Measurement of Ultra-High Energy Cosmic Rays: Present and Future

INSTR-2014, Novosibirsk

2014/02/24 – 3/1

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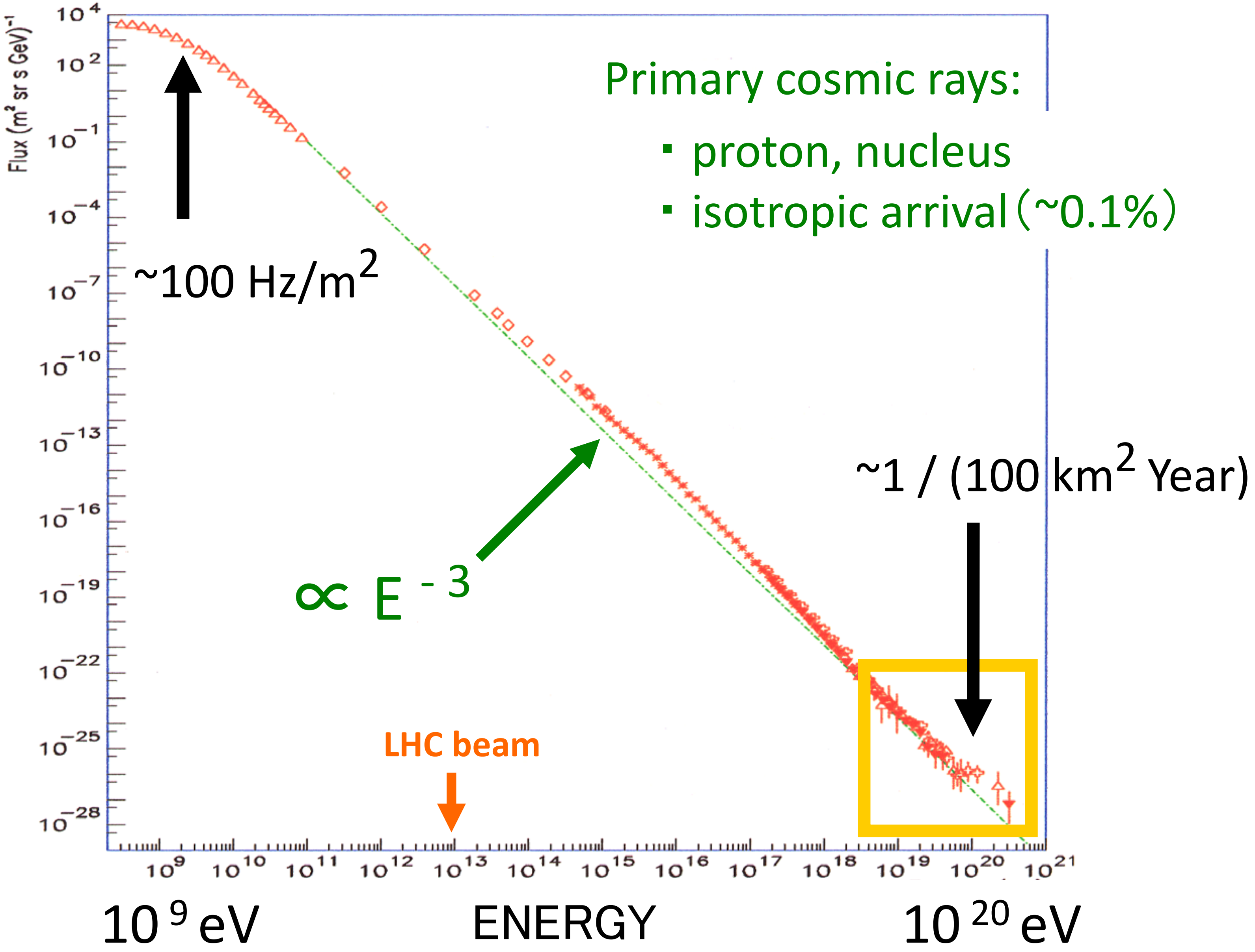
Inst. for Cosmic Ray Research, Univ. of Tokyo

1. Introduction: what is UHECR?
2. Detector: Auger and TA
3. Results: spectrum, particle & anisotropy
4. Prospects

Energy Spectrum of Cosmic Rays



UHECR : Ultra-High Energy Cosmic Ray

- may be extra-galactic origin but
  no identified acceleration site/mechanism
- probes nearby (~100Mpc) HE astrophysical phenomena
  & hadronic + nuclear interactions beyond LHC energy

- Research advanced significantly in the last decade by
  - ✓ 3d shower imaging by telescope
  - ✓ Huge detector (x10 more events)
  - ✓ Energy scale better understood
  - ✓ Accelerator data to calibrate shower simulation

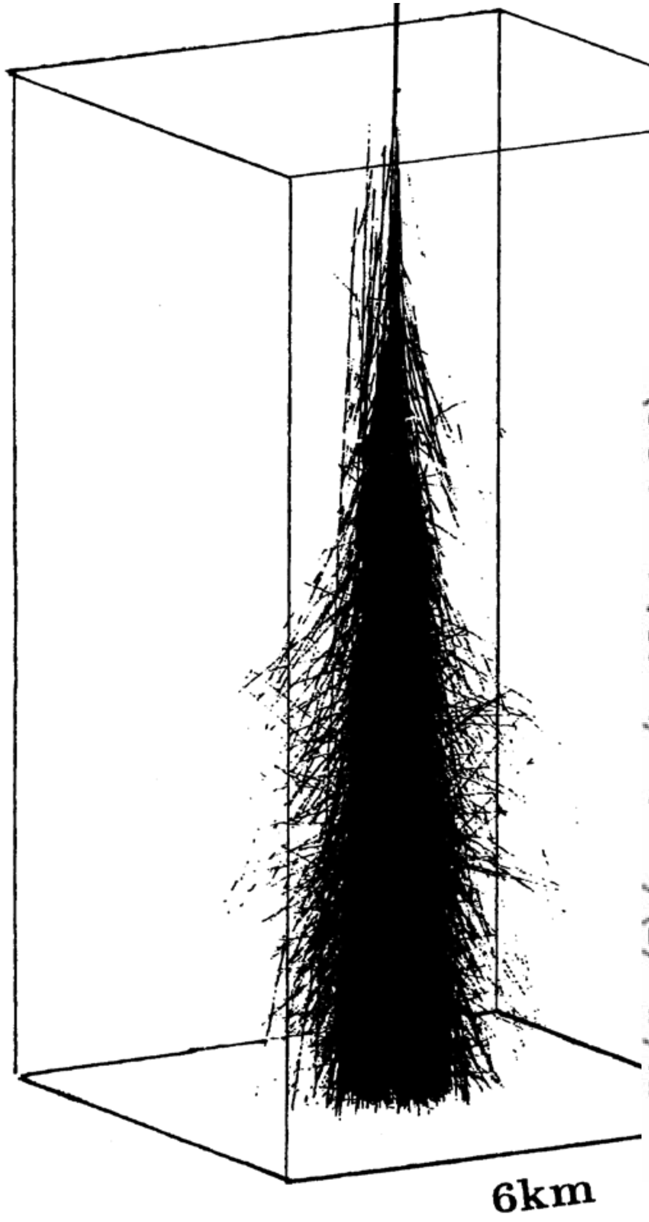
TA: Telescope Array in Utah
Pierre Auger Obs. in Argentina

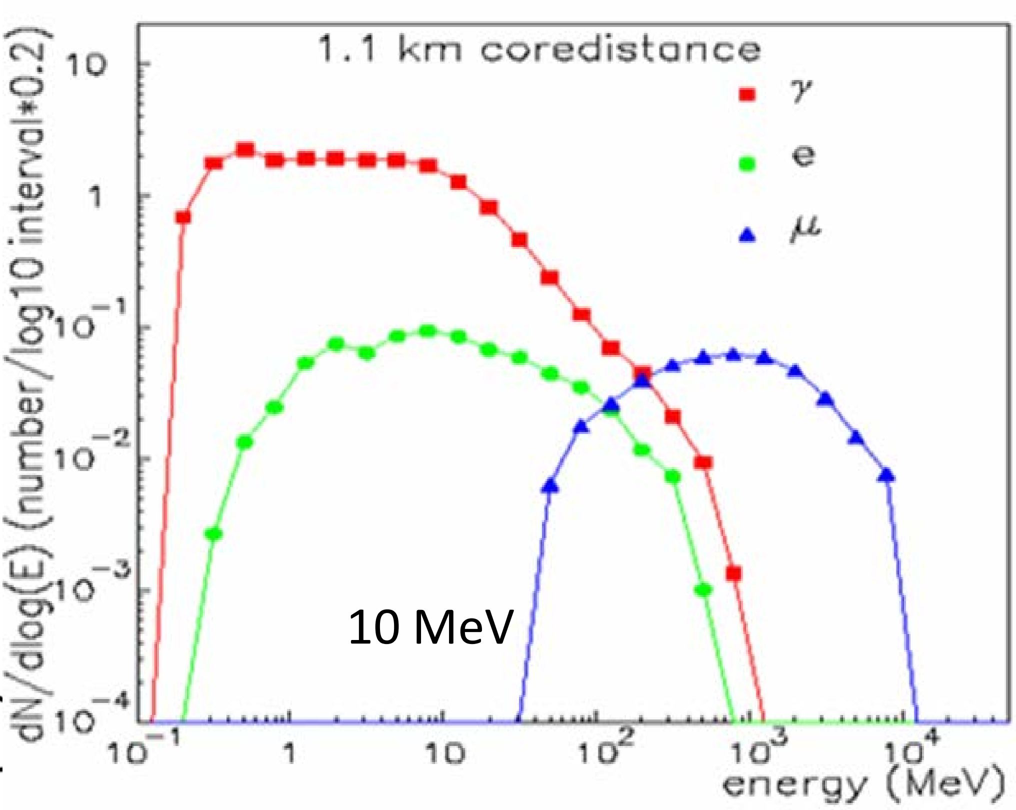
Extensive Air Shower

Atmosphere is a good
Calorimeter Medium.

Radiation Length	36.7 gr / cm^2 ⇨ 28 X_0 in total
Interaction Length	90 gr / cm^2 ⇨ 11 λ_I in total
Critical Energy	81 MeV
Moliere Radius	91 m (ground lev)

and, it scintillates!
~4.5 UV photons
per 1m of charged particle track





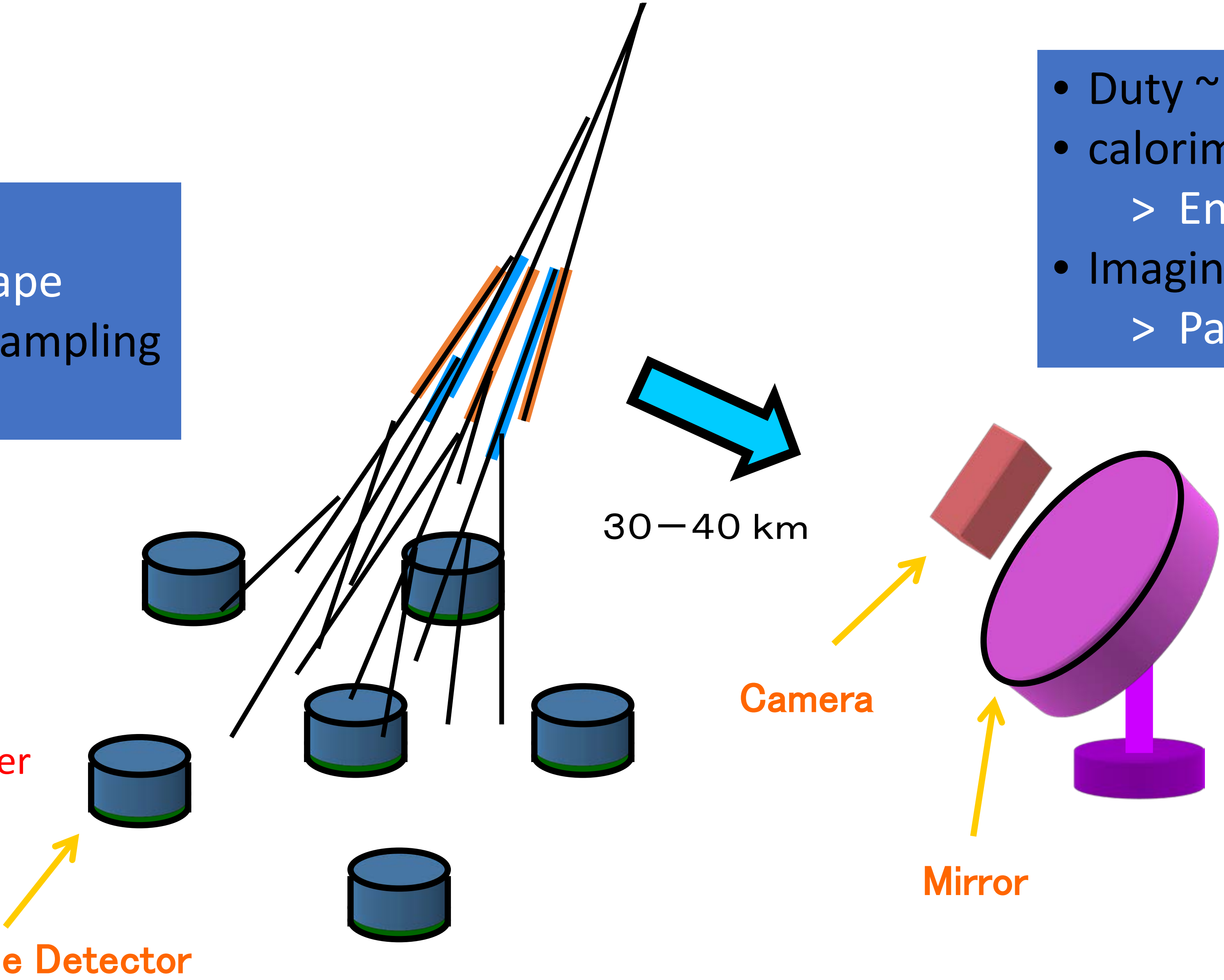
10 MeV

1 GeV

Surface Detector (SD) + Fluorescence Detector (FD)

- Duty ~100%
  - > Spectral shape
- ~Uniform sky sampling
  - > Anisotropy

- Duty ~ 10%
- calorimetry
  - > Energy scale
- Imaging
  - > Particle composition



