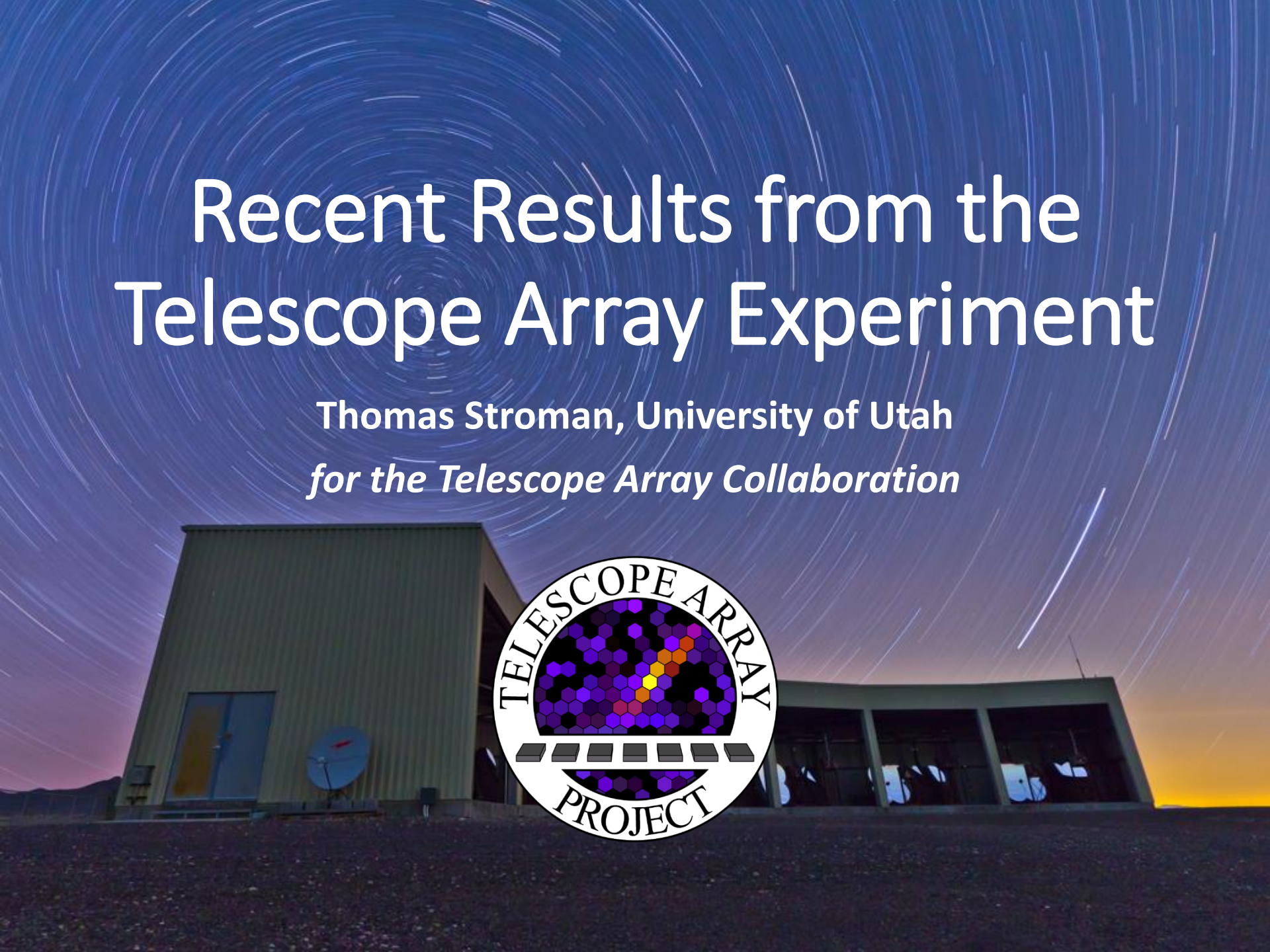
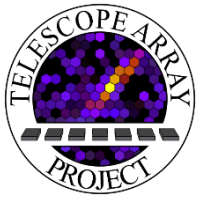
Recent Results from the Telescope Array Experiment

Thomas Stroman, University of Utah

for the Telescope Array Collaboration





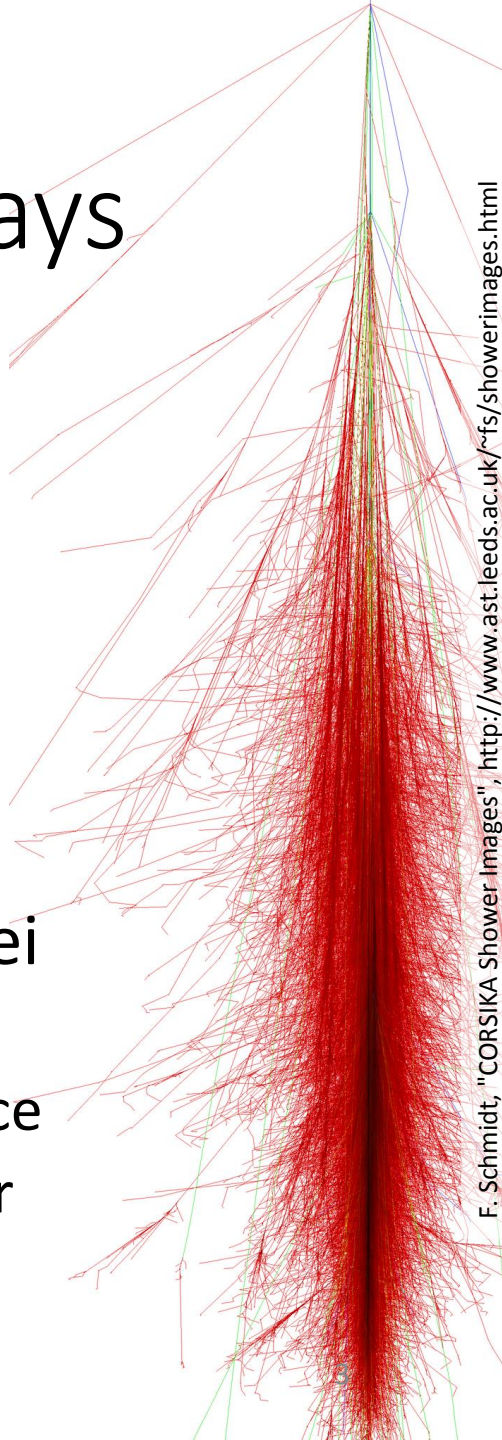
RU Abbasi[1], M Abe[13], T Abu-Zayyad[1], M Allen[1], R Anderson[1], R Azuma[2], E Barcikowski[1], JW Belz[1], DR Bergman[1], SA Blake[1], R Cady[1], MJ Chae[3], BG Cheon[4], J Chiba[5], M Chikawa[6], WR Cho[7], T Fujii[8], M Fukushima[8,9], T Goto[10], W Hanlon[1], Y Hayashi[10], N Hayashida[11], K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

[1]High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA, [2]Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan, [3]Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaaemun-gu, Seoul, Korea, [4]Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea, [5]Department of Physics, Tokyo University of Science, Noda, Chiba, Japan, [6]Department of Physics, Kinki University, Higashi Osaka, Osaka, Japan, [7]Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea, [8]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan, [9]Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Chiba, Japan, [10]Graduate School of Science, Osaka City University, Osaka, Osaka, Japan, [11]Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan, [12]Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan, [13]The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan, [14]Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan, [15]Department of Physics and Astronomy, Rutgers University - The State University of New Jersey, Piscataway, New Jersey, USA, [16]Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan, [17]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia, [18]Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan, [19]Department of Physics, Chiba University, Chiba, Chiba, Japan, [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, Sungkyunkwan University, Jang-an-gu, Suwon, Korea, [24]Service de Physique Theorique, Universite Libre de Bruxelles, Brussels, Belgium, [25]Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea, [26]Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan, [27]Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan, [28]Advanced Science Institute, RIKEN, Wako, Saitama, Japan, [29]National Institute of Radiological Science, Chiba, Chiba, Japan, [30]Department of Physics, Ehime University, Matsuyama, Ehime, Japan

USA, Japan, Korea, Russia, Belgium

Ultra-high-energy cosmic rays

- “Fixed-target” experiment with intergalactic “beamline”
- Primary particle energy > 10^{18} eV
- Inelastic collision with atmospheric nuclei produces cascade of secondary particles
  - Directly detect secondary particles at surface
  - Fluorescence and Cherenkov radiation in air



