平成25年度共同利用研究成果発表会

宇宙線望遠鏡による 極高エネルギー宇宙線の研究

佐川　宏行 (東京大学宇宙線研究所)
Telescope Array Collaboration

2013年12月21日

Outline

- Telescope Array (TA)
  - TA detector/papers
- Recent preliminary TA results
  - Energy spectrum
  - Composition
  - Anisotropy
    - Hot spot?
- TA Extensions, on-going R&Ds, proposals
  - TAx4, TALE
  - Associate experiments: radio (TARA, GHz), TA/LMA
    related to
    TA burst events
- Summary

Telescope Array Collaboration

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~120 collaborators in 5 countries

Japan, USA, Korea, Russia, Belgium

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

平成25年度共同利用研究採択課題

整理番号	課題名	研究代表者	合計額（千円）
F14	宇宙線望遠鏡による極高エネルギー宇宙線の研究	佐川　宏行	900
F15	TA実験サイトでの超高エネルギー宇宙線観測のための新型検出器の開発	野中　敏幸	500
F16	最高エネルギー宇宙線の電波的観測の研究	池田　大輔	800
F17	TA実験における中央レーザー装置ステアリングシステムの開発	有働　慈治	250
F18	ラジコンヘリコプターによるTA大気蛍光望遠鏡キャリブレーション	多米田　裕一郎	350
F19	小型電子加速器による空気シャワーエネルギーの絶対較正の研究	芝田　達伸	600
F20	TA地表検出器の低エネルギー側高感度化（TALE計画）と宇宙線異方性の研究	川田　和正	300
F21	TA-EUSO64chマルチアノードPMTの較正とCRAYSとの比較	竹田　成宏	450
F23	大気分子制動放射マイクロ波の検出と検出器開発	荻尾　彰一	400
合計	9課題		4,550

どうもありがとうございます

Refereed papers in 2013

- The cosmic-ray energy spectrum observed with the surface detector of the Telescope Array experiment
  - T. Abu-Zayyad et al., Astrophysical Journal Letters, 768 (2013) L1

SD spectrum

- The energy spectrum of ultra-high-energy cosmic rays measured by the Telescope Array FADC fluorescence detectors in monocular mode
  - T. Abu-Zayyad et al, Astropart. Phys., 48 (2013) 16

FD mono spectrum

- Search for correlations of the arrival directions of ultra-high energy cosmic rays with extragalactic objects as observed by the Telescope Array Experiment
  - T. Abu-Zayyad et al., Astropart. Phys., 777 (2013) 88

Anisotropy

- Upper limit on the flux of photons with energies above 10^{19} eV using the Telescope Array surface detector
  - T. Abu-Zayyad et al., Phys. Rev. D 88 (2013) 112005

Photon flux limit

ICRC2013 presentations

Subject	ID	O	P	Subject	ID	O	P	Subject	ID	O	P
Highlight talk	128	O		TA SD simu. and analysis	395		P	Hybrid trigger	134		P
TA general	118		P	TALE hybrid simu. and analysis	389		P	Radio echo detection with ELS	360		P
TA next 5 years	121		P	LSS@HE	935		P	TARA	1192	O	
Point-like sources@10^{18}	310		P	SD composition	536		P	CR radar echoes in TARA data	639		P
LSS aniso@10^{18}	311		P	BR/LR hybrid composition	965		P	TALE	717	O	
UHE photon and nu with FD	524		P	TA spectrum summary	221	O		Surface muon detector	298		P
Spectrum fit	136	O		TA composition summary	132	O		FD PMT monitoring	952		P
Shower front structure	130		P	TA anisotropy summary	1033	O		Octocopter light source test	1218	O	
UHE photon and nu with SD	149	O		Composition: TA analysis for PAO model	964	O		GHz radio detection with ELS			P
MD hybrid spectrum and composition	794		P	TA/Auger Large-scale joint anisotropy study	679	O		Shower universality for NICHE	983		P
Correlations of arrival directions	133		P	FD calib. with ELS	507	O					
Stereo mass composition	512		P	CLF	142		P				
BR/LR hybrid spectrum	358		P	Portable laser	526		P				
BR/LR mono spectrum	476		P	Octocopter light source test	504		P				
Data and Corsika simulation	353	O		NICHE	365	O					

TA/Auger joint papers

TA extensions R&D

40 papers (14 oral)
including
4 TA/Auger joint papers (3 oral)
. Auger light source with TA FD
. TA Xmax recon. for Auger ad hoc model
. TA/Auger joint anisotropy study

