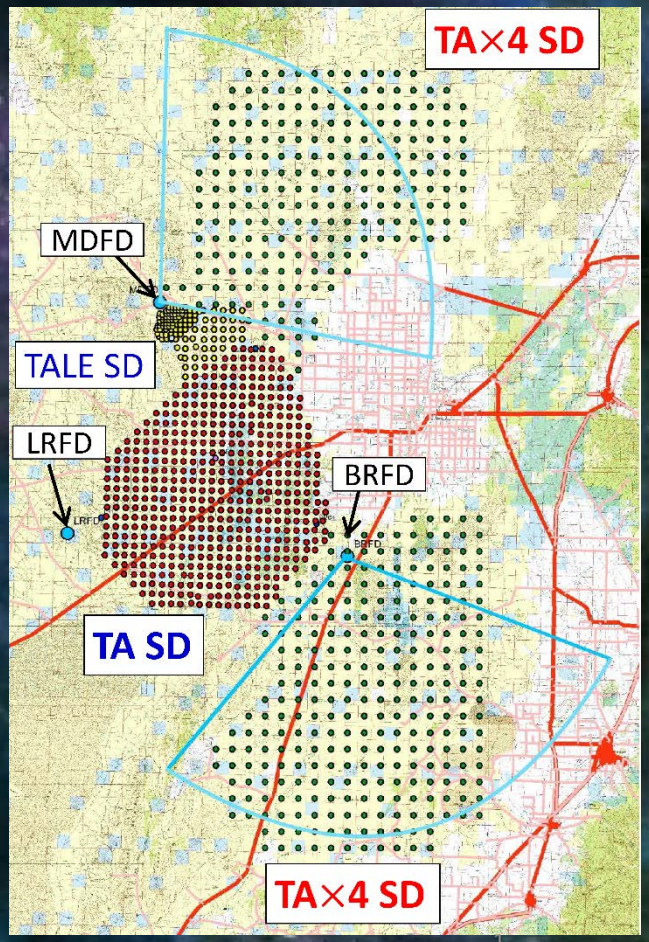
Recent results from the Telescope Array experiment and the extension plan

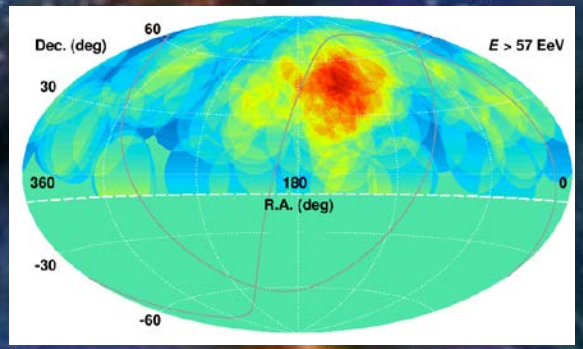
H. Sagawa

Institute for Cosmic Ray Research

The University of Tokyo

for the Telescope Array collaboration



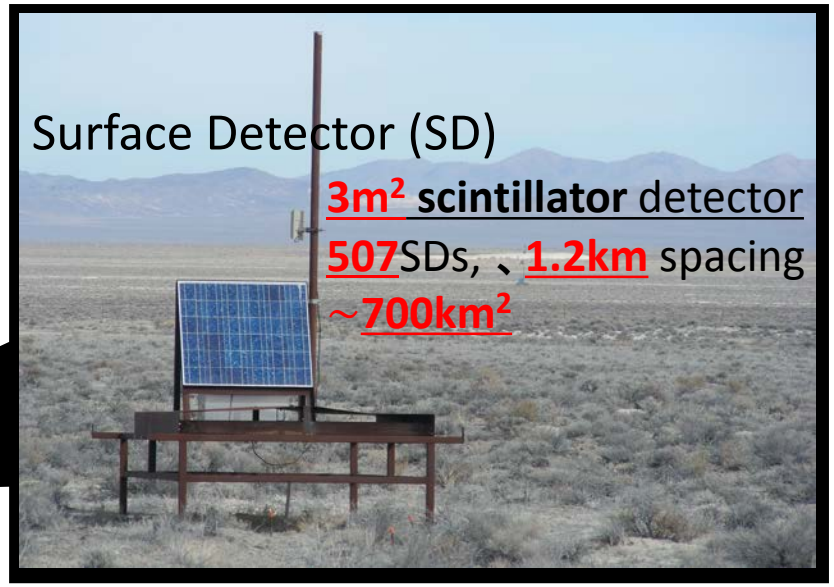


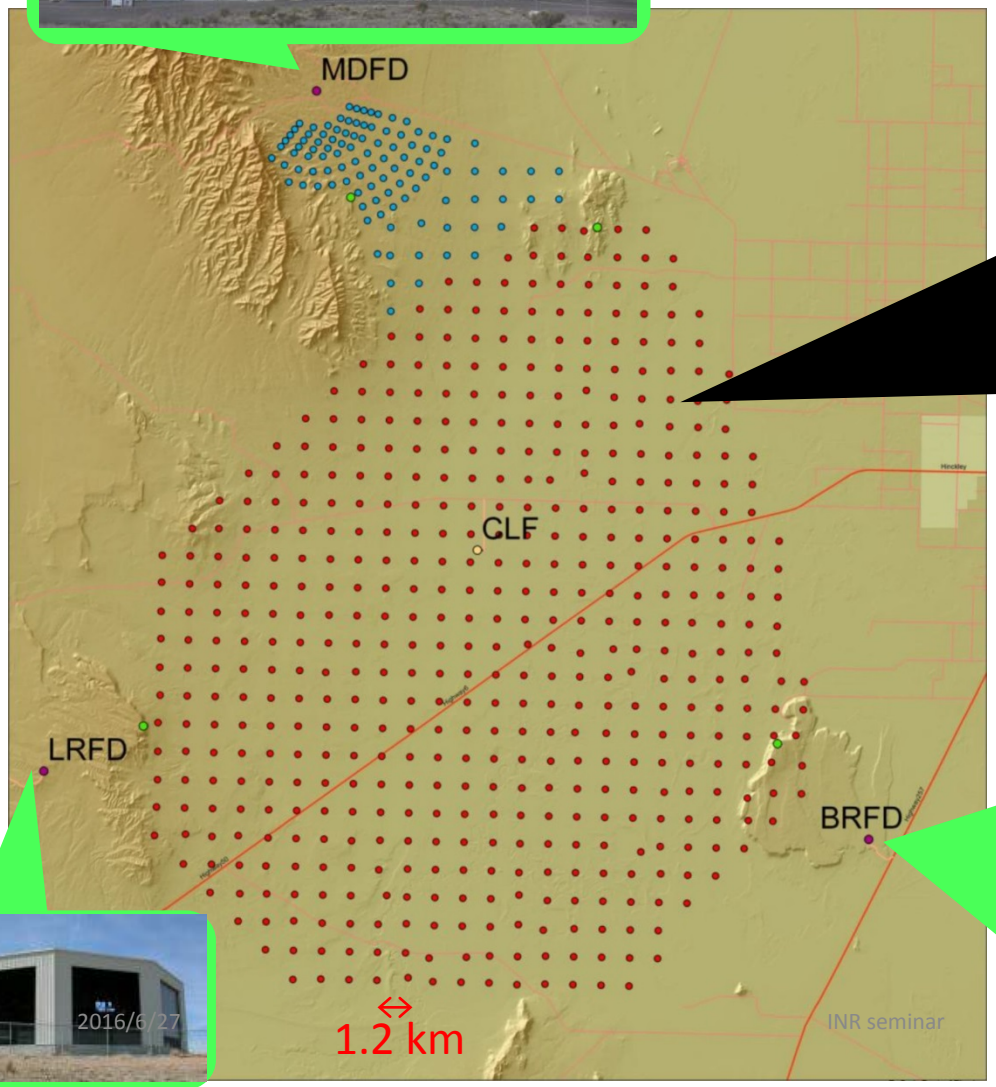
Contents

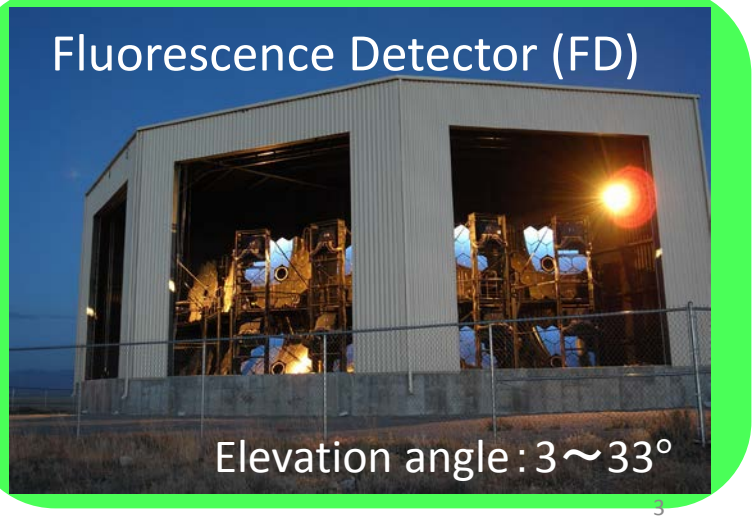
1. Telescope Array experiment
   - Explore the origin of the highest-energy cosmic rays
2. Latest results of Telescope Array (TA)
   - Spectrum
   - Composition
   - Anisotropy
3. TA extension
   - TA×4 (10^{19} eV ~ $10^{20.5}$ eV)
     - TA aperture extension at the highest energies
   - TALE ($10^{15.6}$ eV ~ 10^{19} eV)
     - TA Low-Energy extension

