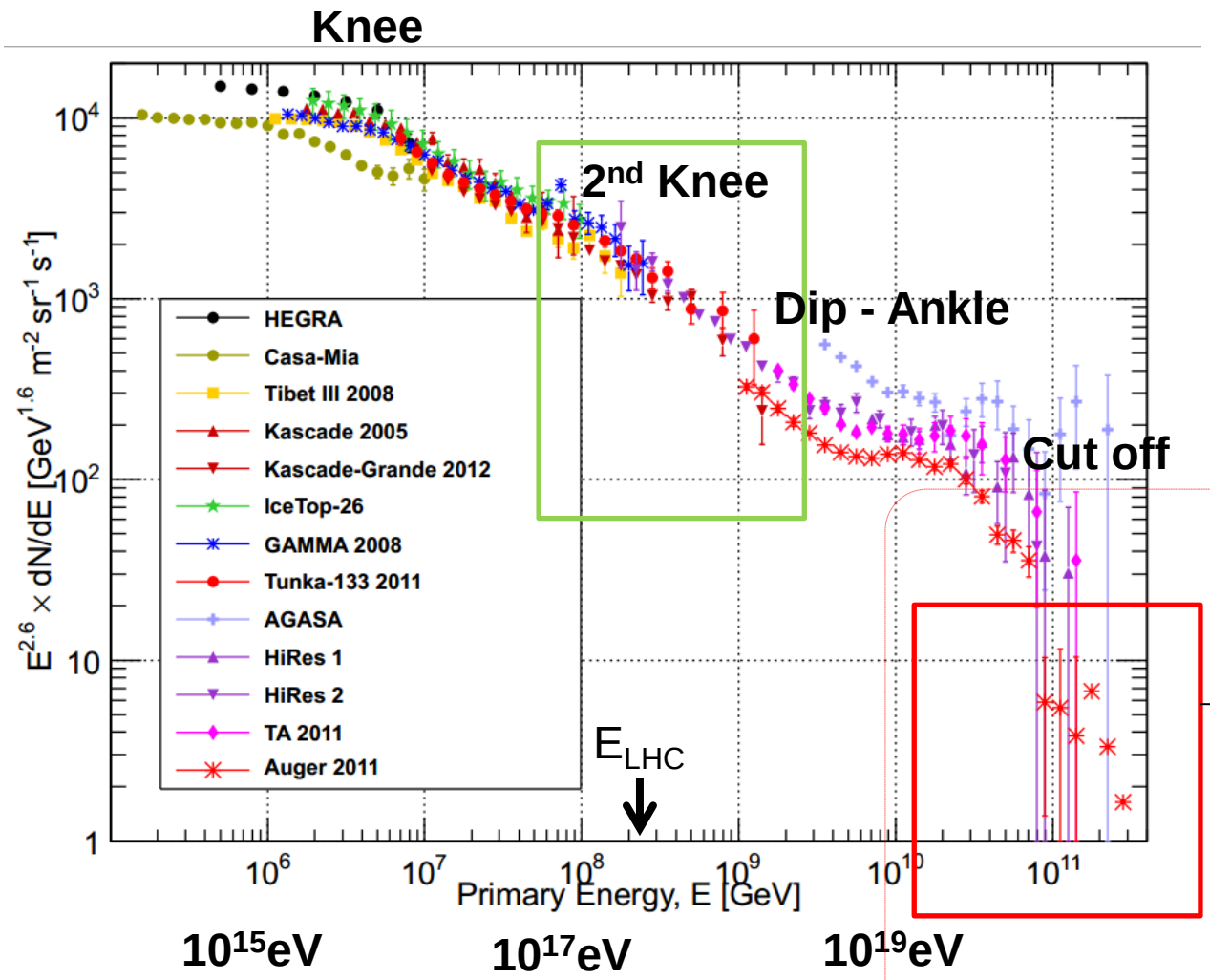
最高エネルギー宇宙線による極限宇宙観測

（研究会　高エネルギーガンマ線で見る極限宇宙2014）

野中敏幸
東京大学宇宙線研究所
Telescope Array Collaboration

Highest energy cosmic ray observation

Cosmic ray energy spectrum 10^{15}eV – 10^{20}eV



Spectrum index
Composition change

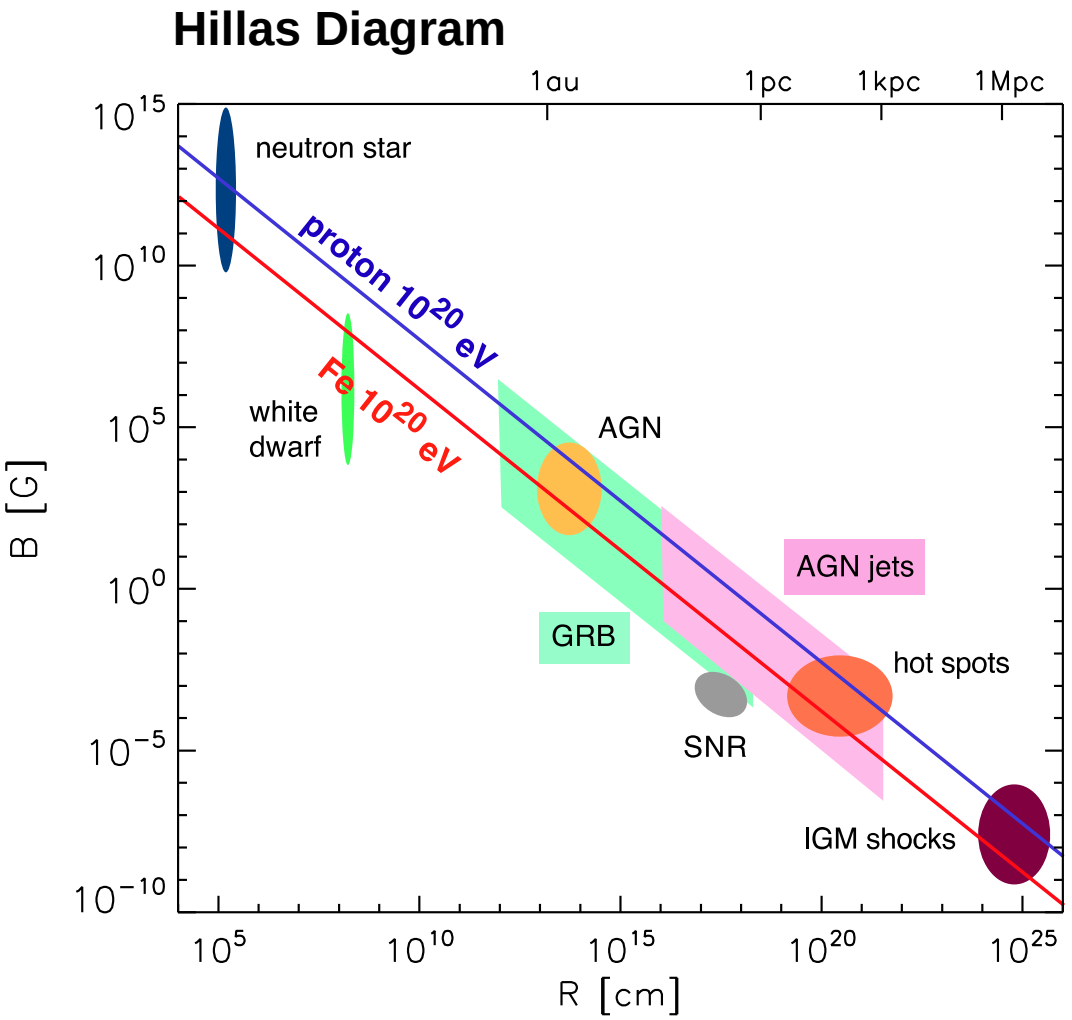
Source transition from galactic - extragalactic

Highest energy 10^{19}eV~

1event /km^2・year

extragalactic origin. (larmor radius)

Candidate of source



Kotera & Olinto, Ann. Rev. Astron. Astrophys (2010)

Hillas condition.
E∝ BxL

Necessary condition from cosmic ray energy

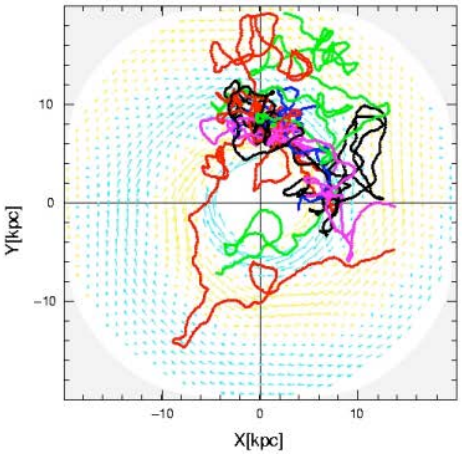
several types of objects remain as source “candidate”.

How to infer the source..

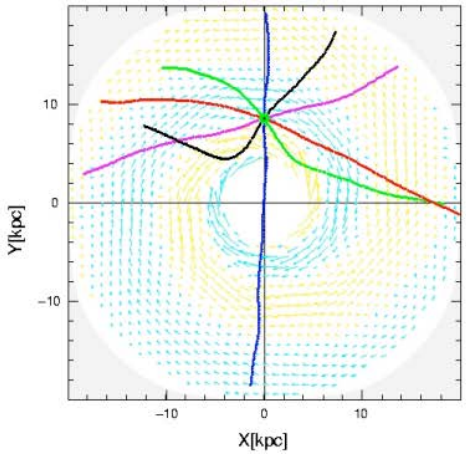
Direction (anisotropy)
Spectrum
Composition
…

Anisotropy

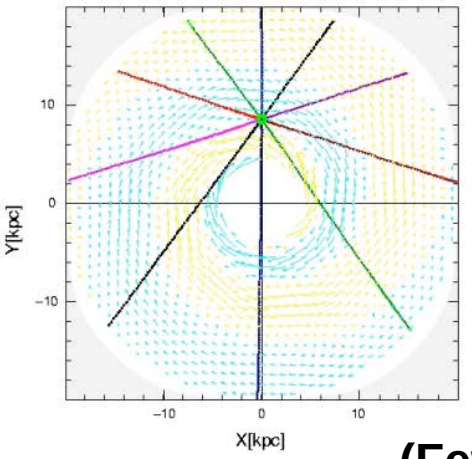
◇ **Trajectory of cosmic ray in galactic magnetic field.**



10^{18}eV



10^{19}eV



10^{20}eV

(Few degree)

Using arrival direction, it is possible to search correlation with Source position

Inter galactic magnetic field:

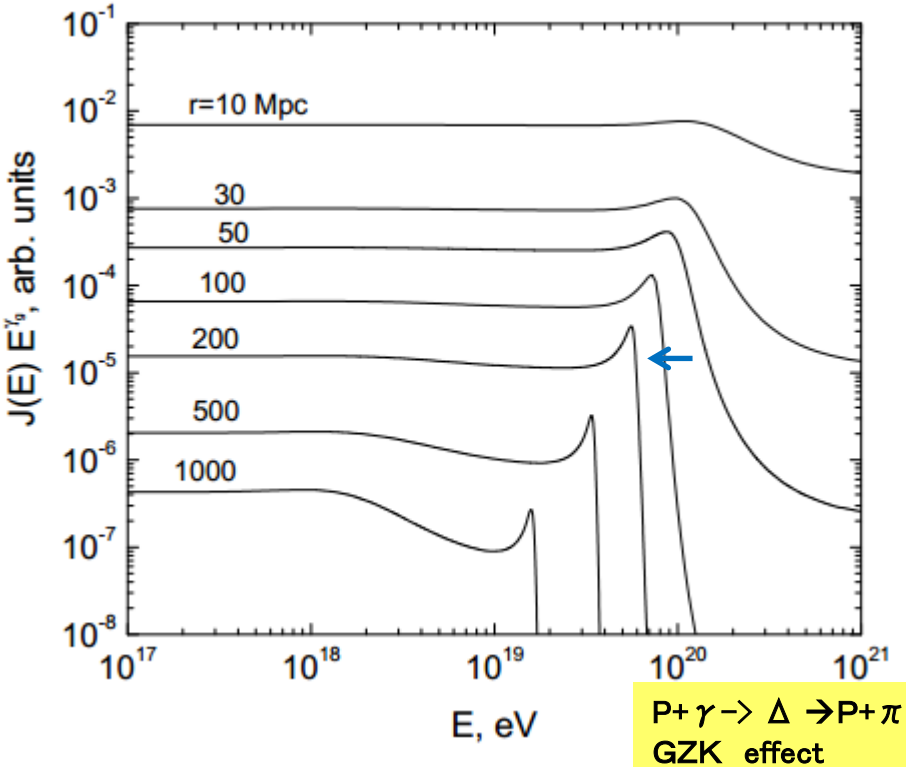
generally random field. B < ~10^{-9}G

$$\theta(E,d) \simeq \frac{(2dl_c/9)^{1/2}}{r_g} \simeq 0.8^{\circ}\, q \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{d}{10\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{l_c}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,\mathrm{G}}\right)$$

