Telescope Array results on UHE cosmic rays and the plan

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Telescope Array Collaboration


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VHEPA2014, Kashiwa campus


Outline

- Telescope Array (TA)
  - TA collaboration/TA detector
- Recent preliminary TA results
  - Energy spectrum
  - Composition
  - Anisotropy
- TA Extension proposal, on-going R&Ds
  - TAx4, TALE
  - R&D, associate experiments
- TA SD burst events
- Summary

Telescope Array Collaboration

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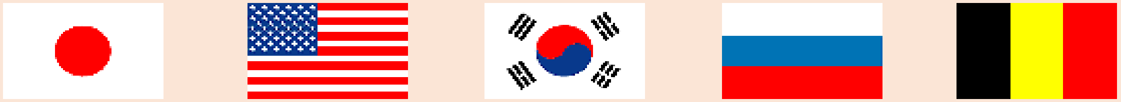
~120 collaborators in 5 countries

Japan, USA, Korea, Russia, Belgium



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TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.

Middle Drum (MD)

3 com. towers

~30 km

CLF

ELS

Long Ridge (LR)

Surface Detector (SD)

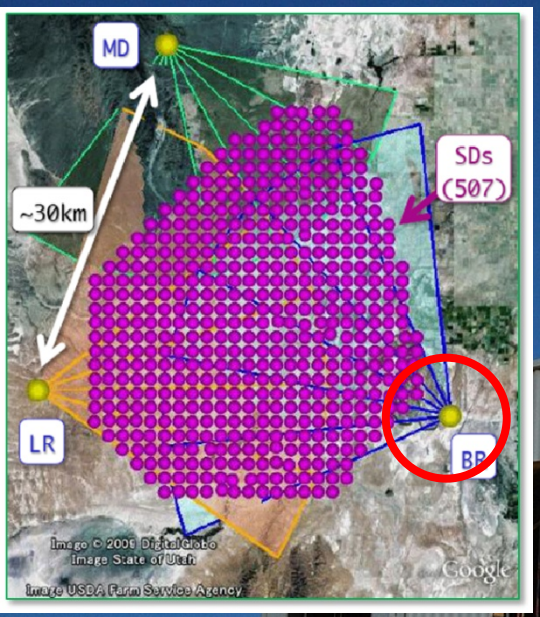
507 plastic scintillator SDs
1.2 km spacing
~700 km²

Fluorescence Detector(FD)

3 stations
38 telescopes

FD and SD: fully operational since 2008/May

Fluorescence Detector stations

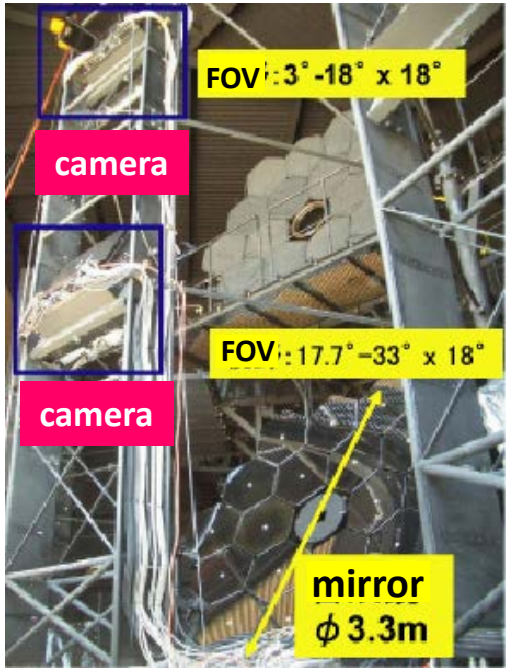


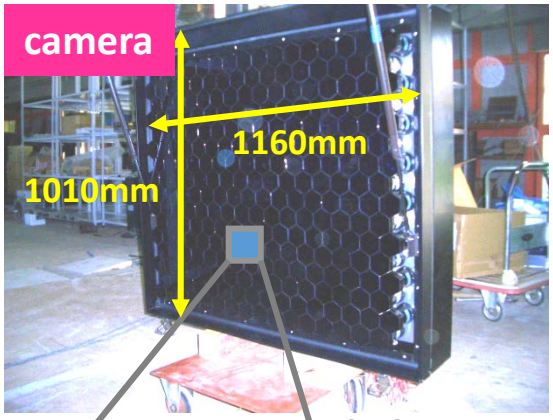
Field of View
3 – 33° in zenith
108° in azimuth

Observation
moonless, clear night
duty cycle ~10%

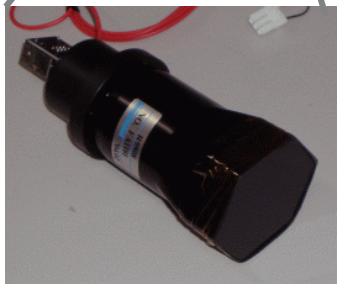
All three stations: observation since Nov., 2007

FD: mirrors & cameras





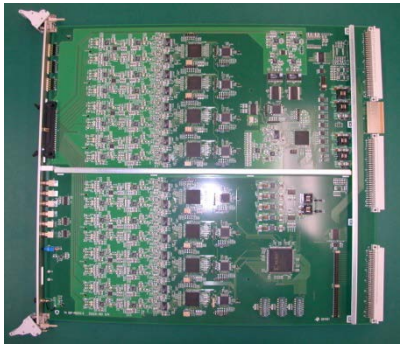
256PMTs



Hexagonal PMT

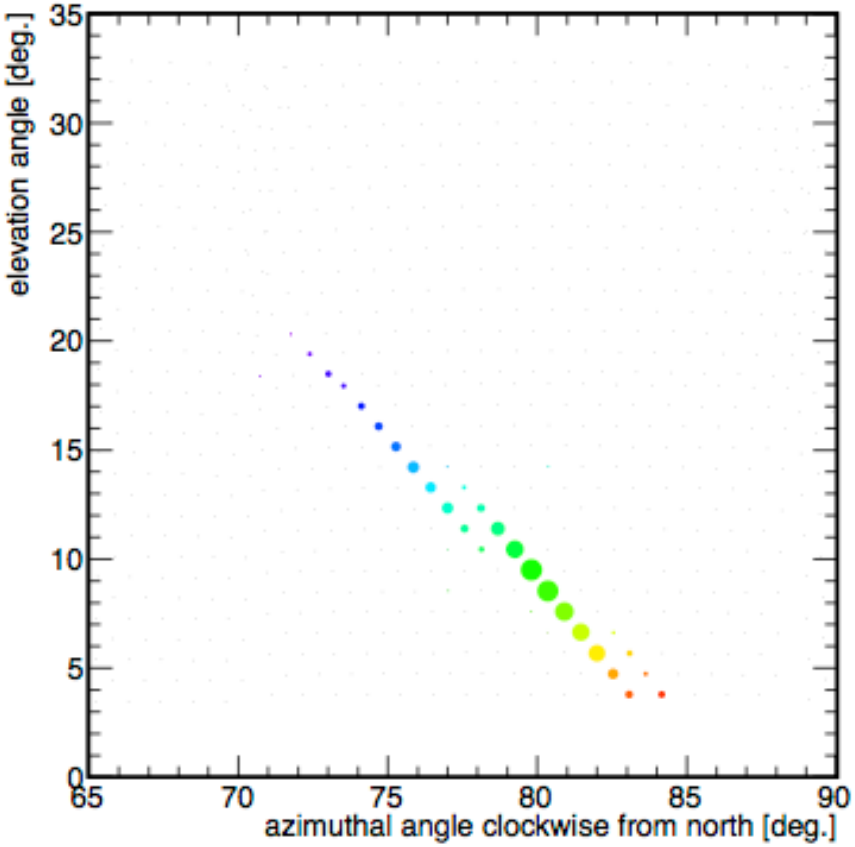
~1° FOV/PMT

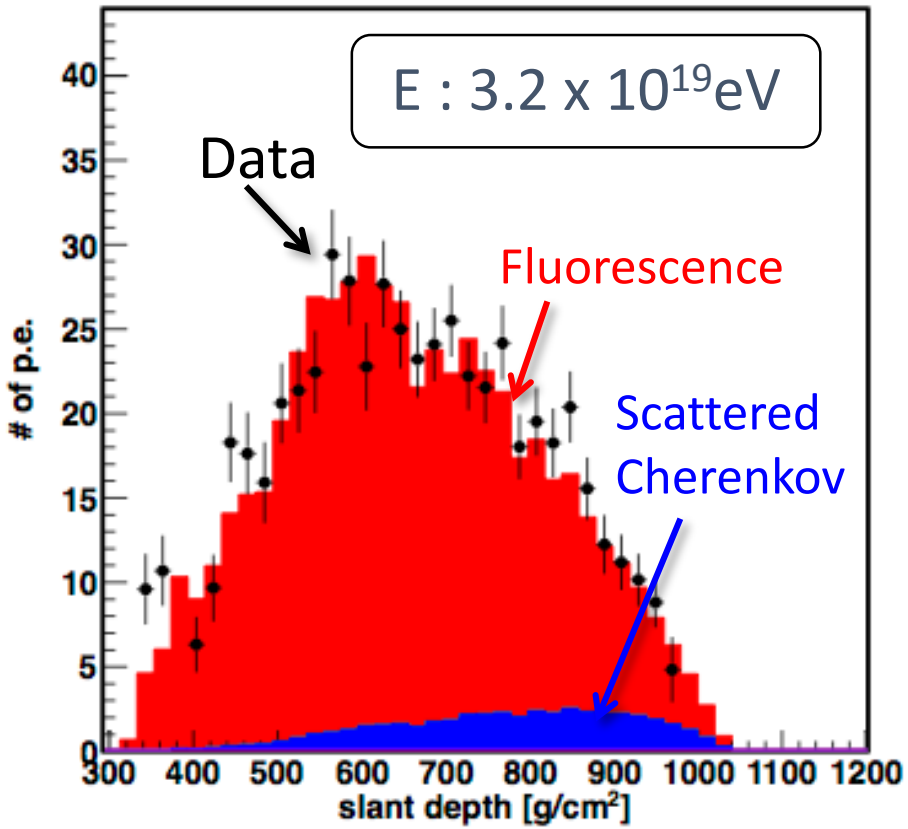
Signal digitizer



14 bit, 100 ns resolution
Record length: 51.2μs

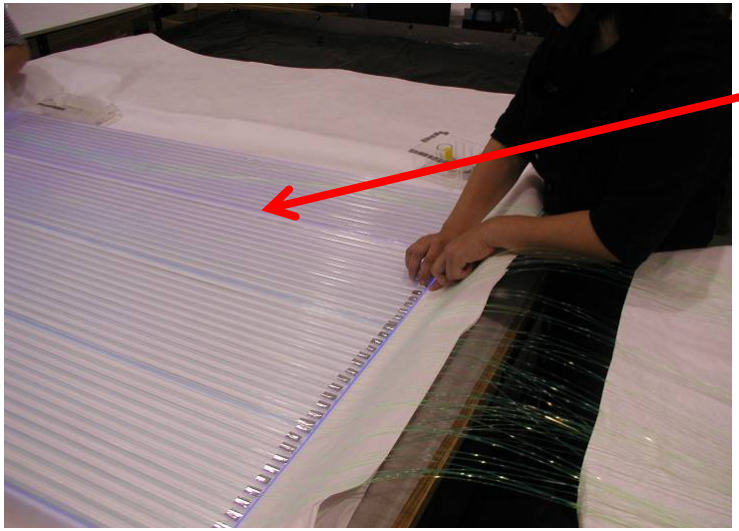
Example





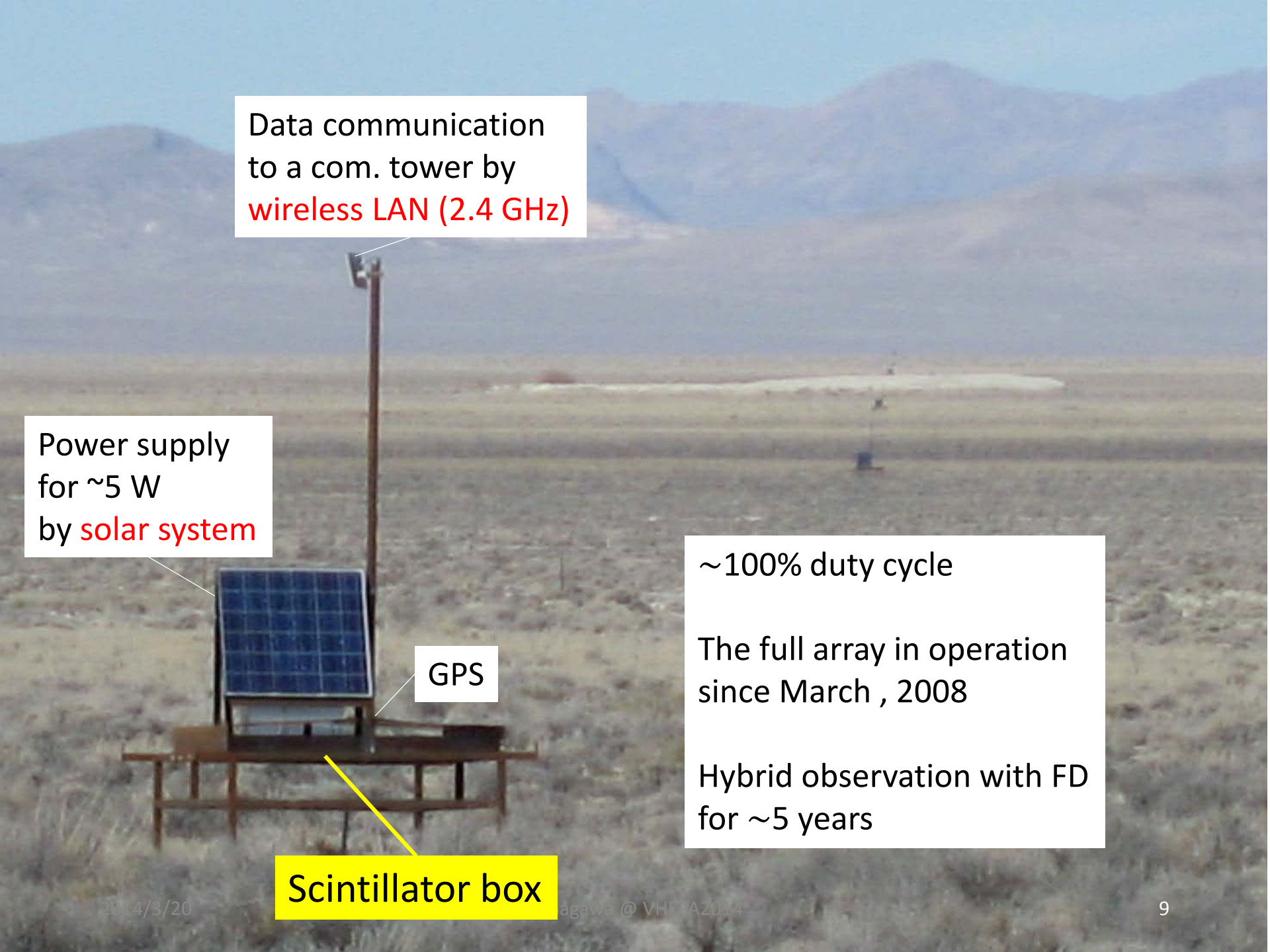
(hybrid events)
Energy resolution: 7%
Angular resolution: 0.9°

