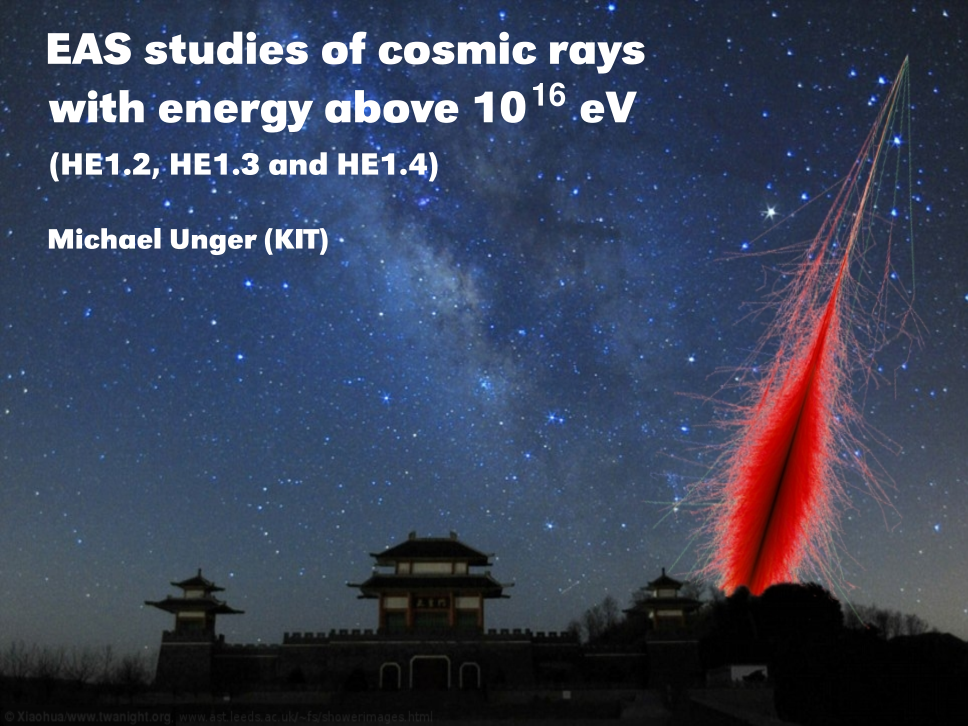
EAS studies of cosmic rays with energy above 10^{16} eV

(HE1.2, HE1.3 and HE1.4)

Michael Unger (KIT)

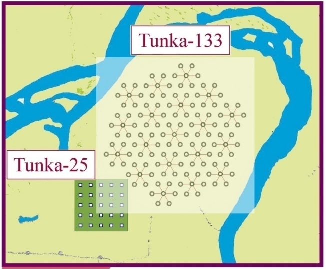


Overview

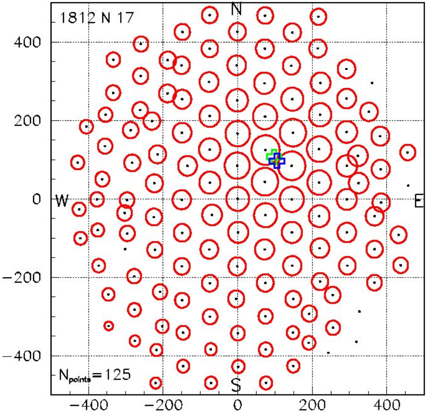
- Towards the ankle
- Measurements of the UHECR energy spectrum
- UHECR composition studies
- Arrival directions of UHECRs
- New techniques and future experiments

