HIGHLIGHTS OF TELESCOPE ARRAY

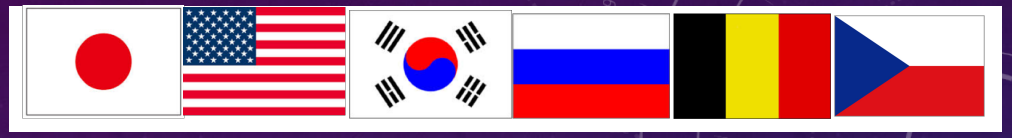
DOUGLAS R BERGMAN

FOR THE TELESCOPE ARRAY COLLABORATION

TEVPA 2021

28 OCTOBER 2021

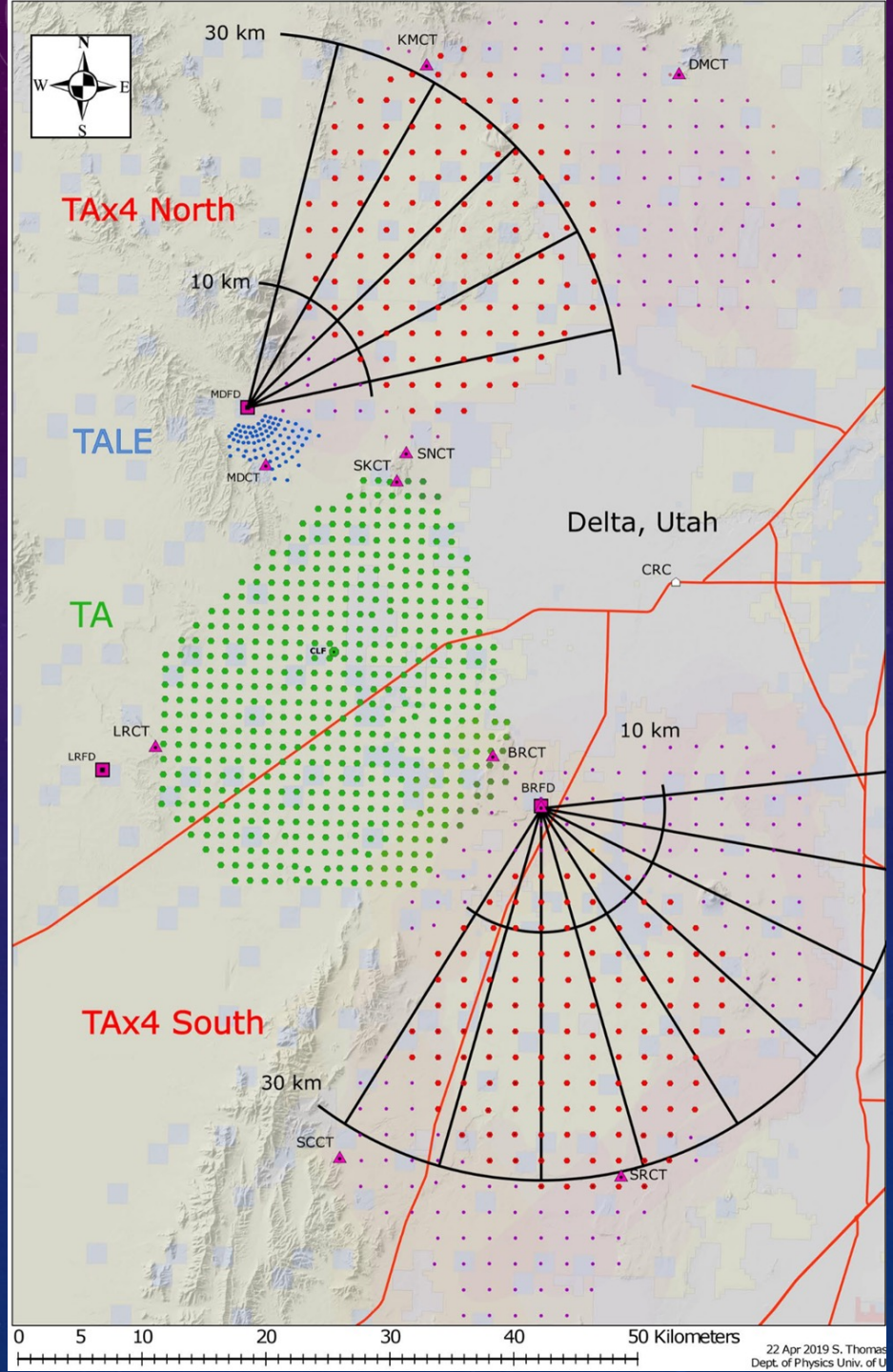
TELESCOPE ARRAY COLLABORATION



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]

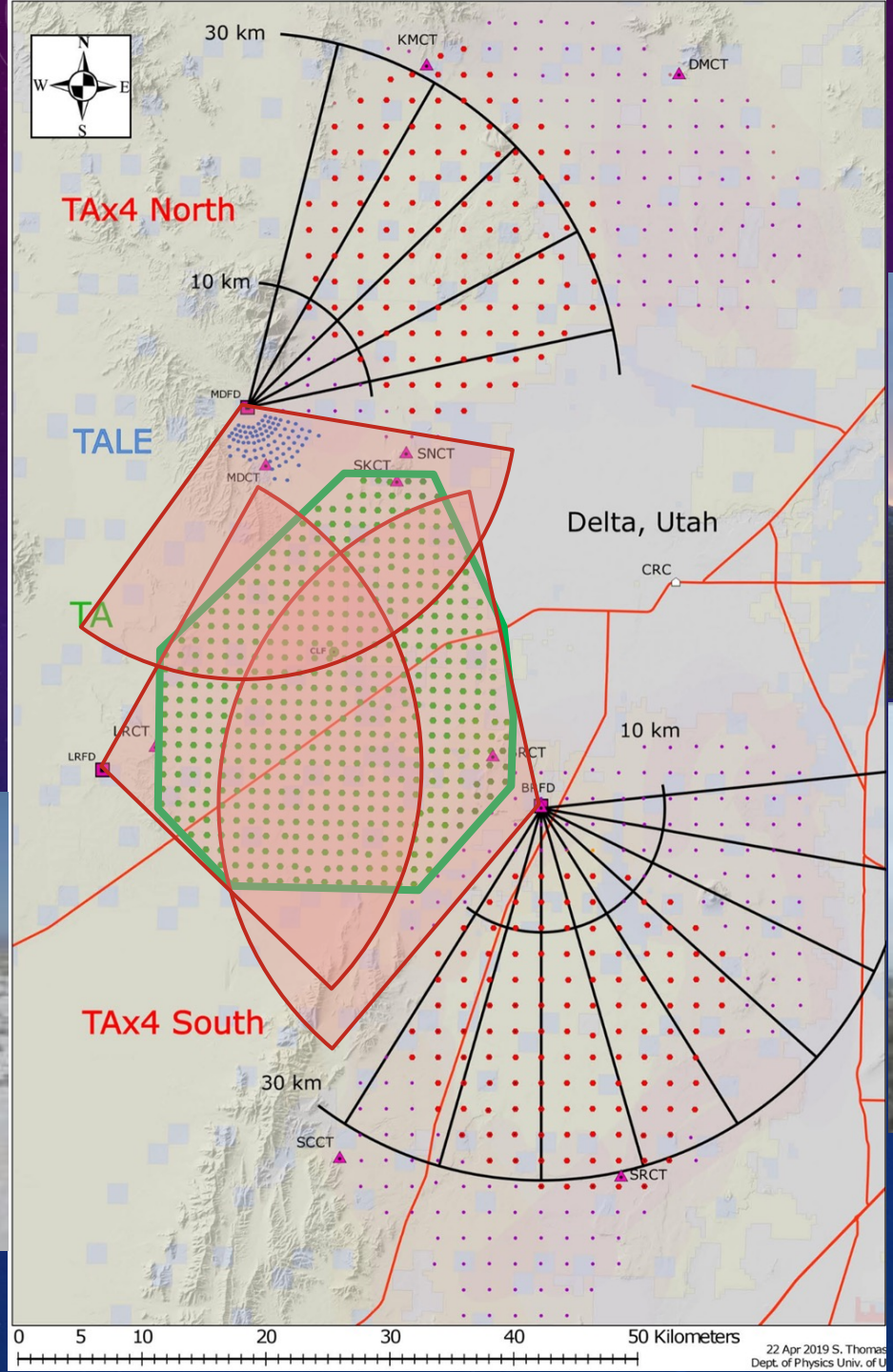
[1] Loyola University Chicago [2] University of Utah [3] Saitama University [4] Osaka City University [5] Hanyang University [6] Tokyo University of Science [7] University of Tokyo (ICRR) [8] Kyoto University [9] Shinshu University [10] Kanagawa University [11] University of Yamanashi [12] Shinshu University (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

TELESCOPE ARRAY



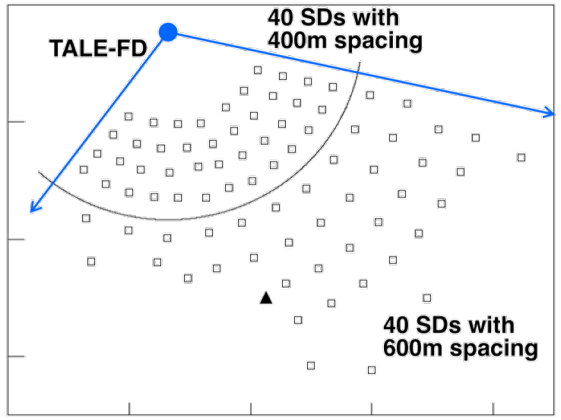
TELESCOPE ARRAY

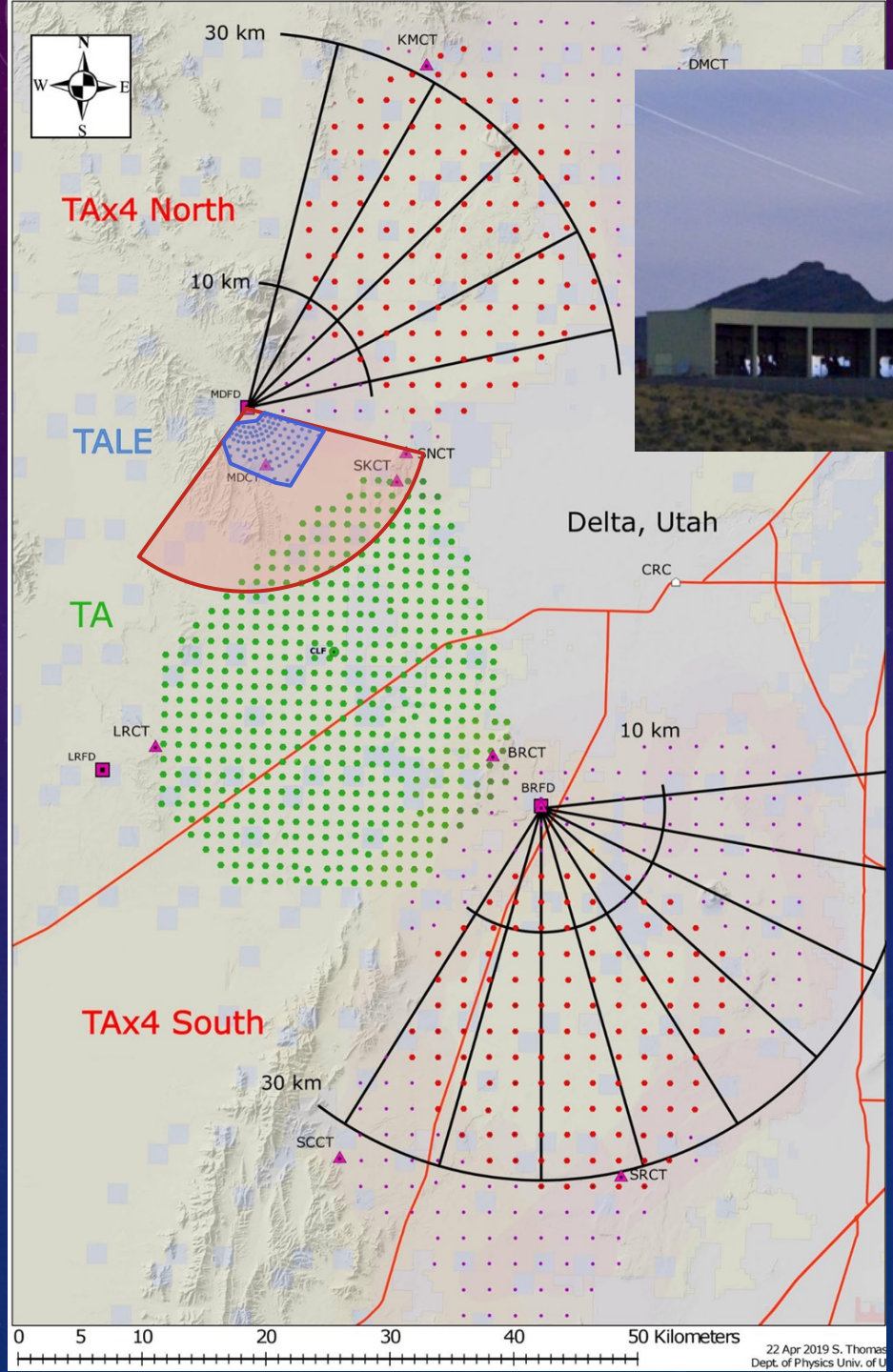
- Telescope Array (since 11/2007)
  - Surface Detector Array
    - 507 Scintillator Counters
    - 1.2 km spacing
    - 3 m^2 area
    - 700 km^2
  - Fluorescence Telescopes
    - 3 sites
    - 12–14 mirrors
    - 3˚–31˚ elevation
    - Cover SD

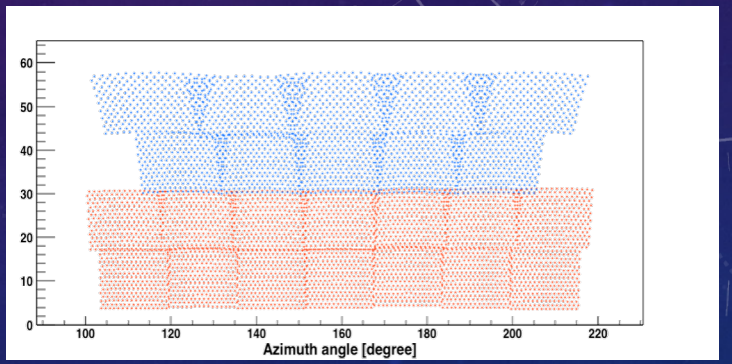


TELESCOPE ARRAY

- TA Low Energy (TALE)
  - Surface Detector infill array
    - Since 03/2018
    - 400 & 600-m spacing
    - Same SD design as TA
  - Fluorescence Telescopes
    - Since 09/2013
    - 10 mirrors (+ 14 from TA)
    - 31˚–59˚ elevation

