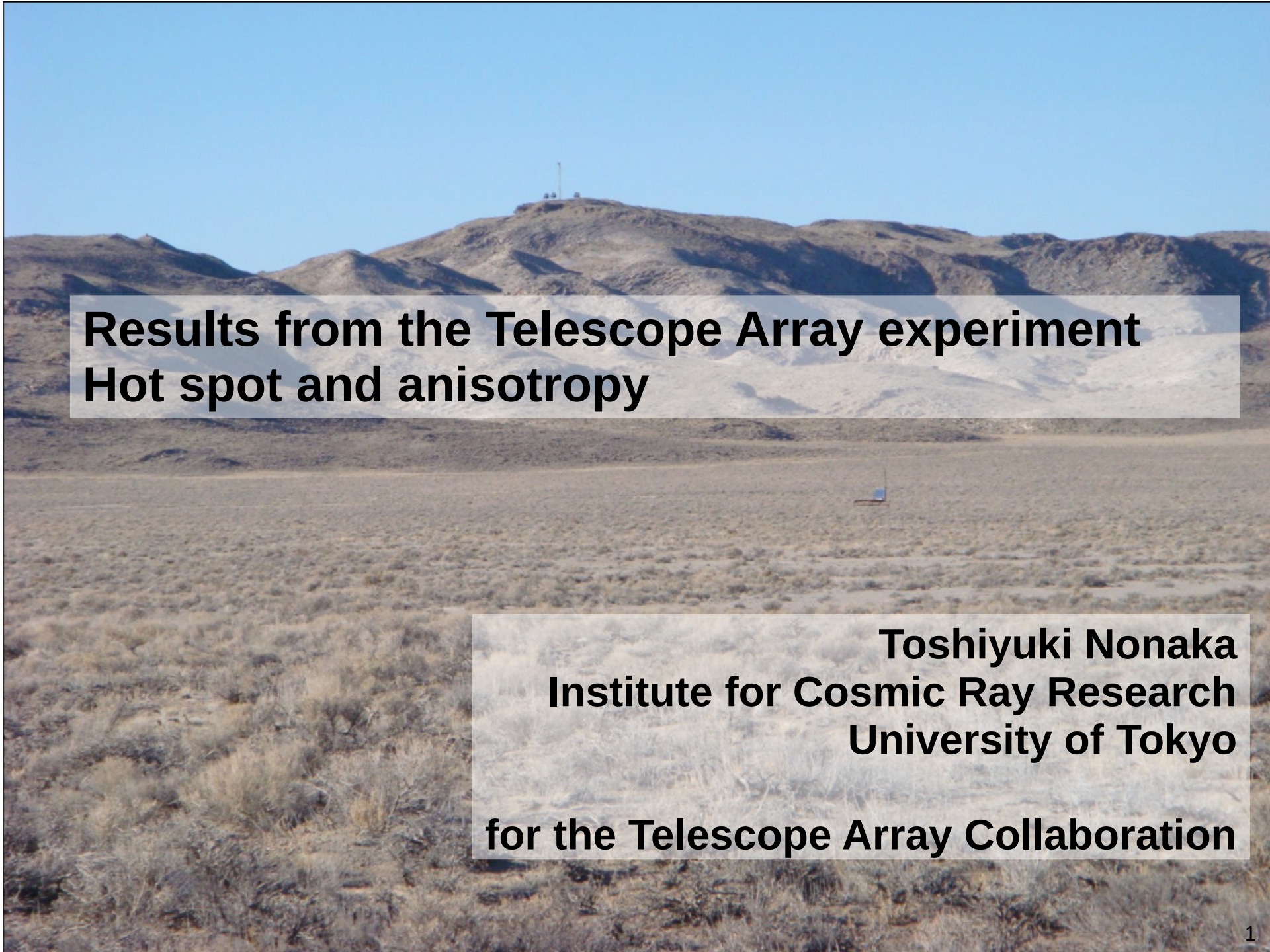

Results from the Telescope Array experiment
Hot spot and anisotropy

Toshiyuki Nonaka
Institute for Cosmic Ray Research
University of Tokyo

for the Telescope Array Collaboration

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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[18]Chiba University, Chiba, Chiba, Japan
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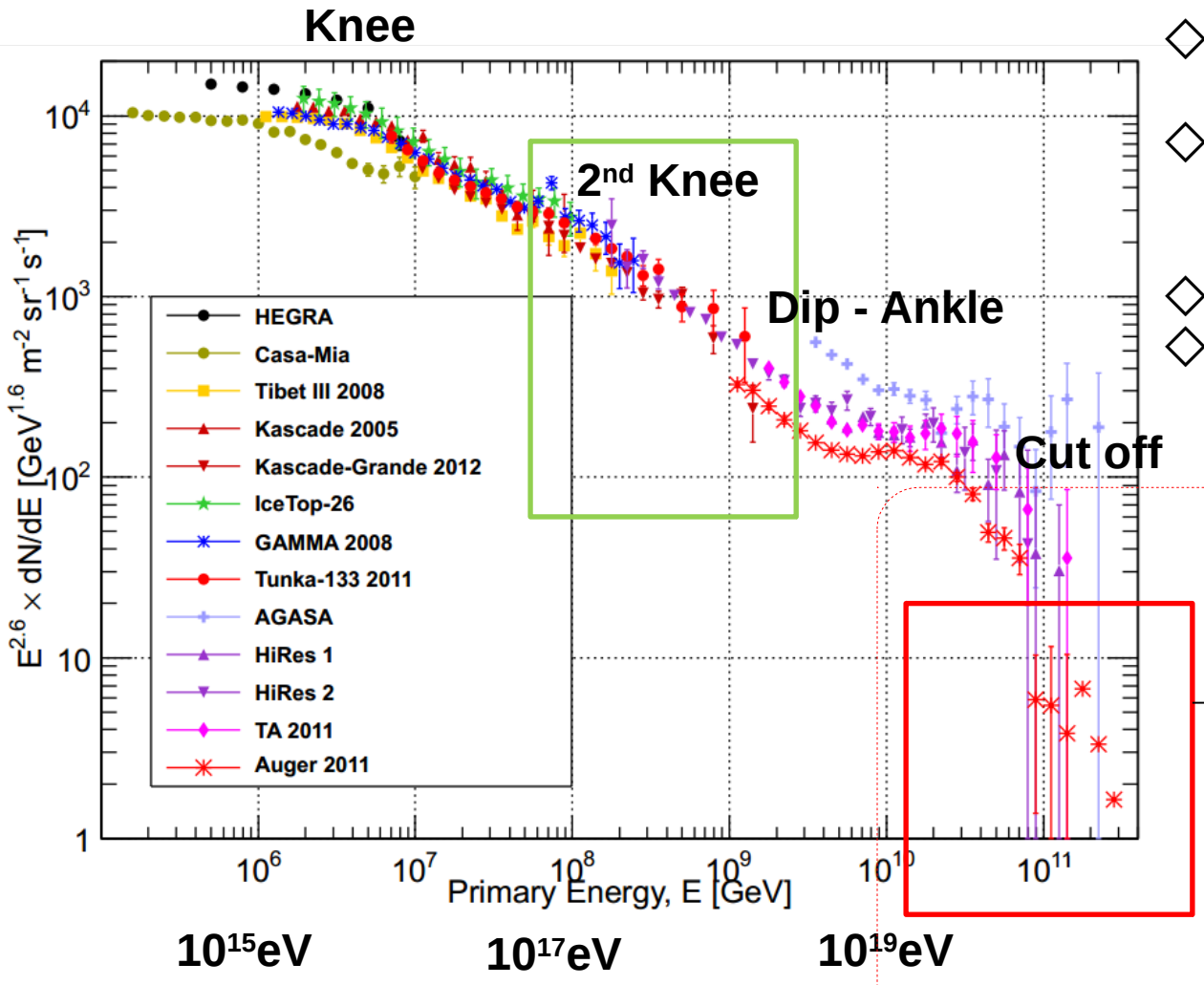
~130 collaborators from 5 countries
Belgium,Japan,Korea,Russia,USA

Ultra High Energy Cosmic Ray

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



◇ TA experiment covers 10^{16}eV – 10^{20}eV range

◇ At highest energy part, rigidity of the particle Is high.

◇ anisotropy is expected

◇ But flux of cosmic ray is very Small.

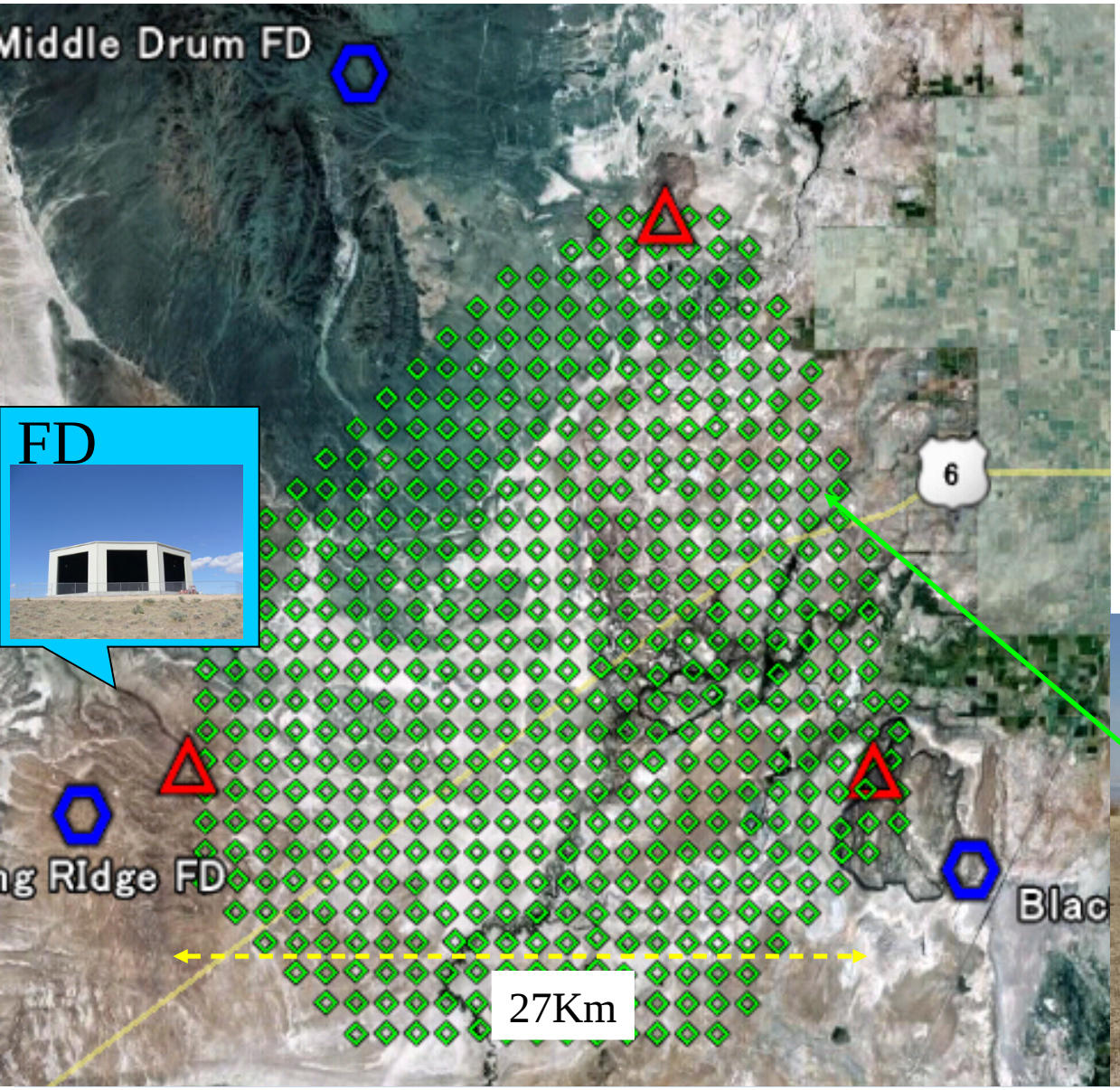
→ Large detection area.

Highest energy 10^{19}eV~

1event /km^2・year

extragalactic origin.

Telescope Array Detector



Location:N39.3° ,W112.9°

Alt 1350-1500m asl

◇ Fluorescence Detector

◇ Surface Detector

△ Comm Tower

●1.2 km grid SD (3m²)

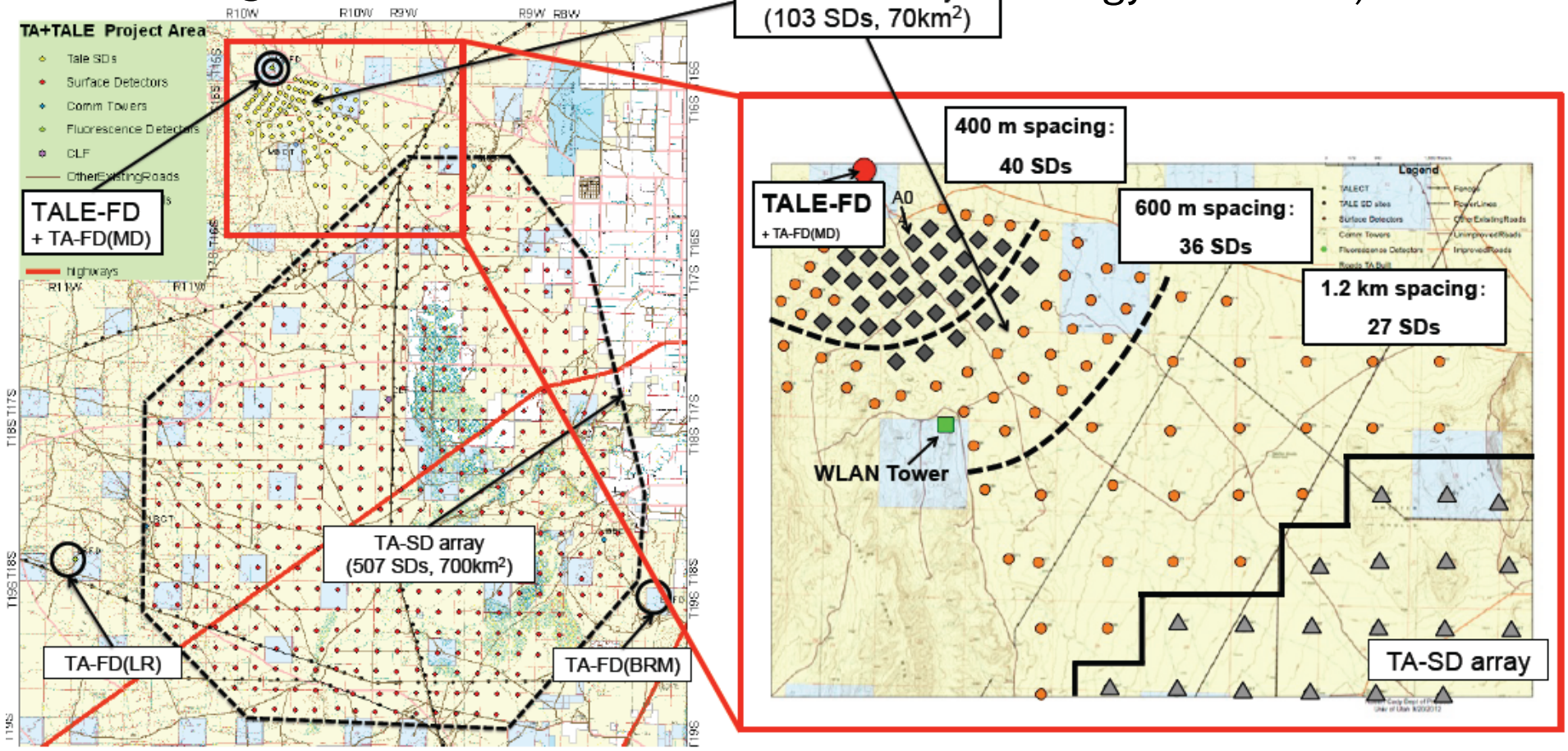
● 3 sub array :
+cross boundary trigger
→ Total 507 SD

●Detection area～700 km²

TA Low Energy extension (TALE)

