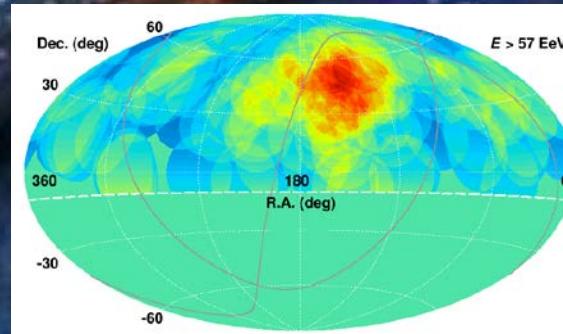


Telescope Array extension: - TA×4 & TALE -



H. Sagawa
Institute for Cosmic Ray Research
The University of Tokyo
for the Telescope Array collaboration



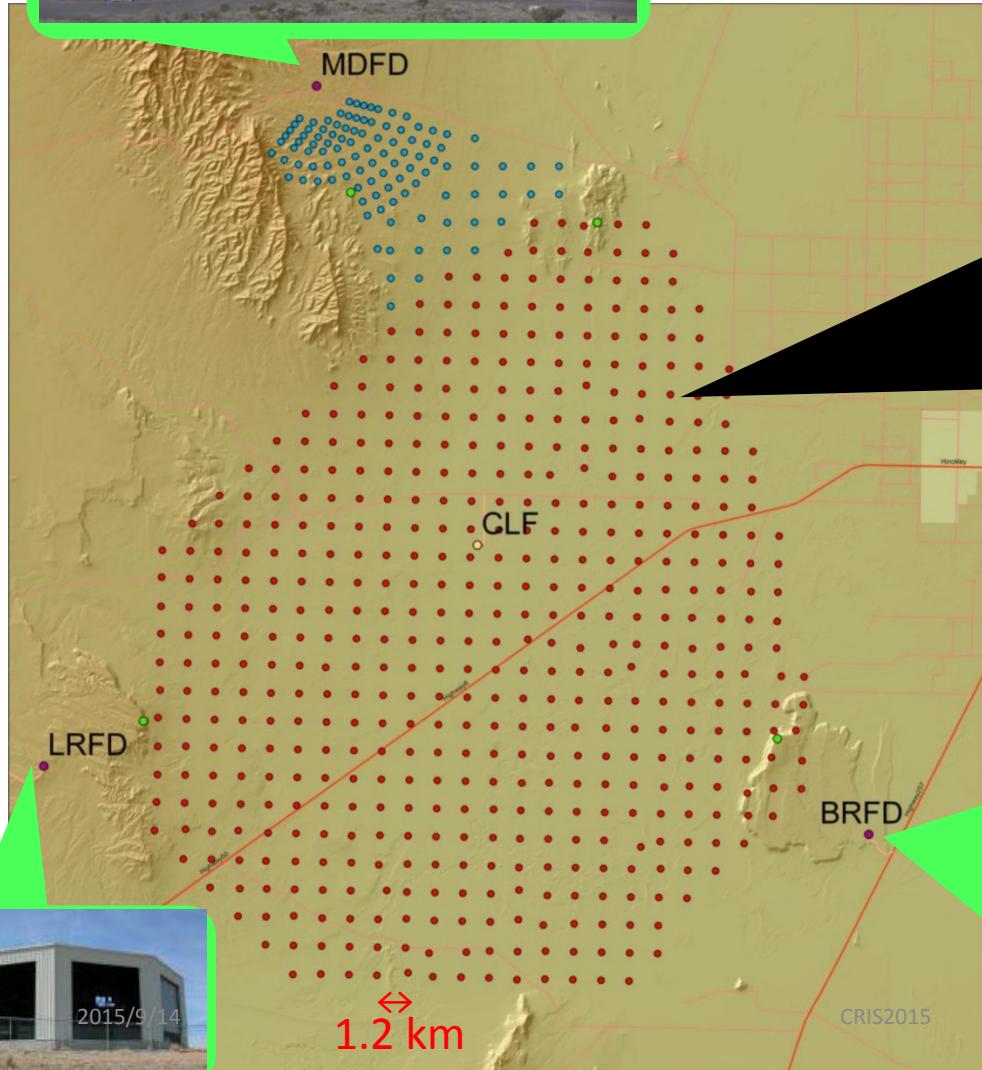
Contents

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 \times 4** (10^{18} eV $\sim 10^{20.5}$ eV)
 - TA aperture extension at the highest energies
 - **TALE** ($10^{15.6}$ eV $\sim 10^{19}$ eV)
 - TA Low-Energy extension

TA detector

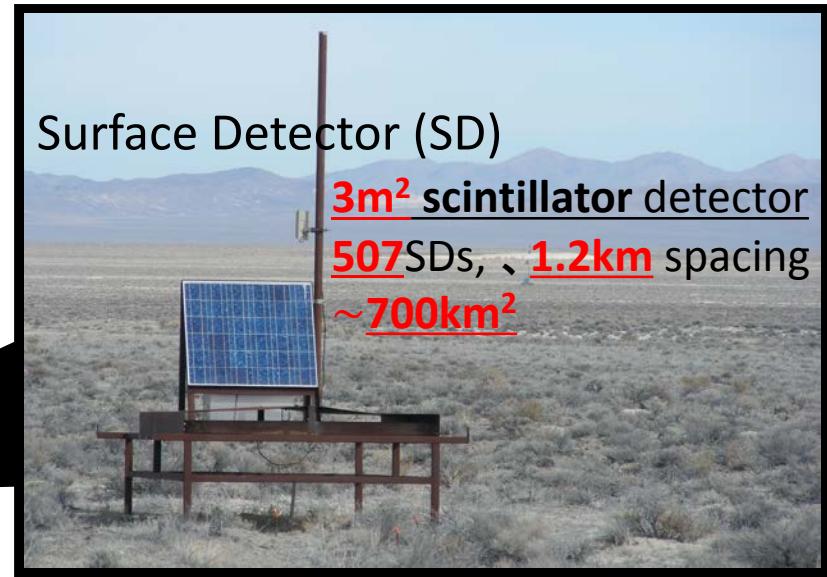
❖ Utah, USA- lat. 39.30°N , long. 112.91°W

Refurbished HiRes TALE MD FD
TA MD FD



Surface Detector (SD)

3m² scintillator detector
507 SDs, 1.2km spacing
~700km²



Fluorescence Detector (FD)



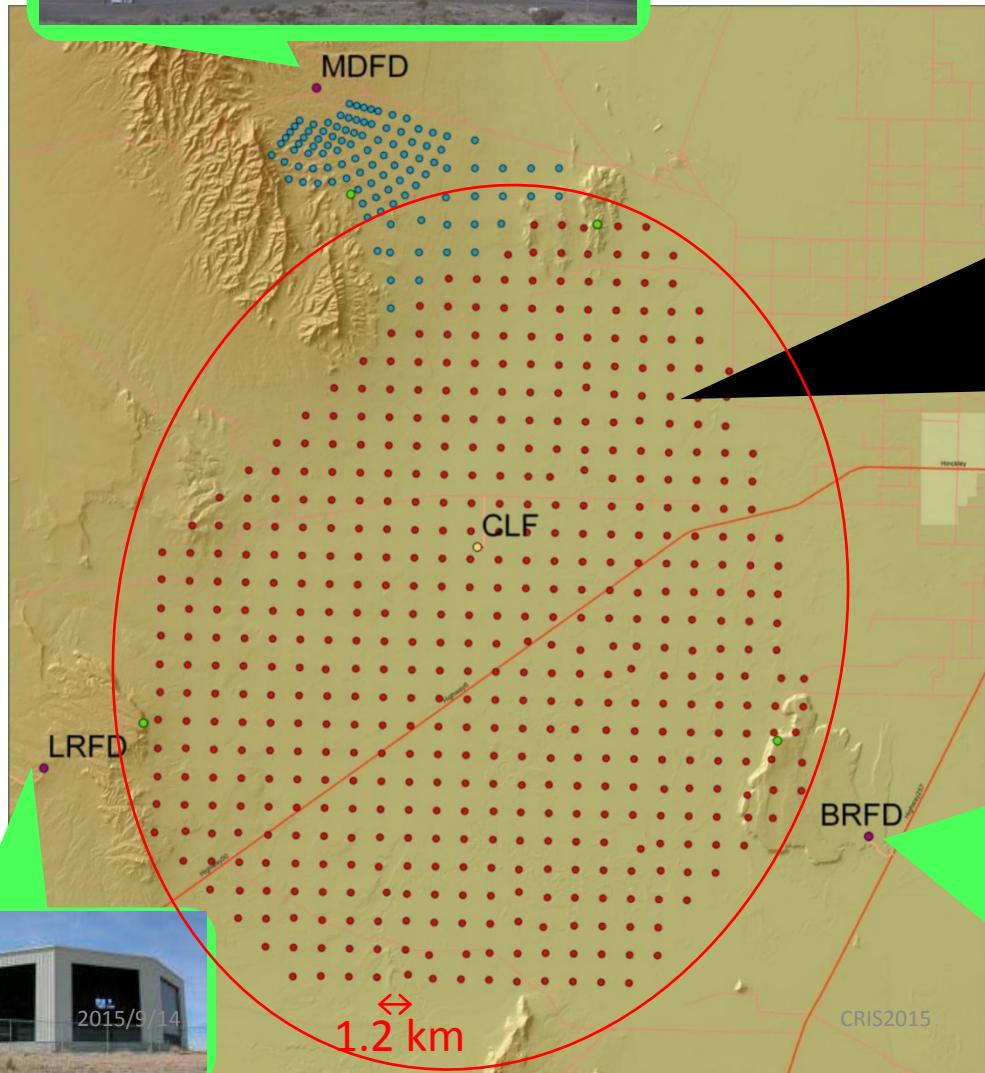
Elevation angle : $3 \sim 33^{\circ}$

Hybrid observation since Mar, 2008

TA detector

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

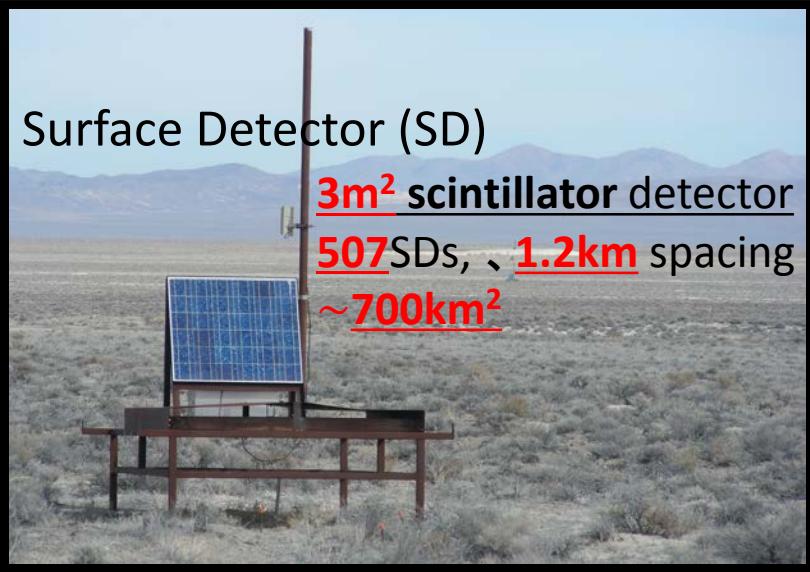
Refurbished HiRes
TALE MD FD
TA MD FD



Surface Detector (SD)

3m² scintillator detector
507 SDs, 1.2km spacing

$\sim 700\text{km}^2$



Fluorescence Detector (FD)



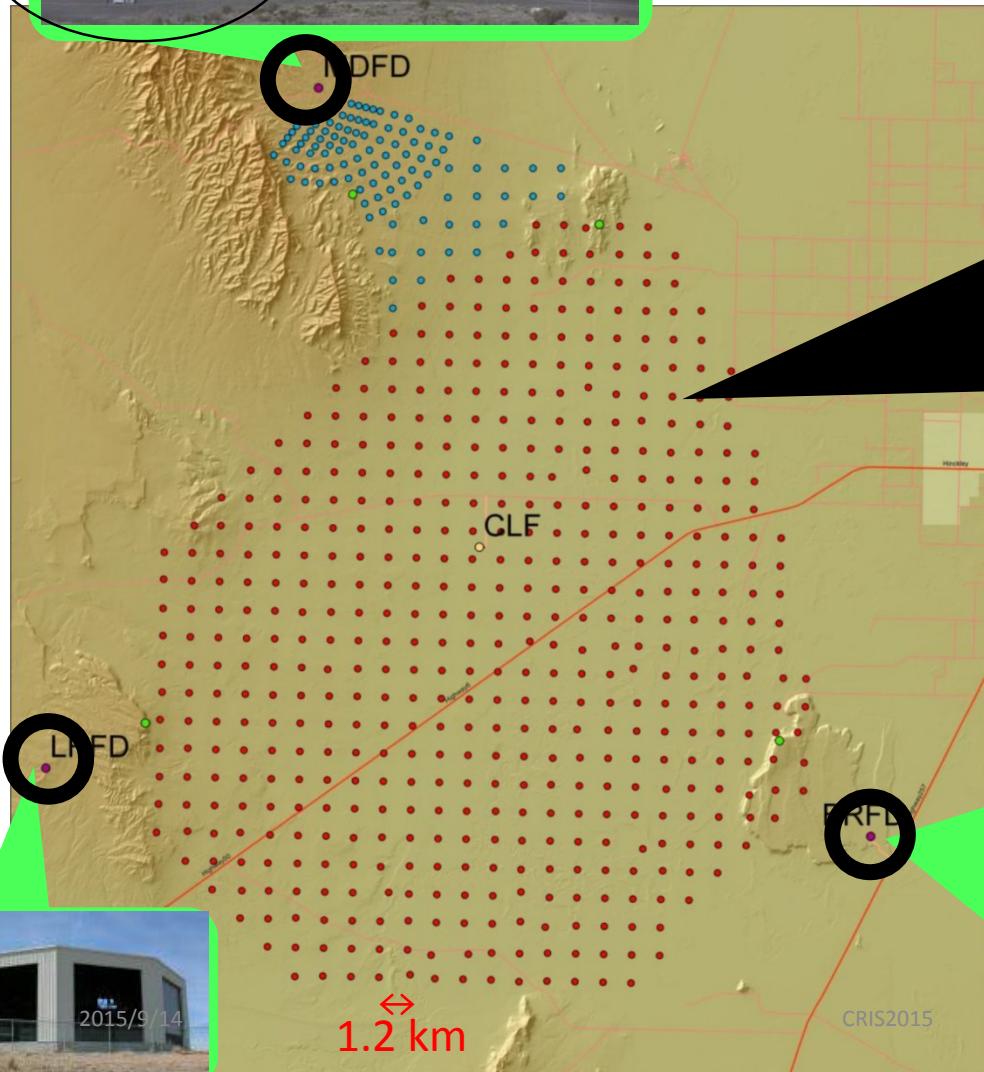
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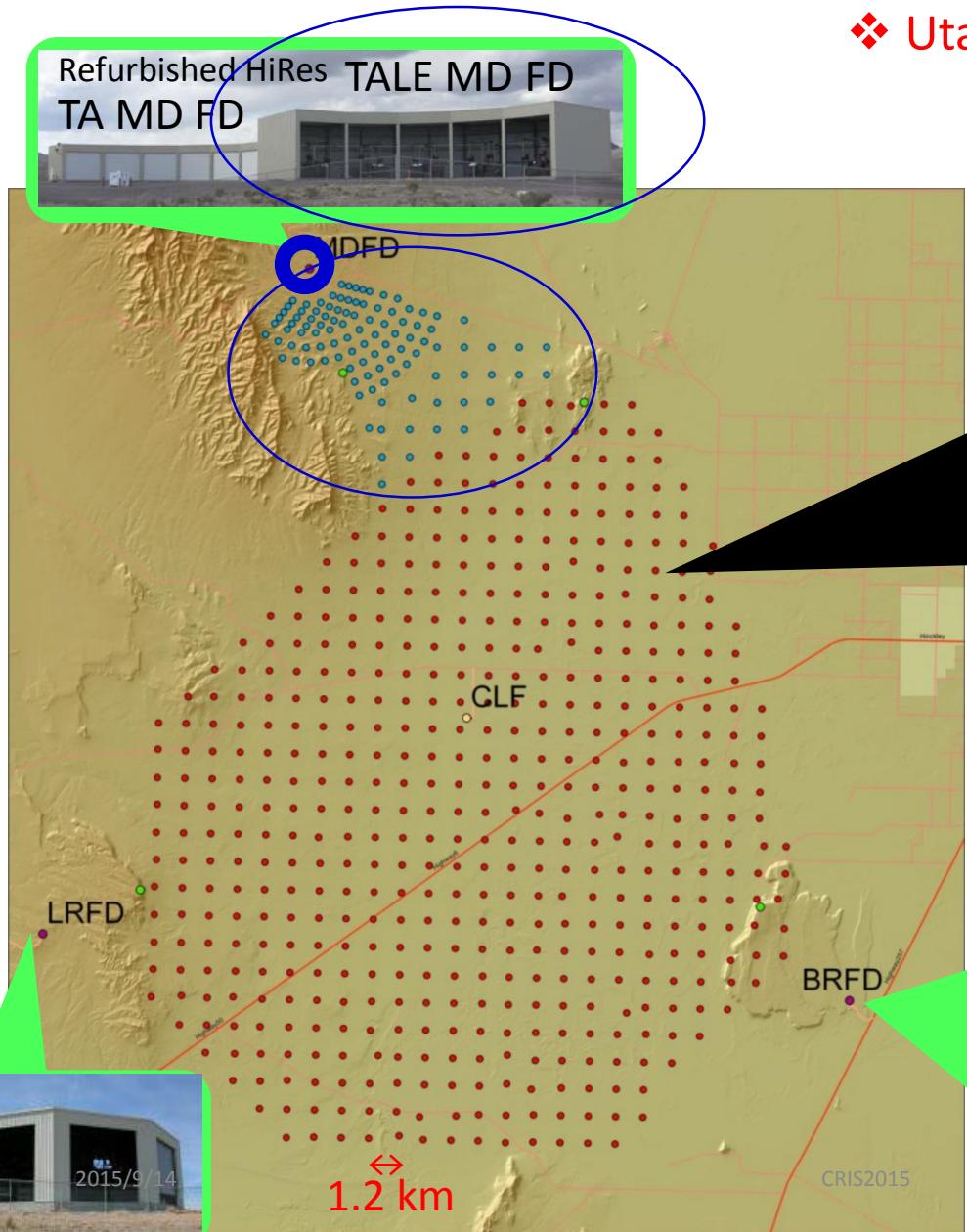
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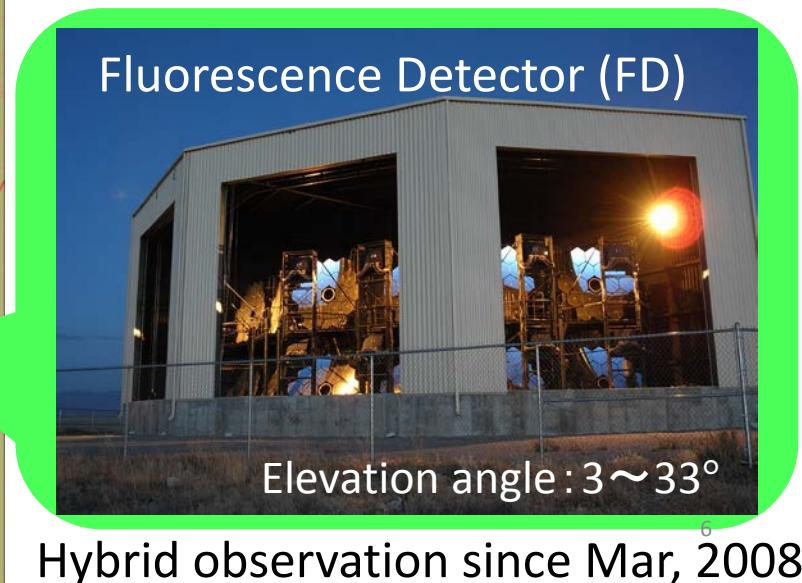
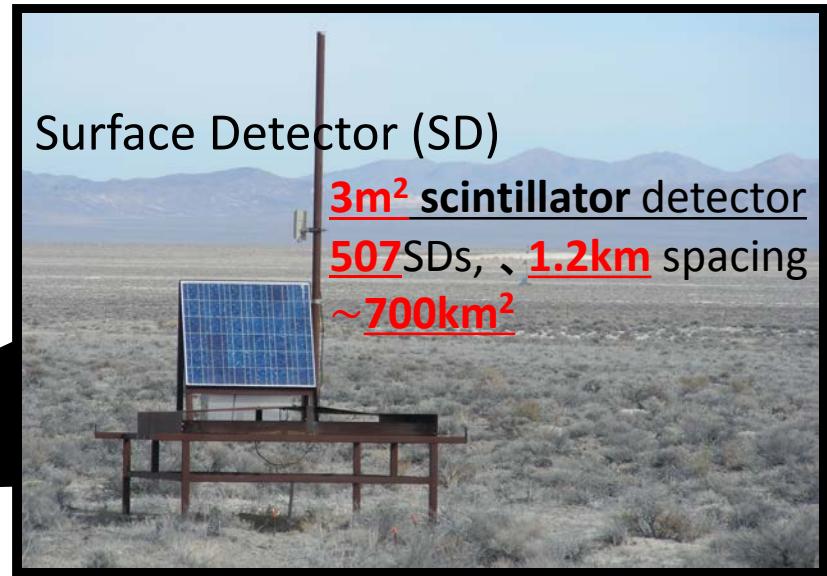
Elevation angle : $3 \sim 33^{\circ}$

