

UHECR観測

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Outline

- UHECR
- UHECR 観測
- TA Augerの各測定結果
- 拡張計画
- まとめ

Ultra High Energy Cosmic Ray

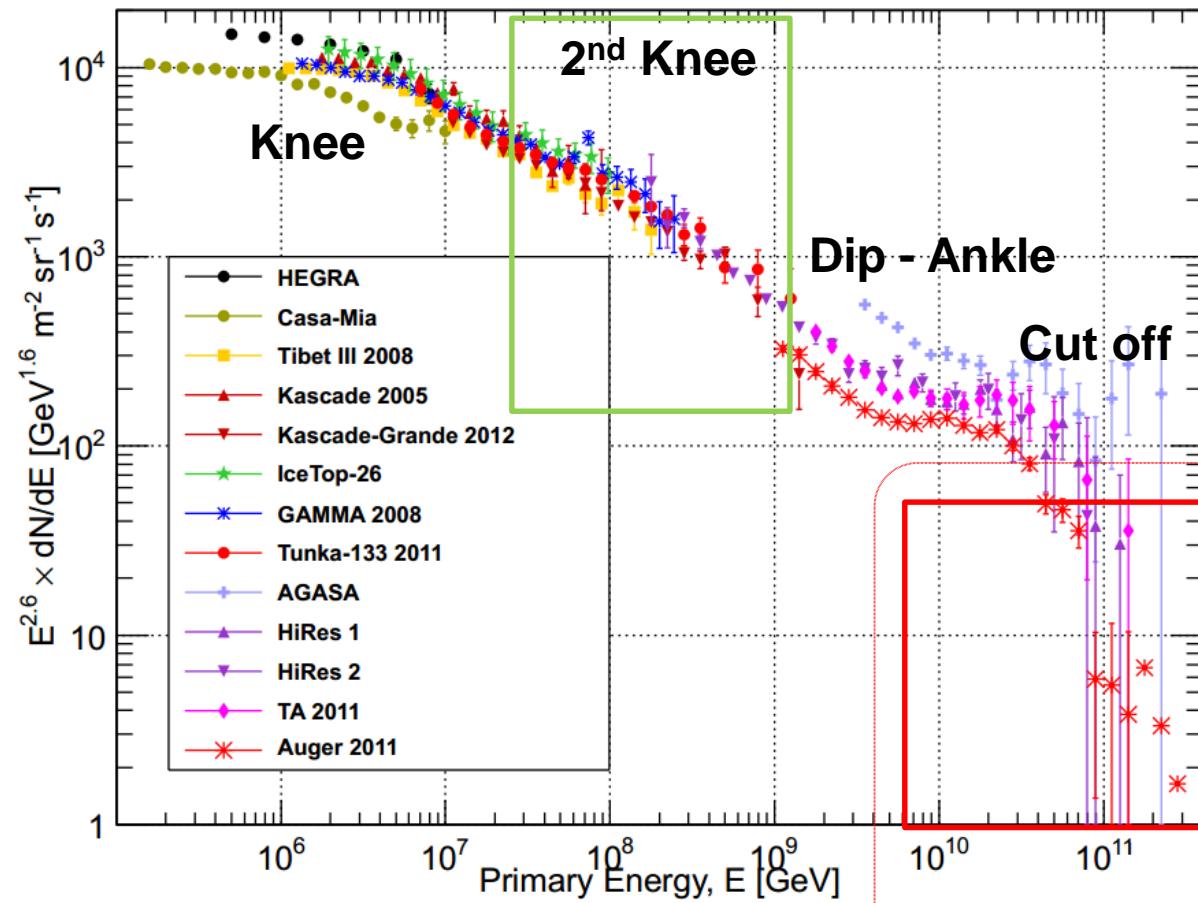
Cosmic ray energy spectrum $10^{15}\text{eV} - 10^{20}\text{eV}$

◇ $10^{16}\text{eV} - 10^{20}\text{eV}$ range

◇ Extragalactic (10^{19}eV)

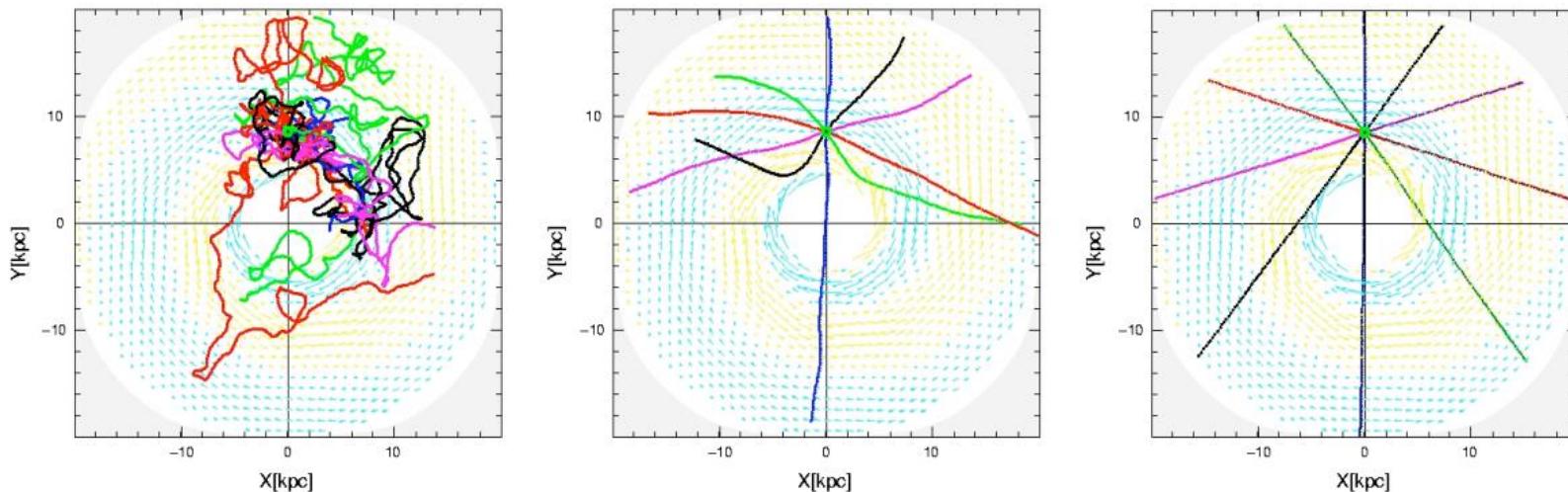
◇ Anisotropy is expected
Directional/Spectrum

◇ Flux of cosmic ray is very
Small.
→ Large detection area.



Highest energy
 $10^{19}\text{eV} \sim$
1 event /km²·year
extragalactic origin.

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



10^{18}eV

10^{19}eV

10^{20}eV

(Few degree)

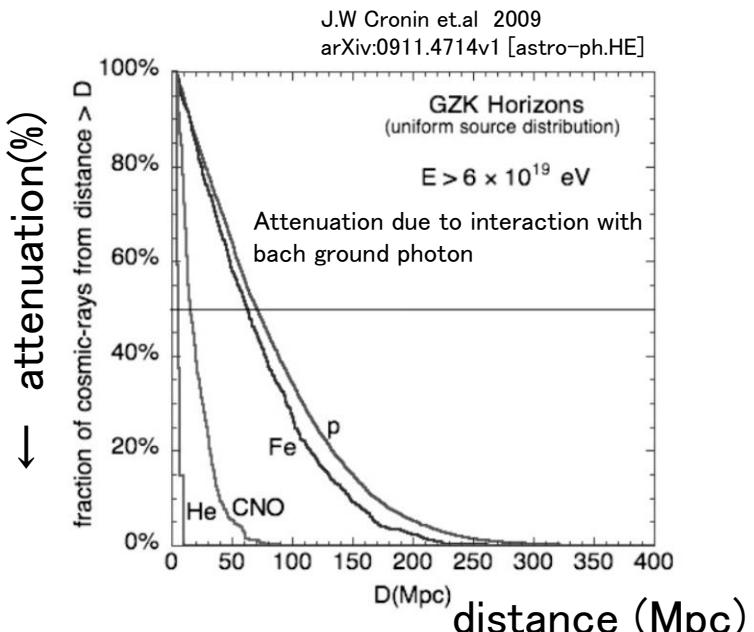
◇ Effect of Inter Galactic Magnetic Field (IGMF):

generally random field. $B < \sim 10^{-9}\text{G}$

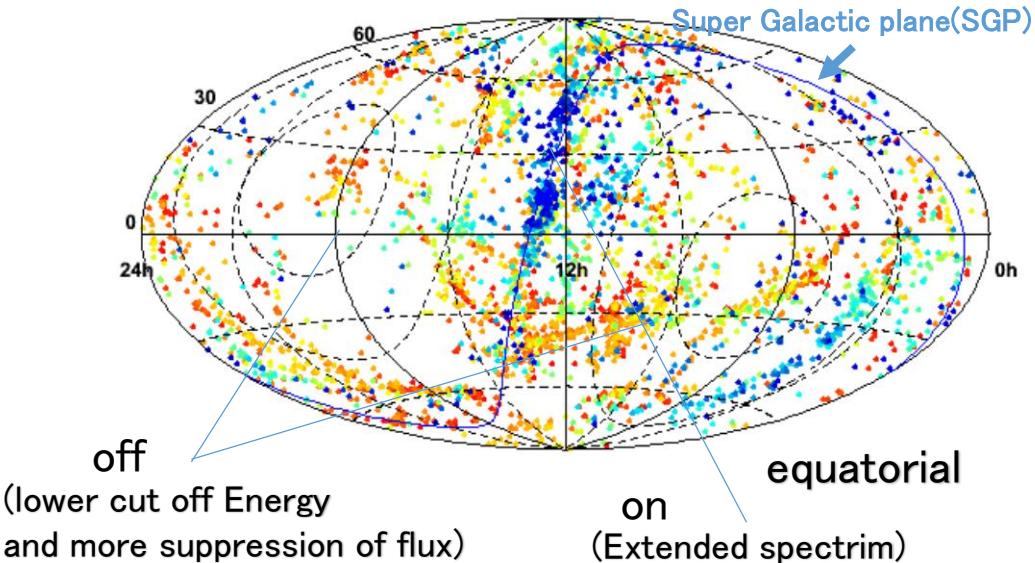
Few degreee → Anisotropy

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

- Matter distribution at near distance



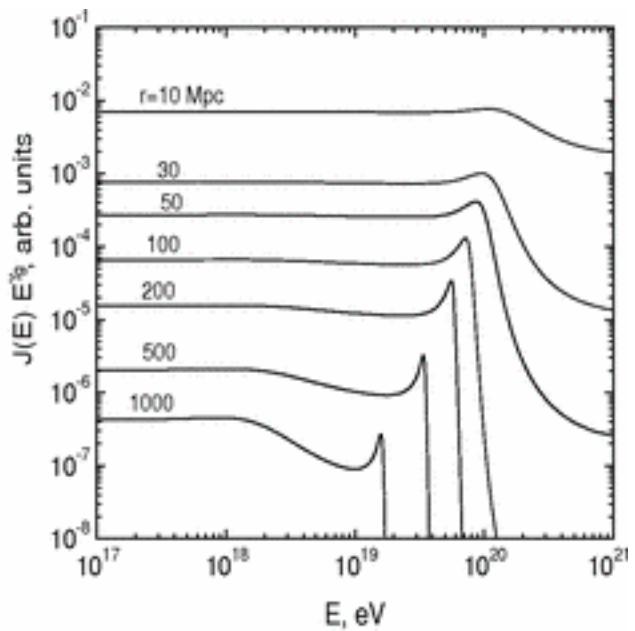
Distribution of Galaxy with in 75Mpc (2MRS)
Most of Galaxy concentrate near SGP direction



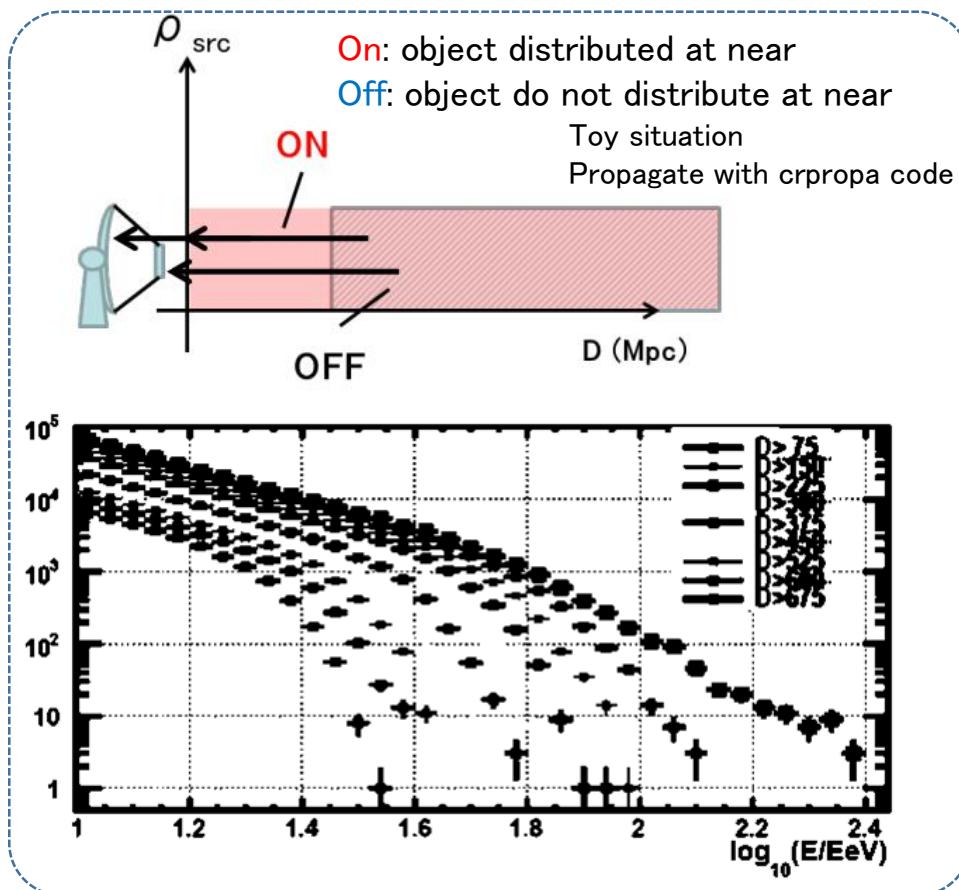
- Interaction with CMBR and IRB
- UHECR attenuate while propagation.
- Matter distribution differ depending on directions
- Cosmic ray sources \propto matter distribution

- Spectrum from single source at various distance (left)
 - Simple simulation of spectrum modulation depending on matter distribution (right side)

Modulated spectrum shape from single source at various distance



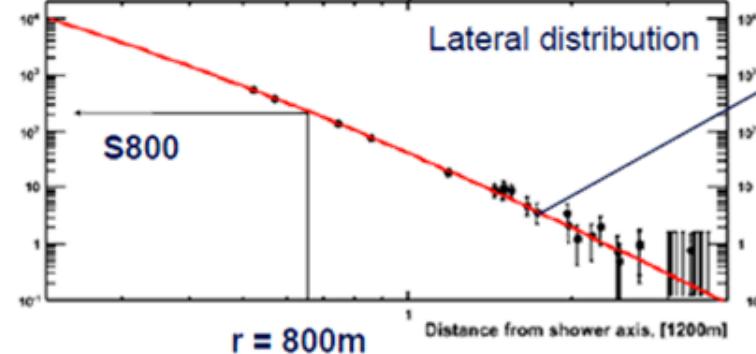
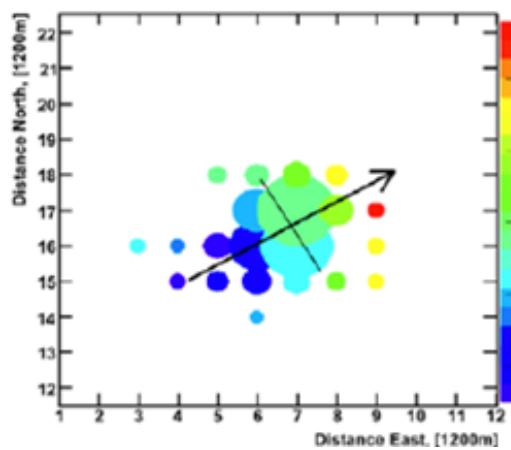
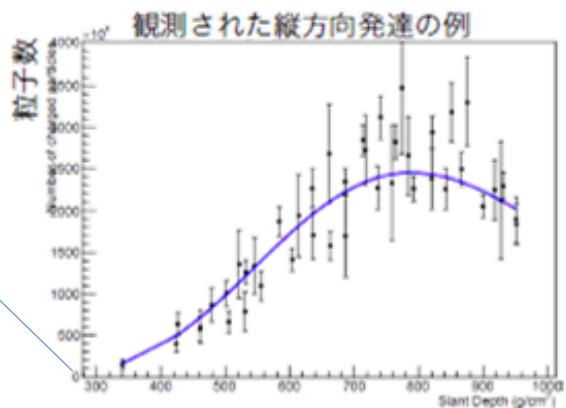
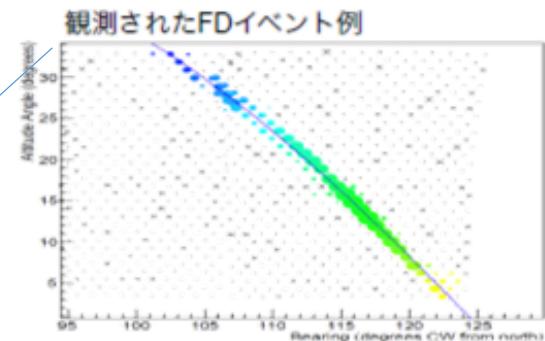
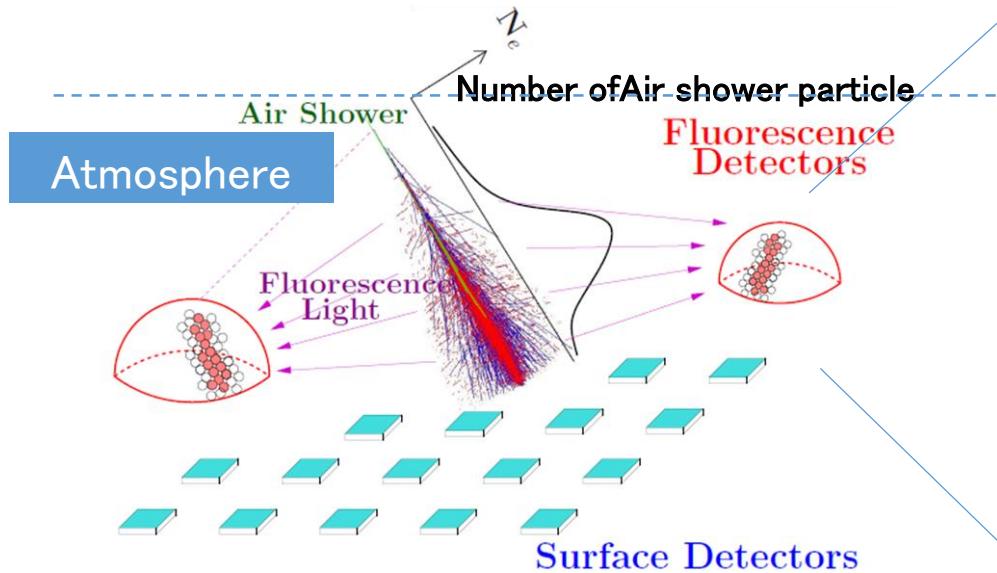
V.Berezinsky et.al Phys. Rev. D 74, 043005 (2006)



