Observation of Ultra-High Energy Cosmic Rays (UHECRs) - status and prospects -

CosPA 2013, Honolulu

November 15th, 2013

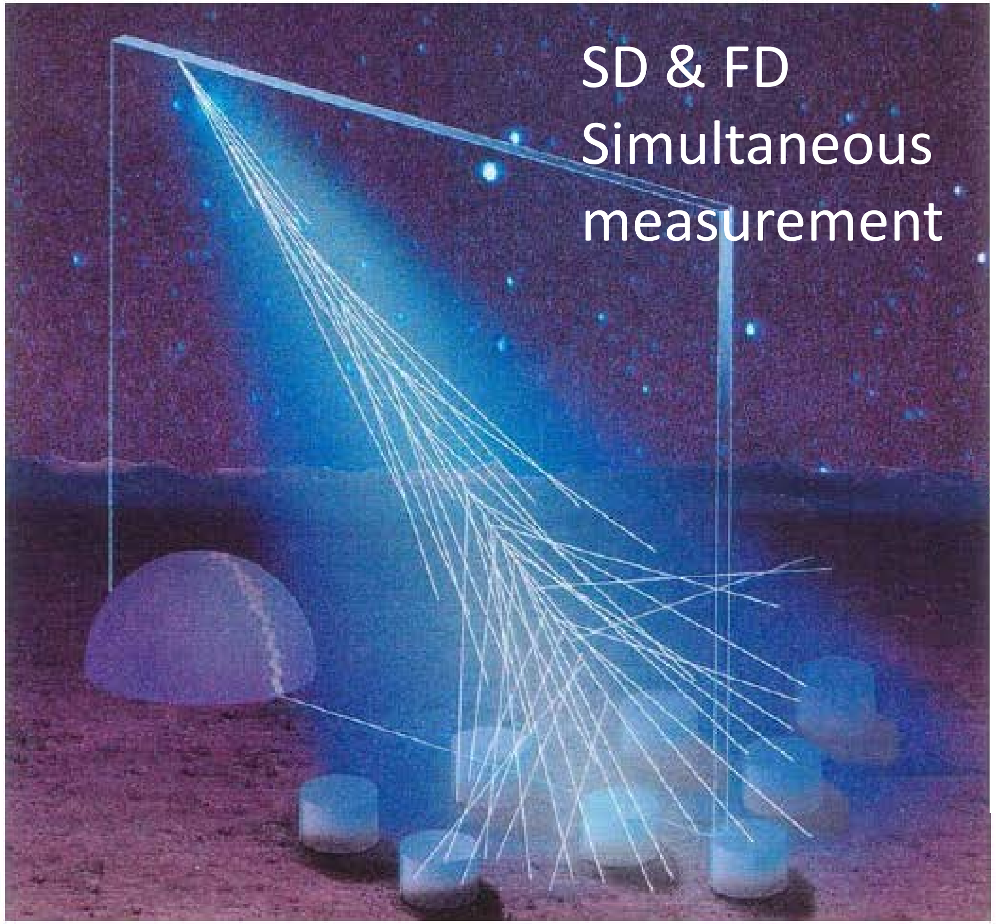
M.Fukushima

ICRR, Univ. of Tokyo

UHECRs Detector

- Pierre Auger Observatory (Auger) in Malargue, Argentina
- Telescope Array (TA) Experiment in Utah, USA

Ground Array + Air Fluorescence Telescope



FD

Fluorescence Detector

SD

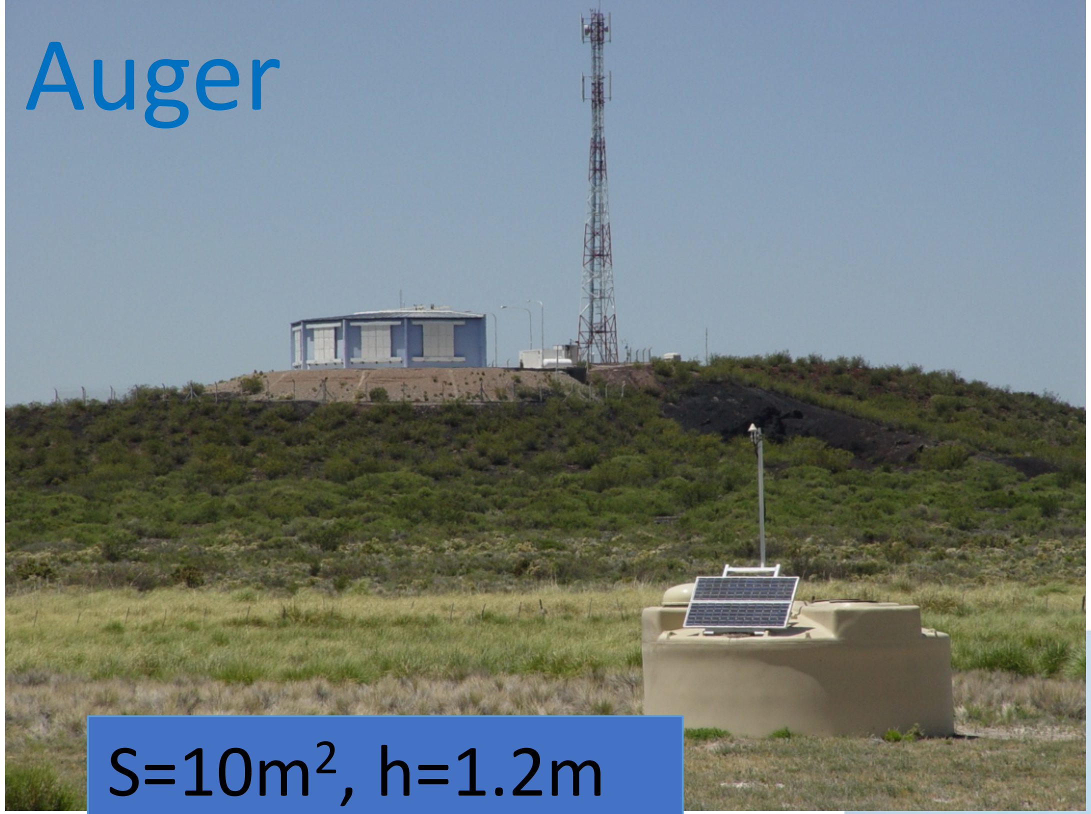
Surface Detector

- Total absorption calorimetry > Energy scale
- Imaging > Xmax > Particle Composition
- Duty ~ 10%

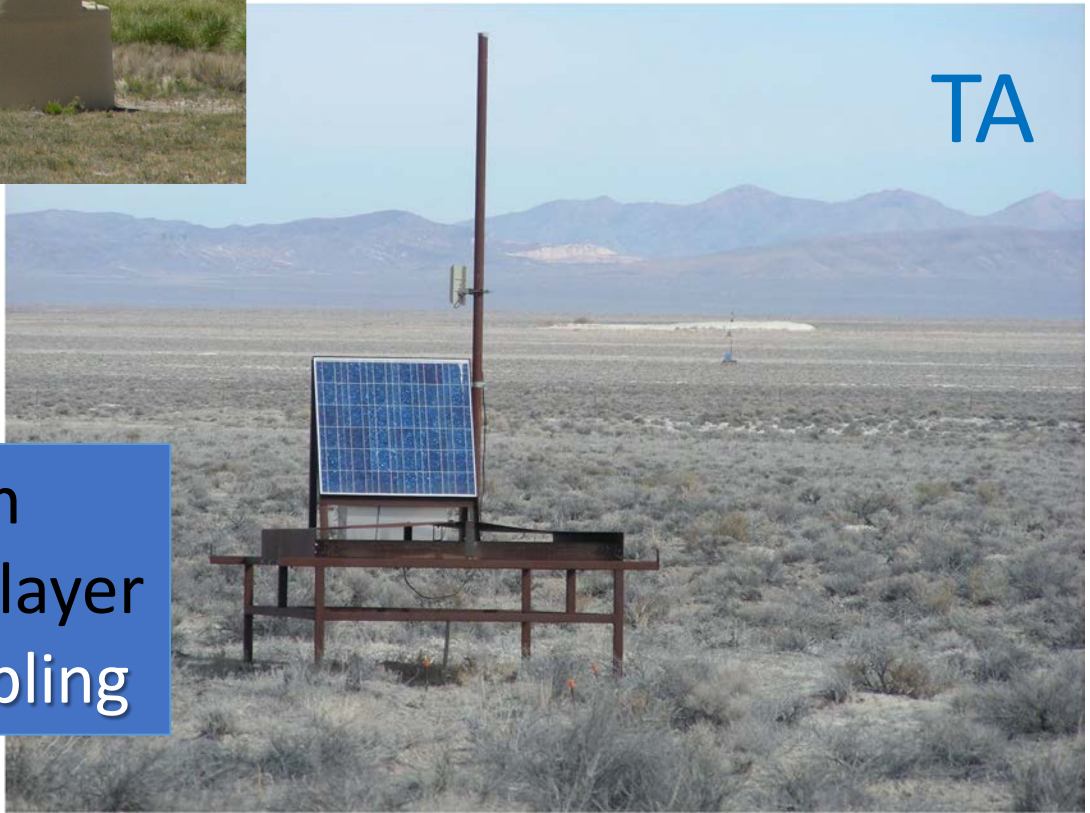
- Duty ~100%
- High Statistics > Spectral shape
- + ~Uniform sky sampling > Anisotropy

SD

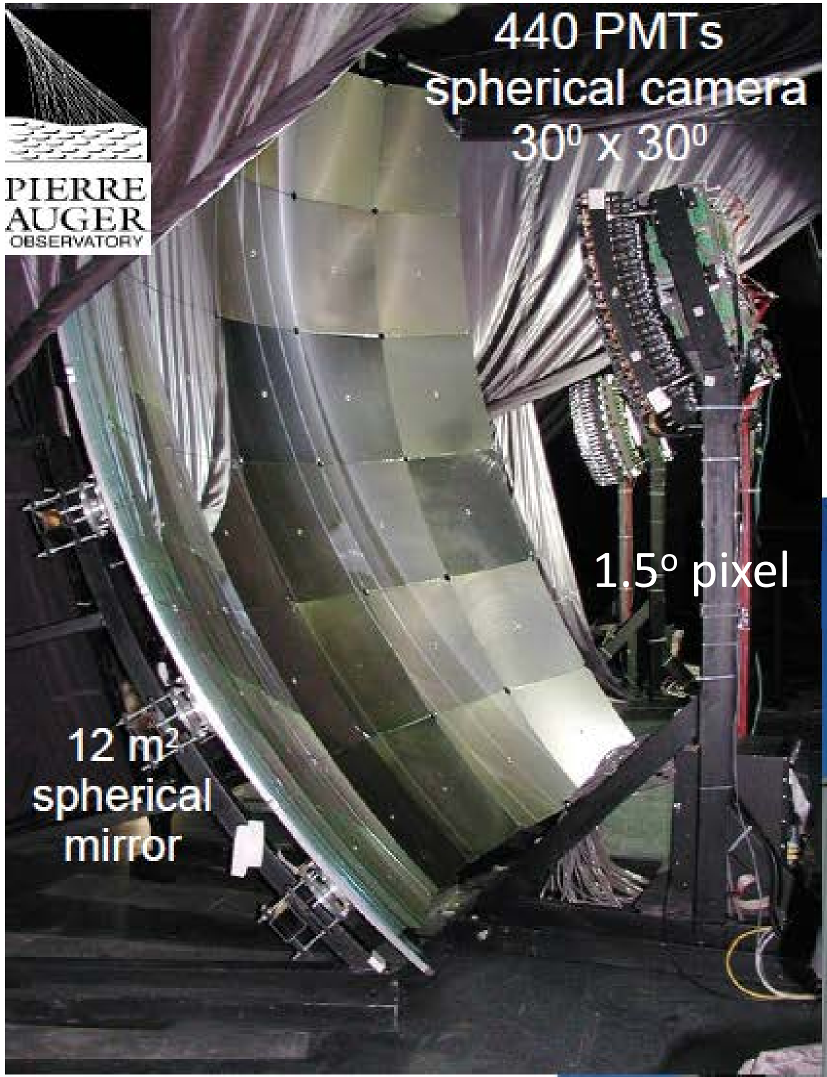
Surface
Detector



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



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

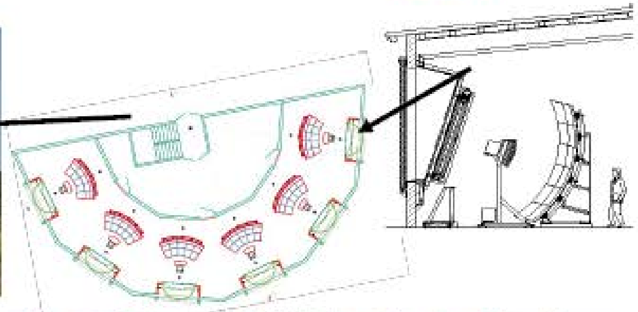


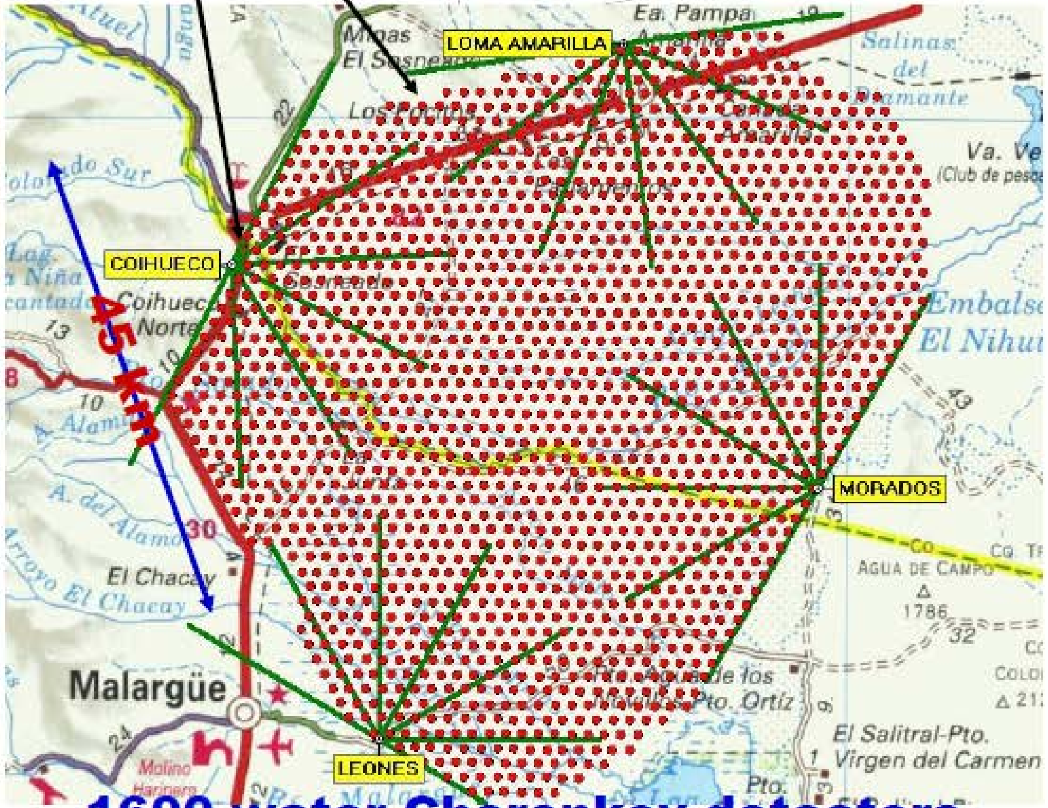
FD

Fluorescence
Detector

The Pierre Auger Observatory

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

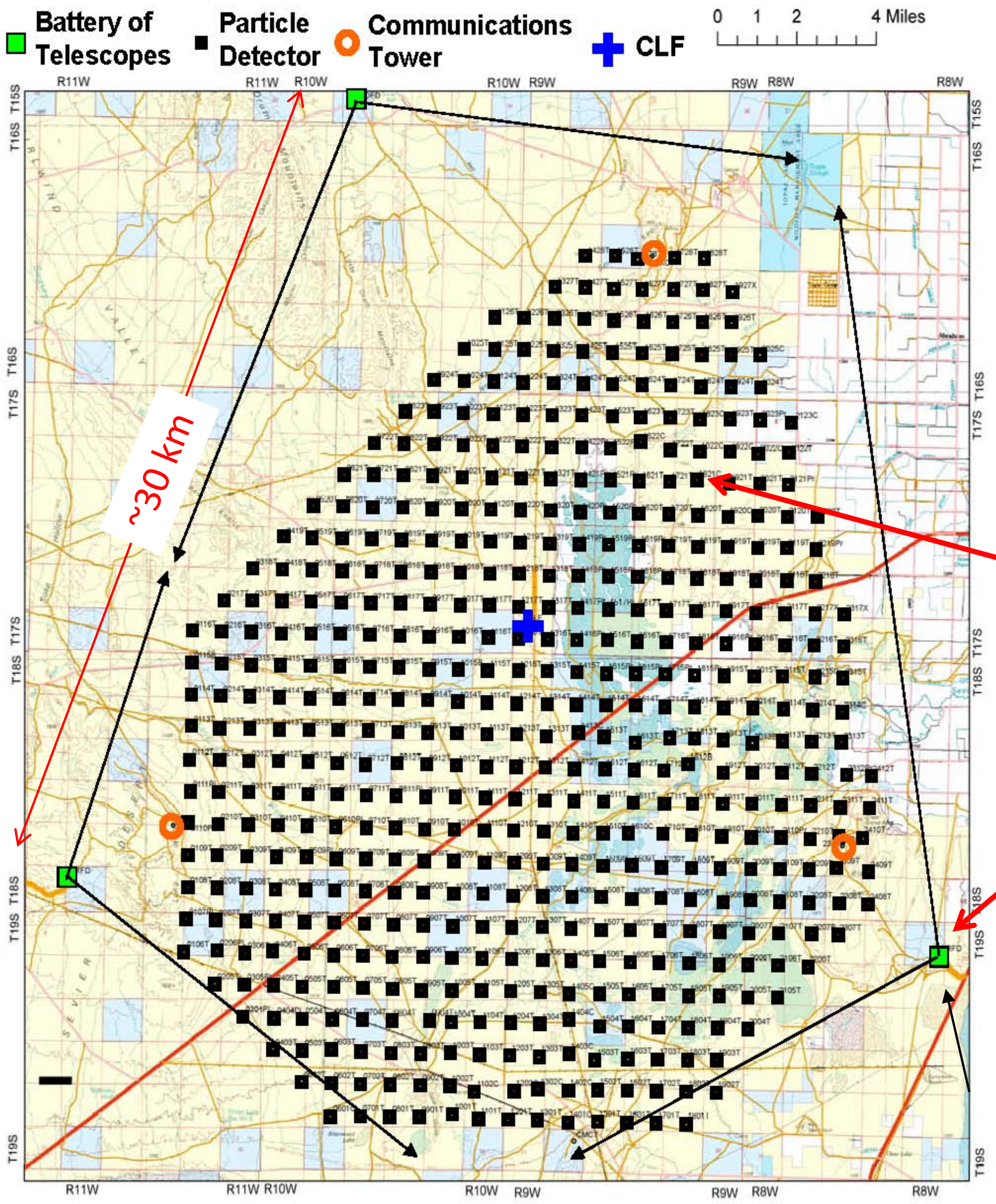




Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*

PIERRE AUGER OBSERVATORY

1600 water Cherenkov detectors,
(a la Haverah Park)
1.5 km spacing, 3000 km², 4 x 6 fluorescence telescopes



507 Surface Particle Detectors cover 680 km^2

3 Fluores. Telescope stations overlook the array.

Utah, USA

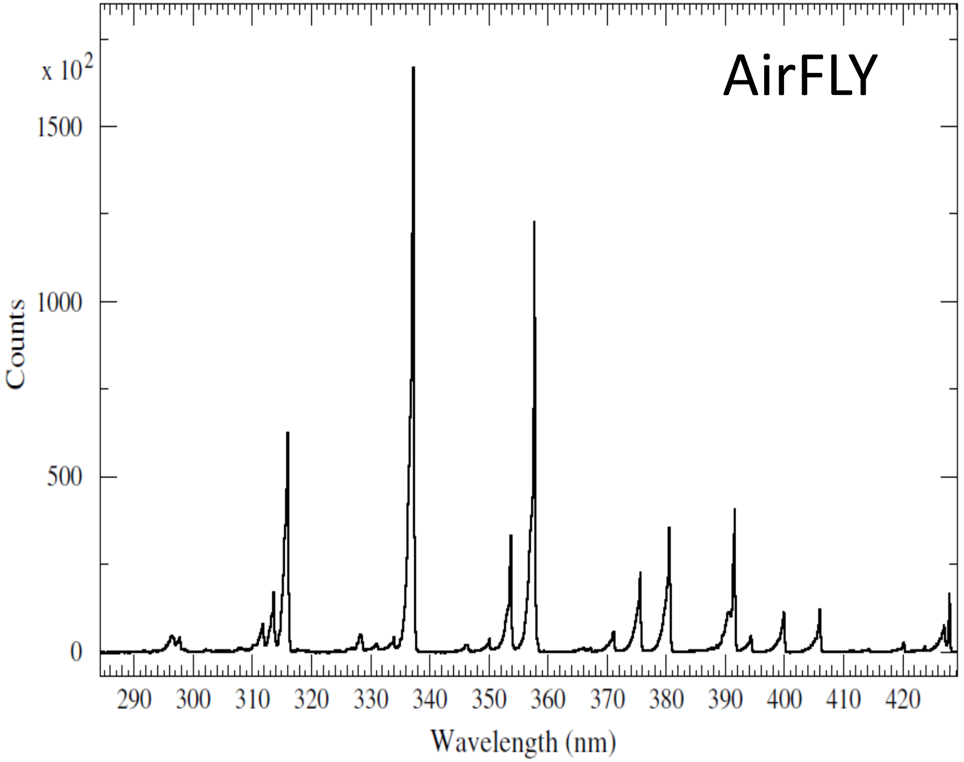
39.3 ^{0} N

112.9 ^{0} W

Alt. 1400 m

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

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

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

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

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

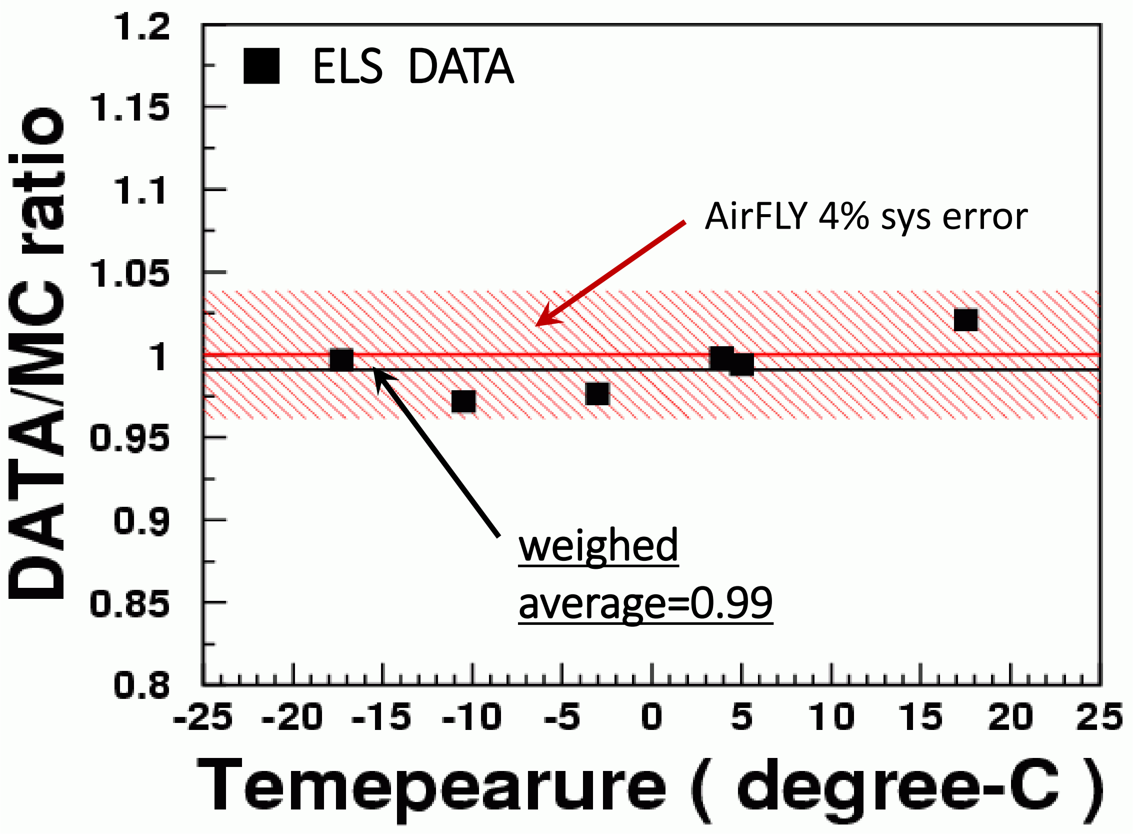
T. Shibata, ICRC 2013

Air Fluorescence : 337nm Yield [photons/MeV]

AirFLY = 5.61 ± 0.06 (stat) ± 0.22 (sys)
for 1013 hPa and 293 K

Controlled laboratory measurement

Integrated Yield from Electron Beam relative to AirFLY yield.



TA measured the AF yield in situ using

- 40 MeV electron beam from linac injected into the air.
- FD telescope with calib. database.
- Reference AF Model (spectrum, P-T-RH dependence)
- ΔE by GEANT-4 converted to photons with AirFLY yield.

Measurement in situ at TA.

ELS (data) / AirFLY (MC)
= 0.96*) ± 0.01 (stat) ± 0.15 (sys)
for ~860 hPa, -17^0 ~ 17^0 C

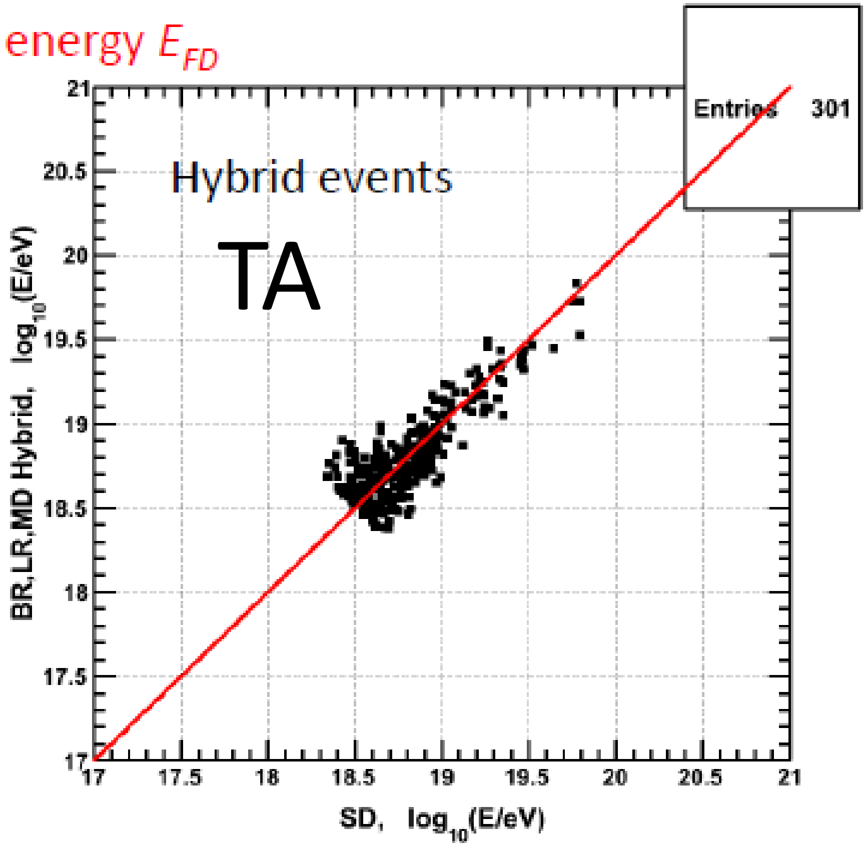
*) 0.99 with -3% correction not included in MC

T. Shibata, ICRC 2013

M. Ave et al. AirFLY collaboration ApP 42(2013)90

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

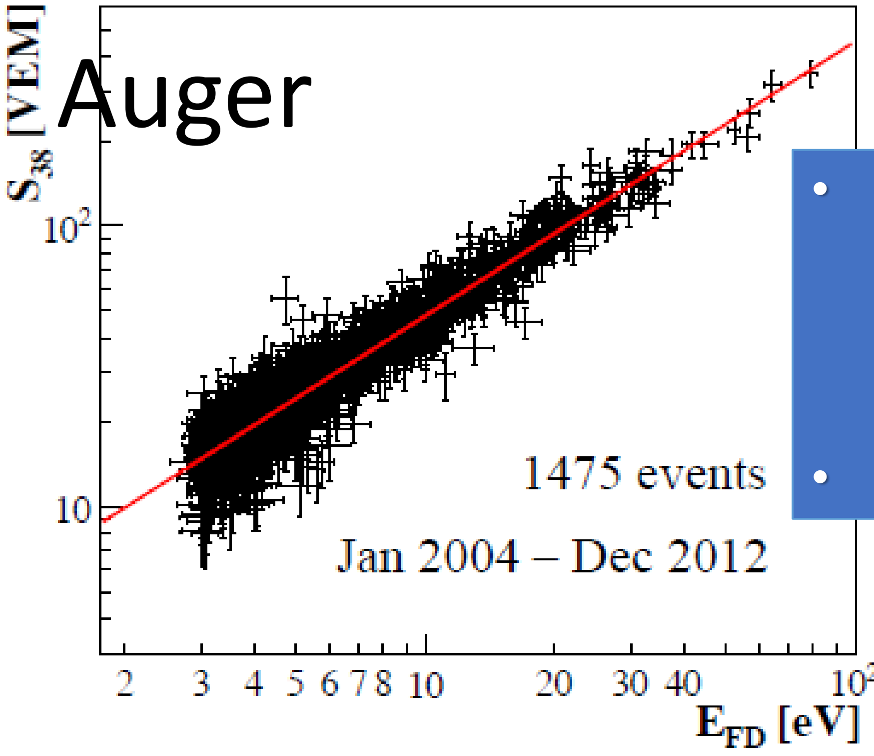
FD energy E_{FD}



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.



