

# SUPERGALACTIC STRUCTURE OF ENERGY-ANGLE CORRELATIONS

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TELESCOPE ARRAY



THE  
UNIVERSITY  
OF UTAH®

# REASONING

- **Hypothesis:**
  - Sources are supergalactic plane correlated.
  - Magnetic fields are correlated with sources.
- **Multiplets (energy-distance/angle correlated events) may exhibit structure indicative of sources**
- **Random fields will diffuse events perpendicular to their average direction. Multiplets should be in 'wedges' not rectangles or circles.**

# DATA SUMMARY

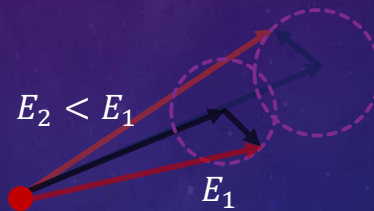
- 10 years of surface detector data 2008-2019 (UHECR 2017 result: 7 years)
  - Cuts: # SD  $\geq 4$ , Zenith  $< 55^\circ$ , Pointing Error  $< 10^\circ$ 
    - Additional (for lower energy zenith distribution):
      - Pointing error  $< 5^\circ$ , boundary distance  $> 1.2$  km, Lateral fit  $\chi^2 < 10$
  - $E \geq 10^{19.0}$  eV - 4321 events
- Simulation:
  - Data positions, energy interpolated from fully reconstructed Monte Carlo (statistics restricted to # of data at energy thresholds)
  - Testing energy direction patterns not densities

8<sup>th</sup> year of data is omitted due to tower communication issues  
creating anisotropy not easily corrected for

# CORRELATION BINNING

## Coherent field deflection

$$\delta \approx 0.5^\circ Z \frac{S}{kpc} \frac{B}{\mu G} \frac{10^{20} eV}{E}$$



## Random field deflection

$$\delta_{rms} \approx 0.1^\circ Z \frac{B_{rms}}{\mu G} \frac{10^{20} eV}{E} \sqrt{\frac{S}{kpc}} \sqrt{\frac{L_c}{100pc}}$$

## Coherent and Random fields



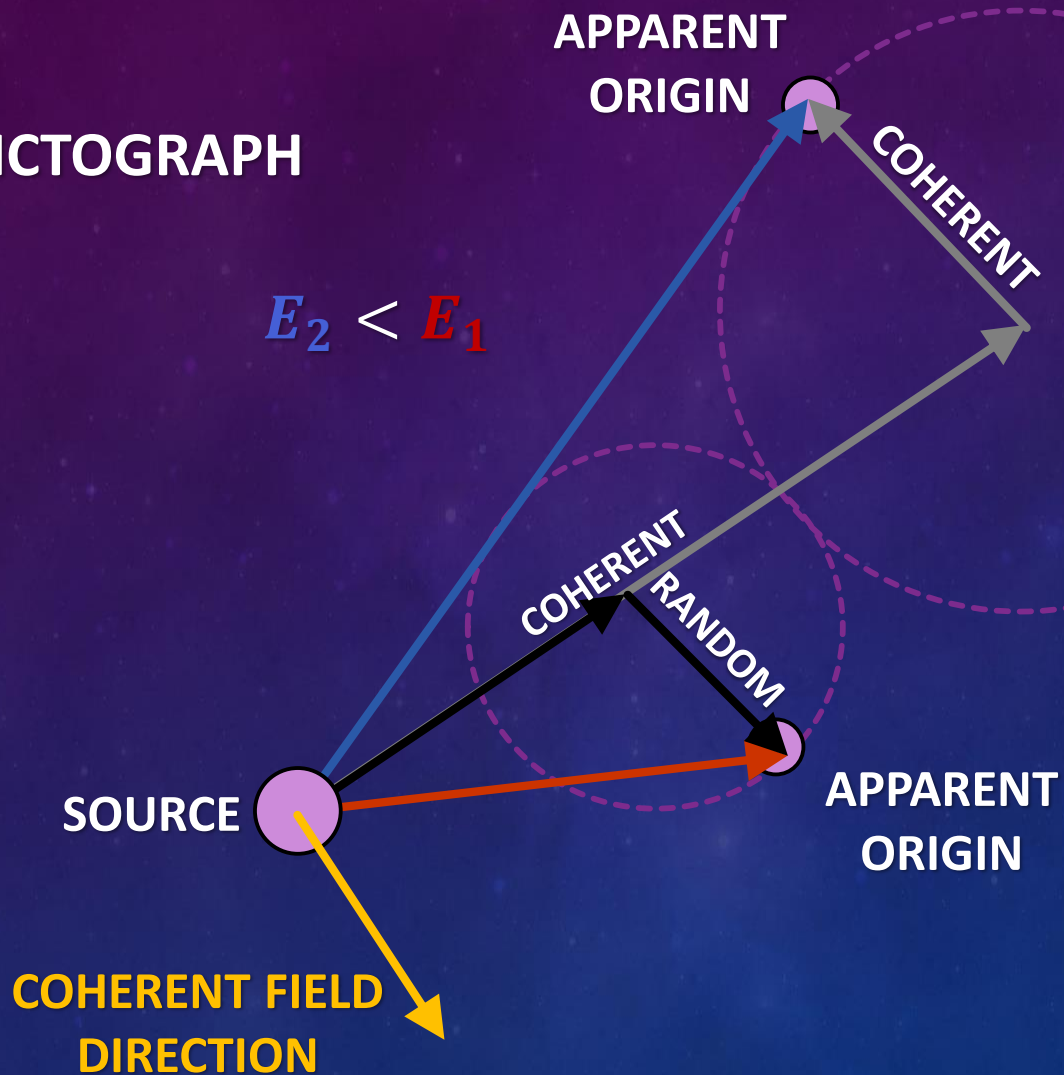
Brownian Motion on Sphere  
(Thanks Wikipedia)

**Drift-diffusion -> Wedge Multiplets**



# PICTOGRAPH

$$E_2 < E_1$$

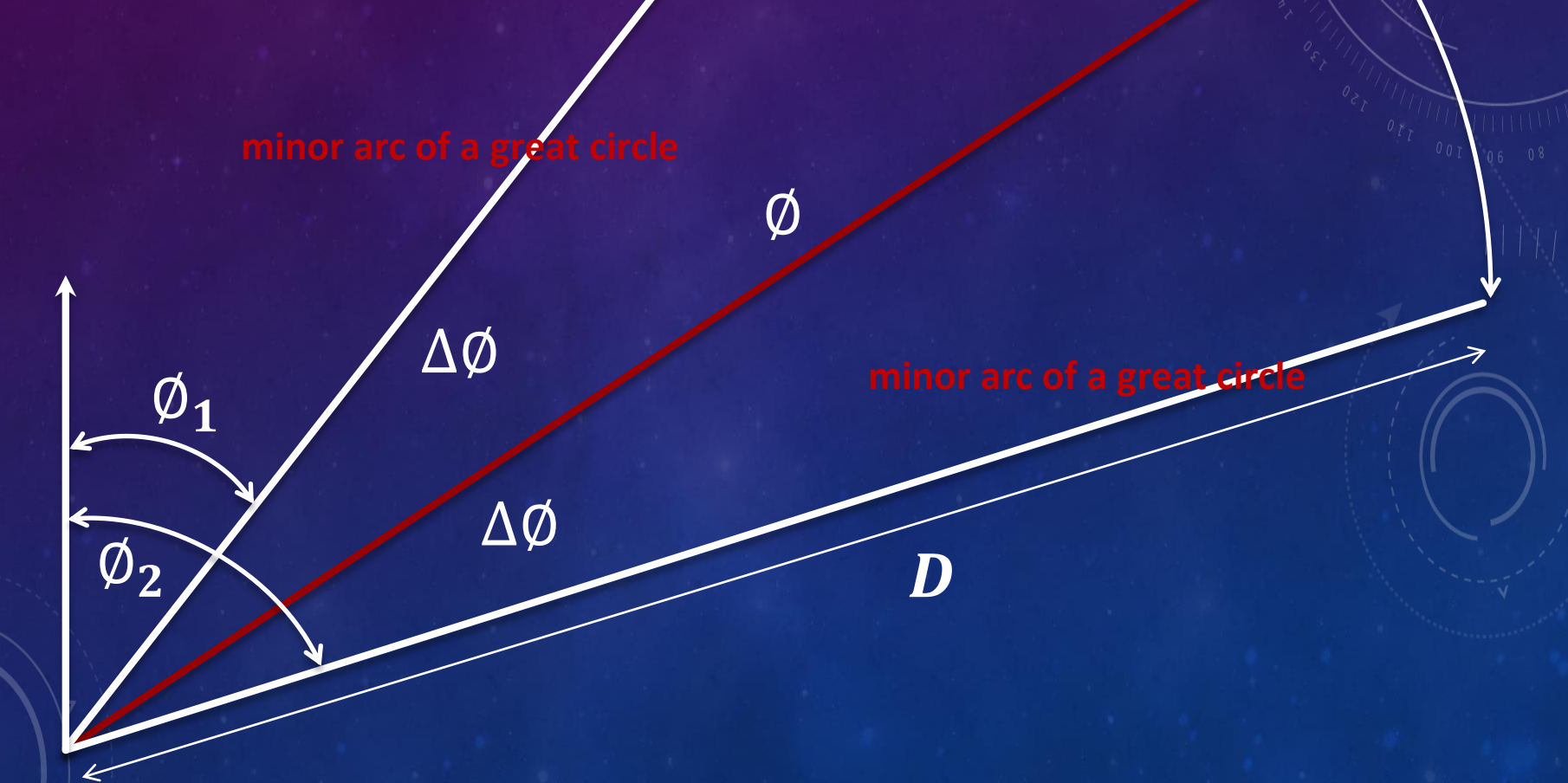




# CORRELATION BINNING

minor arc of spherical cap

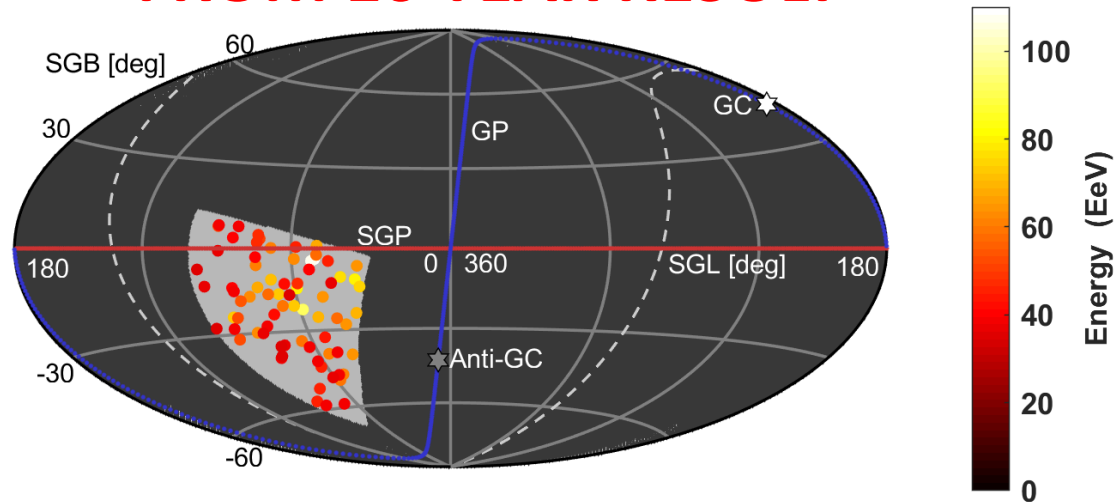
## Spherical Cap Section



# WEDGE MULTIPLETS

- Ranked correlation of energy-angle/distance in spherical cap sections
- Highest significances are negative indicating possible magnetic deflections

## FROM 10 YEAR RESULT



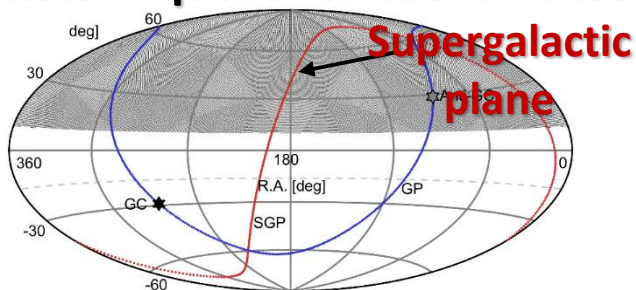
$E \geq 35$  EeV, Wedge Width =  $90^\circ$ , Distance  $\leq 70^\circ$ , Direction =  $120^\circ$

# OVERSAMPLING GRID

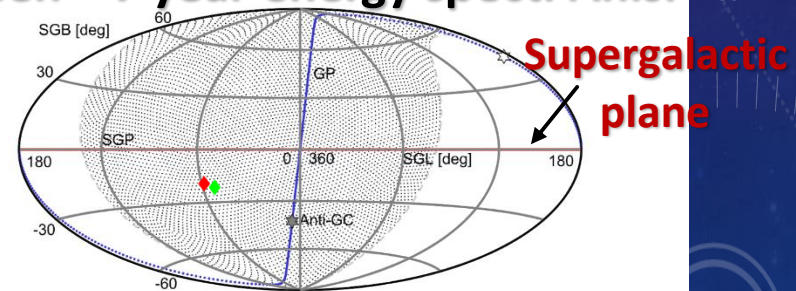
SGL (Supergalactic Longitude) and SGB (Supergalactic Latitude)

