TA Anisotropy Summary

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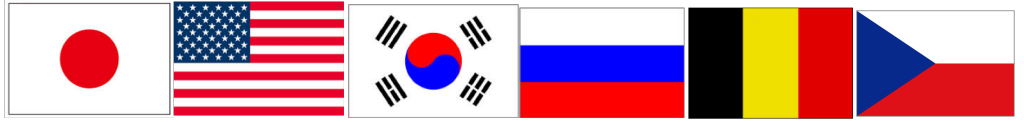
For the TA Collaboration

Outline

- Telescope Array experiment
- Recent results
  - Correlation with LSS
  - Hotspot in the northern sky
  - Spectral anisotropy at Hotspot
  - Small-scale cluster search
  - Correlation with starburst galaxies
  - Supergalactic structure of multiplets
- TAx4 Project



Telescope Array Collaboration

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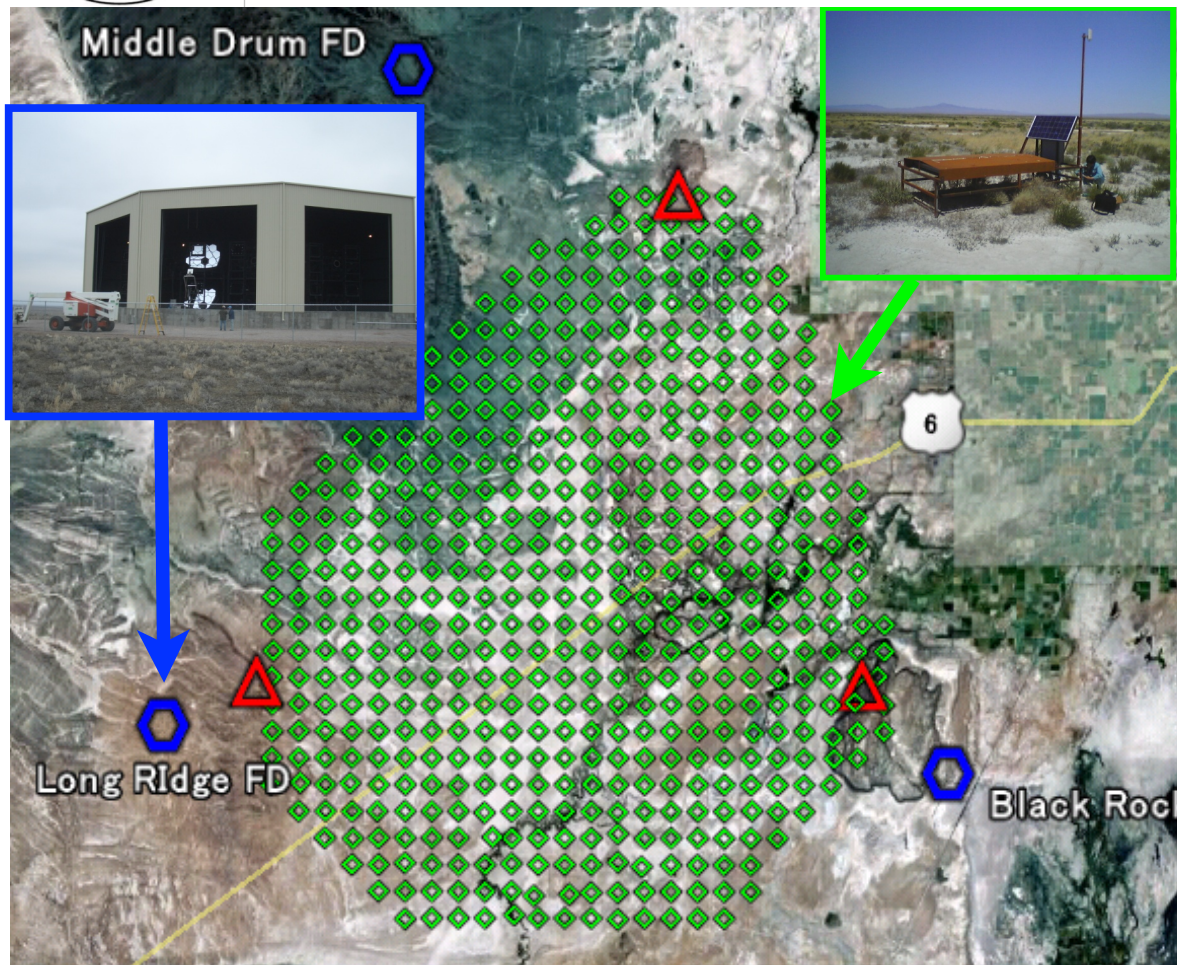
Telescope Array (TA)

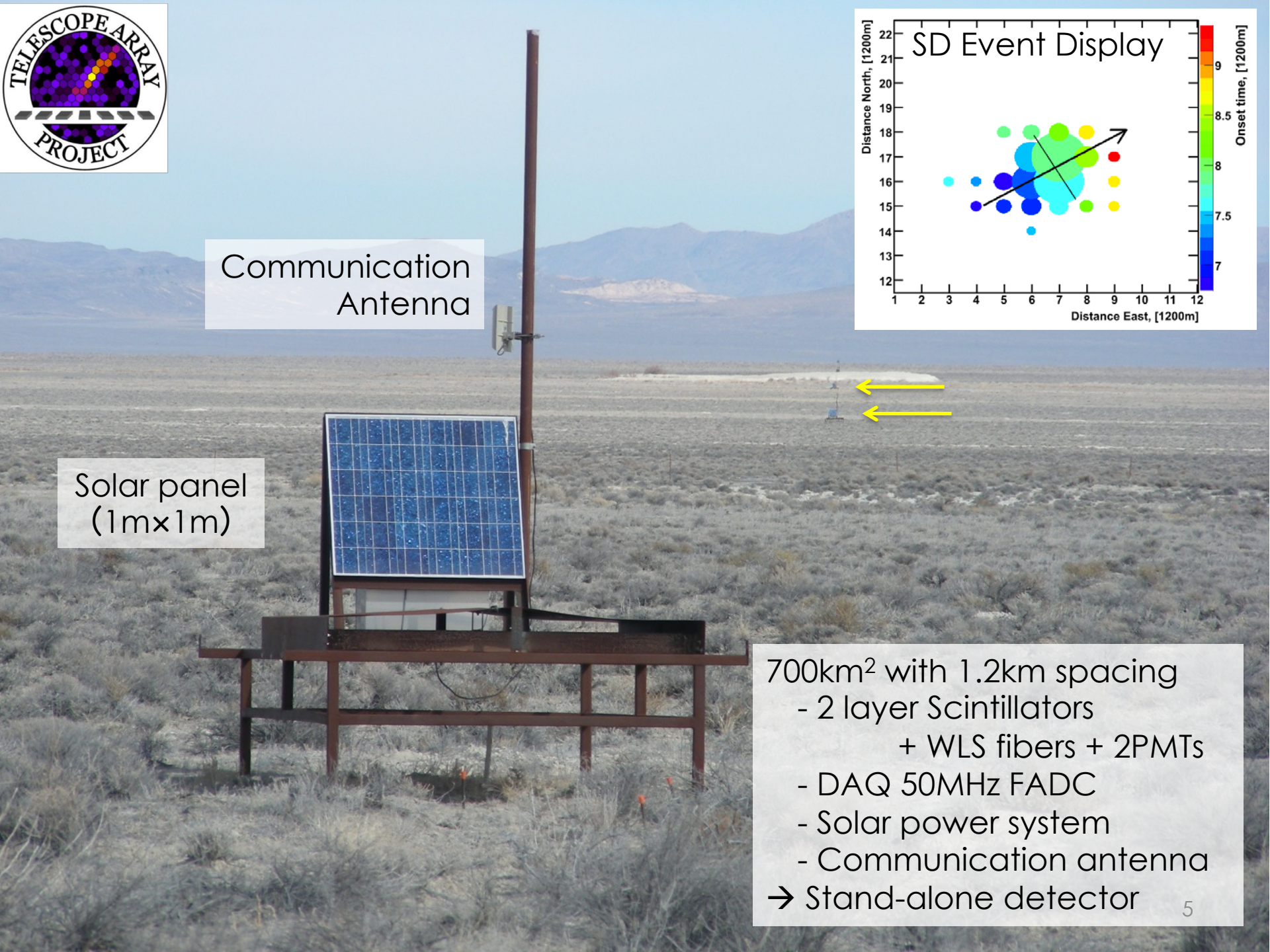


- Utah, USA
  - 39.3°N, 112.9°W
  - 1400m asl.
- Surface Detector (SD)
  - 3m^2 Scintillation det.
  - 507 detectors
  - 1.2km spacing
  - Effective area 700km^2

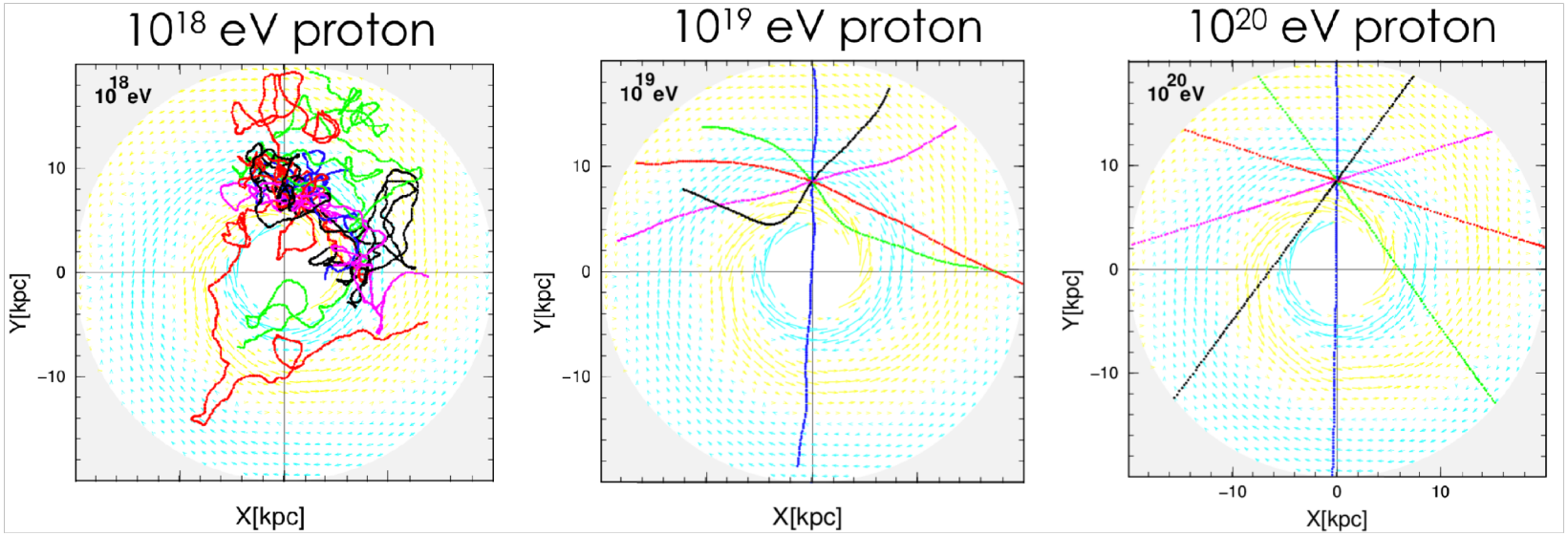
  → high duty cycle
- Fluorescence Det. (FD)
  - 3 stations
  - 12 telescopes/station

  → SD energy is scaled to FD energy (1/1.27)

The TA is the largest aperture hybrid cosmic ray detectors in the northern hemisphere.