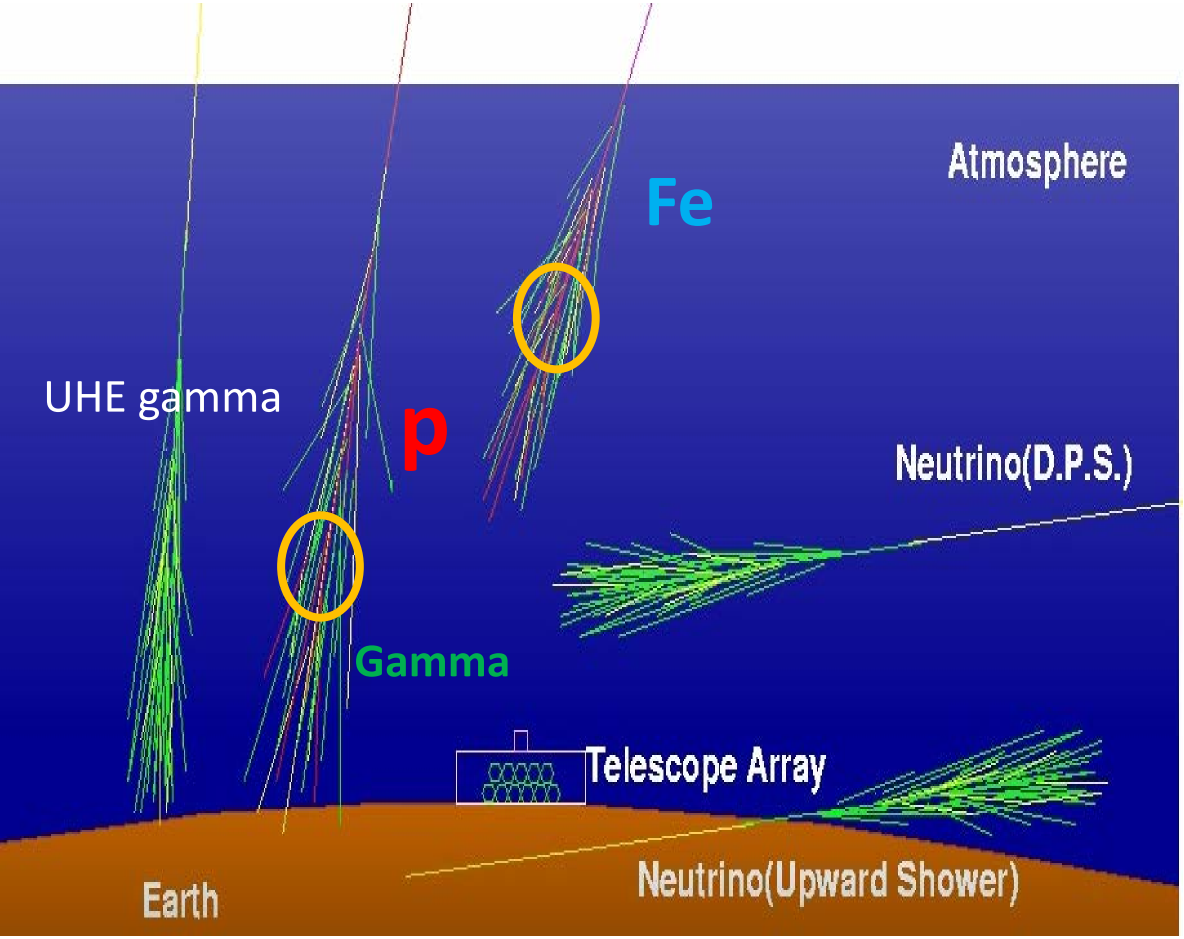
SD

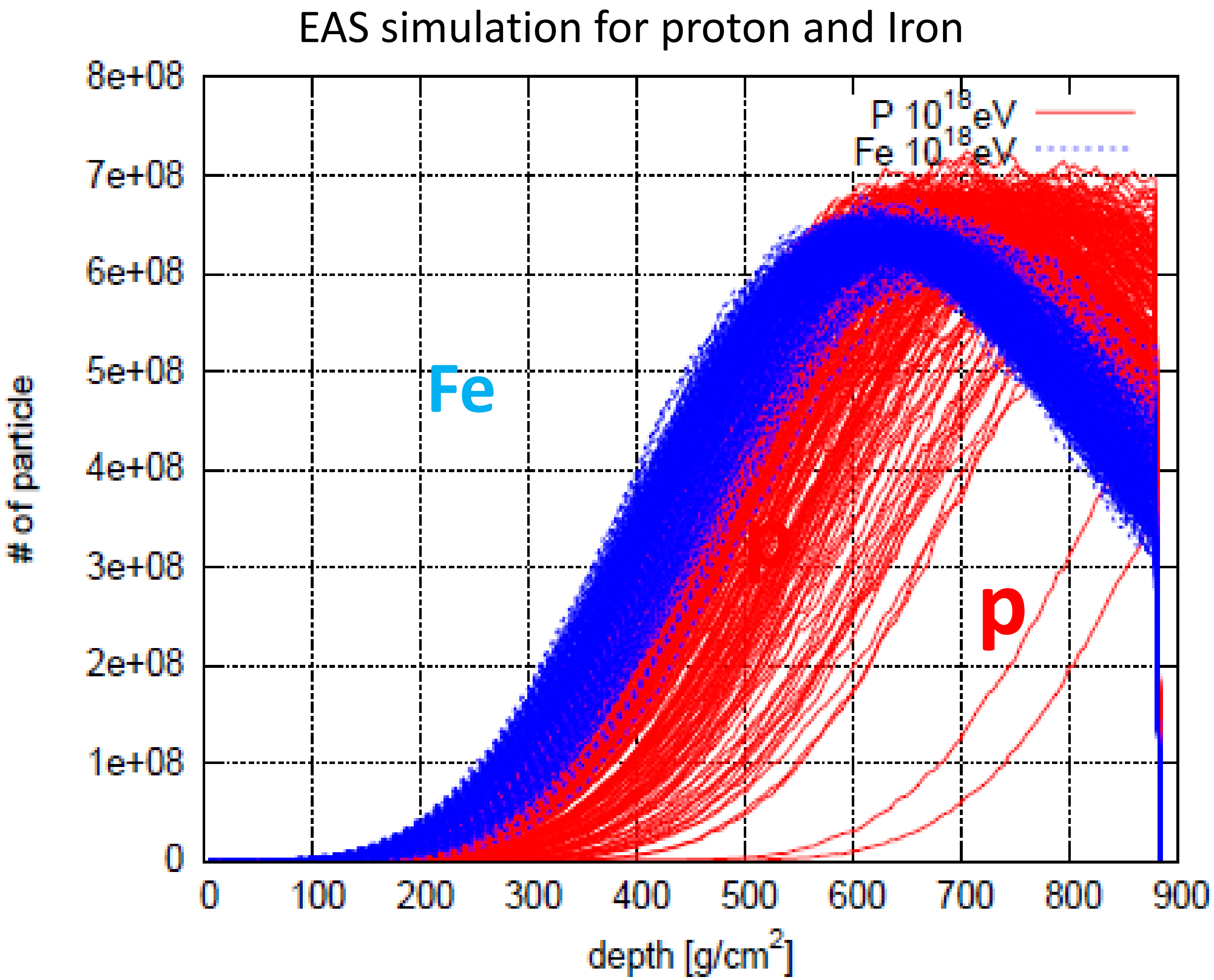
Single-Layer
Sampling Calorimeter

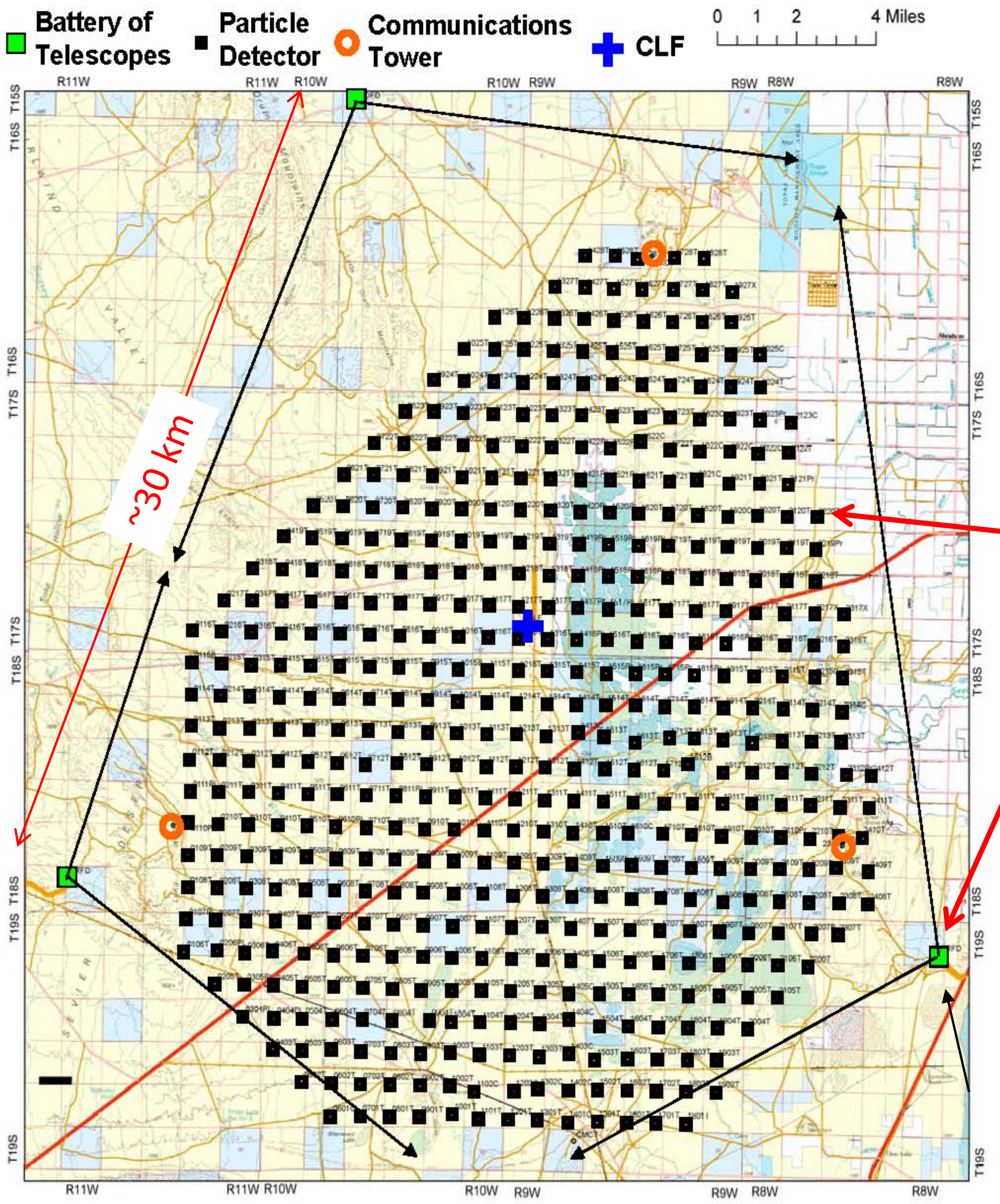
FD

Total Absorption
Imaging Calorimeter

Composition vs Longitudinal Shower Development







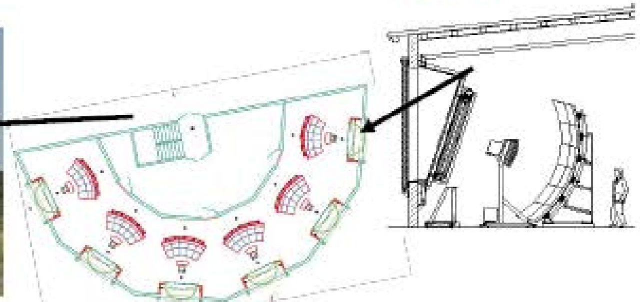
507 Surface Particle Detectors cover 680 km²

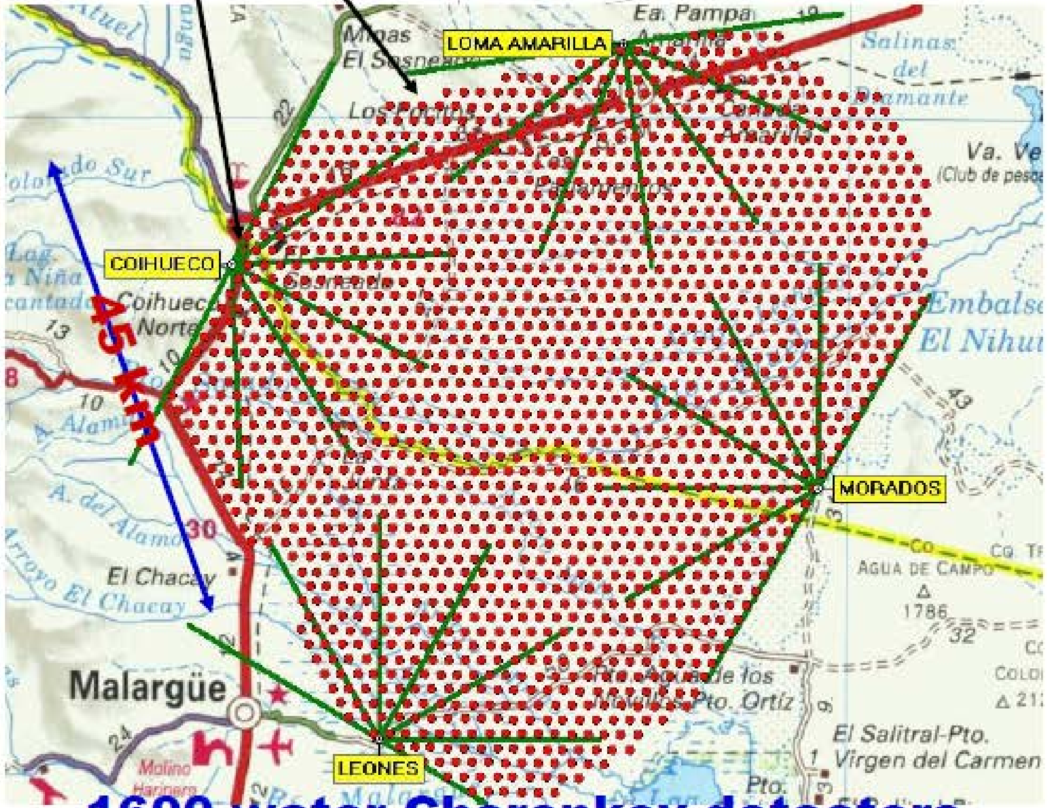
3 Fluores. Telescope stations overlook the array.

Utah, USA
39.3 ^{0} N
112.9 ^{0} W
Alt. 1400 m
2008 –

The Pierre Auger Observatory

Argentina, Mendoza, Malargue
1.4 km altitude, 870 g/cm^2





Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*

PIERRE AUGER OBSERVATORY

1600 water Cherenkov detectors,
(a la Haverah Park)
1.5 km spacing, 3000 km^2,
4 x 6 fluorescence telescopes 7

2004 –

Auger

S=10m^2, h=1.2m
Water Tank
μ based sampling

SD

50 MHz sampling
16-bit H/L scheme
GPS time stamp (~10ns)
2.4 GHz wireless LAN
~200 SDs to a com. tower
Calibration by 700 Hz μ

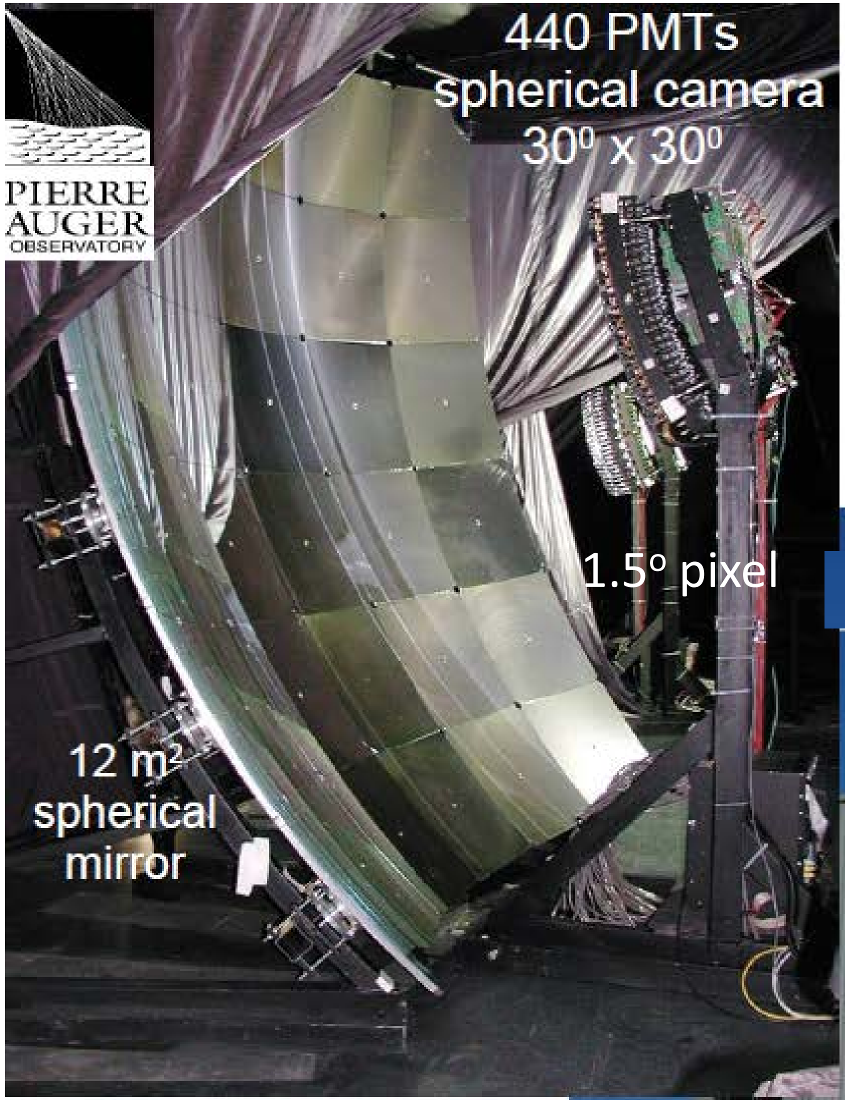
TA

S=3m^2, t=1.2cm
Plastic Scint. 2-layer
EM based sampling

Auger

FD

- -HV operation and DC coupled
- 12-bit 40 MHz FADC
- Online BG subtraction
- 5-6 σ signal recognition @ each PMT
- 5 or more adjacent PMTs for trigger
- 30 ms readout dead time per trigger
- ~2 Hz trigger (~7Hz by freq. airplanes)

