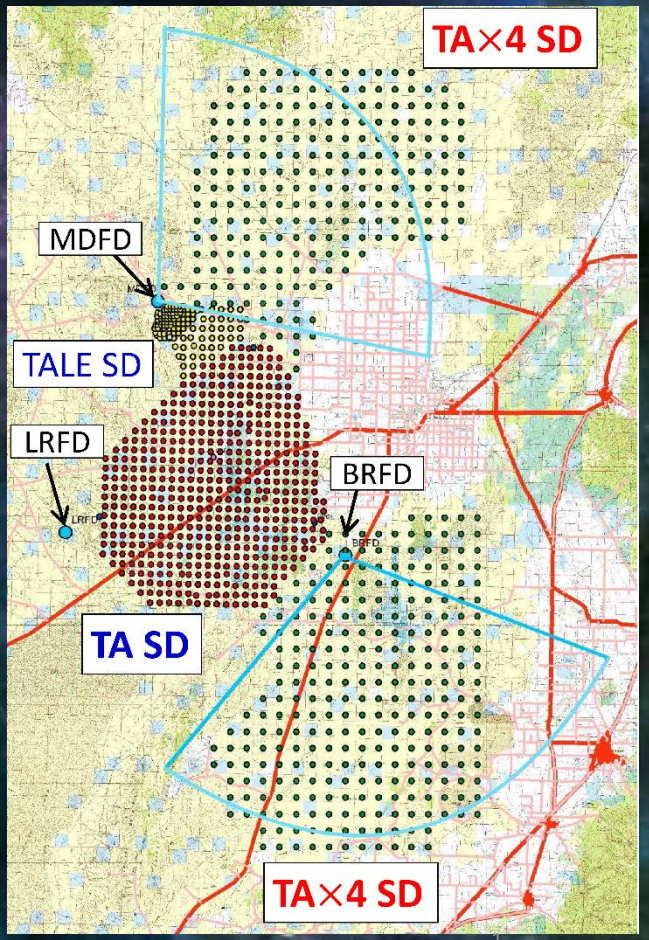
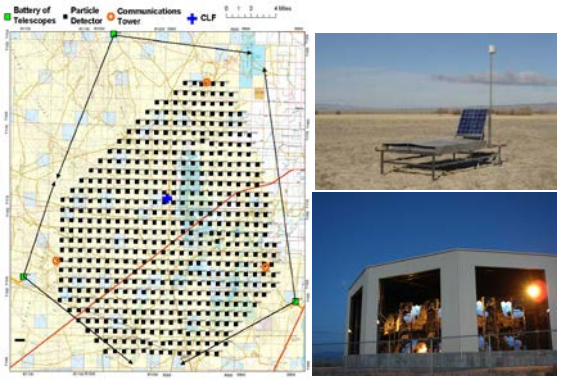
# TA×4

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



# Outline

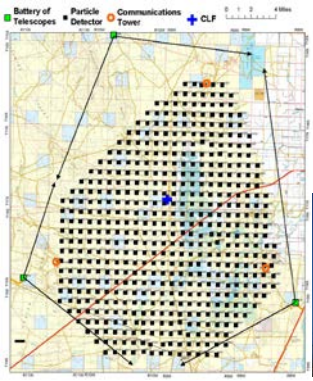
Telescope Array (TA)




Recent TA results
5- or 6-year data

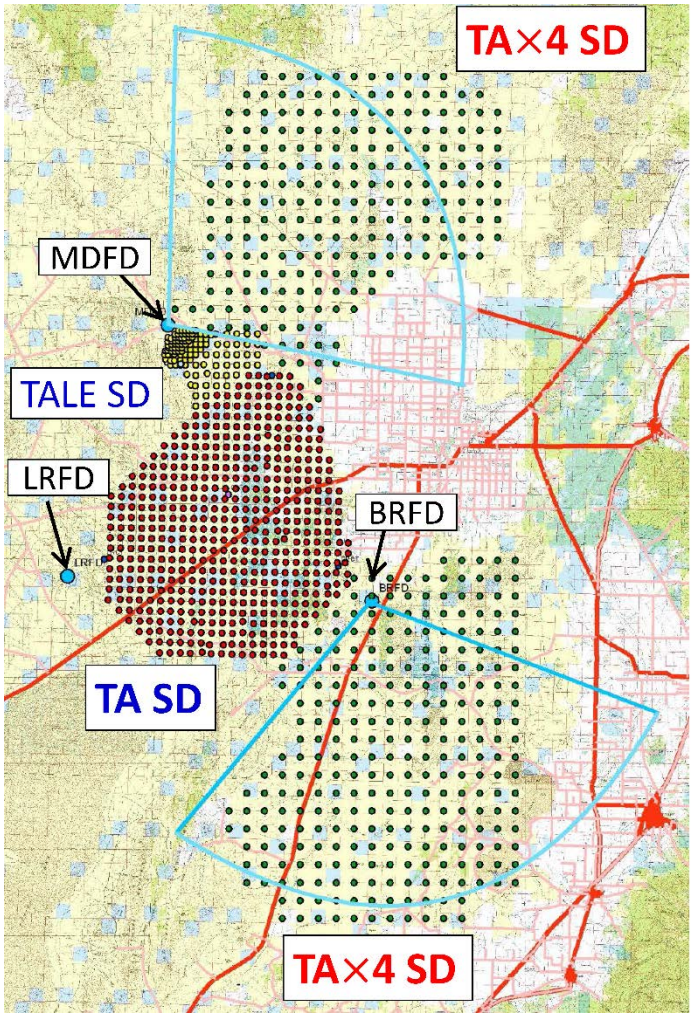
# Outline

Telescope Array (TA)




Recent TA results
5- or 6- year data

TA×4 extension



5 countries, 126 researchers

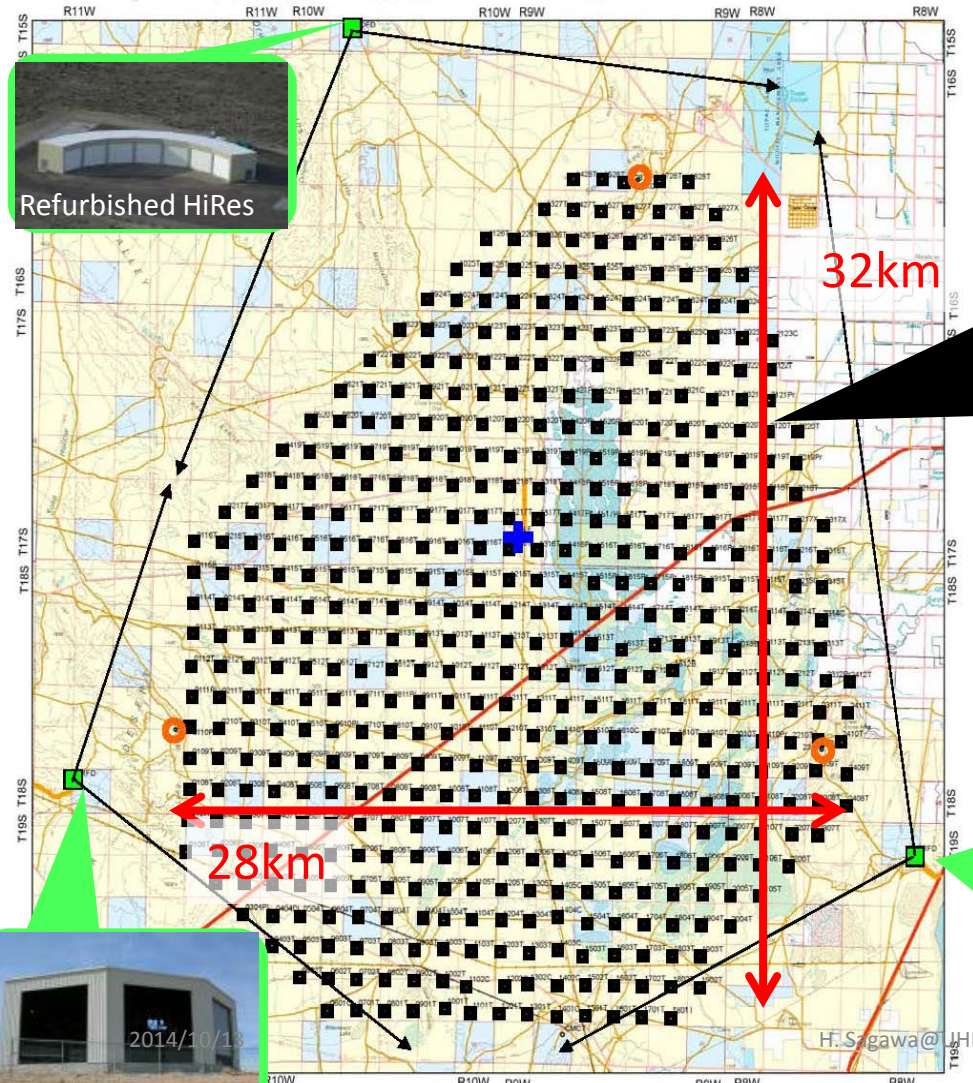
# Telescope Array Collaboration


R.U. Abbasi[1], M. Abe[13], T.Abu-Zayyad[1], M. Allen[1], R. Anderson[1], R. Azuma[2], E. Barcikowski[1], J.W. Belz[1], D.R. Bergman[1], S.A. Blake[1], R. Cady[1], M.J. Chae[3], B.G. Cheon[4], J. Chiba[5], M. Chikawa[6], W.R. 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], C.C.H. 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], H.B. Kim[4], J.H. Kim[1], J.H. Kim[25], S. Kitamura[2], Y. Kitamura[2], V. Kuzmin[17], Y.J. Kwon[7], J. Lan[1], S.I. Lim[3], J.P. Lundquist[1], K. Machida[12], K. Martens[9], T. Matsuda[20], T. Matsuyama[10], J.N. 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], I.H. Park[23], M.S. Pshirkov[24], D.C. Rodriguez[1], G. Rubtsov[17], D. Ryu[25], H. Sagawa[8], N. Sakurai[10], A.L. Sampson[1], L.M. Scott[15], P.D. Shah[1], F. Shibata[12], T. Shibata[8], H. Shimodaira[8], B.K. Shin[4], J.D. Smith[1], P. Sokolsky[1], R.W. Springer[1], B.T. Stokes[1], S.R. Stratton[1,15], T.A. 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], S.B. Thomas[1], G.B. 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 University of Utah 2 Tokyo Institute of Technology 3 Ewha Womans University 4 Hanyang University
5 Tokyo University of Science 6 Kinki University 7 Yonsei University 8 ICRR, University of Tokyo
9 IPMU, the University of Tokyo 10 Osaka City University 11 Kanagawa University 12 University of Yamanashi
13 Saitama University 14 Astrophysical Big Bang Laboratory RIKEN, Wako 15 Rutgers University
16 Tokyo City University17 INR of the Russian Academy of Sciences 18 Waseda University
19 Chiba University 20 KEK 21 Kochi University 22 Ritsumeikan University 23 Sungkyunkwan University
24 Universite de Libre de Bruxelles 25 Ulsan National Institute of Science and Technology
26 ERI, University of Tokyo 27 Hiroshima City University 28 Advanced Science Institute, RIKEN
29 National Institute of Radiological Science 30 Ehime University

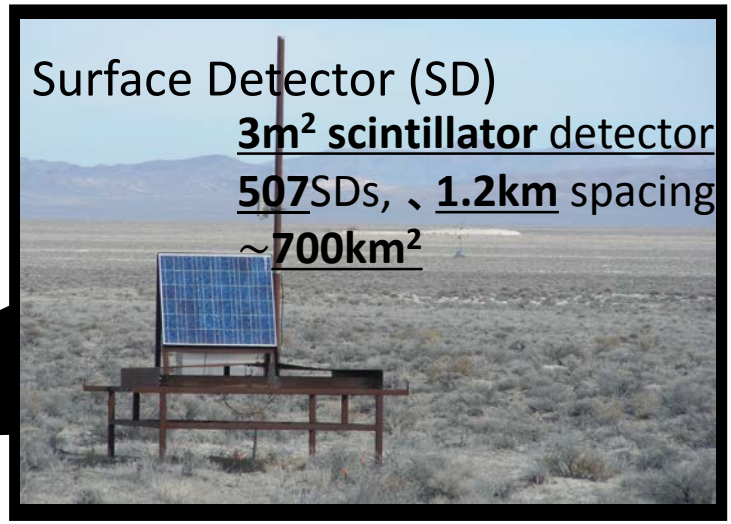
# Telescope Array detector

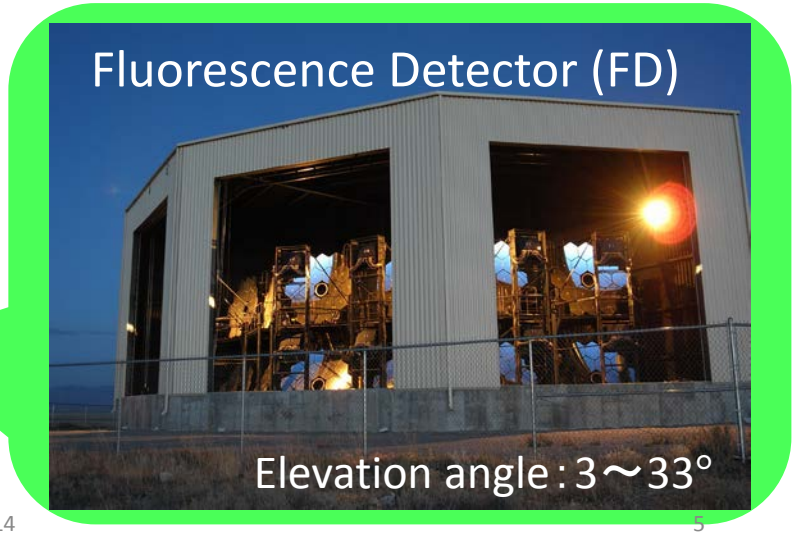
- Utah, USA
  - lat. 39.30°N, long. 112.91°W












Hybrid observation since Mar, 2008

# Recent TA results

Anisotropy (hot spot)

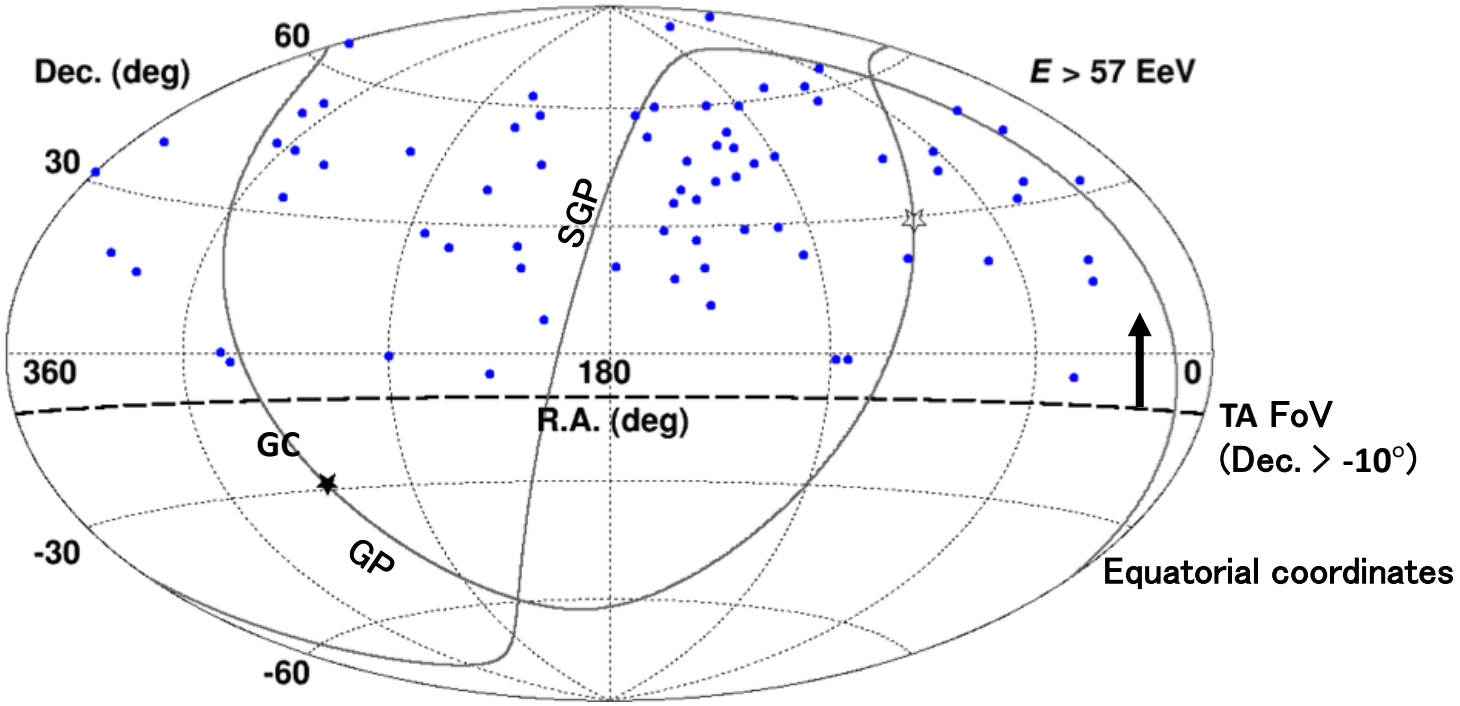
Mass composition (Xmax)

