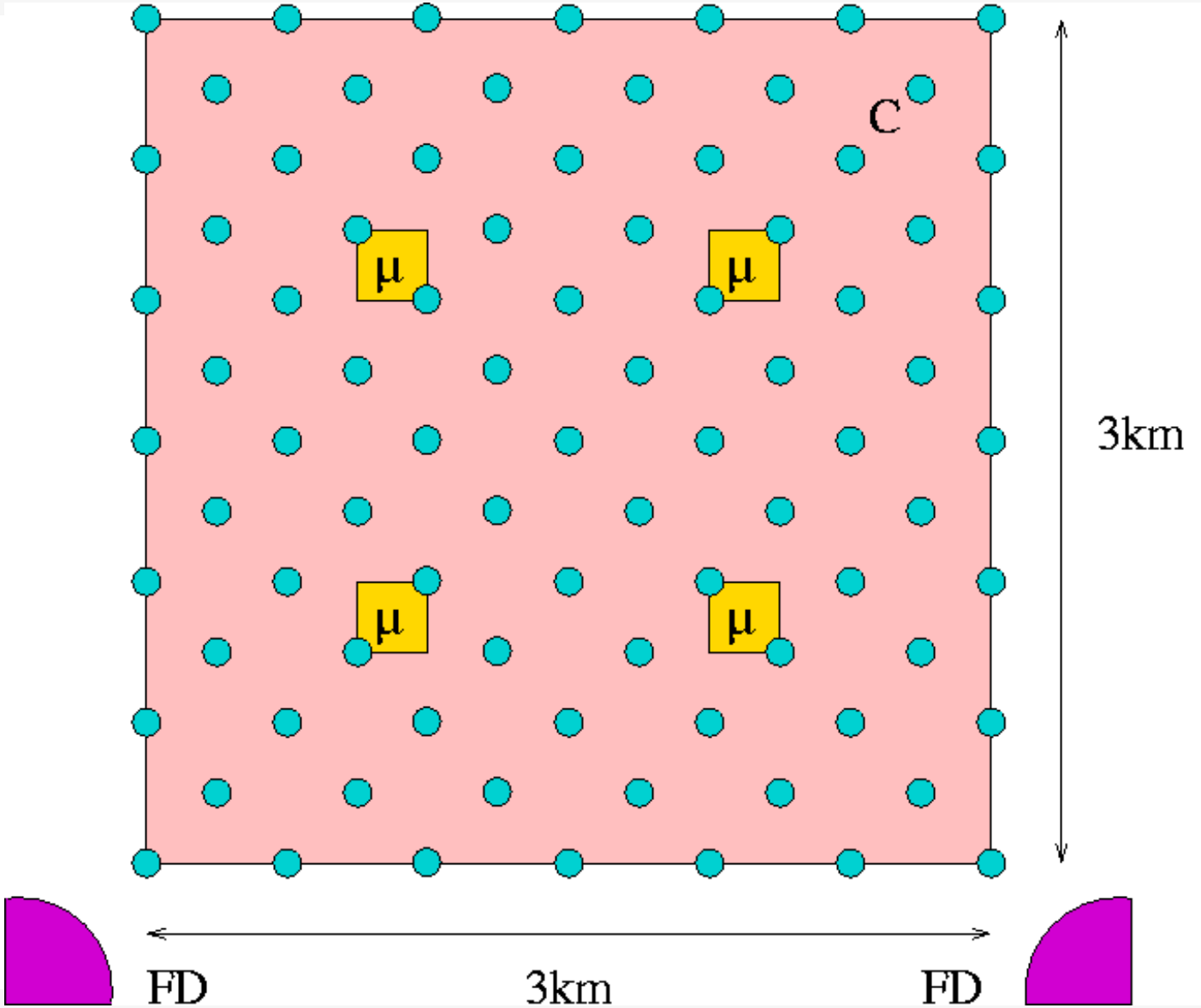
Extragalactic Cosmic Rays

- (Are there any?)
- Pierre Sokolsky
- University of Utah
- LHAASO Symposium
- May, 2023

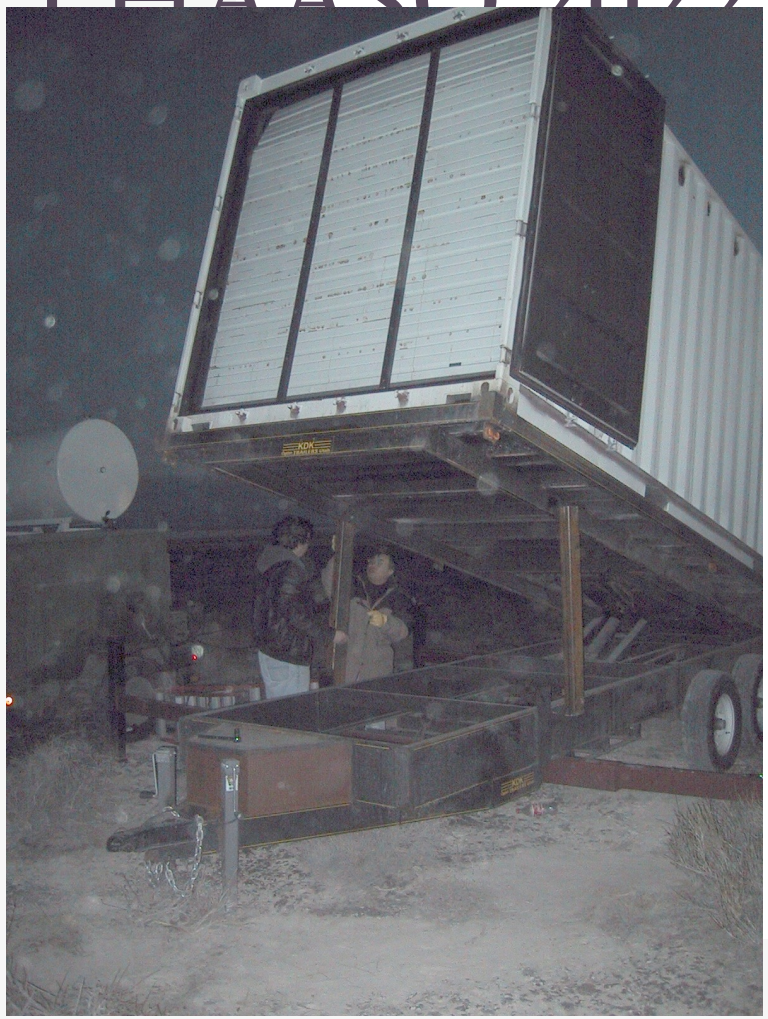
- Interest in ankle region: First Aspen Workshop on the Physics of the End of the Galactic Cosmic Ray Spectrum 2005

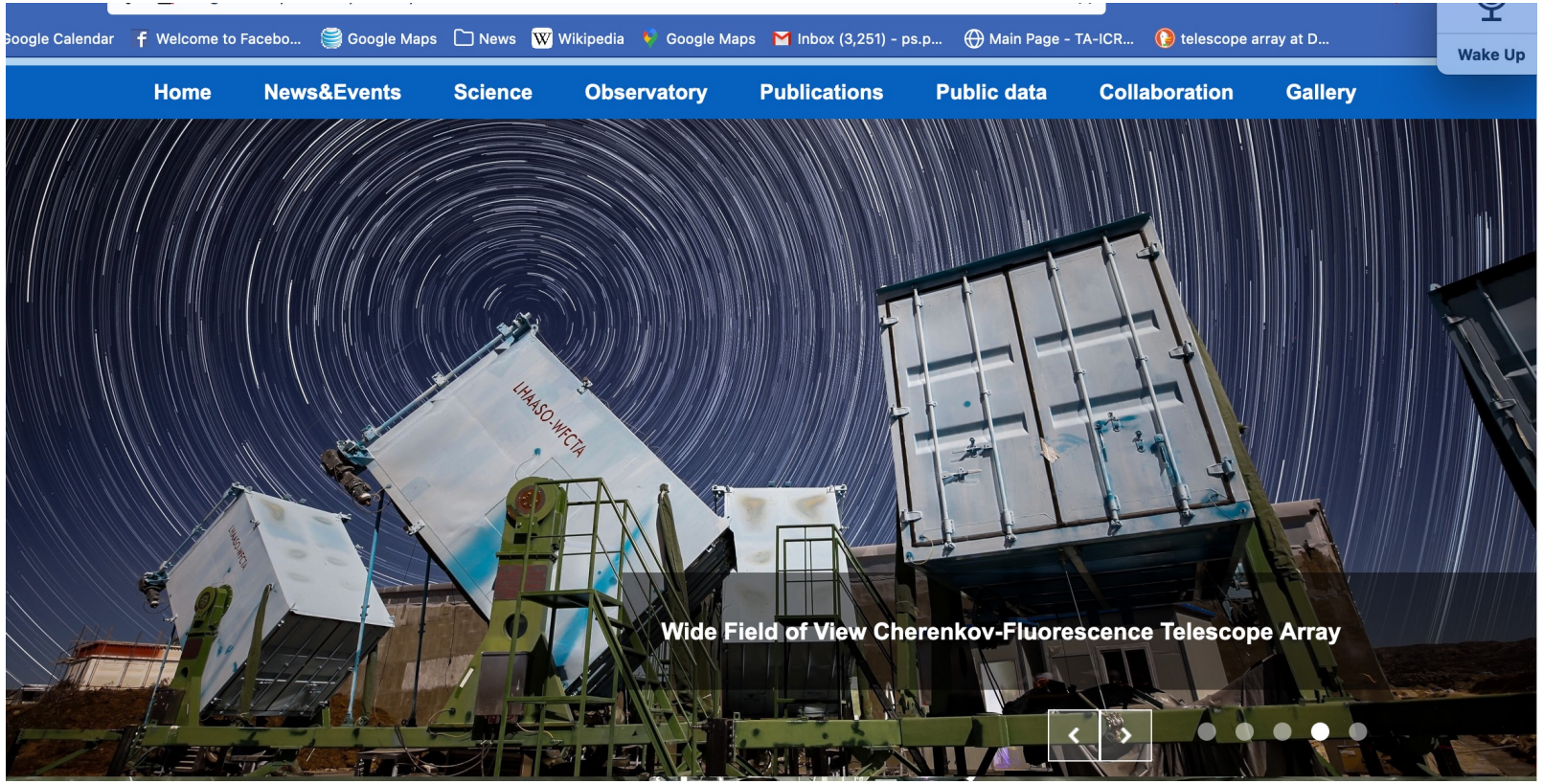
Proposed Cherenkade Detector

- Combination fluorescence + Cerenkov + muon array
- 3km × 3km
- Can probably sparsify the Cerenkov spacing from BLANCA
- May need larger light collectors to reach down to 10^{14} eV
- Infill scintillator array needed for lowest energies.



Wide field Cherenkov / Fluorescence modules –Utah prototype, circa 2000 vs LHAASO 2022





13 years later the LHAASO detector is bringing the world remarkable data.

This required equally remarkable perseverance, foresight and determination.

Congratulations !!

What does the cosmic ray spectrum tell us (about extragalactic sources)

Original results from HiRes and Auger showed > 5 sigma evidence for a cut-off at ~ 5 x 10^19 eV.

HiRes and Auger also had strong evidence for an ankle structure between 10^18 and 10^19 eV. Interpreted as end of galactic spectrum, or evidence for e+e- energy loss of extragalactic protons.

Structures confirmed by TA and further Auger data with very high significance.

Connection between knee at 10^15 eV and these structures becomes very important.

First Observation of the Greisen-Zatsepin-Kuzmin Suppression

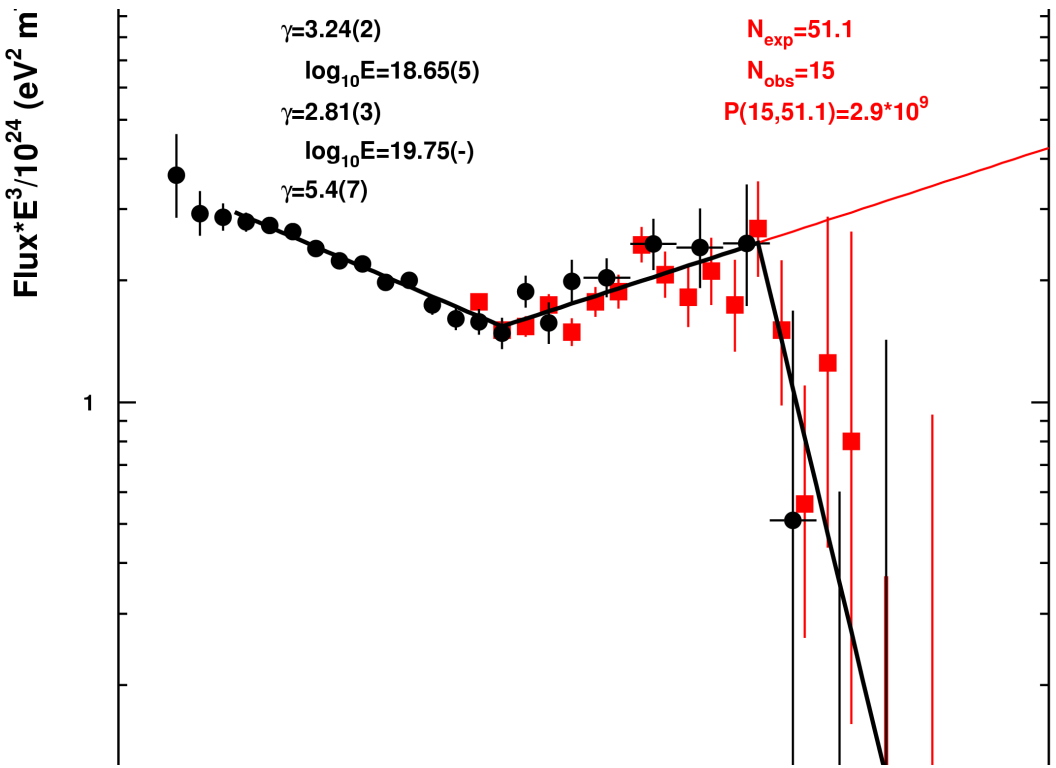
R.U. Abbasi,[1] T. Abu-Zayyad,[1] M. Allen,[1] J.F. Amman,[2] G. Archbold,[1] K. Belov,[1] J.W. Belz,[1] S.Y. Ben Zvi,[3] D.R. Bergman,[4,*] S.A. Blake,[1] O.A. Brusova,[1] G.W. Burt,[1] C. Cannon,[1] Z. Cao,[1] B.C. Connolly,[3] W. Deng,[1] Y. Fedorova,[1] C.B. Finley,[3] R.C. Gray,[1] W.F. Hanlon,[1] C.M. Hoffman,[2] M.H. Holzscheiter,[2] G. Hughes,[4] P. Hüntemeyer,[1] B.F Jones,[1] C.C.H. Jui,[1] K. Kim,[1] M.A. Kirn,[5] E.C. Loh,[1] M.M. Maestas,[1] N. Manago,[6] L.J. Marek,[2] K. Martens,[1] J.A.J. Matthews,[7] J.N. Matthews,[1] S.A. Moore,[1] A. O'Neill,[3] C.A. Painter,[2] L. Perera,[4] K. Reil,[1] R. Riehle,[1] M. Roberts,[7] D. Rodriguez,[1] N. Sasaki,[6] S.R. Schnetzer,[4] L.M. Scott,[4] G. Simmis,[2] J.D. Smith,[1] P. Sokolsky,[1] C. Song,[3] R.W. Springer,[1] B.T. Stokes,[1] S.B. Thomas,[1] J.R. Thomas,[1] G.B. Thomson,[4] D. Tupa,[2] S. Westerhoff,[3] L.R. Wiencke,[1] X. Zhang,[3] and A. Zech[4]