Surface Detector (SD)



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

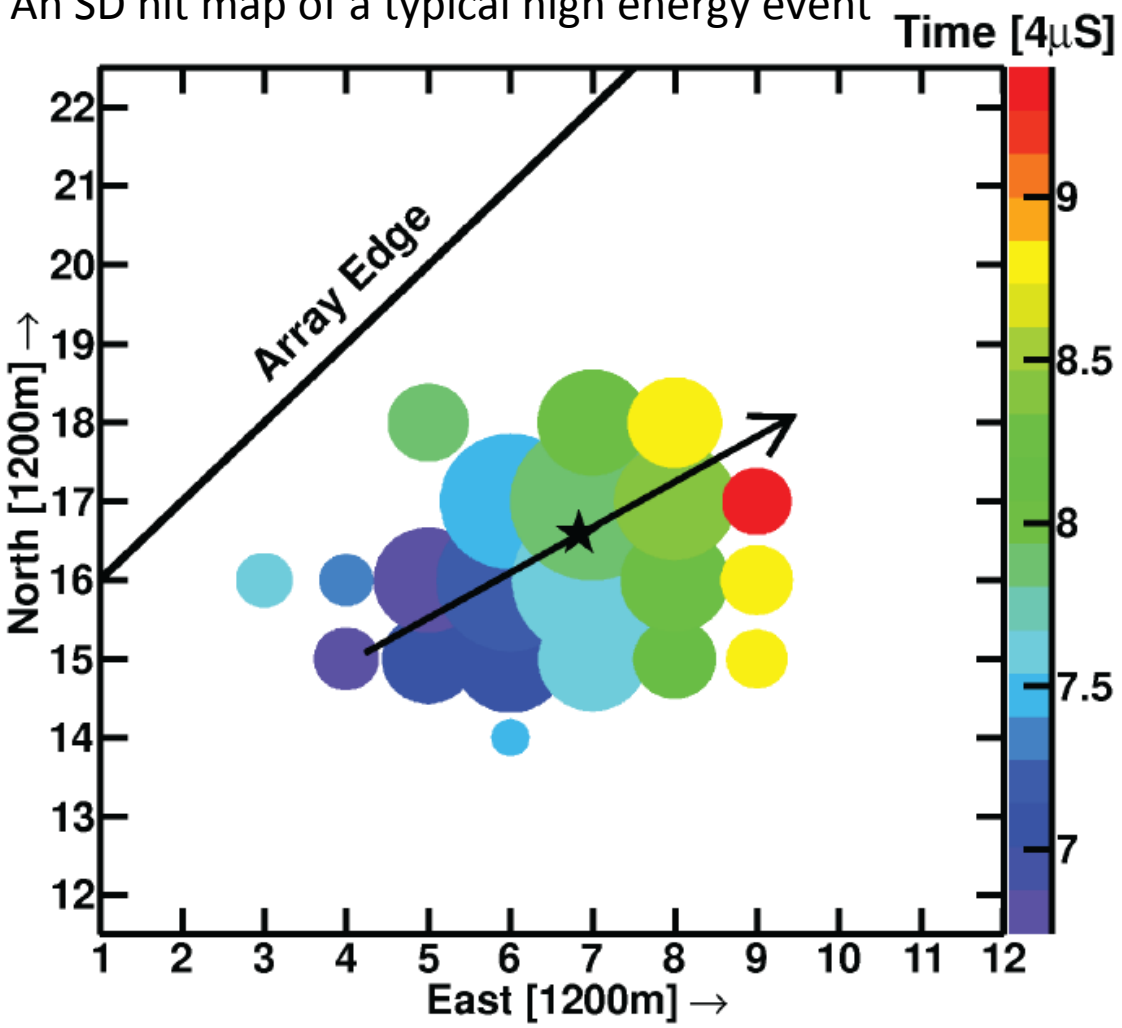
The full array in operation since March , 2008

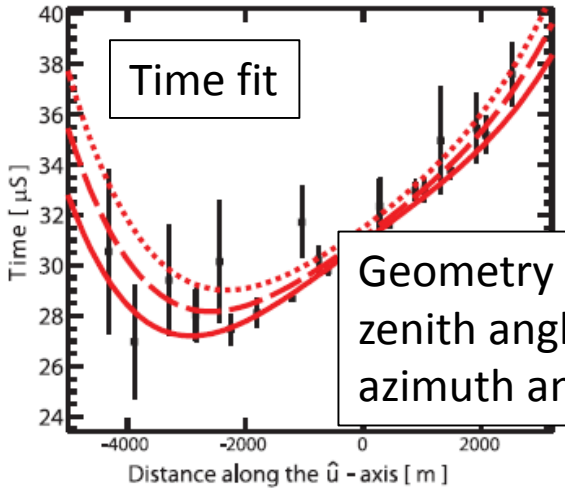
Hybrid observation with FD for ~5 years

Energy spectrum

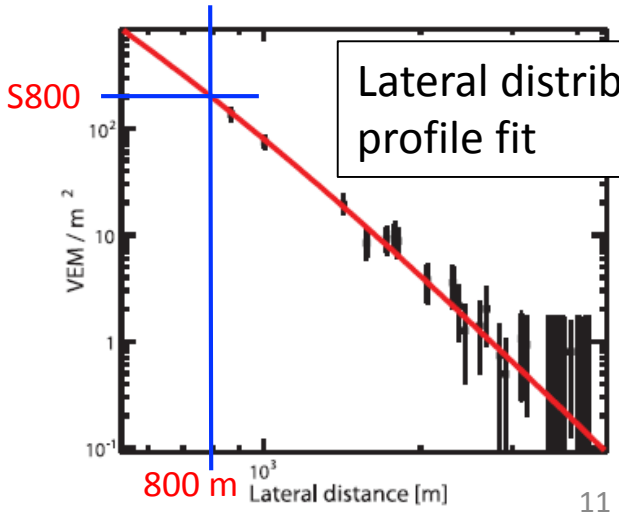
TA shower analysis with SD

An SD hit map of a typical high energy event





Geometry
zenith angle: θ
azimuth angle

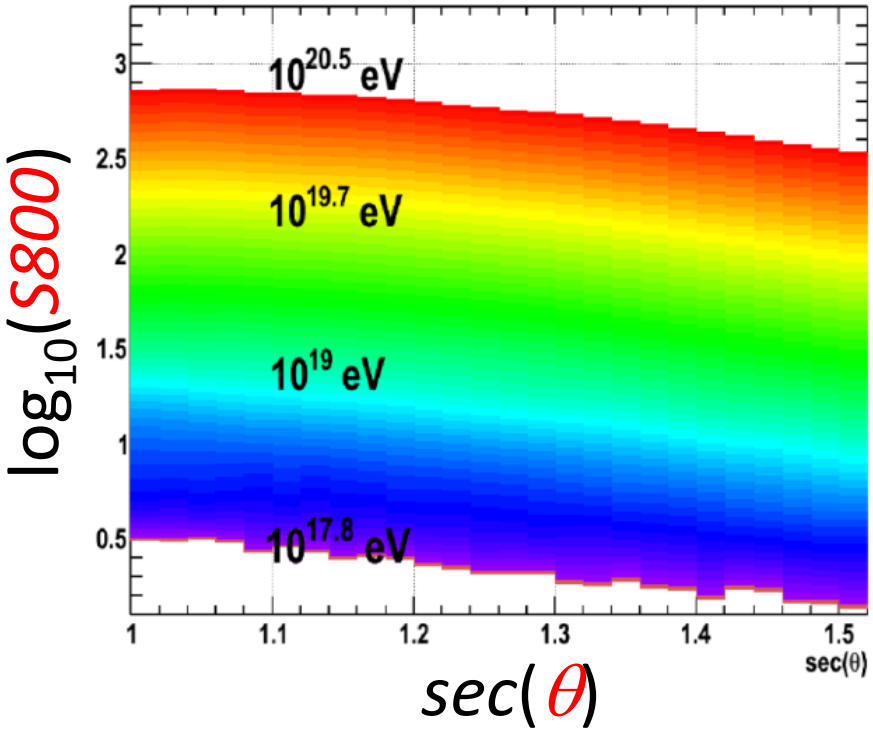


Lateral distribution
profile fit

First estimation of SD energy

Monte Carlo → Energy table

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



TA SD resolution
($E > 10^{19}$ eV)
20% in energy
1.4° in angle

SD energy scale

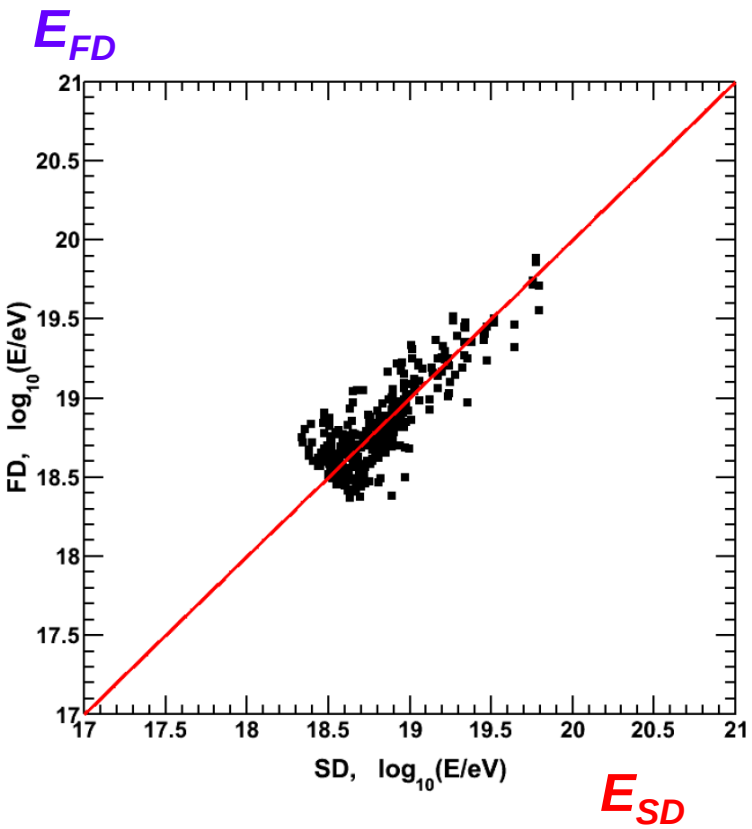
- For hybrid events
  - E'_{SD}: energy table from MC

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

- 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%



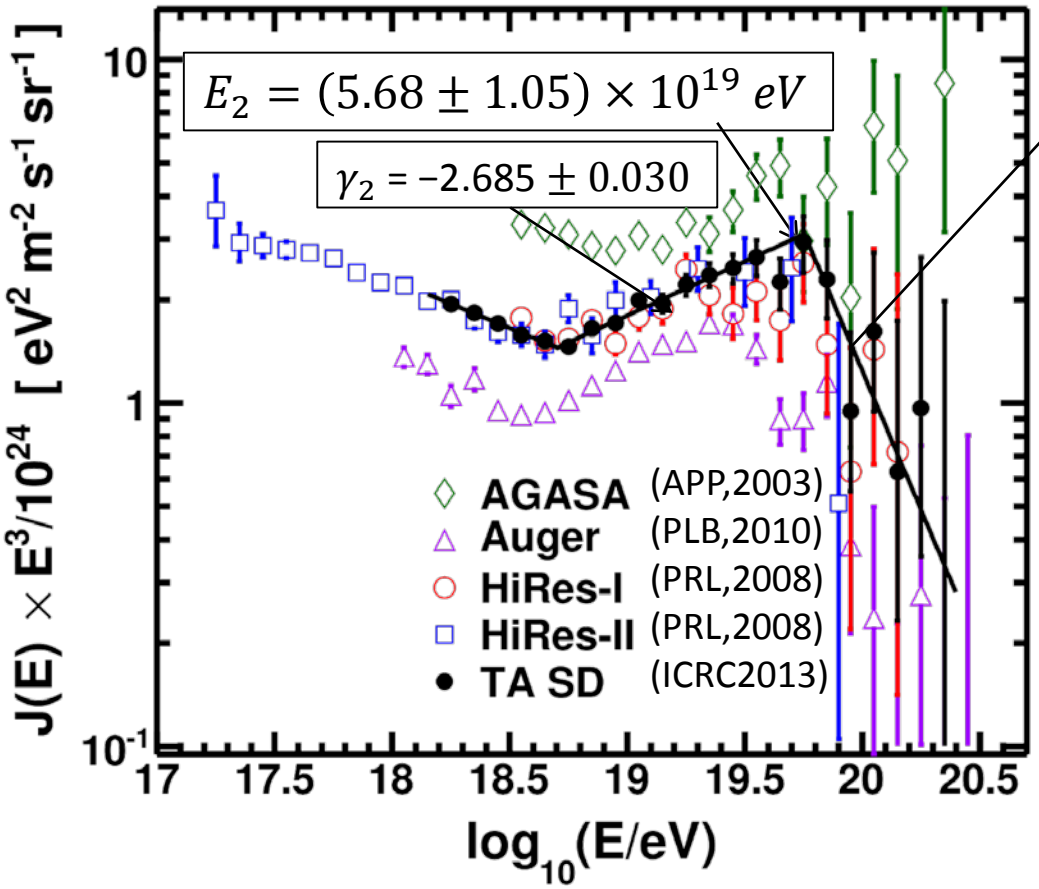
(rescaled SD energy)

TA SD energy spectrum (5-year data)