Energy spectrum

# Anisotropy of arrival directions of highest-energy cosmic rays (hotspot)

- TA SD data 5 years (2008/May ~ 2013/May)
- E > $5.7\times10^{19}$eV以上, zenith angle < 55° : 72 events

distribution of arrival directions (blue points)

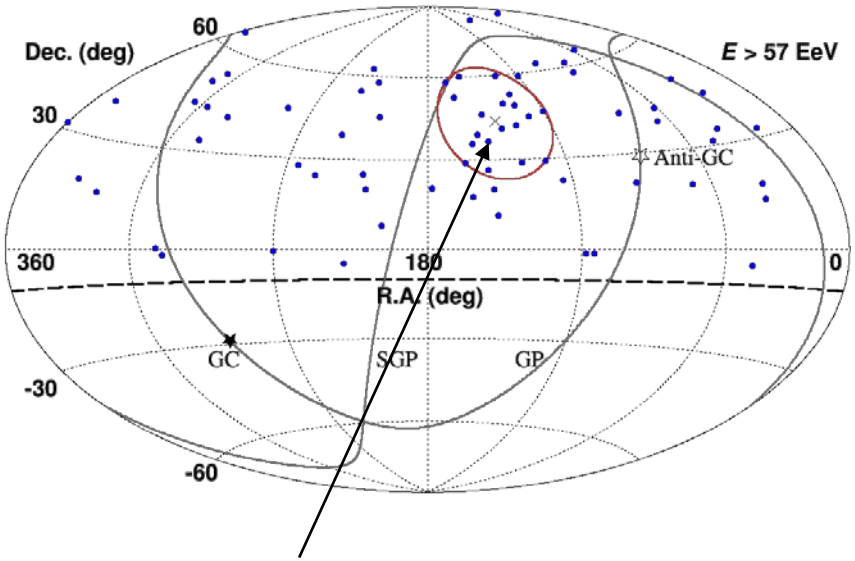


# Hotspot

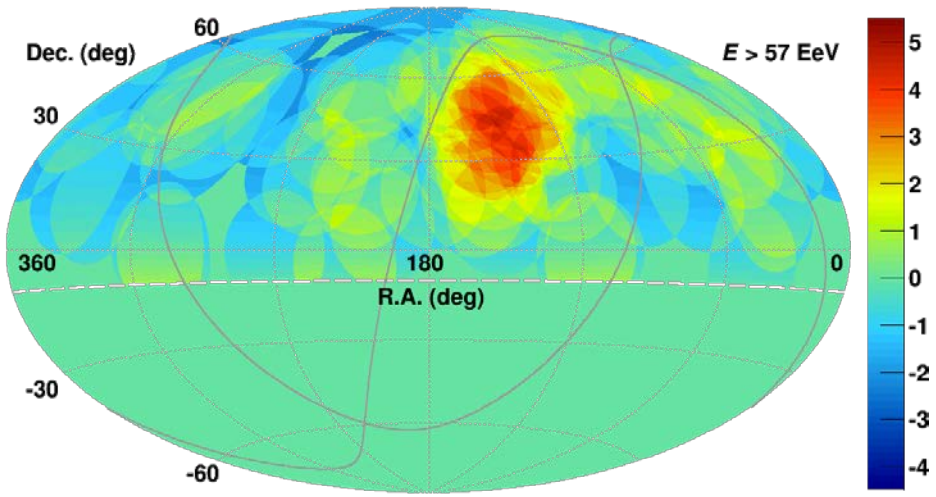
5-year data

## Anisotropy of highest-energy cosmic rays

oversampling using 20-degree radius circles




Significance map




- Maximum significance
  - direction : R.A. = 146.7°, Dec. = 43.2°
  - observed : 19 (19/72=26%)
  - Expected for isotropy : 4.5 (4.5/72=6%)
  - Li-Ma significance: 5.1$\sigma$
- Chance probability to obtain maximum significance of 5.1$\sigma$ : $3.7\times10^{-4}$ (3.4$\sigma$)
  - MC : 15, 20, 25, 30, 35°-radius circles

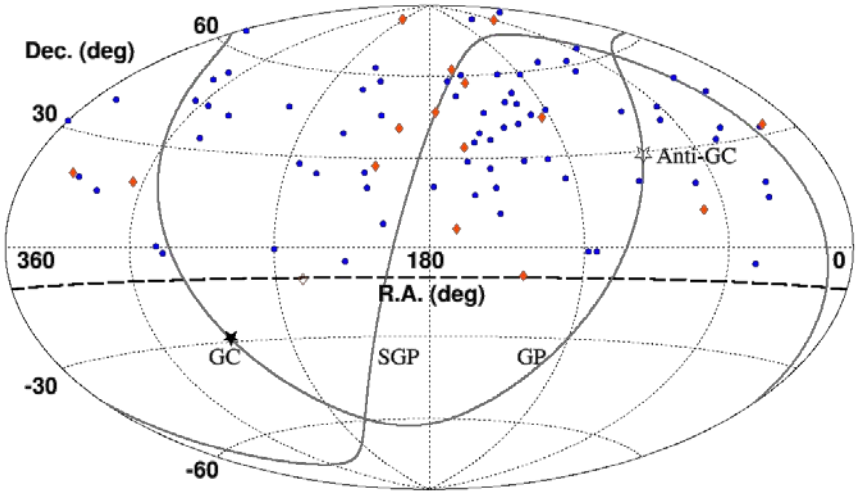
ApJ 790, L21 (2014)

D.Bergman
COSPAR 2014

# Hotspot +1-year data

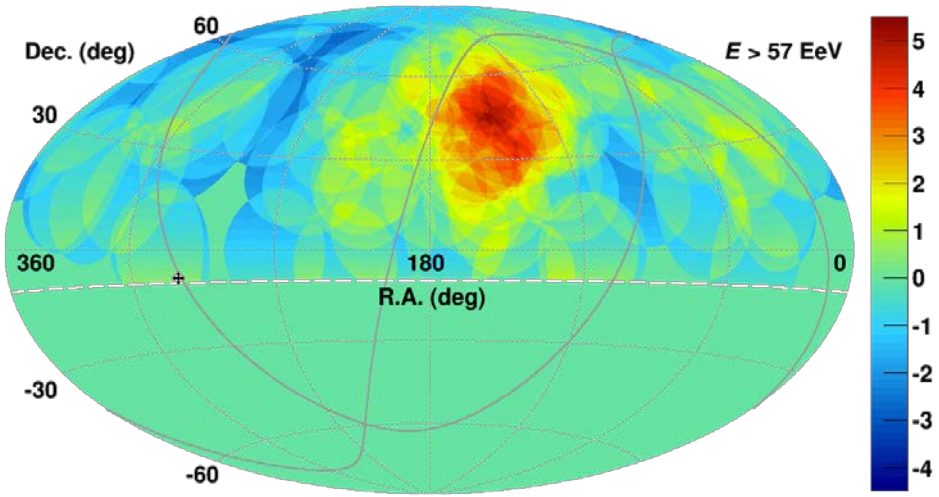
- 2008/May ~ 2014/May (6 years)

Arrival direction distribution




blue : 5-year data
red : recent 1-year data

Significance map




- E > 5.7x10$^{19}$eV: 72 events→87 events (+15)
- Hotspot : 19events→23 events ( +4)

5 yrs +1 yr
(19/72~26%, 4/15~26%)

- Max. Li-Ma significance: 5.1$\sigma$ →5.55$\sigma$ ⟹ Chance prob. = 3.4$\sigma$ →4.0$\sigma$ (3.1x10$^{-5}$)

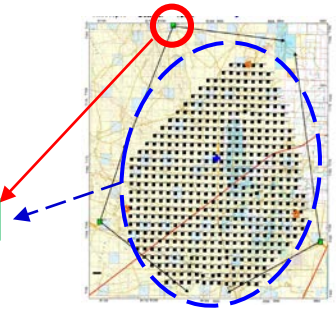
# Compatibility with isotropy

- Autocorrelation $p \sim 0.001$ ($\delta \sim 20^o – 25^o$)
- AGN $p \sim 0.007$
- LSS $p \sim 0.001$

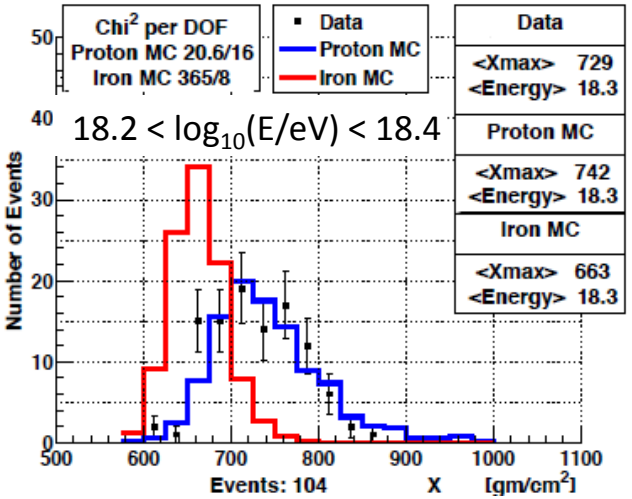
(MD FD + SD)

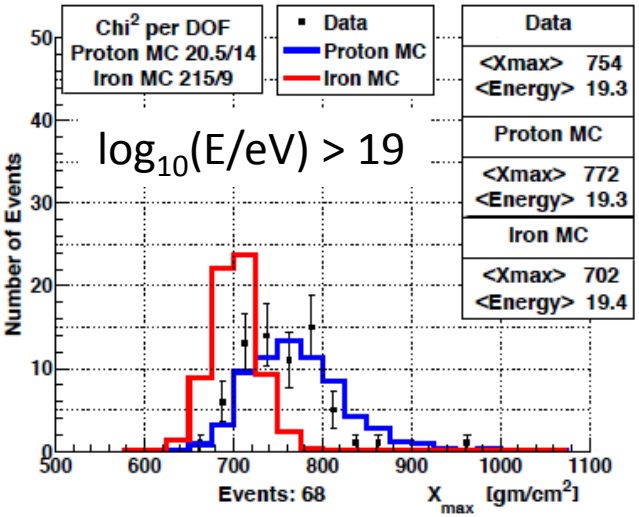
J.N.Matthews
Qui Nhon 2014
arXiv:1408.1726
Submitted to APP

# Xmax analysis by hybrid events

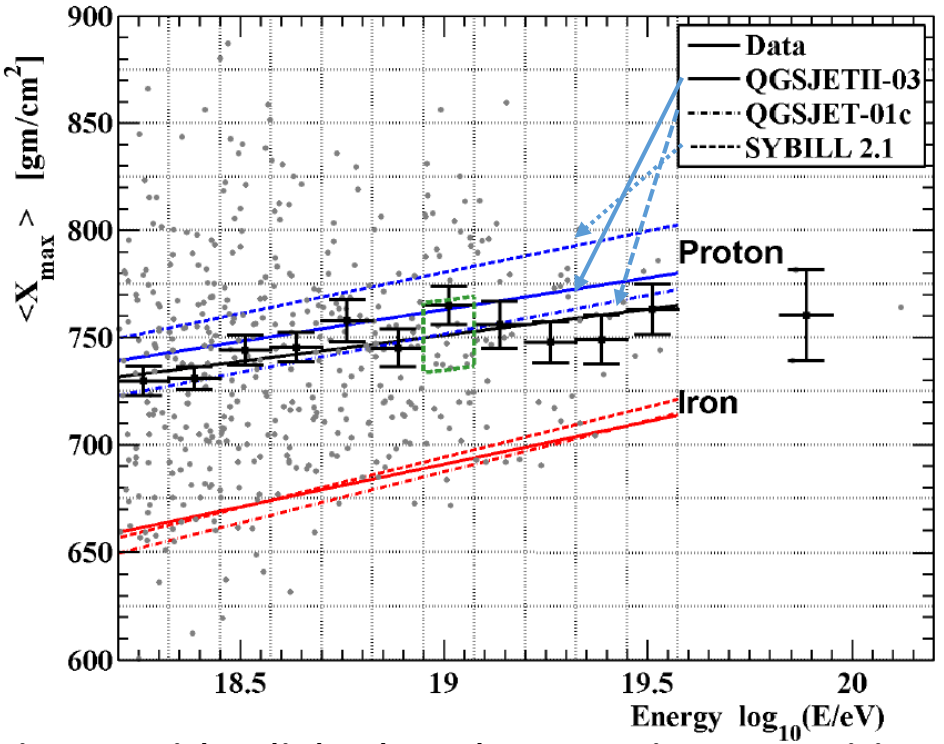



- MD FD: [refurbished HiRes] + SD




Black points : TA data
MC(QGSJET-II-03)
blue : Proton, red : Fe

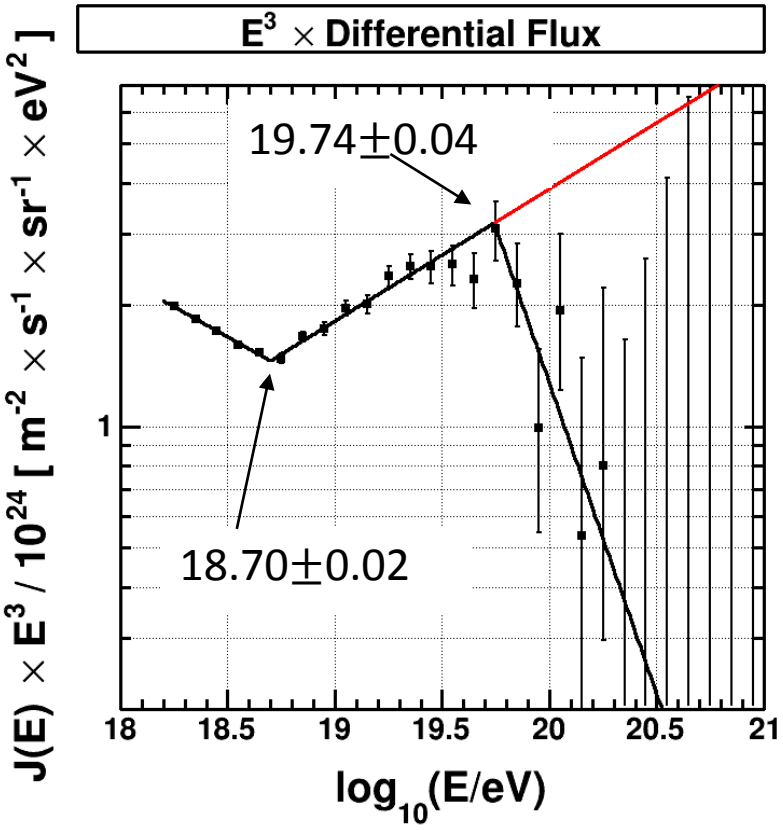



consistent with a light, largely protonic composition

D.Bergman
COSPAR 2014

# TA energy spectrum

- SD data : 2008/May～2014/May (6 years)




ankle
Cutoff consistent with GZK cutoff

$E > 10^{19.8}$eV
Expected (no cutoff) = 85.93
observed = 32
Cutoff chance prob. = $6.59\sigma$

