The Pierre Auger Observatory:
The Big Picture on the Highest Energy Cosmic Rays

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on behalf of the

Pierre Auger Collaboration

with
CWRU HEA group:
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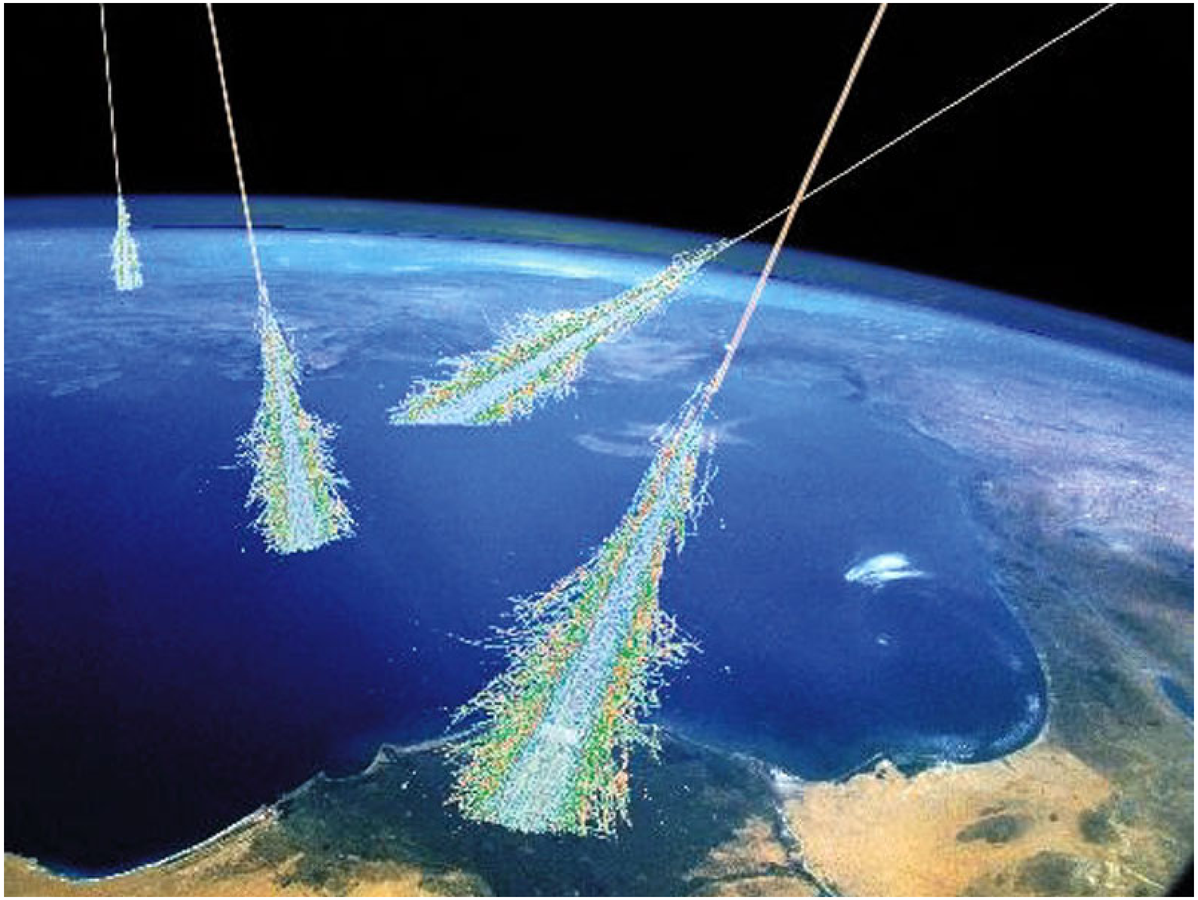
Presented to

PASCOS

June 6, 2018



Outline:

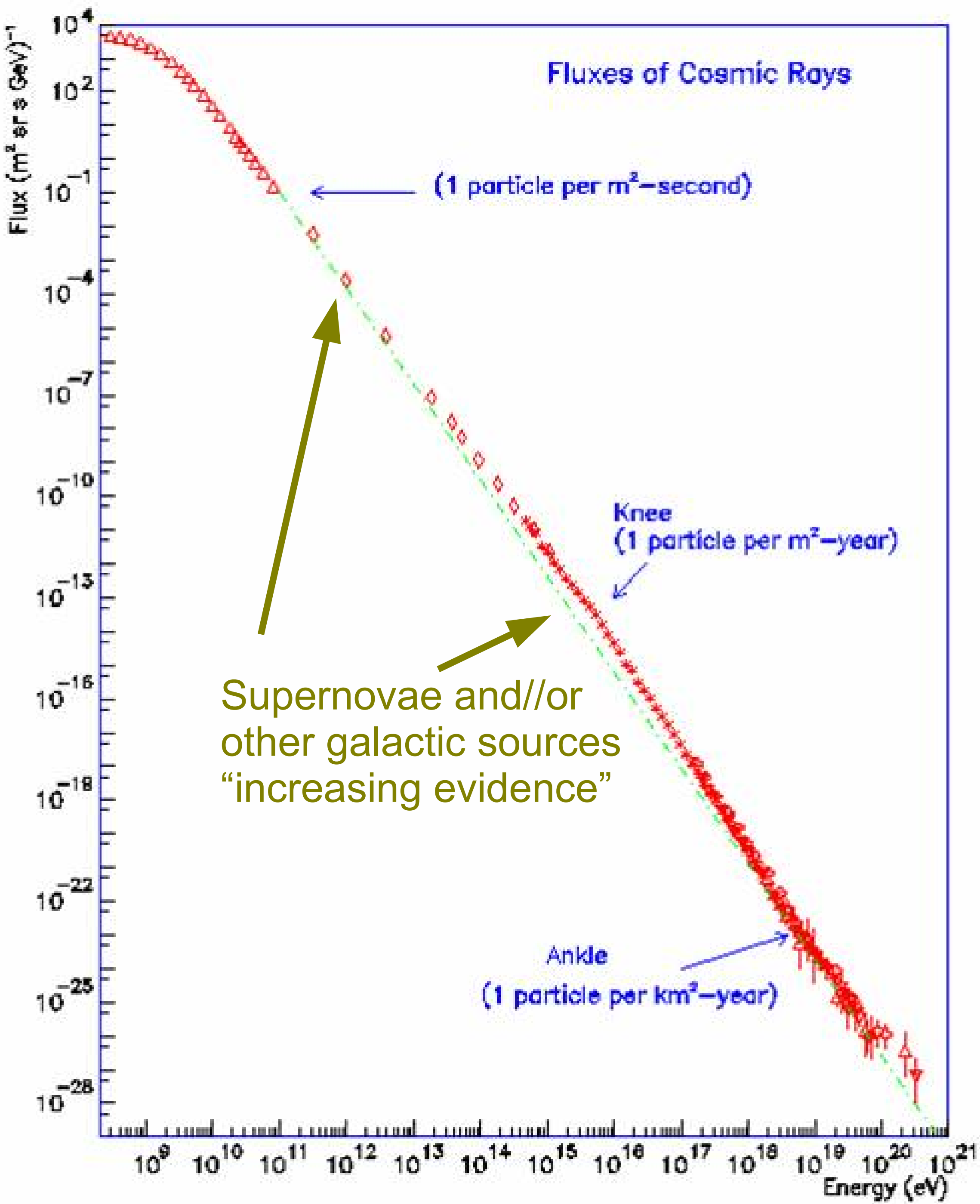
(1) Introduction

(2) Large Scale Anisotropy (dipole)

(3) "Starburst" result

(4) Work-in-progress: Auger@TA

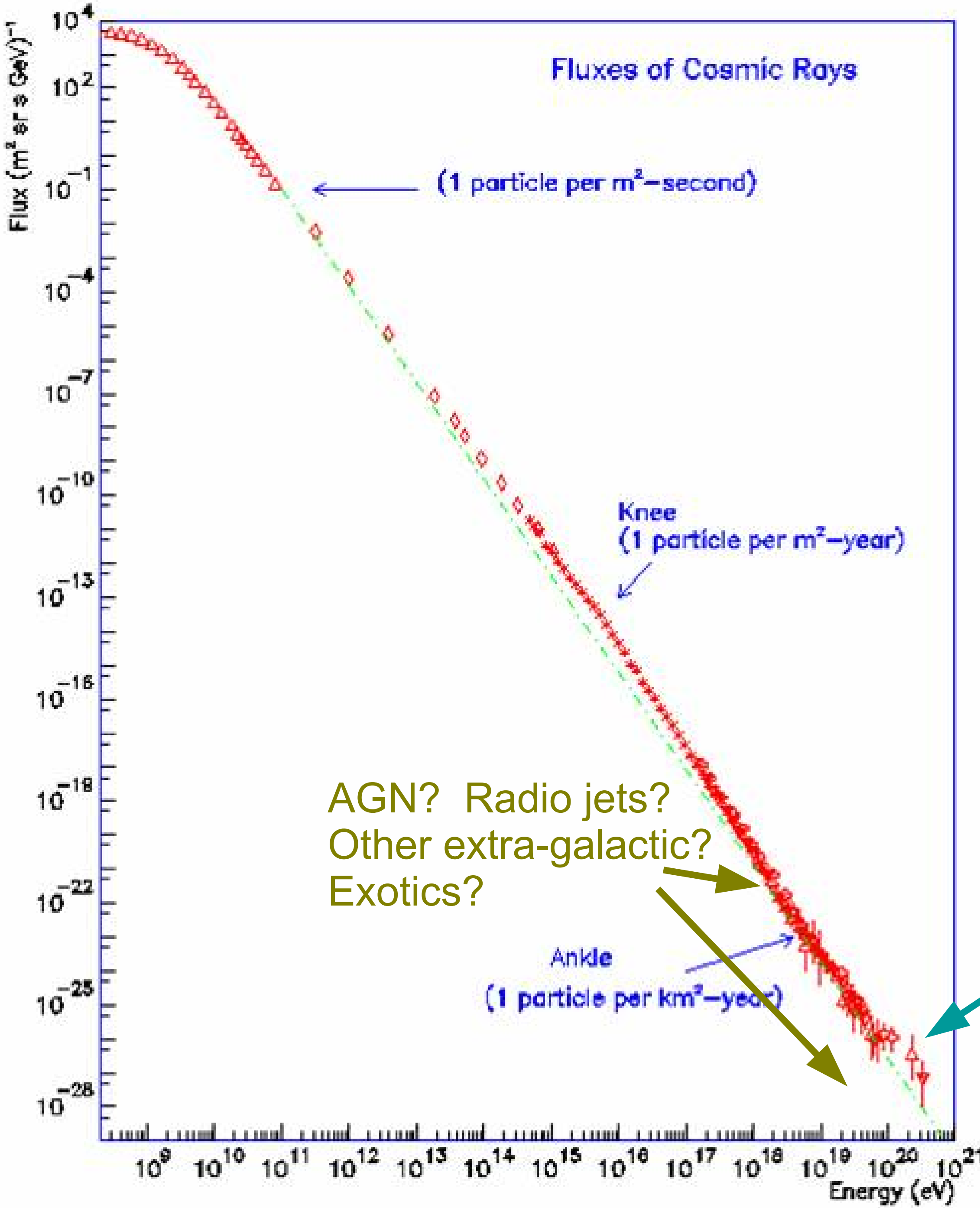
(5) Work-in-progress:
The planned Auger upgrade: AugerPrime



All-particles spectrum of cosmic rays arriving at the earth from all directions in space.

At present there is not a single unified model for explaining where these particles originate in the universe.

Plot from S. Swordy

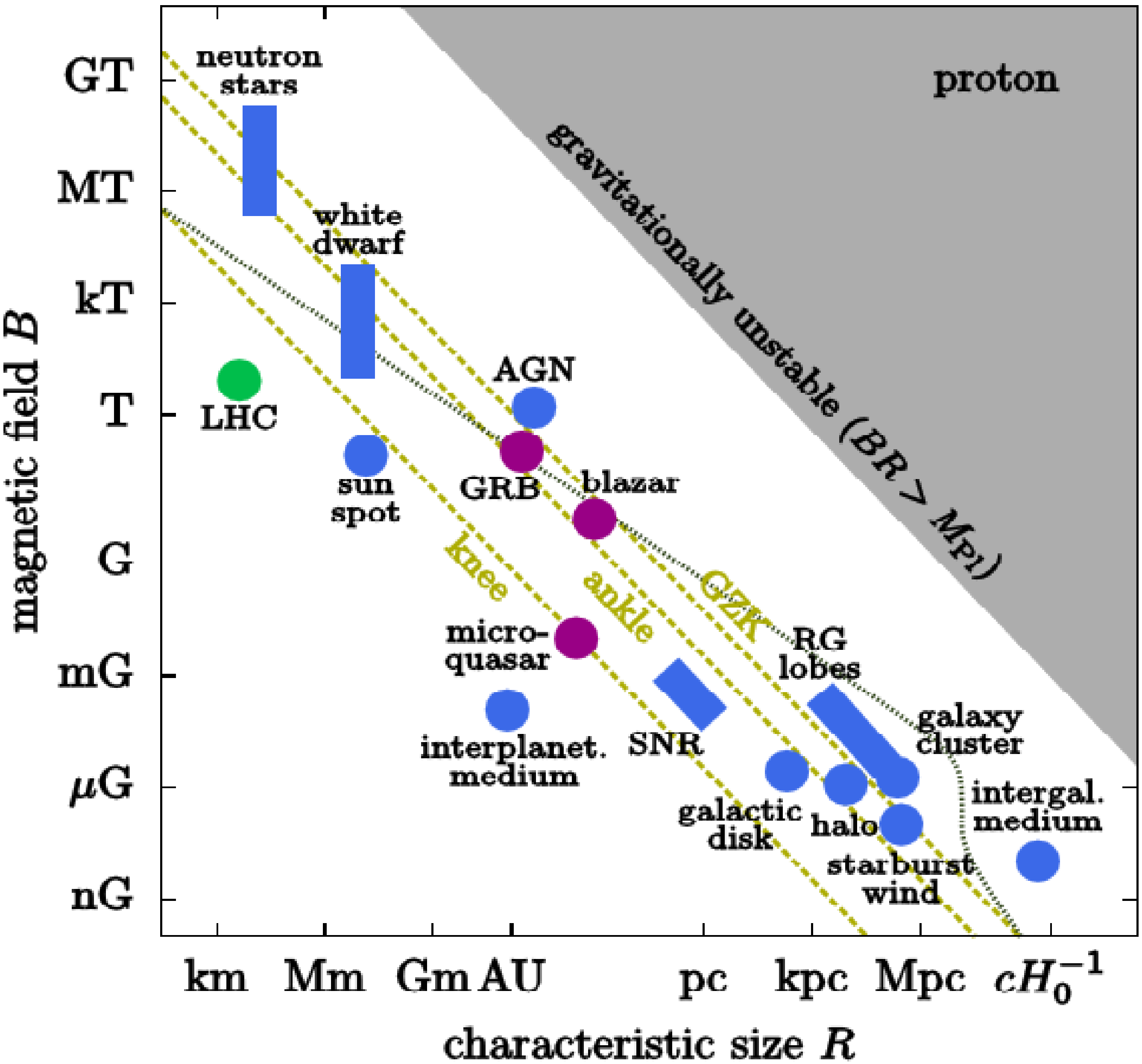


All-particles spectrum of cosmic rays arriving at the earth from all directions in space.

