SUPERGALACTIC STRUCTURE OF MULTIPLETS

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TELESCOPE ARRAY

REASONING

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

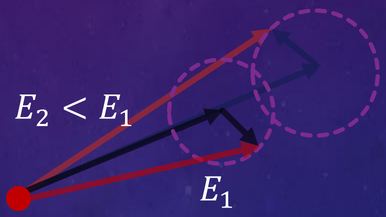
DATA SUMMARY

- **Data:** *Same as Energy Spectrum Anisotropy study Abbasi et al 2018, ApJ, 862, 91*
- **7 years surface detector (SD) data (from ICRC hotspot)**
  # SD >= 4, Zenith < 55°, Pointing Error < 10°
    - **Additional cuts (for low energy zenith distribution):**
        - **Pointing error < 5°, boundary distance > 1.2 km , Lateral fit χ^2 < 10**
  - **E ≥ $10^{19.0}$ eV - 3027 events**
- **Monte Carlo:**
  - **Data positions used, energy interpolated from fully reconstructed Monte Carlo with statistics restricted to the # of data at all energy thresholds**
    - **Testing energy direction patterns not densities**

MULTIPLET SHAPE

Coherent field deflection

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



Random field deflection

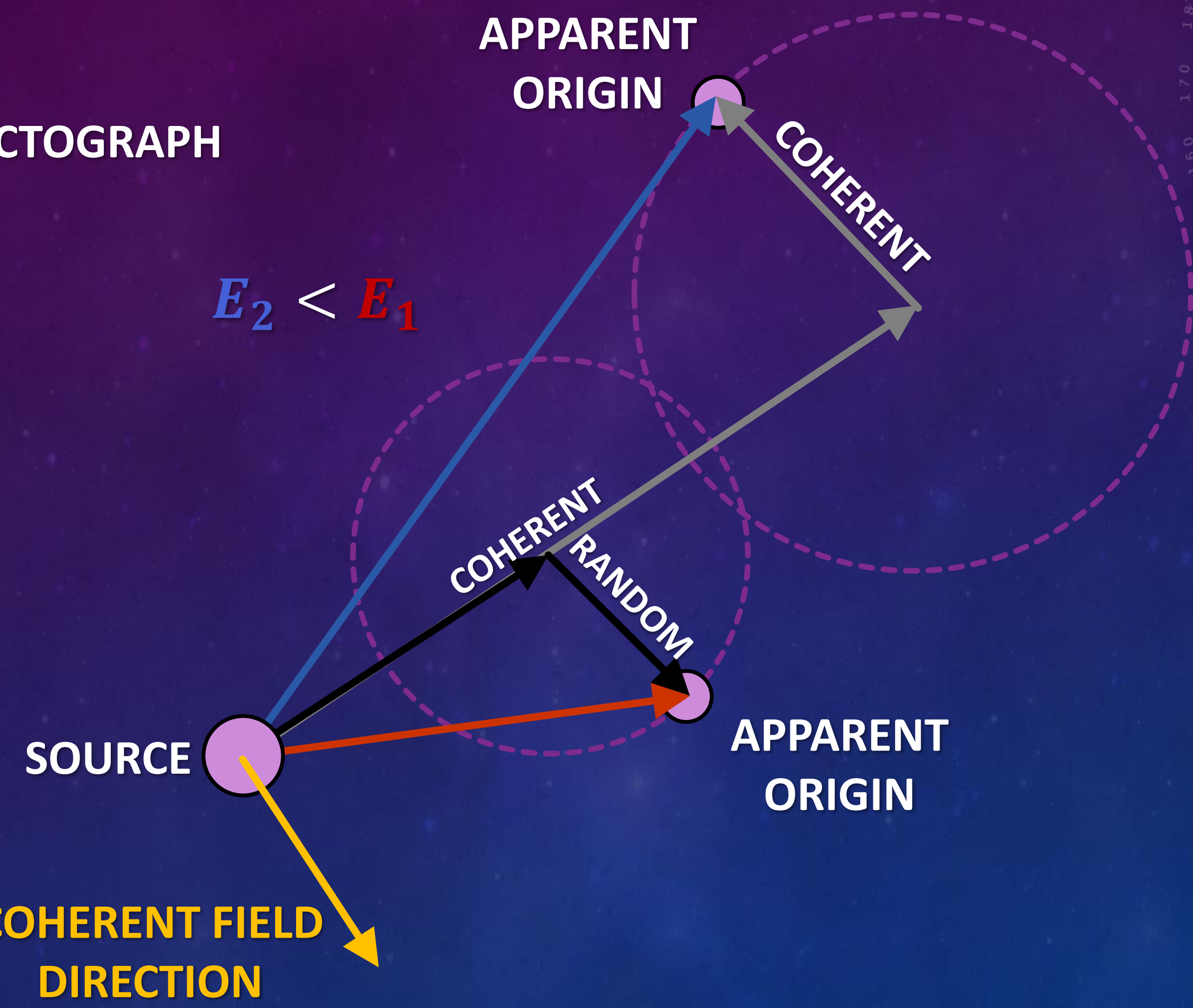
$$\delta_{rms} \approx 0.1^{\circ} Z \frac{B_{rms}}{\mu G} \frac{10^{20} eV}{E} \sqrt{\frac{S}{kpc}} \sqrt{\frac{L_c}{100pc}}$$

Drift-diffusion -> Wedge Multiplets

Coherent and random fields

Brownian Motion on Sphere (Thanks Wikipedia)

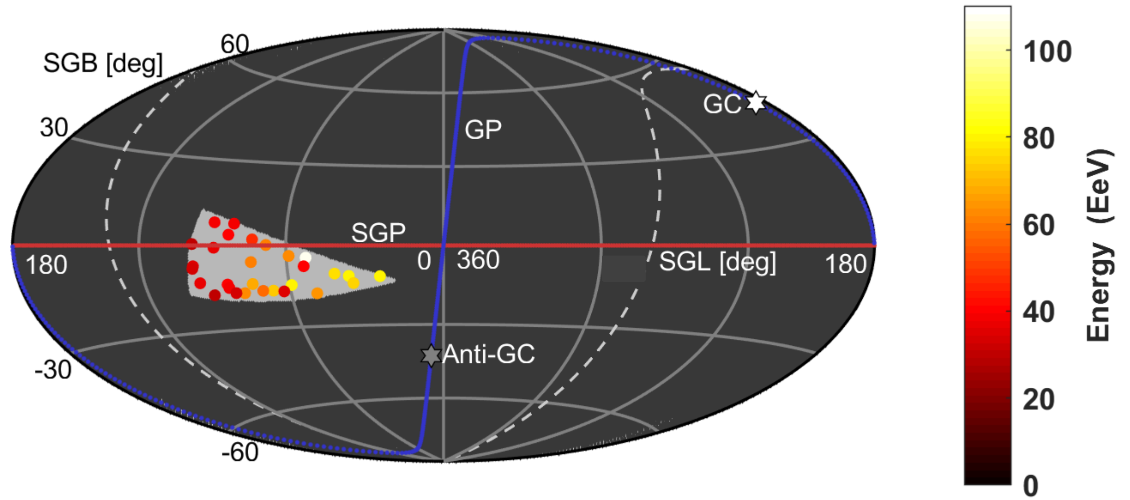
PICTOGRAPH



APPARENT ORIGIN
COHERENT
$E_2 < E_1$
COHERENT
RANDOM
SOURCE
APPARENT ORIGIN
COHERENT FIELD DIRECTION

WEDGE MULTIPLETS

- **Ranked correlation of energy-distance in sections of spherical caps**
- **Highest significance is negative indicating possible magnetic deflection**

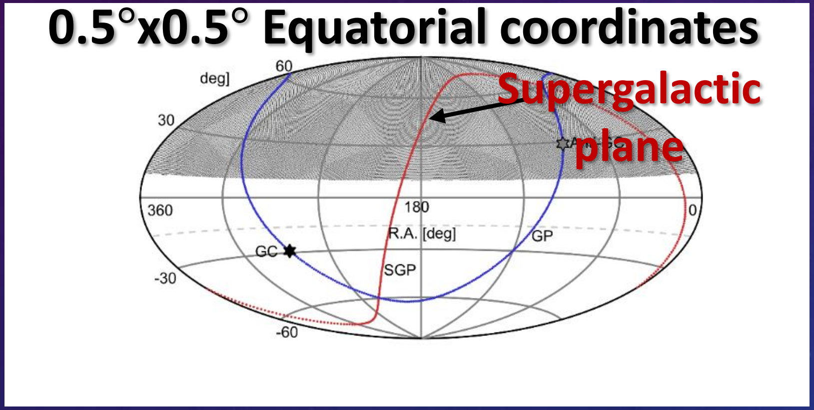


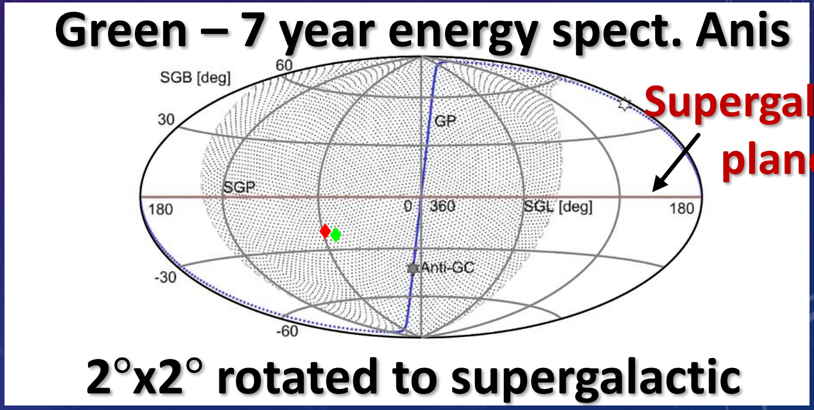
E>=30 EeV, Wedge Width = 30°, Distance<=80°, Direction = 270°

OVERSAMPLING GRID

SGL (supergalactic longitude) and SGB (supergalactic latitude)

Red – 5 year hotspot





- Larger grid spacing due to large parameter scan
  - Single simulation takes >2.5 hours on U of U supercomputers

SCAN PARAMETERS

Scan finds most likely real correlation

Scan result corr. significance is not used for final significance

Scan space limited by computation time, exposure area, statistics.