(The High Resolution Fly's Eye Collaboration)

[1] *University of Utah, Department of Physics, Salt Lake City, UT, USA*
[2] *Los Alamos National Laboratory, Los Alamos, NM, USA*
[3] *Columbia University, Department of Physics and Nevis Laboratory, New York, New York, USA*
[4] *Rutgers University — The State University of New Jersey, Department of Physics and Astronomy, Piscataway, NJ, USA*
[5] *Montana State University, Department of Physics, Bozeman, MT , USA*
[6] *University of Tokyo, Institute for Cosmic Ray Research, Kashiwa, Japan*
[7] *University of New Mexico, Department of Physics and Astronomy, Albuquerque, NM, USA*

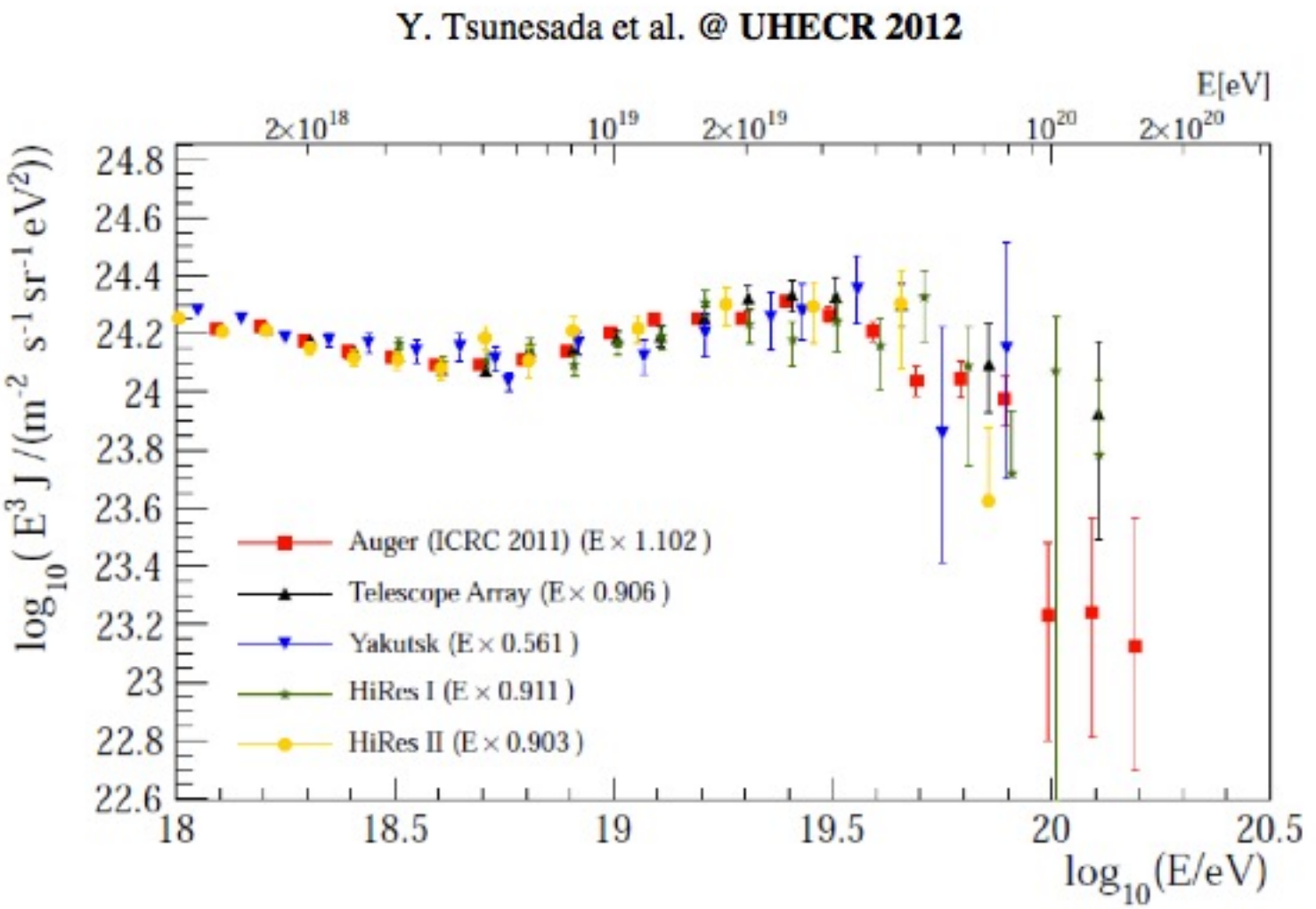
The High Resolution Fly's Eye (HiRes) experiment has observed the Greisen-Zatsepin-Kuzmin suppression (called the GZK cutoff) with a statistical significance of five standard deviations. HiRes' measurement of the flux of ultrahigh energy (UHE) cosmic rays shows a sharp suppression at an energy of 6×10^{19} eV, consistent with the expected cutoff energy. We observe the "ankle" of the cosmic-ray energy spectrum as well, at an energy of 4×10^{18} eV. We describe the experiment, data collection, analysis, and estimate the systematic uncertainties. The results are presented and the calculation of the statistical significance of our observation is described.

PACS numbers: 98.70.Sa, 95.85.Ry, 96.50.sb, 96.50.sd



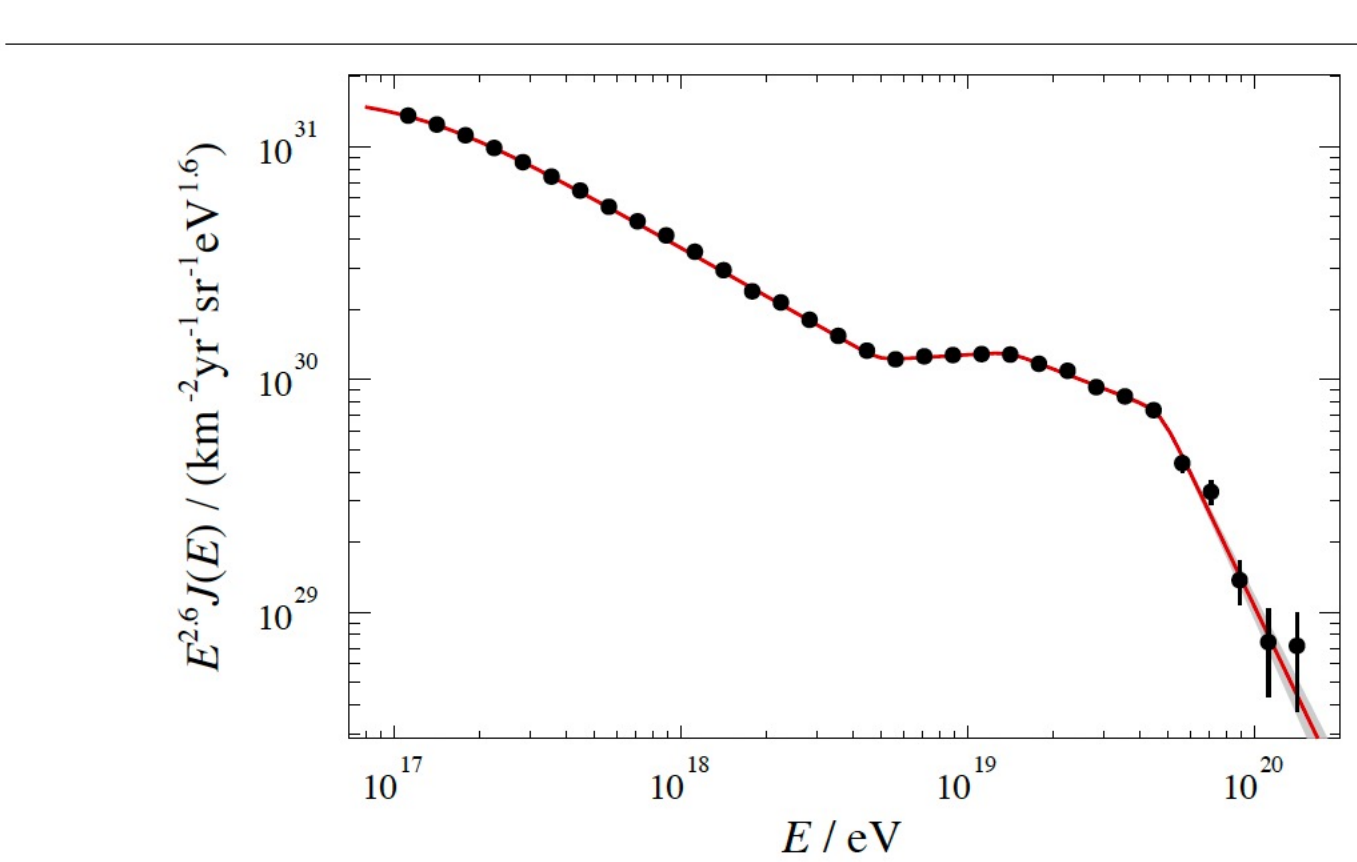
Definite observation Of GZK in 2008

Energy spectrum comparison



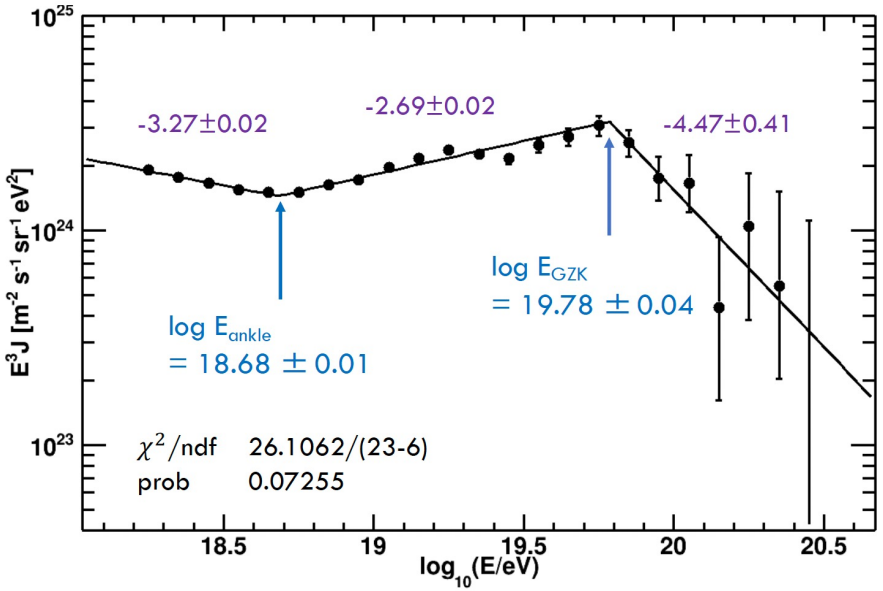
Auger/HiRes/TA compatible within their energy scale systematic uncertainties

- Most recent Auger spectrum.
- Note different energy multiplier

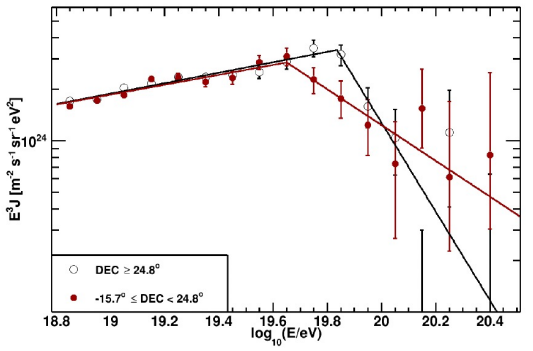


Most recent TA spectrum

Energy Spectrum using 14-year Data (2008-05-11 to 2022-05-11)

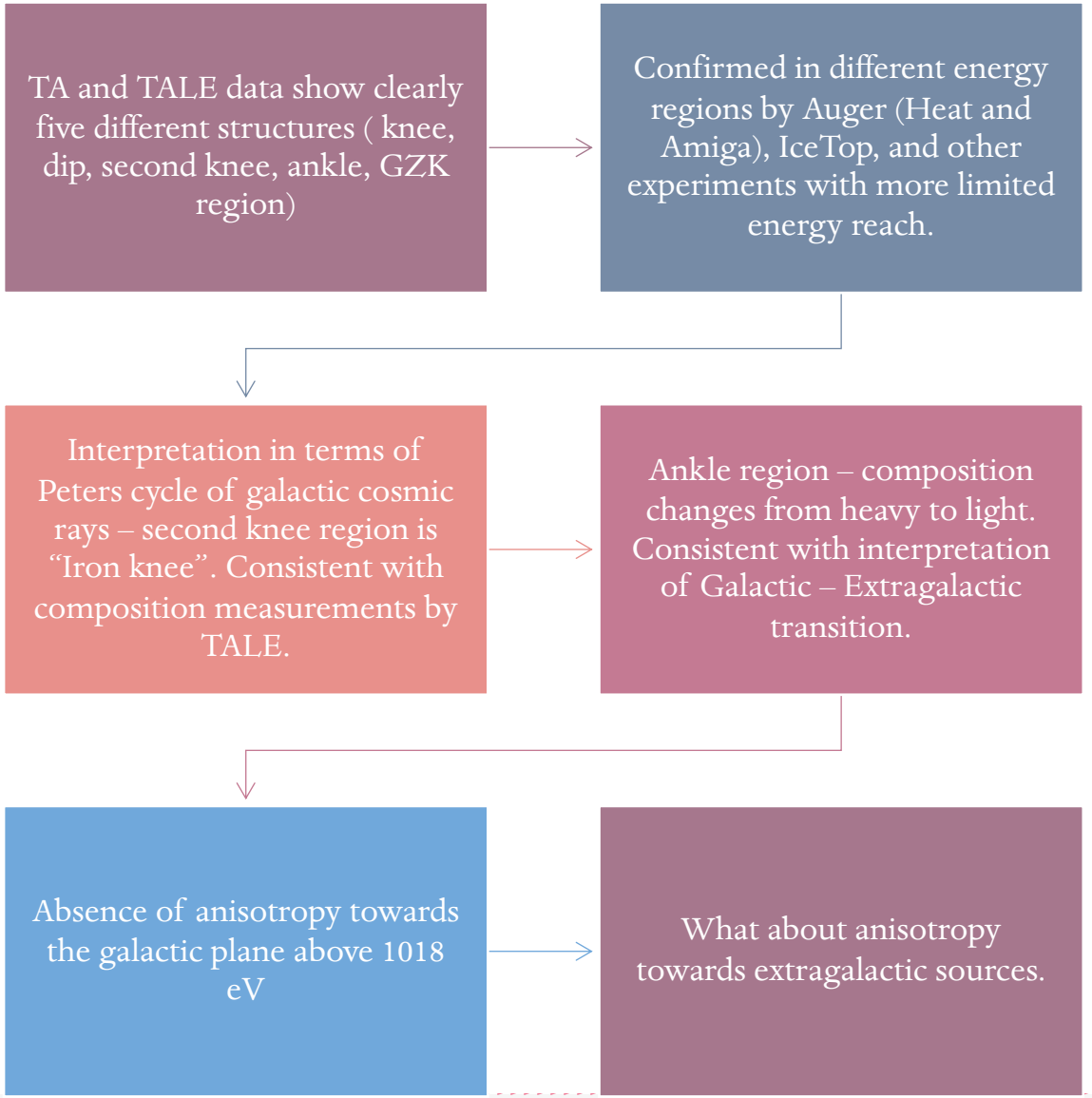


Declination Dependence



- Differences in the cutoff energies
  - log(E/eV)=**19.84 ±0.02** for (24.8°–90°)
  - log(E/eV)=**19.65 ±0.002** for (-16°–24.8°)