# Model of extremely-high-energy cosmic rays

## source

Extragalactic proton CR

Distribution cases
- isotropic
- LSS (2MASS < 250 Mpc)

➢ Evolution $(1+z)^m$

➢ Injection spectrum $E^{-P}$

➢ Energy scale
➢ Flux normalization factor

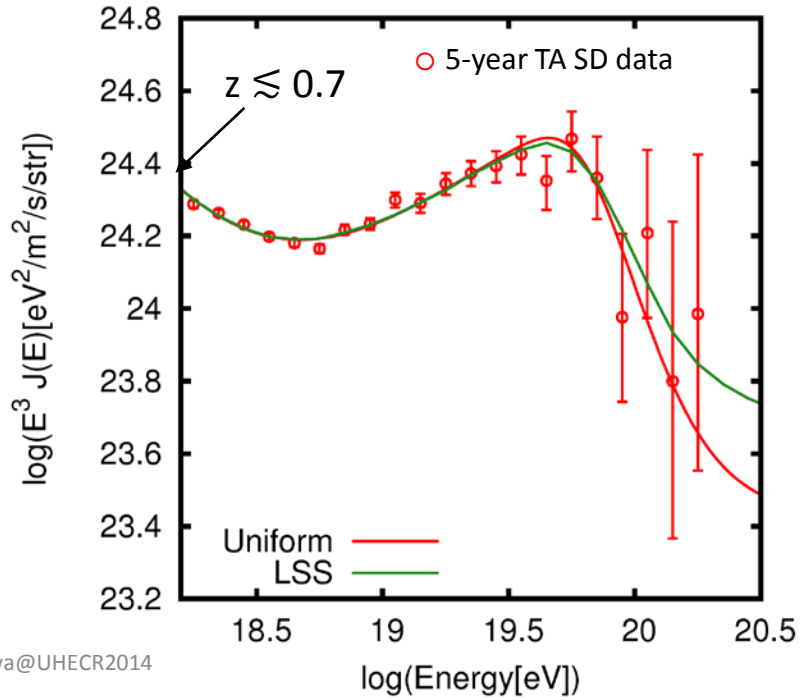
4 fit parameters

## propagation

Propagation code
- Kalashev + Kido, arXiv:1406.0735

Photon background
- CMB
- IRB

No GMF and no extra GMF



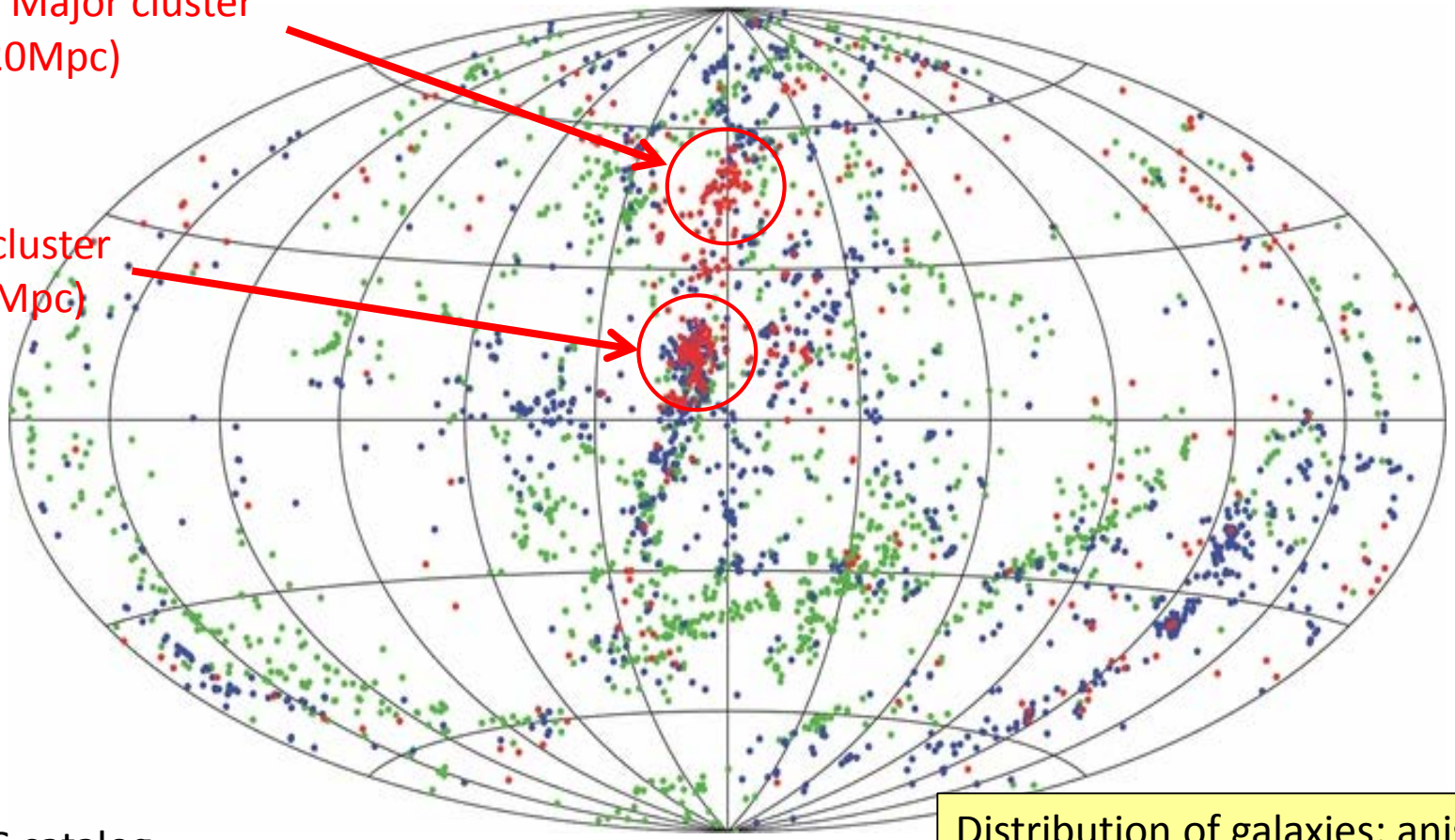

If GZK cutoff exists,
sources of highest-energy CRs which arrive at the earth are restricted to nearby objests

# Nearby galaxies

## (within ~50 Mpc)

Ursa Major cluster
(D=20Mpc)

Virgo cluster
(D=20Mpc)



2MASS catalog
John P. Huchra, et al 2012, ApJ, 199, 26
+ TA 5-year significance (color map)

Distribution of galaxies: anisotropic

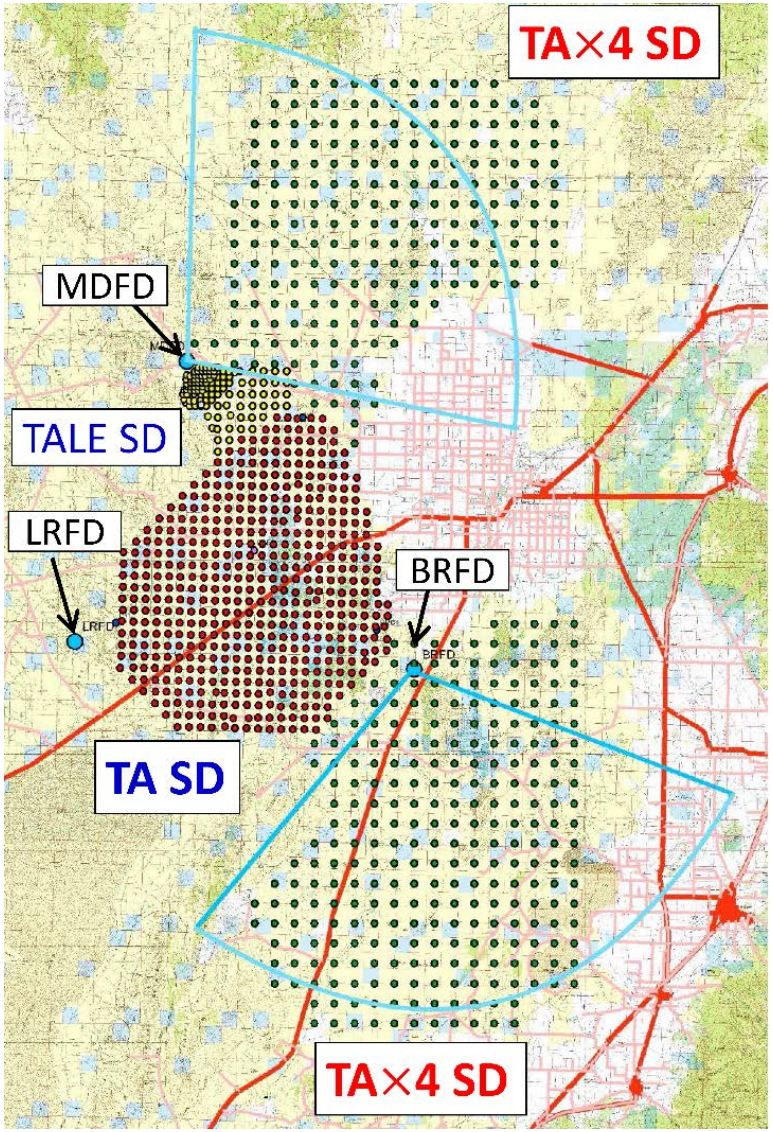
⇩

Anisotropy of arrival directions of highest-energy cosmic rays

# TA×4 proposal

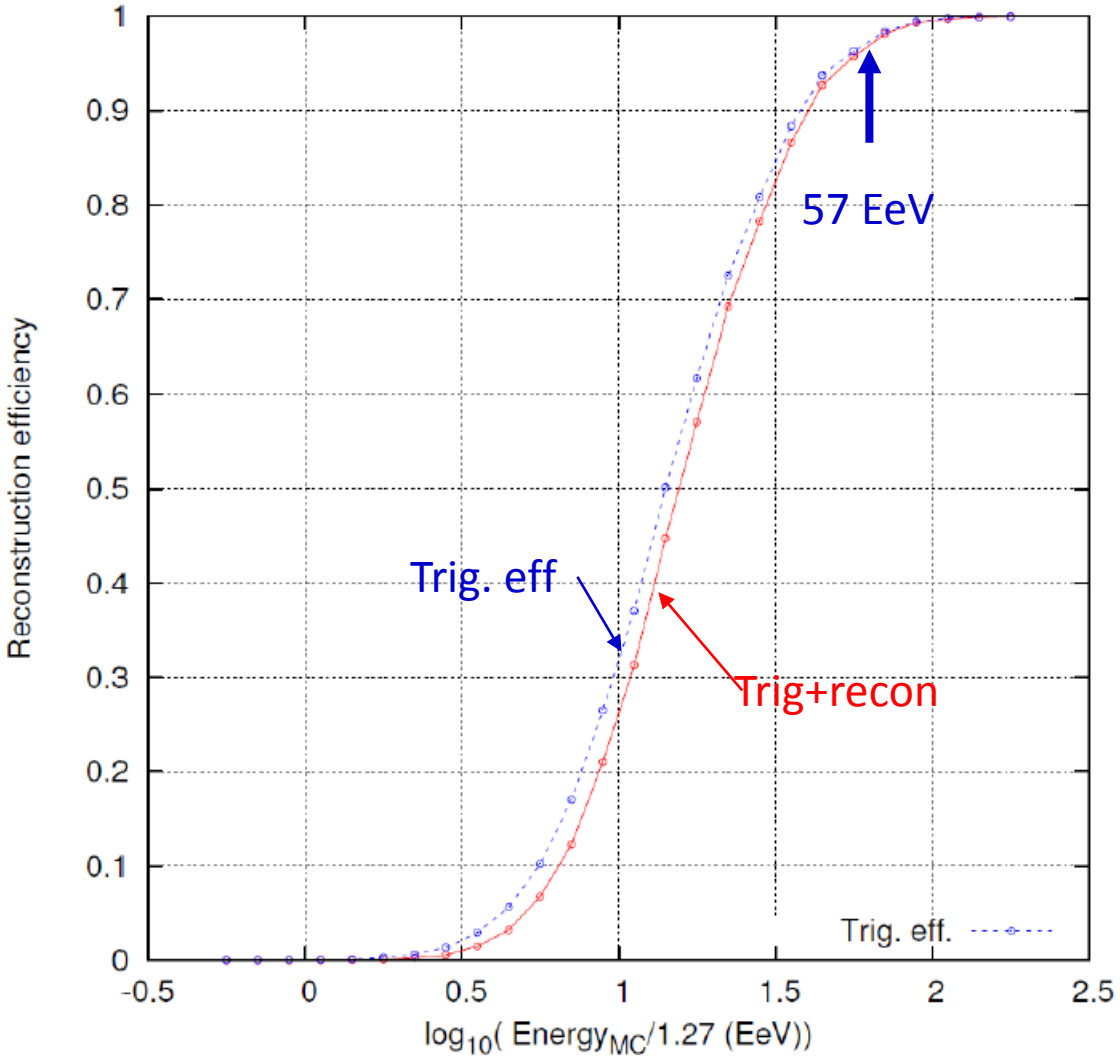
- Quadrule TA SD (~3000 km$^2$)
  - **500** scintillator SDs
    **2.1 km** spacing (**Japan**)
- **2** FD stations each with 10 refurbished HiRes telescopes (US)

- Apply grants this fall (Japan, US)
  + from Korea, Russia
- 2-year construction
- 3-year observation
  - **TA SD: 21 year** data
  - TA hybrid: **18** year data