Few degree

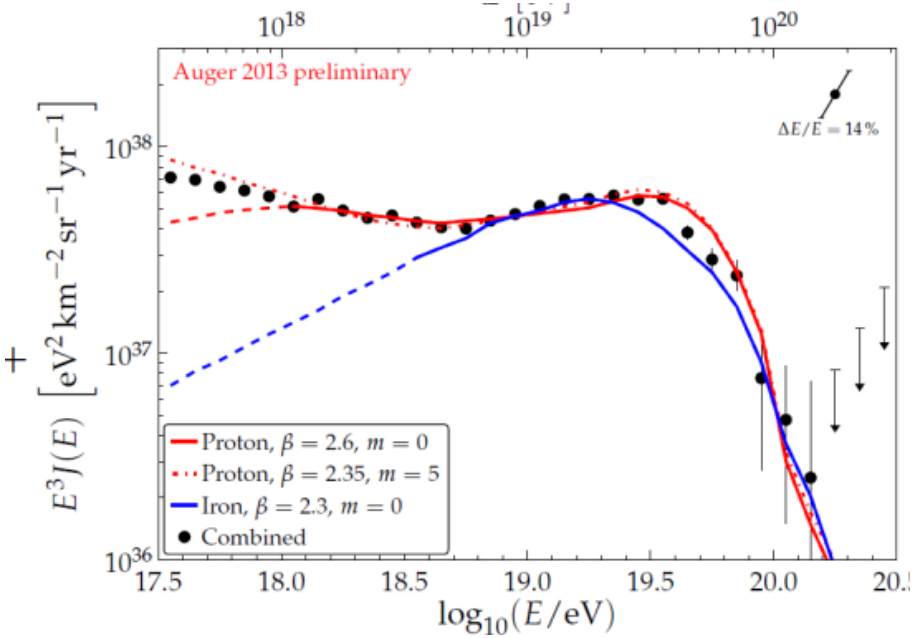
Spectrum

Spectrum modulation from single source



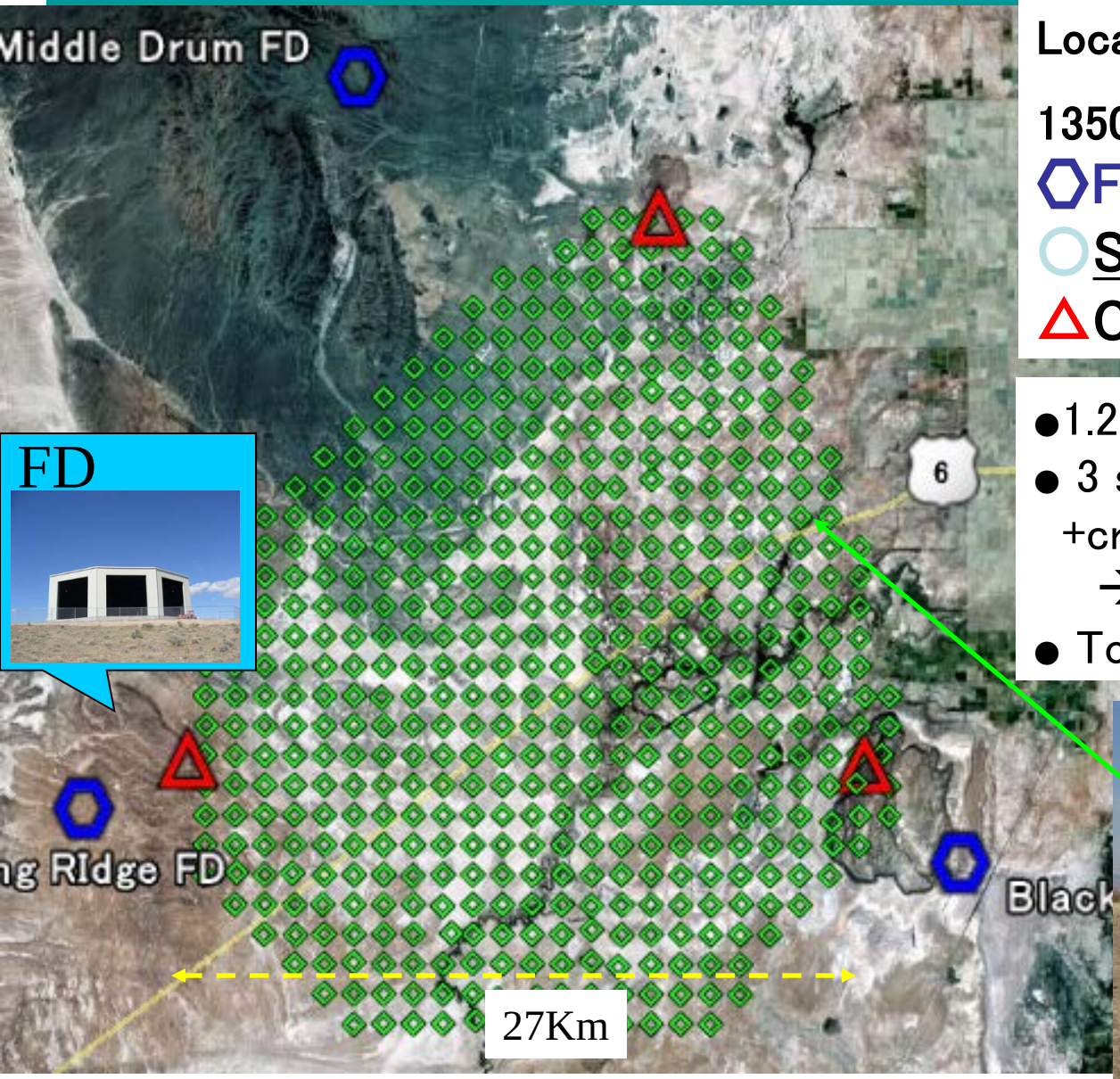
P+ γ -> Δ →P+ π
GZK effect

V.Berezinsky et.al Phys. Rev. D 74, 043005 (2006)



TA experiment , Observation results

Telescope Array Experiment



Location: N39.3° W112.9°

1350–1500m asl

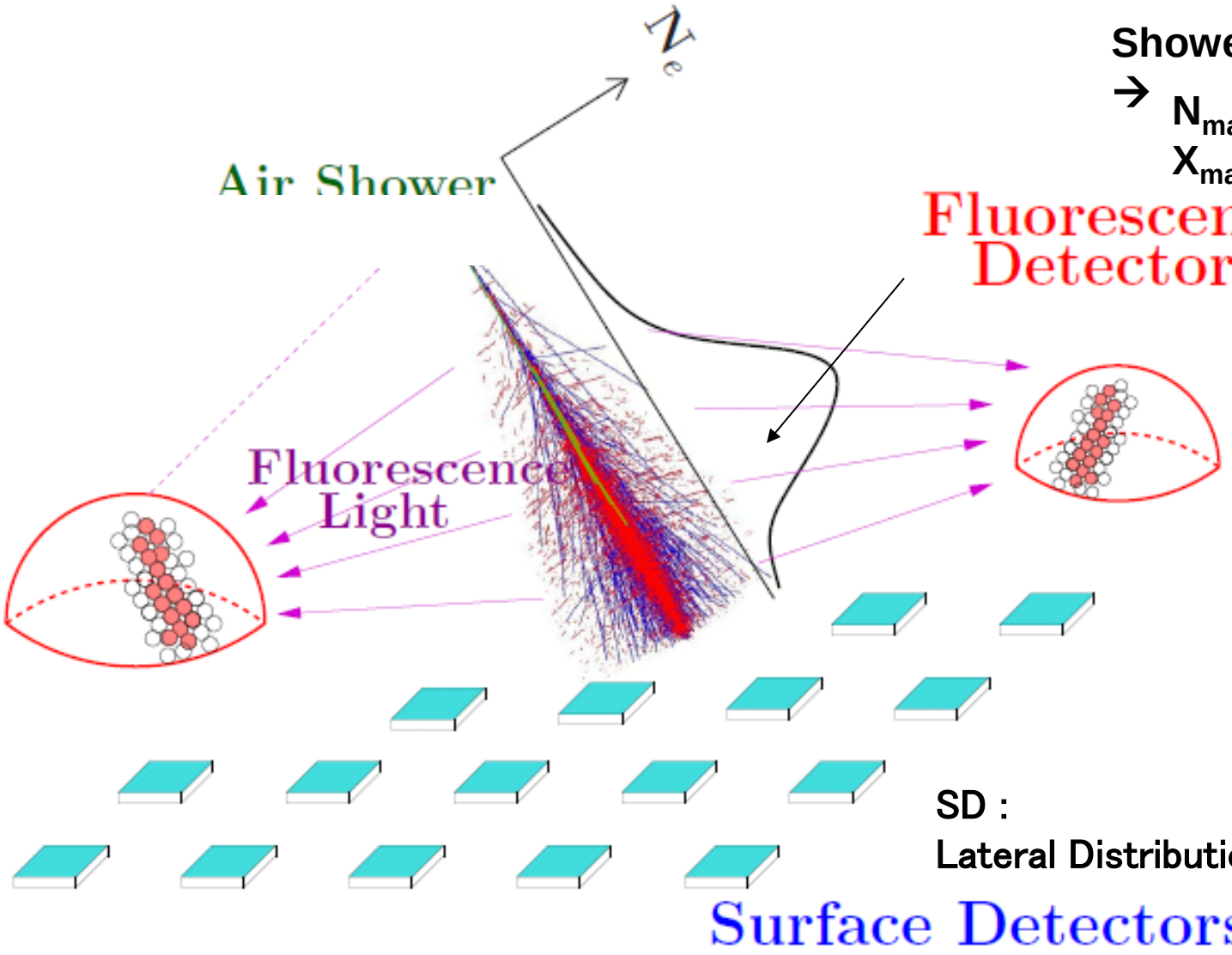
⬡FD station (× 3station)

○Surface Array (507 SD)

△Communication tower

- 1.2 km grid SD (3m^2)
- 3 sub array :
  +cross boundary trigger
  →Total 507 SD
- Total detection area ～700km^2

Observation of highest cosmic ray



Shower development

→ N_{max} ⇔ Energy

X_{max} ⇔ Composition

SD :

Lateral Distribution, ⇔ Energy

Telescope Array Collaboration

T. Abu-Zayyad[1], R. Aida[2], M. Allen[1], T. Arai[4], R. Azuma[3], E. Barcikowski[1], J.W. Belz[1],T. Benno[4], D.R. Bergman[5], S.A. Blake[1], O. Brusova[1], R. Cady[1], B.G. Cheon[6], J. Chiba[7], M. Chikawa[4], E.J. Cho[6], L.S. Cho[8], W.R. Cho[8], F. Cohen[9], K. Doura[4], C. Ebeling[1], H. Fujii[10], T. Fujii[11], T. Fukuda[3], M. Fukushima[9□22], D. Gorbunov[12], W. Hanlon[1], K. Hayashi[3], Y. Hayashi[11], N. Hayashida[9], K. Hibino[13], K. Hiyama[9], K. Honda[2], G. Hughes[5], T. Iguchi[3], D. Ikeda[9], K. Ikuta[2], S.J.J. Innemee[5], N. Inoue[14], T. Ishii[2], R. Ishimori[3], D. Ivanov[5], S. Iwamoto[2], C.C.H. Jui[1], K. Kadota[15], F. Kakimoto[3], O. Kalashev[12], T. Kanbe[2], H. Kang[16], K. Kasahara[17], H. Kawai[18], S. Kawakami[11], S. Kawana[14], E. Kido[9], B.G. Kim[19],H.B. Kim[6], J.H. Kim[6], J.H. Kim[20], A. Kitsugi[9], K. Kobayashi[7], H. Koers[21], Y. Kondo[9], V. Kuzmin[12], Y.J. Kwon[8], J.H. Lim[16], S.I. Lim[19], S. Machida[3], K. Martens[22], J. Martineau[1], T. Matsuda[10], T. Matsuyama[11], J.N. Matthews[1], M. Minamino[11], K. Miyata[7], H. Miyauchi[11], Y. Murano[3], T. Nakamura[23], S.W. Nam[19], T. Nonaka[9], S. Ogio[11], M. Ohnishi[9], H. Ohoka[9], T. Okuda[11], A. Oshima[11], S. Ozawa[17], I.H. Park[19], D. Rodriguez[1], S.Y. Roh[20], G. Rubtsov[12], D. Ryu[20], H. Sagawa[9],N. Sakurai[9], L.M. Scott[5], P.D. Shah[1], T. Shibata[9], H. Shimodaira[9], B.K. Shin[6], J.D. Smith[1], P. Sokolsky[1], T.J. Sonley[1], R.W. Springer[1], B.T. Stokes[5], S.R. Stratton[5], S. Suzuki[10], Y. Takahashi[9], M. Takeda[9], A. Taketa[9], M. Takita[9], Y. Tameda[3], H. Tanaka[11], K. Tanaka[24], M. Tanaka[10], J.R. Thomas[1], S.B.Thomas[1], G.B. Thomson[5], P. Tinyakov[12□21], I. Tkachev[12], H. Tokuno[9], T. Tomida[2], R. Torii[9], S. Troitsky[12], Y. Tsunesada[3], Y. Tsuyuguchi[2], Y. Uchihori[25], S. Udo[13], H. Ukai[2], B. Van Klaveren[1], Y. Wada[14], M. Wood[1], T. Yamakawa[9], Y. Yamakawa[9], H. Yamaoka[10], J. Yang[19], S. Yoshida[18], H. Yoshii[26], Z. Zundel[1]

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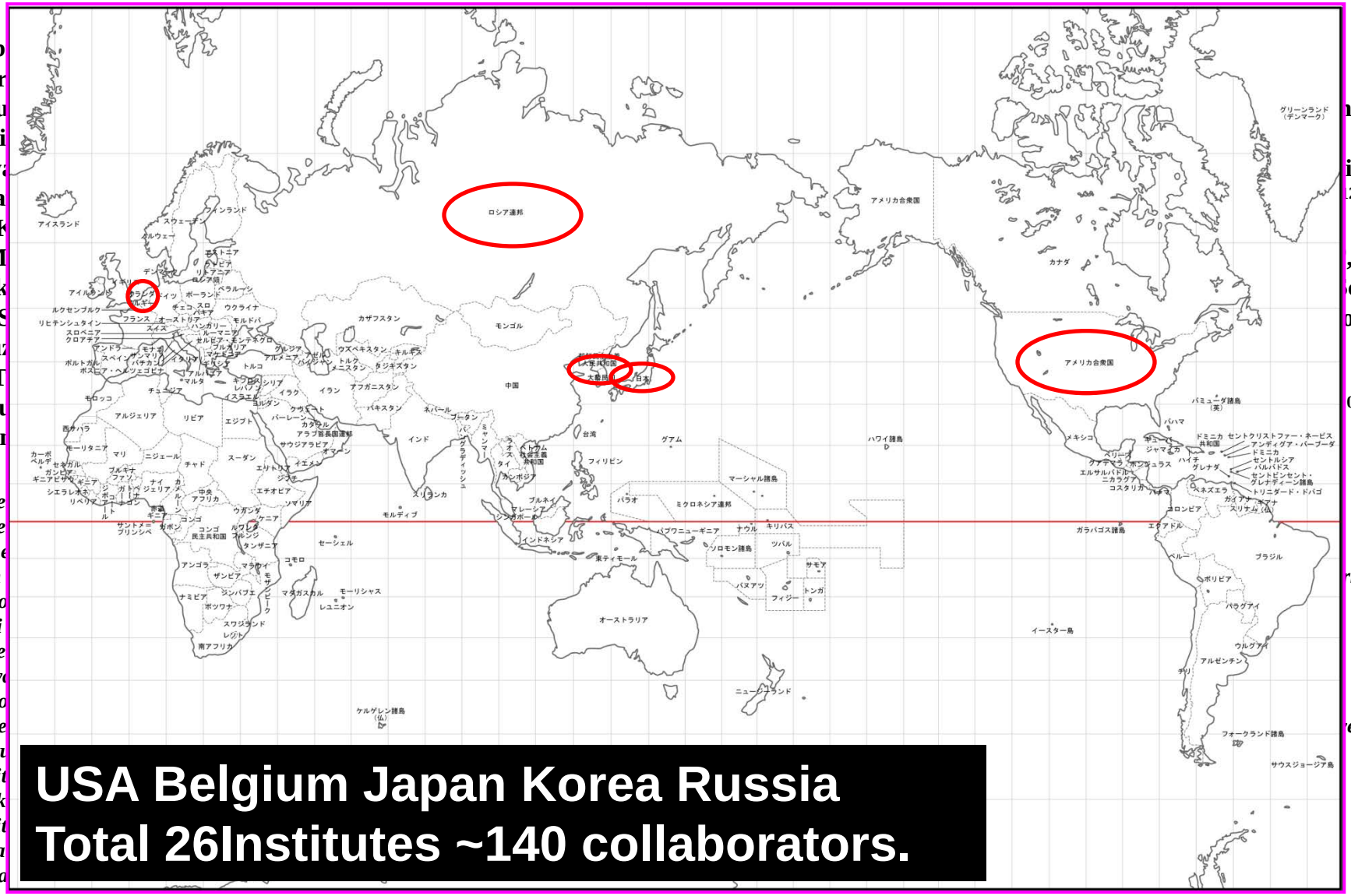
Telescope Array Collaboration



USA Belgium Japan Korea Russia
Total 26Institutes ~140 collaborators.