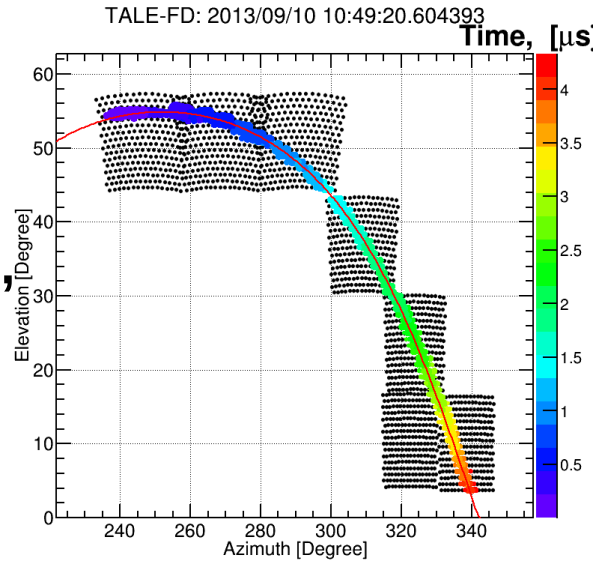
10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

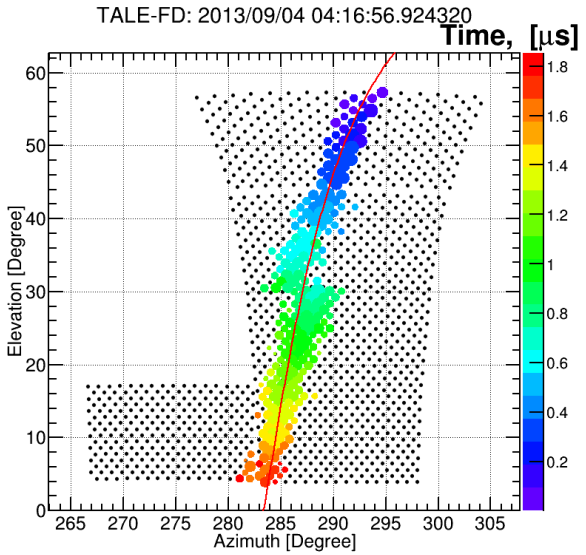
Infill surface detector array of more densely packed surface detectors (lower energy threshold)



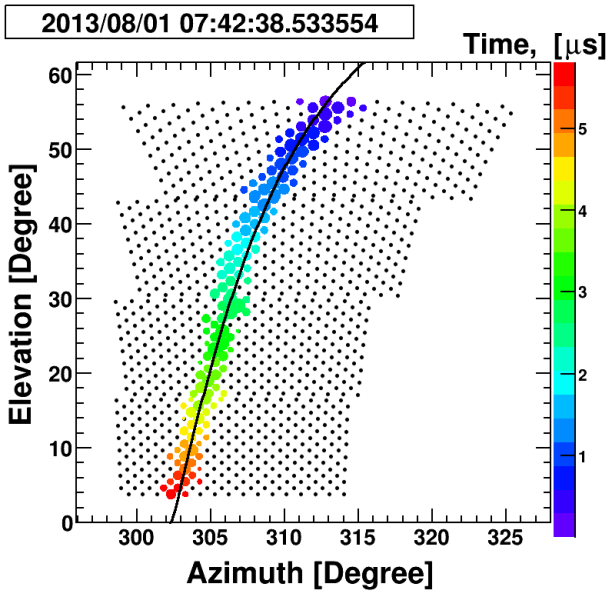
TALE event display

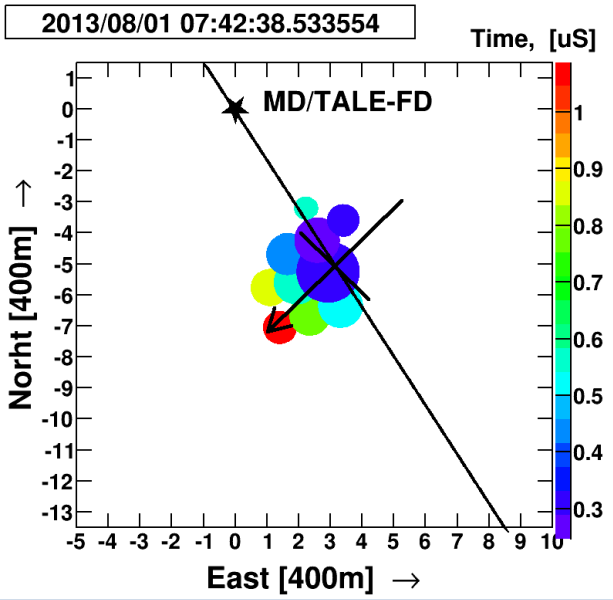
7 mirror event, log(E) = 16.5





Hybrid event



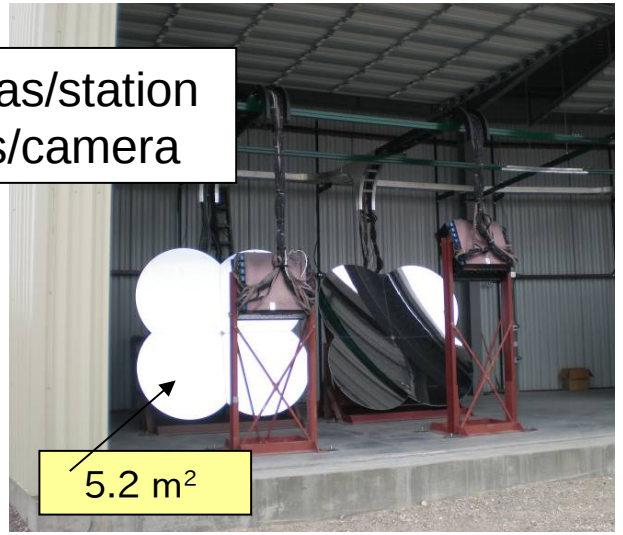


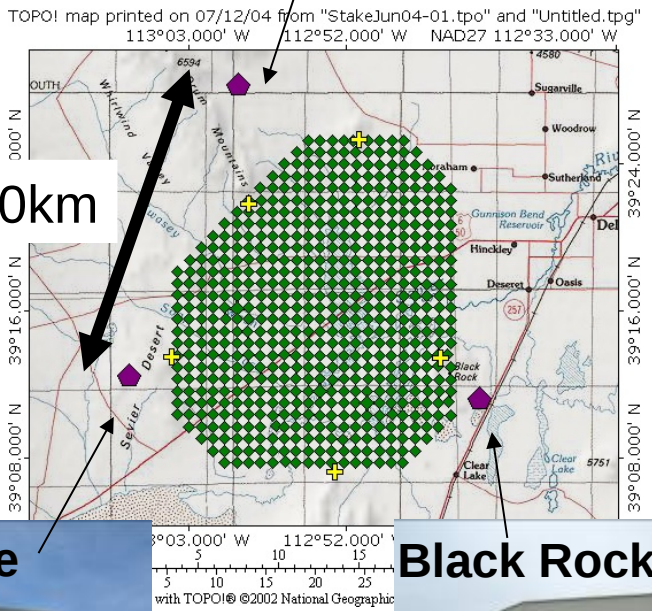
Telescope Array Fluorecence Detector

From HiRes

Middle Drum

14 cameras/station
256 PMTs/camera





~30km

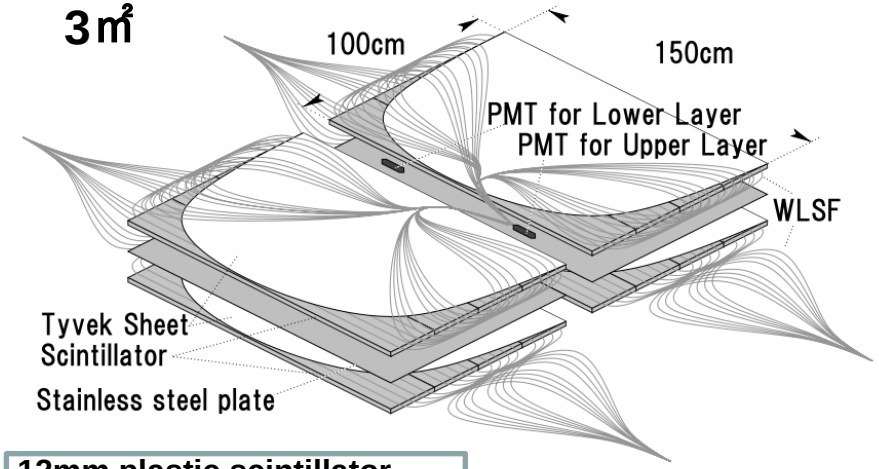
New FDs

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

Long Ridge

Black Rock Mesa

Telescope Array Surface Detector

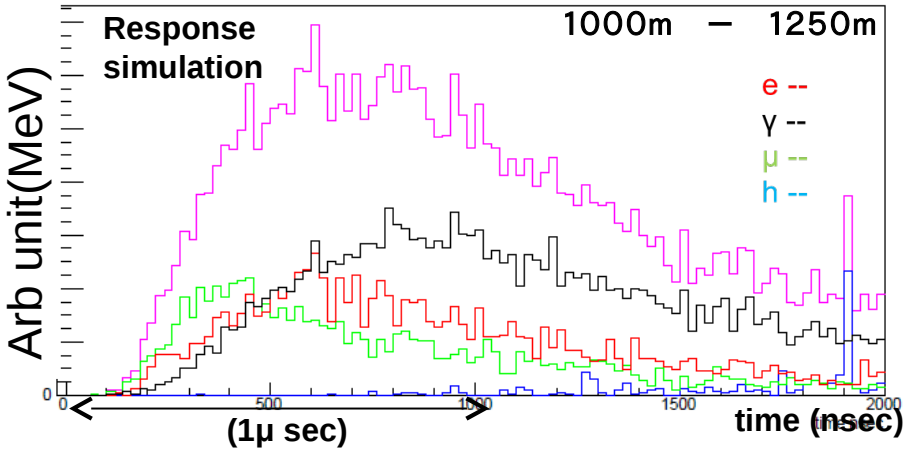


12mm plastic scintillator
1mm SUS
12mm plastic scintillator → **2 independent layer**

WLSF (475nm) x5m PMT ETL9124SA

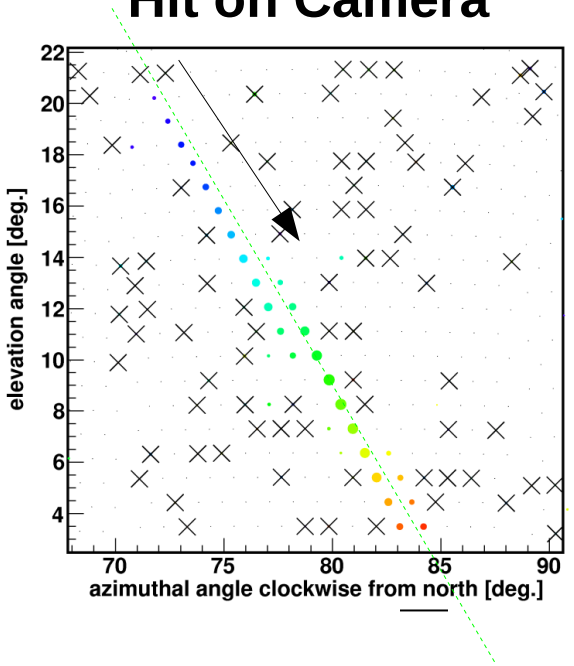
TASD:
- ◇**Signal = Scintillation light in detector**
- ◇**photons collected by WLSFs and guided to PMT**
- ◇**Thin scintillator = Low threshold EM component sensitive.**

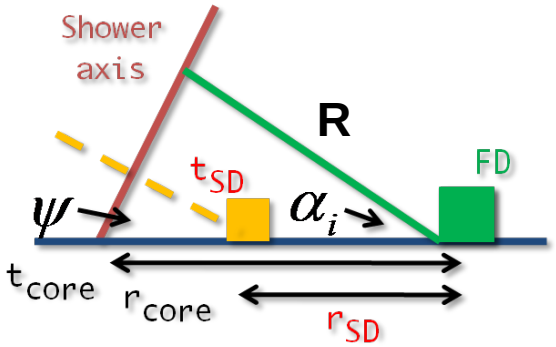
10^{19}eV Proton shower (stacked energy deposit)