The spectrum from the knee to the GZK region

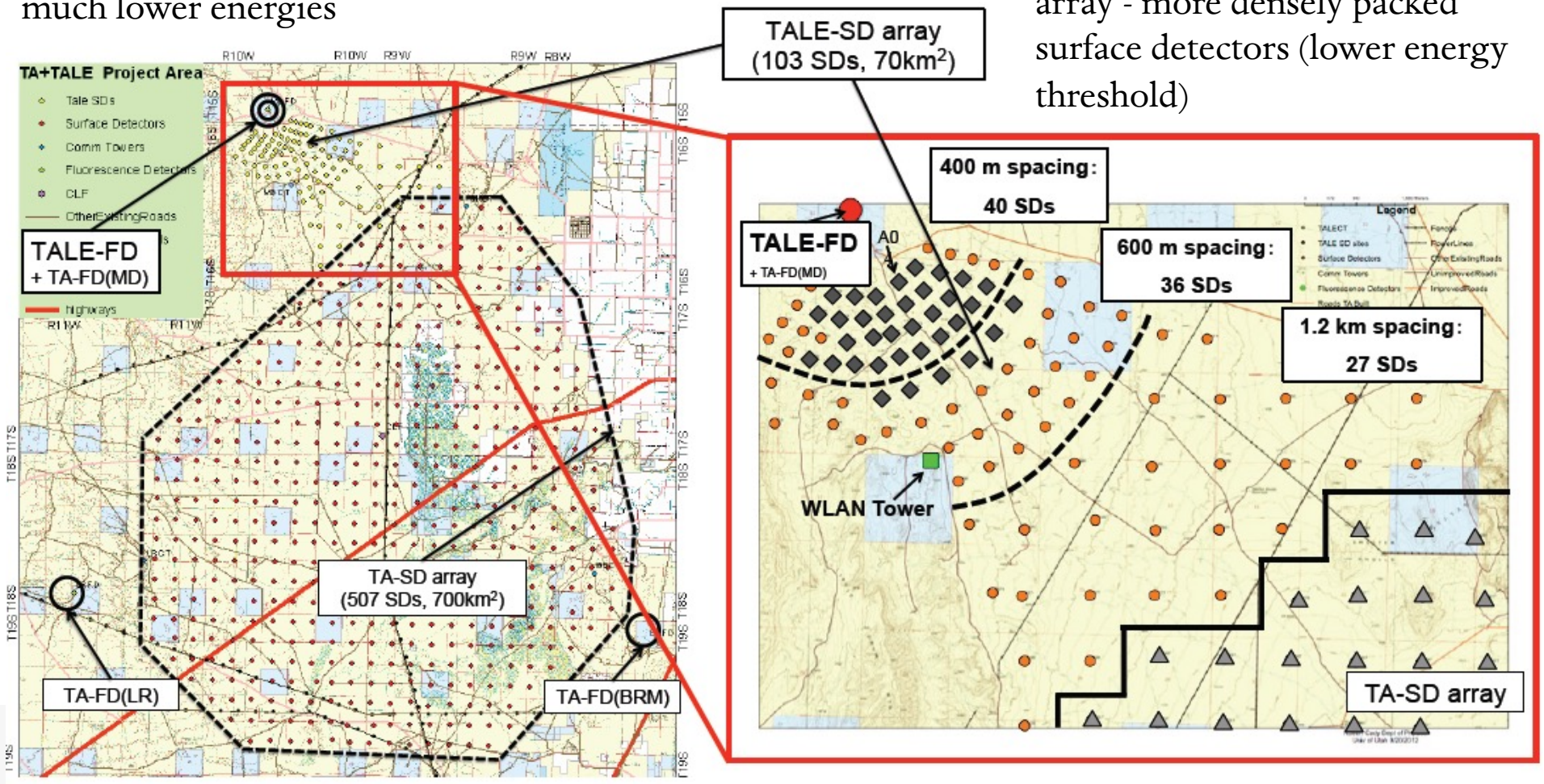


TA and Low Energy Extension (TALE)

Galactic to Extra-Galactic Transition

10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

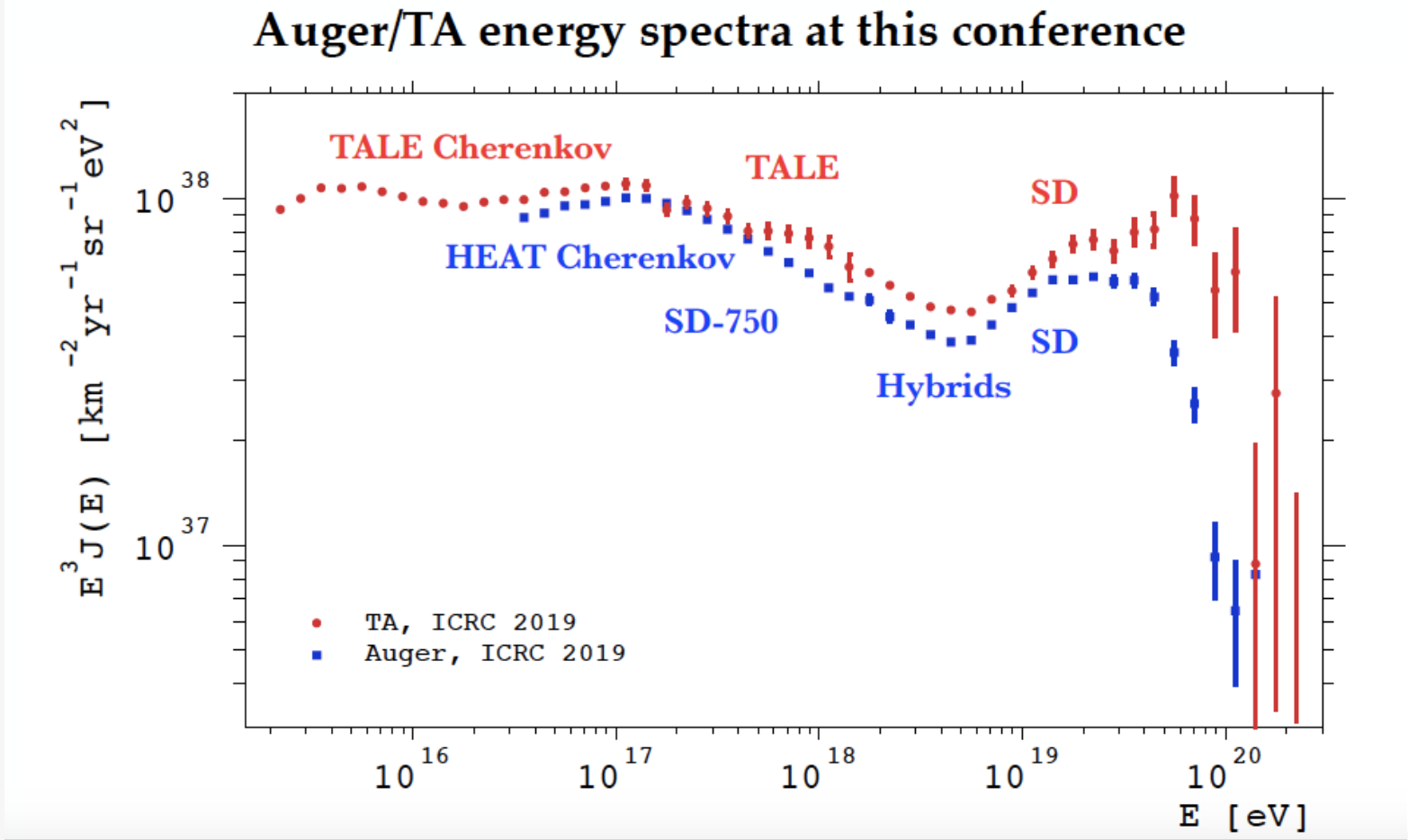
Graded infill surface detector array - more densely packed surface detectors (lower energy threshold)

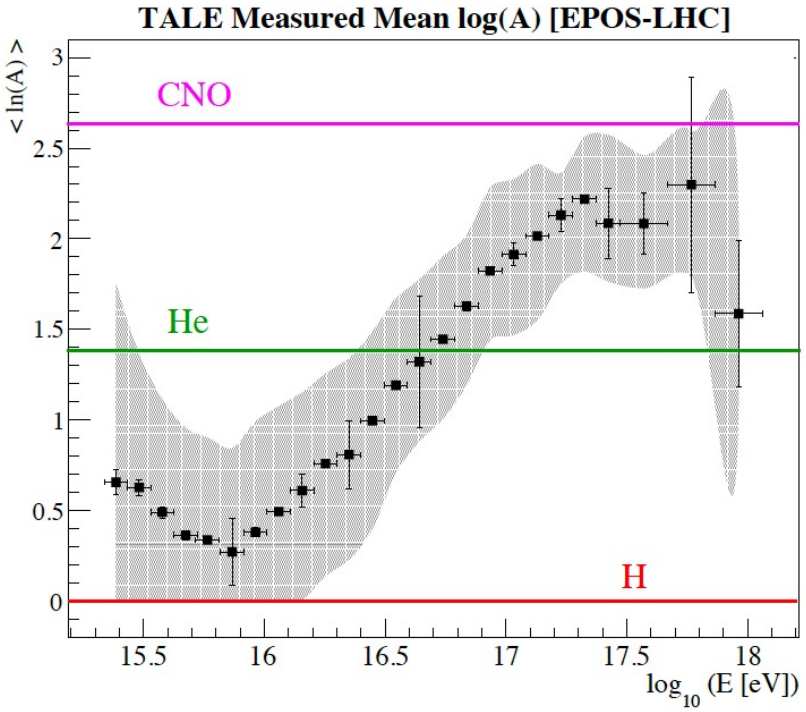


All 10 Telescopes installed and in operation since fall 2013

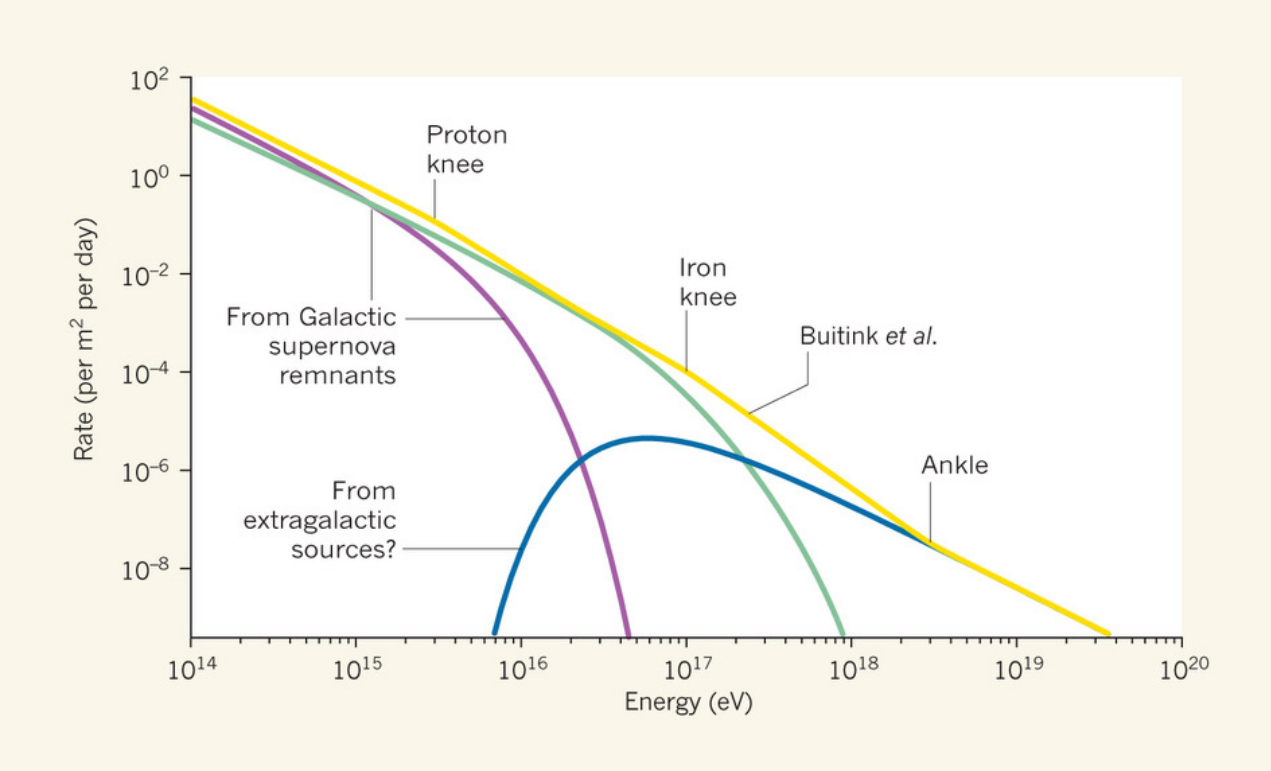
Test array of 16 scintillation surface detectors in operation

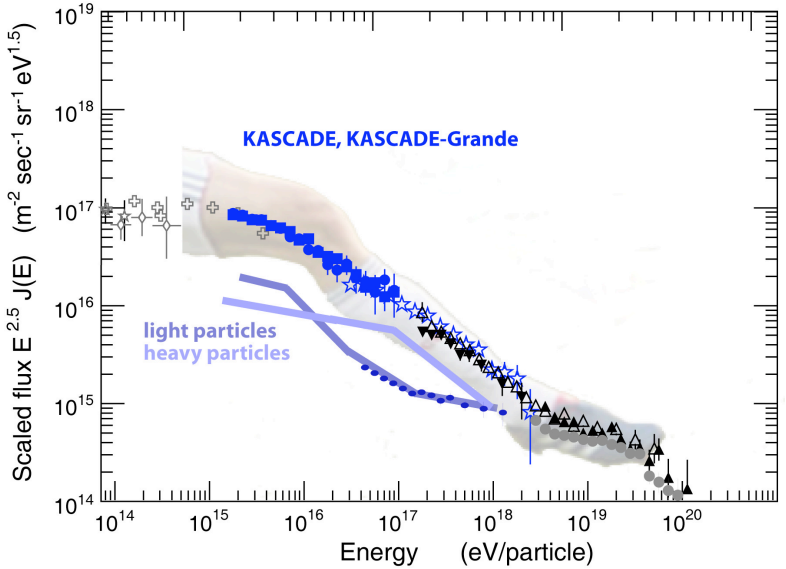
recent results (ICRC 2019)





Leaky-box interpretation of Knees
Proof of extragalactic flux "by exhaustion"





VHEPA, January, 2016

Extragalactic Anisotropy $\sim 10^{19}$ to 10^{20} eV

- Large scale anisotropy conclusively discovered by Auger – Dipole inconsistent with galactic origin.
- Weaker evidence(3-4 sigma) for intermediate scale anisotropy above 1019eV.
- Hot Spot and Perseus excess in N
- Cen A in S.
- Clustering along SGP?

