Selected results on ultra-high energy cosmic rays from Telescope Array

- Rubtsov G.I. (INR RAS), May 24, 2024
- Pereslavl-Zalessky

photo by Oleg Kalashev

Greisen-Zatsepin-Kuzmin cutoff

1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}-10^{22} eV. This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

О ВЕРХНЕЙ ГРАНИЦЕ СПЕКТРА КОСМИЧЕСКИХ ЛУЧЕЙ

Г.Т.Зацепин, В.А.Кузьмин

В недавних измерениях [1,2] обнаружено мощное изотропное тепловое излучение Вселенной, обладающее, по-видимому, распределением Планка с температурой $T \approx 3^0$K. Интенсивность этого излучения такова ($N \approx 550$ фотонов/см^3, $kT \approx 2{,}5.10^{-4}$ эв), что возникают специфические эффекты при прохождении через него космических лучей сверхвысоких энергий, в частности обрезание спектра космических лучей в области 10^{20} эв.

$$p + \gamma_{2.7K} \to \Delta^+ \to n + \pi^+$$
$$\to p + \pi^0$$

$E \gtrsim 10^{19.7}$ eV

Heavy nuclei photodisintegrate at the same energies

Greisen-Zatsepin-Kuzmin cutoff

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The author expresses thanks for the hospitality of the Physics Department of the University of Utah, where this Letter was written.

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$$\to p + \pi^0$$

$$E \gtrsim 10^{19.7}\ \text{eV}$$

Heavy nuclei photodisintegrate at the same energies

The problem of the origin of cosmic rays

Как нам представляется, к 2001 году или во всяком случае к 2012 году можно ожидать выяснения почти всех вопросов, сформулированных в конце предыдущего параграфа.

В.Л. Гинзбург, Астрофизика космических лучей, 1990 г.

(Примечание: речь об источниках космических лучей)

Telescope Array observatory

- The largest cosmic ray observatory in the northern hemisphere

Telescope Array

- Delta, Utah, USA. ~1400 m above sea level
- Collaborators from HiRes, AGASA and other institutes

Scientific Goals

- Origin and nature of the ultra-high energy cosmic rays:
  - spectrum, composition, anisotropy
- Physics of high energy hadronic interactions
- Multi-messenger and interdisciplinary studies
  - photons, neutrinos, dark matters
  - thunderstorms, terrestrial gamma-ray flash
  - meteoroids
- Development of the next-generation experiments

Telescope Array Collaboration

R.U. Abbasi[1], Y. Abe[2], T. Abu-Zayyad[1,3], M. Allen[3], E. Barcikowski[3], J.W. Belz[3], D.R. Bergman[3], S.A. Blake[3], I. Buckland[3], W. Campbell[3], B.G. Cheon[4], M. Chikawa[5], K. Endo[6], A. Fedynitch[5,7], T. Fujii[6,8], K. Fujisue[5], K. Fujita[5], M. Fukushima[5], G. Furlich[3], Z. Gerber[3], N. Globus[*9], W. Hanlon[3], N. Hayashida[10], H. He[9], R. Hibi[2], K. Hibino[10], R. Higuchi[9], K. Honda[11], D. Ikeda[10], N. Inoue[12], T. Ishii[11], H. Ito[9], D. Ivanov[3], H.M. Jeong[13], S. Jeong[13], C.C.H. Jui[3], K. Kadota[14], F. Kakimoto[10], O. Kalashev[15], K. Kasahara[16], S. Kasami[17], Y. Kawachi[6], S. Kawakami[6], K. Kawata[5], I. Kharuk[15], E. Kido[9], H.B. Kim[4], J.H. Kim[3], J.H. Kim[†3], S.W. Kim[13], Y. Kimura[6], R. Kobo[6], I. Komae[6], K. Komori[17], Y. Kusumori[17], M. Kuznetsov[15,18], Y.J. Kwon[19], K.H. Lee[4], M.J. Lee[13], B. Lubsandorzhiev[15], J.P. Lundquist[3,20], T. Matsuyama[6], J.A. Matthews[3], J.N. Matthews[3], R. Mayta[6], K. Miyashita[2], K. Mizuno[2], M. Mori[17], M. Murakami[17], I. Myers[3], S. Nagataki[9], M. Nakahara[6], K. Nakai[6], T. Nakamura[21], E. Nishio[17], T. Nonaka[5], S. Ogio[5], H. Ohoka[5], N. Okazaki[5], Y. Oku[17], T. Okuda[22], Y. Omura[6], M. Onishi[5], M. Ono[9], A. Oshima[23], H. Oshima[5], S. Ozawa[24], I.H. Park[13], K.Y. Park[4], M. Potts[3], M. Przybylak[‡25], M.S. Pshirkov[15,26], J. Remington[3], D.C. Rodriguez[3], C. Rott[3,13], G.I. Rubtsov[15], D. Ryu[27], H. Sagawa[5], R. Saito[2], N. Sakaki[5], T. Sako[5], S. Sakurai[17], D. Sato[2], S. Sato[17], K. Sekino[5], P.D. Shah[3], N. Shibata[17], T. Shibata[5], J. Shikita[6], H. Shimodaira[5], B.K. Shin[27], H.S. Shin[6,8], K. Shinozaki[25], D. Shinto[17], J.D. Smith[3], P. Sokolsky[3], B.T. Stokes[3], T.A. Stroman[3], Y. Takagi[17], K. Takahashi[5], M. Takamura[28], M. Takeda[5], R. Takeishi[5], A. Taketa[29], M. Takita[5], Y. Tameda[17], K. Tanaka[30], M. Tanaka[31], S.B. Thomas[3], G.B. Thomson[3], P. Tinyakov[15,18], I. Tkachev[15], H. Tokuno[32], T. Tomida[2], S. Troitsky[15], Y. Tsunesada[6,8], S. Udo[10], F. Urban[33], I.A. Vaiman[15], M. Vrábel[25], D. Warren[9], T. Wong[3], K. Yamazaki[23], K. Yashiro[28], F. Yoshida[17], Y. Zhezher[5,15], Z. Zundel[3], and J. Zvirzdin[3]

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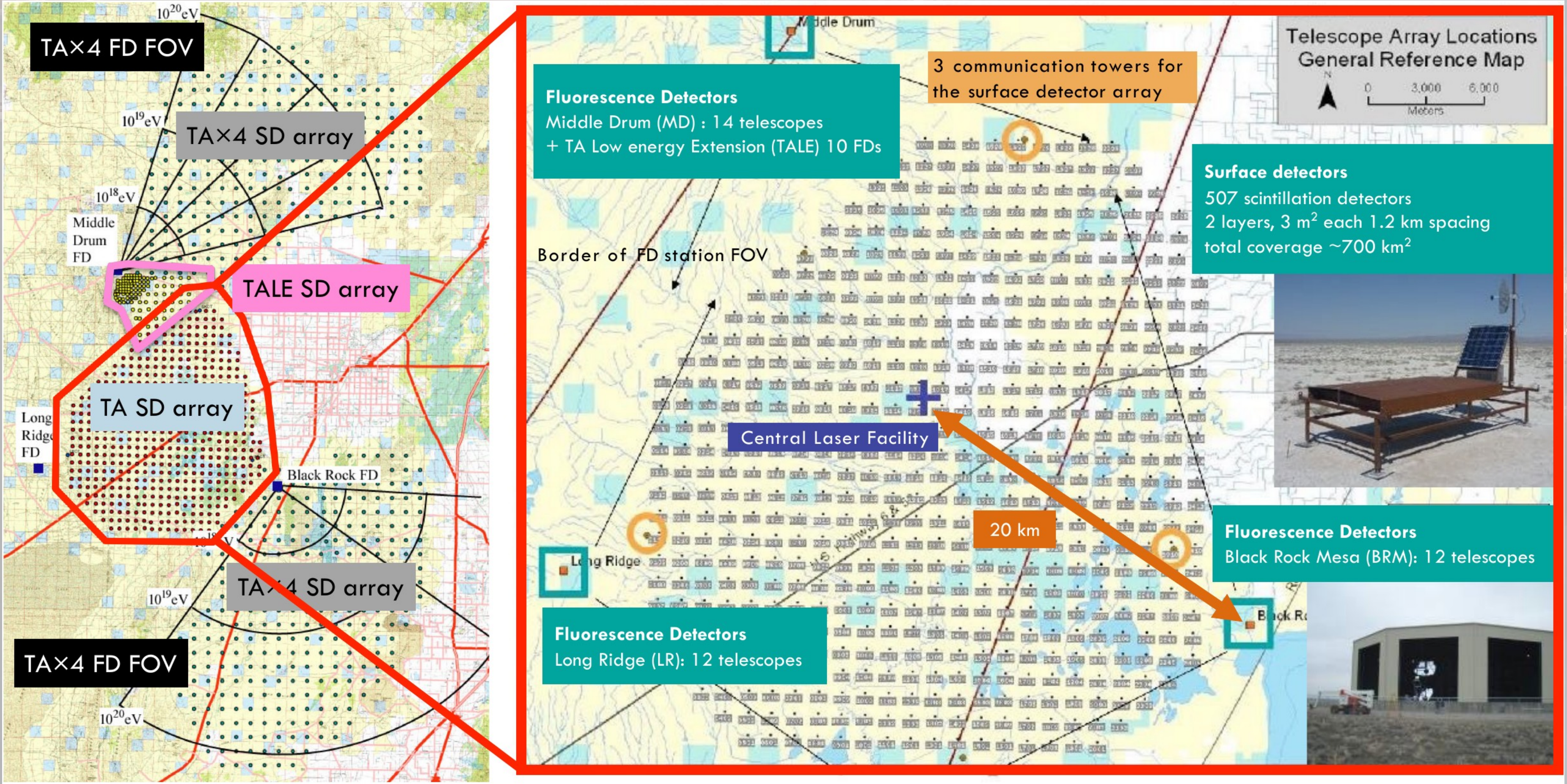
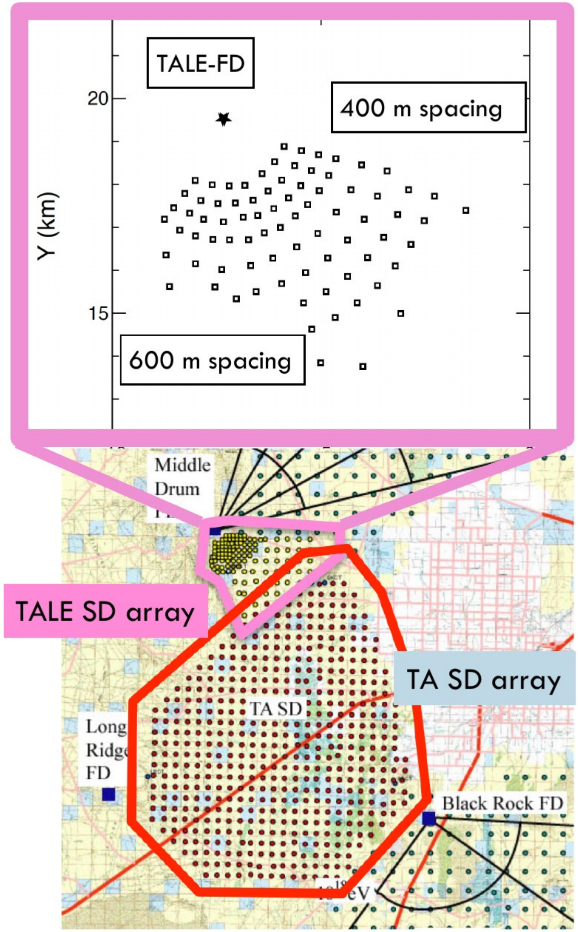
[33] *CEICO, Institute of Physics, Czech Academy of Sciences, Prague 182 21, Czech Republic*

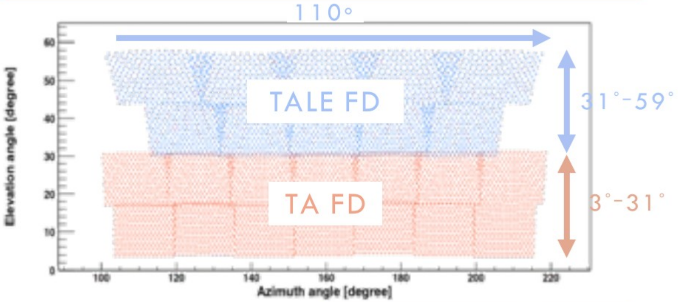
145 members, 33 institutes, 8 countries

Telescope Array observatory



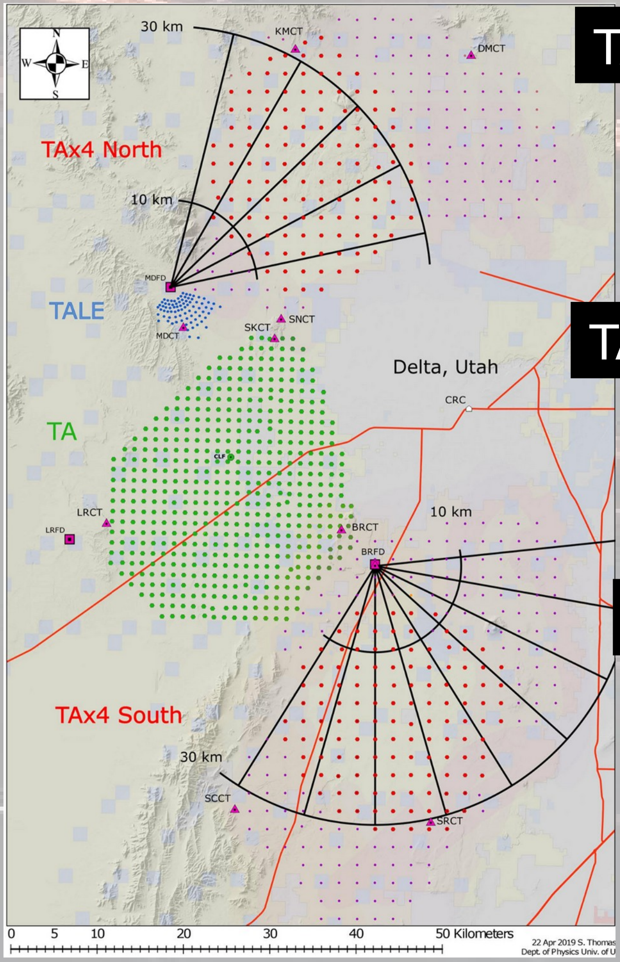
TA Low Energy extension (TALE)





