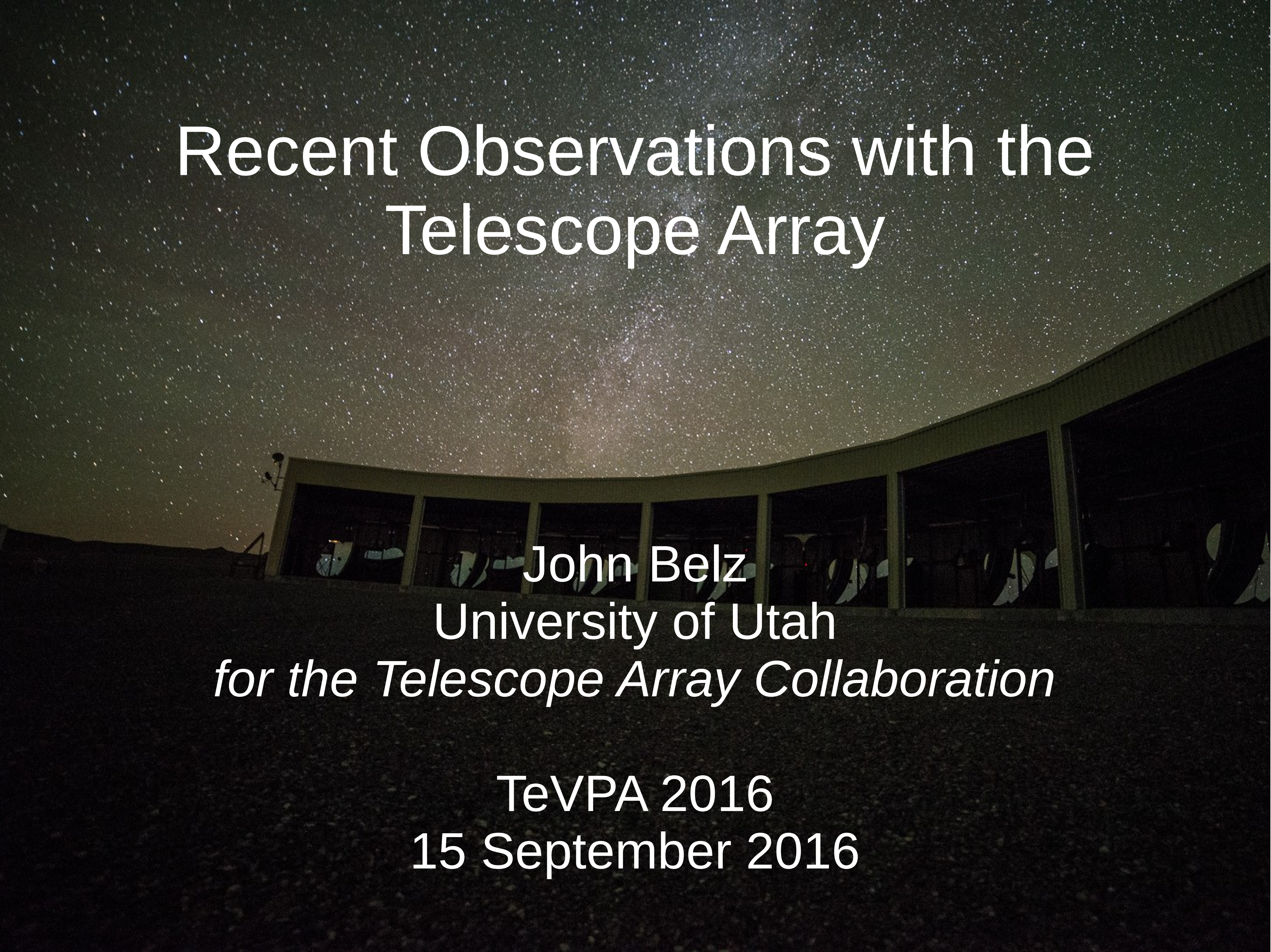


Recent Observations with the Telescope Array

John Belz
University of Utah
for the Telescope Array Collaboration

TeVPA 2016
15 September 2016

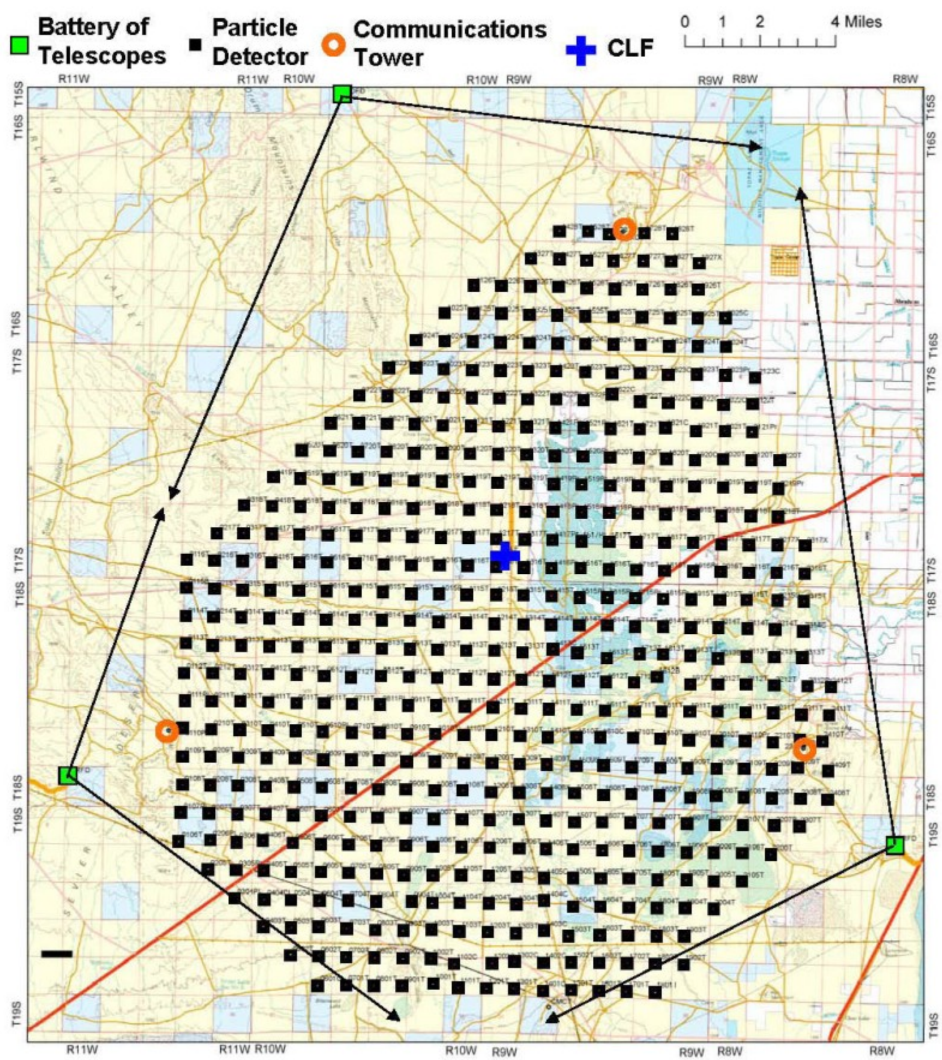
R.U. Abbasi,[1] M. Abe,[2] T. Abu-Zayyad,[1] M. Allen,[1] R. Azuma,[3] E. Barcikowski,[1] J.W. Belz,[1] D.R. Bergman,[1] S.A. Blake,[1] R. Cady,[1] M.J. Chae,[4] B.G. Cheon,[5] J. Chiba,[6] M. Chikawa,[7] W.R. Cho,[8] T. Fujii,[9] M. Fukushima,[9,10] T. Goto,[11] W. Hanlon,[1] Y. Hayashi,[11] N. Hayashida,[12] K. Hibino,[12] K. Honda,[13] D. Ikeda,[9] N. Inoue,[2] T. Ishii,[13] R. Ishimori,[3] H. Ito,[14] D. Ivanov,[1] C.C.H. Jui,[1] K. Kadota,[15] F. Kakimoto,[3] O. Kalashev,[16] K. Kasahara,[17] H. Kawai,[18] S. Kawakami,[11] S. Kawana,[2] K. Kawata,[9] E. Kido,[9] H.B. Kim,[5] J.H. Kim,[1] J.H. Kim,[19] S. Kitamura,[3] Y. Kitamura,[3] V. Kuzmin,[16] Y.J. Kwon,[8] J. Lan,[1] S.I. Lim,[4] J.P. Lundquist,[1] K. Machida,[13] K. Martens,[10] T. Matsuda,[20] T. Matsuyama,[11] J.N. Matthews,[1] M. Minamino,[11] Y. Mukai,[13] I. Myers,[1] K. Nagasawa,[2] S. Nagataki,[14] T. Nakamura,[21] T. Nonaka,[9] A. Nozato,[7] S. Ogio,[11] J. Ogura,[3] M. Ohnishi,[9] H. Ohoka,[9] K. Oki,[9] T. Okuda,[22] M. Ono,[23] A. Oshima,[24] S. Ozawa,[17] I.H. Park,[25] M.S. Pshirkov,[16,26] D.C. Rodriguez,[1] G. Rubtsov,[16] D. Ryu,[19] H. Sagawa,[9] N. Sakurai,[11] L.M. Scott,[27] P.D. Shah,[1] F. Shibata,[13] T. Shibata,[9] H. Shimodaira,[9] B.K. Shin,[5] H.S. Shin,[9] J.D. Smith,[1] P. Sokolsky,[1] R.W. Springer,[1] B.T. Stokes,[1] S.R. Stratton,[1,27] T.A. Stroman,[1] T. Suzawa,[2] M. Takamura,[6] M. Takeda,[9] R. Takeishi,[9] A. Taketa,[28] M. Takita,[9] Y. Tameda,[12] H. Tanaka,[11] K. Tanaka,[29] M. Tanaka,[20] S.B. Thomas,[1] G.B. Thomson,[1] P. Tinyakov,[30,16] I. Tkachev,[16] H. Tokuno,[3] T. Tomida,[31] S. Troitsky,[16] Y. Tsunesada,[3] K. Tsutsumi,[3] Y. Uchihori,[32] S. Udo,[12] F. Urban,[30] G. Vasiloff,[1] T. Wong,[1] R. Yamane,[11] H. Yamaoka,[20] K. Yamazaki,[28] J. Yang,[4] K. Yashiro,[6] Y. Yoneda,[11] S. Yoshida,[18] H. Yoshii,[33] R. Zollinger,[1] and Z. Zundel[1]

[1] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
[2] *The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan*
[3] *Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[4] *Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaaemun-gu, Seoul, Korea*
[5] *Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea*
[6] *Department of Physics, Tokyo University of Science, Noda, Chiba, Japan*
[7] *Department of Physics, Kinki University, Higashi Osaka, Osaka, Japan*
[8] *Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea*
[9] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[10] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Chiba, Japan*
[11] *Graduate School of Science, Osaka City University, Osaka, Osaka, Japan*
[12] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[13] *Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan*
[14] *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan*
[15] *Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan*
[16] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[17] *Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan*
[18] *Department of Physics, Chiba University, Chiba, Chiba, Japan*
[19] *Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea*
[20] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan*
[21] *Faculty of Science, Kochi University, Kochi, Kochi, Japan*
[22] *Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan*
[23] *Department of Physics, Kyushu University, Fukuoka, Fukuoka, Japan*
[24] *Engineering Science Laboratory, Chubu University, Kasugai, Aichi, Japan*
[25] *Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon, Korea*
[26] *Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow, Russia*
[27] *Department of Physics and Astronomy, Rutgers University – The State University of New Jersey, Piscataway, New Jersey, USA*
[28] *Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[29] *Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan*
[30] *Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium*
[31] *Department of Computer Science and Engineering, Shinshu University, Nagano, Nagano, Japan*
[32] *National Institute of Radiological Science, Chiba, Chiba, Japan*
[33] *Department of Physics, Ehime University, Matsuyama, Ehime, Japan*