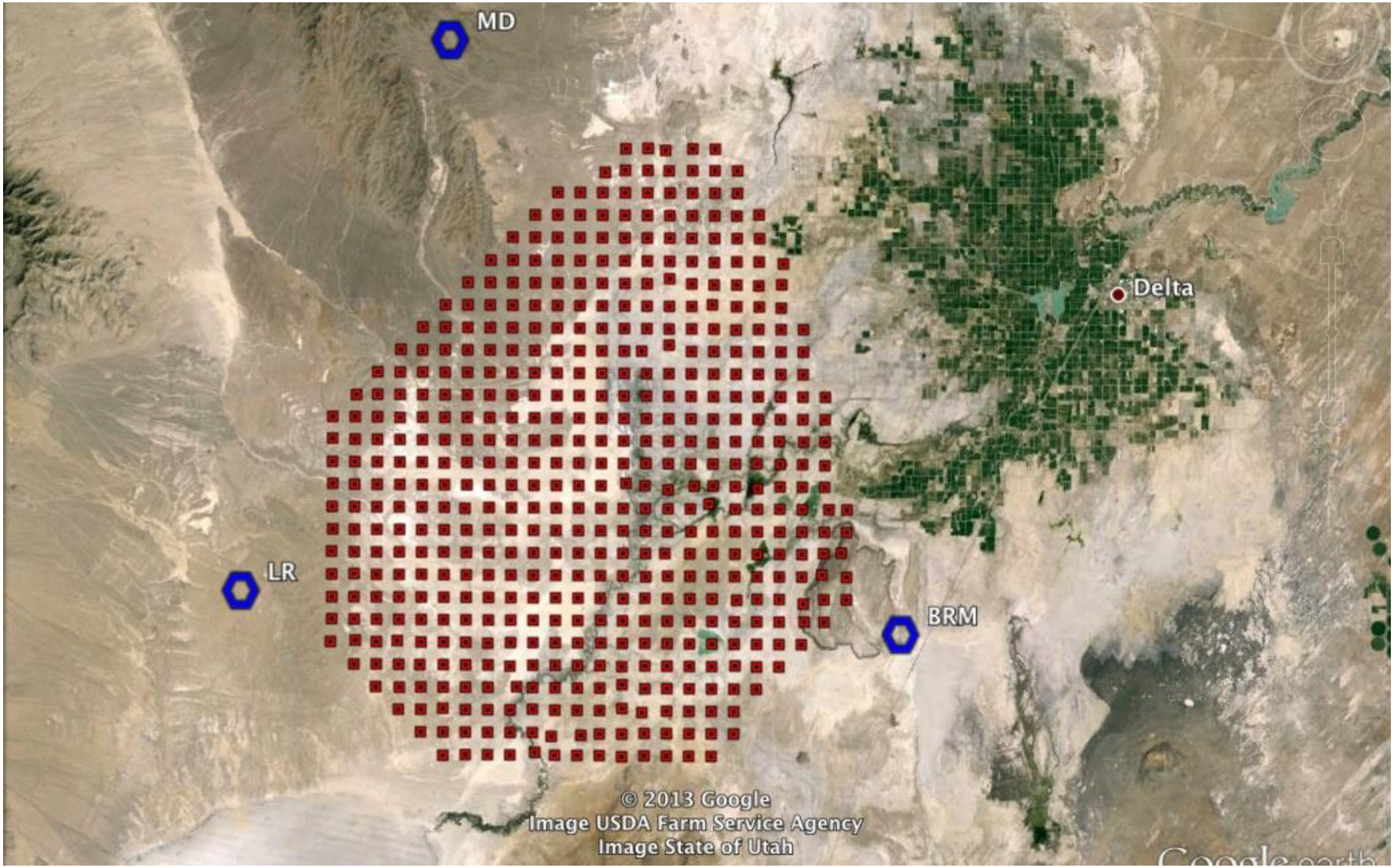
F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html

Telescope Array science objectives

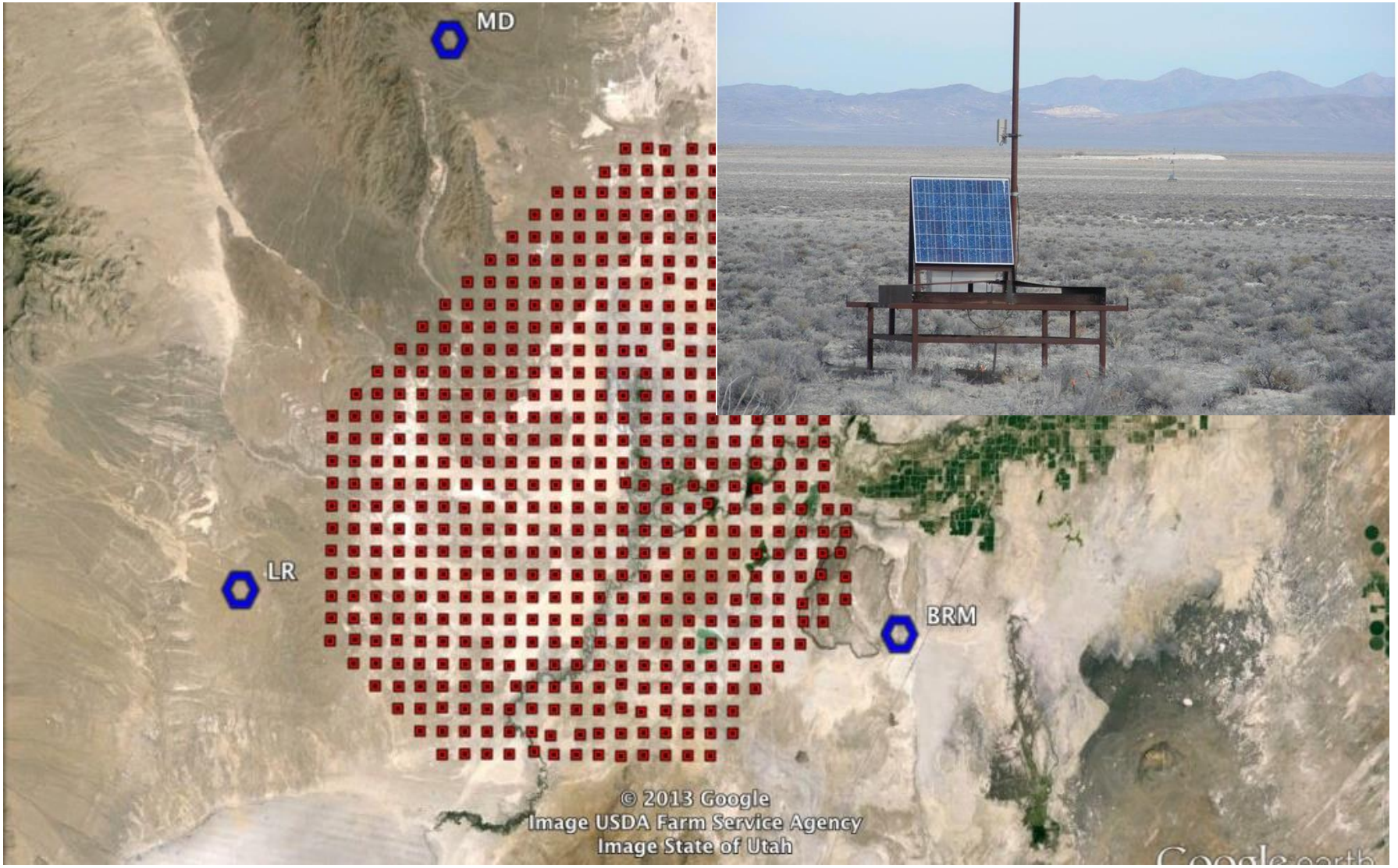
- Measure ultra-high-energy cosmic rays (UHECRs):
  - **Anisotropy** of arrival directions
  - Energy **spectrum**
  - Chemical **composition**

- Extend observation capabilities to lower energies
  - Transition from Galactic to extragalactic sources
  - Overlap with LHC p-p collisions (COM energy)