TA detector

❖ Utah, USA- lat. 39.30°N, long. 112.91°W



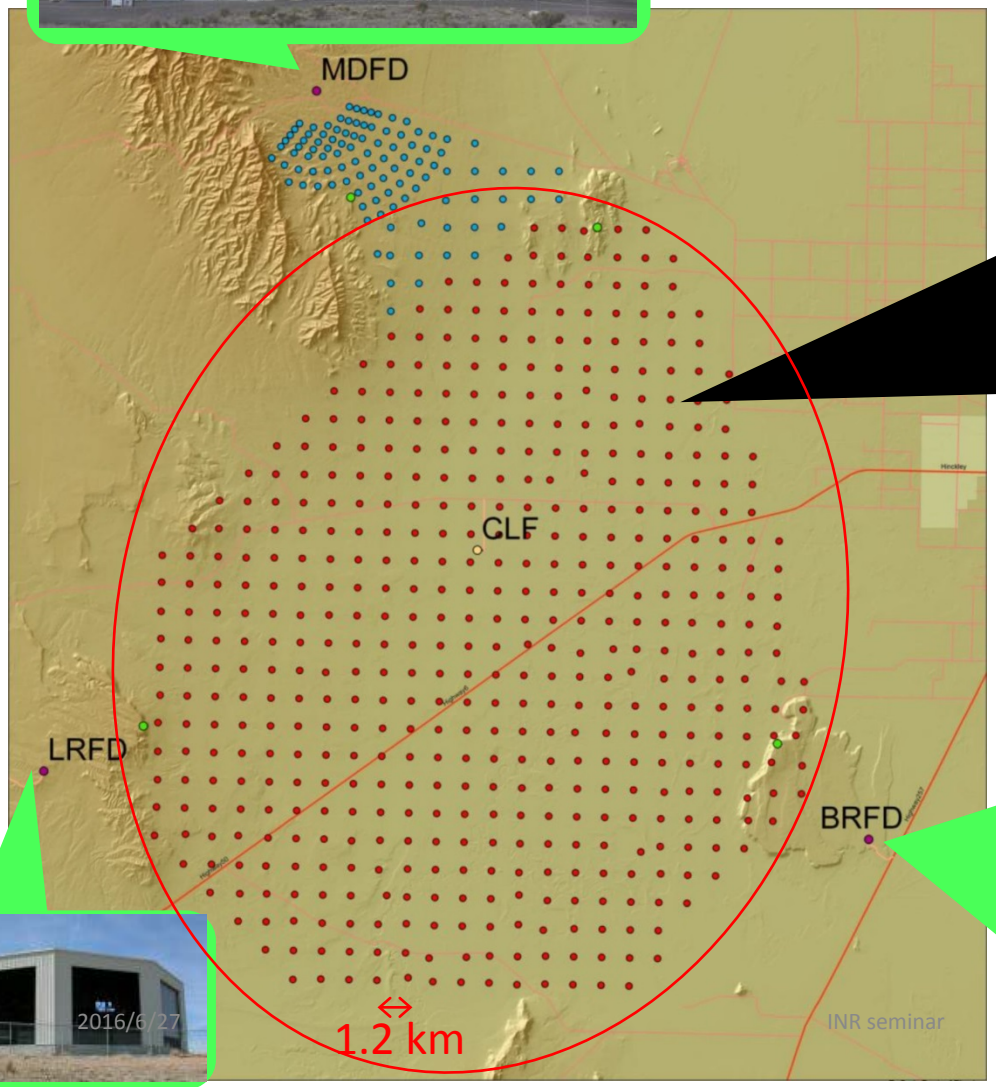


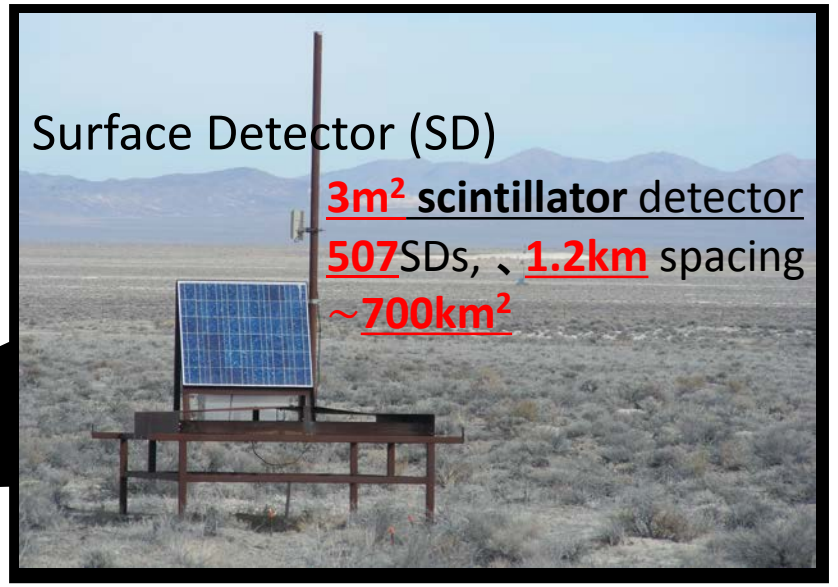


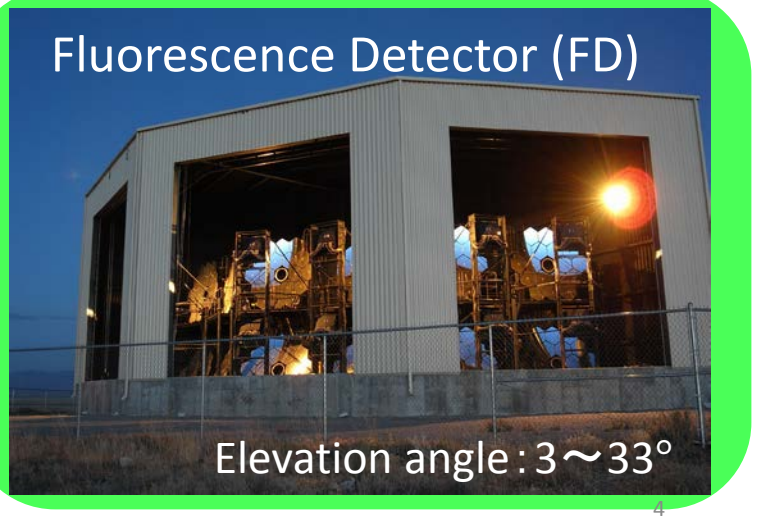
Hybrid observation since Mar, 2008

TA detector

❖ Utah, USA- lat. 39.30°N, long. 112.91°W



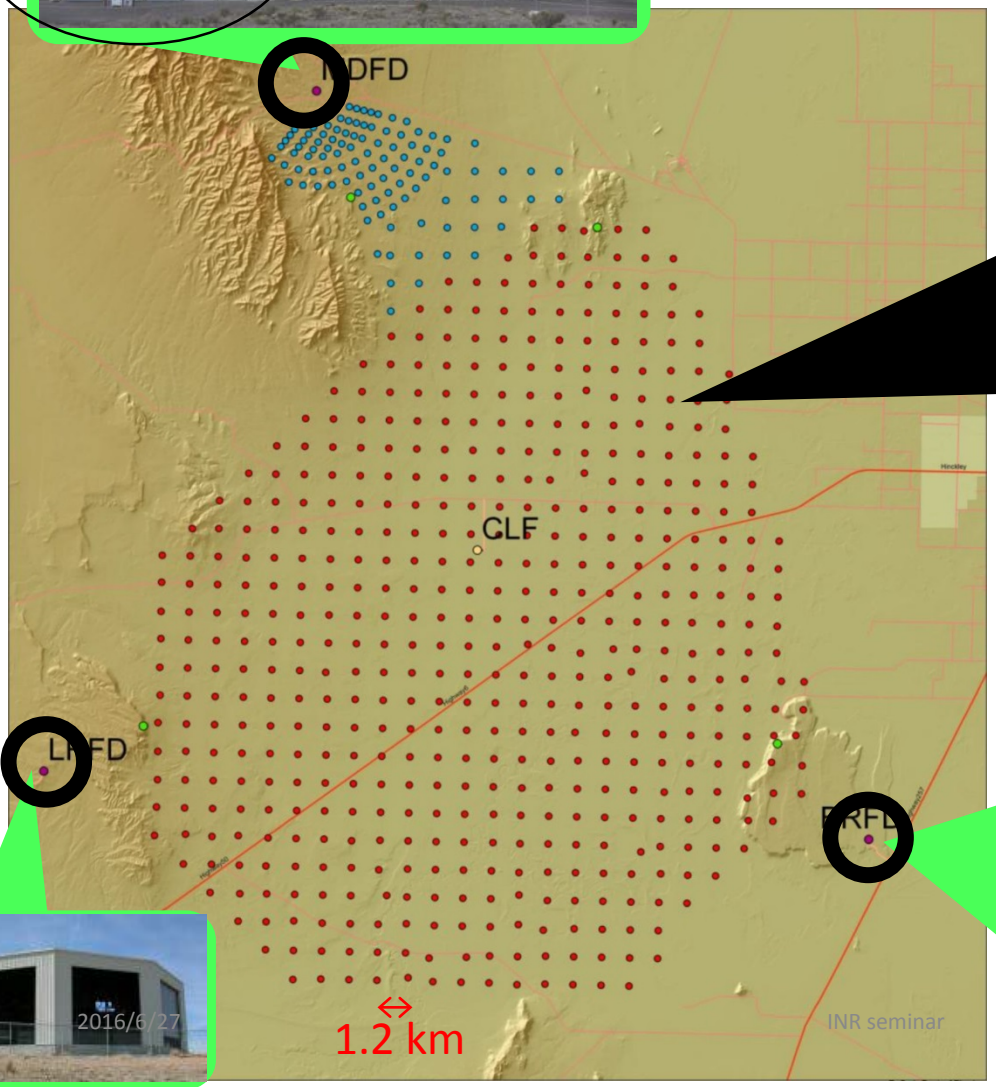


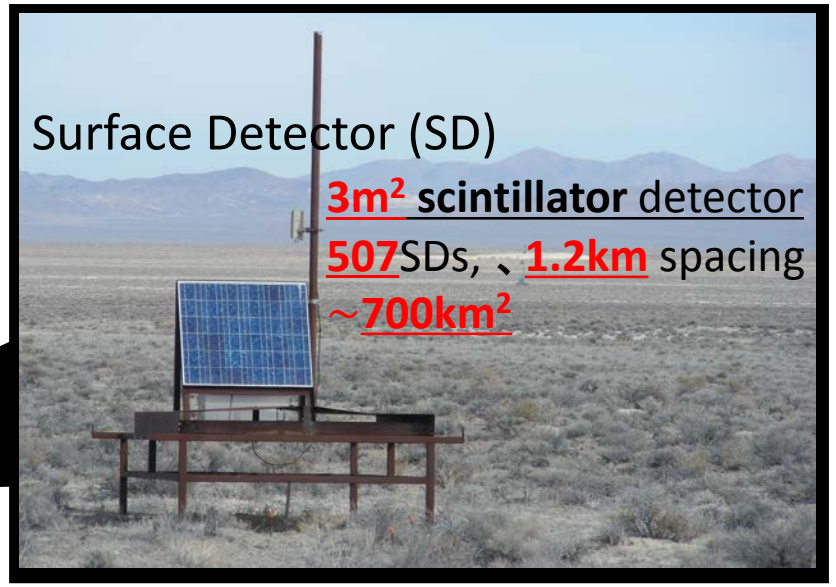


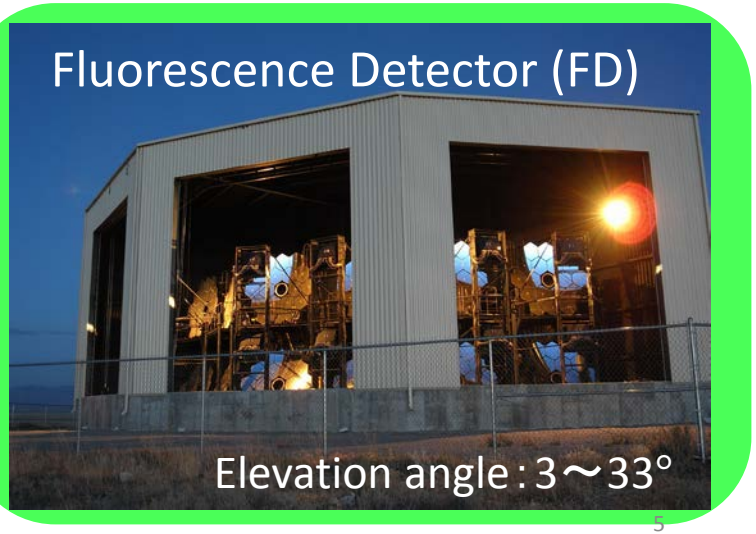
Hybrid observation since Mar, 2008

TA detector

❖ Utah, USA- lat. 39.30°N, long. 112.91°W



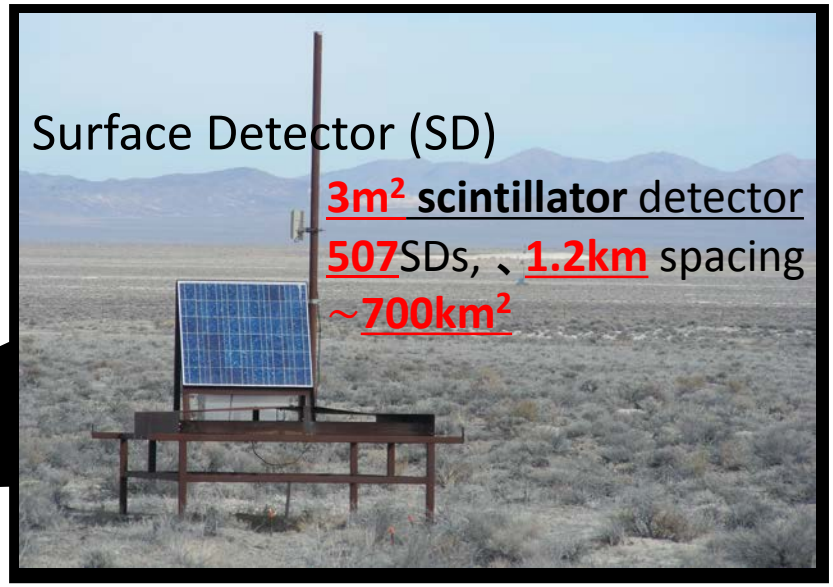


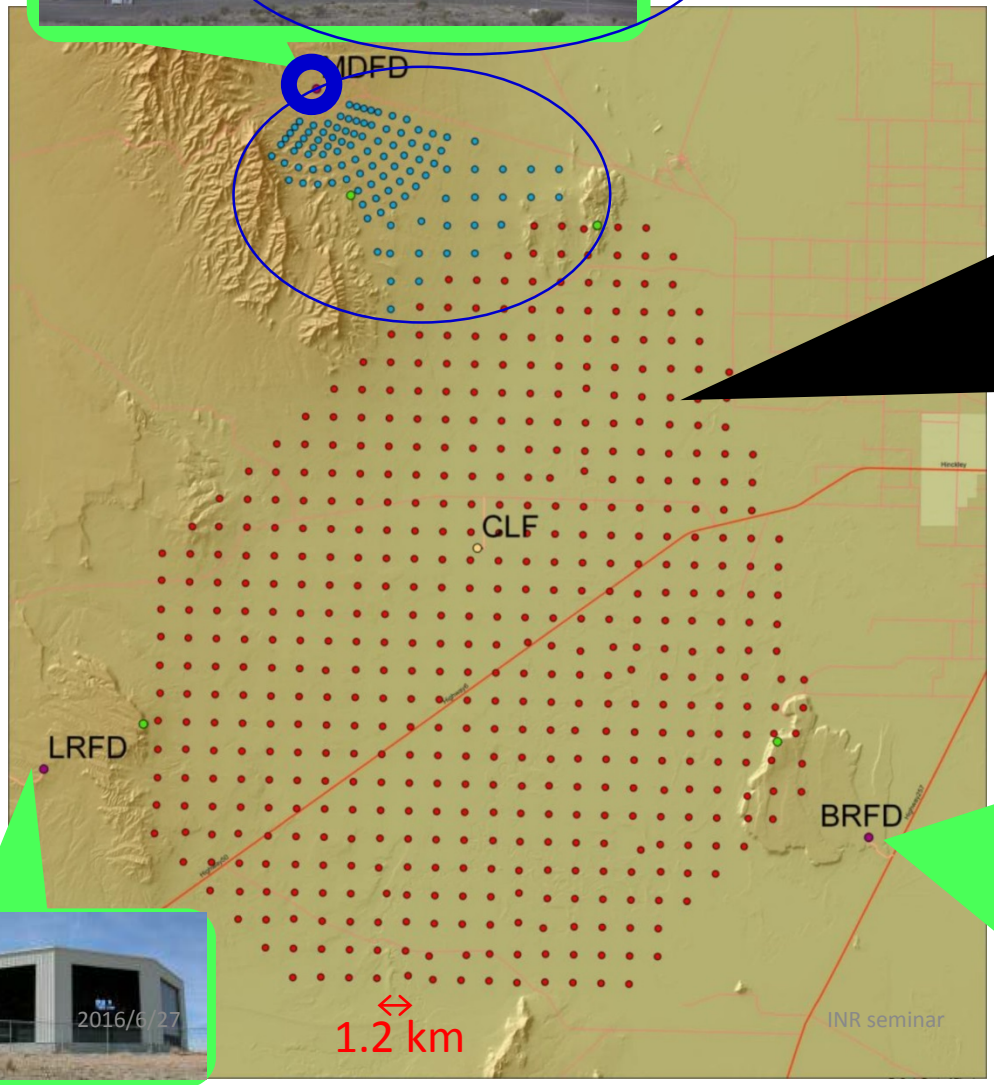


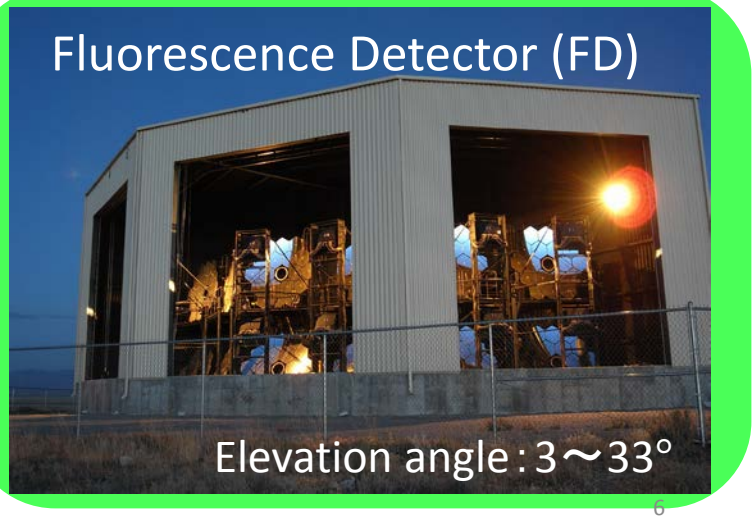
Hybrid observation since Mar, 2008

TA detector

❖ Utah, USA- lat. 39.30°N, long. 112.91°W







Hybrid observation since Mar, 2008

TA Collaboration

~130 researchers

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

Japan, the USA, Korea, Russia, Belgium

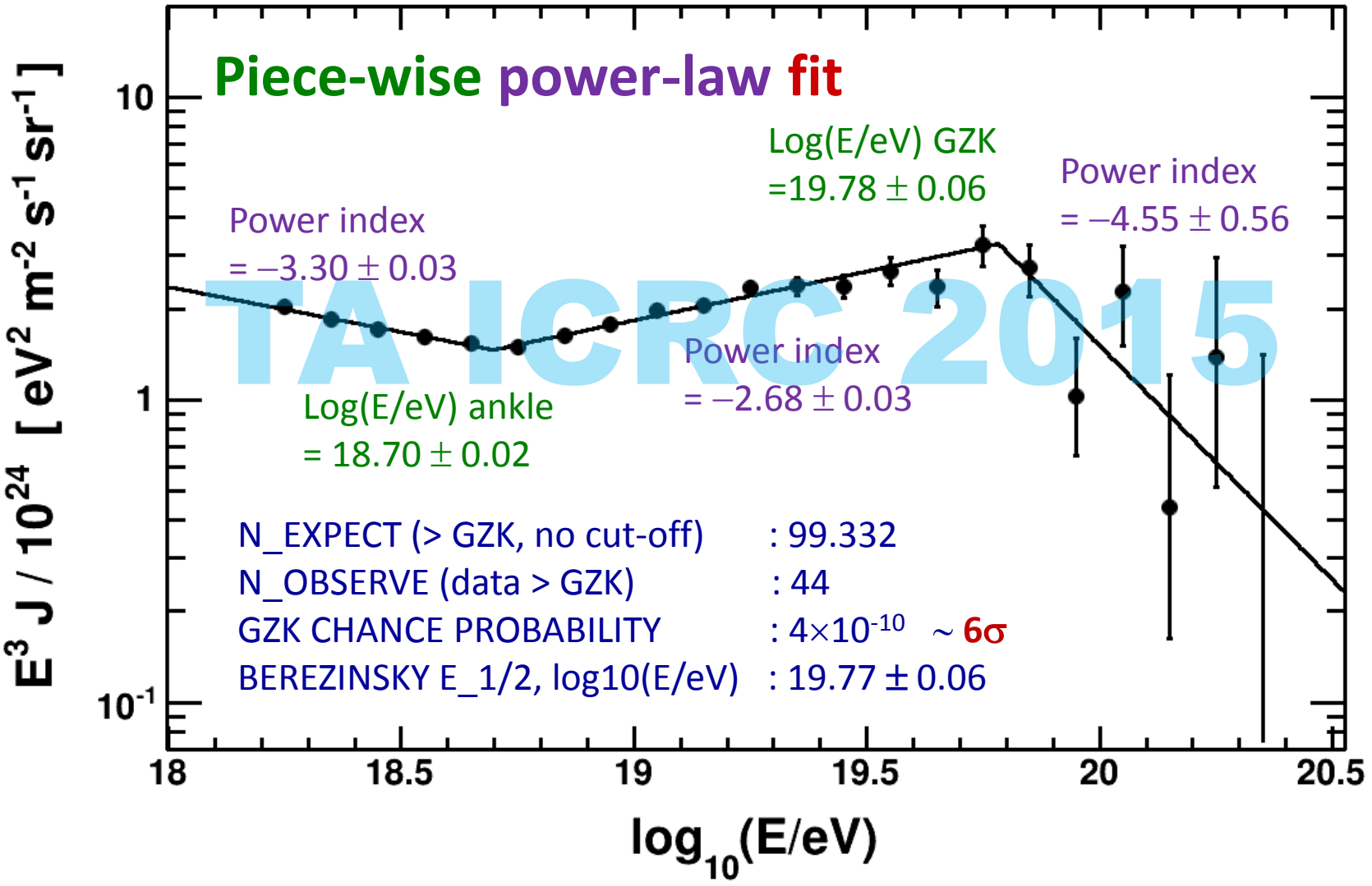
Latest TA results

Energy spectrum

Anisotropy (hotspot)

