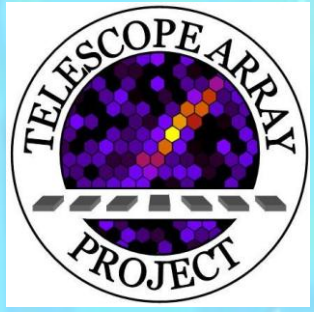
TELESCOPE ARRAY STUDIES OF ULTRA-HIGH-ENERGY COSMIC RAYS: DIRECTION-DEPENDENT FEATURES

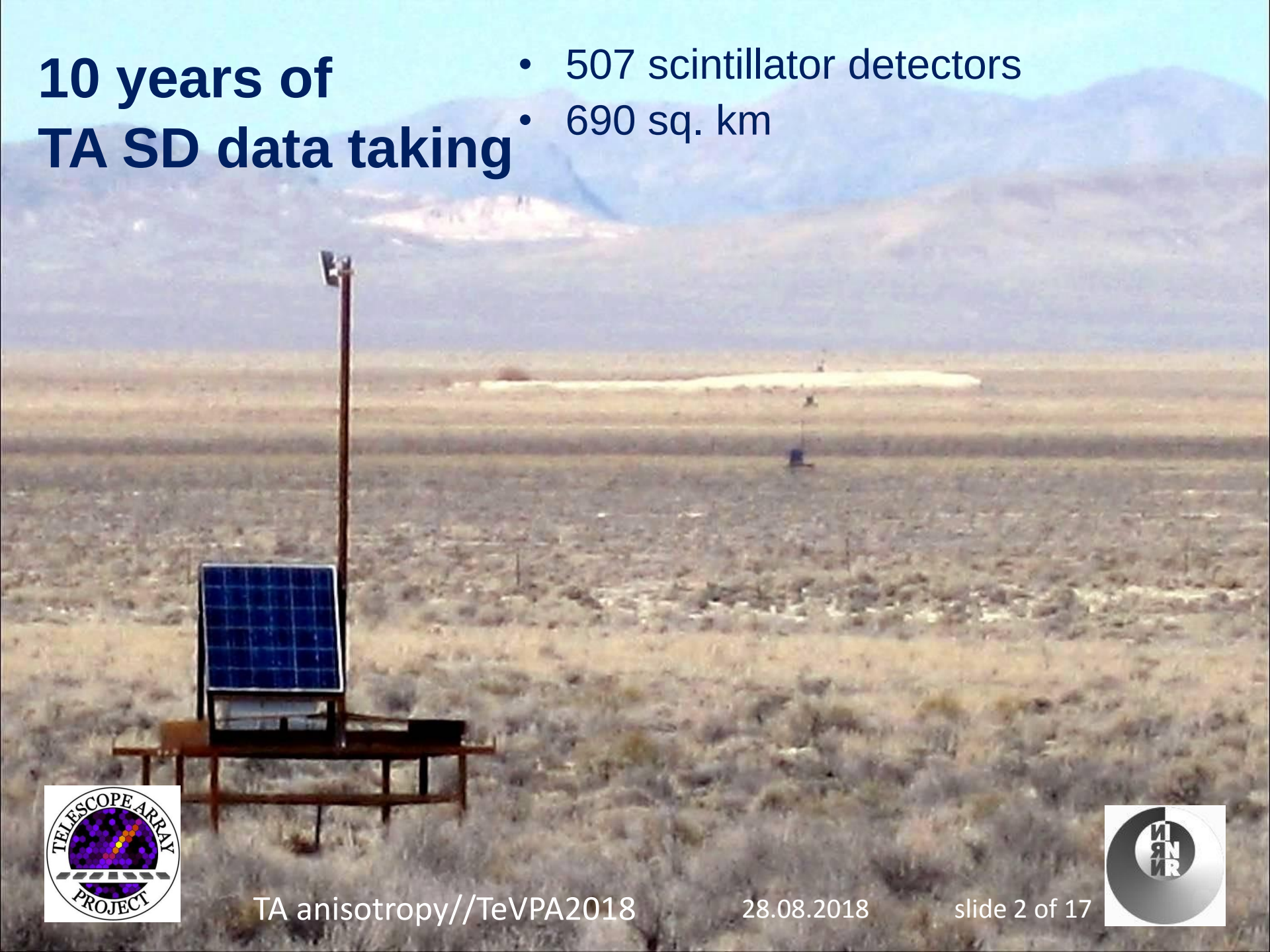
Sergey Troitsky (INR, Moscow)
for the TA collaboration



TeVPA 2018, Berlin, August 28

10 years of TA SD data taking

- 507 scintillator detectors
- 690 sq. km



10 years of TA SD data taking

- 507 scintillator detectors
- 690 sq. km

Arrival direction anisotropy

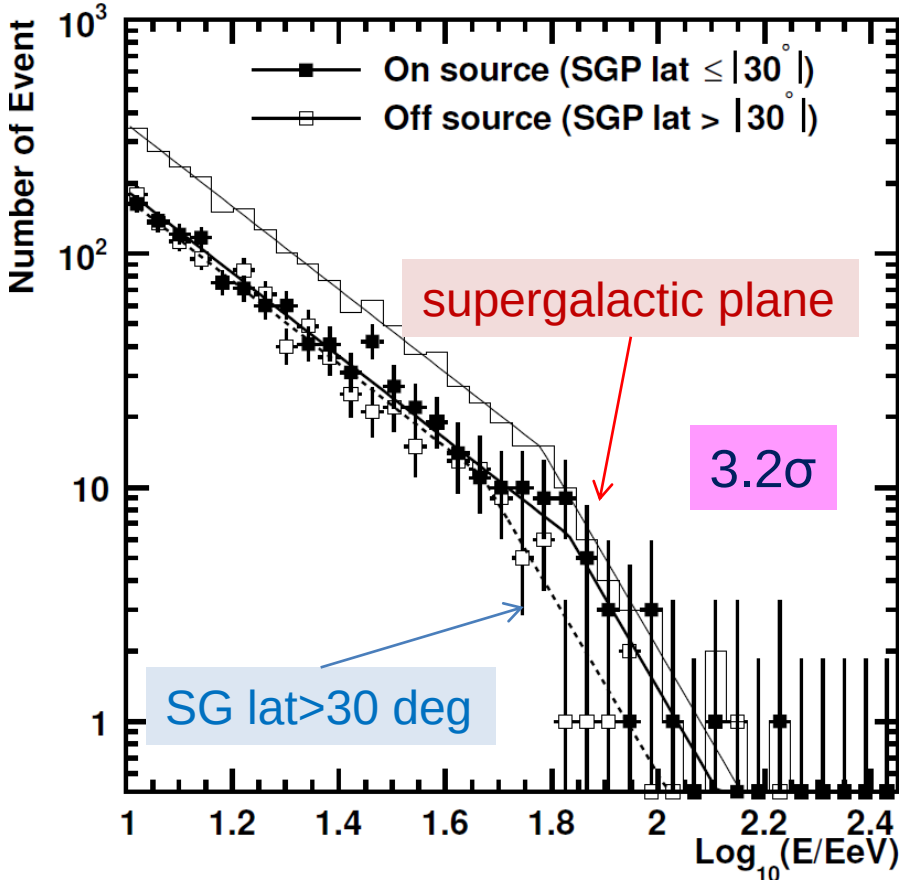
Spectrum anisotropy

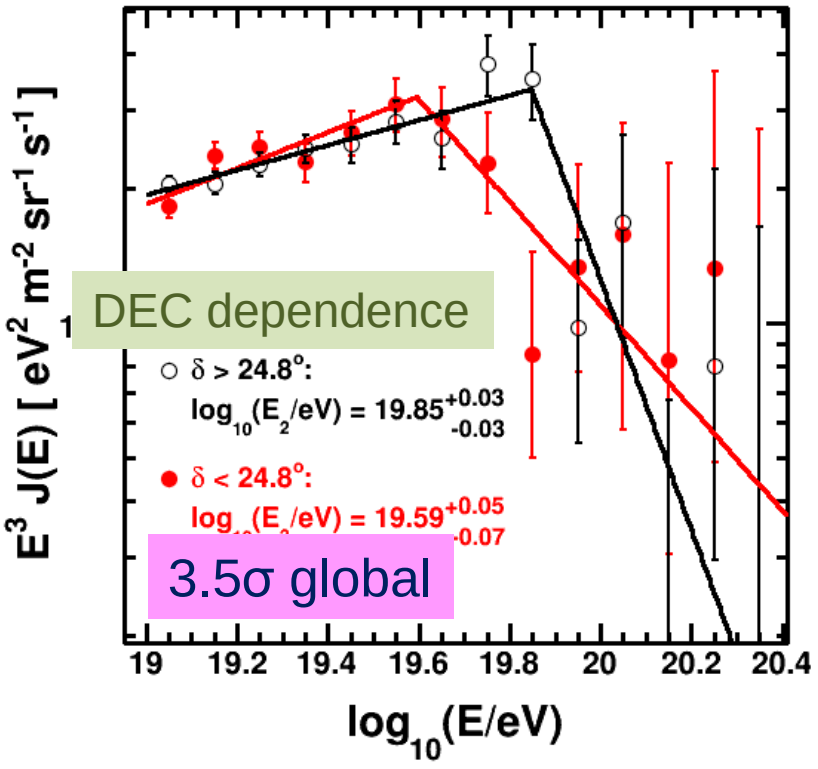
Composition anisotropy

[selected results]