- Low energy extension of TA sensitivity down to $\sim 10^{15}$ eV
- Hybrid measurement
  - 10 FDs observing higher elevation of 30°–59°
  - 80 SDs with 400–600 m spacing
- Precise measurement of the composition
  - FDs installed in Nov. 2012
  - Operation since Sep. 2013

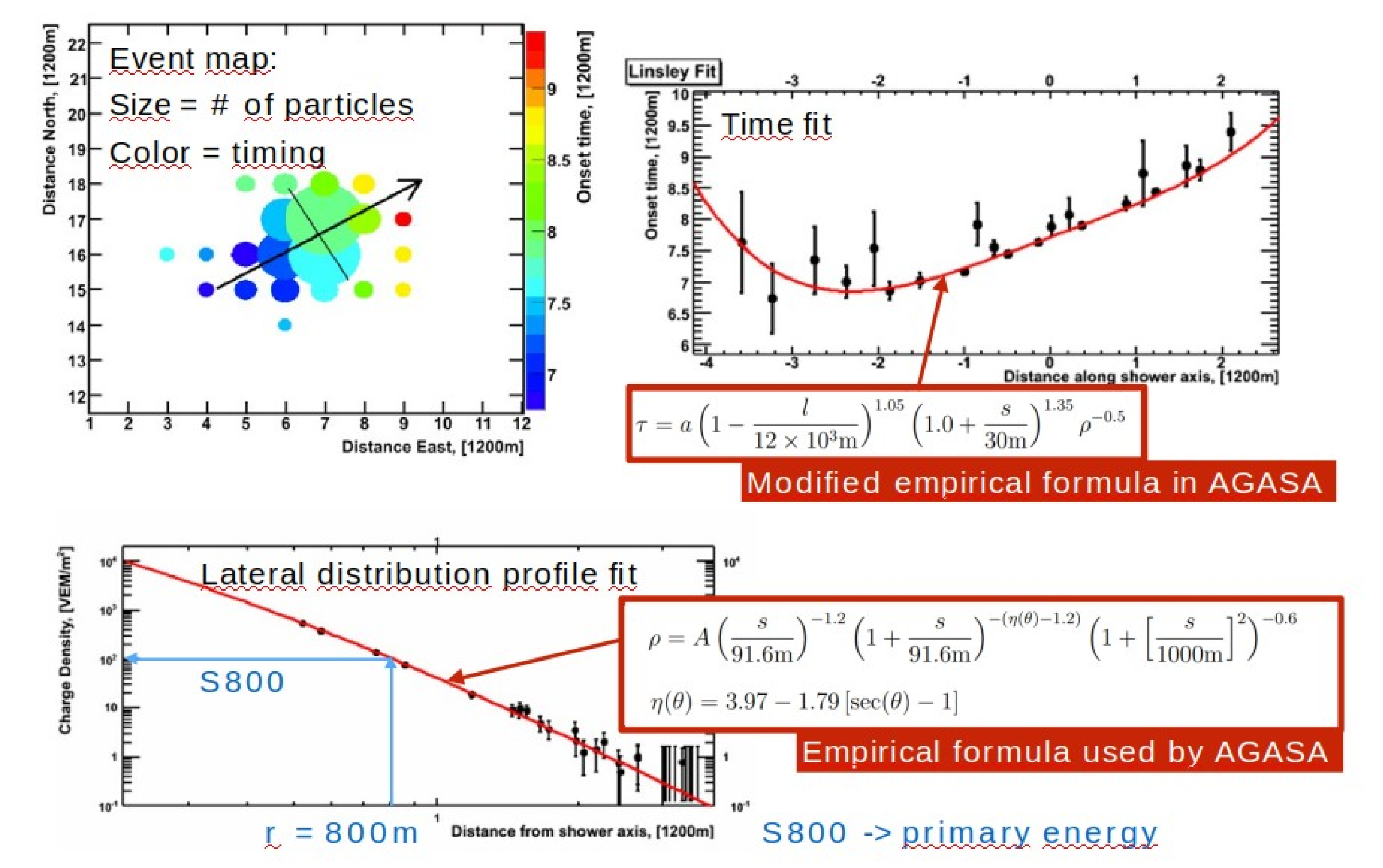
TAx4 project, ~3000 km²



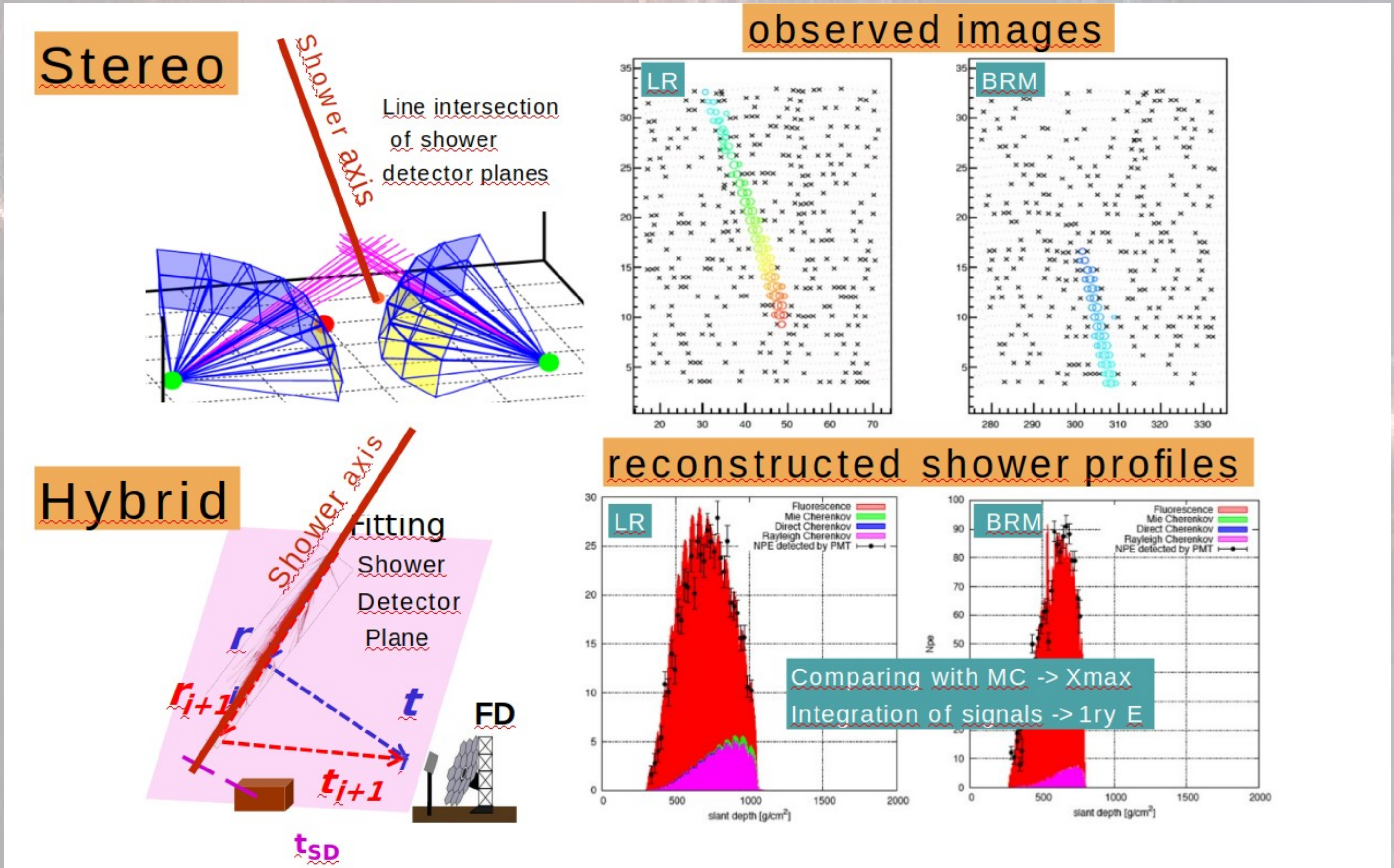
- TA4 motivation
  - greatly increase the data sample at the highest energies in order to identify UHECR sources
- SDs
  - 500 new SDs at 2.08 km spacing
  - 257 deployed thus far and operational
- FDs
  - 12 telescopes deployed and operational
  - 4 North and 8 South

9

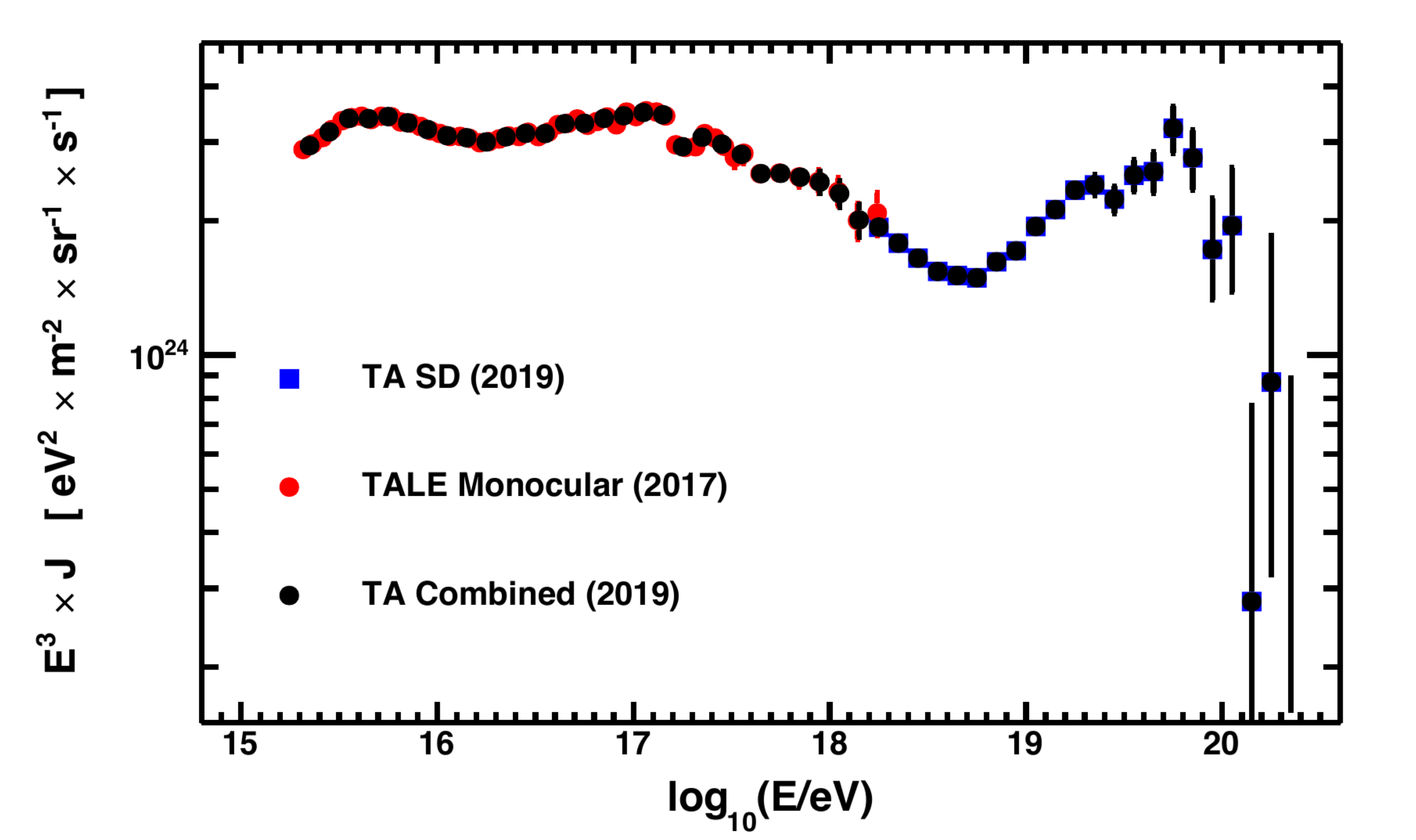
TA surface detector event reconstruction