At present there is not a single unified model for explaining where these particles originate in the universe.

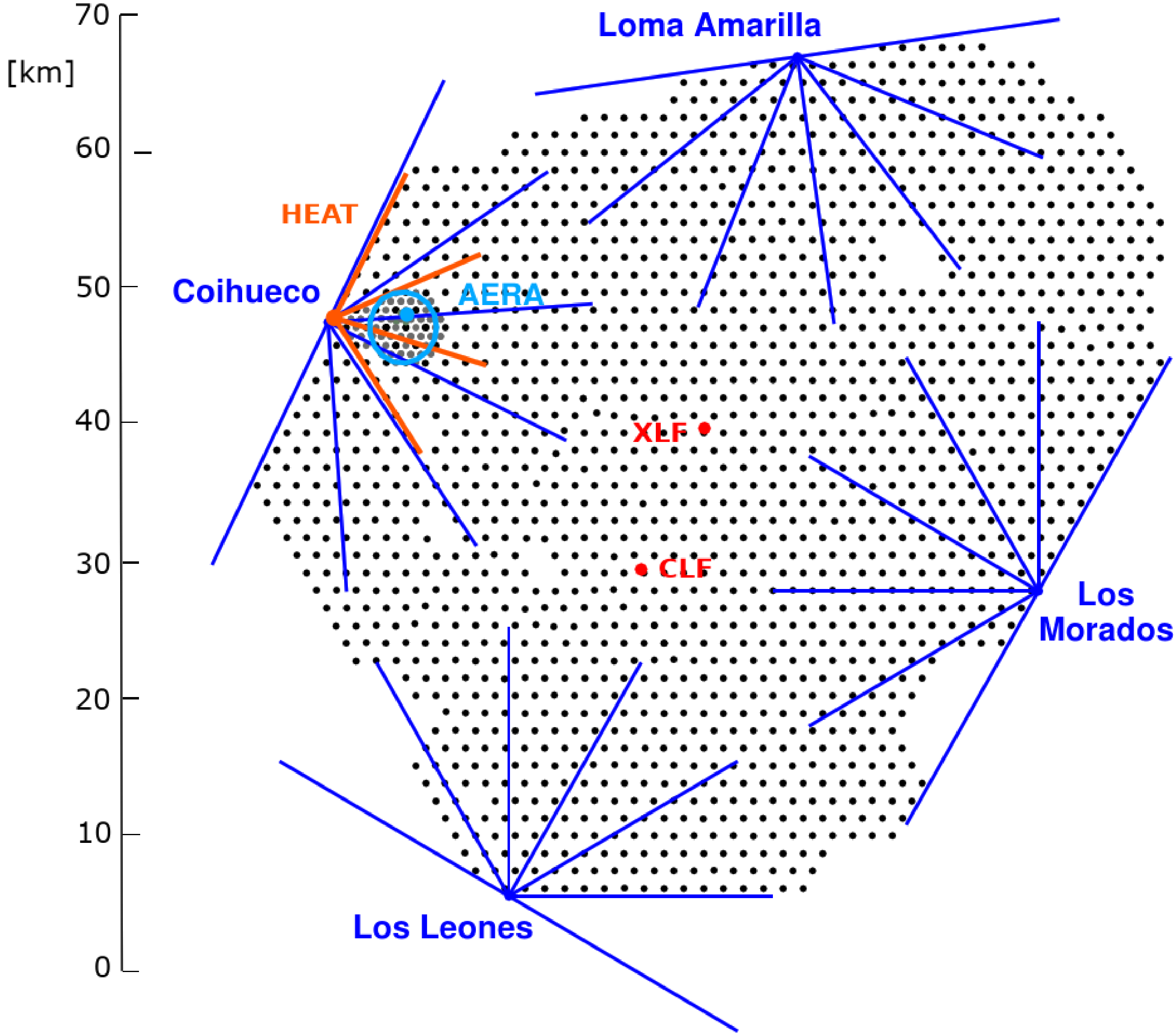
Plot from S. Swordy

One cosmic ray particle per square km per century!



"Hillas Plot" (originally 1984, this version M.T. Dova arXiv 1604.07584)

The Pierre Auger Observatory: Malargue, Argentina

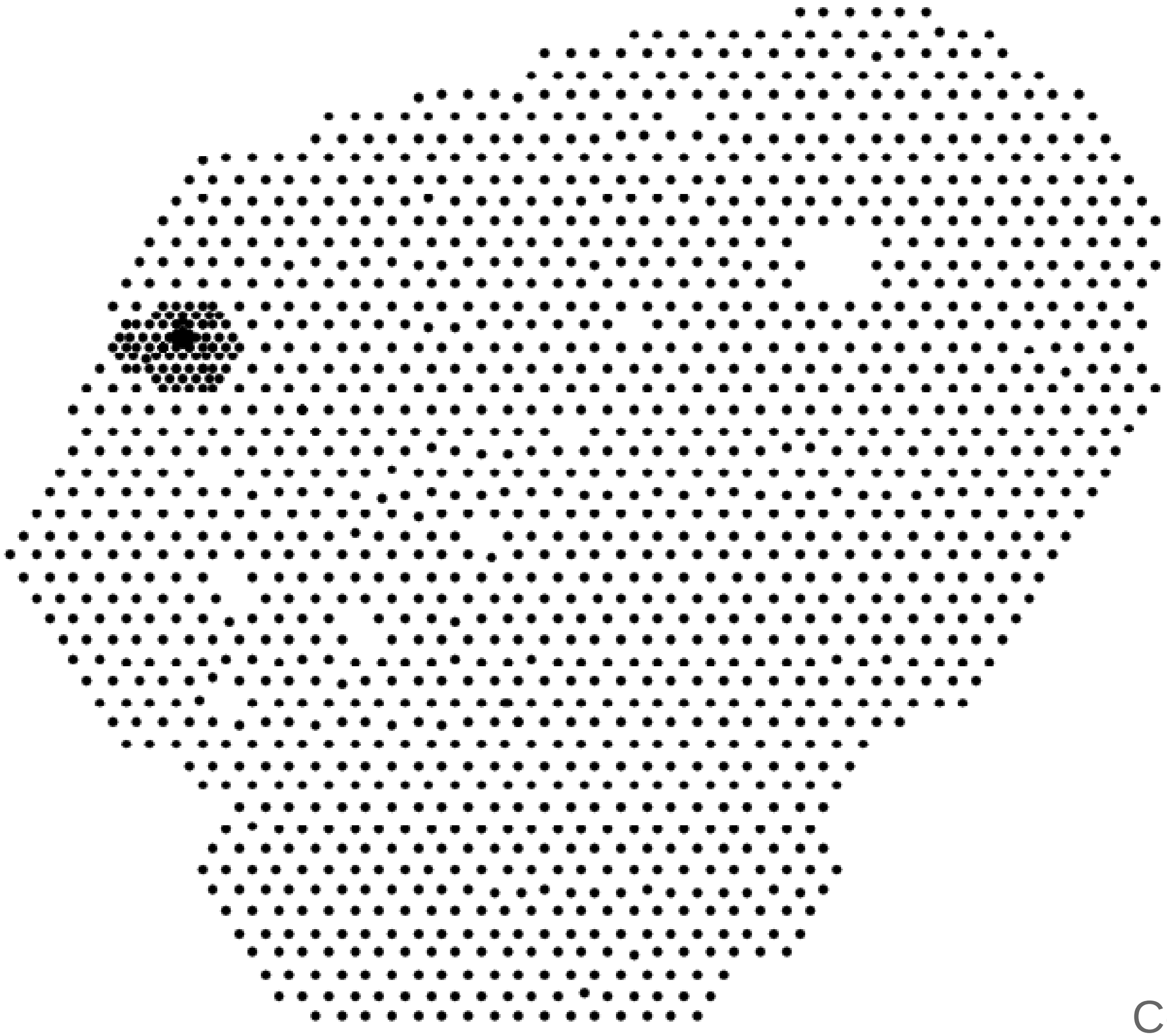


Auger Surface Detector Array

~1,600 Water Cherenkov Tank Detectors

1.5 km hexagonal grid

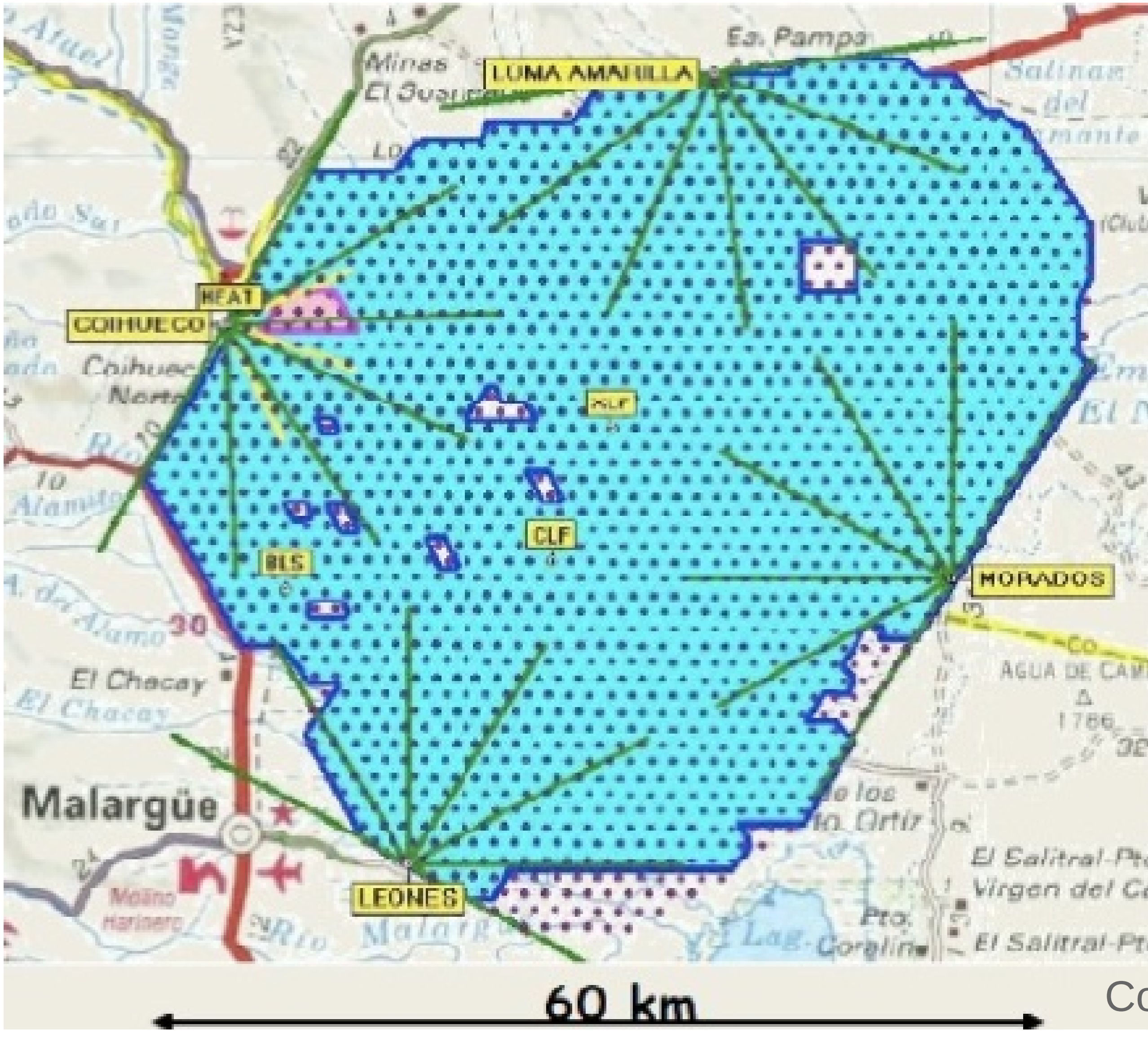
Covers 3,000 square km



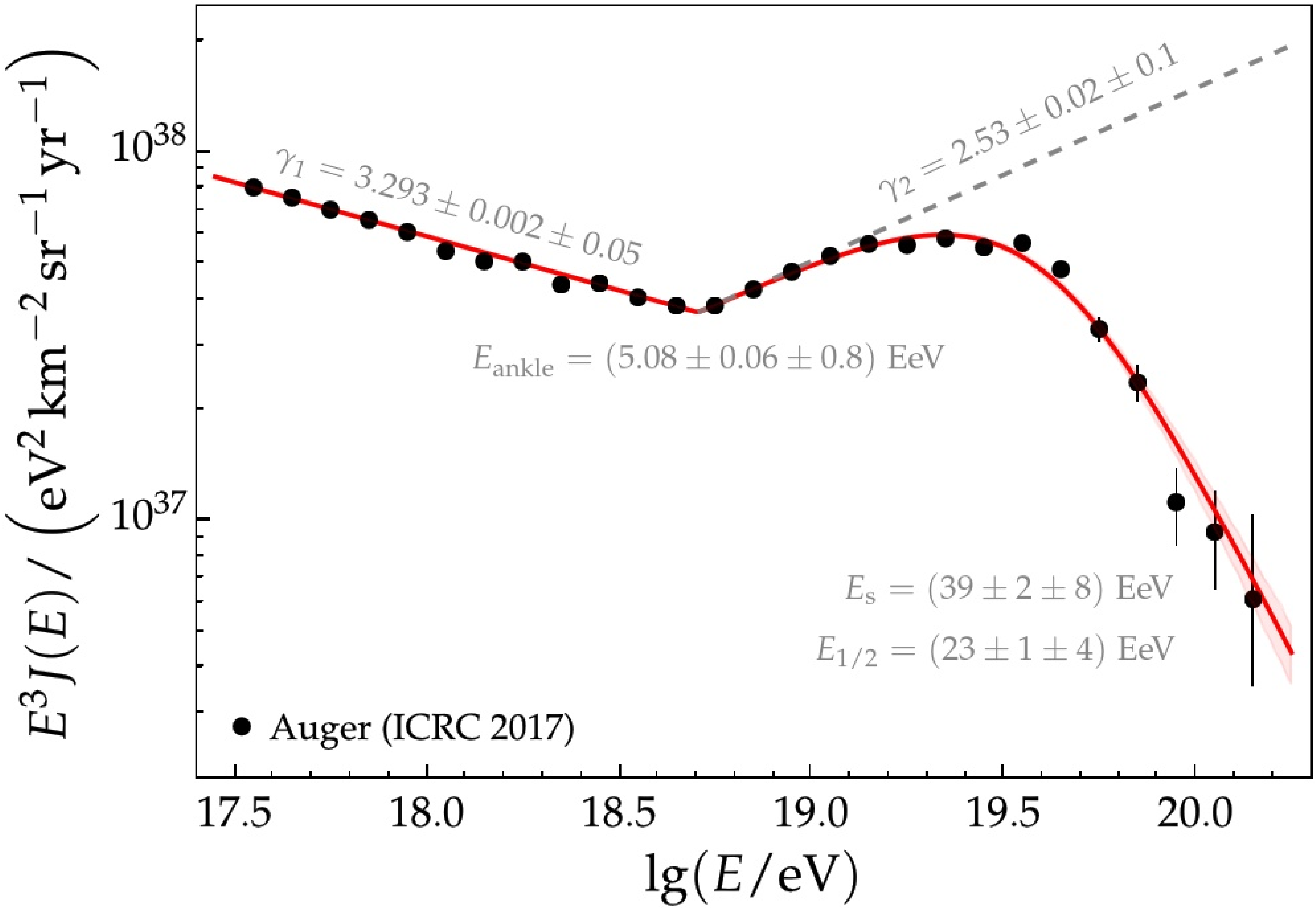
Auger Fluorescence Detectors:

24 fluorescence telescopes 30 deg by 30 deg

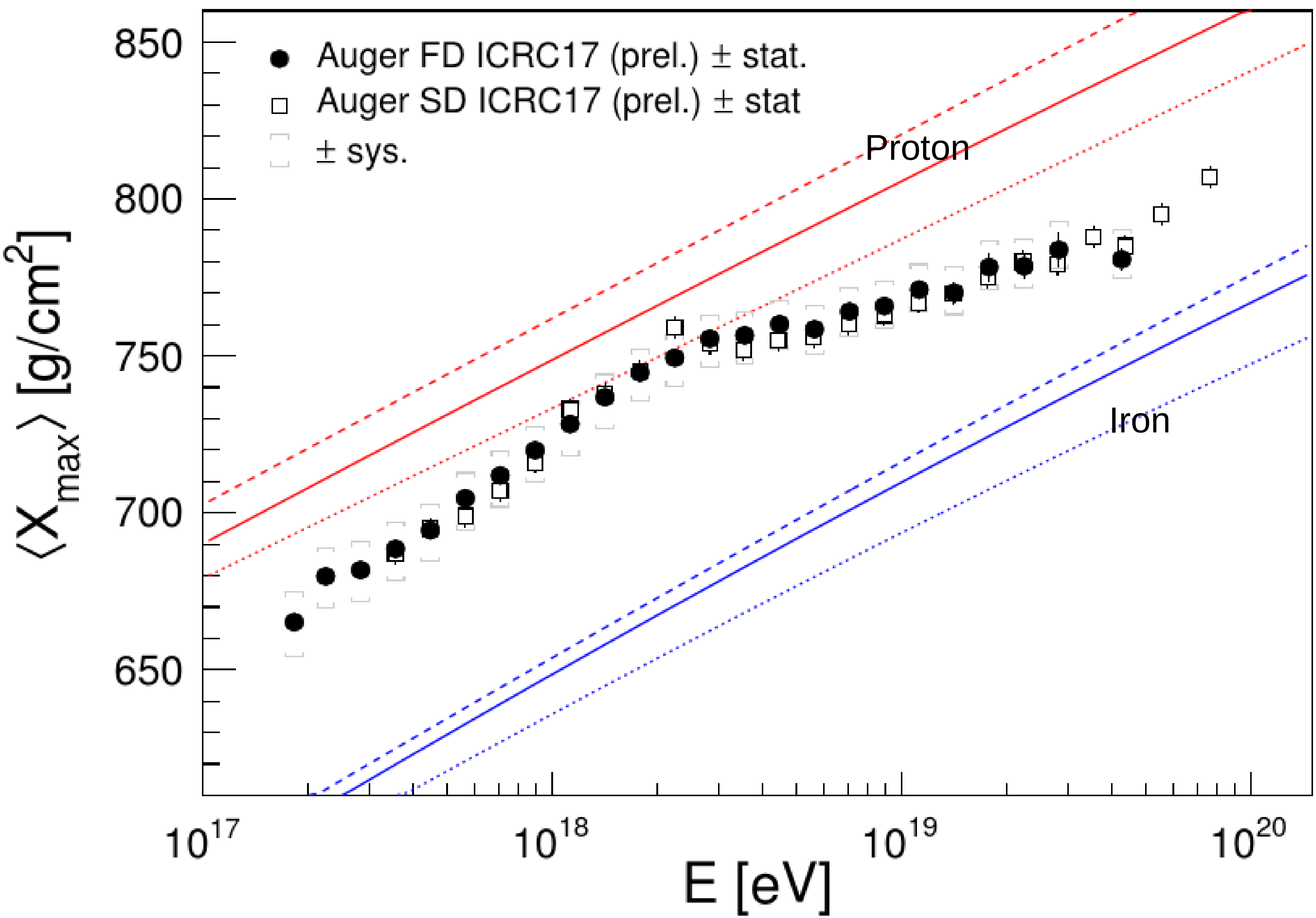
Four sites



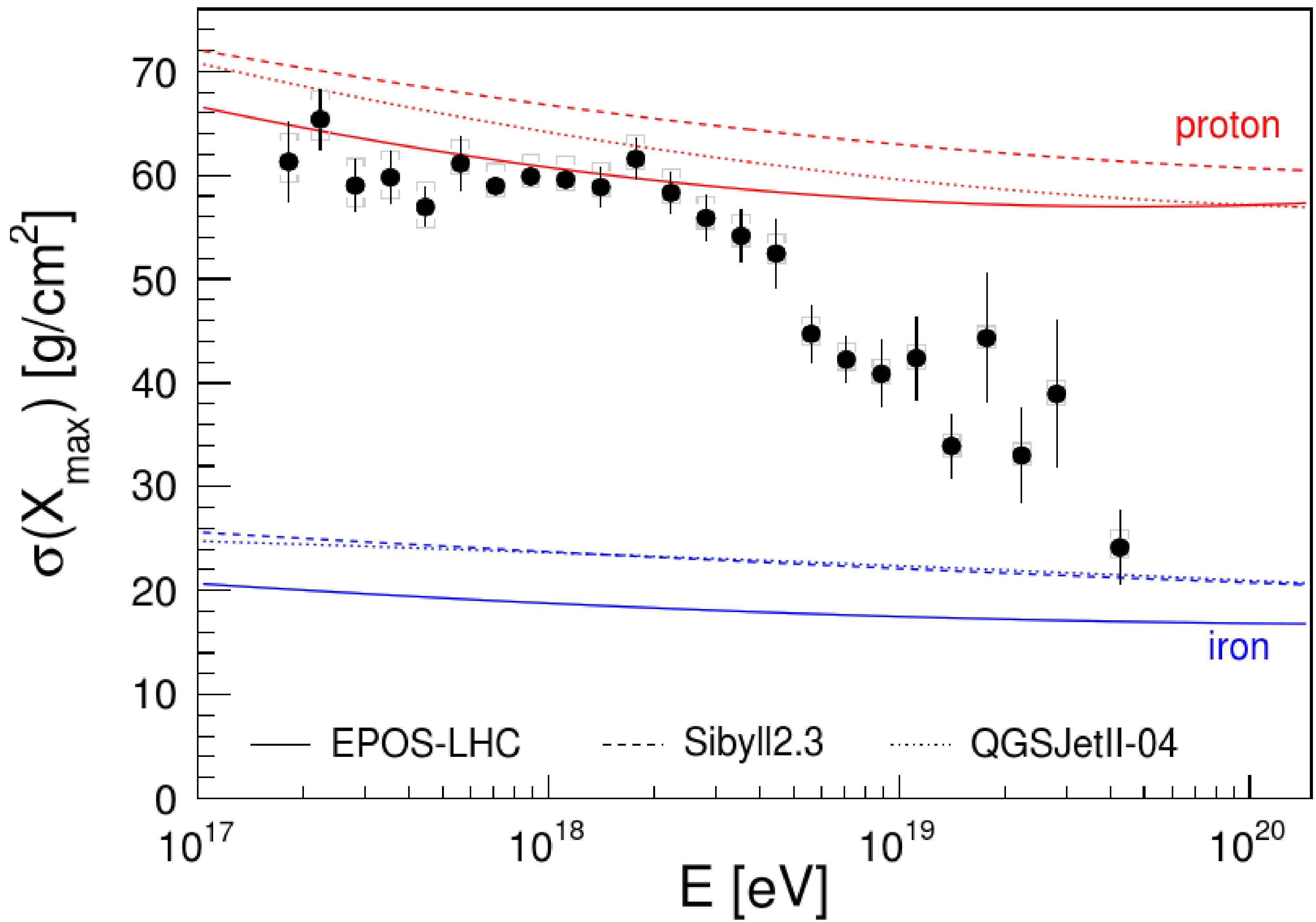
Auger Cosmic Ray Spectrum (ICRC 2017)



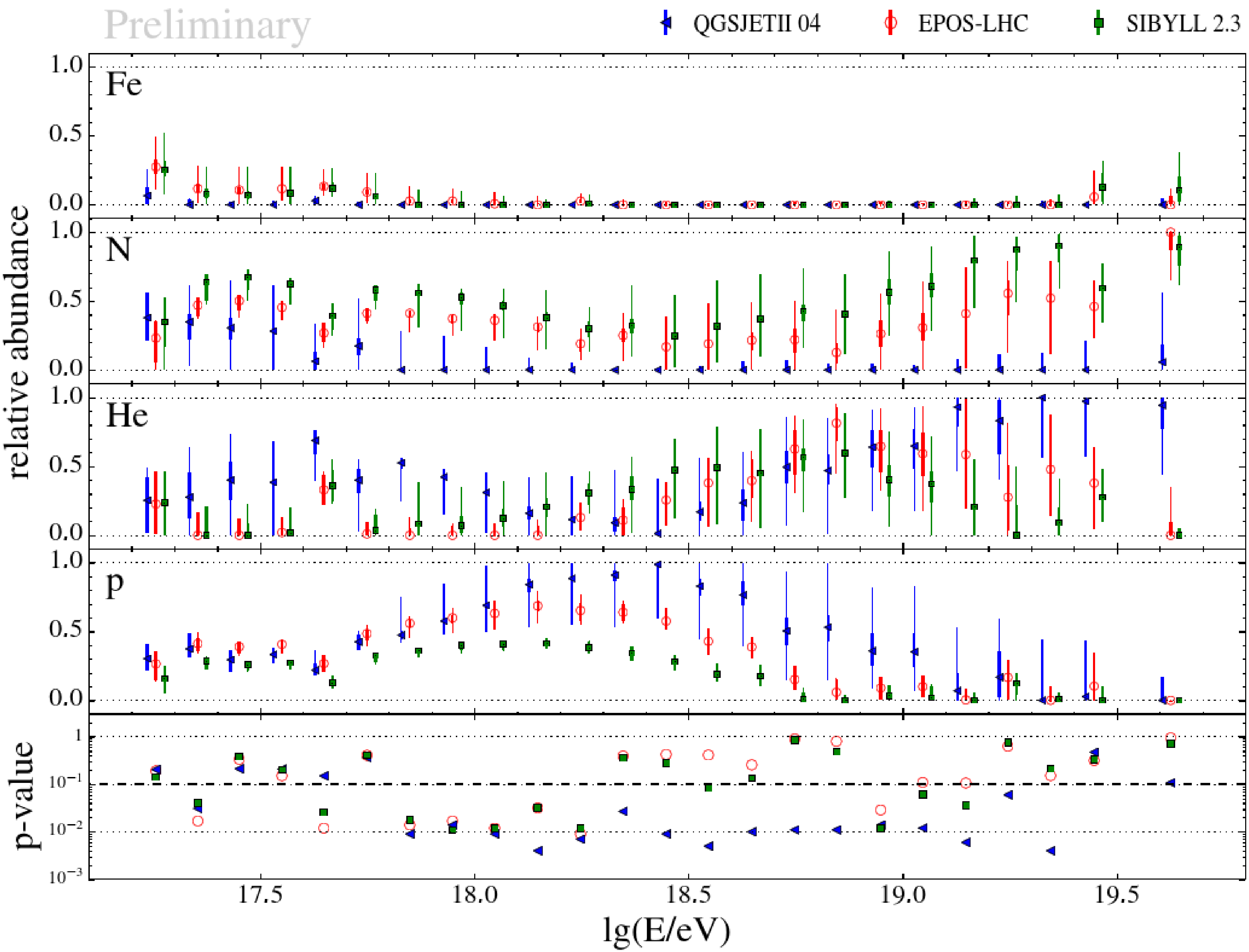
Auger Xmax vs Energy (composition) (ICRC 2017)



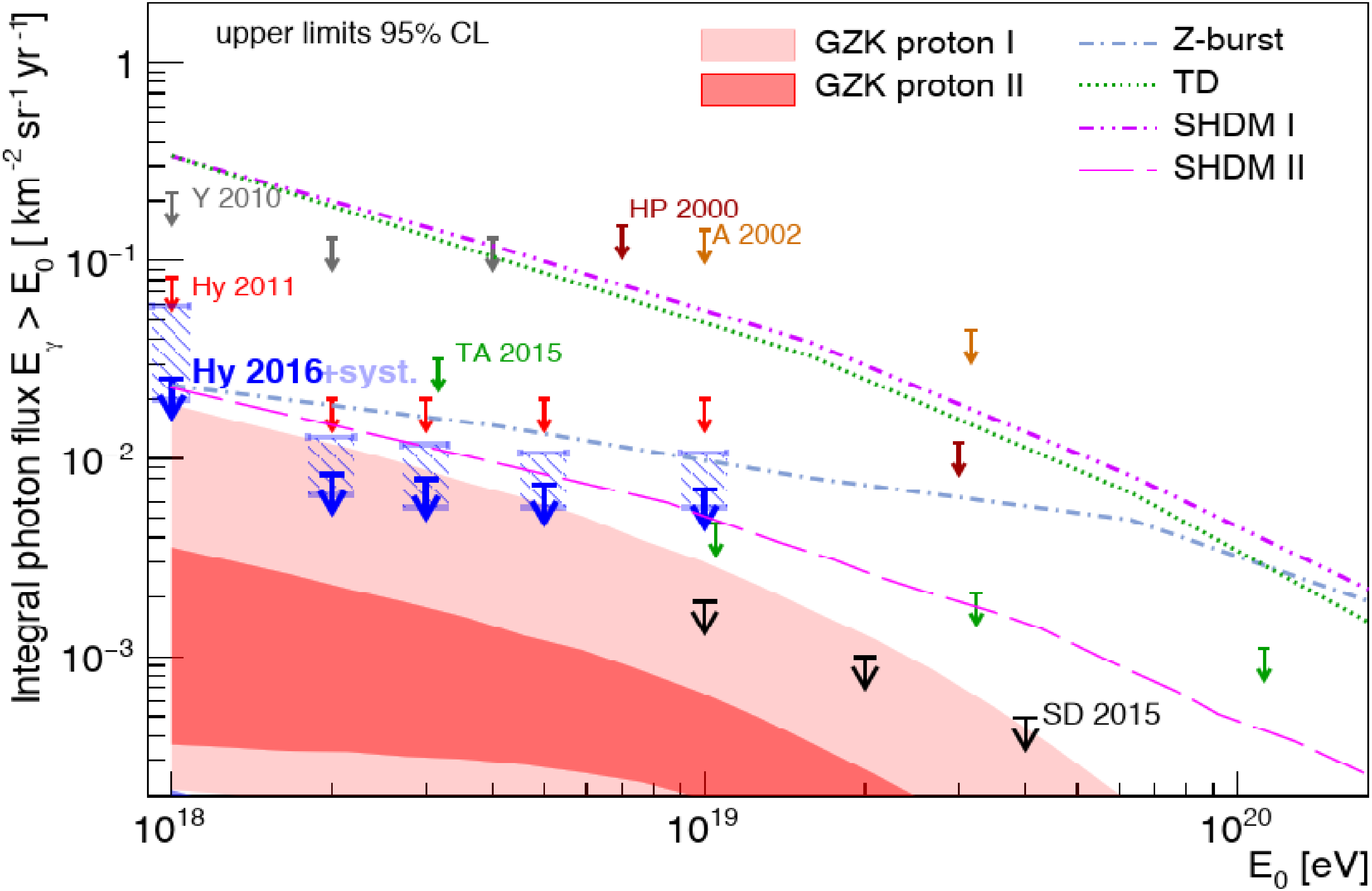
Auger Variance in Xmax vs Energy (composition) (ICRC 2017)



