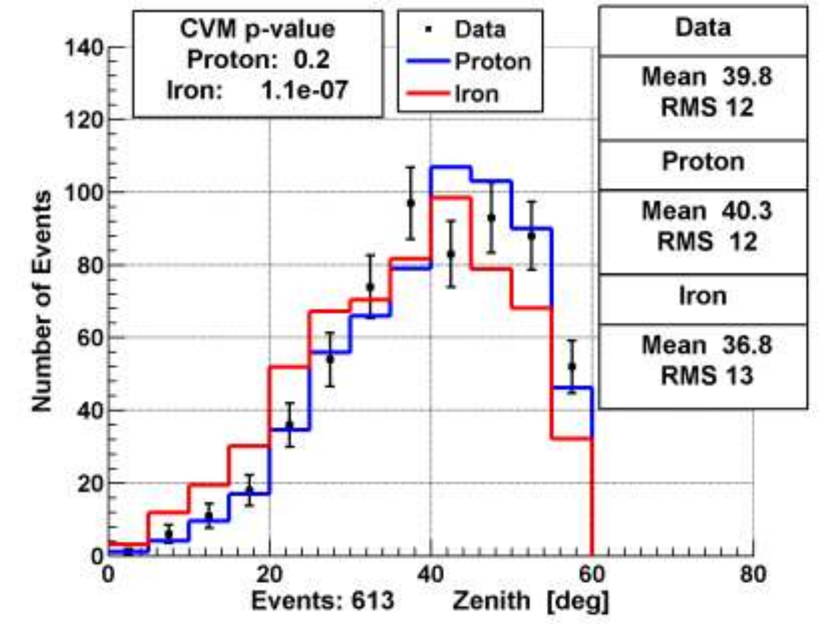
DATA/MC COMPARISONS



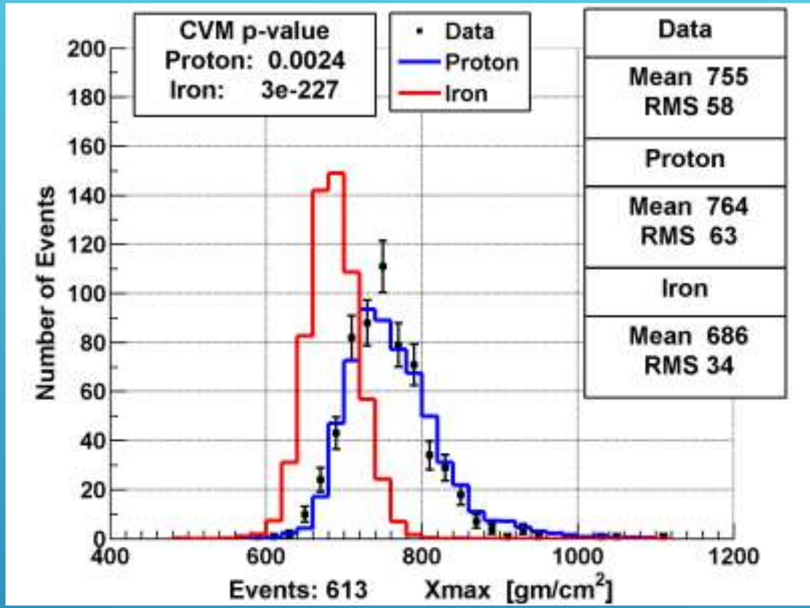




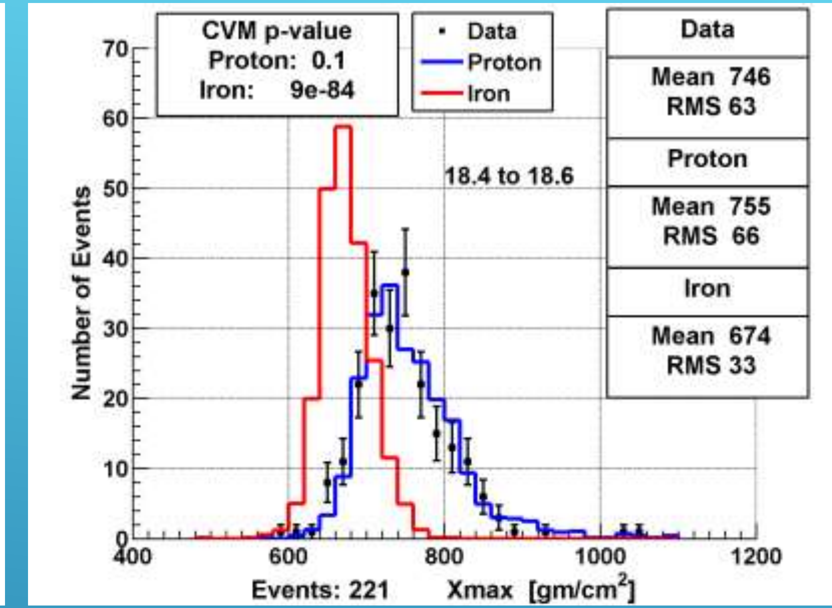




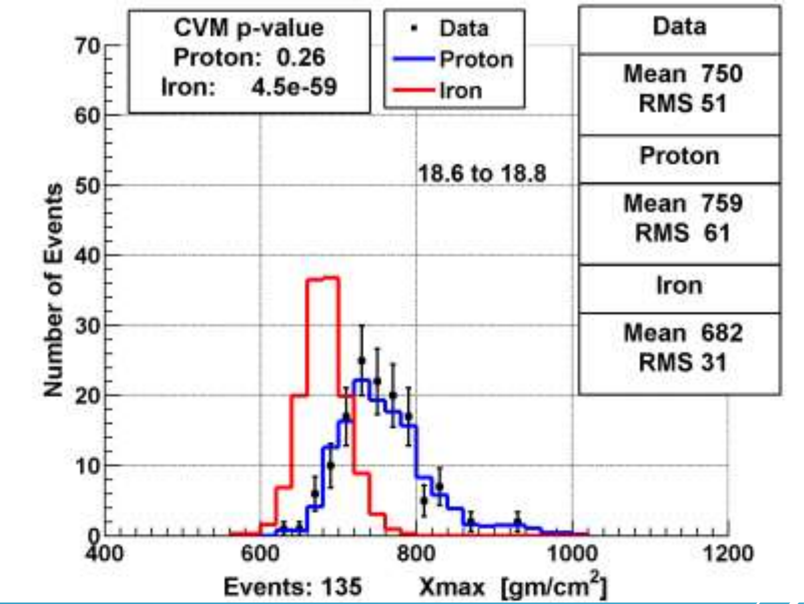
XMAX DISTRIBUTIONS



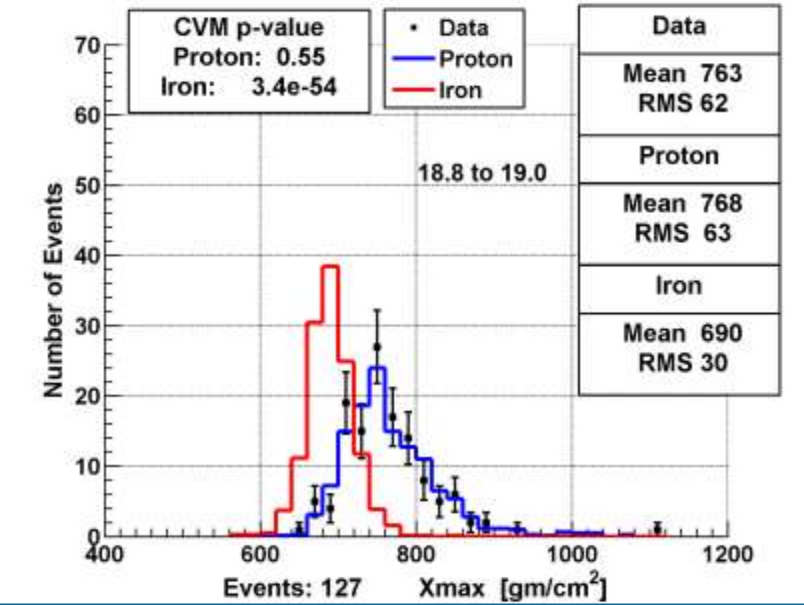
Overall



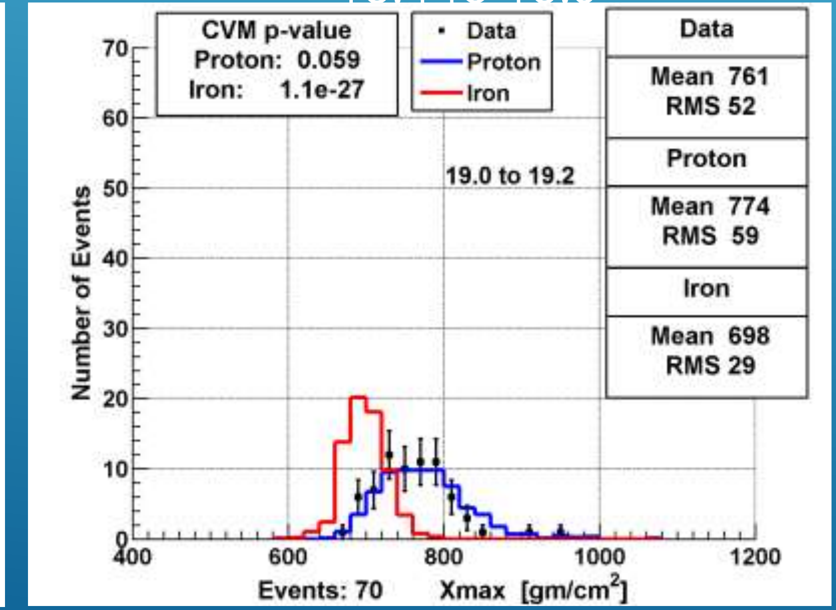
18.4 to 18.6



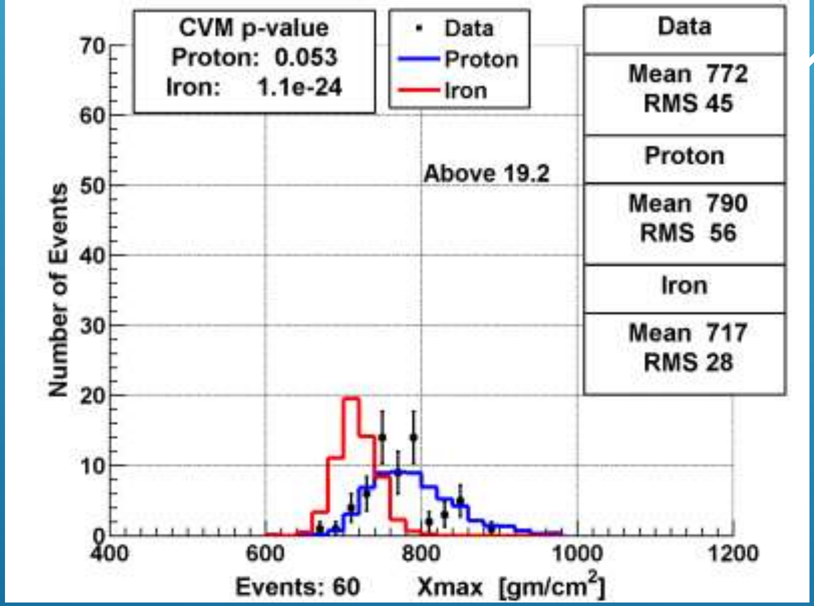
18.6 to 18.8



18.8 to 19



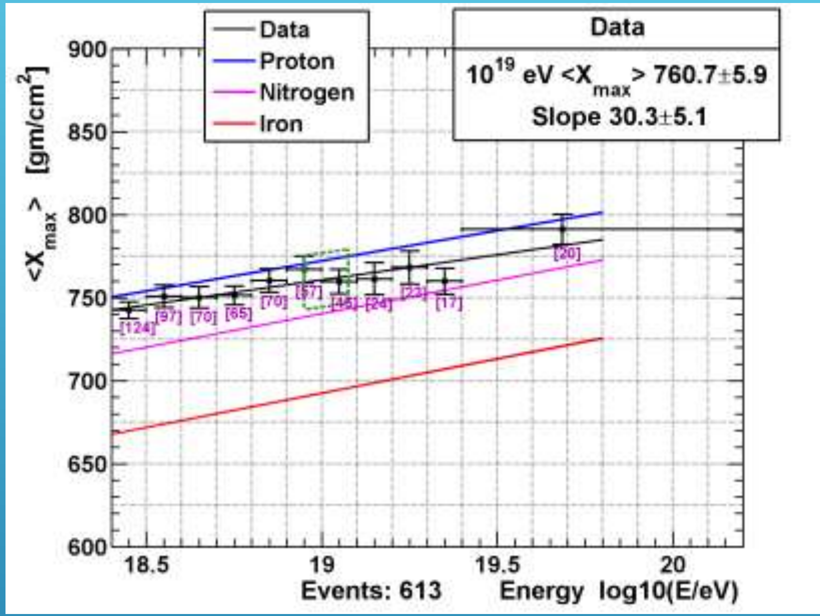
19 to 19.2

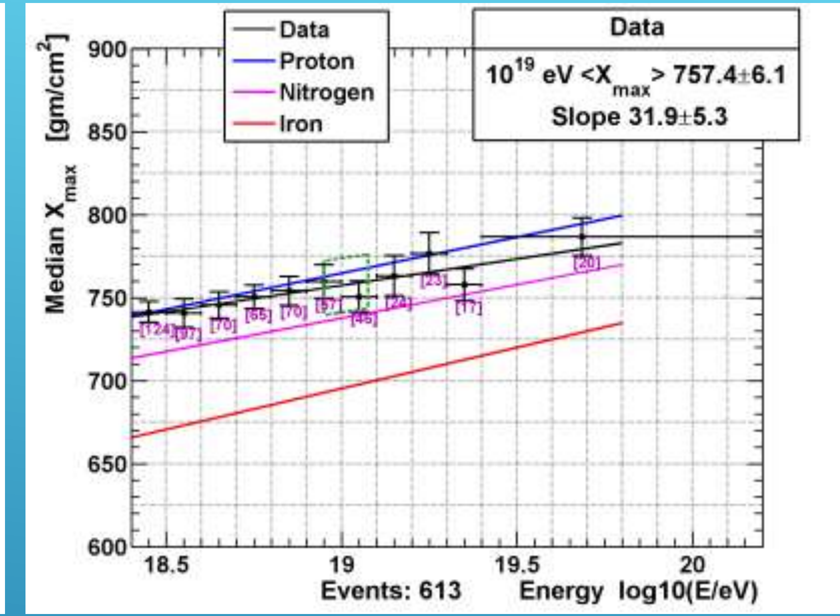


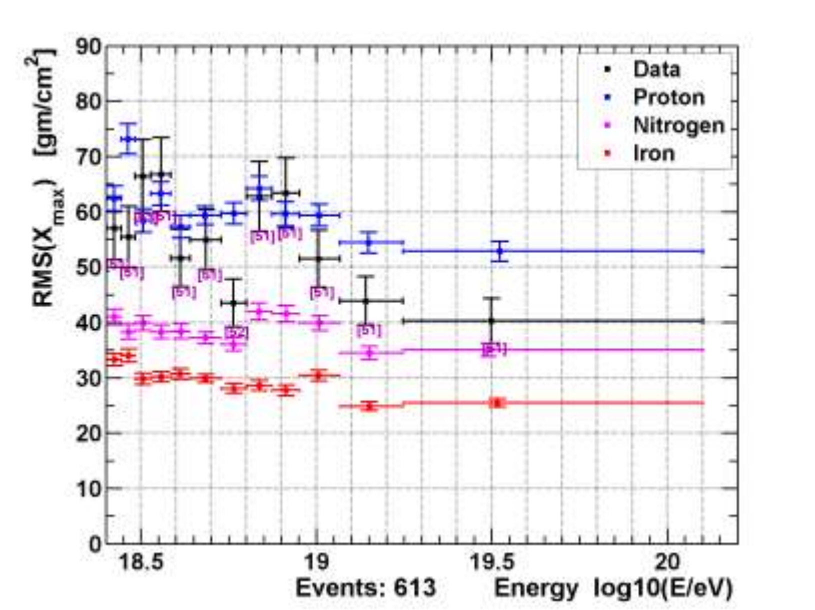
Greater than 19.2

MOMENTS

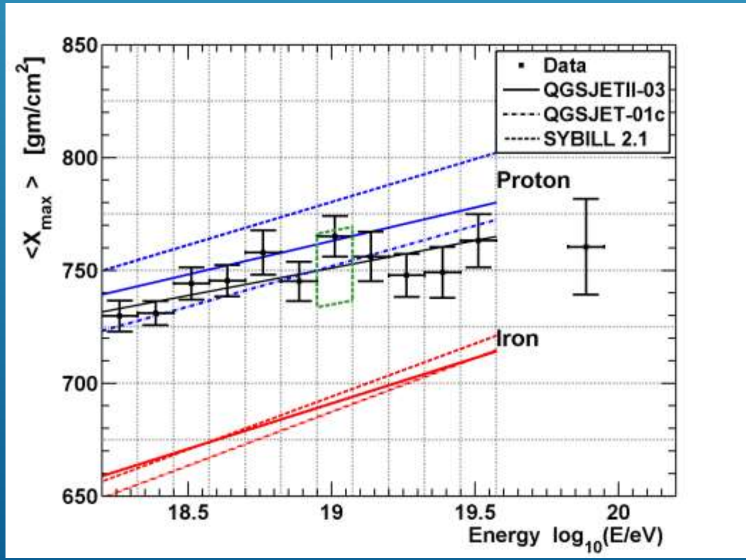
QSJETII-03







Mean **Median** **RMS**



Various models

COMPOSITION WITHOUT $< X_{max} >$

MOTIVATION

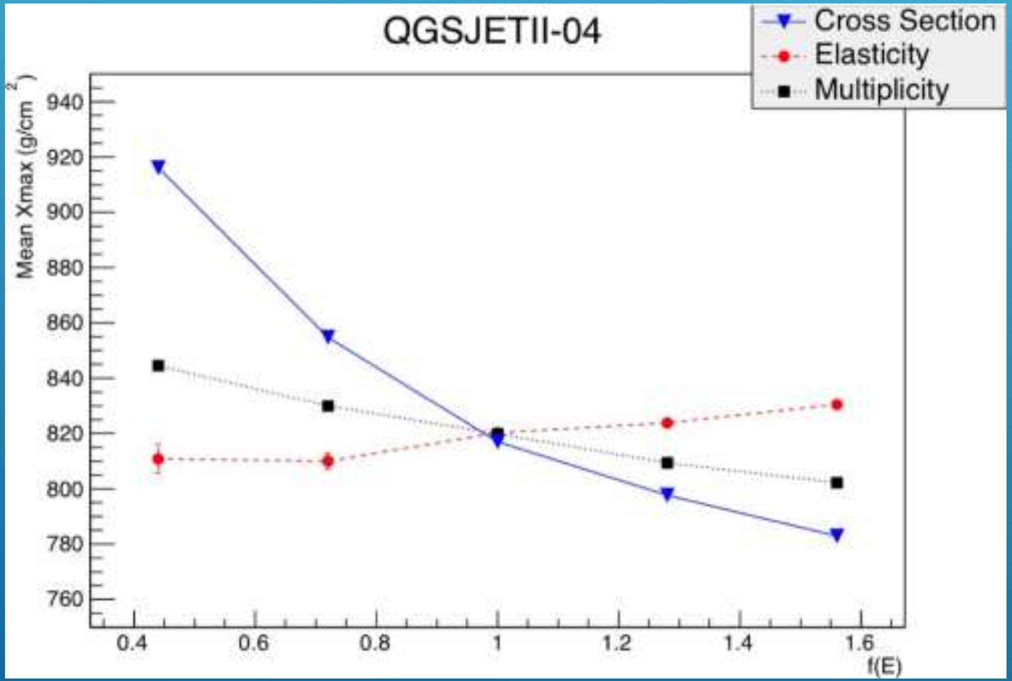
- **Results show *model parameter* uncertainty within a model results in $< X_{max} >$ uncertainty as large as difference between models.**

Model	$< X_{max} >$ uncertainty 10^{17} eV	$< X_{max} >$ uncertainty at $10^{19.5}$ eV
SIBYLL	7 gm/cm^2	36 gm/cm^2
QGSJET01	6 gm/cm^2	32 gm/cm^2
QGSJETII4	6 gm/cm^2	36 gm/cm^2
EPOS-LHC	6 gm/cm^2	36 gm/cm^2

TABLE I: Results of extrapolations of accelerator measurements.

+/- ~15 g/cm^2

Abbasi and Thompson



Dependence of $< X_{max} >$ on cross section, elasticity, and multiplicity at an energy of $10^{19.5}$ eV.

Variation between models: +/- ~15g/cm^2

Data uncertainties:

- **~17 g/cm^2 systematic**
- **~5 g/cm^2 statistical**

↓

Combined: ~30 g/cm^2 (23 without model var.)

Conclusion:

Uncertainties on X_{max} distribution locations complicate the usual statistical inferences about composition

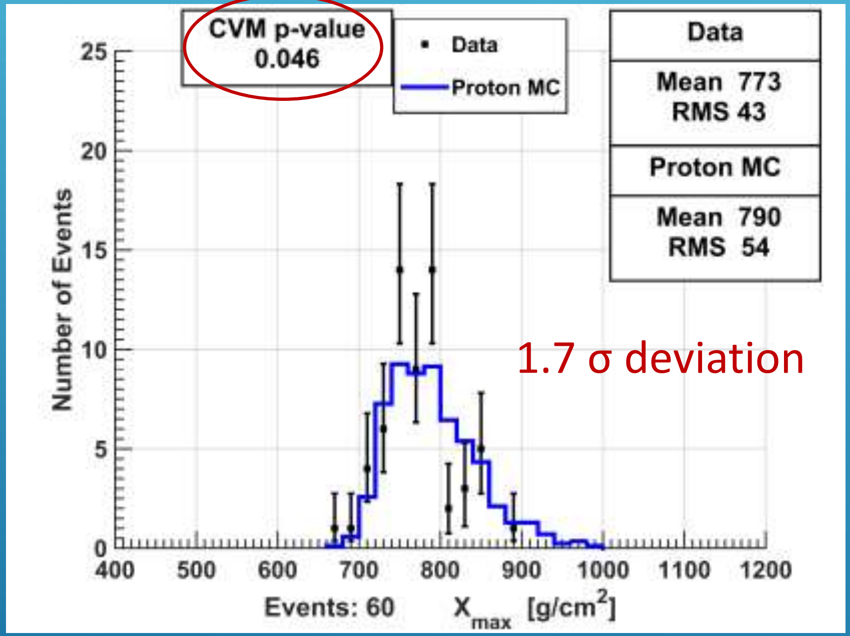
MOTIVATION

Variation between models: +/- ~15g/cm^2

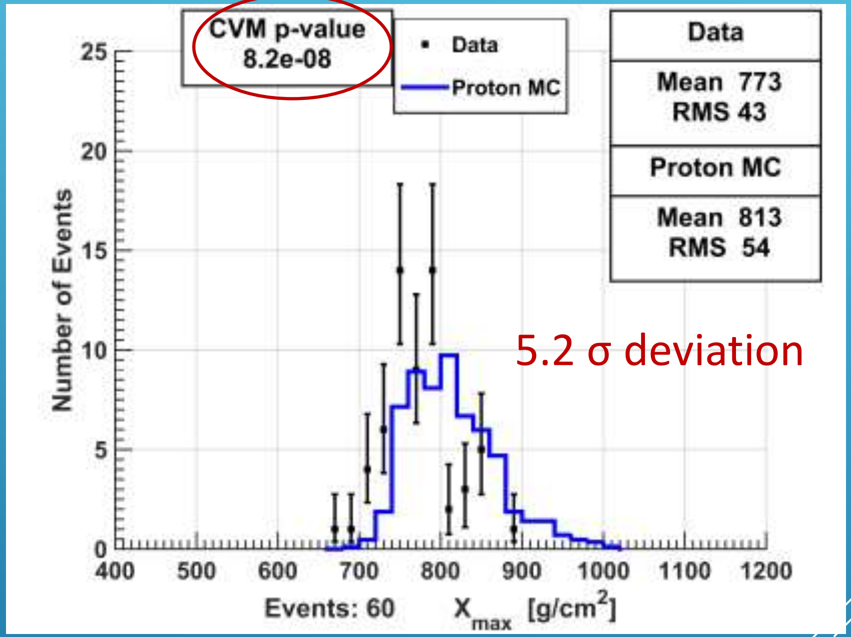
Data uncertainties:

- **~17 g/cm^2 systematic**
- **~5 g/cm^2 statistical**

Combined: ~30 g/cm^2 (23 without model var.)



7 year data, QGSJETII-03 proton
No shift



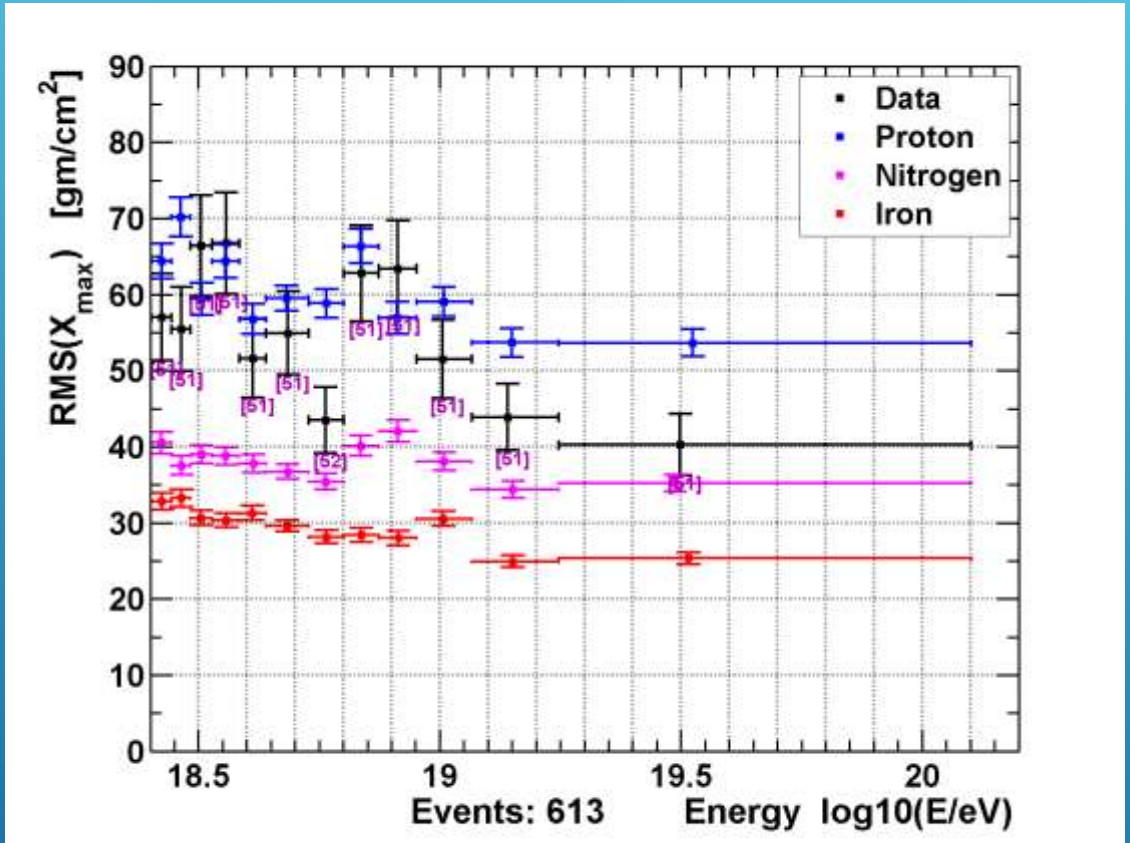
7 year data, QGSJETII-03 proton
+23 g/cm^2 to MC

Conclusion:

Uncertainties on X_{max} distribution locations complicate the usual statistical inferences about composition

VARIANCE - NARROWING

Compare data to models



- RMS(X_{max}) of data and QGSJETII-03
  - Sampling issue or actual change?

- **Question: Significantly different variance?**

  H_0: $\sigma_1^2 = \sigma_2^2$
  H_a: $\sigma_i^2 \neq \sigma_j^2$

- **Method: O'Brien's Test for Homogeneity of Variance**

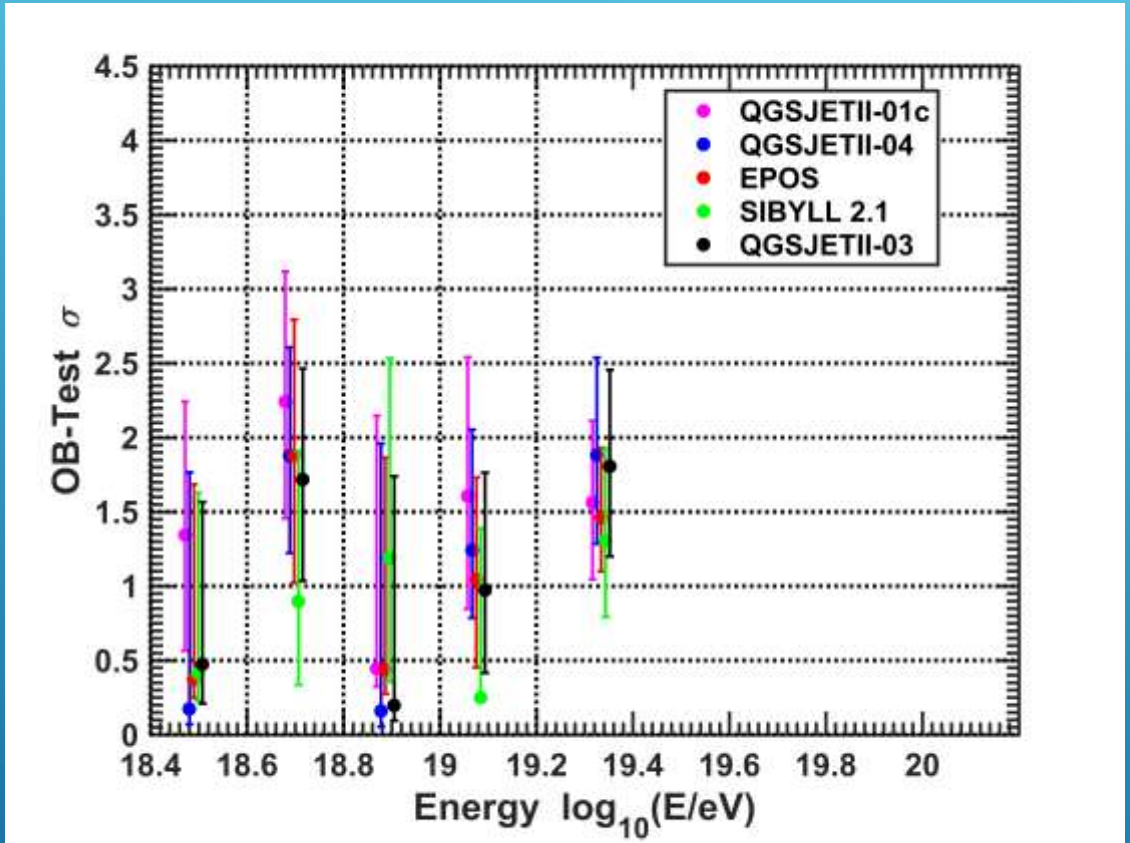
$$W = \frac{(N-k)}{(k-1)} \frac{\sum_{i=1}^{k} N_i(\overline{Z_{i.}} - \overline{Z_{..}})^2}{\sum_{i=1}^{k}\sum_{j=1}^{N_i}(Z_{ij} - \overline{Z_{i.}})^2},$$

$$Z_{ij} = \frac{N_i(N_i - 1.5)\left(y_{ij} - \overline{y_{i.}}\right)^2 - 0.5\sigma_{i.}^2(N_i - 1)}{(N_i - 1)(N_i - 2)}$$

P-value is calculated from $F_{k-1, N-k}$ **the F distribution with k-1 and N-k degrees of freedom.**

VARIANCE - NARROWING

Compare data to models



- Significance of p-value that variance is the same
  - All models are in good agreement
  - No evidence for "narrowing" or change in composition
  - Statistically compatible with pure proton for any model at any energy

Compare data to data: test if $\sigma_1^2 = \sigma_2^2 = \cdots = \sigma_5^2$ for the 5 energy bins of data

Result: Significance of deviation is 0.97σ or 33% probability they are the same.

Again, no statistical evidence for narrowed distribution

MOMENTS ≥ 2

Developed for this thesis work

- Question: Do two samples belong to the same location-family distribution?

H_0: G(x) is sample CDF from F(z-a) & H(y) is sample CDF from F(z-b), for any a and b
$(x \in G(x) \sim F(z-a)\ \&\ y \in H(y) \sim F(z-b))$

- Method: *L-test*. This is a more stringent test.

$$L = log\left\{\min_{a\leq s\leq b} \frac{N_1 N_2}{(N_1+N_2)^2}\sum_{k=1}^{N_1+N_2}[\hat{H}(s)_k - \hat{G}(s)_k]^2\right\},$$

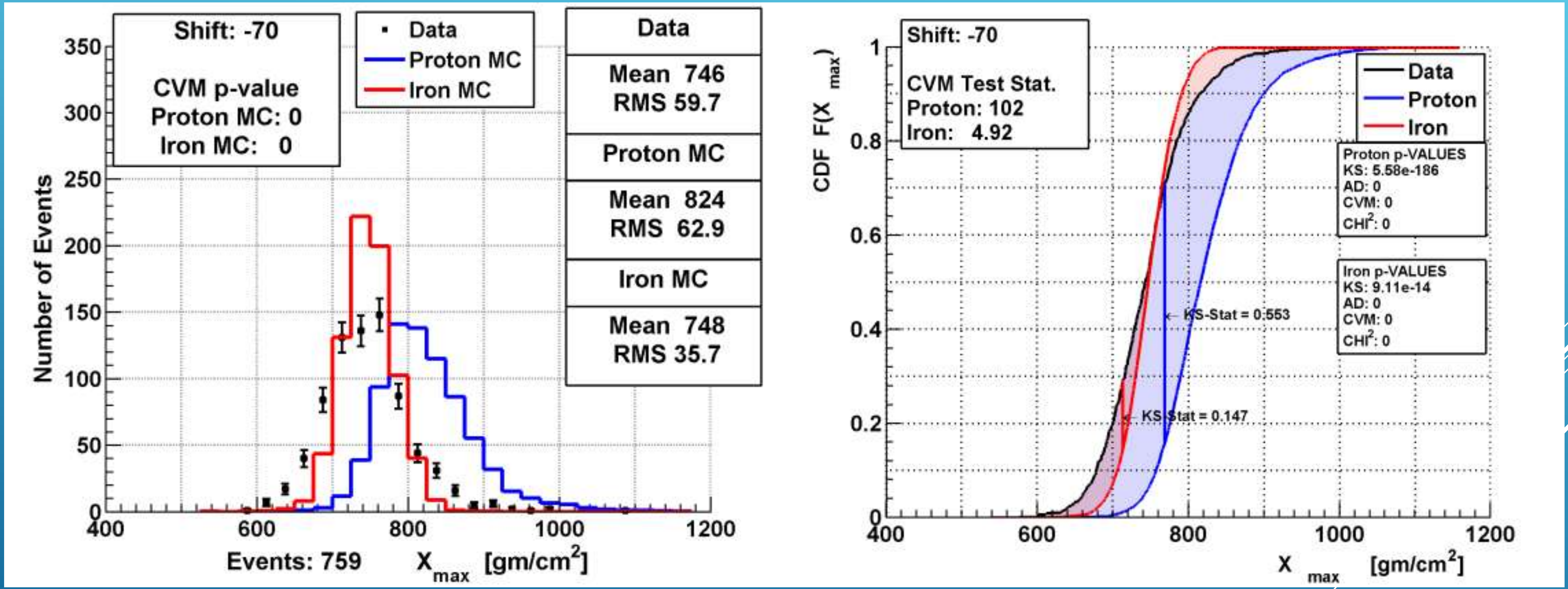
$$\hat{F}(s)_k = \frac{1}{N_1}\sum_{j=1}^{N_1} I[(x_j - s) \leq z(s)_k], \qquad \hat{G}(s)_k = \frac{1}{N_2}\sum_{j=1}^{N_2} I[y_j \leq z(s)_k], \qquad z(s) = (x-s, y)$$

In words:
Log of the minimum, by shifting, of the sum difference squared of two empirical CDF's

Distribution of L is the Generalized Maximum Likelihood distribution

MOMENTS ≥ 2

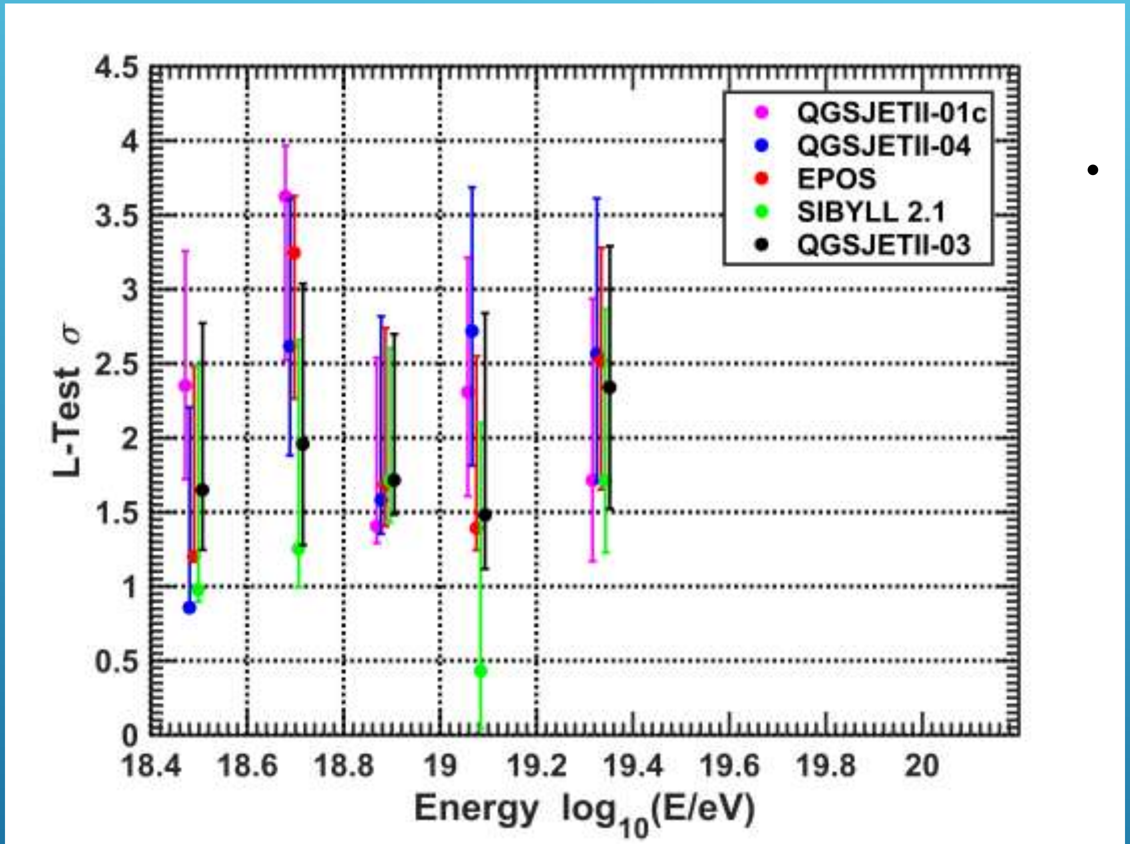
Tight geometry cuts and all energies



QGSJETII-03 distribution histograms and CDF's shifted for best agreements

MOMENTS $\geq$ 2

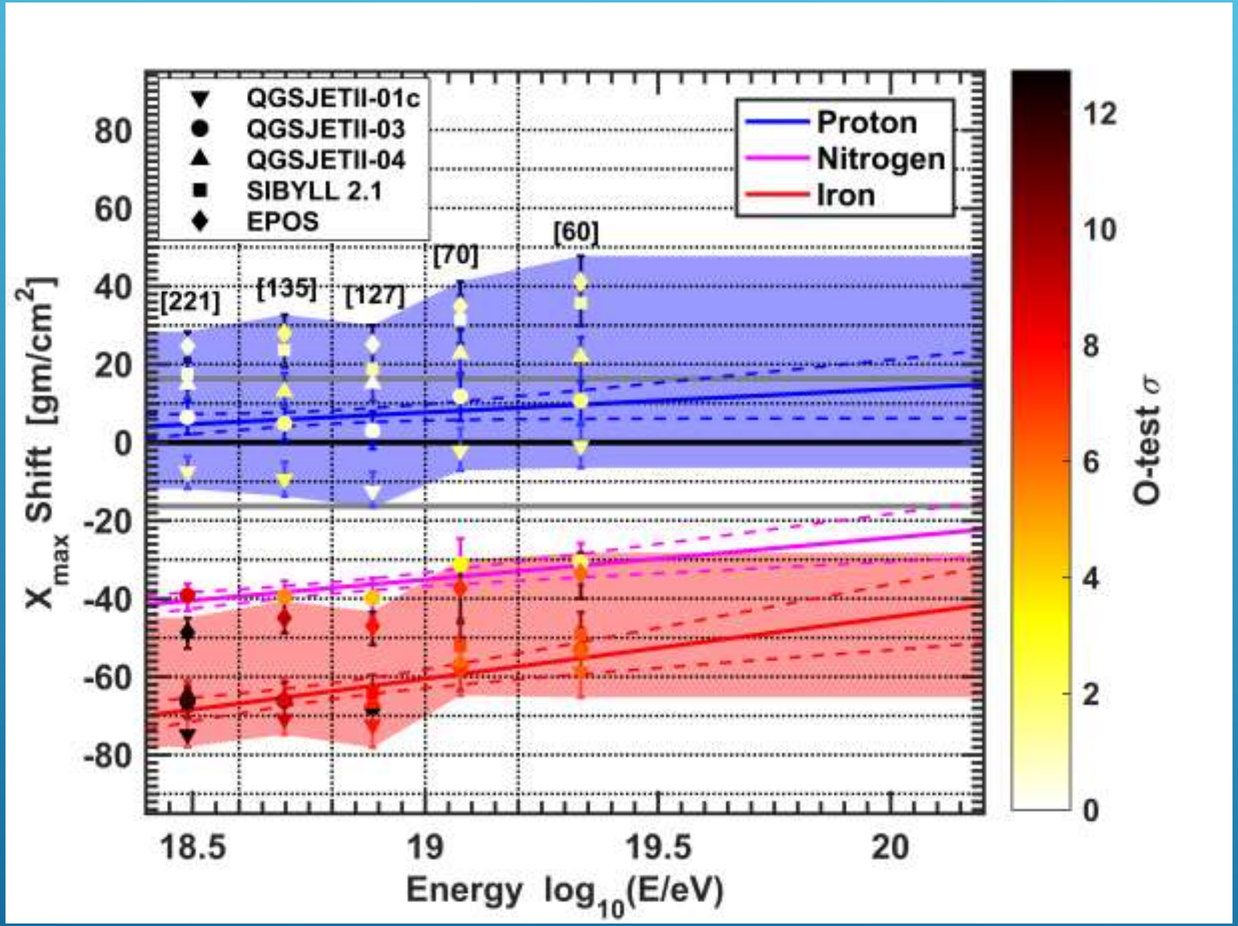
Compare data to models



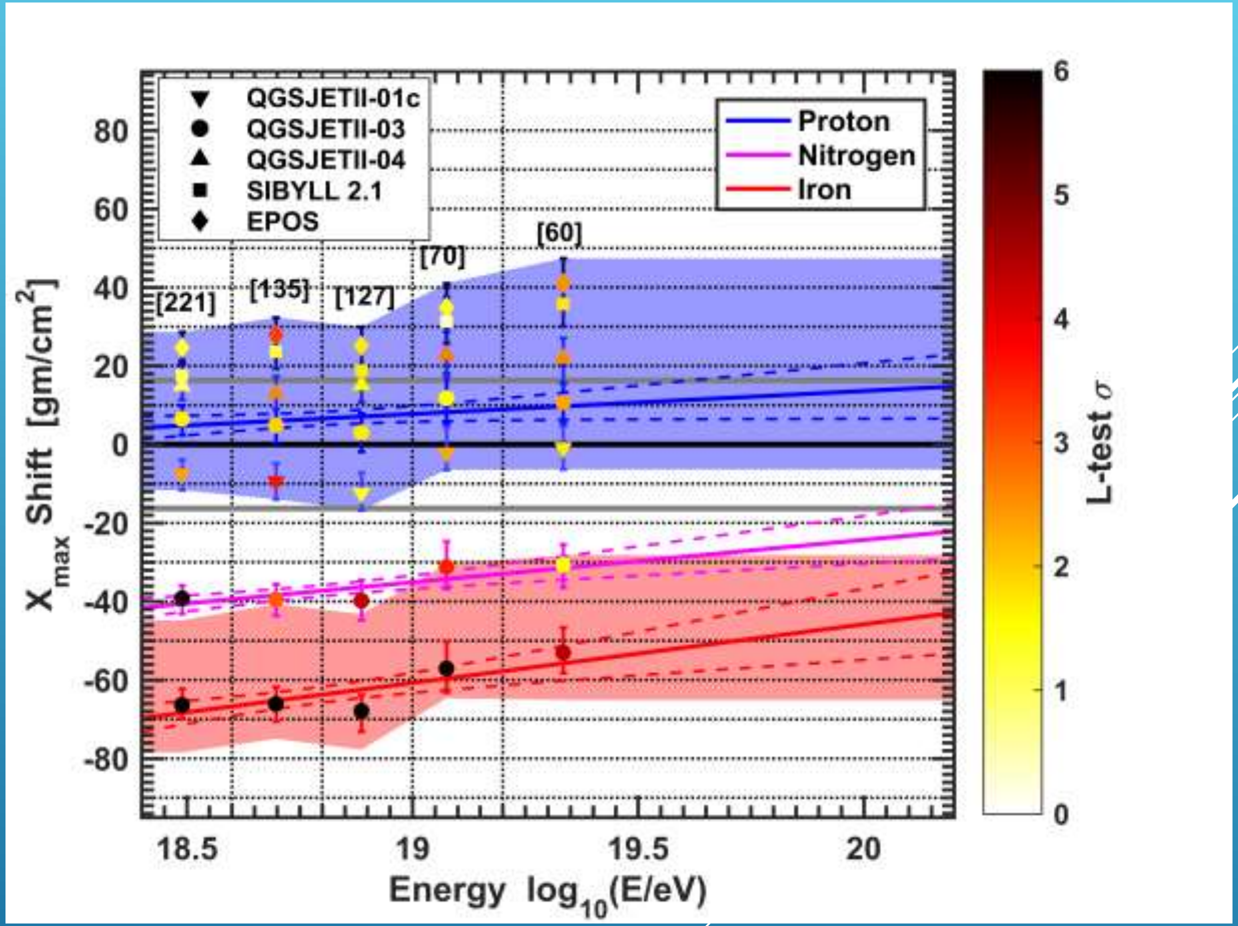
- Significance of p-value that distributions are location family related
  - All models are in good agreement
  - No evidence for "narrowing" or change in composition
  - Statistically compatible with pure proton for any model at any energy

SHIFT PLOT

Shift plot using L-test by combining robust measure of bias and location family test



L-test shifts with O'Brien's **σ**



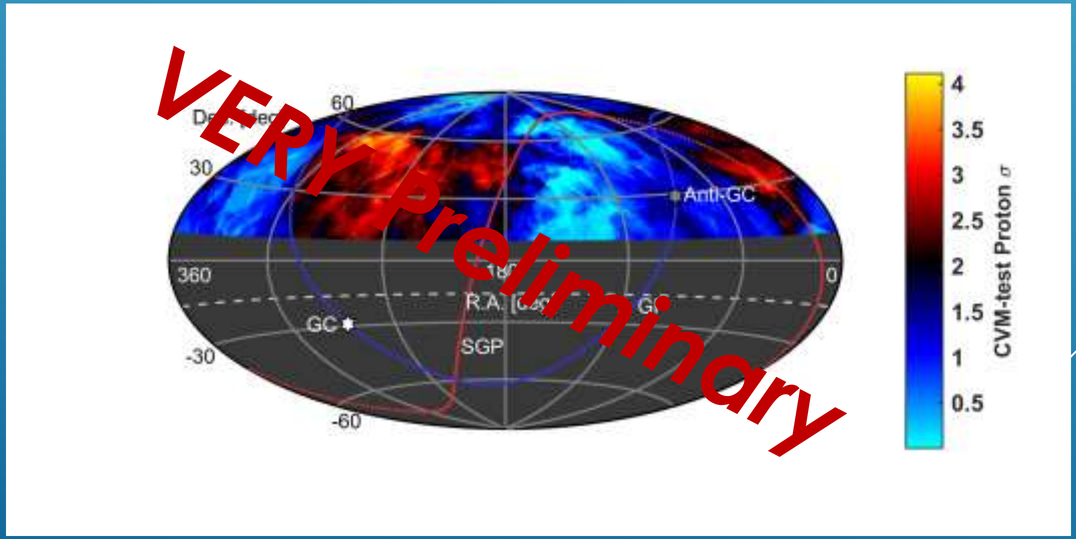
L-test shifts with L-test **σ**
(stopped calculating at 6**σ**)

COMPOSITION CONCLUSIONS

- **Statistical tests using distribution locations are inconclusive:**
  - **Stat. error, sys. error, model parameter uncertainty, model variation**

- **Higher moments agree between all models**
  - ***Data is statistically compatible with pure proton, at all energies, for all models***
  - **Not compatible with iron.**

- **Significance of data being "narrowed" in RMS is 0.97σ.**



Next to do?
Composition
Anisotropy
Using L-test?

THESIS CONCLUSIONS

- Hot/Coldspot Event Denisty Asymmetry Observed with 5.4σ significance
  - Energy Spectrum Anisotropy with 3.74σ
  - Energy-Distance Correlation Anisotropy with 3.4σ
  - *Suggests magnetic deflection of source by possible supergalactic fields*

- Higher moments of Xmax distributions agree between all models
  - *Data is statistically compatible with pure proton, at all energies, for all models*
  - Not compatible with iron.