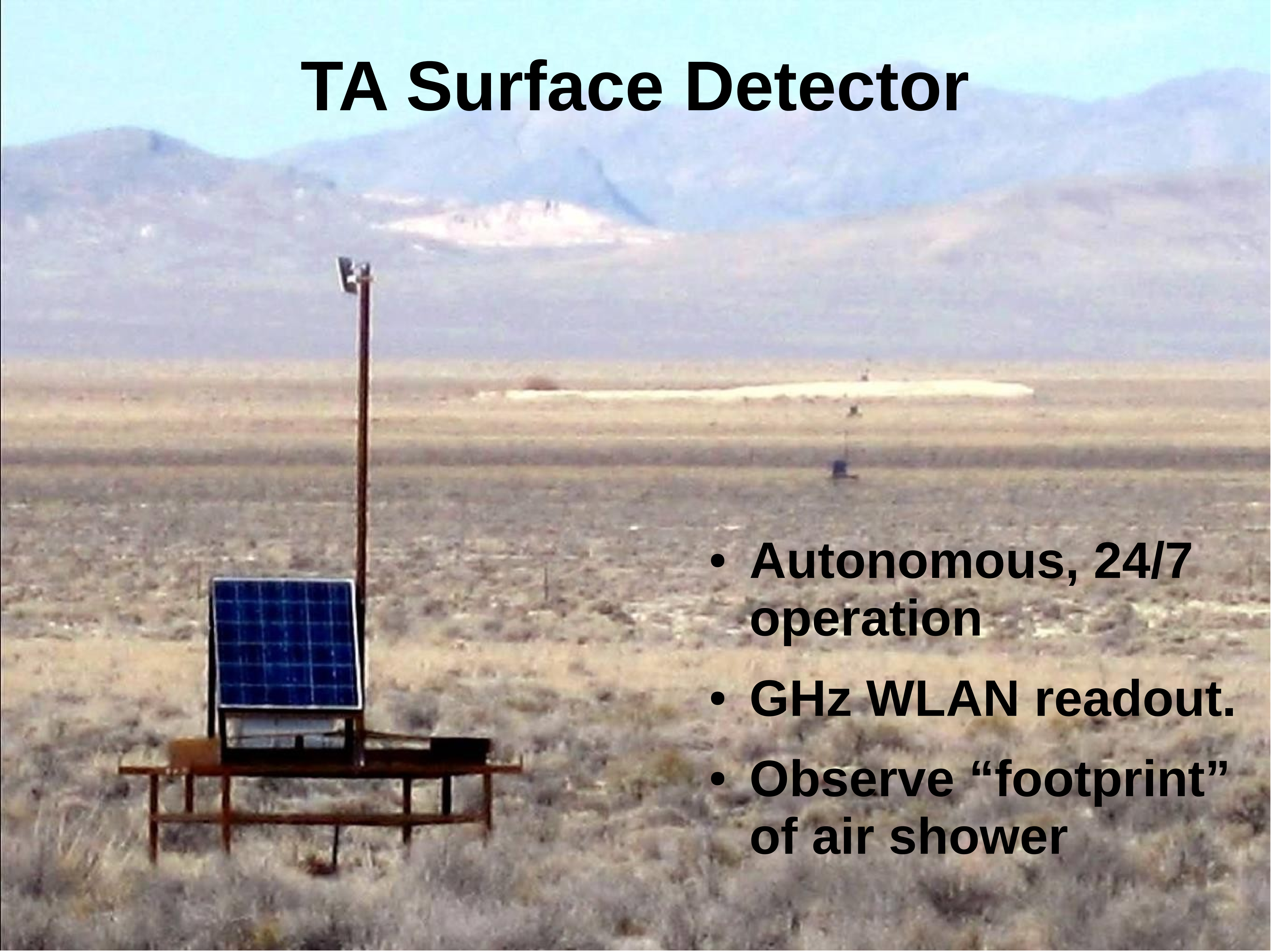
The Telescope Array Collaboration

Telescope Array Observatory

- Surface Detector (SD): 507 scintillation detectors, 1.2 km grid, covering 700 km^2.
- Fluorescence Detector (FD): 3 stations overlooking SD array.
- "Hybrid" operation since March 2008



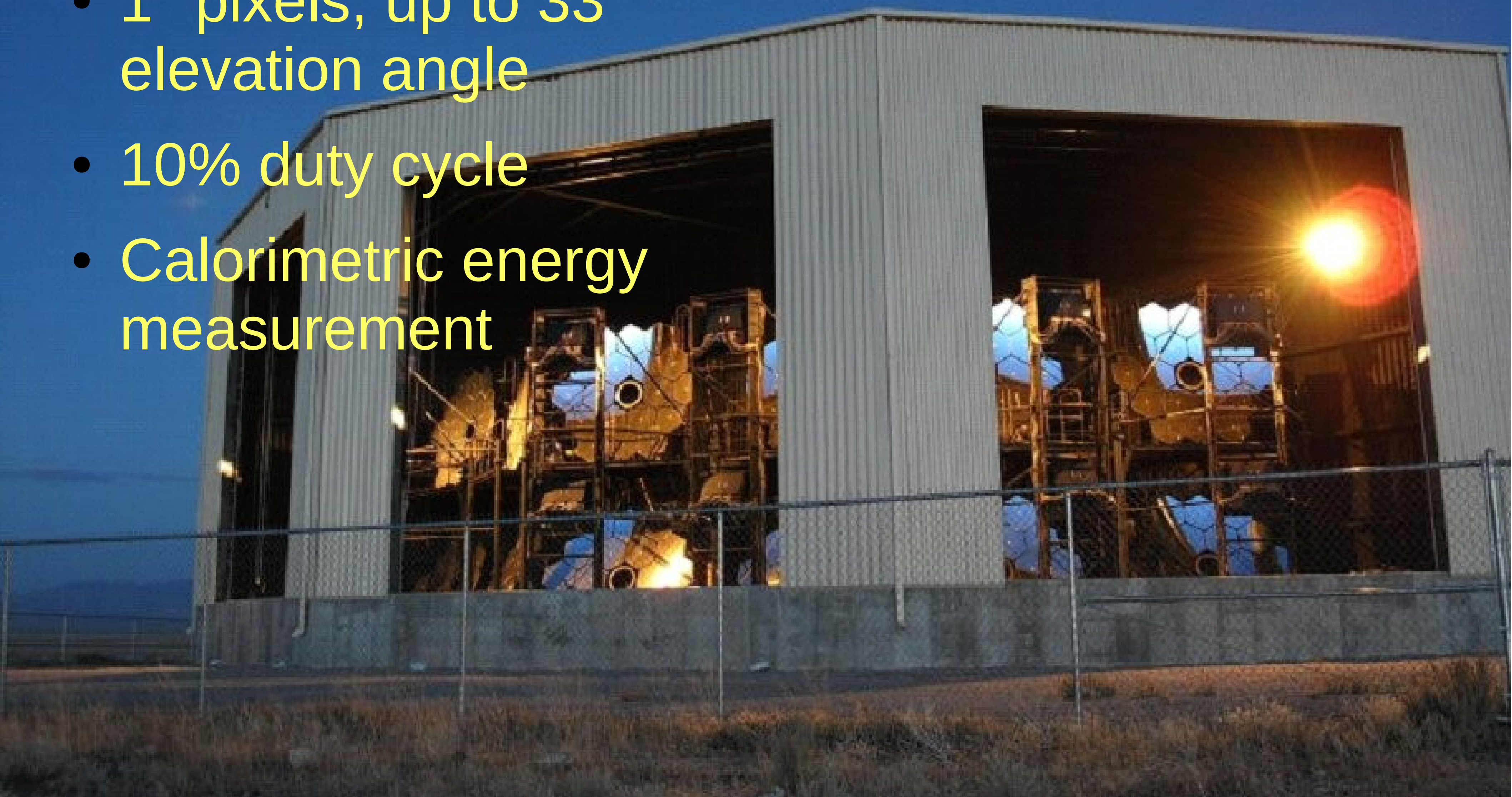
TA Surface Detector



- **Autonomous, 24/7 operation**
- **GHz WLAN readout.**
- **Observe “footprint” of air shower**

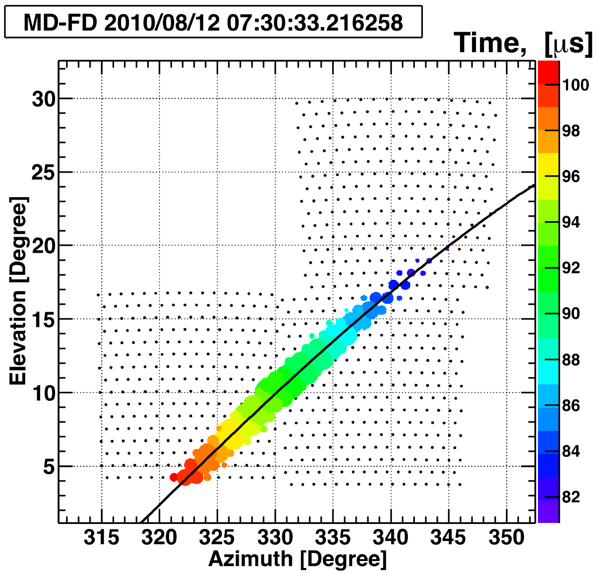
TA Fluorescence Detectors

- Sensitive to near-UV
- 1° pixels, up to 33° elevation angle
- 10% duty cycle
- Calorimetric energy measurement