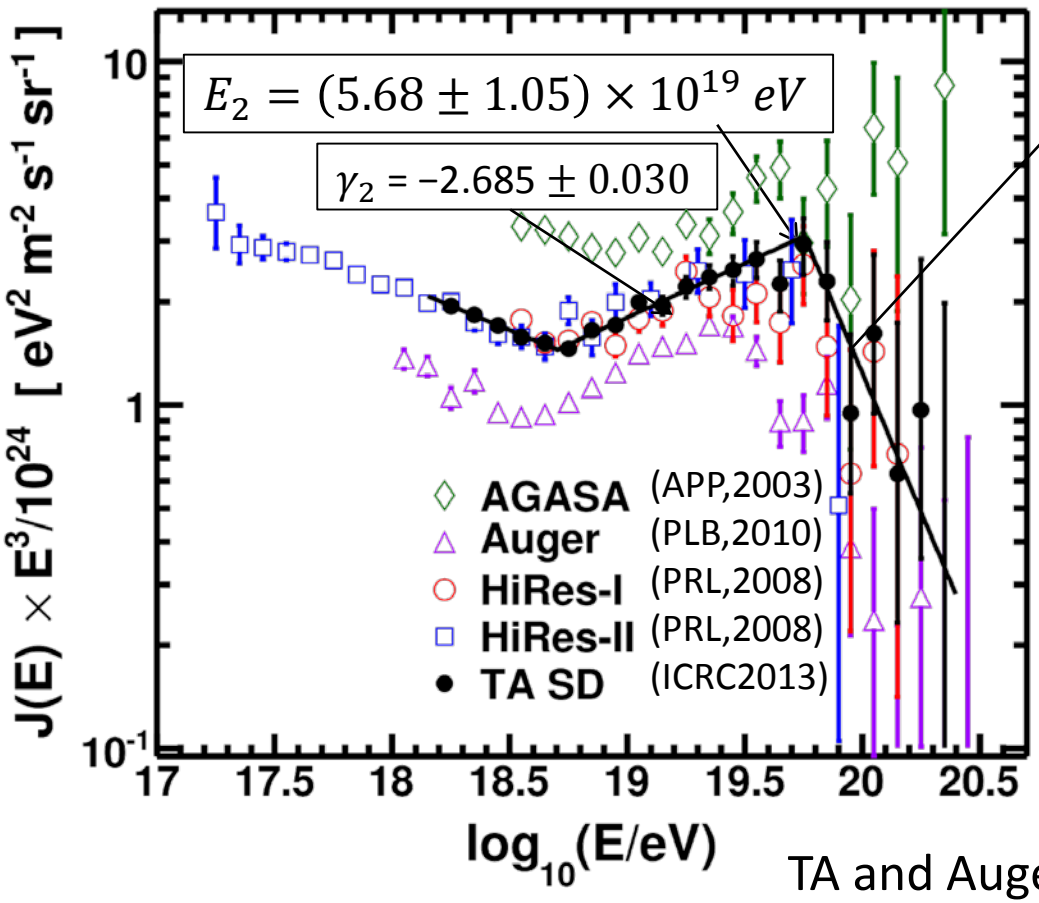
Energy spectrum

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

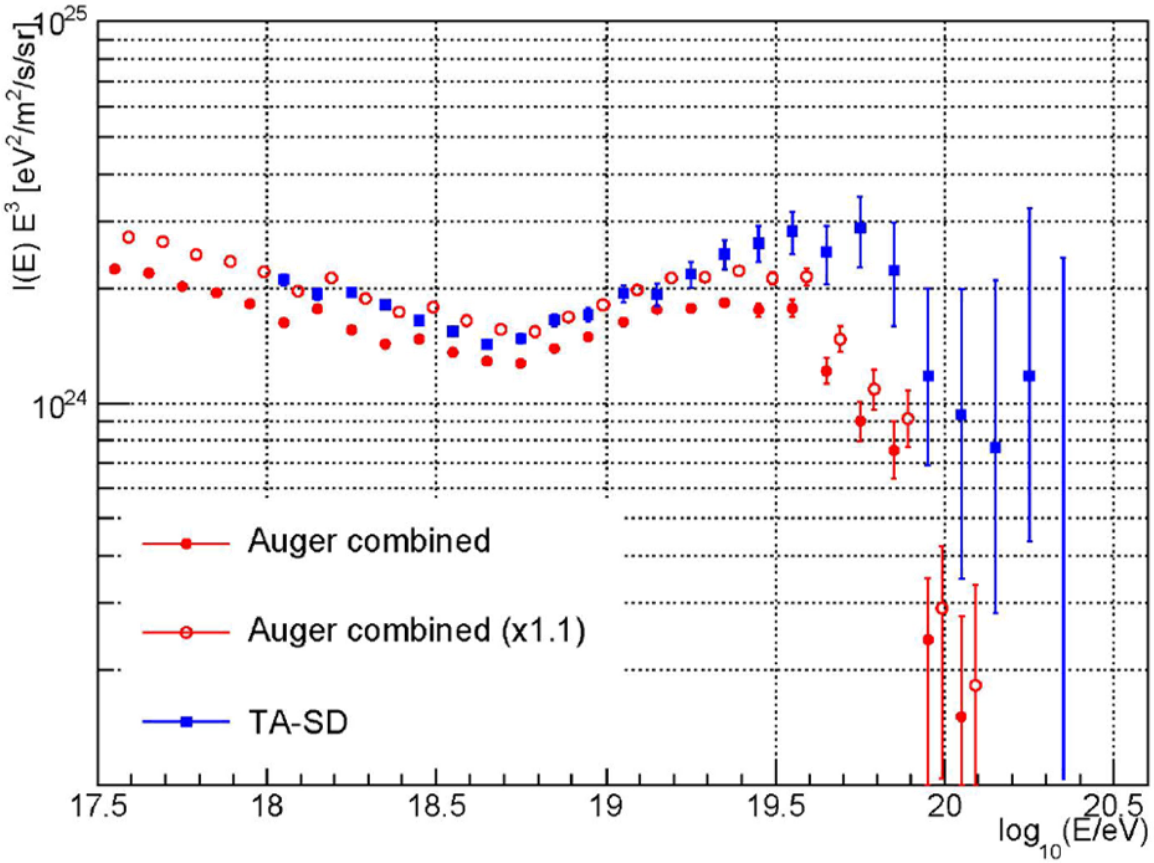
N(observed) = 26

Continuous spectrum is excluded at 5.74σ

TA and Auger fluxes were different by ~25% in energy scale

TA spectrum vs Auger spectrum

Rapporteur talk by Y.Tsunesada at ICRC2013

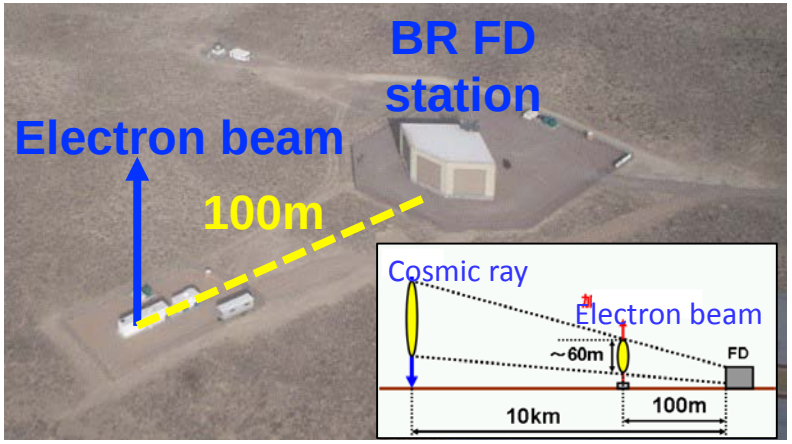


Energy scale uncertainty
. TA: 21%
. Auger: 14%

TA (■) and Auger (Ex1.1) (○)
similar below $10^{19.4}$ eV
different above $10^{19.4}$ eV

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

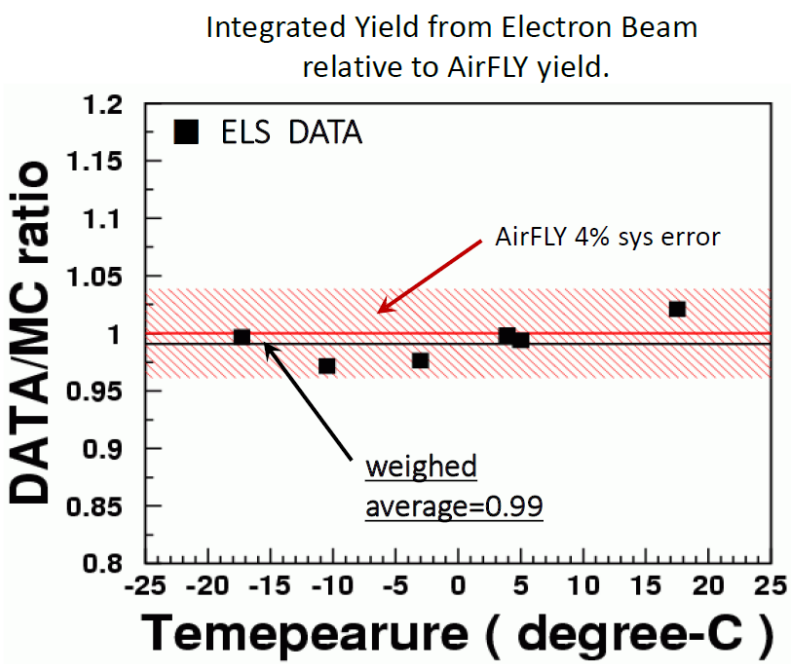
Air Fluorescence Yield (AFY) by using Reference Model proposed by B. Keilhauer et al. (UHECR2012, arXiv:1210.1319)

$$Y_{\lambda}^{NEW2012}(T,P,RH)(\mathrm{ph/MeV}) = Y_{337nm}(T_r,P_r)\cdot I_{\lambda}(T_r,P_r)\cdot \frac{1+\frac{P_r}{P_{air}^{N'}(T_0)}\left(\frac{T_0}{T_r}\right)^{1/2-\alpha}}{1+\frac{P}{P_{air}^{N'}(T_0,RH)}\left(\frac{T_0}{T}\right)^{1/2-\alpha}}$$

T and humidity dep.

Air Fluorescence Yield at 337 nm by ELS

ICRC2013
preliminary



- AirFLY = 5.61 $\pm$ 0.06 (stat) $\pm$ 0.22 (sys)
  at 1013 hPa and 293 K
- Measurement in situ at TA
  - $\frac{\text{ELS(data)}}{\text{AirFLY(MC)}} = 0.96 \pm 0.01(stat) \pm 0.15(syst)$