- Significance of data being "narrowed" in RMS is 0.97σ.

$$E < \frac{E_{max}}{10^{18}\ eV} \cong \frac{1}{2}\beta \cdot Z \cdot \frac{B}{\mu G} \cdot \frac{L}{kpc}$$

This information should be useful for informing future models of magnetic fields and sources

$$\delta = \frac{S}{R_{Larmor}} = 0.5^{\circ} Z \frac{L}{kpc} \frac{B}{\mu G} \frac{10^{20}}{E}$$

*Kernel Density Estimation Hotspot: 3.65σ

PART ONE
ADDITIONAL MATERIAL

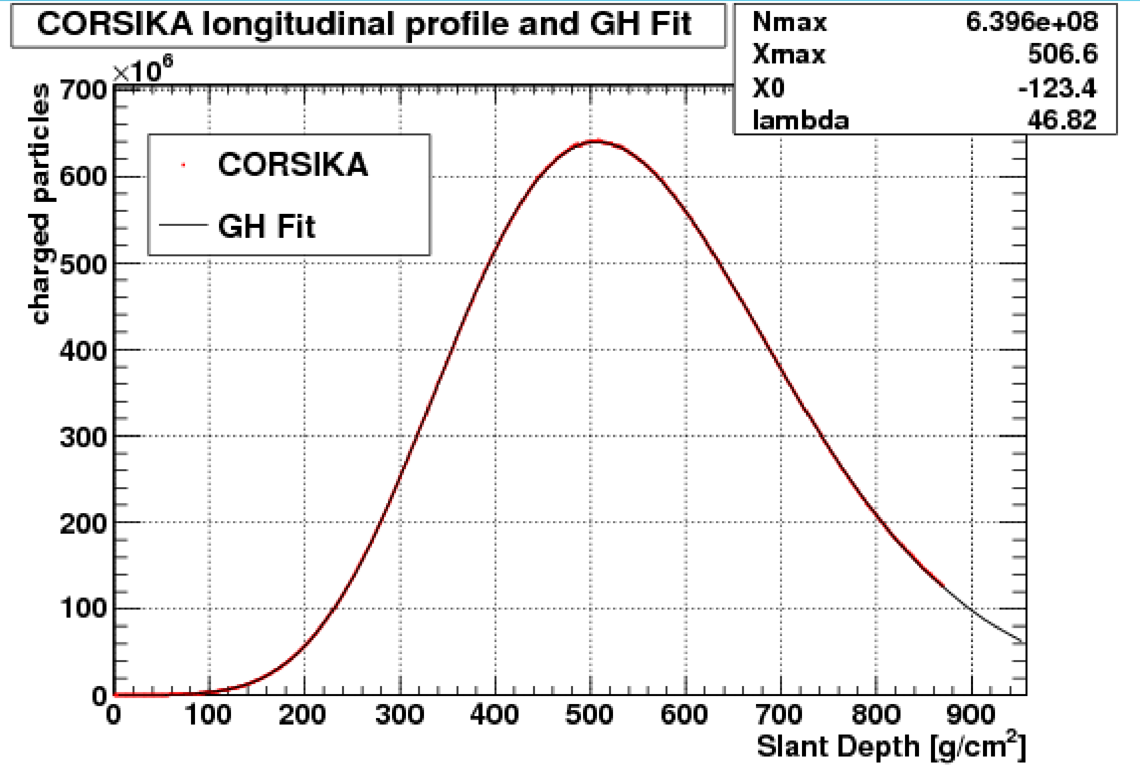
SIMULATION - LONGITUDINAL

CORSIKA Simulated Air Shower 10^{15} eV $45°$ inclination

Red – $e^{+/-}$, γ

Green – $\mu^{+/-}$

Blue – Hadrons ($\pi^{0/+/-}$, $K^{0/+/-}$, p, n)



Gaisser-Hillas Parameterization

$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max}-X_0}{\lambda}} \exp\left(\frac{X_{max} - X}{\lambda}\right)$$

- **Match fit to real event data.**

SIMULATION - LATERAL

Largely from coulomb multiple scattering of electrons

$$\rho(r) = \frac{N}{r^2} f\left(s, \frac{r}{r_M}\right)$$

Nishimura-Kamata-Geisen (NKG) formula.
Lateral density of electrons as function of shower age

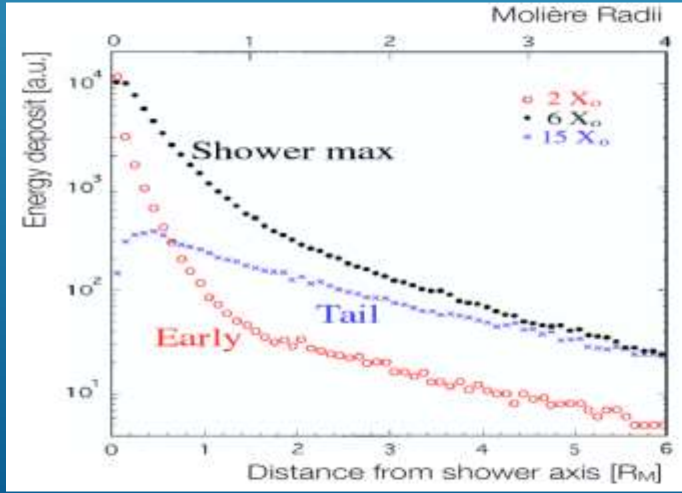
$$f\left(s, \frac{r}{r_M}\right) = \left(\frac{r}{r_M}\right)^{s-2} \left(1 + \frac{r}{r_M}\right)^{s-4.5} \frac{\Gamma(4.5 - s)}{2\pi\Gamma(s)\Gamma(4.5 - 2s)}$$

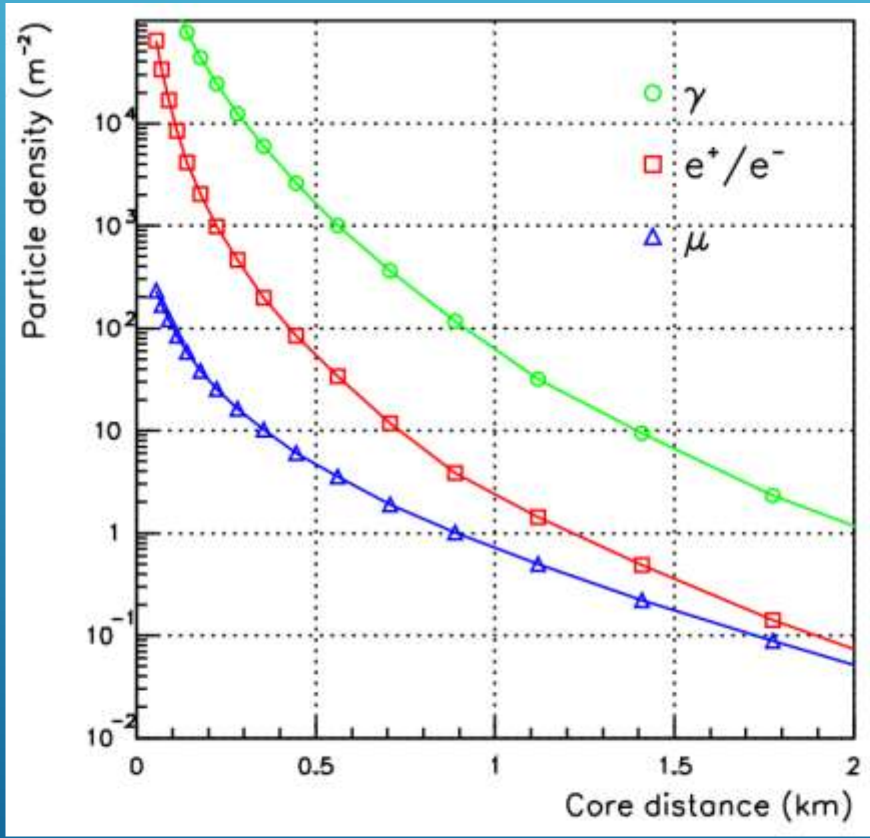
$$s = \frac{3X}{2X + X_{max}}$$

Shower Age: 1 is Xmax

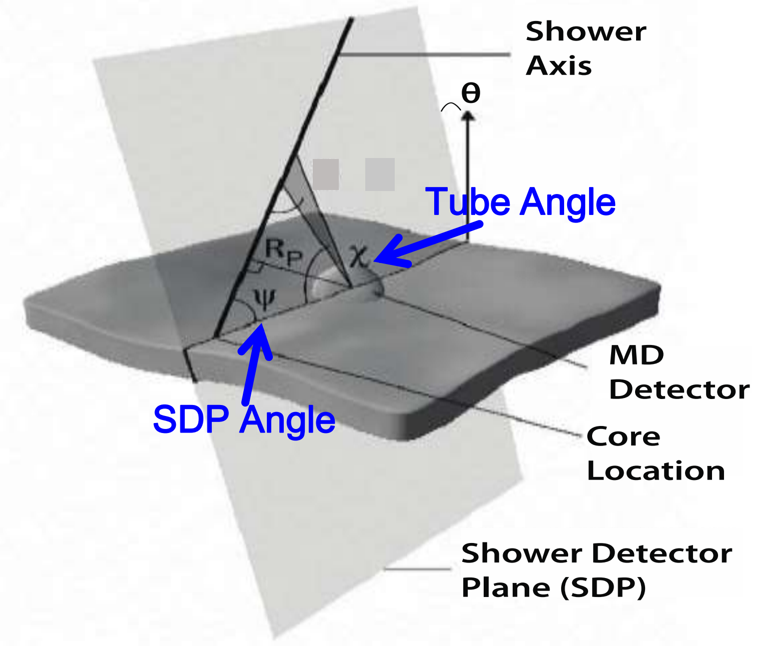
$$R_M = \frac{21\ MeV}{E_c}\lambda \approx 9\ gm/cm^2$$

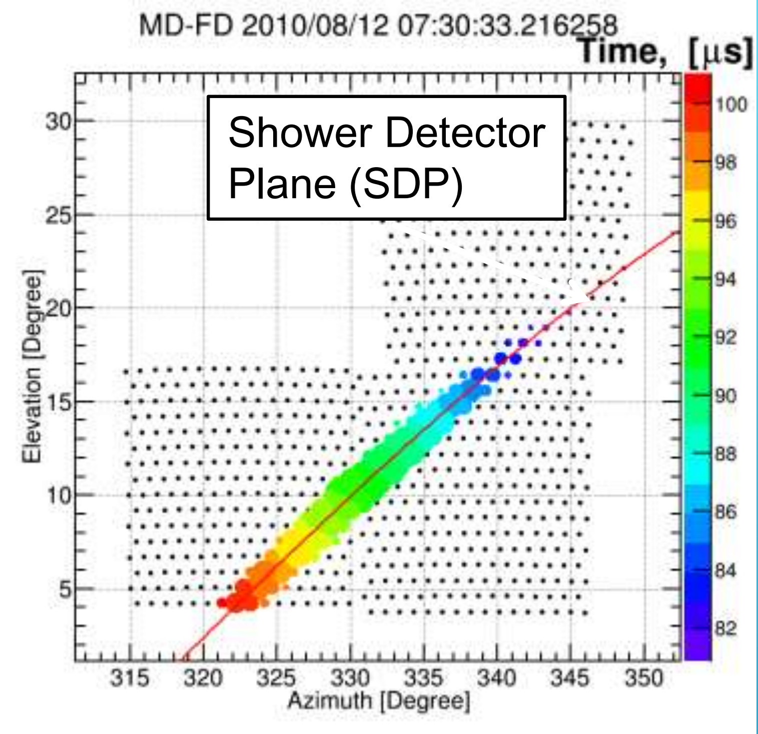
Moliere radius

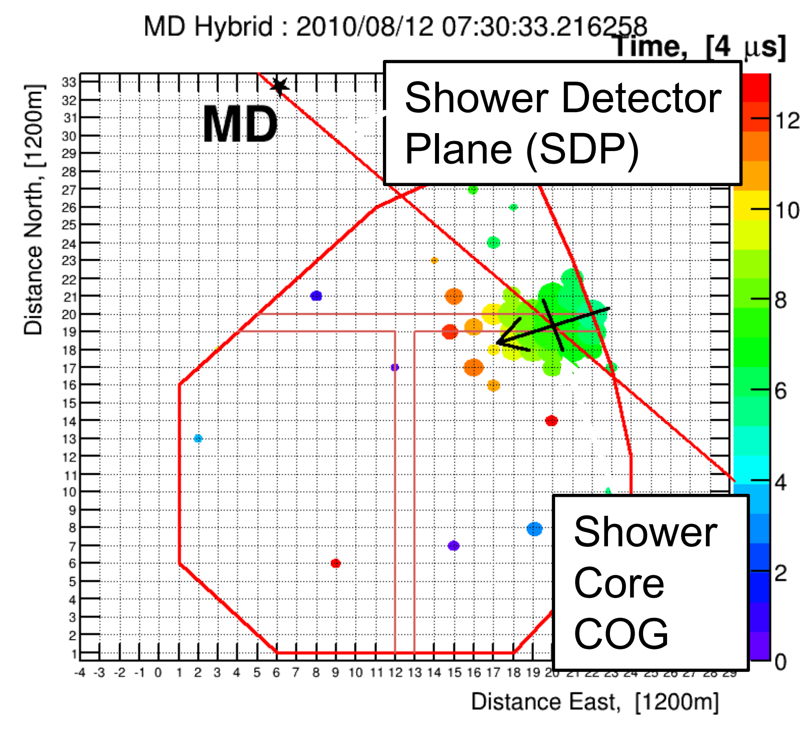




RECONSTRUCTION







SDP Normal — Tube Direction — Charge

First find SDP: $$\chi^2 = \sum_i \frac{(\hat{n} \cdot \hat{n}_i)^2 \cdot w_i}{\sigma_i^2}$$

SD Virtual Tube Timing: $$t_{SD} = t_{SD_{Trig}} + \frac{SD_{Dist}}{c}$$

Timing to Minimize: $$t_i = T_{Rp} + \frac{R_P}{c} tan\left(\frac{\pi - \psi - \chi_i}{2}\right)$$

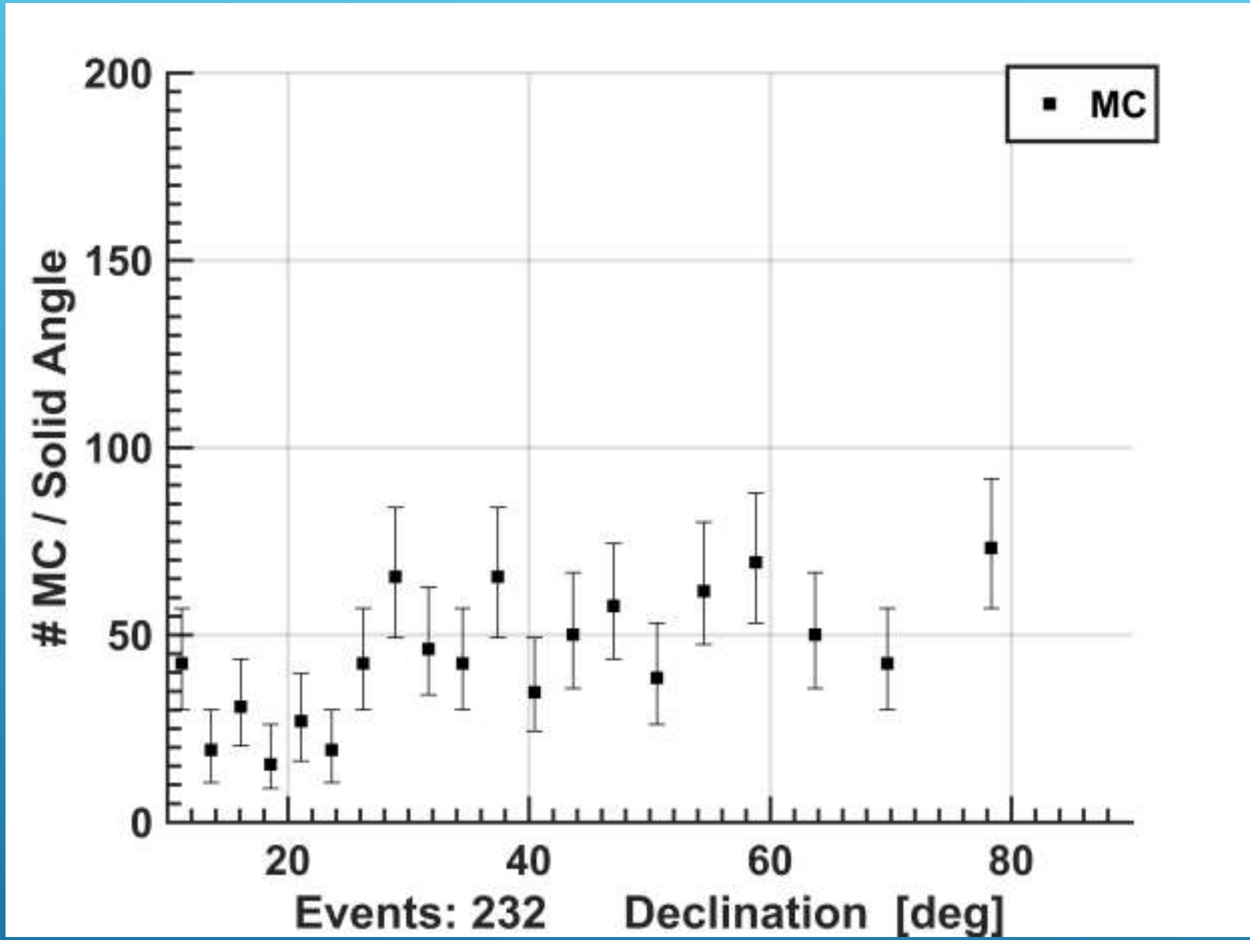
Chi-Square Minimization of Parameters: $\psi, \theta, R_P, R_x, R_y$

$$\chi^2 = \chi^2_{MD_{Timing}} + \chi^2_{SD_{Timing}} + \chi^2_{SD_{Core}}$$

$$\chi^2_{Core} = \sum_1^2 \frac{\|\mathbf{R}_i - \mathbf{R}_{COG}\|^2}{\sigma^2_{\mathbf{R}_{COG}}}$$

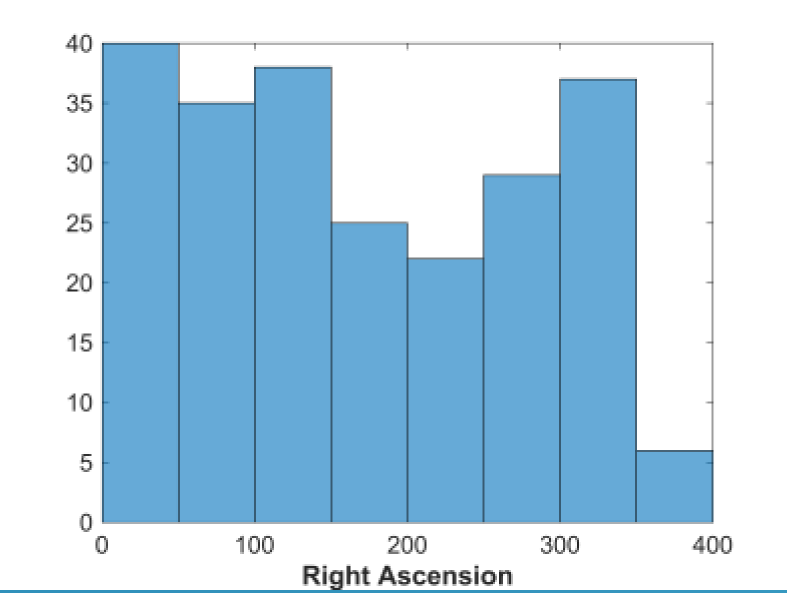
ENERGY SPECTRUM ANISOTROPY ADDITIONAL MATERIAL

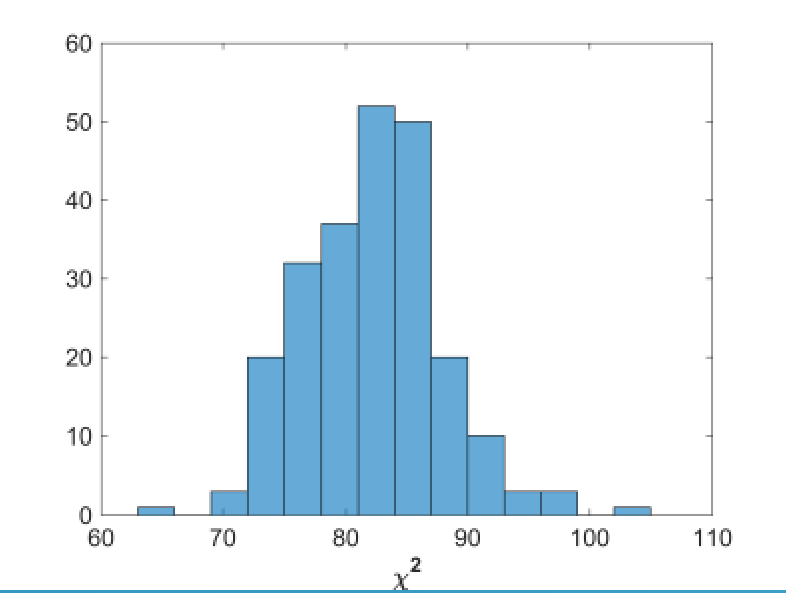
MC DISTRIBUTION OF HITS

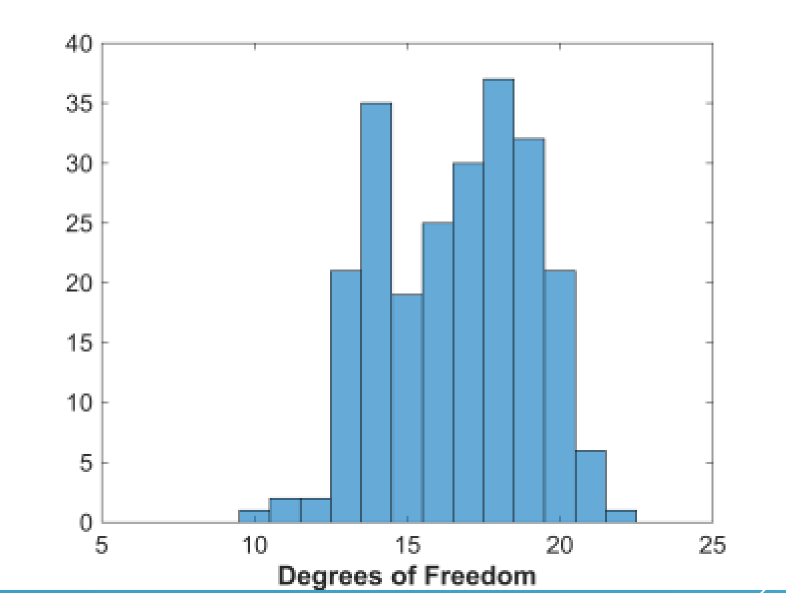


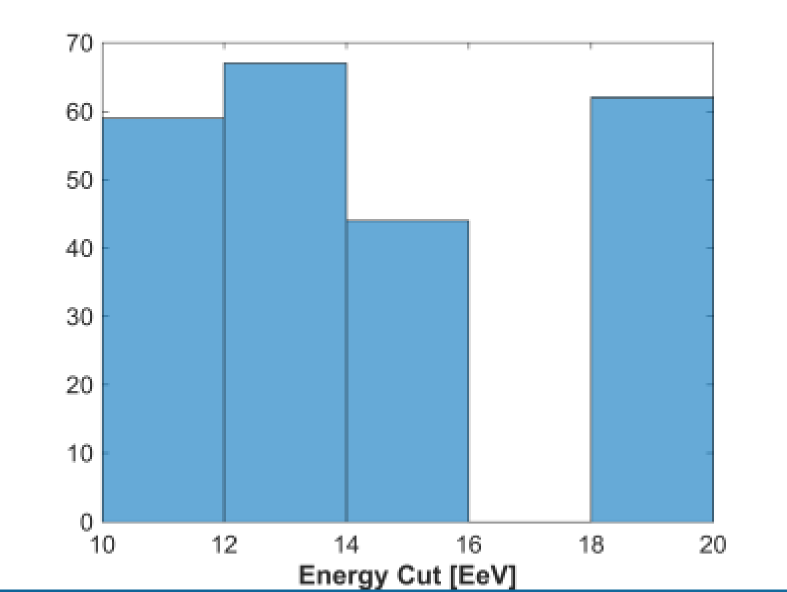
Shows small amount of declination bias in the analysis

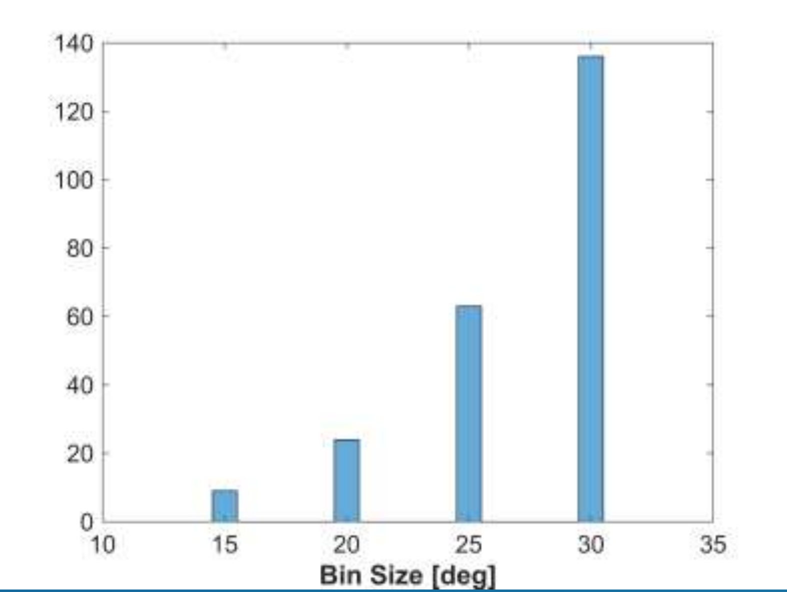
MC DISTRIBUTION OF HITS



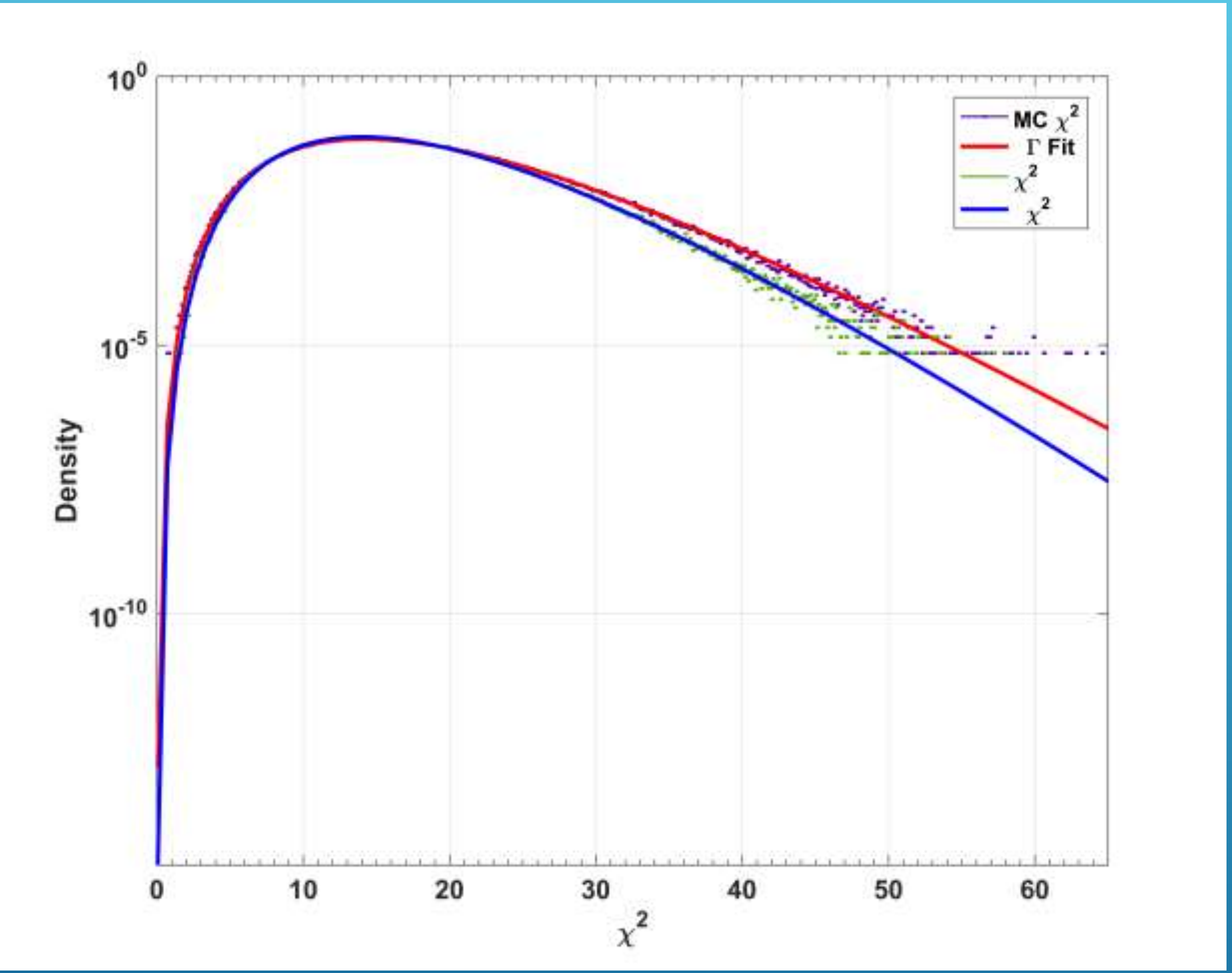








MC CHI^2 DISTRIBUTION AT DATA MAX SIGMA POINT



MC sets with 14 energy bins
Closest to chi^2 with 16 degrees of freedom

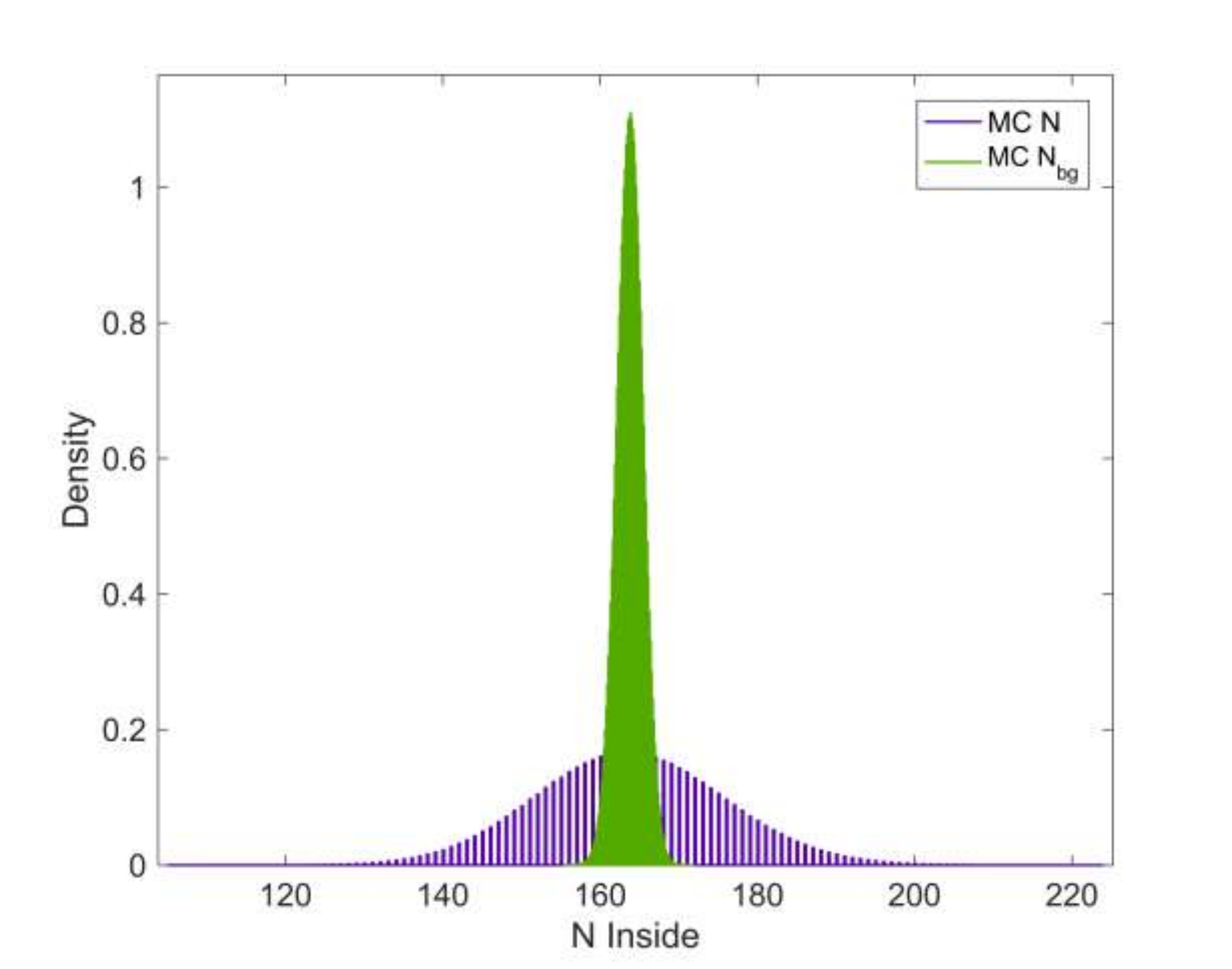
138.8 R.A. 44.8 Dec.
19.2 energy cut
30 deg binning

"Chi square" distribution of MC sets

Data chi square: 78.3 for 14 energy bins

- There are two additional degrees of freedom:
  - Background Fluctuation
  - Rebinning

MC DISTRIBUTIONS AT DATA MAX SIGMA POINT



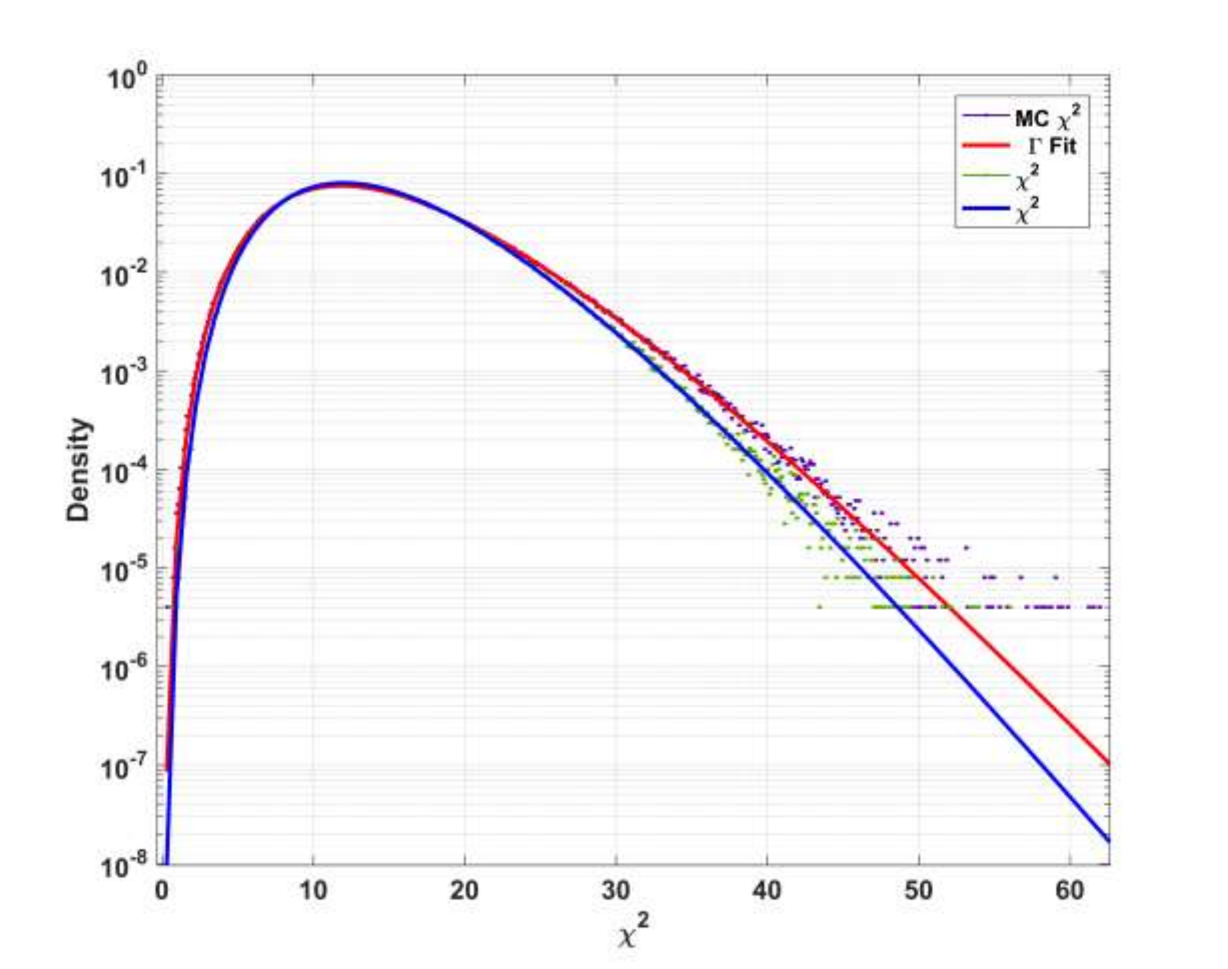
138.8 R.A. 44.8 Dec.
19.2 energy cut
30 deg binning

MC N inside is Poisson: 163.8 +/- 12.0
(sqrt(163.8) = 12.8

MC N_bg background is not Poisson: 163.8 +/- 1.7
Fluctuation is sqrt(N)*0.14 exposure ratio exactly

This is the same background fluctuation Li-Ma uses

MC CHI^2 DISTRIBUTION AT DATA MAX SIGMA POINT



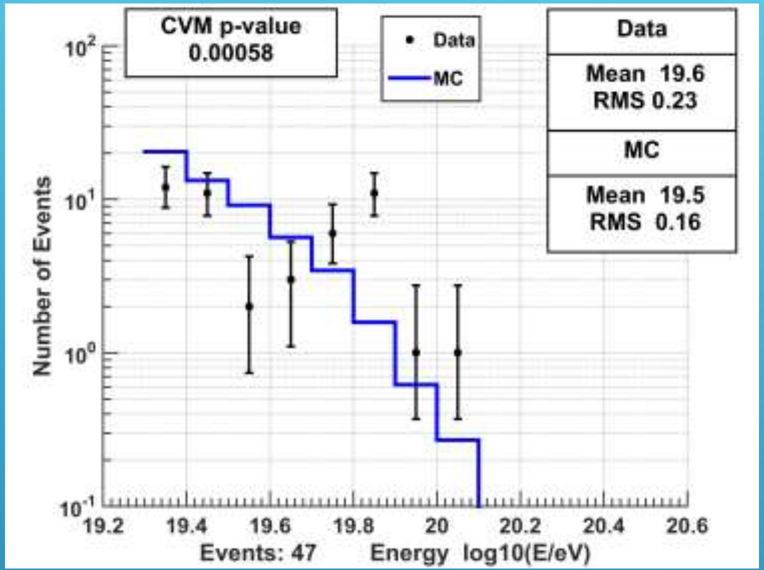
138.8 R.A. 44.8 Dec.
19.2 energy cut
30 deg binning

"Chi square" distribution of MC sets
with no background fluctuation or rebinning

547 MC have infinite chi^2 due to no rebinning

MC sets with 14 energy bins
Closest to chi^2 with 14 degrees of freedom

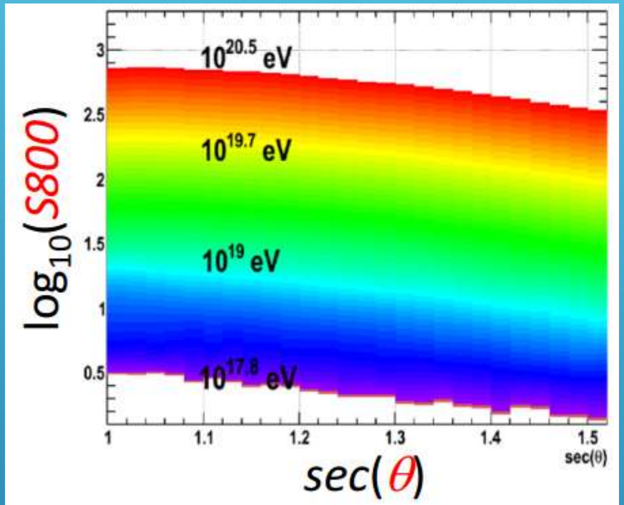
ENERGY SYSTEMATICS – INSIDE VS OUTSIDE



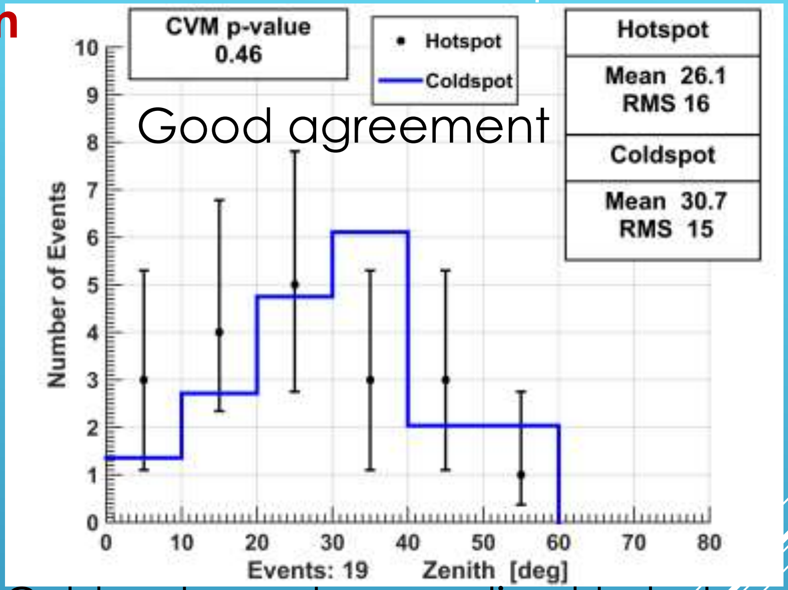
Data Vs MC comparison
(normalized to data/MC outside spot)
3.44 σ different.

At location of Li-Ma hot/cold maximum

“Rainbow Plot”

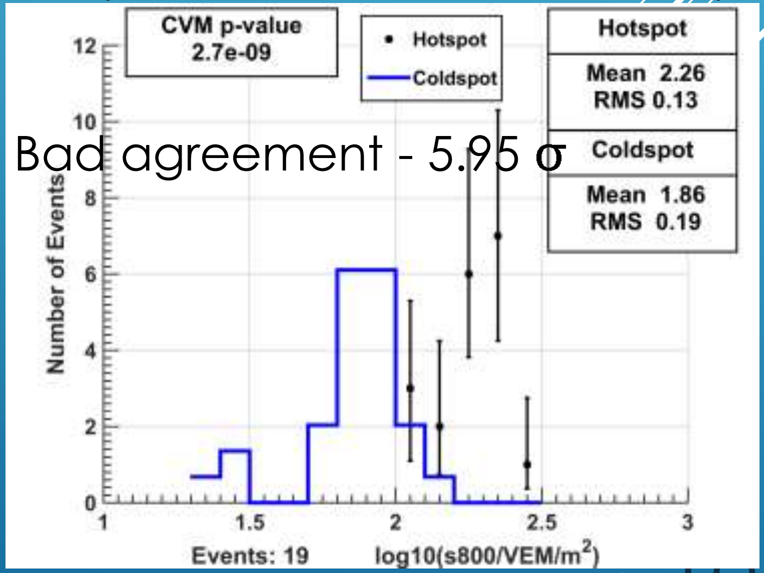


Data Vs Data comparison



Good agreement

Coldspot events normalized to hotspot



Bad agreement - 5.95 σ

Data Vs Data comparison

Could systematics cause events to migrate from Coldspot to Hotspot?

Energy is reconstructed by Zenith angle and s800 signal

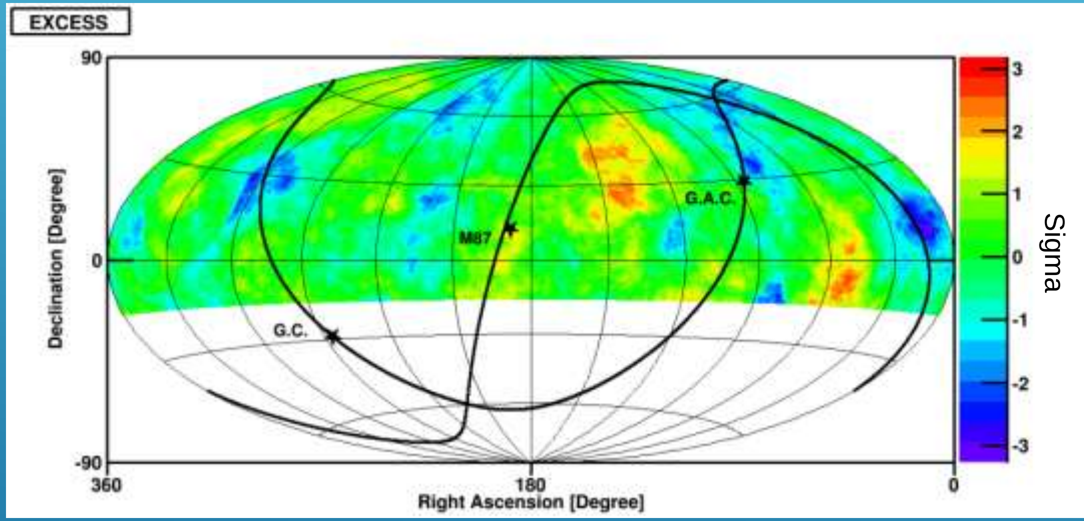
- **Zenith agrees very well. Systematic must come from s800**
- **s800 would have to be increased by 139% for hotspot to be systematic from the coldspot**

E >= 57 EeV events: ~14 over N_{bg} or $3.6N_{bg}$

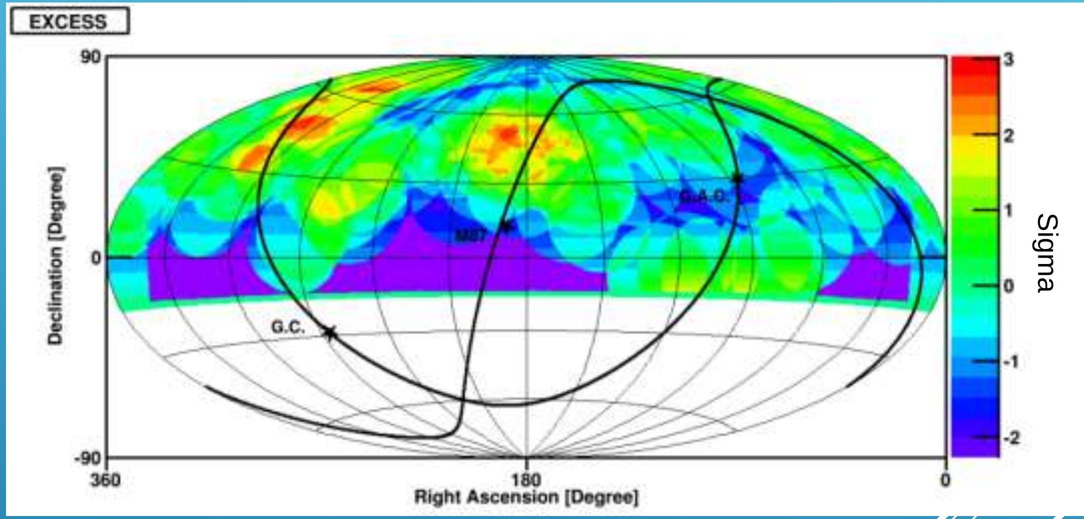
20 <= E < 57 EeV events: ~21 under N_{bg} or $0.57N_{bg}$

OTHER SYSTEMATIC CHECKS

- Seasonal and hourly energy corrections result in little change to joint significance
- Anti-Sidereal time results in no significant excesses, deficits or combinations



20 <= E < 57 EeV Anti-Sidereal



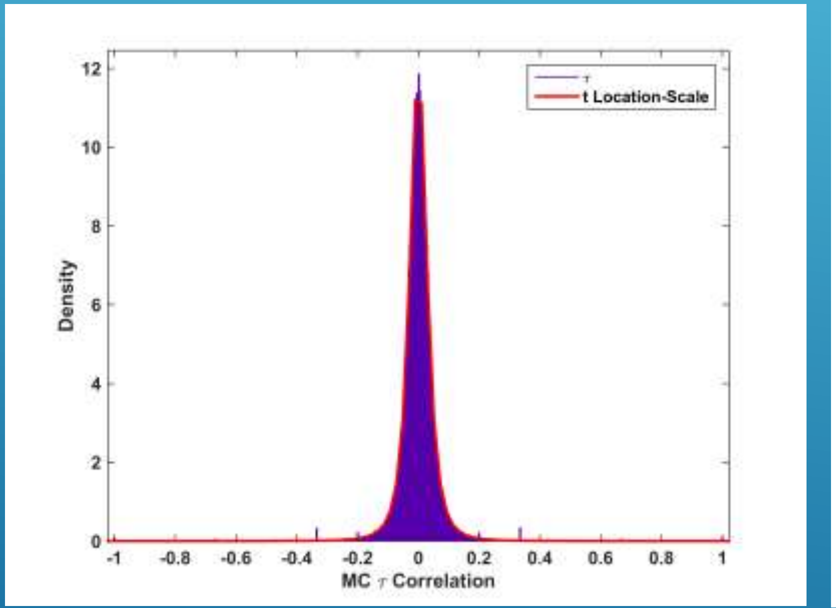
E >=57 EeV Anti-Sidereal

ENERGY-DISTANCE CORRELATION ADDITIONAL MATERIAL

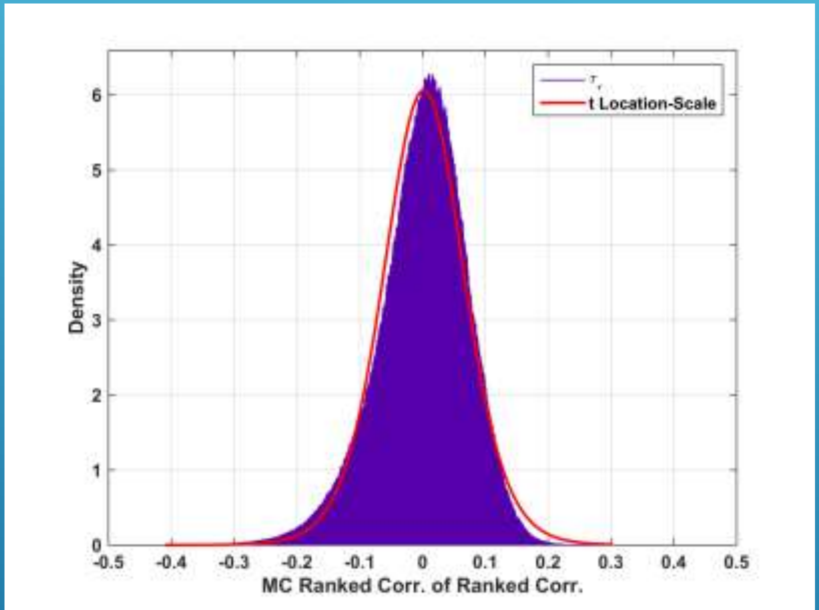
CHECK FOR GOOD BEHAVIOR

- Correlation coefficients follow the t Location-Scale distribution
  - Literature states correlations of correlations should have a wider distribution

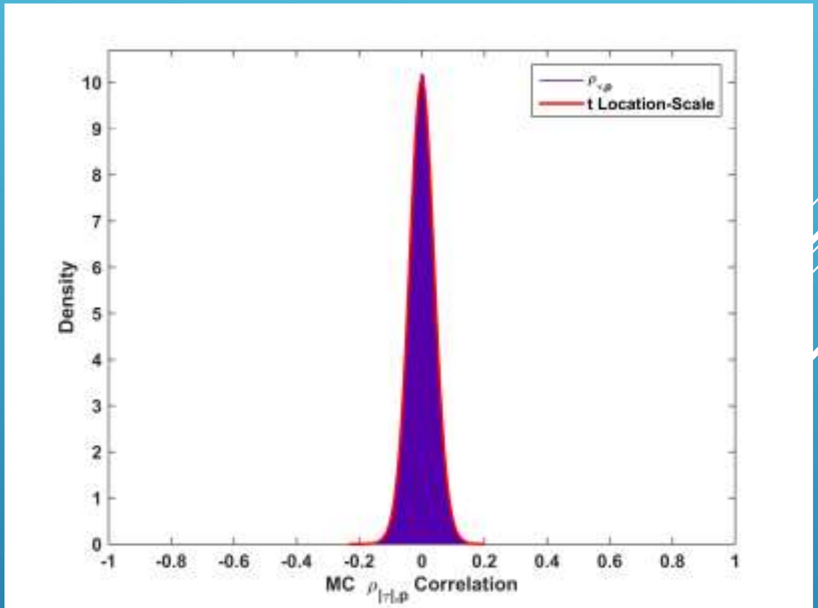
- p-values should be Uniform (Null – single correlation)
  or a Beta distribution (prior information – second correlation)



Ranked correlation τ
Fits well



Double Ranked Correlations $\tau_{|\tau|}$
Doesn't behave properly
Not Used



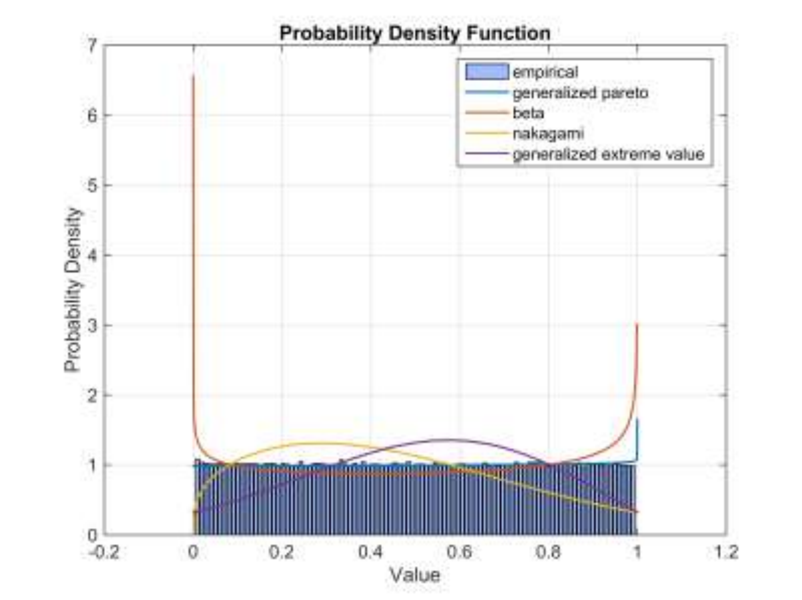
$\rho_{|\tau|,p}$
Fits distribution well
Used for significance test