Towards the Ankle

Results from Tunka133

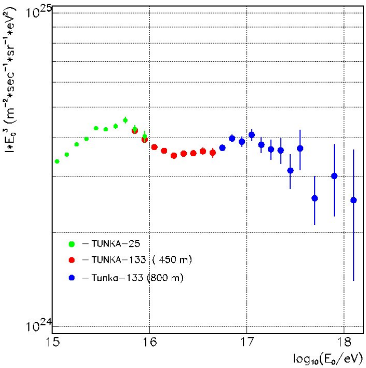


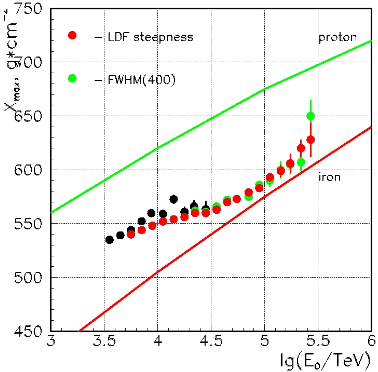
event $E \sim 2 \cdot 10^{17}$ eV



N. Budnev [Tunka Coll.], icrc495

Spectrum and X_{max} from Tunka133

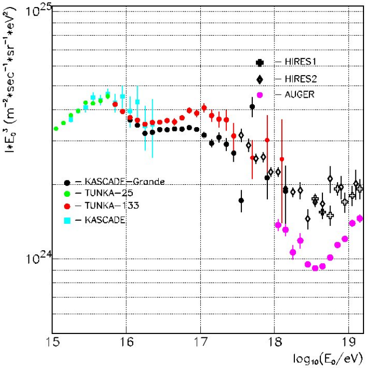


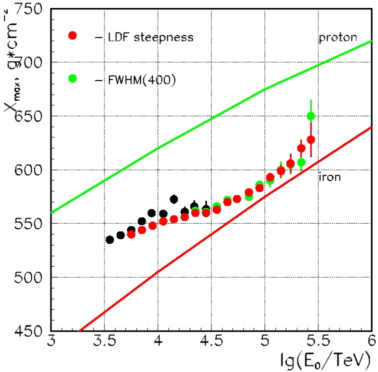


L.A. Kuzmichev [Tunka Coll.], icrc250

V. Prosin [Tunka Coll.], icrc184

Spectrum and $X_{\max}$ from Tunka133

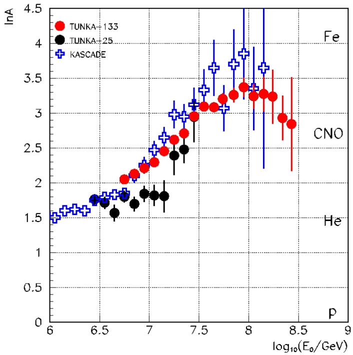


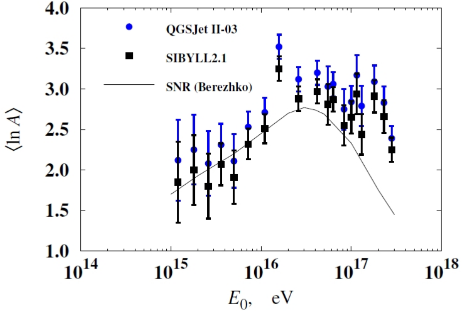


L.A. Kuzmichev [Tunka Coll.], icrc250

V. Prosin [Tunka Coll.], icrc184