  at ~860 hPa and -17 ~ 17°C

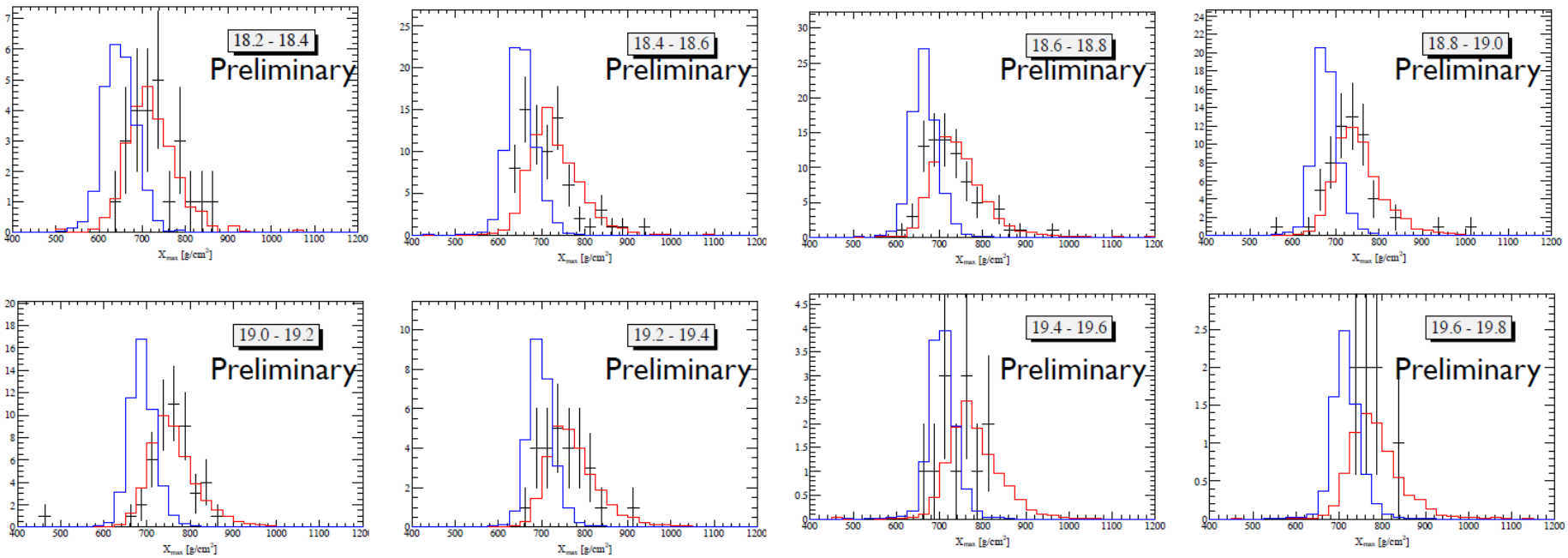
Mass Composition

Y.Tameda
ICRC2013, 512
preliminary

FD stereo Xmax

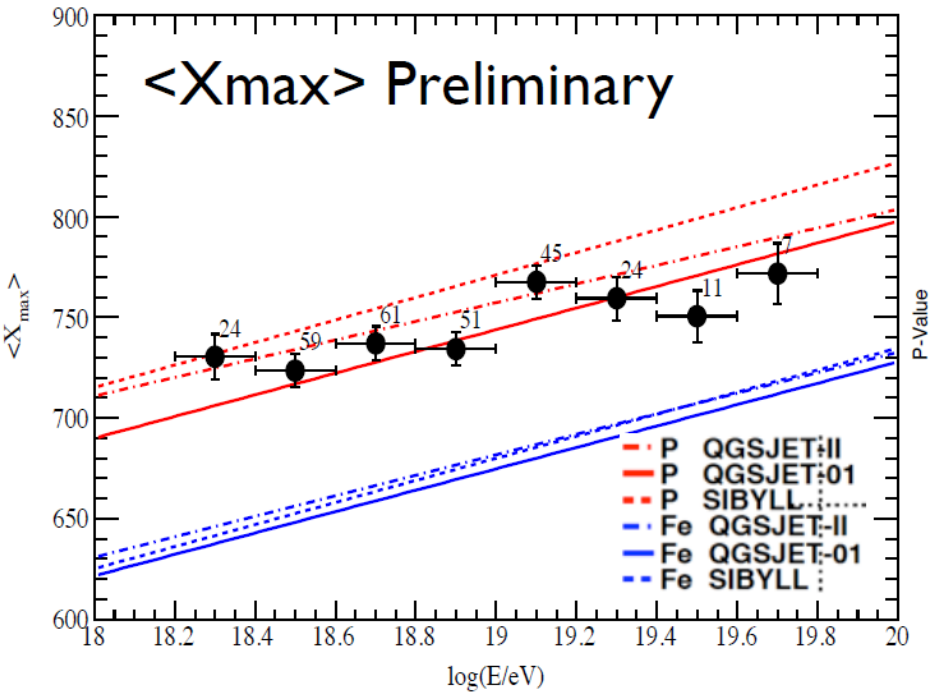
- FD stereo 5-year data (Nov., 2007 – Nov. 2011)
  - Data: TA
  - Red histogram: QGSJET-II-03 proton model
  - Blue histogram: QGSJET-II-03 iron model

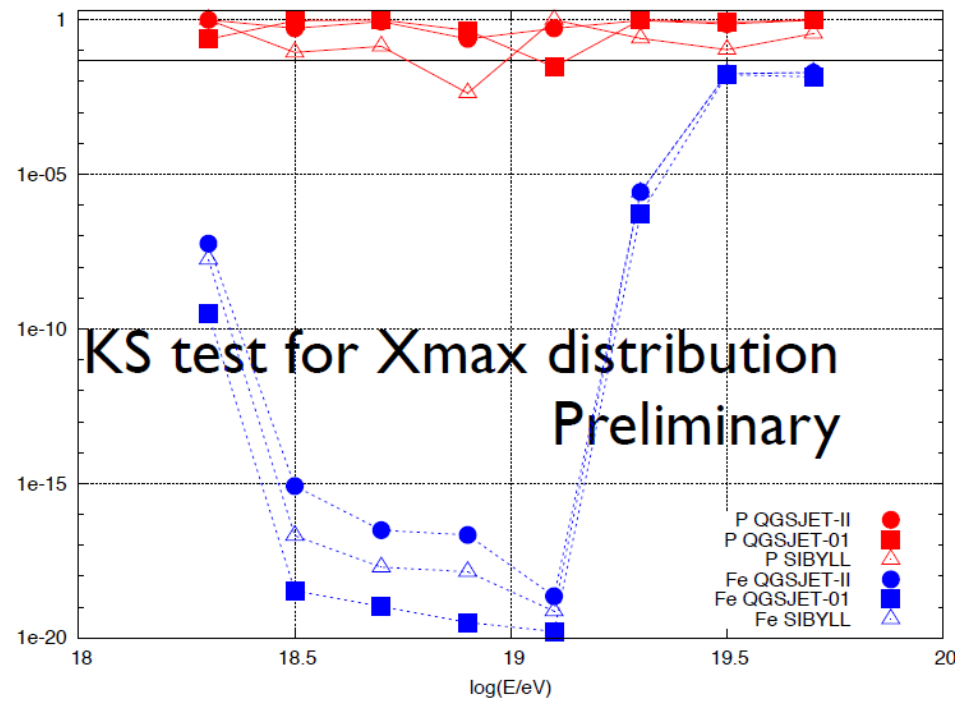
Both Data & MC
with bias of
. Reconstruction
. Cut



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

Similar result is obtained for MD hybrid (FD+SD) Xmax

Anisotropy

TA 5-year SD data

P.Tinyakov
ICRC2013 preliminary

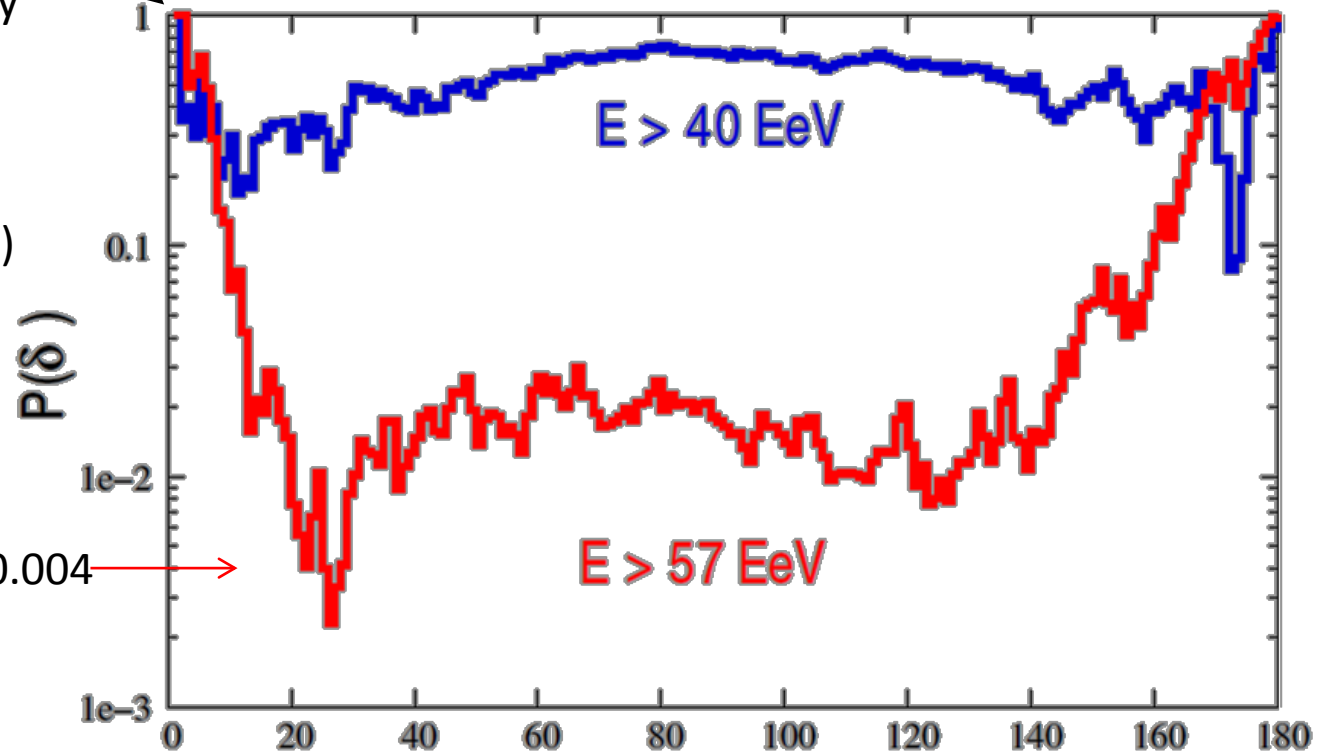
Autocorrelations

No small-scale anisotropy

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

Small P(δ): departure from isotropy

0.004



Separation angle δ

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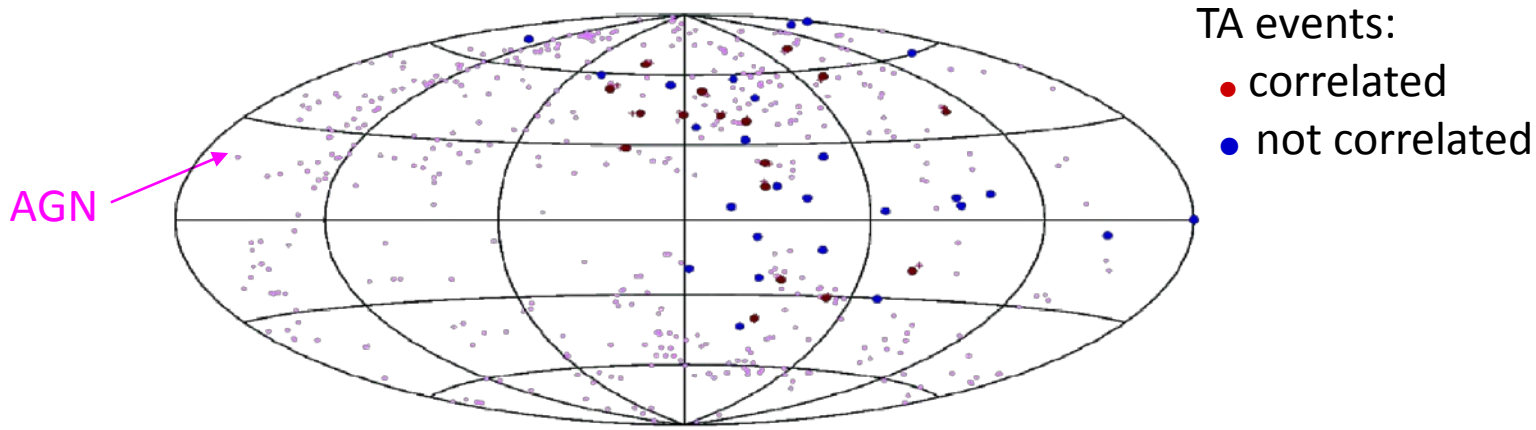
Oral, 1033

