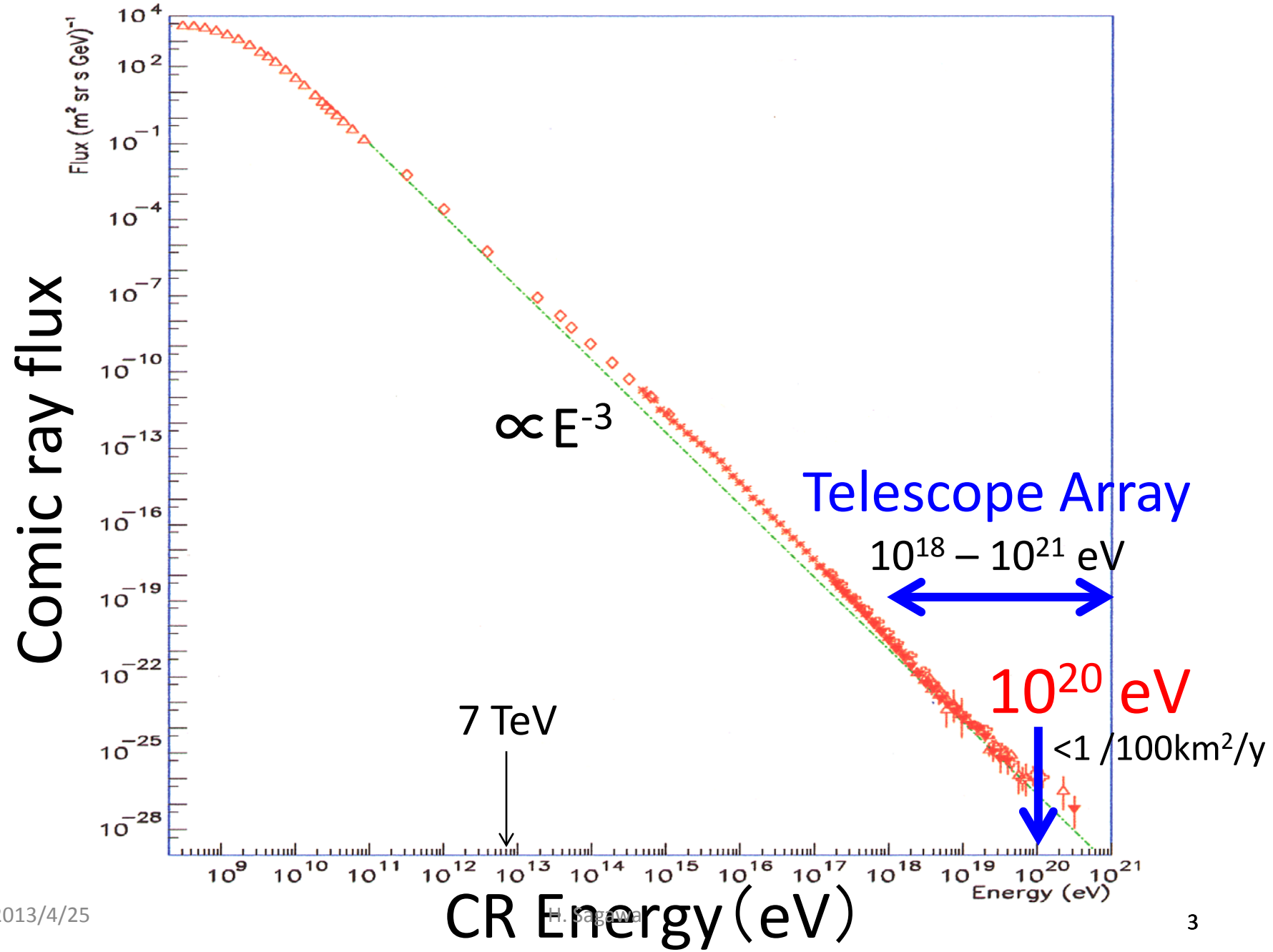
Detection of the Atmospheric Showers with Telescope Array (TA) experiment

H. Sagawa
ICRR, Univ. of Tokyo
on behalf of TA collaboration

CHEF2013 in Paris
April 25, 2013

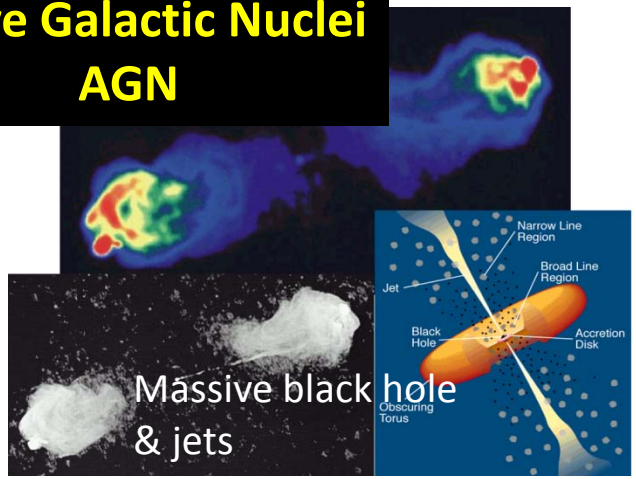
Outline

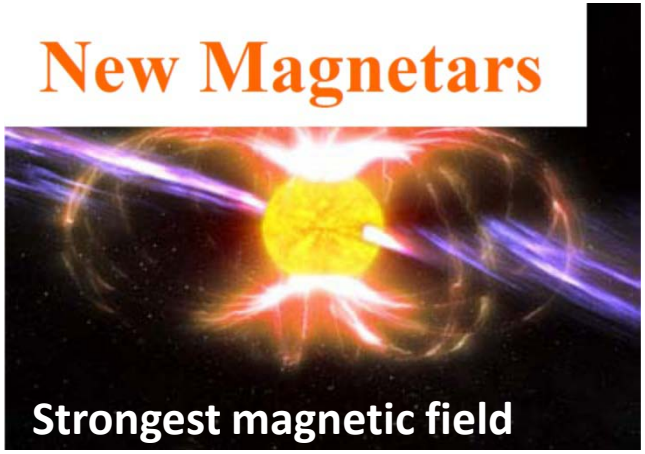
- Physics by highest energy cosmic rays
- TA experiment
- Results from TA
- Summary

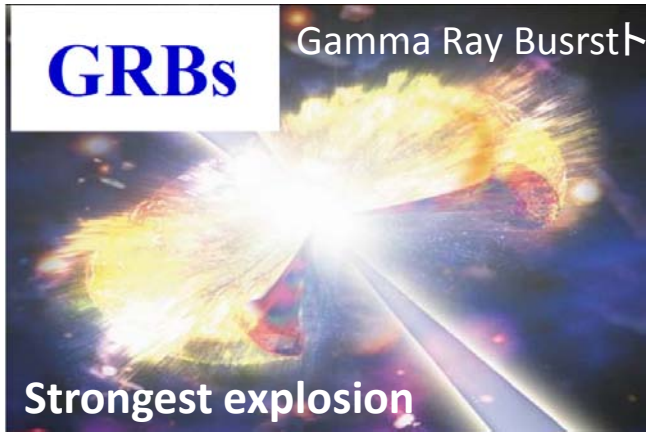

Comic ray flux
Flux (m² sr s GeV)⁻¹
∝E⁻³
Telescope Array
10¹⁸ – 10²¹ eV
10²⁰ eV
<1 /100km²/y
7 TeV
Energy (eV)
CR Energy（eV）

Bottom-up scenarios

Active Galactic Nuclei
AGN

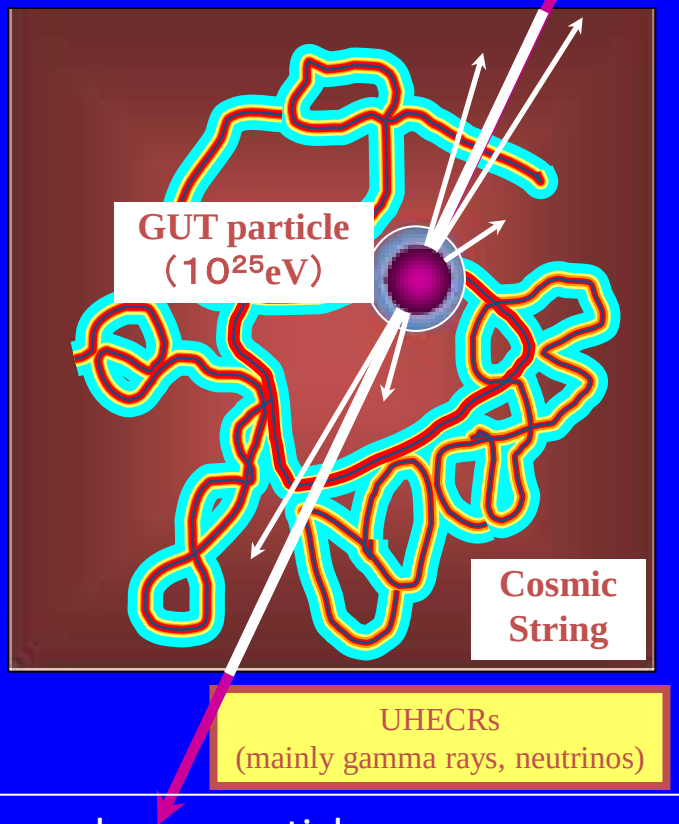




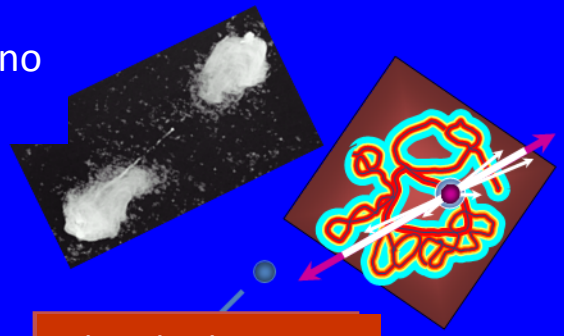


Top down scenario

BIG BANG



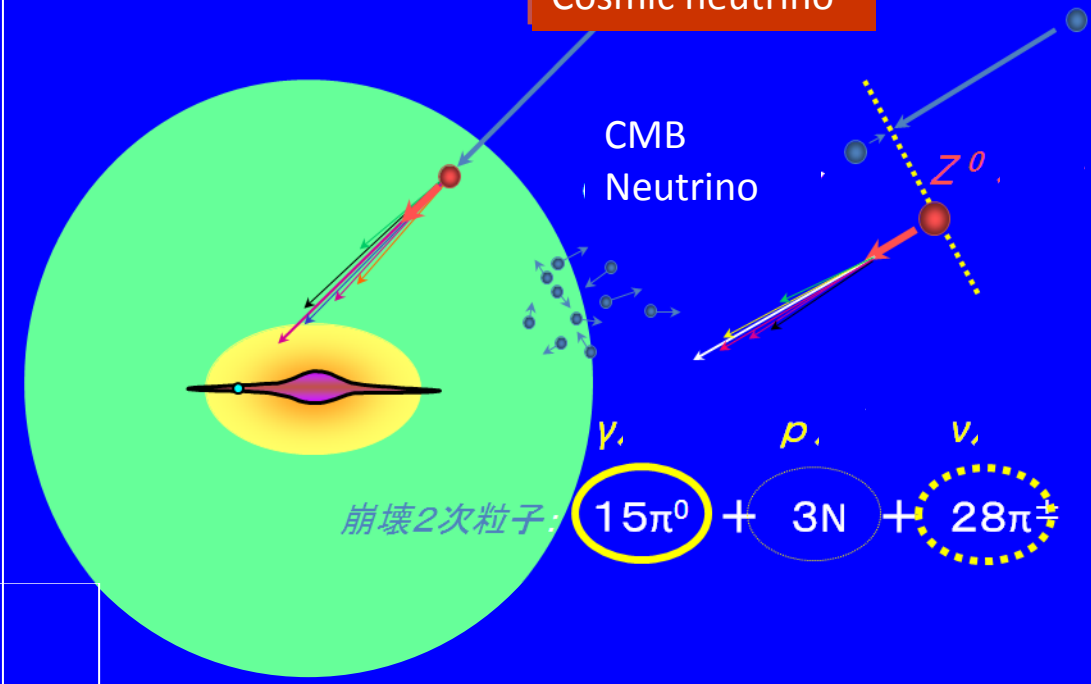
Interaction of an UHE neutrino with a CMB neutrino