Hybrid observation since Mar, 2008

TA detector



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





TA Collaboration

~130 researchers

RU Abbasi¹, M Abe¹³, T Abu-Zayyad¹, M Allen¹, R Anderson¹, R Azuma², E Barcikowski¹, JW Belz¹, DR Bergman¹, SA Blake¹, R Cady¹, MJ Chae³, BG Cheon⁴, J Chiba⁵, M Chikawa⁶, WR Cho⁷, T Fujii⁸, M Fukushima^{8,9}, T Goto¹⁰, W Hanlon¹, Y Hayashi¹⁰, N Hayashida¹¹, K Hibino¹¹, K Honda¹², D Ikeda⁸, N Inoue¹³, T Ishii¹², R Ishimori², H Ito¹⁴, D Ivanov¹, CCH Jui¹, K Kadota¹⁶, F Kakimoto², O Kalashev¹⁷, K Kasahara¹⁸, H Kawai¹⁹, S Kawakami¹⁰, S Kawana¹³, K Kawata⁸, E Kido⁸, HB Kim⁴, JH Kim¹, JH Kim²⁵, S Kitamura², Y Kitamura², V Kuzmin¹⁷, YJ Kwon⁷, J Lan¹, SI Lim³, JP Lundquist¹, K Machida¹², K Martens⁹, T Matsuda²⁰, T Matsuyama¹⁰, JN Matthews¹, M Minamino¹⁰, K Mukai¹², I Myers¹, K Nagasawa¹³, S Nagataki¹⁴, T Nakamura²¹, T Nonaka⁸, A Nozato⁶, S Ogio¹⁰, J Ogura², M Ohnishi⁸, H Ohoka⁸, K Oki⁸, T Okuda²², M Ono¹⁴, A Oshima¹⁰, S Ozawa¹⁸, IH Park²³, MS Pshirkov²⁴, DC Rodriguez¹, G Rubtsov¹⁷, D Ryu²⁵, H Sagawa⁸, N Sakurai¹⁰, AL Sampson¹, LM Scott¹⁵, PD Shah¹, F Shibata¹², T Shibata⁸, H Shimodaira⁸, BK Shin⁴, JD Smith¹, P Sokolsky¹, RW Springer¹, BT Stokes¹, SR Stratton^{1,15}, TA Stroman¹, T Suzawa¹³, M Takamura⁵, M Takeda⁸, R Takeishi⁸, A Taketa²⁶, M Takita⁸, Y Tameda¹¹, H Tanaka¹⁰, K Tanaka²⁷, M Tanaka²⁰, SB Thomas¹, GB Thomson¹, P Tinyakov^{17,24}, I Tkachev¹⁷, H Tokuno², T Tomida²⁸, S Troitsky¹⁷, Y Tsunesada², K Tsutsumi², Y Uchihori²⁹, S Udo¹¹, F Urban²⁴, G Vasiloff¹, T Wong¹, R Yamane¹⁰, H Yamaoka²⁰, K Yamazaki¹⁰, J Yang³, K Yashiro⁵, Y Yoneda¹⁰, S Yoshida¹⁹, H Yoshii³⁰, R Zollinger¹, Z Zundel¹

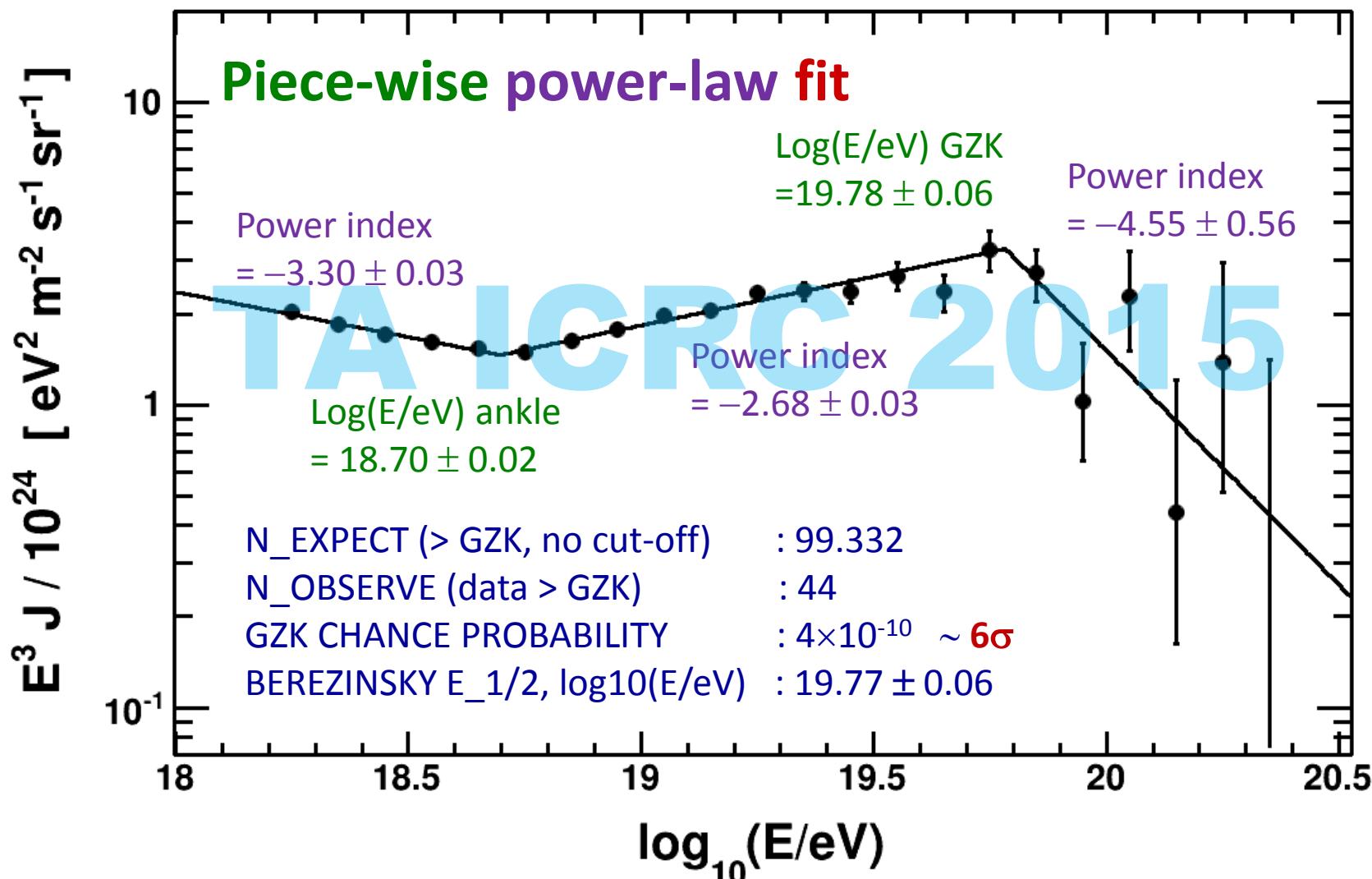
¹High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA, ²Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan, ³Department of Physics and Institute for the Early Universe, Ewha Womans University,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

Japan, the USA, Korea, Russia, Belgium

Latest TA results

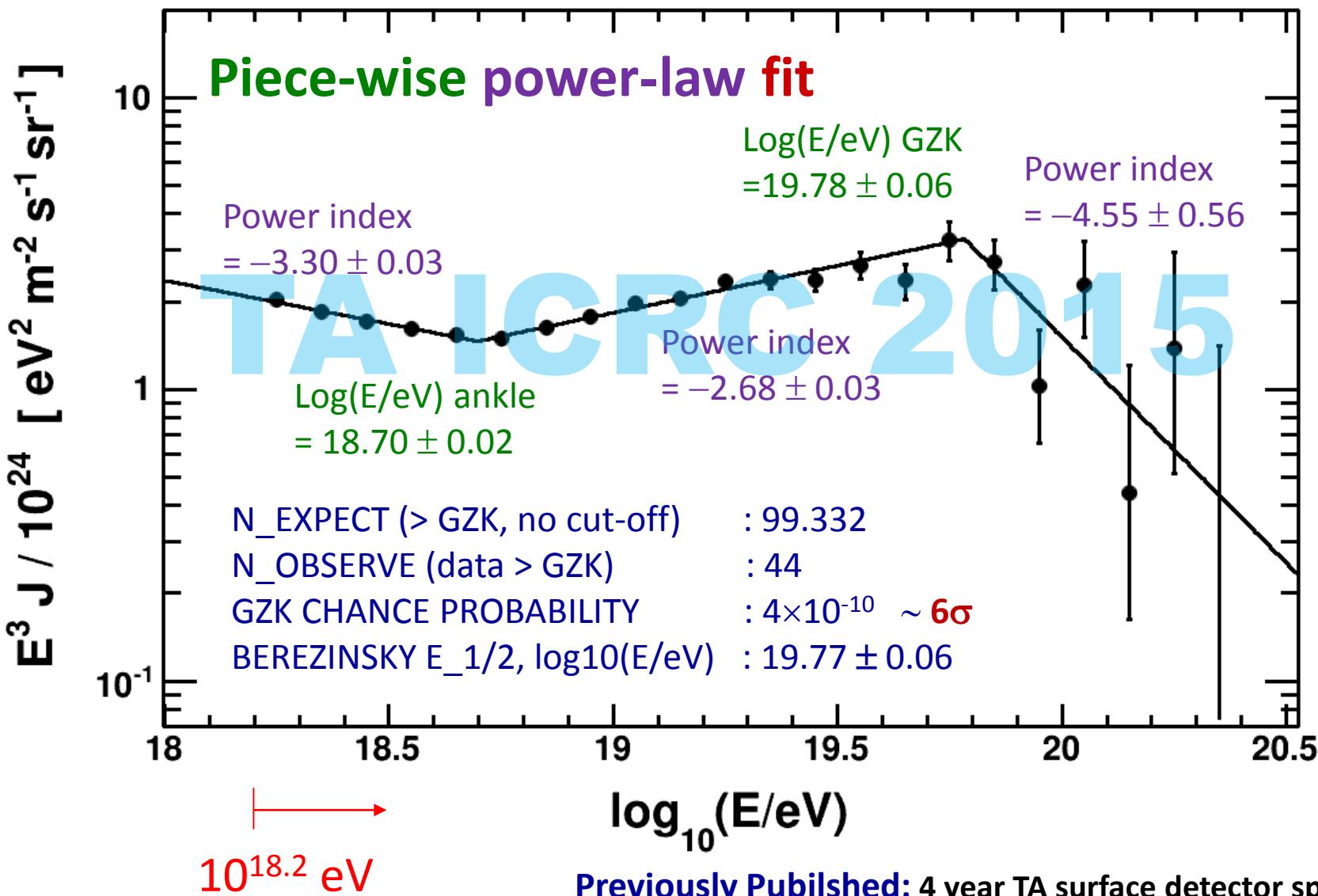
Energy spectrum
Anisotropy (hotspot)
Mass composition (Xmax)