Red – 5 year hotspot

**0.5°x0.5° Equatorial coordinates**



**Green – 7 year energy spect. Anis.**



**2°x2° rotated to supergalactic**

- Large spacing due to large parameter scan
  - Single simulation  $t > 2$  hours on U of U supercomputers



# SCAN PARAMETERS

Scan for most significant correlation

Result is not used for supergalactic structure significance

Scan space limited by reasonableness, computation time, exposure area

- Energy Threshold
  - 10, 15, 20...100 EeV
- Wedge width (spherical cap sections)
  - $10^\circ, 20^\circ, 30^\circ \dots 90^\circ$  (+ $5^\circ$  on each side of center)
- Maximum Distance
  - $15^\circ, 20^\circ, 25^\circ \dots 90^\circ$
- Pointing Direction ( $0^\circ$  “up” clockwise)
  - $0^\circ, 5^\circ, 10^\circ \dots 355^\circ$

Mean number of scans

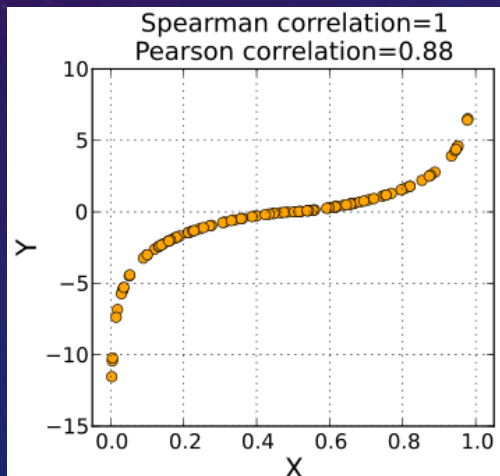
~60,000

# RANKED ENERGY-ANGLE CORRELATION

- Kendall's correlation. Values ranked 1<sup>st</sup> to n<sup>th</sup>.

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

- Any monotonic function  $F(x,y)$  results in  $\tau = \pm 1$ . Removes model assumption



Source: wikipedia

- p-Values
  - Calculated by permutation
  - p-Value is probability correlation is zero

# SIMPLE SHEET FIELD SIMULATION

Biermann, et al, astro-ph/9709250

- $1/E$  supergalactic plane deflection
  - Random “source” position. Gaussian  $\sigma=5^\circ$
- Isotropic Exposure and uniform SGL
- Total energy spectrum of data

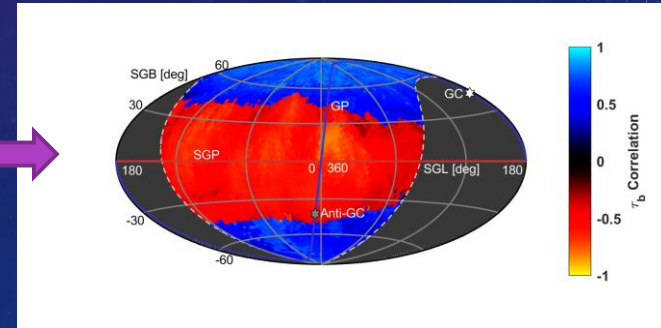
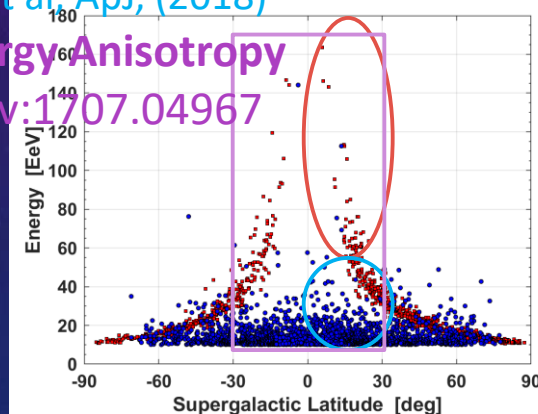
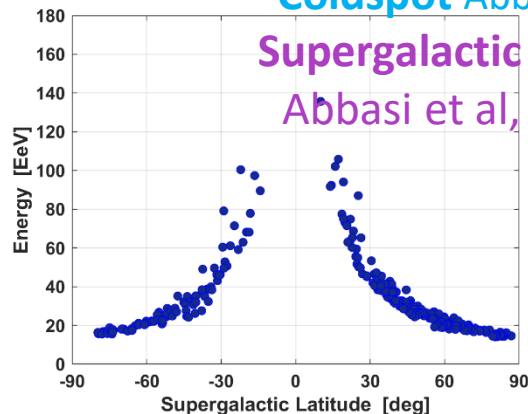
$$\delta \approx 0.5^\circ Z \frac{S}{\text{kpc}} \frac{B}{\mu\text{G}} \frac{10^{20} \text{eV}}{E}$$

**Hotspot** Abbasi et al, Astrophys. J, (2014)

**Coldspot** Abbasi et al, ApJ, (2018)

**Supergalactic Energy Anisotropy**

Abbasi et al, arXiv:1707.04967



$1/E$  for 10% of events.  $\frac{S}{\text{kpc}} \frac{B}{\mu\text{G}} = 18.5$

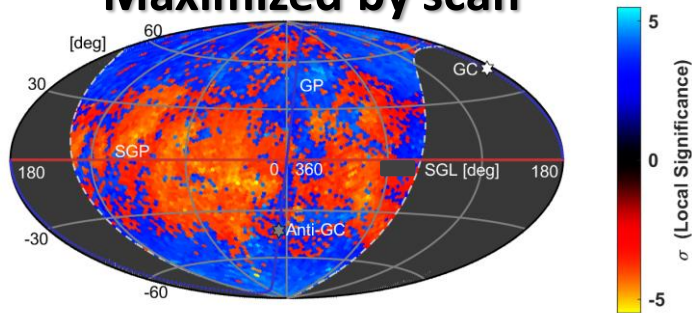
3027 events  $E \geq 10^{19.0}$

- Isotropic positions
- Published spectrum

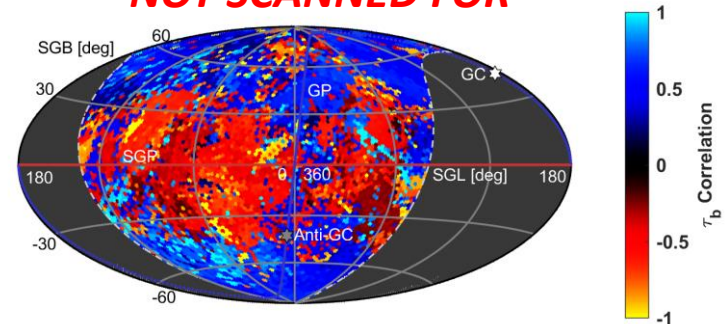
Analysis applied to simulation shows supergalactic structure

# MULTIPLY SEARCH RESULT – 7 YEAR

**Maximized by scan**



**NOT SCANNED FOR**



**FROM 7 YEAR RESULT WITH LIGHTNING BURST CUT**

**Correlation significance**  
*NOT USED IN FINAL SIGNIFICANCE*

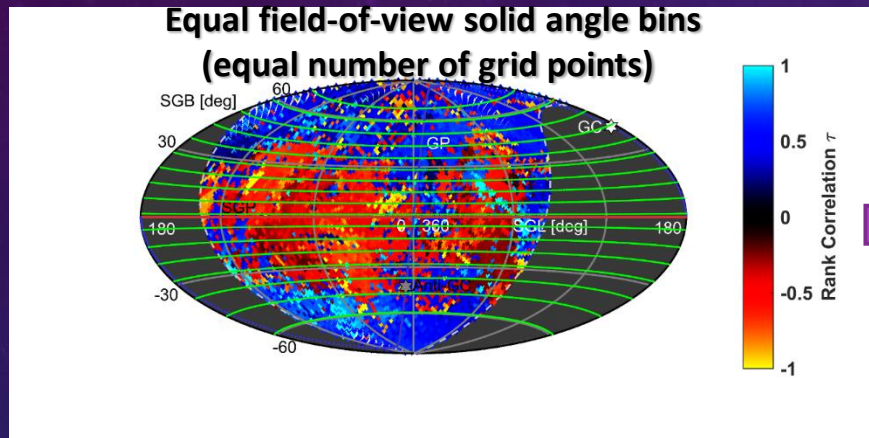
**Strength/sign of correlation**  
*USED TO CALCULATE SIGNIFICANCE*

*Negative correlations of greater significance correlated with supergalactic plane*



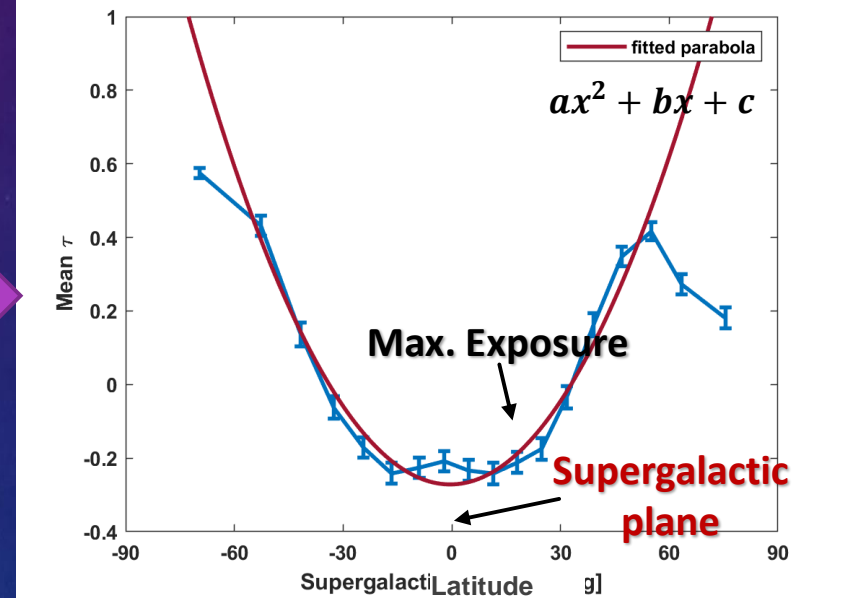
# SUPERGALACTIC STRUCTURE – 7 YEAR

FROM 7 YEAR UHECR 2017 RESULT



Significance test not *a priori* obvious

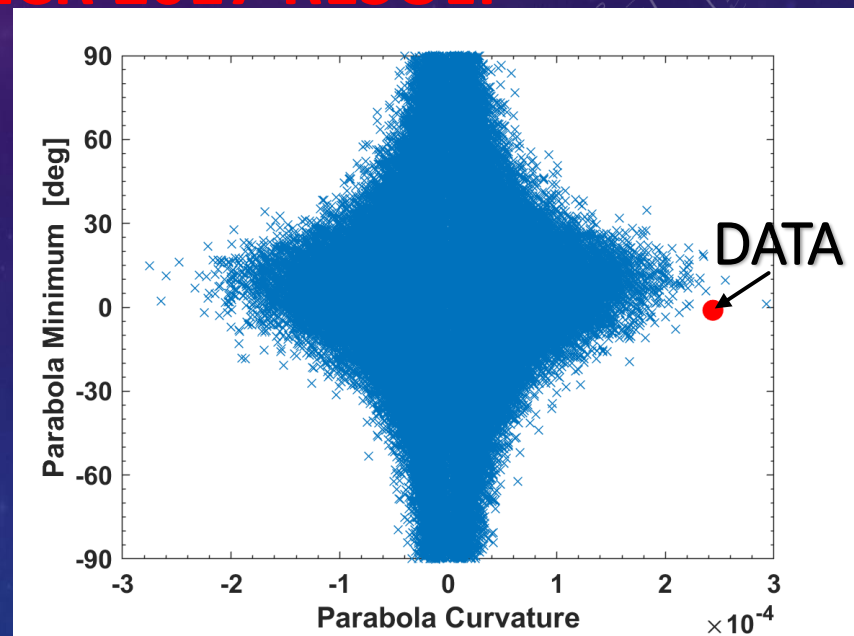
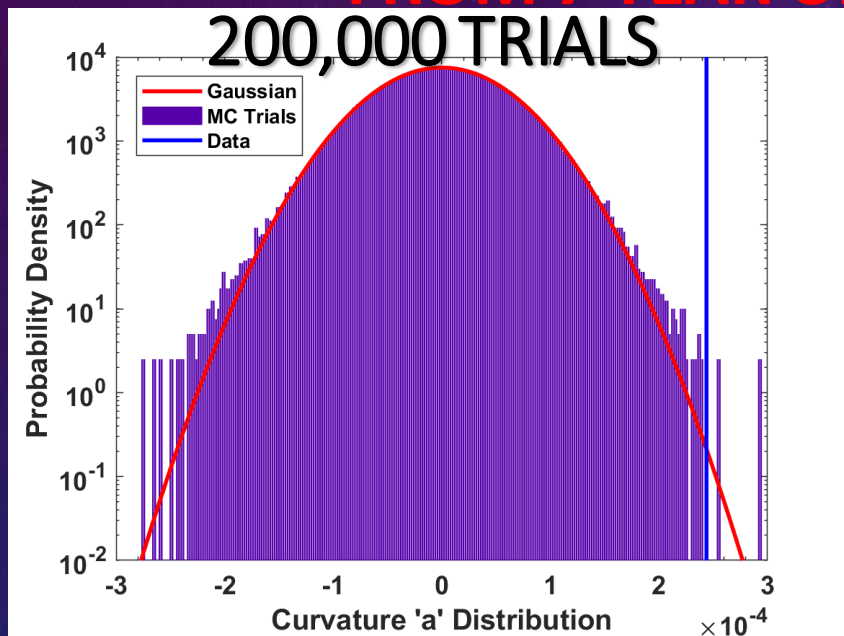
Average correlation strength  
shows correlation with supergalactic plane



