Recent results on UHE cosmic rays from the Pierre Auger Observatory

Bruce Dawson
The University of Adelaide, Australia

The Pierre Auger Collaboration

Collaboration founded in 1995

Observatory founded in 1999, construction completed in 2008

~500 members, 89 institutions

20th Anniversary

of the Foundation of the

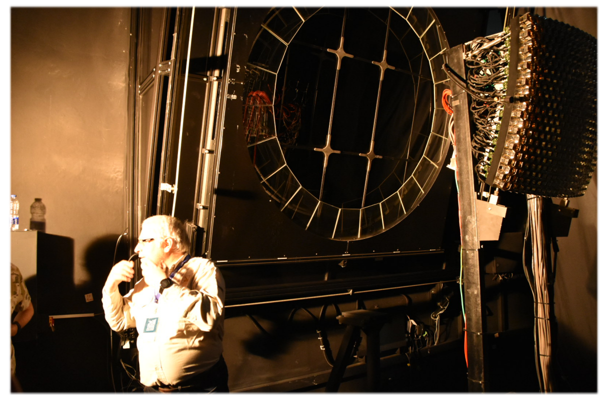
Pierre Auger Observatory

November 2019
14-15 : Scientific Symposium
Guided tour to the Observatory
16 : Anniversary Celebration

https://www.auger.org/

We will celebrate in Malargüe
... Join us!

Tour to the field



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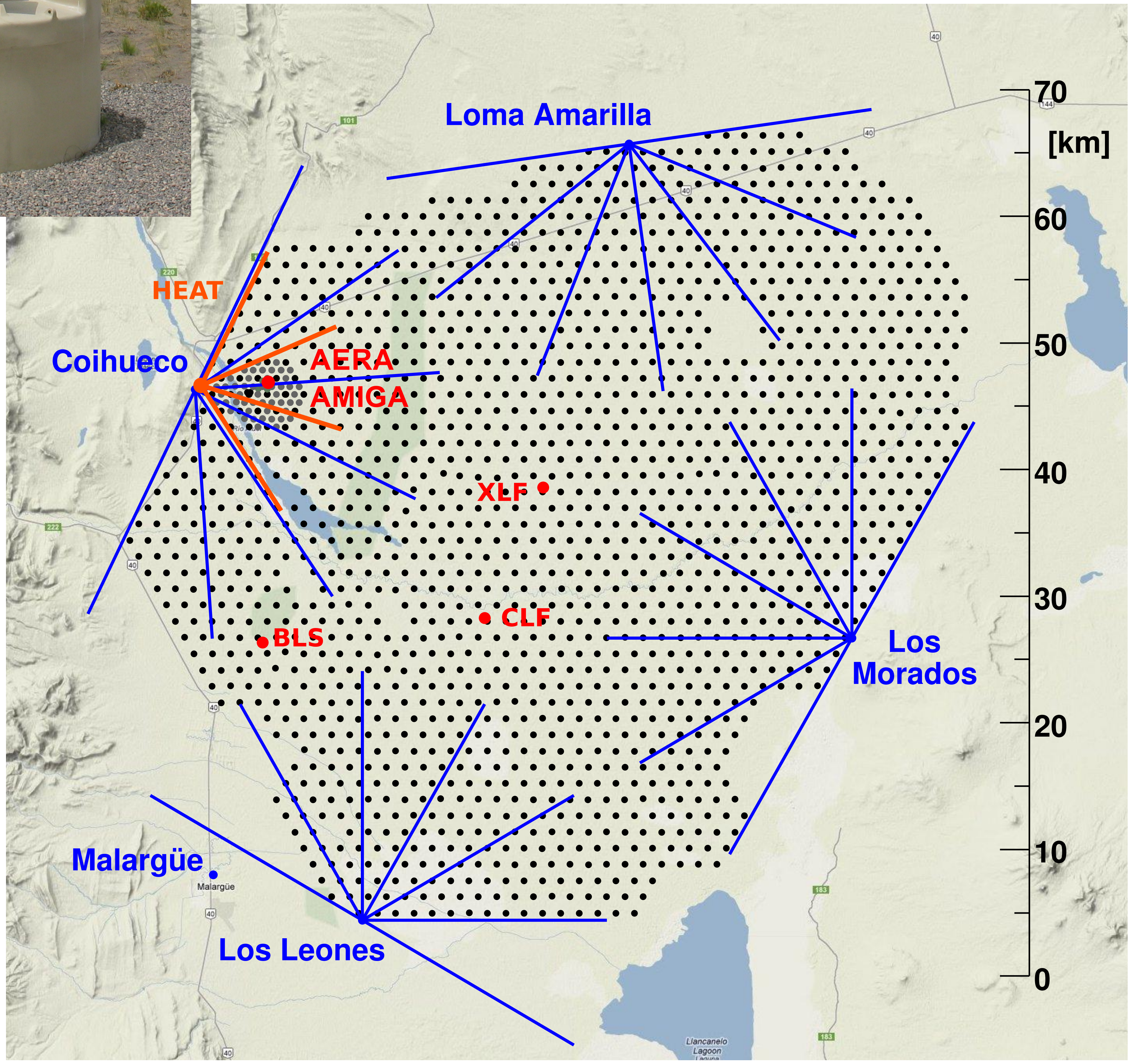
Adelaide Design Workshop on Techniques for the Study of Cosmic Rays with Energies above 10^{19}eV

January 4 - 15 1993

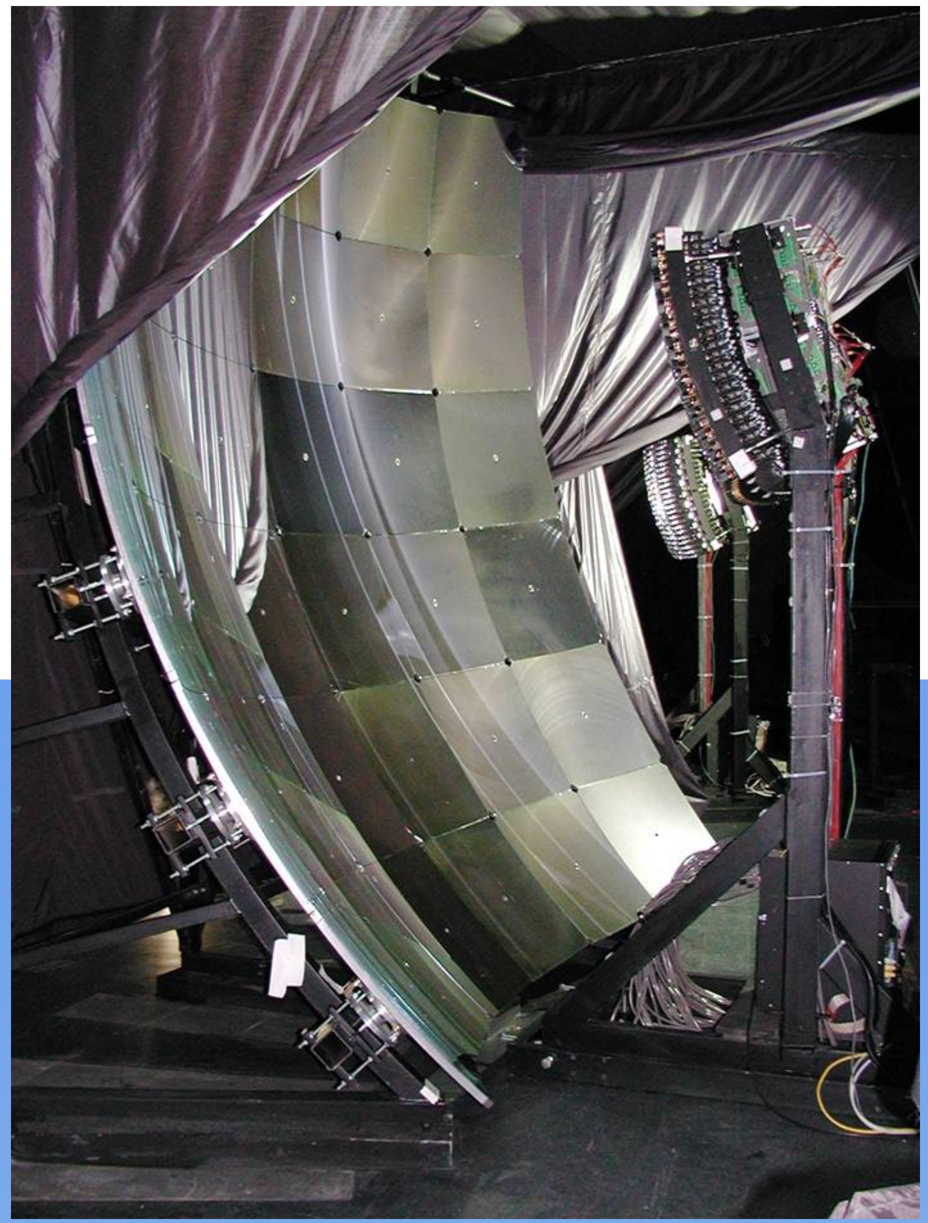
Workshop where the idea that Auger should be a “hybrid” observatory was born!

The Pierre Auger Observatory

Water-Cherenkov detector
10 m², 1.2 m deep



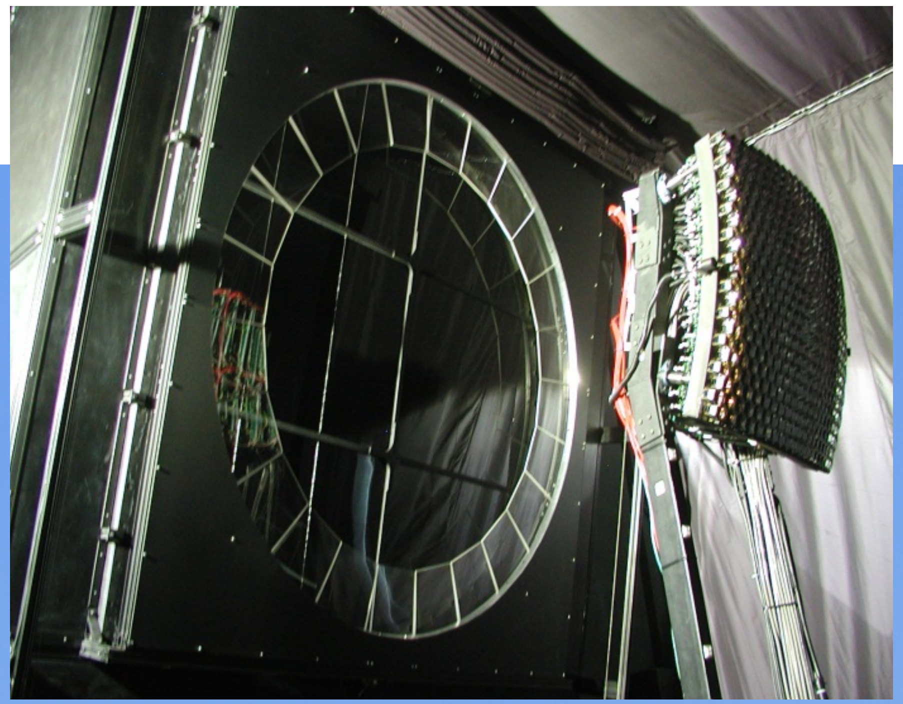
3000 km²
1661 water-Cherenkov detectors
(on 1500 m or 750 m triangular grid)
27 fluorescence telescopes (4 sites)



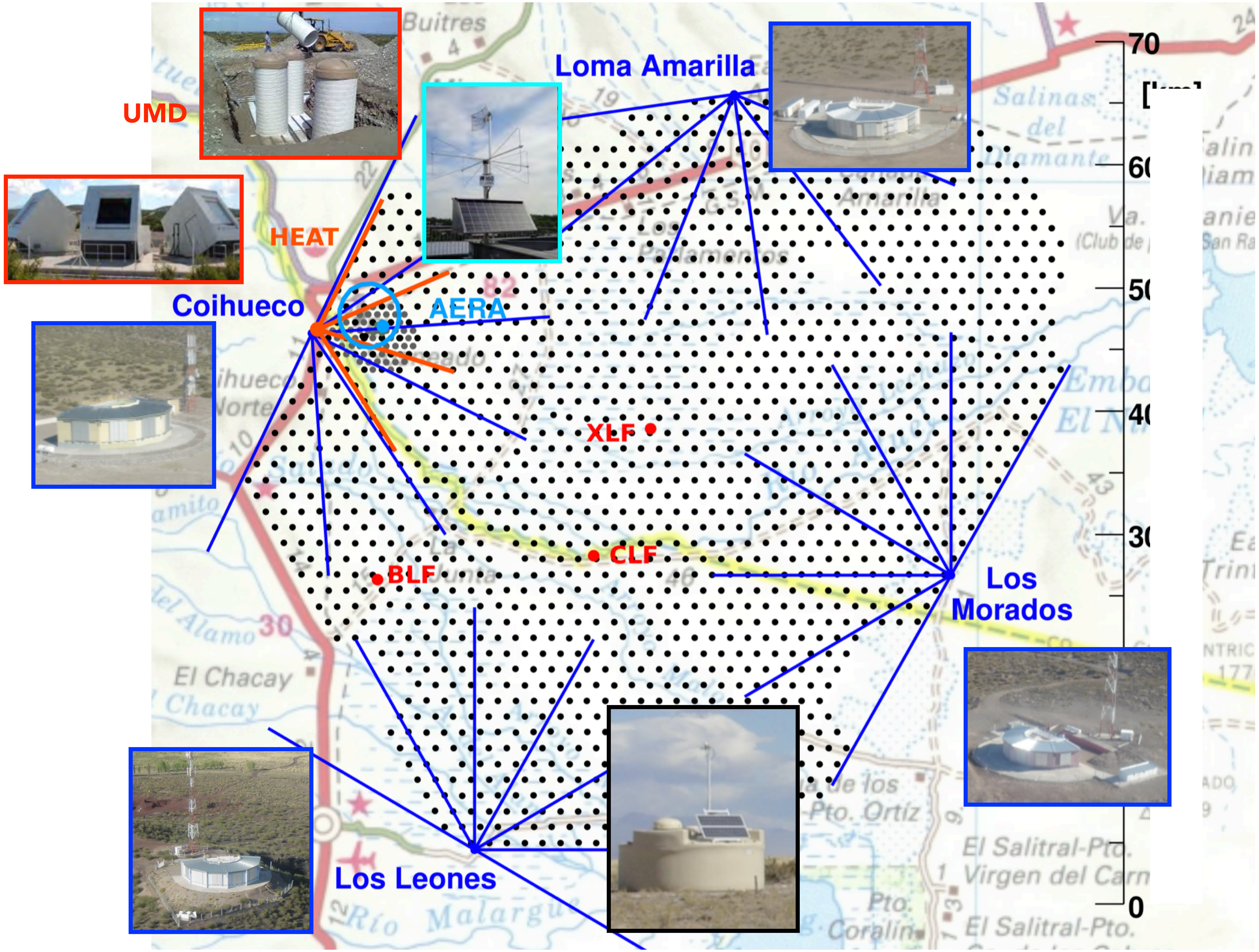
Schmidt telescope

3.4 m diameter mirror
2.2 m diameter aperture

440-pixel camera
UV filter and corrector lenses



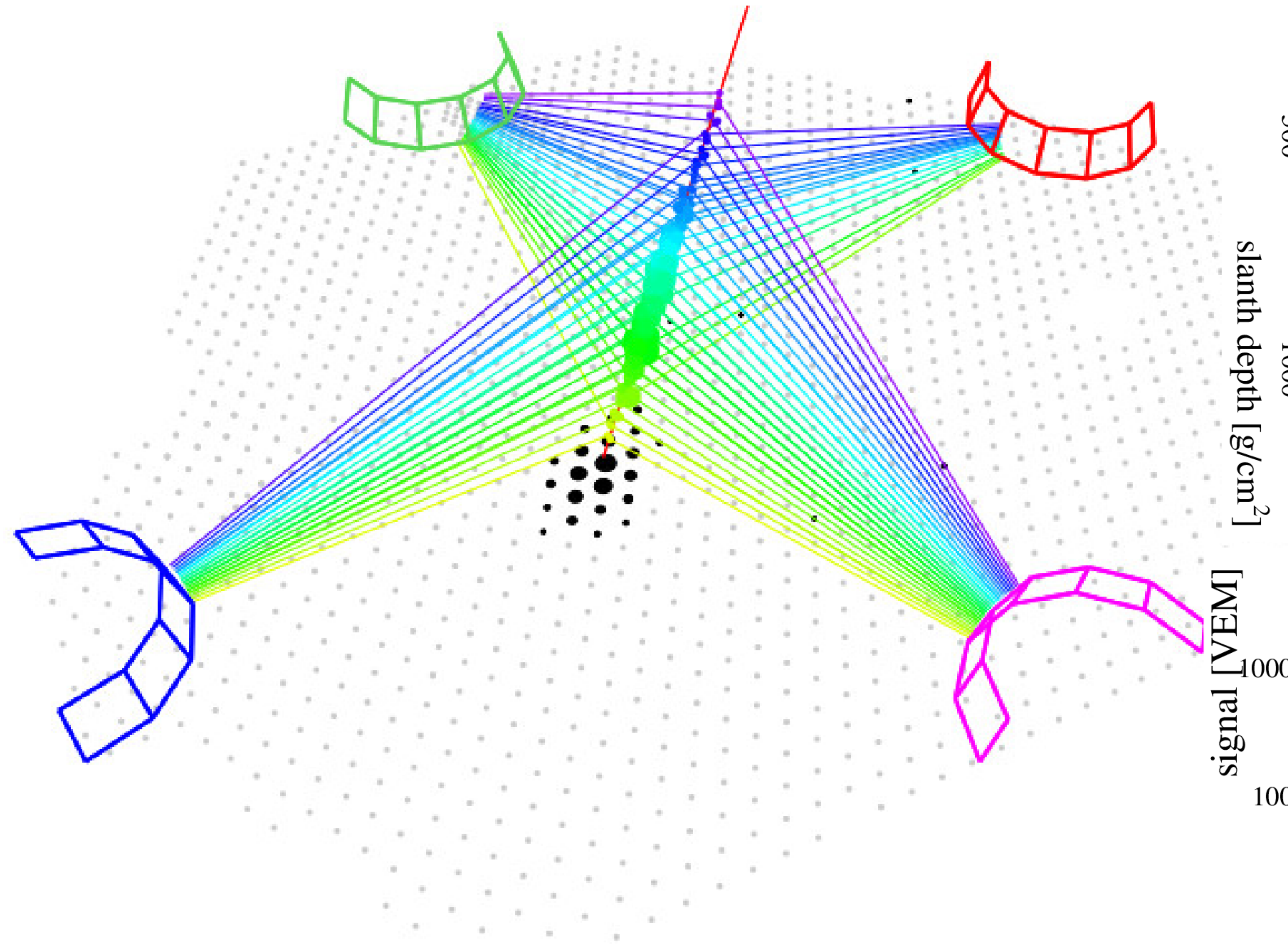
The Pierre Auger Observatory

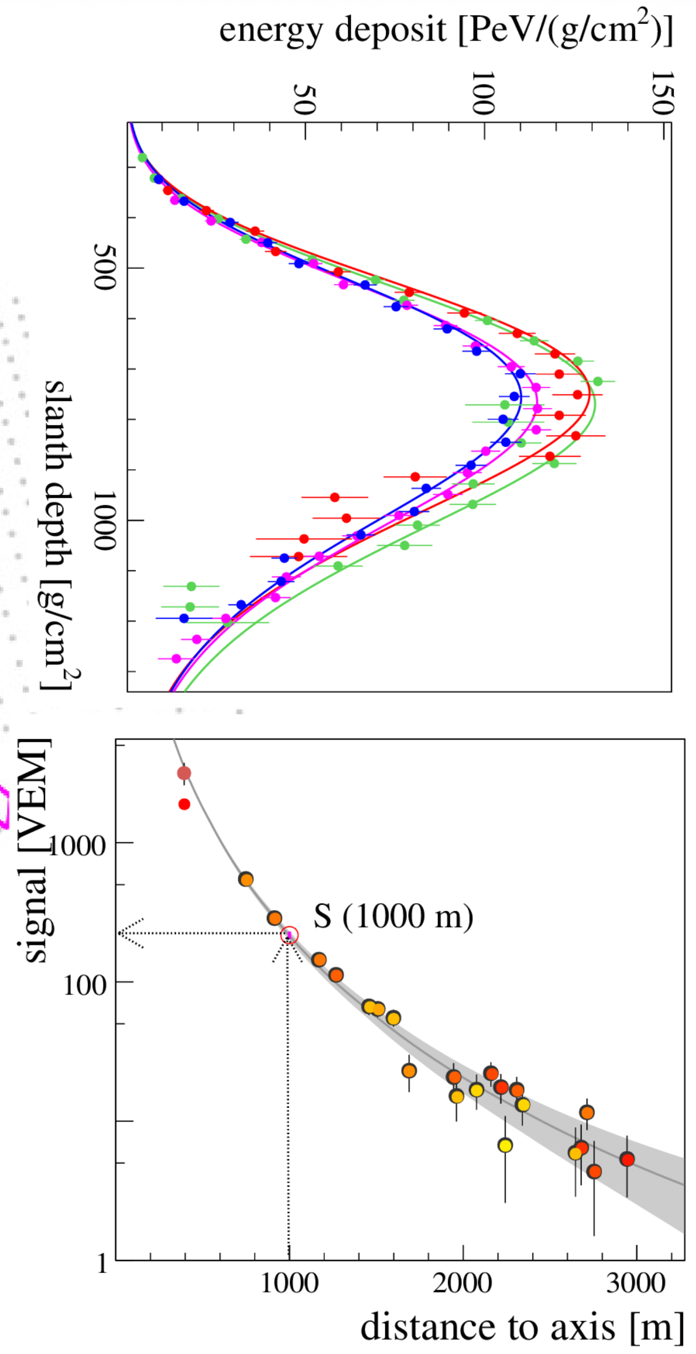


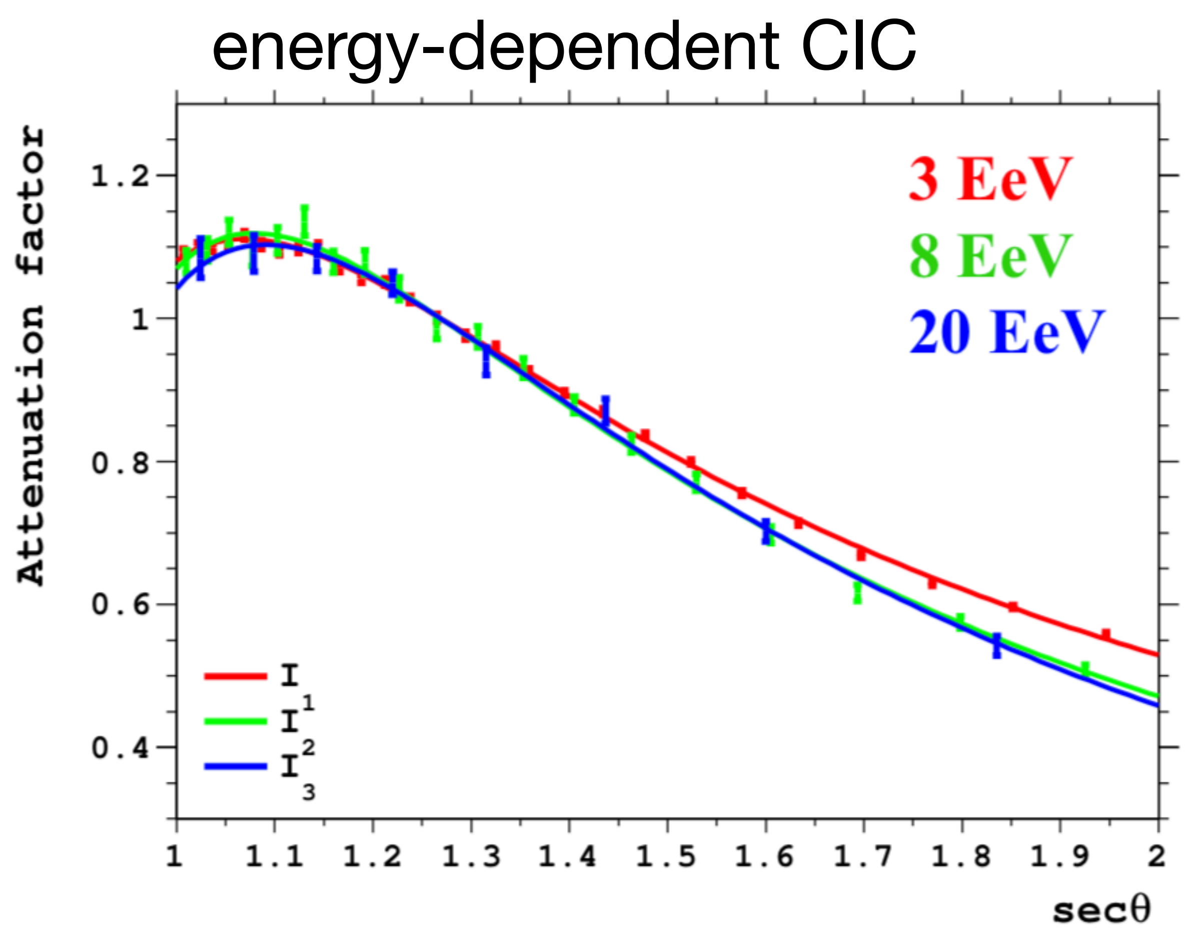
- Water-Cherenkov stations
  - ➡SD1500 : 1600, 1.5 km grid, 3000 km^2
  - ➡SD750 : 61, 0.75 km grid, 25 km^2
- 4 Fluorescence Sites
  - ➡24 telescopes, 1-30^0 FoV
- Underground Muon Detectors
  - ➡7 in engineering array phase - 61 aside the Infill stations
- HEAT
  - ➡3 high elevation FD, 30-60^0 FoV
- AERA radio antennas
  - ➡153 graded 17 km^2