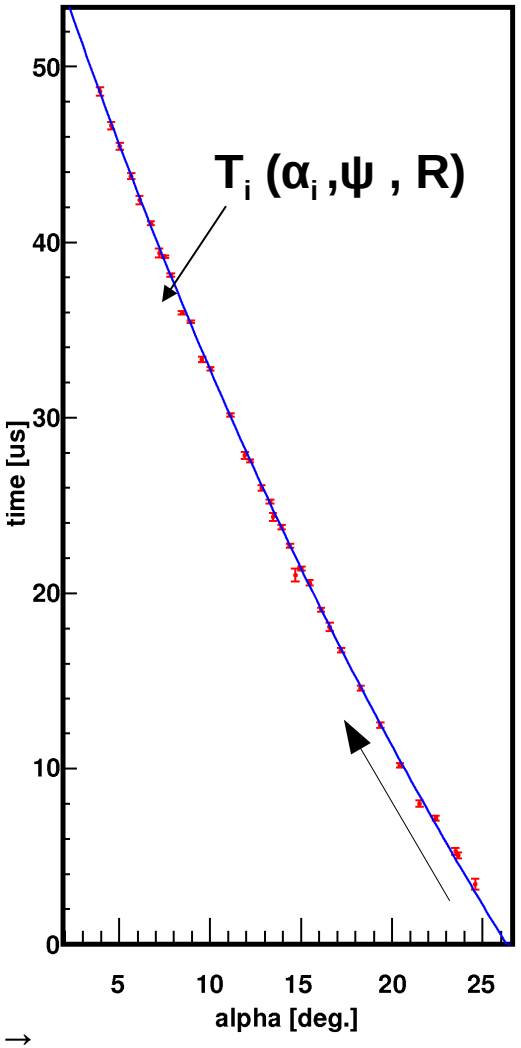
Telescope Array Fluorecence Detector

Hit on Camera

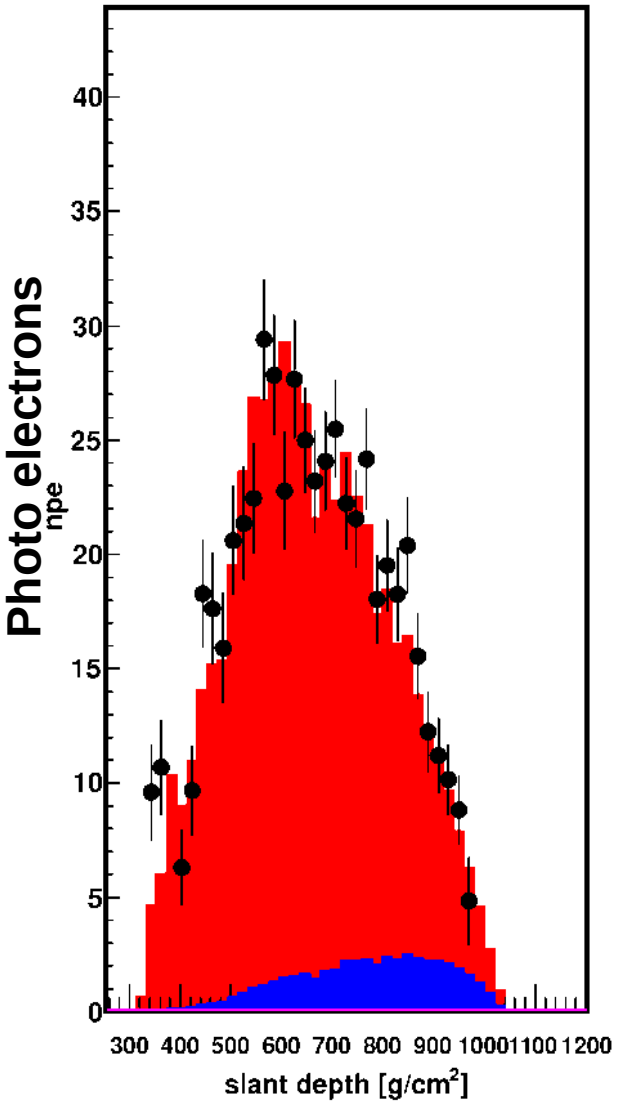




Geometry



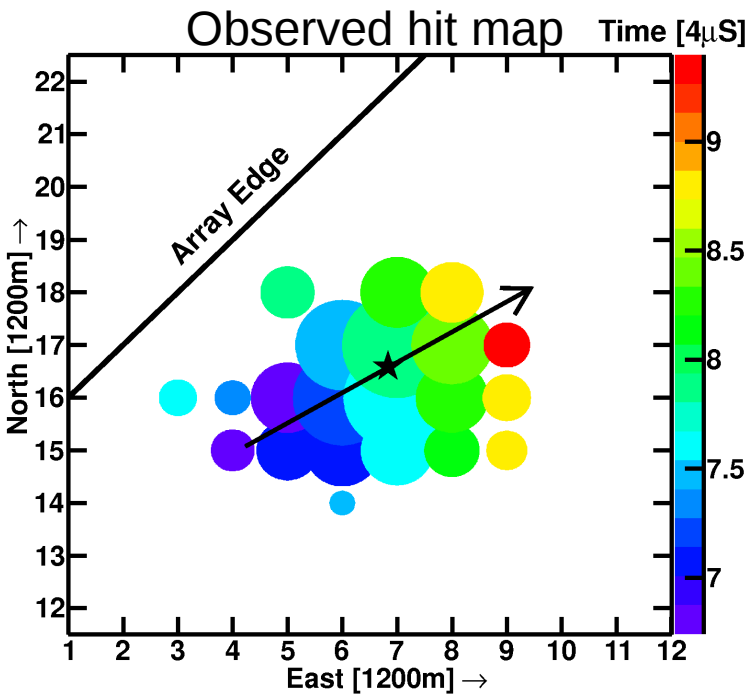
Energy

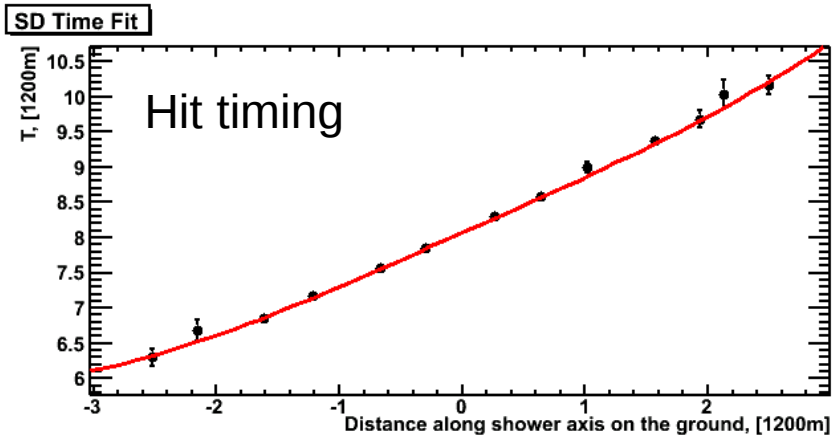


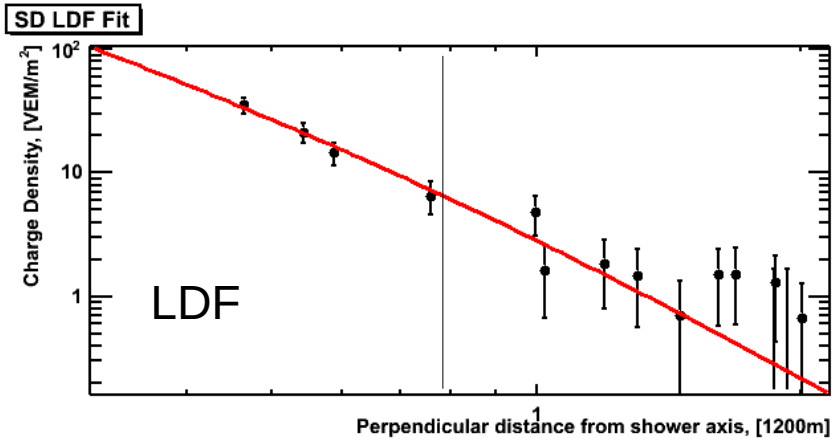
Use SD timing information →
Ψ、R resolution improve (Hybrid analysis)

Telescope Array Surface Detector

- An event hit map are shown
- Geometrical and LDF reconstruction fit is shown for this event.





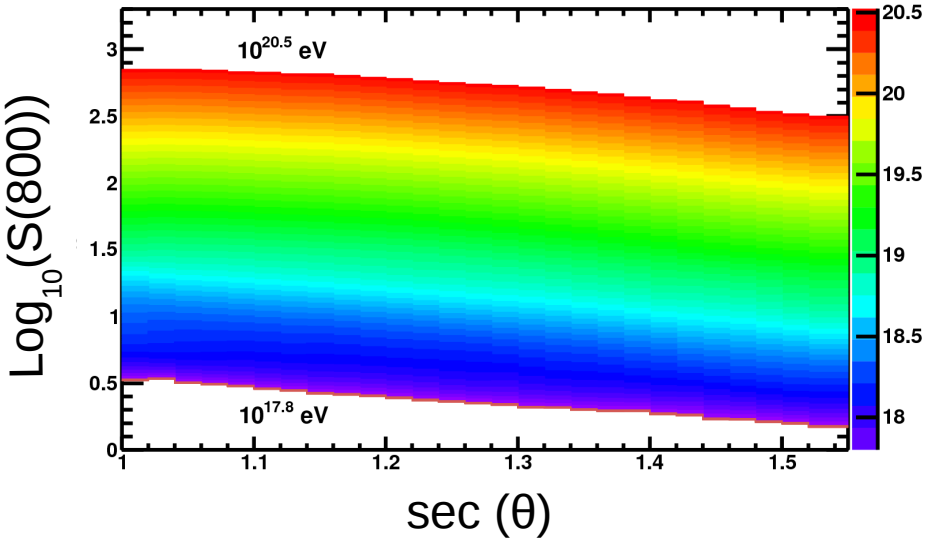


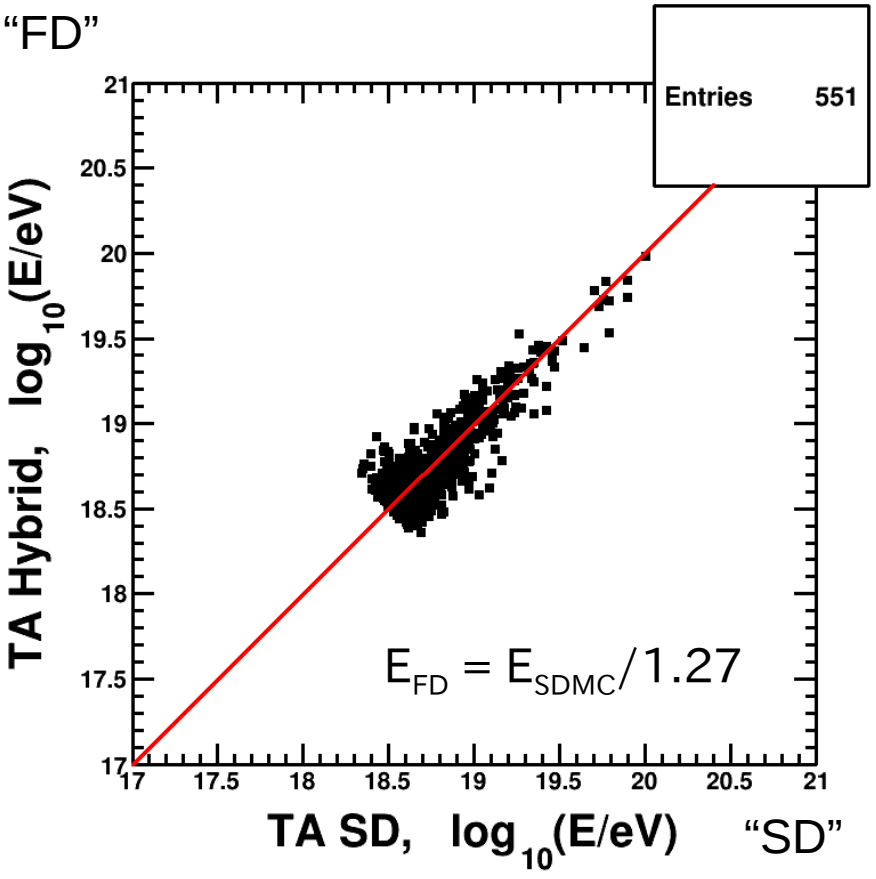
Hit timing : → Arrival direction
Lateral distribution of energy deposit → <u>Energy estimator "S(800)"</u>
(Energy deposit at 800m)

Telescope Array Surface Detector

Energy determination at SD

- Energy look up table generated by “MC”
- FD gives calorimetric energy.
- SD energy obtained by “MC” is calibrated with FD energy obtained at hybrid events.



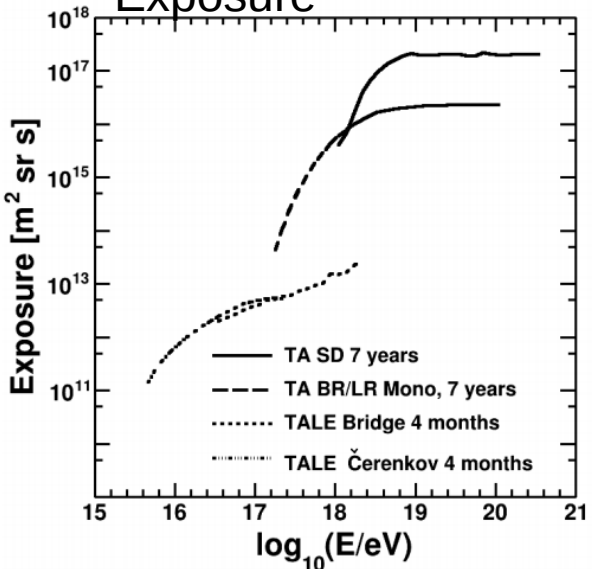


Results of Spectrum studies

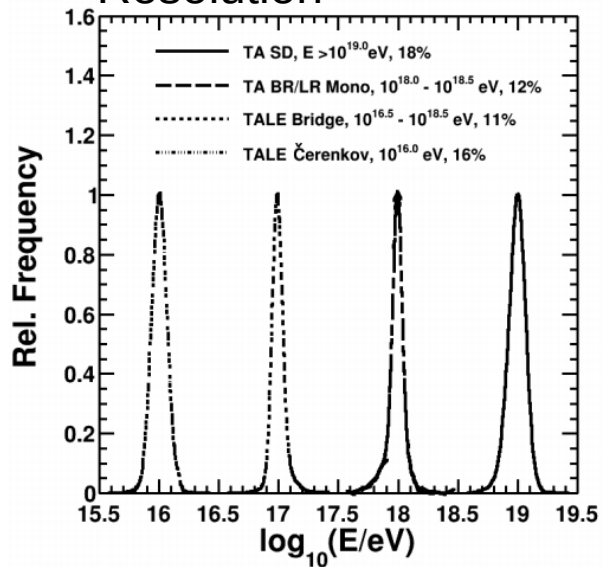
◇ New lower energy range spectrum from TALE FD observation
◇ TASD 7 year spectrum for higher energy range

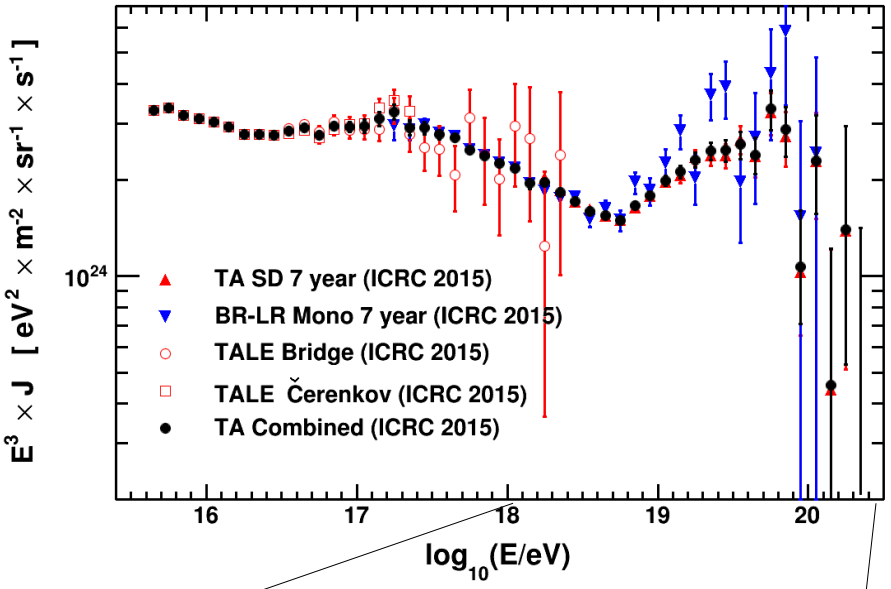
TA spectrum from E $10^{15.6}$ – $10^{20.3}$ eV