Correlations with AGN

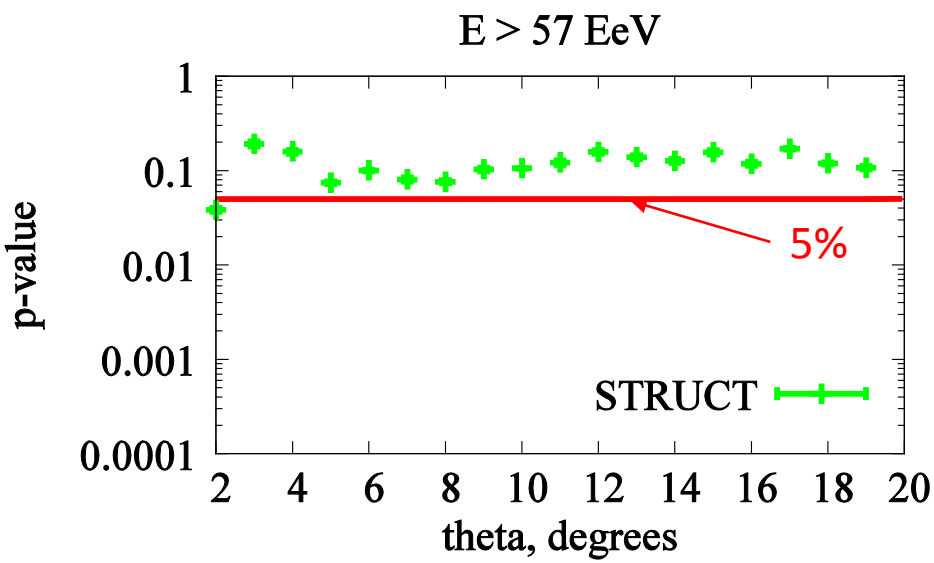
- 472 AGN from 2006 Veron catalog with z < 0.018
- E > 57 EeV, zenith angle < 45°, N = 42 (5 yr)
- Separation angle = 3.1°



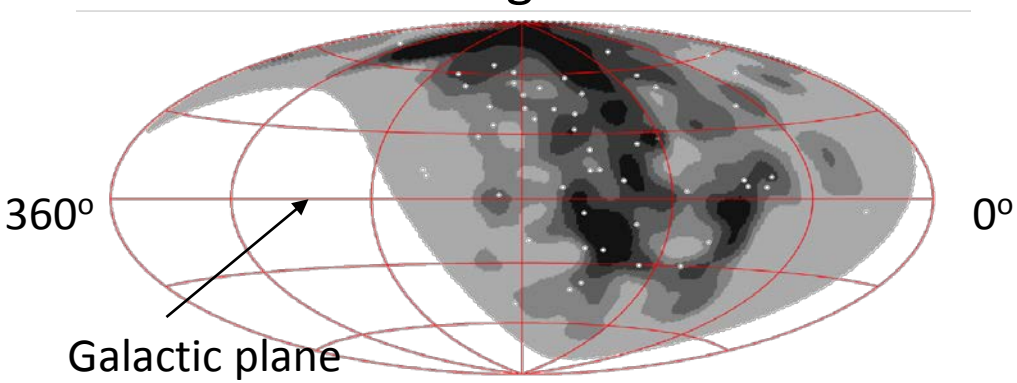
- Probability to hit AGN with a single event $p_o = 0.24$
- 17 events correlate out of 42 (0.40) $\Longrightarrow p = 1.4\%$

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

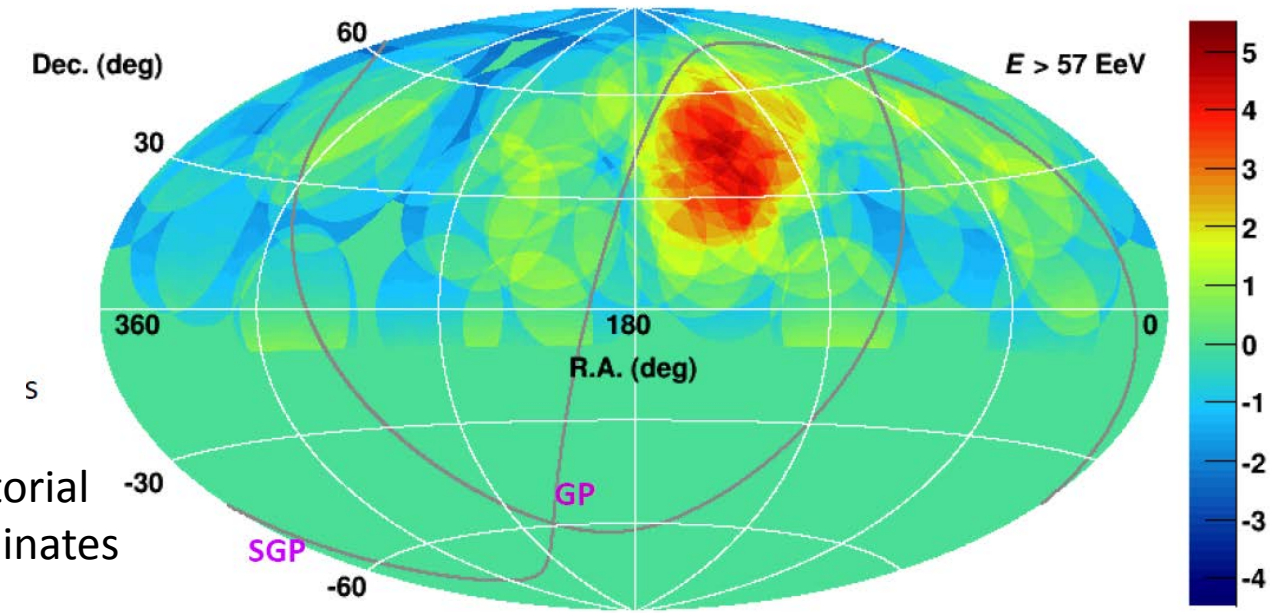


p-value of Structure (LSS) model ~10%

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

Hot spot

- Loose cut: 52 events -- > 72 events (E > 57 EeV)
  - No 1.2-km border cut, …
  - Angular resolution does not change very much
- Oversampling with circles of 20-degree radius