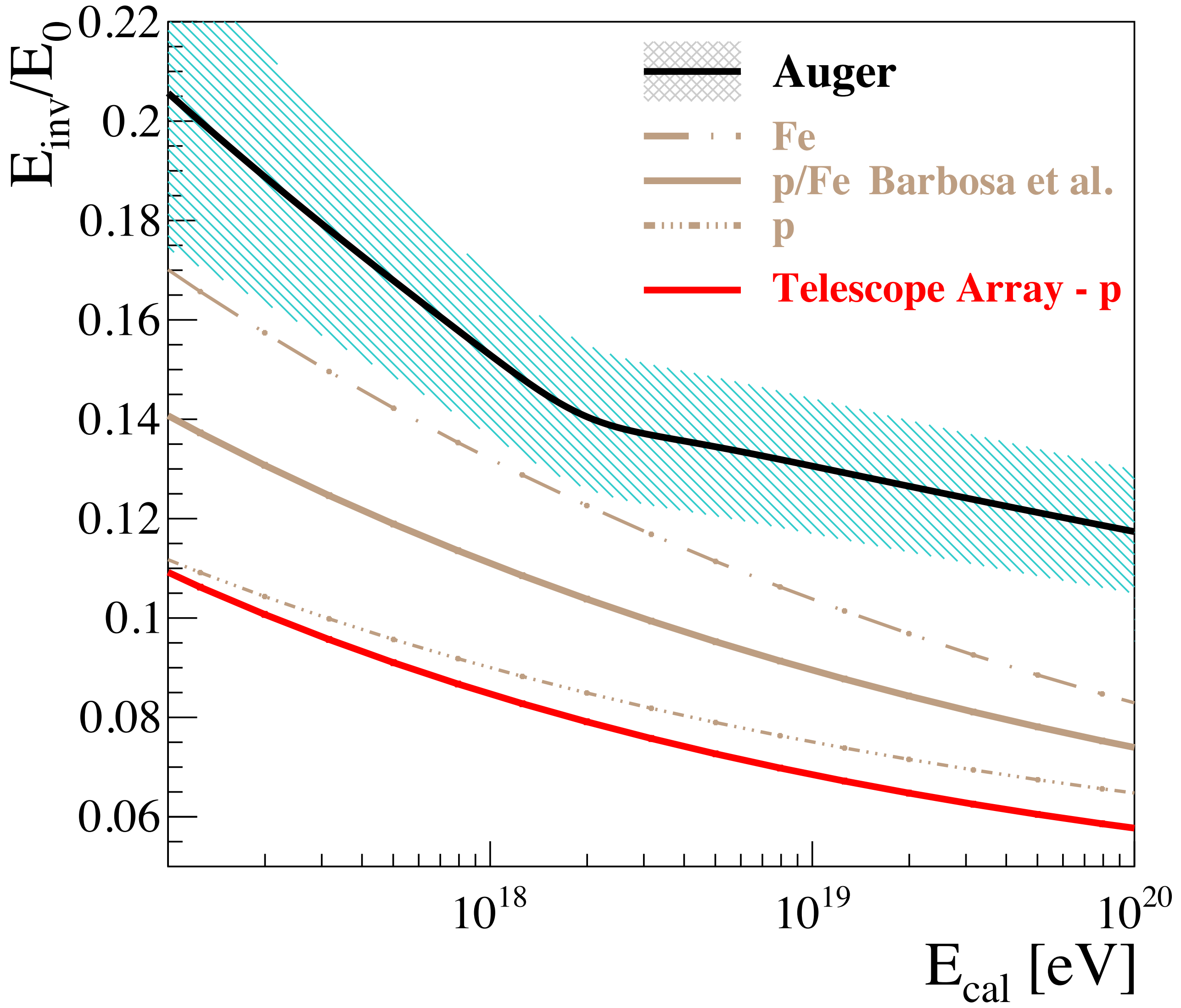
+Atmospheric monitoring devices CLF, XLF, Lidars, …

Energy Scale of the Observatory is Based on Fluorescence Measurements





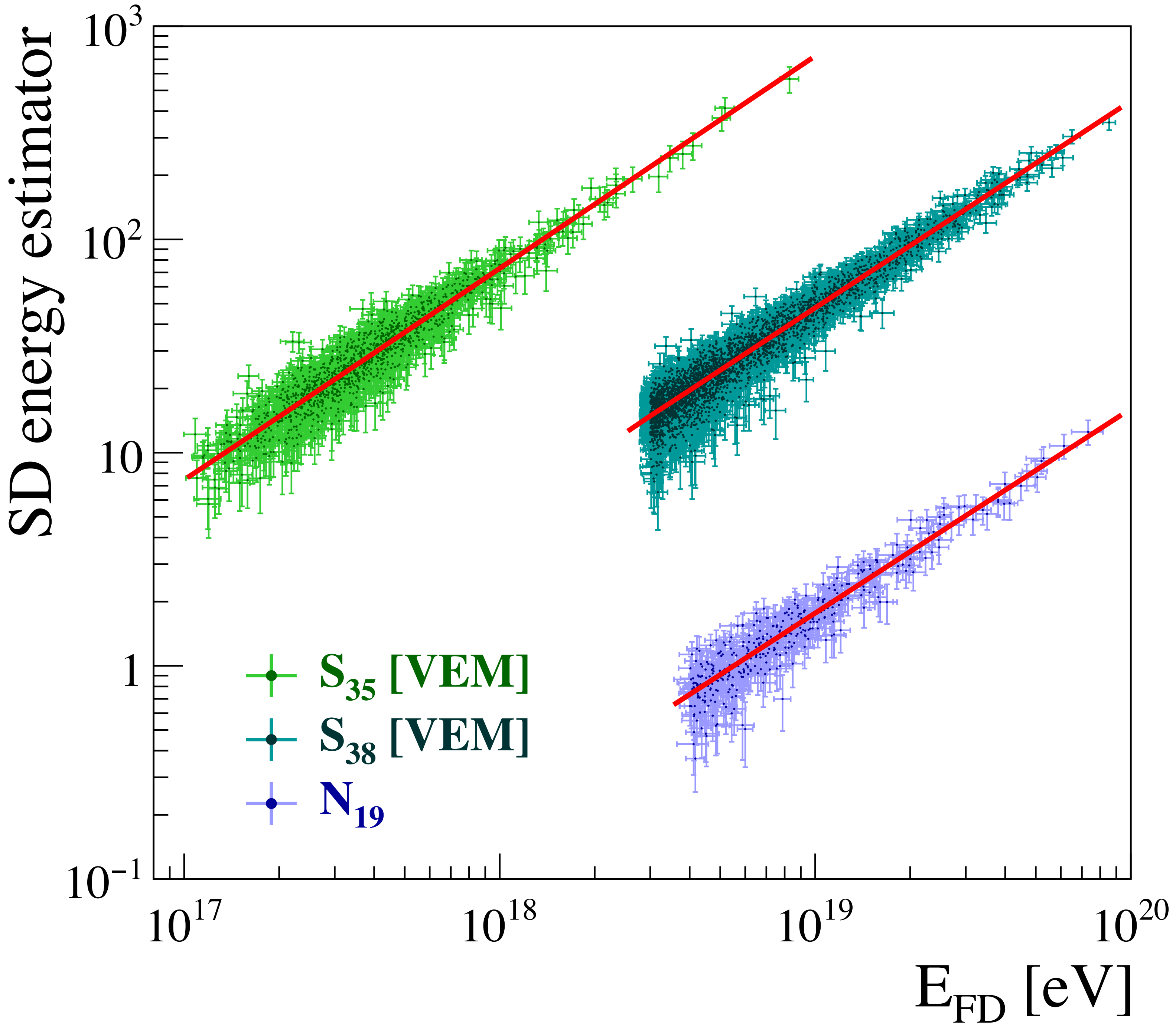




$$E_{FD} = E_{cal} + E_{inv}$$

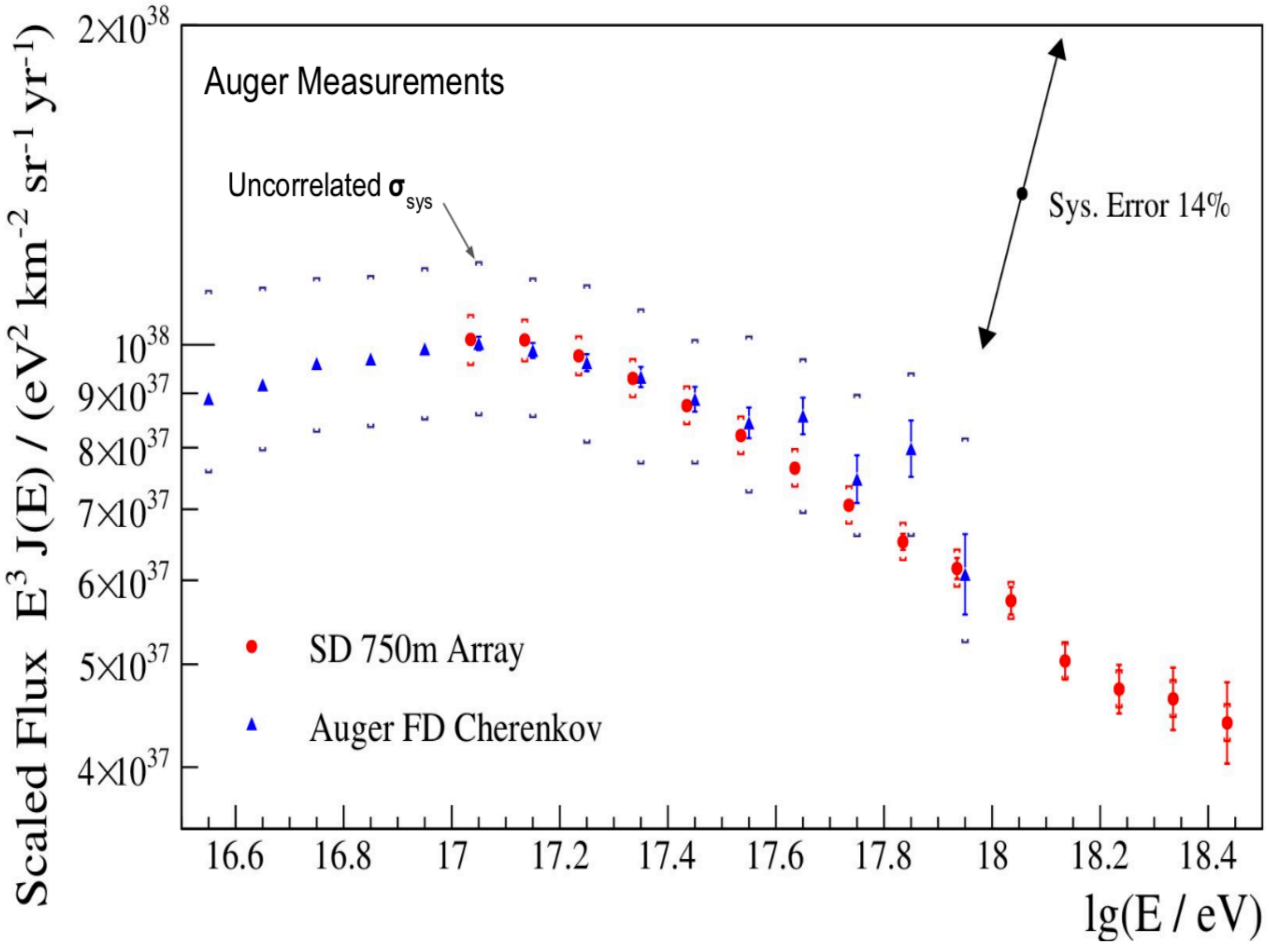
$\sigma(E_{FD})/E_{FD}$ ~ 8%

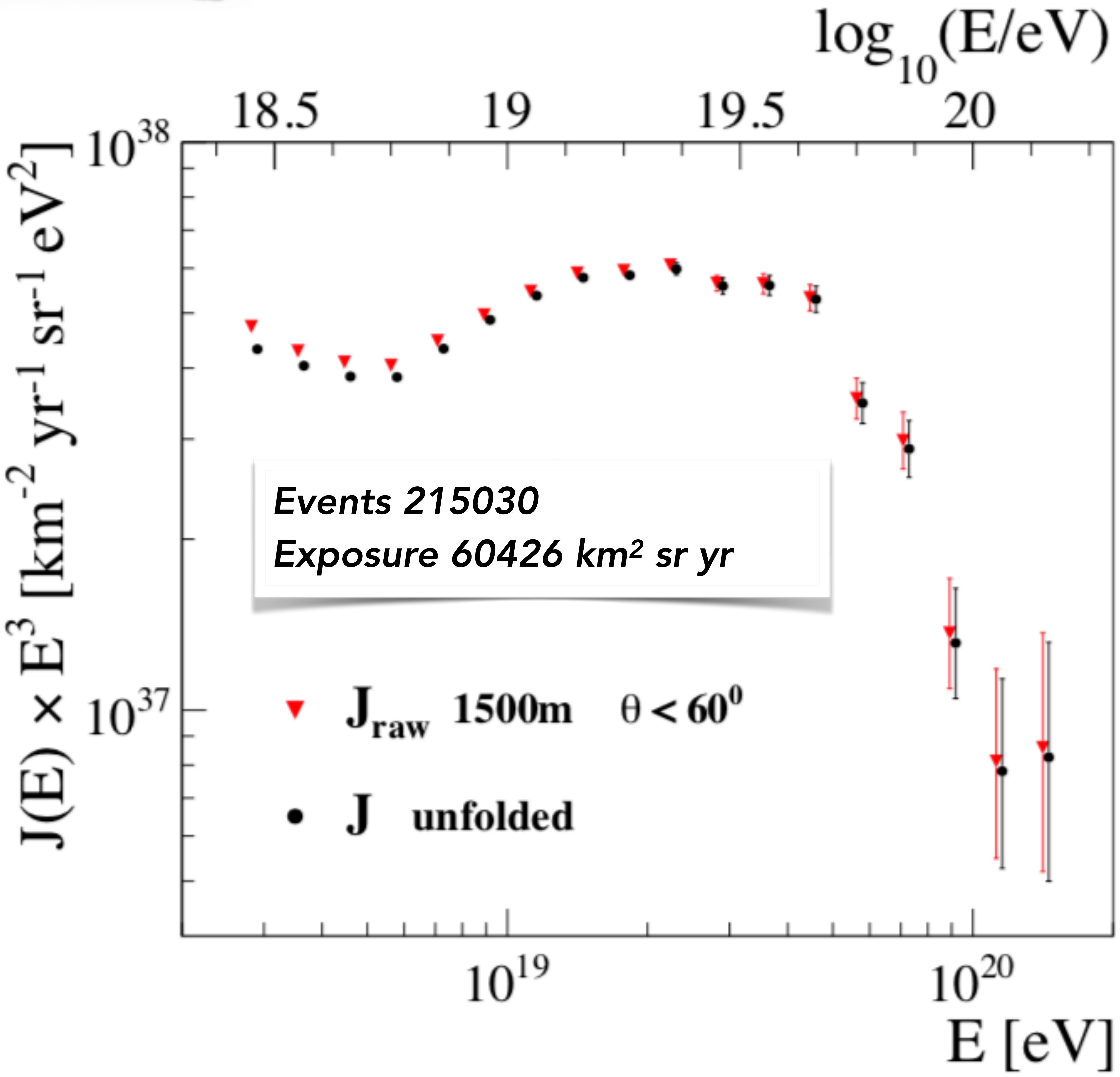
systematic uncertainty ~ 14%



A.Aab et al., [Auger Collaboration] PRD 100, 082003 2019

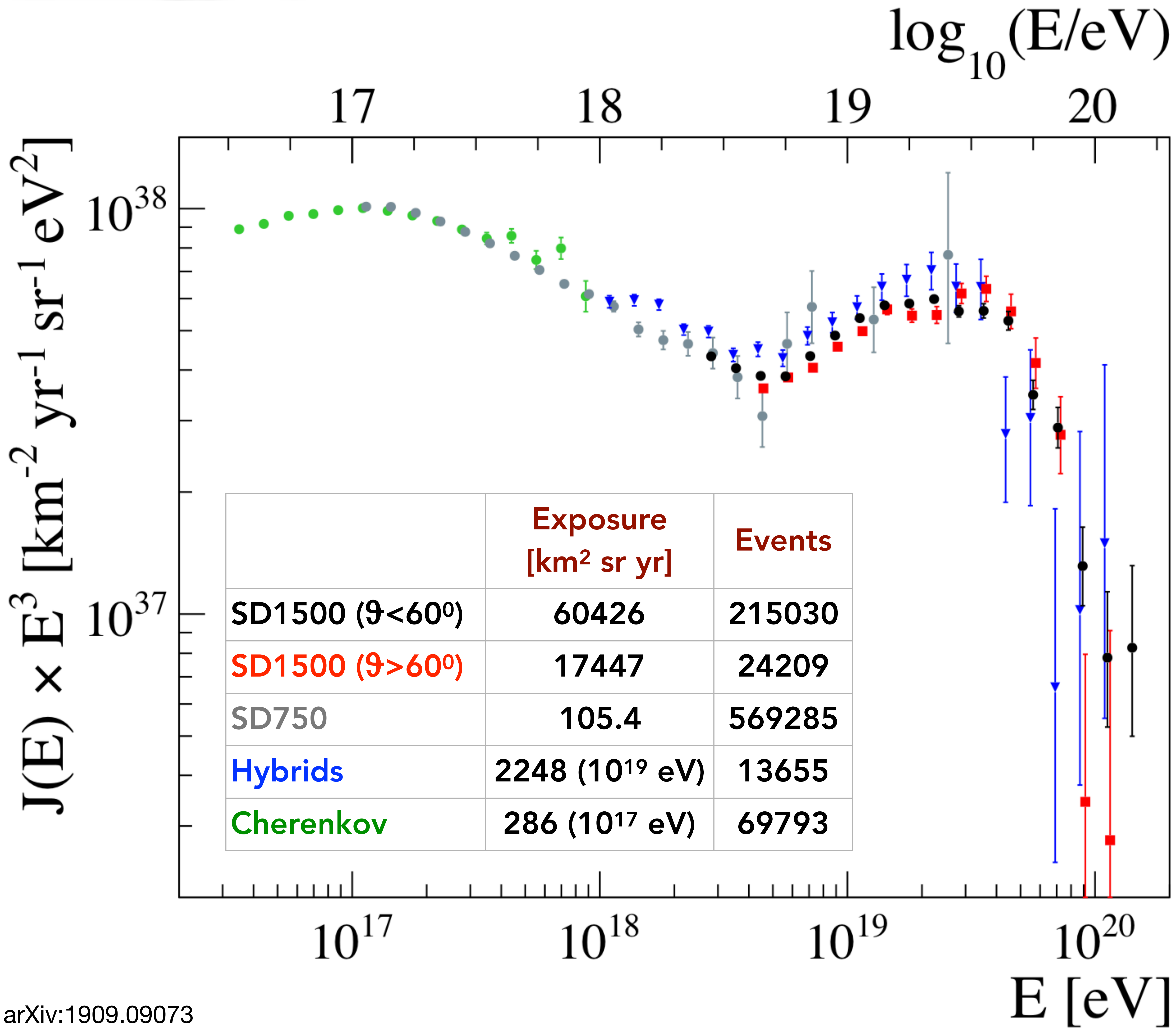
Energy Spectrum





V. Verzi [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Energy Spectrum

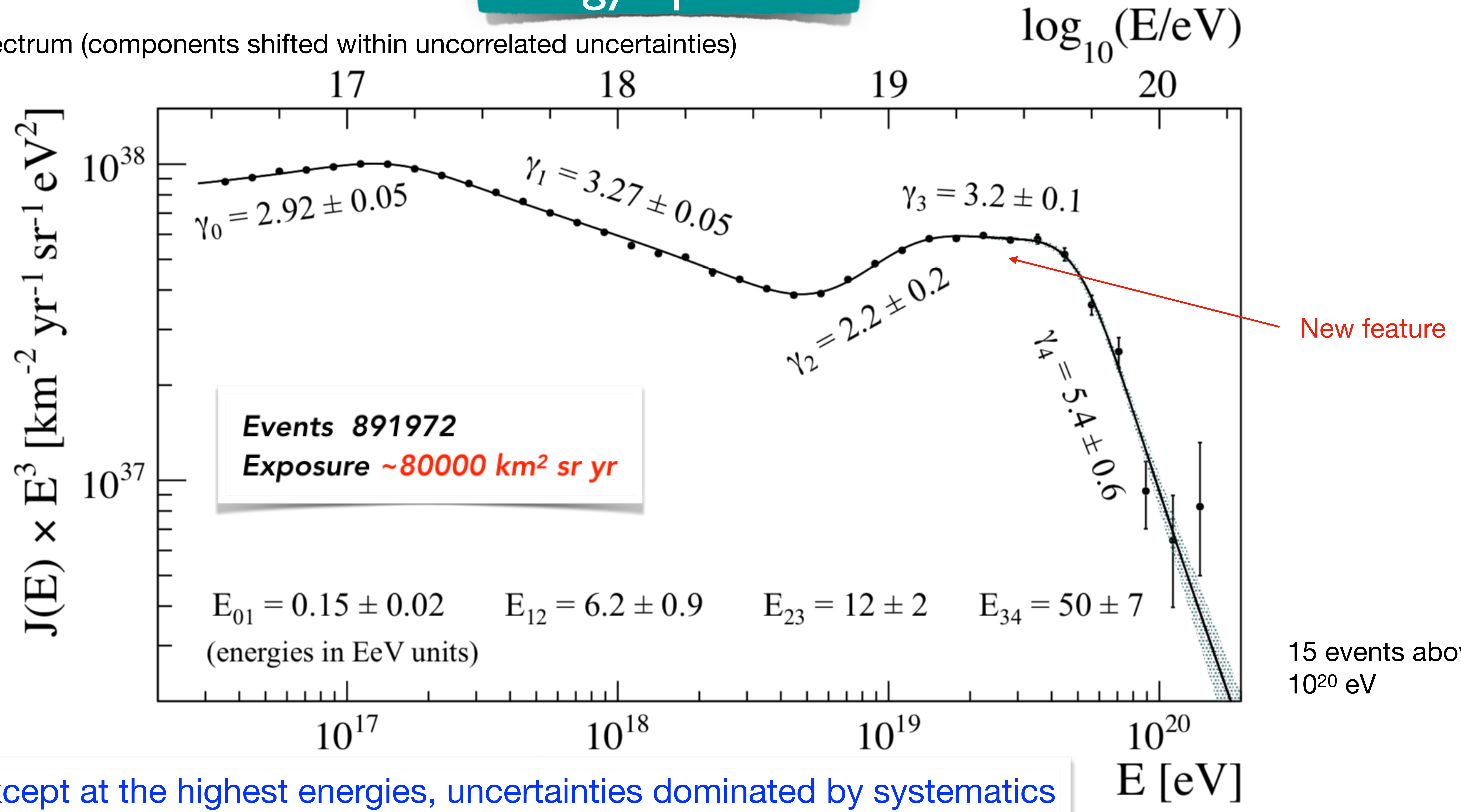


	Exposure [km² sr yr]	Events
SD1500 (ϑ<60⁰)	60426	215030
SD1500 (ϑ>60⁰)	17447	24209
SD750	105.4	569285
Hybrids	2248 (10^{19} eV)	13655
Cherenkov	286 (10^{17} eV)	69793

V. Verzi [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Energy Spectrum

Combined spectrum (components shifted within uncorrelated uncertainties)