# Efficiency for additional TA × 4 SD array

## Differential for energies




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

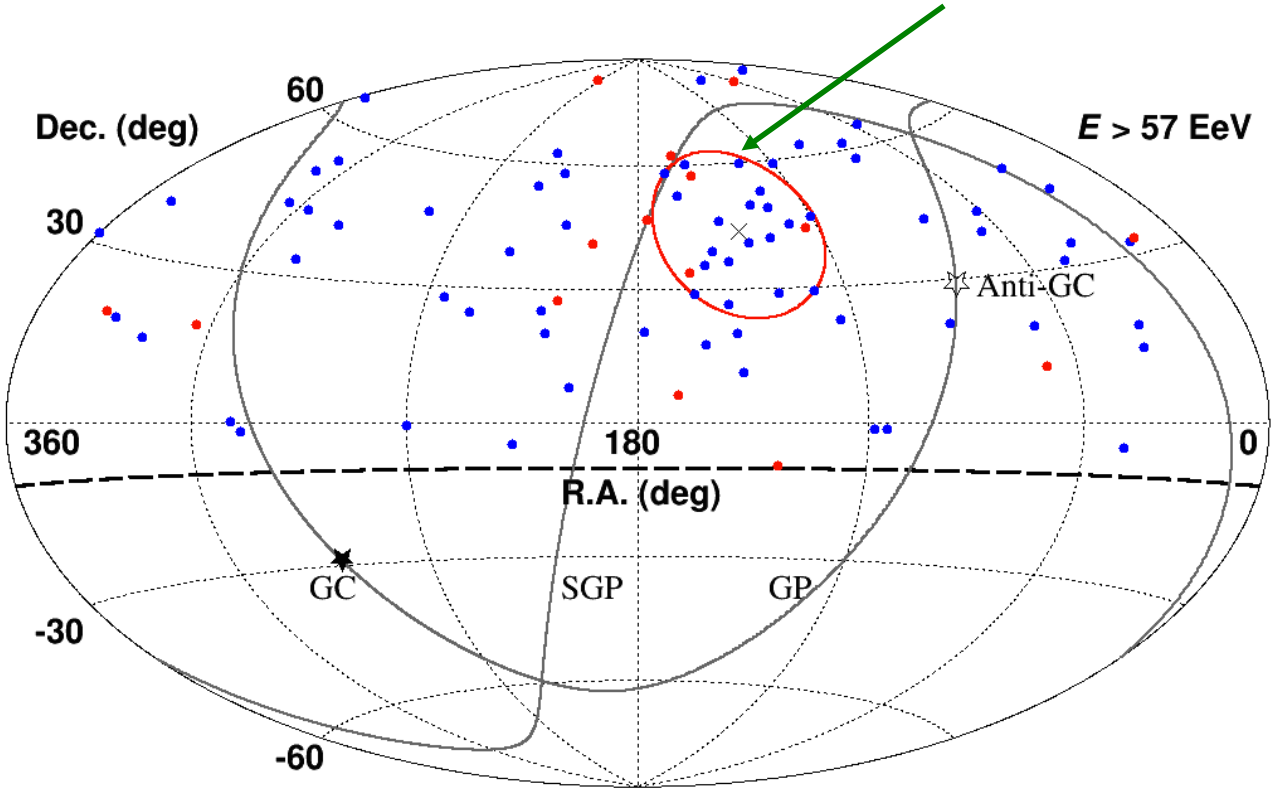
Reconstruction
. NSD≥ 4

TA SD reconstruction efficiency =100% for $E > 10^{19}$eV

# 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

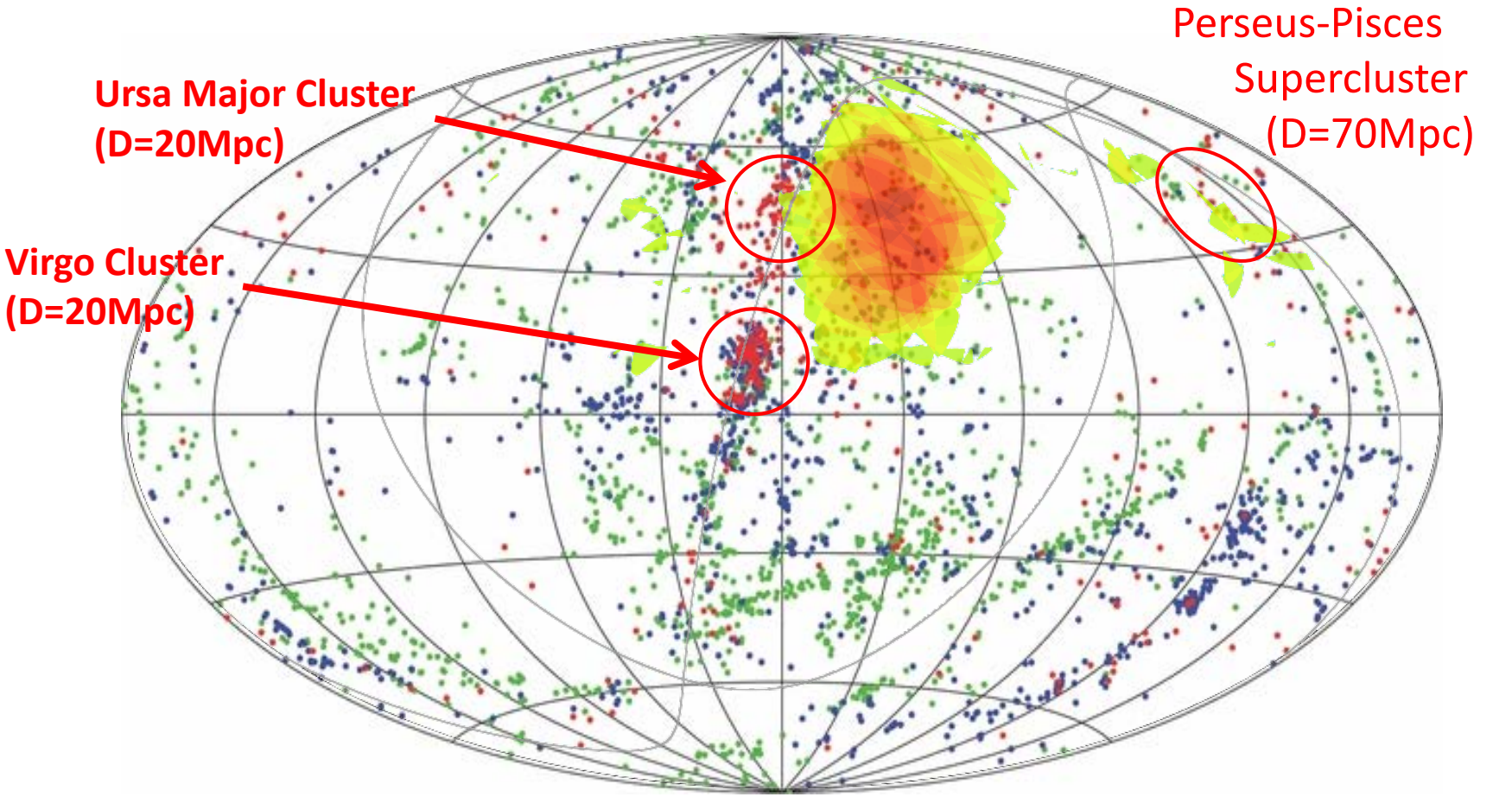
# Arrival directions of TA 6-year data



# 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

# Nearby Galaxy Clusters and hotspot



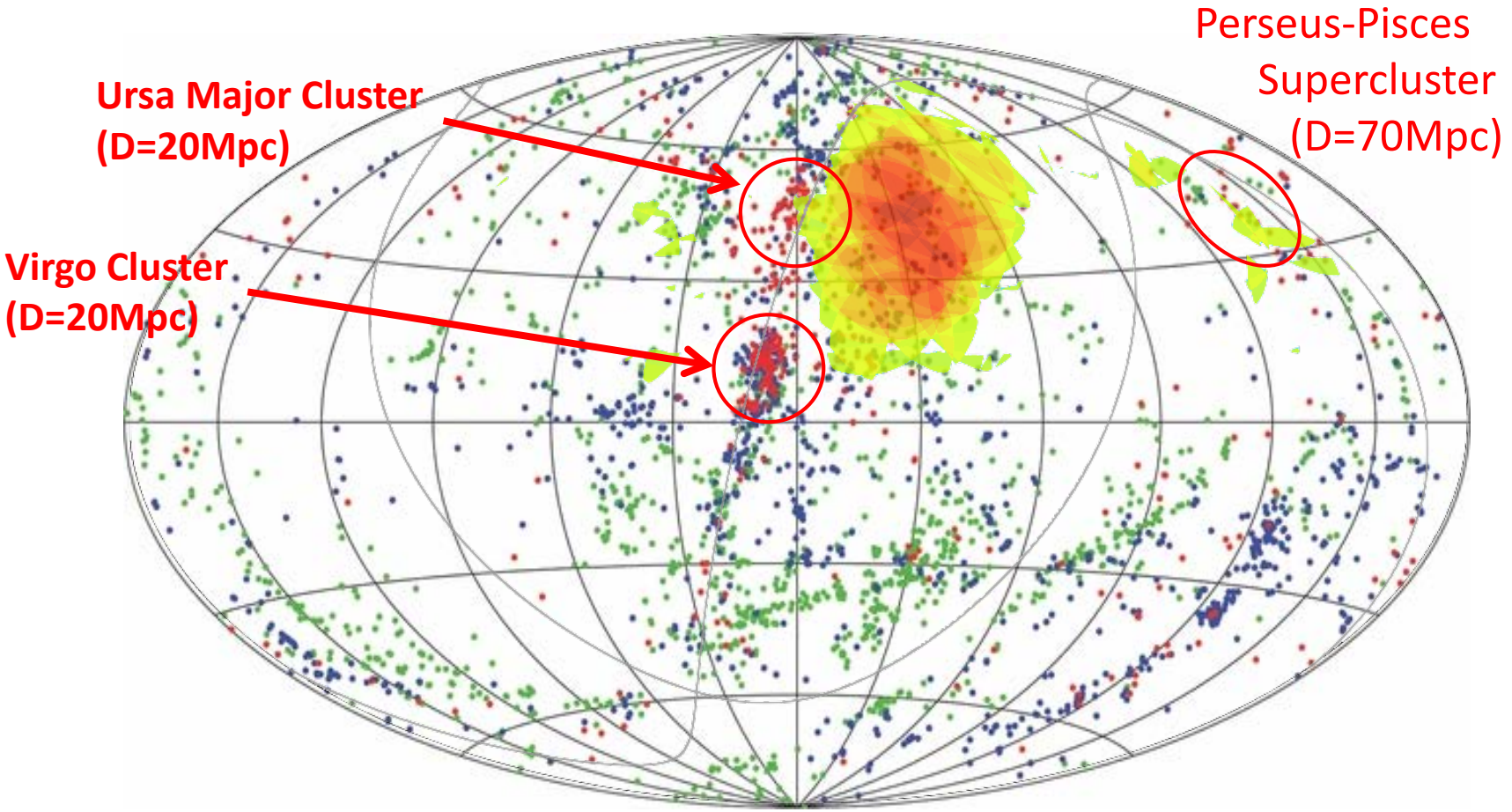

2MASS catalog velocity 0 – 3000 km/s
John P. Huchra, et al 2012, ApJ, 199, 26
+ 5-year TA data (Color contour)

Heliocentric velocity (Rough Distance)
Red: 0-1000km/s (D = 0-15Mpc)
Blue: 1000-2000km/s (D = 15-30Mpc)
Green: 2000-3000km/s (D = 30-45Mpc)

# Prospect of TA×4

- Arrival direction
  - Hotspot
    - Confirmation at > 5$\sigma$ level
    - Fine structure?
    - Other excess spots?
    - Study of galactic MF and extragalactic MF  Galactic filaments?
  - 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

# Nearby Galaxy Clusters and hotspot



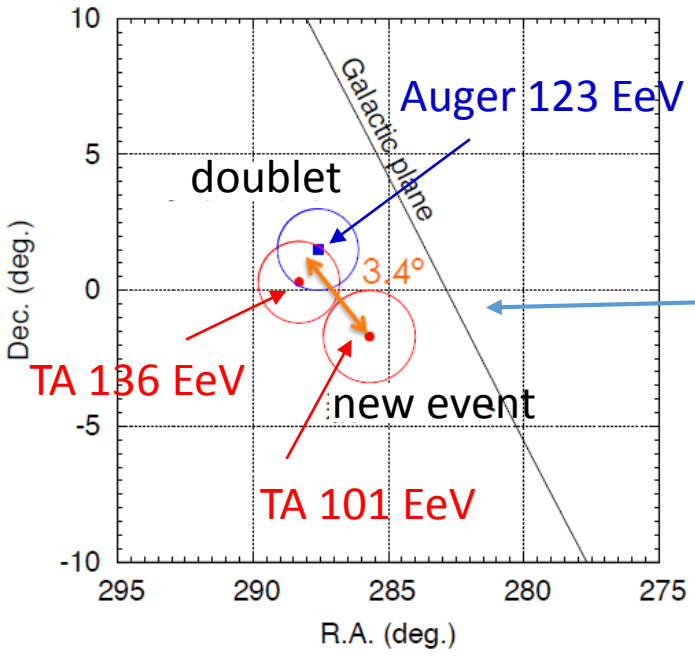

2MASS catalog velocity 0 – 3000 km/s
John P. Huchra, et al 2012, ApJ, 199, 26
+ 5-year TA data (Color contour)

Heliocentric velocity (Rough Distance)
Red: 0-1000km/s (D = 0-15Mpc)
Blue: 1000-2000km/s (D = 15-30Mpc)
Green: 2000-3000km/s (D = 30-45Mpc)

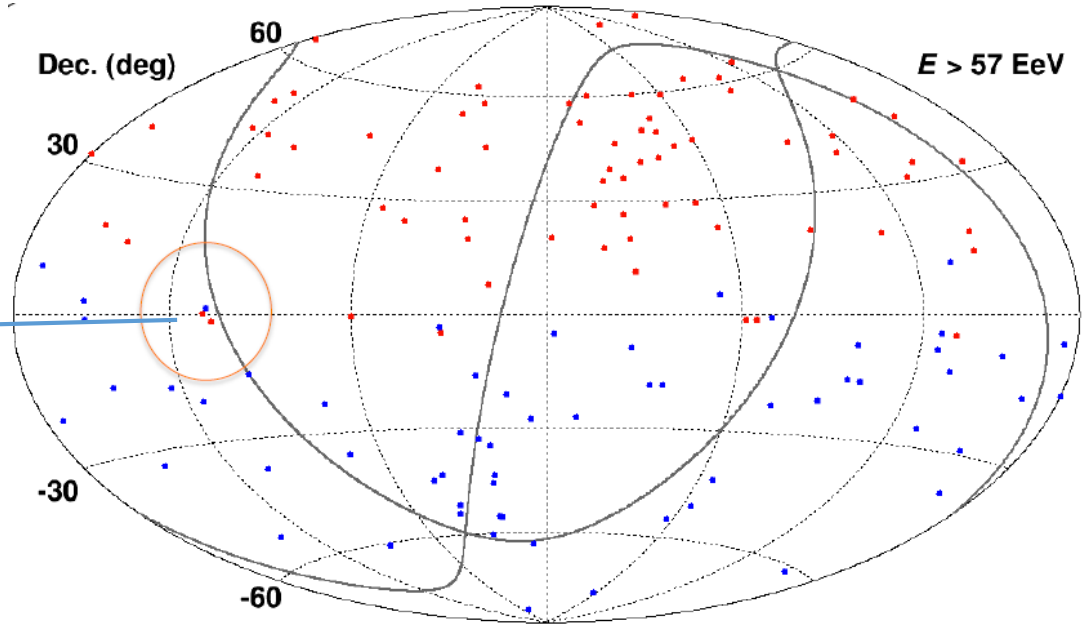
# Prospect of TA×4

- 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

# Search for clusters of highest energy cosmic rays




$E > 5.7 \times 10^{19}$eV




TA: 2008/May – 2013/May (5 yrs) 72 events [ApJ 790 (2014) L21]
Auger: 2004/Jan – 2009/Dec (5.5yrs) 62 events [APP 34 (2010) 314]

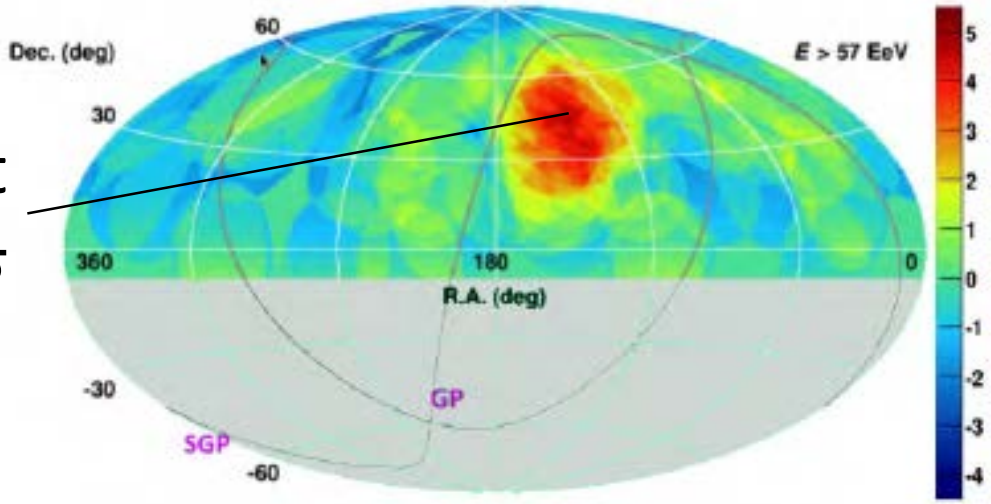
Hint of a point source?

