Обзор результатов Обсерватории Telescope Array

12-е Зацепинские чтения, 27 мая 2022

Г.И. Рубцов, ИЯИ РАН
от имени коллаборации Telescope Array

фото Олега Калашева

Outline

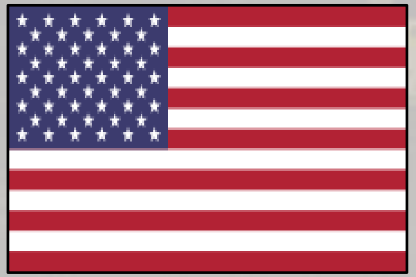
- Telescope Array observatory and TAx4 upgrade
- Energy Spectrum results
- Composition and hadronic interactions results
- Anisotropy results
- Interdisciplinary results
- Summary

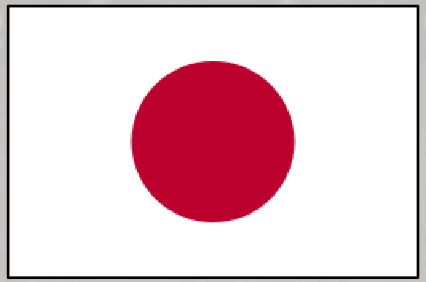
Telescope Array Collaboration

R.U. Abbasi[1,2], M. Abe[3], T. Abu-Zayyad[1,2], M. Allen[2], Y. Arai[4], R. Arimura[4], E. Barcikowski[2], J.W. Belz[2], D.R. Bergman[2], S.A. Blake[2], I. Buckland[2], R. Cady[2], B.G. Cheon[5], J. Chiba[6], M. Chikawa[7], T. Fujii[8], K. Fujisue[7], K. Fujita[4], R. Fujiwara[4], M. Fukushima[7], R. Fukushima[4], G. Furlich[2], R. Gonzalez[2], W. Hanlon[2], M. Hayashi[9], N. Hayashida[10], K. Hibino[10], R. Higuchi[7], K. Honda[11], D. Ikeda[10], T. Inadomi[12], N. Inoue[3], T. Ishii[11], H. Ito[13], D. Ivanov[2], H. Iwakura[12], A. Iwasaki[4], H.M. Jeong[14], S. Jeong[14], C.C.H. Jui[2], K. Kadota[15], F. Kakimoto[10], O. Kalashev[16], K. Kasahara[17], S. Kasami[18], H. Kawai[19], S. Kawakami[4], S. Kawana[3], K. Kawata[7], I. Kharuk[16], E. Kido[13], H.B. Kim[5], J.H. Kim[2], J.H. Kim[2], M.H. Kim[14], S.W. Kim[14], Y. Kimura[4], S. Kishigami[4], Y. Kubota[12], S. Kurisu[12], V. Kuzmin[16], M. Kuznetsov[16,20], Y.J. Kwon[21], K.H. Lee[14], B. Lubsandorzhiev[16], J.P. Lundquist[2,22], K. Machida[11], H. Matsumiya[4], T. Matsuyama[4], J.N. Matthews[2], R. Mayta[4], M. Minamino[4], K. Mukai[11], I. Myers[2], S. Nagataki[13], K. Nakai[4], R. Nakamura[12], T. Nakamura[23], T. Nakamura[12], Y. Nakamura[12], A. Nakazawa[12], T. Nonaka[7], H. Oda[4], S. Ogio[4,24], M. Ohnishi[7], H. Ohoka[7], Y. Oku[18], T. Okuda[25], Y. Omura[4], M. Ono[13], R. Onogi[4], A. Oshima[4], S. Ozawa[26], I.H. Park[14], M. Potts[2], M.S. Pshirkov[16,27], J. Remington[2], D.C. Rodriguez[2], G.I. Rubtsov[16], D. Ryu[28], H. Sagawa[7], R. Sahara[4], Y. Saito[12], N. Sakaki[7], T. Sako[7], N. Sakurai[4], K. Sano[12], K. Sato[4], T. Seki[12], K. Sekino[7], P.D. Shah[2], Y. Shibasaki[12], F. Shibata[11], N. Shibata[18], T. Shibata[7], H. Shimodaira[7], B.K. Shin[28], H.S. Shin[7], D. Shinto[18], J.D. Smith[2], P. Sokolsky[2], N. Sone[12], B.T. Stokes[2], T.A. Stroman[2], T. Suzawa[3], Y. Takagi[4], Y. Takahashi[4], M. Takamura[6], M. Takeda[7], R. Takeishi[7], A. Taketa[29], M. Takita[7], Y. Tameda[18], H. Tanaka[4], K. Tanaka[30], M. Tanaka[31], Y. Tanoue[4], S.B. Thomas[2], G.B. Thomson[2], P. Tinyakov[16,20], I. Tkachev[16], H. Tokuno[32], T. Tomida[12], S. Troitsky[16], R. Tsuda[4], Y. Tsunesada[4,24], Y. Uchihori[33], S. Udo[10], T. Uehama[12], F. Urban[34], T. Wong[2], K. Yada[7], M. Yamamoto[12], K. Yamazaki[10], J. Yang[35], K. Yashiro[6], F. Yoshida[18], Y. Yoshioka[12], Y. Zhezher[7,16], and Z. Zundel[2]

[1] Loyola University Chicago [2] University of Utah [3] Saitama University [4] Osaka City University [5] Hanyang University [6] Tokyo University of Science [7] University of Tokyo (ICRR) [8] Kyoto University [9] Shinshu University [10] Kanagawa University [11] University of Yamanashi [12] Shinshu University (Inst. of Engineering) [13] RIKEN [14] Sungkyunkwan University [15] Tokyo City University [16] Institute for Nuclear Research of the Russian Academy of Sciences [17] Shibaura Institute of Technology [18] Osaka Electro-Communication University [19] Chiba University [20] Université Libre de Bruxelles [21] Yonsei University [22] University of Nova Gorica [23] Kochi University [24] Osaka City University (Nambu Yoichiro Institute) [25] Ritsumeikan University [26] National Inst. for Information and Communications Technology, Tokyo [27] Lomonosov Moscow State University [28] Ulsan National Institute of Science and Technology [29] University of Tokyo (Earthquake Inst.) [30] Hiroshima City University [31] KEK [32] Tokyo Institute of Technology [33] National Instit. for Quantum and Radiological Science and Technology [34] CEICO, Institute of Physics, Czech Academy of Sciences [35] Ewha Womans University

160 members , 35 institutes, 7 countries

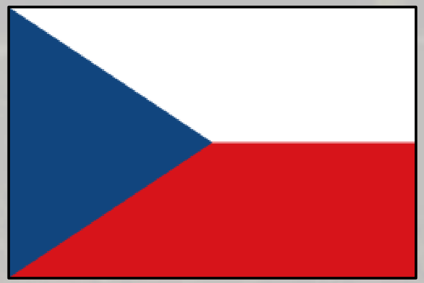

USA

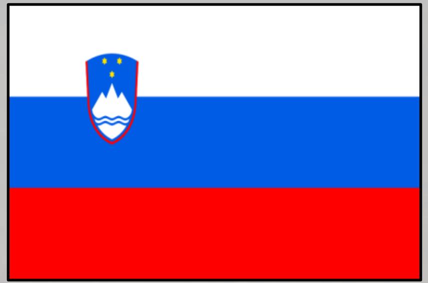

Japan


Korea

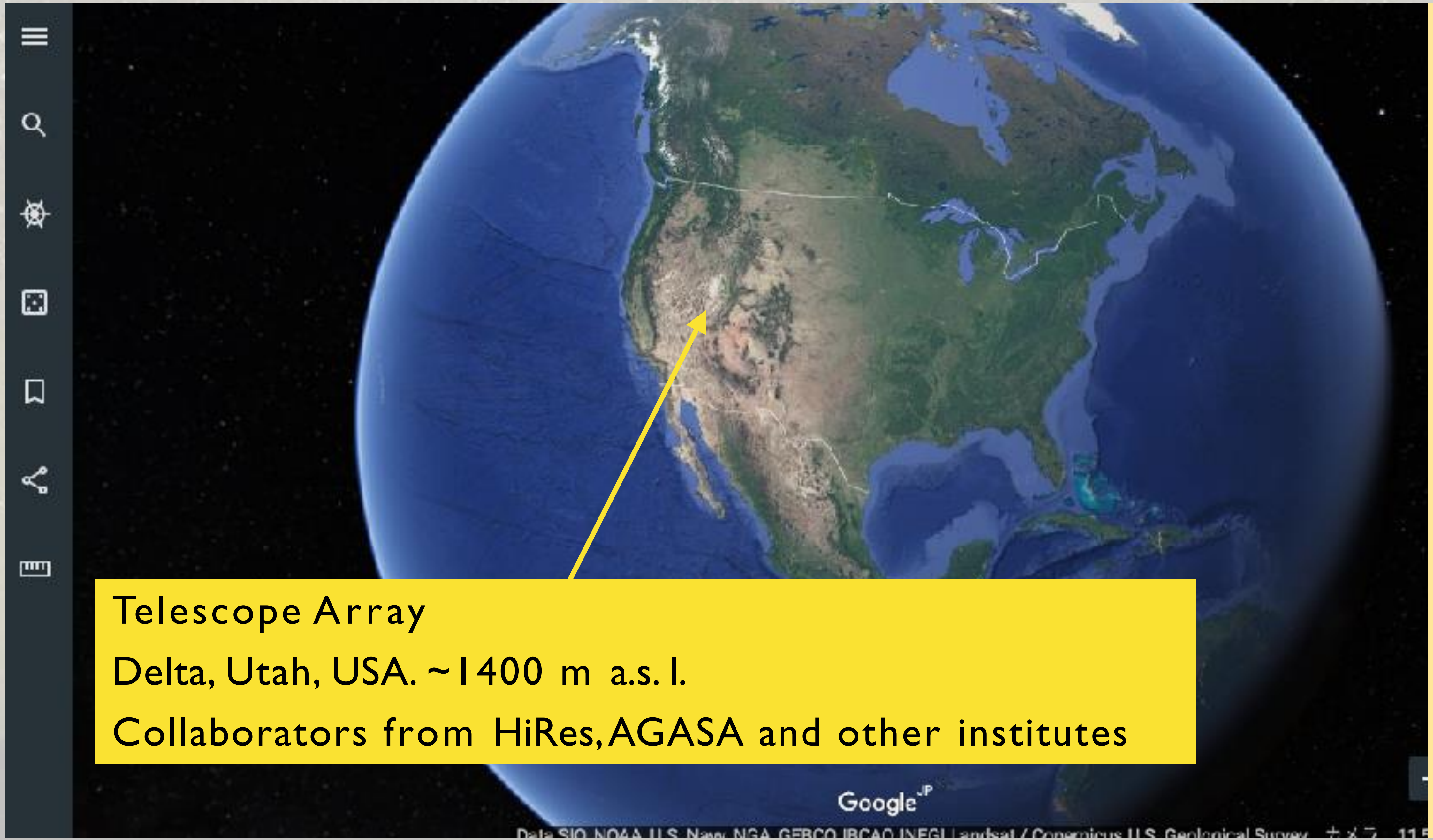

Russia


Belgium


Czech Republic


Slovenia

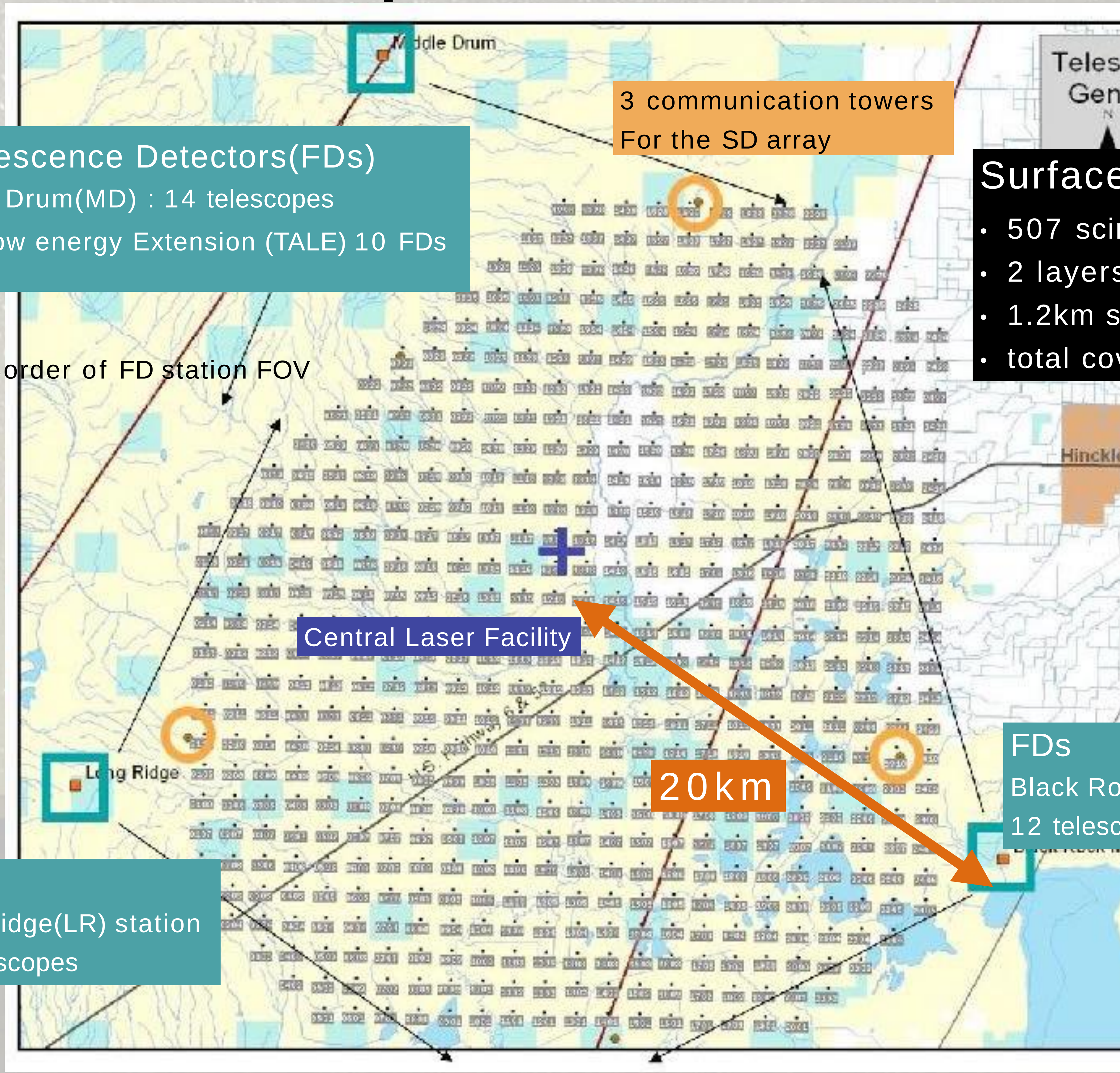
Telescope Array: The largest cosmic ray observatory in the Northern Hemisphere



Science goals:

- Origin and properties of the ultra-high energy cosmic rays:
  - spectrum, composition, anisotropy
- Physics of HE hadronic interactions
- Multi-messenger and interdisciplinary studies
  - photons, neutrino, dark matter
  - thunderstorms, TGFs
  - meteoroids
- Development of the next generation experiments

Map of theTA site



Fluorescence Detectors(FDs)

Middle Drum(MD) : 14 telescopes

+ TA Low energy Extension (TALE) 10 FDs

3 communication towers
For the SD array

Border of FD station FOV

Central Laser Facility

20km

Surface detectors(SDs)

- 507 scintillation detectors
- 2 layers, $3m^2$ each
- 1.2km spacing
- total coverage ~$700km^2$

FDs

Black Rock Mesa(BRM) station

12 telescopes

FDs

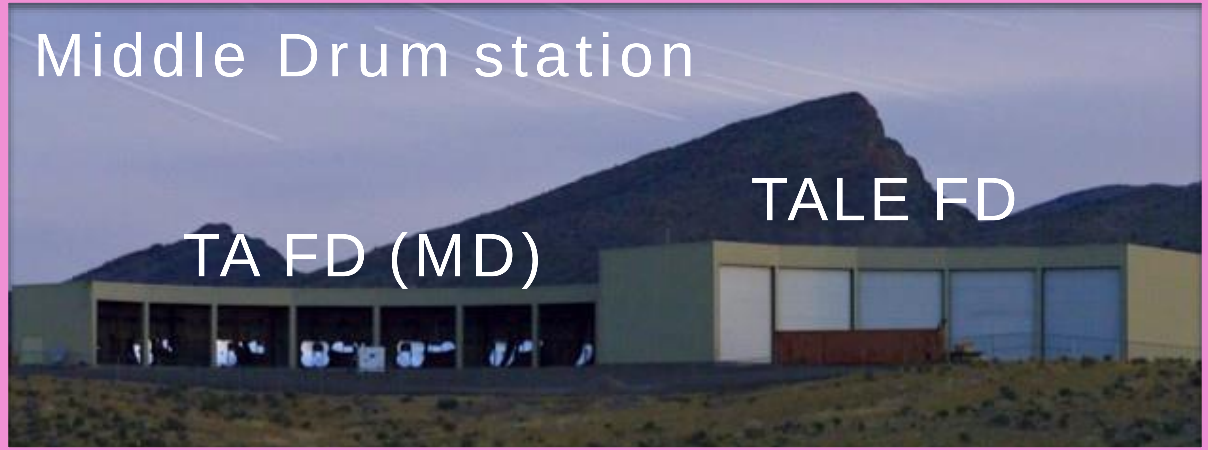
Long Ridge(LR) station

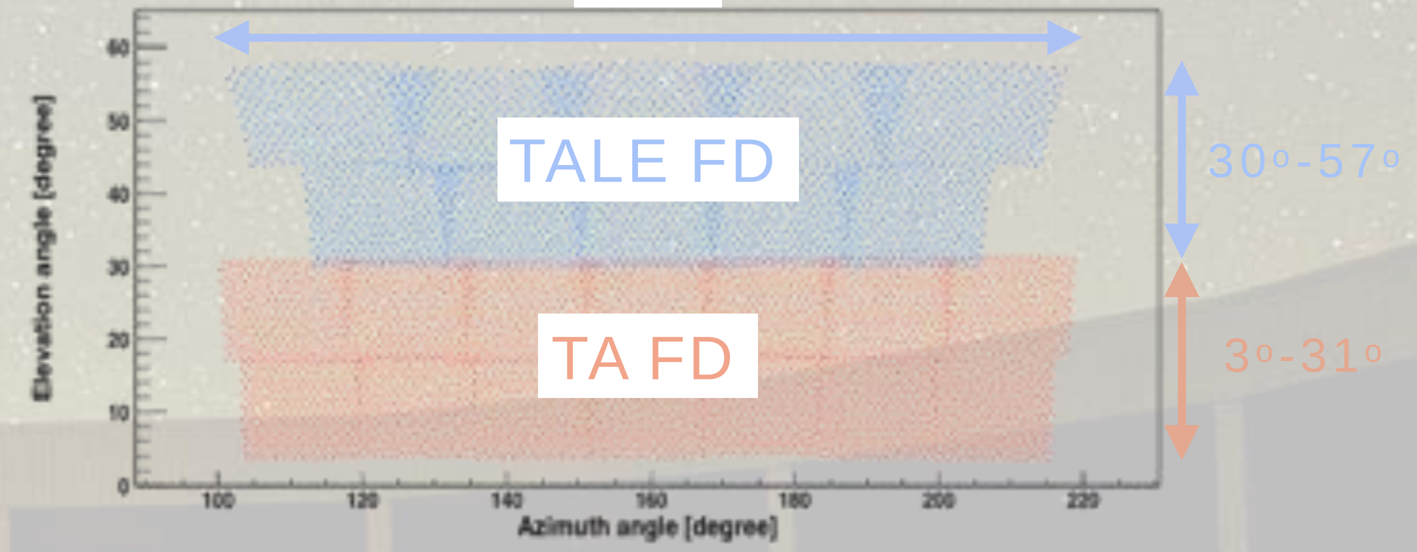
12 telescopes

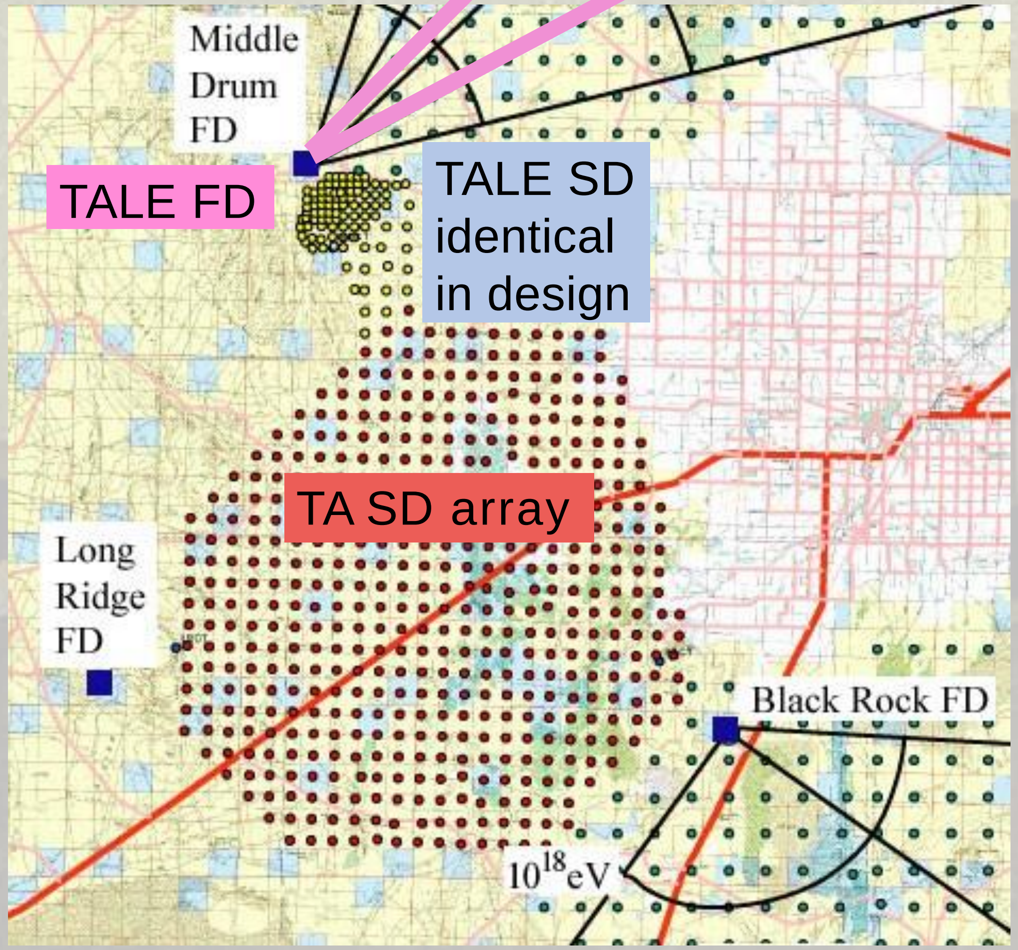
TALE

Located in TA MD site
10 FDs in the TALE station
Elevation: 30^{o}-57^{o} (higher elevation than MD) Azimuthal: 114^{o}