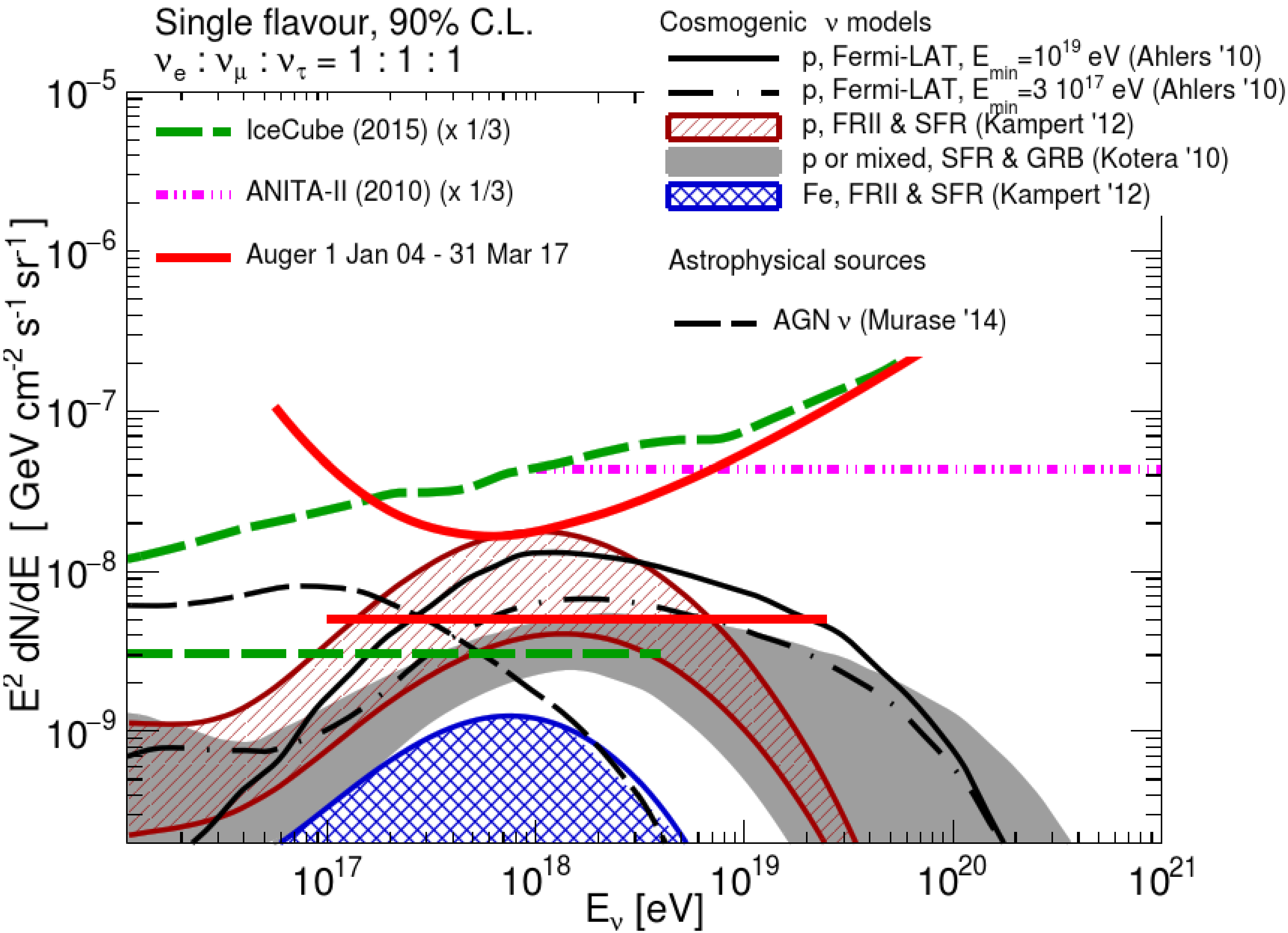
Constraints on atomic abundances (preliminary) (ICRC 2017)



Auger Limits against isotropic photon fraction
arXiv: 1612.01517



Auger Limits against isotropic neutrinos (ICRC 2017, preliminary)



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Science 357, 1266-1270 (Sep 2017) Auger Dipole
arXiv: 1709.07321

Raleigh analysis for dipole

$$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos \alpha_i$$

$$b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin \alpha_i$$

Amplitude

$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}$$

and

Phase

$$\tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha}$$

Auger Dipole Anisotropy results: (arXiv: 1709.07321)

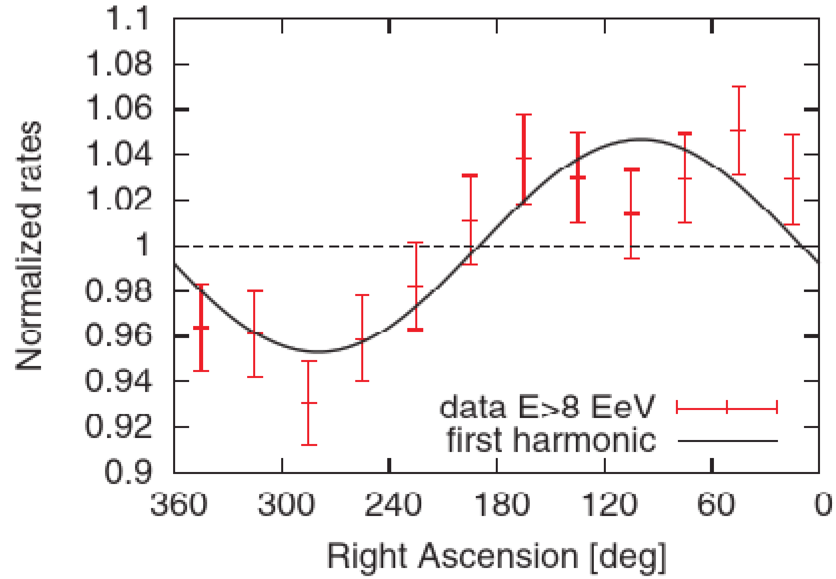
Table 1. First harmonic in right ascension. Data are from the Rayleigh analysis of the first harmonic in right ascension for the two energy bins.

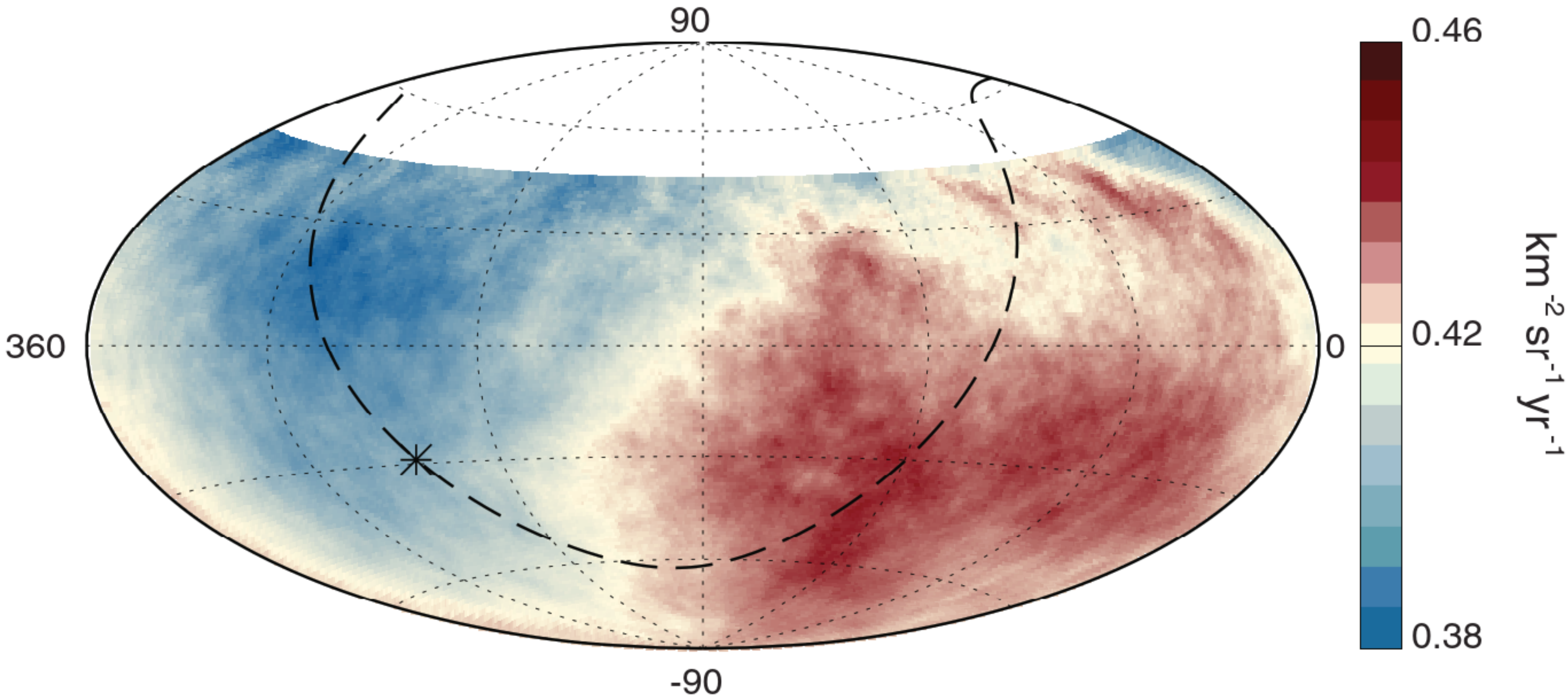
Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 8	81,701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥8	32,187	−0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

Table 2. Three-dimensional dipole reconstruction. Directions of dipole components are shown in equatorial coordinates.

Energy (EeV)	Dipole component d_z	Dipole component $d_\perp$	Dipole amplitude d	Dipole declination δ_d (°)	Dipole right ascension α_d (°)
4 to 8	−0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
≥8	−0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

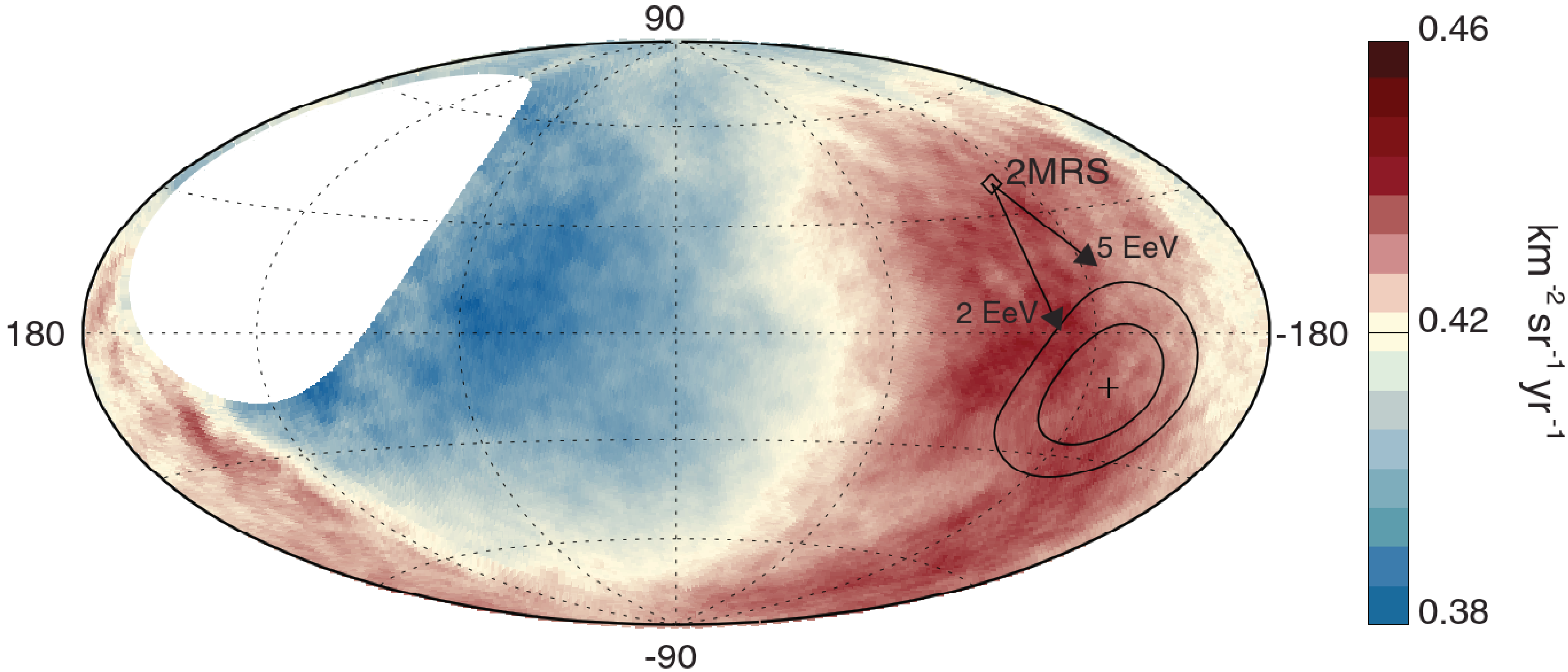
Auger Dipole Anisotropy results:
(arXiv: 1709.07321)
Celestial coordinates