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5Rutge
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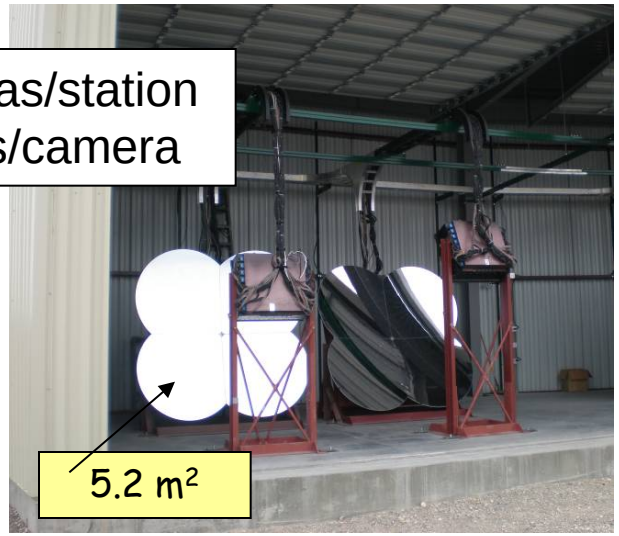
7Tokyo
8Yonse
9Institu
10Instit
11Osak
12Instit
Russia
13Kana

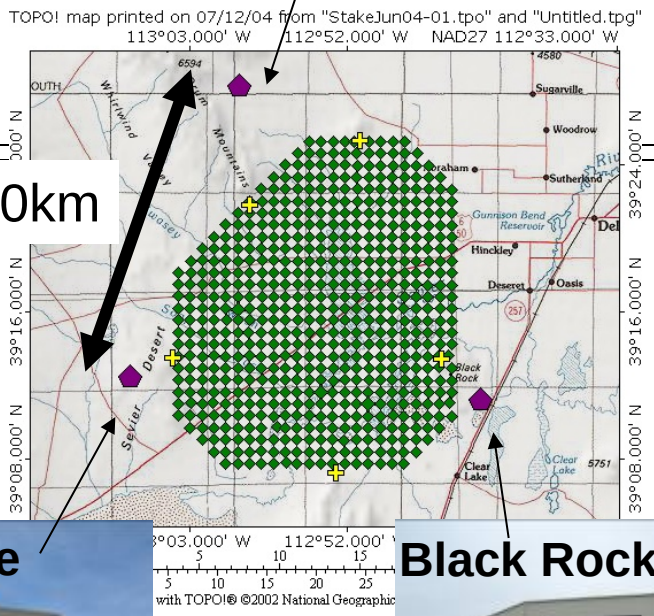
Fluorescence Detectors

From HiRes

Middle Drum

14 cameras/station
256 PMTs/camera





~30km

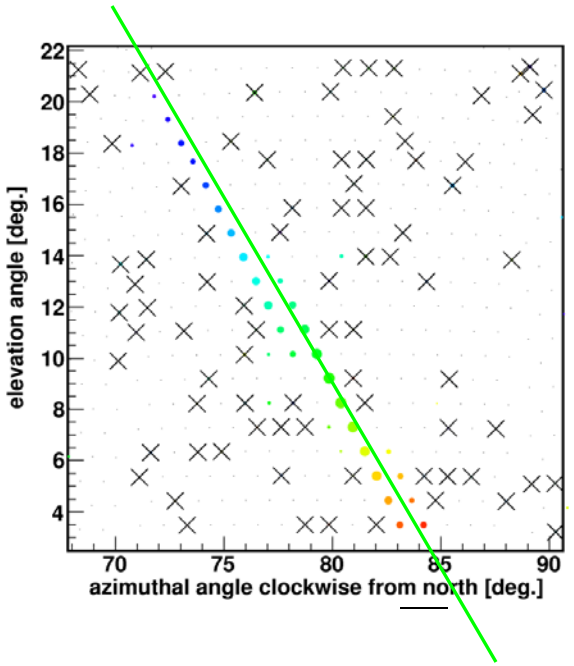
New FDs

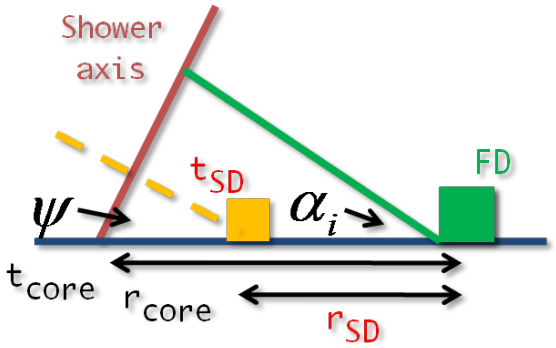
256 PMTs/camera
HAMAMATSU R9508
FOV~15x18deg
12 cameras/station

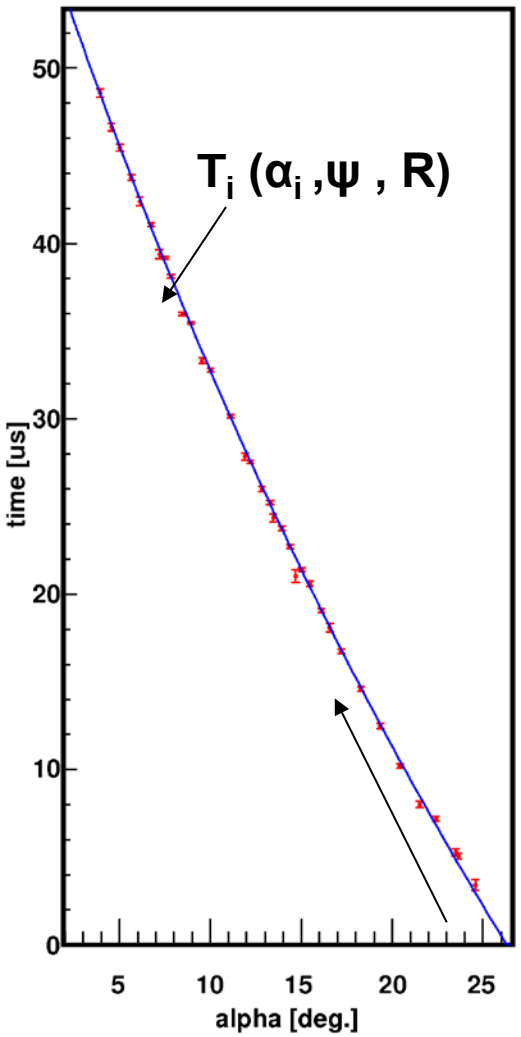
Long Ridge

Black Rock Mesa

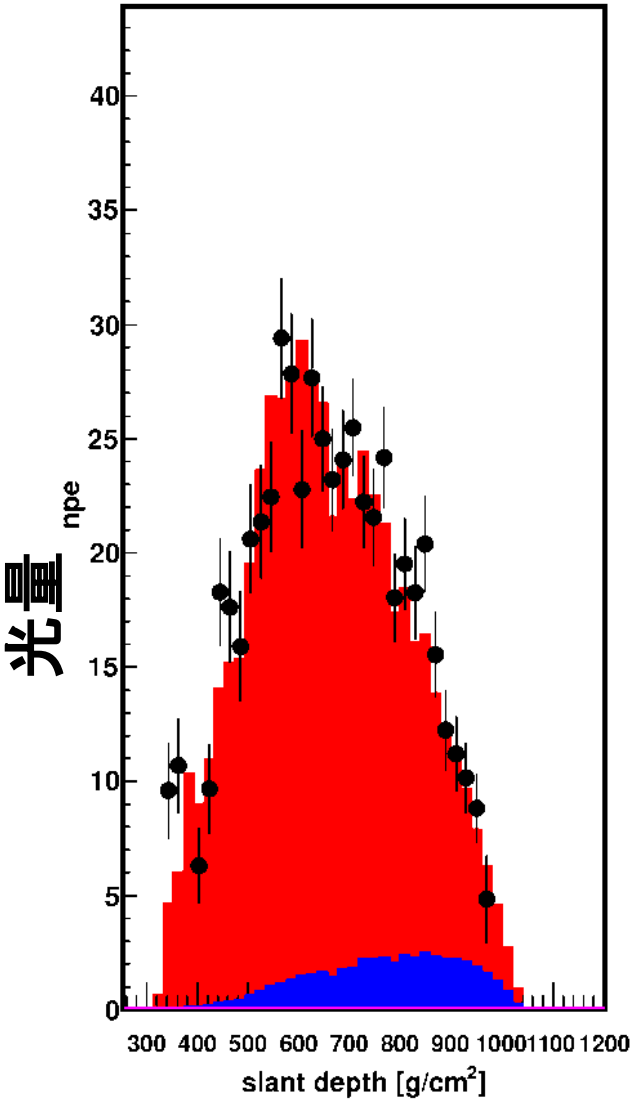
FD event example





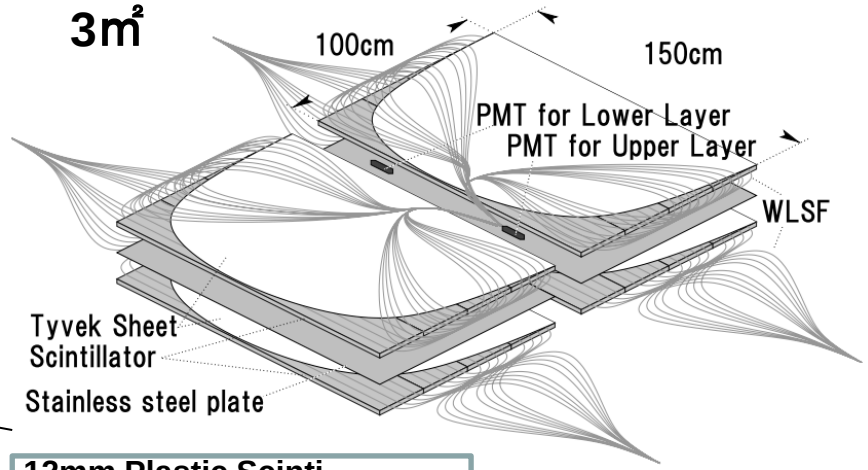


Energy estimation



Use SD timing information→
Ψ、R resolution improve **(Hybrid analysis)**

TA Surface Detector



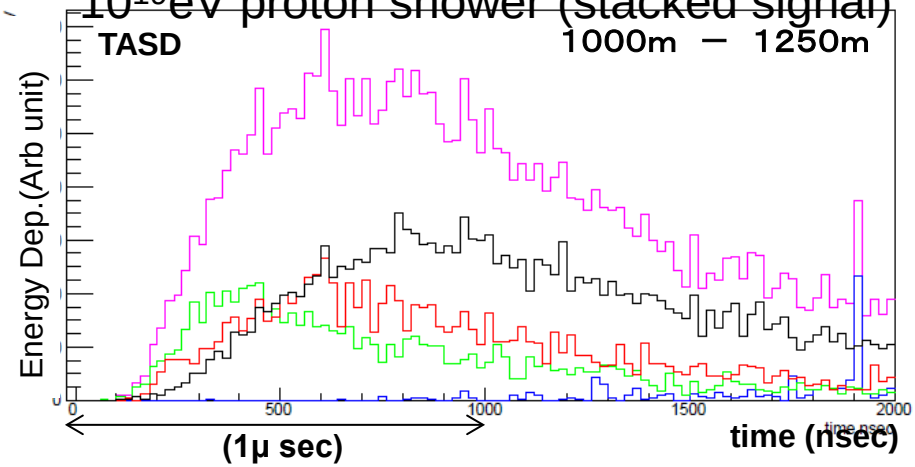
12mm Plastic Scinti.
1mm SS steel plate
12mm Plastic Scinti.

Up/Low 2 independent layer.

reflector :Tyvek
Wls fiber (475nm) x5m → PMT ETL9124SA

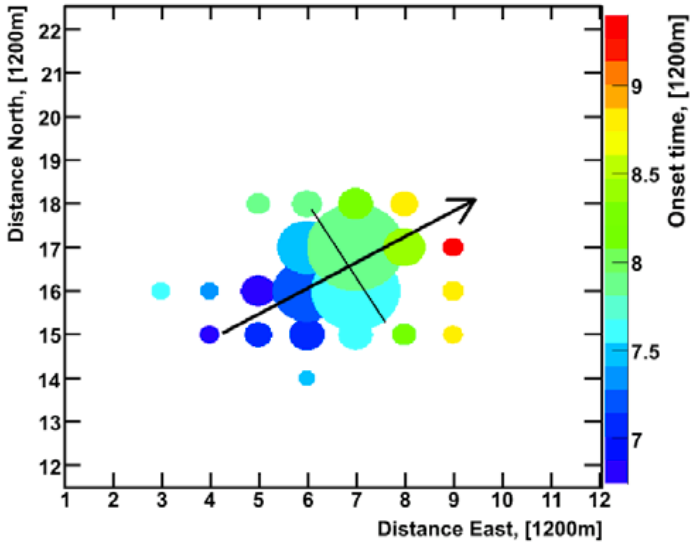
- Solarcell ＋ Battery
- Wireless LAN (2.4GHz)
- GPS syncronization ~20nsec
- Sample rate 50Msps FADC
- 1.2km square grid array.

Simulated energy deposit
10^{19}eV proton shower (stacked signal)

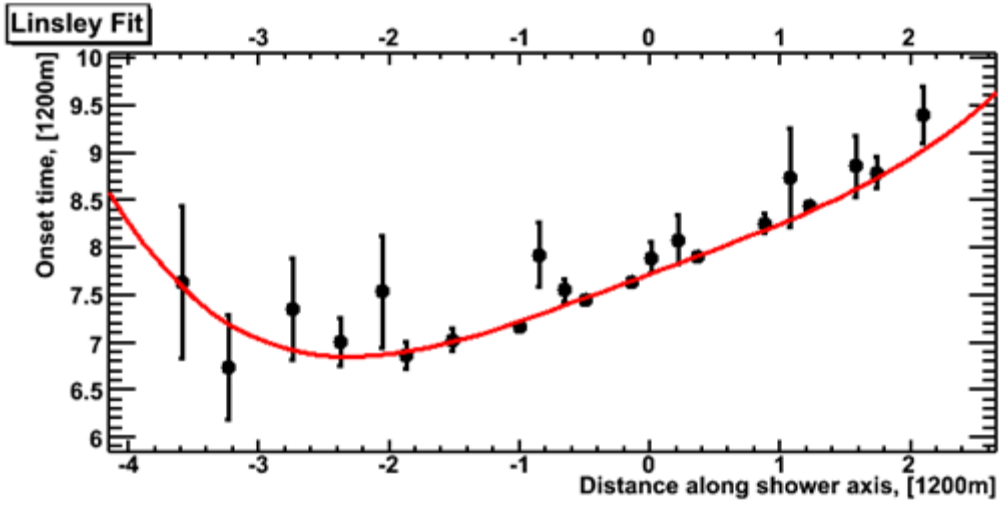


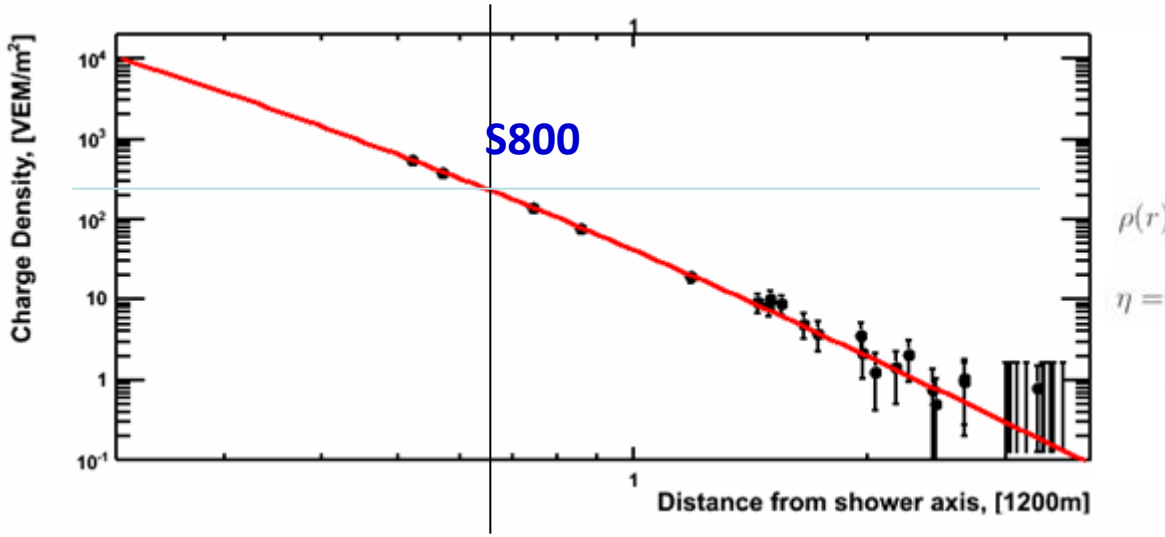
SD event example

2008/Jun/25 - 19:45:52.588670 UTC



Particle arrival time → shower direction





$$\rho(r) \propto \left(\frac{r}{R_M}\right)^{-1.2} \left(1+\frac{r}{R_M}\right)^{-(\eta-1.2)} \left\{1+\left(\frac{r}{1000}\right)^2\right\}^{-0.6}$$

$$\eta = (3.97 \pm 0.13) - (1.79 \pm 0.62)\,(\sec\theta - 1)$$

S(800)→（Primary Energy）

r = 800m

Energy spectrum at E>$10^{18.2}$eV

- Period :
  2008 May – 2014 May
  (6 years)