Histograms of 852 test points from 300 MC – 2.6e5

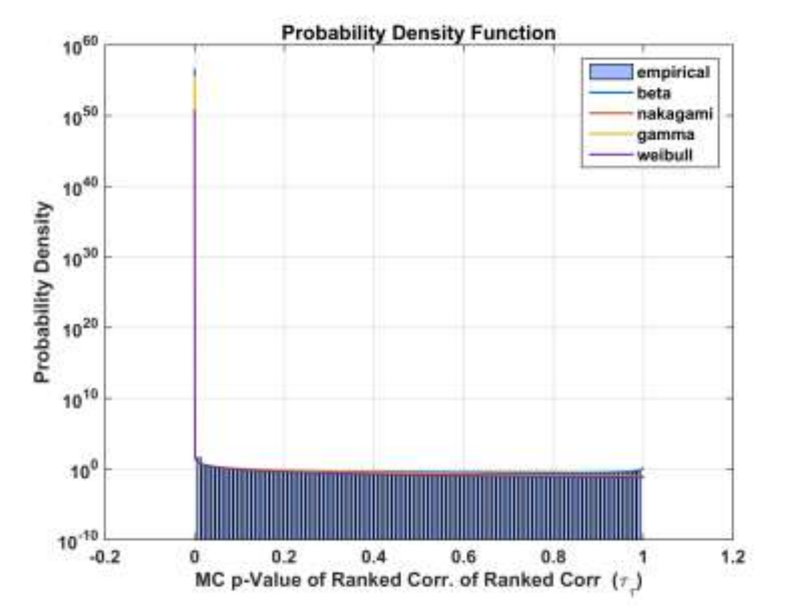
CHECK FOR GOOD BEHAVIOR

- Correlation coefficients follow the t Location-Scale distribution
  - Literature states correlations of correlations should have a wider distribution

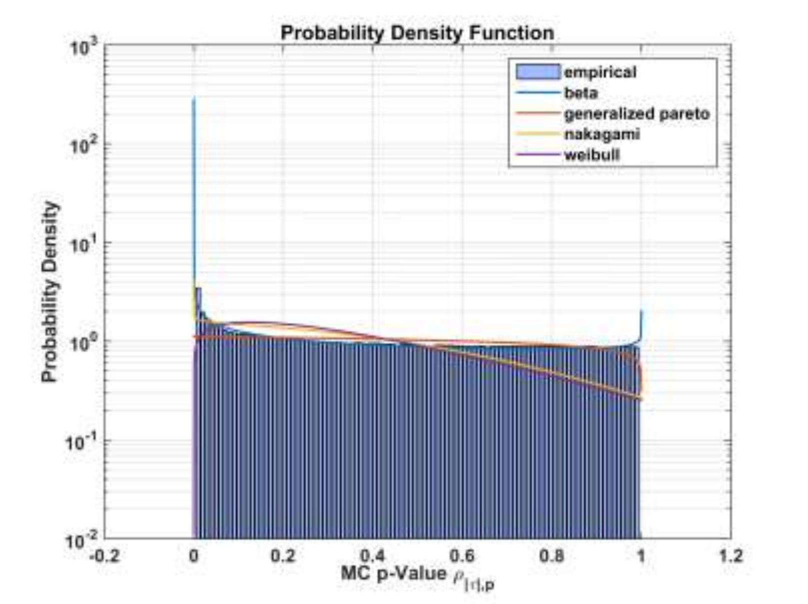
- p-values should be Uniform (Null – single correlation)
  or a Beta distribution (prior information – second correlation)



Ranked correlation p-Value
Uniform Distribution



Double Ranked Correlations p-Value
Beta Distribution
Not Used

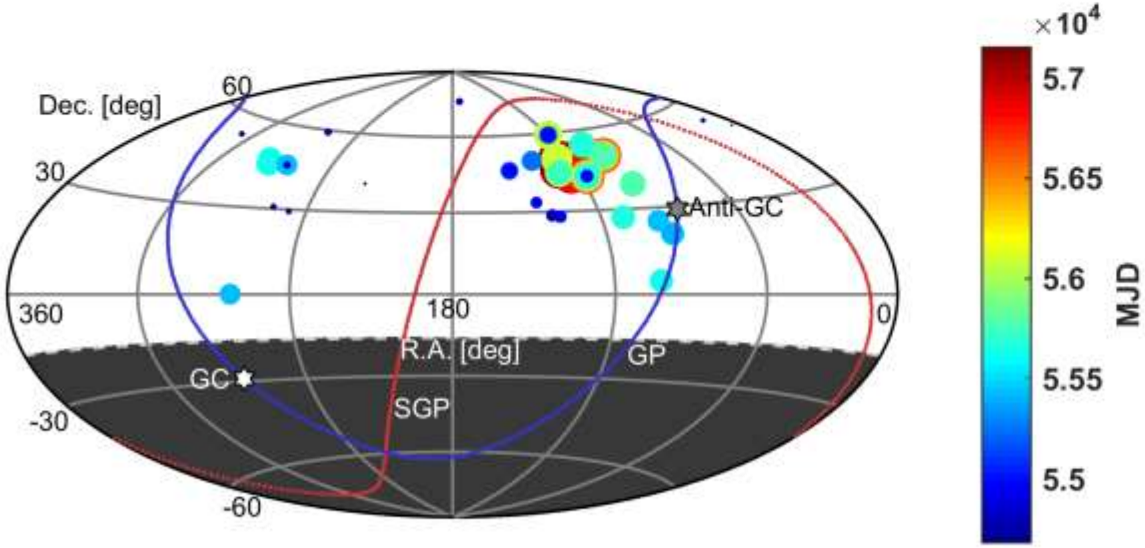


$\rho_{|\tau|,p}$'s p-Value
Fits Beta Distribution Better
Used for significance test

Histograms of 852 test points from 300 MC – 2.6e5

INTEGRAL DAY SIGNIFICANCE

- Blue line is linear fit — 0 to 7 years
- Red line is linear fit — 5^{th} to 7 years



- Location of maximum colored/sized by MJD
  - General location is found within ~3 years

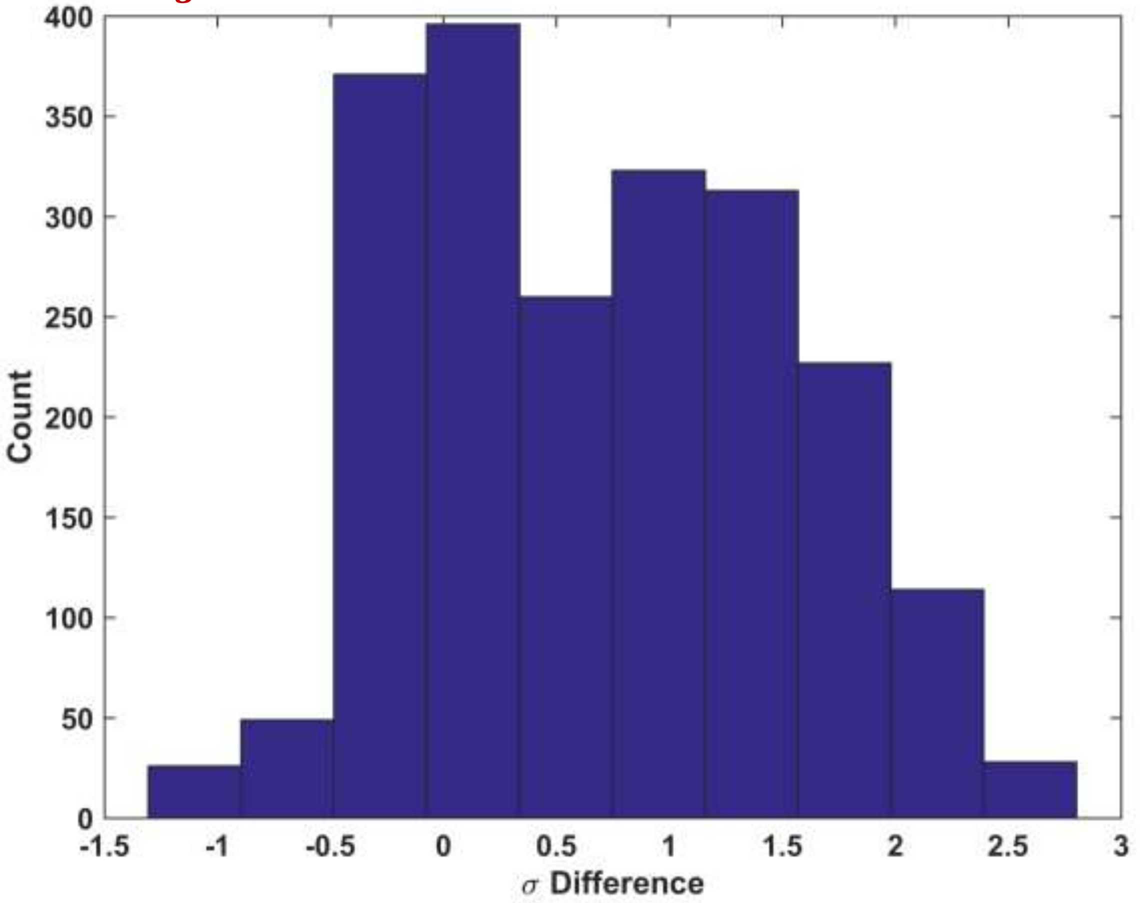
8 year estimate **~4σ_{global}**

- **Maximum σ_{local} on map**
- **Linear correlation 0.905 (0.935 after 5^{th} year)**

YEAR BY YEAR TREND

We only use integral year data

8 year estimate ~$4\sigma_{global}$

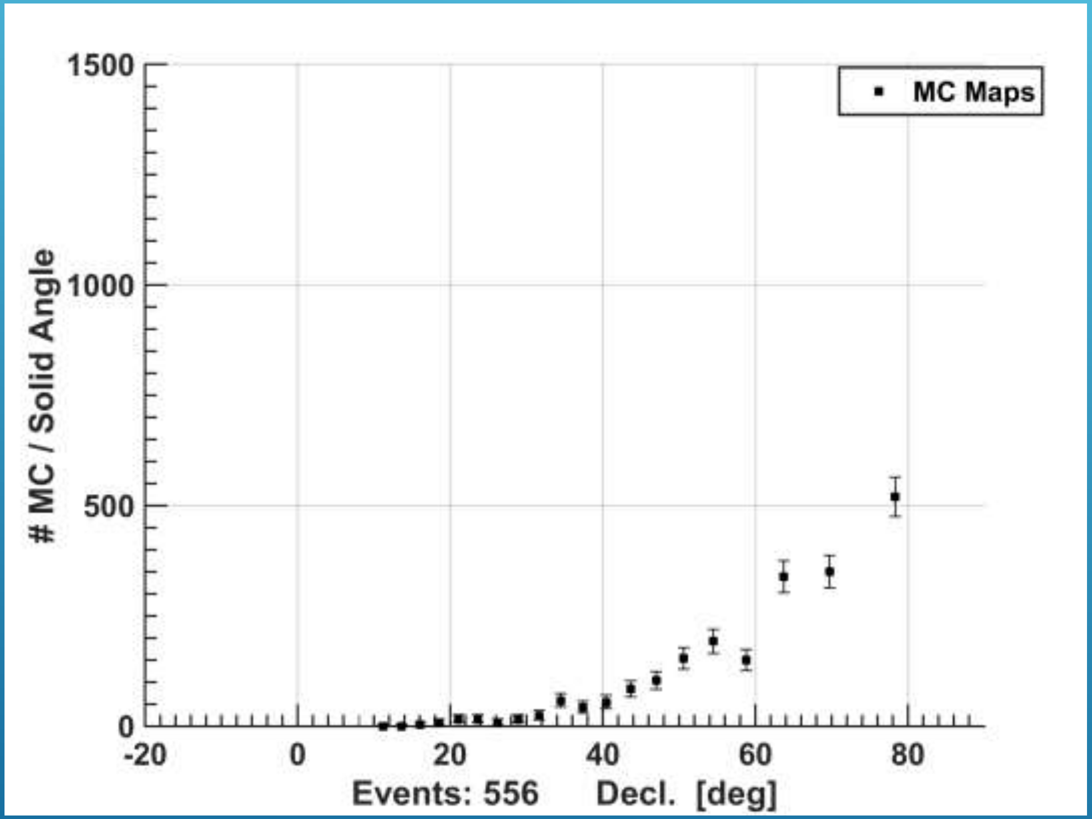


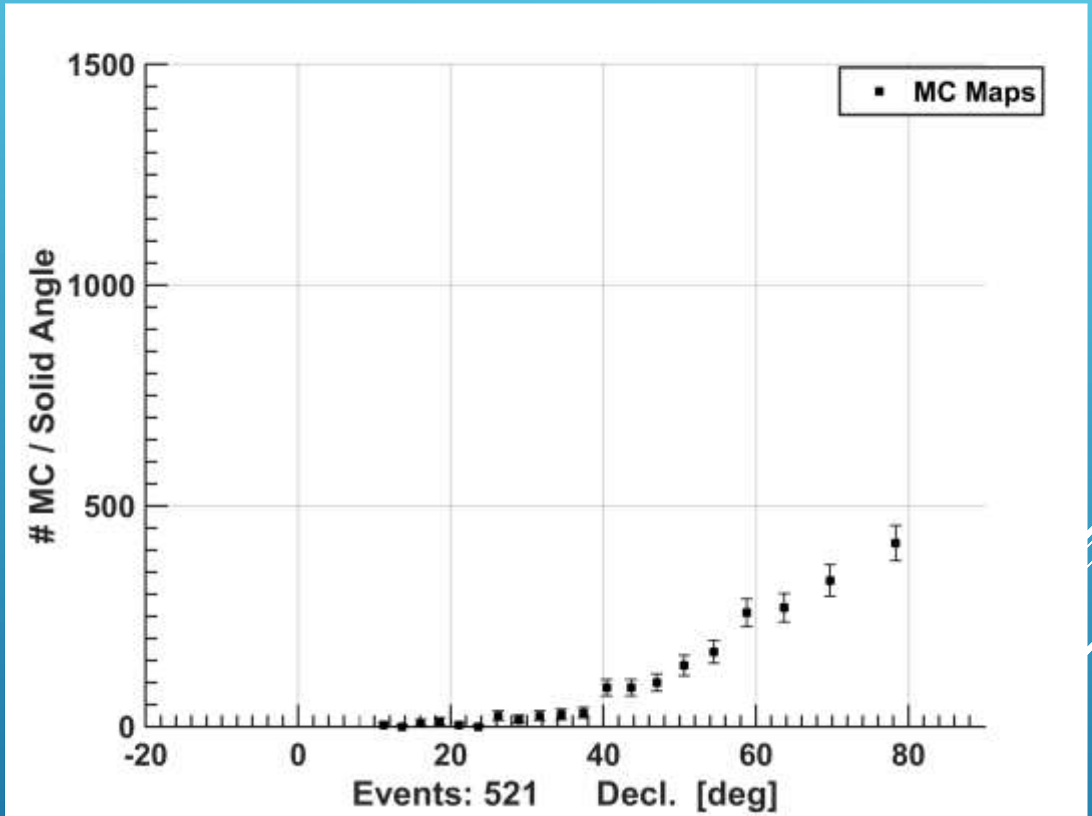
- Median sliding 1 year change
  - 0 to 7 years — +0.7 σ/year
  - 5 to 7 years — +1.8 σ/year
- 2,107 sliding 1 year σ differences (0 to 7 years)
  - 1554 σ increases
  - 553 σ decreases

DECLINATION COUNT DISTRIBUTION

This is for *negative* $\rho_{|\tau|,p}$ only. The data was negative

MC **Equal Solid Angle bins** **Energy Scrambled Data**



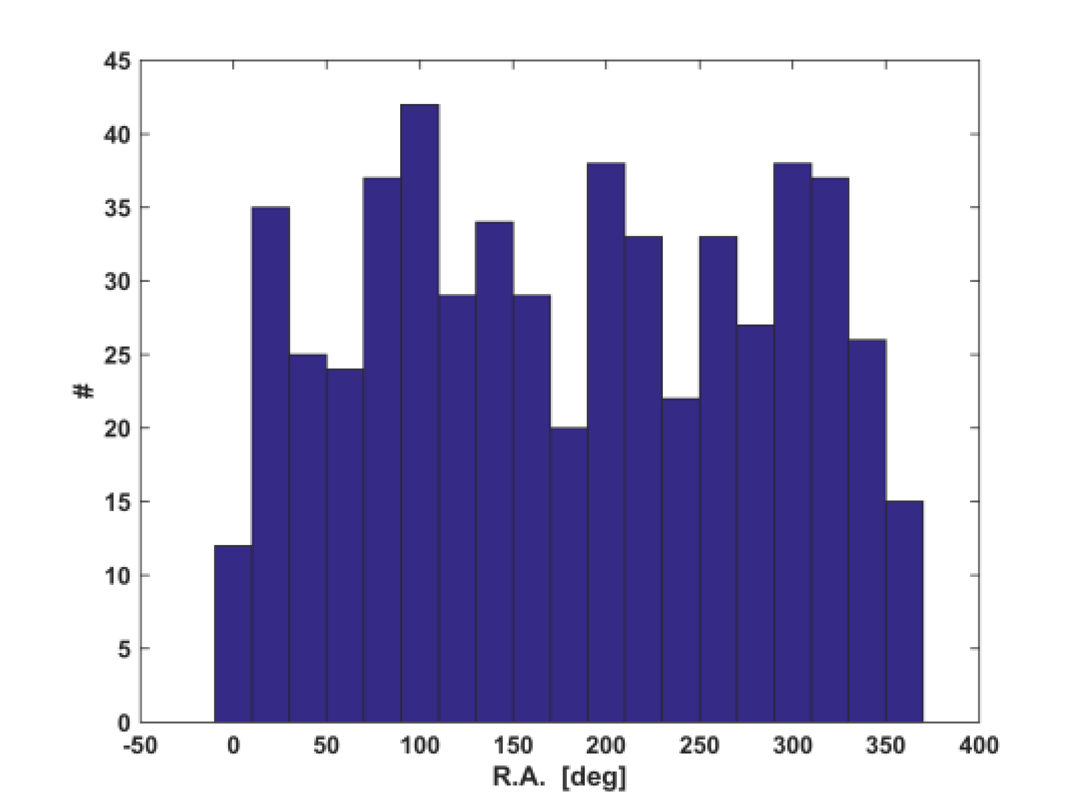


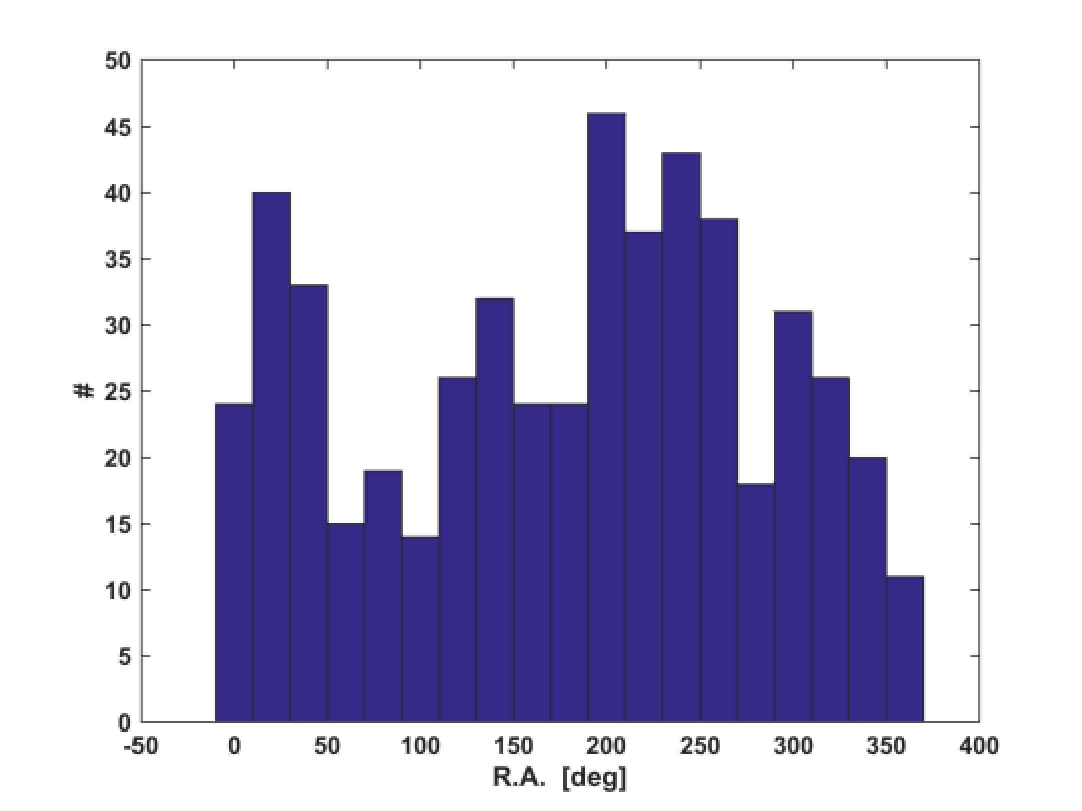
Position is dependent on over/under-density but significance is not
Position is also more sensitive to energy anisotropy as shown by integral day data figures

RIGHT ASCENSION COUNT DISTRIBUTION

This is for *negative* $\rho_{|\tau|,p}$ only. The data was negative

MC **Equal Solid Angle bins** **Energy Scrambled Data**





Position is dependent on over/under-density but significance is not
Position is also more sensitive to energy anisotropy as shown by integral day data figures

SEASONAL CORRECTION TEST

DATA RESULT

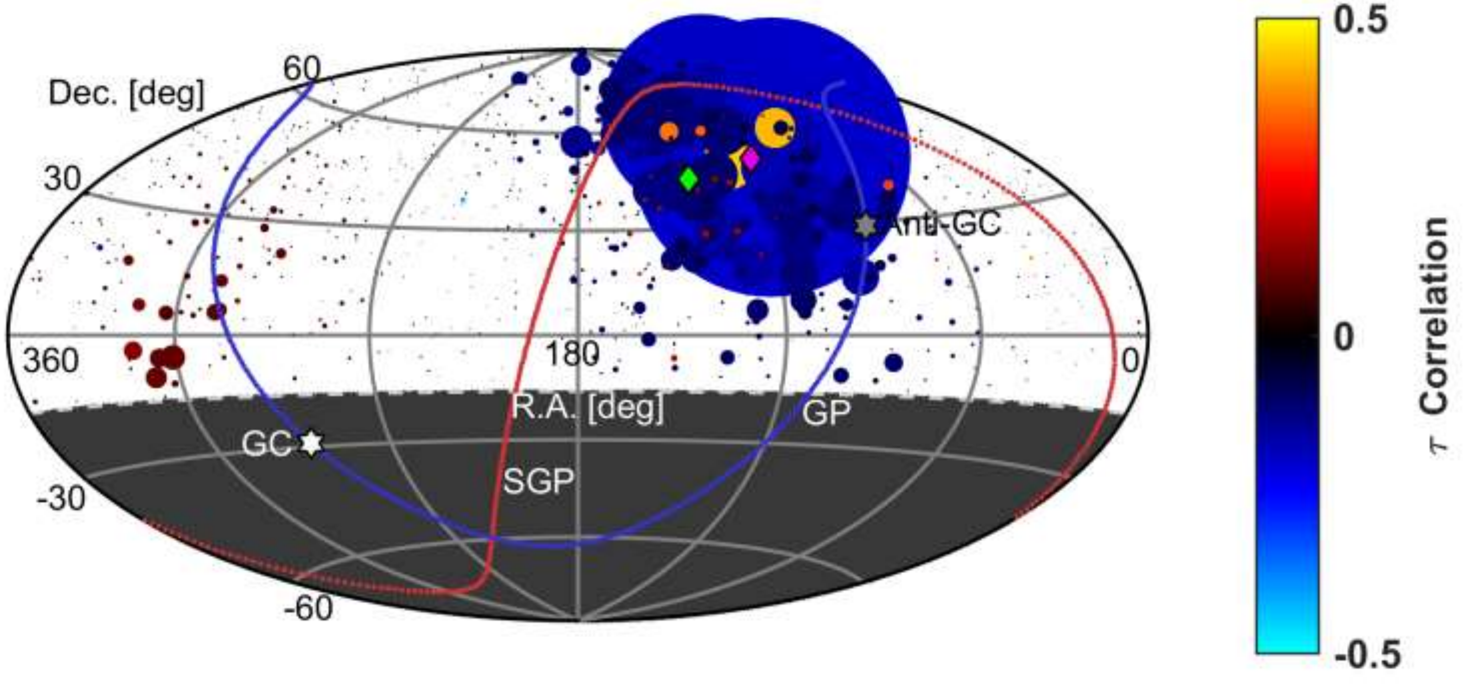
- **Each test point (i) calculate Kendall's τ correlation $F_i[E_j(E_j > E_i), \theta_{ij}(E_j > E_i)]$**

  Choosing events with Energy > test point energy - removes adjacent double counting.

  - Negative Correlation: Energy Increases → Angle *decreases*
  - Positive Correlation: Energy Increases → Angle *Increases*

- **Size proportional to 1/p-Value**
- **Color is Opening angle/Energy correlation**

Data: 833 events
E >20 EeV after adjustment

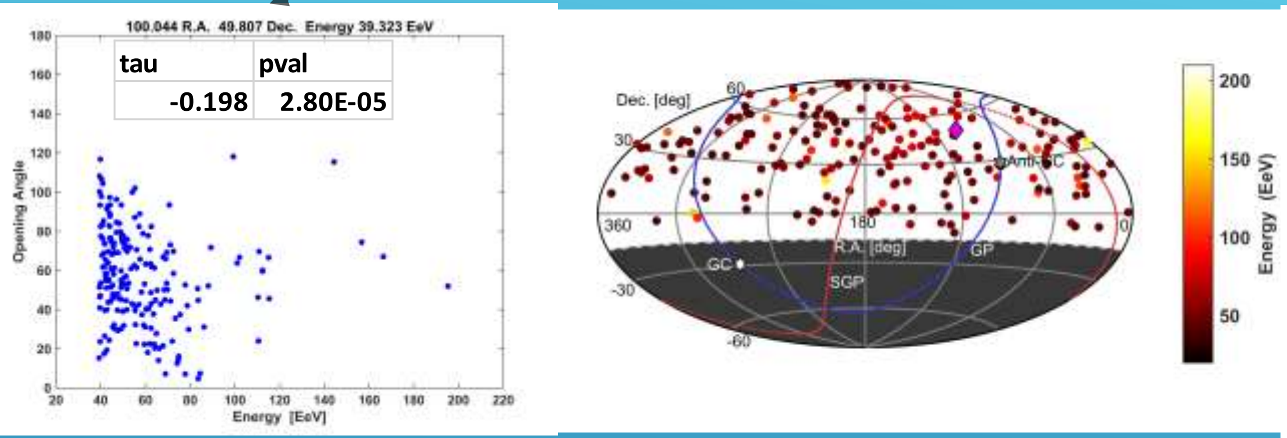


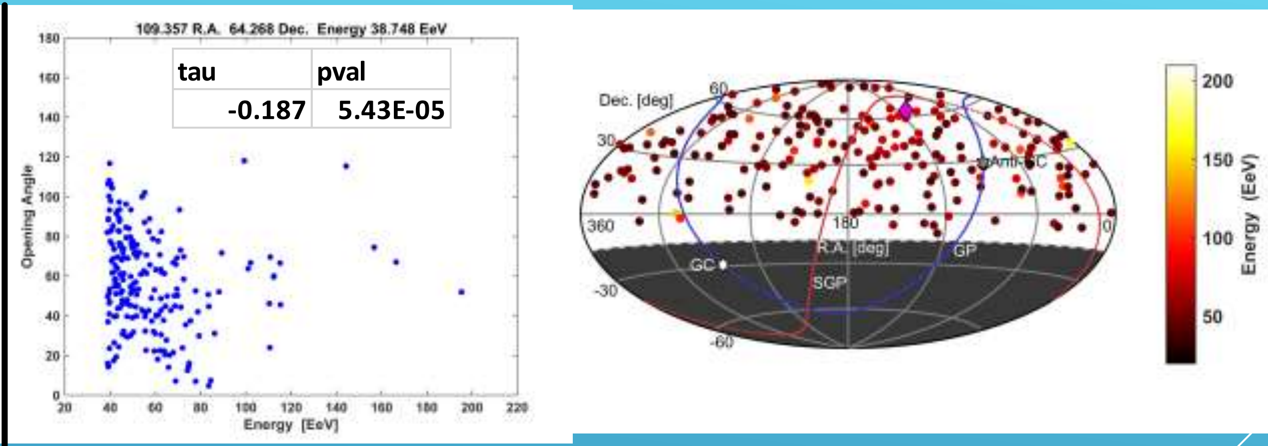
Each Test Point sample size is different

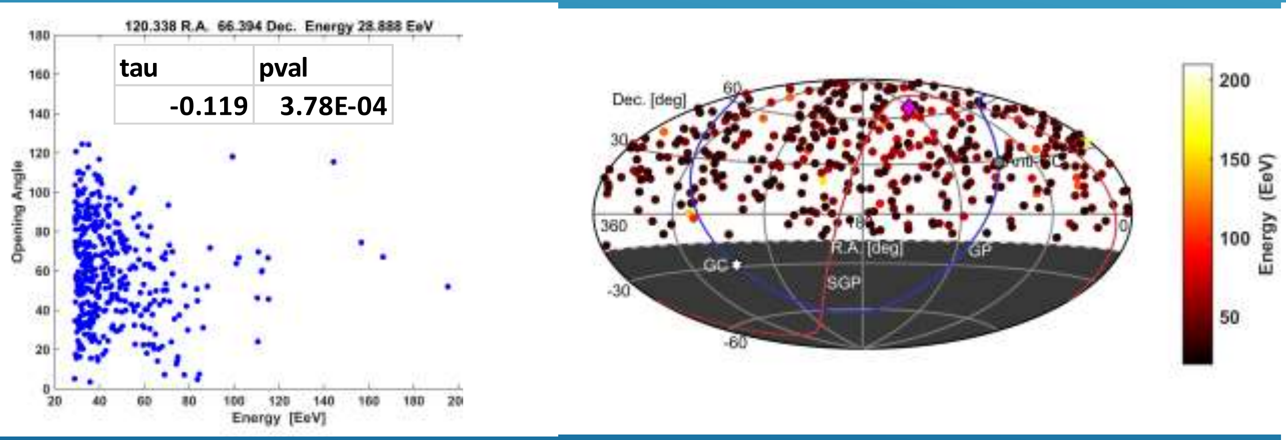
- **Spectrum Anisotropy center: 138.8° R.A., 44.8° Dec.**
- **Correlation Weighted (1/p-val) Average: 109.0° R.A. , 49.7° Dec.**

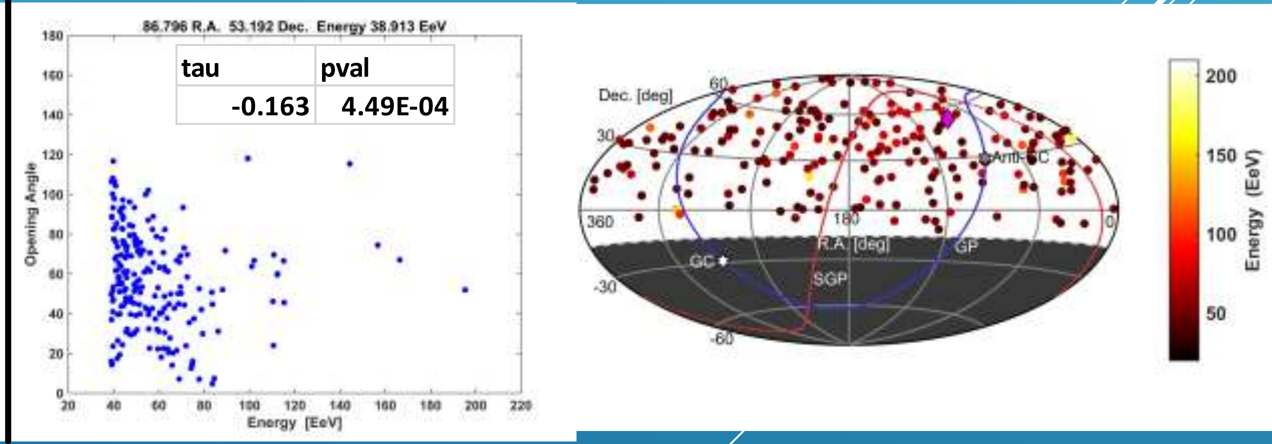
4 MOST SIGNIFICANT POINTS

Test Point location and Energy Cut









Energy Vs Distance

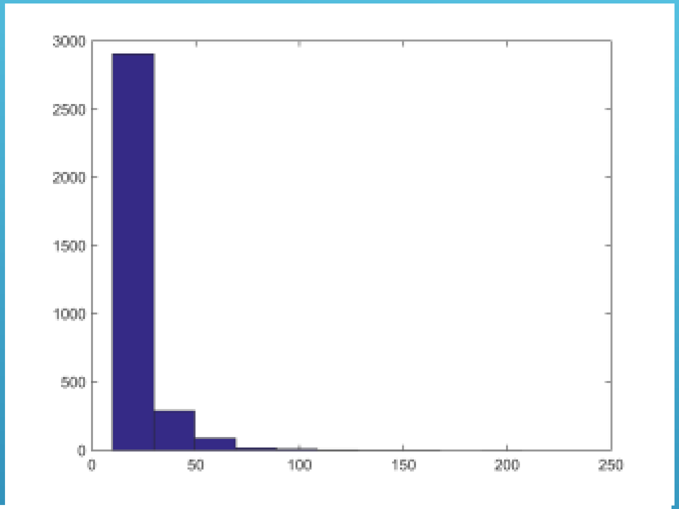
$E \geq E_i$

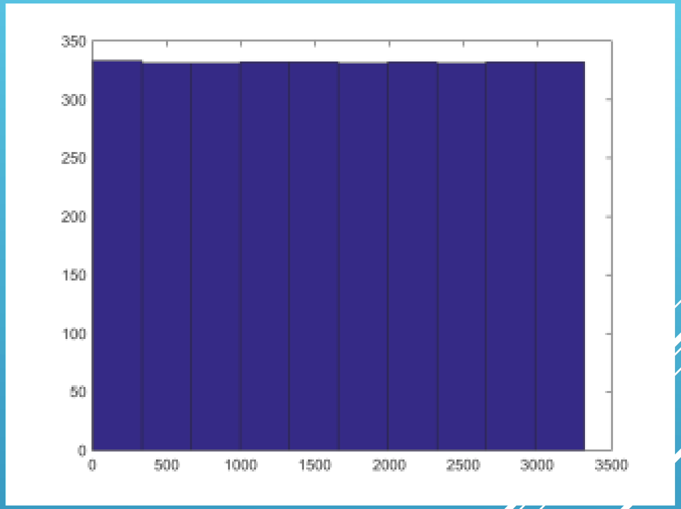
Energy Vs Distance

$E \geq E_i$

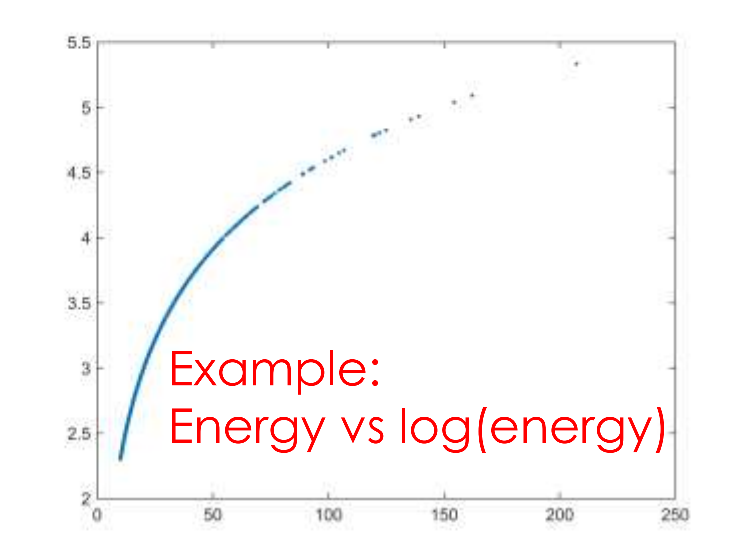
RANKING

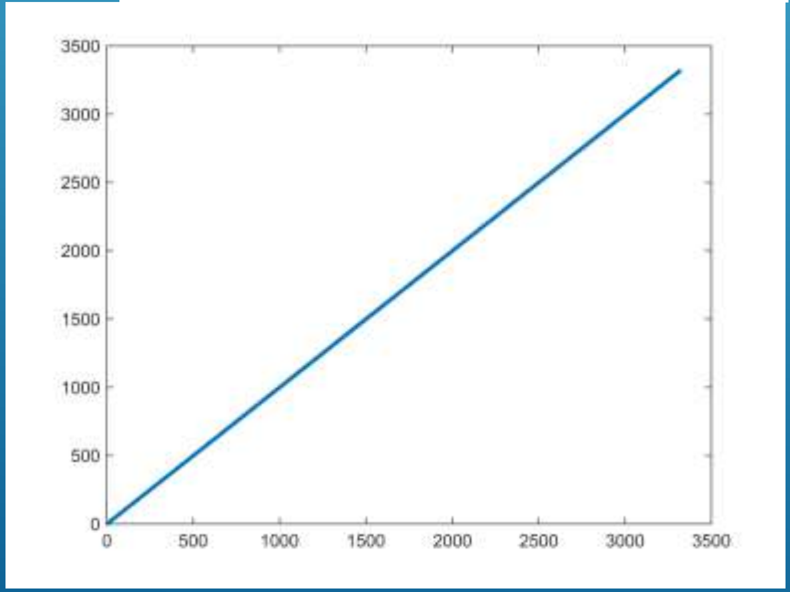
- An ordered list of magnitude.
- Ranking removes functional form of dependence.
- Lowest variable value = 1.
- Highest variable value = N events.





Linear Correlation: 0.92



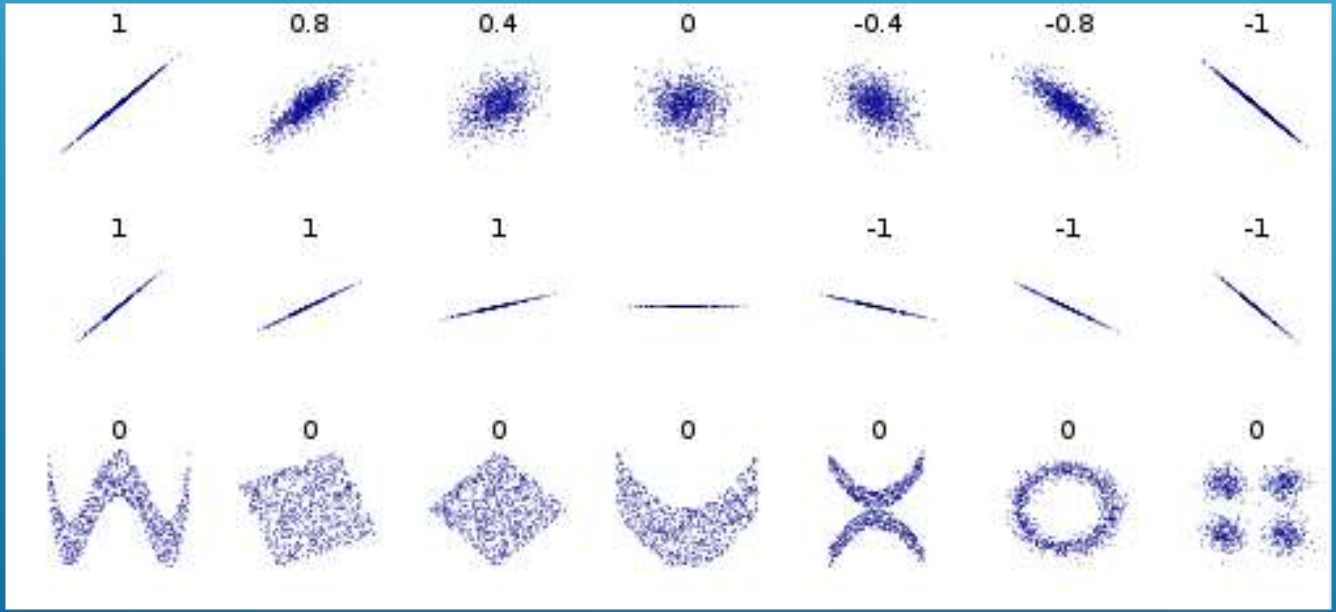


Rank Correlation: 1

LINEAR CORRELATION (PEARSONS)

$$\rho_{X,Y} = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y}$$

$$r = r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$



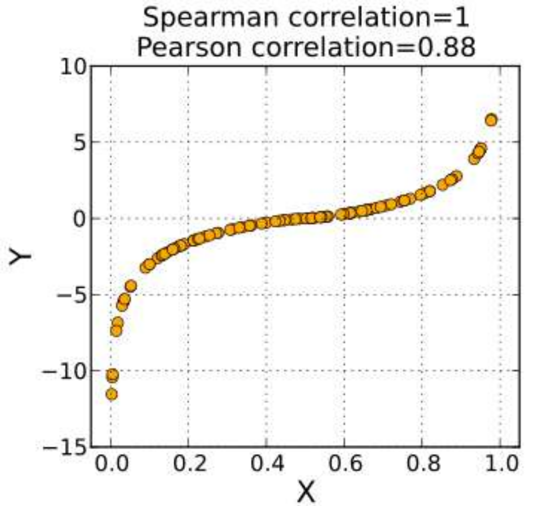
Measurement of linear dependence

RANK CORRELATION

- **All values are ranked. Kendall's correlation is used.**

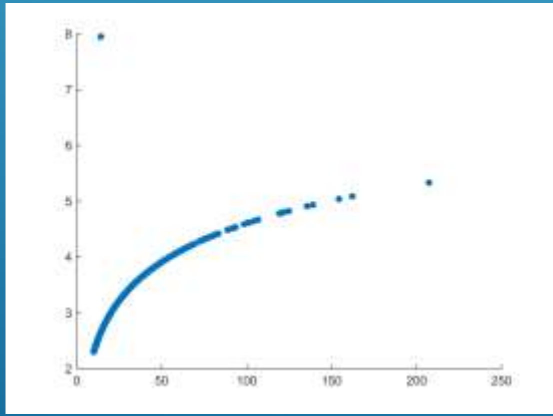
$$\tau = \frac{(\text{number of concordant pairs}) - (\text{number of discordant pairs})}{\frac{1}{2}n(n-1)}.$$

- **Ranked correlations are permissive**: any perfectly monotonic function F(x,y) results in correlation = 1. **Removes model assumption**



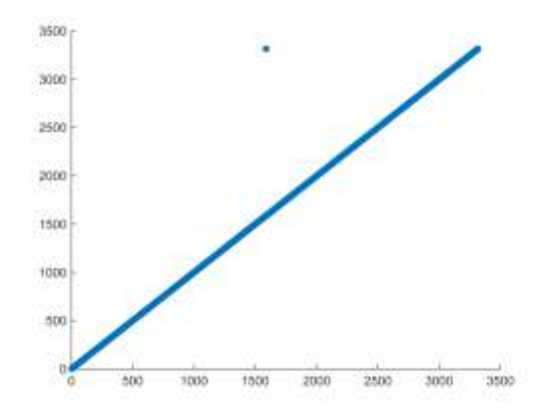
Source: wikipedia

- **p-Values**
  - **calculated by permutation**
  - **null hypothesis is zero correlation.**
  - **p-Value is probability correlation is zero.**



Linear Corr: 0.903
Outlier decreases corr: ~0.02

Robust against outliers



Rank Corr: 0.9994
Outlier decreases corr: 0.0006

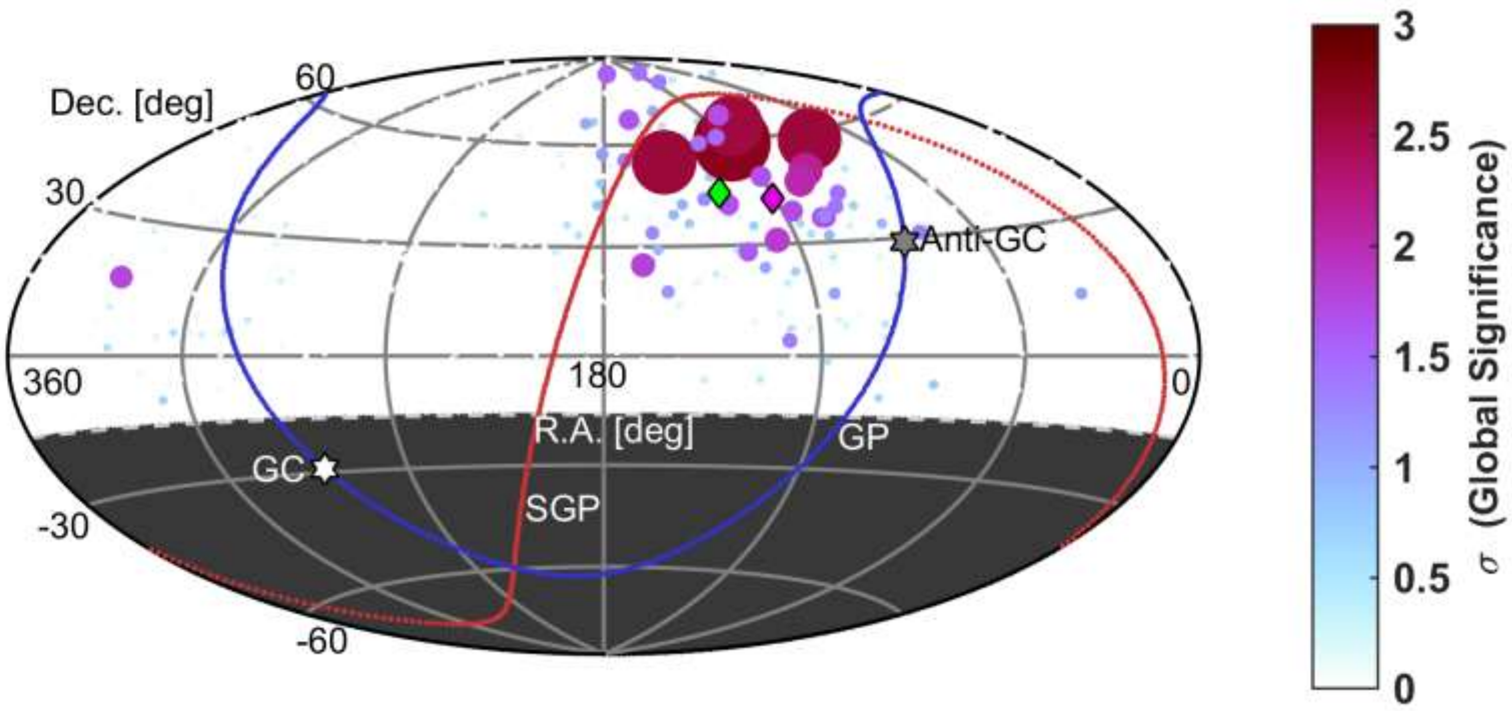
GLOBAL POINT SIGNIFICANCE

- 1,000,000 Isotropic MC maps the size of data
  - Count maps with at least one test point with:
    - $|\tau| \geq |\tau_{data}| \,\&\, sign(\tau) = sign(\tau_{data}) \,\&\, p \leq p_{data}$

      (At least as ordered change in same direction, with greater or equal samples)

- **Size proportional to 1/p_global**
- **Color is Global Significance**

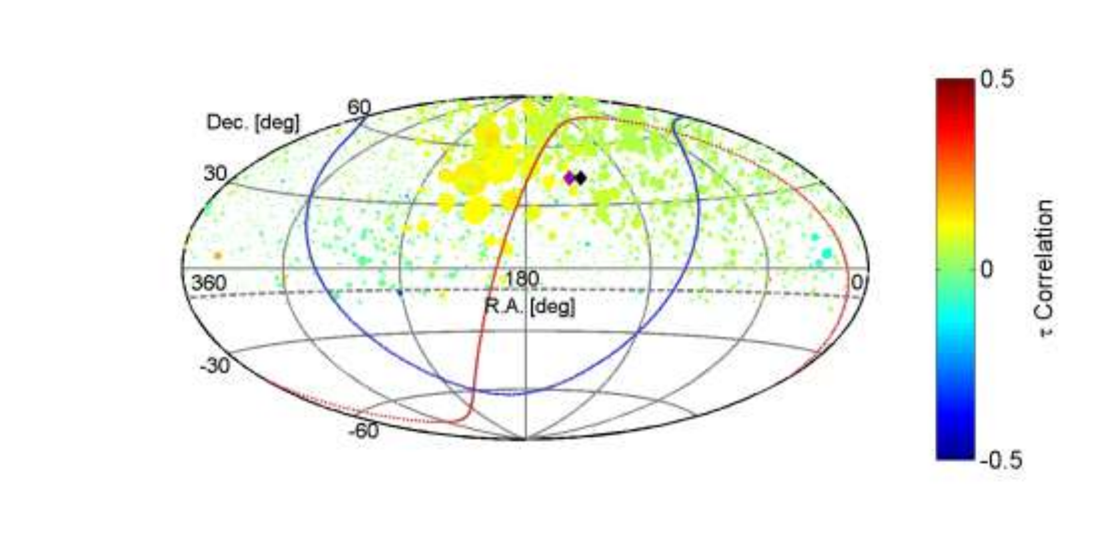
- Highest Significant test point: **2.7σ**



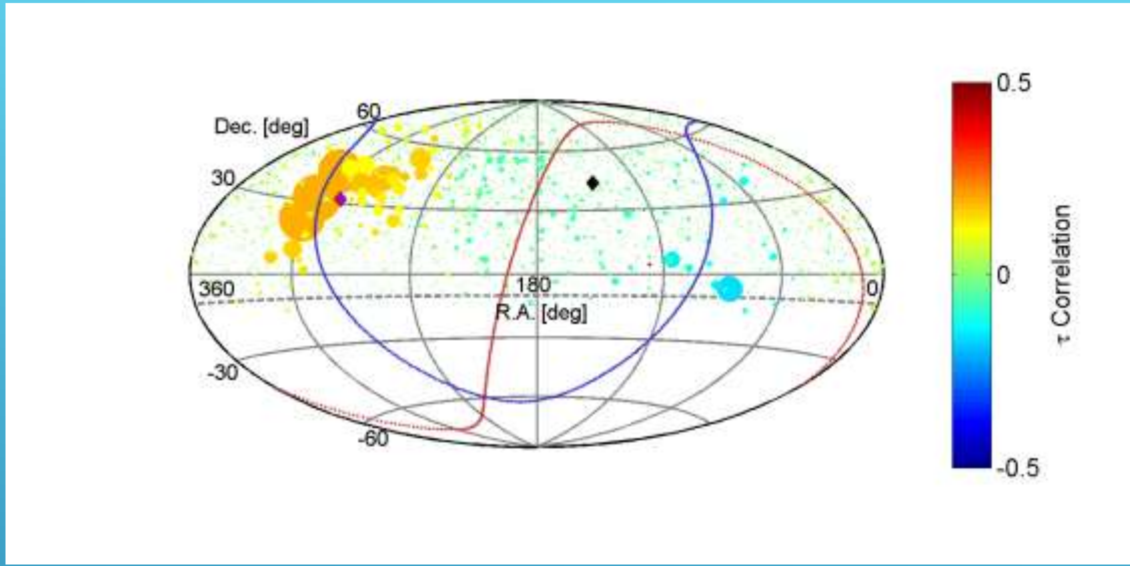
Sigma	tau
4.571	-0.1747
4.643	-0.1879
4.643	0.4302
4.736	0.4523