Z burst

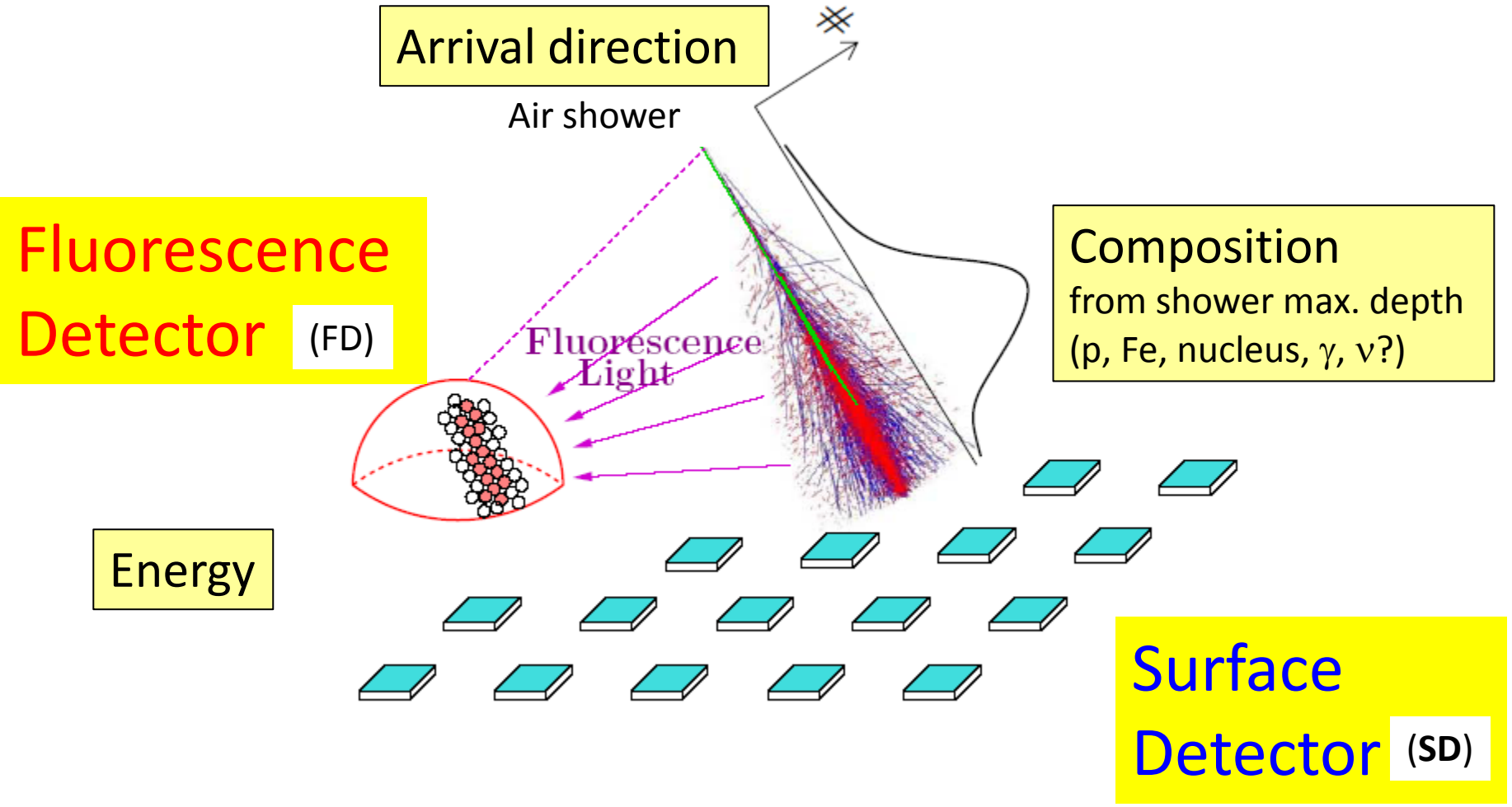
$\nu + \bar{\nu} \rightarrow Z^0$

Ultra-high energy Cosmic neutrino



- Super heavy particle
- GUT particle from COSMIC STRING decay

Detectors of highest energy cosmic rays



Telescope Array (TA) Collaboration

T. Abu-Zayyad[1], R. Aida[2], M. Allen[1], R. Anderson[1], R. Azuma[3], E. Barcikowski[1], J.W. Belz[1], D.R. Bergman[1], S.A. Blake[1], R. Cady[1], B.G. Cheon[4], J. Chiba[5], M. Chikawa[6], E.J. Cho[4], W.R. Cho[7], H. Fujii[8], T. Fujii[9], T. Fukuda[3], M. Fukushima[10,11], W. Hanlon[1], K. Hayashi[3], Y. Hayashi[9], N. Hayashida[10], K. Hibino[12], K. Hiyama[10], K. Honda[2], T. Iguchi[3], D. Ikeda[10], K. Ikuta[2], N. Inoue[13], T. Ishii[2], R. Ishimori[3], H. Ito[21], D. Ivanov[1,14], S. Iwamoto[2], C.C.H. Jui[1], K. Kadota[15], F. Kakimoto[3], O. Kalashev[16], T. Kanbe[2], K. Kasahara[17], H. Kawai[18], S. Kawakami[9], S. Kawana[13], E. Kido[10], H.B. Kim[4], H.K. Kim[7], J.H. Kim[1], J.H. Kim[4], K. Kitamoto[6], S. Kitamura[3], Y. Kitamura[3], K. Kobayashi[5], Y. Kobayashi[3], Y. Kondo[10], K. Kuramoto[9], V. Kuzmin[16], Y.J. Kwon[7], J. Lan[1], S.I. Lim[20], S. Machida[3], K. Martens[11], T. Matsuda[8], T. Matsuura[3], T. Matsuyama[9], J.N. Matthews[1], M. Minamino[9], K. Miyata[5] , Y. Murano[3], I. Myers[1], K. Nagasawa[13], S. Nagataki[21], T. Nakamura[22], S.W. Nam[20], T. Nonaka[10], S. Ogio[9], M. Ohnishi[10], H. Ohoka[10], K. Oki[10], D. Oku[2], T. Okuda[23], M. Ono[21], A. Oshima[9], S. Ozawa[17], I.H. Park[20], M.S. Pshirkov[24], D.C. Rodriguez[1], S.Y. Roh[19], G. Rubtsov[16], D. Ryu[19], H. Sagawa[10], N. Sakurai[9], A.L. Sampson[1], L.M. Scott[14], P.D. Shah[1], F. Shibata[2], T. Shibata[10], H. Shimodaira[10], B.K. Shin[4], J.I. Shin[7], T. Shirahama[13], J.D. Smith[1], P. Sokolsky[1], B.T. Stokes[1], S.R. Stratton[1,14], T. Stroman[1], S. Suzuki[8], Y. Takahashi[10], M. Takeda[10], A. Taketa[25], M. Takita[10], Y. Tameda[10], H. Tanaka[9], K. Tanaka[26], M. Tanaka[9], S.B. Thomas[1], G.B. Thomson[1], P. Tinyakov[16,24], I. Tkachev[16], H. Tokuno[3], T. Tomida[27], S. Troitsky[16], Y. Tsunesada[3], K. Tsutsumi[3], Y. Tsuyuguchi[2], Y. Uchihori[28], S. Udo[12], H. Ukai[2], G. Vasiloff[1], Y. Wada[13], T. Wong[1], M. Wood[1], Y. Yamakawa[10] , R. Yamane[9], H. Yamaoka[8], K. Yamazaki[9], J. Yang[20], Y. Yoneda[9], S. Yoshida[18], H. Yoshii[29], X. Zhou[6], R. Zollinger[1], Z. Zundel[1]

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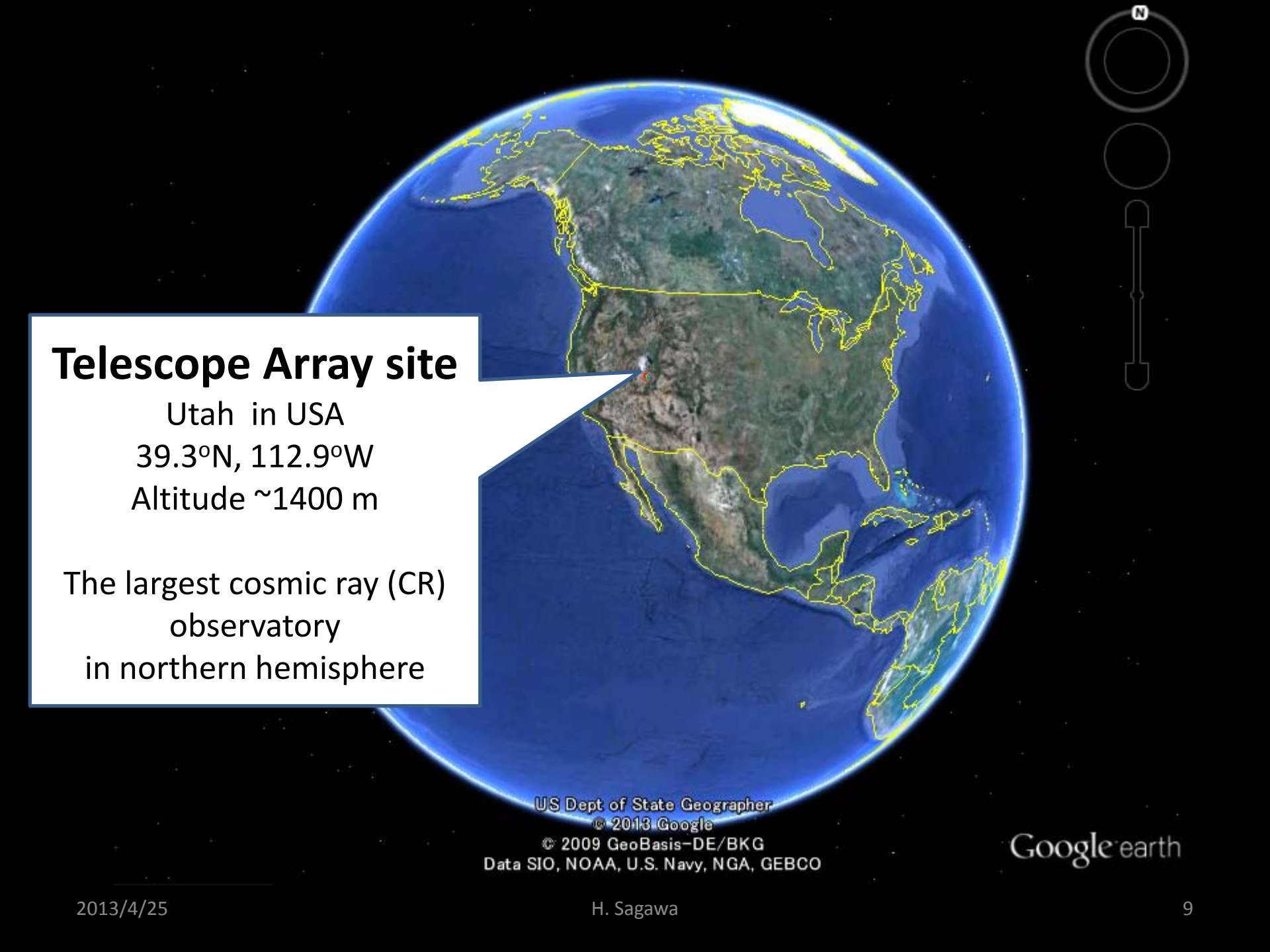
~140 researchers

[1]University of Utah, [2]University of Yamanashi, [3]Tokyo Institute of Technology, [4]Hanyang University, [5]Tokyo University of Science, [6]Kinki [illegible]ity University, [10]Institute for Cosm[illegible]s of the Universe, University of Toky[illegible]versity, [16]Institute for Nuclear Resea[illegible]ungnam National University, [20]Ew[illegible]ochi University, [23]Ritsumeikan Uni[illegible]okyo, [26]Hiroshima City University, [27]RIKEN, [28]National Institute of Radiological Science, [29]Ehime University

29 universities/institutes

(Japan, USA, Korea, Russia, Belgium)


Telescope Array site
Utah in USA
39.3°N, 112.9°W
Altitude ~1400 m
The largest cosmic ray (CR) observatory in northern hemisphere
US Dept of State Geographer
© 2013 Google
© 2009 GeoBasis-DE/BKG
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth

Telescope Array

3 com. towers

~30 km

Surface Detector

(SD)

507(1.2 km spacing)

700 km²

Fluorescence Detector

(FD)

3 stations

H. Sagawa

Telescope Array

3 com. towers

Surface Detector

(SD)

507(**1.2 km** spacing)

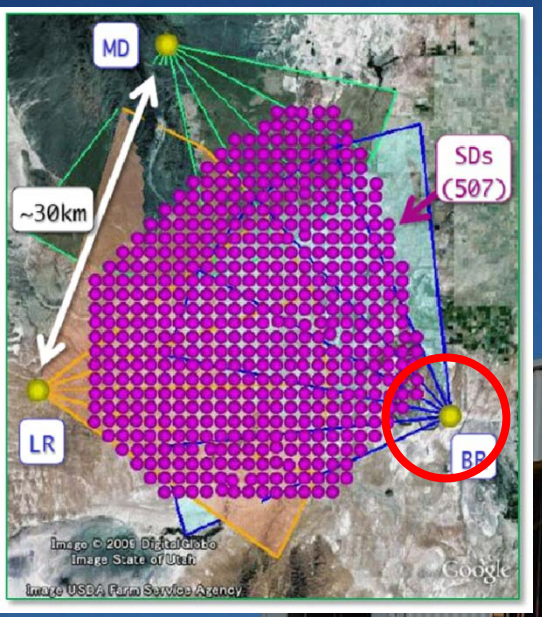
700 km²

Fluorescence Detector

(FD)

3 stations

Fluorescence Detector stations

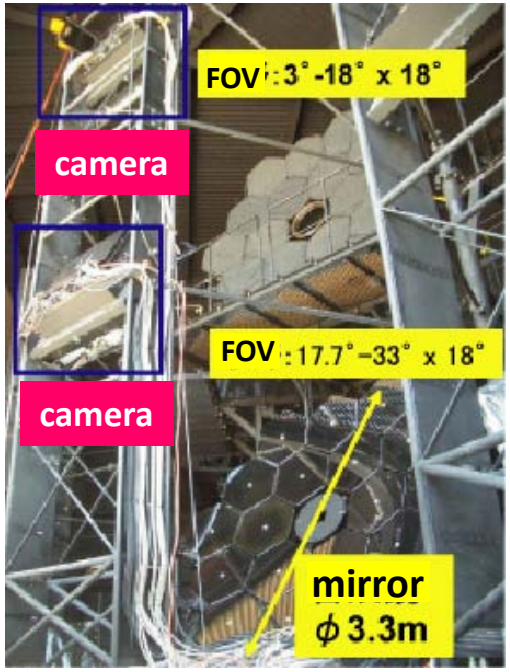


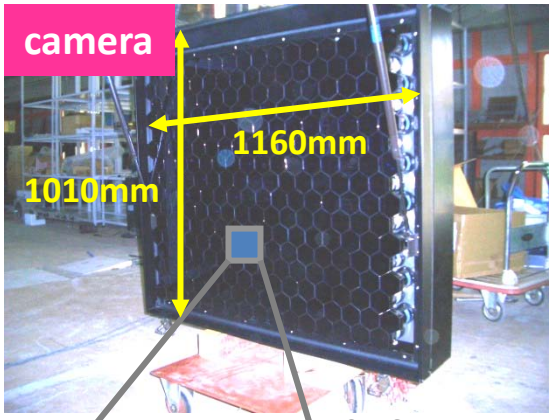
Field Of View
3 – 33° in zenith
108° in azimuth

Observation
Moonless, clear night
Duty cycle ~10%

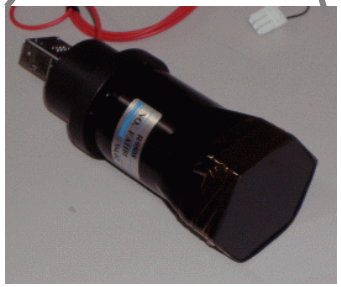
All three stations: observation since Nov., 2007