104 SD infill array identical to main TA SD
Variable spacing up to 400m





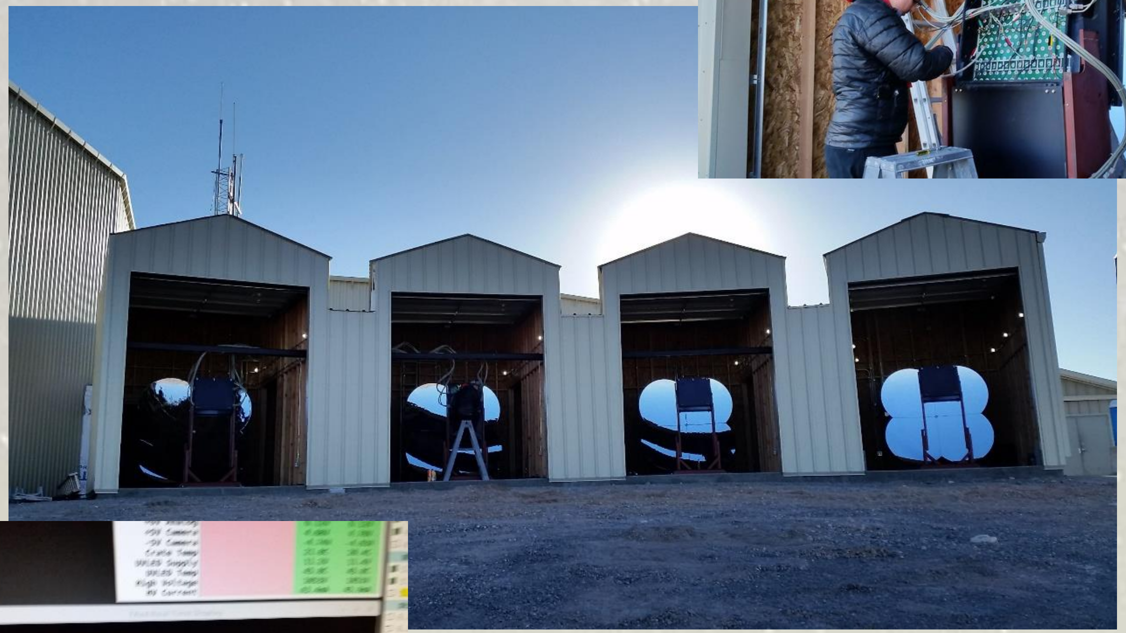


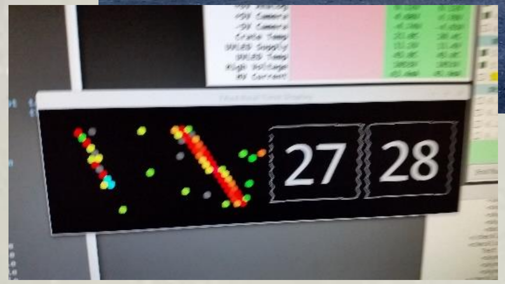
TALE FD Installed in Nov. 2012
Operation since Sep. 2013

TALE SD completed Mar. 2018
Hybrid trigger: Sep. 2018

TA × 4

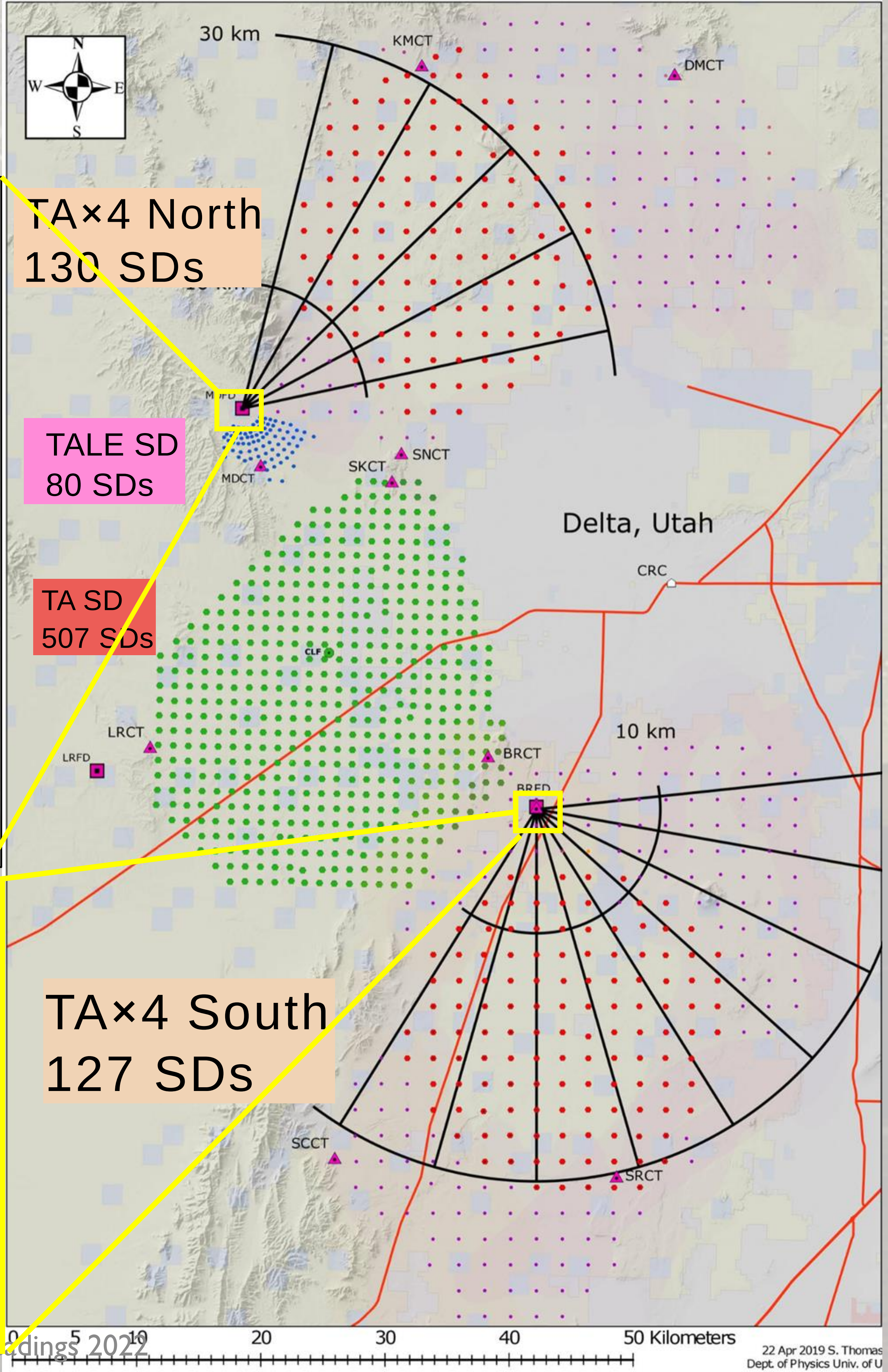
TA×4 northern FD station





routine observation
since Jun. 2019

TA×4 southern FD station

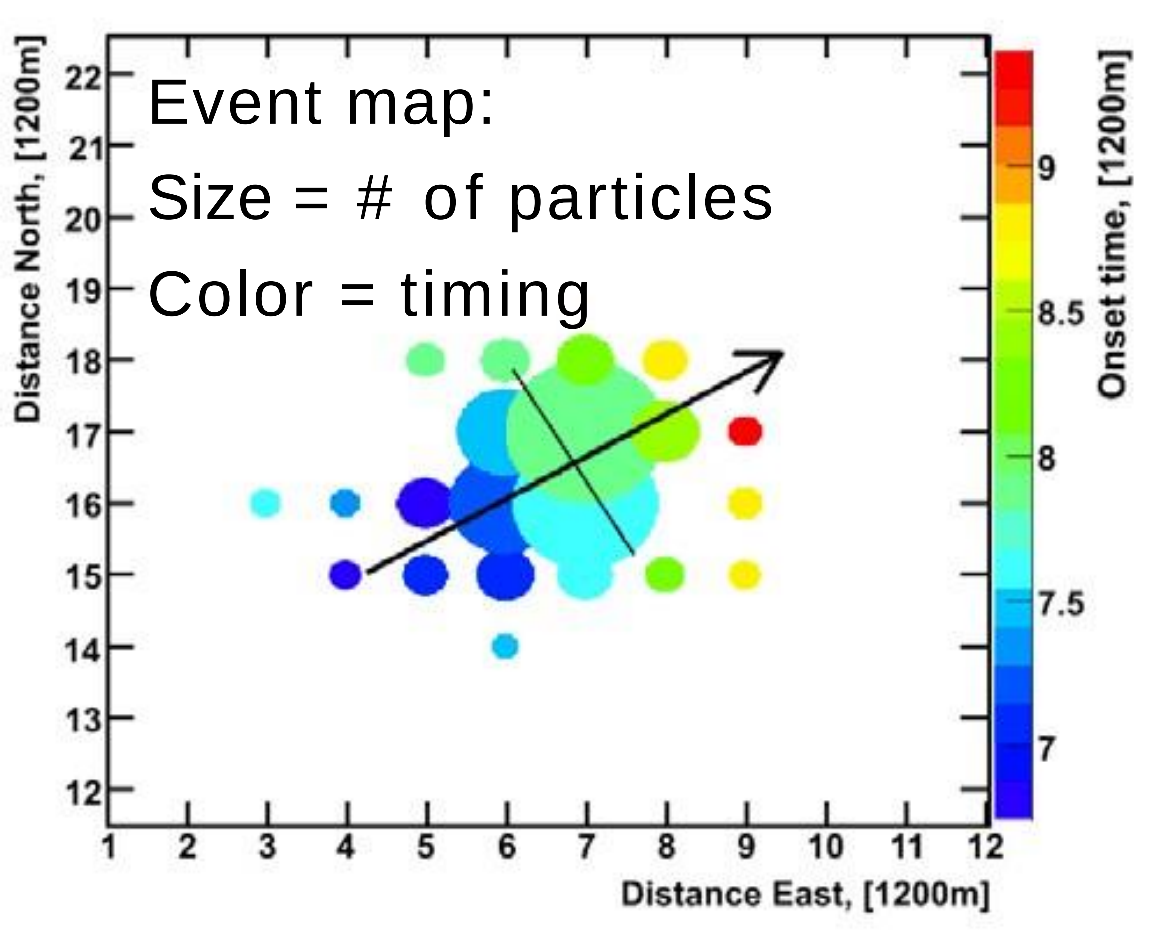


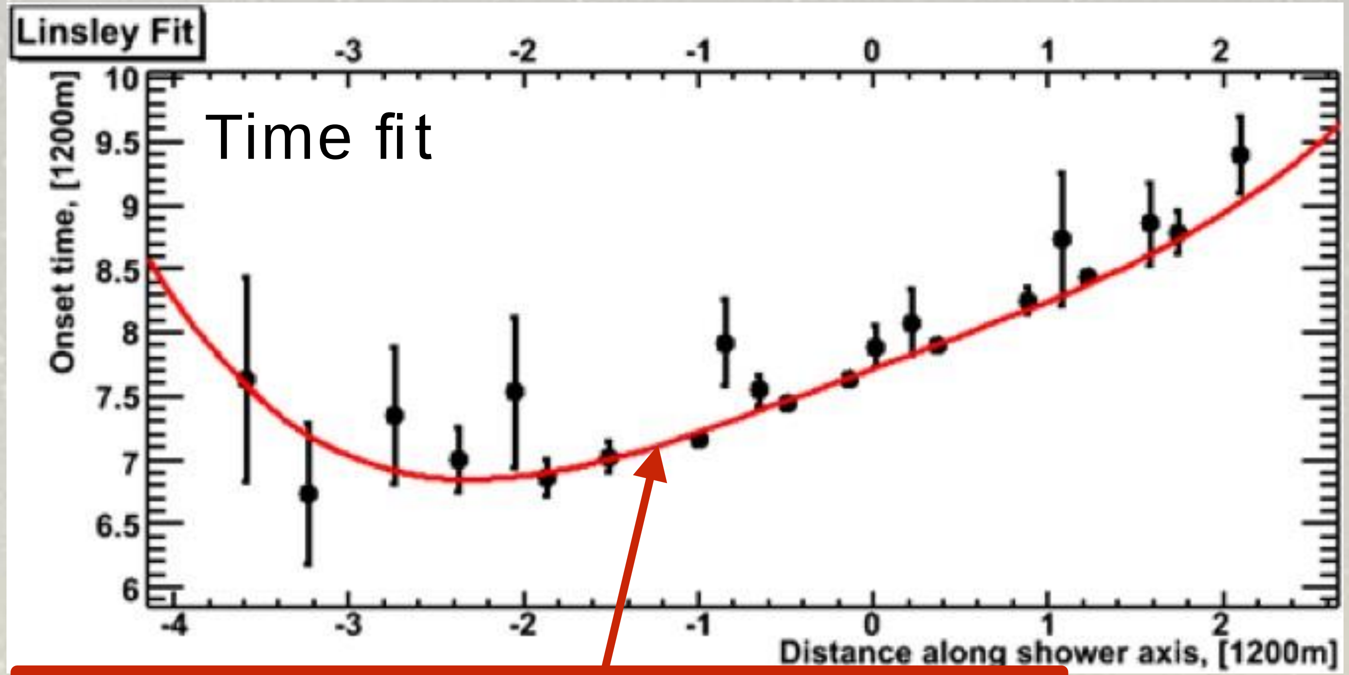
- Goal: fourfold increase in size of TA SD array (up to 3000 km^2).
- Triple statistics for E>20 EeV in 5 years.

- Hybrid experiment:
- 2 FD stations, 12 telescopes are installed

- 257 SD scintillators out of 500 are installed and operational since Nov. 2019

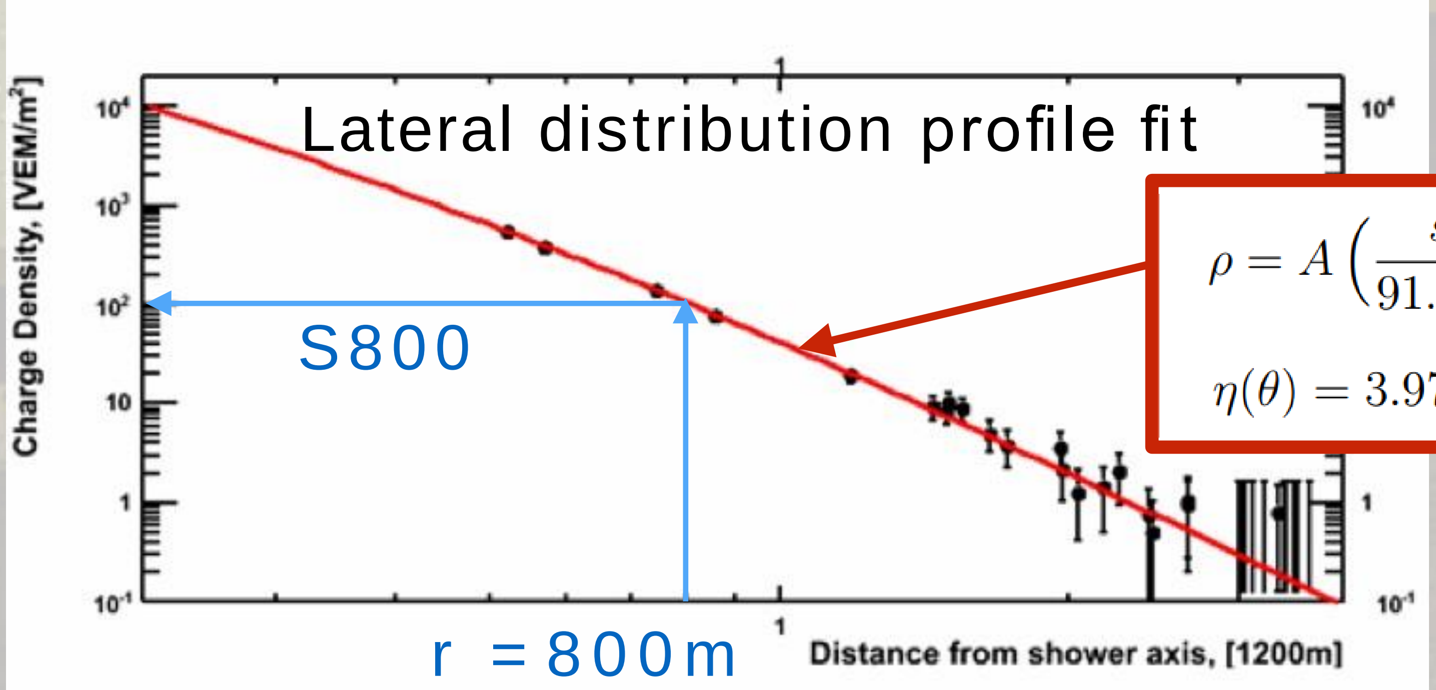
SD Event Reconstruction





$$\tau = a\left(1 - \frac{l}{12 \times 10^3\mathrm{m}}\right)^{1.05}\left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.35}\rho^{-0.5}$$

Modified empirical formula in AGASA



$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1 + \frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1 + \left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

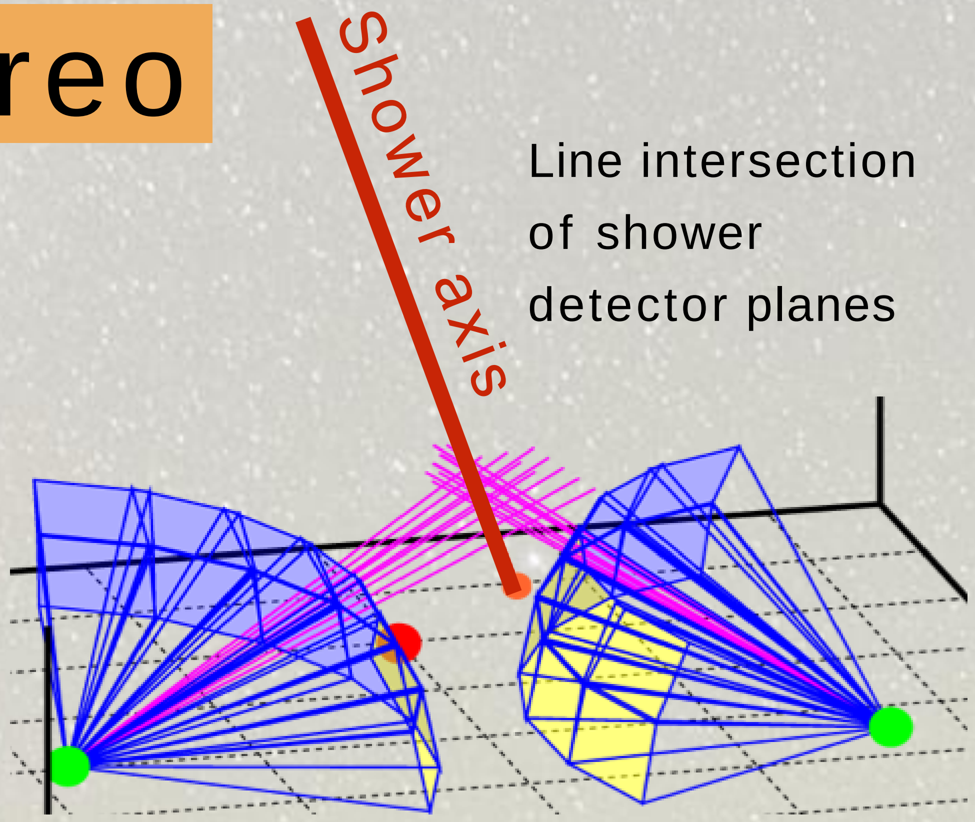
$$\eta(\theta) = 3.97 - 1.79\left[\sec(\theta) - 1\right]$$