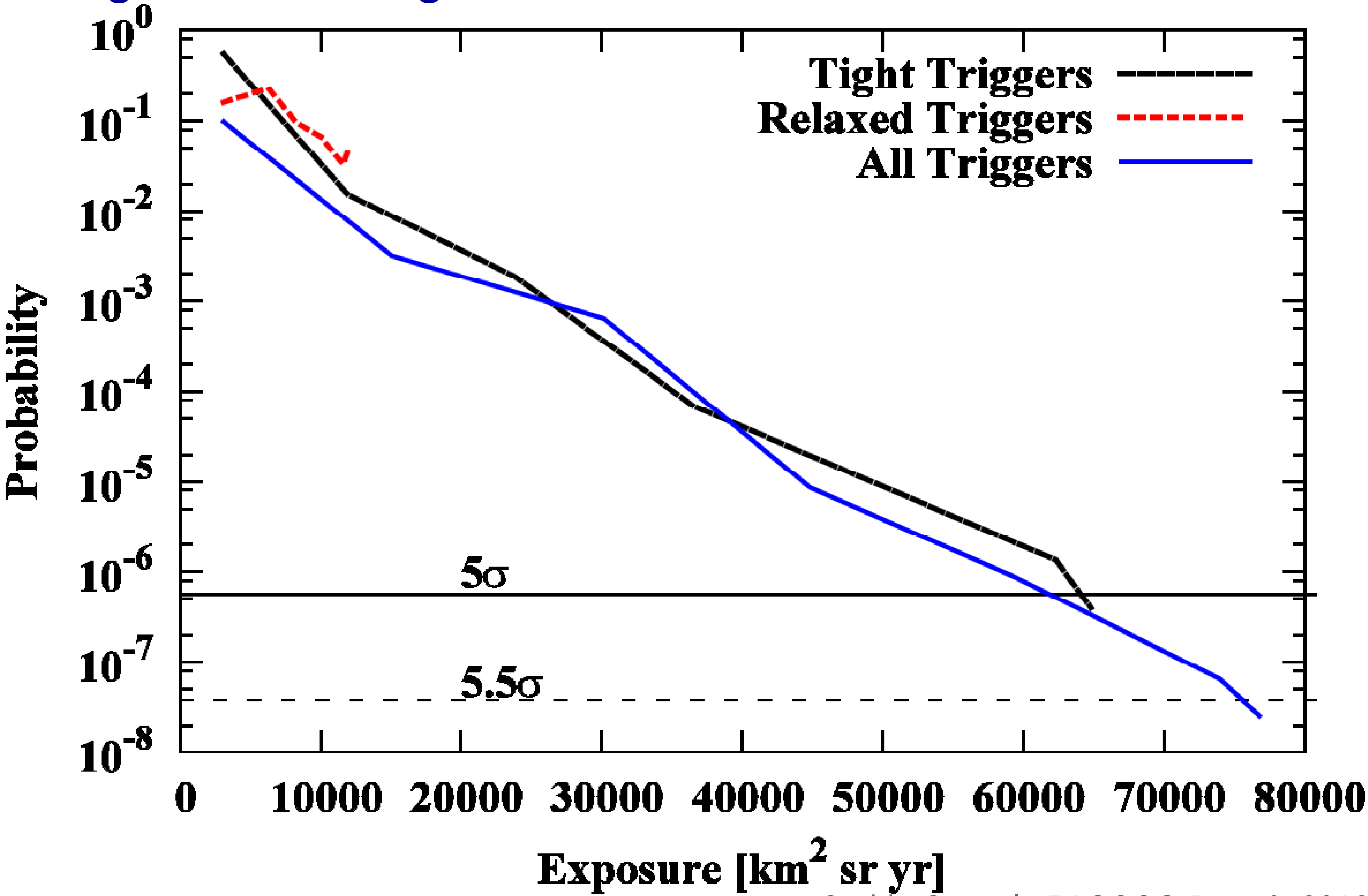


Auger Dipole Anisotropy results: (arXiv: 1709.07321)

Galactic coordinates



Auger Dipole Anisotropy results: (arXiv: 1709.07321)
Significance of signal vs. time



Science 357, 1266-1270 (Sep 2017) Auger Dipole

>> Prob 2.6 x 10^(-8) ==> 5.6 sigma

>> Penalty for trials for 2 ++ energy bins:
Effectively down to 5.2 sigma

>> Approximate match with expectation based on source distribution matching 2MRS galaxy distribution. Taking into account plausible magnetic deflection improves position match.

>> Result places constraints against galactic source models. Sources > 8 EeV almost certainly mostly extra-galactic.

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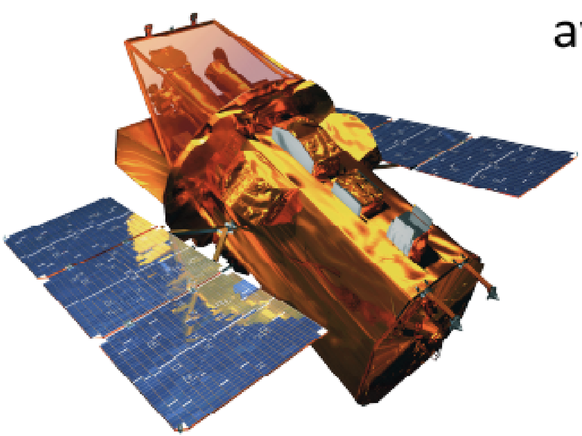
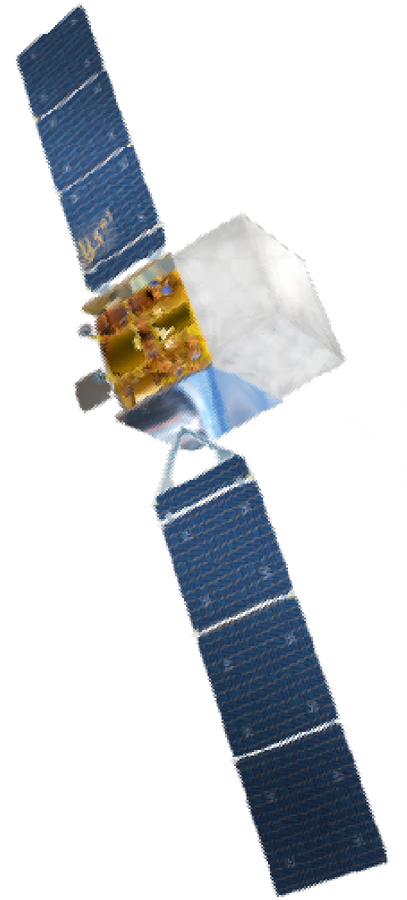
"Starburst" Result: ApJ Letters 853, L29 (Feb 2018) arXiv: 1801.06160

Basic Idea

- Compare Fermi-LAT and Swift BAT AGN and Starburst Galaxy (SBG) catalogs with flux of UHECRs
- Catalogs (only considering sources <250 Mpc away):
  - Fermi-LAT (Large Area Telescope) contributes the 2FHL catalog of sources, including 63 suspected SBGs, 23 of which are considered due to flux and GZK cutoff (next slide)
  - Swift-BAT (Burst Alert Telescope + Ultra-Violet/Optical Telescope) telescope mounted
  - 2MRS (2MASS Redshift Survey) from telescopes on Mt Hopkins and CTIO (Chile)



Swift Telescope



Fermi Telescope

"Starburst" Result: ApJ Letters 853, L29 (Feb 2018)
arXiv: 1801.06160

23 flux select starburst galaxies within 250 Mpc

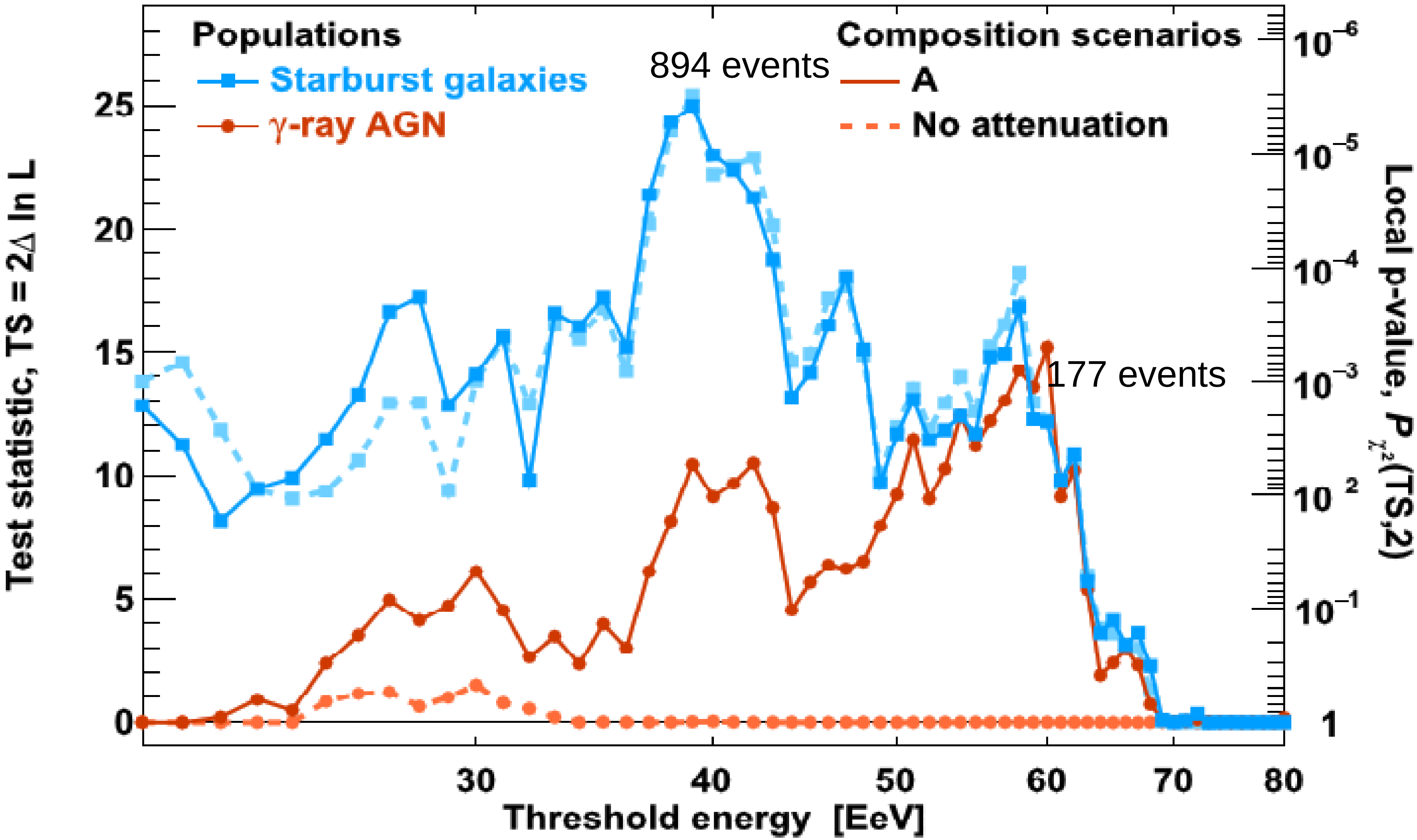
19 selected AGN within 150 Mpc

Table 1
Populations Investigated

SBGs	l (°)	b (°)	Distance[a] (Mpc)	Flux Weight (%)	Attenuated Weight: A/B/C (%)	% Contribution[b]: A/B/C (%)
NGC 253	97.4	−88	2.7	13.6	20.7/18.0/16.6	35.9/32.2/30.2
M82	141.4	40.6	3.6	18.6	24.0/22.3/21.4	0.2/0.1/0.1
NGC 4945	305.3	13.3	4	16	19.2/18.3/17.9	39.0/38.4/38.3
M83	314.6	32	4	6.3	7.6/7.2/7.1	13.1/12.9/12.9
IC 342	138.2	10.6	4	5.5	6.6/6.3/6.1	0.1/0.0/0.0
NGC 6946	95.7	11.7	5.9	3.4	3.2/3.3/3.5	0.1/0.1/0.1
NGC 2903	208.7	44.5	6.6	1.1	0.9/1.0/1.1	0.6/0.7/0.7
NGC 5055	106	74.3	7.8	0.9	0.7/0.8/0.9	0.2/0.2/0.2
NGC 3628	240.9	64.8	8.1	1.3	1.0/1.1/1.2	0.8/0.9/1.1
NGC 3627	242	64.4	8.1	1.1	0.8/0.9/1.1	0.7/0.8/0.9
NGC 4631	142.8	84.2	8.7	2.9	2.1/2.4/2.7	0.8/0.9/1.1
M51	104.9	68.6	10.3	3.6	2.3/2.8/3.3	0.3/0.4/0.5
NGC 891	140.4	−17.4	11	1.7	1.1/1.3/1.5	0.2/0.3/0.3
NGC 3556	148.3	56.3	11.4	0.7	0.4/0.6/0.6	0.0/0.0/0.0
NGC 660	141.6	−47.4	15	0.9	0.5/0.6/0.8	0.4/0.5/0.6
NGC 2146	135.7	24.9	16.3	2.6	1.3/1.7/2.0	0.0/0.0/0.0
NGC 3079	157.8	48.4	17.4	2.1	1.0/1.4/1.5	0.1/0.1/0.1
NGC 1068	172.1	−51.9	17.9	12.1	5.6/7.9/9.0	6.4/9.4/10.9
NGC 1365	238	54.6	22.3	1.3	0.5/0.8/0.8	0.9/1.5/1.6
Arp 299	141.9	55.4	46	1.6	0.4/0.7/0.6	0.0/0.0/0.0
Arp 220	36.6	53	80	0.8	0.1/0.3/0.2	0.0/0.2/0.1
NGC 6240	20.7	27.3	105	1	0.1/0.3/0.1	0.1/0.3/0.1
Mkn 231	121.6	60.2	183	0.8	0.0/0.1/0.0	0.0/0.0/0.0
γAGNs						
Cen A Core	309.6	19.4	3.7	0.8	60.5/14.6/40.4	86.8/56.3/71.5
M87	283.7	74.5	18.5	1	15.3/7.1/29.5	9.7/12.1/23.1
NGC 1275	150.6	−13.3	76	2.2	6.6/6.1/7.5	0.7/1.6/1.0
IC 310	150.2	−13.7	83	1	2.3/2.4/2.6	0.3/0.6/0.3
3C 264	235.8	73	95	0.5	0.8/1.0/0.8	0.4/1.3/0.5
TXS 0149 + 710	127.9	9	96	0.5	0.7/0.9/0.7	0.0/0.0/0.0
Mkn 421	179.8	65	136	54	11.4/48.3/14.7	1.8/19.1/2.8
PKS 0229-581	280.2	−54.6	140	0.5	0.1/0.5/0.1	0.2/2.0/0.3
Mkn 501	63.6	38.9	148	20.8	2.3/15.0/3.6	0.3/5.2/0.6
1ES 2344 + 514	112.9	−9.9	195	3.3	0.0/1.0/0.1	0.0/0.0/0.0
Mkn 180	131.9	45.6	199	1.9	0.0/0.5/0.0	0.0/0.0/0.0
1ES 1959 + 650	98	17.7	209	6.8	0.0/1.7/0.1	0.0/0.0/0.0
AP Librae	340.7	27.6	213	1.7	0.0/0.4/0.0	0.0/1.3/0.0
TXS 0210 + 515	135.8	−9	218	0.9	0.0/0.2/0.0	0.0/0.0/0.0
GB6 J0601 + 5315	160	14.6	232	0.4	0.0/0.1/0.0	0.0/0.0/0.0
PKS 0625-35	243.4	−20	245	1.3	0.0/0.1/0.0	0.0/0.5/0.0
I Zw 187	77.1	33.5	247	2.3	0.0/0.2/0.0	0.0/0.0/0.0