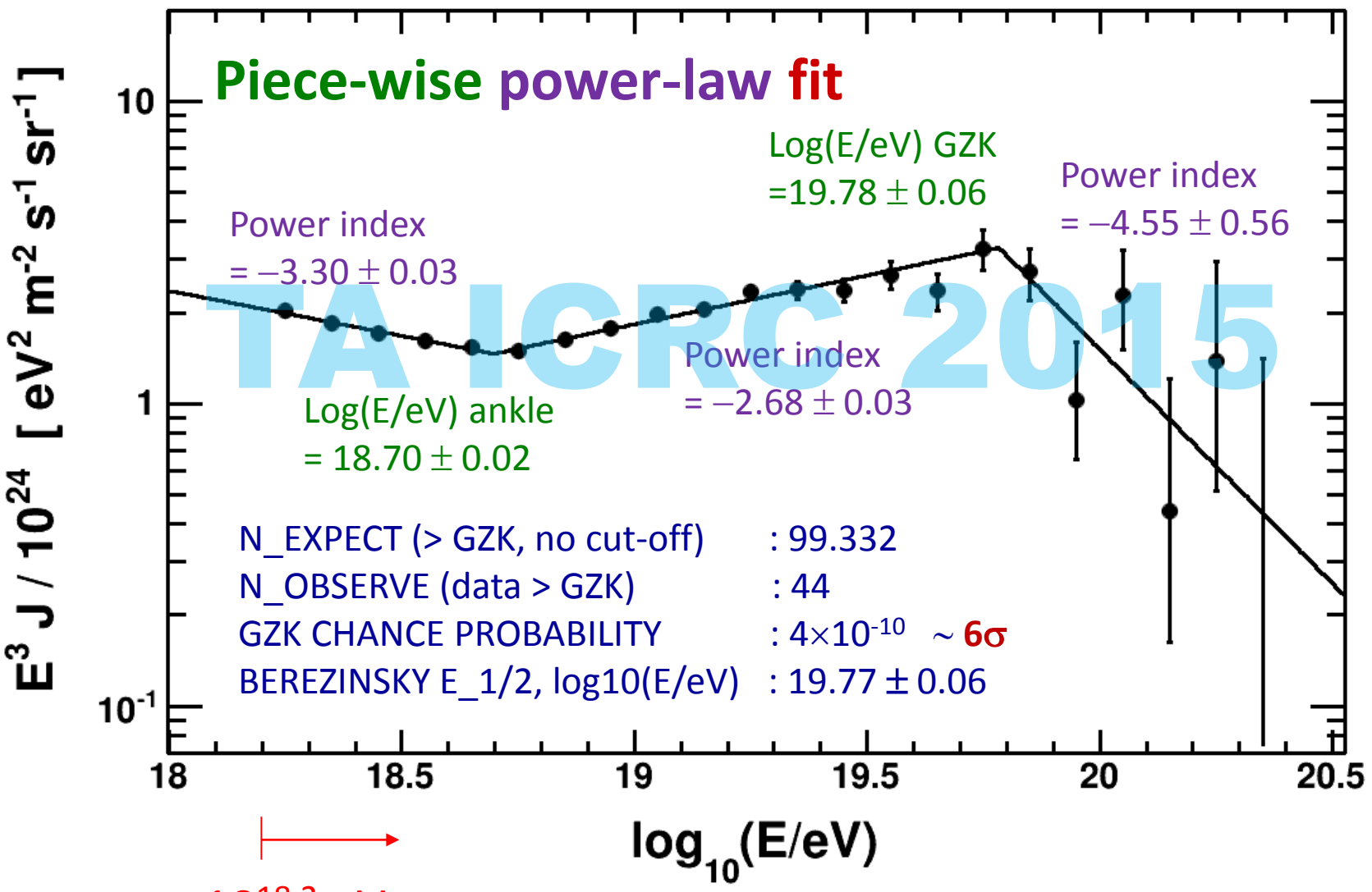
Mass composition (Xmax)

7 year TA SD spectrum



Previously Pubilshed: **4 year TA surface detector spectrum**
Astrophysical Journal Letters 768 L1 (2013)

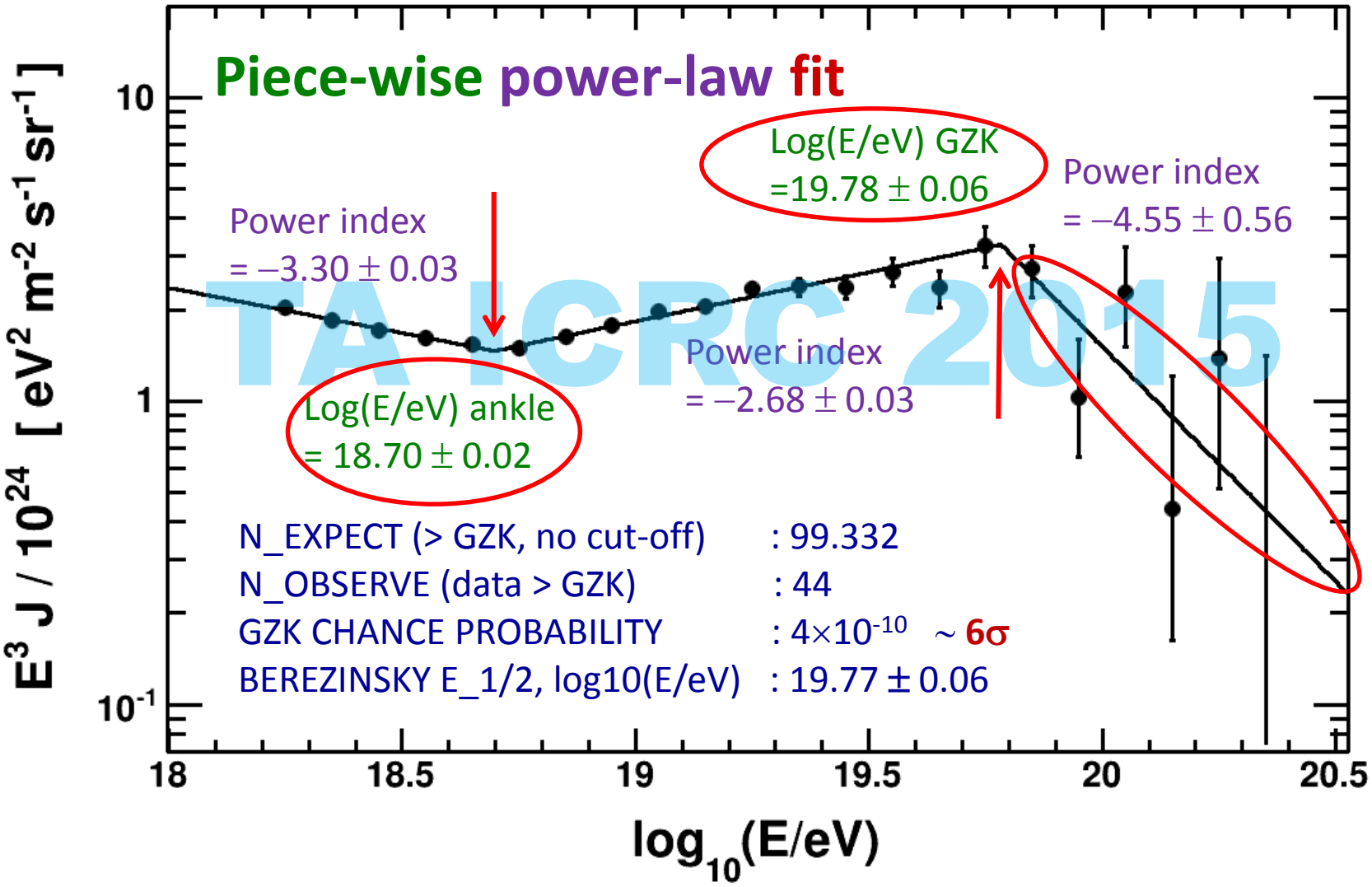
7 year TA SD spectrum



$10^{18.2}$ eV

Previously Pubilshed: **4 year TA surface detector spectrum**
Astrophysical Journal Letters 768 L1 (2013)

7 year TA SD spectrum



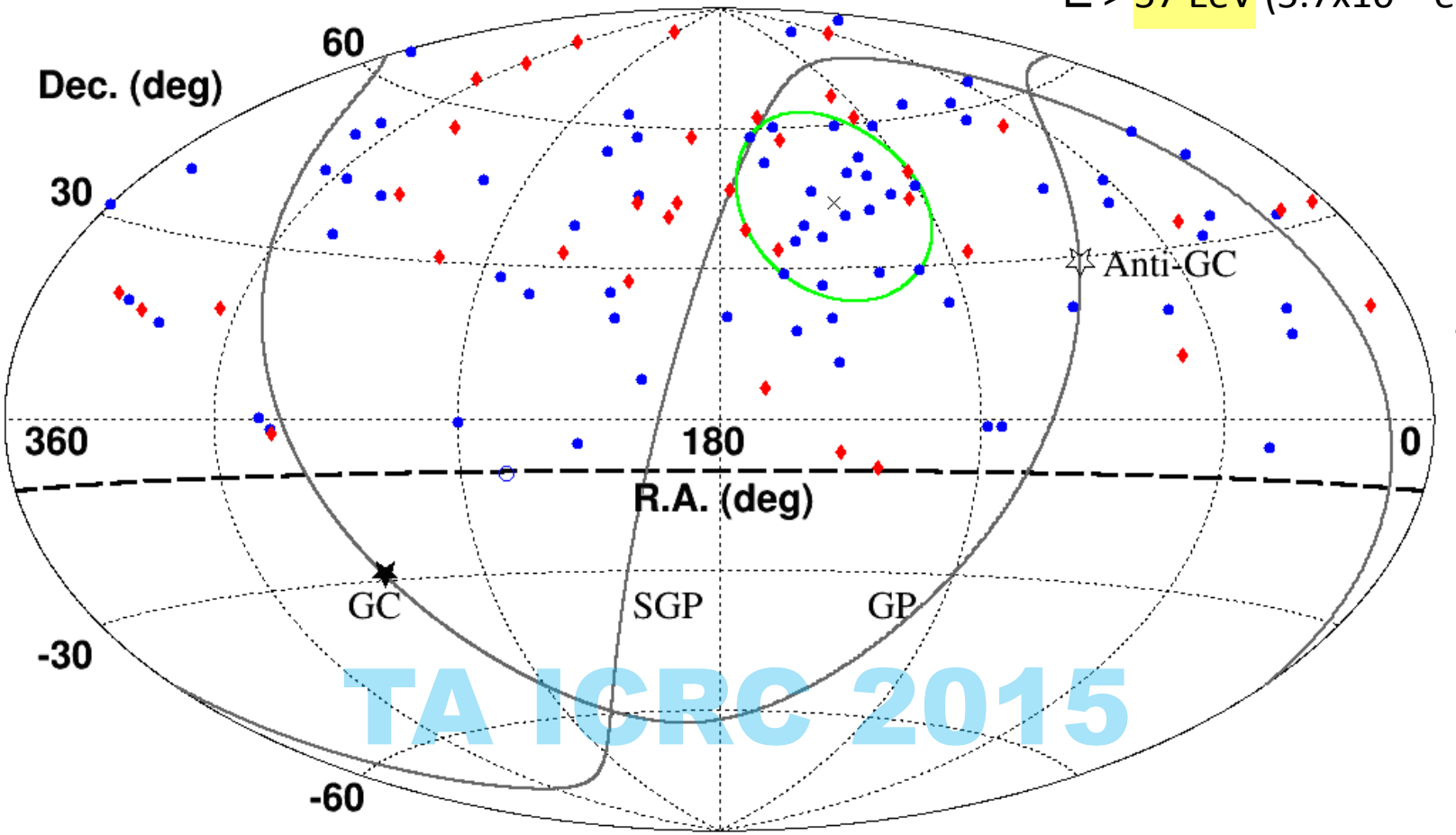
Previously Pubilshed: **4 year TA surface detector spectrum**
Astrophysical Journal Letters 768 L1 (2013)

Hot Spot update: 7 years

by Kazumasa KAWATA

2008 May 11 – 2015 May 11

E > 57 EeV (5.7×10^{19} eV)



TA FOV

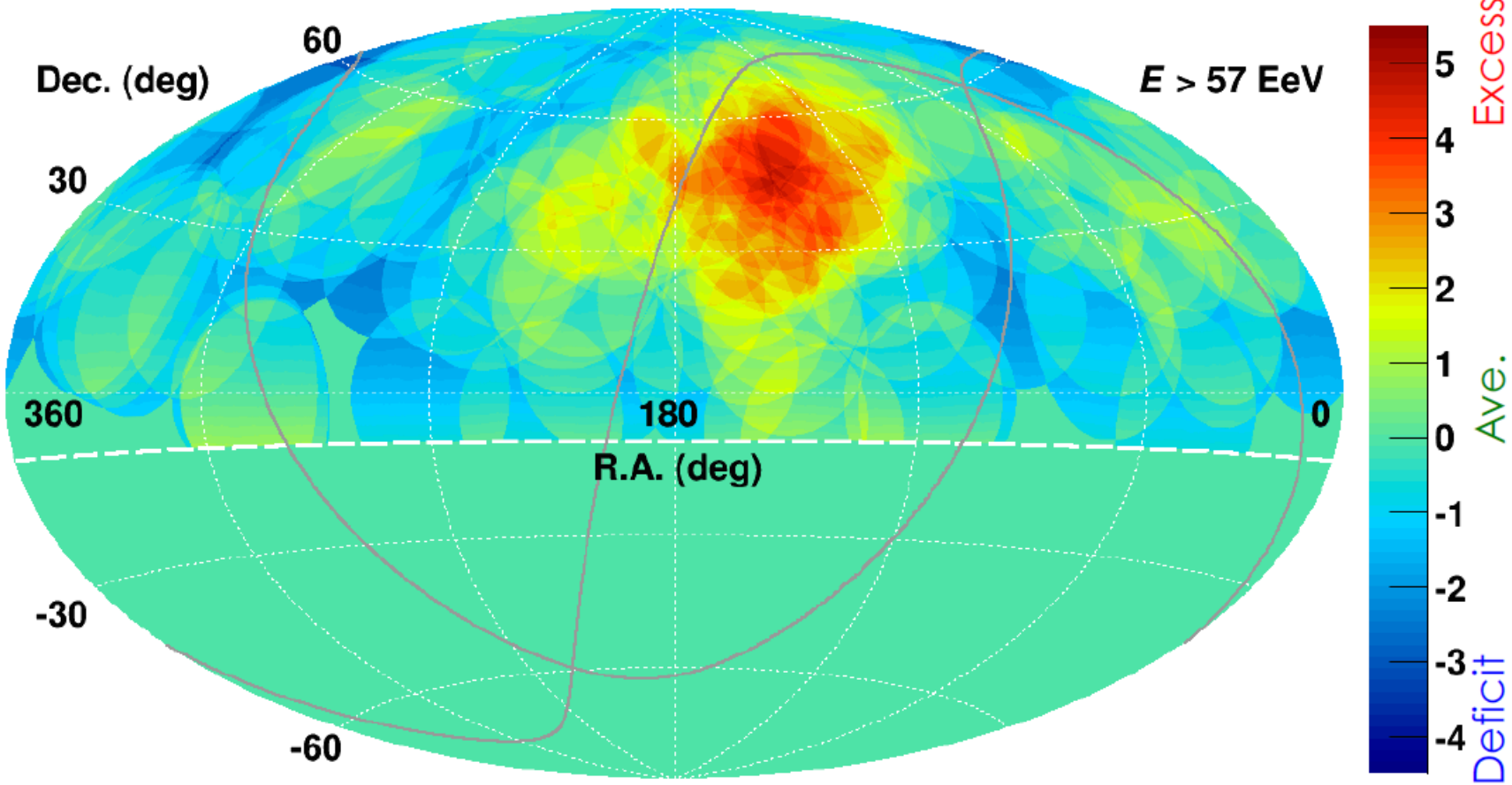
First 5-year data (72 events) -- ApJ 790 L21 (2014)

New 2-year data (37 events)

Total 7-year data(109 events)