FD: Mirrors & cameras





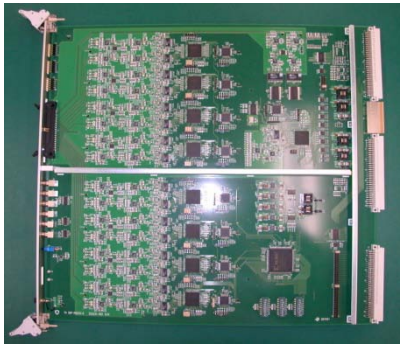
256PMTs



Hexiagonal PMT

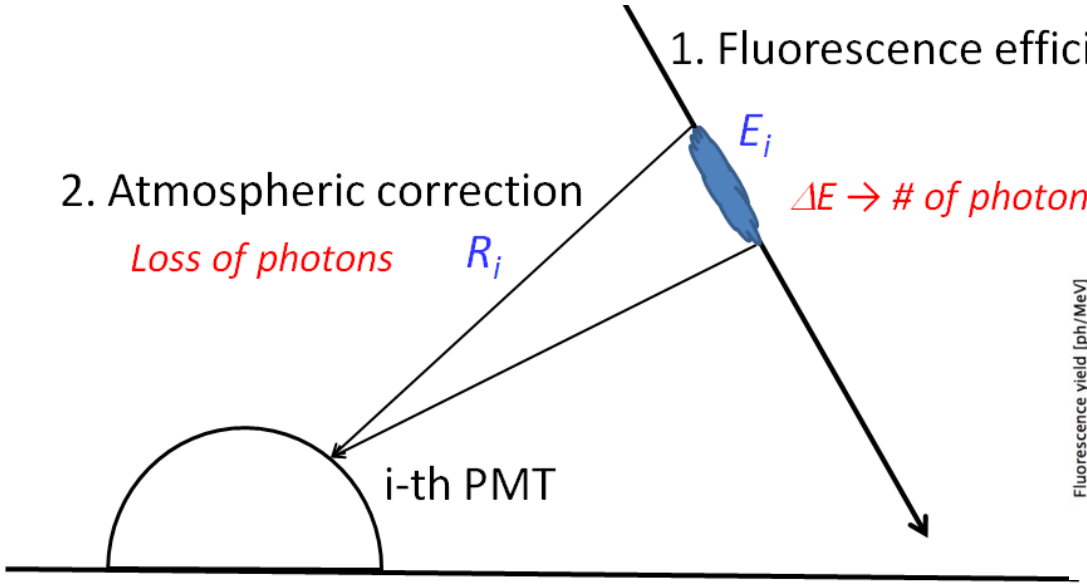
~1° FOV/PMT

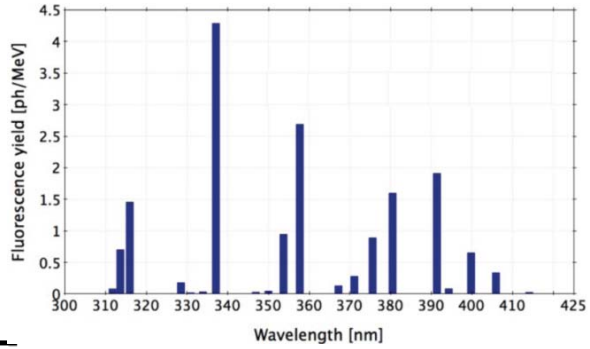
Signal digitizer



14 bit, 100 ns resolution
Record length: 51.2μs

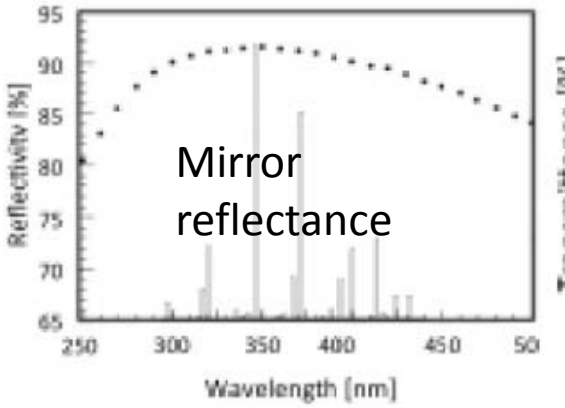
FD as an absorption calorimeter

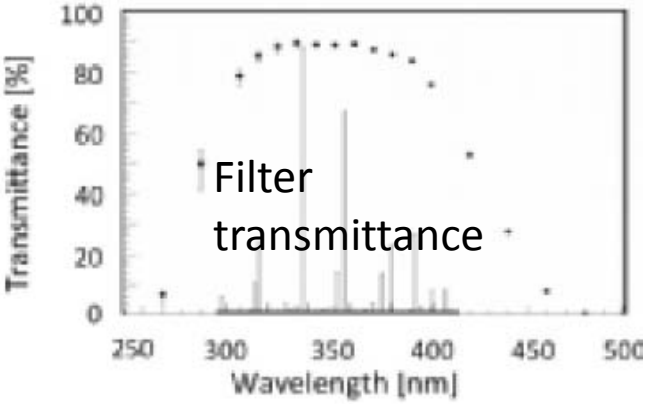


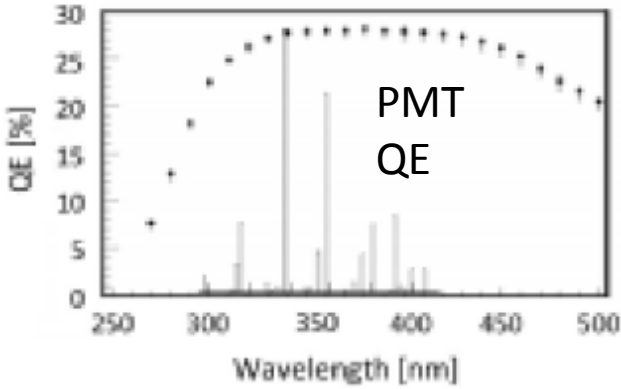


3. Telescope calibration

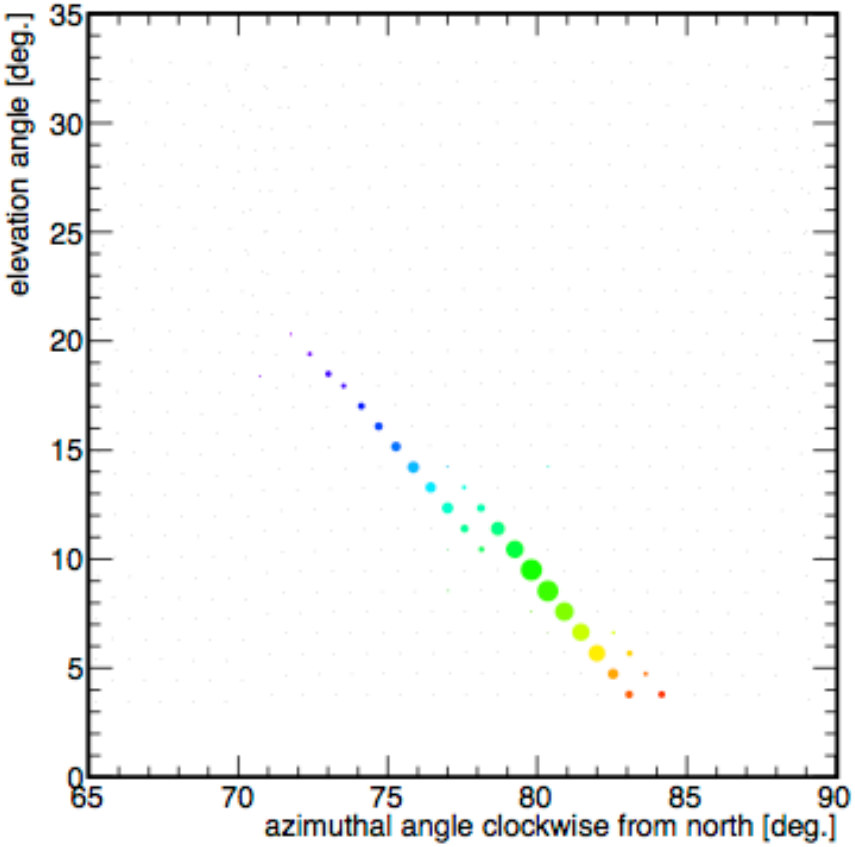
# of photons → ADC channels

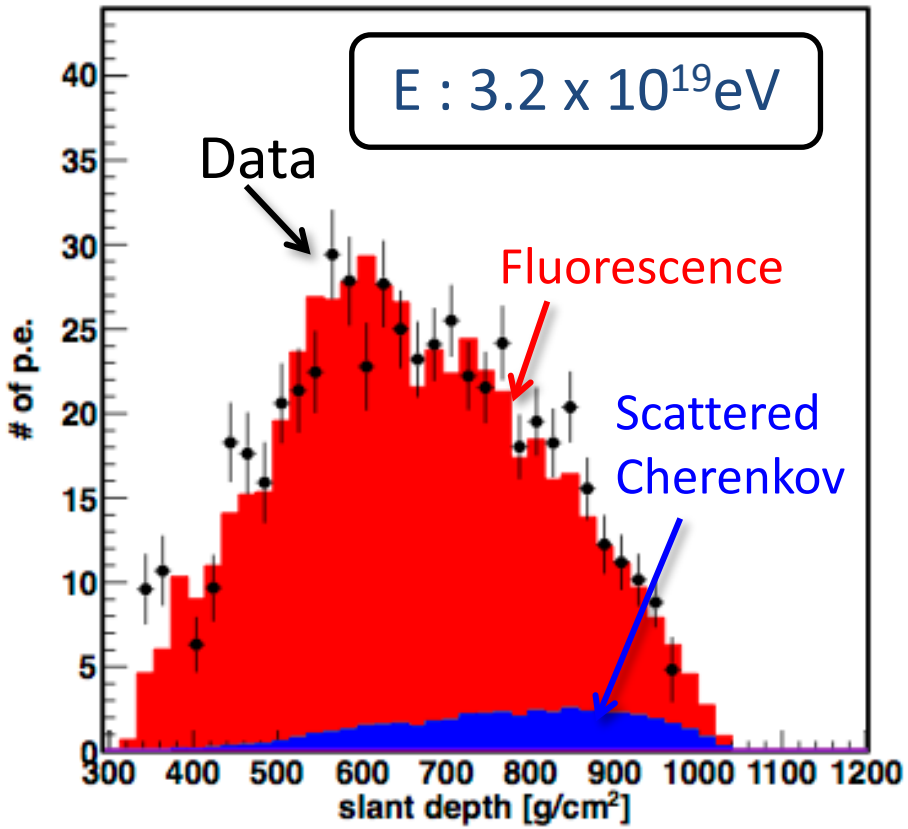






Example



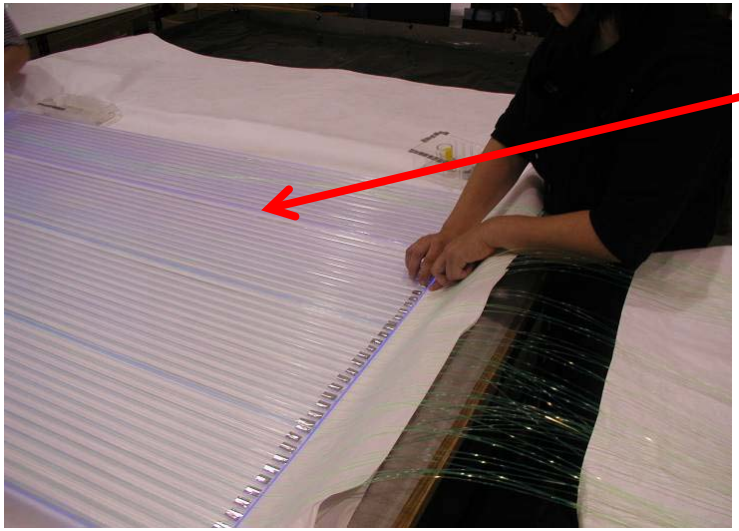


(hybrid events)