First symmetric Taylor expansion of  
average strength/sign of correlation  
used to calculate significance

# TEST STATISTIC

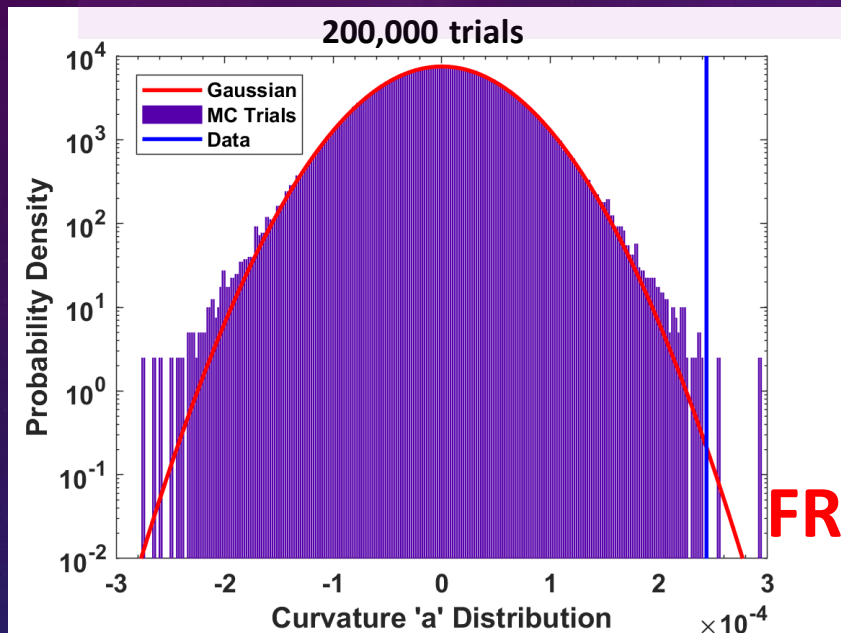
FROM 7 YEAR UHECR 2017 RESULT



$$ax^2 + bx + c$$

HIGHER CURVATURE  
CLOSER TO SUPERGALACTIC PLANE

# SIGNIFICANCE – 7 YEARS DATA



Use variable not scanned for:  $\tau$  correlation

- Fit to parabola  $ax^2 + bx + c$
- Find probability that  $a \geq 2.44 \times 10^{-4}$  (curvature)

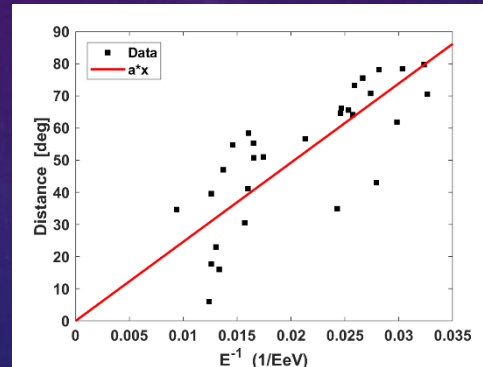
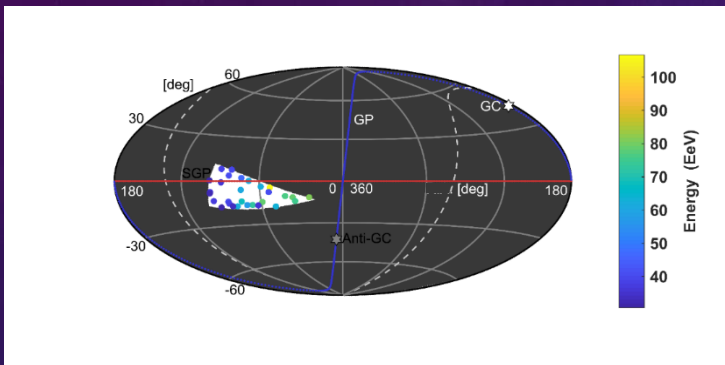
**FROM 7 YEAR UHECR 2017 RESULT**

According to Gaussian fit to MC distribution  
data significance is  **$4.56\sigma$**

According to two passed MC it is  **$4.21\sigma$  (large uncertainty)**

# COHERENT FIELD ESTIMATES – 7 YEAR

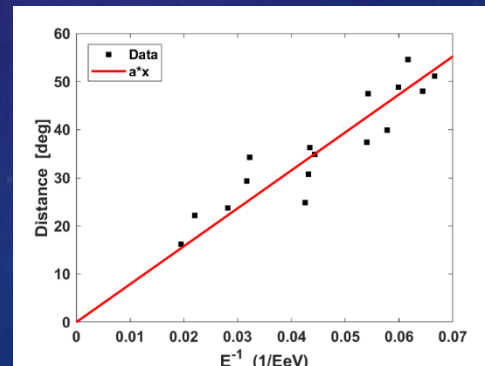
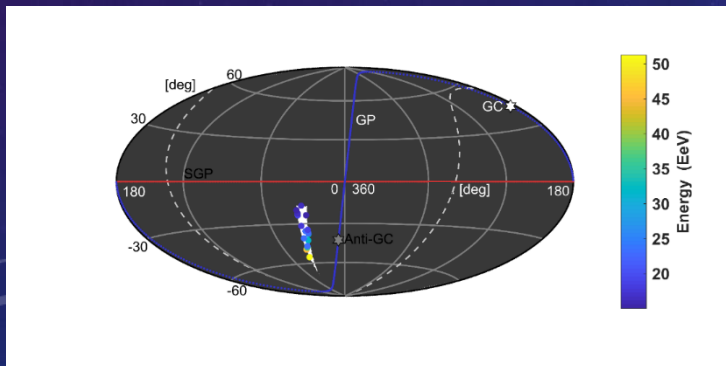
- Fit  $1/E$  to straight line



$$\delta \approx 0.5^\circ Z \frac{S}{\text{kpc } \mu\text{G}} \frac{B}{10^{20} \text{ eV}} \frac{1}{E}$$

- If  $Z = 1$ ,  $\frac{S}{\text{kpc } \mu\text{G}} = 49.24$
- If  $S = 3.7 \text{ Mpc (M82)}$   
 **$B = 13 \text{ nG}$**

$E \geq 30 \text{ EeV}$ , Width =  $30^\circ$ , Distance  $\leq 80^\circ$ , Direction =  $270^\circ$

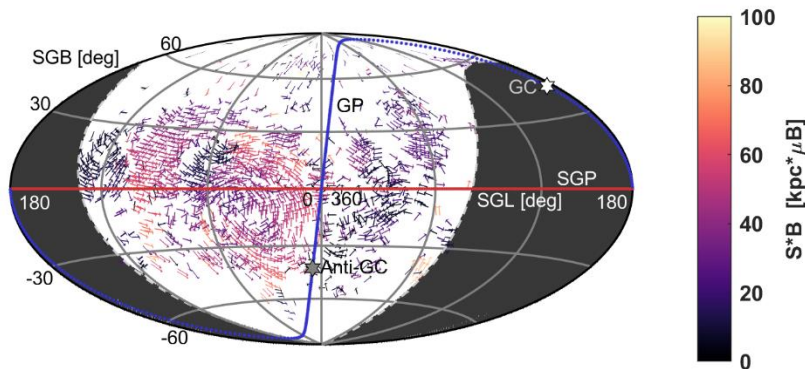
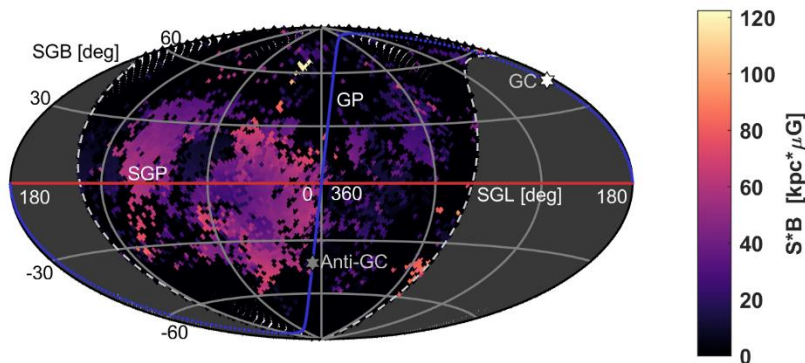


- If  $Z = 1$ ,  $\frac{S}{\text{kpc } \mu\text{G}} = 15.77$
- If  $S = 3.7 \text{ Mpc (M82)}$   
 **$B = 4 \text{ nG}$**

$E \geq 15 \text{ EeV}$ , Width =  $10^\circ$ , Distance  $\leq 55^\circ$ , Direction =  $345^\circ$



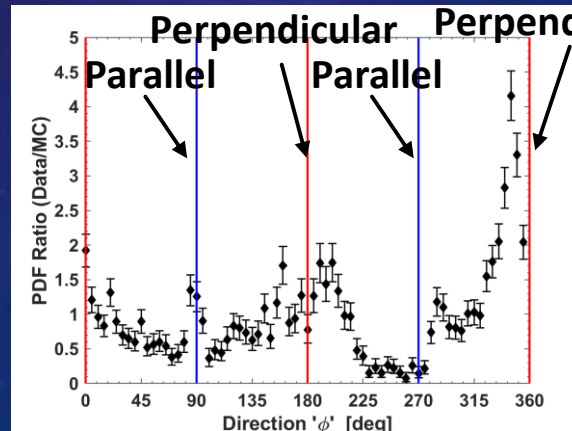
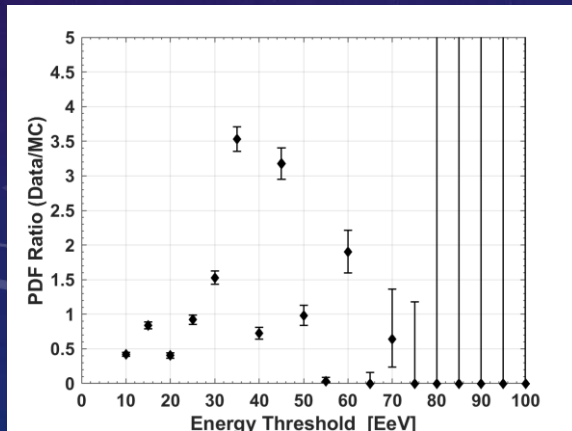
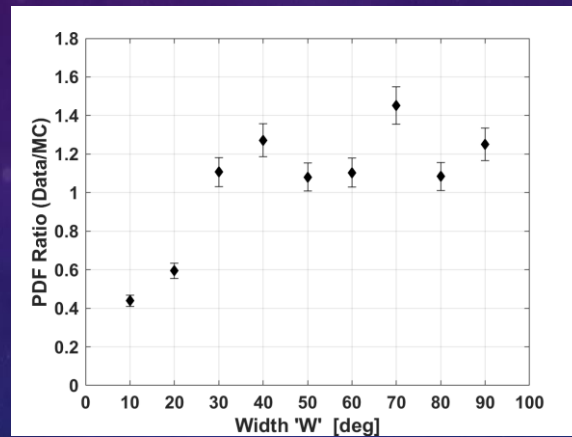
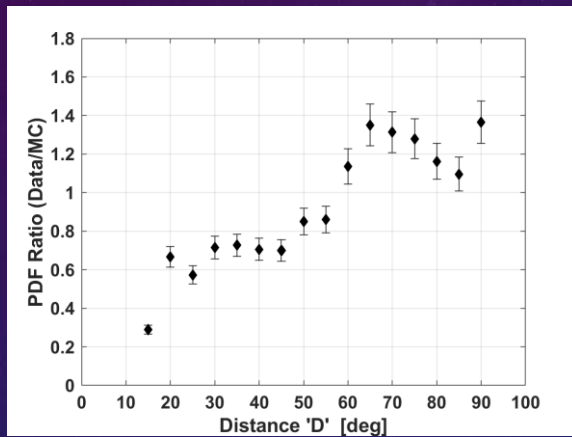
# COHERENT FIELD ESTIMATES – 7 YEAR



- $R^2 < 0$  fits no better than horizontal line (all random field) and  $\tau \geq 0$ 
  - $S*B = 0$
- Field directions rotated  $90^\circ$  from wedge direction
- Apparent sheet and filament?