# Prospect of TA×4

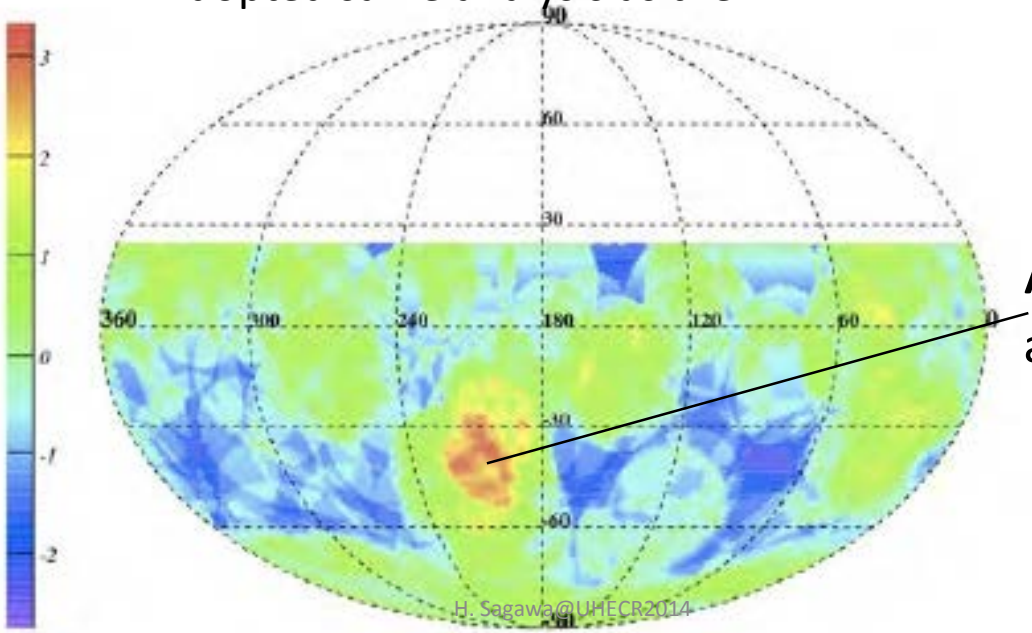
- Arrival direction
  - Hotspot
    - Confirmation at > 5$\sigma$ level
    - Fine structure?
    - Other excess spots?
    - Study of galactic MF and extragalactic MF
  - Point source search
  - Correlation with the results by other experiments
    - TA/Auger whole sky analysis
    - Search for correlation 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

# TA and Auger pretrial significance summed over with 20$^{o}$-radius Circle

TA Hotspot
5.1$\sigma$




Adopted same analysis as the TA




Auger ~3$\sigma$
around Cen A

# 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

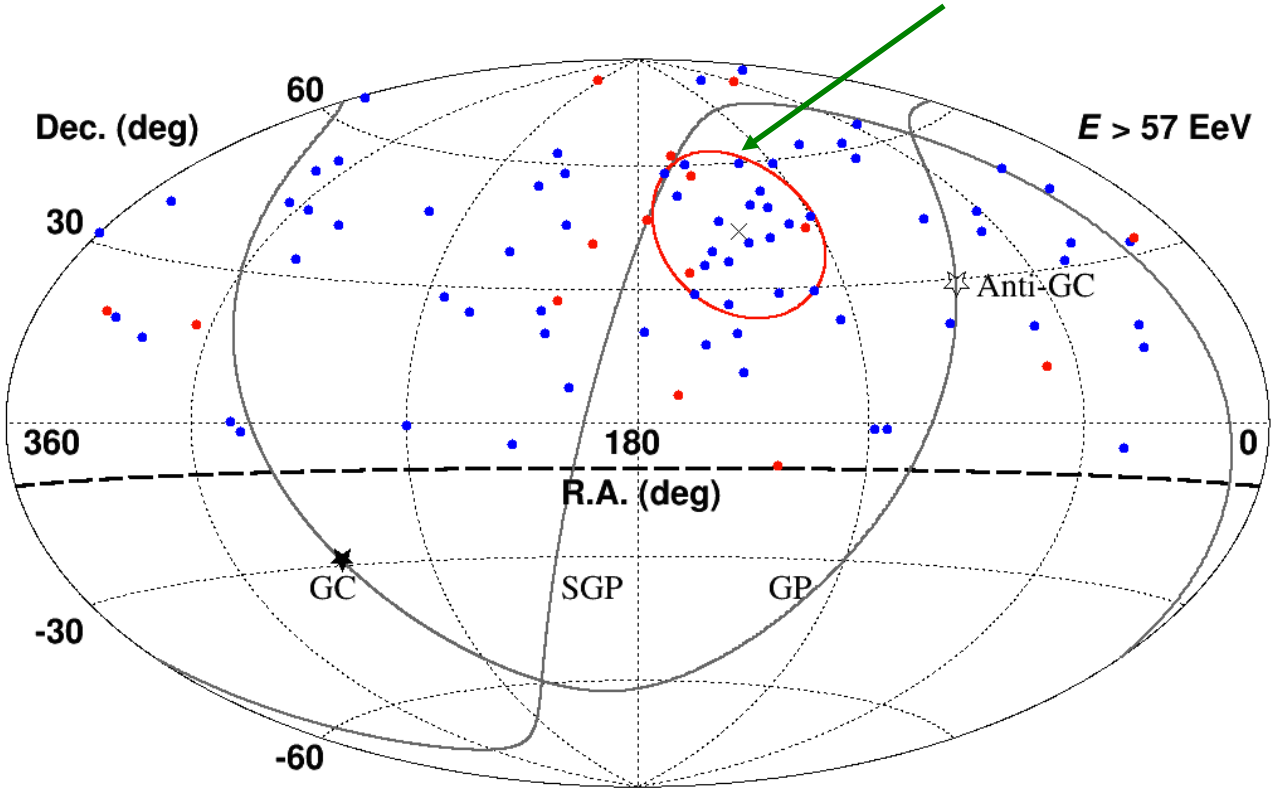
# Prospect in the summer of 2020

If we start TAx4 project in 2015,

2015-2016 construction of new detectors

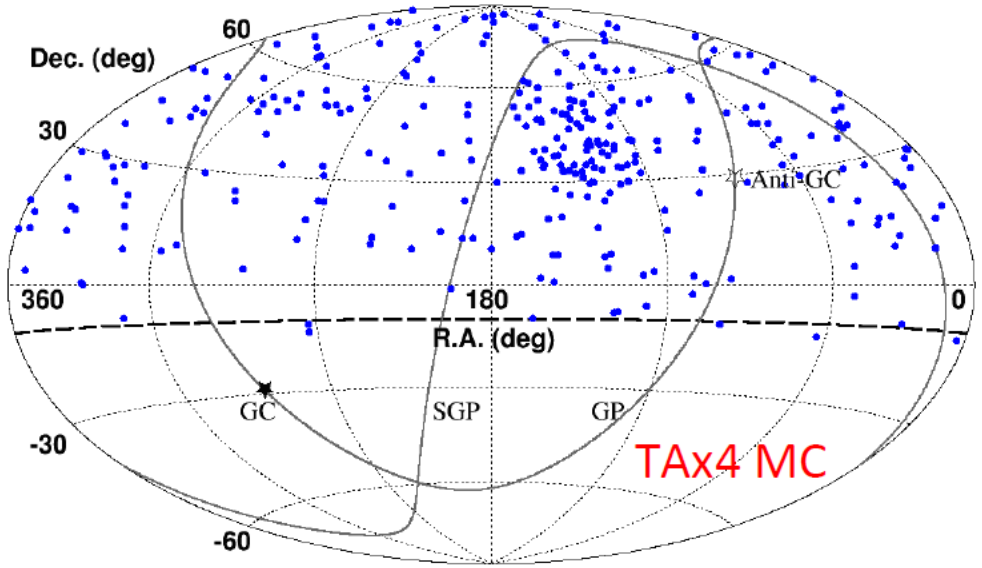
2017-2019 operation of full TAx4

# Arrival directions of TA 6-year data



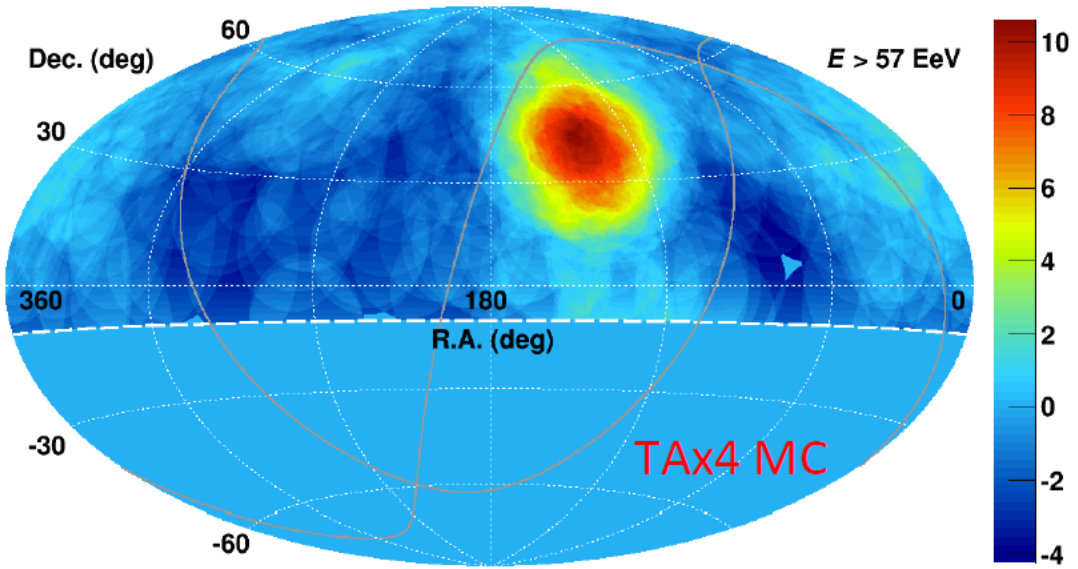
# 1 cluster in the hotspot in the summer of 2020

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

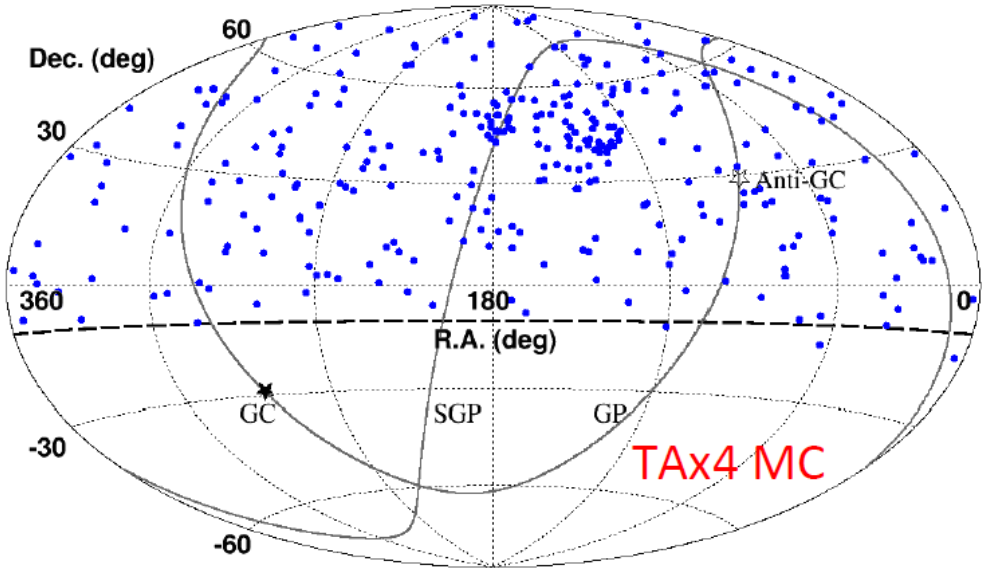
# 2 clusters in the hotspot in the summer of 2020

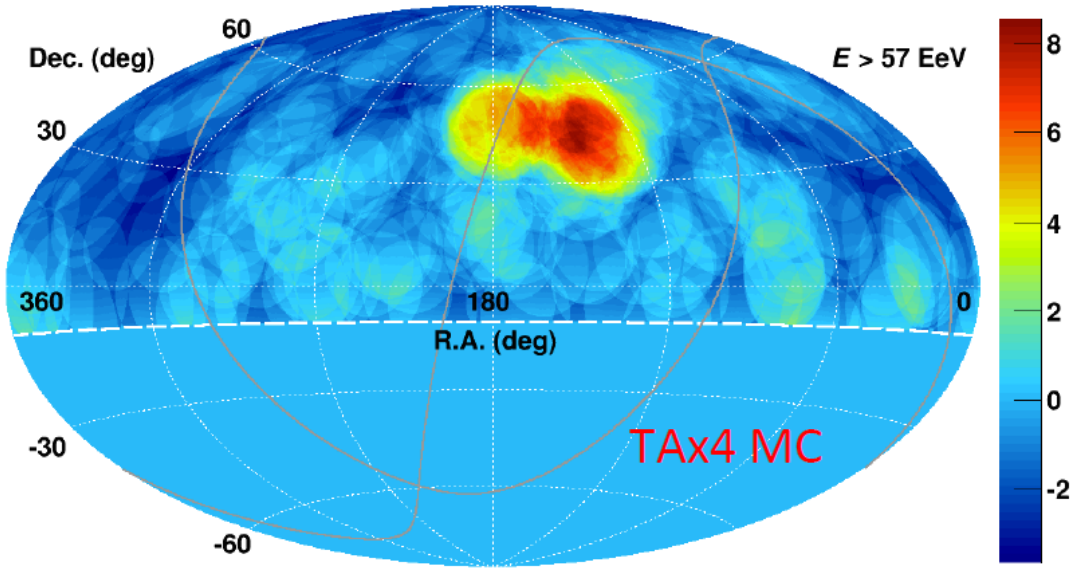
## (2) Double Hotspot

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



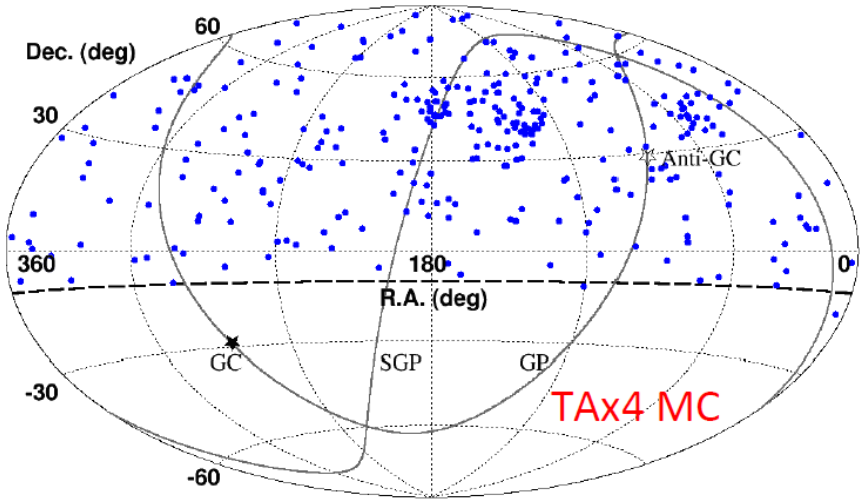
# 2 clusters in the hotspot+Perseus cluster in the summer of 2020