Global anisotropy

energy spectrum

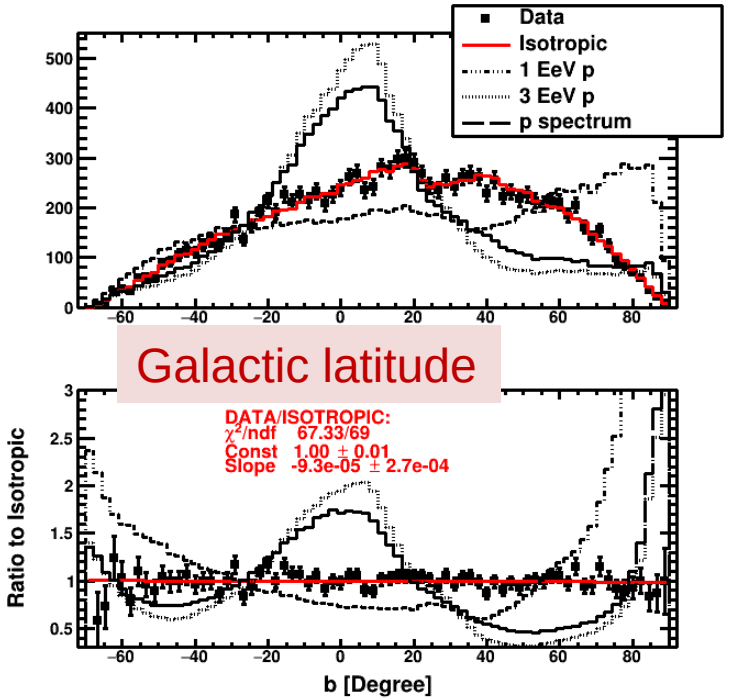




TA 2017

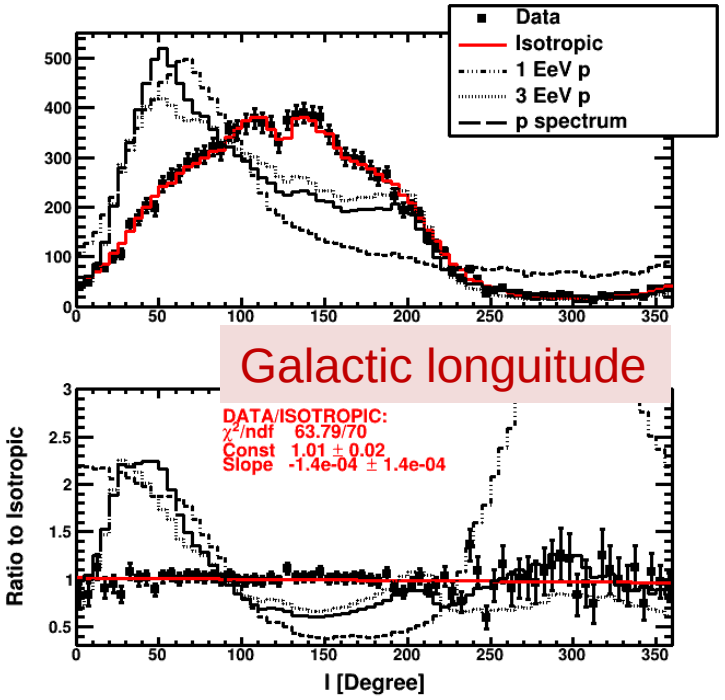
Global anisotropy

Galactic protons @ $10^{18.0\text{-}18.3}$ eV



Galactic latitude

TA 2016



Galactic longuitude

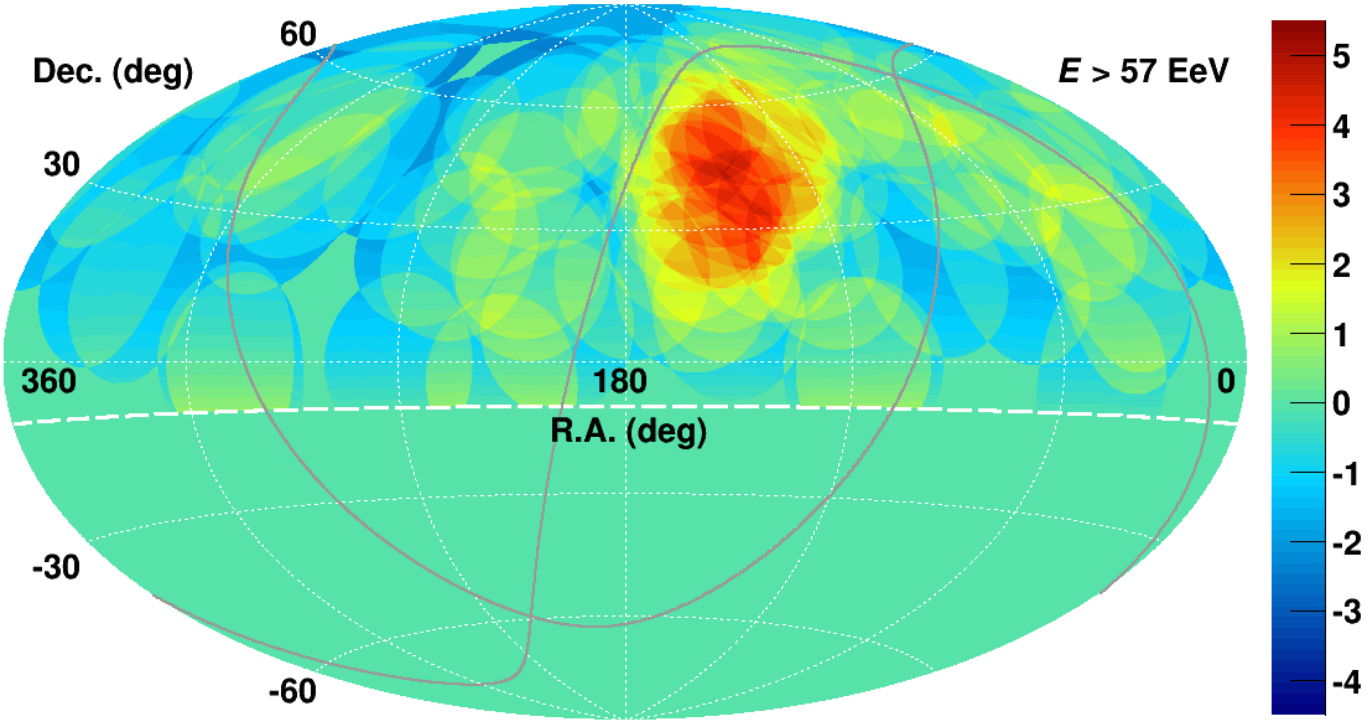
- TA data vs. predictions (modern GMF models)
- Sub-percent upper limits on the Galactic proton flux
- All experiments agree on light composition

CRs of E>10^{18} eV are extragalactic

Hot spot

E>57 EeV - Years 1-5 excess map

TA 2014

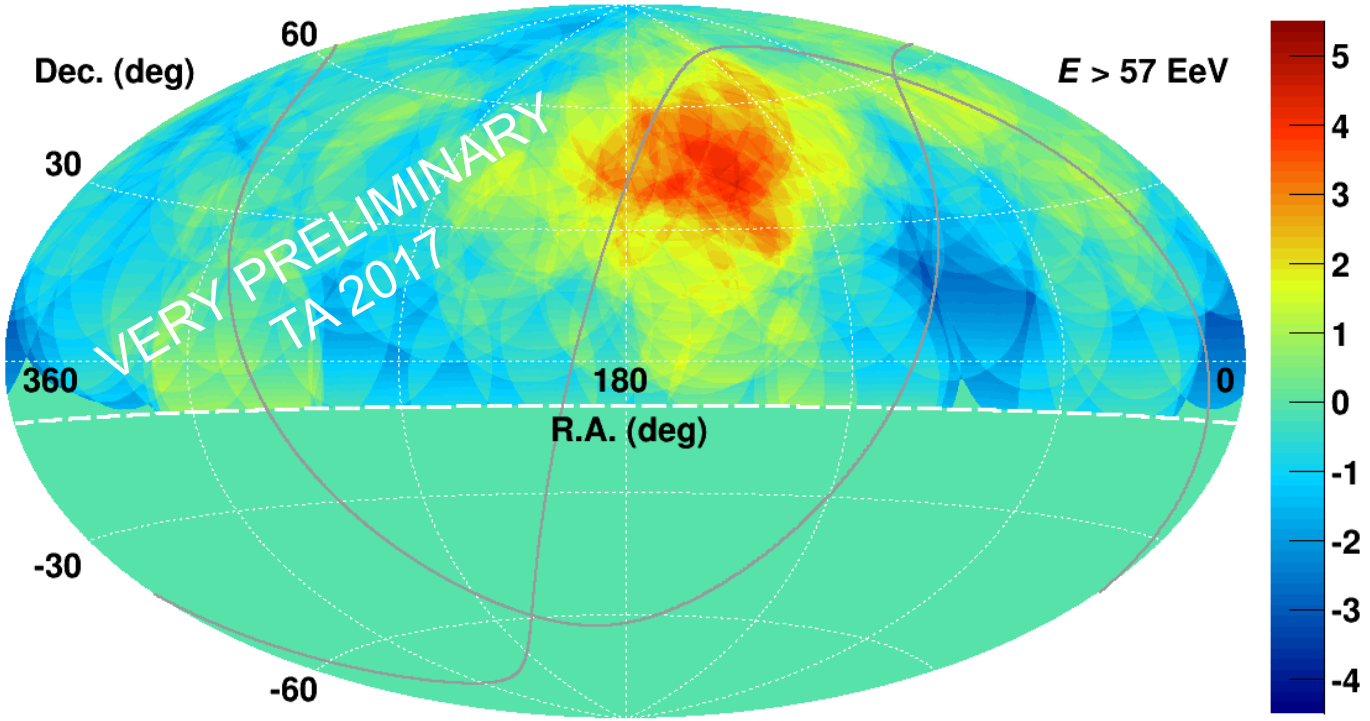


Total events: 72
Observed: 19
Expected : 4.5

Best circle center: RA=146.7^{o}, Dec=+43.2^{o}
Best circle radius: 20^{o}
Local significance : 5 σ
Global significance : 3 σ

Hot spot

E>57 EeV - Years 1-9 excess map



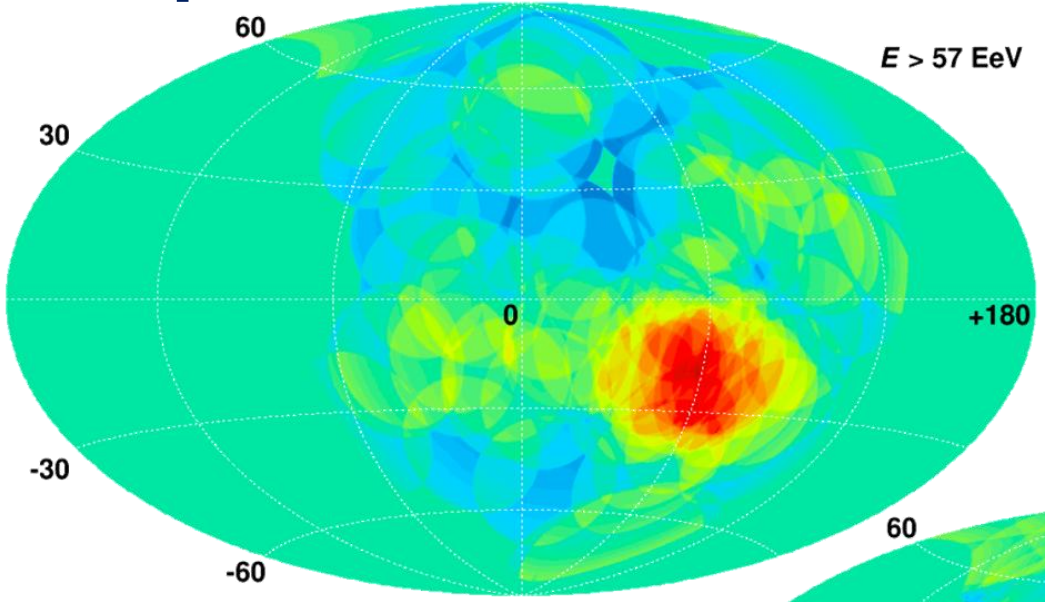
Total events: 143
Observed: 34
Expected : 13.5

Best circle center: RA=144.3^{o}, Dec=+40.3^{o}
Best circle radius: 25^{o}
Local significance : 5 σ
Global significance : 3 σ