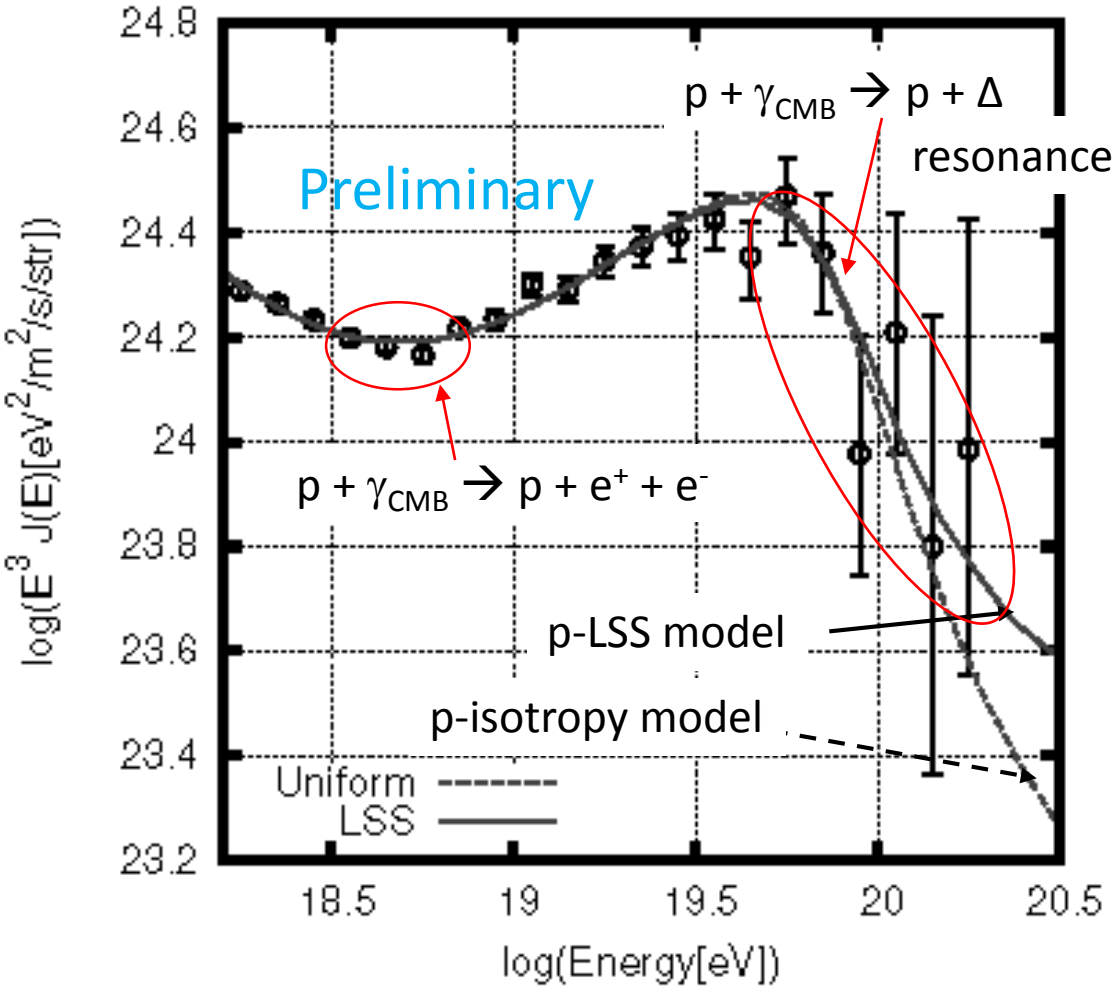


Equatorial coordinates

- Significance 5.1σ (before correction)
- Chance probability : being estimated (~ 3.6σ)

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

m = 5 (AGN)
m = 4.8 (GRB)
m = 3 (QSO)

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

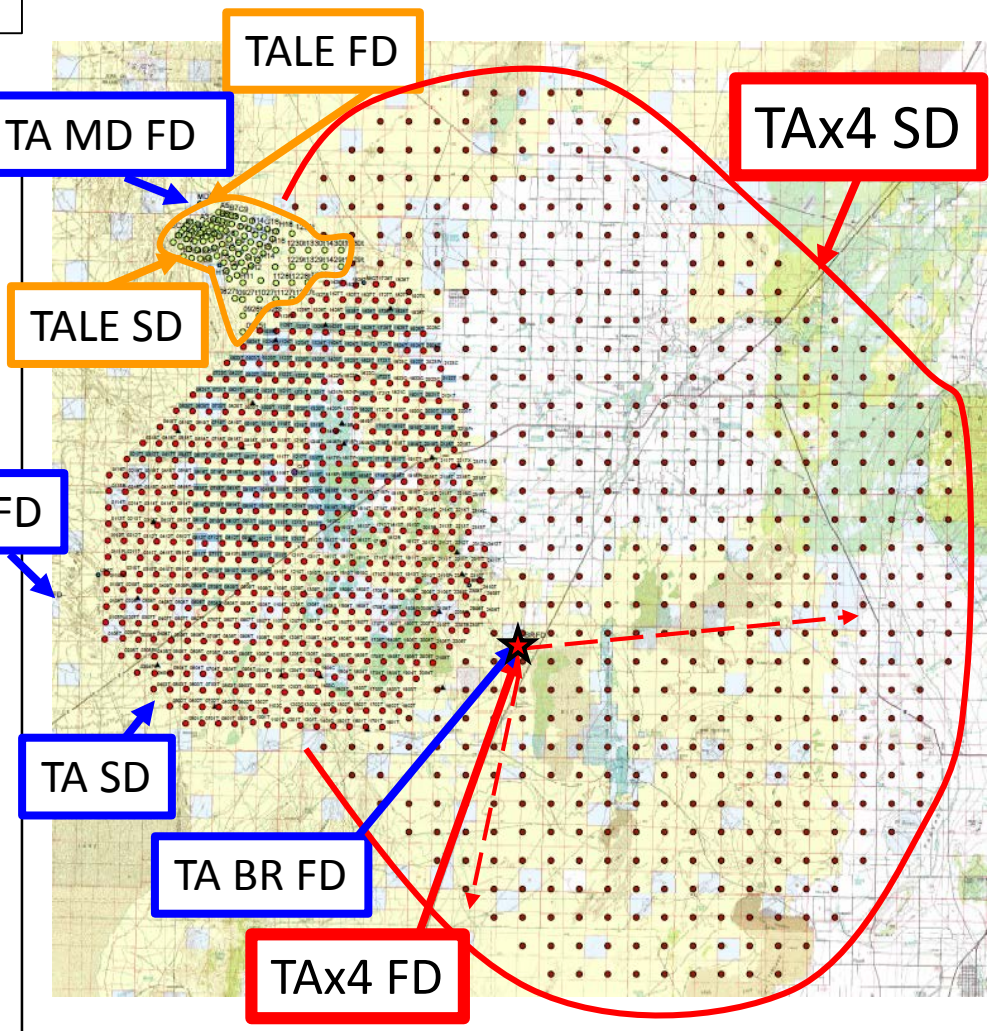
TA extension plans and on-going R&D

- 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 anisotropy.
- Now there are hints at 3σ level for TA

- Plan to expand TA by 4 times (~3000 km^2)
  - 500 scintillator counters with 2.1 km spacing (Japanese side)
    - Proposal submitted for a grant this Oct.
  - 10 refurbished HiRes telescopes ★ (US side)
- JFY2014 – 2015: 2-year construction
- JFY2016 – 2018: 3-year observation
- By Mar, 2019
  - 20 years of TA SD data
  - 14 years of TA hybrid data (Escale, Xmax)
- Study of anisotropy
  - Anistoropy at 3σ level (5-year TA SD data)
    ↓
  - Expect 5σ level anisotropy (20-year TA SD data)
- More statistics for
  - the spectrum above suppression
  - Xmax around suppression
- UHE gamma and neutrino search



TALE (TA Low-energy Extension)

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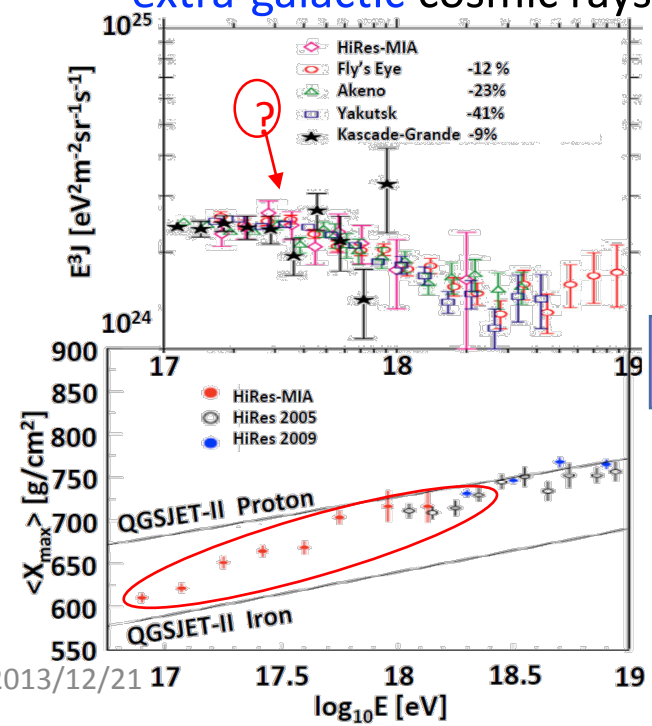
Oral, 717

down to $10^{16.5}$ eV

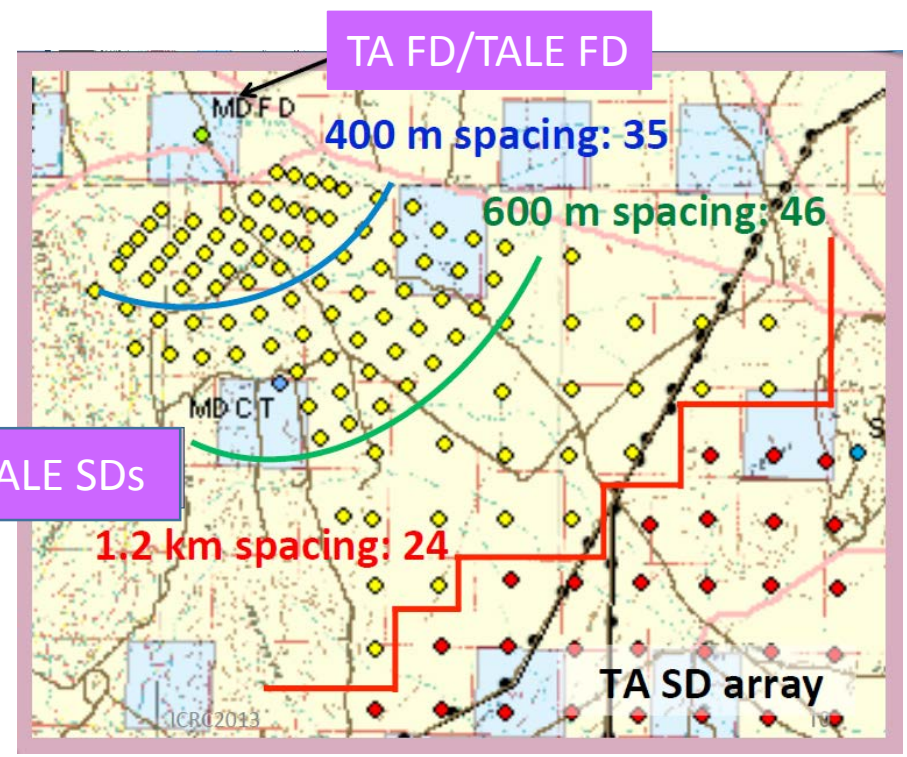
- E = $10^{16.5}$ – 10^{19} eV
  - Second knee at ~$10^{17.5}$ eV?
  - Drastic change of composition at 10^{17}~10^{18} eV?