# SCAN PARAMETER DISTRIBUTIONS – 7 YEAR

- Data scan parameter probability distribution ratios to MC
  - For negative correlations  $\pm 40$  deg from supergalactic plane



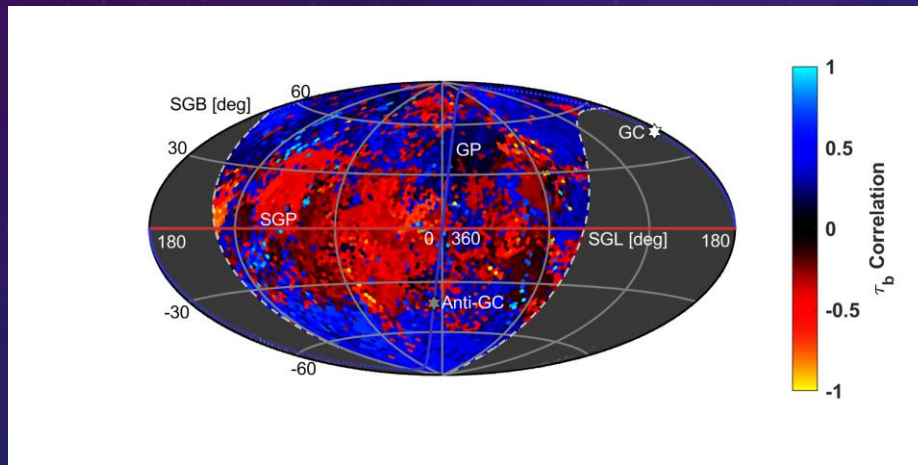
- Generally biased to more statistics inside bin
- Not small scale correlations

- Most common directions perpendicular ( $\pm \sim 10$ ) to the supergalactic plane (and parallel)

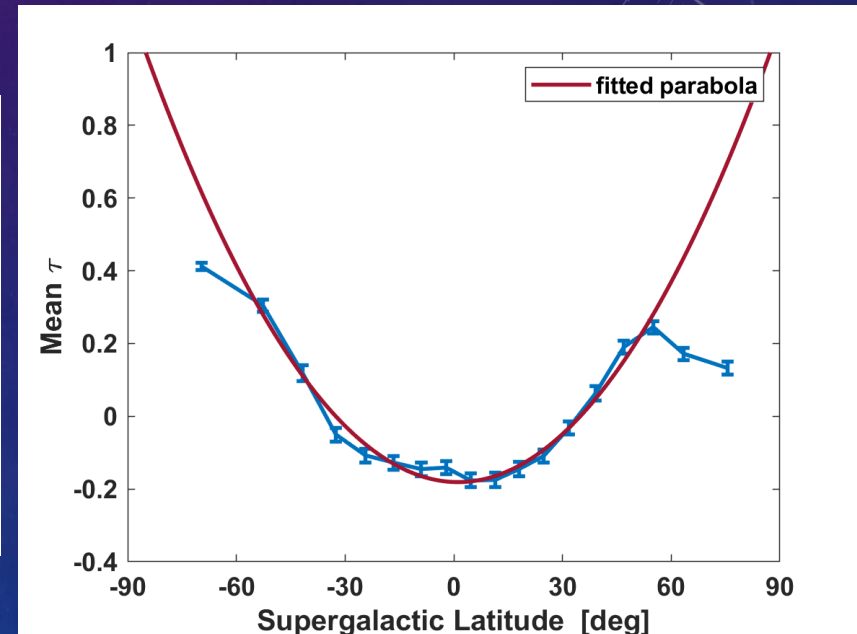
# 10 YEARS OF DATA USING 7 YEAR SCAN PARAMETERS

All wedge parameters the same as 7 years: No new scan for maximum correlation significance.

**NOT SCANNED FOR**



$\tau$  correlation

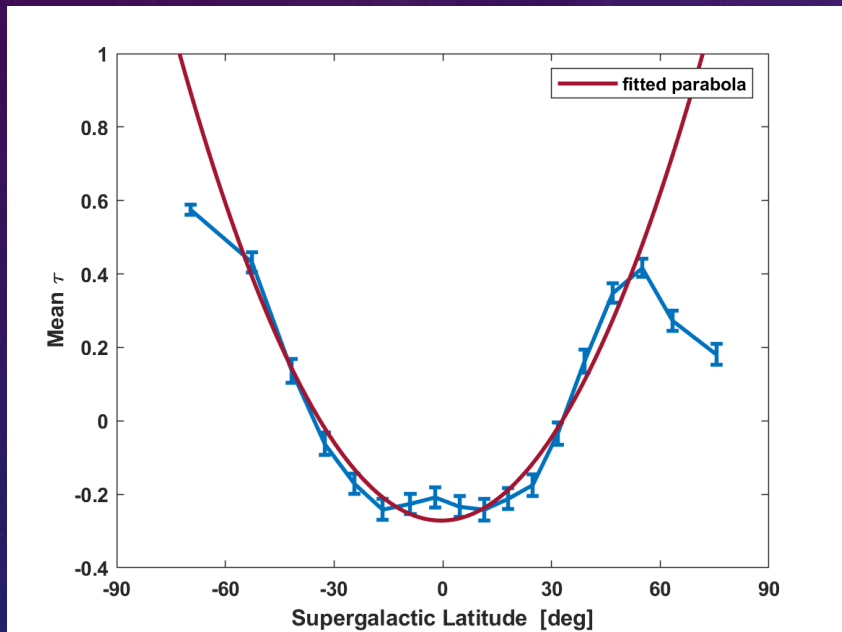


Average  $\tau$  correlation

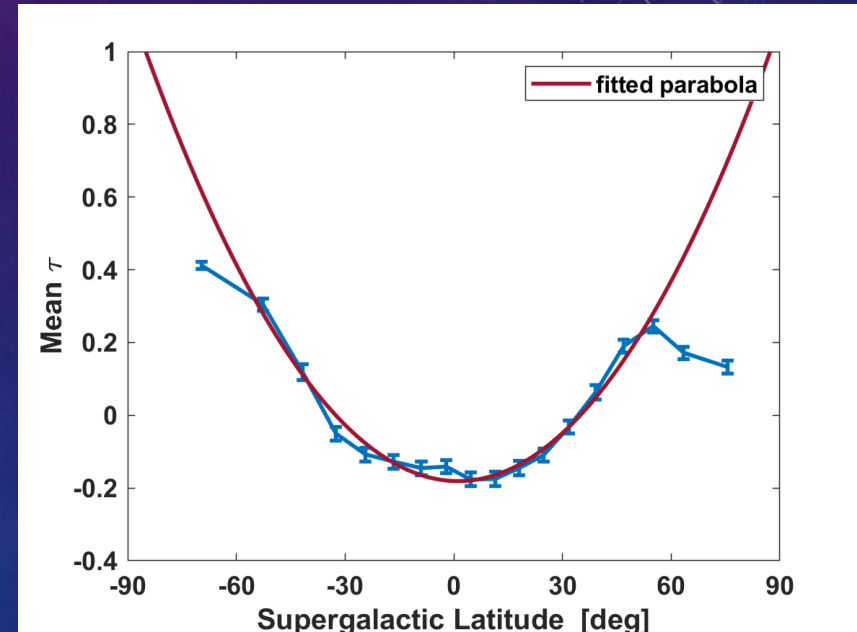
Average  $\tau$  correlation curvature ' $\alpha$ ' lower than 7 years of data.  
New significance not calculated due to computation time.

# 10 YEARS OF DATA USING 7 YEAR SCAN PARAMETERS

All parameters the same as 7 years: No new scan for maximum correlation significance.



7 years average  $\tau$  correlation  
Curvature  $a = 2.4 \times 10^{-4}$

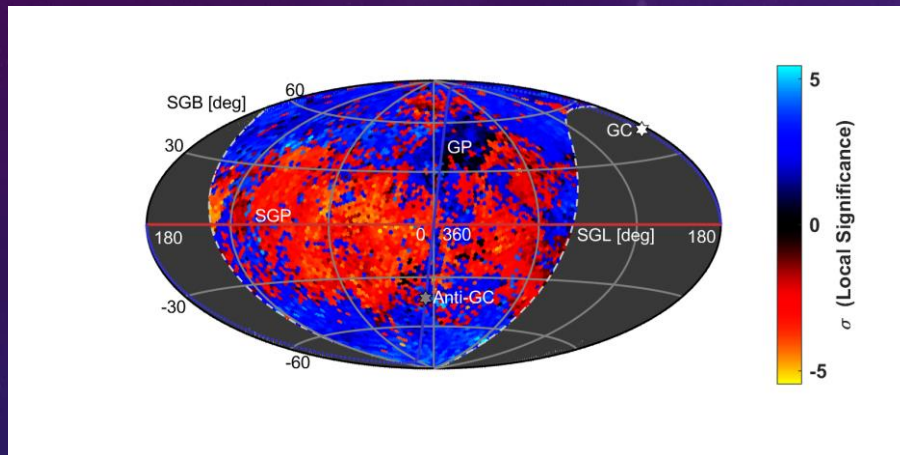


10 years average  $\tau$  correlation  
Curvature  $a = 8.6 \times 10^5$

Average  $\tau$  correlation curvature ' $\alpha$ ' lower than 7 years of data.  
New significance not calculated due to computation time.

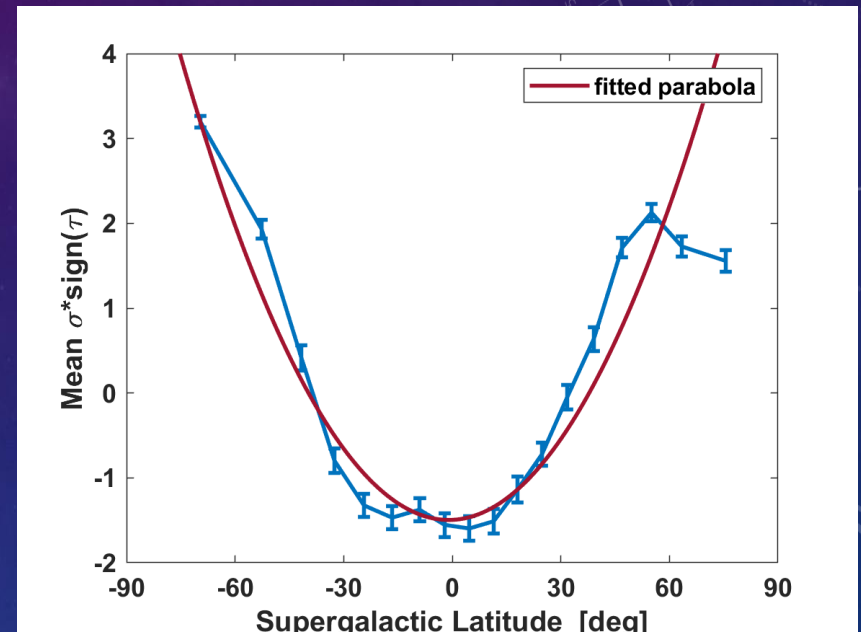


# SUPERGALACTIC CORRELATION SIGNIFICANCE



Significance \*  $\text{sign}(\tau)$

$\sigma$  is closer to post-trial due to scan not being redone.

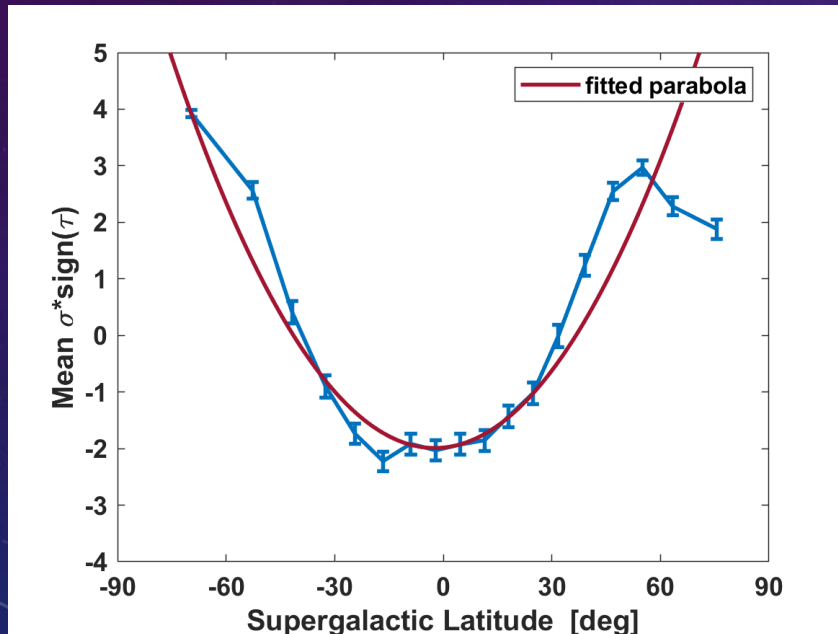


Other possible test statistic for independent data set:  
Average  $\sigma$  significance \*  $\text{sign}(\tau)$