Observation

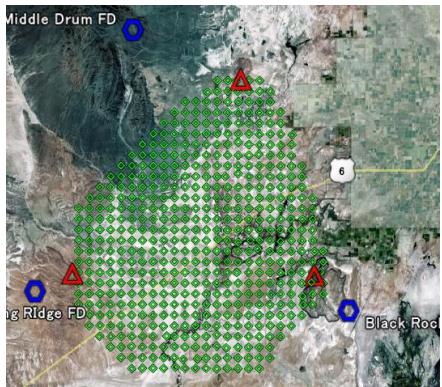
Observation by ground detectors

Calorimetric observation (Fluorescence detector)

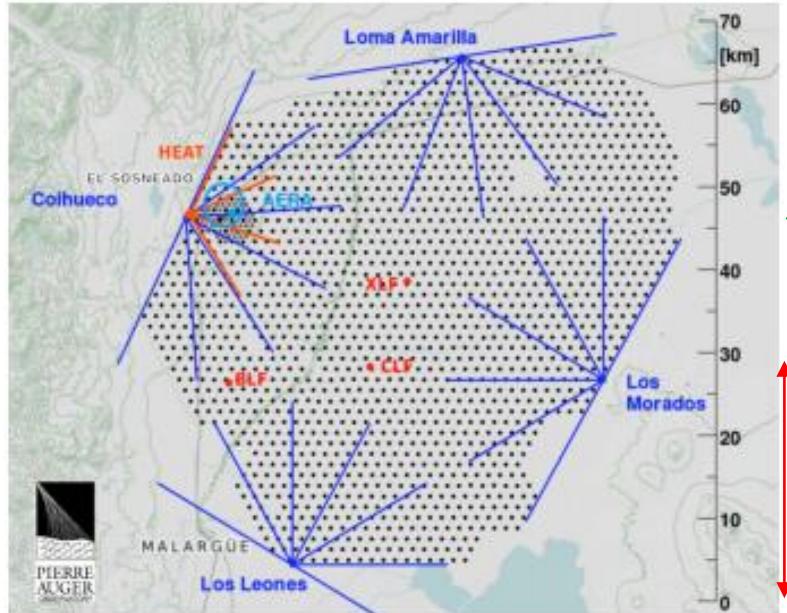


Northern / Southern hemisphere

Telescope Array



Auger Observatory



Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

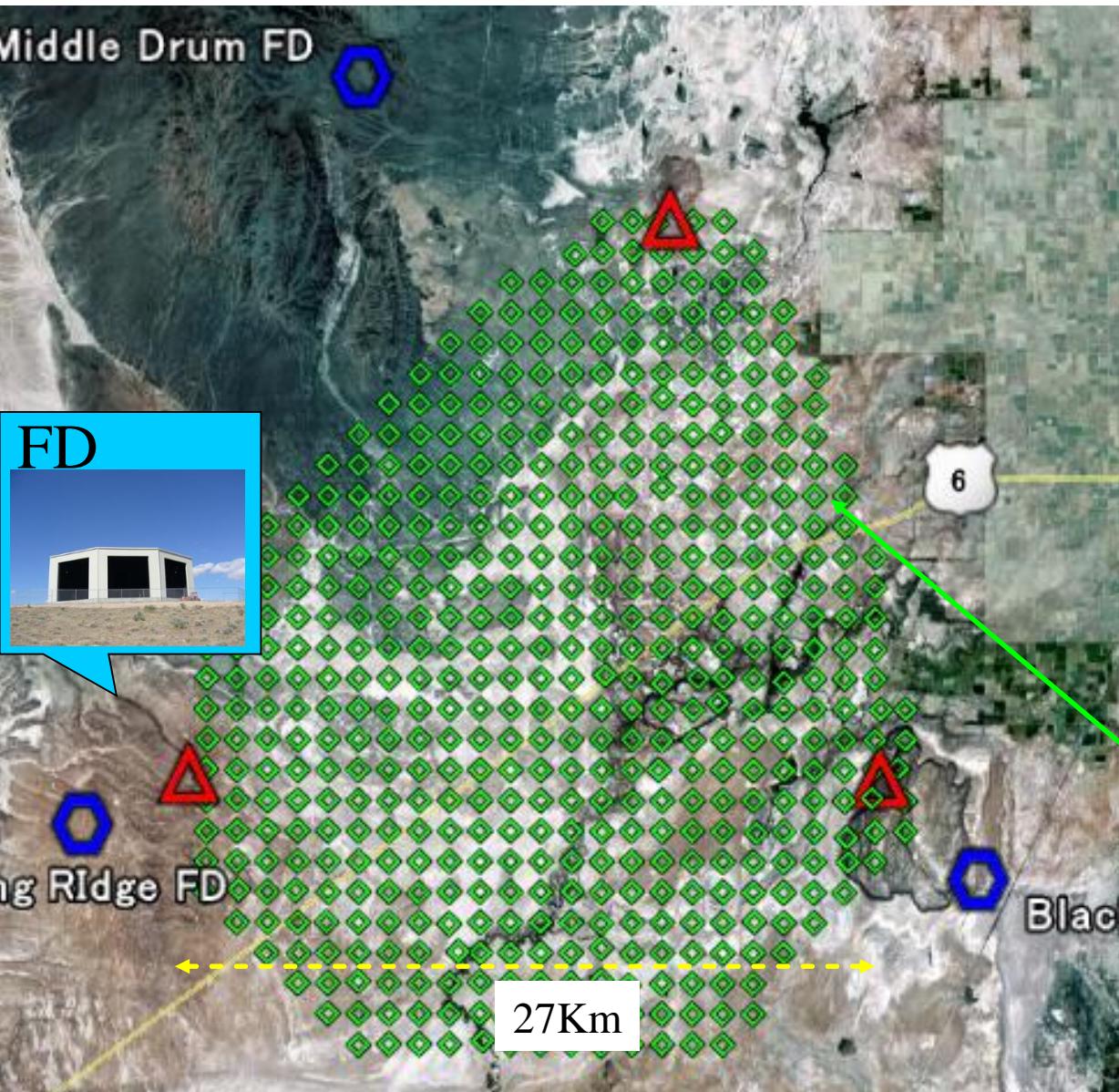


Existing CR detectors at highest energies

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

UHECR2016 M.Roth

Telescope Array detector



Location: N39.3° , W112.9°
Alt 1350-1500m asl

- ◊ Fluorescence Detector
- ◊ Surface Detector
- △ Comm Tower

- 1.2 km grid SD (3m^2)
- 3 sub array :
 - +cross boundary trigger
 - Total 507 SD
- Detection area $\sim 700 \text{ k}\text{m}^2$



Pierre Auger Observatory

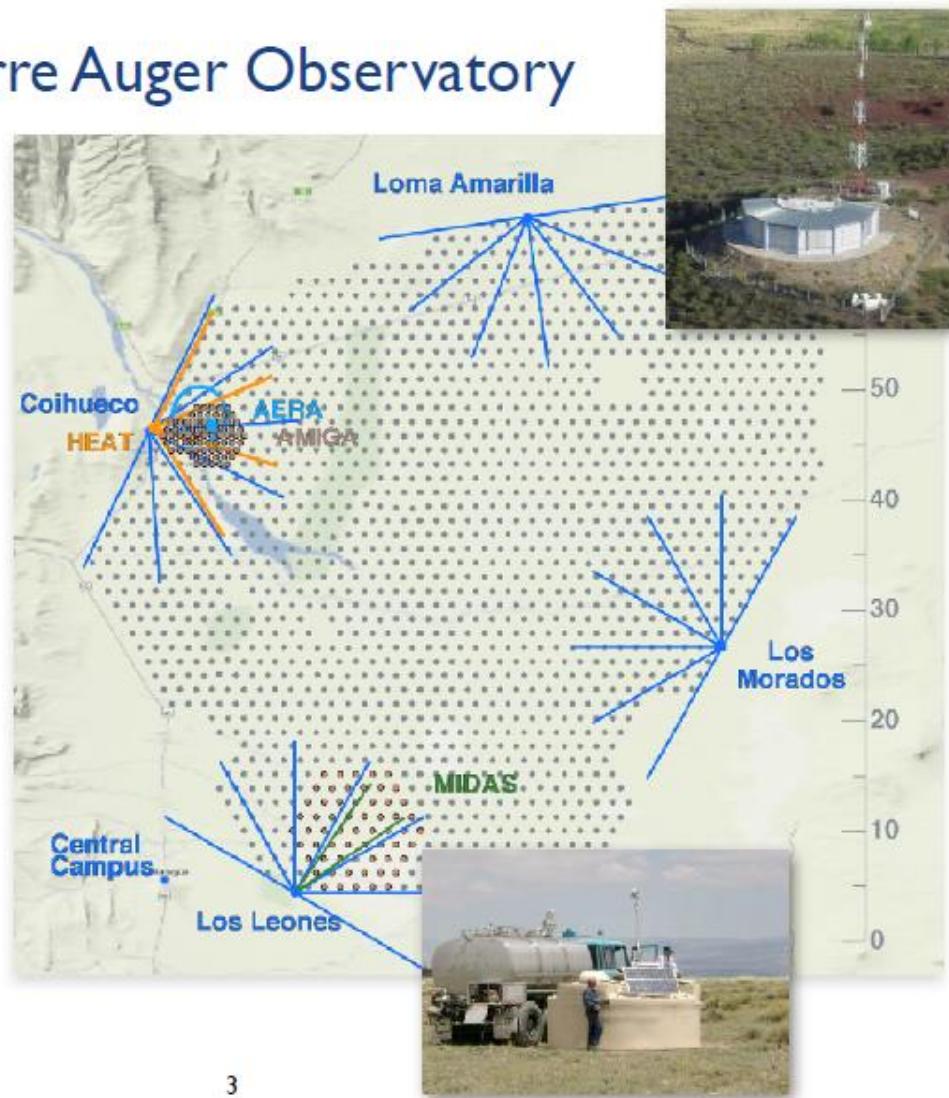
The Pierre Auger Observatory

Fluorescence detector (FD)

- 4 sites
 - 0-30°
 - $E > 10^{18}$ eV
- HEAT
 - 30°-60°
 - $E > 10^{17}$ eV

Surface detector array (SD)

- Grid of 1500 m
 - 3000 km²
 - 1660 stations
 - $E > 10^{18.5}$ eV
- Grid of 750 m
 - 24 km²
 - 61 stations
 - $E > 10^{17.5}$ eV



3

UHECR2016 M.Roth

Fluorescence Detector (TA)

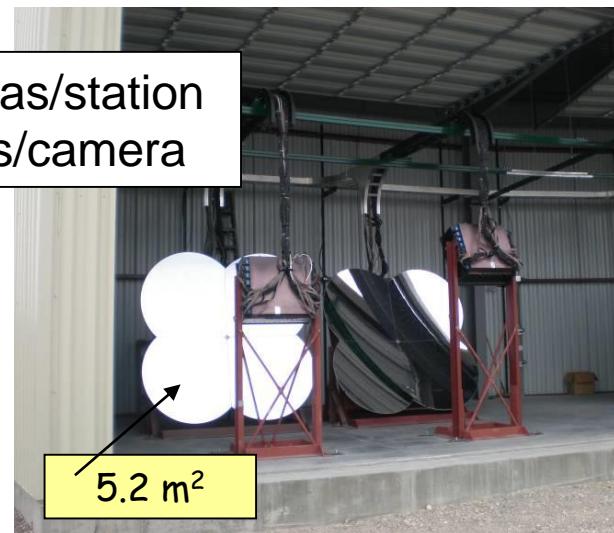
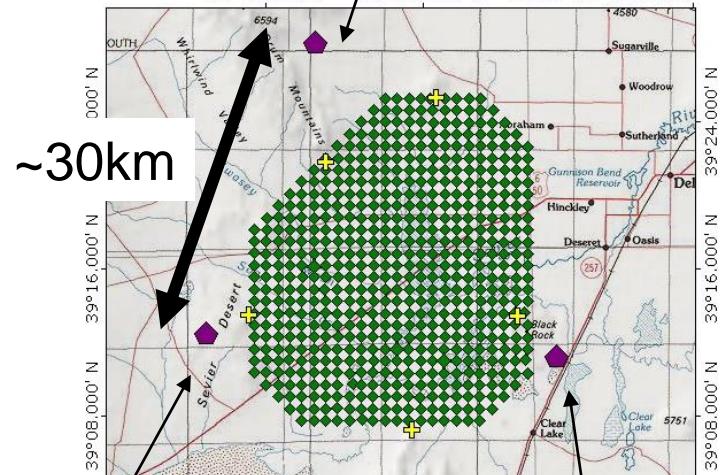
From HiRes

Middle Drum



14 cameras/station
256 PMTs/camera

TOPO! map printed on 07/12/04 from "StakeJun04-01.tpo" and "Untitled.tpo"
113°03.000' W 112°52.000' W NAD27 112°33.000' W



Long Ridge



Black Rock Mesa



New FDs

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

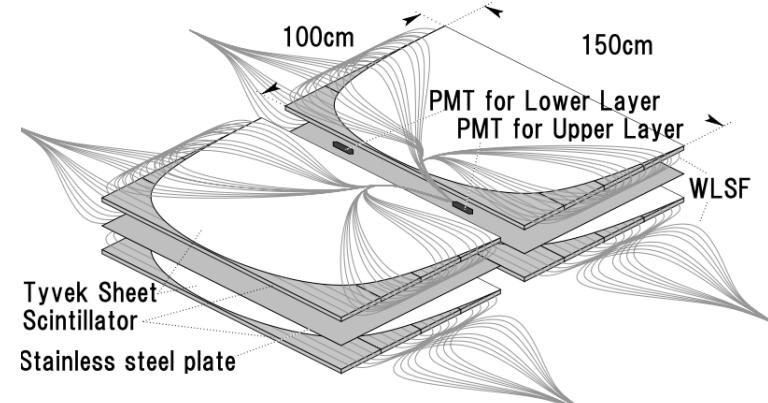


Surface Detector (TA)

- Solar Panel + Battery
- Wireless LAN (2.4GHz)
- GPS ~20nsec
- WF sample 50Msps FADC



3m²

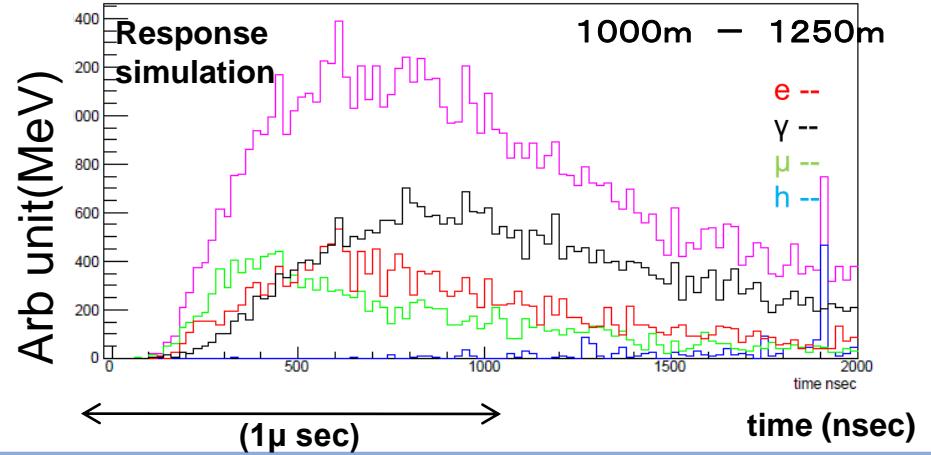


12mm plastic scintillator
1mm SUS
12mm plastic scintillator

→ 2 independent layer

WLSF (475nm) x5m PMT ETL9124SA

10¹⁹eV Proton shower (stacked energy deposit)