TA 2017

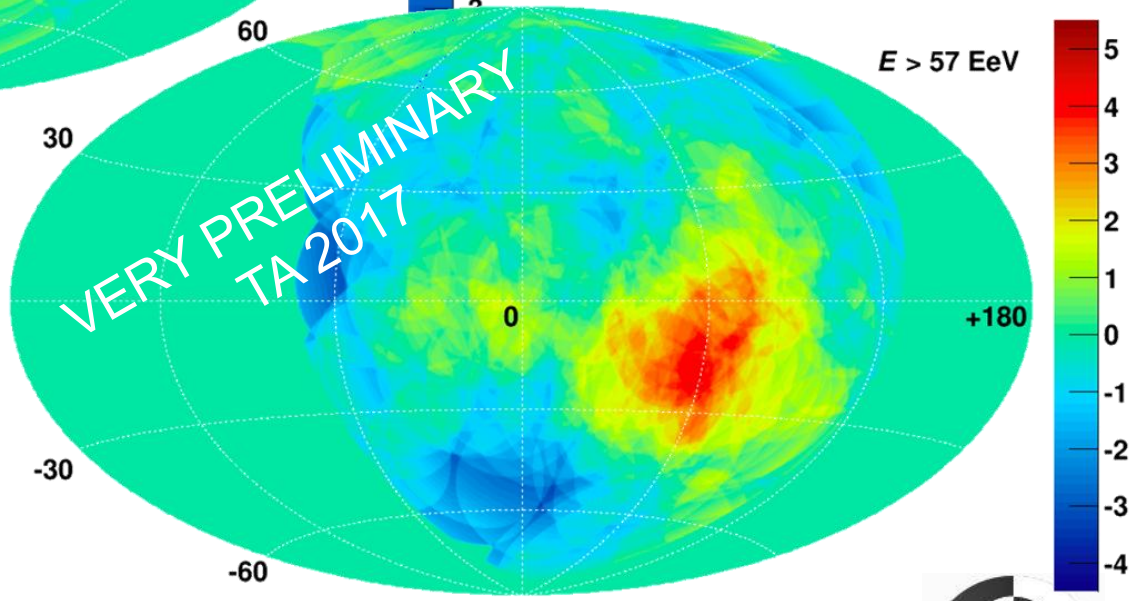
Hot spot

Supergalactic coordinates



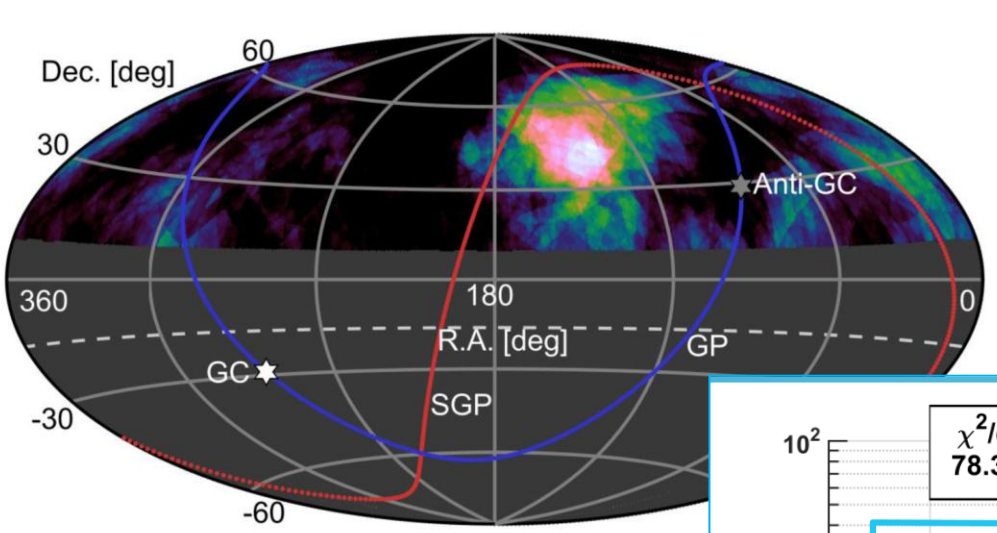
years 1-5
20° circles

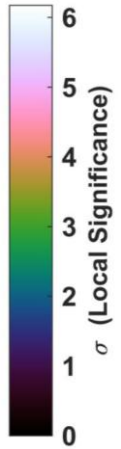
years 1-9
25° circles



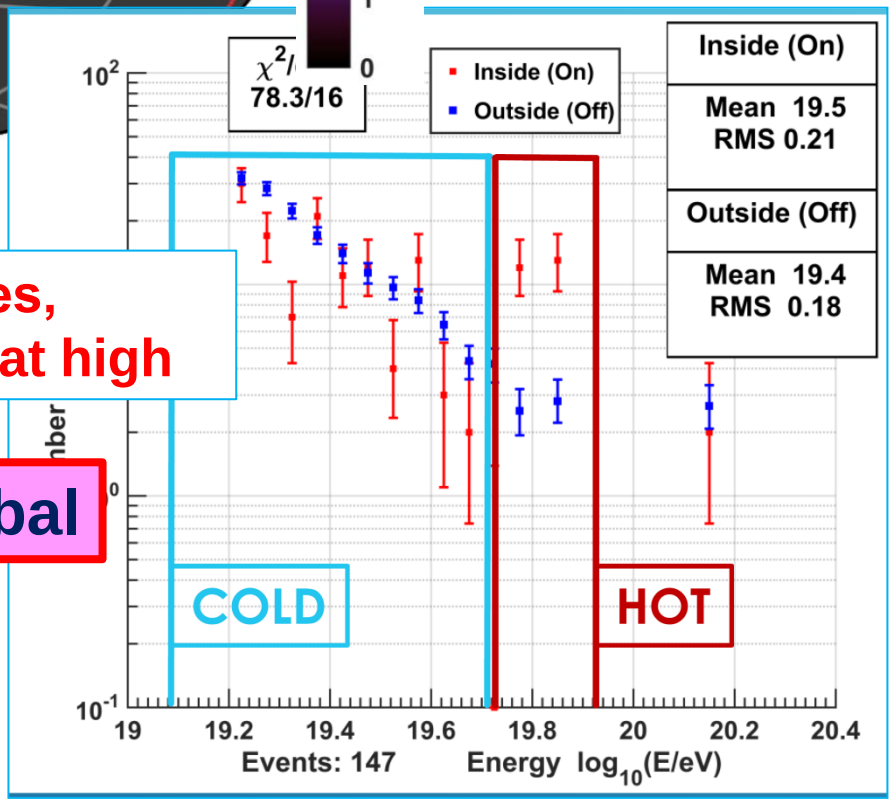
TA 2017

Spectral anisotropy at the hot spot





$E \geq 10^{19.2}$ eV



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

3.7σ global

TA 2017

Small scale: starburst correlations

Auger starburst correlation hypothesis:

- catalog of SBG selected for γ-ray studies
  (69 sources, most undetected in γ) – *Fermi LAT 2012*
- radio flux @1.4 GHz: >0.3 Jy
- Local Group removed ⇒ 23 sources

- CR flux proportional to 1.4 GHz flux
- smearing angle 12.9°
- CR energies >39 EeV

- ❑ 9.7% of the CR flux: from these sources
- ❑ the rest: isotropic

Auger 2017

// ~4σ favoured over 100% isotropic
// ~3σ favoured over matter distribution

Small scale: starburst correlations

TA test of the hypothesis: everything fixed, no scans

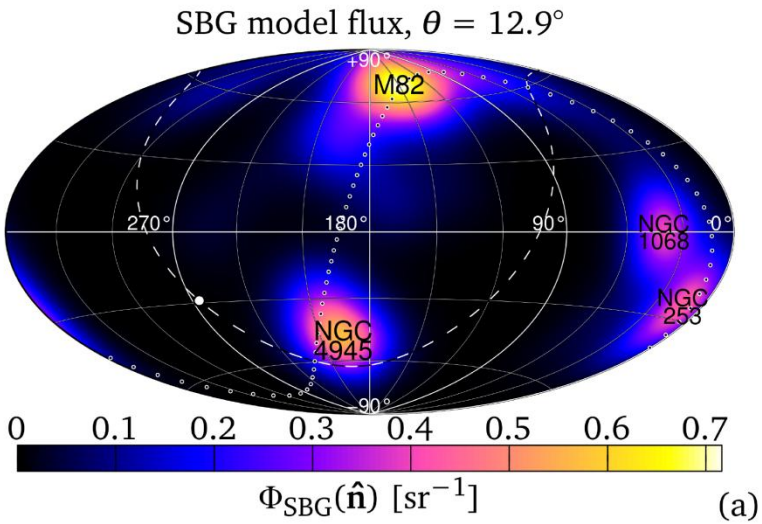
- same sources
- same flux assumptions
- same smearing angle
- CR energies >43 EeV

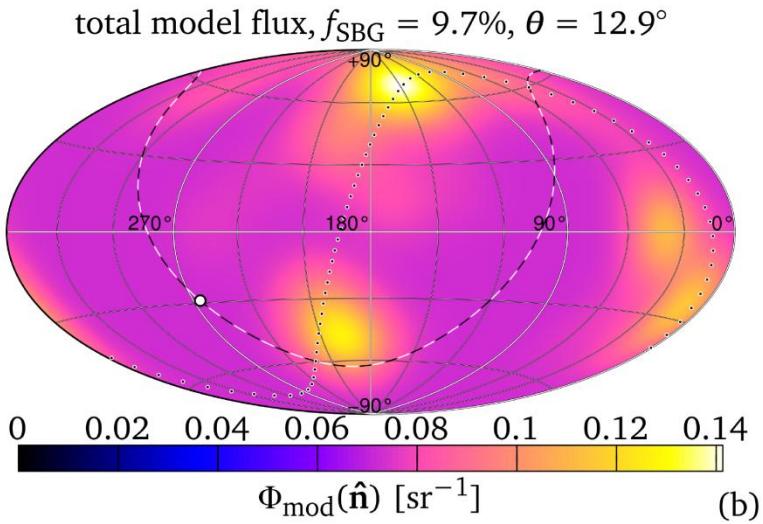
  (10.4% Auger/TA systematic energy shift)

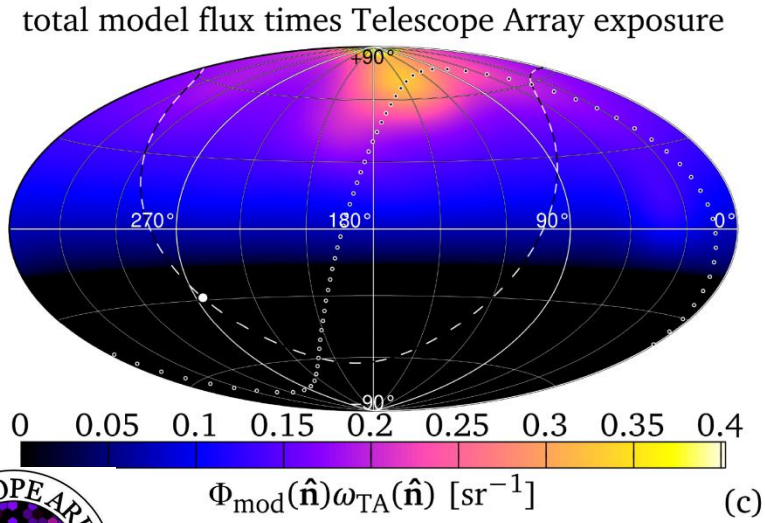
- 9.7% of the CR flux: from these sources
- the rest: isotropic