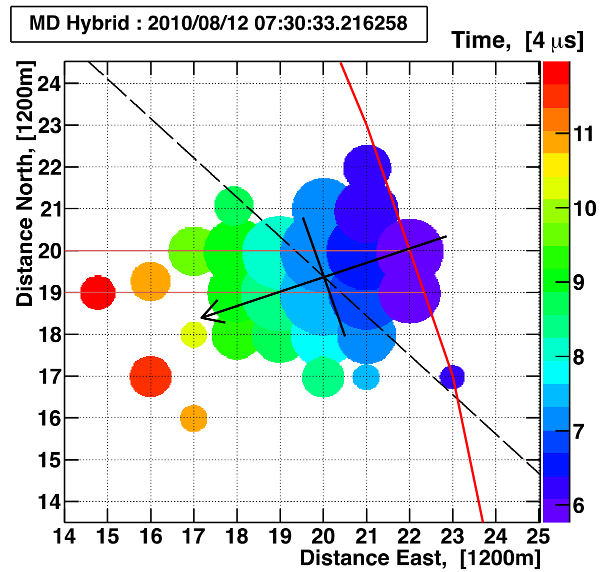


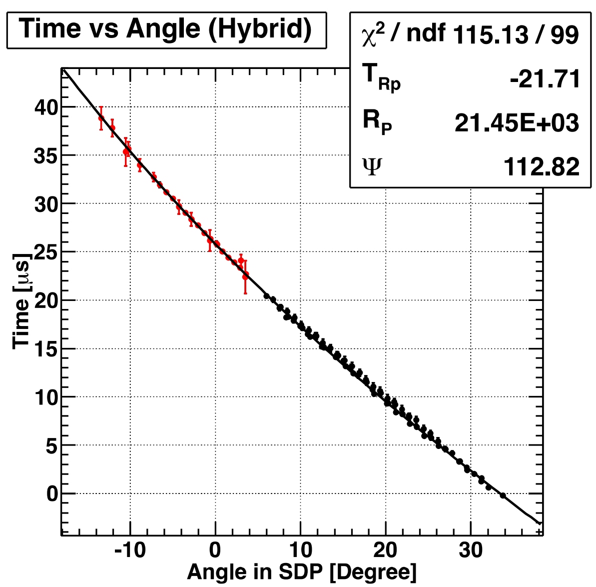
"Hybrid" Event Reconstruction

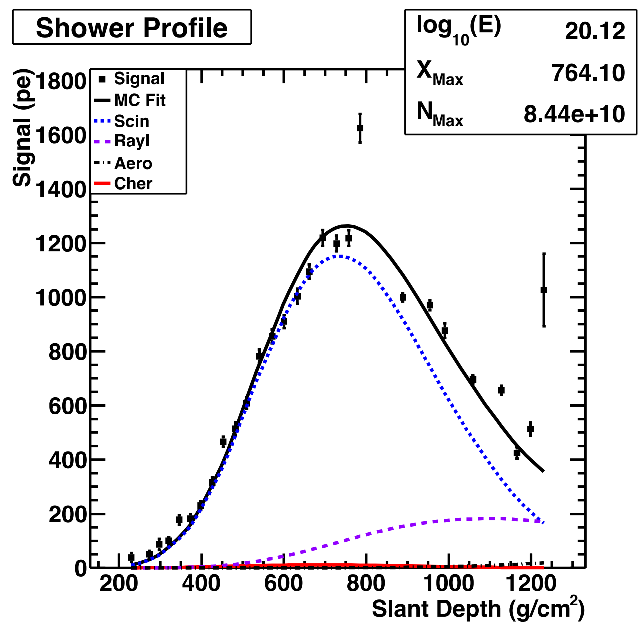
Fluorescence Detector



Surface Scintillator Detector

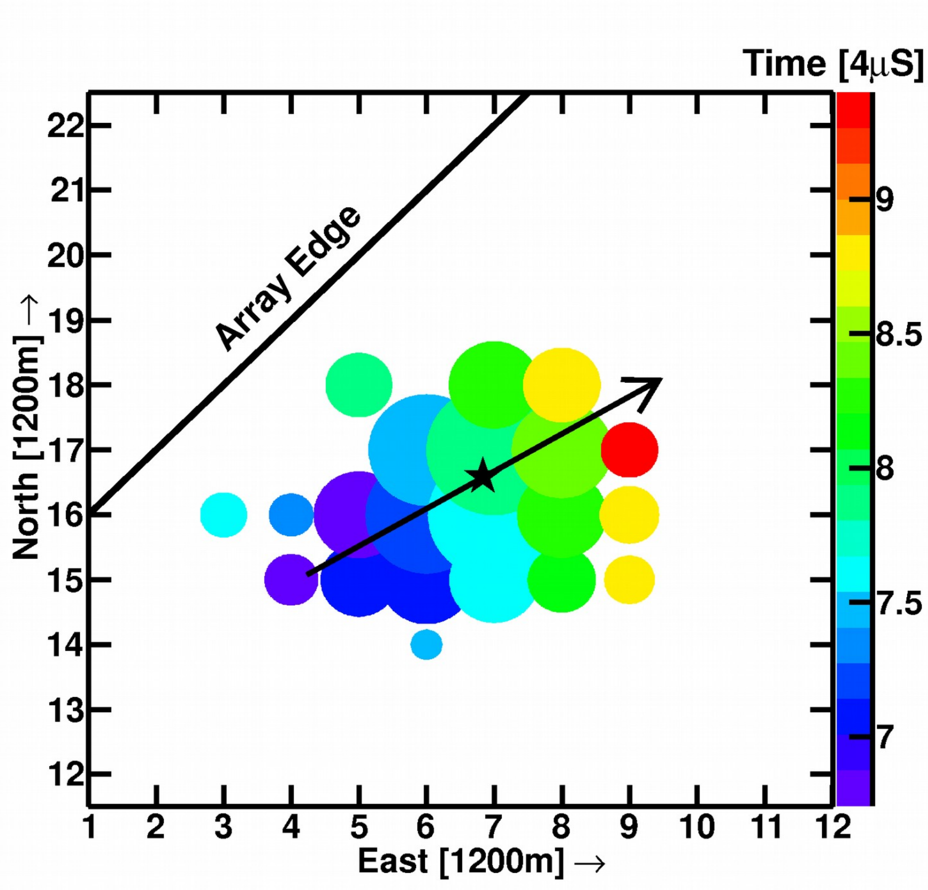




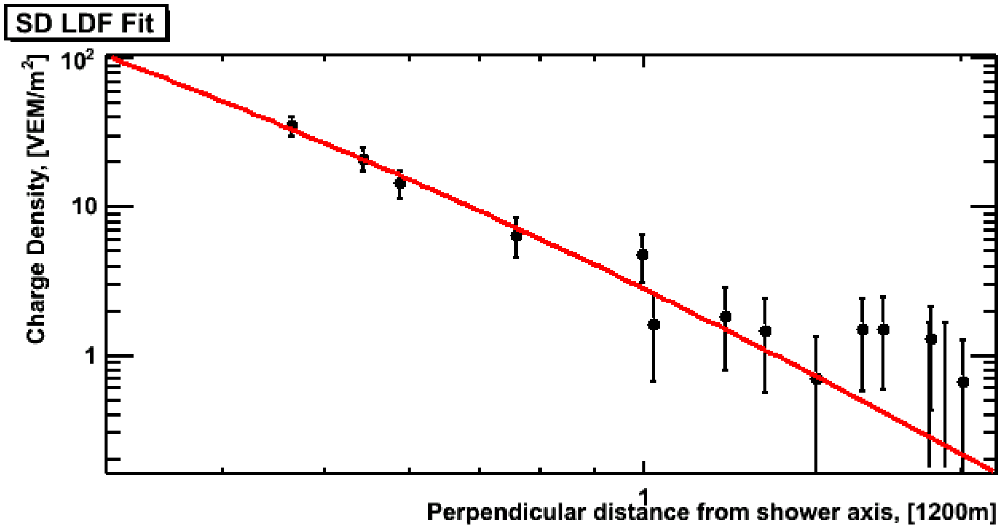


- Shower-detector plane (FD)
- Shower core location (SD)
- Timing fit provides geometry
- Fit profile to determine E, X_{max}
- **E = 1.3 x 10^{20} eV**

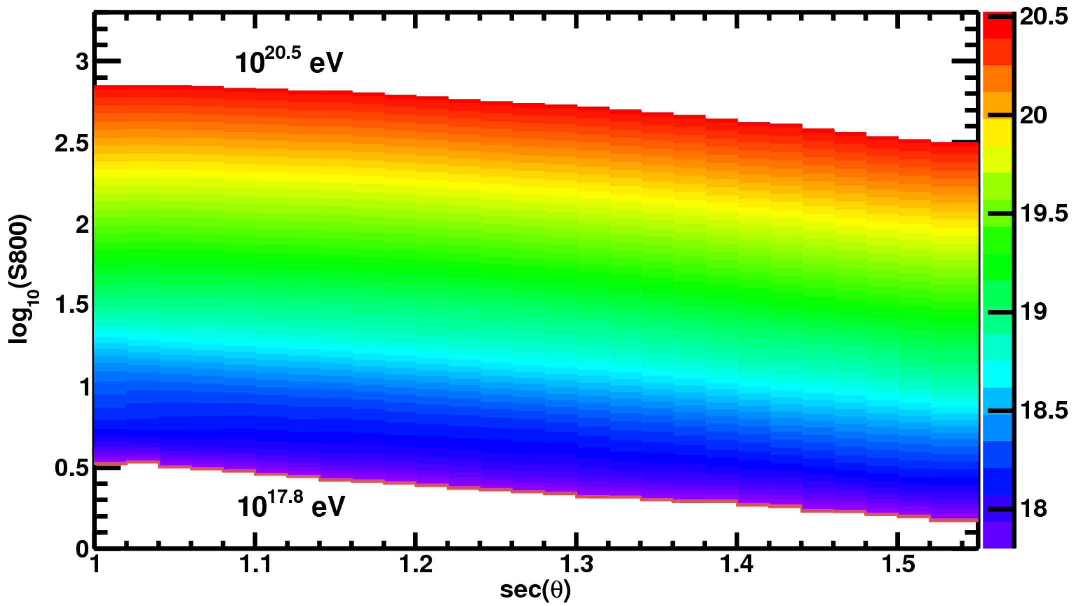
TA Surface Detector: Reconstruction



Overhead "Hit Map"



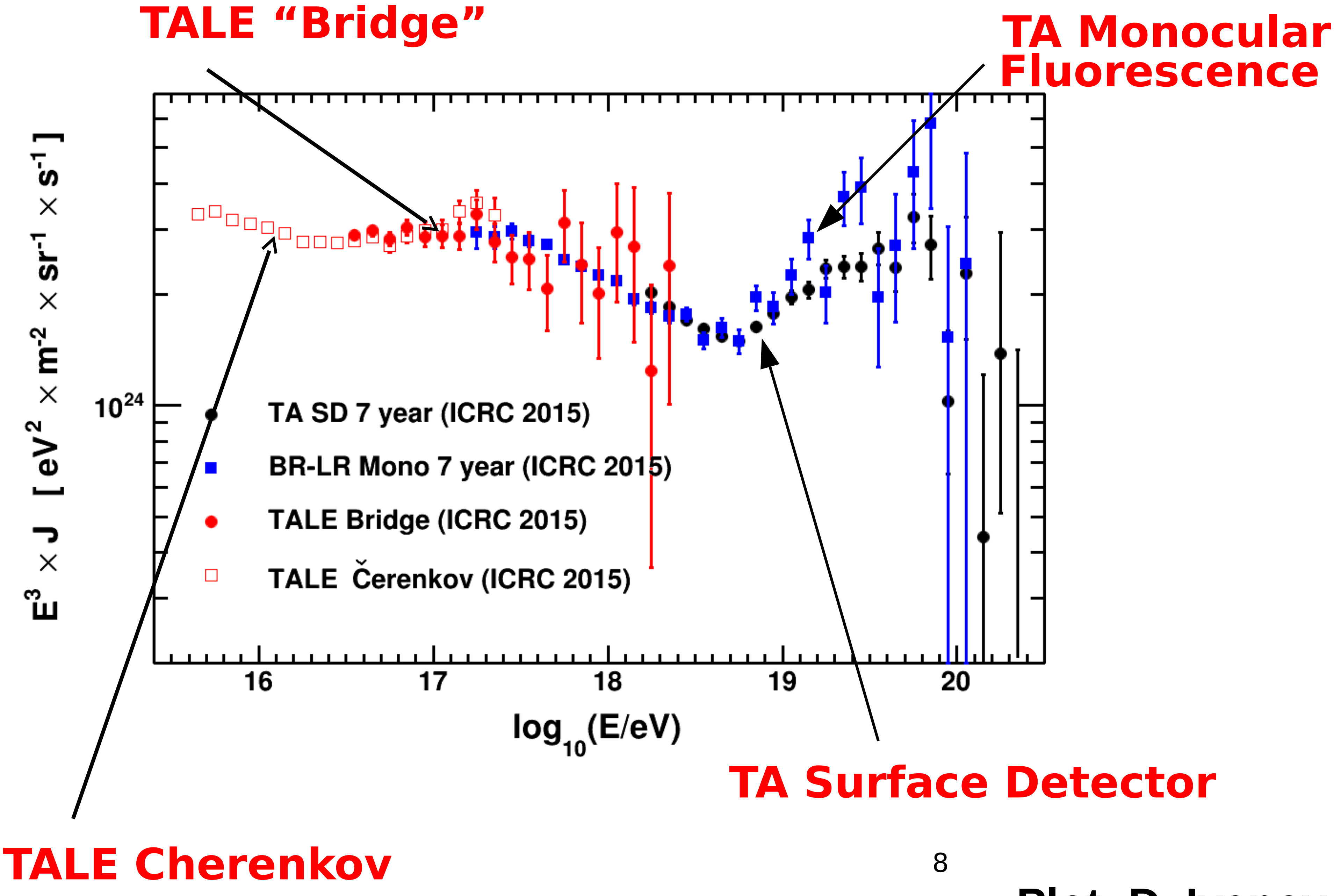
Lateral Distribution Fit



Energy look-up table (MC)