TA hybrid and stereo event reconstruction

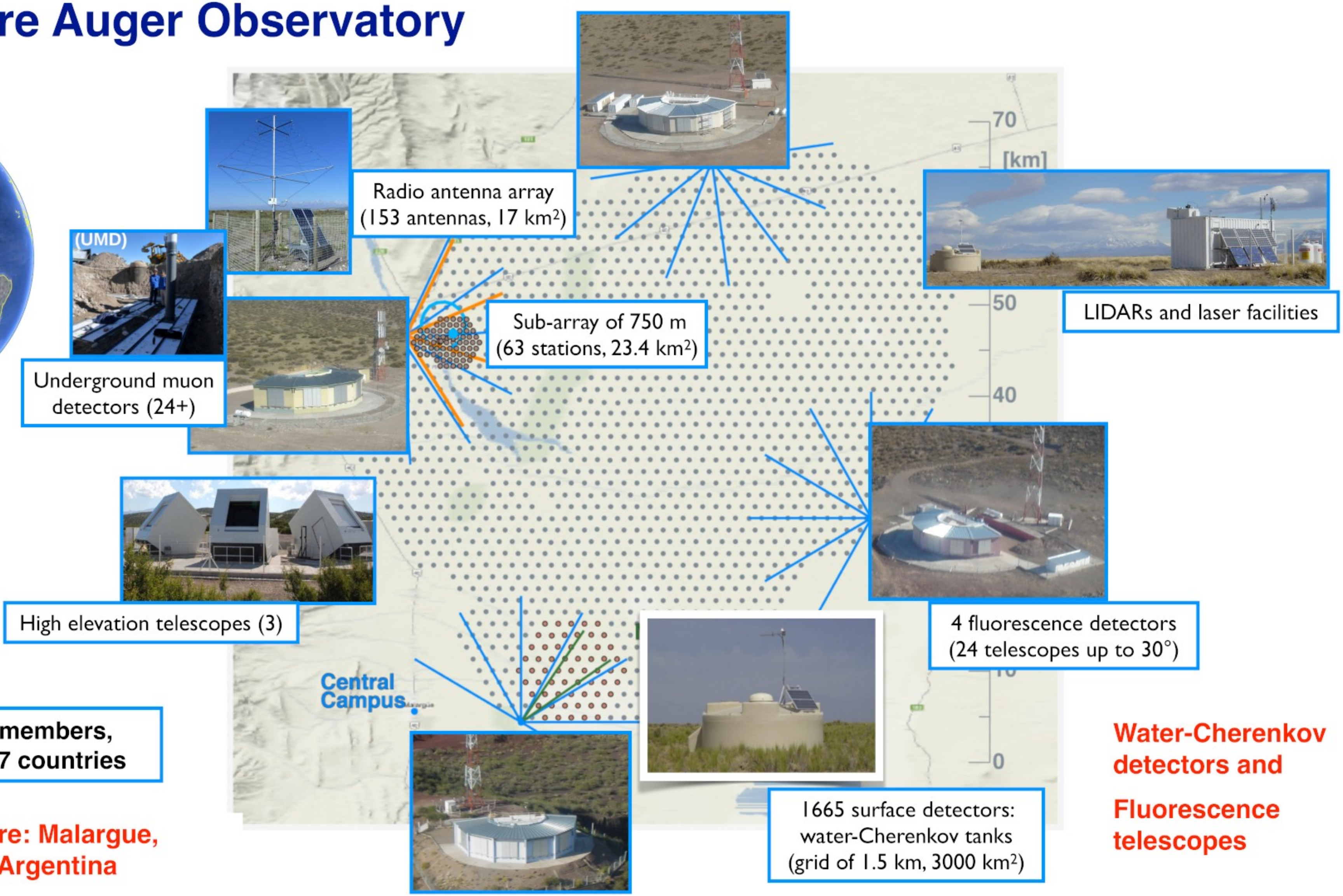


From 10^{15} eV to more than 10^{20} eV within one observatory



J. Kim, ICRC'2023

The Pierre Auger Observatory



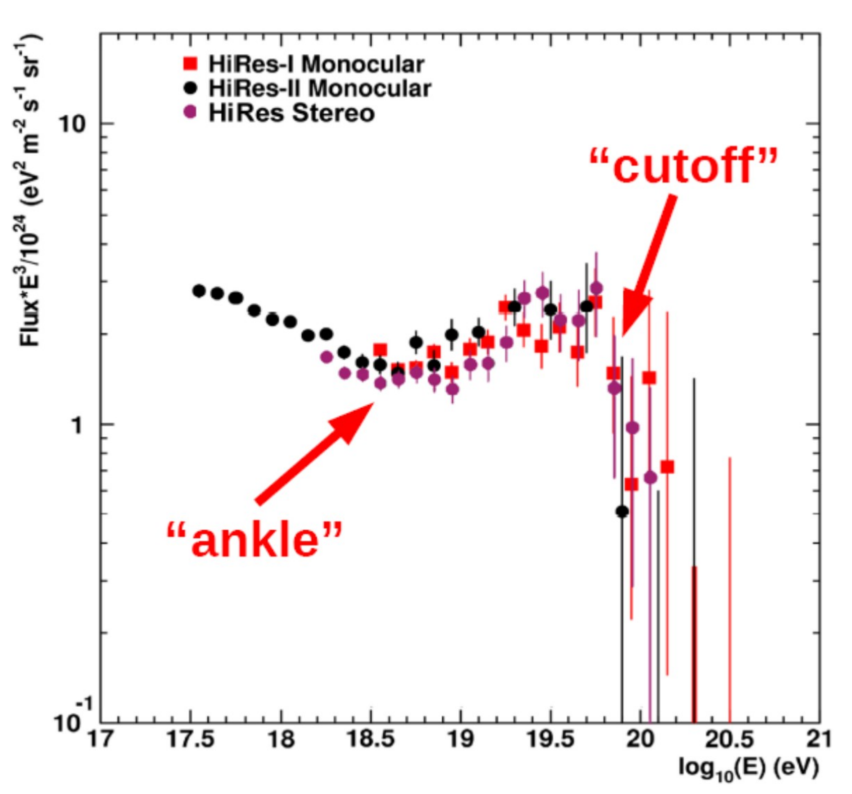
More than 400 members,
98 institutes, 17 countries

Southern hemisphere: Malargue, Province Mendoza, Argentina

Water-Cherenkov detectors and

Fluorescence telescopes

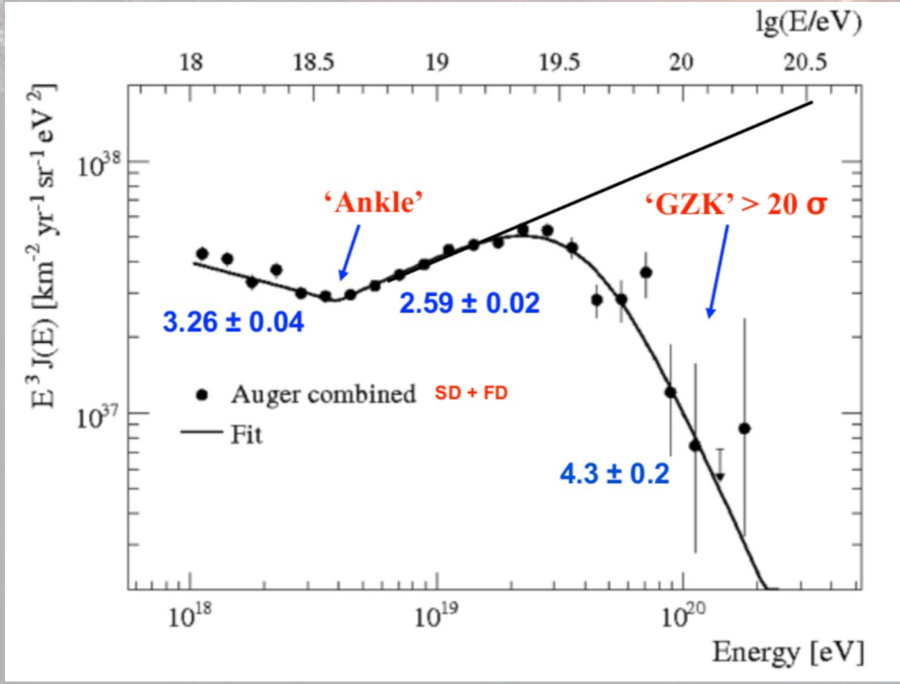
Observation of GZK cut-off by HiRes experiment



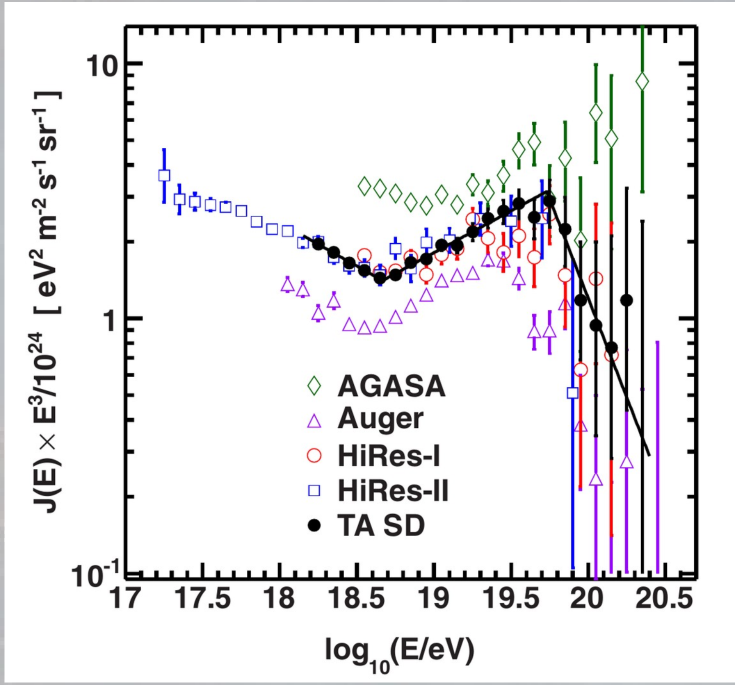
First observation at 5σ confidence level!

Monocular: Quarks'06; PRL 100 (2008)
Stereo: Astropart. Phys. 32 (2010)

GZK effect confirmation by Auger and TA observatories

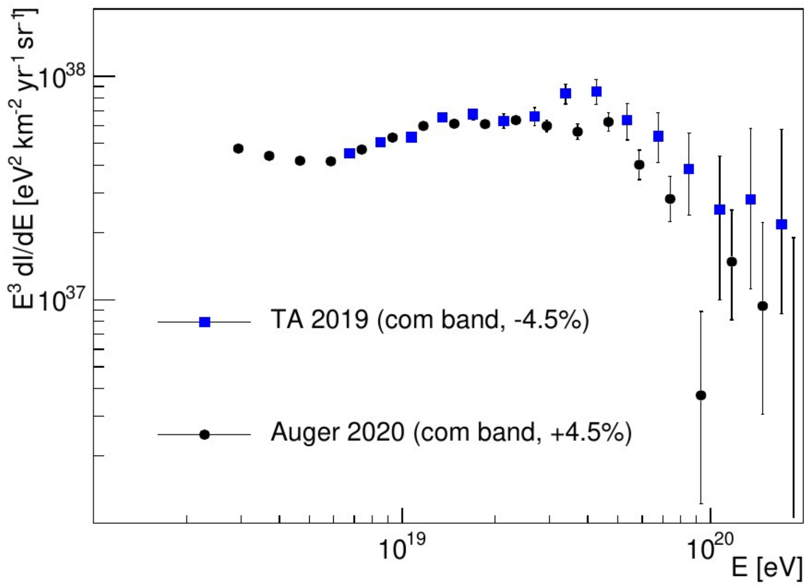


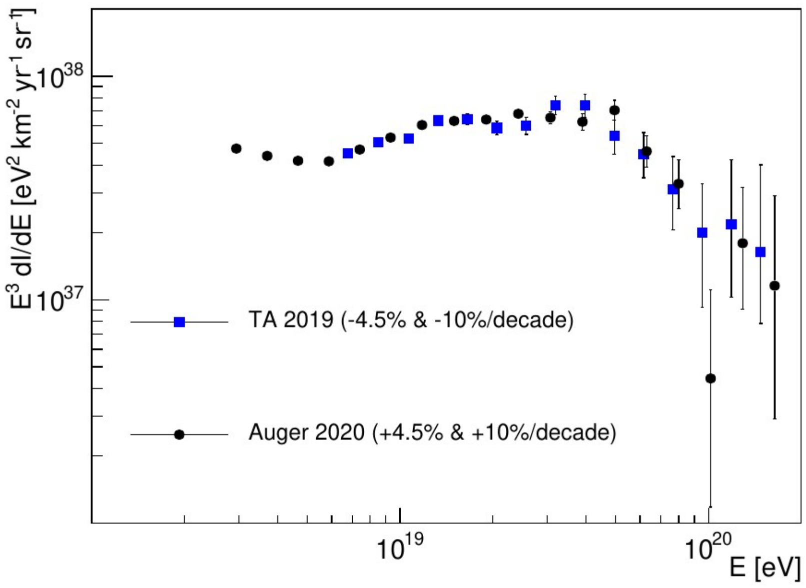
Pierre Auger Collaboration
PRL 101 (2008)
Phys. Lett. B 685 (2010)



Telescope Array Collaboration
Astrophys.J.Lett. 768 (2013) L1
5.5σ confidence level