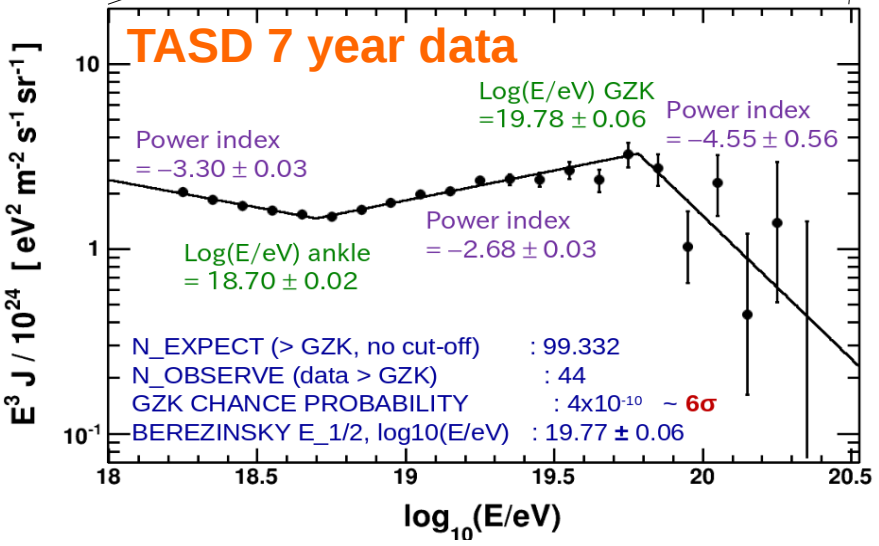
Exposure



Resolution



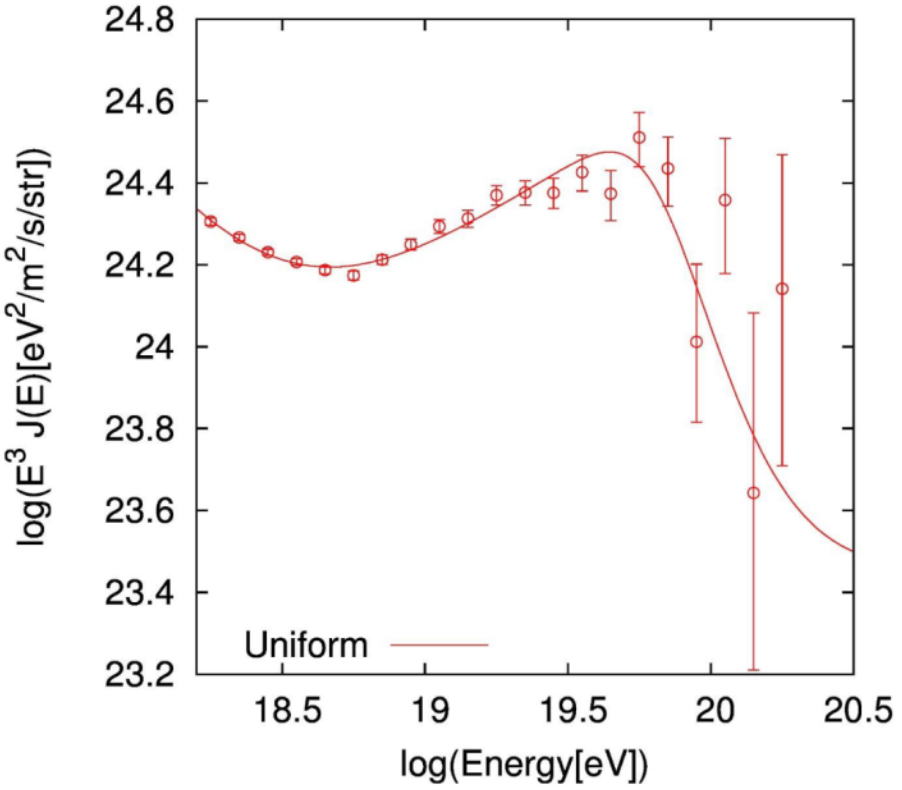


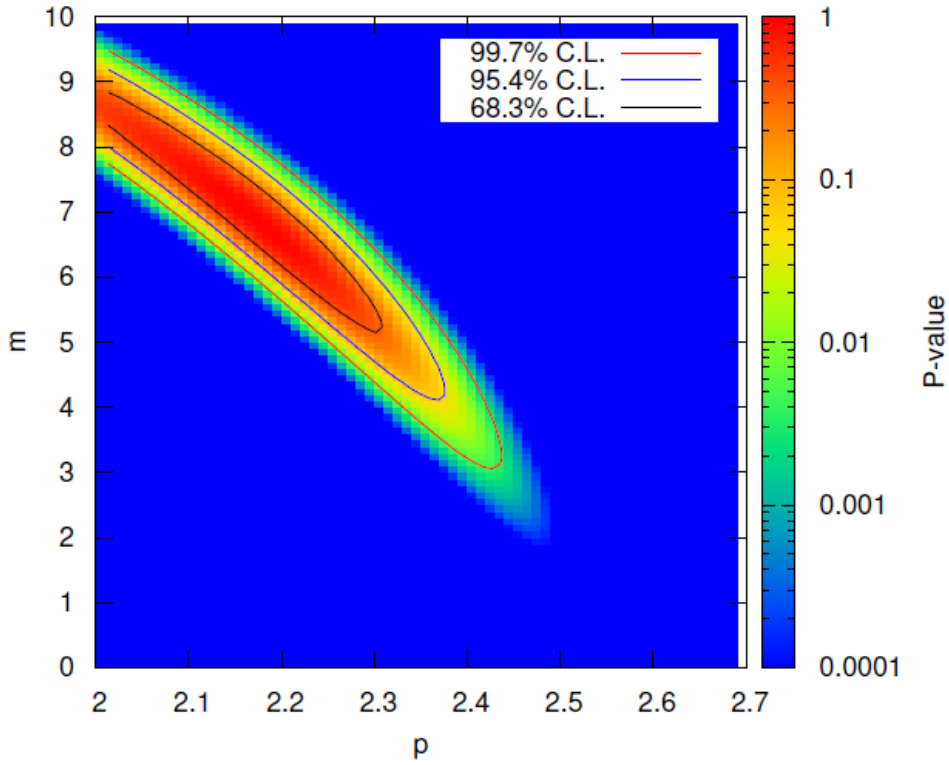


Fitting TA spectrum with proton model

- Uniform proton source distribution, $E > 10^{18.2}$ eV
- Injection spectrum E^{-p}, Emax = 10^{21} eV
- Source density $\propto (1 + z)^m$
- Consider energy losses with CMB and
- $z < 0.7$, $B_{IGMF} < 0.1$ nG

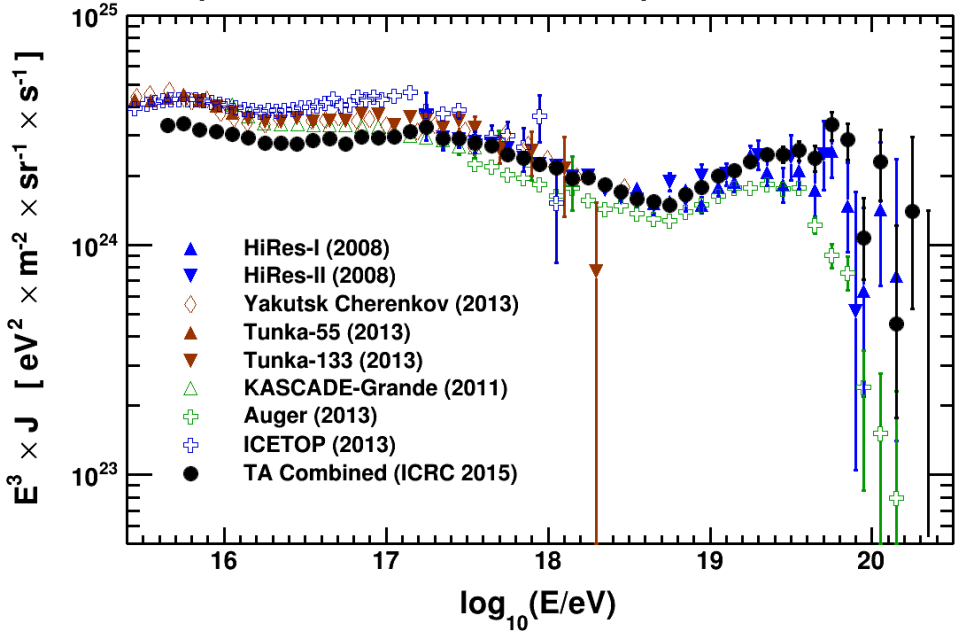
p = 2.18 + 0.08 - 0.14 [stat. + sys.]
m = 6.8 + 1.6 - 1.1 [stat. + sys.]
ΔlogE = -0.04 (-9%) + 0.04 – 0.03 [stat. + sys.]
$\chi 2$ = 18.0/17

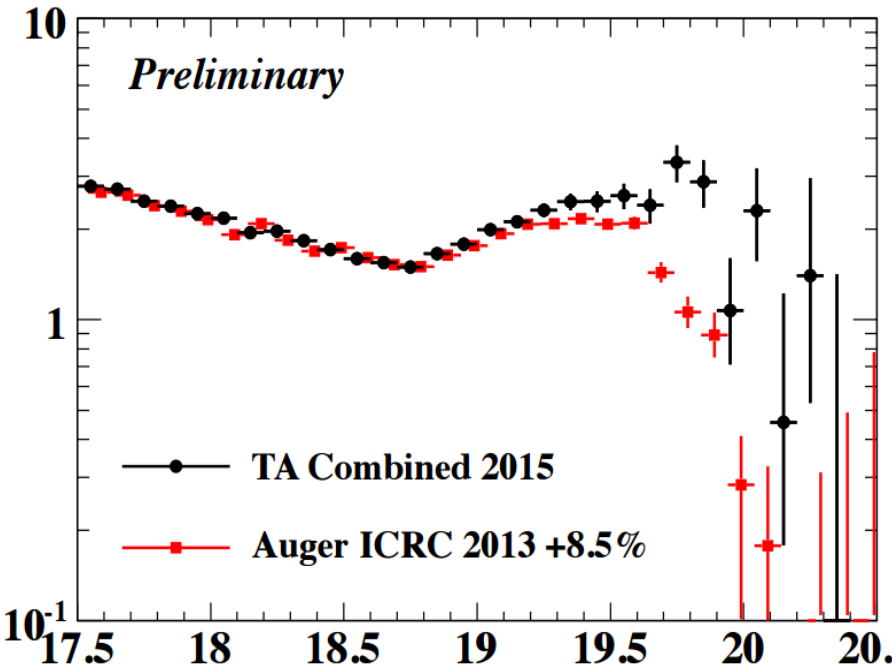




TA spectrum from E $10^{15.6}$ – $10^{20.3}$ eV

◇ Comparison with other experiments





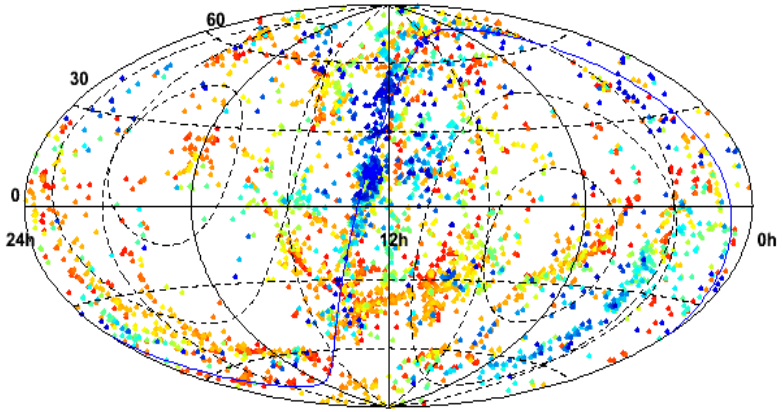
<Summary of Spectrum observation>

- TA measured the energy spectrum for 4.7 orders of magnitude ($10^{15.6}$- $10^{20.3}$ eV).
- Found 4 structure : "low energy ankle"@$10^{16.34}$eV "2^{nd} Knee"@$10^{17.3}$ eV "Ankle"@$10^{18.72}$eV "suppression" @ $10^{19.8}$eV
- @ E>$10^{18.2}$ eV spectrum shape are fitted with pure proton model
- Discrepancy with Auger in spectrum shape. @ E> $10^{19.3}$eV

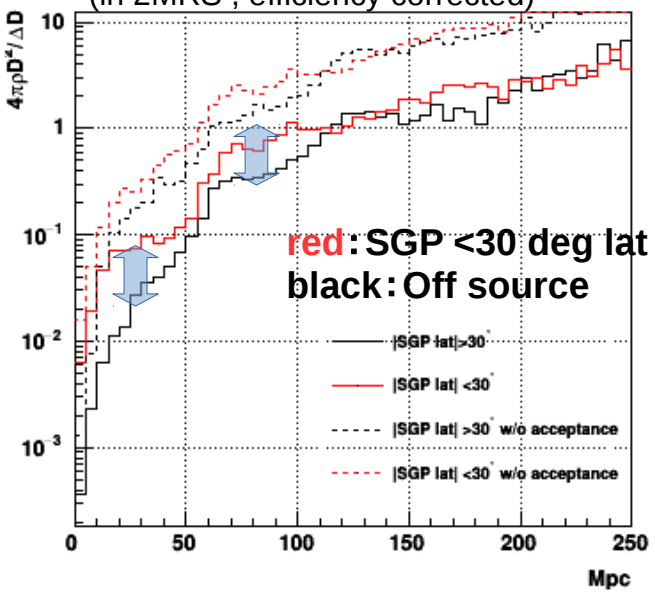
  Systematics or some hint for cosmic ray source?

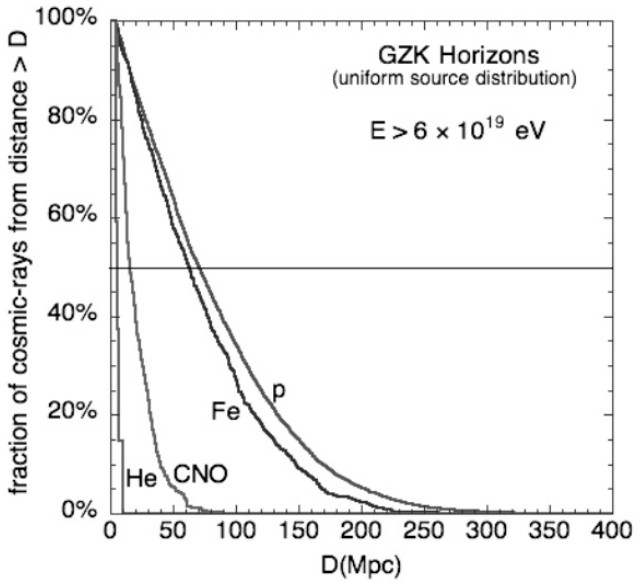
Anisotropy of spectrum shape in TA FOV

2MRS catalogue D<75Mpc
Blue～Redは corresponds to 0～75Mpc



Relative amount of objects
(in 2MRS , efficiency corrected)



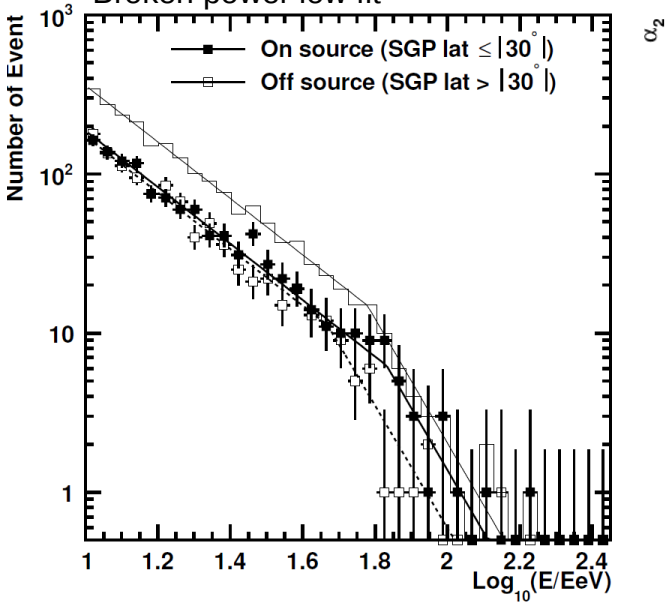


○ Matter distribution is different between direction of SGP, and not SGP
→ Reflecting energy loss process, spectrum Shape's difference should emerge
(More distance → More attenuation)

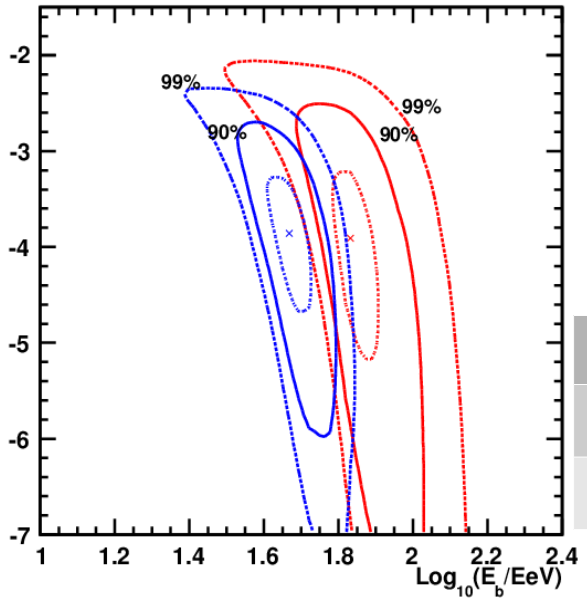
○ The attenuation depends on composition
→ Check attenuation and see consistency with an assumption of composition

Anisotropy of spectrum shape in TA FOV

Observed Energy distribution
Broken power low fit



Broken power low fit confidence contour
Break Energy and spectrum index at higher energy

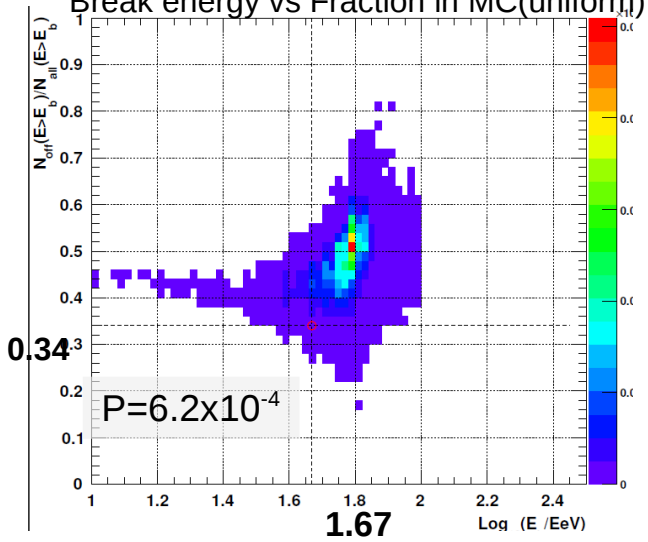


- Exposure ratio is 52:48 (**harf / harf , On/ Off**)
- identical observing condition. (eg. zenith angle)
-Off source shows early break and sudden attenuation.

	$\mathrm{Log_{10}(E_b/EeV)}$		Fraction (E>Eboff)	
On	1.83	(1.78)	0.66	(0.52)
Off	1.67	(1.78)	0.34	(0.48)

() expected
@ null hypo

Break energy vs Fraction in MC(uniform)



$\mathrm{Log_{10}(E_b/EeV)} = 1.67$

$\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} = 0.34$

- Observed feature agree with assumption from matter distribution qualitatively .
- C**hance probability** was evaluated by repeating same procedure to MC distribution (null hypo)
  P=6.2x10^{-4}（3.2σ）

Spectrum shape differ in TA FOV!