ICRC2013
preliminary

SD energy is scaled to FD energy

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



Suppression consistent with GZK cutoff

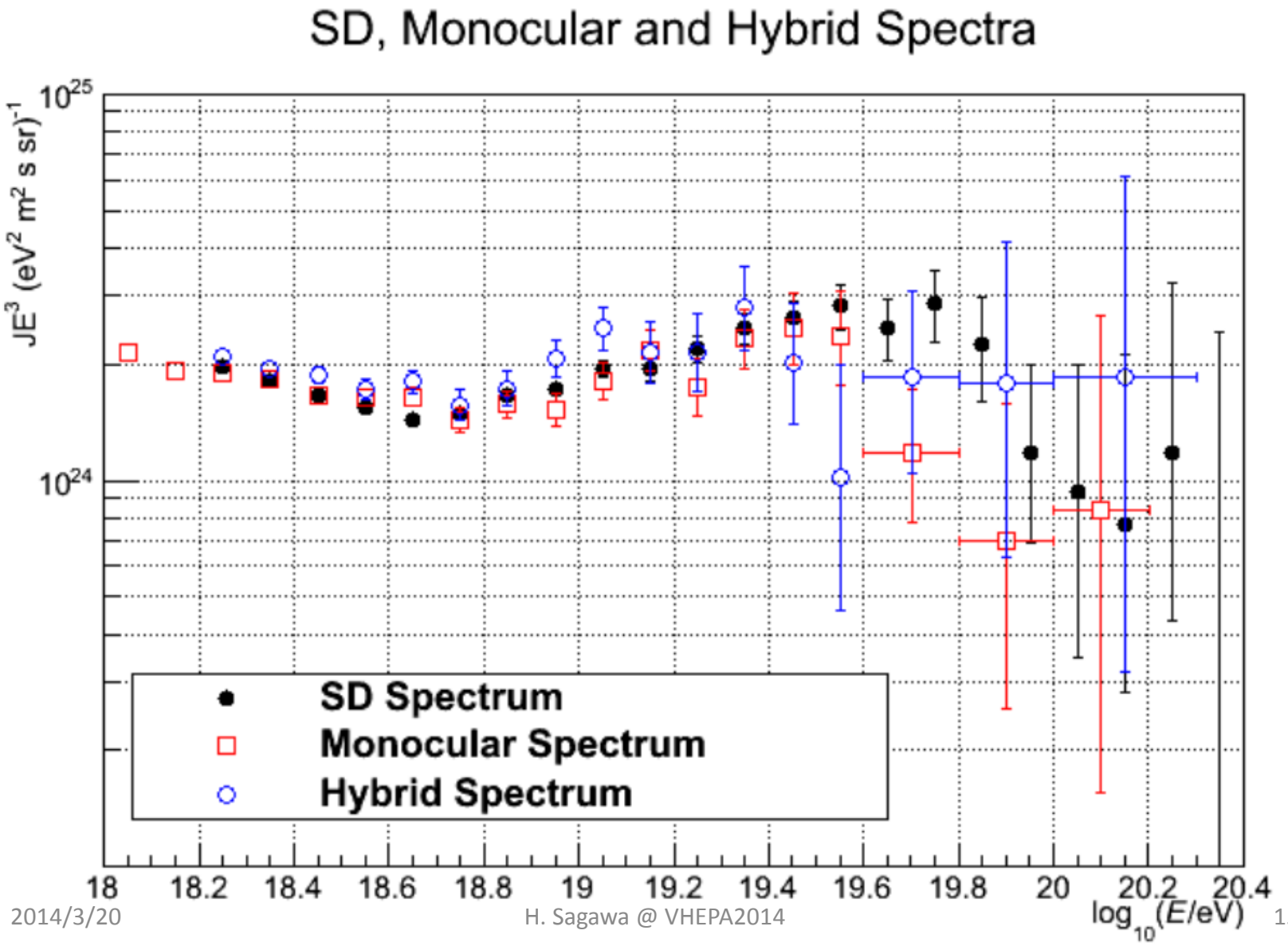
Significance of suppression

For E > $10^{19.8}$ eV,
N(cont. spectrum) = 68.1
N(observed) = 26

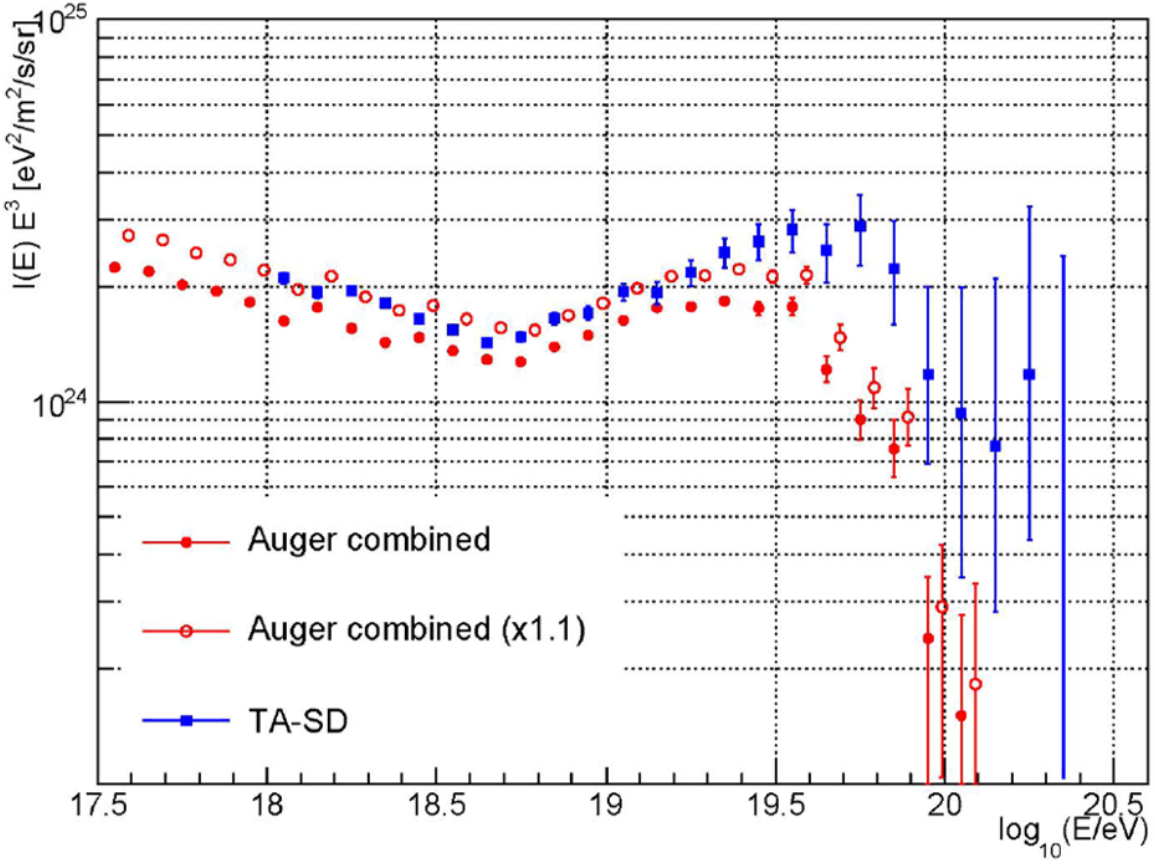
Continuous spectrum is excluded with 5.74σ

ICRC preliminary

Spectrum overview



TA spectrum and Auger spectrum



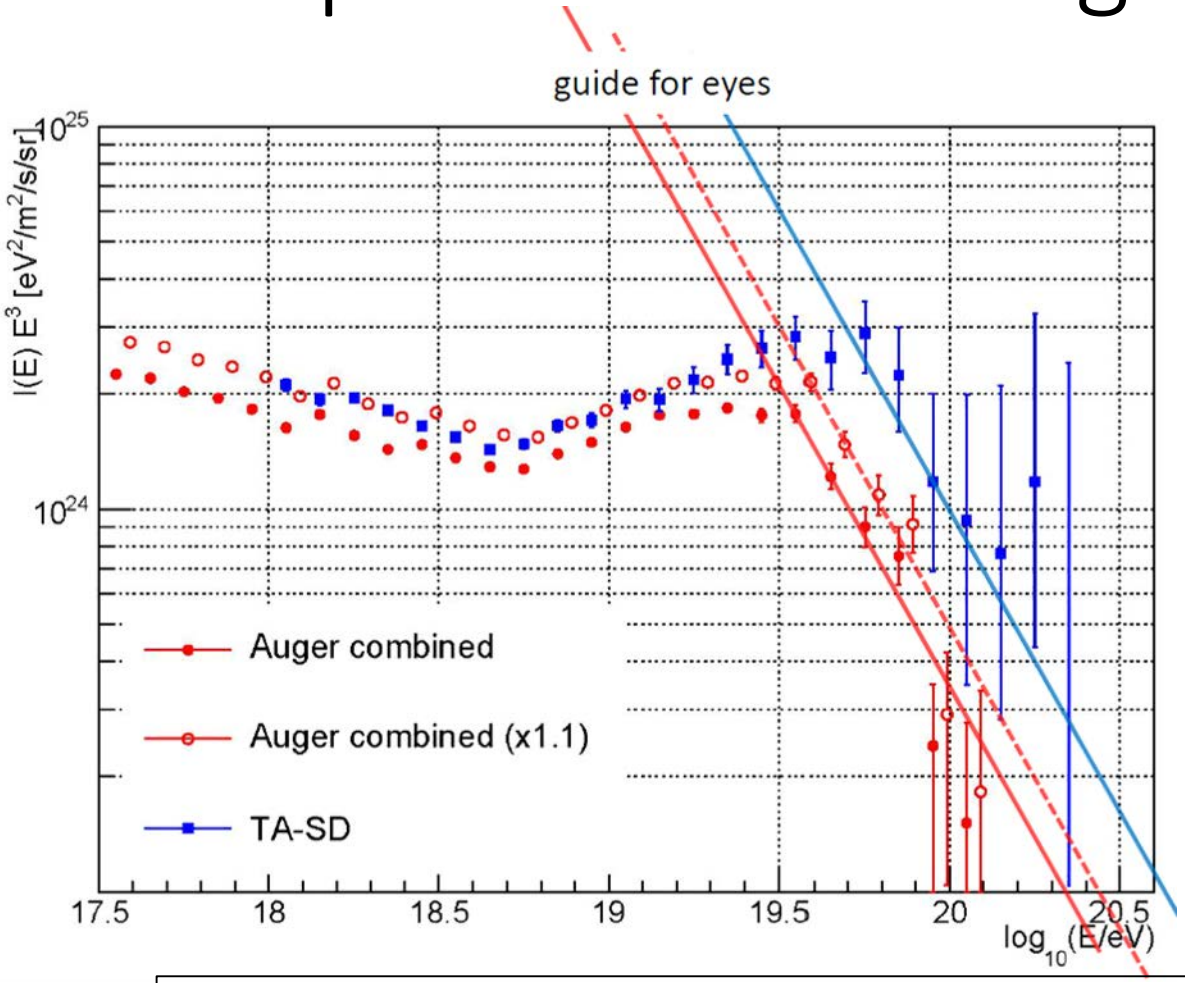
Rapporteur talk by Y.Tsunesada at ICRC2013

Energy scale uncertainty

. TA: 21%

. Auger: 14%

TA spectrum and Auger spectrum



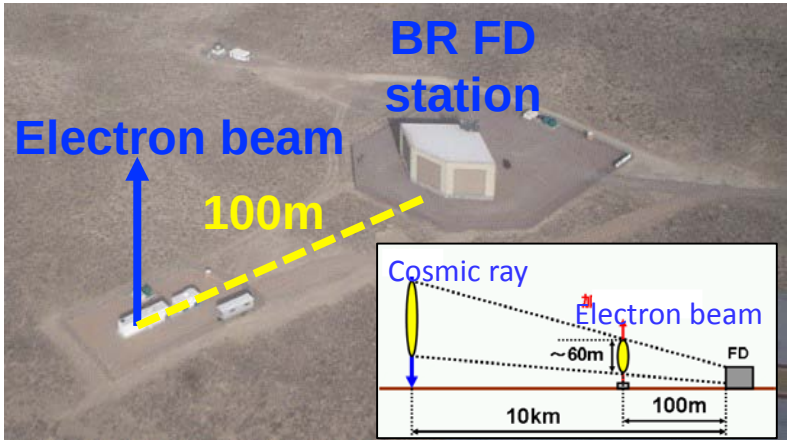
Rapporteur talk by Y.Tsunesada at ICRC2013

Energy scale uncertainty
. TA: 21%
. Auger: 14%

TA (■) and Auger (Ex1.1) (○)
- shapes agree below$10^{19.4}$ eV
- cutoff positions are different

Electron Light Source (ELS)

T.Shibata
ICRC2013
preliminary



- 40-MeV, 10^9 electrons (typical)
- End-to-end FD energy calibration

An image of data
Measured with FD

- Real data
  - ELS
    - Energy/beam current from monitor
    - FADC counts from FD

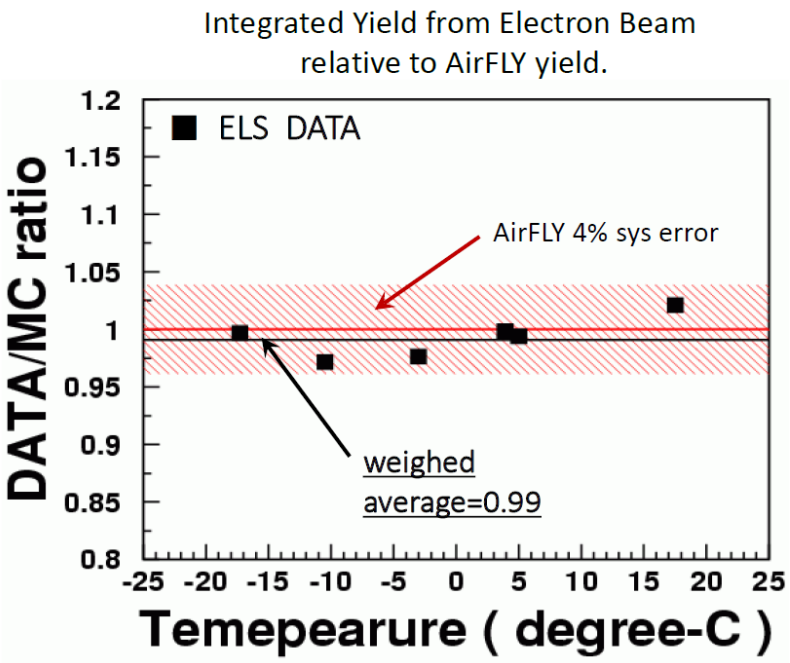
⟺

- MC data
  - Shower generation
    - Geant4.9.5 or 4.9.6 (ΔE → AFY)
  - FD simulation
    - TA official software

⇒ Air Fluorescence Yield (AFY) by using Reference Model proposed by B. Keilhauer et al. (UHECR2012, arXiv:1210.1319) for spectrum, P-T-RH dependence

Air Fluorescence Yield at 337 nm by ELS

ICRC2013
preliminary



- AirFLY = 5.61 ± 0.06 (stat) ± 0.22 (sys)
  at 1013 hPa and 293 K
  M.Ave et al. (AirFLY collab), ApP 42 (2013) 90
- Measurement in situ at TA
  - $\frac{\mathrm{ELS(data)}}{\mathrm{AirFLY(MC)}} = 0.96 \pm 0.01(stat) \pm 0.15(syst)$