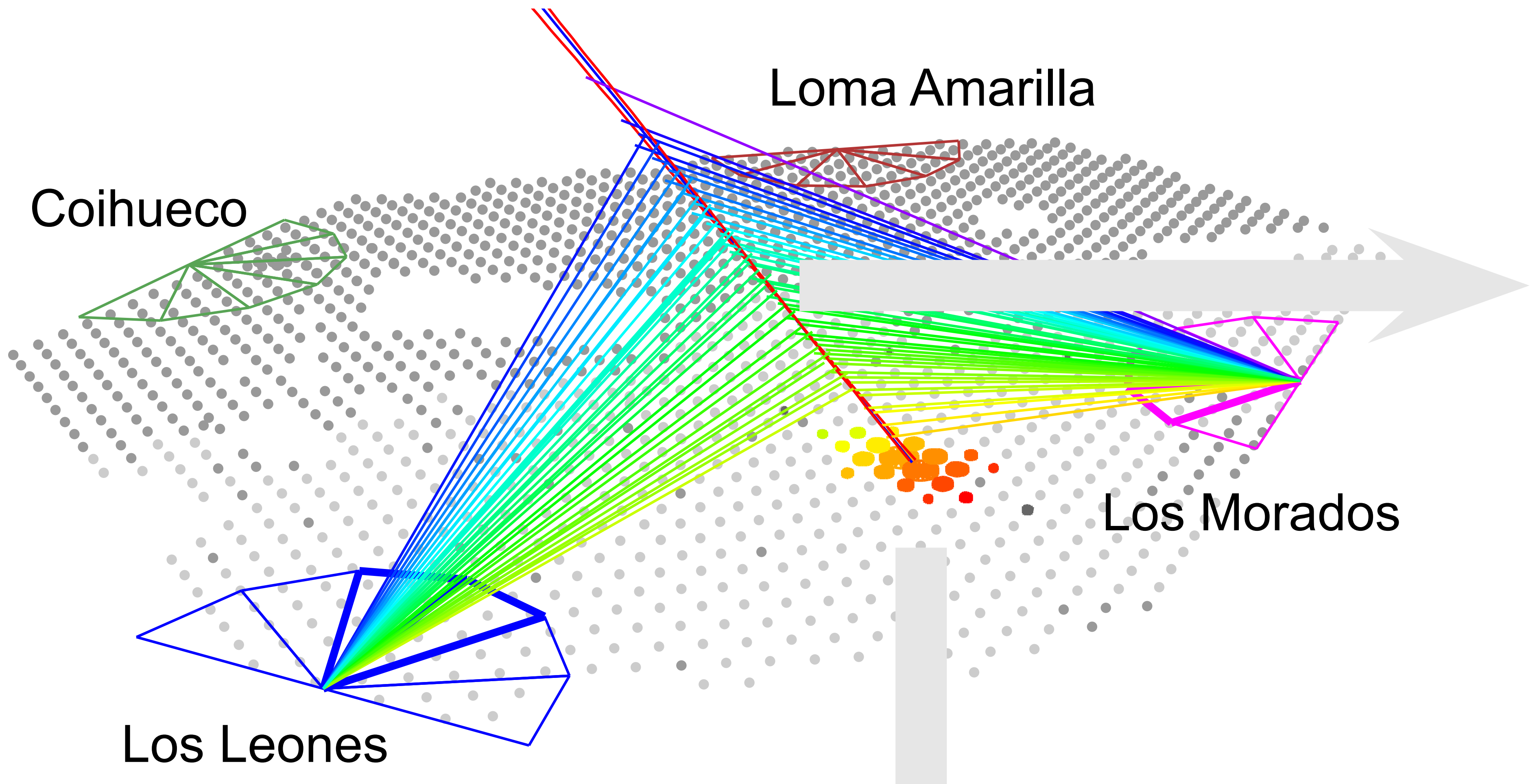


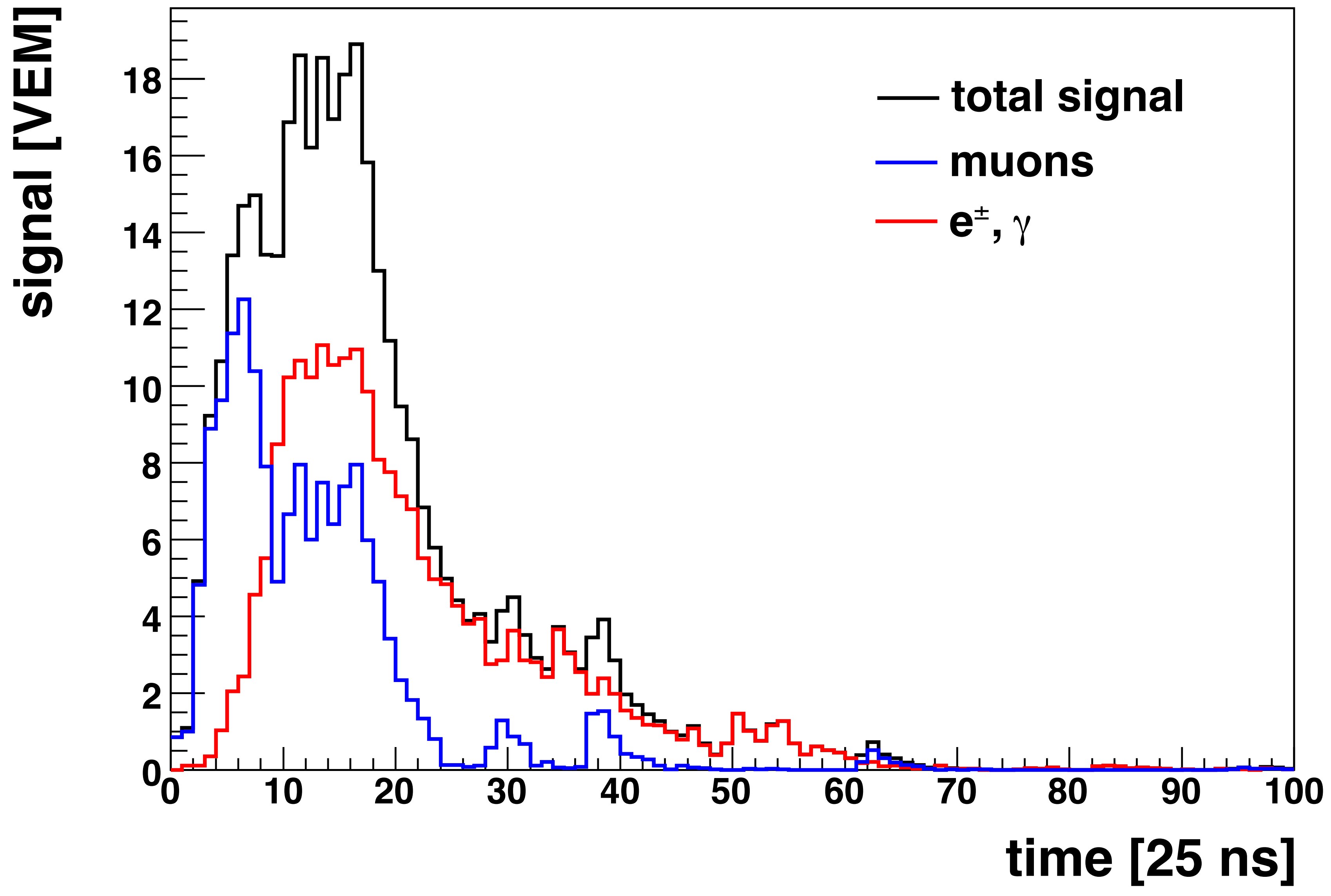
15 events above 10^{20} eV

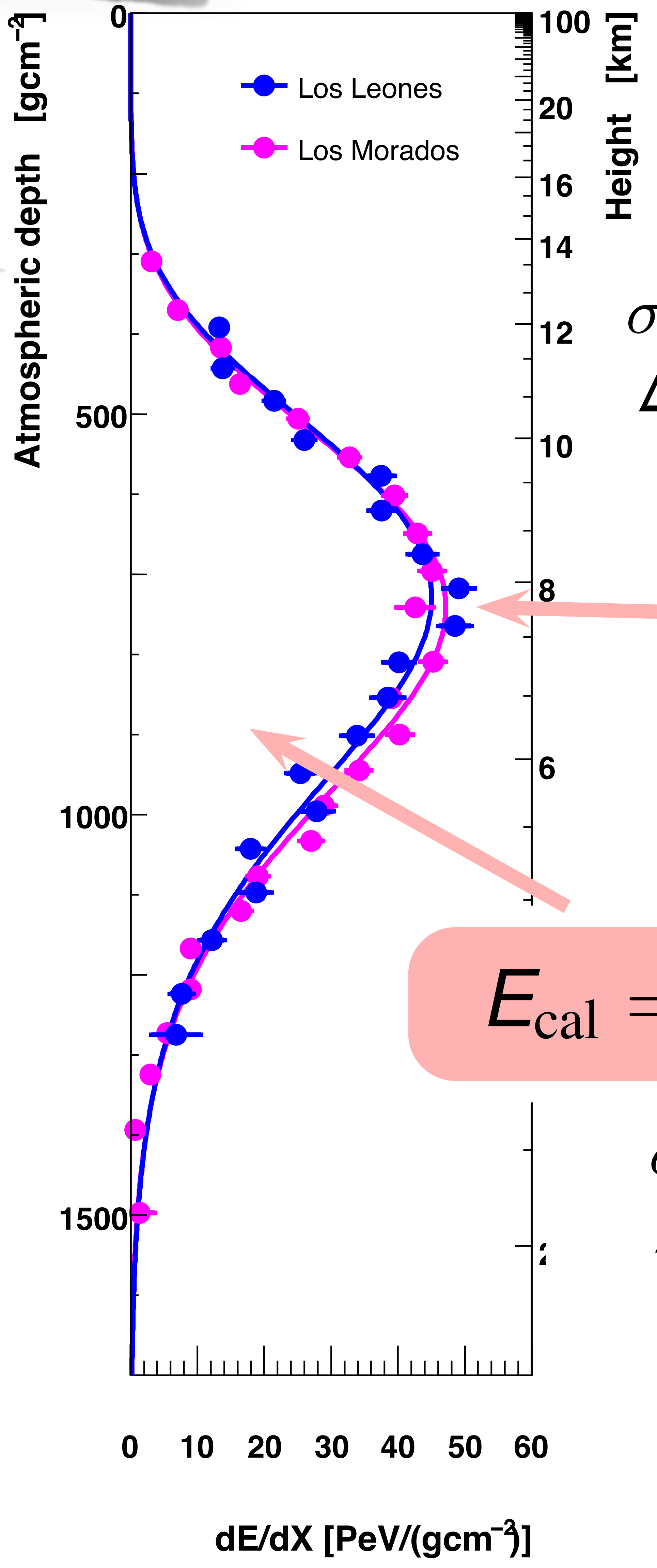
Except at the highest energies, uncertainties dominated by systematics

V. Verzi [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Mass Composition







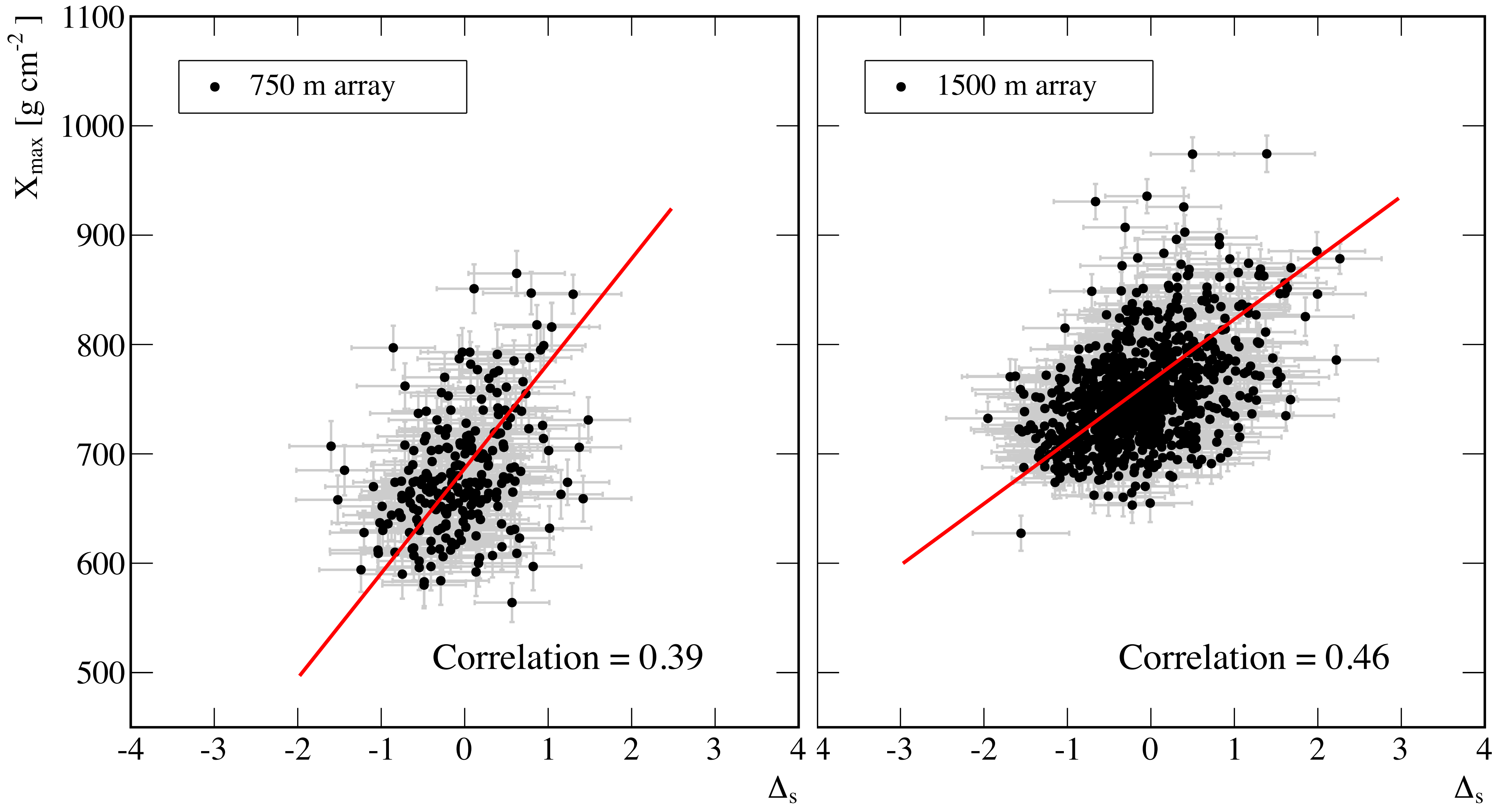
$\sigma_{X_\mathrm{max}} \lesssim 20\,\mathrm{g/cm^2}$
$\Delta_\mathrm{sys} \lesssim 10\,\mathrm{g/cm^2}$

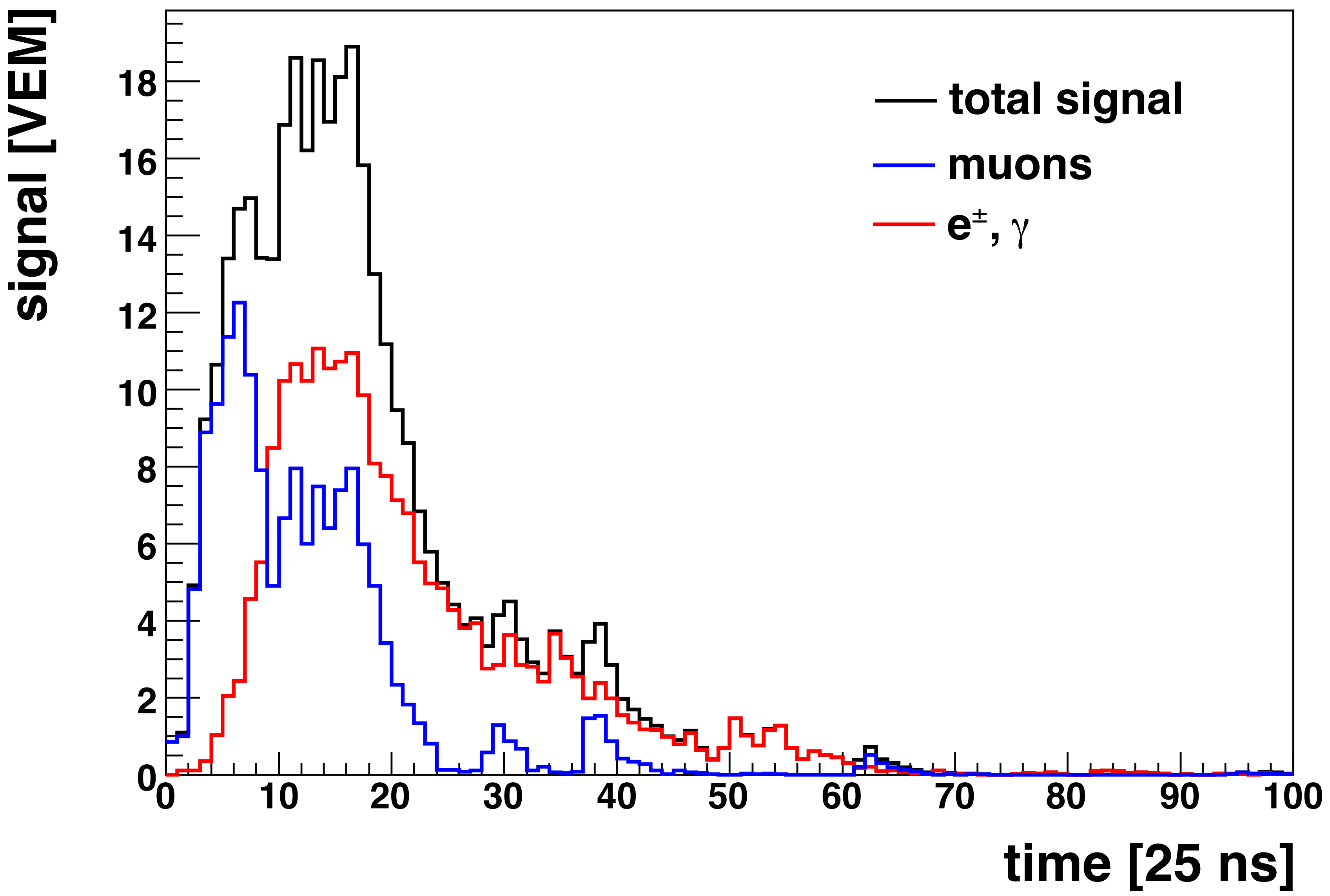
X_max

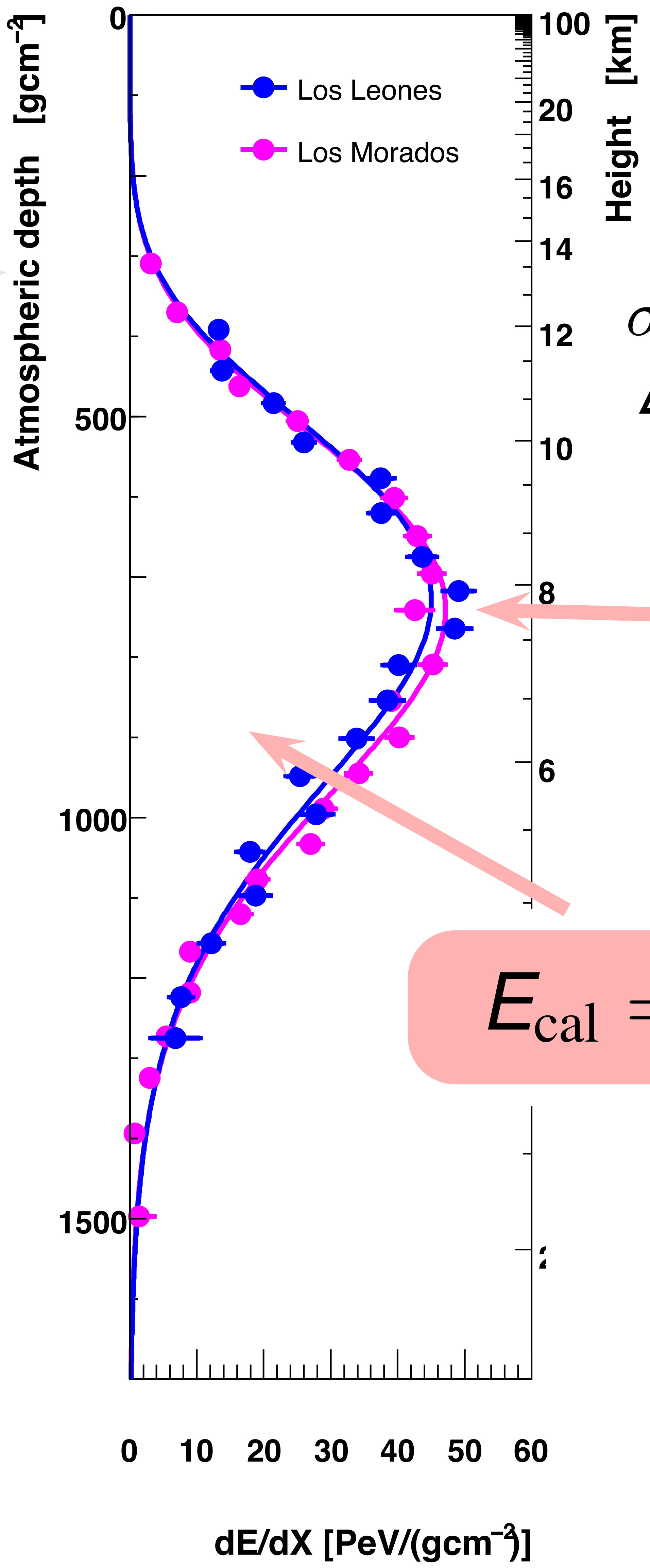
$E_\mathrm{cal} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$

$\sigma_E/E \sim 8\,\%$
$\Delta_\mathrm{sys} \approx 15\,\%$

Mass Composition







$\sigma X_{\text{max}} \lesssim 20\,\text{g/cm}^2$
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X_{max}

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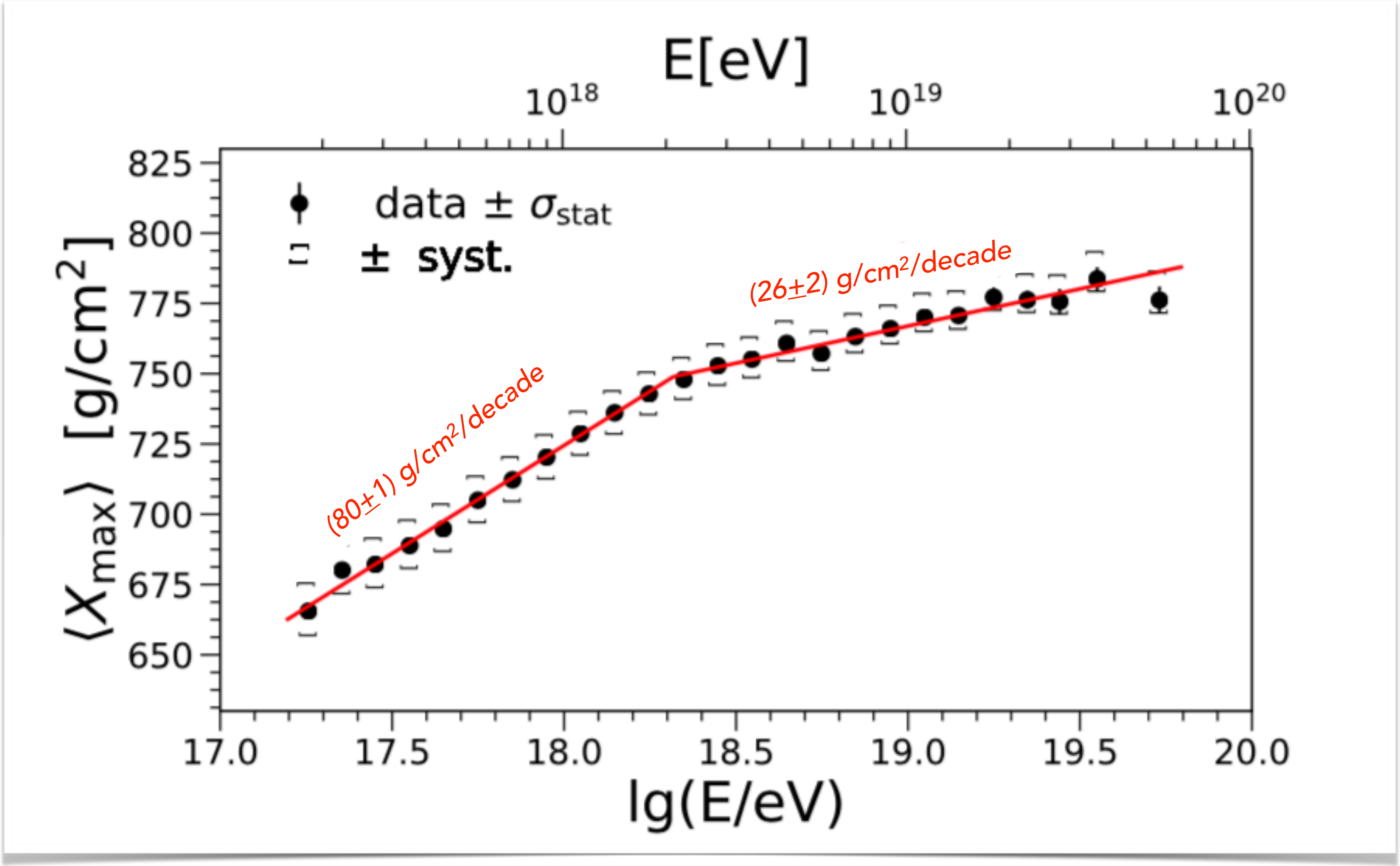
Energy Dependance of Xmax



X_{max} resolution

~25 g cm^{-2} at $10^{17.8}$ eV

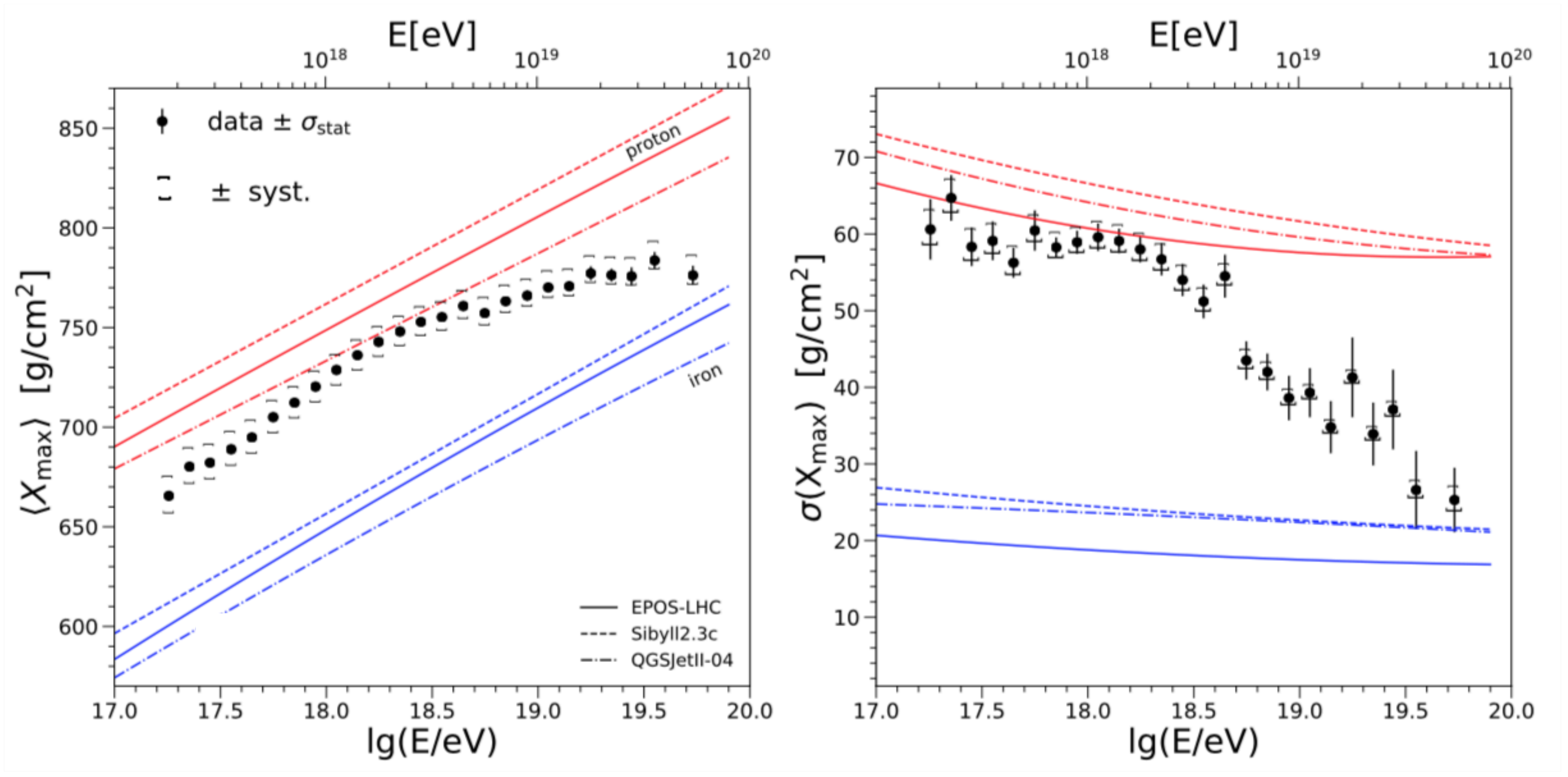
~15 g cm^{-2} for E> 10^{19} eV

σ_{sys} ≤ 10 g cm^{-2}

$\log_{10}$(E/eV)	FD
18.5-18.6	1098
18.6-18.7	834
18.7-18.8	578
18.8-18.9	469
18.9-19.0	356
19.0-19.1	281
19.1-19.2	191
19.2-19.3	131
19.3-19.4	111
19.4-19.5	66
> 19.5	62
Total	4177

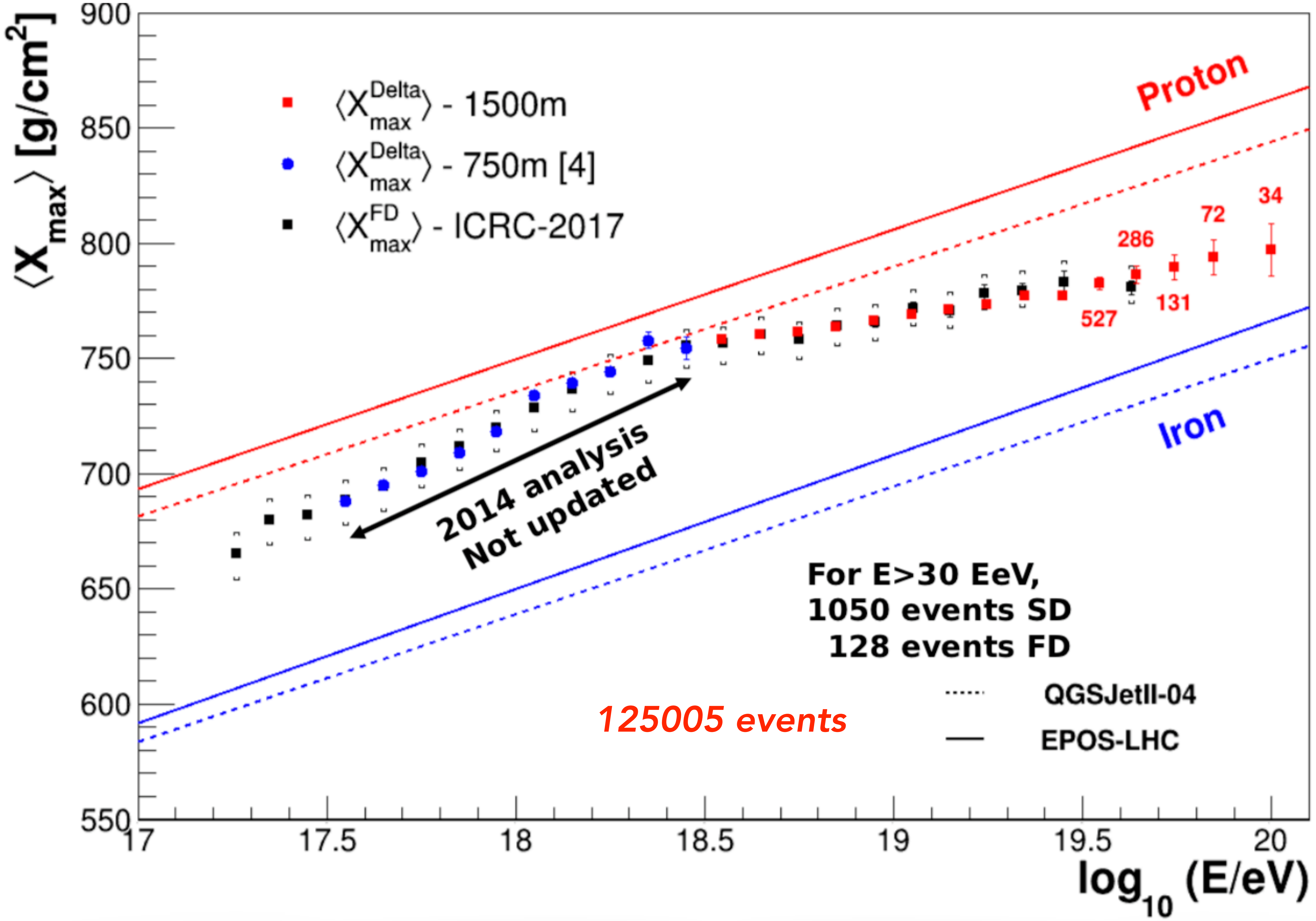
A. Yushkov [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Mean Xmax and its fluctuations