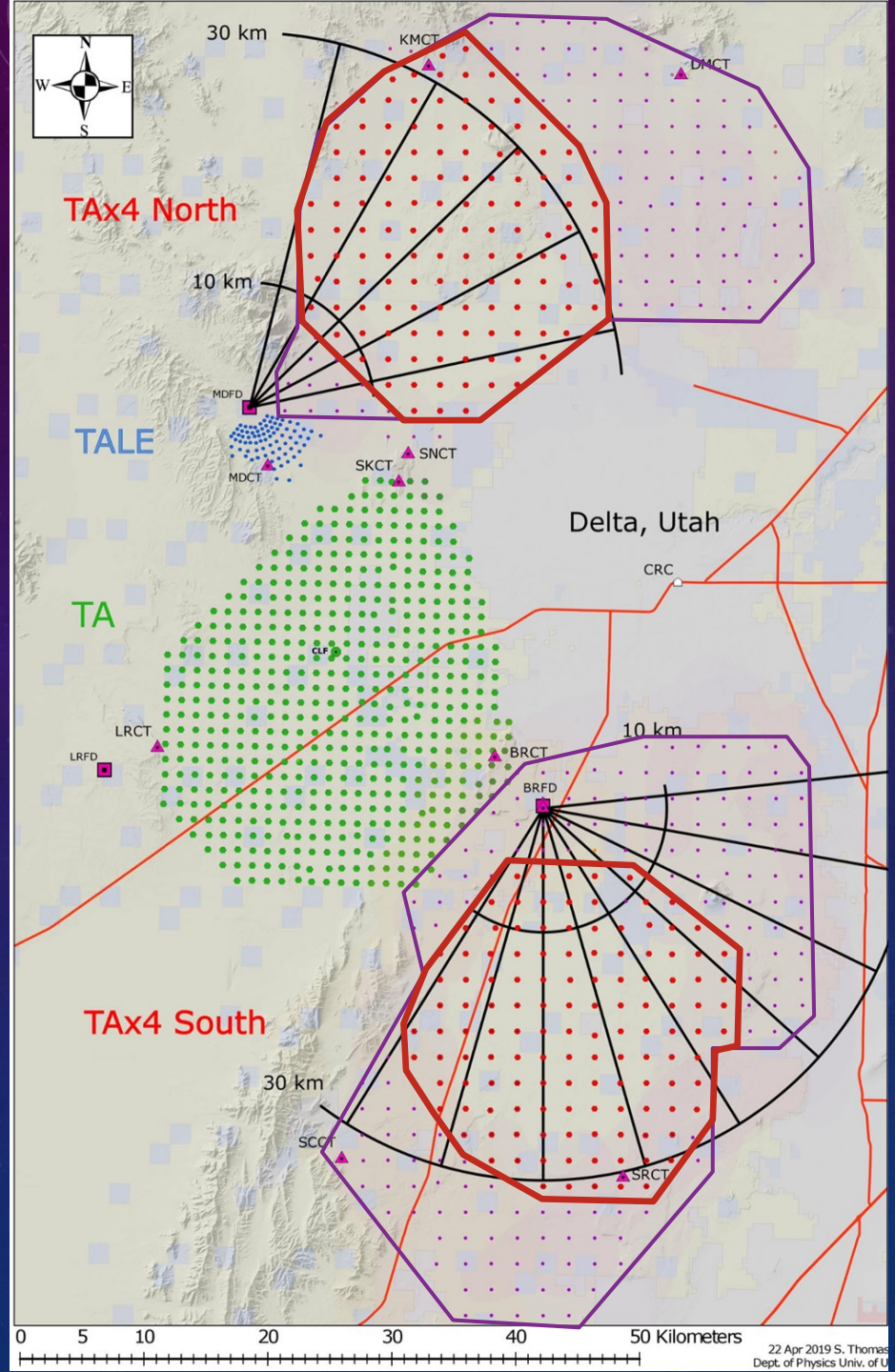






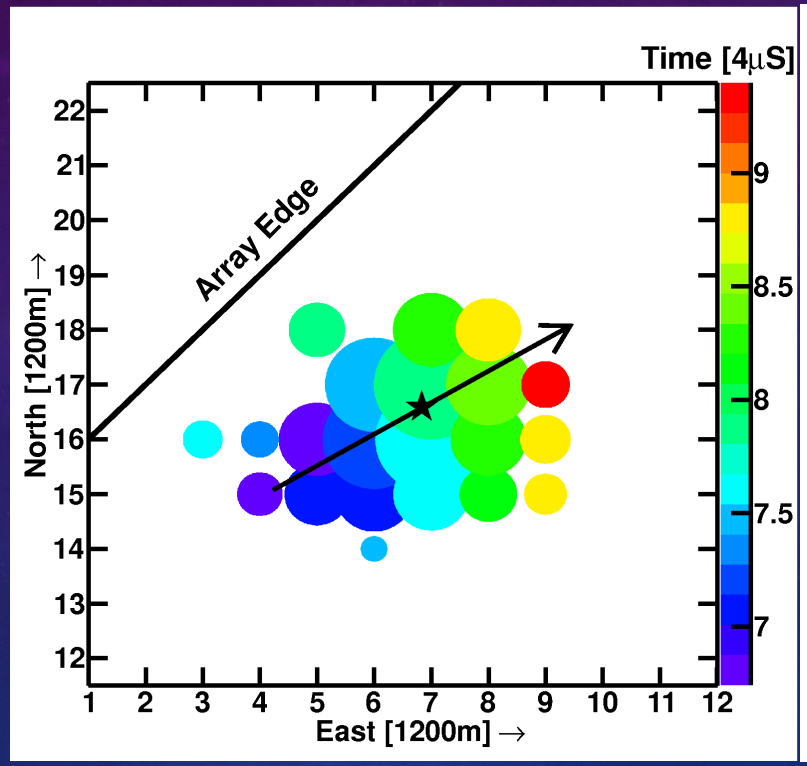
TELESCOPE ARRAY

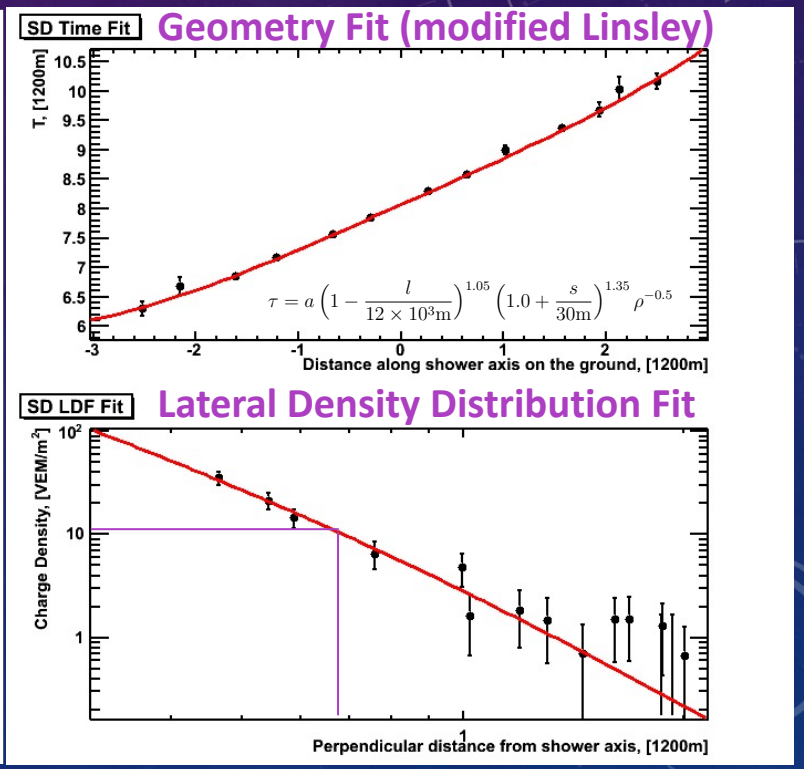
- TA x 4
  - Expanded Surface Array
    - 2.08-km spacing
    - Similar SD design as TA
    - 257 of planed 500 deployed (since 11/2019)
  - Fluorescence Telescopes
    - 4 mirrors in NE lobe (since 06/2019)
    - 8 mirrors in SE lobe (since 08/2020)



EVENT RECONSTRUCTION

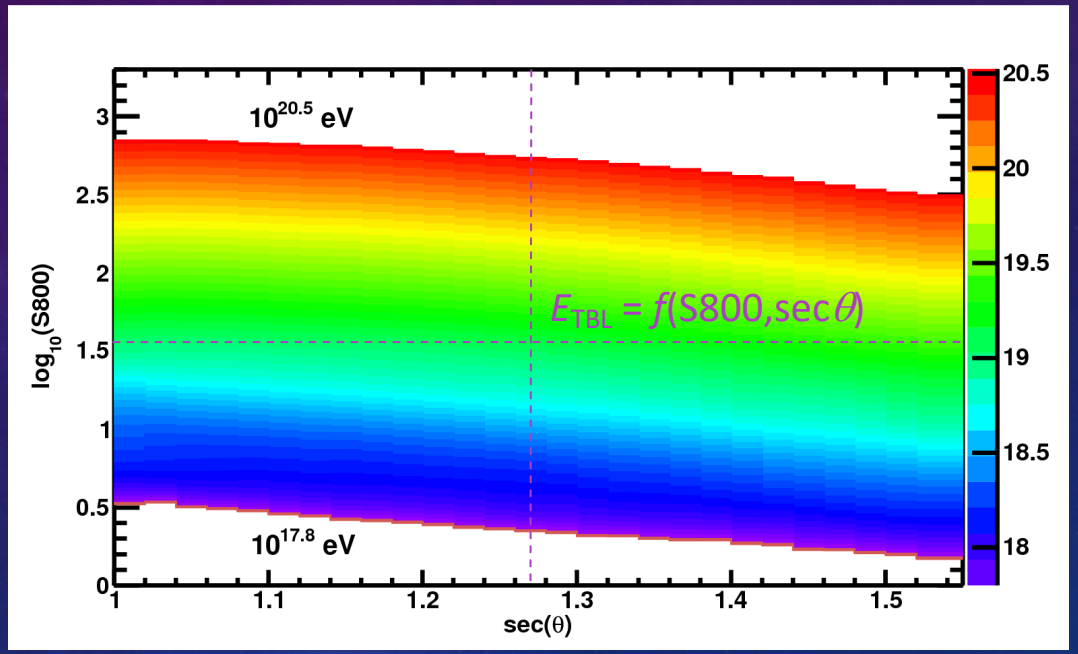
- Use counter location and timing to locate shower core and direction
- Fit counter signal size to find lateral distribution
- Signal size at 800 m, S800, is the energy indicator

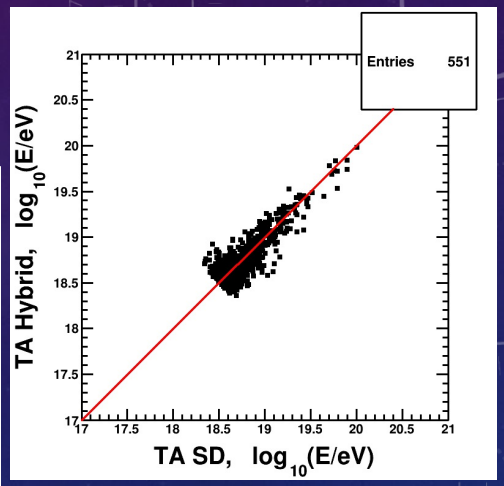


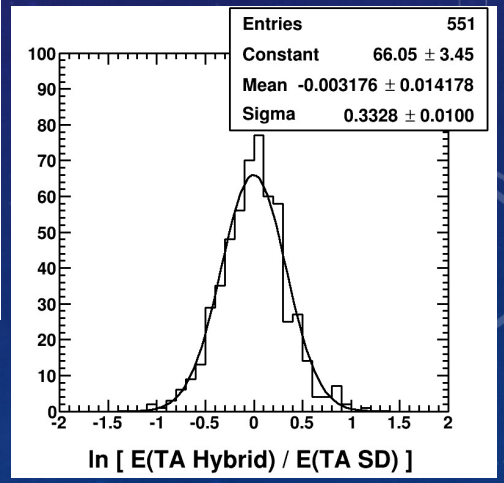


EVENT RECONSTRUCTION

- Use counter location and timing to locate shower core and direction
- Fit counter signal size to find lateral distribution
- Signal size at 800 m, S800, is the energy indicator
- Use S800 and zenith angle to look up energy (from CORSIKA-produced table)
- Hybrid fluorescence provides energy scale: $E_{final} = E_{TBL}/1.27$

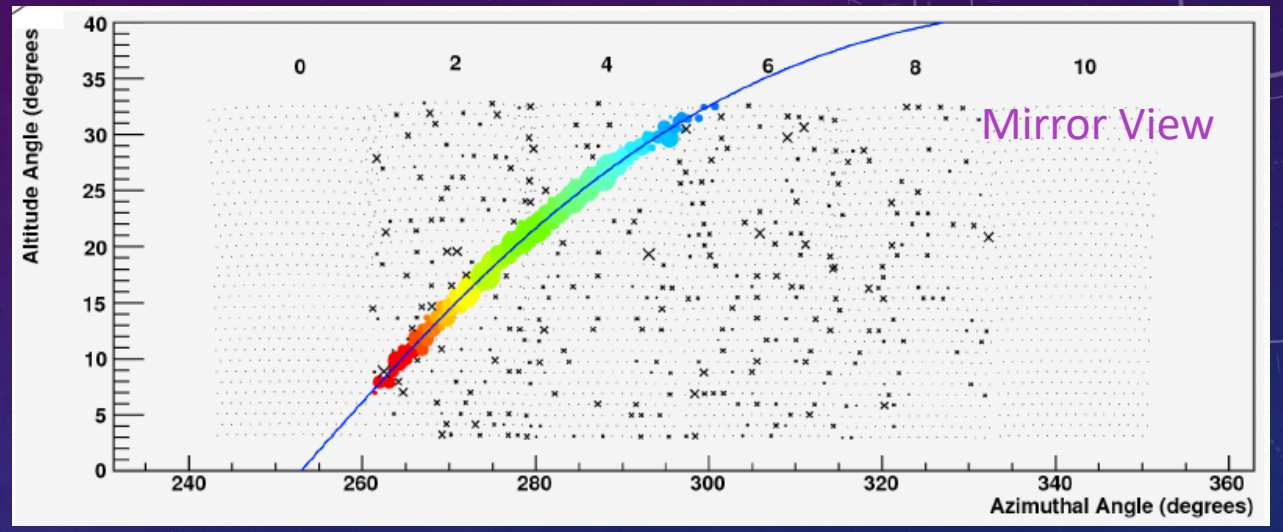


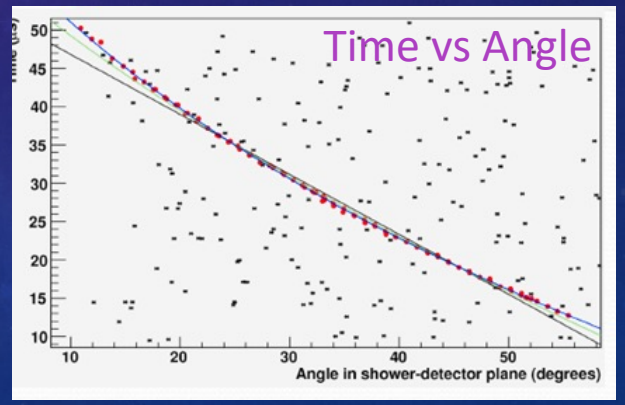


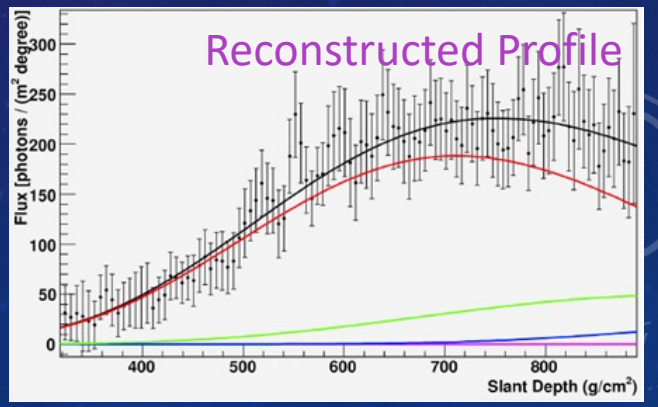


EVENT RECONSTRUCTION

- In fluorescence we see the shower sweep across the mirror
- Reconstruct Shower-Detector Plane
- Fit time-vs-angle to get geometry (add in SD times for hybrid, giving much more lever arm for fit)
- Reconstruct size of shower vs depth