Auger Dipole Anisotropy – inconsistent with Galactic effect

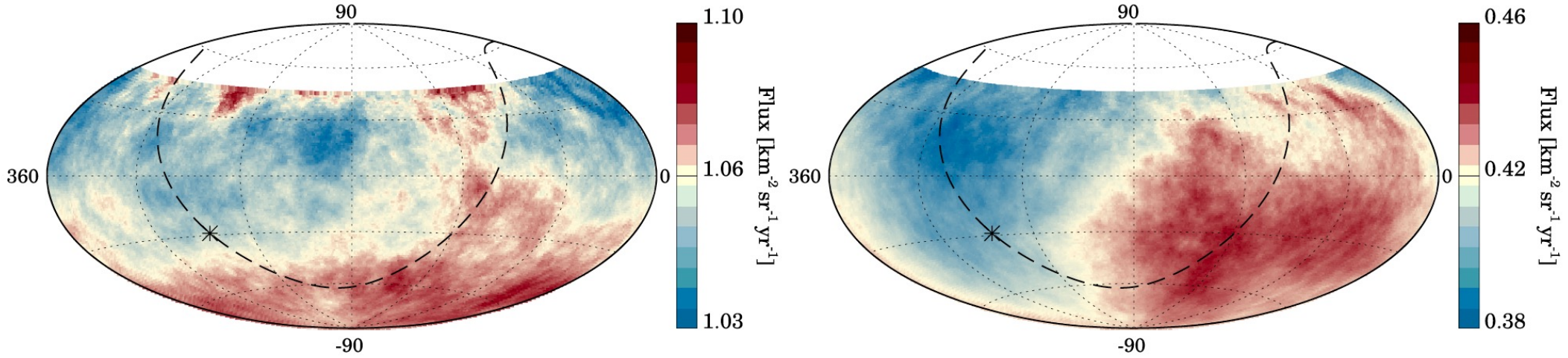
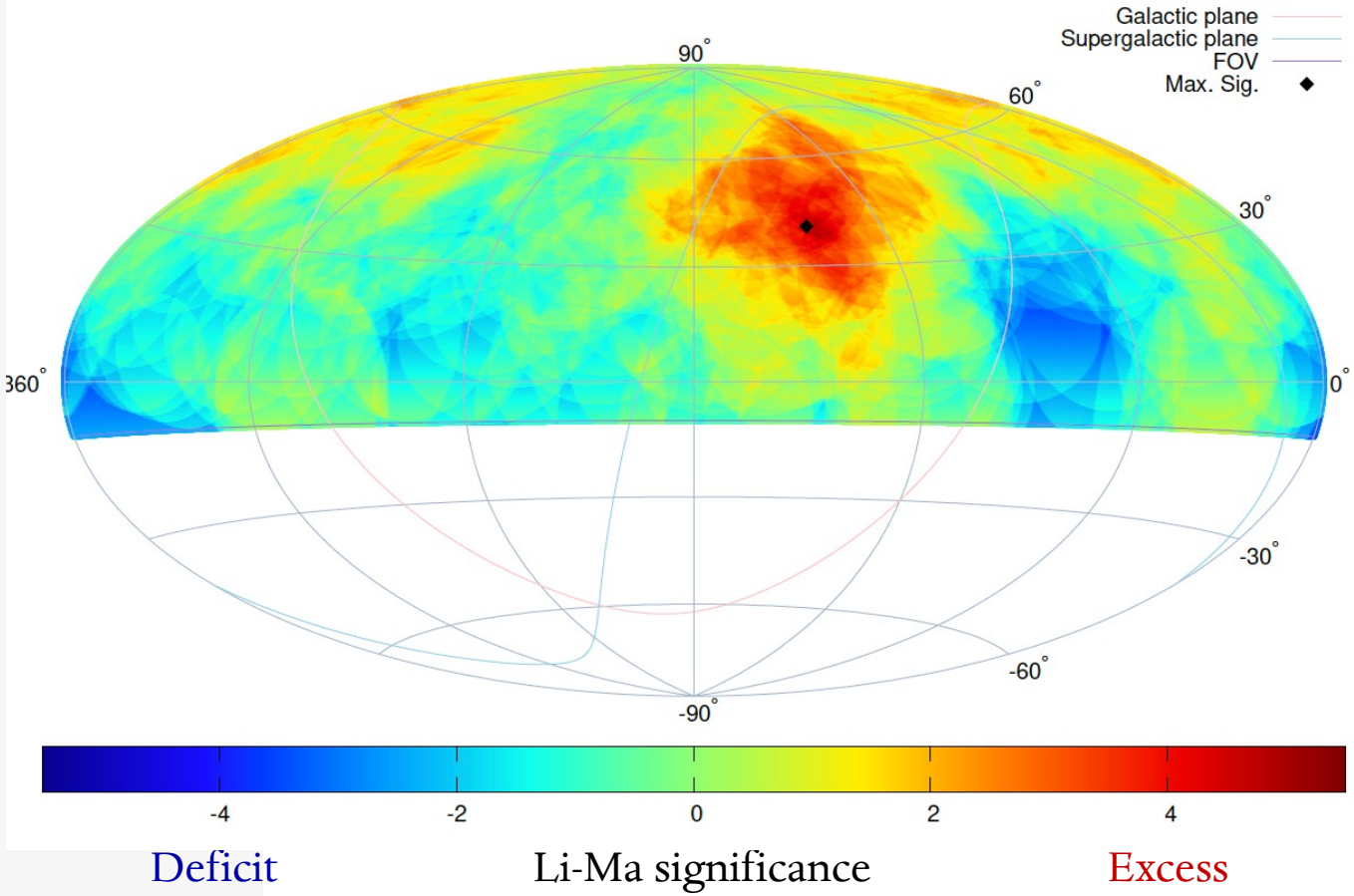


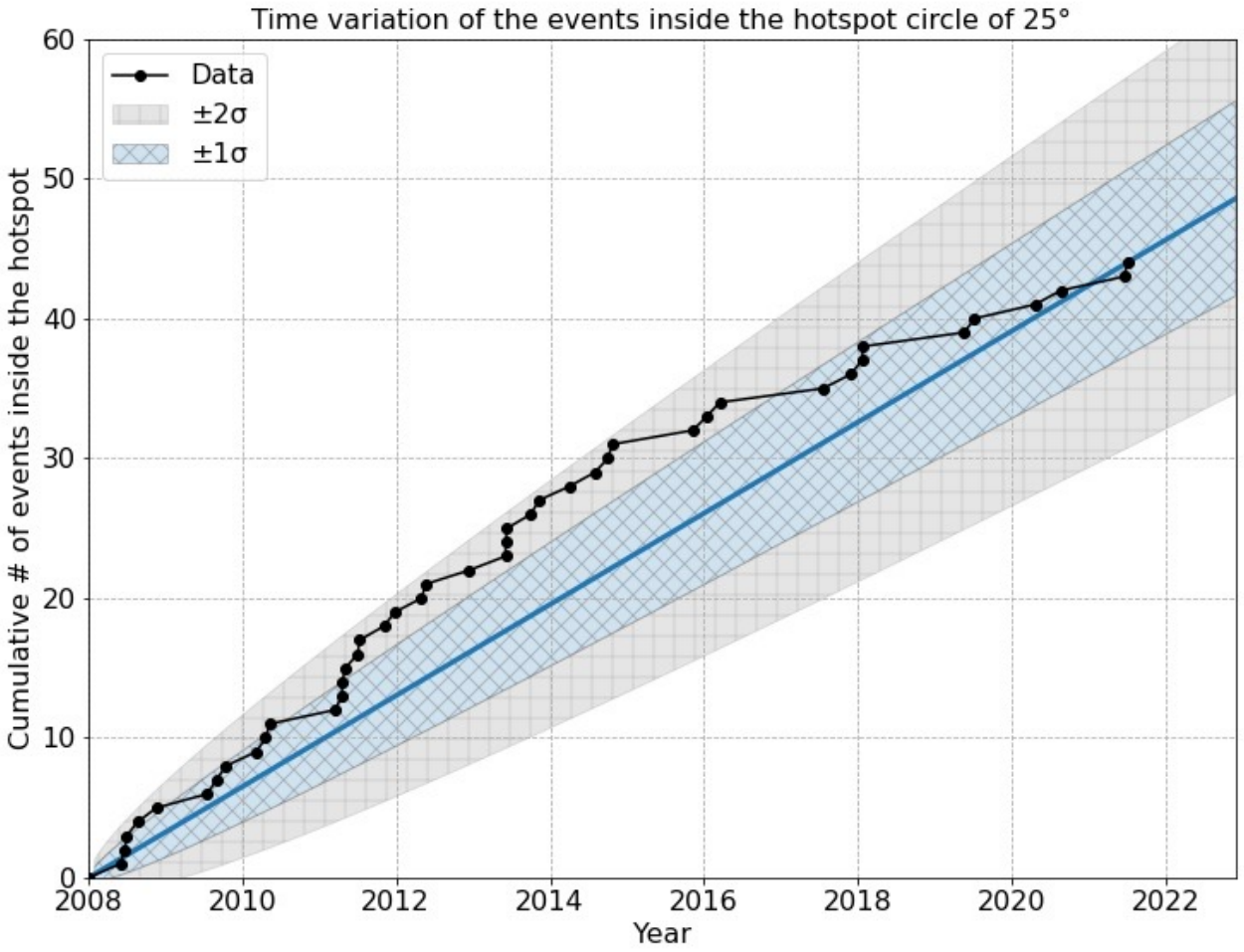
Figure 2. Maps in equatorial coordinates of the CR flux, smoothed in windows of 45°, for the energy bins [4, 8] EeV (left) and $E \geqslant 8$ EeV (right). The Galactic plane is represented with a dashed line, and the Galactic center is indicated with a star.

TA Hot Spot Li-Ma significance map with E ≥ 57 EeV



- 205 events (14-year TA SD data)
- Max local sig.: **5.1σ** at (144.0°, 40.5°)
  - Obs.: 44 events
  - N_{bg}: 16.9 events
  - } ~160% excess
- Post-trial probability:

$$P(S_{MC} > 5.1\sigma) = 7.4\times10^{-4} \rightarrow \mathbf{3.2\sigma}$$

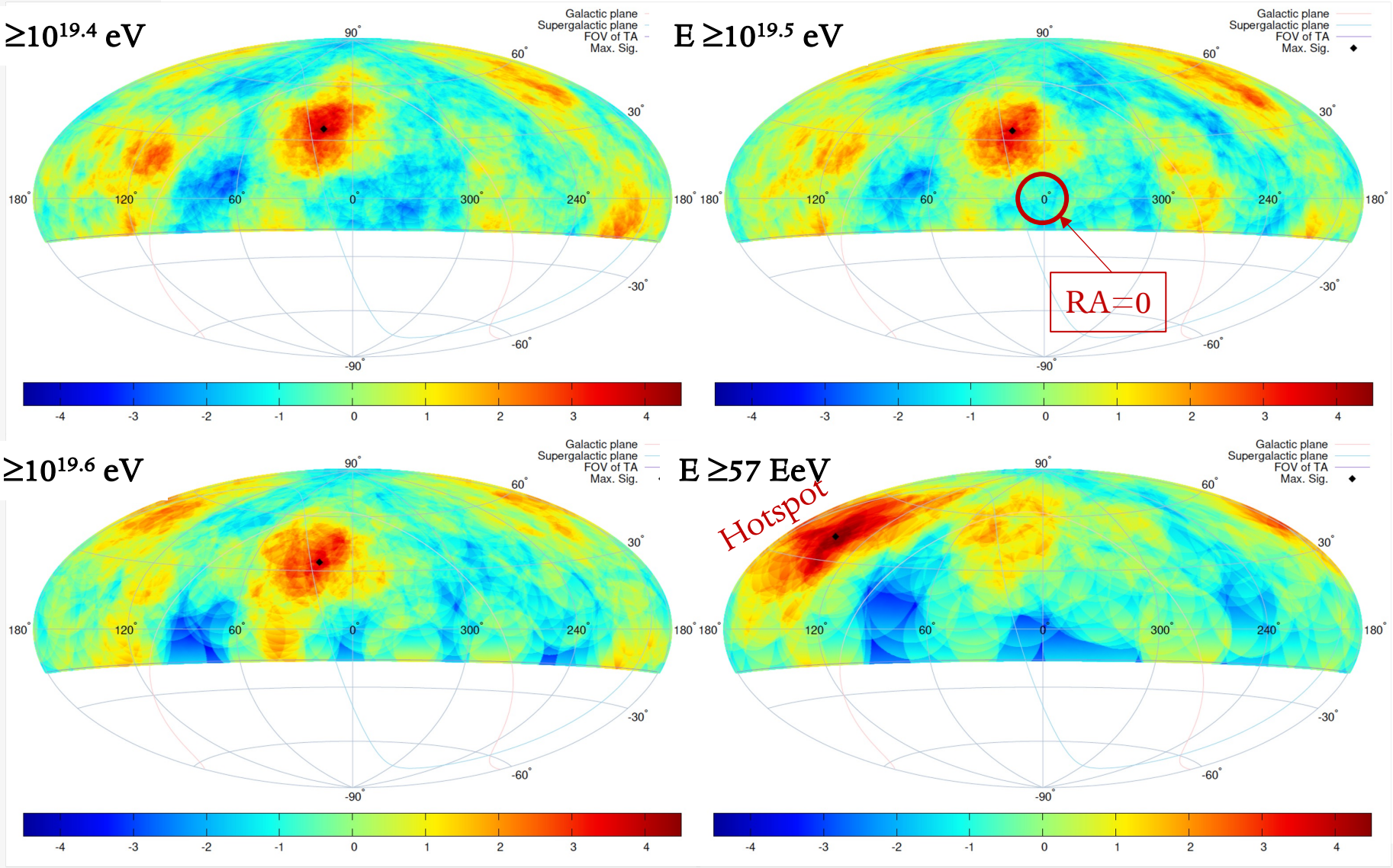


- Black dots: cumulative # of events falling inside the hotspot circle of 25° from (144.0°, 40.5°)