Composition becoming lighter up to $\sim 2 \times 10^{18}\,\mathrm{eV}$, heavier above this energy

Mean Xmax from Auger's surface detector



$\log_{10}$(E/eV)	SD
18.5-18.6	45872
18.6-18.7	27783
18.7-18.8	17011
18.8-18.9	11631
18.9-19.0	7960
19.0-19.1	5489
19.1-19.2	3582
19.2-19.3	2290
19.3-19.4	1473
19.4-19.5	864
19.5-19.6	527
19.6-19.7	286
19.7-19.8	131
19.8-19.9	72
>19.9	34
Total	125005

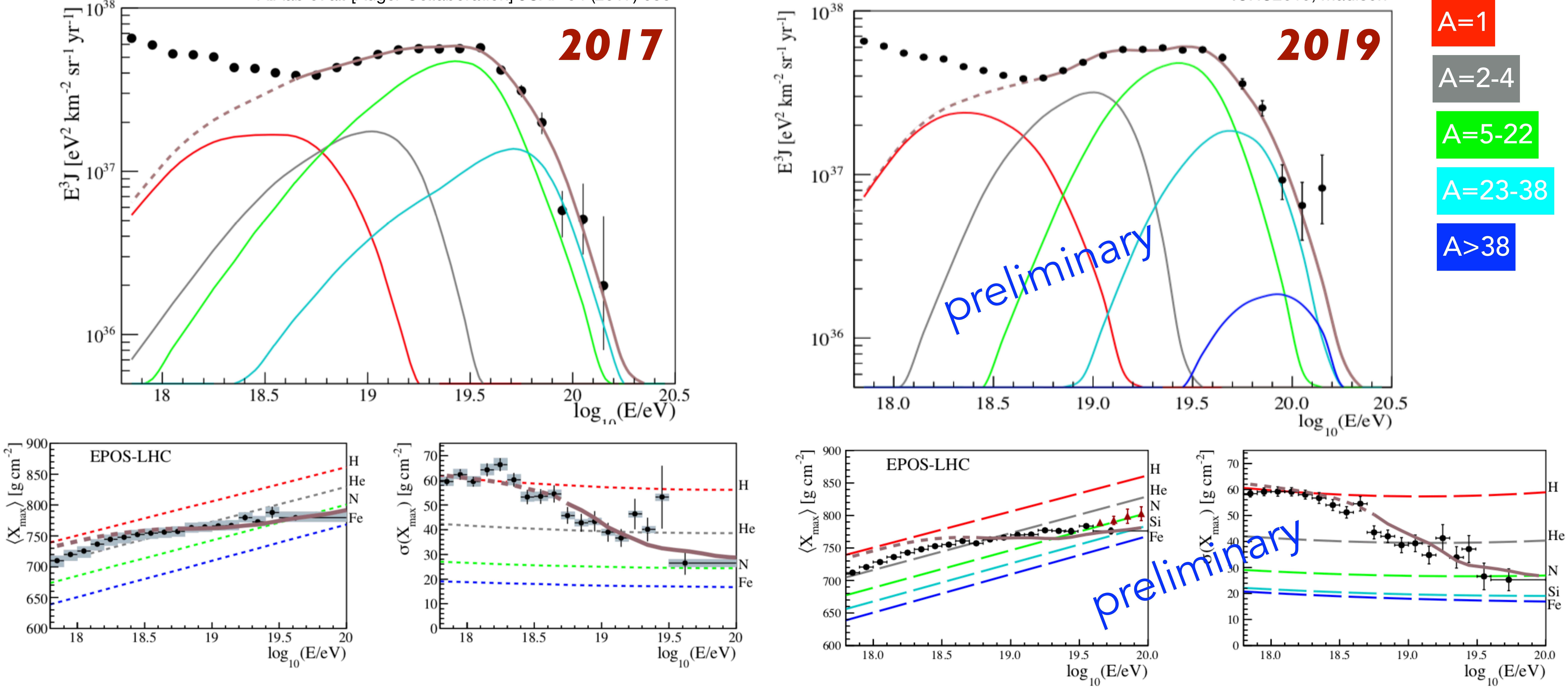
Primary mass not constant with energy, in agreement with more direct fluorescence measurements

C.J. Todero Peixoto [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Combined fit of spectrum and Xmax data - astrophysics

A.Aab et al. [Auger Collaboration] JCAP 04 (2017) 038

ICRC2019, Madison

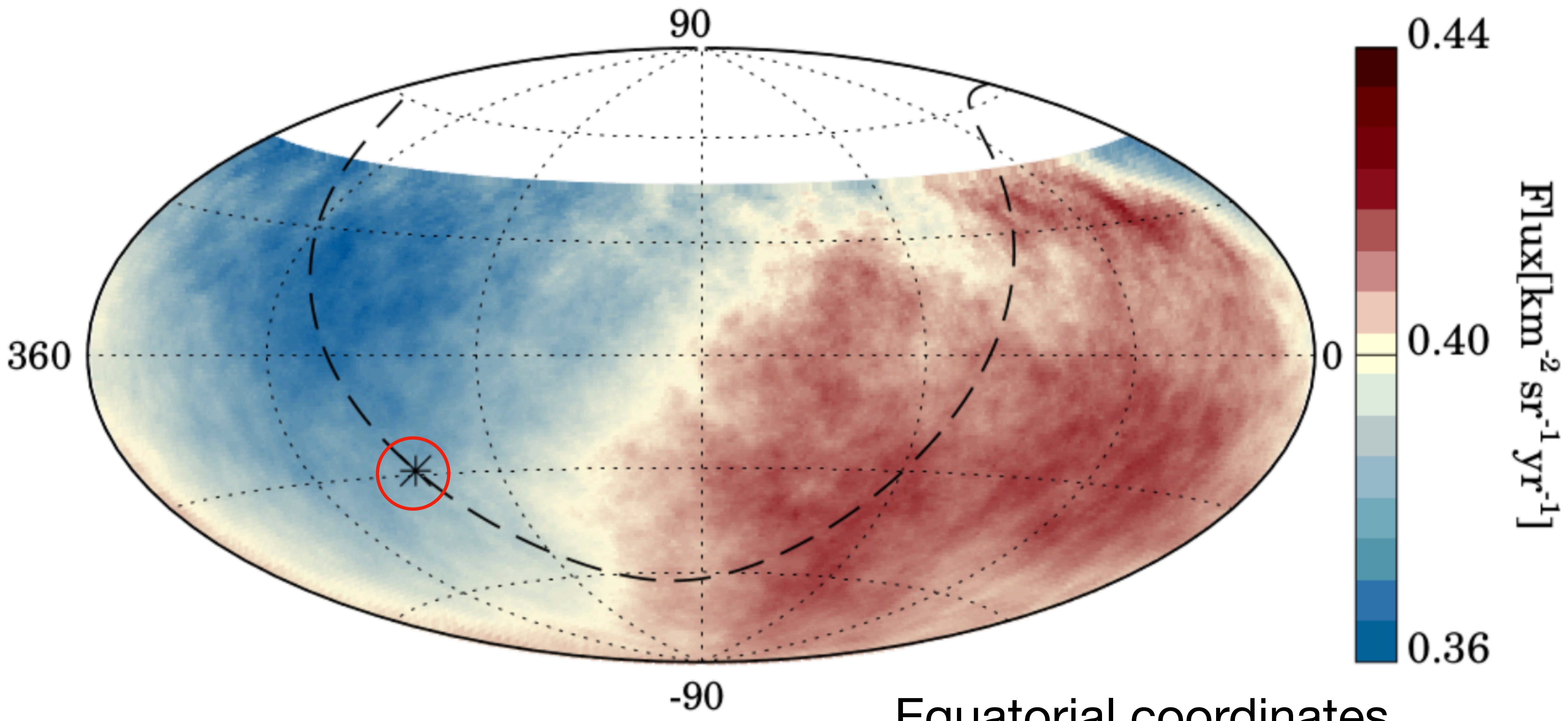


Simple model: uniformly distributed identical sources, nuclei accelerated via a rigidity-dependent mechanism.
Result: relatively low maximum acceleration energies, hard spectra and heavy chemical composition.

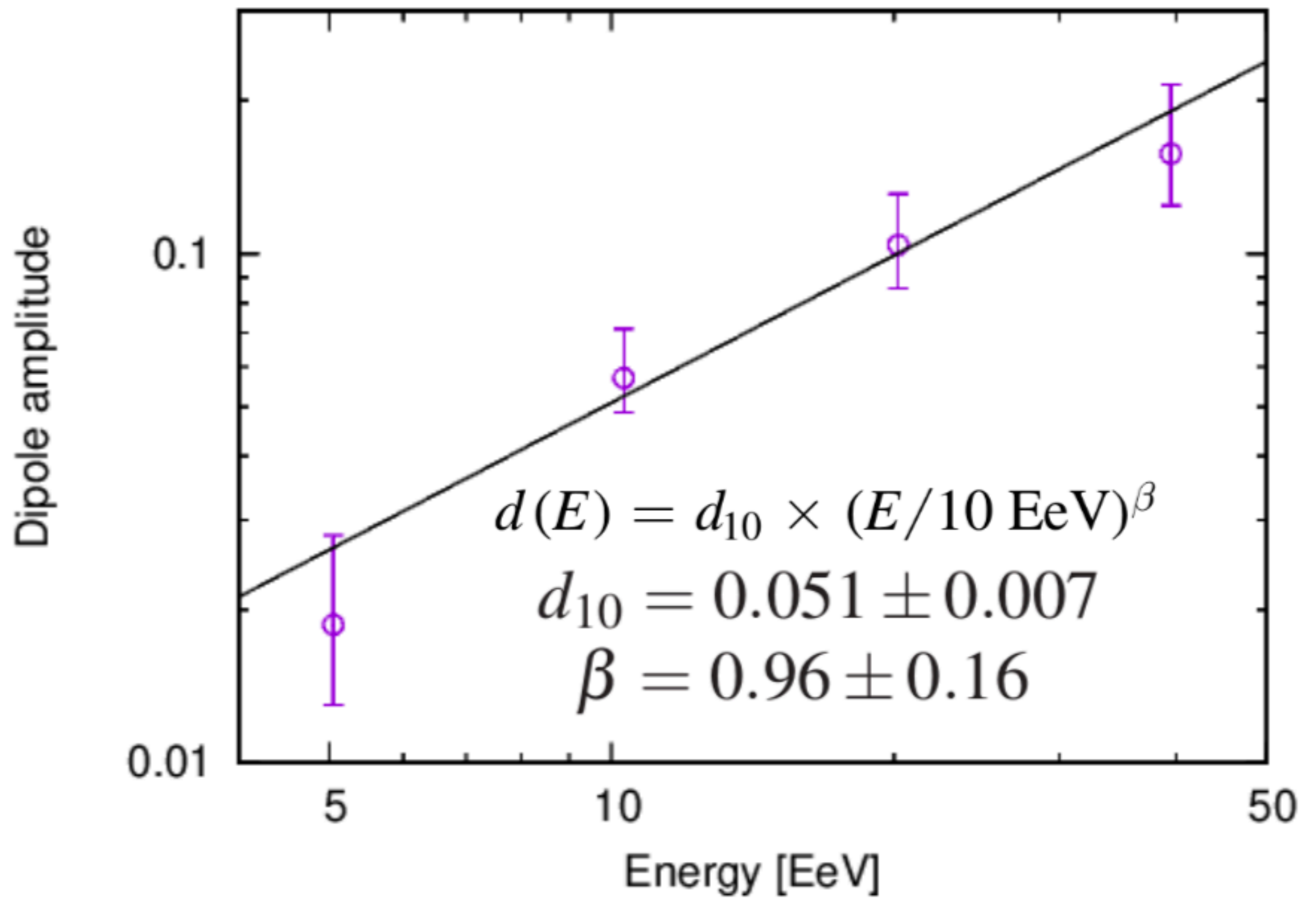
Large-scale anisotropy

Energy [EeV] interval	median	N	$d_\perp$	d_z	d	α_d [°]	δ_d [°]
4 - 8	5.0	88,317	$0.010^{+0.007}_{-0.004}$	-0.016 ± 0.009	$0.019^{+0.009}_{-0.006}$	70 ± 34	-57^{+24}_{-20}
≥ 8	11.5	36,924	$0.060^{+0.010}_{-0.009}$	-0.028 ± 0.014	$0.066^{+0.012}_{-0.008}$	98 ± 9	-25 ± 11

Exposure $> 92000\,\mathrm{km^2\,sr\,yr}$
for events with $\theta < 80°$



Equatorial coordinates



3D dipole above 8×10^{18}eV at (α, δ) = ($98°, -25°$): $(6.6^{+1.2}_{-0.8})$ %
Amplitude increasing with energy

A. Aab et al. [Auger Collaboration], Science **357** 1266 (2017); E. Roulet [Auger Collaboration], ICRC 2019 arXiv:1909.09073

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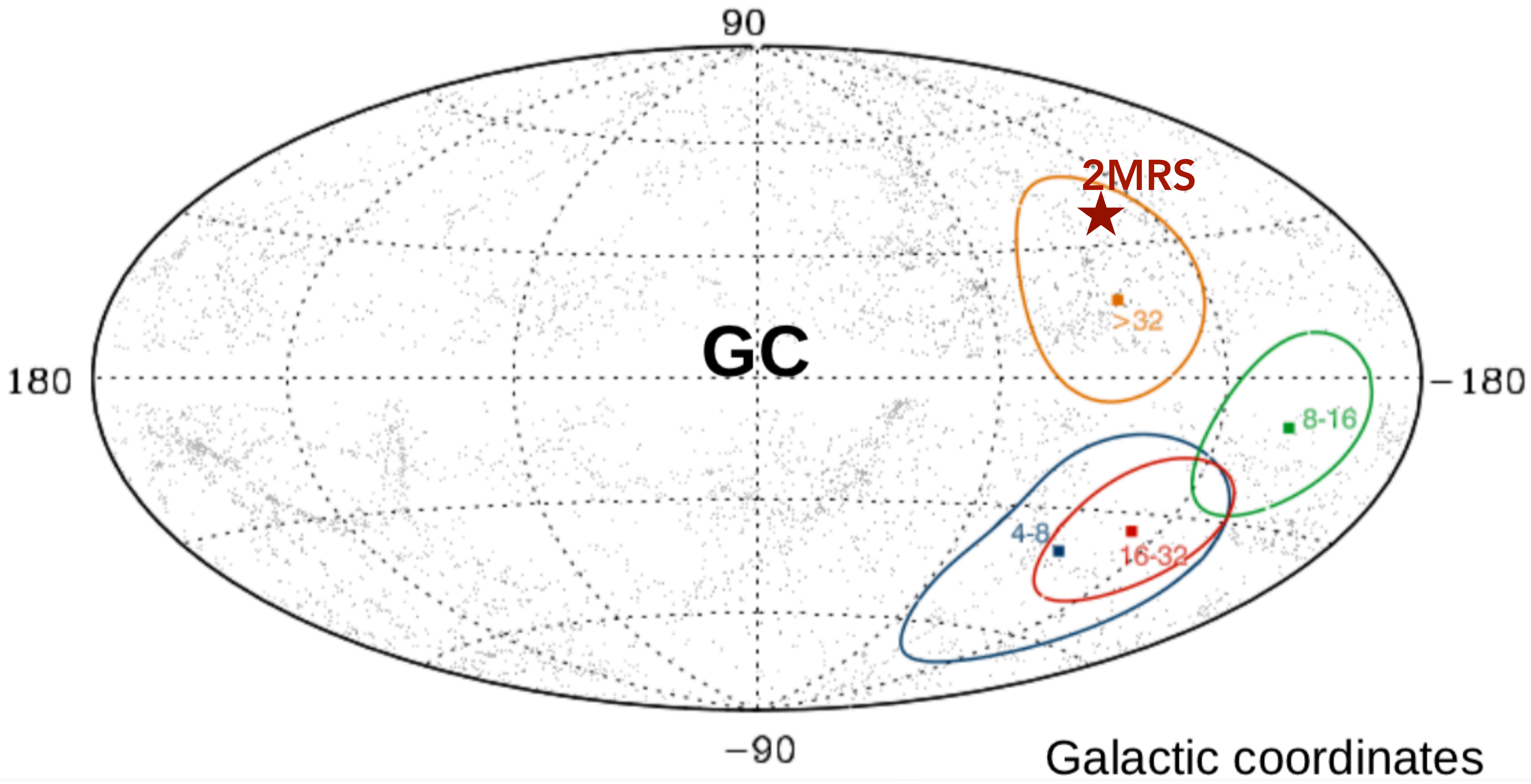

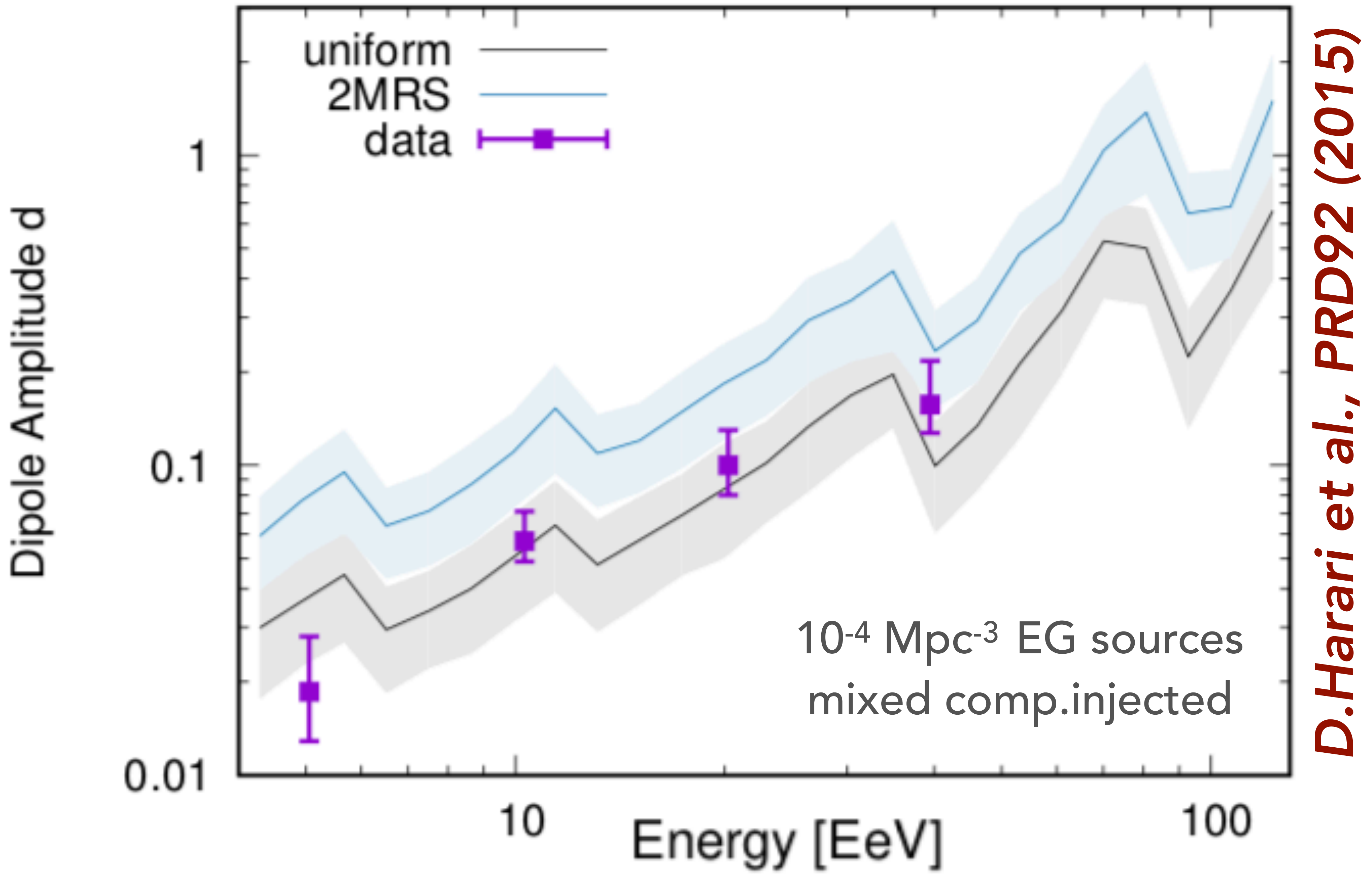

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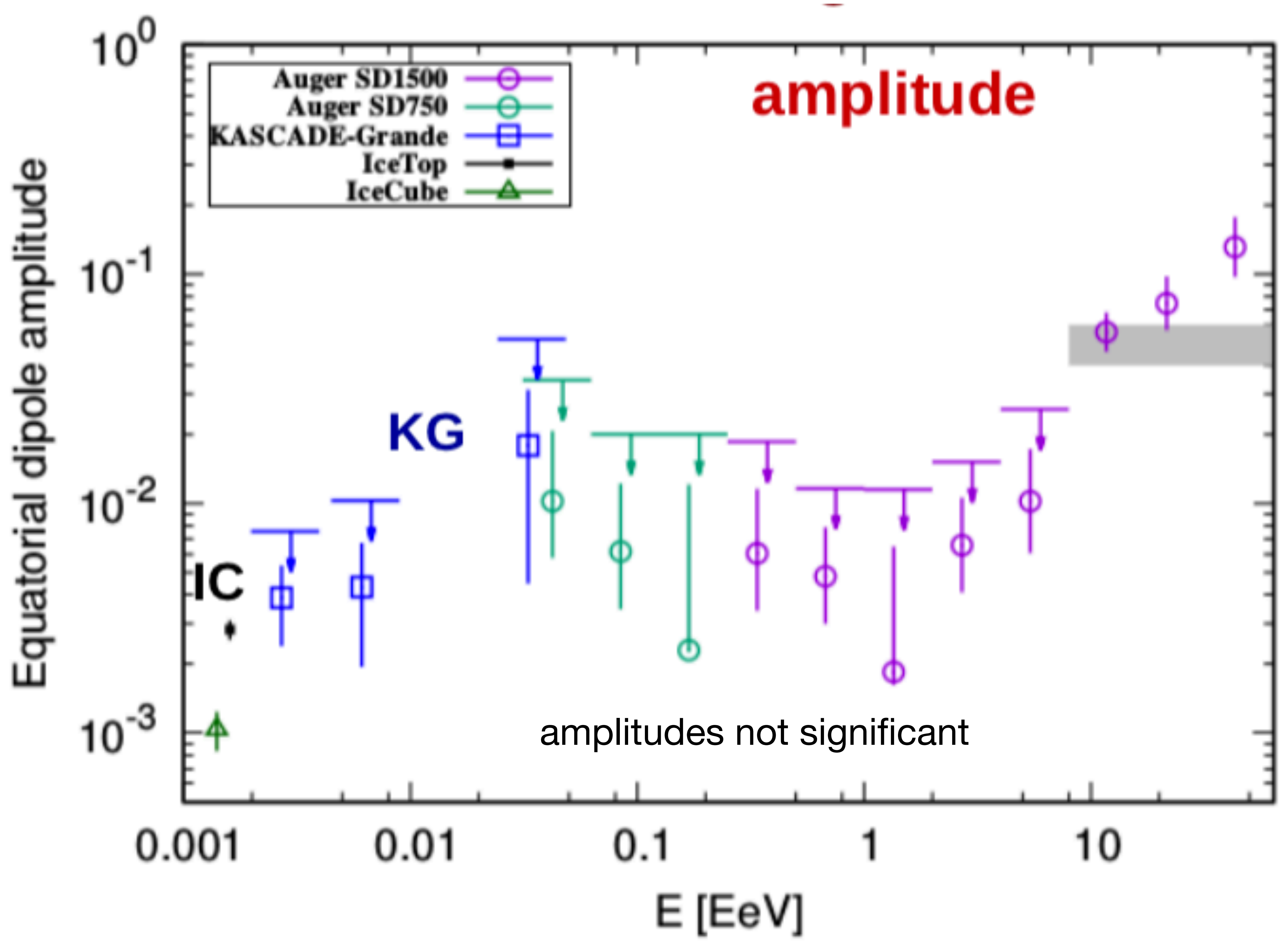
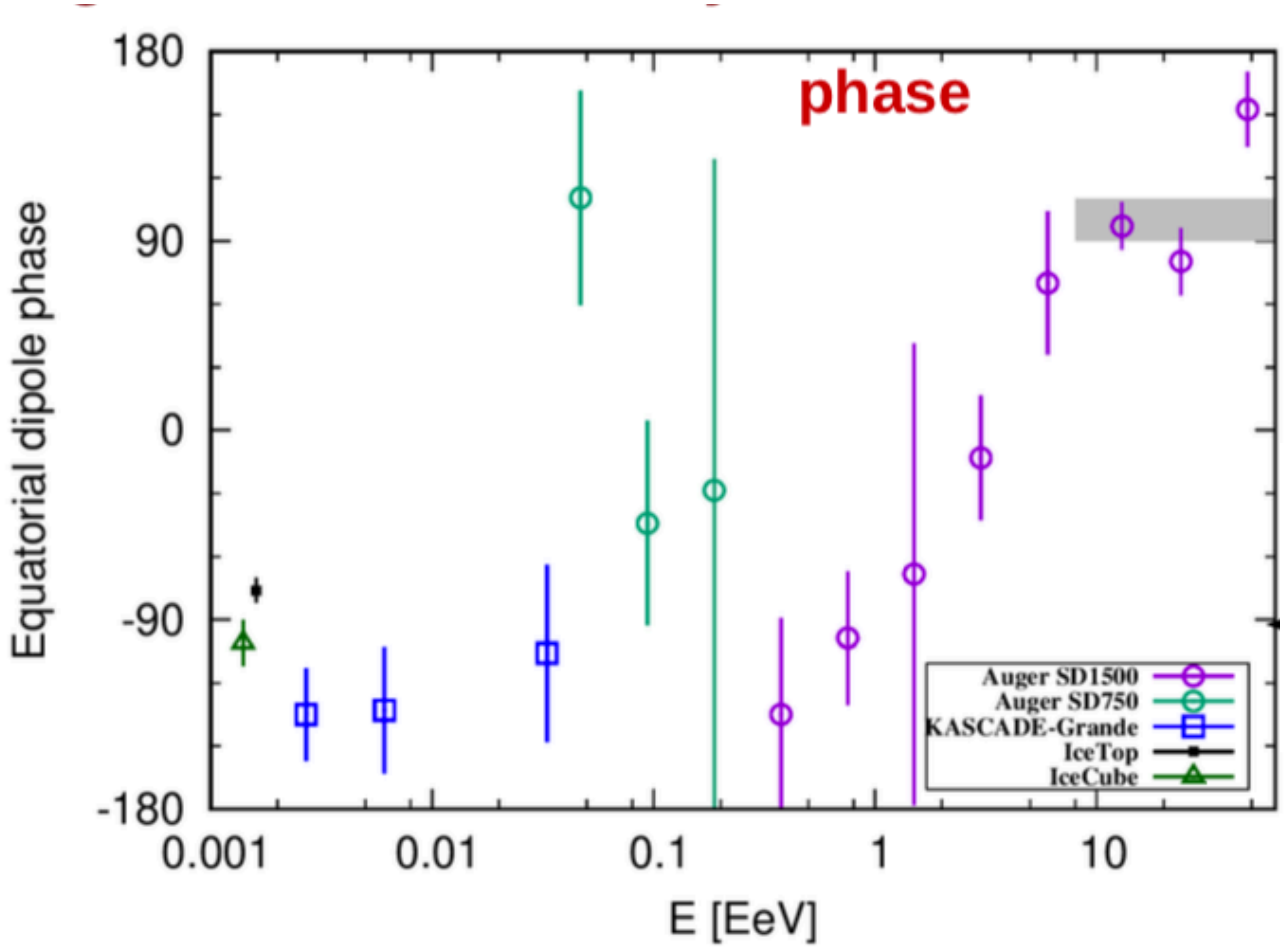
Large-scale anisotropy