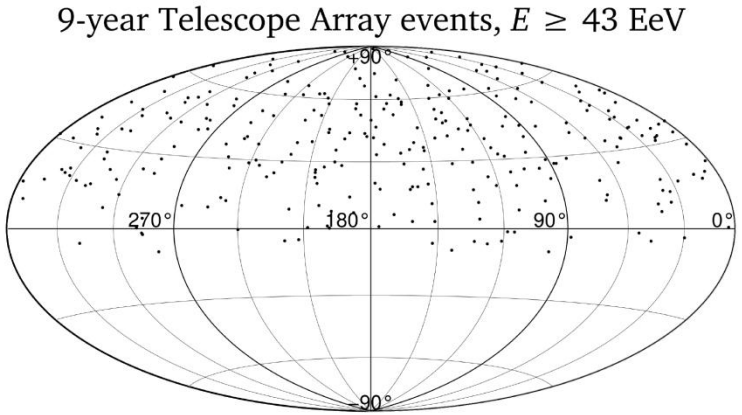
TA 2018

Small scale: starburst correlations



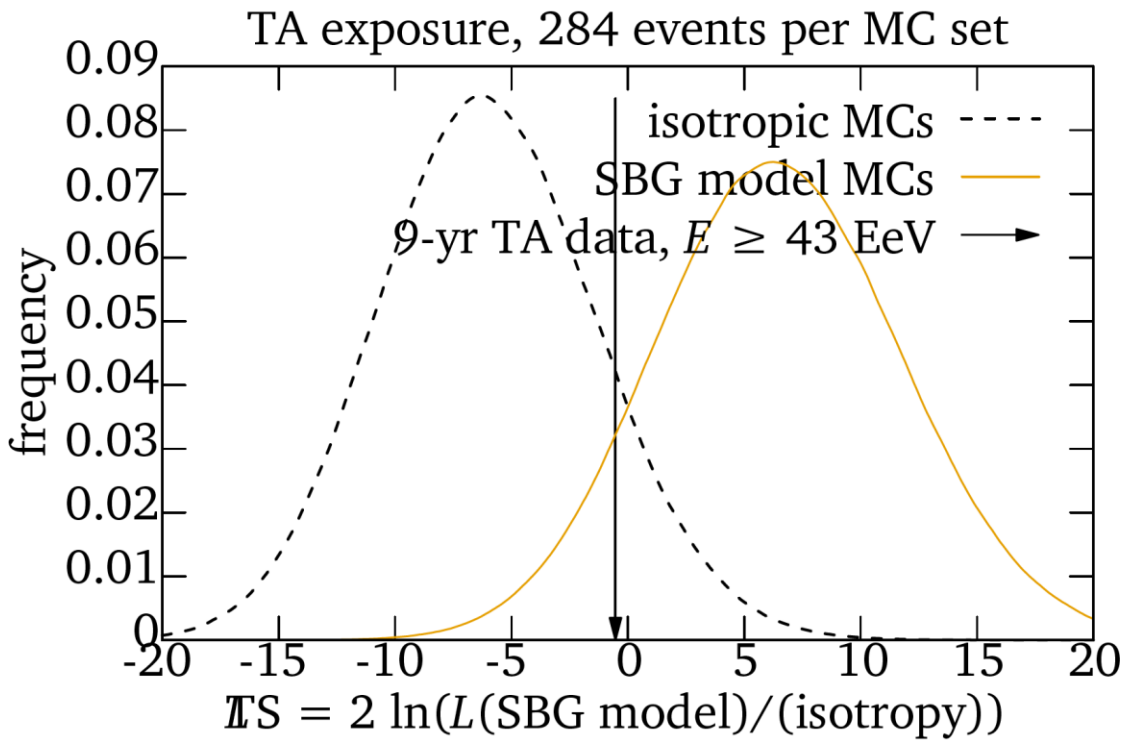






TA 2018

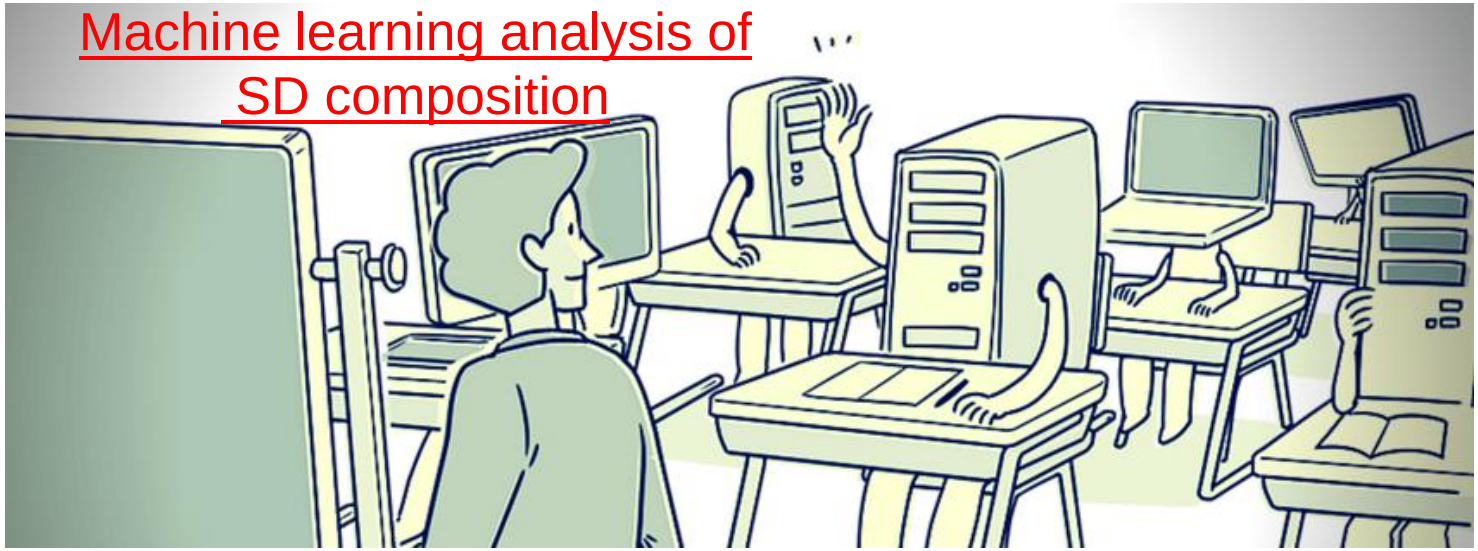
Small scale: starburst correlations



// ~1.2σ compatible with 100% isotropic
// ~1.3σ compatible with starbursts

TA 2018

Towards direction-dependent composition



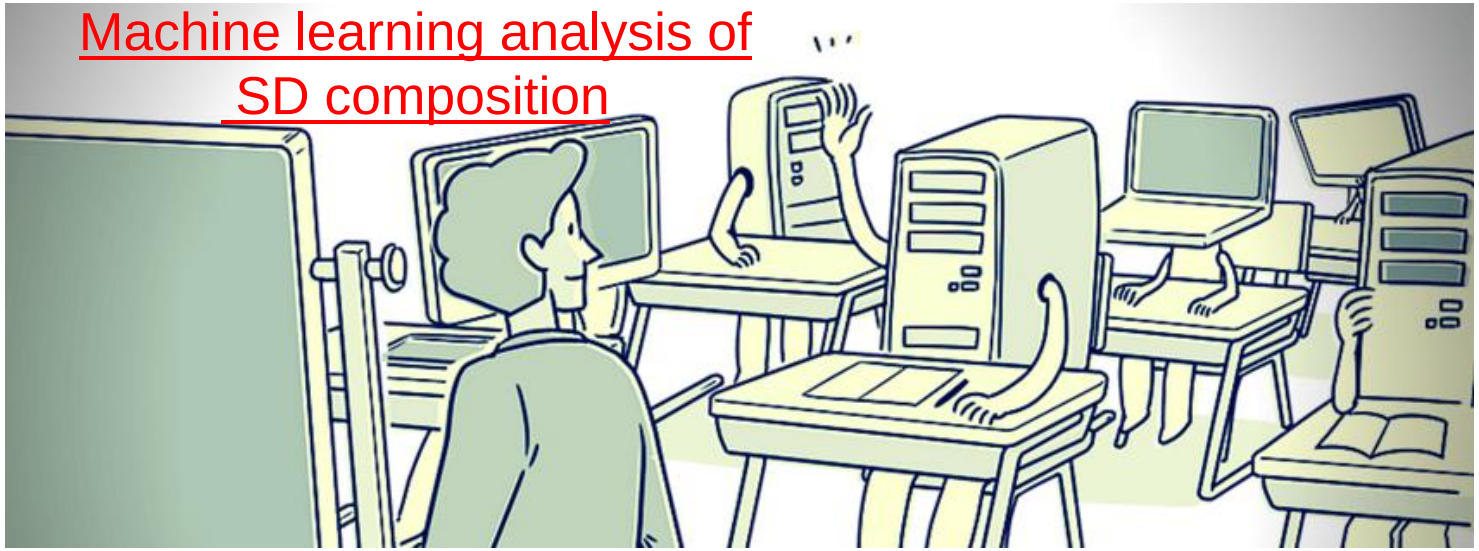
14 composition-dependent parameters from SD

Primary type info for ~18K SD events (E>1 EeV)

TA 2018

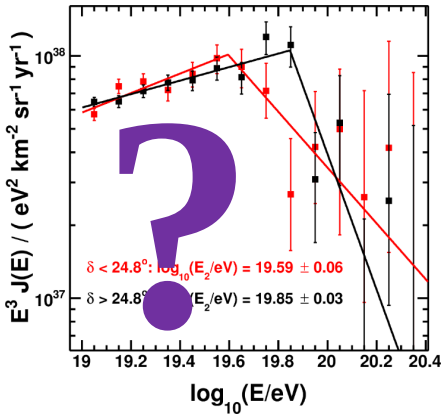
Towards direction-dependent composition

Machine learning analysis of SD composition



14 composition-dependent parameters from SD

Primary type info for ~18K SD events (E>1 EeV)



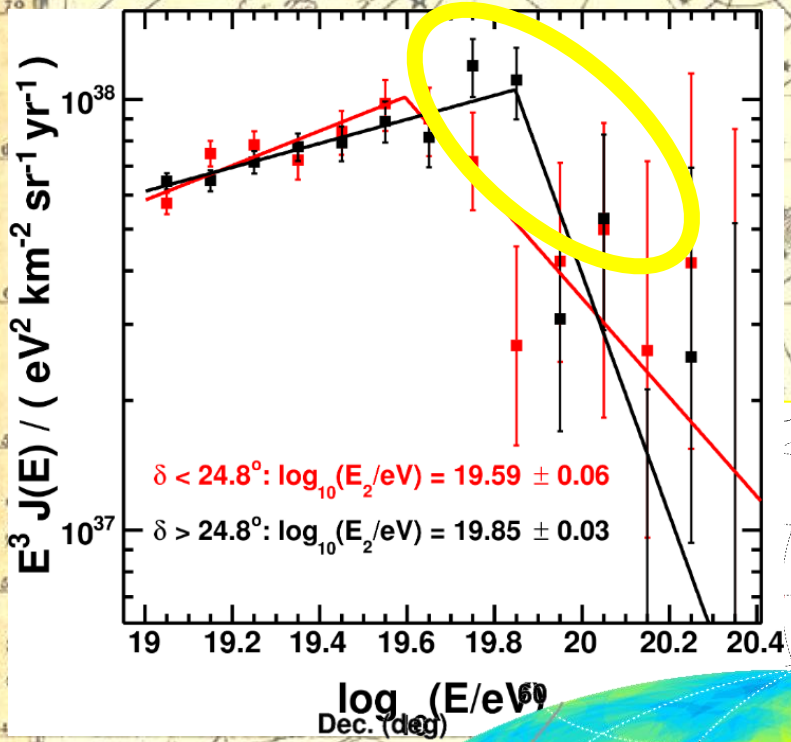
STAY TUNED
TA 2019

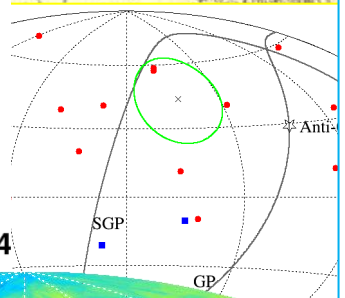
Conclusions

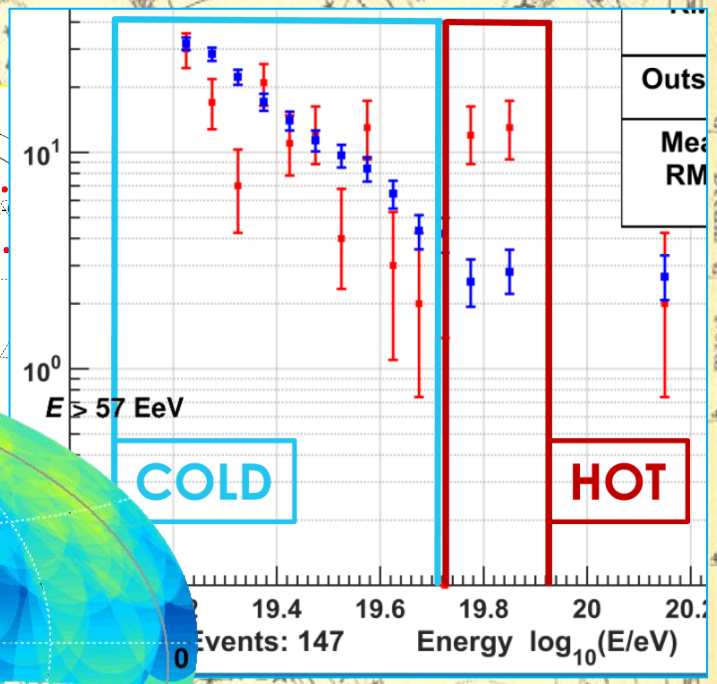
- hints of large-scale anisotropy at E>57 EeV
  - ✓supergalactic latitude/LSS
  - ✓supergalactic plane spectrum
  - ✓declination dependence of the spectrum
- medium-scale anisotropy at E>57 EeV
  - ✓hot spot
  - ✓cold spot at lower energies in the same place
- small-scale
  - ✓doublets at E>10^{20} eV, not significant
  - ✓ no confirmation of Auger starburst correlations
- coming soon: direction-dependent composition