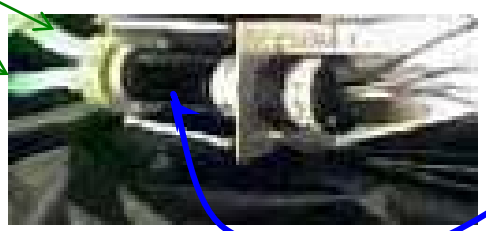
Energy resolution: 7%

Angular resolution: 0.9°

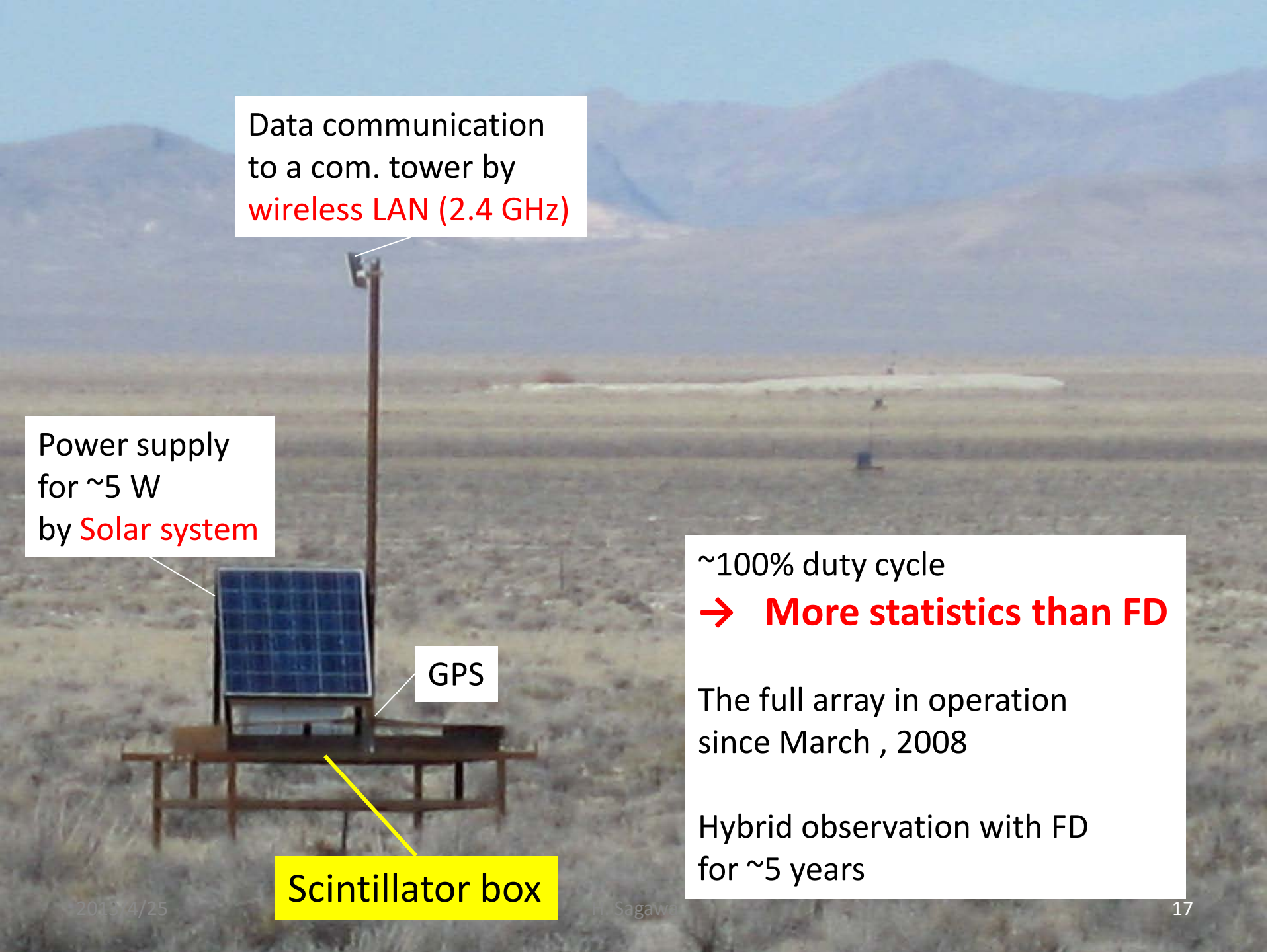
Surface Detector



WLS fibers



- 2 layers of plastic scintillator
  - 3 m^2 /layer
  - 1.2 cm thick/layer
- WLS fibers
  - 1 mm ϕ
  - ~100 fibers/layer
- 1 PMT for 1 layer
  - 1-inch ϕ
- 50 MHz FADC readout

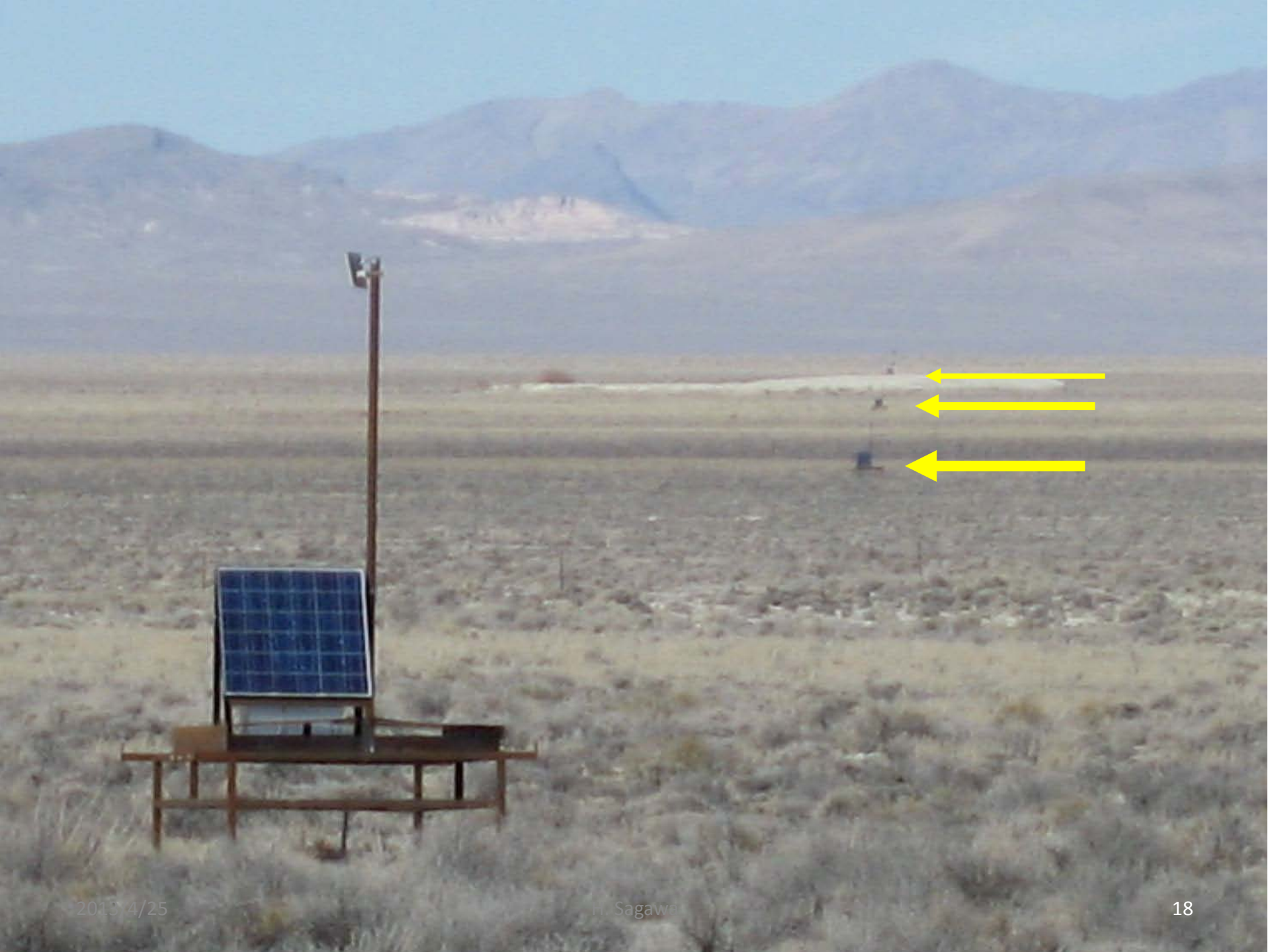


~100% duty cycle

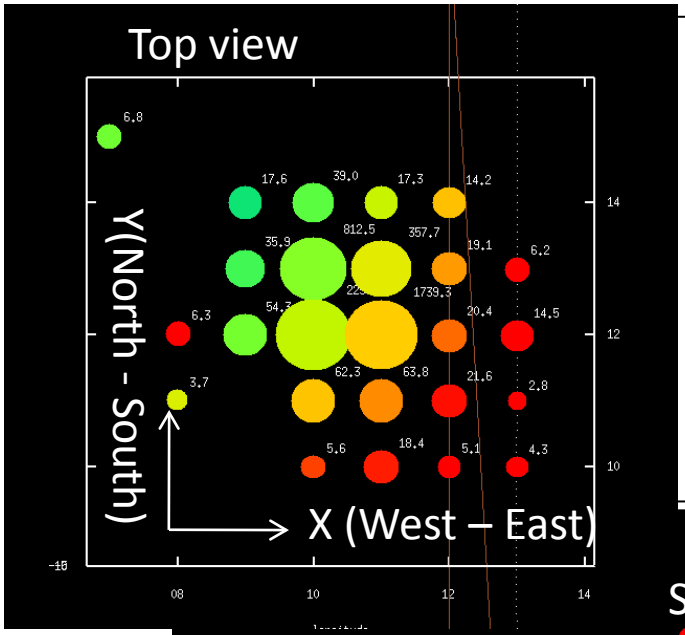
→ **More statistics than FD**

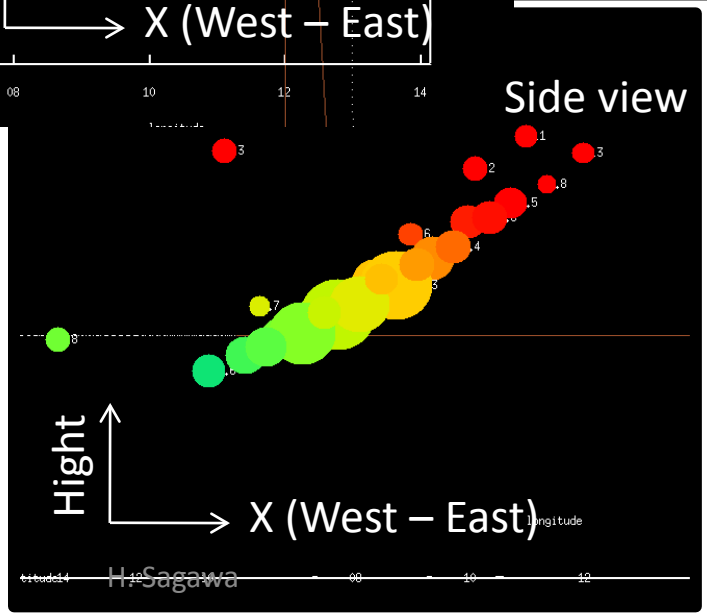
The full array in operation
since March , 2008