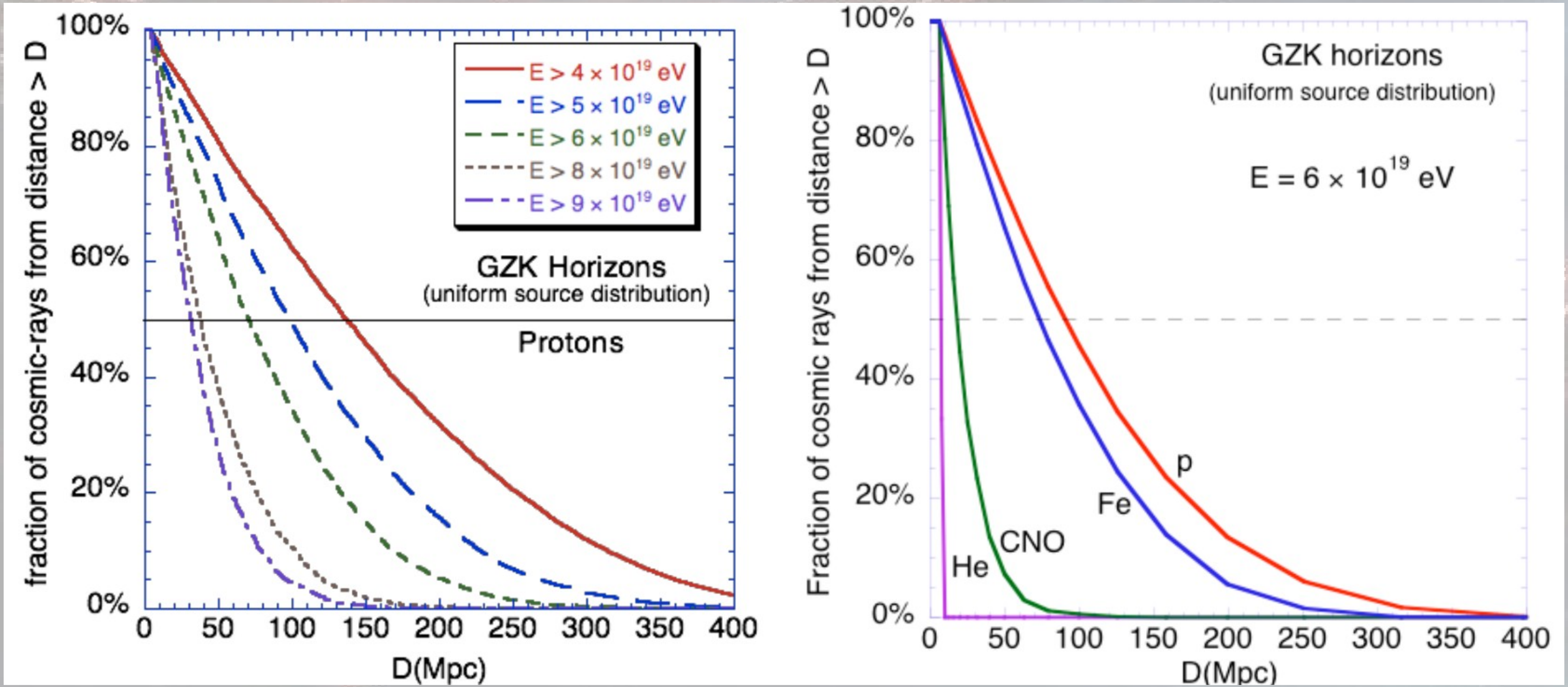
Auger and TA spectrum results





Auger and TA spectrum Working group
Y. Tsunesada, ICRC’2023

GZK horizons

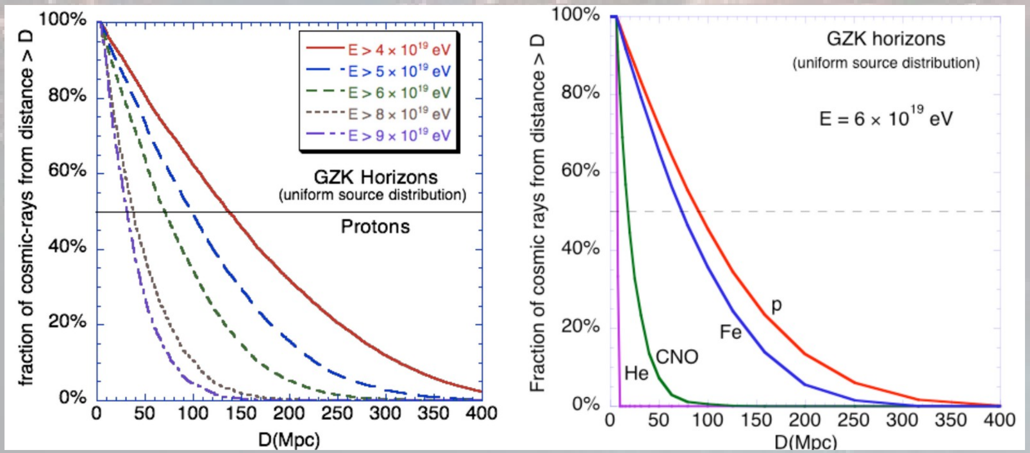


A. Olinto et. al., White paper on UHECR (2009)

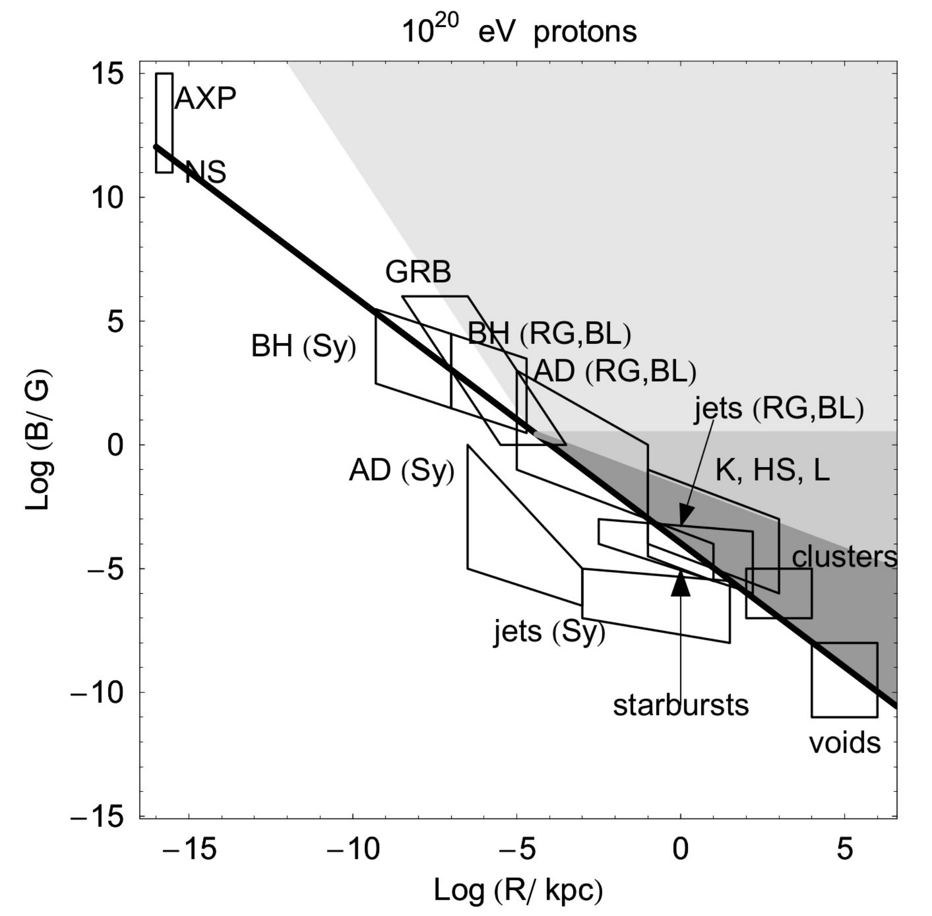
Is charged particle astronomy possible?

- Deflection of 60 EeV protons in the galactic magnetic field is about 2°-6°
- The highest energy cosmic rays should trace back to their sources
- Cosmogenic photons and neutrinos are produced in interactions with CMB and EBL

Berezinsky, Zatsepin, Phys. Lett B 28, 423 (1969)

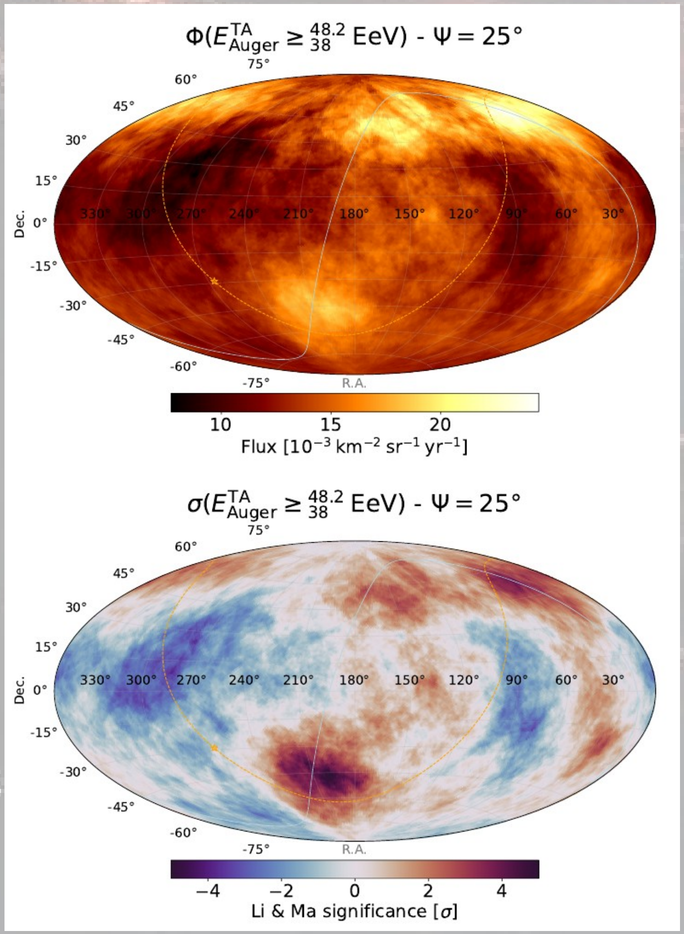


Hillas plot: possible UHECR sources



Ptytsina, Troitsky,
UFN 53 (2010) 691

Observed UHECR sky



- Joint Auger + TA data
- Flux excess is overved in Centaurus A are at South and Ursa Major constellation and Perseus-Pisces Supercluster regions at North
- No individual sources are observed

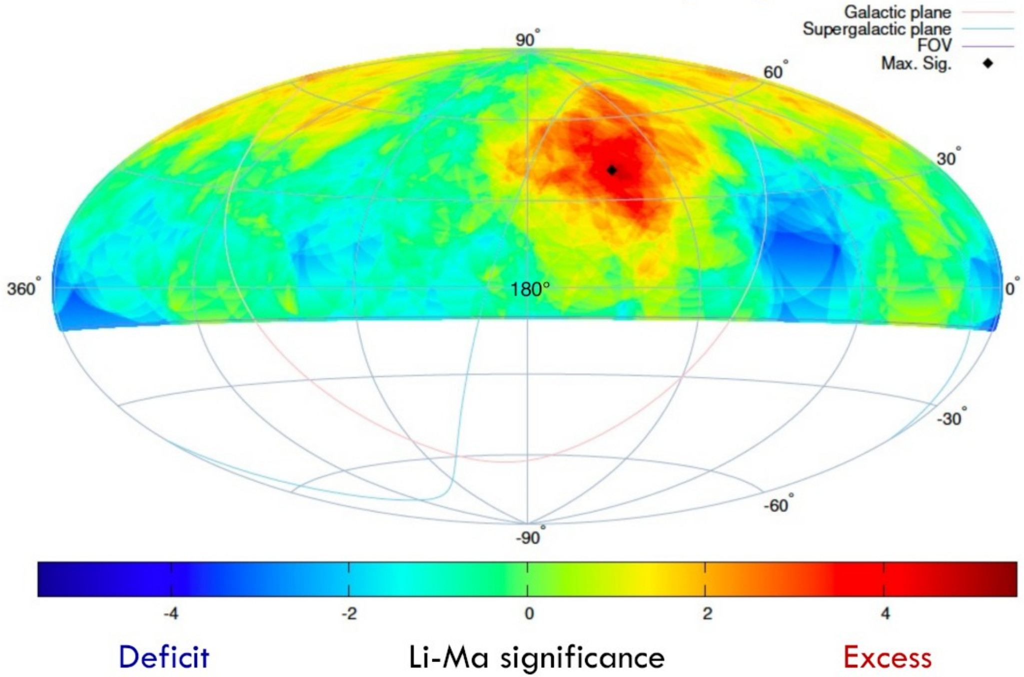
L. Caccianiga, ICRC’2023

See talk by K. Dolgikh (this conference)

Telescope Array hot spot

Li-Ma Significance Map with E ≥ 57 EeV

25°-radius oversampling



- 205 events (14-year TA SD data)
- Max local sig.: **5.1σ** at (144.0°, 40.5°)

  Obs. : 44 events

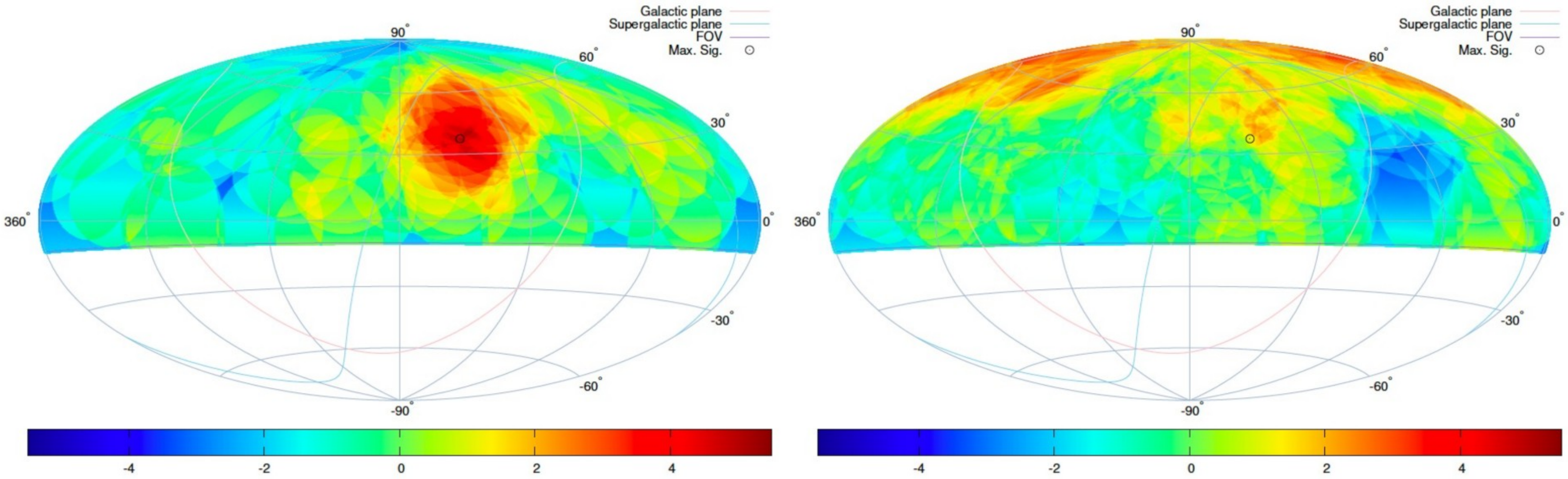
  N_{bg} : 16.9 events

  ~160% excess
- Post-trial probability:

  $P(S_{MC} > 5.1\sigma) = 7.4\times10^{-4}$ → **3.2σ**

Telescope Array hot spot

Independent Dataset Analysis



- 72 events (First 5-year)
- **5.0σ** at (144.0°, 40.5°)