Individual correlations clearly don't tell the whole story

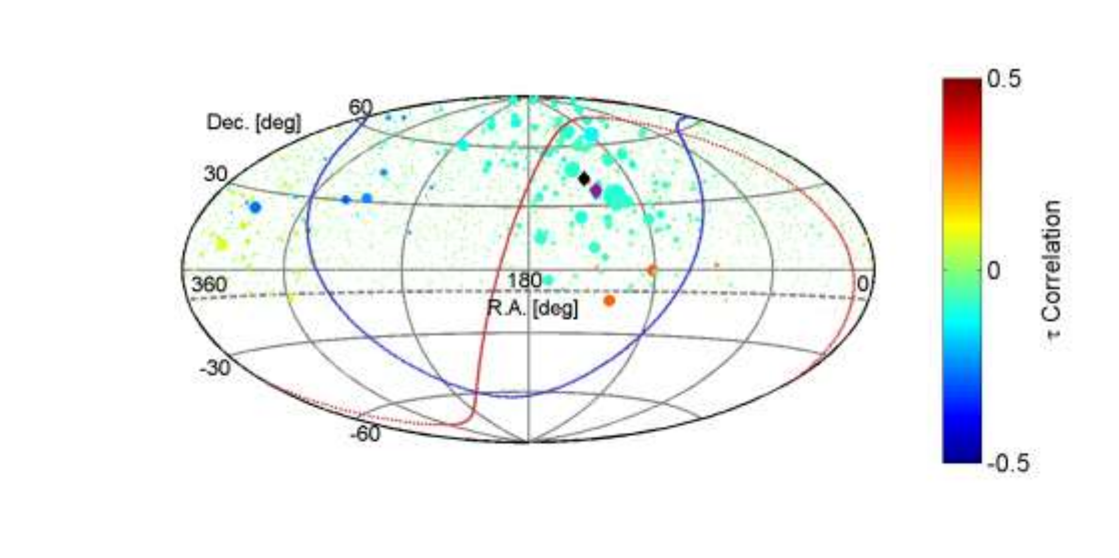
EXAMPLE MC MAPS



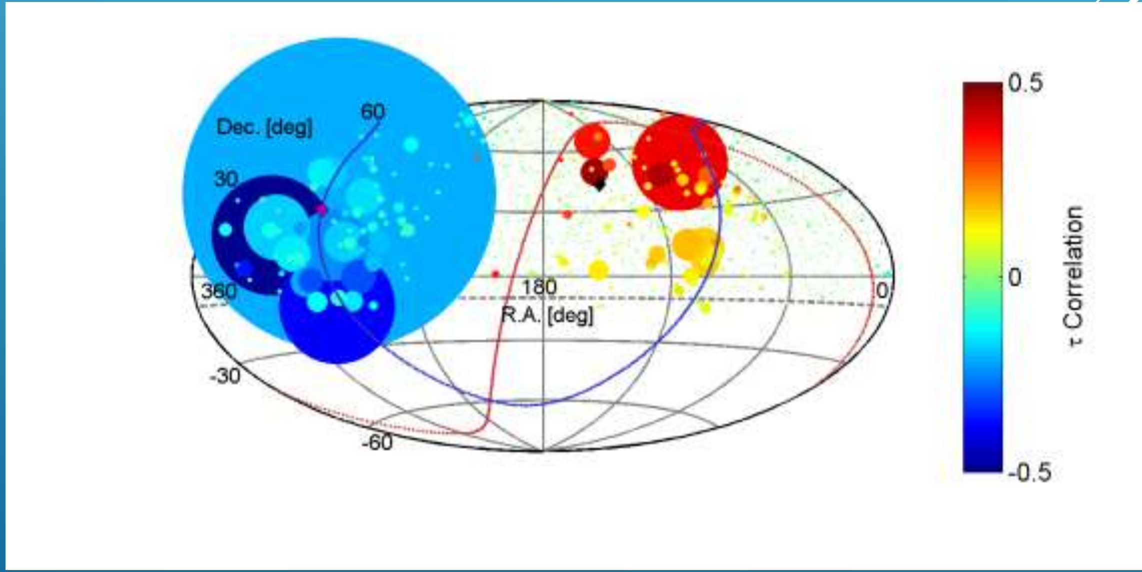
Distribution of p-vals and tau least like data



Distribution of p-vals most like data

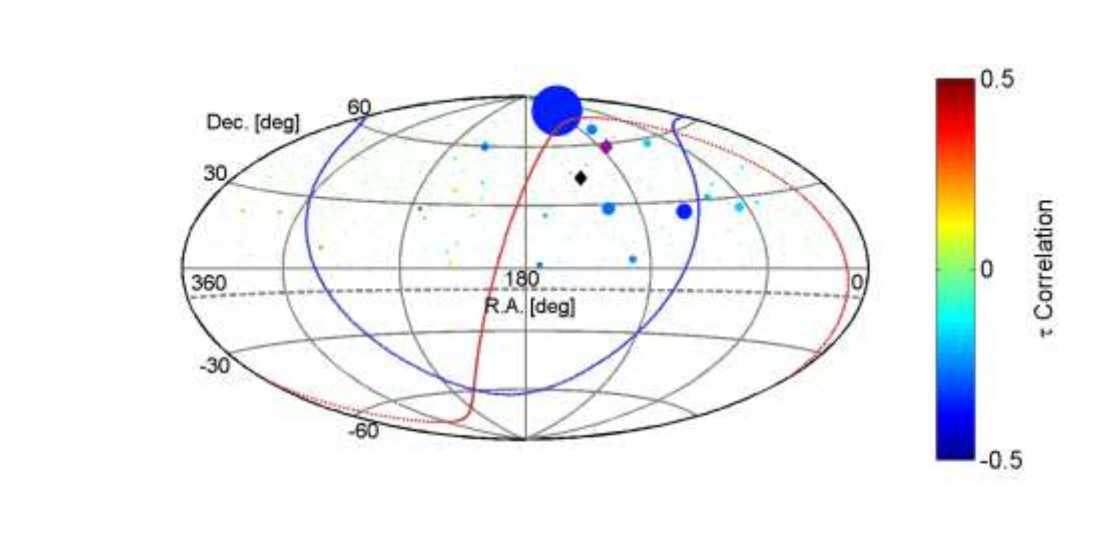


Distribution of tau most like data

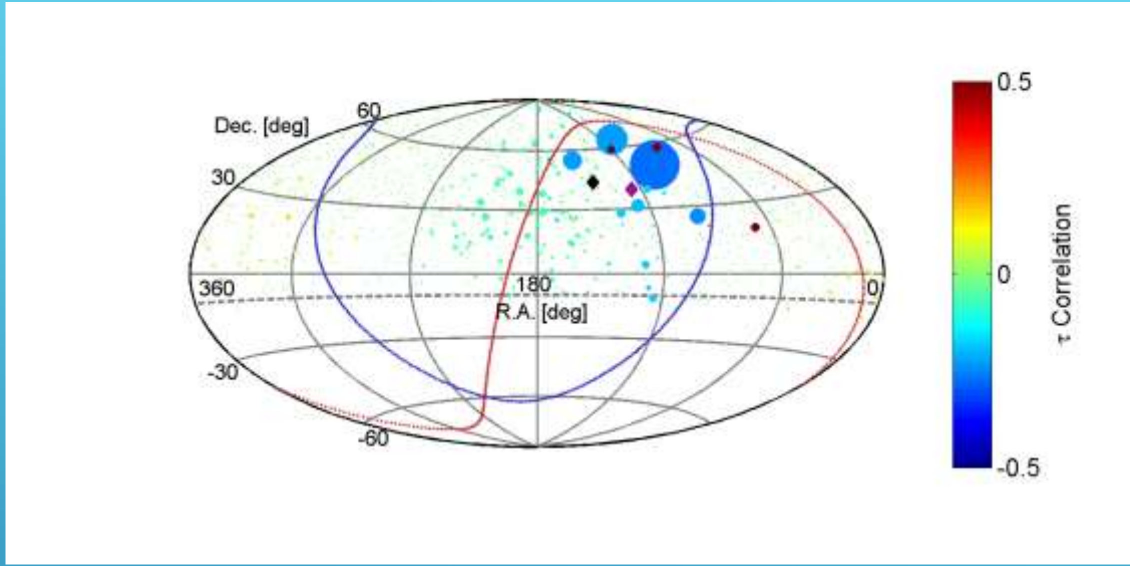


Most points like best p-val point from data. (2 points)

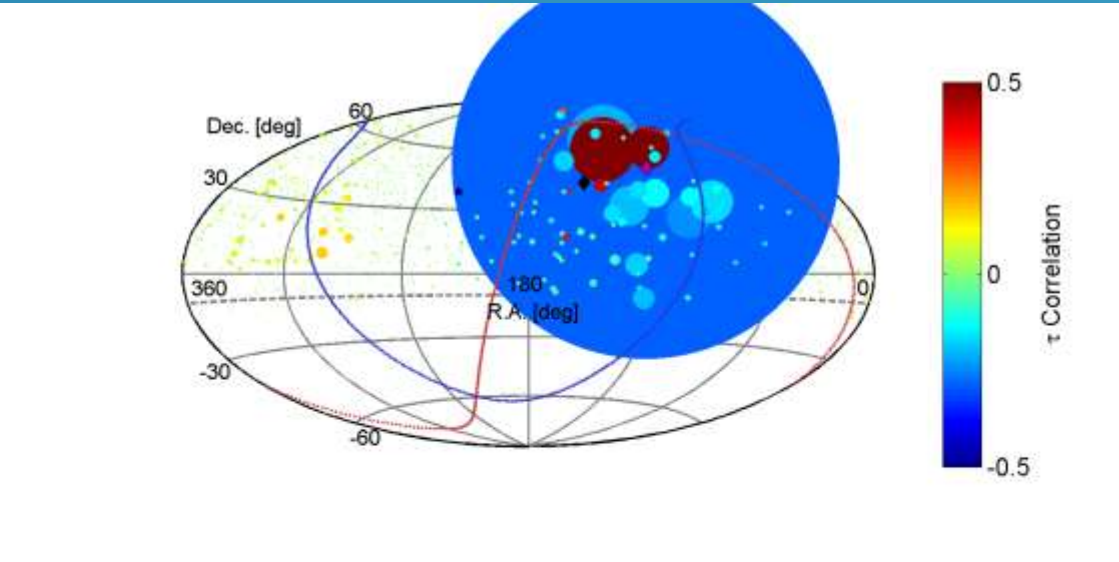
DATA CUMULATIVE TIME QUANTILES



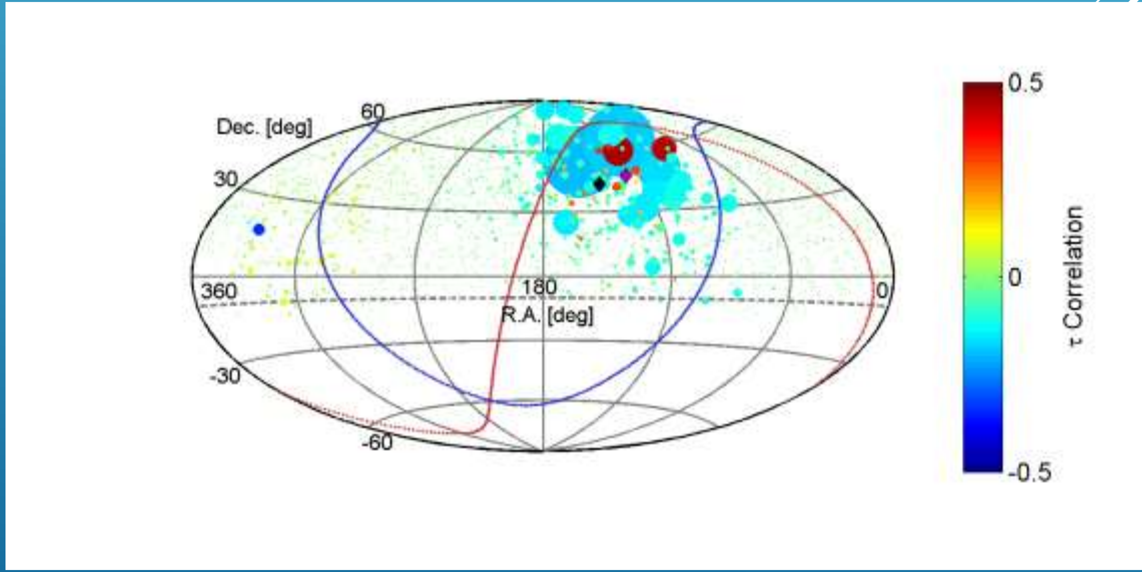
Quartile 1



Quartiles 1 and 2

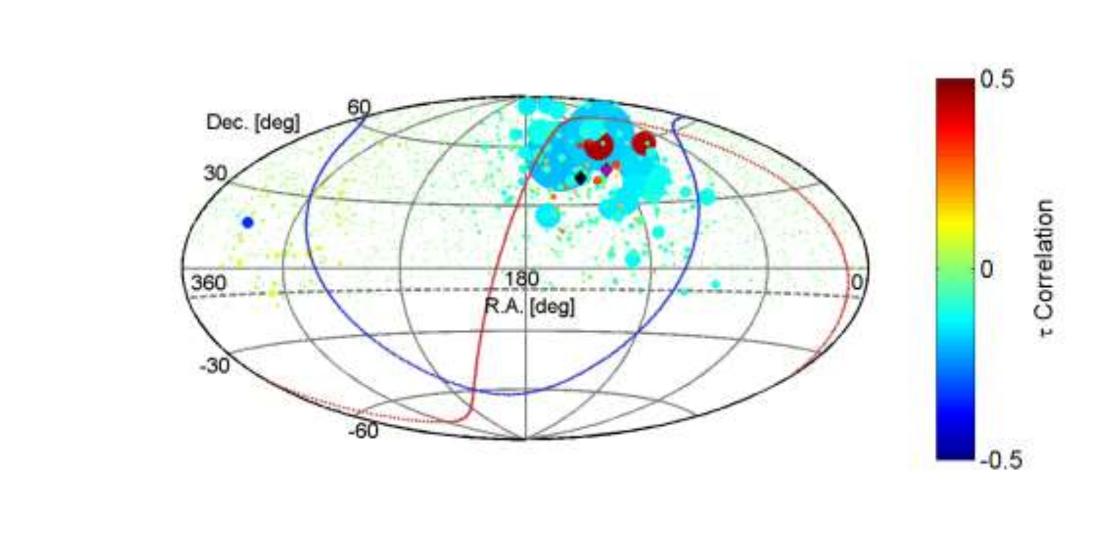


Quartiles 1 to 3

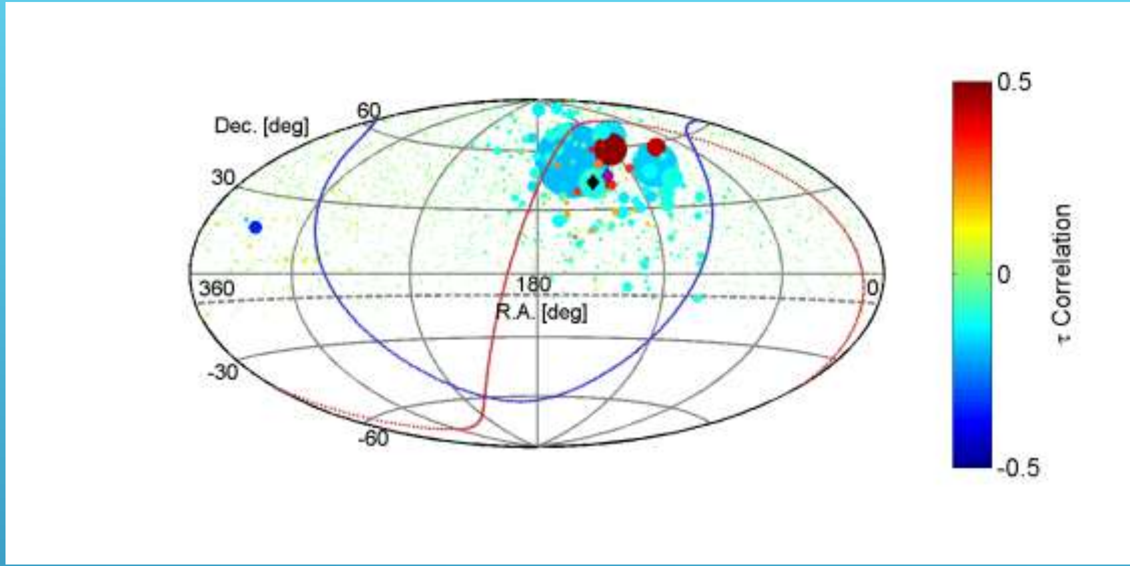


All

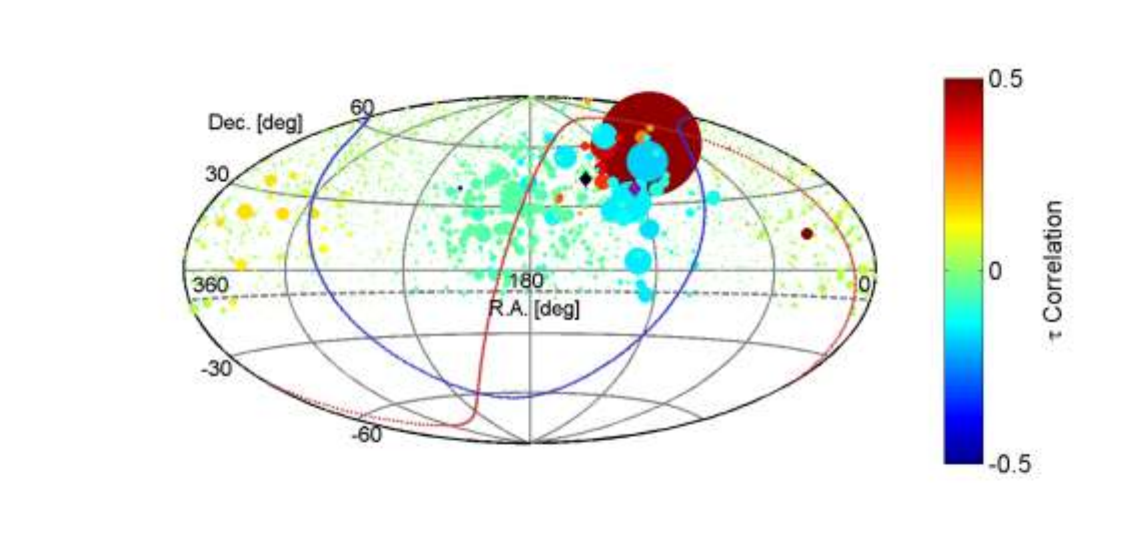
DIFFERENT DATA SUBSETS



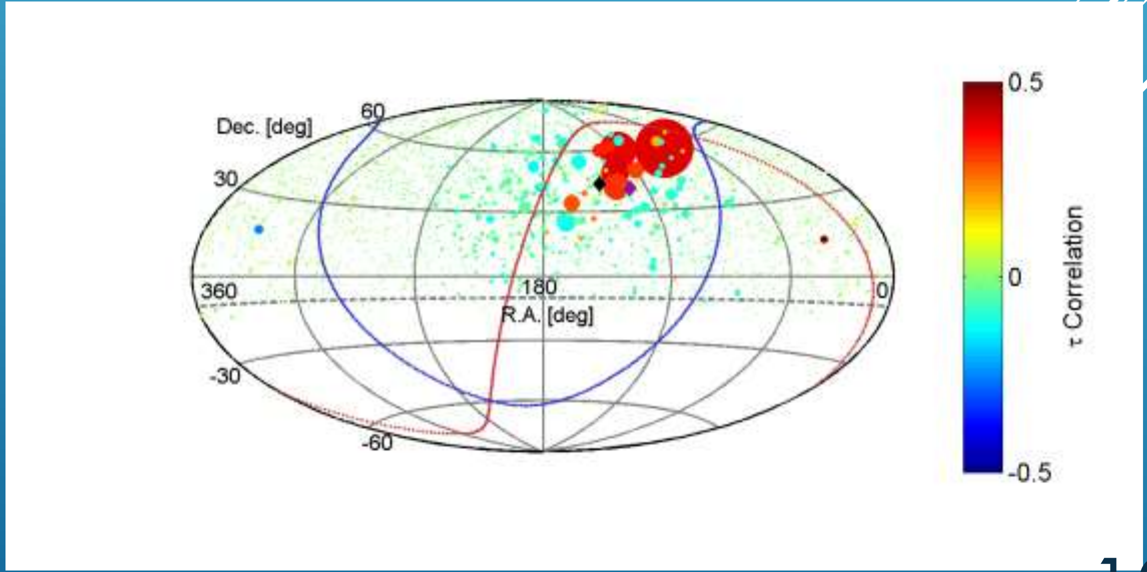
7 Year Kawata-san data with additional cuts



7 Year Dmitri's data (tighter cuts)



5 Year Kawata-san hotspot paper data

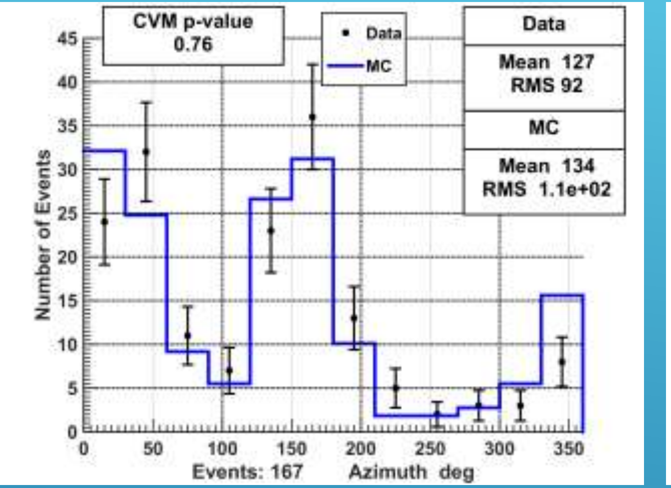


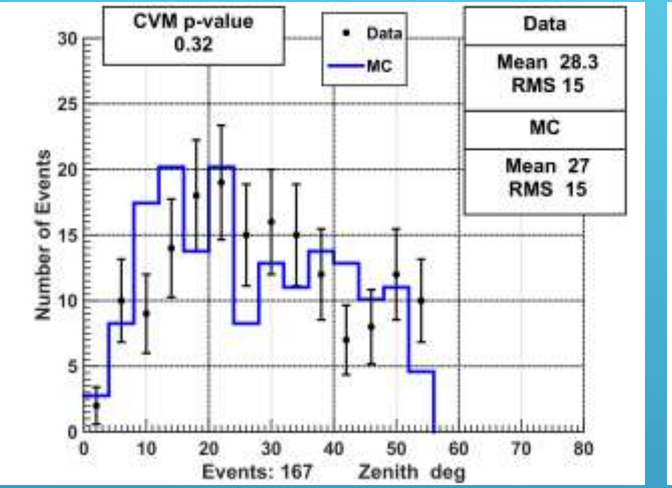
7 Year Kawata-san ICRC data

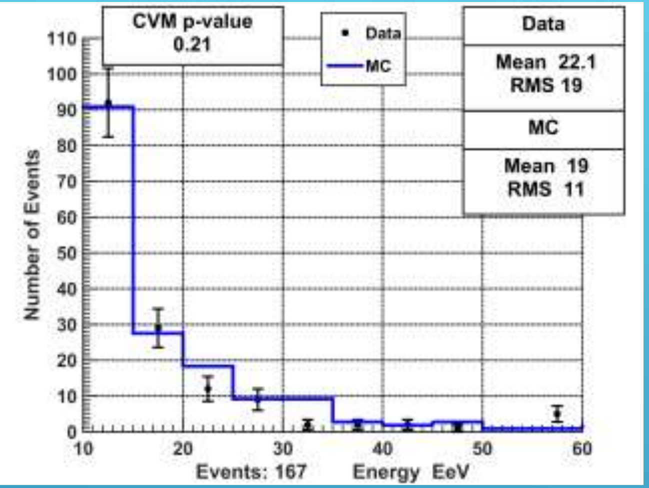
HOT/COLDSPOT SUMMARY ANALYSIS ADDITIONAL MATERIAL

ISOTROPIC MC VS DATA IN HOTSPOT – ALL ENERGIES

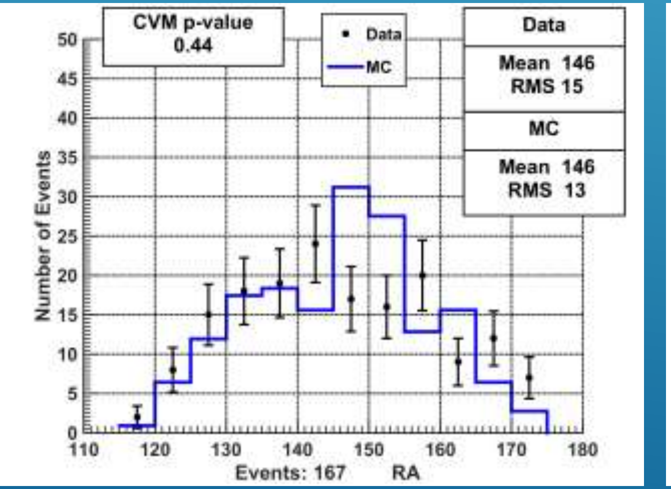
10 EeV cut – 20 degree radius spherical cap

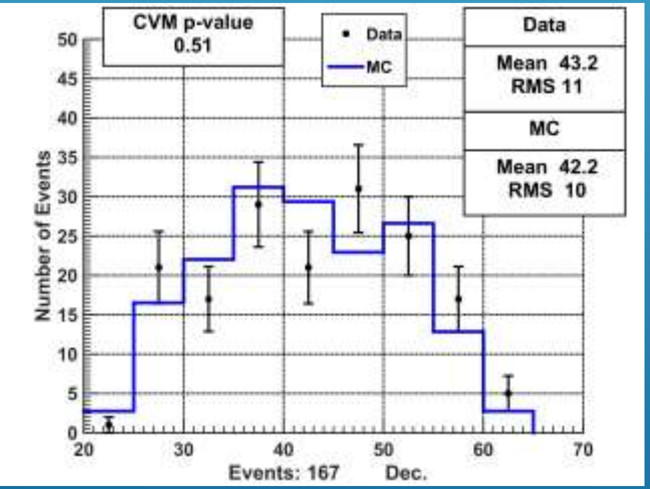






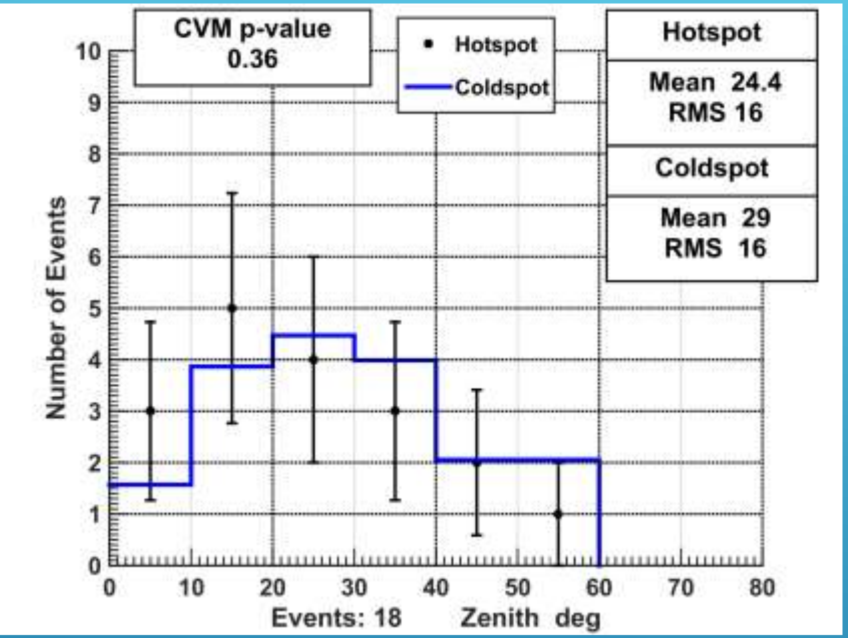
One random isotropic MC map the size of the data

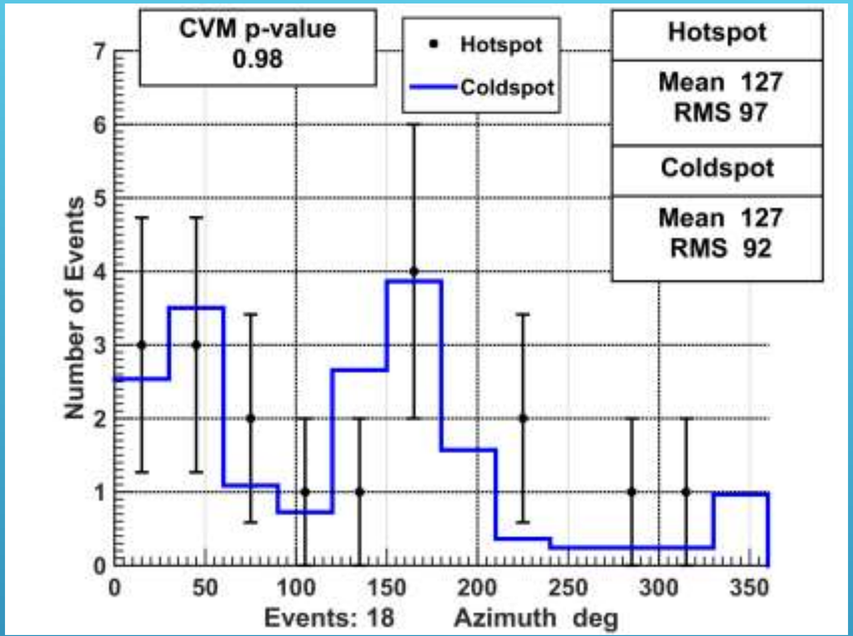


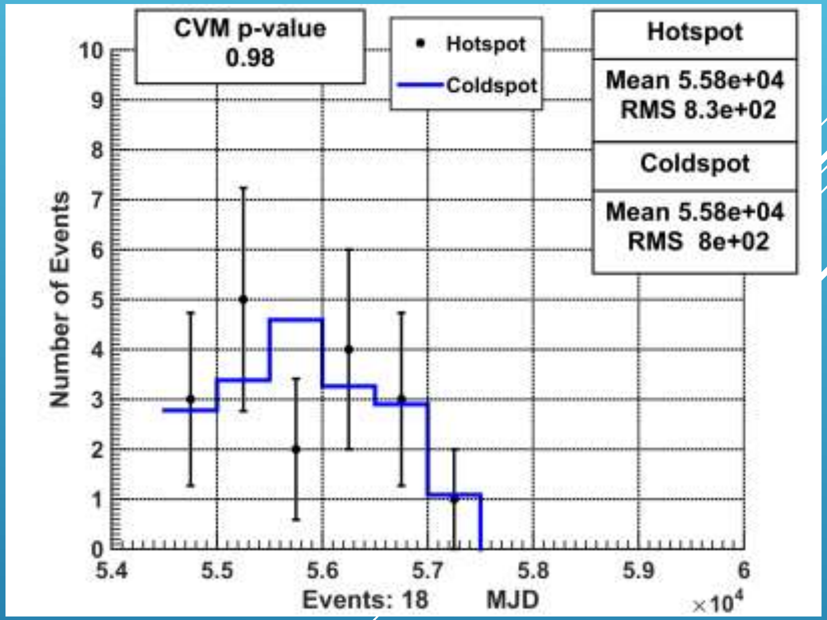


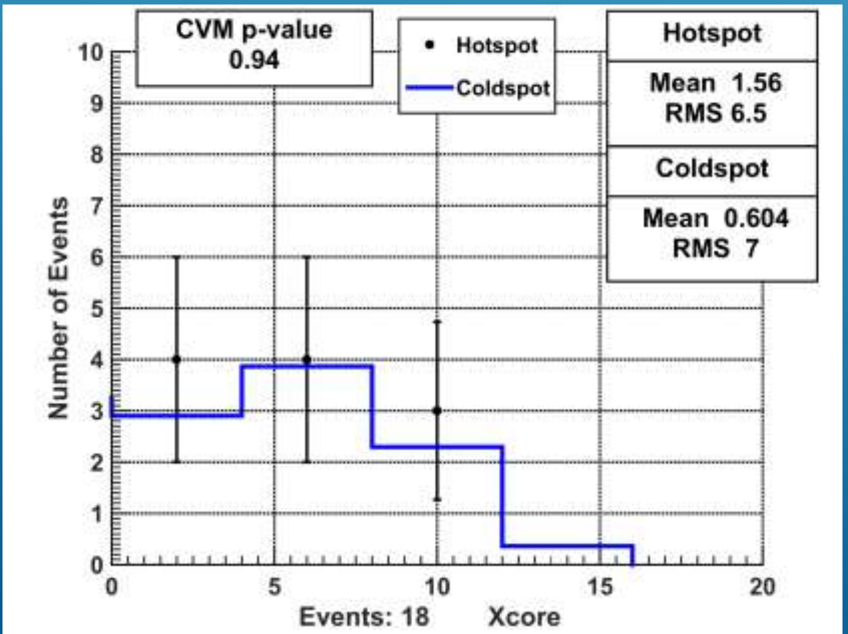
Inside hotspot there is possibly something
Different with zenith, energy, and RA.

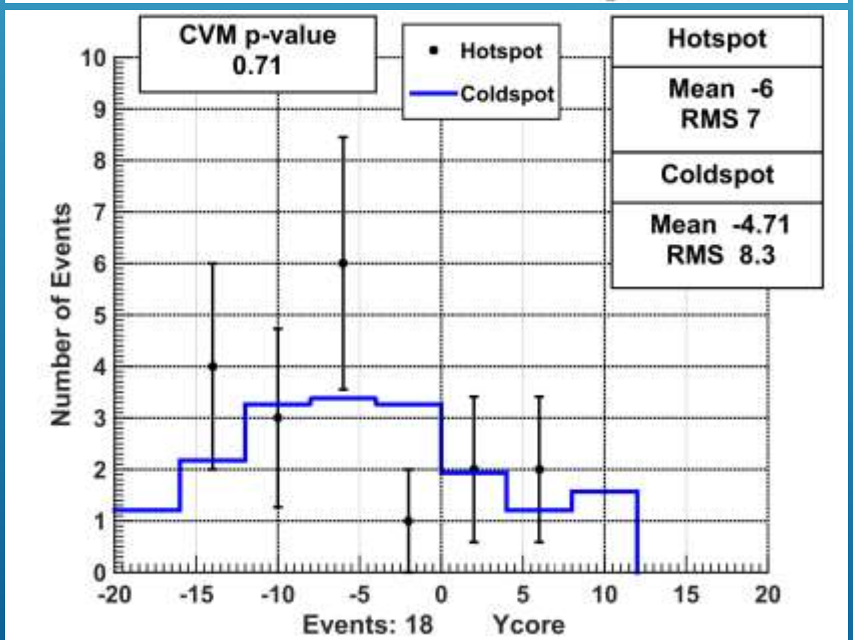
COMPARISON WITHIN HOT/COLD SPOT – E > 57 VS E < 57



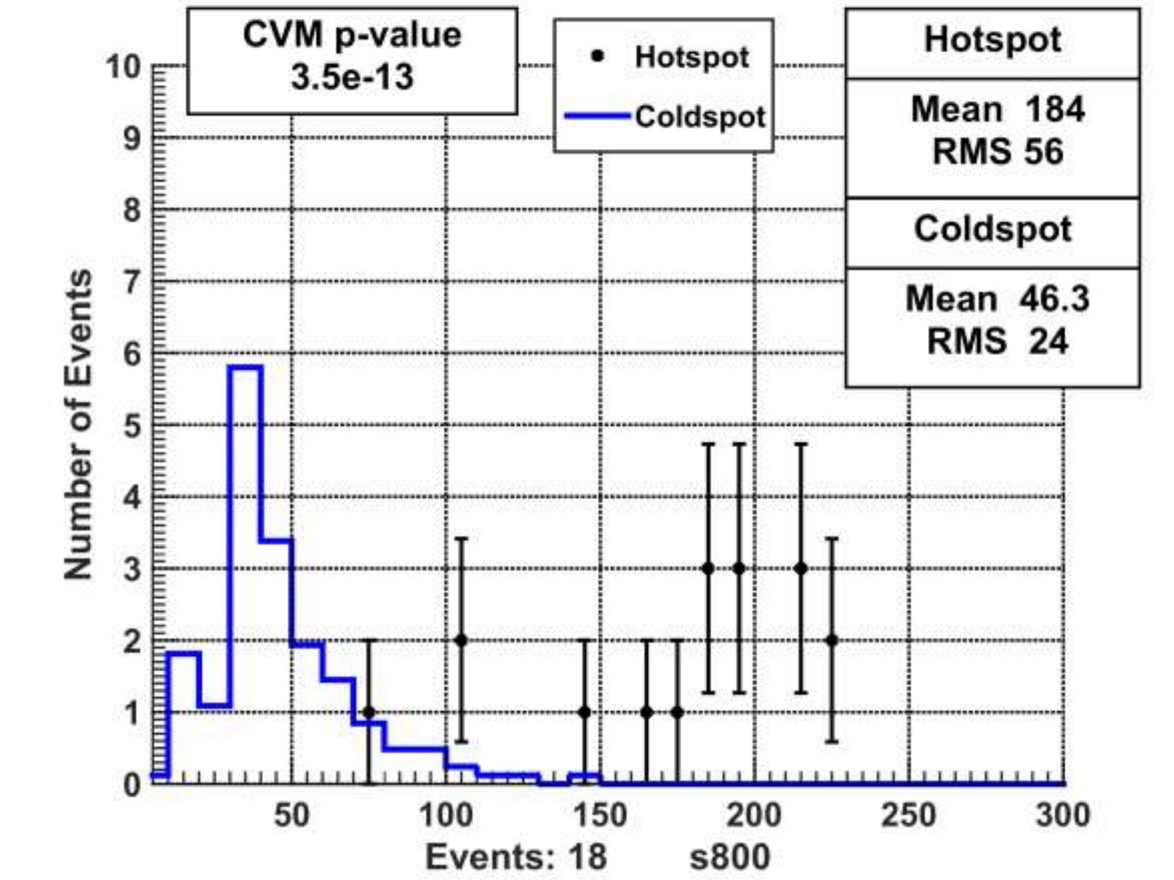


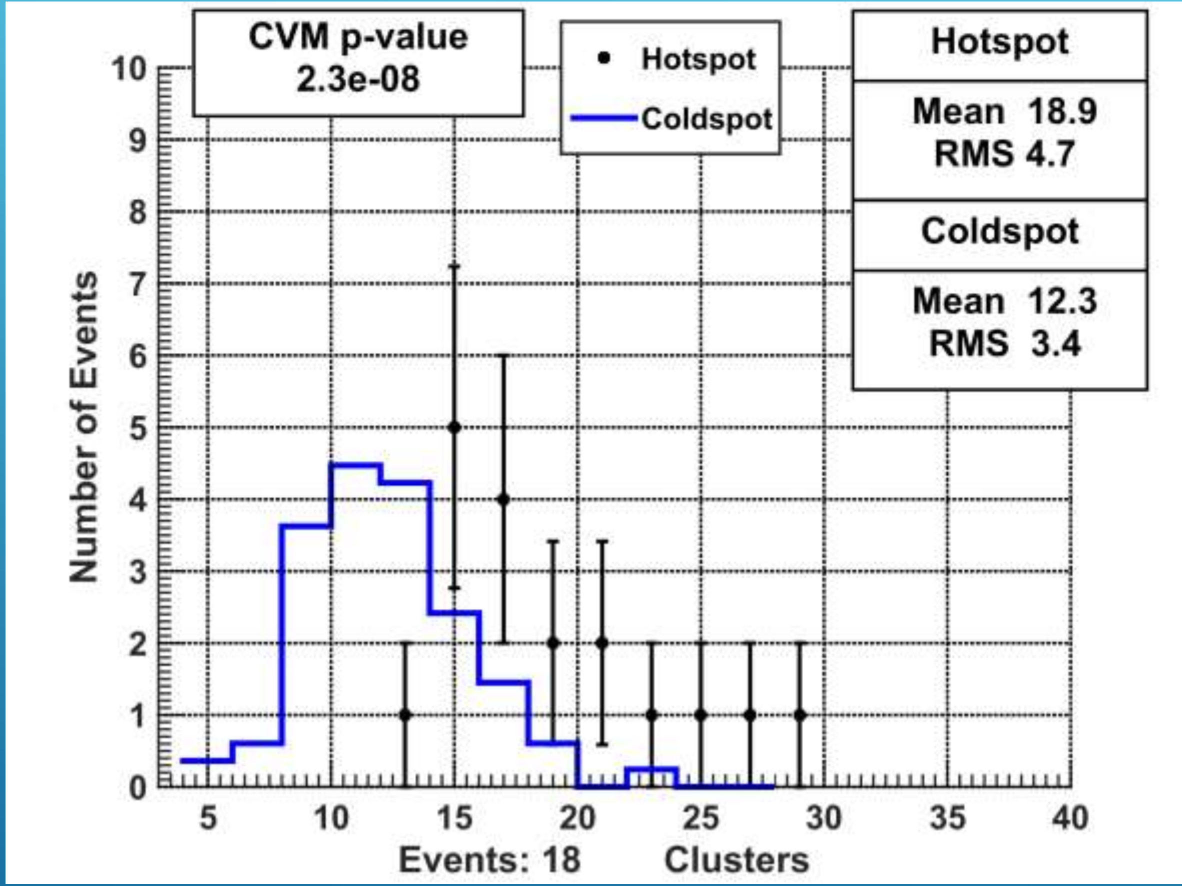




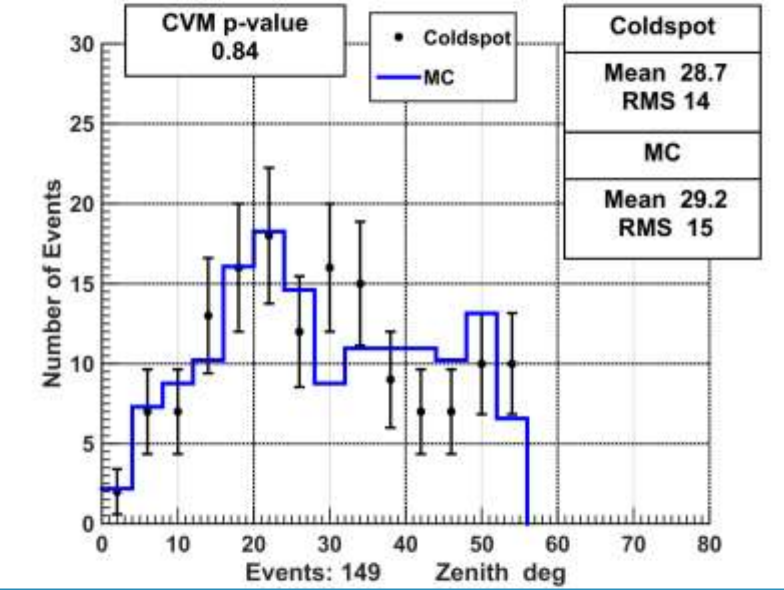


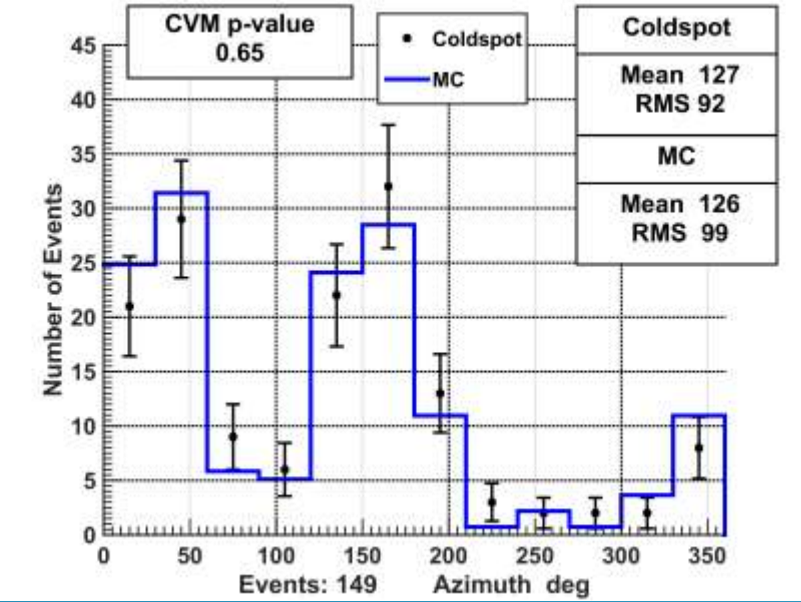
S800 AND CLUSTERS – SHOULD NOT BE THE SAME



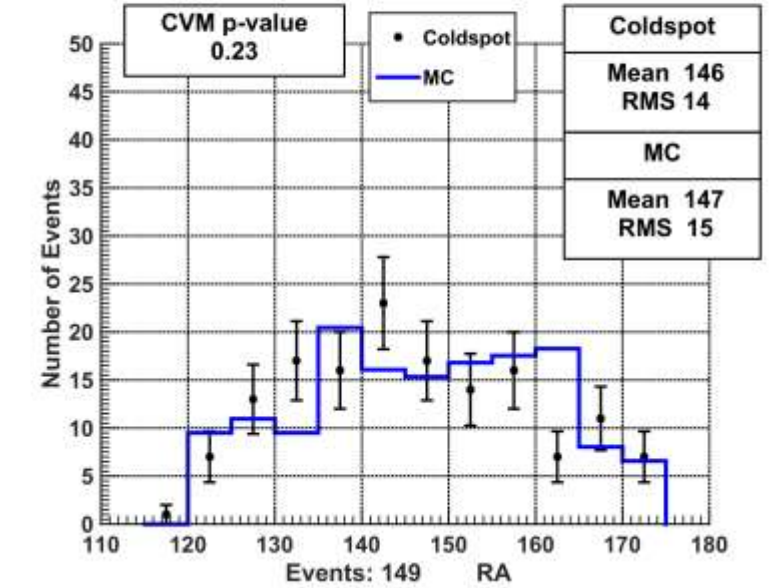


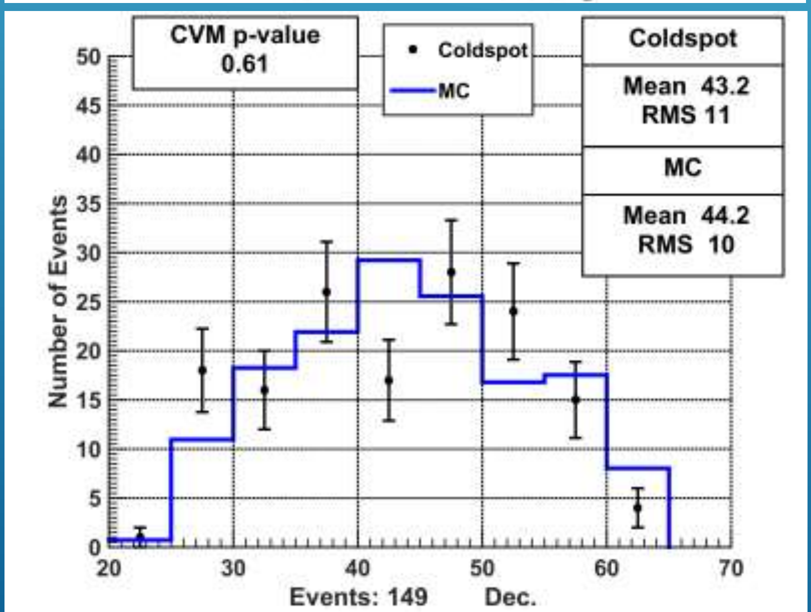
COMPARE COLDSPOT TO ISOTROPIC MC

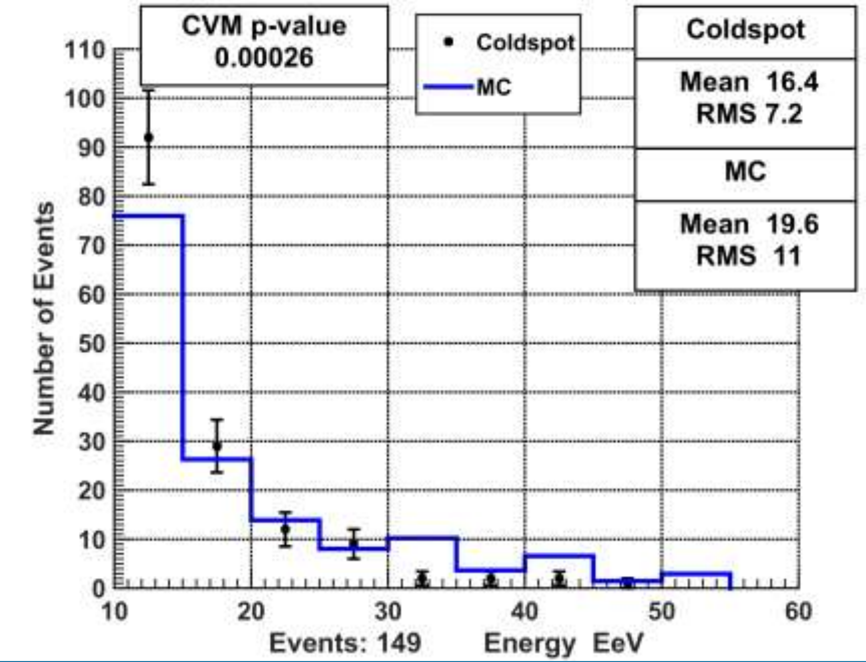




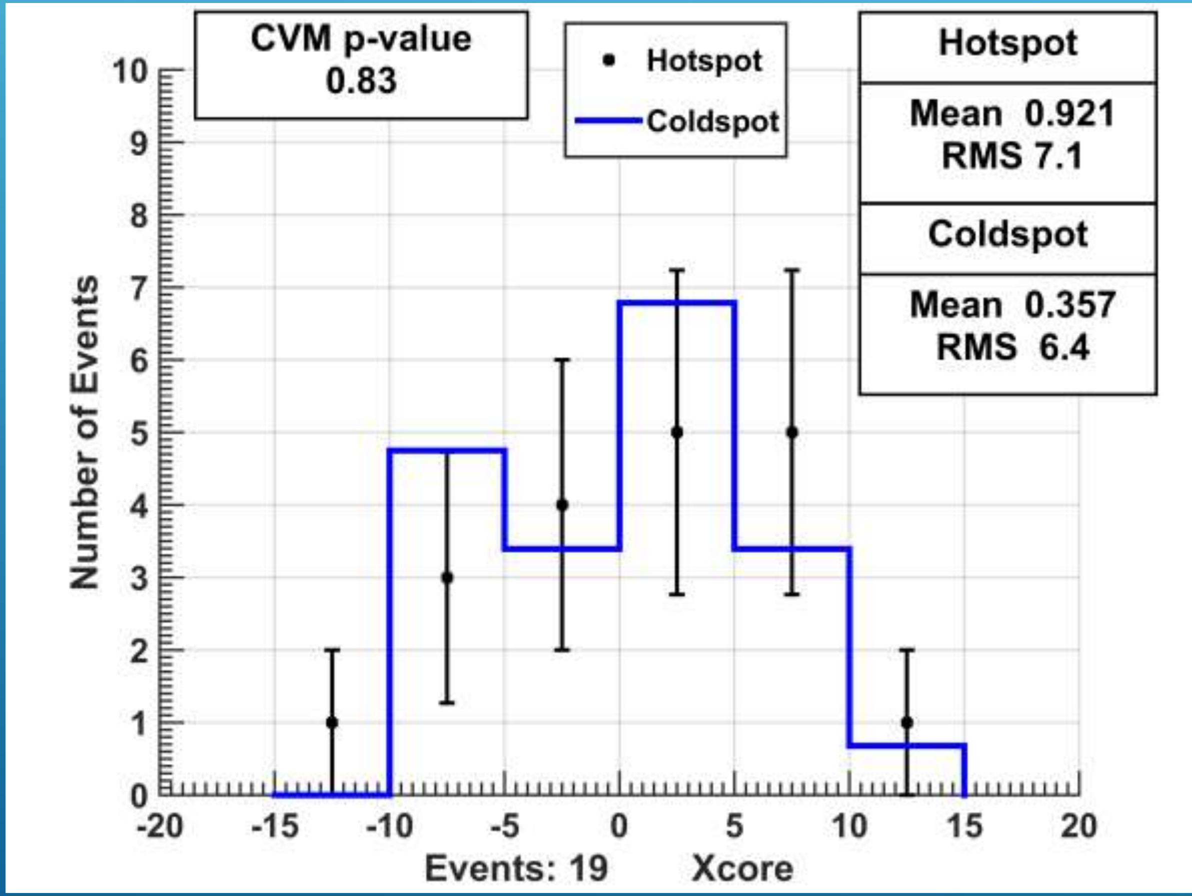
Energy and RA are a bit different.



