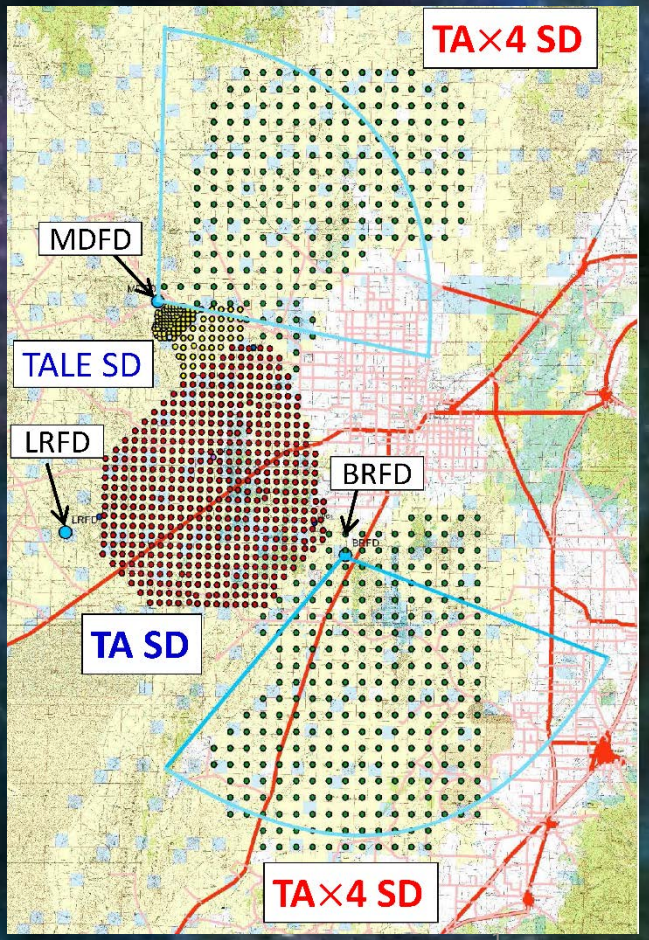
Recent results from the Telescope Array
– studies of ultra-high energy cosmic rays and the prospect -

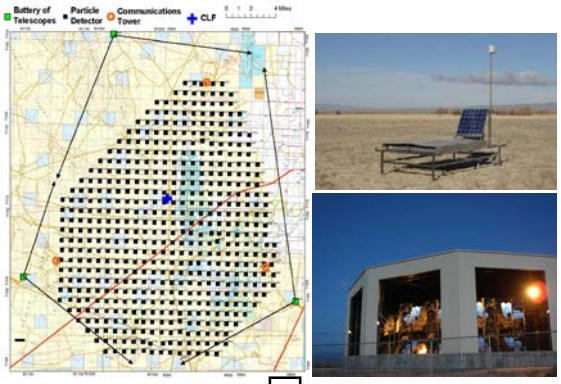
H. Sagawa
Institute for Cosmic Ray Research
The University of Tokyo
for Telescope Array collaboration

Photon 2015



Outline

Telescope Array (TA)

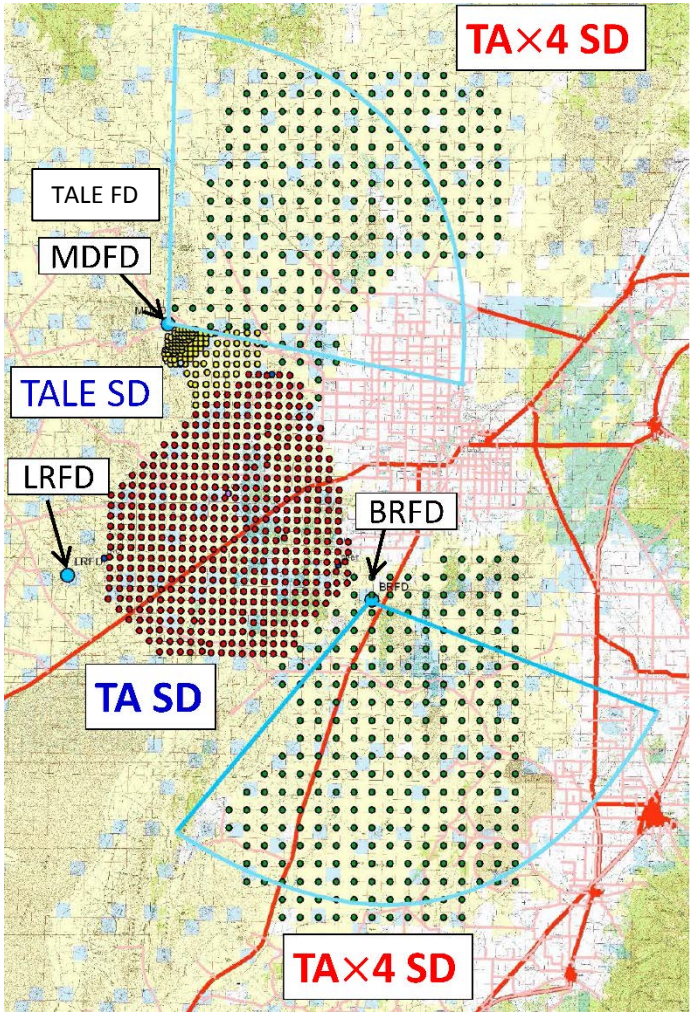


Recent TA results
5- or 6- year data

TALE (TA Low E extension)
FD result

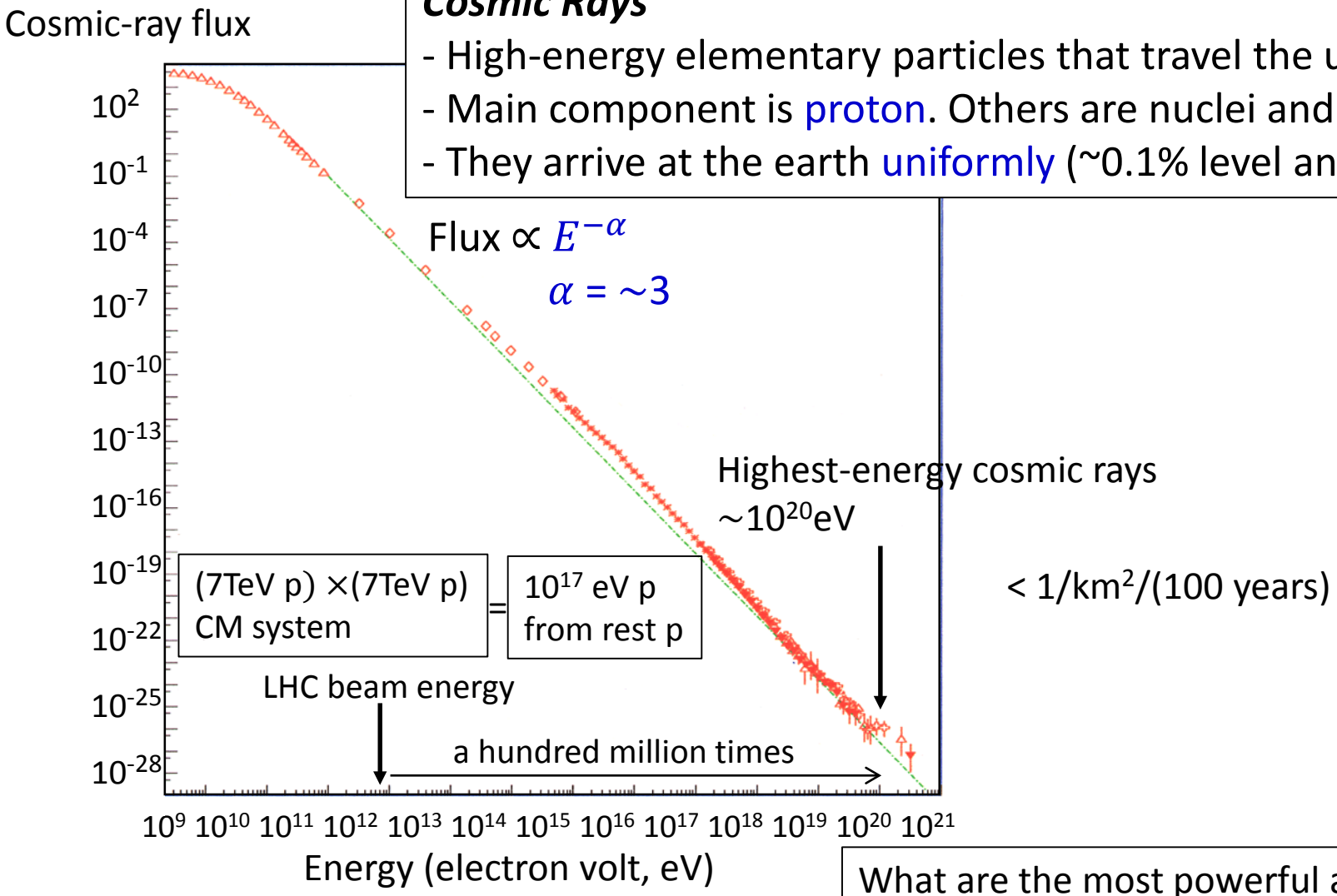
TA×4 extension

TALE SD



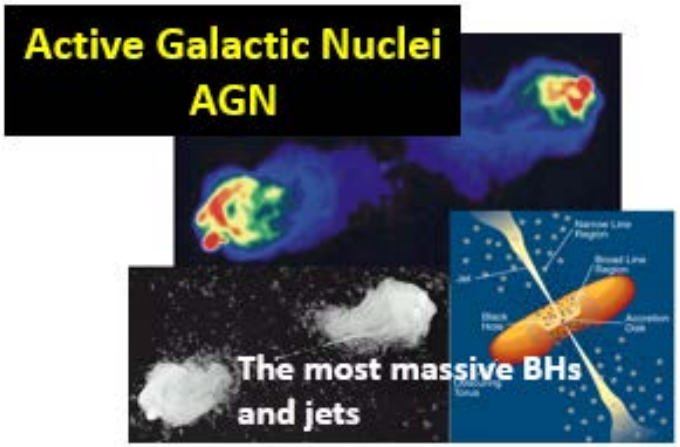
Energy spectrum of cosmic rays

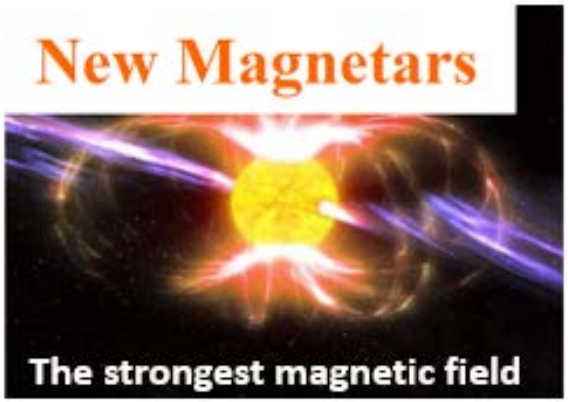
Cosmic Rays
- High-energy elementary particles that travel the universe
- Main component is proton. Others are nuclei and electrons
- They arrive at the earth uniformly (~0.1% level anisotropy)



What are the most powerful accelerators that generate cosmic rays of 10^{20} eV in the universe?