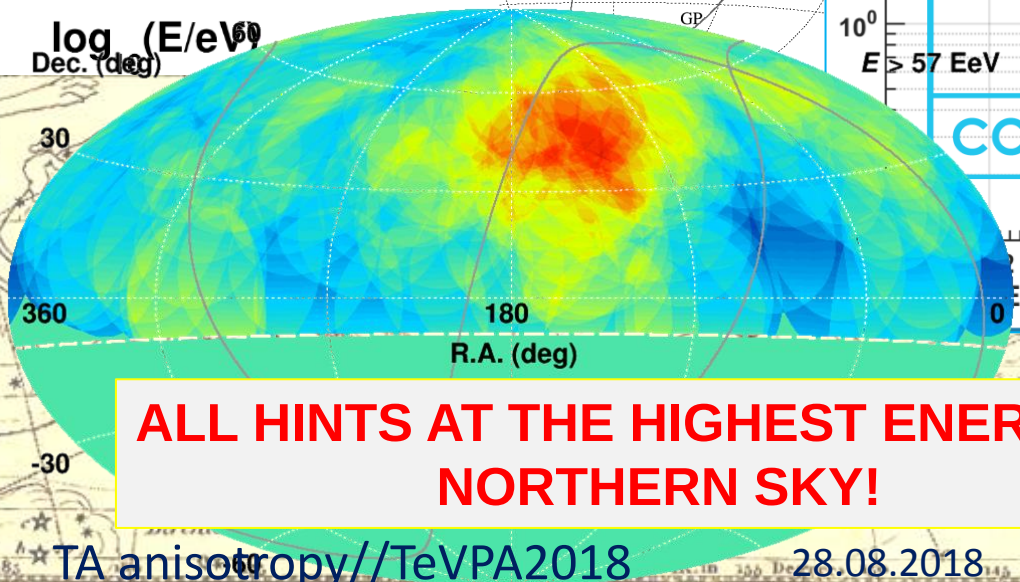
ALL HINTS AT THE HIGHEST ENERGIES!

Conclusions









ALL HINTS AT THE HIGHEST ENERGIES, NORTHERN SKY!

Conclusions

ALL HINTS AT THE HIGHEST ENERGIES, NORTHERN SKY!

Backup slides follow

TA SD data

9-year data: 12.05.2008 – 11.05.2017

"anisotropy set"

- zenith angle <55°
- core inside array boundary
- angular resolution: <1.5°
- energy resolution: ~20%

- 3691 above 10 EeV
- 257 above 40 EeV
- 108 above 57 EeV

"hotspot set"

- loose cuts (4 stations)
- angular resolution: <1.7°

- 143 above 57 EeV
- 23 above 100 EeV

Global anisotropy

dipole sensitivity

Auger: dipole

- E>8 EeV
- 6.5% dipole towards *RA*=100°, *DEC*=-24°
- 5.2 σ

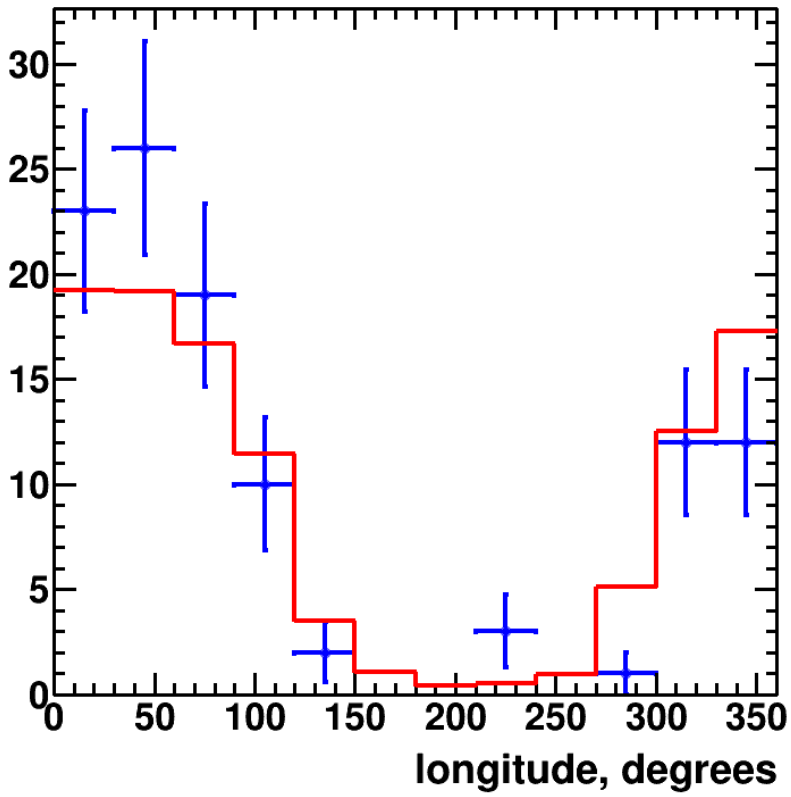
TA: dipole sensitivity estimate

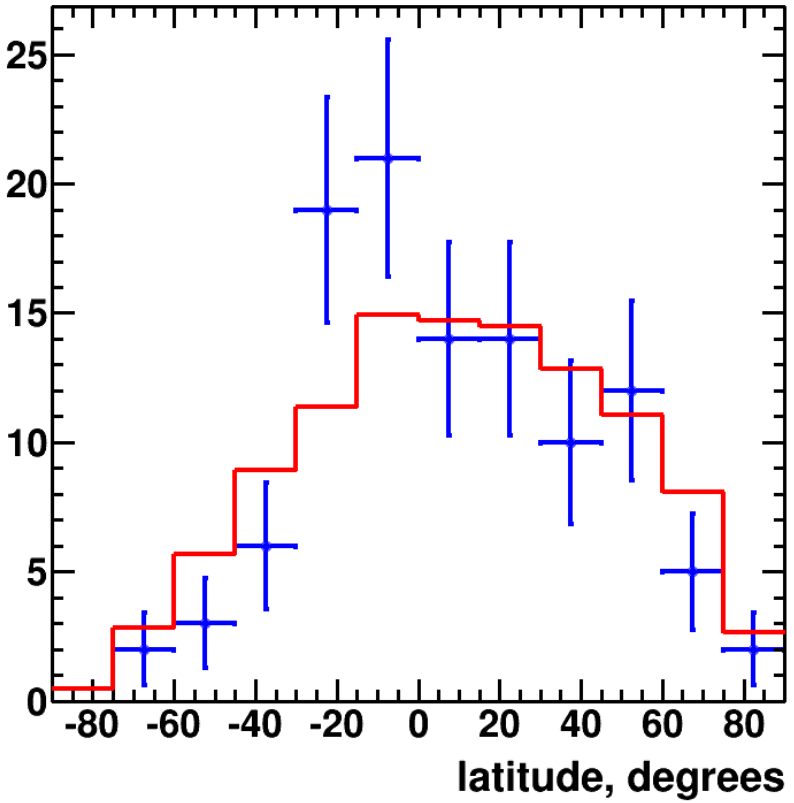
- E>8.9 EeV (energy systematic shift)
- 6.5% dipole towards *RA*=100°, *DEC*=-24°
- 2.1 σ EXPECTED