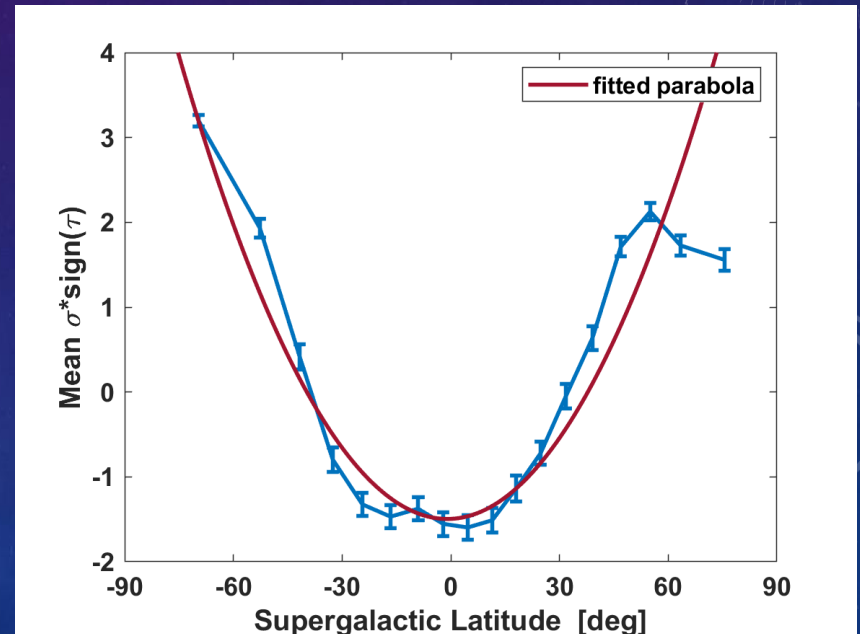
# SUPERGALACTIC CORRELATION SIGNIFICANCE

Other possible test statistic to use with independent data set:

**Mean significance \* sign( $\tau$ )**



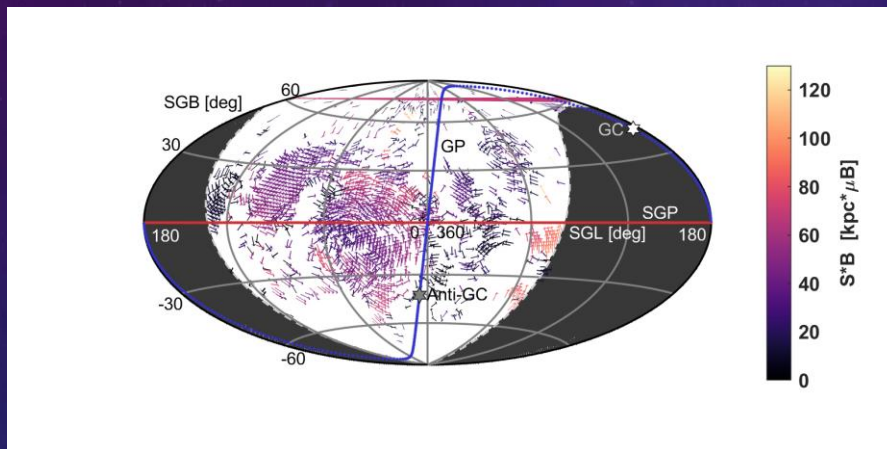
7 years of data  
Curvature  $a = 0.0013$



10 years of data  
Curvature  $a = 0.0010$

# SUPERGALACTIC FIELD CORRELATION

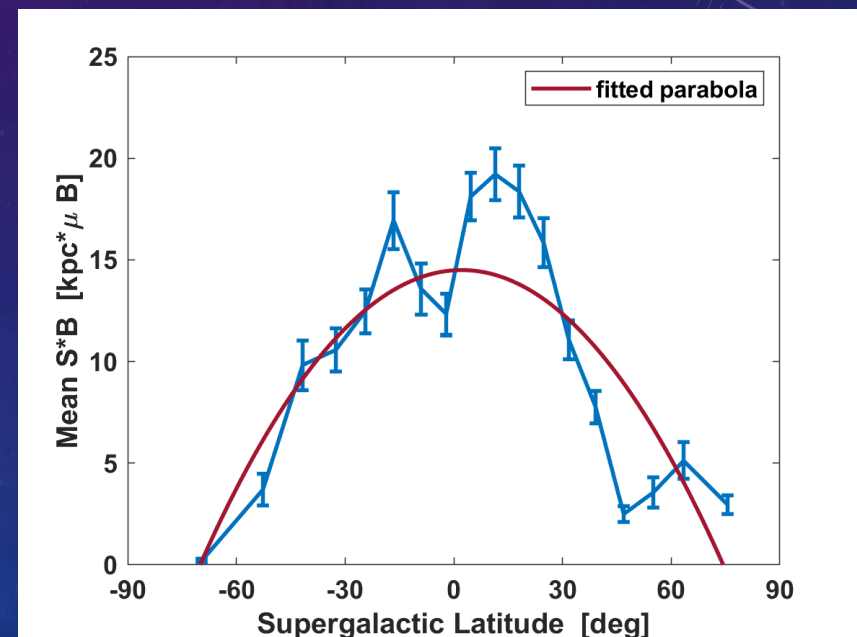
**NOT SCANNED FOR**  
(Remember: signed ranked correlations)



Magnetic field \* distance  
From linear fit to  $1/E$  vs distance

- Fit shows field is consistent with  $S*B \approx \sim 15 \text{ kpc} * \mu\text{G}$  at supergalactic plane

Other supergalactic symmetry:  
Mean field in equal solid angle bins

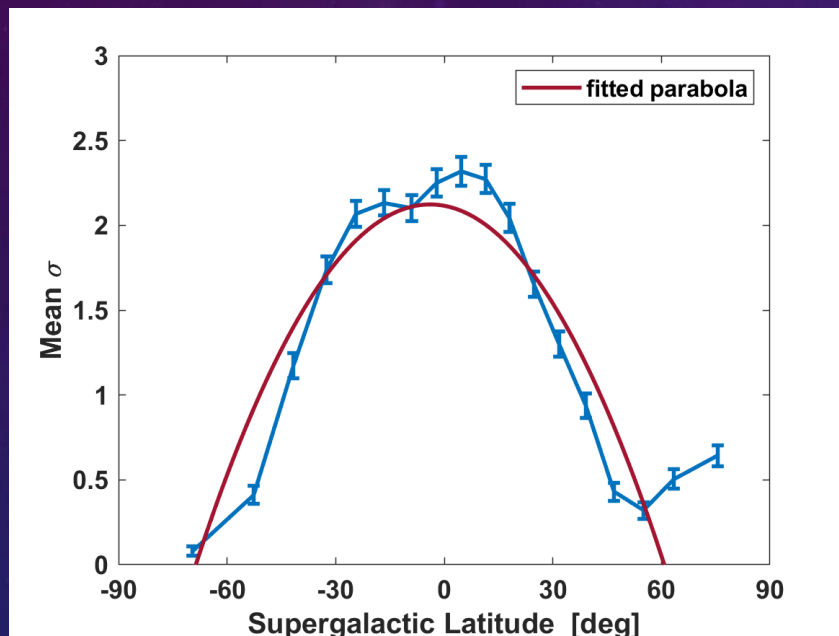


$\tau > 0 \rightarrow SB = 0$

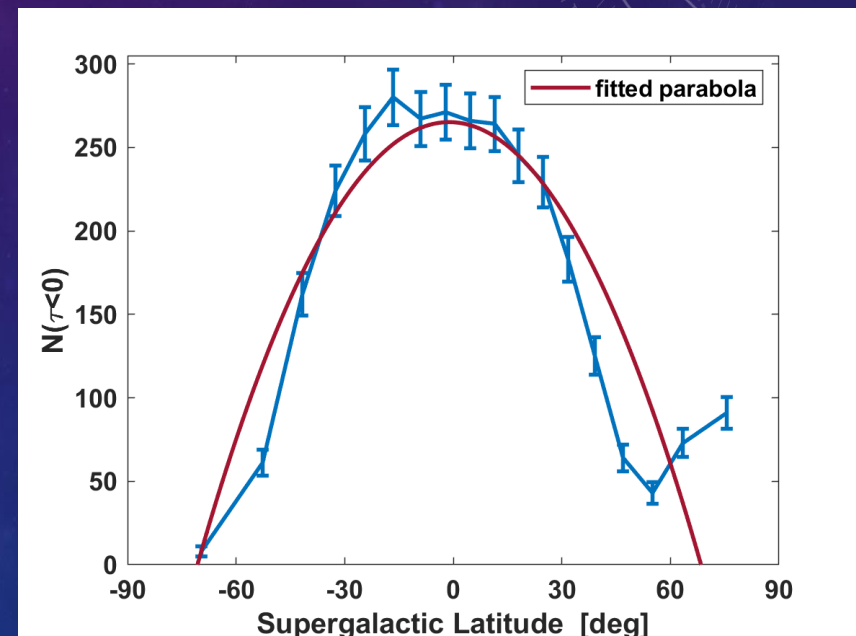
$R^2 < 0 \rightarrow SB = 0$

# SUPERGALACTIC NEGATIVE CORRELATIONS

NOT SCANNED FOR



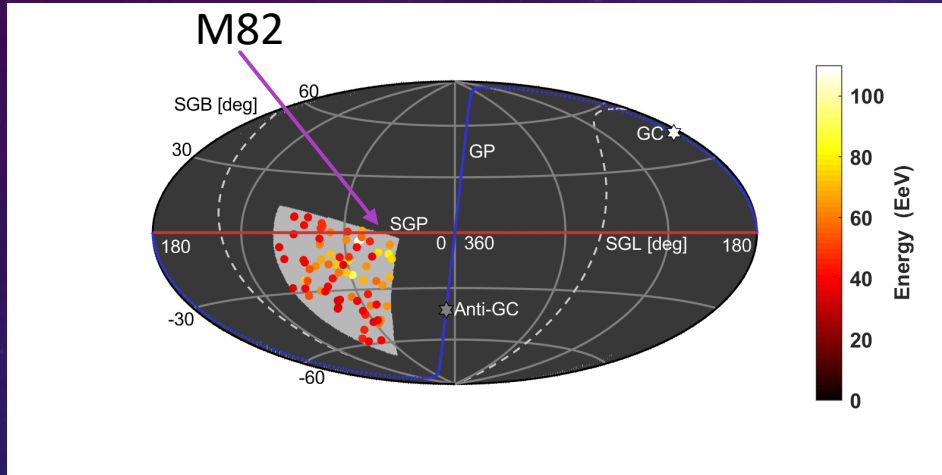
Other supergalactic symmetries:  
Average significance of  $\tau < 0$



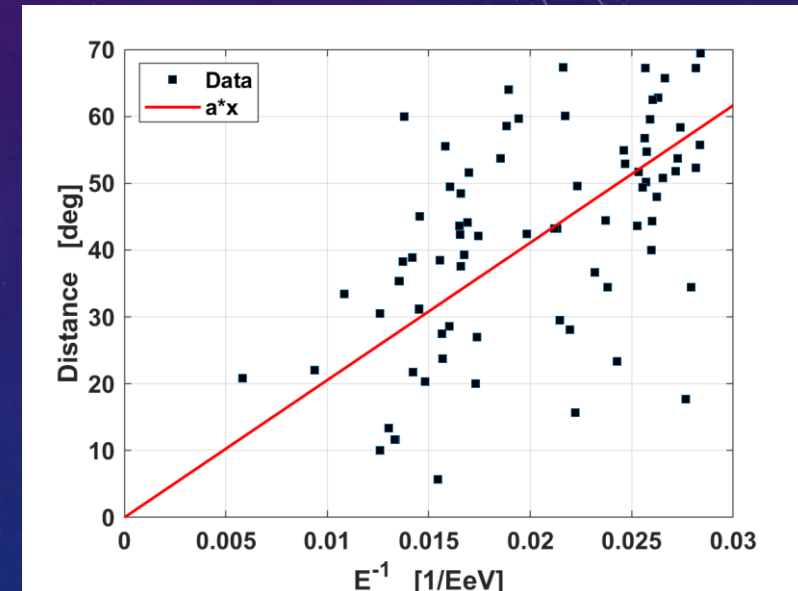
Other supergalactic symmetries:  
Number of negative correlations



# MAXIMUM SIGNIFICANCE CORRELATION



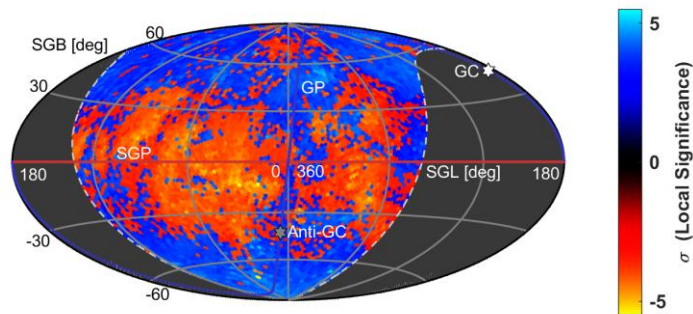
Maximum significance wedge ( $5.1\sigma$ ) at 30.3 SGL, -3.2 SGB:  
 Close to M82 (40.7 SGL, 1.1 SGB) over hotspot  
 Increased from  $4.6\sigma$



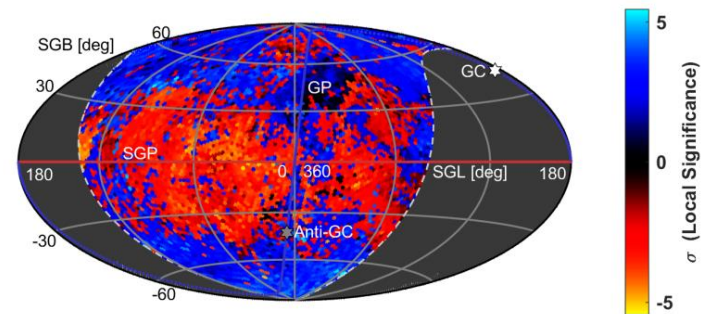
$S \cdot B = 41.1$  If  $S = 3.7$  Mpc (M82)  
 **$B = 12nG$**