7 year TA SD spectrum

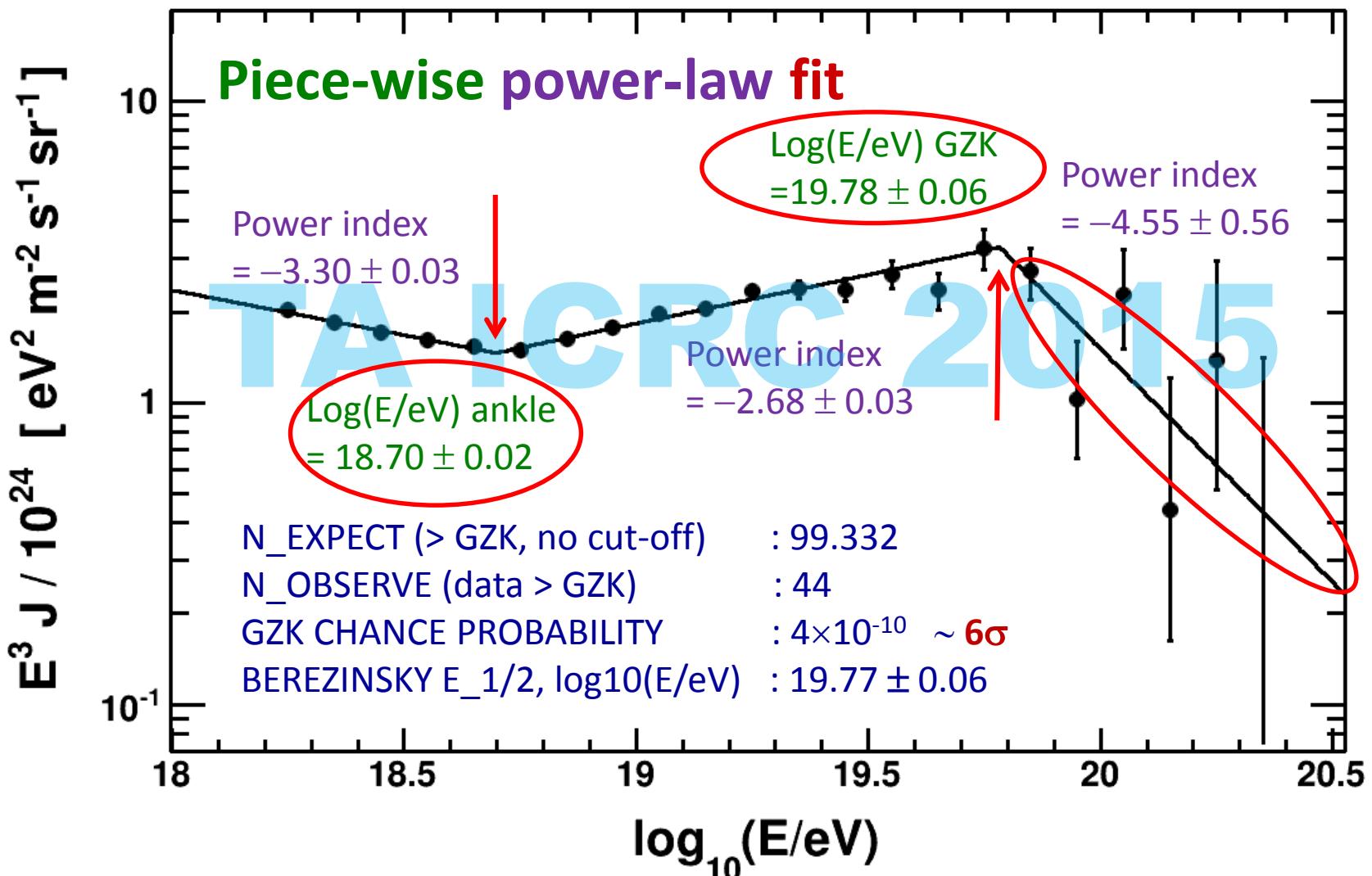


Previously Published: 4 year TA surface detector spectrum
Astrophysical Journal Letters 768 L1 (2013)

7 year TA SD spectrum



7 year TA SD spectrum



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

Comparison of a CR propagation model with TA spectrum

E. Kido at ICRC 2015

- Inputs:

1. Source model:

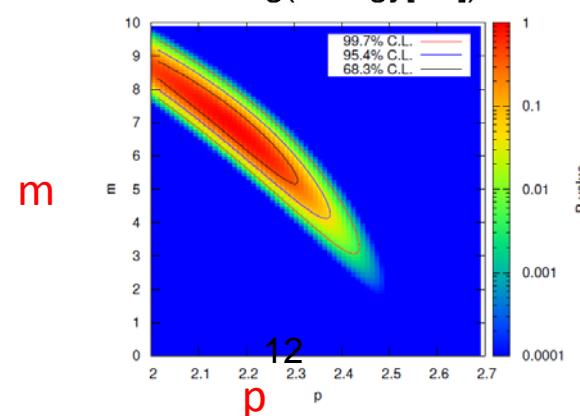
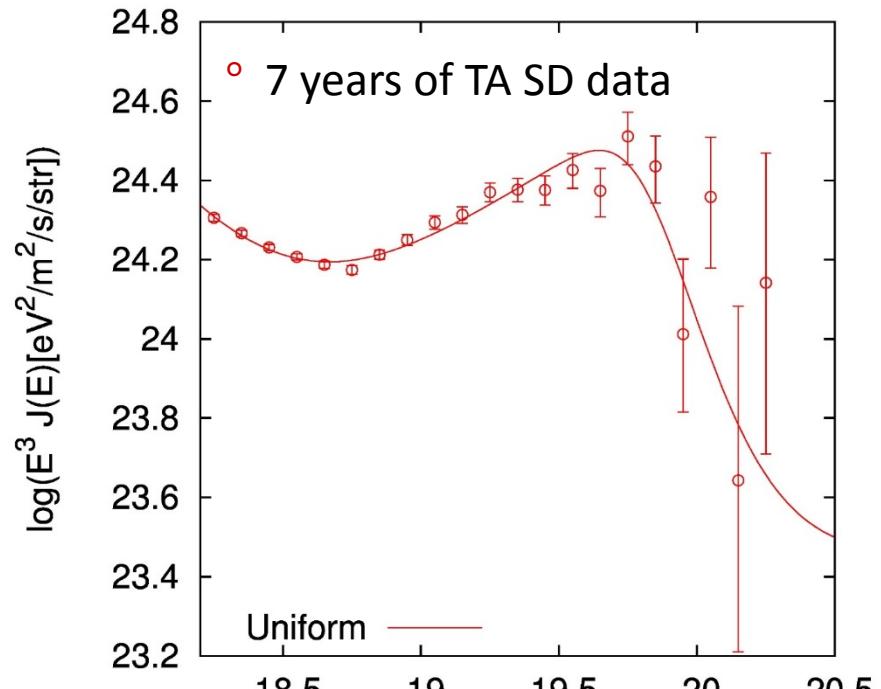
- Uniform or LSS

2. Cosmic rays:

1. **Extragalactic protons** ($E > 10^{18.2}$ eV)
2. Generation: $E^{-p}(1+z)^{3+m}$
3. Interactions with CMB + IR photons
4. Interaction processes
 1. Photoproduction + Pair creation

- Fitting parameters:

1. Index of power law at the source: p
2. Evolution of the sources: m
3. Energy scale
4. Flux normalization



Comparison of a CR propagation model with TA spectrum

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- Inputs:

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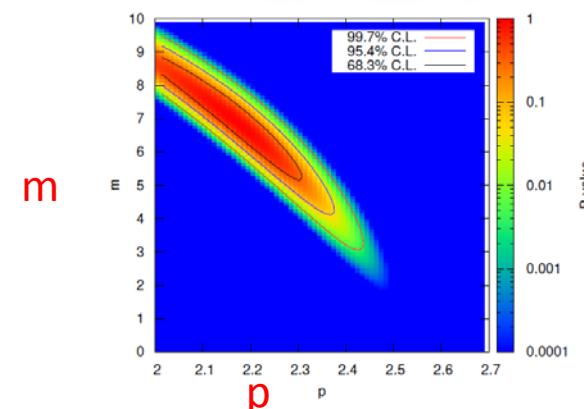
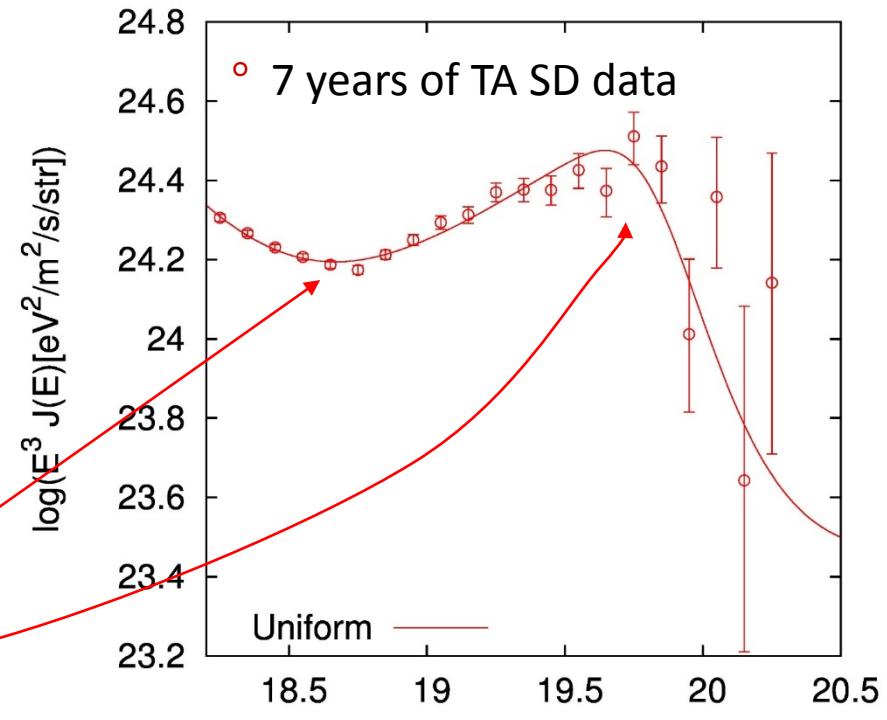
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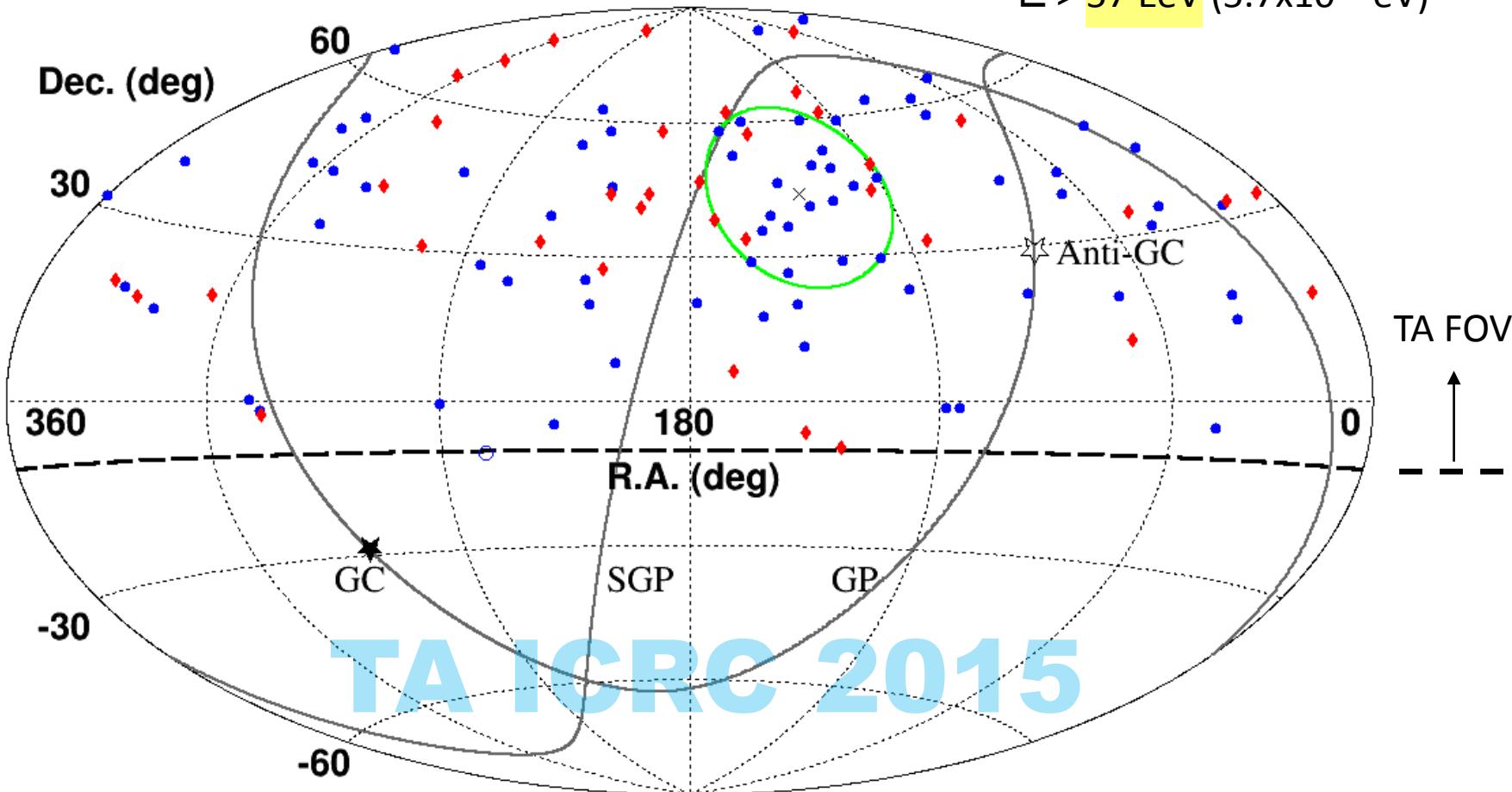


Hot Spot update: 7 years

by Kazumasa KAWATA

2008 May 11 – 2015 May 11

$E > 57 \text{ EeV} (5.7 \times 10^{19} \text{ eV})$



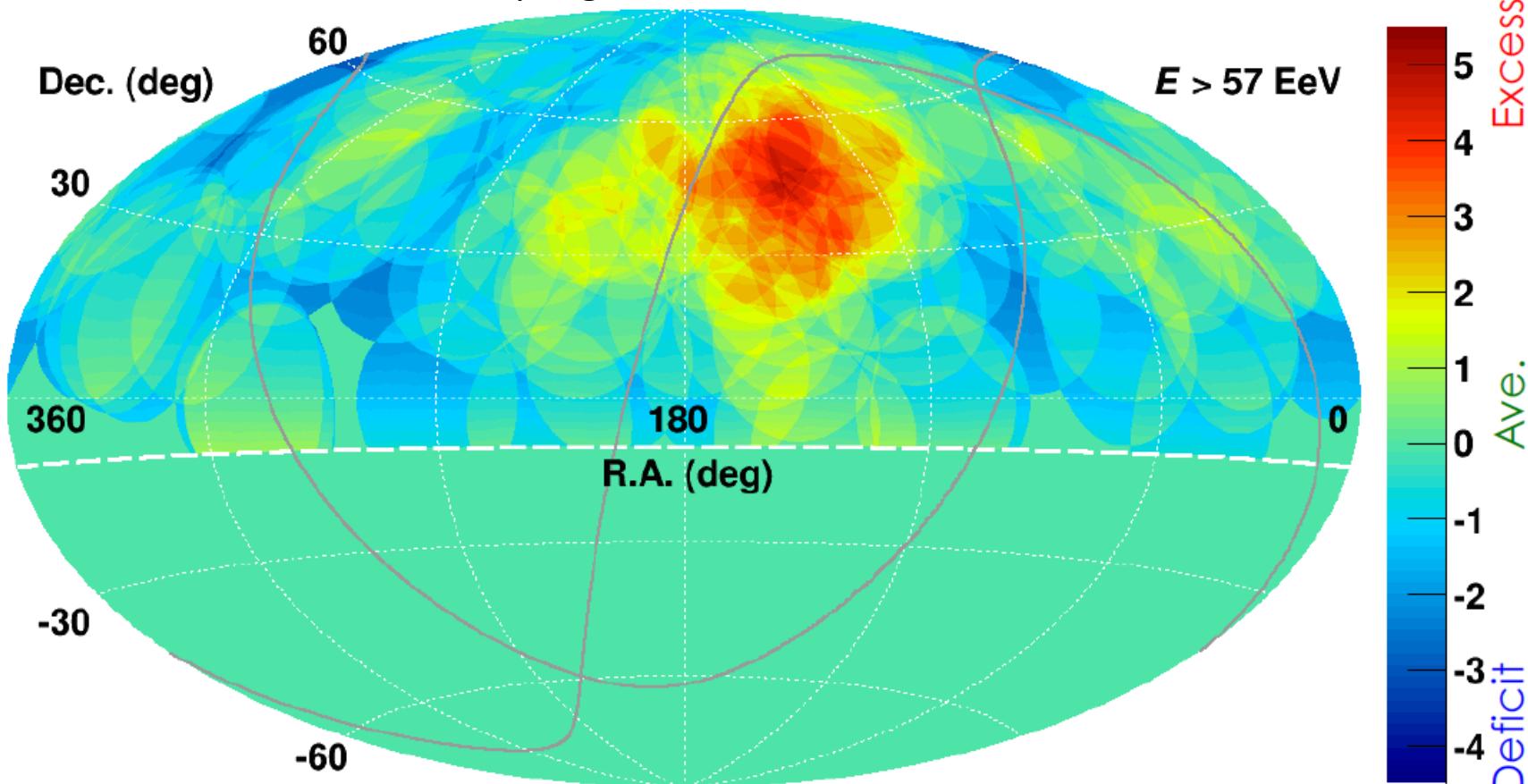
First 5-year data (72 events) -- ApJ 790 L21 (2014)