Empirical formula used by AGASA

S800 -> primary energy

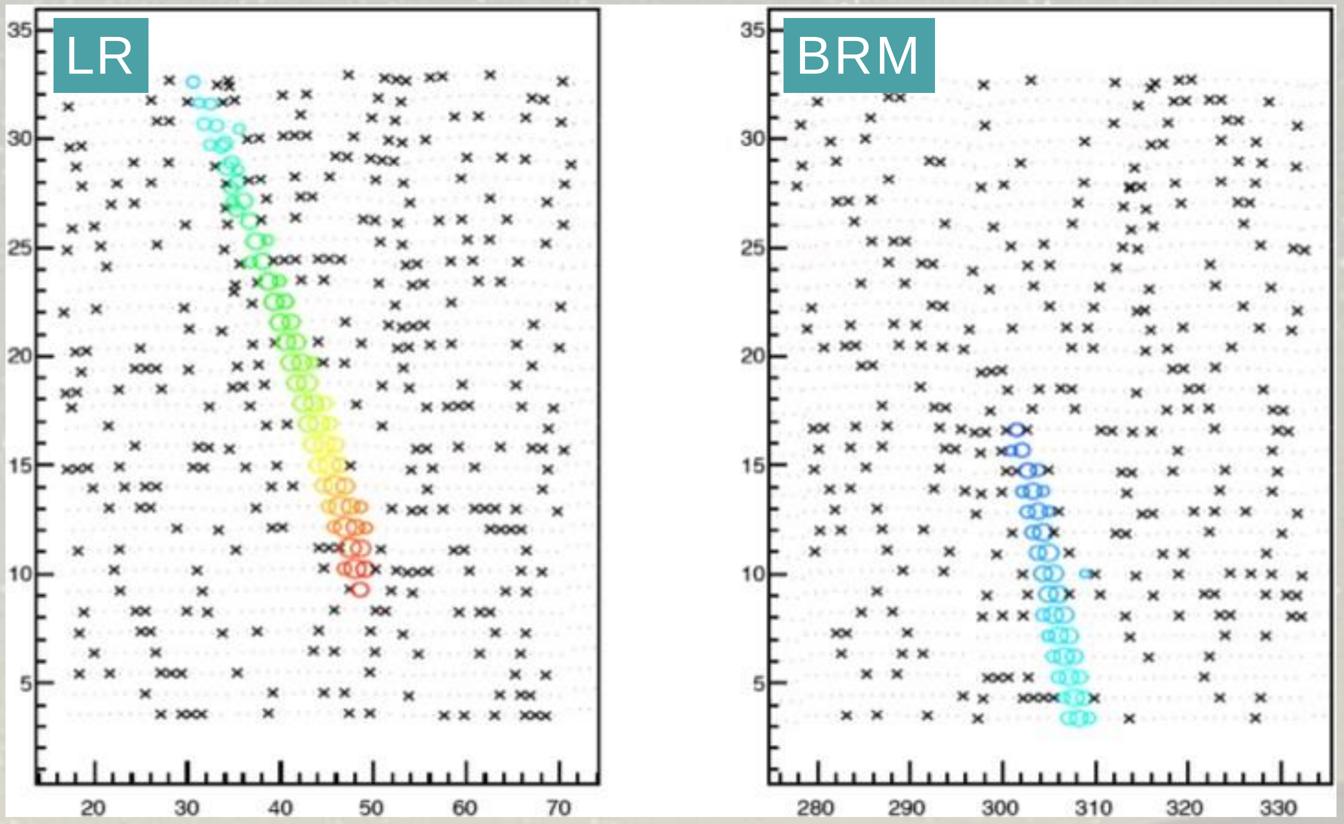
Event reconstruction

Stereo

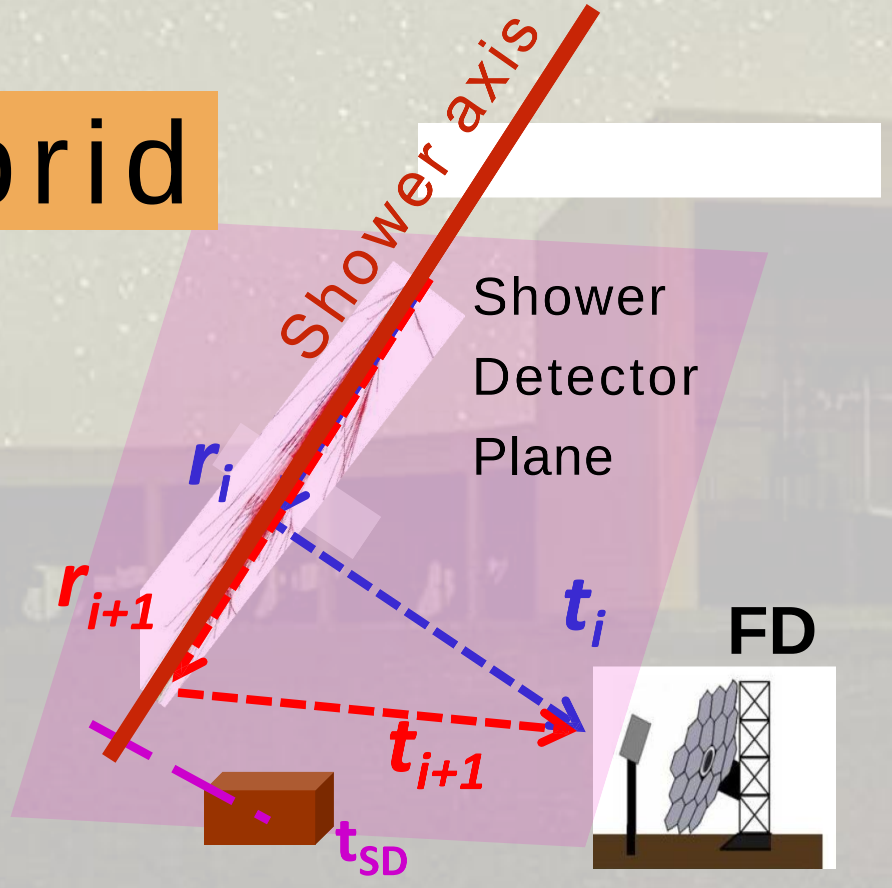


Line intersection
of shower
detector planes

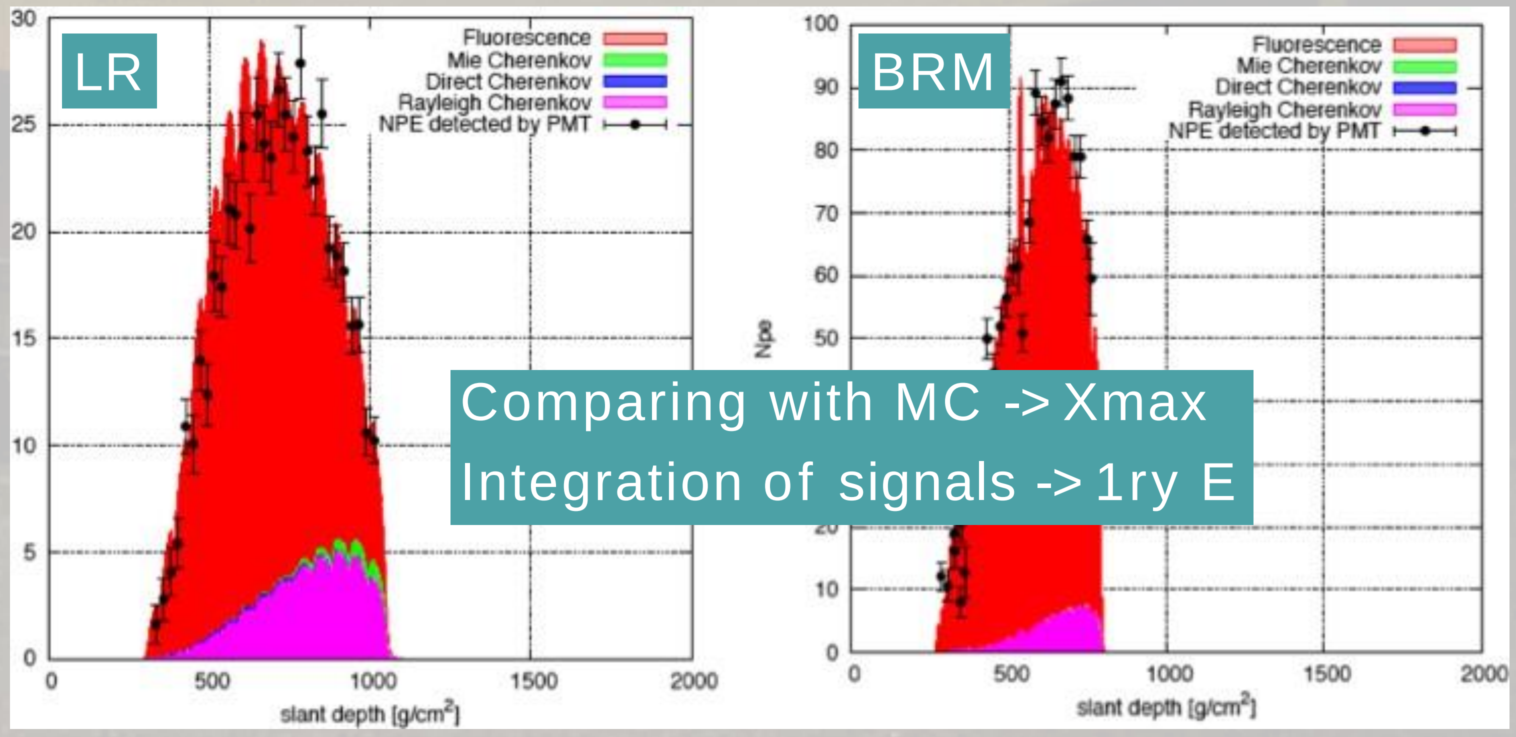
observed images



Hybrid

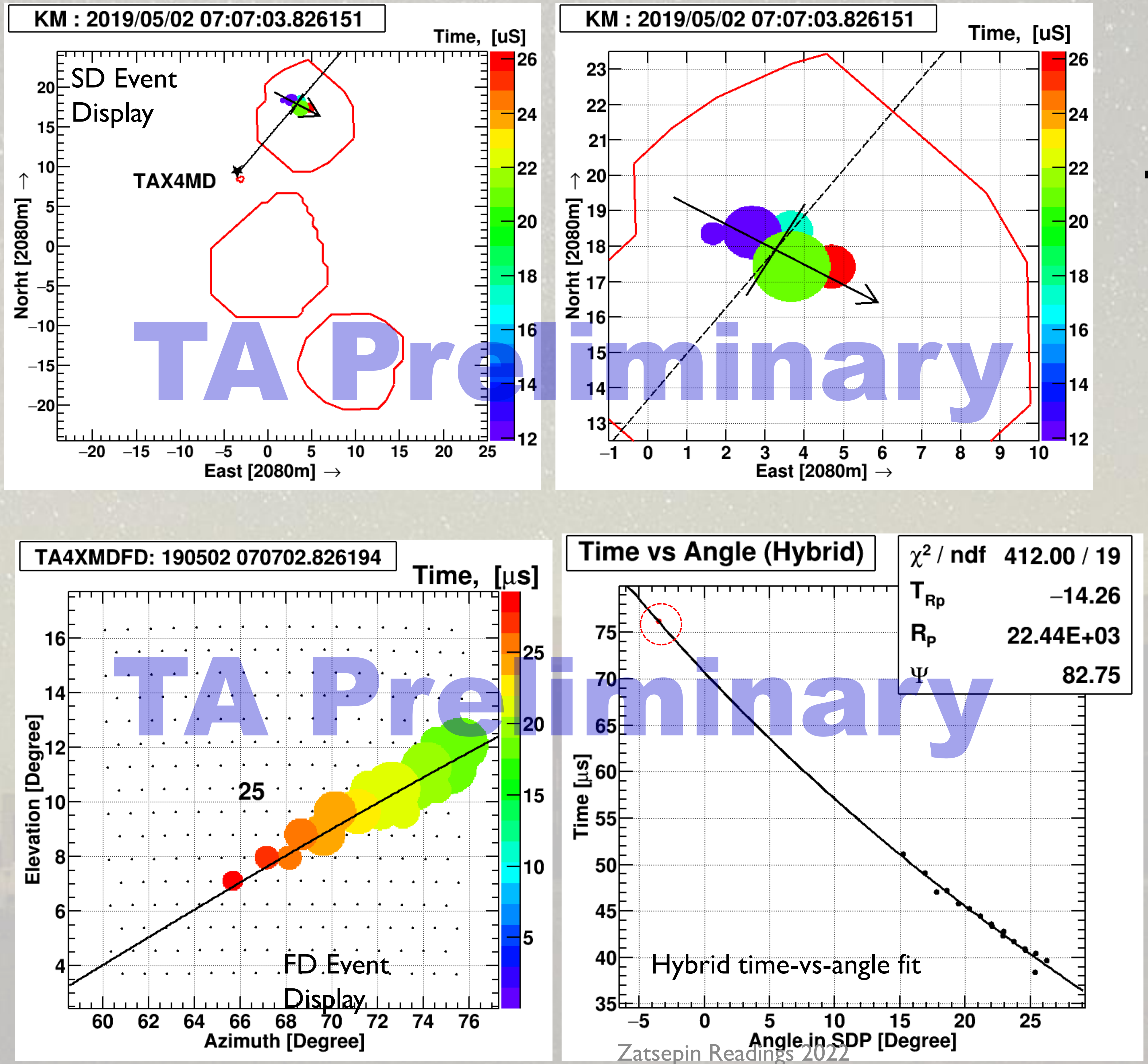


reconstructed shower profiles



Comparing with MC -> Xmax
Integration of signals -> 1ry E

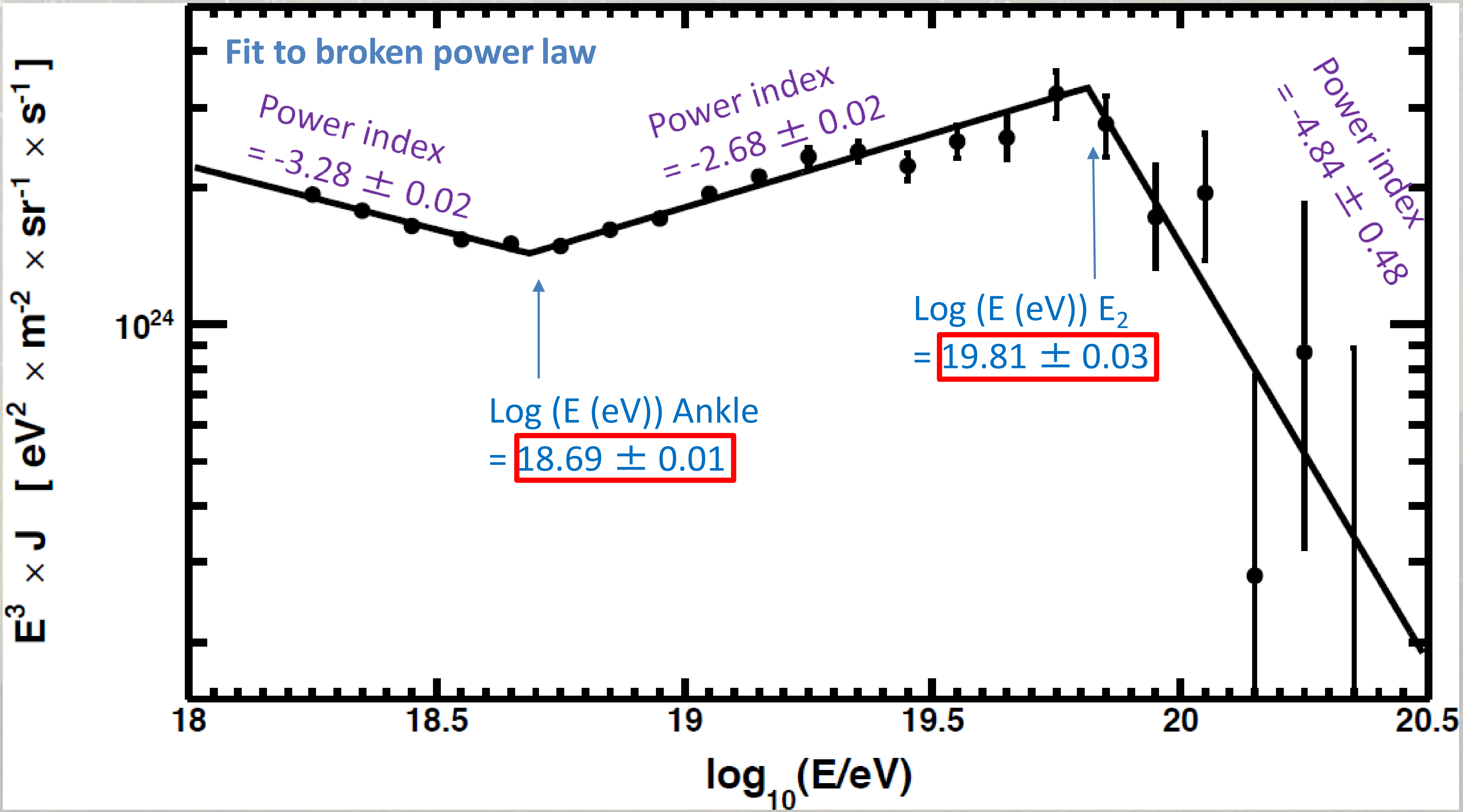
TAx4 Hybrid Event Example



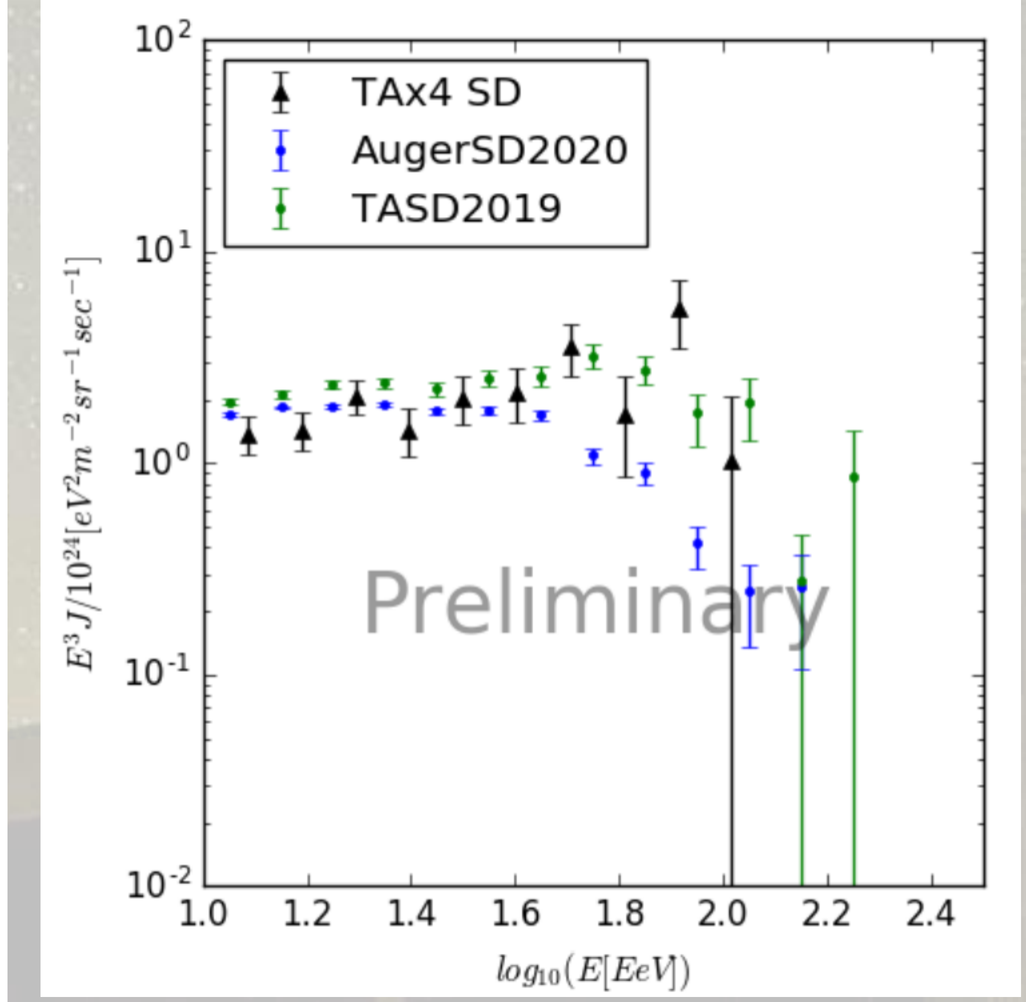
Energy spectrum

TA SD Energy Spectrum

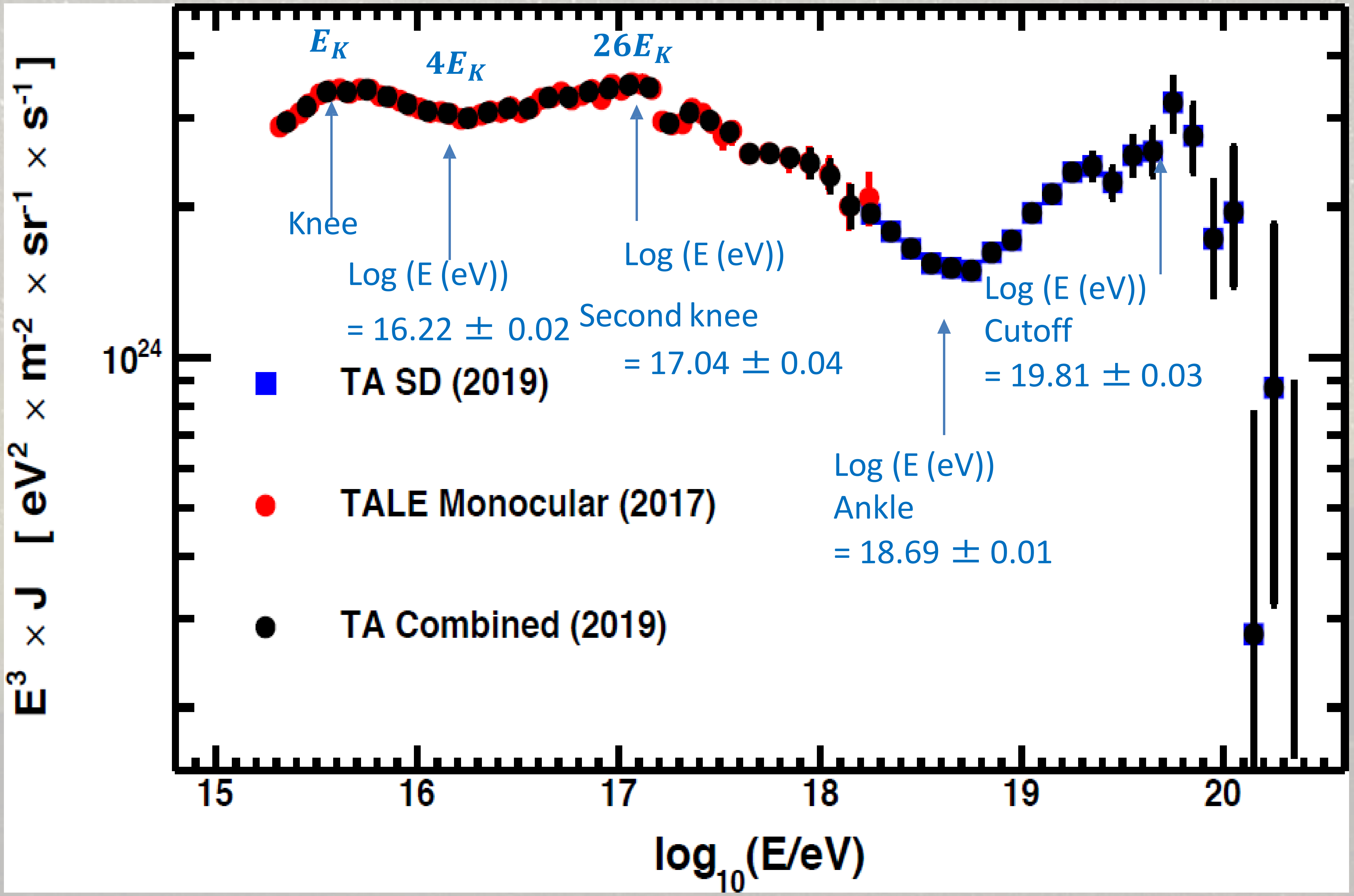
TA SD 11 years data



TAx4 SD 1 year data



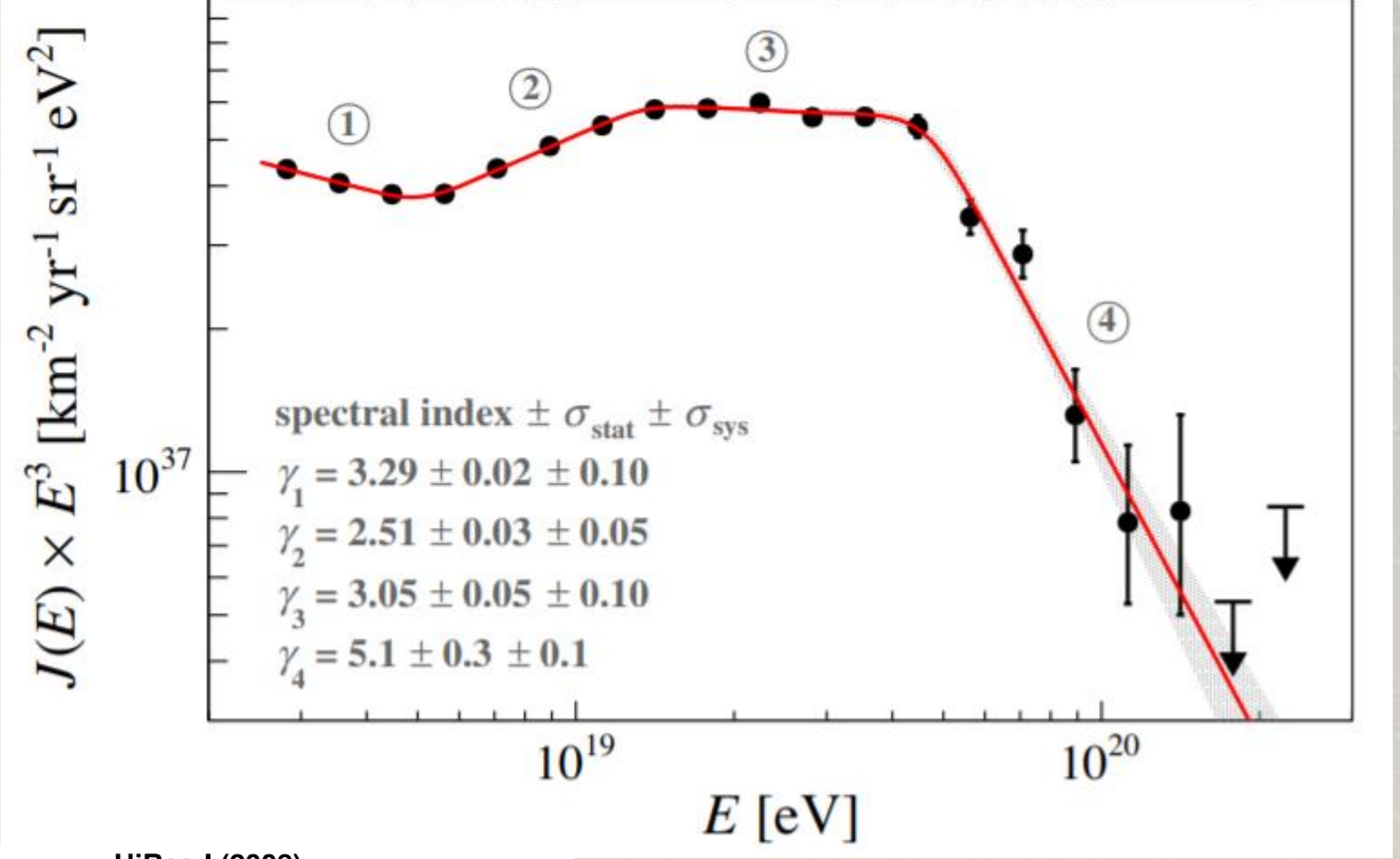
Combined Energy Spectrum



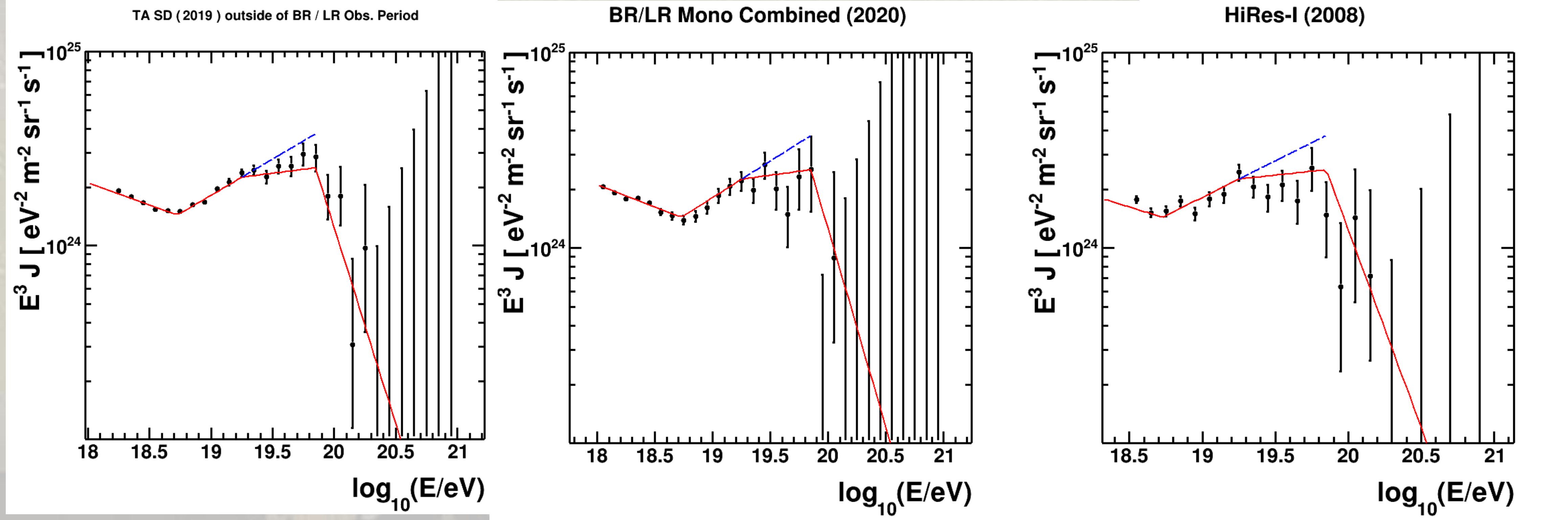
Combined TA spectrum using 22 months TALE FD monocular data + 11 years TA SD data