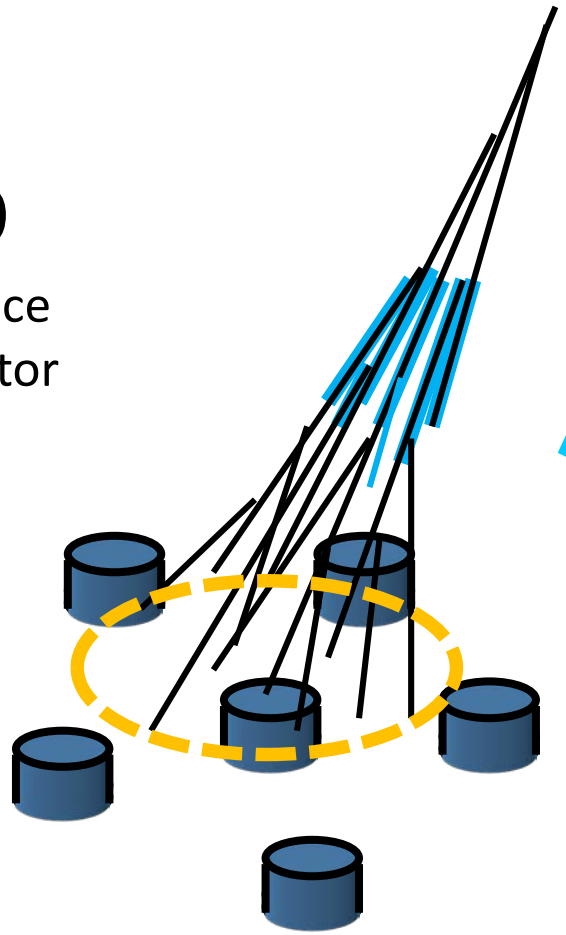
Candidates of accelerators of highest-energy cosmic rays





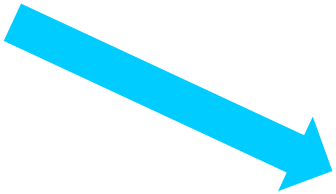
Calorimetric Measurement of Air Showers

~10^{20} eV primary cosmic ray:
Energy, Direction and Particle Species



SD
Surface
Detector

Air
Fluorescence

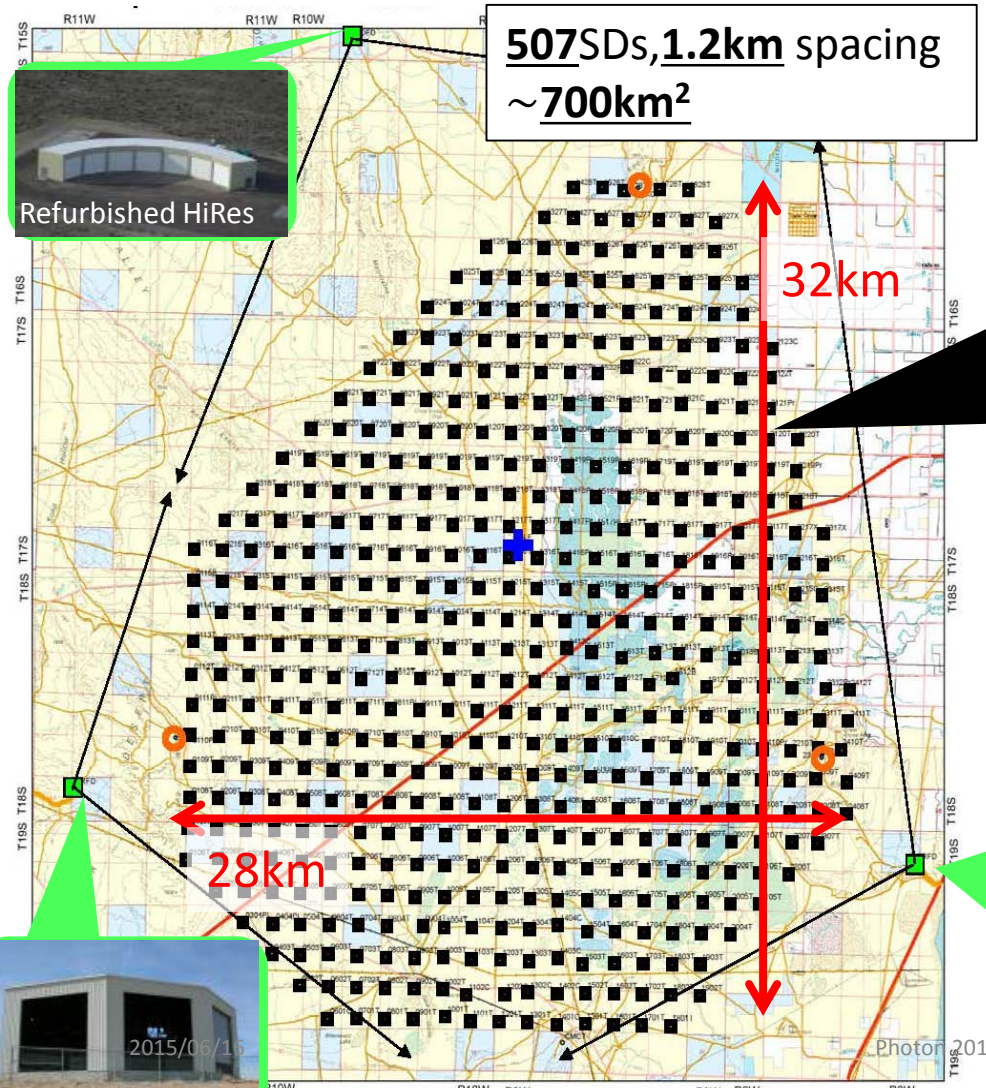


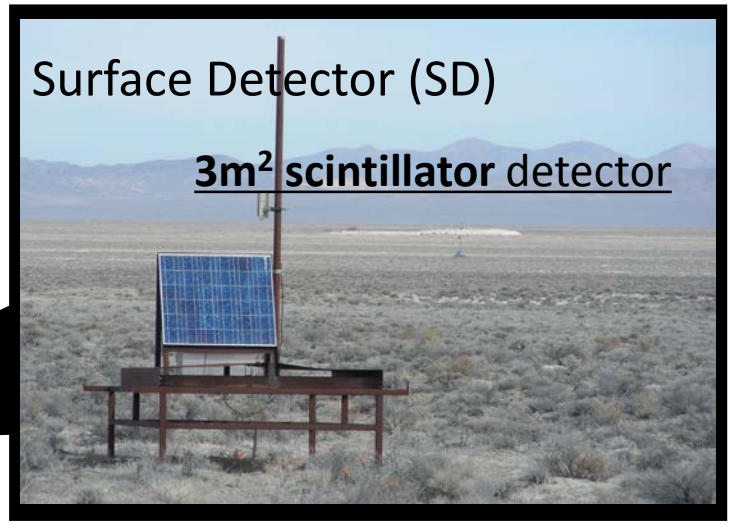
FD
Fluorescence
Detector

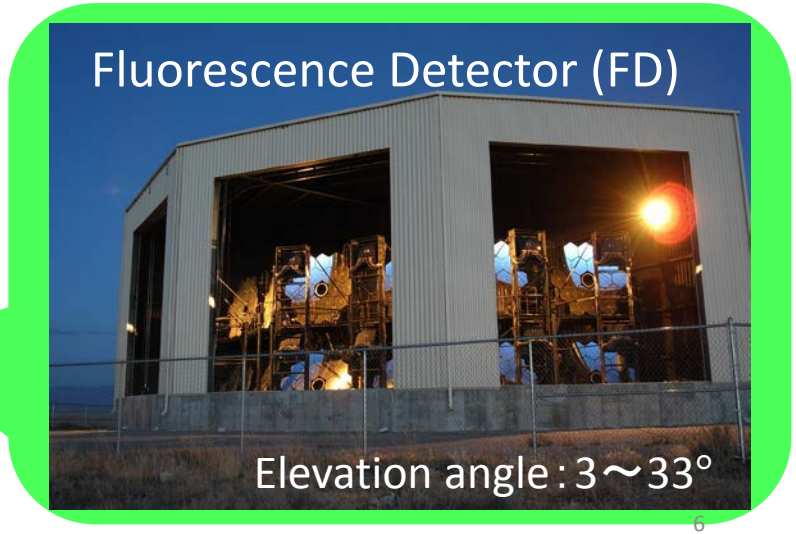
Charged Particles

Telescope Array detector

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







Hybrid observation since Mar, 2008

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]

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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

Recent TA results

Energy spectrum

Anisotropy (hot spot)

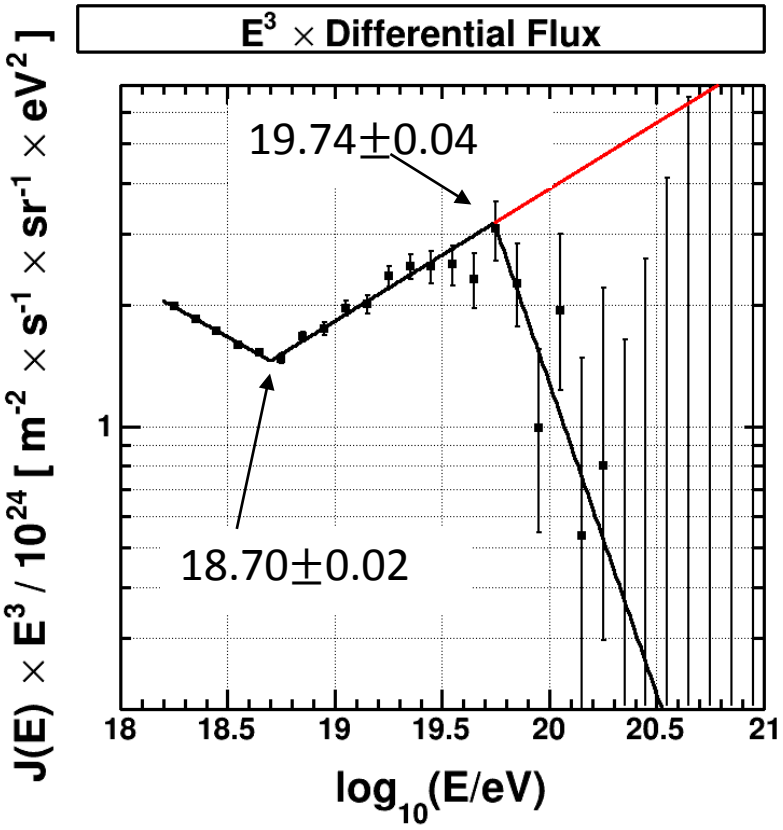
Mass composition (Shower maximum depth, Xmax)

Energy spectrum

D.Bergman
COSPAR 2014

TA energy spectrum

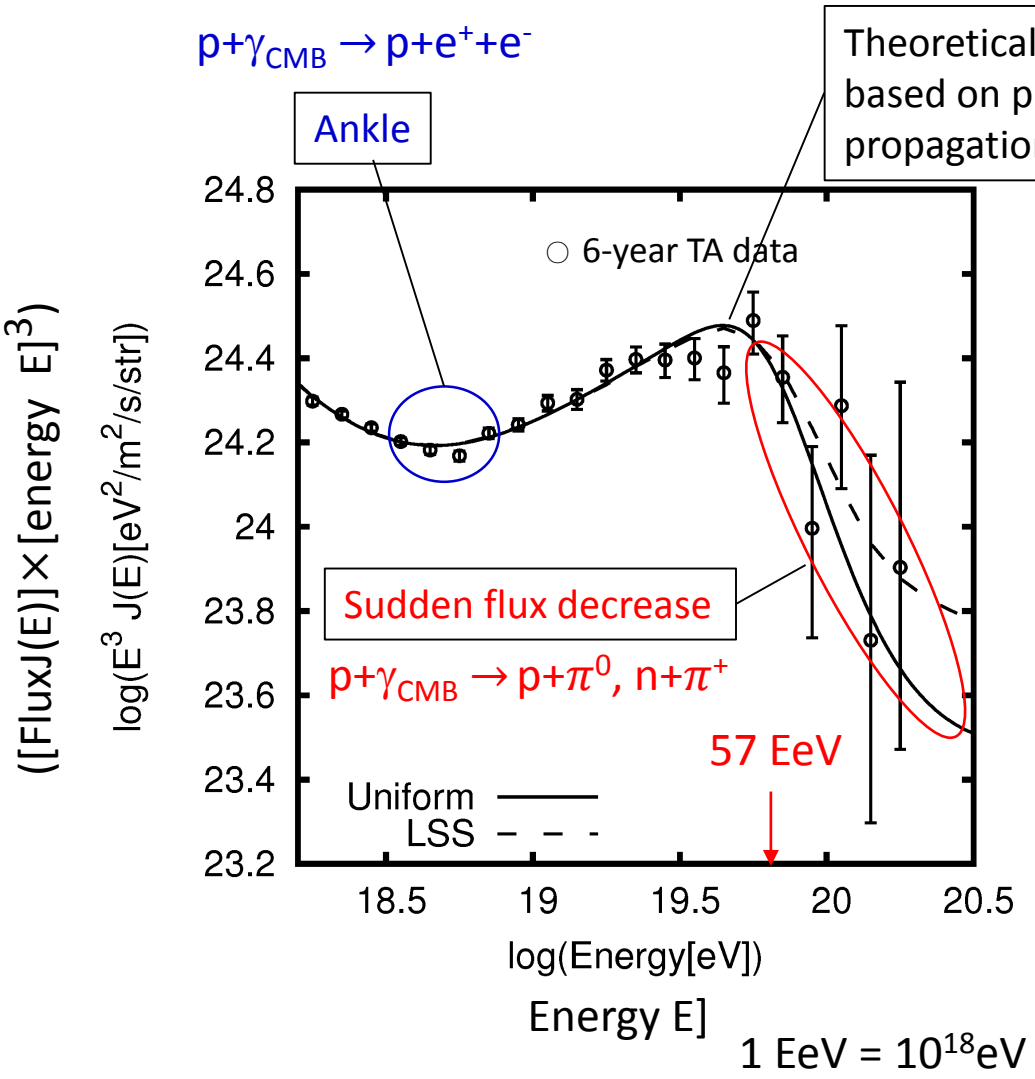
- SD data : 2008/May～2014/May (6 years)