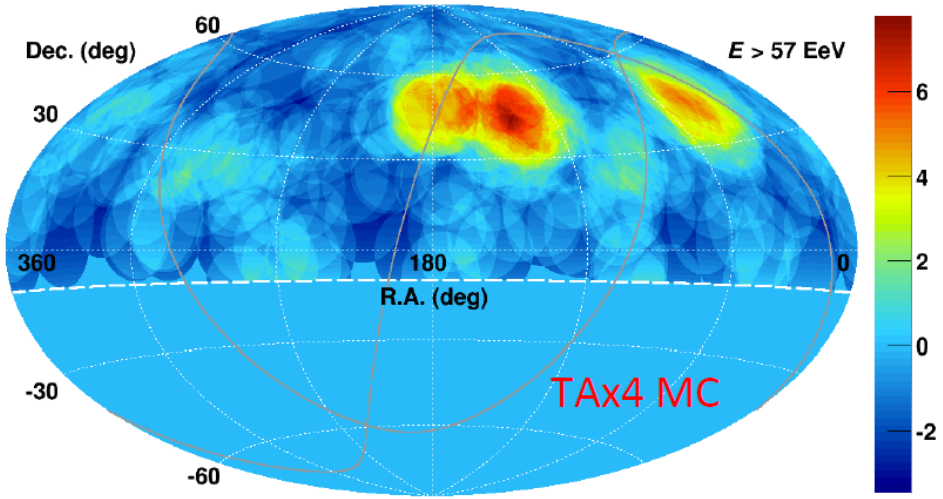
Double
Hotspot
+ Perseus

<u>Hotspot Signal</u>
Total 61 events
1. 41events
   (RA, Dec)=(145°,45°)
   Gaussian σ=10°
2. 20events
   (RA, Dec)=(175°,45°)
   Gaussian σ=5°
3. 20events
   (RA, Dec)=(50°,40°)
   Gaussian σ=5°

<u>Isotropic B.G.</u>
305-61-20=224events

Oversampling
15° radius circle

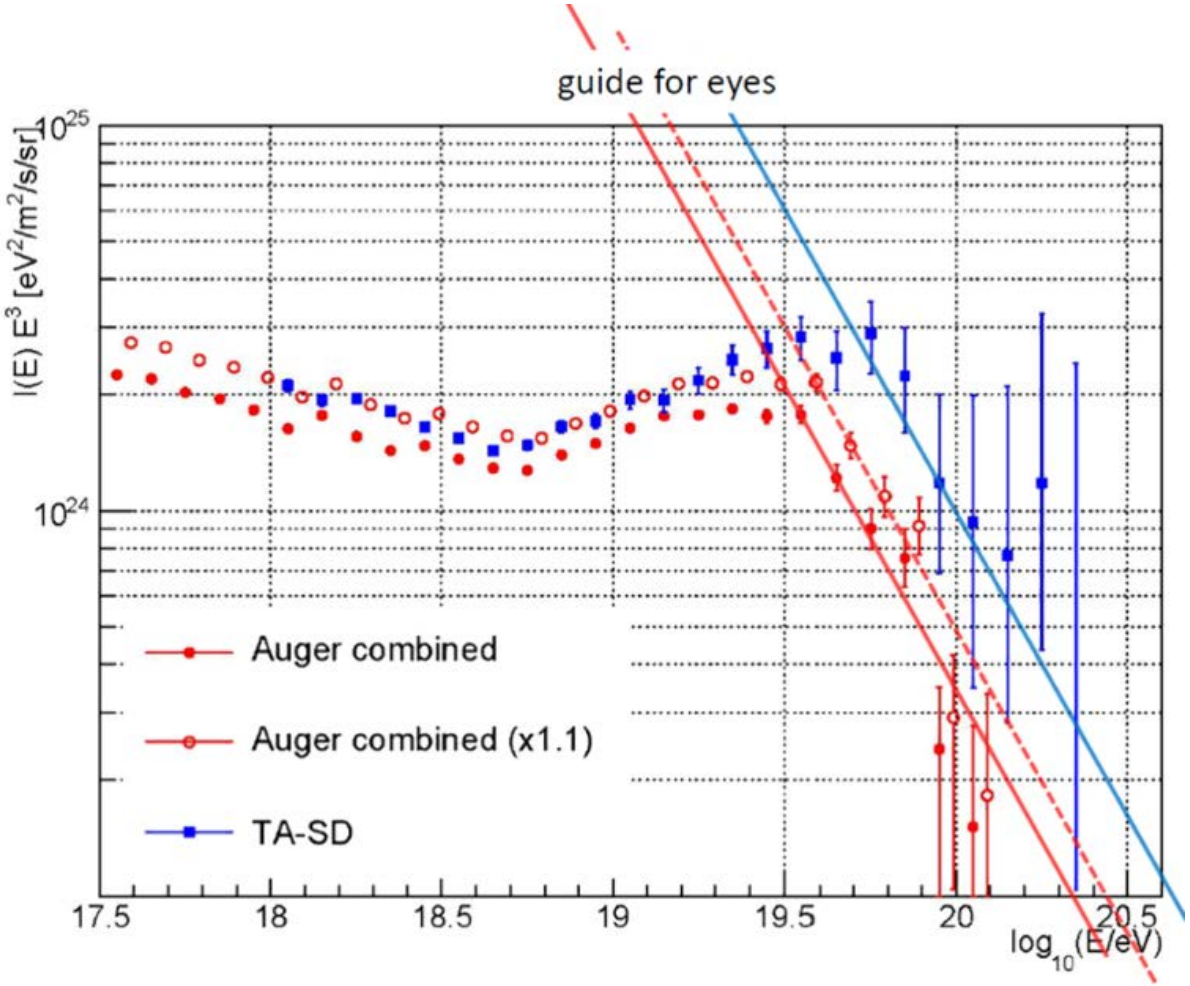


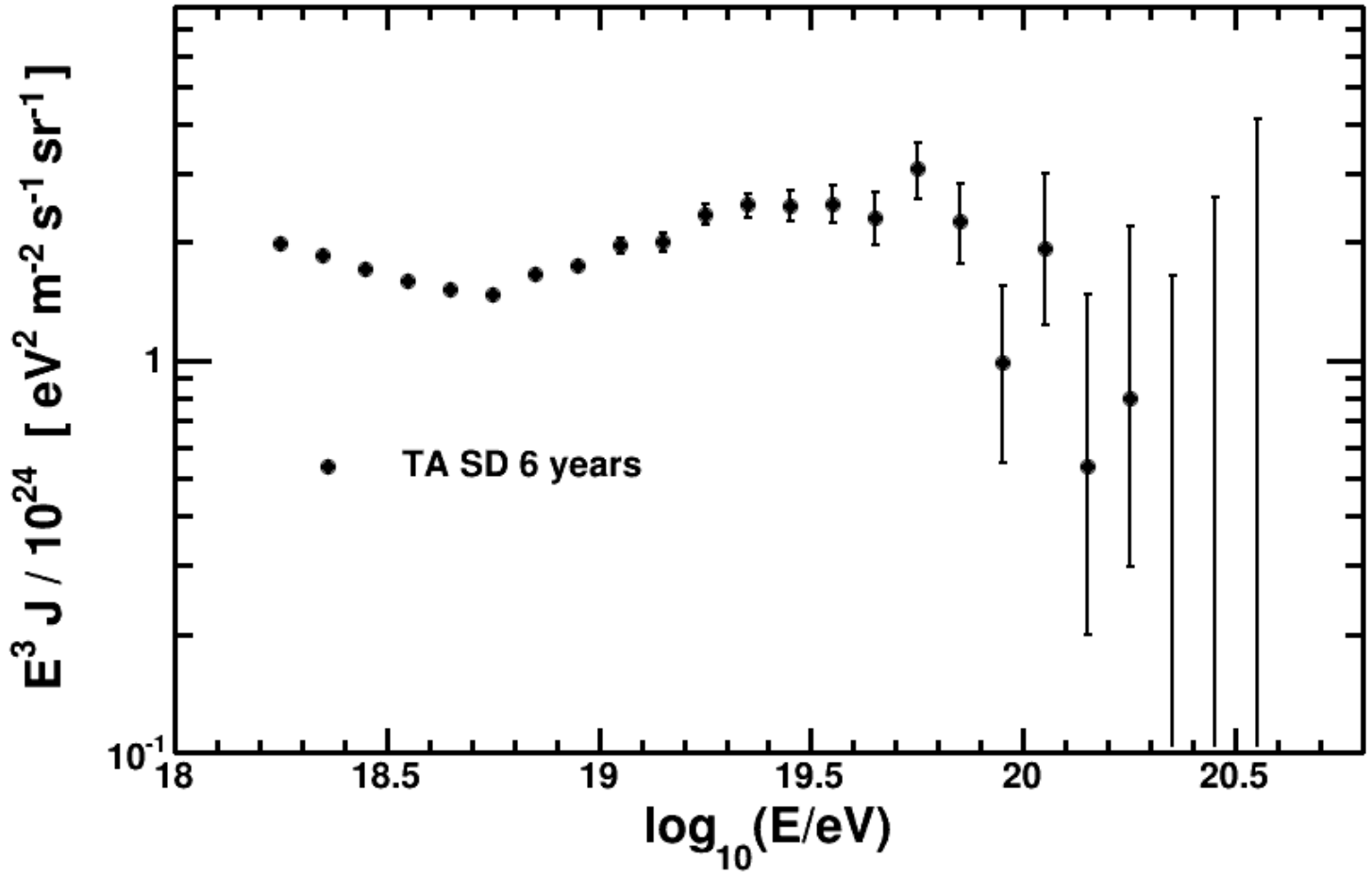
# Prospect of TA×4

- 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

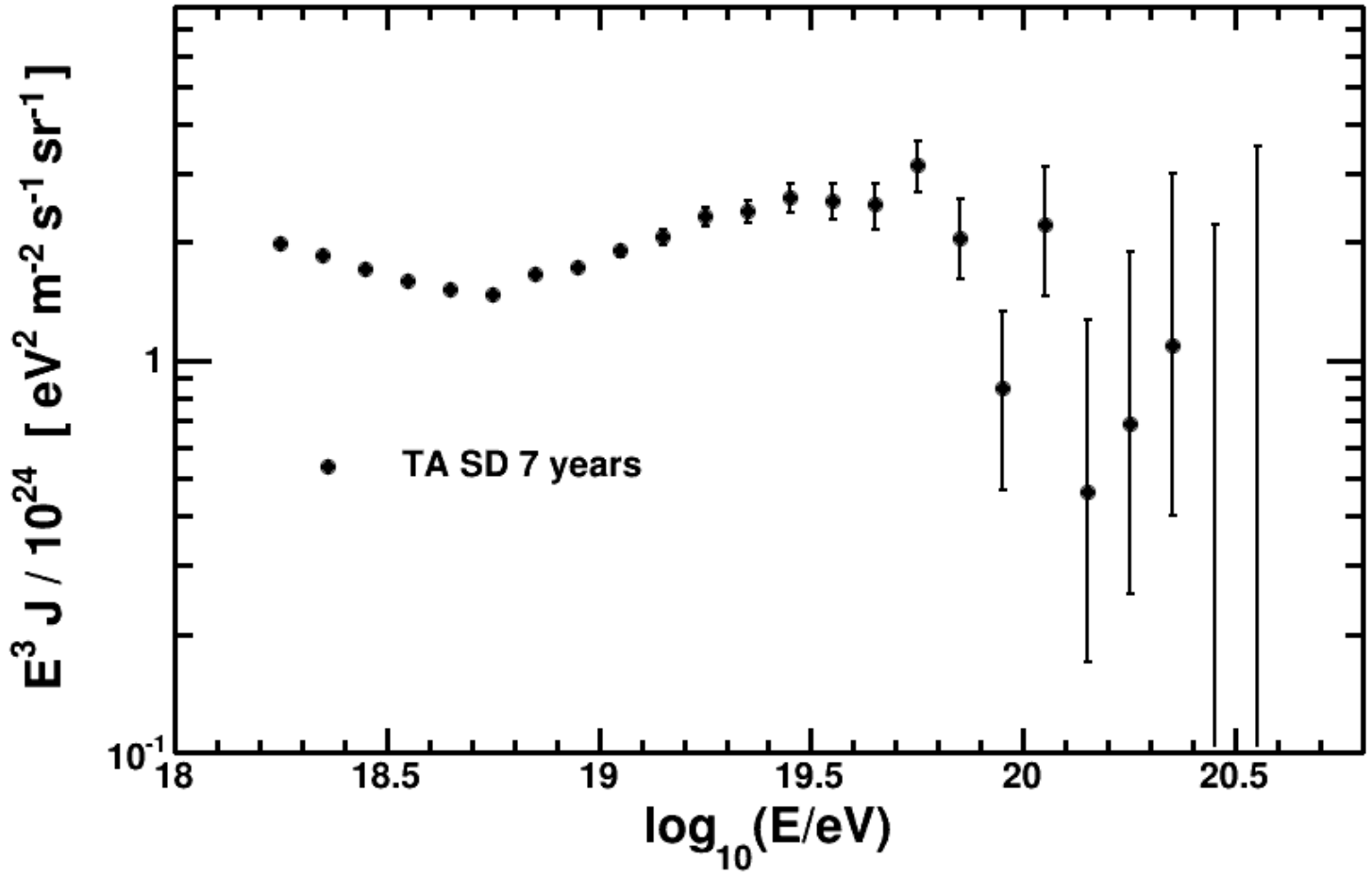
# TA and Auger energy spectrum



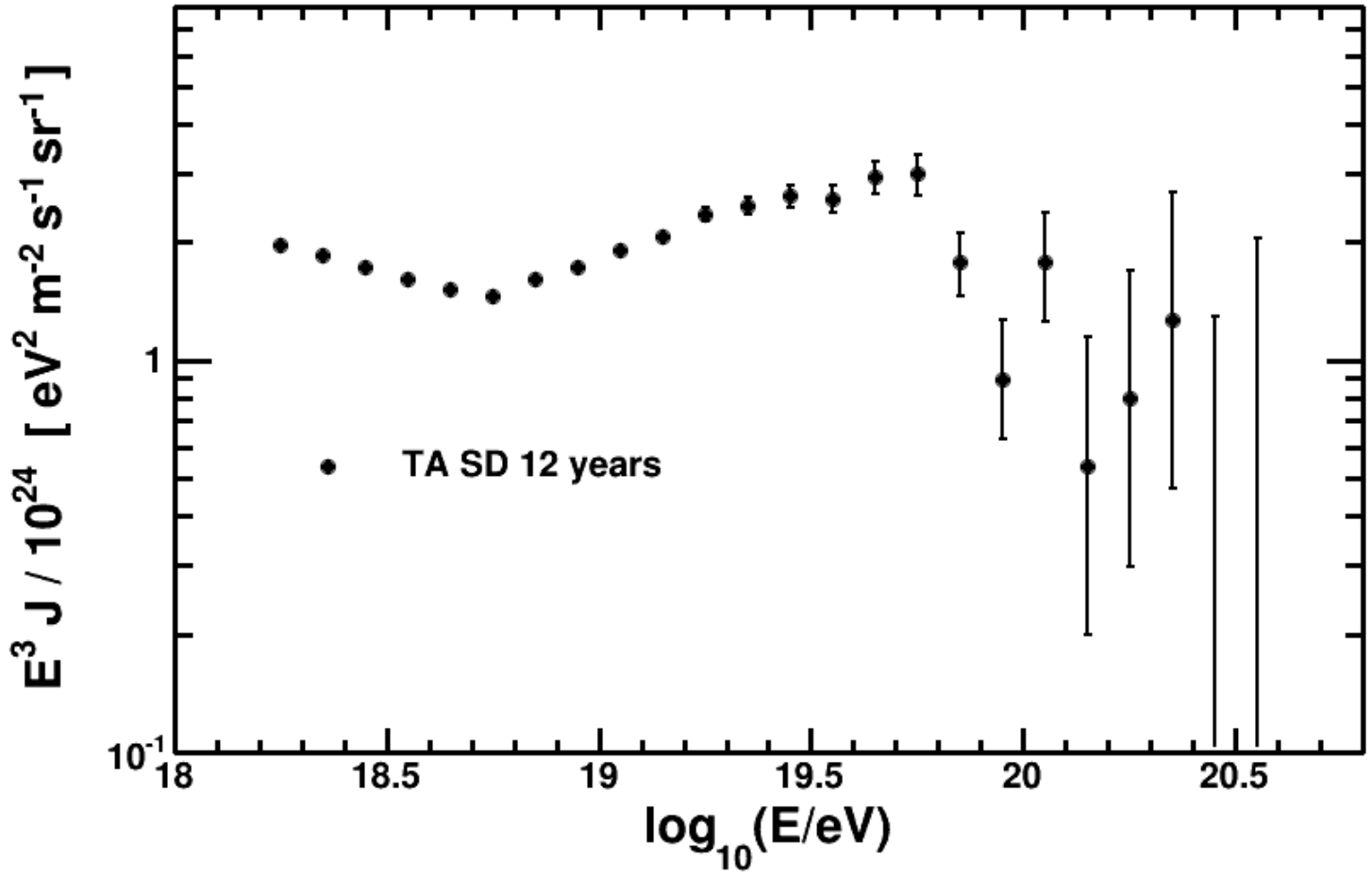
# Spectrum by TA SD for 6 years (this conf.)