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

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

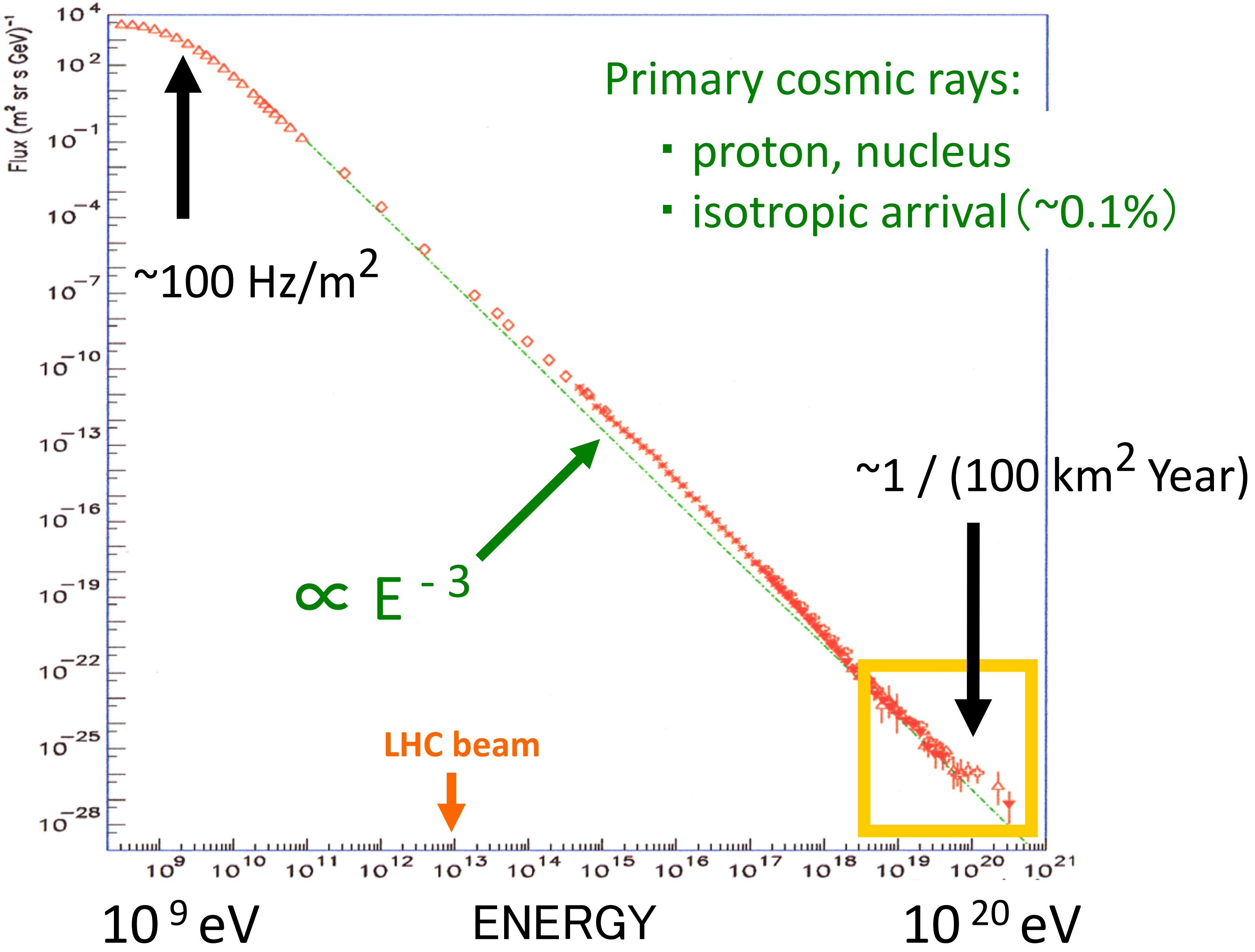
- Good correlation (~linear) with particle density at 1000m (Auger) , 800m (TA) from core for $10^{18.5} < E < 10^{19.8}$ eV.
- Limited statistics for $10^{19.5}$ eV < E

- 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

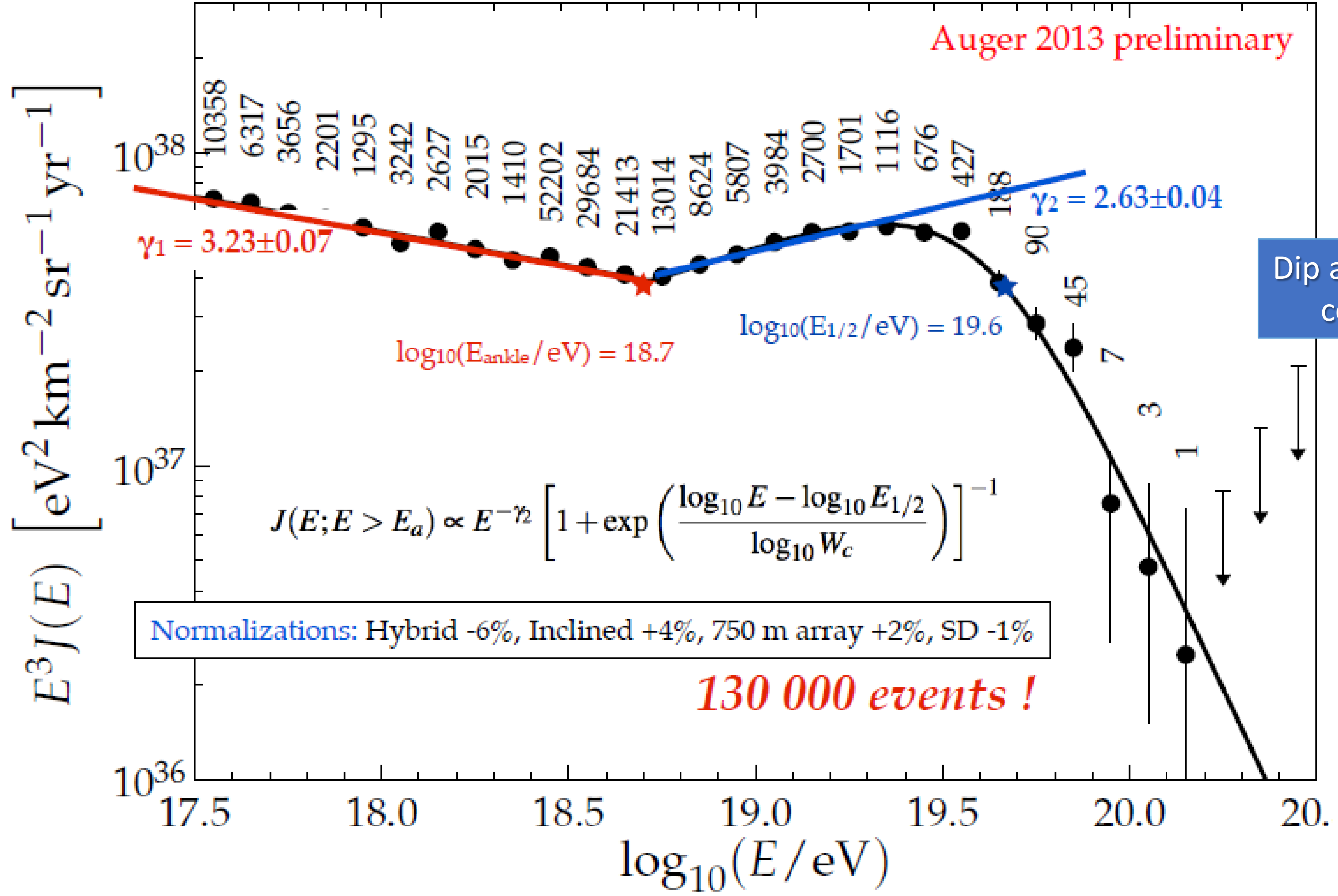
Energy Spectrum

Energy Spectrum of Cosmic Rays



THE AUGER ENERGY SPECTRUM

Updated at ICRC2013
with New Energy analysis



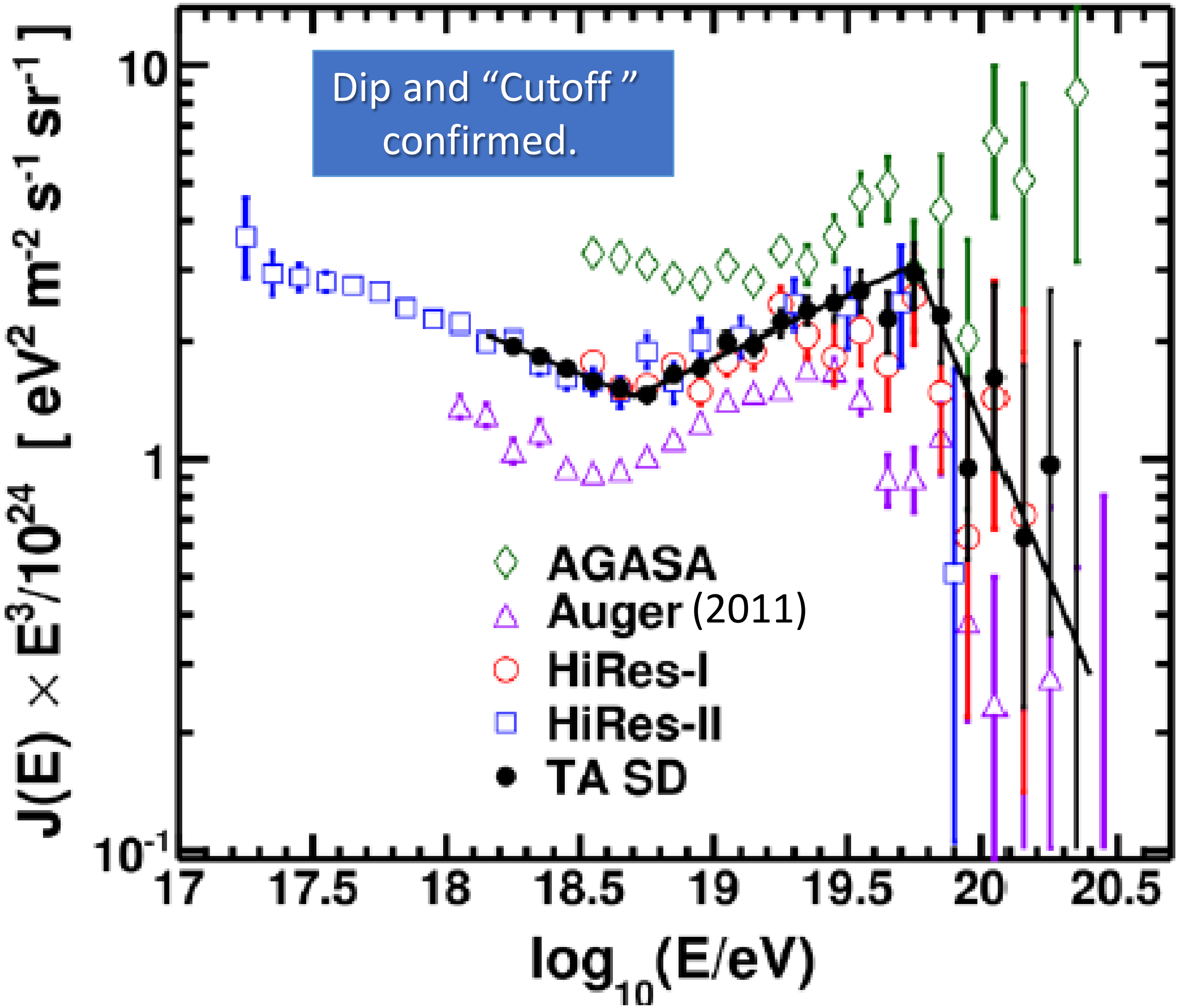
Energy Increased by
16% at $10^{18.0}$ eV and
10% at 10^{19} eV
(mainly not by new AFY)

Dip and "Cutoff" confirmed.

Y. Lettessier-Selvon, ICRC 2013

5 year TA SD spectrum

Updated at ICRC2013



TA data

May, 2008 – May, 20013

Zenith angle < 45°

14787 ev. (E > $10^{18.2}$ eV)

Exposure 4500 km^2 sr yr

Broken power law fit

γ_1 = -3.283±0.032

E_{ankle} = (5.04±0.27)×10^{18} eV

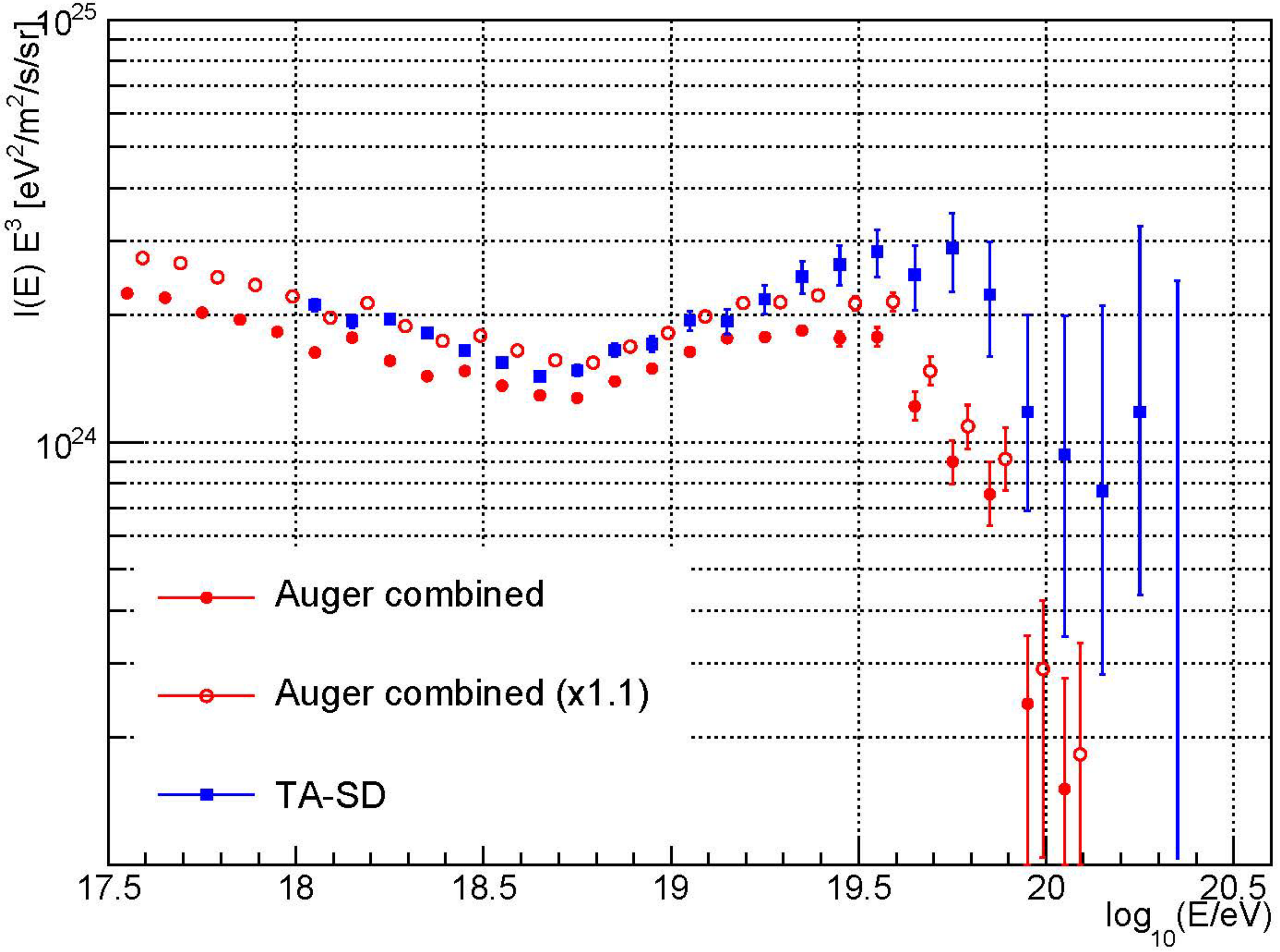
γ_2 = -2.685±0.030

E_{GZK} = (5.68±1.05)×10^{19} eV

γ_3 = -4.62± 0.74

H. Sagawa
D.Bergman
ICRC 2013

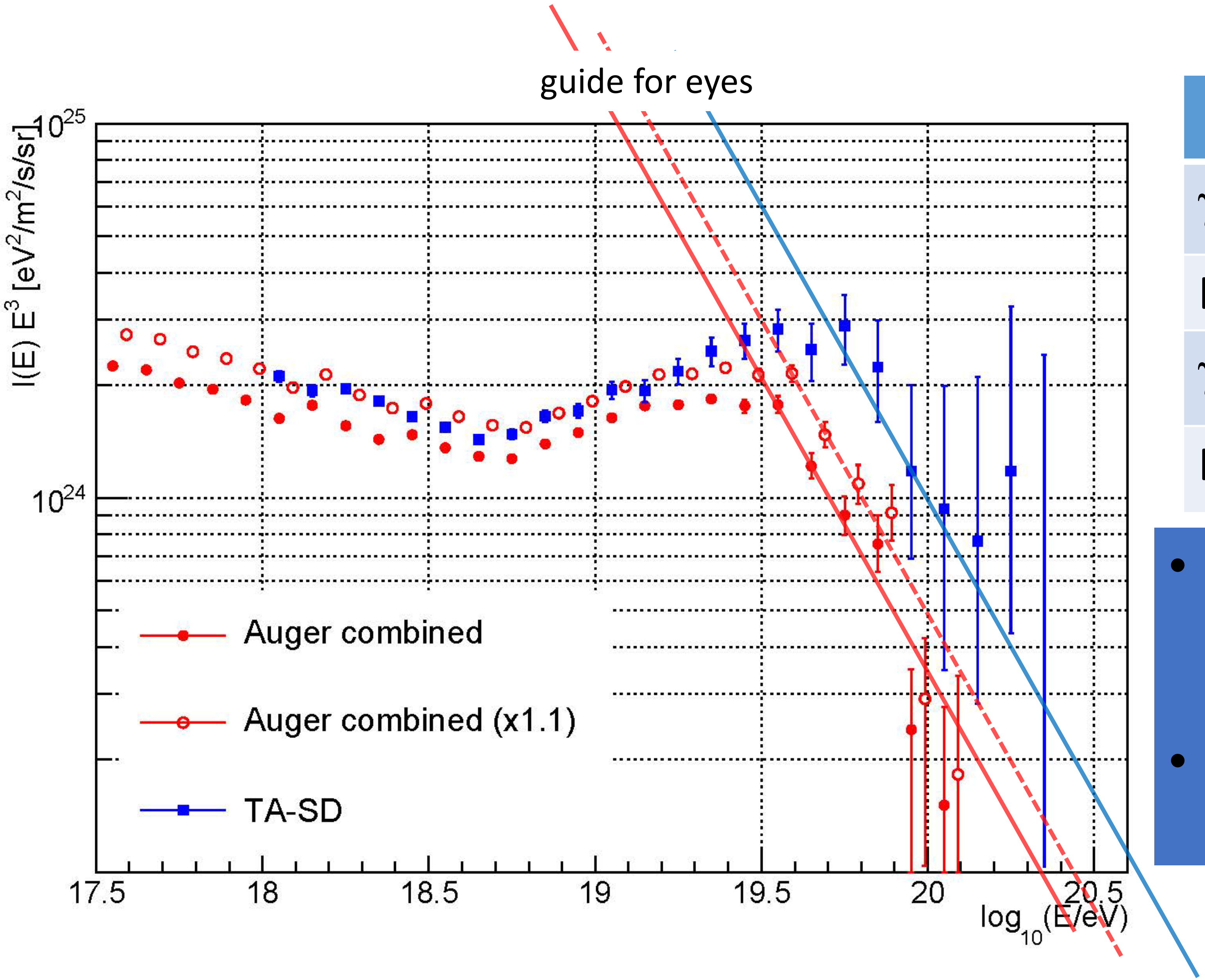
Spectrum at UHE : Auger and TA



D. Bergman
ICRC 2013

From Y. Tsunesada
ICRC 2013
Rapporteur Talk

Spectrum at UHE : Auger and TA



Results of Broken Power Law Fit

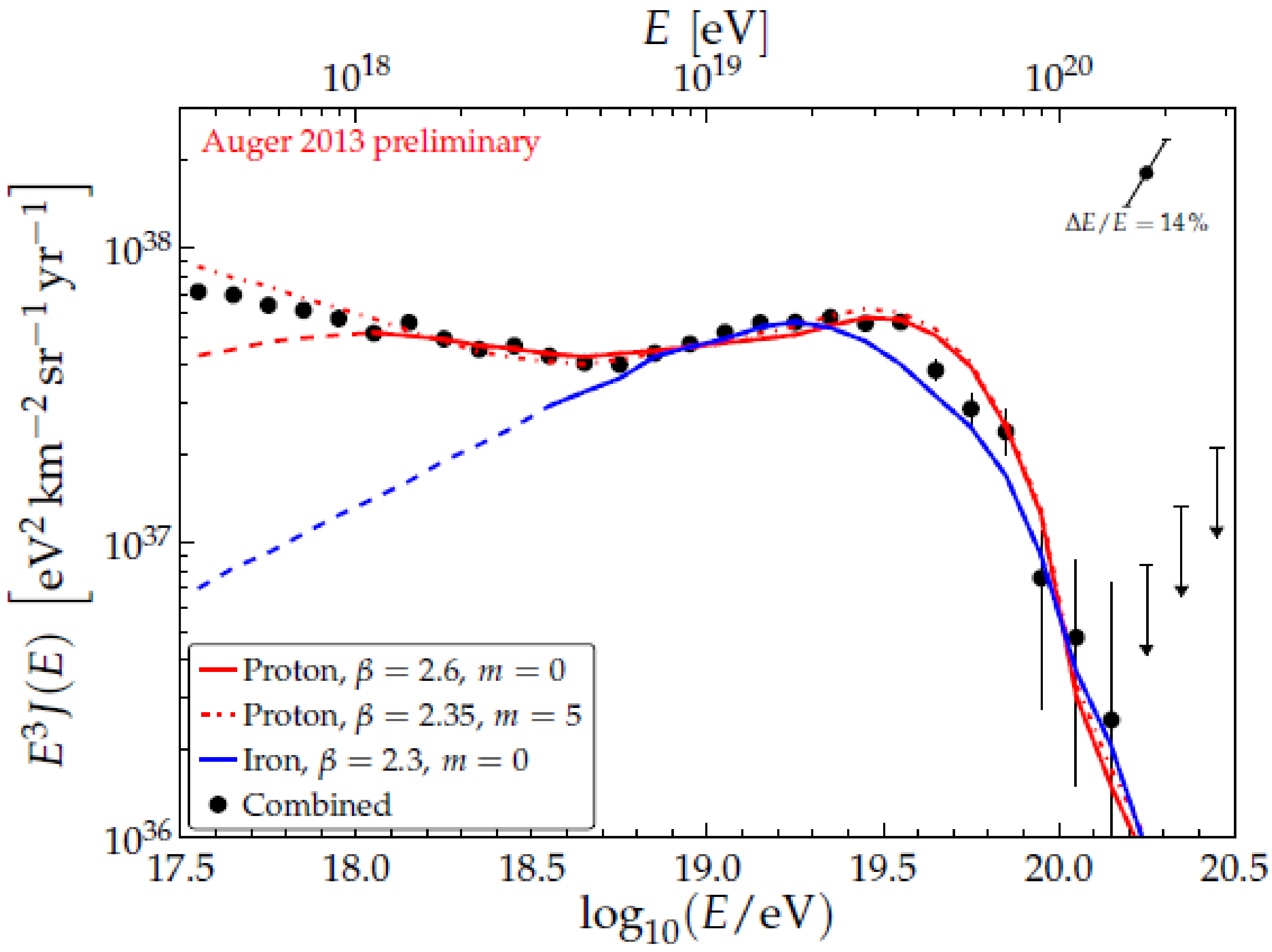
	Auger	TA
γ-1	3.23±0.01	3.28±0.03
E_{ANKLE}	$10^{18.72}$ eV	$10^{18.70}$ eV
γ-2	2.63±0.02	2.69±0.03
$E_{1/2}$	$10^{19.63}$ eV	$10^{19.74}$ eV

- Spectral shape: Auger and TA agree well for E < ~$10^{19.3}$ eV if overall E-scale shifted by 10%.
- $E_{1/2}$: $E_{AUGER} = 0.78 \times E_{TA}$ (w/o 10% rescale)

D. Bergman
ICRC 2013

From Y. Tsunesada
ICRC 2013
Rapporteur Talk

Astrophysical Scenario : AUGER

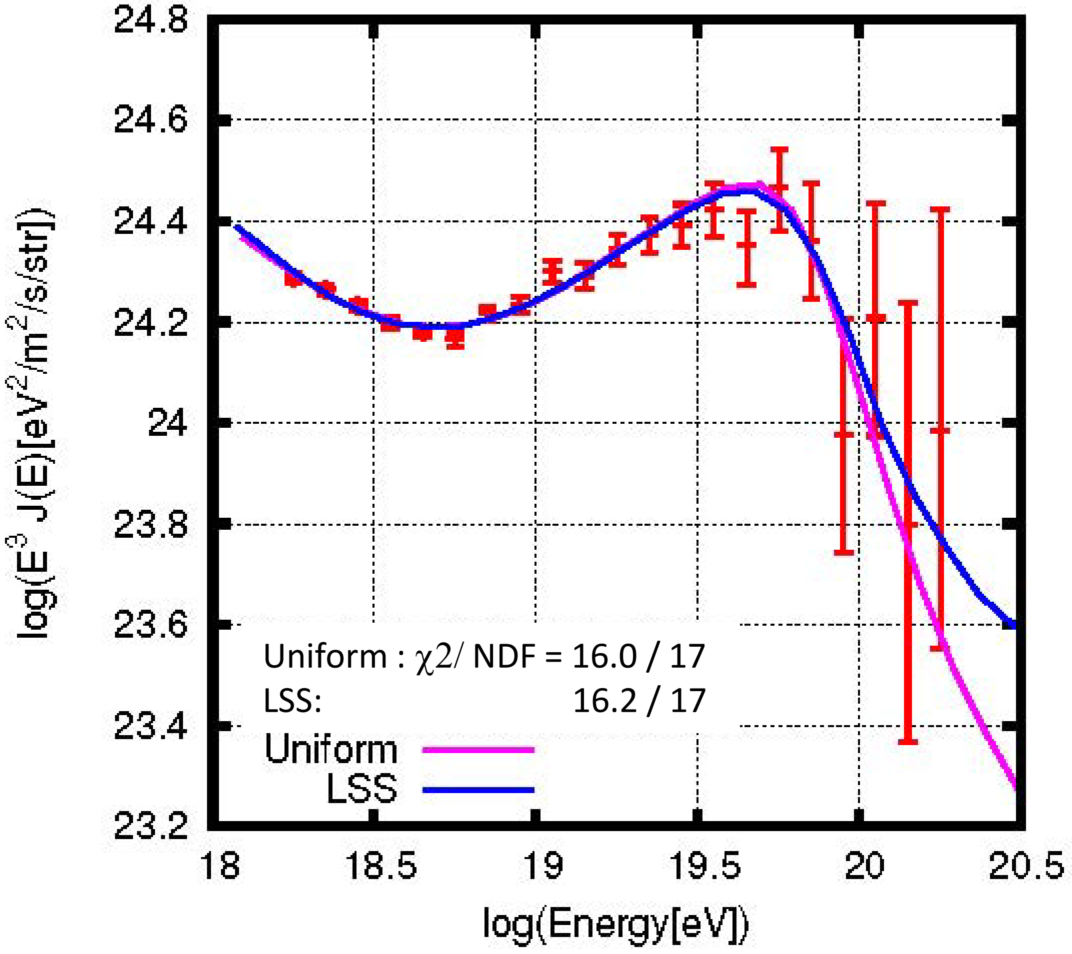


- Models calculated with CRPropa and validated with SimProp.
- Spectrum alone is not enough to Discriminate between scenarios.
- Cutoff by Acceleration limit is not excluded?