- Blue solid line: estimated event rate inside the hotspot

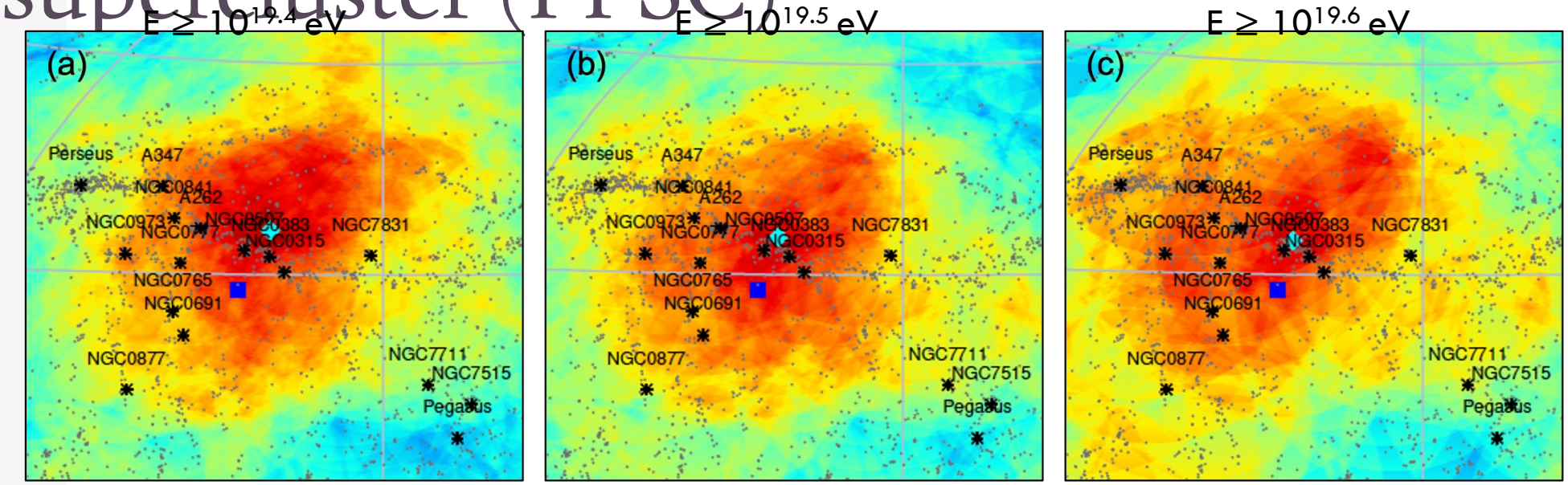
The increase rate of the events inside the hotspot circle is **consistent with the linear increase within ~2σ.**

New excess (PP) in slightly lower energy events TA Collab., ICRC2021



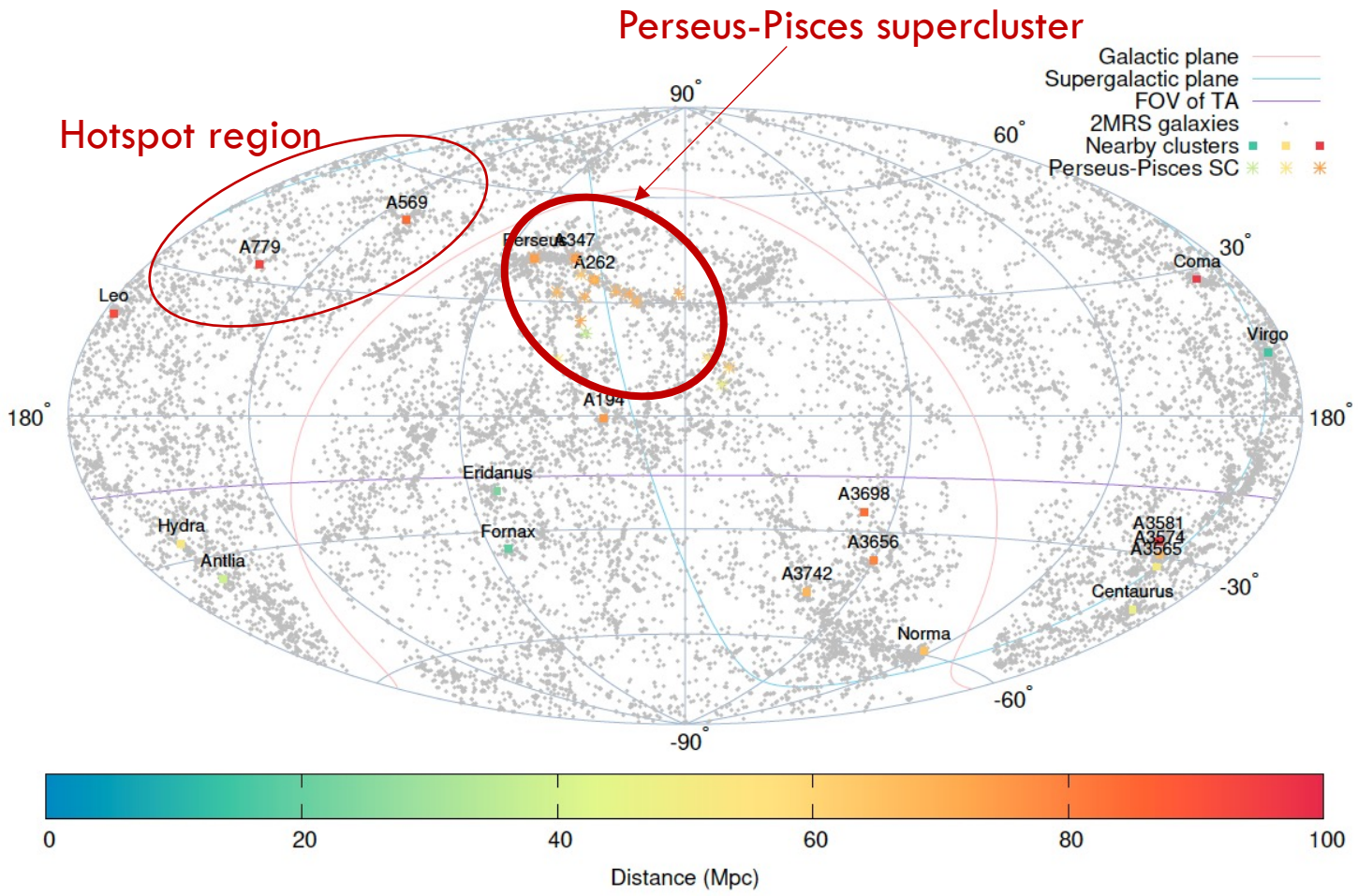
- Li-Ma significance map: excess (red) / deficit (blue) of events compared to isotropy
- Black diamond (◆): the maximum Li-Ma significance position
- Equatorial coords. having RA=0 at center

New excess with the Perseus-Pisces supercluster (PPSC)



- Black asterisks (*): the representative elements of the PPSC; Gray dots (·): Galaxies from the 2MASS Redshift Survey catalog (35–100 Mpc); Cyan diamonds (◆): the positions of maximum excesses; Blue squares (■): the center of the PPSC.
- It is seen that the excess is coincident with the overall distribution of the PPSC. The angular separations between the positions of the maximum excesses and the center of the PPSC are less than ~10°.

What is Behind the New Excess?



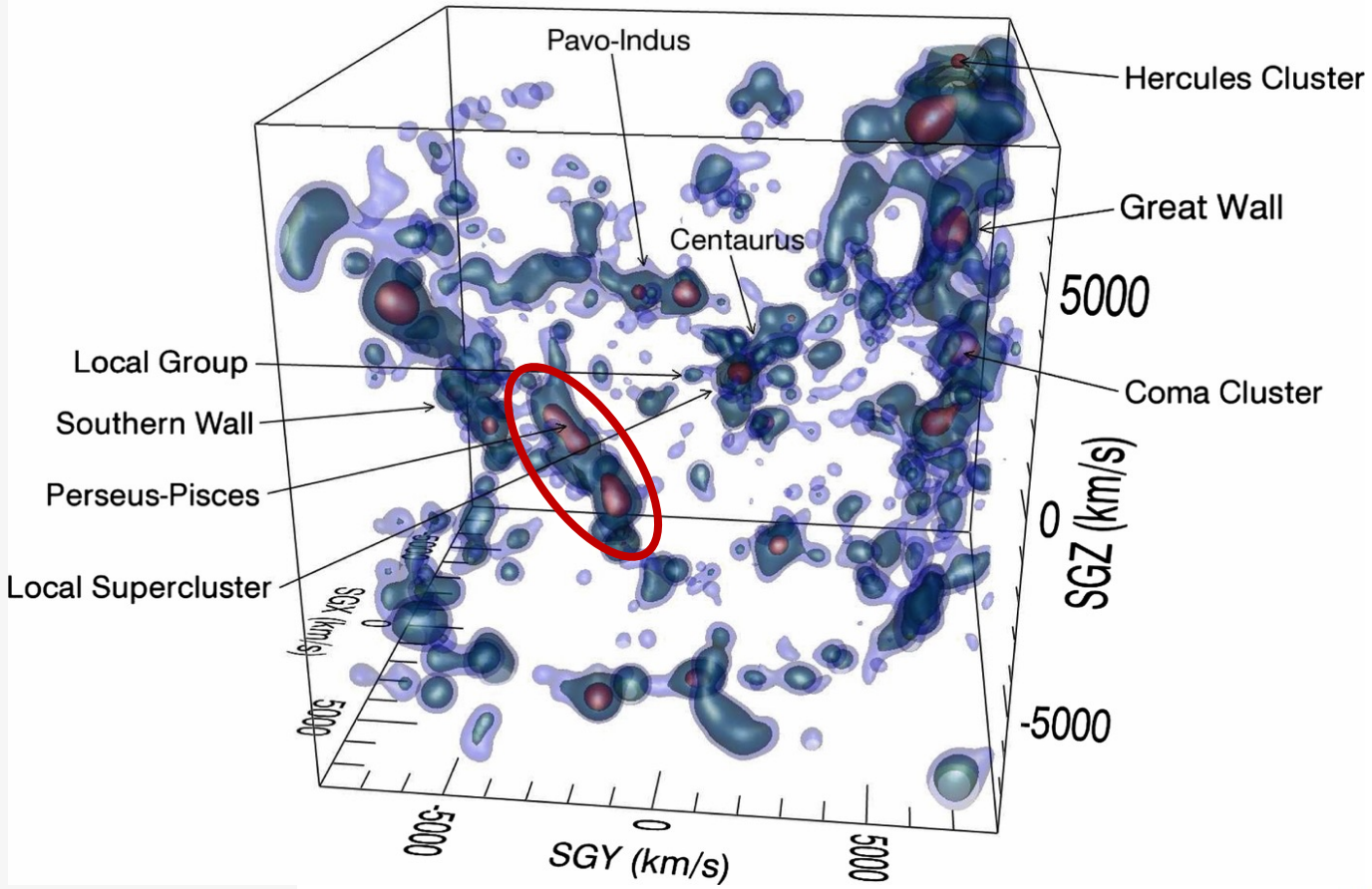
Sky map with nearby galaxies and clusters of galaxies in equatorial coordinates

- Gray dots (·): nearby galaxies from the 2MASS Redshift Survey catalog
- Colored squares (■): nearby clusters of galaxies
- Colored asterisks (*): representative elements of Perseus-Pisces supercluster

Equatorial coordinates

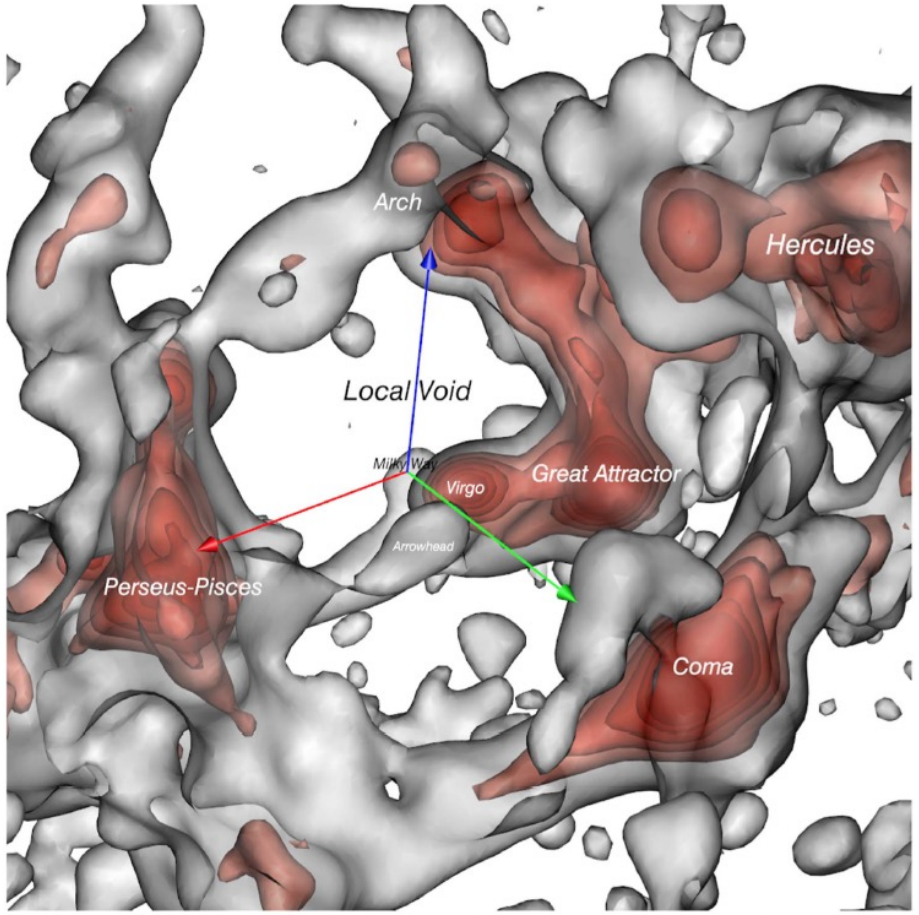
Characteristic of the Perseus-Pisces Supercluster (PPSC)