Final step: 27% correction to lock SD & FD energy scales

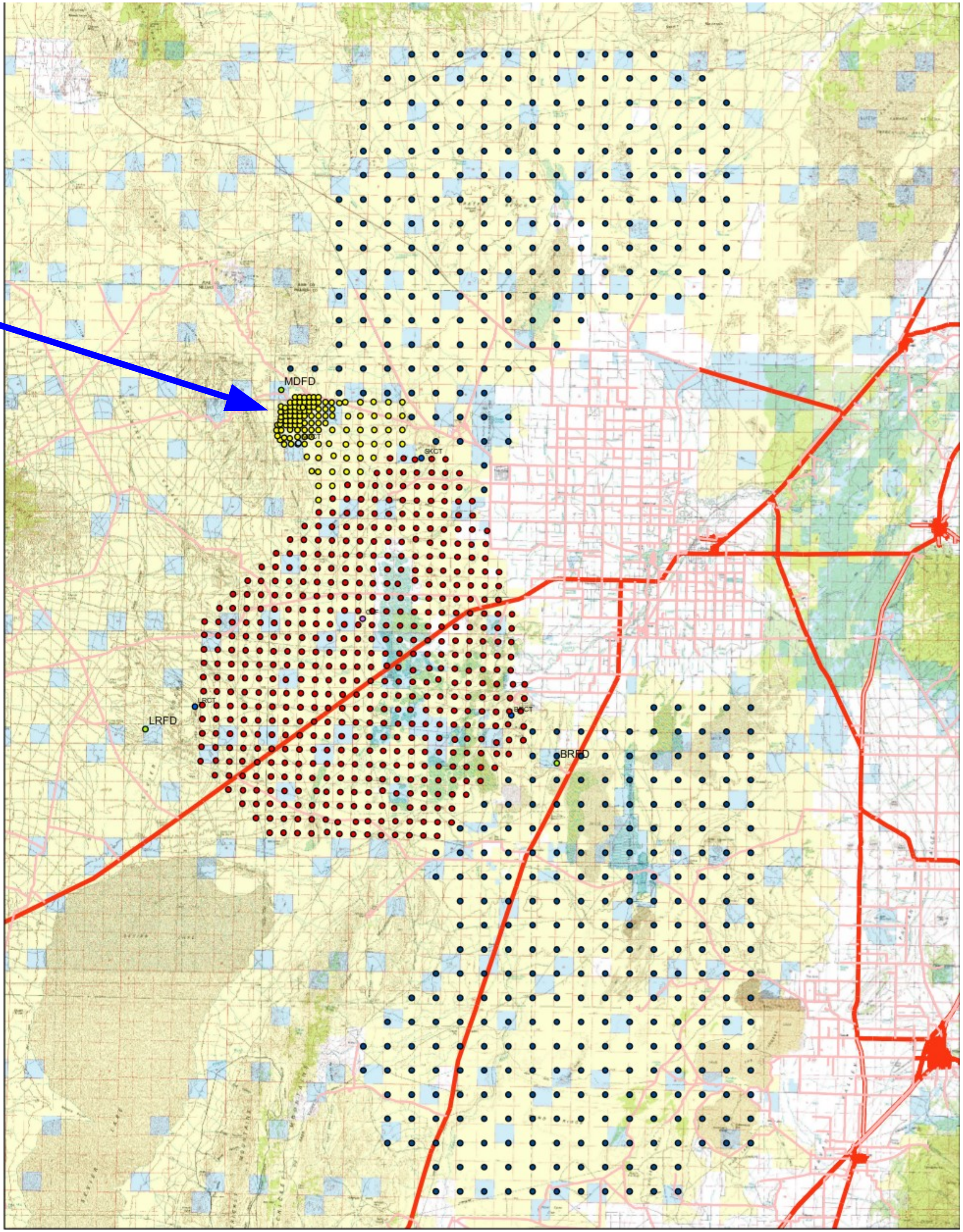
TA Energy Spectrum



Plot: D. Ivanov

TA Upgrades

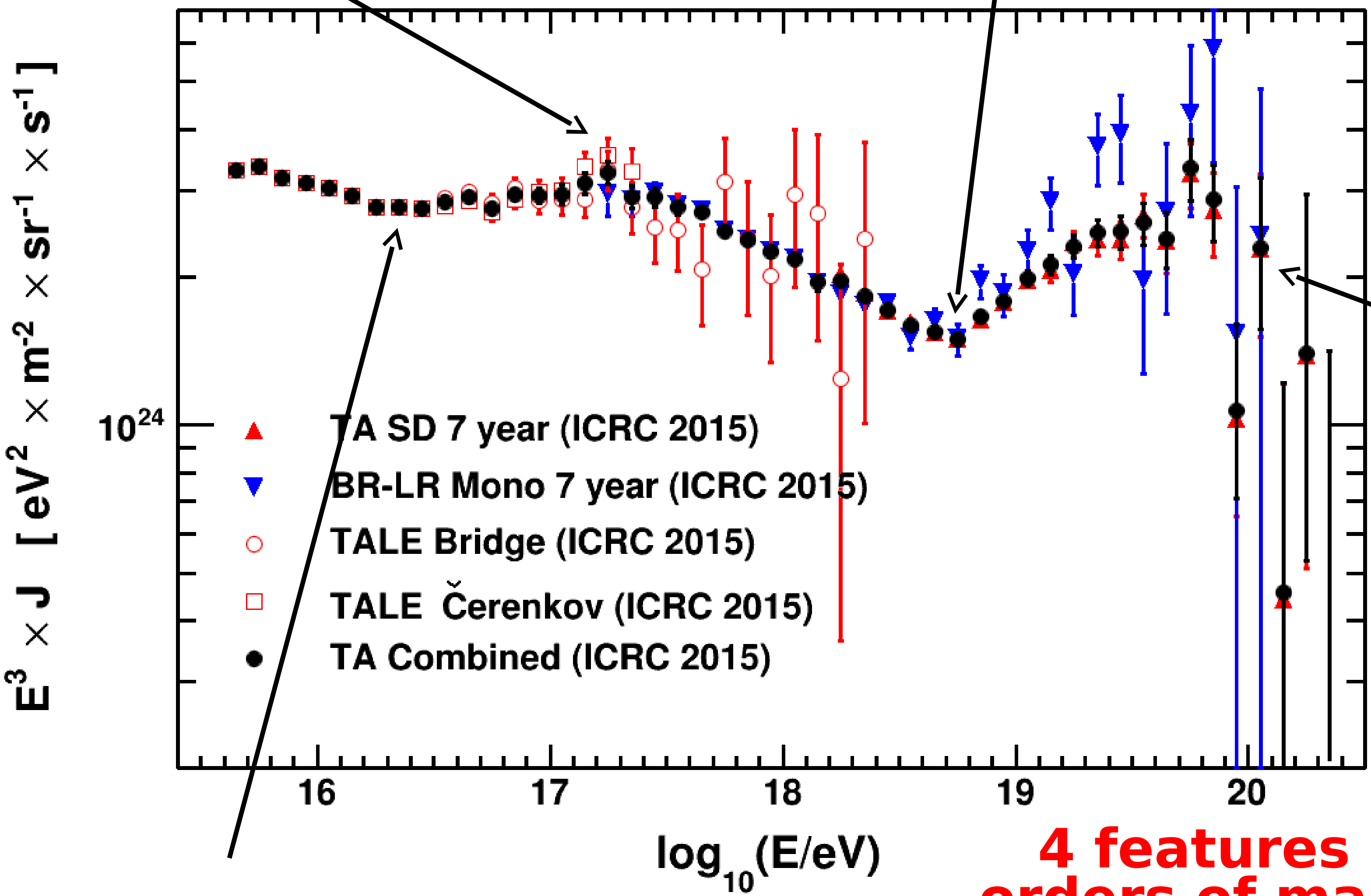
- Low-energy extension; TALE



Combined TA Spectrum

“2nd knee” at E = $10^{17.3}$ eV

“Ankle” at E = $10^{18.72}$ eV



GZK Break at $10^{19.8}$ eV

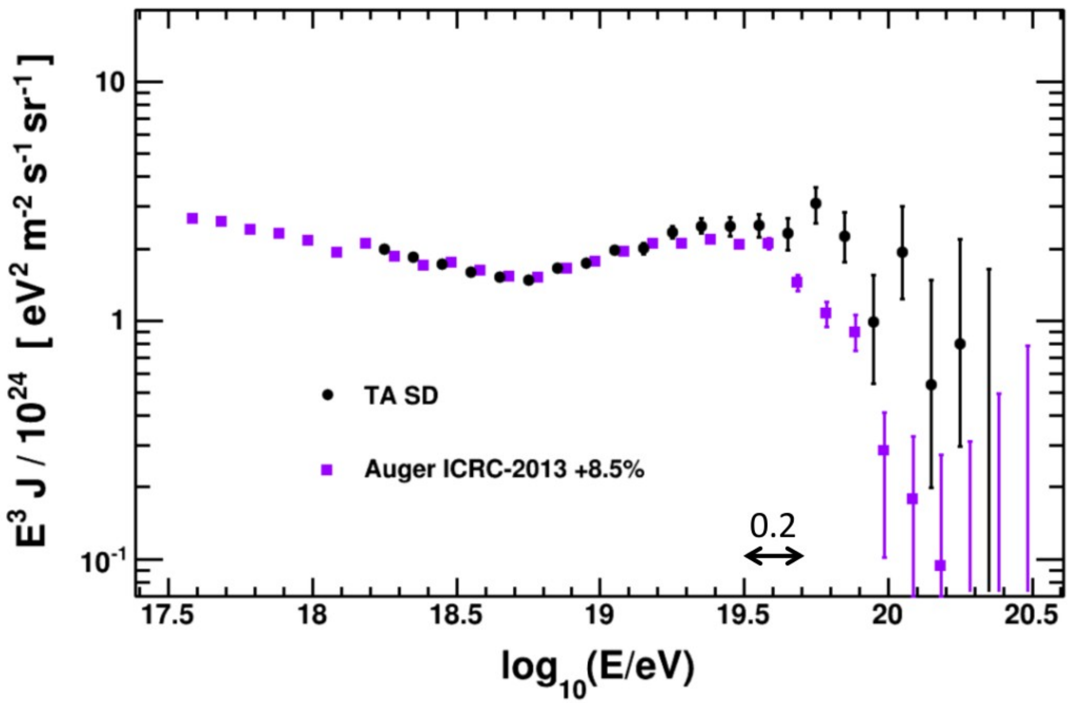
“Low” energy dip at $10^{16.34}$ eV

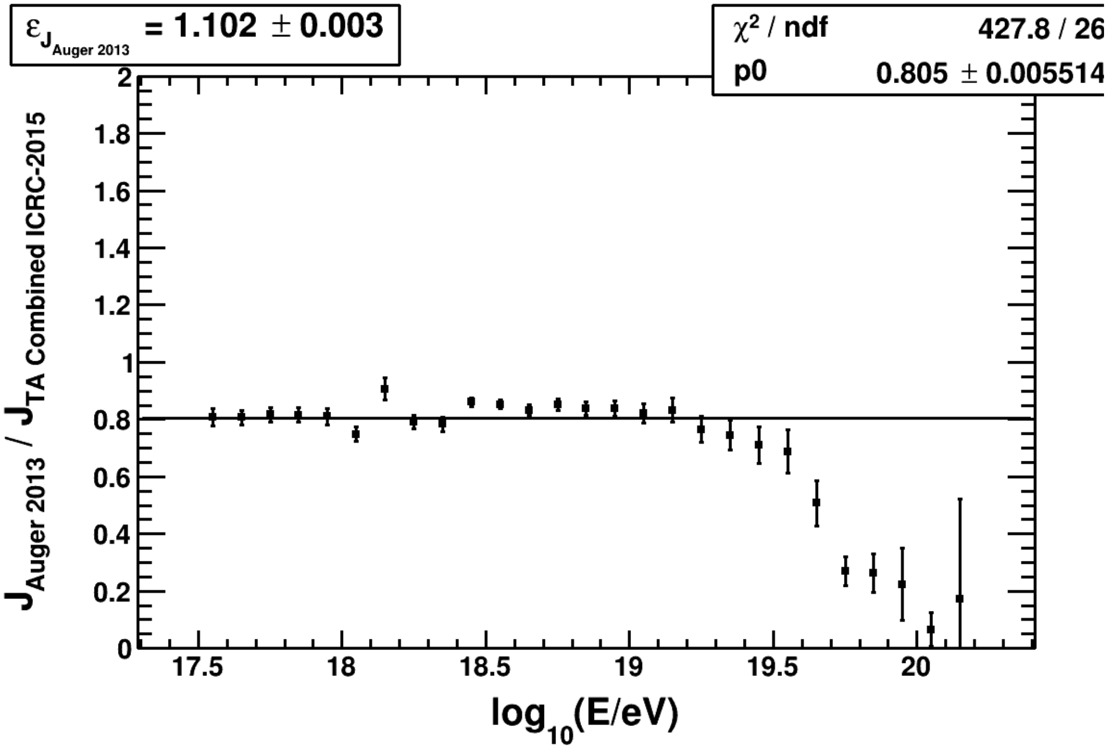
4 features over 4.7 orders of magnitude in energy

Plot: D. Ivanov

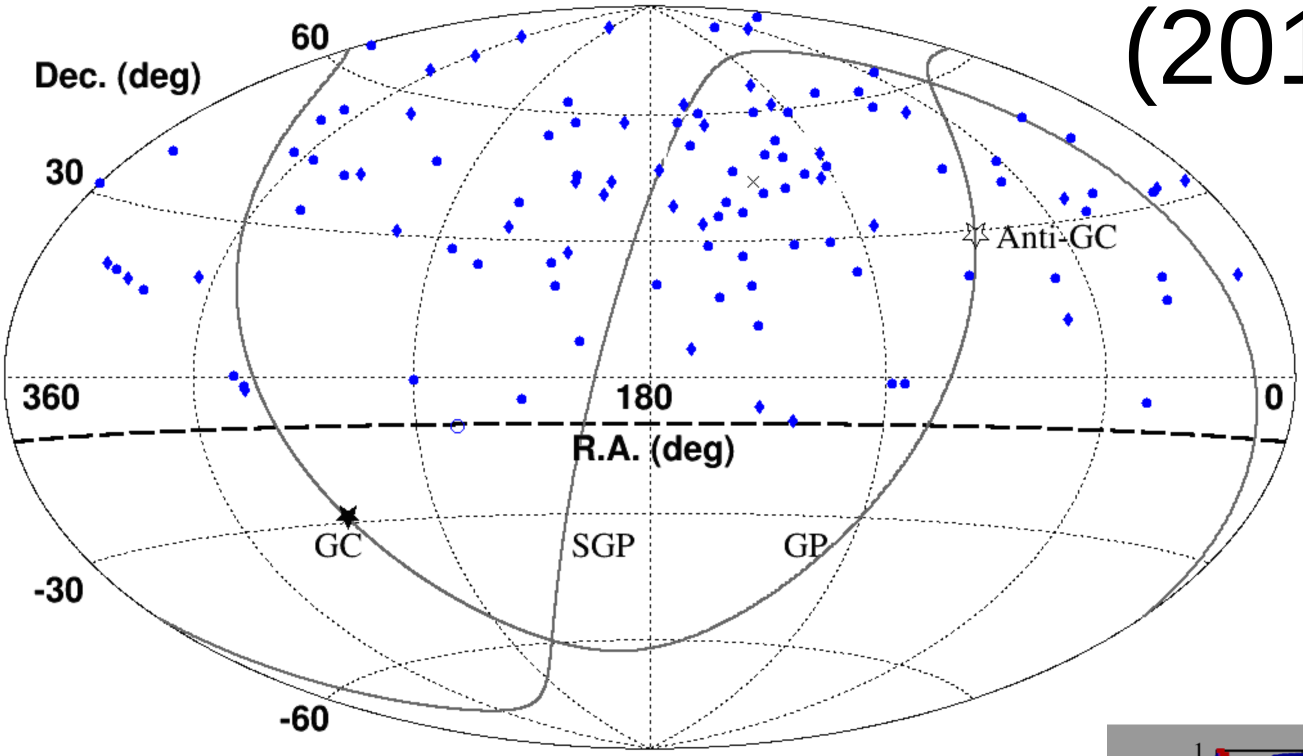
Compare w/ Southern Hemisphere

- 8.5% energy scaling brings TA/Auger into agreement at low energy.
- Disagree above log(E/eV) = 19.3.
- North/South difference?





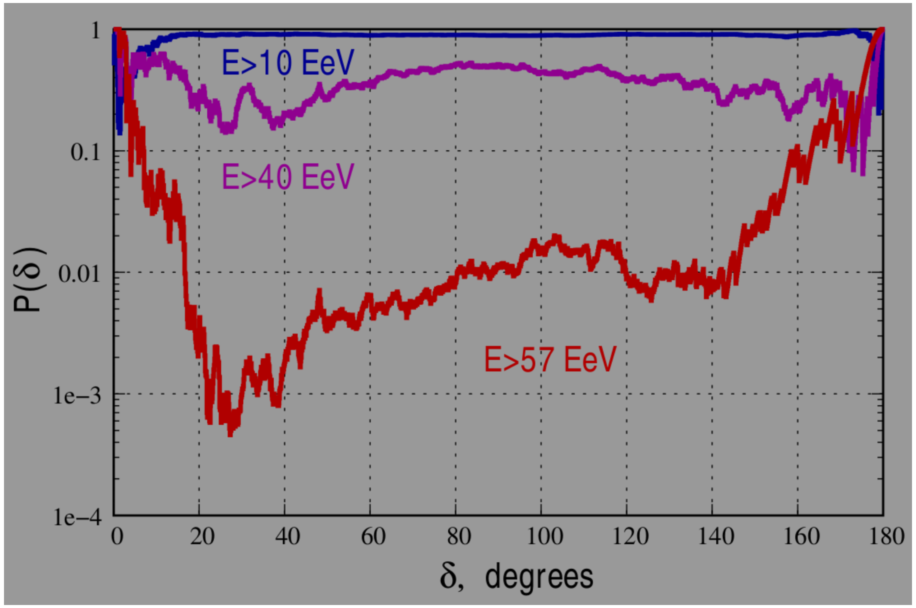
7 Year TA Skymap (2015), E > 57 EeV



Plot: K. Kawata.