A. Schulz, ICRC 2013

Astrophysical Scenario: TA

Fit with extra-galactic proton



Source Distribution

- Uniform
- LSS (~2MASS XSCz)

Energy Loss with

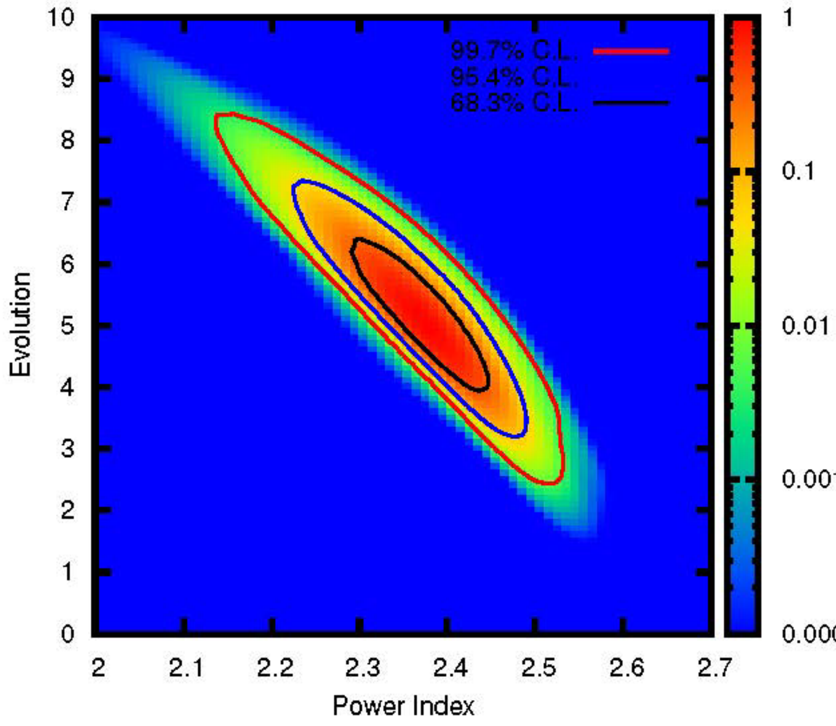
- CMB
- Infra-Red

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

E. Kido
ICRC 2013

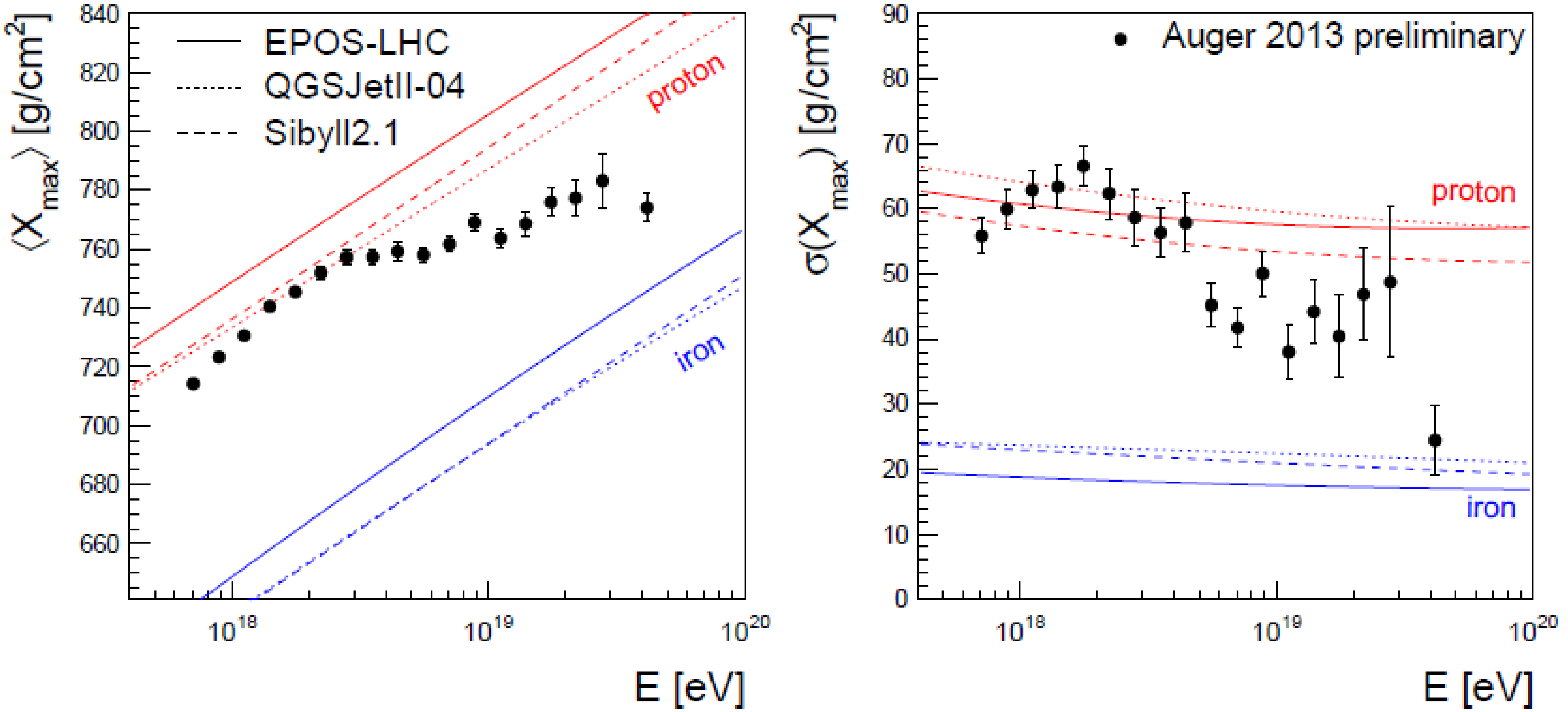
Particle Composition

Auger Xmax (updated at ICRC 2013)

- + statistics
- AFY updated.
- PSF updated.
- Calibration etc.

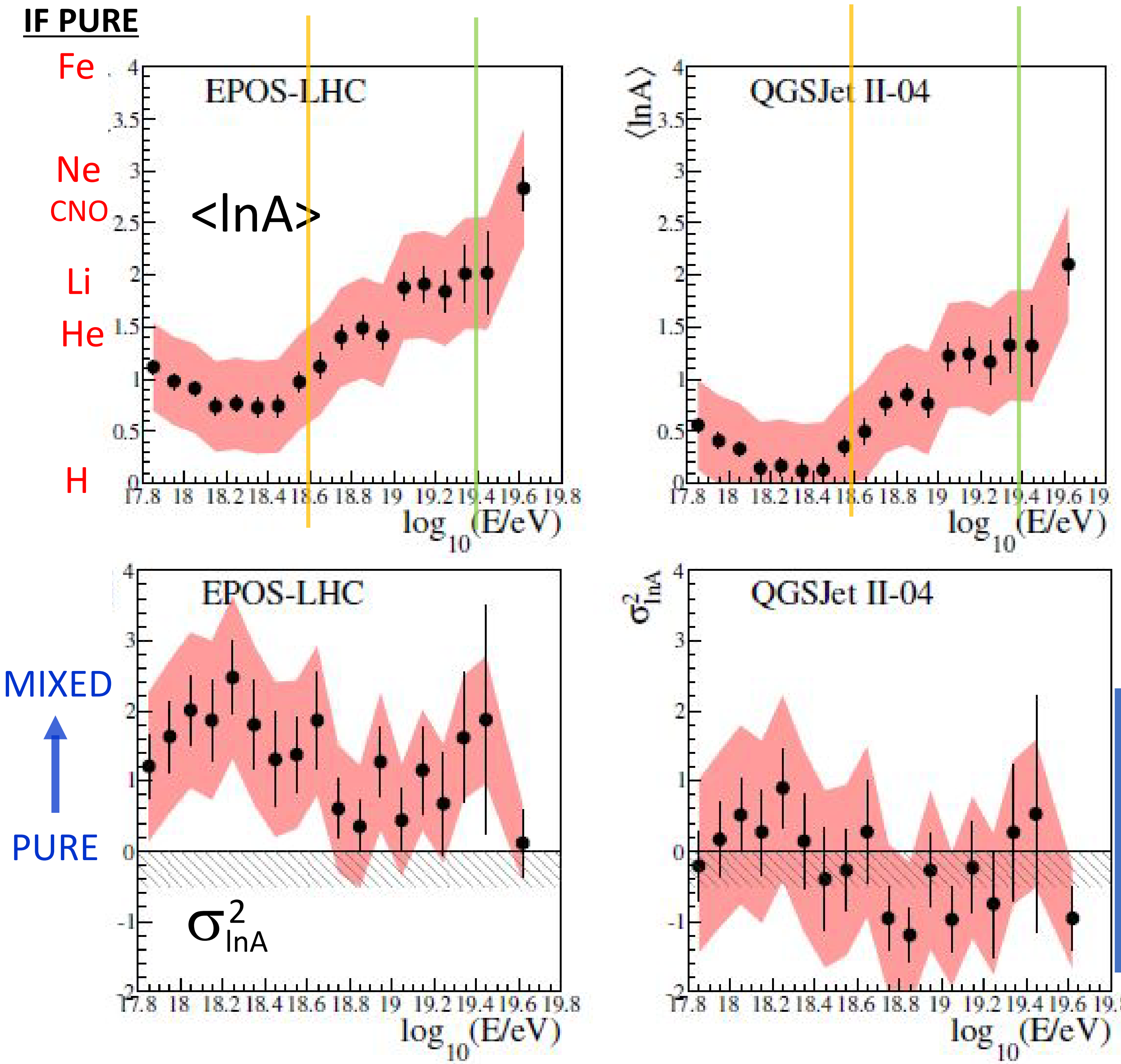
<Xmax> larger
+13 g/cm² at 10^{18}eV ~
+6 g/cm² at $10^{19.5}$eV

RMS(Xmax) larger
< 10 g/cm²
for $10^{18\text{-}19}$ eV



Updated models: EPOS-LHC and QGSJET-II-04 are used for MC rails.

E.J. Ahn, M. Unger
ICRC 2013



Auger LnA Study

$\langle X_{max} \rangle$, $\sigma(X_{max})$ → $\langle \ln A \rangle$, $\sigma_{\ln A}$

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

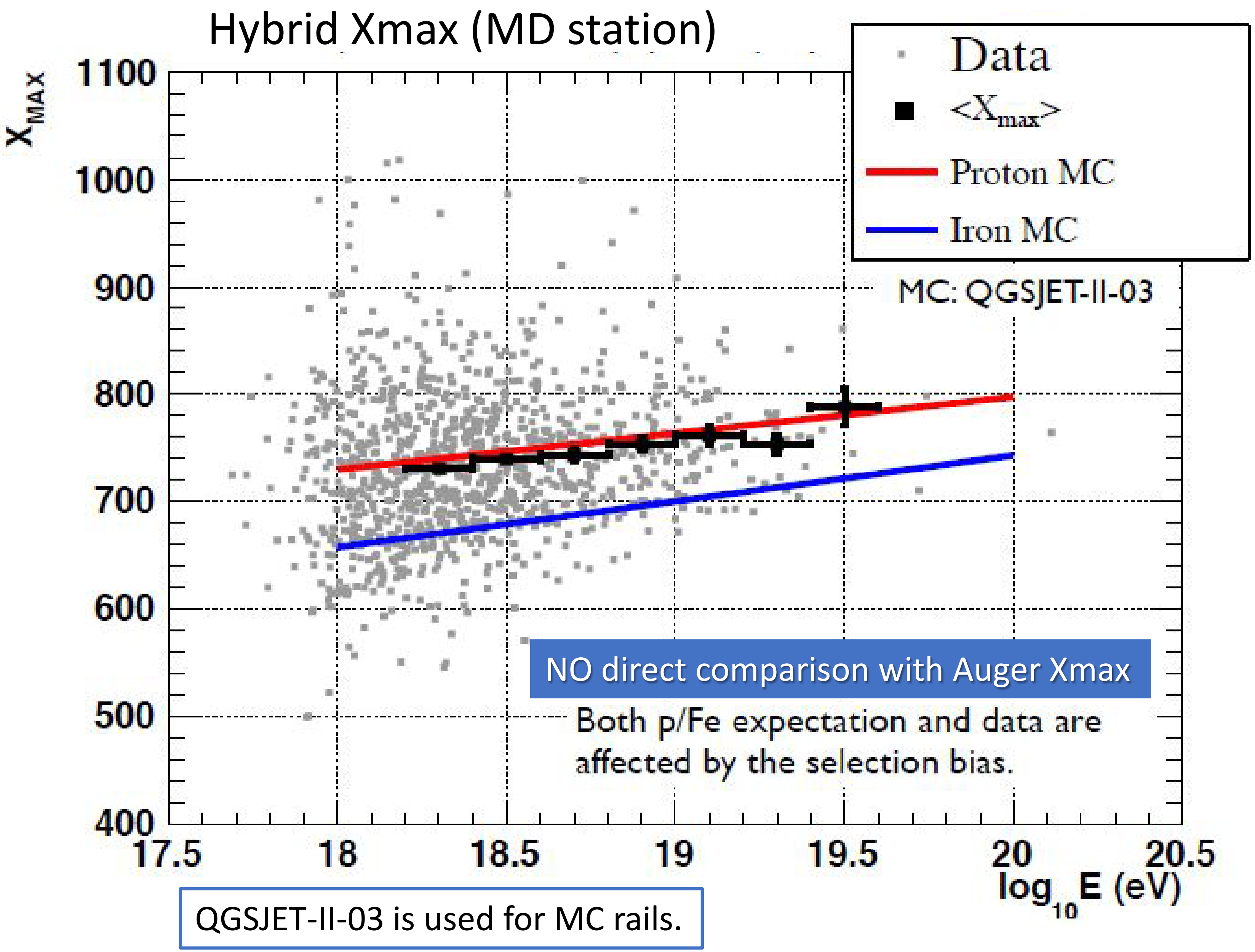
E.J. Ahn, M. Unger
ICRC 2013

TA Xmax

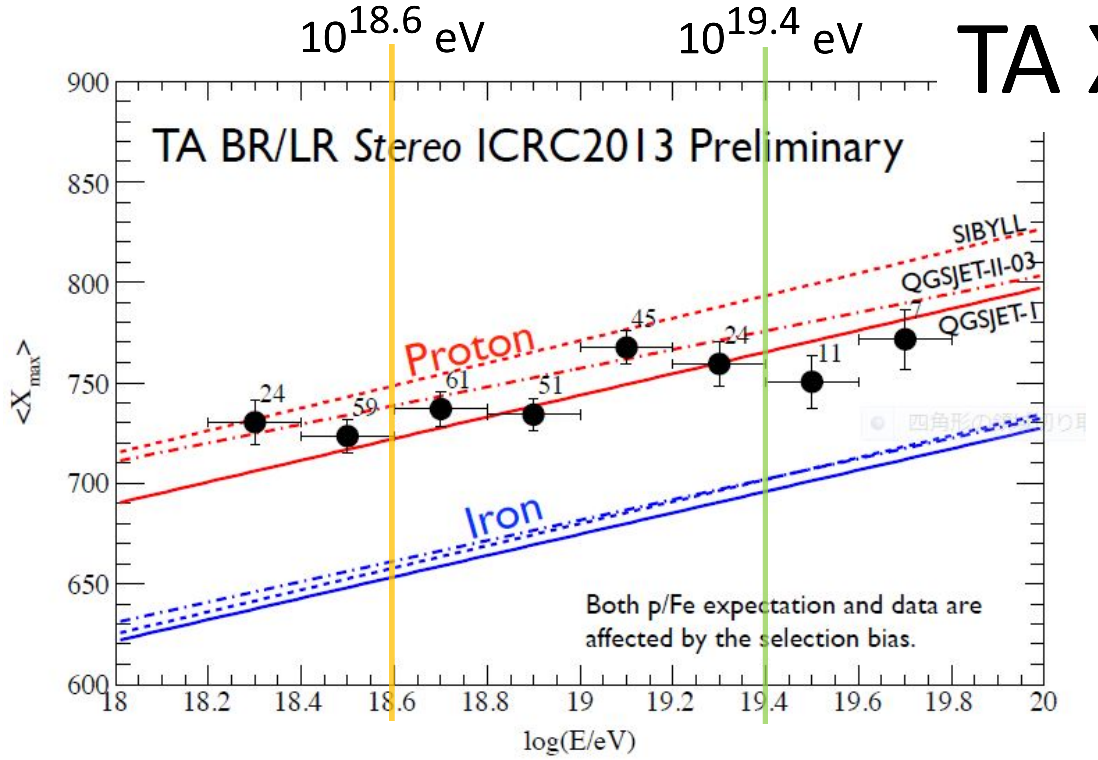
(updated @ICRC2013)

- Hybrid Xmax added
- + statistics and Analysis updated for Stereo Xmax

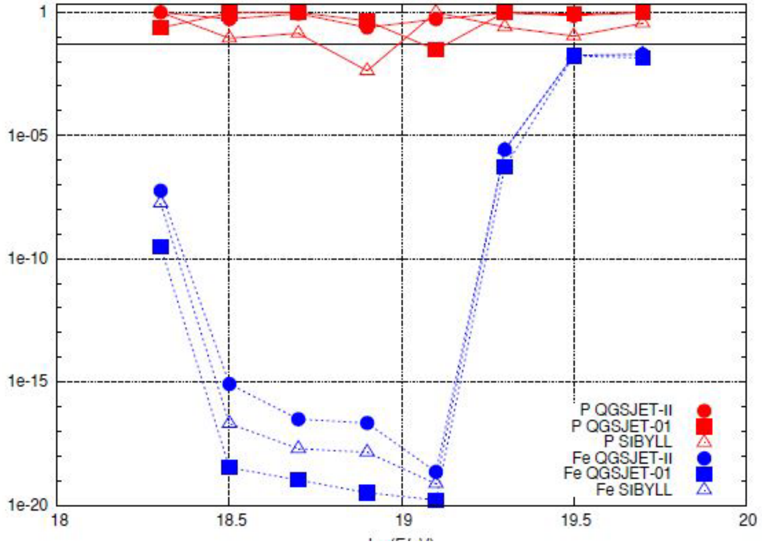
- Analysis using
  QGSJET-II-03
  SIBYLL
  QGSJET-I

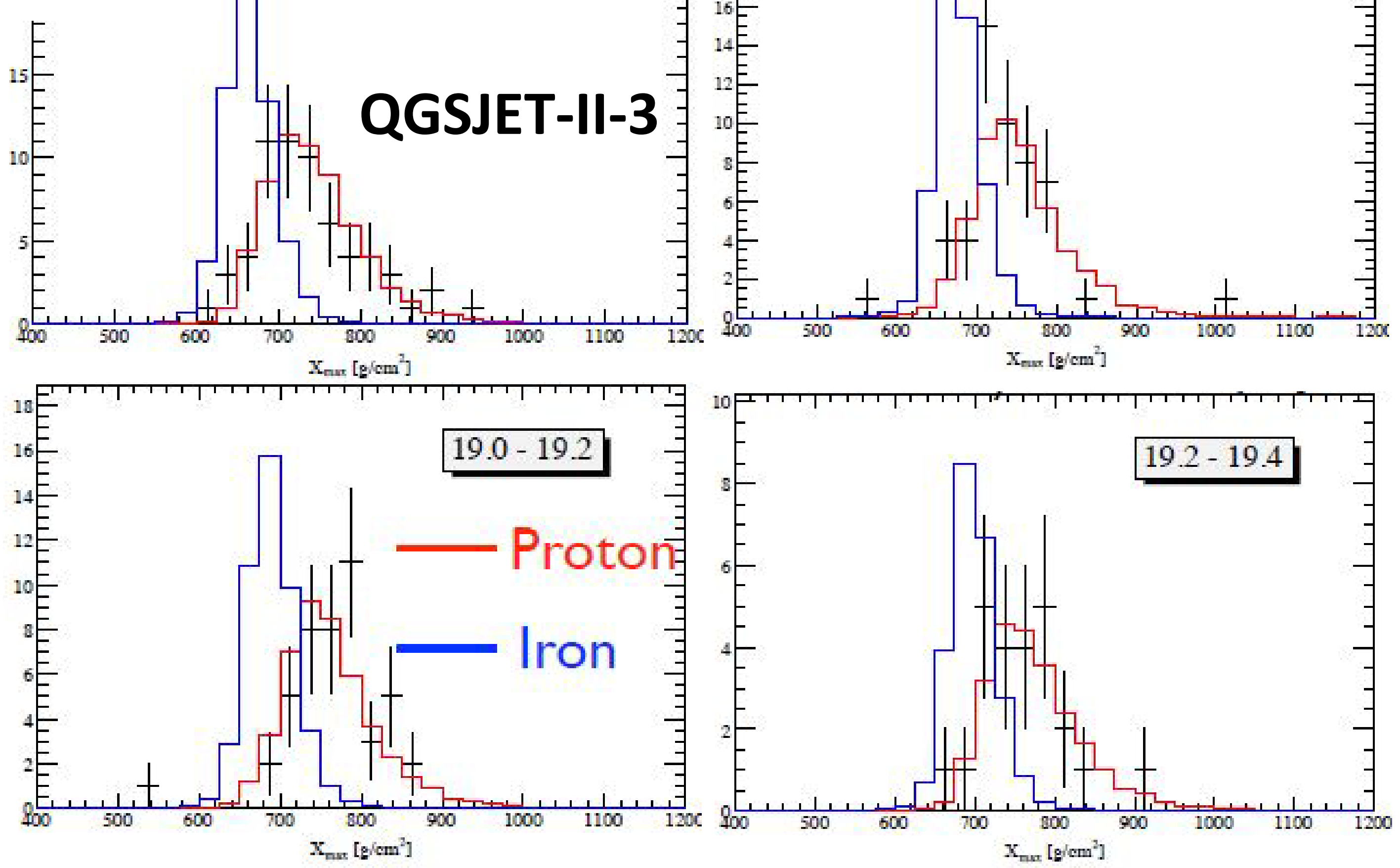


TA Xmax



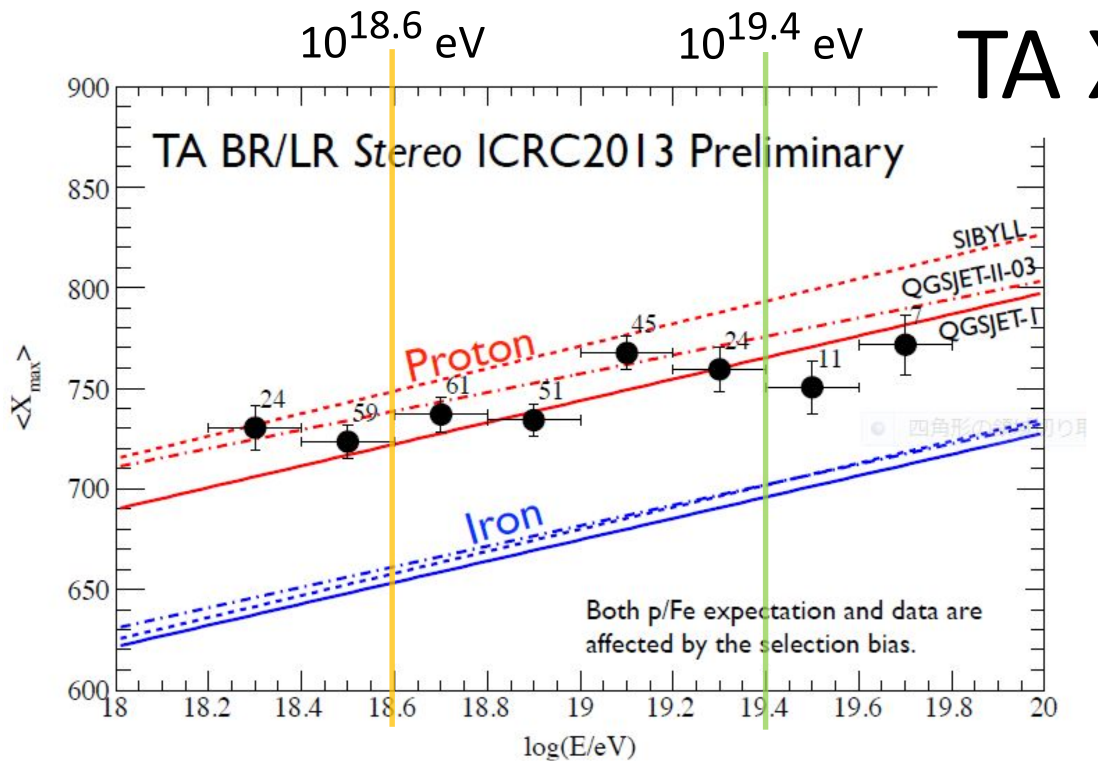
K-S test: proton vs Fe

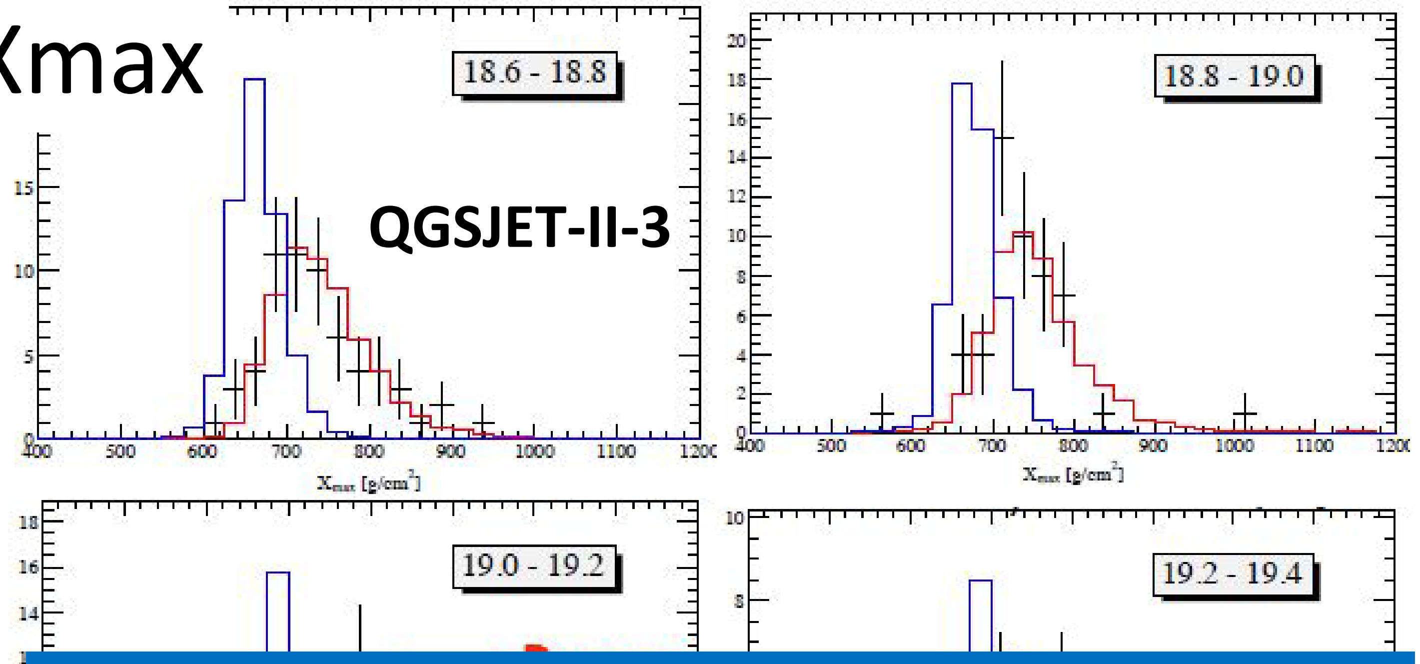




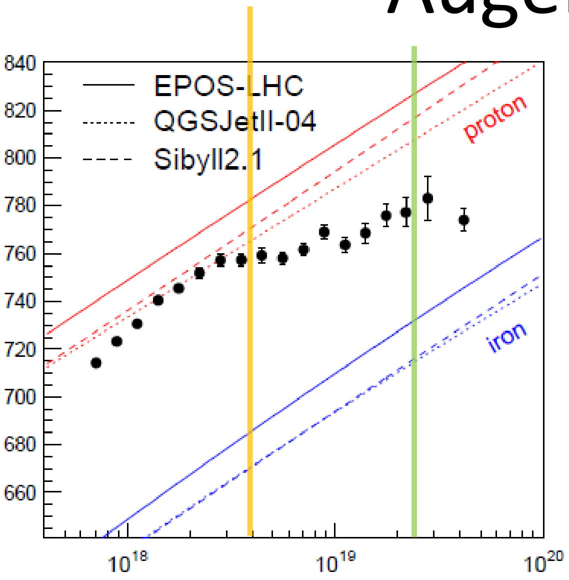
<Xmax> and Xmax distribution
is consistent with proton by stereo and hybrid analyses.