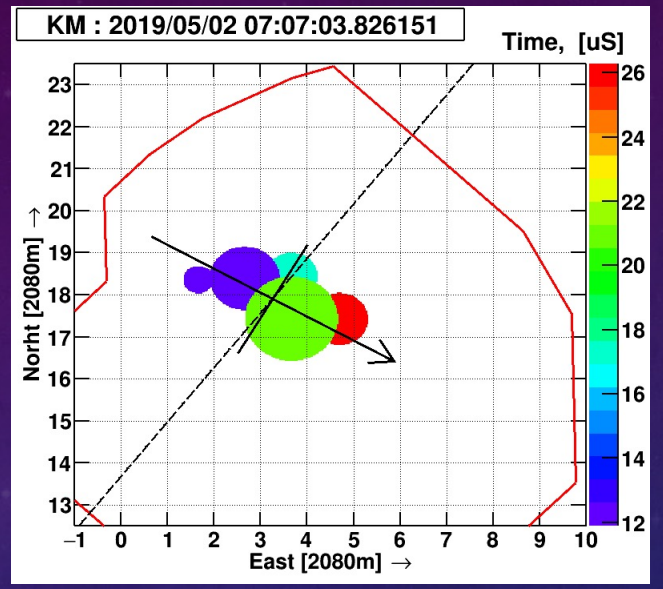


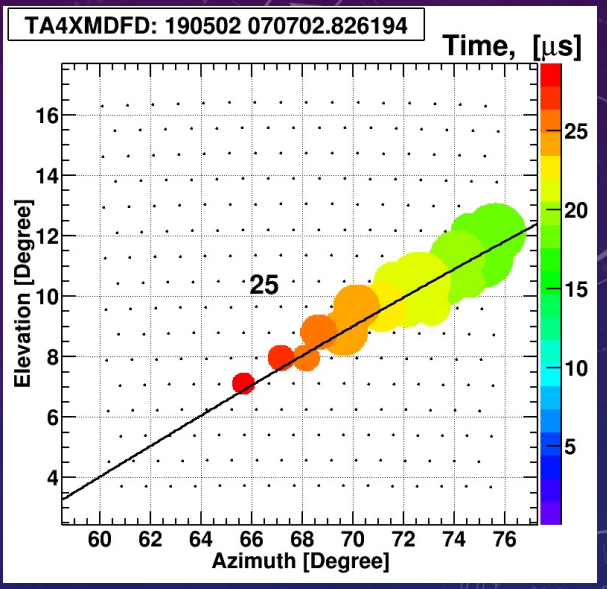


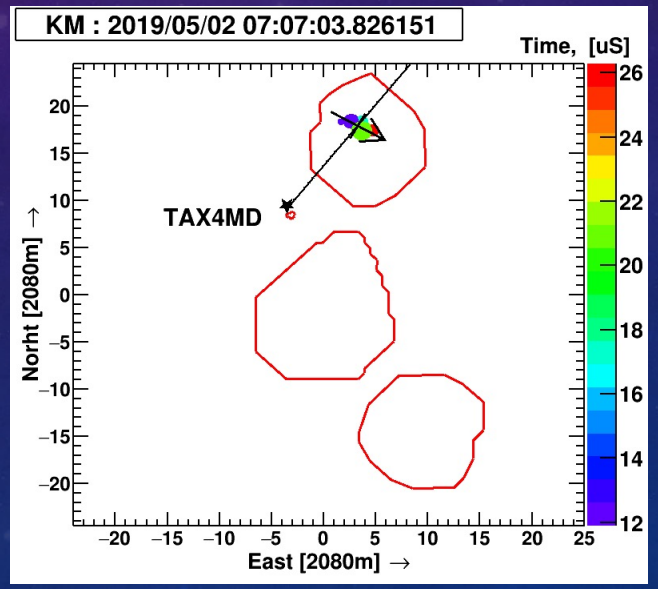


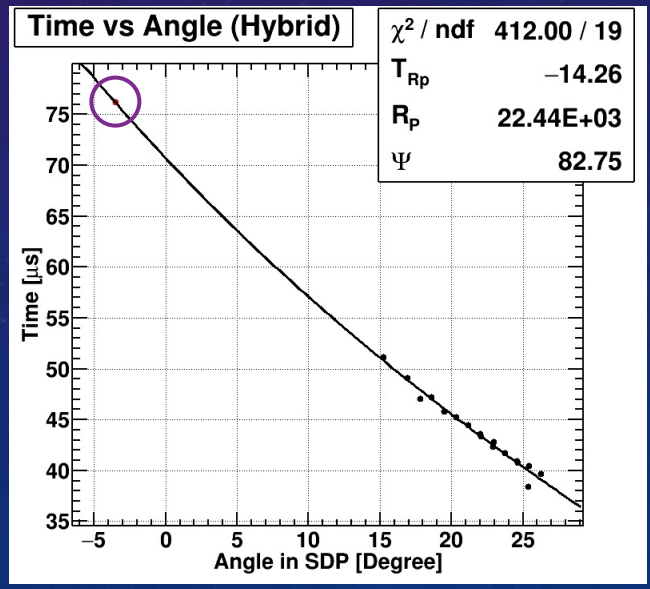
TAX4 HYBRID EXAMPLE EVENT

- Hybrid Analysis
  - Surface detector event
  - Fluorescence Telescope event
  - Time-matched within 1 ms
  - Very accurate event geometry
    - SDP-ground intersection
    - Time vs Angle fit with long lever arm