Hybrid observation with FD
for ~5 years



An example of an air shower observed with surface detectors



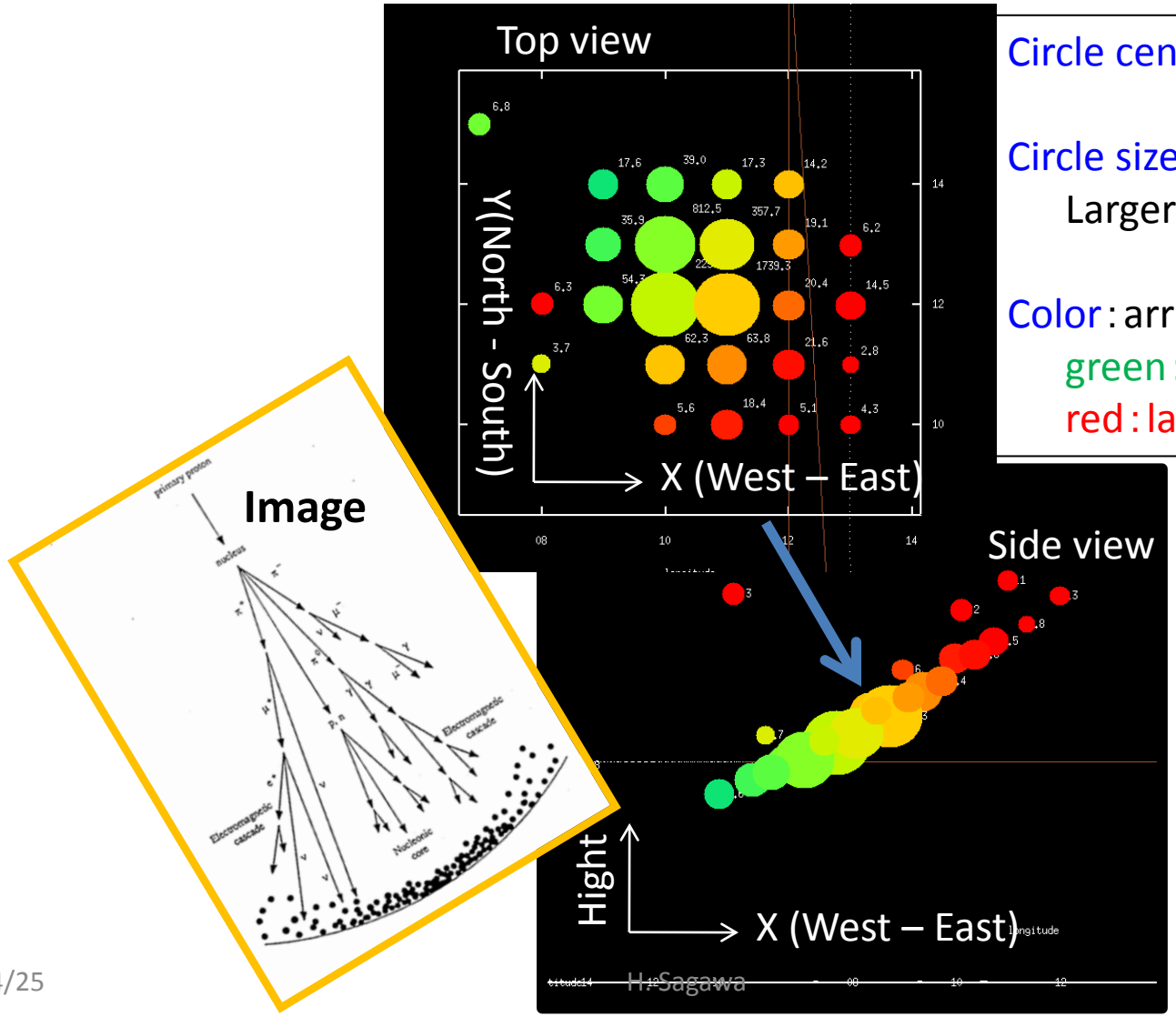


Circle center : SD position

Circle size :
Larger signal for larger size

Color : arrival time
green : early
red : late

An example of an air shower observed with surface detectors



Circle center : SD position

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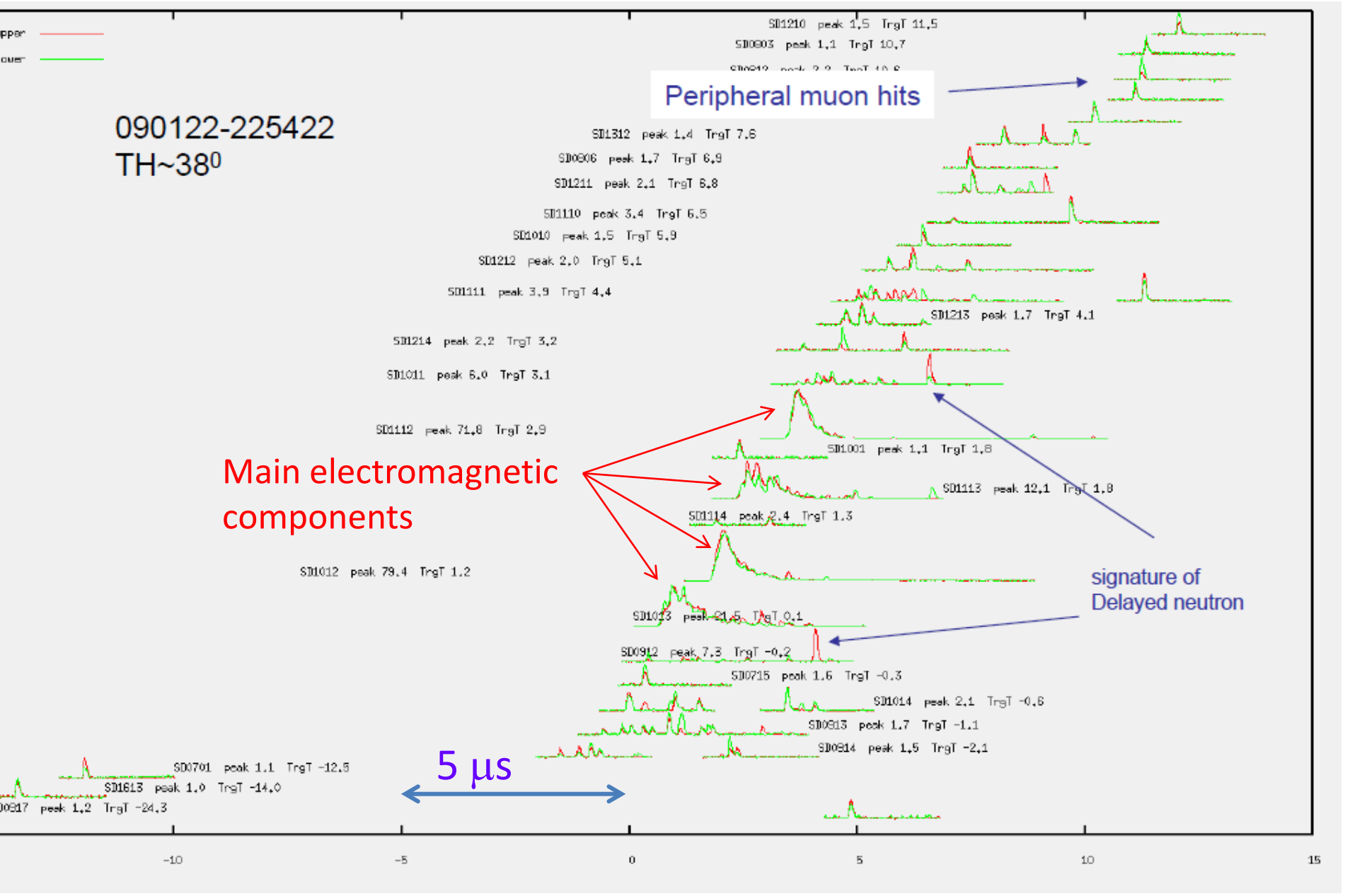
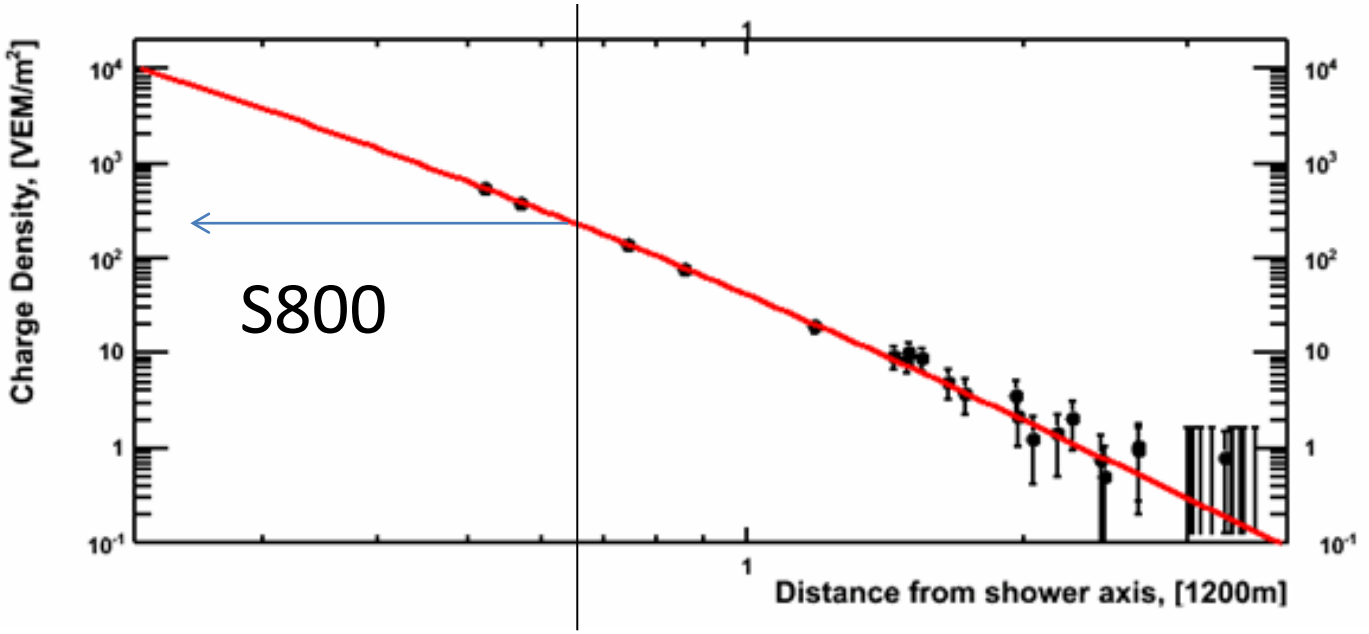

090122-225422
TH~38⁰
Peripheral muon hits
Main electromagnetic components
signature of Delayed neutron
5 μs
SD1210 peak 1.5 TrgT 11.5
SD0803 peak 1.1 TrgT 10.7
SD1312 peak 1.4 TrgT 7.6
SD0806 peak 1.7 TrgT 6.9
SD1211 peak 2.1 TrgT 6.8
SD1110 peak 3.4 TrgT 6.5
SD1010 peak 1.5 TrgT 5.9
SD1212 peak 2.0 TrgT 5.1
SD1111 peak 3.9 TrgT 4.4
SD1213 peak 1.7 TrgT 4.1
SD1214 peak 2.2 TrgT 3.2
SD1011 peak 6.0 TrgT 3.1
SD1112 peak 71.8 TrgT 2.9
SD1001 peak 1.1 TrgT 1.8
SD1113 peak 12.1 TrgT 1.8
SD1114 peak 2.4 TrgT 1.3
SD1012 peak 79.4 TrgT 1.2
SD1013 peak 21.5 TrgT 0.1
SD0912 peak 7.3 TrgT -0.2
SD0715 peak 1.6 TrgT -0.3
SD1014 peak 2.1 TrgT -0.6
SD0813 peak 1.7 TrgT -1.1
SD0914 peak 1.5 TrgT -2.1
SD0701 peak 1.1 TrgT -12.5
SD1613 peak 1.0 TrgT -14.0
-10
-5
0
5
10
15

SD Analysis: Lateral Density Fit

- **Fit with empirical LDF**
- **Charge density at 800 m (S800)**

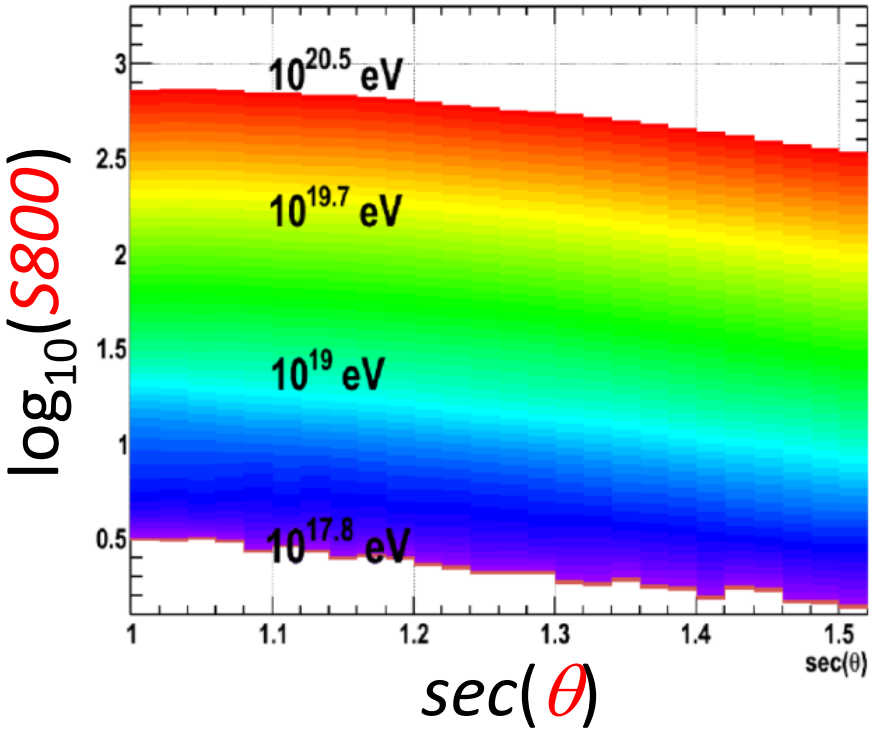


r = 800m

First estimation of SD energy

Monte Carlo → Energy table

$E'_{SD} = E'_{SD}(S800, \theta)$



SD energy resolution
20% ($E > 10^{19}$ eV)

SD energy scale

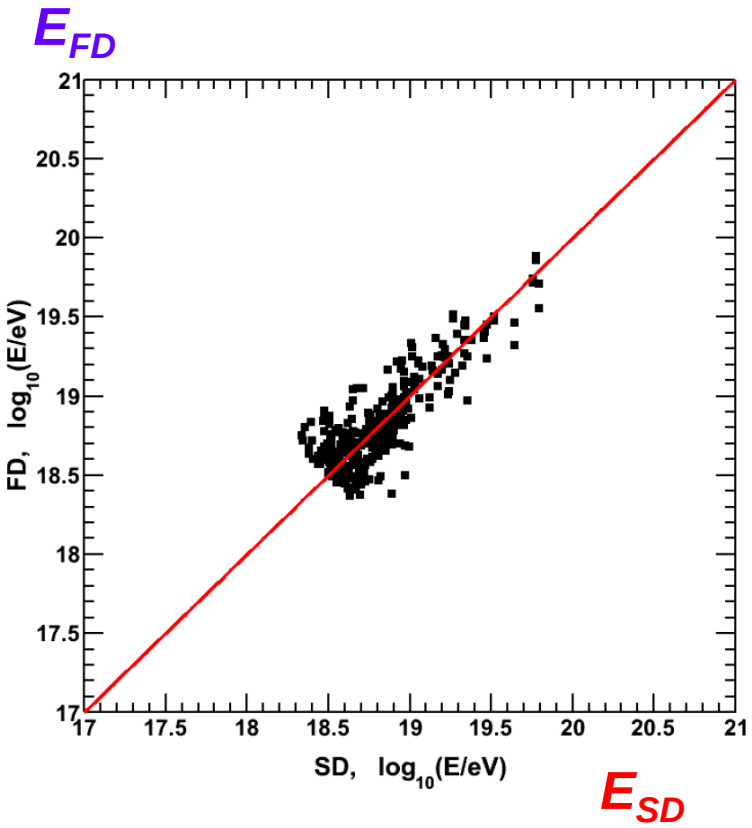
- For hybrid events
  - E'_{SD}: energy table from MC

$$\left\langle \frac{E'_{SD}}{E_{FD}} \right\rangle_{hyb} = 1.27$$

- Rescale SD energy

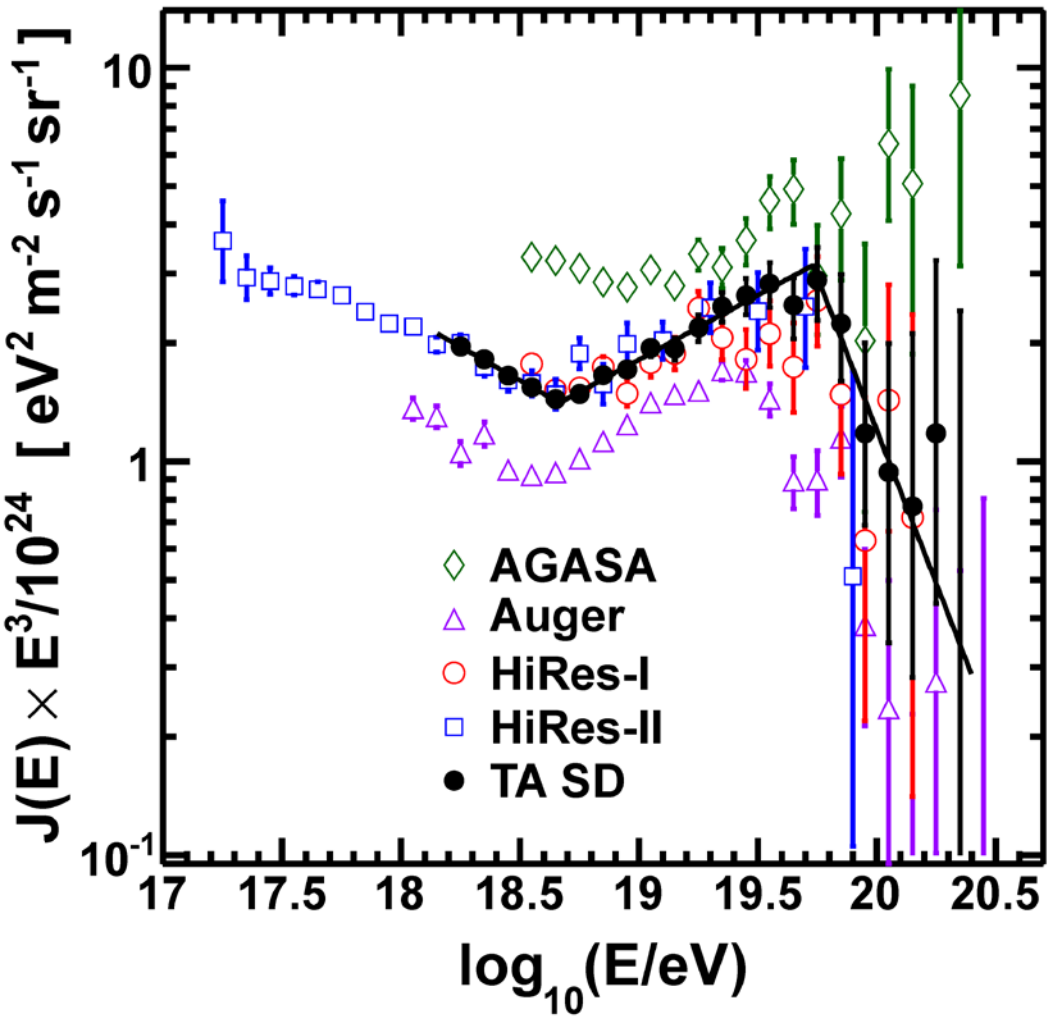
$$E_{SD} = \frac{1}{\left\langle \frac{E'_{SD}}{E_{FD}} \right\rangle_{hyb}} E'_{SD} = \frac{1}{1.27} E'_{SD}$$