9

The "*Instep*" feature



A. Aab *et al.* (The Pierre Auger Collaboration) Phys. Rev. Lett. **125**, 121106 (2020)



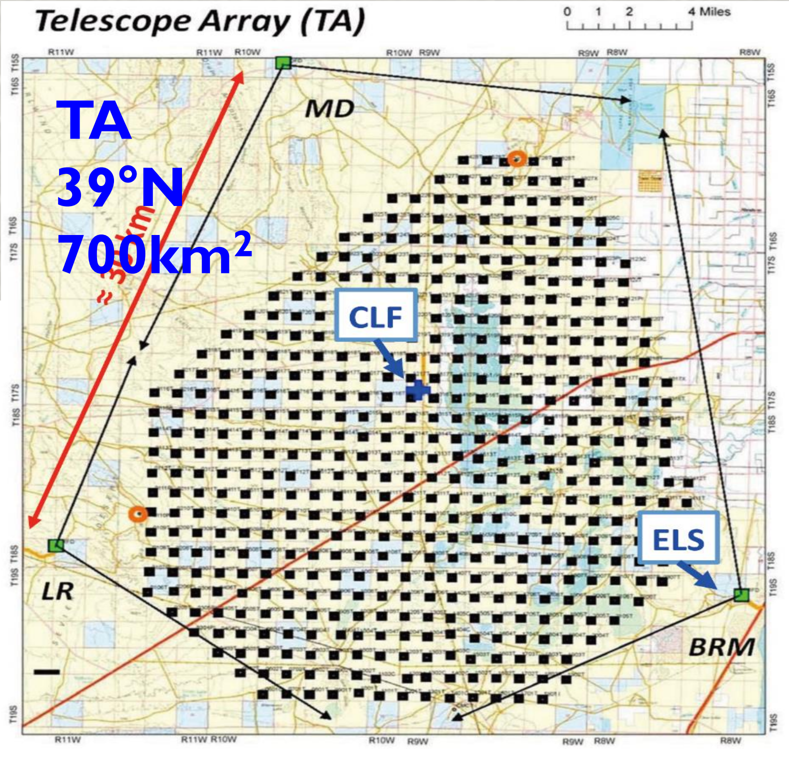
Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
E_{ankle}/EeV	5.0 ± 0.1	5.4 ± 0.1
E_{instep}/EeV	13 ± 1	18 ± 1
E_{cut}/EeV	46 ± 3	71 ± 3

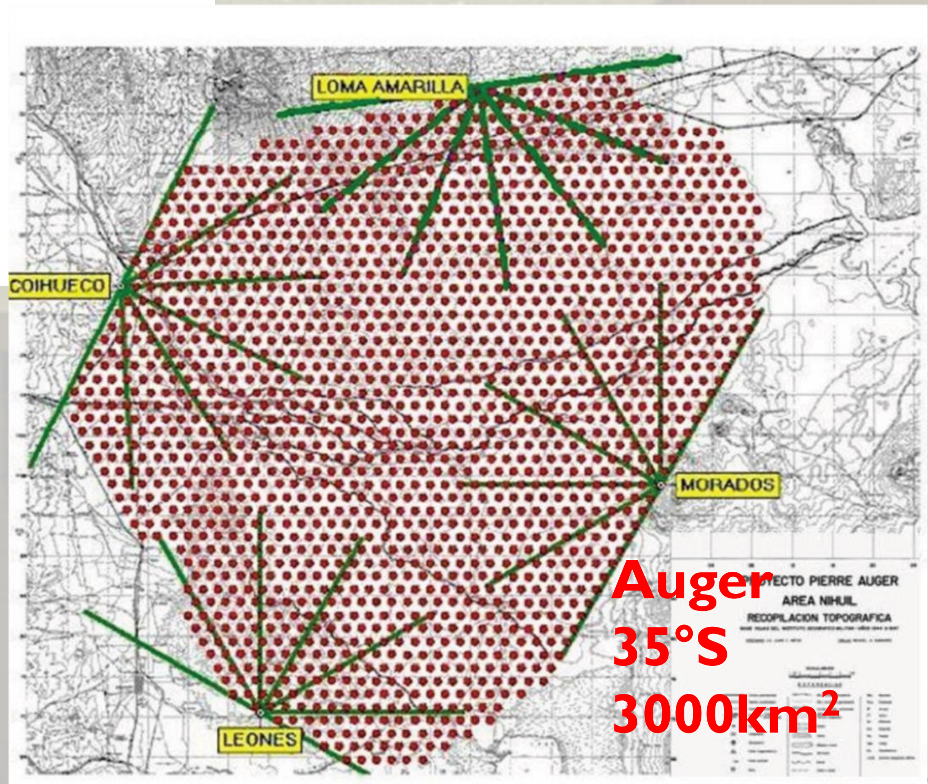
Pierre Auger found a spectrum softening in $10^{19} - 10^{19.5}$ eV range
Combining TA SD, FD and HiRes data, we observe the *Instep* feature in the Northern Hemisphere at $10^{19.25\pm0.03}$ eV with a 5.3 σ significance

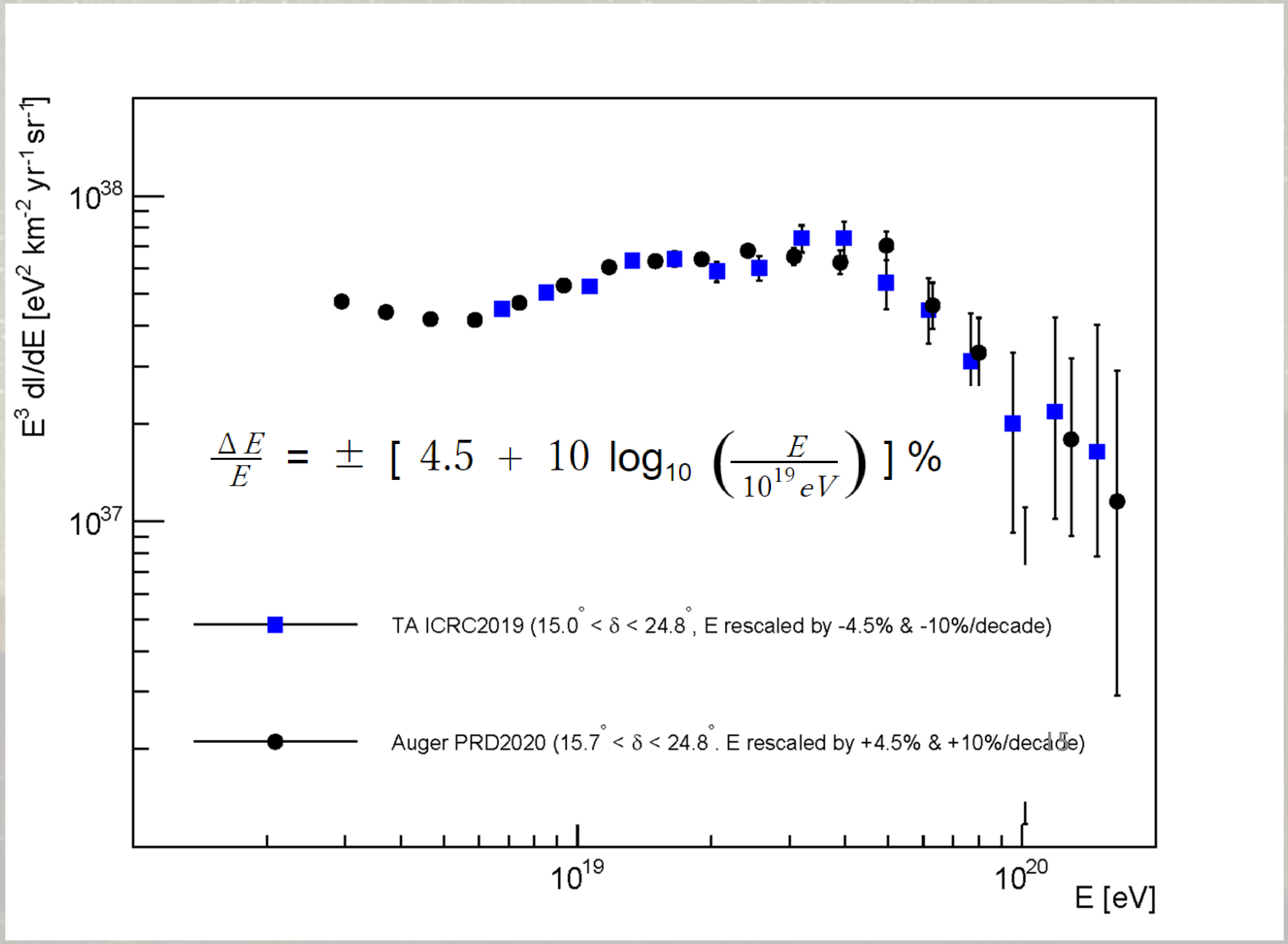
Dmitry Ivanov, ICRC'2021

Yoshiki Tsunesada, Auger+TA spectrum WG , ICRC'2021

Joint Auger + TA spectrum WG result





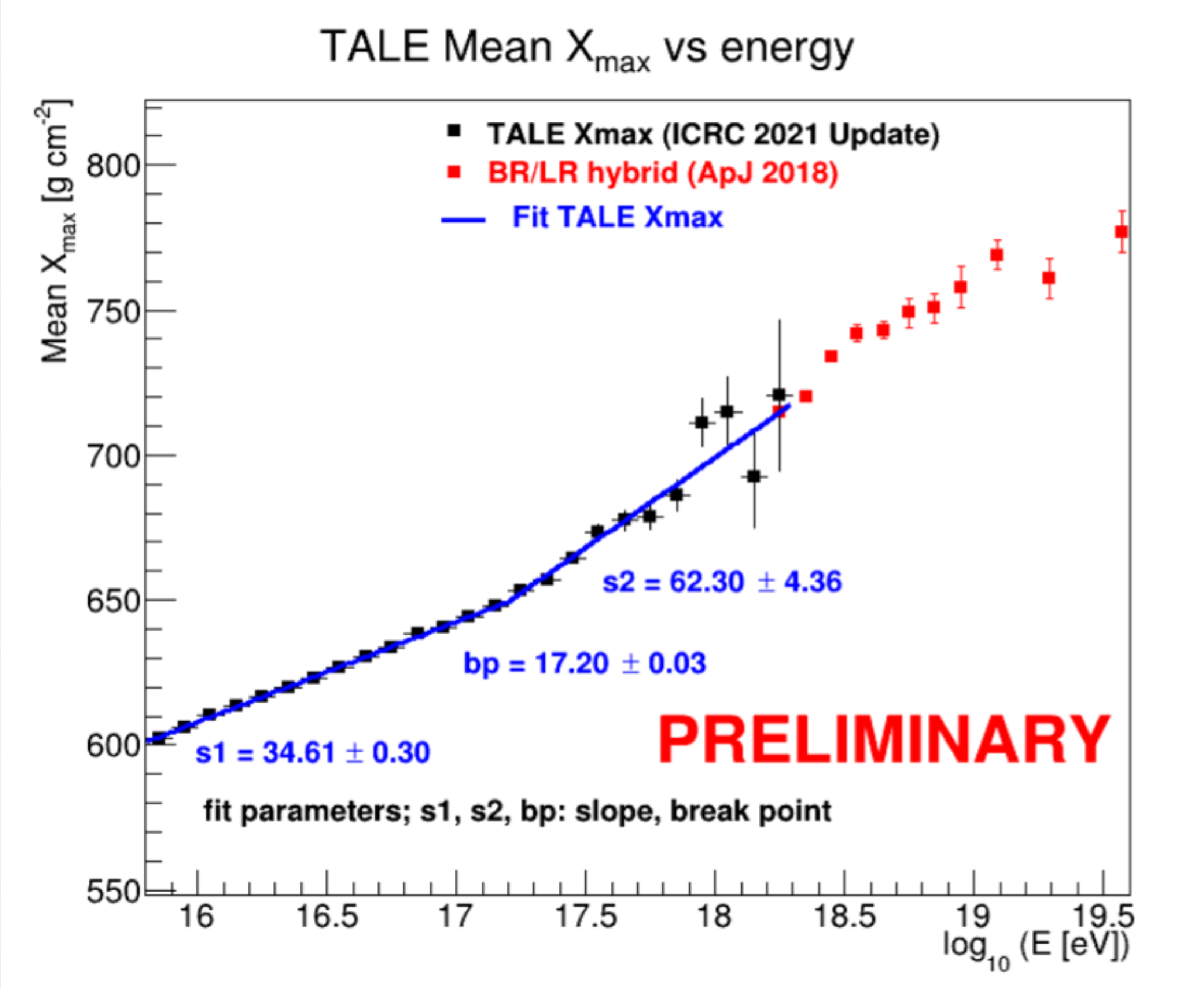


Absolute energy scale difference 9% + energy-dependent shift of ±10% per decade

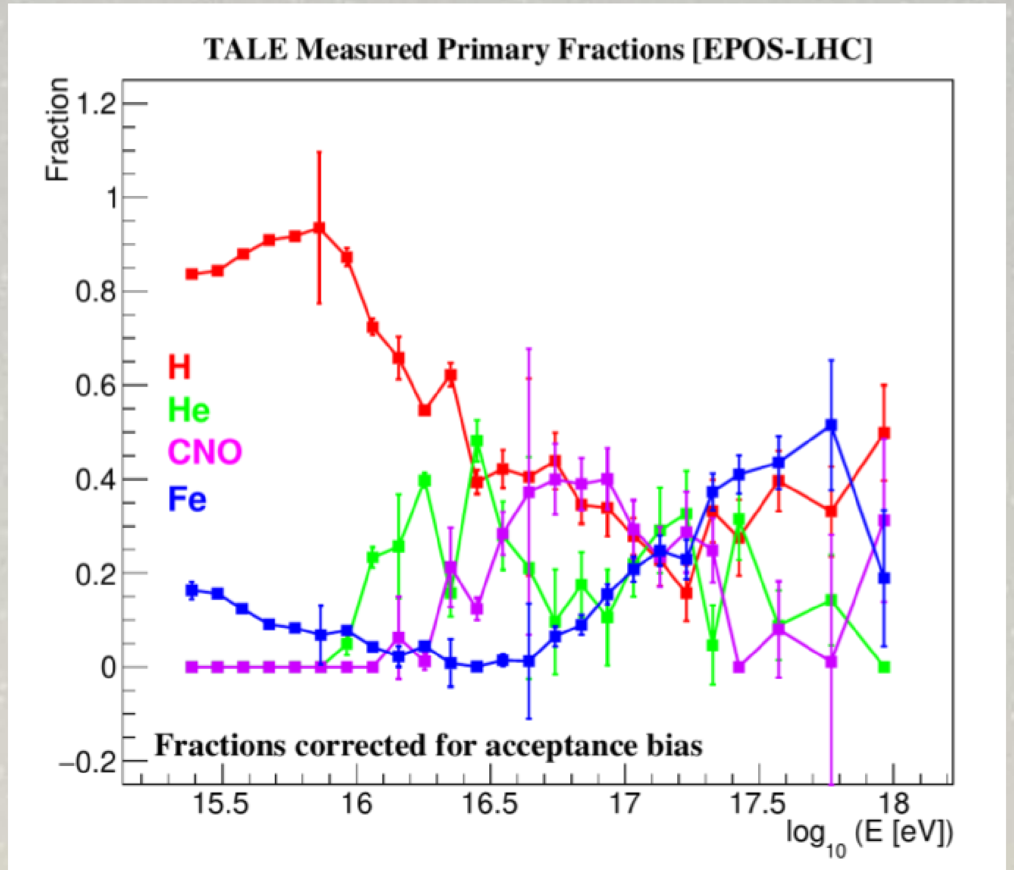
Yoshiki Tsunesada, ICRC'2021

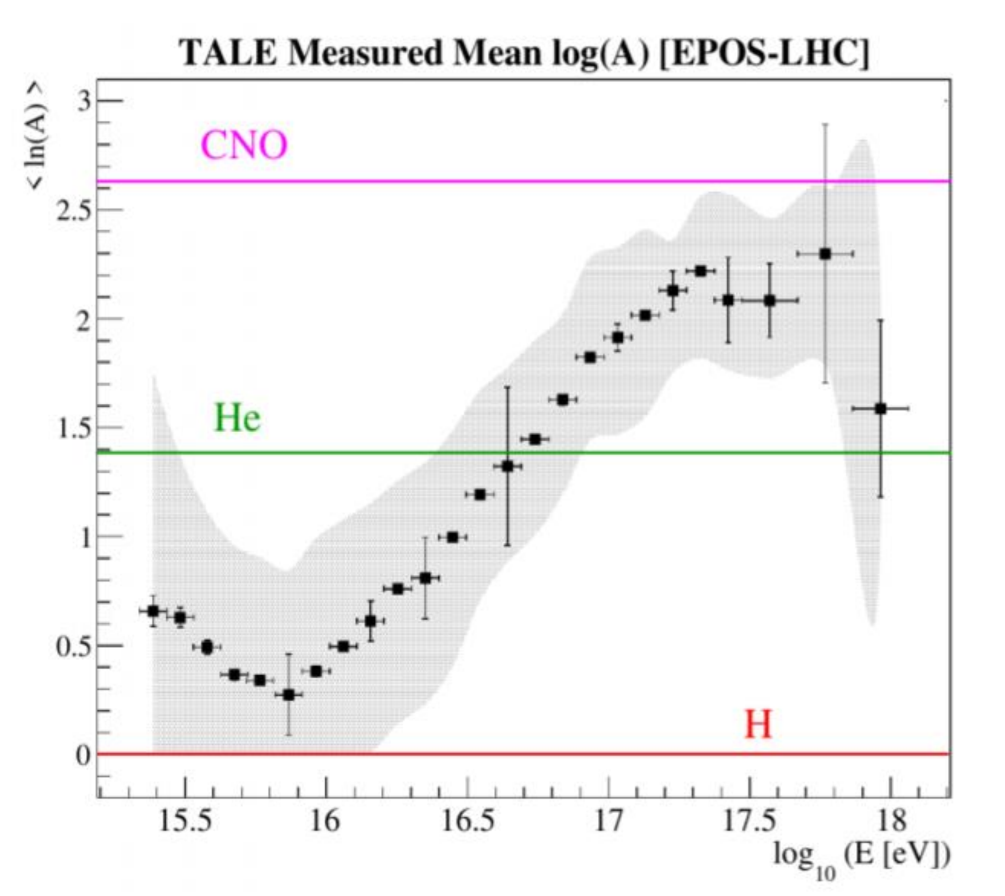
Chemical composition and hadronic interactions

TALE FD monocular XMAX



Tareq AbuZayyad, ICRC'2021



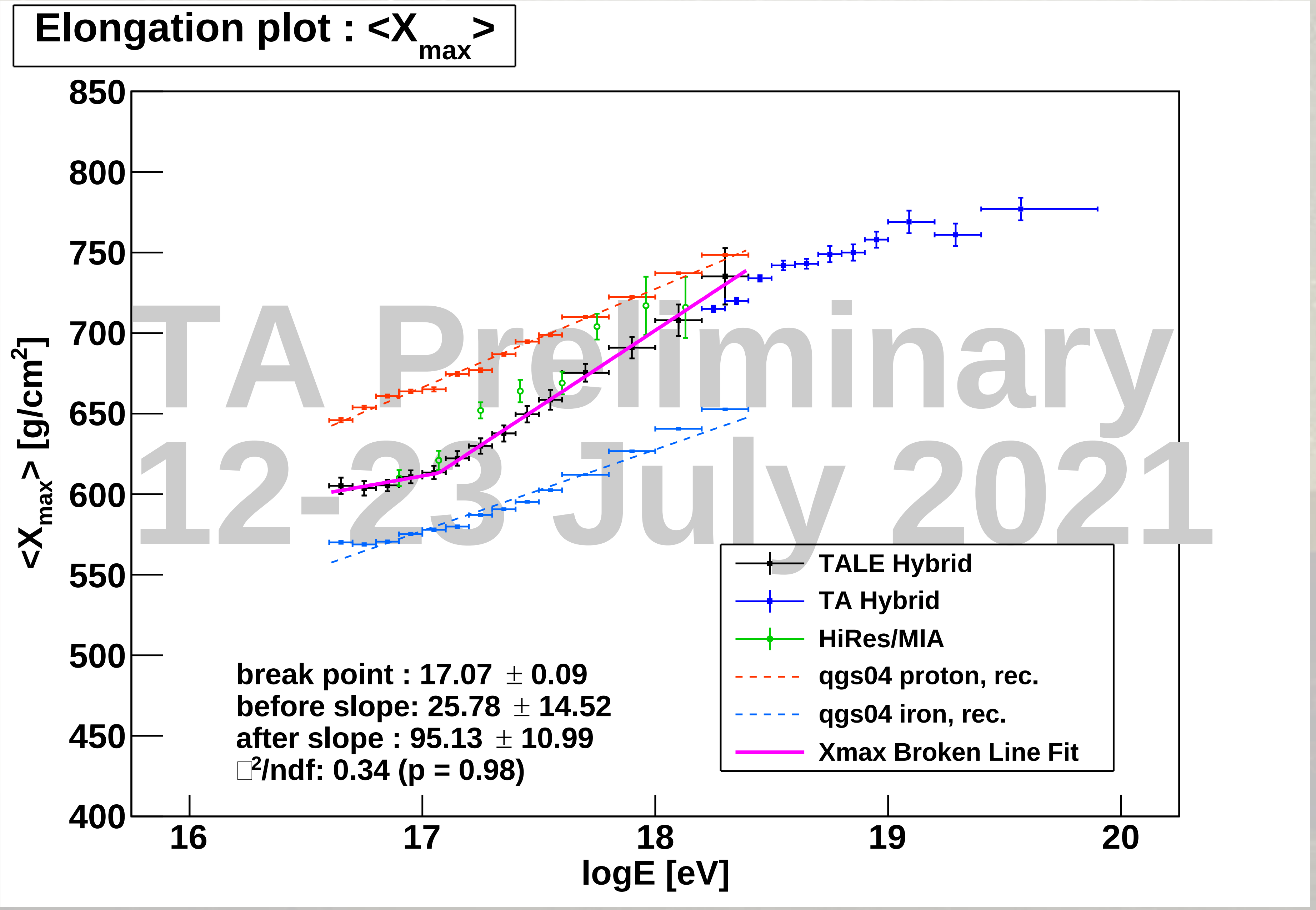


TA Collaboration ApJ 909 (2021)