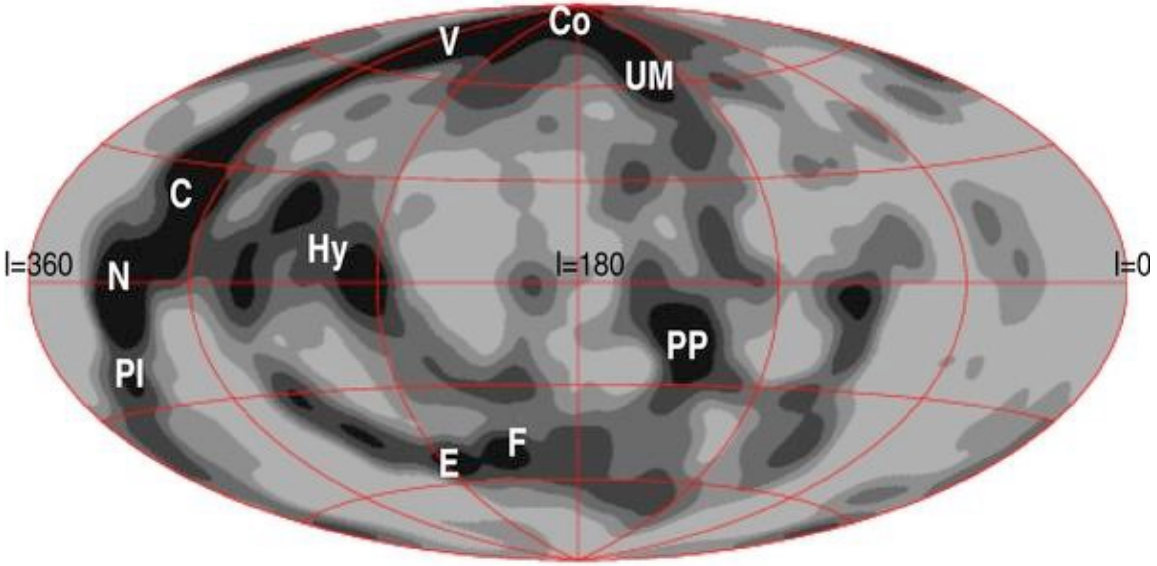

Communication Antenna
Solar panel (1m×1m)
SD Event Display
Distance North, [1200m]
Distance East, [1200m]
Onset time, [1200m]
700km^2 with 1.2km spacing
- 2 layer Scintillators
+ WLS fibers + 2PMTs
- DAQ 50MHz FADC
- Solar power system
- Communication antenna
→ Stand-alone detector

UHECR Anisotropy Search



Possible particle astronomy?

Correlation with LSS



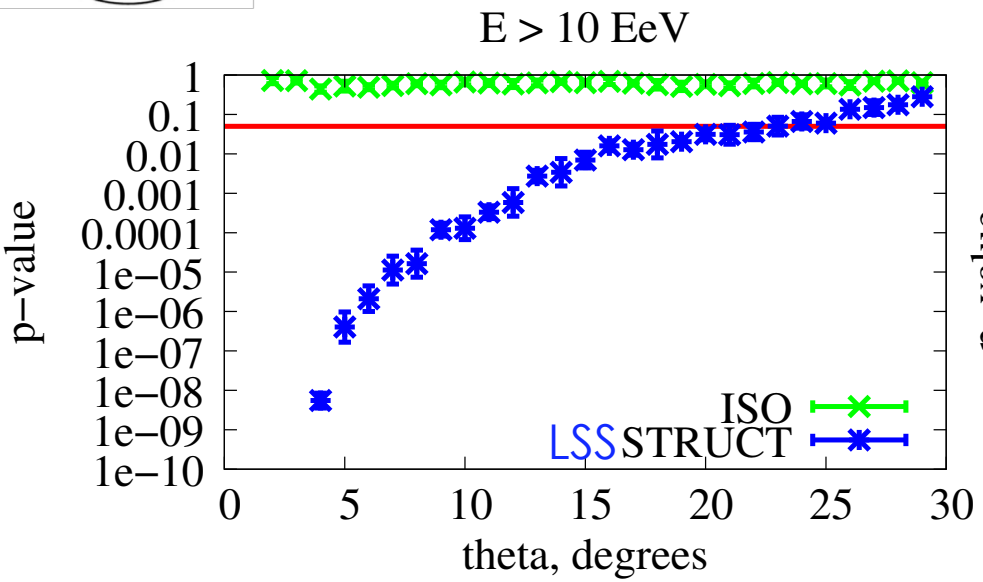
C: Centaurus SCl (60 Mpc);
Co: Coma Cl (90 Mpc);
E: Eridanus Cl (30 Mpc);
F: Fornax Cl (20 Mpc);
Hy: Hydra SCl (50 Mpc);
N: Norma SCl (65 Mpc);
PI: Pavo-Indus SCl (70 Mpc);
PP: Perseus-Pisces SCl (70 Mpc);
UM: Ursa Major Cl (20 Mpc);
and V: Virgo Cl (20 Mpc).

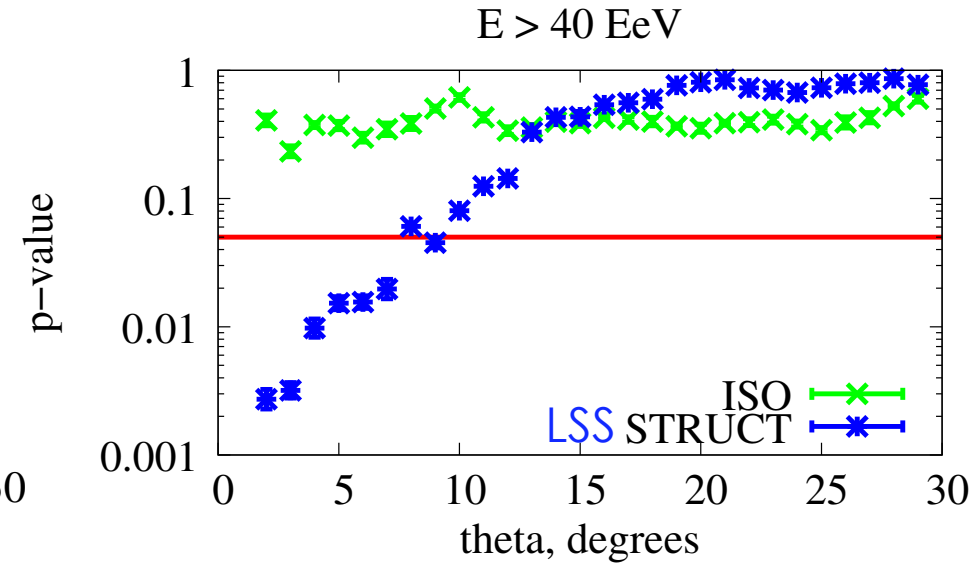
- Large-Scale Structure model 2MASS Galaxy catalog (XSCz)
- Grey Pattern: flux model with 6° radius circle smearing angle
  → Matter density ∝ Cosmic-ray luminosity

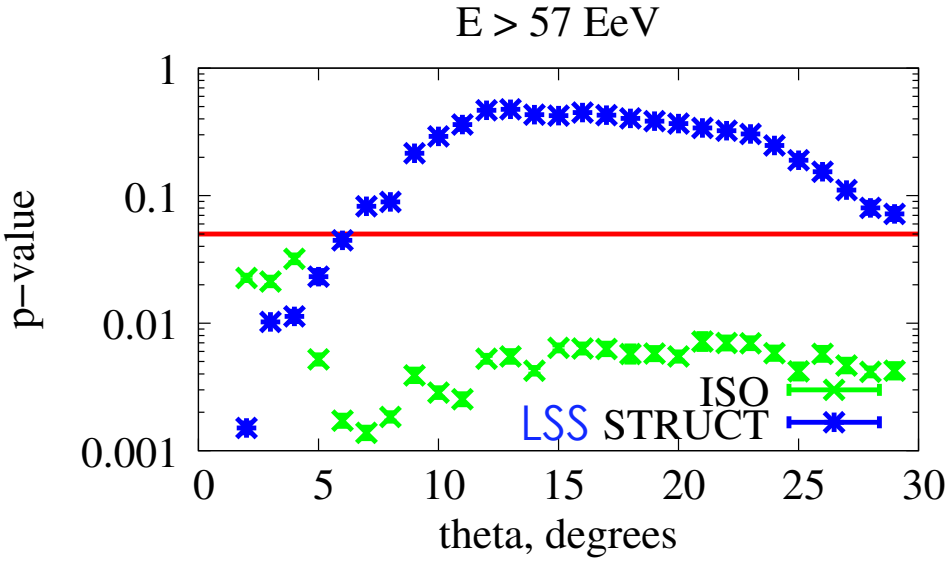
We investigate correlation between arrival directions of the UHECRs and the LSS model (and isotropic model).

From ICRC2017 S. Troitsky

Correlation with LSS





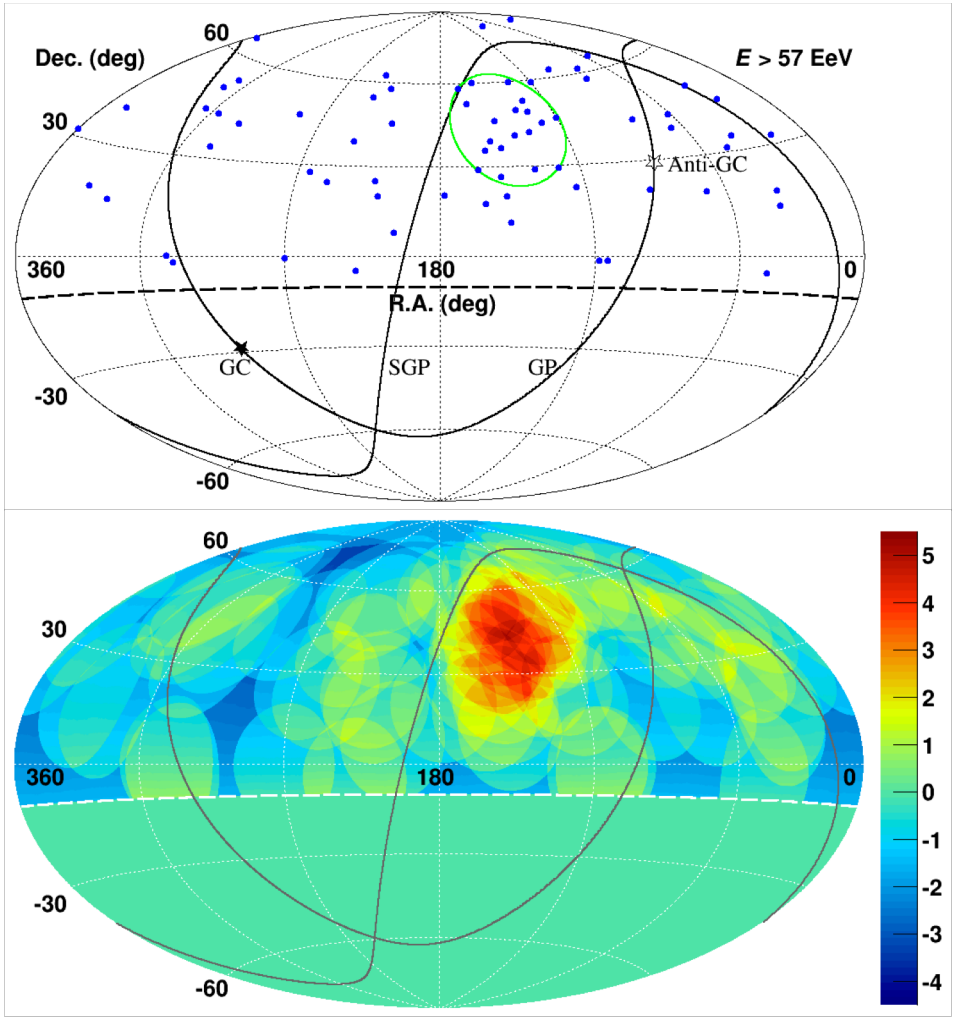


x-axis : smearing angle
Y-axis : compatibility between the expected and the data

$E>5.7\times10^{19}$ eV
Consistent with LSS
Inconsistent with isotropy
(9-year data)

ICRC2017 S. Troitsky

Hotspot (>57EeV, 5 years)



R.U. Abbasi+2014, ApJL

- ✓ 5-year observation by the TA SD
- ✓ Observed 72 events with E>57 EeV
- ✓ Indication of UHECR hotspot
- ✓ Local significance 5.1σ