# CONCLUSION

- Multiplets (energy-angle correlations) seem correlated with the supergalactic plane
- Suggests sources, coherent, and random fields may be correlated with SGP
  - A measure of magnetic fields using UHECR
- Consistent with an average supergalactic sheet field of  $\sim 15 \text{ kpc} \cdot \mu\text{G}$  (estimate of data and simulation)
  - Simulation exhibits multiplet curvature and hot/coldspot behavior



**7 YEAR UHECR 2017 RESULT**

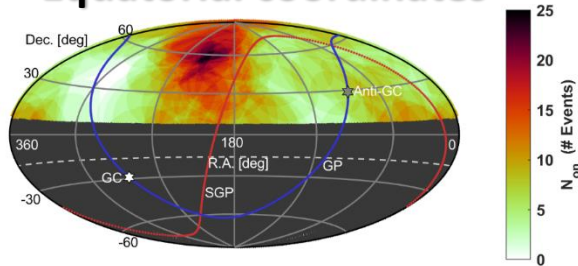


**10 YEARS OF DATA**

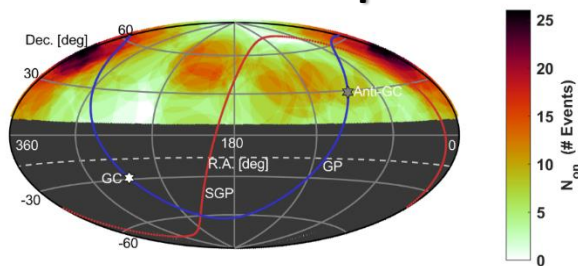
# SIMPLE SIMULATION - HOTSPOT

- 1/E supergalactic deflection
- Isotropic Exposure and uniform SGL
- Energy distribution published average

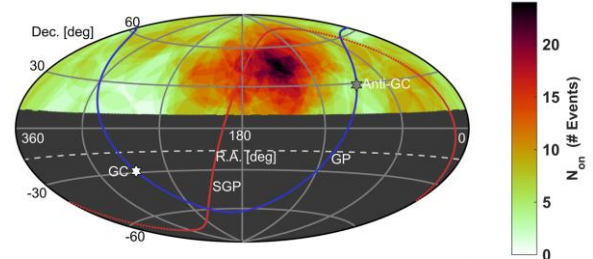
## Equatorial coordinates



## Simulation Examples



Hotspots occur at  $\sim 2\sigma$  frequency



Data =  $5.24\sigma$  pre-trial

- Hotspots not directly in supergalactic plane
  - Average ( $\sigma > 5.24$ ) location  $18.9^\circ$  from SGP ( $9.3^\circ$  uncertainty). Data Hotspot is at  $17^\circ$ .

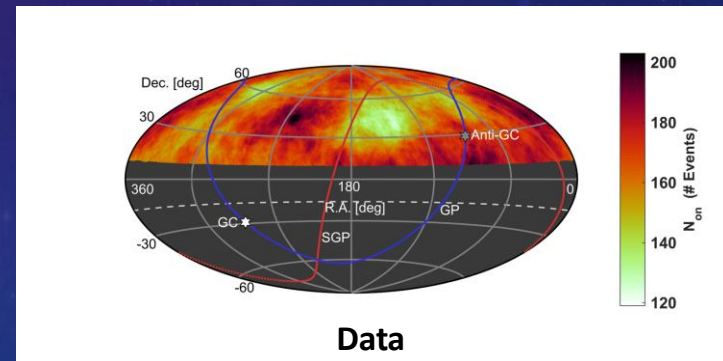
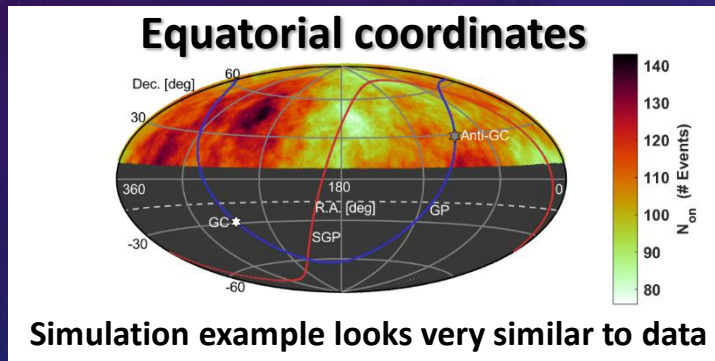
N events inside average  $30^\circ$  equal exposure bins with  $E \geq 10^{19.75}$  eV



# SIMPLE SIMULATION - COLDSPOT

- $1/E$  supergalactic deflection
- Isotropic Exposure and uniform SGL
- Energy distribution published average

COLDSPOT  
MORE LIKELY



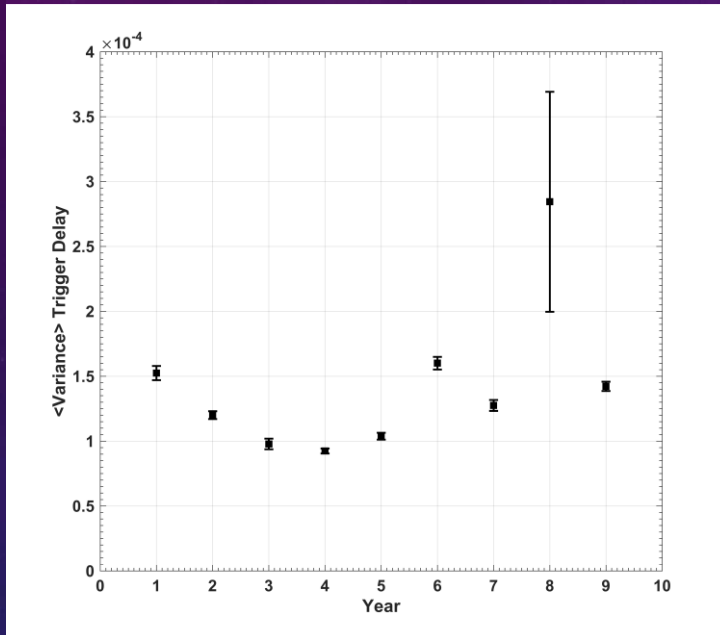
N events inside average  $30^\circ$  equal exposure bins with  $E \geq 10^{19.2}$  eV and  $E < 10^{19.75}$  eV



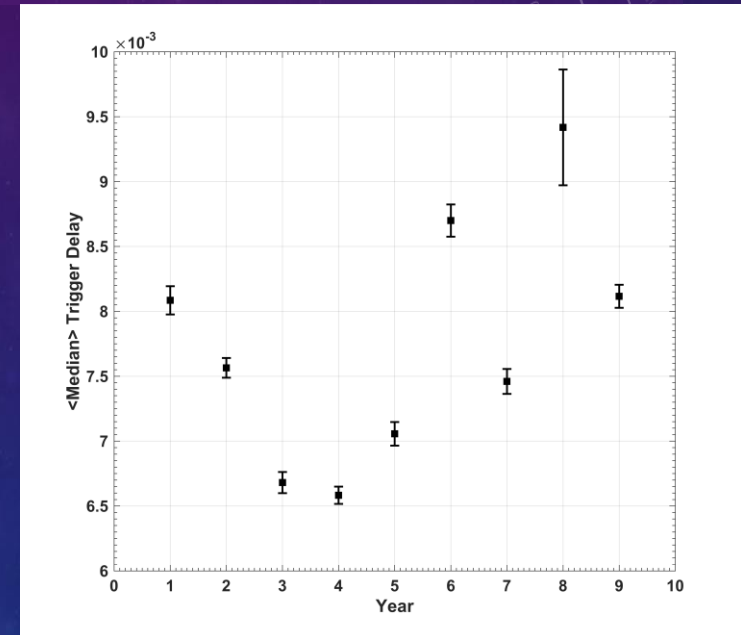


ADDITIONAL

# 8<sup>TH</sup> YEAR OMITTED DUE TO TRIGGER ANISOTROPY



Average over year:  
variance of each day's time between triggers

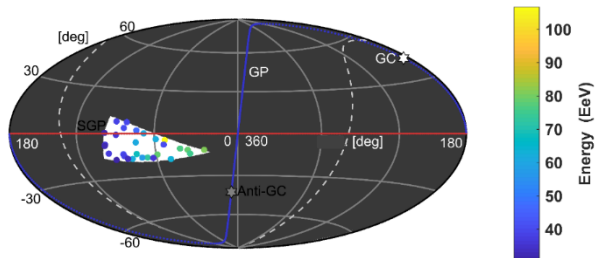


Average over year:  
median of each day's time between triggers

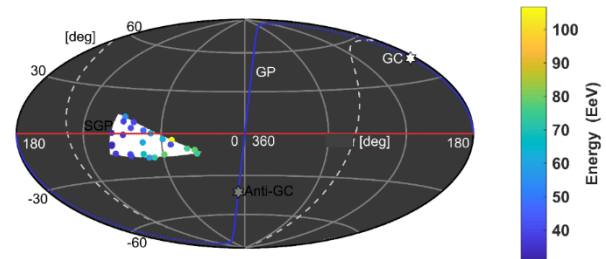
Tower communication issue caused anisotropy not easily corrected for  
Hence 8<sup>th</sup> year of data is omitted in this analysis

# DATA WEDGE EXAMPLES

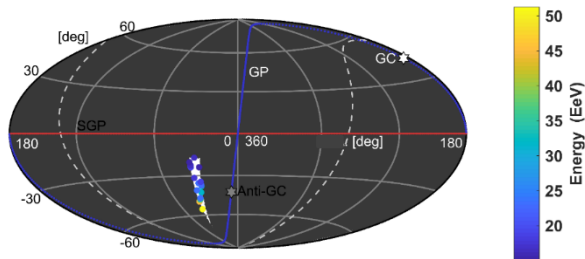
- Ranked correlation of energy-distance in sections of spherical caps
  - 4 highest significances are negative correlations as expected



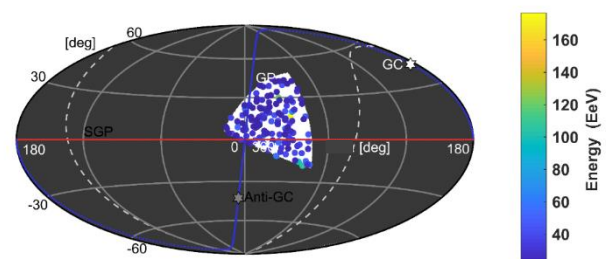
**$E \geq 30$  EeV, Width =  $30^\circ$ ,  
Distance  $\leq 80^\circ$ , Direction =  $270^\circ$**



**$E \geq 30$  EeV, Width =  $30^\circ$ , Dist.  $\leq 70^\circ$ , Dir. =  $275^\circ$**

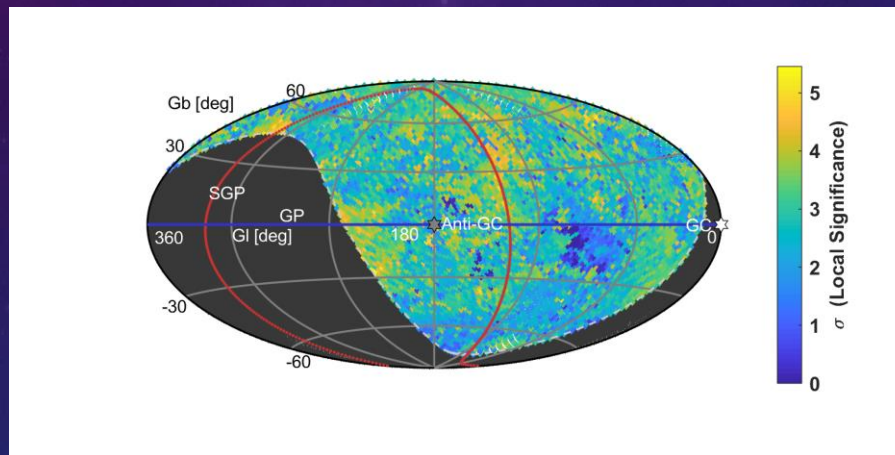


**$E \geq 15$  EeV, Width =  $10^\circ$ , Dist  $\leq 55^\circ$ , Dir =  $345^\circ$**



**$E \geq 20$  EeV, Width =  $70^\circ$ , Dist.  $\leq 70^\circ$ , Dir. =  $320^\circ$**

# 10 YEARS OF DATA USING 7 YEAR SCAN PARAMETERS



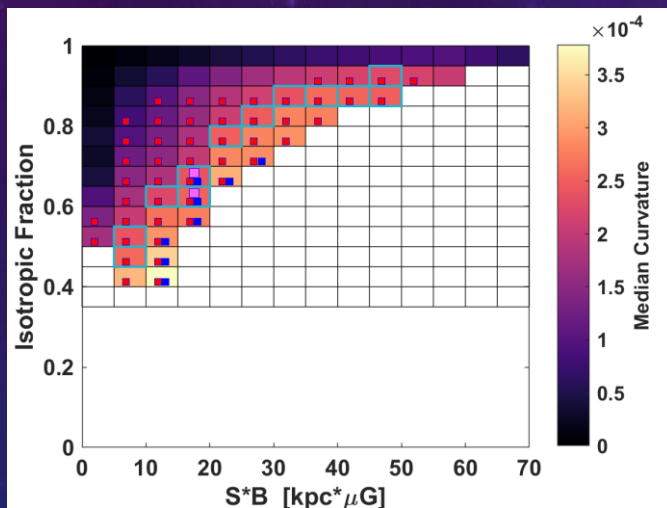
Significance in galactic coordinates



# SIMULATION FIELD ESTIMATE – 7 YEAR

- 1/E supergalactic plane deflection
- Isotropic exposure and uniform SGL
- Energy distribution published average

$$\delta \approx 0.5^\circ Z \frac{S}{kpc} \frac{B}{\mu G} \frac{10^{20} eV}{E}$$