Search for large scale anisotropies down to 0.03 EeV
- SD1500 + SD750 data,
- East-West method below 2 EeV (to minimise detector systematics)



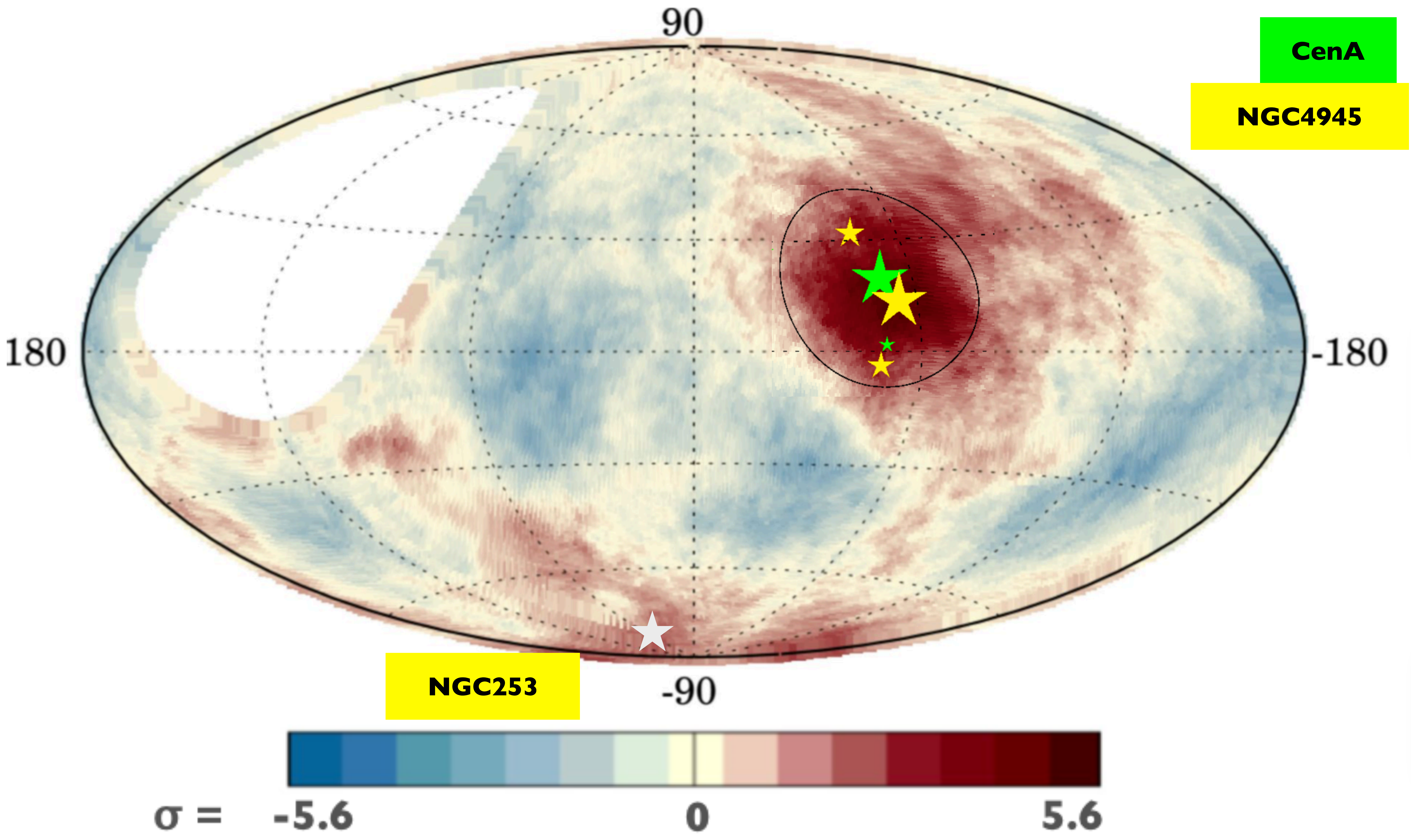


Predominantly galactic origin below 1-2 EeV, extragalactic origin above

E. Roulet [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Intermediate-scale anisotropy - blind scan & Cen A

Total SD events with E>32 EeV : 2157
Total exposure 101,400 km² sr yr



Blind search

Scan ranges:
32 EeV ≤ Eth ≤ 80 EeV (1 EeV steps)
1° ≤ ψ ≤ 30° (1° steps)

Most significant excess for E>38 EeV
($\alpha=202^0$, $\delta= -45^0$) ~2^0 from CenA

2.5% post-trial chance probability

Centaurus A

3.9 σ effect (post-trial)
for E>37 EeV, 28^0 window

L. Caccianiga [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Intermediate-scale anisotropy - catalog search

γ AGNs

3FHL catalog < 250 Mpc
33 sources (CenA, Fornax A, M87…)
Flux proxy ϕ(>10 GeV)

Starburst Galaxies

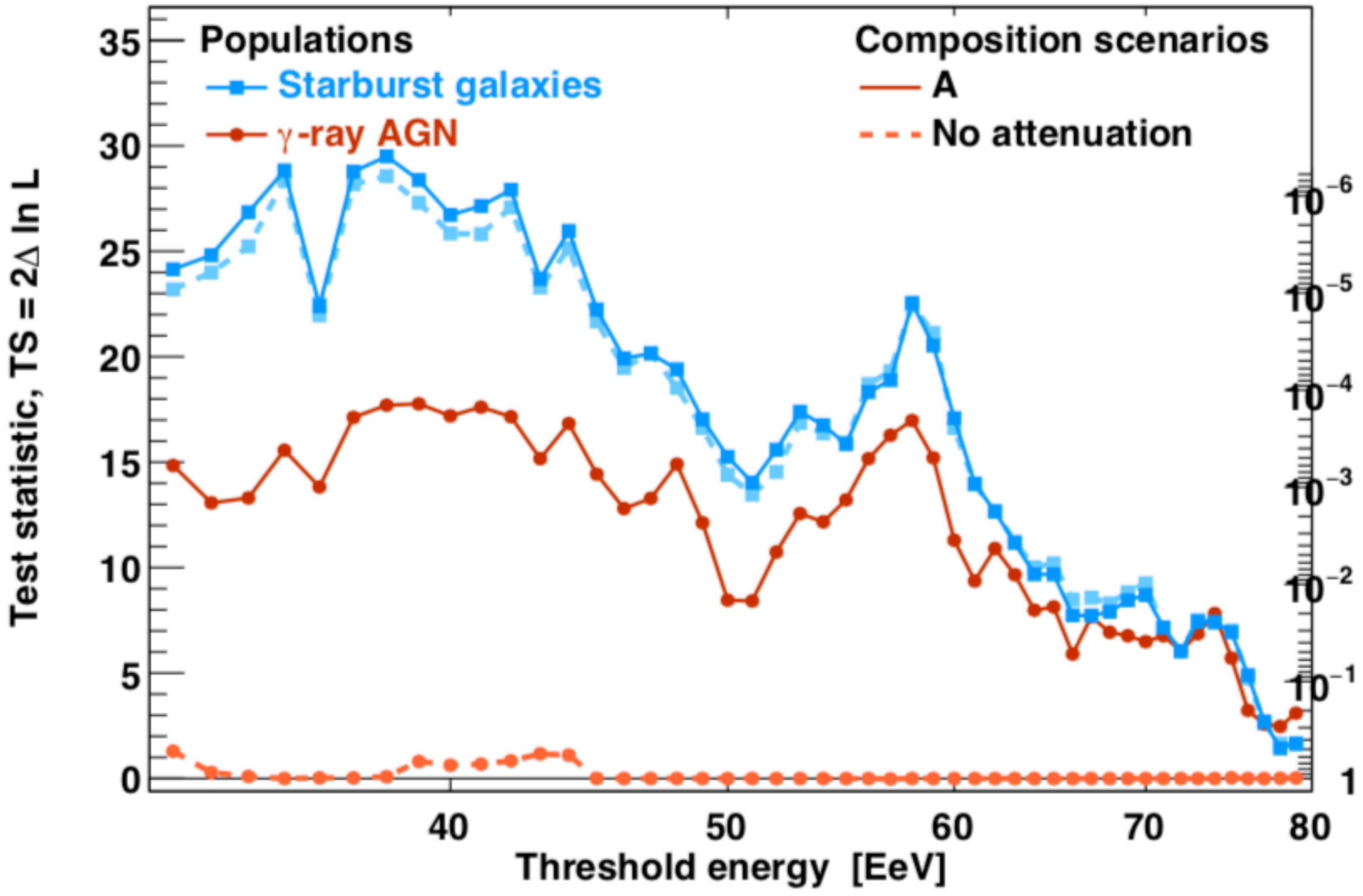
32 sources (Circinus, M82, M83,…)
<250 Mpc
Flux proxy ϕ(>1.4 GHz), > 0.3 Jy

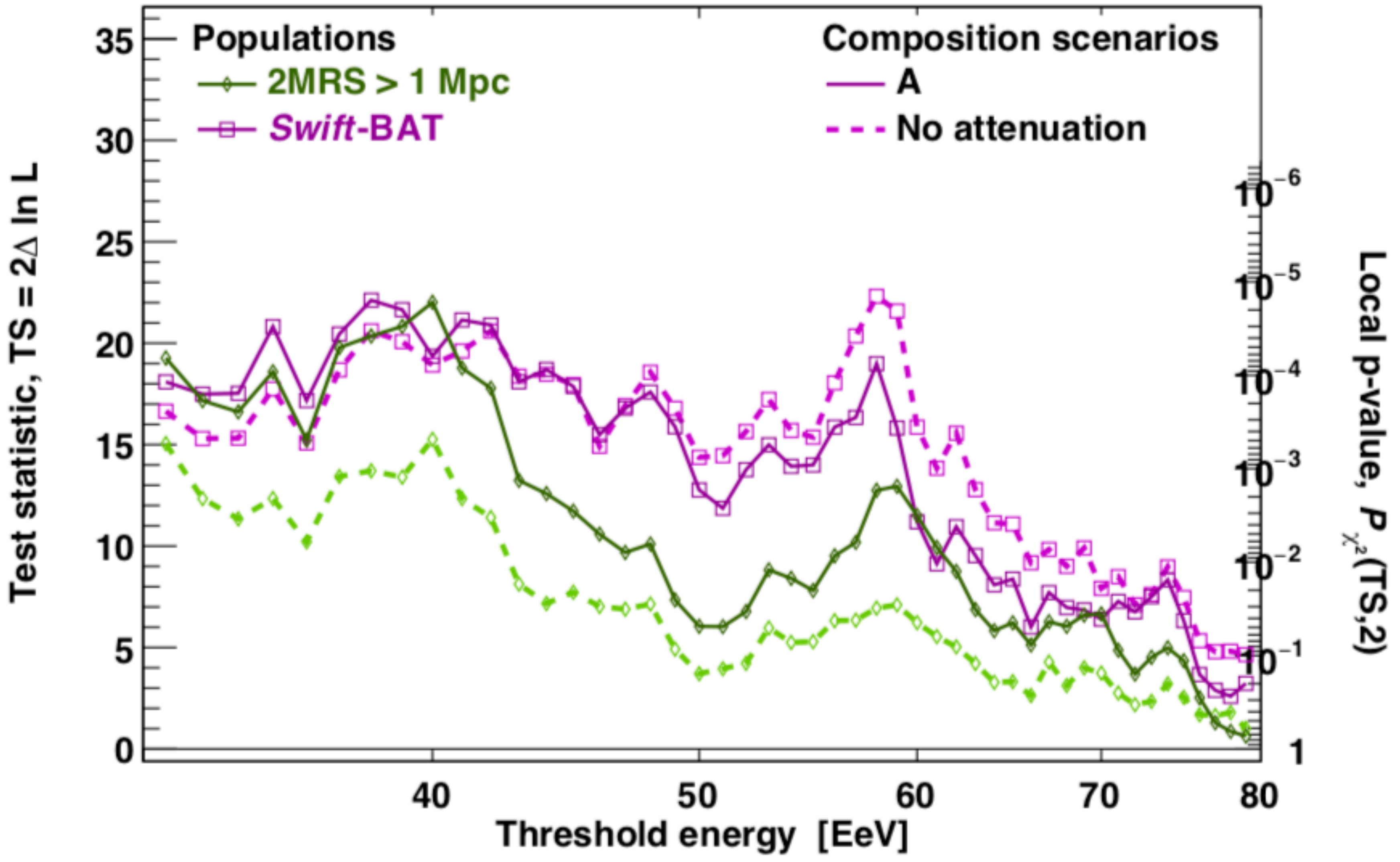
Swift-BAT

>300 radio loud and quiet sources
<250 Mpc
ϕ>13.4 10^{-12} erg cm^{-2} s^{-1}

2MRS

~10^4 sources with D>1 Mpc
<250 Mpc
Flux proxy K-band flux.





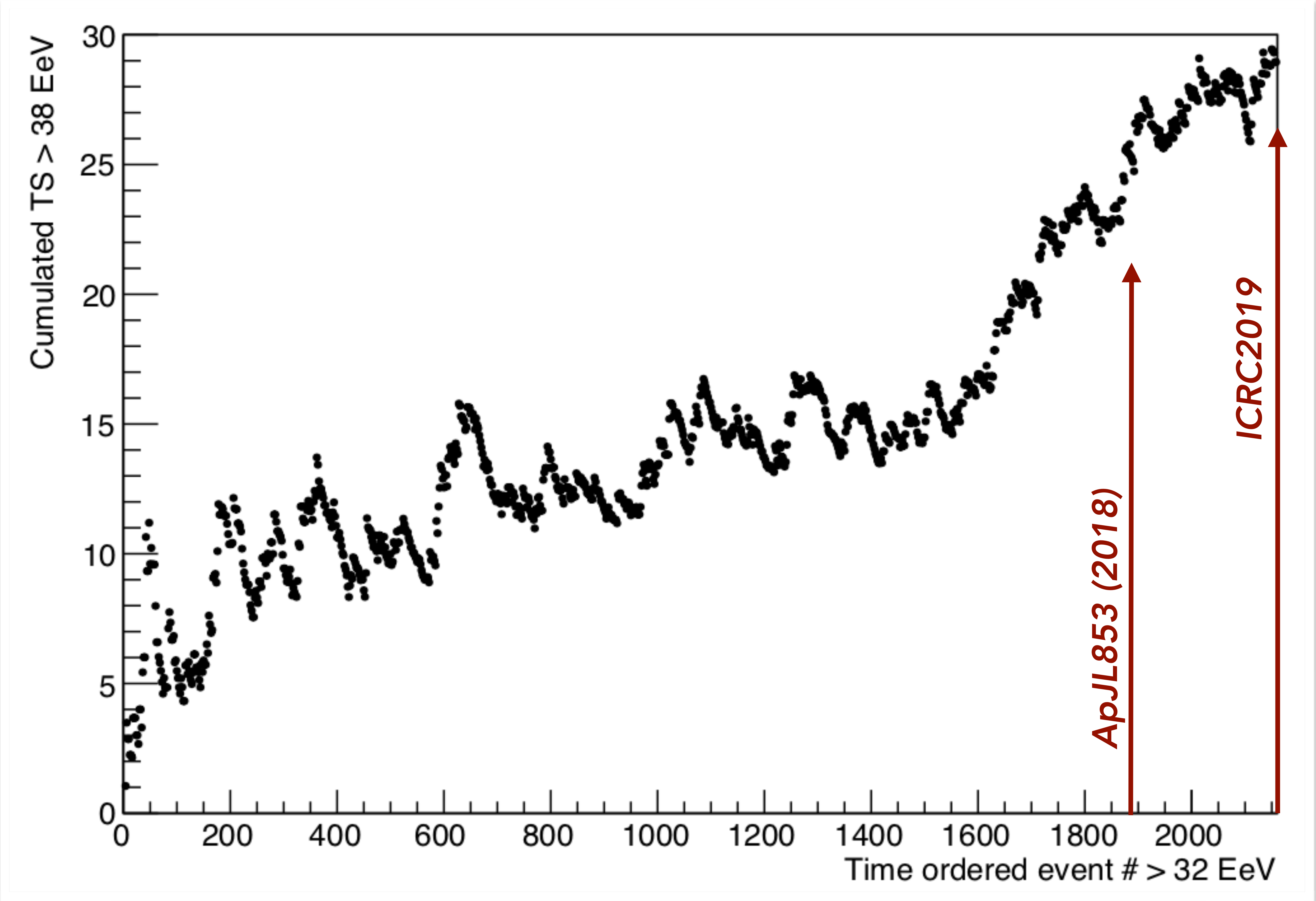
Likelihood analysis $TS = 2Log\left[L(\psi, f_{anis})/L(f_{anis}=0)\right]$

Catalog	$E_{\rm th}$	TS	Local p-value	post-trial	$f_{\rm aniso}$	θ
Starburst	38 EeV	29.5	4×10^{-7}	4.5 σ	$11^{+5}_{-4}\%$	$15^{+5}_{-4}{}^\circ$
γ–AGN	39 EeV	17.8	1×10^{-4}	3.1 σ	$6^{+4}_{-3}\%$	$14^{+6}_{-4}{}^\circ$
Swift-BAT	38 EeV	22.2	2×10^{-5}	3.6 σ	$8^{+4}_{-3}\%$	$15^{+6}_{-4}{}^\circ$
2MRS	40 EeV	22.0	2×10^{-5}	3.6 σ	$19^{+10}_{-7}\%$	$15^{+7}_{-4}{}^\circ$

(given source smearing, clearly some overlap between catalogs)

L. Caccianiga [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Intermediate-scale anisotropy - catalog search



A.Aab et al. [Auger Collaboration], ApJ Lett. **853** L29 (2018)
L. Caccianiga [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Rejection of isotropy hypothesis

ApJ Lett. [Jan 2004-Apr 2017]	4.0σ for SBGs 2.7σ for $\gamma-$AGN
ICRC2019 [Jan 2004-Aug 2018]	4.5σ for SBGs 3.1σ for $\gamma-$AGN

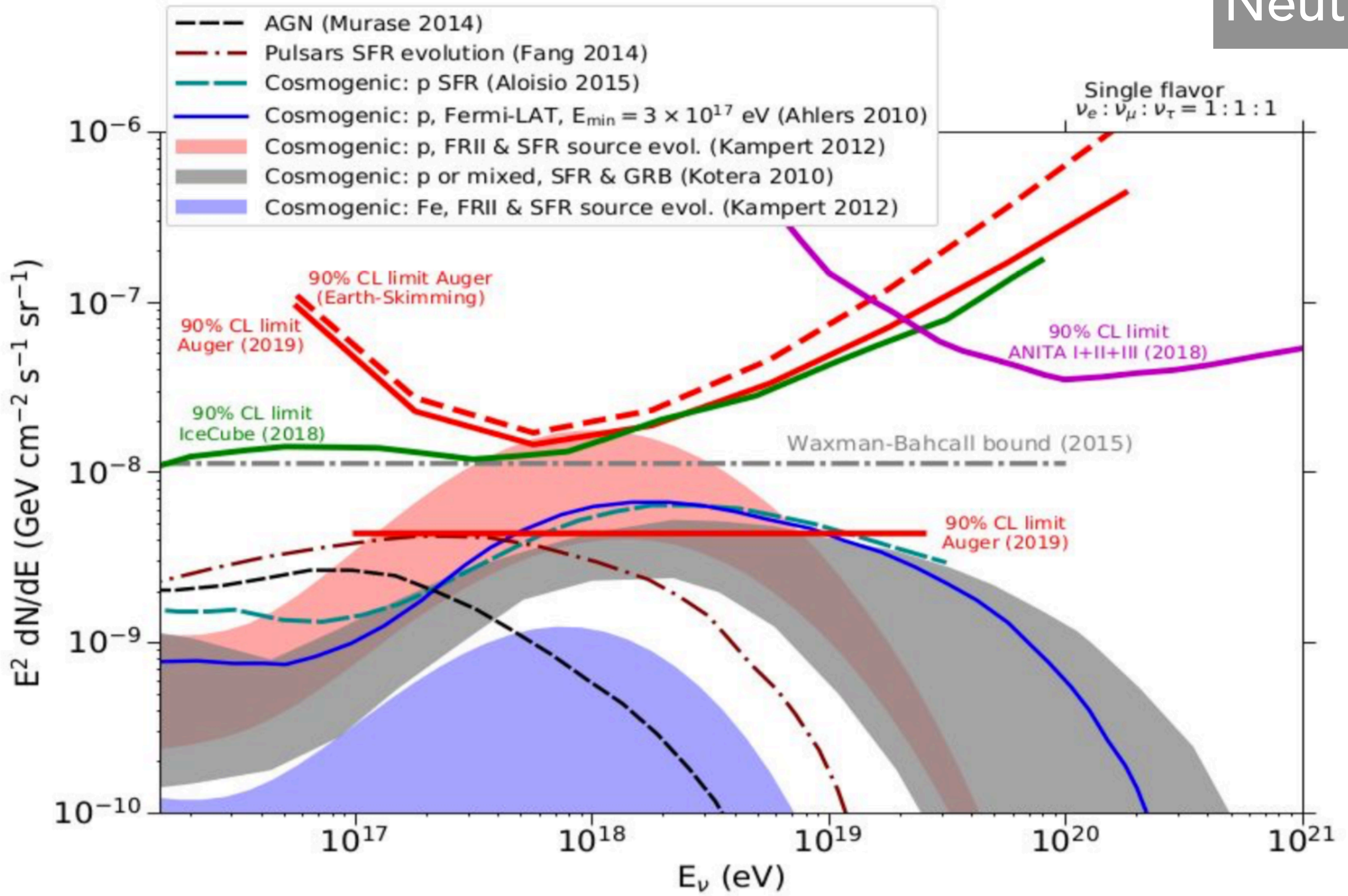
Significance increasing with time!

Cosmogenic neutrino and photon limits

$$p + \gamma \rightarrow n + \pi^+$$
$$\rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \overline{\nu}_\mu + \nu_e$$

$$k = \frac{N_{up}}{\int_{E_\nu} E_\nu^{-2} \epsilon_{tot}(E_\nu) dE_\nu}$$

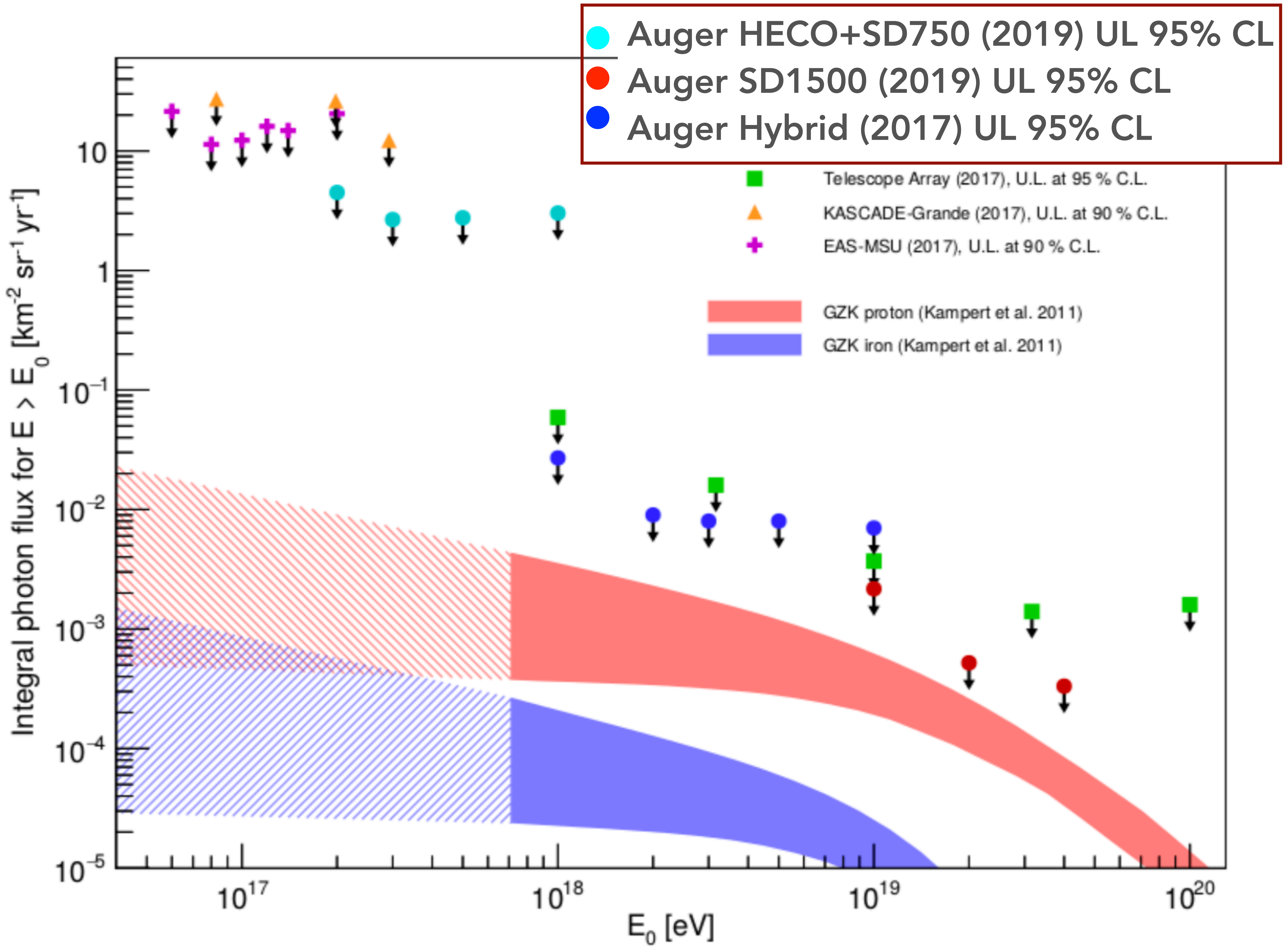
Neutrinos



Maximum sensitivity around EeV
k (90% CL) < 4.4. 10^{-9} GeV cm^{-2} s^{-1} sr^{-1}