  Obs. : 22 events

  N_{bg} : 5.2 events

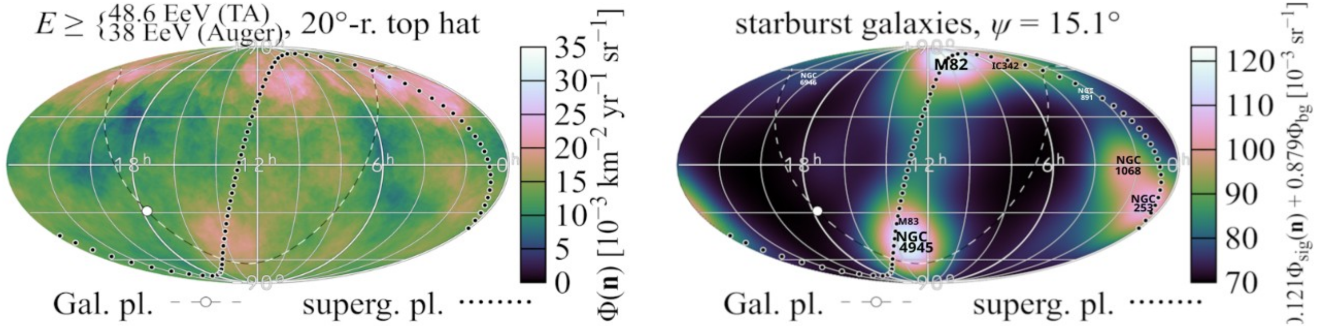
- 133 events (Last 9-year)
- **2.5σ** at (144.0°, 40.5°)

  Obs. : 22 events

  N_{bg} : 11.6 events

TA-Auger: correlations with starburst galaxies

catalogue	$E_{min}^{(Auger)}$	$E_{min}^{(TA)}$	ψ [deg]	f [%]	TS	significance
all galaxies	40 EeV	51 EeV	29^{+11}_{-12}	41^{+29}_{-18}	14.3	$2.7\sigma_{global}$
starburst	38 EeV	49 EeV	$15.1^{+4.6}_{-3.0}$	$12.1^{+4.5}_{-3.1}$	31.1	$4.6\sigma_{global}$



Composition \ Sources model	SBG only	SBG only (EGMF)	SBG-LSS	LSS only
Intermediate nuclei	$> 2\sigma$	$> 2\sigma$	$> 2\sigma$	$> 2\sigma$
Light nuclei + iron	2σ	1σ	1σ	1σ

Table 1: Summary of degree of compatibility between given UHECR flux models and the data.

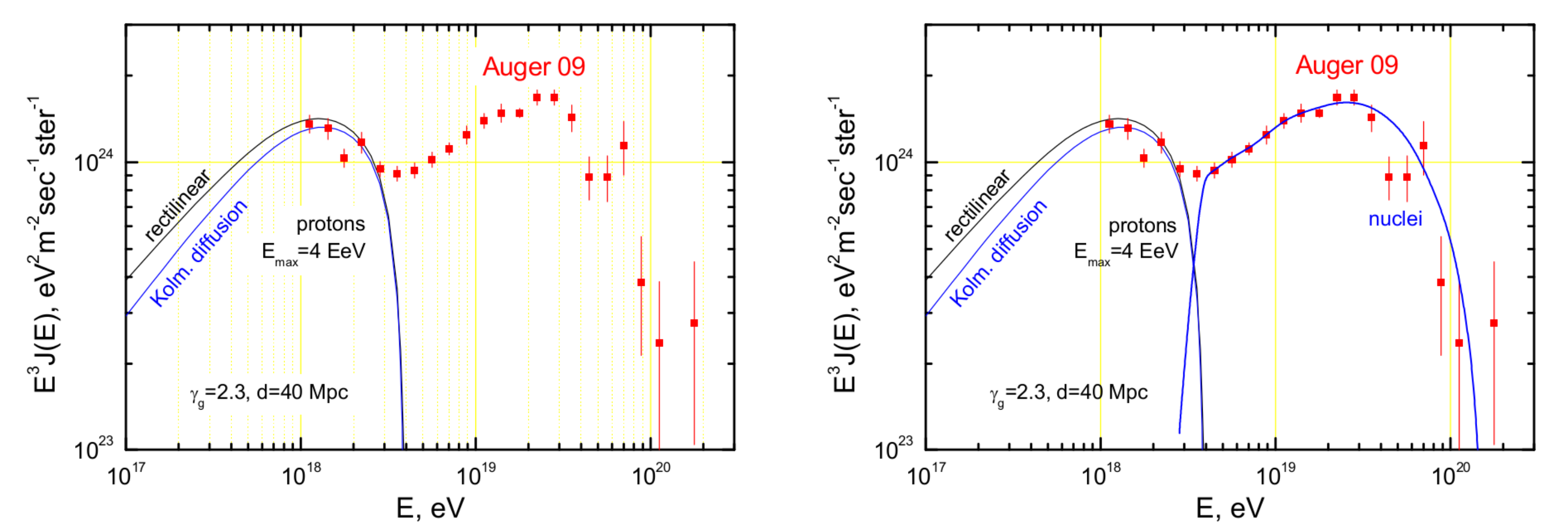
L. Caccianiga
ICRC’2023

M. Kuznetsov
ICRC’2023

Why don’t we see the sources?

- Disappointing model

R. Aloisio, V. Berezinsky, A. Gazizov Astropart.Phys. 34 (2011) 620

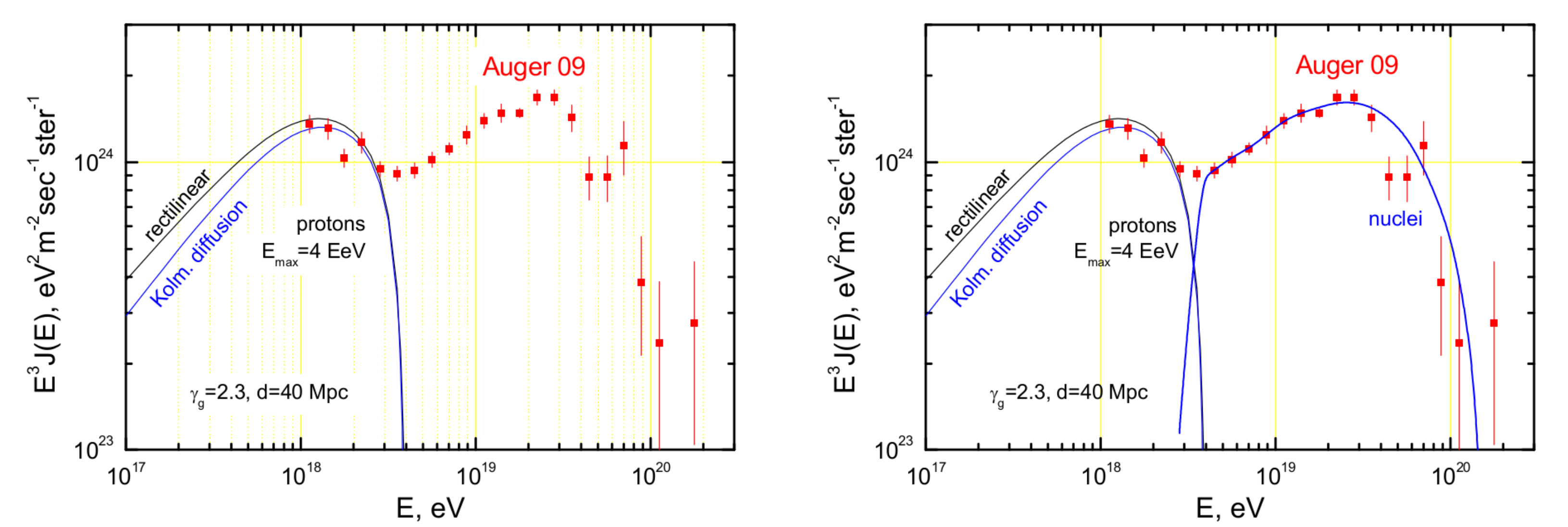


- No cosmogenic photons, no cosmogenic neutrinos
- We will not see the sources

Why don’t we see the sources?

- Disappointing model

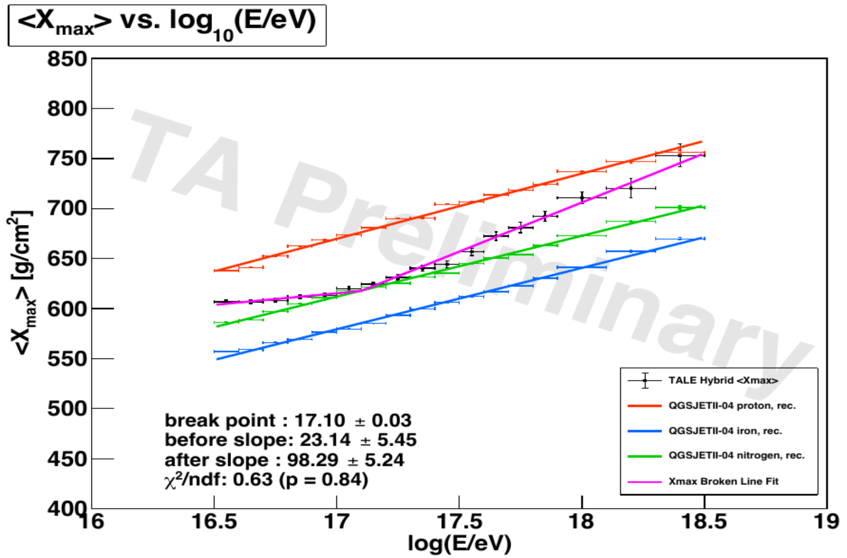
R. Aloisio, V. Berezinsky, A. Gazizov Astropart.Phys. 34 (2011) 620

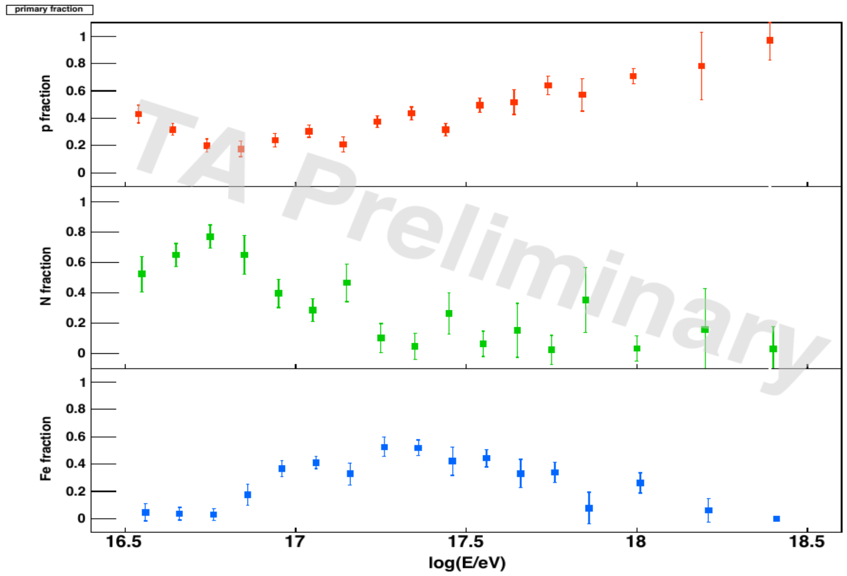


- No cosmogenic photons, no cosmogenic neutrinos
- We will not see the sources
- **Is this the case? The primary composition is a key**

Composition at lower energies

- Five-year TALE hybrid data set (Nov. 2017–Mar. 2023)