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

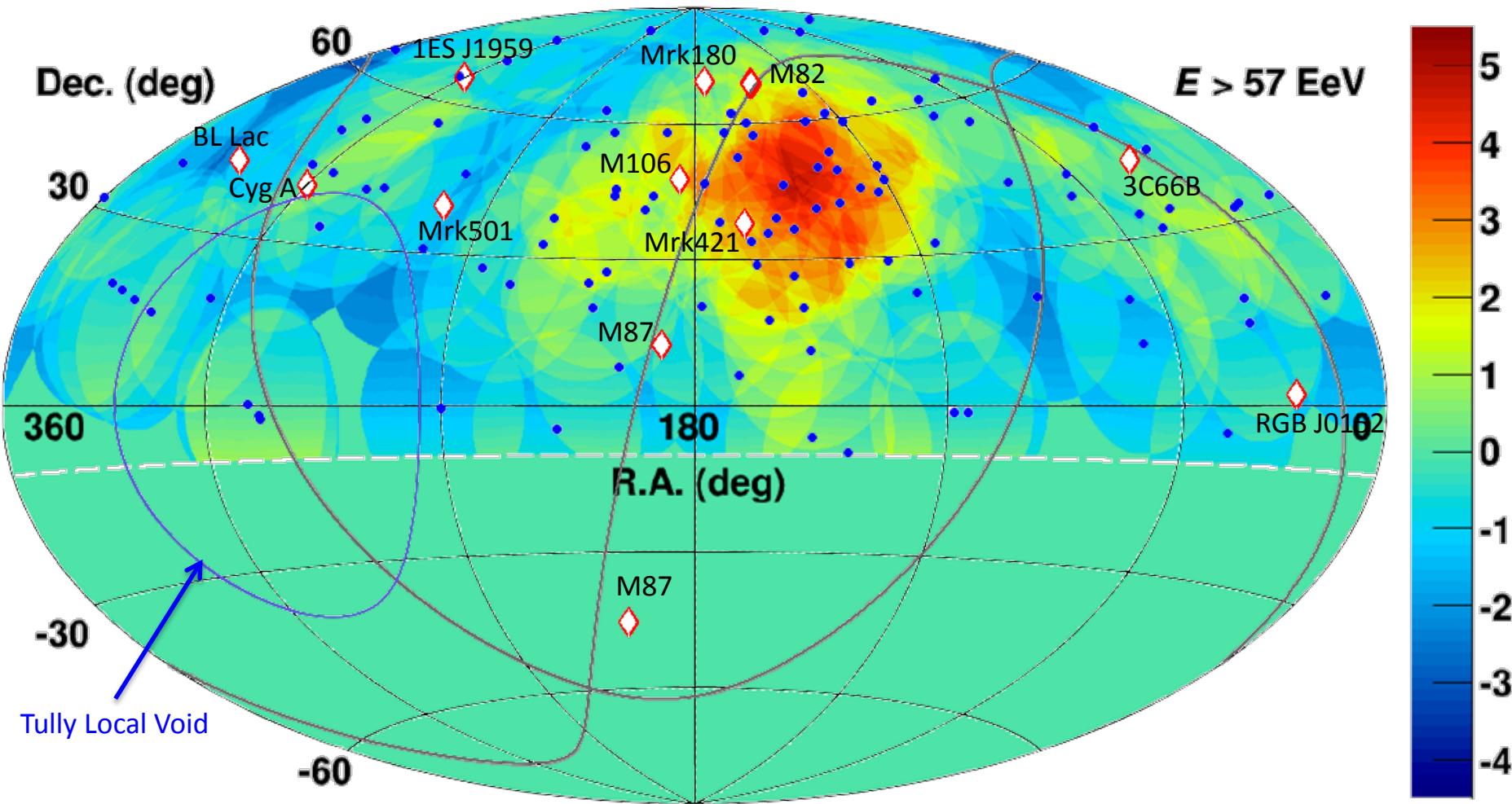


Ma significance 5.07σ ($N_{\text{on}} = 24$, $N_{\text{bg}} = 6.88$)

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

2015/9/14

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

CRIS2015

16

Composition from Xmax

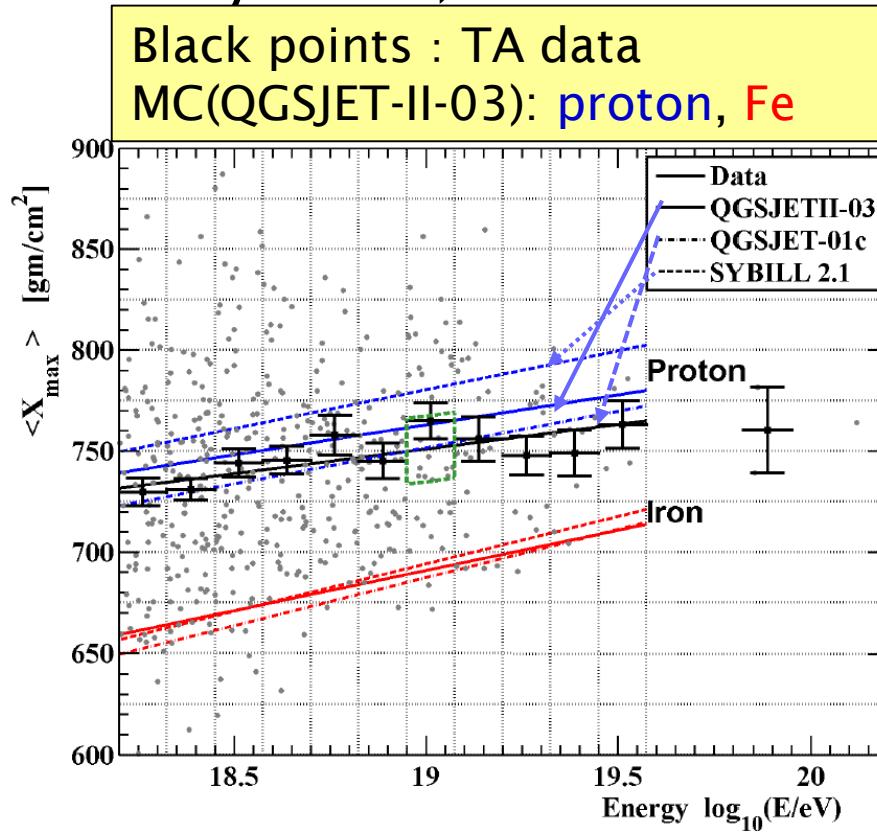
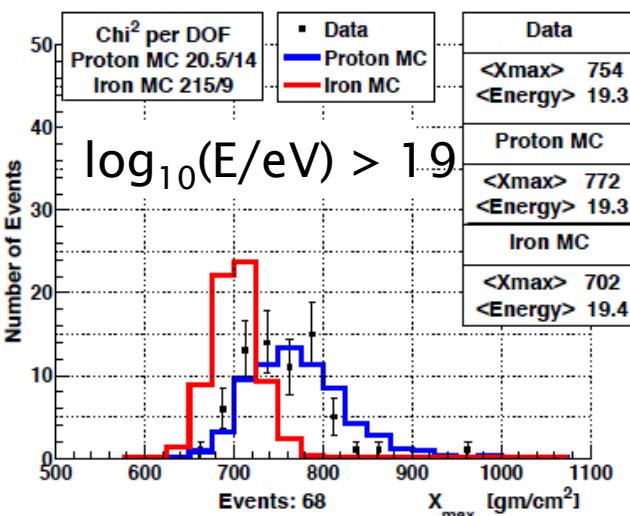
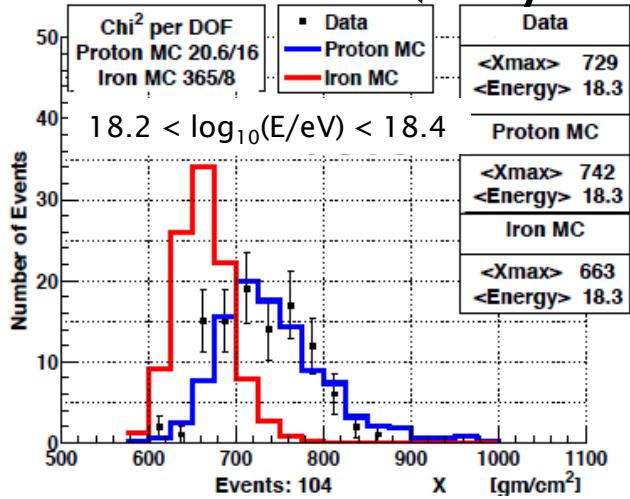
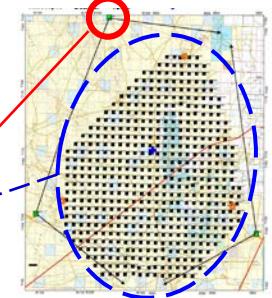
(MD FD +SD)

TA Middle Drum hybrid data

(May 2008 - May 2013)

APP 64 (2015) 49-62

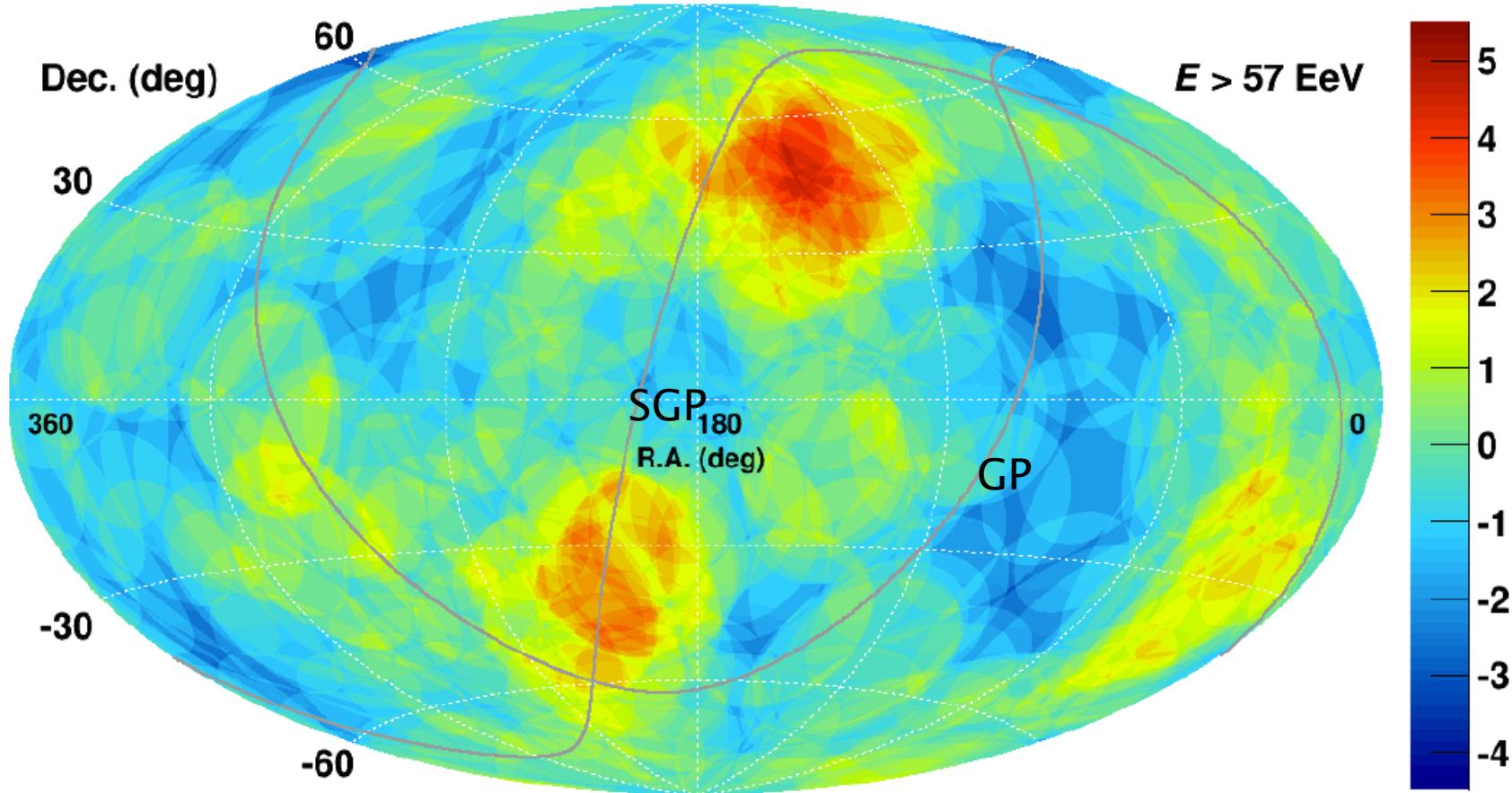
hybrid



Consistent with light composition
Poor statistics beyond $10^{19.5}$ eV

All sky survey with TA and Auger

Oversampling with 20°-radius circle



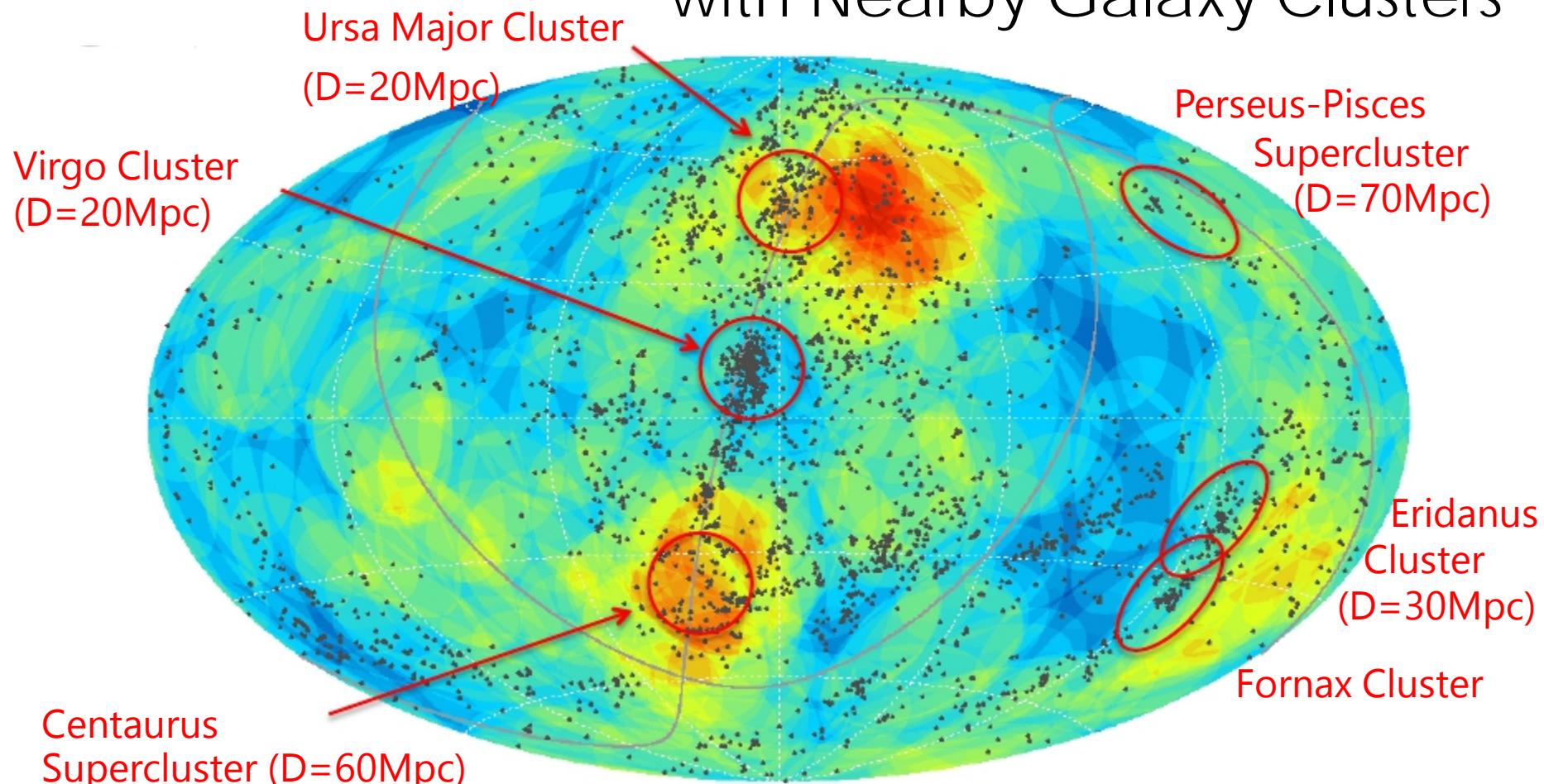
No correction for
E scale difference
b/w TA and PAO !!