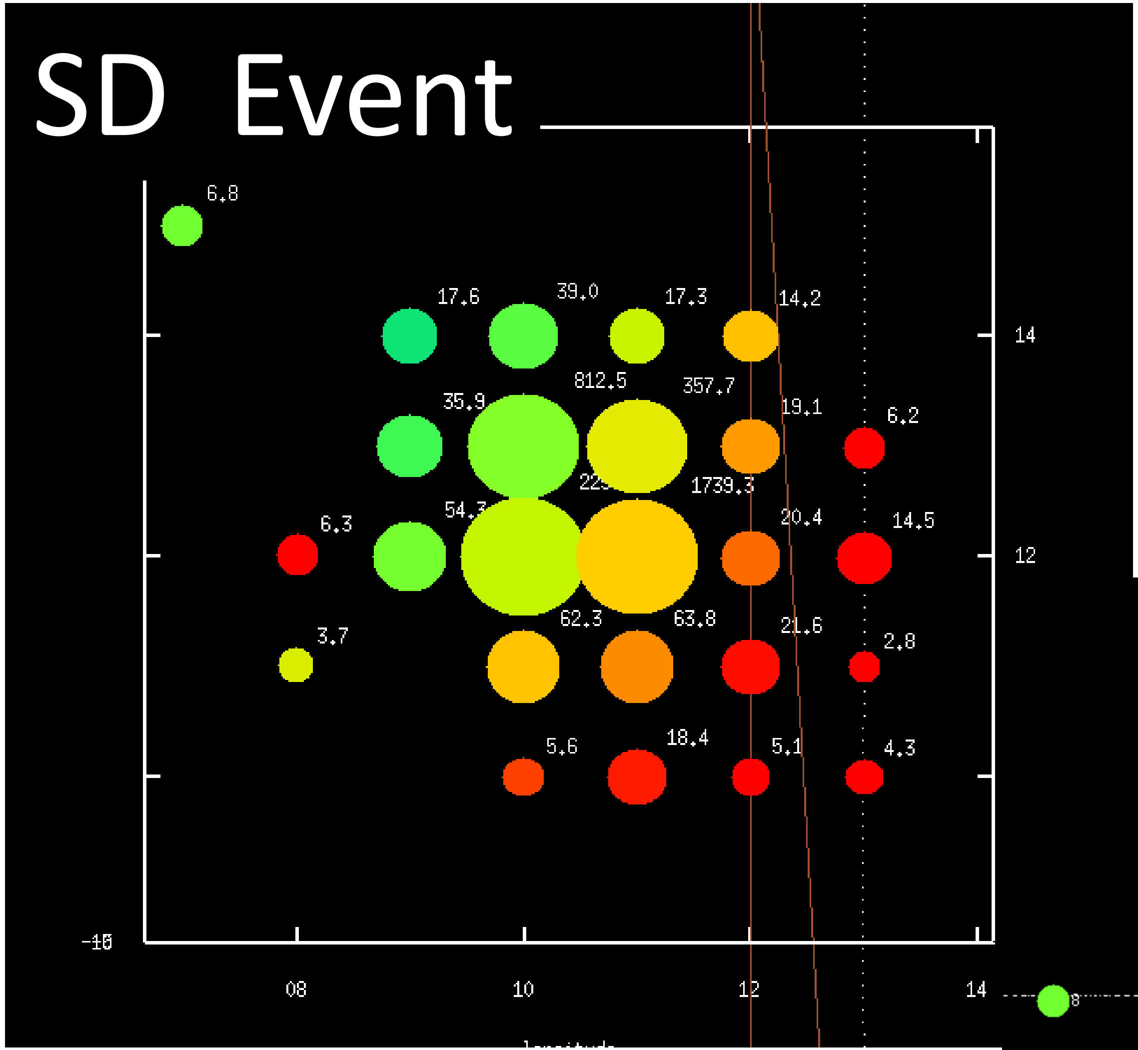


TA

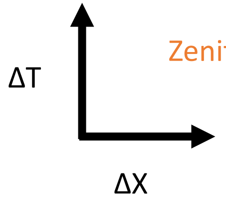
SD Event

090122-225422
TH~38^0

TA

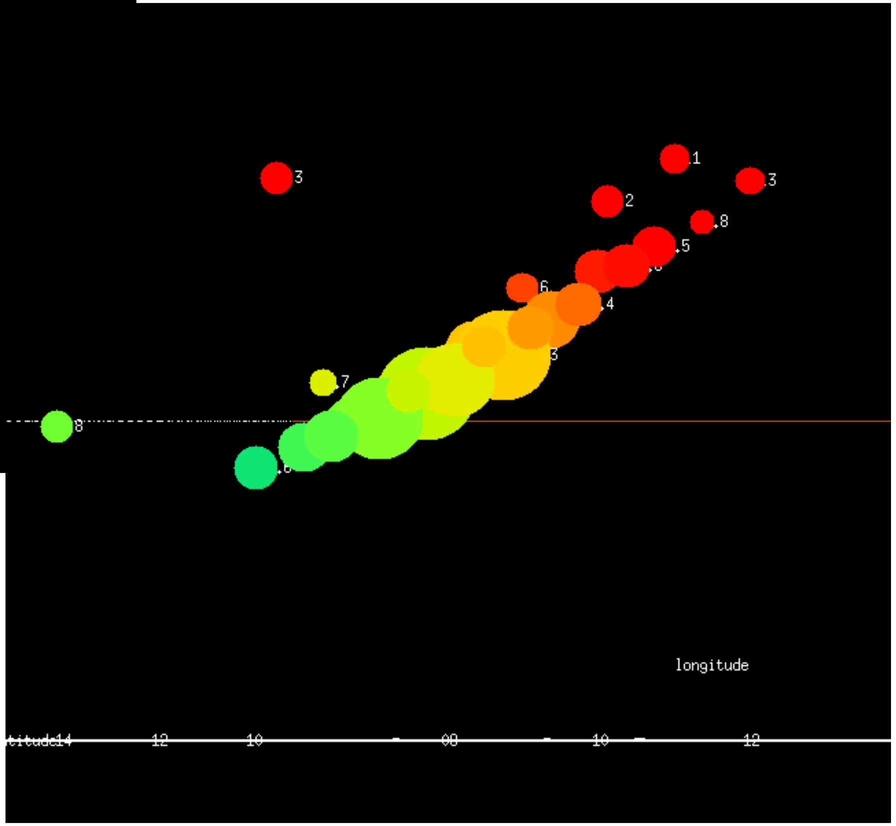


Event Top View



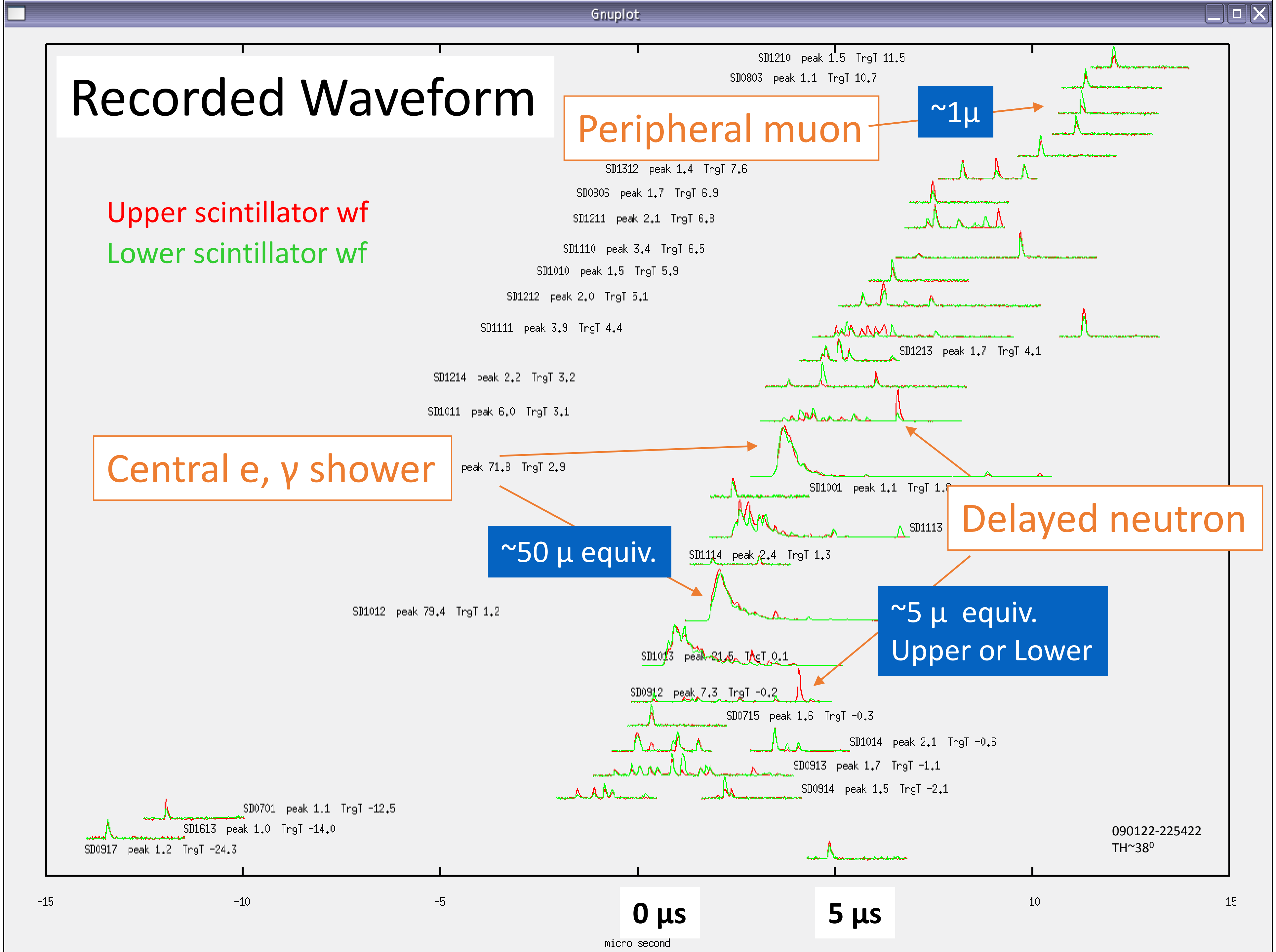
Zenith ~ arcsine (ΔT / ΔX)

Event “Side” View

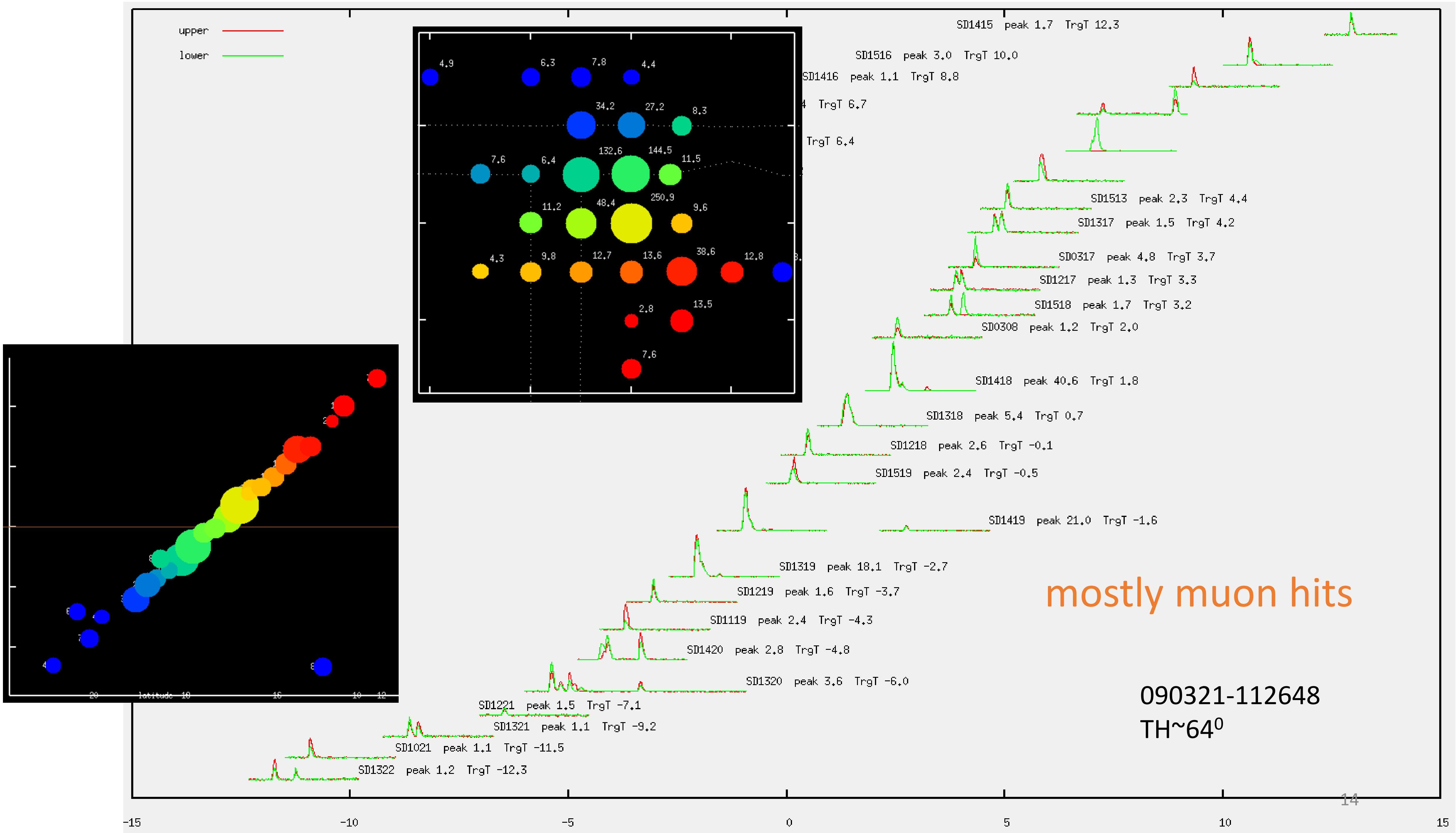


X,Y = counter #
number = MeV energy deposit (av U+D)
~ 2.5 MeV for vertical mu

TA



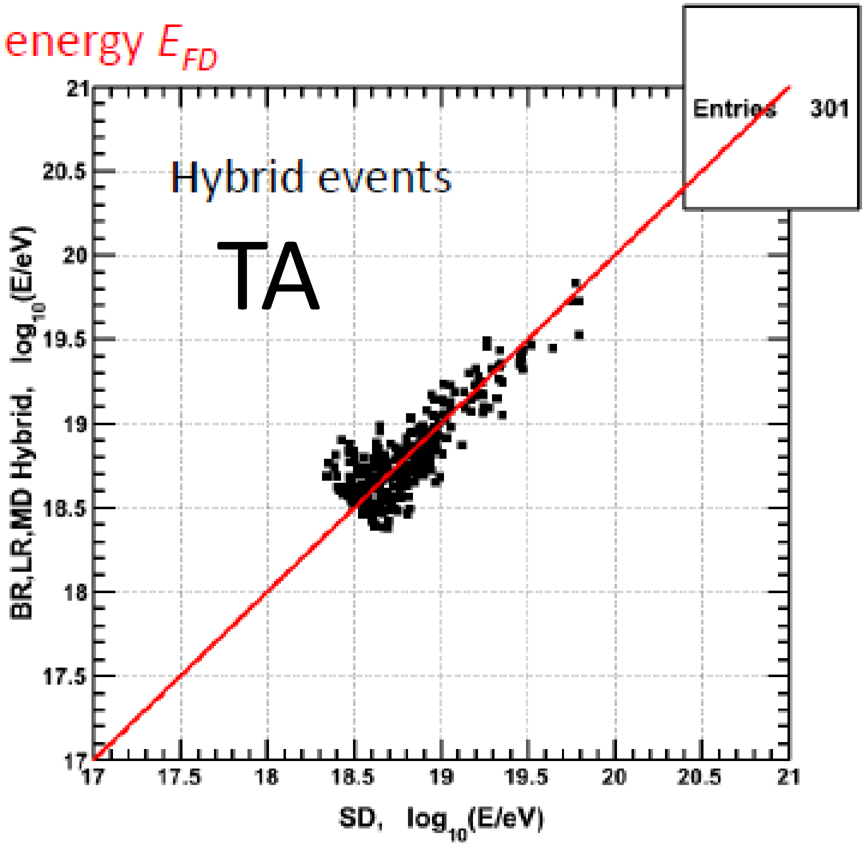
Gnuplot
Recorded Waveform
Upper scintillator wf
Lower scintillator wf
Peripheral muon
~1μ
Central e, γ shower
~50 μ equiv.
Delayed neutron
~5 μ equiv.
Upper or Lower
SD1210 peak 1.5 TrgT 11.5
SD0803 peak 1.1 TrgT 10.7
SD1312 peak 1.4 TrgT 7.6
SD0806 peak 1.7 TrgT 6.9
SD1211 peak 2.1 TrgT 6.8
SD1110 peak 3.4 TrgT 6.5
SD1010 peak 1.5 TrgT 5.9
SD1212 peak 2.0 TrgT 5.1
SD1111 peak 3.9 TrgT 4.4
SD1213 peak 1.7 TrgT 4.1
SD1214 peak 2.2 TrgT 3.2
SD1011 peak 6.0 TrgT 3.1
peak 71.8 TrgT 2.9
SD1001 peak 1.1 TrgT 1.8
SD1113
SD1114 peak 2.4 TrgT 1.3
SD1012 peak 79.4 TrgT 1.2
SD1013 peak 21.5 TrgT 0.1
SD0912 peak 7.3 TrgT -0.2
SD0715 peak 1.6 TrgT -0.3
SD1014 peak 2.1 TrgT -0.6
SD0913 peak 1.7 TrgT -1.1
SD0914 peak 1.5 TrgT -2.1
SD0701 peak 1.1 TrgT -12.5
SD1613 peak 1.0 TrgT -14.0
SD0917 peak 1.2 TrgT -24.3
090122-225422
TH~38°
-15
-10
-5
0 μs
5 μs
10
15
micro second



upper
lower
SD1415 peak 1.7 TrgT 12.3
SD1516 peak 3.0 TrgT 10.0
SD1416 peak 1.1 TrgT 8.8
TrgT 6.7
TrgT 6.4
SD1513 peak 2.3 TrgT 4.4
SD1317 peak 1.5 TrgT 4.2
SD0317 peak 4.8 TrgT 3.7
SD1217 peak 1.3 TrgT 3.3
SD1518 peak 1.7 TrgT 3.2
SD0308 peak 1.2 TrgT 2.0
SD1418 peak 40.6 TrgT 1.8
SD1318 peak 5.4 TrgT 0.7
SD1218 peak 2.6 TrgT -0.1
SD1519 peak 2.4 TrgT -0.5
SD1419 peak 21.0 TrgT -1.6
SD1319 peak 18.1 TrgT -2.7
SD1219 peak 1.6 TrgT -3.7
SD1119 peak 2.4 TrgT -4.3
SD1420 peak 2.8 TrgT -4.8
SD1320 peak 3.6 TrgT -6.0
SD1221 peak 1.5 TrgT -7.1
SD1321 peak 1.1 TrgT -9.2
SD1021 peak 1.1 TrgT -11.5
SD1322 peak 1.2 TrgT -12.3
4.9
6.3
7.8
4.4
34.2
27.2
8.3
7.6
6.4
132.6
144.5
11.5
11.2
48.4
250.9
9.6
4.3
9.8
12.7
13.6
38.6
12.8
2.8
13.5
7.6
latitude
mostly muon hits
090321-112648
TH~64^0
-15
-10
-5
0
5
10
15