- **Energy Threshold**
  - **10, 15, 20…100 EeV**
- **Wedge width (spherical cap sections)**
  - **10°, 20°, 30°…90° (+5° on each side of center)**
- **Maximum Distance**
  - **15°, 20°, 25°…90°**
- **Pointing Direction (0° "up" clockwise)**
  - **0°, 5°, 10°…355°**

Mean scan number

(minus less than three events

or scans with no change of events)

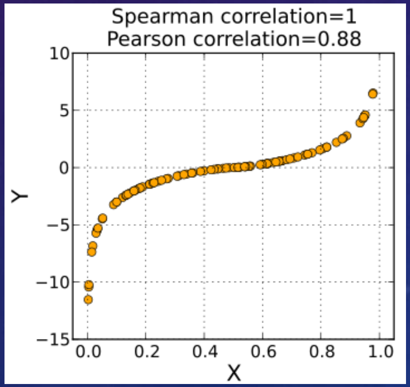
~53,000

RANKED ENERGY/DISTANCE CORRELATION

- **Values are ranked 1 to n. Kendall's correlation is used**

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

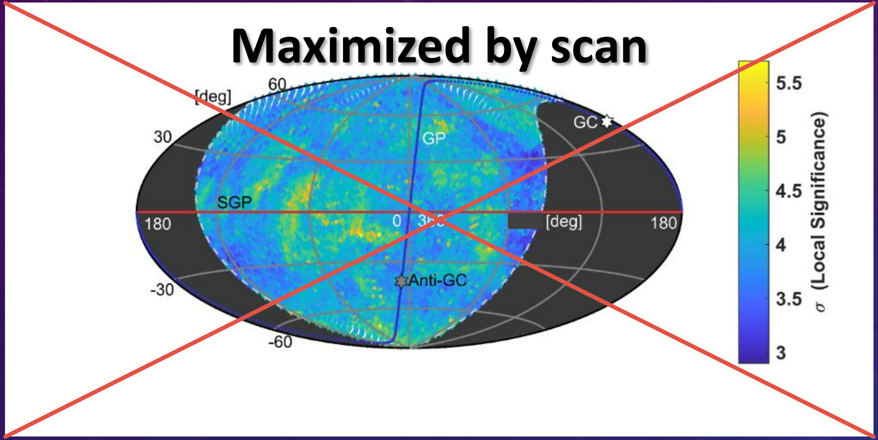
- **Any monotonic function F(x,y) results in $\tau = 1$. Removes model assumption**

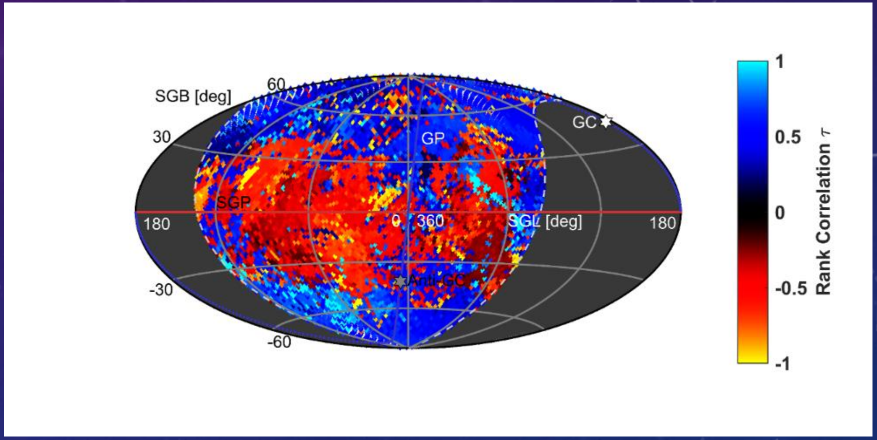


Source: wikipedia

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

MULTIPLET SEARCH RESULT





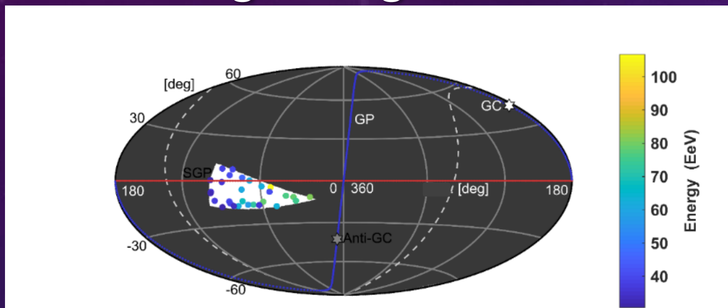
Correlation significance
Maximized by scan
NOT USED IN FINAL SIGNIFICANCE

Strength/sign of correlation
USED TO CALCULATE SIGNIFICANCE

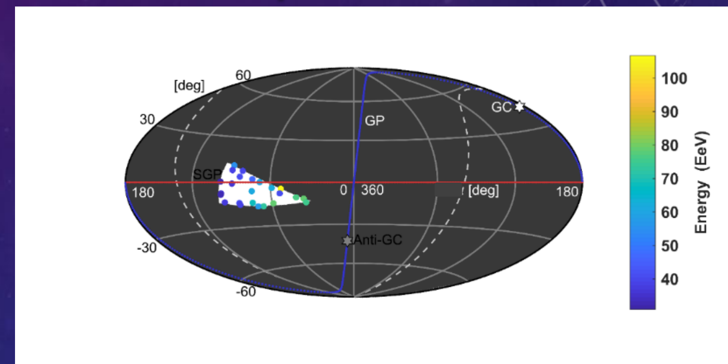
Negative correlations of greater significance correlated with supergalactic plane

DATA WEDGE EXAMPLES

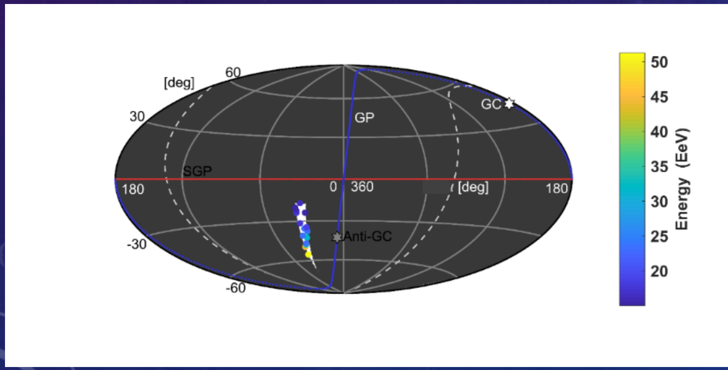
- Ranked correlation of energy-distance in sections of spherical caps
  - 4 highest significances are negative correlations as expected



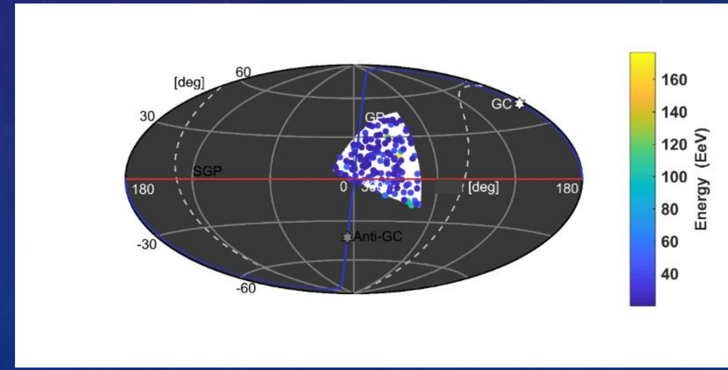
E>=30 EeV, Width = 30°, Distance<=80°, Direction = 270°



E>=30 EeV, Width = 30°, Dist.<=70°, Dir. = 275°

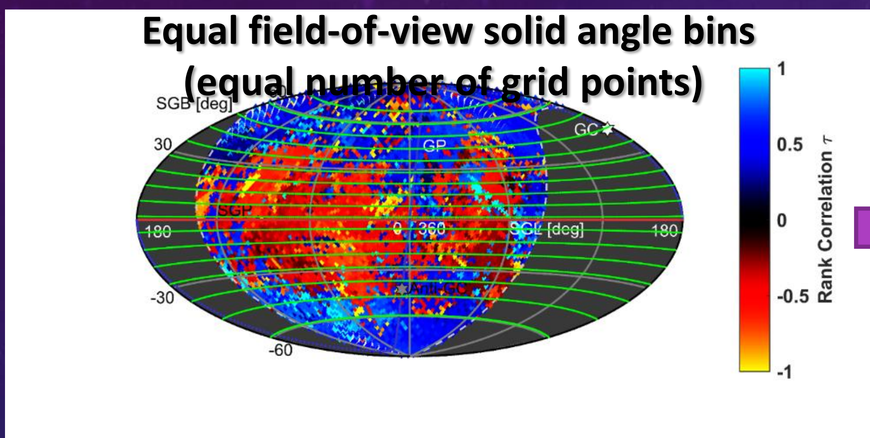


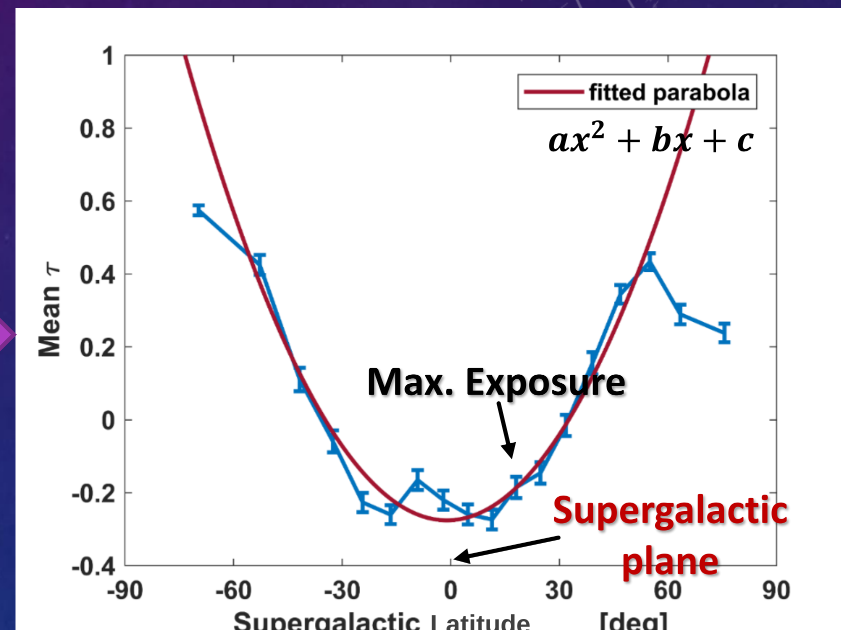
E>=15 EeV, Width = 10°, Dist<=55°, Dir = 345°



E>=20 EeV, Width = 70°, Dist.<=70°, Dir. = 320°

SUPERGALACTIC STRUCTURE



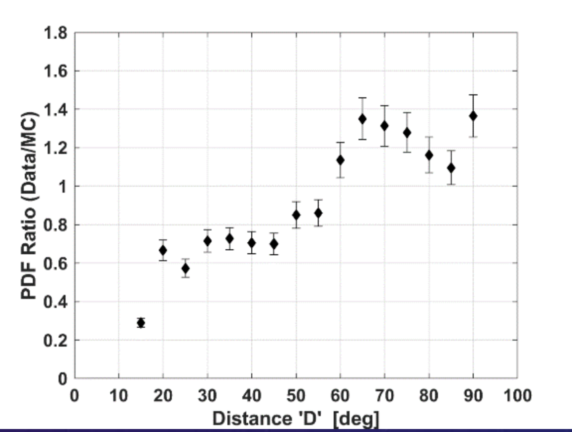


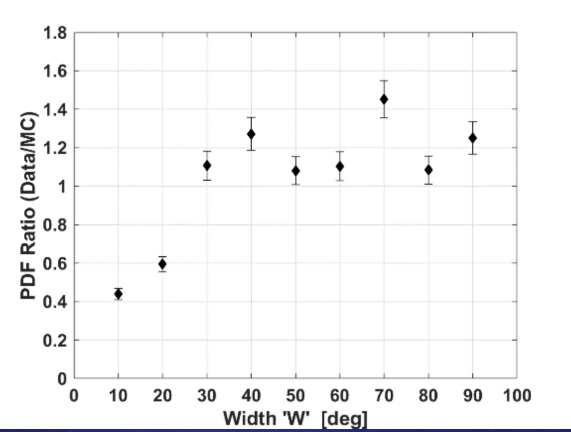
Strength/sign of correlation
USED TO CALCULATE SIGNIFICANCE

Average value of correlation
shows correlation with supergalactic plane

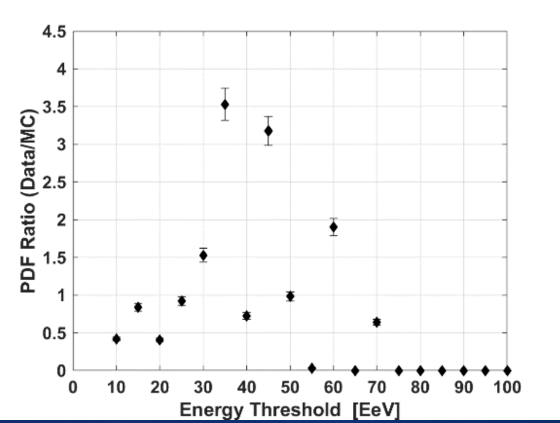
PARAMETER DISTRIBUTIONS

- **Data scan parameter probability distribution ratios to MC**
  - **For negative correlations +/- 40 deg from supergalactic plane**