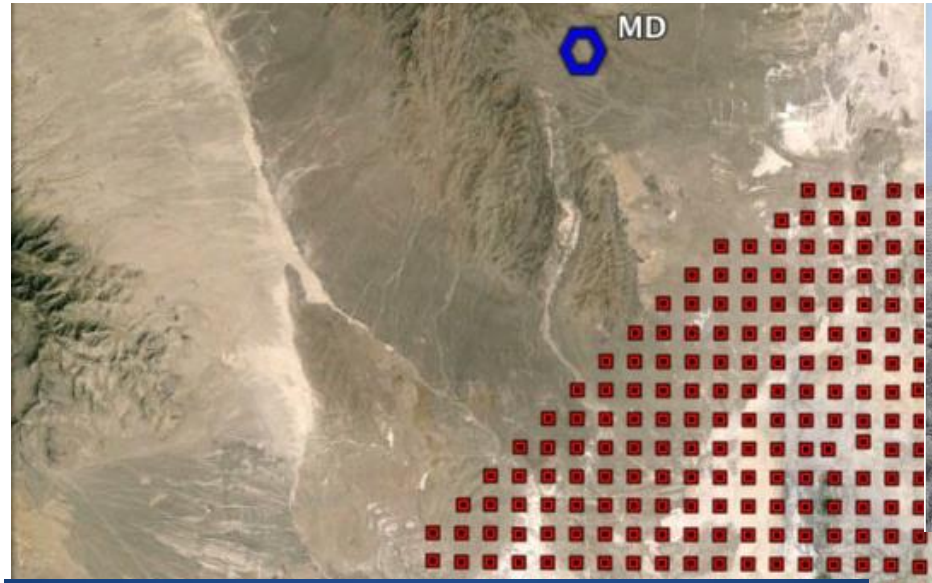
TA detectors

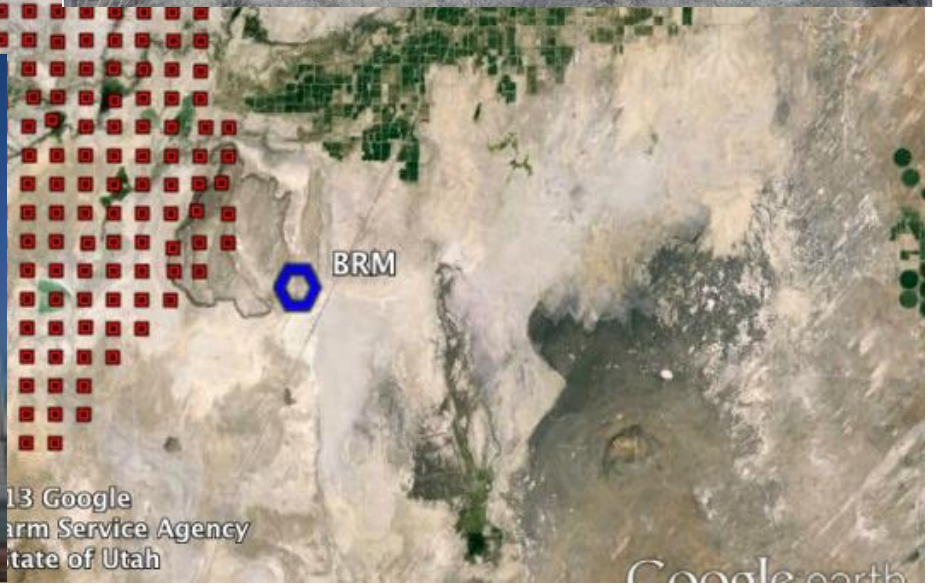


TA detectors

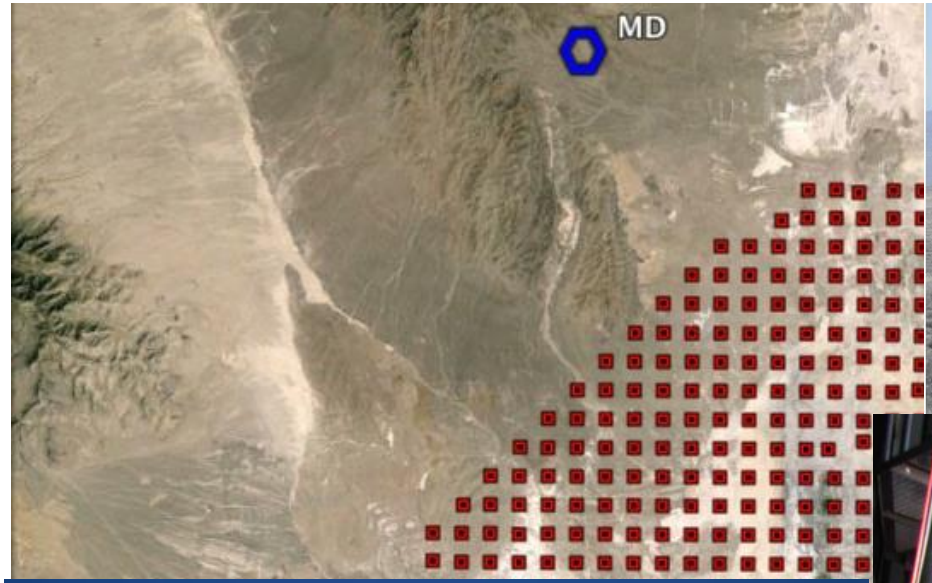


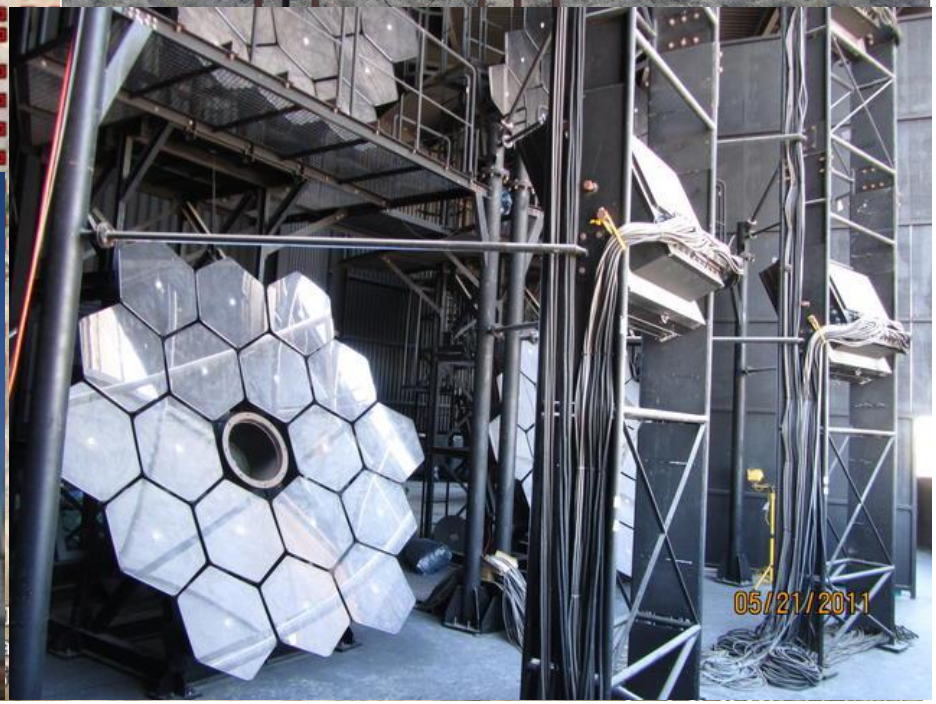
TA detectors



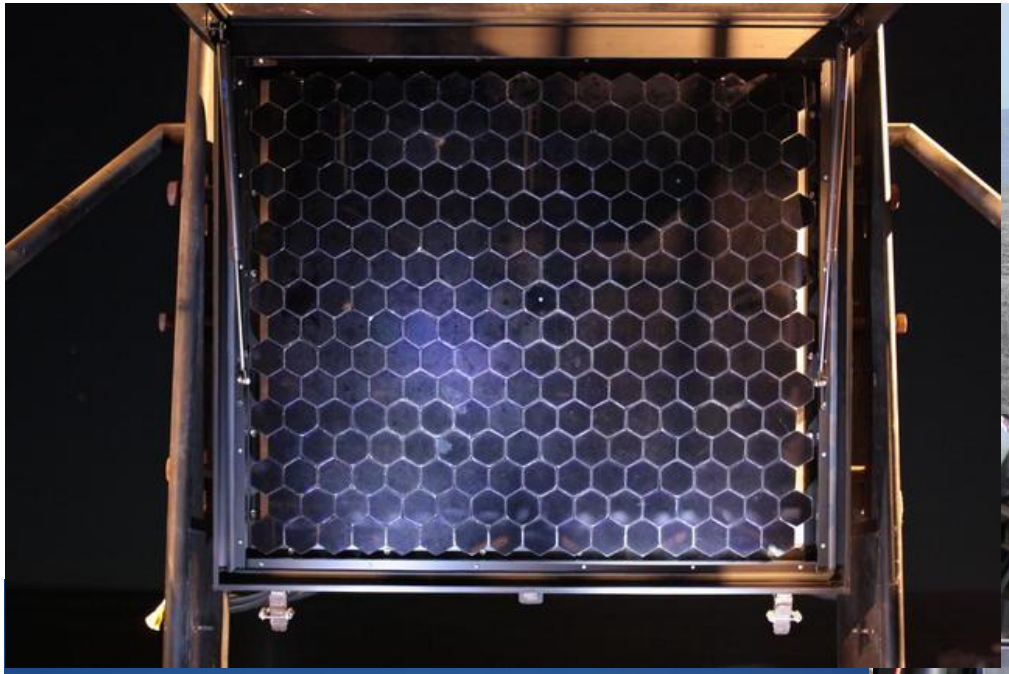


TA detectors

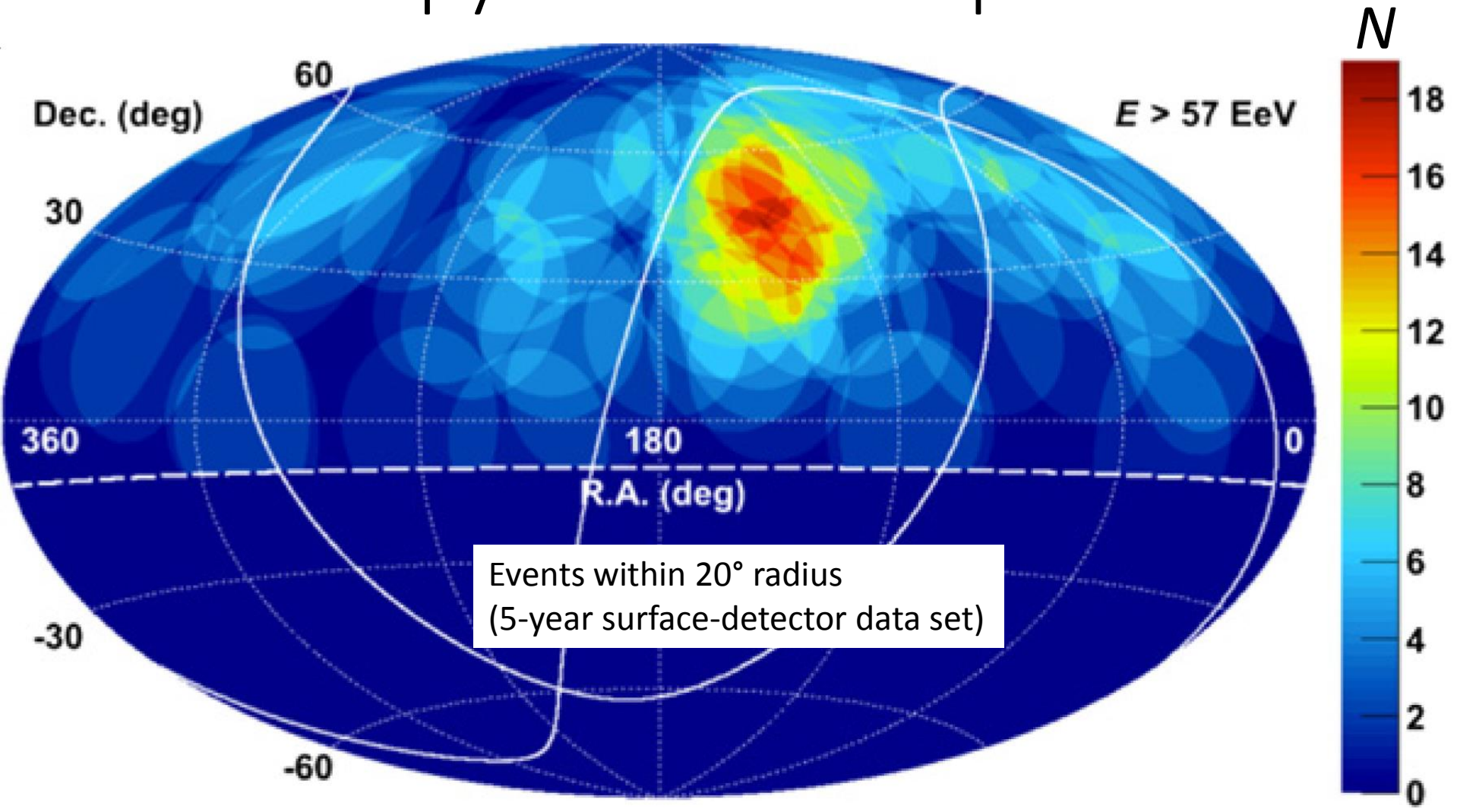




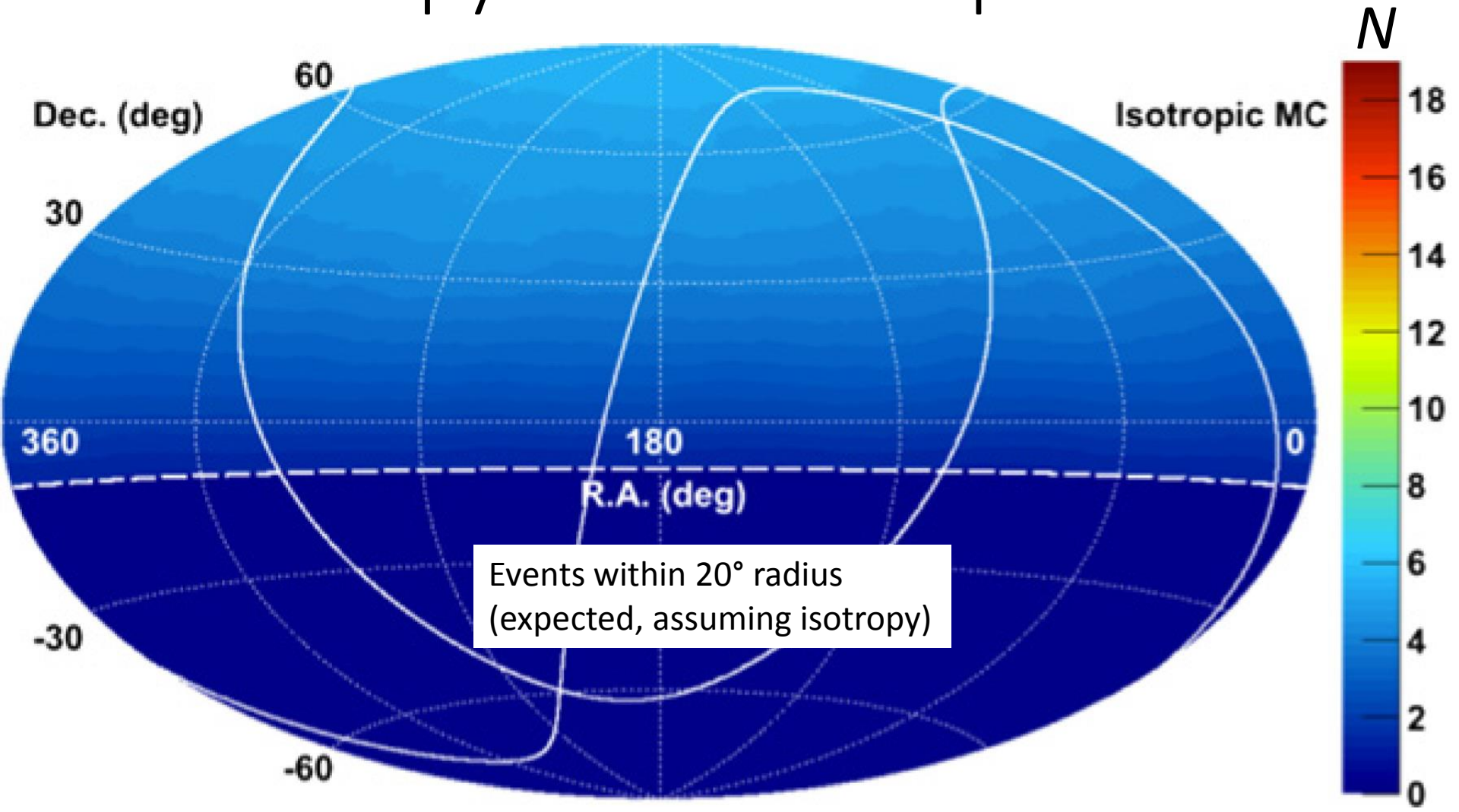
TA detectors



Anisotropy: 57 EeV hotspot