Directional comparison (w proton model)

◇ Assume 2MRS matter dist and Proton composition

Procedure

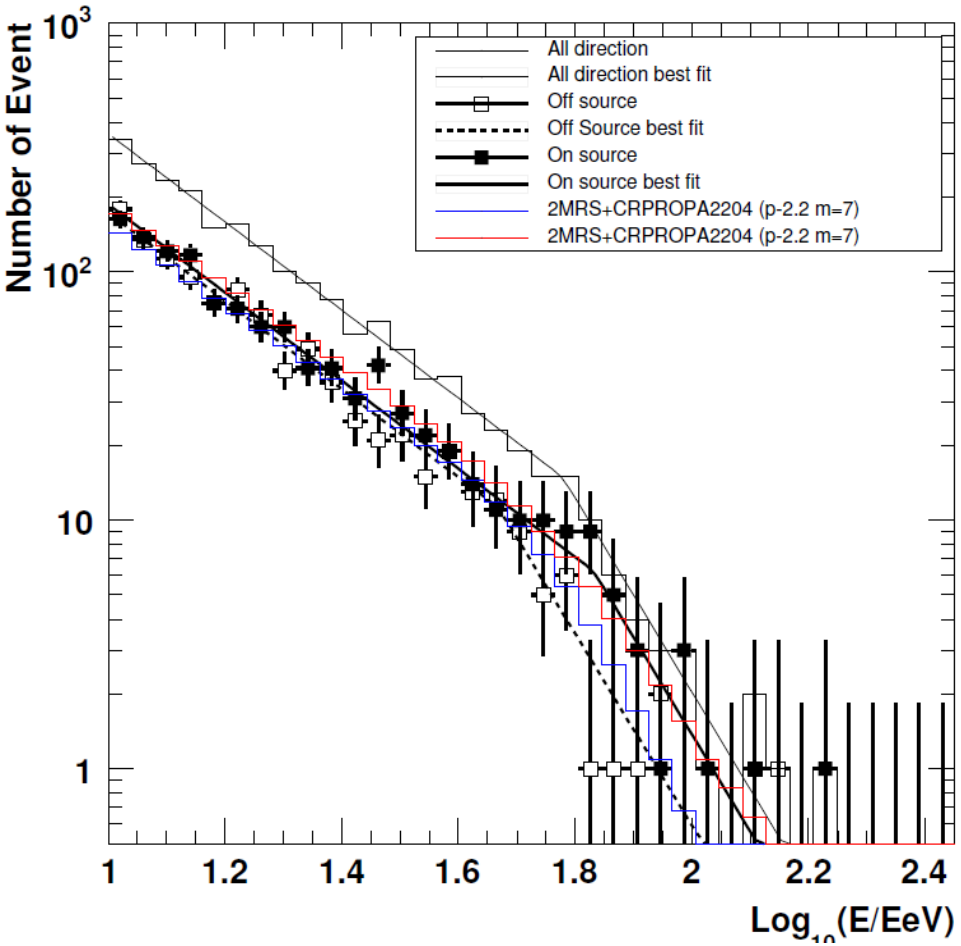
-Extract matter distribution from 2MRS catalog

- Propagate proton assuming source spectrum and evolutionParameter (CRPROPA 2.0.4) (P=-2.2 m=7 obtained E.Kido et.al)

- Calculate expected distribution of observed energy

- Scale the distribution with number of event in the data ($E>10^{19}$eV)

-result is shown in right side
- Red | SGP lat |< 30° (on source)
- Blue | SGP lat |> 30° (off source)



Off source : $E_b = 10^{19.67}$eV

MC expect E> E_b : 40(±0.4%) event

Data E> E_b : 30 event

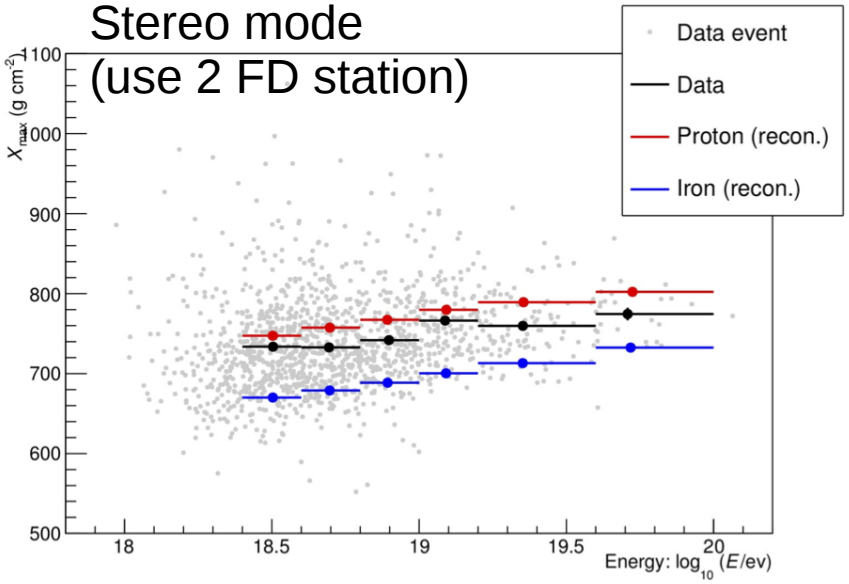
P~6%

■Spectrum attenuation observed at Off source region is still consistent with pure proton.

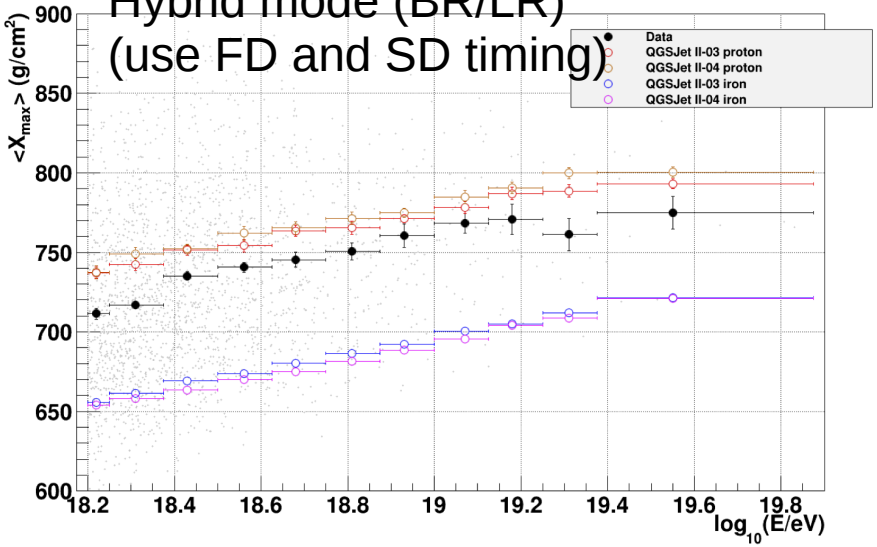
Results of Composition studies

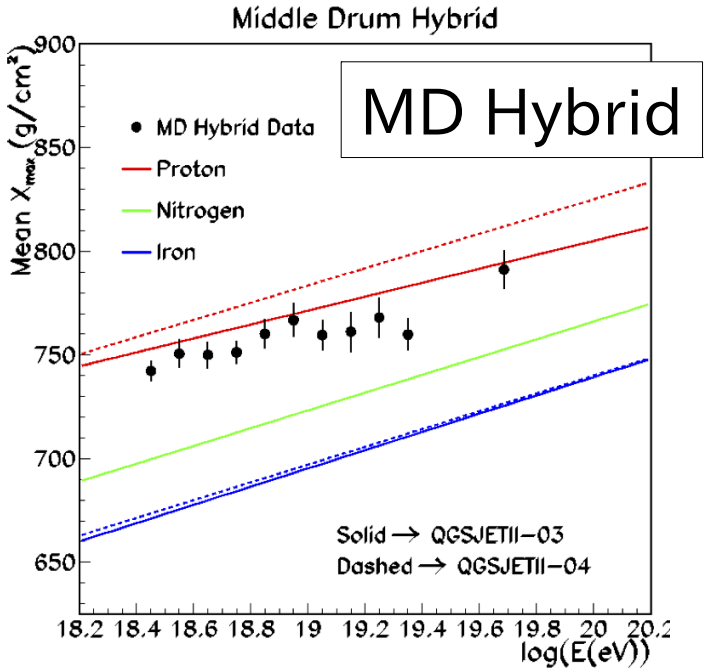
X_{max} measurements in TA

Stereo mode
(use 2 FD station)



Hybrid mode (BR/LR)
(use FD and SD timing)



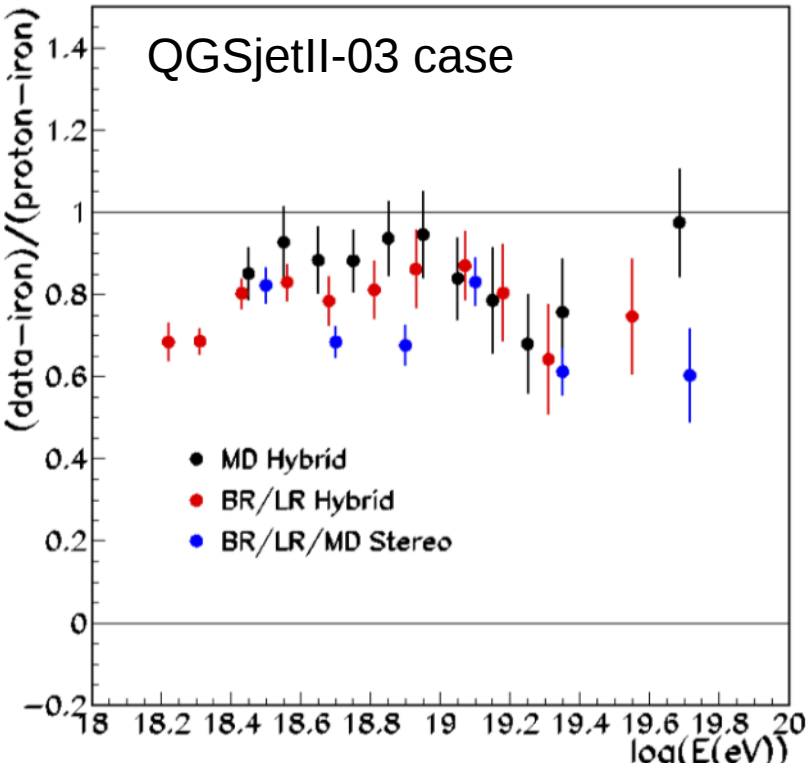


Xmax is composition sensitive parameter.
"Depth of shower maximum"

For all observing mode, slight shift from proton line. (stereo, hybrid, MD hybrid)
Red: Proton MC prediction.
Blue: Iron MC prediction.
Black : Observed data.

X_{max} measurements in TA

◇ For each analysis ,(data -iron) / (proton-iron) are calculated at each data point and compared with corresponding values of each composition



← P

← He

← N

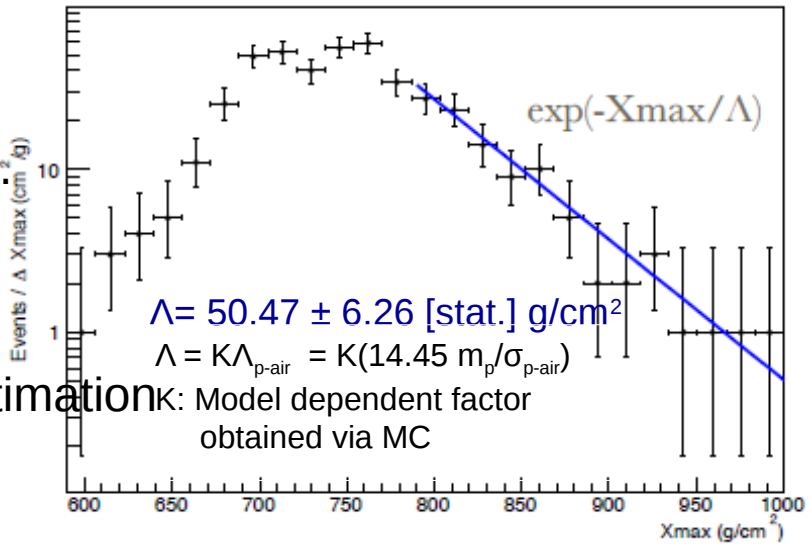
← Fe

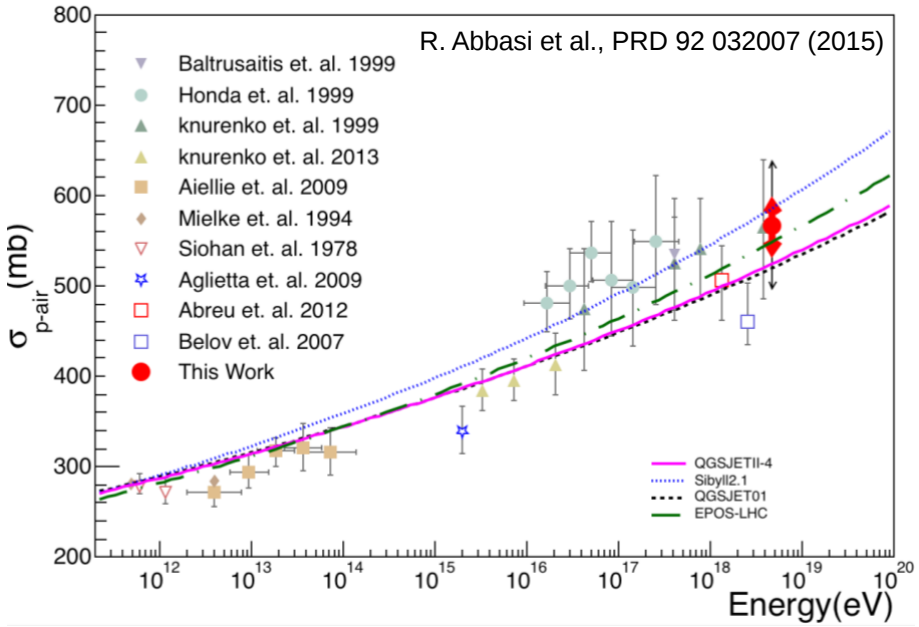
◇ Corresponding average lnA value is “light component”.
◇ It depends on Hadron Interaction model large.
◇ Difference of N and He makes large difference while understanding anisotropy.
◇ → **Hadron Interaction is important.**

P-air Inelastic Cross section

Methodology :

- ○ Using deep penetrating shower (proton),
- ○ Mean free path(Λ) is extracted from Xmax.
- ○ The factor k between ratio extracted Λ and true mean free path $\Lambda_{p\text{-}air}$ is estimated with MC.
- ○k's systematic is considered while error estimation.