Energy Calibration E'_{SD} (S_{38} for Auger) vs E_{FD} using hybrid events

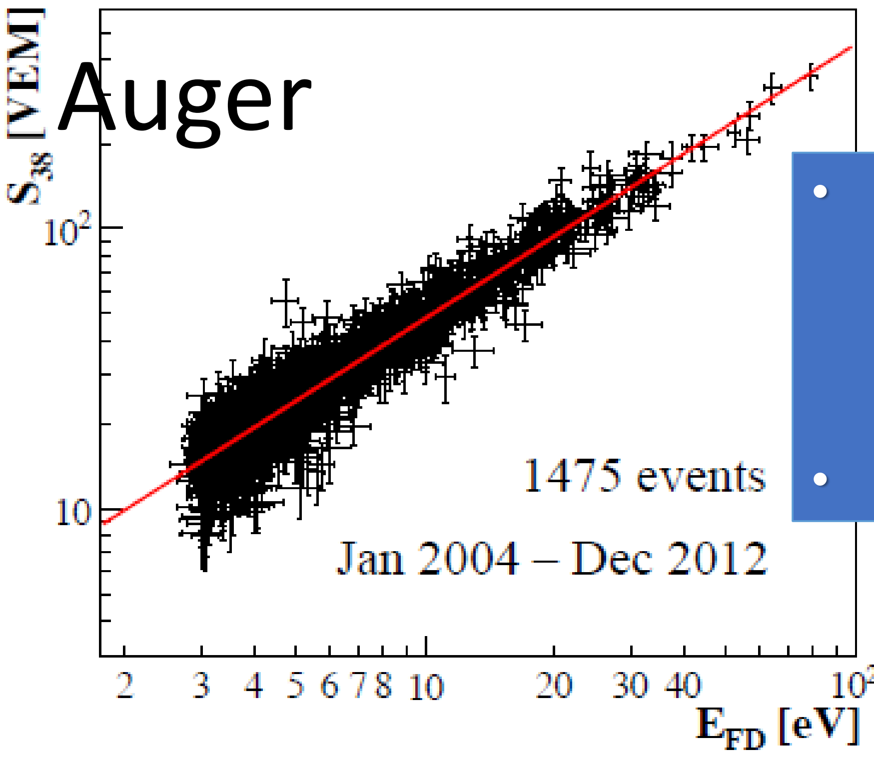
FD energy E_{FD}



SD energy E_{SD}

$$E_{SD} = E'_{SD}/1.27$$

- S-800 = # of particles at D=800m
- S-800(E'_{SD} , th) map is obtained by air shower simulation.



$$E_{SD} = A\,S_{38}^{B} \qquad A = 0.190 \times 10^{18}\ \mathrm{eV} \qquad B = 1.025$$

- S_{38} = # of VEMs at $\theta=38^0$ and D=1000m
- Zenith attenuation of VEMs obtained from Constant Intensity Cut (CIC)

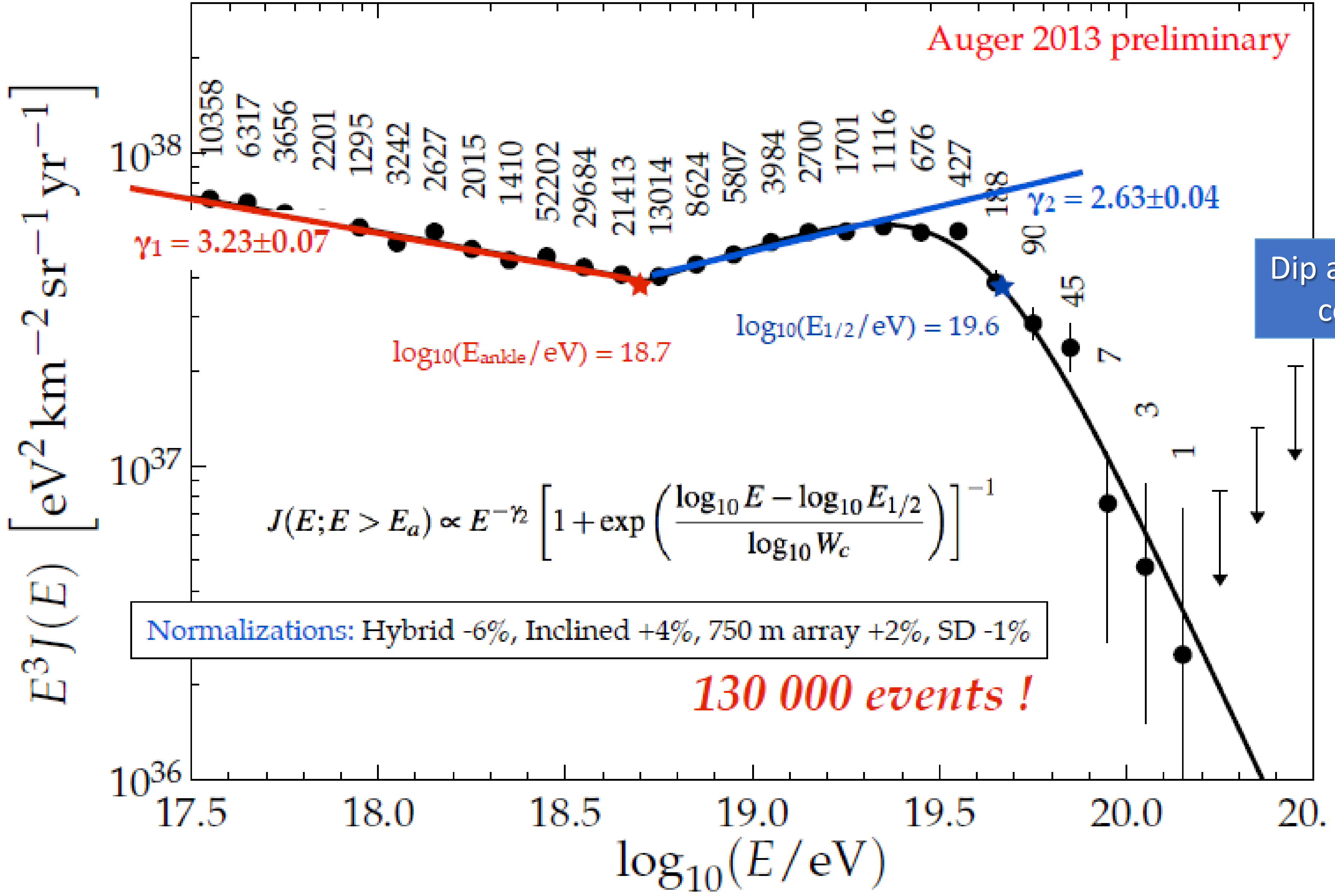
- Good correlation (~linear) with particle density at 1000m (Auger) , 800m (TA) from core for $10^{18.5} < E < 10^{19.8}$ eV.
- Limited statistics for $E > 10^{19.5}$ eV

- Auger E-scale updated (ICRC2013) using (nearly) reference model.
- TA E-scale unchanged:
  - Spectrum: FLASH
  - Yield: Kakimoto et al. extended
  - same as HiRes

V. Verzi, ICRC2013

THE AUGER ENERGY SPECTRUM

Updated at ICRC2013
with New Energy analysis

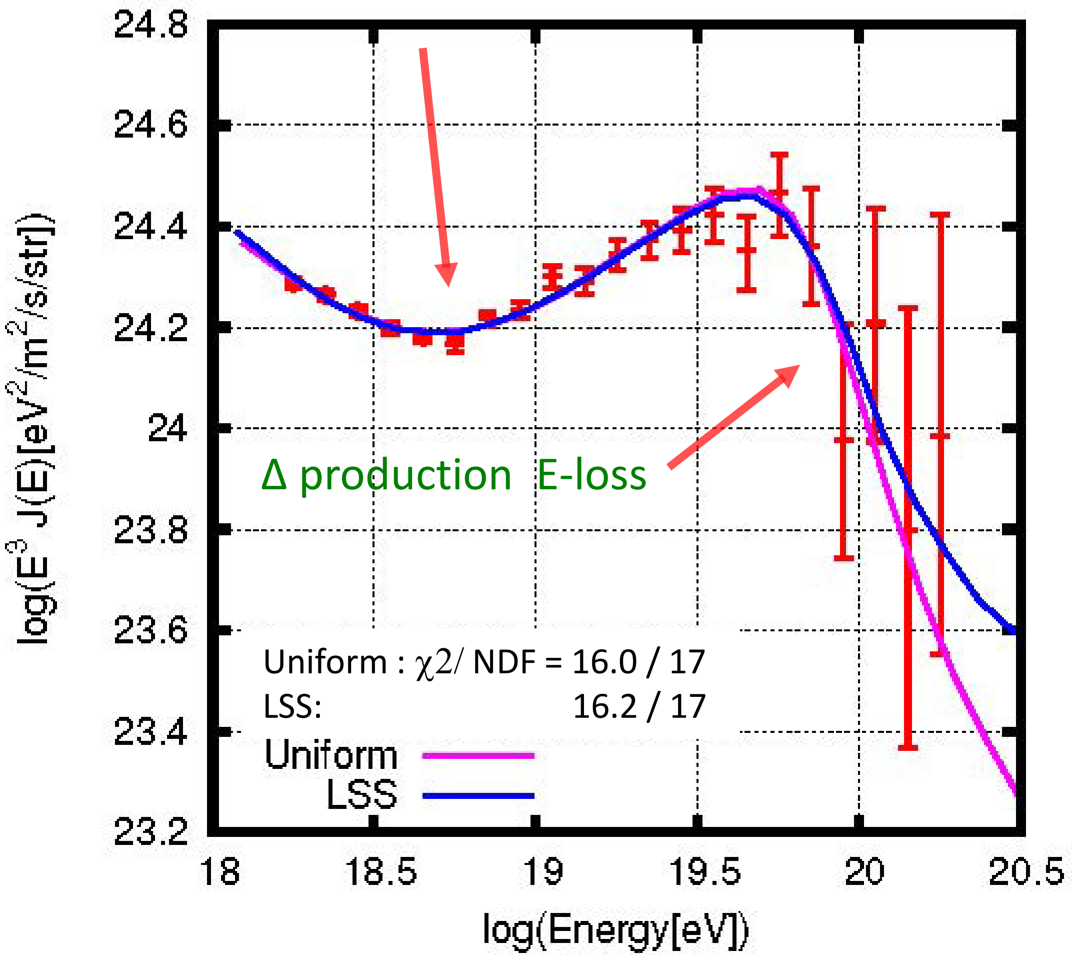


Energy Increased by
16% at $10^{18.0}$ eV and
10% at 10^{19} eV
(mainly not by new AFY)

Dip and "Cutoff" confirmed.

Y. Lettessier-Selvon, ICRC 2013

TA Energy spectrum and Astrophysical Scenario



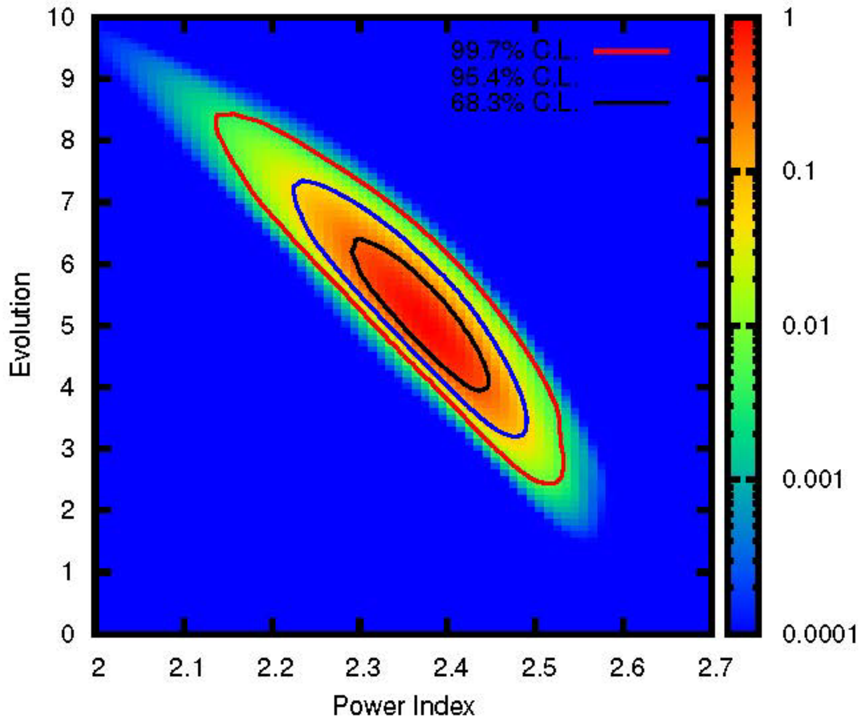
Fit with extra-galactic proton

Source Distribution
- Uniform
- LSS (~2MASS XSCz)

Energy Loss with
- CMB
- Infra-Red

using CRPropa 2.0 simulation
checked with analytic ΔE.
No magnetic field.

4-parameter fit
- Injection spectrum : E^{-p}
  $E_{max} = 10^{21}$ eV
- Evolution : $(1+z)^m$
- Flux normalization
- Energy scale