FD	Energy uncertainty
Calibration	10%
Fluorescence yield	11%
Atmosphere	11%
reconstruction	10%
Total	21%

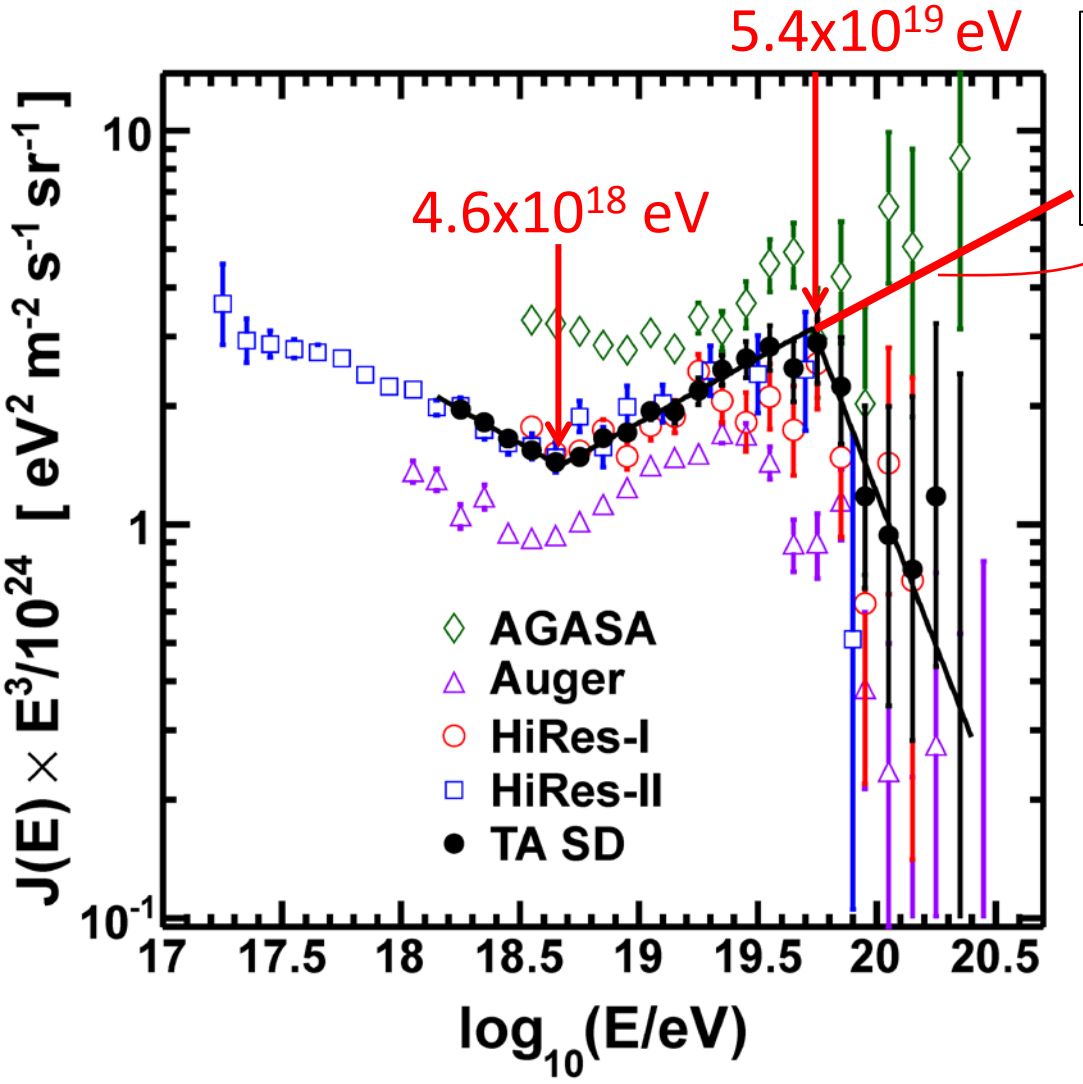


(rescaled SD energy)

Energy spectrum



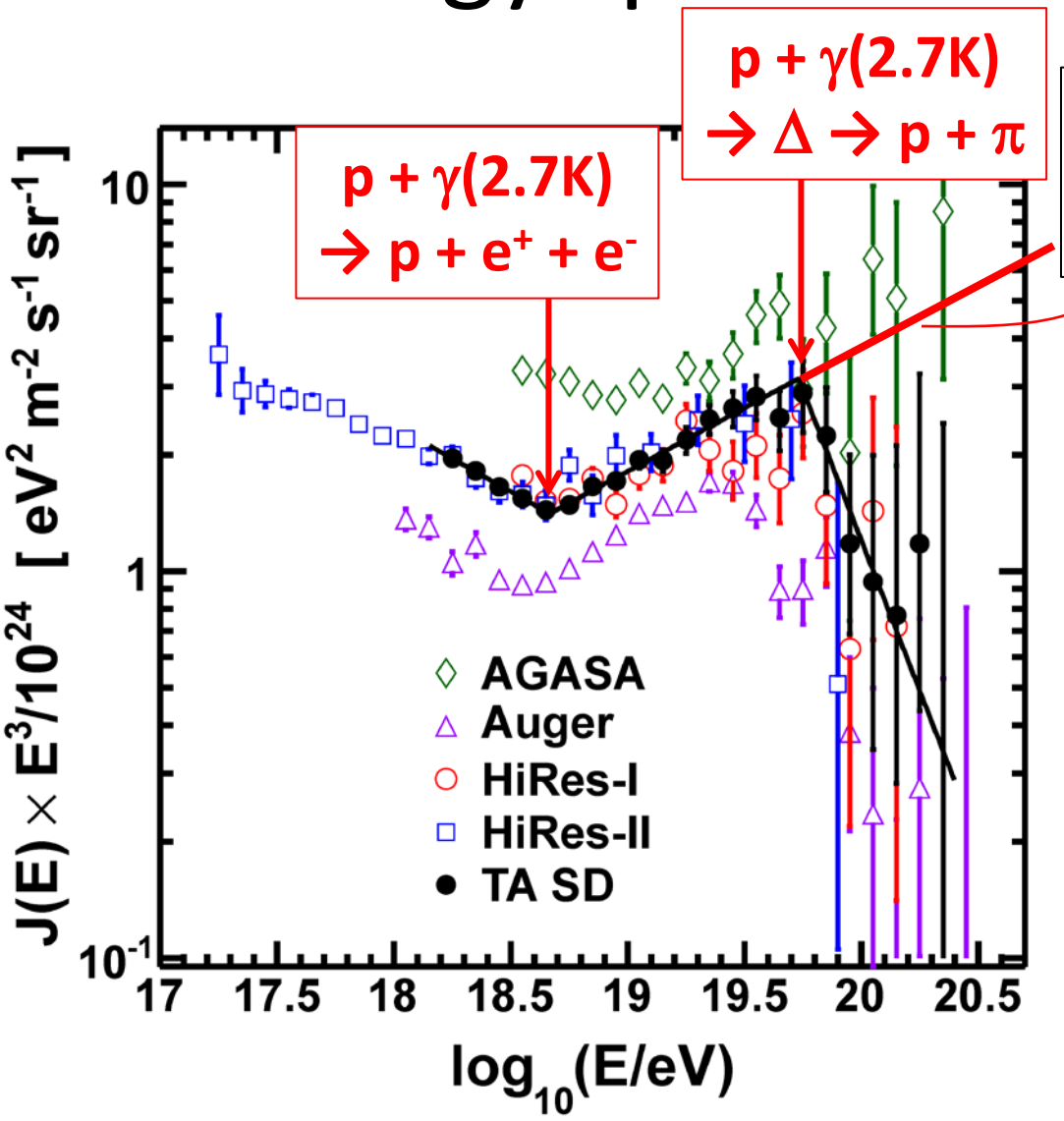
Energy spectrum



Above 5.4×10^{19} eV
21 events observed
58.6 events

Significance of Suppression
5.5 sigma

Energy spectrum



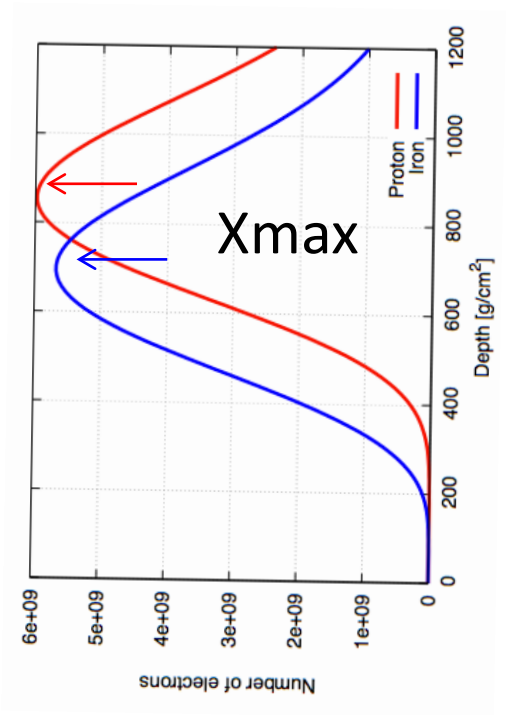
Above 5.4×10^{19} eV
21 events observed
58.6 events