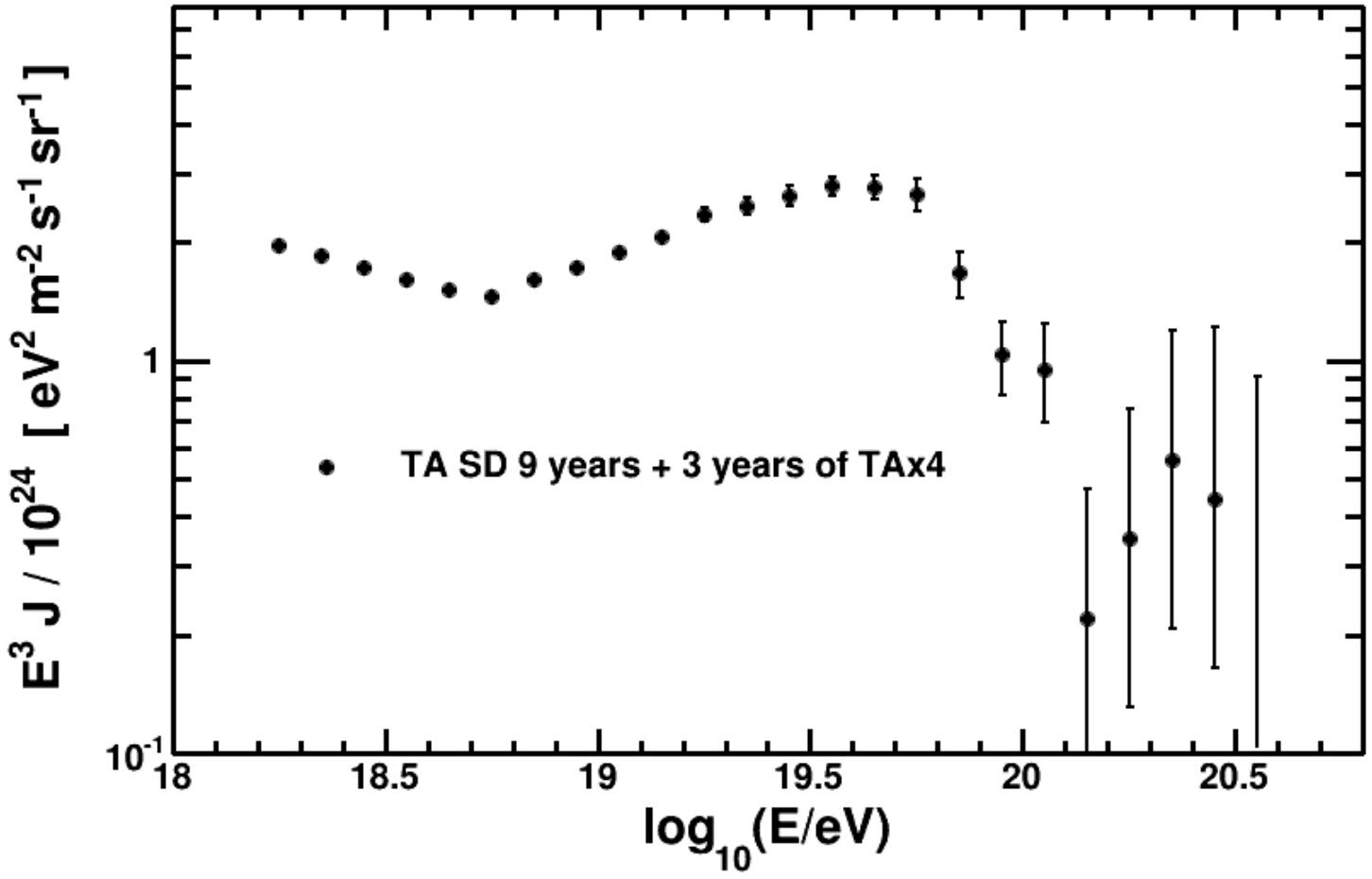
# Spectrum by TA SD for 7 years in the summer of 2015



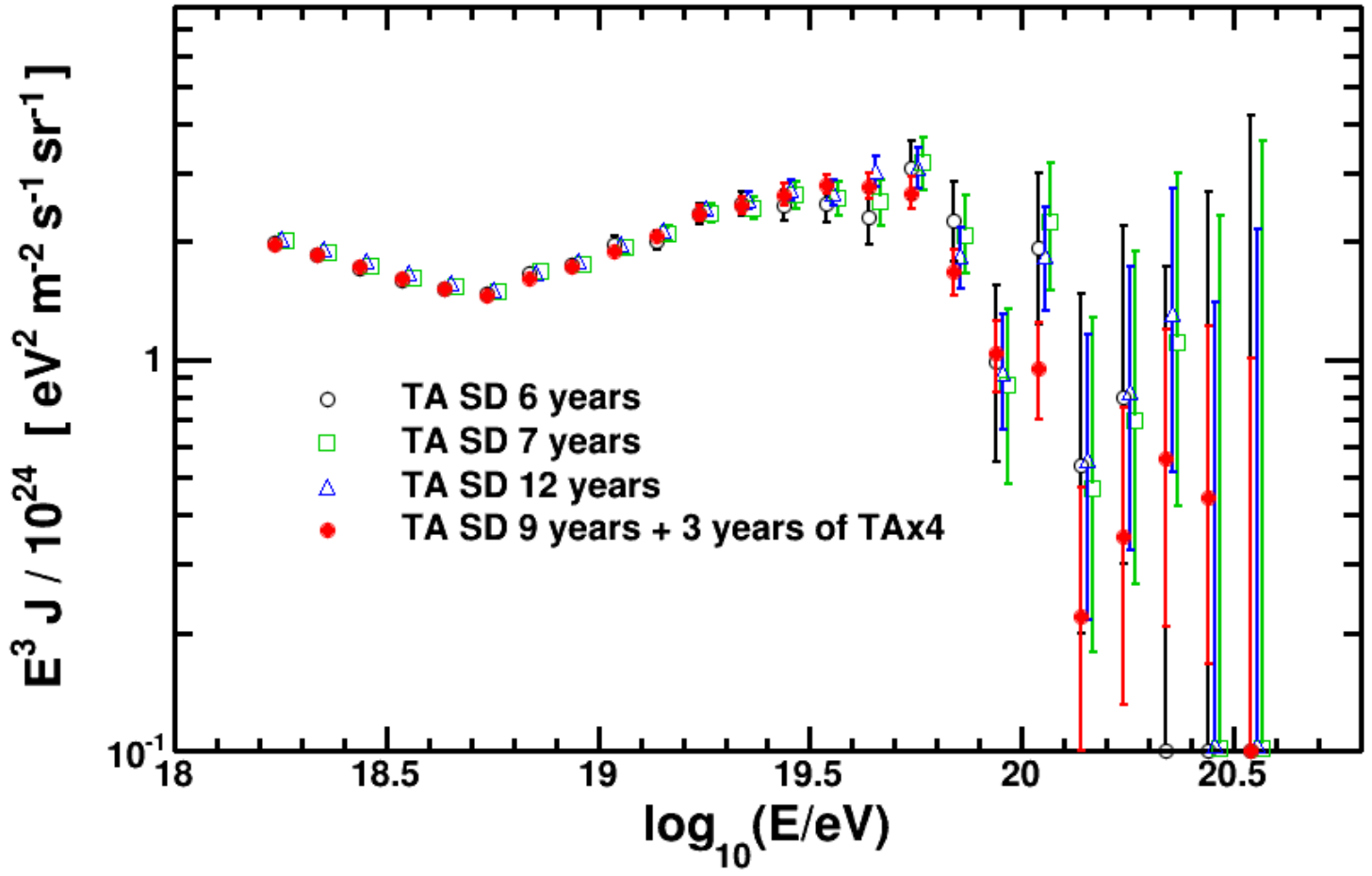
# Spectrum only by TA SD for 12 years in the summer of 2020



# Spectrum by (TA SD for 9 years and TAx4 for 3 years) in the summer of 2020



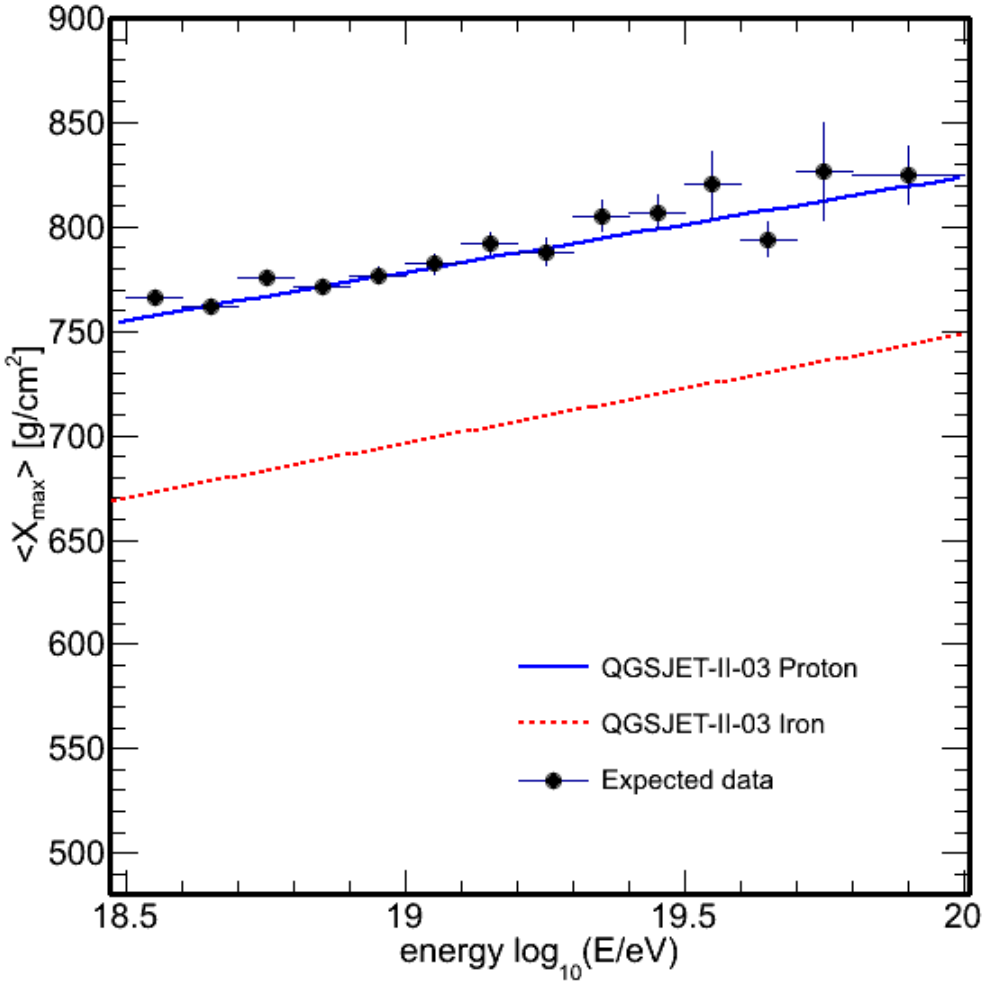
# Spectrum by (TA SD for 9 years and TAx4 for 3 years) together with other cases



# 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

# Xmax for TA hybrid events for 9 years and TAx4 hybrid events for 3 years (assuming proton QGSJET II-03 model)

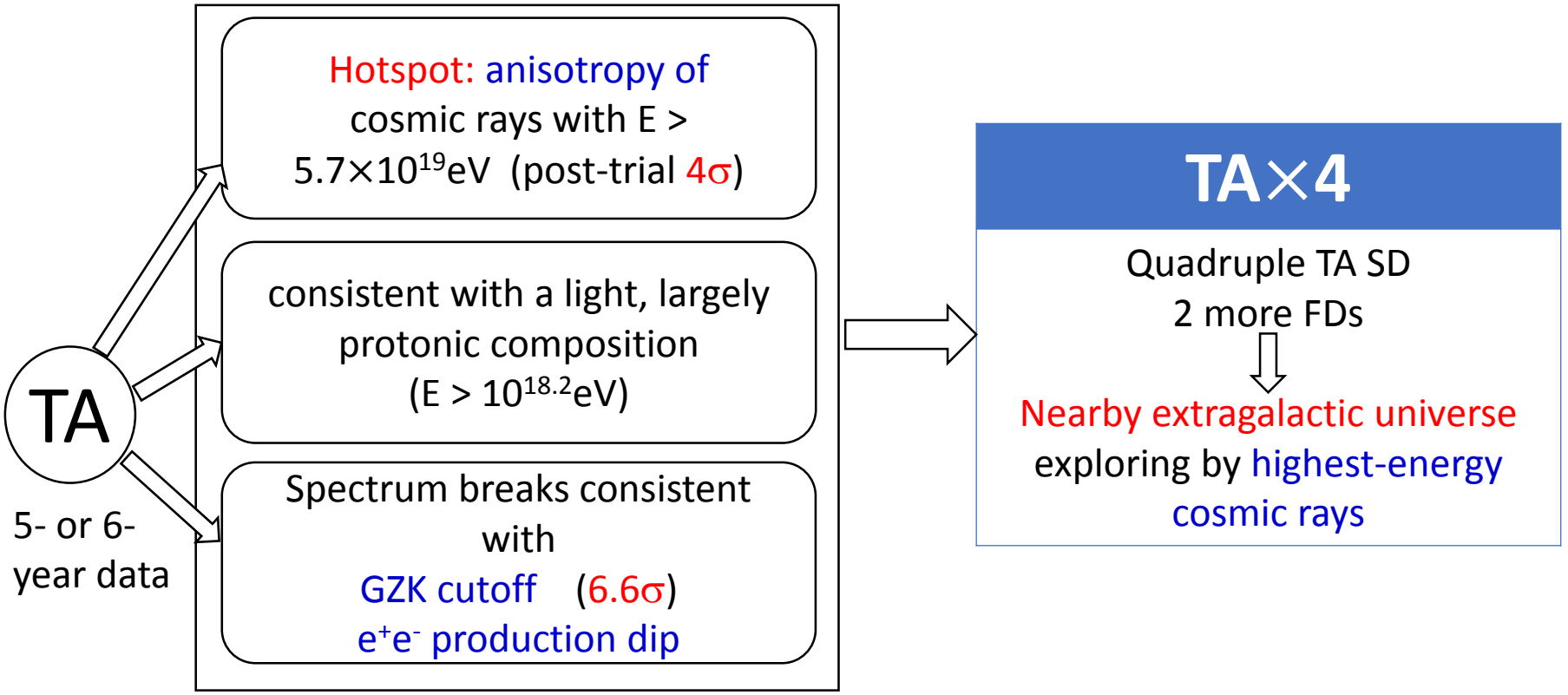



TA hybrid events for corresponding to 18-year TA hybrid events

# 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  by MAGIC etc.
    - Search for correlation with IceCube neutrinos
- Measurement of spectrum and Xmax of cosmic rays above cutoff with high statistics
- Search for UHE gamma rays and neutrinos