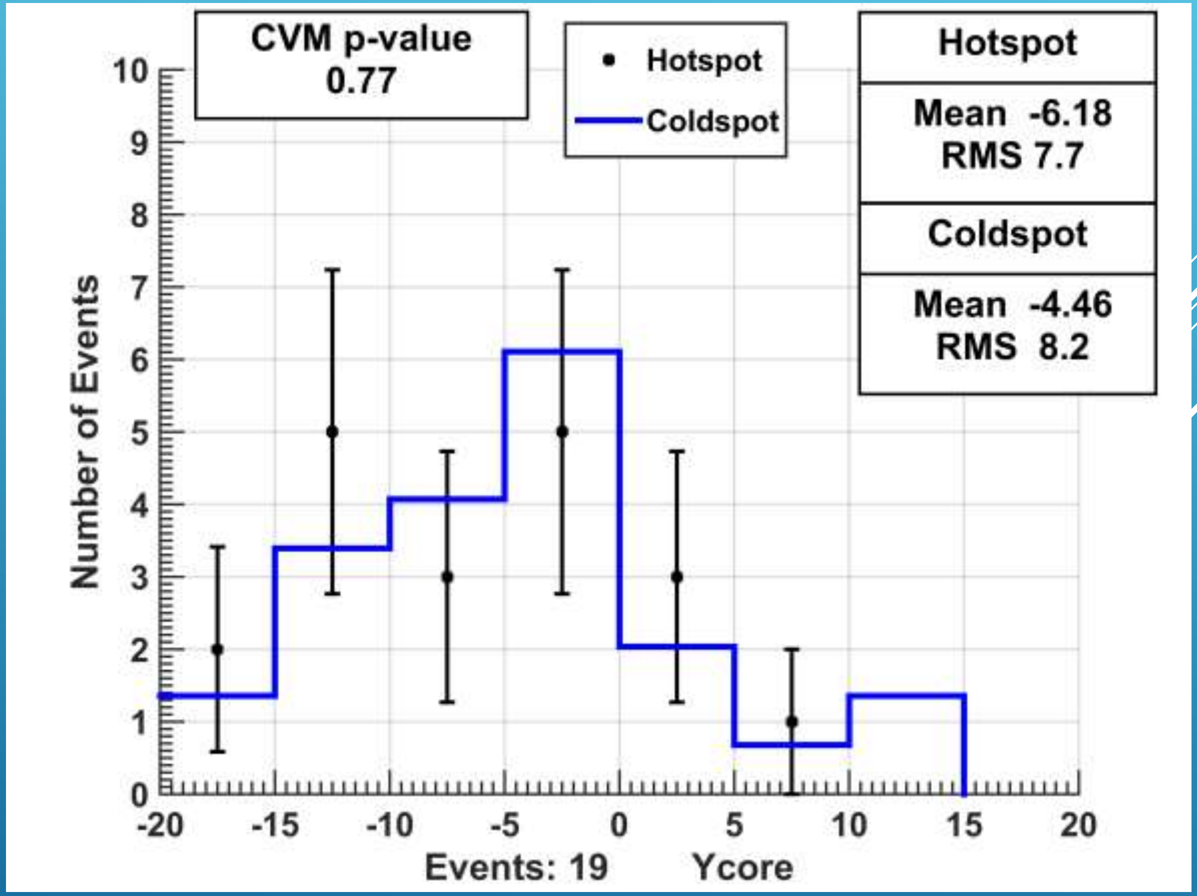




CORE

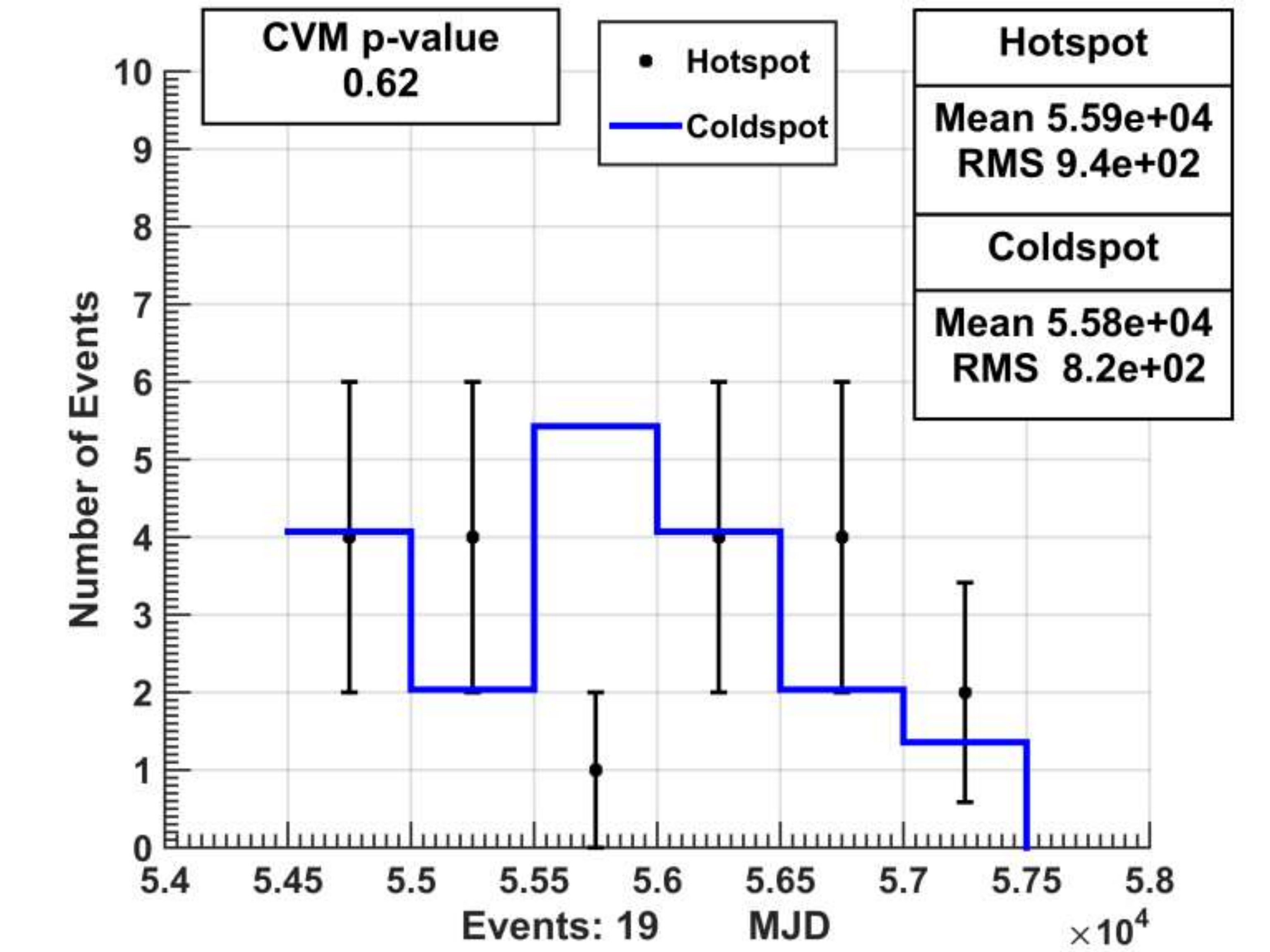


CVM p-value
0.83
Hotspot
Coldspot
Hotspot
Mean 0.921
RMS 7.1
Coldspot
Mean 0.357
RMS 6.4
Number of Events
Events: 19
Xcore



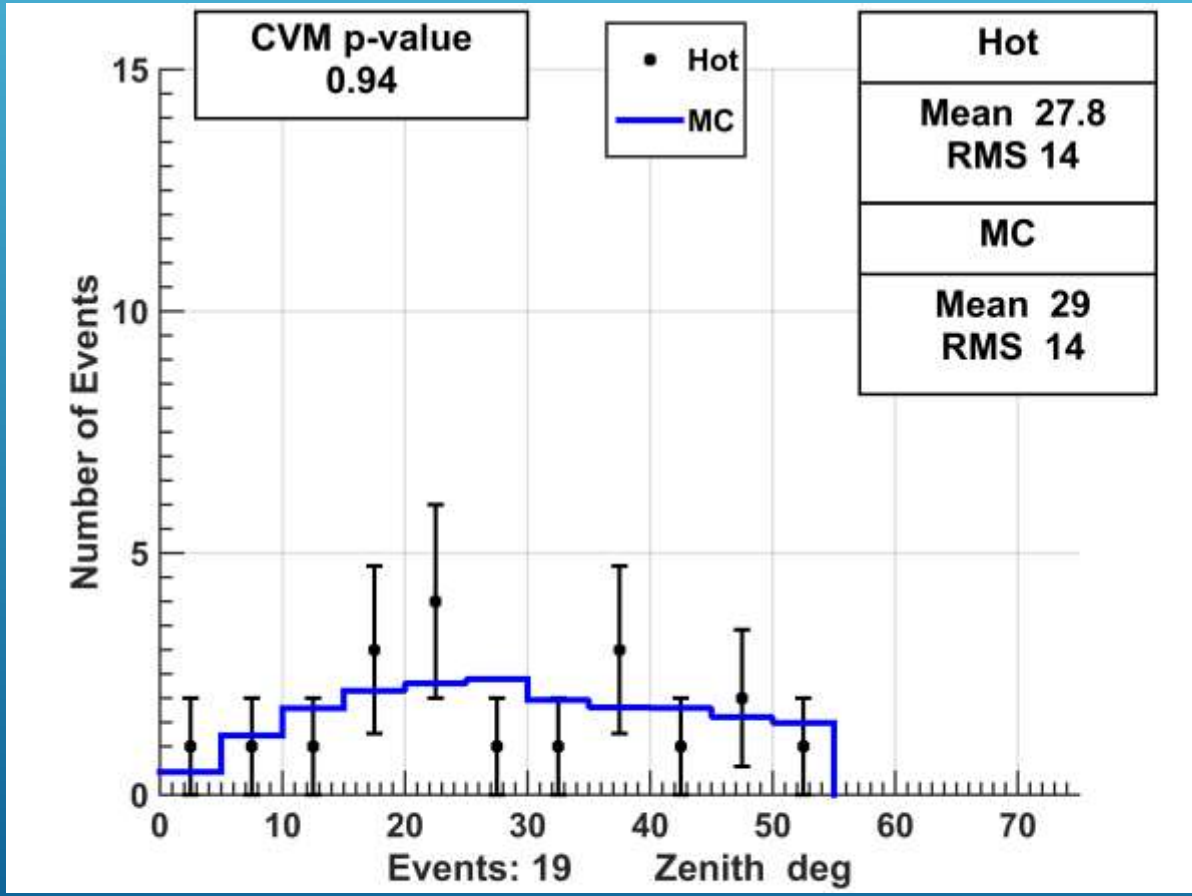
CVM p-value
0.77
Hotspot
Coldspot
Hotspot
Mean -6.18
RMS 7.7
Coldspot
Mean -4.46
RMS 8.2
Number of Events
Events: 19
Ycore

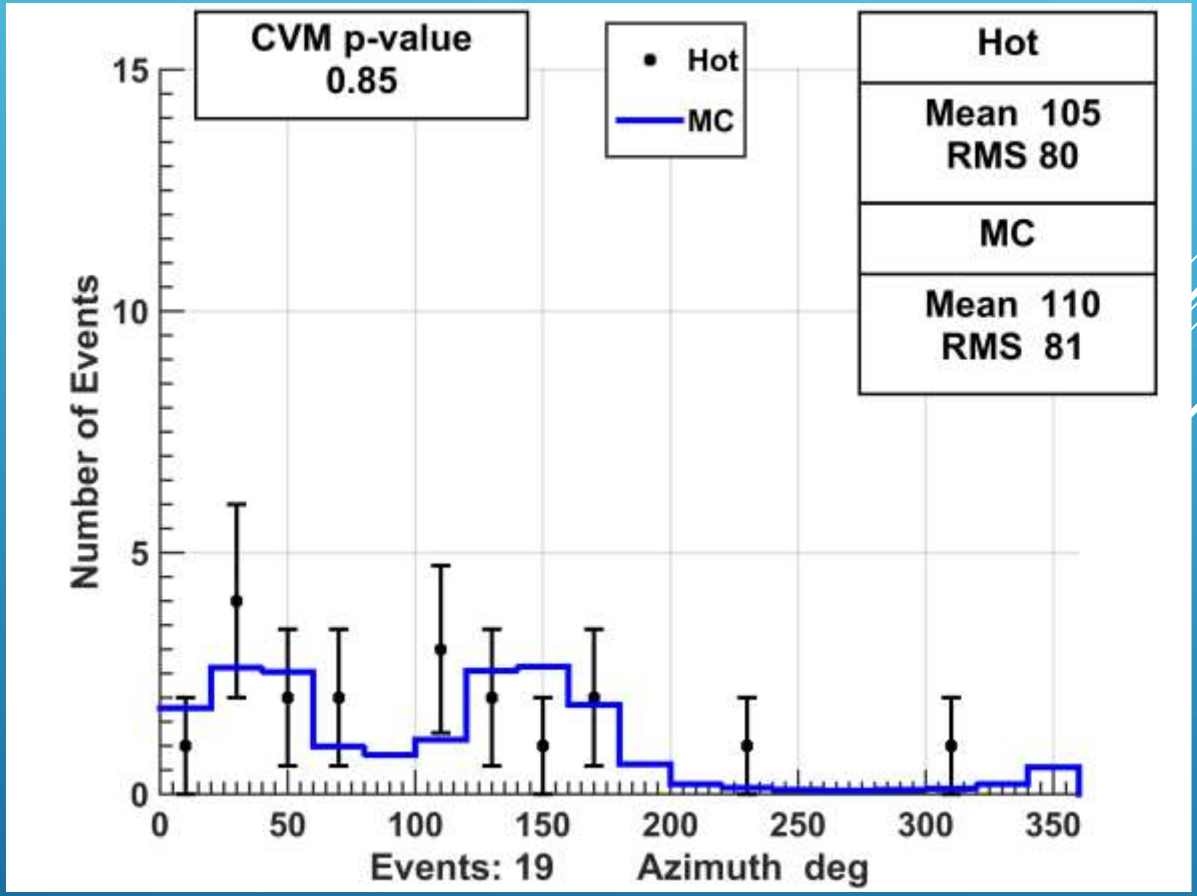
DATE



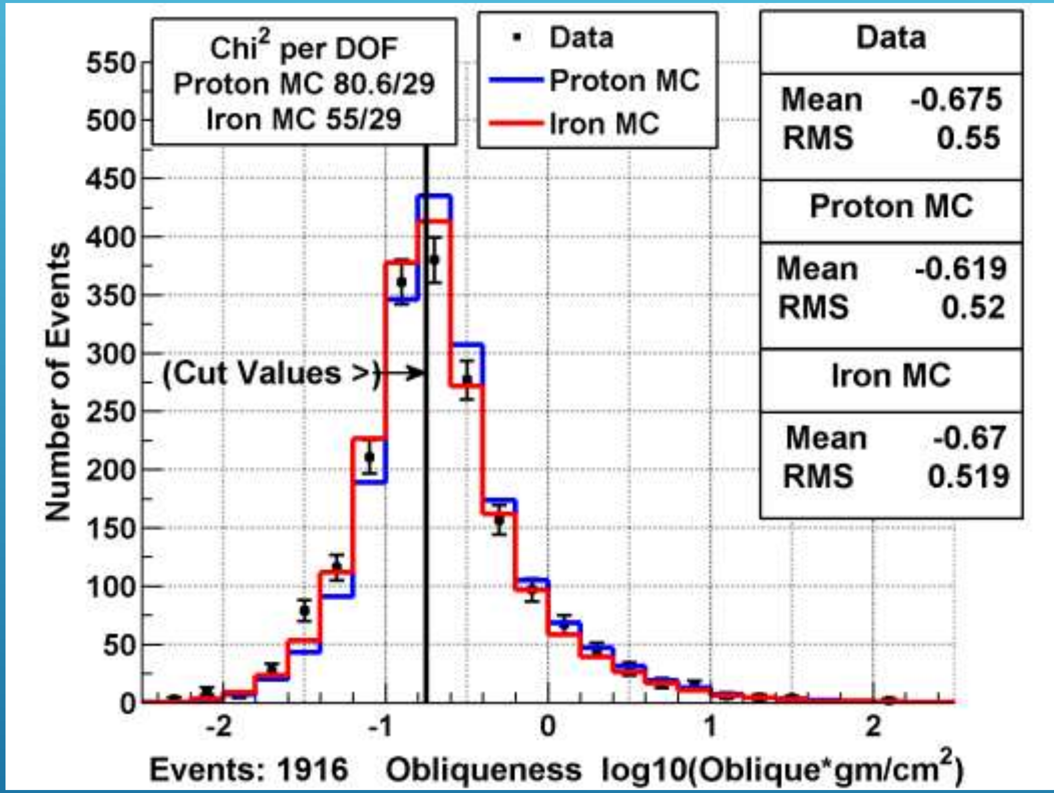
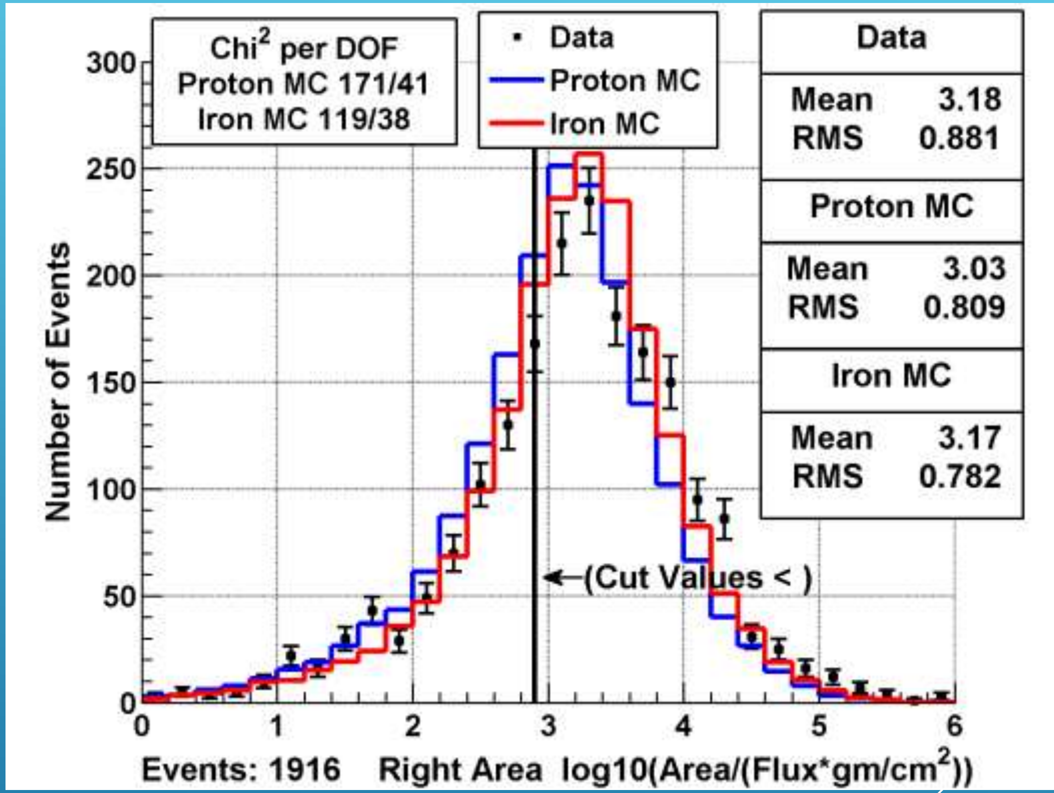
CVM p-value
0.62
Hotspot
Coldspot
Hotspot
Mean 5.59e+04
RMS 9.4e+02
Coldspot
Mean 5.58e+04
RMS 8.2e+02
Number of Events
0
1
2
3
4
5
6
7
8
9
10
5.4
5.45
5.5
5.55
5.6
5.65
5.7
5.75
5.8
Events: 19
MJD
×10^4

COMPARE HOTSPOT TO ISOTROPIC MC





COMPOSITION
ADDITIONAL MATERIAL


Chi2 per DOF
Proton MC 80.6/29
Iron MC 55/29
Data
Proton MC
Iron MC
Data
Mean -0.675
RMS 0.55
Proton MC
Mean -0.619
RMS 0.52
Iron MC
Mean -0.67
RMS 0.519
(Cut Values >)
Number of Events
Events: 1916 Obliqueness log10(Oblique*gm/cm2)

Chi2 per DOF
Proton MC 171/41
Iron MC 119/38
Data
Proton MC
Iron MC
Data
Mean 3.18
RMS 0.881
Proton MC
Mean 3.03
RMS 0.809
Iron MC
Mean 3.17
RMS 0.782
(Cut Values <)
Number of Events
Events: 1916 Right Area log10(Area/(Flux*gm/cm2))

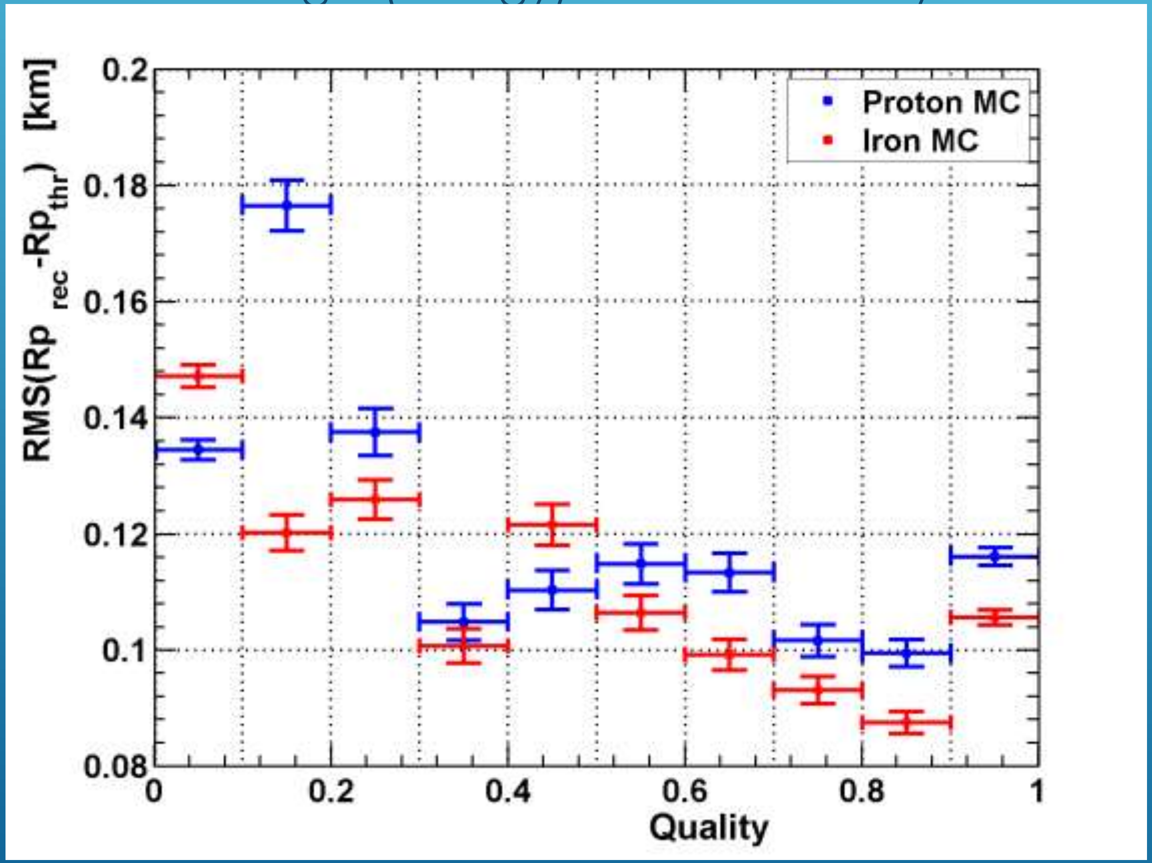
COMPUTER OBSERVER (YES/NO PRA) CUTS

Examples of attributes

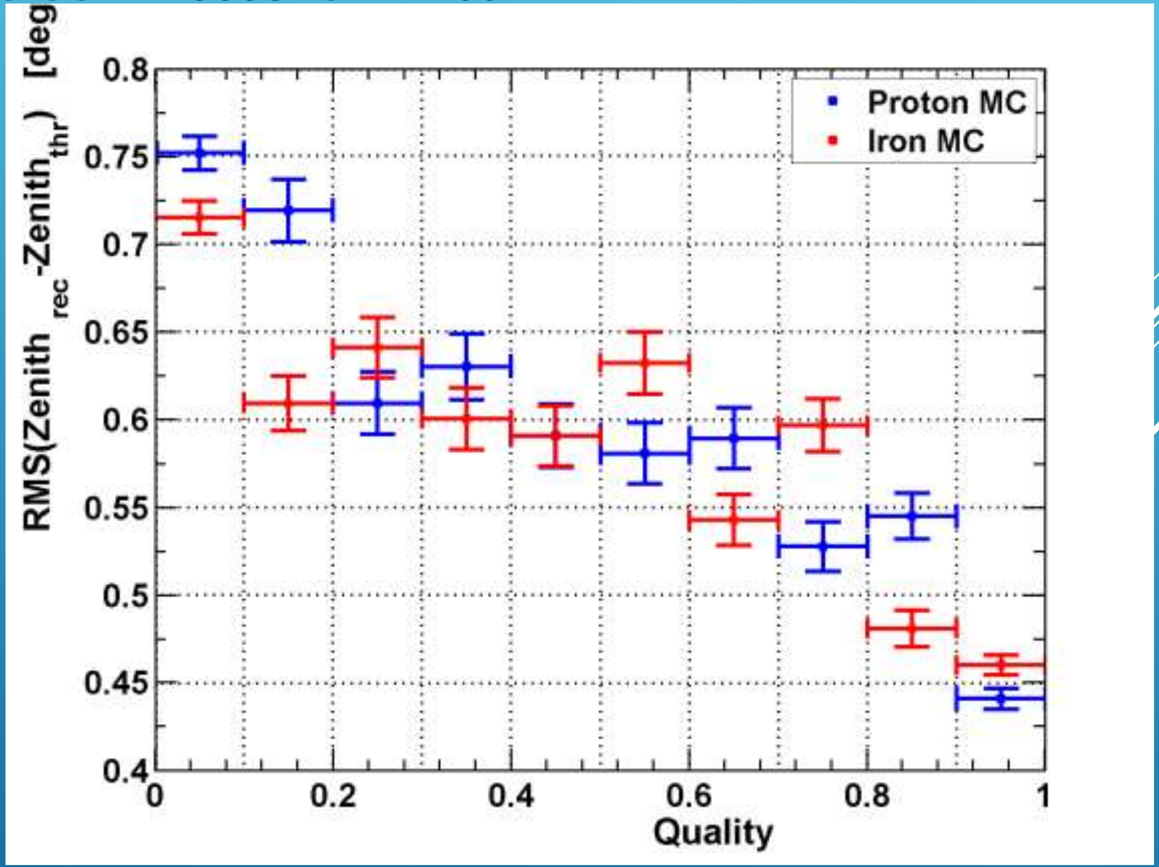
- At least 2 bins before apex and either end.
- Cubic term of quadratic fit used to find triangle apex.
- Size of small side of large triangle.
- Standard deviation of signal flux.
- Normalized maximum missing slant depth in profile.
- Obliqueness (perimeter/area) of large triangle.
- Allowed missing area between bins.
- Normalized Largest side of under right triangle.
- Ratio of normalized largest side of large triangle to apex angle.

RECONSTRUCTED VS. THROWN

- (Reconstructed – Thrown) Vs. Quality
- Minimum cuts applied to make limits of MC and data the same:
  - log10(energy)>18.2&boundarydist>-1500&corediff<2500&zenith<60



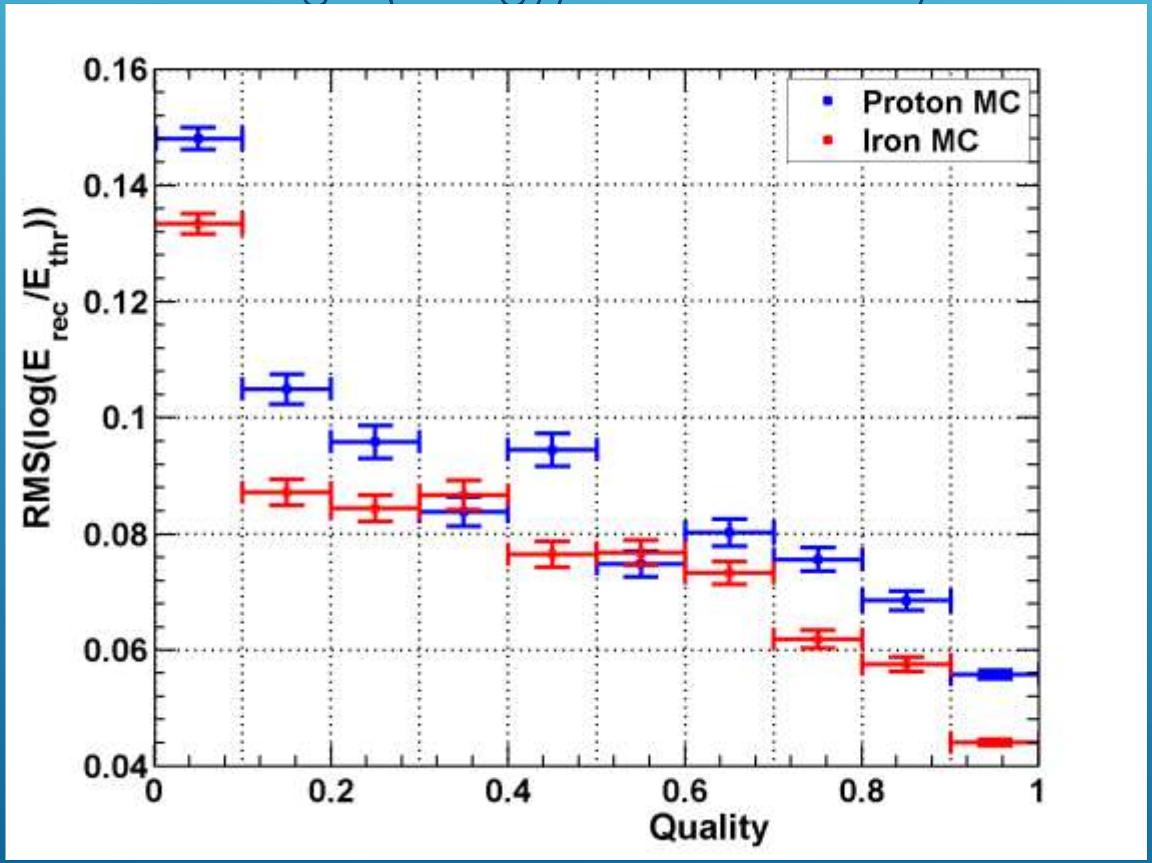
Rp

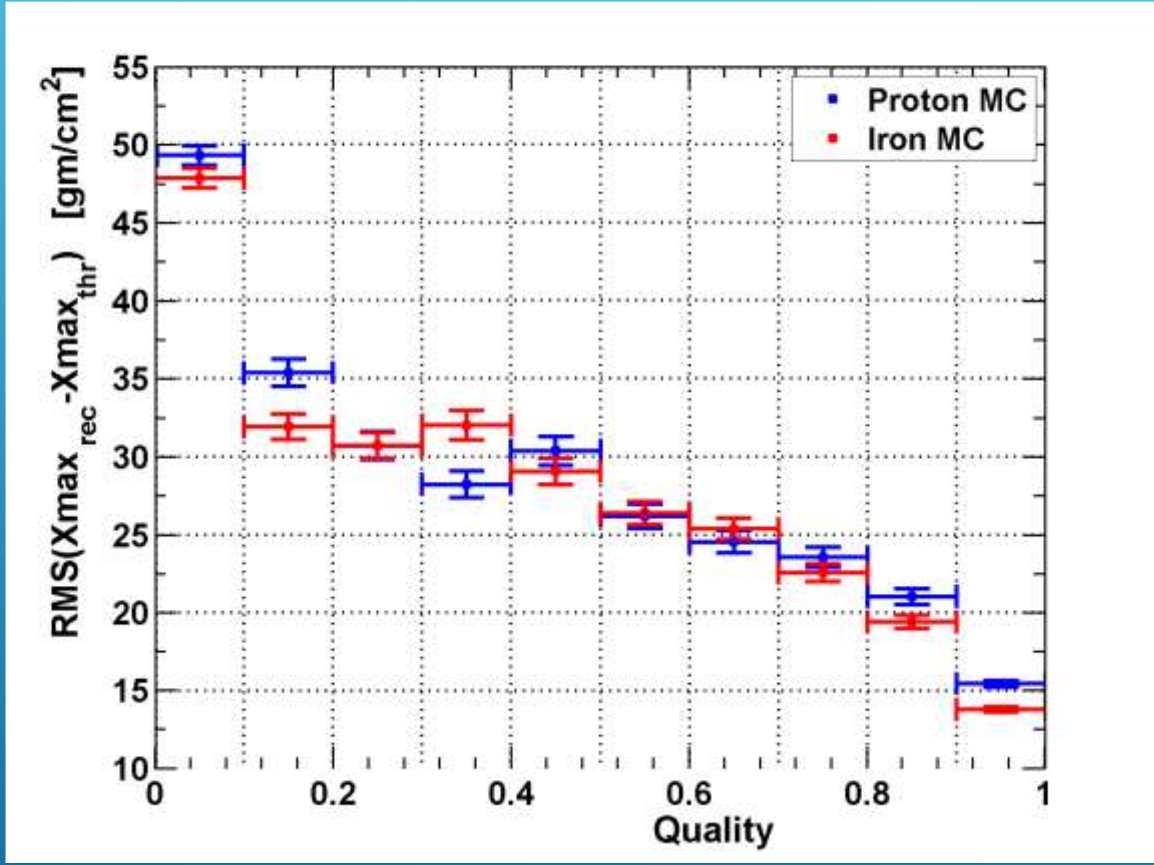


Zenith

RECONSTRUCTED VS. THROWN

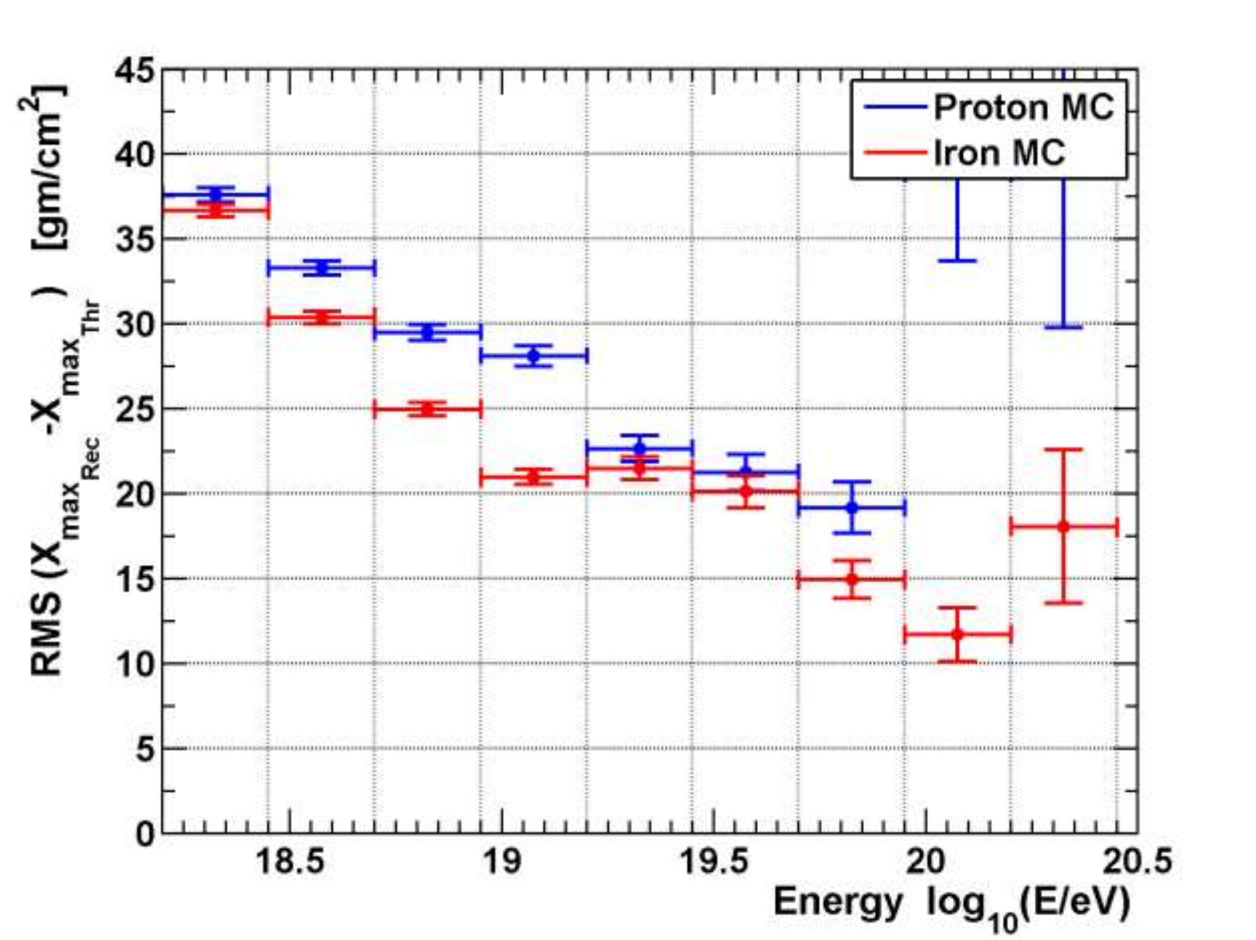
- (Reconstructed – Thrown) Vs. Quality
- Minimum cuts applied to make limits of MC and data the same:
  - log10(energy)>18.2&boundarydist>-1500&corediff<2500&zenith<60