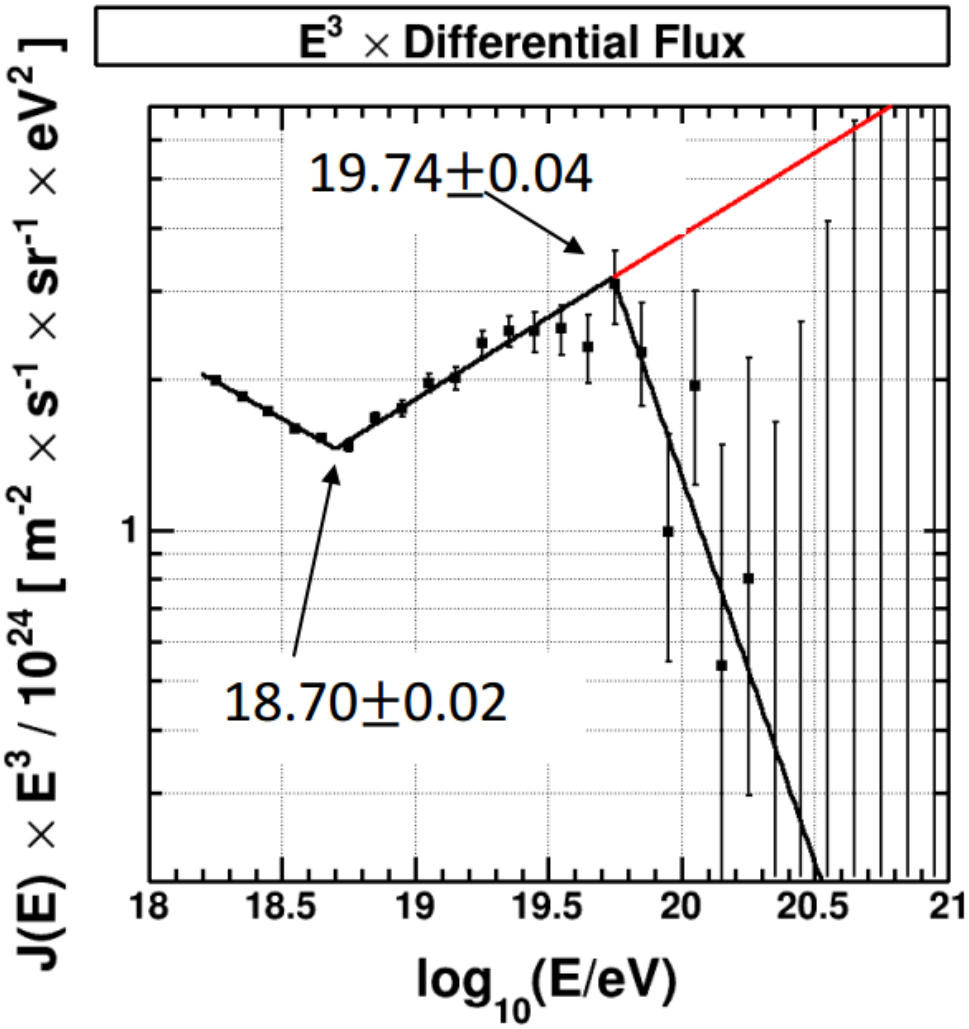
- Cut conditions :
  - # of used detectors >=5
  - Zenith angle < 45°
  - Energy > $10^{18.2}$eV
  - w boundary cut

- Dip energy E_d
  $Log10(E_d/eV) = 18.70 \pm 0.02$

- Break energy E_b
  $Log_{10}(E_b/eV) = 19.74 \pm 0.04$
  → Consistent with GZK cut off

- Significance of suppression
  @ E >$10^{19.8}$eV
  N_{exp} = 85.9
  N_{obs} = 32 → 6.59 σ

◇ 6year TA SD spectrum

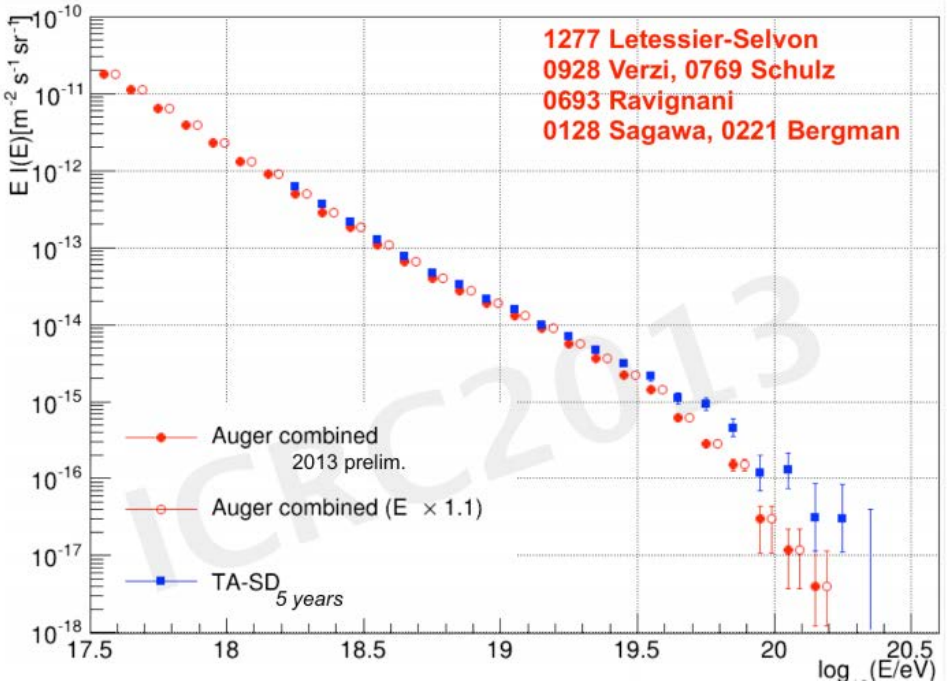


D.Bergman @COSPA 2014

Energy spectrum at $E>10^{18.2}$eV

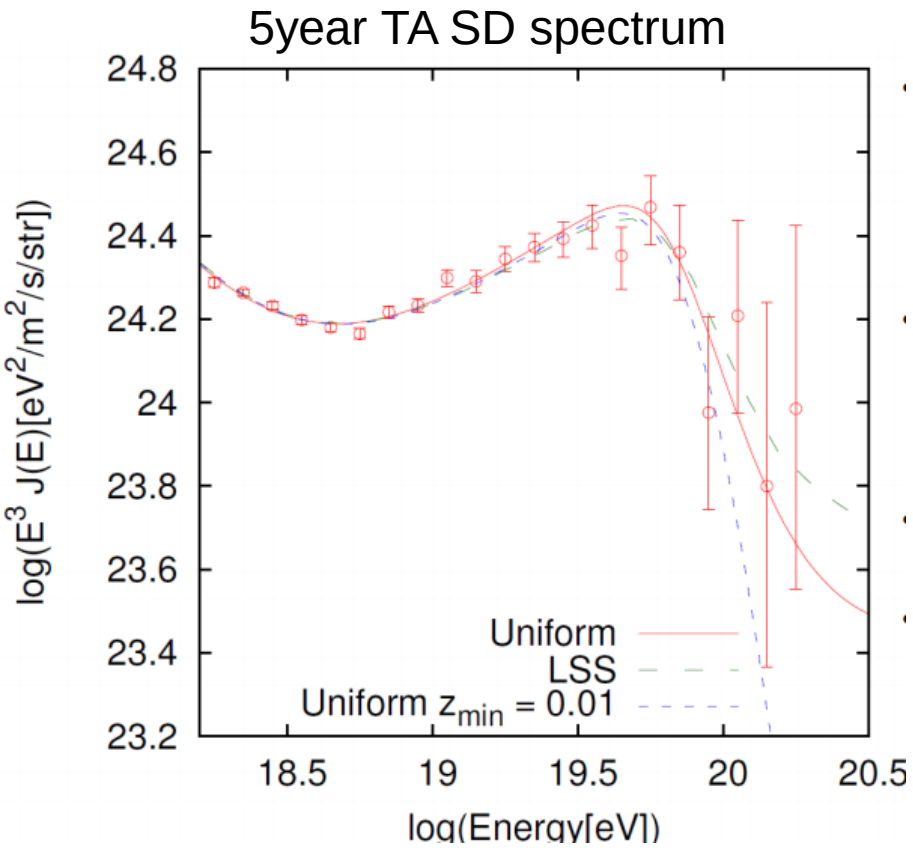
- Comparison with Auger spectrum
- Energy scale shifted artificially at Auger x 1.1
- spectrum shape agree well at Dip region ($10^{18.5}$eV) start disagree E> $10^{19.6}$eV
- Plot is from 2013 ICRC. TA spectrum shape is almost same in updated data.
- Study of Declination dependence of the spectrum is on going.

(Collaboration study between Auger-TA)



ICRC2013 Y.Tsunesada

Cosmic ray model E>$10^{18.2}$eV



E.Kido JPS meeting Sep. 2014

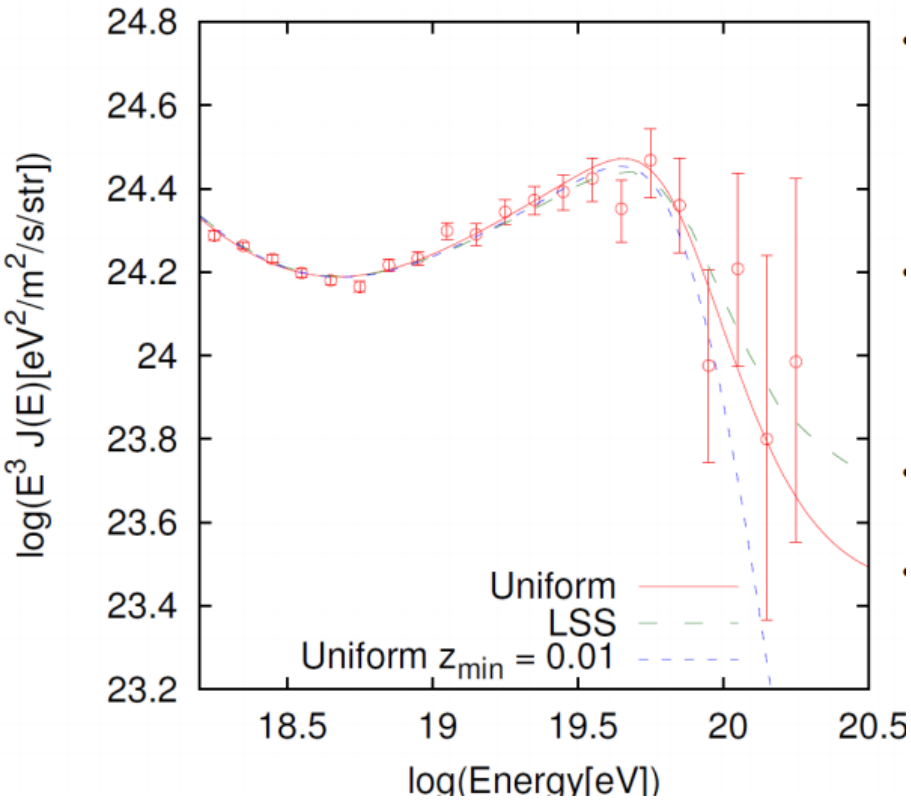
Composition: Proton.
Evolution index m:
$\rho \propto (1+z)^m$
Spectrum index origin p:
$dN/dE \propto E^{-P}$

Propagation :
Karashev , E.Kido
arXiv:1406.0735
Back gorund photon
CMB, IRB
– No magnetic field

Search best fit parameter
-p , m ,$\Delta\log_{10}(E)$, C_{n*}

Cn_* (normalization factor)

Modeling source distribution E>$10^{18.2}$eV



E.Kido JPS meeting Sep. 2014

<Best fit source parameter (*uniform)>

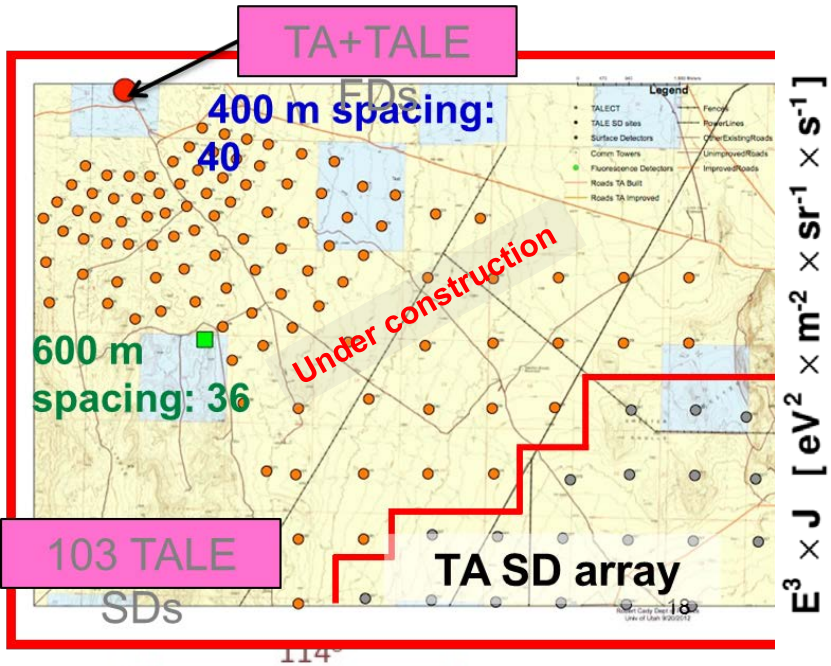
P=2.21
m = 6.4
ΔLogE -0.04* (uniform)

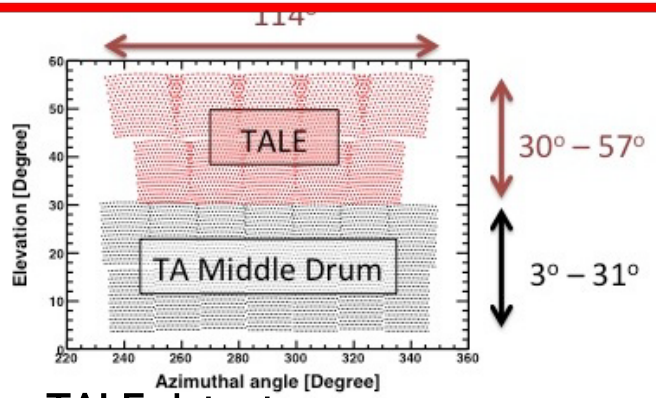
Z_{min} :
Distance of closest source in the model

Increase Z_{min} to find 95% incompatibility between model spectrum and data point.