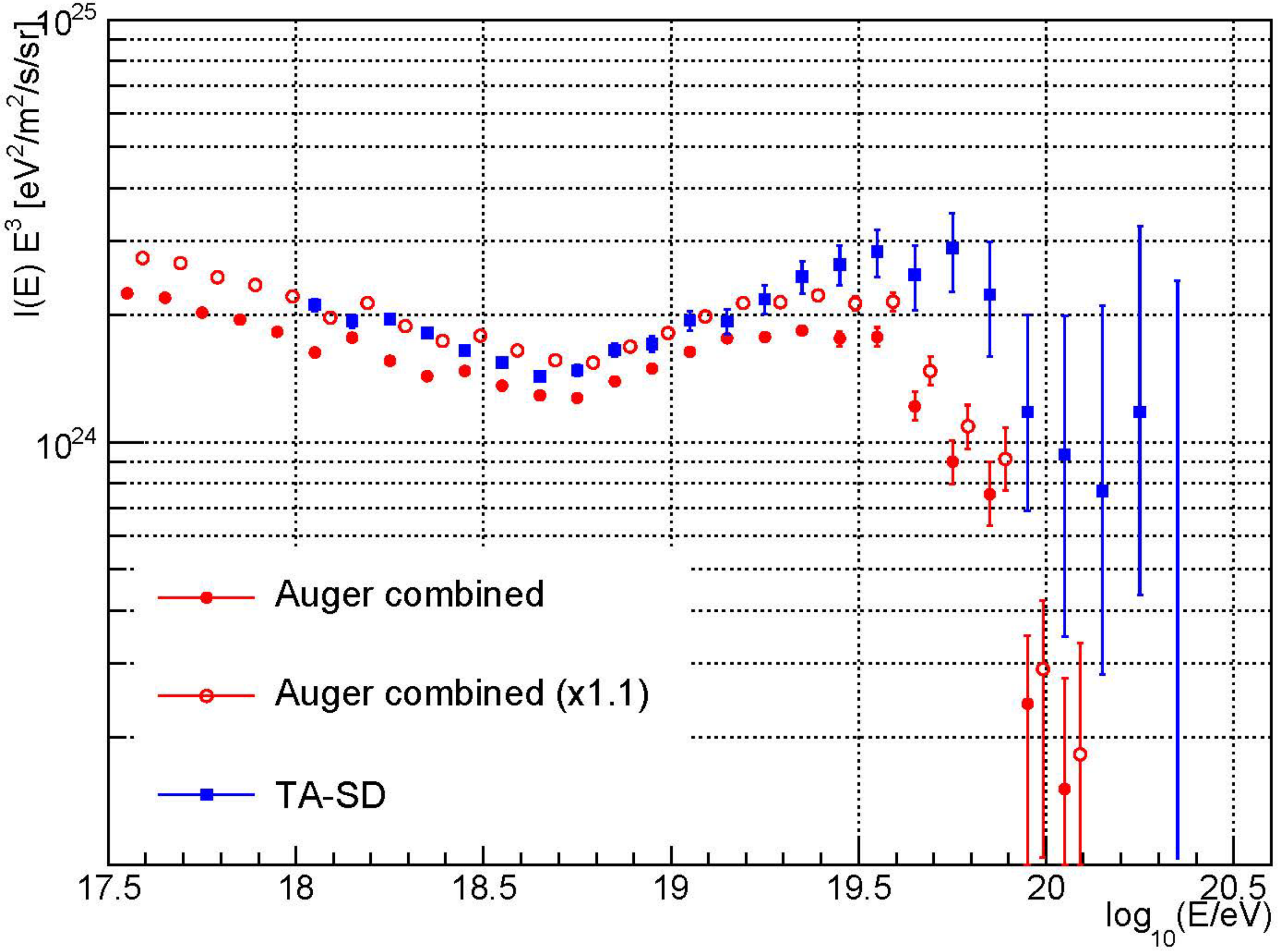


For LSS
P = 2.37 +0.08 –0.08
m = 5.2 +1.2 -1.3
Log E'/E = - 0.02 +0.04 –0.05

preliminary

E. Kido
ICRC 2013

Spectrum at UHE : Auger and TA

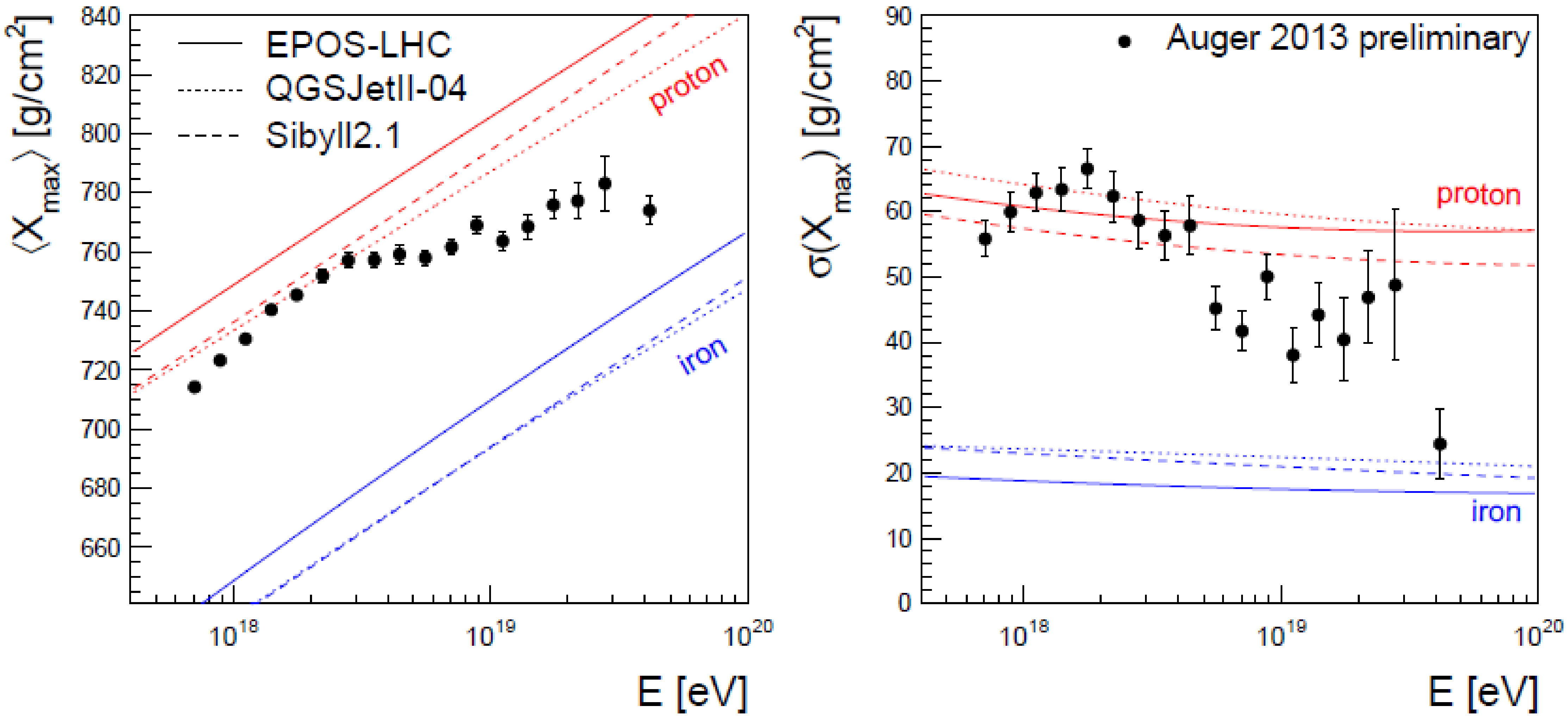


Flux suppression (E>$10^{19.7}$ eV) may be caused by the CR acceleration limit (Auger)

D. Bergman
ICRC 2013

From Y. Tsunesada
ICRC 2013
Rapporteur Talk

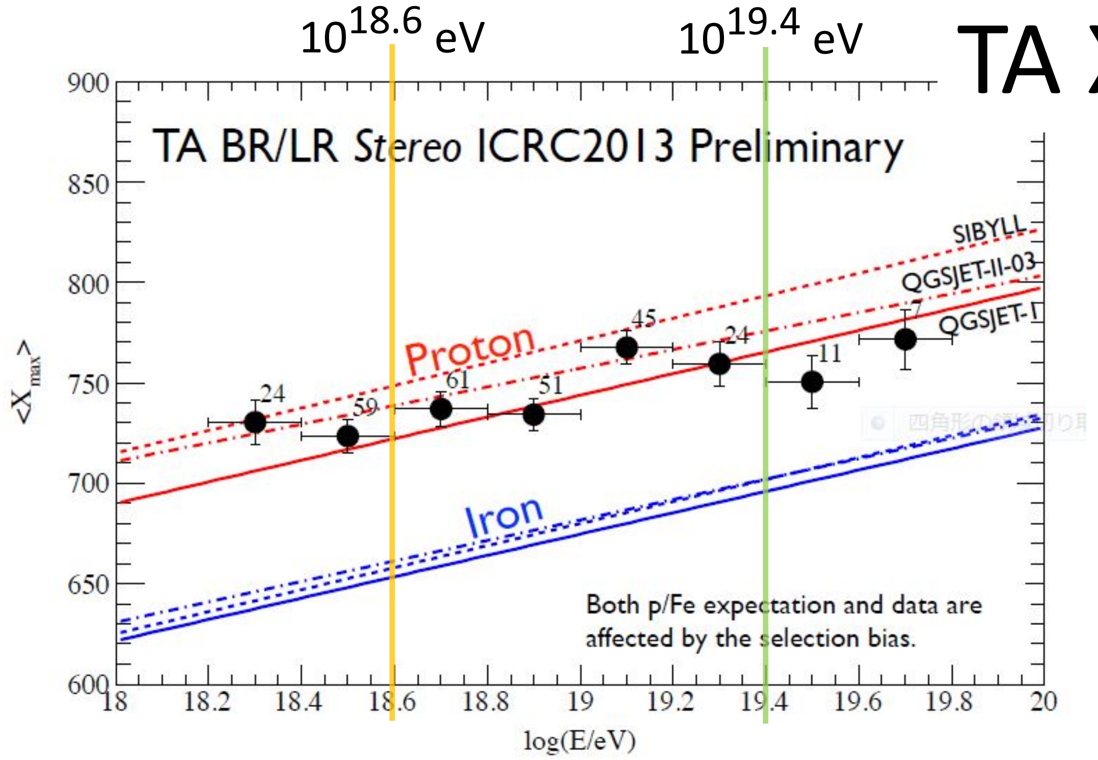
Auger Xmax



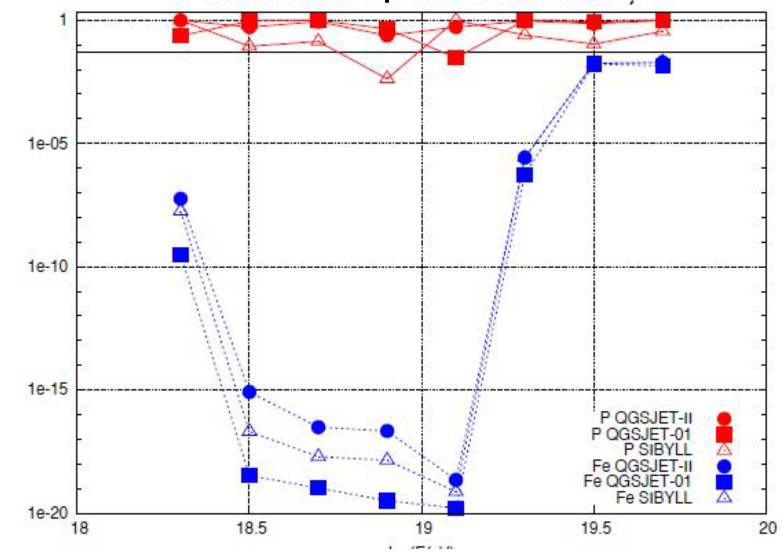
<Xmax> and Xmax fluctuation
indicate a shift from proton to heavier nuclei.

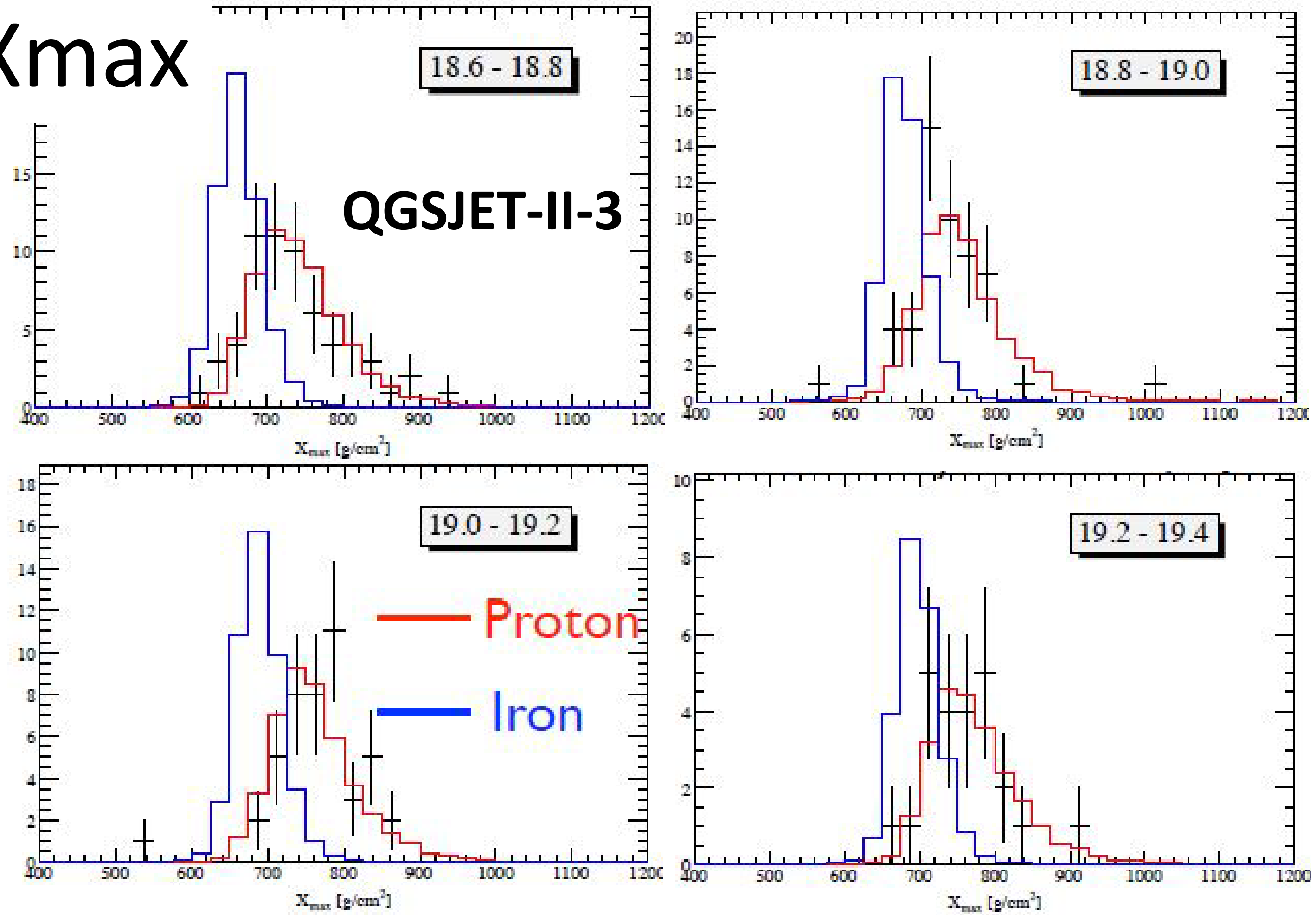
E.J. Ahn, M. Unger
ICRC 2013

TA Xmax



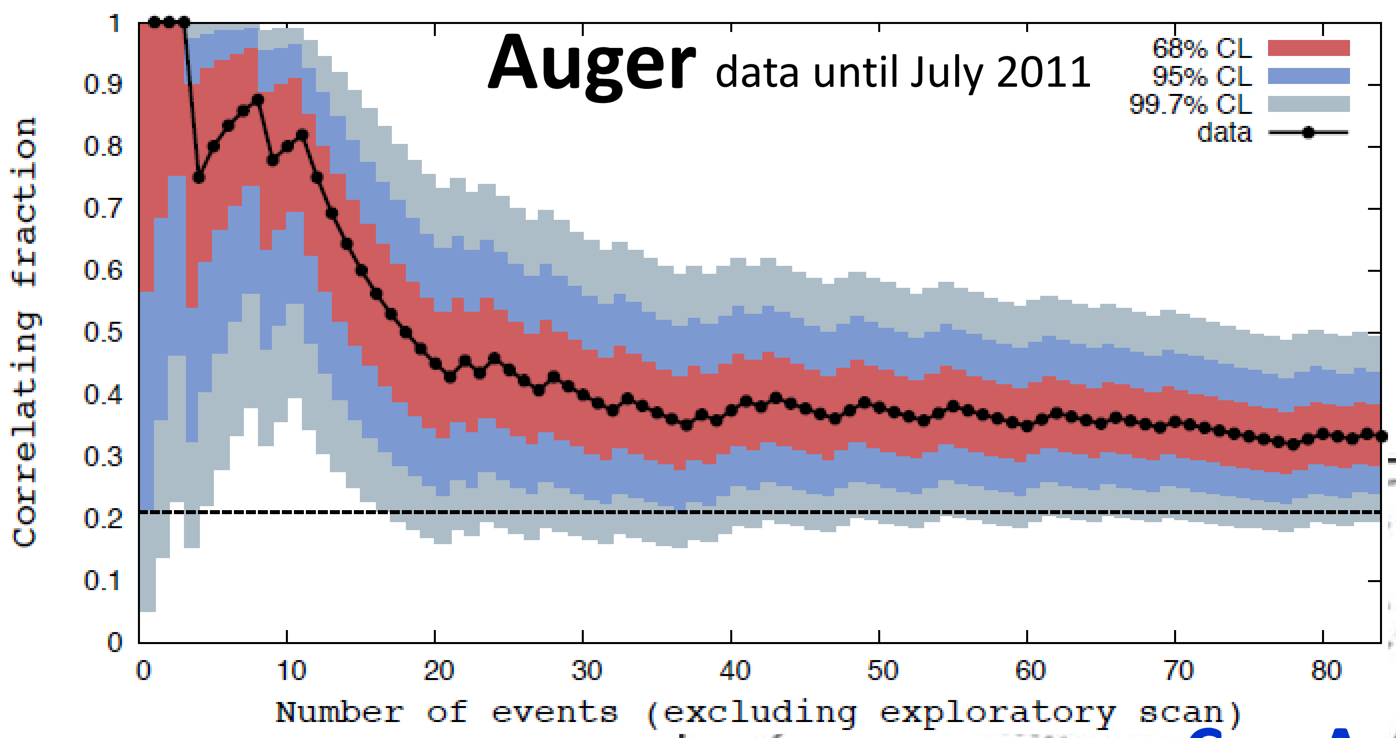
K-S test: proton vs Fe



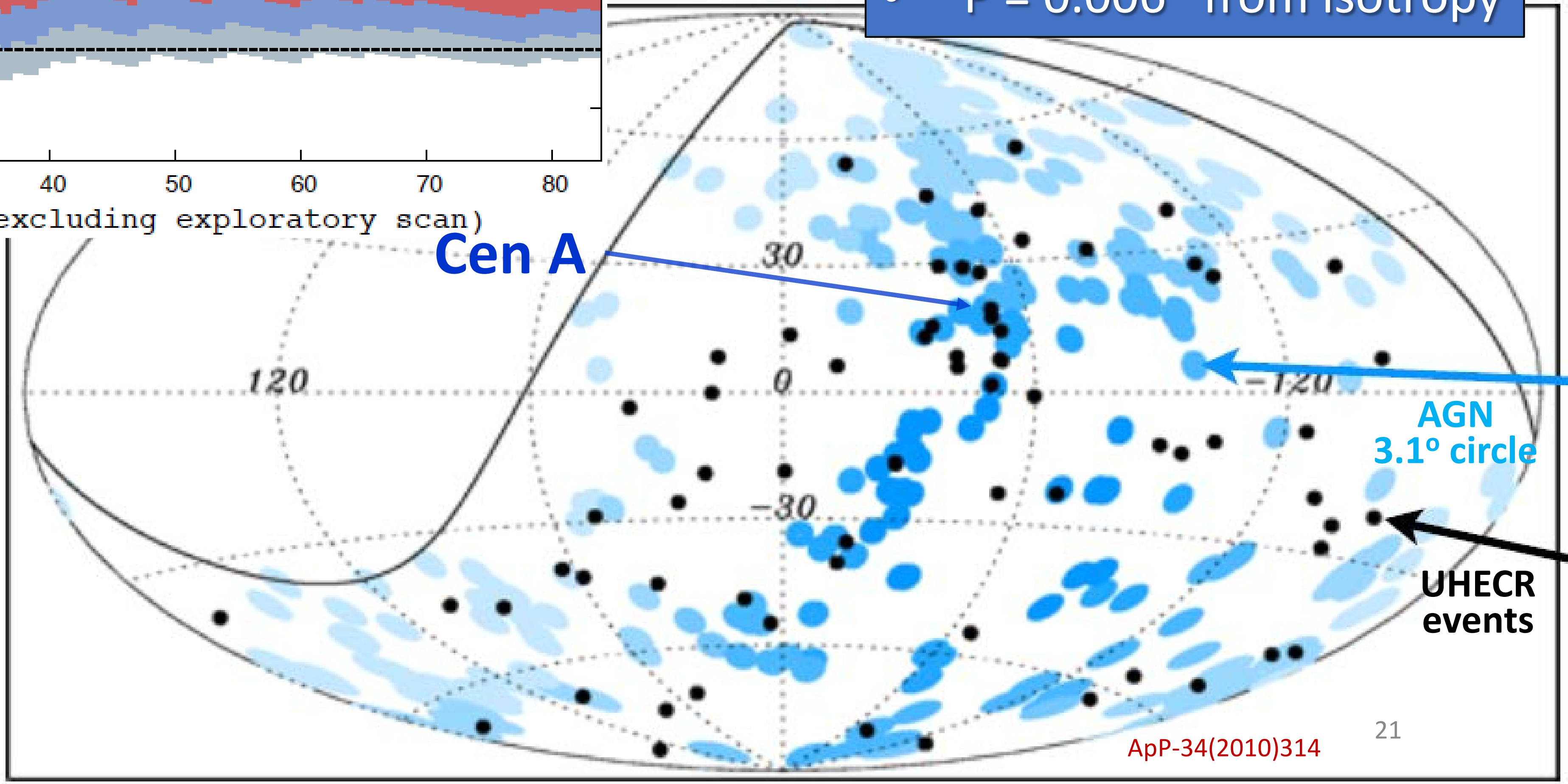


<Xmax> and Xmax distribution
is consistent with proton by stereo and hybrid analyses.