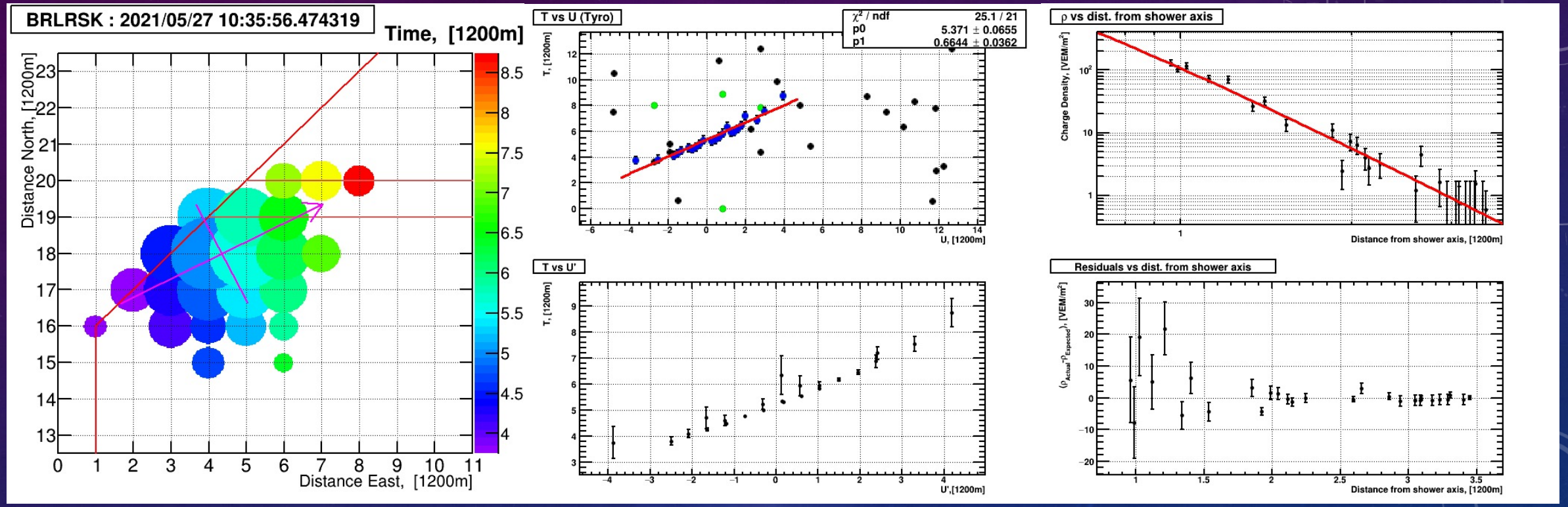






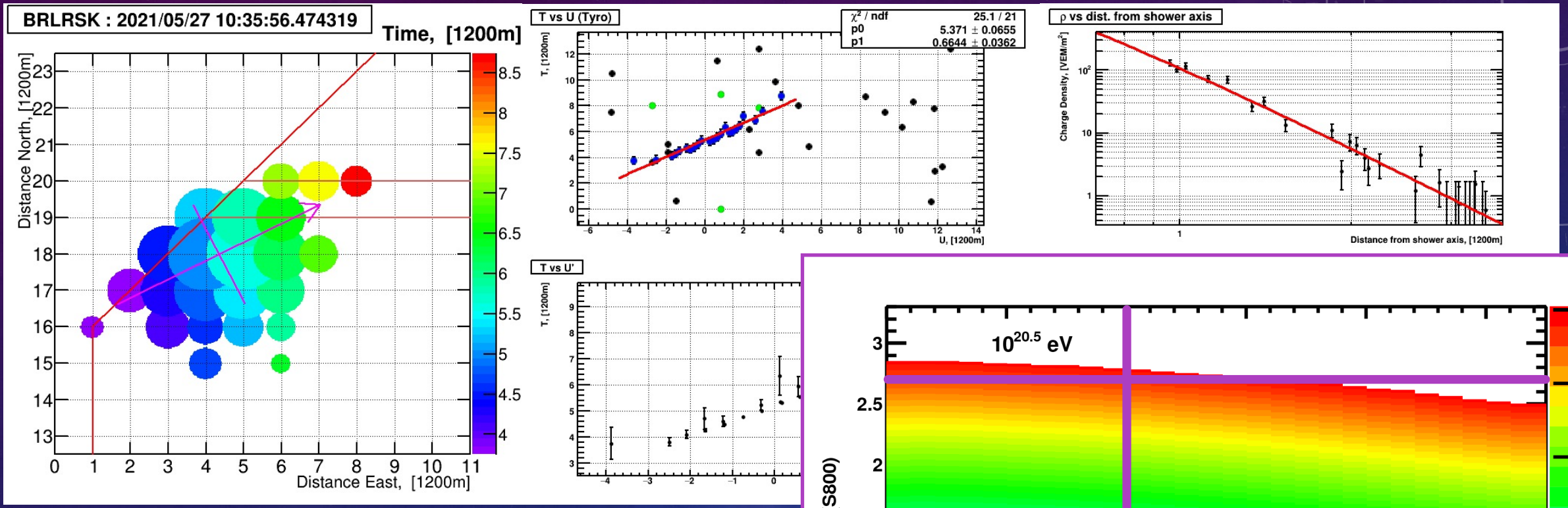


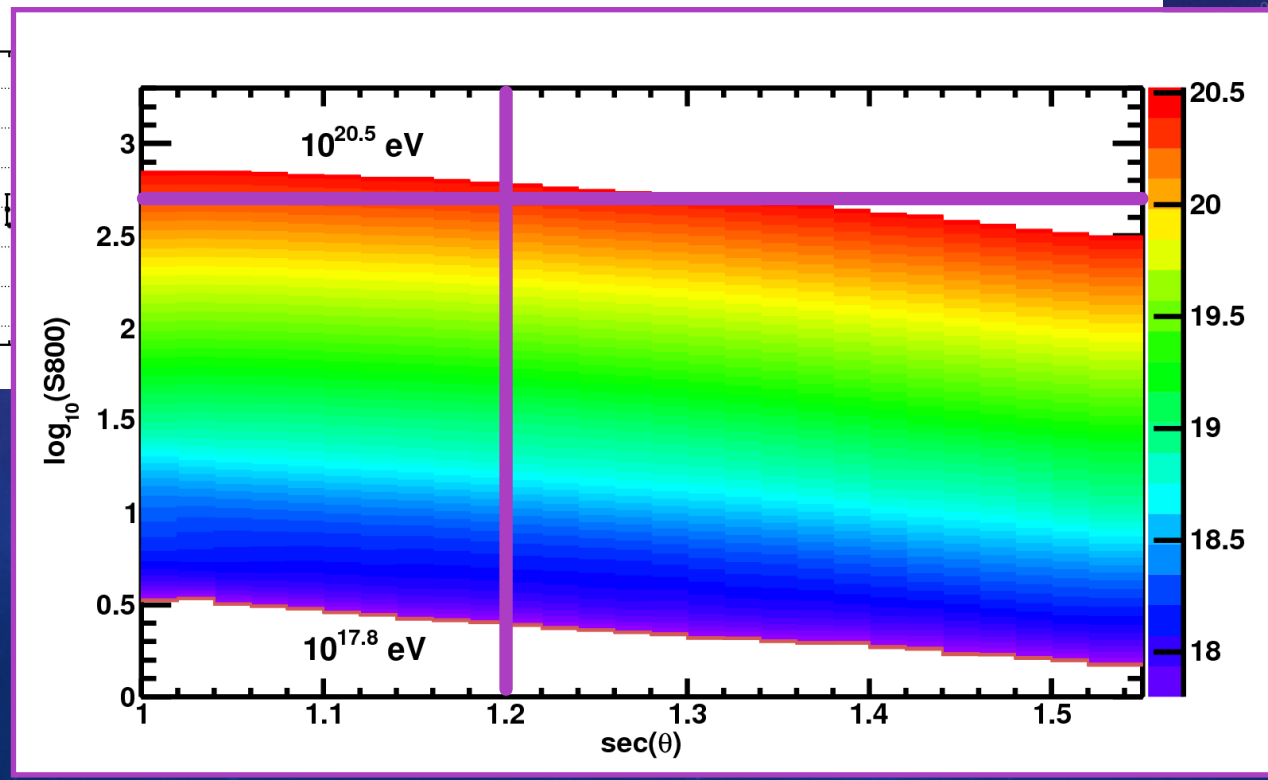
HIGHEST ENERGY EVENT SEEN IN A SURFACE DETECTOR



- Observed: 27 May 2021
- Zenith angle: ~30˚
- S800: ~500

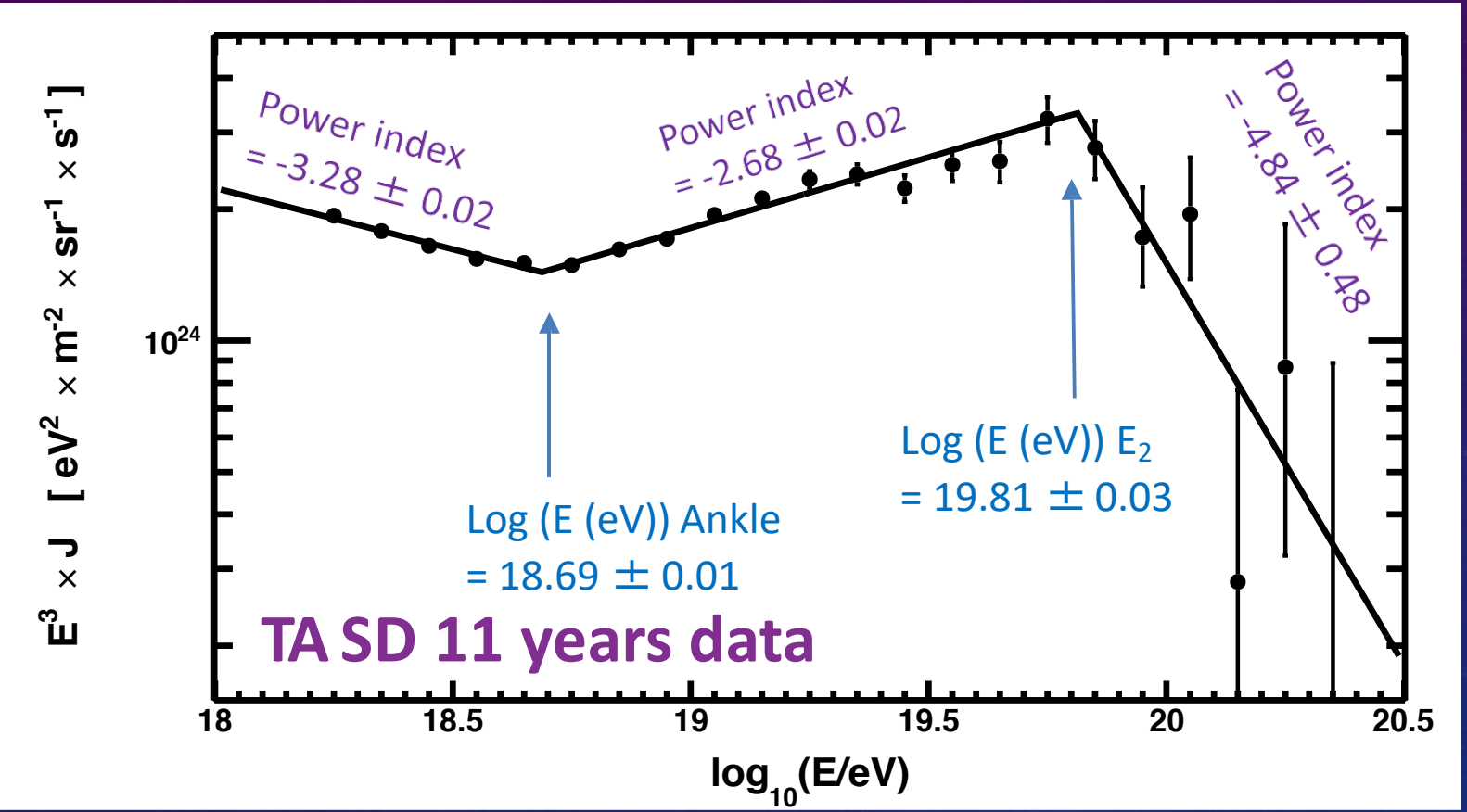
HIGHEST ENERGY EVENT SEEN IN A SURFACE DETECTOR

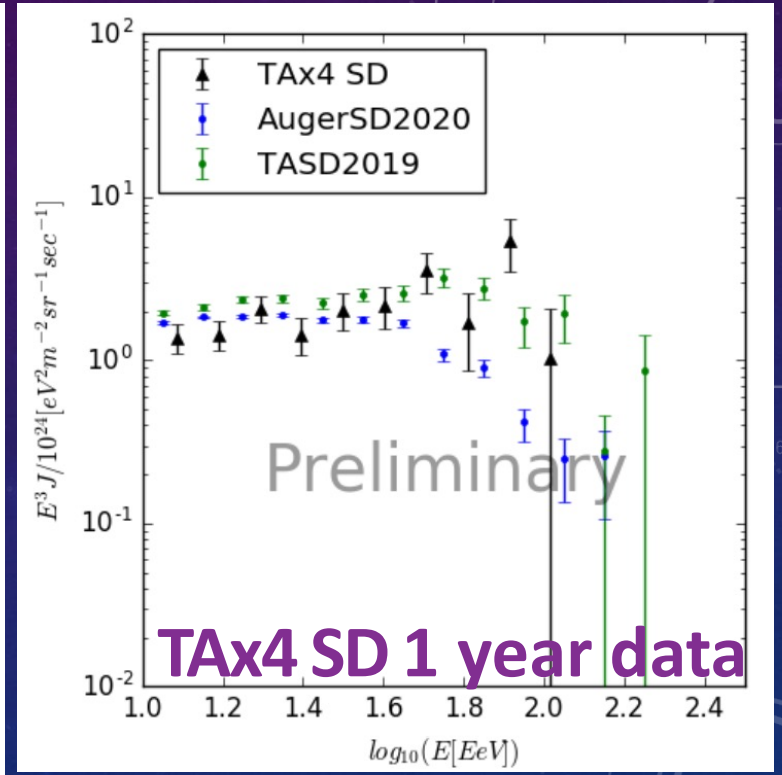




- Observed: 27 May 2021
- Zenith angle: ~30˚
- S800: ~500
- Energy: 244 EeV (*after* 1/1.27 scaling)

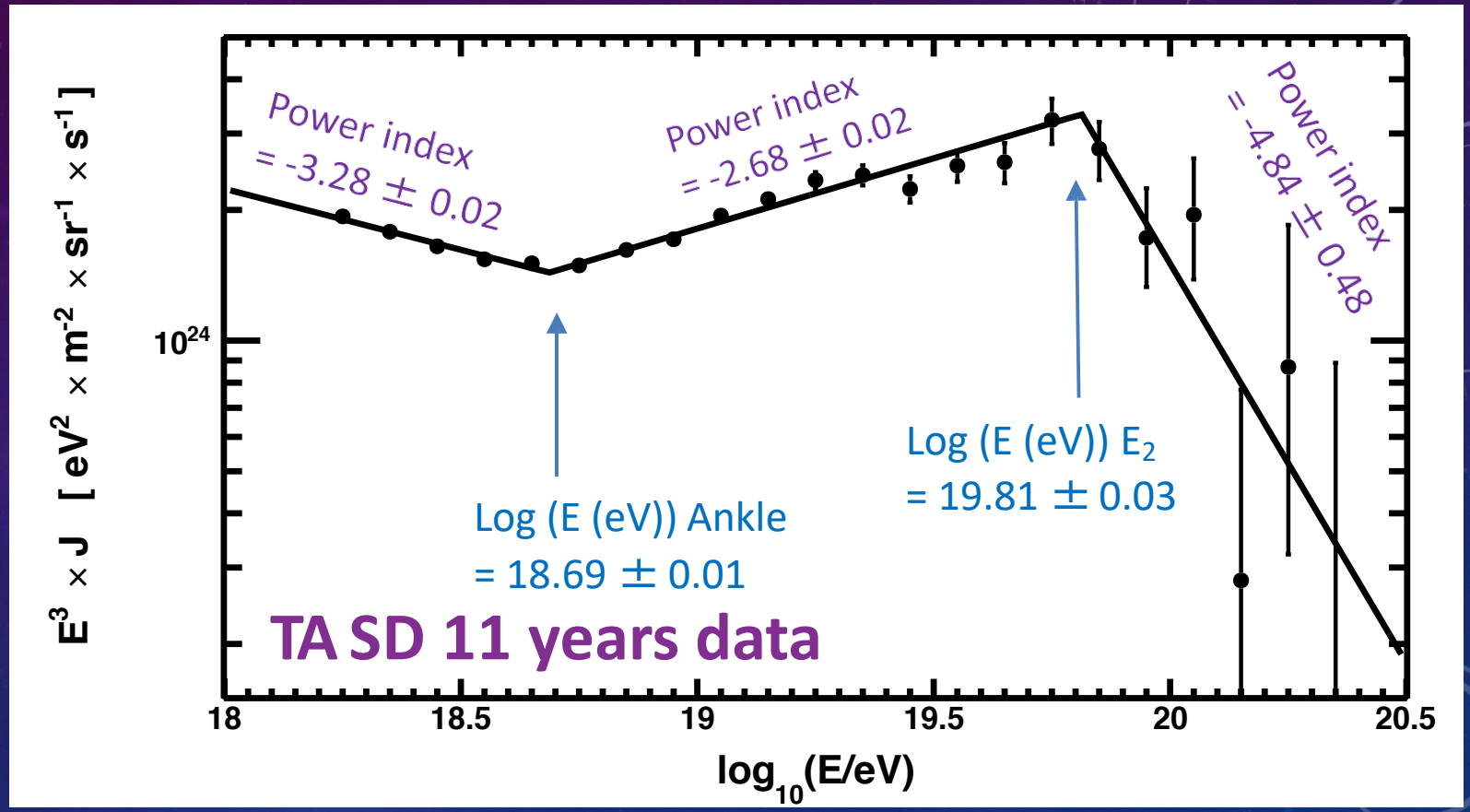
ENERGY SPECTRUM





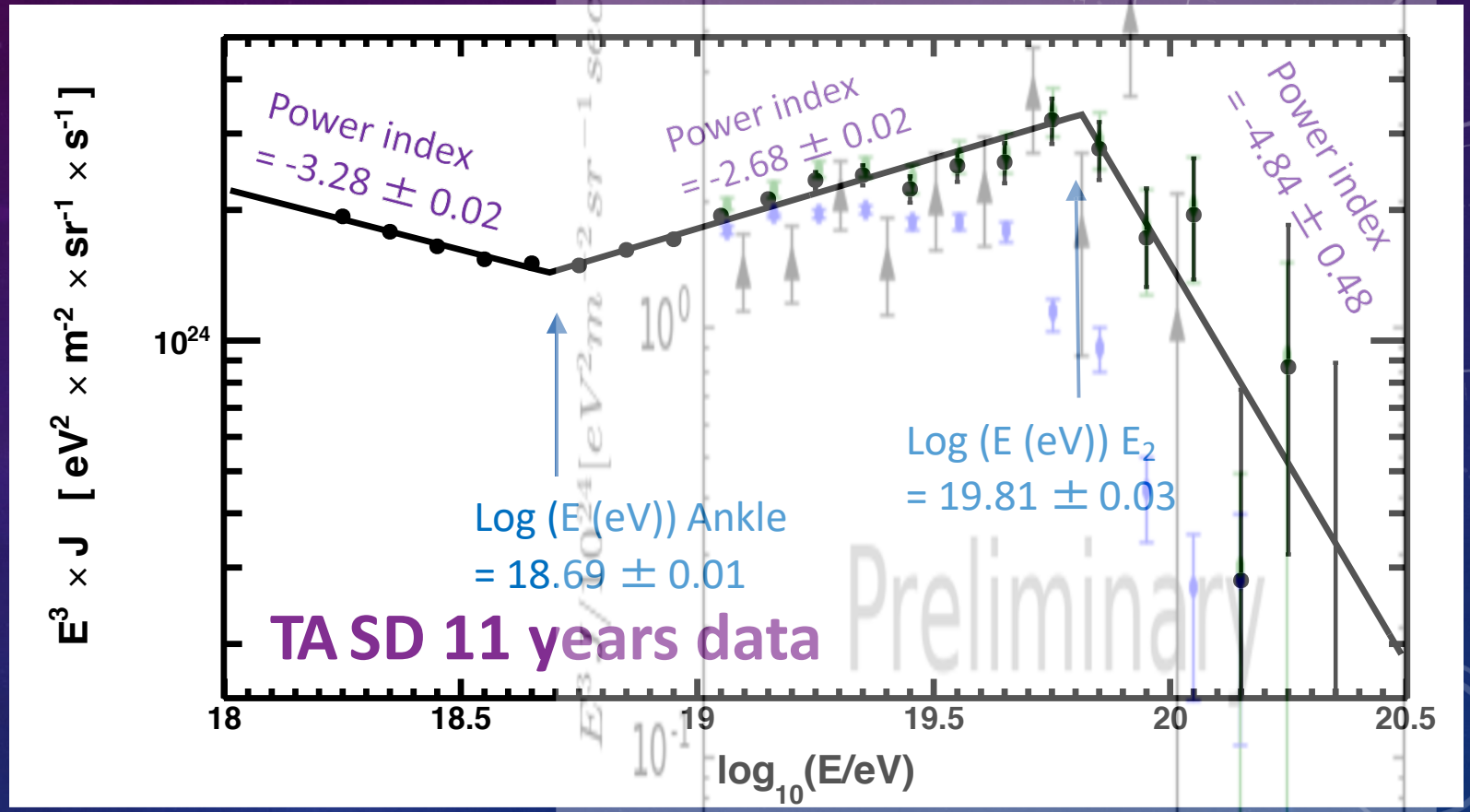
ENERGY SPECTRUM

- TA Energy Spectrum (from 2019)



ENERGY SPECTRUM

- TA Energy Spectrum (from 2019)
- TAx4 1-year spectrum superimposed



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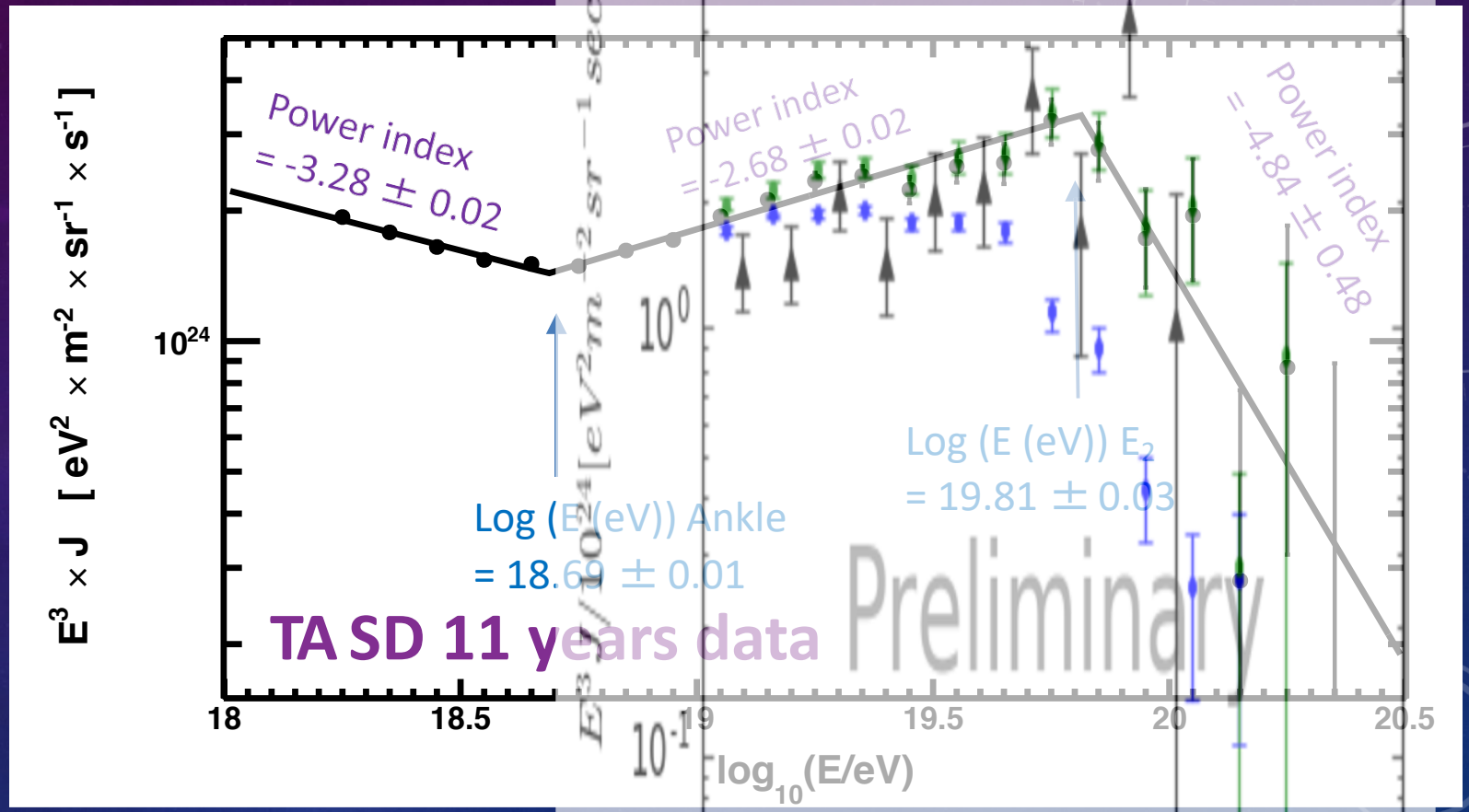