3-dimensional density maps



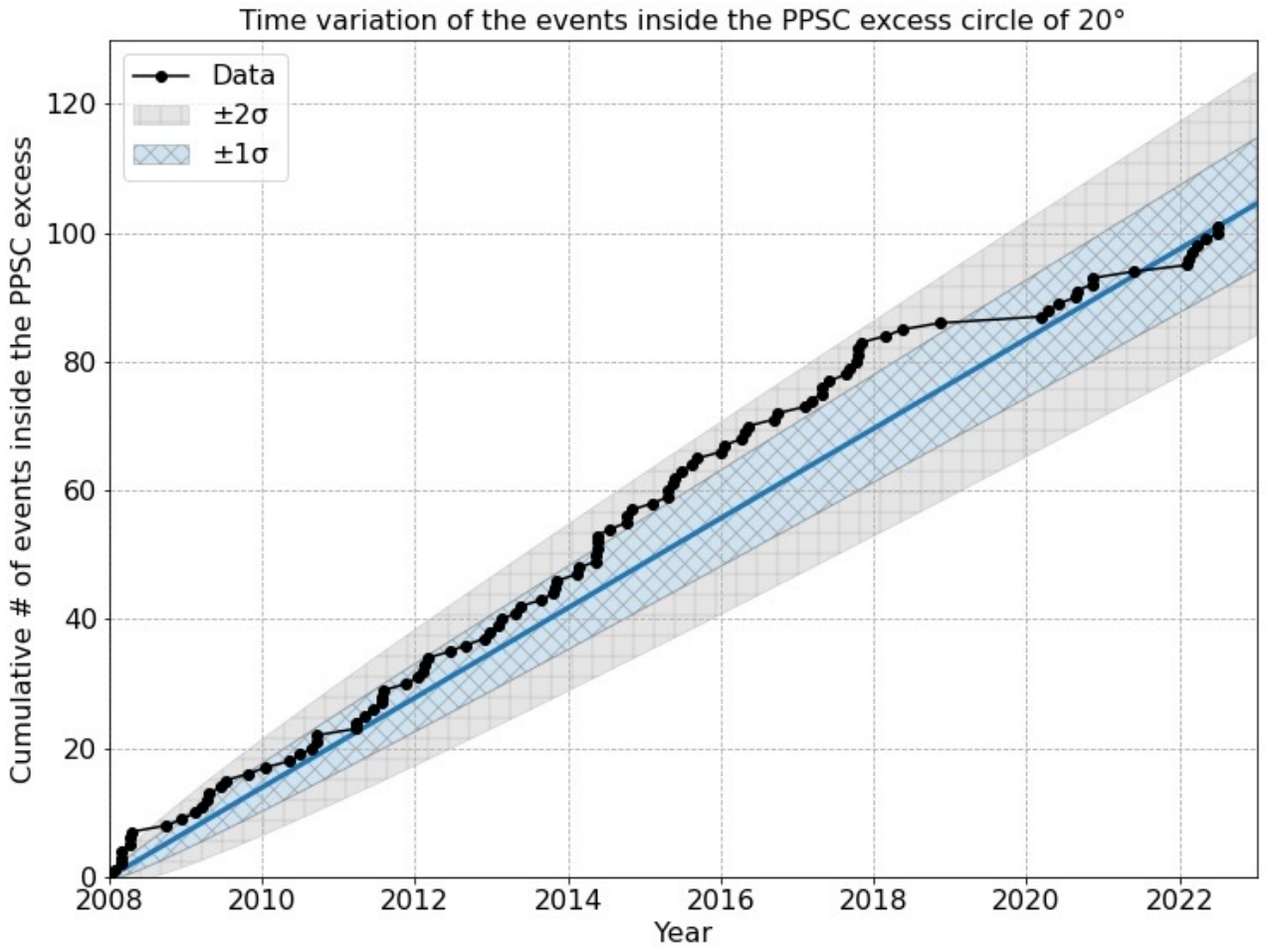
Courtois *et al.* (2013)

The Astrophysical Journal, 880:24 (14pp), 2019 July 20



Tully *et al.* (2019)

Growth of the PPSC Excess with E $\geq 10^{19.4}$ eV



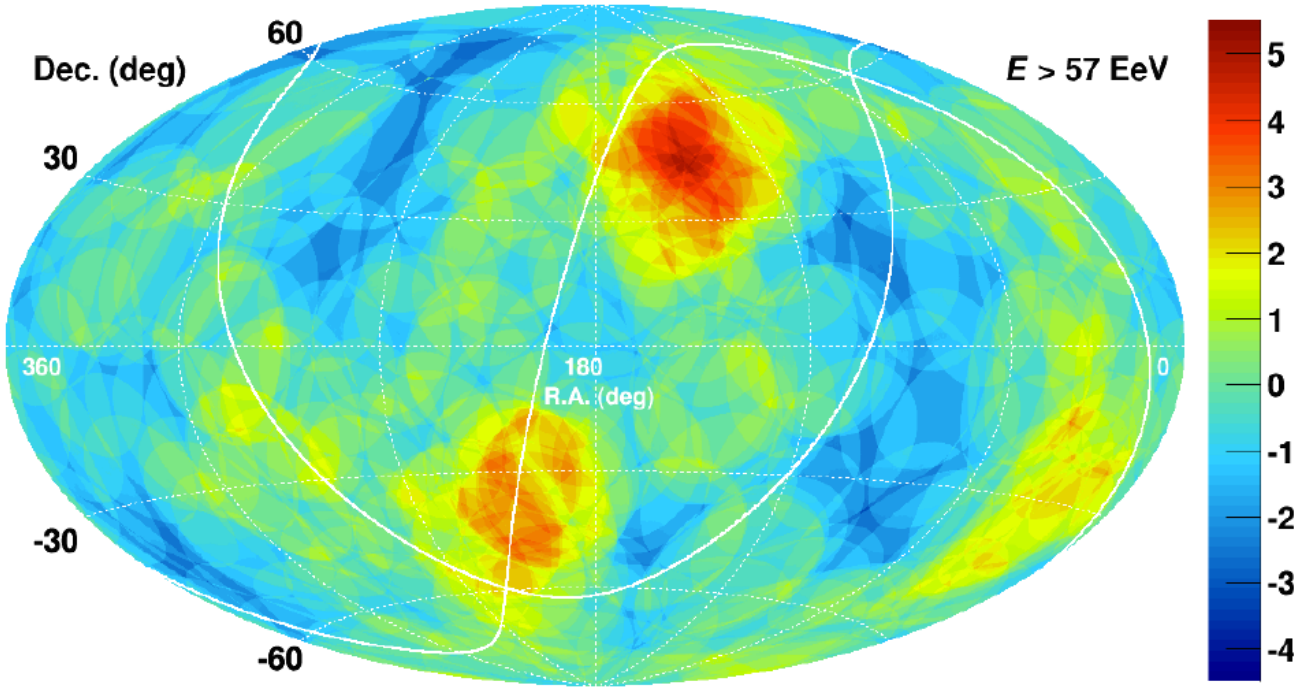
- Black dots: cumulative # of events falling inside the PPSC excess circle of 20° from (17.9°, 35.2°)

- Blue solid line: estimated event rate inside the hotspot

The increase rate of the events inside the PPSC excess circle is **consistent with the linear increase within ~2σ.**

Auger also sees excess from Cen A (at 3.8 Mpc)

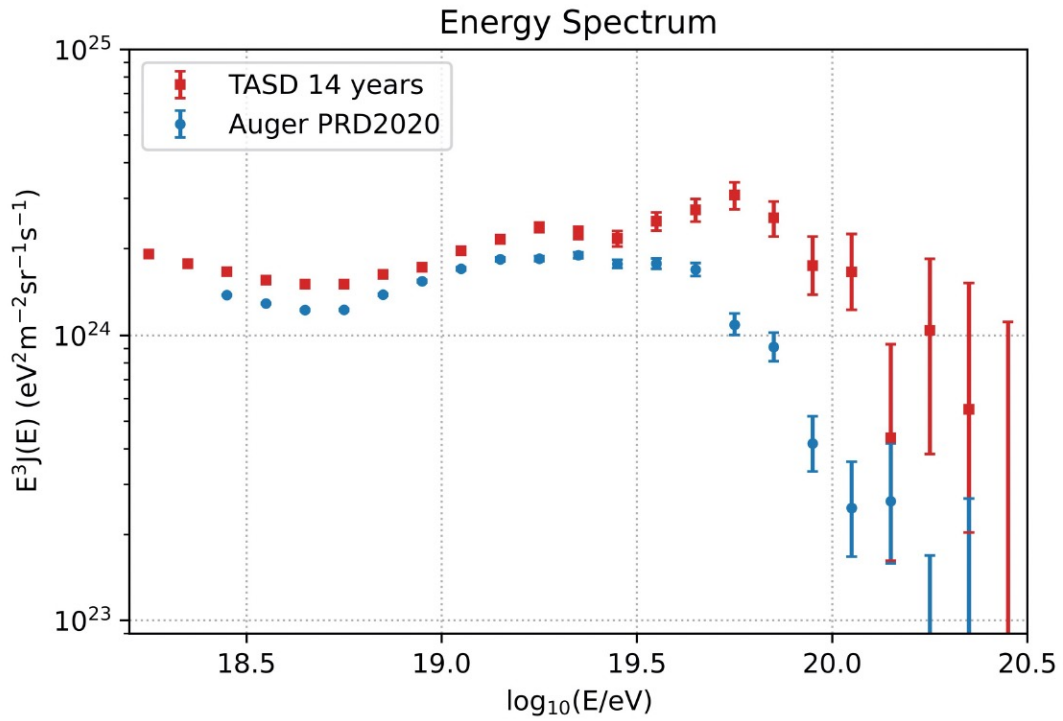
- E > 57EeV
- r = 20°



Possible N-S Spectrum differences at highest energies

- Overall Auger and TA spectra, shifted within +/- 10% systematic errors agree up to a few times 10^19 eV. However tail of the spectrum appears different. Systematics?
- Check systematics using common declination band (– 15 to -24.8 degrees dec). Spectrum should agree if systematics under control.
- Recent re-analysis of TA data using exact Auger reconstruction assumptions shows good agreement in common declination band. Rules out systematic effects.
- End of spectrum looks different above the common declination band.
- Possible evidence for difference in sources N and S

TA – Auger unshifted spectrum comp.



Note differences in air fluorescence, missing energy, etc.

Rescaled Auger, TA and HiRes spectra

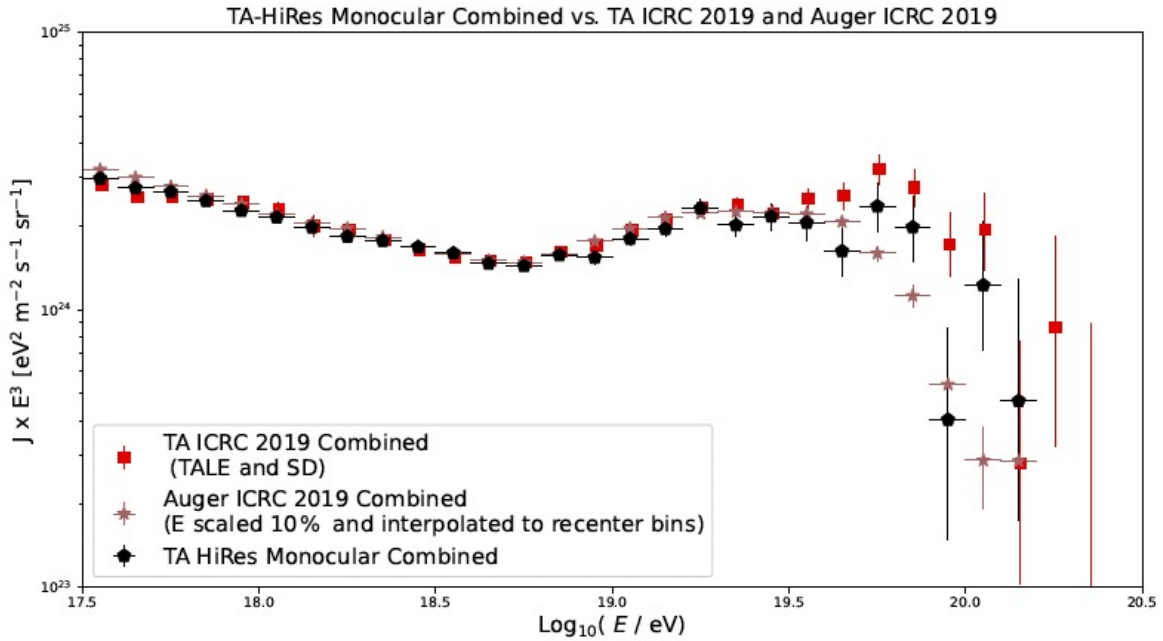
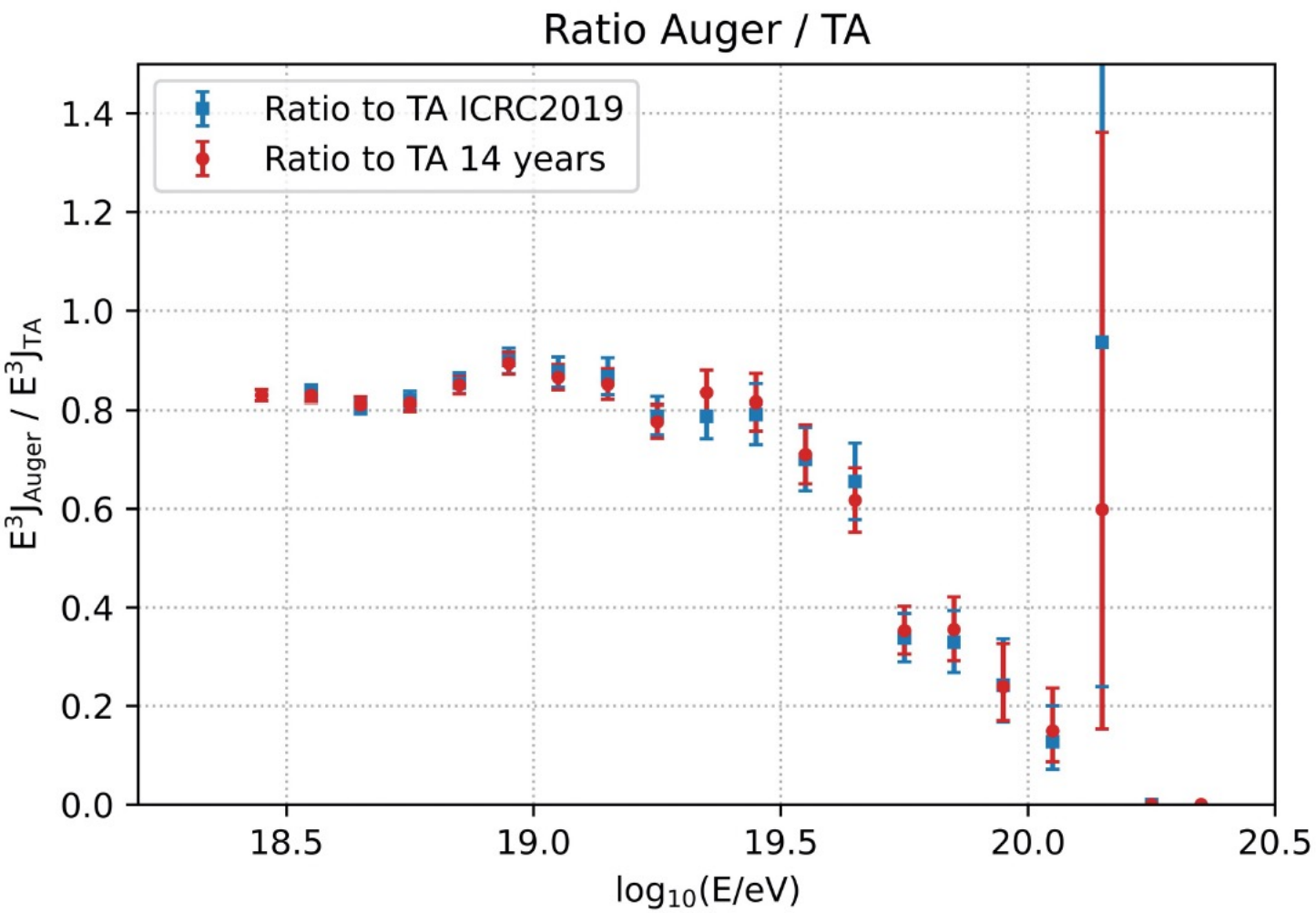
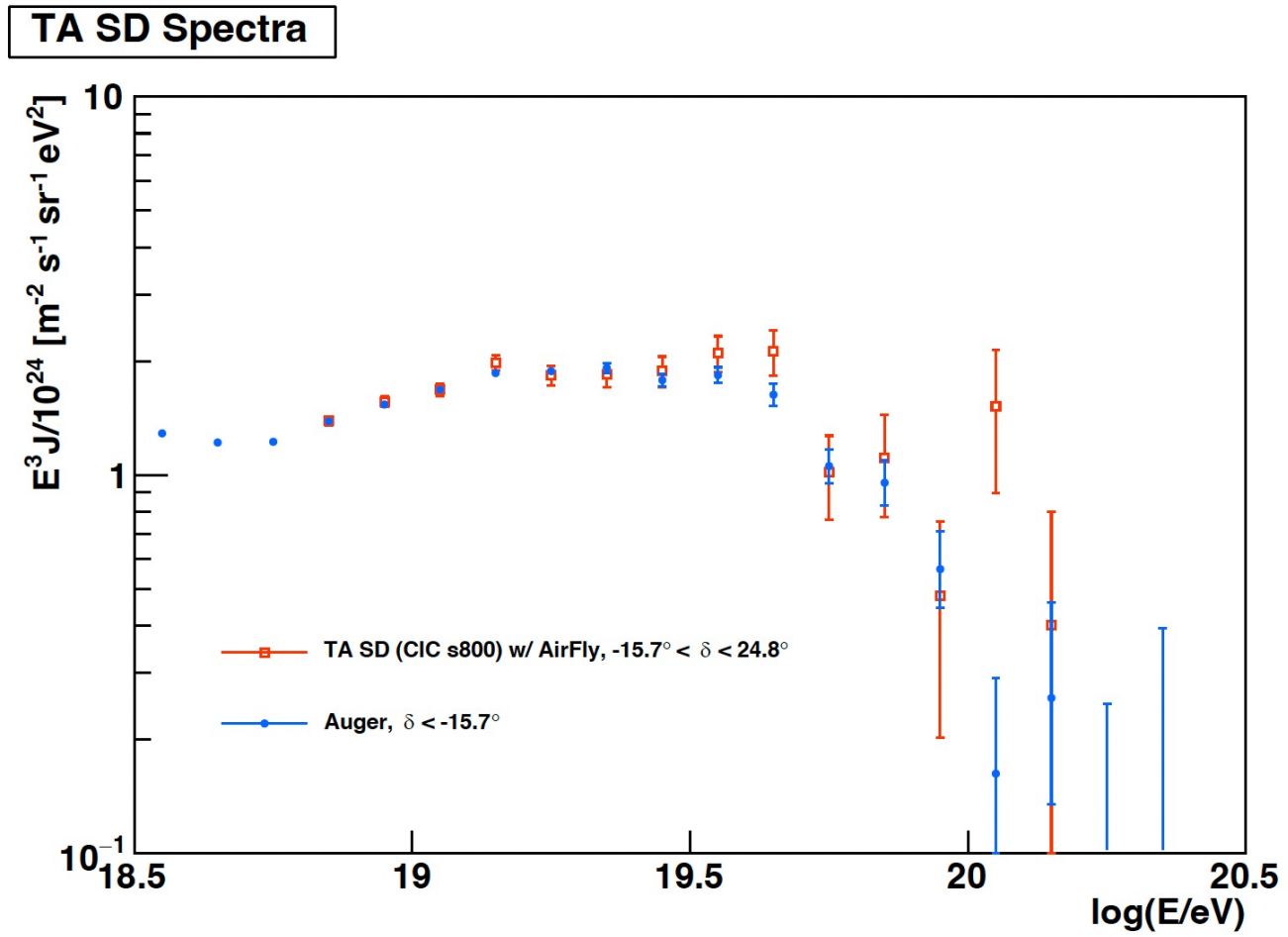