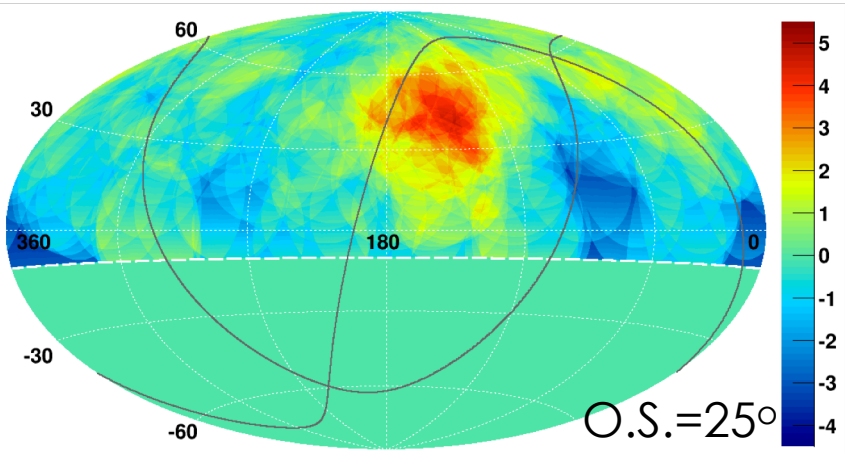
- ✓ Assuming 5 search window radii (15°, 20°, 25°, 30°, 35°), Global significance 3.4σ

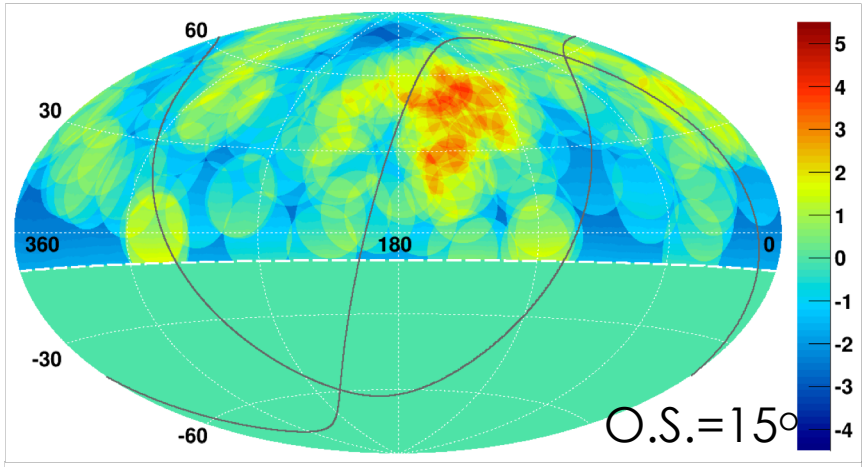
10-year observation
→double exposure

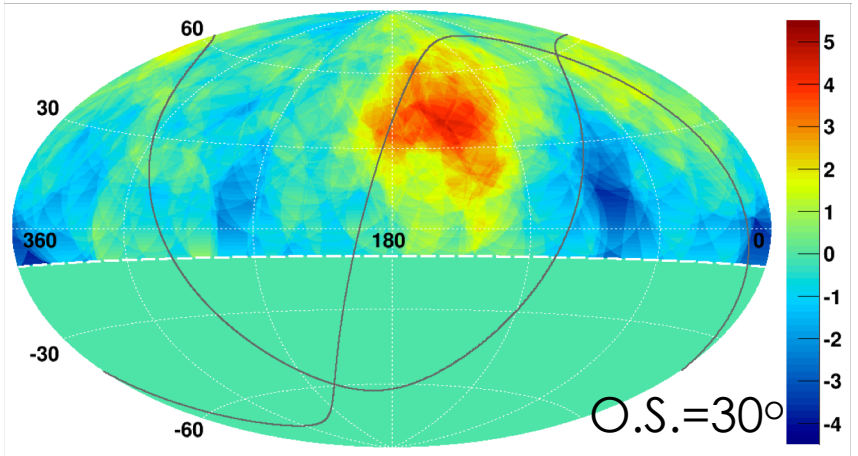
Angular Scan (>57EeV,10 years)

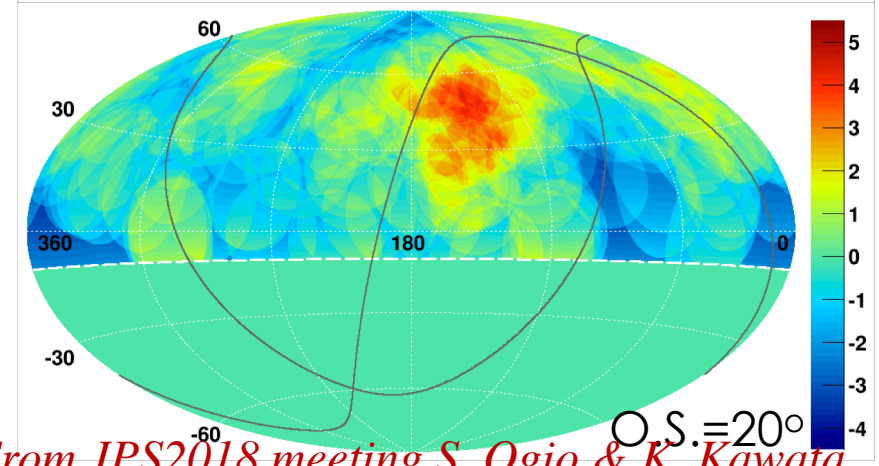
Preliminary

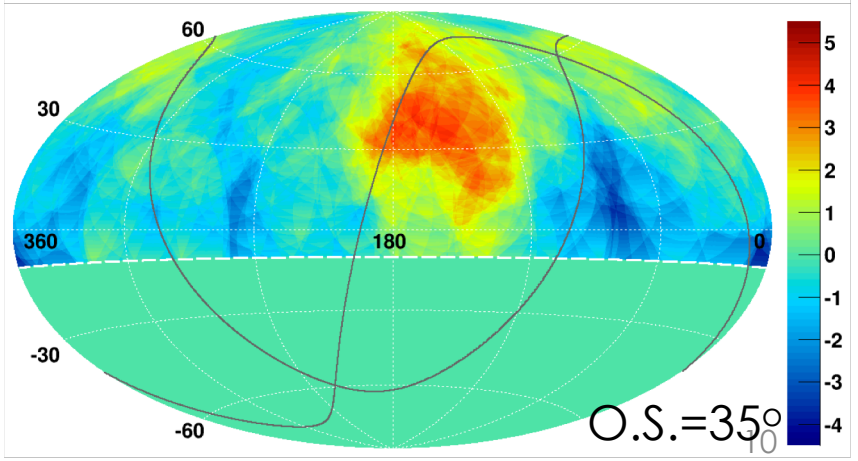
O.S. : oversampling radius











From JPS2018 meeting S. Ogio & K. Kawata

Results of the Angular Scanning for 10 years

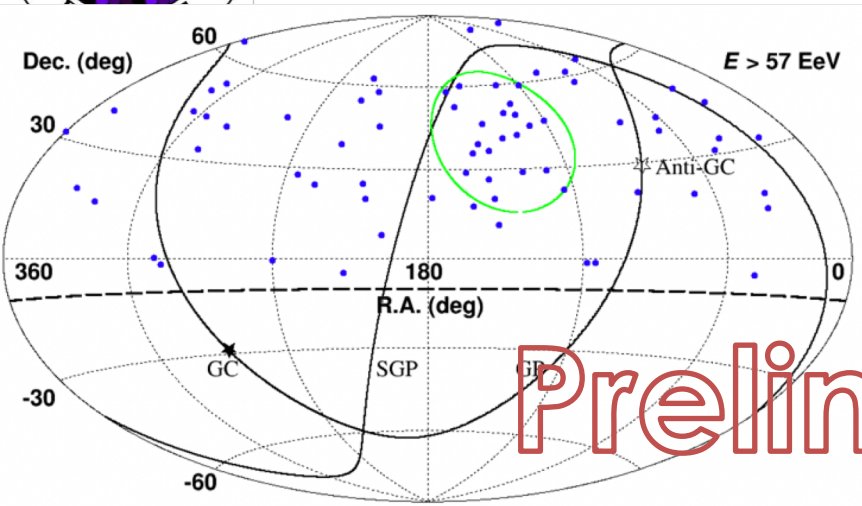
Preliminary!

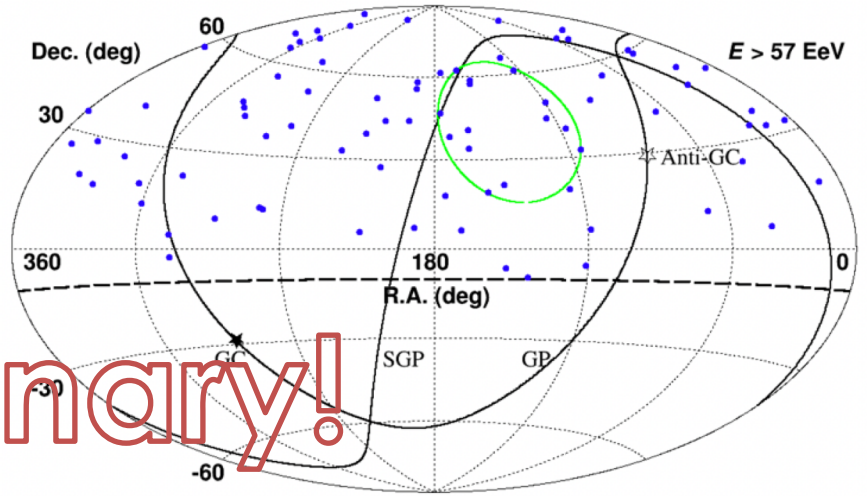
O.S. radius	15°	20°	25°	30°	35°
Maximum Significance for 10 years (σ)	4.1	4.6	5.0	4.7	4.2
Location of Maximum Significance	RA:140.4° Dec: 53.2°	RA:149.4° Dec: 49.0°	RA:144.3° Dec: 40.3°	RA:152.8° Dec: 39.8°	RA:157.4° Dec: 38.5°

Hotspot position published in ApJL2014 → RA: 146.7° Dec: 43.2°

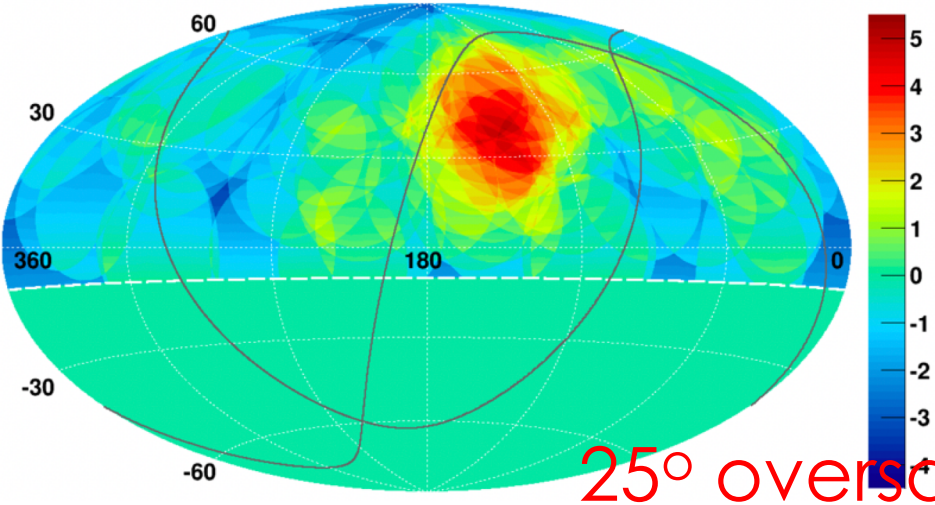
From JPS2018 meeting S. Ogio & K. Kawata

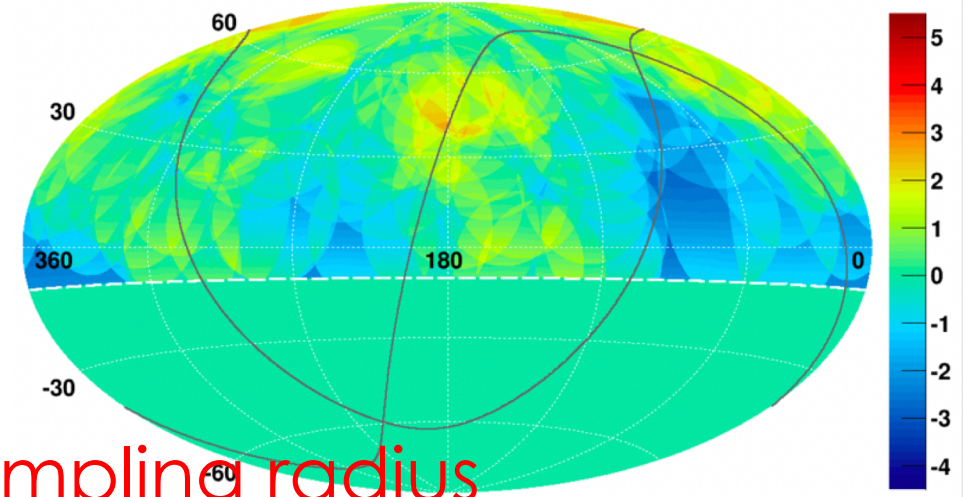
Independent Analysis (>57EeV)





Preliminary!