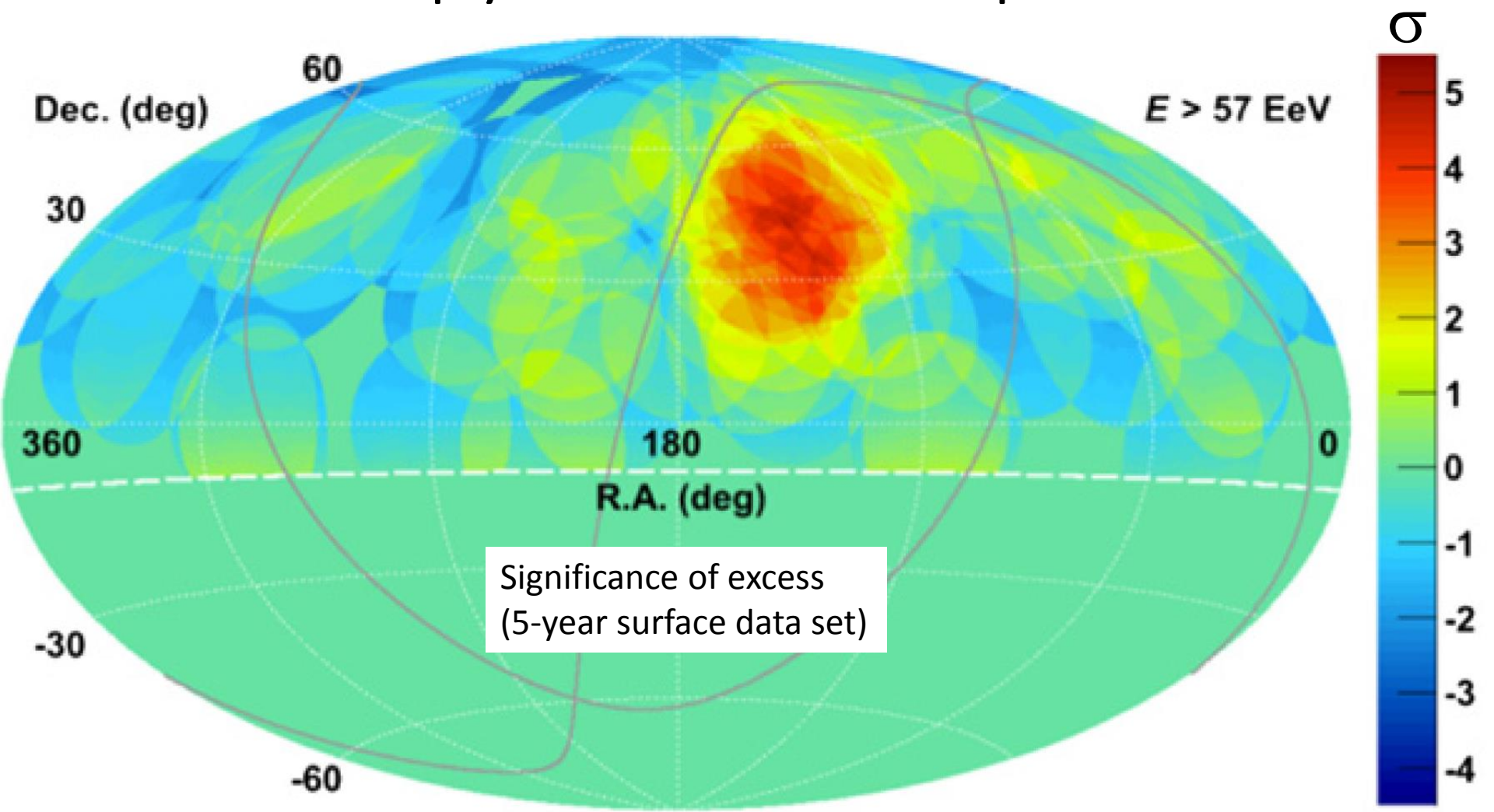


Anisotropy: 57 EeV hotspot



Events within 20° radius
(expected, assuming isotropy)

Anisotropy: 57 EeV hotspot



Anisotropy: 57 EeV hotspot

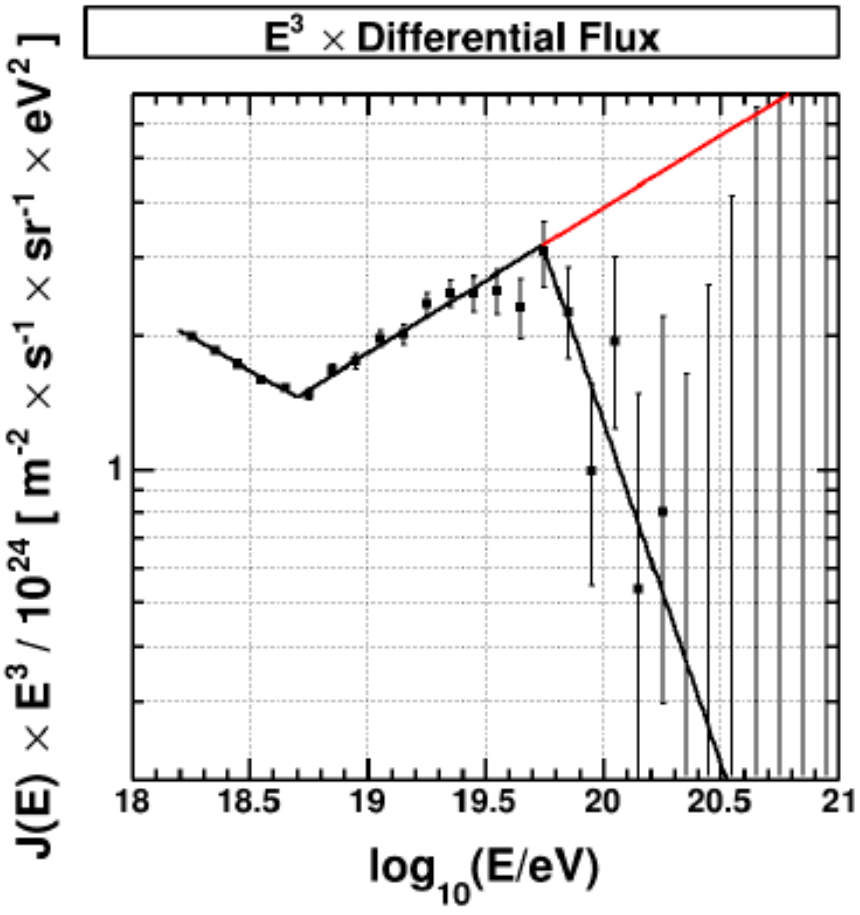
- Excess with 5.1σ significance in region of 20° radius
- Chance probability of 5.1σ cluster anywhere in sky: 3.65×10^{-4} (3.4σ)
- **Publication**: R. U. Abbasi et al., ApJ 790 (2014) L21

- Including newly processed sixth year of data:
  - 5.1σ → 5.55σ
  - Chance probability: now 4.0σ

Spectrum: GZK regime

- Ankle and cutoff clearly visible in 6-year SD data
  - Ankle: $10^{18.698 \pm 0.020}$ eV
  - GZK: $10^{19.742 \pm 0.038}$ eV
  - post-GZK: $E^{-4.539 \pm 0.441}$
- Cutoff significance: 6.59σ
- Berezinsky $E_{1/2}$: $10^{19.729}$ eV