A break in the elongation rate at energy $10^{17.2}$ eV

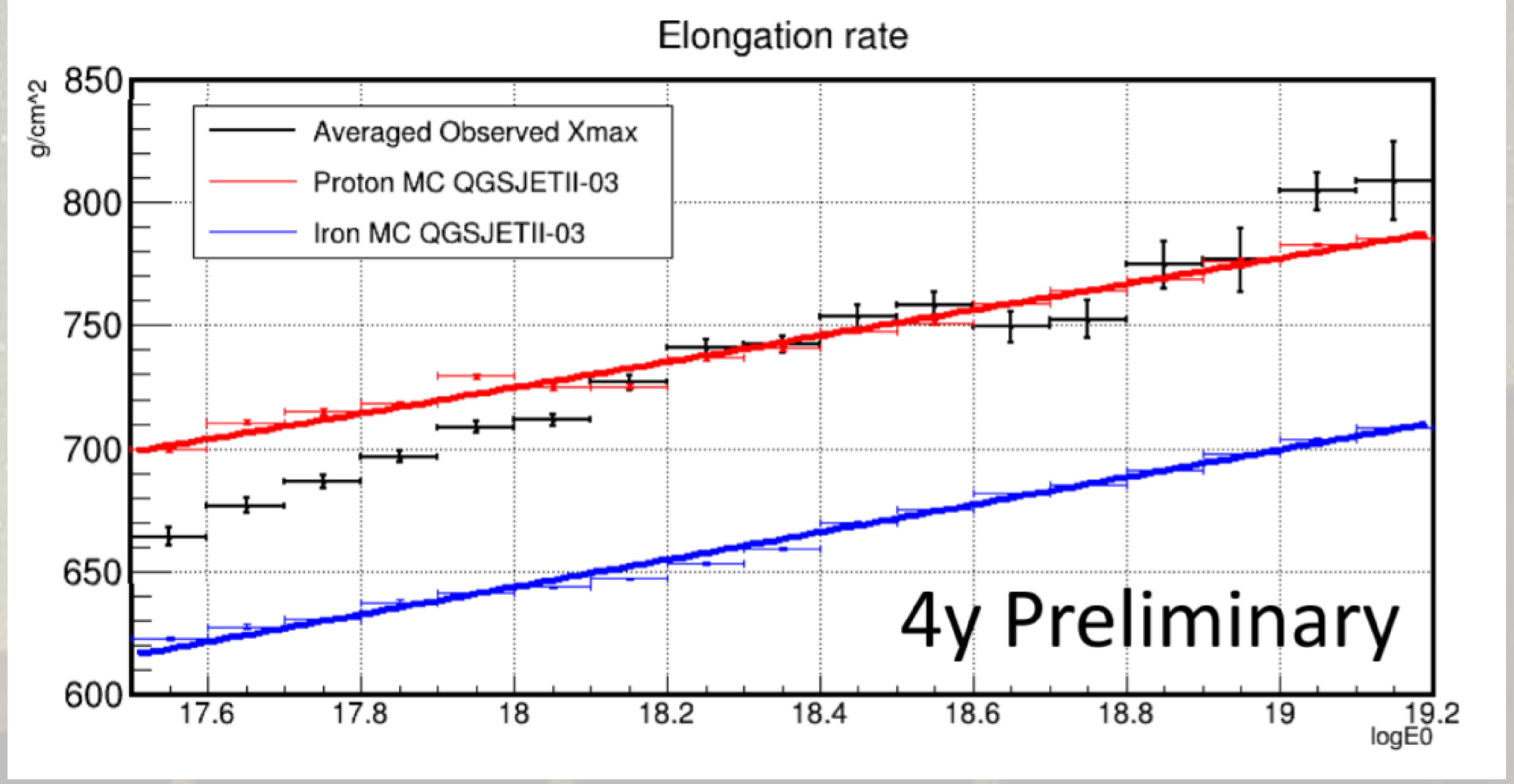
TA and TALE hybrid XMAX

TALE hybrid



Keitaro Fujita, ICRC'2021

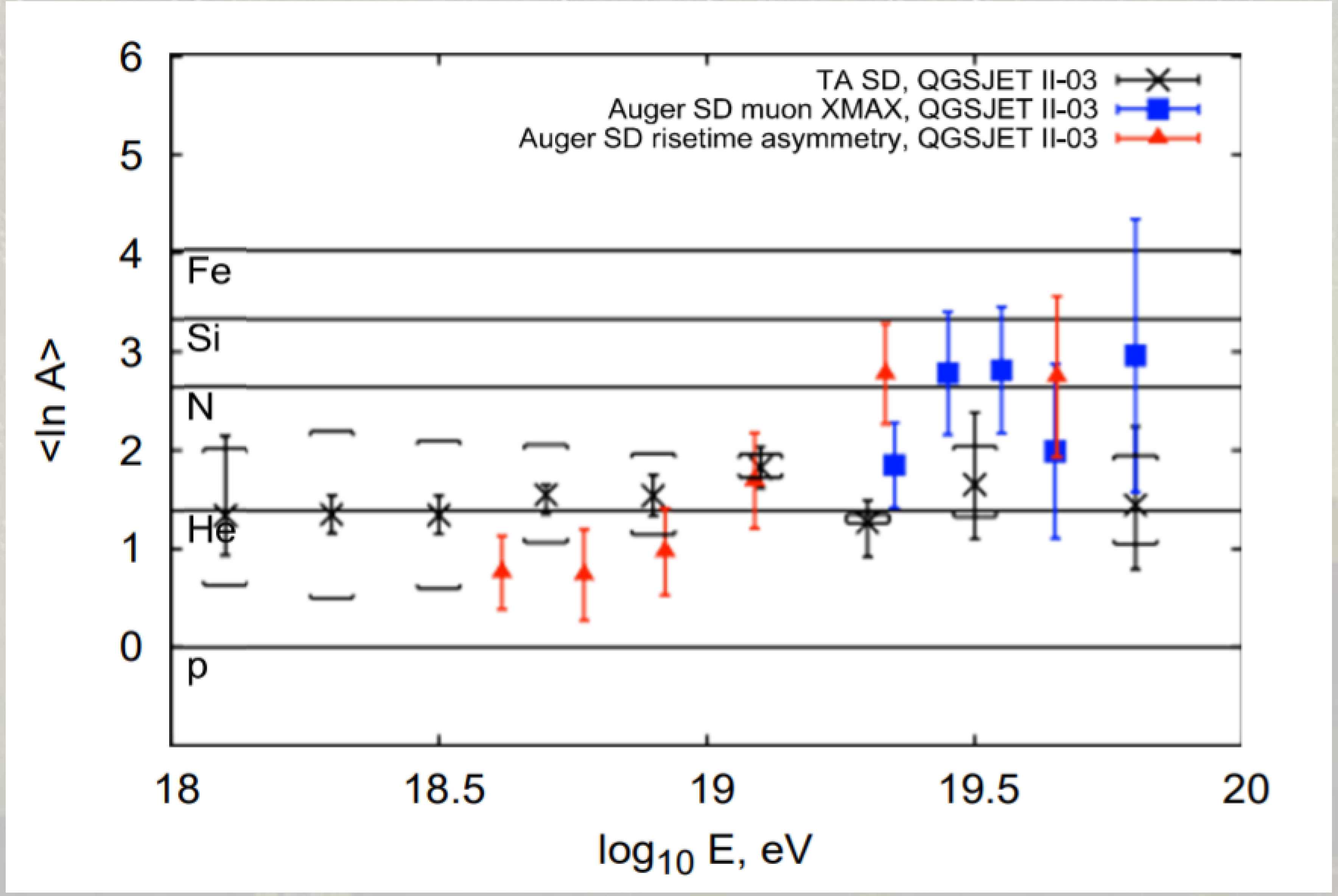
TA hybrid

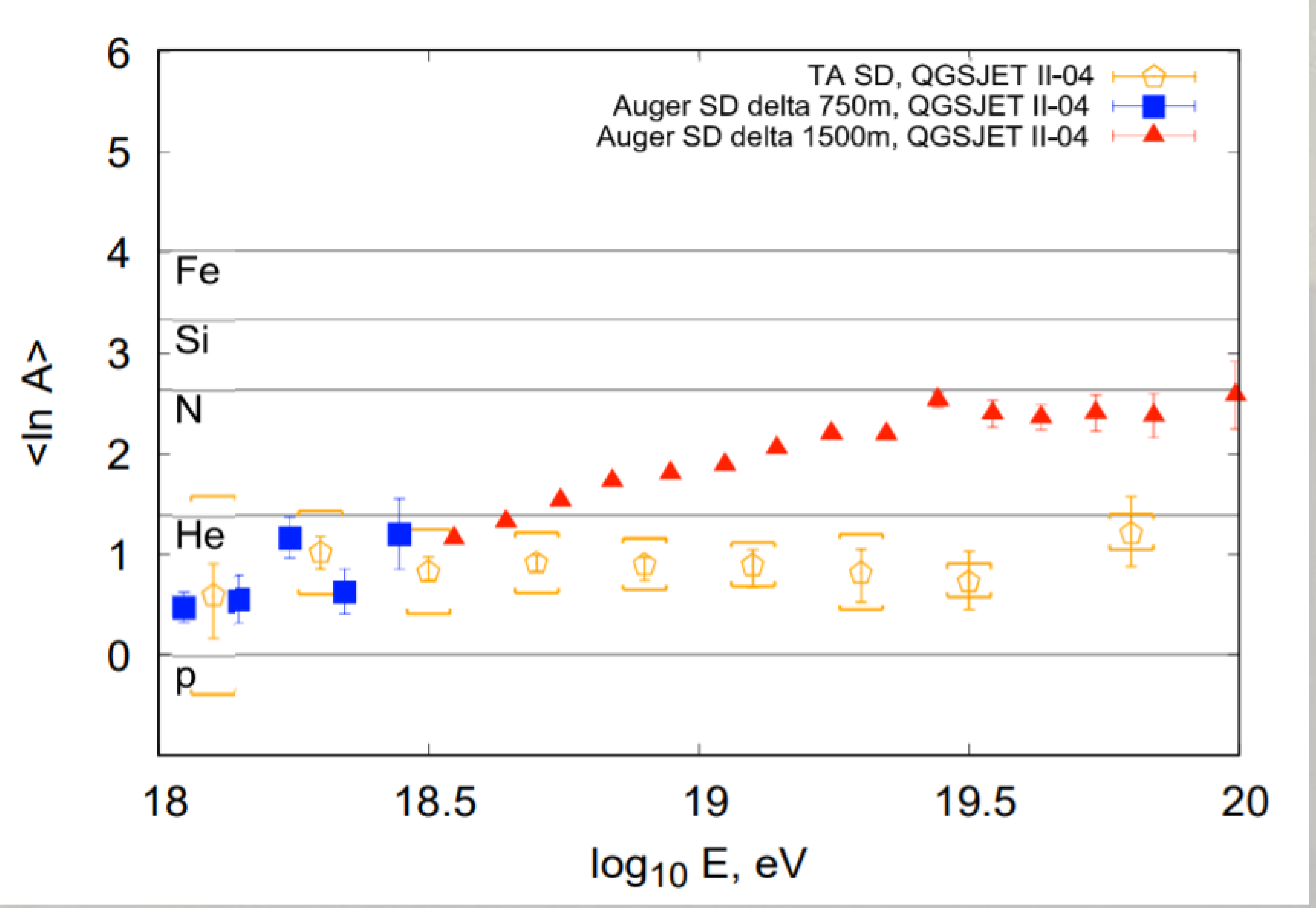


Heungsu Shin, ICRC'2021

TA SD composition

Machine learning technique based on BDT and 16 composition-sensitive observables with 12 years of TA SD data



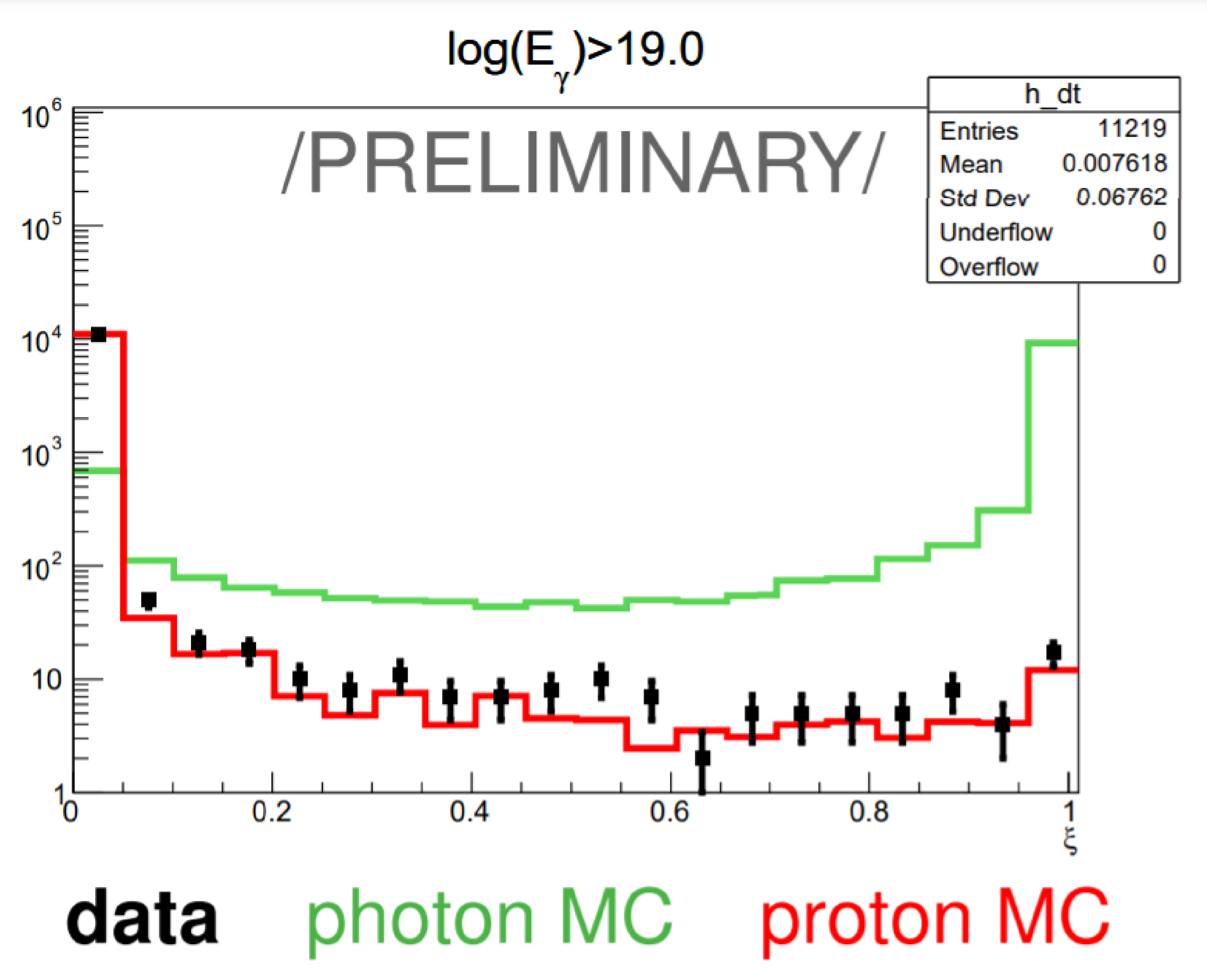


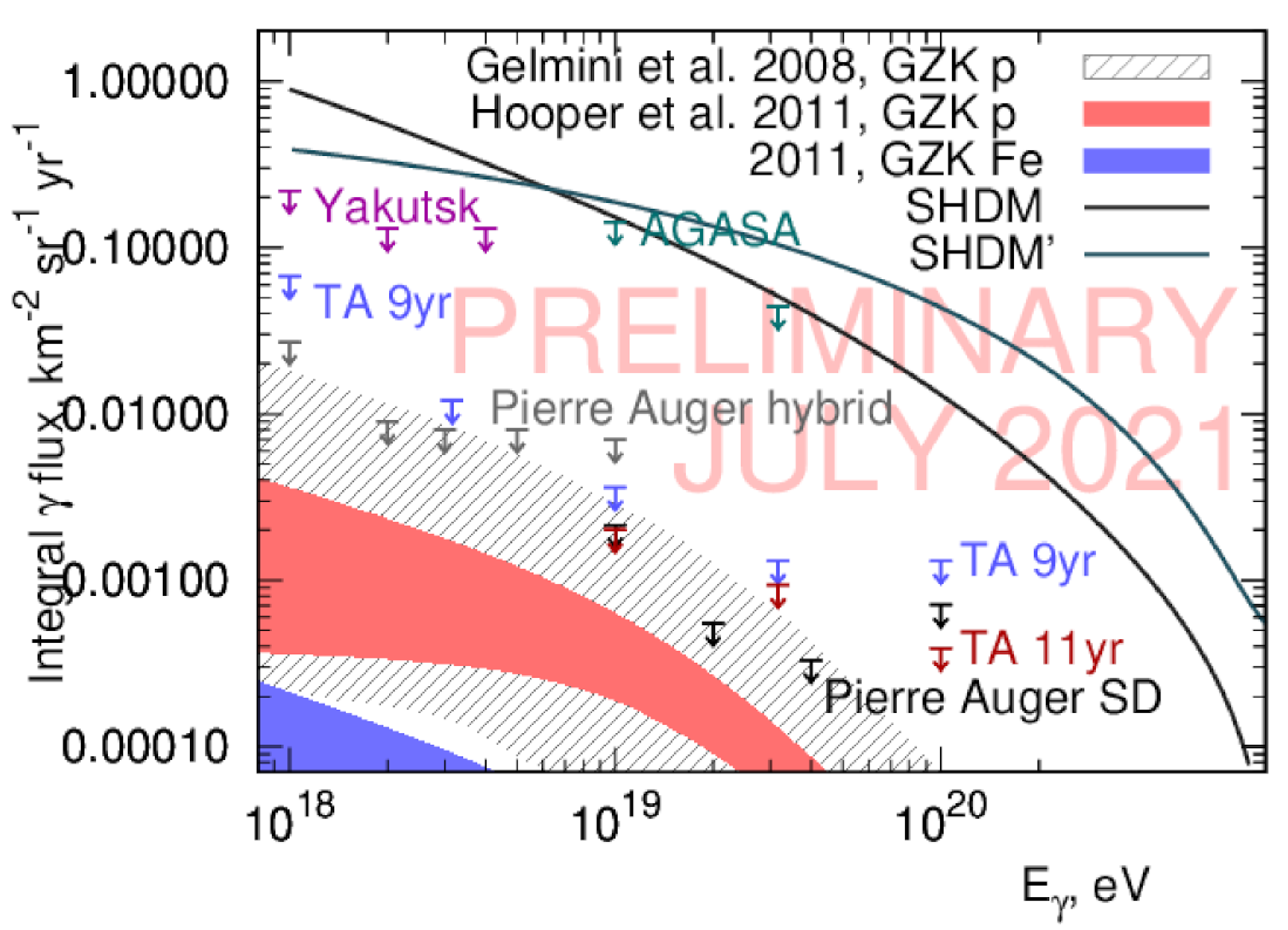
Yana Zhezher, ICRC'2021

TASD UHE photon limits

New p-γ classifier based on neural network. Classifier uses full time-resolved signals from all triggered SD stations along with 16 composition-sensitive observables.