Figure 20: The TA-HiRes combined monocular spectrum compared to the TA spectrum presented at the 2019 ICRC[15] and the Pierre Auger spectrum presented at the 2019 ICRC[42].


Ratio Auger / TA
Ratio to TA ICRC2019
Ratio to TA 14 years
E^3J_{Auger} / E^3J_{TA}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/eV)$

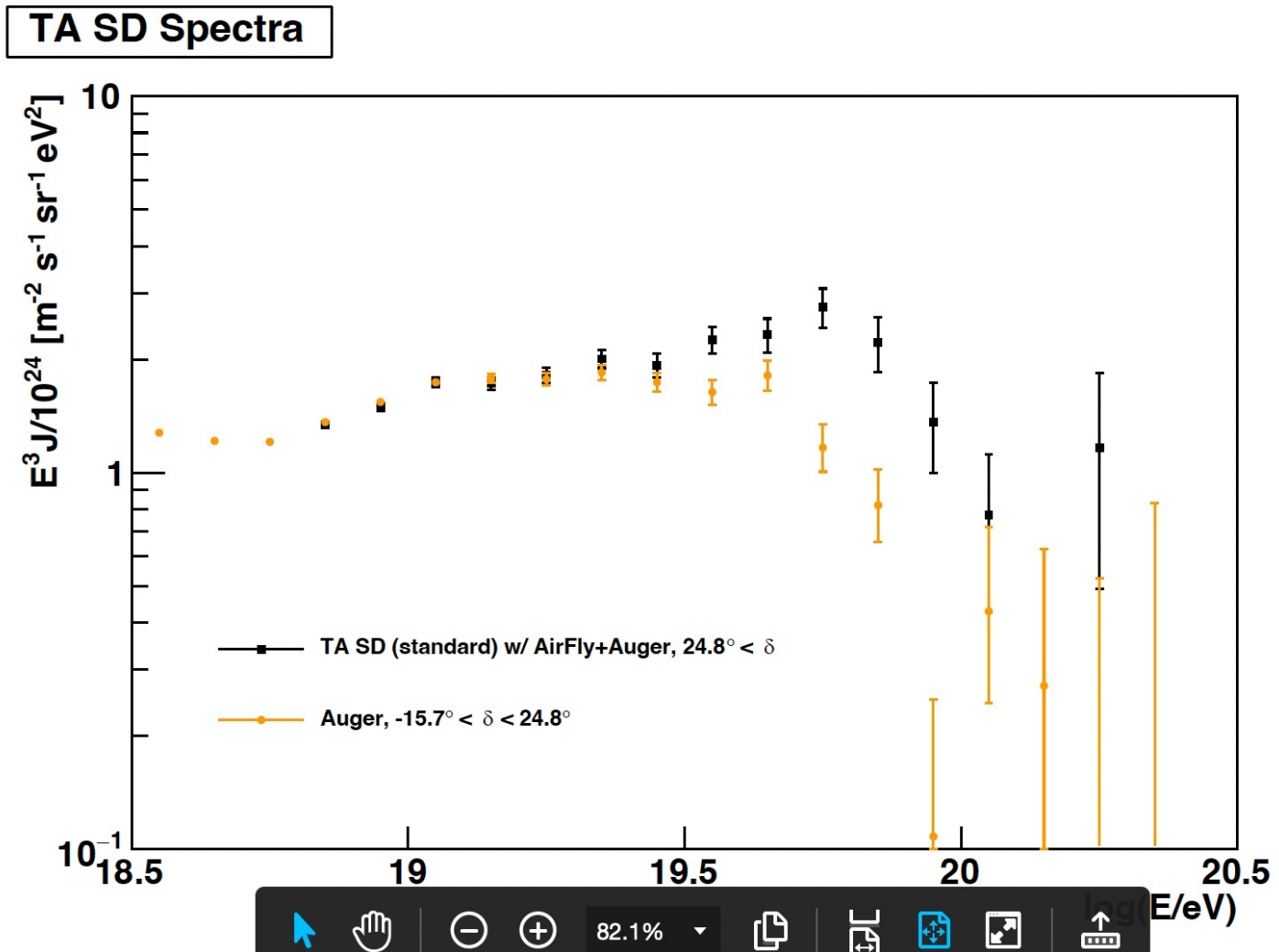
Common declination band comparison
TA analyzed with Auger parameters

Spectrum Comparison



TA > 24.8 delta declination vs Auger declination band spectrum

Spectrum Comparison



~ 5 sigma difference

What does data above 10^{20} eV tell us?

- Expectation that sources would become more pronounced at the highest energies have not materialized
- Events look surprisingly isotropic
- Highest energy event seen by TA (second highest after FE ("Oh My God" particle) points towards void.
- Difficult to assign source even for Fe assumption and taking account of bending in galactic B field.
- Tentative conclusion: events above 10^{20} are either very heavy, the extragalactic B field is much stronger than expectations, or both.

Highest energy event observed by SD

~ 240 EeV

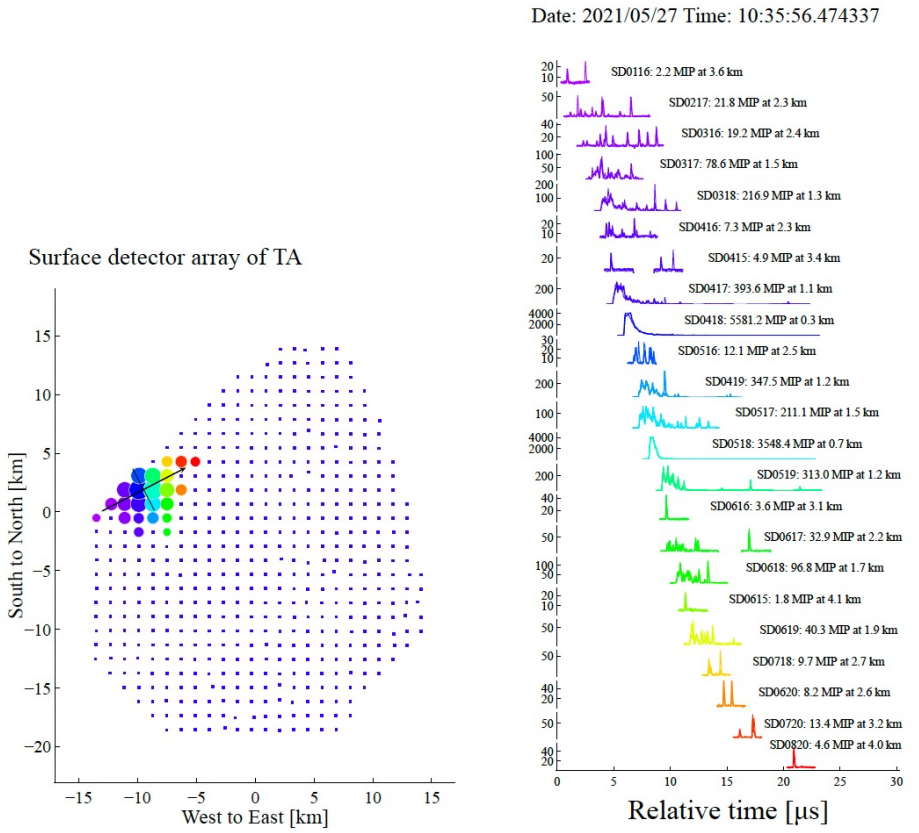


Figure 1: Event display of the highest-energy particle detected by the surface detector array of the Telescope Array experiment. This event was observed on May 27th 2021. On the left is a map of the Telescope Array SD. Each dot represents location of a SD station. The arrow indicates the shower direction projected on the ground. The core position at ground is located at (-9471 ± 31 m, 1904 ± 23 m). The size of the colored circles is logarithmic proportional to the number of particles detected by each station while the color denotes the arrival timing with blue being early and red being later. The corresponding detector waveforms of flash ADC counts for each station are shown in the right figure, with total signal in units of the minimum ionizing particle (MIP) and distance from the shower axis indicated.

Possible source location for 240 EeV Event.

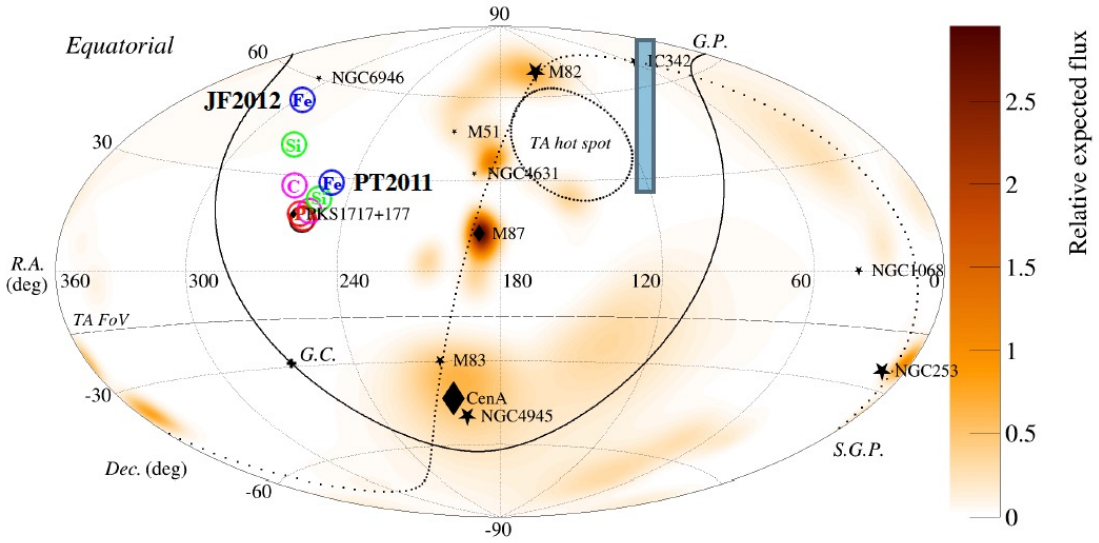


Figure 2: Map showing the arrival direction of the highest energy cosmic ray particle (black circle, just behind the red one) in equatorial coordinates and its back-tracked directions in two models of the regular galactic magnetic field, JF2012 (*31*) and PT2011 (*32*), assuming four cases of primaries: proton (P, red), carbon (C, purple), silicon (Si, green), and iron (Fe, blue). The background contour coloring shows the relative flux expected from the inhomogeneous source-density distribution in the local LSS, smeared with a random galactic magnetic field. The nearby γ-ray-emitting active galactic nuclei are shown by filled diamonds, and nearby starbu
flux s
Area
large circle centered around (R.A., Dec.) = (146.7°, 43.2°) shows the location of the TA hot