25° oversampling radius

1st-half 5 years : 72 events

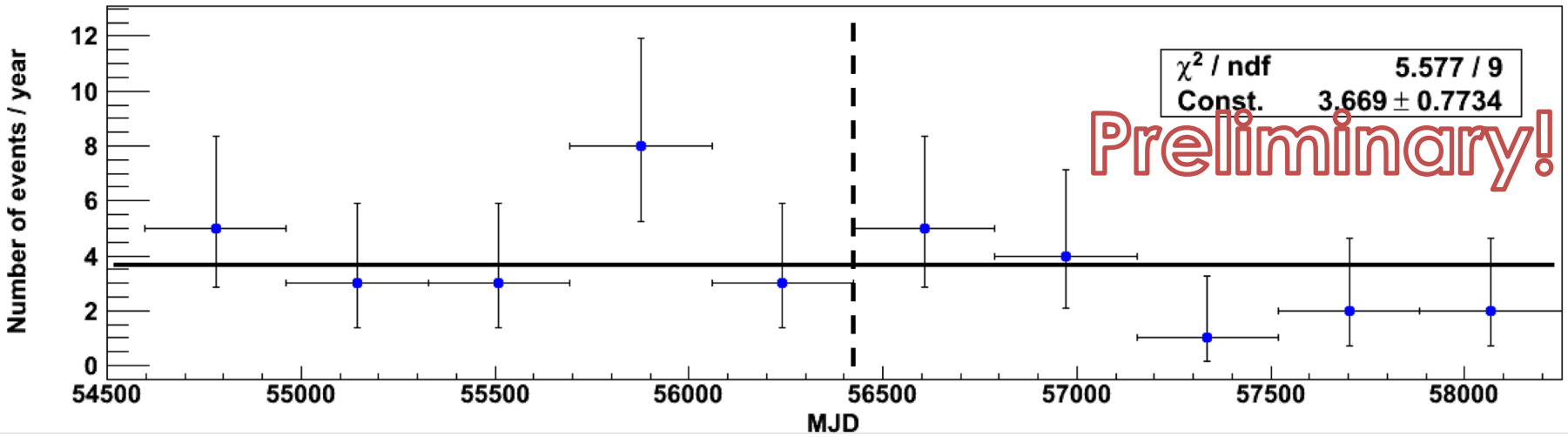
Hotspot position = 5.0σ

2nd-half 5 years : 85 events

Hotspot position = 2.0σ

From JPS2018 meeting S. Ogio & K. Kawata

Differential Time Variation of the Hotspot

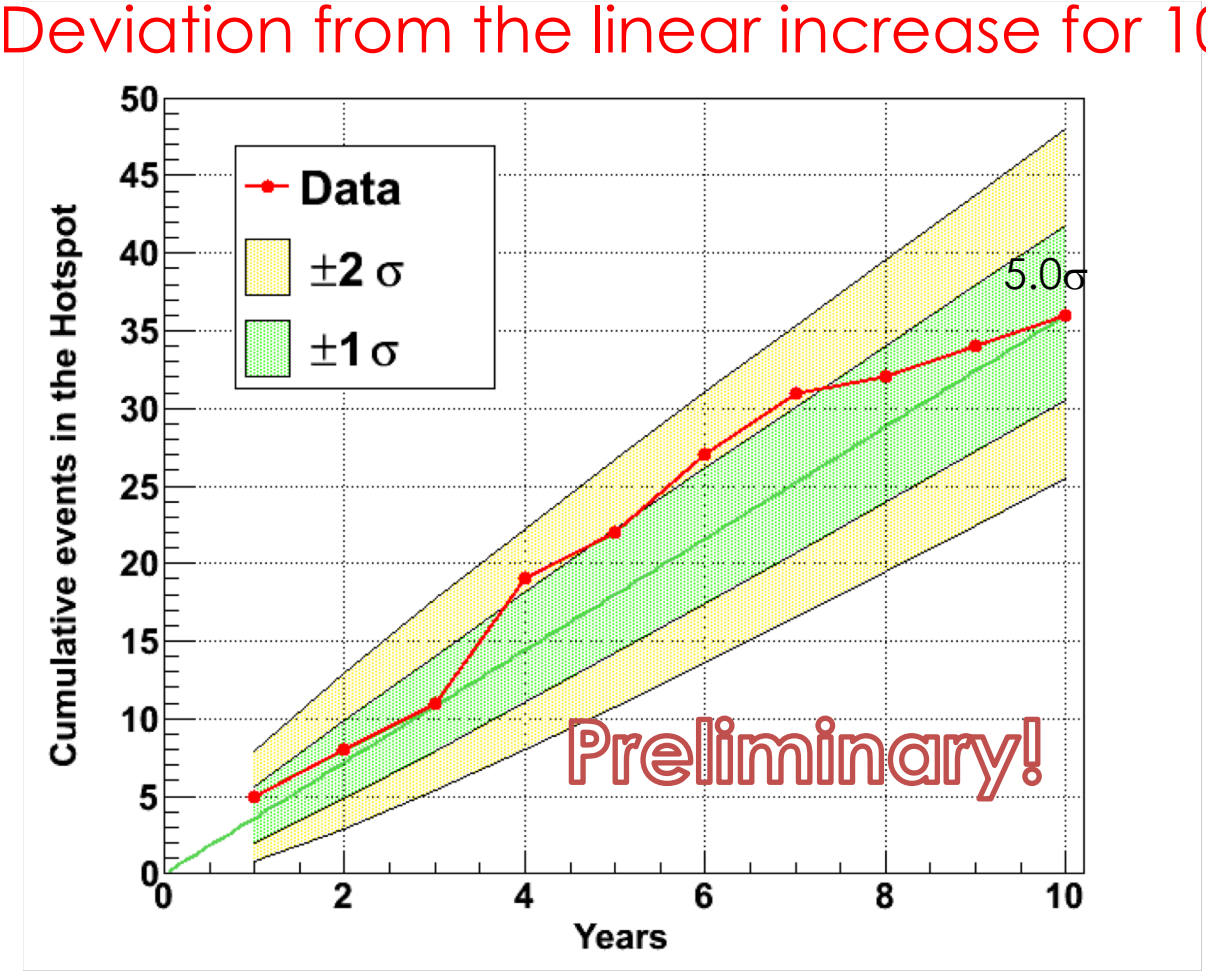


Hotspot position	Search radius	ON	α*OFF (OFF)	ON/OFF ratio (α)	σ
RA:144.3° Dec: 40.3°	25°	36	12.6 (121)	0.10435	5.0

From JPS2018 meeting S. Ogio & K. Kawata

Integral Time Variation of the Hotspot

Deviation from the linear increase for 10 years



→ Consistent with linear increase within 2σ

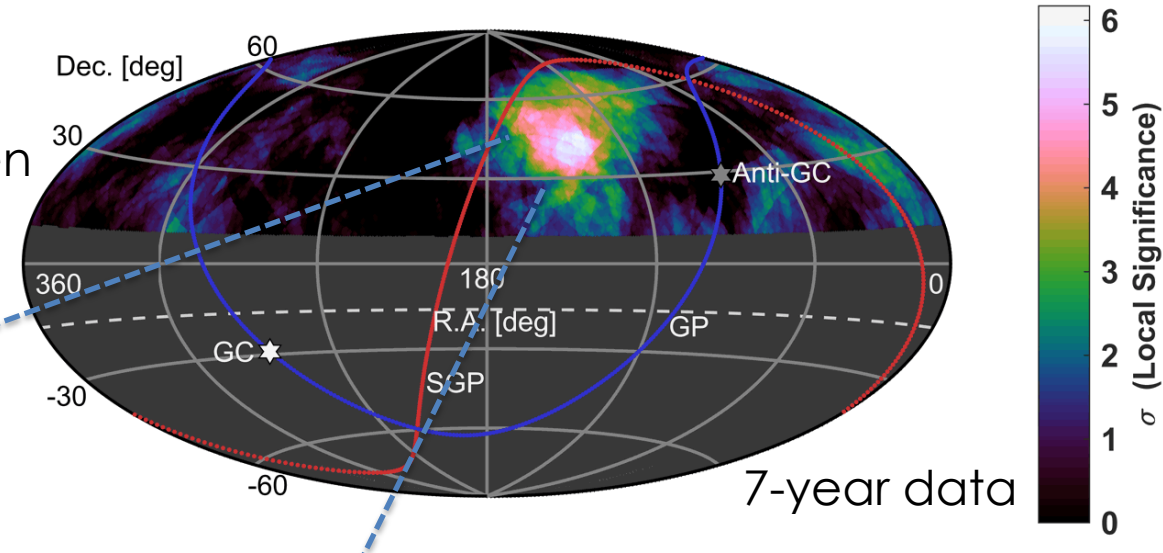
From JPS2018 meeting S. Ogio & K. Kawata

Spectral Anisotropy at Hotspot

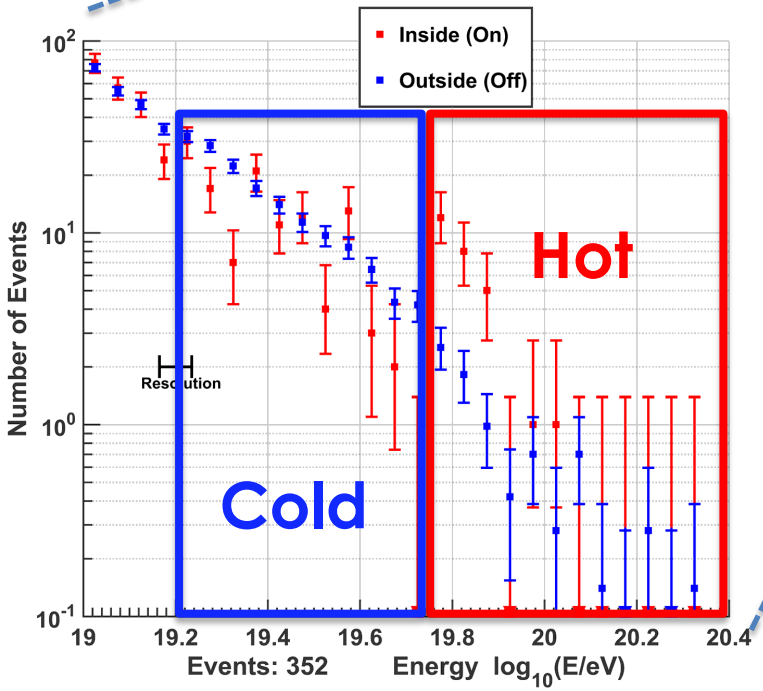
Abbasi+2018, ApJ, 862, 91

Comparison of spectra between inside and outside of hotspot

→ Probabilities of spectral anomaly are calculated in the all sky .