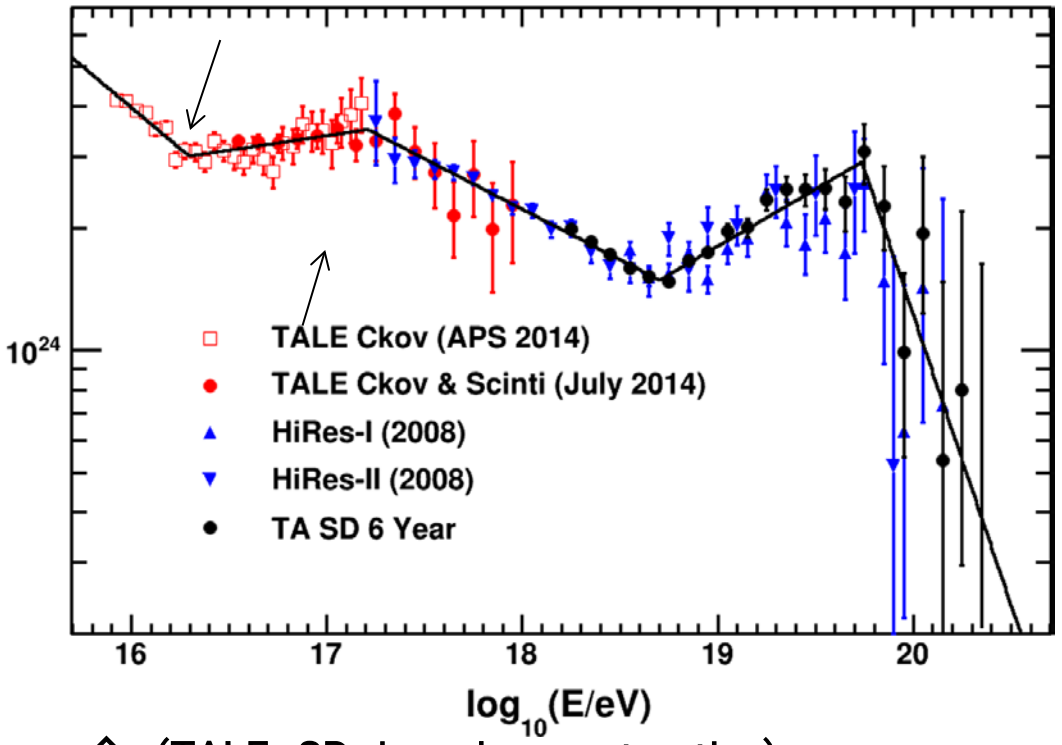
Data compatible with pure proton model at E>$10^{18.2}$eV
Under the condition of best fit model , constraint on Z_{min}:
Z_{min} < 0.010 (～40 Mpc) in 95% C.L.

New result from TA Low energy Extension





TALE detector :
High elevation tel + density SD
→ Low energy hybrid



◇ (TALE SD is under construction)
◇ Period : 2013/09/06 – 12/06

144hr data

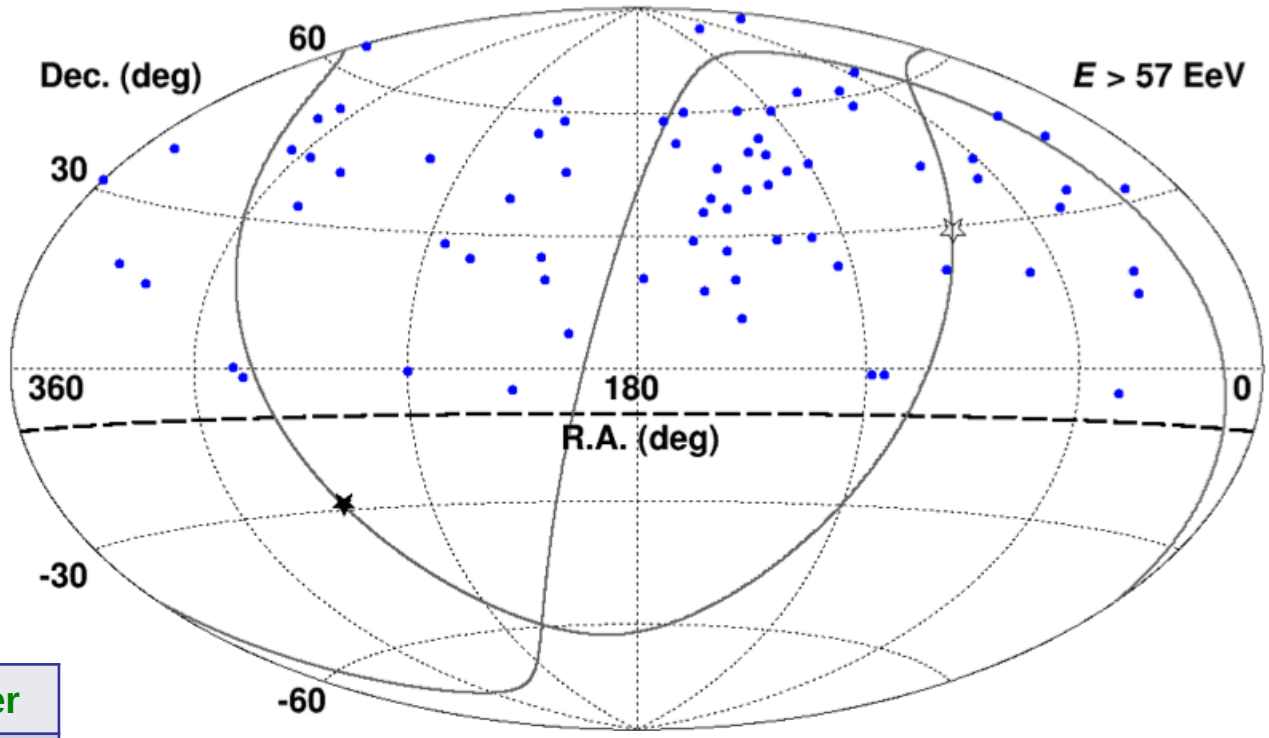
◇ SDs are not used ,not hybrid analysis
◇ Break @ $10^{16.2}$ eV
$10^{17.3}$ eV found.
→ Interesting to see X_{max} elongation.
Need more SD

Anisotropy of Cosmic Rays E>57EeV

- Period :
  2008 May – 2013 May
  (5 years)

- Cut conditions :
  - # of used detectors >=4
  - Zenith angle < 55°
  - Energy > 57EeV
  - No boundary cut

72 events

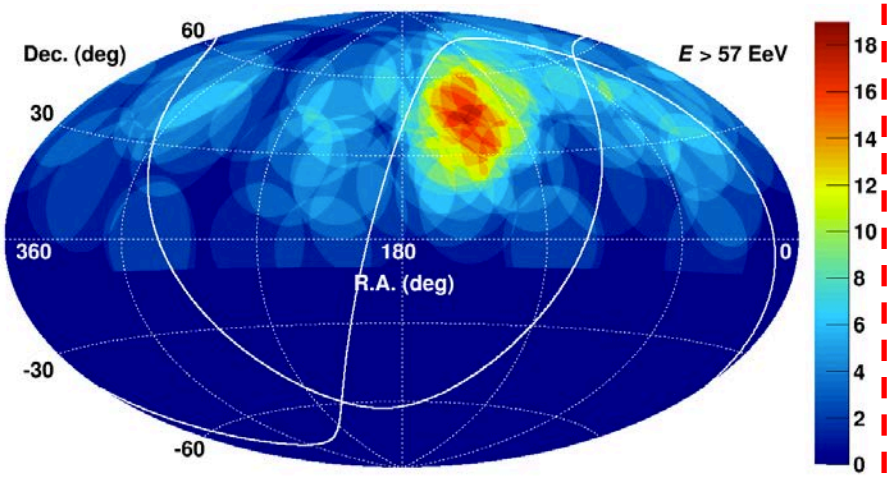


Resolutions	Inner	Outer
Angular	1.0°	1.7°
Energy	15%	20%

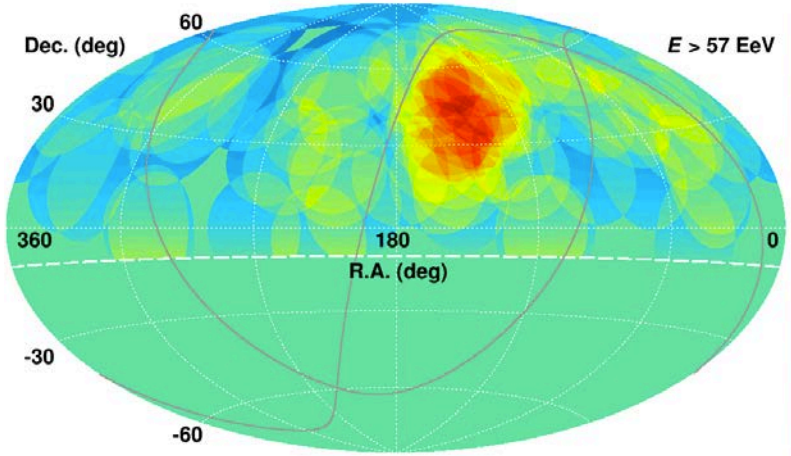
Full event table is available in the ApJL online journal :

http://iopscience.iop.org/2041-8205/790/2/L21/suppdata/apjl498370t1_mrt.txt

Anisotropy of Cosmic Rays E>57EeV



Count number of event within 20° circle

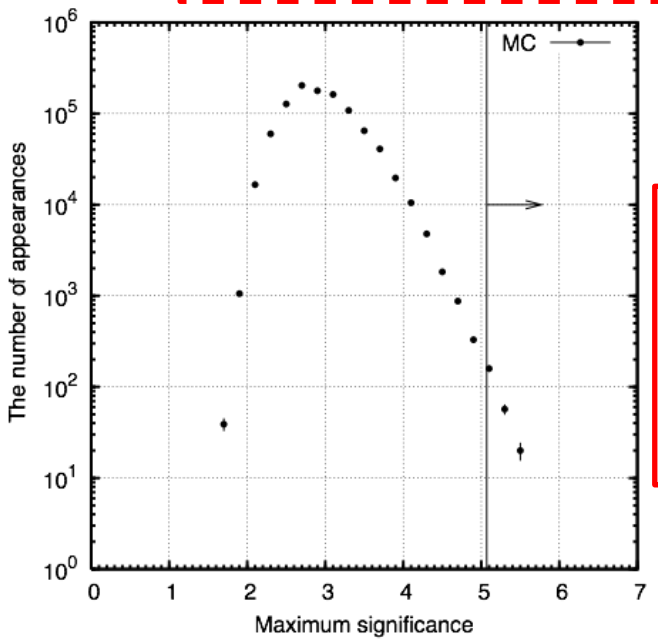


R.A, Dec =(146.7° , 43.2°) 5.1σ

Random 72 events
assuming isotropy
(TA geometrical exposure)

Adopt same analysis &
create significance maps
(by five oversampling radius
: 15, 20, 25, 30, 35 deg.)

Search for maximum
significance in the FoV



P = 371 / 10^6 trials
= **3.7 x 10^{-4} (3.4σ)**
"hotspot"

ApJ 790, L21 (2014)

Figure's comment:
K.Kawata ICRR seminar

Anisotropy of Cosmic Rays E>57EeV

◇ Eye comparison with 2MASS catalog

① **Ursa Major Cluster (20Mpc)**

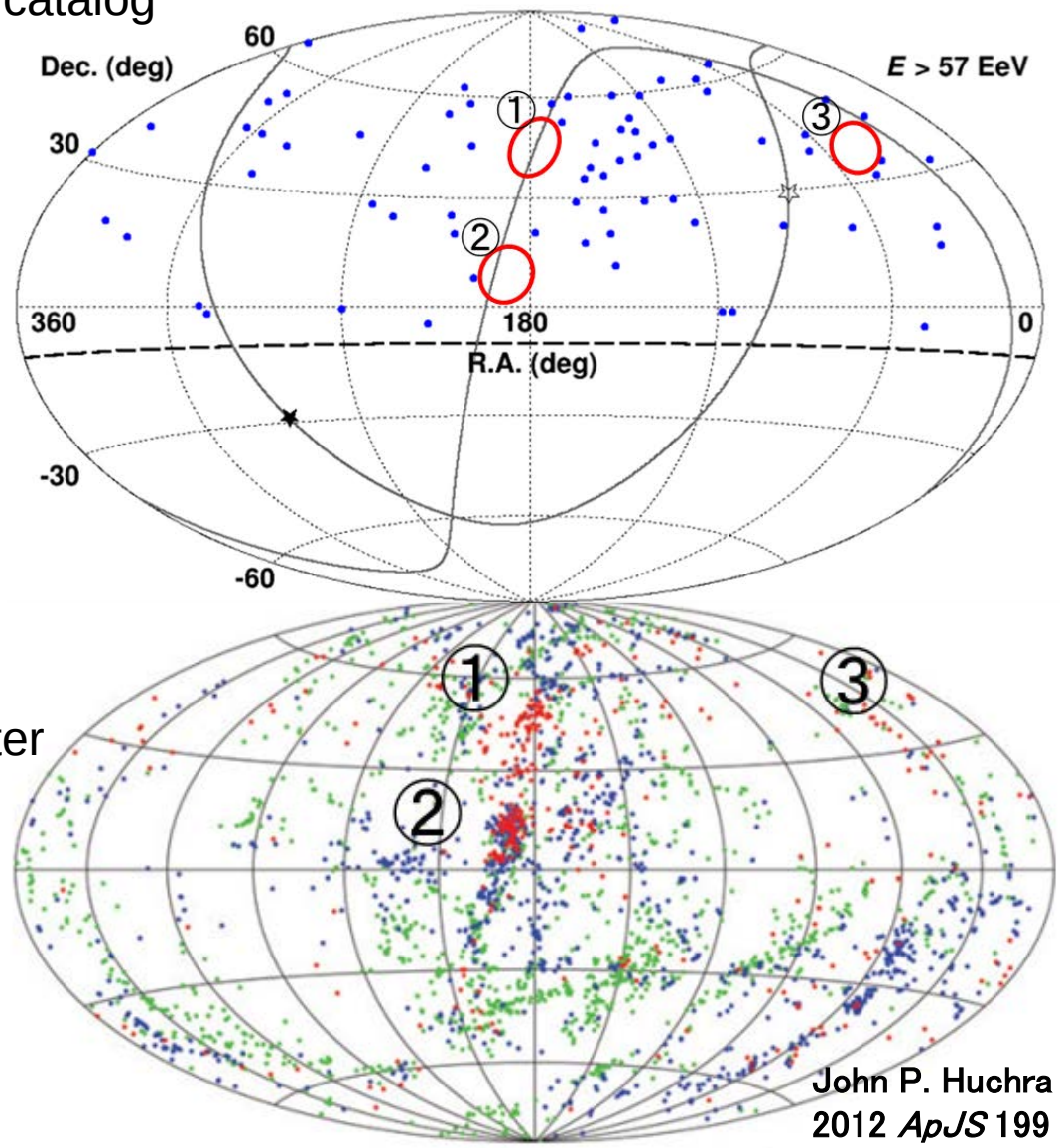
② **Virgo Cluster (20Mpc)**

③**Perseus-Pisces Supercluster (70Mpc)**

◇ Hot spot is not on SGP or Galaxy cluster

◇ "Perseus" close to event cluster but the area's significance is ~2σ

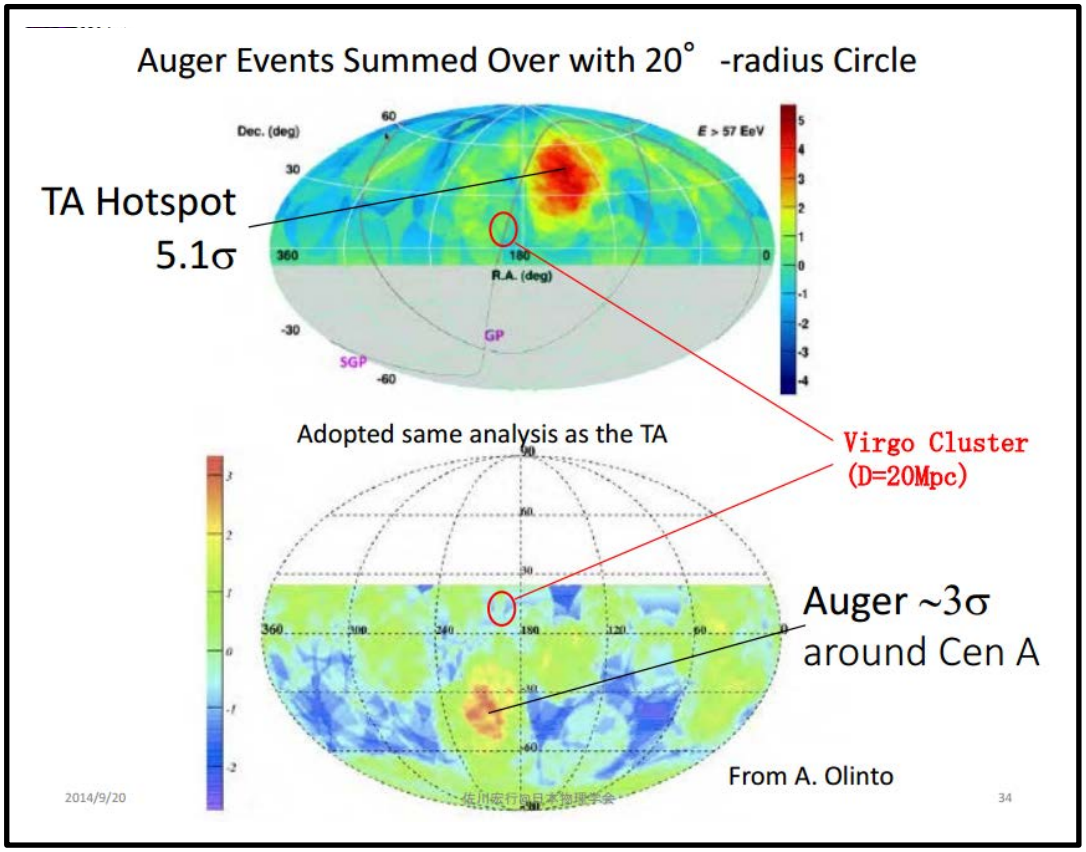
More quantitative study is needed.