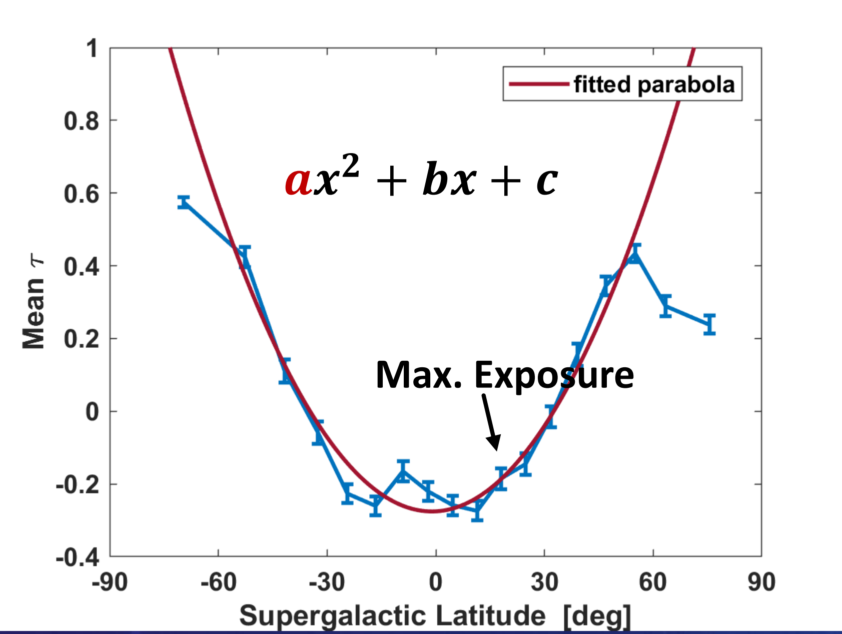


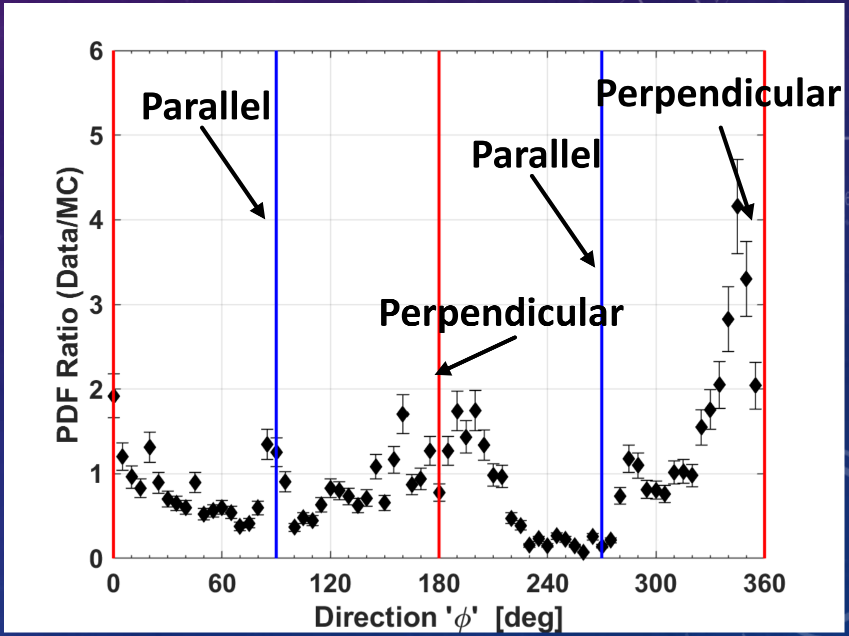


- **Generally biased to more statistics inside the wedge**
- **Not small scale correlations**



PARAMETER DISTRIBUTIONS

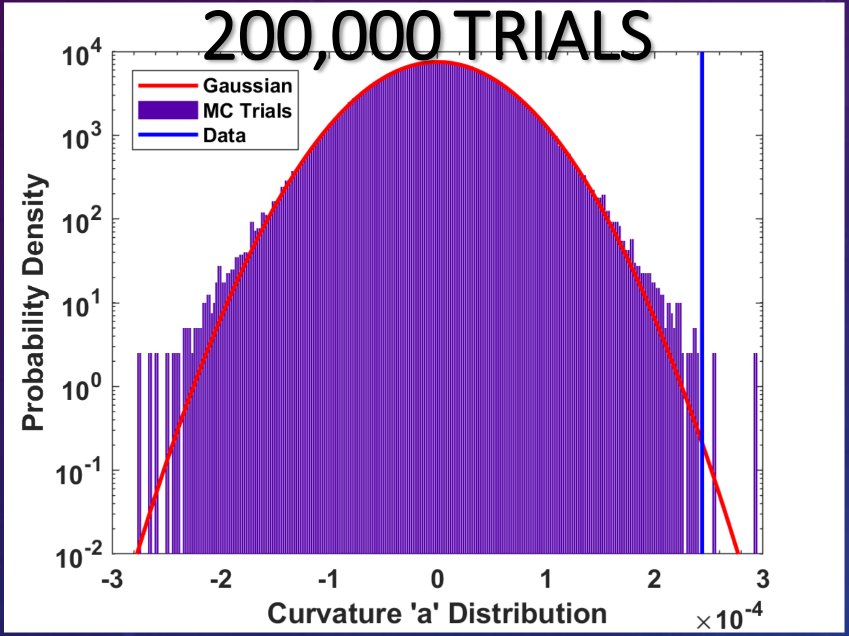


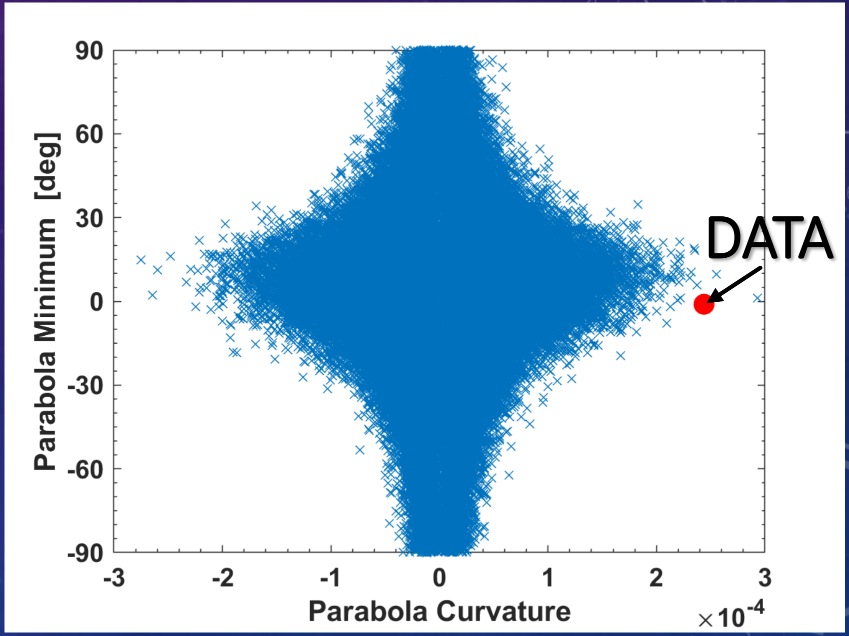


Histogram of pointing directions for *negative bin averages* cutting at different significances

Most common directions are perpendicular (+/- ~10) to the supergalactic plane (and parallel to the left)

TEST STATISTIC

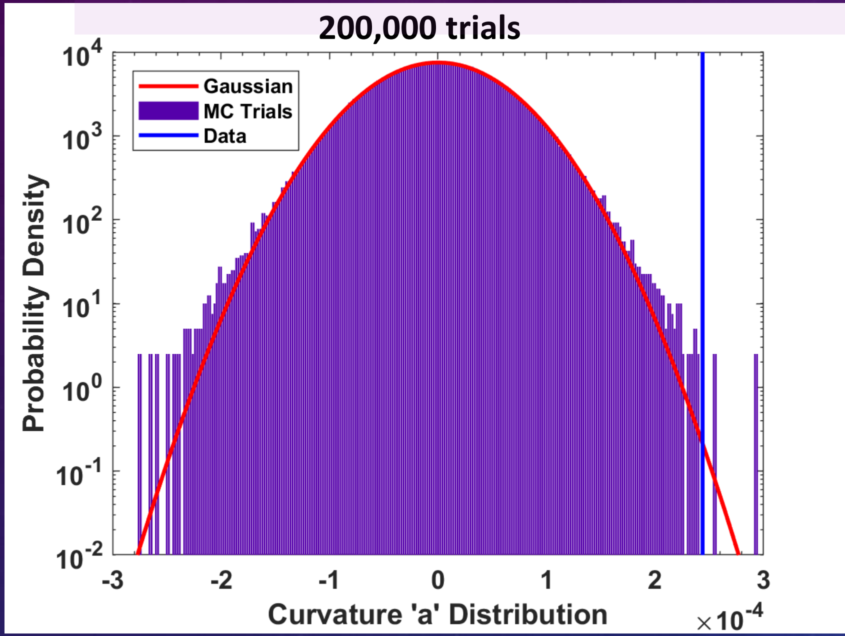




$$ax^2 + bx + c$$

HIGHER CURVATURE
CLOSER TO SUPERGALACTIC PLANE

SIGNIFICANCE



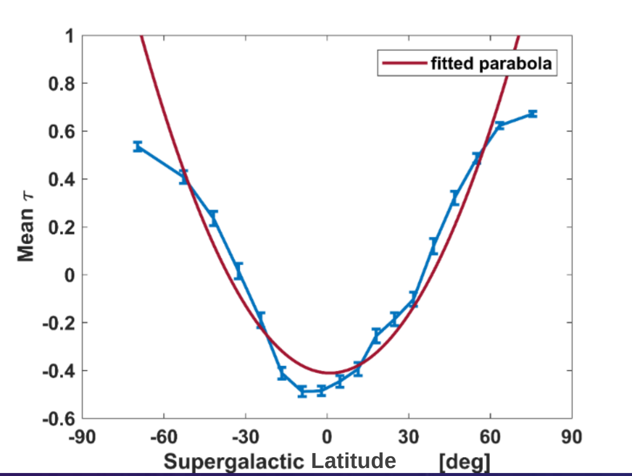
Use variable not scanned for: τ correlation

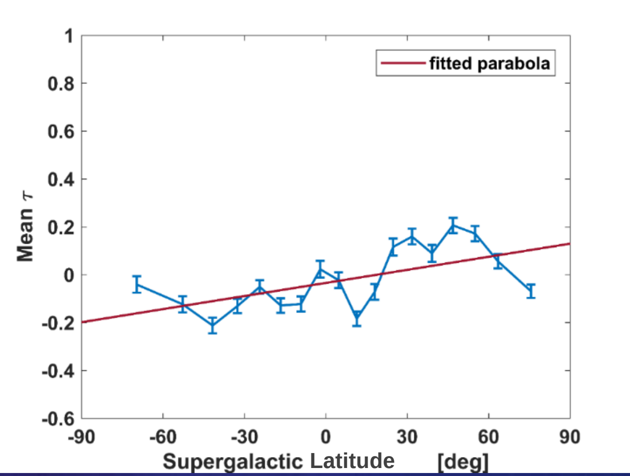
- Fit to parabola $ax^2 + bx + c$
- Find probability that a>=0.000244 (curvature)

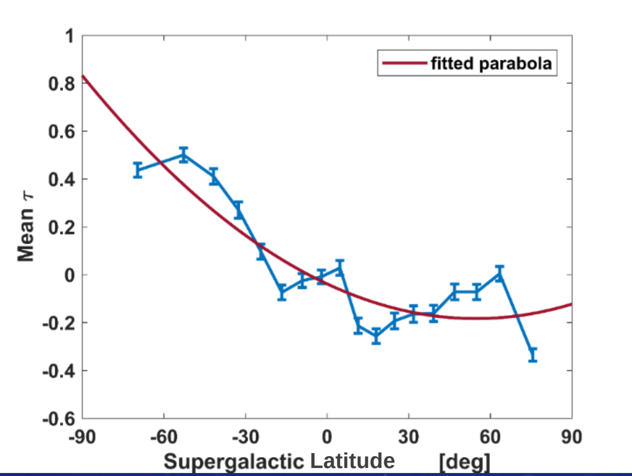
According to Gaussian fit to MC distribution
data significance is 4.56σ