- **Publication** (4-year): Abu-Zayyad et al., ApJ 768 (2013) L1

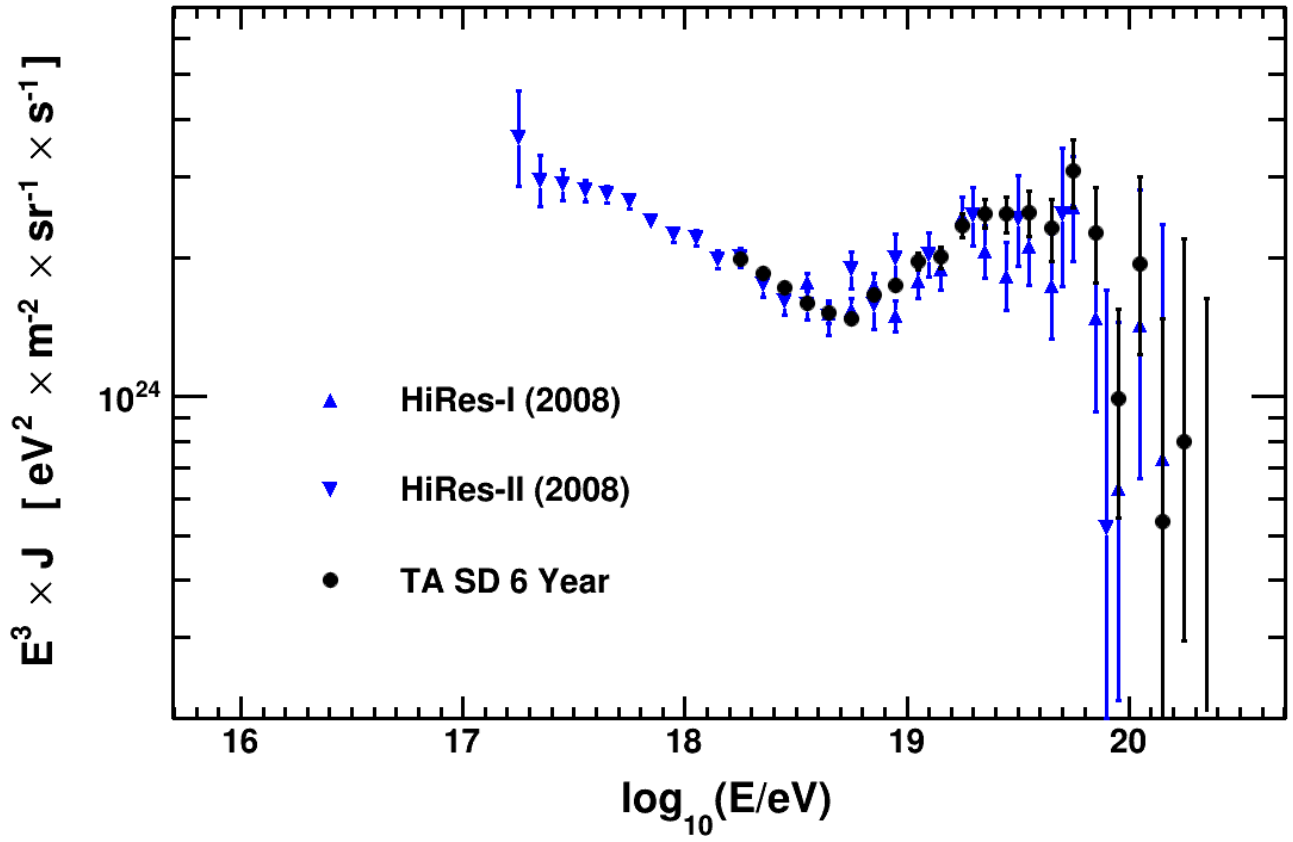


Extend spectrum to low energy

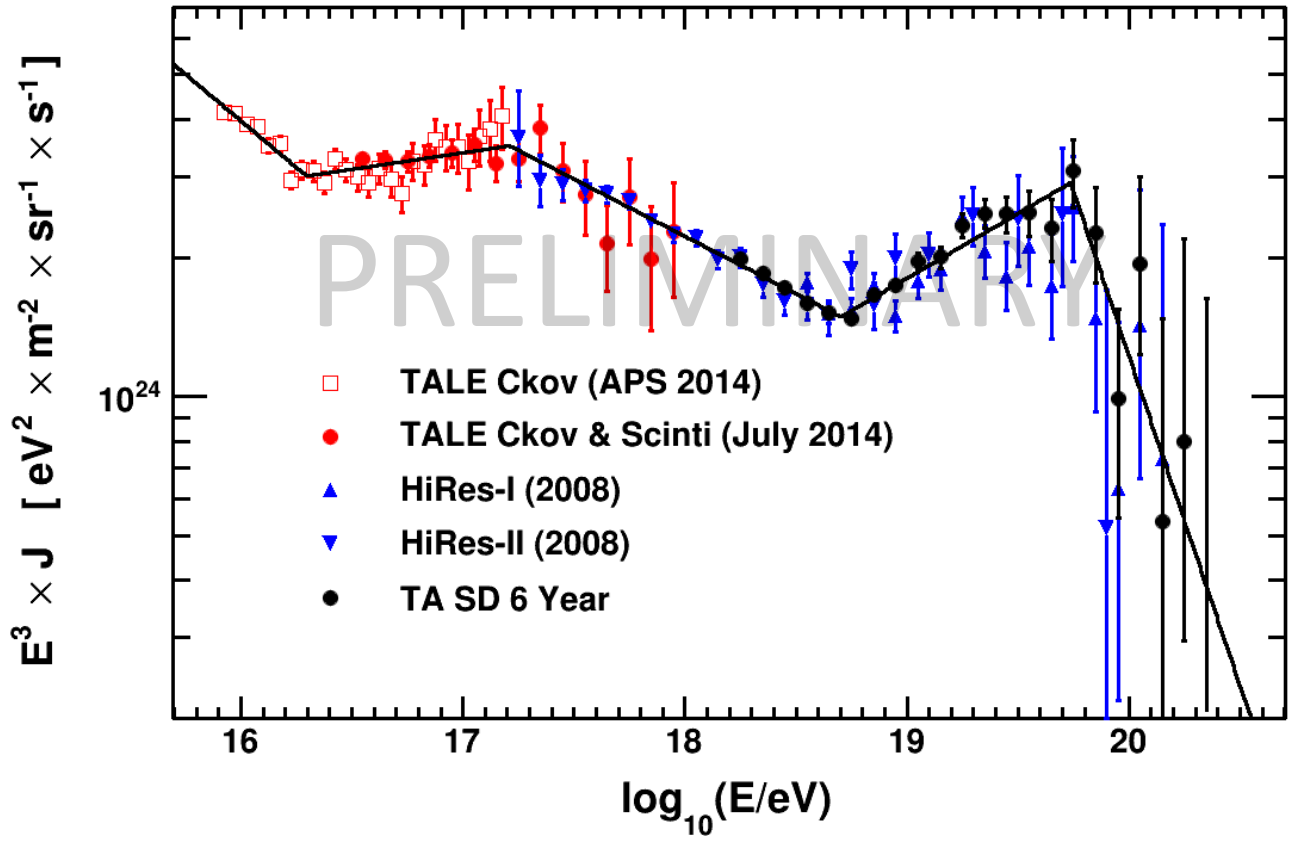
- TALE = TA Low-energy Extension
  - High-density SD array (400 m grid)
  - High-elevation-angle (33°–59°) FD telescopes

- Two analyses for TALE FD data
  - Fluorescence-based (same as standard TA)
  - Cherenkov-based