John P. Huchra *et al.*
2012 *ApJS* 199 26

Anisotropy of Cosmic Rays E>57EeV

How it looks at south hemisphere with same analysis?



From Slide H.Sagawa @ JPS symposium 09/22 2014

- **No adjustment energy scale Use original energy at both experiment**
- **Cen-A region enhancement ~3σ**
- **Virgo cluster position is not bright at Auger data also. (~20MPC)**

Hotspot cosmic ray comes from very close distance like Cen-A?

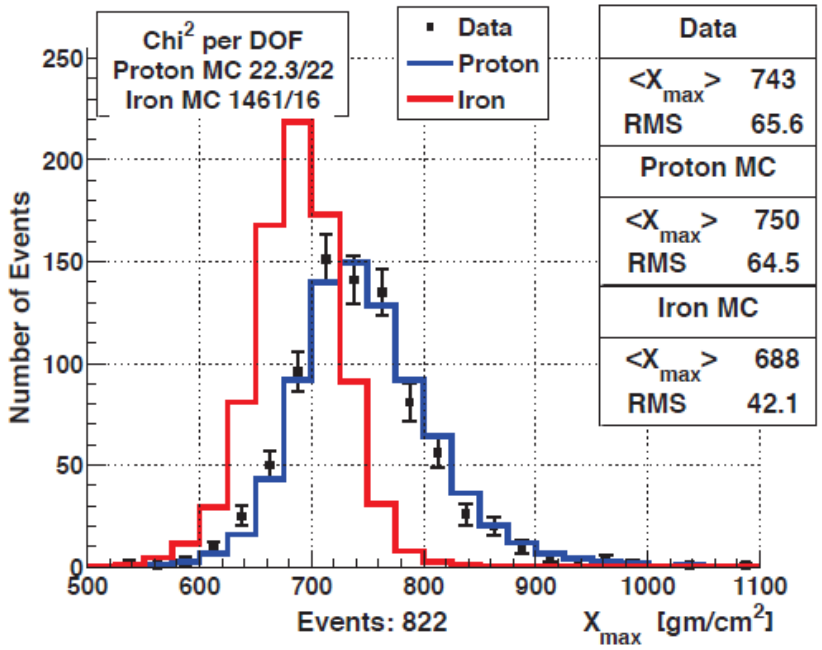
Is it consist from single source? or coincidence of two source?

If consist from single source why very large structure? 20° ?

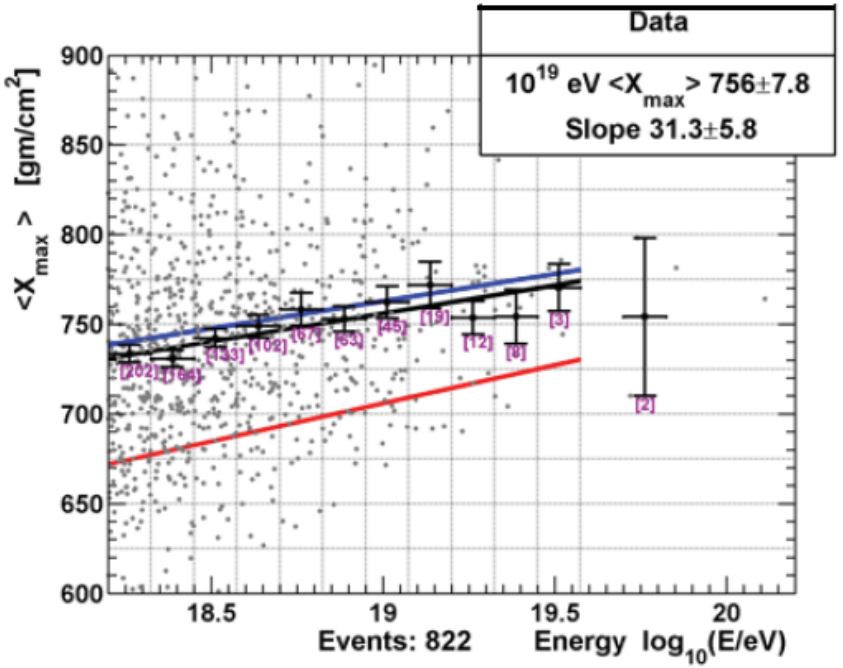
Chemical composition from X_{max}

- Period :
  2008 May – 2014 May
  (5 years)

MD station + TASD (Hybrid analysis) *arXiv:1408.1726*
(pattern recognition cut -> better resolution of Xmax)



X_{max} distribution and comparison with Proton, Iron MC simulation

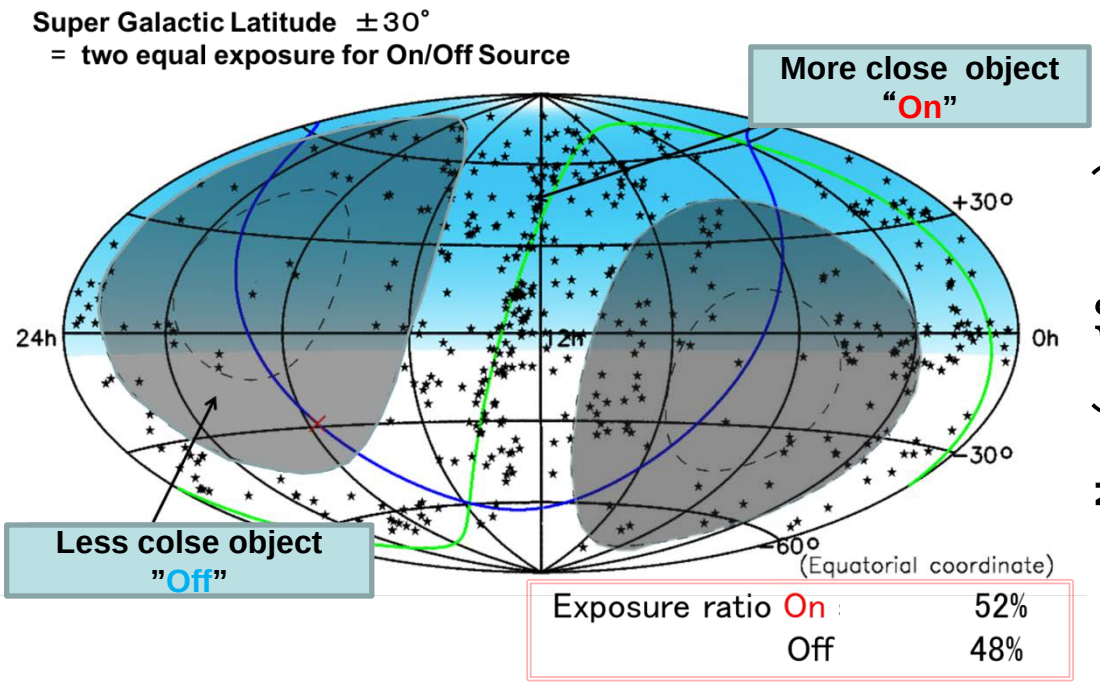


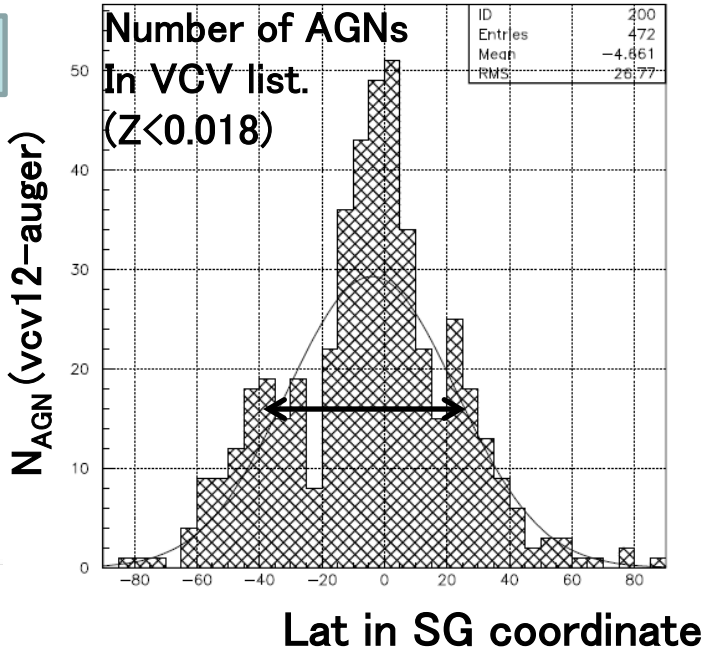
Average X_{max} along energy

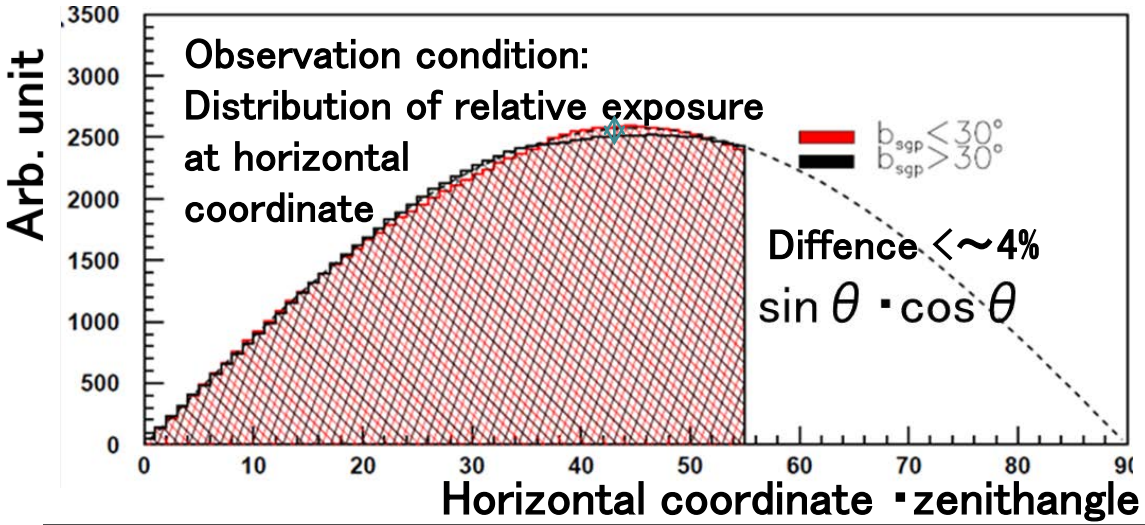
- ◇ Consistent with proton.
- ◇ Inconsistent with Iron
- ◇ Hot spot E>10*19.7 eV X_{max} : E>$10^{19.4}$ eV statistics small !

arXiv:1408.1726

Look for other information



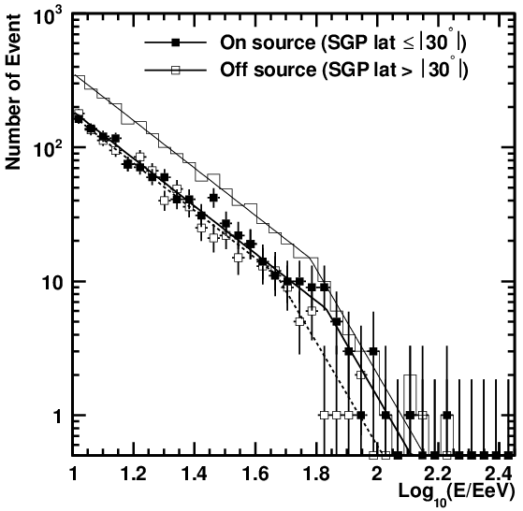


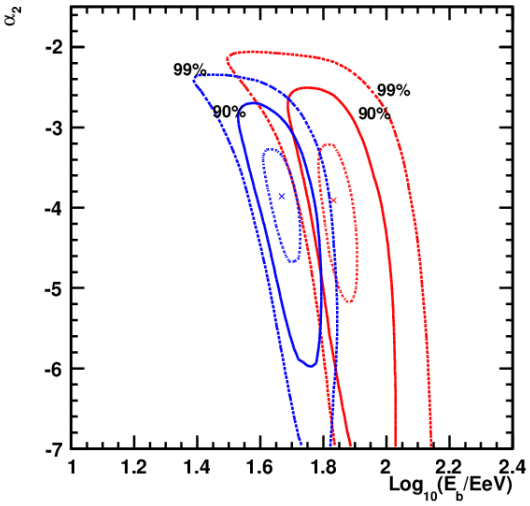


◎Divide sky
|SGP lat |< 30 and >30
(exposure 52 : 48)
" ½, and ½ "
◎Observation condition
is almost equal.

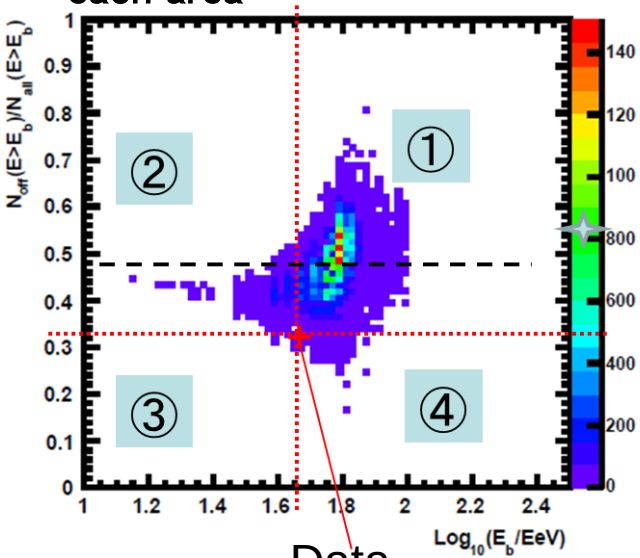
Analysis for spectrum difference b/w Sky area

Preliminary result :





Number of Chance events in each area



SGP 30 deg

Area	Number of cases	fraction
①	41580	0.831766
②	7996	0.159952
③	31	6.2×10^{-4}
④	383	0.007662

X 1 (scan penalty)

Off source spectrum:
Break energy is small at off source sky $10^{19.66}$ eV

Summary

Anisotropy

Hotspot found E>57EeV

→ More event to resolve structure of Hot spot.
More spot , Composition study with SD,

⇨ **TAx4**

Spectrum shape

Dip at $10^{18.5}$eV → e+ e- energy loss - >Dip

Cut off at $10^{19.7}$eV → consistent with GZK

Comparison between Sky area (new)

Composition

E>$10^{18.2}$eV consistent with proton,
(E>$10^{19.4}$eV need more statistics)