ankle
Cutoff consistent with GZK cutoff

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

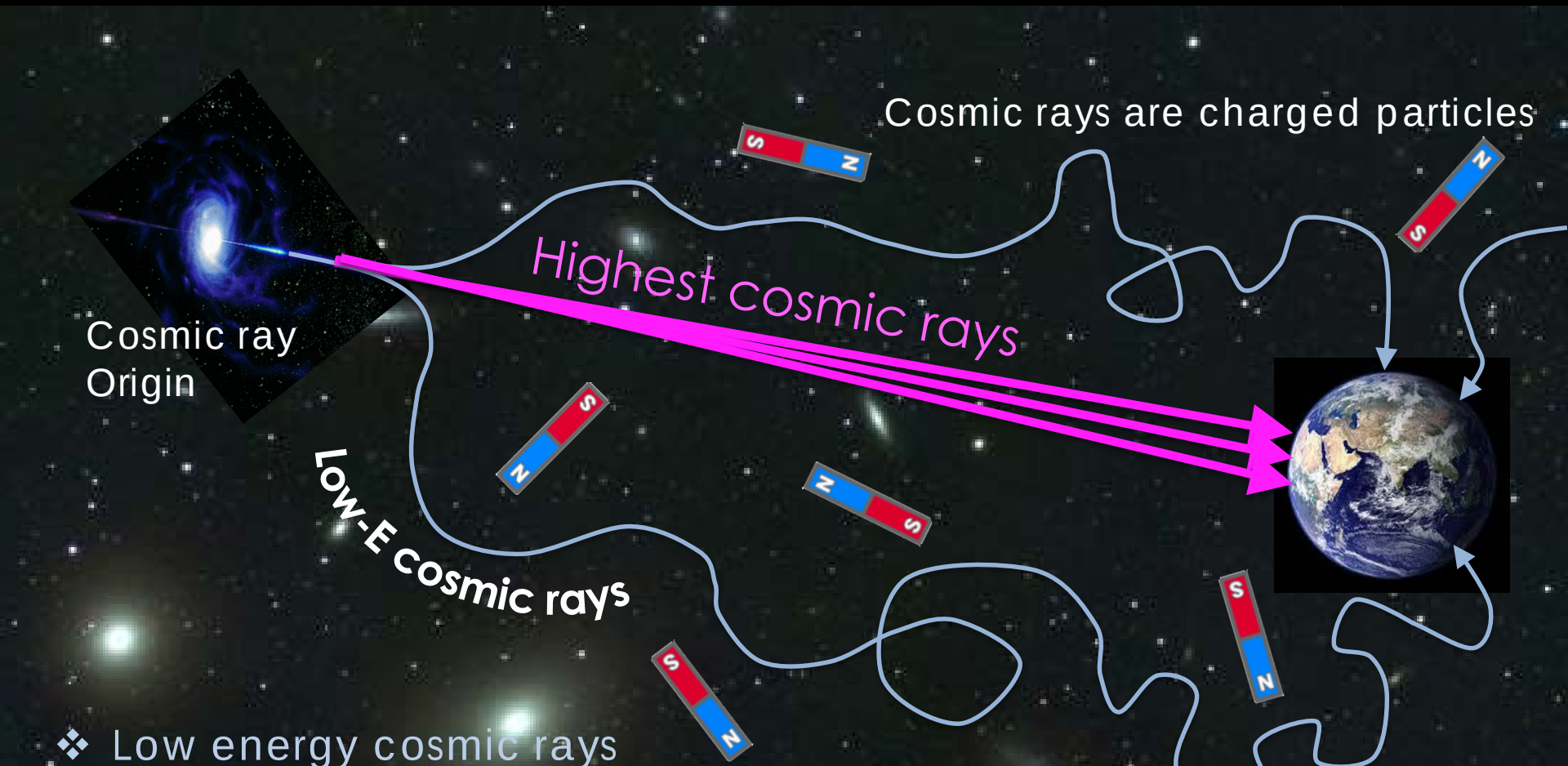
Physics picture from TA energy spectrum



- Cosmic rays ($E > 10^{18.2}$ eV)
  - Extragalactic protons
- Suppression consistent with GZK cutoff
  - 2.7-K CMB photon = gamma rays with E > 100 MeV at rest system of 10^{20}eV proton
    - Special theory of relativity of Lorentz factor of 10^{11}
  - Lose energy by pion production
  - Proton energy limit and arrival distance limit (horizon~100Mpc)
- Ankle consistent with e^-e^+ pair creation
- Source spectral index ~2.2

Anisotropy

Why highest energy cosmic rays?



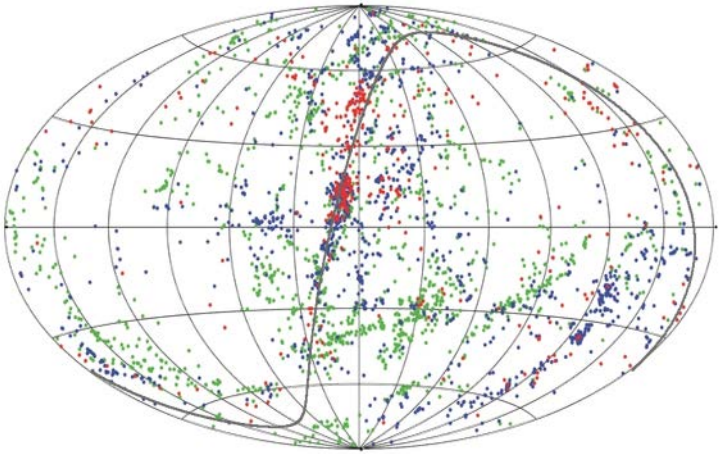
- Low energy cosmic rays
  - → bend by the magnetic field
  - → Isotropy at the Earth
- Highest energy cosmic rays
  - → Almost go straight against magnetic field
  - → Possible to find cosmic-ray origin directly

A feature expected in the arrival directions of highest-energy cosmic rays

① GZK cutoff

– Arrival distance limit (Horizon~100 Mpc)

② Nearby matter distribution in the universe (~50 Mpc)



Very anisotropic

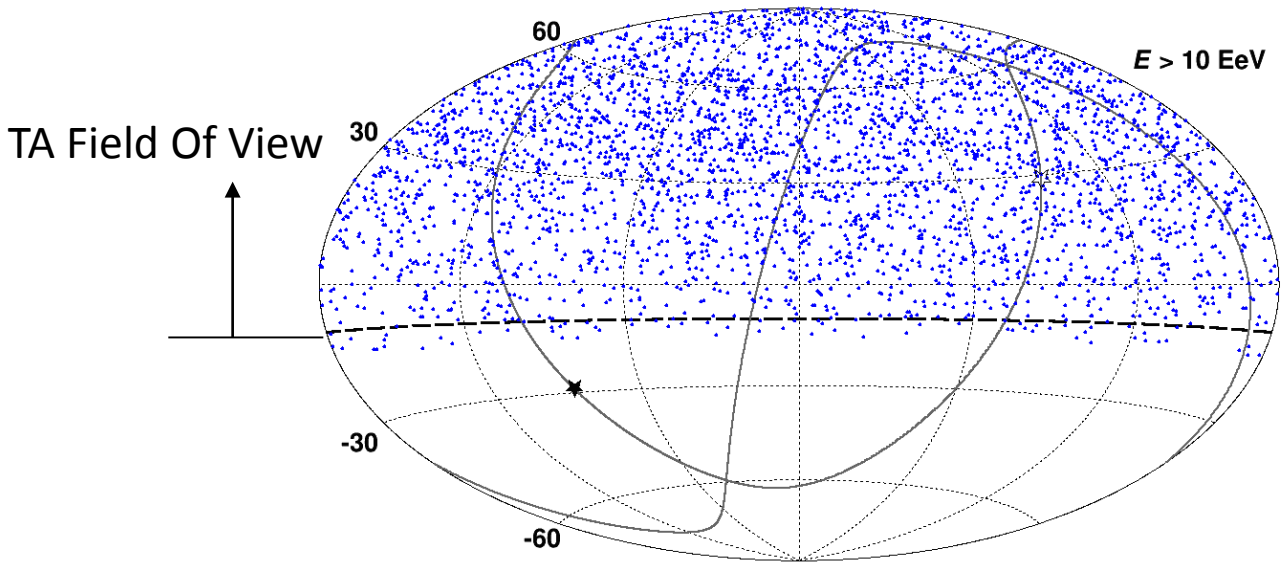
③ Rectilinear

– Source identification

Anisotropy of arrival directions of highest energy cosmic rays originated from ② is expected!

Distribution of arrival directions of cosmic rays with energies greater than 10^{19} eV

- 10^{19} eV ~ ~1/6 of cutoff energy
- TA SD data for 6 years : 3316 events



Isotropic

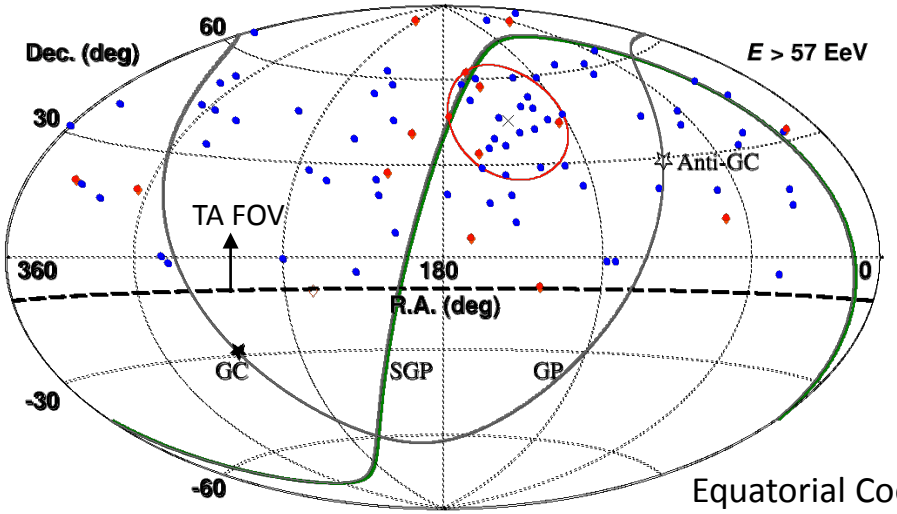
Medium-scale anisotropy of highest-energy cosmic rays

(TA SD 6-year data)