Spectrum: low-energy w/ TALE FD



Spectrum: low-energy w/ TALE FD



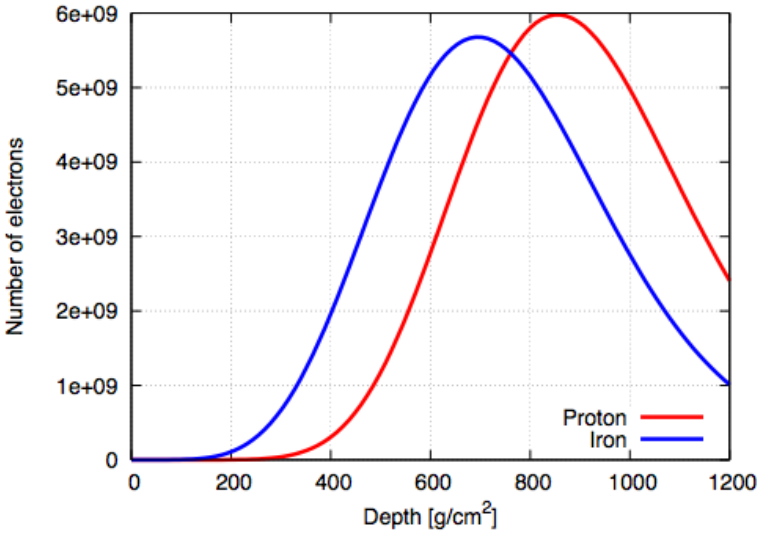
Spectrum: summary

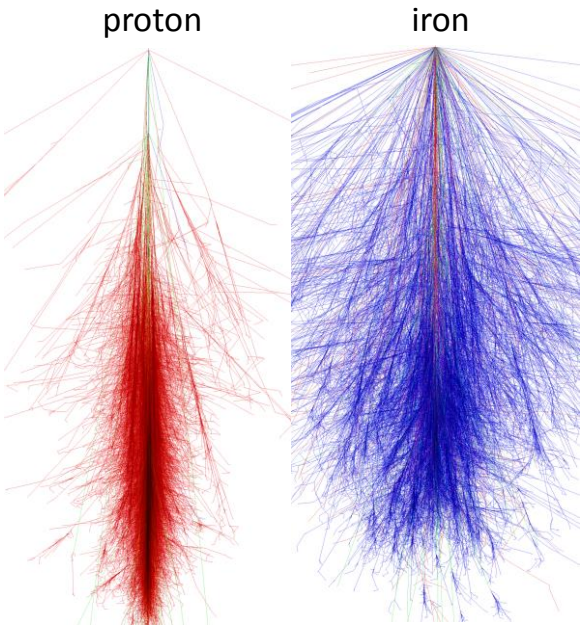
- TA spectrum shows strong internal agreement
  - SD measurement at high energy
  - FD measurement at low energy
  - Previous generation experiment (HiRes)

- 4 orders of magnitude!

Composition: longitudinal shower profile (X_{max})

- X_{max} = slant depth of shower maximum
- proportional to primary UHECR energy per nucleon





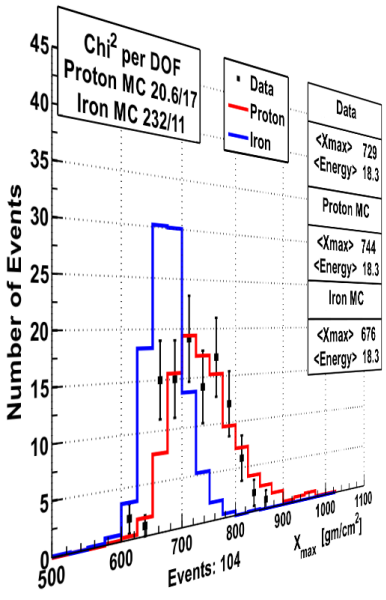
CORSIKA simulations of 1 TeV showers, showing different longitudinal development for protons (left) and ^{56}Fe (right).

F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html

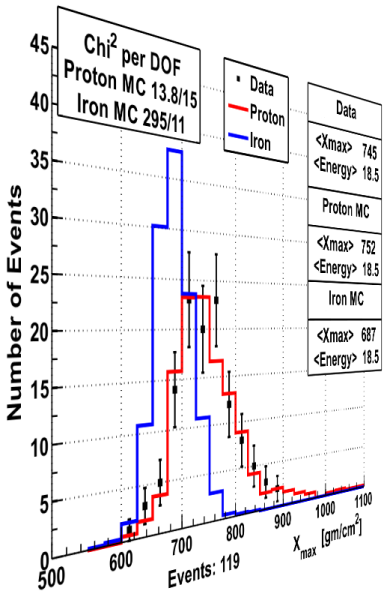
Composition

- Data: hybrid detection and reconstruction
  - Simultaneous observation by SD + FD
  - Accurate shower trajectory and longitudinal profile
- Interpretation: Monte Carlo simulation
  - known composition: pure protons or pure iron
  - hadronic interaction: QGSJet II-03
  - simulate full detector response; identical data analysis
- Compare data with MC at several energies

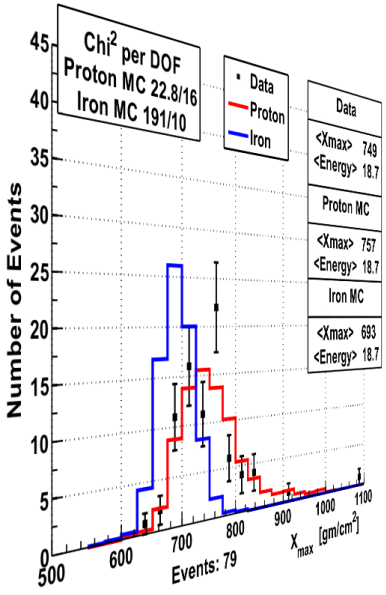
Data/Monte Carlo comparisons: X_{max} distribution by UHECR energy