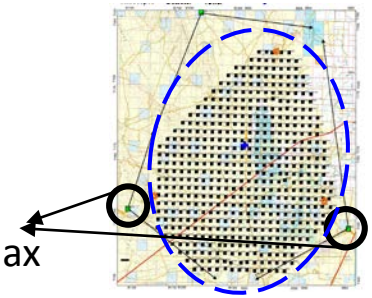
  at ~860 hPa and -17 ~ 17°C

Systematic errors are being checked

Mass Composition

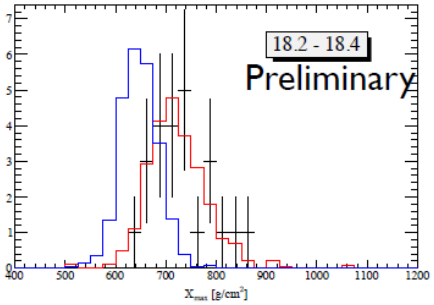
Y.Tameda
ICRC2013, 512
preliminary

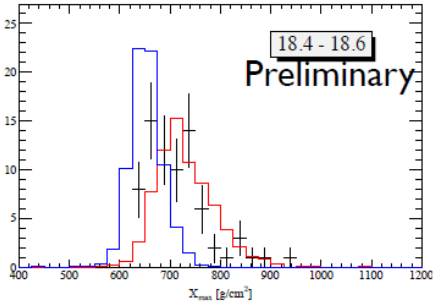
FD stereo Xmax

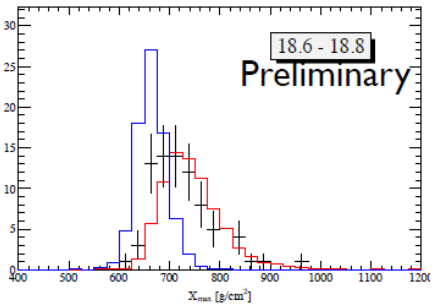


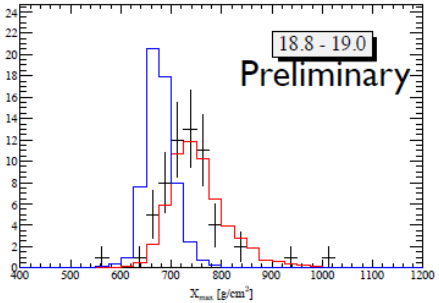
- FD stereo 5-year data (Nov., 2007 – Nov. 2011)
  - Data: TA
  - Red histogram: QGSJET-II-03 proton model
  - Blue histogram: QGSJET-II-03 iron model

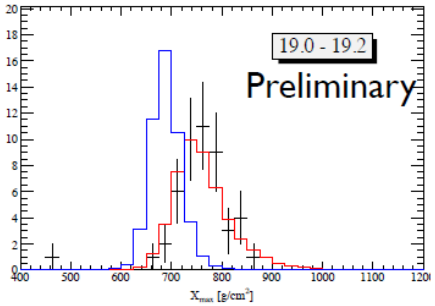
Both Data & MC with bias of
. Reconstruction
. Cut

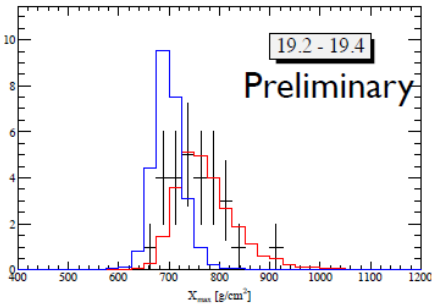


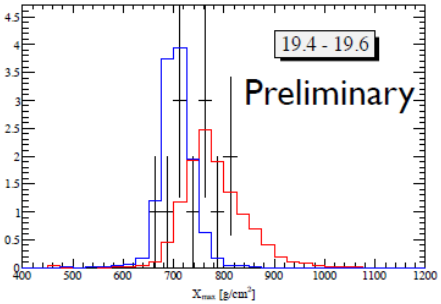


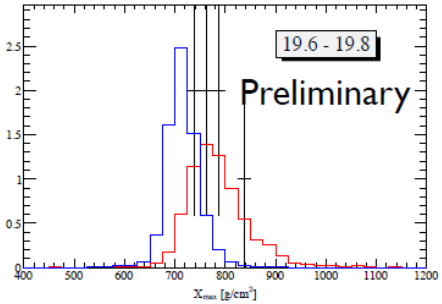






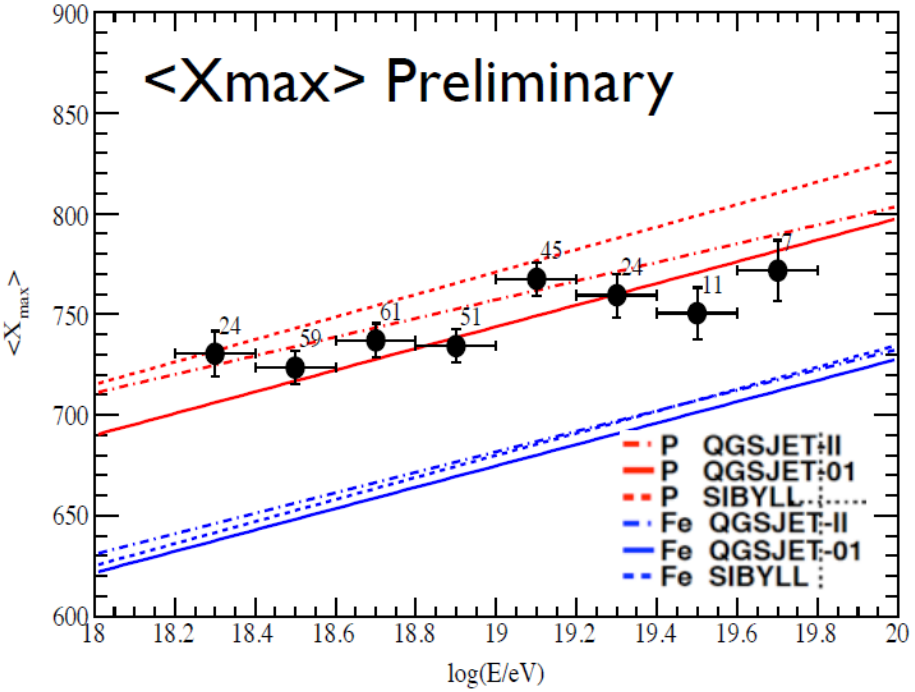


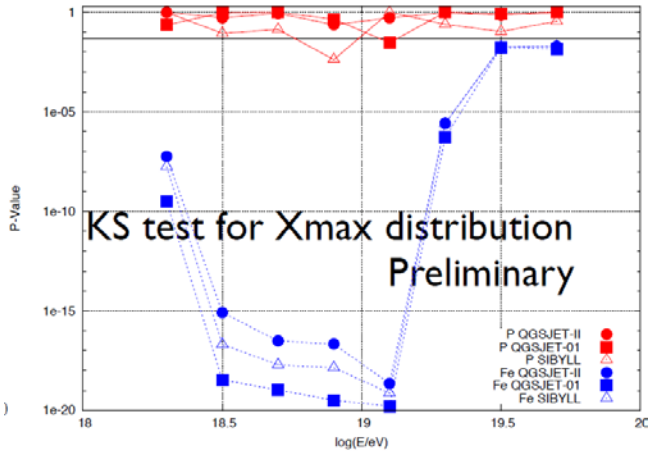




The TA data is consistent with QGSJET-II-03 proton prediction.

FD stereo Xmax



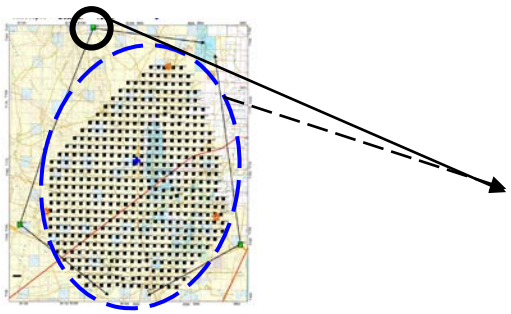


TA data: consistent with QGSJET-II-03 proton prediction ($E > 10^{18.2}$ eV)

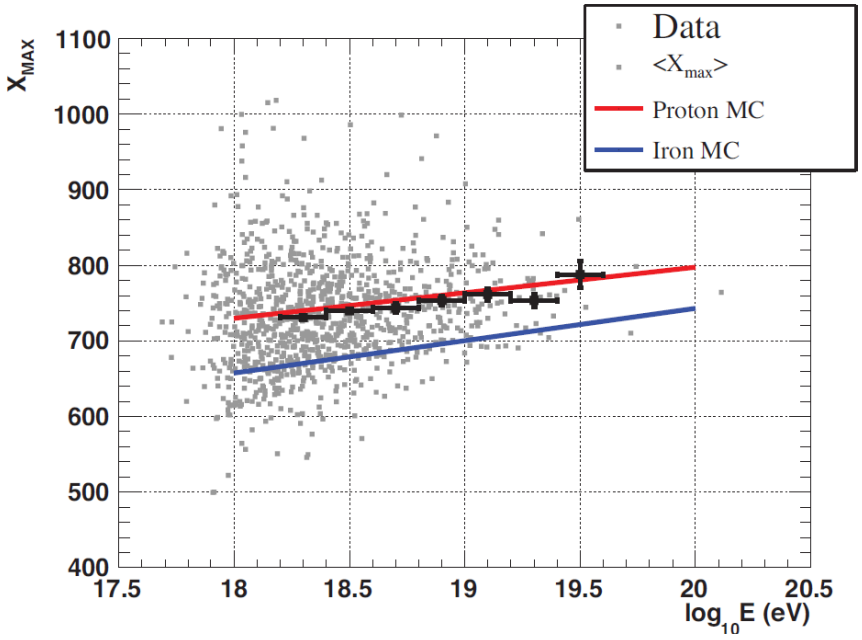
Need more data for $E > 10^{19.4}$ eV

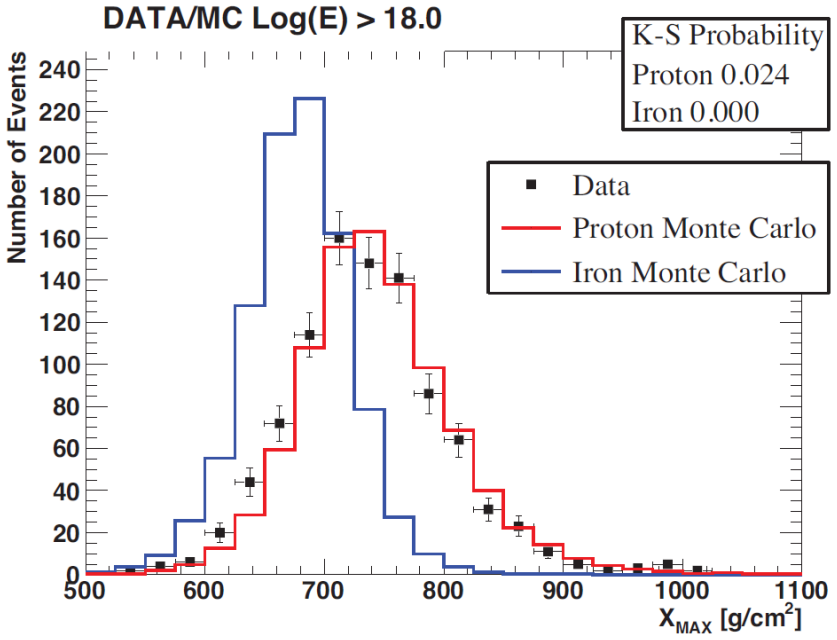
Hybrid Xmax

M. Allen, ICRC2013
preliminary
MD FD + SD, 4 yrs



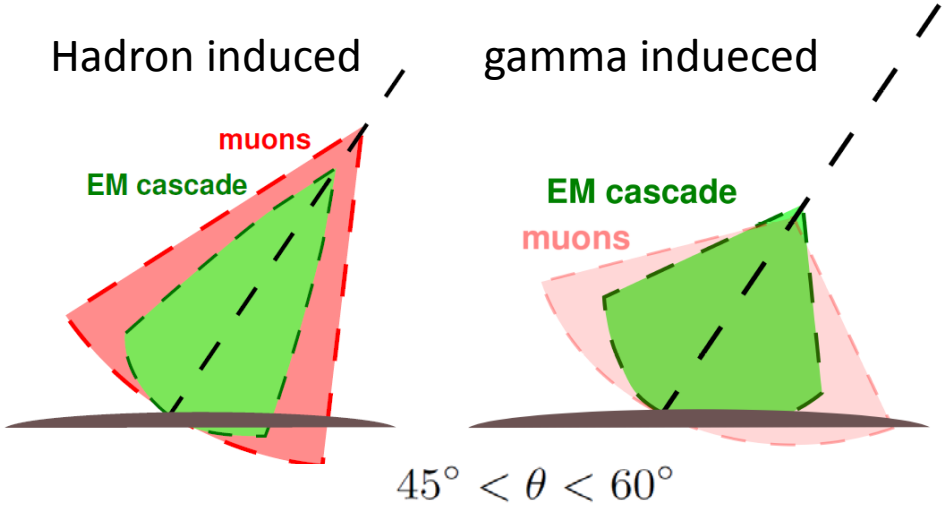
hybrid
(MD FD + SD)

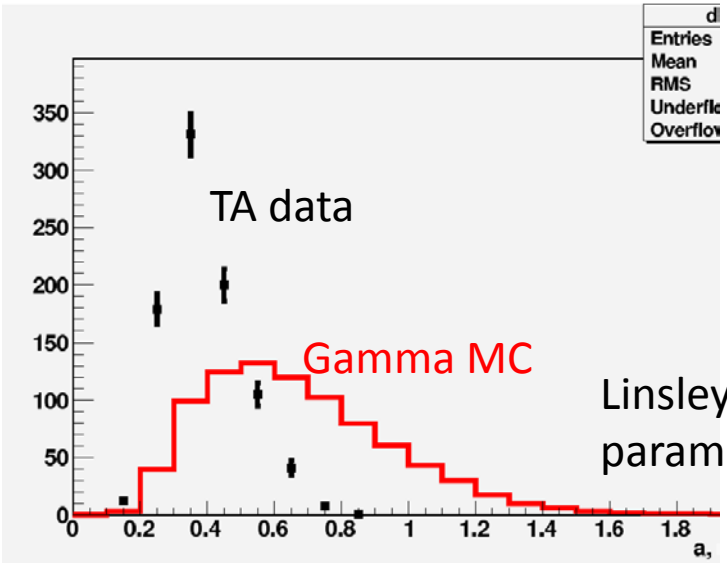




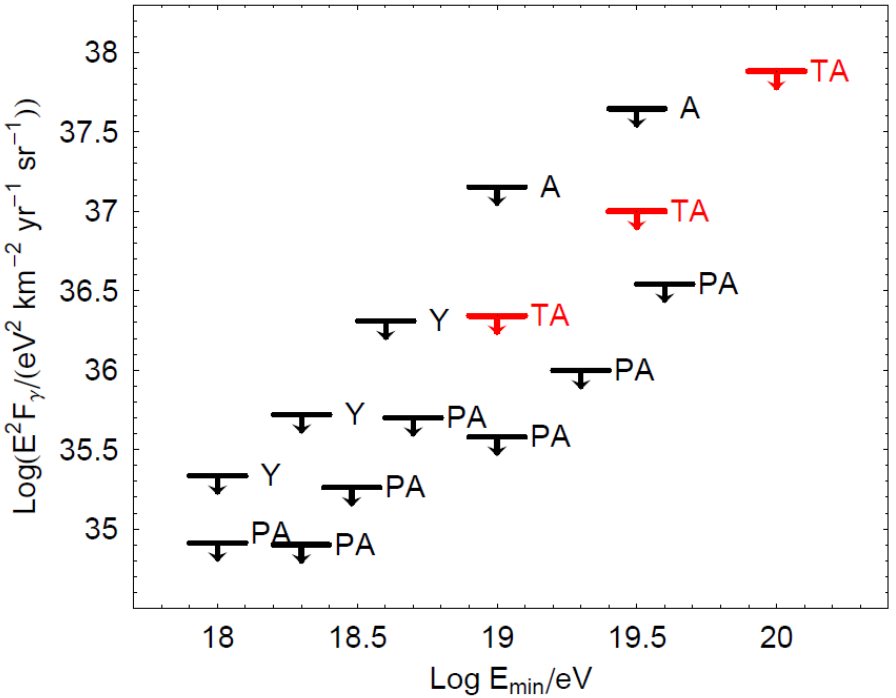
Consistent with QGSJET-II-03 proton model