# Summary

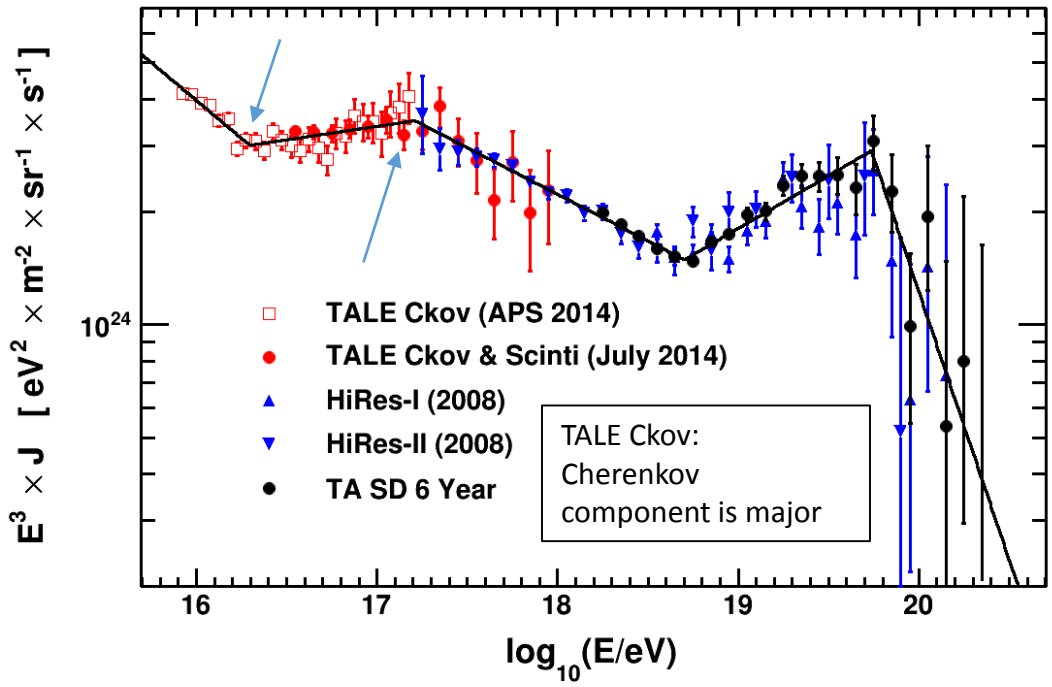

Hotspot: anisotropy of cosmic rays with E > 5.7×10^19eV (post-trial 4σ)
consistent with a light, largely protonic composition (E > 10^18.2eV)
Spectrum breaks consistent with GZK cutoff (6.6σ) e+e- production dip
TA
5- or 6-year data
TA×4
Quadruple TA SD
2 more FDs
Nearby extragalactic universe exploring by highest-energy cosmic rays

# END

# TALE+TA spectrum ($E > 10^{15.9}$ eV)

（FD） (SD)

Energy region over > 4 decades




Breaks at around $10^{16.2}$eV and $10^{17.3}$eV

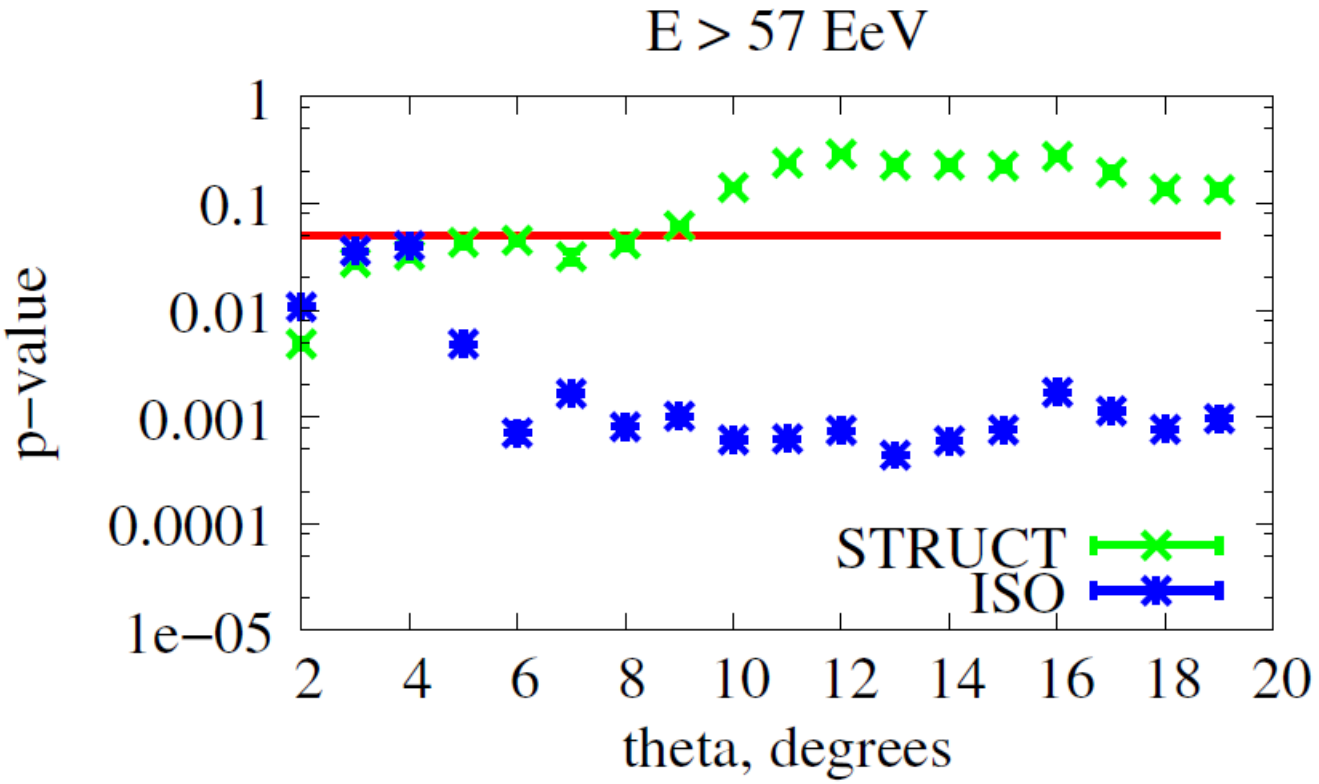
TA: 6 year SD data

TALE

Observation time:144 hours

（2013/Sep/6 ~ 2013/Dec/6)

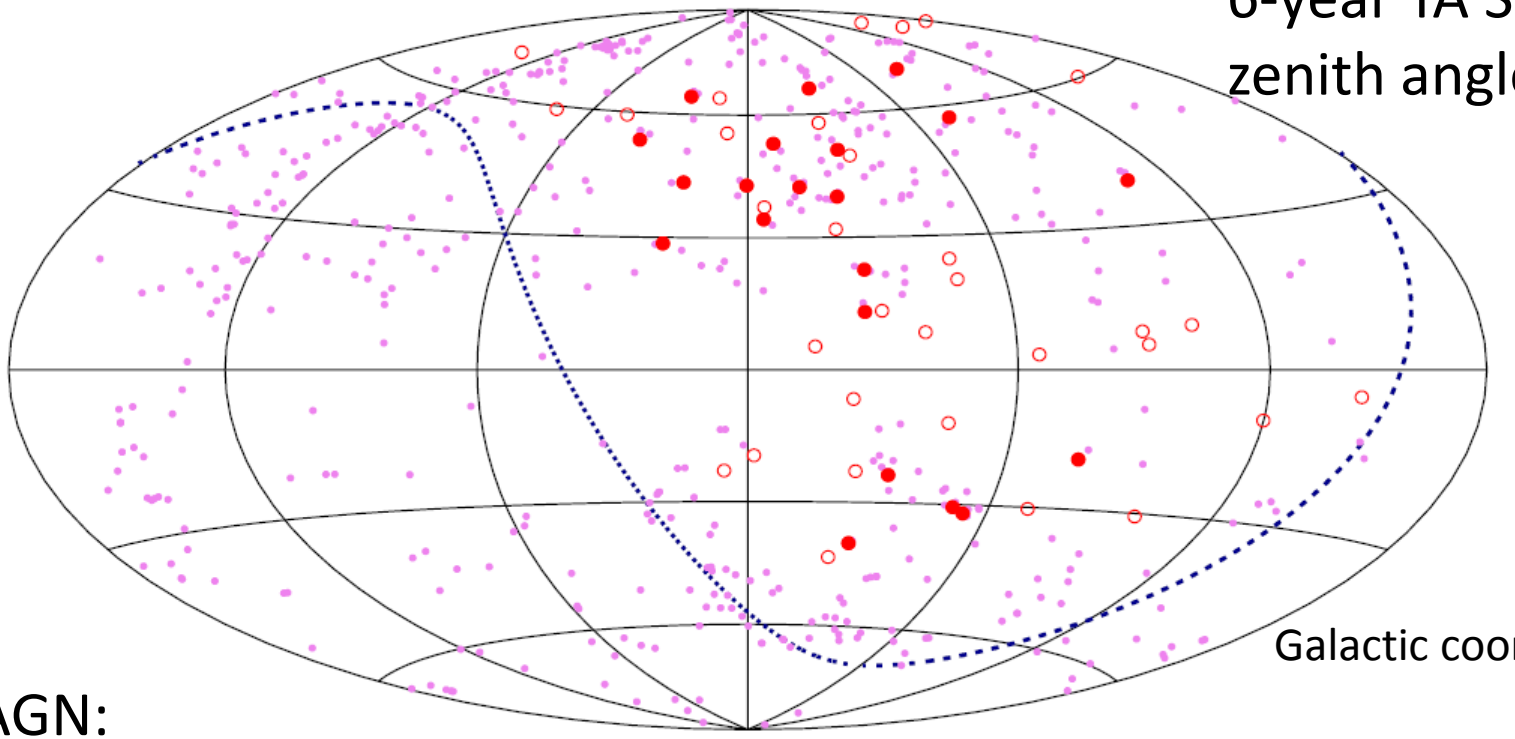
# Statistical test for compatibility with LSS and isotropy




Compatibility at different smearing angles theta. Low p-values = incompatible. The test shows incompatibility with isotropy and compatibility with LSS.

# Correlation with AGN from VCV catalog

6-year TA SD data
zenith angles < 45°

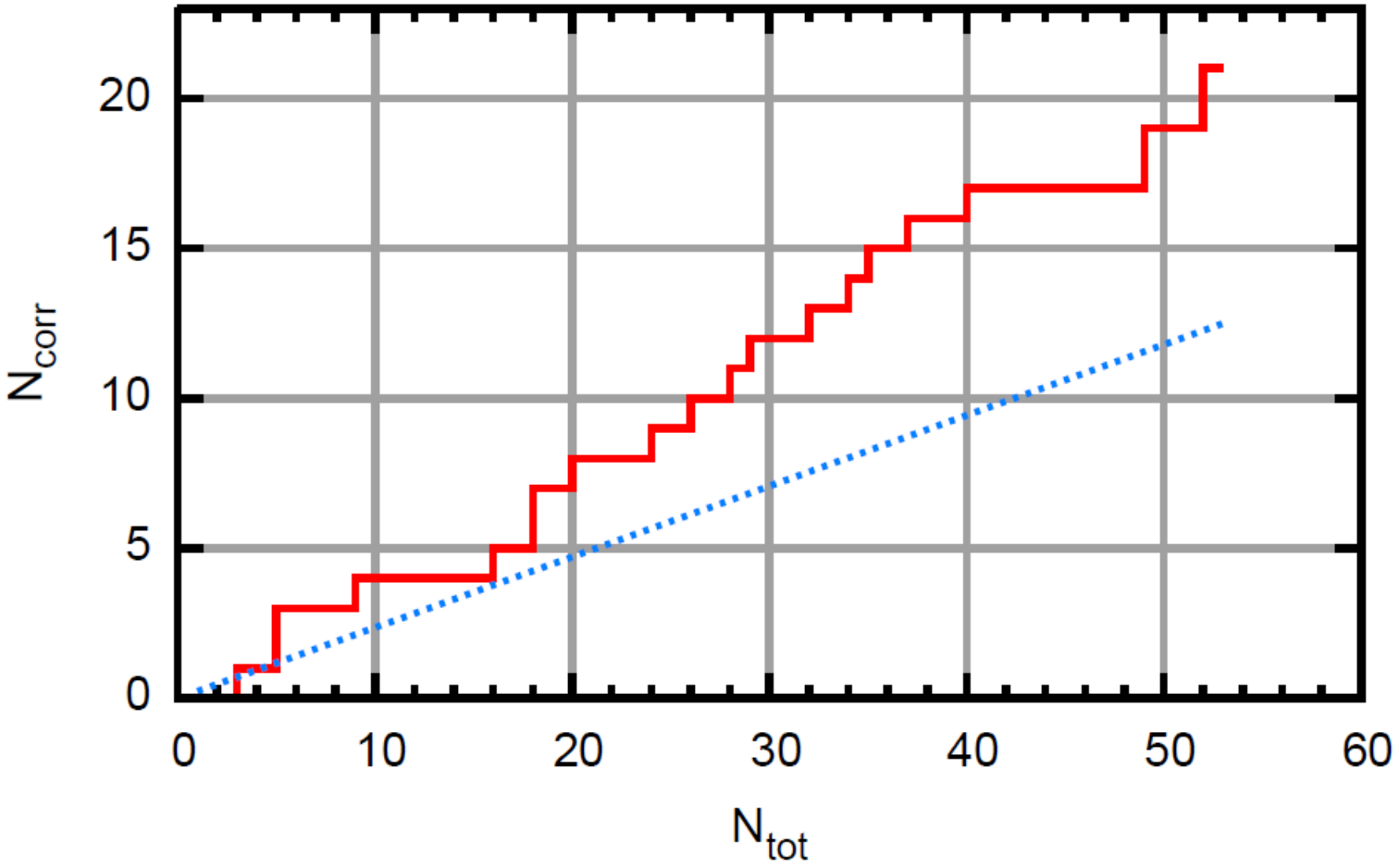


Galactic coordinates

- : AGN:
- : TA events correlating within 3.1°
- : non-correlating events

Ntot = 53,
Ncor = 21, (40%)
Nbg = 12.5 (24%)
p-value = 0.007 ($2.7\sigma$)

# Correlation with AGN from VCV catalog




Correlating events (red solid) vs. background (blue dotted).
$N_{tot} = 53$, $N_{cor} = 21$, $N_{bg} = 12.5$, p-value $= 0.007$ $(2.7\sigma)$.