7-year data

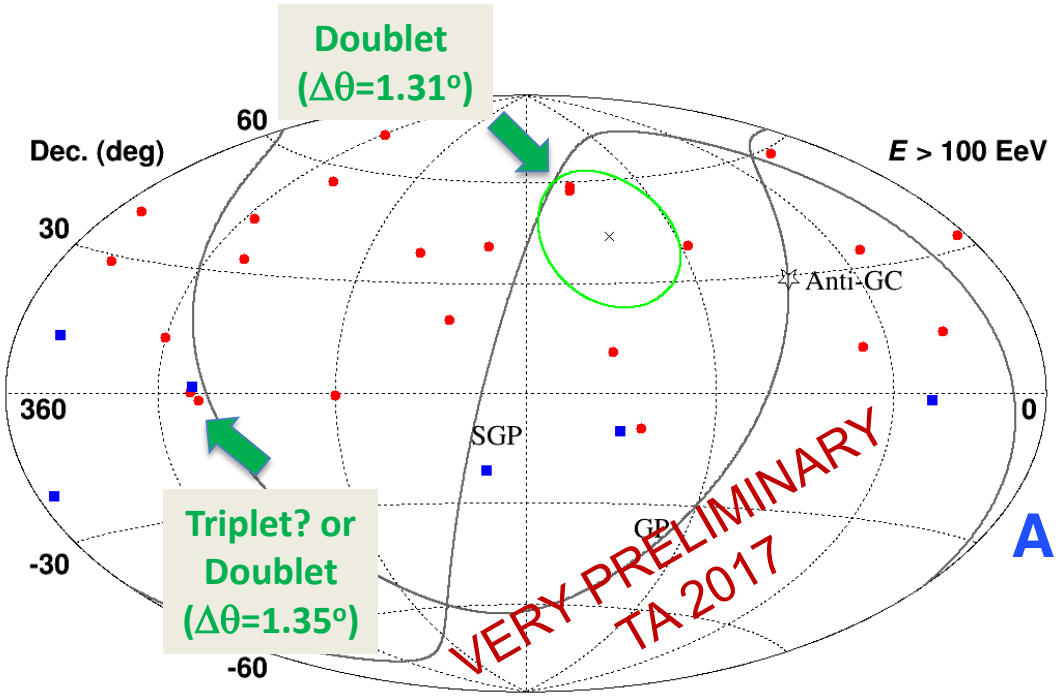


"cold spot" at lower energies, same place as the hot spot at high

$>10^{19.2}$ eV

3.7σ post-trial significance

Cluster Events >100EeV



No correction for
E scale difference
b/w TA and Auger !

TA 9 years (23 events)

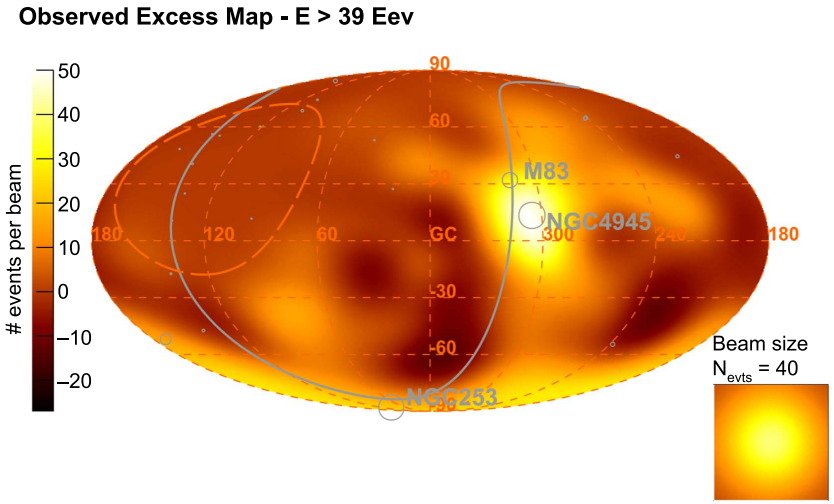
Auger 6 years (6 events)

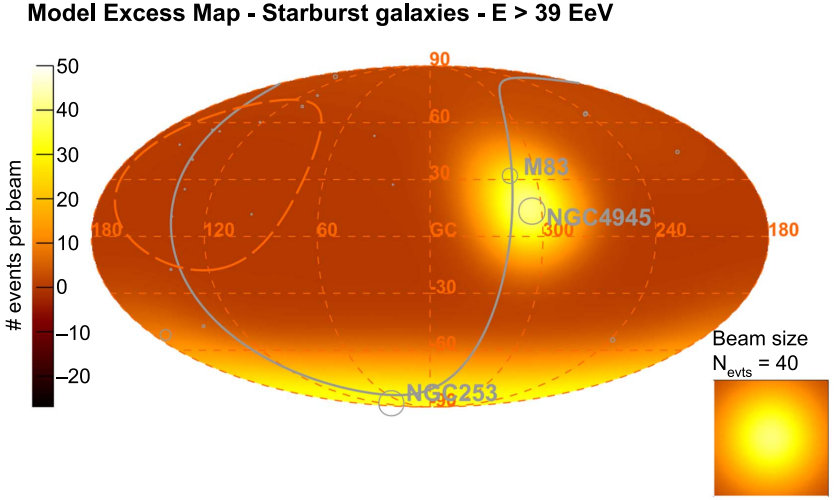
2 doublets above 100 EeV.

→ the probability to have ≥2 doublets at $\leq\sqrt{2}$ deg is

$P = 0.30\%\ (2.8\sigma)$

Auger - *A. Aab+2018, ApJL*
Correlation with Starburst Galaxies





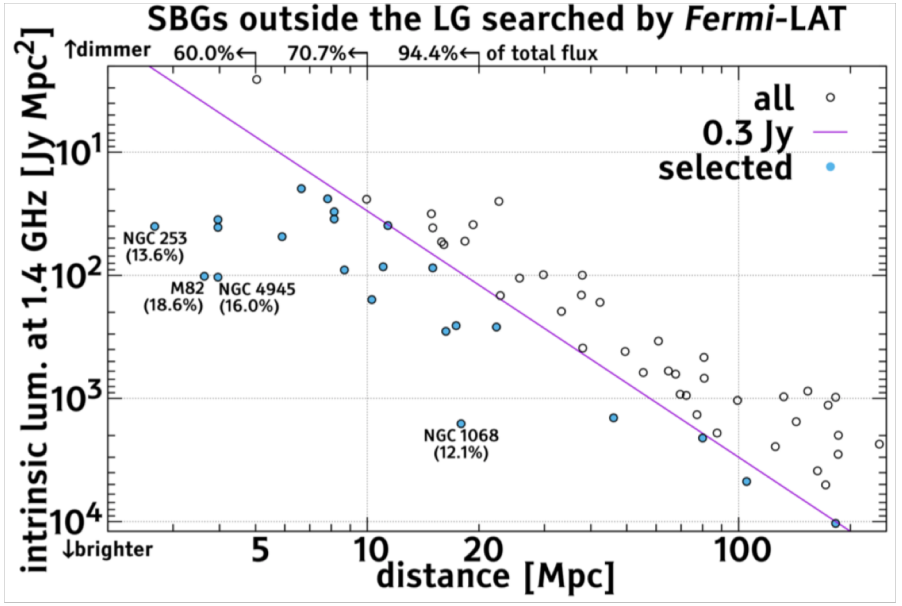
- ✓ Correlation of UHECRs with catalogs
- ✓ Scanning the following parameters
  - Energy threshold E_{TH}
  - Search radius ψ
  - Anisotropic fraction f_{ani}
- ✓ Results (Post-trial significances)
  - Starburst galaxies : 4.0σ
  - γ-ray AGNs : 2.7σ
  - Swift-BAT (X-ray)AGNs : 3.2σ
  - 2MASS galaxies : 2.7σ

Northern sky?
→ Test the Auger best-fit parameter model

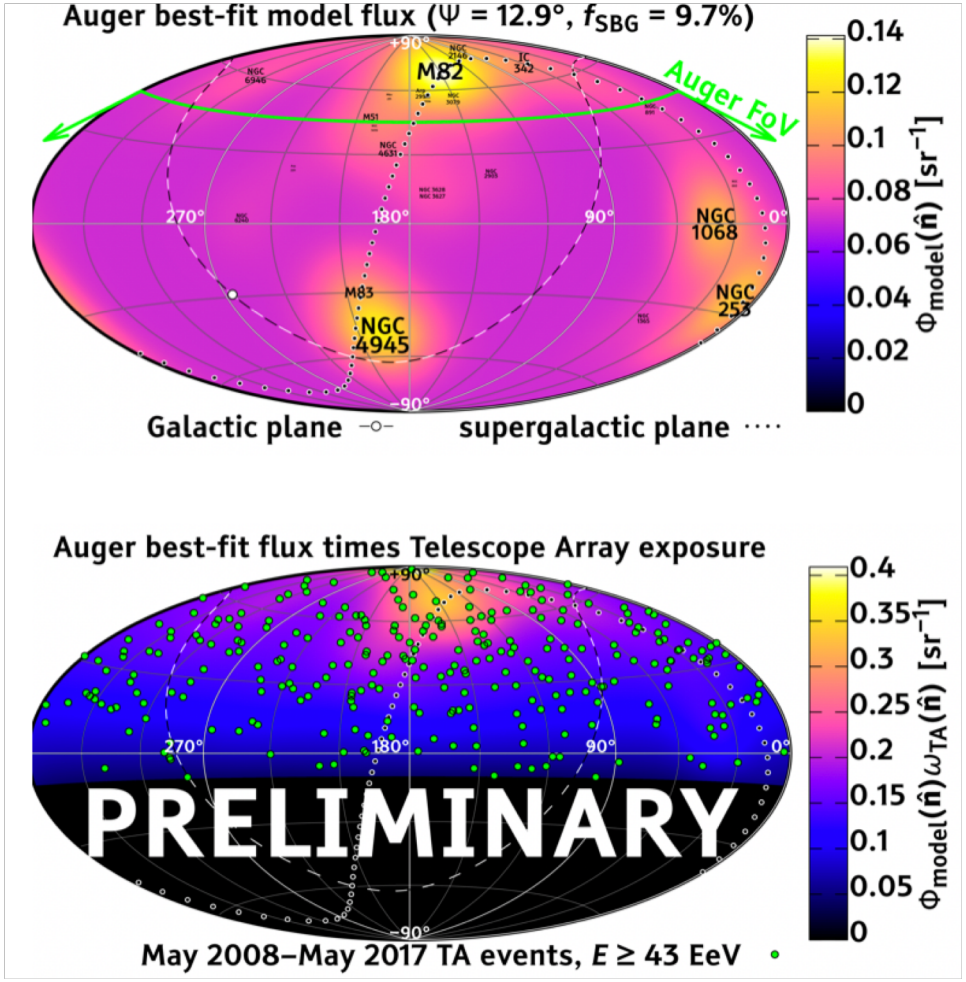
Auger hypothesis for Starburst Galaxy Correlation

- SBG selected for γ-ray studies *Fermi-LAT 2012*
  - 63 sources (within 250Mpc), 4 detected in γ
  - Radio flux@1.4GHz > 0.3Jy
    Proxy for UHECR flux

  → 23 sources remain
- Local Group
  Not included
  - Milky way, LMC, SMC, M33 and M31



Search for Correlation with SBG by TA in the Northern Sky



- ✓ Auger best-fit parameters
  - Anisotropic fraction f_{ani}=9.7%
  - Search radius ψ=12.9°
  - Energy threshold E_{TH}=39EeV (43EeV in the TA energy scale)
- ✓ Strong radio source : M82 in the northern sky

- ✓ Same sources and parameters as Auger-best fit
- ✓ No scan over parameters, no statistical penalty
- ✓ UHECR attenuation neglected, found negligible by Auger (most of the flux from within a few Mpc)