UHE γ search





Linsley curvature parameter

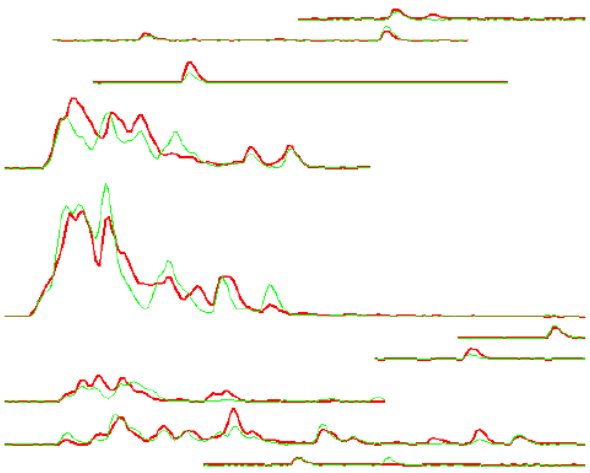


ICRC preliminary

UHE ν search

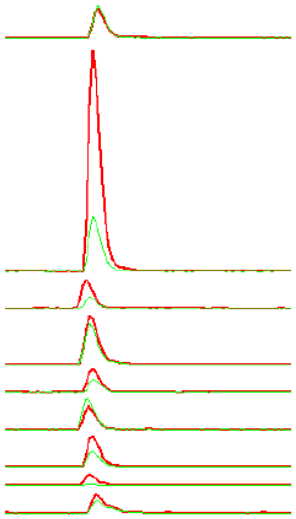
- Neutrino produces very inclined young shower

young shower, $\theta = 19.5°$

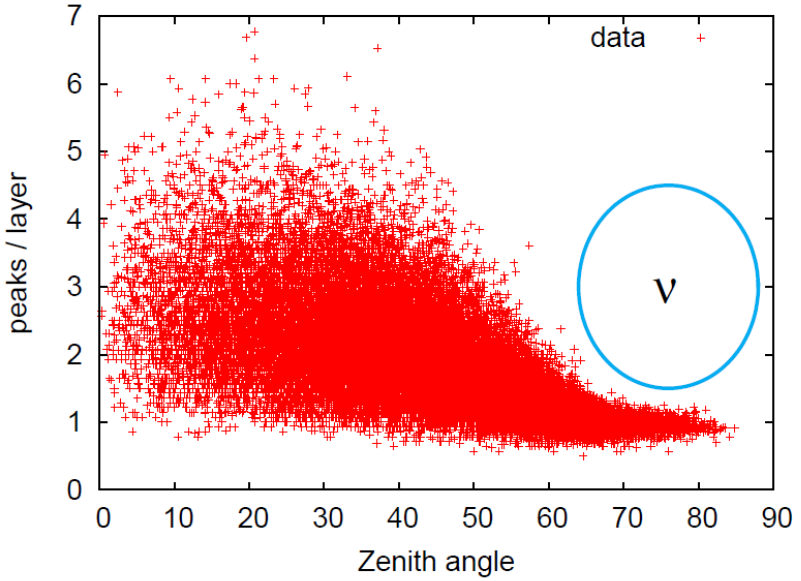


long, indented wafeforms

old shower, 78.3°



one peak



No young inclined showers in the dataset
$\Rightarrow$ no neutrino candidates.

$E^2 < 5 \times 10^{-5}$ GeV cm^{-2} s^{-1} sr^{-1} (90% CL)

Anisotropy

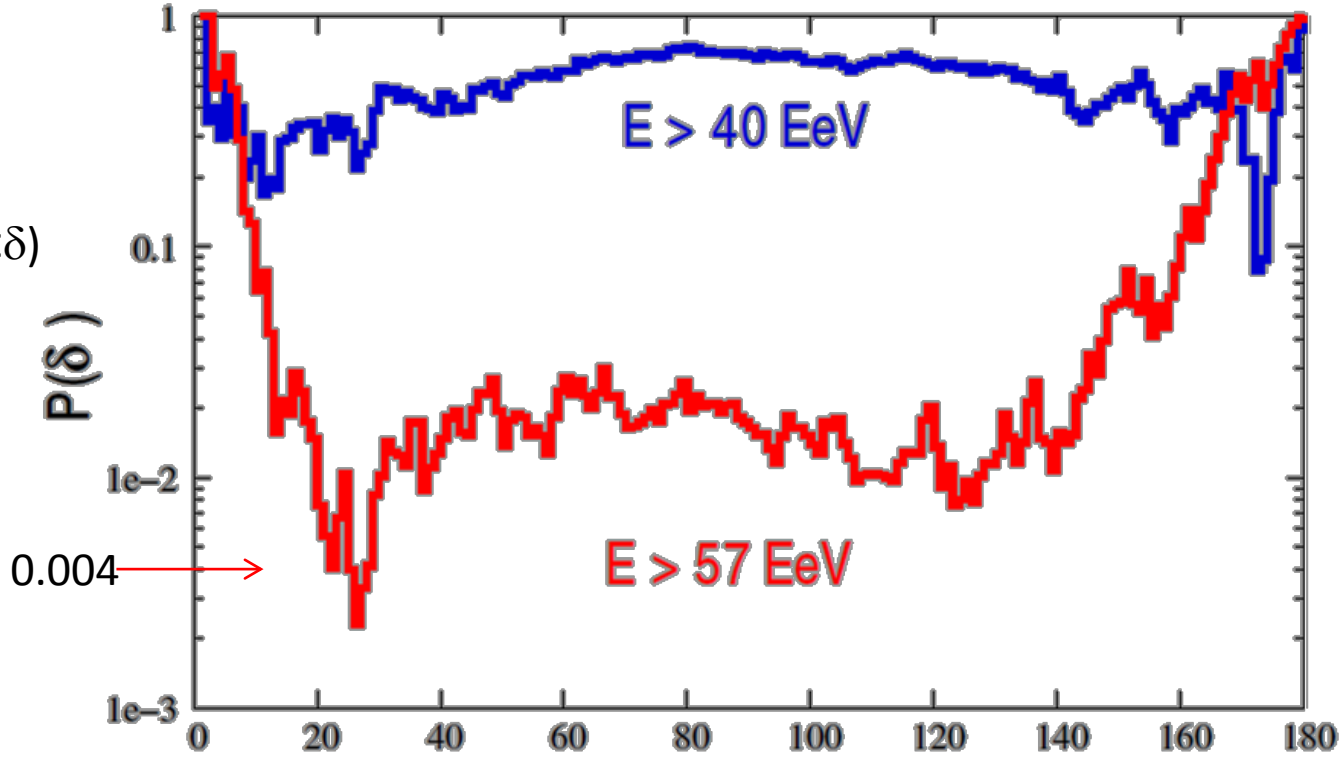
TA 5-year SD data

P.Tinyakov
ICRC2013 preliminary

Autocorrelations

P(δ):
The probability that the excess of pairs (<δ) occurs in a uniform distribution

Small P(δ): departure from isotropy

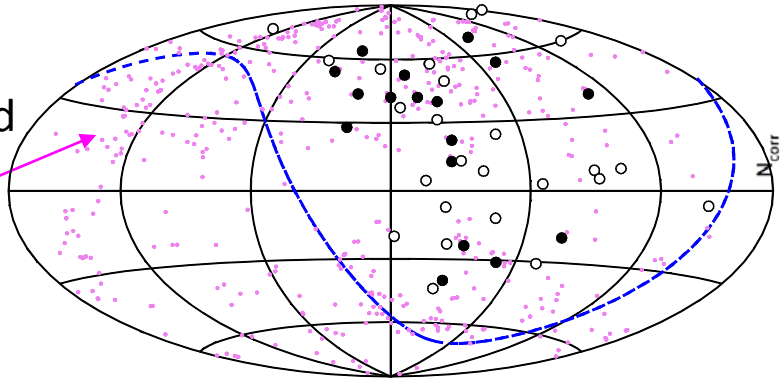


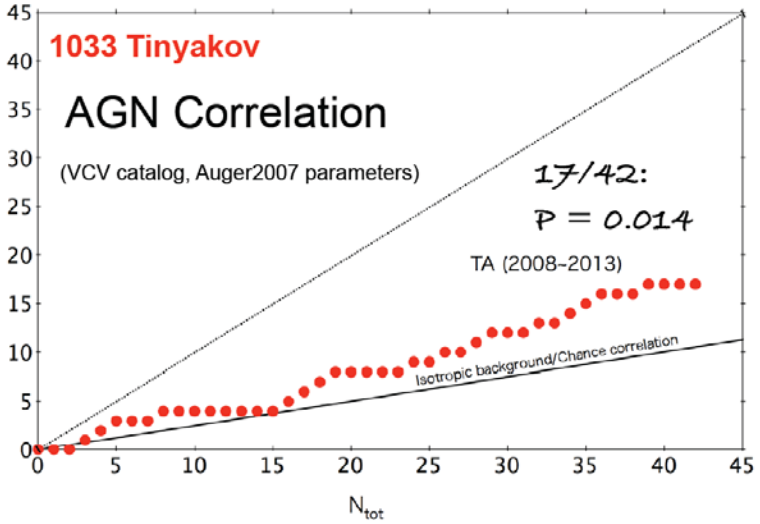
Correlations with AGN

- 472 AGN from 2006 Veron catalog with z < 0.018
- E > 57 EeV, zenith angle < 45°, N = 42 (5 yr)
- Separation angle = 3.1°

TA events:
- ● correlated
- ○ not correlated

AGN

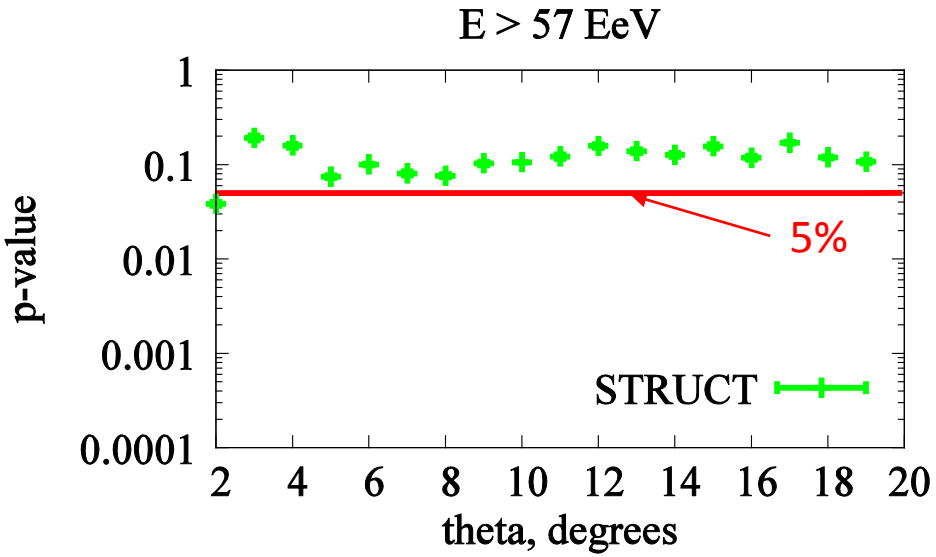




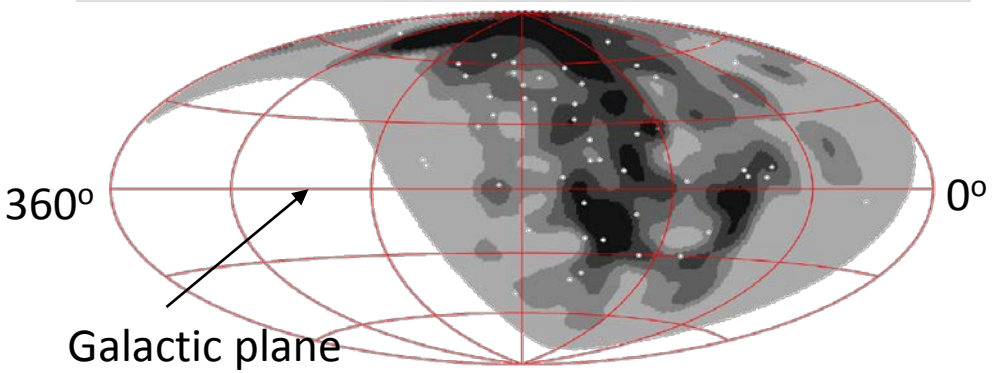
- Probability to hit AGN with a single event $p_o = 0.24$
- 17 events correlate out of 42 (0.40) $\Longrightarrow$ $p = 1.4\%$

Correlations with LSS (Large-Scale Structure)

- Proton LSS model:
  - 2MASS Galaxy Redshift catalog (XSCz)
  - gray pattern
    - E > 57 EeV, 6° smearing
- White dots: 52 TA data
  - E > 57 EeV
  - zenith angle < 55°



Theta: Gaussian deflection angle



p-value of Structure (LSS) model ~10%

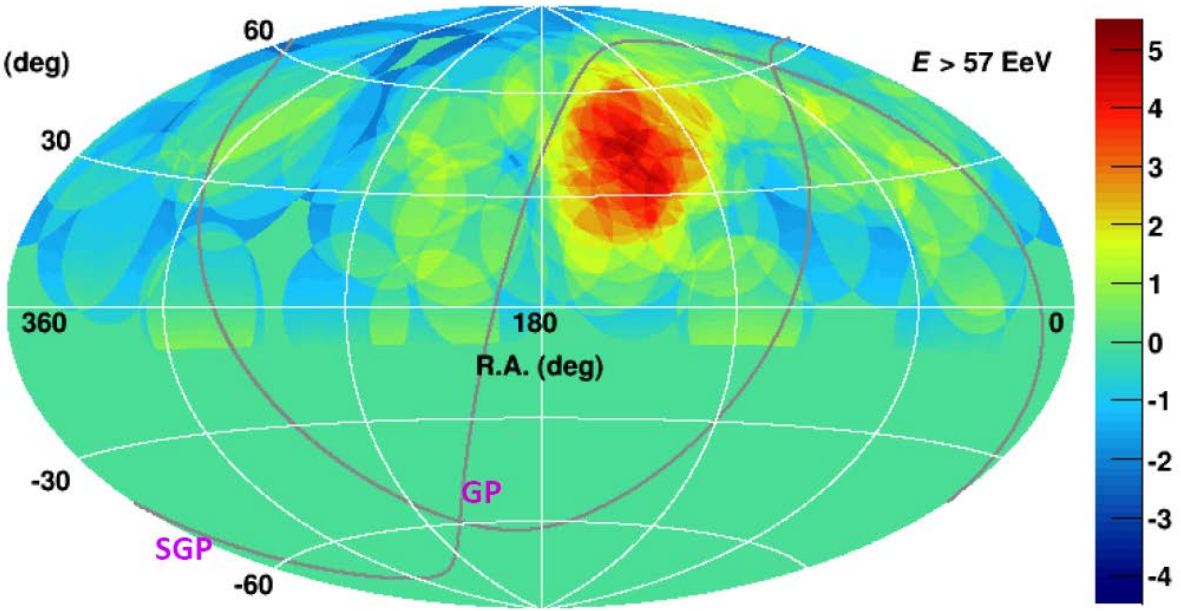
p-value of Isotropy model ~ 0.1%
for 6° smearing