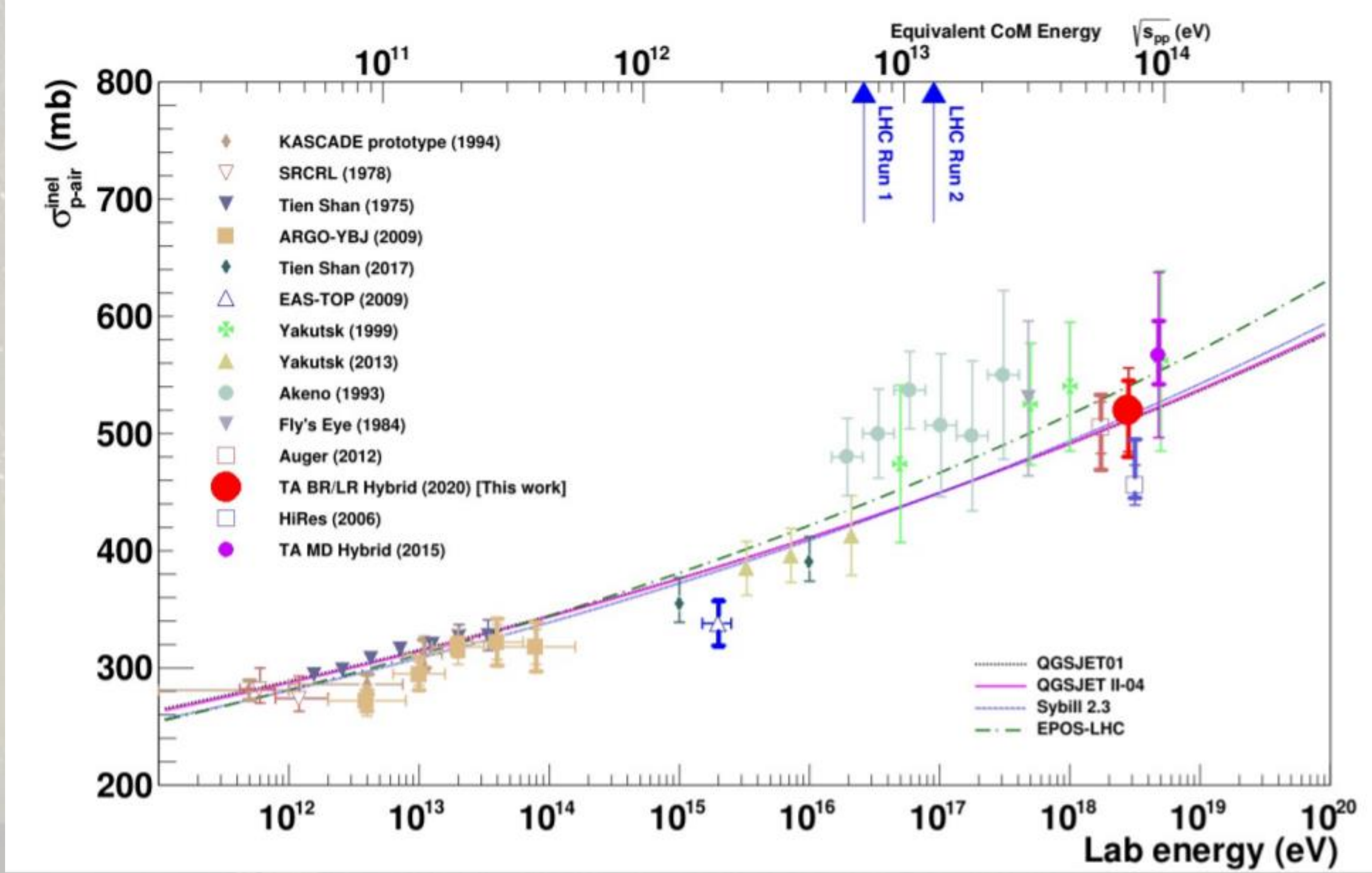
E_0, eV	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	2	1	0
$\bar{n}$ <	6.72	5.14	3.09
A_{eff}	3428	5546	7875
F_γ <	2.0×10^{-3}	9.3×10^{-4}	3.9×10^{-4}

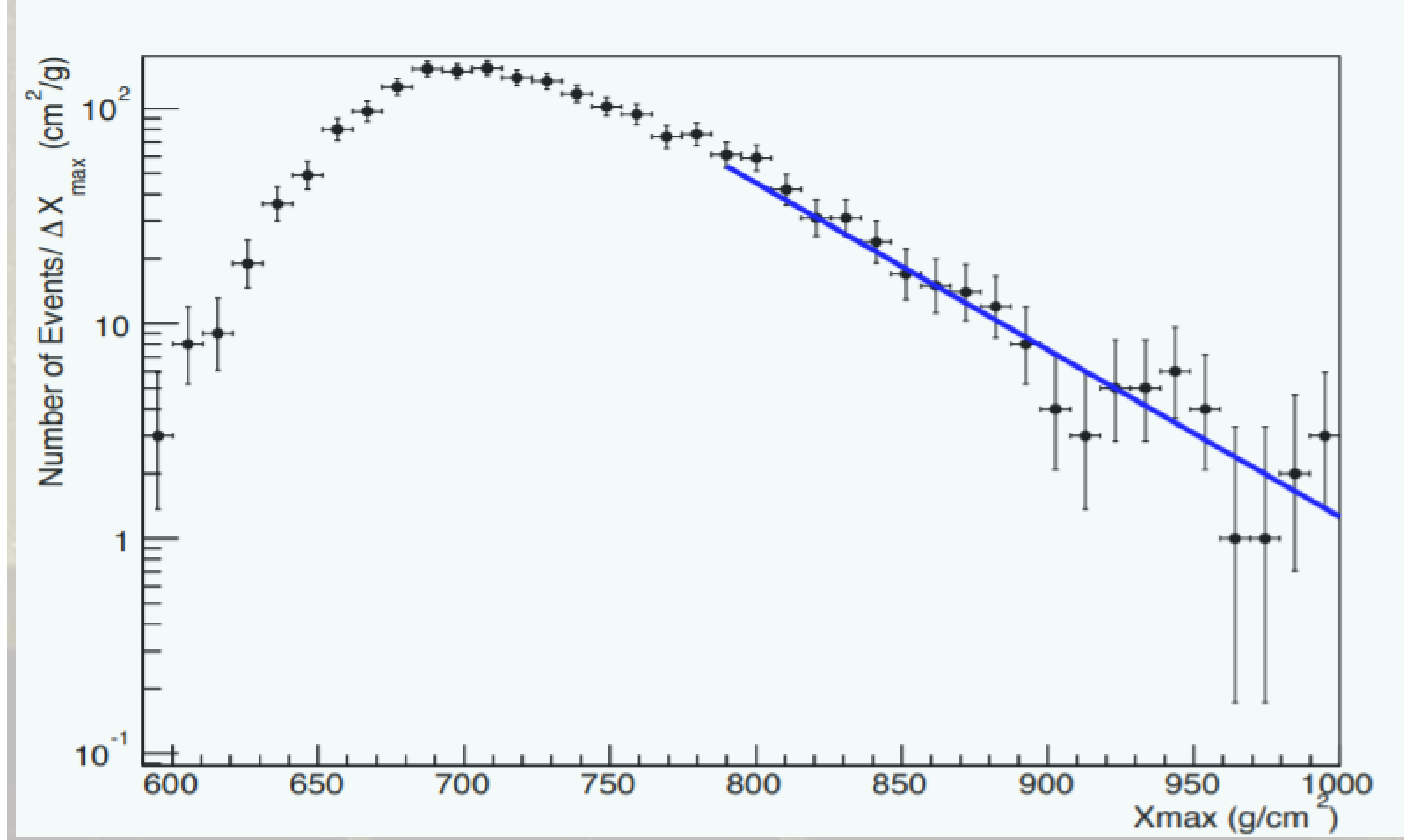




Oleg Kalashev, Ivan Kharuk, GR, ICRC'2021

TA proton-air cross-section



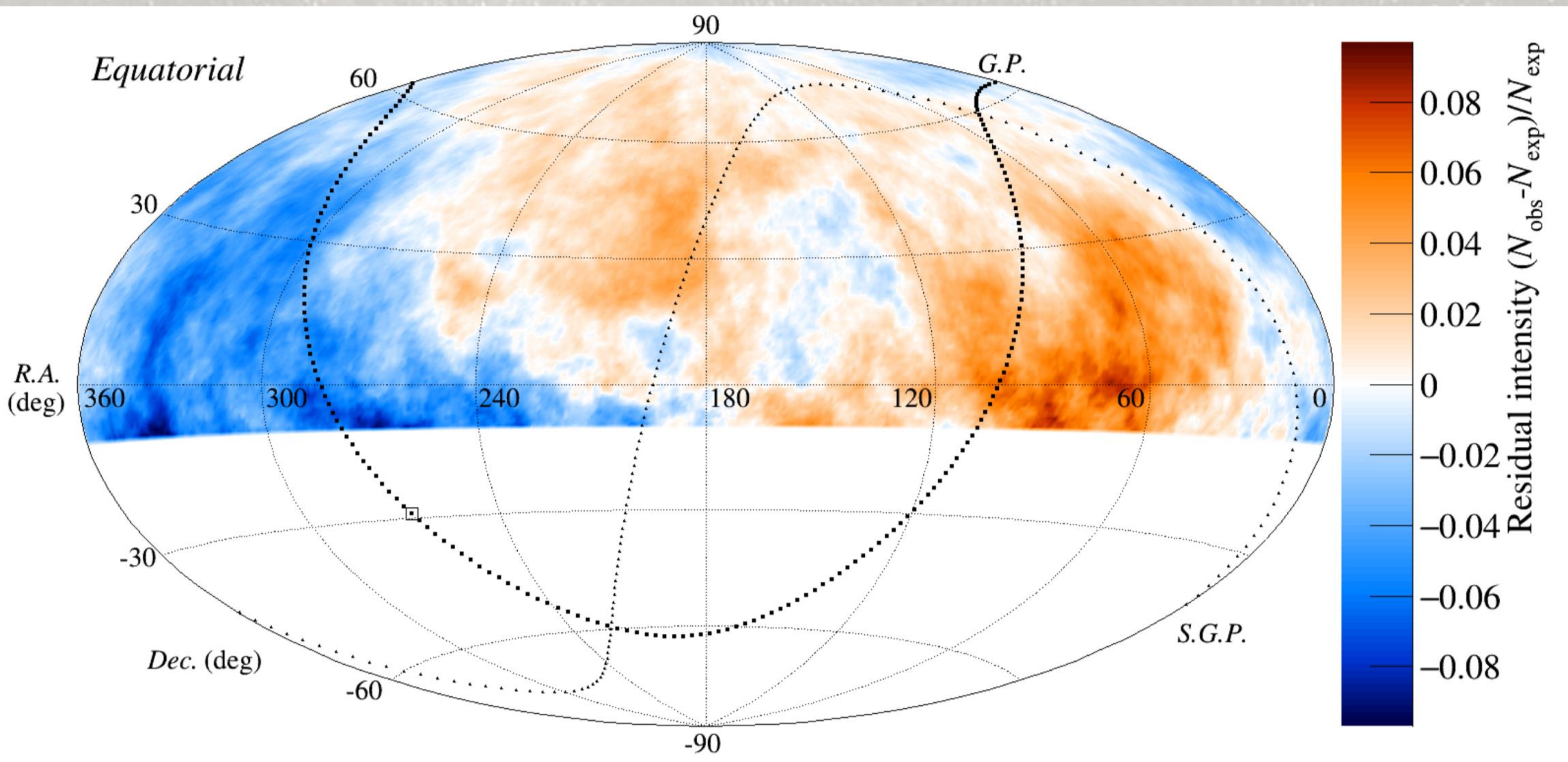


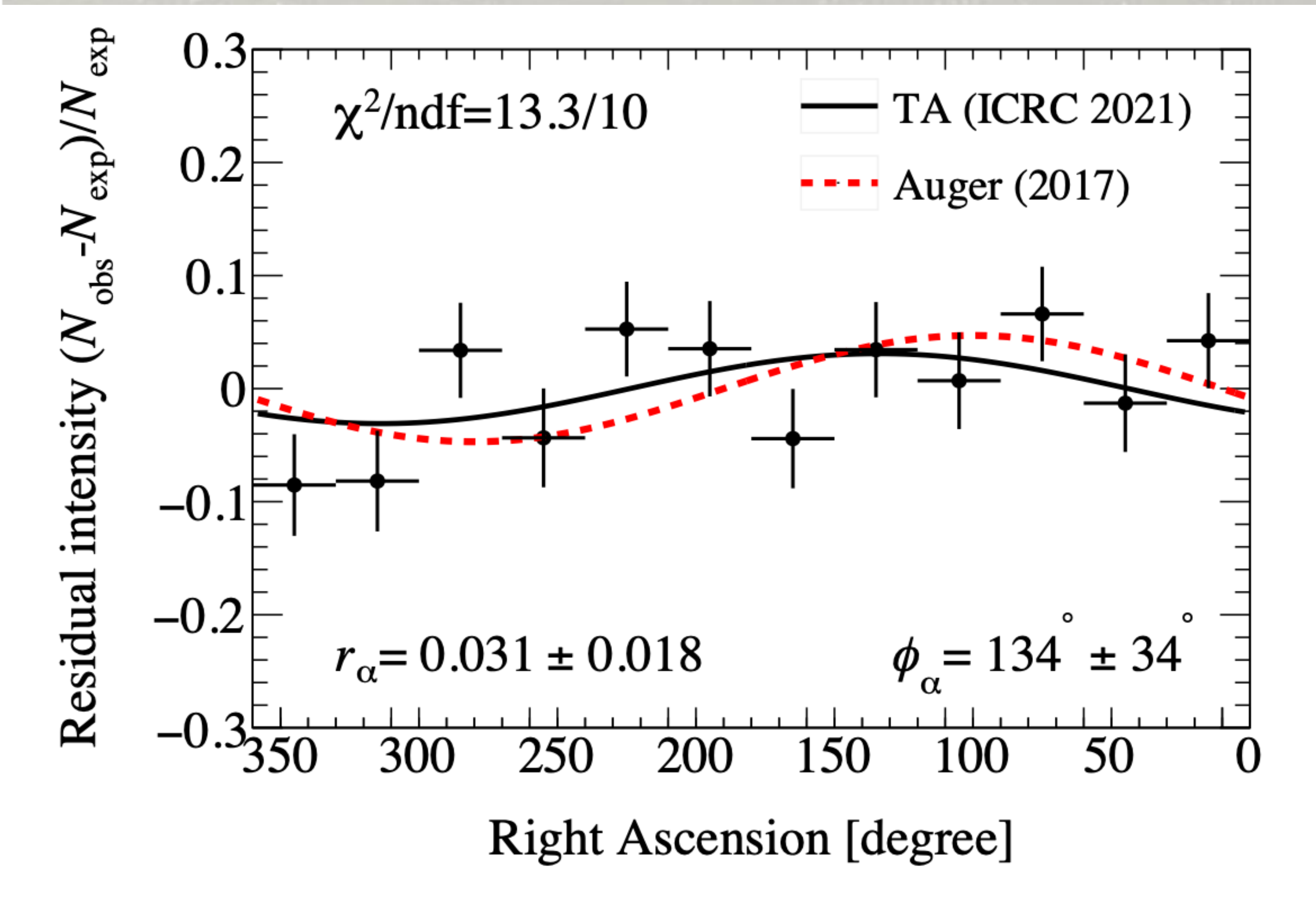
Measuring XMAX attenuation length in hybrid mode.

TA Collaboration, Phys. Rev. D 102, 062004

Anisotropy

CR clustering: Dipole update (12-yr)



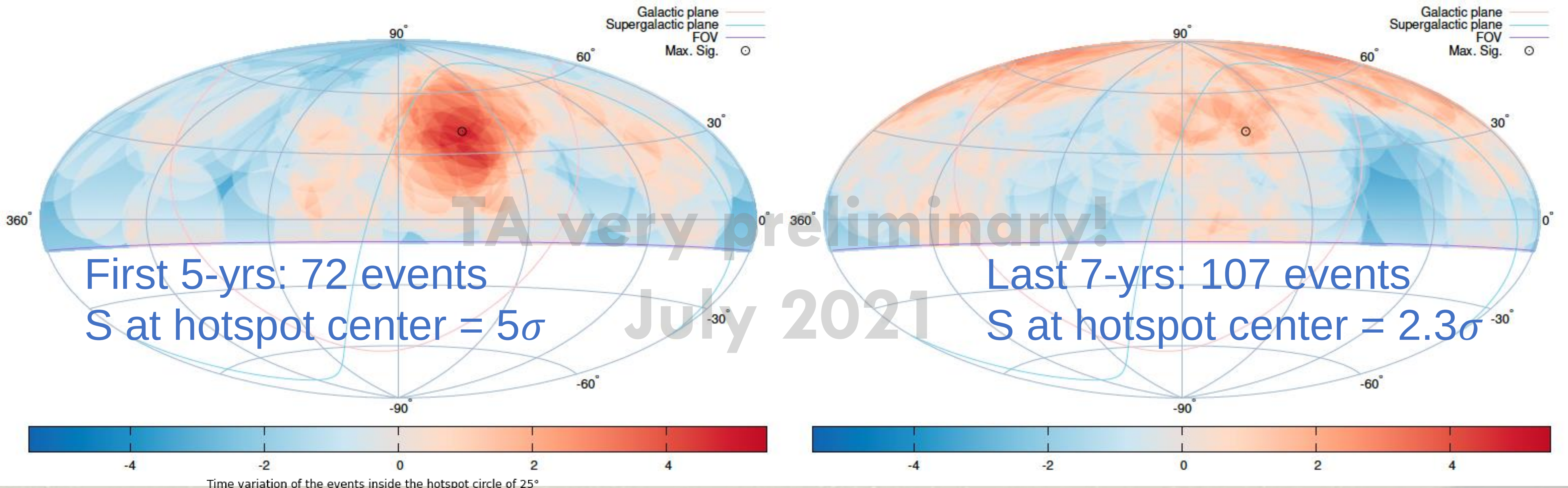


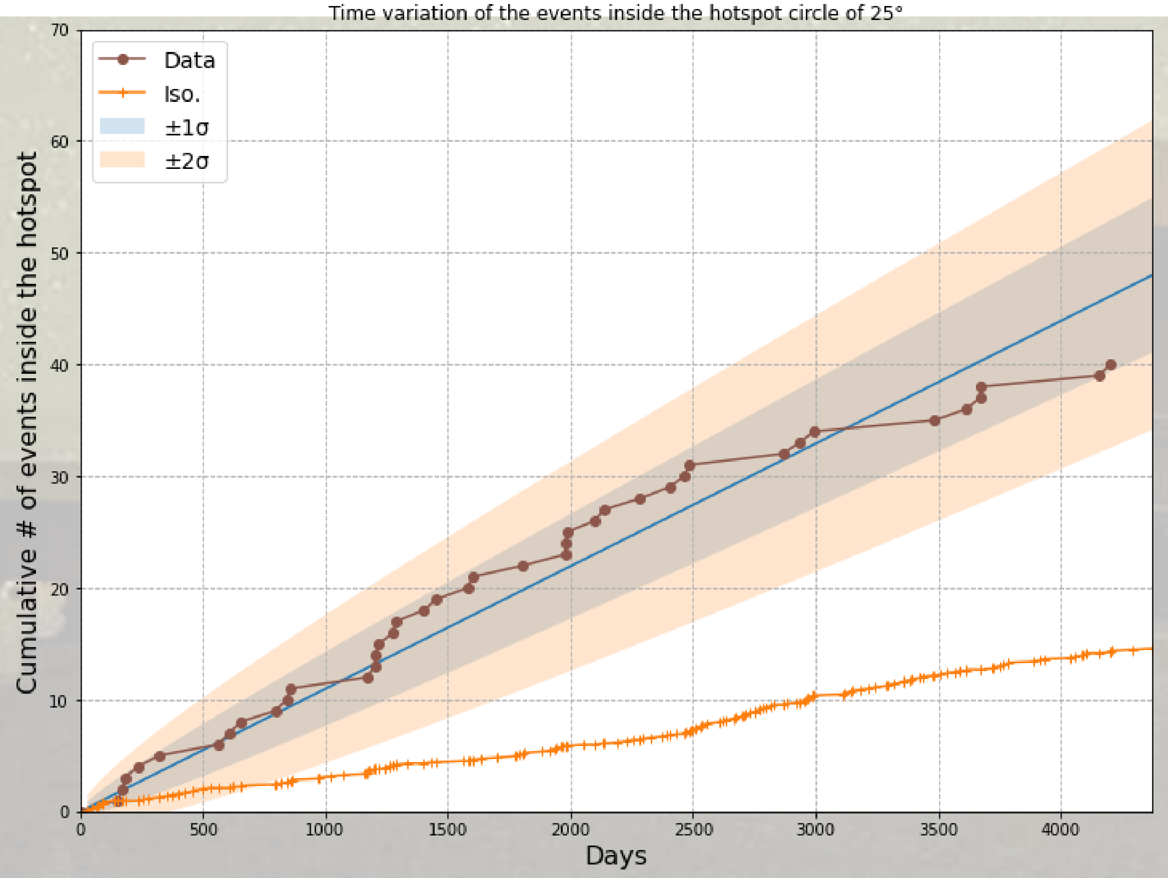
Sky map of residual intensity between TA data and an isotropic distribution for E > 8.8 EeV (energy cut corresponds to E > 8 EeV used by Auger).

TA 12-yr result : $r_\alpha \simeq 3.1\%; \phi_\alpha \simeq 134°$
Auger 2017 result : $r_\alpha \simeq 4.7\%; \phi_\alpha \simeq 100°$

Toshihiro Fujii, ICRC'2021

CR clustering: Hot spot update (12-yr)





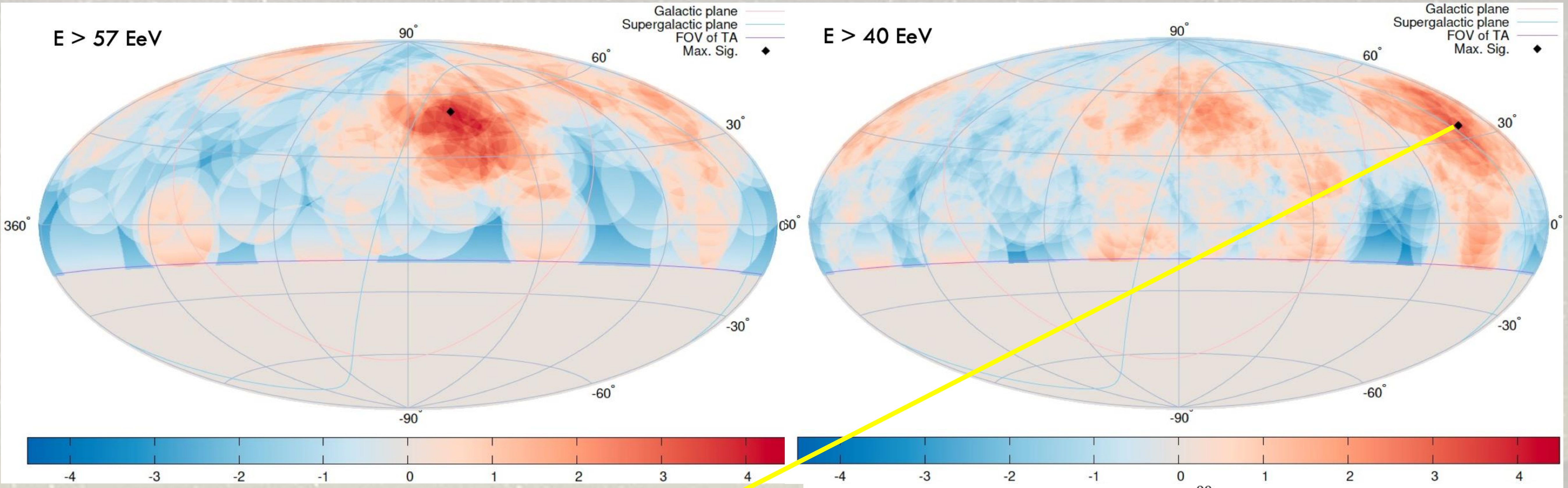
Energy E > 57 EeV

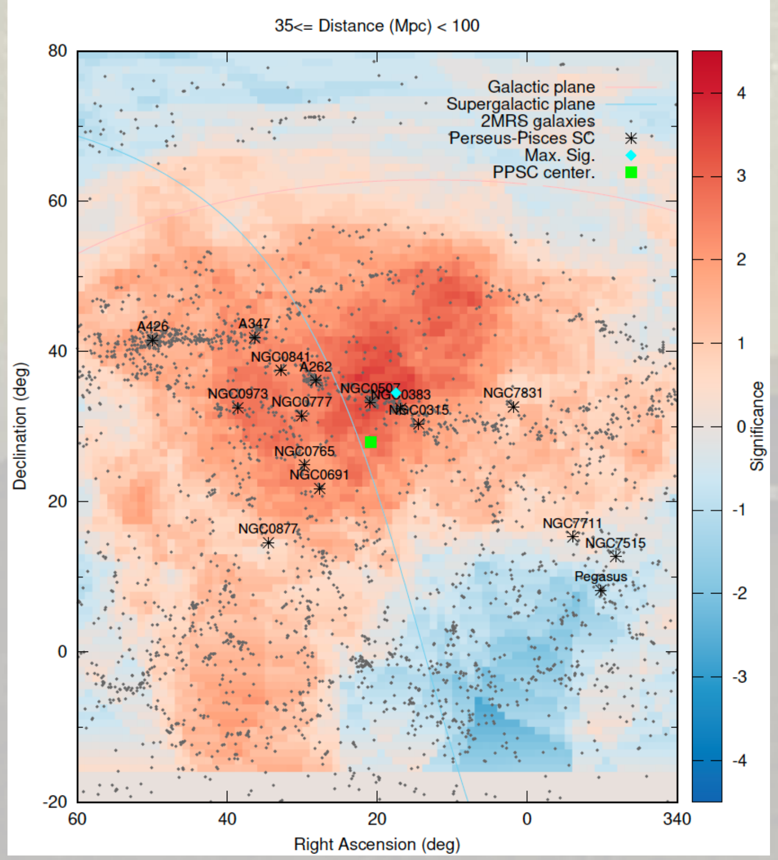
Overall post-trial significance has dropped from 3.4σ to 3.2σ