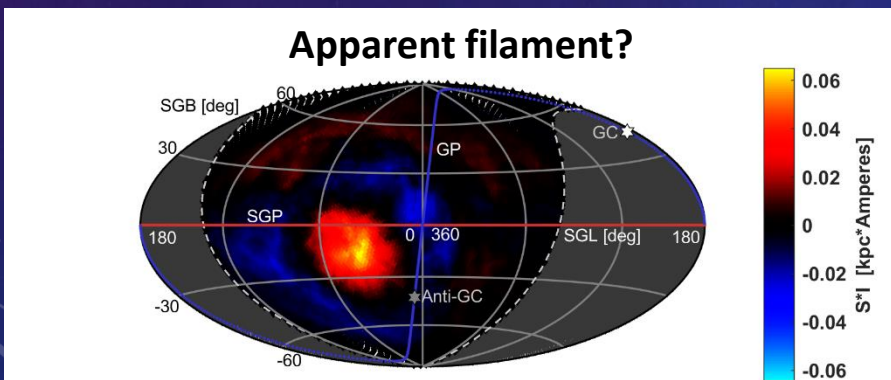
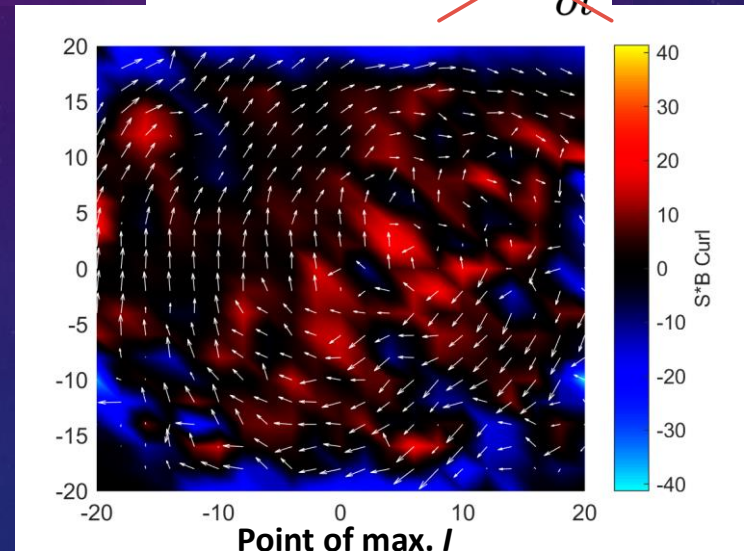
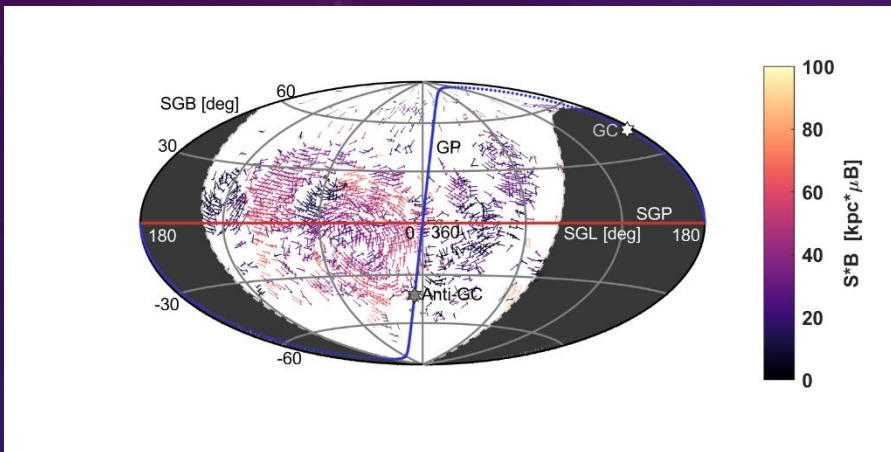


- Light blue outline curvature 'a' like data
- Red boxes hotspots in >1/100 trials
- Blue boxes hot/coldspot in >1/100 trials
- Big purple boxes match all three tests
- **RESULT:  $15 < S*B < 20 \text{ kpc}*\mu G$  and 60 to 70% isotropic**
  - *Agrees with data only determination of  $19 \text{ kpc}*\mu G$*

1/E for 100-10\*Y% of events.  $\frac{S}{kpc} \frac{B}{\mu G} = X$

# POSSIBLE FILAMENT? – 7 YEAR

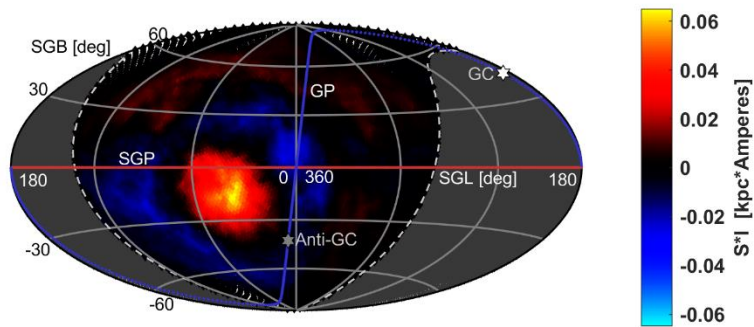
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \cancel{\mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}}$$



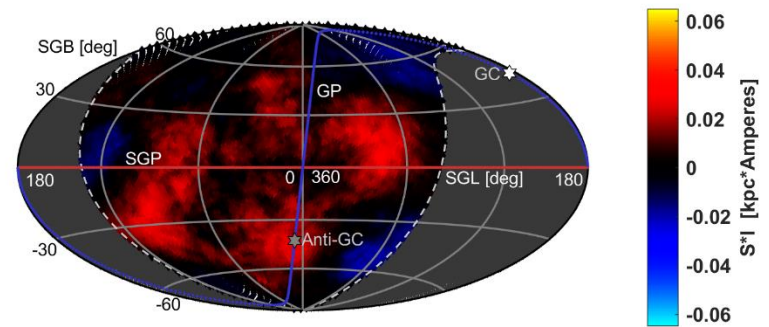
$$I = \frac{\sum(\nabla \times B) * 10^{-10} * 2\pi(1 - \cos 25^\circ)}{4\pi 10^{-7} Tm/A}$$

Apparent current flowing towards us inside  $25^\circ$  bin

# POSSIBLE FILAMENT? – 7 YEAR

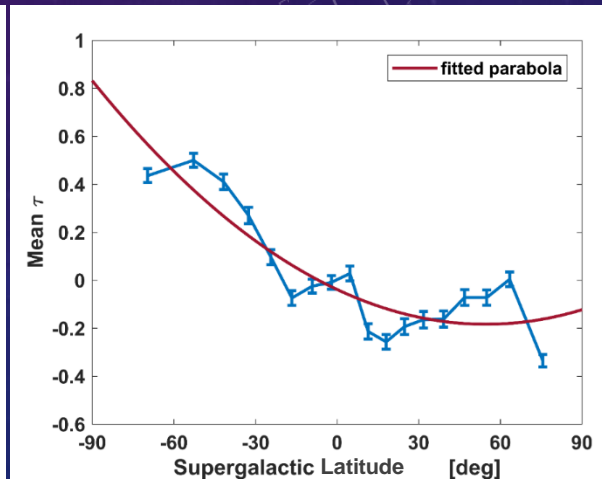
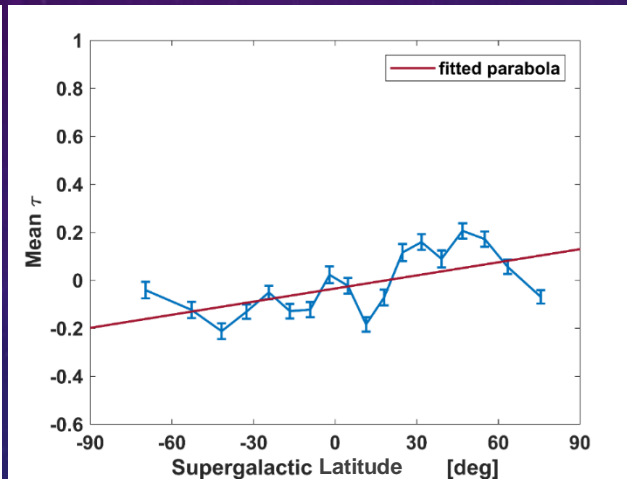
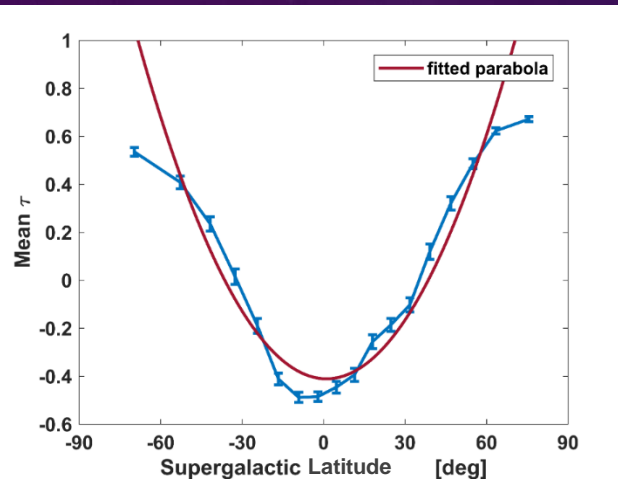


**Apparent current flowing towards us**



**MC Example**

# MC TRIAL EXAMPLES

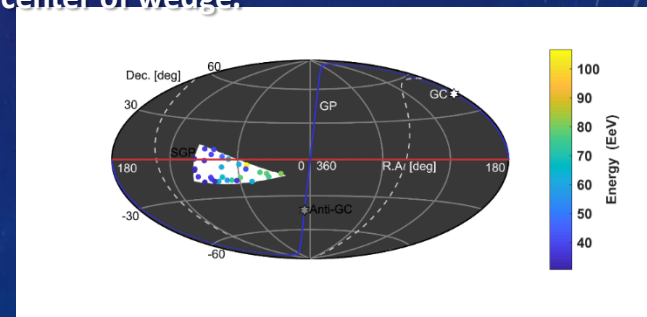


Passed MC  
(greater curvature than data)



# Steps

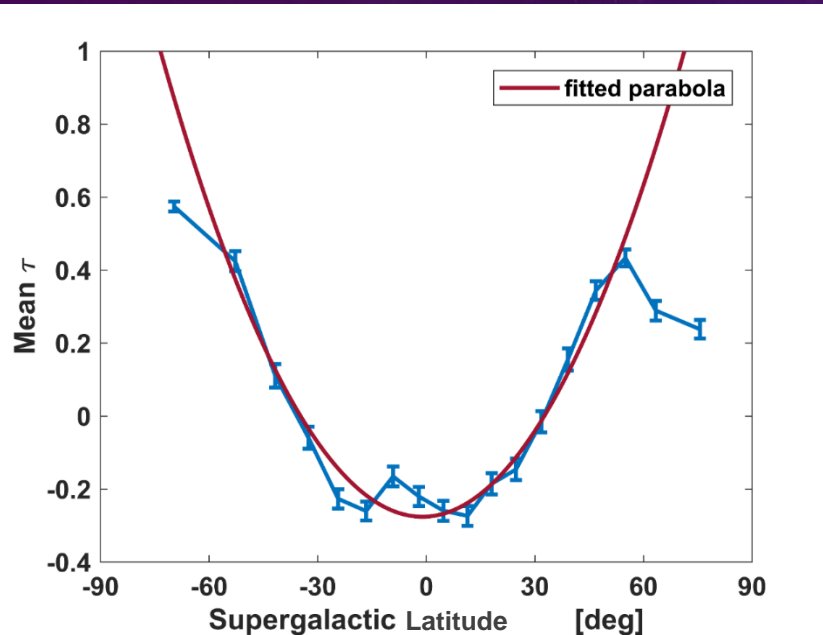
- **Data: tight cuts for  $10^{19}$  eV resolution (like energy spectrum anisotropy).**
  - Variables needed: energy and pointing direction in supergalactic coords.
- **Field of view  $2^\circ$  equally spaced grid (down to -16 Dec).**
  - Rotated into supergalactic coords (supergalactic hypothesis).
- **Wedges:**
  - Spherical caps centered on grid point (like hotspot analysis).
    - Angular distance Haversine formula:  $\text{distance} = 2 * \text{atan2}(\sqrt{a}, \sqrt{1-a})$ ;  $a = \sin^2((\text{lat2}-\text{lat1})/2) + \cos(\text{lat1}) * \cos(\text{lat2}) * \sin^2((\text{lon2}-\text{lon1})/2)$ ;
  - Take section of some angular size out of spherical cap. Rotation angle is clockwise from 90deg latitude.
    - $\text{direction} = \text{atan2}(\cos(\text{lat2}) * \sin(\text{lon2}-\text{lon1}), \cos(\text{lat1}) * \sin(\text{lat2}) - \sin(\text{lat1}) * \cos(\text{lat2}) * \cos(\text{lon2}-\text{lon1}))$ ;
  - Point wedge section in some direction. Defined by grid point and center of wedge.