Northern TA : 7 years 109 events ($> 57 \text{ EeV}$)
Southern Auger : 10 years 157 events ($> 57 \text{ EeV}$)

Southern hotspot is seen at Cen A (Pre-trial $\sim 3.6\sigma$)

All sky survey with TA and Auger

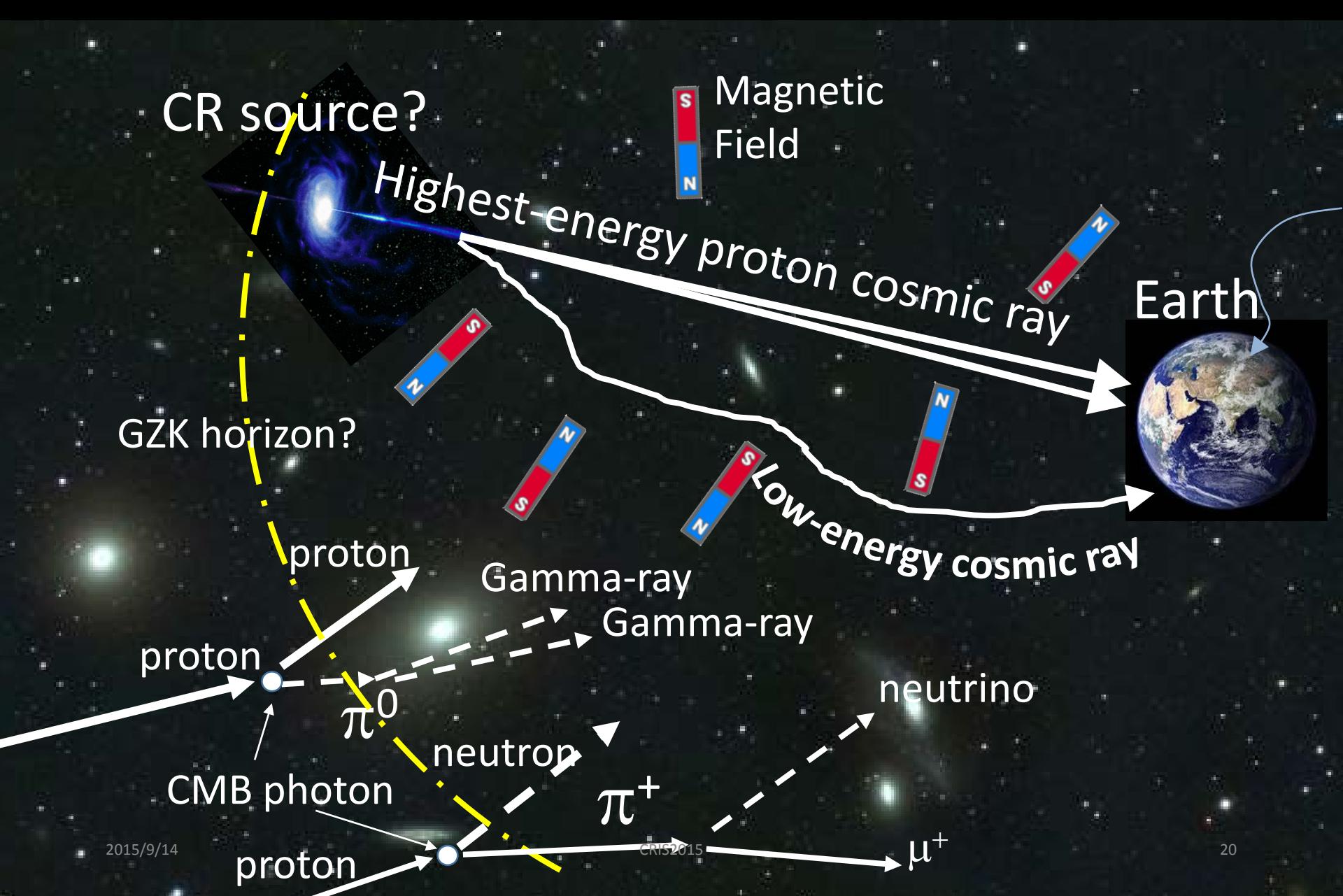
with Nearby Galaxy Clusters



Huchra, et al, ApJ, (2012)
dots (•) : 2MASS catalog Heliocentric velocity $<3000 \text{ km/s}$ ($D < \sim 45 \text{ Mpc}$)

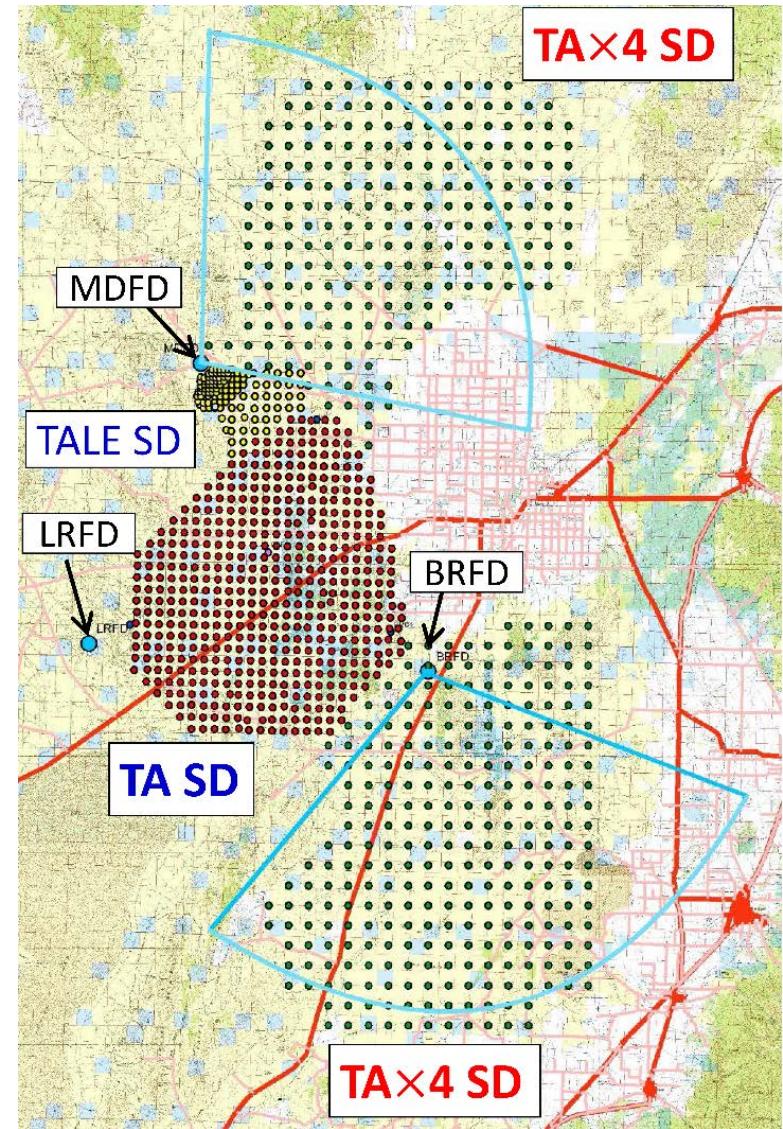
TA hotspot is found near the Ursa Major Cluster

GZK cutoff



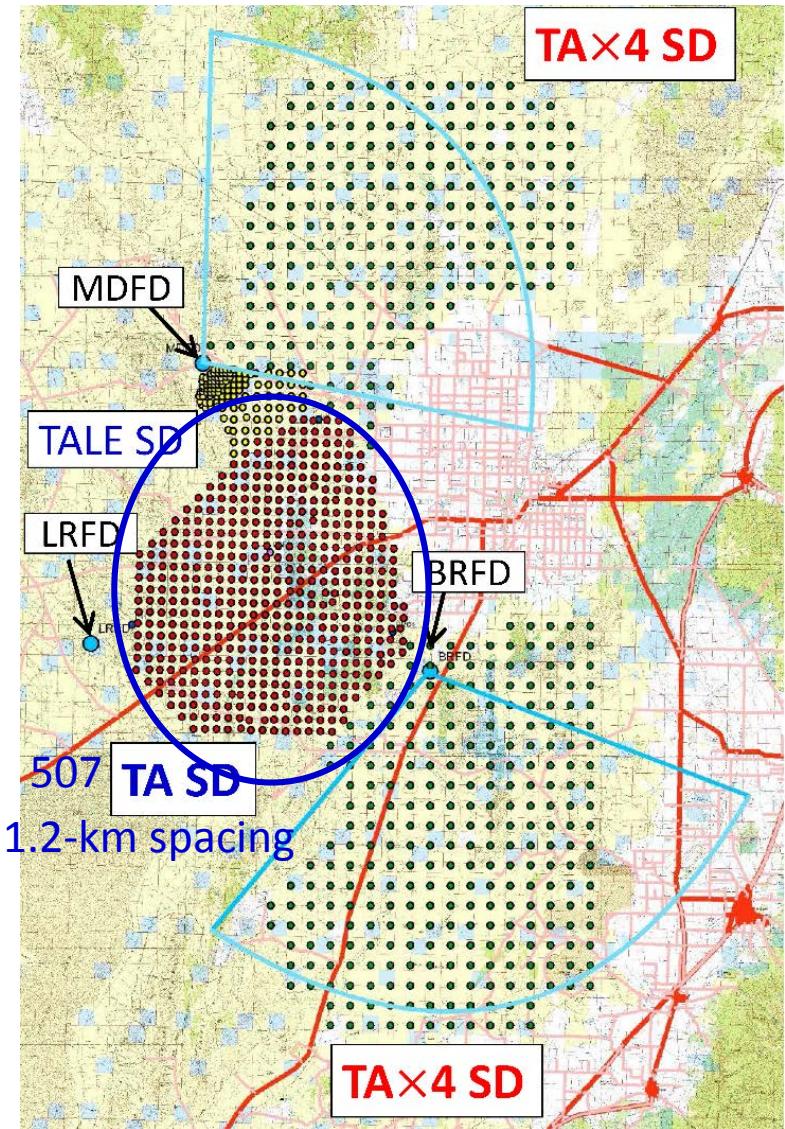
TA×4

- Quadruple TA SD ($\sim 3000 \text{ km}^2$)
 - 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
 - 2.7-year construction (by Dec. 2017)
 - 2.3-year observation
- **19 years of TA SD data by May 2020**
 - ~ 300 highest-energy cosmic rays ($E > 57 \text{ EeV}$)
 - 16.3 TA years of hybrid data



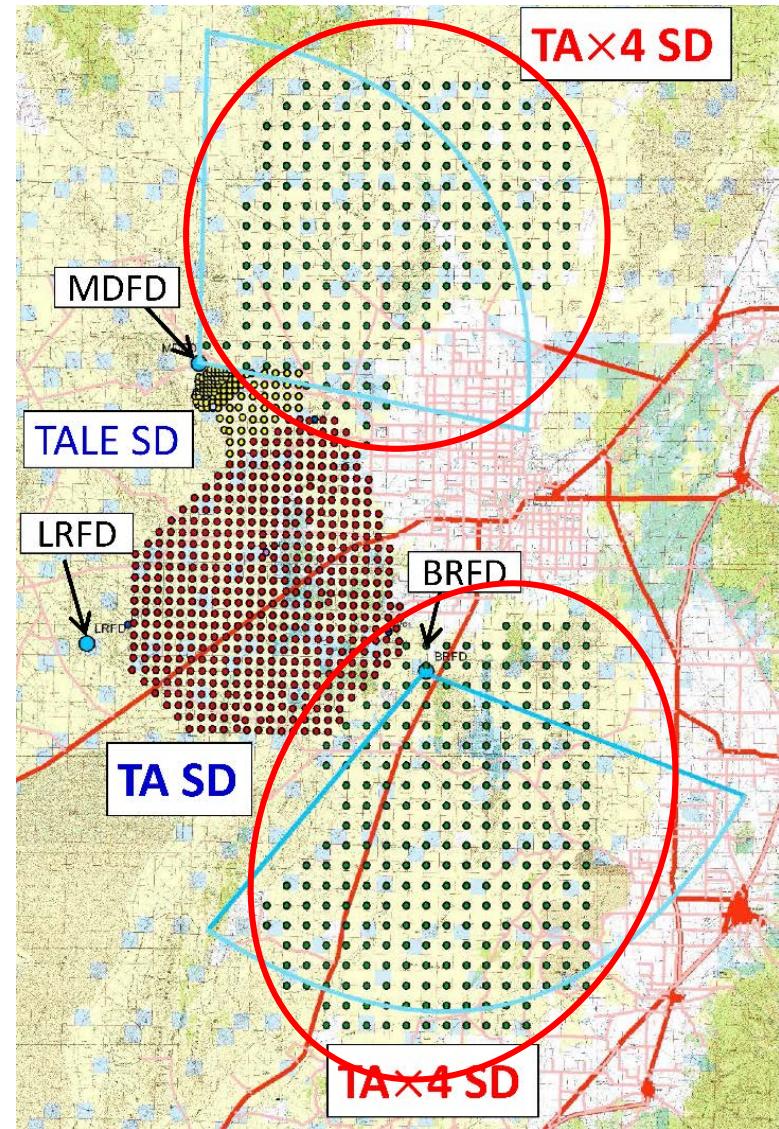
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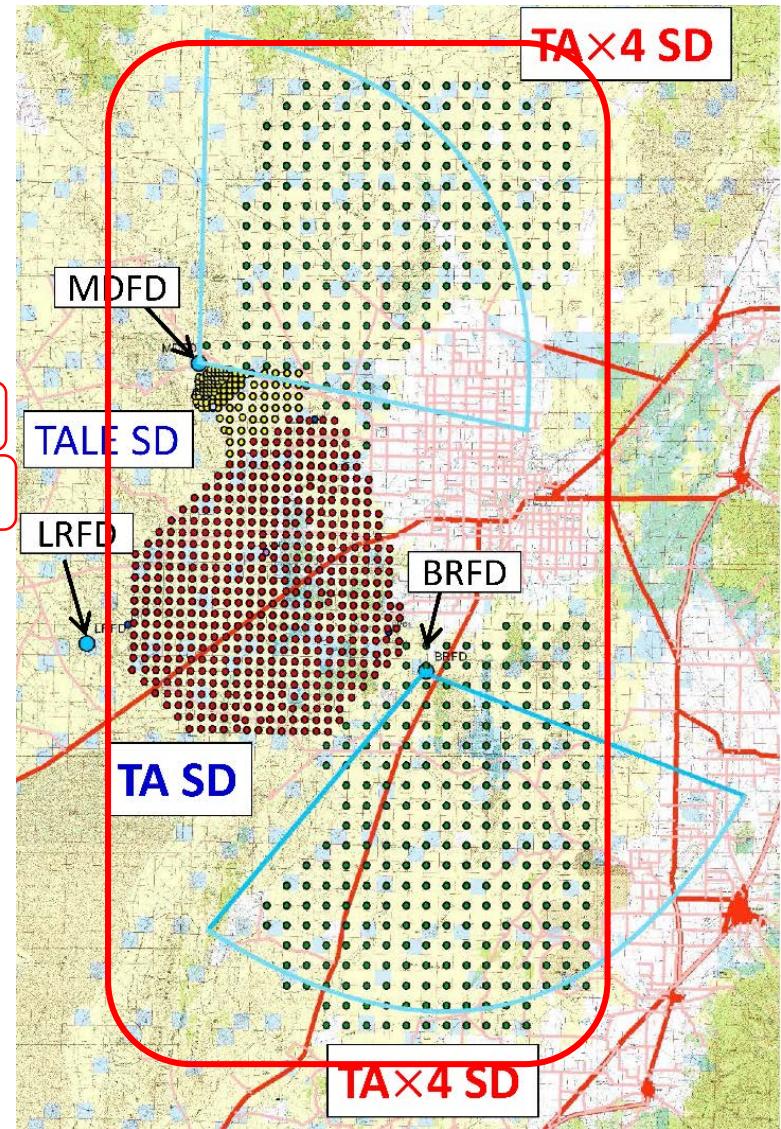
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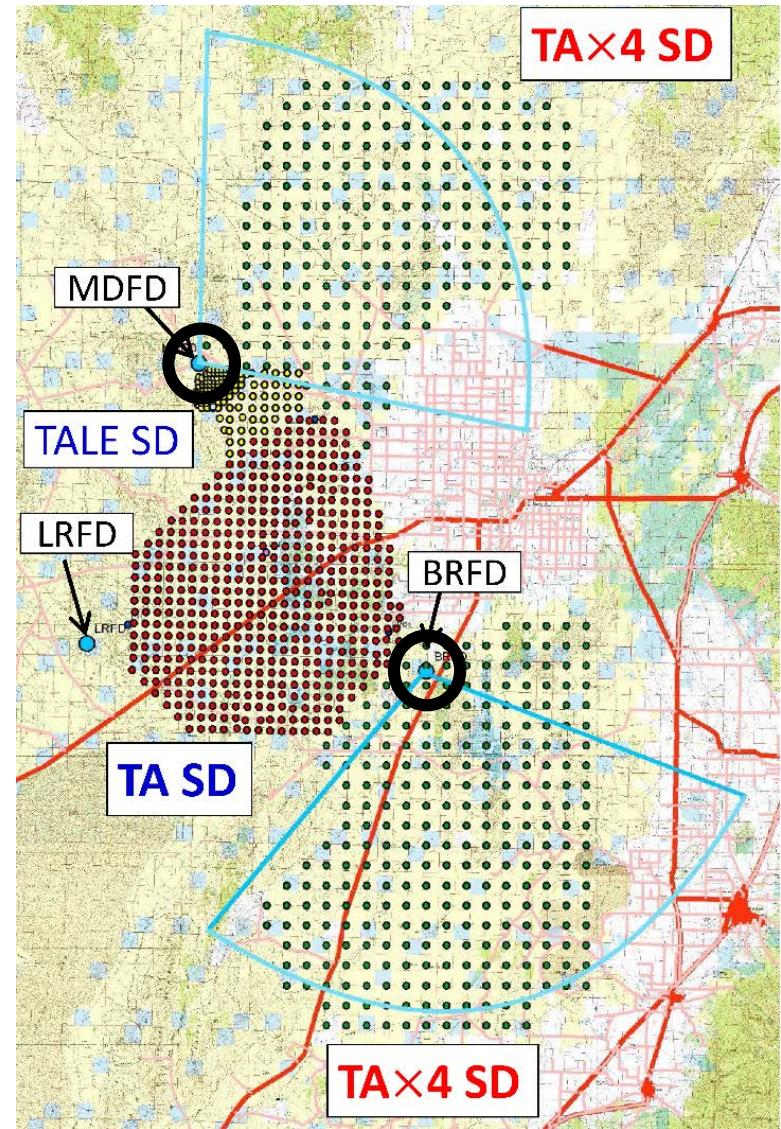
TA×4