STAY TUNED
TA 2018

Global anisotropy

supergalactic coordinates



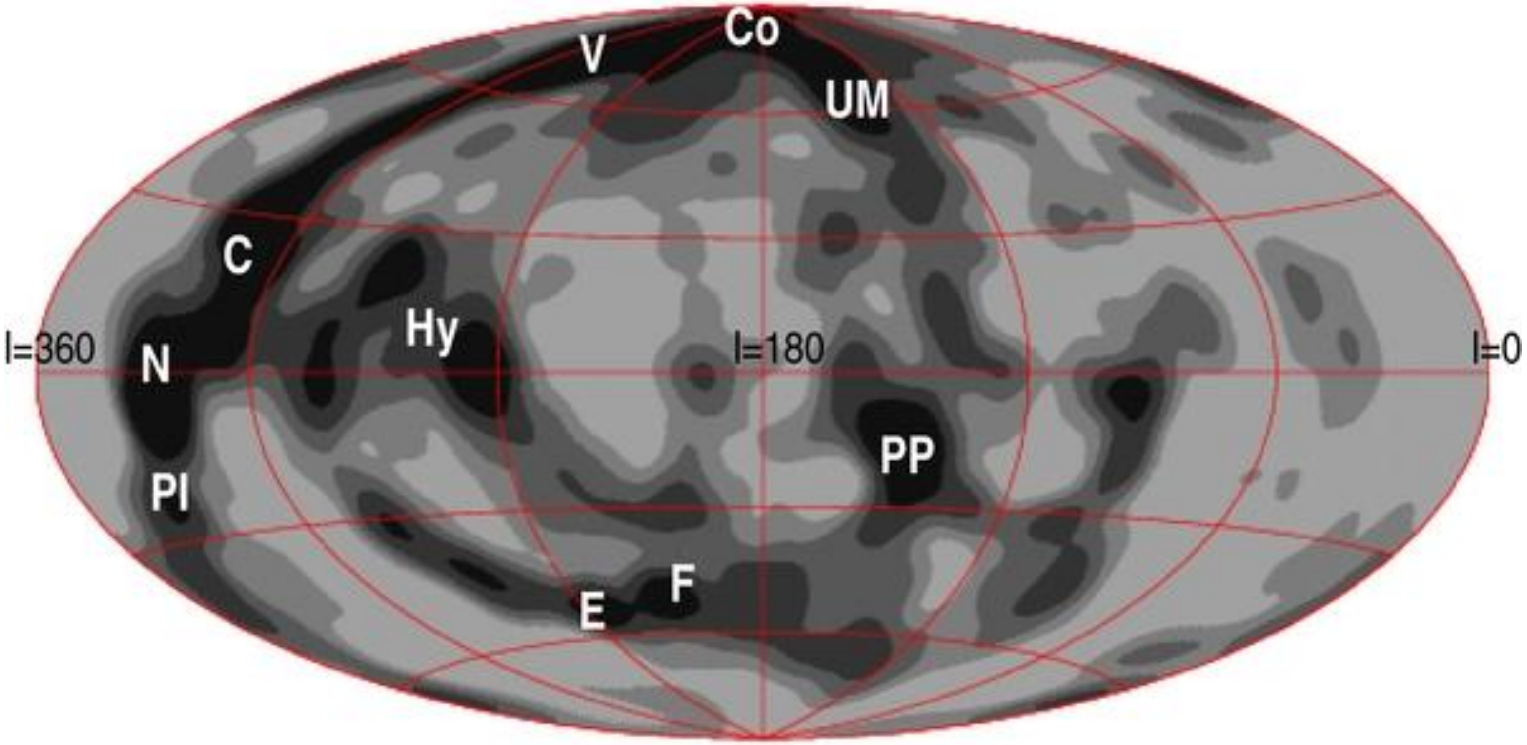


Kolmogorov-Smirnov p-value = 0.01 for SG latitude, E>57 EeV

other thresholds/coordinates = isotropic

Global anisotropy

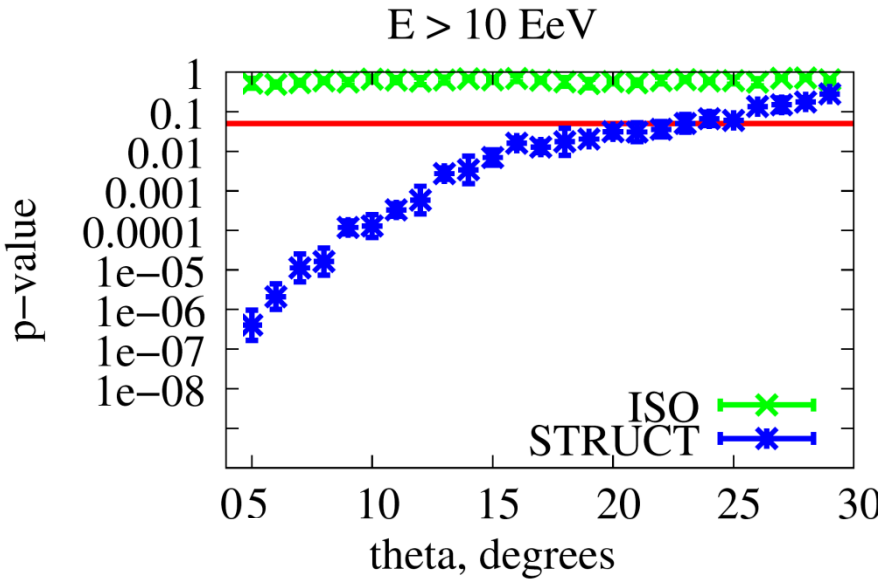
Large-scale structure

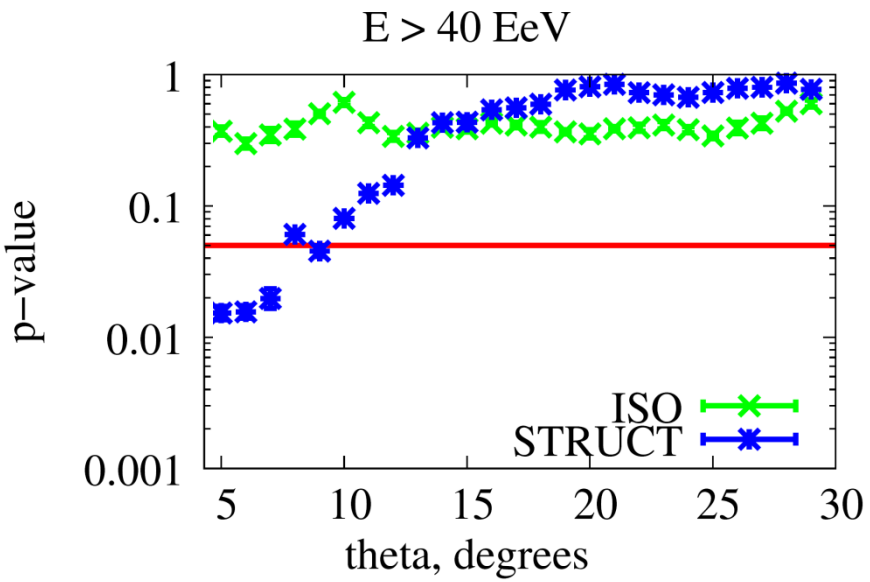


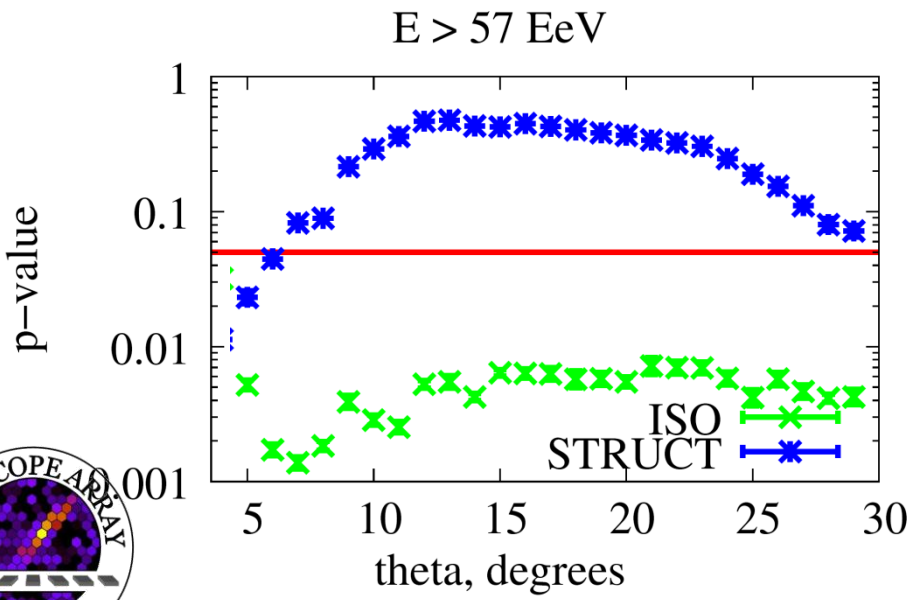
C: Centaurus SCl (60 Mpc); Co: Coma Cl (90 Mpc); E: Eridanus Cl (30 Mpc); F: Fornax Cl (20 Mpc); Hy: Hydra SCl (50 Mpc); N: Norma SCl (65 Mpc); PI: Pavo-Indus SCl (70 Mpc); PP: Perseus-Pisces SCl (70 Mpc); UM: Ursa Major Cl (20 Mpc); and V: Virgo Cl (20 Mpc).

Sky map of expected flux at *E* > 57 EeV (Galactic coordinates). The smearing angle is 6°.