Significance map for TA 7 years of SD data

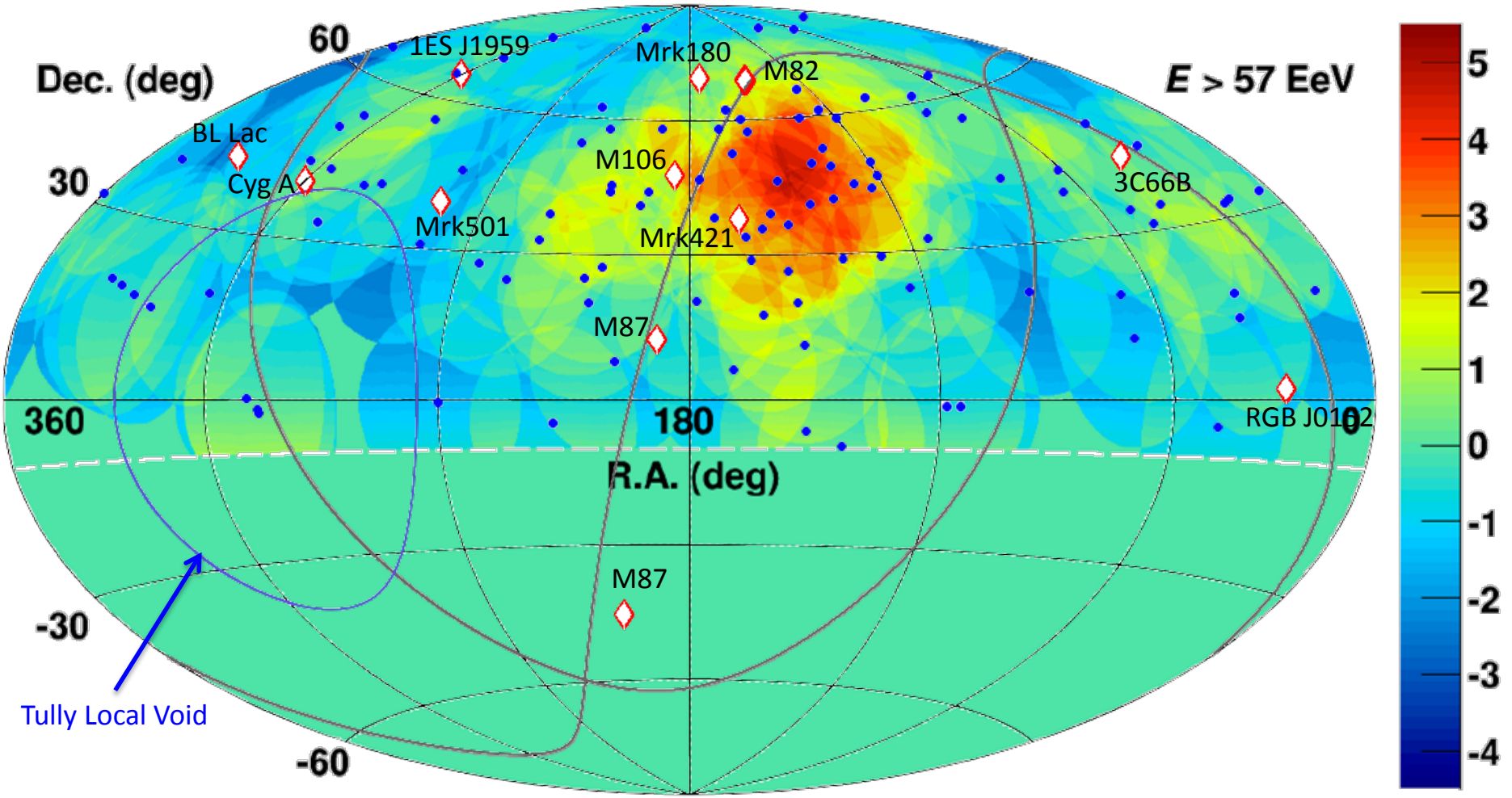
Oversampling with 20°-radius circles



Ma significance 5.07σ (N_{on} = 24, N_{bg} = 6.88)
Centered at RA = 148.4°, Dec. = 44.5° (shifted from SGP by 17°)

Chance Prob. = 3.7×10^{-4} (3.4σ)

TA hotspot and nearby prominent sources



Mrk 421, Mrk 180: blazars
M82: starburst galaxy

K. Fang, et al., ApJ, 794, 126 (2014)
H.-N. He, et al., arXiv:1411.5273 (2014)

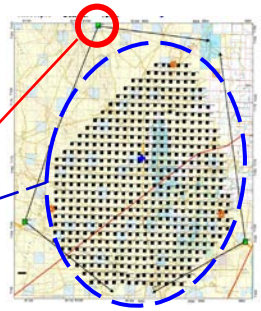
Composition from Xmax

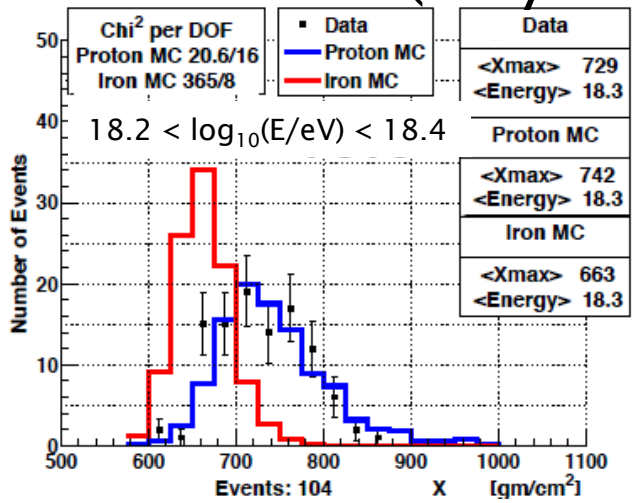
(MD FD +SD)

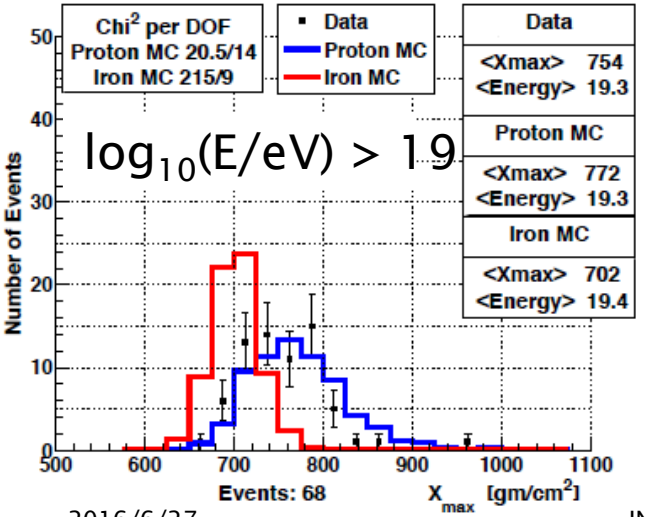
APP 64 (2015) 49-62

TA Middle Drum hybrid data

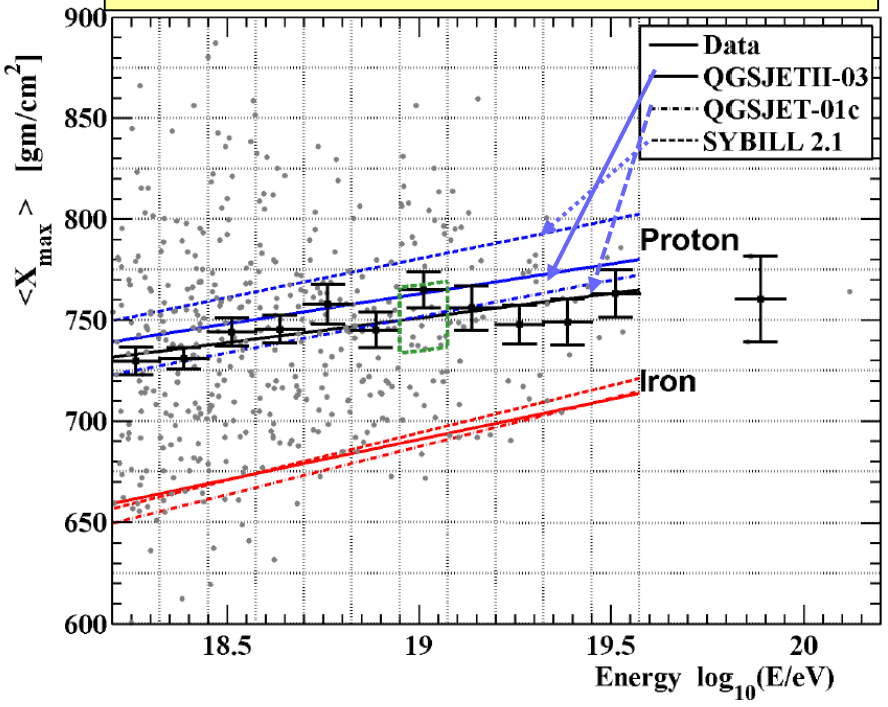
(May 2008 - May 2013)







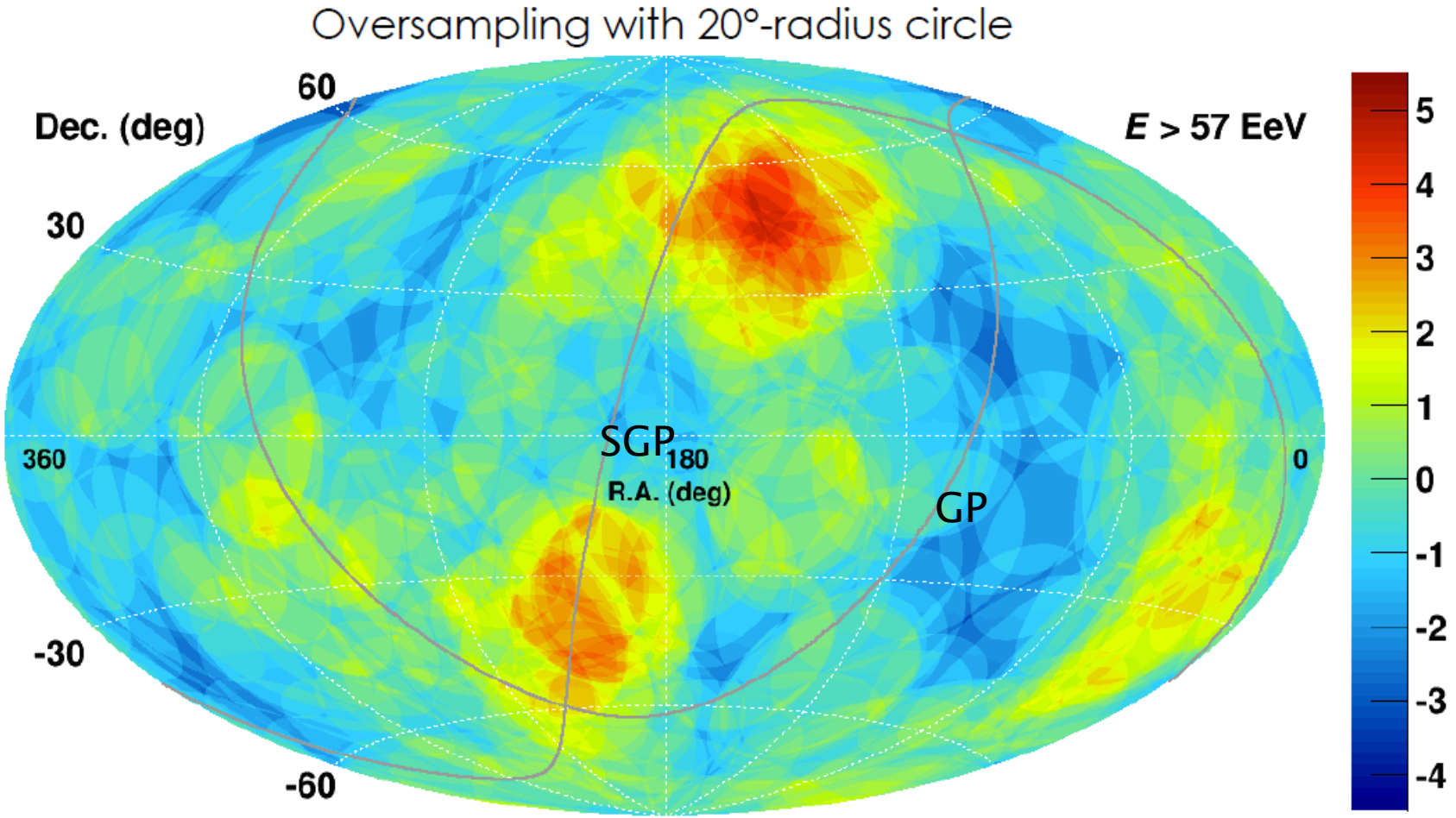
Black points : TA data
MC(QGSJET-II-03): proton, Fe



Consistent with light composition

Poor statistics beyond $10^{19.5}$ eV

All sky survey with TA and Auger



No correction for E scale difference b/w TA and PAO !!

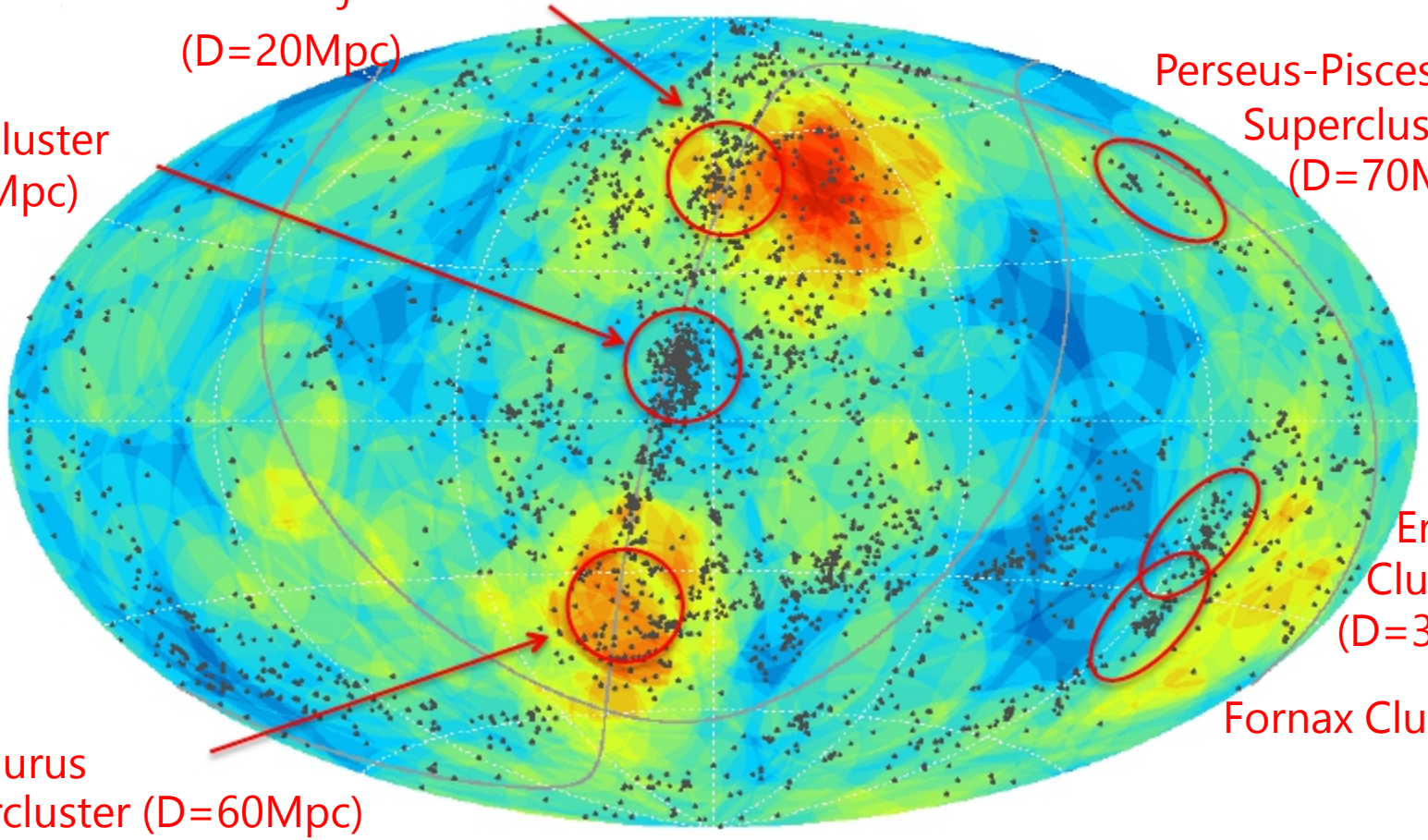
Northern TA : 7 years 109 events (>57EeV)

Southern Auger : 10 years 157 events (>57EeV)

Southern hotspot is seen at Cen A(Pre-trial ~3.6σ)