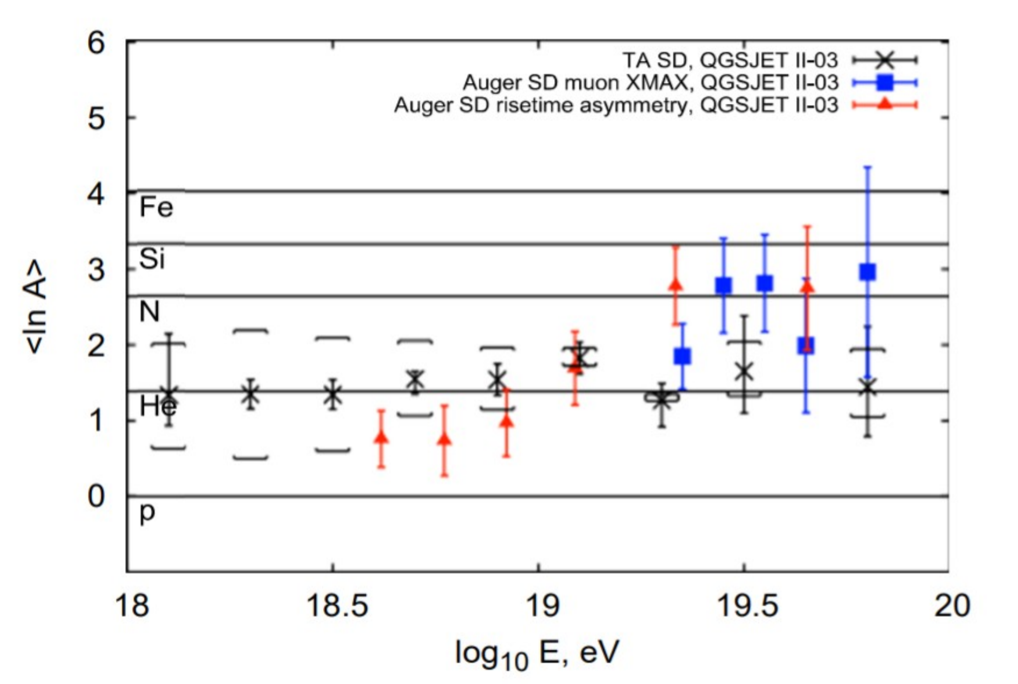


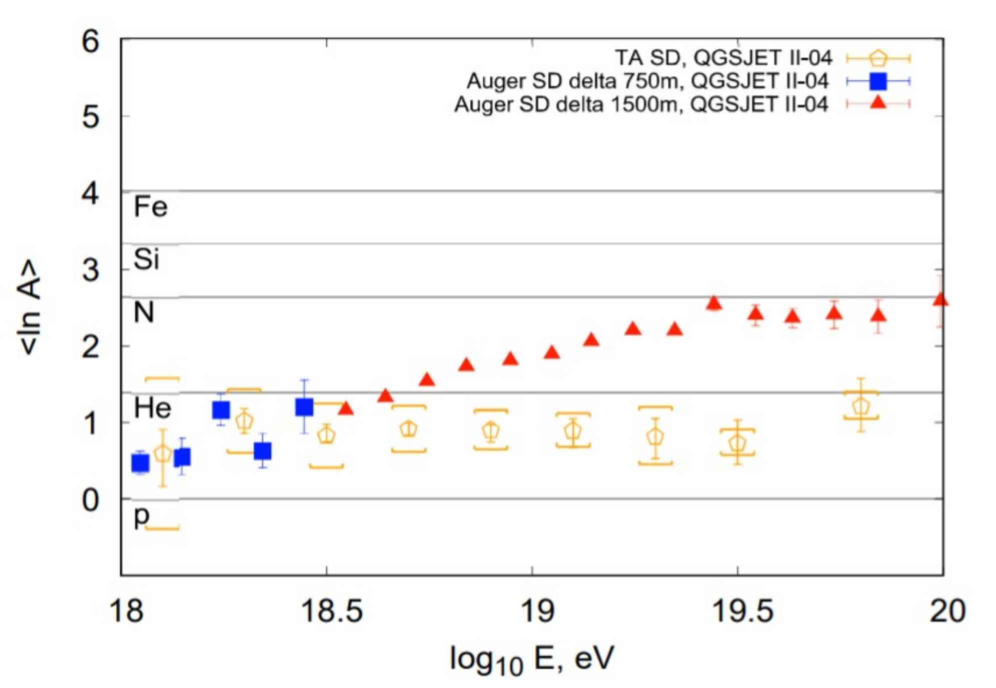
- A break in the elongation rate at energy $10^{17.10\pm0.03}$ eV (2nd knee).
- Light-heavy-light pattern in $10^{16.5}$–$10^{18.5}$ eV.

Peter's cycle scenario is supported
What do we have at the highest energies?

K.Fujita, ICRC'23

Primary composition

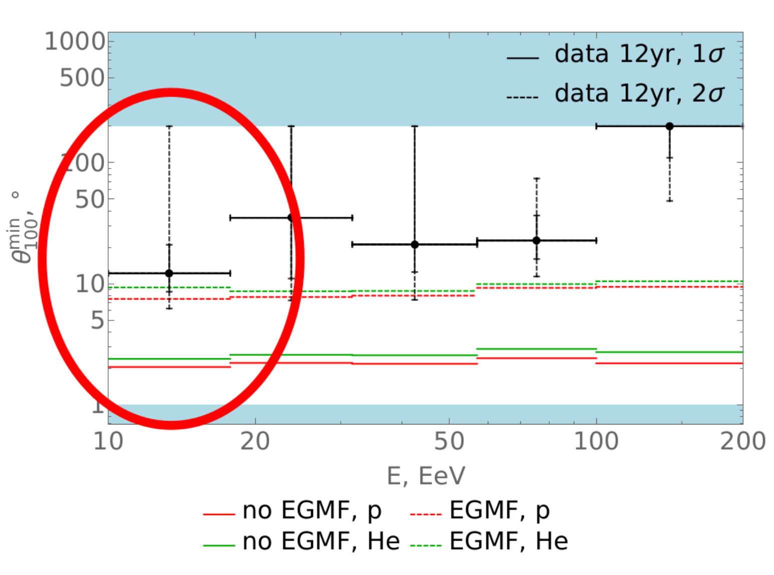


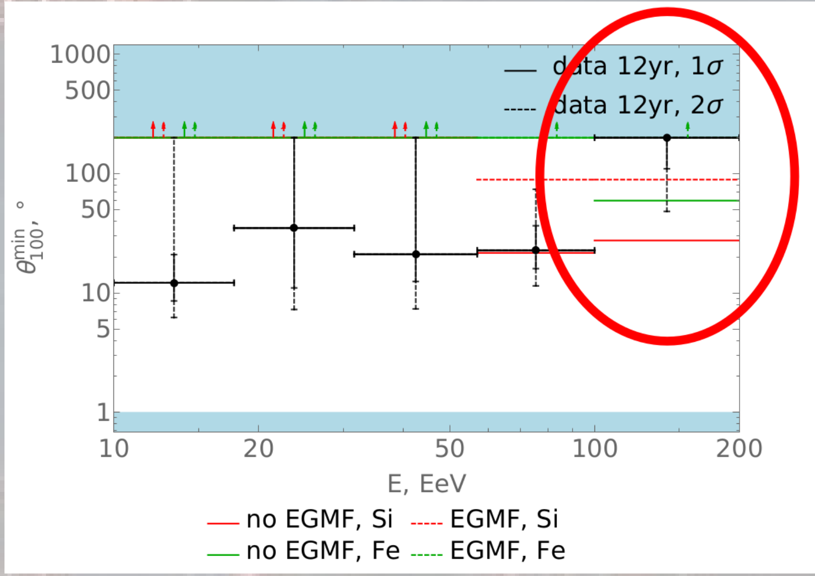


Machine learning technique based on Boosted decision trees

Phys.Rev.D 99 (2019) 2

Mass composition from anisotropy of the arrival directions

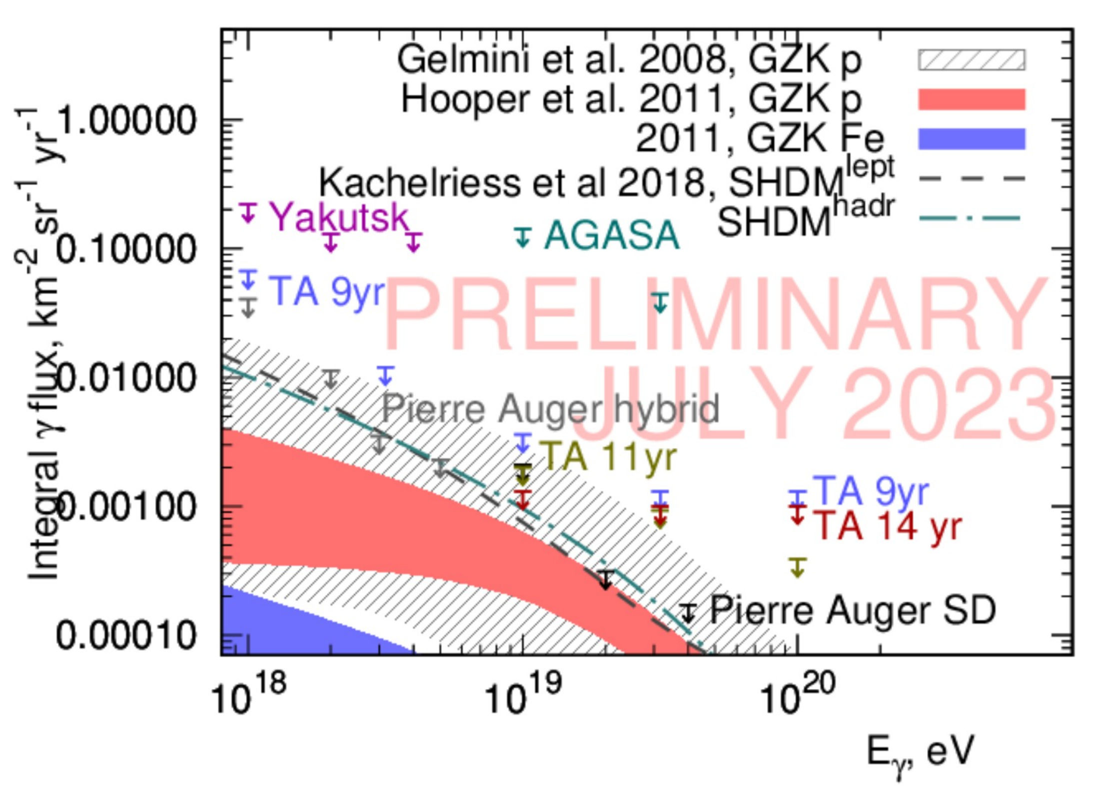




Heavy composition at the highest energies (E>100 EeV)!

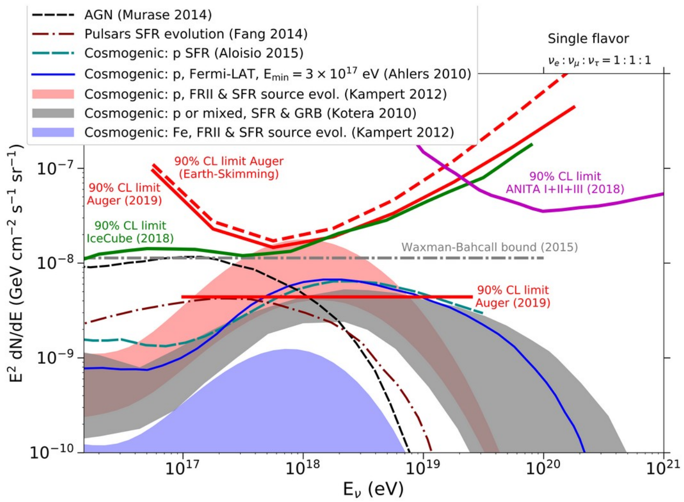
See talk by M. Kuznetsov (this conference)
Telescope Array Collaboration, accepted to PRD and PRL during Quarks-2024

Search for primary photons

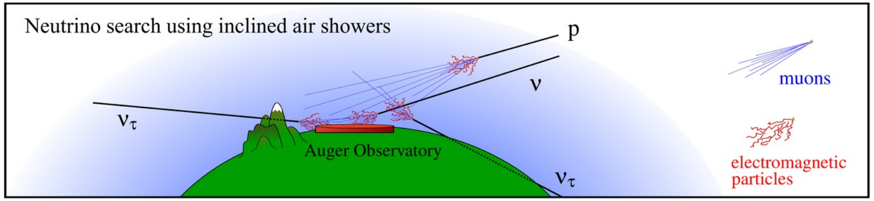


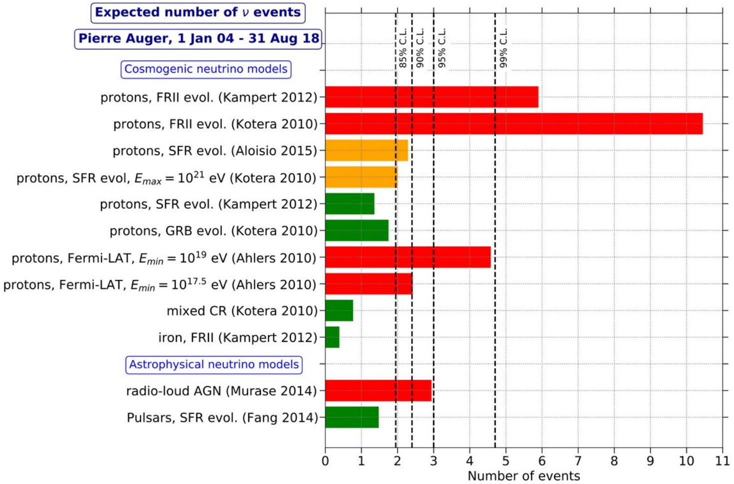
See talk by I. Kharuk (this conference)

UHE neutrino search



(JCAP 10 (2019) 022,
JCAP 11 (2019) 004)

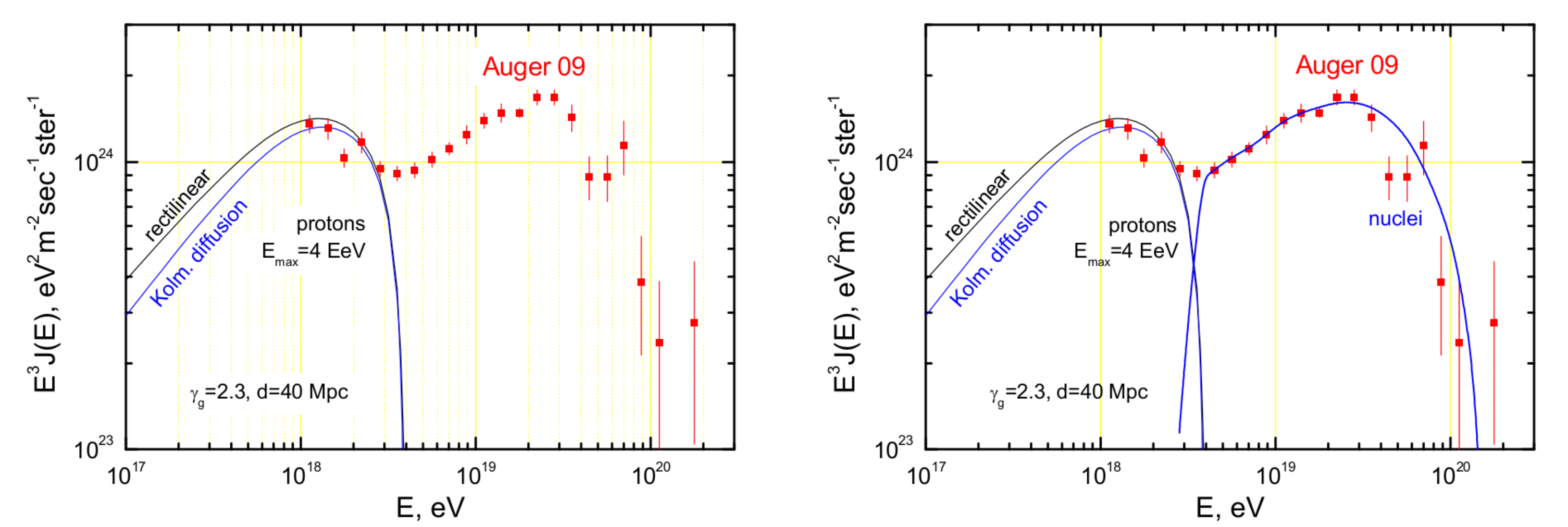




Aperture comparable to IceCube if direction of source is favorable
Multi-messenger: searches for neutrinos in coincidence with GW events
Phase II: lowering of detection threshold (new electronics)