APJL, 790:L21 (5pp), 2014
for 5-year data

87 cosmic rays above 5.7×10^{19} eV

Northern sky



Southern sky

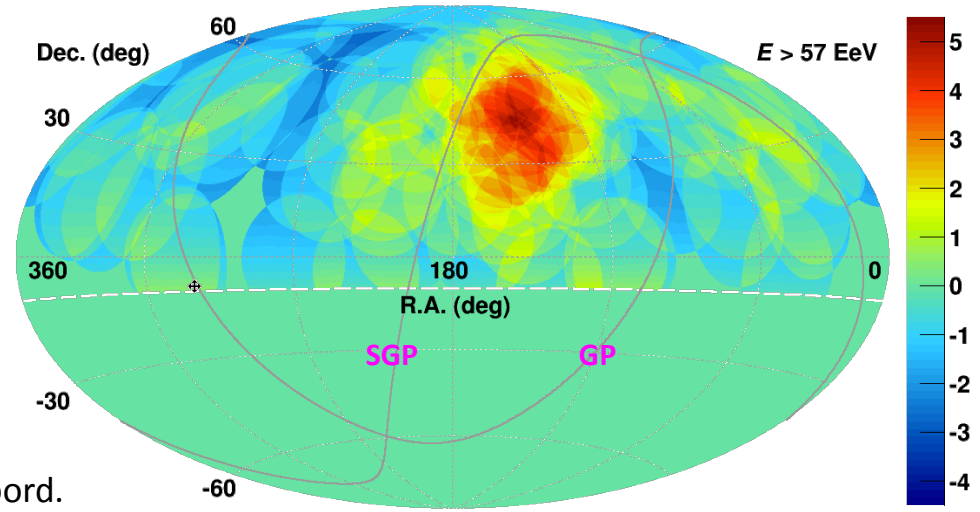
Inside a 20°-radius circle

Expected events for isotropy : 5.5

Observed events : 23

23/5.5 ~400% excess

- Oversampling by 20°-radius circles

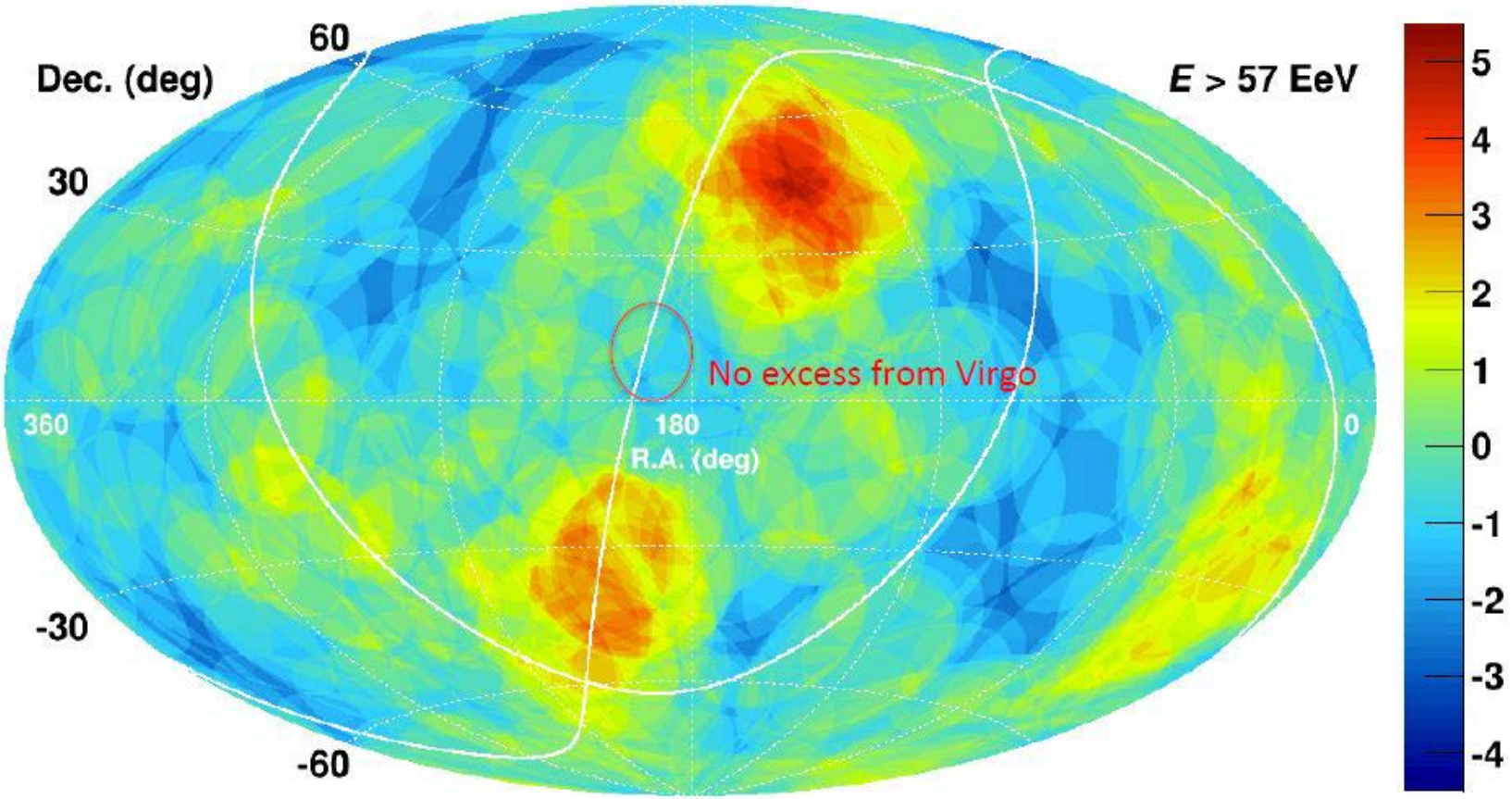


Equatorial Coord.

- Maximum pretrial significance: 5.55 σ
- Chance probability of exceeding 5.55 σ
  3.1×10^{-5} (**4.0 σ**)

Hotspot!

TA 6 Years + Auger 10 Years



North: S_{MAX} = 5.19σ, (R.A, Dec.) = (148.4°, 44.5°)
South: S_{MAX} = 3.57σ, (R.A, Dec.) = (210.9°, -48.2°)

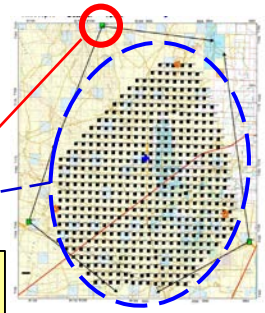
A.Aab et al, arXiv:1411.6111v1
K.Kawata, 2014/12/17

Composition

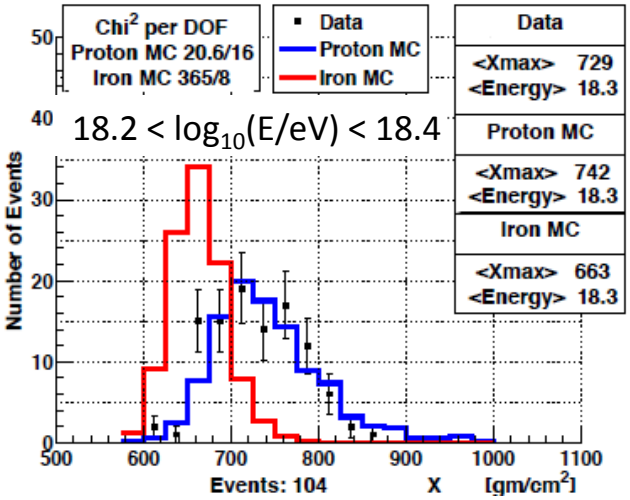
Xmax analysis by hybrid events

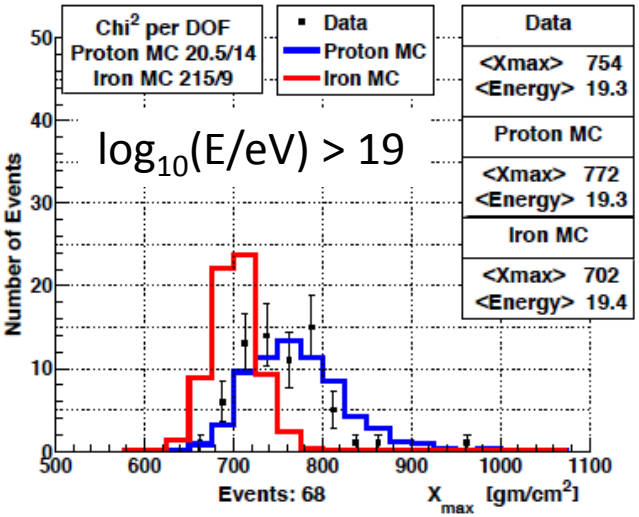
(MD FD + SD)

APP64 (2015) 49-62

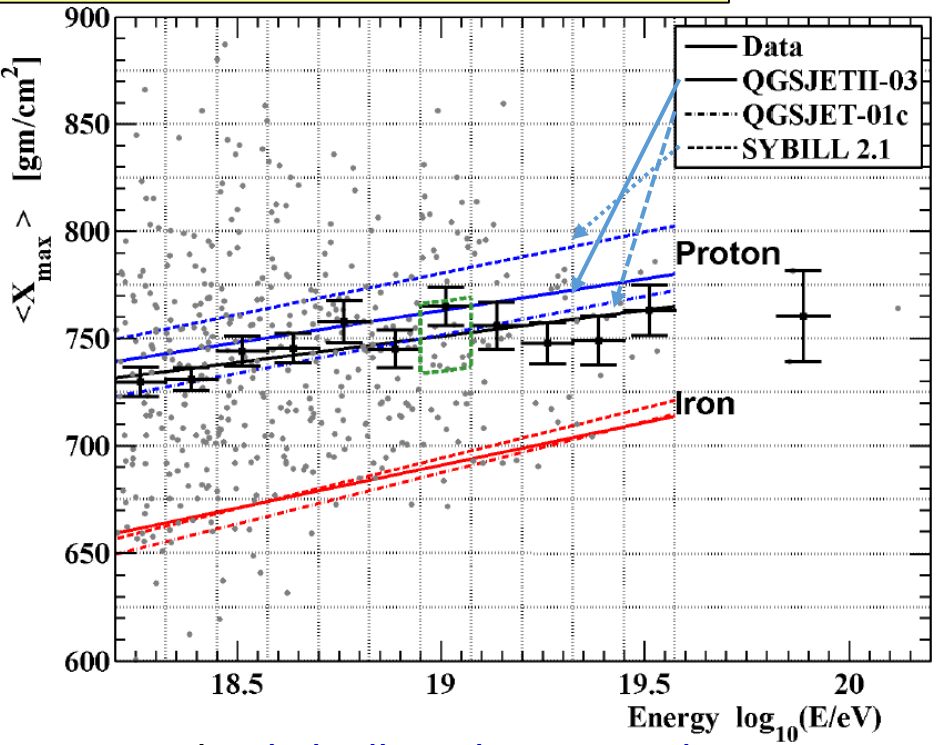


- MD FD: [refurbished HiRes] + SD





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



consistent with a light (largely protonic) composition

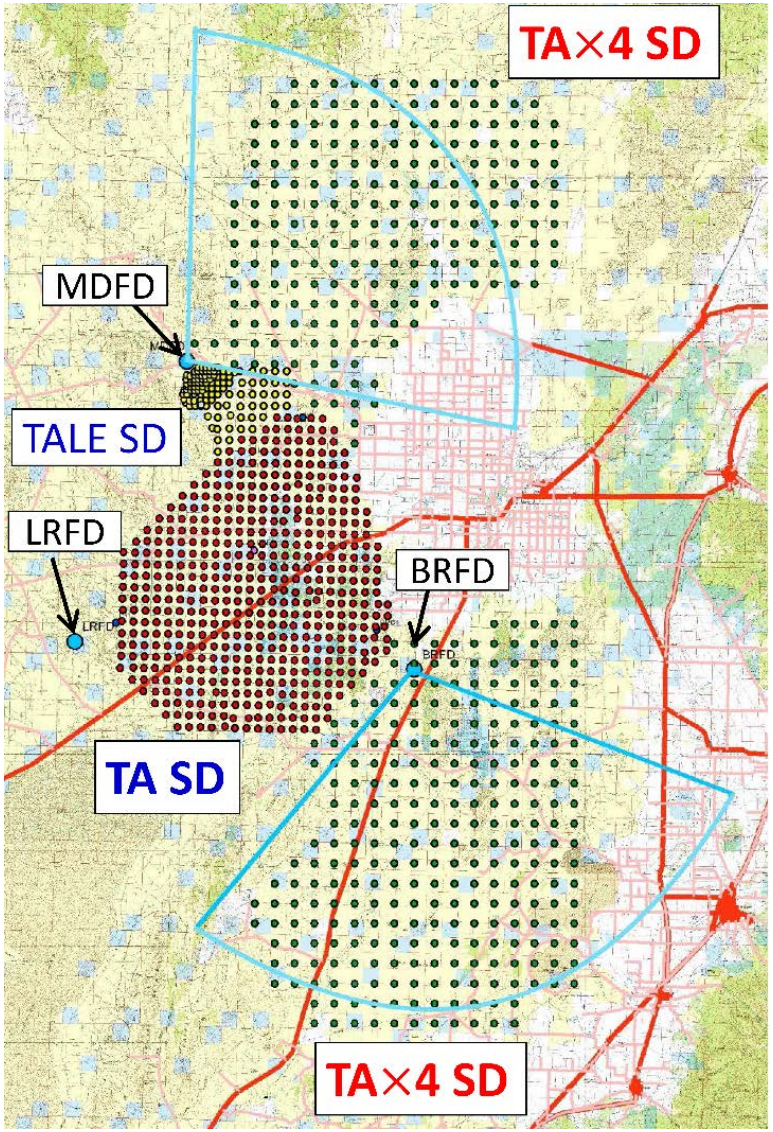
Comparison with recent models: on-going
(QGSJETII-4, EPOS-LHC)

TAx4

TA×4 proposal

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

- 5-year project of SD part was approved by Japanese funding agency last April (3.7M$)
- 2.7-year construction for new SDs
  - **TA SD: 19 year** data
  - 300 cosmic rays (E>5.7x10^{19} eV) expected

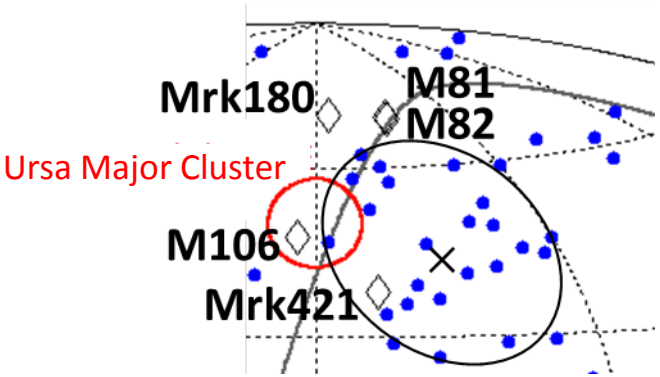


May 27, 2015

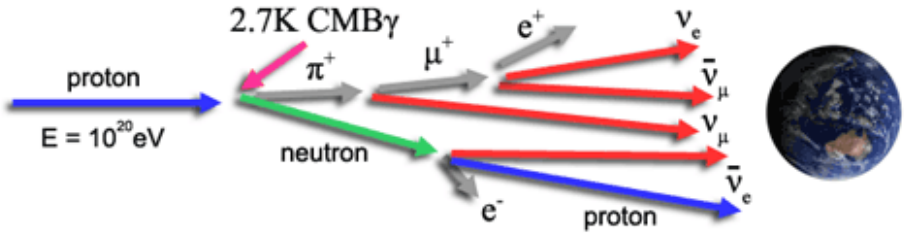
Science Breaking News about TA ×4!