All sky survey with TA and Auger

with Nearby Galaxy Clusters

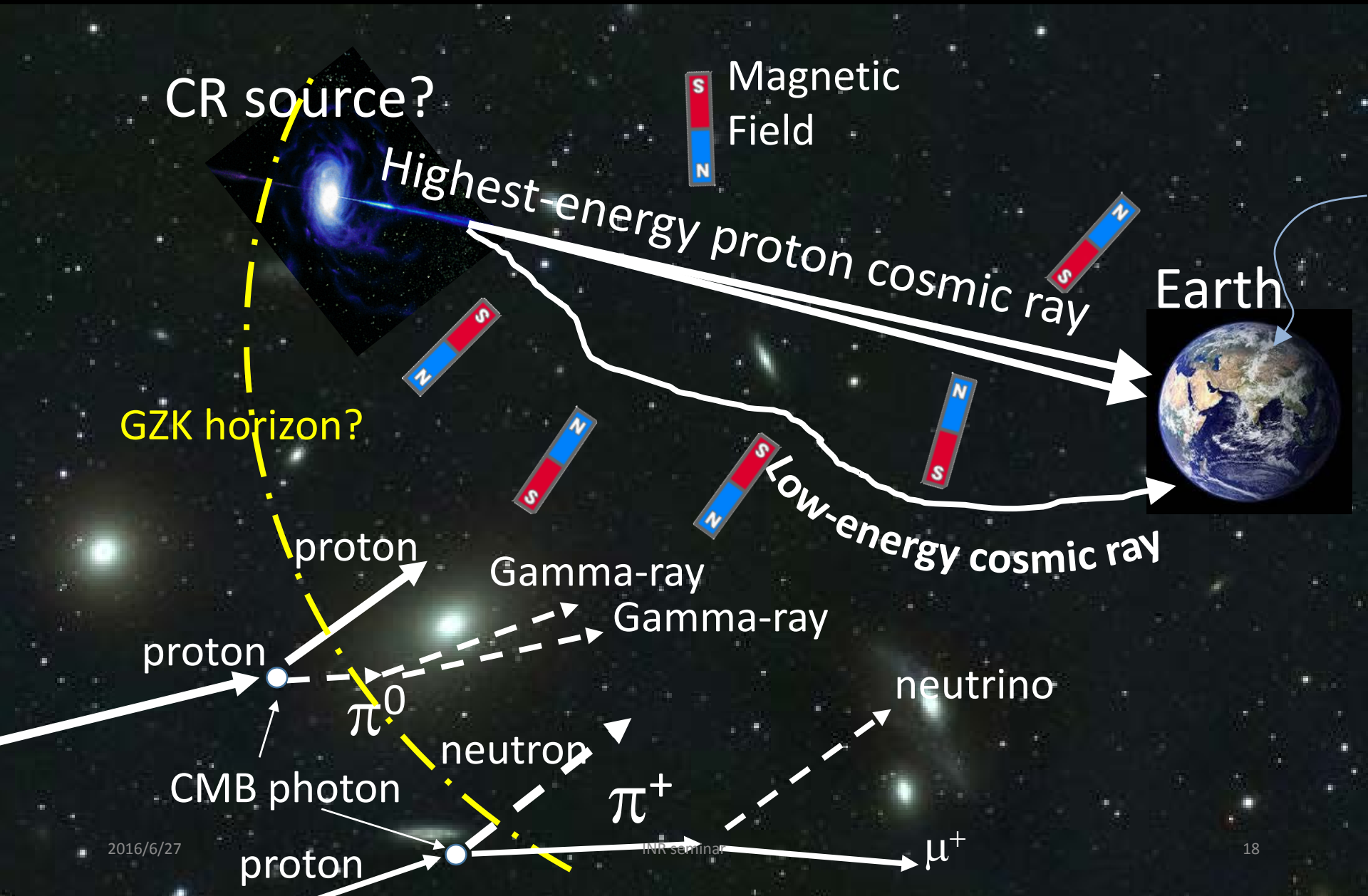


Huchra, et al, ApJ, (2012)

dots (·) : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

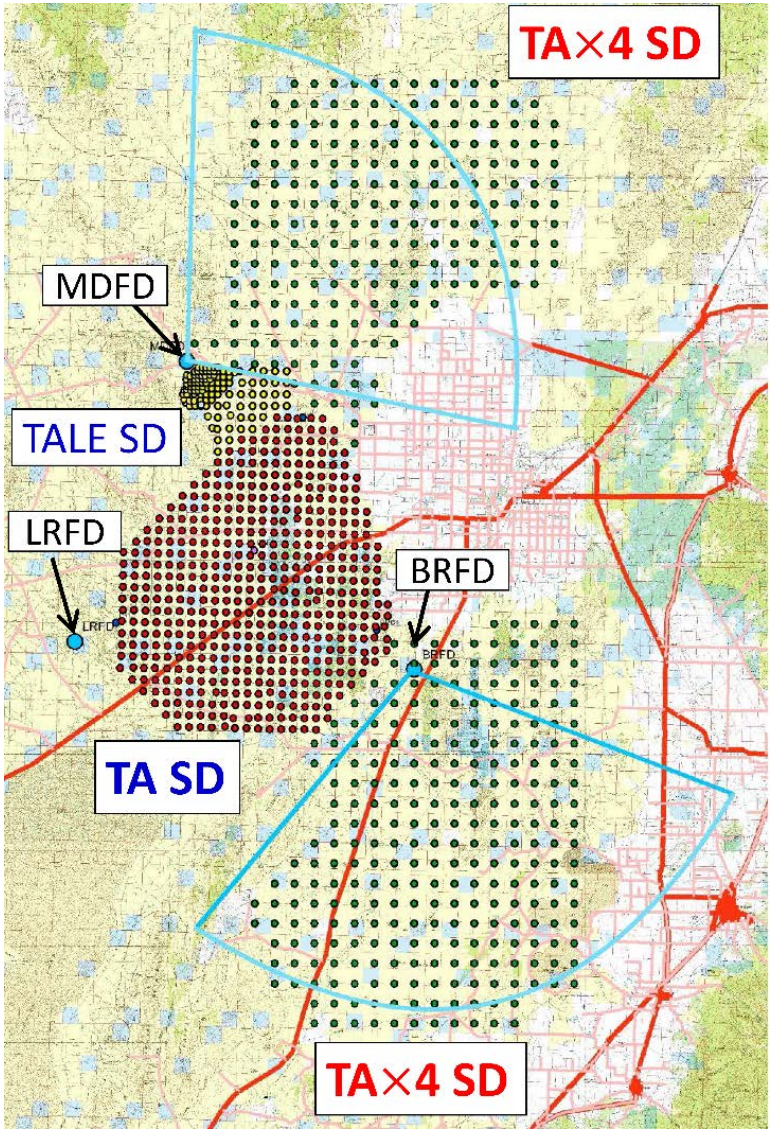
TA hotspot is found near the Ursa Major Cluster

GZK cutoff


CR source?
Magnetic Field
Highest-energy proton cosmic ray
Earth
GZK horizon?
Low-energy cosmic ray
proton
Gamma-ray
Gamma-ray
proton
neutrino
π^0
neutron
CMB photon
π^+
proton
μ^+

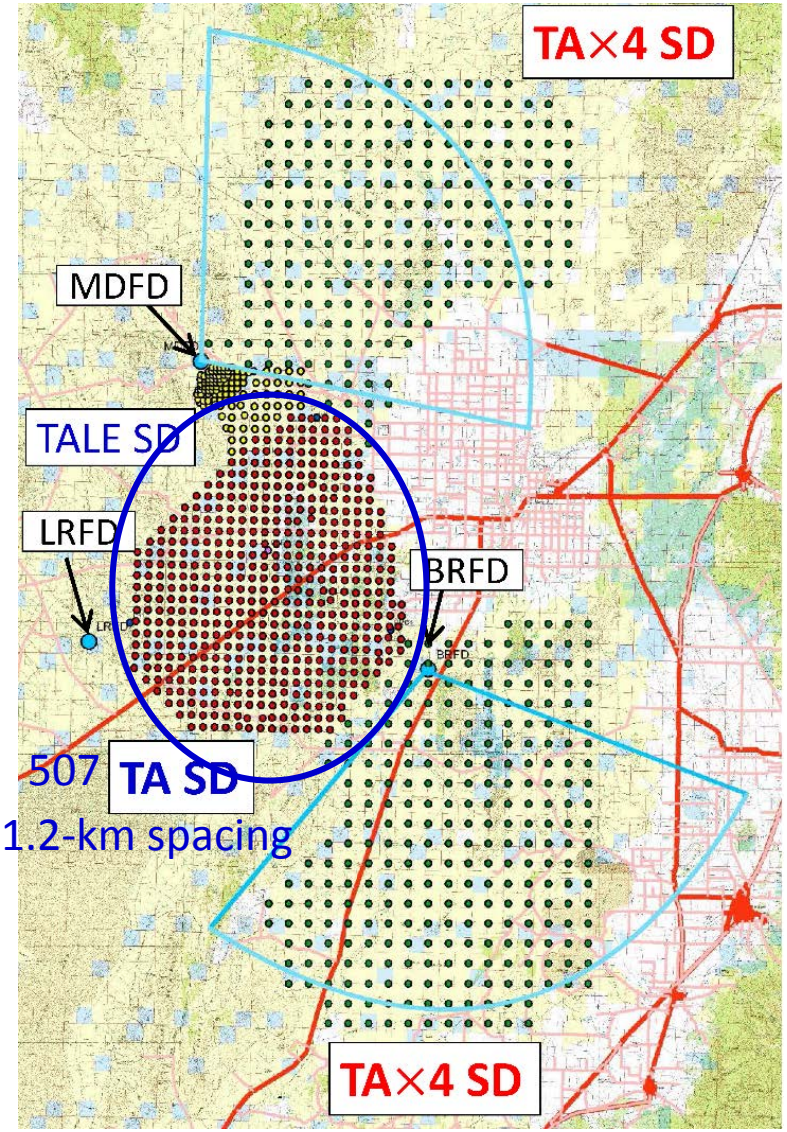
TA×4

- Quadruple TA SD (~3000 km^2)
  - 500 scintillator SDs
    2.08 km spacing
- 2 FD stations
  - Refurbished HiRes telescopes
- Proposals
  - SD: approved in Japan in April 2015
  - FD: submit in US in October 2015
- Schedule
  - TA in operation
  - ~3-year construction
  - ~2-year observation
- ~19 years of TA SD data by May 2020
  - ~300 highest-energy cosmic rays (E>57EeV)
  - ~16 TA years of hybrid data



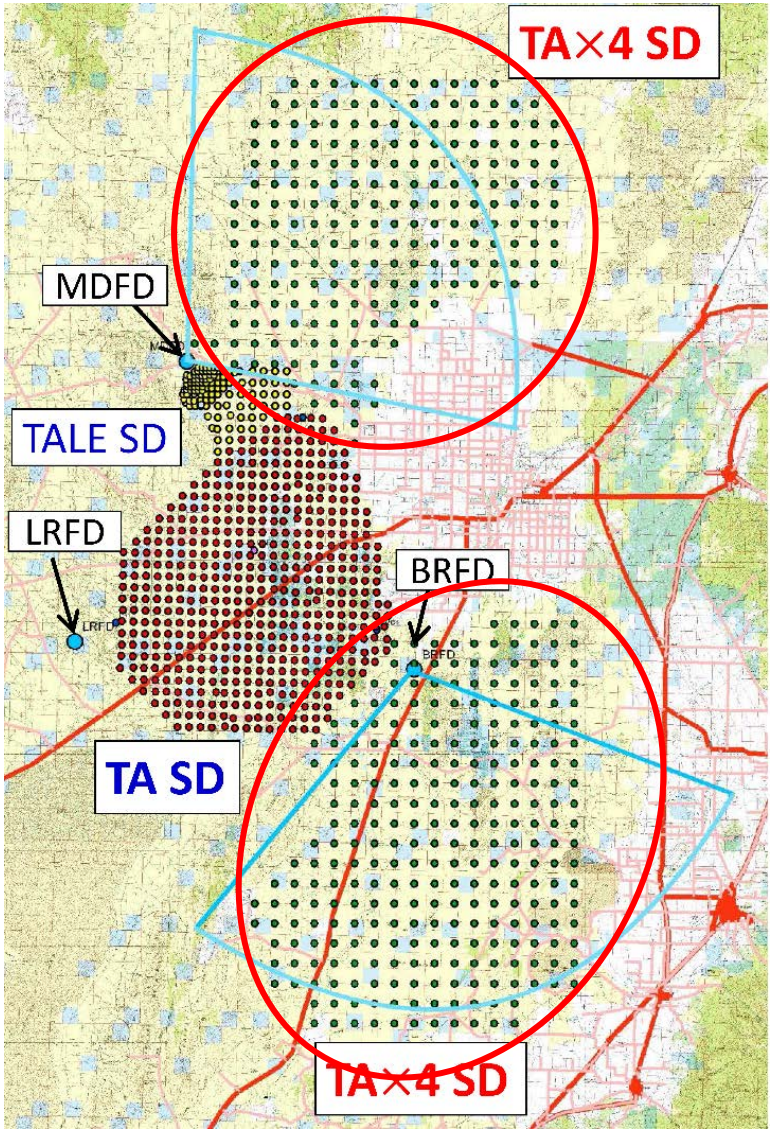
TA×4

- Quadruple TA SD (~3000 km^2)
  - 500 scintillator SDs
    2.08 km spacing
- 2 FD stations
  - Refurbished HiRes telescopes
- Proposals
  - SD: approved in Japan in April 2015
  - FD: submit in US in October 2015
- Schedule
  - TA in operation
  - ~3-year construction
  - ~2-year observation
- ~19 years of TA SD data by May 2020
  - ~300 highest-energy cosmic rays (E>57EeV)
  - ~16 TA years of hybrid data



TA×4

- Quadruple TA SD (~3000 km^2)
  - 500 scintillator SDs
    2.08 km spacing
- 2 FD stations
  - Refurbished HiRes telescopes
- Proposals
  - SD: approved in Japan in April 2015
  - FD: submit in US in October 2015
- Schedule
  - TA in operation
  - ~3-year construction
  - ~2-year observation
- ~19 years of TA SD data by May 2020
  - ~300 highest-energy cosmic rays (E>57EeV)
  - ~16 TA years of hybrid data

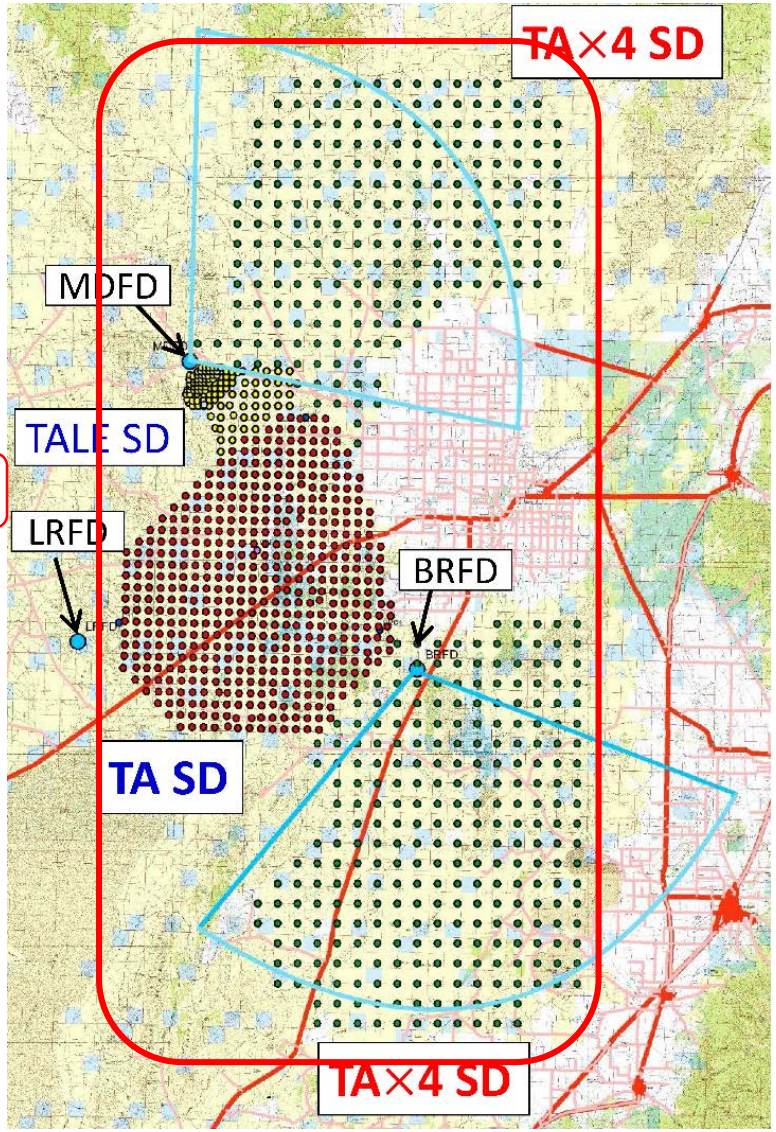


TA×4

- Quadruple TA SD (~3000 km^2)
  - 500 scintillator SDs
    2.08 km spacing
- 2 FD stations
  - Refurbished HiRes telescopes
- Proposals
  - SD (5 years): approved in Japan in April 2015
  - FD: submit in US in October 2015