A. di Matteo, T. Fujii, K. Kawata (UHECR2018 Poster)
Abbasi+2018, arXiv:1809.01573

Search for Correlation with SBG by TA in the Northern Sky

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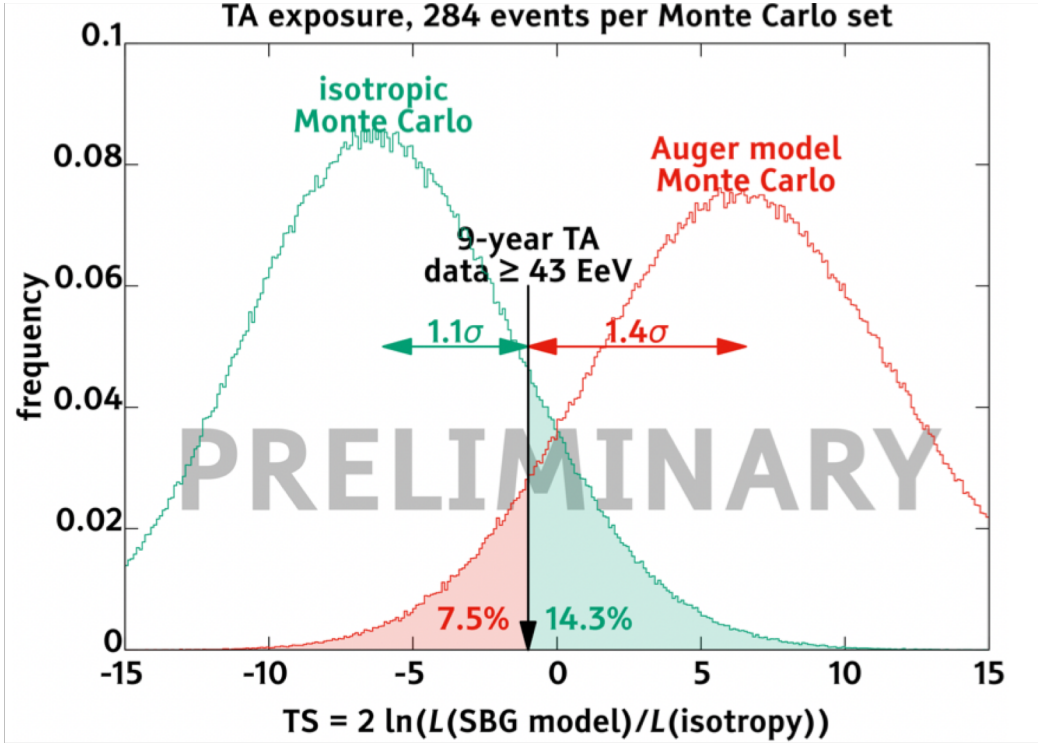


Likelihood for model map

$$TS = 2\log\left[\frac{L(\phi, f_{\rm ani})}{L(f_{\rm ani}=0)}\right]$$

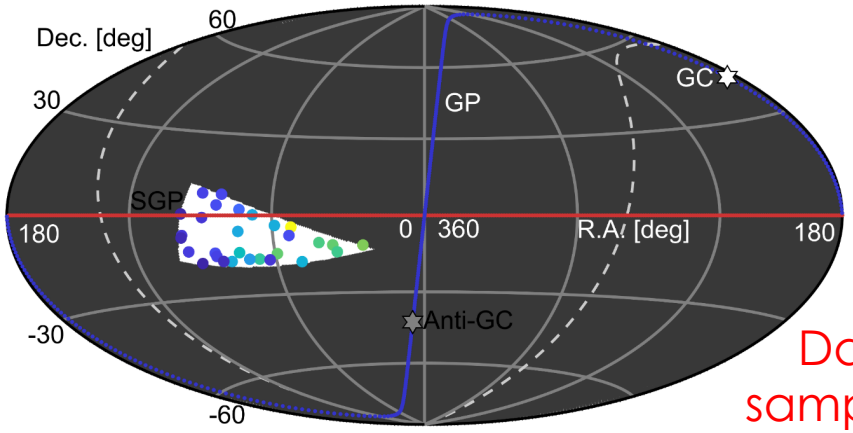
Likelihood for Isotropy

~1.1σ compatible with 100% isotropic
~1.4σ compatible with starbursts

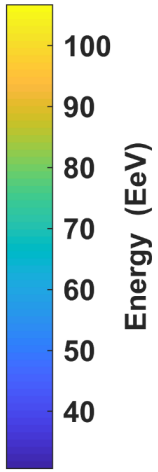
Supergalactic Structure of Multiplets

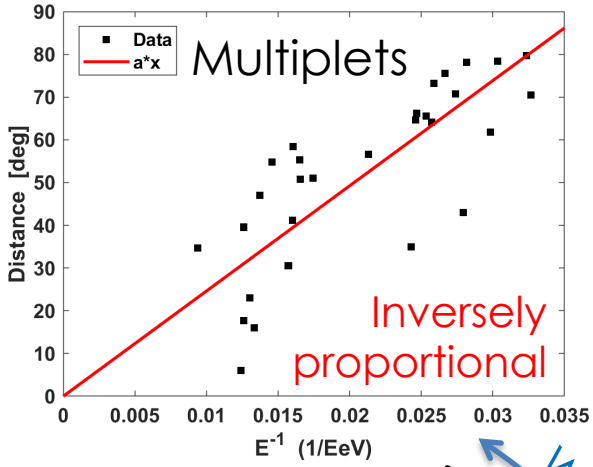
J.P. Lundquist, UHECR2018
Paper in preparation

Correlation between CR energies and distances in the "Wedge"

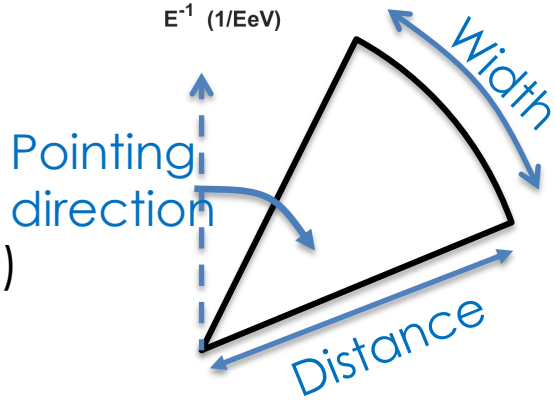


Data sample





- **Energy Threshold : 10, 15, 20…100 EeV**
- **Wedge width : 10°, 20°, 30°…90°**
  (steps of 5° on each side of the pointing direction)
- **Maximum Distance : 15°, 20°, 25°…90°**
- **Pointing Direction : 0°, 5°, 10°…355°**



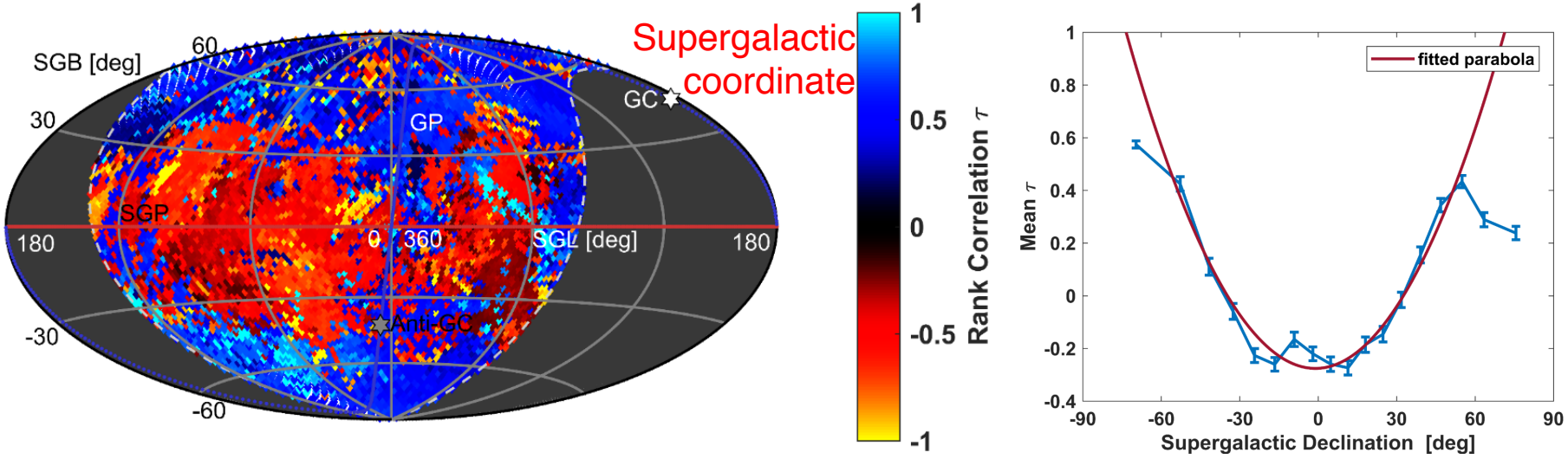
Supergalactic Structure of Multiplets

J.P. Lundquist, UHECR2018
Paper in preparation

- ✓ **Rank Correlation Analysis**
  - → **All values are ranked 1 to n. Kendall's correlation is used.**

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

Negative τ : Energies are inversely-proportional to distances
Positive τ : Energies are proportional to distances



Negative correlations of greater significance appear correlated with supergalactic plane (post-trial significance >~4σ)

Summary

- Large/intermediate-scale anisotropy (>57EeV)
  → Consistent with LLS, Inconsistent with isotropy 2-3σ
  → Hotspot still exists for 10-year observation
  → Spectral anisotropy 3.7σ (7-year data)
- Small-scale cluster >100EeV
  → 2 doublets : 2.8σ
- Correlation with starburst galaxies :
  Test Auger's parameters (E_{TH}=39EeV, ψ=12.9°, f_{ani}=9.7%)
  → No significance so far
- Supergalactic structure of multiplets
  → multiplet-like events do appear correlated with supergalactic plane >~4σ

Hints of UHECR anisotropies in the northern sky

- TA Extension : **TAx4** (TA aperture x4)
  → Under construction

TAx4 Experiment

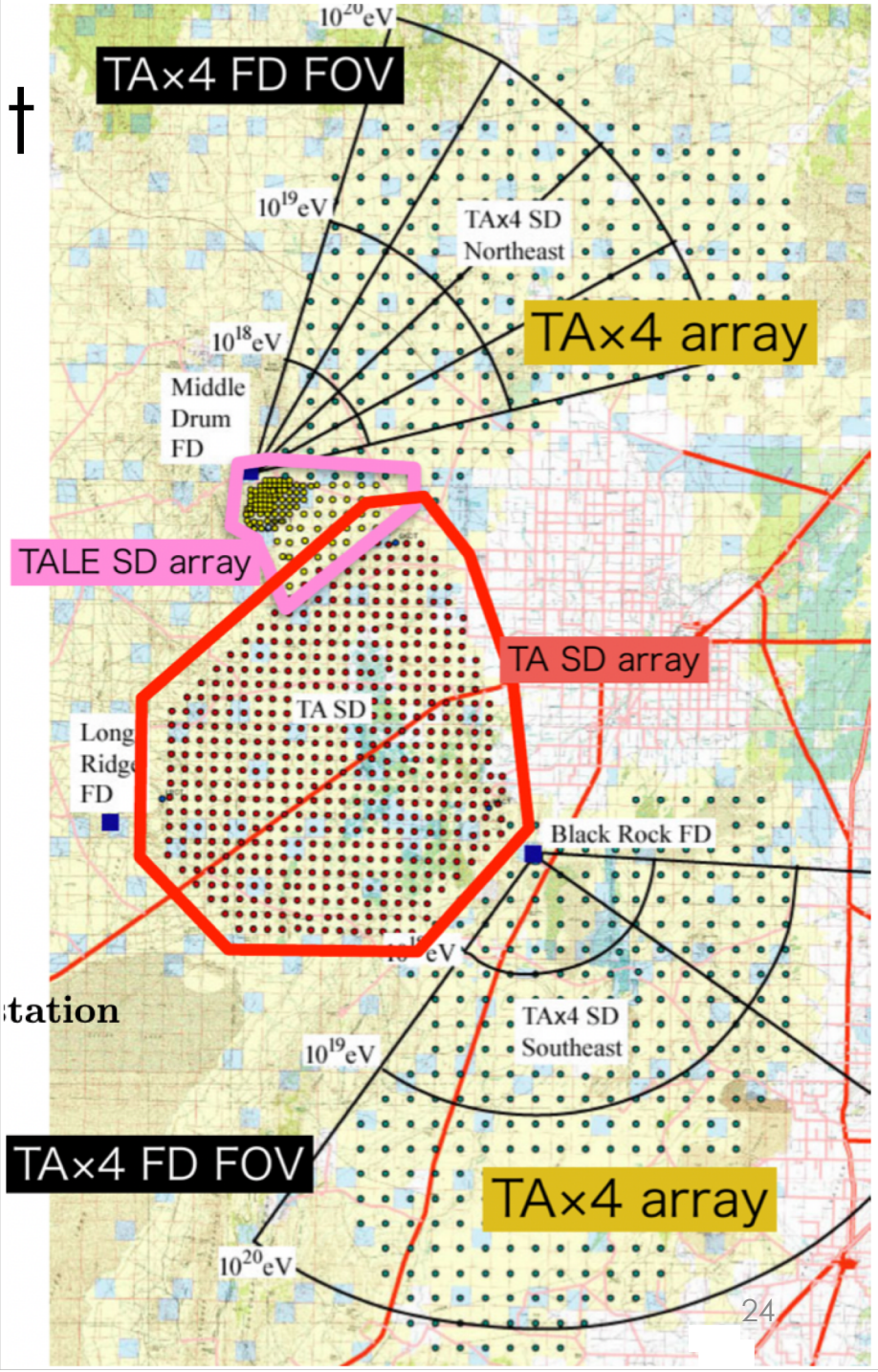
E. Kido, UHECR2018 (12th Oct.)