Correlation with AGN in VCV Catalogue within 75Mpc



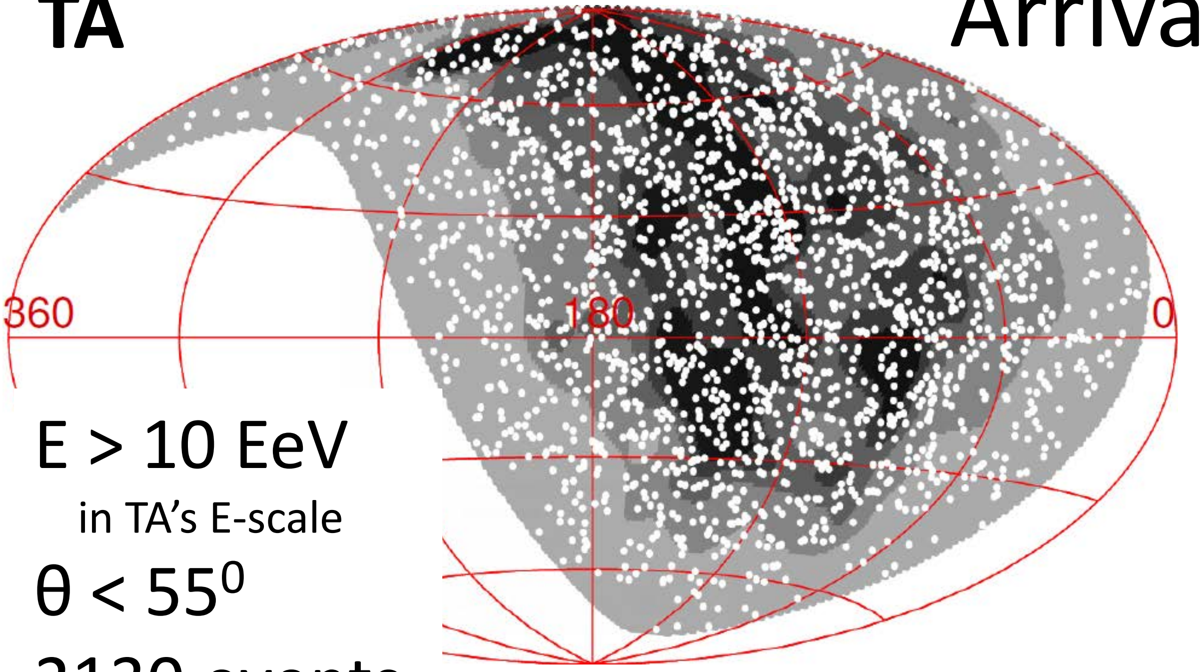
- E > 55 EeV in 2011 E-scale
- 28/84(tot) correlated
- P = 0.006 from isotropy



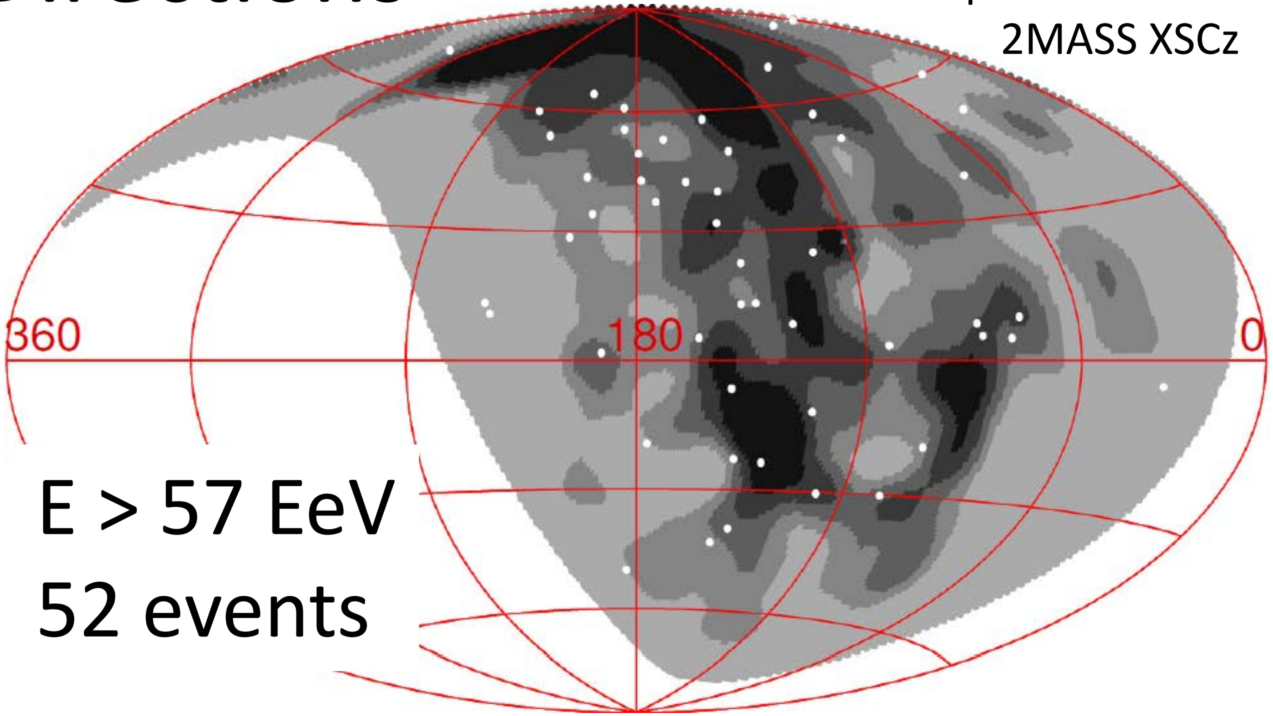
Arrival Directions

TA

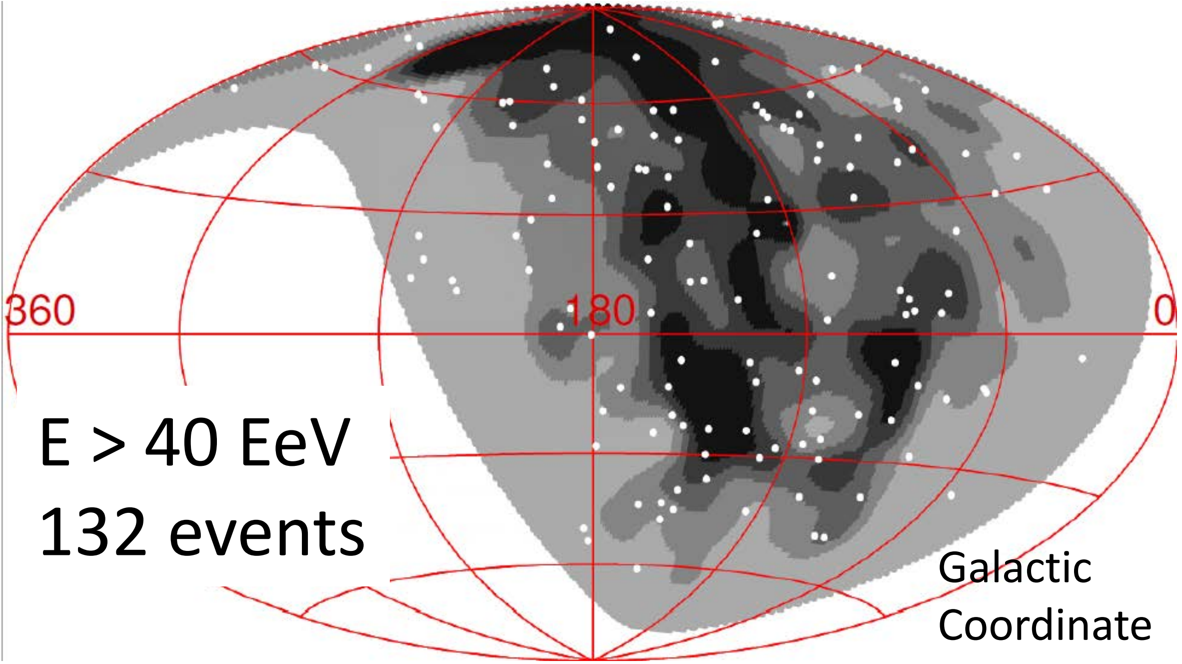
Shades: expectation from 2MASS XSCz



E > 10 EeV
in TA's E-scale
$\theta < 55^0$
2130 events



E > 57 EeV
52 events



E > 40 EeV
132 events

Galactic Coordinate

Compatibility with Large Scale Structure of galaxies (shade): P ~ 0.1

Compatibility with Isotropy: p ~ 0.001

TA preliminary

A large flux enhancement in hotspot

Looser cuts:

- No 1.2 km boarder cut
- $\theta < 55^0$
- E > 57 EeV

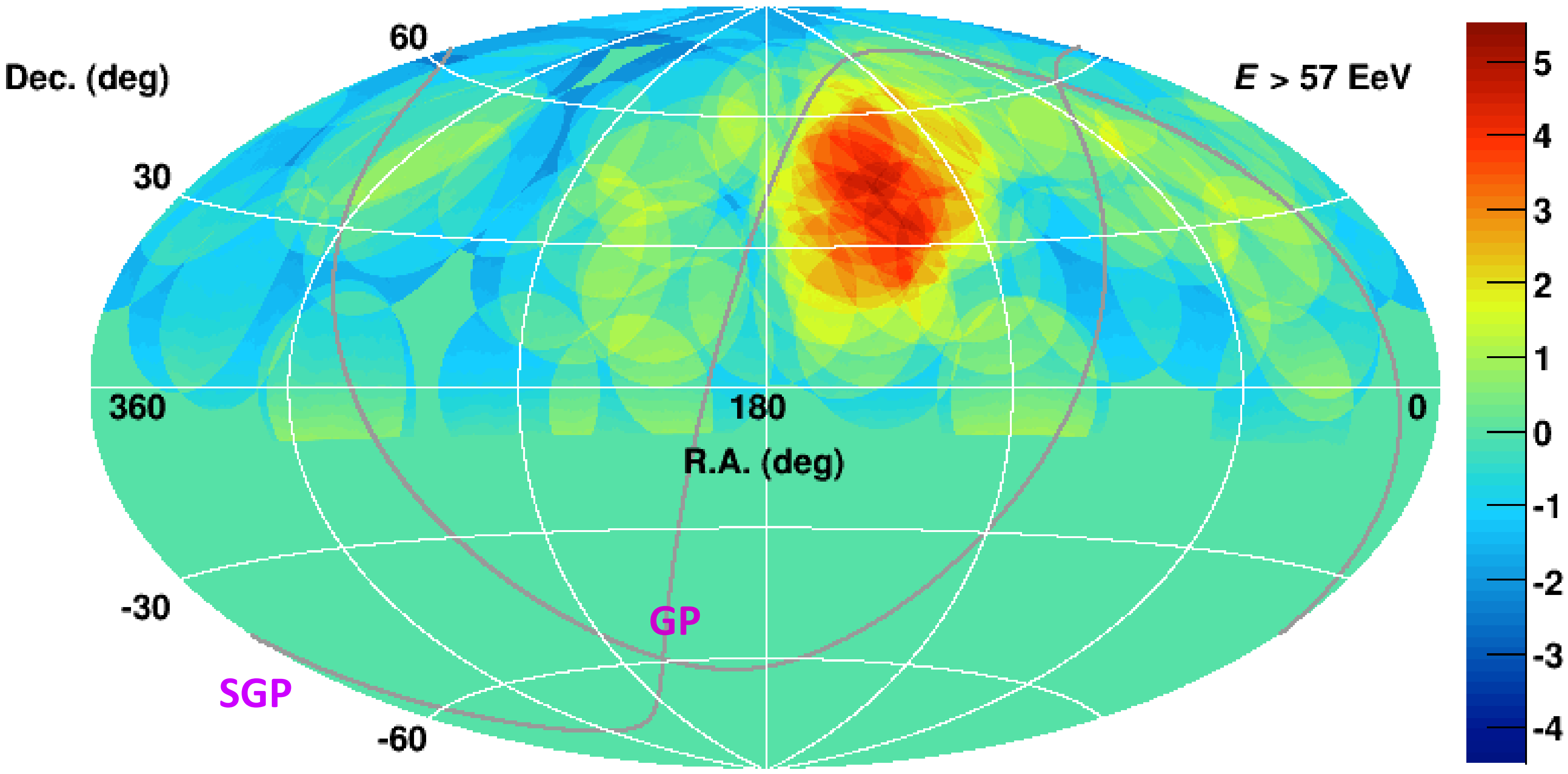
2008 May – 2013 May:
A Total of 72 events selected.

Overlaying with r = 20^0 circle

Background from 72 random isotropic events estimated by MC

Significance of hot spot is 5.1 σ (4.49 ev. expected, 19 ev. seen)

1.4×10^{-4} (3.6 σ) probability to see 5.1 σ enhancement anywhere in TA's aperture.



Auger and TA collaborate in data analysis for

- ◆ All sky (North+South) coverage, common anisotropy/source analysis
- ◆ Understand differences in composition and E-scale
  by exchanging calibration, analysis, simulation, tank/scint.

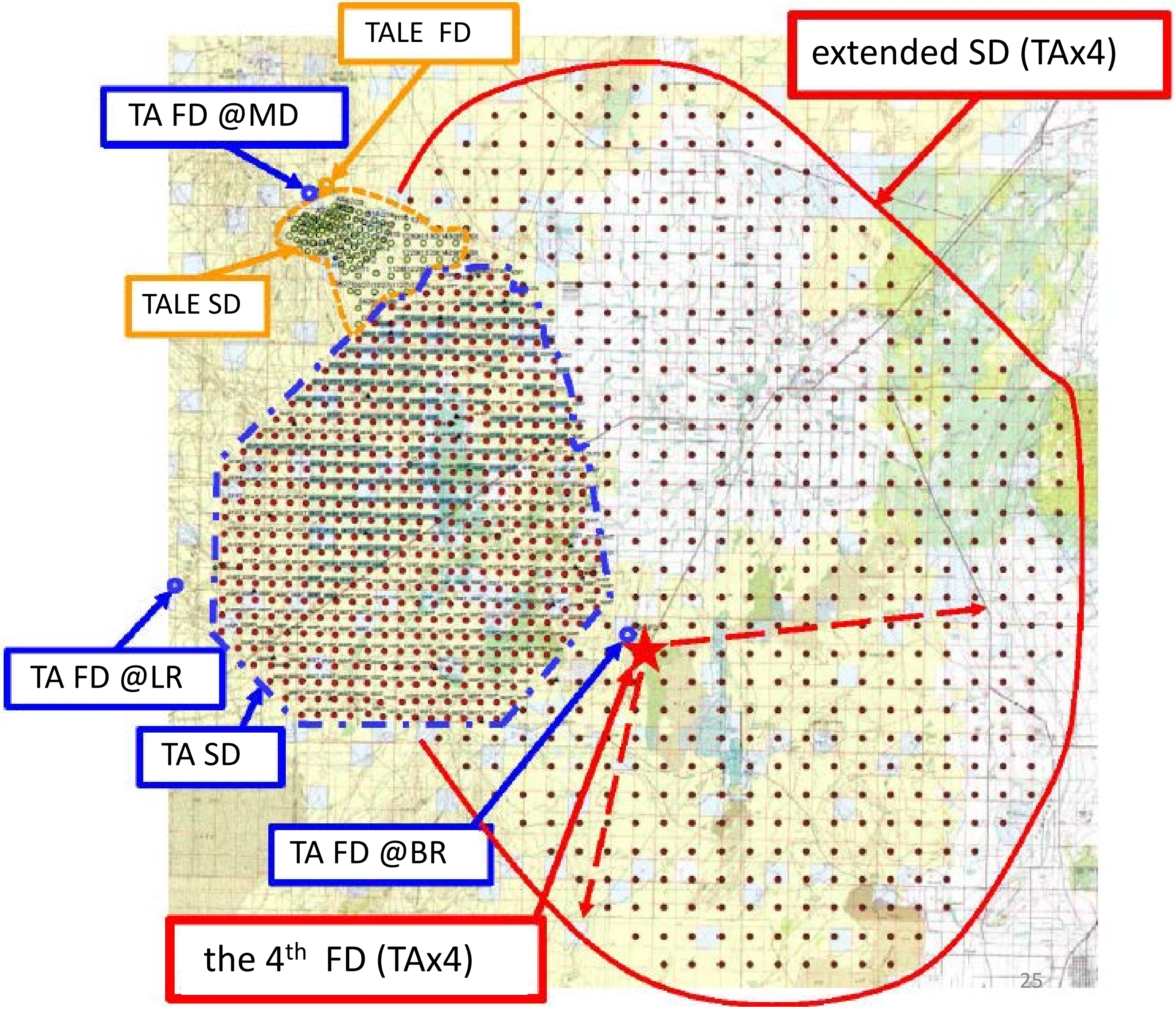
Both continue UHECR observation with

- ◆ TA extension for x 4 acceptance (+500 SDs and +1 FD)
- ◆ Auger extension for improved muon tag.