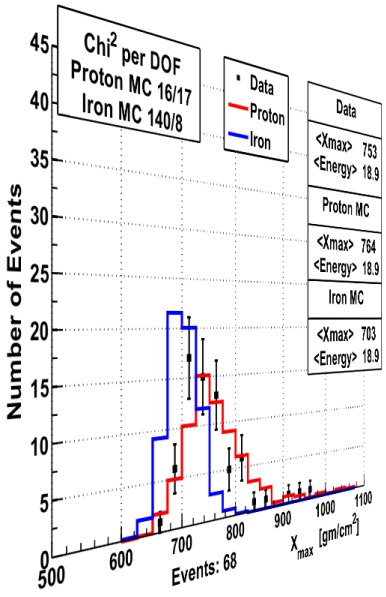
$10^{18.2}$ eV to $10^{18.4}$ eV



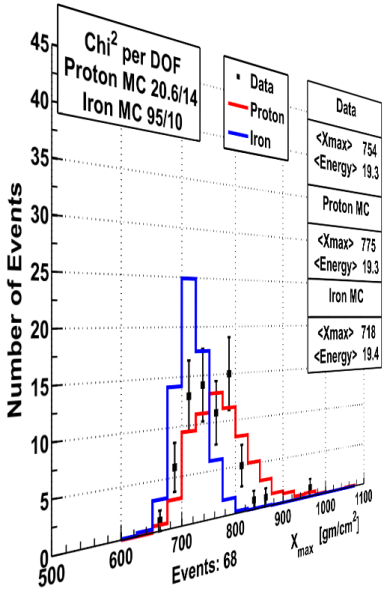
$10^{18.4}$ eV to $10^{18.6}$ eV



$10^{18.6}$ eV to $10^{18.8}$ eV

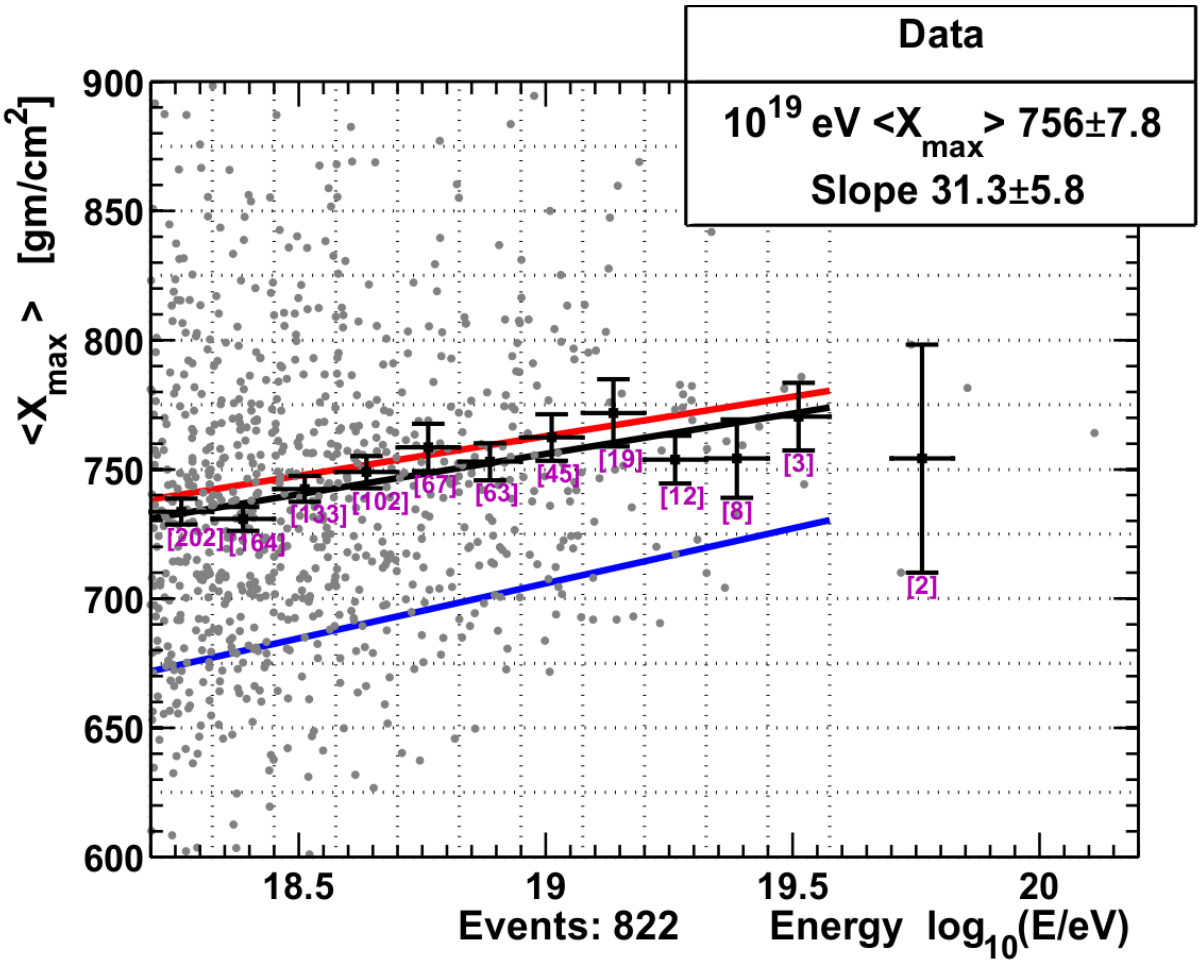


$10^{18.8}$ eV to $10^{19.0}$ eV



$10^{19.0}$ eV and up

Composition: elongation rate



Composition: summary

- Presented here: hybrid analysis
  - data from surface detectors and only one FD site
  - consistent with protons above $10^{18.2}$ eV

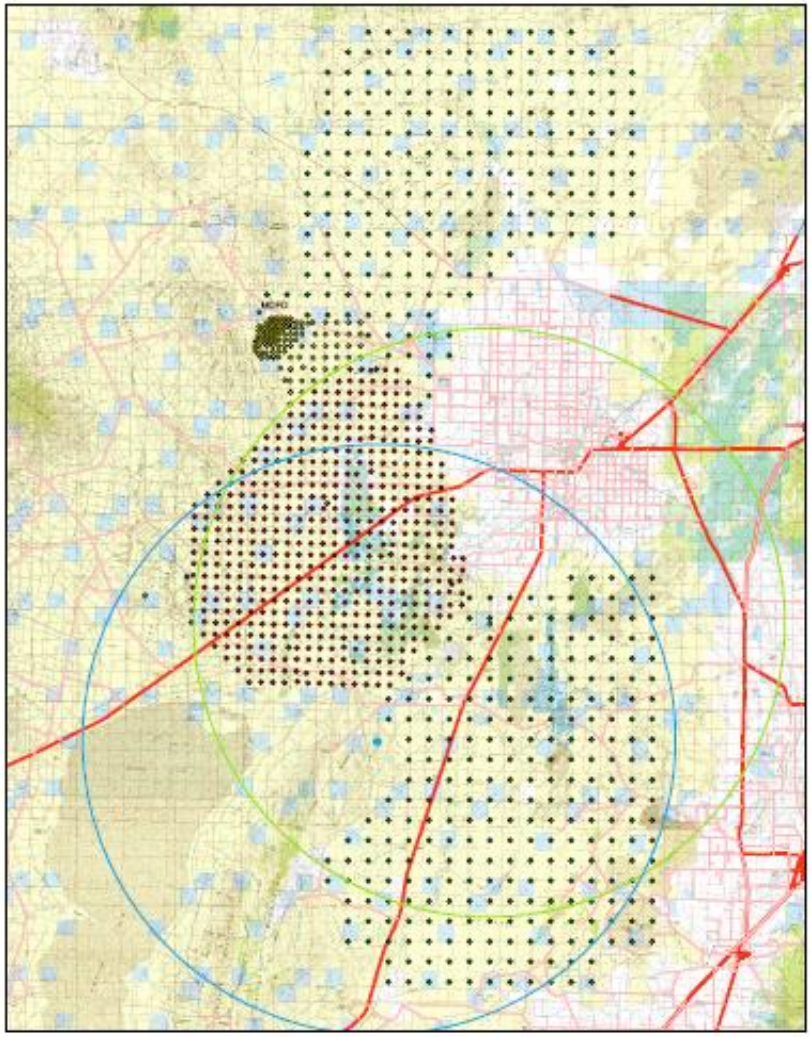
- **Publication**:
  - submitted to Astroparticle Physics
  - arXiv: http://arxiv.org/abs/1408.1726

- Several parallel analyses, in preparation, corroborate proton interpretation
  - hybrid using other two FD sites
  - stereo using all three FD sites
  - other hadronic interaction models

Telescope Array: future plans

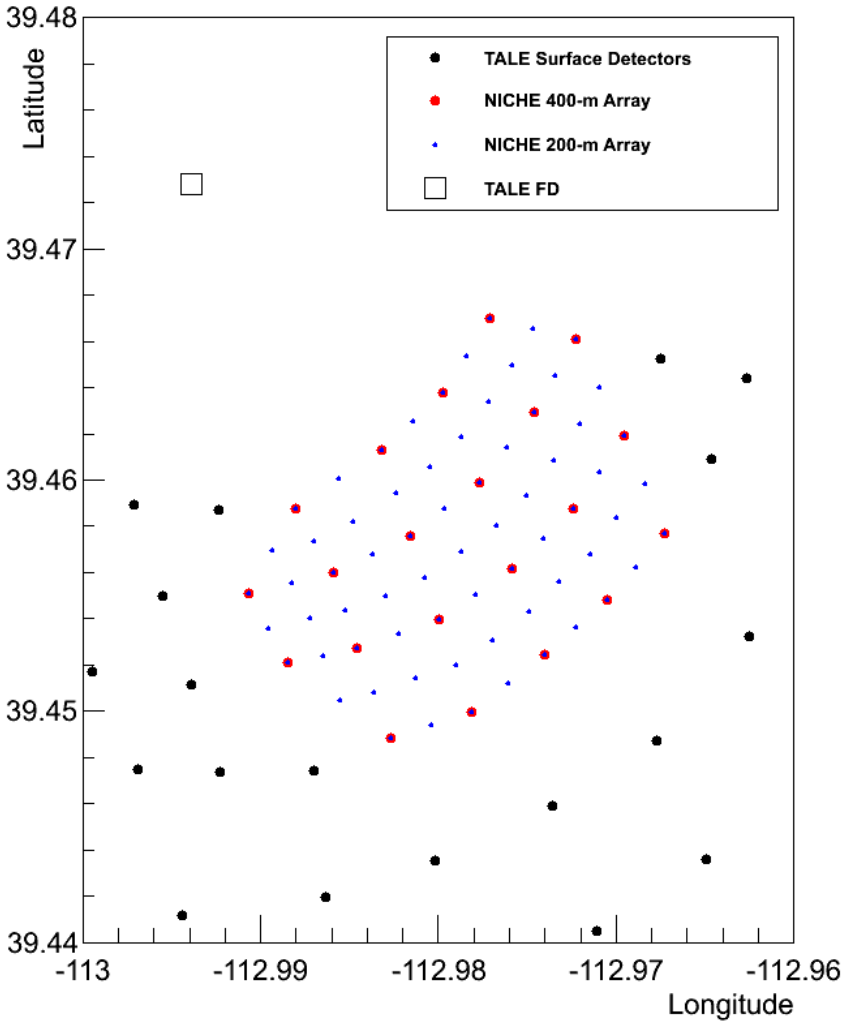
- **Expand**: TA × 4

- 500 new SDs, one new FD station
  - greater SD spacing to improve GZK-regime exposure
  - 20 “TA years” by 2019 for definitive anisotropy results



Telescope Array: future plans

- **Extend**: NICHE array
- Non-Imaging CHErenkov
  - Below TALE energy (PeV)
  - Observe near “knee”
- Build within TALE field of view



Telescope Array: future plans

- **Explore**: TARA and TALMA
- TARA: bistatic radar UHECR detection using analog TV channel 2
- TALMA: search for lightning with coincident particle detection

Conclusions

- Telescope Array is meeting its UHECR science objectives
  - Anisotropy: 4σ and counting
  - Spectrum: 4+ decades in energy
  - Composition: converging on protons above $10^{18.2}$ eV

- Forthcoming analyses and new hardware: many more results yet to come!