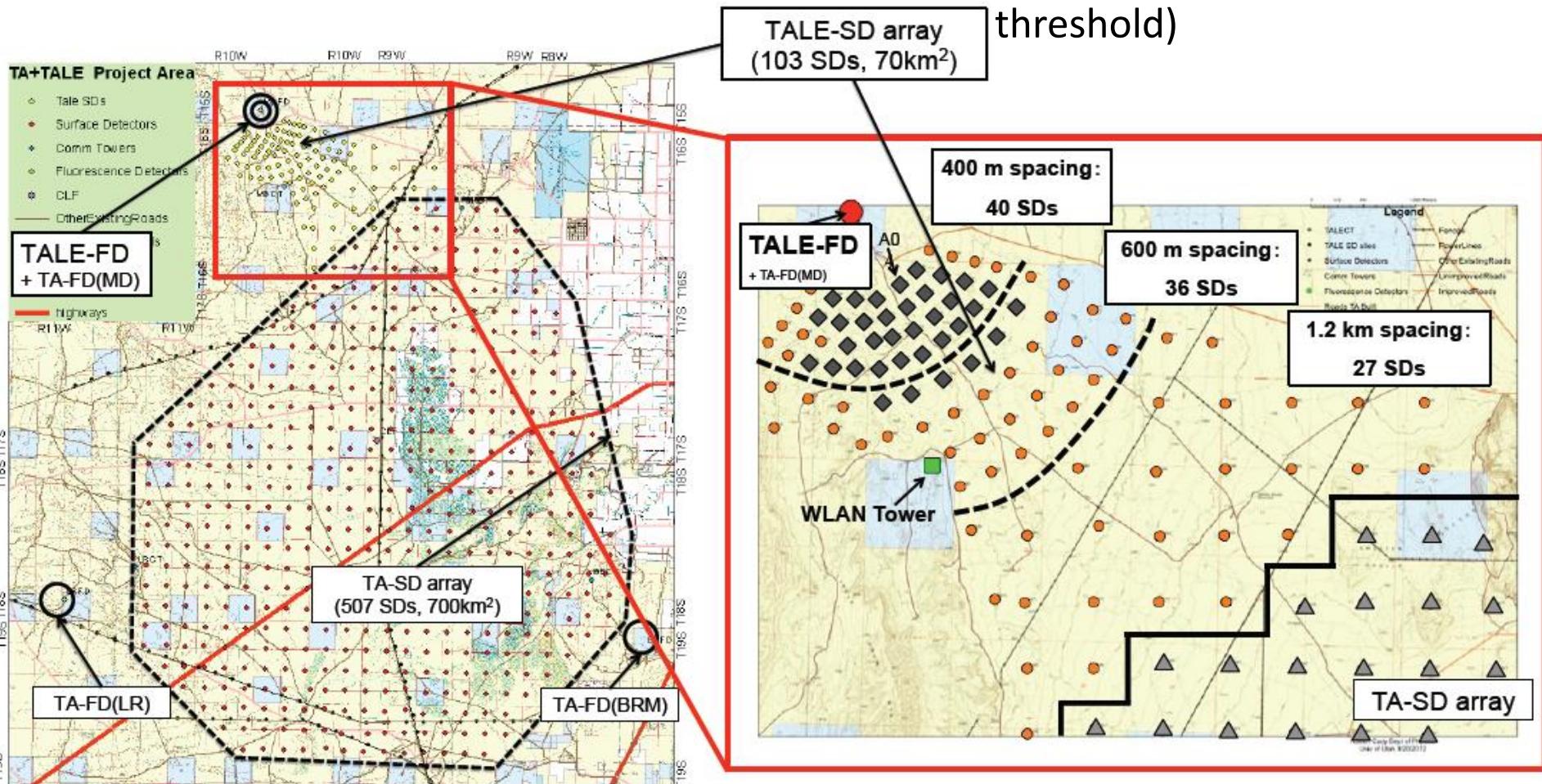
TASD:

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

TA Low Energy extension (TALE)

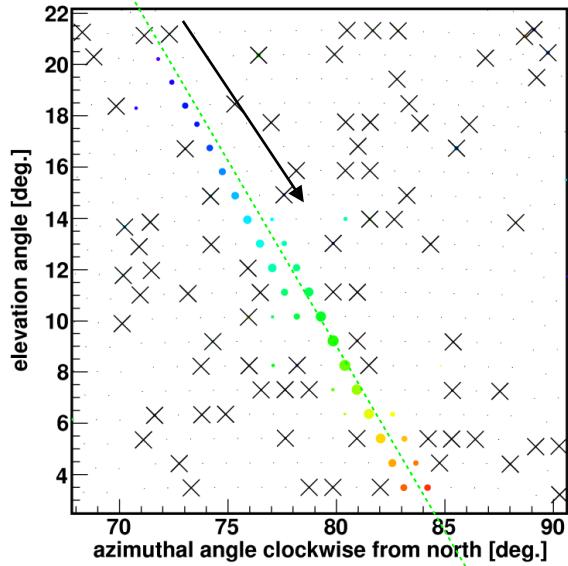
10 new telescopes to look higher in the sky ($31\text{-}59^\circ$) to see shower development to much lower energies

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

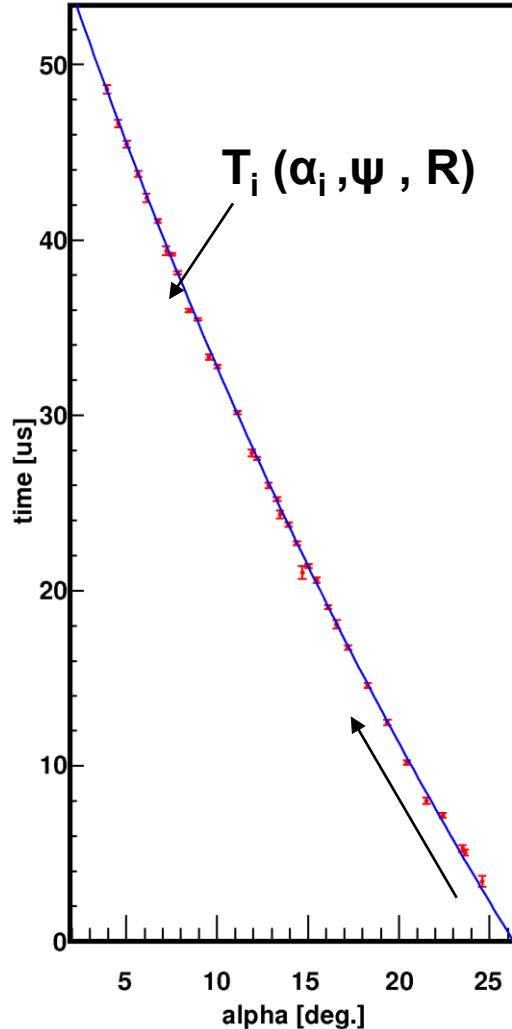


Event reconstruction

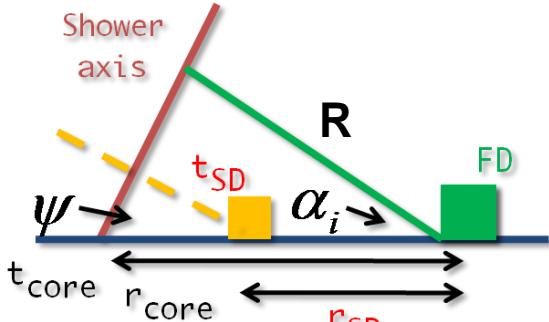
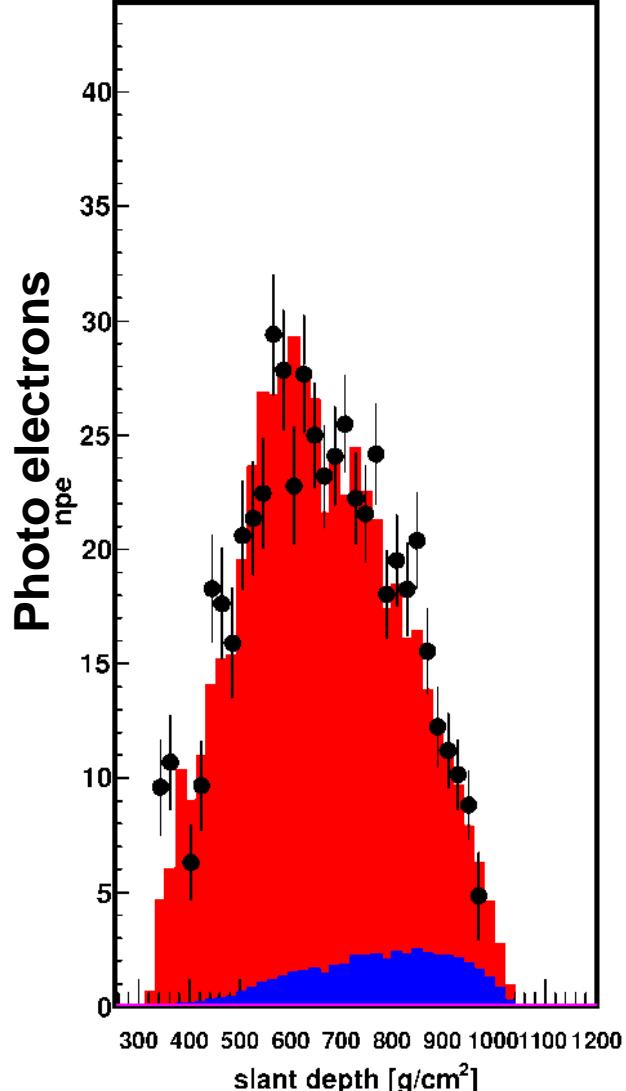
Hit on Camera



Geometry



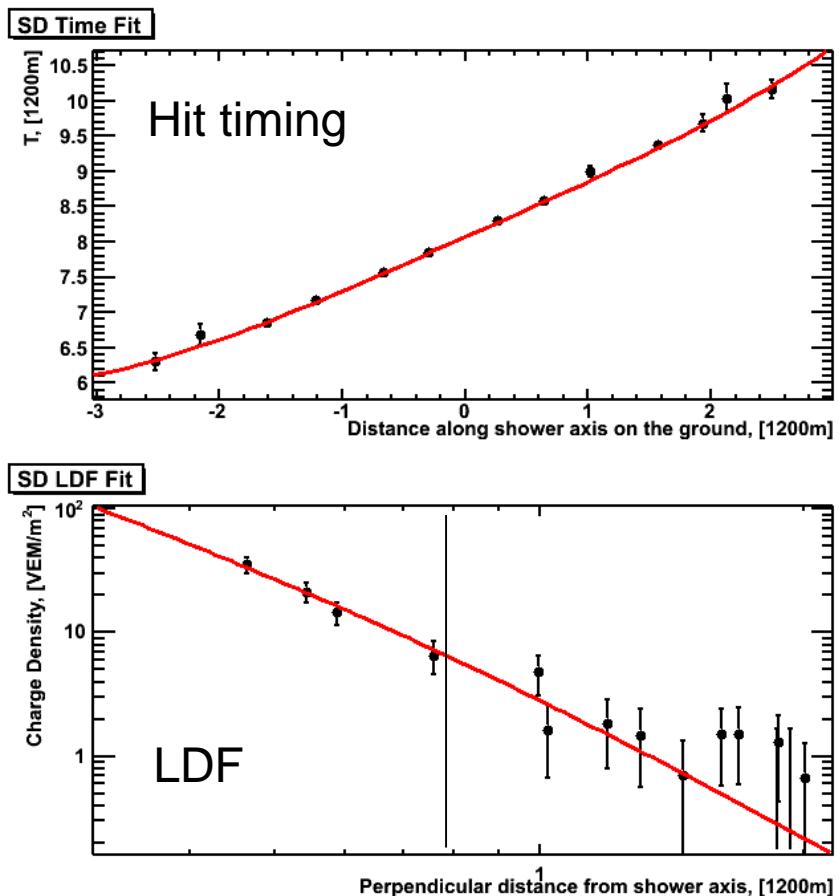
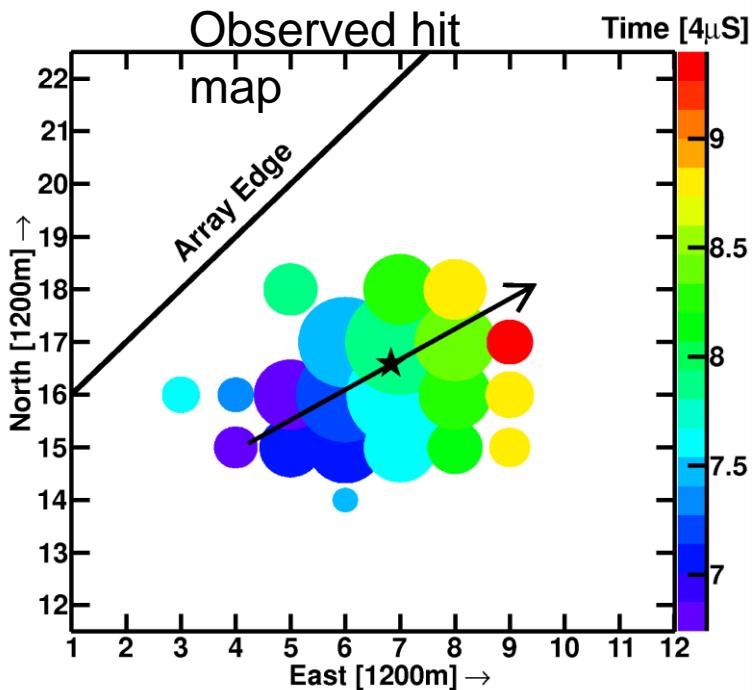
Energy



Use SD timing information →
 ψ, R resolution improve (Hybrid analysis)

Surface Detector

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



Hit timing : → Arrival direction

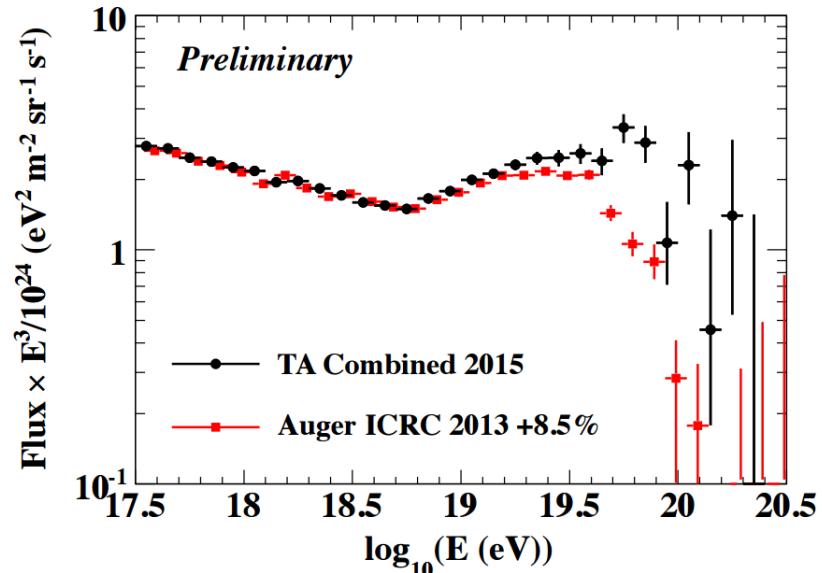
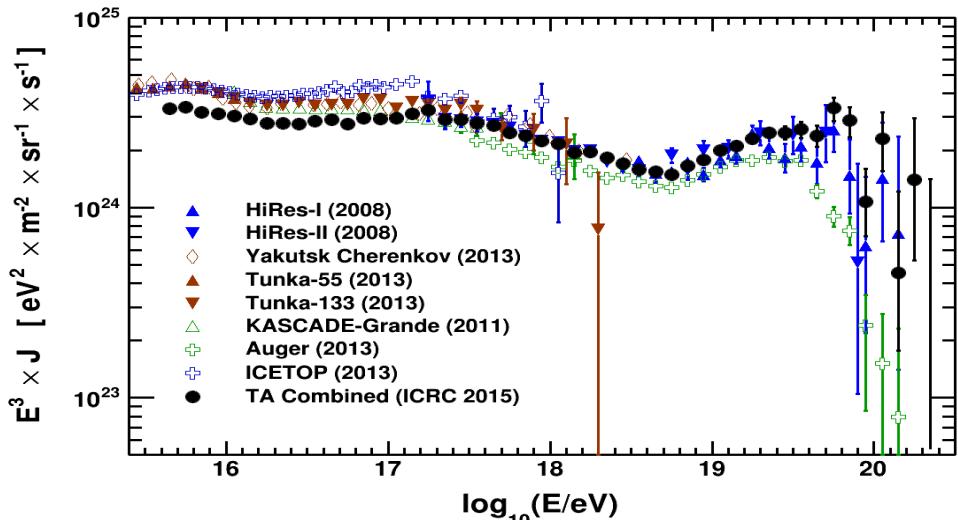
Lateral distribution of energy deposit → Energy estimator “S(800)”
(Energy deposit at 800m)