$$p + \gamma \rightarrow p + \pi^0$$
$$\rightarrow \gamma + \gamma$$

Photons

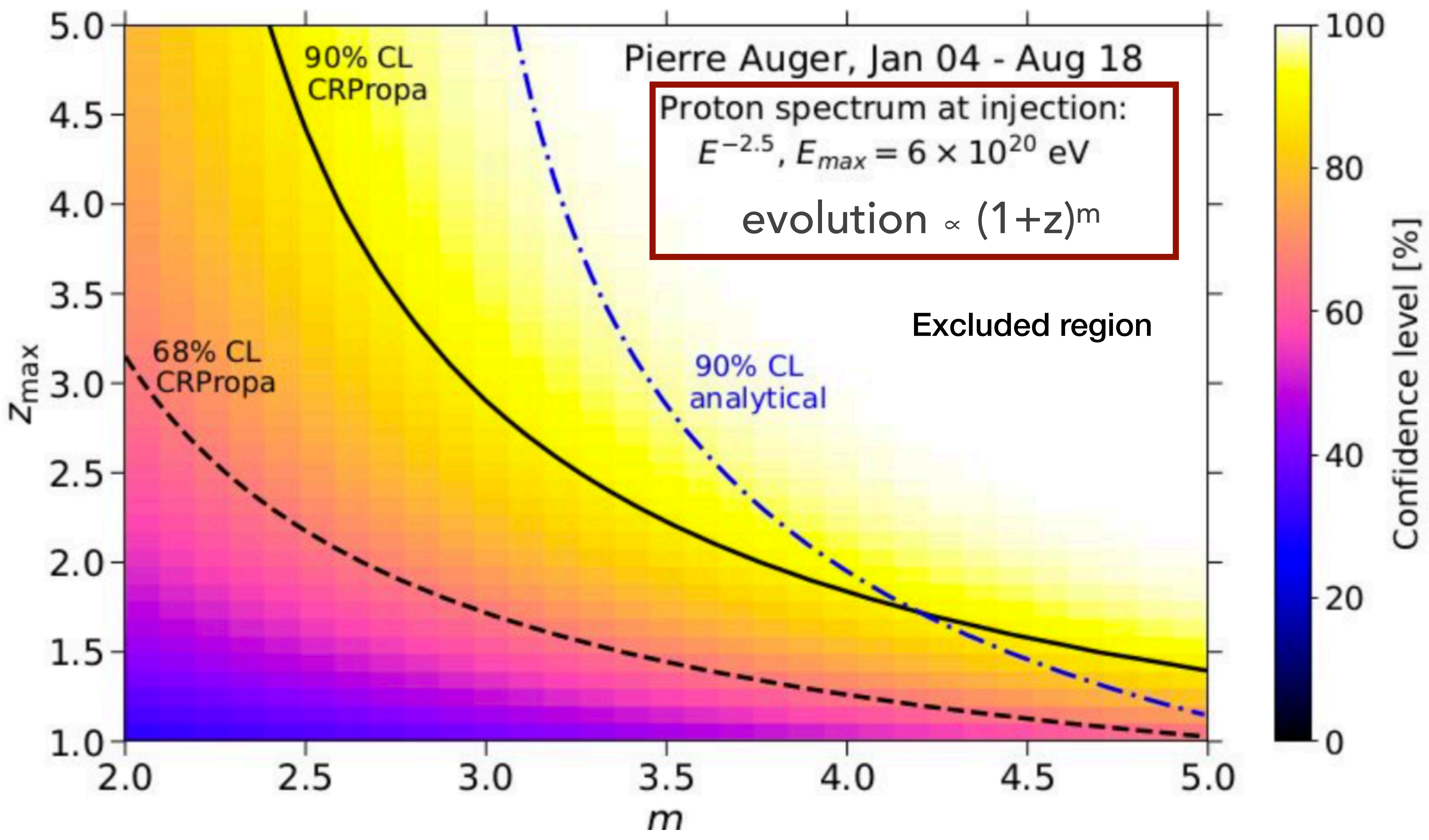


Most sensitive EAS detector for E_γ>0.2 EeV

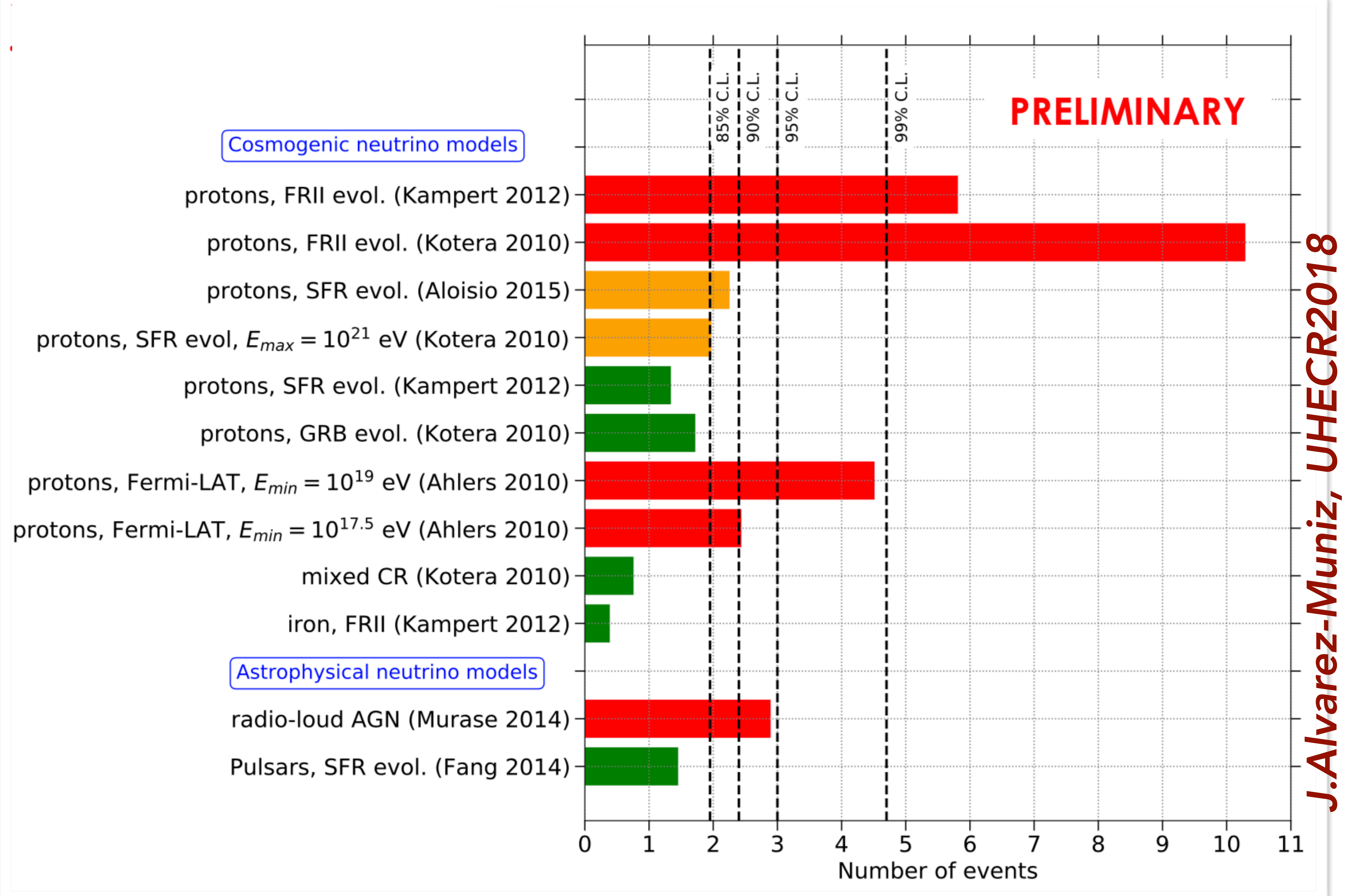
F. Pedreira [Auger Collaboration], ICRC 2019 arXiv:1909.09073

J. Rautenberg [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Constraining cosmogenic neutrino models



Black lines & colored background: ν fluxes obtained with Monte Carlo CRPropa 3 (A. Van Vliet et al.) - proton flux at Earth normalized to Auger spectrum at E = 7 x 10^{18} eV.
Blue line: fluxes obtained with approx. analytical approach (Yoshida et al.)



Exclusion of a significant region of parameter space $(z_{\rm max}, m)$ from non-observation of neutrinos

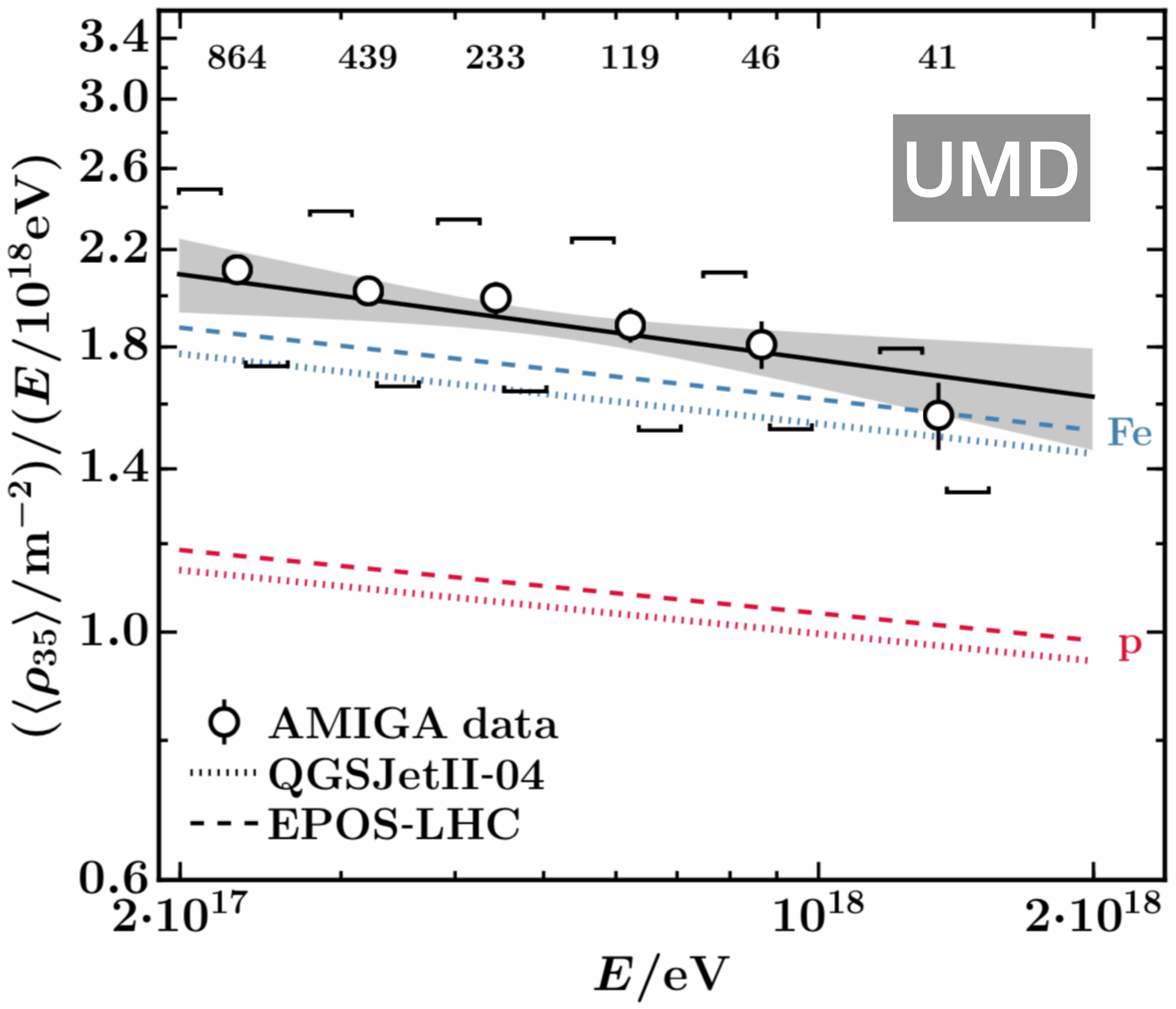
Excluded: high max z of CR acceleration and/or rapid source evolution

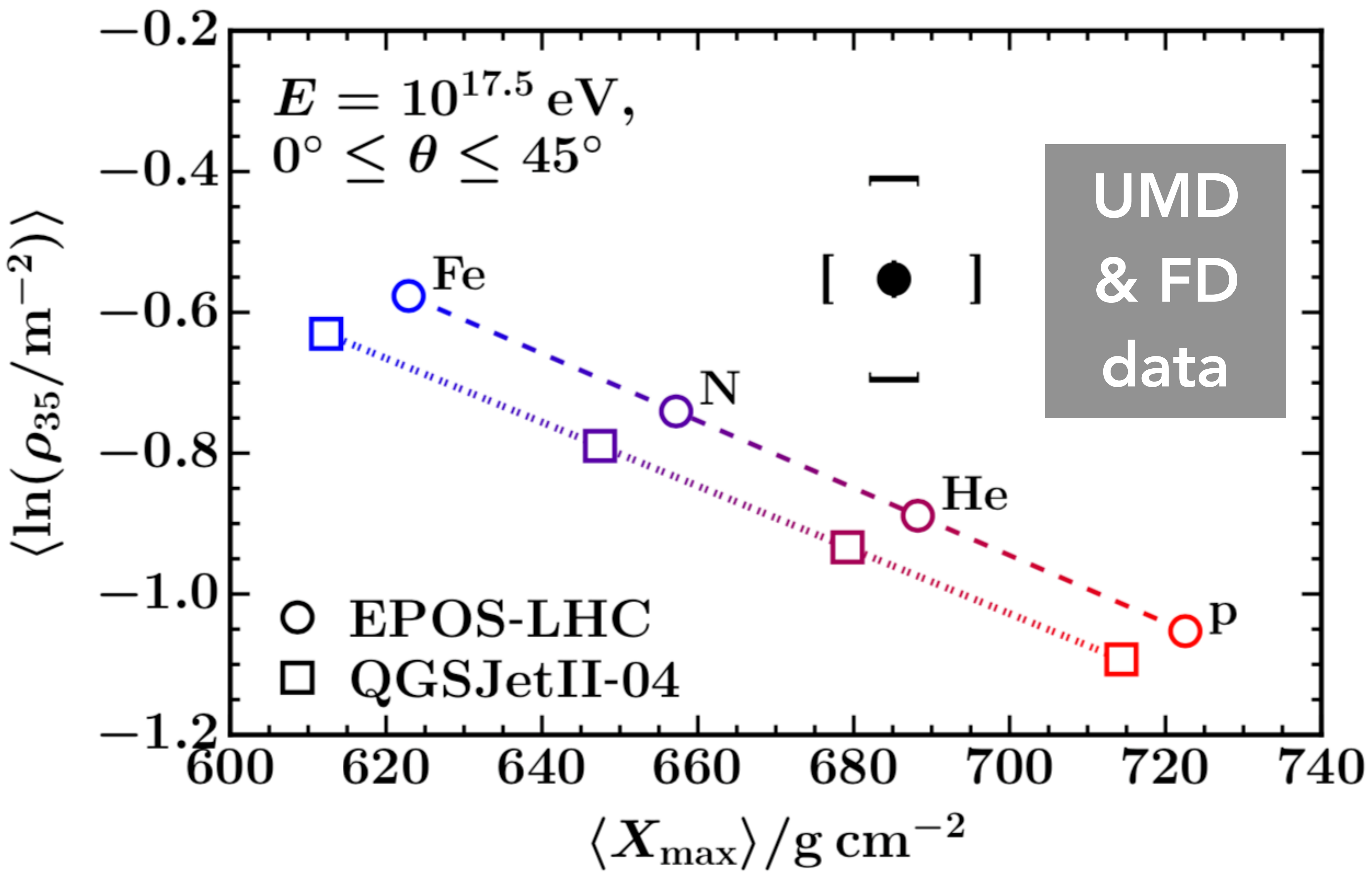
F. Pedreira [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Muon content of air showers - hadronic interaction physics

The UMD is providing the latest evidence for deficit of muons in air shower simulations

(also see talk of Jose Bellido last Tuesday)





Auger's Underground Muon Detector

In the energy range 3×10^{17} eV to 2×10^{18} eV simulations fail to reproduce muon densities.

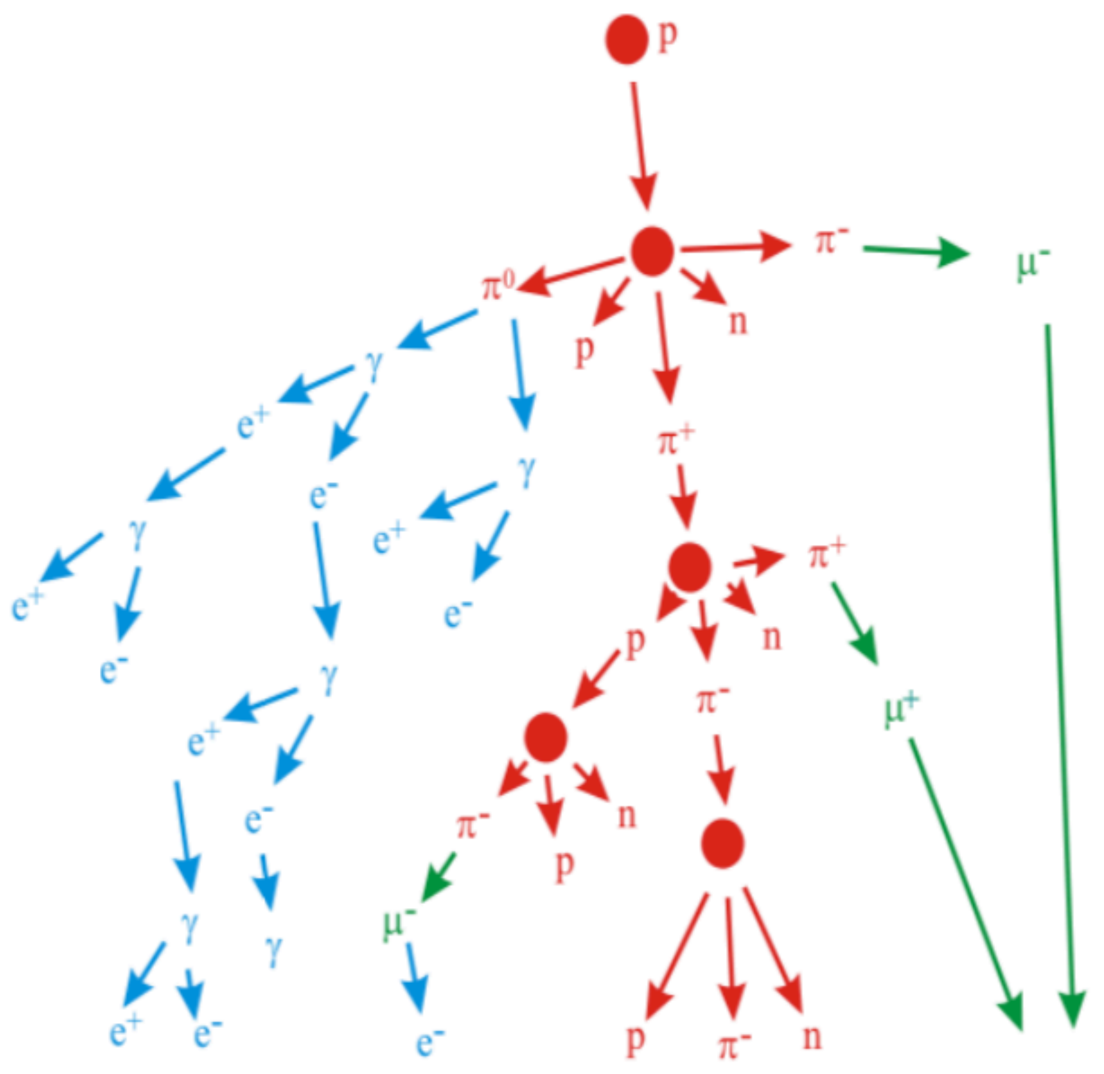
38% (53%) increase in $< N_\mu >$ at 1EeV needed for EPOS-LHC (QGSJetII-04)

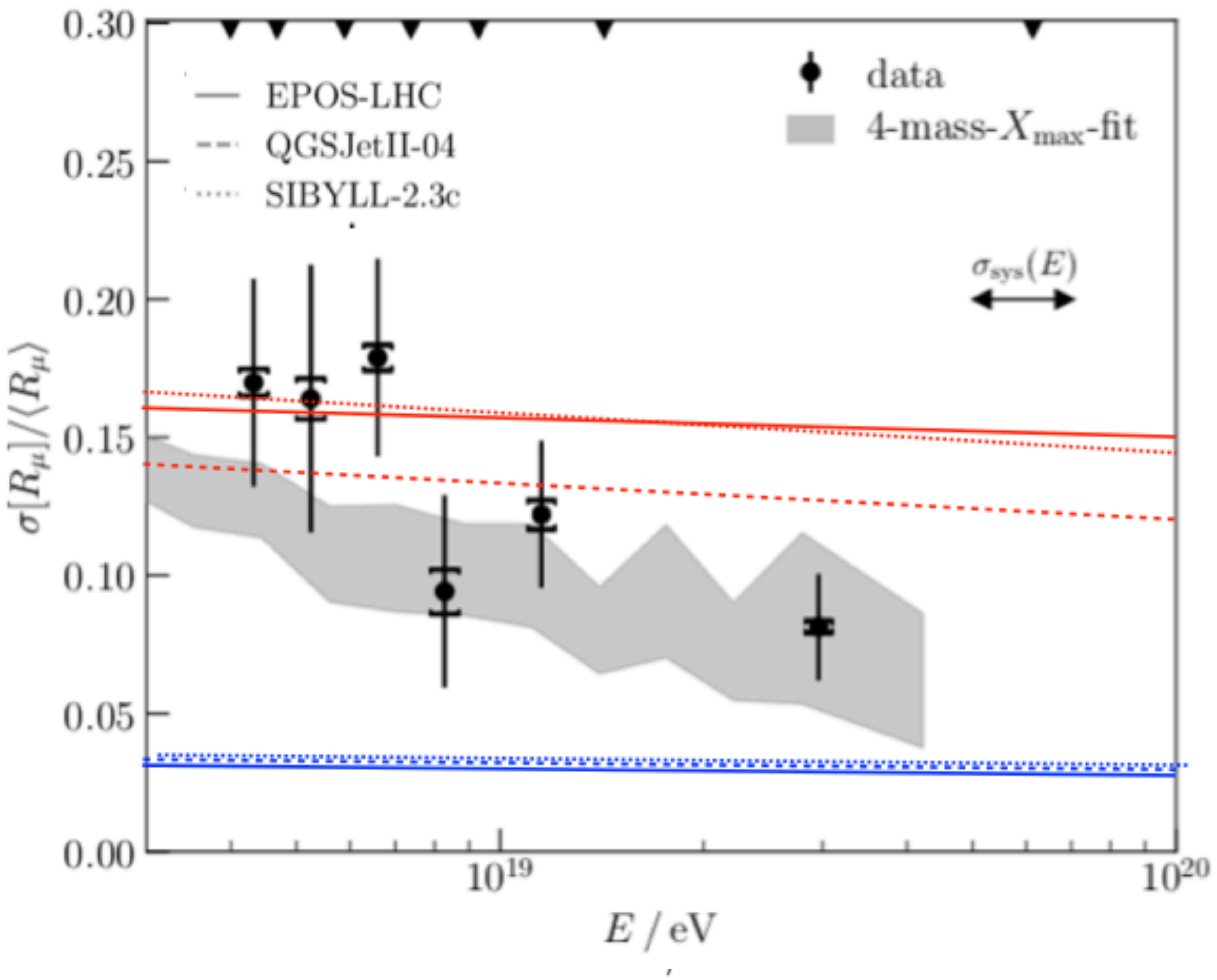
(consistent with a number of other measurements at Auger)

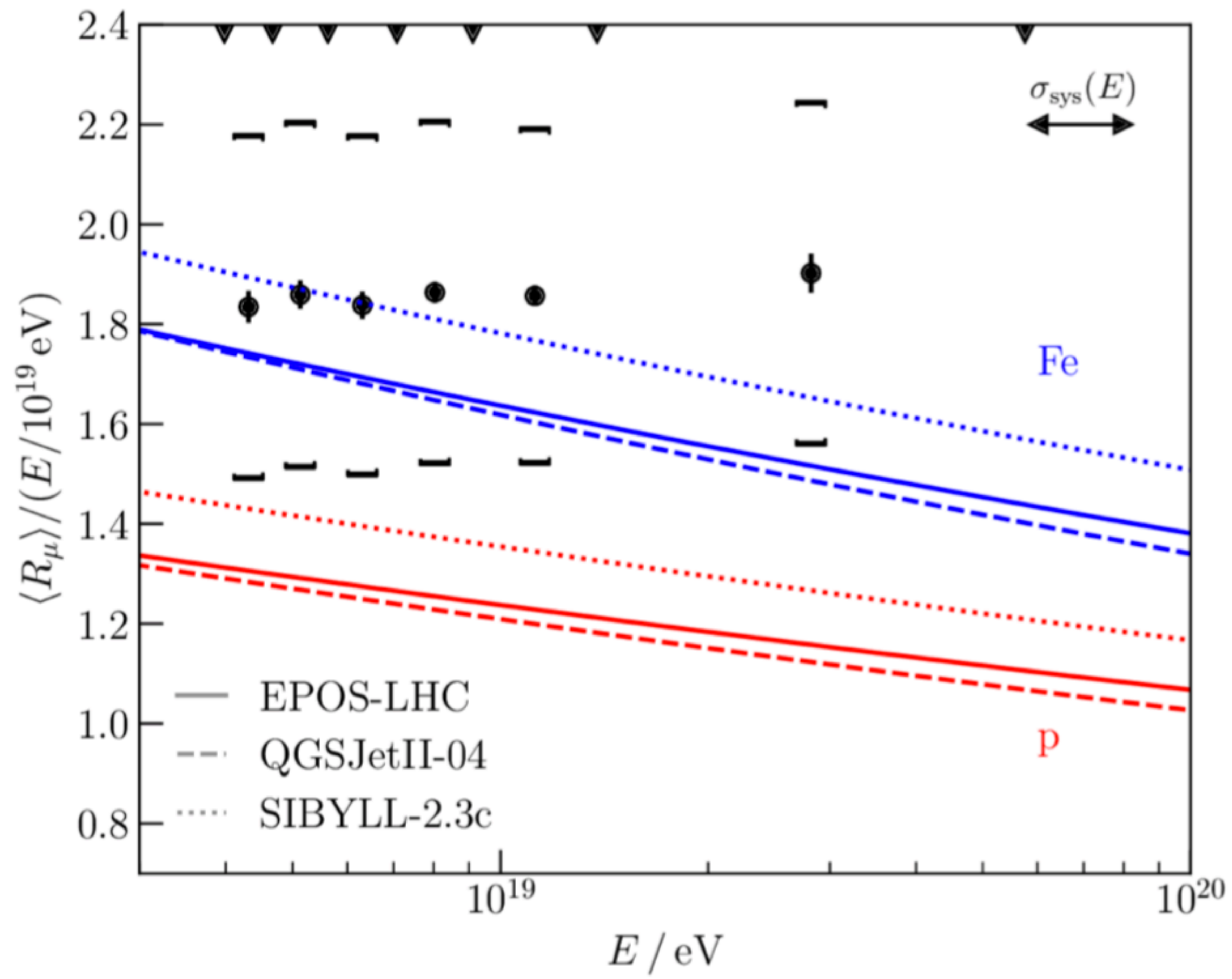
F. Sanchez [Auger Collaboration], ICRC 2019 arXiv:1909.09073

Fluctuations in the muon content of air showers

Observing very inclined air showers with the main surface detector array







Fluctuations in the muon number — a probe of the first interaction at ultra-high energy.