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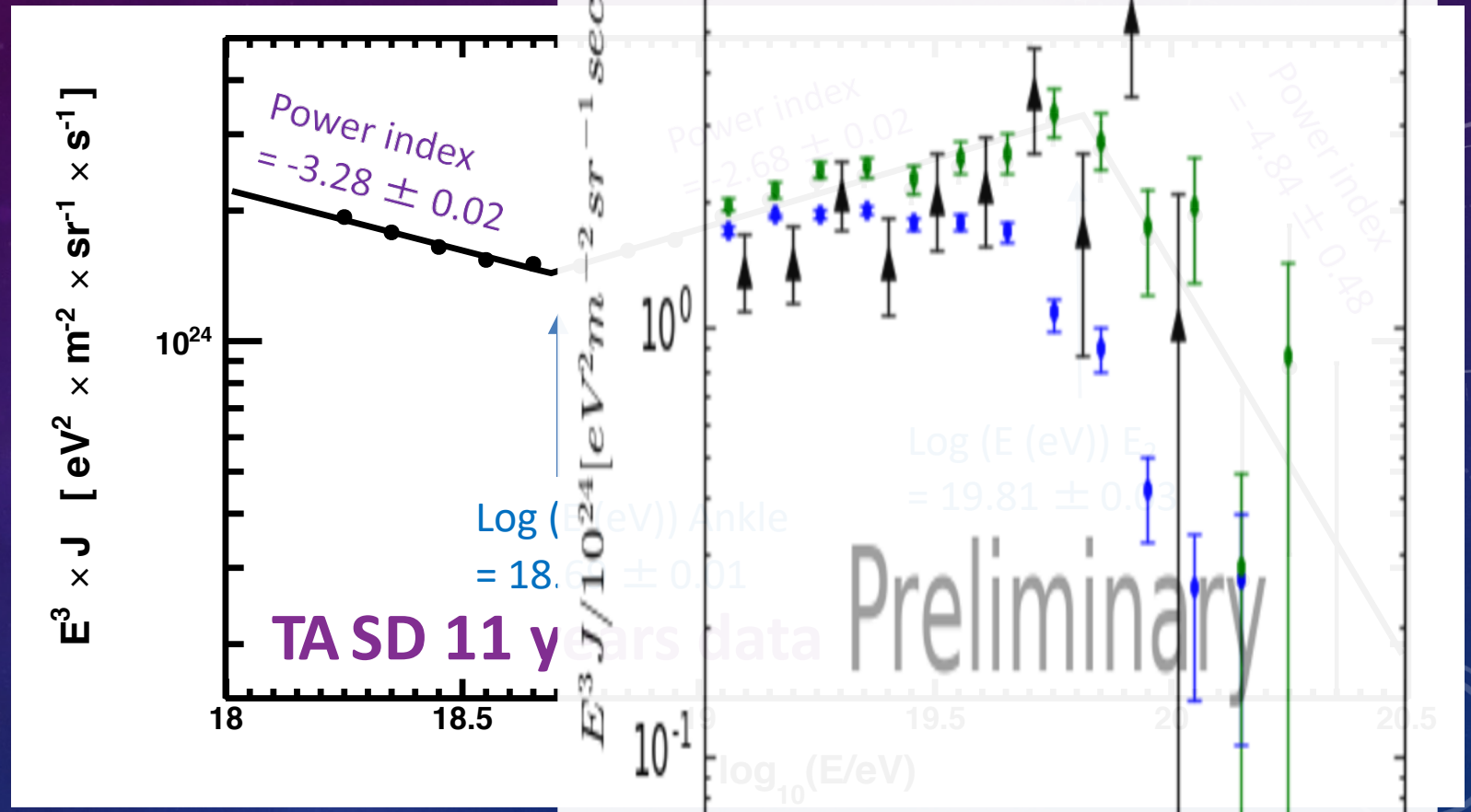
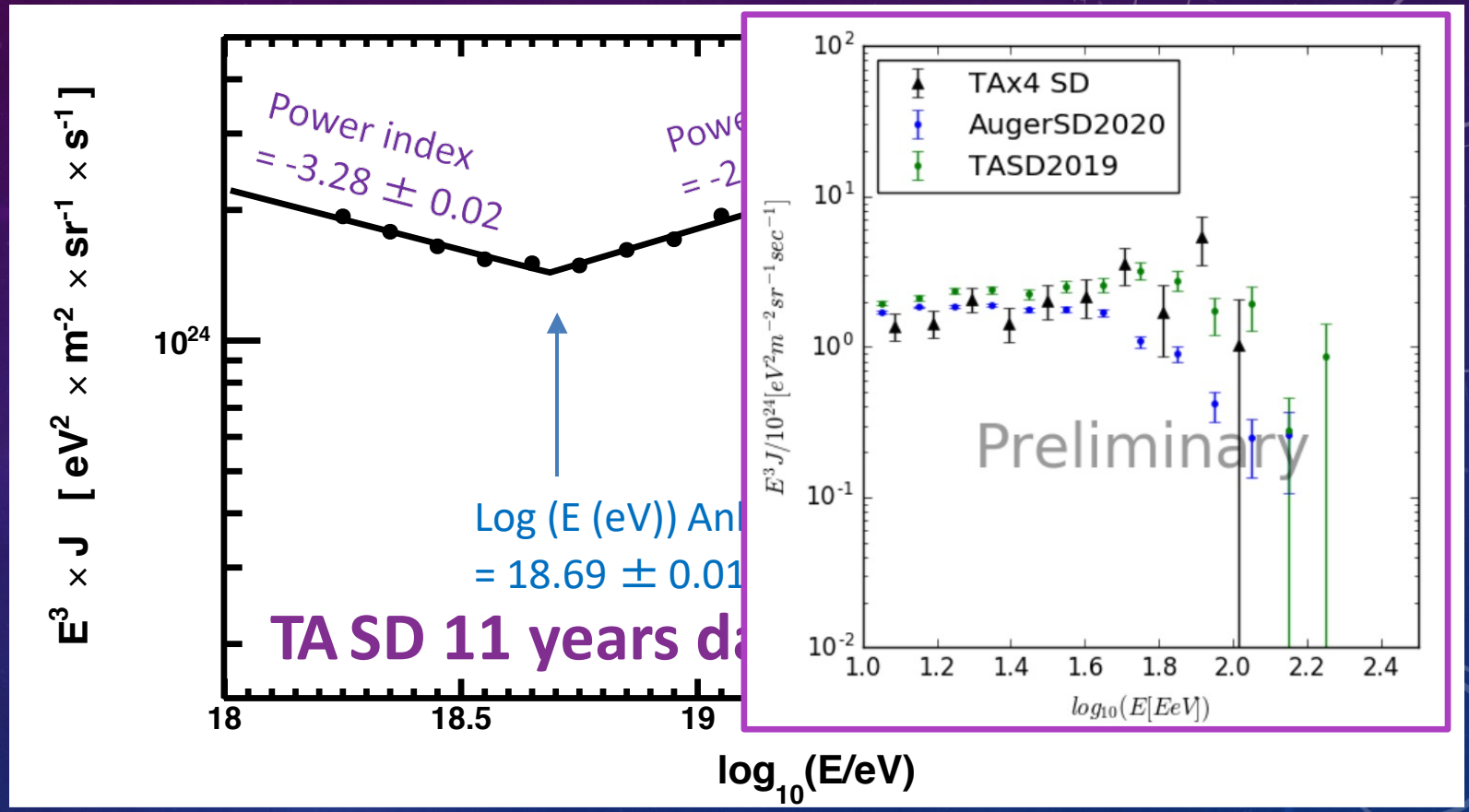


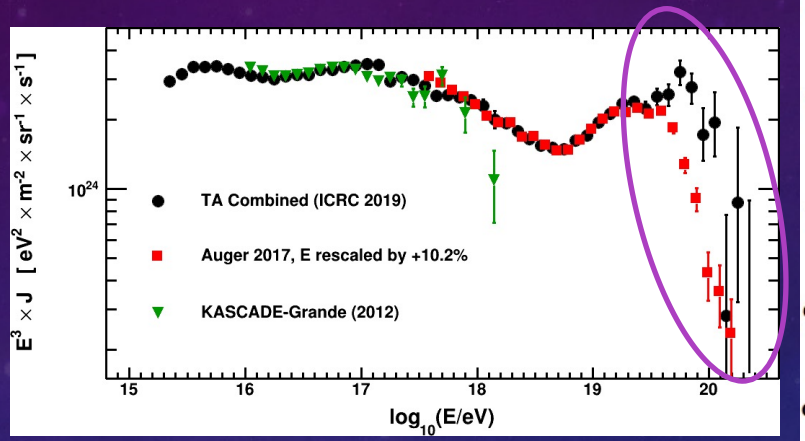
ENERGY SPECTRUM

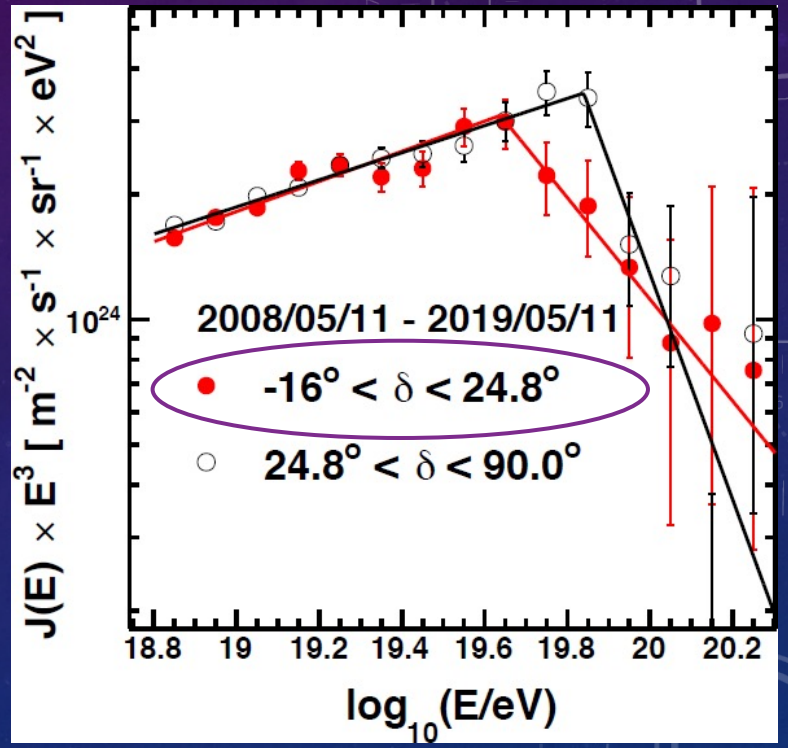
- TA Energy Spectrum (from 2019)
- TAx4 1-year spectrum superimposed
- With 1-year of (half of) the TAx4 expansion, can already corroborate higher GZK threshold



ENERGY SPECTRUM

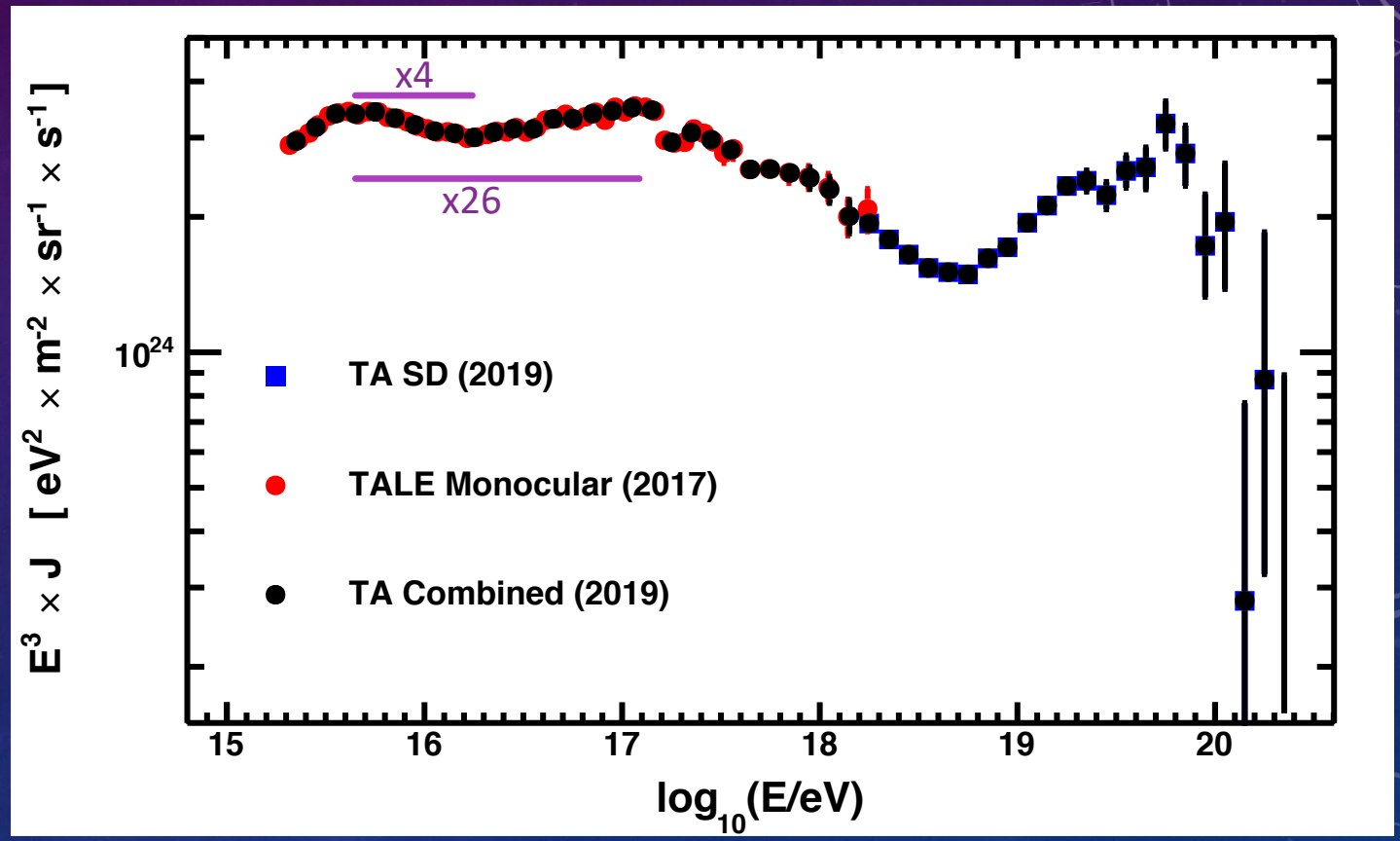
- There is a declination dependence in the TA SD spectrum
  - Difference of the cutoff energies of energy spectra
    - log(E/eV) = 19.64 ± 0.04 for lower dec. band (-16˚–24.8˚)
    - log(E/eV) = 19.84 ± 0.02 for higher dec. band (24.8˚–90˚)
  - The global significance of the difference is estimated to be 4.3σ



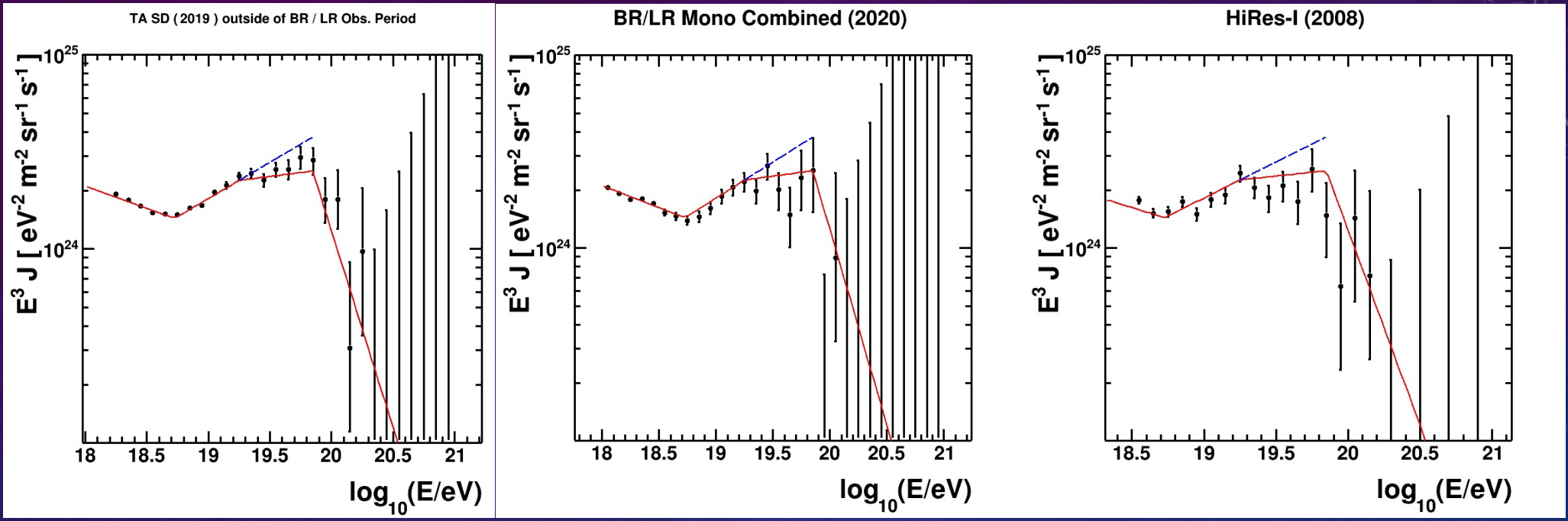


ENERGY SPECTRUM

- Combine TA SD spectrum (11 years) with TALE FD monocular (22 months) to get CR spectrum covering 5 orders-of-magnitude
  - Knee: $\log_{10}(E/\mathrm{eV}) \sim 15.5$
  - LE ankle: $\log_{10}(E/\mathrm{eV}) = 16.22(2)$
  - 2nd Knee: $\log_{10}(E/\mathrm{eV}) = 17.04(4)$
  - Ankle: $\log_{10}(E/\mathrm{eV}) = 18.69(1)$
  - Cutoff: $\log_{10}(E/\mathrm{eV}) = 19.81(3)$