(smaller p-value: lesser compatibility)

Significance Map

Oversampling with a 20° radius for 72 events above 57 EeV

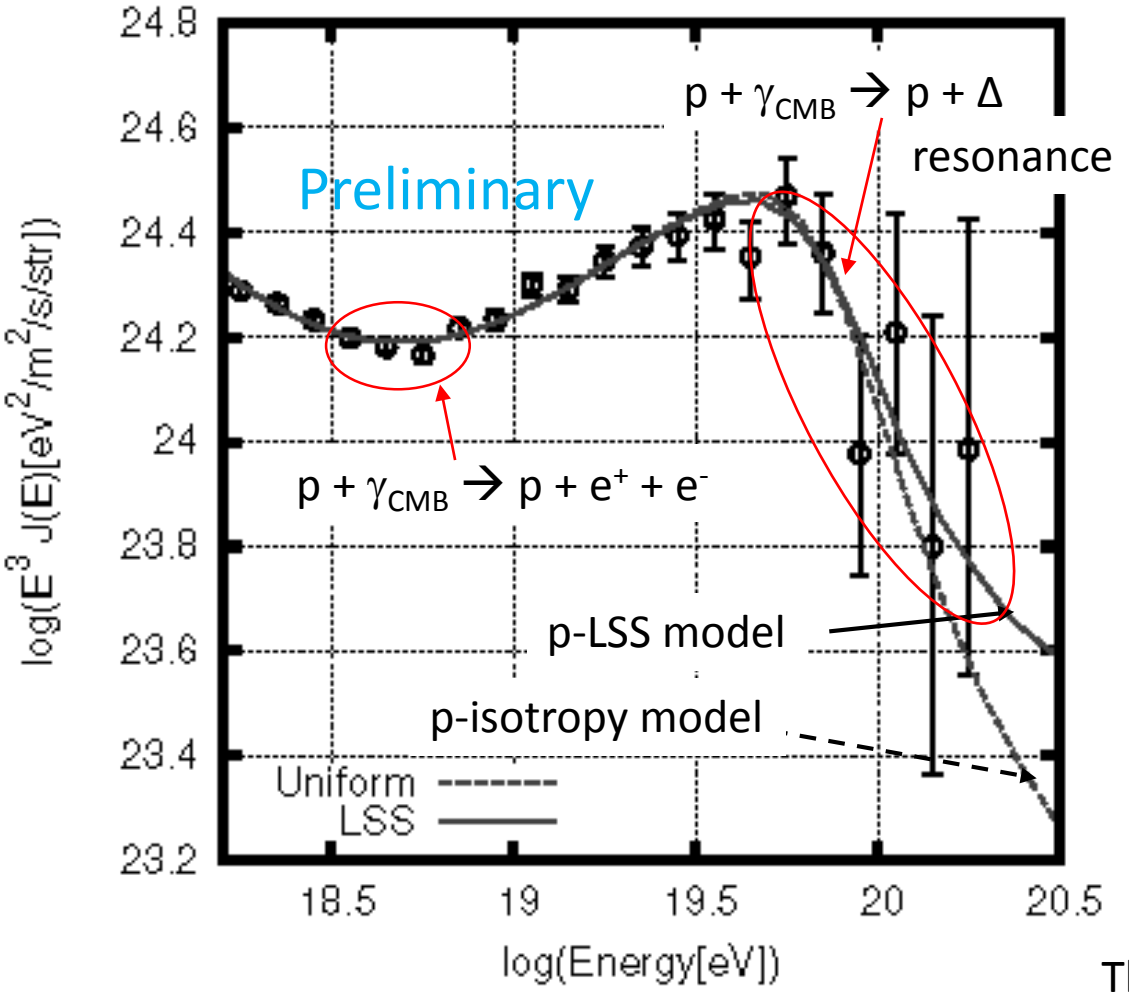
Equatorial coordinates



- Statistical significance 5.1σ (before correction)
- Chance probability : 3.6σ (1.4×10^{-4})

Energy spectrum by TA SD with fit

E.Kido
Preliminary



Fit with extragalactic protons
. LSS (~2MASS XSCz)
. isotropy

Fit curve
. The spectrum at the source is a power law of index γ
. The source density is a constant times a factor $(1+z)^m$
m: the evolution parameter
z : redshift
. and E and normalizaton

Fit result (γ, m, E) for LSS
γ = -2.37+-0.08
m = 5.2+1.2-1.3
logE'/E = -0.02+0.04 – 0.05

Propagation: CRPropa v2.0, SOPHIA: pion prod.

The result is being checked by O. Kalashev's analytical calculation.
→ will be updated

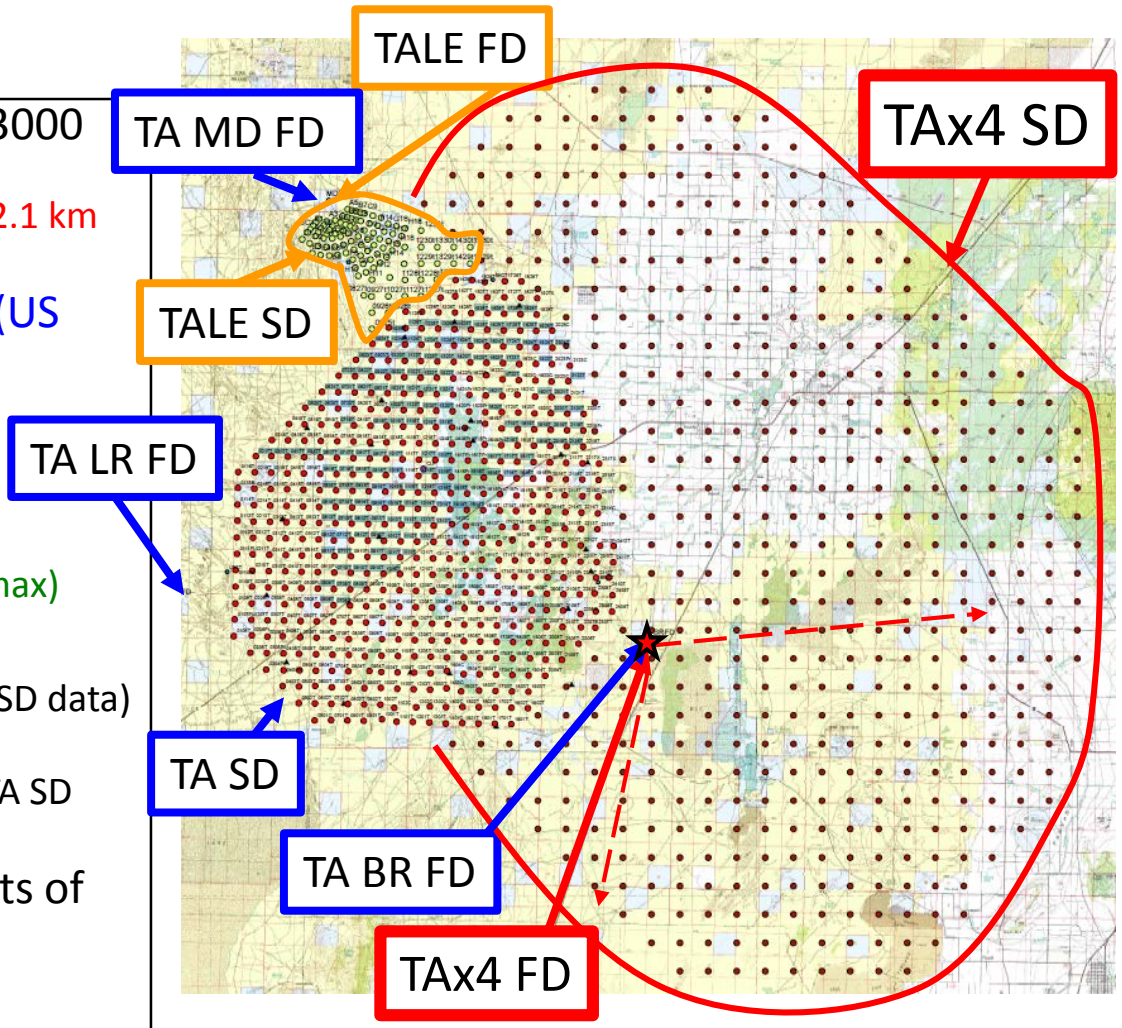
TA extension plans and on-going R&D

- TAx4: quadruple aperture extension for highest energy cosmic rays
- TALE: TA low energy extension down to $10^{16.5}$eV
- Associate experiments

TA×4 proposal

- If the suppression is proton GZK cutoff, we would observe CR anisotropy.

- Plan to expand TA SD by 4 times (~3000 km^2)
  - 500 scintillator counters (3 m^2) with 2.1 km spacing (Japanese side)
- 10 refurbished HiRes telescopes ★ (US side)
- 2-year construction
- 3-year observation
  - 20 years of TA SD data
  - 14 years of TA hybrid data (Escale, Xmax)
- Study of anisotropy
  - Hint of anistoropy at ~3σ (5-year TA SD data)
    ↓
  - Expect 5σ level anisotropy (20-year TA SD data)
- More statistics for the measurements of
  - the spectrum and Xmax
- UHE gamma and neutrino search



TALE (TA Low-energy Extension)

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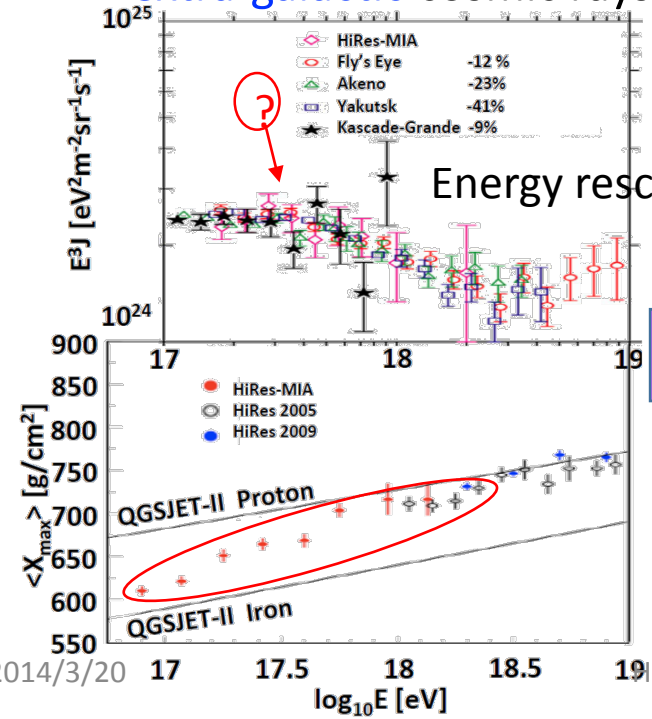
Oral, 717

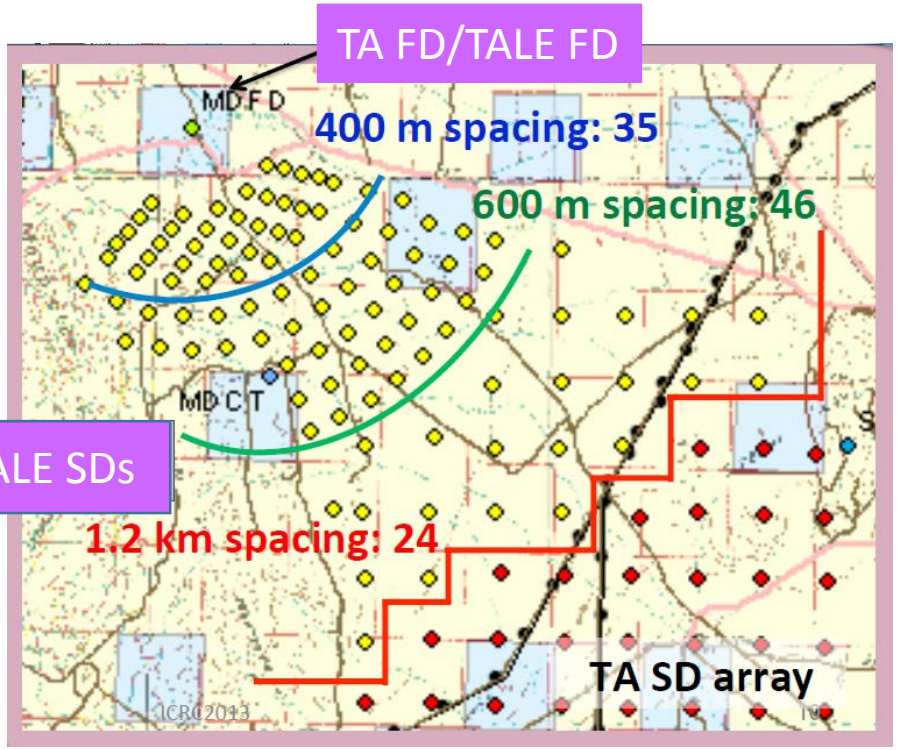
down to $10^{16.5}$ eV

- E = $10^{16.5}$ – 10^{19} eV
  - Second knee at ~$10^{17.5}$ eV?
  - Drastic change of composition at 10^{17}~10^{18} eV?
    ↓
  - Transition from galactic to extra-galactic cosmic rays?