http://news.sciencemag.org/physics/2015/05/japan-enlarge-massive-cosmic-ray-array-utah

Prospect of TA×4



- Arrival direction
  - Hotspot
    - Hotspot source
    - Confirmation at > 5σ level
    - Fine structure?
    - Other excess spots?
    - Study of galactic MF and extragalactic MF
  - Point source search
  - Correlations 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

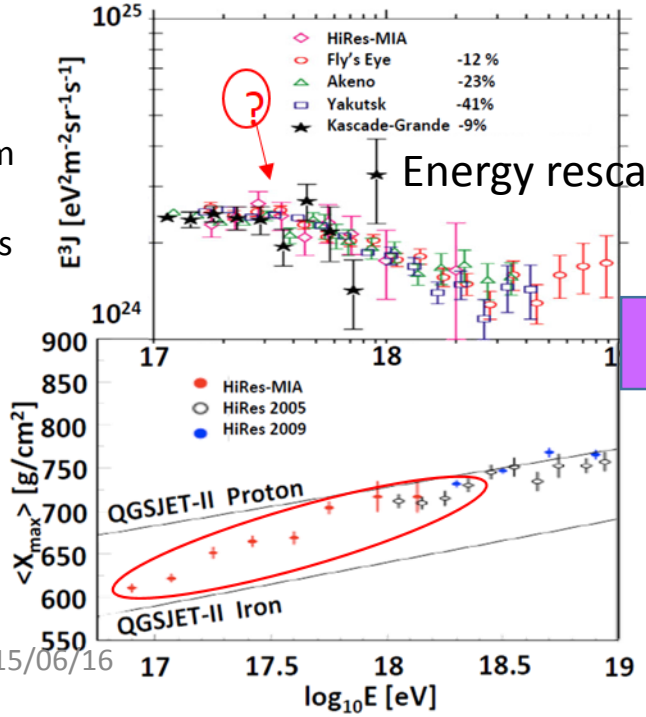


TA low energy extension

TALE (TA Low-energy Extension)
down to $10^{15.9}$ eV

- E = $10^{15.9}$ – 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?

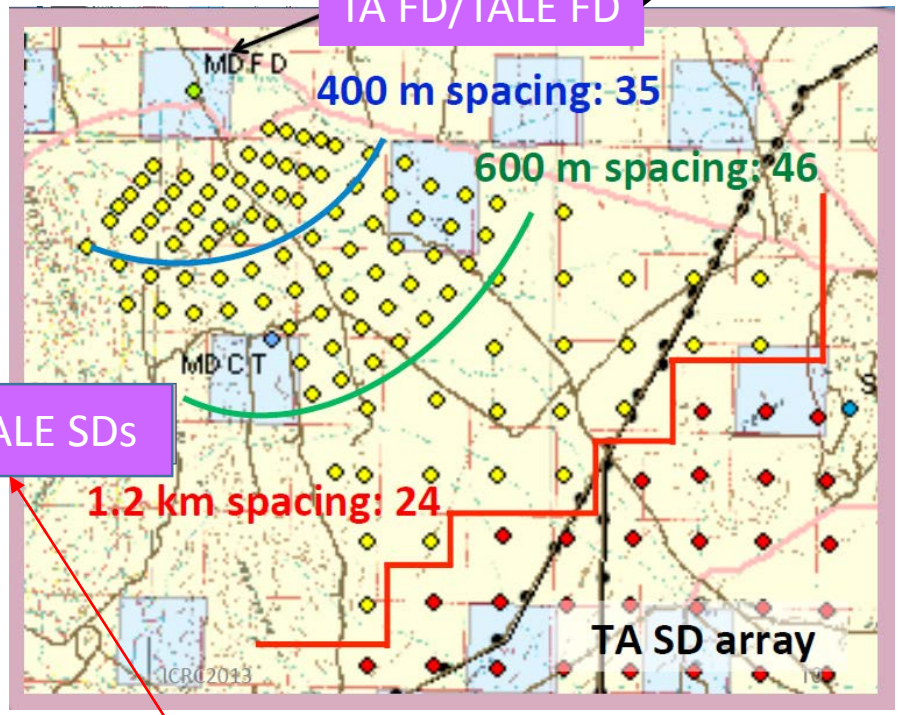
Results from Previous experiments



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

TALE layout

Construction completed

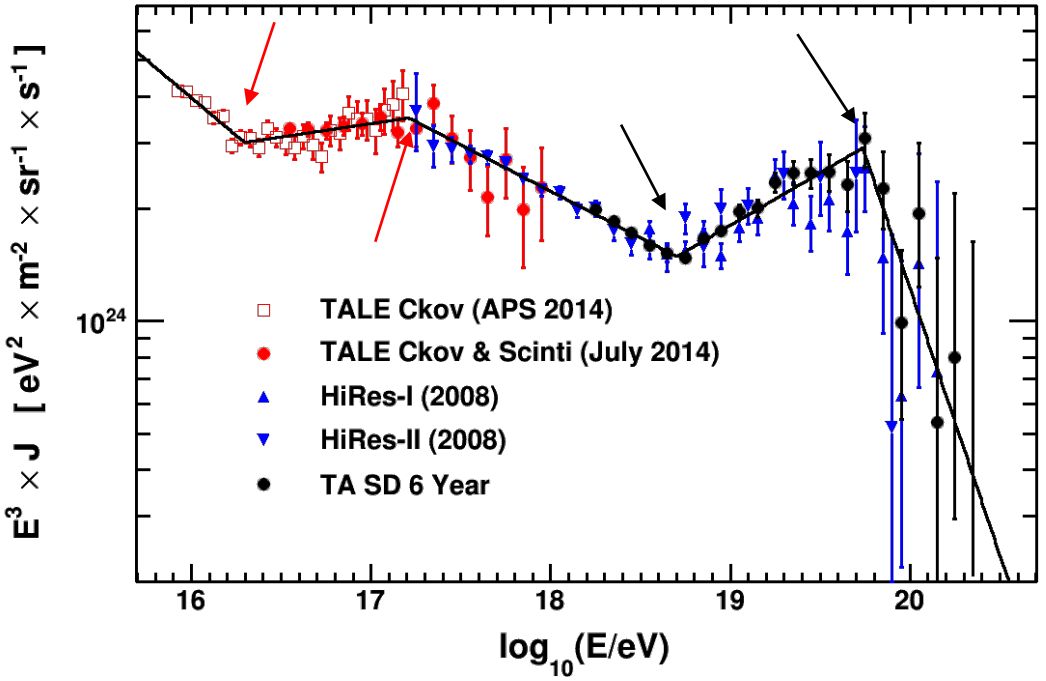


Partially constructed
16 TALE SDs running

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

(FD) (SD)

4.4 decades in energy



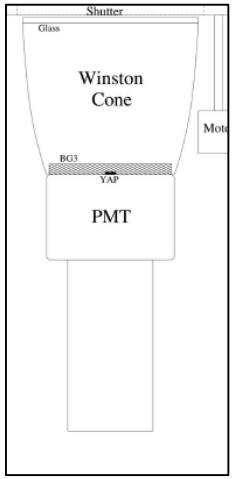
Composition meas. with **good Xmax resolution** is an urgent subject → **Hybrid (FD+SD)** analysis by constructing the full TALE SD array (with meas. of core on the ground)

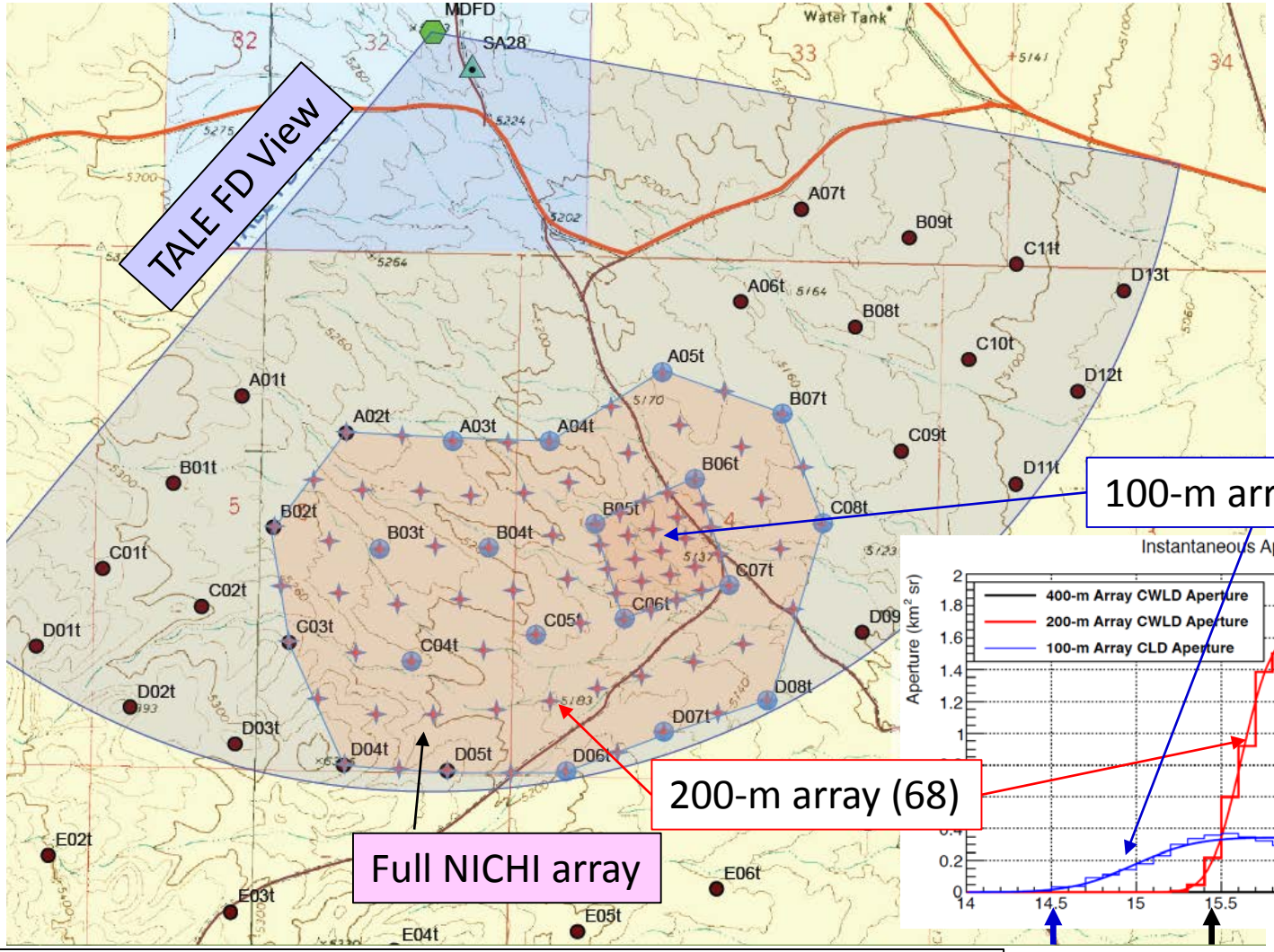
TALE SD 5-year project for the completion of TALE was approved by Japanese funding agency this May (~1M$)

NICHE proposal (E > $10^{14.5}$ eV)

Non-Imaging CHErenkov array (1.5-2 km^2)