"Starburst" Result: ApJ Letters 853, L29 (Feb 2018)
arXiv: 1801.06160

Thresholding scan: E>39 EeV for SBG, E>60 EeV for AGN



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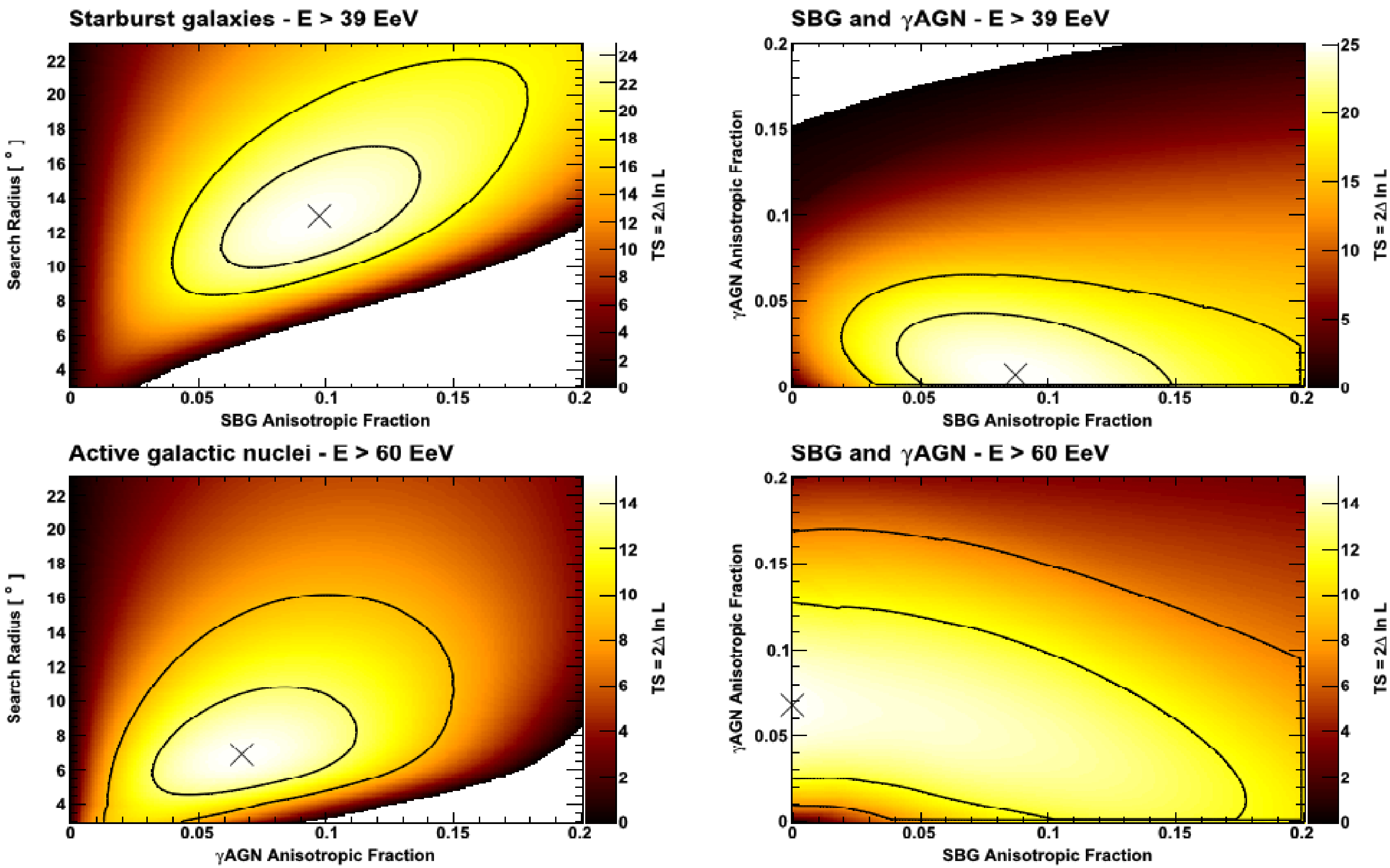
Above 39 EeV:

- SBGs: 13° +4°/-3° search radius, and 10% +/- 4% anisotropic fraction with 4.0σ deviation from isotropy
- AGNs: 7° +4°/-2° search radius, and 7% +/- 4% anisotropic fraction with 2.7σ deviation from isotropy

Similar searches for IR & x-ray galaxies yield lower significance.



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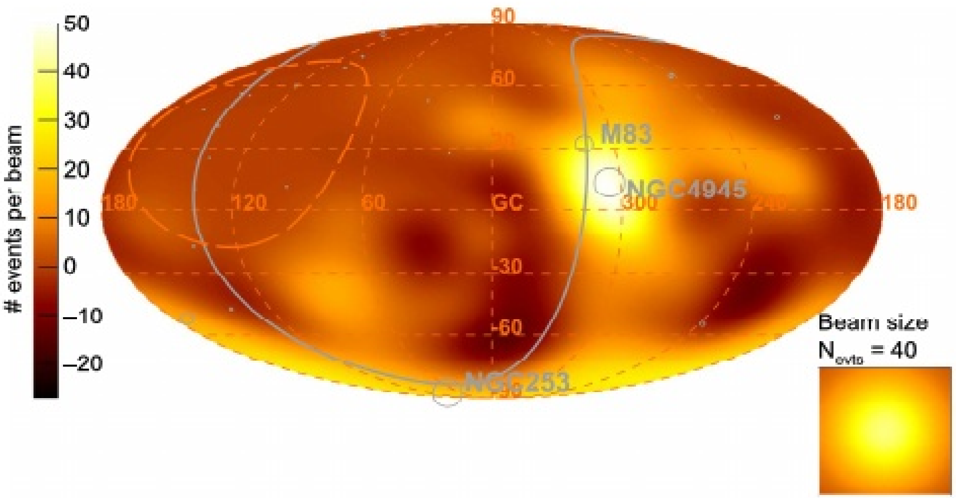
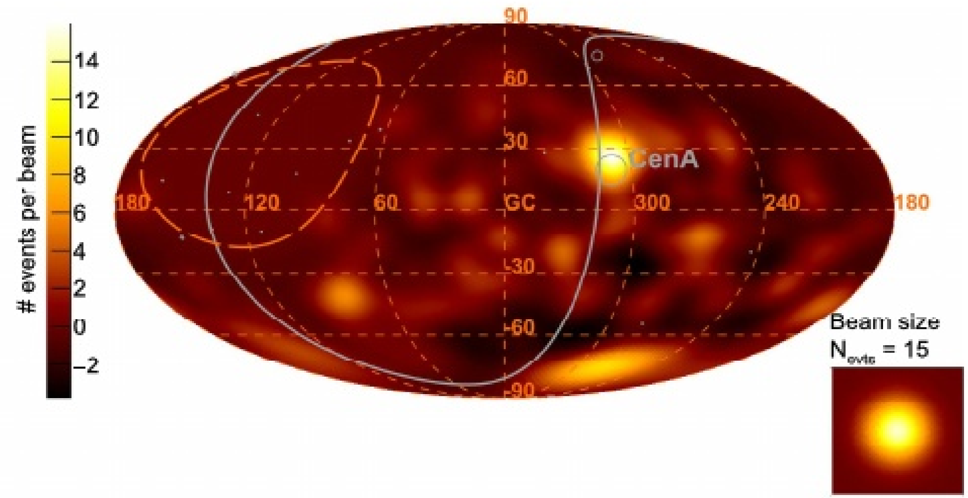
Observed Excess Map - E > 39 Eev

SBGs



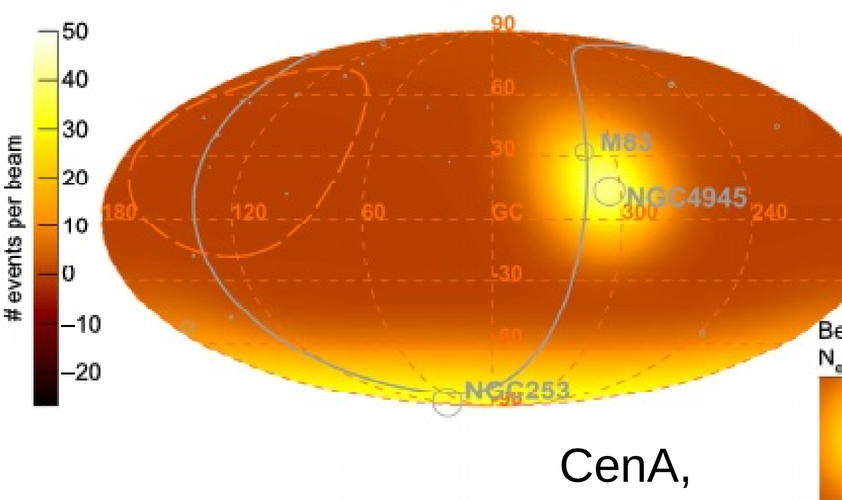
Observed Excess Map - E > 60 Eev

AGN



Model Excess Map - Starburst galaxies - E > 39 EeV

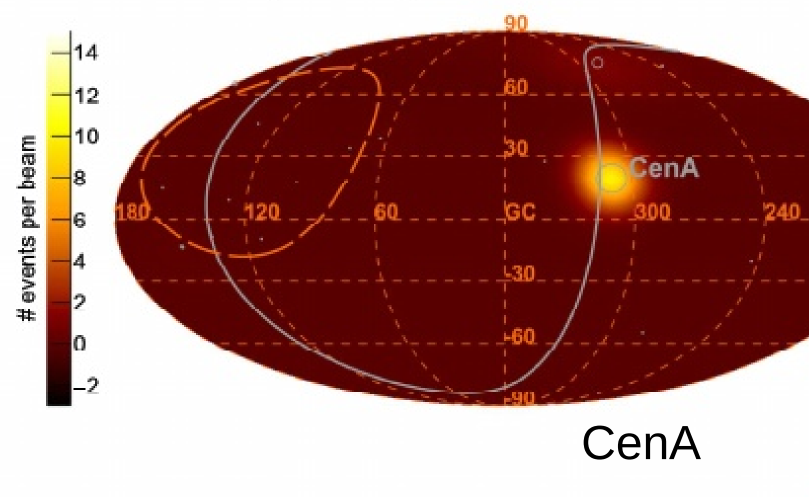
SBGs



CenA,
M83,
NGC4945

Model Excess Map - Active galactic nuclei - E > 60 EeV

AGN



CenA

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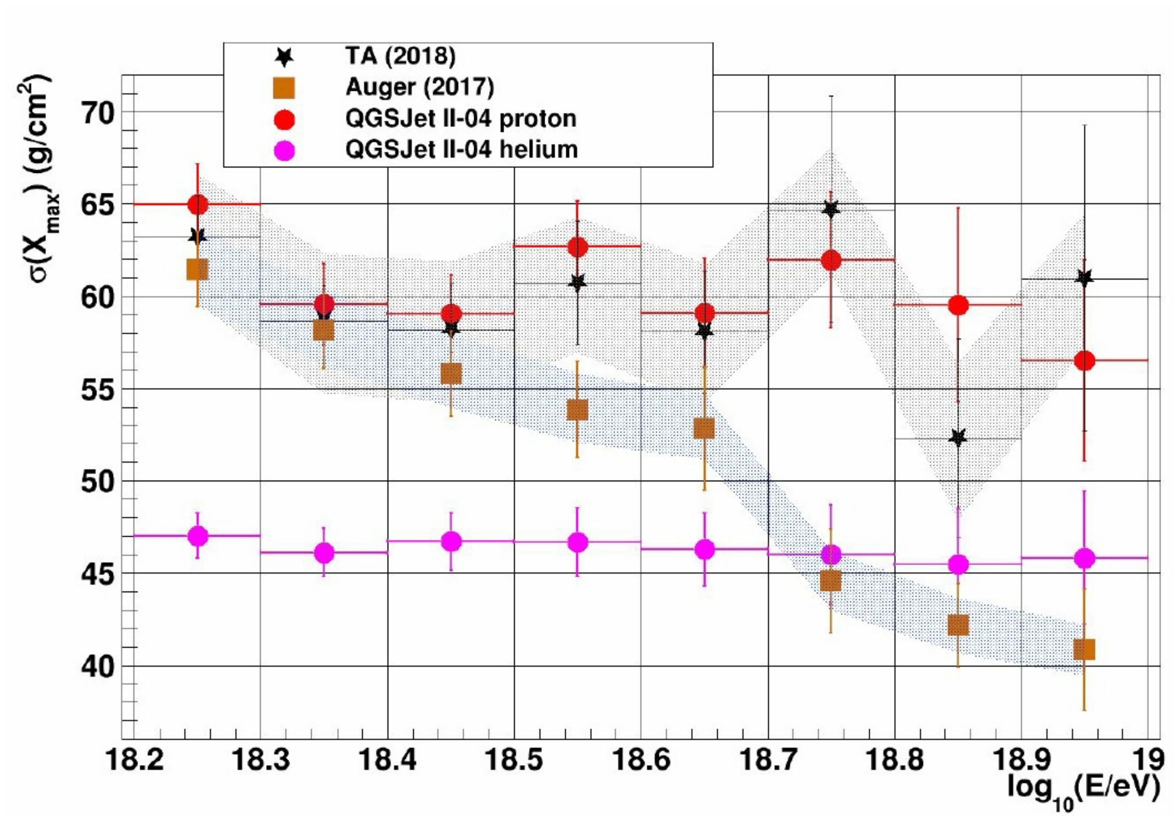
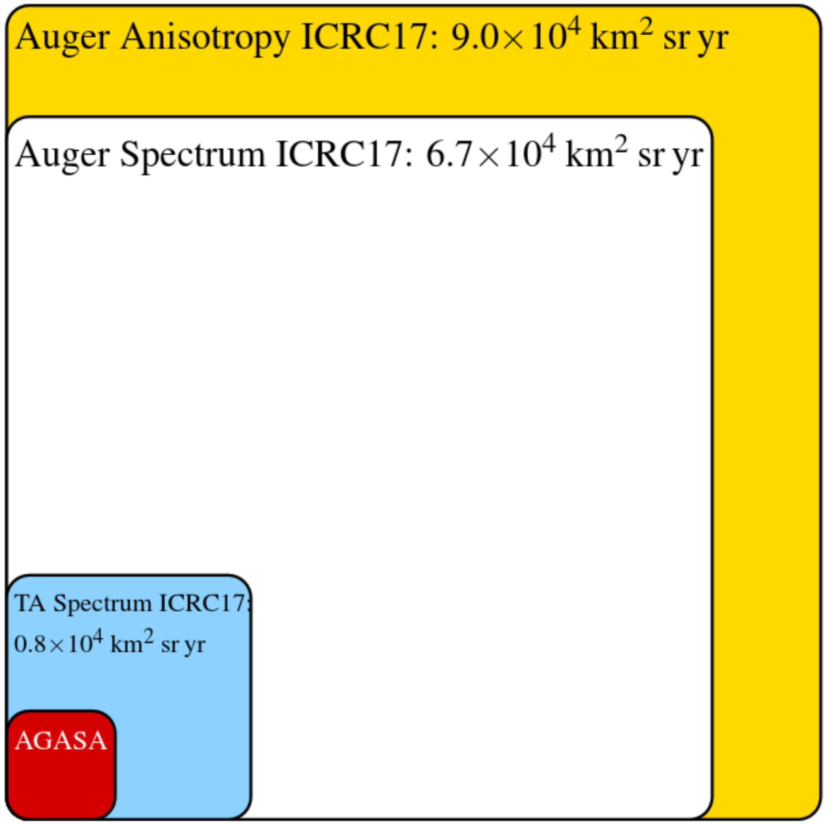
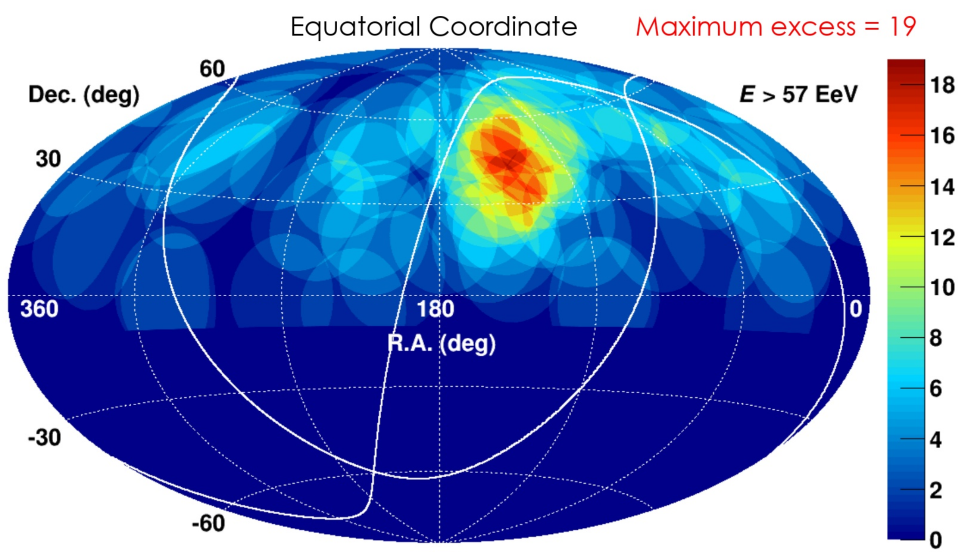
Some tension between Auger and Telescope Array/HiRes





from Hanlon et al ISVHECRI 2018



“Arguable” differences between”