■ Results of Spectrum studies

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

Spectrum from $E = 10^{15.6} - 10^{20.3}$ eV

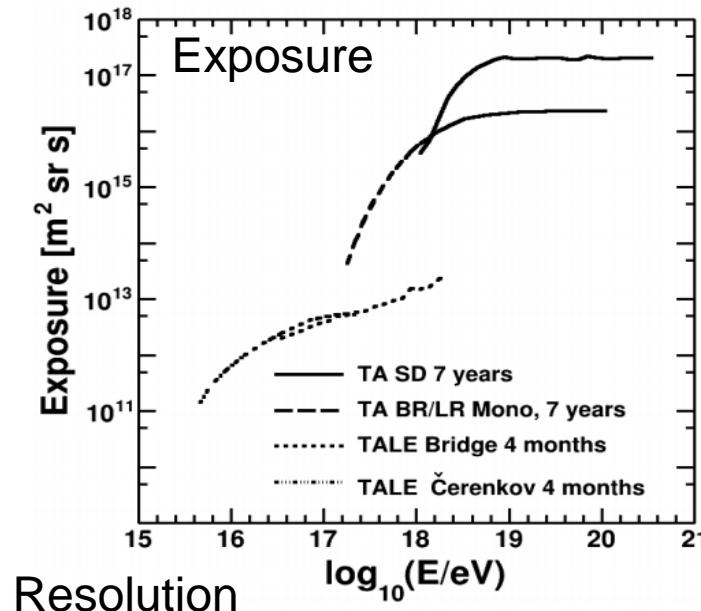
◇ Comparison with experiments



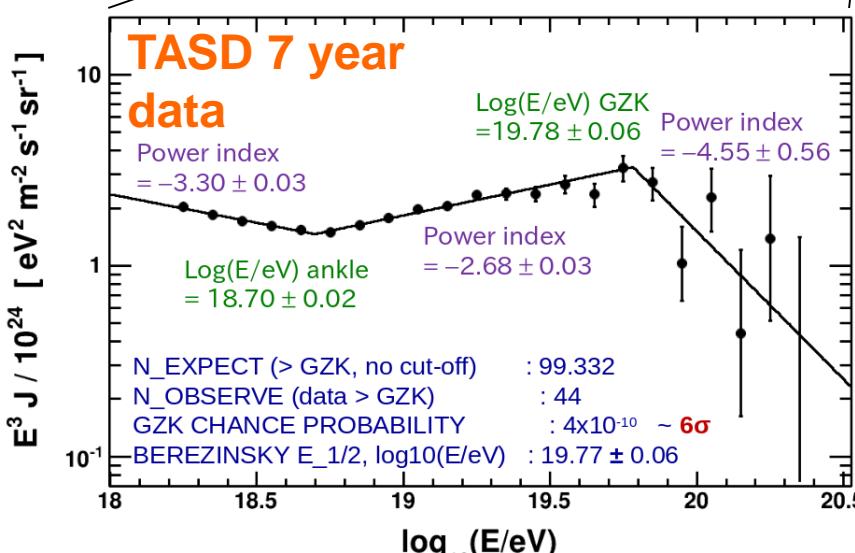
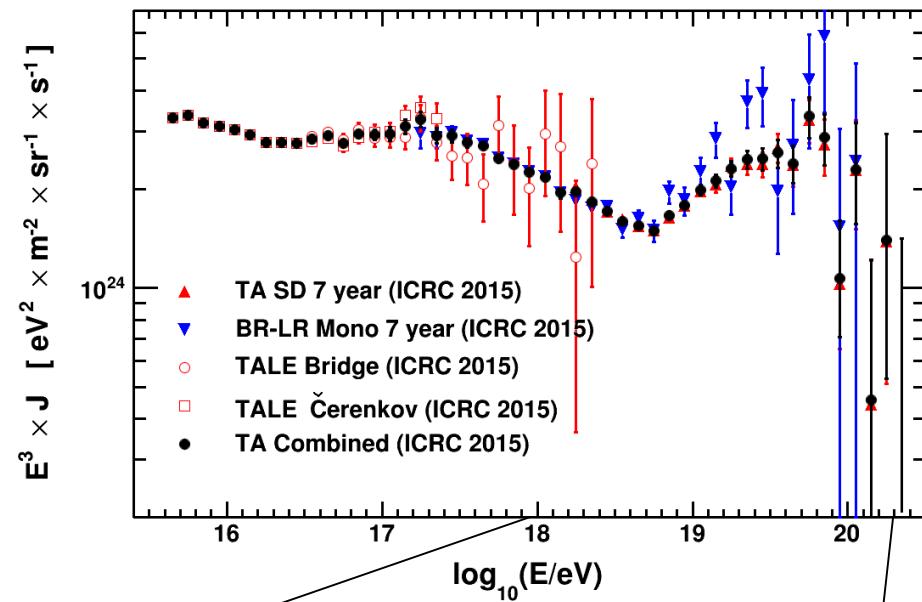
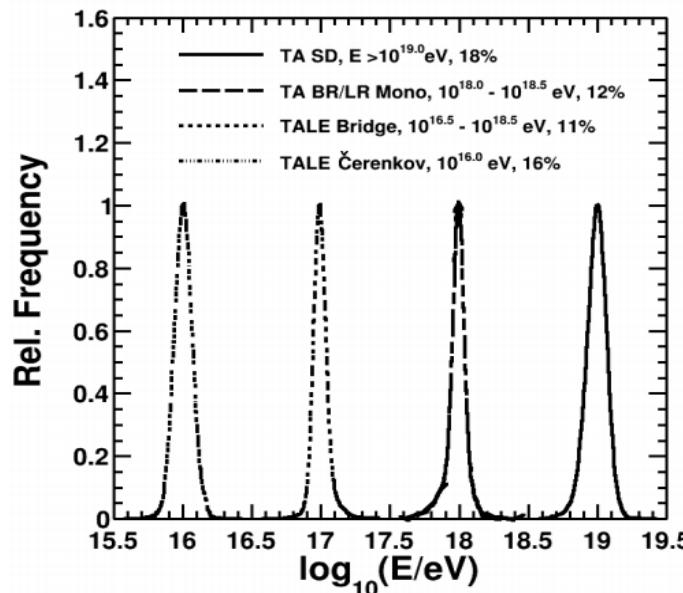
<Summary of Spectrum observation>

- 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 “2nd 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?

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



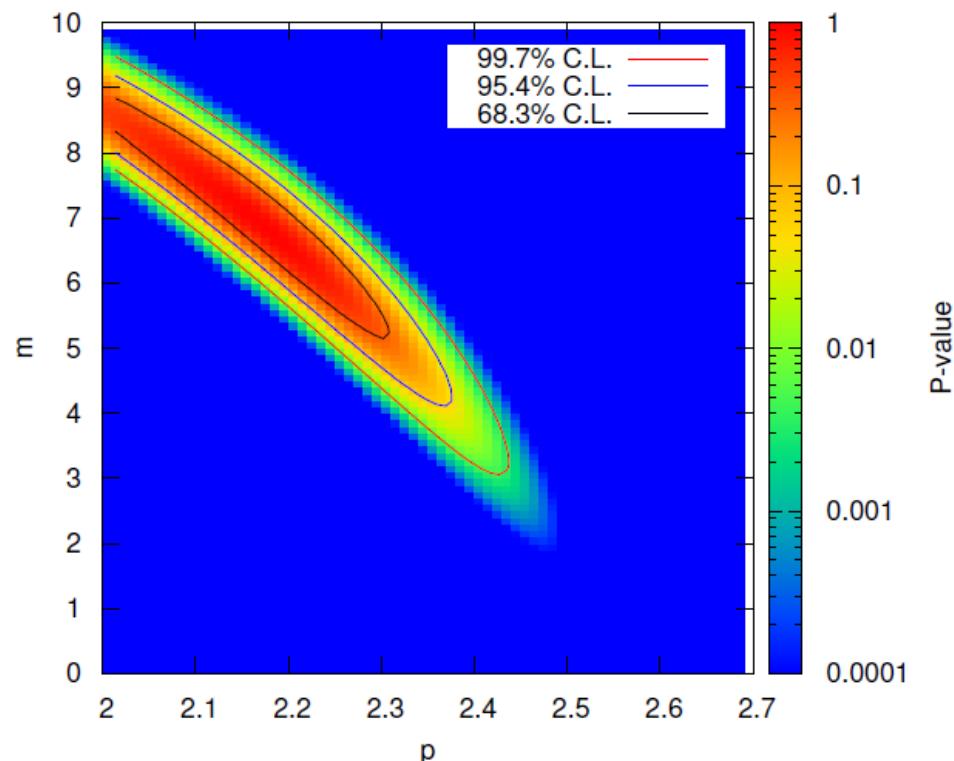
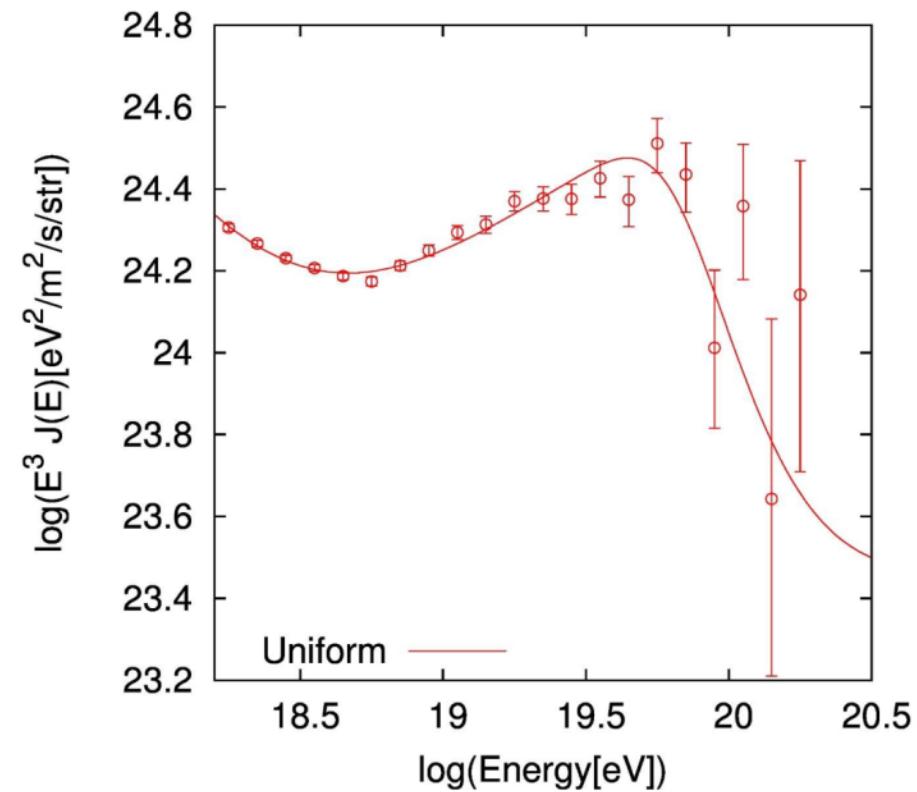
Resolution



Fitting TA spectrum with proton model

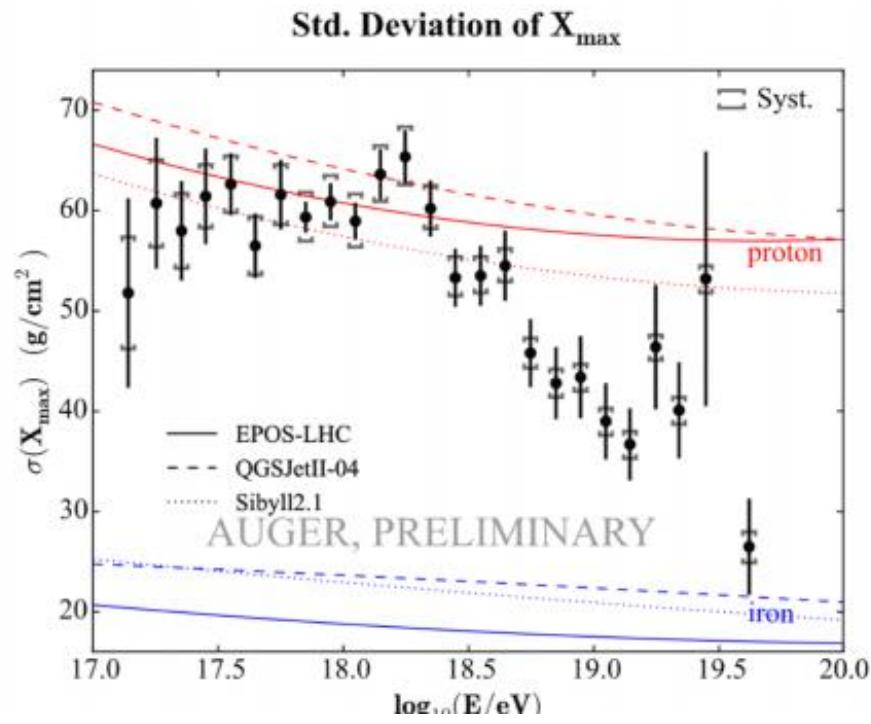
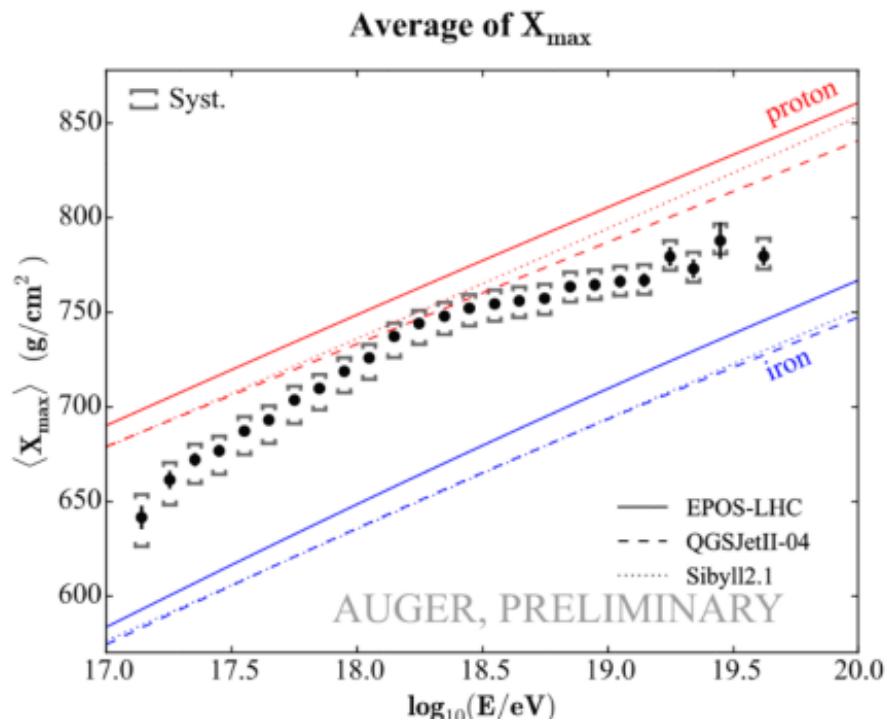
- Uniform **proton** source distribution, $E > 10^{18.2}$ eV
- Injection spectrum E^{-p} , $E_{\text{max}} = 10^{21}$ eV
- Source density $\propto (1 + z)^m$
- Consider energy losses with CMB and IRB
- $z < 0.7$, $B_{\text{IGMF}} < 0.1$ nG

$p = 2.18 + 0.08 - 0.14 \text{ [stat. + sys.]}$
 $m = 6.8 + 1.6 - 1.1 \text{ [stat. + sys.]}$
 $\Delta \log E = -0.04 \text{ (-9\%)} + 0.04 - 0.03 \text{ [stat. + sys.]}$
 $\chi^2 = 18.0/17$



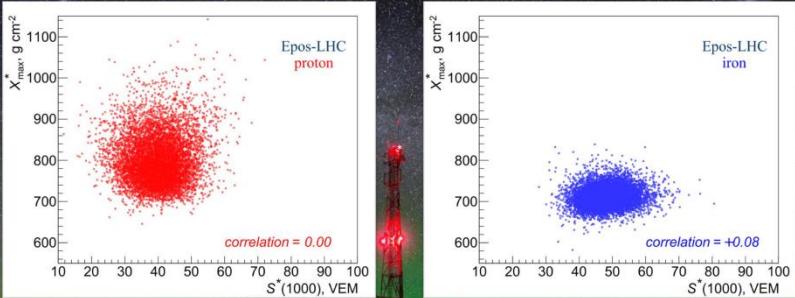
„Results of Composition studies

Auger X_{max} UHECR2016



Mixed Composition?

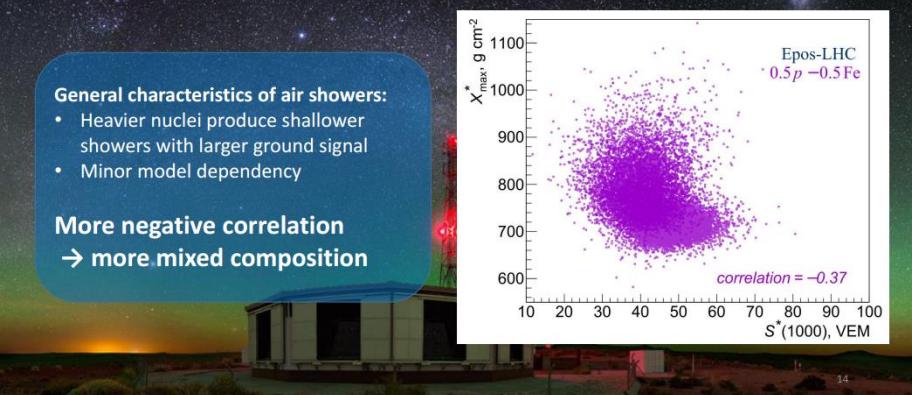
Correlation $r_G(X_{\max}^*; S^*(38))$ in Monte Carlo



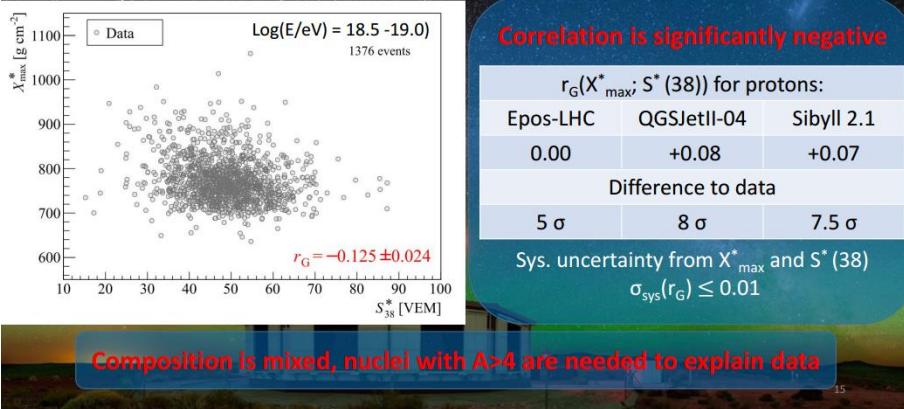
Correlation between X_{\max}^* and $S^*(38)$ depends on the purity of the primary beam
❖ Use ranking coefficient r_G [R. Gideon, R. Hollister, JASA 82 (1987) 656]