- Quadruple TA SD ($\sim 3000 \text{ km}^2$)
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 - Refurbished HiRes telescopes
- Proposals
 - SD (5 years): approved in Japan in April 2015
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 - 16.3 TA years of hybrid data



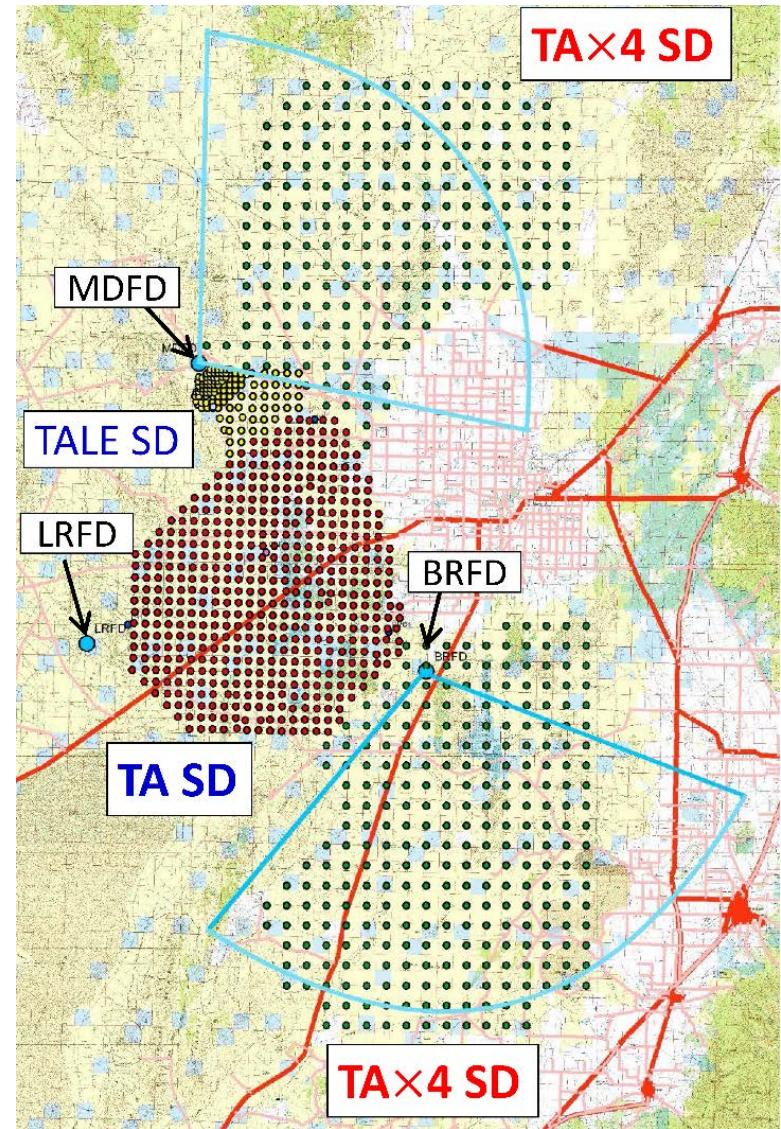
TA×4

- Quadruple TA SD ($\sim 3000 \text{ km}^2$)
 - 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
 - 2.7-year construction (by Dec. 2017)
 - 2.3-year observation
- **19 years of TA SD data by May 2020**
 - ~ 300 highest-energy cosmic rays ($E > 57 \text{ EeV}$)
 - 16.3 TA years of hybrid data

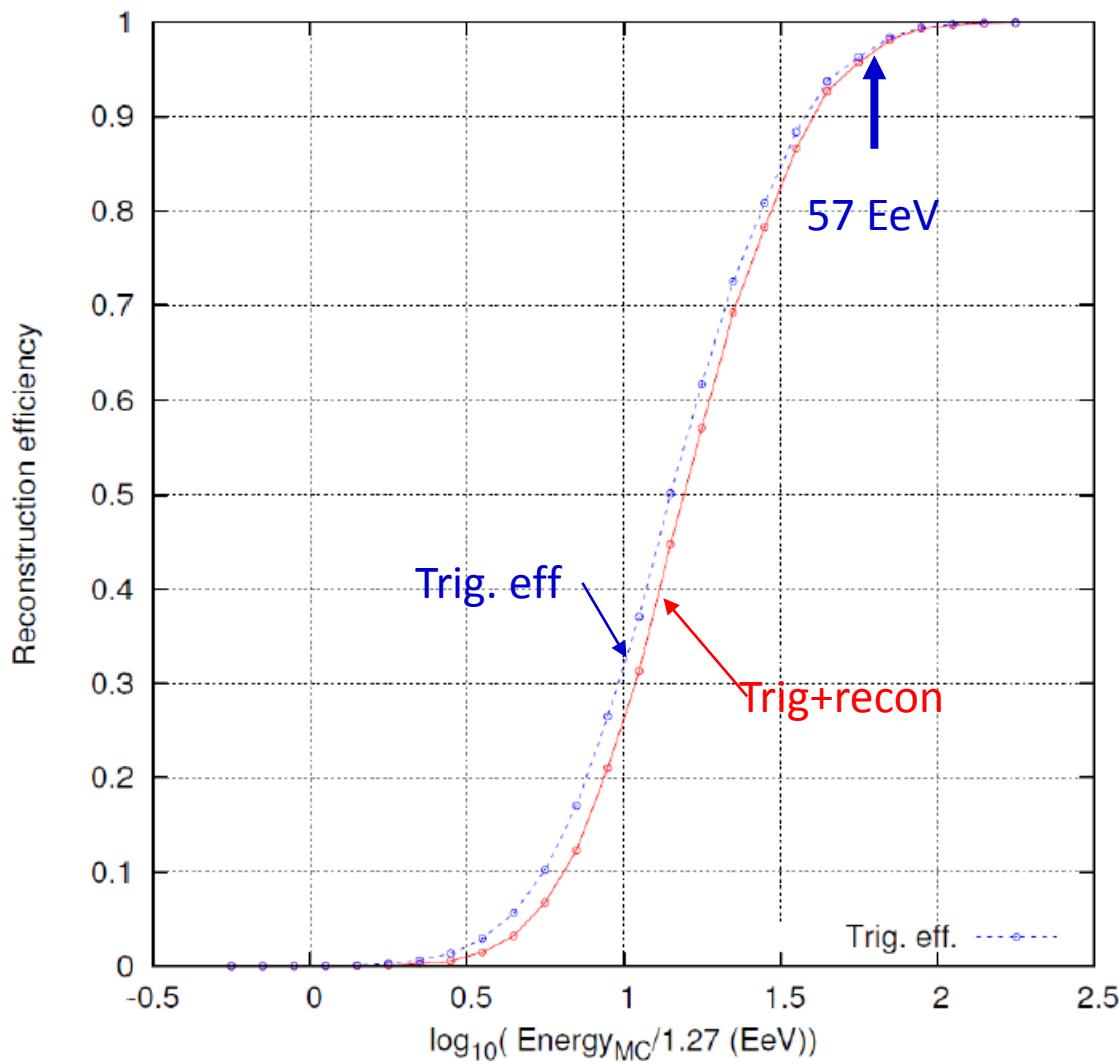


TA×4

- Quadruple TA SD ($\sim 3000 \text{ km}^2$)
 - 500 scintillator SDs
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- 2 FD stations (refurbished HiRes telescopes)
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Efficiency for additional TA \times 4 SD array Differential for energies (2.08 km spacing)



Trigger condition

- . 3 MIPS
- . 3-fold SDs
- . $< 8 \times 2.08 / 1.2 \mu\text{sec}$

Reconstruction

- . $\text{NSD} \geq 4$

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

Prospect of TA×4

- Arrival direction
 - Hotspot
 - Confirmation at $> 5\sigma$ 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)

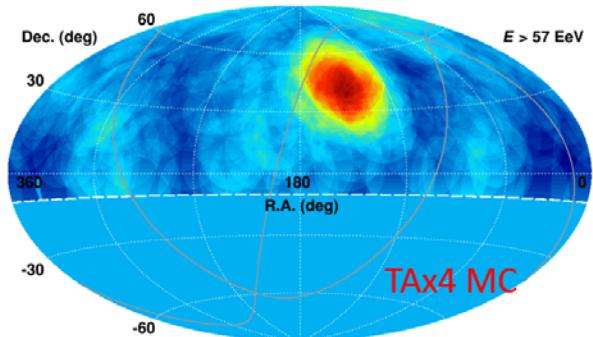
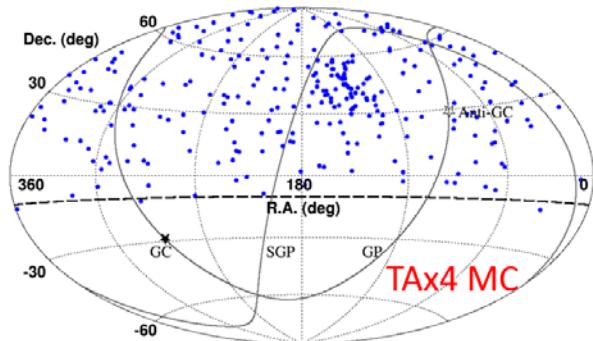
(1) One Hotspot

Hotspot Signal
 72-17.1=55events
 (RA,
 Dec)=(148° , 45°)
 Gaussian $\sigma=10^{\circ}$

Isotropic B.G.
 276-55=221events

Pretrial significance
 $\sim 8.7\sigma$

Oversampling
 20° radius circle

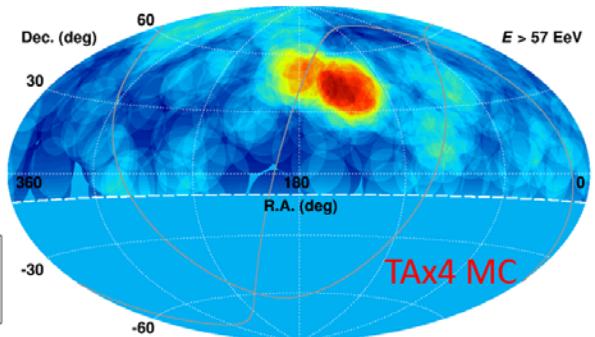
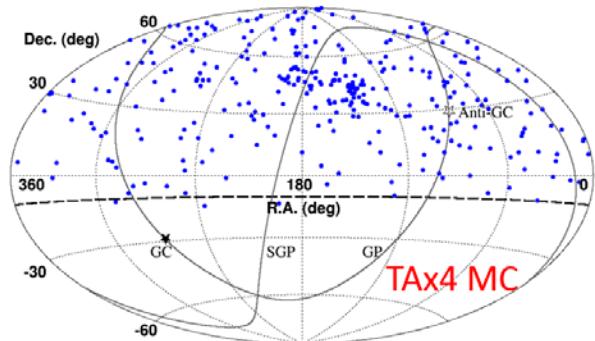


(2) Double Hotspot

Hotspot Signal
 Total 55 events
 1. 36events
 (RA, Dec)=(148° , 45°)
 Gaussian $\sigma=8^{\circ}$
 2. 19events
 (RA, Dec)=(180° , 50°)
 Gaussian $\sigma=5^{\circ}$

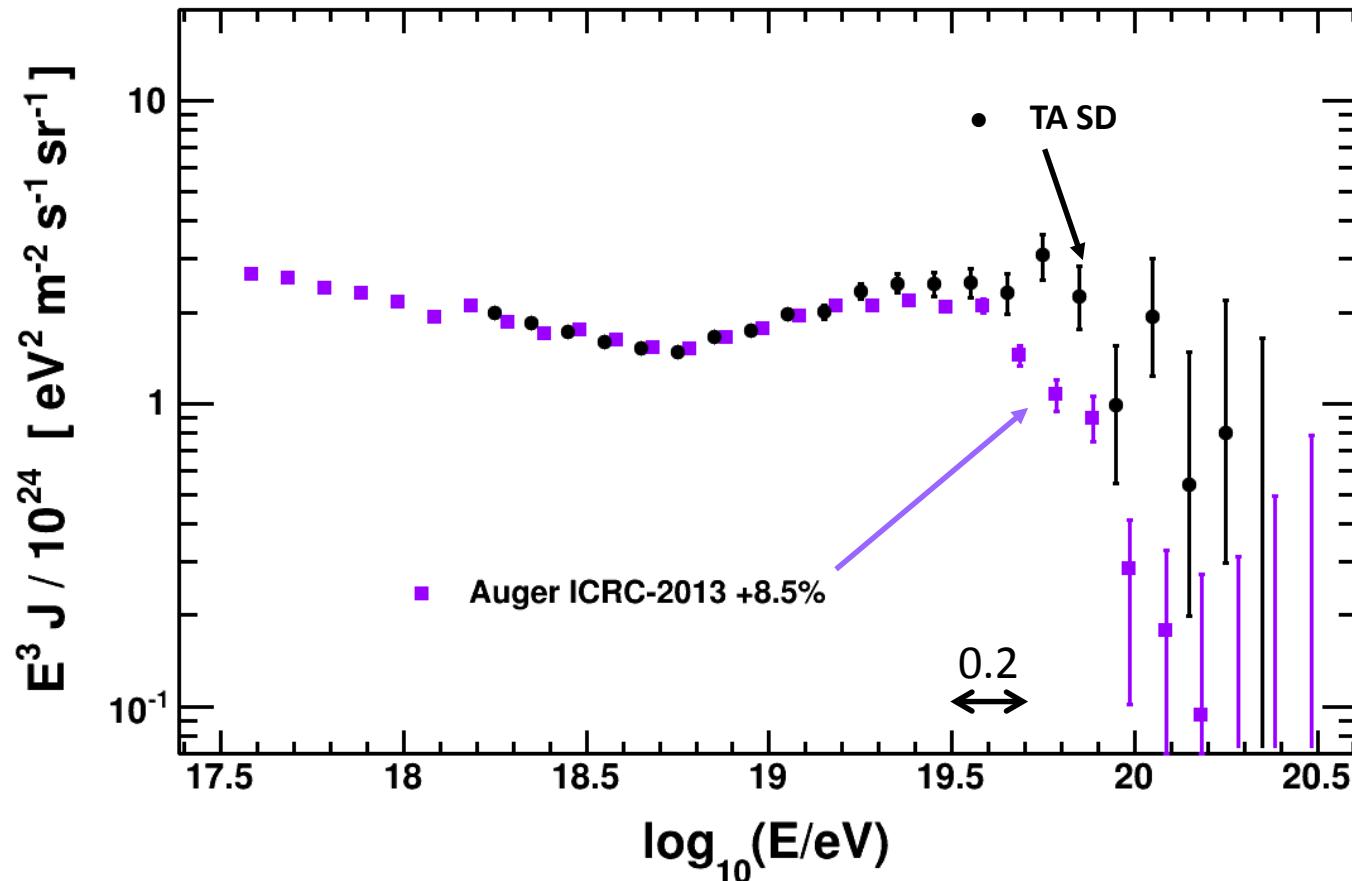
Isotropic B.G.
 276-55=221events

Oversampling
 15° radius circle



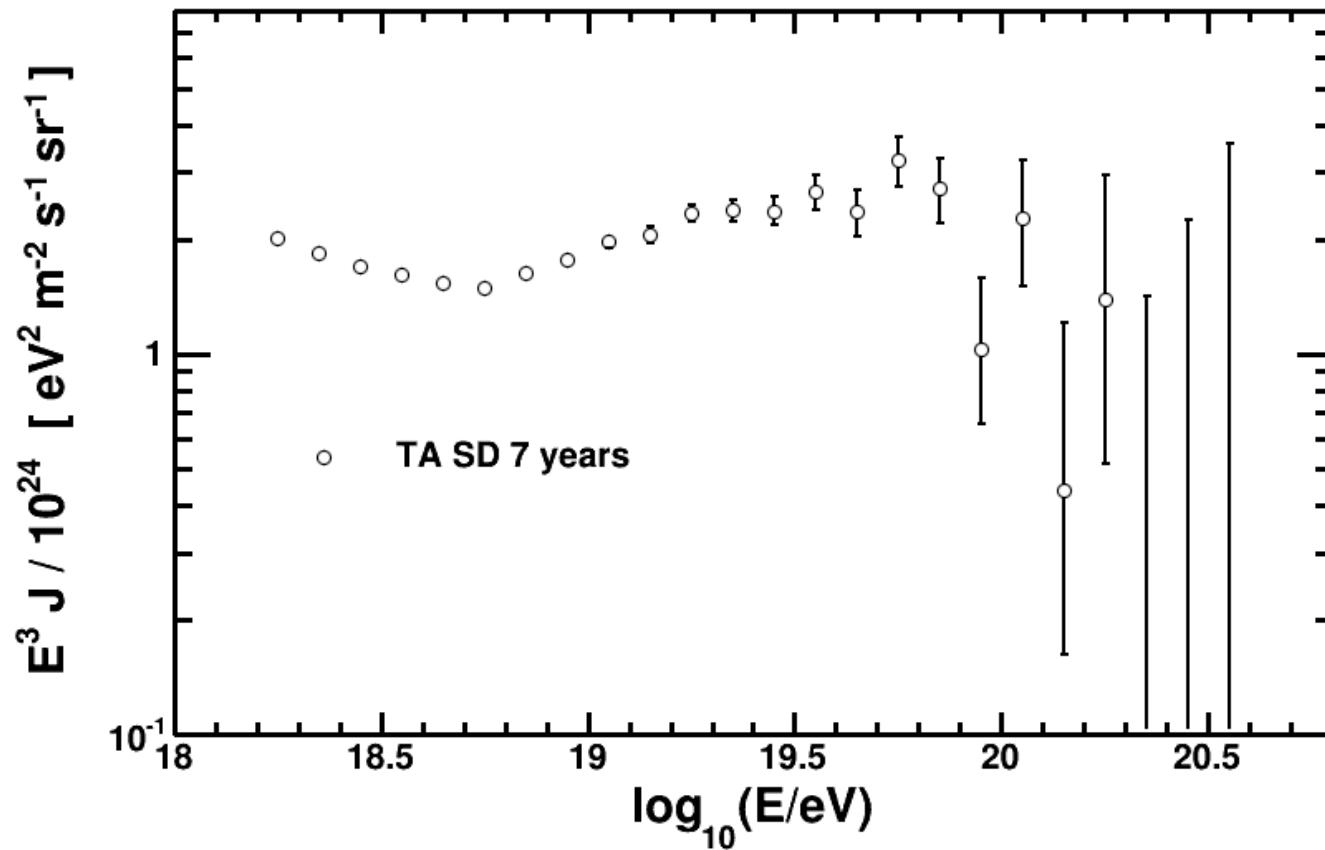
TAX4 will clarify the nature of the hotspot