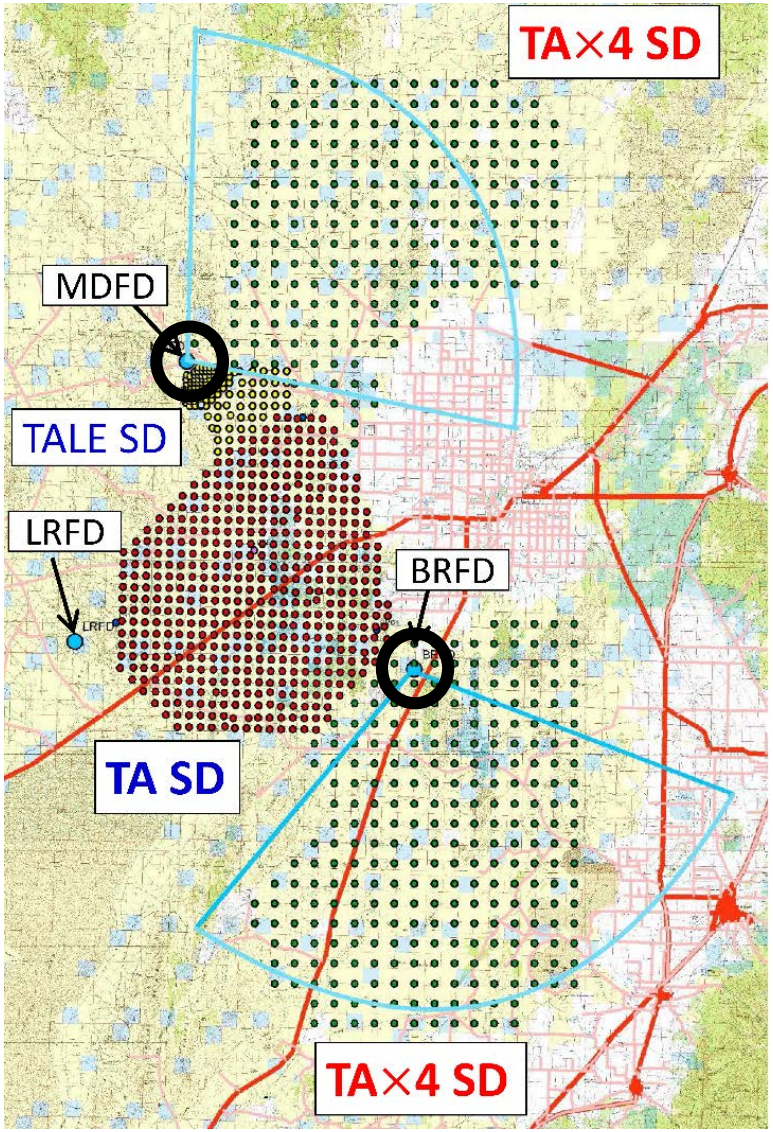
Start construction this year

- Schedule
  - TA in operation
  - ~3-year construction
  - ~2-year observation
- ~19 years of TA SD data by May 2020
  - ~300 highest-energy cosmic rays (E>57EeV)
  - ~16 TA years of hybrid data



TA×4

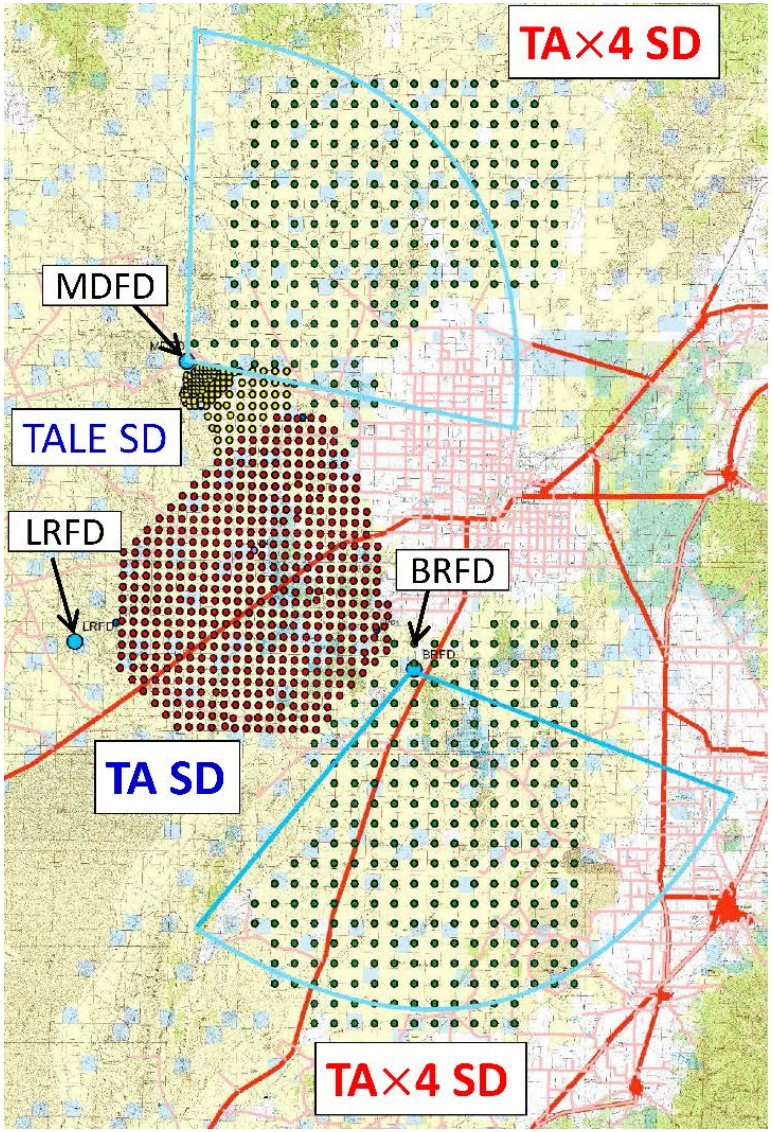
- Quadruple TA SD (~3000 km^2)
  - 500 scintillator SDs
    2.08 km spacing
- 2 FD stations (refurbished HiRes telescopes)
  - Confirm **energy scale**
  - Increase the number of **hybrid** data
- Proposals
  - SD: approved in Japan in April 2015
  - FD: submit to NSF in US in October 2015
- Schedule
  - TA in operation
  - ~3-year construction (by Dec. 2017)
  - ~2-year observation
- ~19 years of TA SD data by May 2020
  - ~300 highest-energy cosmic rays (E>57EeV)
  - ~16 TA years of hybrid data



TA×4

- Quadruple TA SD (~3000 km^2)
  - 500 scintillator SDs
    2.08 km spacing
- 2 FD stations (refurbished HiRes telescopes)
  - Confirm energy scale
  - Increase the number of hybrid data
- Proposals
  - SD: approved in Japan in April 2015
  - FD: submit to NSF in US in October 2015

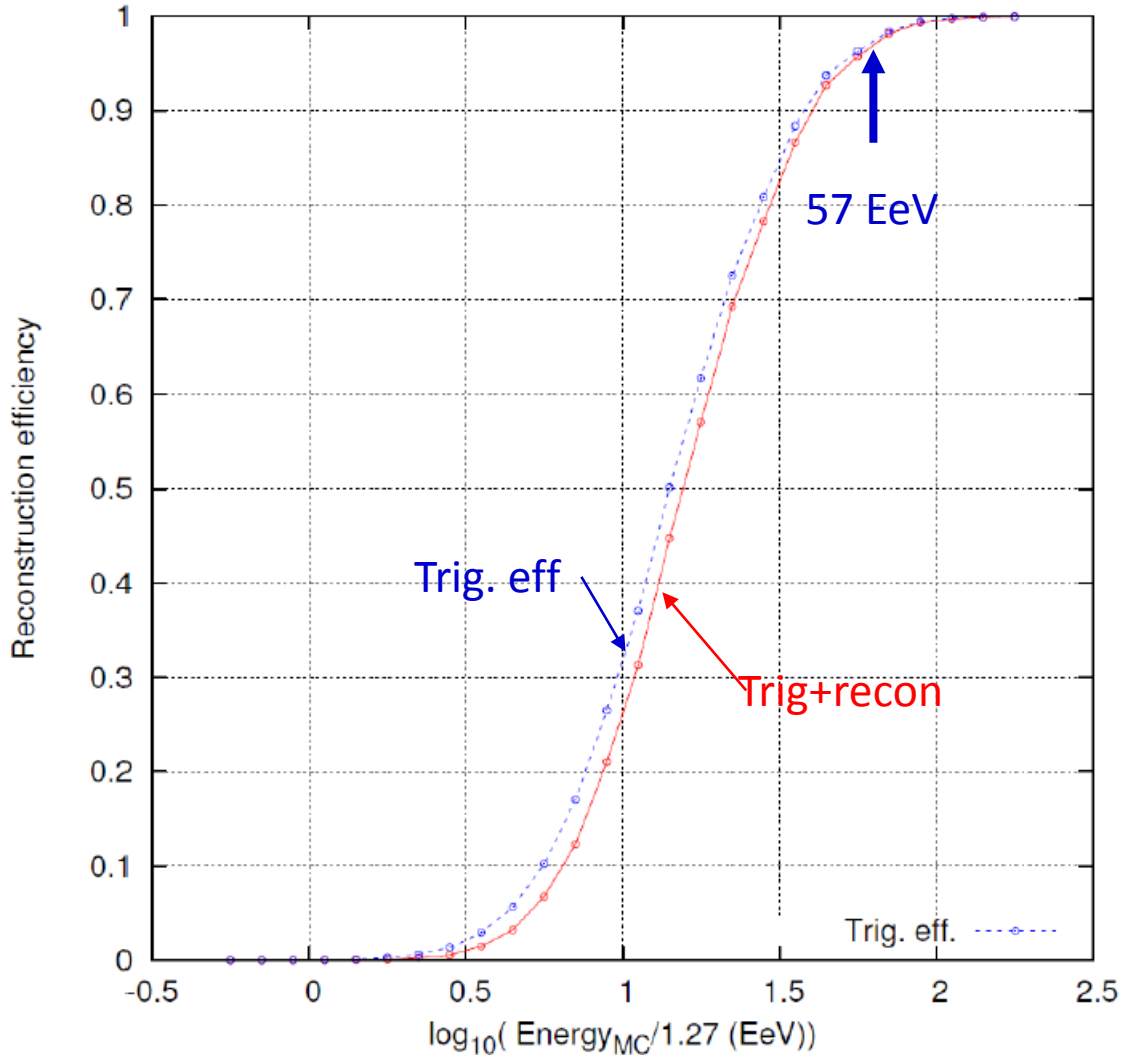
- Schedule
  - TA in operation
  - ~3-year construction
  - ~2-year observation
- ~19 years of TA SD data by May 2020
  - ~300 highest-energy cosmic rays (E>57EeV)
  - ~16 TA years of hybrid data



Efficiency for additional TA × 4 SD array

Differential for energies

(2.08 km spacing)



Trigger condition
. 3 MIPS
. 3-fold SDs
. < 8x2.08/1.2usec

Reconstruction
. NSD≥ 4

TA SD reconstruction efficiency =100% for $E > 10^{19}$eV
(1.2 km spacing)

Prospect of TA×4

- Arrival direction
  - Hotspot
    - Confirmation at > 5σ level
    - Fine structure?
    - Other excess spots?
    - Study of galactic MF and extragalactic MF
  - Point source search
  - Correlation with the results by other experiments
    - TA/Auger whole sky analysis
    - Search for correlation with gamma-ray sources
    - Search for correlation with IceCube neutrinos
- Measurement of spectrum and Xmax of cosmic rays around cutoff with high statistics
- Search for UHE gamma rays and neutrinos

Hotspot
Summer 2020 (19 years of TA SD data)

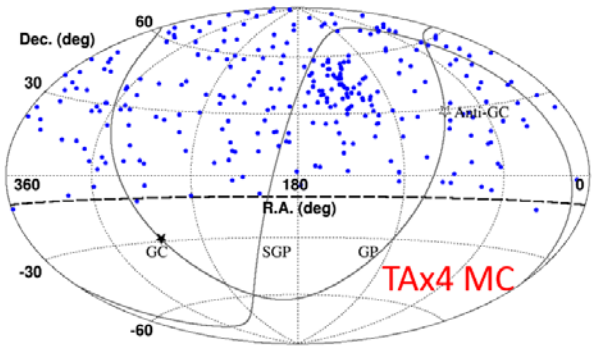
(1) One Hotspot

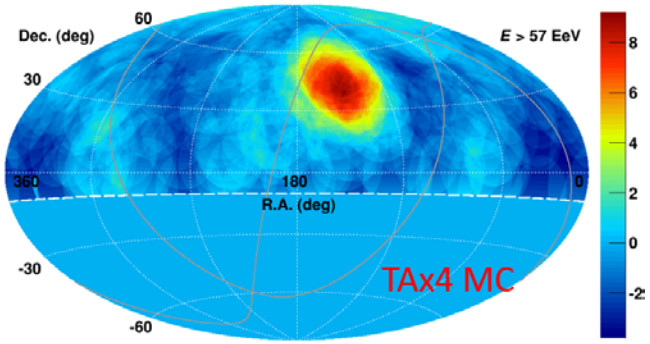
Hotspot Signal
72-17.1=55events
(RA,
Dec)=(148° ,45°)
Gaussian σ=10°

Isotropic B.G.
276-55=221events

Pretrial significance
~8.7σ

Oversampling
20° radius circle



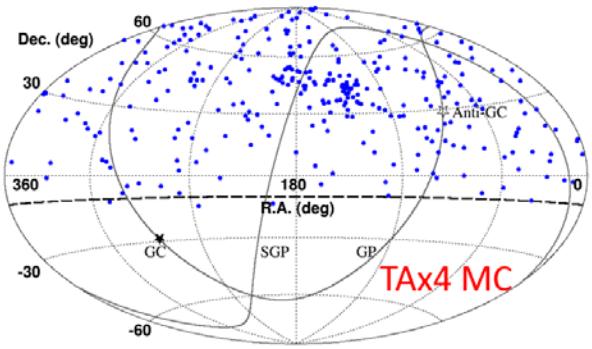


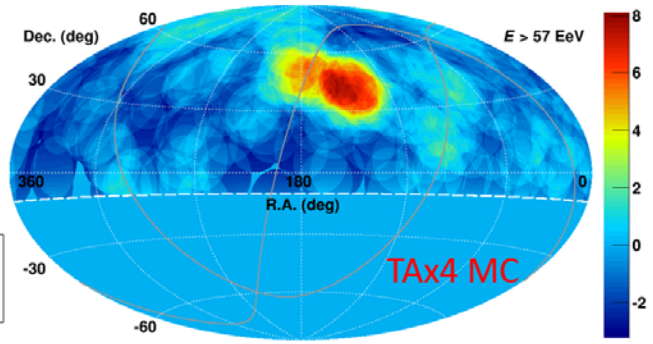
(2) Double Hotspot

Hotspot Signal
Total 55 events
1. 36events
(RA, Dec)=(148° ,45°)
Gaussian σ=8°
2. 19events
(RA, Dec)=(180° ,50°)
Gaussian σ=5°