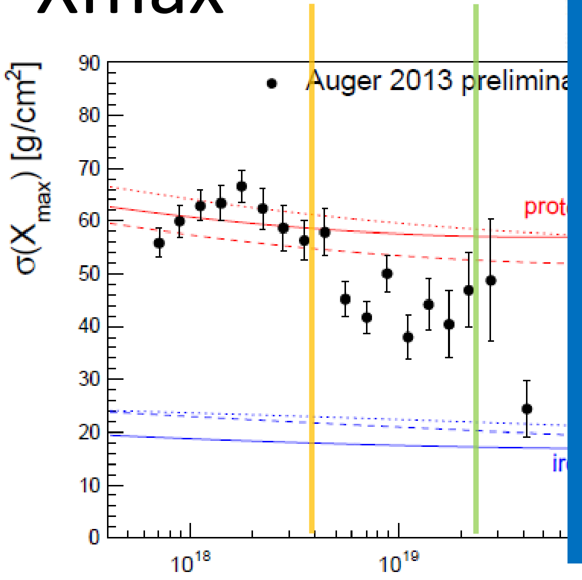
TA Xmax





Auger Xmax



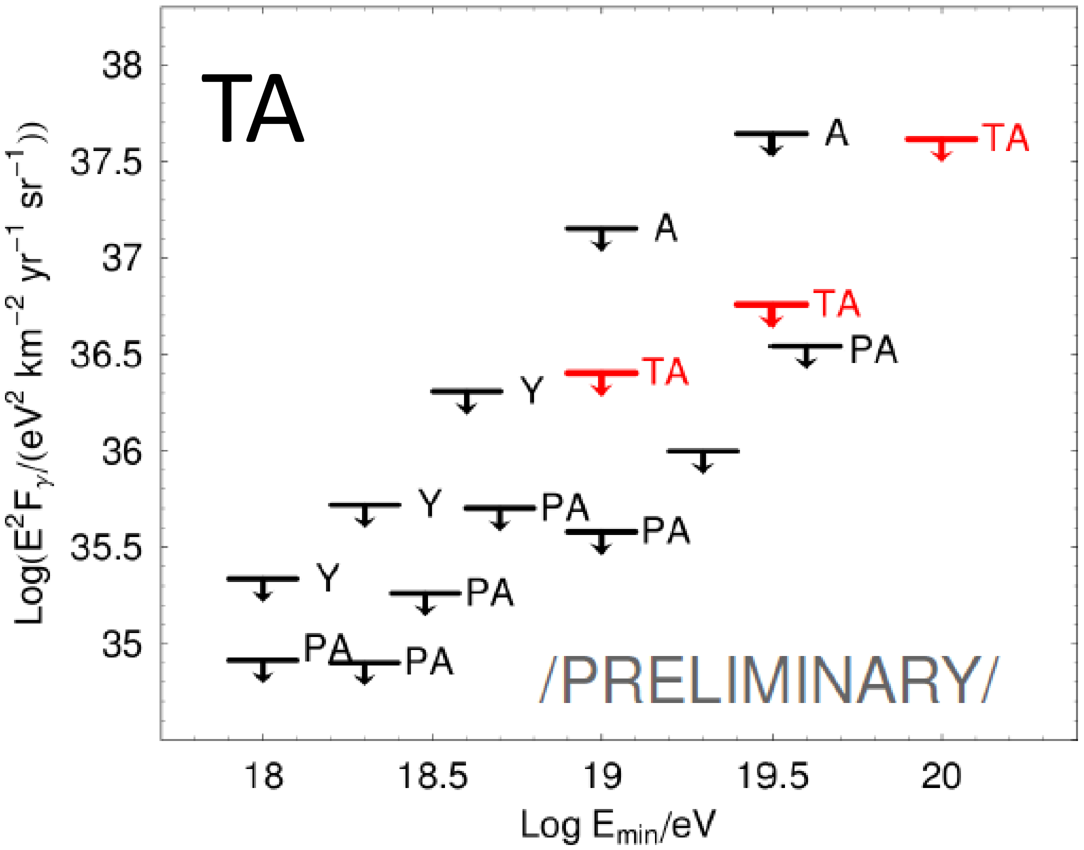


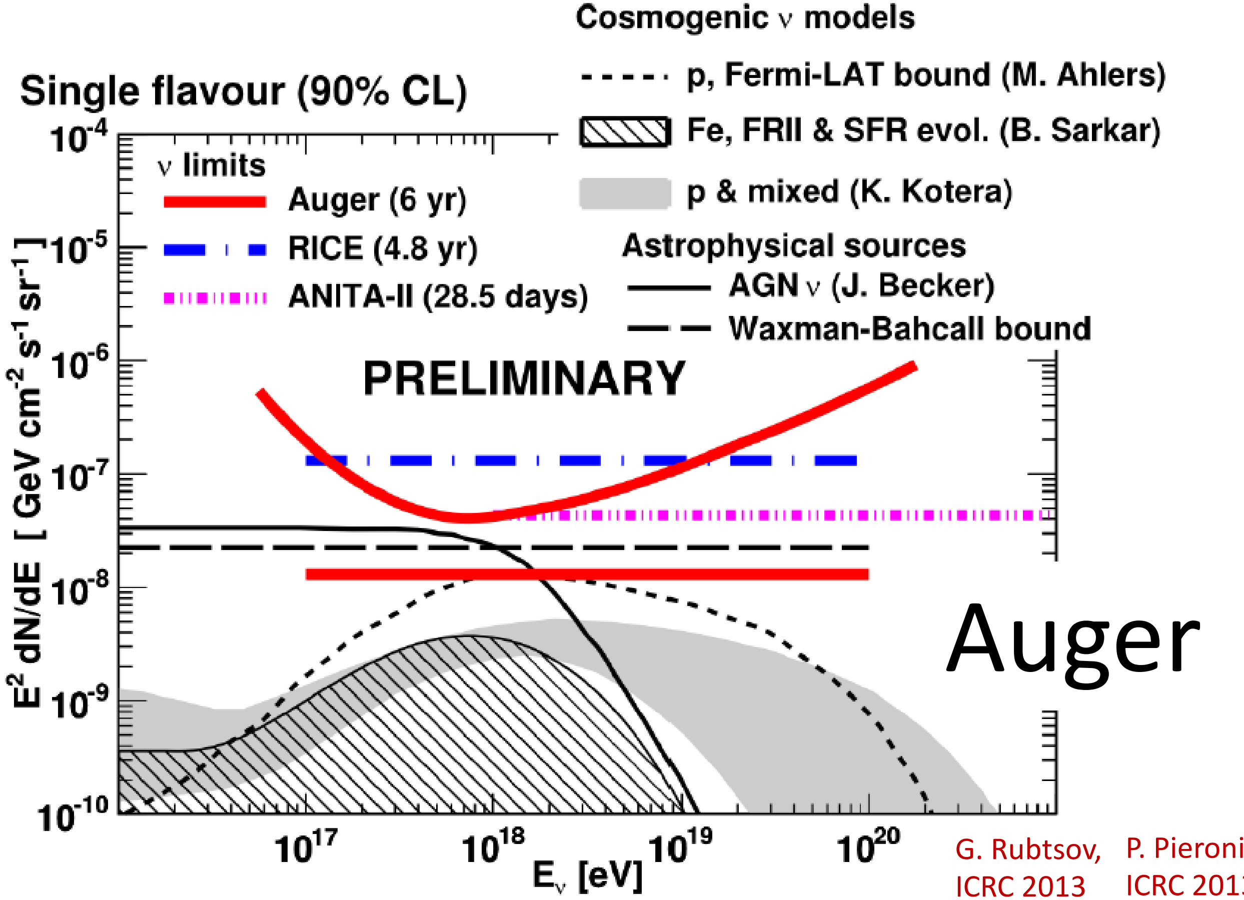
Difference between Auger and TA on Xmax:

- For $10^{18.6} < E < 10^{19.4}$ eV , where Auger's <LnA> analysis with QGSJET-II-04 simulation suggests a transition from proton to <Helium>, TA's <Xmax> and Xmax distribution are consistent with proton using QGSJET-II-03.
- Above $10^{19.4}$ eV, TA has no stat. power to separate p/Fe.
- Auger's last point for $E > 10^{19.5}$ eV is somewhat singular suggesting pure Li or CNO depending on models.

UHE Gammas and Neutrinos

- No candidates found. Limits are updated.
- Some Top-down models are strongly constrained.
- Cosmogenic neutrinos maybe showing up soon.
- GZK gammas may be seen in next generation array.



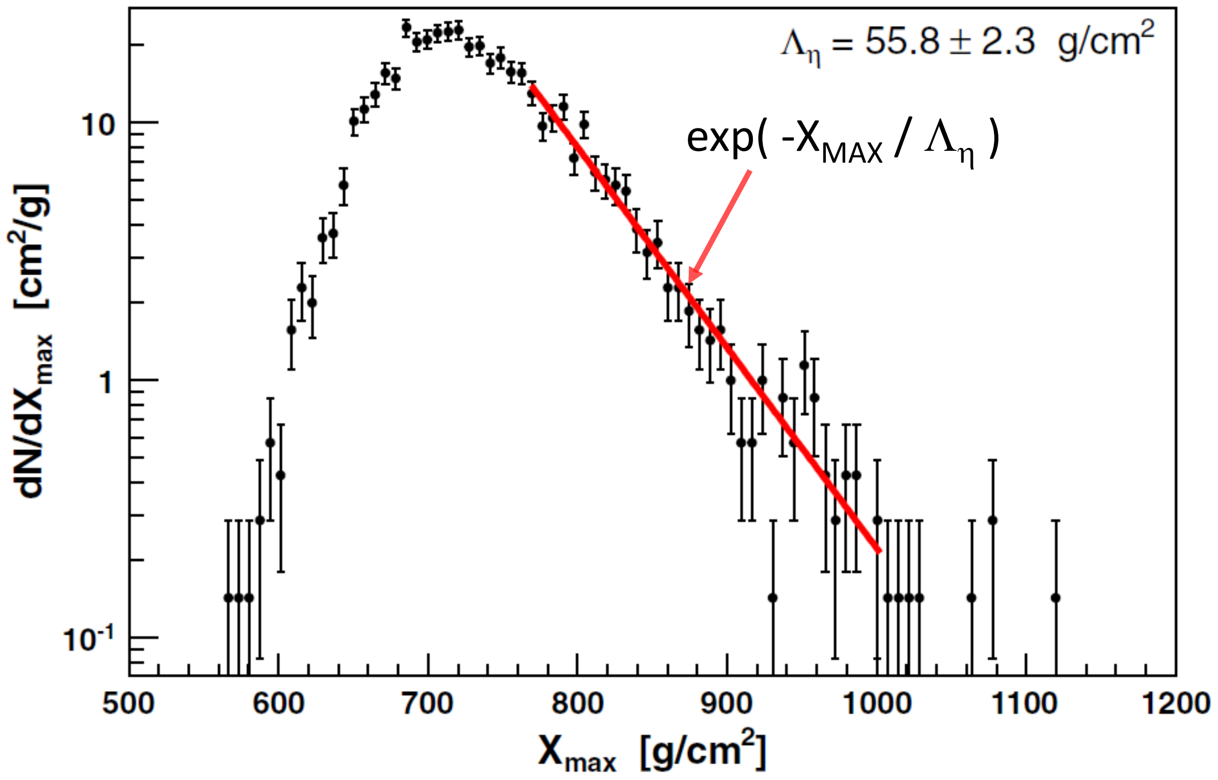


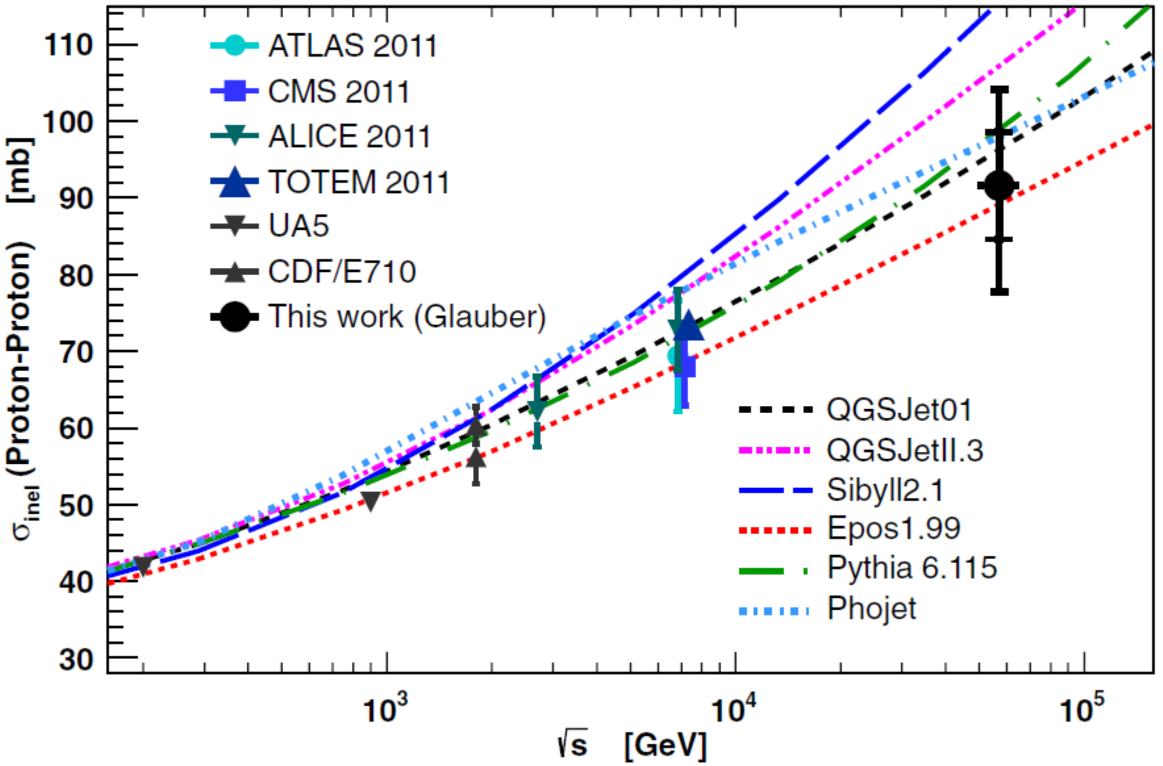
G. Rubtsov, ICRC 2013 P. Pieroni, ICRC 2013

Hadronic and Nuclear Intercation above LHC

Air Shower Simulation

p-Air Cross Section by Auger ($10^{18} < E < 10^{18.5}$ eV)





Observed Λ_η matched by tuning $\sigma_{p\text{-}Air}$ in model

Inelastic $\sigma_{p\text{-}p}$ obtained by Glauber model.

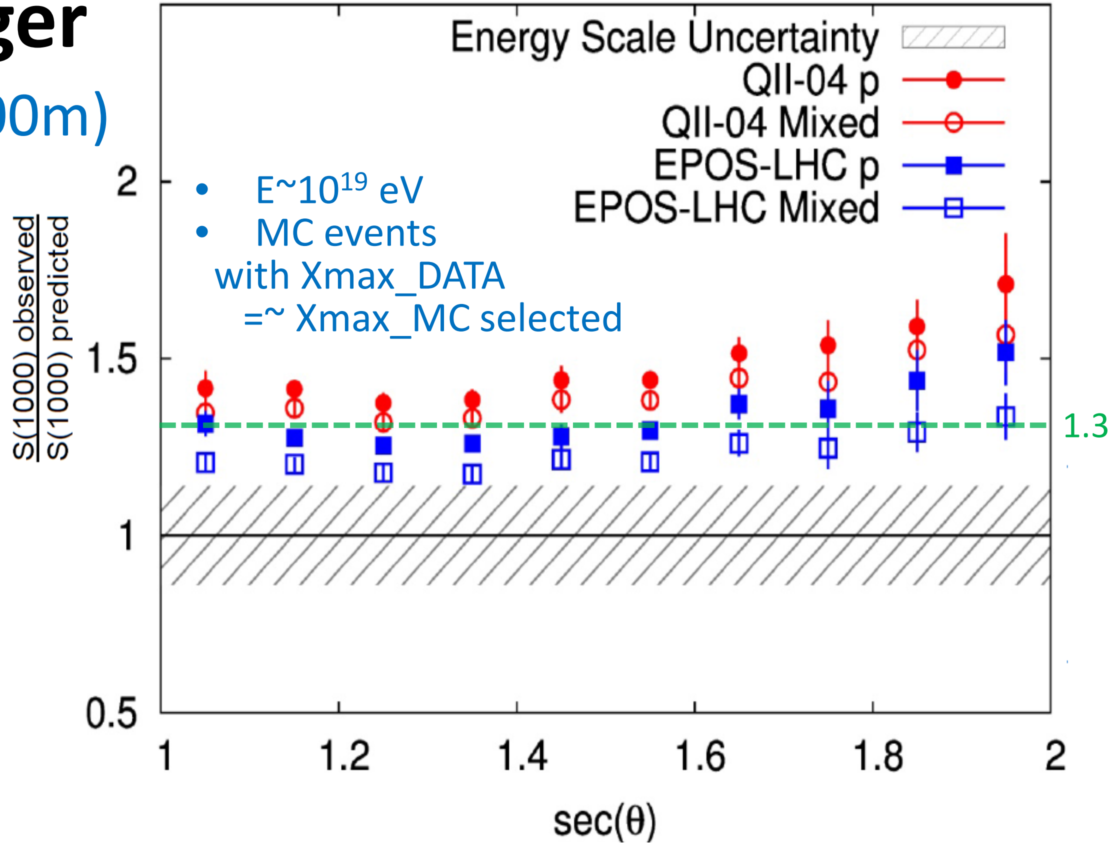
$$\sigma_{pp}^{inel} = [92 \pm 7(\mathrm{stat})^{+9}_{-11}(\mathrm{syst}) \pm 7(\mathrm{Glauber})]\ \mathrm{mb}$$

PRL 109(2012) 062002 R. Ulrich, ICRC 2011 K.H. Kampert ICRC 2011

Observed SD Signal vs Air Shower Simulation

Auger

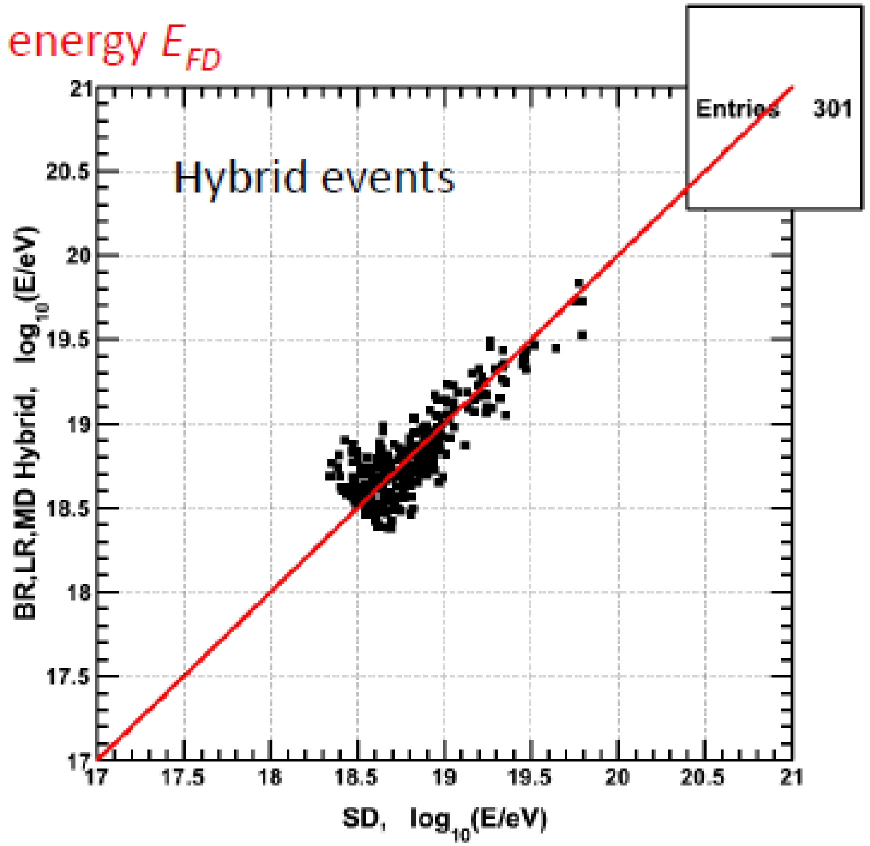
S(1000m)



TA

S(800m)

FD energy E_{FD}



SD energy E_{SD}

(scaled to FD energy)

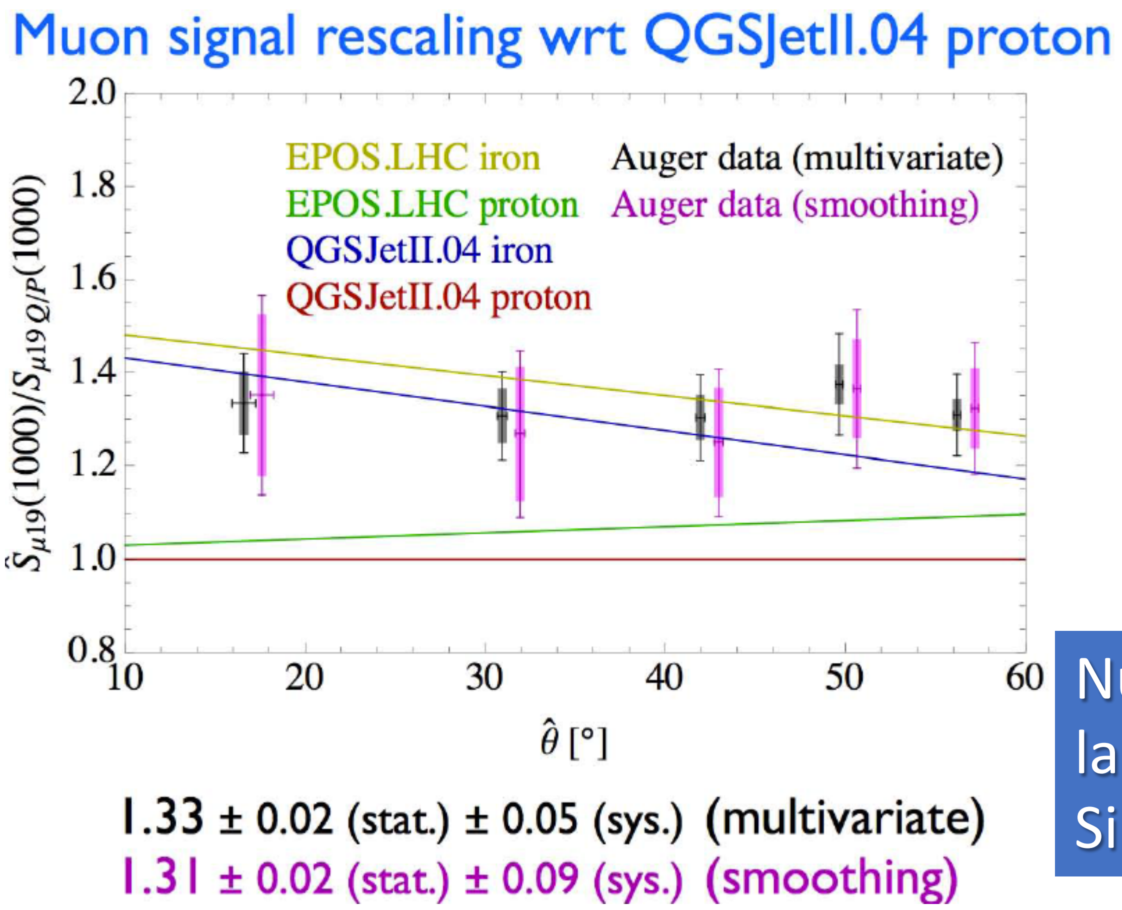
$$E_{SD} = E'_{SD}/1.27$$

SD signal is ~1.3 or more larger
than Air Shower simulation at d=800-1000m,
Water Tank (~μ) or Scintillator (~EM).

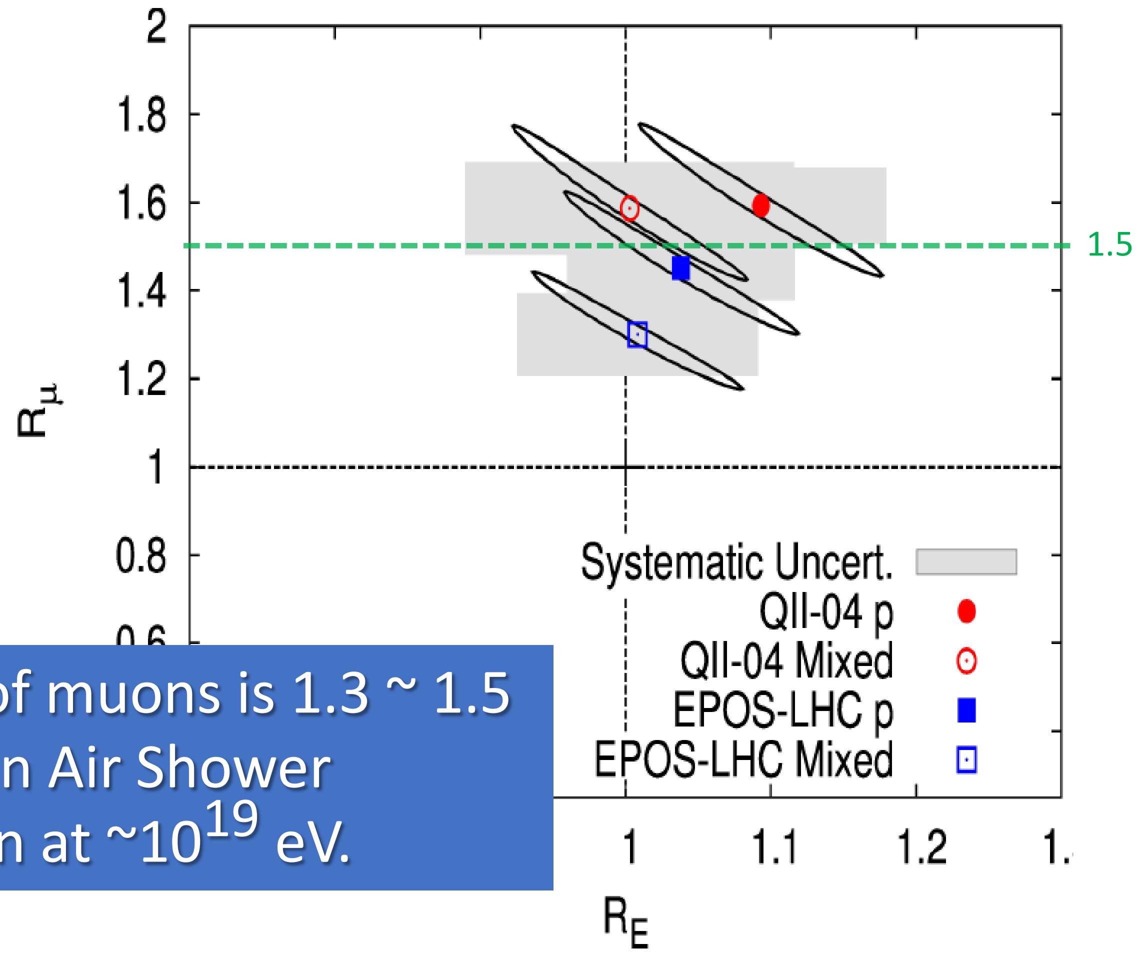
G. Farrar, ICRC 2013 H. Sagawa, ICRC 2013

Observed μ Signal vs Air Shower Simulation

Auger



Auger



Number of muons is 1.3 ~ 1.5 larger than Air Shower Simulation at ~10^{19} eV.

- Separating μ and EM signal by wave form and timing.
- E ~ 10^{19} eV and d ~ 1000m

- Energy and μ rate of MC can be fitted
- Using Xmac_DATA ~ Xmax_MC events.

B. Kegl, ICRC 2013

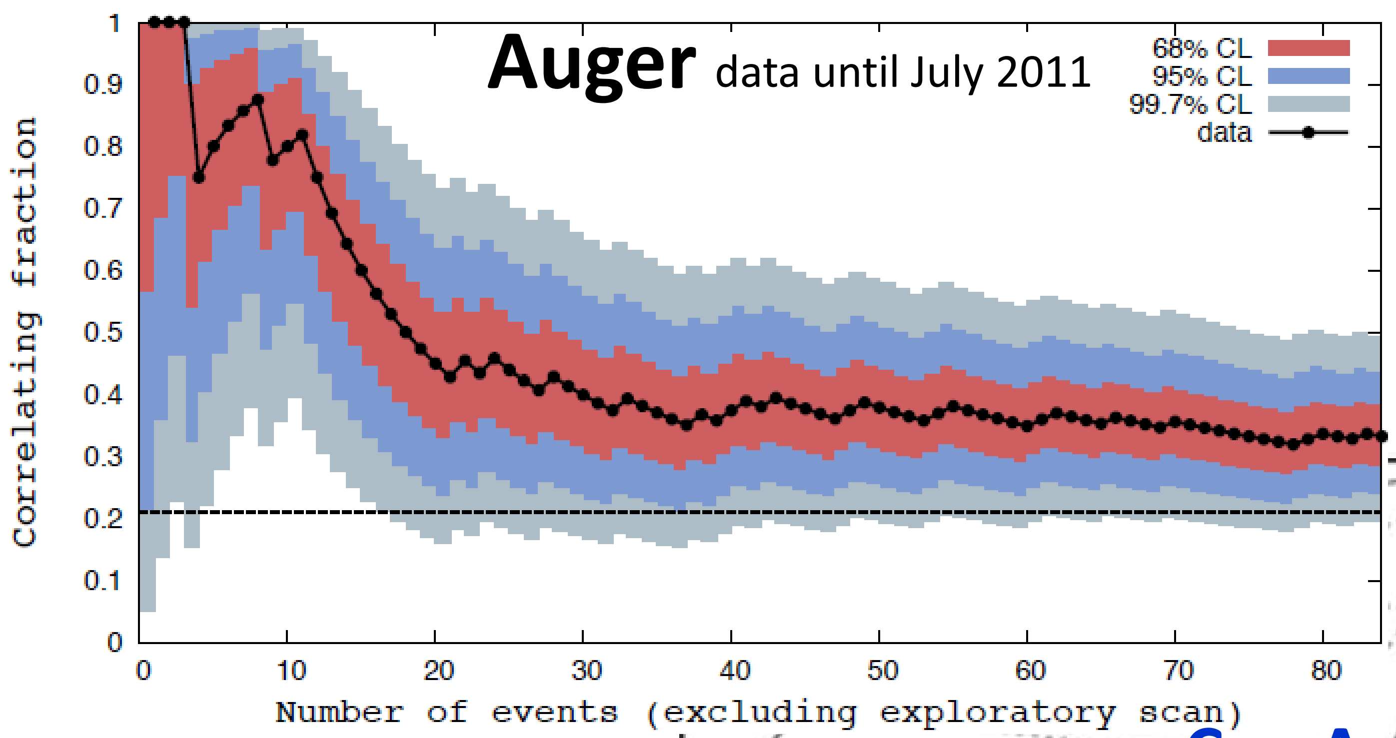
G. Farrar, ICRC 2013

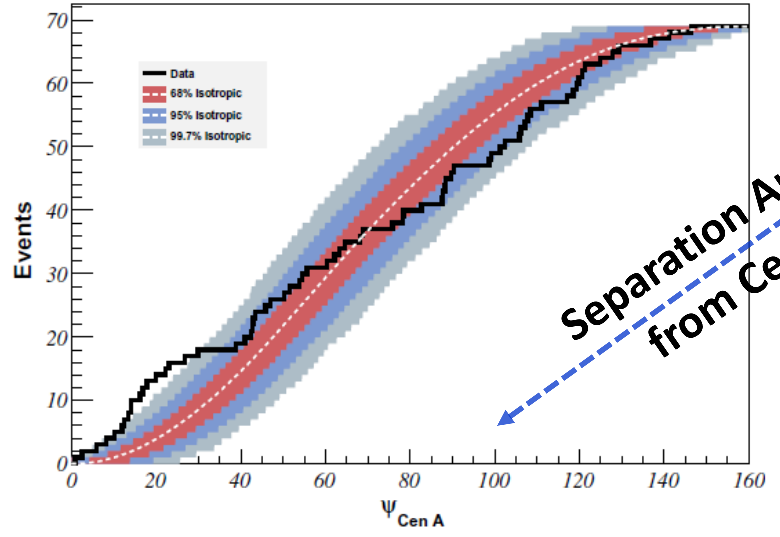
Arrival Directions

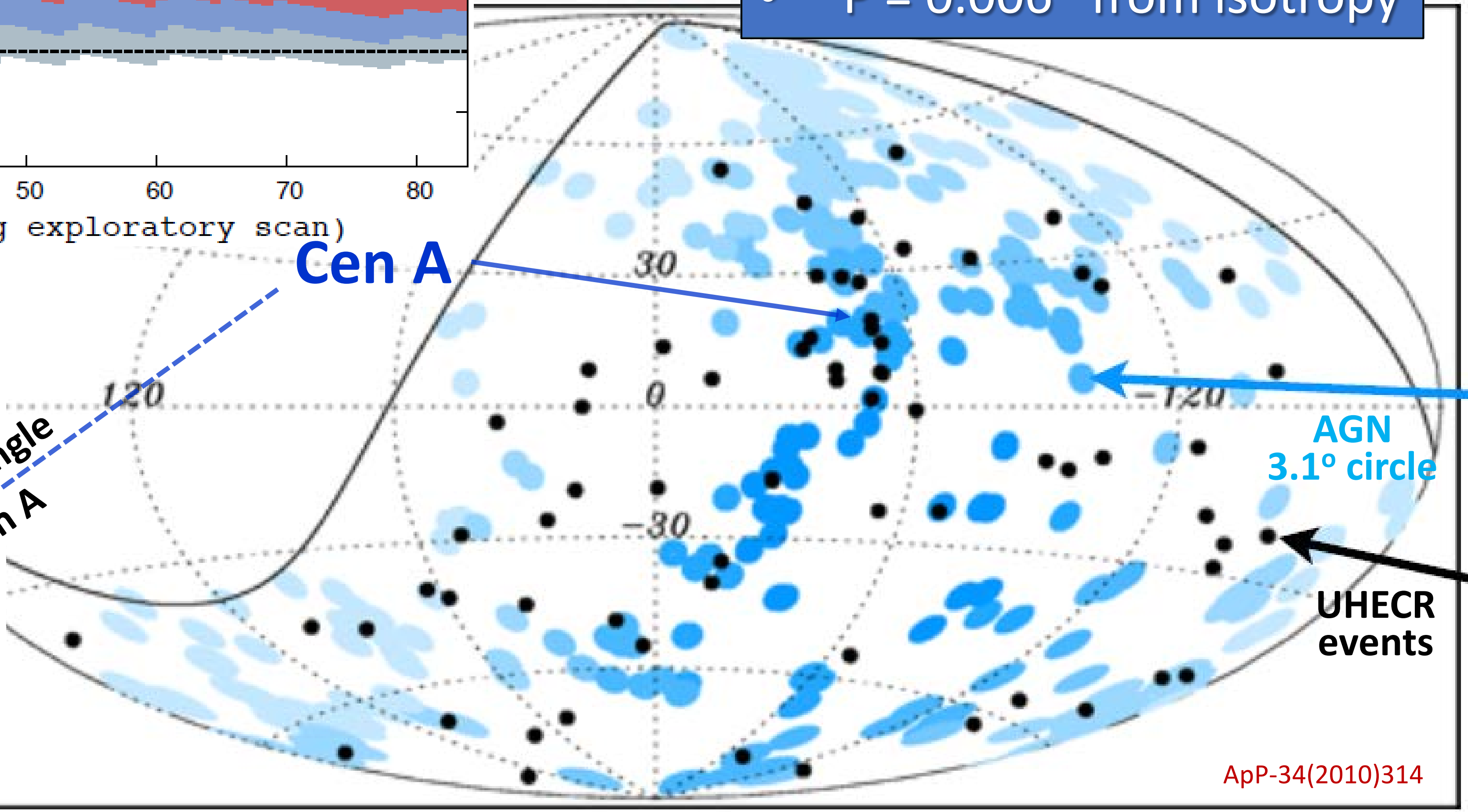
- Anisotropy
- Association with Astronomical Objects
- Clusters of events