Comparison of TA and Auger (+8.5%) spectra



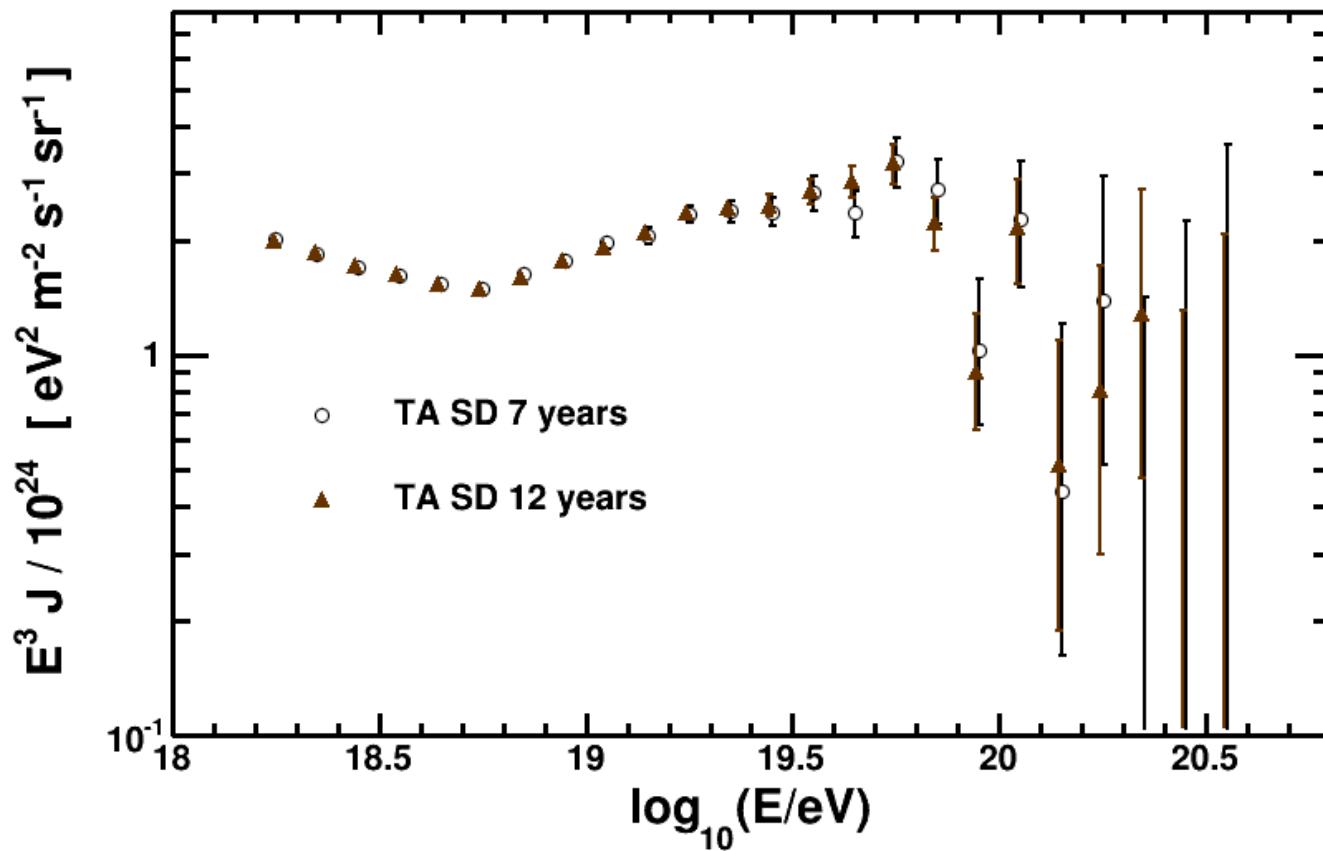
Spectrum

Summer 2015 (7 years of TA SD data)



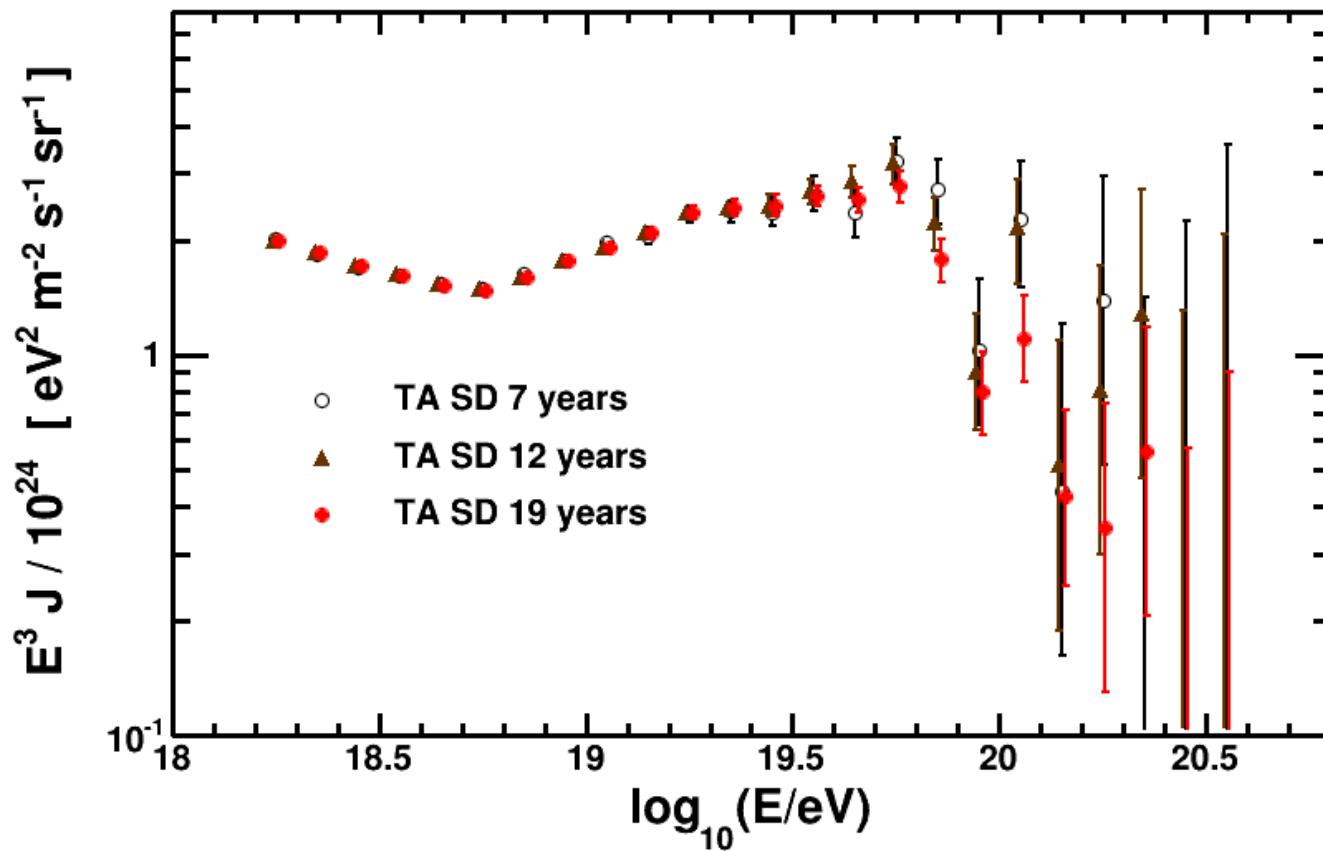
Spectrum

Summer 2020 (12 years of TA SD data)



Spectrum

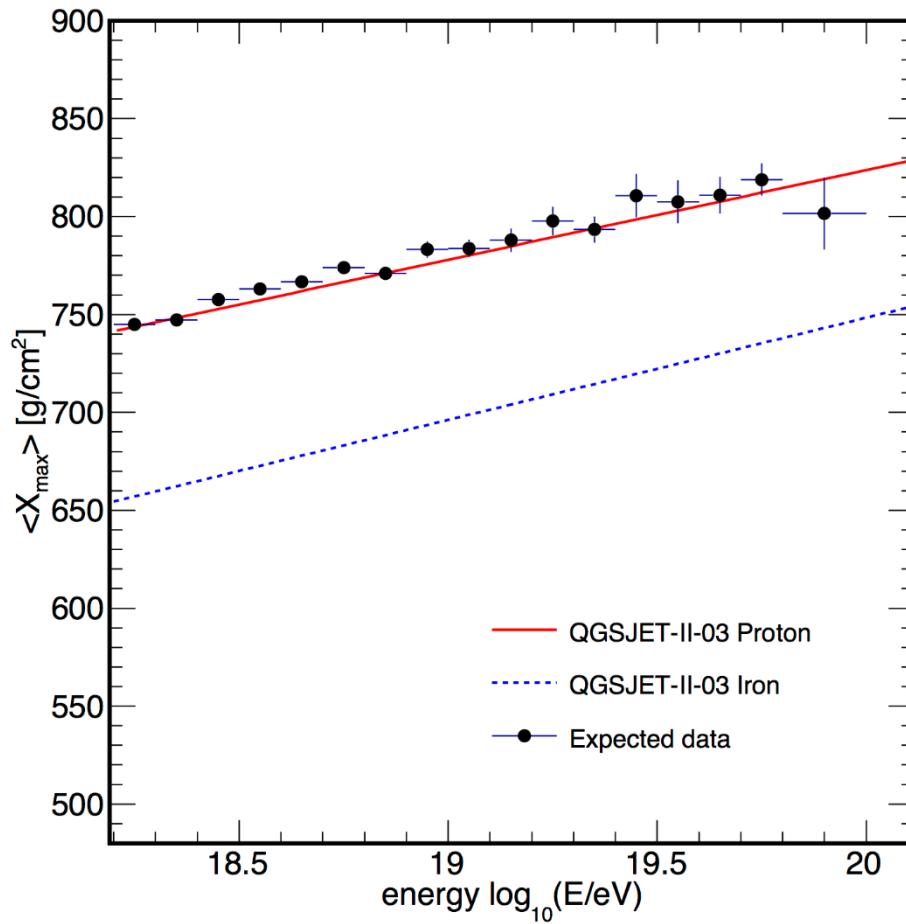
Summer 2020 (19 years of TA SD data)



Xmax in summer 2020

An example of 16.3 years of TA hybrid data

(assuming proton QGSJETII-03 model)



Low-energy extension

TALE
NICHE

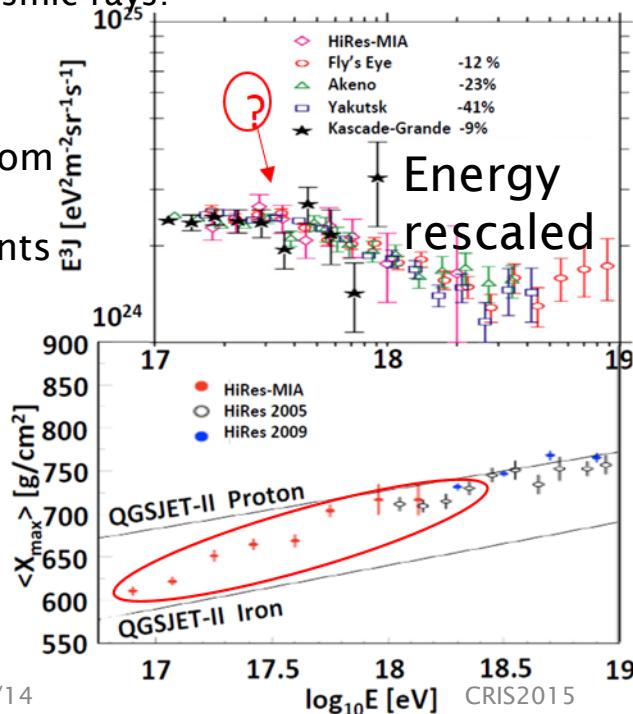
TALE (TA Low-energy Extension) down to $10^{15.6}$ eV

- $E = 10^{15.6} - 10^{19}$ eV
- Second knee at $\sim 10^{17.5}$ eV?
- Drastic change of composition at $10^{17} \sim 10^{18}$ eV?



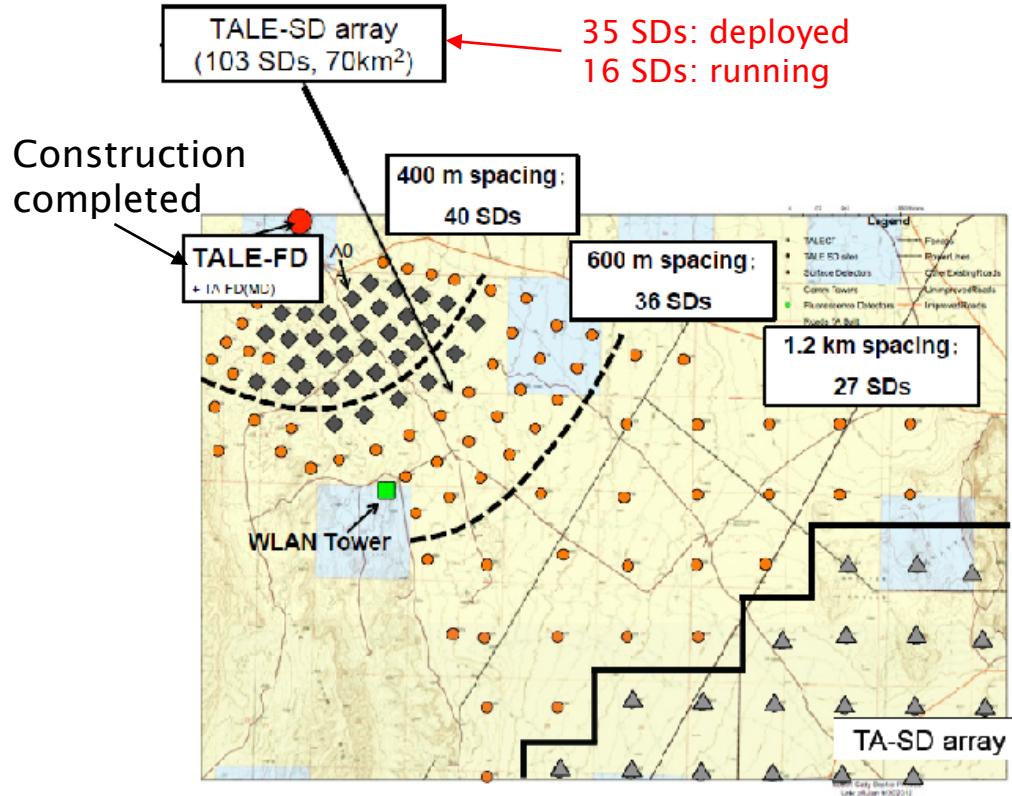
- Transition from galactic to extra-galactic cosmic rays?