Pure compositions \rightarrow correlation ≥ 0

Correlation $r_G(X_{\max}^*; S^*(38))$ in Monte Carlo

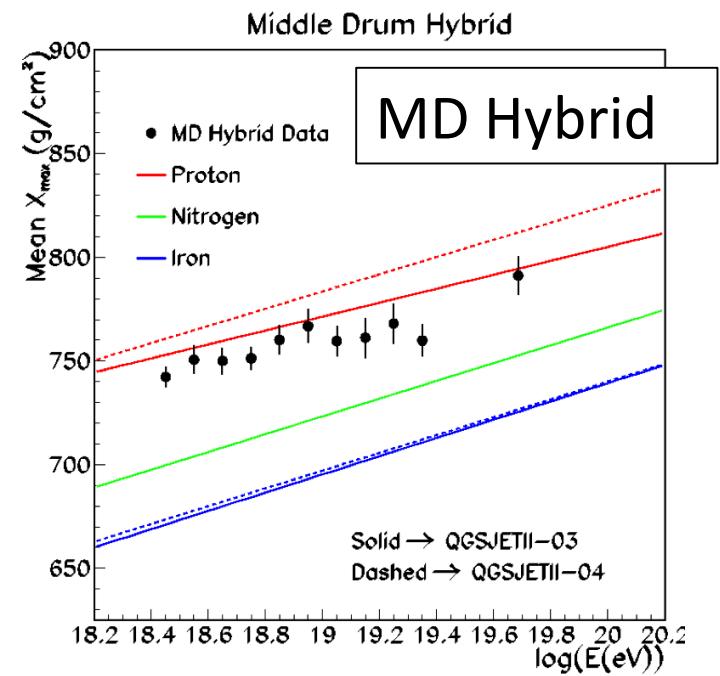
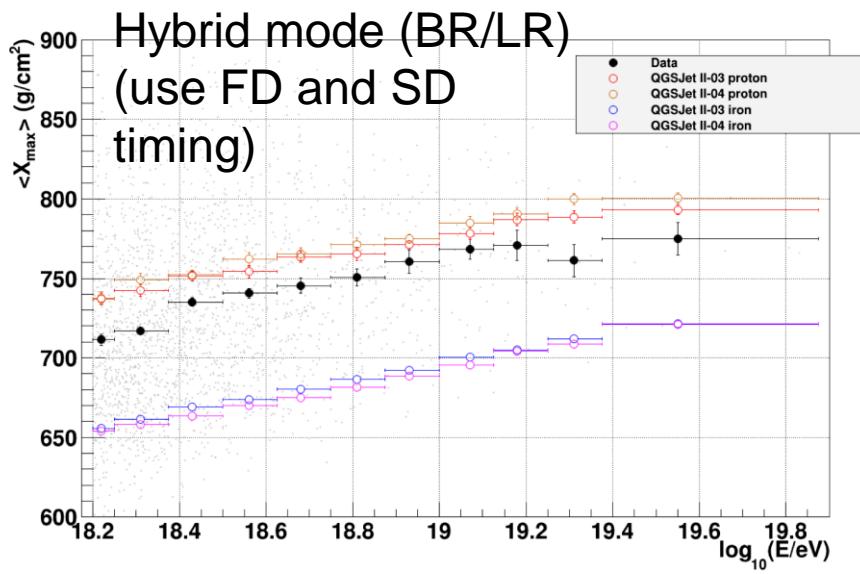
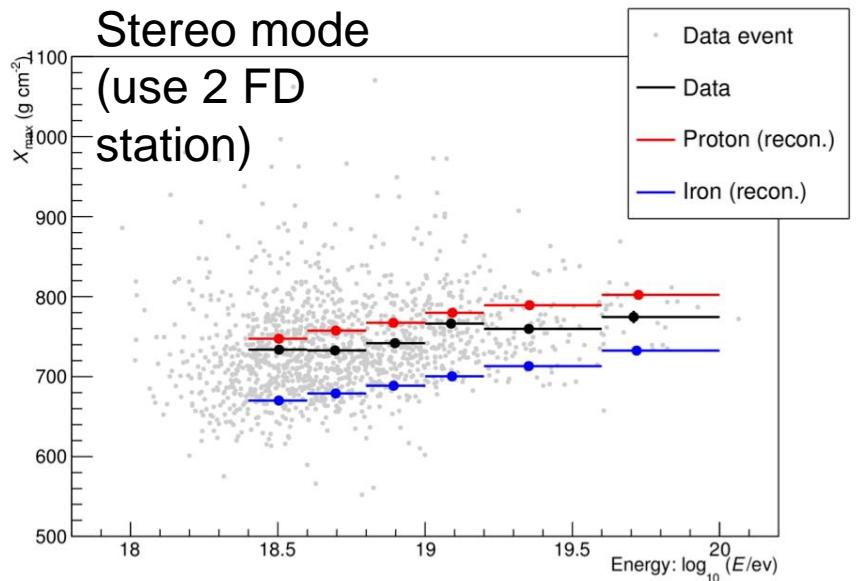


Correlation $r_G(X_{\max}^*; S^*(38))$ in data



UHECR2016 Matthias Plum

X_{\max} measurements in TA

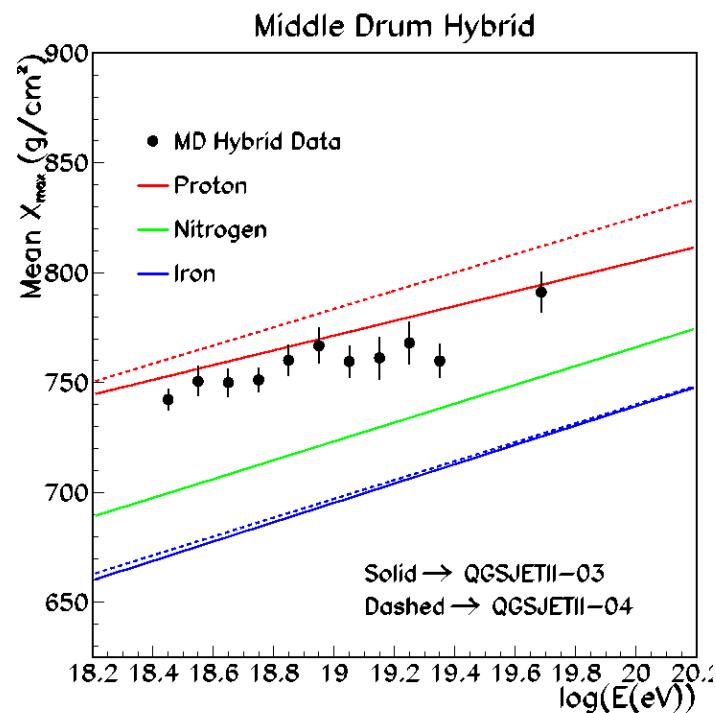


X_{\max} is composition sensitive parameter.
“Depth of shower maximum”

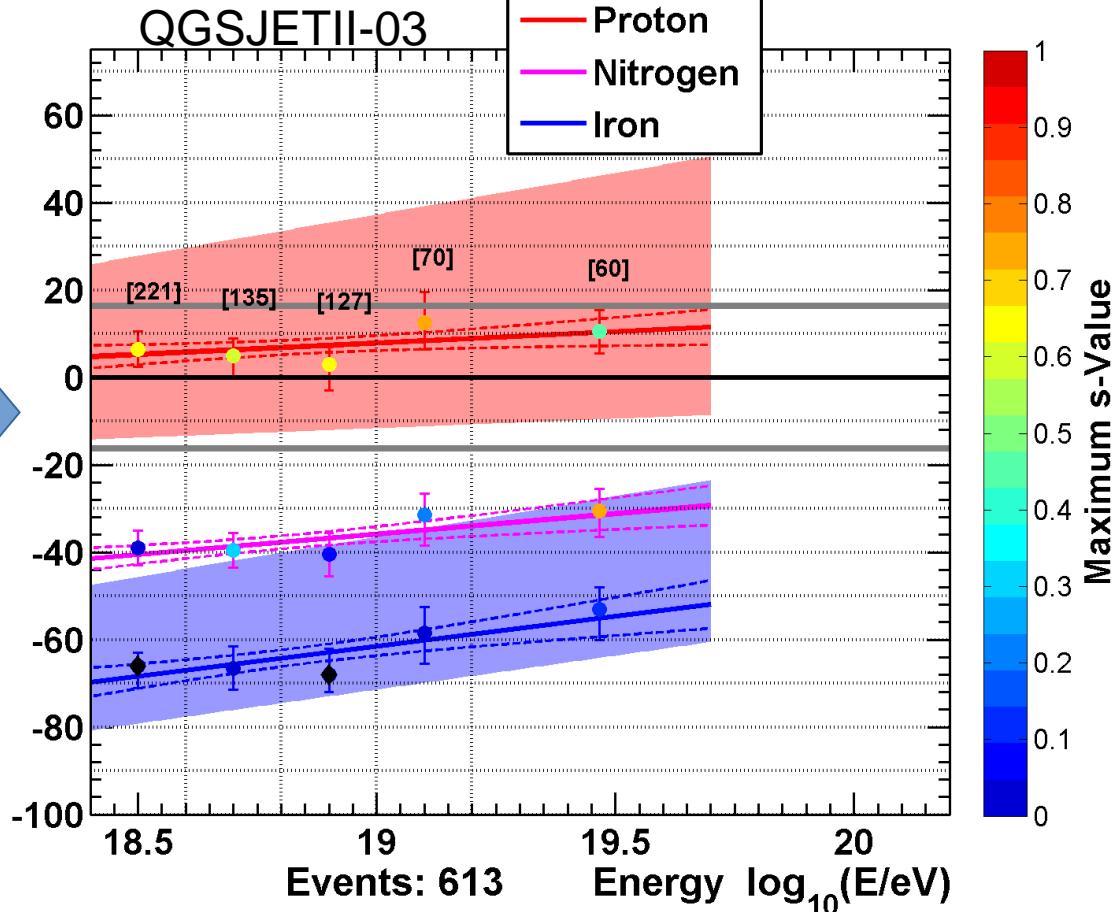
Red: Proton MC prediction.
Blue: Iron MC prediction.
Black : Observed data.

X_{\max} distribution shape

Standard mean vs log(E) plot



ΔX_{\max}



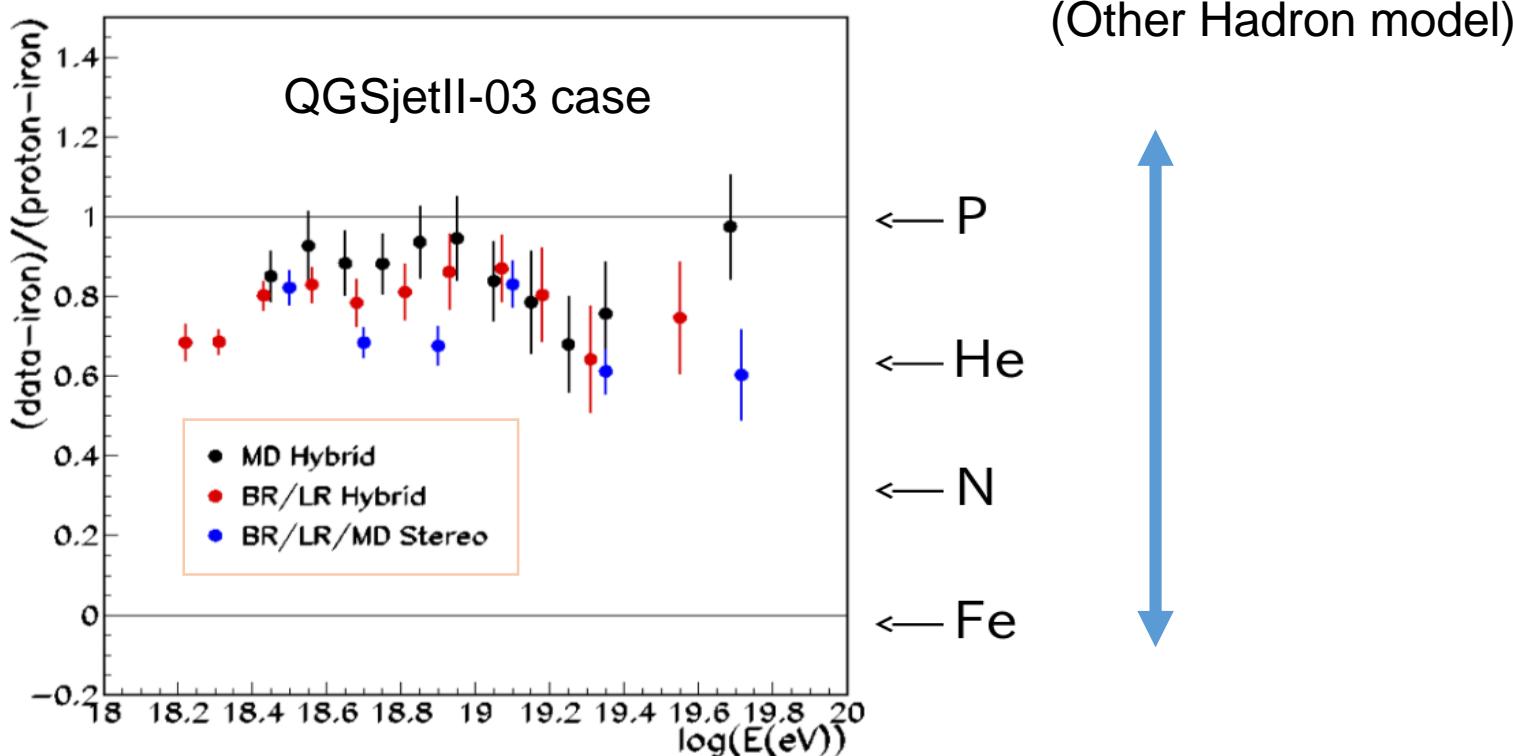
“Shift Plot”

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/cm² systematic uncertainty.

X_{\max} measurements in TA

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



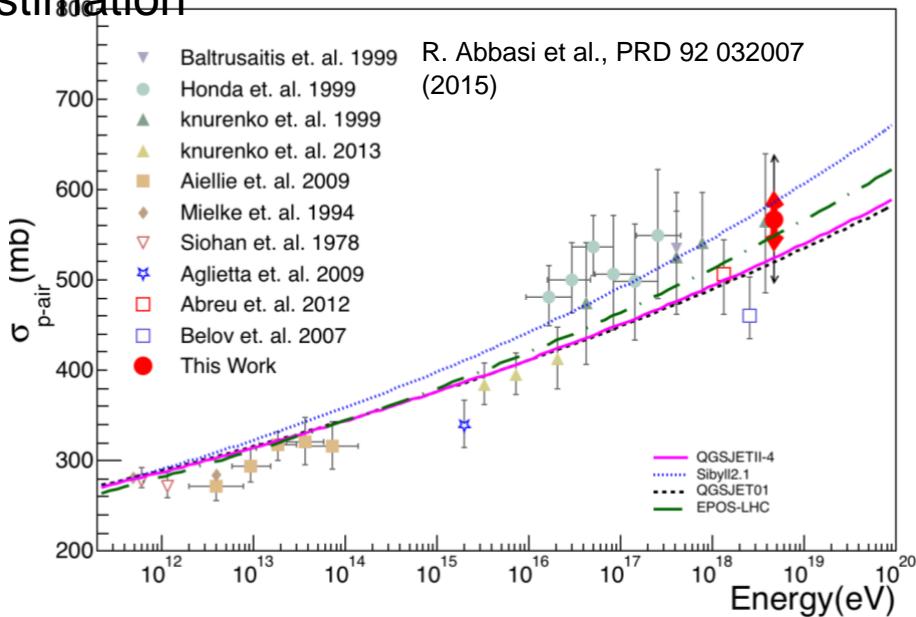
- ◇ Corresponding average InA value is “light component”.
- ◇ It depends on Hadron Interaction model large.
- ◇ N and He have large difference in mean free path in CMB
→ **Hadron Interaction is very important while understanding anisotropy.**

Proton Cross section

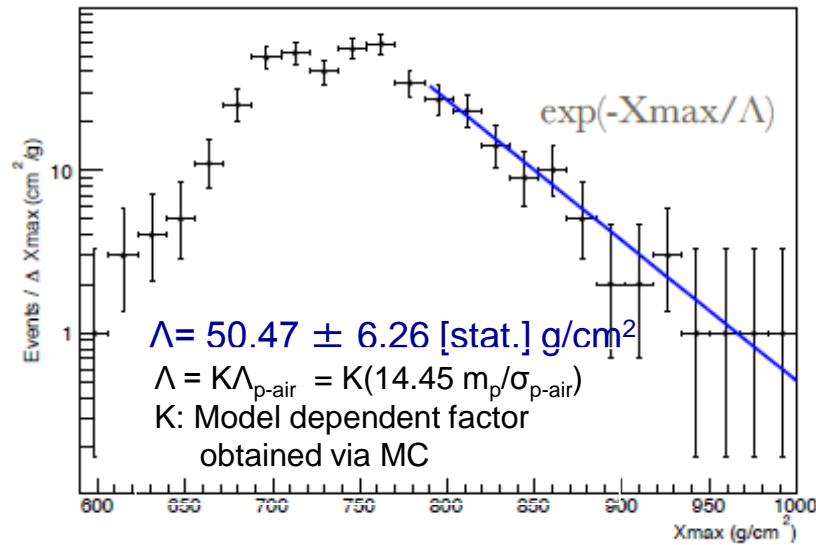
P-air Inelastic Cross section

Methodology :

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



- ◇ $\sigma_{\text{p-air}}(\text{inelast.})$ @ 95TeV of \sqrt{S} is $567.0 \pm 70.5[\text{Stat.}] (+25, -29)[\text{Sys.}]$ mb
- ◇ The value observed is between EPOS-LHC and Sibyll2.1.

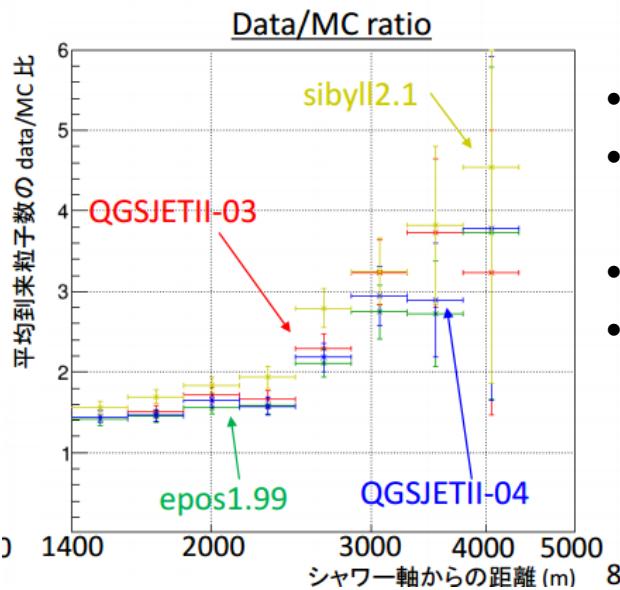


	Systematic [mb]
Model	+/- 17
20% He	+18
Gamma < 1%	-23
Total	(+25, -29)

■ Study of Air shower

Air shower study

- Muon excess in observed shower ($\sim 10^{19}$ eV)



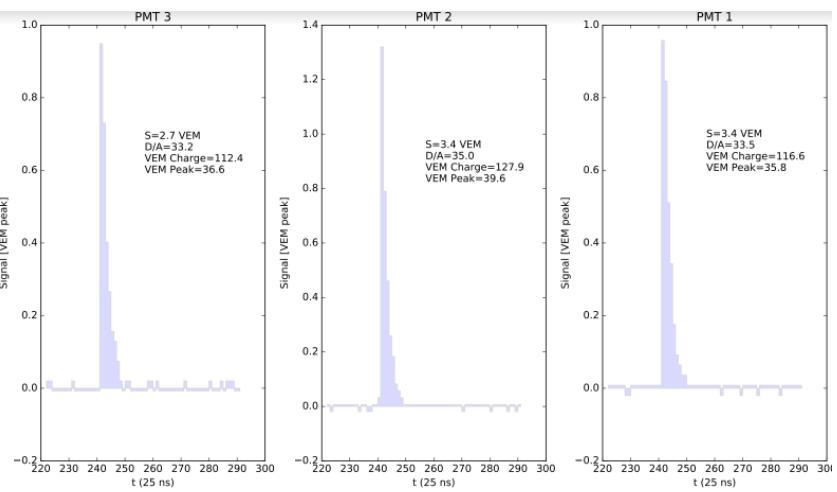
- Using detector observe shower in deeper atmosphere
 - Compare signal with MC under condition of higher muon purity
 - Higher muon purity leads larger discrepancy.
 - Muon excess . .
- R.Takeisi (ICRR)

Shower observation with different detector



Collaboration with Auger group
in US
Colorado School of Mine (CSM),
Case Western Univ

Operation of Auger SD in TA site.