According to two passed MC it is 4.21σ (large uncertainty)

MC TRIAL EXAMPLES





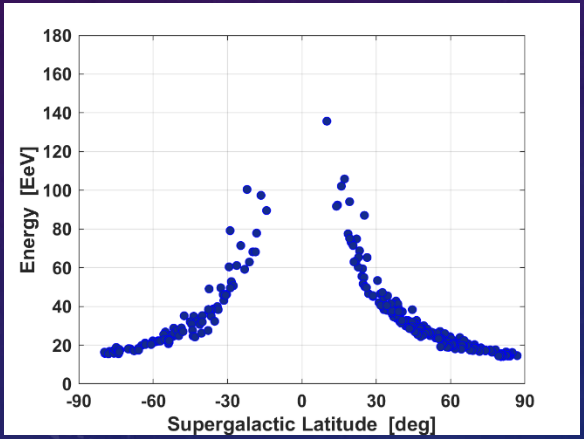


Passed MC
(greater curvature than data)

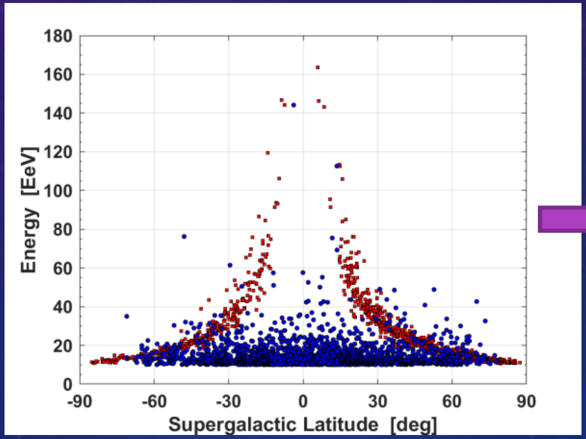
SIMPLE SIMULATION

- 1/E supergalactic plane deflection for event fraction
  - Random “source” position. Gaussian σ=5° plus 1/E deflection
- Isotropic Exposure and uniform SGL
- Total energy distribution matches data

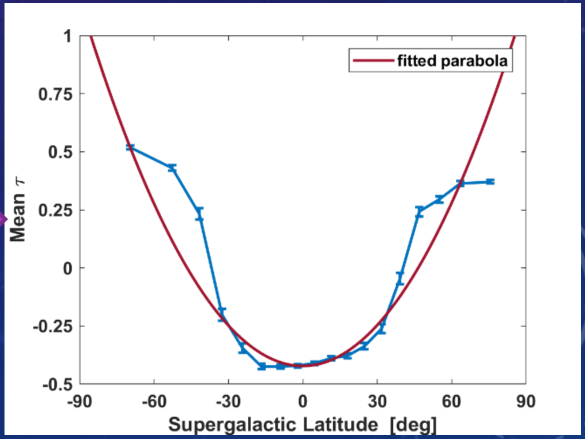
$$\delta \approx 0.5^{\circ} Z \frac{S}{kpc}\frac{B}{\mu G}\frac{10^{20}eV}{E}$$



1/E for 10% of events. $\frac{S}{kpc}\frac{B}{\mu G} = 25$



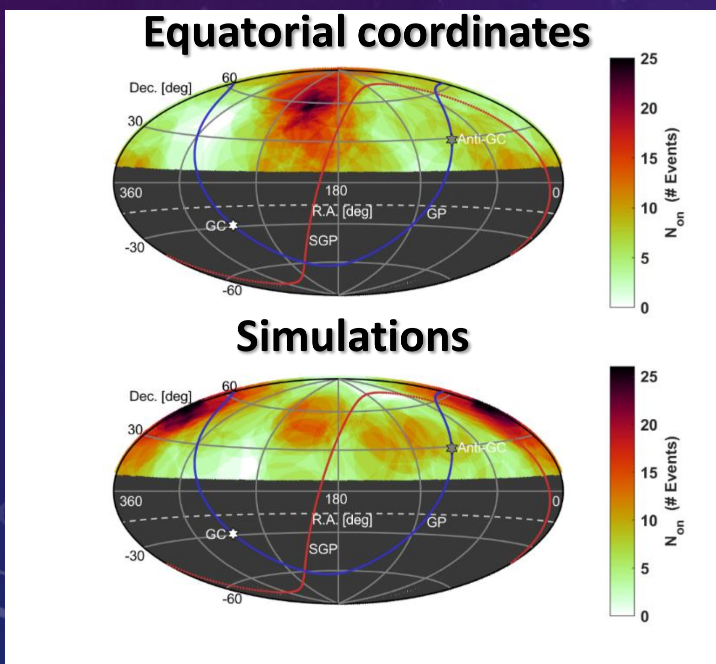
3027 events E>=10^19.0
- Isotropic positions
- Published spectrum



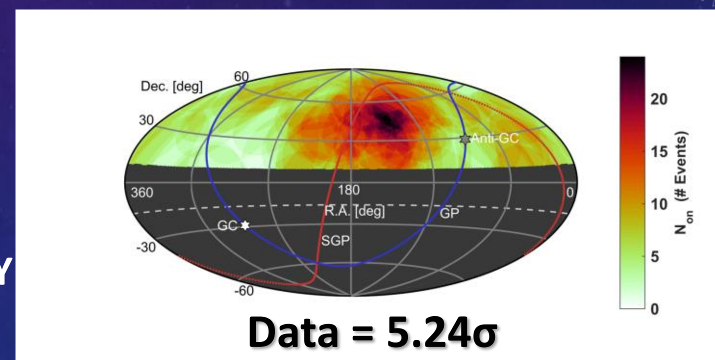
Analysis applied to simulation

SIMPLE SIMULATION - HOTSPOT

- **1/E supergalactic deflection for event fraction**
- **Isotropic Exposure and uniform SGL**
- **Energy distribution published average**



HOTSPOT MORE LIKELY



- **Hotspots not expected on supergalactic plane**
  - **Average (σ>5.24) location 18.9° from SGP (9.3° uncertainty). Hotspot is 17°.**

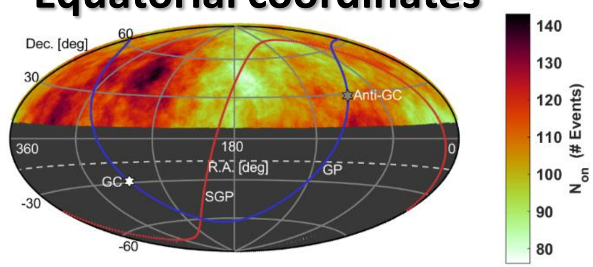
N events inside average 30° equal exposure bins with E>=10^19.75 eV

SIMPLE SIMULATION - COLDSPOT

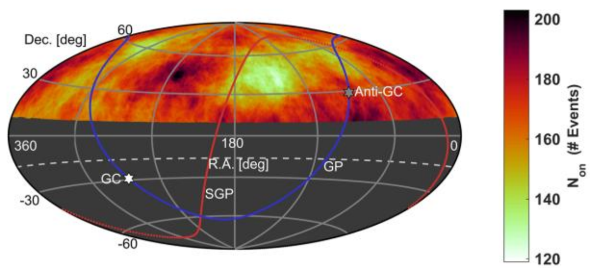
- 1/E supergalactic deflection for event fraction
- Isotropic Exposure and uniform SGL
- Energy distribution published average

COLDSPOT
MORE LIKELY

Equatorial coordinates



Simulation looks very similar to data



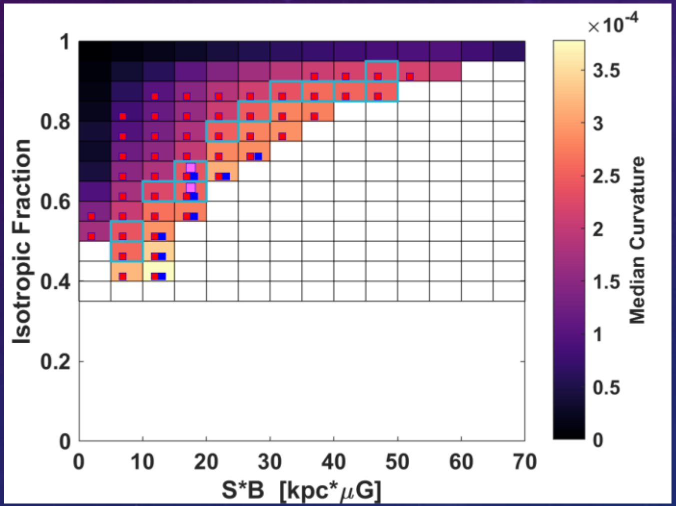
Data

N events inside average 30° equal exposure bins with E>=10^19.2 eV and E<10^19.75 eV

SIMULATION FIELD ESTIMATE

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

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



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

- Light blue outline curvature 'a' like data
- Red boxes hotspots in >1/100 trials
- Blue boxes hot/coldspot in >1/100 trials

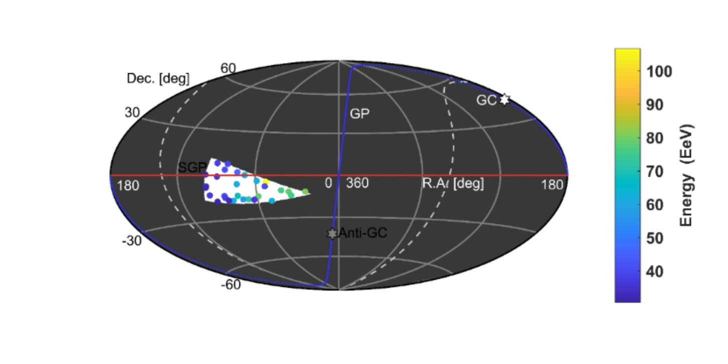
- Big purple boxes match all three tests

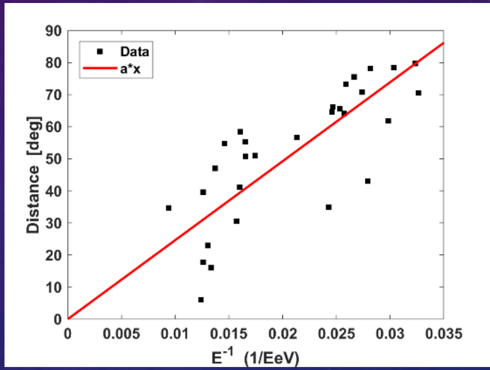
- RESULT: 15 < S*B < 20 kpc*μG and 60 to 70% isotropic
  - *Agrees with data only determination of 19 kpc*μG*

COHERENT FIELD ESTIMATES

- Fit 1/E to straight line

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

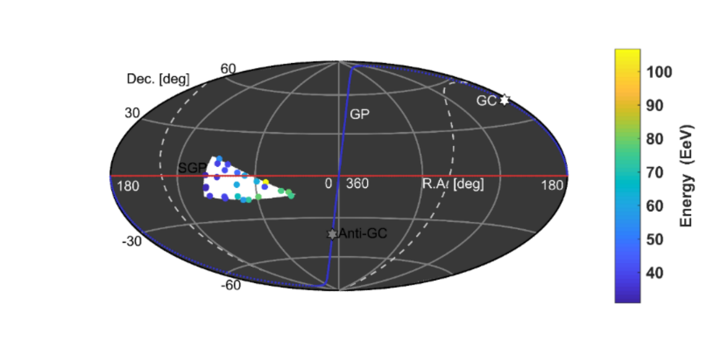


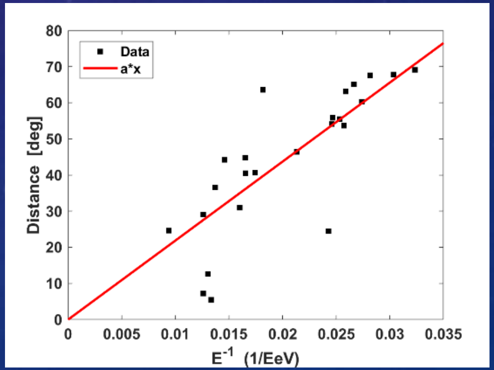


E>=30 EeV, Width = 30°, Distance<=80°, Direction = 270°

- If Z = 1 then $\frac{S}{kpc} \frac{B}{\mu G} = 49.24$
- If S = 3.7 Mpc (M82)