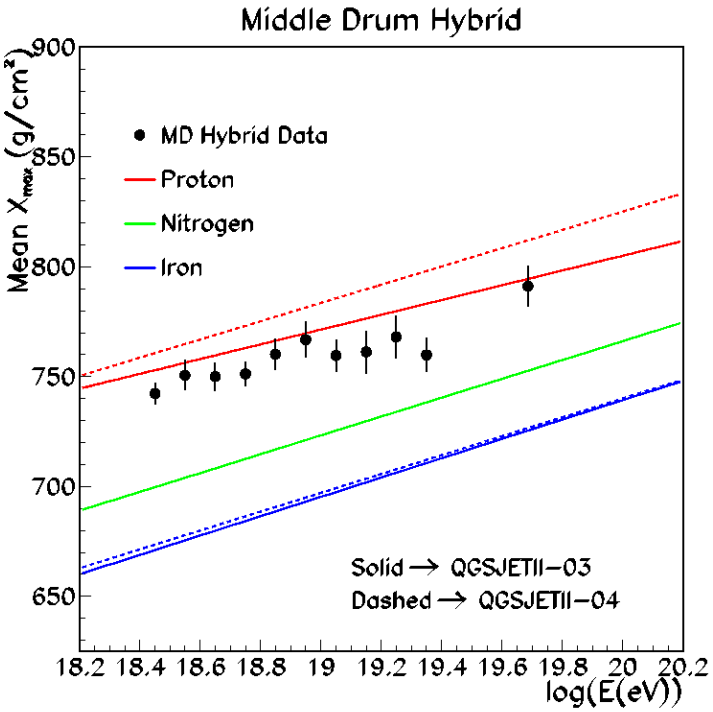
	Systematic [mb]
Model	+- 17
20% He	+18
Gamma < 1%	-23
Total	(+25, -29)

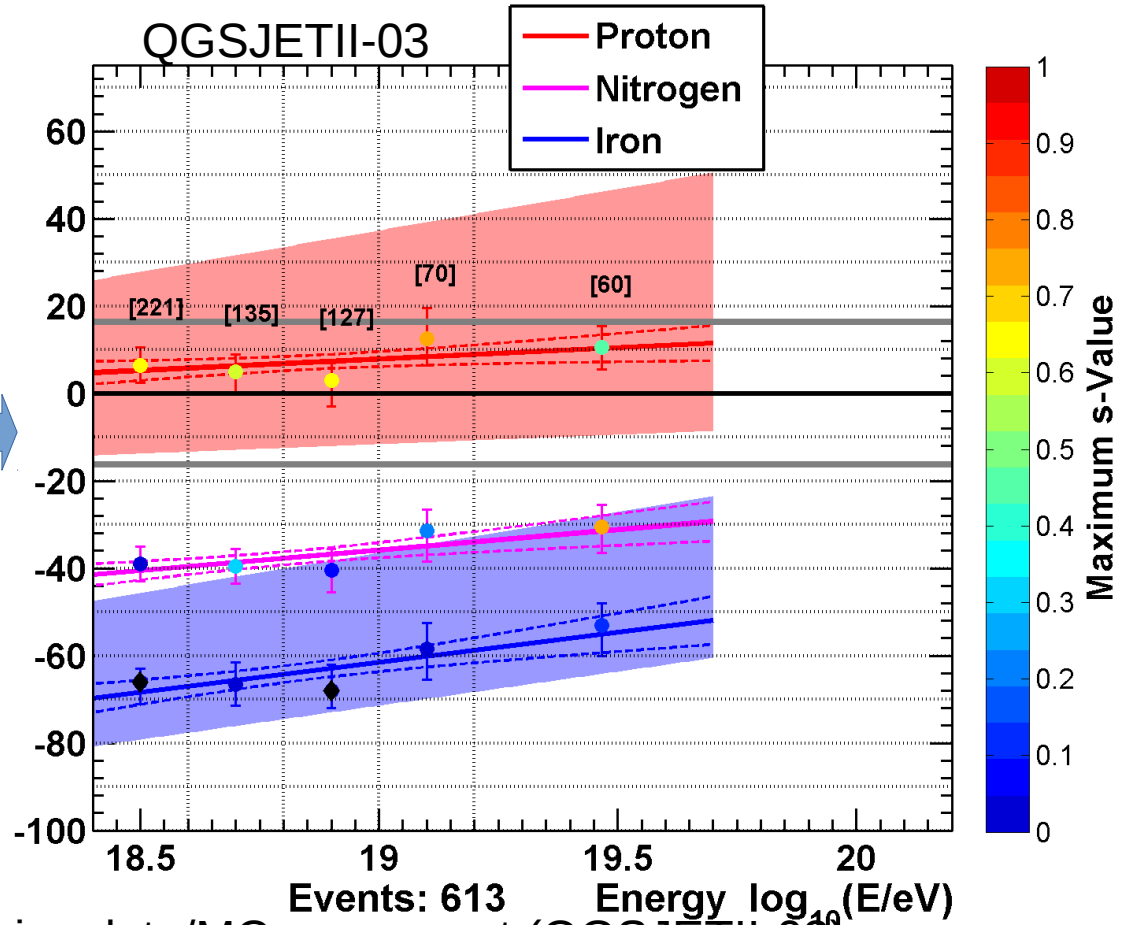
◇ $\sigma_{p\text{-}air}$(inelast.) @ 95TeV of √S is 567.0±70.5[Stat.] (+25,-29)[Sys.] mb

◇ The value observed is between EPOS-LHC and Sibyl2.1.

X_{max} distribution shape

Standard mean vs log(E) plot





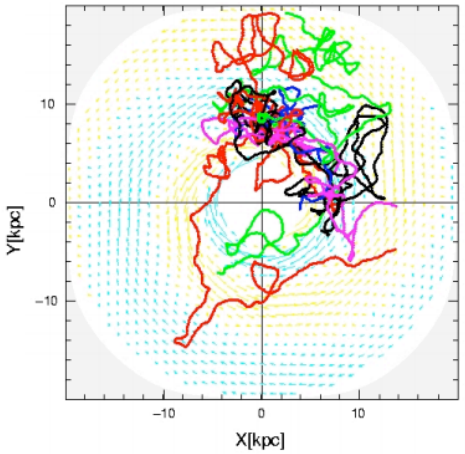
"Shift Plot"

Plot shows ΔX_{max} required to maximize data/MC agreement (QGSJETII-03). Color= Pvalue

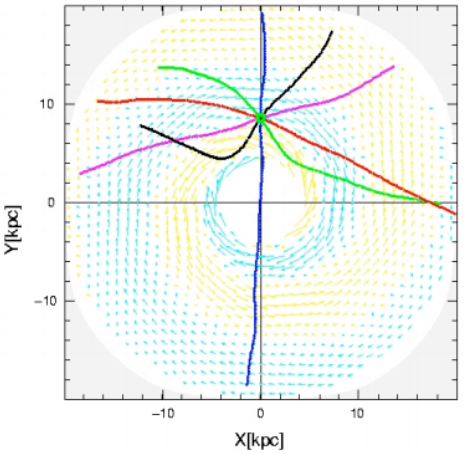
- ◇ Comparisons were done for single composition assumption.
- ◇ "Shape" is consistent with "proton".
- ◇ Standard statistical test on shifted distribution (points) Pink, blue bands for other hadronic models. 16 g/cm^2 systematic uncertainty.

Results of anisotropy studies

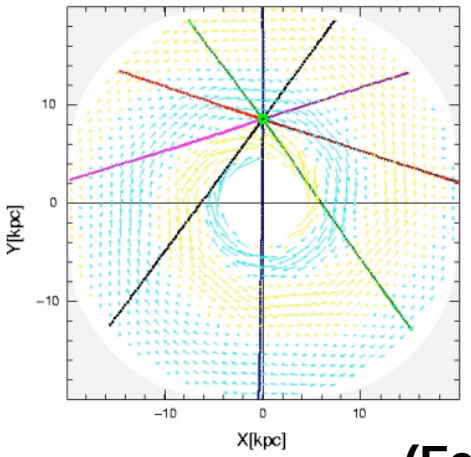
◇ **trajectory of cosmic ray in galactic magnetic field.** **Proton**



10^{18}eV



10^{19}eV



10^{20}eV **(Few degree)**

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

◇ **Effect of Inter Galactic Magnetic Field (IGMF): generally random field. B < ~10-^{9}G**

Few degree

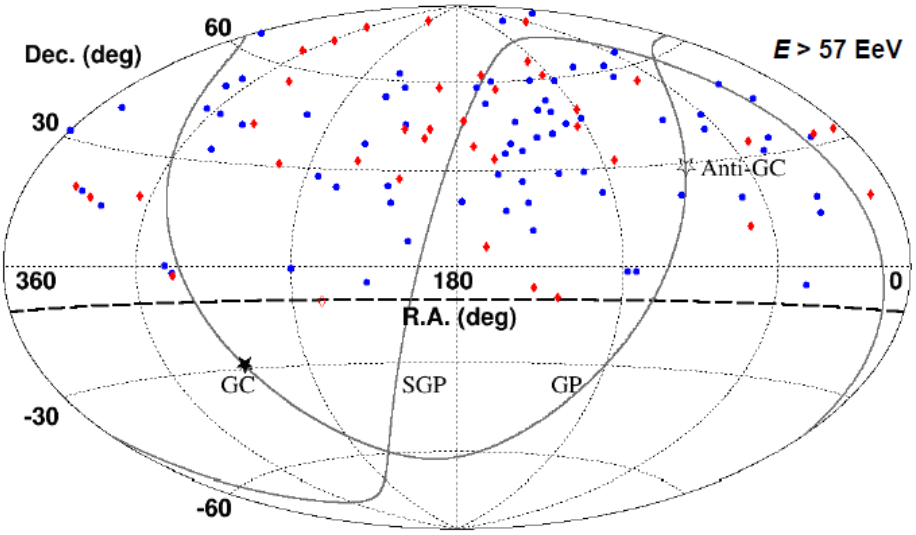
$$\theta(E,d) \simeq \frac{(2dl_c/9)^{1/2}}{r_g} \simeq 0.8^{\circ}\, q \left(\frac{E}{10^{20}\,eV}\right)^{-1} \left(\frac{d}{10\,Mpc}\right)^{1/2} \left(\frac{l_c}{1\,Mpc}\right)^{1/2} \left(\frac{B}{10^{-9}\,G}\right),$$

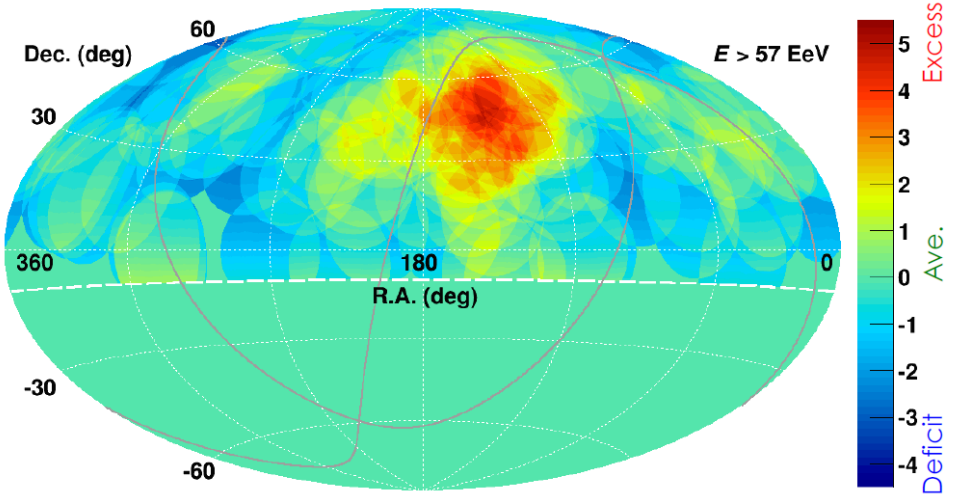
Anisotropy!

Updated Hot spot analysis (7 Year data)

Arrival direction of high energy event obtained from 7 year data.

- Oversampling using 20 deg. radius circles, Li-Ma significance.





Blue: 5 year data (published in *ApJL 790, L21 (2014)*)
Red: 6 and 7 year data (37 events)

Equatorial coordnate
ICRR 2015 Kawata

- **7 year** data 109 events (Zenith angle < 55 (deg.))
- Max significance: RA 148.4 (deg.) Dec 44.5 (deg.) (“Hotspot”)
  Observed: 24 events, isotropy: 6.88 events → Significance: 5.1σ (Li-Ma)
- Chance probability to exceed 5.1σ in the exposure: **3.4σ (0.037 %)** (post-trial)
  (15, 20, 25, 30, 35 (deg.) radius circles are searched.)
  3.4σ (0.037 %) was also obtained in **5 year** data in *ApJL 790, L21 (2014)*

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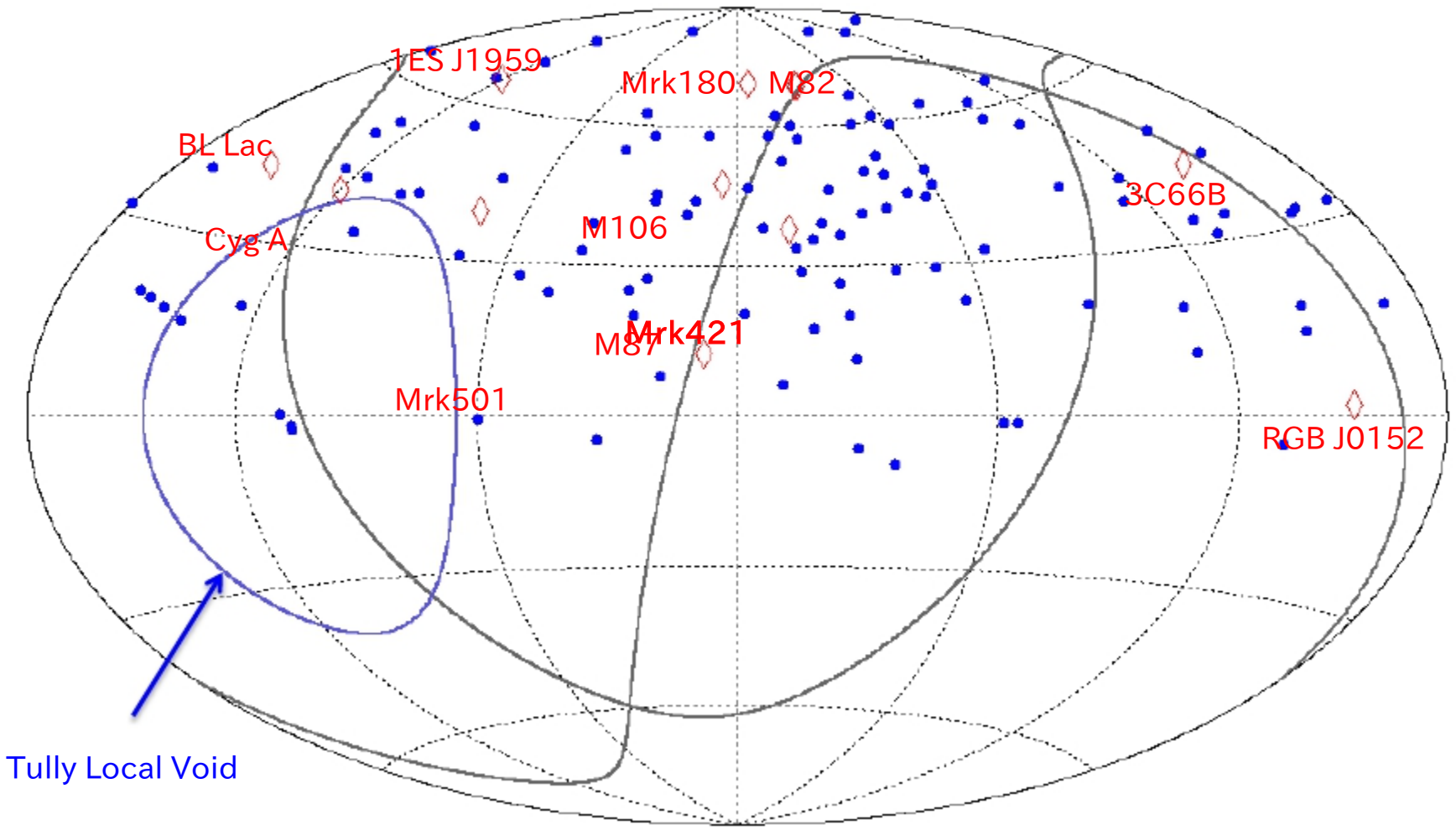
Nearby prominent source candidates

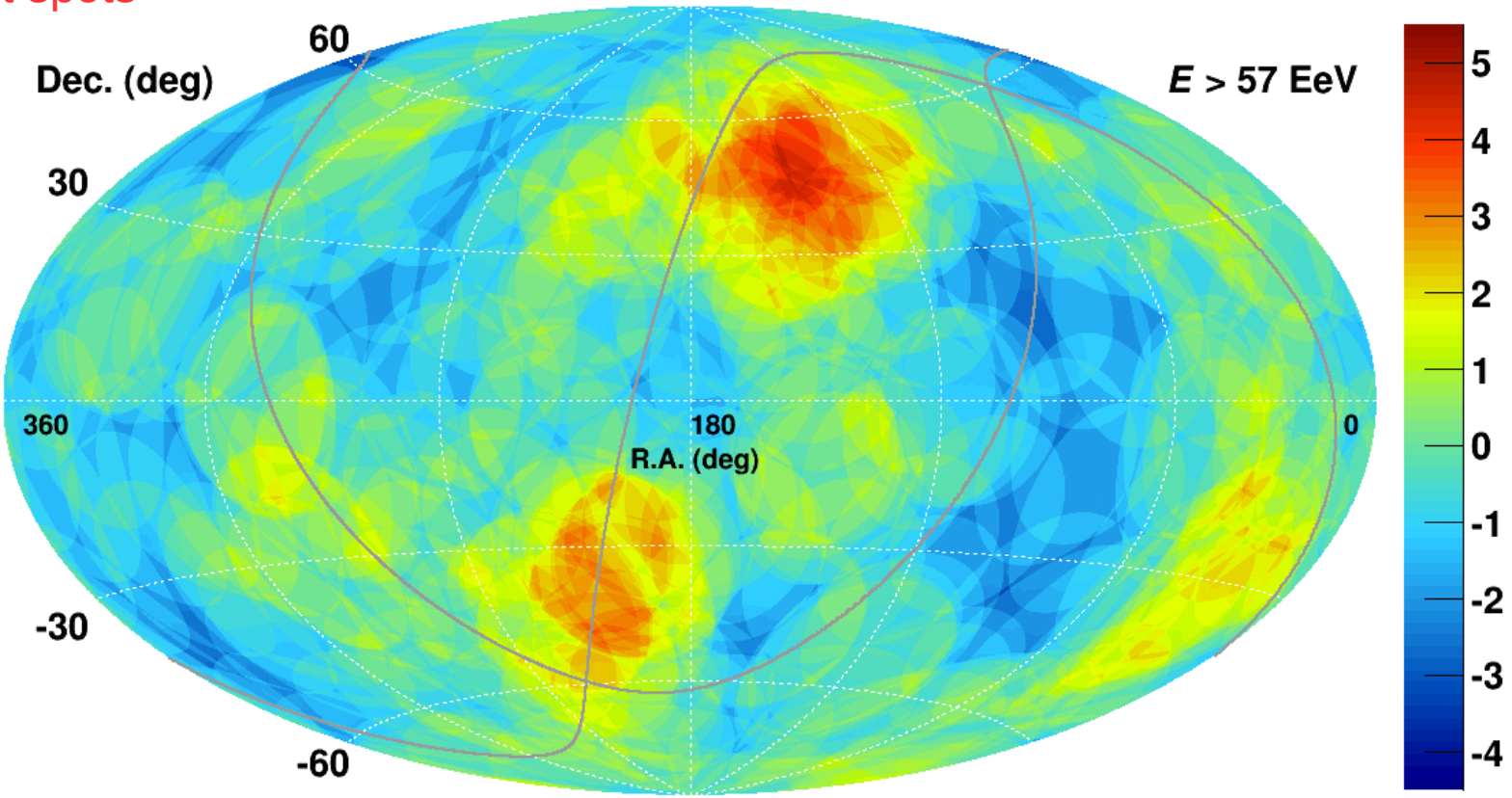


The blazar Mrk421, Mrk180 and starburst galaxy M82 are candidates?