Global anisotropy



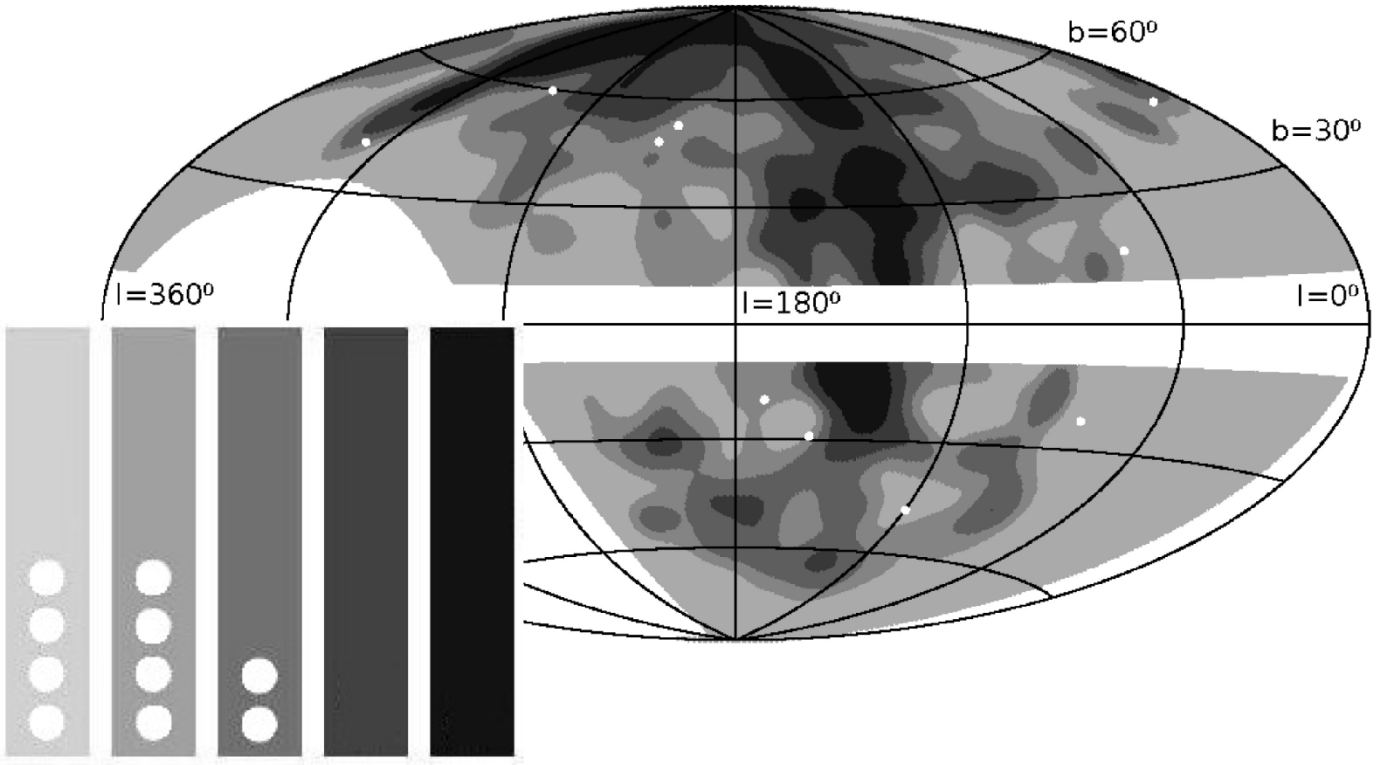




E>57 EeV
consistent with LSS
inconsistent with isotropy

Global anisotropy

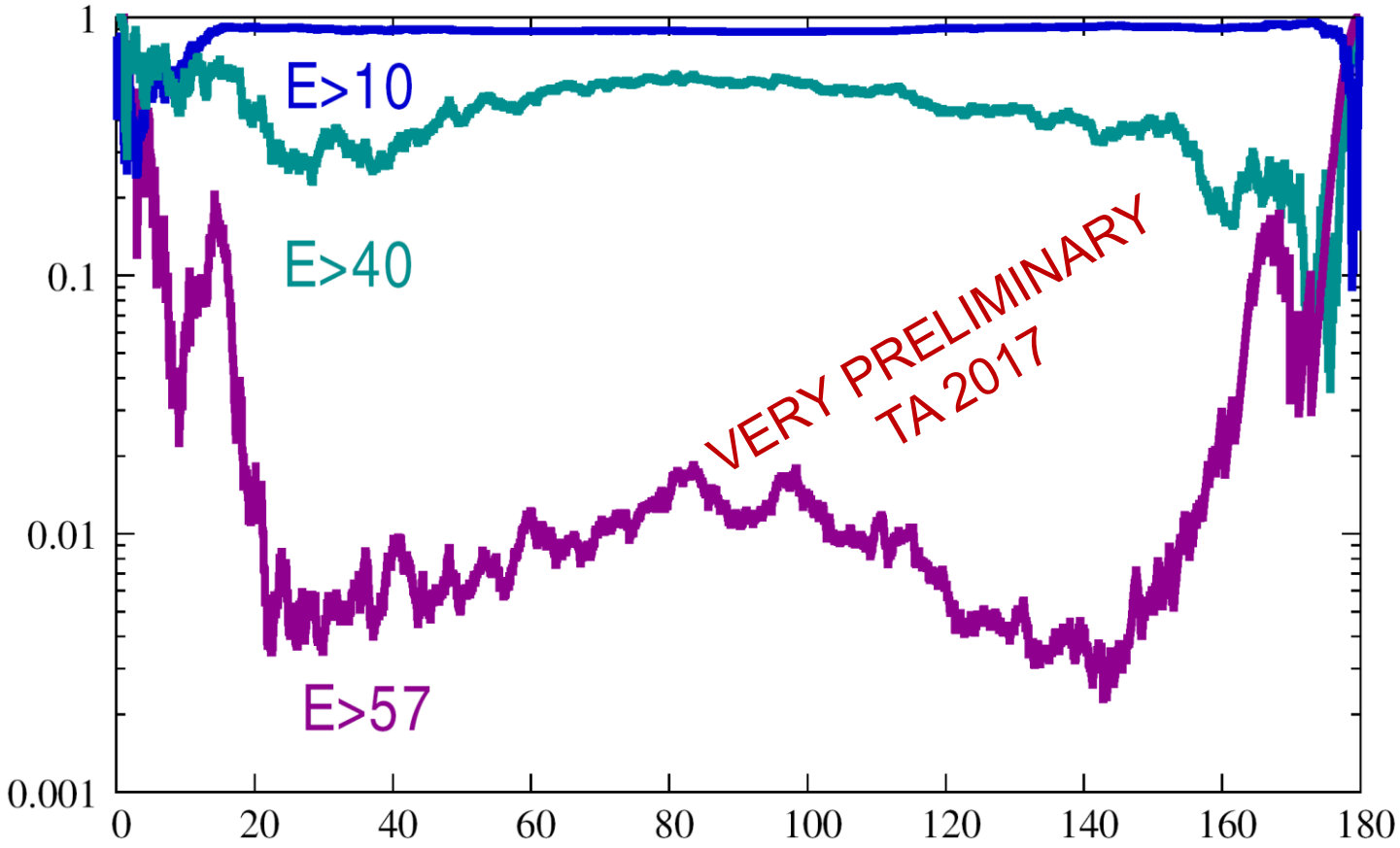
LSS correlations - method



- Events following the model would produce uniform distribution over the bands
- No binning is actually needed (on the picture it is for illustration only): two distributions may be compared by the Kolmogorov-Smirnov test

Medium-scale anisotropy

Autocorrelations



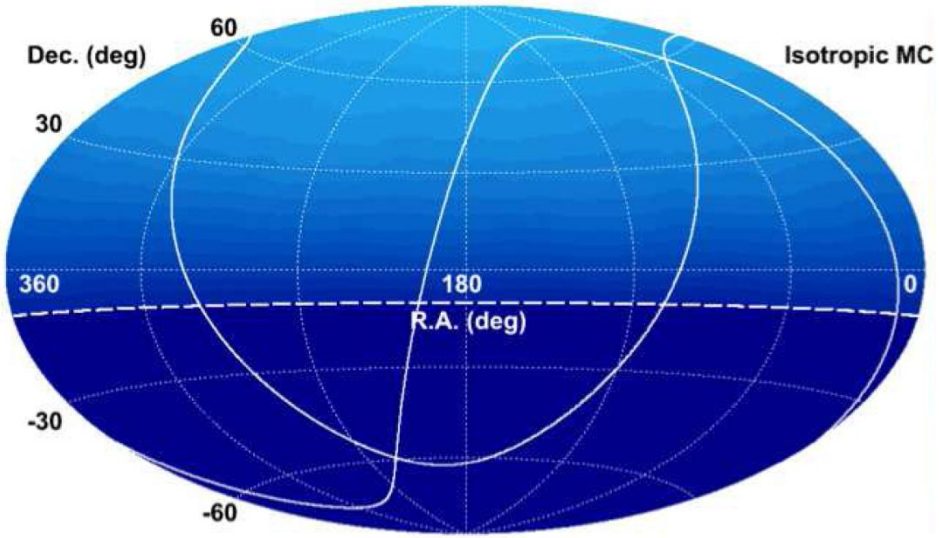
Hot spot

Significance estimation

TA 2014

"Li-Ma":
approximation to Poisson statistics based on on-source/off-source exposure

- "On": inside the circle, "off": the rest
- Scan for circle center (0.1 deg steps) and radius (15^o, 20^o, 25^o, 30^o, 35^o)
- Find the strongest excess ⇨ local significance
- Repeat the procedure for isotropic Monte-Carlo sets ⇨ global significance
  (look-elsewhere correction = penalty factor)



Hot spot

Years 1-9 bin scan

TA preliminary

"Li-Ma":
approximation to Poisson statistics based on on-source/off-source exposure

- "On": inside the circle, "off": the rest
- Scan for circle center (0.1 deg steps) and radius (15^o, 20^o, 25^o, 30^o, 35^o)

Bin size	15	20	25	30	35
σ	4.4	4.7	5.1	5.0	4.7

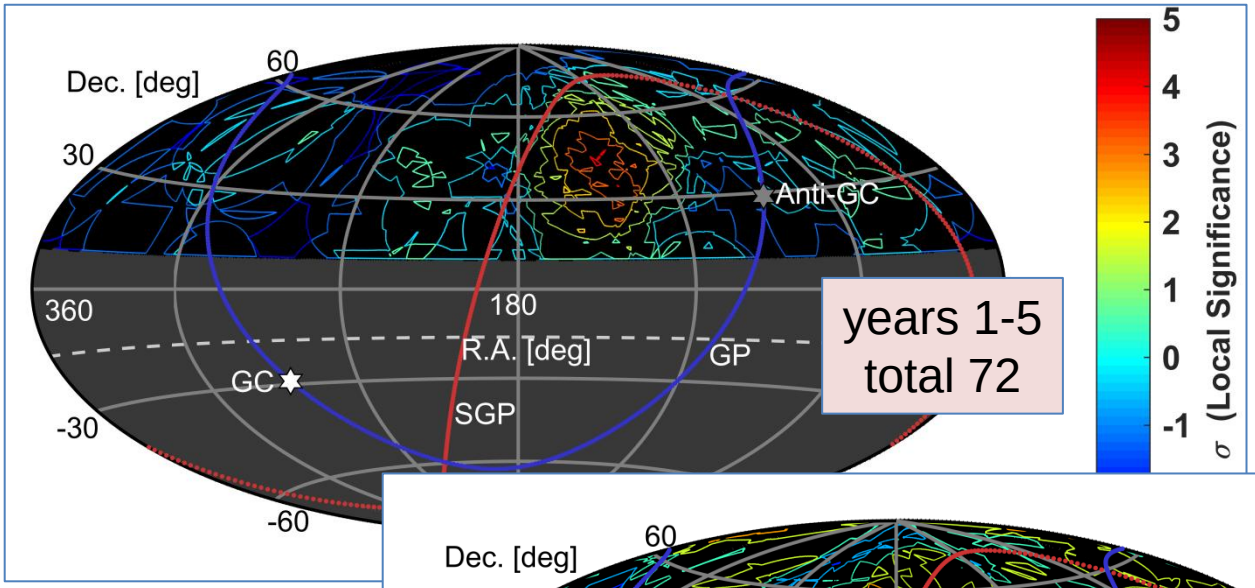
- Find the strongest excess ⇨ local significance
- Repeat the procedure for isotropic Monte-Carlo sets ⇨ global significance
  (look-elsewhere correction = penalty factor)

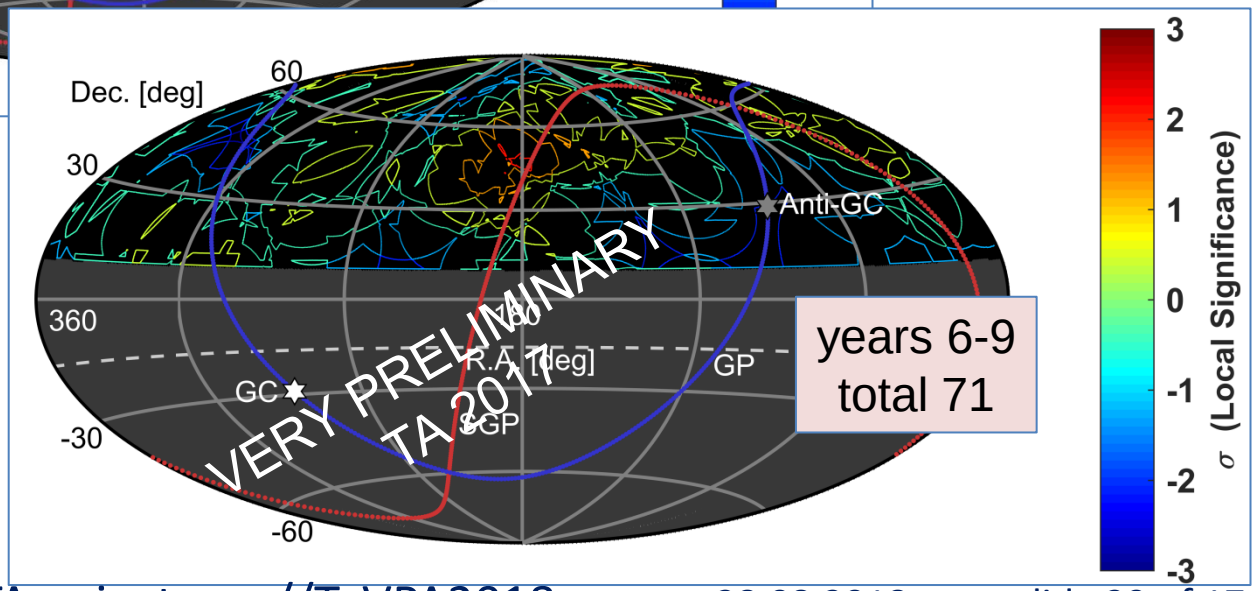
TA 2017

Hot spot

Years 6-9 vs. 1-5

no hypothesis – no tests





Hot spot

Years 6-9 vs. 1-5

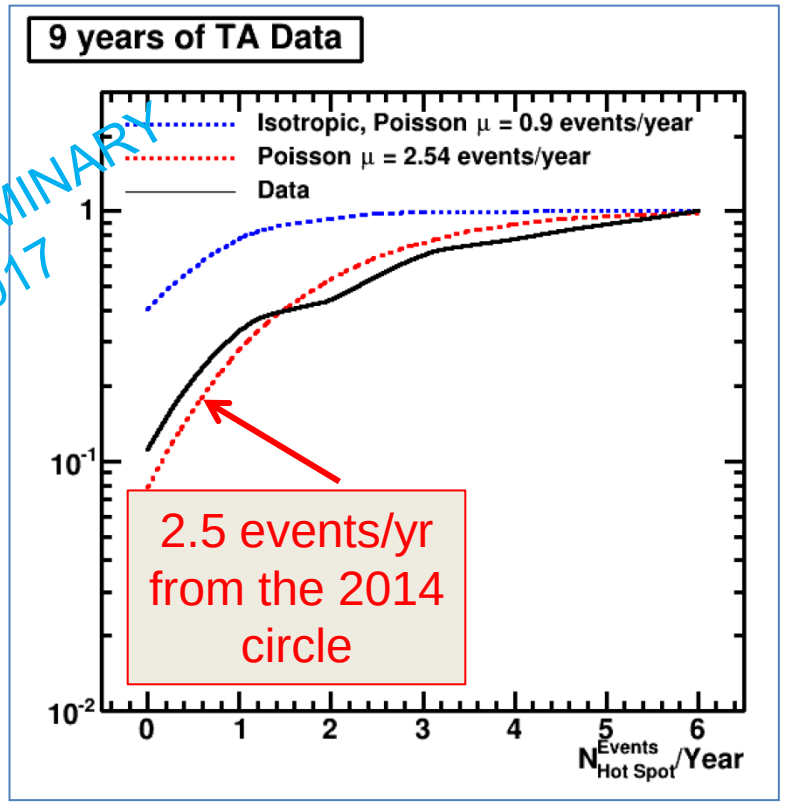
"would-be hypothesis" – "would-be tests"

global ≠ local P-value ➡ positive fluctuation, need to correct our expectations

circle defined in *[TA, ApJ 2014]* = years 1-5:
center RA=146.7°, Dec=+43.2°, radius: 20°