  $B = 13nG$





- If Z = 1 then $\frac{S}{kpc} \frac{B}{\mu G} = 40.16$
- If S = 3.7 Mpc (M82)

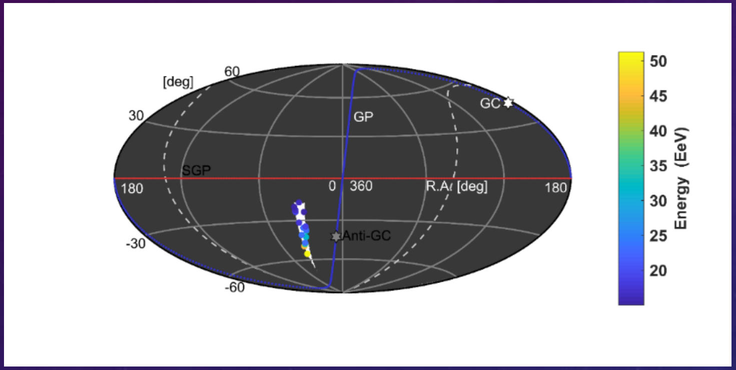
  $B = 12nG$

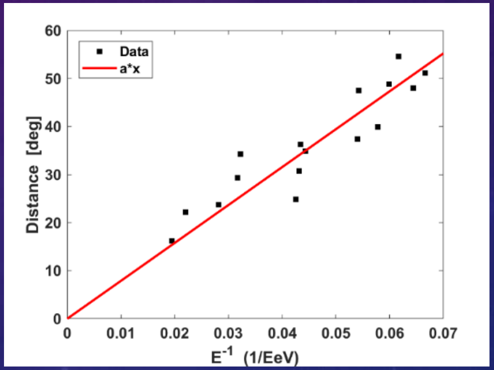
E>=30 EeV, Width = 30°, Distance<=70°, Direction = 275°

COHERENT FIELD ESTIMATES

- **Fit 1/E to straight line**

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

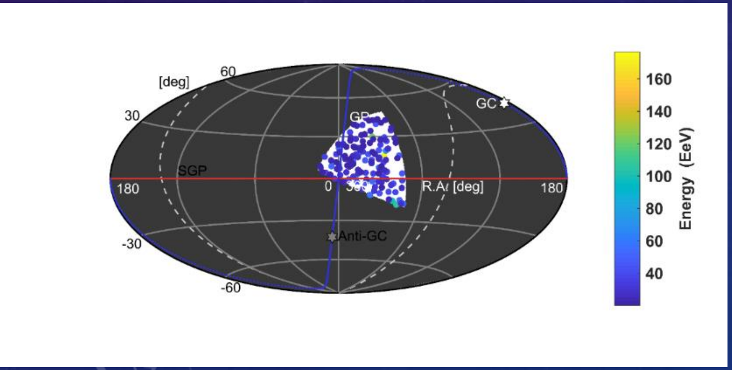


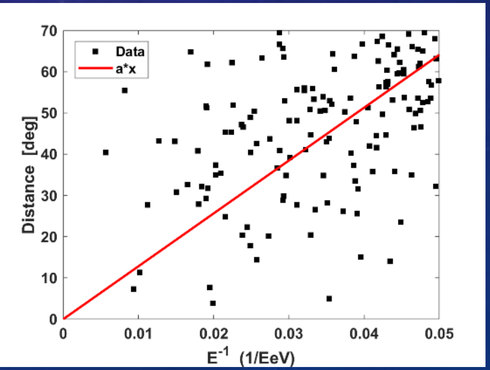


E>=15 EeV, Width = 10°, Distance<=55°, Direction = 345°

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

  B = 4nG



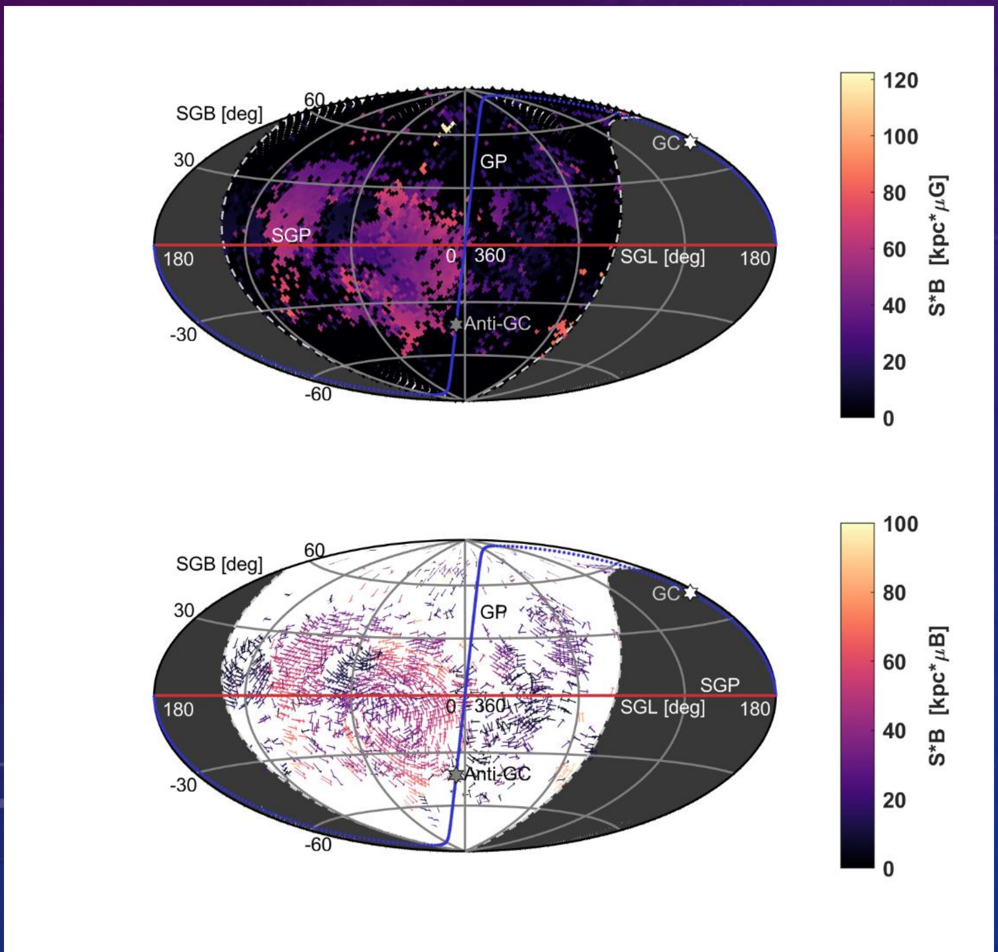


E>=30 EeV, Width = 30°, Distance<=70°, Direction = 320°

- **If Z = 1 then** $\frac{S}{kpc}\frac{B}{\mu G} = 22.56$
- **If S = 3.7 Mpc (M82)**

  B = 6nG

COREHENT FIELD ESTIMATES

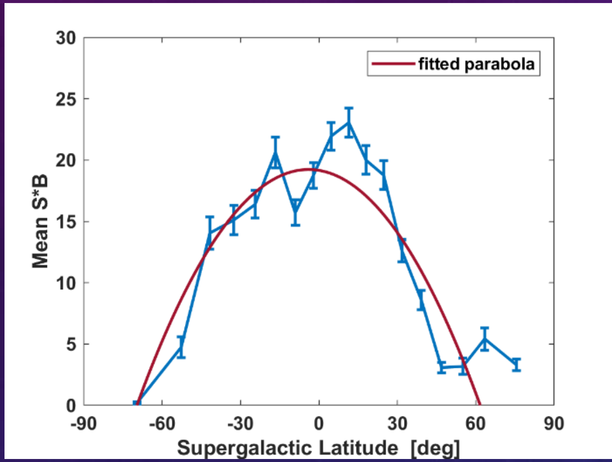


- R^2<0 fits no better than horizontal line (all random field)
  - S*B = 0

- Field directions rotated 90° from wedge direction

- Apparent sheet and filament?

SUPERGALACTIC FIELD CORRELATION

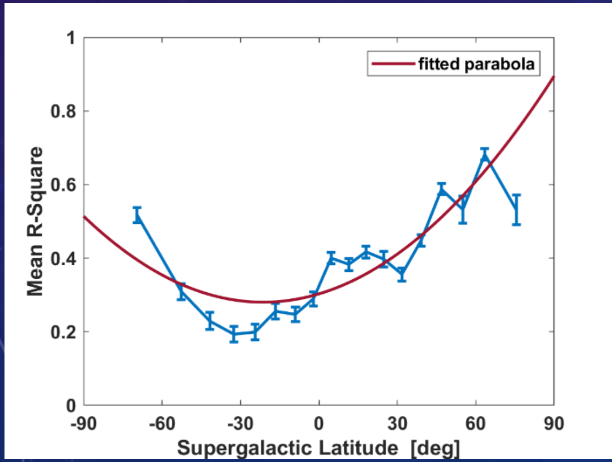


NOT SCANNED FOR

(signed ranked correlations)

- **Average field in equal solid angle bins**
  - **Fit shows field is consistent with $S*B \approx 19$ kpc* μG at supergalactic plane**

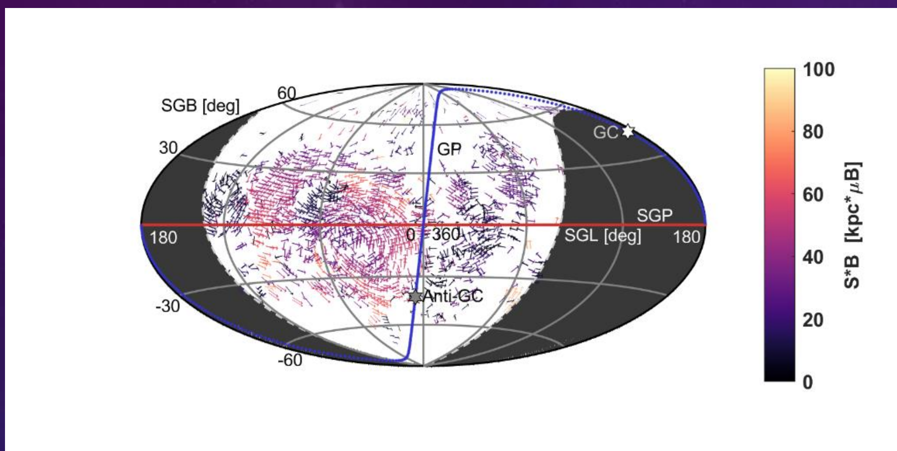
Agrees with simulation determination of $15 < S*B < 20$ kpc*μG



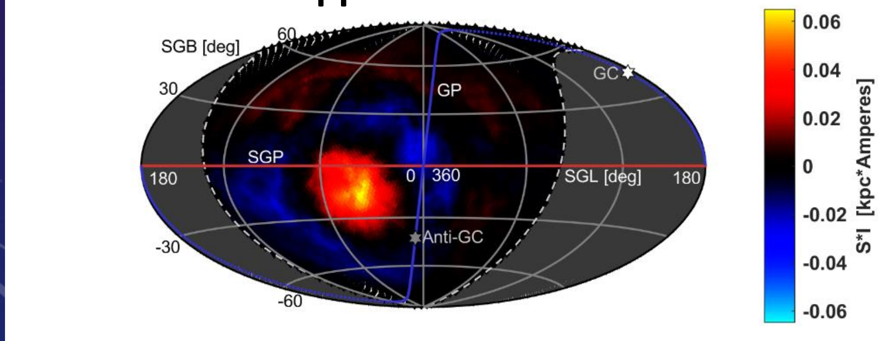
- **R-Square is proportional to random component**
- **Maximum random field is at hot/coldspot**

POSSIBLE FILAMENT?