Correlation with AGN in VCV Catalogue within 75Mpc

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





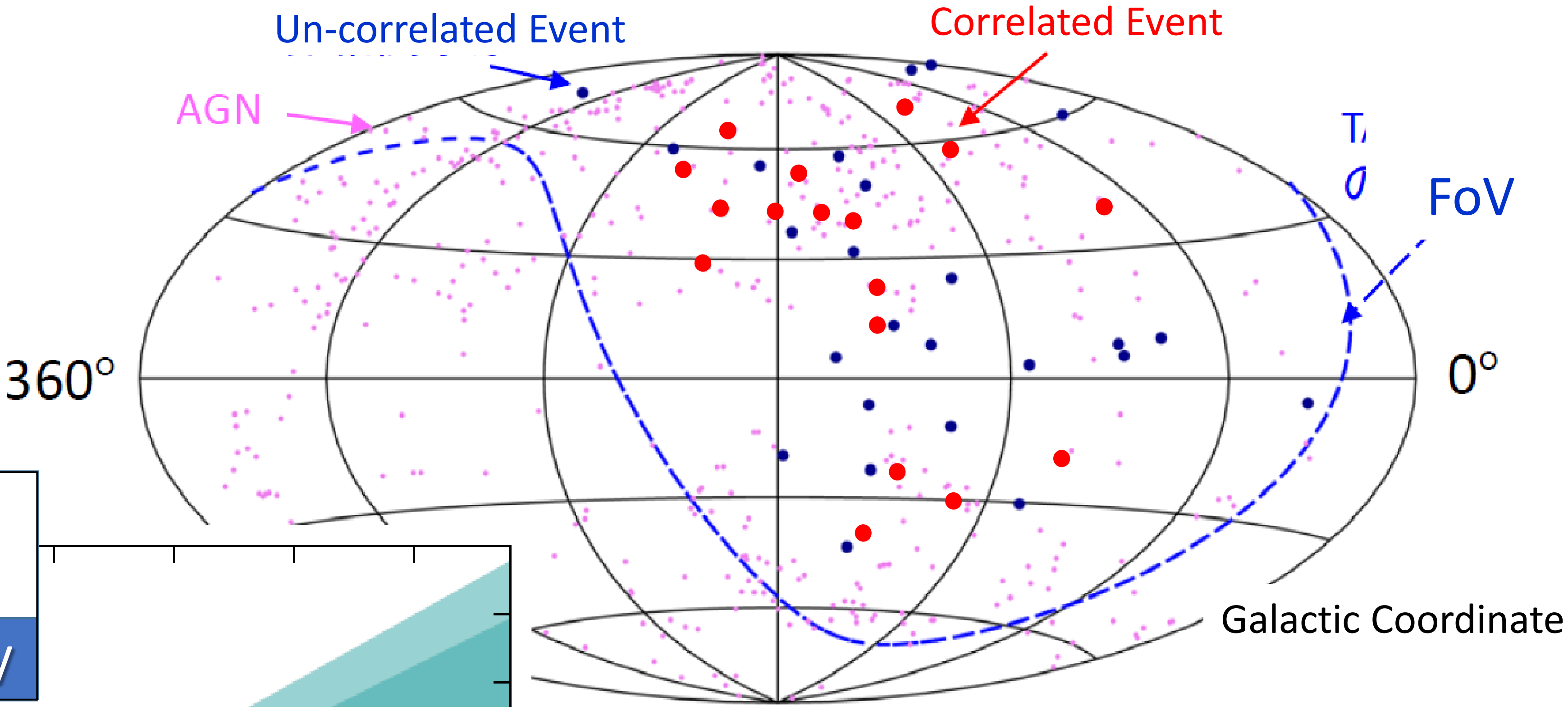


ApP-34(2010)314

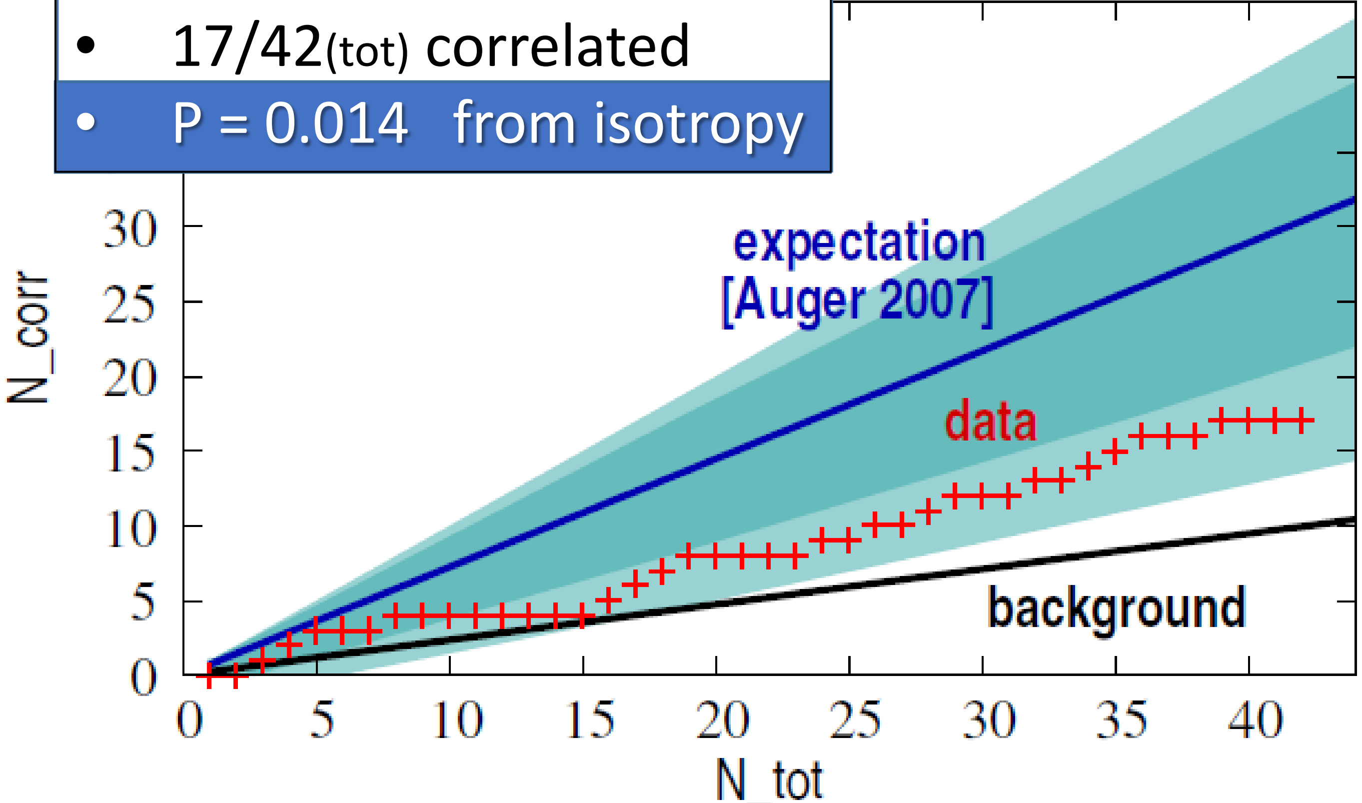
TA

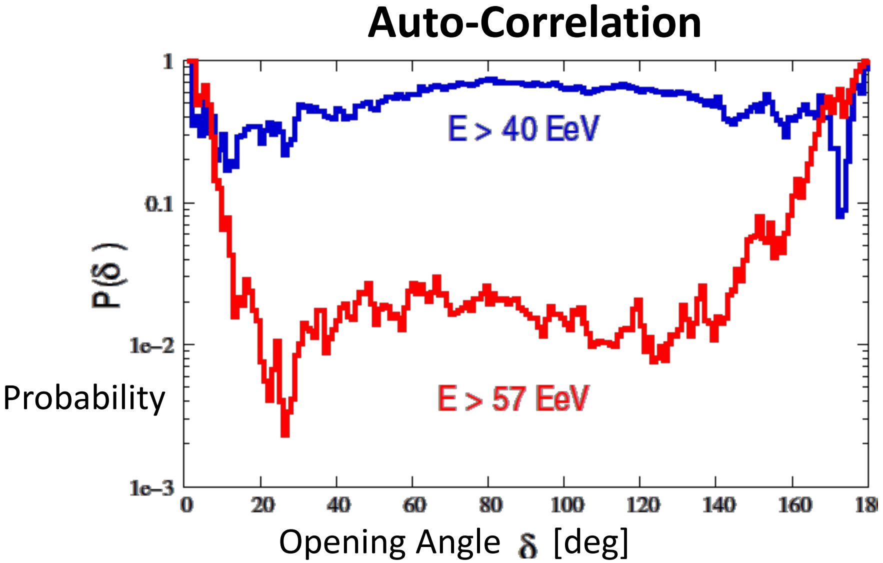
Correlation with VCV in the north

- 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



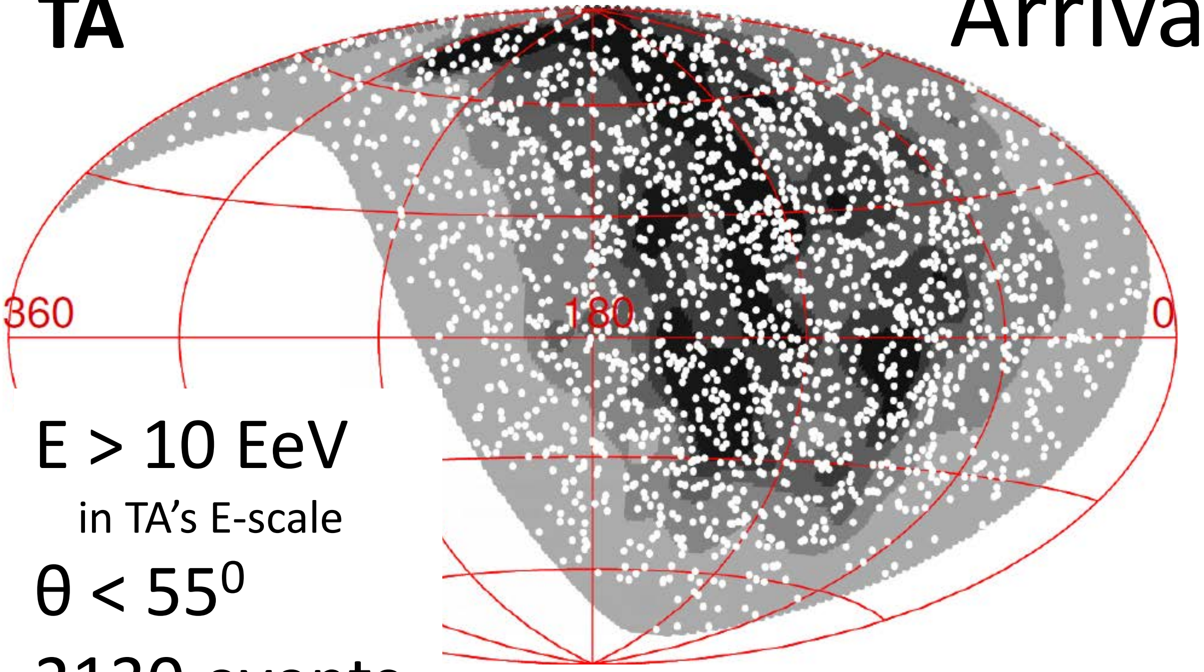


P. Tinyakov, ICRC2013

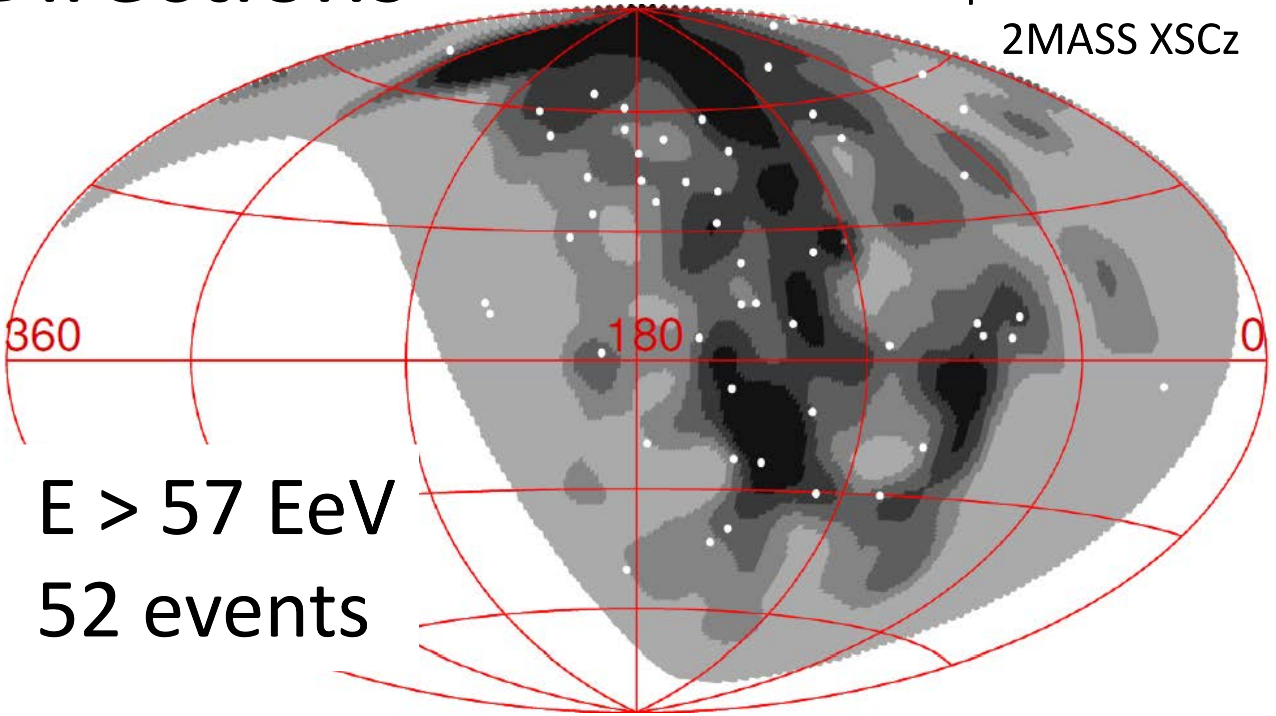
TA

Arrival Directions

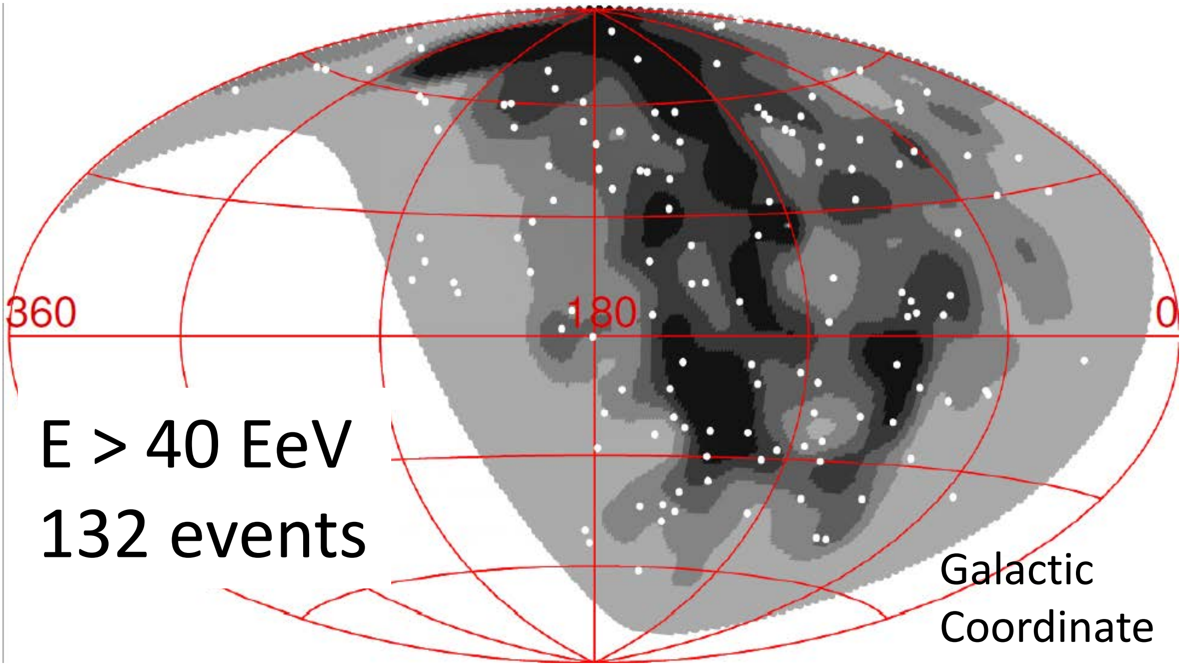
Shades: expectation from 2MASS XSCz



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



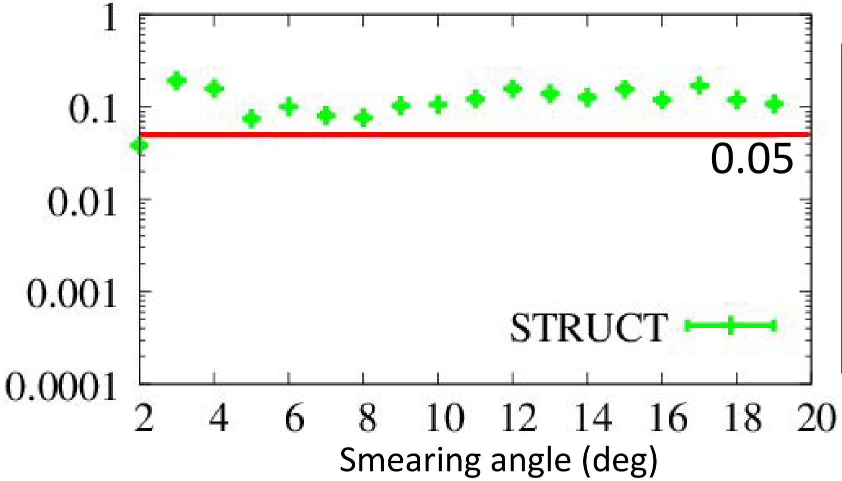
E > 57 EeV
52 events



E > 40 EeV
132 events

Galactic Coordinate

Compatibility with LSS expectation (shades)



Compatibility with Isotropy:
p ~ 0.001
for 6^0 smearing

TA

A Cluster of Events in Hotspot

Looser cuts:

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

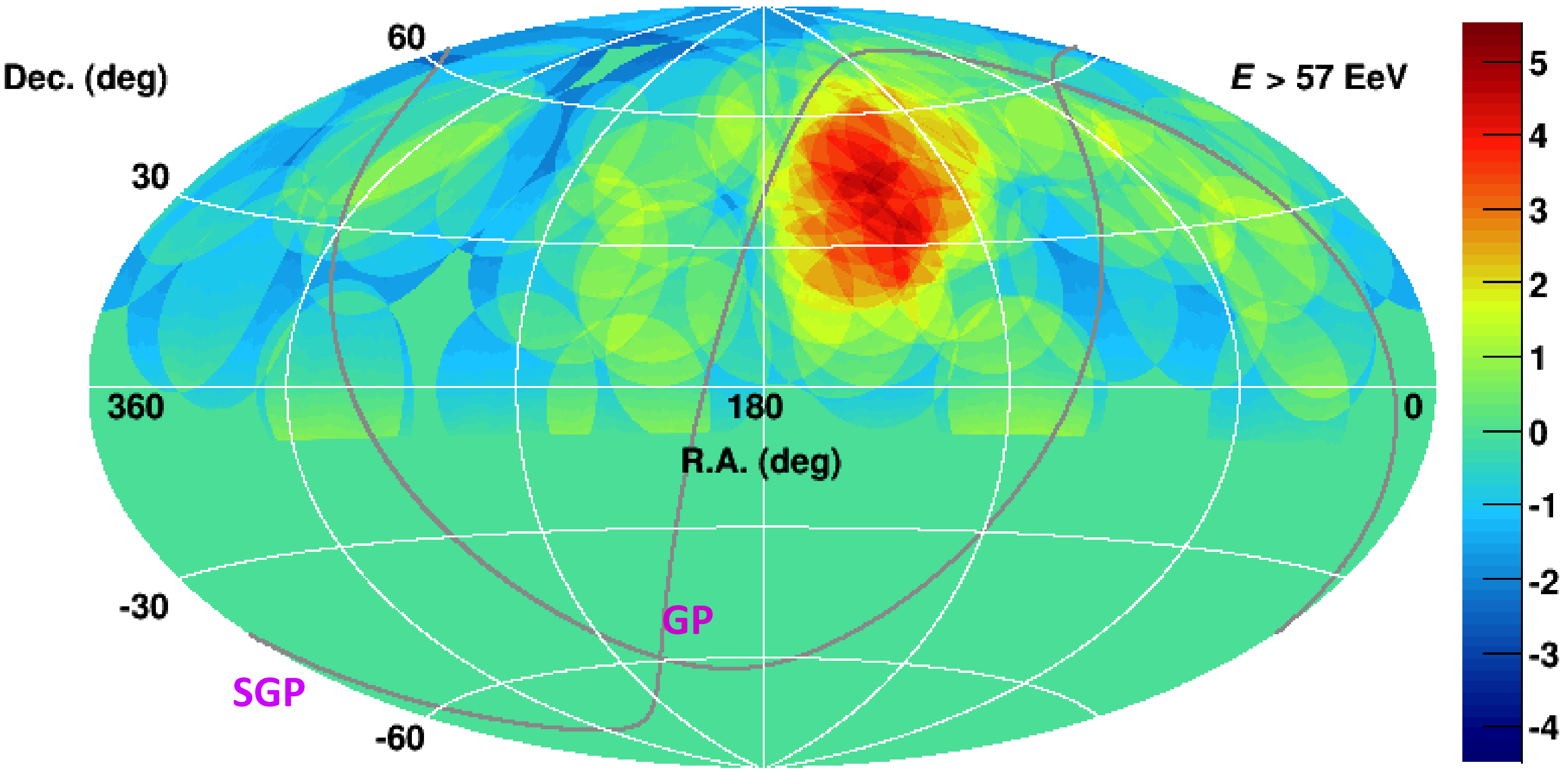
2008 May – 2013 May:
A Total of 72 events selected.

Oversampling with r = 20^0 circle

Background from 72 random isotropic events estimated by MC

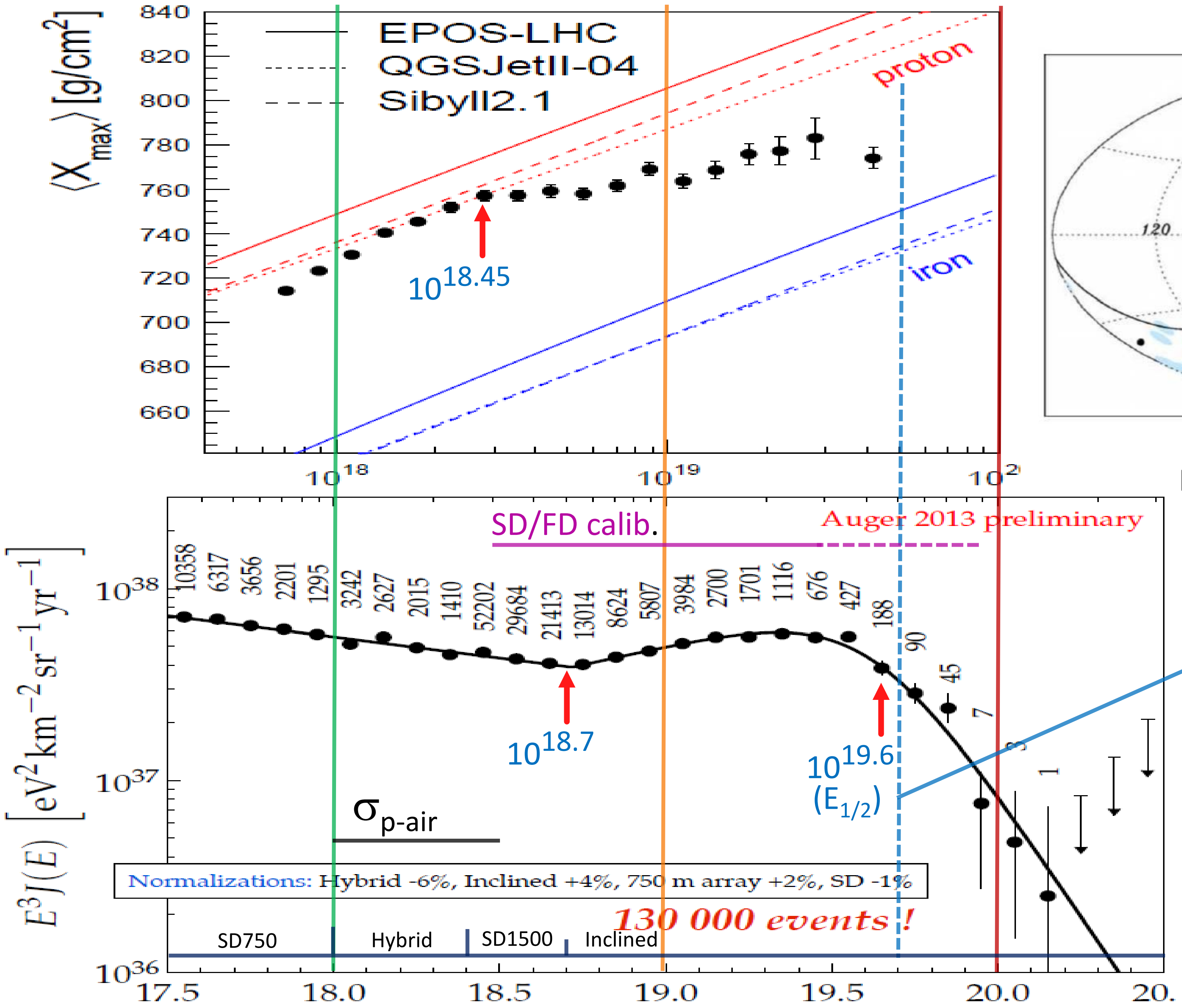
Maximum significance in hot spot is 5.1 σ by Li-Ma method

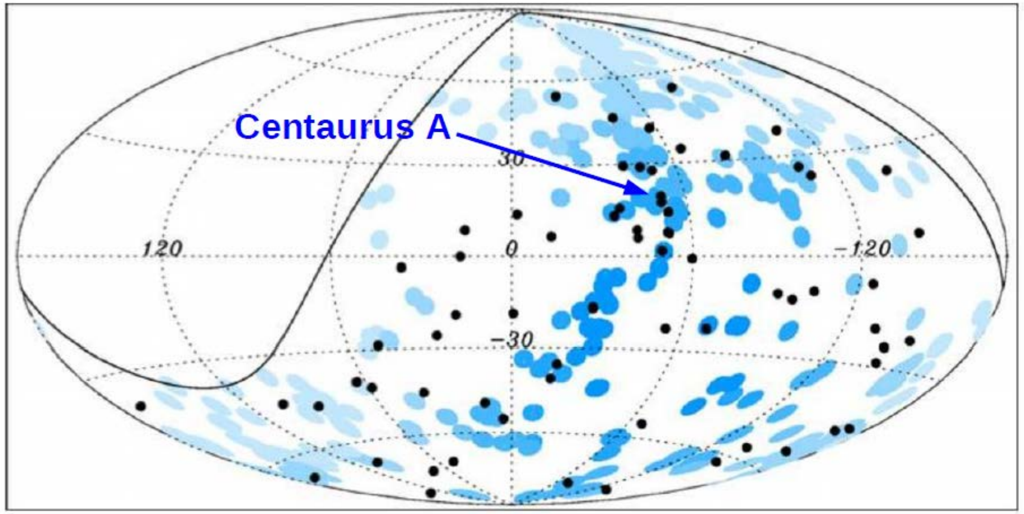
Post-trials chance probability is being estimated.