Isotropic B.G.
276-55=221events

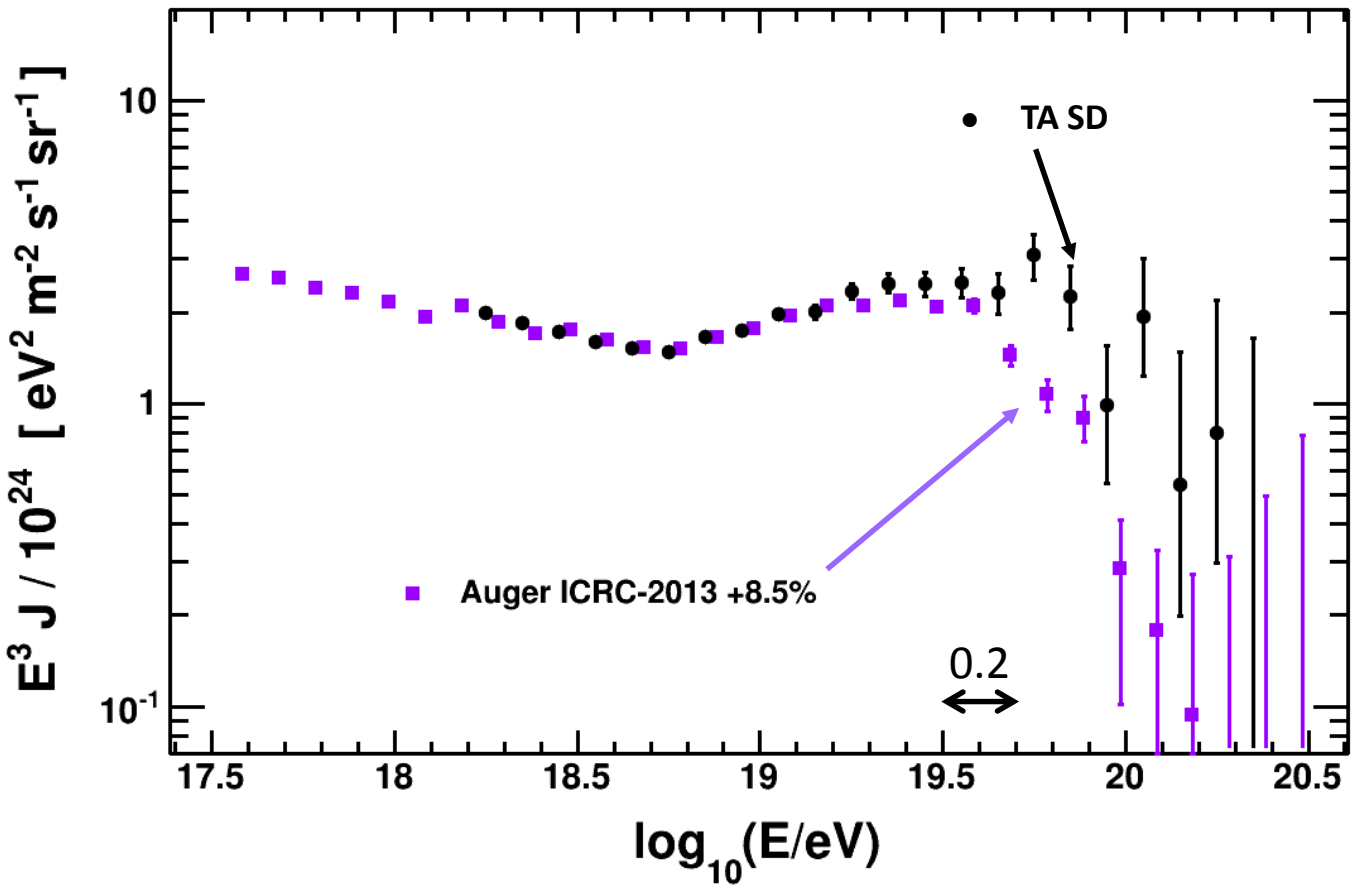
Oversampling
15° radius circle



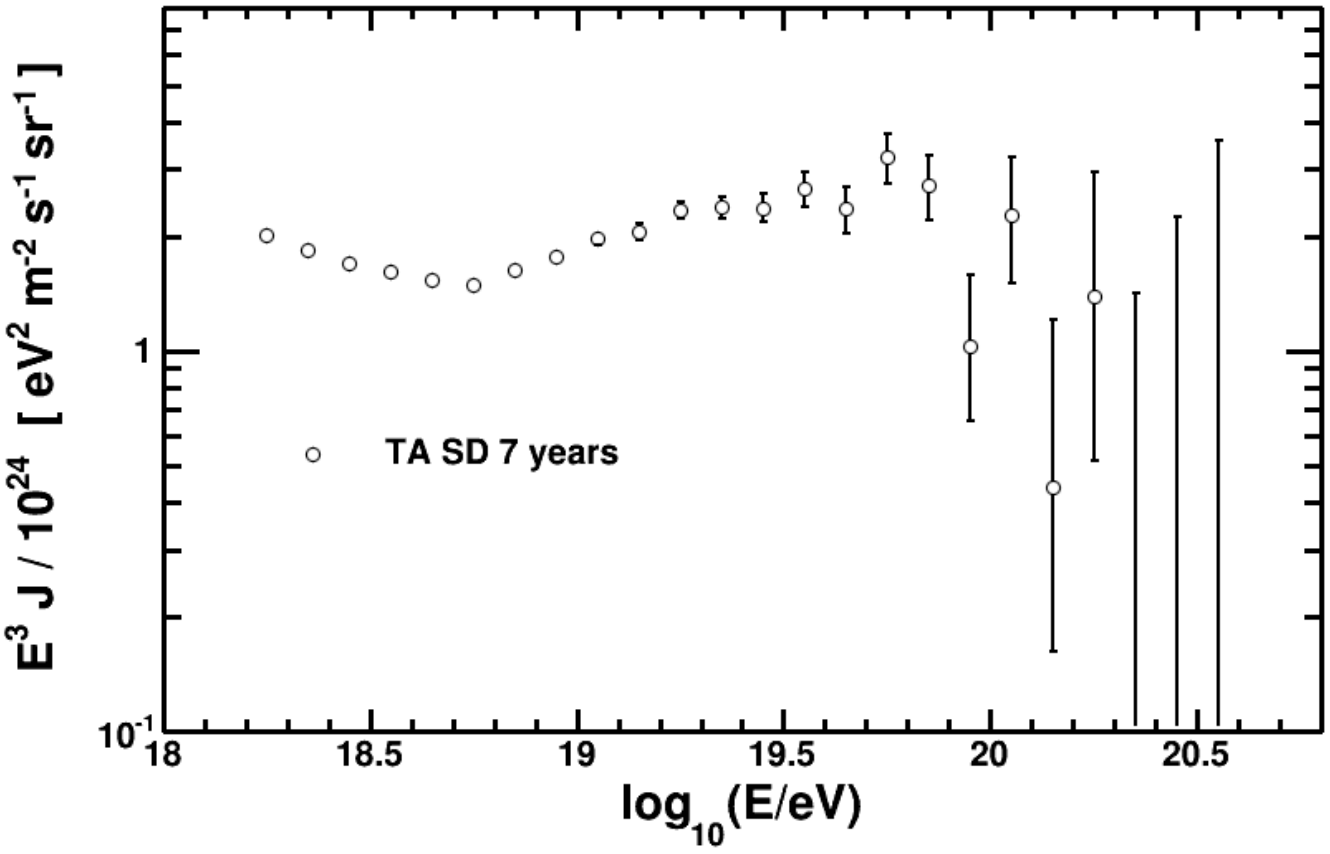


TA×4 will clarify the nature of the hotspot

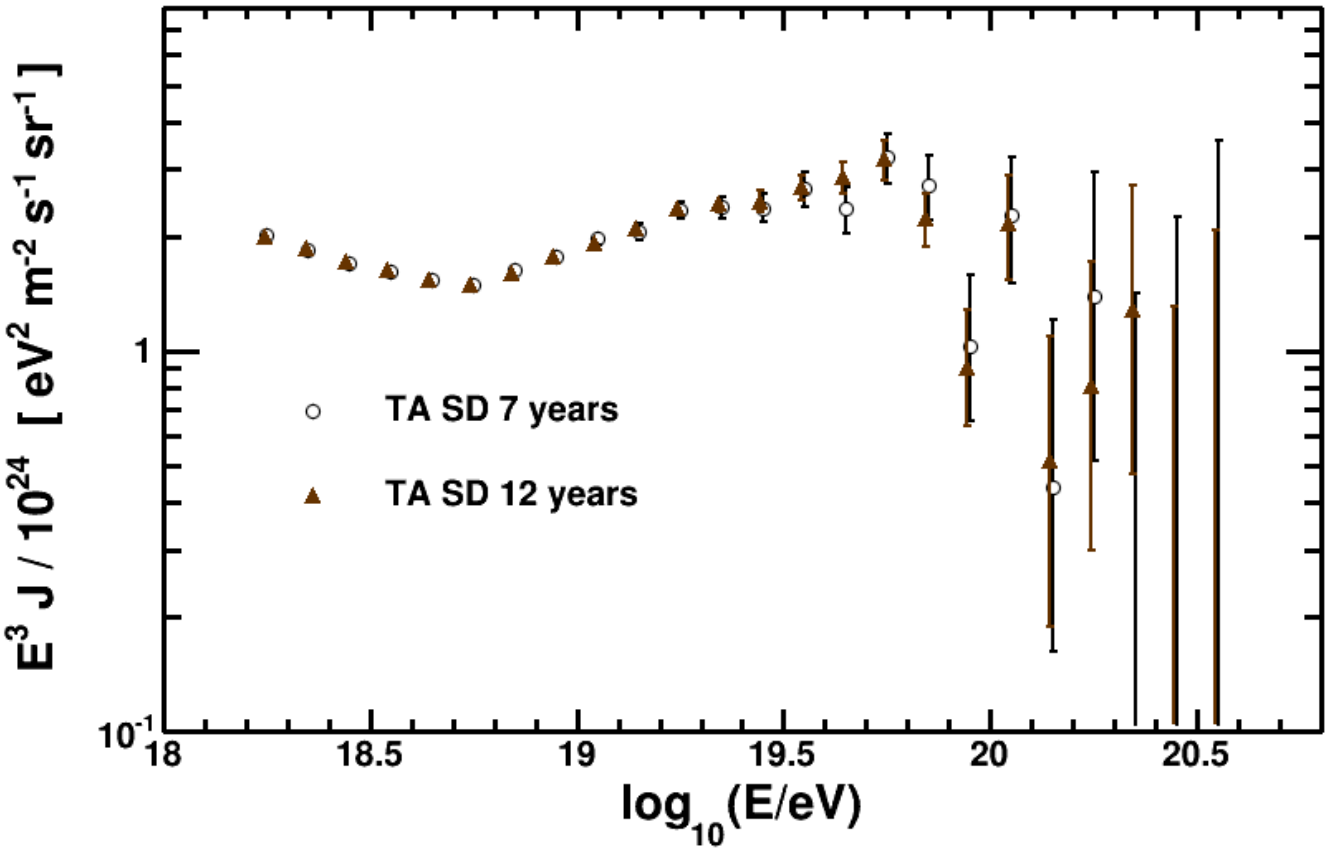
Comparison of TA and Auger (+8.5%) spectra



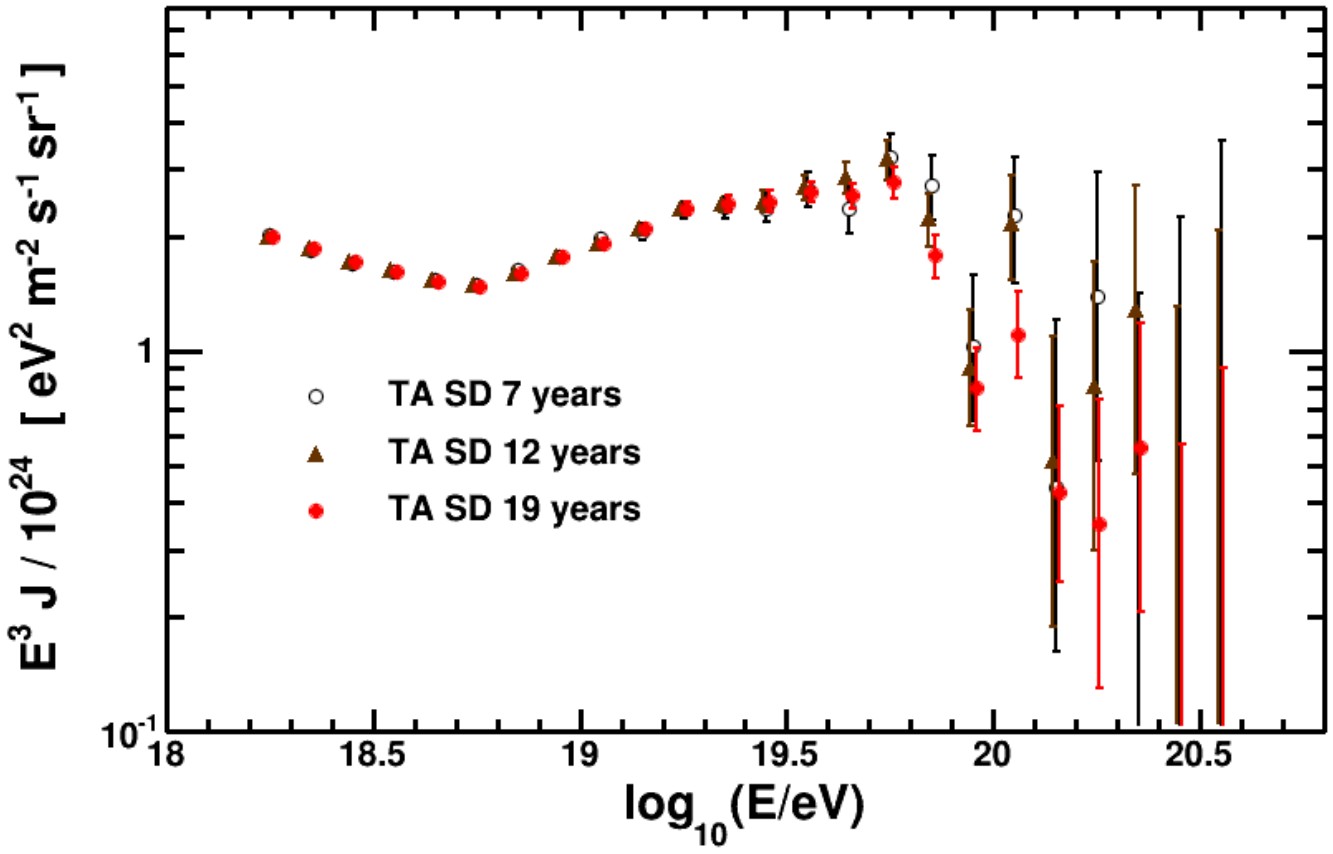
Spectrum
Summer 2015 (7 years of TA SD data)



Spectrum
Summer 2020 (12 years of TA SD data)



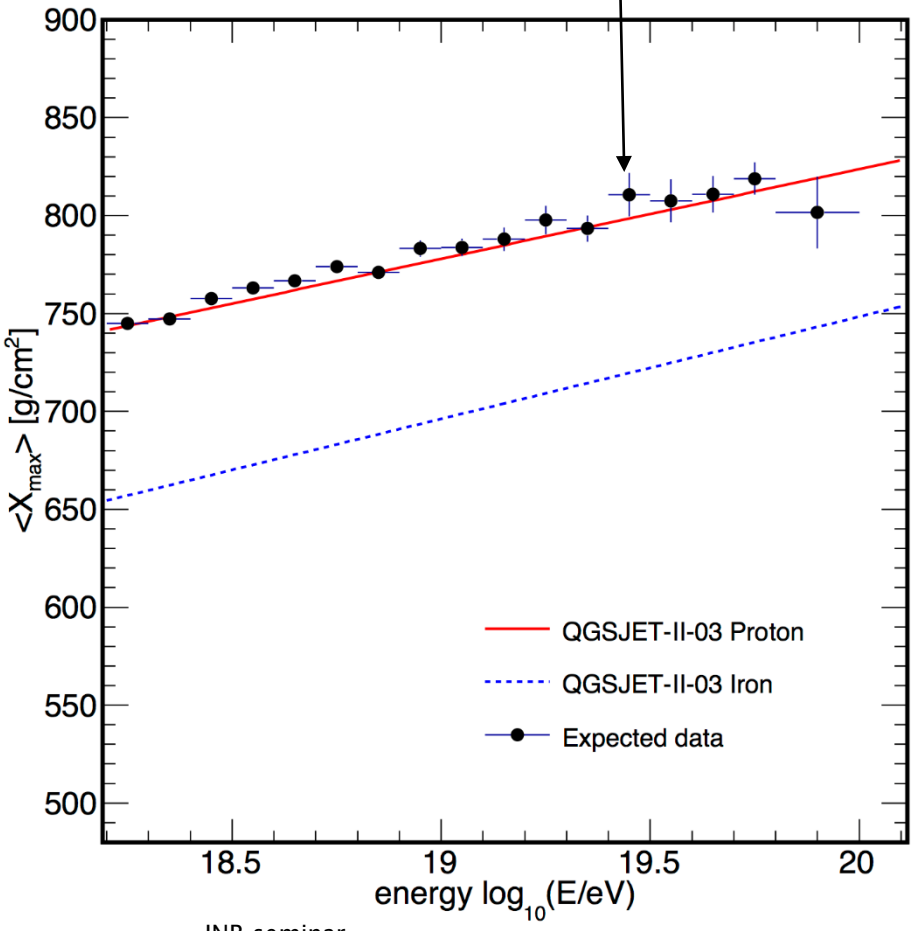
Spectrum
Summer 2020 (19 years of TA SD data)