- --- Energy spectra
- --- Composition
- --- Anisotropy

Could be:

- --- Analysis differences (biases)
- --- Detector instrument response
- --- Real astrophysics North vs. South

Auger@TA (CWRU, Colorado School of Mines)

There exists some tension in the interpretation of results between Auger and the Telescope Array

→ Spectrum (arguments made on boths sides)

→ Composition (less about data than interpretation?)

→ Anisotropy (South: dipole, North no-dipole, “hot spot”)

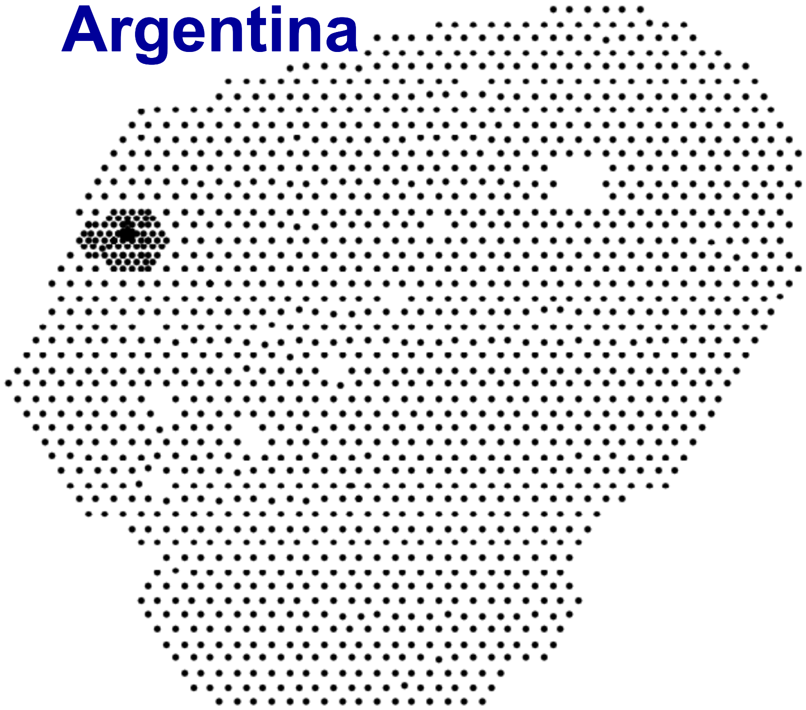
Plausibly most of these differences live within reasonable fluctuation boundaries of statistical, systematic and modeling differences. But their may be real astrophysical differences.

Many co-collaborators aiming for more combined analyses (full sky, equivalent modeling, etc., etc.)

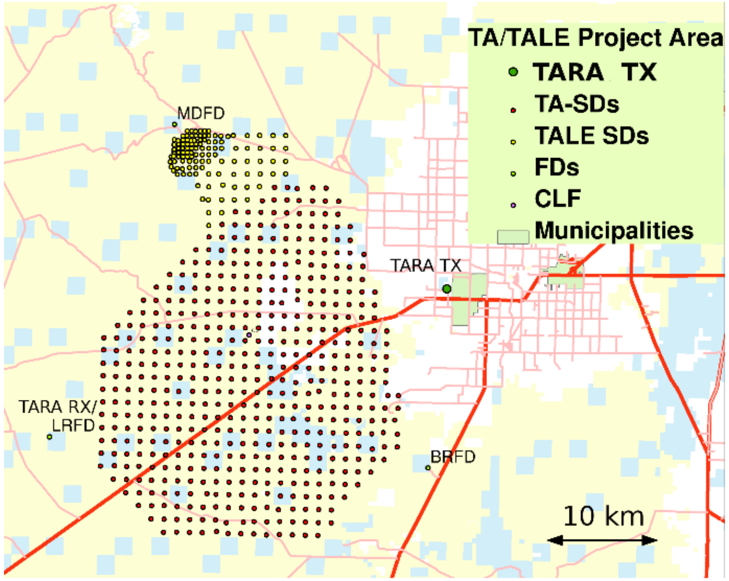
Can we develop a “ground-up” in-situ cross-calibration?

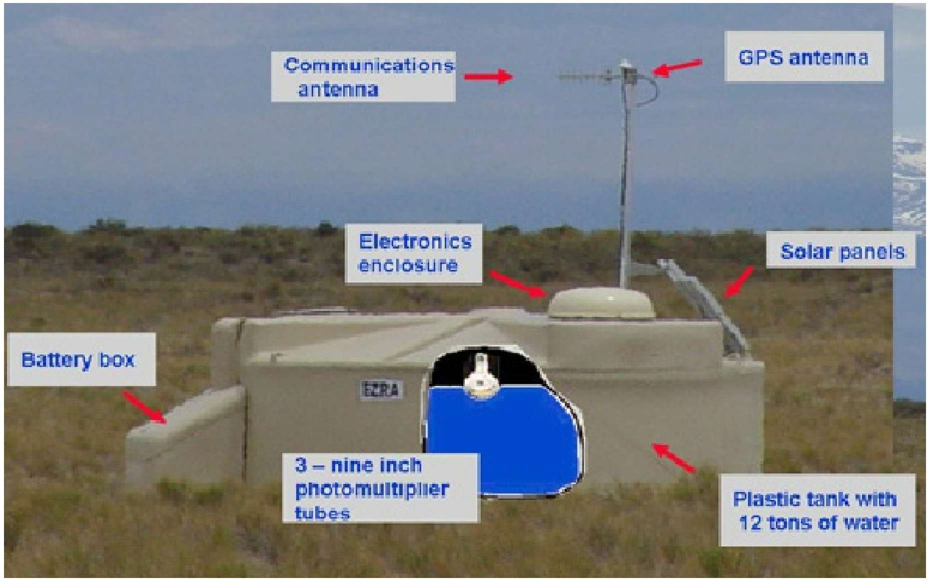
Auger@TA (CWRU, Colorado School of Mines)

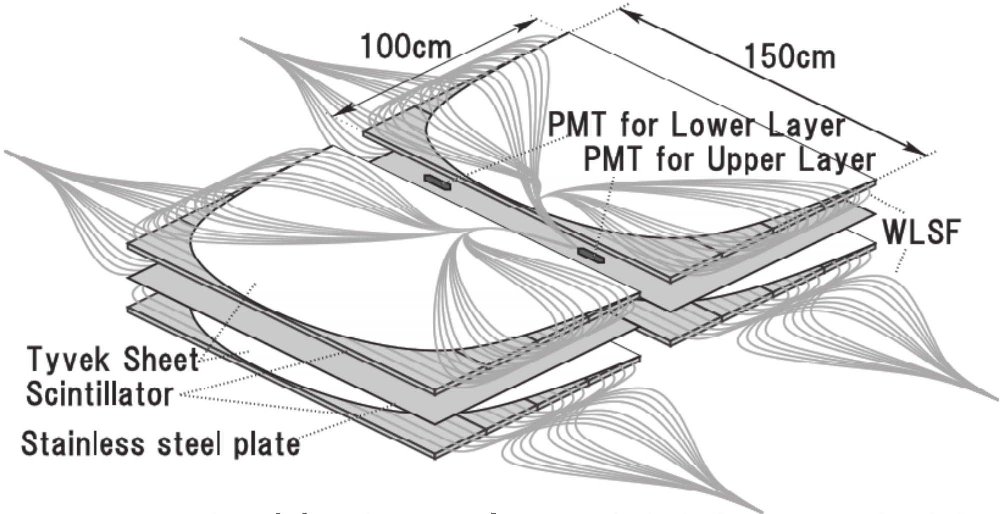
Argentina



Utah:

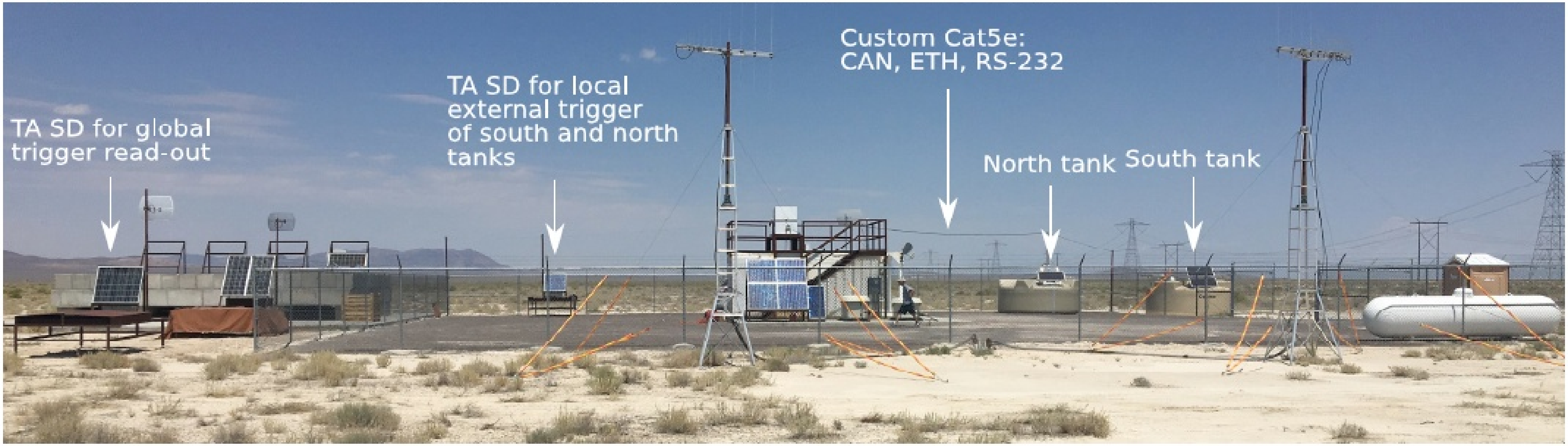






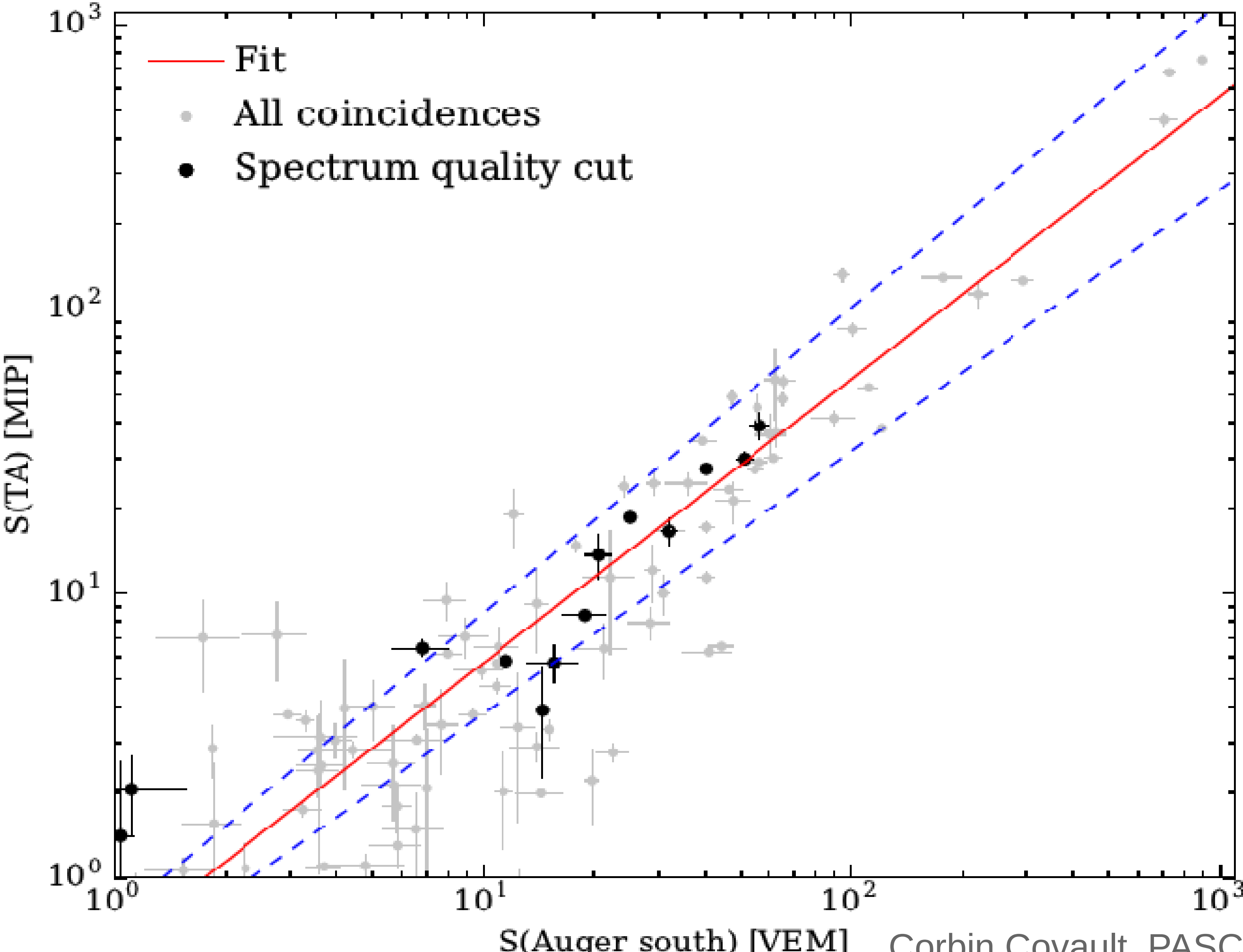
Auger@TA (CWRU, Colorado School of Mines)

Two Auger Water Tank detectors installed at TA CLF:



CWRU involved in deployment and instrumentation of detectors.