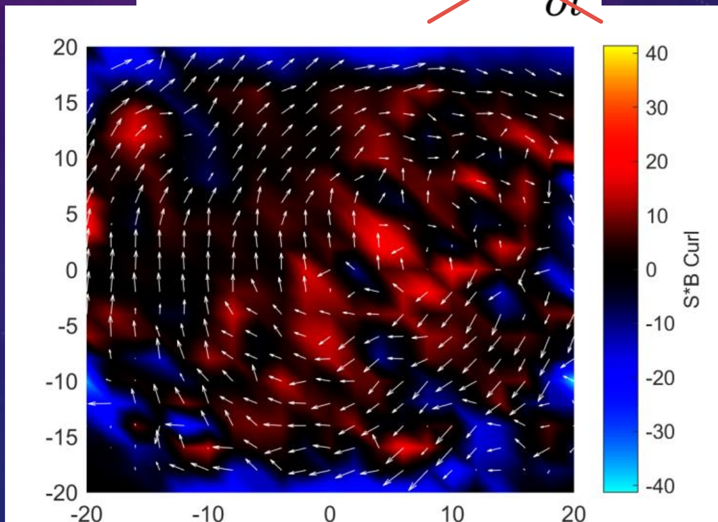
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \cancel{\mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}}$$



Apparent filament?



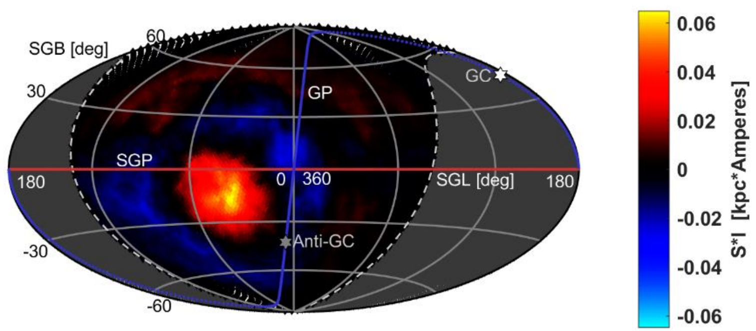
Apparent current flowing towards us inside 25° bin



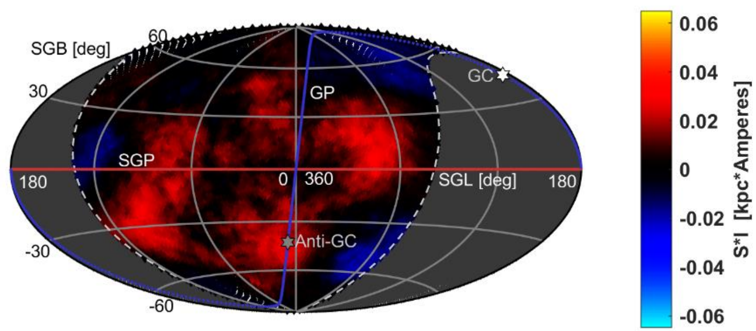
Point of max. *I*

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

POSSIBLE FILAMENT?



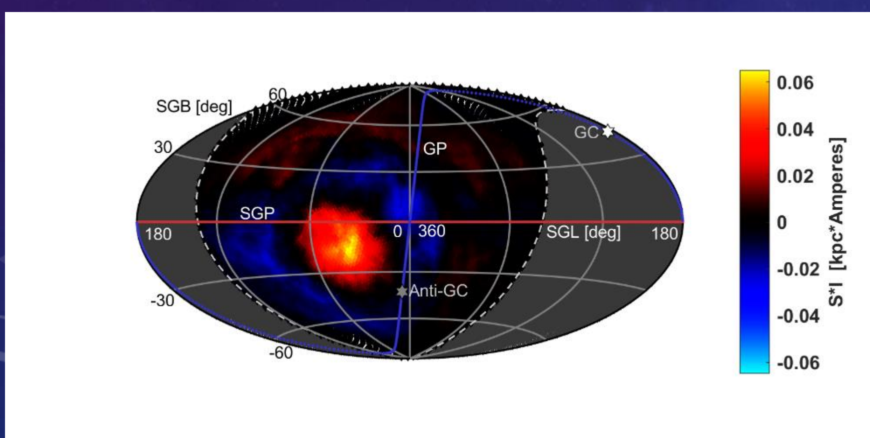
Apparent current flowing towards us



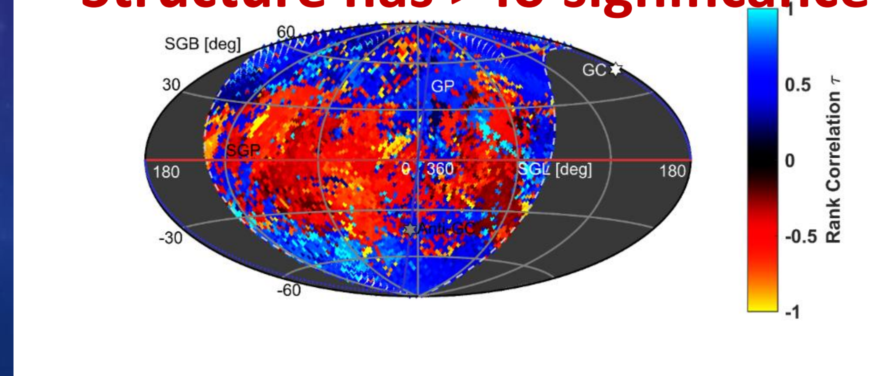
MC Example

CONCLUSION

- Multiplet structure correlates with the supergalactic plane
- Suggests sources, coherent, and random fields correlated with SGP
  - A measure of magnetic fields using UHECR
- Consistent with supergalactic sheet field of ~19 kpc*μG (estimate of data and simulation)
  - Simulation exhibits multplet curvature and hot/coldspot behavior



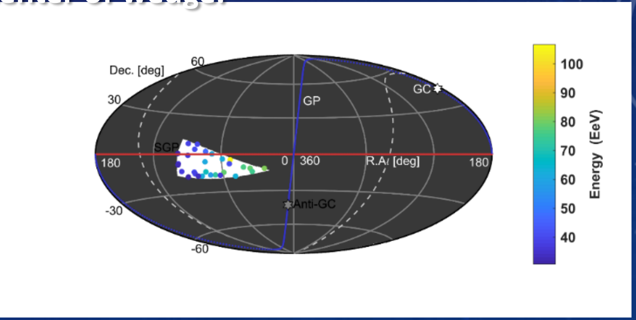
- Structure has >4σ significance



ADDITIONAL

Steps

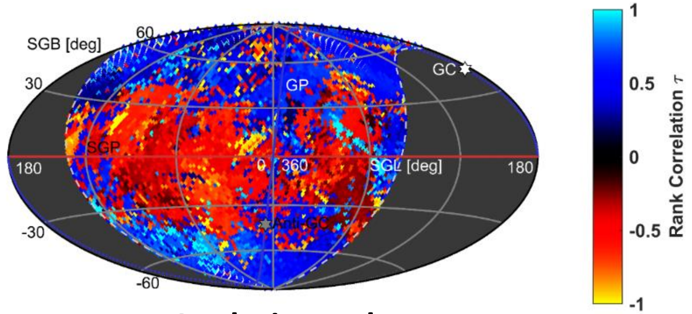
- Data: tight cuts for 10^19 eV resolution (like energy spectrum anisotropy).
  - Variables needed: energy and pointing direction in supergalactic coords.
- Field of view 2° equally spaced grid (down to -16 Dec).
  - Rotated into supergalactic coords (supergalactic hypothesis).
- Wedges:
  - Spherical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



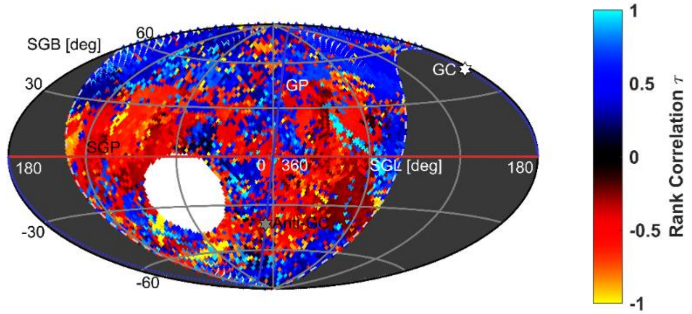
Steps

- 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.