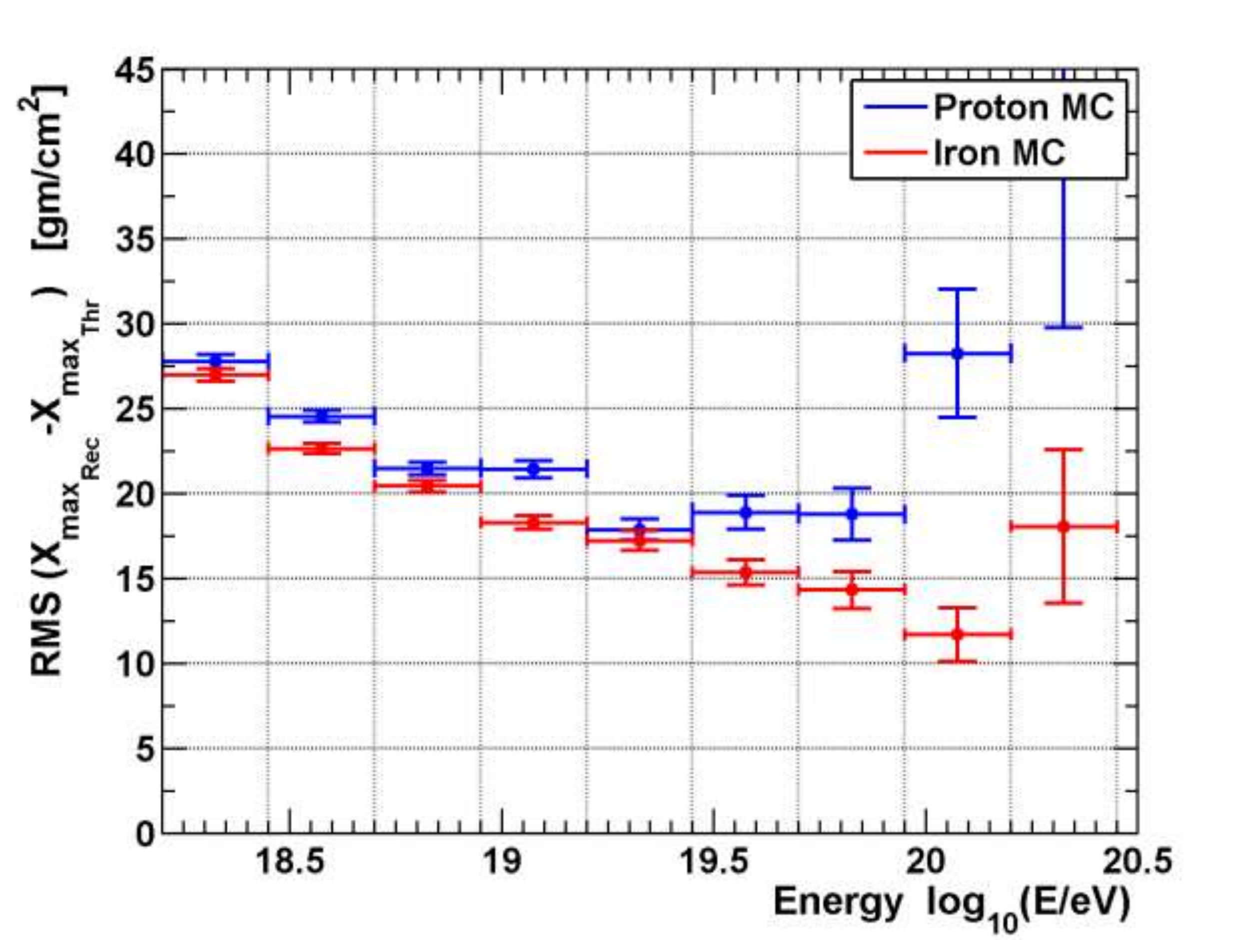


Energy Less spread at higher quality. Xmax

RESOLUTION VS. ENERGY VS. Q THRESHOLD

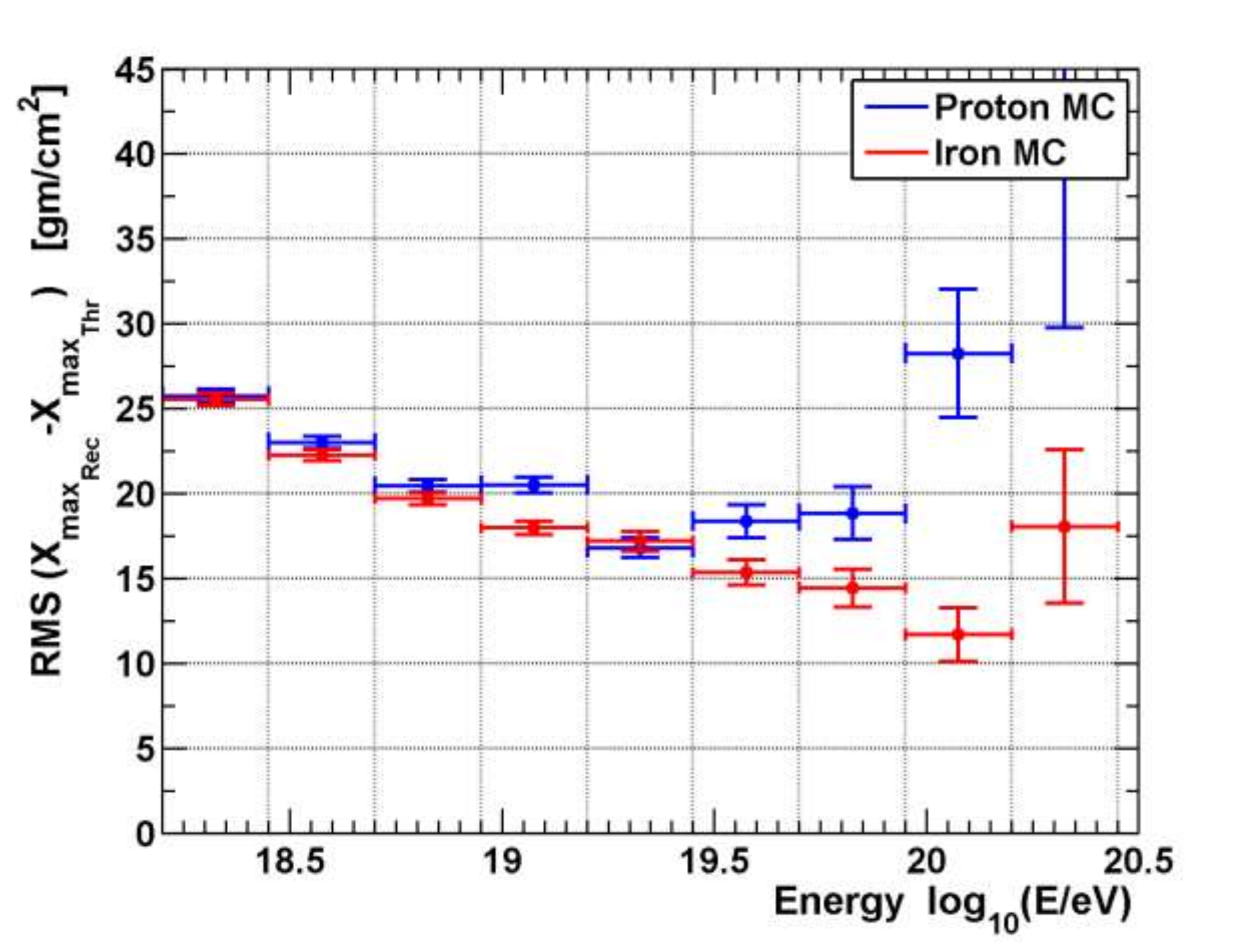


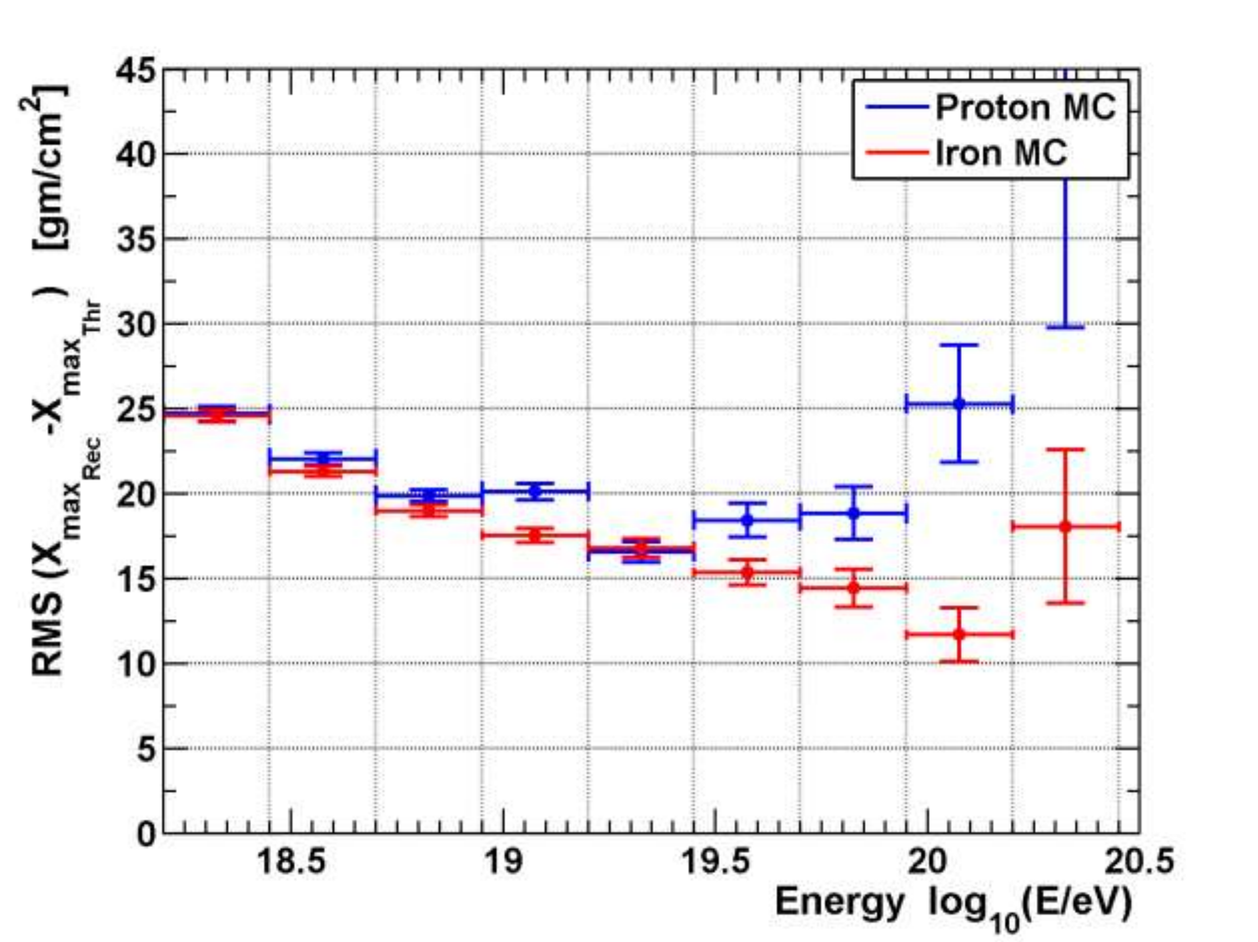
Q>0



Q>=0.1

RESOLUTION VS. ENERGY VS. Q THRESHOLD

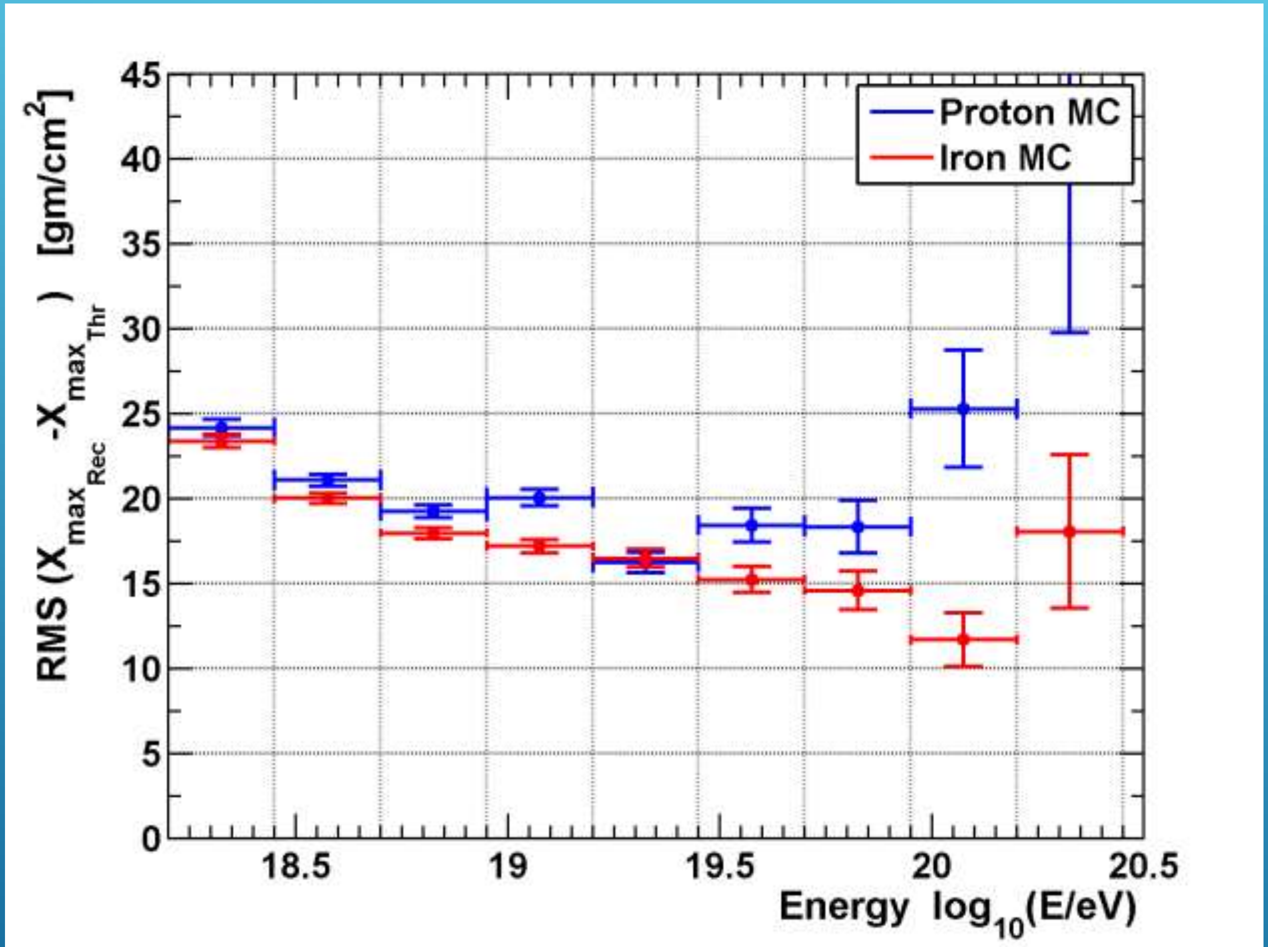




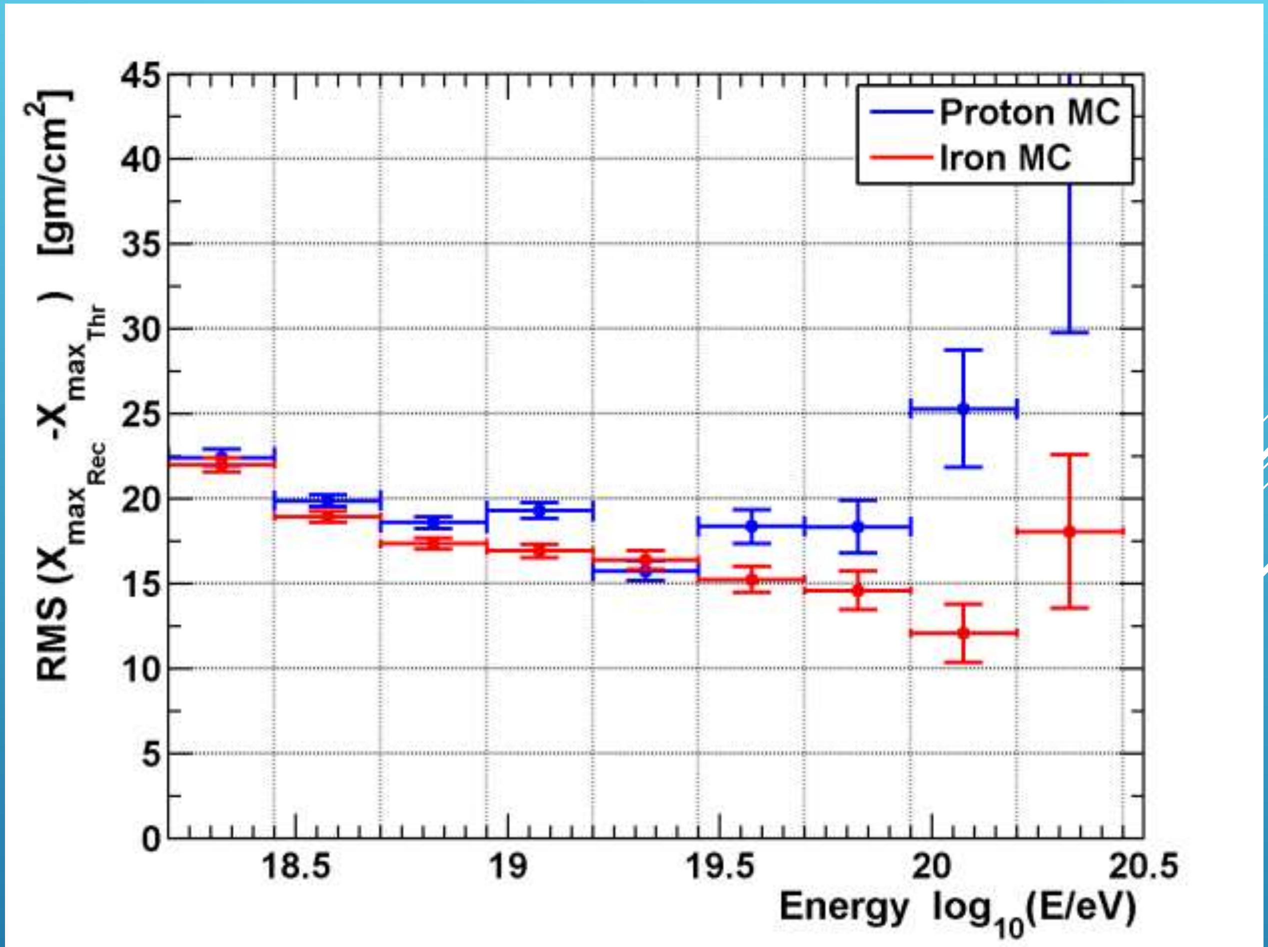
Q>=0.2

Q>=0.3

RESOLUTION VS. ENERGY VS. Q THRESHOLD

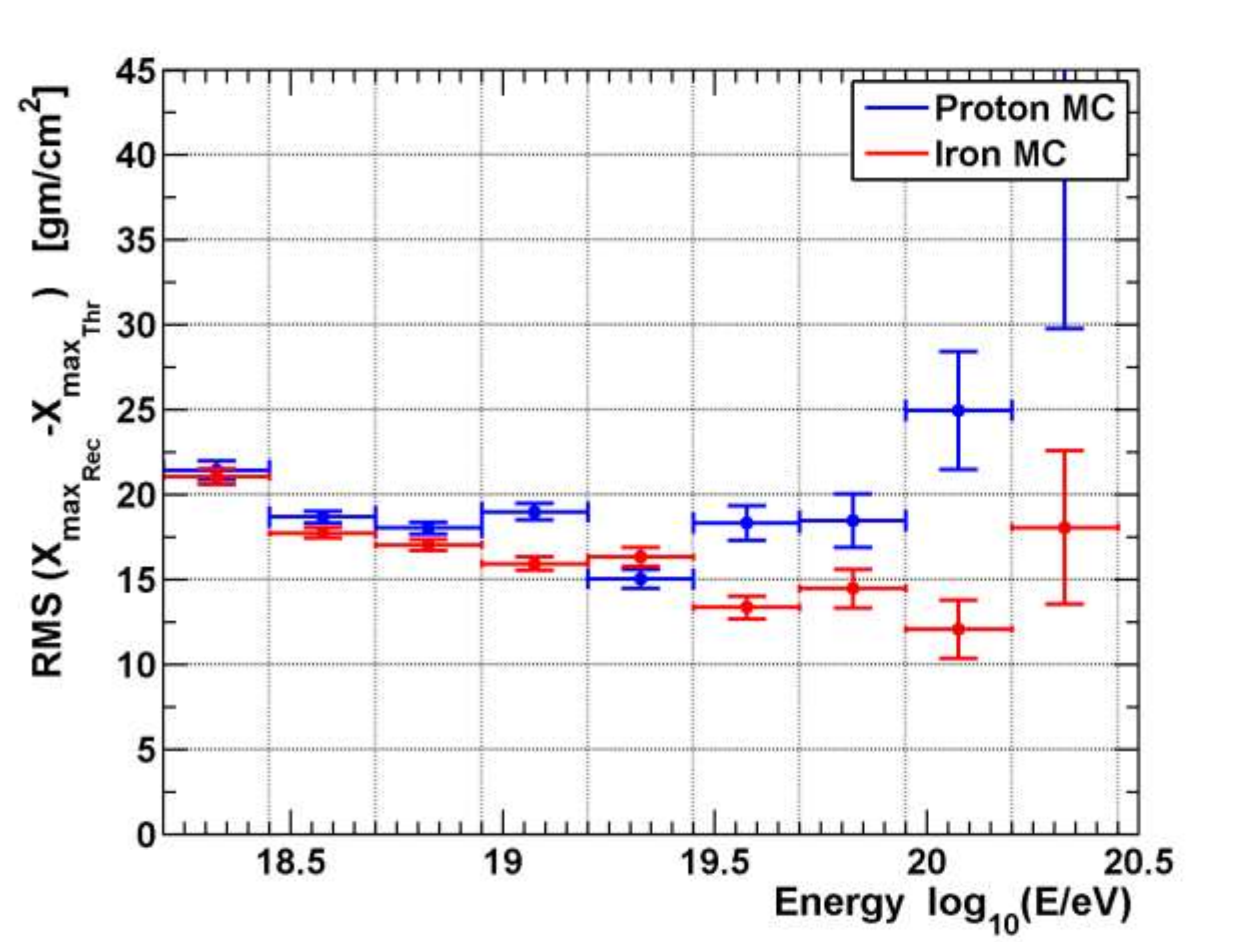


Q>=0.4

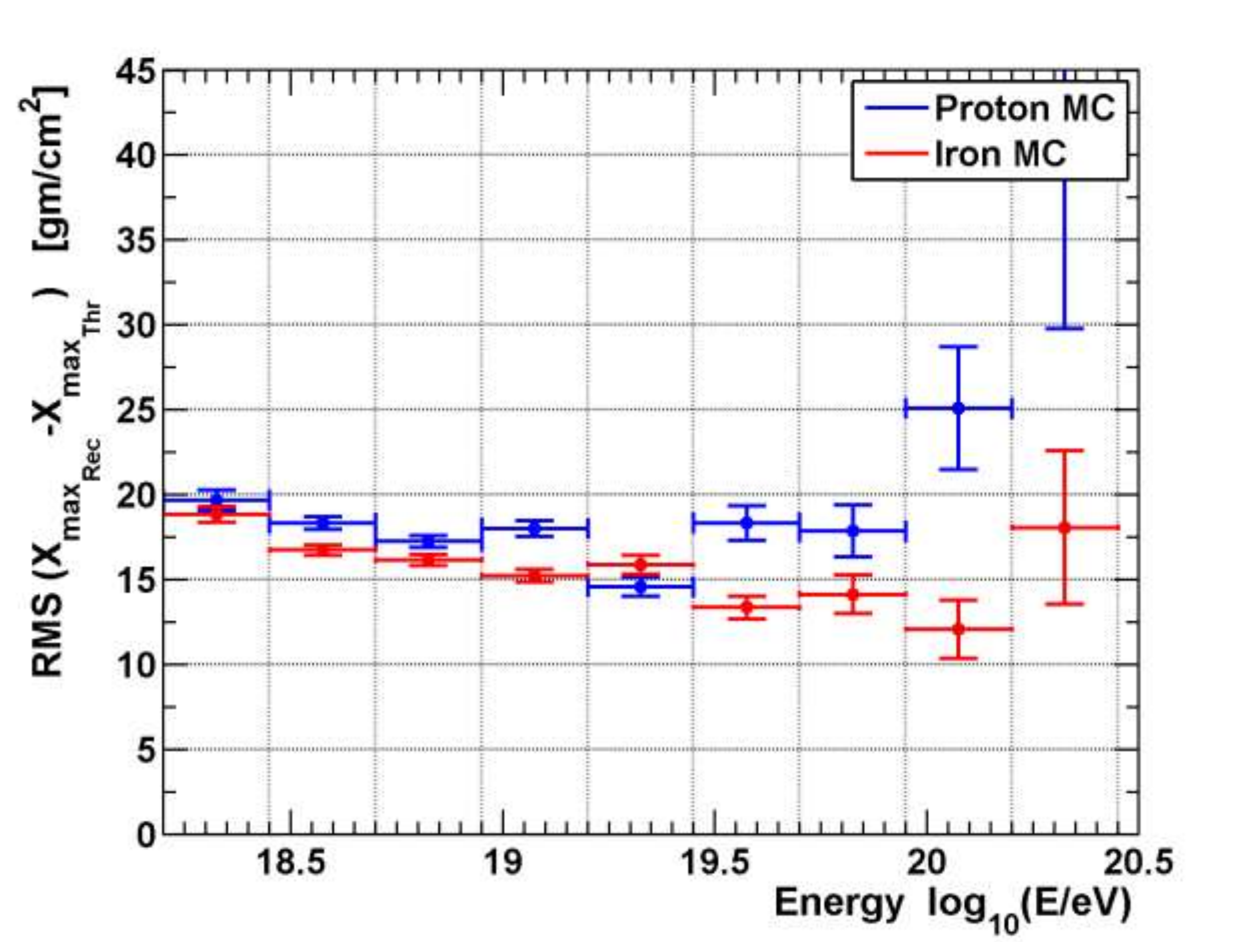


Q>=0.5

RESOLUTION VS. ENERGY VS. Q THRESHOLD



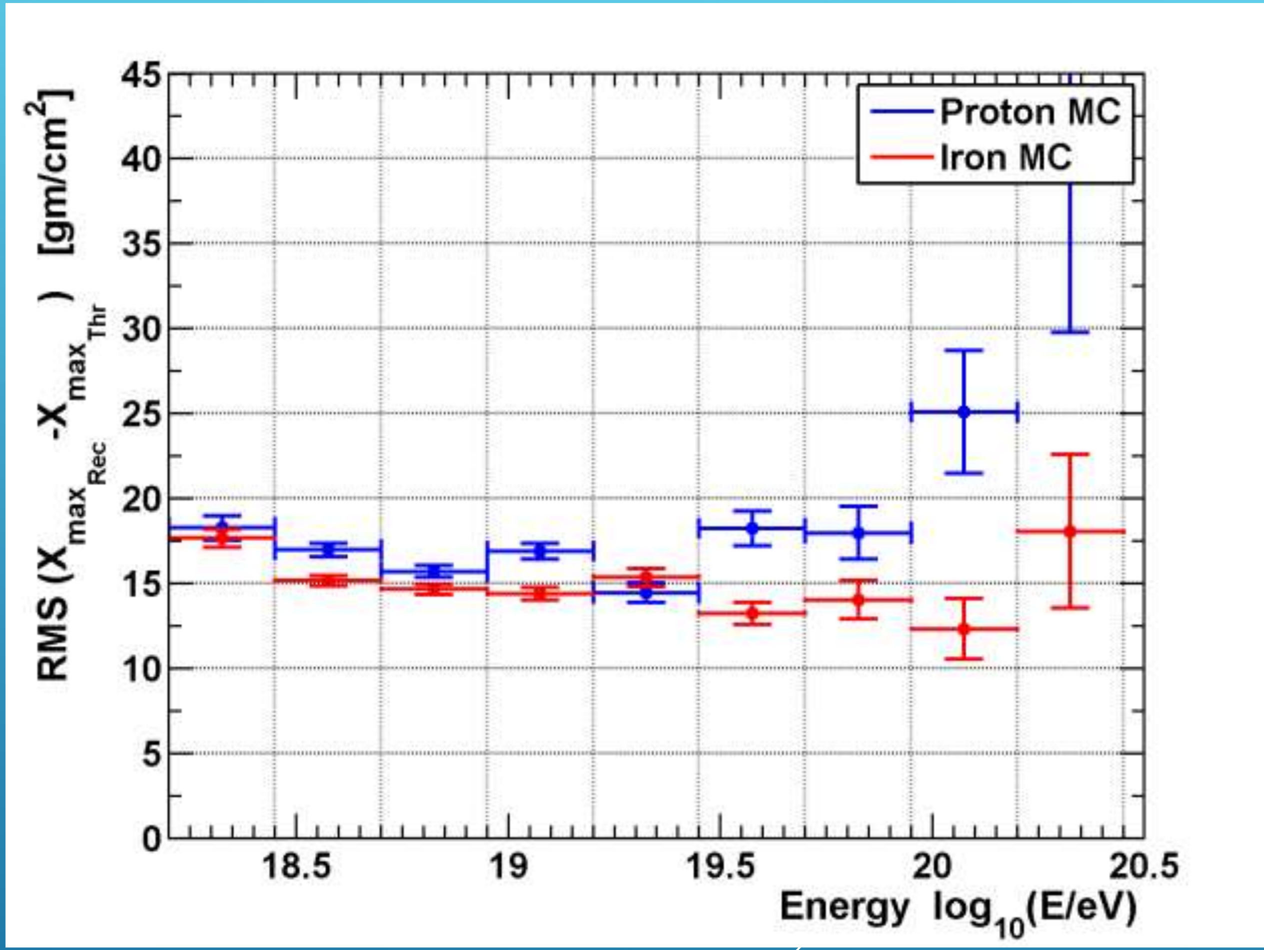
Q>=0.6



Q>=0.7

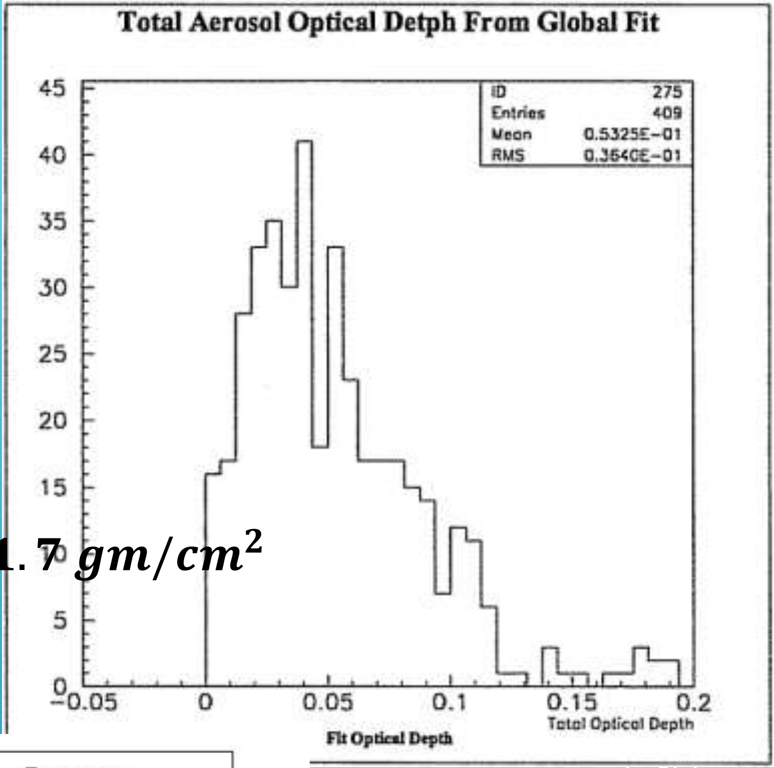
RESOLUTION VS. ENERGY VS. Q THRESHOLD

Resolution with respect to energy flattens with increasing Quality



Q>=0.8

SYSTEMATIC ERRORS



$\langle X_{max} \rangle = 751 \pm 16.3\ sys. \pm 9.4\ stat.\ gm/cm^2$ at log10(E) = 19

$\langle X_{max} \rangle$ Systematic errors include:
Mirror alignment (known to $\pm 0.05^{\circ}$): $\pm 2.6\ gm/cm^2$
Atmosphere Density (US 1976 Standard Vs. Yearly Ave. Radiosonde): $\pm 11.7\ gm/cm^2$
Vertical Aerosol Optical Depth (VAOD) Nightly Variation: $\pm 2\ gm/cm^2$

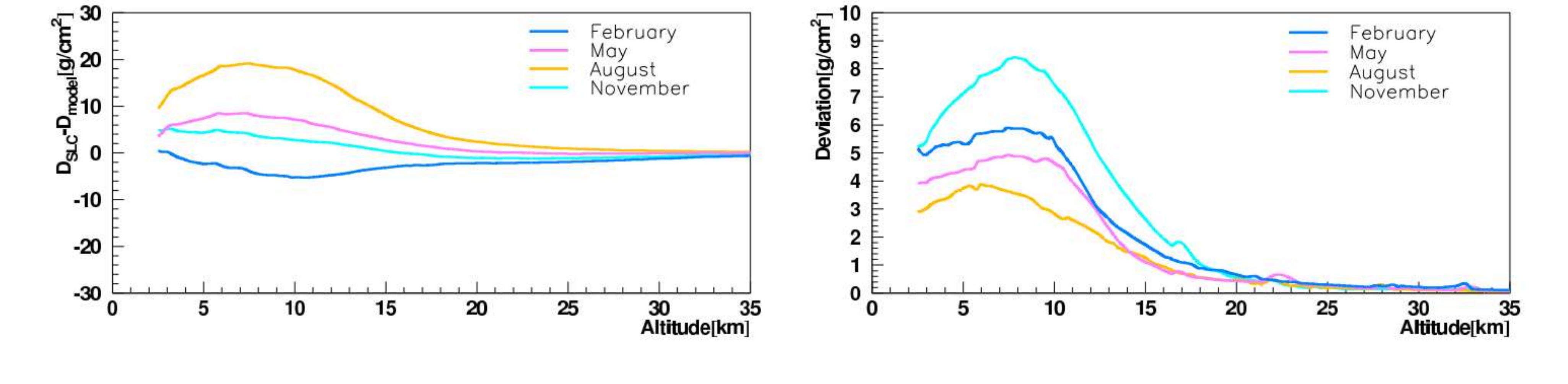


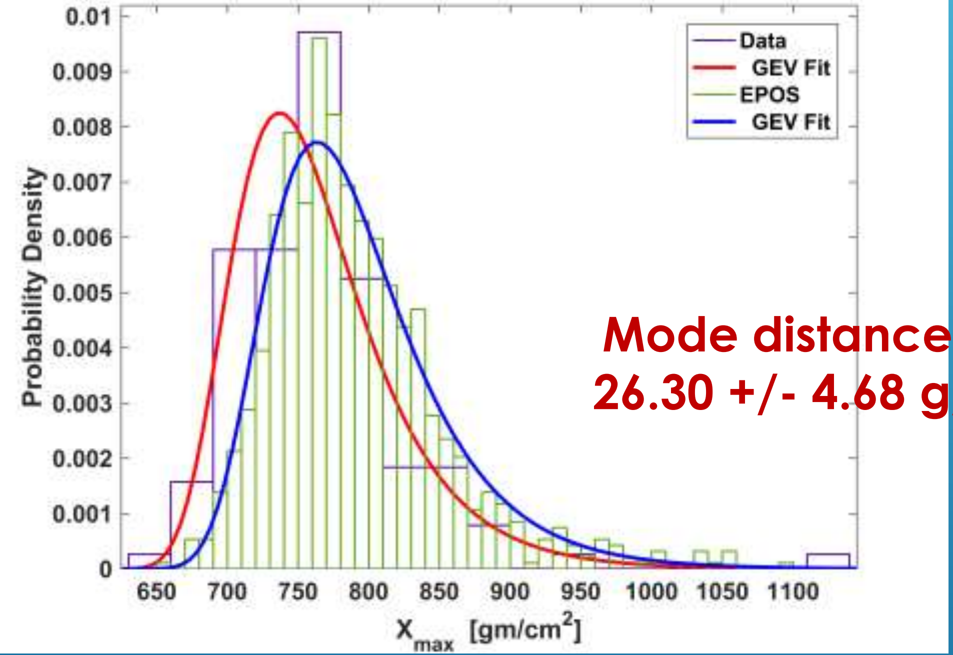
Figure 1. Differences of atmospheric depth from the US-SA model (left: average, right:standard deviation)

Systematic effects of Cerenkov light subtraction is negligible due allowed hybrid shower directions.

ROBUST MEASURE OF BIAS

L-test shift - robust bias measure for skewed distributions
(Distance between population modes/locations)

EPOS PROTON
18.8 to 19



Procedure: 5000 random number sets from fitted distributions and measure distances

Test: Measure L-test Shifts, Difference of sample modes
Difference of medians, and Difference of Means

Mode distance of GEV fit distributions
26.30 +/- 4.68 g/cm^2 (fit uncertainty)

Data Set

#data = 127, #MC = 937

- Shift: 25.2 g/cm^2
- Mode: 95.5 g/cm^2
- Median: 28.2 g/cm^2
- Mean: 22.2 g/cm^2

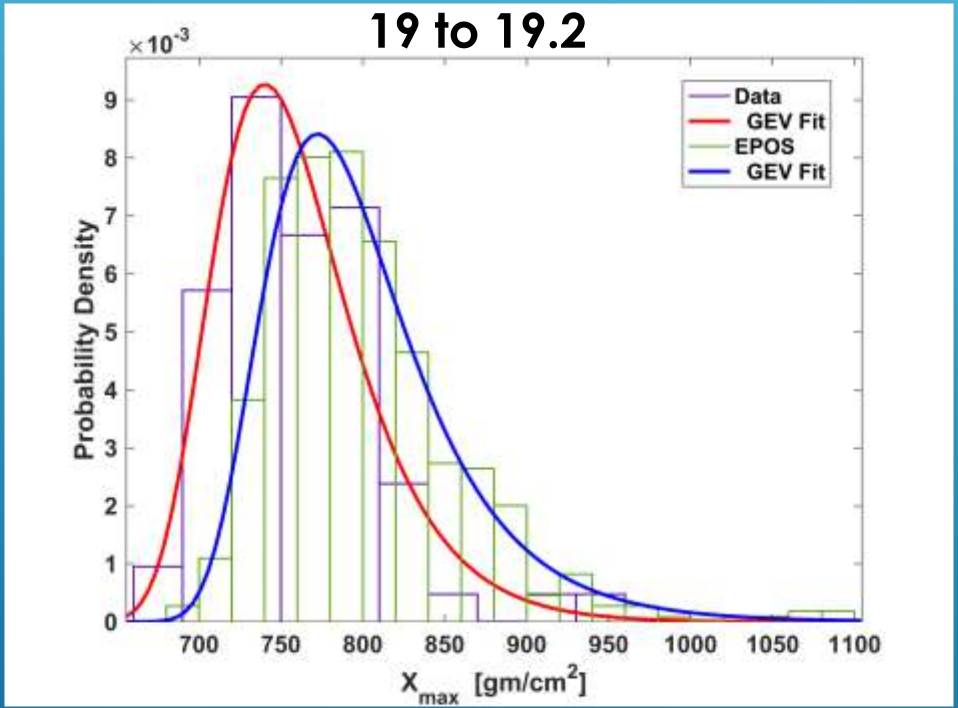
Distances of 5000 MC

- Shift: 26.7 RMS 4.8 g/cm^2
- Mode: 5.9 RMS 12.3 g/cm^2
- Median: 27.3 RMS 6.1 g/cm^2
- Mean: 27.9 RMS 5.6 g/cm^2

ROBUST MEASURE OF BIAS

L-test shift - robust bias measure for skewed distributions
(Distance between population modes /locations)

EPOS PROTON
19 to 19.2



#data = 70, #MC = 549

Data Set

- **Shift: 34.83 g/cm^2**
- **Mode: 114.87 g/cm^2**
- **Median: 30.45 g/cm^2**
- **Mean: 39.77 g/cm^2**

Mode distance of GEV fit distributions
34.78 +/- 5.68 g/cm^2

Procedure: 5000 random number sets from fitted distributions and measure distances

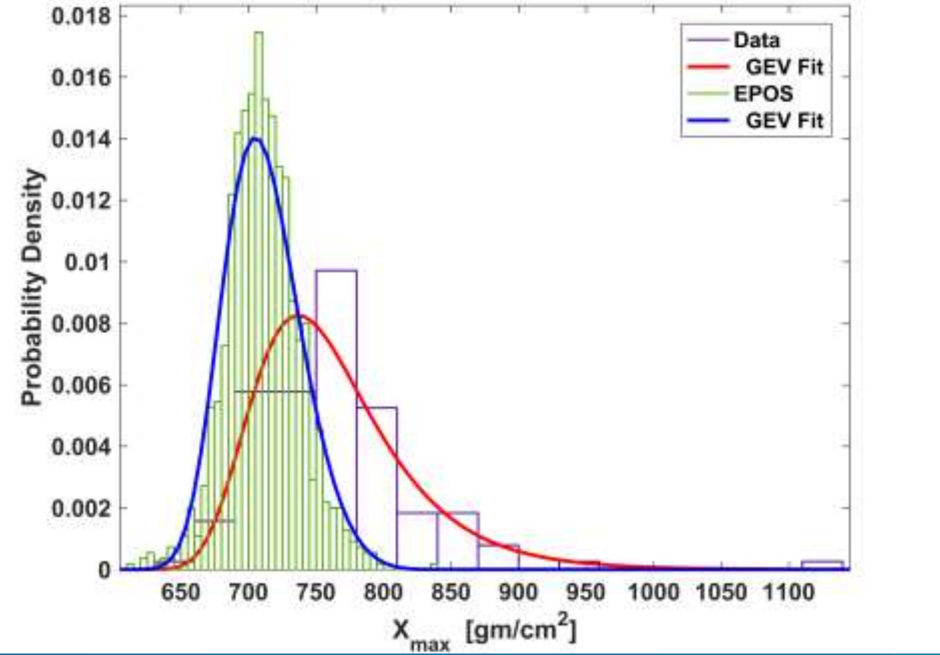
Distances of 5000 MC

- **Shift: 36.1 RMS 5.8 g/cm^2**
- **Mode: 16.4 RMS 12.7 g/cm^2**
- **Median: 36.4 RMS 7.3 g/cm^2**
- **Mean: 39.8 RMS 6.4 g/cm^2**

ROBUST MEASURE OF BIAS

L-test shift - robust bias measure for skewed distributions
(Distance between population modes /locations)

EPOS IRON
18.8 to 19



Mode distance of GEV fit distributions
-37.4 +/- 4.4 g/cm^2

Data Set

#data = 127, #MC = 1100

- Shift: -46.9 g/cm^2
- Mode: +36.5 g/cm^2
- Median: -48.0 g/cm^2
- Mean: -52.5 g/cm^2

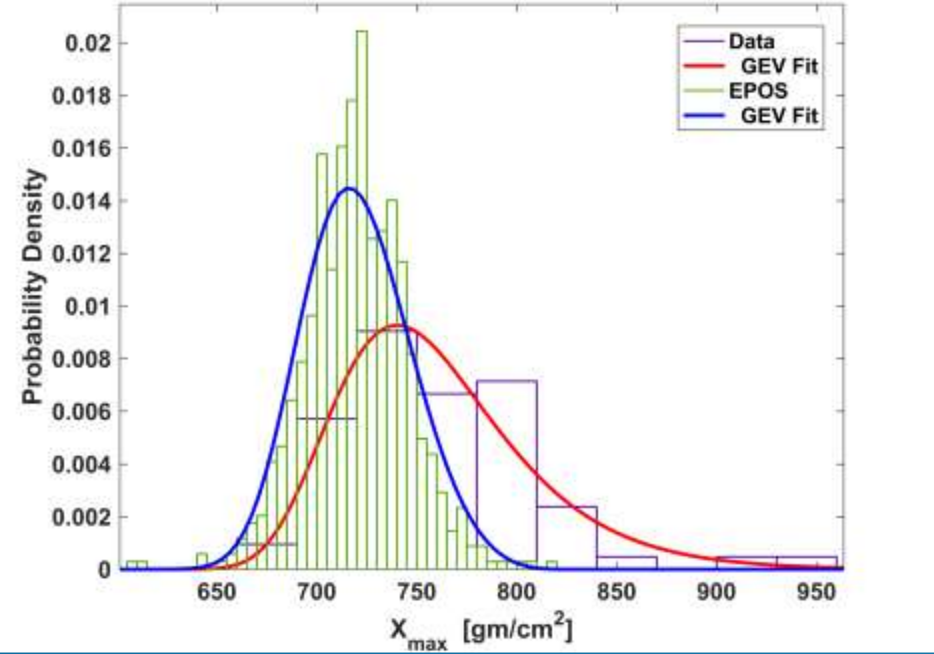
Distances of 5000 MC

- Shift: -43.1 RMS 5.2 g/cm^2
- Mode: -28.6 RMS 11.6 g/cm^2
- Median: -44.3 RMS 5.8 g/cm^2
- Mean: -52.3 RMS 5.2 g/cm^2

ROBUST MEASURE OF BIAS

L-test shift - robust bias measure for skewed distributions
(Distance between population modes /locations)

EPOS IRON
19 to 19.2



Data Set

#data = 70, #MC = 685

- Shift: -37.3 g/cm^2
- Mode: +16.8 g/cm^2
- Median: -39.9 g/cm^2
- Mean: -40.7 g/cm^2

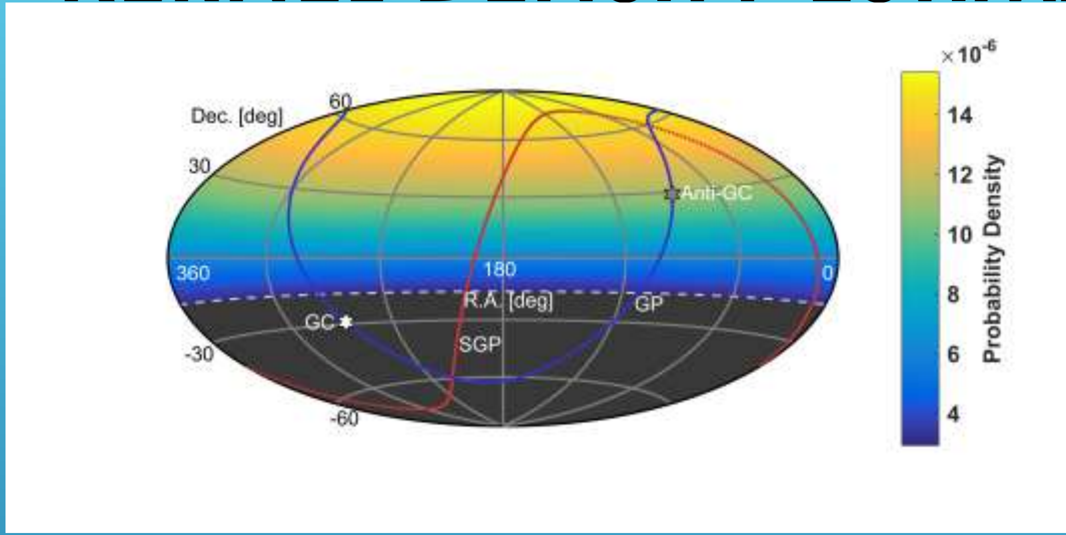
Mode distance of GEV fit distributions
-28.92 +/- 5.39 g/cm^2

Distances of 5000 MC

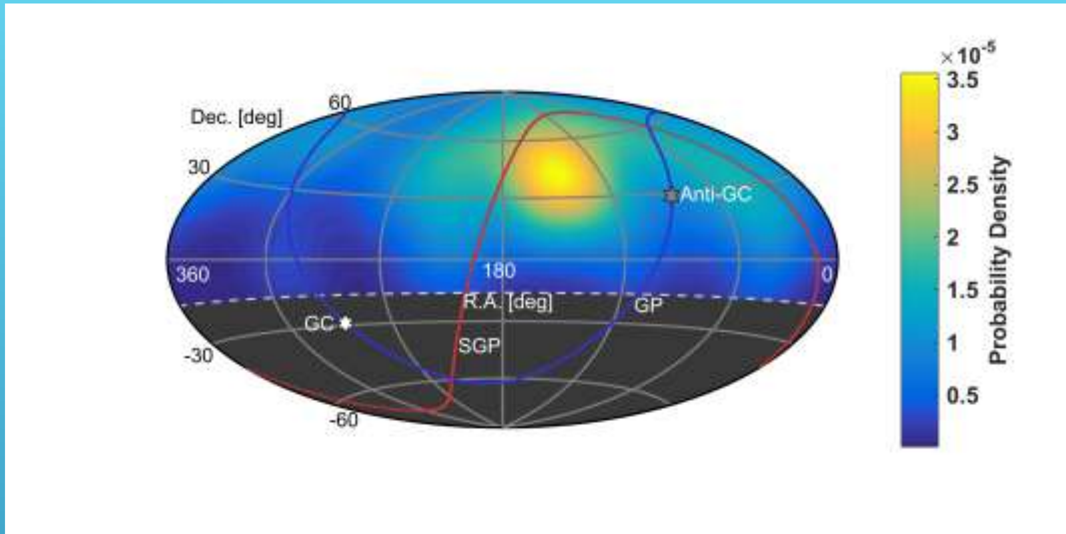
- Shift: -33.87 RMS 6.16 g/cm^2
- Mode: -29.3 RMS 12.6 g/cm^2
- Median: -34.26 RMS 6.86 g/cm^2
- Mean: -40.22 RMS 5.98 g/cm^2

KERNEL DENSITY ESTIMATION ADDITIONAL MATERIAL

KERNEL DENSITY ESTIMATION



5 year
tight cuts
shown

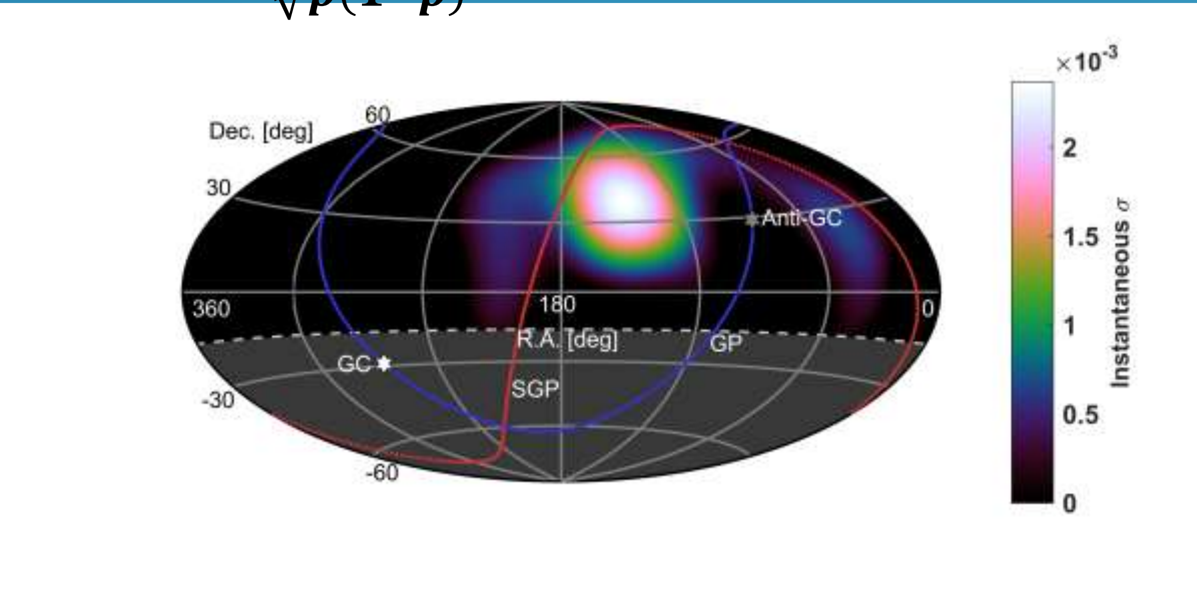


Test statistic: Wald's Proportion test

$$Z = \frac{\hat{p} - p_{bg}}{\sqrt{\hat{p}(1-\hat{p})}}$$

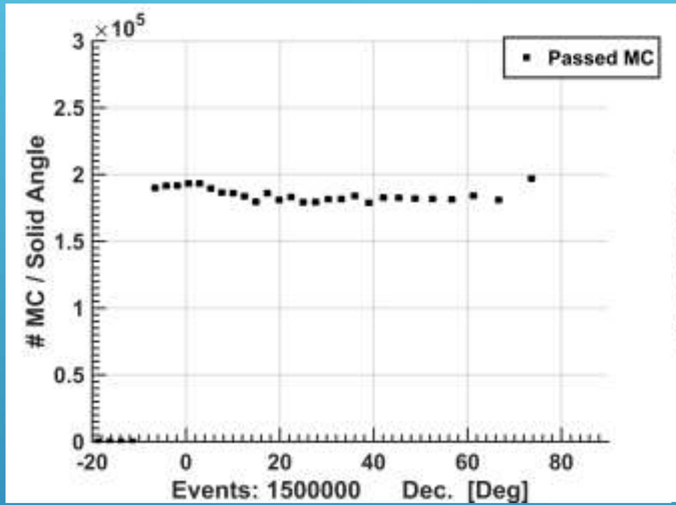
Flattest Dec. Response

Optimal von-Mises-Fisher kernel concentration for PDF found automatically for data and MC

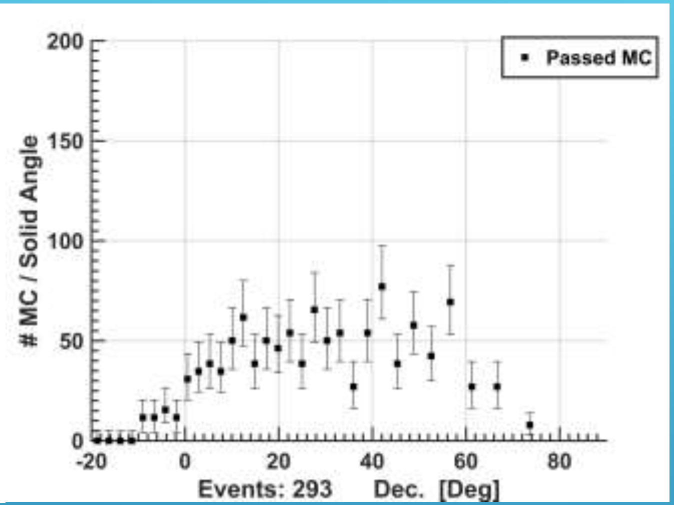


Post-trial sigmas
5 to 9 year
Loose cuts: 3.89, 4.36, 3.84, 2.92, 2.78
Tight cuts: 3.72, 4.39, 3.81, 3.06, 2.98

KDE DECLINATION RESPONSE

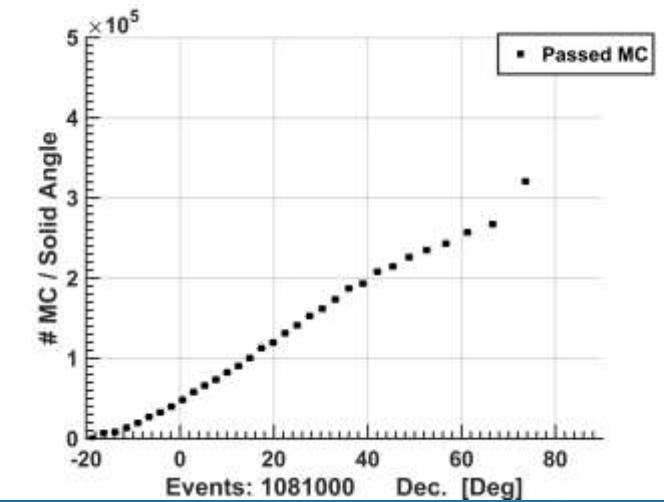


5 year simulation
Wald Test Statistic
All maximums

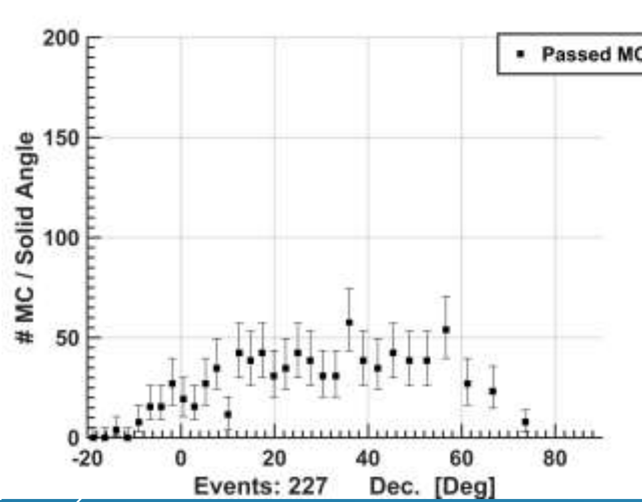


5 year simulation
Wald Test Statistic
Passed maximums

Next best statistic: p/sqrt(p_bg)



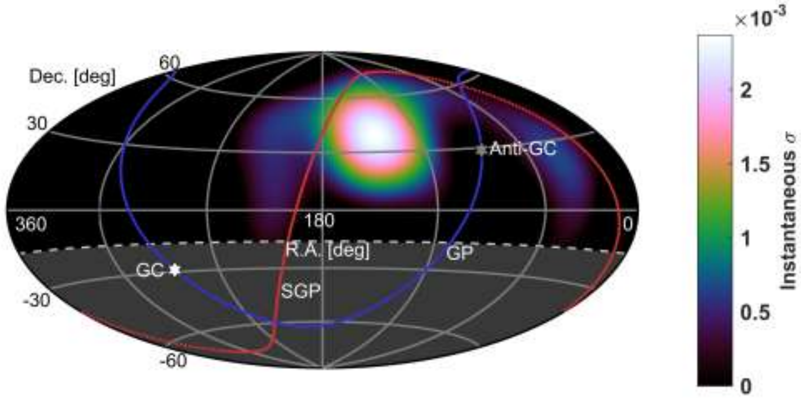
5 year simulation
All maximums



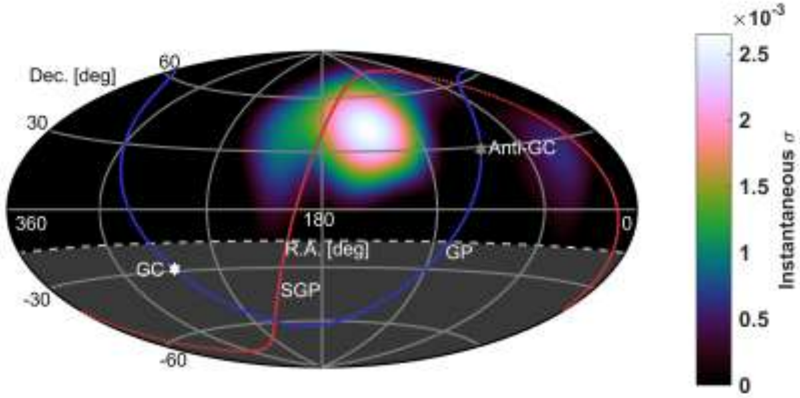
5 year simulation
Passed maximums

Equal opening angle grid. p_bg calculated with trigger times for each year.

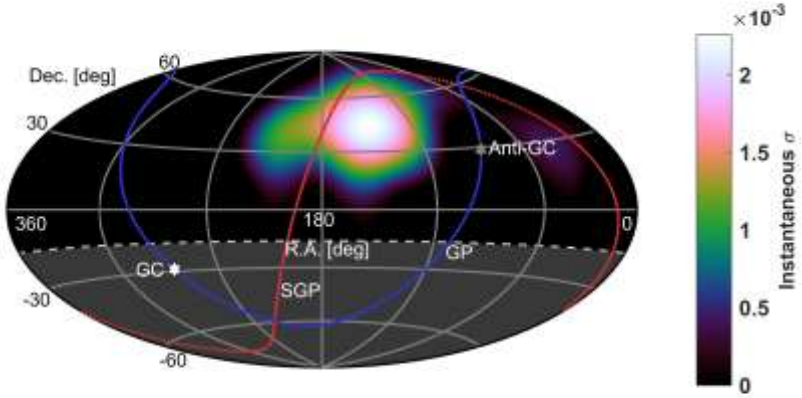
KDE PDF TIGHT CUTS



5 year

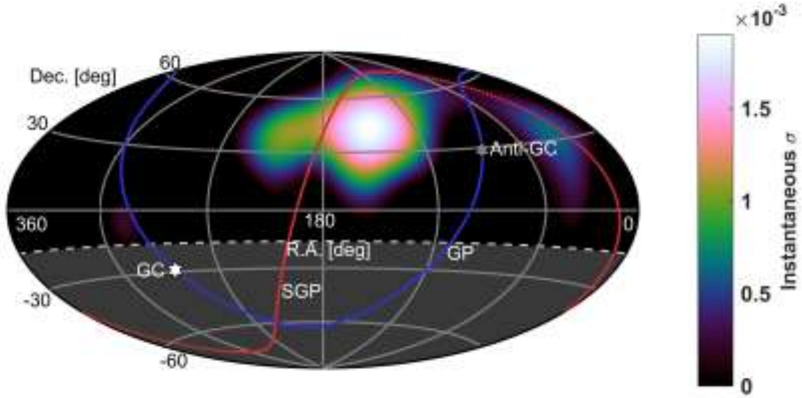


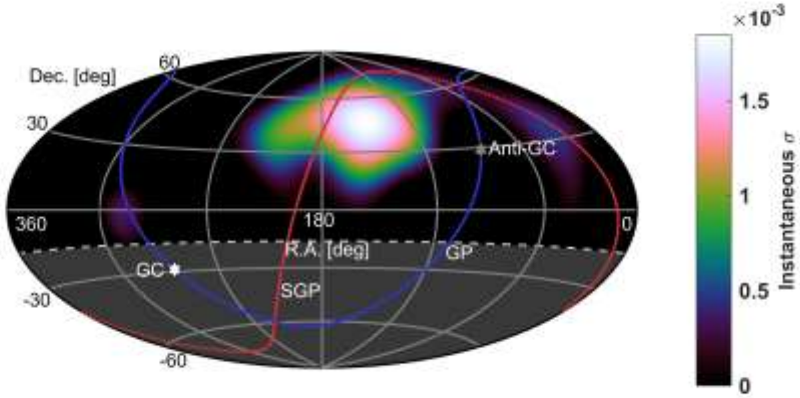
6 year



7 year

8 year

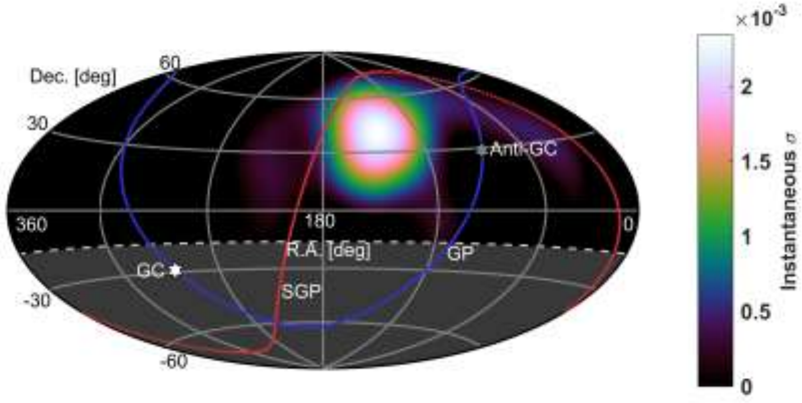




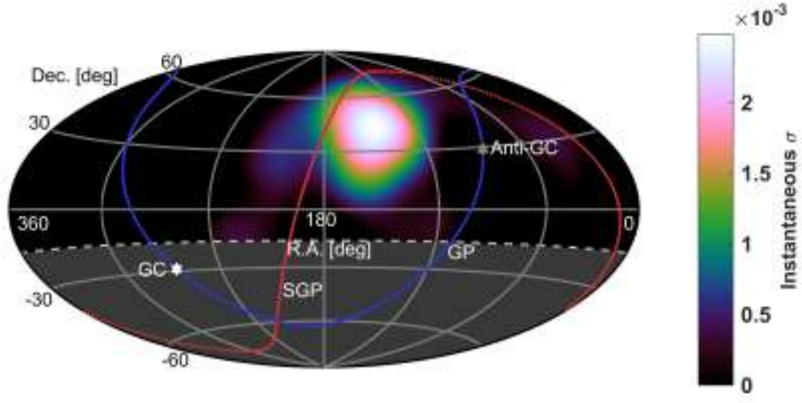
9 year

Equal opening angle grid. p_bg calculated with trigger times for each year.