Summary

- Pierre Auger Observatory
- Telescope Array





E> 57 EeV

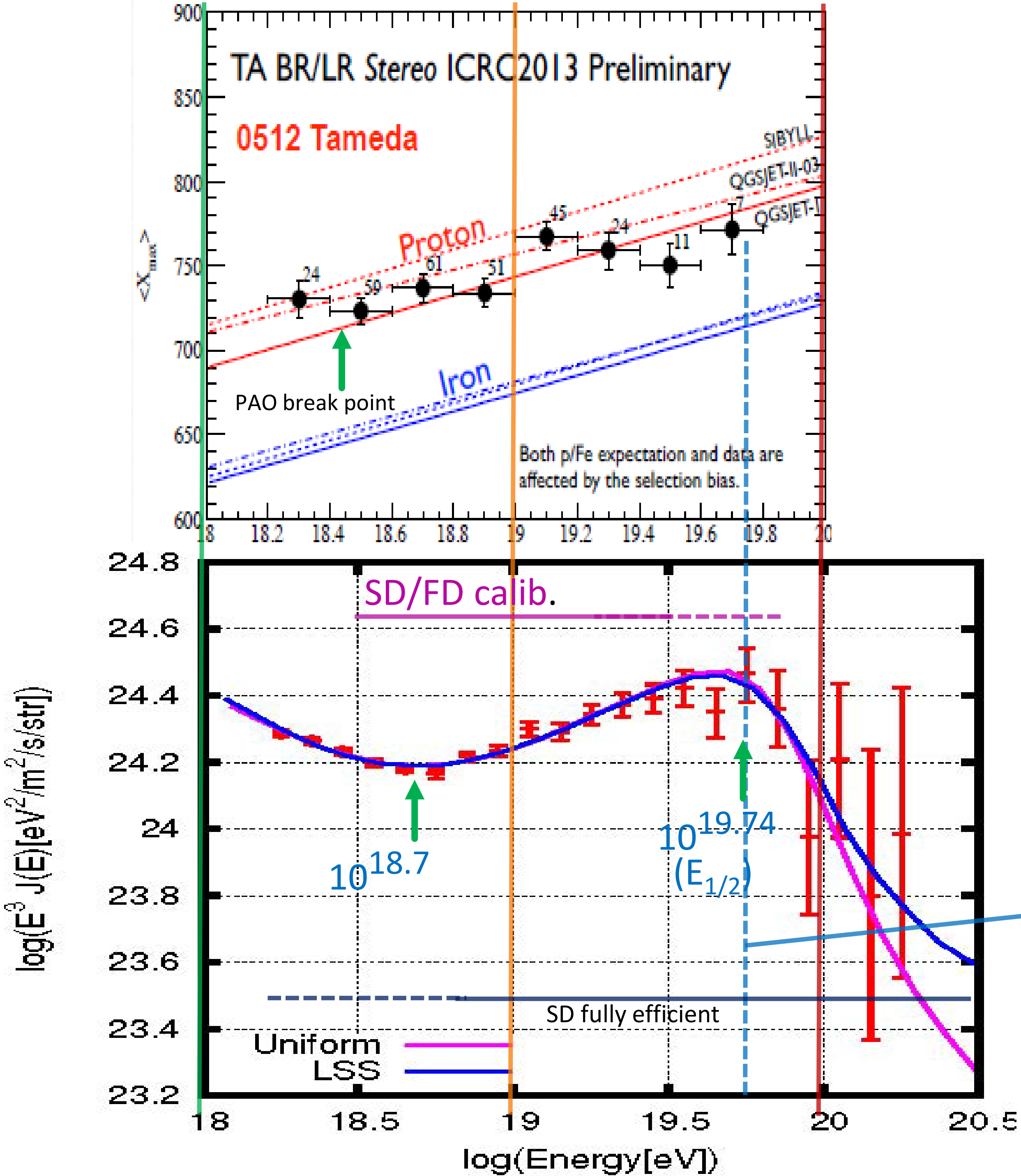
AUGER AGN correlation

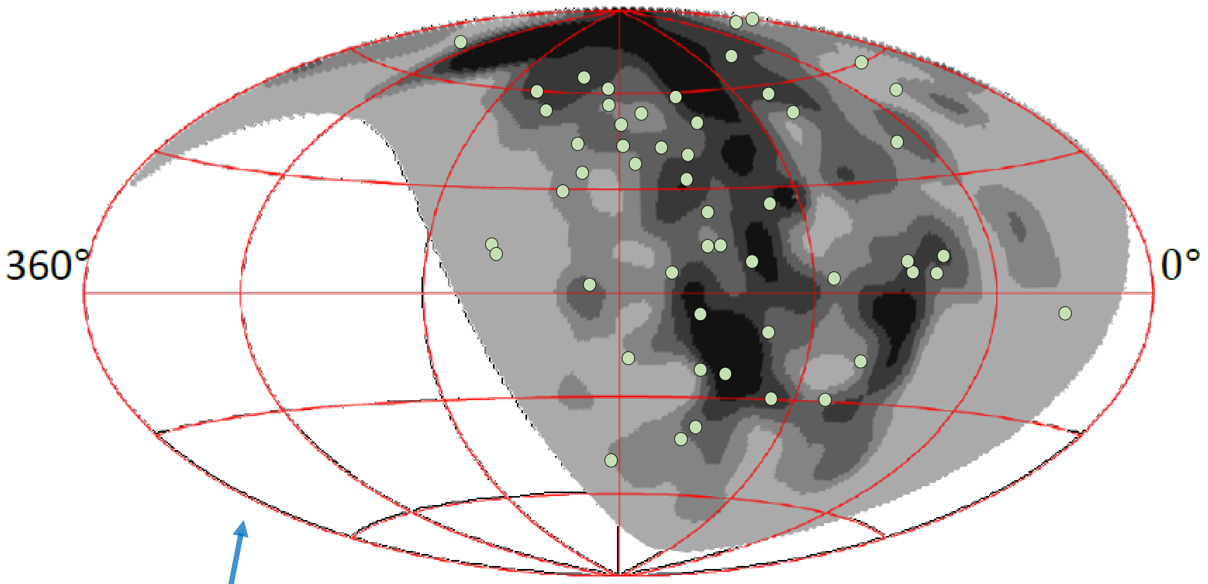
- 28/84 correlated
- P = 0.006 from randoms
- Cluster at Cen A?

TA with same selection

- 17/42 correlated
- P = 0.041

Summary of Auger

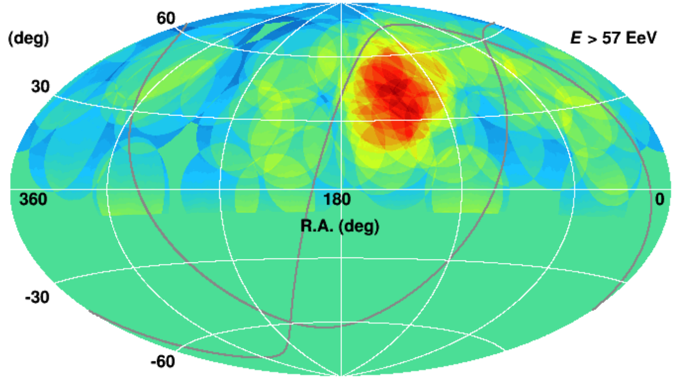




E> 57 EeV

LSS correlation (6^0 smearing)

- P = 0.1 from LSS
- P = 0.001 from isotropy
- Cluster of ~20^0 radius near the SG plane



Summary of TA

prospects

Auger and TA run for next 10 years with

- ◆ Auger extension for efficient mu-tag at each SD and
- ◆ TA extension for x4 acceptance (+500 SDs and +1 FD)

Collaboration started on

- ◆ S+N all sky coverage, common anisotropy analysis
- ◆ understand differences in composition and E-scale by exchanging calib, analysis, simulation, tank/scint…

Both are harboring RD projects for

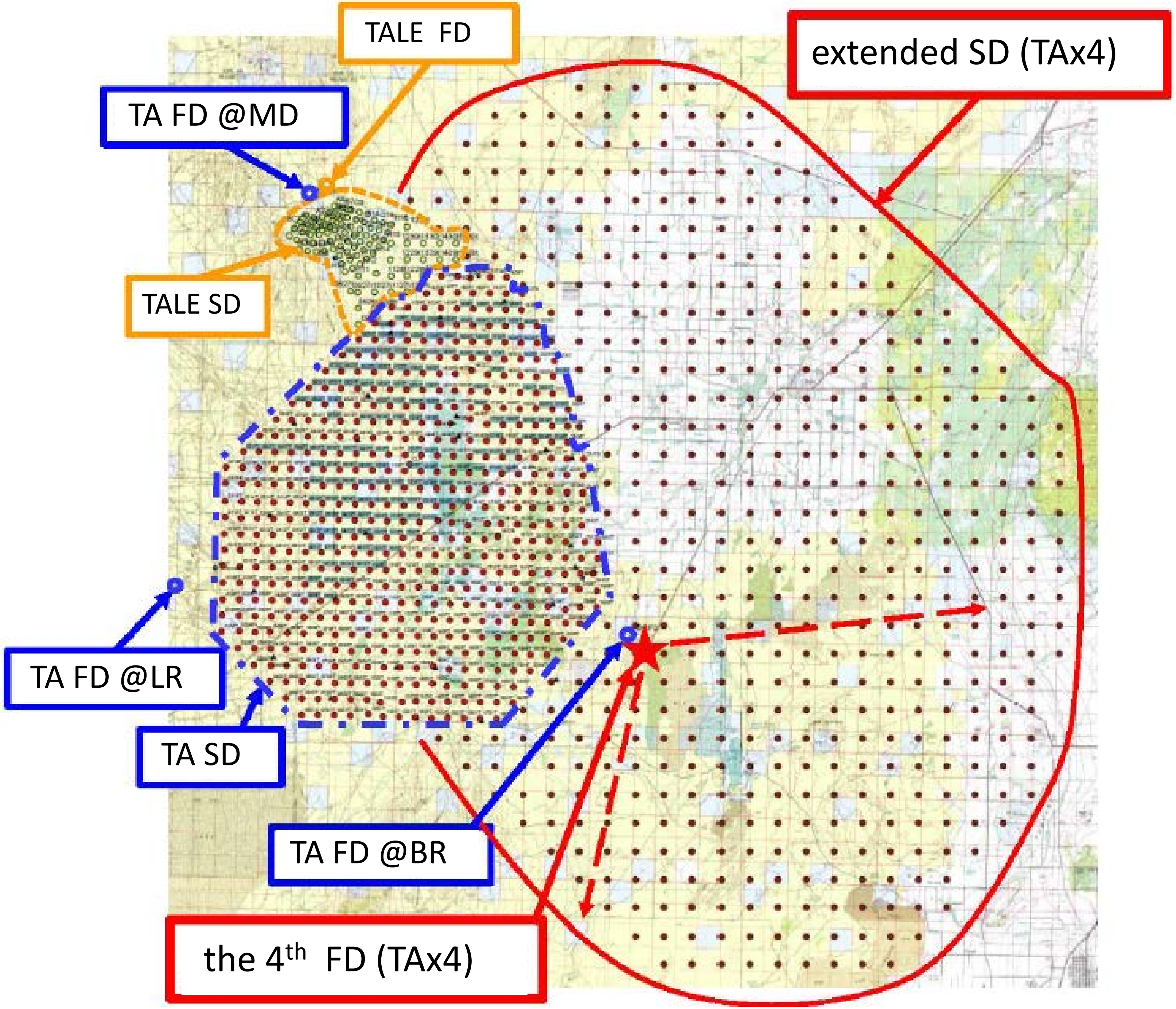
- ◆ Radio detection (MHz, GHz, Radar,…)
- ◆ Testing and calibrating JEM-EUSO prototype
- ◆ High performance SD/FD/RD for future super-Ground-Array
- ◆ Earth and atmospheric science

JEM-EUSO on ISS (2017 -)

super-Ground-Array

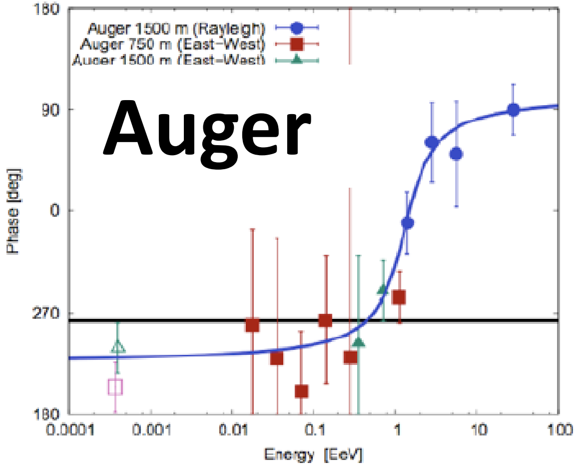
TAx4:
Near Future Operations of TA

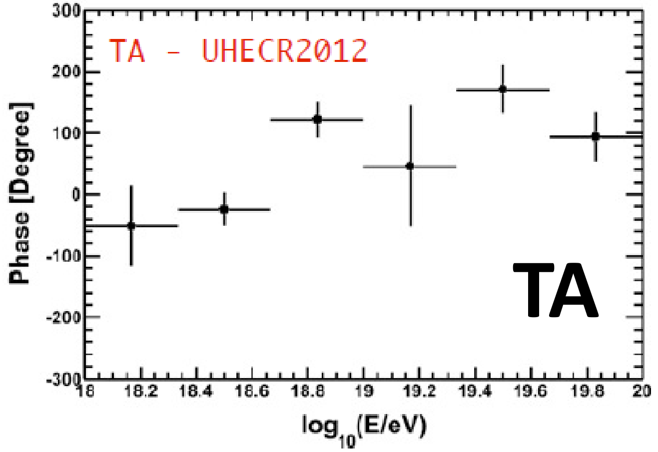
- Construction expected in 2014-2015.
- Anisotropy and Hotspot : ~5σ confirmation by 2019.



Upper limit on 1st harmonic amplitude (Auger), but change of phase seen?

Common Isotropy Analysis using Auger and TA data



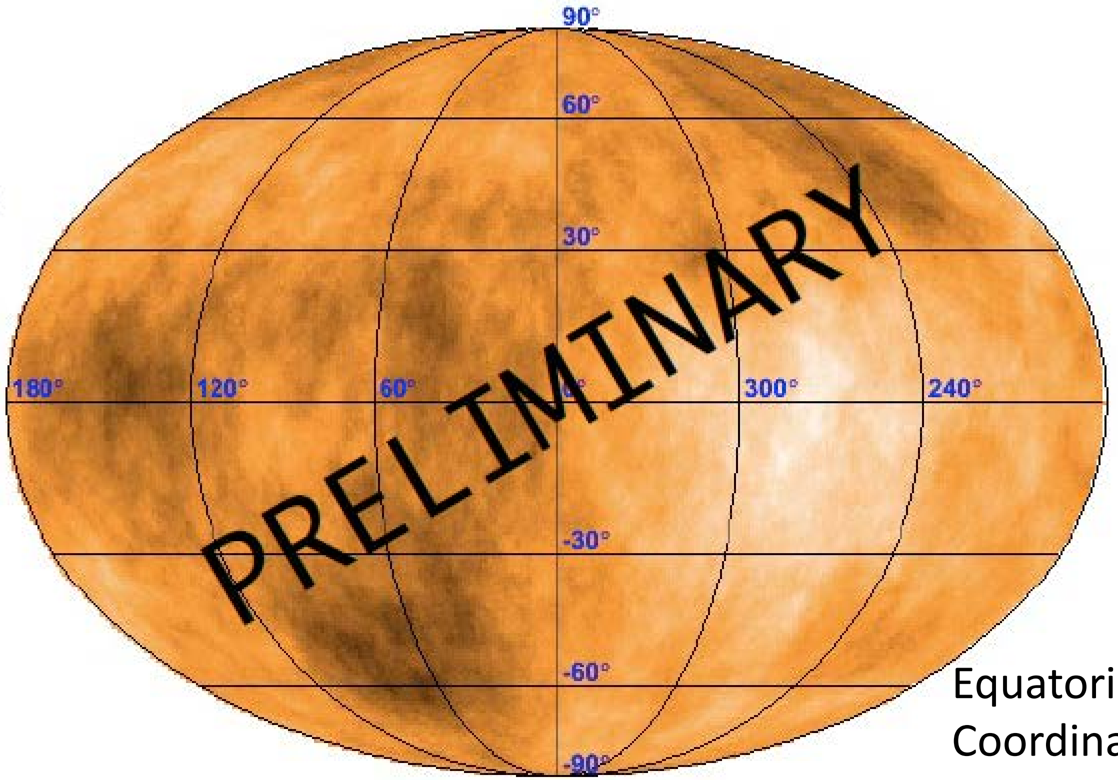


- Auger/TA acceptance matching
- E > 10^{19} eV in TA scale
- Fitting with spherical harmonics

N_{TA}~1800
(~5200 km^2 sr yr)

TA
+
Auger

N_{Auger}~10900
(~32000 km^2 sr yr)

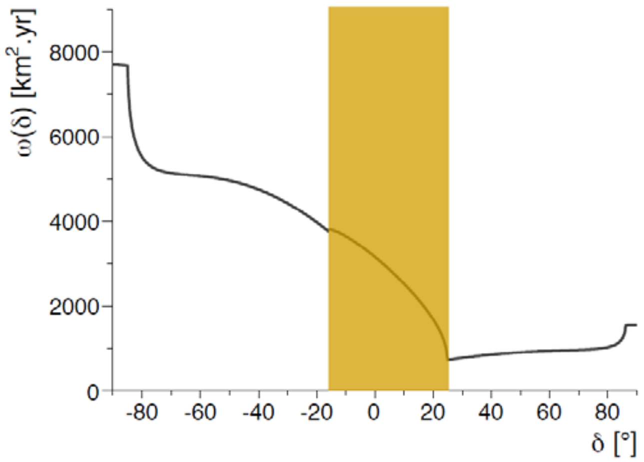


Equatorial Coordinate

In the overlap :

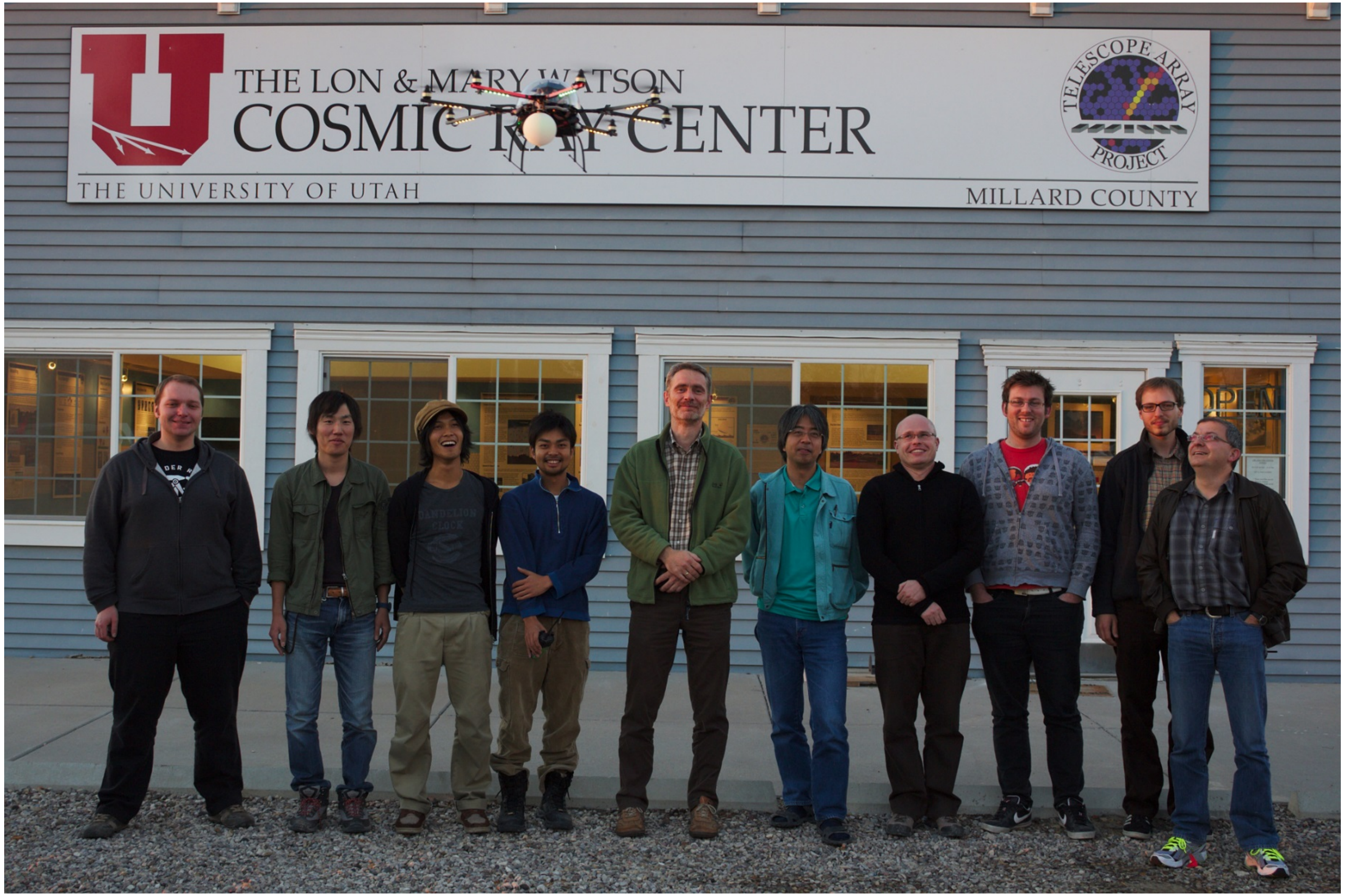
N_{TA}~650

N_{Auger}~3400

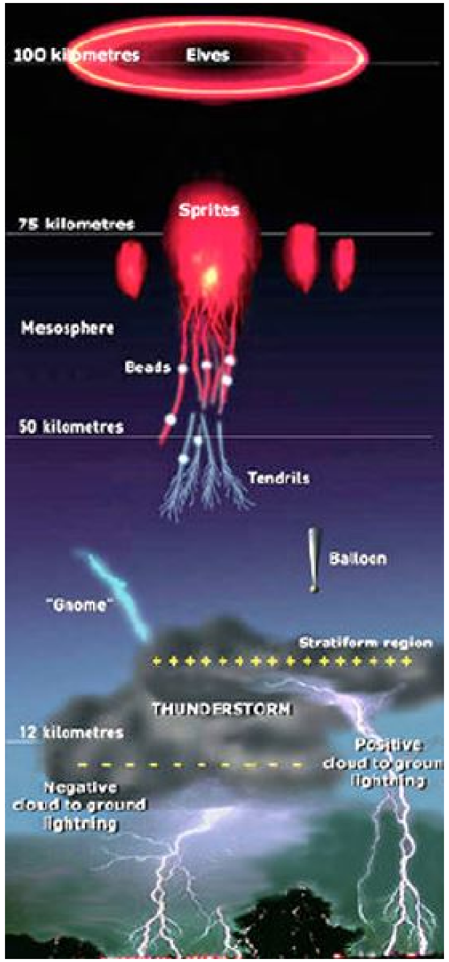


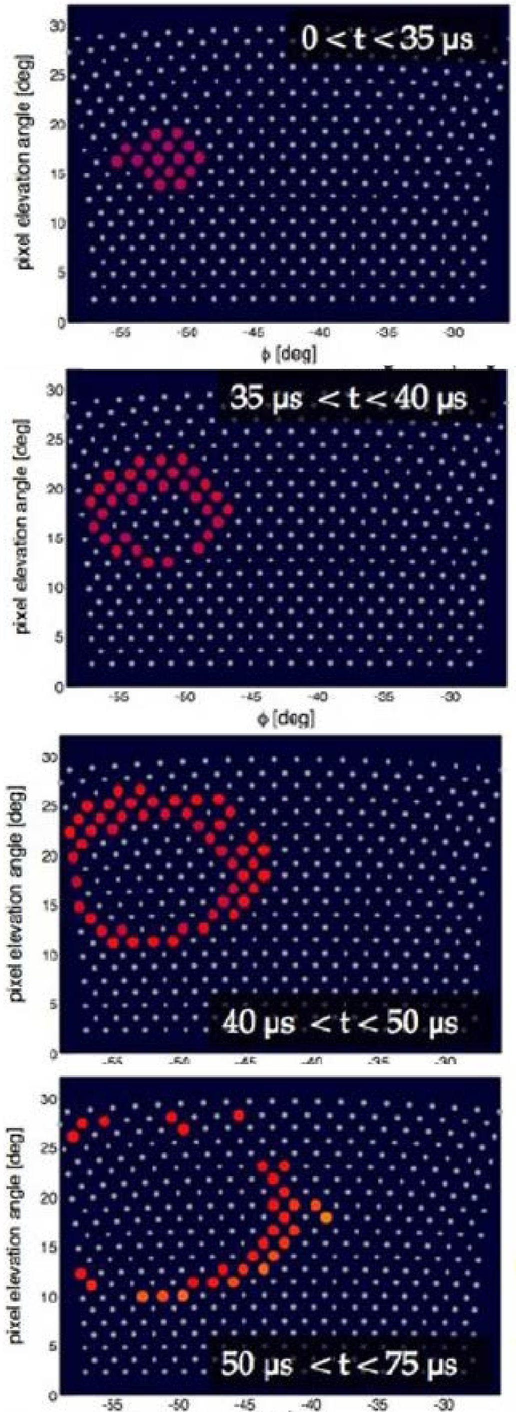
O. Deligny, ICRC 2013

Octocopter of Auger flew twice in 2012 and 2013 over TA's night sky with calibrated UV-LED light source.



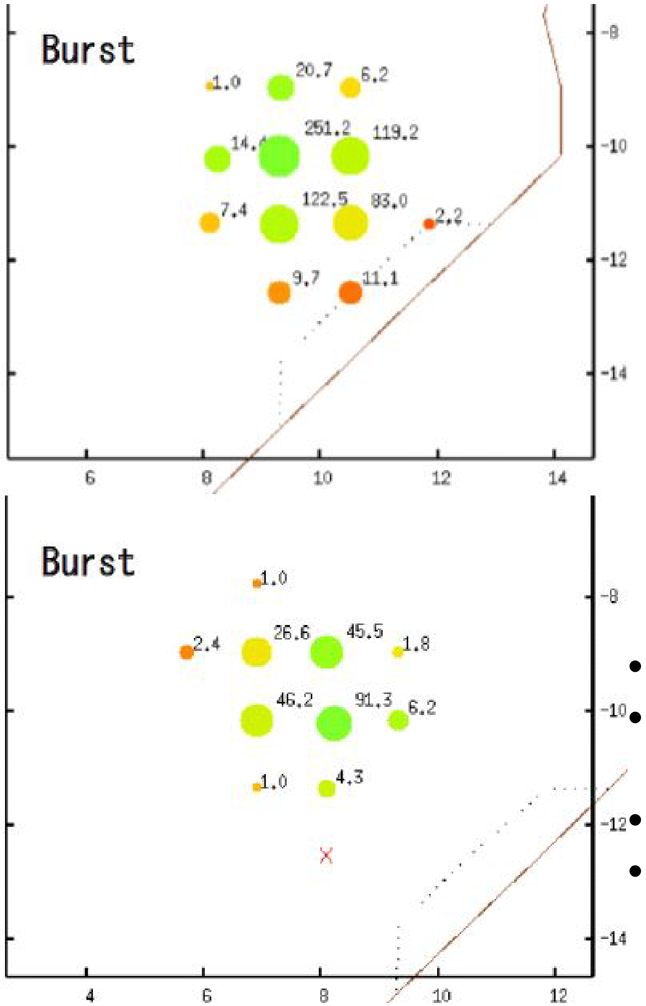
ELVES observed by Auger FD



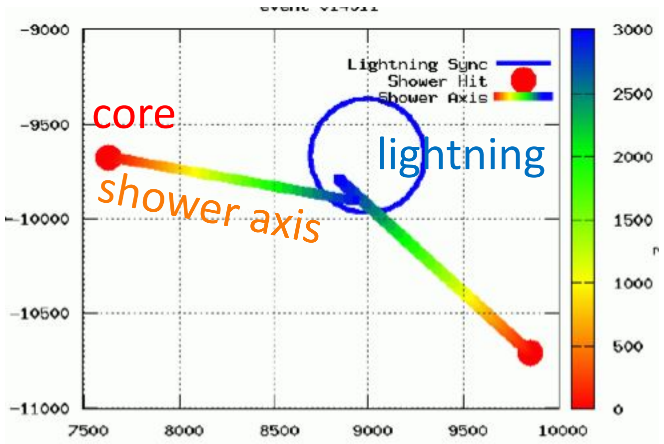


Burst of particle showers observed by TA SD associated with lightning

5 bursts in 5 years



- Example of one burst
- 2 particle showers within 1ms.
- ~10^{-4} event from randoms.