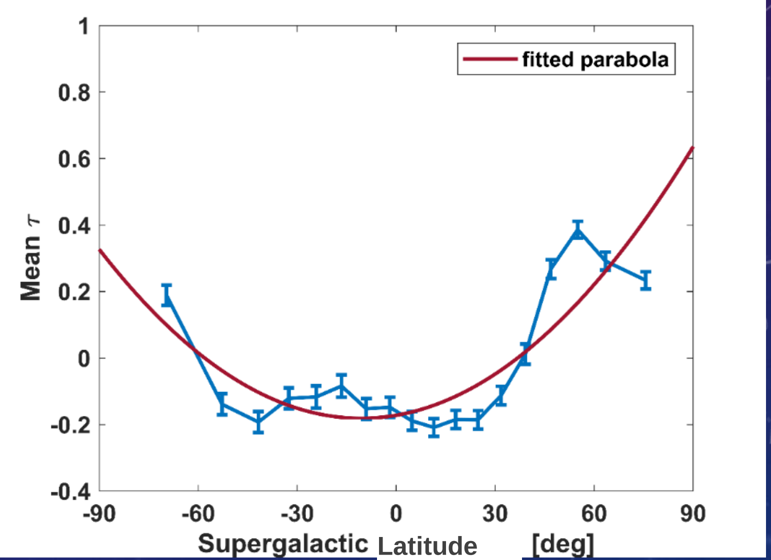
HOTSPOT AREA CONTRIBUTION



Analysis result

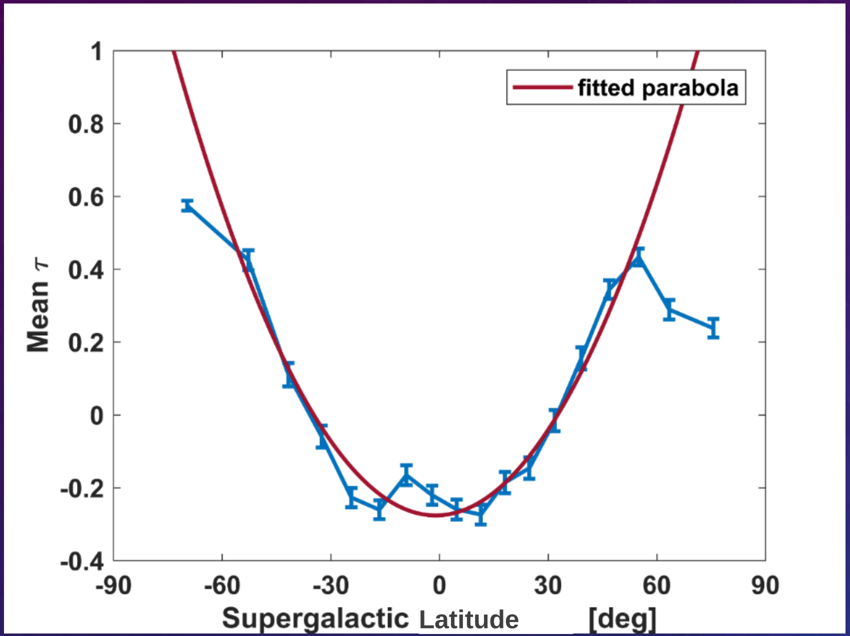


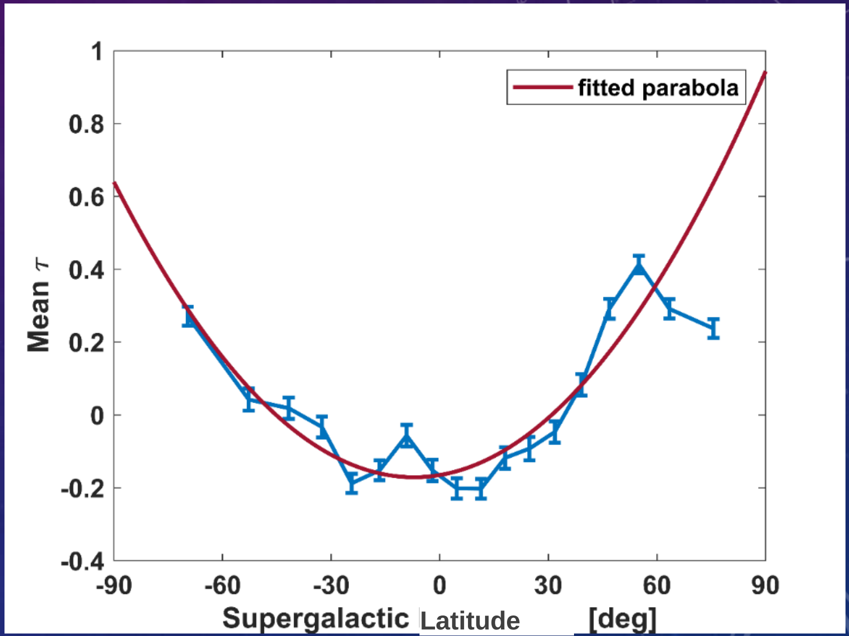
Removing hotspot area (144, 41 equatorial)



Removing events and grid 25° around hotspot

HOTSPOT AREA SCRAMBLING



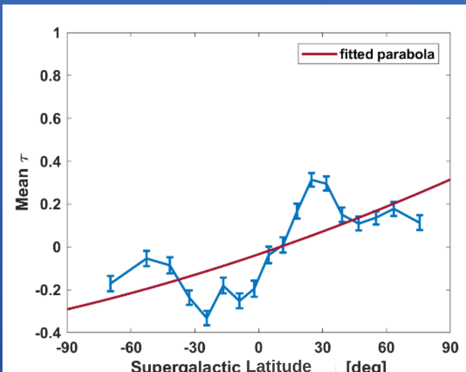


Analysis result

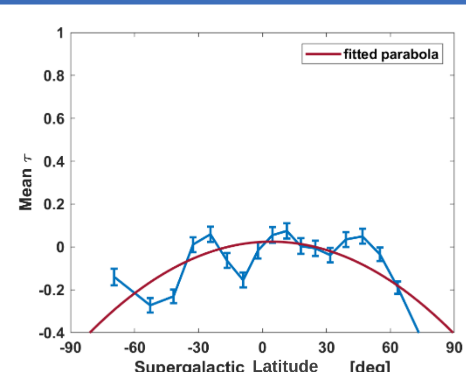
Scrambling energies of hotspot events E>57 EeV

Configuration of events E>57 EeV within hotspot area matters

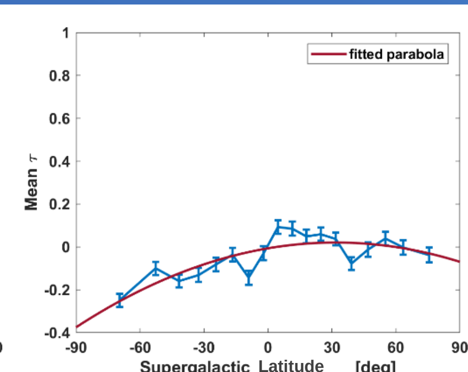
EACH YEAR OF DATA



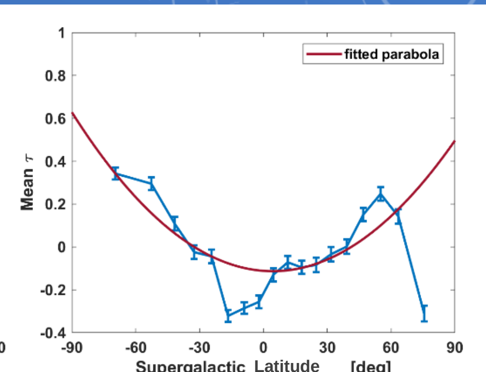
First year



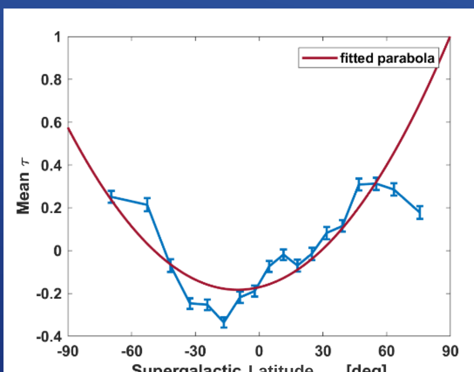
Two years



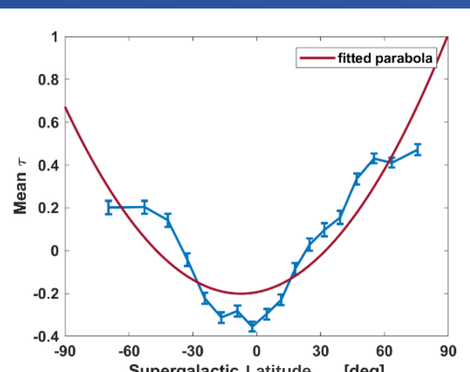
Three years



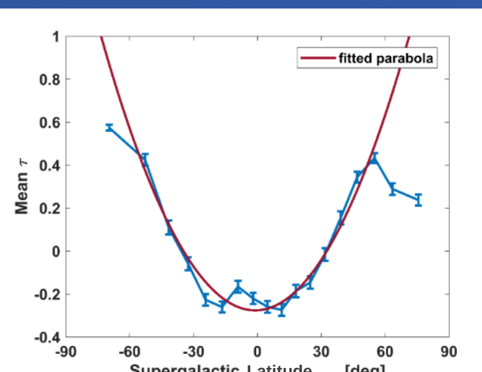
Four years



Five years

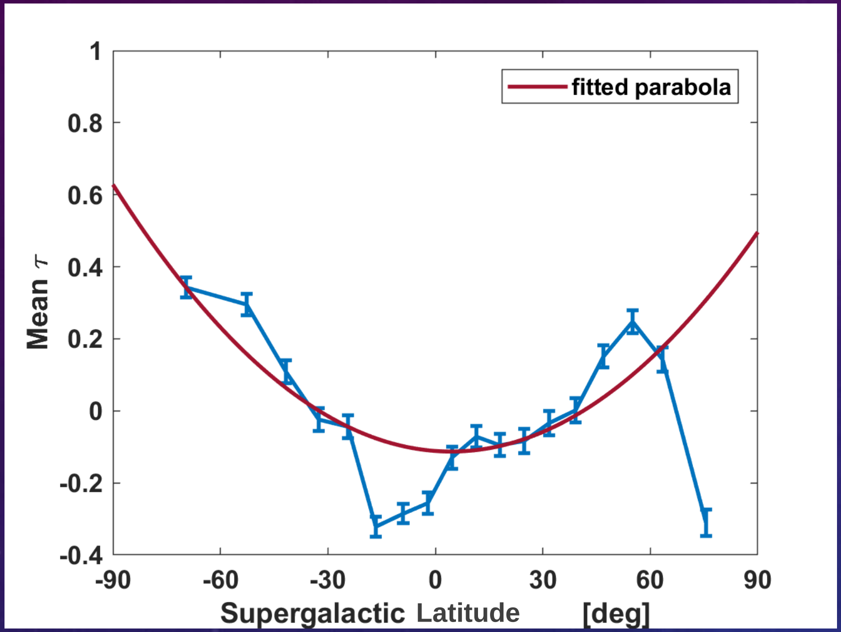


Six years

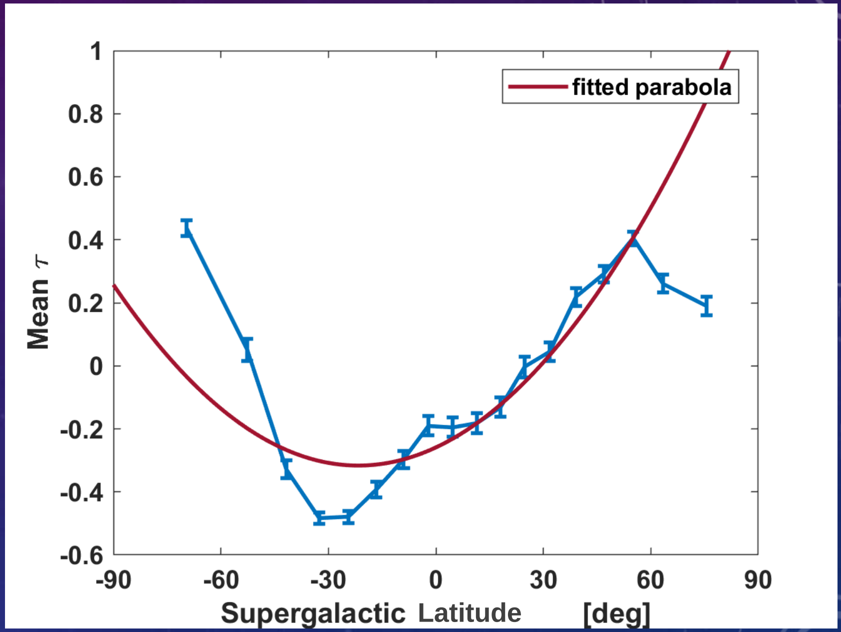


Seven years

FIRST FOUR AND LAST FOUR YEARS



First Four Years

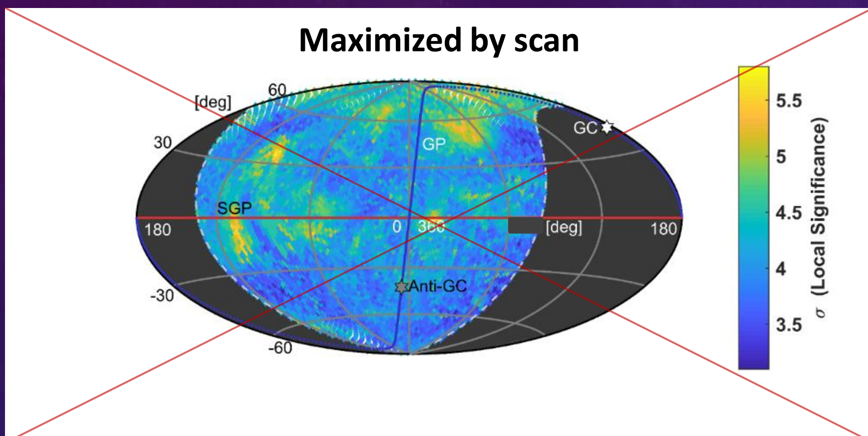


Last Four Years

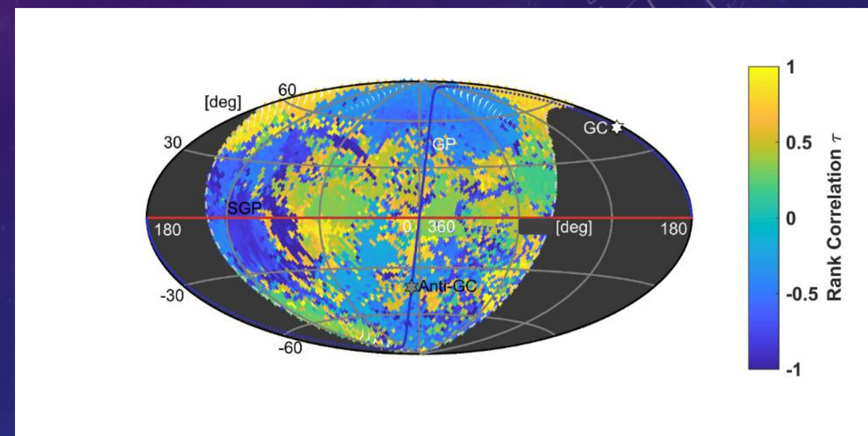
Seven Years Data (one year overlap)