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

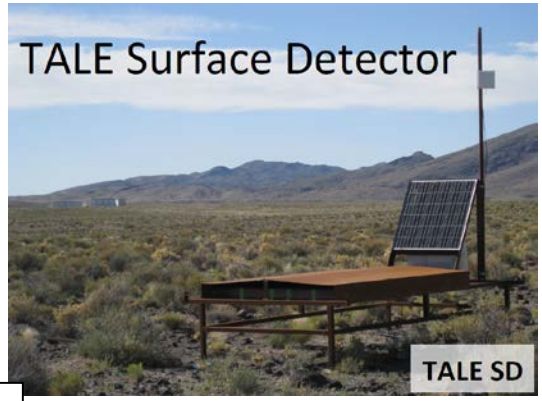
TALE layout

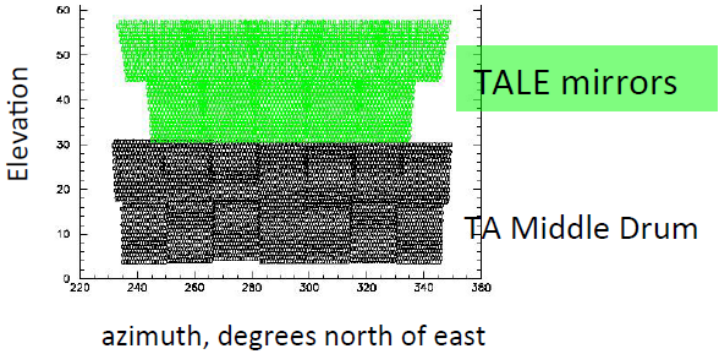


TALE (TA Low-energy Extension)

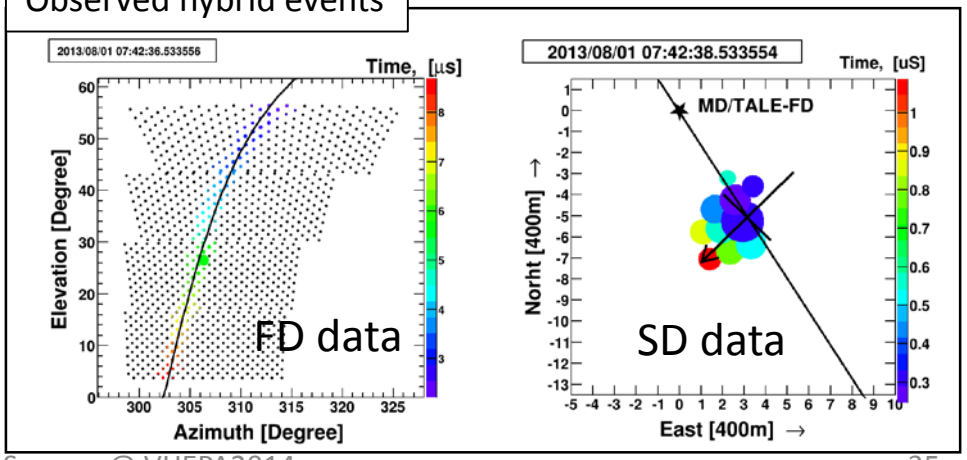
- 10 TALE FDs:
  - refurbished HiRes telescopes
  - installed and running.

- TALE SDs
  - 35 TALE SDs were deployed among 101 SDs.
  - partially in operation





Observed hybrid events

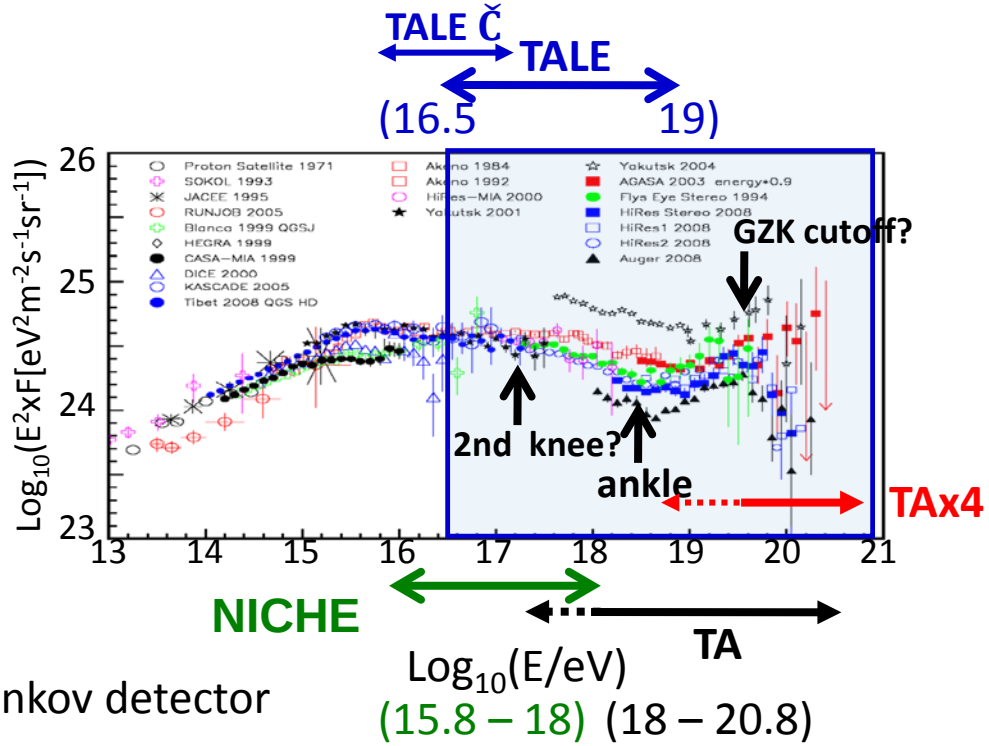


TA + TAx4 + TALE + NICHE

(proposal)

FD fully
SD partially
in operation

(proposal)



NICHE:
Non-Imaging CHErenkov detector

Measurement of energy, composition and anisotropy
over 5-decade energy region ($10^{15.8}$ ~ >$10^{20.8}$ eV),
with absolute end-to-end energy calibration of FD with ELS at TA

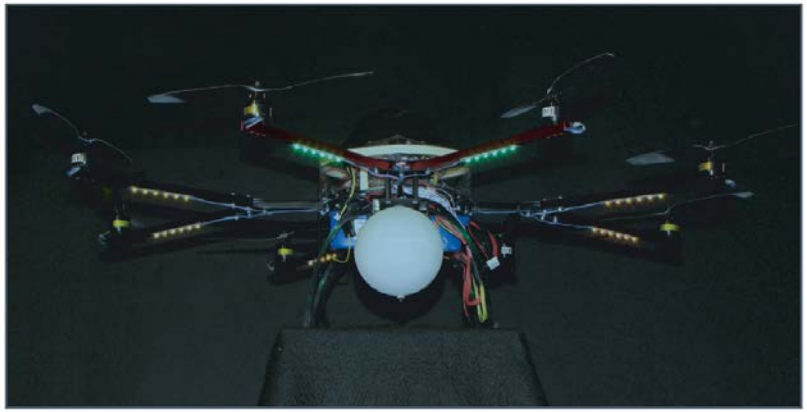
TA/Auger joint research

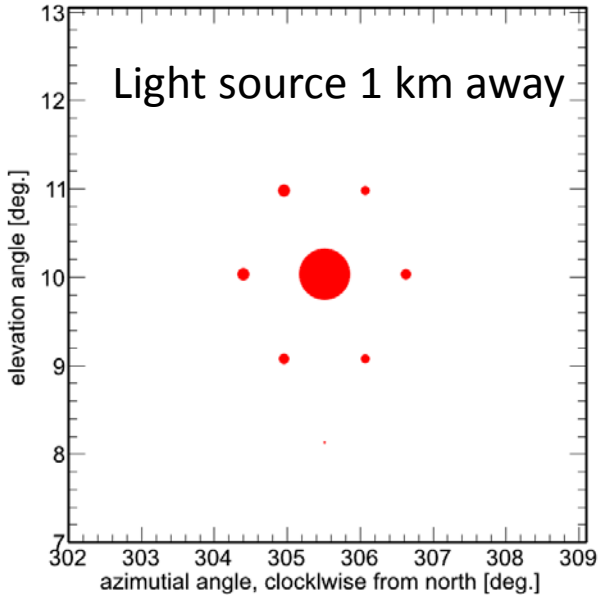
@ICRC2013

type	title	Primary author	P/O	id
Joint research	Octocopter light source test	J. N. Matthews	O	1218
	Octocopter light source test	K. Honda	P	504
	Composition	W. Hanlon	O	964
	anisotropy	O. Deligny (Auger)	O	679

Light Source Test

- A joint calibration campaign for the fluorescence telescopes
  - Optical end-to-end calibration with a portable calibrated light source carried by an octocopter provided by Auger
  - Known position: GPS





Data with TA FD

Full-sky anisotropy analysis

- Large-scale anisotropy at TA and Auger for $E > 10^{19}$ eV
- Any anisotropy fingerprint is encoded in the set of spherical harmonics coefficients
- Partial coverage degrades the resolution→require full coverage
- A method to obtain full-sky coverage by combining data sets from different observatories

Xmax analysis of an adhoc data compatible with Auger composition model via TA reconstruction

- Auger Xmax result

  ↓

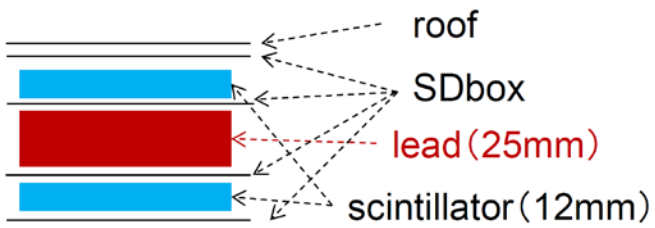
  ad hoc composition model (p, helium, nitrogen, iron)

- TA detector simulation and reconstruction

- How well can the TA SD detector distinguish between Auger mixed composition and pure proton compositions?

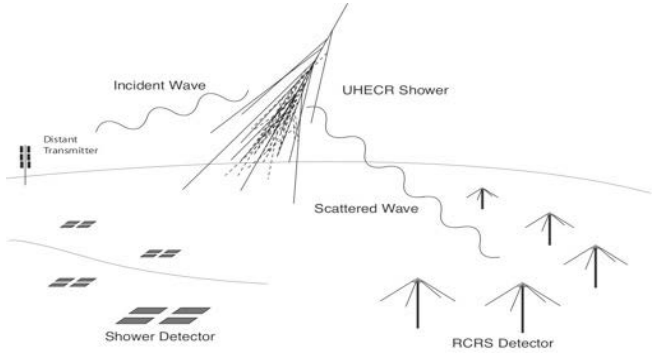
Muon detector project at TA site (ongoing)

- One set of 24-m^2 scintillator detector with concrete absorber on the top
  - 8×(3-m^2 scintillator detectors)
- Lead layer sandwiched between two scintillators
  - First 9 m^2: 12 segments×(0.75 m^2)
    - 1 segment was deployed inside CLF site
- Auger water tanks
  - Colorado R&D site → TA site

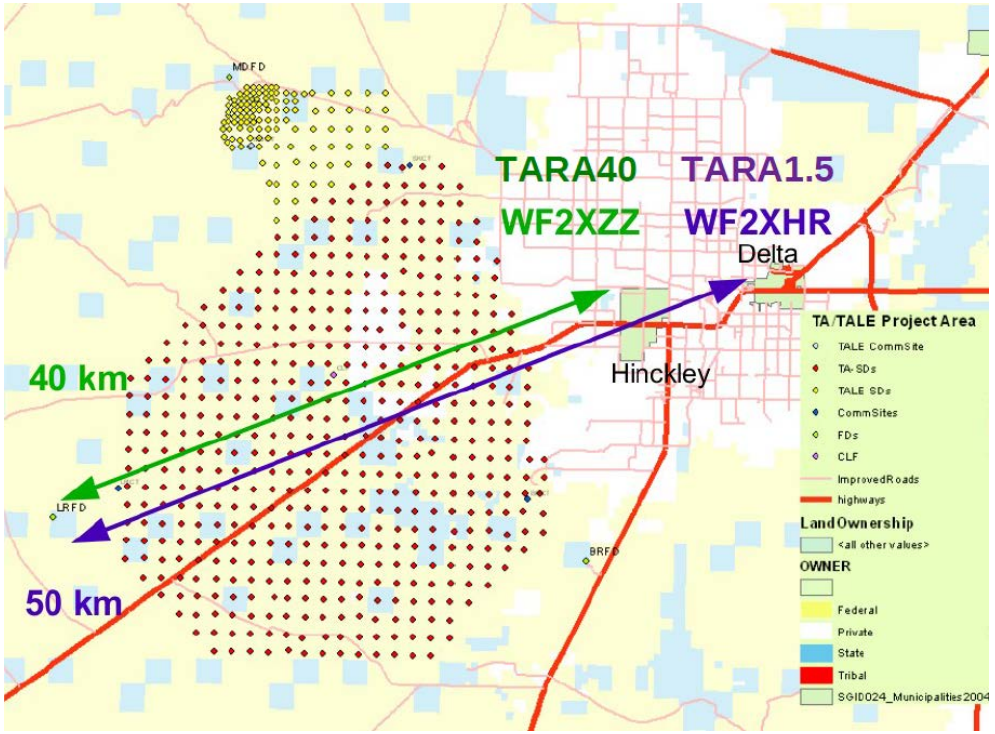


TARA (TA Radar)

- An R&D project to observe radar reflections from cosmic-ray air showers



- TARA1.5
  - April 2011 to July 2012
  - 54.1 MHz @ 1.5 kW
- TARA40
  - Summer 2013~
  - 54.1 MHz @ 40 kW



Other associate experiments

- Test of the detection of GHz molecular bremsstrahlung radio from air showers
  - KIT/Univ. of Chicago
  - Konan Univ./Osaka City Univ.
- TA-EUSO
  - JEM-EUSO prototype test at TA site
- FAST (Fluorescence detector Array of Single-pixel Telescope)
  - Fresnel lens + one 8-inch PMT
  - Univ. of Chicago

TA burst events

TA burst events (in 5-year SD data)

T.Okuda
COSPA2013
preliminary

- 10 bursts of shower triggers
  - Burst: N(shower trigger) ≥ 3 in 1 ms
    - ≥3/1ms ~ 5000 triggers/sec
      (average trigger rate ~5×10^{-3} triggers/sec)
    - Shower triggers
      - 3 neighboring SDs
      - ≥ 3 MIP
      - 8μs window

- 5 bursts had reconstructed events
  - Event: an SD data set recorded by a shower trigger
    - Trigger information
    - Wave forms from SDs

Burst > events > SDs > waveforms
(shower trigger) (FADC values)

Date time **Core position**

	AS	YYMMDD	hhmmss	usec	X[m]	Y[m]	H[m]	
TA burst	AS	101004	165842	930565	11356	−7425	3963	← event
	AS	101004	165842	930612	10478	−7368	4400	
	AS	101004	165842	930835	11142	−8159	3270	
	AS	110727	080615	124319	3447	1952	4070	
	AS	110727	080615	124543	2897	2232	3070	
	AS	110916	194056	567481	−3210	−9285	3253	
	AS	110916	194056	567566	−3524	−9413	3134	
	AS	120706	014911	184219	9847	−10702	3770	
	AS	120706	014911	184307	7635	−9674	3361	
	AS	120907	015545	380684	−8636	1254	4446	
	AS	120907	015545	380755	−9857	−337	4805	
	AS	120907	015545	380881	−9450	−961	3361	

(H: height above sea level)