TAとAugerの共同実験
水タンク(Muonにより感度)

TA SD と同期したイベントの取得
(2013- 繼続)
概ね安定に稼動

2016年度

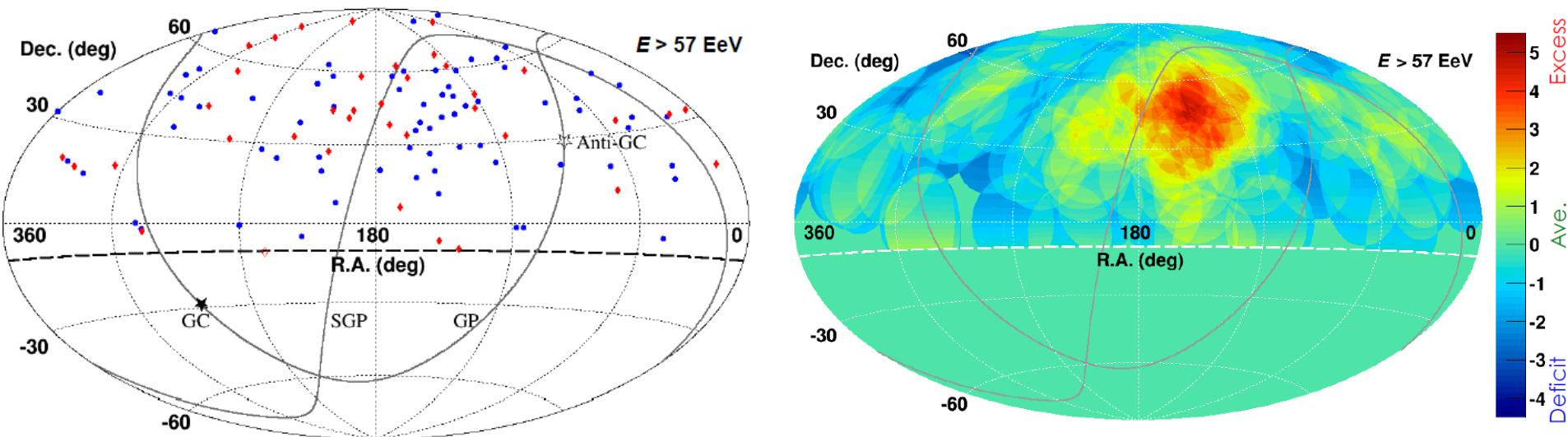
- TAアレイからのトリガー配信
 - TCP/IP接続で取得することができる。
 - TAサイトでの他の測定でも利用可能。
- アレイのDAQに負荷をかけずに測定を付加できる。

導入したトリガー配信によって
TAに同期してAuger検出器で波形が取得さ
れていることを確認

„Results of anisotropy studies

Hot spot (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 coordinate
ICRR 2015 Kawata

7 year data 109 events (Zenith angle $< 55^\circ$ (deg.))

Max significance: RA 148.4 (deg.) Dec 44.5 (deg.) ("Hotspot")

Observed: 24 events, isotropy: 6.88 events \rightarrow 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)*

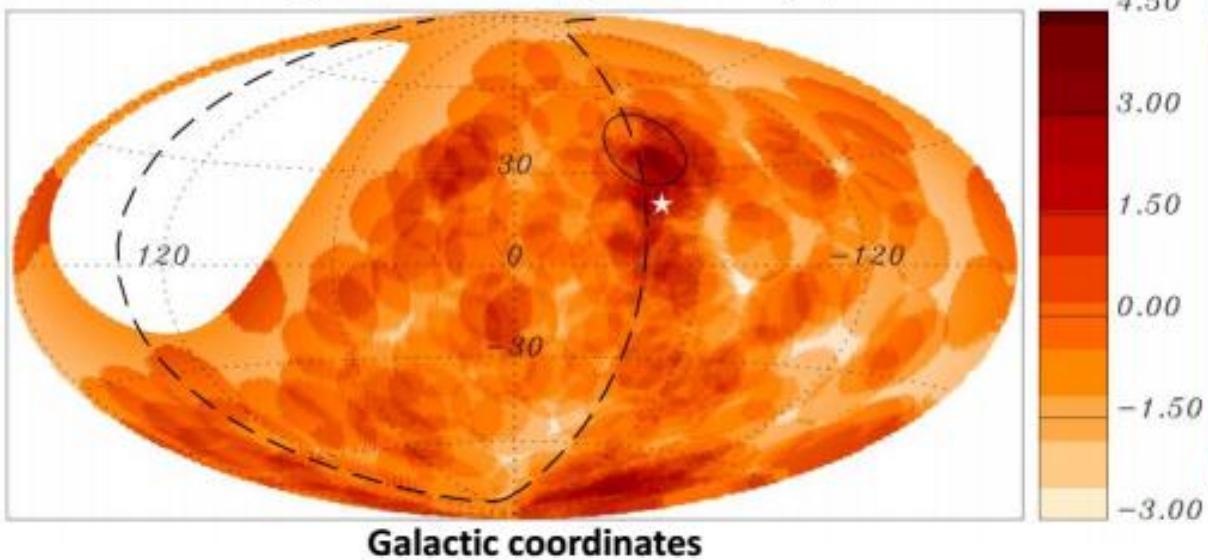
Correlation: “Intrinsic” anisotropy

Auger, ApJ, 804, 15 (2015)

2 Methods used to search for intrinsic correlation

1. Search for local excesses: Scan in energy threshold E_{th} (40-80 EeV), circular windows ψ (1° - 30°), compare number of obs. vs exp. events from isotropy
2. Autocorrelation: As above but compare number of event pairs

1. Lima-Significance map, $E > 54$ EeV, $\psi = 12$



Results

- Most sig. excess using method 1. on the left
- Local sig. 4.3σ
- Post trial probability $P = 69\%$
(fraction of isotropic simulations with more sig. excess under same scan)
- Method 2 also not sig.

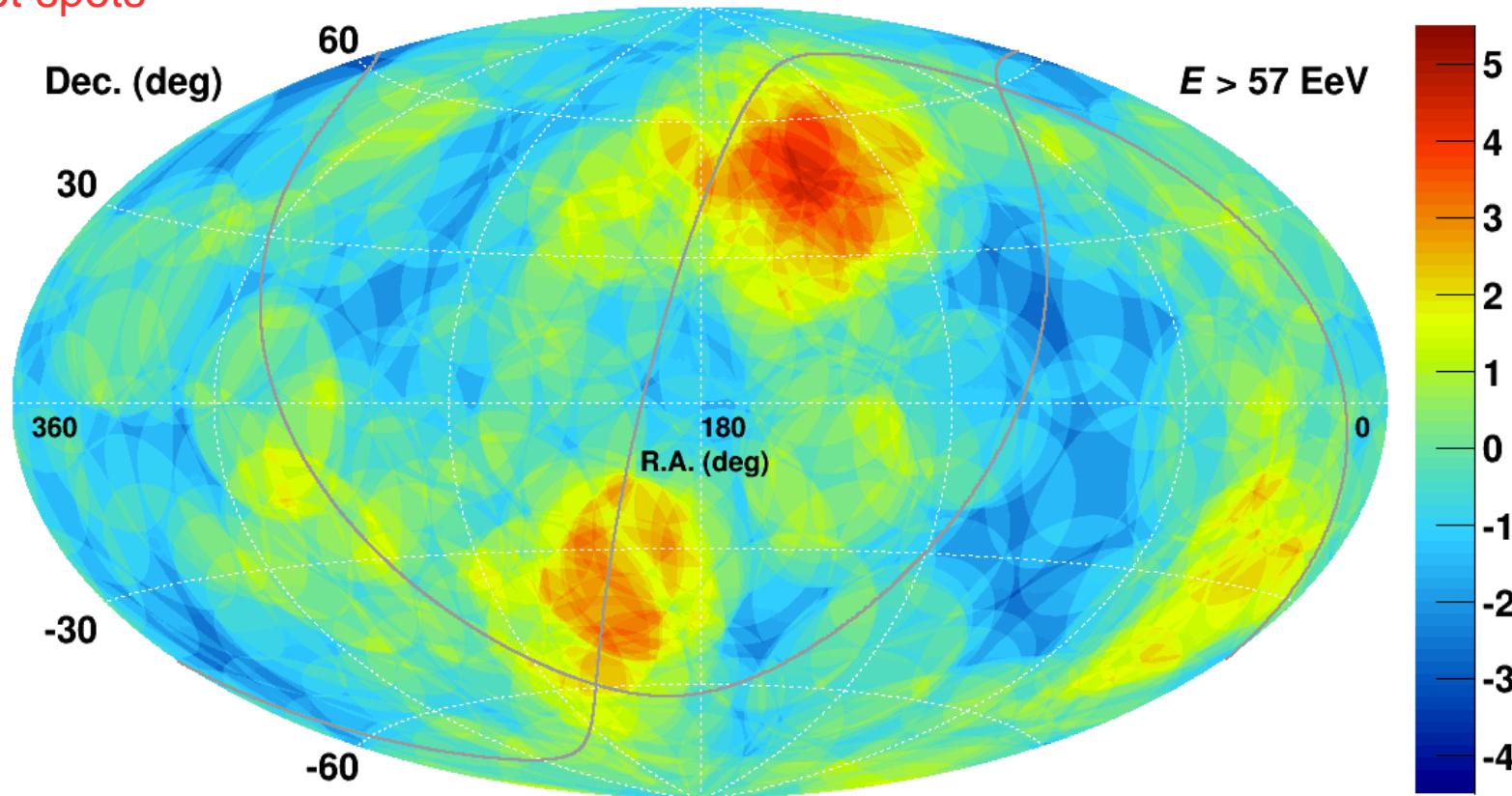
Markus Lauscher | RWTH Aachen

Anisotropy Search with the Pierre Auger Observatory

12

TA + Auger Sky map (57EeV vs 57EeV)

Hot spots

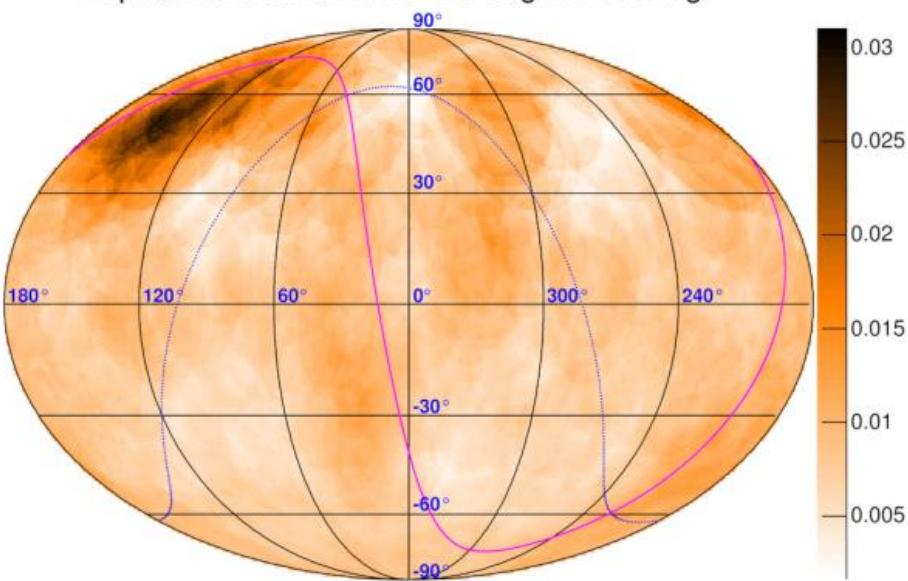


No correction for
Energy scale difference
b/w TA and Auger !!

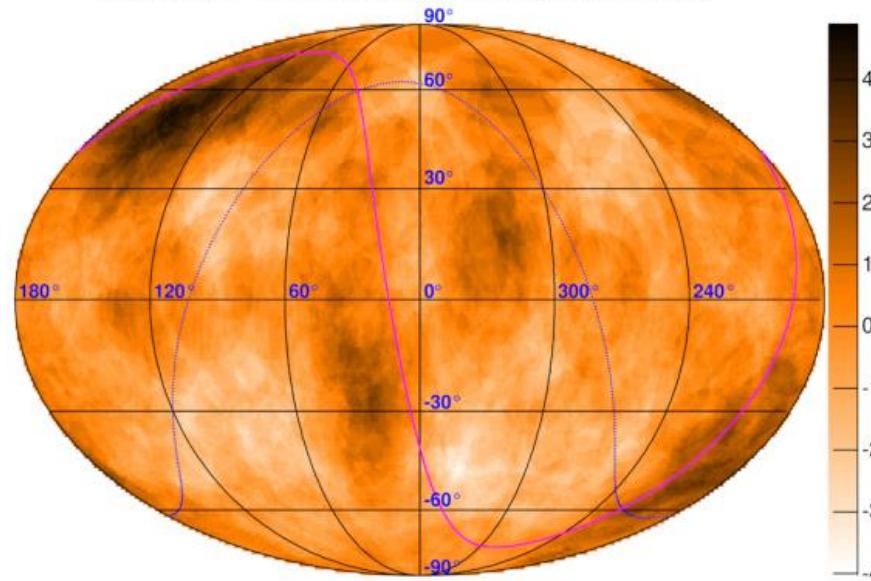
TA : 7 years 109 events ($>57\text{EeV}$)
Auger : 10 years 157 events ($>57\text{EeV}$)
Southern hotspot is seen at Cen A(Pre-trial $\sim 3.6\sigma$)

TA + Auger Sky map (57EeV vs 42EeV)

Equatorial Coordinates - 20 deg. smoothing



Equatorial Coordinates - 20 deg. smoothing



UHECR2016
Arrival directions at ultra-high energies – A review

- TA flux $E_{\text{TA}} > 57.0 \text{ EeV}$: $(0.0470 \pm 0.0055) \text{ km}^{-2} \text{ yr}^{-1}$ over 5.66 sr (12% rel. stat. unc.)
- PA flux $E_{\text{PA}} > 42.0 \text{ EeV}$: $(0.0470 \pm 0.0033) \text{ km}^{-2} \text{ yr}^{-1}$ over 5.66 sr (7% rel. stat. unc.)
→ their ratio = 1.00 ± 0.14
- (also, $\approx 3\%$ systematic uncertainty on exposures)

- This means that $E_{\text{TA}} = 57 \text{ EeV}$ corresponds to $E_{\text{Auger}} = 42.0^{+2.5}_{-1.5} \text{ EeV}$.
- Solution: we use fixed energy thresholds for both experiments, but we scale the Auger exposure by a nuisance parameter b to compensate for any over- or under-estimate of the E_{Auger} matching $E_{\text{TA}} = 57.0 \text{ EeV}$.

共通するDeclination 領域を
用いて対応する
閾値エネルギーを調整

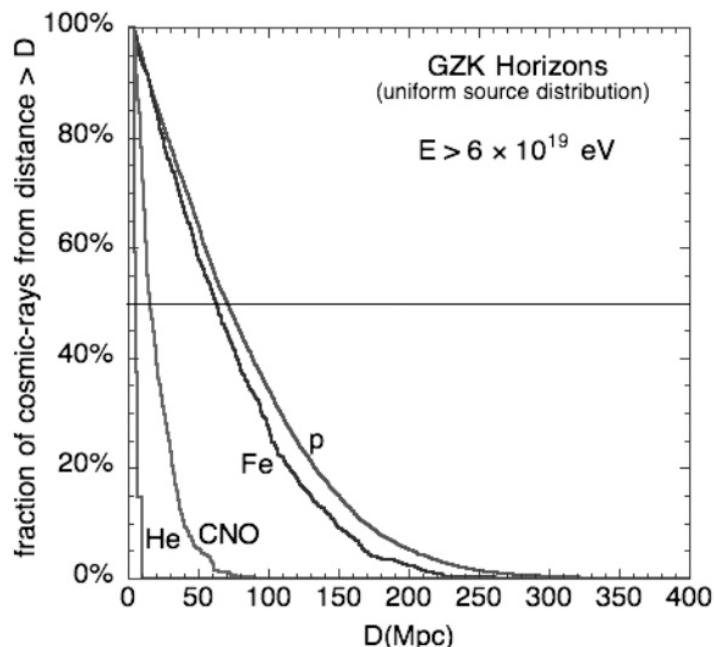
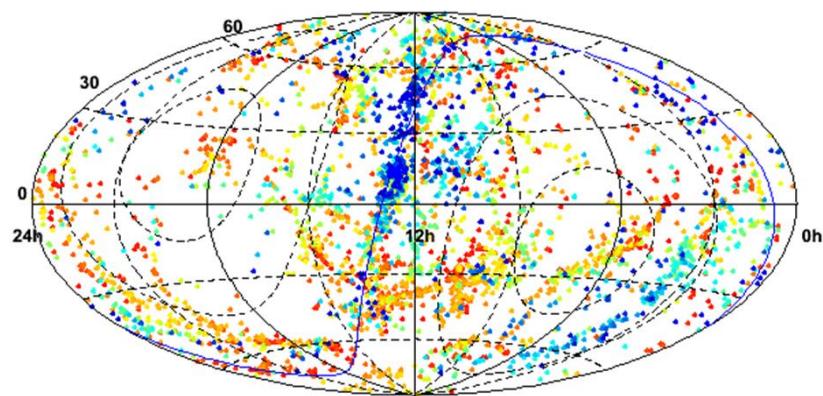
$$\omega_{\text{total}}(\mathbf{n}; b) = \omega_{\text{TA}}(\mathbf{n}) + b\omega_{\text{Auger}}(\mathbf{n})$$

Other anisotropy studies

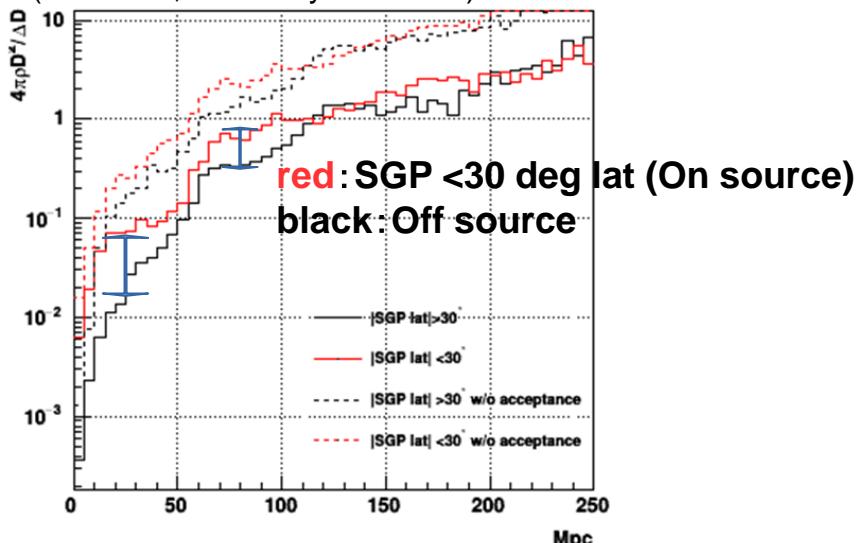
A search for anisotropy in spectrum shape in TA FOV