✧ Now there is hint of anisotropy at 3σ level for northern sky.

❖ extend SD array by 4 times (3,000km^2)
1. Add 500 scint. counters with 2.1 km spacing
2. Add two FD stations

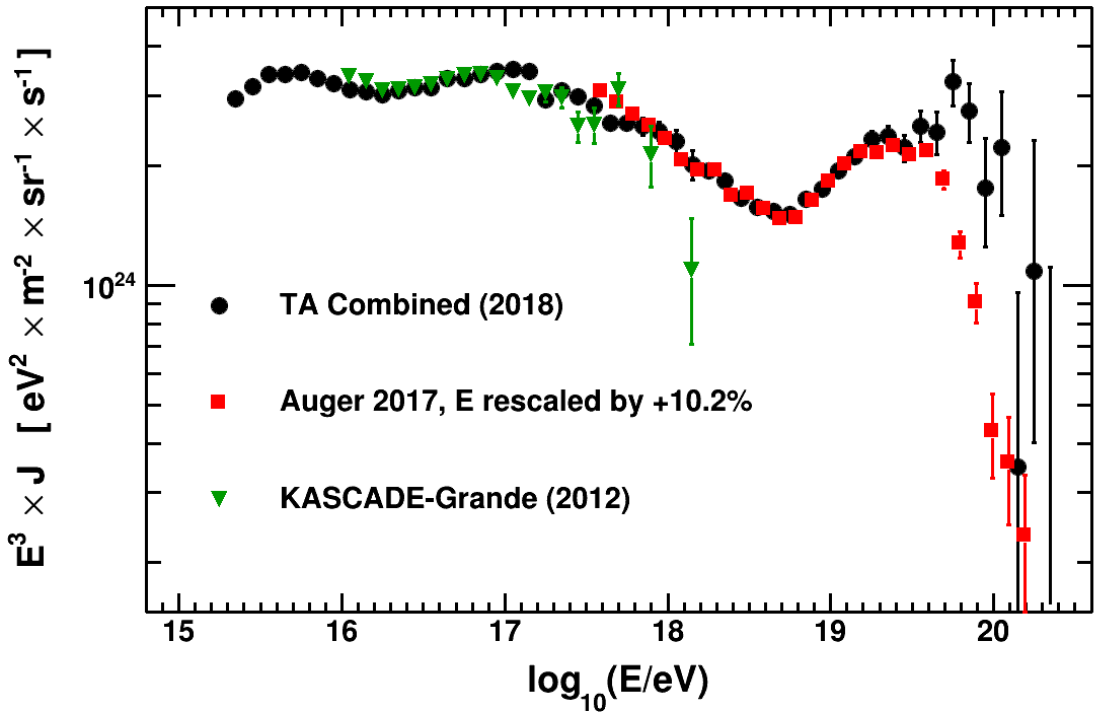
→ Approved and under construction

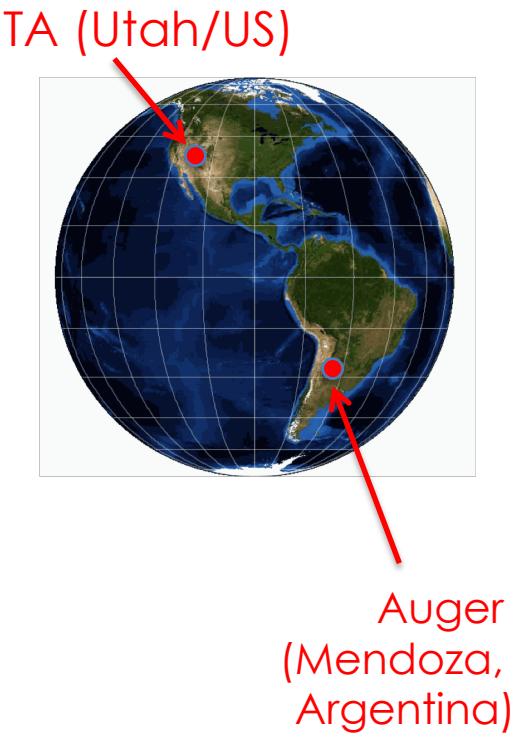
❖ Science
1. Anisotropy study → Expect >5σ
2. Xmax at highest energy region
3. UHE photon & neutrino search



BACK POCKETS

Comparison with Auger

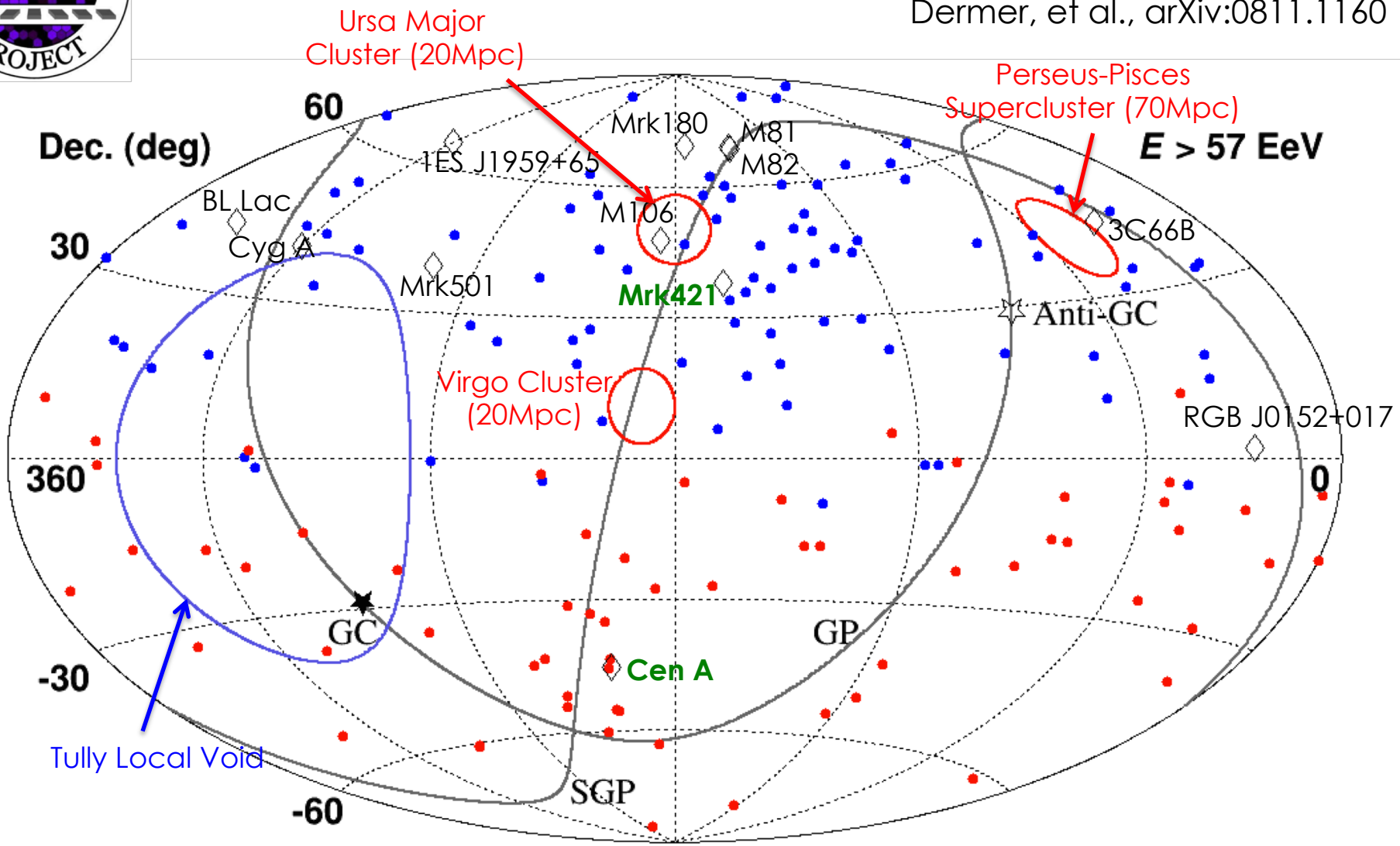




After matching energy scale at the ankle break,
the location of the suppression energy is clear different.
→ Systematics or physics?