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

TA + Auger Sky map

Hot spots

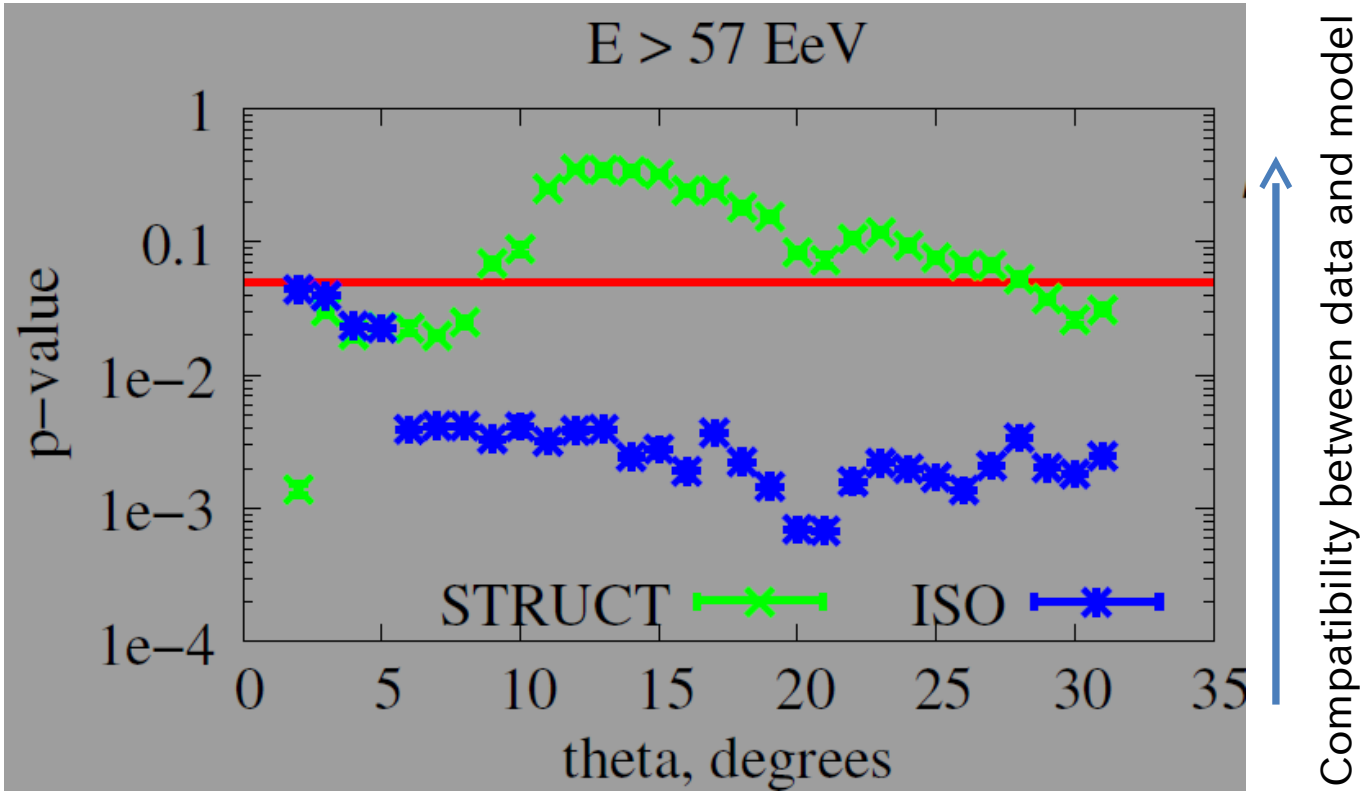


No correction for Energy scale difference b/w TA and Auger !!

TA : 7 years 109 events (>57EeV)
Auger : 10 years 157 events (>57EeV)
Southern hotspot is seen at Cen A(Pre-trial ~3.6σ)

Compativility with Large Scale Structure

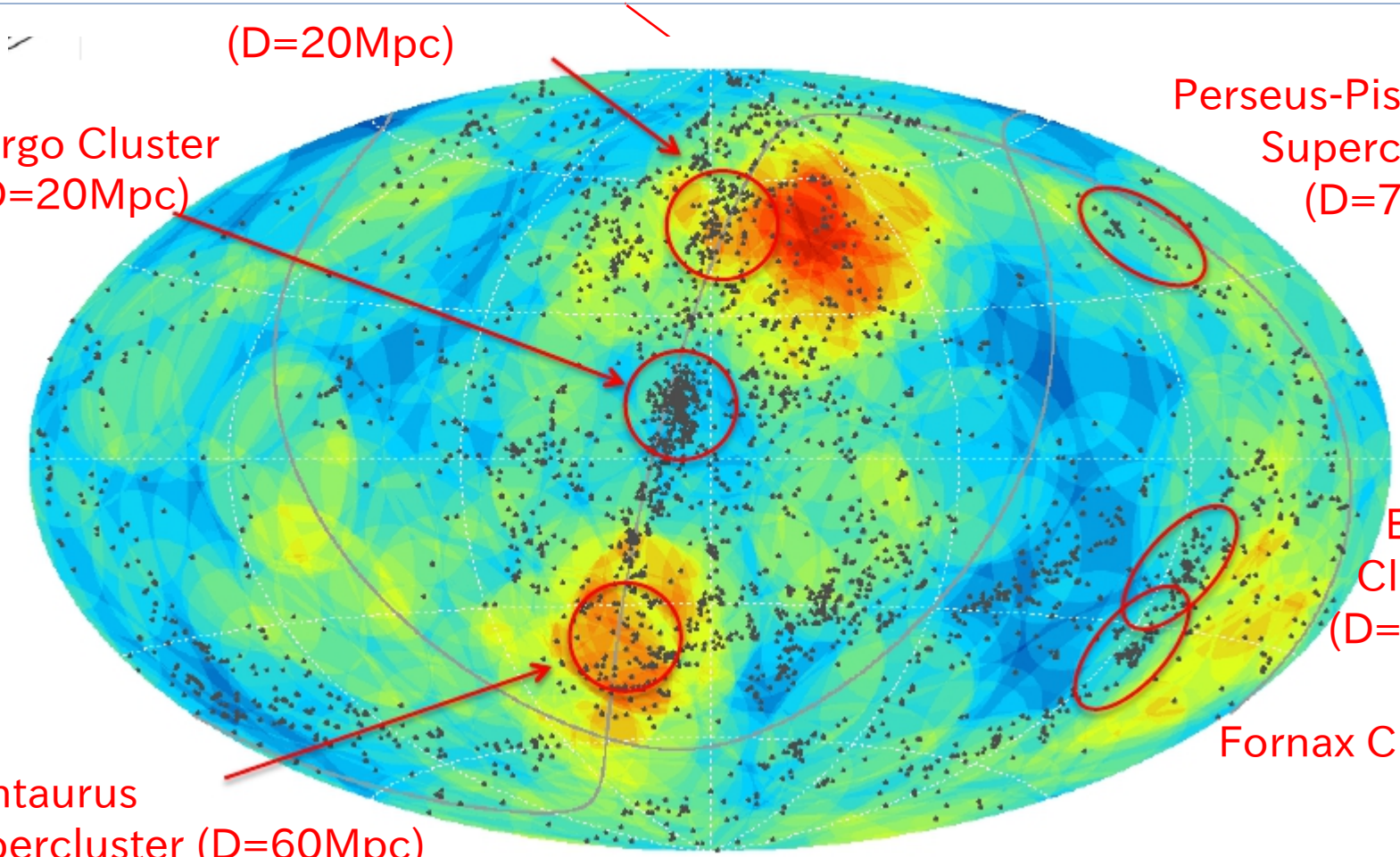
◇Map of expected event density is calculated from 2MRScat for all smearing angle. Distribution of number of observed events at the sky categorized with the expected event density are compared.



ICRC 2015 P. Tinyakov

◇ Data is incompatible with isotropic distribution. (smearing angle >5 deg)
◇ Data is most compatible with LSS when smearing angle is around 10-15 deg.

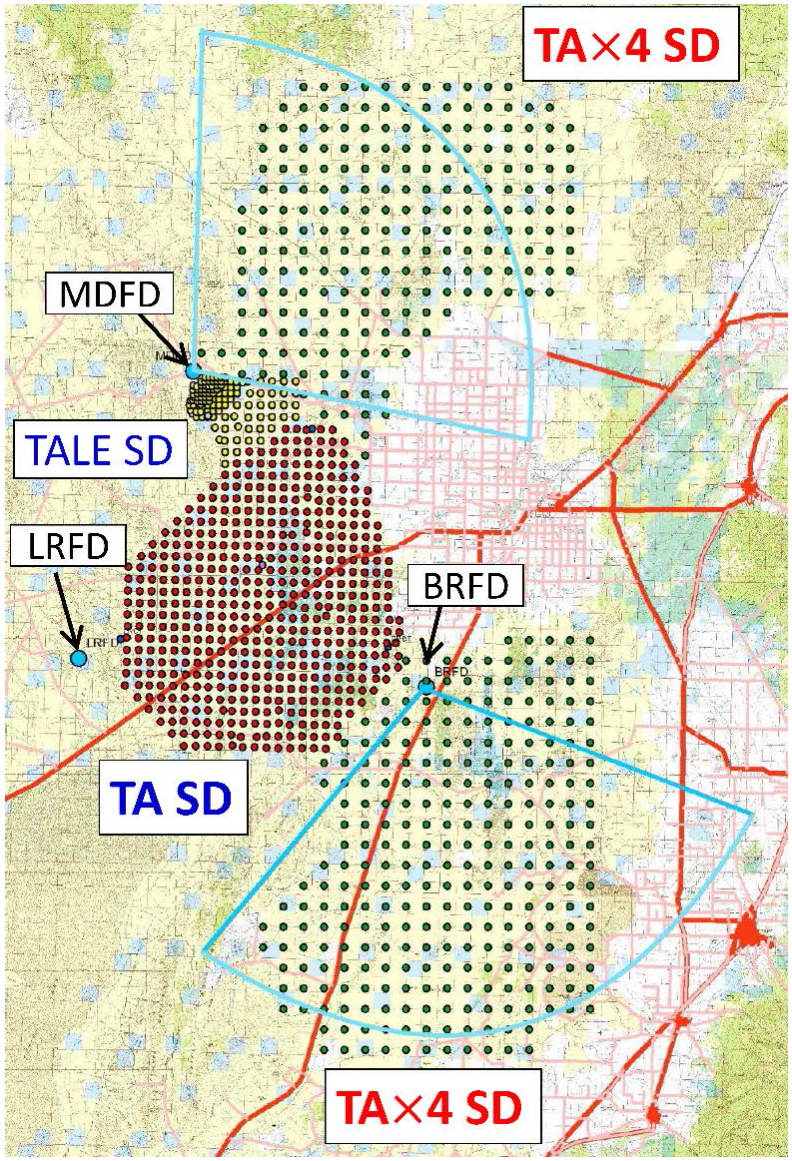
TA + Auger and nearby galaxy clusters



Huchra, et al, ApJ, (2012)

◇ Dots : 2MASS catalog Heliocentric velocity <3000 km/s
◇ TA hotspot is found near the Ursa Major Cluster
◇ TA & Auger found no excess in the direction of Virgo.

TAx4 Experiment



500 SDs, 2.08 km spacing

covers

~3x TA SD (about 2100 km^2)

Total about 4x TA SD 3000 km^2

(full operation:2017 Dec -)

→ ～ 12 year TA SD

～ 7 year TA SD from the extension

→～19 year TA SD data until 2020

2015 April approved

Summary

Spectrum :

- Spectrum for 4.7 orders of magnitude ($10^{15.6}$- $10^{20.3}$ eV).
- Composition around 2nd knee need to be confirmed.

→ **TALE hybrid observation. (Budget for TALE SD construction also approved)**

- E>$10^{18.2}$ eV, spectrum shape are fitted with pure proton model (E.Kido et.al ICRC2015)
- There is a discrepancy with Auger in spectrum shape. @ E> $10^{19.3}$eV
- Spectrum shape differ inside TA FOV depending on the direction.
  The difference is qualitatively consistent with matter distribution.

Composition:

- Observations of Xmax show mean <Xmax> as “Light component”.
- The result depends on Hadron interaction model largely.
- Using FD Xmax, P-Air cross section were obtained.
- more measurement to check Hadronic interaction model is needed.

→ **Multi component measurement in air shower. (muon timing, mu/electron)**

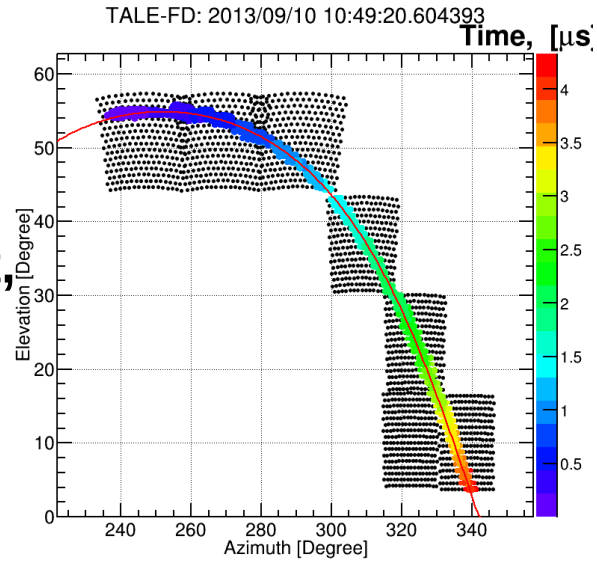
Anisotropy: (many studies)

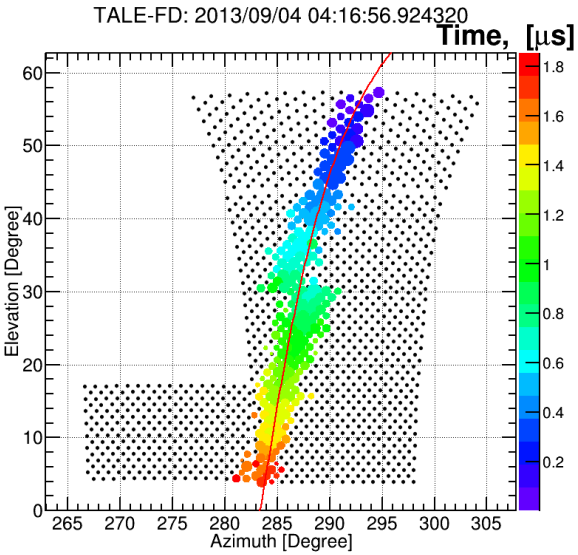
- Hot spot result is updated to 7 year data. Statistical significance is 3.4 sigma.
- Combining Auger data, entire sky map were drawn with 20deg over sampling.
  It shows 2-3 area at where event density is high. They align near SGP.
- Distribution of E>57EeV events are most compatible to LSS while smearing angle is 10-15 deg.