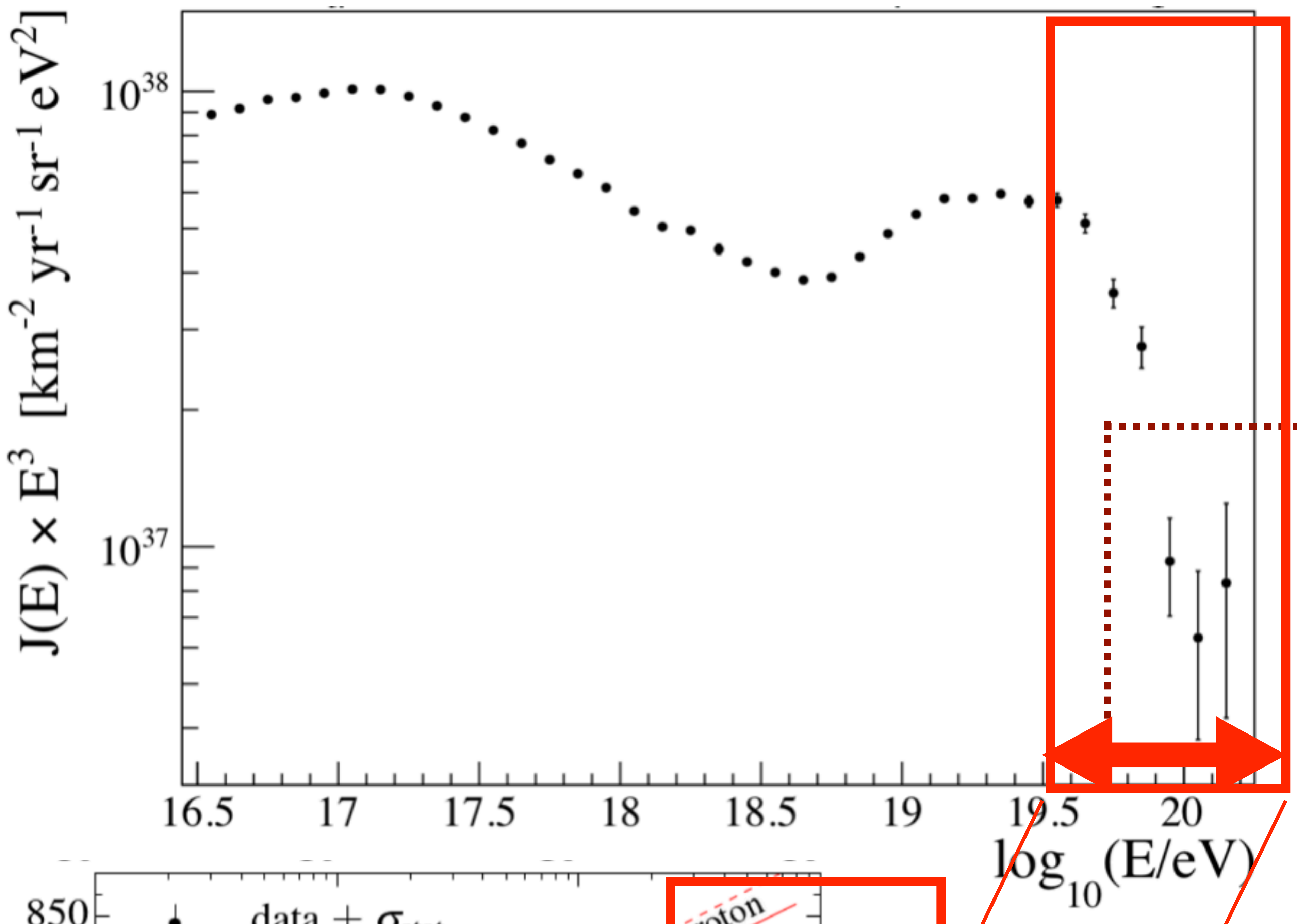
Post-LHC models give a good description of particle production in the first interaction.

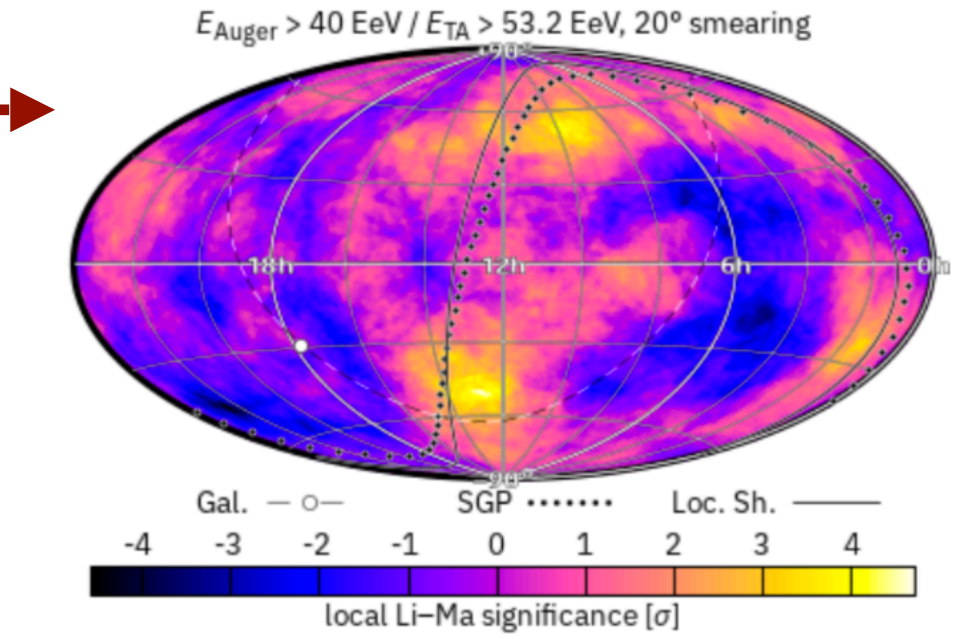
F. Riehn [Auger Collaboration], ICRC 2019 arXiv:1909.09073

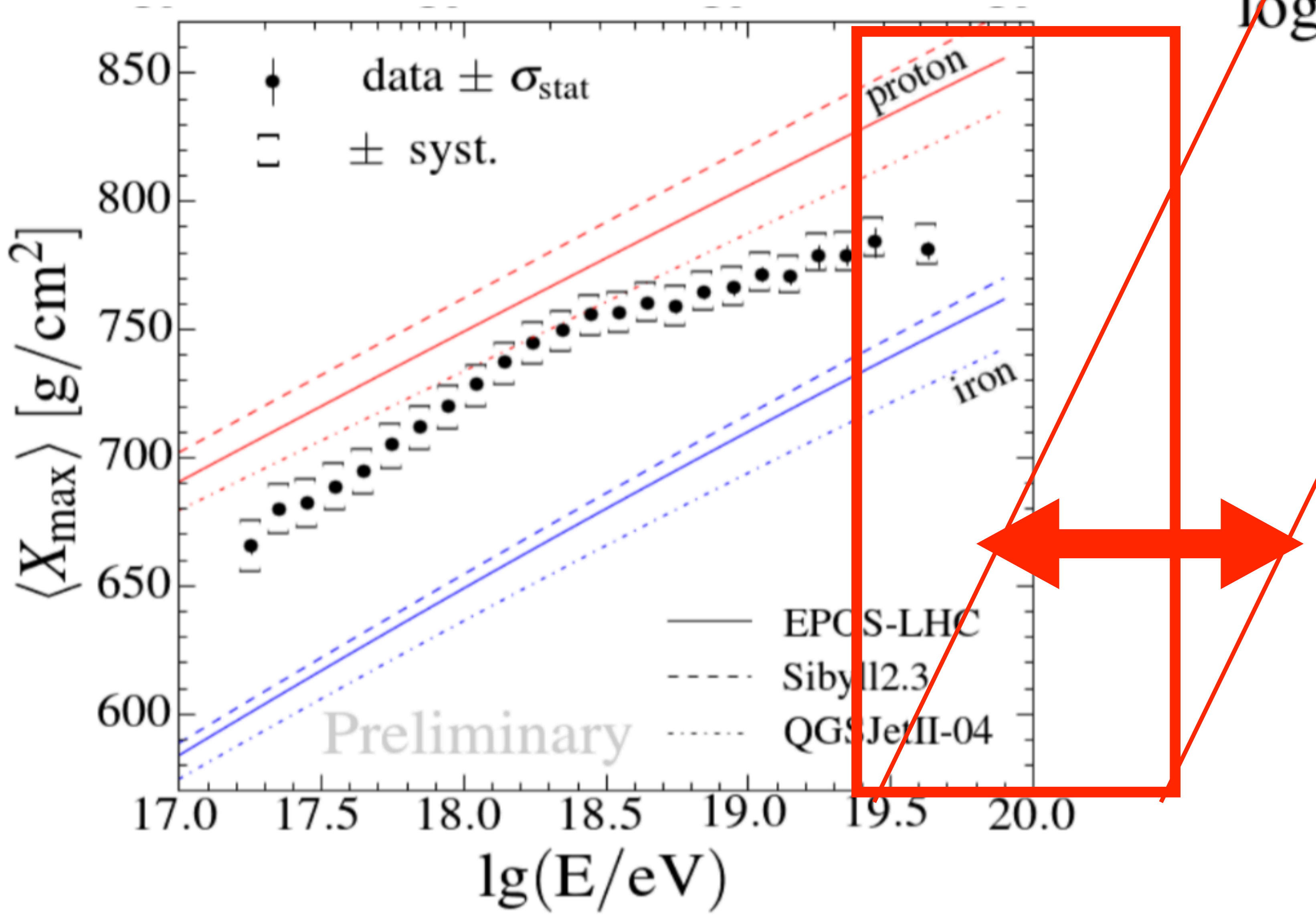
AugerPrime - science case for the upgrade

- Study the highest energy cosmic rays (spectral suppression region) with mass composition information
- Select light primaries for charged particle astronomy
- Provide better estimates of the UHE neutrino and photon fluxes. Establish potential for future experiments.
- Better measure shower components, study hadronic physics, search for non-standard physics

Auger operations extended to beyond 2025





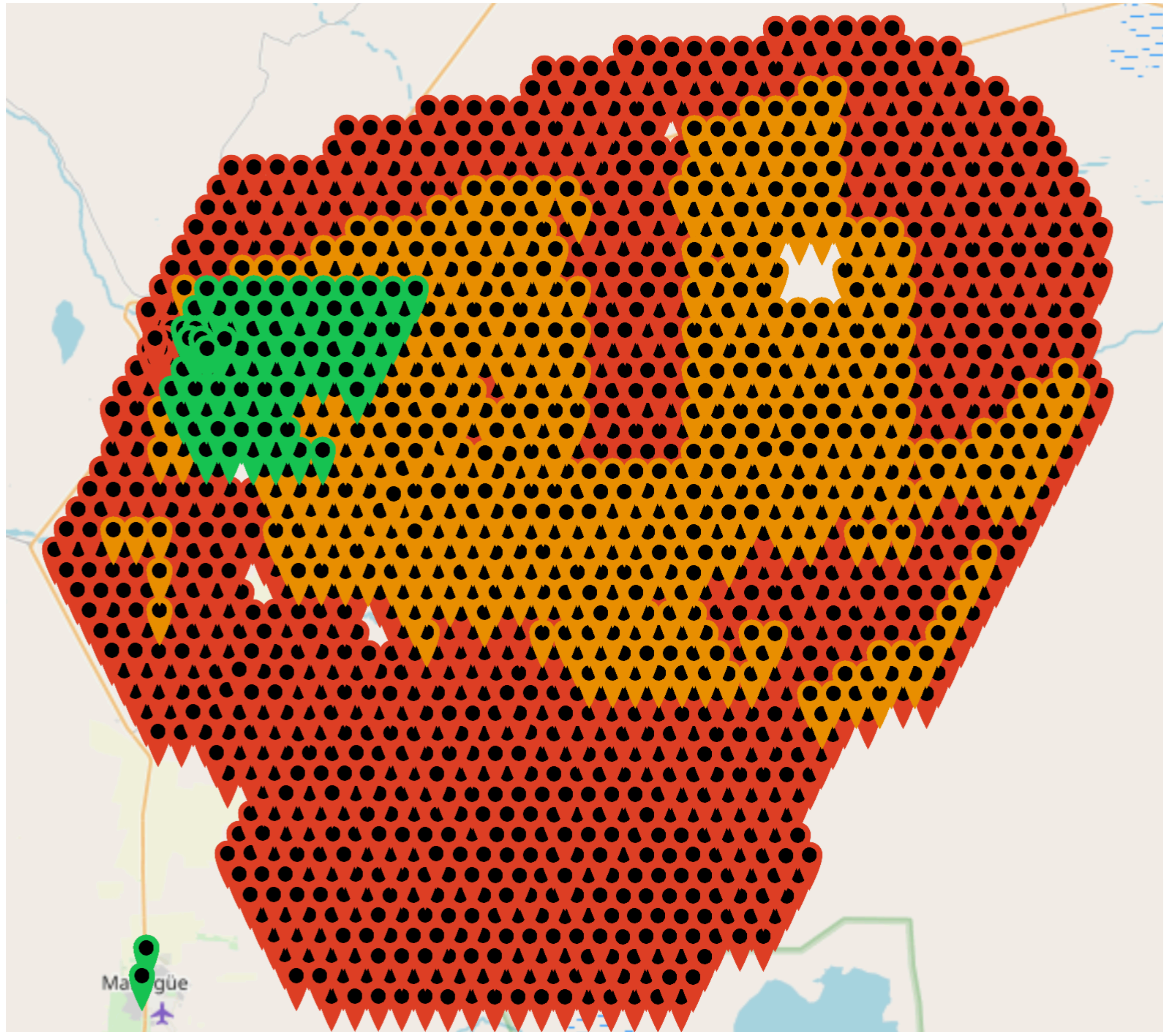


So far, event by event mass estimates limited to 13% FD duty cycle

AugerPrime - deployment underway

Mass-composition information for all events, including the very highest energies.

- Engineering array (12 stations) since 2016, scintillator (SSD), new electronics (faster sampling, increased dynamic range)
- Pre-production SSD array (80 stations) since March 2019.
- 559 SSD stations installed up to now (Nov 2019)
- Underground muon detector (UMD) construction continues
- New: 3000 km^2 radio detector

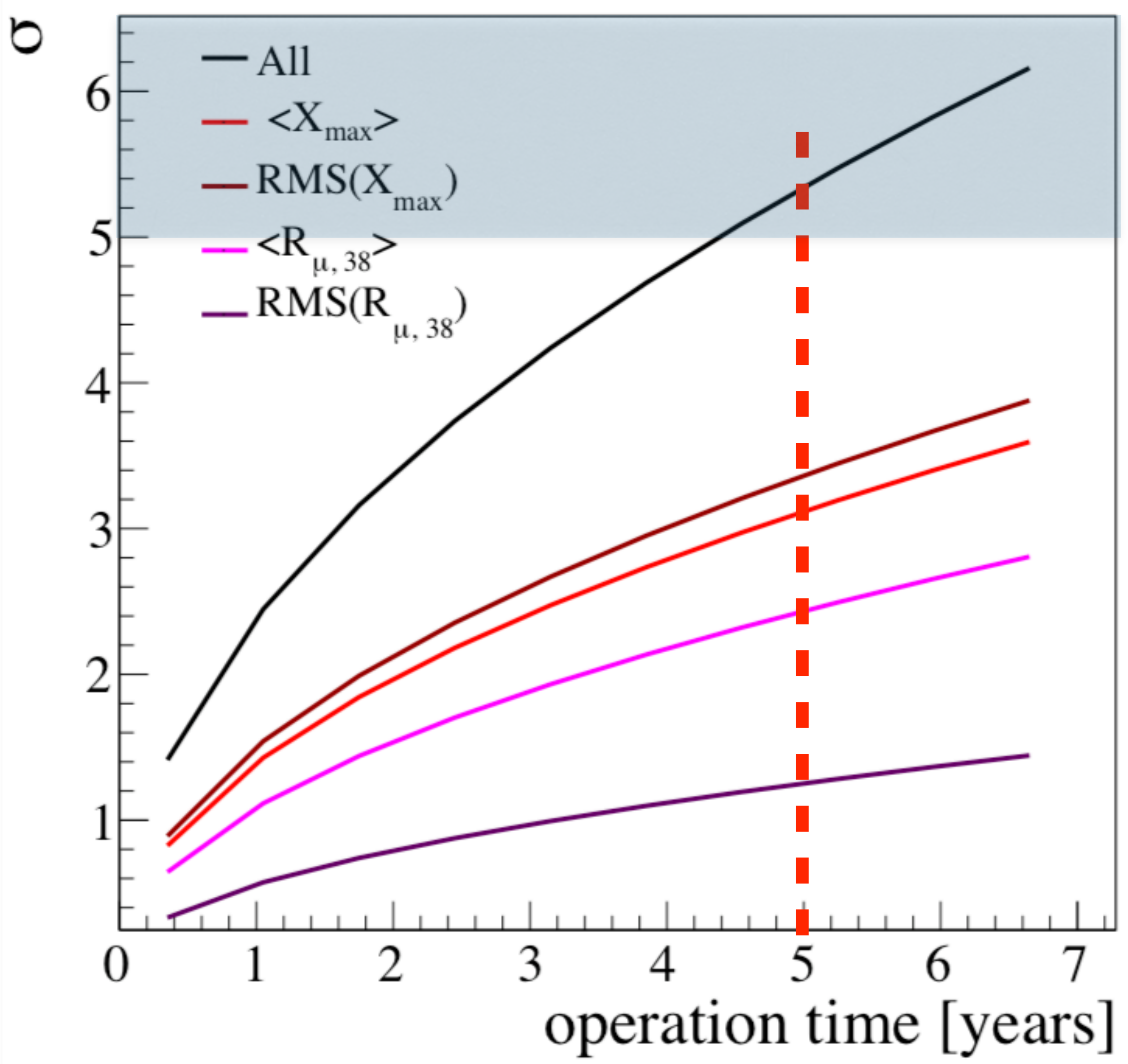


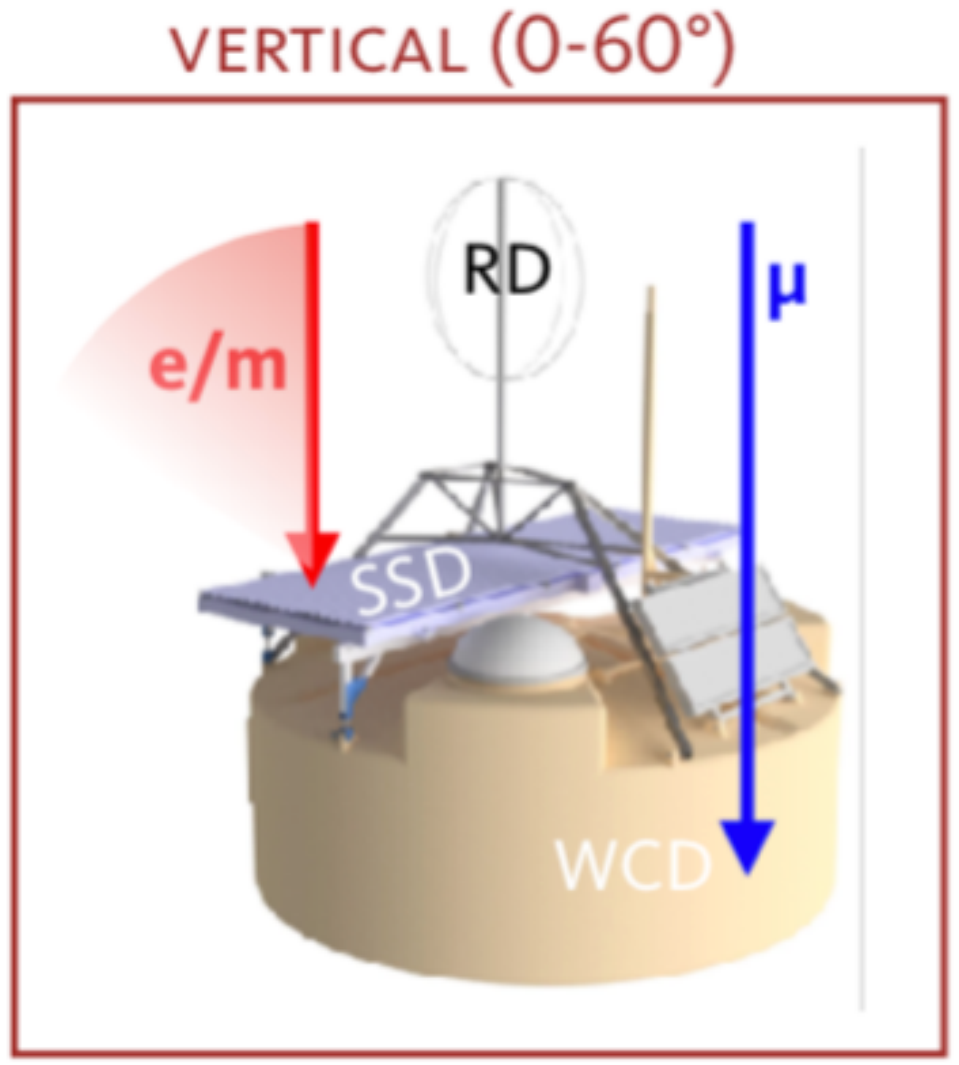
November 17, 2019

Water-Cherenkov detector (WCD) with new surface scintillator detector (SSD) and new radio antenna.

AugerPrime - the new detectors

Vertical showers





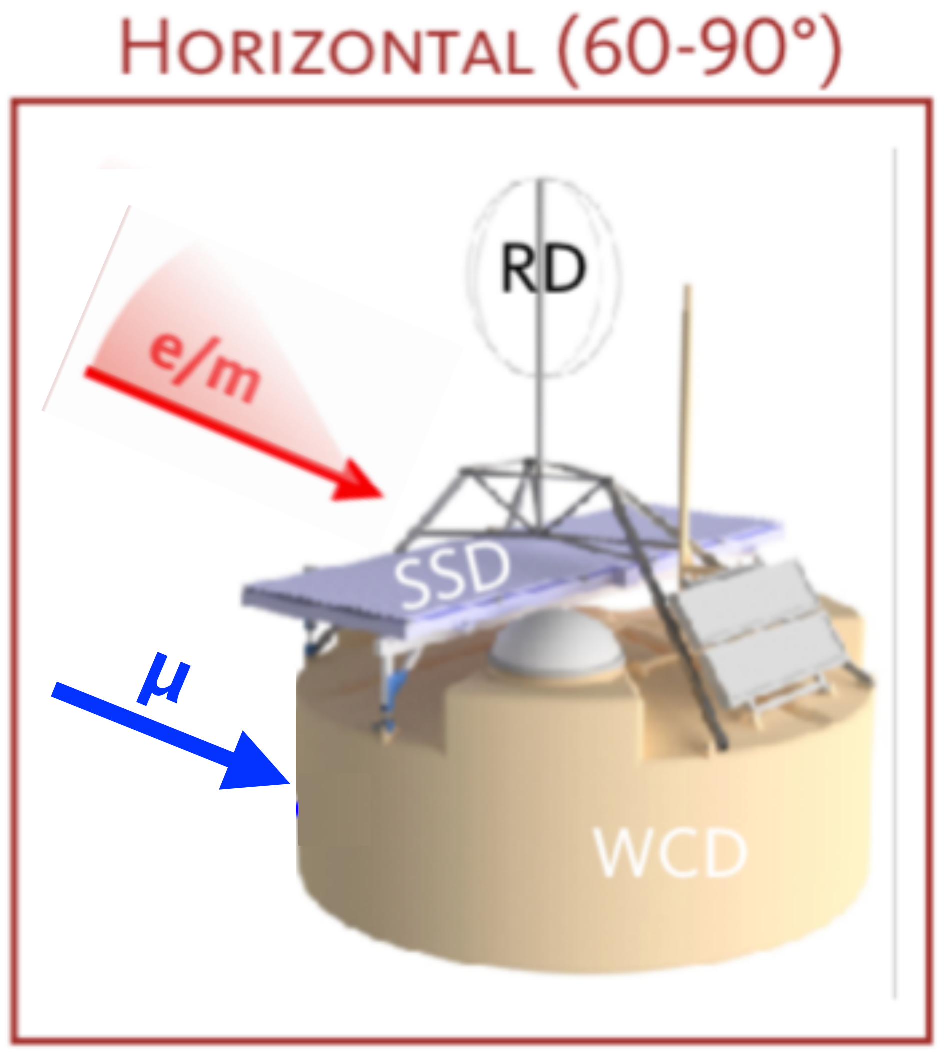
Significance of distinguishing two different realisations of Scenario 1 (maximum rigidity model) :

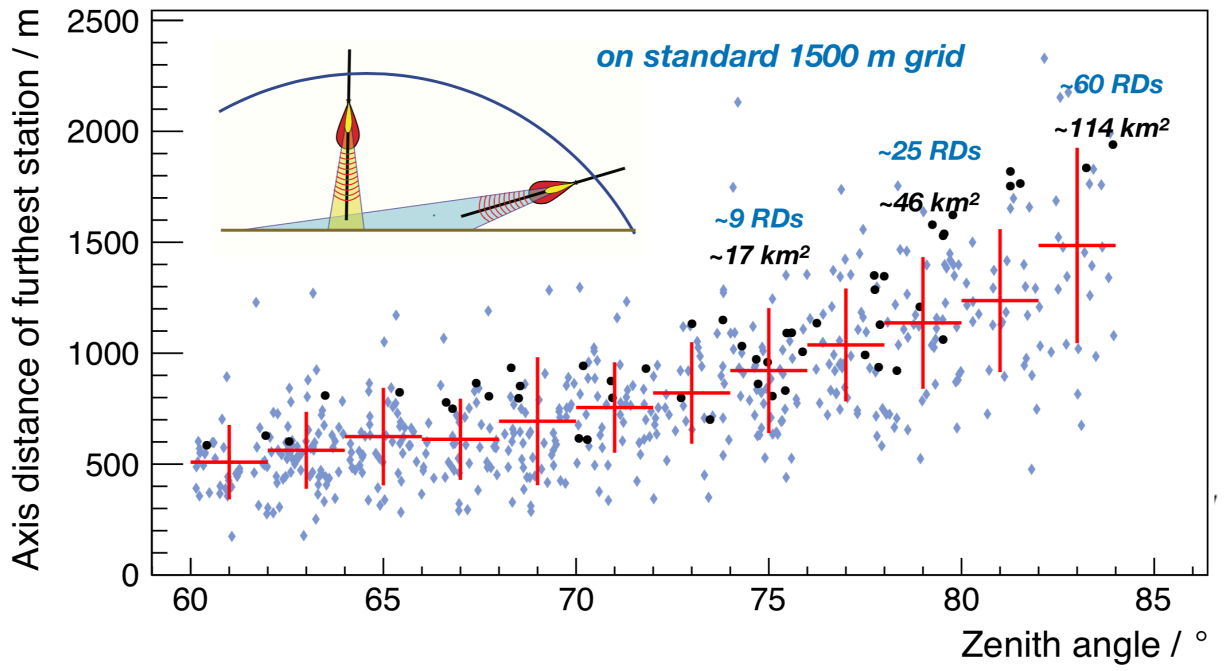
- as it predicts, i.e. no protons at UHE
- adding 10% protons

>5σ in 5 years of operations

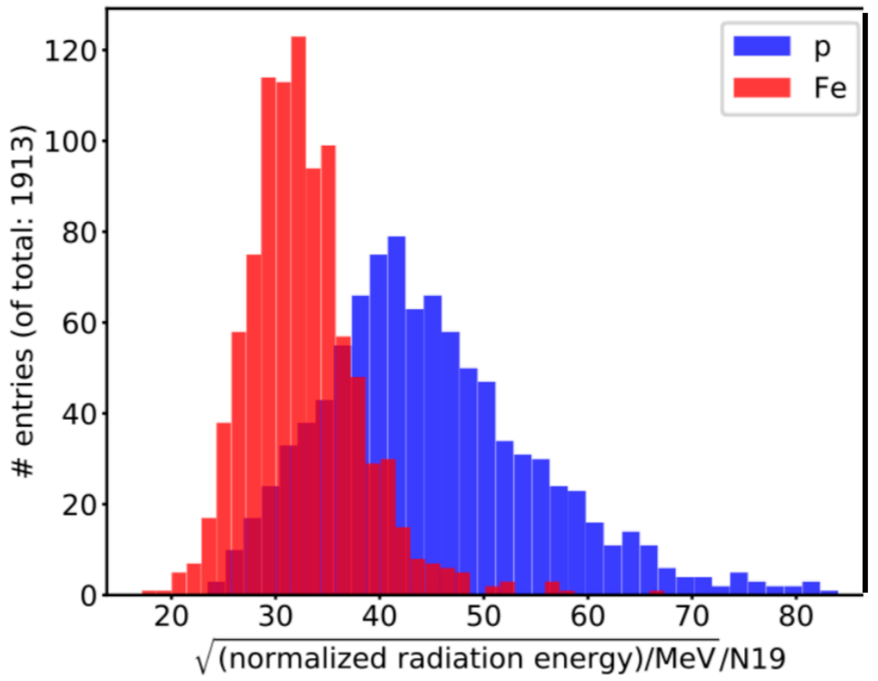
R. Engel [Auger Collaboration], ICRC 2015 arXiv:1509.03732