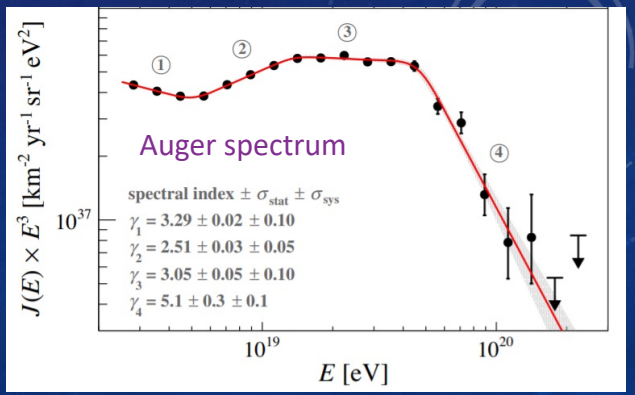


THE INSTEP FEATURE



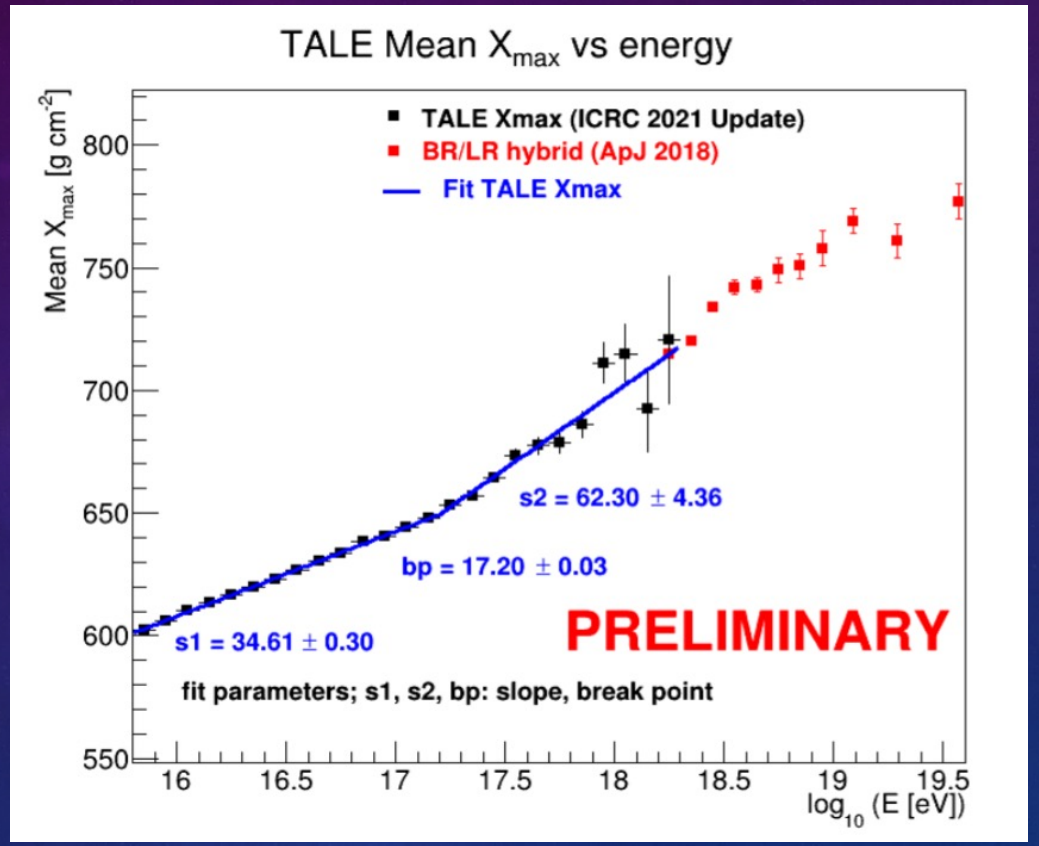
Combined fit of TASD, TA Monocular and HiRes
Finds the instep feature (first seen by Auger)
with 5.3σ significance

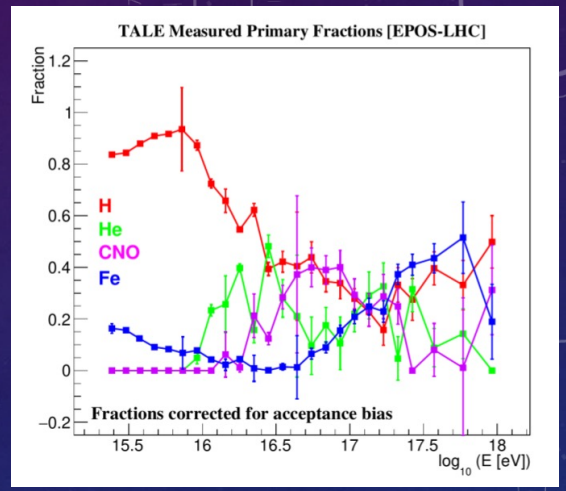
Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
$E_{\rm ankle}$/EeV	5.0 ± 0.1	5.4 ± 0.1
$E_{\rm instep}$/EeV	13 ± 1	18 ± 1
$E_{\rm cut}$/EeV	46 ± 3	71 ± 3

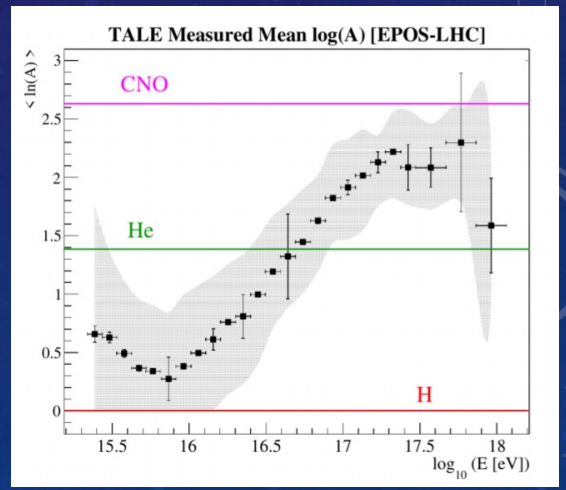


COMPOSITION

- Detailed measurement of composition from 2 PeV to 2 EeV
  - Using TALE with Cherenkov-light dominated events
  - ApJ 909 (2021)178
- Fit to four species
  - Reduction in protons above the Knee
  - Getting heavier
- Elongation rate fit
  - Break at 160 PeV, 2nd Knee
  - Getting lighter above that

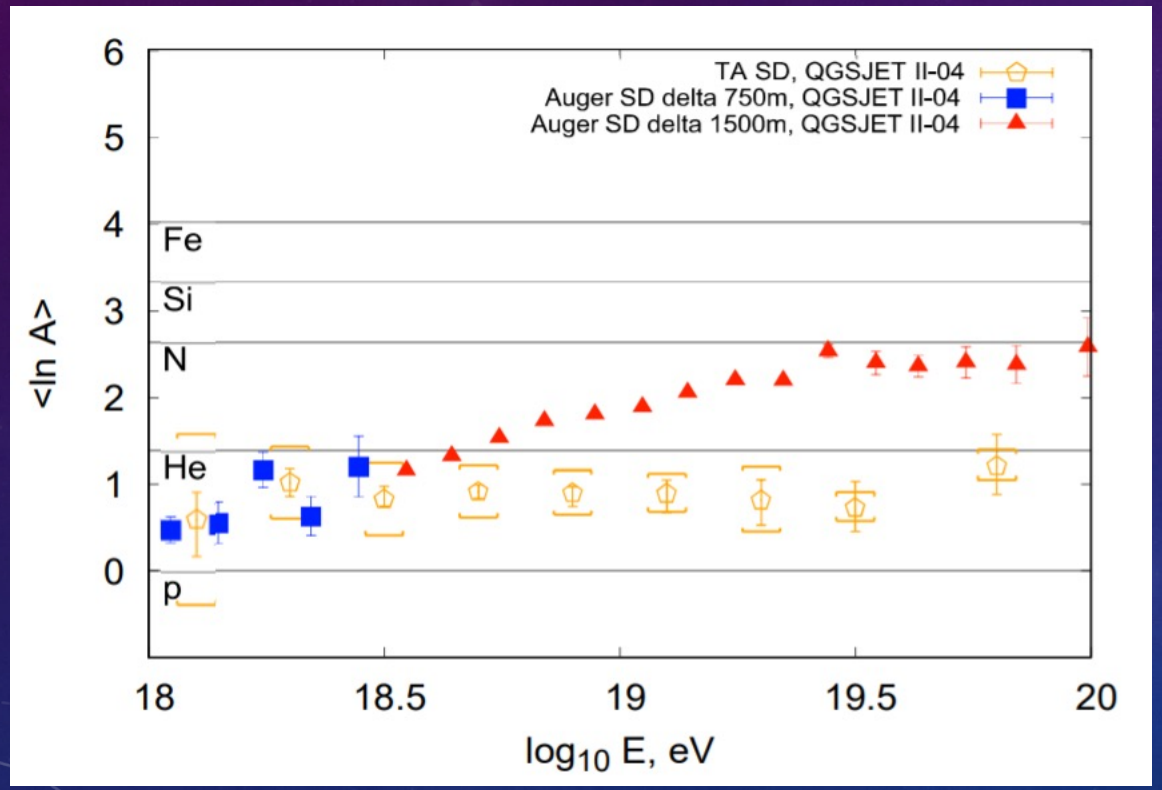


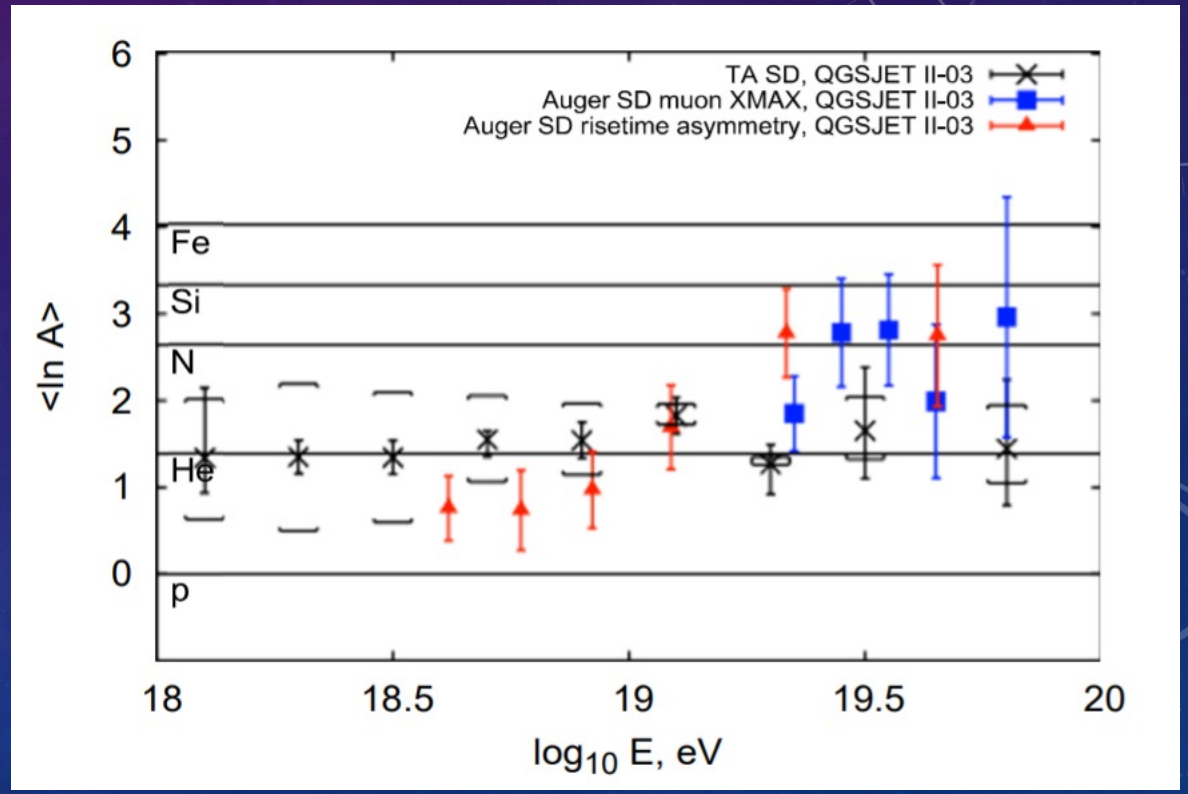




COMPOSITION

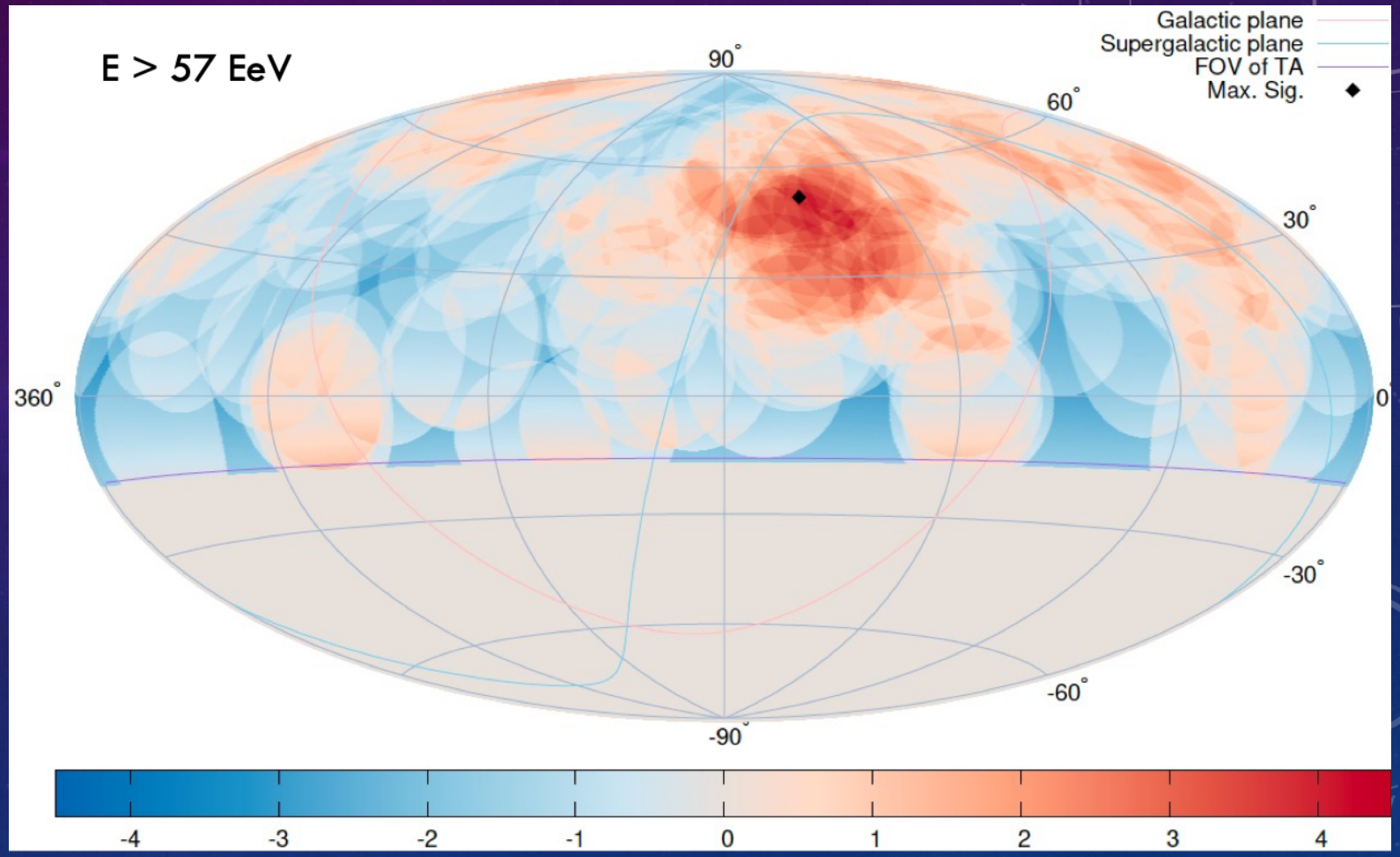
- TA SD composition: BDT analysis using 16 composition sensitive signals (12 years: 2008–2020)
  - Find light, unchanging composition above 1 EeV, with two different high-energy interaction models