~ 3,000 km^2 coverage in North and South

TAx4:
Near Future Operations of TA

- Construction expected in 2014-2015.
- Anisotropy and Hotspot : ~5σ confirmation by 2019.



Summary: Present Status

Clear end-point structure in energy spectrum.
Is it by UHECR - CMB interaction (GZK)?

Composition: is it proton, or changing to heavier nuclei?
Ambiguities in data and shower MC.
Information on UHE hadronic and nuclear interactions.

Indication of AGN correlation at 2-3 σ.
Large flux enhancement in hot spot (3.6σ) to be confirmed.

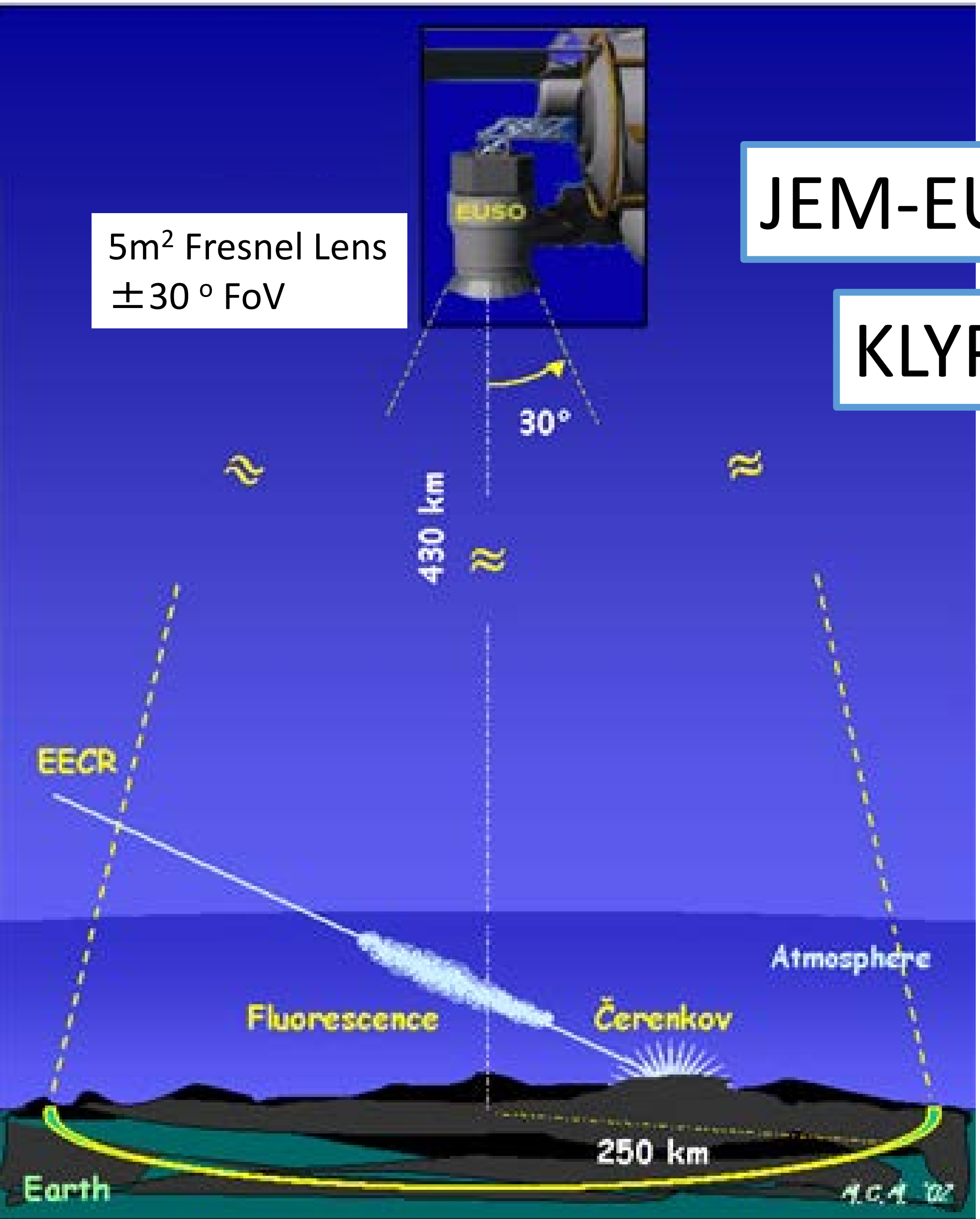
Next Generation Detector
to collect 1-10k events ($E>10^{19.7}$ eV)
for identifying individual source "star".

~100,000 km^2 coverage.

1. Radio detection (MHz, GHz, Radar,…)

2. Telescope in space: TUS/KLYPVE and JEM-EUSO

3. super-Ground-Array (with PID and tracking)

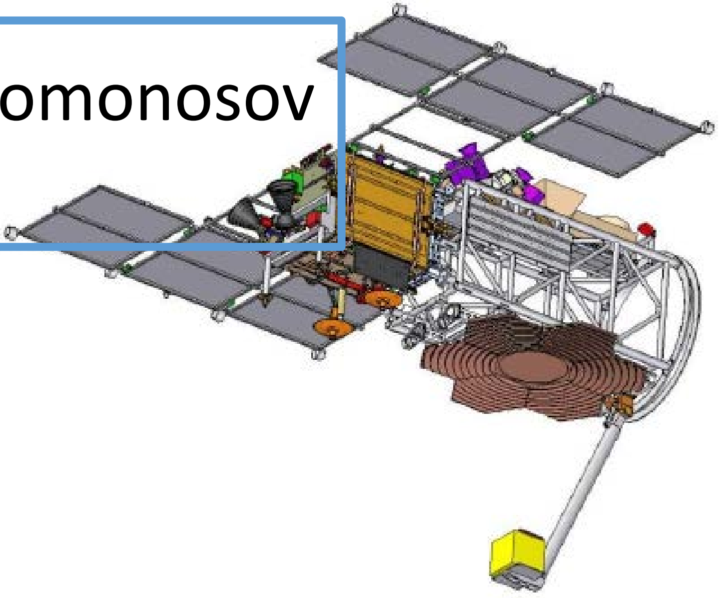


5m² Fresnel Lens
±30 ° FoV

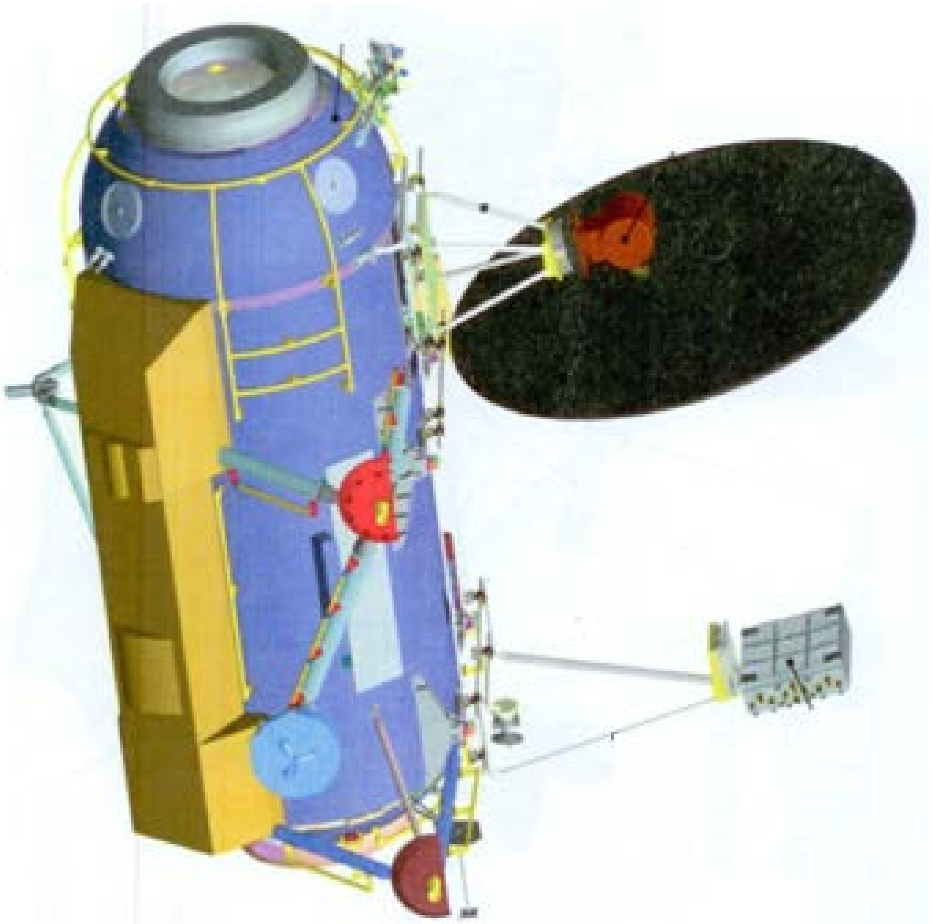
JEM-EUSO

KLYPVE @ ISS

TUS @ Lomonosov satellite



2m² Mirror
±2.5° FoV



10m² Fresnel Mirror
±7.5° FoV

super Ground Array   in brain storming discussion

- **Key for SD: Good PID, esp. for muon.**
    1. Nuclear Z-tagging by muon ratio
    2. UHE gamma is mu-less “vertical” shower
    3. UHE neutrino is EM “horizontal” shower
    4. (Lightning causes gamma ray shower)
- **Key for FD: good optics, esp. for flat-fielding.**
- **RD (radio detector) hybrid?**
- **Operable in the field with no life lines.**
- **Remote and distributed DAQ**
- **Affordable (economy and ecology).**
- **Frontier Detector Technology of HEP may be applied!**

Backup

Plastic Scintillator

3 m^2, 12 mm t

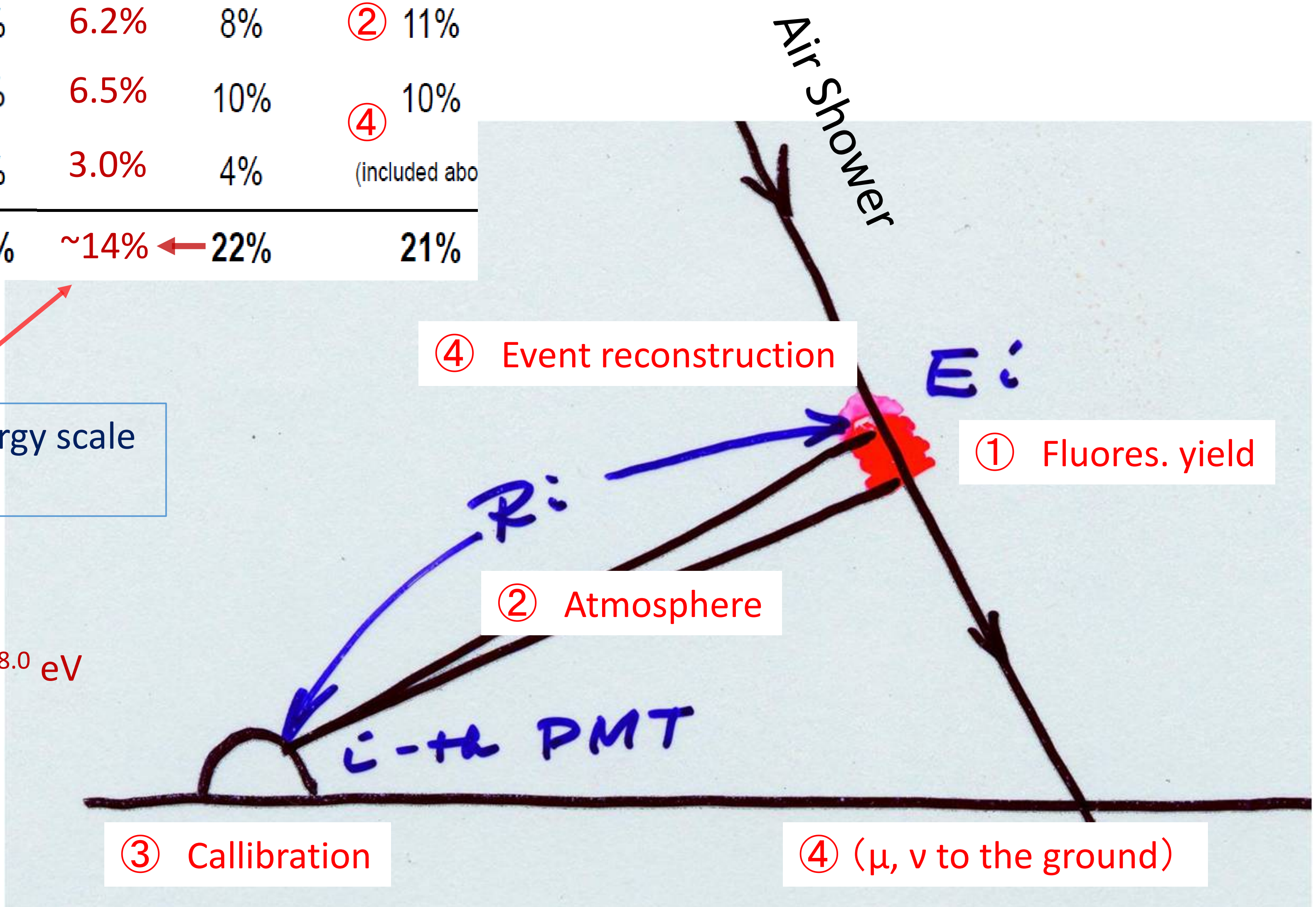
WLSF readout, 2 layers overlaid

FD Energy Scale

	HiRes		Auger	TA
Calibration	10%	9.9%	9.5%	③ 10%
Fluorescence yield	6%	3.6%	14%	① 11%
Atmosphere	5%	6.2%	8%	② 11%
Reconstruction	10%	6.5%	10%	④ 10%
Invisible energy	5%	3.0%	4%	(included abo
Total Systematic Uncertainty	17%	~14% ←	22%	21%

Auger updated energy scale in ICRC 2013

Energy Increased by 16% at $10^{18.0}$ eV and 10% at 10^{19} eV

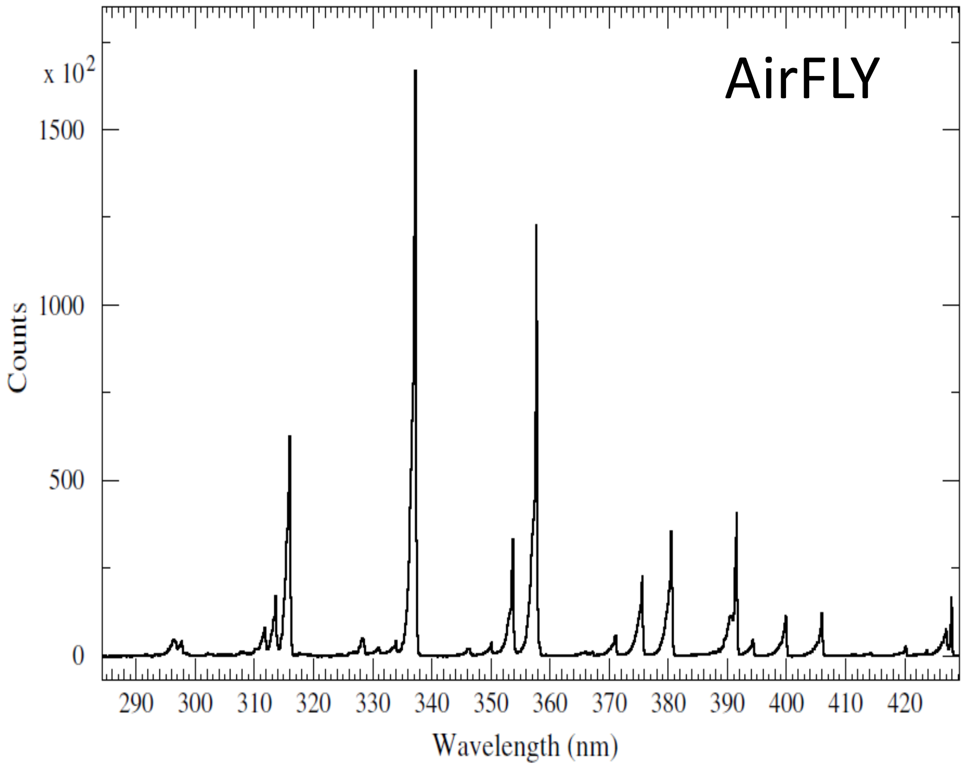


V. Verzi, ICRC2013

A. Lettessier-Selvon ICRC2013

Air Fluorescence : Reference model established

Reference Model proposed by B. Keilhauer & experimental groups at UHECR2012 @CERN.