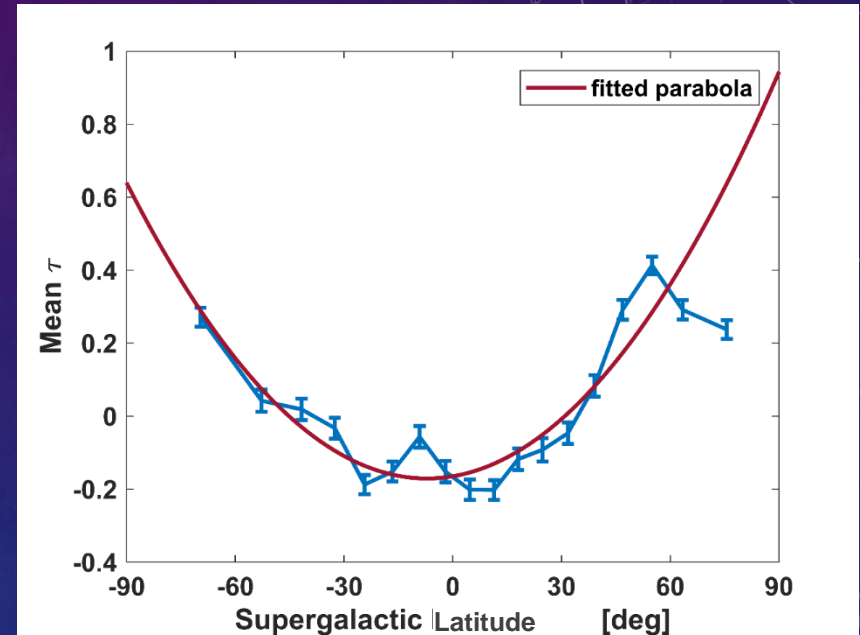
# Steps

- Define scan space for parameters.
  - Wedge distances (Haversine distance formula)
  - Wedge widths
  - Wedge directions
  - Minimum energy thresholds
- Calculate how event energies inside wedge change with distance from grid point.
  - Rank correlations used to calculate likelihood and strength of functional dependence between two variables. Robust and model independent.
- At each grid point scan parameters for wedge that maximizes correlation significance.
  - Resulting correlations can be negative or positive of any strength.
- Find correlation between strength of correlations and the supergalactic plane.
  - Bin field of view into equal solid angle bins of supergalactic latitude (each containing equal number of grid points).
  - Calculate mean correlations in each FOV bin.
- Parabolic dependence of correlations expected by hypothesis and simulation. Fit latitude correlation mean to parabola. Find how often this happens in isotropic simulation.

# HOTSPOT AREA SCRAMBLING



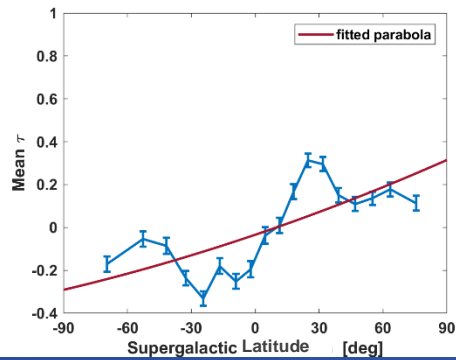
Analysis result



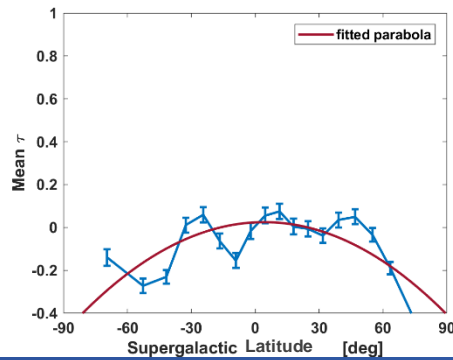
Scrambling energies of hotspot events  $E > 57$  EeV

Configuration of events  $E > 57$  EeV within hotspot area matters

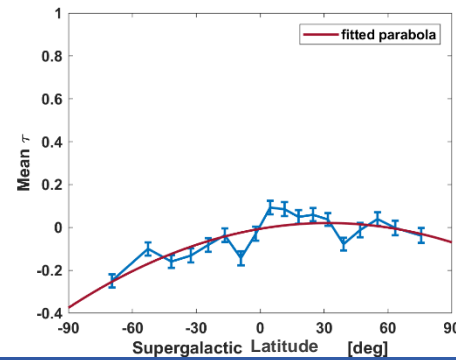
# EACH YEAR OF DATA



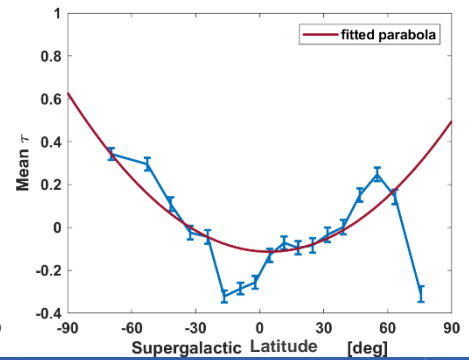
First year



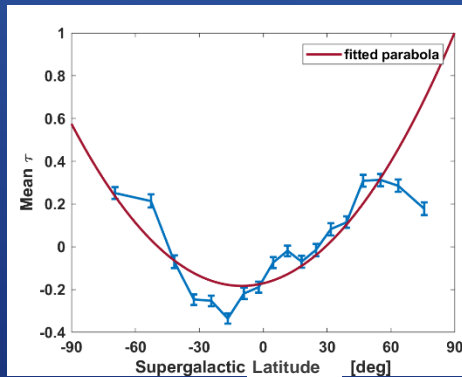
Two years



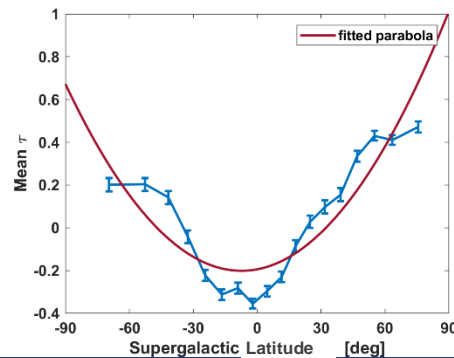
Three years



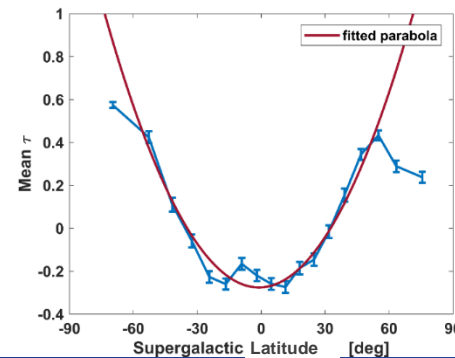
Four years



Five years



Six years

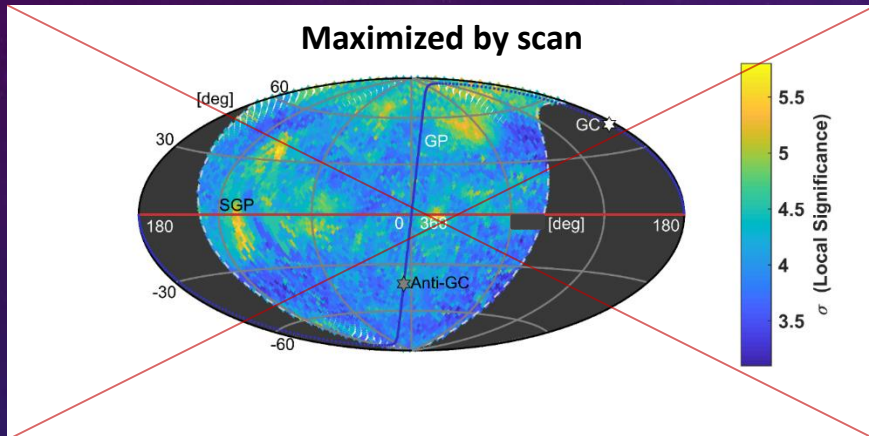


Seven years

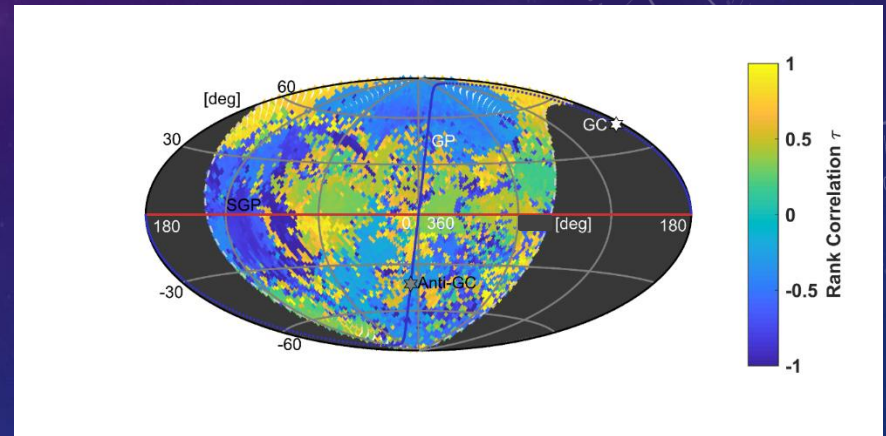


# RANDOM MONTE CARLO EXAMPLE

MC created using *data positions*  
with random energies from spectrum



Significance of correlation  
**NOT USED IN FINAL SIGNIFICANCE**

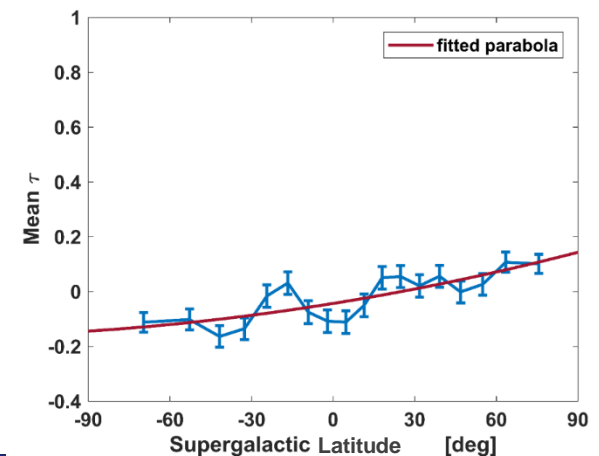
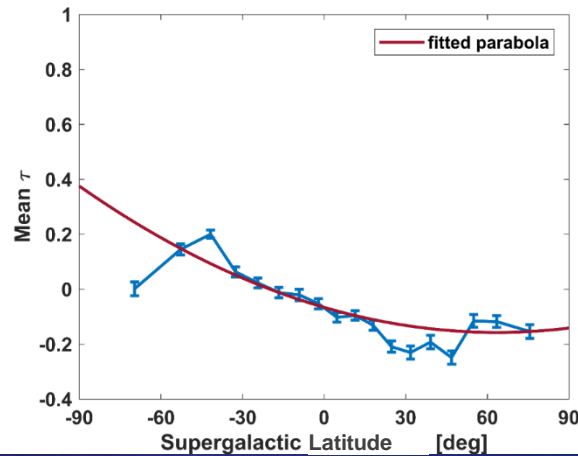
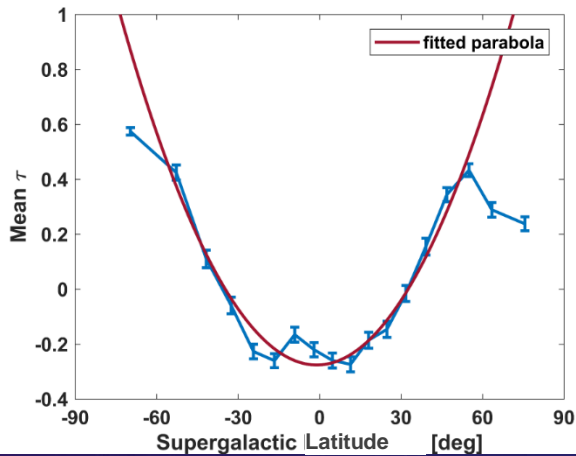


Strength/sign of correlation  
**USED TO CALCULATE SIGNIFICANCE**

# CORR. FILTER SHAPE

- *Test of magnetic field configuration*

THESE ARE ALL DATA



- **Wedges** (spherical cap sections)
  - *Test of uniform and random fields*

- **Spherical caps**
  - *Test of random fields*

- **Squares**
  - *Test of uniform fields*
    - 0.5 to 3 deg wide