Results from Previous experiments



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

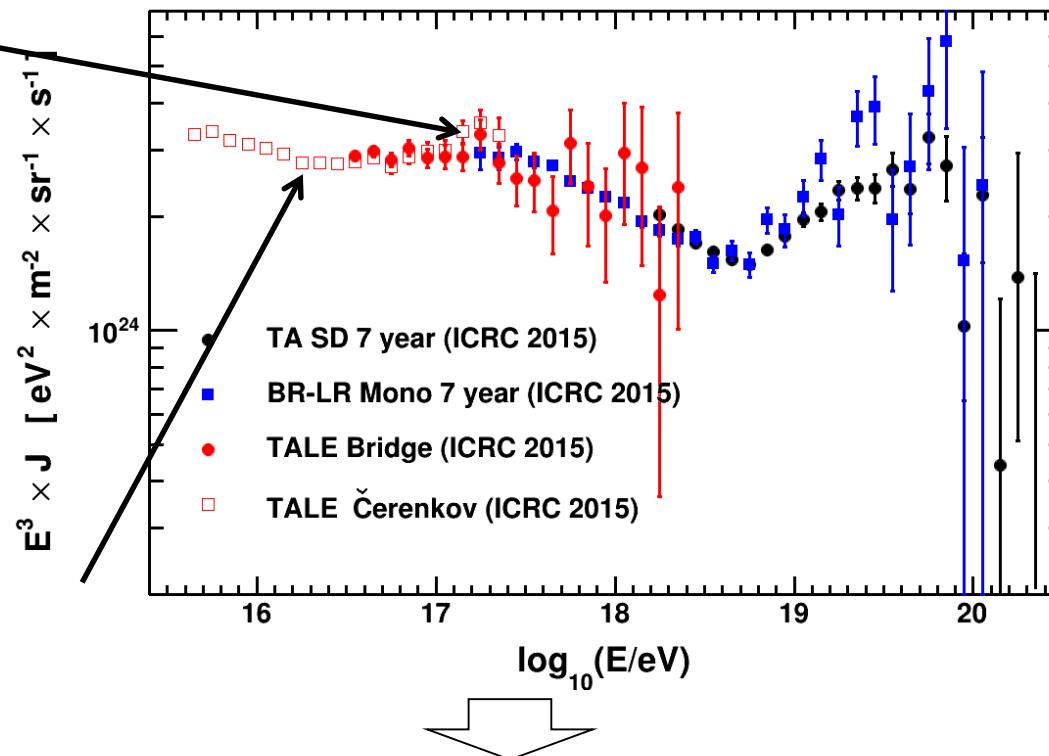
TALE layout



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

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

Energy region over 4.7 orders of magnitude



D. Ivanov
at ICRC2015

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

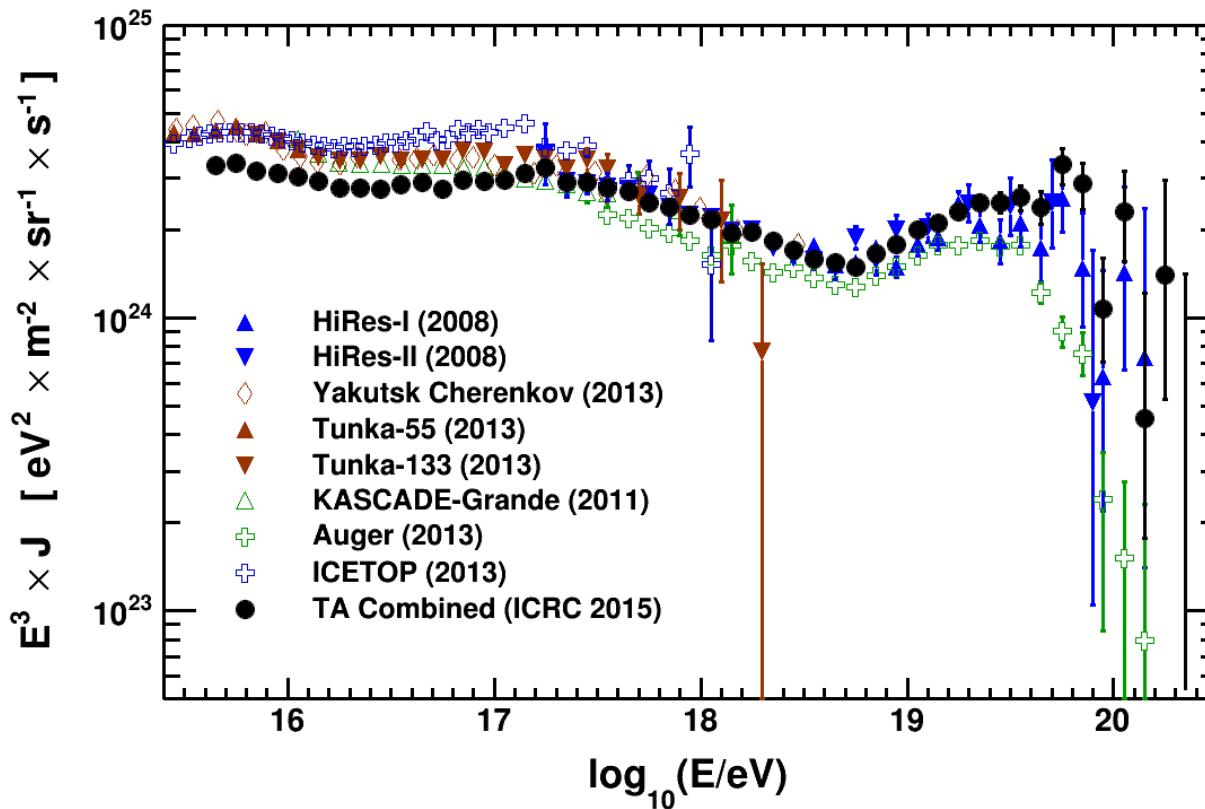
Composition meas. with better Xmax resolution: urgent issue

→ **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

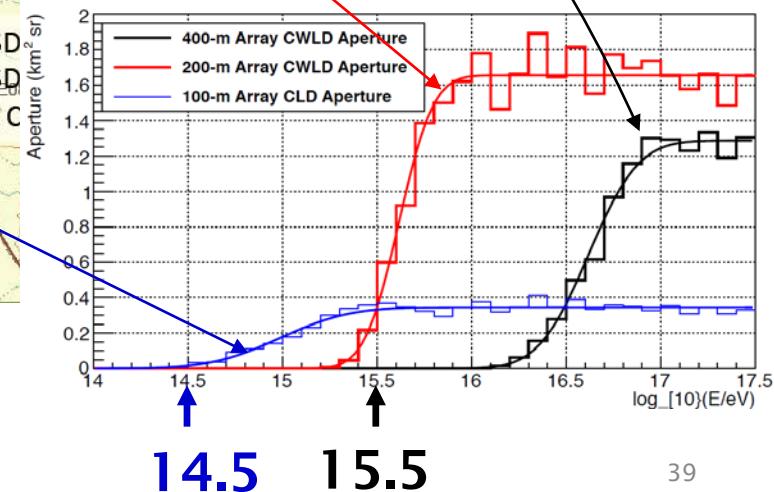
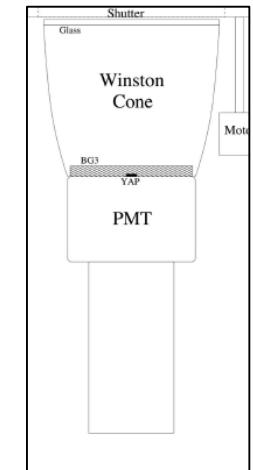
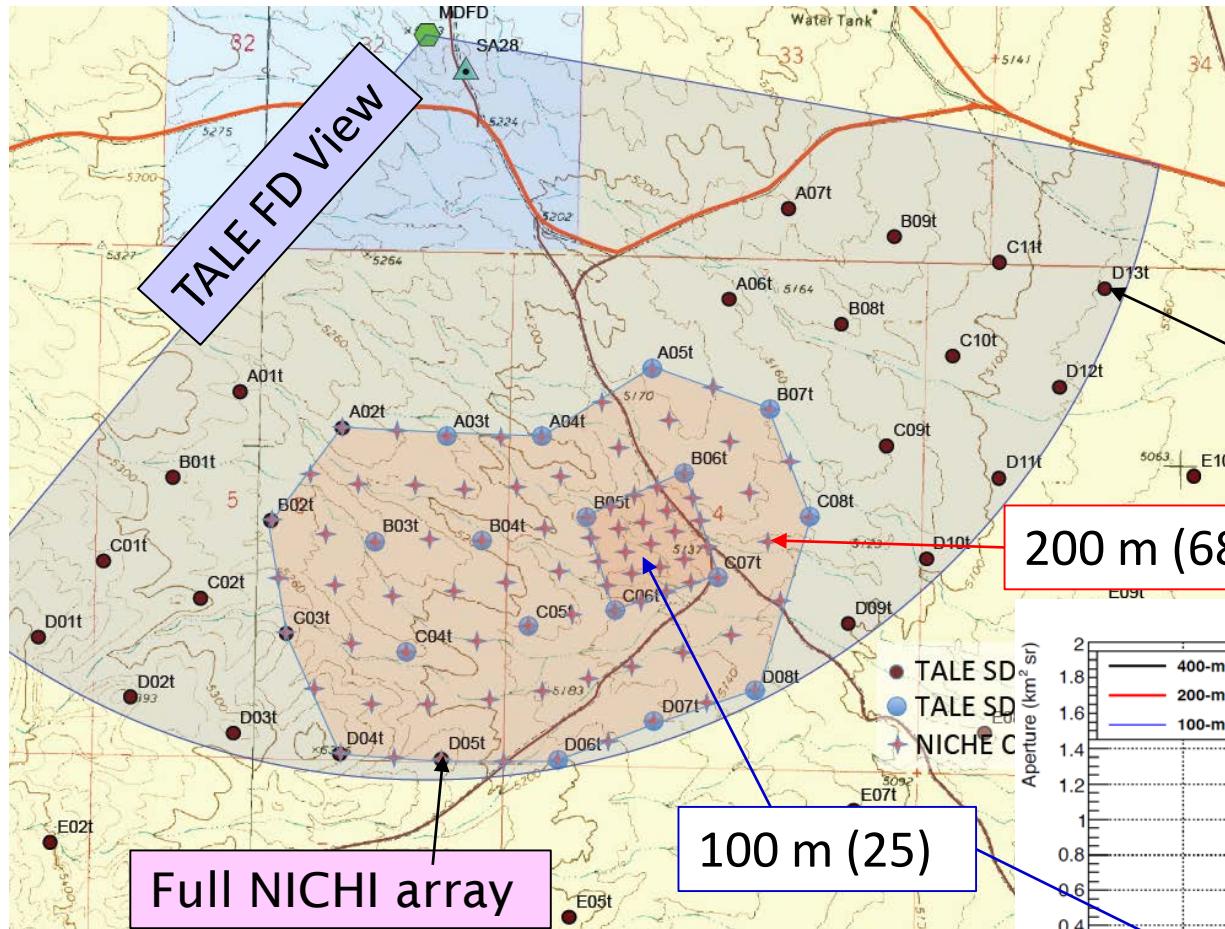
Combined TA with Other Experiments



NICHE proposal ($E > \sim 10^{15}$ eV)

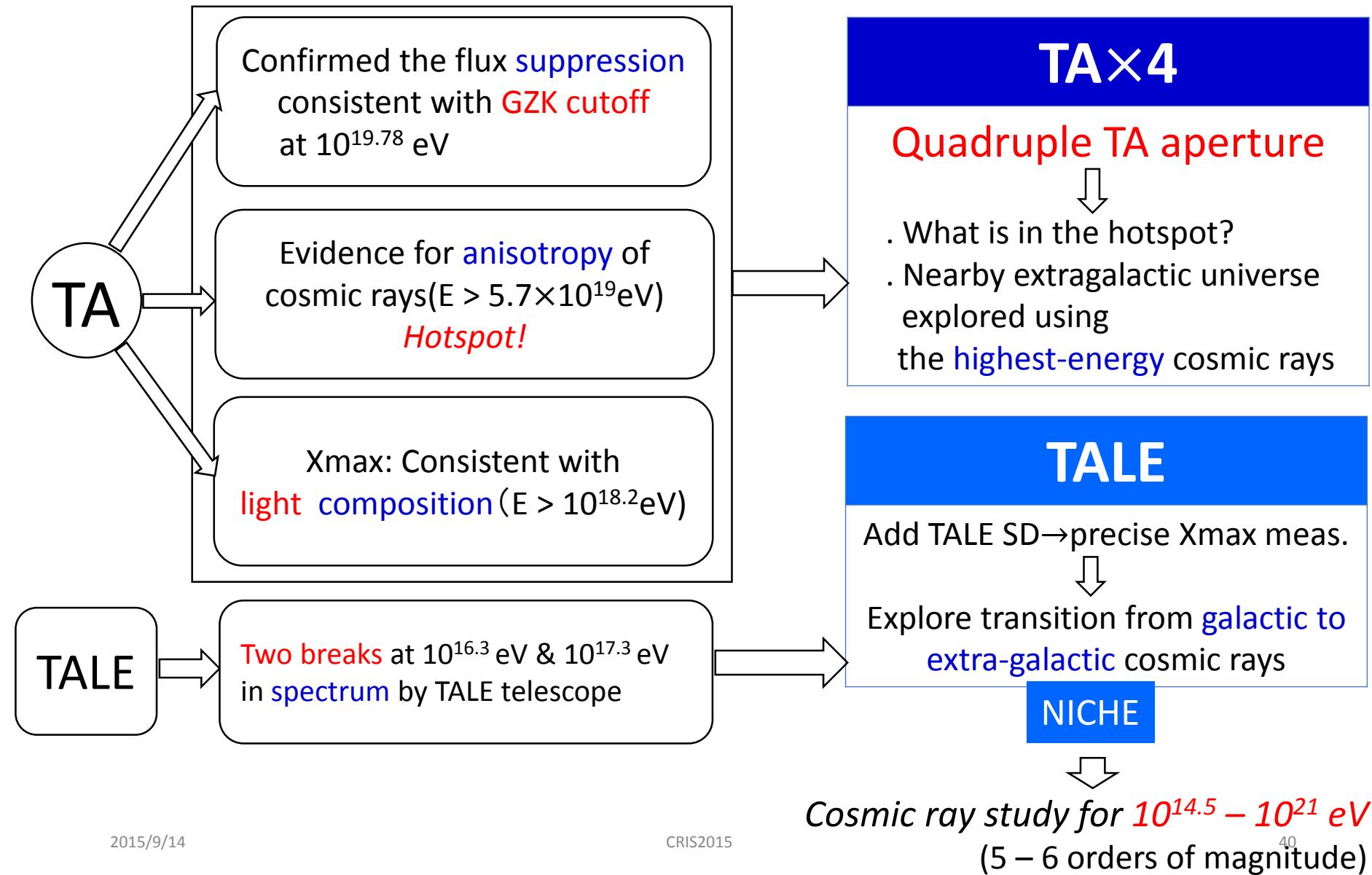
Non-Imaging CHErenkov array (1.5-2 km²)

Upward 3"-PMT



jNICHE: an array with 15 PMTs:
funded by Japanese funding agency last year

Summary



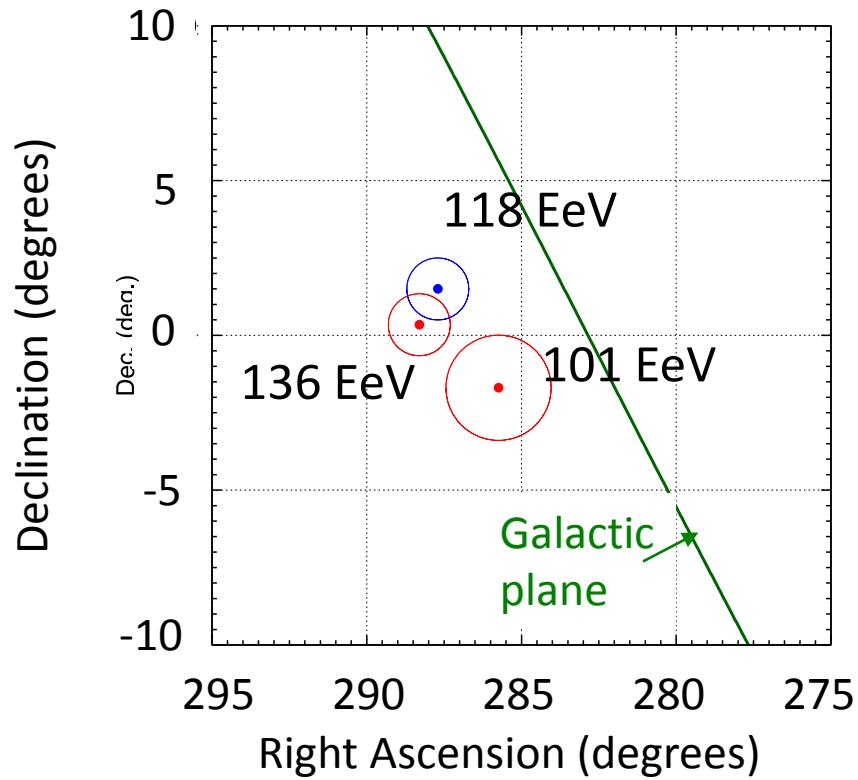
Backup

Schedule of TA×4

JFY	construction or observation	surface detector (SD)		hybrid (HYB)	
		TA SD (=1) (=1)	additional SD (=3)	TA HYB (=1)	additional HYB (=3)
2008-2014	observation	7	0	7	0
2015	construction	1	0	1	0
2016	construction	1	0	1	0
2017	construction/(2/3) observation(1/3)	1	1	1	0.3
2018	observation	1	3	1	2
2019	observation	1	3	1	2
subtotal		12	7	12	4.3
total		19		16.3	

JFY: Japanese Fiscal Year that starts in April

A cluster of TA and Auger cosmic rays above 100EeV?



TA 2 events and Auger 1 event are clustered within 3.7 degrees

Hint of a point source?