	Years 1-5	Years 6-9
Expected (isotropic)	4.5	3.6
Expected (hot spot)	12.5	10.0
Observed	19	5

VERY PRELIMINARY
TA 2017



Hot spot

Years 6-9 vs. 1-5

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VERY PRELIMINARY
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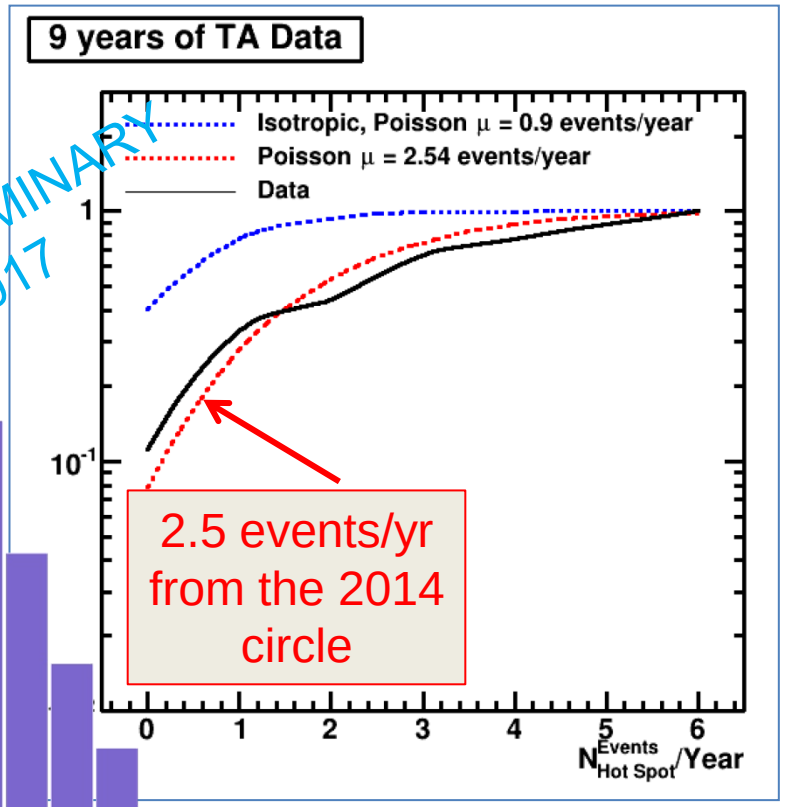
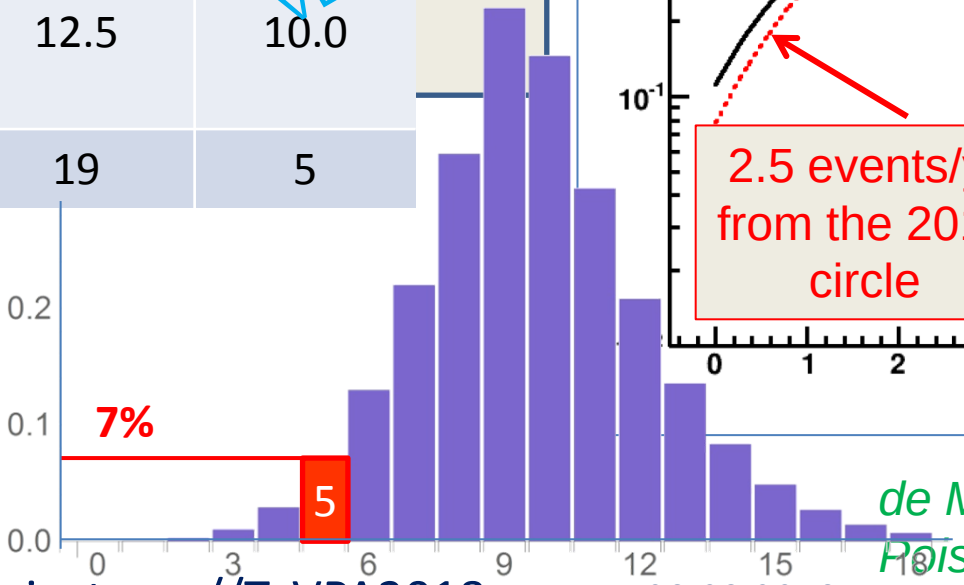




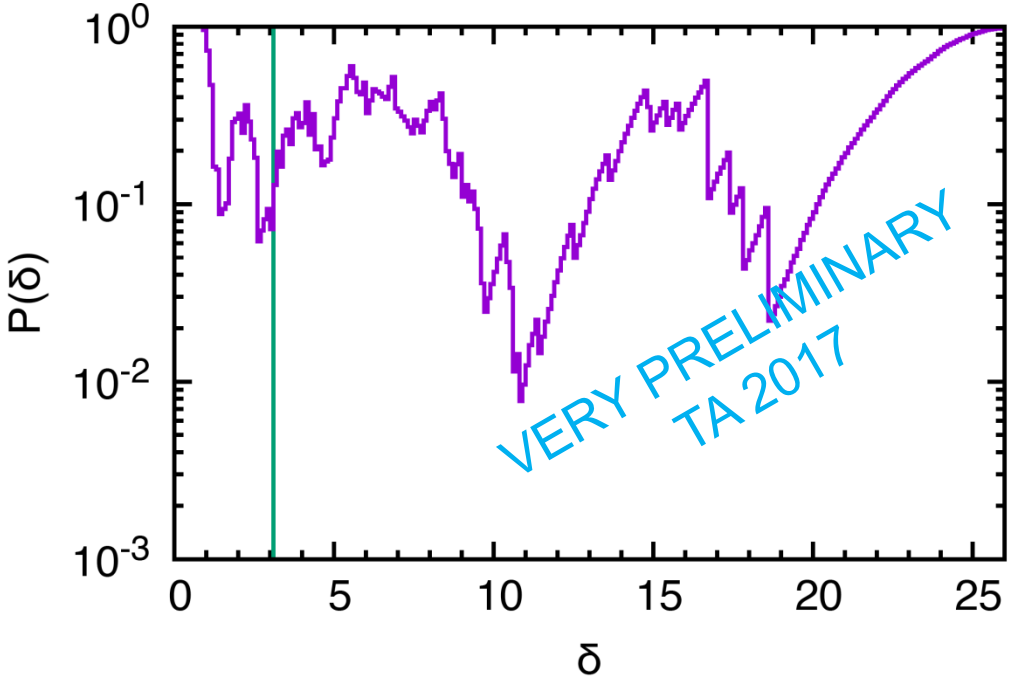
de Moivre 1711
Poisson 1837

Small-scale anisotropy

AGN correlations

testing the original Auger hypothesis

- Sources:
  Veron 2006 catalog
  - AGN, QSO, BL Lac sections.
  - Cut on redshift $0 < z < 0.018$
- Energy $E > 57$ EeV
- Zenith angle $ZA < 55°$
- Angular scale
  - $\delta = 3.1°$



7% probability of random coincidence

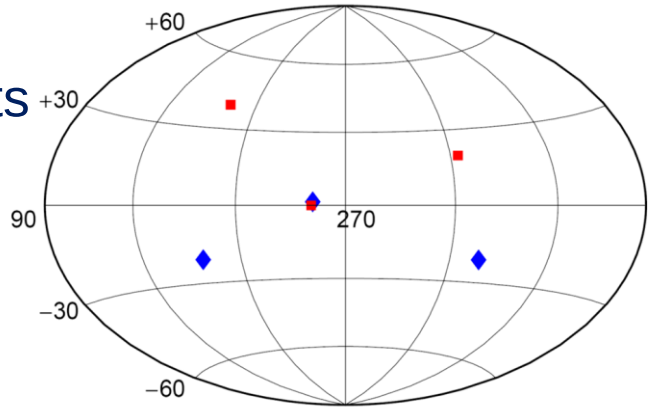
Small-scale anisotropy

Autocorrelations

- E> (10, 40, 57) EeV, scan over [small] angles, no significant clustering

- high E = small deflections, spread determined by angular resolution
- E> 100 EeV, resolution = 1°, pre-determined angle = $\sqrt{2}\times$resolution

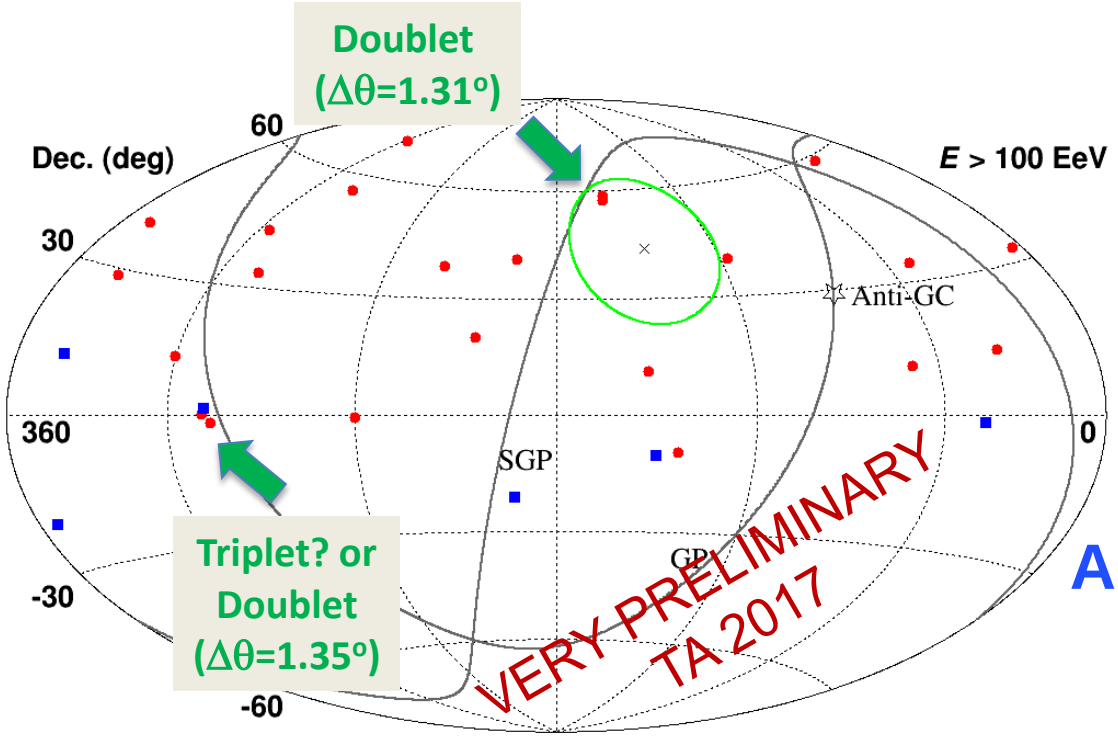
- doublet in TA/Auger joint dataset of 6 events [ST 2012]



- became a triplet (2 TA + 1 PAO) with more TA data [TA 2014]

Small-scale anisotropy

Autocorrelations



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

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

Small scale: starburst correlations

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

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

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

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

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

$$f_{\mathrm{SBG}} = 9.7\%$$