RANDOM MONTE CARLO EXAMPLE

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



Significance of correlation
NOT USED IN FINAL SIGNIFICANCE

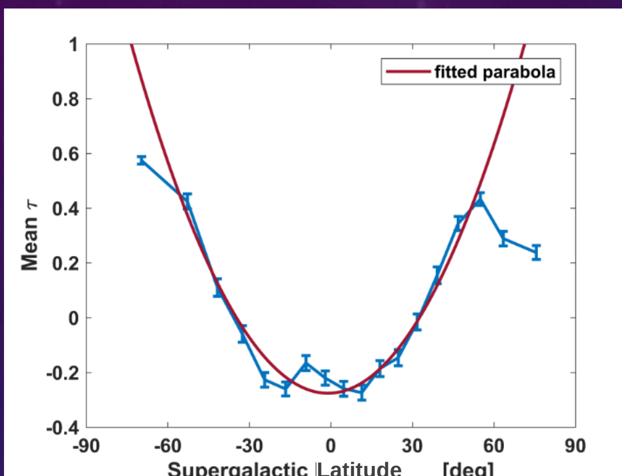


Strength/sign of correlation
USED TO CALCULATE SIGNIFICANCE

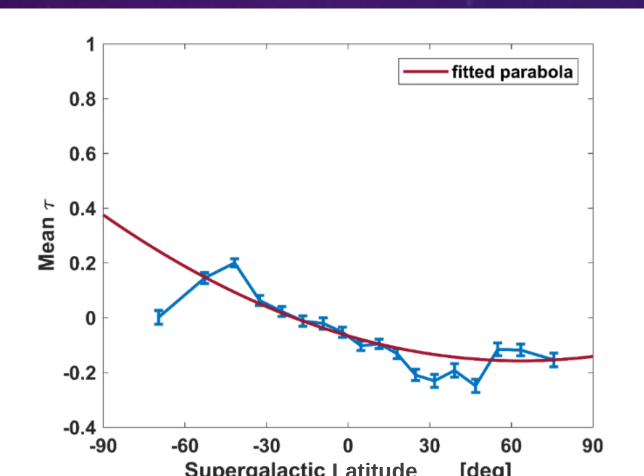
CORR. FILTER SHAPE

- *Test of magnetic field configuration*

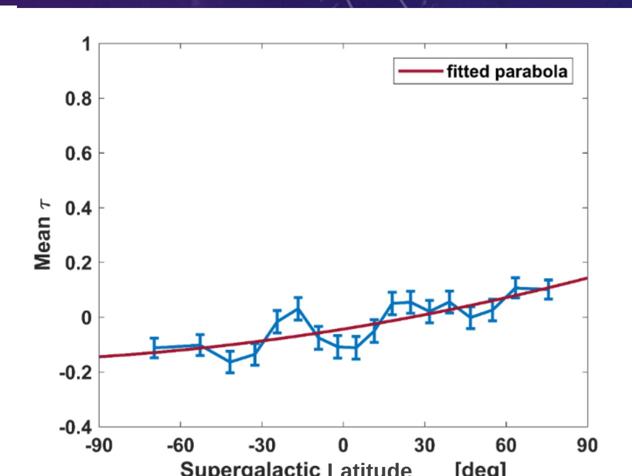
THESE ARE ALL DATA



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

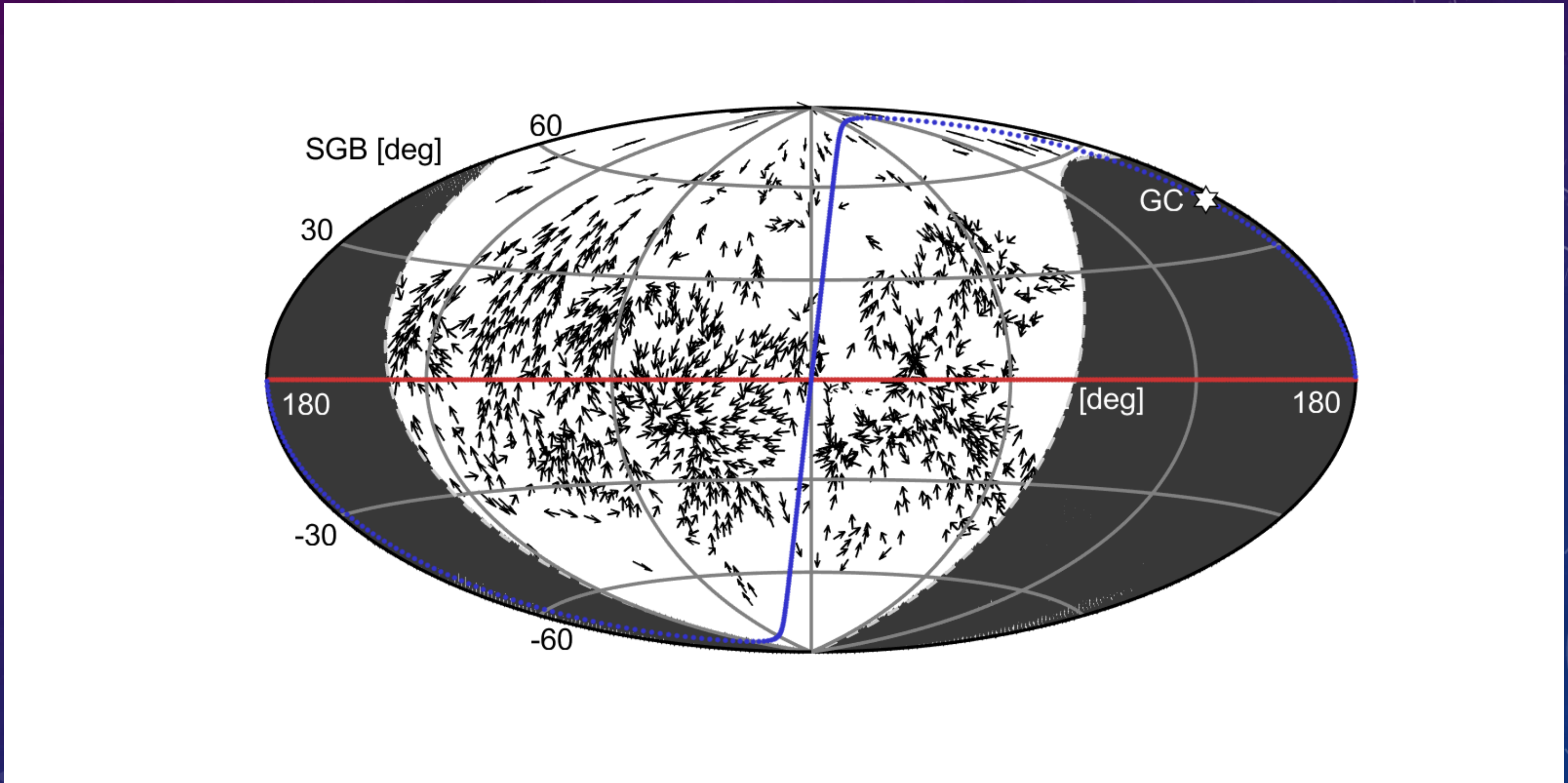


- Spherical caps
  - *Test of random fields*



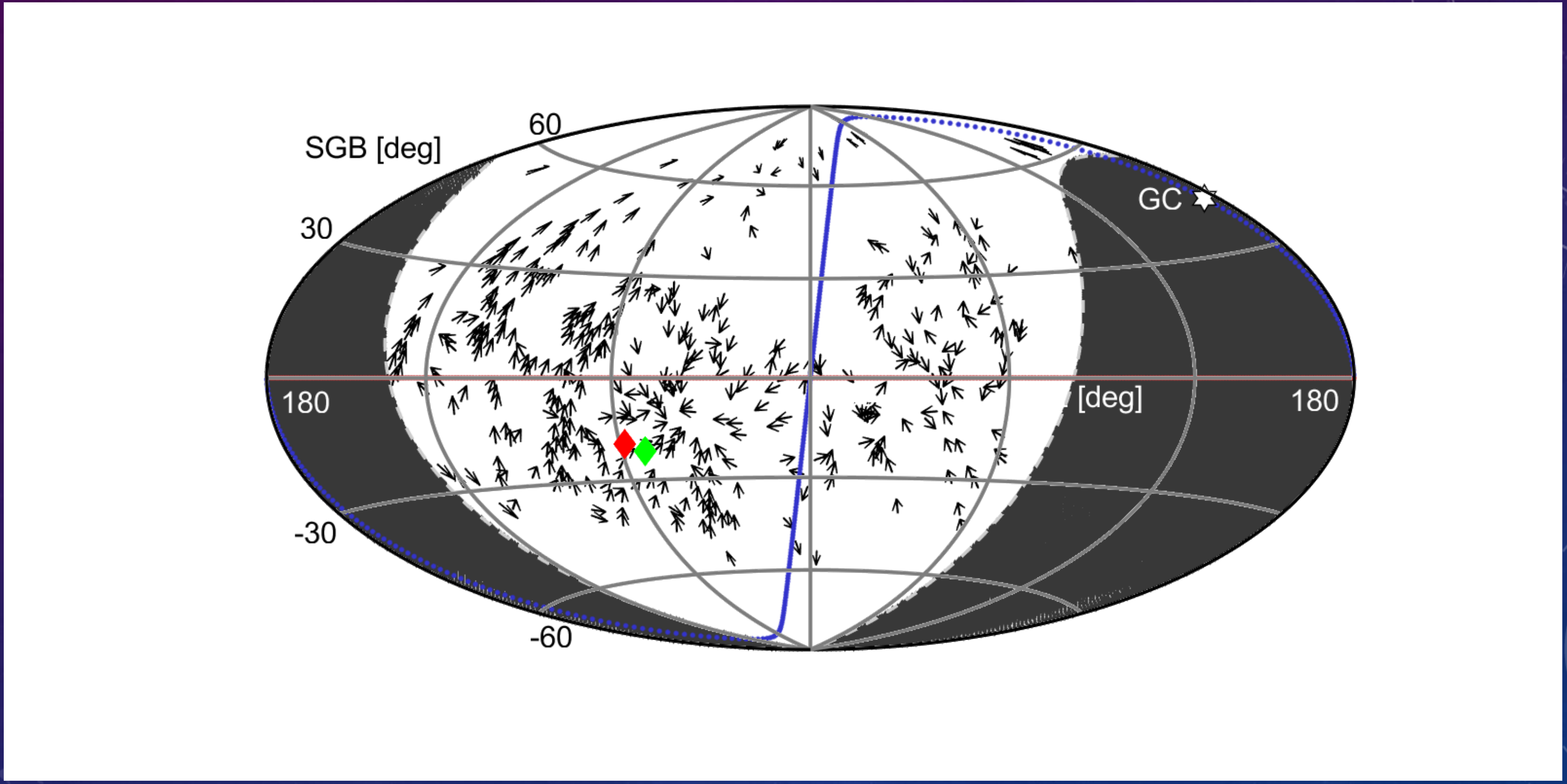
- Squares
  - *Test of uniform fields*
    - 0.5 to 3 deg wide

DIRECTION OF CORRELATIONS



1/3 grid points greater than 3 sigma

DIRECTION OF CORRELATIONS



Grid points greater than 4.5 sigma