→ **More statistics. (TAx4 array)**

TALE Events

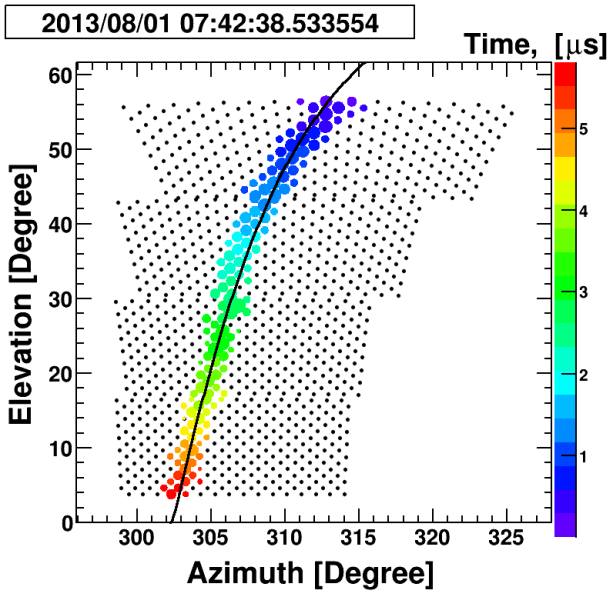
7 mirror event, log(E) = 16.5

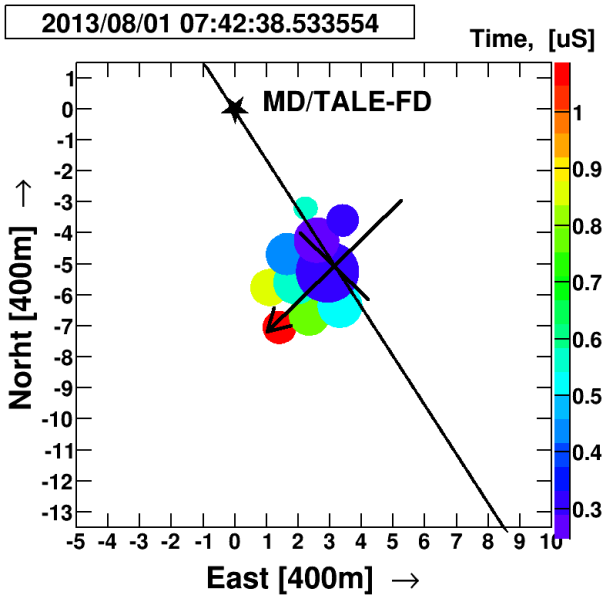




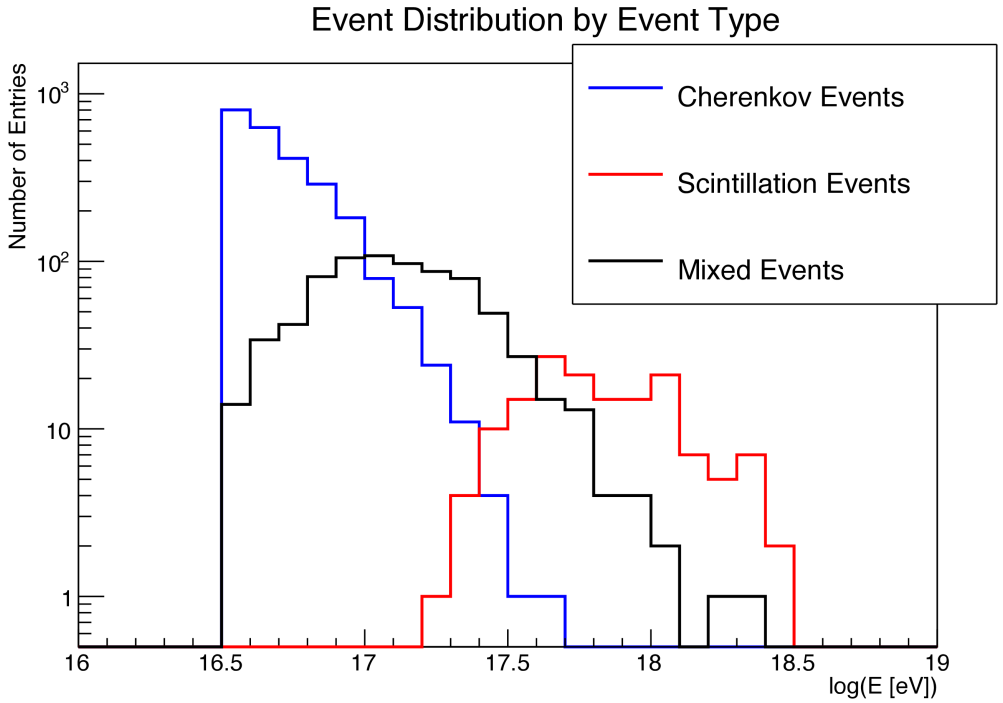
Parallax event, R_p=800m

Hybrid event



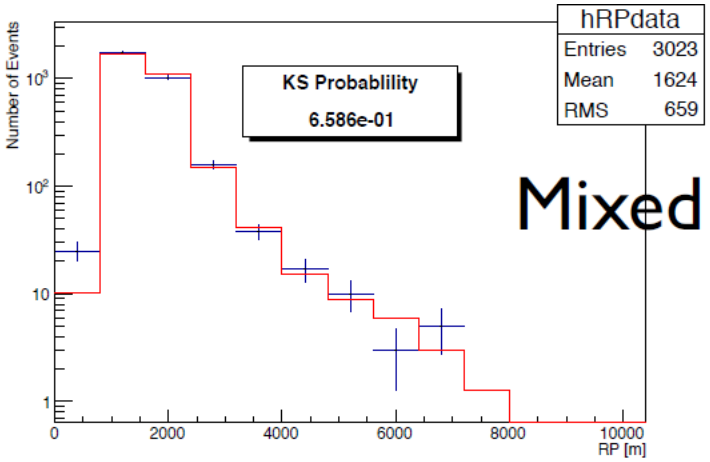


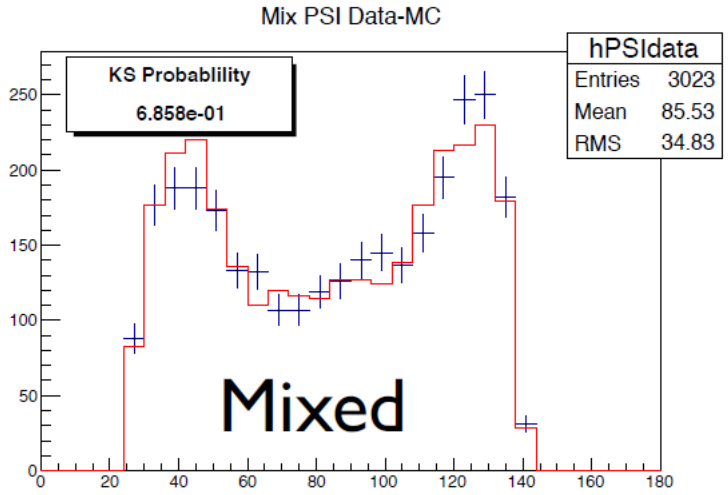
TALE Cherenkov vsFluorescence

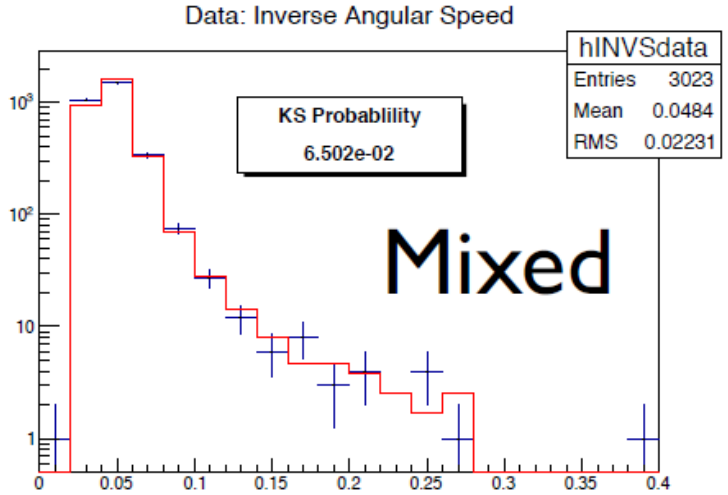


Unexpected result: many Cherenkov events are seen as tracks (most land ~0.5 km from FD). Use profile constrained reconstruction. Cherenkov light is bright → can go lower in energy than expected.

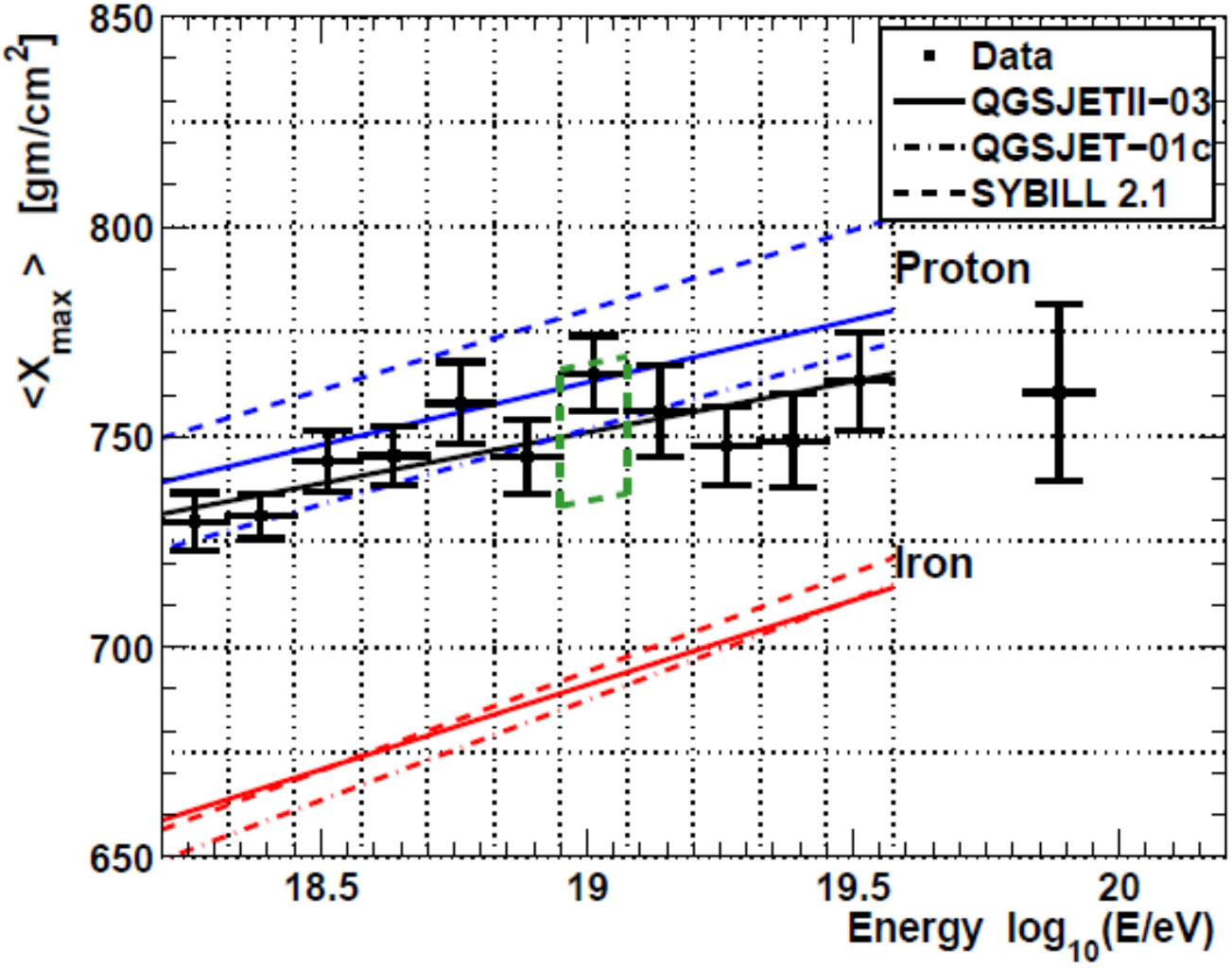
TALE DATA/MC Comparisons







Published Hybrid Composition

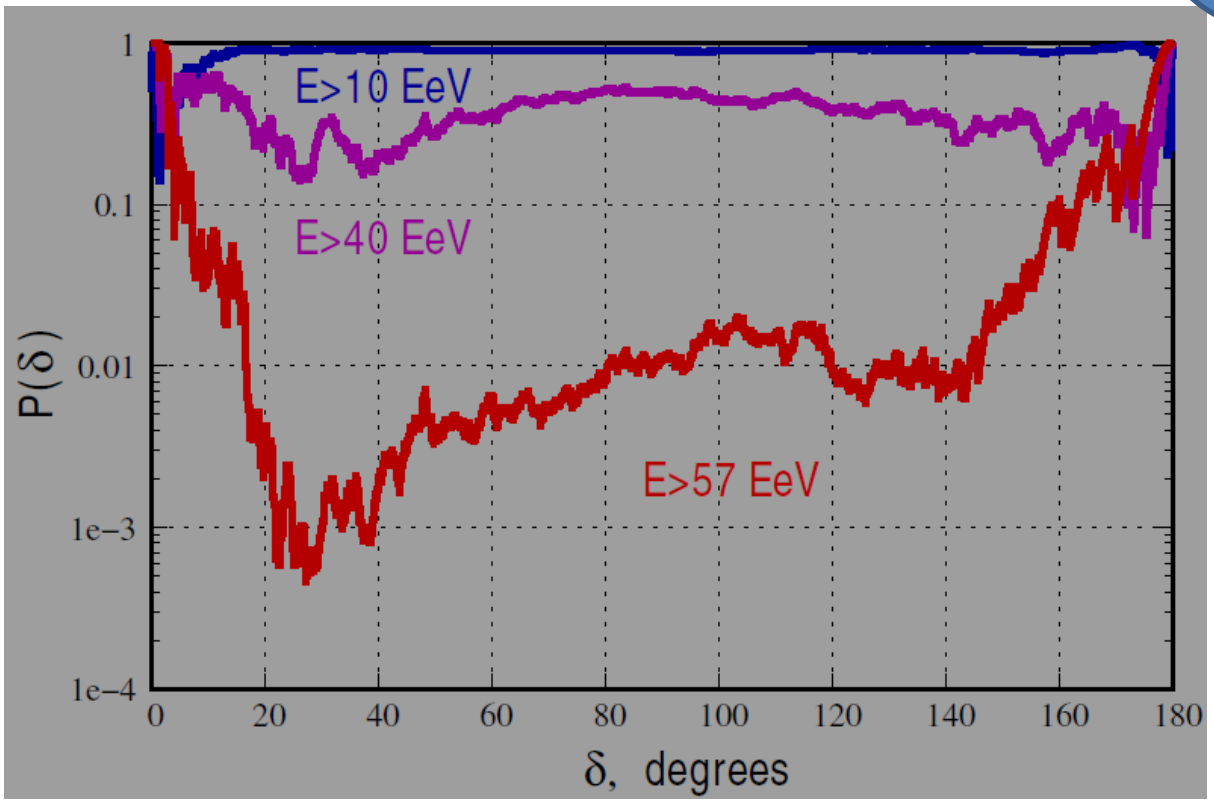


R. Abbasi *et al.* (TA Collaboration) Astropart Phys. (2014) **11** 004

TA auto – correlation study

◇ Probability of Number of pairs in a opening angle < δ (deg) is evaluated.

Chance probability



E > 10 EeV and E > 40 EeV
Compatible with isotropy.

E> 57EeV
Chance probability ～ 0.1% (pre-trial)
at around δ～20-30 (deg.)

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[906 –PoS 362] Poster 1 CR Track: CREX
Board #: 230
Presented by Daisuke IKEDA, Dr. William HANLON
on 30 Jul 2015 at 15:30