TALE

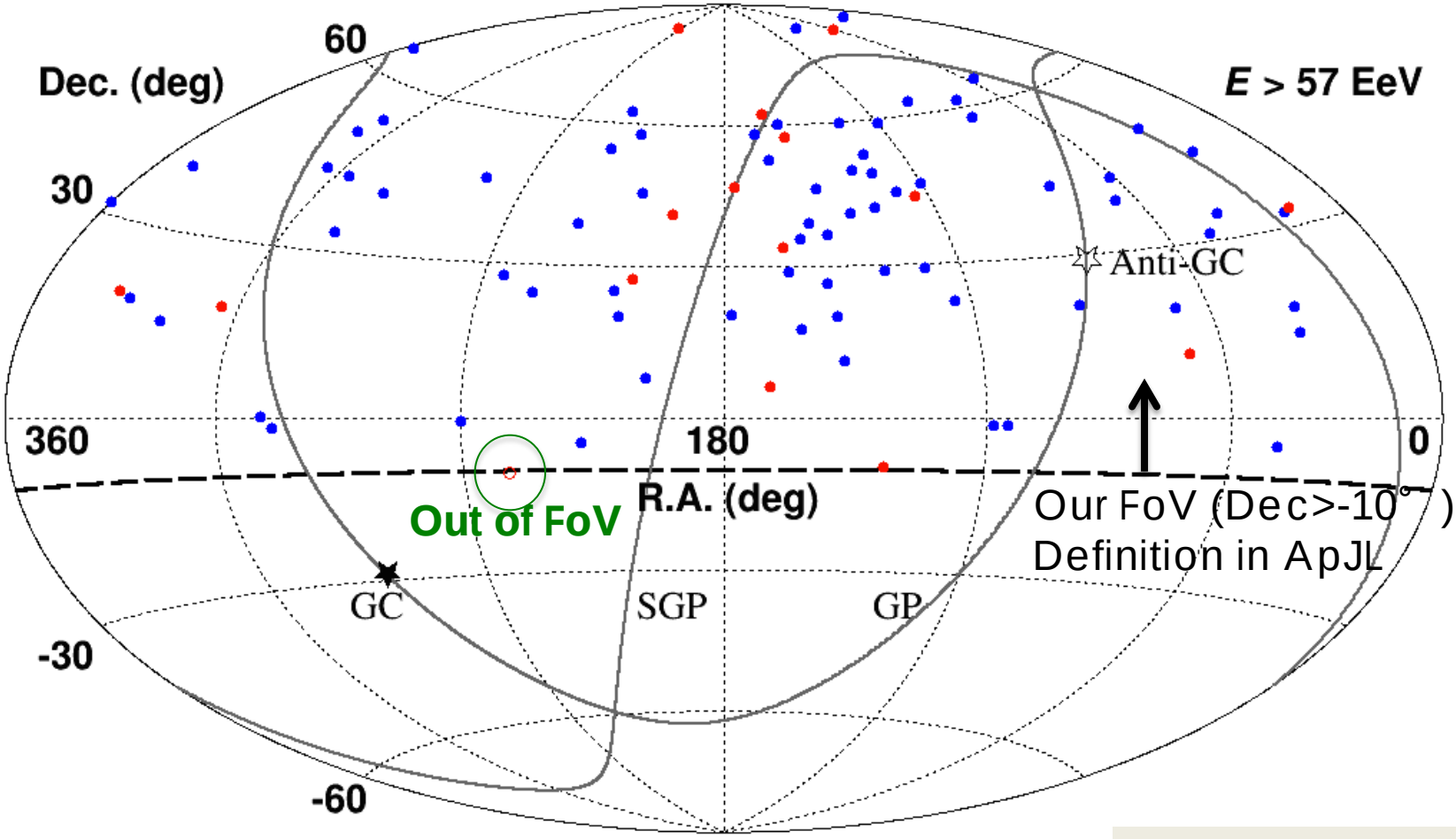
Start Data taking ,

⇨ **TALE**

Obtain spectrum E > 10^{17}eV structure in spectrum .

Need more SD area for good resolution Xmax (w Hybrid)

6-Year Data by TA



Slide K.Kawata @ ICRR seminar

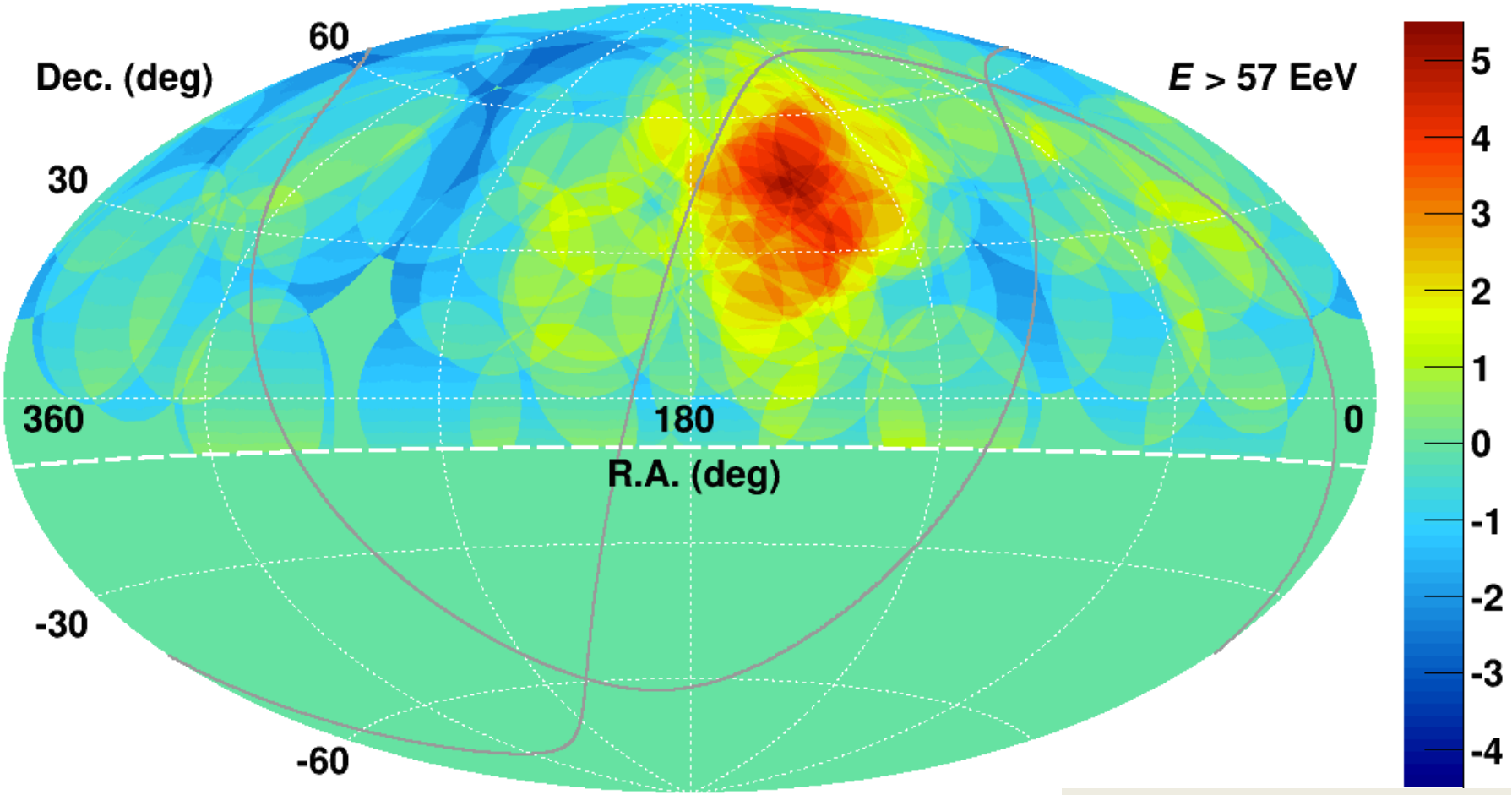
5-year data

New 1-year data

Period:
2008 May 11 – 2014 May 11 (87 events)

Significance Map 6 years

Oversampling with 20° -radius circle



Slide K.Kawata @ ICRR seminar

Max significance **5.55σ** (N_{on} = 23, N_{bg}=5.49)

Centered at R.A=148.4° , Dec.=44.5° (shifted from SGP by 17°)

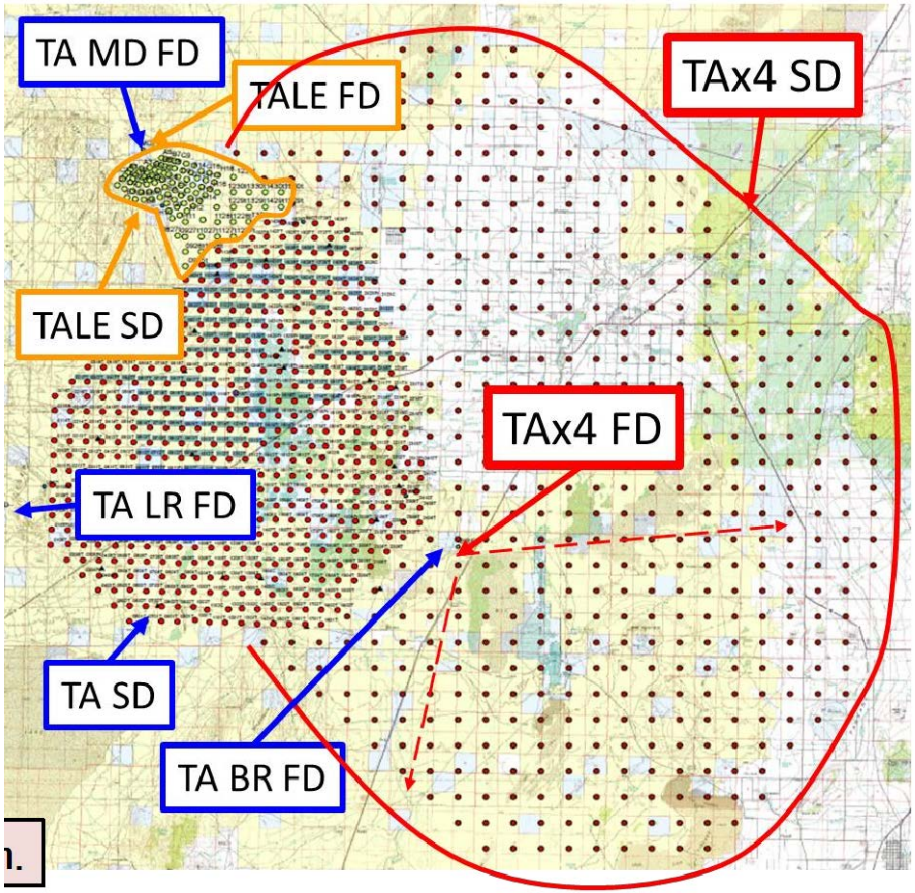
Chance probability of appearing in isotropic sky → **4.0σ**

TAx4

- Plan to expand TA by 4 times ($3{,}000\,km^2$)
  1. Add 500 scint. counters with 2.1 km spacing
  2. 10 refurbished HiRes tels

- Science (3-year observation)
  1. Anisotropy study → Expect >>5σ
  2. Xmax & E Spectrum at the highest energy region
  3. Search UHE photon & neutrino
  4. correlation search with Other observation. :

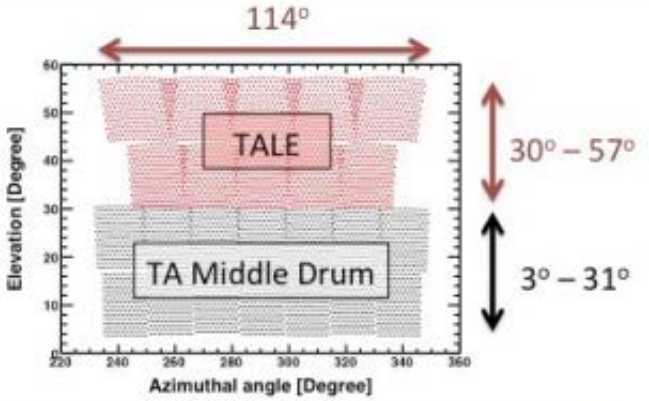
  ex) Fang, Fujii, Linden & Olinto, arXiv:1404.6237 (IceCube event x TA Hot spot.)

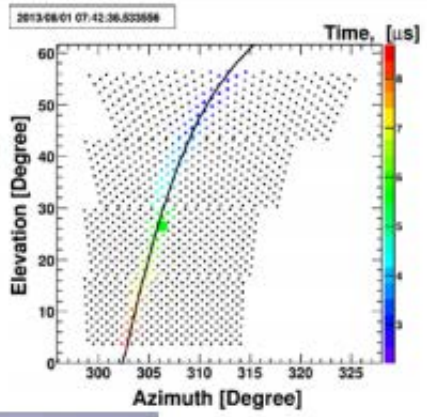


Slide K.Kawata @ ICRR seminar

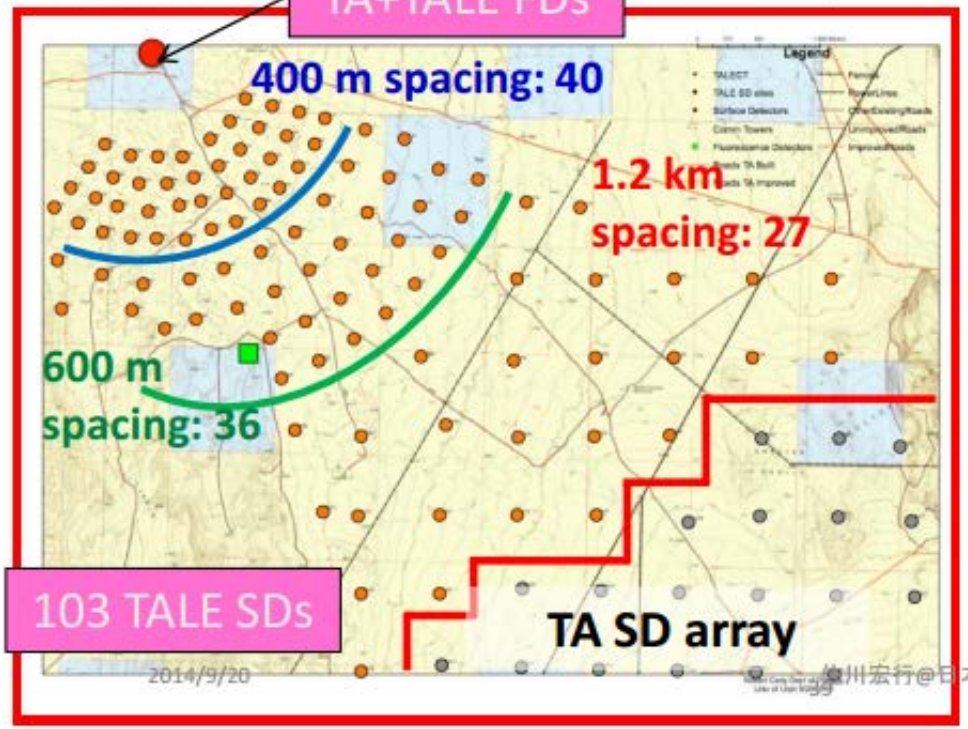
TALE実験

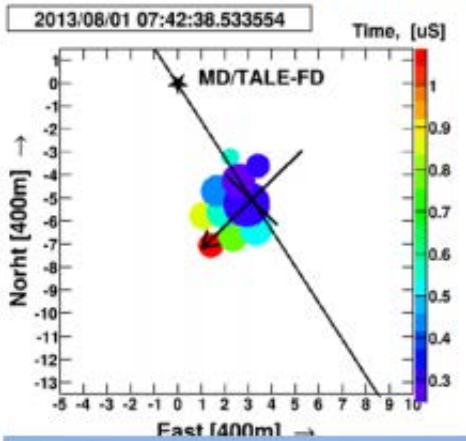
FDs + SDs =ハイブリッド
→高分解能
高仰角(30°~57°)、高密度配置
→10^{16}eV < E < $10^{18.5}$eV
TAとの接続
→単一のエネルギースケール
電子加速器による較正





TA+TALE FDs





35台設置
部分的に稼働

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Composition study with SD,

⇨ **TAx4**

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TALE

Start Data taking , ⇨ **TALE**

Obtain spectrum E > 10^{17}eV structure in spectrum .