Examples of timing and waveforms

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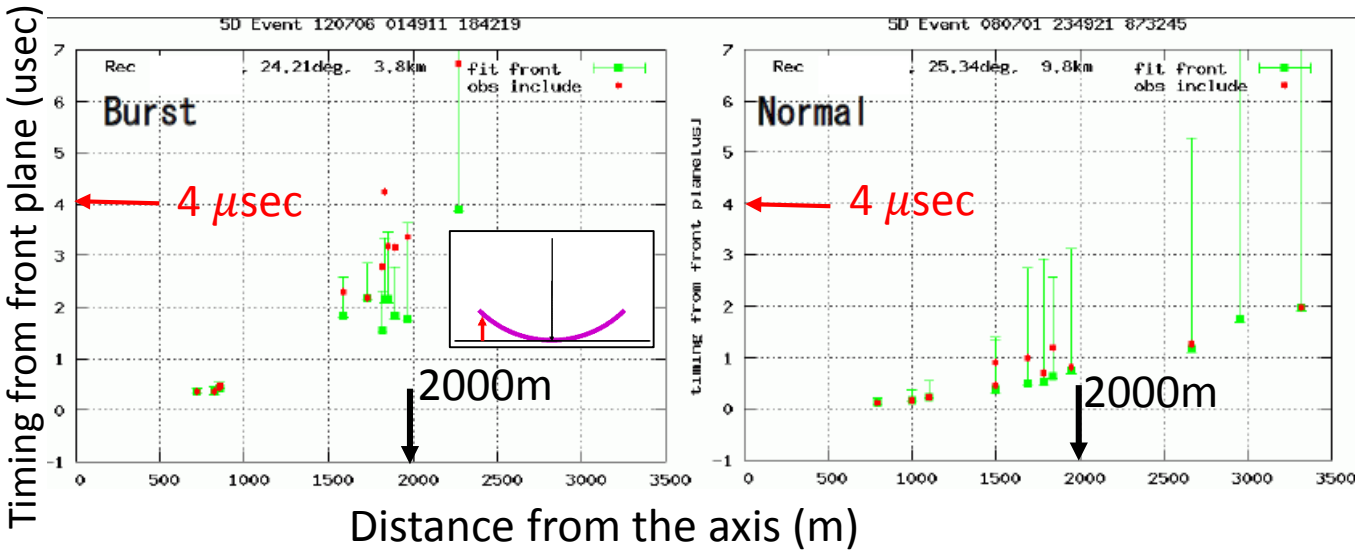
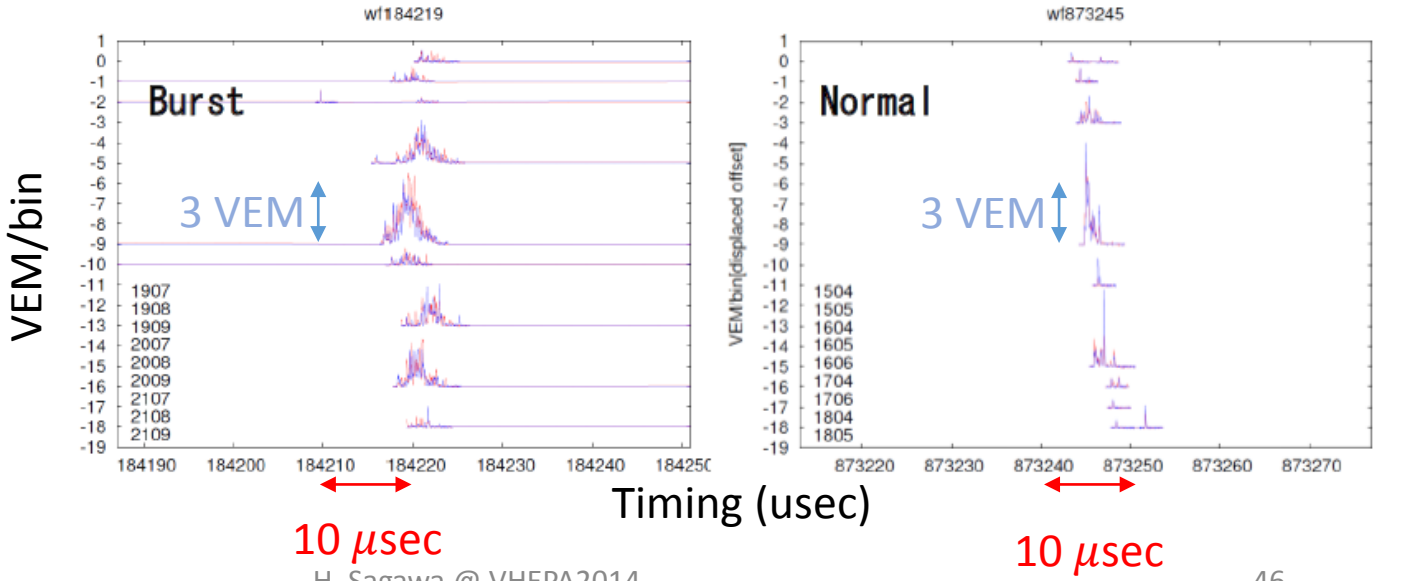
Lateral arriving Time

Shower front is curved more for burst events
→ Development seems to start at lower height in the sky



Waveforms

Slower rising edge for burst events



TA burst events (in 5-year SD data)

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preliminary

- 10 bursts of shower triggers
  - Burst: N(shower trigger) ≥ 3 in 1 ms
    - ≥3/1ms ~ 5000 triggers/sec
      (average trigger rate ~5×10^{-3} triggers/sec)
    - Shower triggers
      - 3 neighboring SDs
      - ≥ 3 MIP
      - 8μs window

- 5 bursts had reconstructed events
  - Event: an SD data set recorded by a shower trigger
    - Trigger information
    - Wave forms from SDs

Burst > events > SDs > waveforms
(shower trigger) (FADC values)

Date time **Core position**

TA burst

AS	YYMMDD	hhmmss	usec	X[m]	Y[m]	H[m]	
AS	101004	165842	930565	11356	−7425	3963	← event
AS	101004	165842	930612	10478	−7368	4400	
AS	101004	165842	930835	11142	−8159	3270	
AS	110727	080615	124319	3447	1952	4070	
AS	110727	080615	124543	2897	2232	3070	
AS	110916	194056	567481	−3210	−9285	3253	
AS	110916	194056	567566	−3524	−9413	3134	
AS	120706	014911	184219	9847	−10702	3770	
AS	120706	014911	184307	7635	−9674	3361	
AS	120907	015545	380684	−8636	1254	4446	
AS	120907	015545	380755	−9857	−337	4805	
AS	120907	015545	380881	−9450	−961	3361	

(H: height above sea level)

TA burst events associated with lightning

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COSPA2013
preliminary

- NLDN: National Lightning Detection Network
  - VLF detection
  - Information
    - Time, 2D coordinates, peak current
    - flag: intracloud (C)/Cloud-Ground(G)

In the right table,
light blue line: <±1ms from the burst:
these 4 LGs were intracloud (C) LGs
red line: ±1ms ~ ± 200ms from the burst:
these LGs were cloud-ground (G) LGs
Here LG = lightning discharge

	Date	time		Core position		
AS / LG	YYMMDD	hhmmss	usec / usec	X[m] / X[m]	Y[m] / Y[m]	H[m] / Flag
AS	101004	165842	930565	11356	−7425	3963 ← event
AS	101004	165842	930612	10478	−7368	4400
AS	101004	165842	930835	11142	−8159	3270
LG	101004	165842	930608	12480	−5068	C
LG	101004	165842	934058	10619	−8069	G
AS	110727	080615	124319	3447	1952	4070
AS	110727	080615	124543	2897	2232	3070
LG	110727	080615	124303	3653	2285	C
LG	110727	080615	130887	3084	1996	G
AS	110916	194056	567481	−3210	−9285	3253
AS	110916	194056	567566	−3524	−9413	3134
AS	120706	014911	184219	9847	−10702	3770
AS	120706	014911	184307	7635	−9674	3361
LG	120706	014911	184122	8997	−9670	C
AS	120907	015545	380684	−8636	1254	4446
AS	120907	015545	380755	−9857	−337	4805
AS	120907	015545	380881	−9450	−961	3361
LG	120907	015545	380675	−8942	668	C
LG	120907	015545	390411	−9635	−1952	G
LG	120907	015545	409370	−8608	−1653	G

TA burst

NLDN lightning

An example of TA reconstructed events with lightning

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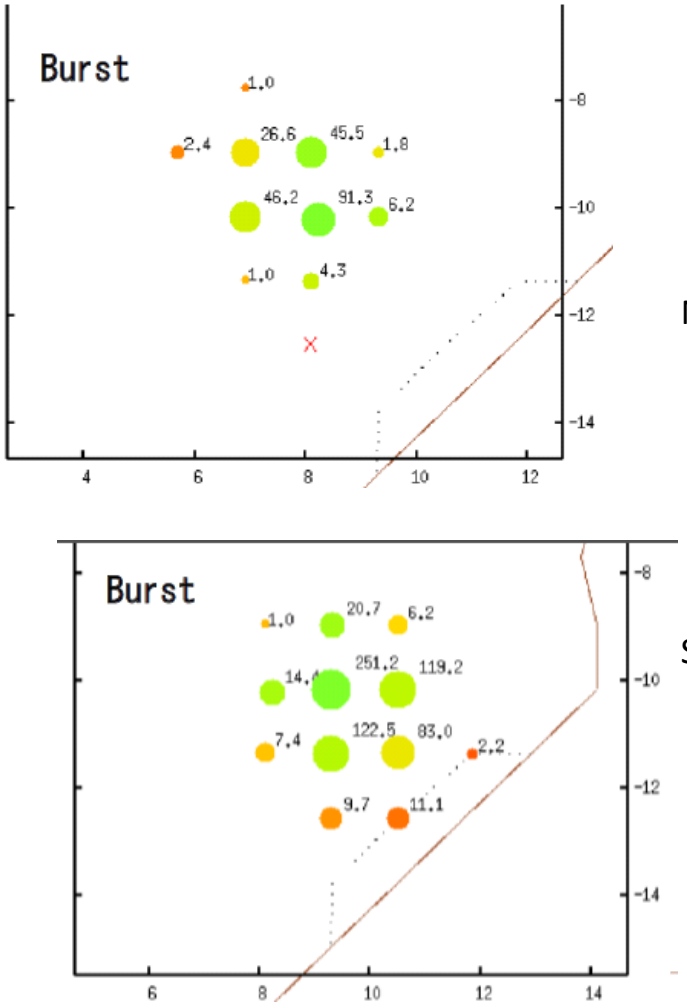
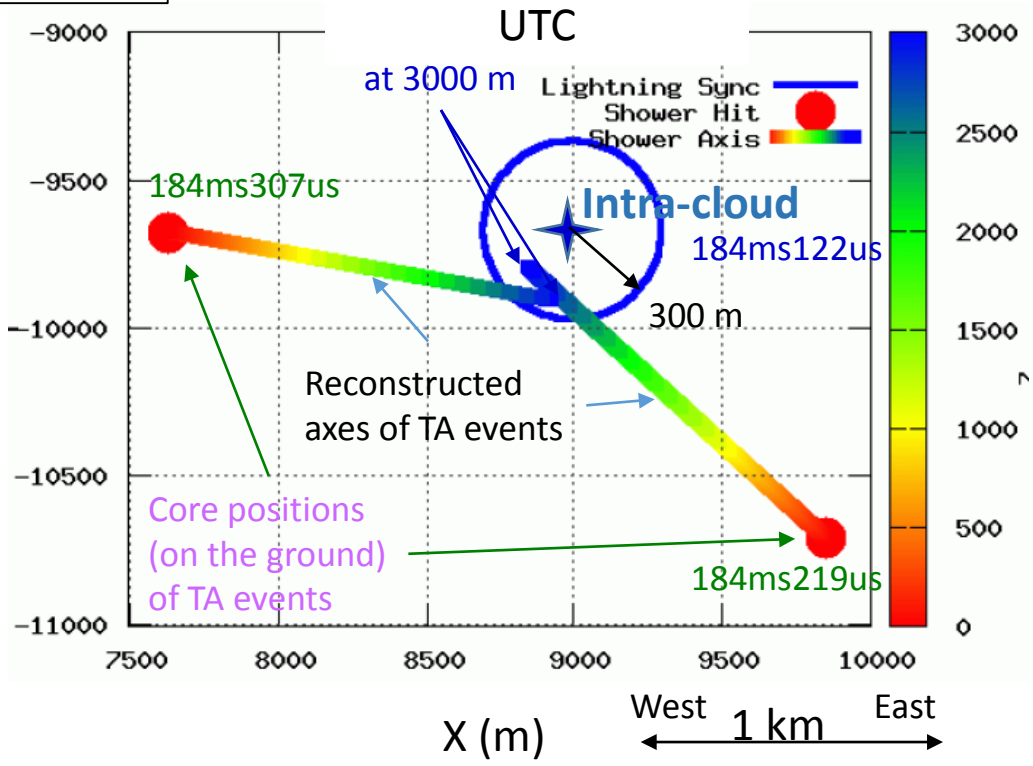
COSPA2013
preliminary



300 m radius:
50% error

July 6, 2012
01hr49min11sec
UTC

Height above ground (m)



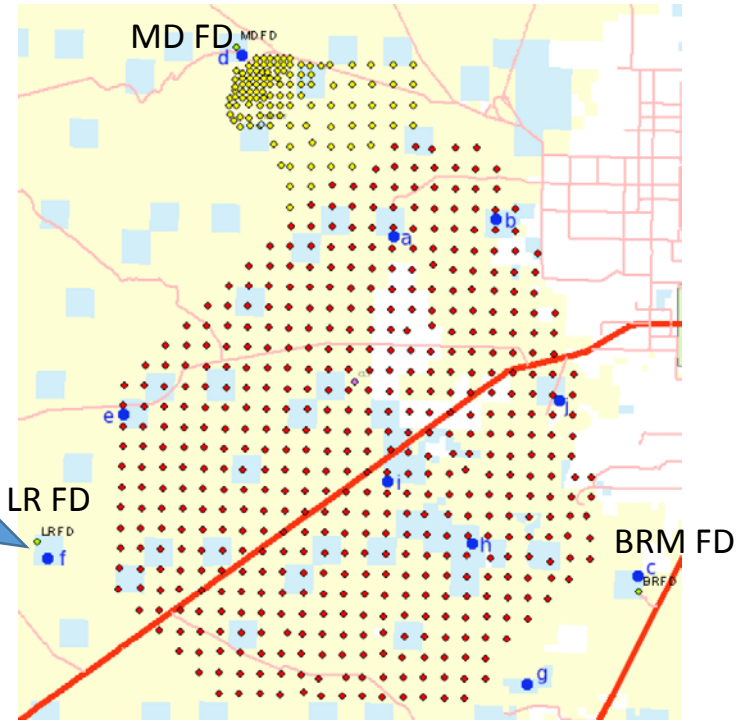
(X, Y): distances are from CLF

TA/LMA
(associate experiment for lightning detection)

- LMA: Lightning Mapping Array
  - Array of VHF receiver stations developed by New Mexico Institute of Mining and Technology (NMT)
  - 3-D reconstruction, better resolution

LMA detector unit at Long Ridge
(with R. Thomas, NMT)

- TA/LMA: Test LMA in the TA site (since Sep 2013)
  - 10 receiver stations
    - (blue points in the figure)



Summary

- Recent results for 5-year data
  - Energy spectrum
    - Suppression at 5.7×10^{19} eV consistent with GZK cutoff
      - Statistical significance of suppression: 5.7σ above $10^{19.8}$eV
  - Composition
    - Consistent with proton
  - Anisotropy
    - Hints of anisotropy: significance of $\sim3\sigma$
      - Hot spot (20^{o}-radius oversampling) 3.6σ
- TA extension plans
  - TAx4: proposal to quadruple TA aperture
    - Towards 5σ anisotropy observation in 5 years
  - TALE: low energy extension down to $10^{16.5}$ eV
    - Currently operating 10 full FDs and a part of SD array
- Associated experiments: performed, ongoing, will come
- TA SD burst events associated with lightning were observed