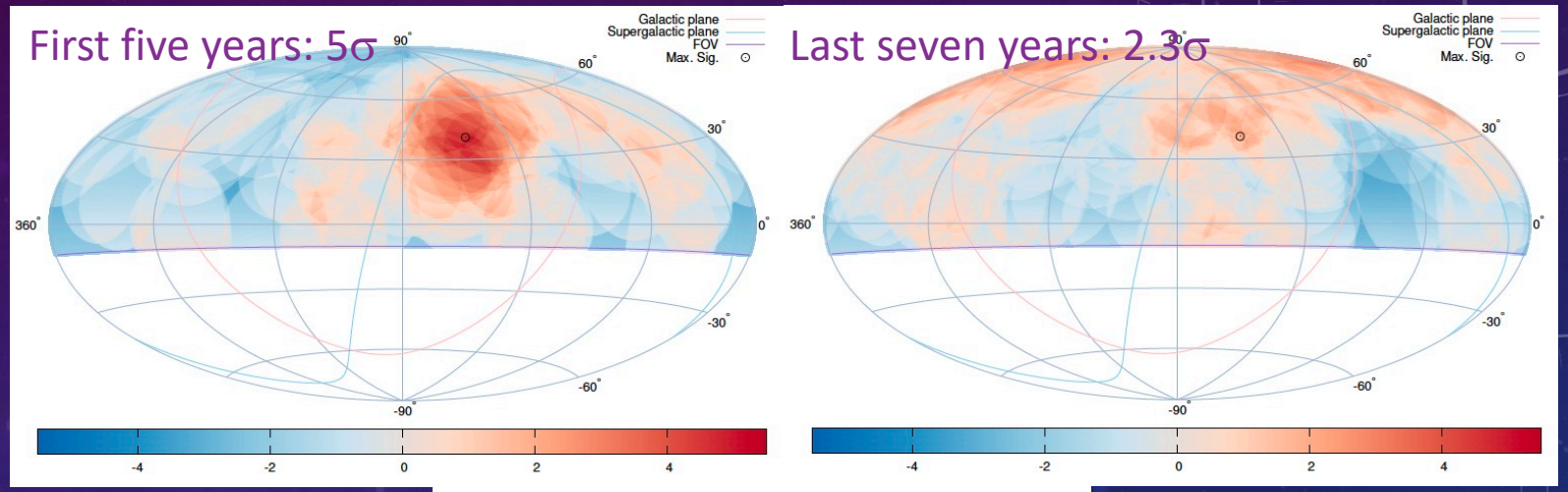
ANISOTROPY

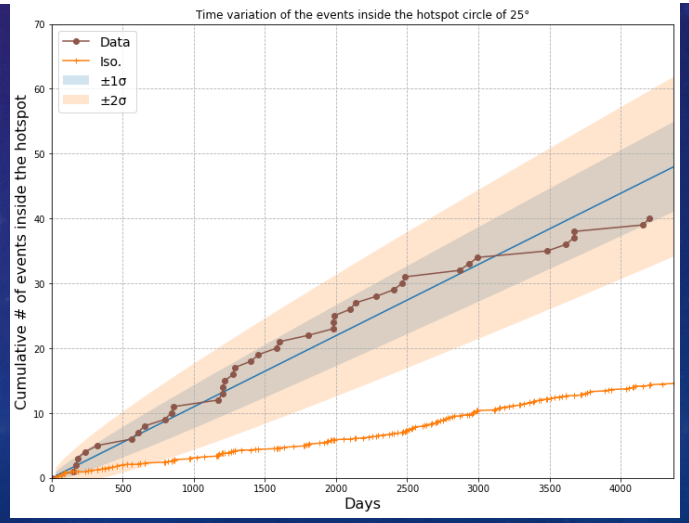
- The TA hot-spot with 12 years of data
  - 179 events with $E > 57$ EeV
  - 40 events in hot-spot, 25˚ top-hat, local 4.5σ significance, 3.2σ local



ANISOTROPY

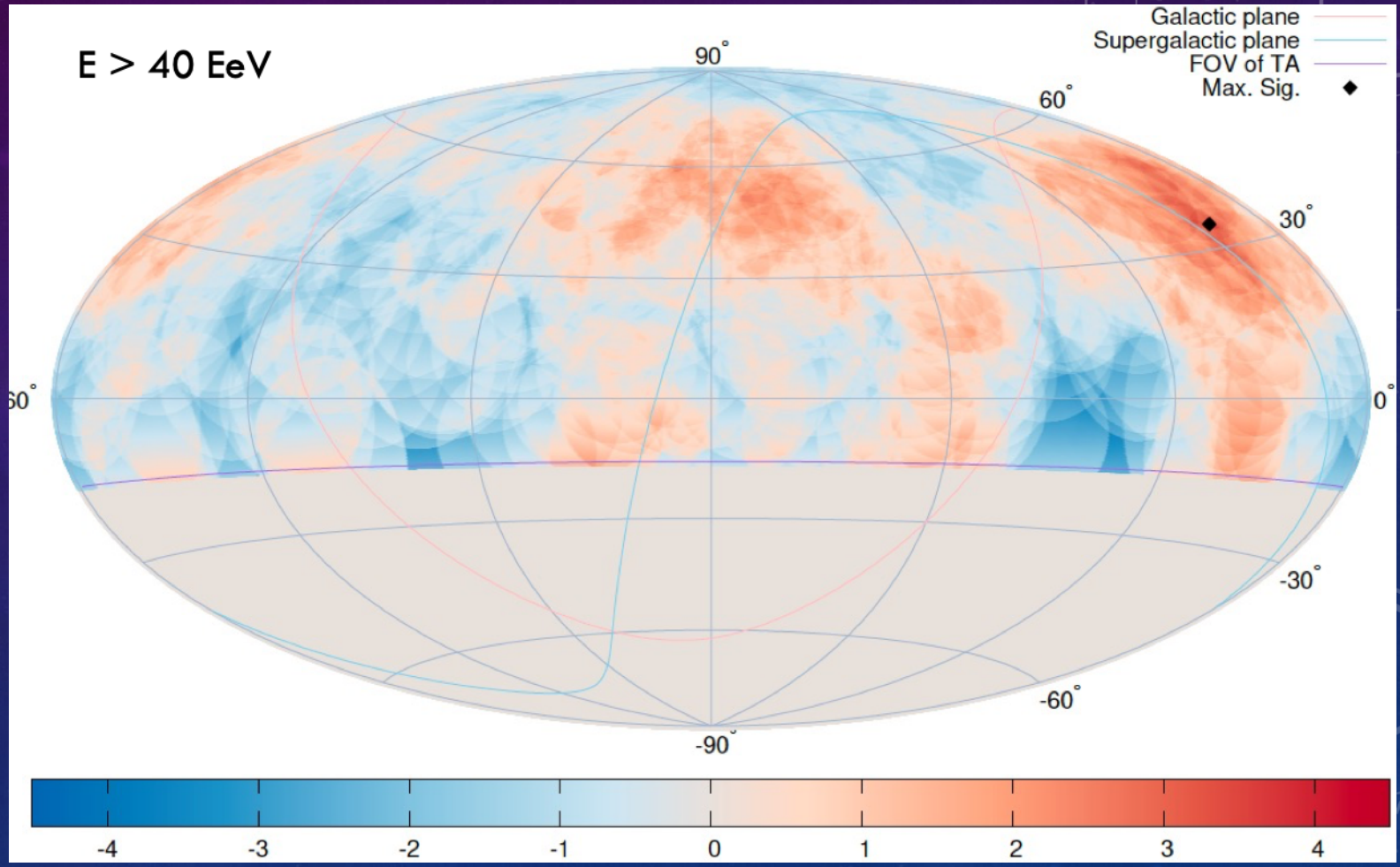
- The TA hot-spot with 12 years of data
  - 179 events with $E > 57$ EeV
  - 40 events in hot-spot, 25˚ top-hat, local 4.5σ significance, 3.2σ local
- The original brightness (ApJ **790** (2014) L21) seems to not be sustained
  - But still significantly higher than background
  - Growth rate consistent with linear





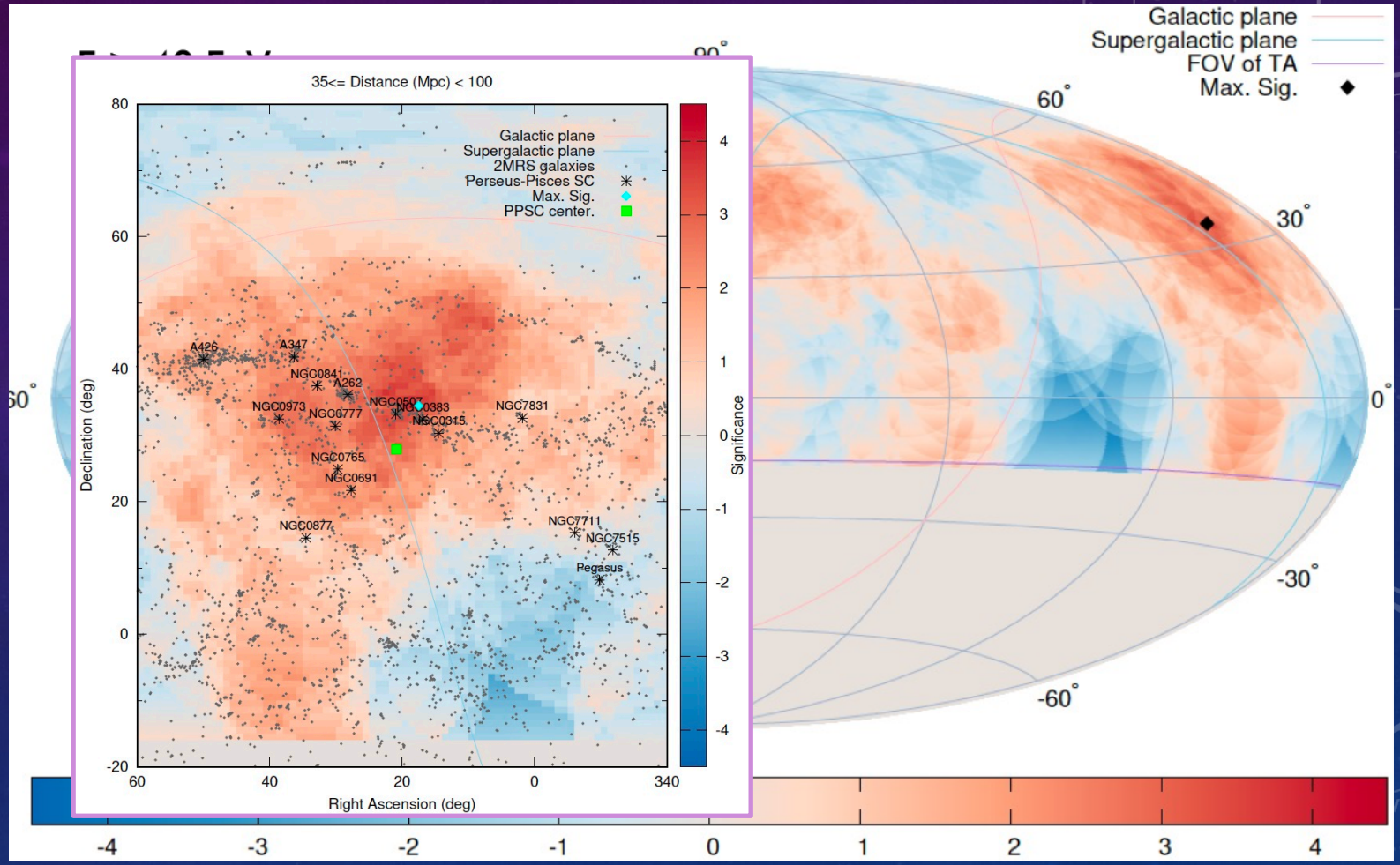
ANISOTROPY

- At lower energies (above 40 EeV) see a new excess
  - In the direction of the Perseus-Pisces Supercluster



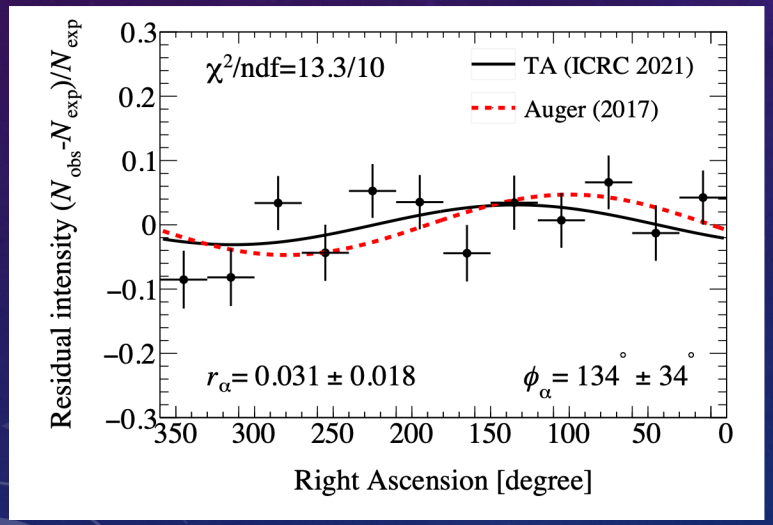
ANISOTROPY

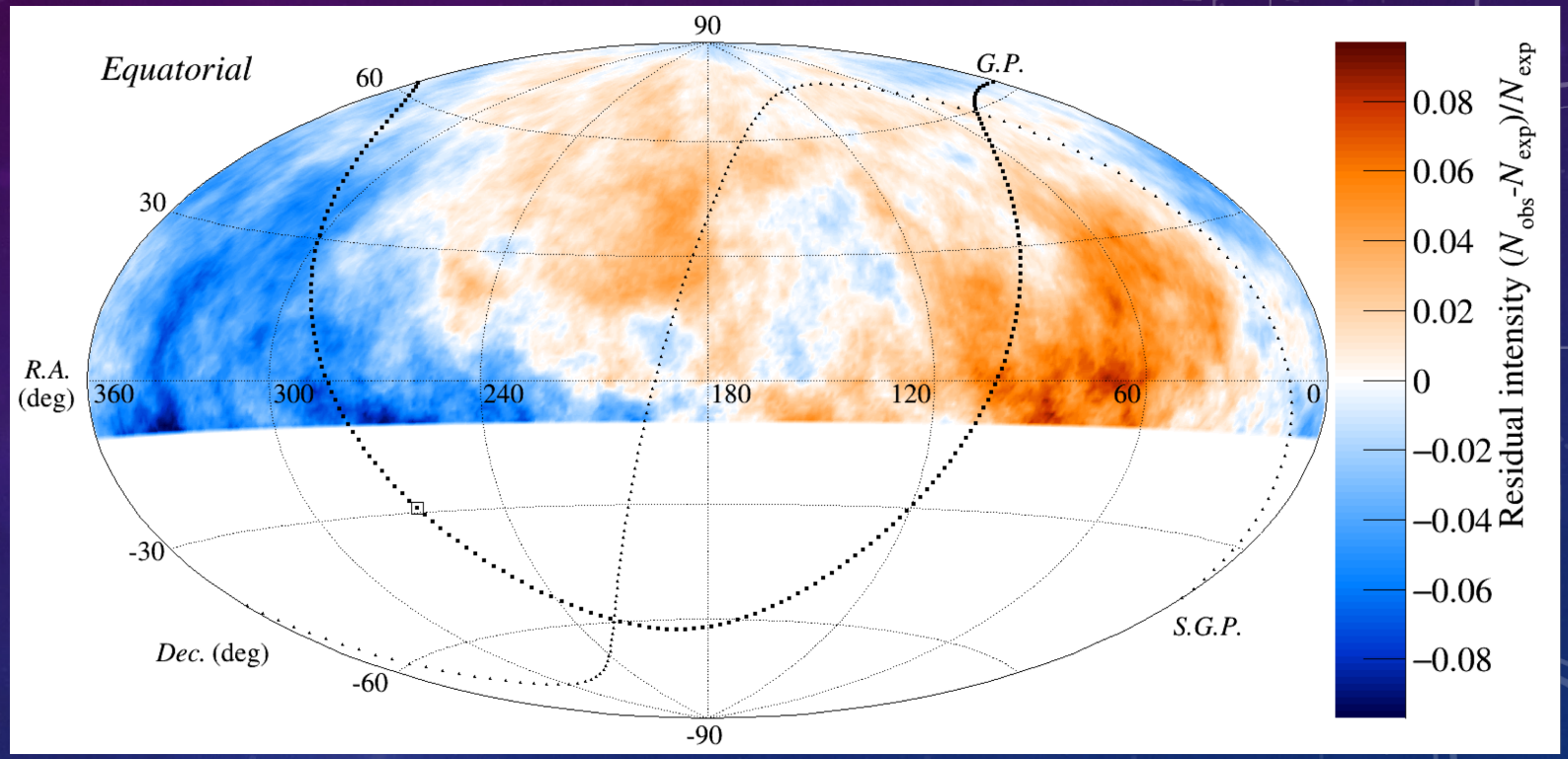
- At lower energies (above 40 EeV) see a new excess
  - In the direction of the Perseus-Pisces Supercluster
- Significant excess at energies $\log_{10} E/\text{eV} > 19.4$, 19.5, and 19.6
  - 4.4σ, 4.2σ, and 4.0σ, resp.
- Chance that excess within 9˚ of supercluster center is about 3.5σ