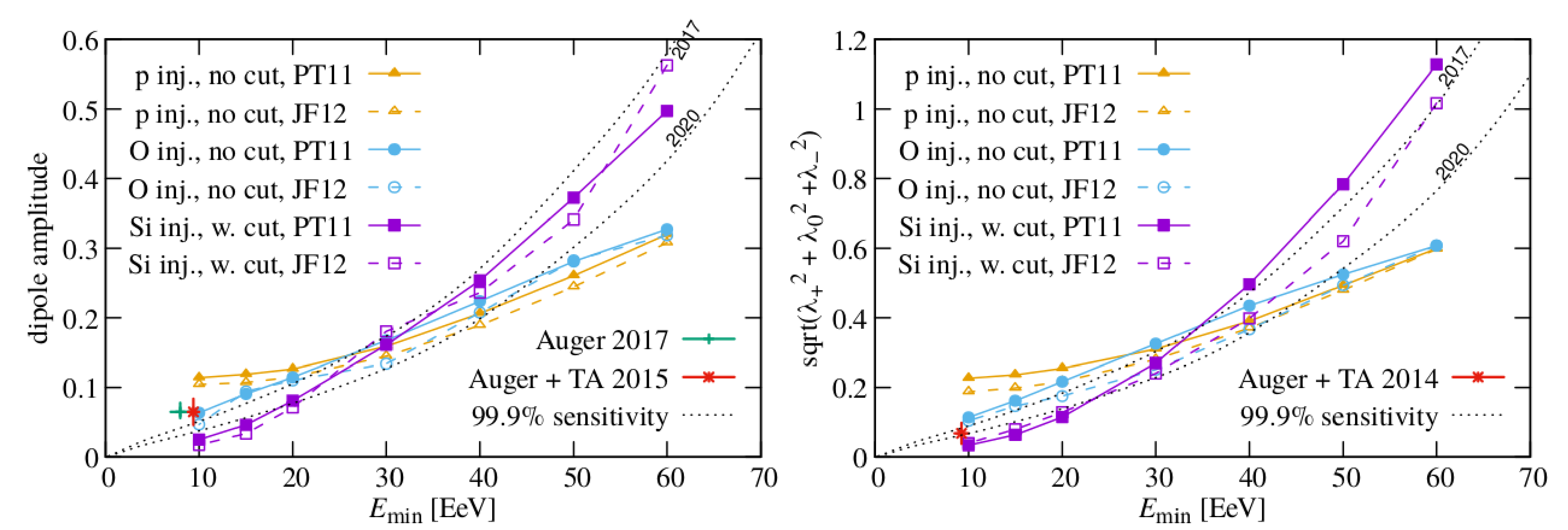
Michail Schimp (Pierre Auger Collaboration), ICRC’2021

Disappointing model?



- No cosmogenic photons, no cosmogenic neutrinos
- What we expect:
  - Dipolar and quadrupolar anisotropy
  - Astronomy with the highest energy particles

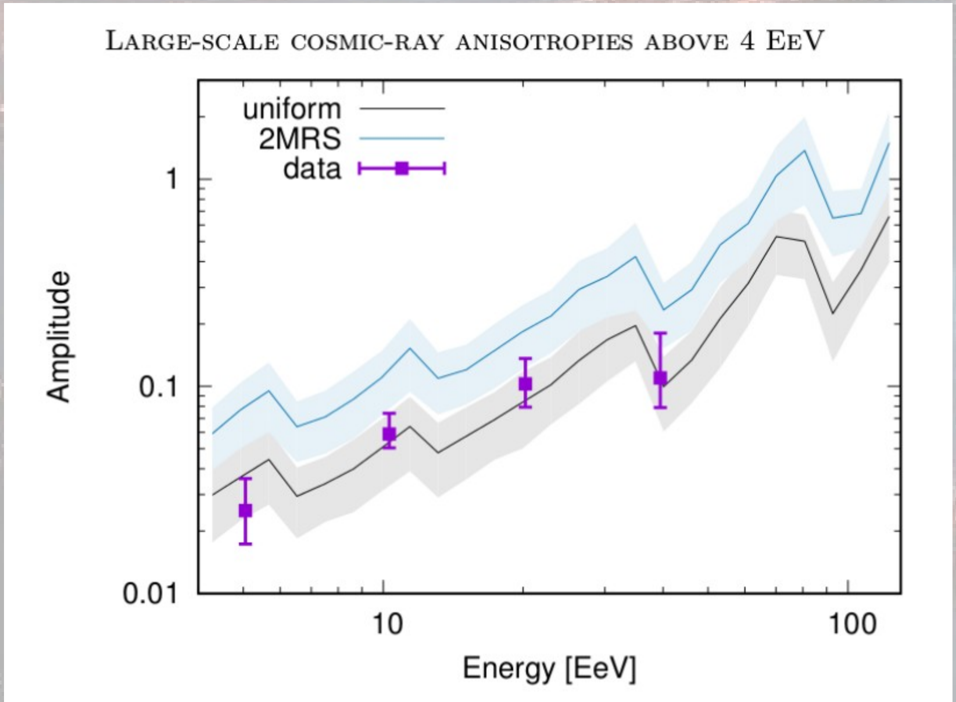
Search for dipole and quadrupole



di Matteo, Tinyakov, MNRAS 476 (2018) 715

- If the source distribution tracks the overall matter distribution, the dipole and quadrupole anisotropy should be observable

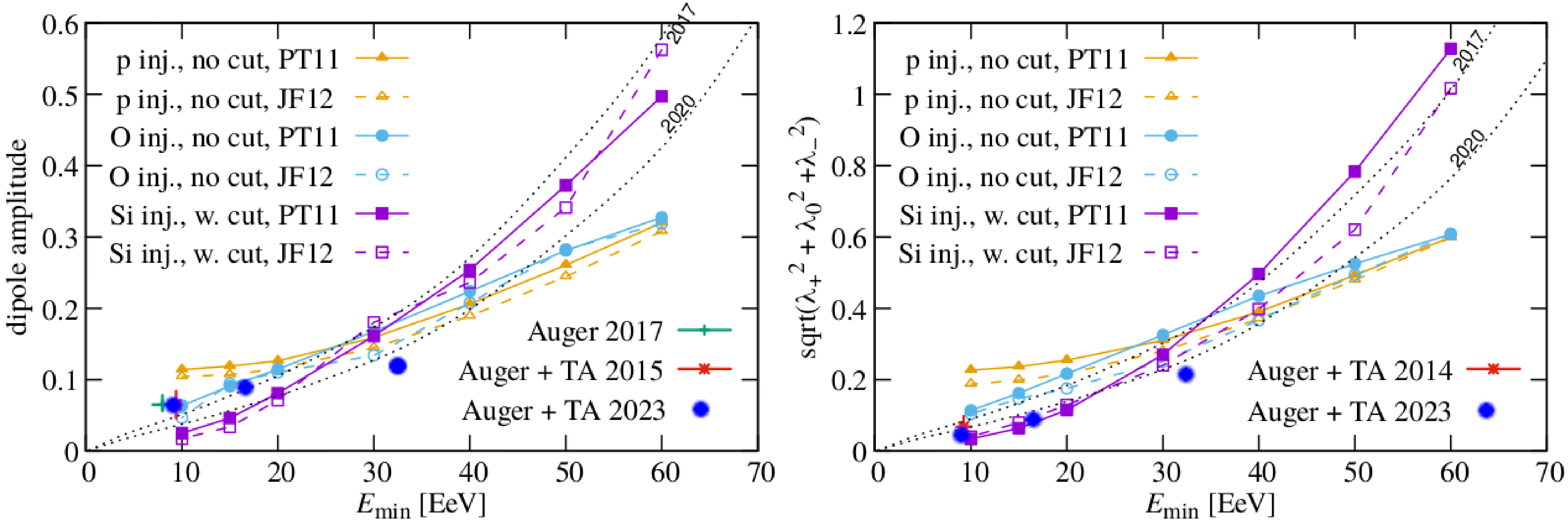
The dipole discovery by Auger



Pierre Auger collaboration, ApJ 868 (2018) 4

- The dipole has been discovered at 5σ confidence level at E>8 EeV
- Consistent with the isotropic sources model with the source density $\rho=10^{-4}$ Mpc^{-3}

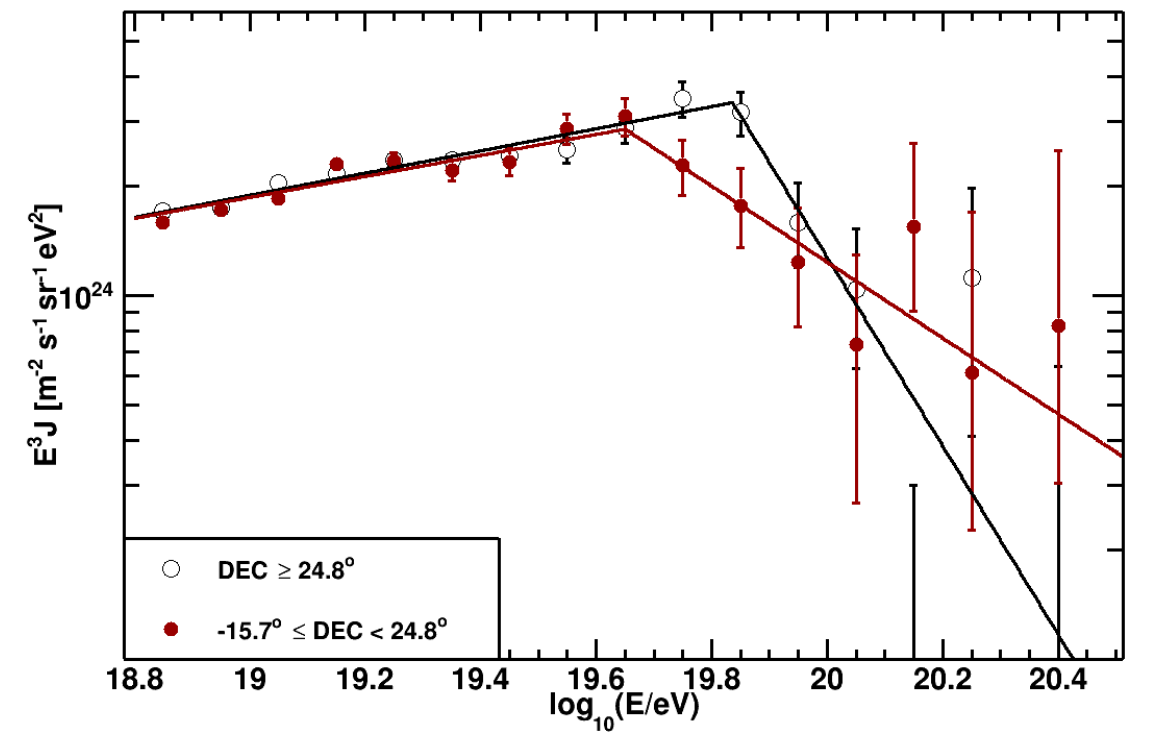
Dipole and quadrupole results by Auger+TA joint working group



Heavier composition is preferred!
Alternative: stronger EG magnetic fields.

di Matteo, Tinyakov, MNRAS 476 (2018) 715
L. Caccianiga, ICRC'2023

Declination Dependence in the TA SD Spectrum



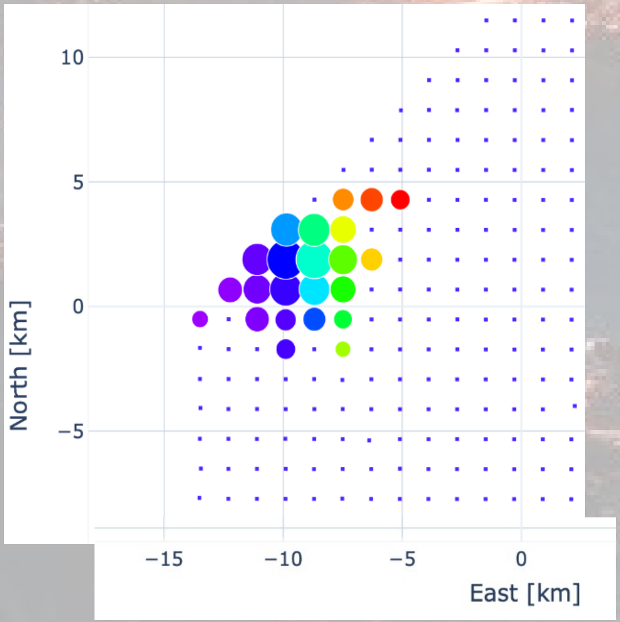
- Differences in the cutoff energies

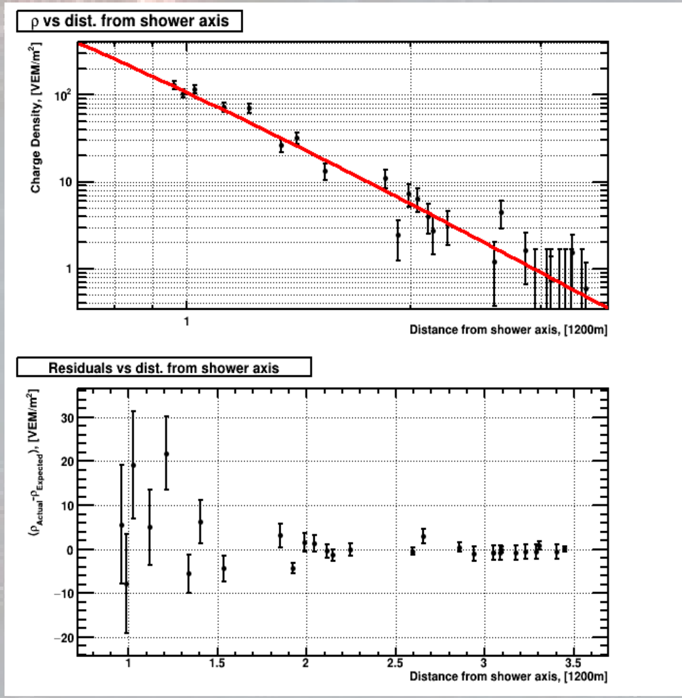
  - log(E/eV)=**19.84 ±0.02** for higher declination (24.8°–90°)