Significance of Suppression
5.5 sigma

Consistent with GZK suppression

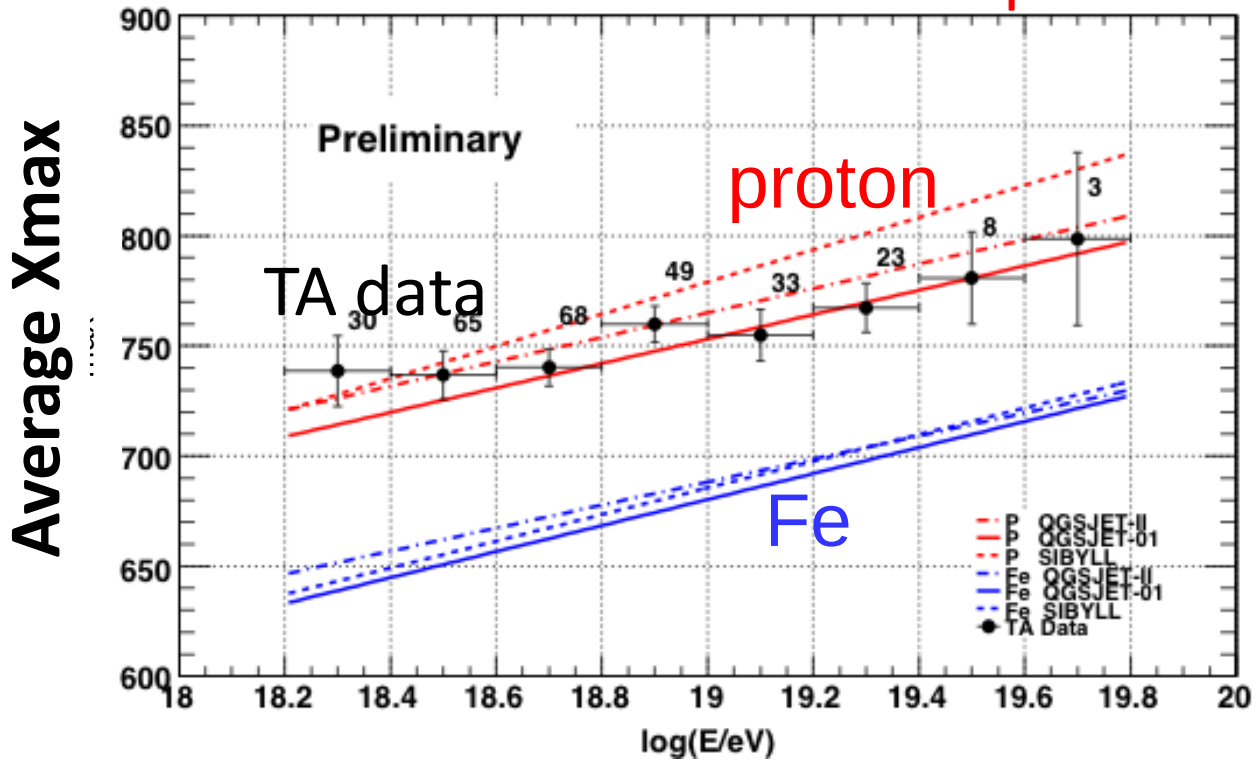
Mass composition

Longitudinal shower profile



deep

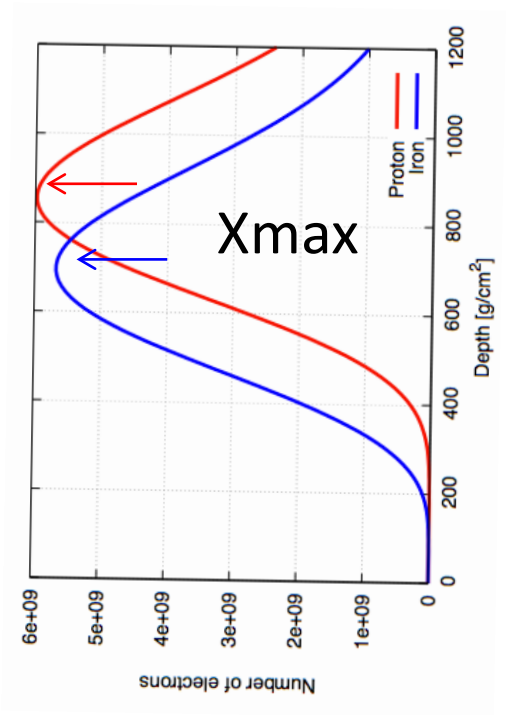
TA data: consistent with proton



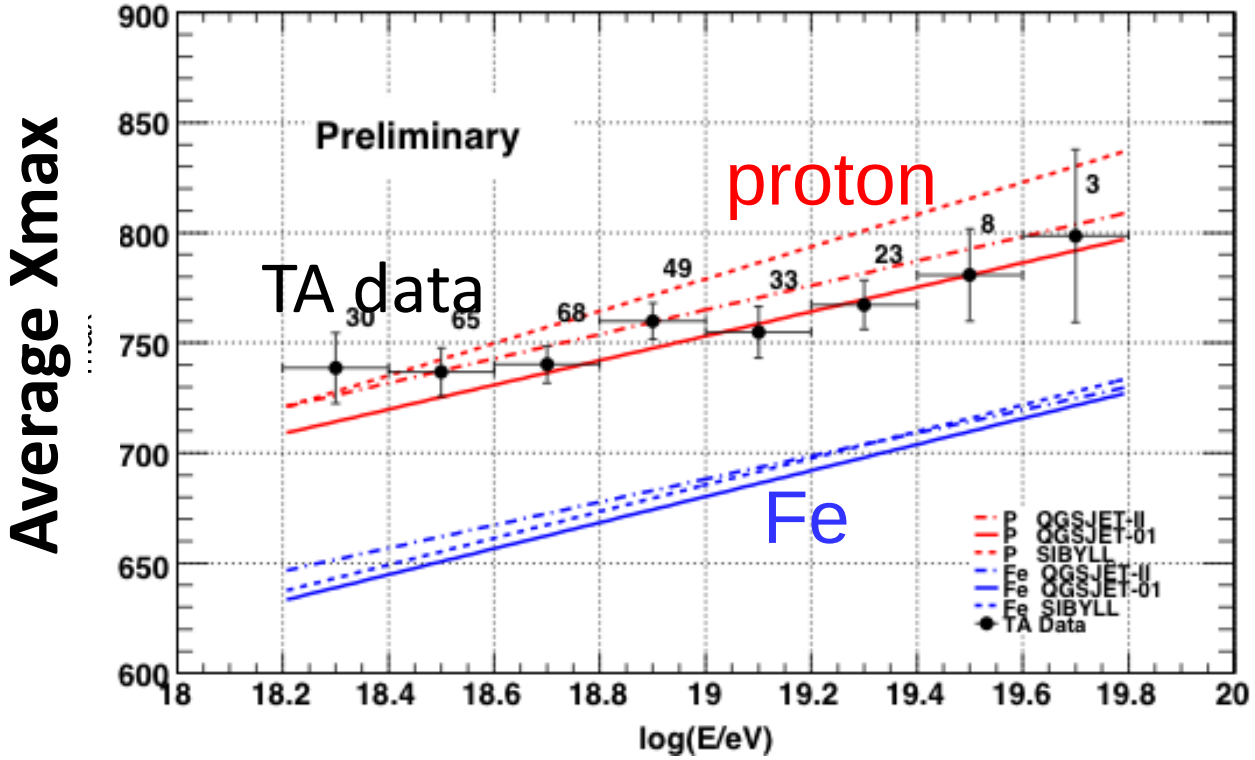
shallow

Mass composition

Longitudinal shower profile



deep

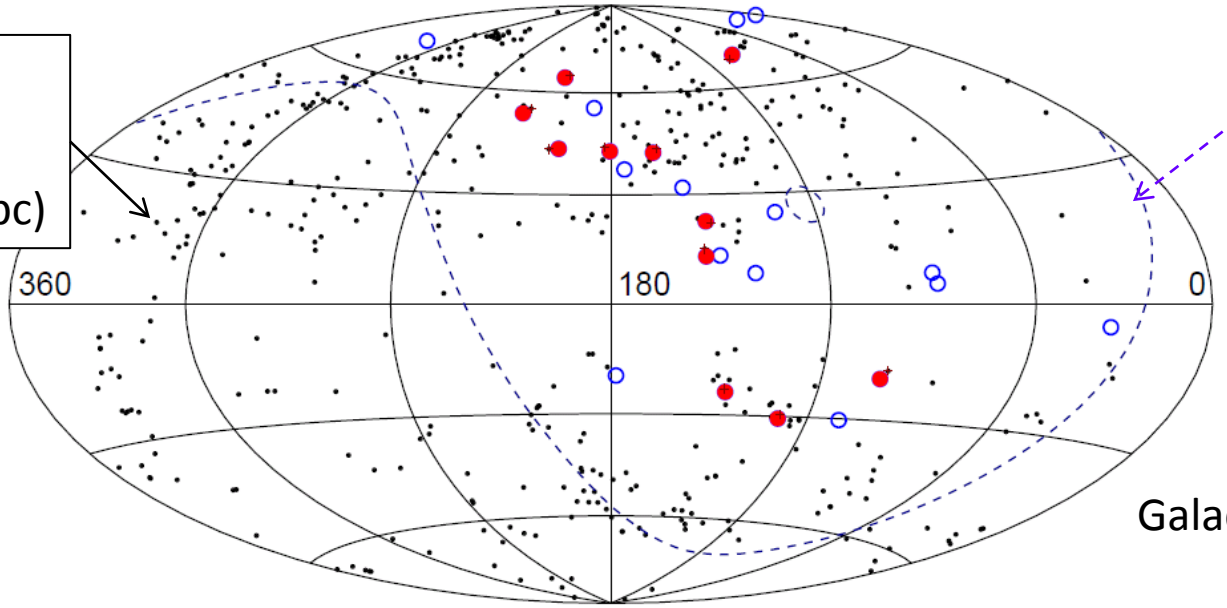


shallow

Atmosphere : superb calorimeter for highest energy CRs!

Correlations with AGNs

AGN (·)
VCV catalog
z<0.018 (75 Mpc)



TA FOV

Galactic center

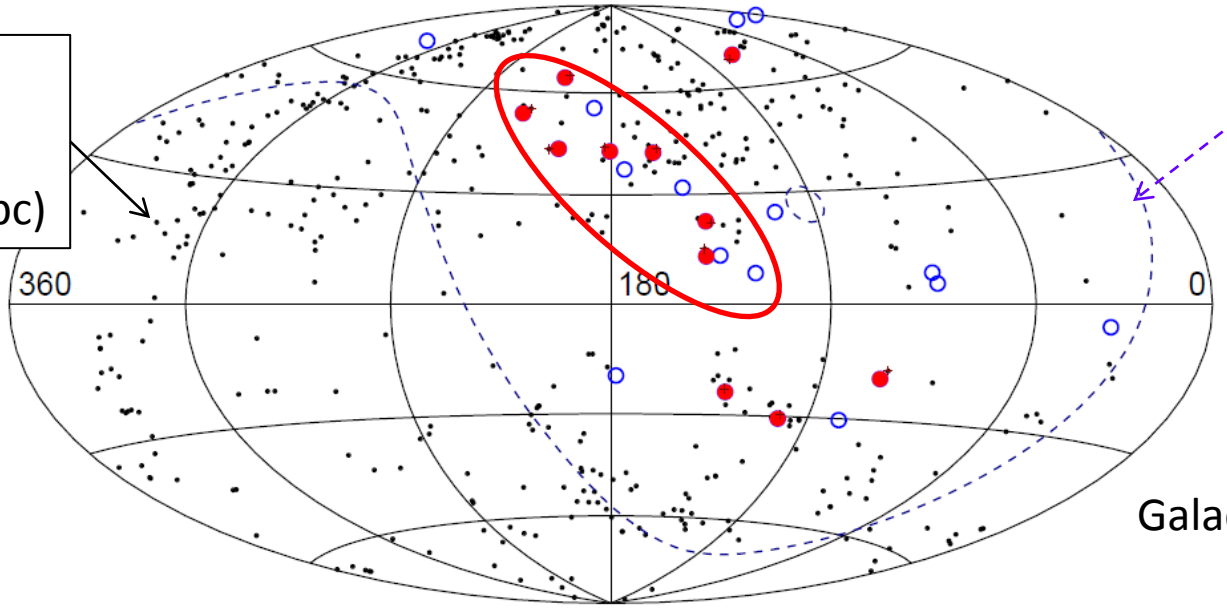
Galactic coordinates

TA SD 25 events (E > 5.7×10^{19} eV) (● + ○)
11 events within 3.1° (●)

Isotropy model expectation: 5.9 events
- Chance probability to observe 11 events: 2%

Correlations with AGNs

AGN (·)
VCV catalog
z<0.018 (75 Mpc)



TA FOV

Galactic center

Galactic coordinates

TA SD 25 events (E > 5.7×10^{19} eV) (● + ○)
11 events within 3.1° (●)

Hint of anisotropy?

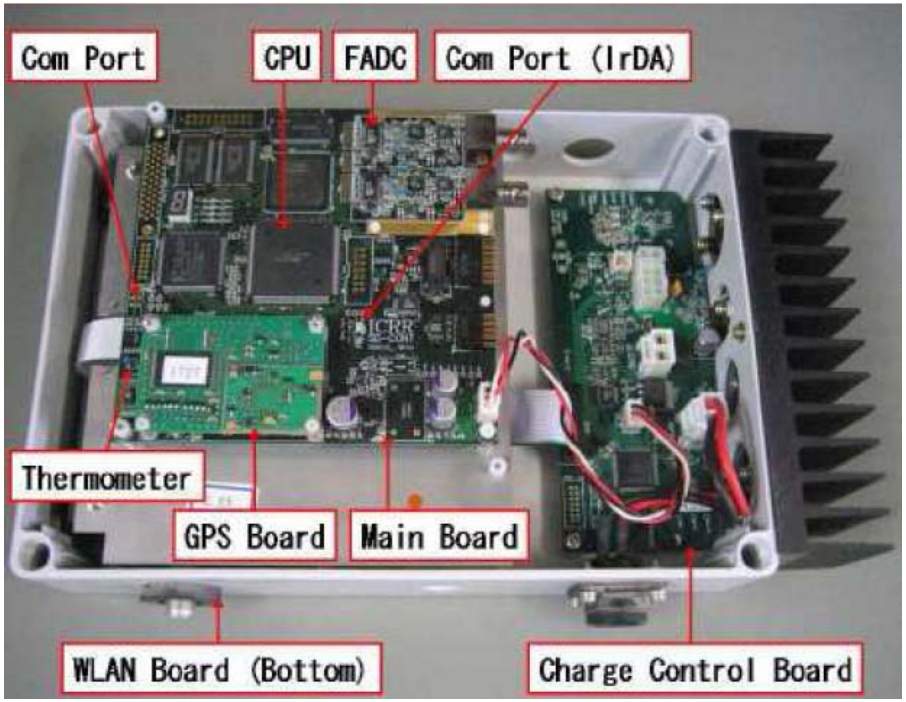
Isotropy model expectation: 5.9 events
- Chance probability to observe 11 events: 2%

Summary

- TA: the largest CR detector in the northern hemisphere
- The SDs and FDs: operating stably for ~5 years
- Measured energy spectrum, Xmax and arrival directions of UHECRs
  - Consistent with proton model with GZK suppression

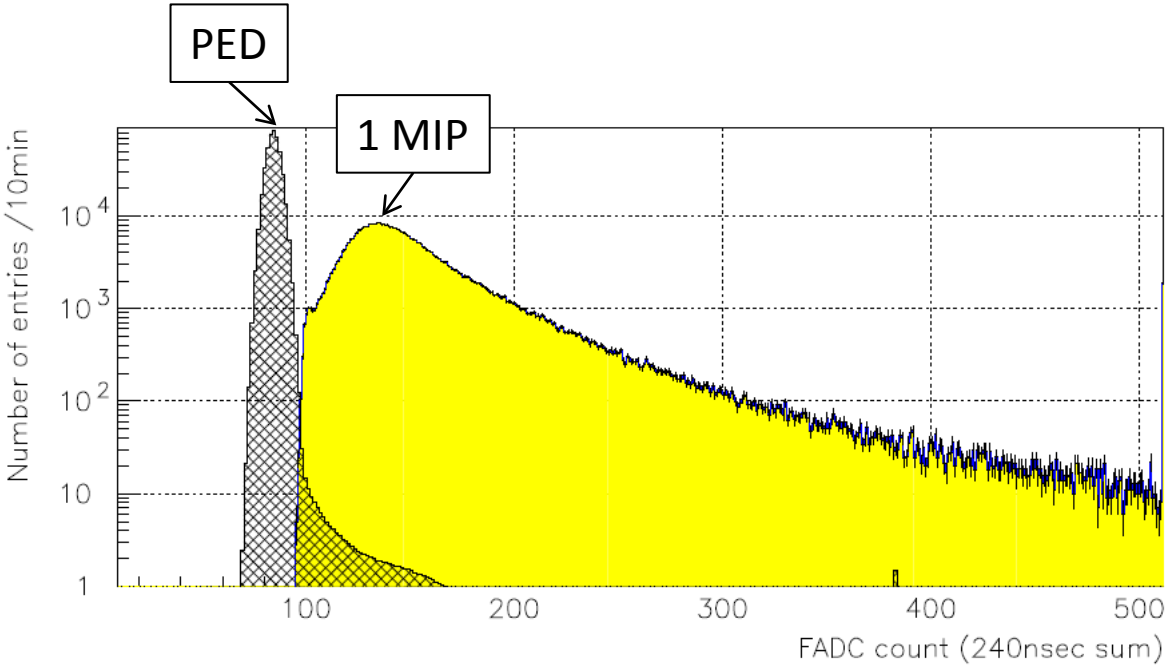
backup

Electronics



- Main board
  - FADC
    - 20 MHz sampling
    - 12 bit
- Charge controller
- WLAN modem
  - Under main board