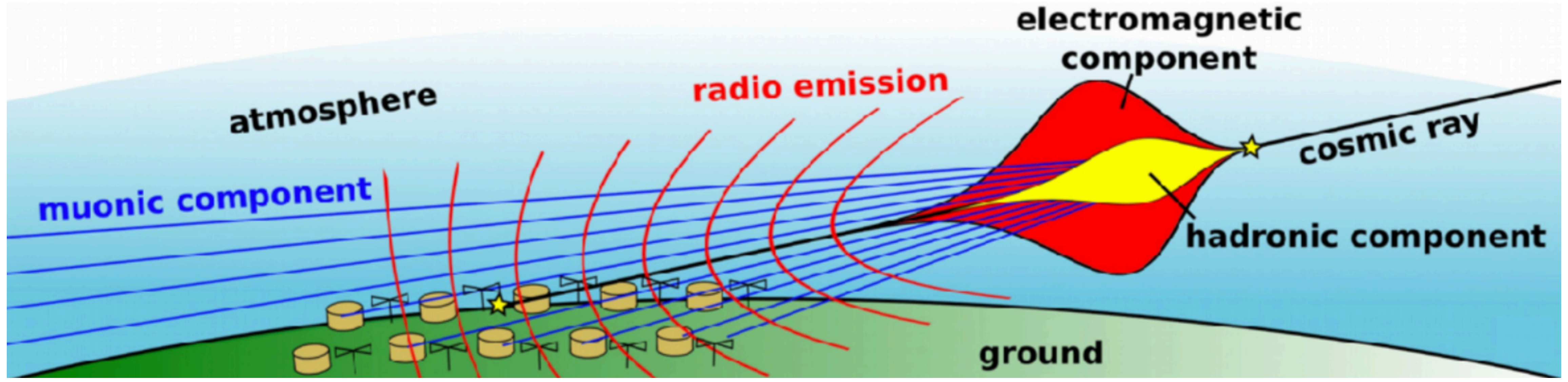
Horizontal showers



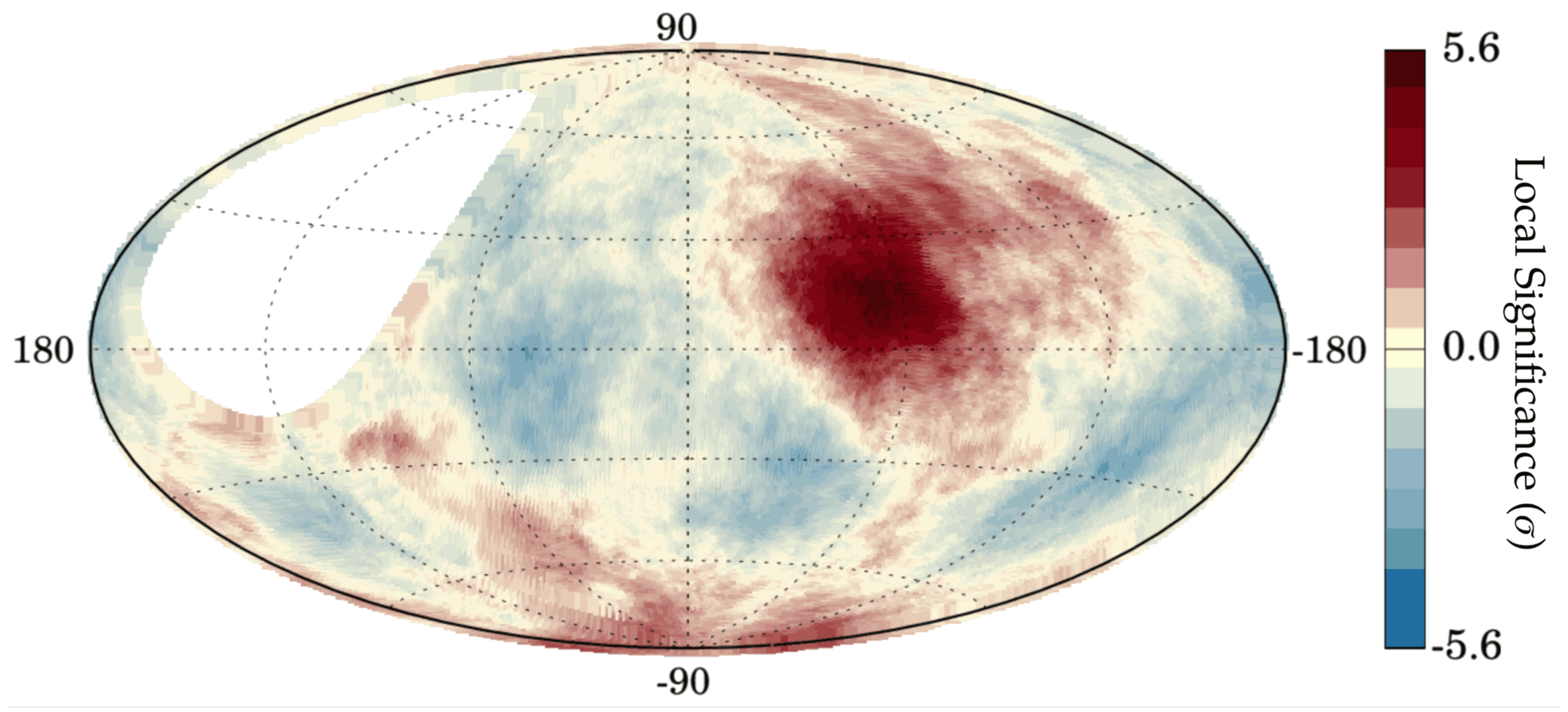


Hybrid:
E_{rad} from radio
muons from WCD

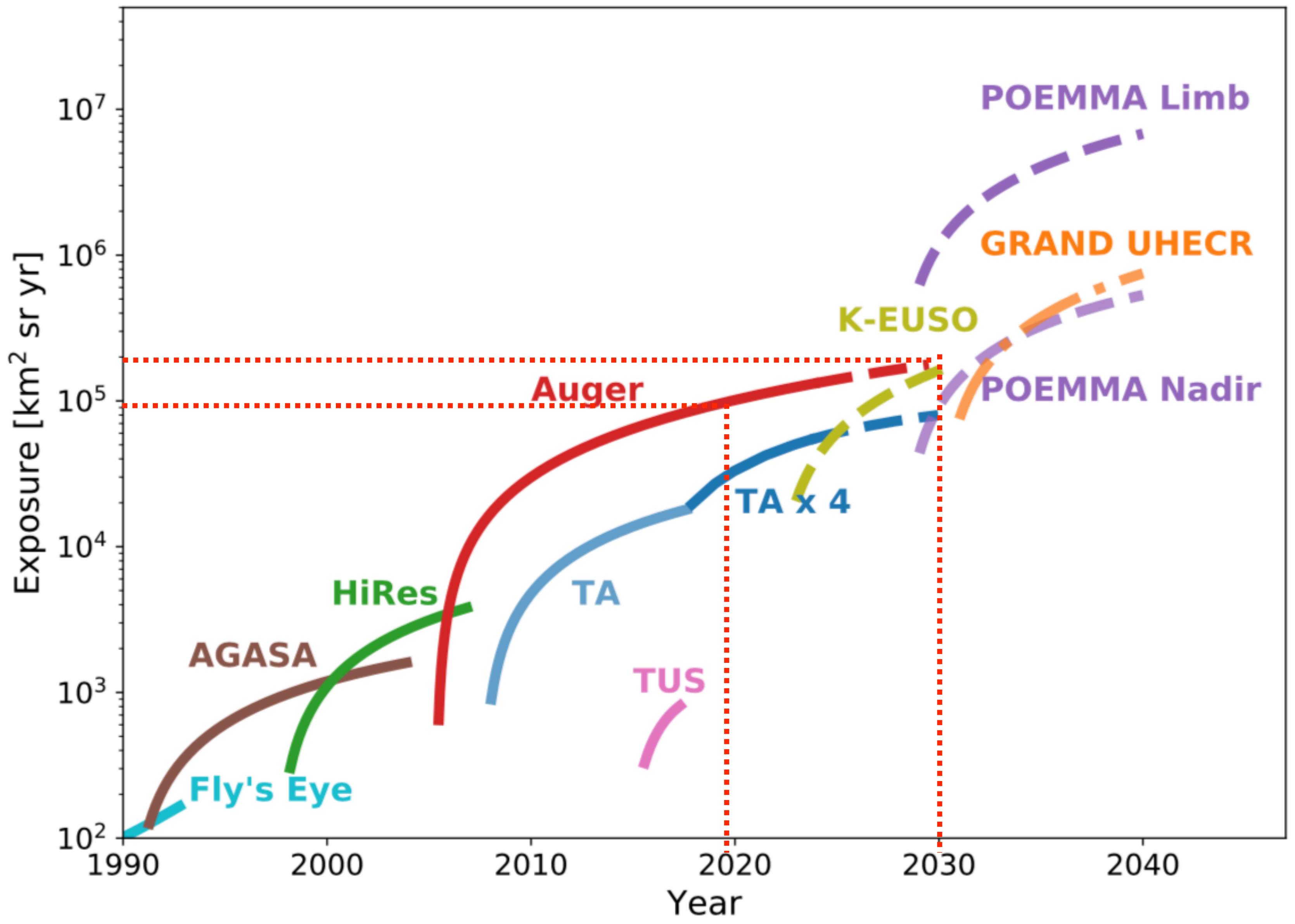




Conclusion and Outlook



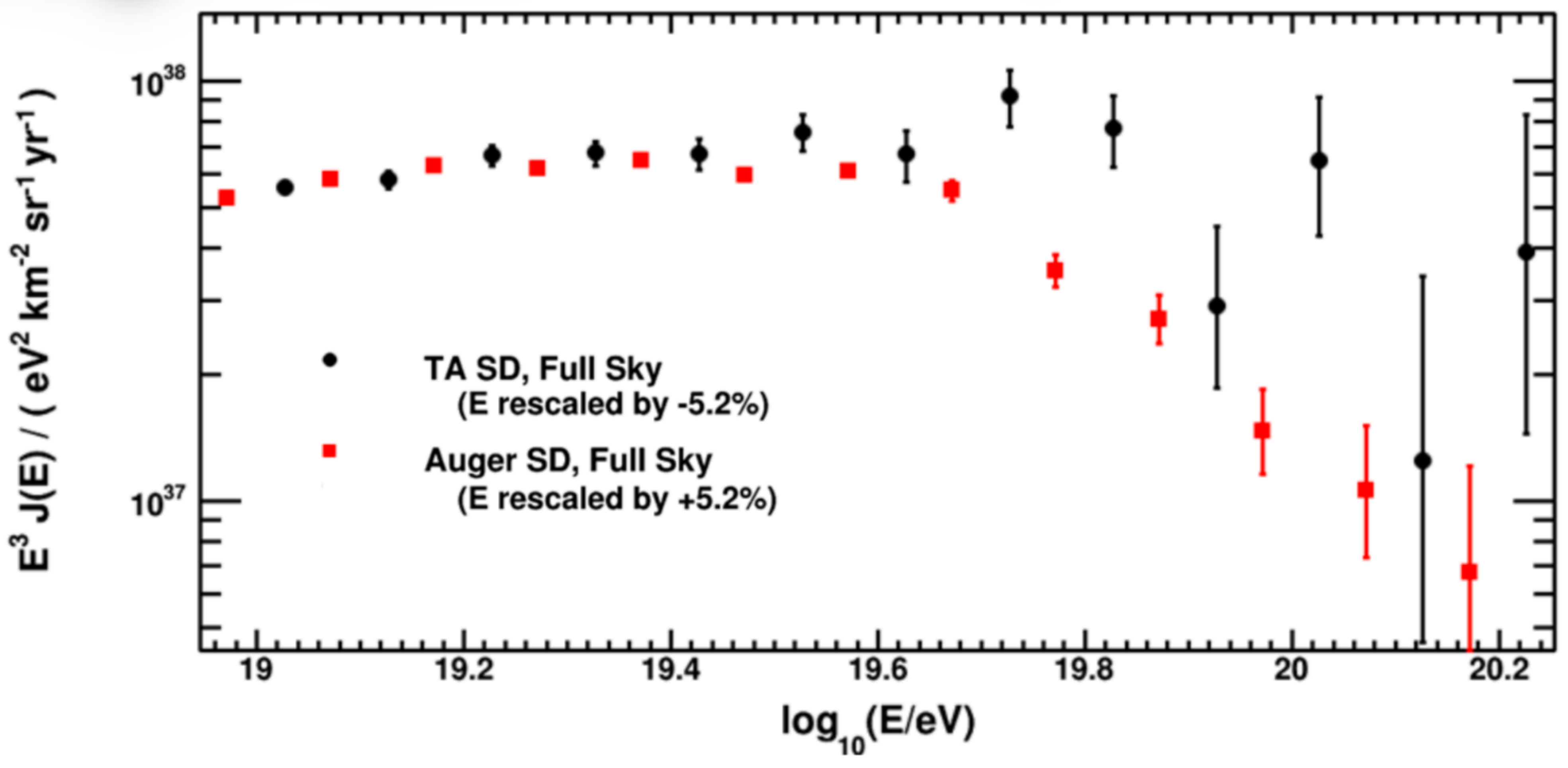
- Auger continues to provide a rich array of results, including increasingly significant anisotropies.
- AugerPrime will offer mass (charge) estimates for 100% of events (improved sky maps).
- We will double our exposure in the next 10 years, before any future observatory takes over.

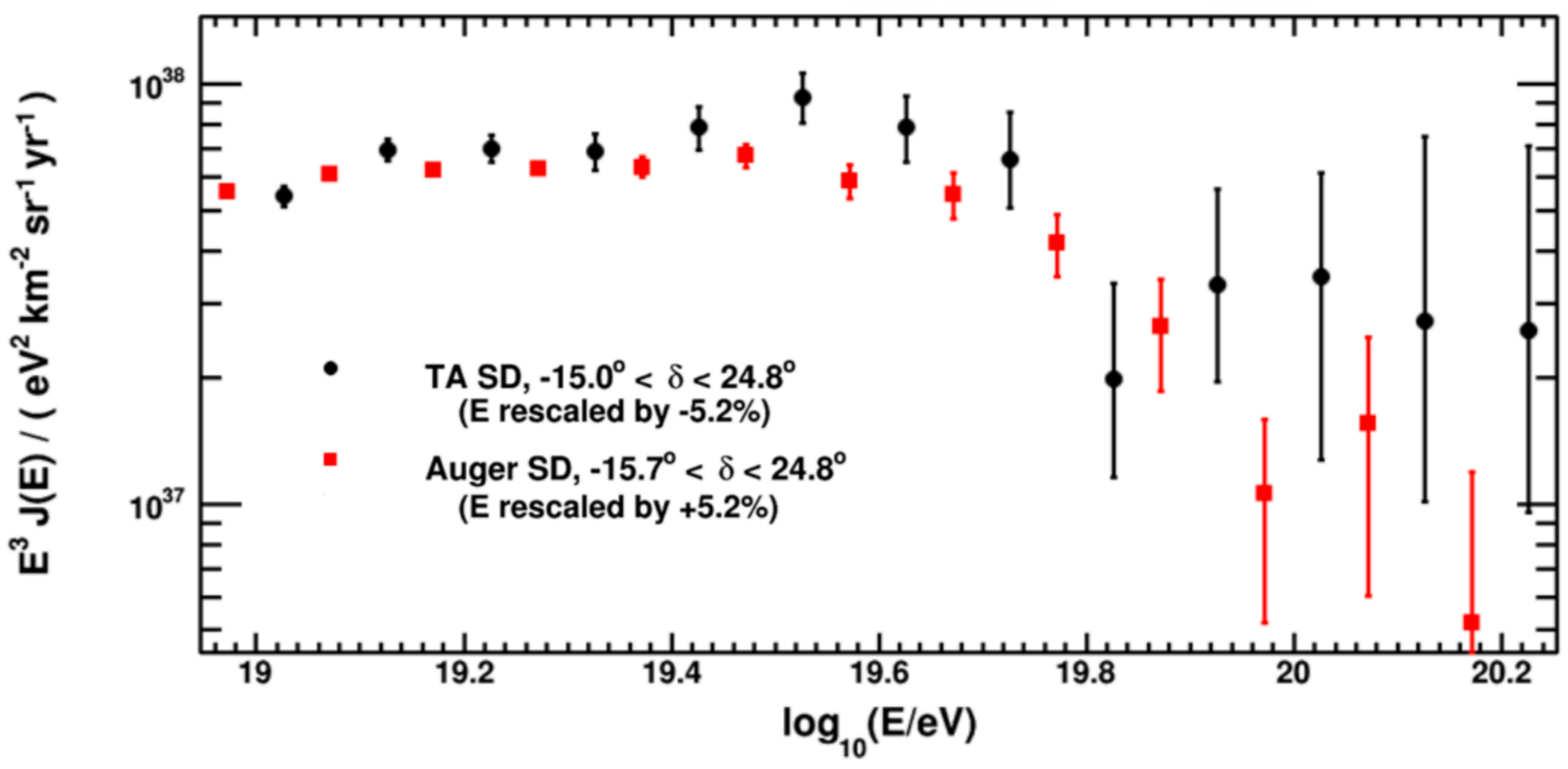


R.Batista et al., arXiv:1903.06714

Backup

Auger and Telescope Array spectrum working group





D.Ivanov, UHECR2018

- Agree in the ankle region $10^{18.4}$ eV < E < $10^{19.4}$ eV after rescaling
- **Difference above $10^{19.4}$ eV persists after locking energy scales of experiments**

Better agreement between TA and Auger in the common declination band

Source of Nonlinearity	Amount (percent per decade above 10^{19} eV)
FD missing energy correction	1% +/- 1%
FD Fluorescence Yield Model	-1% +/- 1%
FD Atmospheric Conditions	1.7% +/- 1%
SD and FD comparison:	-2% +/- 9%
Net	-0.3% +/- 9%

Sources of Energy-Dependent Energy Reconstruction Bias in Auger

Sources of nonlinearities	% per decade > 10 EeV
Aerosols	± 1%
stat. uncertainties calib. param.	± 1%
check with hybrids SD/FD comparison	± 2%
energy dependent CIC	± 2%
Net	**≈ ± 3%**

Full sky search with Auger and Telescope Array

Large Scale Anisotropy

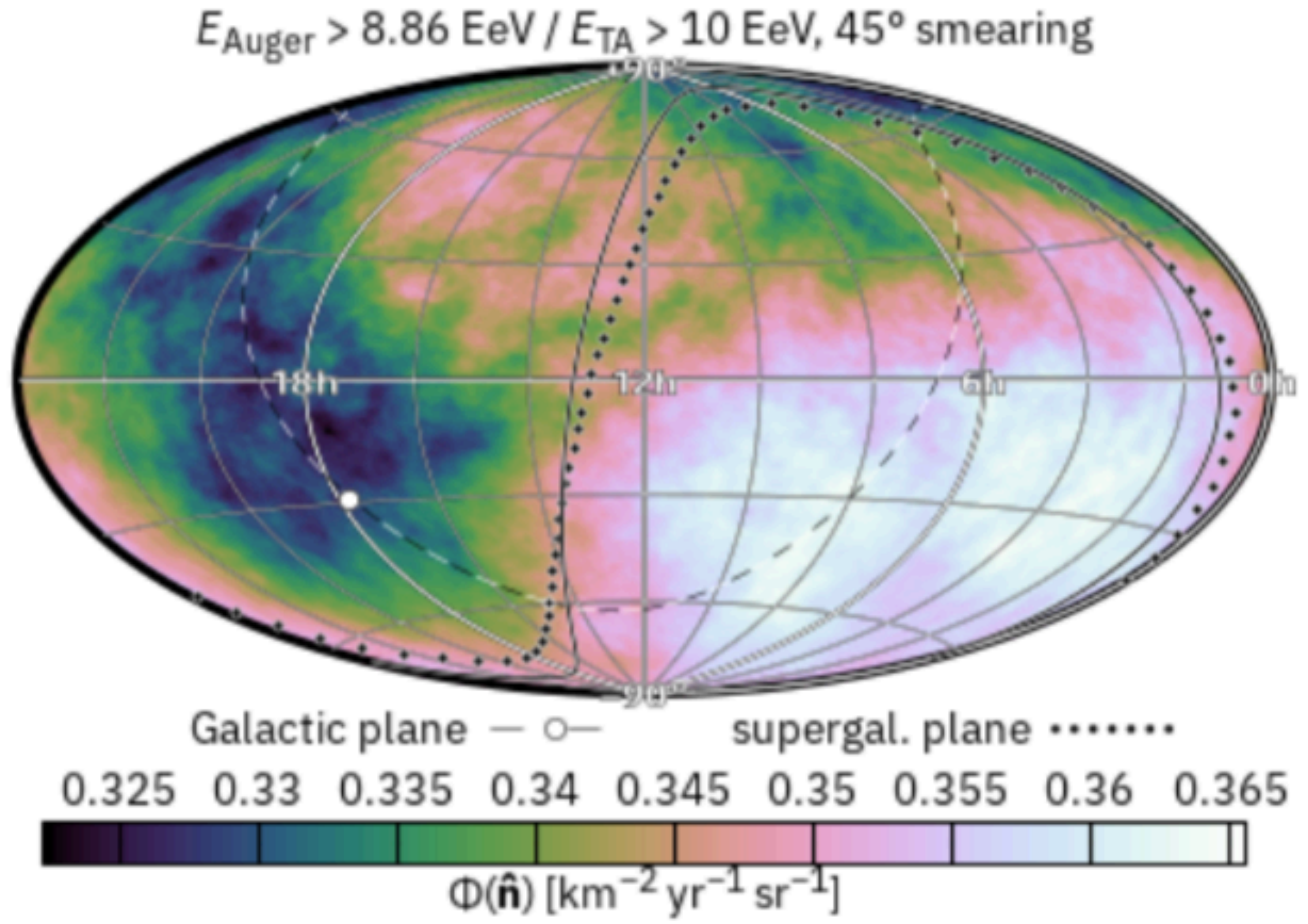
Energy threshold

8.86 EeV (Auger)

10 EeV (Telescope Array)

Events

~31000 events



$$d_x = (-0.7 \pm 1.1_{stat} \pm 0.01_{calib})\%$$
$$d_y = (+4.2 \pm 1.1_{stat} \pm 0.04_{calib})\%$$
$$d_z = (-2.6 \pm 1.3_{stat} \pm 1.4_{calib})\% \; (\pm 1.9\%_{tot})$$

Agreement with Auger alone, smaller uncertainty
Hint for a quadrupole moment

Intermediate Scale Anisotropy

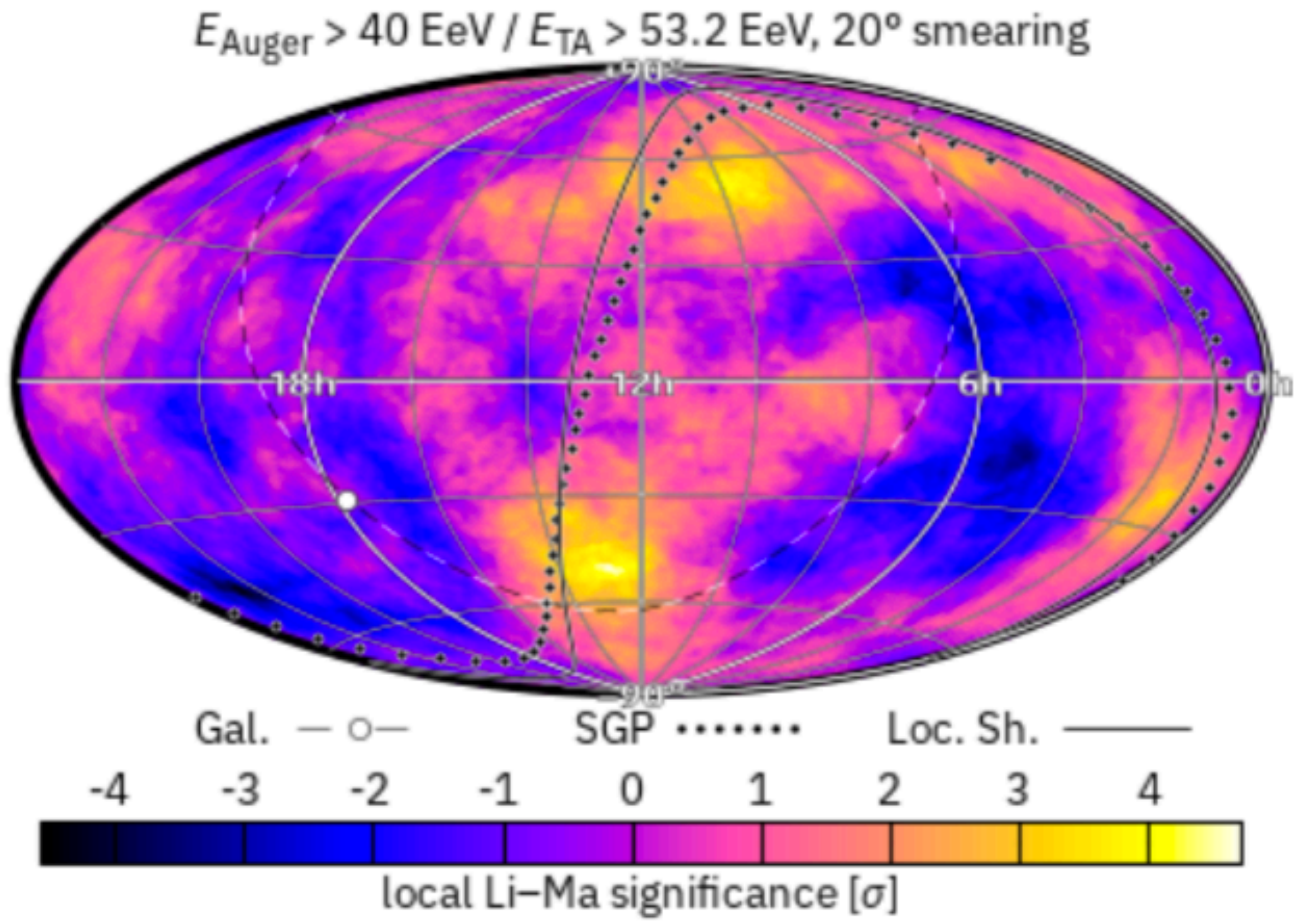
Energy threshold

40 EeV (Auger)

53.2 EeV (Telescope Array)

Events

969 events



Blind search

(α=12^h50^m, δ= - 50^0), 4.7 local sign (2.6 post-trial)
(α= 9^h30^m, δ= +54^0), 4.2 local sign (1.5 post-trial)

Local Sheet

26% higher flux in a band of $\pm 24^0$ around the Local Sheet (global significance 2.8σ)

A.di Matteo #439 ICRC 2019

Summary

A. Yushkov et al. (Auger/TA mass working group)
UHECR2018, Paris

$\langle X_{max}^{TA} \rangle < \langle X_{max}^{Auger} \rangle$ for almost all energies

agreement within $(\mathrm{stat} + \mathrm{sys})$ errors

$\sigma(X_{max}^{TA}) > \sigma(X_{max}^{Auger})$ for $\lg(E/\mathrm{eV}) = 18.6 - 19.0$

Next: comparison to Auger ICRC (2017) data and energies $\lg(E/\mathrm{eV}) > 19.0$