    ↓
  - Transition from galactic to extra-galactic cosmic rays?



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

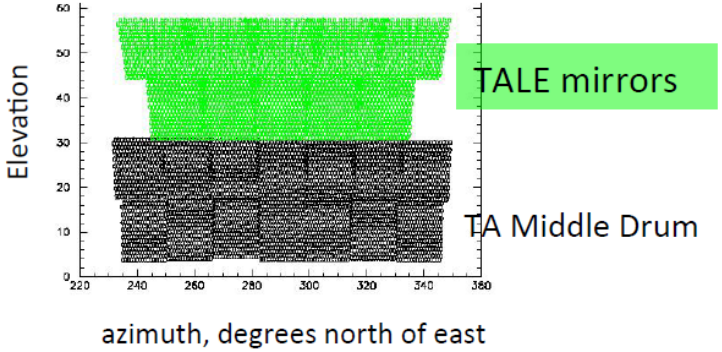
TALE layout



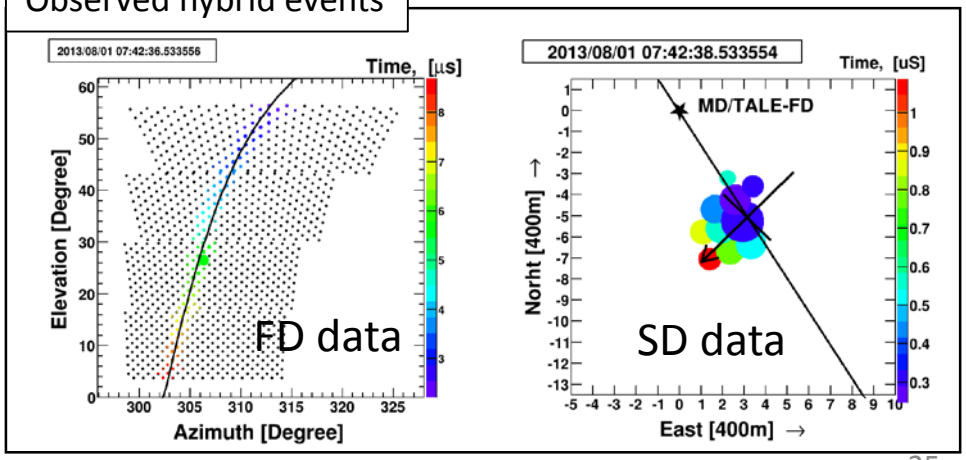
TALE (TA Low-energy Extension)

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

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

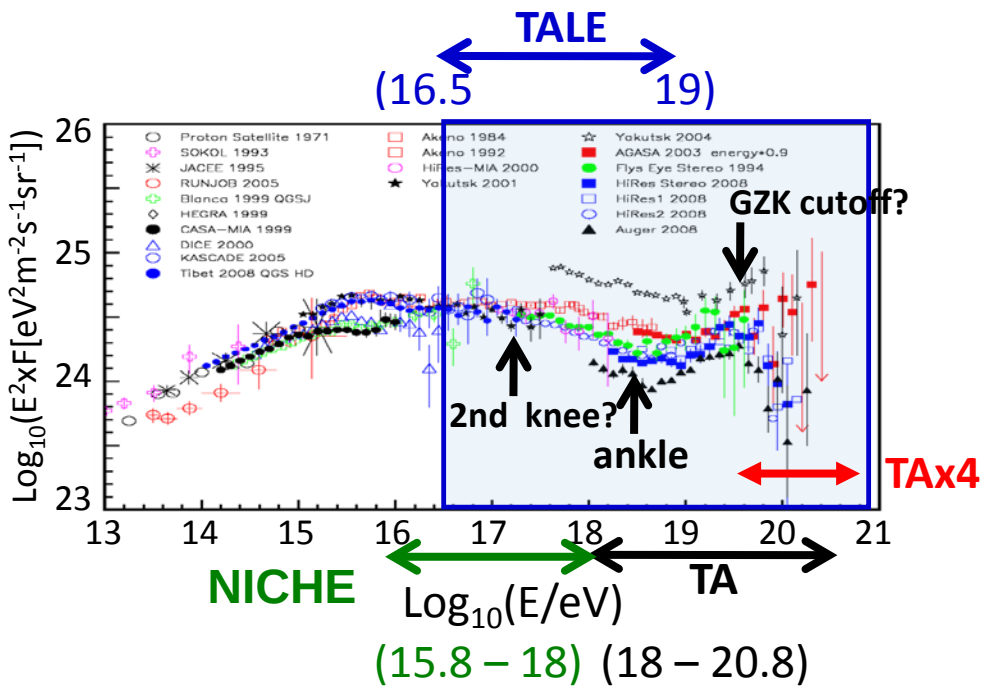


Observed hybrid events



TA + TAx4 + TALE + NICHE

(proposal) FD full SD partially In operation (proposal)



(15.8 – 18) (18 – 20.8)

Precise energy and composition measurements
with between TA and TAx4, and TA and TALE, and TALE and NICHE*,
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

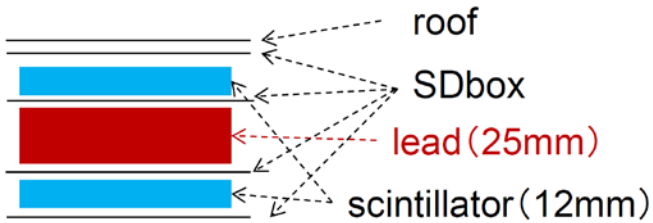
NICHE: Non-Imaging CHErenkov detector

ICRC2013
Poster, 118, 298

TA muon detector project

- One set of 24-m^2 scintillator detector with concrete absorber on the top
  - 8x(3-m^2 scintillator detectors)
- Lead layer sandwiched between two scintillators
  - First 9 m^2: 12x(0.75 m^2)
    - 1 segment was deployed inside CLF

will be installed outside CLF early next year

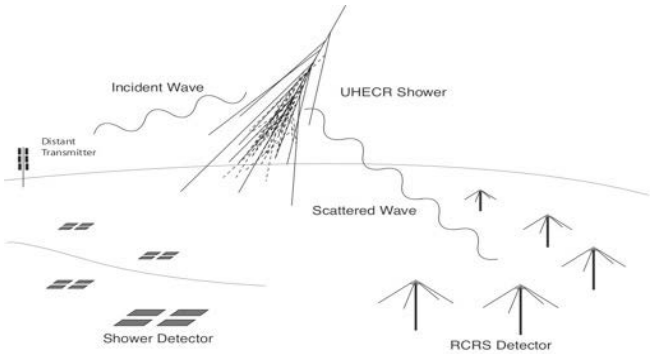


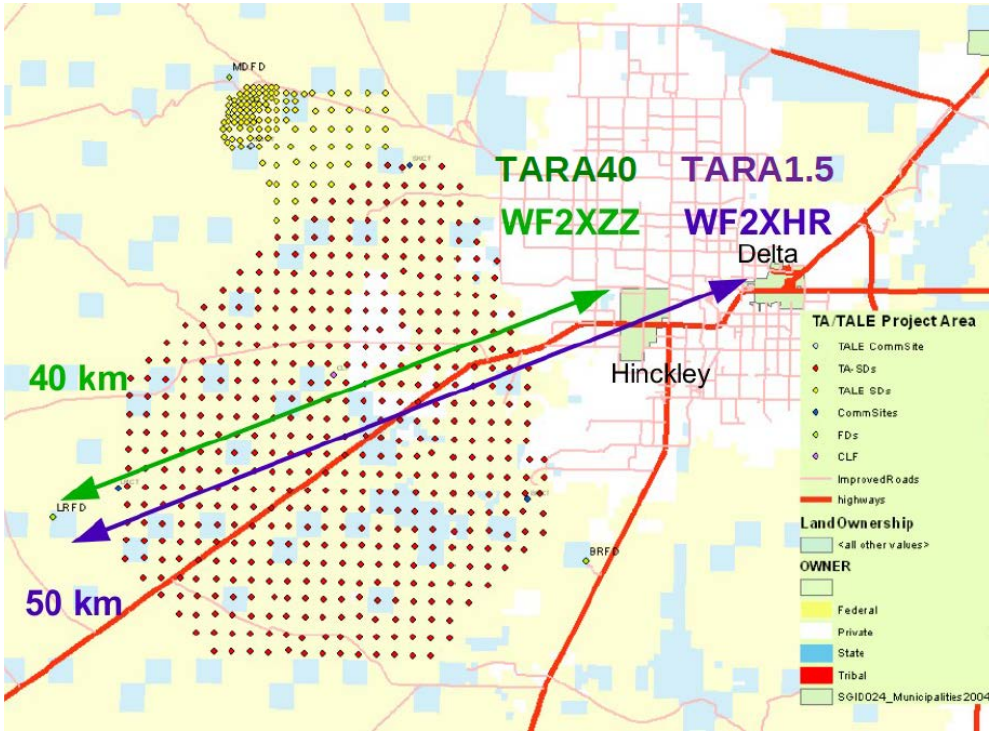
- Auger water → TA site

ICRC2013
Oral, 1192

TARA (TA Radar)