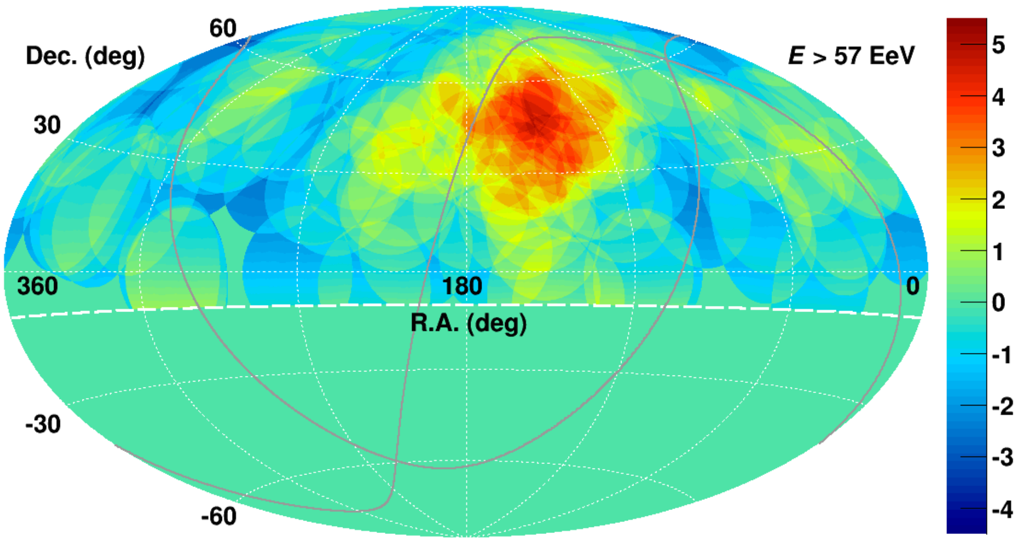
Indications of Intermediate Scale Anisotropy...,
R. Abbasi et al, ApJ Lett (2014).

Observation with 3.4 σ significance

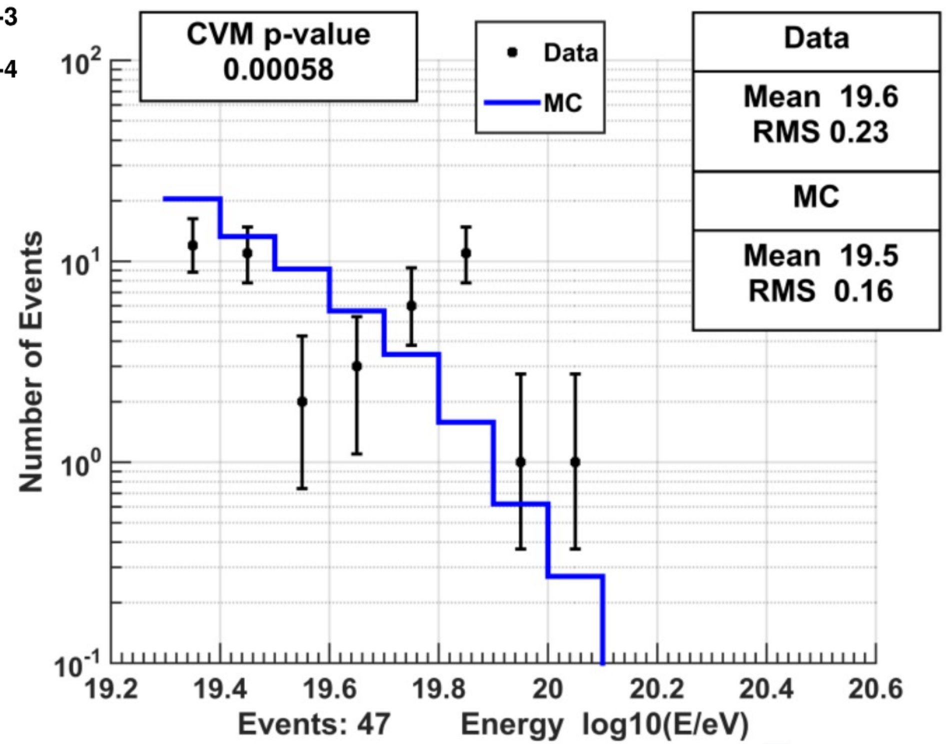


P. Tinyakov et al, ICRC 2015.

Energy Spectrum Anisotropy



“Hotspot” in TA data above 57 EeV, 7-year data. (plot K. Kawata).

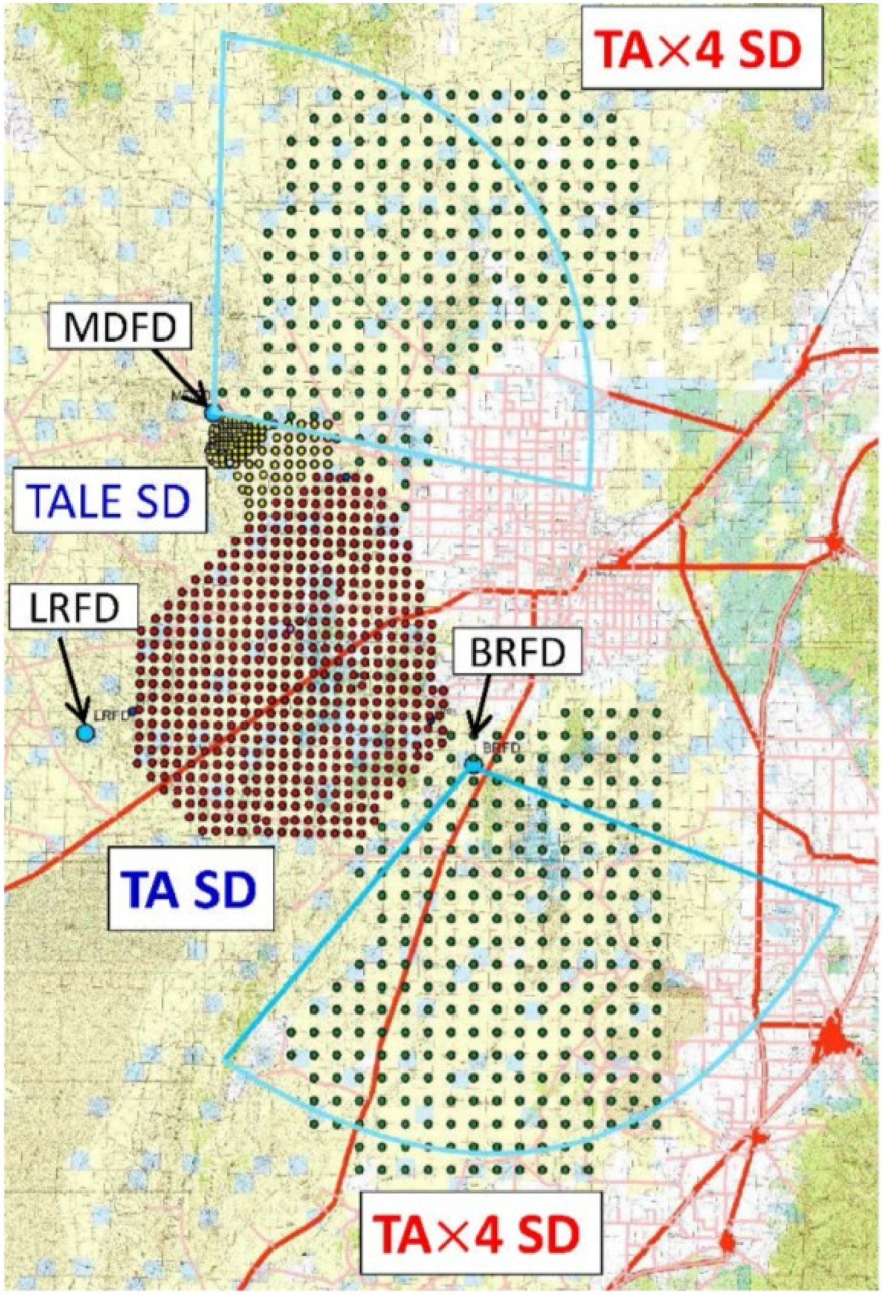


Data vs Monte Carlo Comparison.
Energy spectrum inside hotspot. Normalization is to data outside hotspot (J.P. Lundquist).

This appears to be a significant local difference in the energy spectrum. Very exciting if this persists!

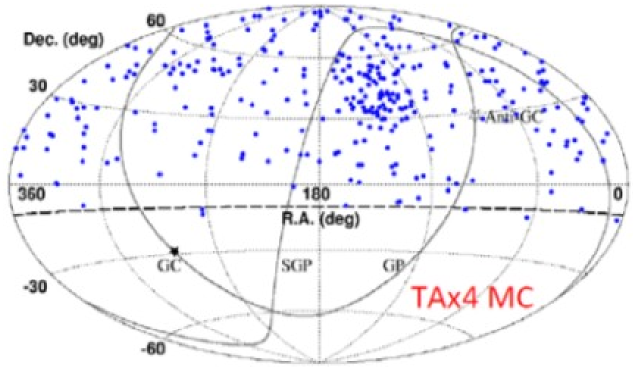
TA x 4 Project

- Quadruple TA SD (~3,000 km^2)
  - + 500 scintillator detectors
  - 2.08 km grid
- 2 new FD stations
- Funding
  - SD (Japan) Approved Summer 2015
  - FD (US) Approved Summer 2016
- Goal:
  - 19 years of TA SD data by 2020
  - 16 years TA hybrid data
- Construction underway!



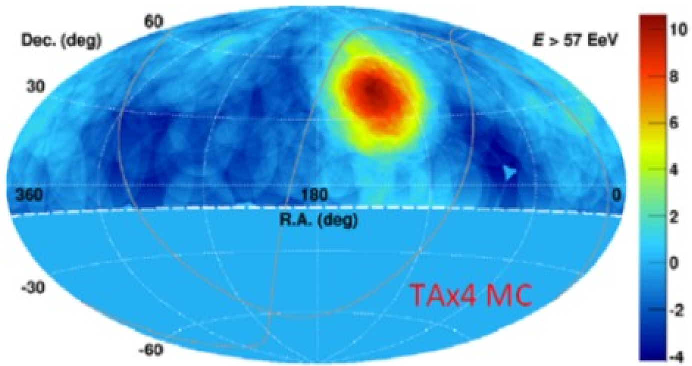
Hotspot
from TA 19 years of SD data by 2020

(1) One Hotspot



Hotspot Signal
80-18.9=61events
(RA, Dec)=(145°,45°)
Gaussian σ=10°

Isotropic B.G.
305-61=244events

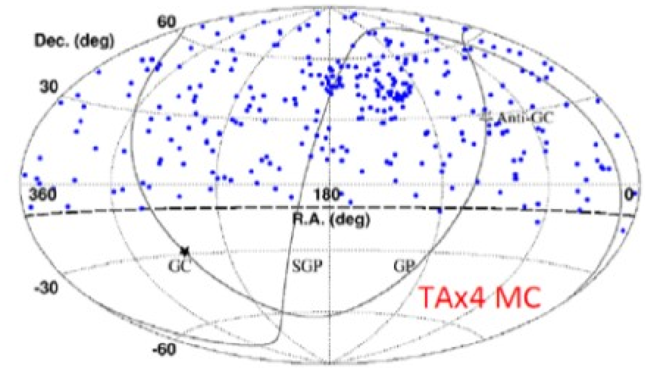


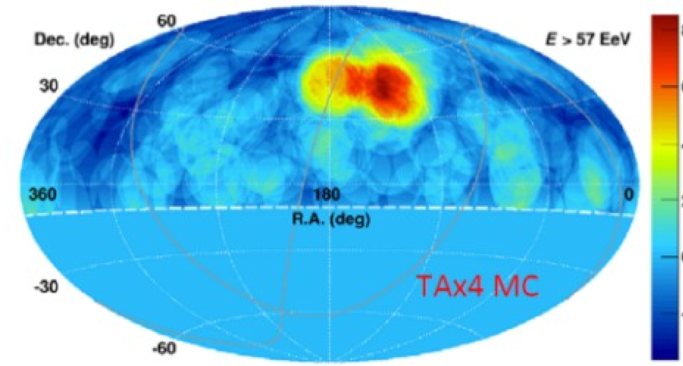
Oversampling
20° radius circle

(2) Double Hotspot

Hotspot Signal
Total 61 events
1. 41events
(RA, Dec)=(145°,40°)
Gaussian σ=10°
2. 20events
(RA, Dec)=(175°,40°)
Gaussian σ=5°