- Core locations ~2km apart.
- Common "origin" ~3km above Ground. (highly curved shower front r~3km)
- Lightning found within 1ms (NLDN-db)
- Lightning location ~ core location

Tonachini, K.H. Kampert
ICRC 2011

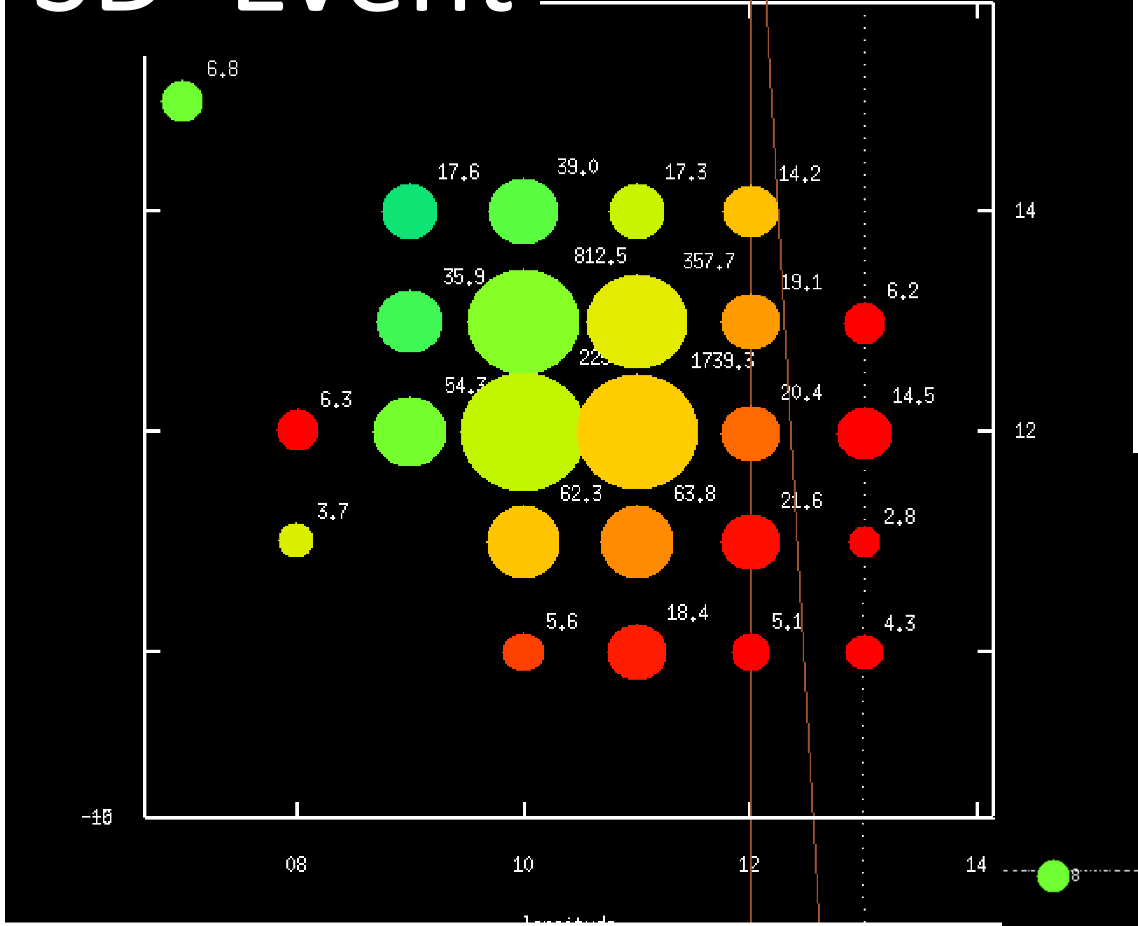
T. Okuda
CosPA 2013

End

SD Event

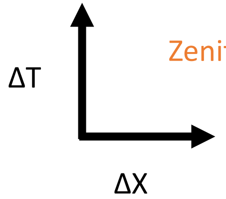
090122-225422
TH~38^0

TA

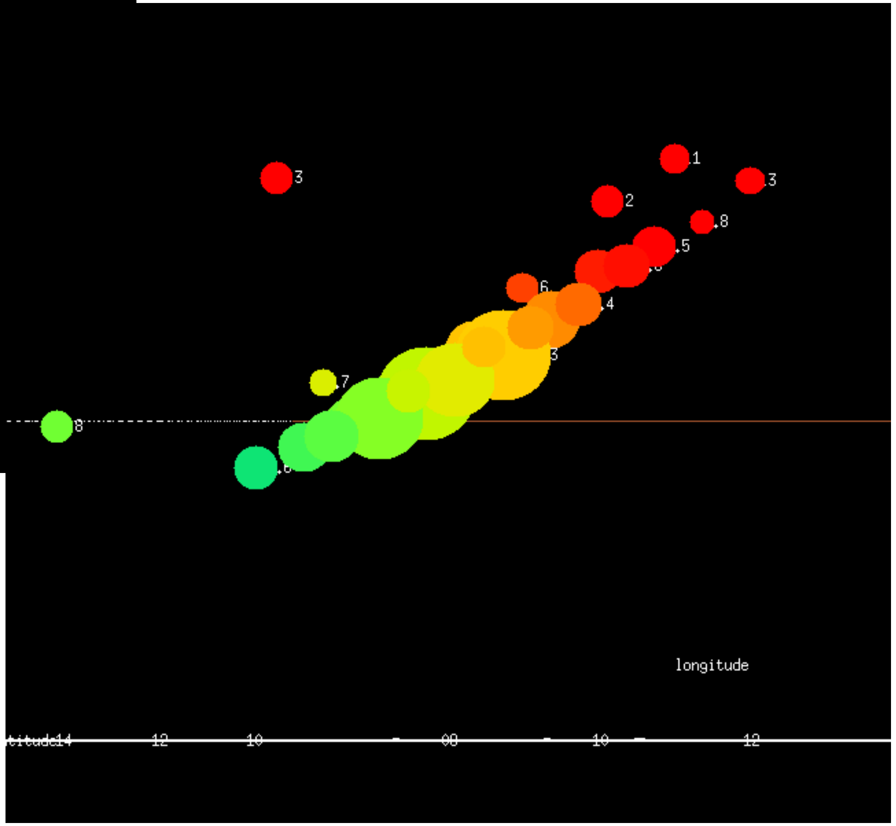


Event Top View

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

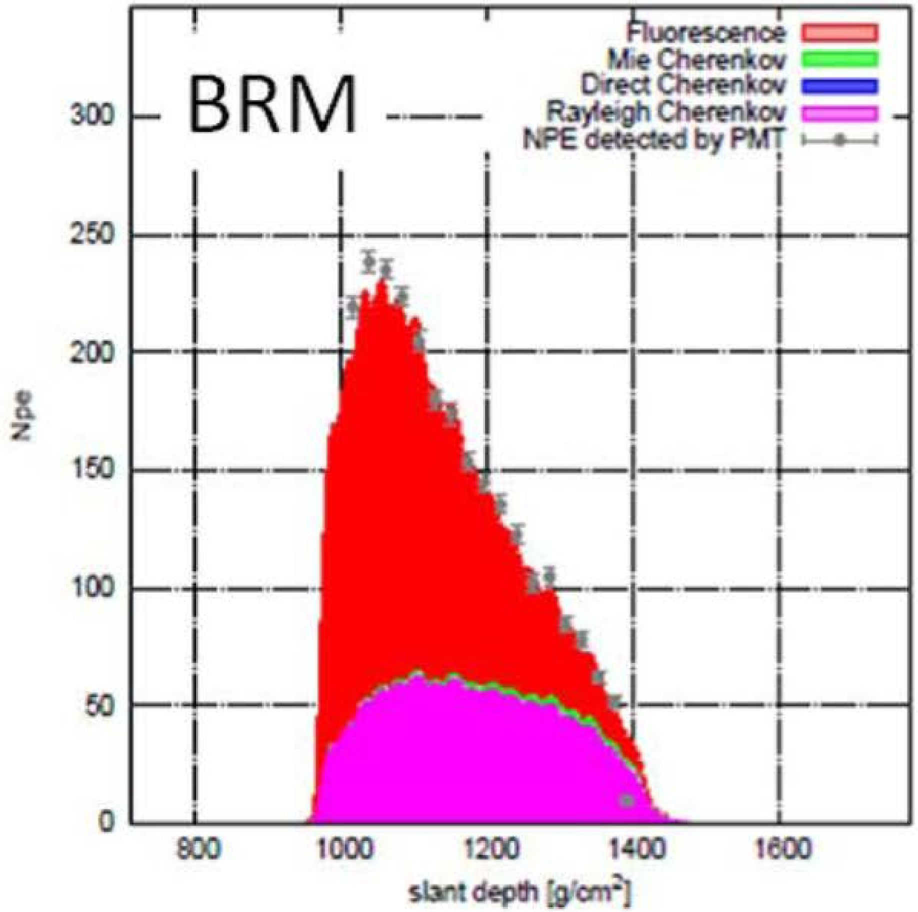


Event "Side" View

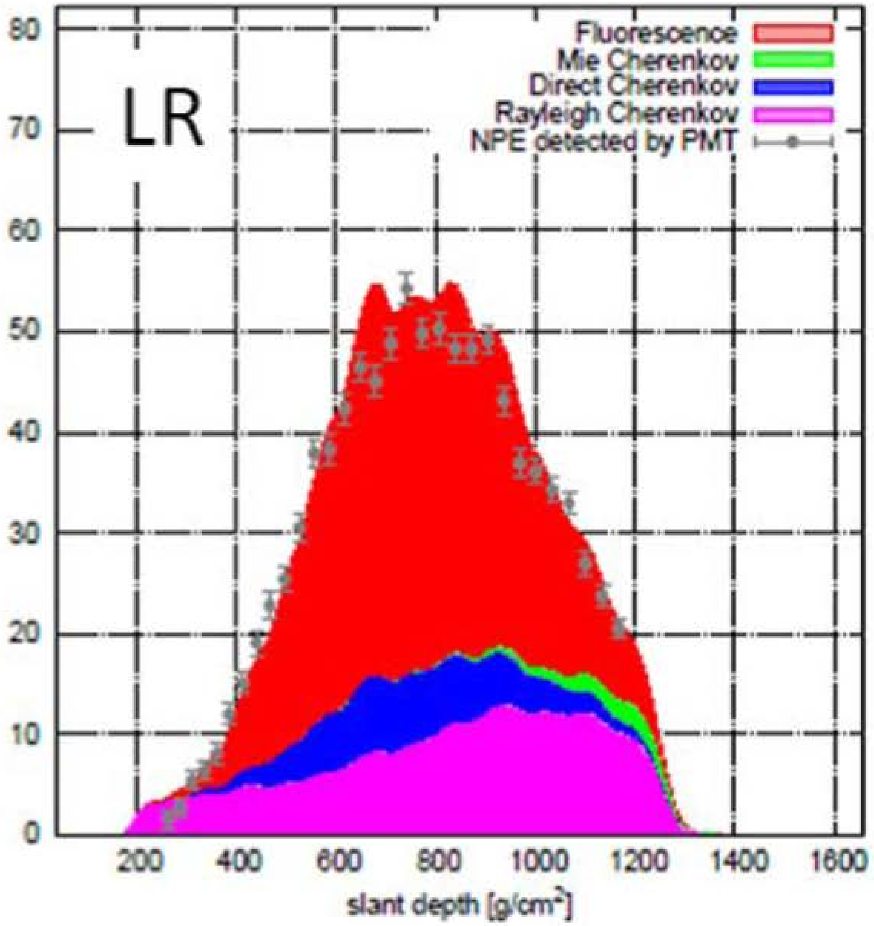


TA

FD Event



BRM
Fluorescence
Mie Cherenkov
Direct Cherenkov
Rayleigh Cherenkov
NPE detected by PMT
Npe
0
50
100
150
200
250
300
800
1000
1200
1400
1600
slant depth [g/cm^2]



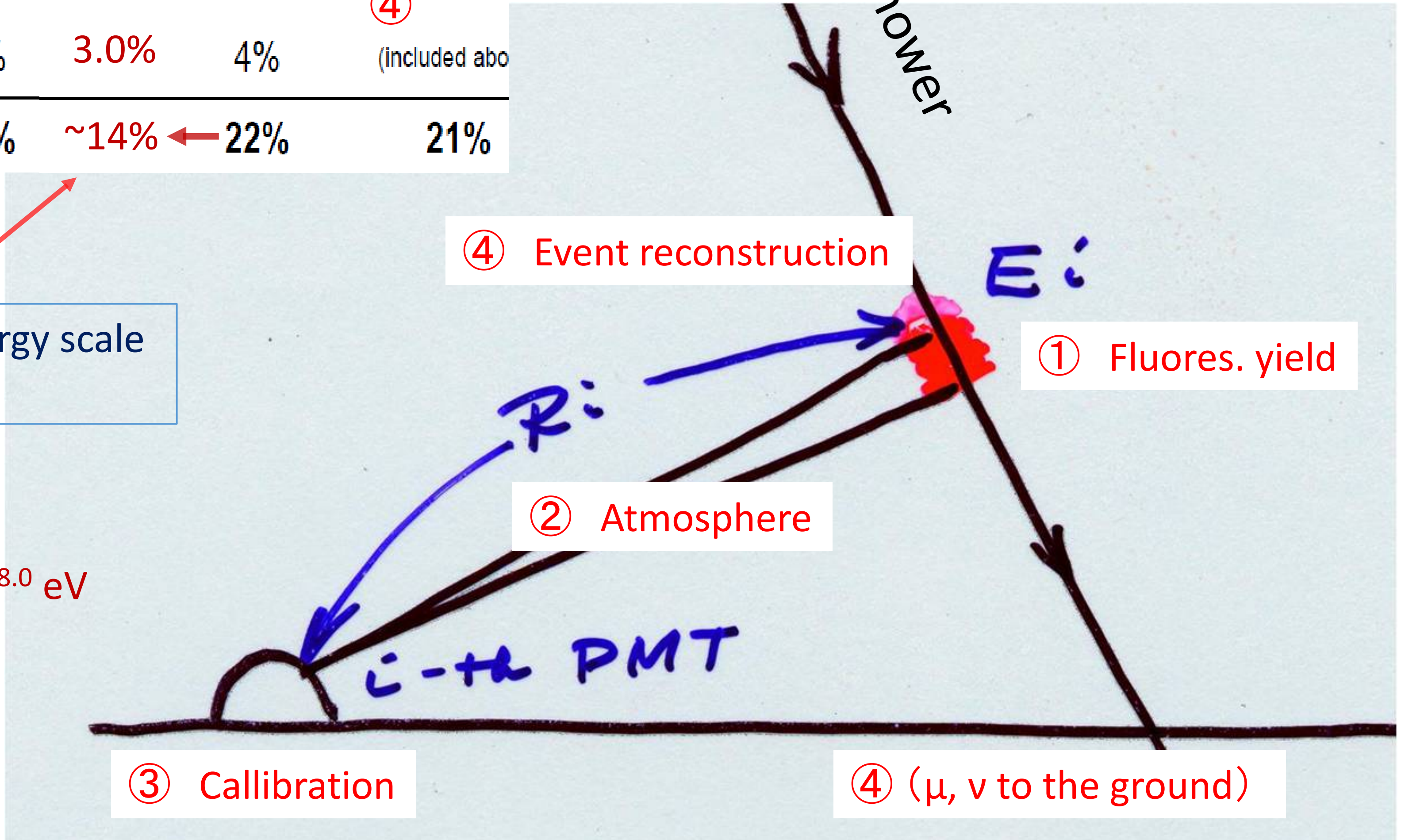
LR
Fluorescence
Mie Cherenkov
Direct Cherenkov
Rayleigh Cherenkov
NPE detected by PMT
0
10
20
30
40
50
60
70
80
200
400
600
800
1000
1200
1400
1600
slant depth [g/cm^2]

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

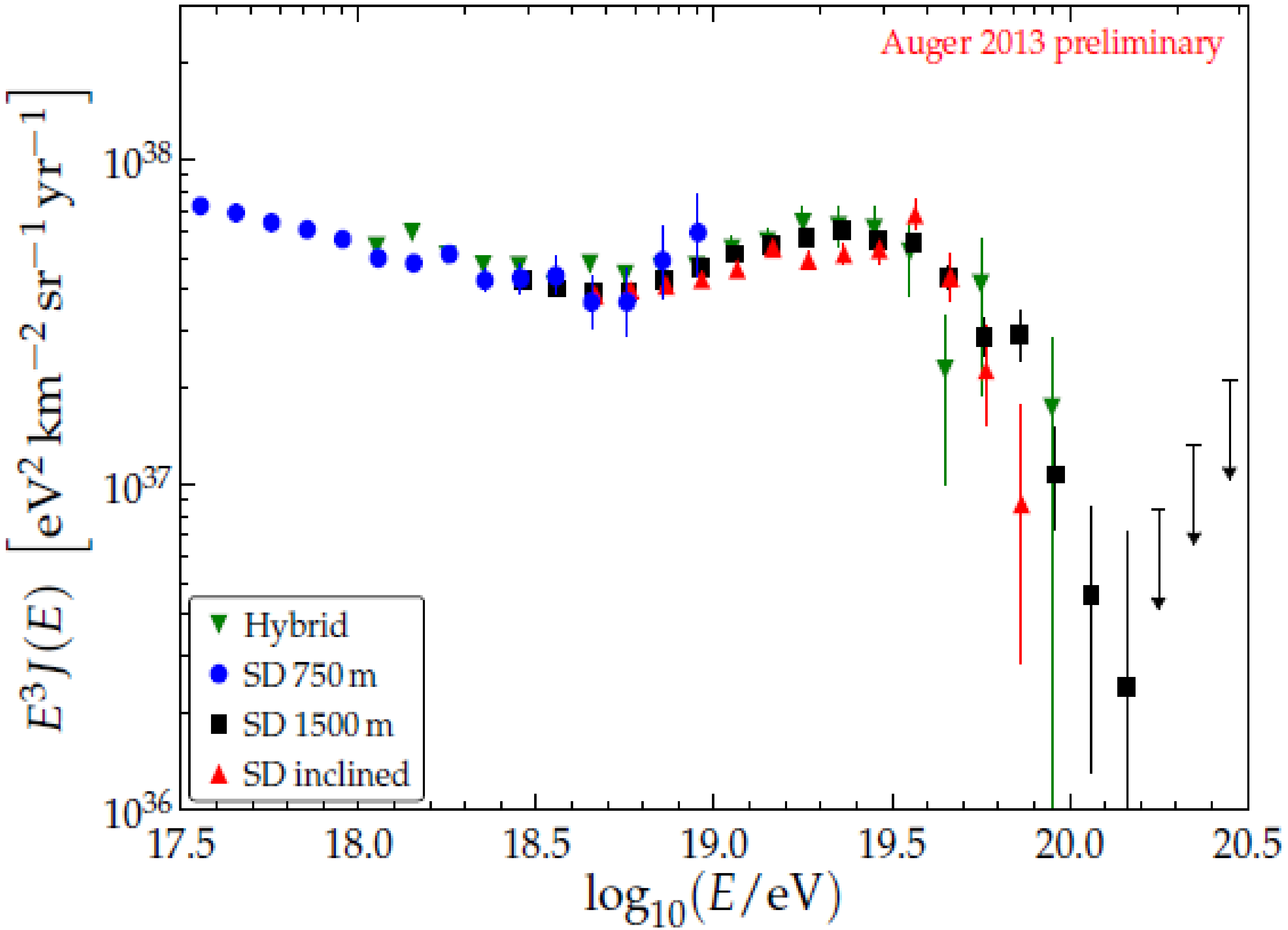


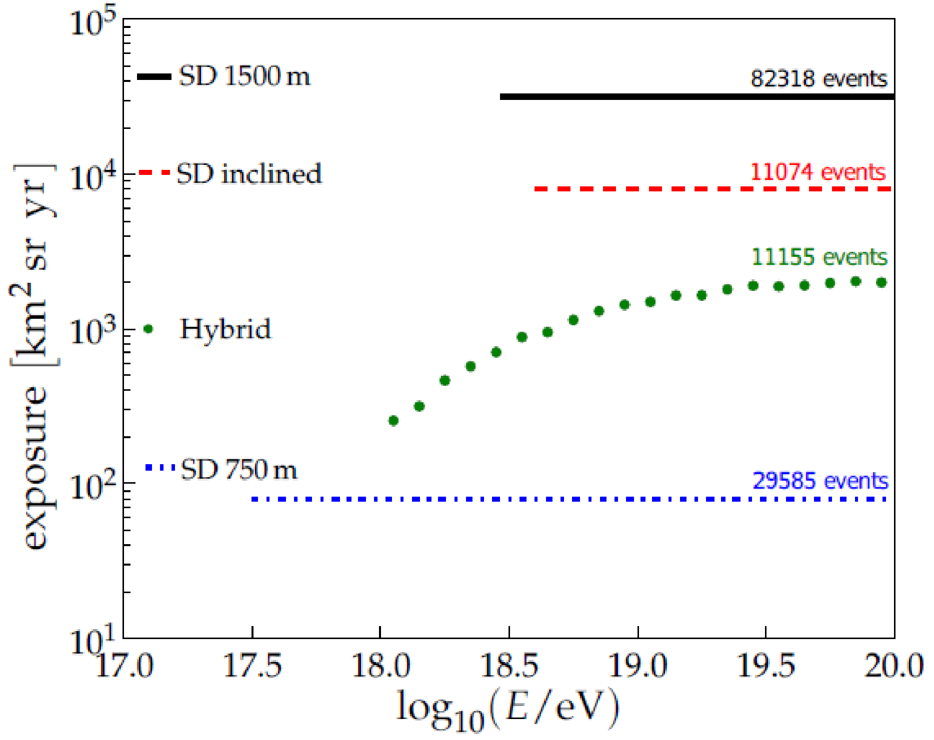
V. Verzi, ICRC2013

A. Lettessier-Selvon ICRC2013

SD_{1500m} - $SD_{inclined}$ - SD/FD Hybrid & SD_{750m} Spectra

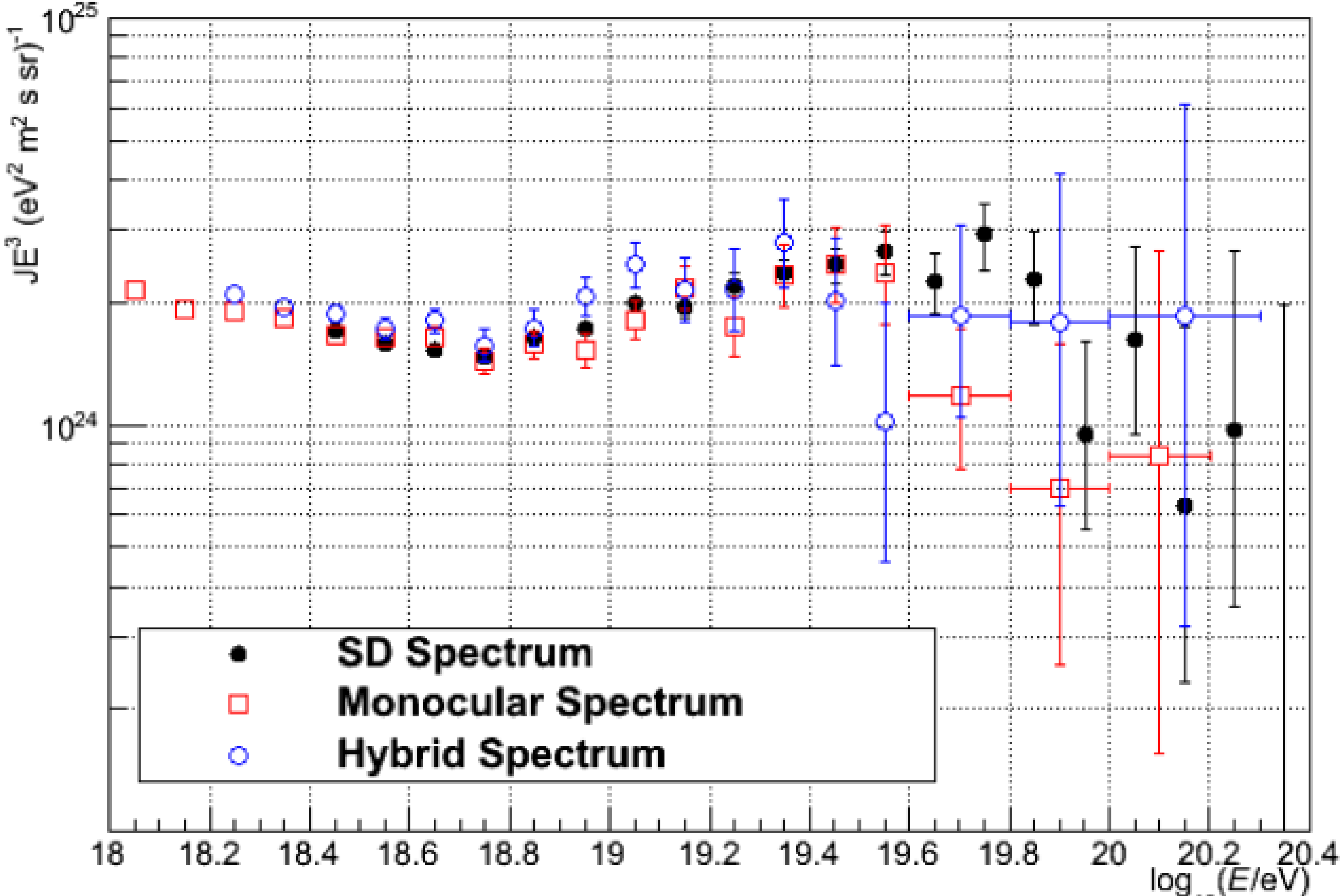
Consistent among Different methods





A Schulz
ICRC 2013

SD - FD $_{\text{monocular}}$ - SD/FD Hybrid Spectra

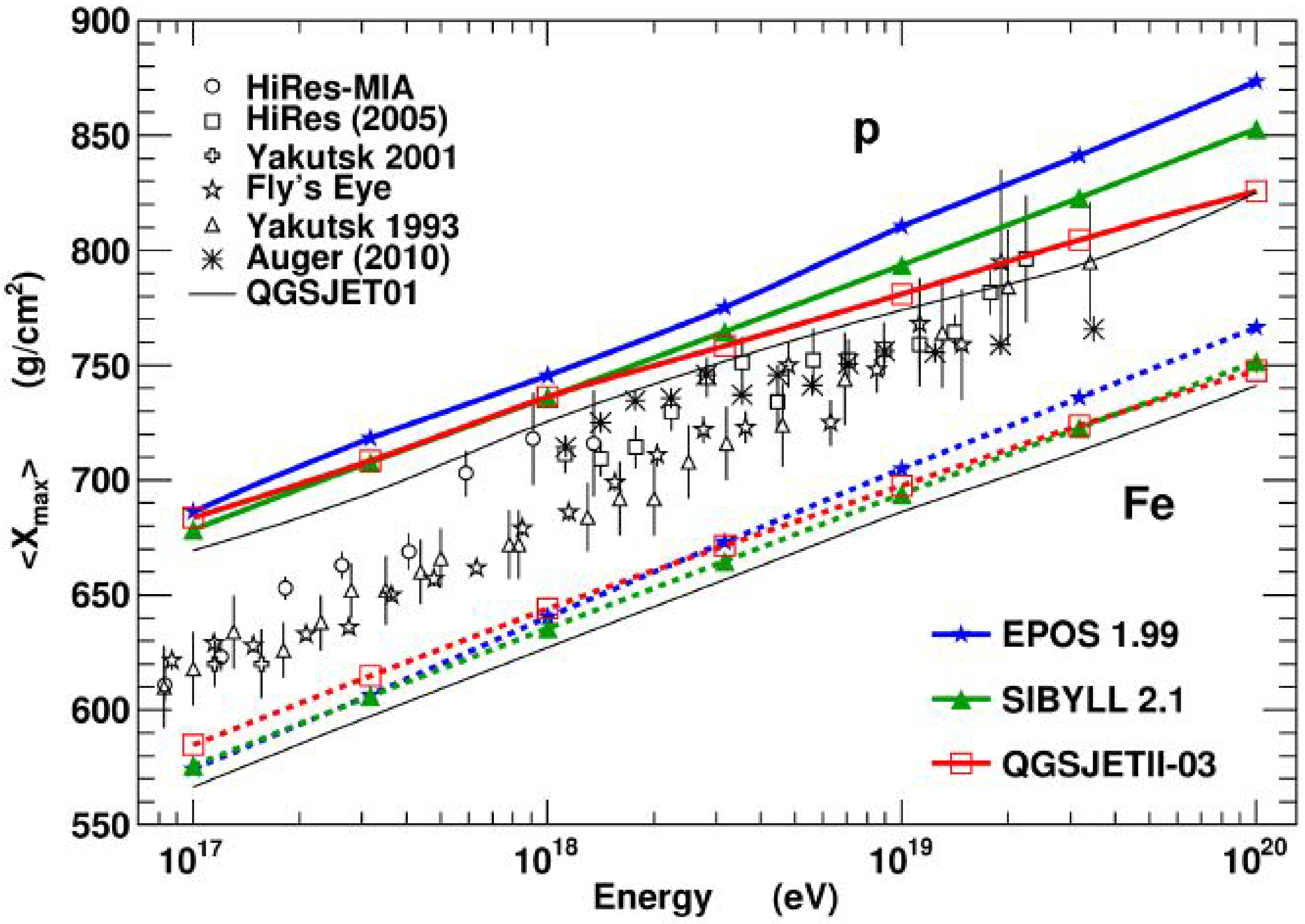


Consistent among Different methods.

Statistics limited Below $10^{19.6}$ eV.