Upward 3”-PMT





jNICHE: a 15-PMT array funded by Japanese funding agency last year

14.5 **15.5**

Other activities including associate experiments from the world

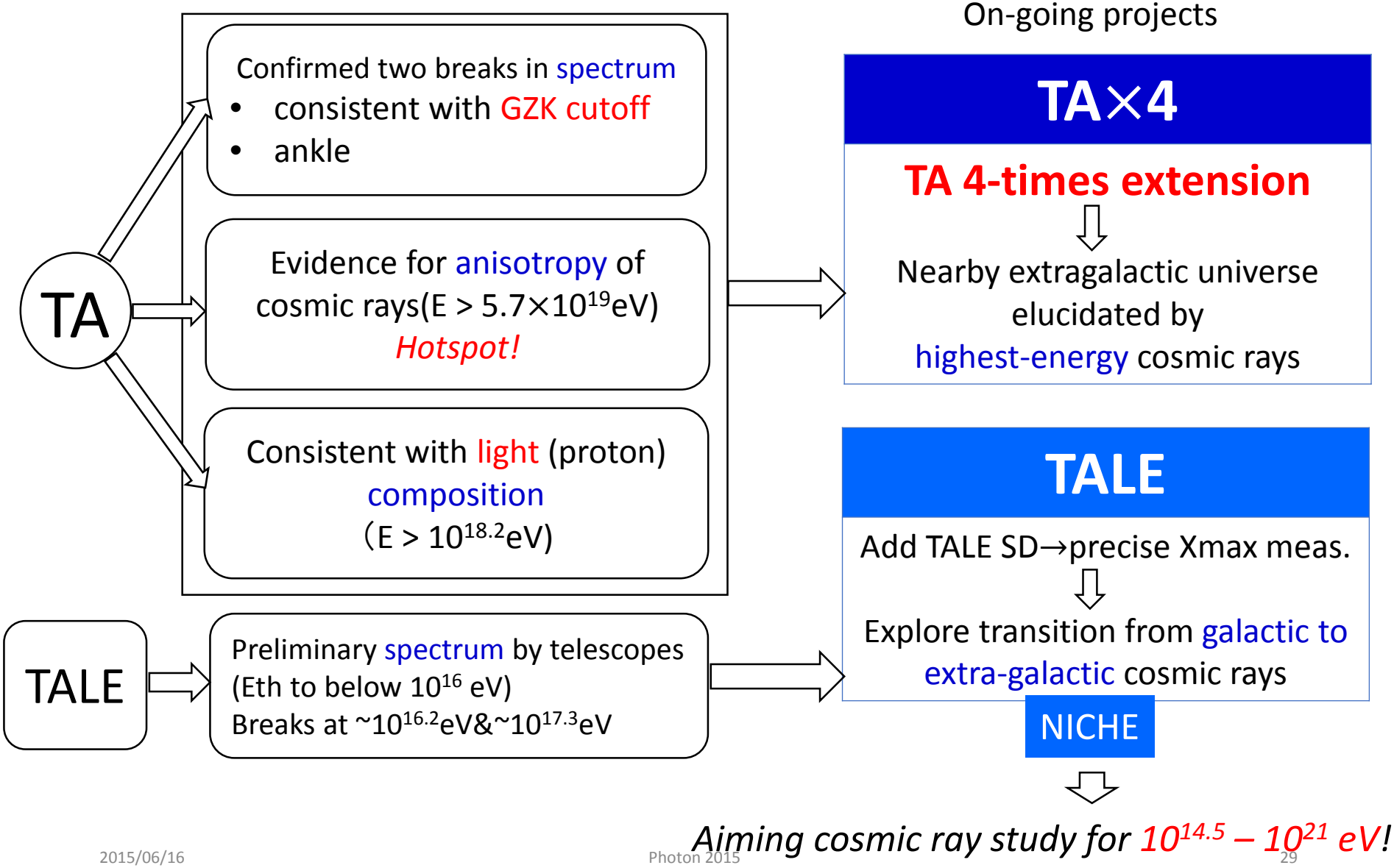
- ELS (Electron Light Source, electron accelerator)
  - On-site FD calibration by pseudo air shower generated by known energy of electrons
    - 10^9 electrons of 40 MeV

- Associate experiments
  - Test of several CR detections by radio
    - TARA (TA Radar): transmitter → shower → radio echo
    - Molecular Bremsstrahlung detection
    - Test of Askarian Radio Array (ARA) with Ice at ELS
  - Test of next-generation Fluorescence Detector
    - TA-EUSO: Test of prototype of JEM-EUSO (or K-EUSO) at TA site
    - Mono-eye FD test

by S.Prohira @this conf.

- TA extensive SD burst events associated with lightning
- TA muon detector projects
  - Check Auger muon excess (1.8xMC)
    - Scintillator with absorber
    - Auger water tanks deployed at the TA site
- etc.

Summary

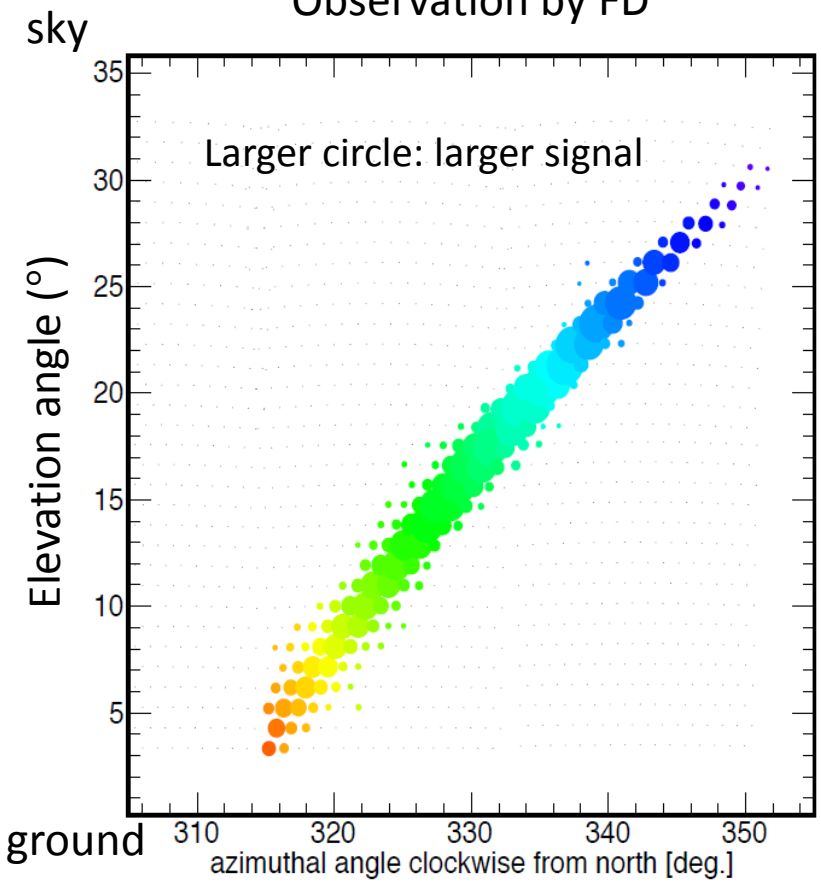

TA
Confirmed two breaks in spectrum
• consistent with GZK cutoff
• ankle
Evidence for anisotropy of cosmic rays(E > 5.7×10^19eV)
Hotspot!
Consistent with light (proton) composition
(E > 10^18.2eV)
TALE
Preliminary spectrum by telescopes
(Eth to below 10^16 eV)
Breaks at ~10^16.2eV&~10^17.3eV
On-going projects
TA×4
TA 4-times extension
Nearby extragalactic universe elucidated by highest-energy cosmic rays
TALE
Add TALE SD→precise Xmax meas.
Explore transition from galactic to extra-galactic cosmic rays
NICHE
Aiming cosmic ray study for 10^14.5 – 10^21 eV!