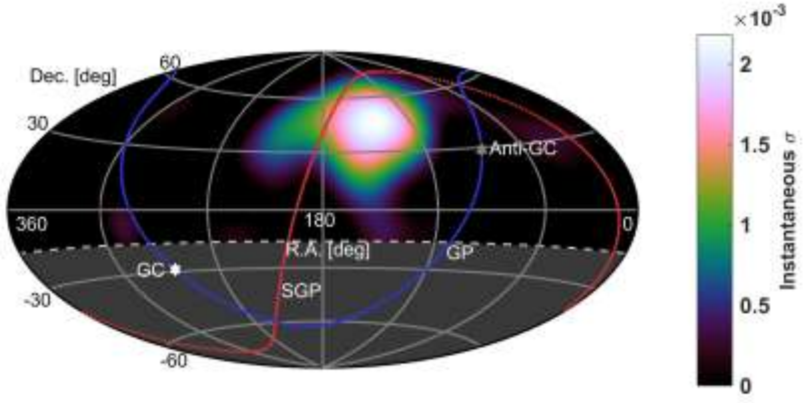
KDE PDF LOOSE CUTS



5 year

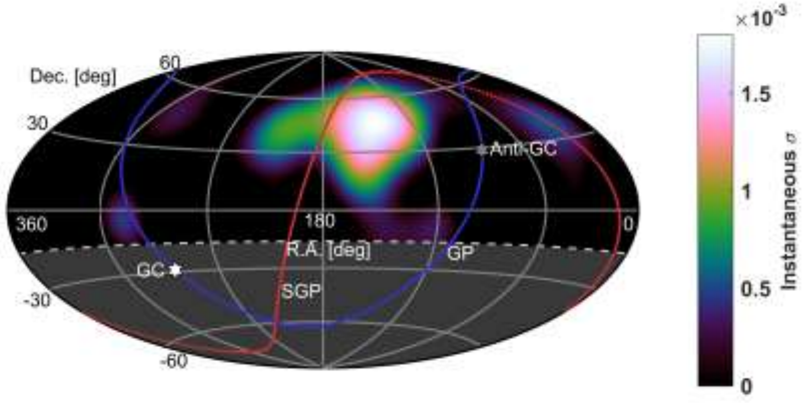


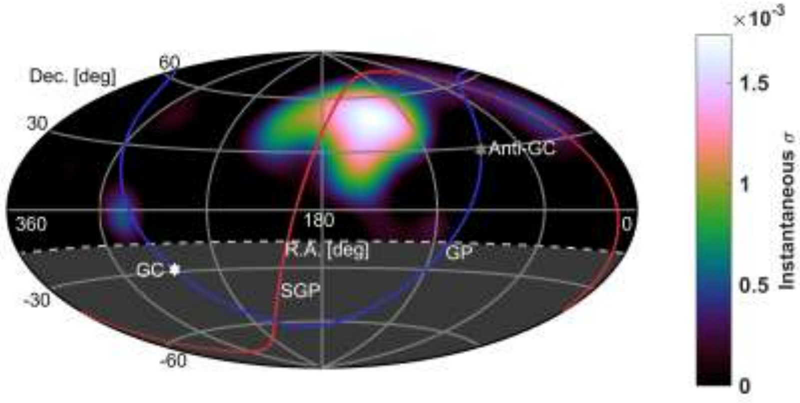
6 year



7 year

8 year





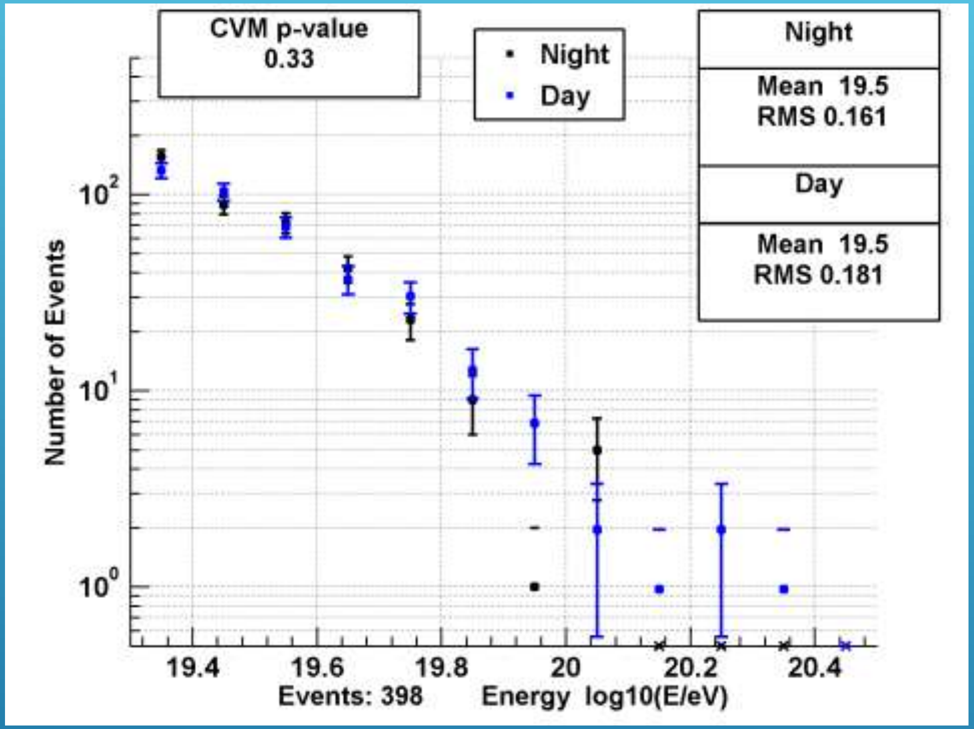
9 year

EVEN MORE HOT/COLD ADDITIONAL MATERIAL

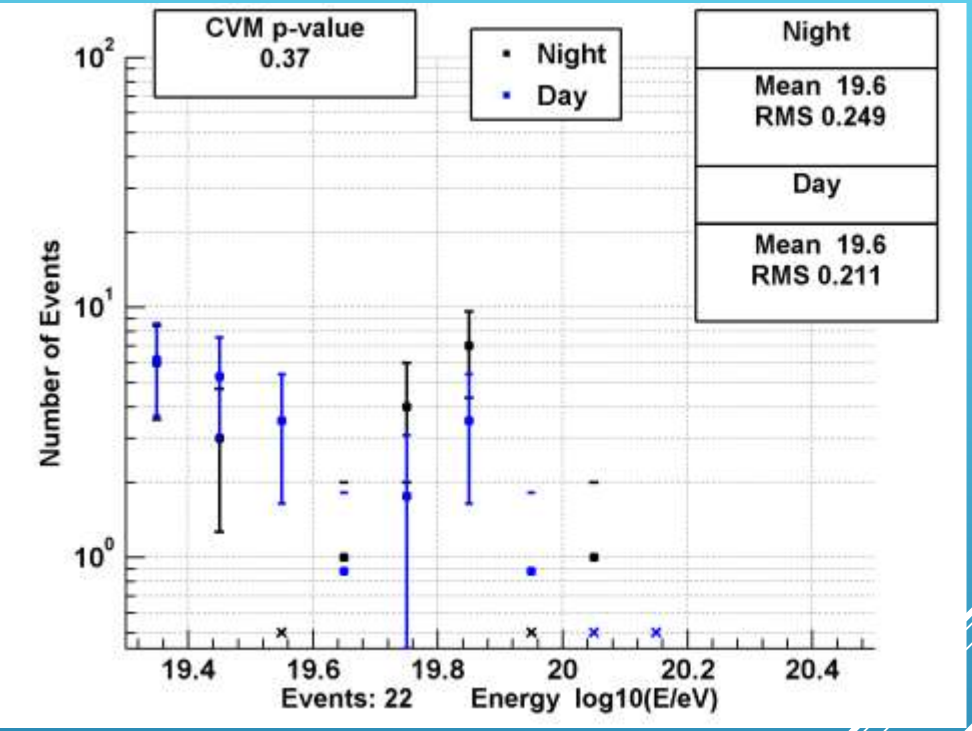
HOT/COLD SPOT
-SUMMER/WINTER AND NIGHT/DAY

Jon Paul Lundquist

DAY/NIGHT ENERGY DISTRIBUTION COMPARISON



Outside hot/cold spot

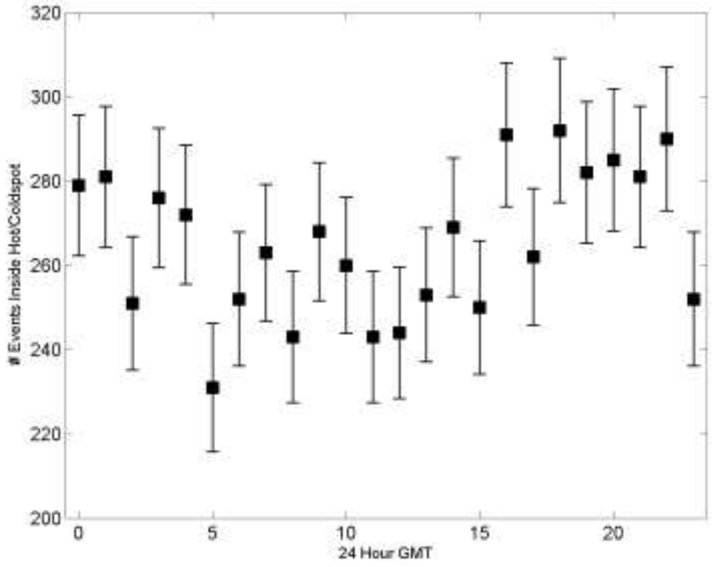


Inside hot/cold spot

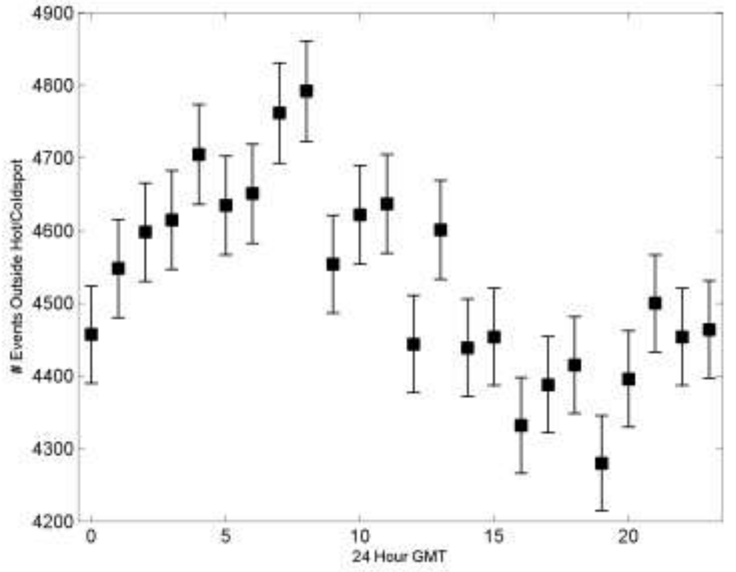
Energy distributions agree within statistics

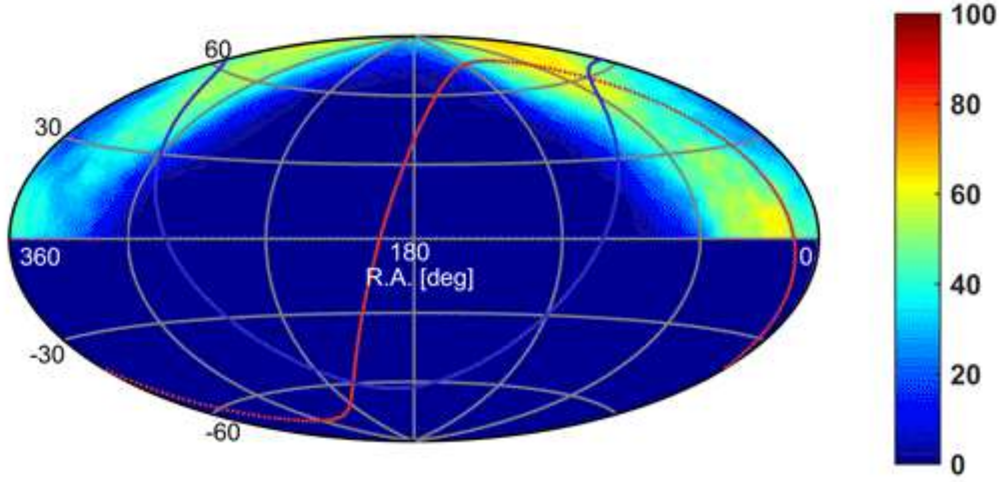
FIELD OF VIEW PROBLEM

INSIDE



OUTSIDE

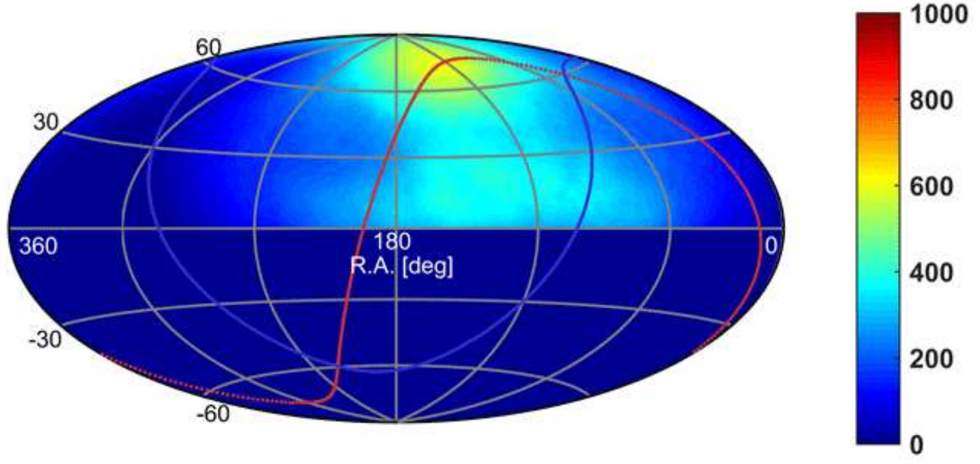


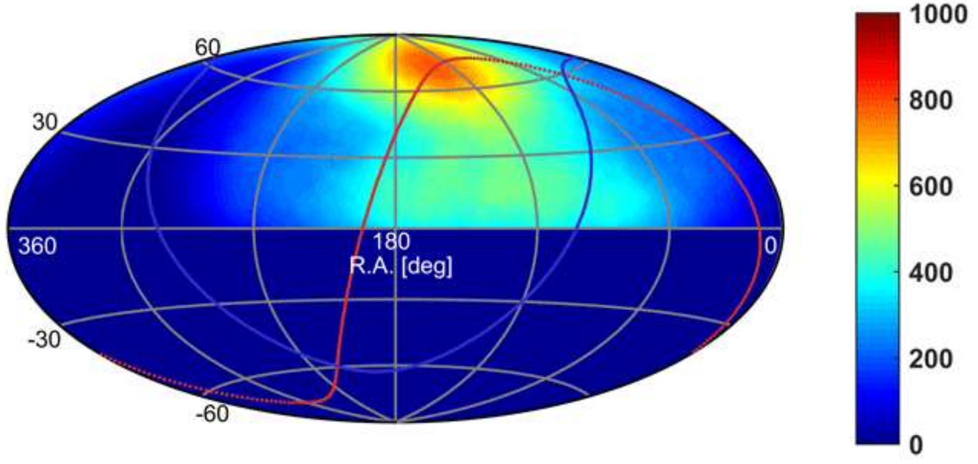


Inside hot/cold spot number of Events per hour is different than overall sky due to TA decl. = 40

Per hour per month
24*12 = 288 frames

FIELD OF VIEW PROBLEM





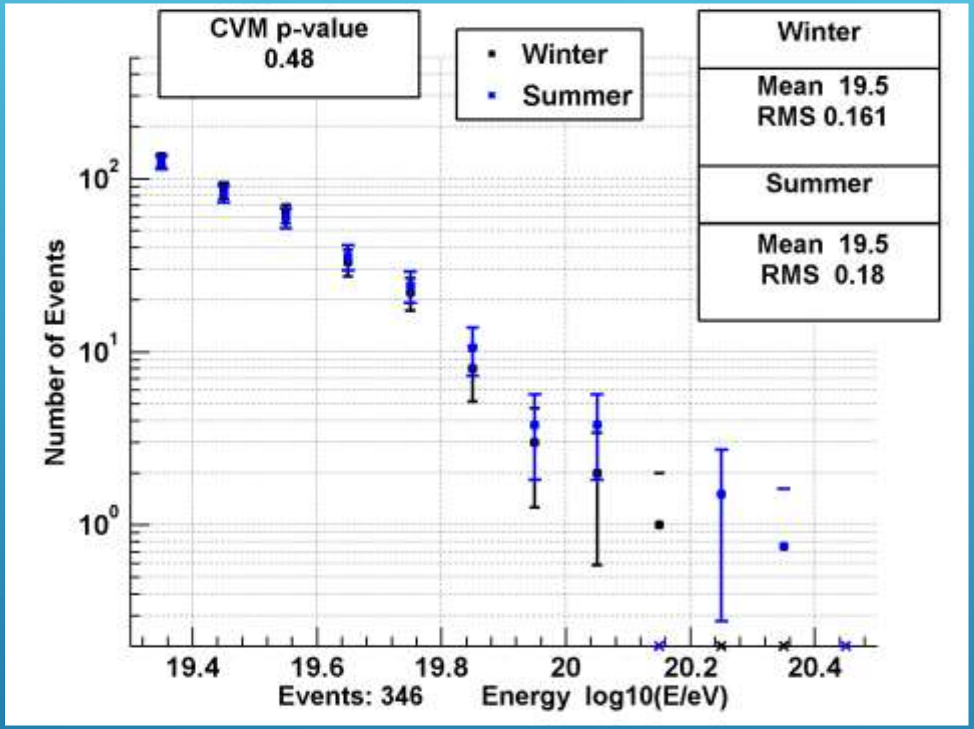
Night – January to December

Uneven in RA

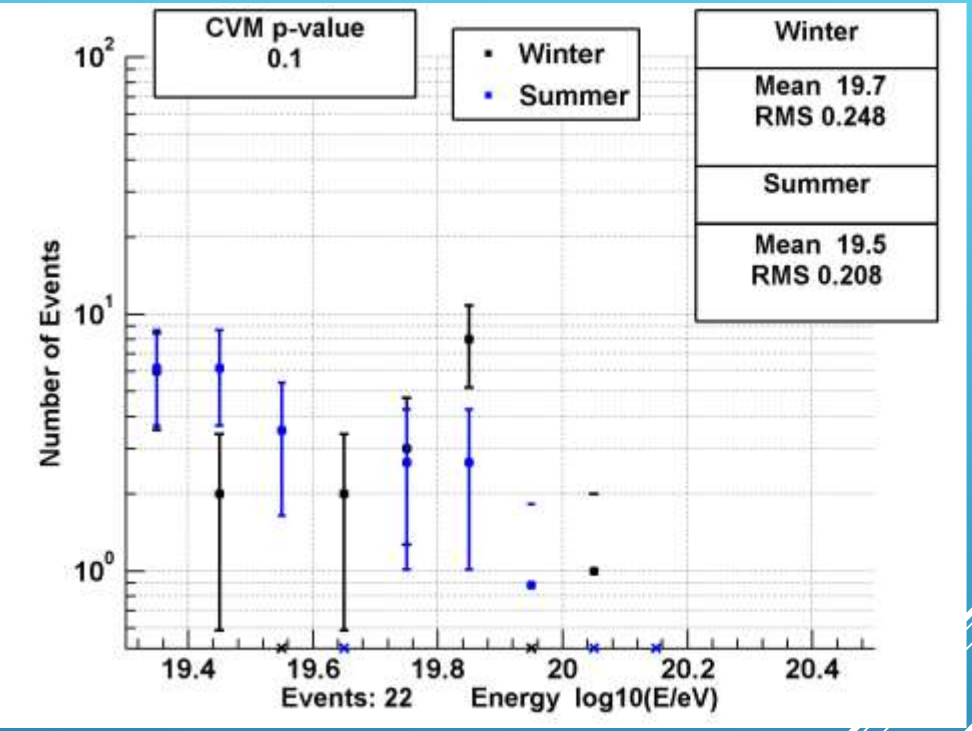
Day – July to June (6 months offset)

Uneven in Declination

SUMMER/WINTER ENERGY DISTRIBUTION COMPARISON



Outside hot/cold spot



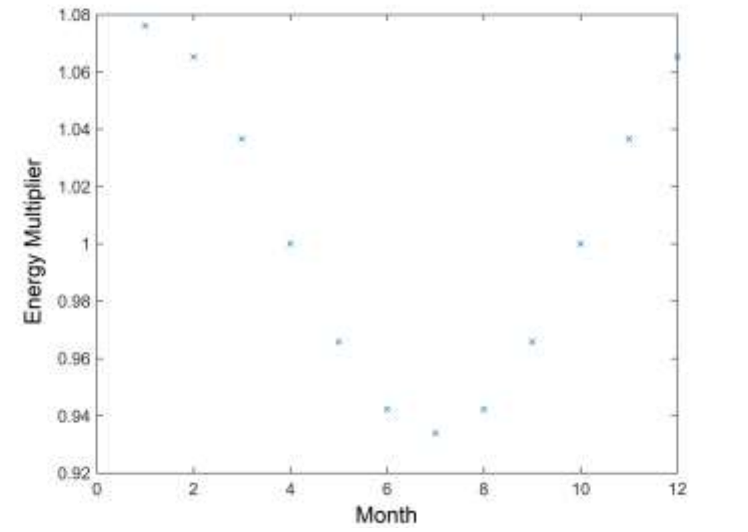
Inside hot/cold spot

Energy distributions agree within statistics

SEASONAL ENERGY CORRECTION

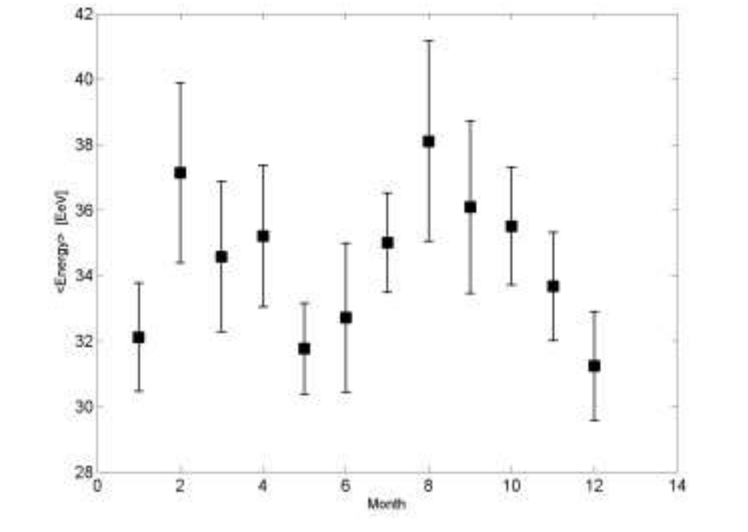
- Energy correction found from reconstructed MC using Elko radiosonde data (D.Ivanov)
- Lateral dist. change from atmos. temperature changes

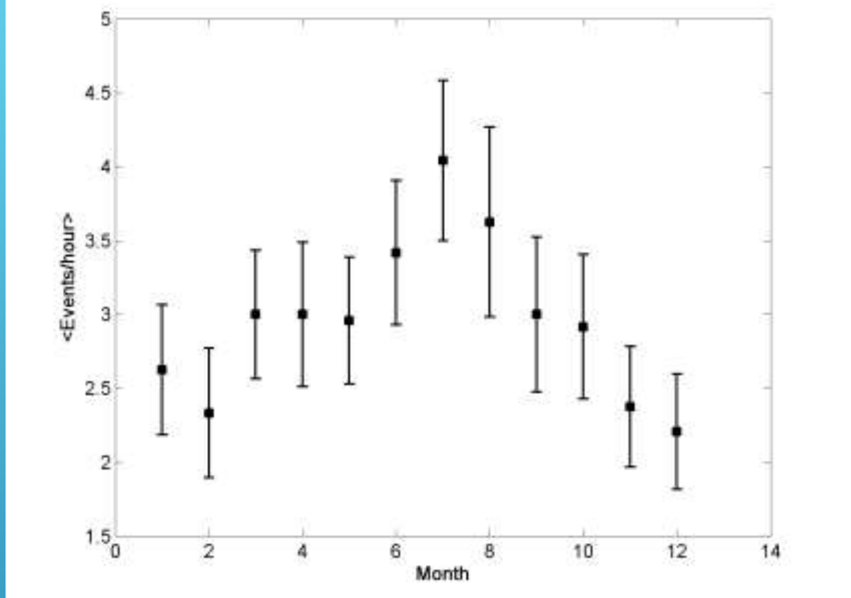
Correction +/- 7%



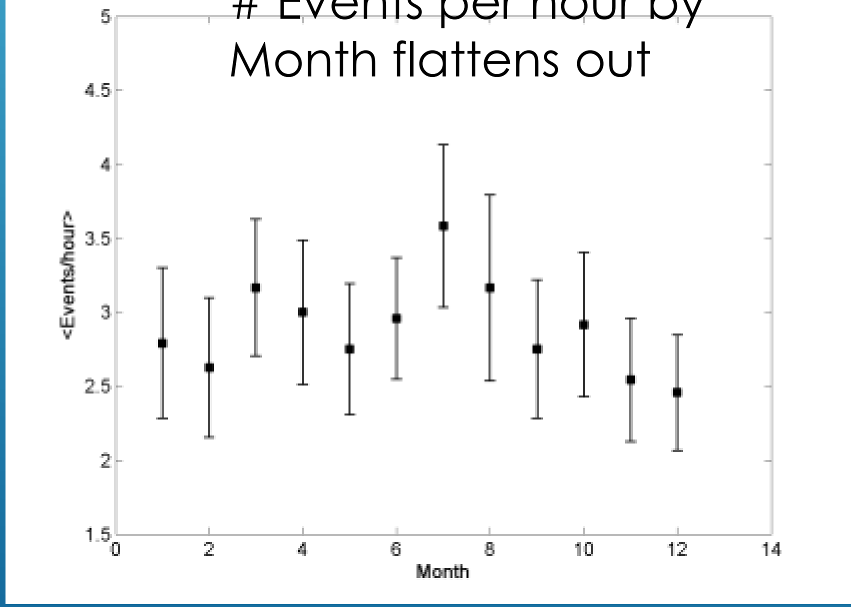
Affects 20 EeV cut and 57 EeV energy split

Energy Vs Month

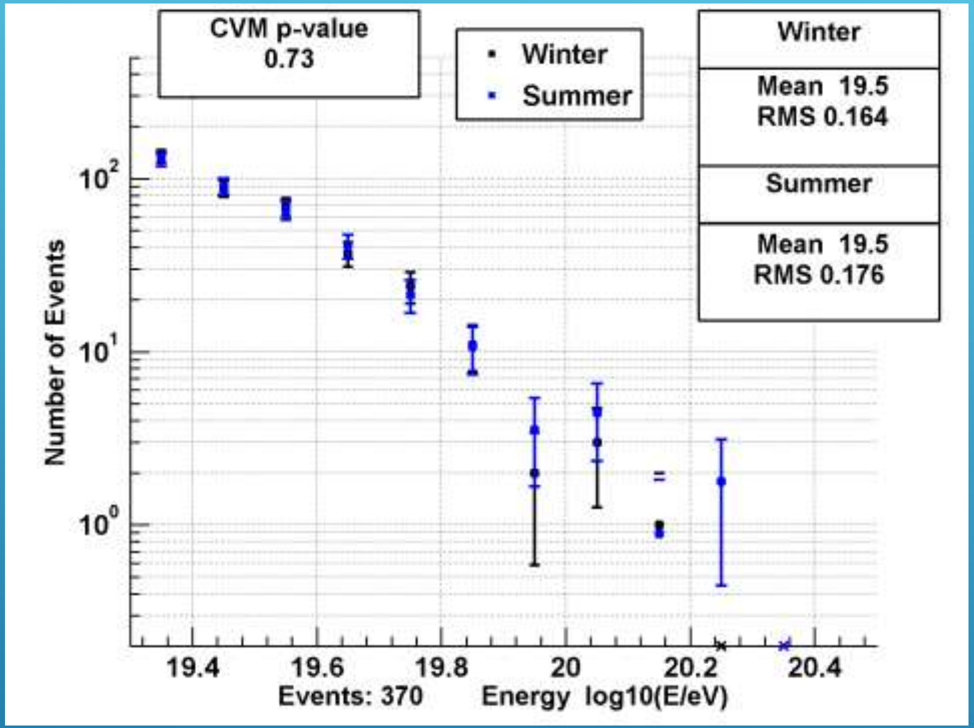


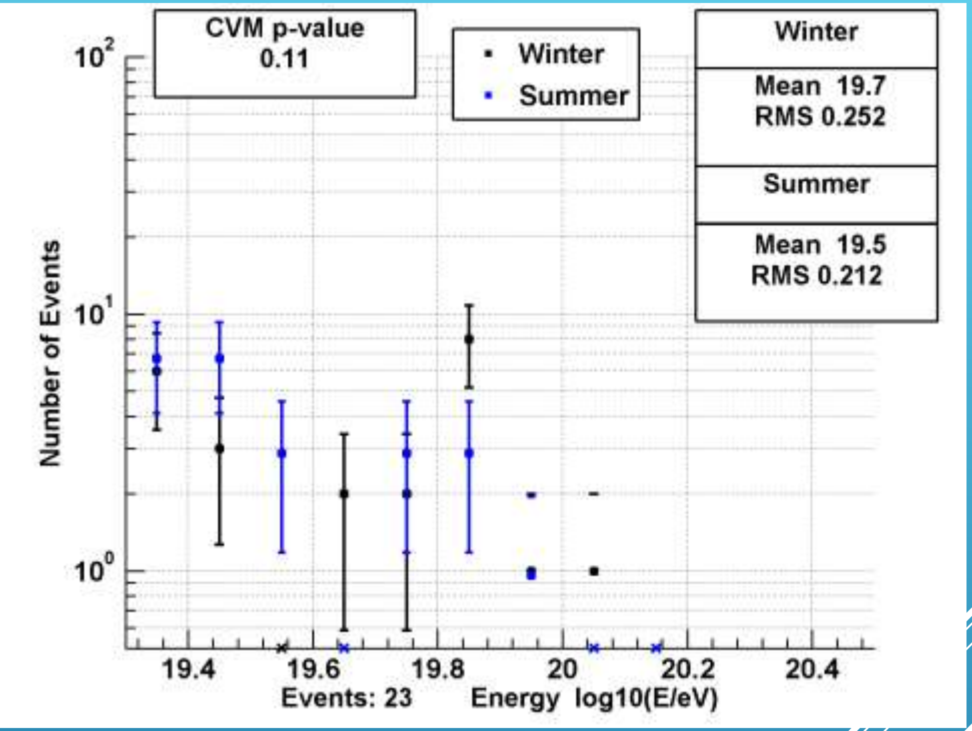


Events per hour by Month flattens out



SUMMER/WINTER ENERGY AFTER CORRECTION





Outside hot/cold spot

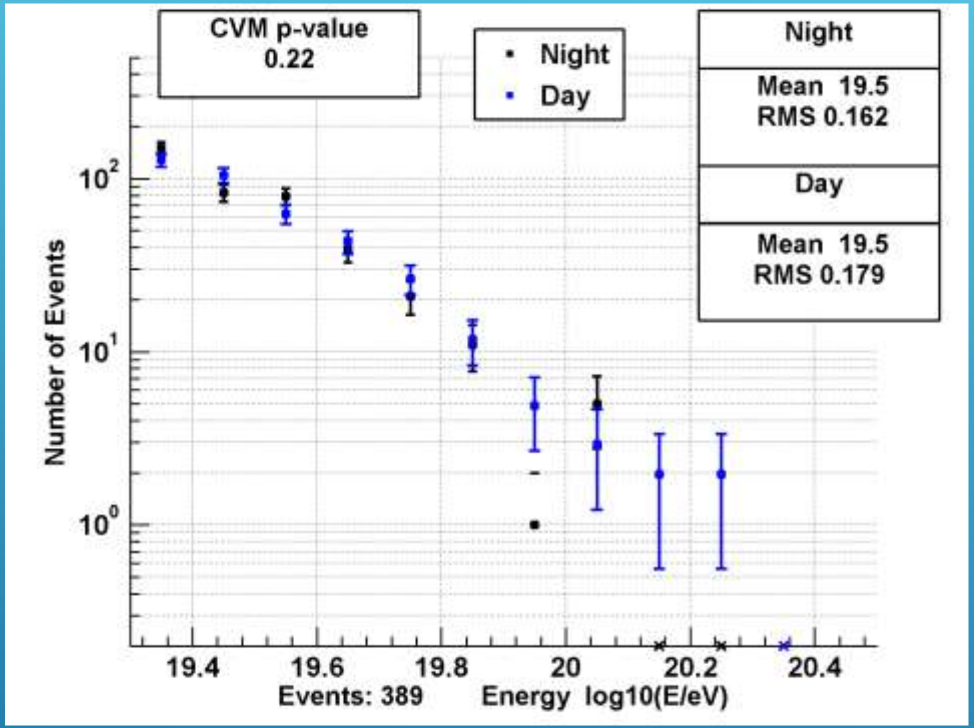
Agreement improved

Inside hot/cold spot

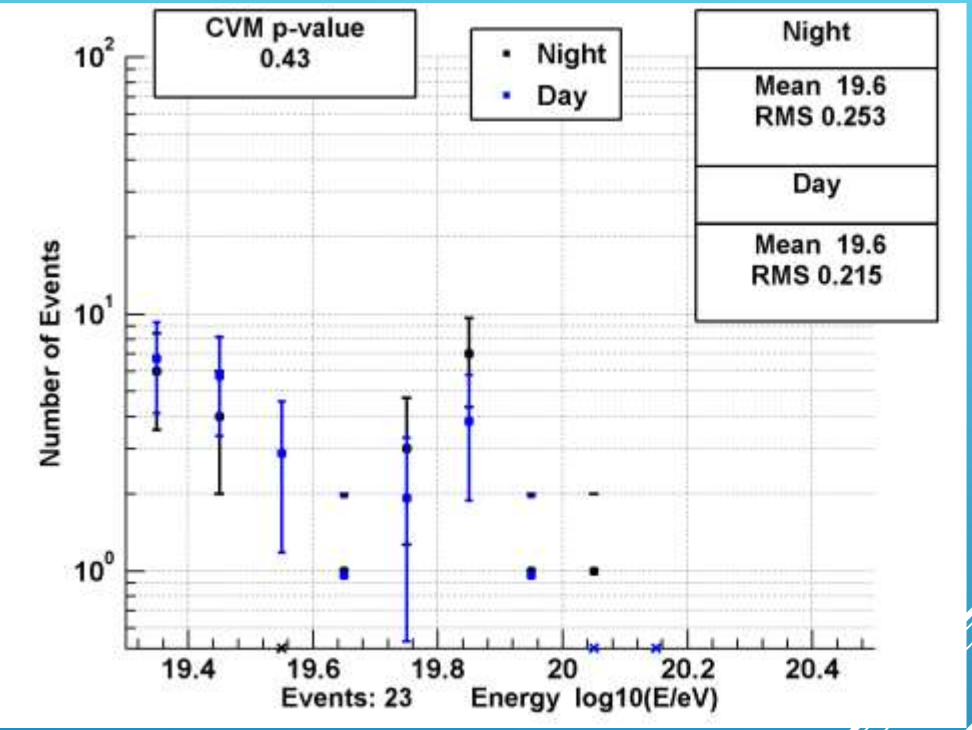
Agreement improved

Energy distributions agree within statistics

DAY/NIGHT ENERGY AFTER CORRECTION



Outside hot/cold spot



Inside hot/cold spot

Agreement improved

Energy distributions agree within statistics

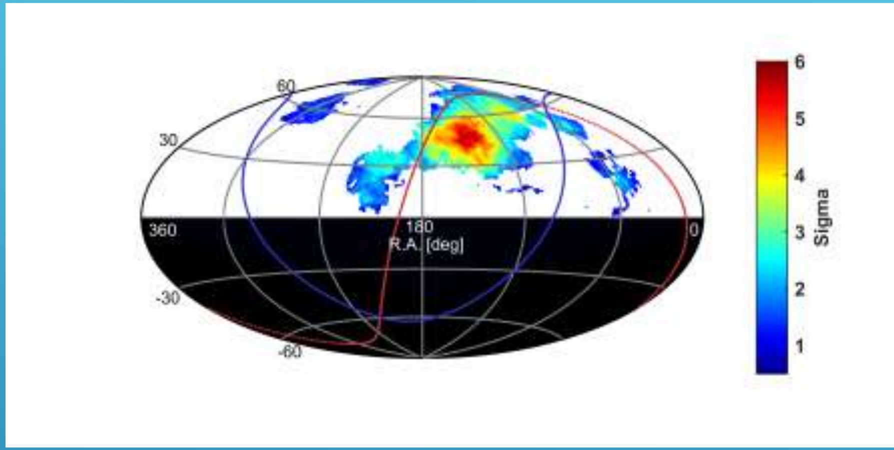
SEASONAL ENERGY CORRECTION

852 events

Original σ Combined

Max: 5.92

At max:
R.A. = 139
decl. = 48
Cold = -3.25
Hot = 4.54

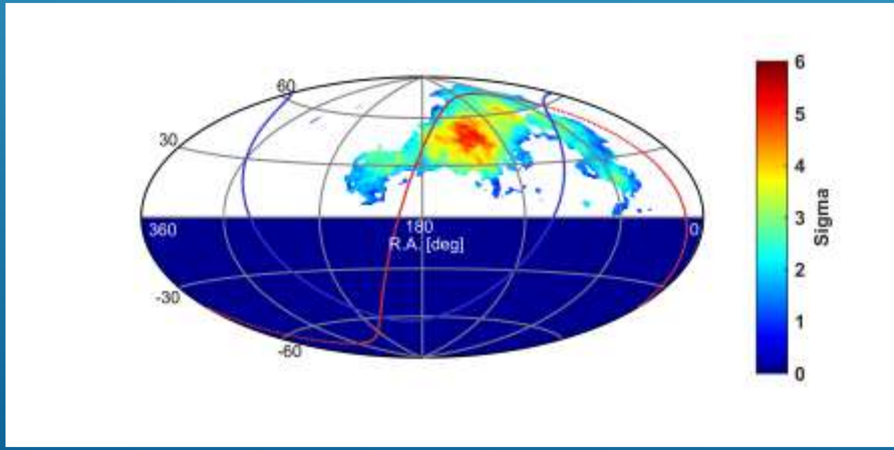


833 events

Seasonal Energy Corrected σ Combined

Max: 5.36

At max:
R.A. = 137
decl. = 48
Cold = -2.80
Hot = 4.16



5000 random samples of 833 events:
Combined Median: 5.90 - 0.14 + 0.12

Corrected Combined
is 3.86 error bars from median.

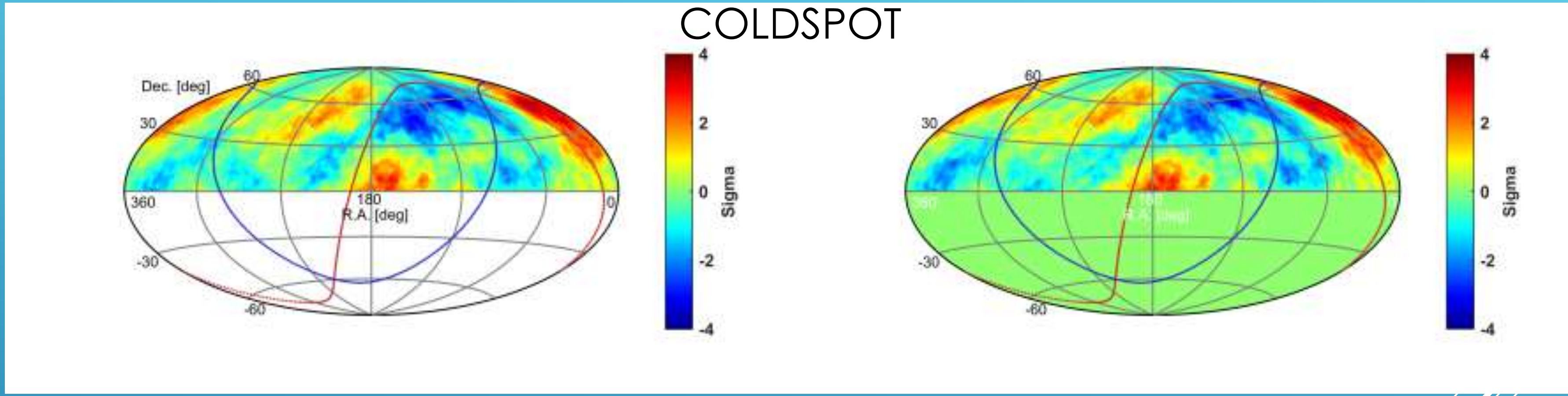
SEASONAL ENERGY CORRECTION

852 events

Original σ E < 57 EeV

833 events

Seasonal Corrected σ E < 57 EeV

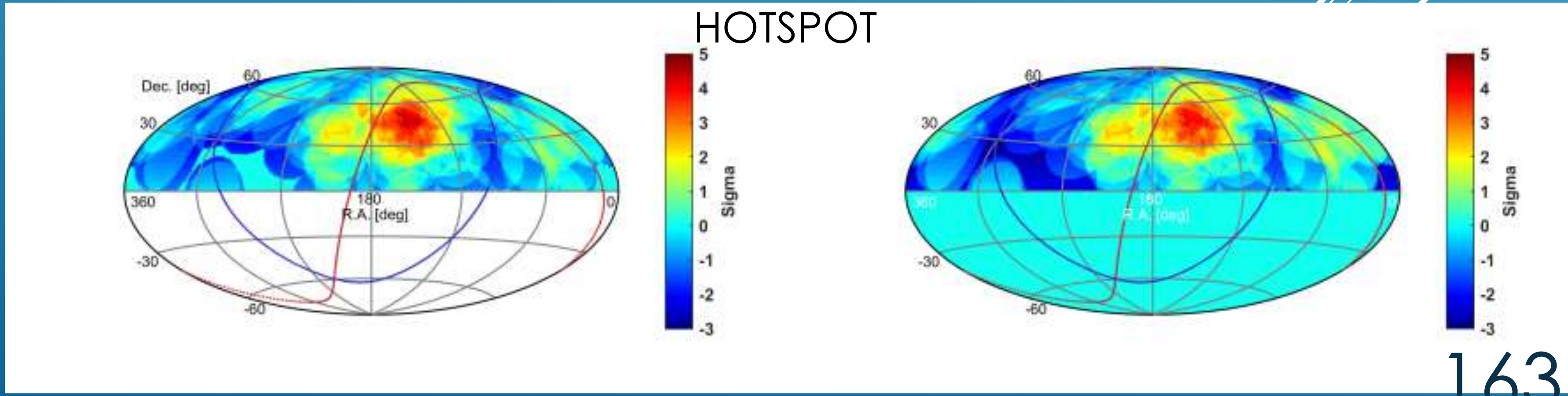


Original σ E > 57 EeV

Max: 4.61

Seasonal Corrected σ E > 57 EeV

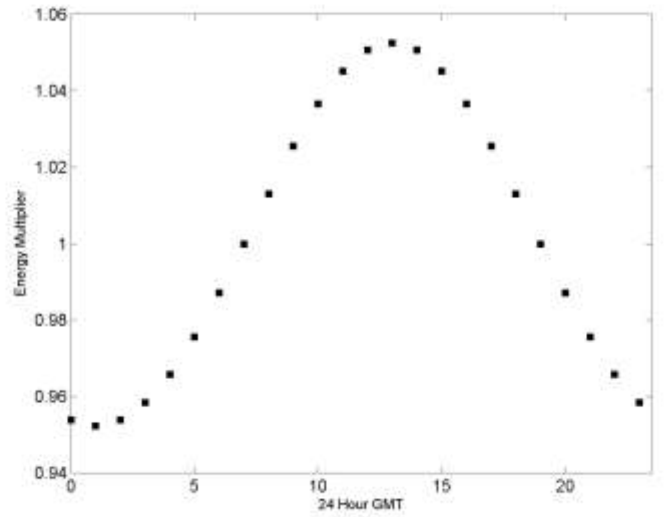
Max: 4.22



HOURLY ENERGY CORRECTION

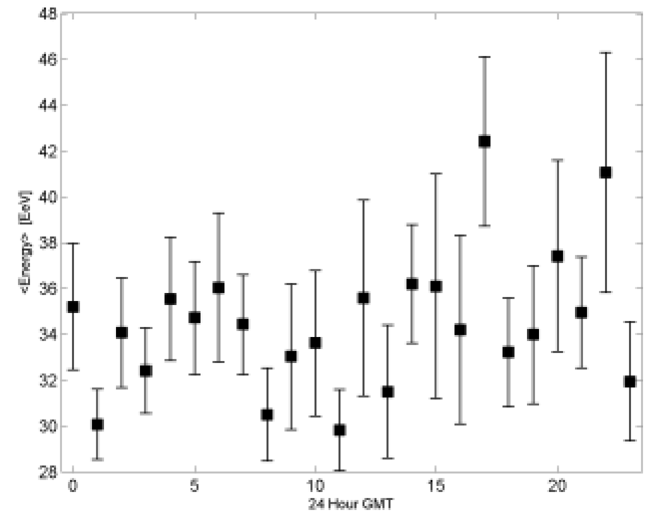
- Energy correction found from hourly events rates (D.Ivanov)
- Lateral dist. change from atmos. temperature changes

Correction +/- 5%
after seasonal correction

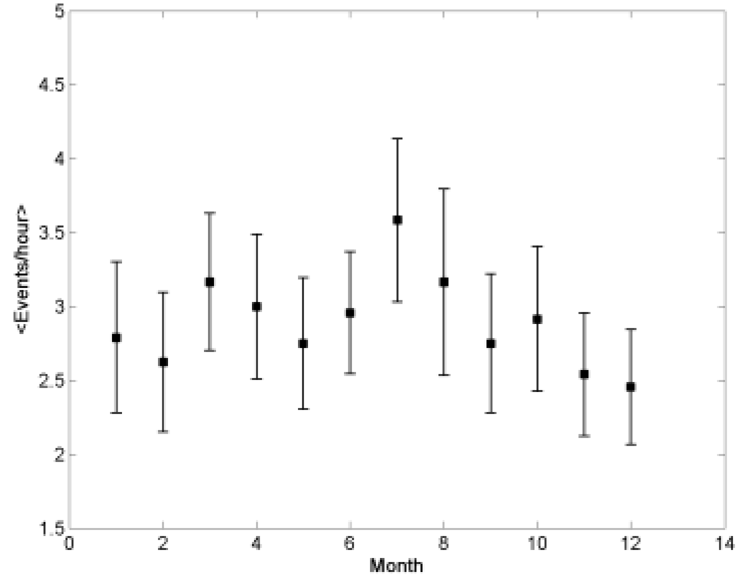


Affects 20 EeV cut and 57 EeV energy split

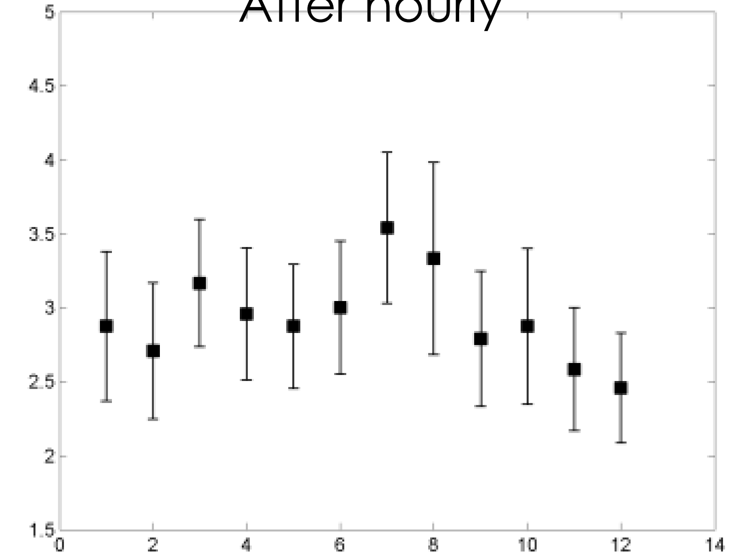
Energy Vs Hour



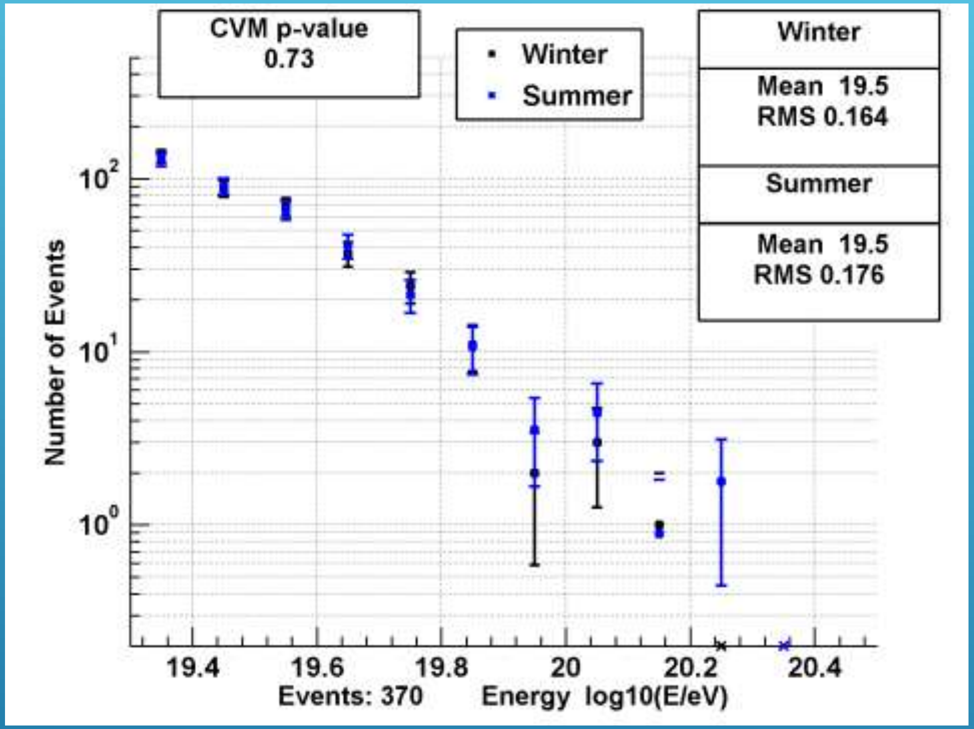
After seasonal

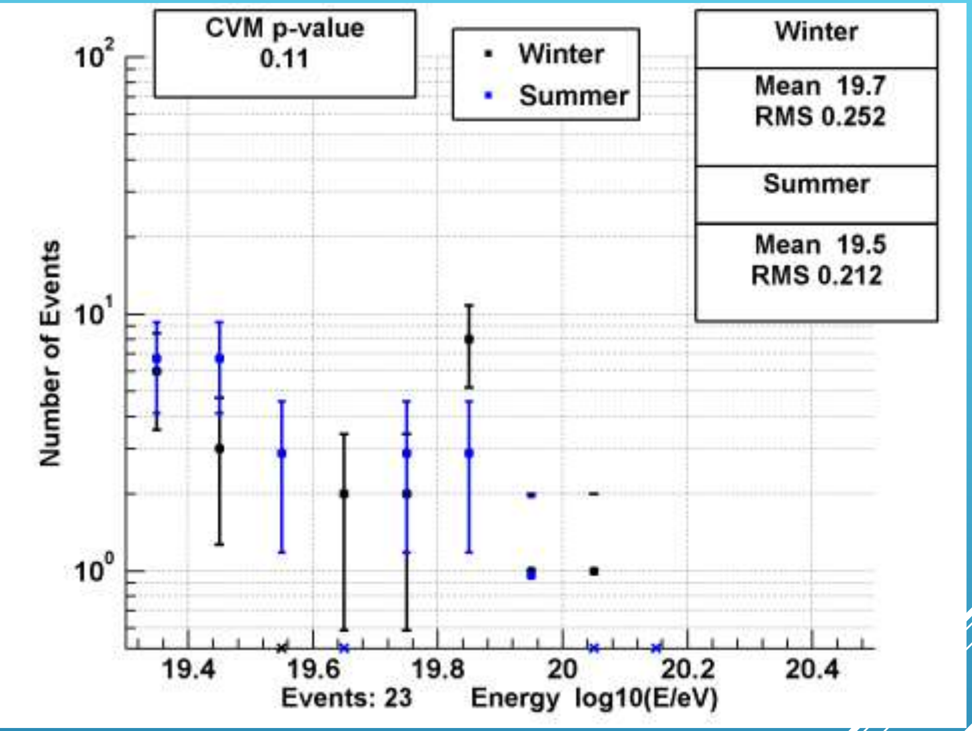


After hourly



SUMMER/WINTER ENERGY AFTER HOURLY CORRECTION





Outside hot/cold spot

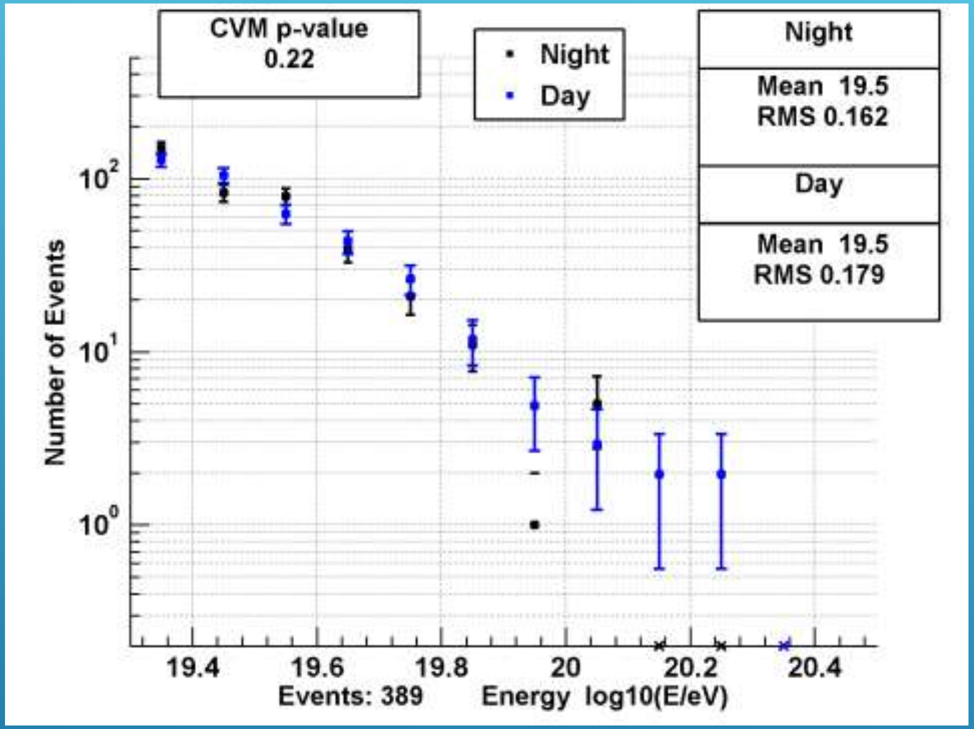
Agreement improved

Inside hot/cold spot

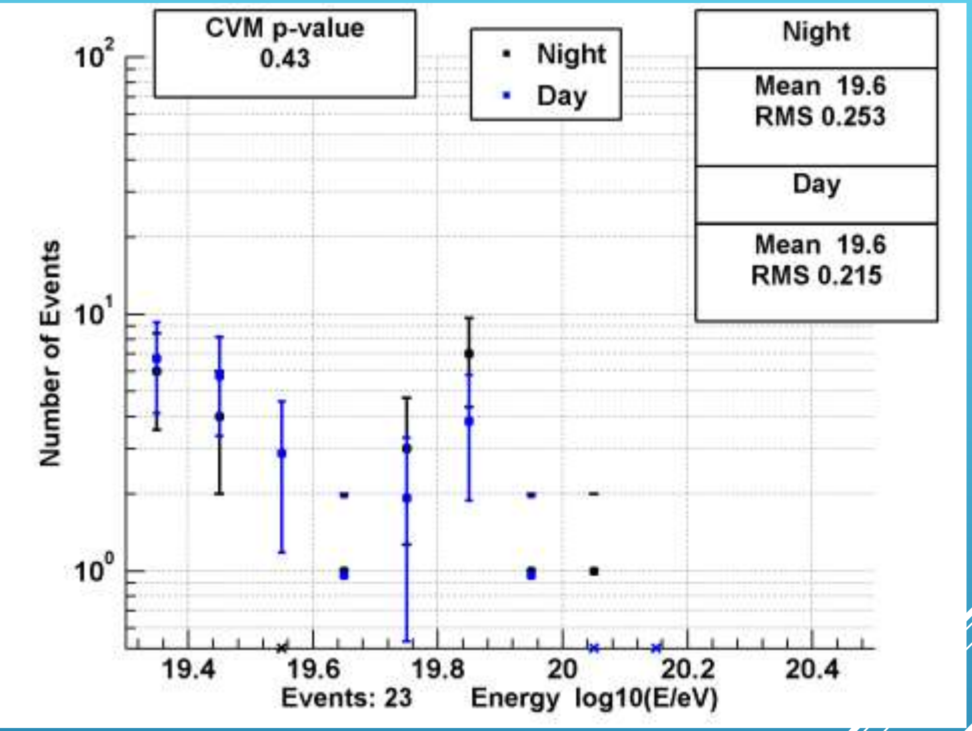
Agreement improved

Energy distributions agree within statistics

DAY/NIGHT ENERGY AFTER HOURLY CORRECTION



Outside hot/cold spot



Inside hot/cold spot

Agreement improved

Energy distributions agree within statistics

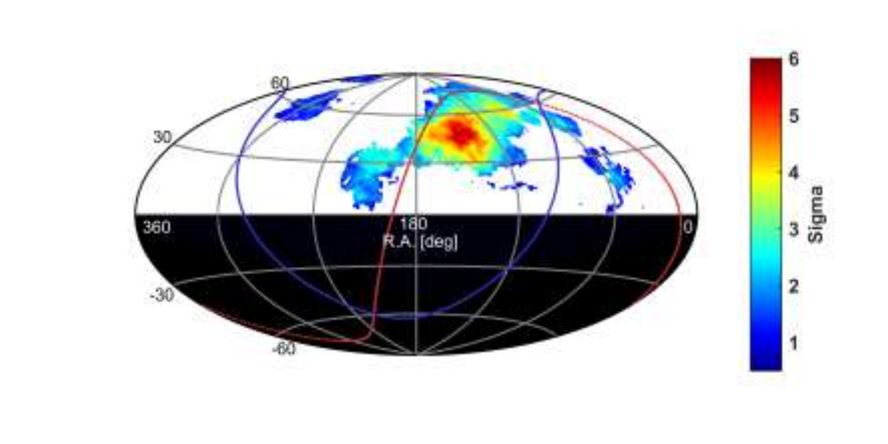
HOURLY ENERGY CORRECTION

852 events

Original σ Combined

Max: 5.92

At max:
R.A. = 139
decl. = 48
Cold = -3.25
Hot = 4.54

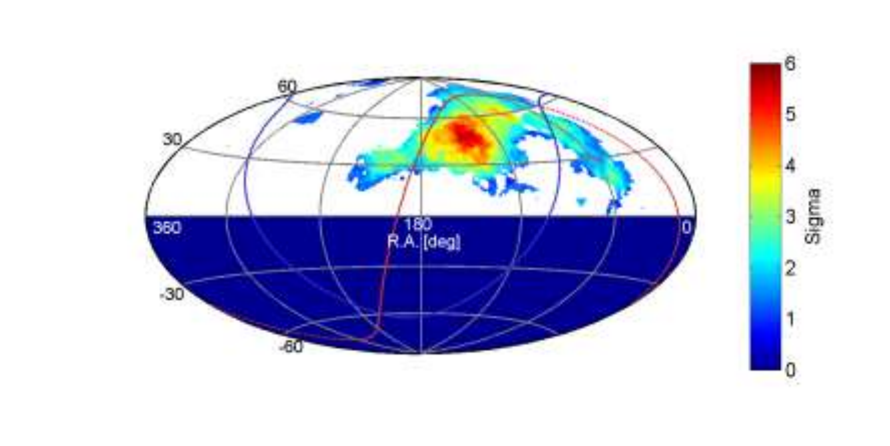


844 events

Hourly Energy Corrected σ Combined

Max: 5.86

At max:
R.A. = 139
decl. = 48
Cold = -3.23
Hot = 4.48



5000 random samples of 844 events:
Combined Median: 5.90 - 0.07 + 0

Corrected Combined
is 1.7 error bars from median.