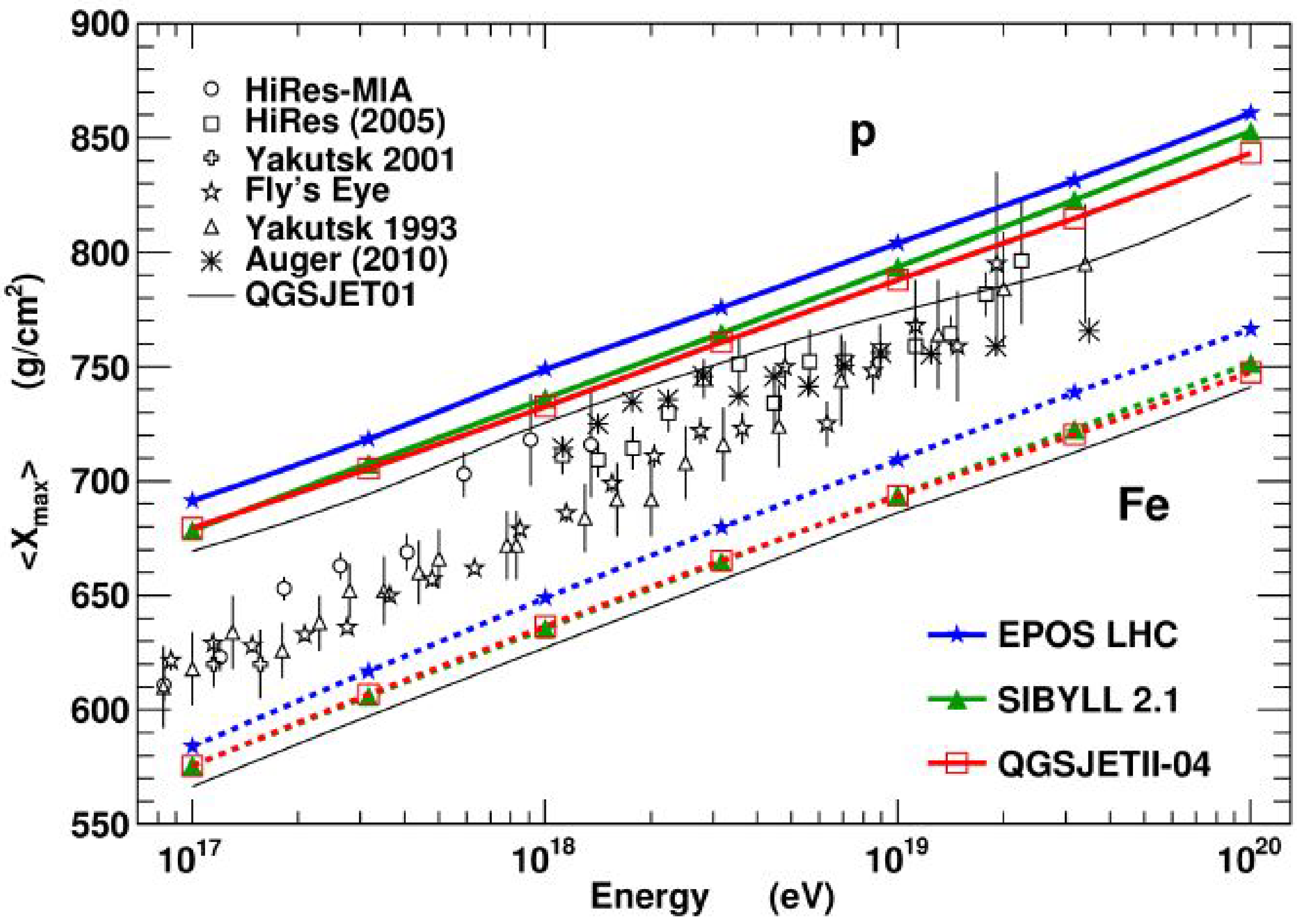
D. Bergman
ICRC 2013

EAS with Old CR Models : X_{max}



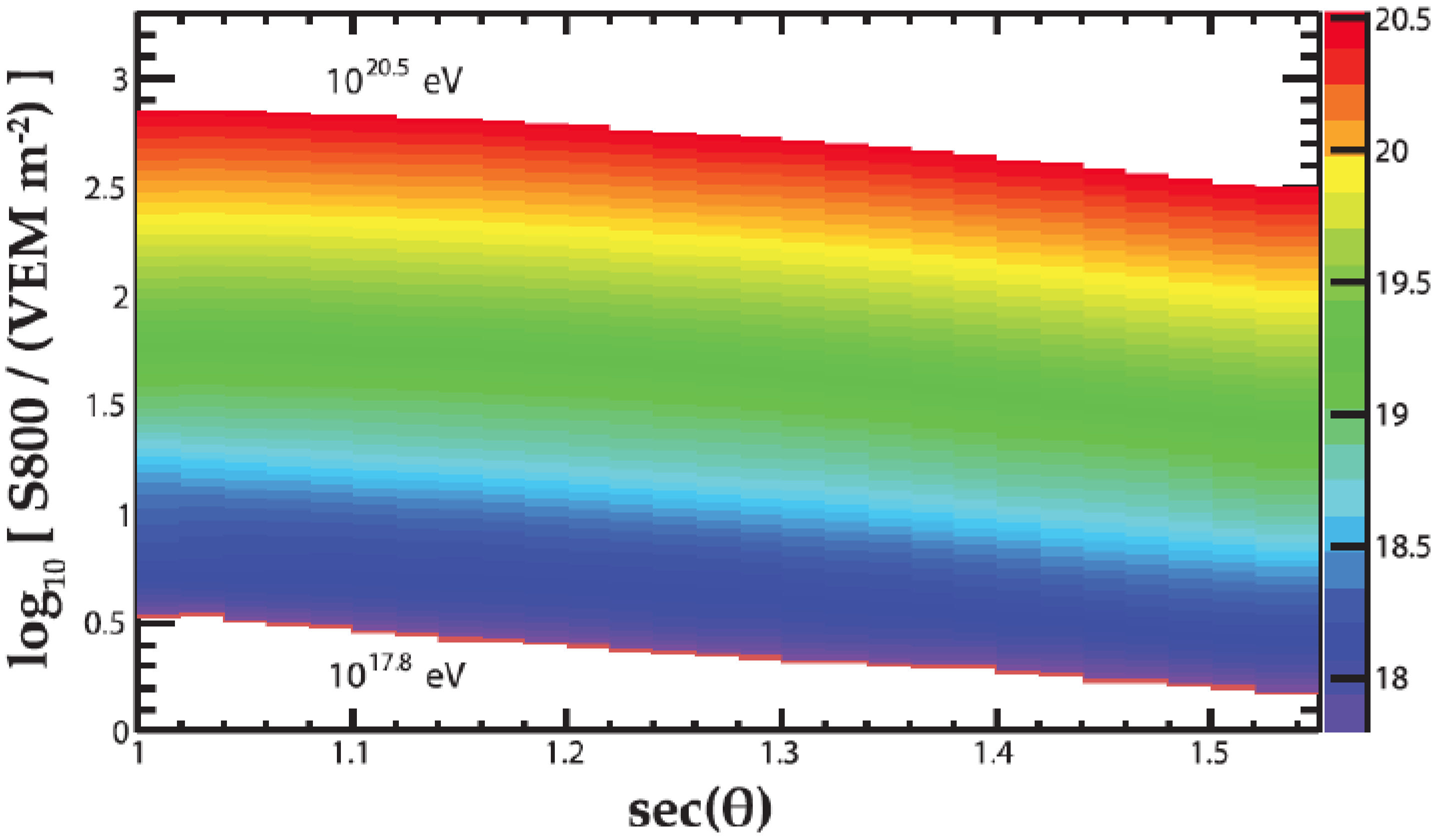
T. Pierog and D. Heck
ICRC 2013

EAS with Re-tuned CR Models : X_{max}



T. Pierog and D. Heck
ICRC 2013

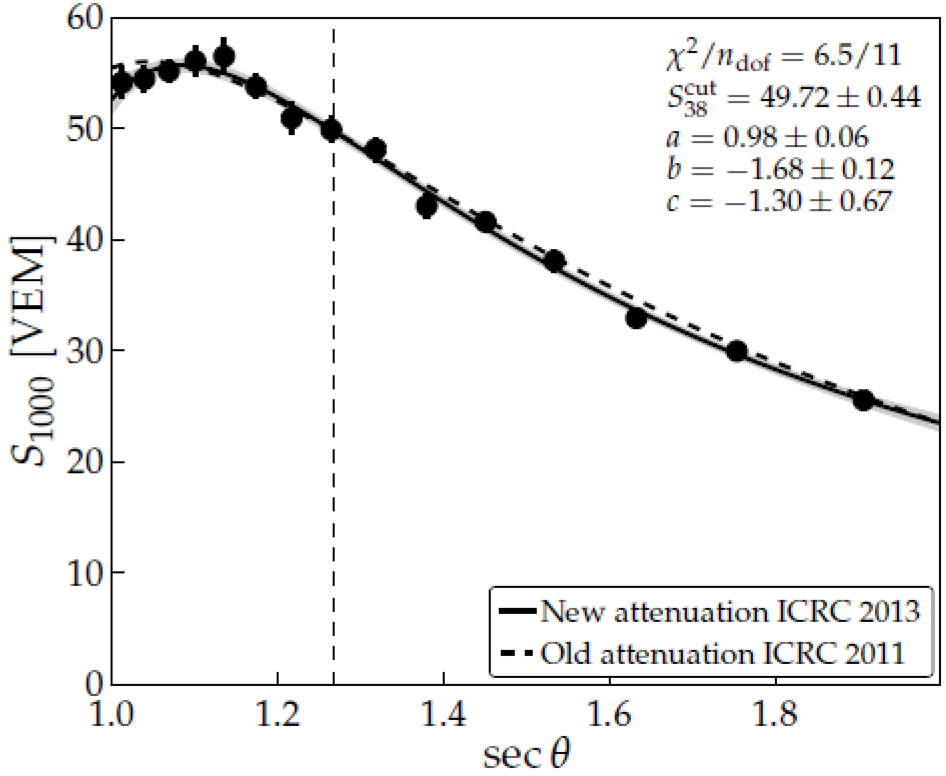
SD Analysis



$10^{20.5}$ eV
$10^{17.8}$ eV
$\log_{10}$ [S800 / (VEM m^{-2})]
sec(θ)
0
0.5
1
1.5
2
2.5
3
1
1.1
1.2
1.3
1.4
1.5
18
18.5
19
19.5
20
20.5

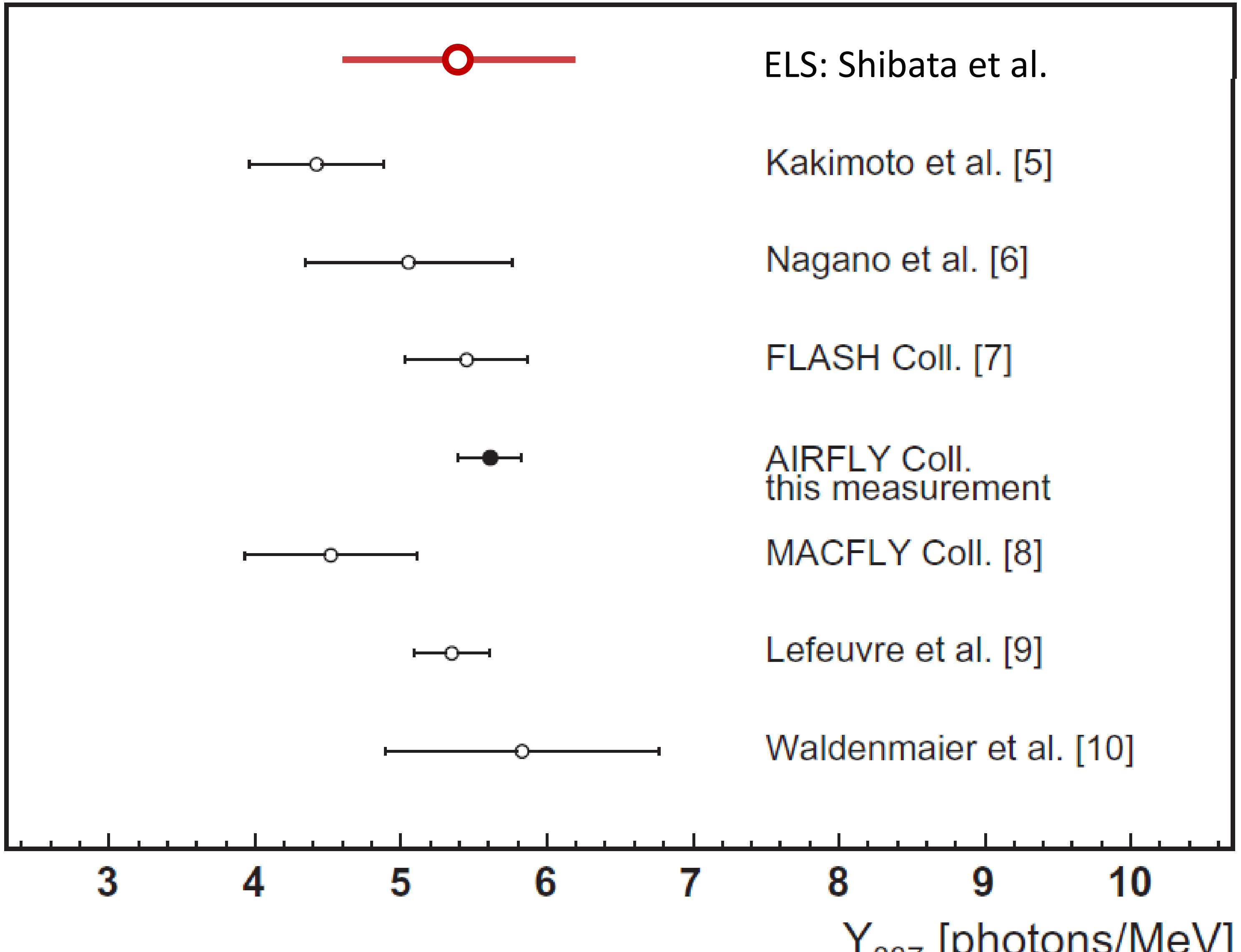
$S(1000)$ attenuation function

- Empirical correction with 3rd deg. polynomial
  $\mathrm{CIC}(\theta) = 1 + ax + bx^2 + cx^3 \ \ (x = \cos^2\theta - \cos^2 38^\circ)$
- Zenith angle independent energy estimator $S_{38} = S(1000)/\mathrm{CIC}(\theta)$



- In case of SD 750 m array: $S(450) \Rightarrow S_{35}$. Separate attenuation function.

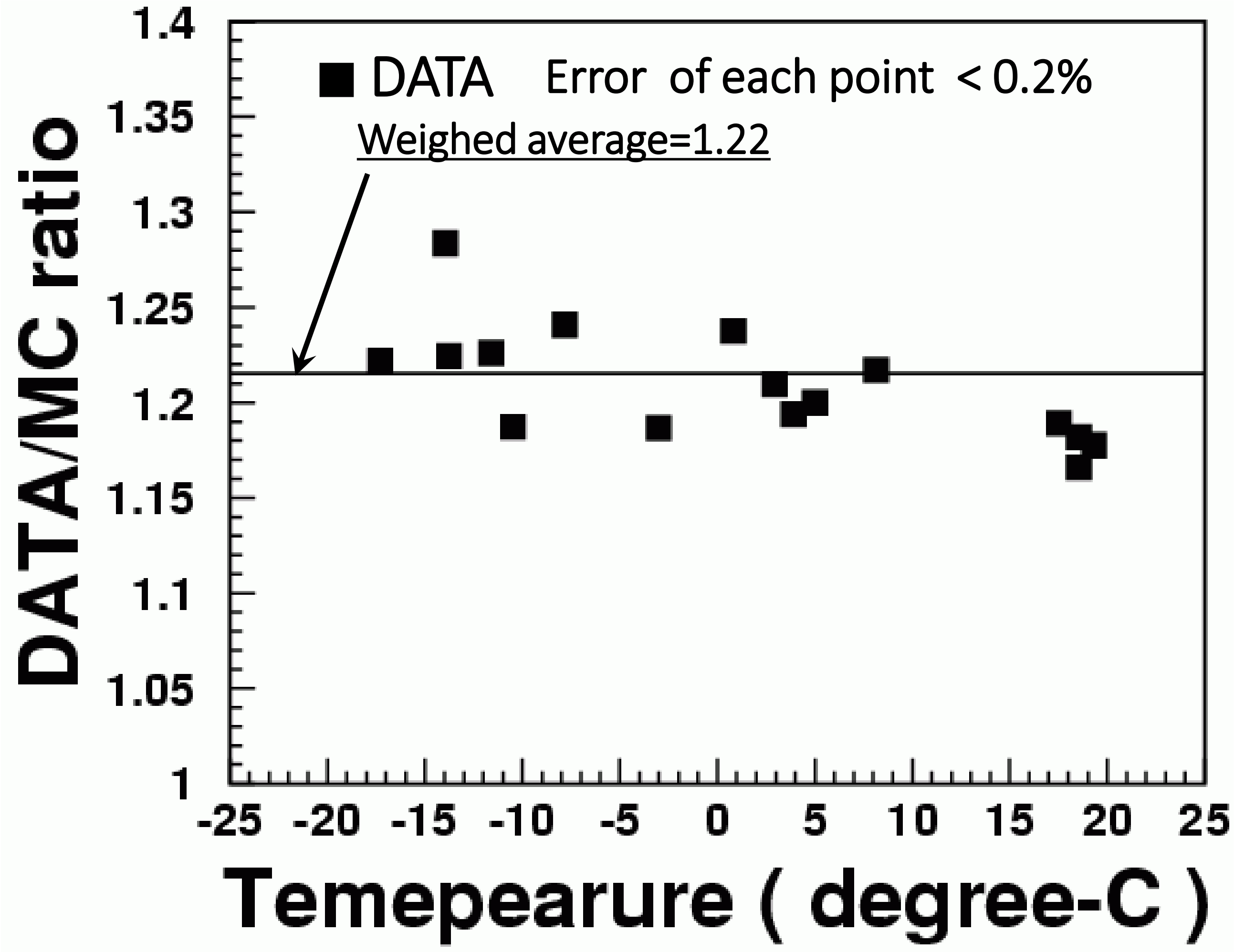
Air Fluorescence : 337nm Yield by TA electron beam calibration



M. Ave et al.
AirFLY collaboration
ApP 42(2013)90

T. Shibata,
ICRC 2013

Air Fluorescence Yield using ELS beam



TA and HiRes use

- FLASH spectrum
- Modified Yield of Kakimoto et al.

ELS (data) / TA (MC)

= 1.18*) ± 0.01 (stat) ± 0.18 (sys)

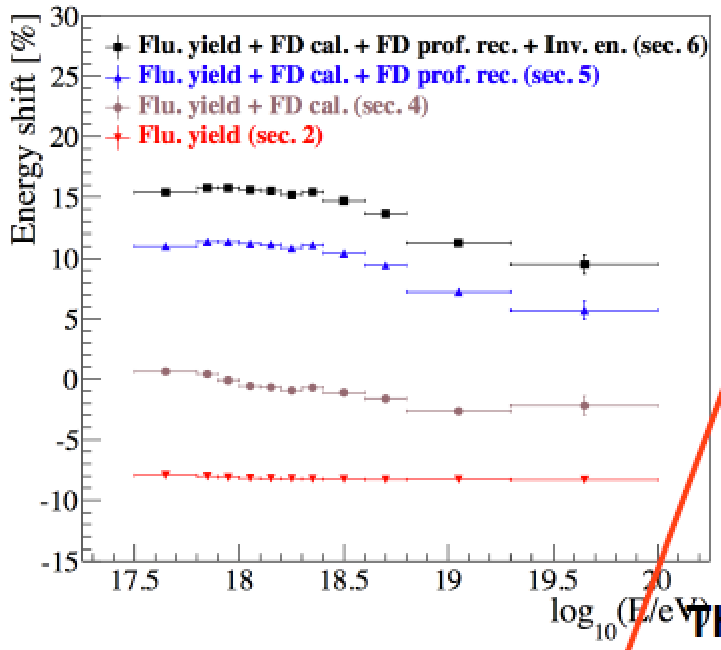
for ~860 hPa, -17^0 ~ 19^0 C

*) 1.22 with -3% correction not included in MC

Ravignani (693), Tueros (705), Schulz (769), Bäuml (806), Verzi (928), Matthews (1218)

ENERGY SCALE III

PIERRE AUGER OBSERVATORY



Uncertainties entering into the SD calibration fit		
Sub total FD energy resolution	7%	8%
Sub total SD energy resolution	17%	12%

1 EeV — 10 EeV

Changes in FD energies at 10^{18} eV	
Airfly fluorescence yield (sec. 2)	-8.2%
New optical efficiency	4.3%
Calibr. database update	3.5%
Sub total (FD calibration - sec. 4)	7.8%
Likelihood fit of the profile	2.2%
Folding with the point spread function	9.4%
Sub total (FD profile reconstruc. - sec. 5)	11.6%
New invisible energy (sec. 6)	4.4%
Total	15.6%

Systematic uncertainties on the energy scale	
Absolute fluorescence yield	3.4%
Fluor. spectrum and quenching param.	1.1%
Sub total (Fluorescence yield - sec. 2)	**3.6%**
Aerosol optical depth	3%÷6%
Aerosol phase function	1%
Wavelength depend. of aerosol scatt.	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere - sec. 3)	**3.4%÷6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration - sec. 4)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec. - sec. 5)	**6.5% ÷5.6%**
Invisible energy (sec. 6)	**3%÷1.5%**
Stat. error of the SD calib. fit (sec. 7)	**0.7%÷1.8%**
Stability of the energy scale (sec. 7)	**5%**
Total	**14%**

The fluorescence yield

The atmosphere

The absolute calibration of the telescopes

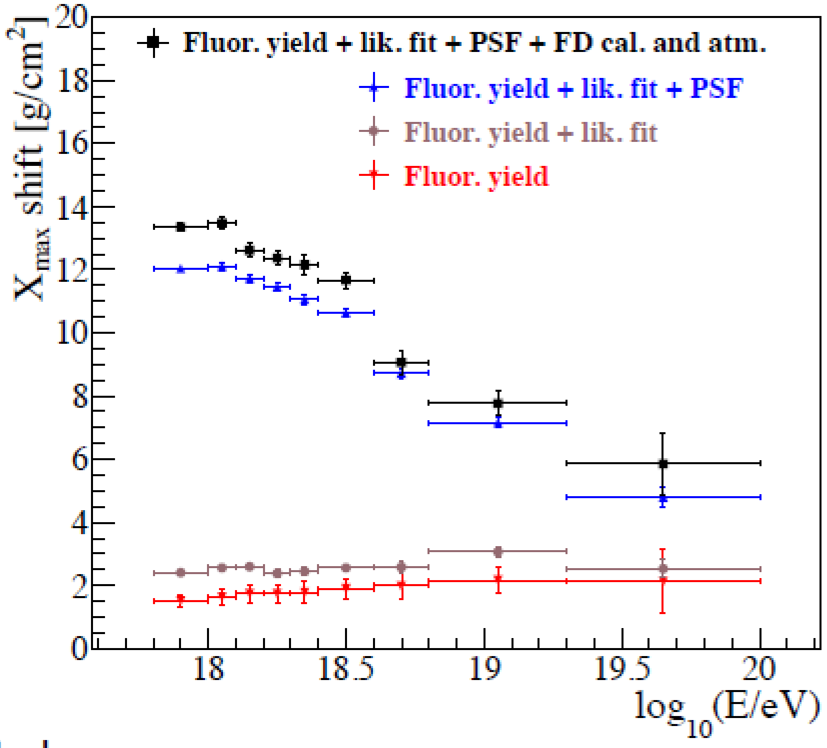
Reconstruction of the longitudinal profile of the showers

The invisible energy

A. Lettessier-Selvon, ICRC2013

Update of X_{max} Results

accumulated effect of **improved reconstruction and calibration**†:



most important change:

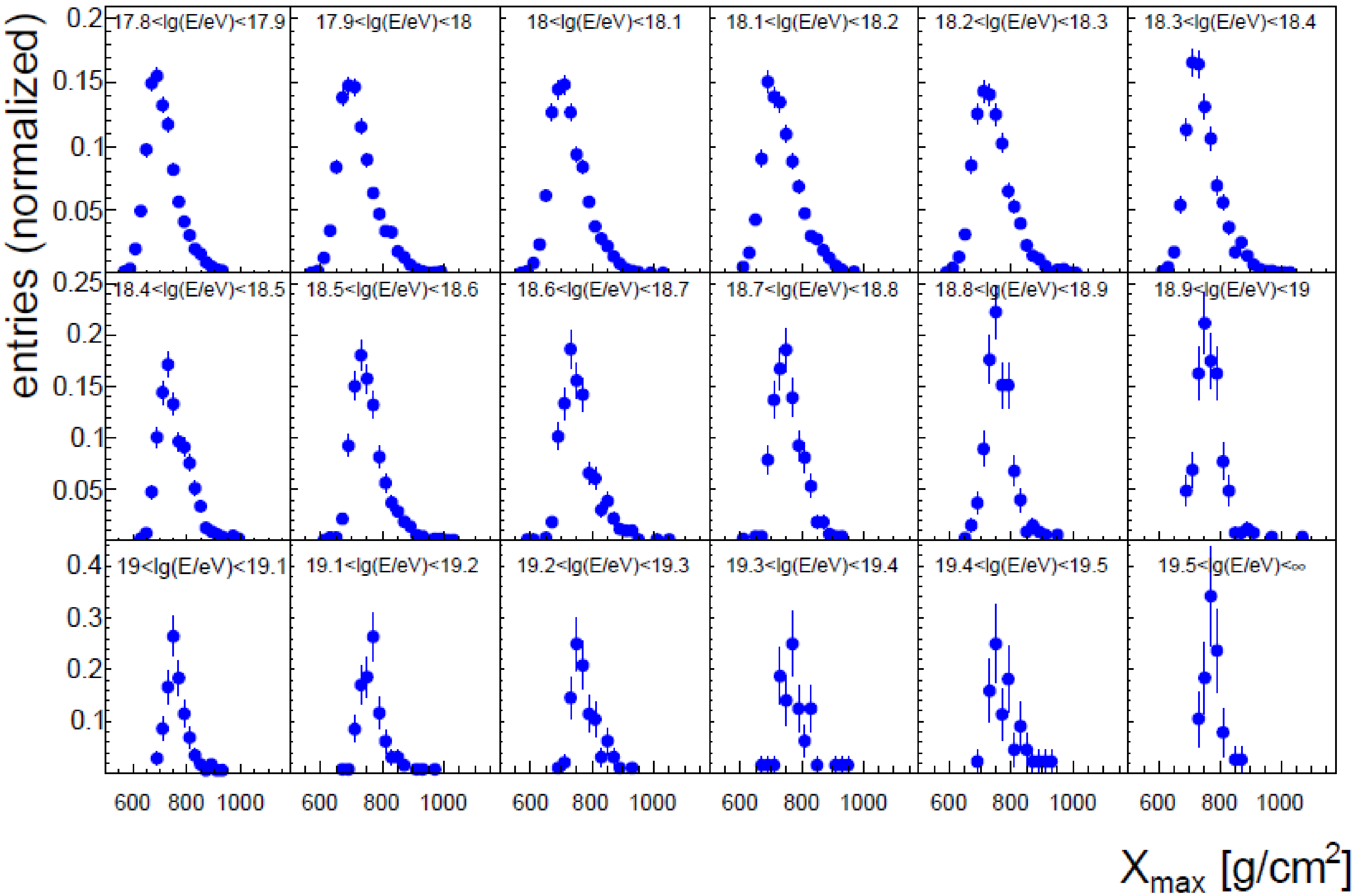
convolution of point spread function‡ with lateral shower width

$\rightarrow \Delta X_{max} \sim +10$ g/cm^2 at low energies

†V. Verzi for the Auger Collab., ICRC #0928, ‡J. Bäuml for the Auger Collab., ICRC #0806

X_{max} Distributions

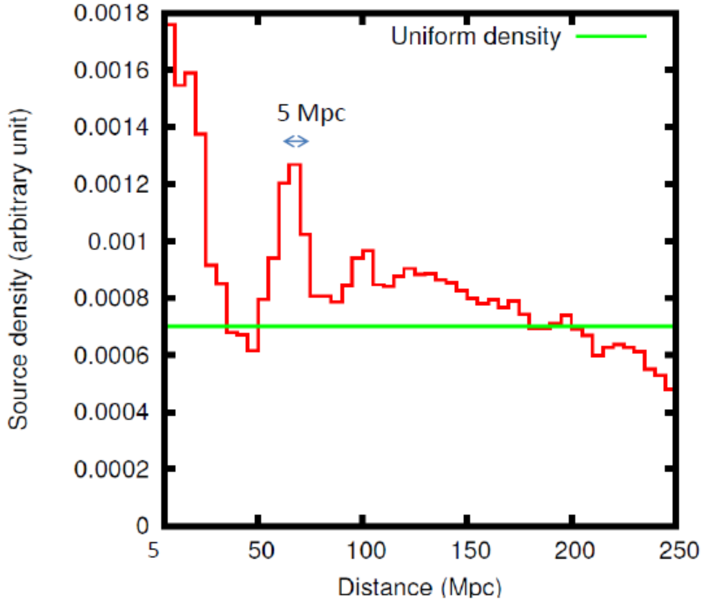
Auger 2013 preliminary



EJ. Ahn, M. Unger
ICRC 2013

Expectation from LSS

- Sources:
  with 5 < D < 250 Mpc : 2MASS galaxy redshift catalog (XSCz)
  Apparent magnitude < 12.5 and
  extrapolate with luminosity density function
  Galactic center is extrapolated from surroundings
  with D > 250 Mpc: uniform distribution
- Propagation:
  proton with $E^{-2.4}$ at origin
  -dE with CMB interactions (average energy loss)
- Magnetic Field:
  Gaussian smearing (6^0 for shown plots)
  No regular GMF deflection is introduced



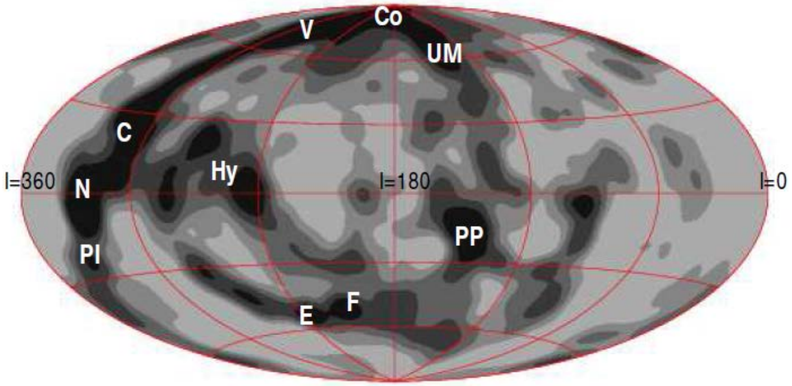


FIG. 5.— Sky map of expected flux at $E > 57$ EeV (Galactic coordinates). The smearing angle is 6°. Letters indicate the nearby structures as follows: **C**: Centaurus supercluster (60 Mpc); **Co**: Coma cluster (90 Mpc); **E**: Eridanus cluster (30 Mpc); **F**: Fornax cluster (20 Mpc); **Hy**: Hydra supercluster (50 Mpc); **N**: Norma supercluster (65 Mpc); **PI**: Pavo-Indus supercluster (70 Mpc); **PP**: Perseus-Pisces supercluster (70 Mpc); **UM**: Ursa Major (20 Mpc); **V**: Virgo cluster (20 Mpc).

ApJ-757(2012)26