The growth rate of events inside the hotspot is consistent with the linear one within ~ 1σ

Jihyun Kim, ICRC'2021

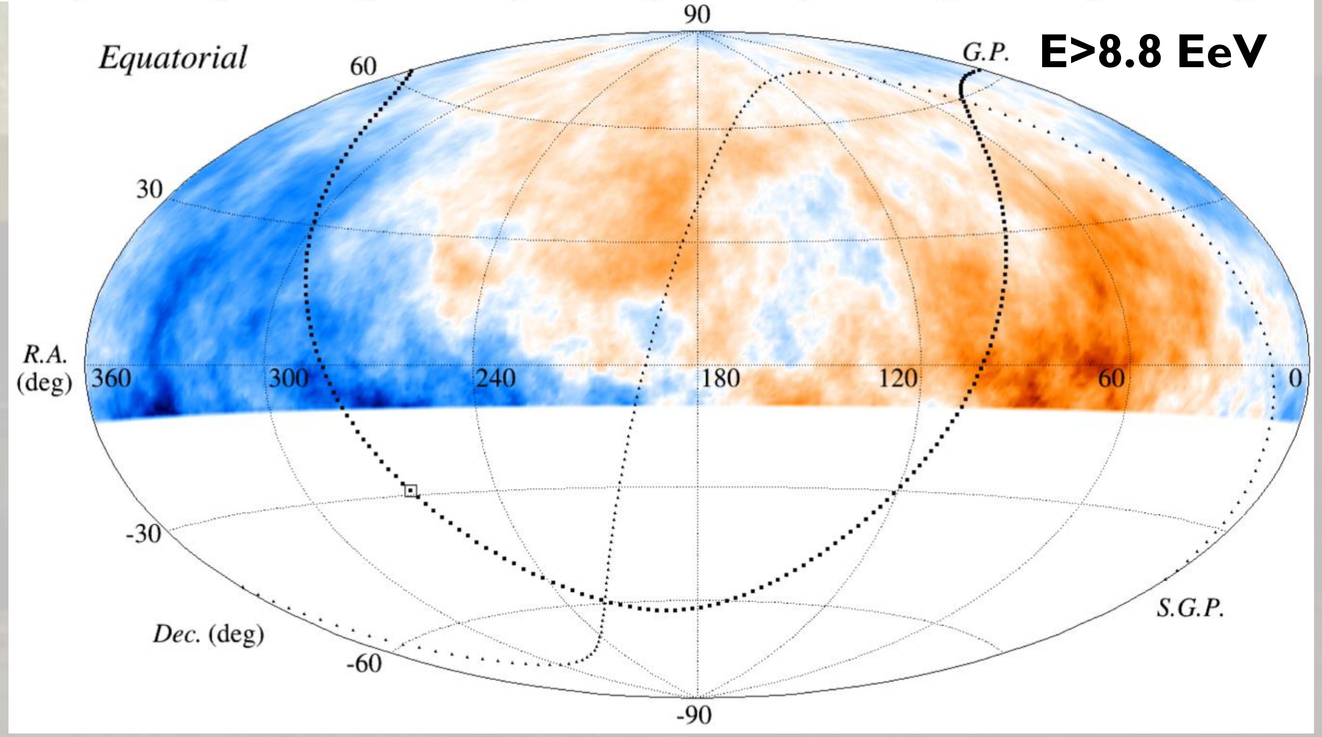
CR clustering: Medium scales



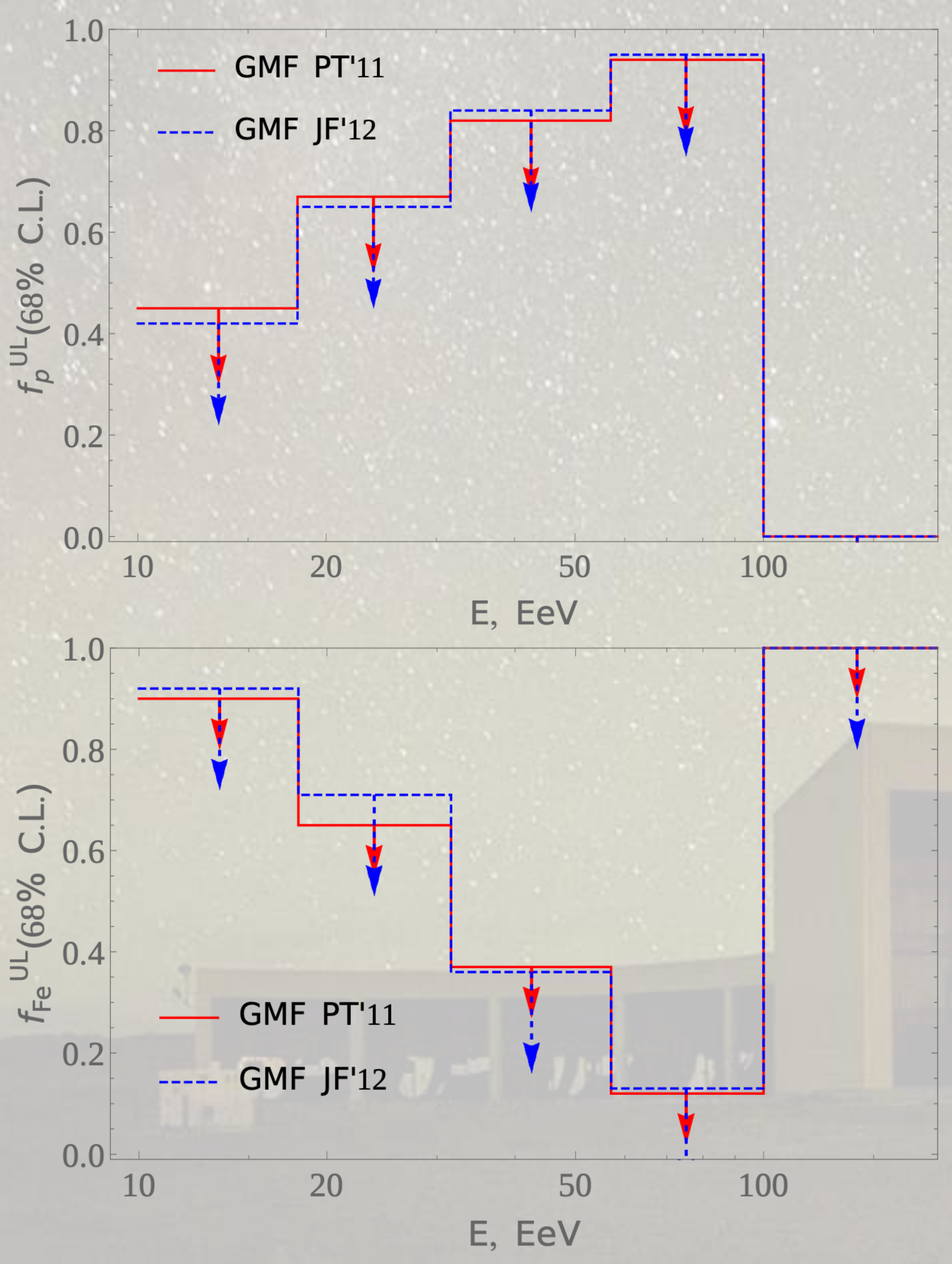


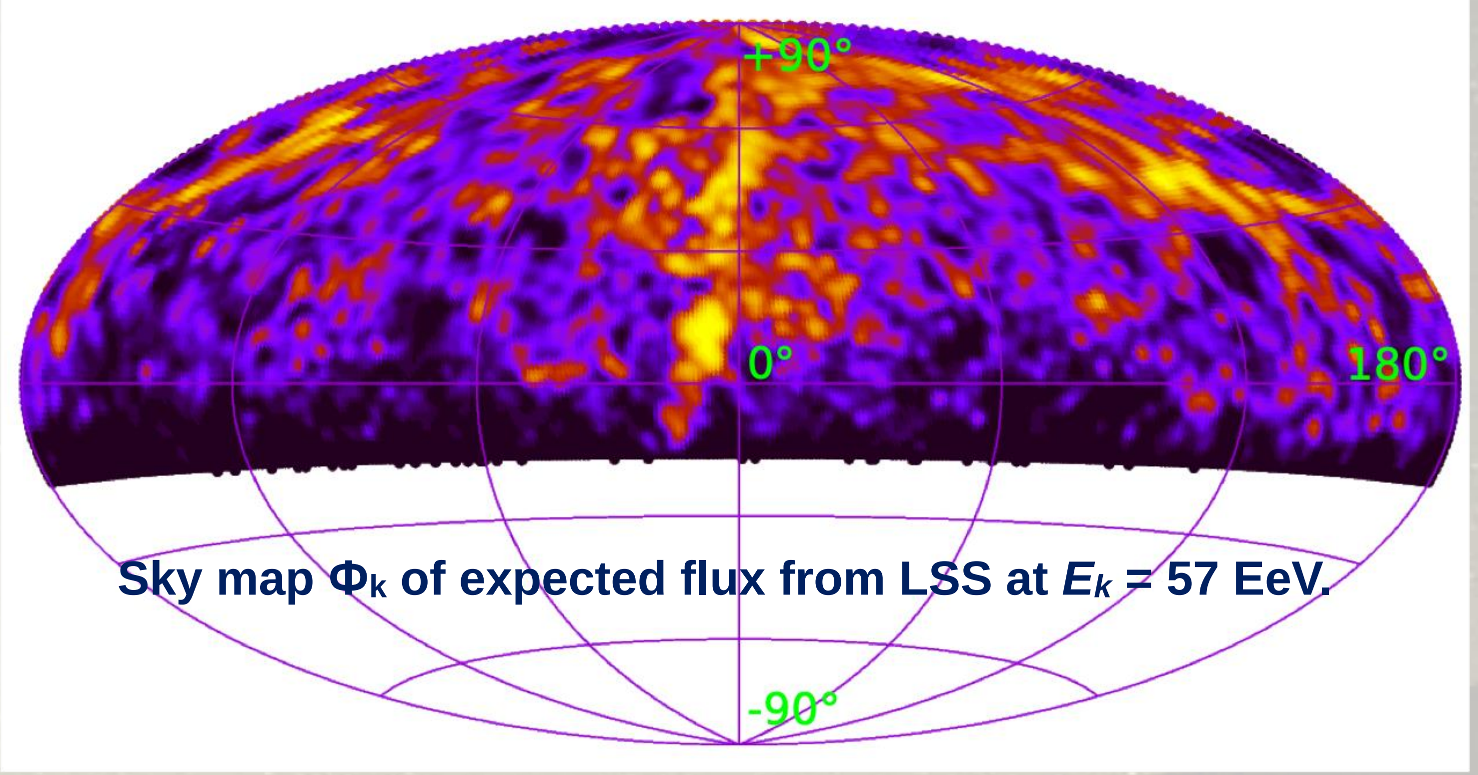
Hint of excess in the direction of Perseus-Pisces supercluster

TA Collaboration, arXiv:2110.14827



Correlation with LSS: chemical composition



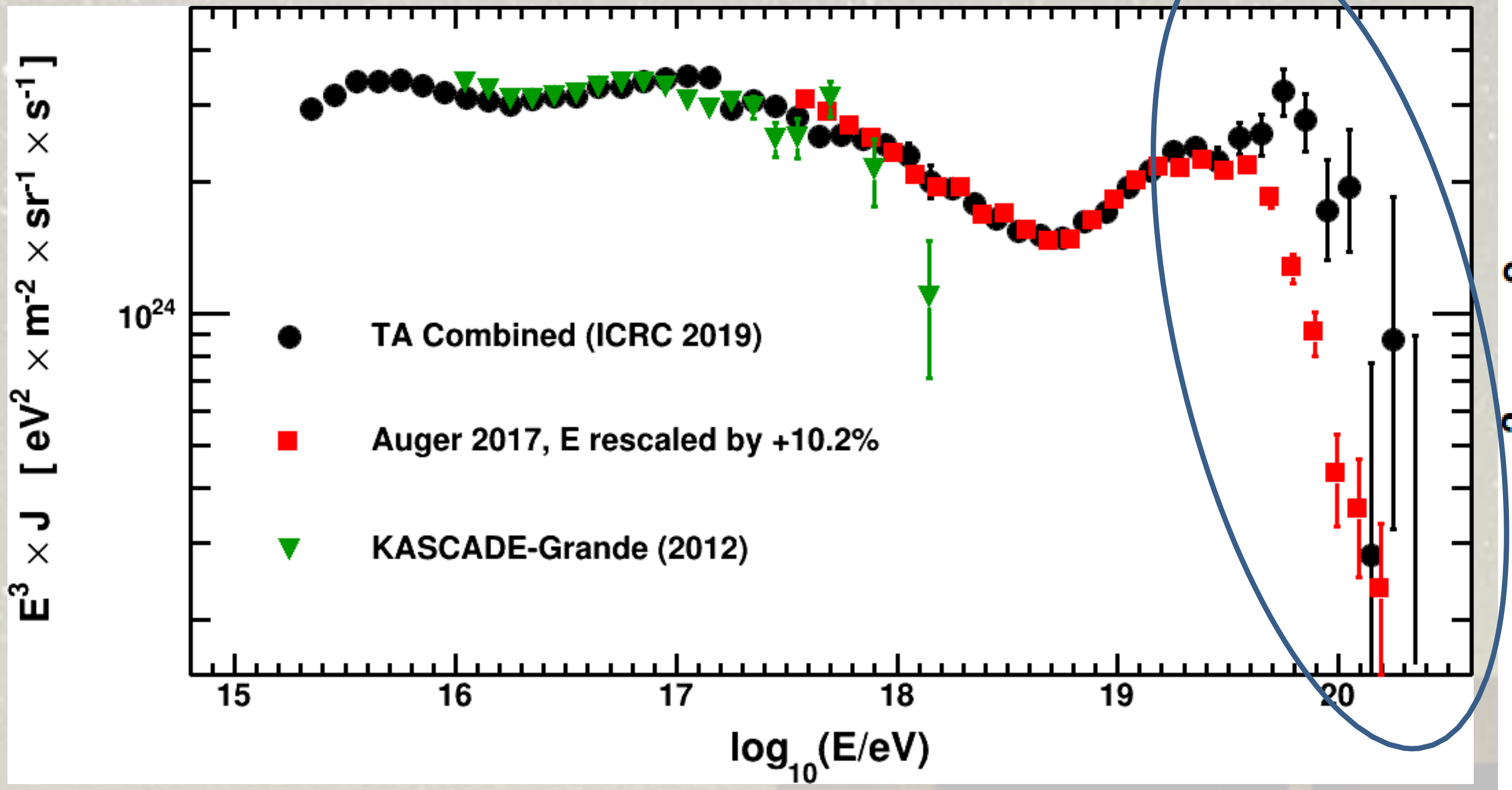


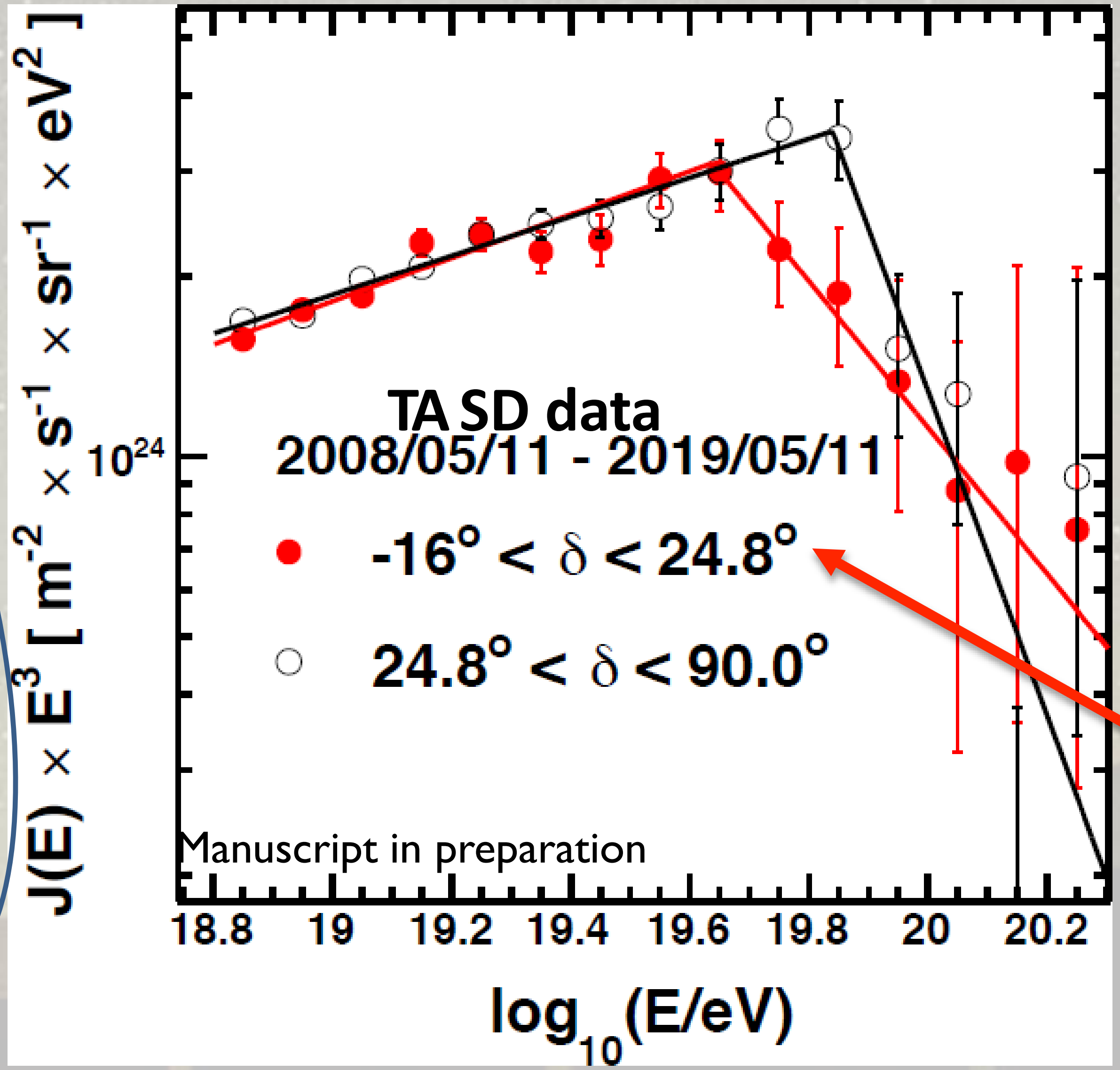
Sky map Φ_k of expected flux from LSS at E_k = 57 EeV.

Upper limits on proton and iron fractions at 68% C.L. as functions of energy, derived from correlation with LSS

Mikhail Kuznetsov, ICRC'2021

Declination Dependence of Spectrum

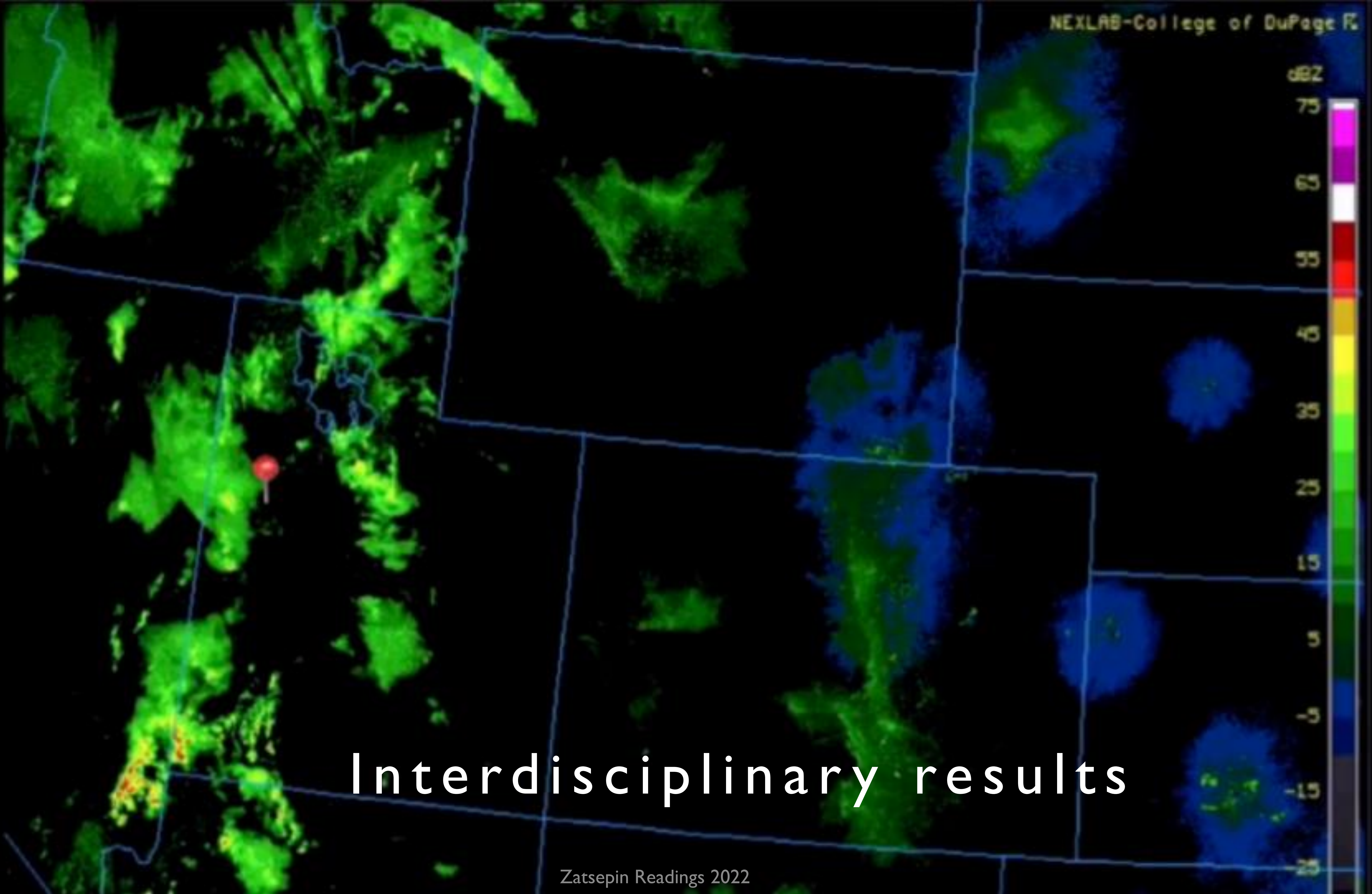




Common with Auge

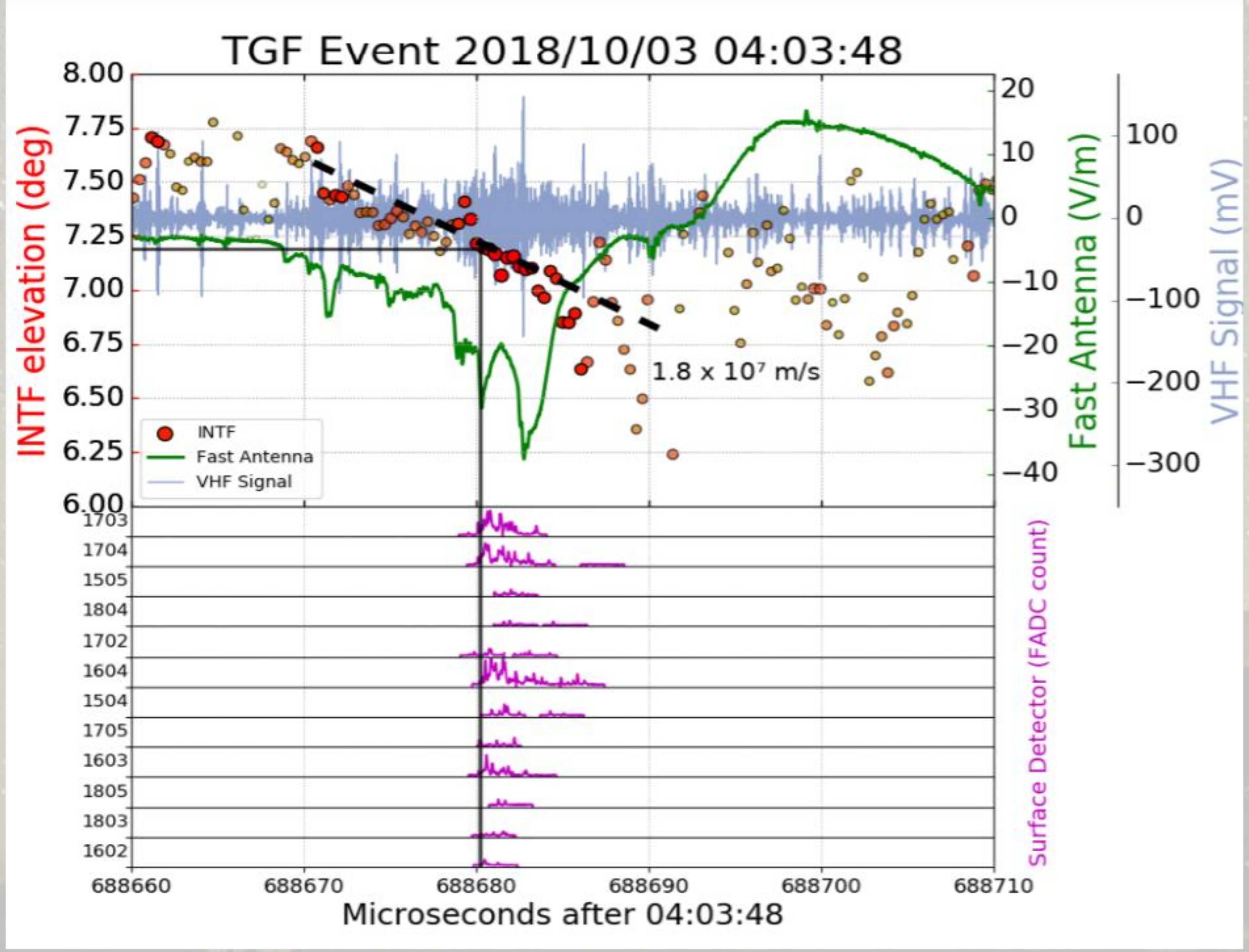
- Difference of the cutoff energies of energy spectra
  - log(E/eV) = 19.64 ± 0.04 for lower dec. band (-16° - 24.8°)
  - log(E/eV) = 19.84 ± 0.02 for higher dec. band (24.8° - 90°)
- The global significance of the difference is estimated to be **4.3σ**