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



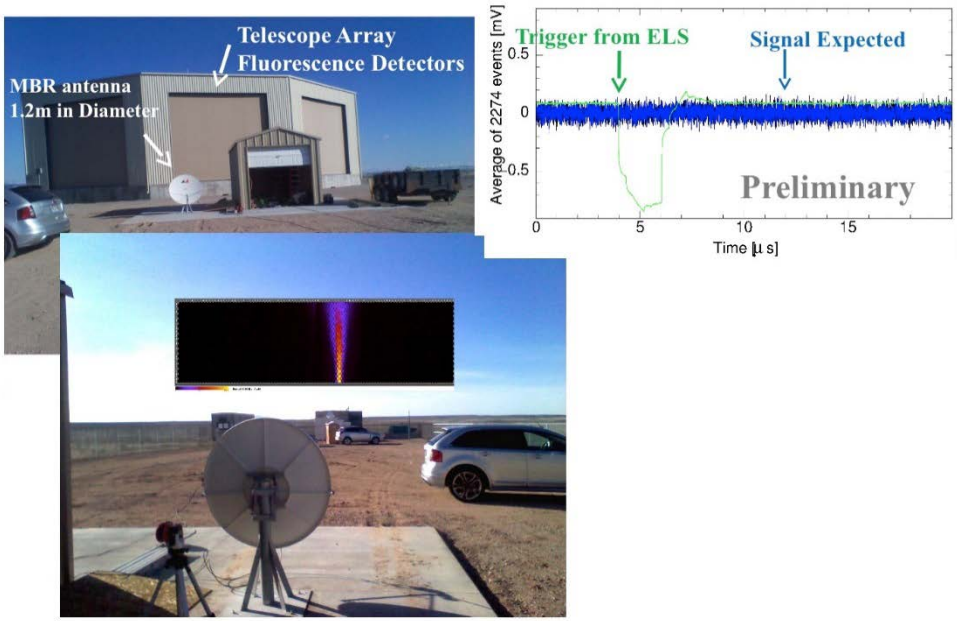


- TARA1.5
  - April 2011 to July 2012
  - 54.1 MHz @ 1.5 kW
- TARA40
  - Summer 2013~
  - 54.1 MHz @ 40 kW

Test of detection of Molecular Bremsstrahlung Radiation from cosmic-ray air shower

- The system of the detection of 12-GHz radio wave to observe cosmic-ray air-showers was developed
- Test: none of the below observed signal
  - 12-antenna array @ Konan Univ. (T.Yamamoto)
  - Coincidence with air-shower array @ Osaka City Univ. (S.Ogio)
  - Pseudo shower using electrons from ELS @ TA (T.Yamamoto et. al.)

Test at TA site



TA burst events

TA burst events (in 5-year SD data)

T.Okuda
COSPA2013
preliminary

- 10 bursts of shower triggers
  - Burst: N(shower trigger) $\geq$ 3 in 1 ms
- Some events in 5 bursts are reconstructed (right table)
  - 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

event

AS	YYMMDD	hhmmss	usec	X[m]	Y[m]	H[m]
AS	101004	165842	930565	11356	-7425	3963
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

Examples of timing and waveforms

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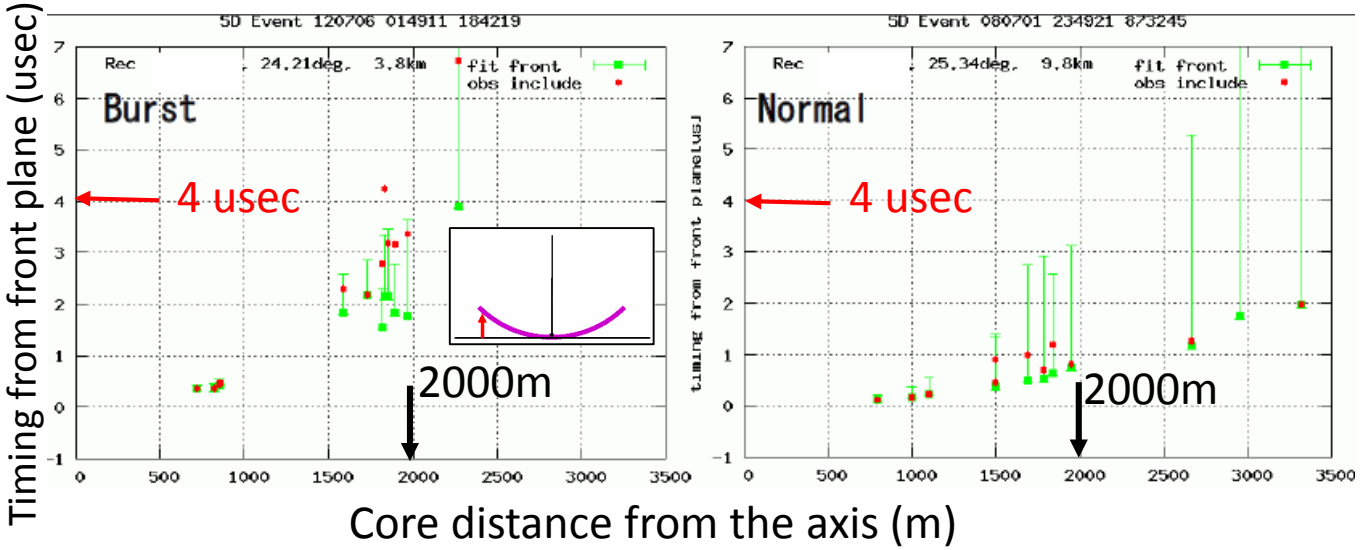
preliminary

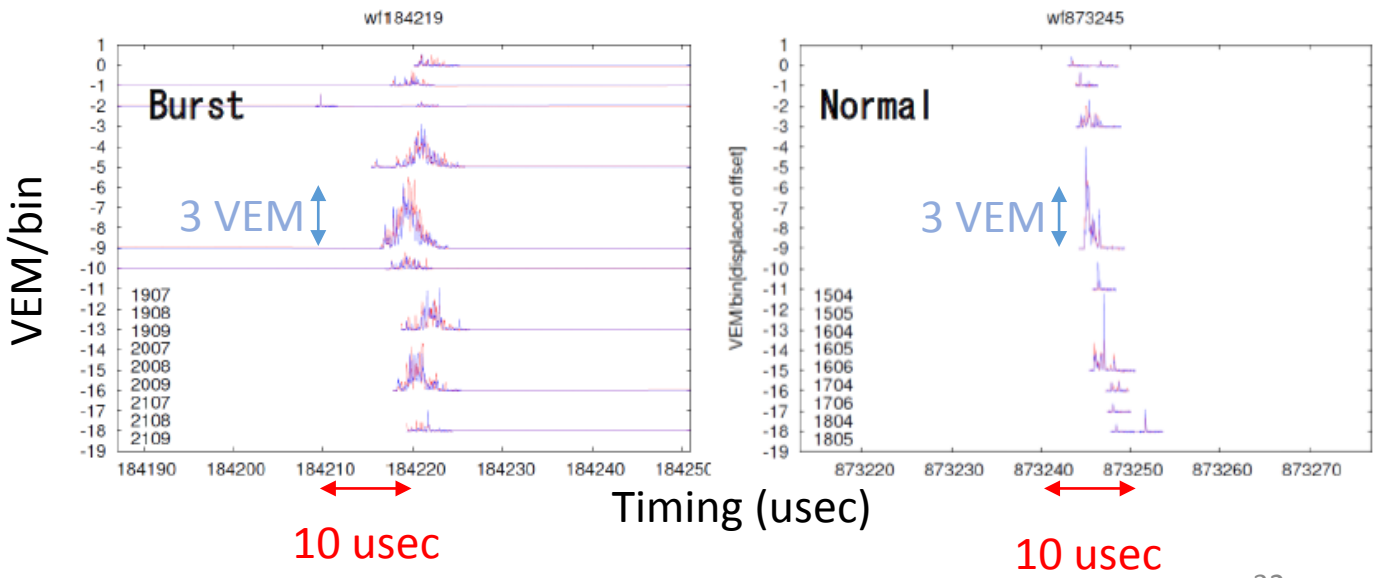
Lateral arriving Time

Shower front is curved more for burst events → Development seems to start lower sky