Isotropic B.G.
305-61=244events

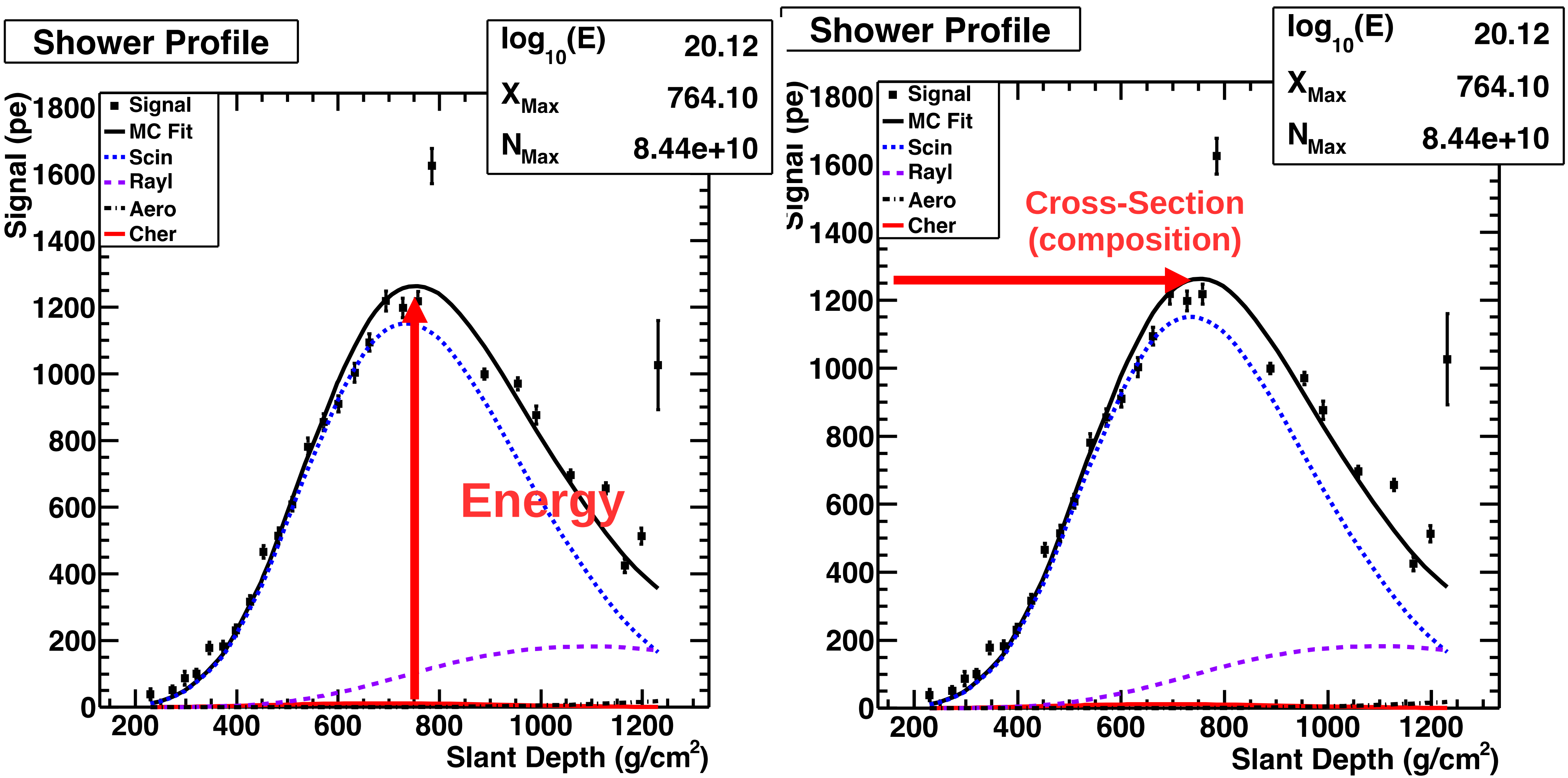




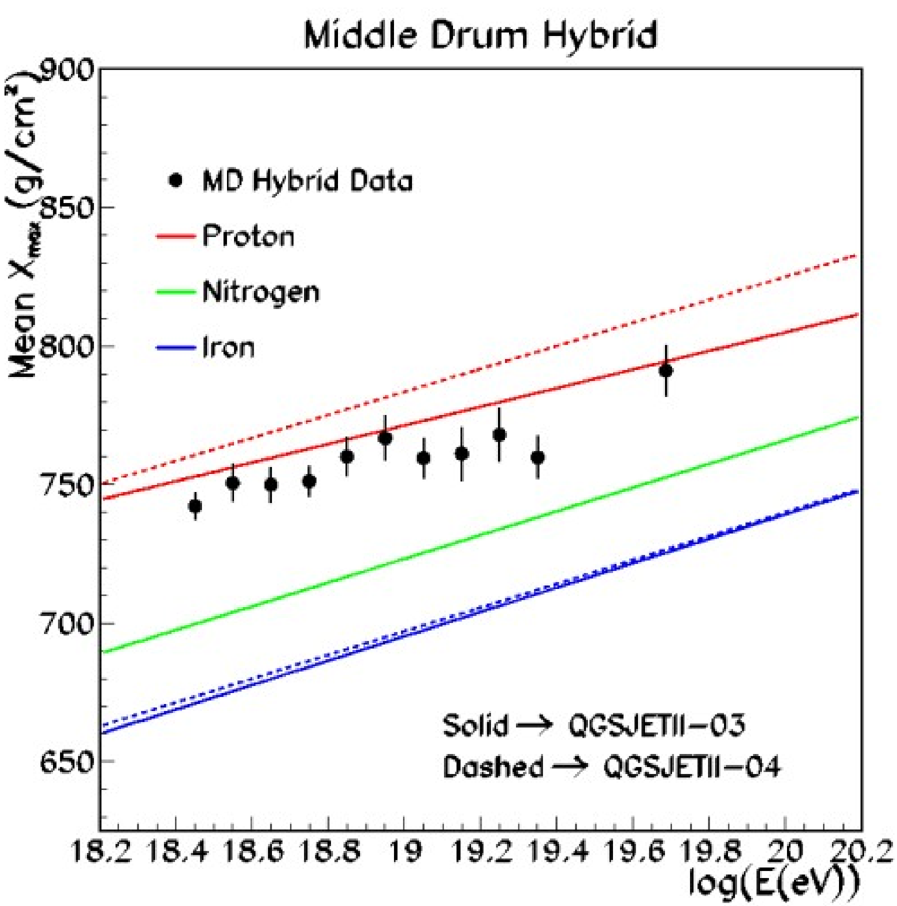
Oversampling
15° radius circle

TA×4 will clarify the nature of the hotspot

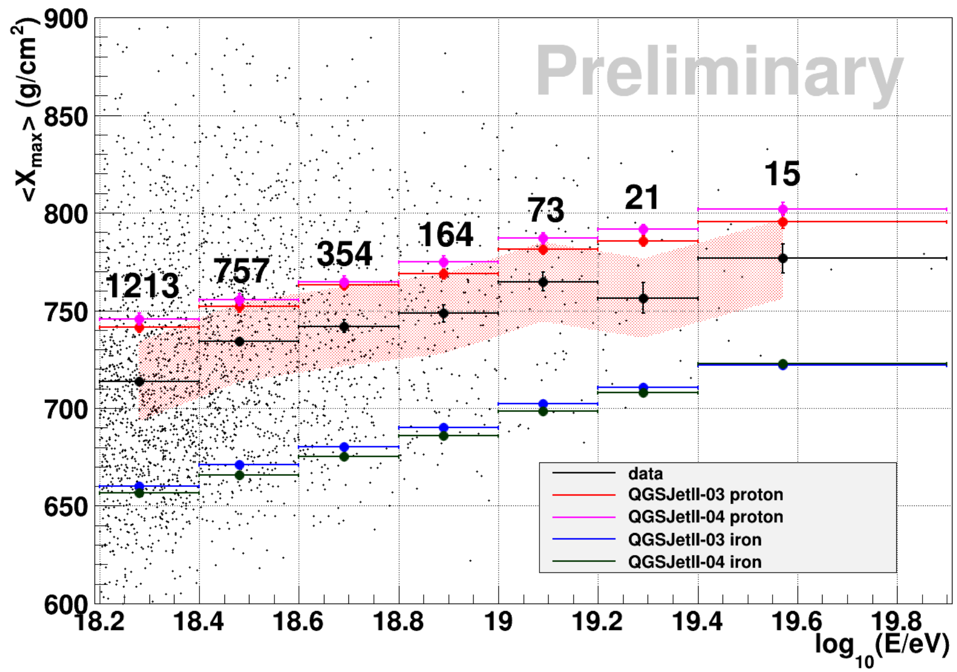
Primary Composition via Depth of Shower Maximum X_{max}