END

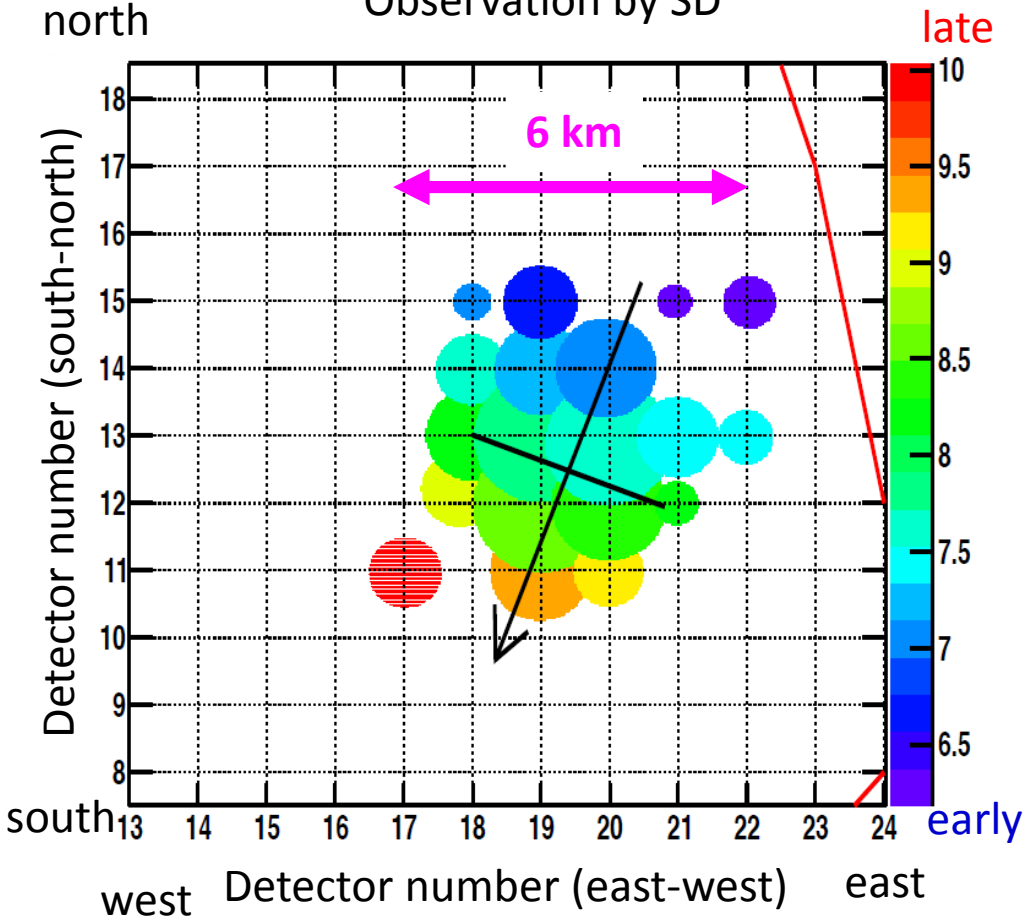
An example of hybrid observation

5h51m50sUTC, Oct.26, 2008

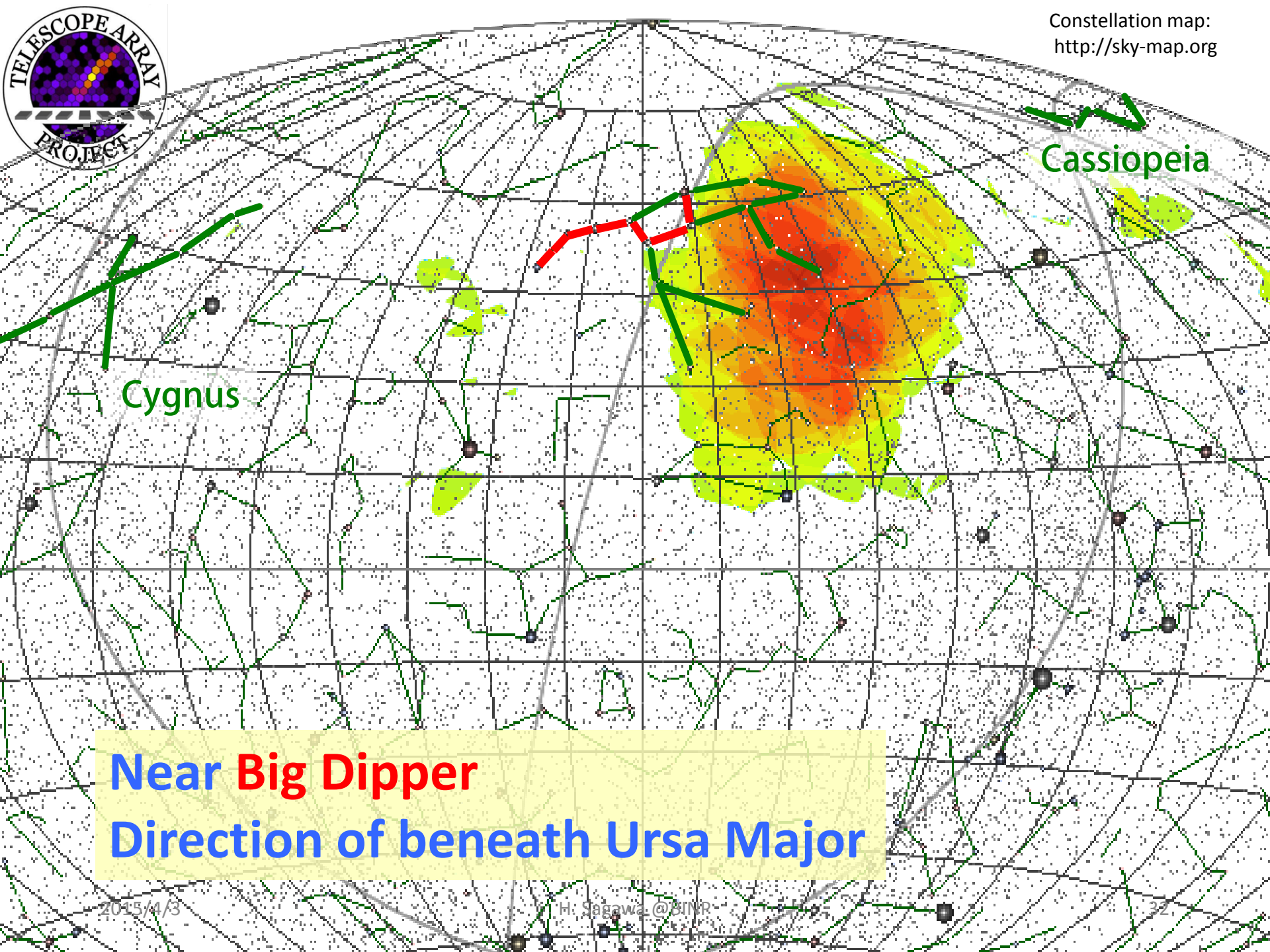
Observation by FD



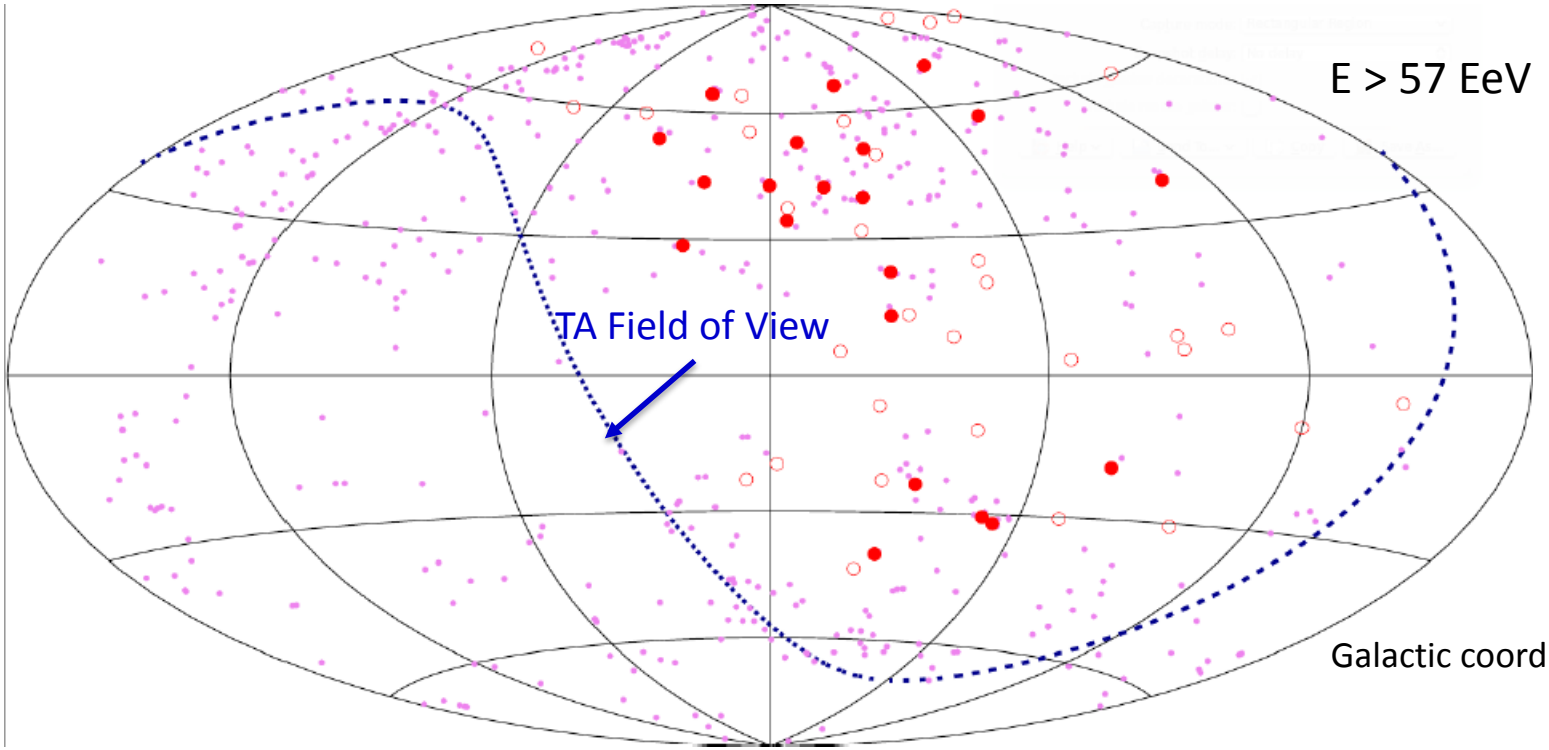
Observation by SD



An air shower of a cosmic-ray with 2×10^{19} eV


Constellation map:
http://sky-map.org
Cassiopeia
Cygnus
Near Big Dipper
Direction of beneath Ursa Major

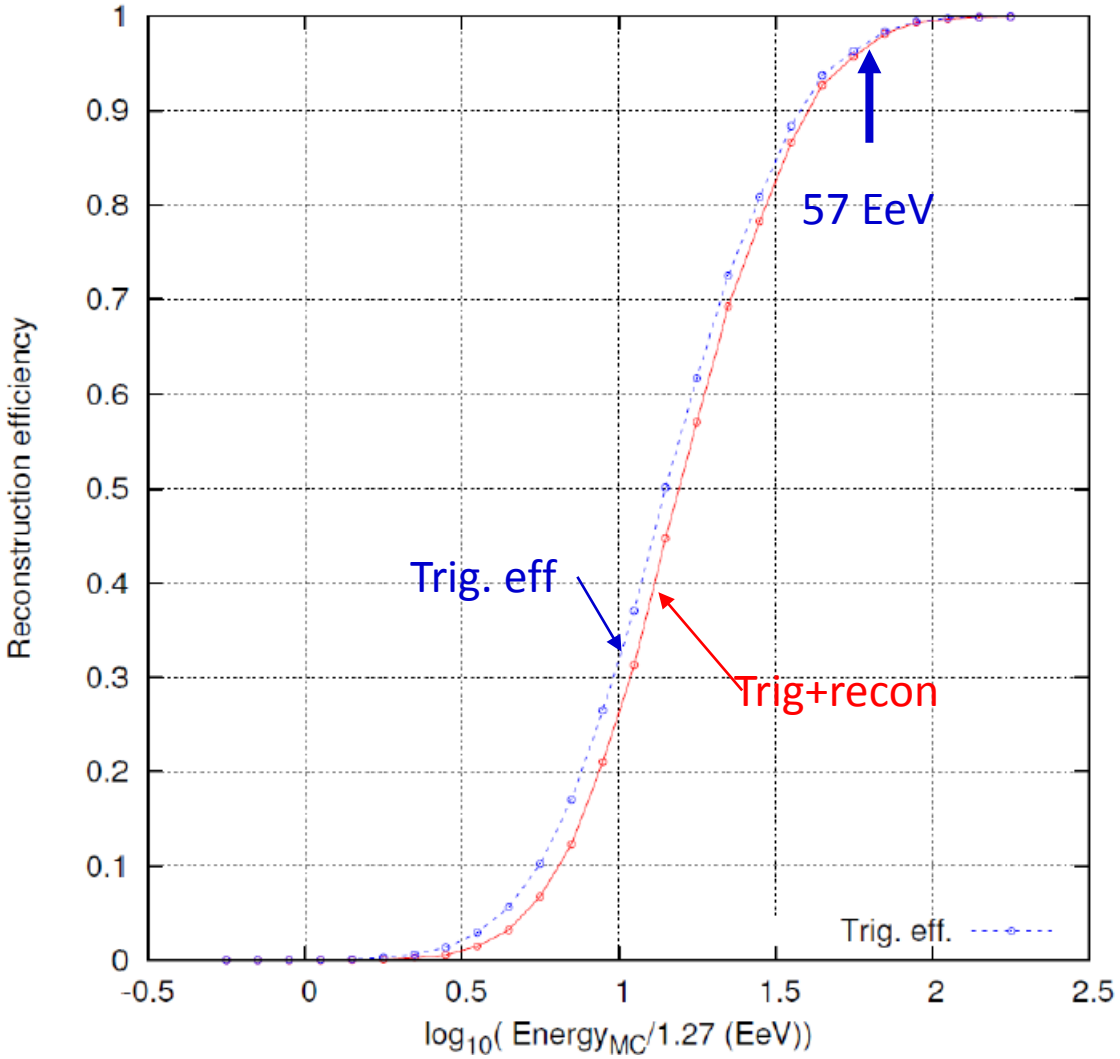
Correlation of cosmic rays above 57 EeV with Active Galactic Nuclei（AGN）



- AGN ($z < 0.018$)
- No. of TA events correlated with AGNs within 3.1 deg. (21) 40%
  Background (isotropy) (12.5) 24%
  P-value 0.7% (2.7σ)
- TA events without correlation (32)

Efficiency for additional TA × 4 SD array

Differential for energies



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

Reconstruction
. NSD≥ 4

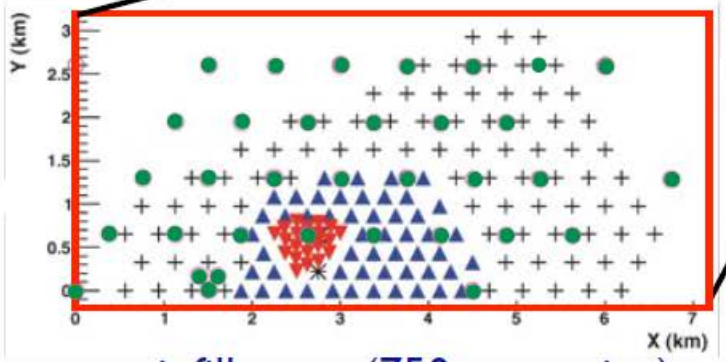
TA SD reconstruction efficiency =100% for $E > 10^{19}$eV