- Spectrum at 1013 hPa and 293 K: AirFLY
- Extinction, T and humidity dep. : AirFLY, N.Sakaki et al.
- Normalization (AF Yield at 337nm) : open

Yield_λ（P, T, humidity)

$$Y_{\lambda}^{NEW\,2012}(T,P,RH)(\mathrm{ph/MeV}) = Y_{337nm}(T_r,P_r)\cdot I_{\lambda}(T_r,P_r)\cdot \frac{1+\dfrac{P_r}{P'^{\nu'}_{air}(T_0)}\left(\dfrac{T_0}{T_r}\right)^{1/2-\alpha}}{1+\dfrac{P}{P'^{\nu'}_{air}(T_0,RH)}\left(\dfrac{T_0}{T}\right)^{1/2-\alpha}}$$

$T_r = T_0 = 293K$
$P_r = 800hPa$

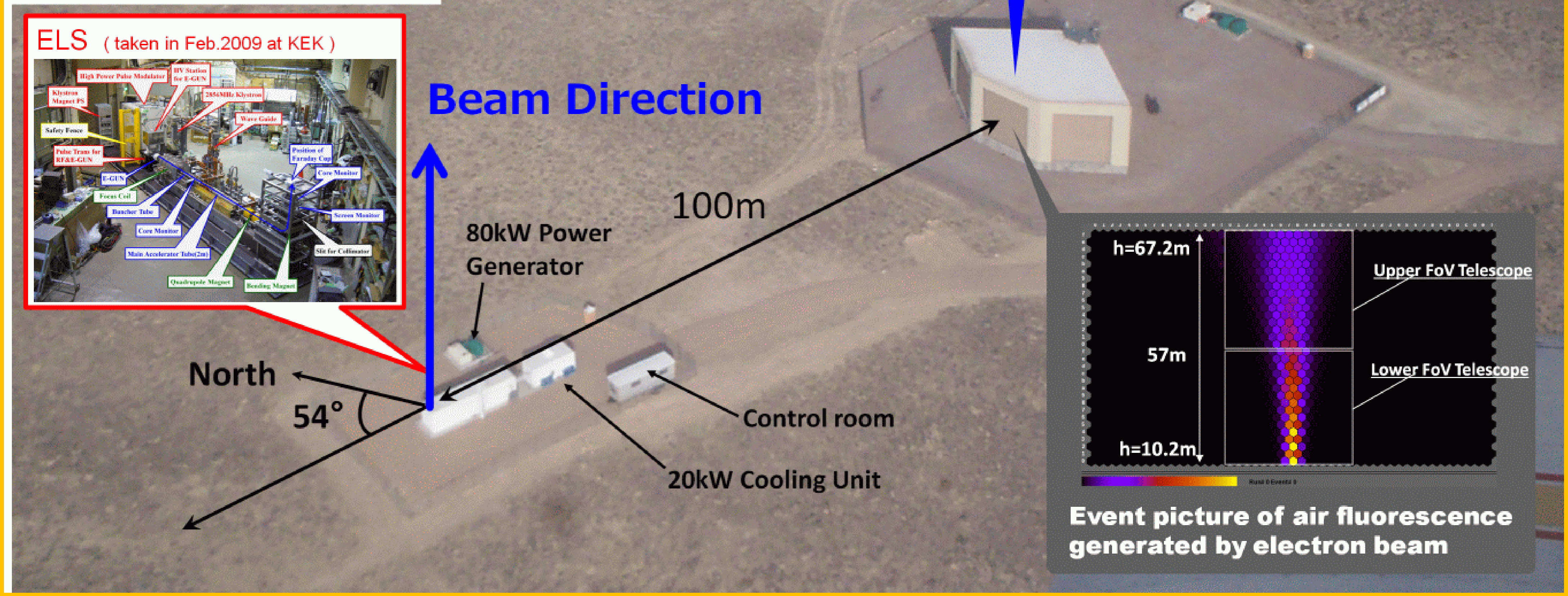
B. Keilhauer et al., UHECR 2012 arXiv:1210.1319

M. Ave et al. AirFLY collaboration ApP 28(2007)41

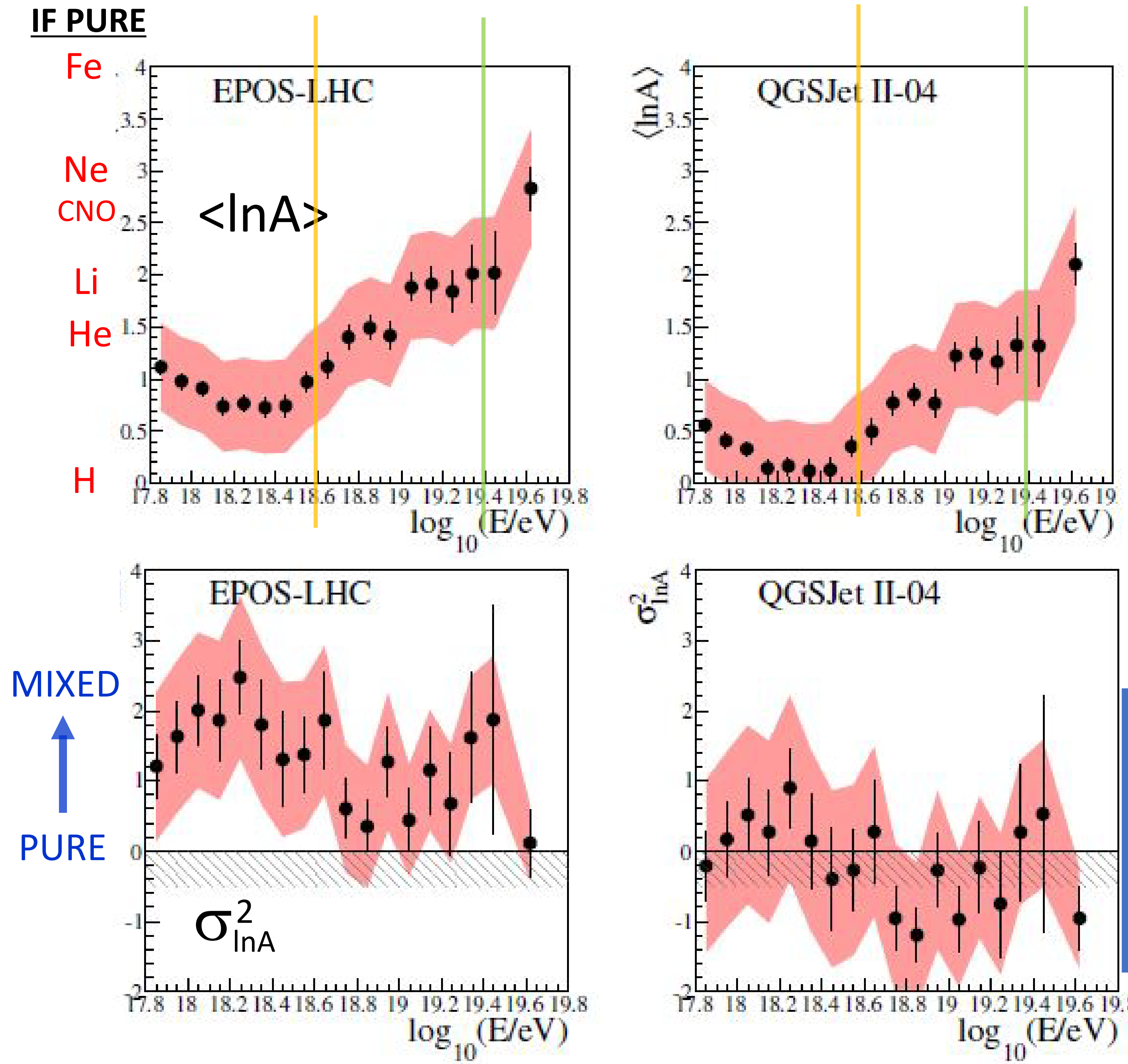
ELS in TA-BRM Site

<Specification of ELS >

- Beam Energy 40MeV (Max)
- Beam Intensity $10^9 e^-$/pulse
- Pulse width 1 μsec
- Repetition 0.1-1 Hz



Auger LnA Study



<Xmax>, σ(Xmax) → <lnA>, $\sigma_{\ln A}$

Using
$$\langle X_{\max}\rangle \approx \langle X^p_{\max}\rangle - D_p \langle \ln A\rangle$$
$$\sigma(X_{\max})^2 \approx \langle \sigma_i^2\rangle + D_p^2\, \sigma(\ln A)^2$$

DP : elongation rate
σj^2 : mass averaged shower fluctuation

- $\langle \ln A\rangle$ decreases until $\sim 10^{18.3}$ eV
- increase of $\langle \ln A\rangle$ at higher energies.
- small $\sigma^2_{\ln A} \lesssim 1$ at high energies

Bottom Line of Auger Xmax study:

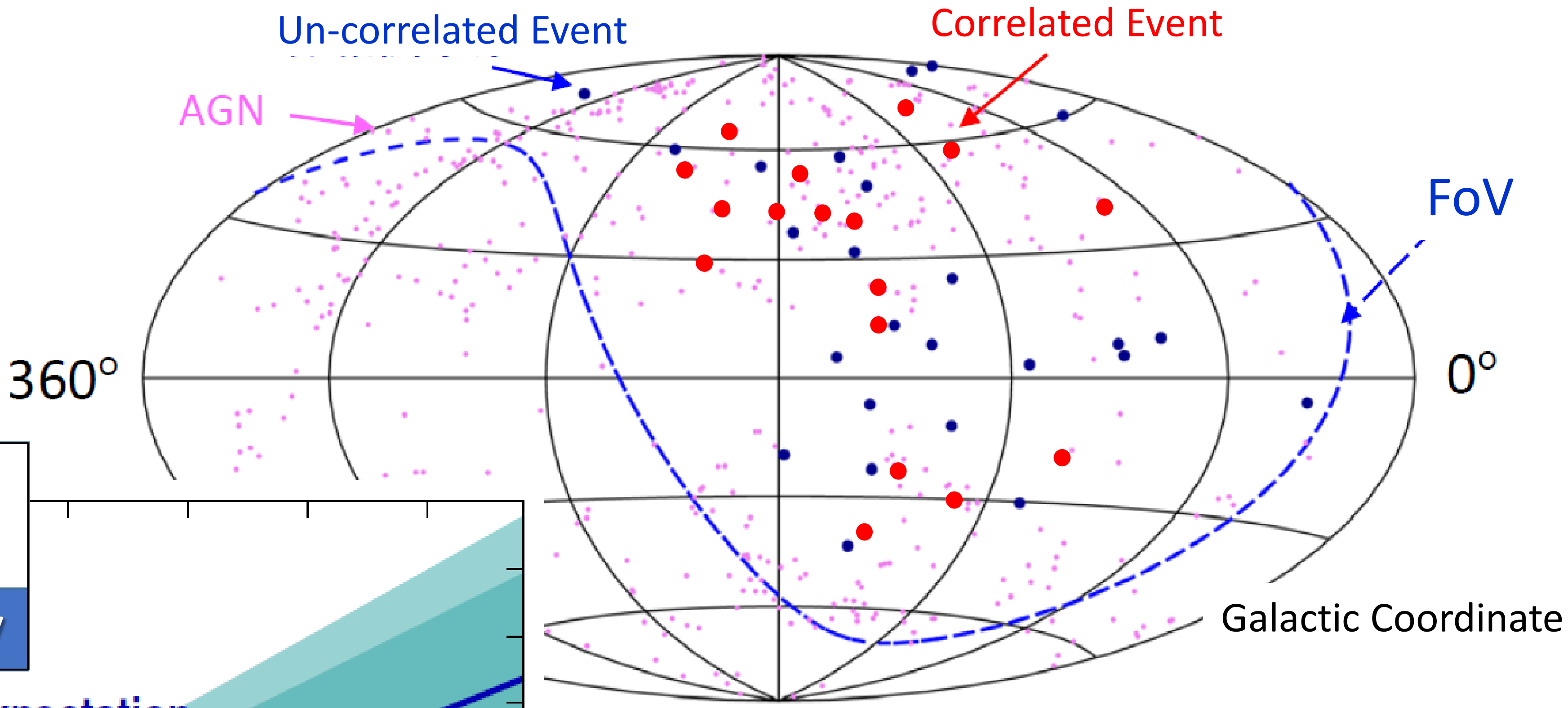
- showers at ultrahigh energies are shallower and fluctuate less than proton simulations

E.J. Ahn, M. Unger
ICRC 2013

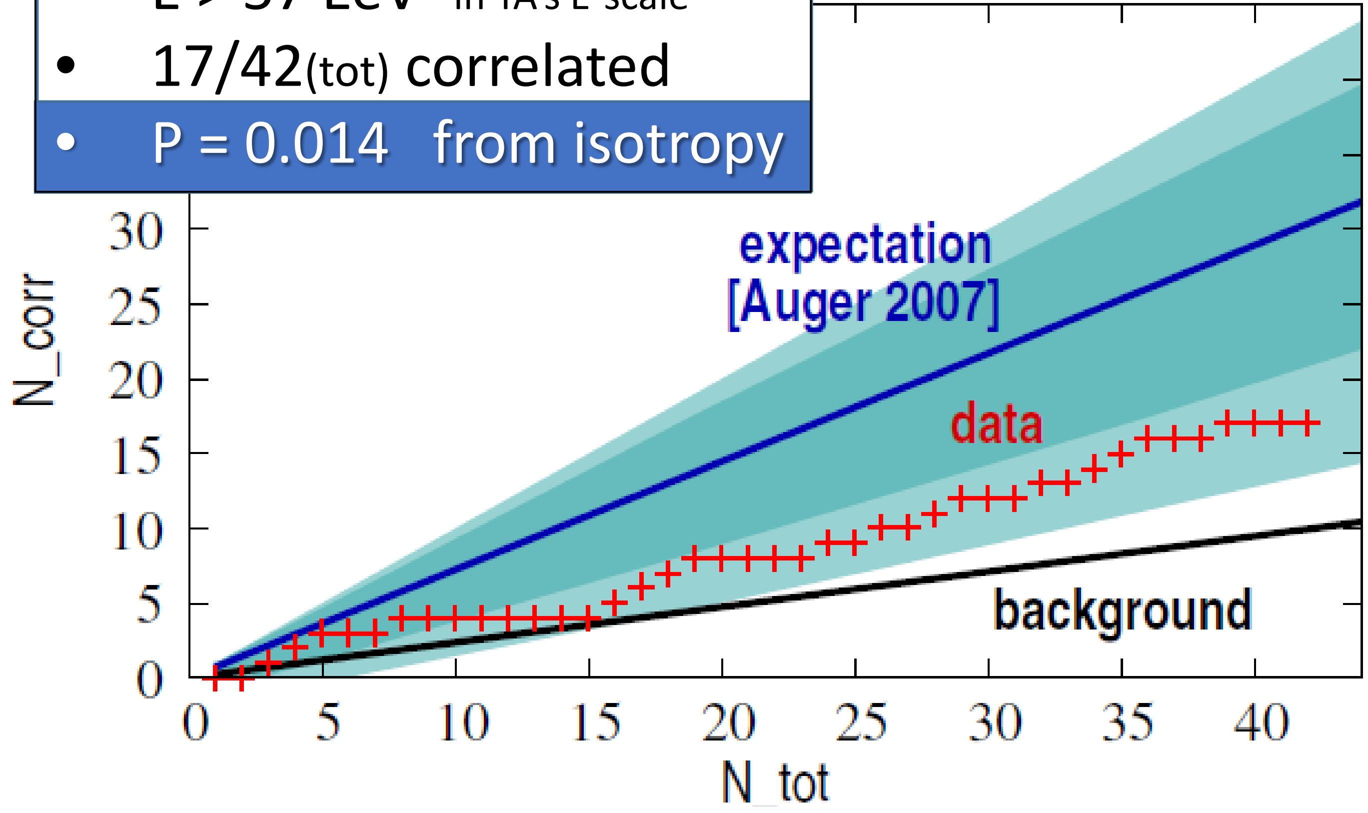
TA

Correlation with VCV in the north

- Data until May 2013
- Same condition as Auger



- E > 57 EeV in TA's E-scale
- 17/42(tot) correlated
- P = 0.014 from isotropy



P. Tinyakov, ICRC2013