2MRS catalogue D<75Mpc

Blue~Redは corresponds to 0~75Mpc

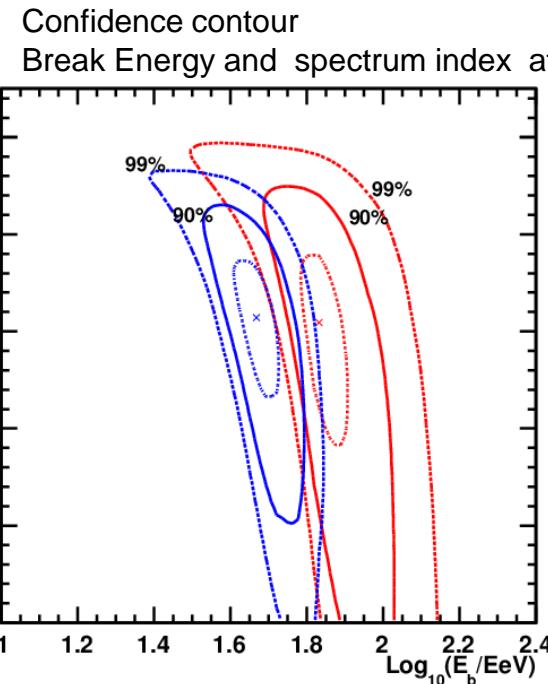
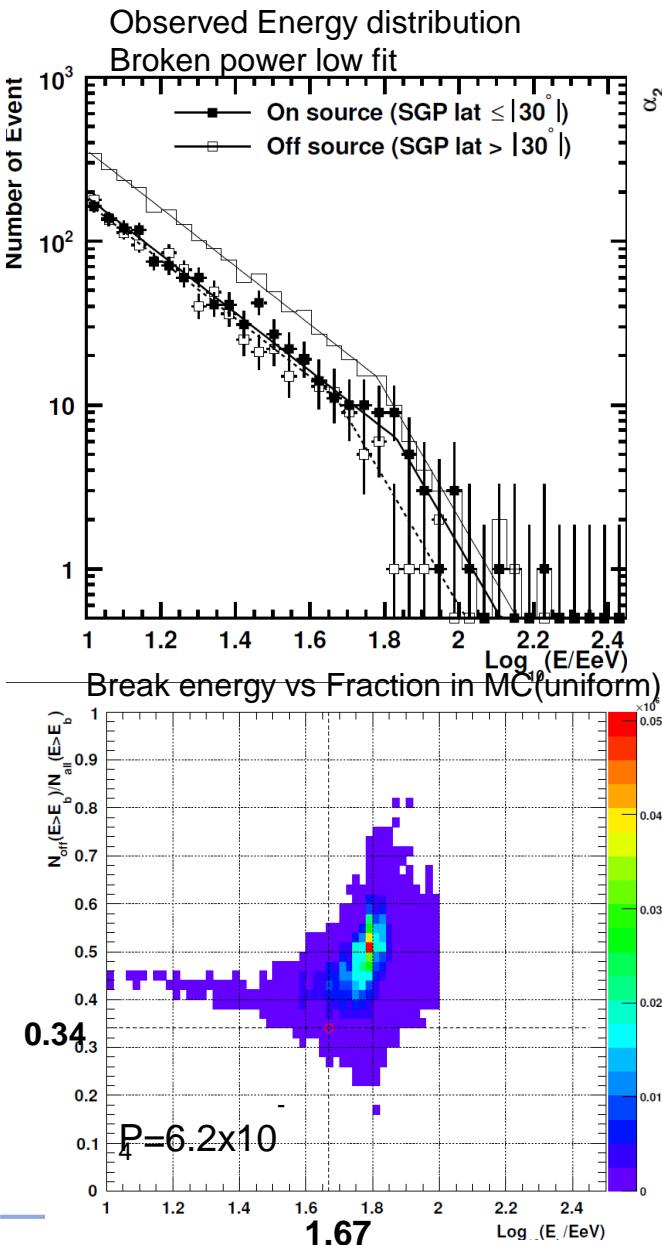


Relative amount of objects
(in 2MRS , efficiency corrected)



- Distance distribution of matter 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

A search for anisotropy in spectrum shape in TA FOV



	$\log_{10}(E/\text{EeV})$	Fraction ($E>E_{\text{b}}$)
On	1.83 (1.78)	0.66 (0.52)
Off	1.67 (1.78)	0.34 (0.48)

(-) expected
@ null hypo

- Exposure ratio is 52:48 (harf / harf , On/ Off)
- Off source shows early break and sudden attenuation.

- Observed feature agree with assumption from matter distribution qualitatively .
 - Chance probability was evaluated by repeating same procedure to MC distribution (null hypo)
- $P=6.2 \times 10^{-4} \quad (3.2\sigma)$

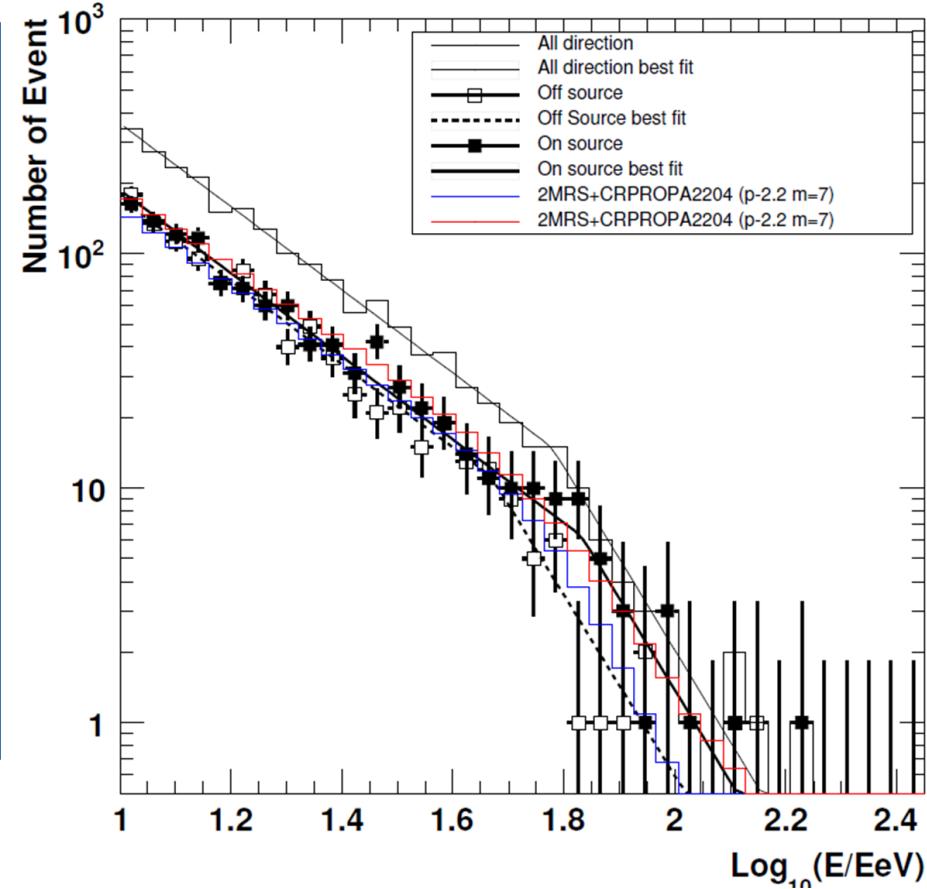
Spectrum shape differ in TA FOV

Comparison with proton model

Assume 2MRS matter dist ,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 ($E>10^{19.67}$ eV)
- result is shown in right side
 - Red | SGP lat $|< 30^\circ$ (on source)
 - Blue | SGP lat $> 30^\circ$ (off source)



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

MC expect $E > E_b$: $40(\pm 0.4\%)$ event

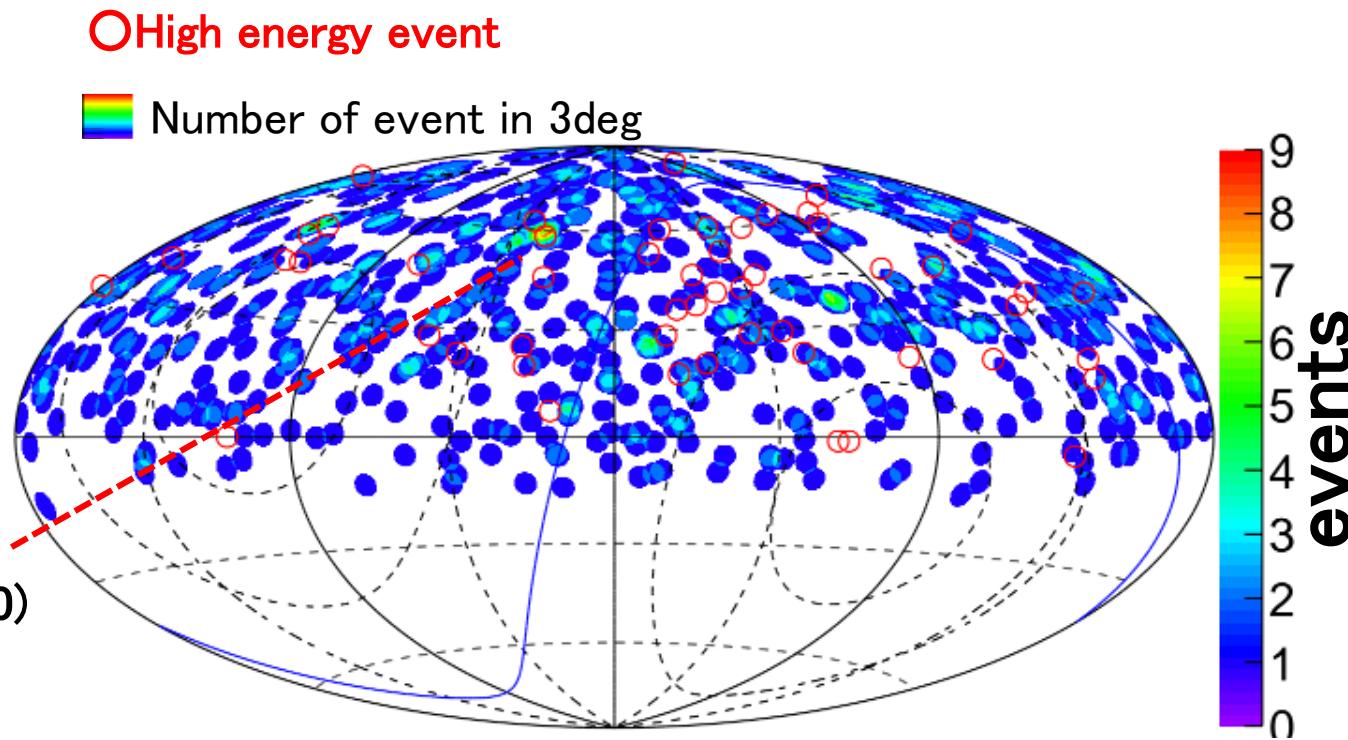
Data $E > E_b$: 30 event

$P \sim 6\%$

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

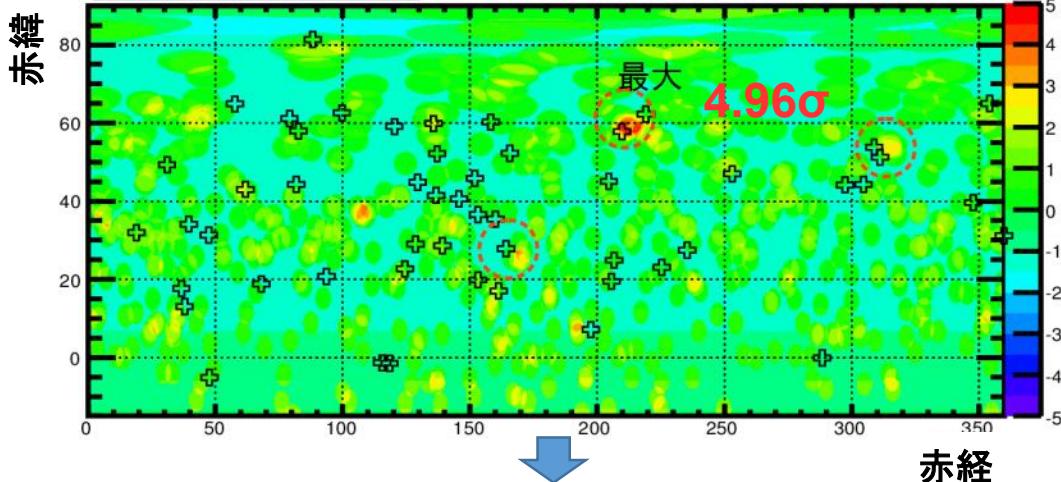
Energy correlation between events

- Low energy events ($19 < E < 57 \text{ EeV}$) near high energy event ($E > 57 \text{ EeV}$)
- Small window 3°
- What Physics could be the cause of such correlation?
 - ① Heavier particle at high energy exist → small scale clustering
 - ② very small magnetic field → small scale clustering

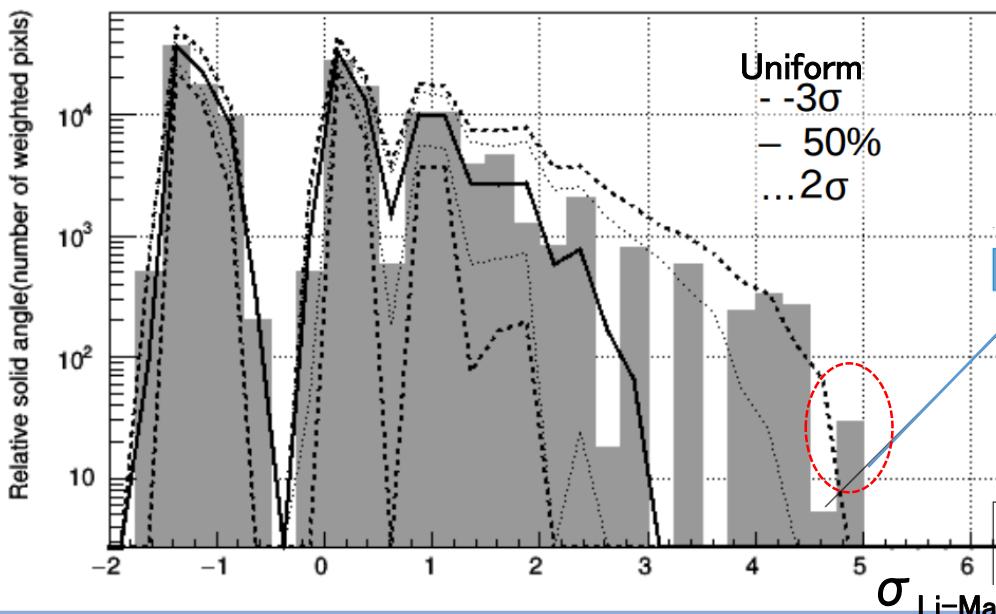


Result (coincidence of LE clustering and HE event)

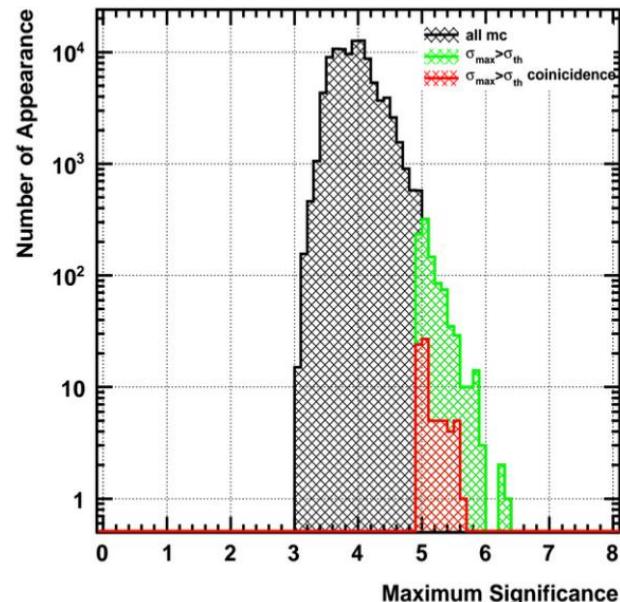
- Li-Ma σ



- $\sigma_{\text{Li-Ma}}$ distribution at high energy event direction



- MC > 4.96 σ



黒: 10^5 set MC

緑: $\sigma_{\text{Li-Ma}} > 4.96$ 963 case (2.3σ)

赤: coincidence with $E > 57\text{EeV}$

76 time $P = 7.6 \times 10^{-4}$ (3.2σ)

At least 1 event $E > 57\text{EeV}$ correlate
with low energy prob 3.2σ

拡張計画

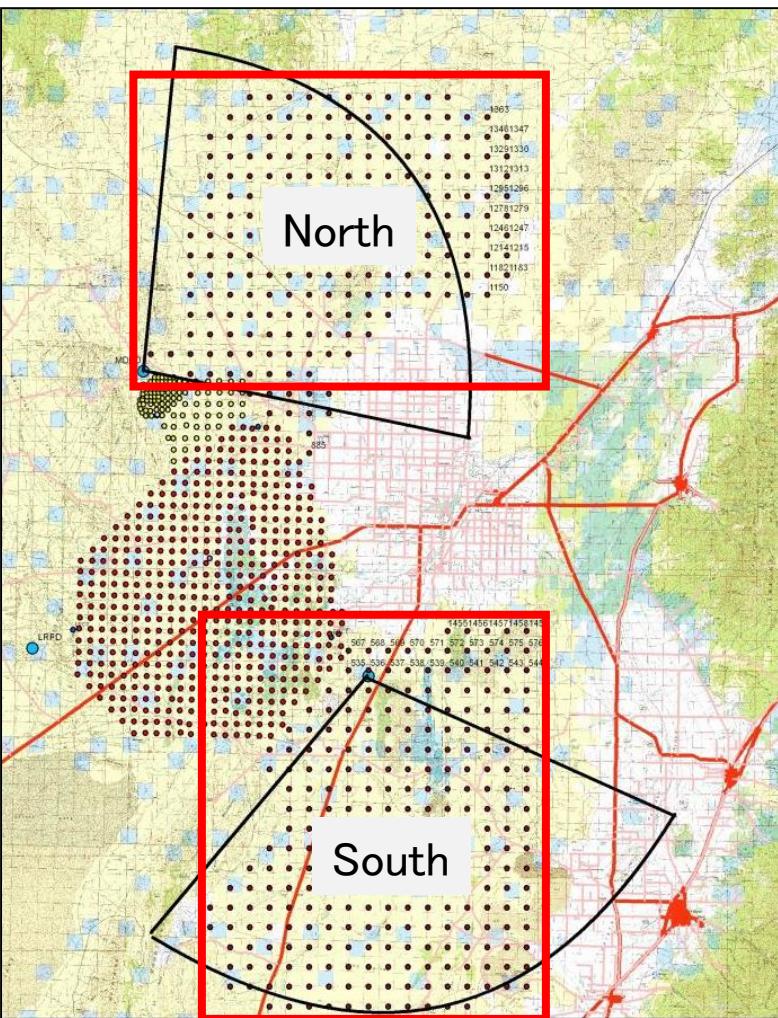
TAx4 :