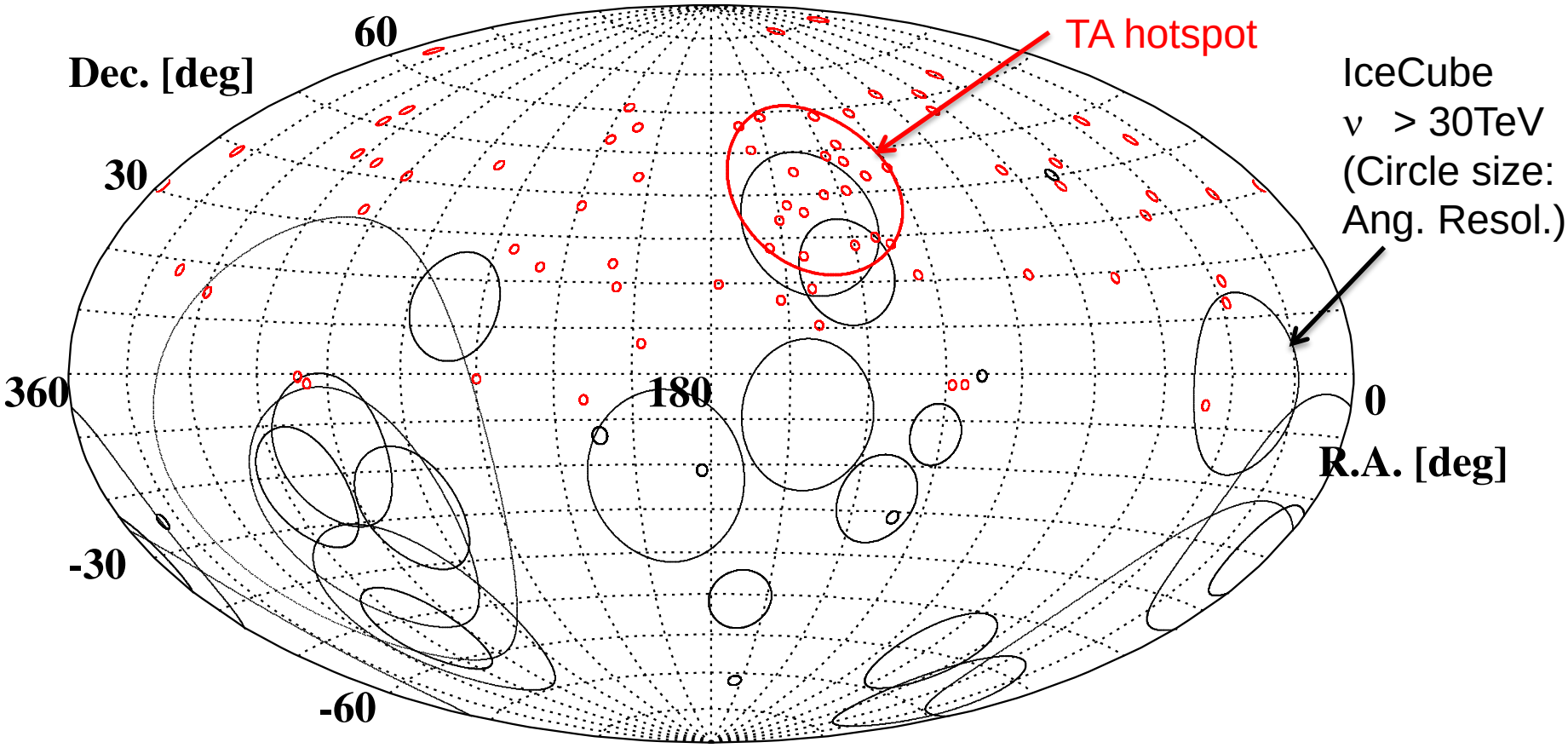
Need more SD area for good resolution Xmax (w Hybrid)

Back up

Other type of observation

Fang, Fujii, Linden & Olinto, arXiv:1404.6237

UHECRs + photons → TeV-PeV Neutrinos



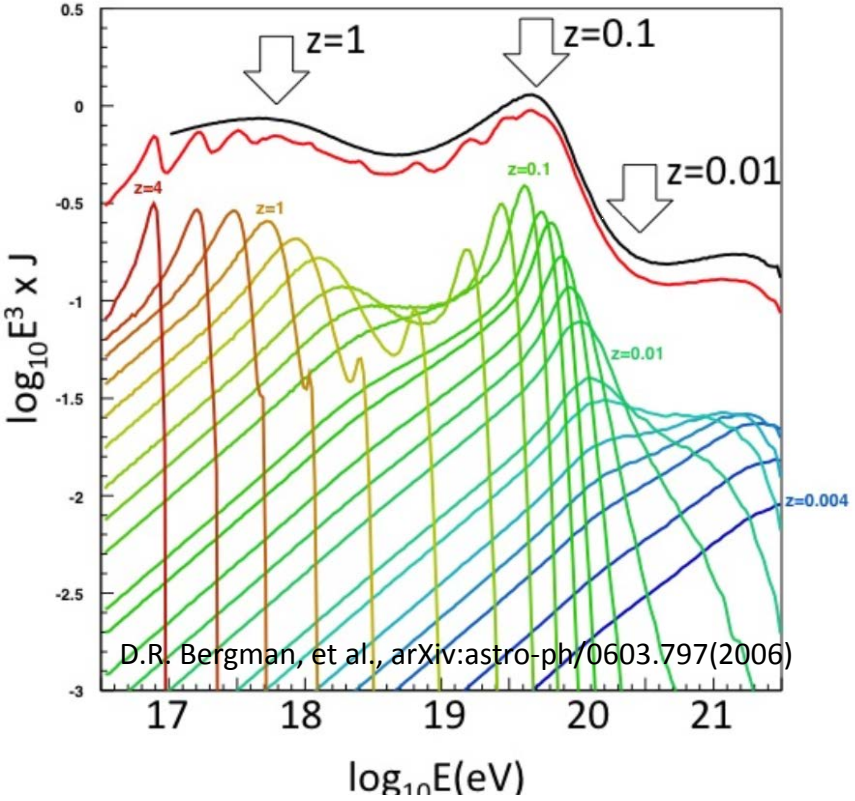
Two IceCube neutrinos among northern 4 events are coincident with the TA hotspot. → 2σ level by chance

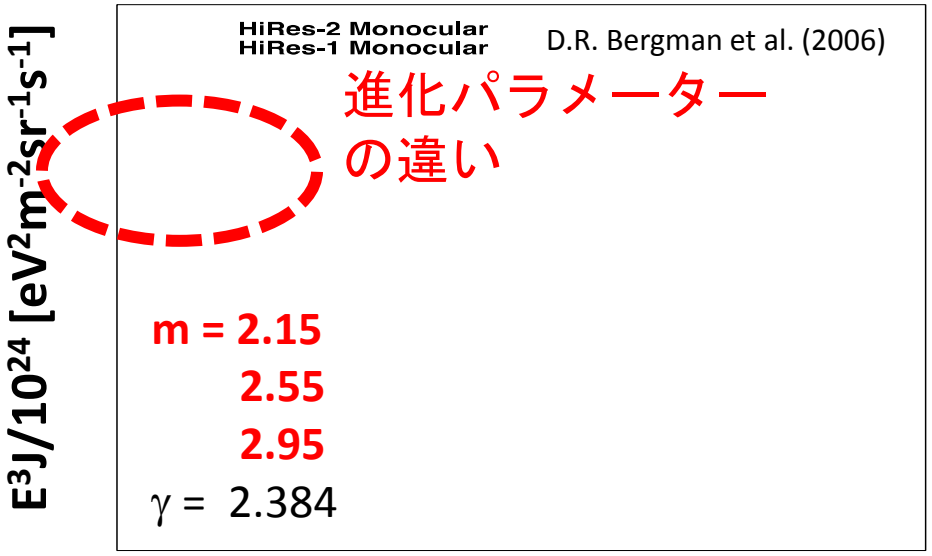
銀河系外宇宙線源の進化パラメーター

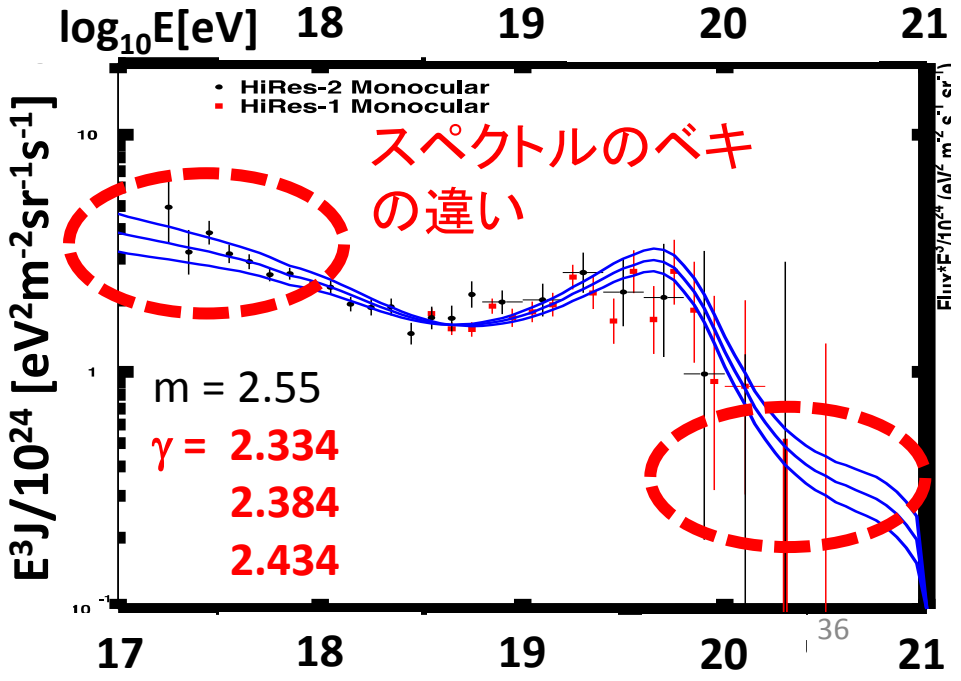
進化パラメーター：m

$\rho \propto (1+z)^m$

10^{20}eVではz=0.05
10^{18}eVではz=1
10^{17}eVではz=4
の宇宙線源が寄与する







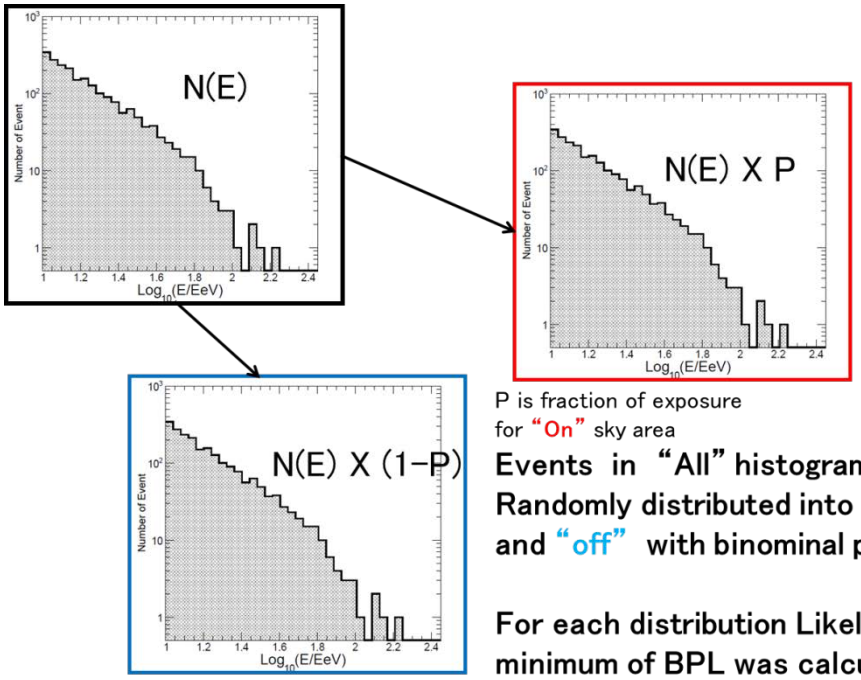
Map of $\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)}$ and E_b at random distribution

Simulation:

1)Create On/Off distribution from same population

2) Calculate E_b and $\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)}$ at likelihood minimum

→collect simulation events



P is fraction of exposure for "On" sky area

Events in "All" histograms are Randomly distributed into "On" and "off" with binominal probability P

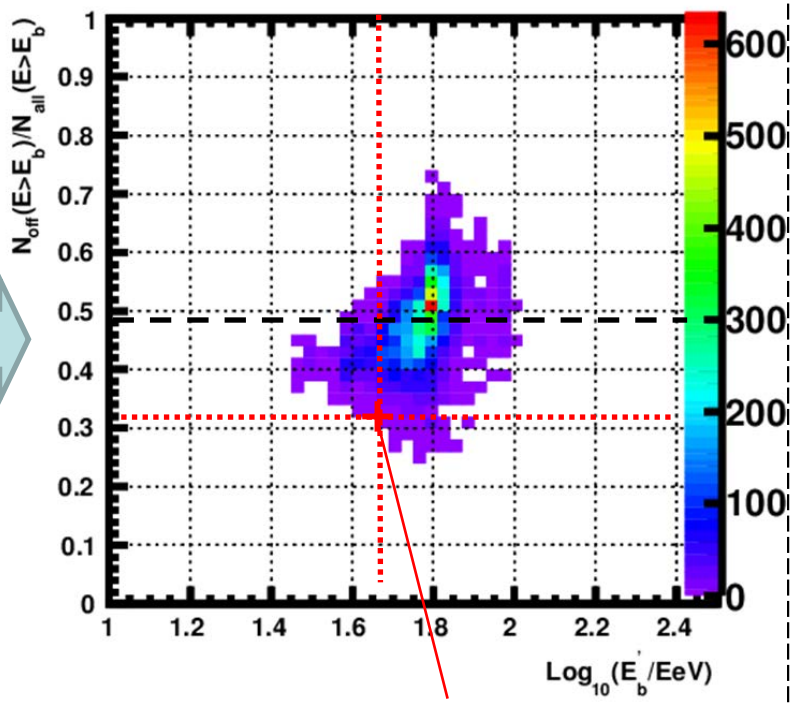
For each distribution Likelihood minimum of BPL was calculated

exposure ratio=0.52 (SGP 30)

10^4 simulation

X : Eb obtained at Off source side

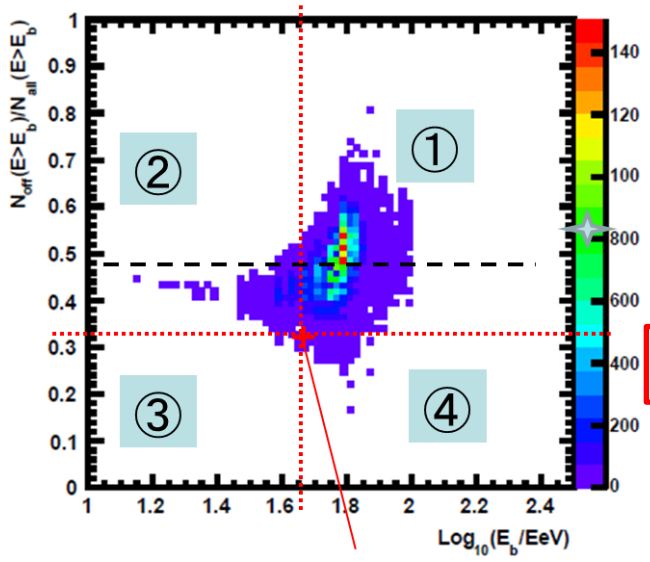
Y : Fraction at off source side



Here, Eb is off source Eb

Count chance cases

Preliminary Result :



Number of Chance events in each area

Total 4.999×10^4

Area	Number of events	fraction
①	41580	0.831766
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③	31	6.2×10^{-4}
④	383	0.007662

SGP 30 deg

X 1
(scan penalty)