Map of > 100 EeV arrival directions in TA data

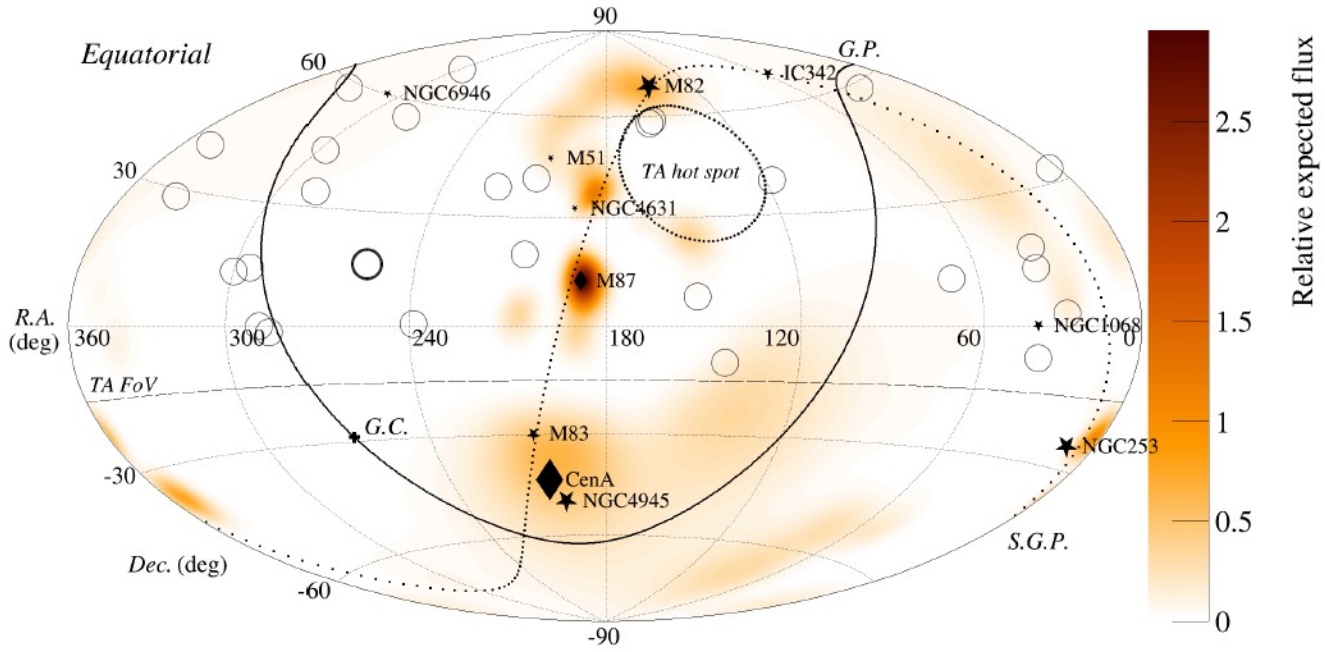


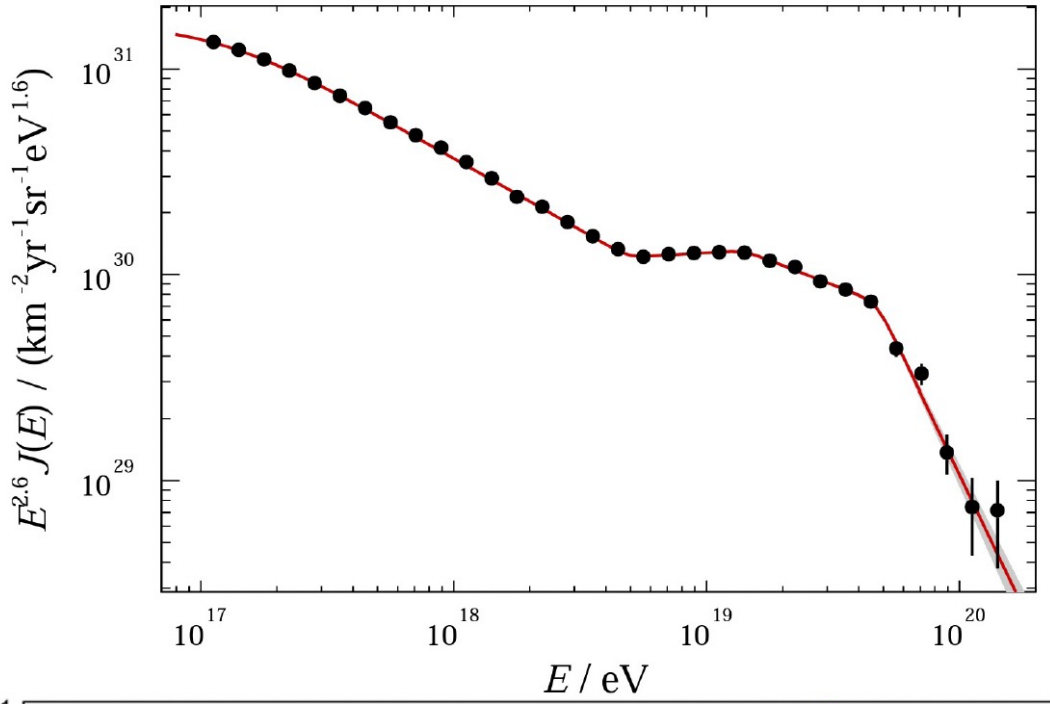
Figure 3: Map of arrival directions of the highest energy particles observed by the Telescope Array SD during 13.5 years operation, overlaid on relative expected flux and nearby active astronomical objects as shown in Figure 2. The events shown have calorimetric energies greater 100 EeV. No clustering around the highest-energy event indicated as the thick circle was detected.

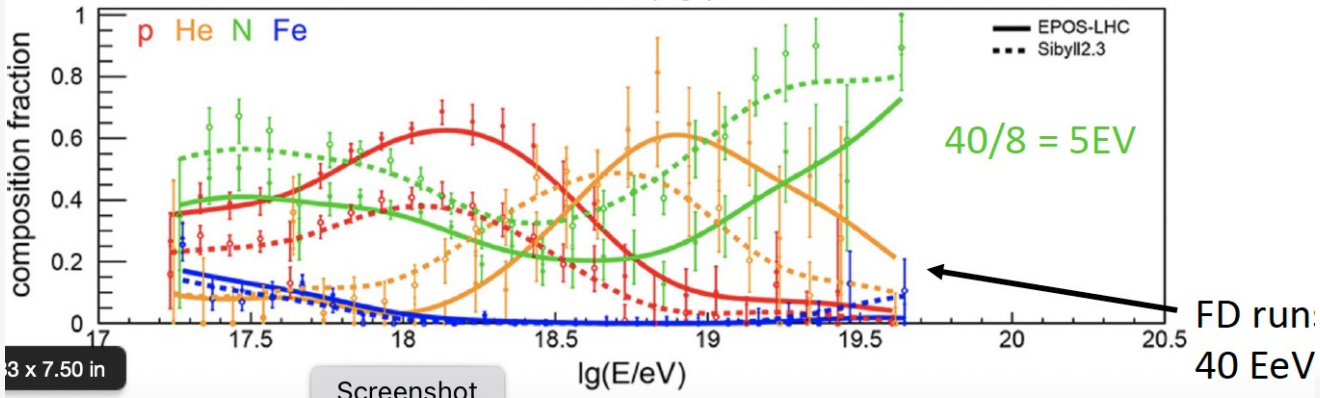
Auger composition result

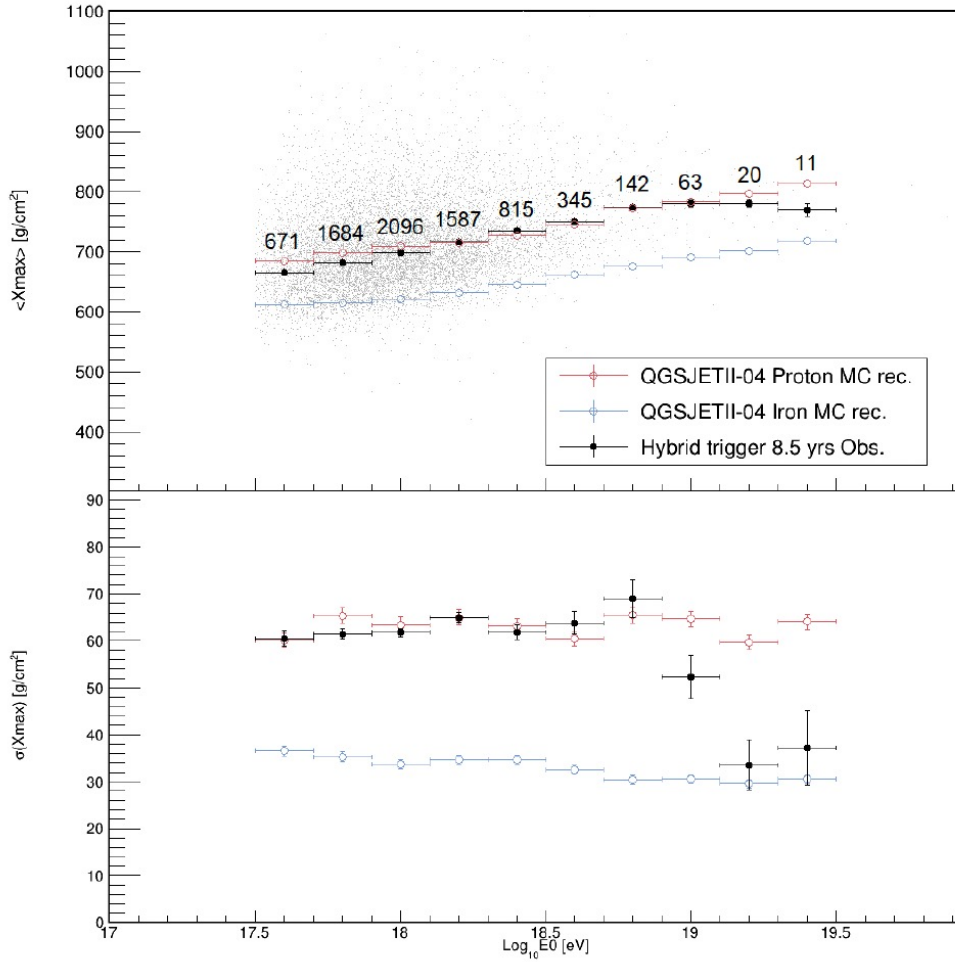
TA composition result

Interpretation of UHECR mass composition

O. Deligny (PAO), CRIS 2022

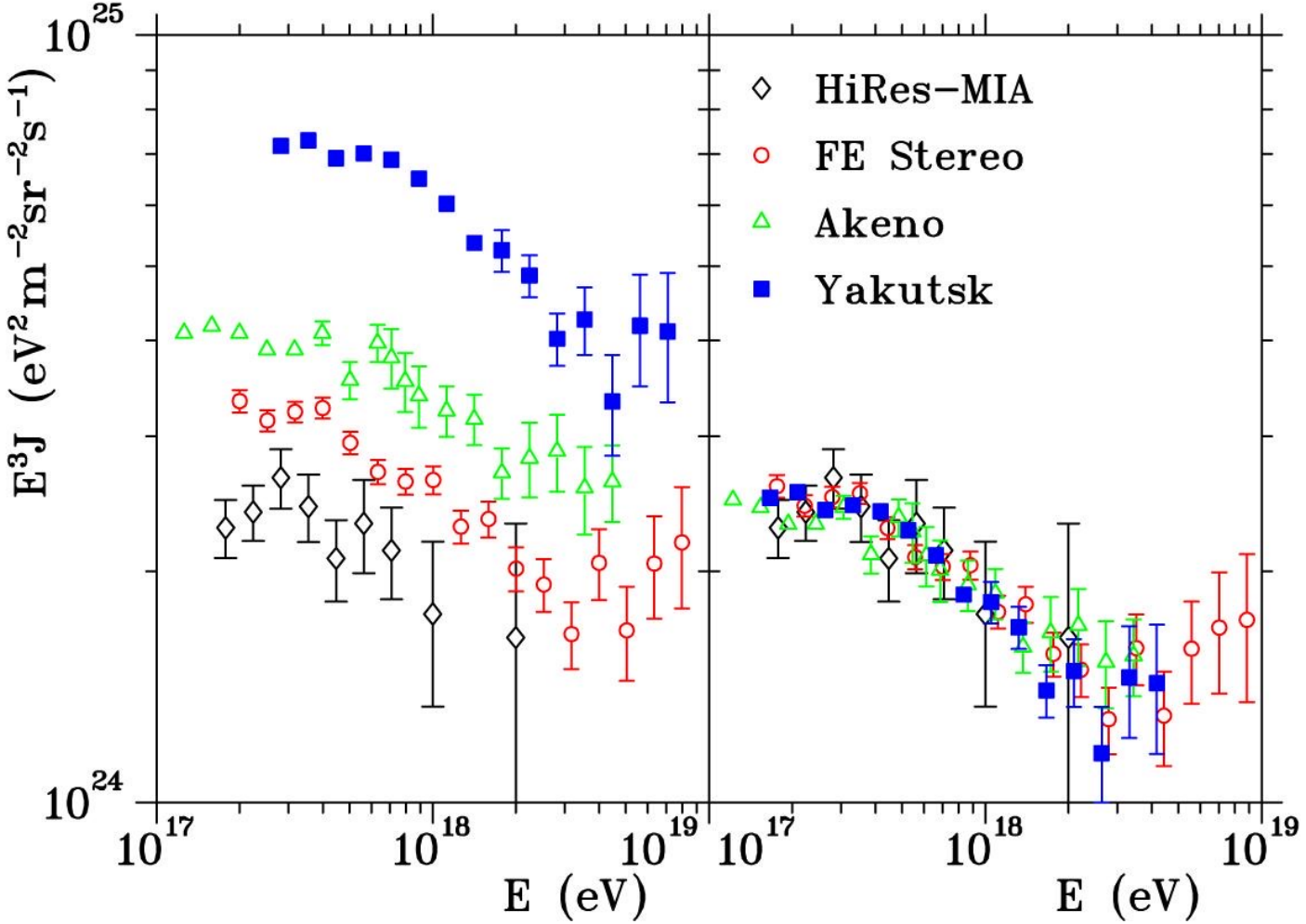






The lack of anisotropy at $> 10^{20}$ eV is a puzzle (some evidence of heavy composition)

- But-- it is **clear evidence of an extragalactic component!** (if you didn't believe the Aguer dipole was enough evidence).
- Further progress depends on more data: TAx4, Auger+
- NB: A N-S spectrum anisotropy is good ammunition for space based detectors such as EUSO and POEMMA.


HiRes–MIA
FE Stereo
Akeno
Yakutsk
E^3J $(eV^2 m^{-2} sr^{-2} s^{-1})$
10^{25}
10^{24}
10^{17}
10^{18}
10^{19}
E (eV)