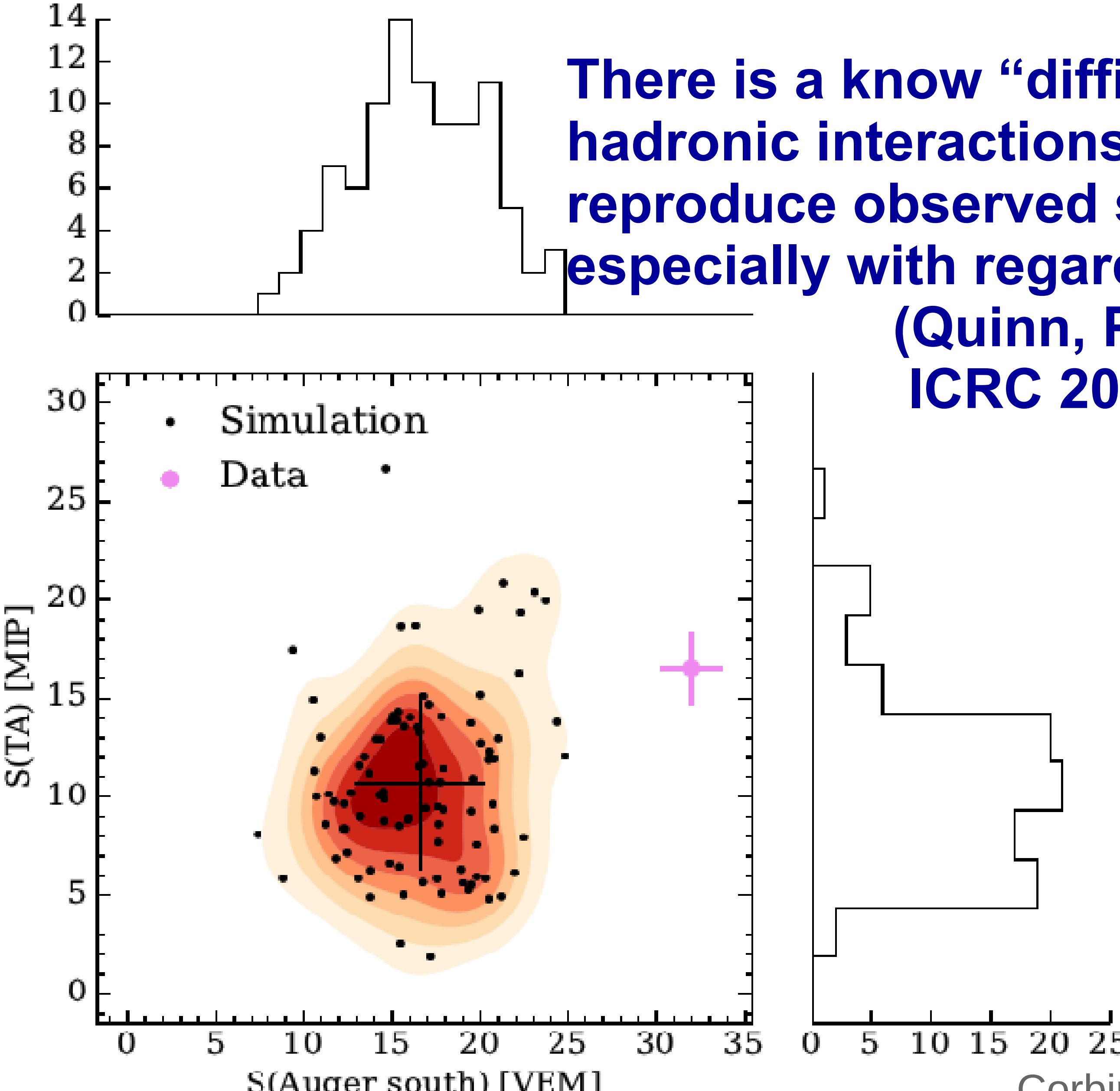
Auger@TA (CWRU, Colorado School of Mines)
TA MIPS (minimum Ionizing Particle) vs.
Auger VEM (Vertical Equivalent Muon) (ICRC 2017, prelim)



Auger@TA (CWRU, Colorado School of Mines)
TA MIPS (minimum Ionizing Particle) vs. Auger VEM (Vertical Equivalent Muon)

There is a know "difficulty" in that current hadronic interactions models do not reproduce observed shower physics, especially with regards to muons.

(Quinn, PhD and ICRC 2017 prelim)



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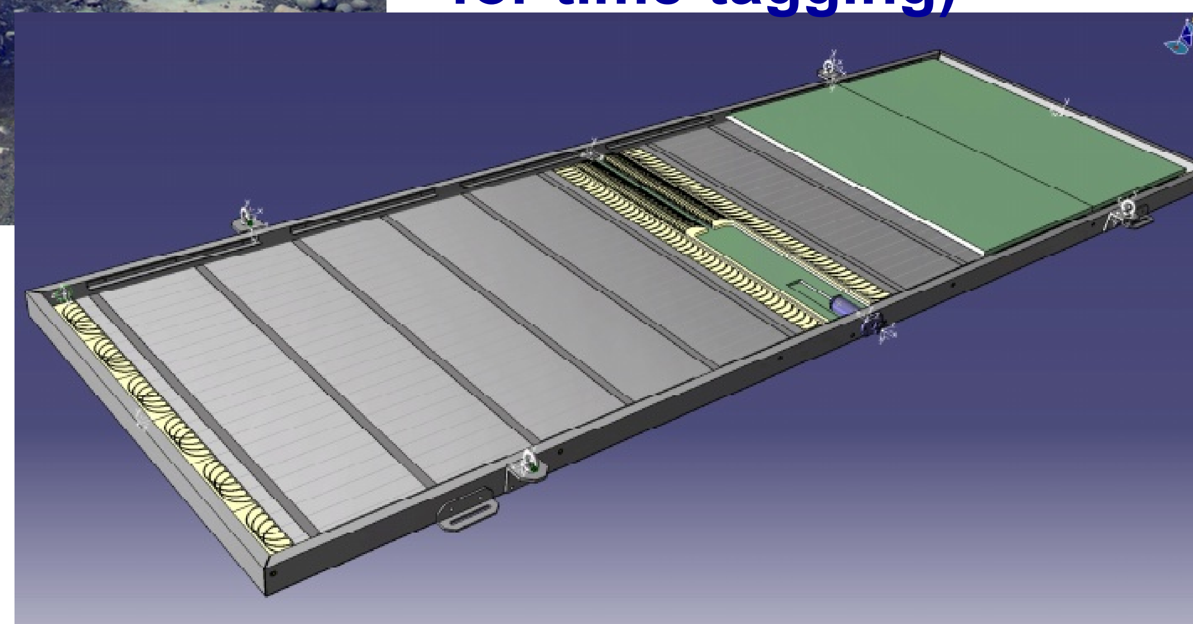
AugerPrime upgrade: Scintillator detectors mounted to existing water tank detectors for improved particle differentiation: electrons vs. muons

Also:
Improved electronics with new GPS receivers (CWRU responsible for time-tagging)

AugerPrime: complete by 2019,
Operate thru 2015 (2X statistics)

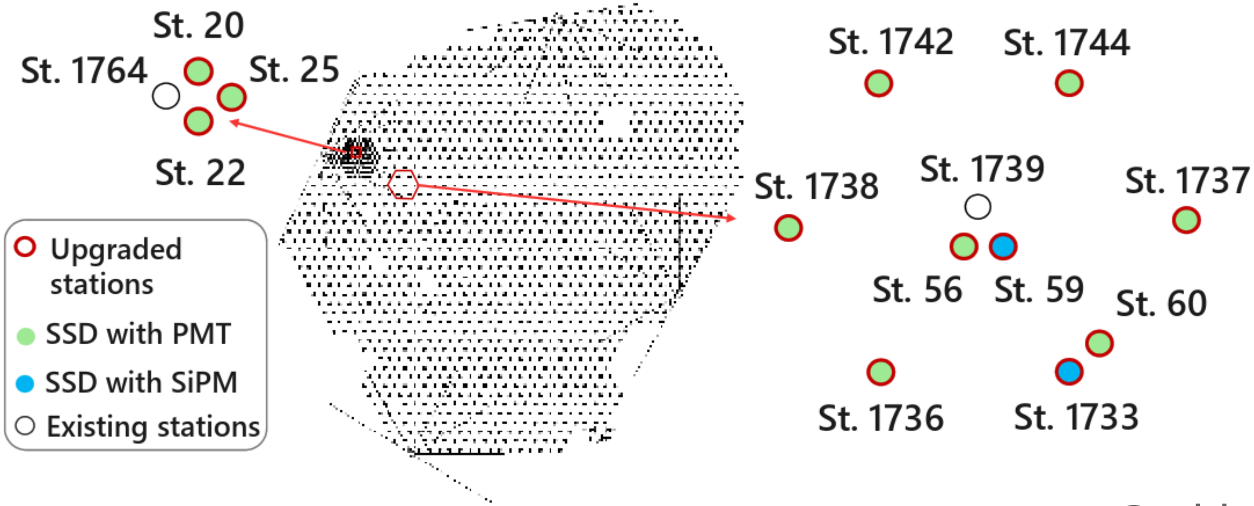
Key Science Goal:

– Extend composition measurements to higher energy.



AugerPrime upgrade Engineering Array: 12 stations deployed

ICRC 2017 preliminary



Conclusions (part 1): What have we learned?

(1) Energy spectrum attenuation

(2) "Dipole" large-scale anisotropy

(3) Correlation with local LLS: SBG and AGN

(4) Mixed composition

All of these point to Extra-galactic sources with acceleration of "regular" galactic material: e.g., large wind shocks among and/or outside wind-generating galaxies and/or extended jets.

Largely Ruled out: `galactic' sources, top-down models.

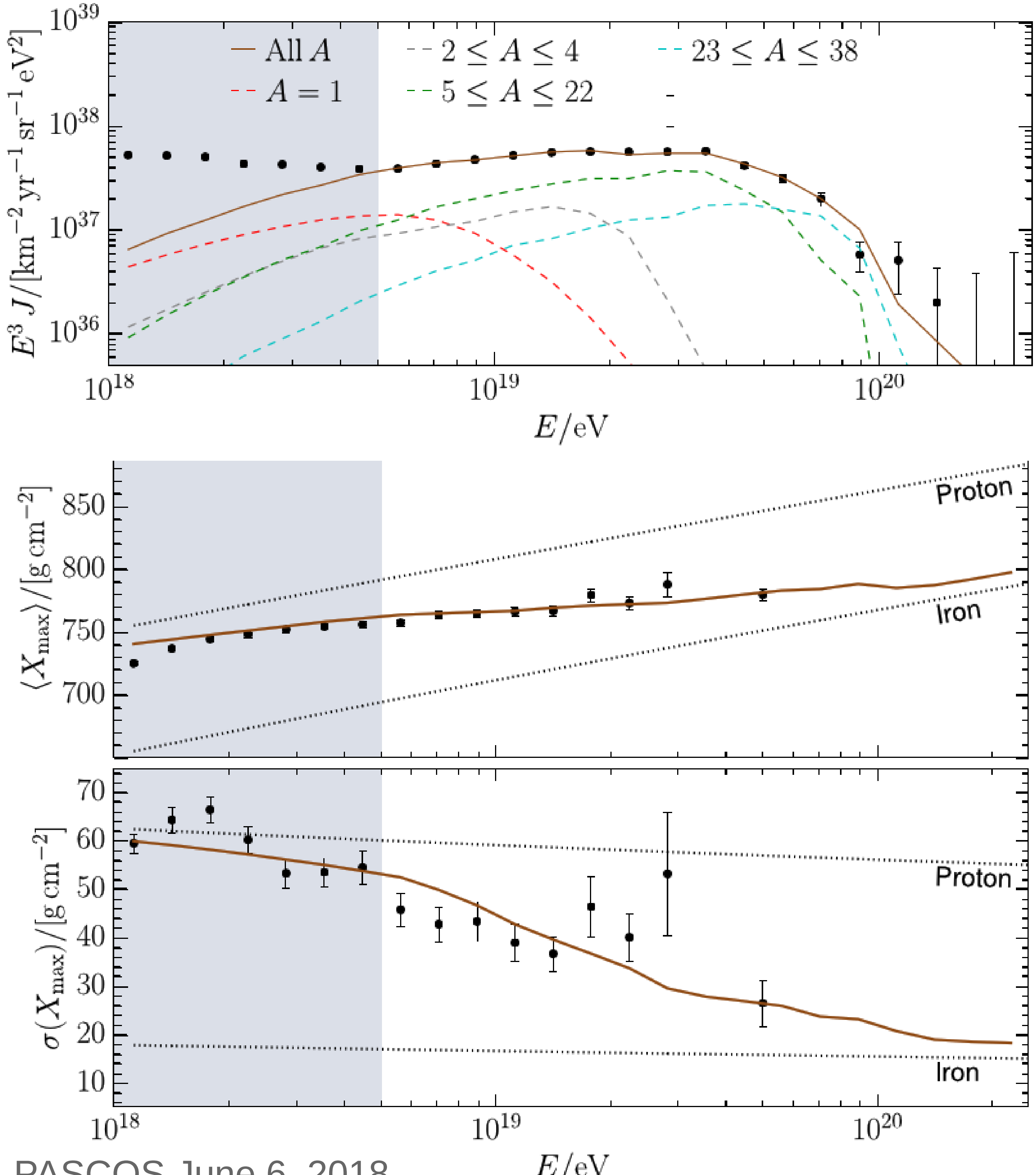
The Big Picture seems to be getting less fuzzy

Astrophysical Scenarios:

Preliminary efforts to combine spectral, composition and even anisotropy into unified extra-galactic source model with rigidity dependent mixed composition models AND discrete source models.

Emerging picture: Cosmic Rays with energy ~> 10 EeV are due to extragalactic sources accelerating mixed atomic nuclei.

Auger Collaboration ICRC 2017 Preliminary



Conclusions (part 2): Remaining Puzzles

(1) We have NOT (yet) definitively identified specific sources or source classes, much less specific acceleration mechanisms

(2) Composition measurement does not extend to highest energies and is hampered by persistent discrepancies between direct measurements and hadronic interaction models (even with LHC).

(3) Tension between Telescope Array (North) and Auger (South) requires further investigation. Need to resolve to get the best “all sky” picture.

Conclusions (part 3): Goals for the Future:

AugerPrime Upgrade

(1) Origin of the flux suppression. Sources or attenuation?

(2) Particle Astronomy: With improved composition measurements to higher energy, can we select low-Z primary cosmic rays to identify sources? (hand-in-hand with improved magnetic field modeling)

(3) Can we "seamlessly" merge Auger and upcoming TA x 4 to provide a consistent "all-sky" picture of the highest energy cosmic rays?

(4) Fundamental Physics: Can we use improved particle ID in hybrid data to resolve persistent discrepancies between air shower measurements and hadronic model predictions?