Nearby Prominent AGNs

Dermer, et al., arXiv:0811.1160

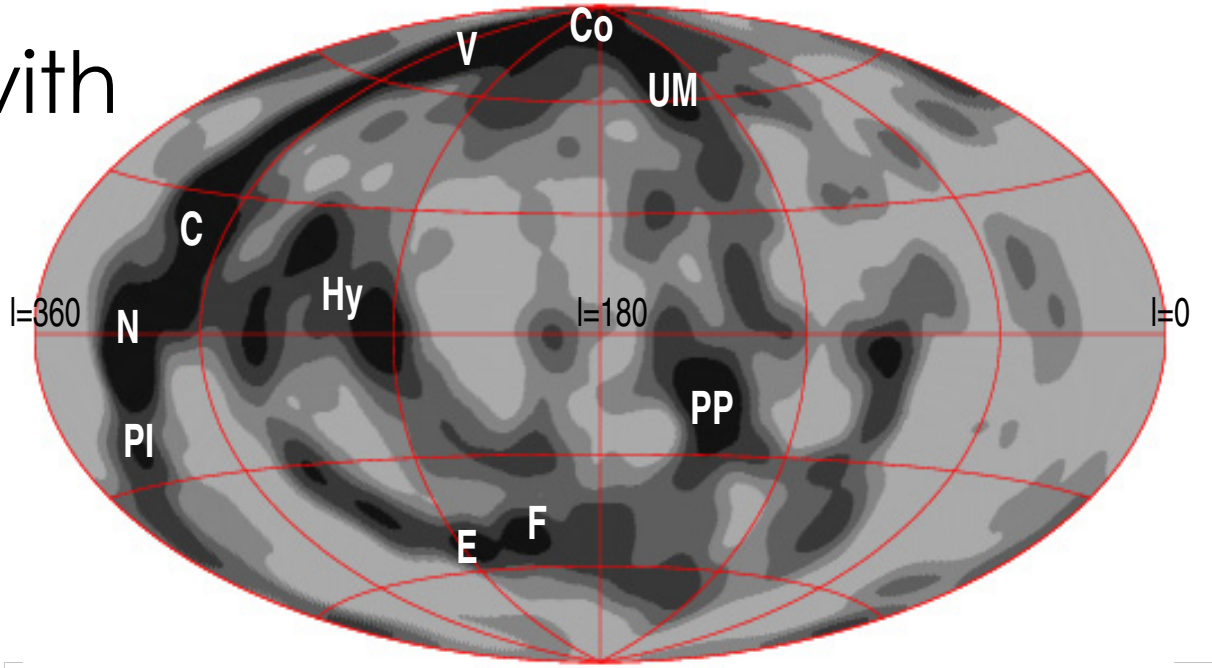


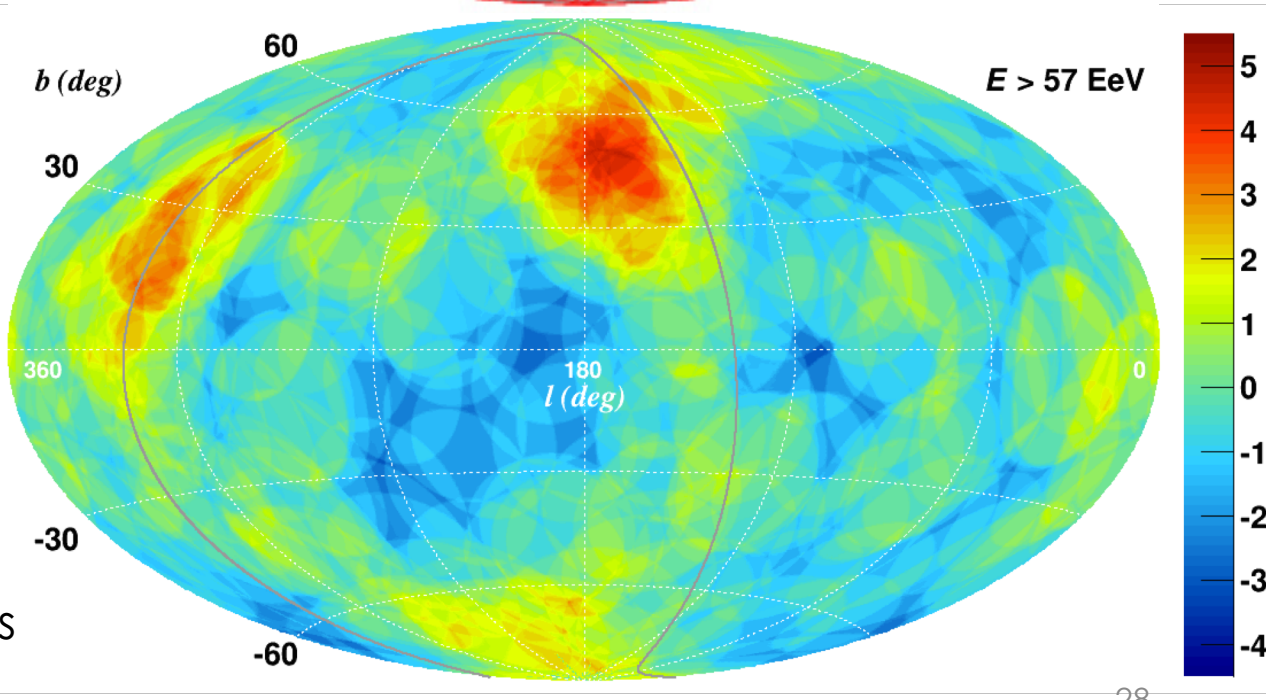
TA : 2008 May – 2014 May (6.0 years) 87 events

Auger : 2004 May – 2009 Nov (5.5 years) 62 events

Comparison with Large-Scale Structure

Sky map of expected flux at E > 57 EeV (Galactic coordinates). The smearing angle is 6°. The letters indicate the nearby structures as follows: C: Centaurus supercluster (60 Mpc); Co: Coma cluster (90 Mpc); E: Eridanus cluster (30 Mpc); F: Fornax cluster (20 Mpc); Hy: Hydra supercluster (50 Mpc); N: Norma supercluster (65 Mpc); PI: Pavo-Indus supercluster (70 Mpc); PP: Perseus-Pisces supercluster (70 Mpc); UM: Ursa Major (20 Mpc); and V: Virgo cluster (20 Mpc).





No correction for E scale difference b/w TA and Auger !

TA 7 years + PAO 10 years

Small scale: starburst correlations

$$\mathrm{TS} = 2\ln\left(L(\Phi_2)/L(\Phi_1)\right),$$

$$L(\Phi_j) = \prod_i \frac{\Phi_j(\hat{\mathbf{n}}_i)\omega(\hat{\mathbf{n}}_i)}{\int_{4\pi}\Phi_j(\hat{\mathbf{n}})\omega(\hat{\mathbf{n}})\,\mathrm{d}\Omega},$$

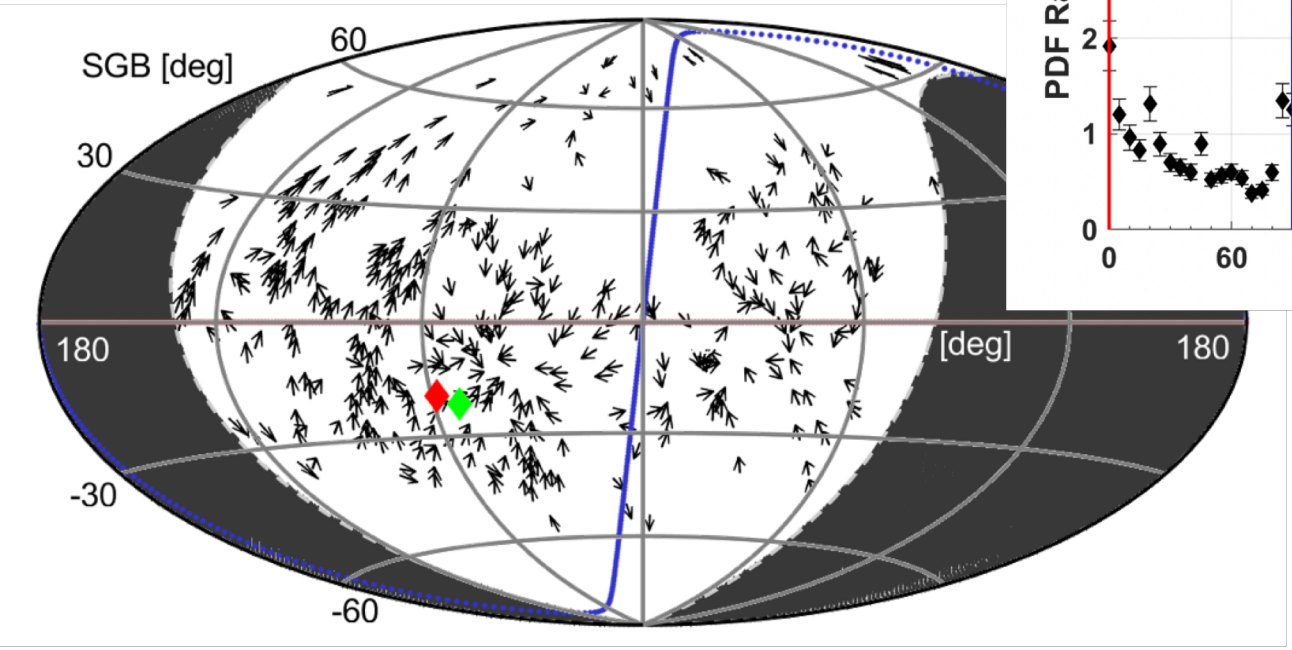
$$\Phi_1(\hat{\mathbf{n}}) = \Phi_{\mathrm{iso}} = 1/4\pi$$

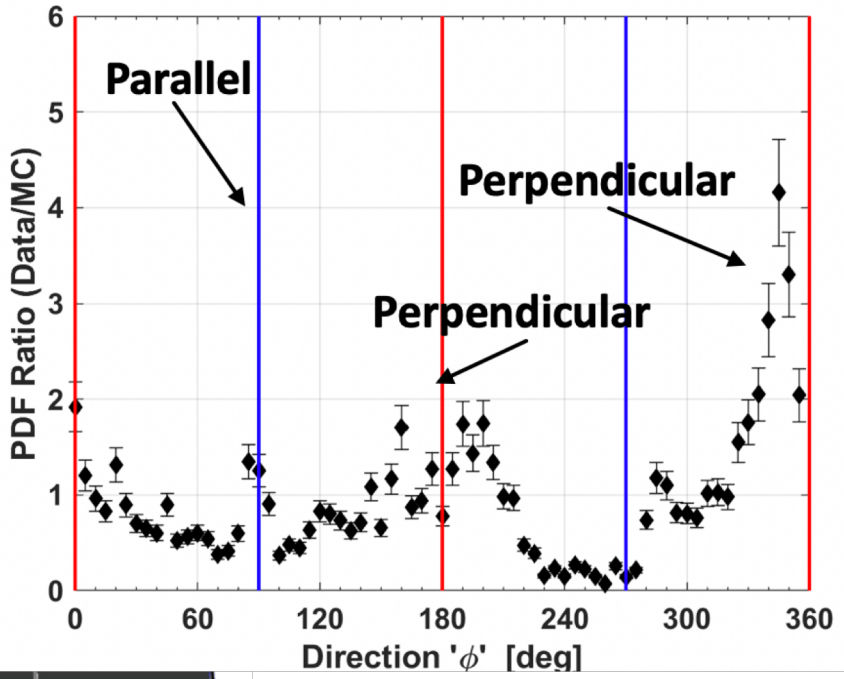
$$\Phi_{\mathrm{mod}}(\hat{\mathbf{n}}) = f_{\mathrm{SBG}}\Phi_{\mathrm{SBG}}(\hat{\mathbf{n}}) + (1 - f_{\mathrm{SBG}})\Phi_{\mathrm{iso}},$$

$$\Phi_{\mathrm{SBG}}(\hat{\mathbf{n}}) = \frac{\sum_k \phi_k \exp\left(\hat{\mathbf{n}}_k \cdot \hat{\mathbf{n}}/\theta^2\right)}{\int_{4\pi}\sum_k \phi_k \exp\left(\hat{\mathbf{n}}_k \cdot \hat{\mathbf{n}}/\theta^2\right)\,\mathrm{d}\Omega}$$

DIRECTION OF CORRELATIONS

Grid points greater than 4.5 sigma



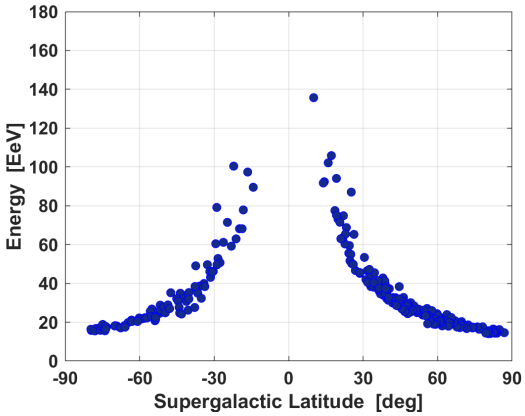


- **Sources are correlated with the supergalactic plane.**
- **Magnetic fields are correlated with sources.**
- **Multiplets will exhibit a structure indictive of clustering of sources**
  - **Random fields will diffuse events perpendicular to their average direction. Multiplets should be in 'wedges' not rectangles or circles.**

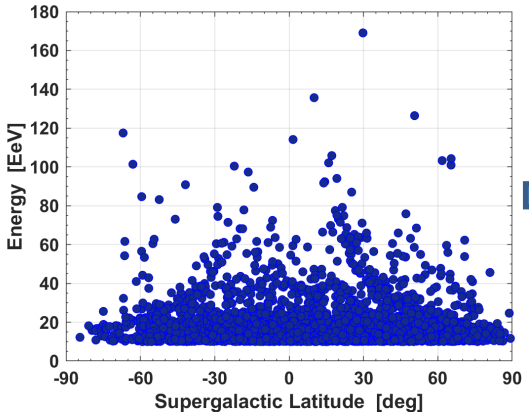
Simple simulation

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

- 1/E supergalactic plane deflection for fraction of events
  - Random "source" position. Gaussian $\sigma=5^{\circ}$ plus 1/E deflection.
- Isotropic Exposure
- Total energy distribution matches published average

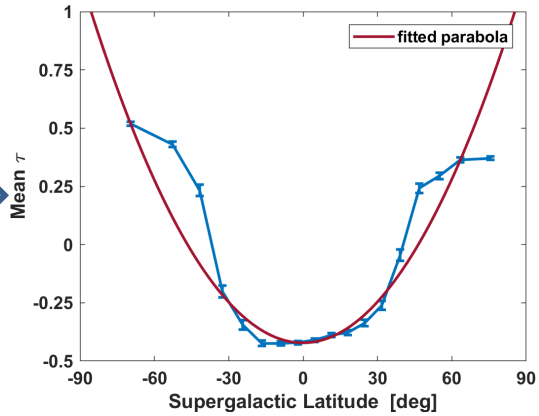


1/E for 10% of events. $\frac{S}{kpc} \frac{B}{\mu G} = 25$



All 3027 events E>=10^19.0

- Isotropic positions
- Published spectrum



Analysis applied to simulation result