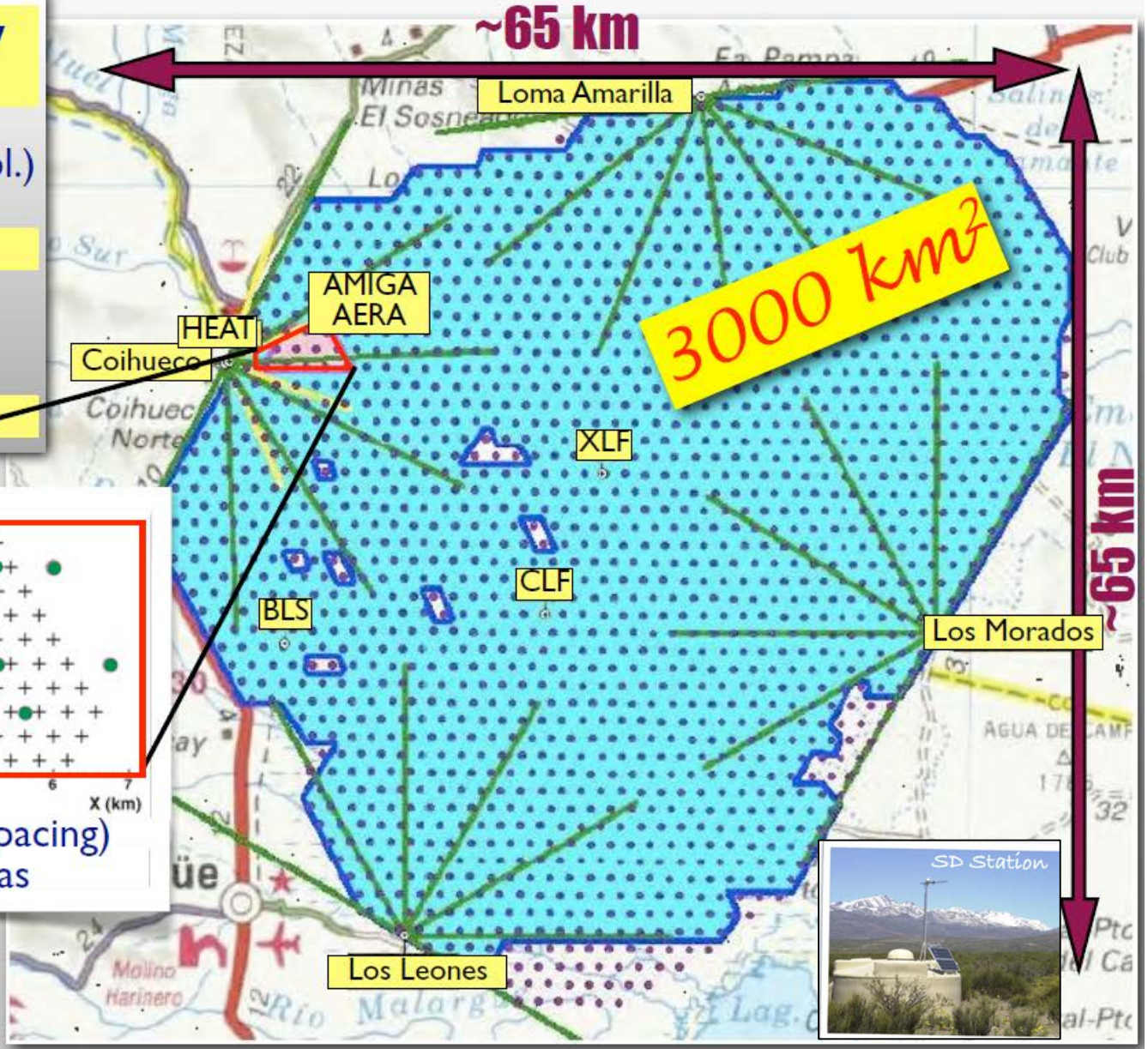
Pierre Auger Observatory in Argentina

1660 Water-Cherenkov tanks
1.5 km standard grid
0.75 km infill-grid (53/61 depl.)

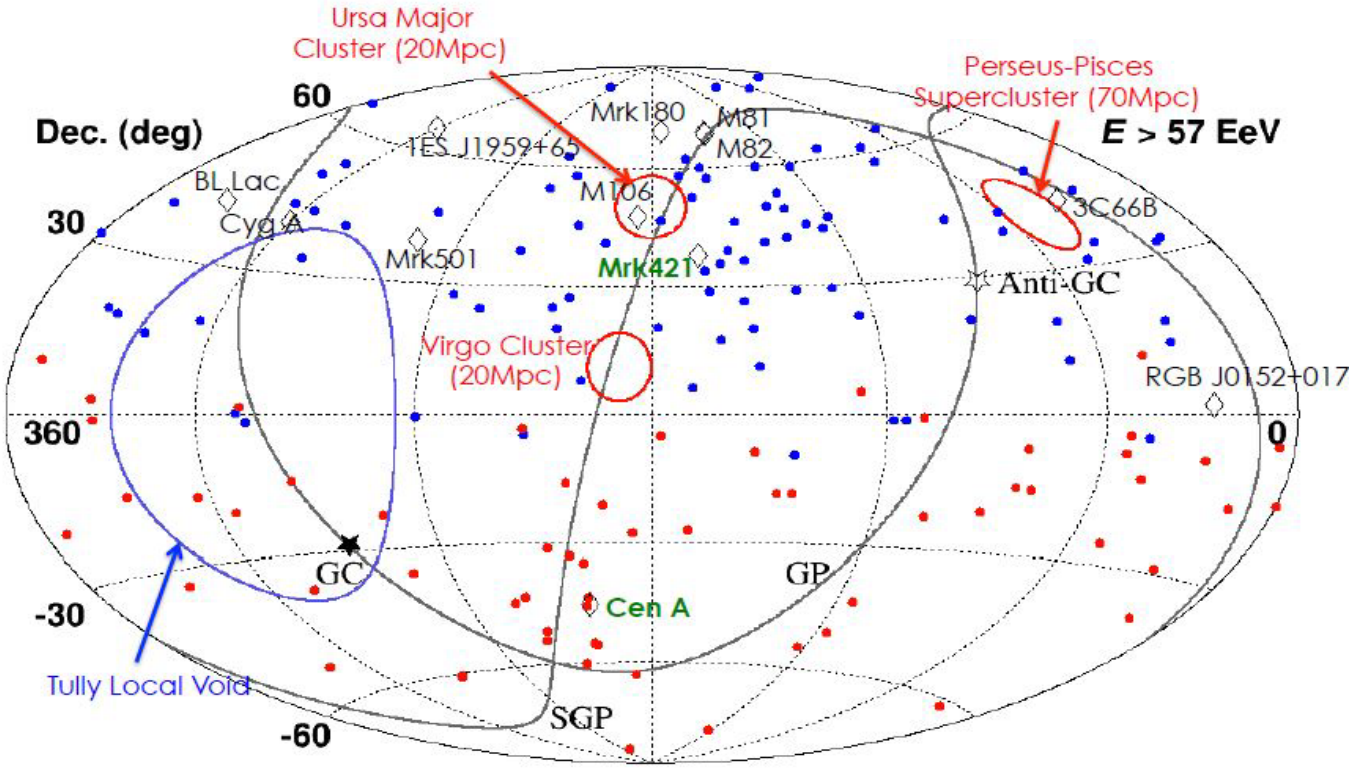
27 telescopes
in 4+1 buildings at the periphery

3000 km² area





Nearby Prominent AGNs



TA : 2008 May – 2014 May (6.0 years) 87 events
Auger : 2004 May – 2009 Nov (5.5 years) 62 events

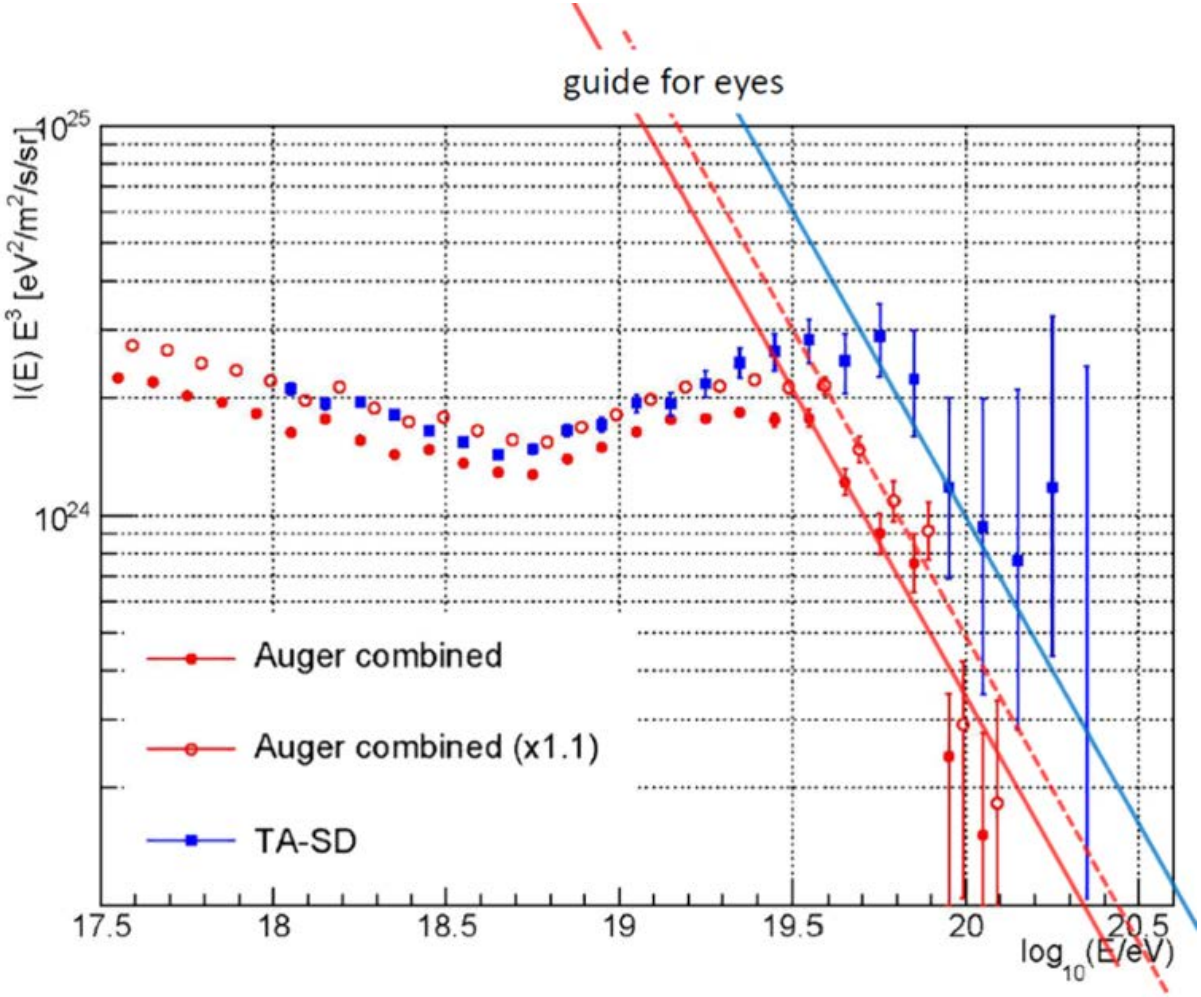
TA hotspot: 19^{o} off from SGP. No obvious source candidate.

Auger warm-spot: Cen A as a source candidate.

Other enhancements may show up with more exposure.

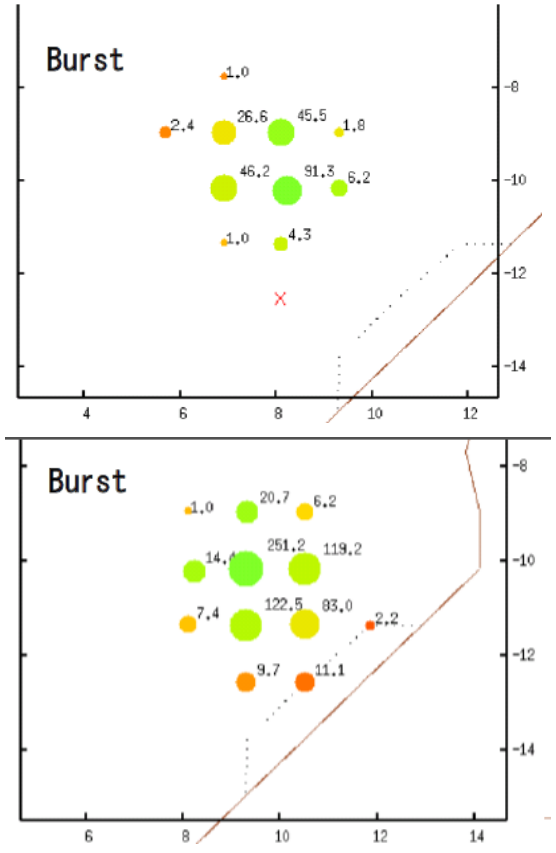
K.Kawata, ICRR seminar, 2014/08/27
C.D. Dermer et al., arXiv:0811.1160v3

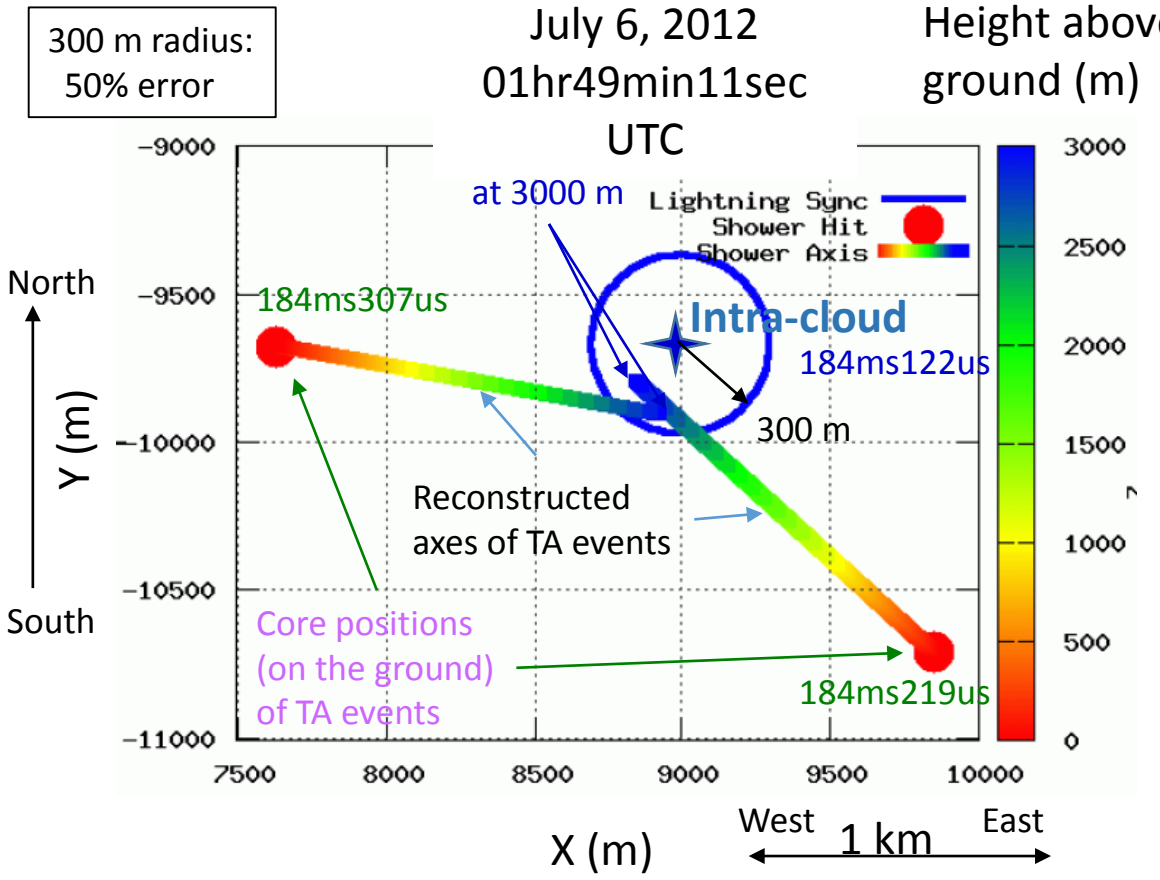
TA and Auger energy spectrum



An example of TA reconstructed events with lightning

T.Okuda
COSPA2013
preliminary





(X, Y): distances are from CLF