TA: Depth of Shower Maximum

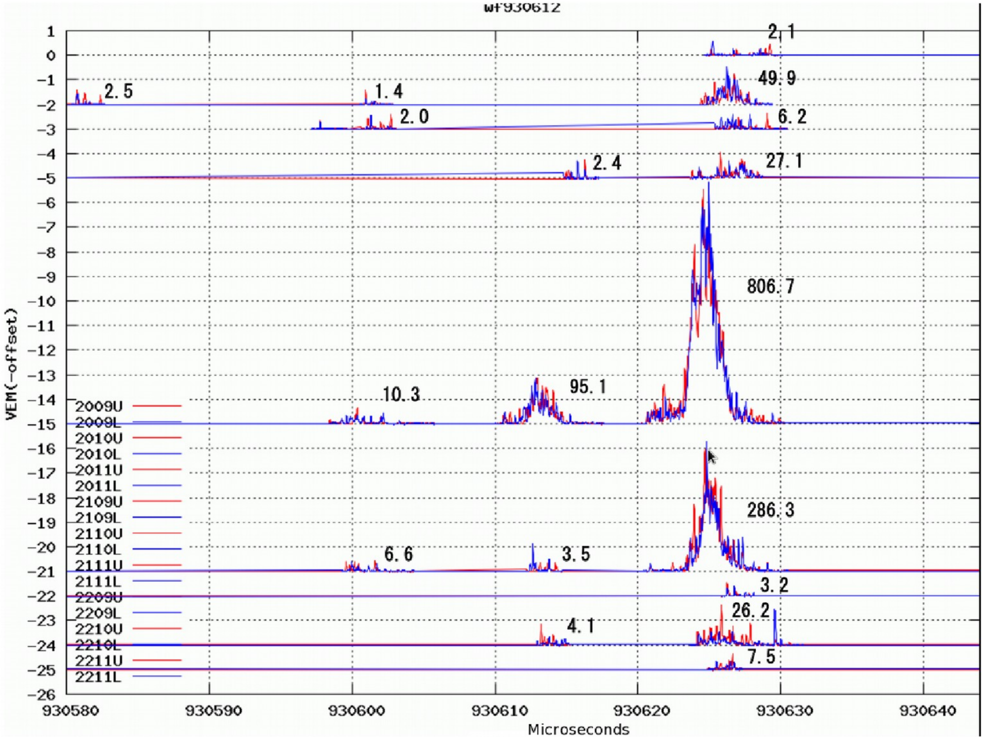


Telescope Array 2015
“Middle Drum” Hybrid Analysis

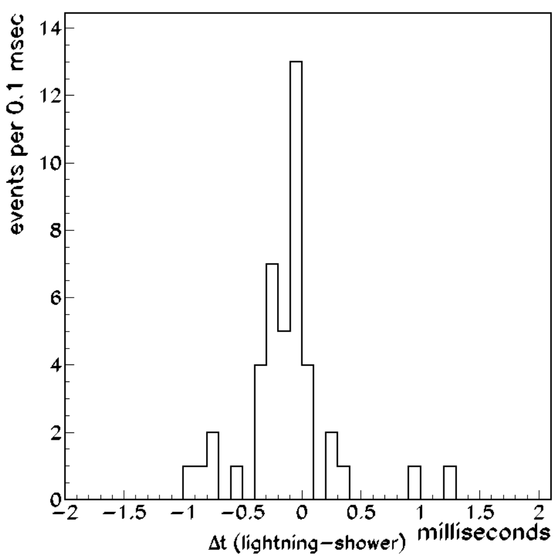


Telescope Array 2016
“Black Rock/Long Ridge” Hybrid Analysis

New TA Observation: "Burst" Events

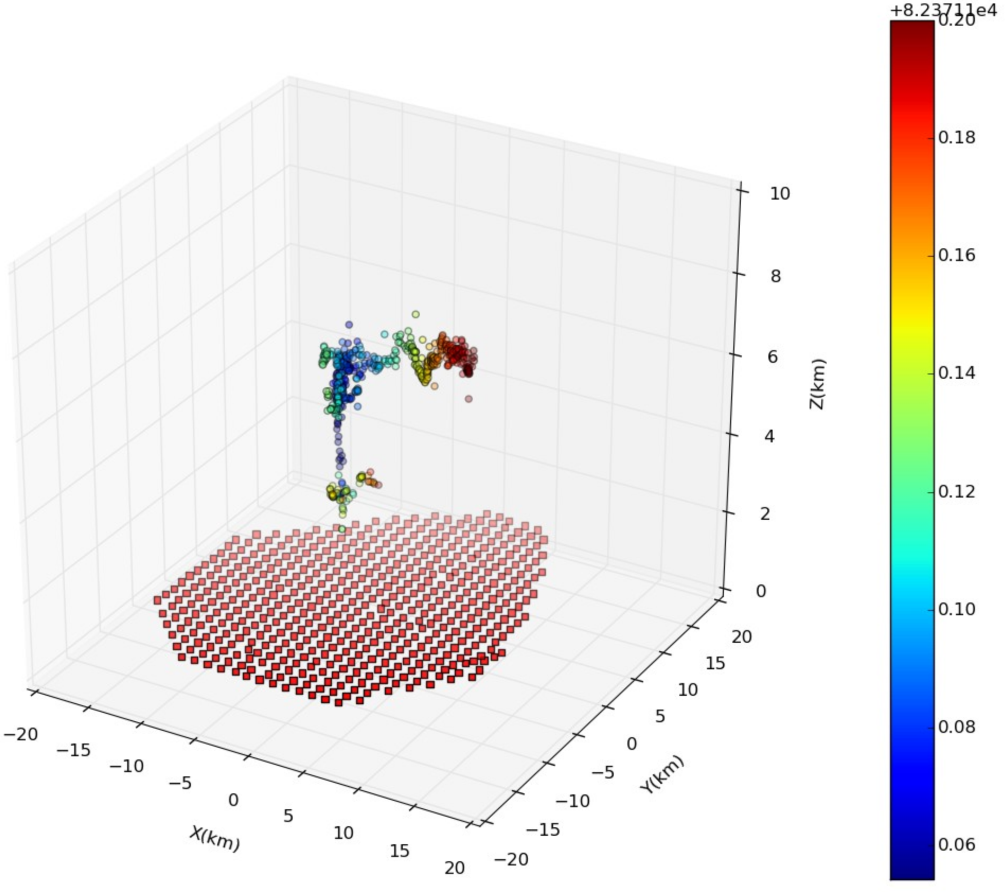


Plot: T. Okuda

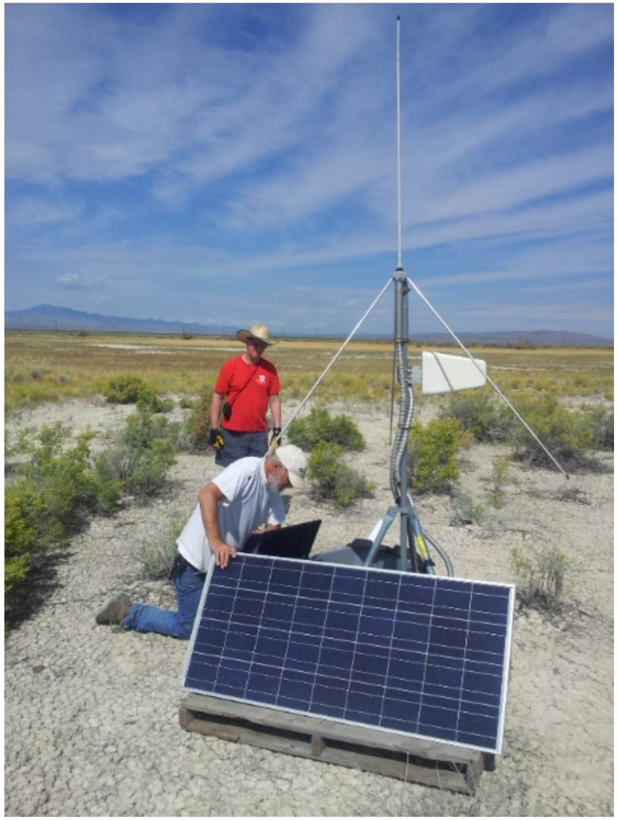


- 5 year data (2008-2013)
- 10 surface detector bursts seen
  - 3 or more SD triggers
  - Δt < 1 msec
  - Occasional Δt ~ 1 μsec
- "Normal" SD trigger rate < 0.01 Hz. *These cannot be cosmic ray air showers*.
- Found to have close temporal coincidence with *National Lightning Detection Network* (NLDN) activity.

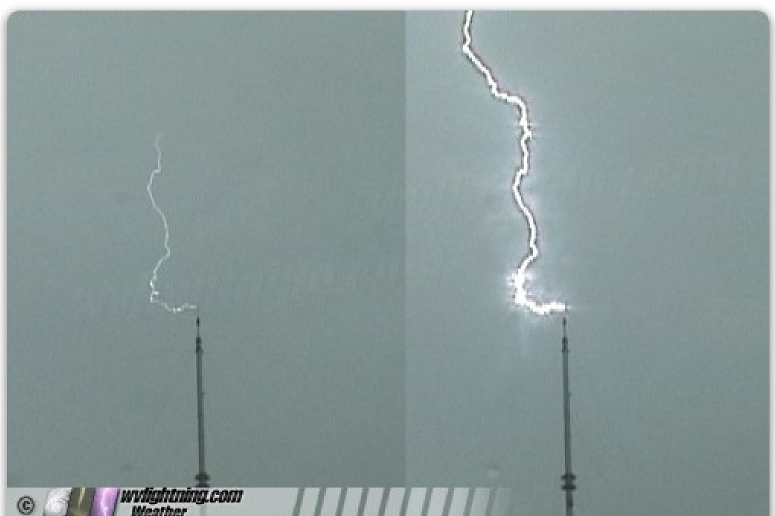
Study with "Lightning Mapping Array"



- Observe impulsive radiation from lightning at multiple sites
- Fit to find coordinates of impulse
- Sum to map lightning flash



Leaders Followed by Cloud-to-Ground Stroke

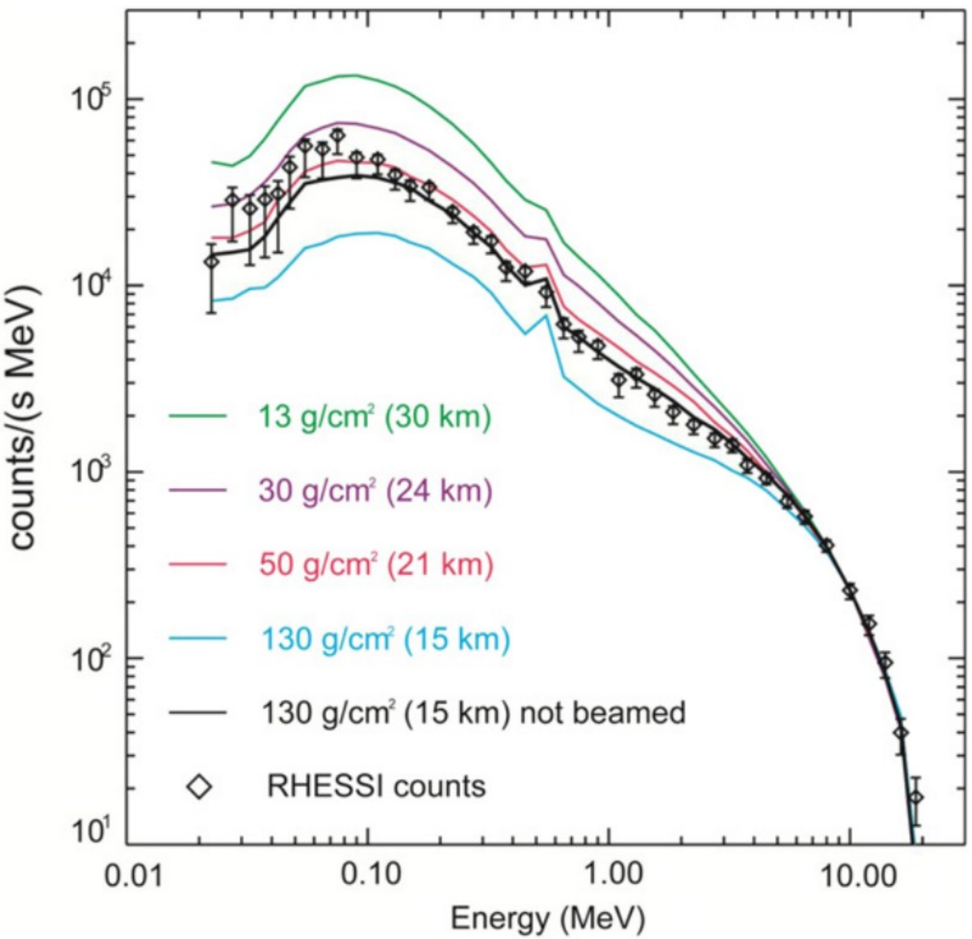


- "Leaders" (here upward) precede main flash.
- Responsible for current-carrying channel which is followed by flash.
- High potential gradients responsible for *Terrestrial Gamma Flashes* (TGFs)

http://www.stormhighway.com

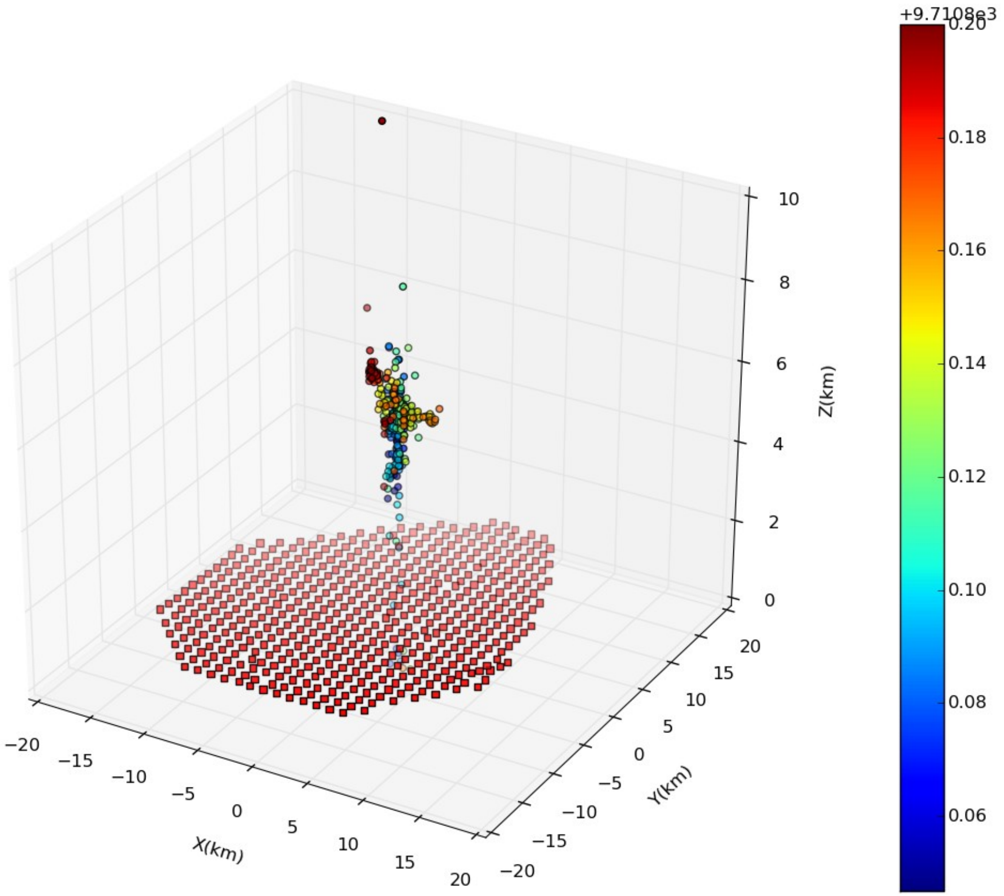
Terrestrial Gamma Flashes

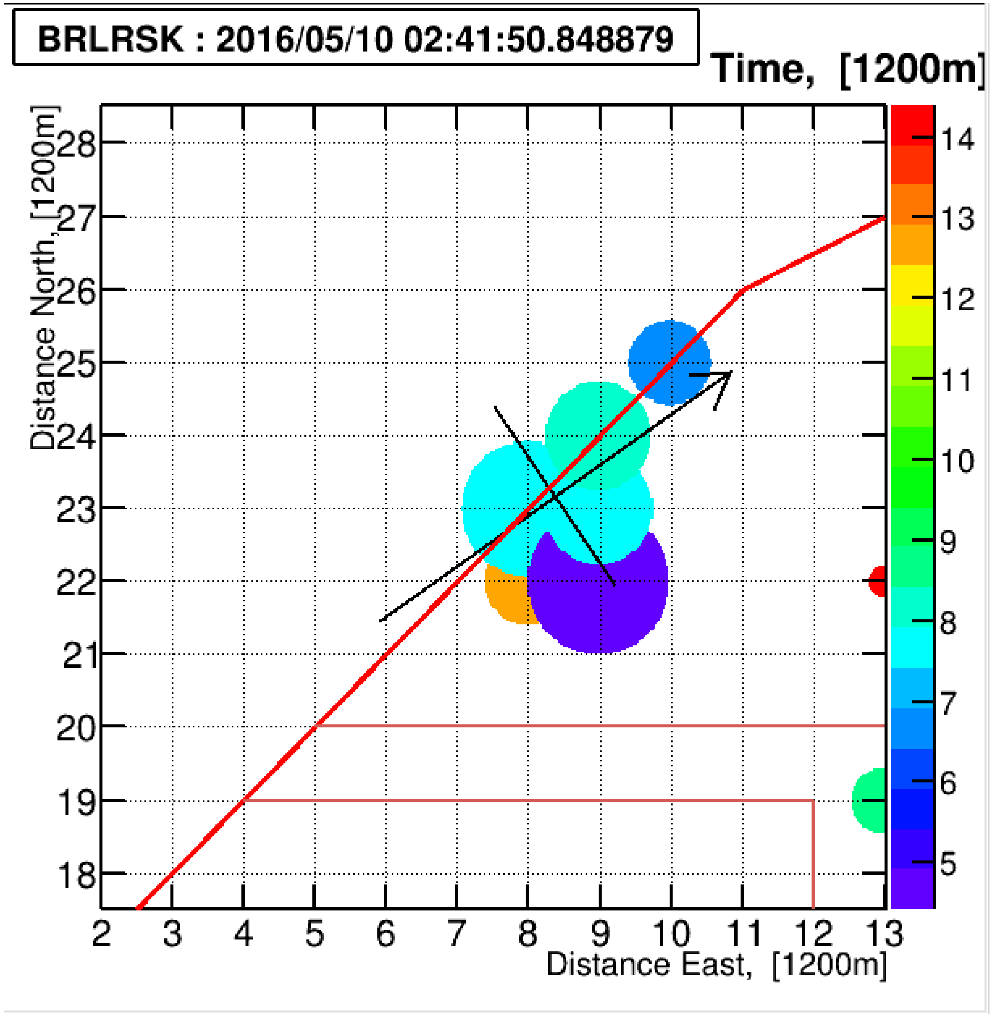
- Discovered with BATSE (CGRO) 1992
  - Assumed to arise from sprites
  - Now known to be associated with leader stage in intracloud discharges
- RHESSI (>2002) 805 TGFs
- Fermi Gamma Burst Monitor
- AGILE