TA Collaboration, arXiv:1801.07820



Interdisciplinary results

Observation of Terrestrial Gamma-Ray Flashes with TA SD

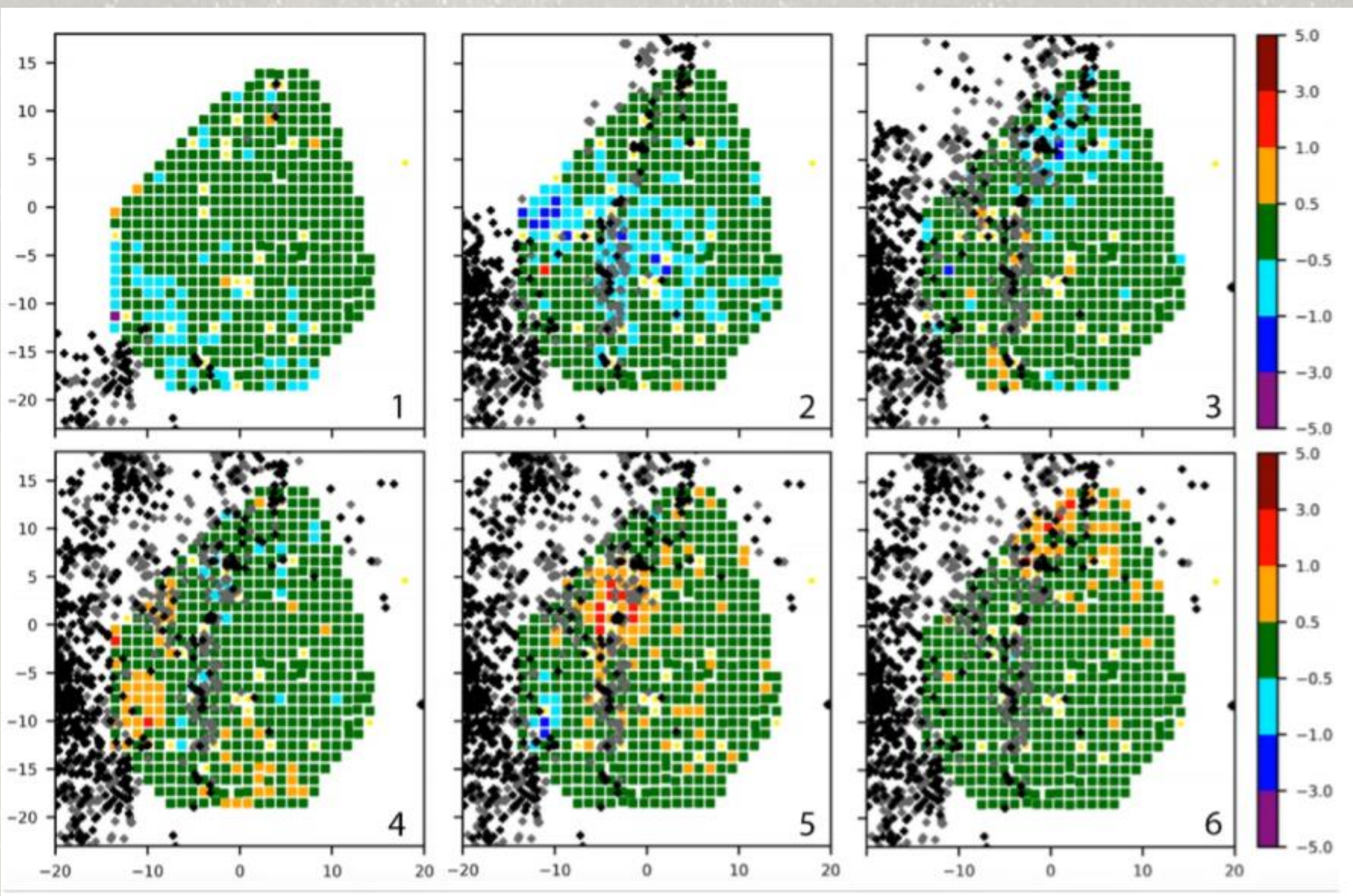


- Broadband Interferometer (INTF):
  - Three 20-80 MHz flatplate antennas
  - 2D high-resolution reconstruction of lightning sources
- Fast Sferic Sensor (FA):
  - Detects electric field change
  - Identifies substructure: initial breakdown pulses (IBPs)

- Clearly defined TGF onset during the flash's strongest initial breakdown pulse

TA Collaboration, arXiv:2205.05115

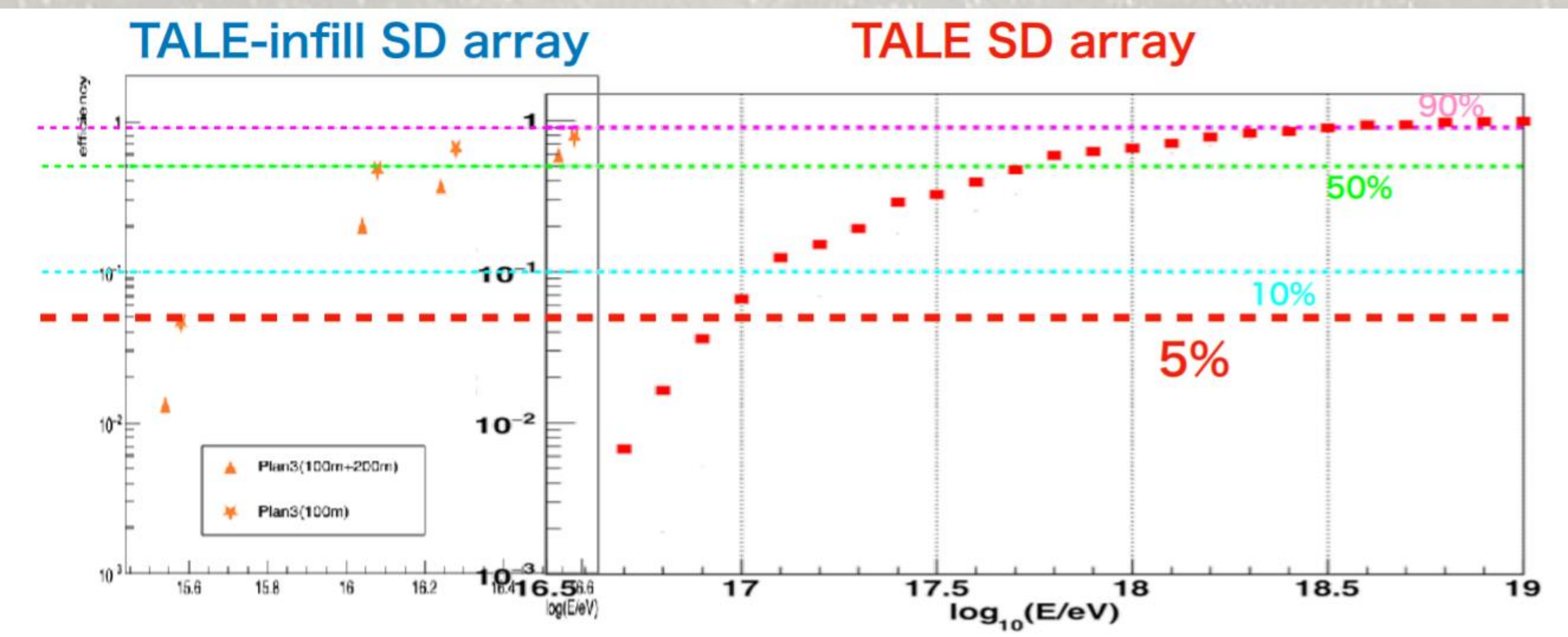
Variation of Level-0 trigger rate during Thunderstorms

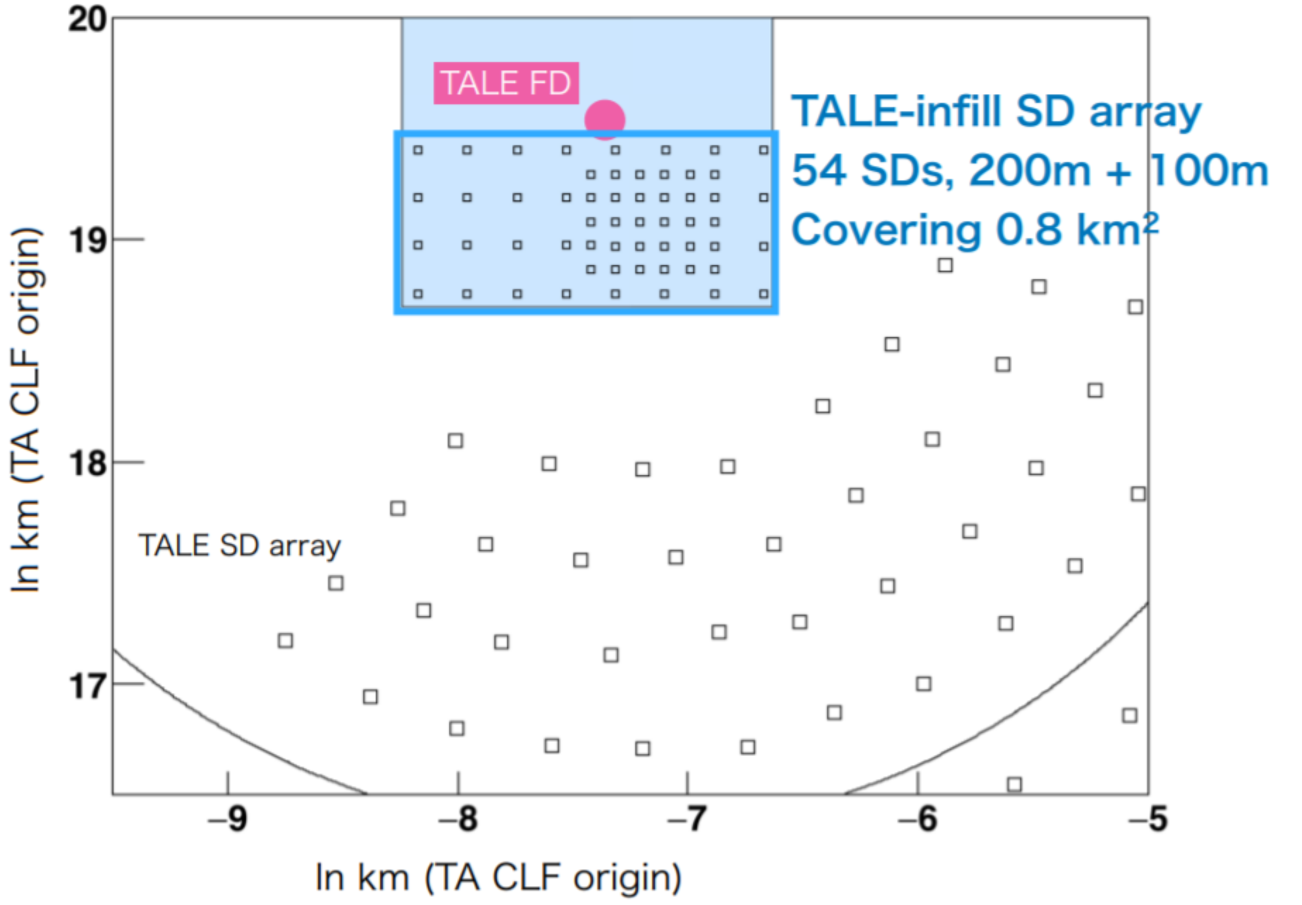


- Level-0 trigger rate is monitored at 10 min resolution at each SD station.
- Thunderstorm detected by NLDN changes the trigger rate.
- The result may be interpreted by using EFIELD option of CORSIKA.
- Intensity increase or deficit depends on electric field type (intracloud or cloud to ground) and thunderstorm polarity

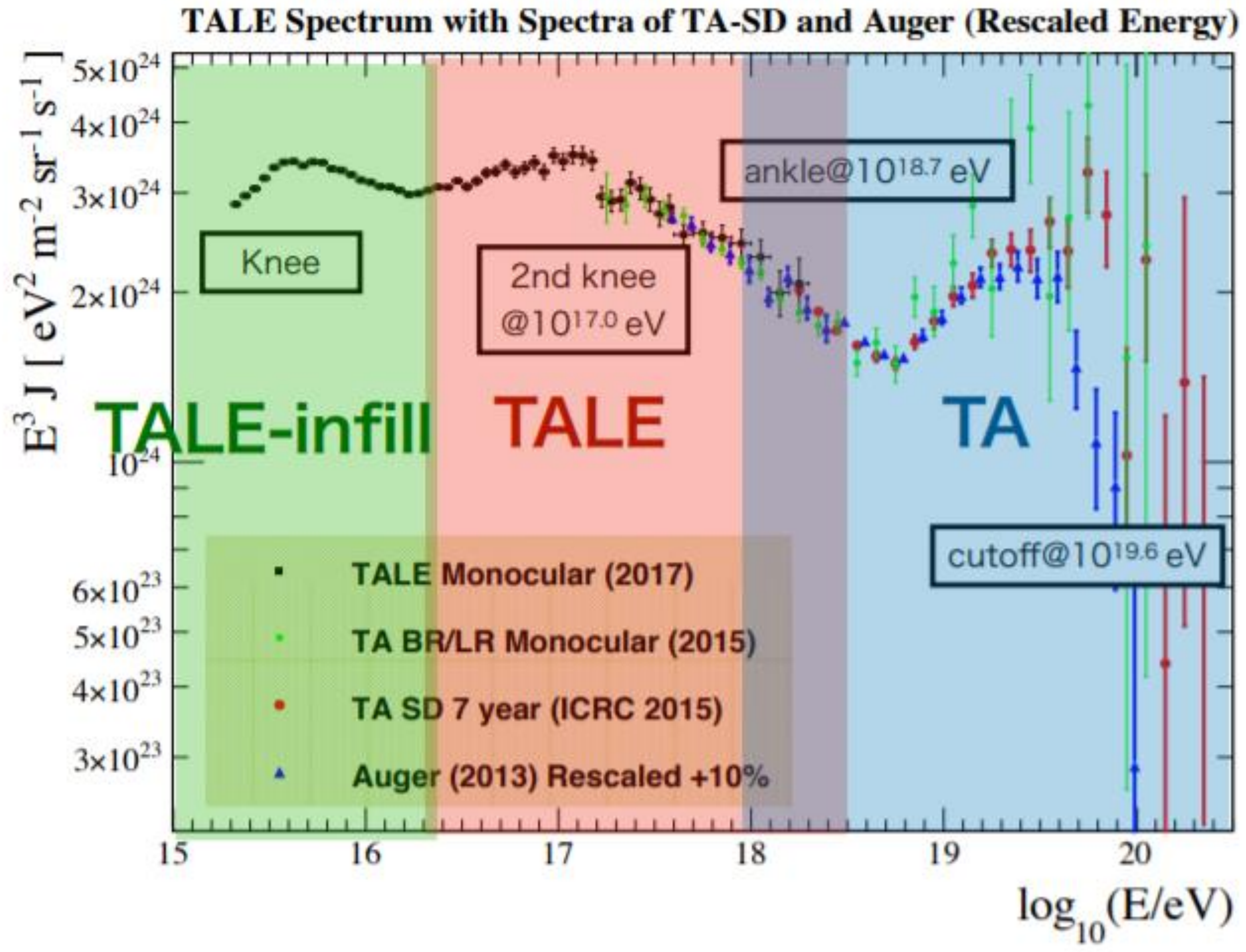
TA Collaboration, Phys. Rev. D 105, 062002

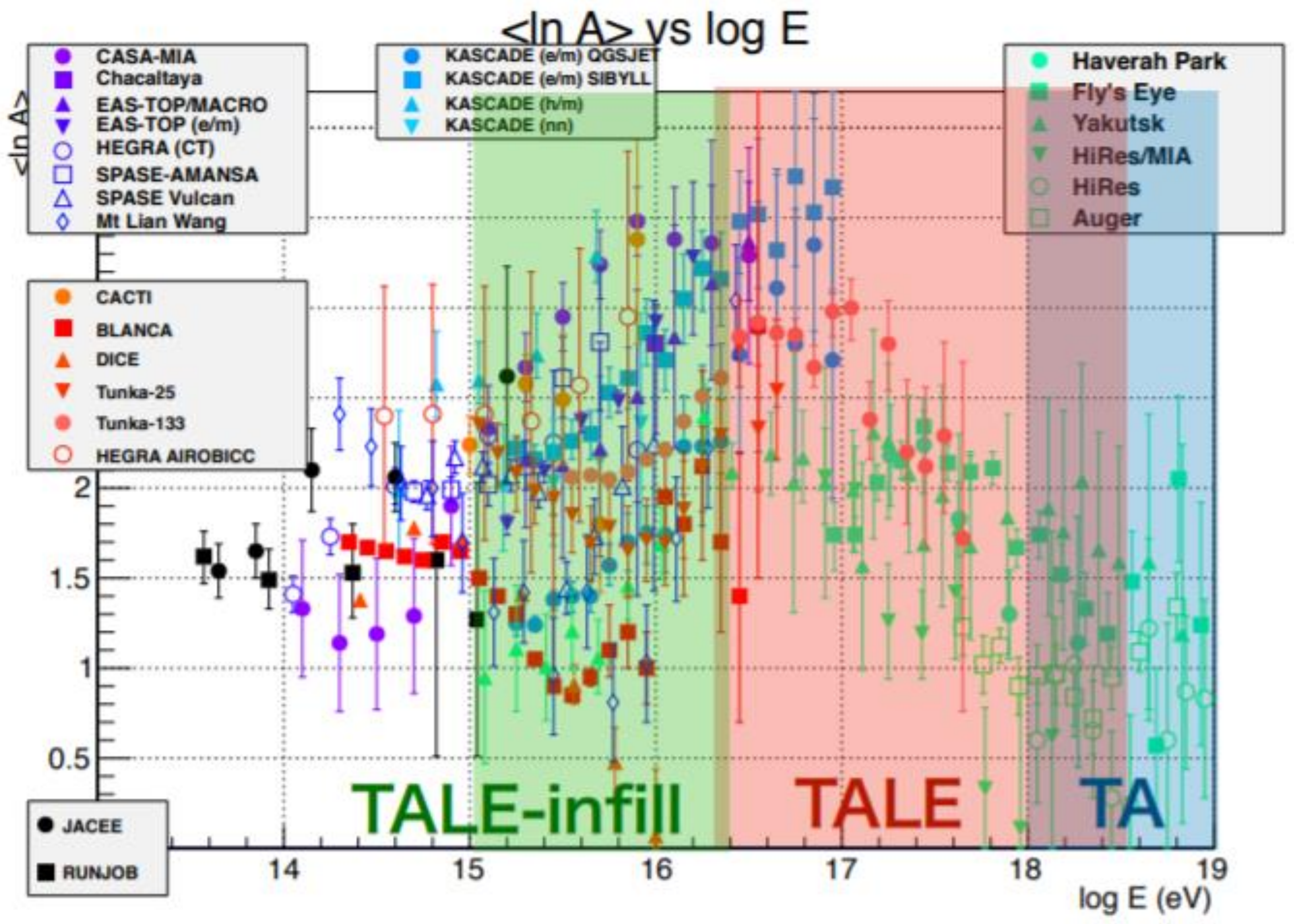
Extension of TALE SD: TALE-infill





Ap. J., 865, 74(2018), arXiv: 1803.01288





Shoichi Ogio, ICRC'2021

Summary

- Telescope Array is UHECR Observatory in the Northern Hemisphere
- Energy spectrum is measured from $10^{15.5}$ to $10^{20.5}$ eV (5 decades)
  - New feature in the energy spectrum at $\sim 10^{19.3}$eV
  - TA Low Energy Extension (TALE) energy spectrum indicated that second knee may result from Peters cycle ($10^{15.6}$eV→$10^{17.1}$eV)
- TALE Xmax shows composition becoming heavier between first and second knee, consistent with Peters Cycle interpretation
- Between $10^{18.0}$ eV and $10^{19.1}$eV TA hybrid data is compatible with predominantly light elements such as protons and helium
- Indications of anisotropy at highest energy
  - Hot spot from 12 years of data in the direction of Ursa Major (3.2σ post trial)
  - Hint of excess in the direction of Perseus Pisces E > $10^{19.3}$eV
  - Correlation with LSS consistent with large fraction of protons
  - Declination dependence of the spectrum
- We need much more data at high energy end –>TAx4 in operation!