  - log(E/eV)=**19.65 ±0.03** for lower declination (-16°–24.8°)

- The global significance of the difference is estimated to be **4.4σ.**

An extreme Energy Event registered by TA SD



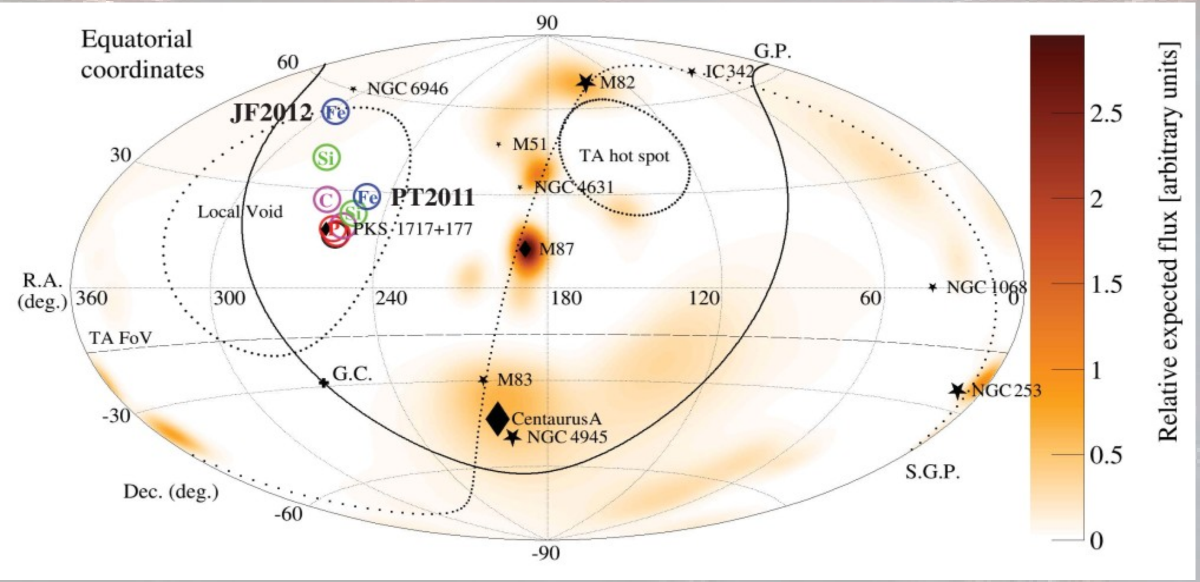


- Observed with TA SD at 10:35:56 on 27 May 2021 (UTC). No FD observation

Science 382, 903–907 (2023).

- E = **244 ± 29(stat.) ± 51(syst.) EeV**, zenith angle $\theta = 38.6°$

Observation of the event with extremely high energy

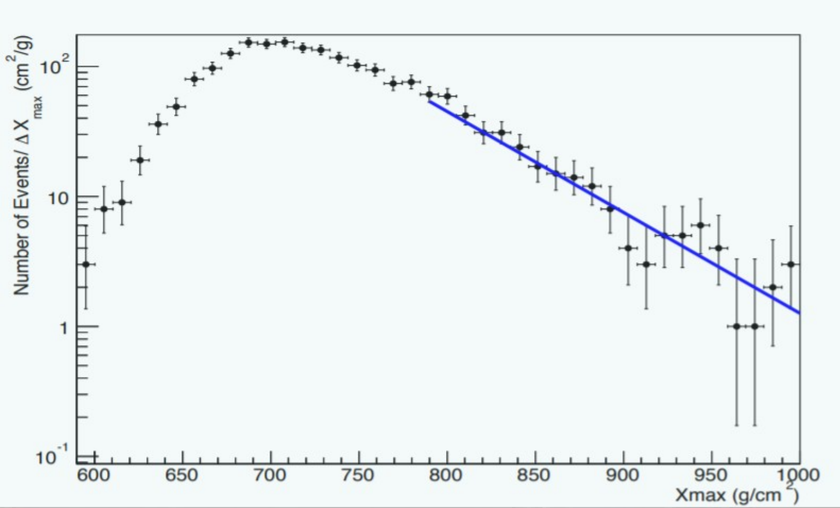


- E = 2.44x10^{20} эВ
- Event is coming from cosmic void
- Not a gamma-ray
- Primary particle should be a heavy nuclei
- The source is closer than 5 Mpc

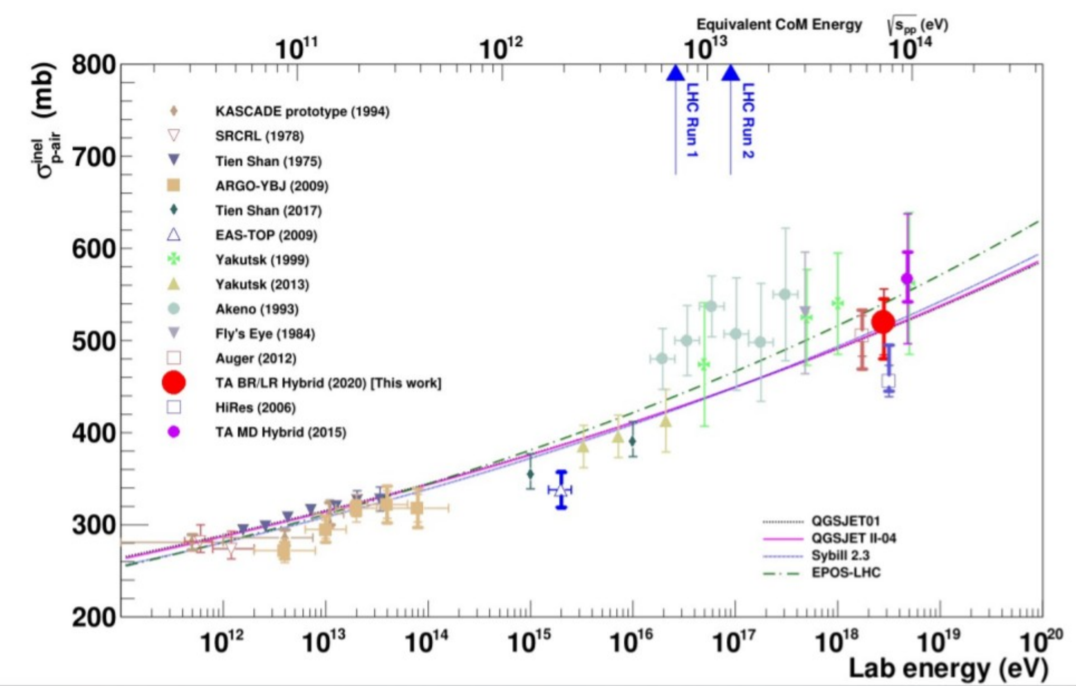
Telescope Array Collaboration, Science 382, 903–907 (2023).
M. Kuznetsov, JCAP 04 (2024) 042

See the talk by M. Kuznetsov (this conference)

TA proton-air cross-section



Measuring XMAX attenuation length in hybrid mode.



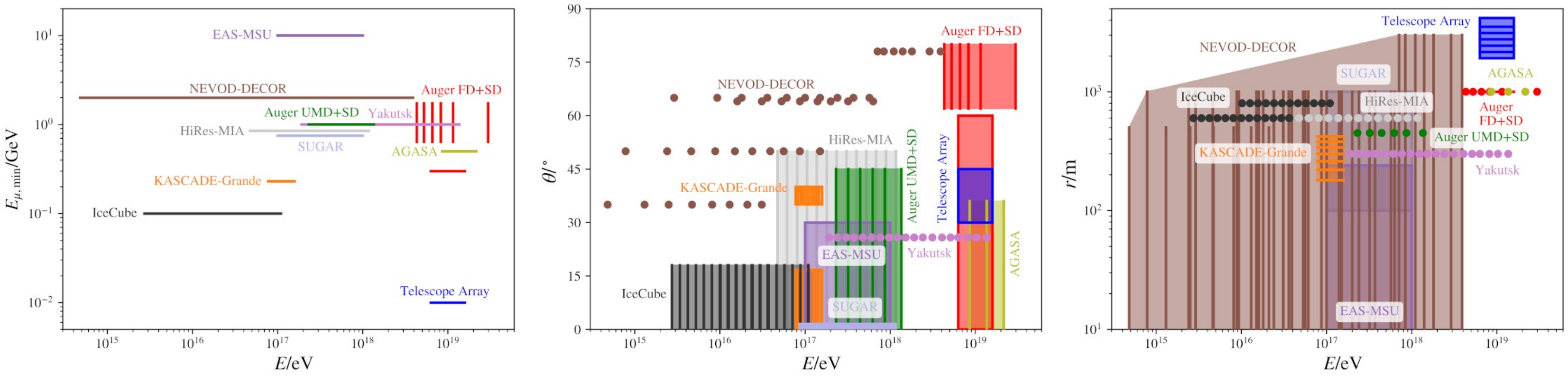
TA Collaboration, Phys. Rev. D 102 (2020) 062004

Muon content analysis

- 9 experiments: Data taken over large parameter space under very different experimental conditions!
- Muon content is expressed in terms of z-scale:

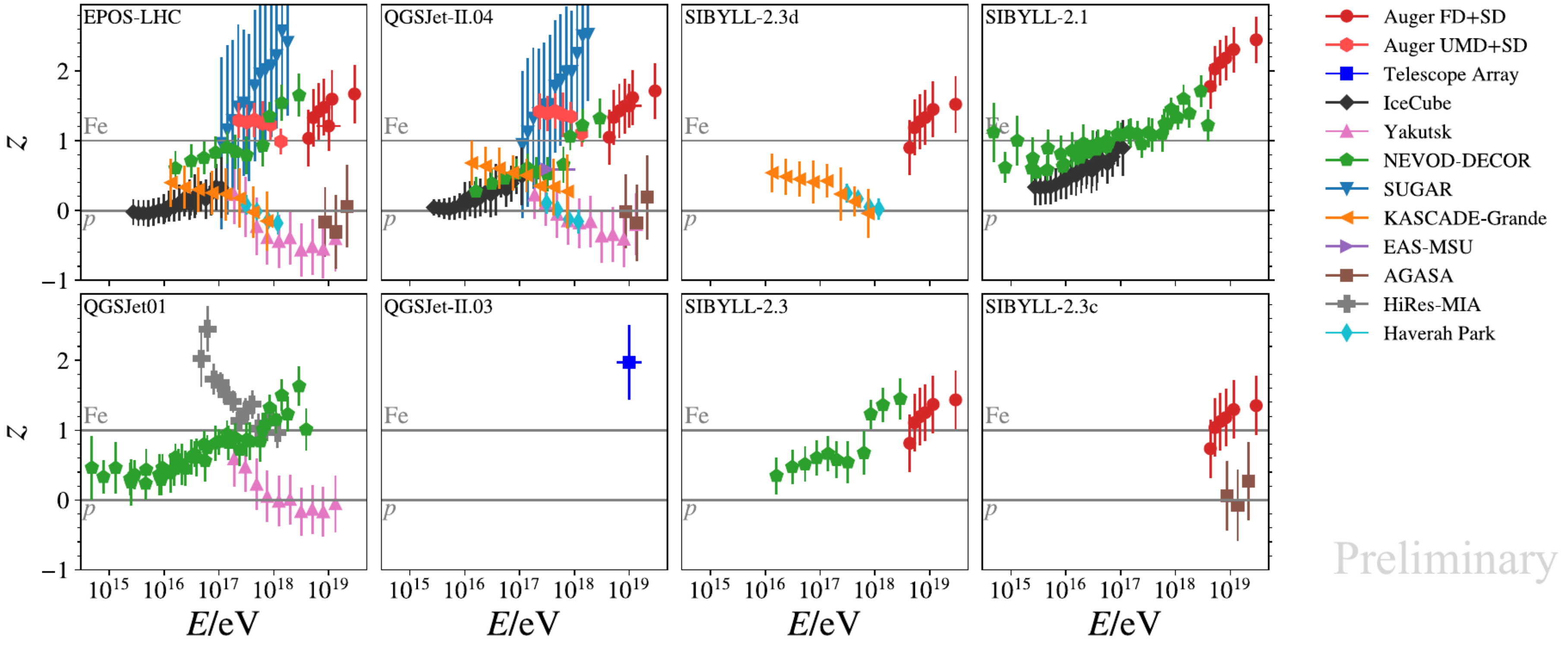
$$z = \frac{\ln(N_{\mu}^{\text{det}}) - \ln(N_{\mu,\text{p}}^{\text{det}})}{\ln(N_{\mu,\text{Fe}}^{\text{det}}) - \ln(N_{\mu,\text{p}}^{\text{det}})} \quad , \quad z = 0\text{: proton, } z = 1\text{: iron}$$

  - N_{μ}^{det}: muon content measured in the detector
  - $N_{\mu,\text{p}}^{\text{det}}, N_{\mu,\text{Fe}}^{\text{det}}$: muon content in simulated EAS (proton/iron) at the detector



Dennis Soldin, UHECR’2022

Muon excess problem



Arteaga-Velázquez, ICRC’2023
See the talk by N. Martynenko (this conference)

Conclusions

- Telescope Array Observatory has the largest UHECR statistics at the Northern Hemisphere
- An extremely high energy event ($E = 2.44 \times 10^{20}$ eV) have been observed at TA
- There are several evidences of cosmic ray composition hardening at the highest energies
- The charged particle astronomy is possible for the highest energy events. The nearest source is not far away
- An enhanced statistics of TAx4 is crucial for determining the origin of cosmic rays

Thank you!

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