Calibration

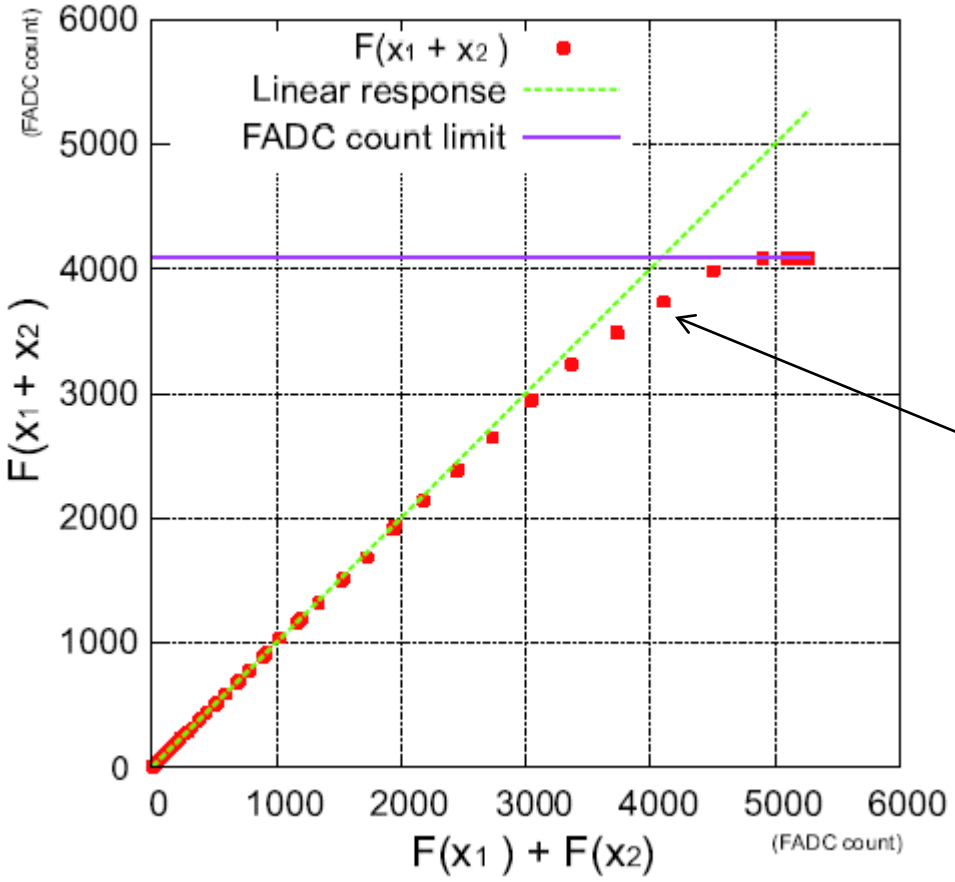


- Background monitor
  - Each distribution update per 10 min.
  - Temperature coefficient of gain: ~ -0.8%/^{o}C
  - Temperature meas. per 1 min.

Trigger rate

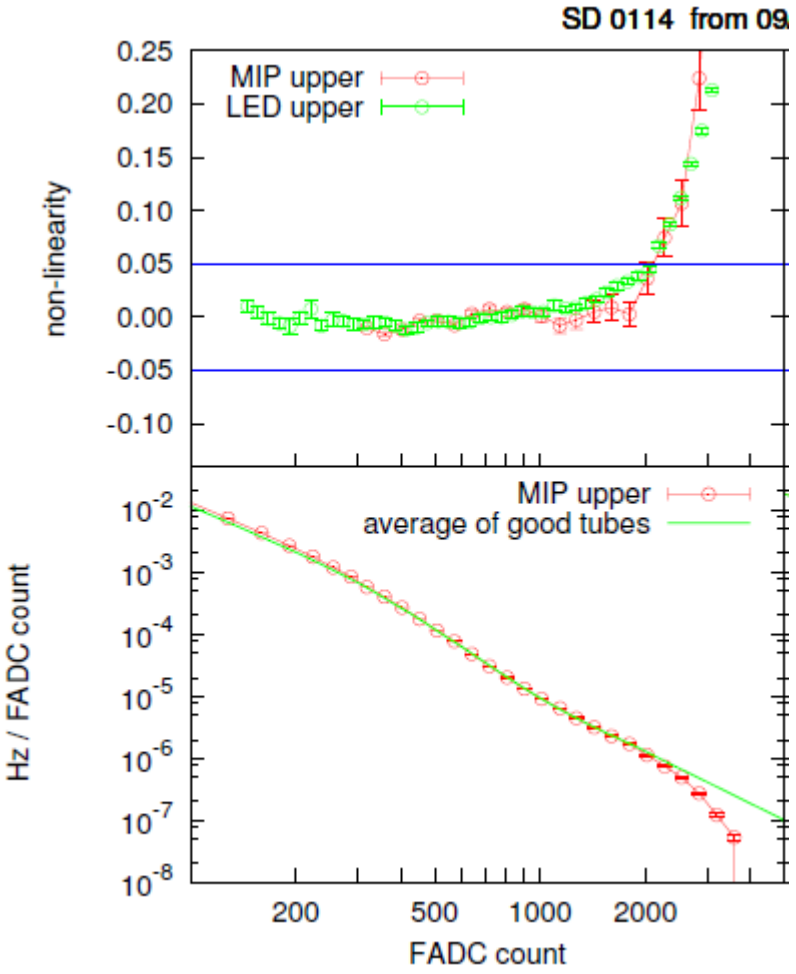
- Level-0 trigger (>0.3 MIPs): ~700 Hz
- Level-1 trigger (>3 MIPs): ~20 Hz
- Level-2 trigger (shower trigger): ~600/day
  - >3 MIPs
  - neighboring 3 detectors
  - <8 μsec window

Linearity measurement by LED



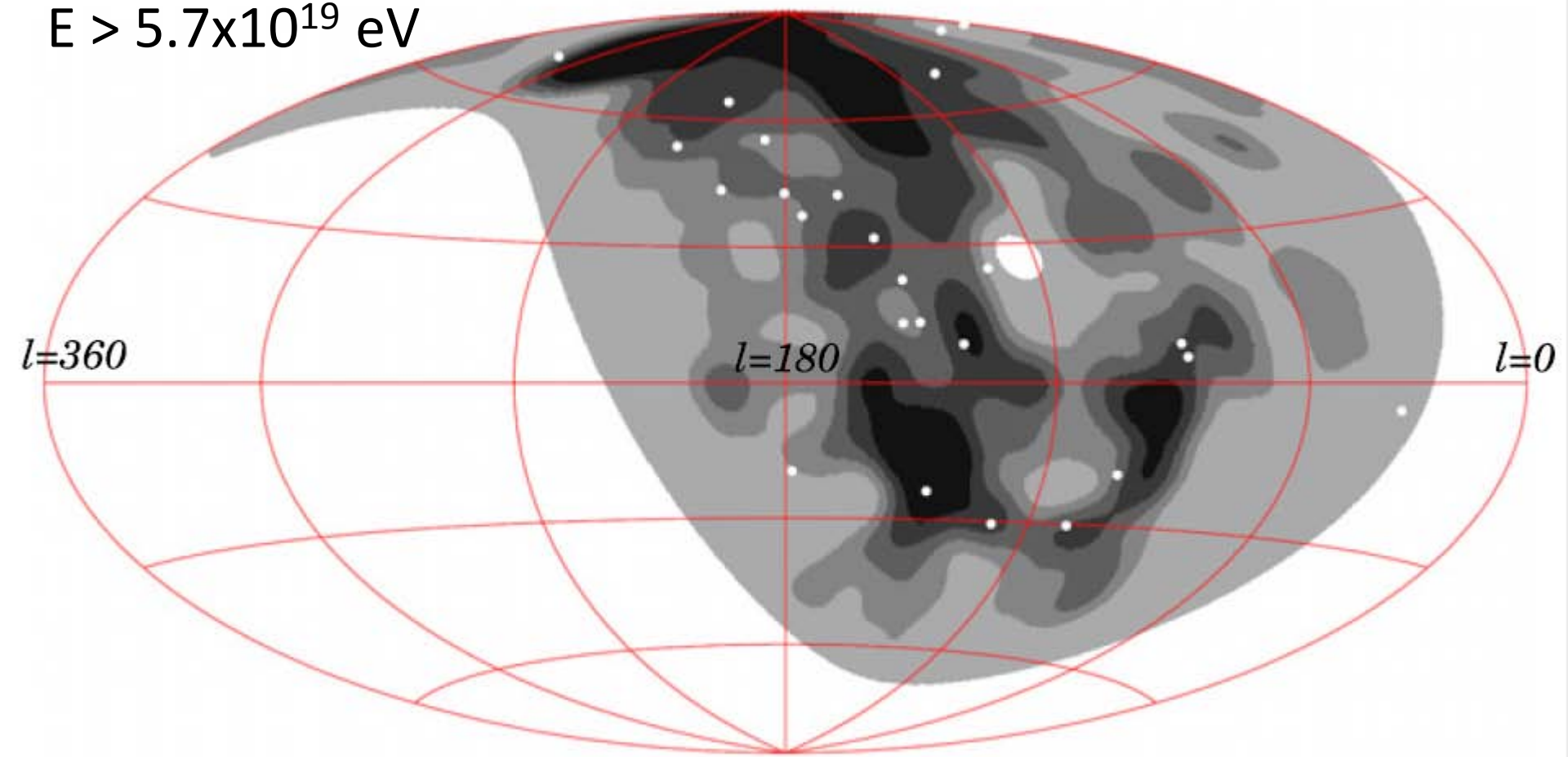
- 2 LEDs per layer
  - $F(x_1)$: only LED1 is ON
  - $F(x_2)$: only LED2 is ON
  - $F(x_1+x_2)$: both LED1 and LED2 are ON
- This case
  - We know $F(x_1)$ and $F(x_2)$ are not saturated
  - But $F(x_1+x_2)$ is saturated.

Linearity measurement by data



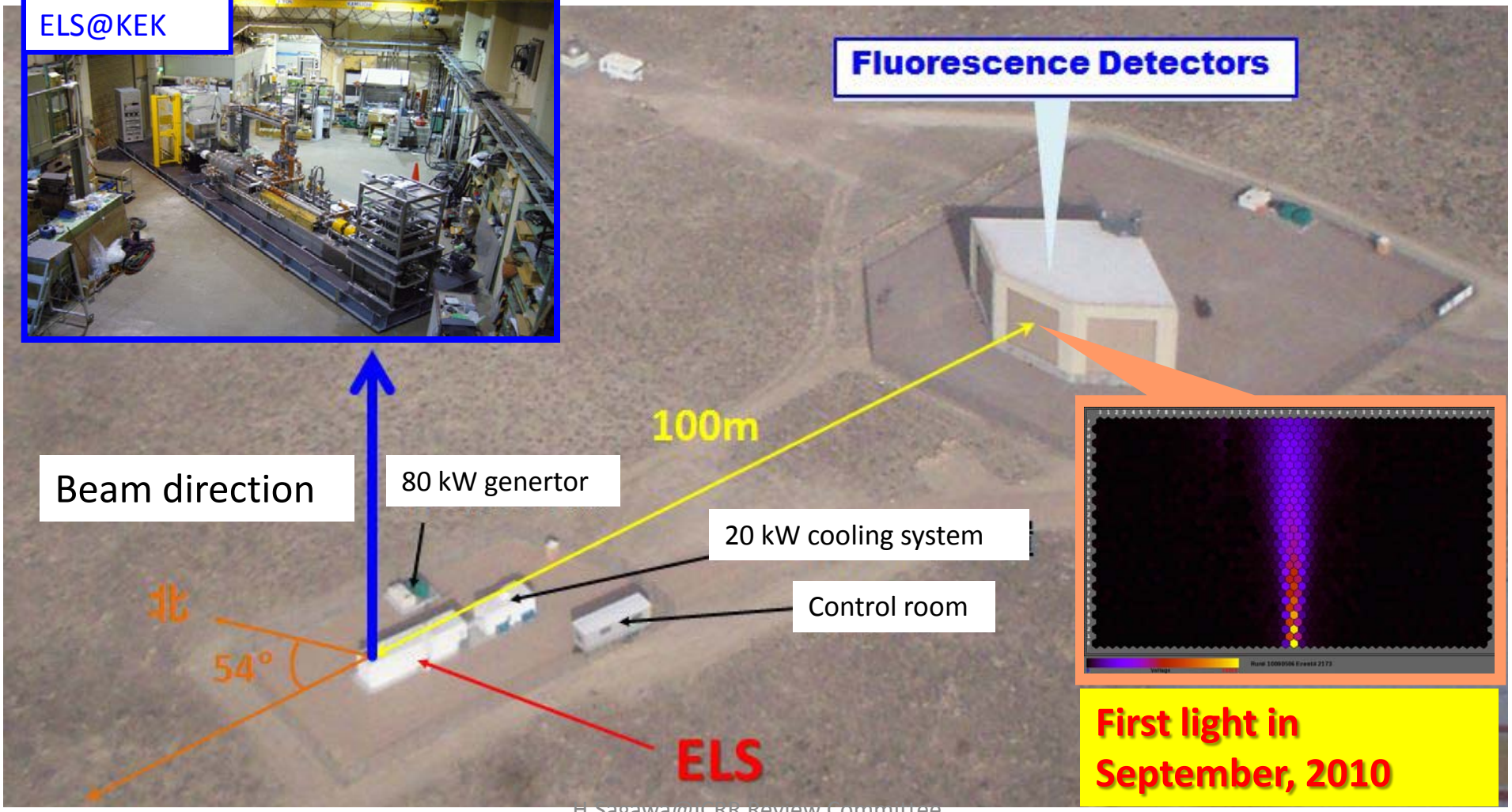
Arrival directions

Correlations with Large Scale structure (LSS)



Electron Light Source (ELS)

Source of electron beam = end-to-end energy calibration of FD



Output power=40 MeV×10^9e-/pulse×0.1-0.5 Hz, pulse width: 1μsec