TALE 低エネルギー拡張

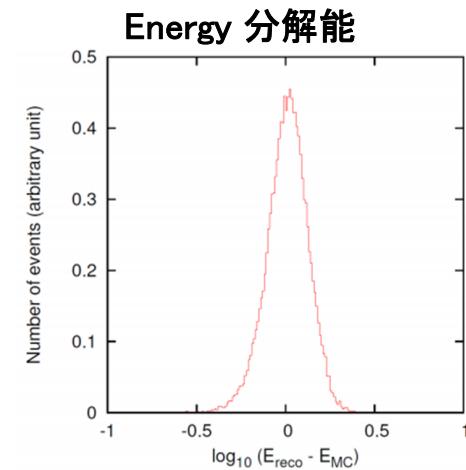
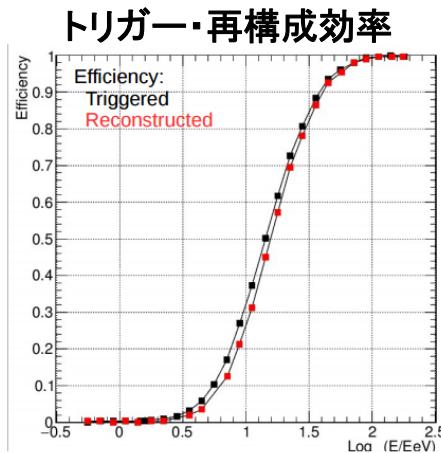
TAX4 拡張計画

既存TAアレイの南北2領域に2.08 km 間隔で新規SDを追加。

TA地表アレイとあわせて、合計3000 km² の観測面積 (~Auger) の面積で観測



- Hot spot 宇宙線起源 の解明
- 広い検出器間隔 57EeV で Efficiency > 95%
- エネルギー分解能 -29% +22%
- 角度分解能 ~2.2度
- HiRes II 望遠鏡を移設 ハイブリッド観測



北半球の異方性の精査観測
エネルギースペクトルの詳細な測定
質量組成の特定

TAX4 Experiment

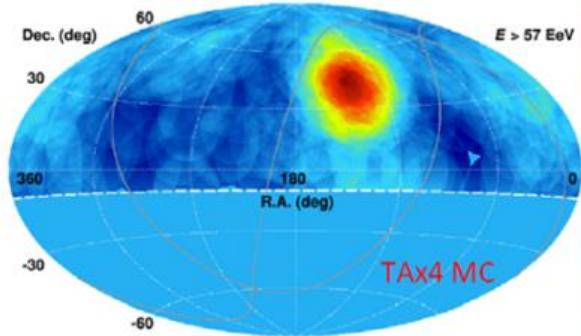
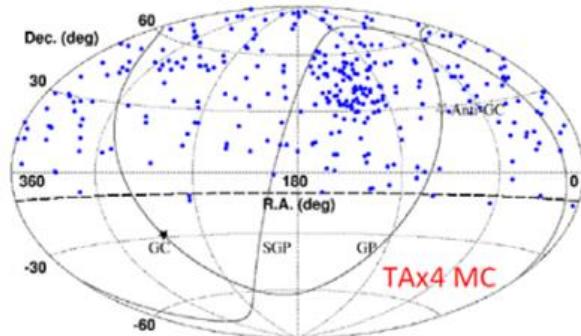
- TAX4 experiment gives statistics correspond to 19 years of observation by TA

(1) One Hotspot

Hotspot Signal
80-18.9=61events
(RA, Dec)=(145°, 45°)
Gaussian $\sigma=10^\circ$

Isotropic B.G.
305-61=244events

Oversampling
20° radius circle

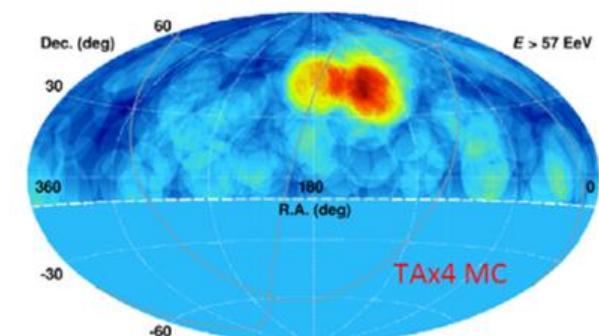
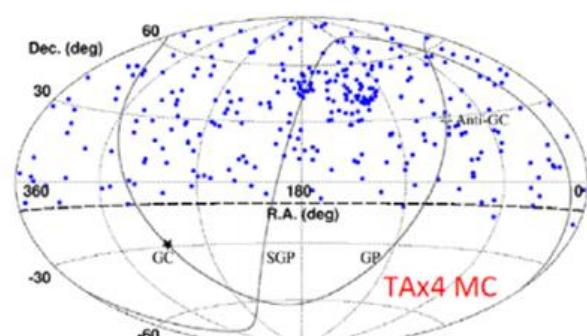


(2) Double Hotspot

Hotspot Signal
Total 61 events
1. 41events
(RA, Dec)=(145°, 40°)
Gaussian $\sigma=10^\circ$
2. 20events
(RA, Dec)=(175°, 40°)
Gaussian $\sigma=5^\circ$

Isotropic B.G.
305-61=244events

Oversampling
15° radius circle

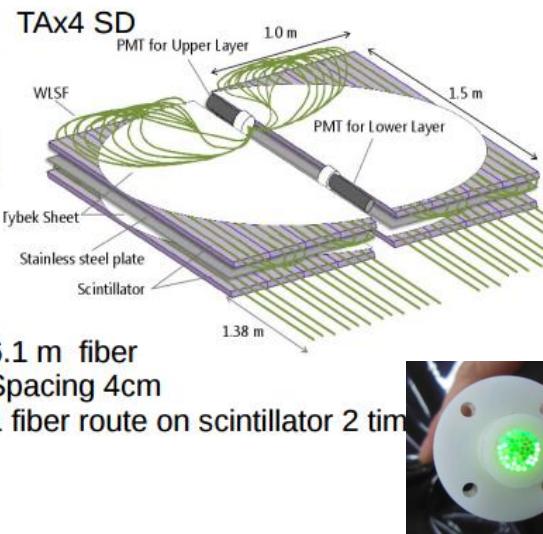
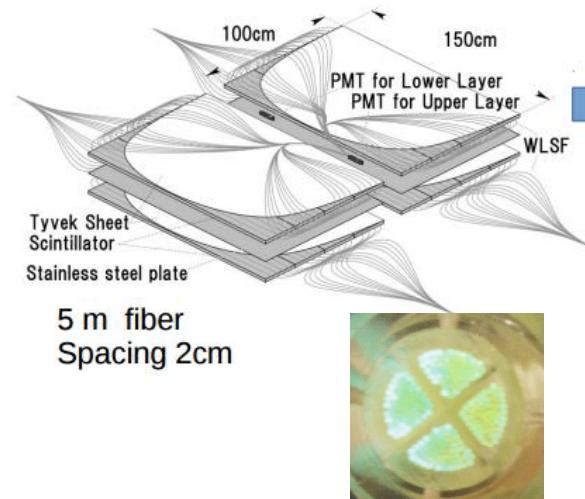


- Figures are simulations of the expected anisotropy at statistics of TAX4 data .
- These simulations are done in 2 scenarios.
Left side is the case that hot spot have origin at one location.
Right side is the case that hot spot have origin at two location.

検出器開発・アセンブリ

ファイバーレイアウトのR&D

TA SD



PMT ETL → Hamamatsu

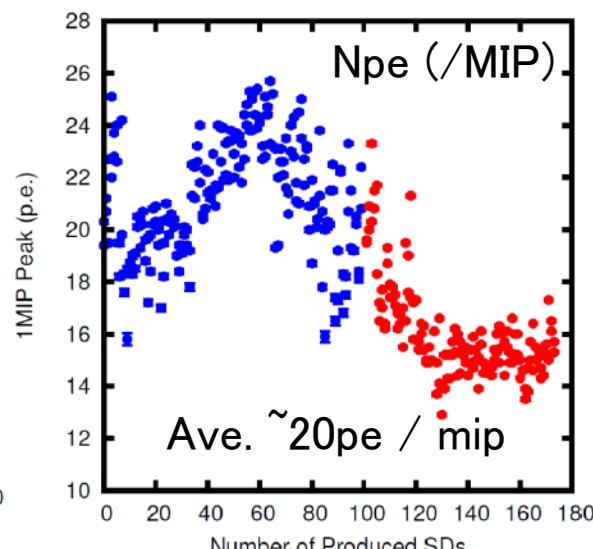
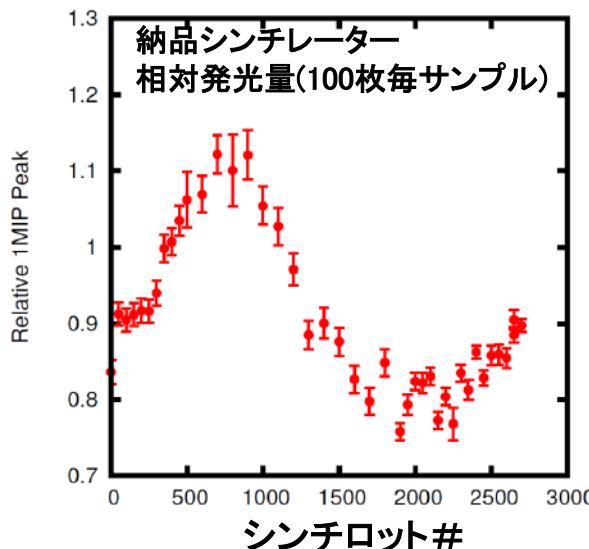
PMT 量子効率ばらつき小@475nm

PMT 管面の一様性向上

8月に行われた明野観測所での作業風景
国内大学・ロシアからの研究者学生が参加
ファイバーを張っているところ



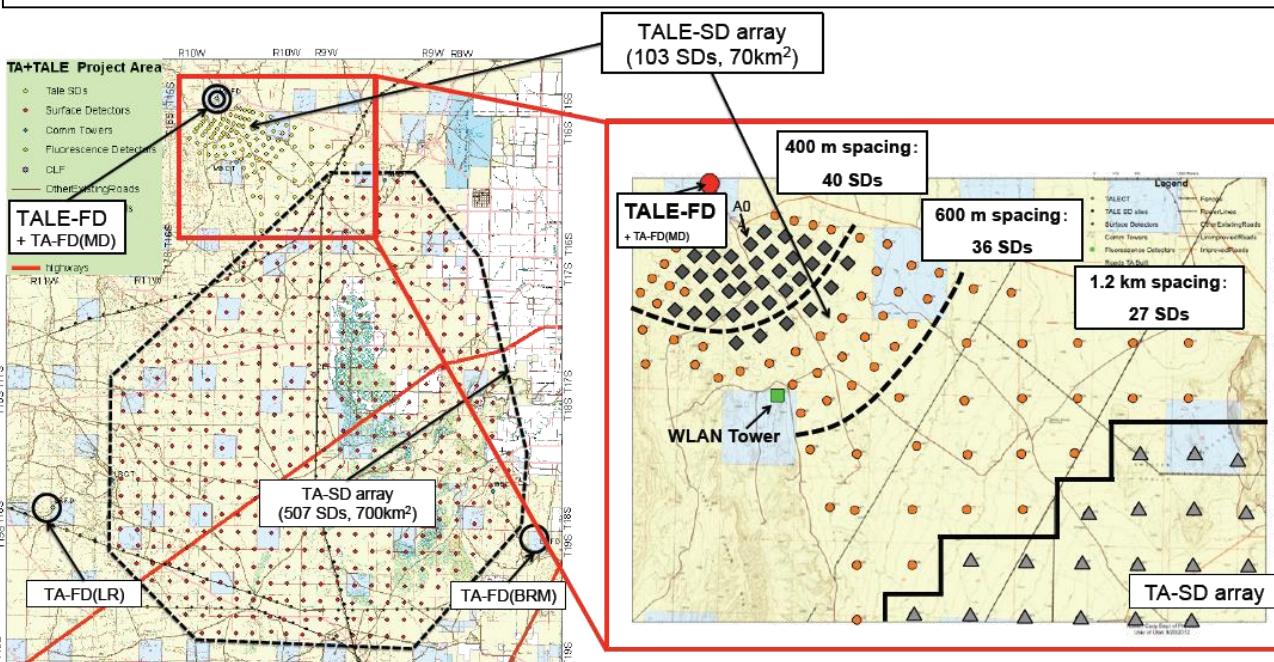
製作したSDのMIP count (Npe)



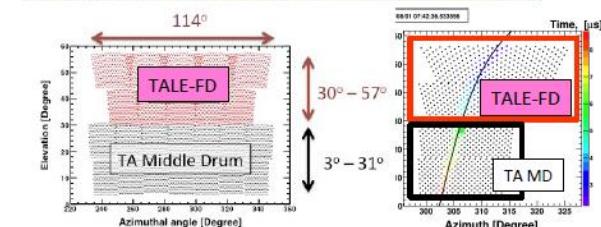
- 16/01月 PMT輸送振動試験→OK
- 16/02月 100台製作@明星電気
- 16/03月 アメリカへ輸送
輸送後の状態確認→OK
- 16/08月 75台製作@明野観測所
- 16/11月 アメリカへ輸送
- 17/01月-02月 最終アセンブリ
TALE サイトへ設置

TA Low Energy Extension (TALE)

10基の高仰角 望遠鏡 (31–59°)で低エネルギー側の浅く発達するシャワーを観測
Hybrid観測のために密集した地表粒子検出器を配置 (400m, 600m, 1200m 間隔)



望遠鏡は先行して稼動



HiRes実験(1993年~2006年)
のFDシステムを改良して再利用

TA実験MDステーションに隣接

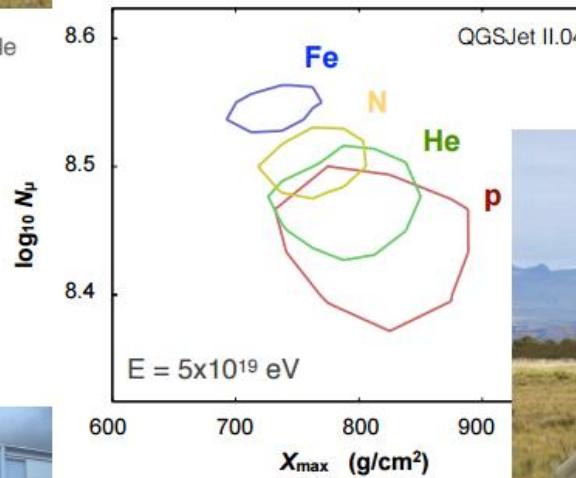
10¹⁶eV–10¹⁸eVにかけての スペクトルとX_{max}(化学組成)の高統計・精密観測
~ΔE_{fd} 16% @10¹⁶eV, 11% @10^{18.5} eV ~ΔX_{max} 10g/cm²

Auger prime Upgrade

Auger Upgrade: composition sensitivity at $E > 6 \times 10^{19}$ eV



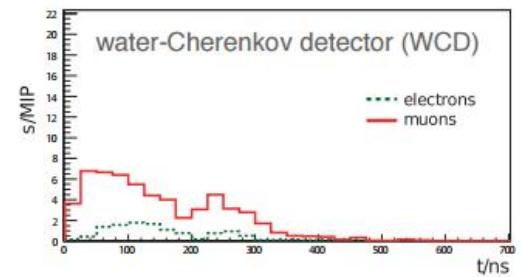
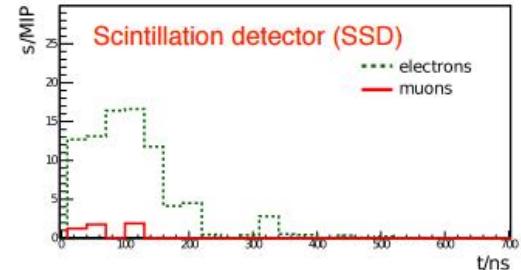
100% duty cycle



15% duty cycle



(AugerPrime design report 1604.03637)



$$S_{\mu, \text{WCD}} = a S_{\text{WCD}} + b S_{\text{SSD}}$$
$$S_{\text{em}, \text{WCD}} = c S_{\text{WCD}} + d S_{\text{SSD}}$$

E-mu 分別をすべての検出器で行う。

まとめ

- 観測結果
 - $10^{15.6} - 10^{20.3}$ eVで宇宙線スペクトルの測定
 - TA Xmax の測定結果は 陽子 (または軽元素)と無矛盾
 - Auger 明確に mixed composition. と主張
 - 北半球 $E \sim 5.7 \times 10^{19}$ eV 以上で異方性の兆候(Hot Spot)
 - Spectrum 超銀河面方面とそれ以外での差異
 - 全球での異方性解析 (Hotspot 解析 Dipole)
- 拡張計画
 - TAx4 : 高統計で高エネルギーでの異方性を調べる。(TA19年分)
 - TALE: 低エネルギーで精密測定 宇宙線源の遷移を見る
- 関連観測 R&D
 - 雷との相関観測
 - μ 粒子検出器、Augerとの共同観測 空気シャワーの詳細測定
 - 電磁シャワーからの電波測定 将来の測定方法のR&D
 - 新型大気蛍光望遠鏡のR&D (FAST等)
 - Auger, EUSO等との同時観測