Xmax in summer 2020
An example of 16.3 years of TA hybrid data

(black points assuming proton QGSJETII-03 model)

Just to see statistical fluctuation



Low-energy extension

TALE

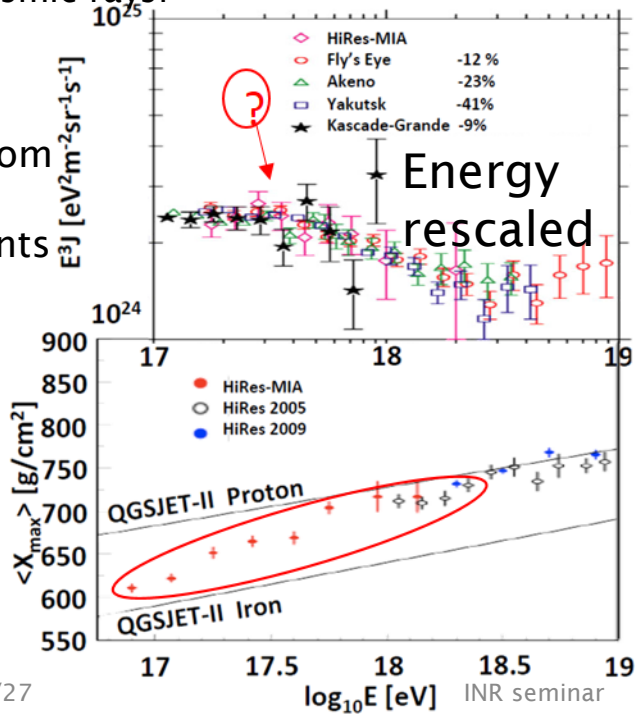
NICHE

TALE (TA Low-energy Extension)
down to $10^{15.6}$ eV

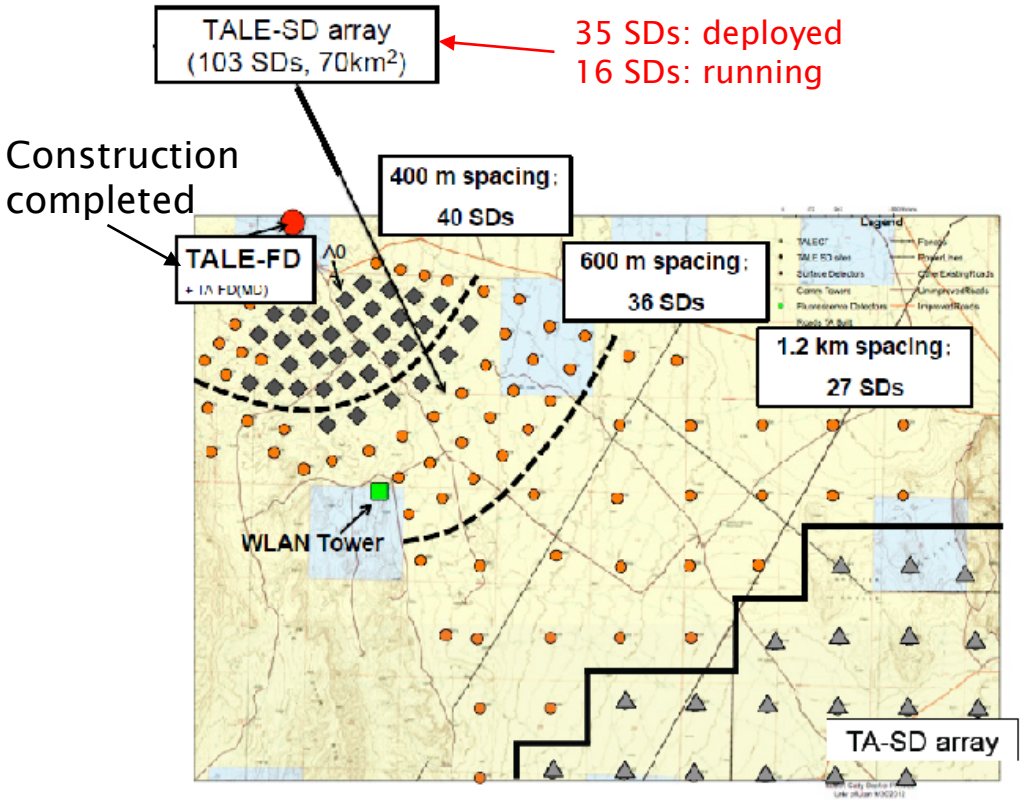
- E = $10^{15.6}$ – 10^{19} eV
  - Second knee at ~$10^{17.5}$ eV?
  - Drastic change of composition at 10^{17}~10^{18} eV?
  - Transition from galactic to extra-galactic cosmic rays?

- ~10^{17} eV cosmic ray shower: compatible with LHC center-of-mass energy

Results from Previous experiments



TALE layout

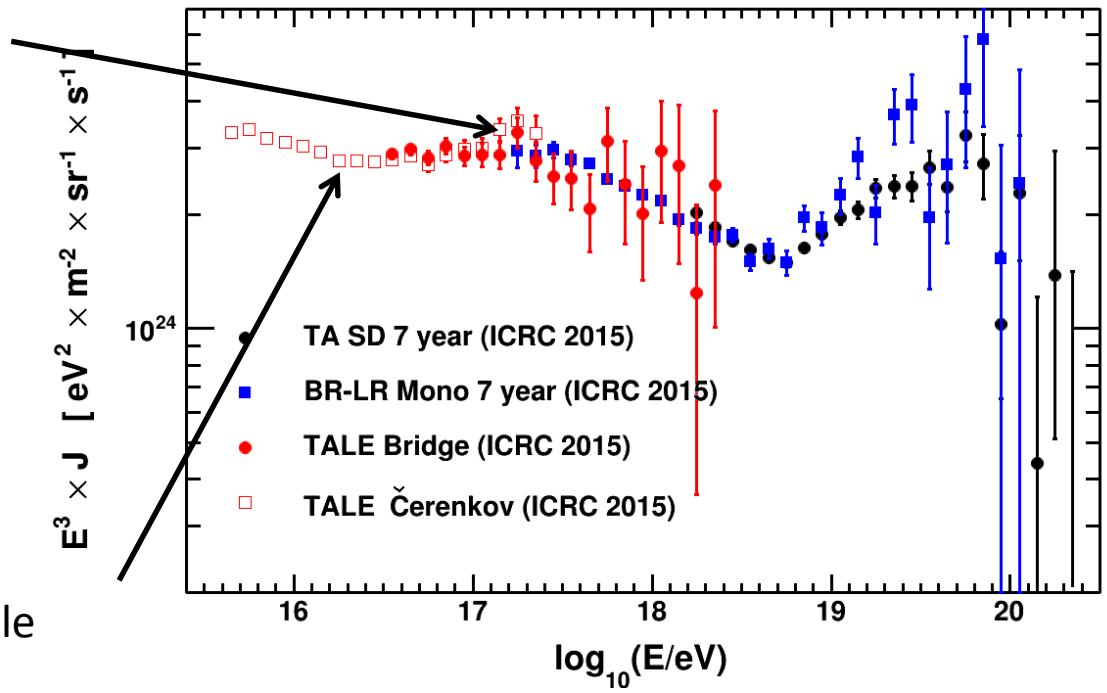


TALE+TA spectrum (E > $10^{15.6}$ eV)

(FD) (SD)

Energy region over 4.7 orders of magnitude

Second knee
at E = $10^{17.3}$ eV



D. Ivanov
at ICRC2015

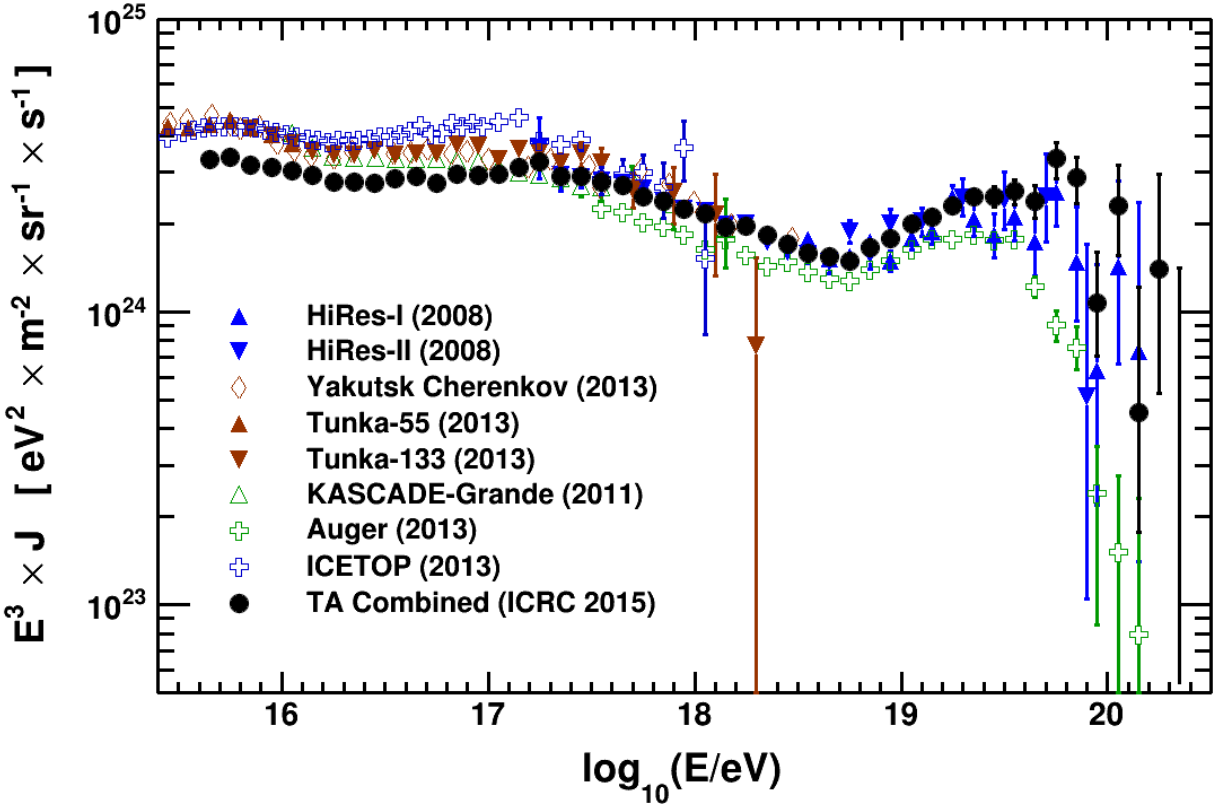
Low energy ankle
at $10^{16.34}$ eV

Composition meas. with **better Xmax resolution**: urgent issue
→ **Hybrid (FD+SD)** analysis by the full TALE SD
(with time information near the core on the ground)

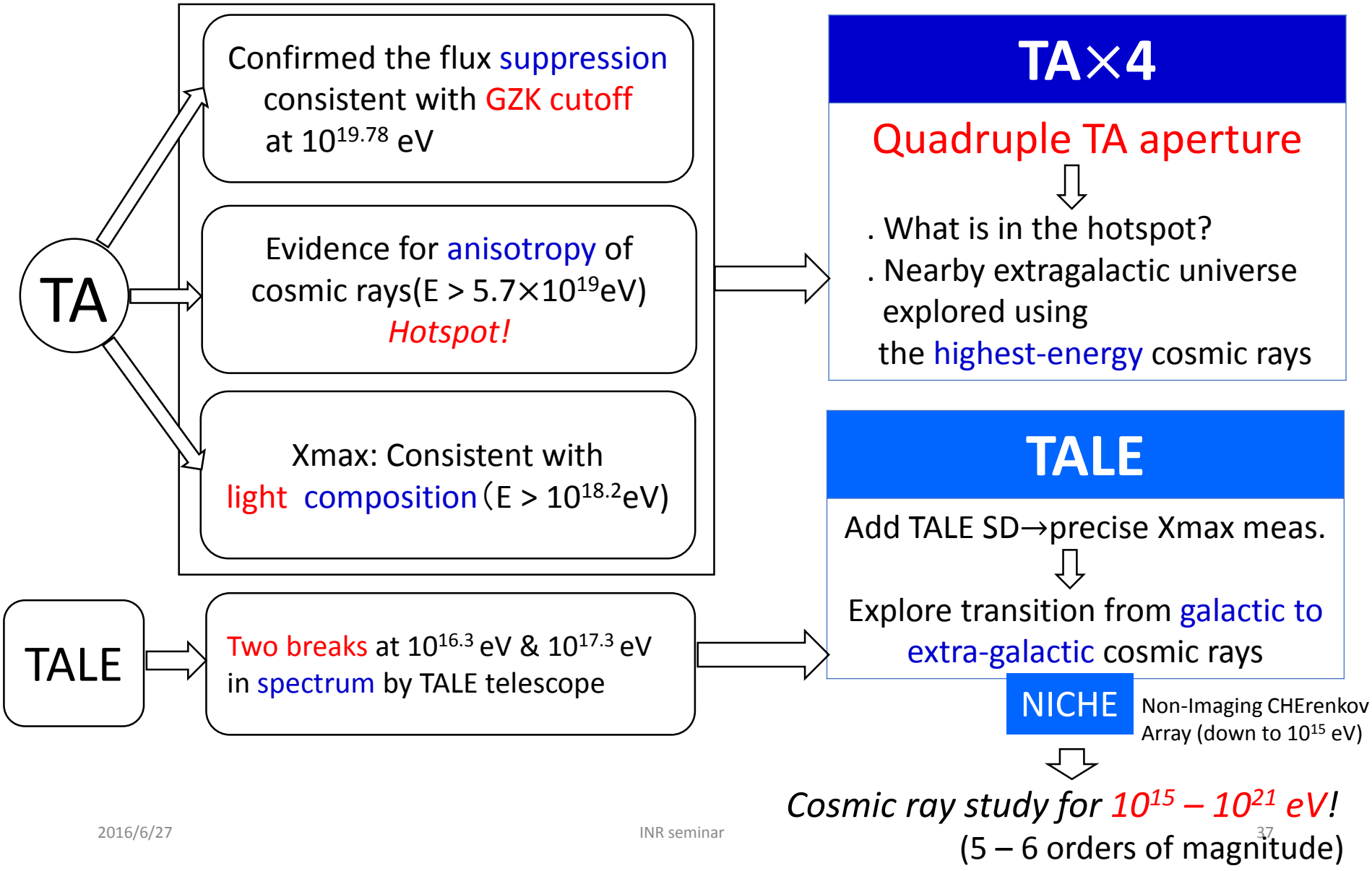
5,000 TALE SD events/year
500 TALE hybrid events/year

5-year proposal of TALE SD: funded in Japan in May, 2015

Combined TA with Other Experiments



Summary


TA
Confirmed the flux suppression consistent with GZK cutoff at $10^{19.78}$ eV
Evidence for anisotropy of cosmic rays(E > 5.7×10^{19}eV) *Hotspot!*
Xmax: Consistent with light composition (E > $10^{18.2}$eV)
TALE
Two breaks at $10^{16.3}$ eV & $10^{17.3}$ eV in spectrum by TALE telescope
TA×4
Quadruple TA aperture
. What is in the hotspot?
. Nearby extragalactic universe explored using the highest-energy cosmic rays
TALE
Add TALE SD→precise Xmax meas.
Explore transition from galactic to extra-galactic cosmic rays
NICHE
Non-Imaging CHErenkov Array (down to 10^{15} eV)
Cosmic ray study for 10^{15} – 10^{21} eV!
(5 – 6 orders of magnitude)