Waveforms

Slower rising edge for burst events



TA burst events associated with lightning

T.Okuda
COSPA2013
preliminary

- 10 bursts of shower triggers
  - Burst: N(shower trigger) ≥ 3 in 1 ms
- Some events in 5 bursts are reconstructed
  - Event: an SD data set recorded by a shower trigger
    - Trigger information
    - Wave forms from SDs

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

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

Date time Core position

AS YYMMDD	hhmmss	usec	X[m]	Y[m]	H[m]
LG		usec	X[m]	Y[m]	Flag
AS 101004	165842	930565	11356	−7425	3963
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

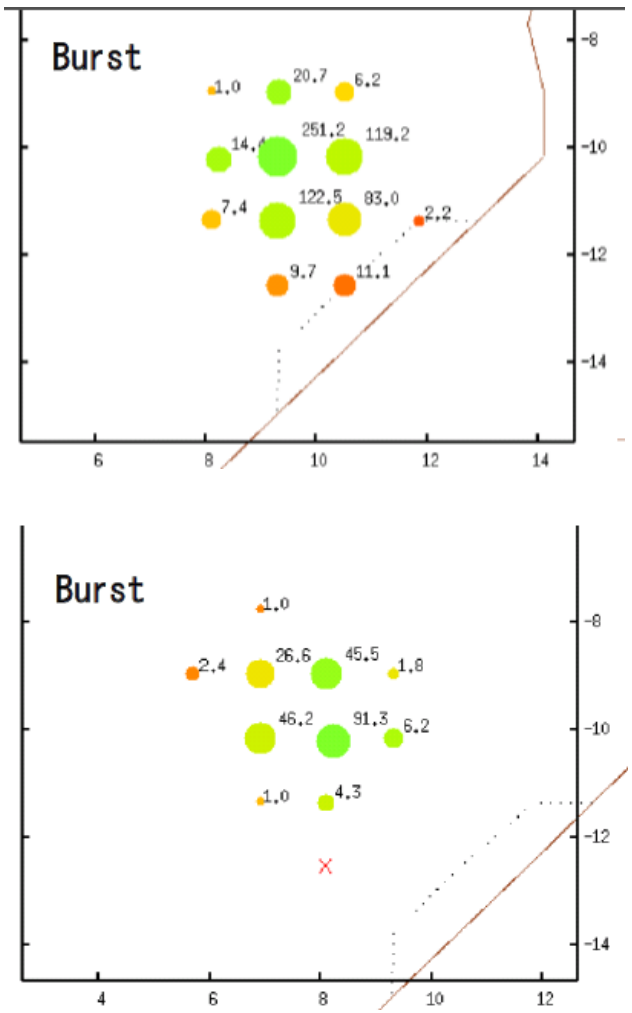
TA burst

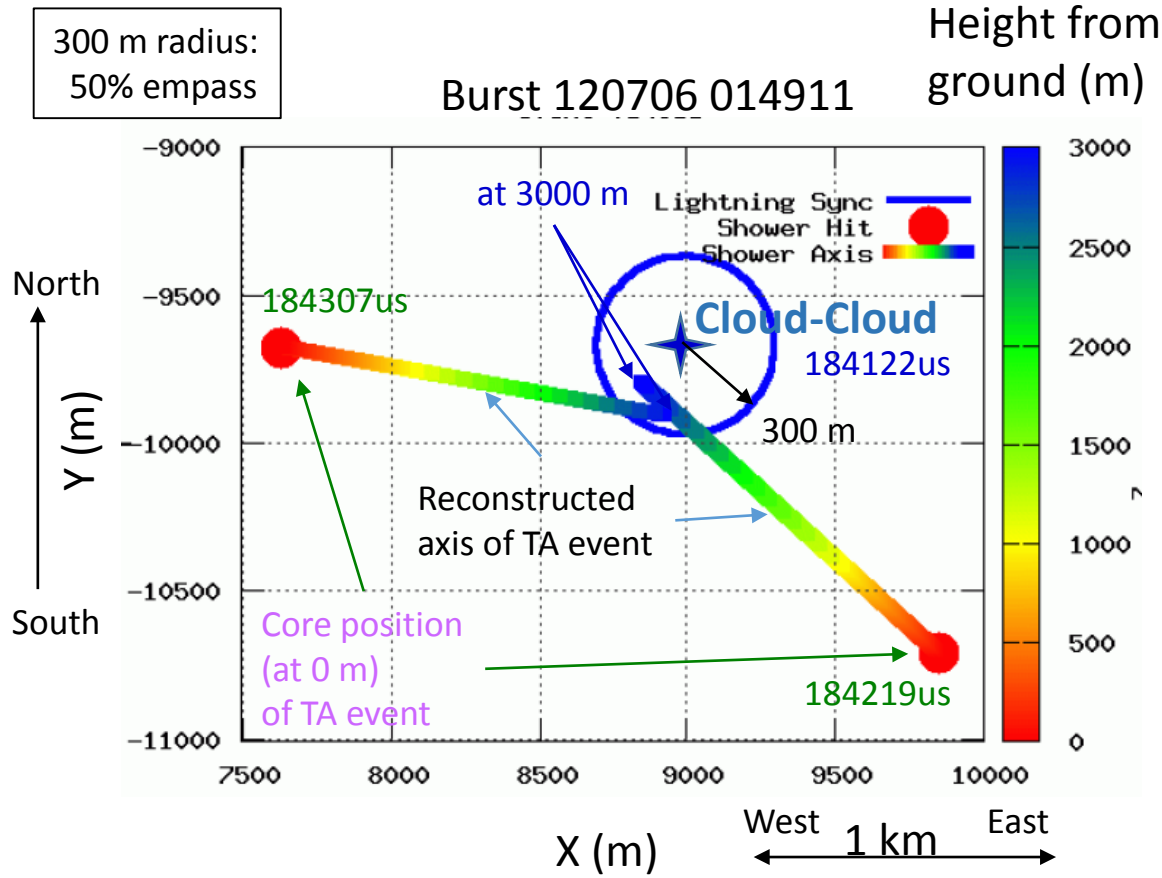
NLDN lightning

event

An example of TA reconstructed events with lightning

T.Okuda
COSPA2013
preliminary





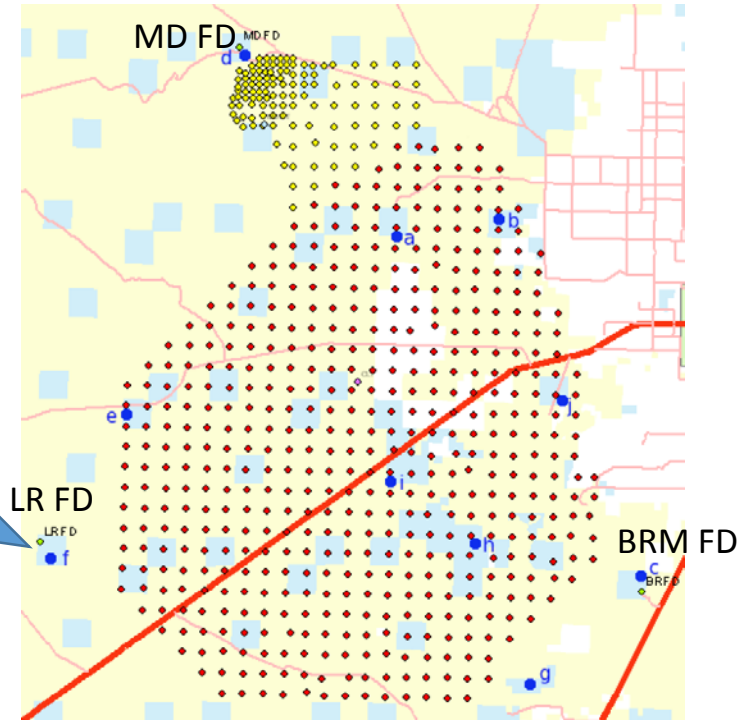
(X, Y): distances are from CLF

Associate experiment: TA/LMA

- 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 (Sep~)
  - 10 receiver stations
    - (blue points in the figure)



Summary

- Recent results for 5-year data
  - Energy spectrum
    - Significance of the suppression consistent with GZK cutoff
      - 5.7σ above $10^{19.8}$eV
  - Composition
    - Consistent with proton
  - Anisotropy
    - Hints of anisotropy: significance of ~3σ
      - Hot spot (20°) ~3.6σ
- TA extension plans
  - TAx4: proposal to quadruple TA aperture
    - Towards ~5σ anisotropy in 5 years
  - TALE: low energy extension down to $10^{16.5}$ eV
    - Currently operating 10 full FDs and a part of SD array
- TA SD burst events associated with lightning were observed
- Associated experiments: performed, ongoing, will come