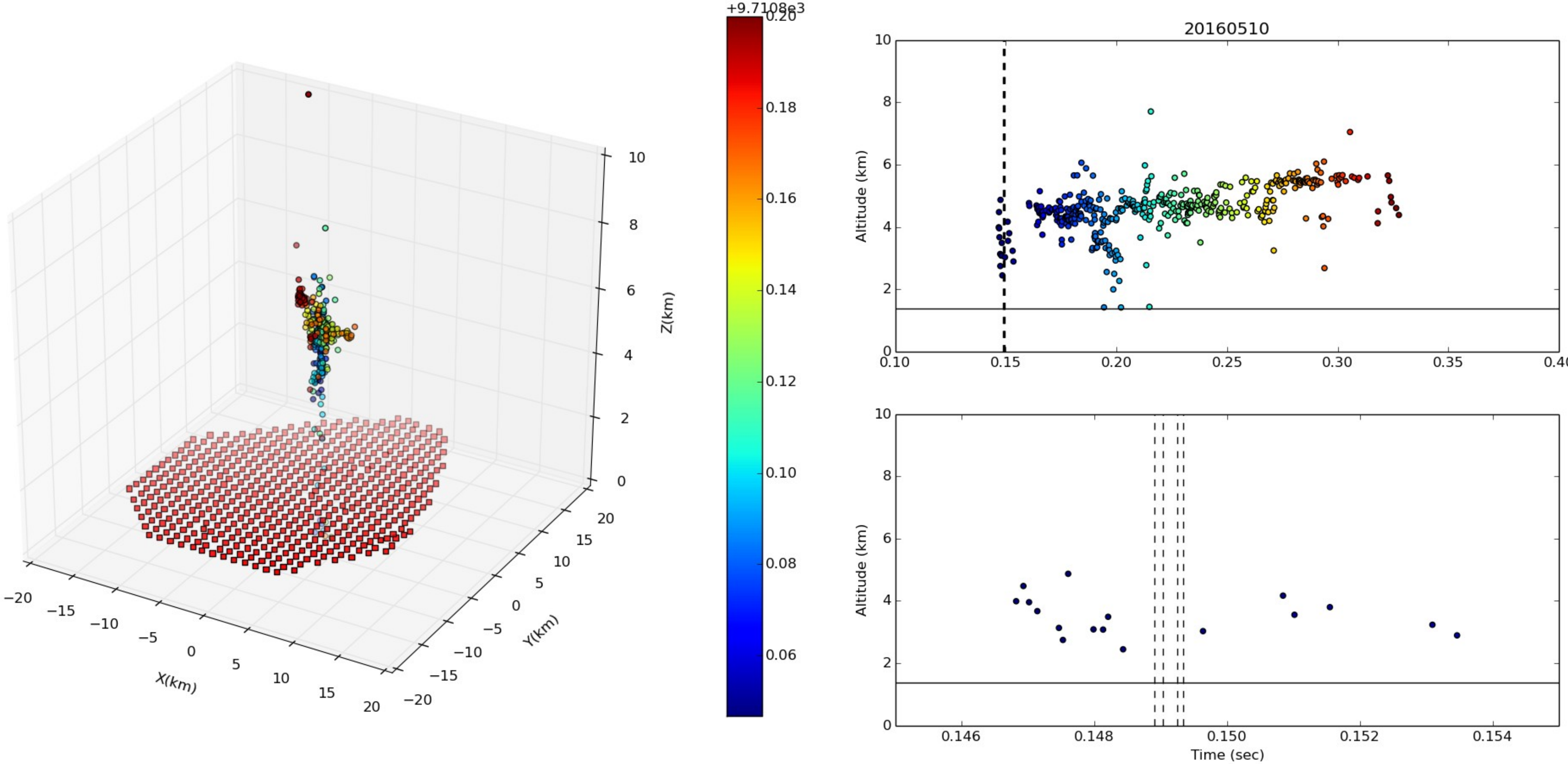
RHESSI TGF spectrum compared with various RREA models. (Dwyer et al 2005)

LMA Event 20160510-024150

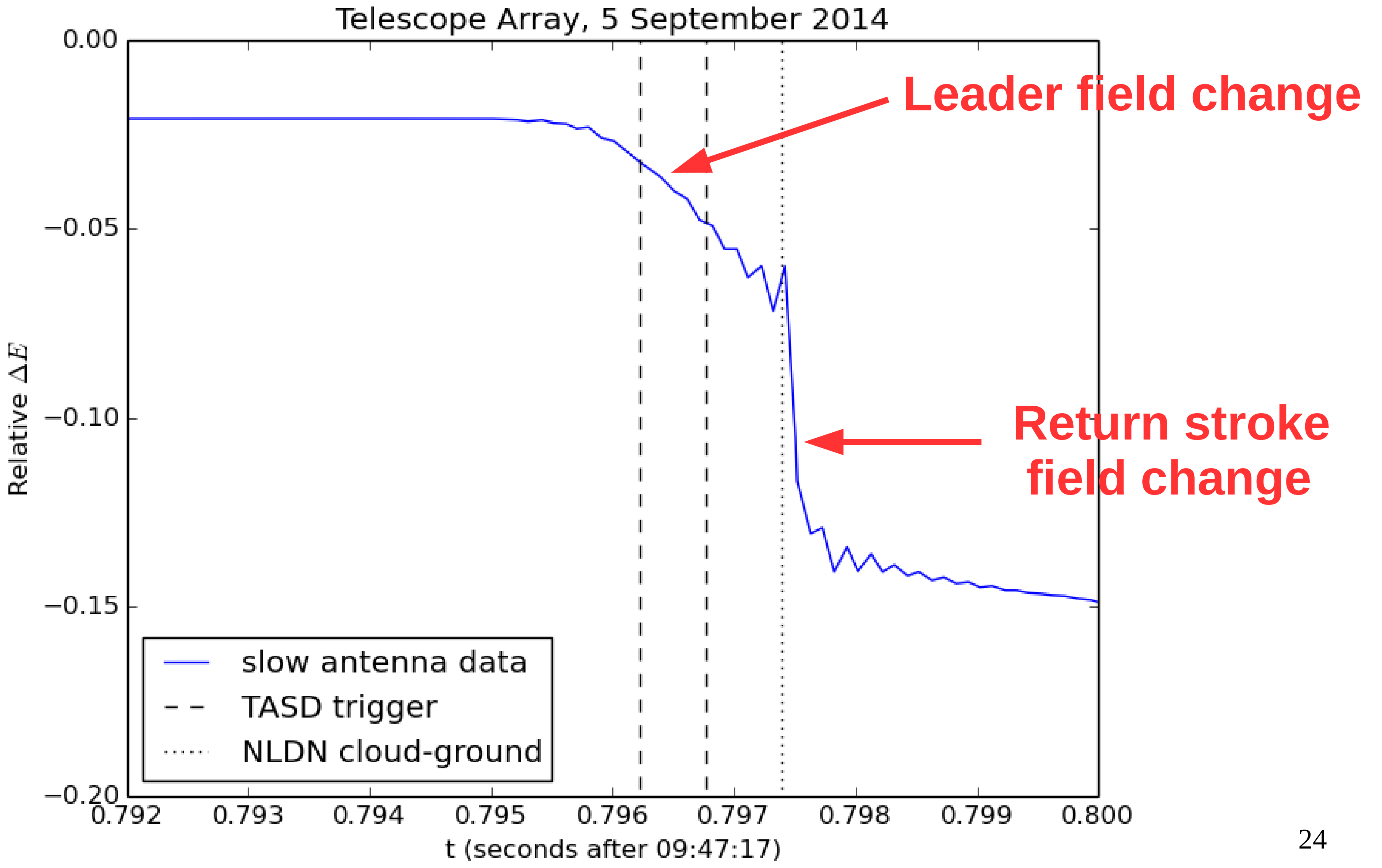




LMA Event 20160510-024150



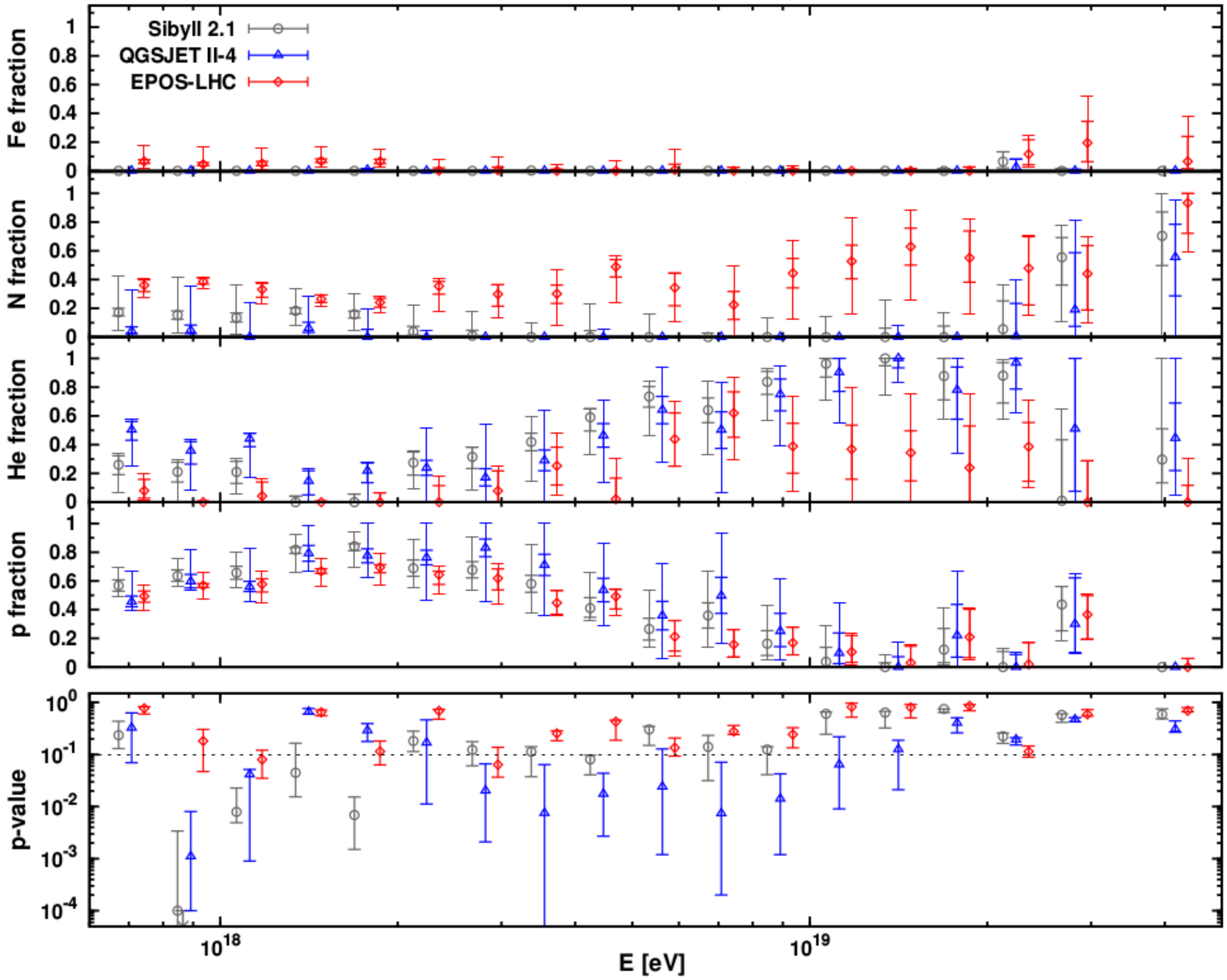
SD Trigger Burst 20140905, “Slow Antenna”



Conclusion/Summary

- Over the past decade, TA's enhanced aperture has enabled discoveries in UHECR anisotropy and energy spectrum. TAx4 promises a more detailed look at these discoveries in the coming decade.
- Composition/cross-section measurements are pressuring
  - experimentalists to understand systematics
  - high-energy hadronic modellers
  - LHC measurements.
- TA has begun to study high-energy radiation from lightning, and likely observed terrestrial gamma flashes from the ground. Papers in preparation.

Auger Composition Mix (Fit)



ArXiv:1409.5083v1