ANISOTROPY

- At energies above 8.8 EeV
  - Look for dipole (a la Auger)
  - TA 12-yr result :
    $r_\alpha \simeq 3.1\%; \phi_\alpha \simeq 134^\circ$
  - Auger 2017 result :
    $r_\alpha \simeq 4.7\%; \phi_\alpha \simeq 100^\circ$





SUMMARY

- Results from TA, the largest cosmic-ray observatory in the Northern Hemisphere, including TALE and TAx4
- Spectrum
  - TAx4 SD has begun to measure, and has enough events to make a meaningful contribution to the TA spectrum above 10 EeV
  - TA finds a significant difference in its own spectra above and below 25˚ declination (agrees with Auger in overlapping region)
  - Spectrum measurements over 5.5 orders-of-magnitude in energy
  - Observation of the “instep” feature
- Composition
  - Light-heavy-light pattern in PeV energy range using TALE-Cherenkov
  - Light and steady in EeV using TA SD with machine-learning BDT analysis
- Anisotropy
  - Hotspot persists, but significance not increasing very quickly
  - New significant excess at slightly lower energy in conjunction with the Perseus-Pisces Supercluster
    - Found while looking for difference in TA and Auger energy spectra
  - See a similar dipole to the Auger published result
- There’s the NICHE array to talk about too, but no time…

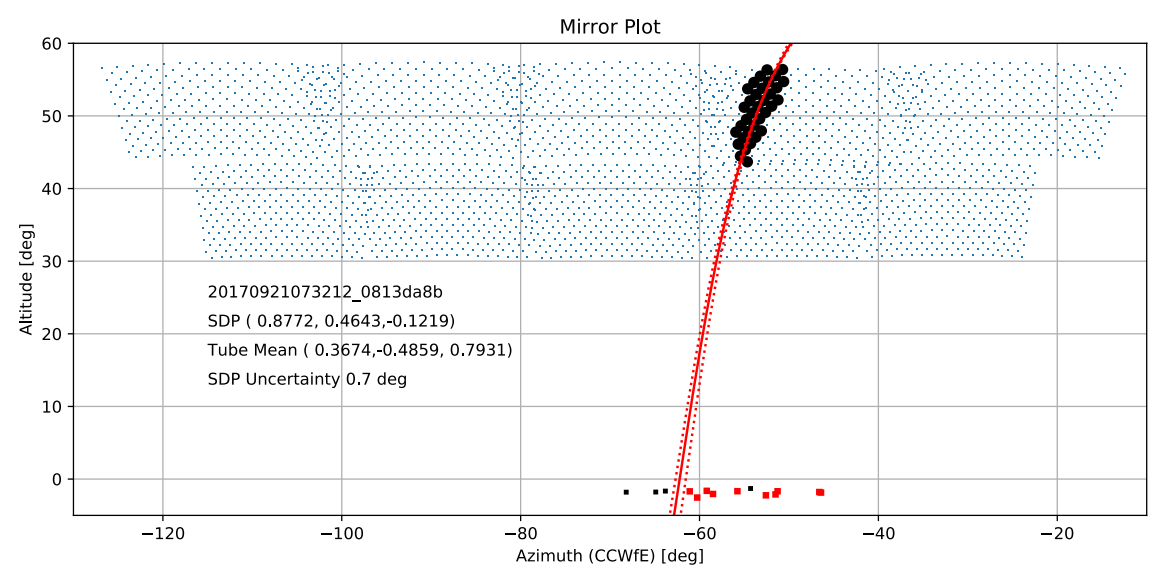
NICHE ARRAY

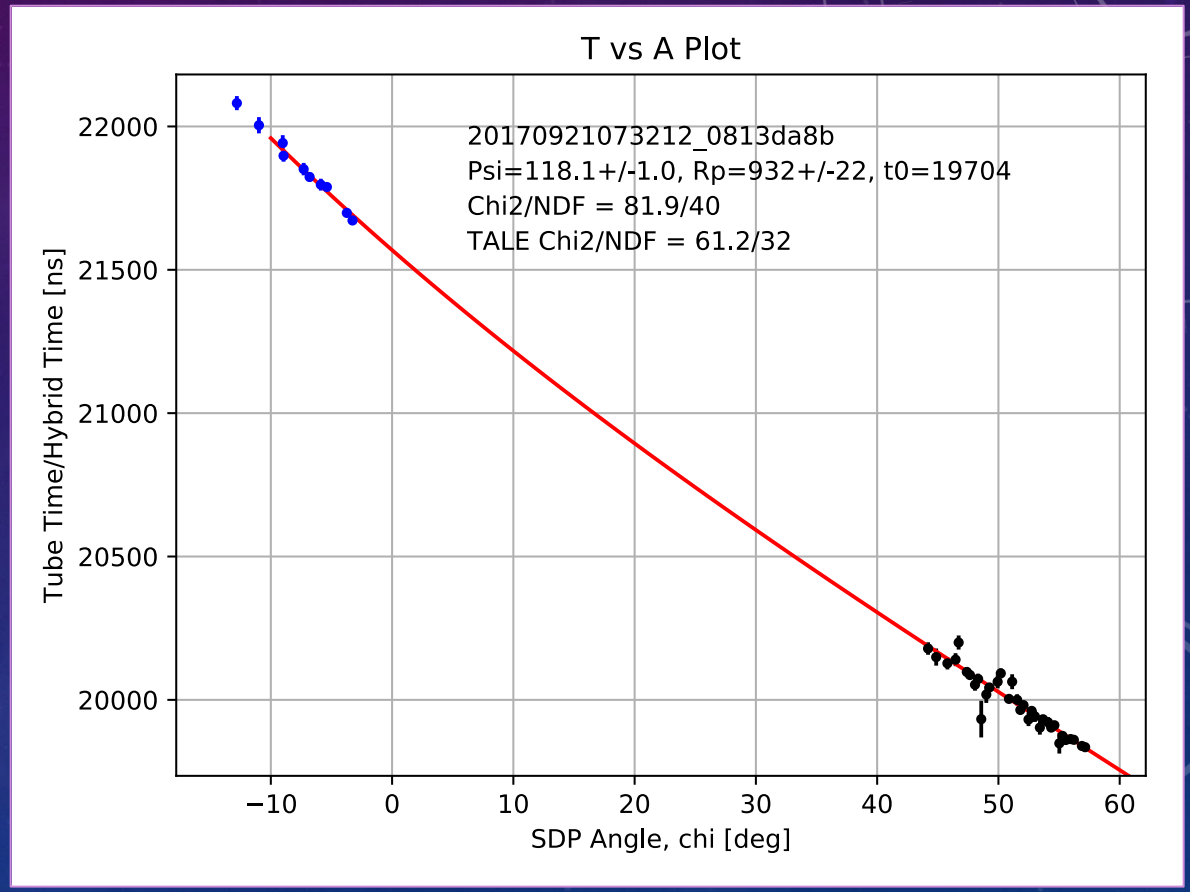

einstein
noether
rutherford
curie
yukawa
feynman
bardeen
rubin
meitner


YUKAWA

NICHE ARRAY

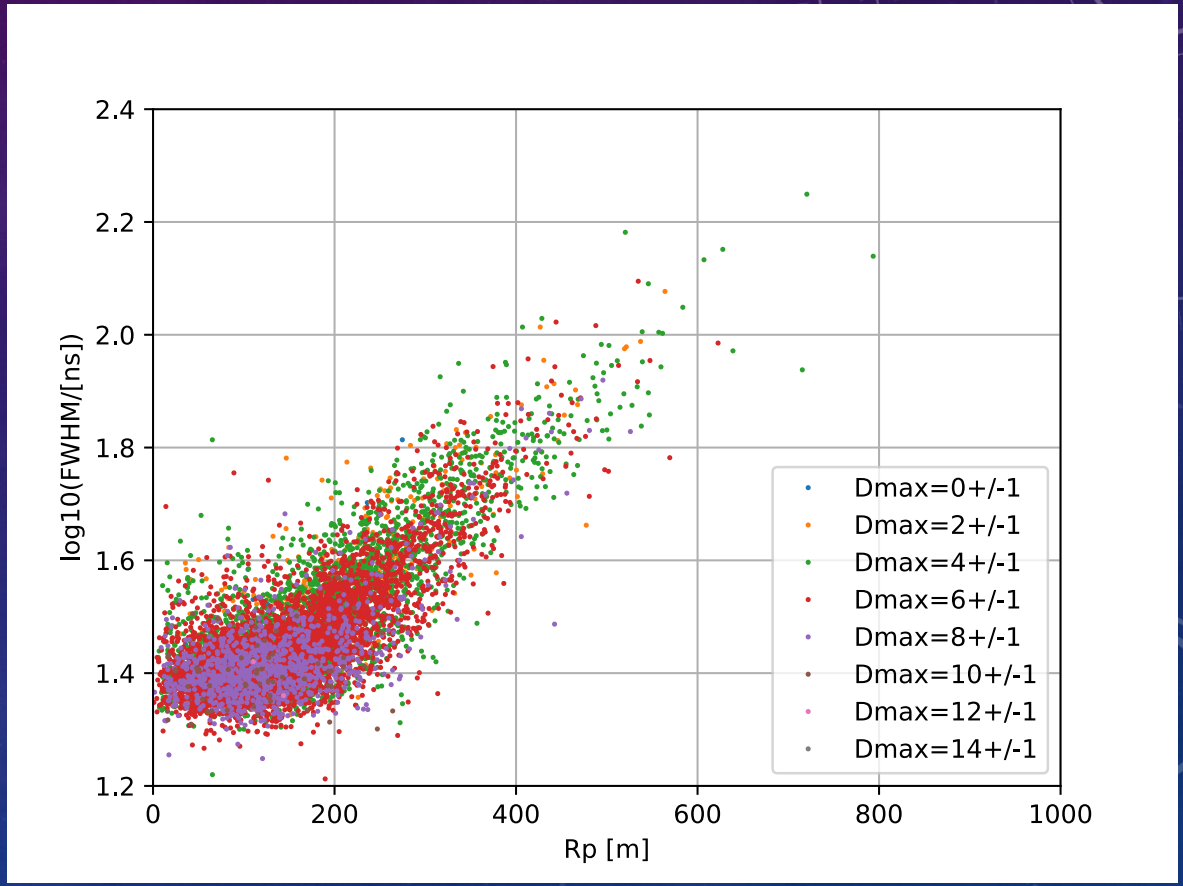
- NICHE works with TALE as a non-imaging and imaging Cherenkov hybrid detector





NICHE ARRAY

- Can show that the time width of NICHE signal at a given distance from the shower core depends on how far it is to the shower maximum
  - Shower core position from TALE reconstruction is uncertain at the 100-m level (smears left-right)
  - X_{max} , D_{max} comes from TALE reconstruction and geometry
  - Take average over 100-m bins, require 40 events



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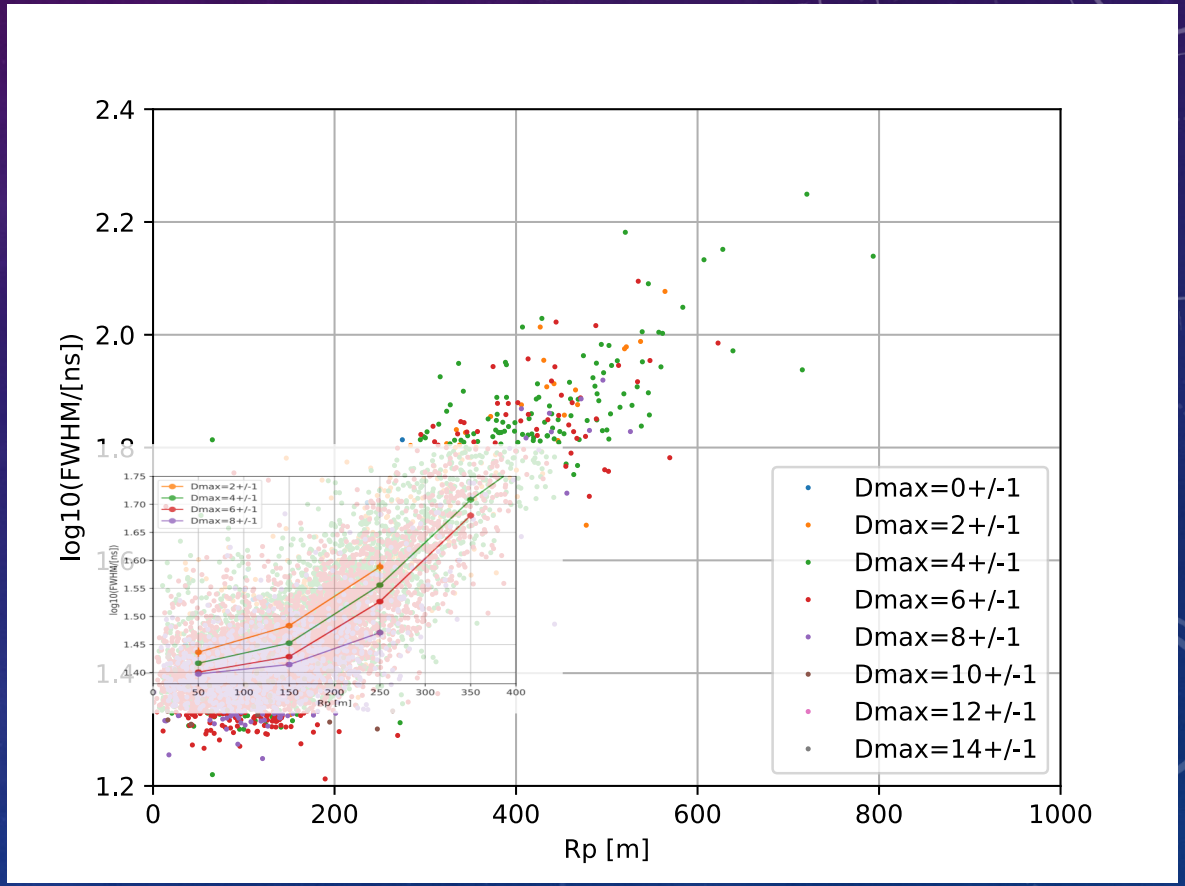

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  - Take average over 100-m bins, require 40 events
- Can now use width in NICHE as a composition measure