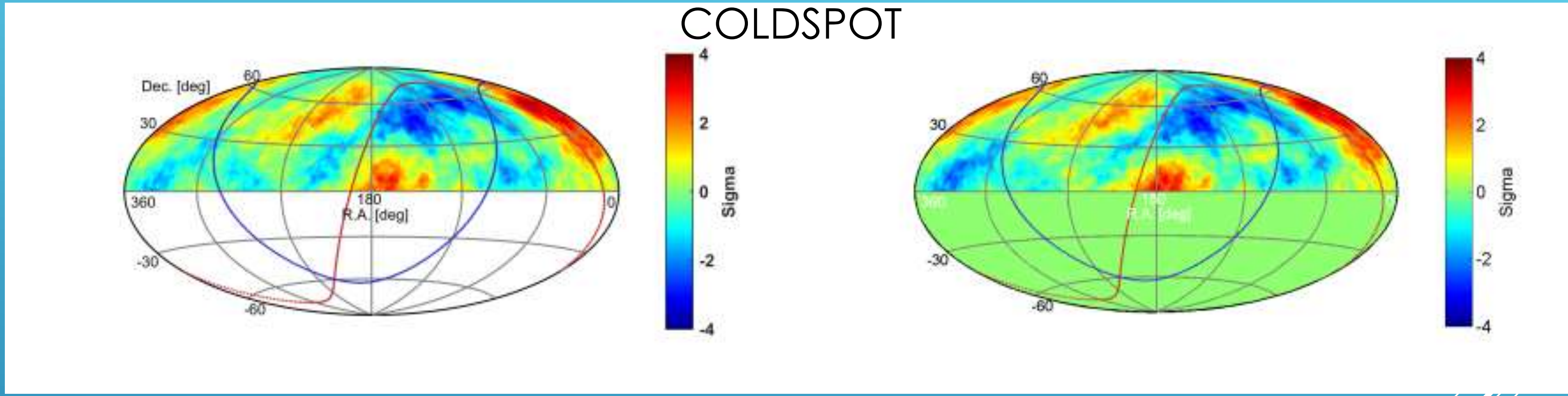
HOURLY ENERGY CORRECTION

852 events

Original σ E < 57 EeV

844 events

Hourly Corrected σ E < 57 EeV

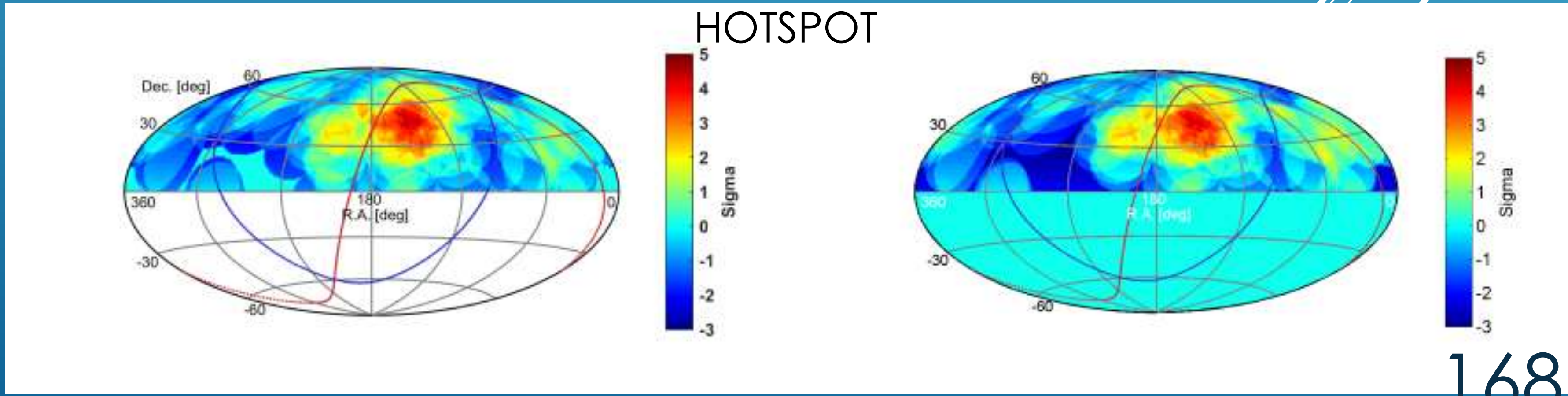


Original σ E > 57 EeV

Max: 4.61

Hourly Corrected σ E > 57 EeV

Max: 4.52



CONCLUSION

- Energy distributions between day/night and summer/winter agree within statistics.
- After MC derived energy correction energy distributions still agree.
- Hot/Coldspot is stable after energy correction. Affects both hotspot and coldspot almost equally.

APPENDIX

SPLIT CONCLUSION

No statistically significant difference from full data set is found by splitting data in half.

SUMMER-WINTER SPLIT

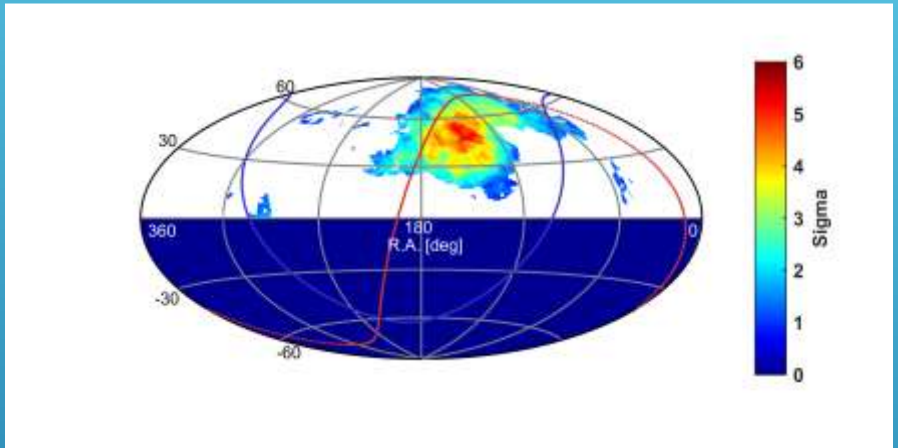
SPLIT SUMMER – WINTER

368 events

Winter σ Combined

Max: 5.52

At max:
R.A. = 139
decl. = 48
Cold = -3.90
Hot = 3.89



Rand data (same #) σ, Combined

Hot/Cold Median: 4.64 – 0.55 + 0.63

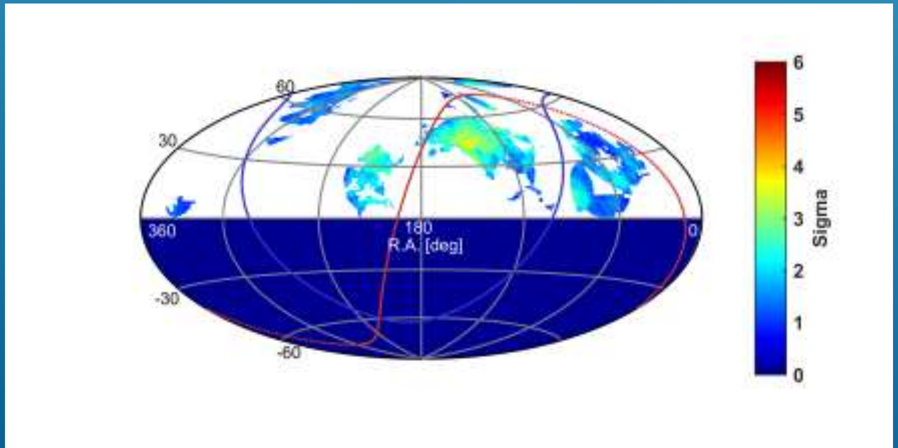
Significance higher than random sampling by 1.4 sigma.

484 events

Summer σ Combined

Max: 4.08

At max:
R.A. = 146
decl. = 42
Cold = -1.78
Hot = 3.24

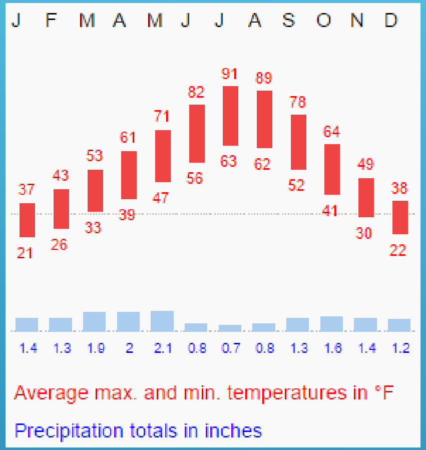


Random data (same # events) σ, Combined

Hot/Cold Median: 5.01 – 0.56 + 0.55

Significance lower than random sampling by 1.7 sigma.

SPLIT SUMMER – WINTER

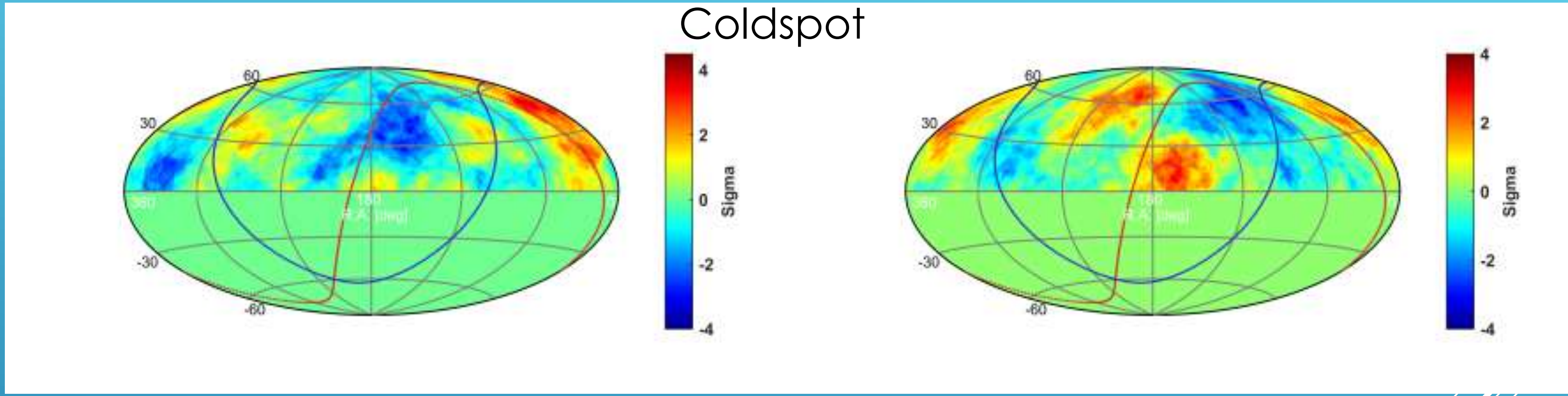


368 events

Winter σ E < 57 EeV

494 events

Summer σ E < 57 EeV

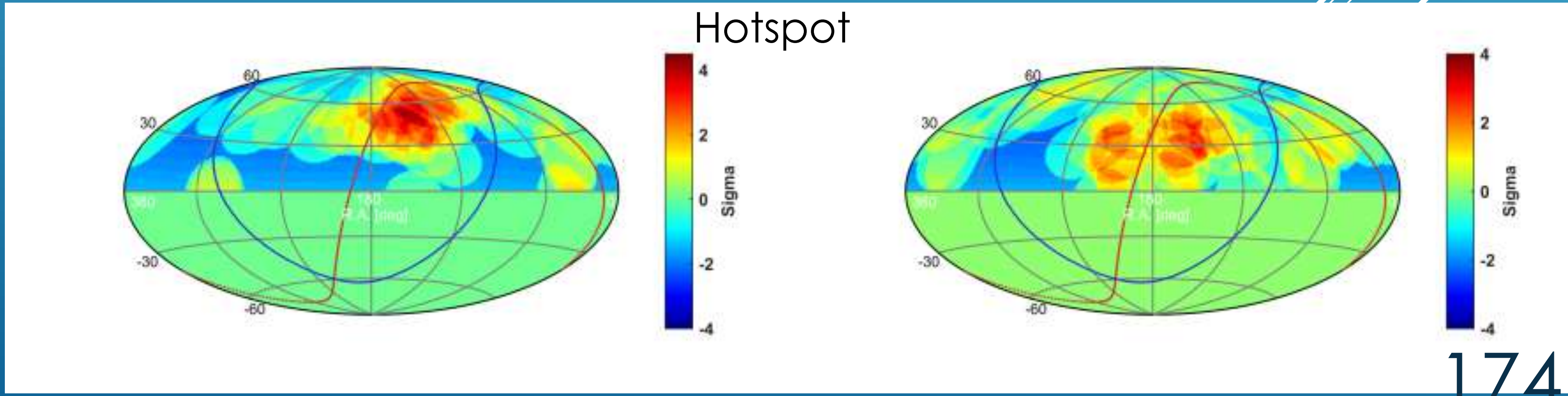


Winter σ E > 57 EeV

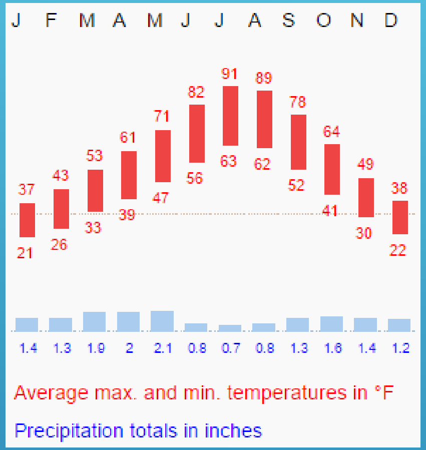
Max. Hot: 4.43

Summer σ E > 57 EeV

Max. Hot: 3.24



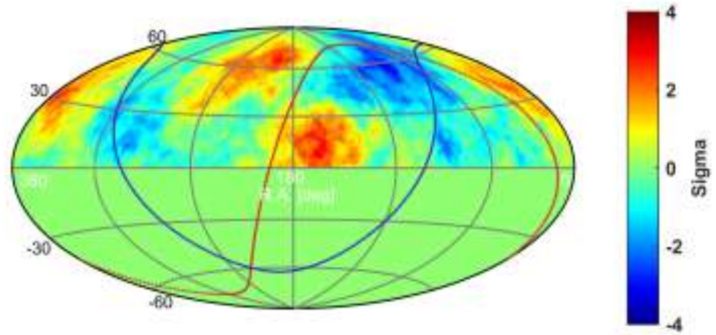
HOT/COLD SOURCE SIGNIFICANCE – SUMMER ONLY



437 events

σ E < 57 EeV

Min Cold: -3.46

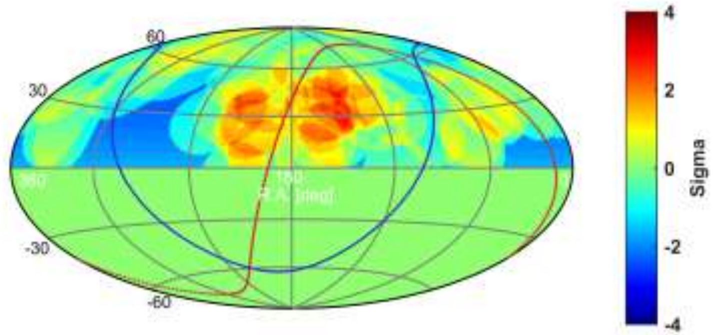


Coldspot

47 events

σ E > 57 EeV

Max Hot: 3.24



Hotspot

- Summer – April, 15th to October, 15th.

At Hot/Cold Spot: -1.99

At Hot/Cold Spot: 1.95

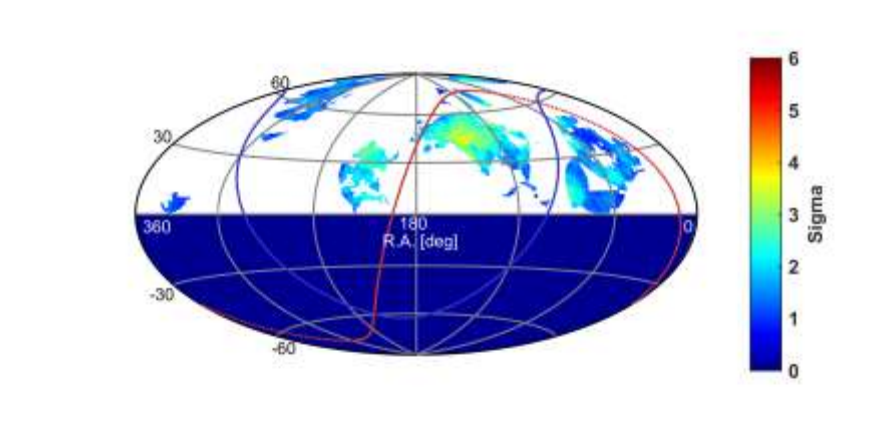
5000 random selections of 494 events

HOT/COLD SOURCE SIGNIFICANCE – SUMMER ONLY

494 events

Summer σ Combined

Max Hot/Cold: 4.08



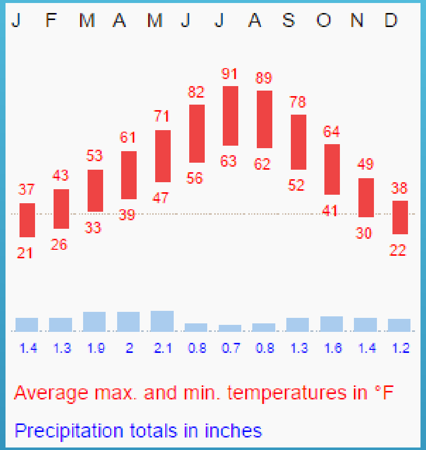
- Summer – April, 15th to October, 15th.

Random data (same # events) σ, Combined

Hot/Cold Median: 5.01 – 0.56 + 0.55

Significance lower than random sampling by 1.7 sigma.
Change not significantly different from random sampling

HOT/COLD SOURCE SIGNIFICANCE – WINTER ONLY



331 events

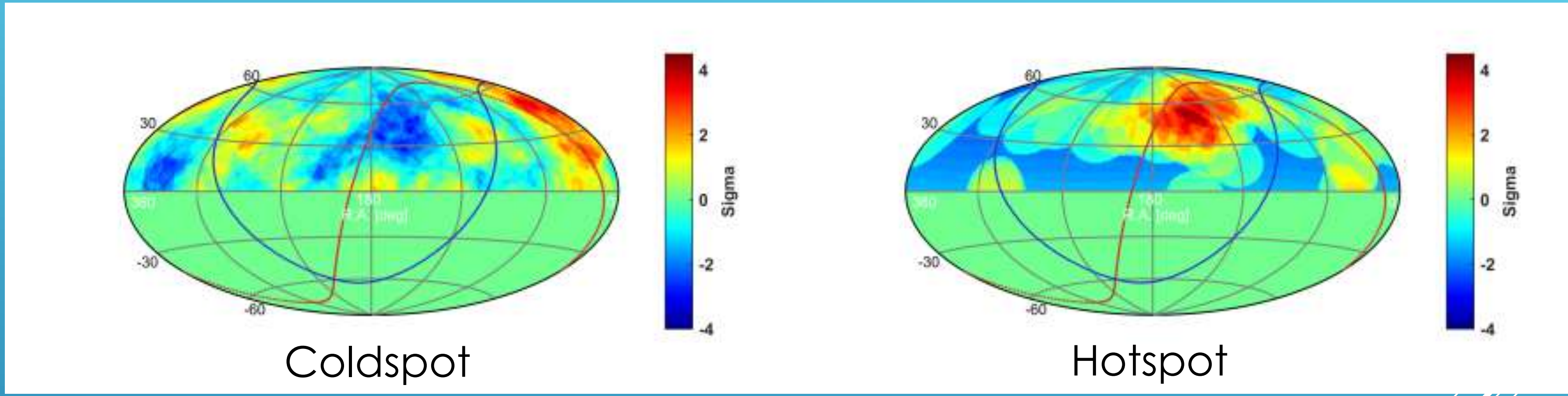
σ E < 57 EeV

Min Cold: -3.3

37 events

σ E > 57 EeV

Max. Hot: 4.43



- Winter – October 16th to April, 14th

At Hot/Cold Spot -2.69

At Hot/Cold Spot 4.42

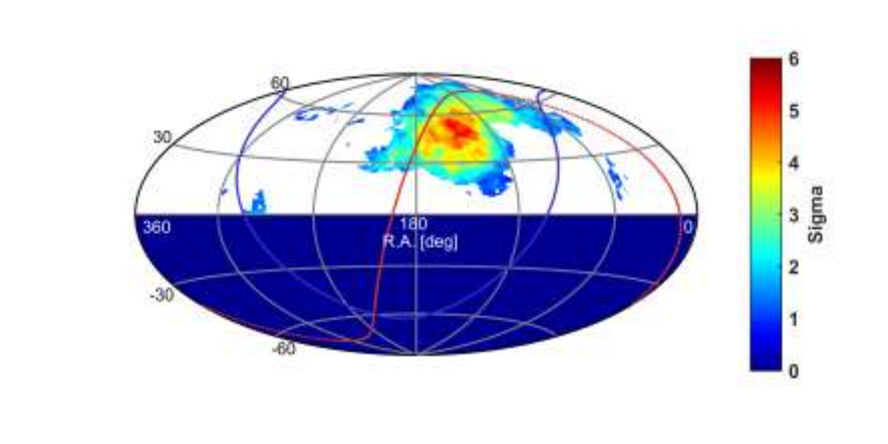
5000 random selections of 368 events

HOT/COLD SOURCE SIGNIFICANCE – WINTER ONLY

368 events

Winter σ Combined

Max Hot/Cold: 5.52



- Winter – October 16th to April, 14th

Rand data (same #) σ, Combined

Max: 4.64 – 0.55 + 0.63

Significance higher than random sampling by 1.4 sigma.
Change not significantly different from random sampling

DAY-NIGHT SPLIT

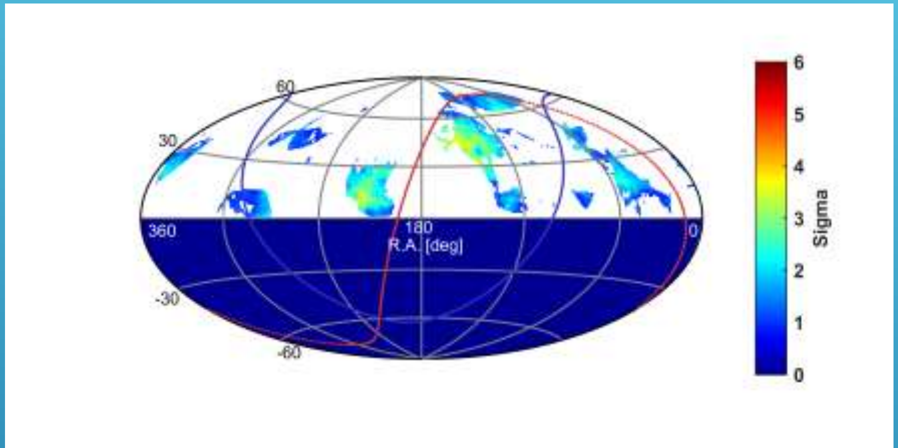
SPLIT DAY – NIGHT

432 events

Day σ Combined

Max: 3.95

At max:
R.A. = 146
dec. = 42
Cold = -1.42
Hot = 3.29



Rand data (same #) σ, Combined

Hot/Cold Median: 4.87 - 0.57 + 0.58

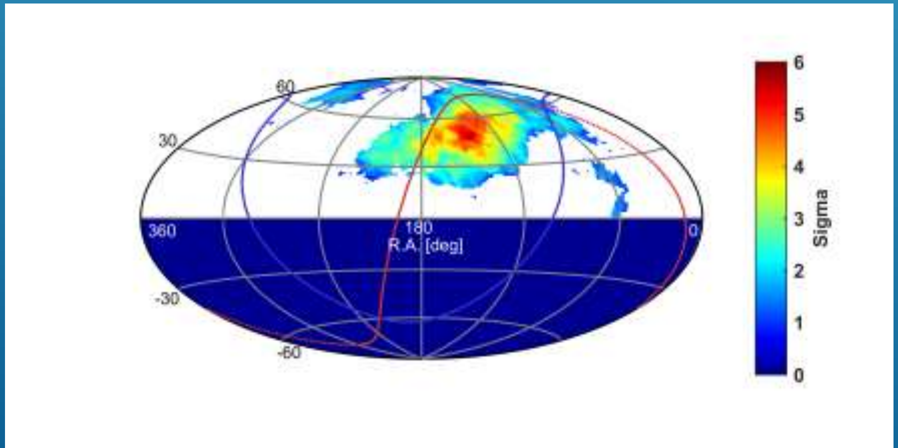
Significance lower than random sampling by 1.6 sigma.

420 events

Night σ Combined

Max: 5.82

At max:
R.A. = 139
dec. = 48
Cold = -3.30
Hot = 4.37



Rand data (same #) σ, Combined

Hot/Cold Median: 4.82 – 0.56 + 0.60

Significance higher than random sampling by 1.7 sigma.

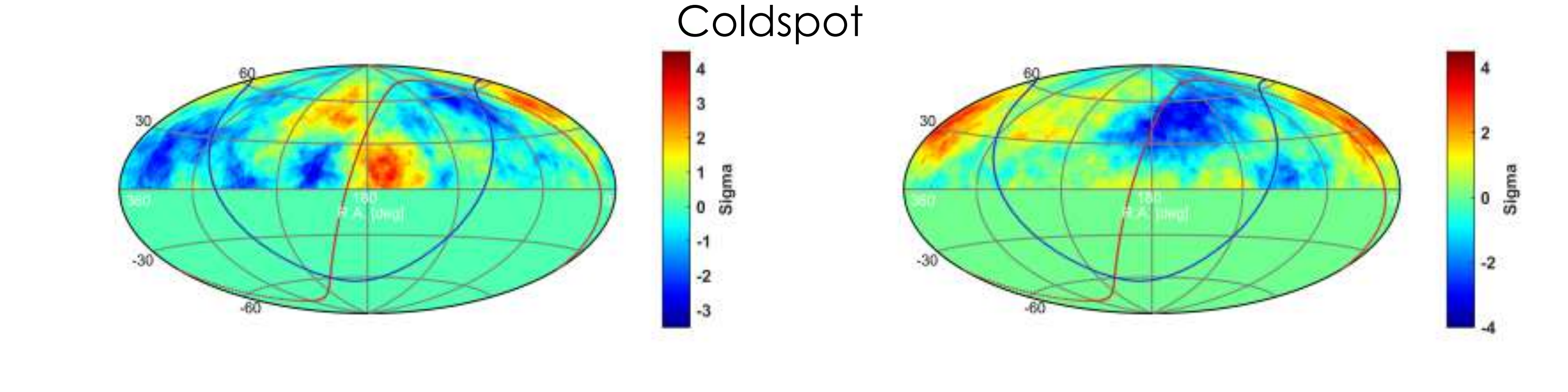
SPLIT DAY – NIGHT

432 events

Day σ E < 57 EeV

420 events

Night σ E < 57 EeV

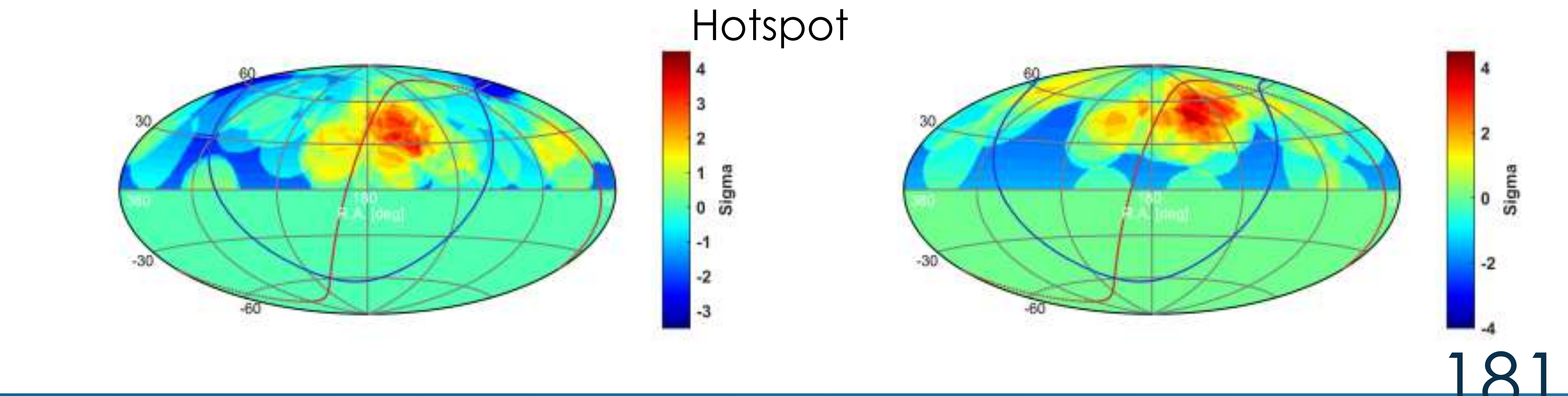


Day σ E > 57 EeV

Max: 3.63

Night σ E > 57 EeV

Max: 4.37



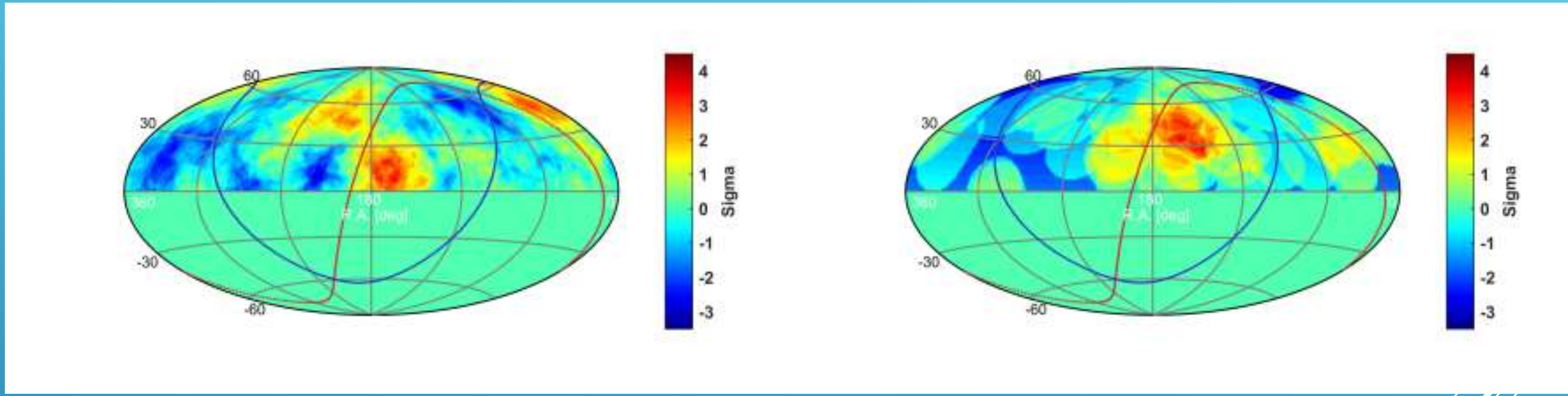
HOT/COLD SOURCE SIGNIFICANCE – DAY ONLY

386 events

Day σ E < 57 EeV

46 events

Day σ E > 57 EeV



- Day – 9am to 9pm
  - 15 to 3 GMT

Coldspot

At Hot/Cold Spot: -1.39

Hotspot

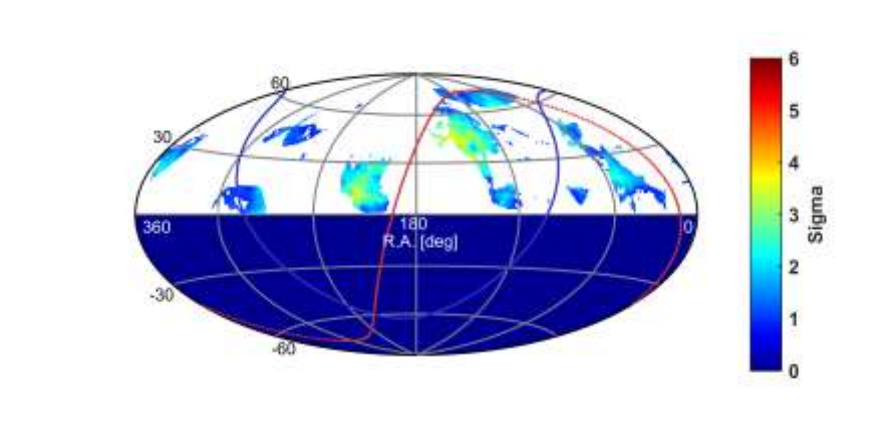
At Hot/Cold Spot: 2.00

HOT/COLD SOURCE SIGNIFICANCE – DAY ONLY

432 events

Day σ Combined

Max: 3.95



- Day – 9am to 9pm

Rand data (same #) σ, Combined

Max: 4.87 - 0.57 + 0.58

Significance lower than random sampling by 1.6 sigma.
Change not significantly different from random sampling

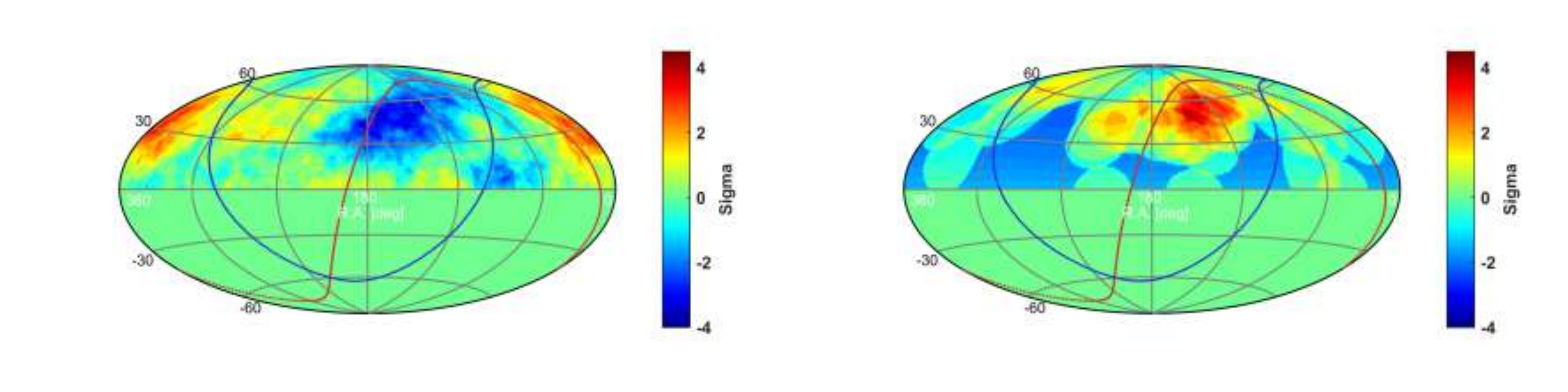
HOT/COLD SOURCE SIGNIFICANCE – NIGHT ONLY

382 events

Night σ E < 57 EeV

38 events

Night σ E > 57 EeV



Coldspot

Hotspot

- Night – 9pm to 9am

At Hot/Cold Spot: -3.30

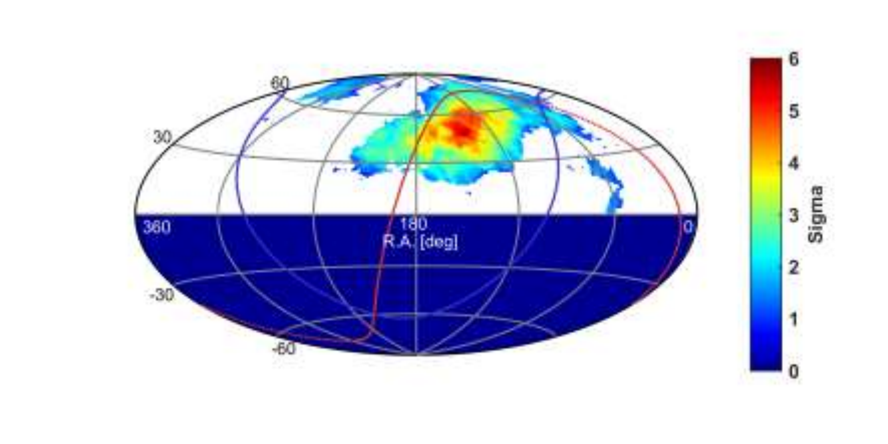
At Hot/Cold Spot: 4.37

HOT/COLD SOURCE SIGNIFICANCE – NIGHT ONLY

420 events

Night σ Combined

Max: 5.82



- Night – 9pm to 9am

Rand data (same #) σ, Combined

Max: 4.82 – 0.56 + 0.60

Significance higher than random sampling by 1.7 sigma.
Change not significantly different from random sampling

3 COMPONENT COMPOSITION – FIT XMAX AND S800

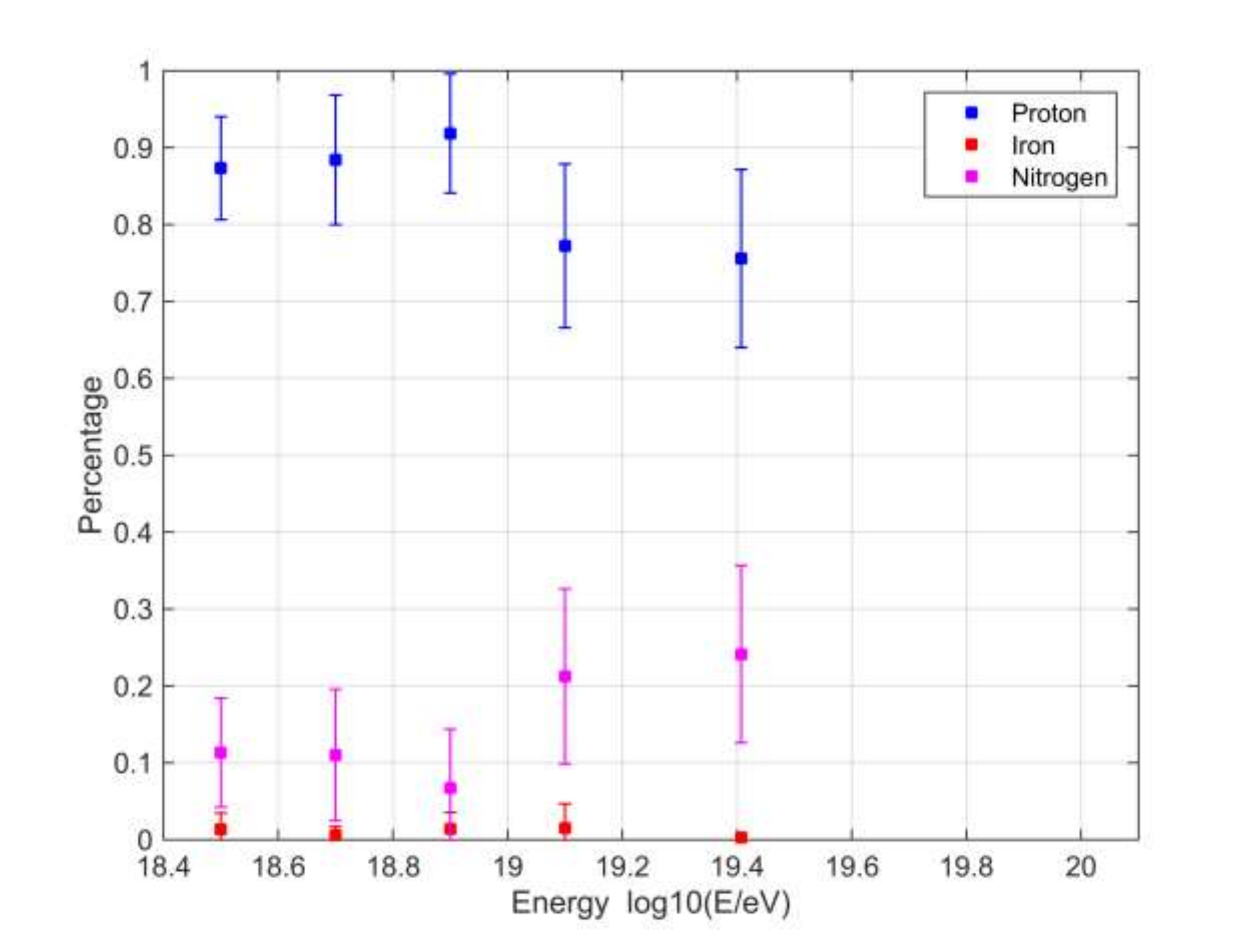
Jon Paul Lundquist

METHOD

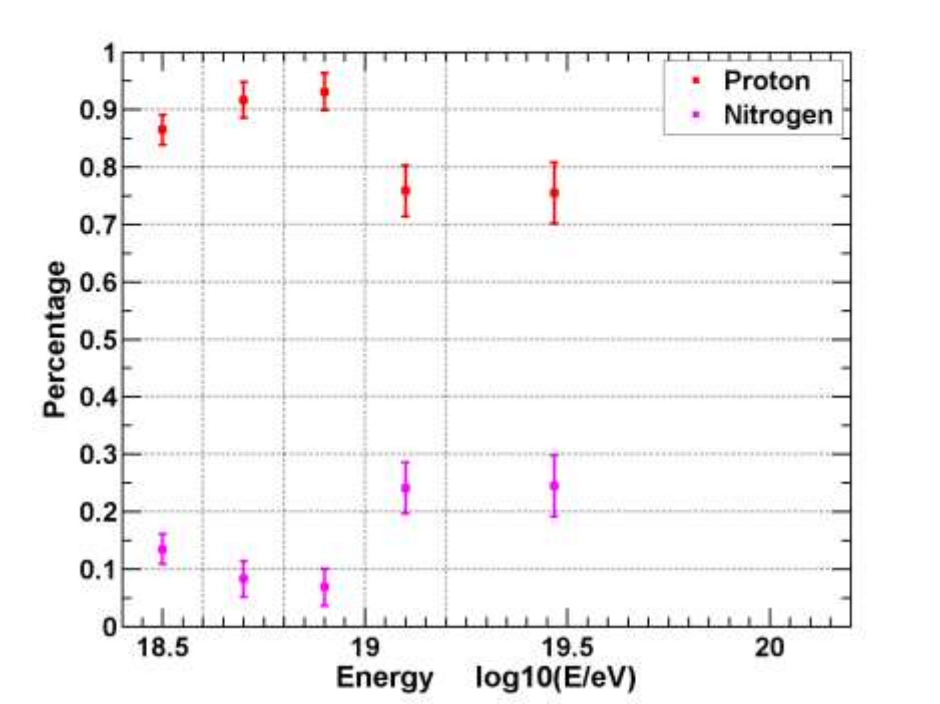
- Use Proton, Iron, and Nitrogen primaries.
- Find best fit to Xmax and s800 distributions simultaneously
  - Maximize combined p-Value (p1*p2) from CVM test.
- For each energy bin
  - For each ratio
    - Calculate combined p-Value for 100 different samples Ndata*5.
  - Find ratio which maximizes the mean combined p-value.
  - Iterate 100 times (using a different data sample with replacement – bootstrap) to find error on ratio which maximizes the p-value.

QGSJETII-03

RESULT



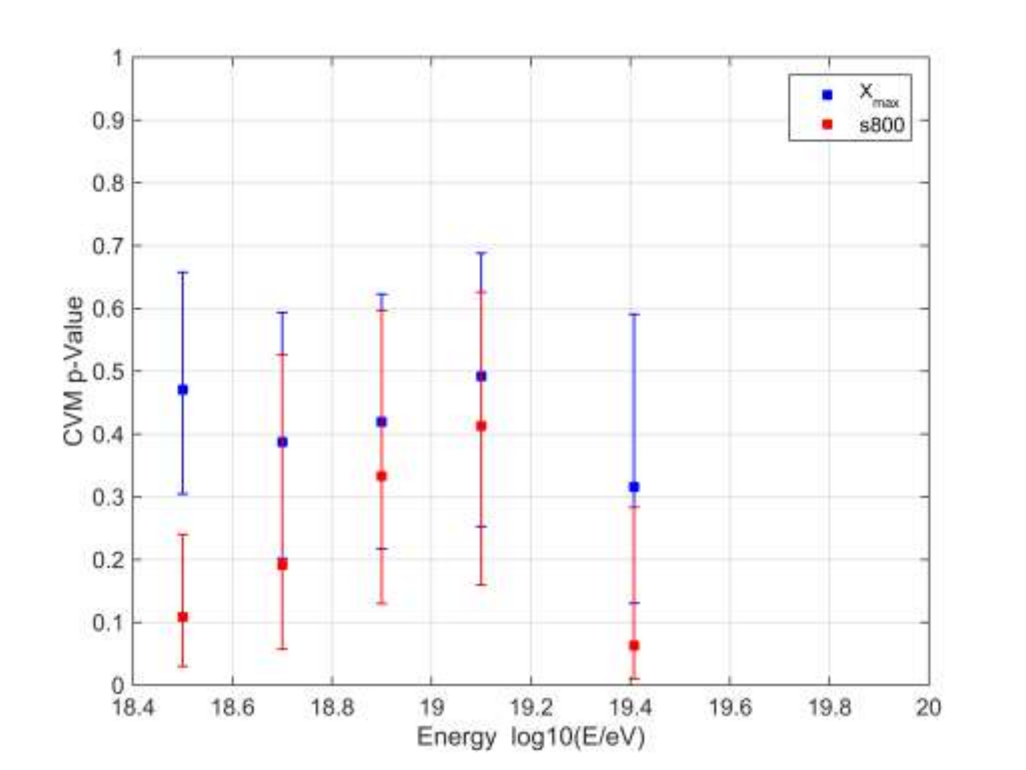
Consistent with zero iron.
Consistent with 2 component fit using only Xmax



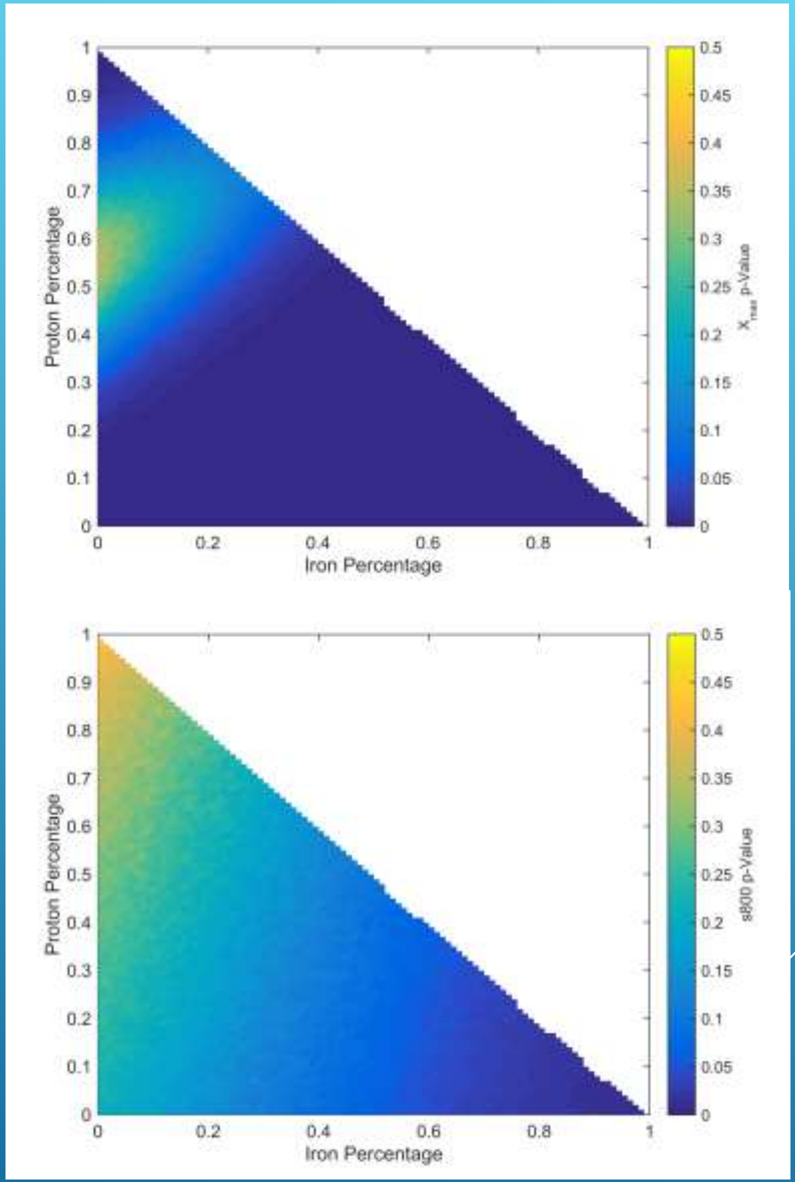
2 component

PVALUES

Log10(E/eV) > 19.2 – 1 iteration



Distribution p-Values Vs Energy



Xmax p-Values

s800 p-Values