$\langle \ln A \rangle$ Tunka vs. Yakutsk

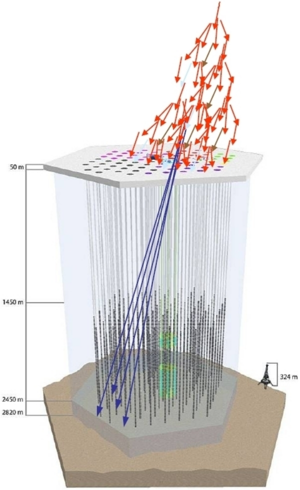


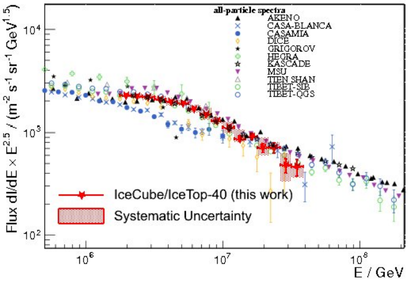


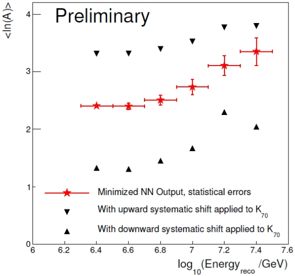
V. Prosin [Tunka Coll.], icrc184

S. Knurenko [Yakutsk Coll.], icrc182

IceTop/Cube Hybrid Analysis





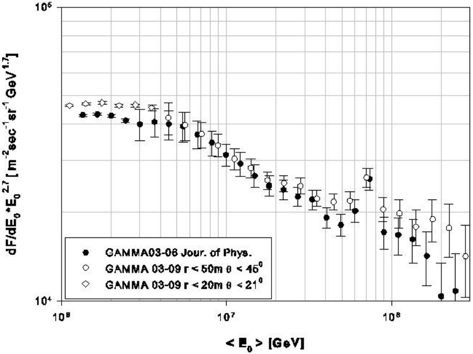


H. Kolanoski [IceCube Coll.], icrc807

K. Rawlins [IceCube Coll.], icrc923

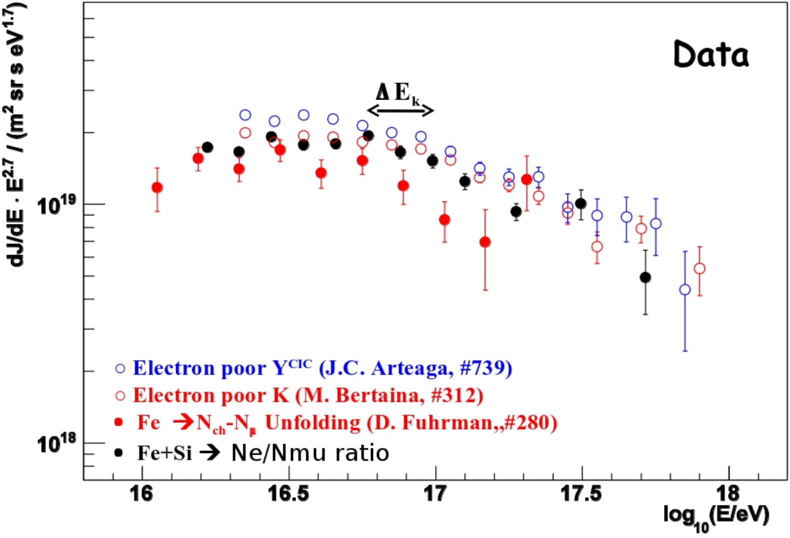
Update of GAMMA spectrum

three years more data



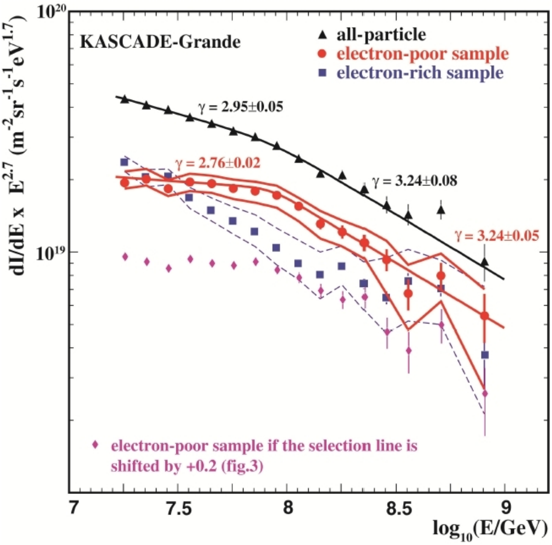
R.M. Martirosov [GAMMA Coll.], icrc134

Evidence for a 'heavy knee' by KASCADE-Grande



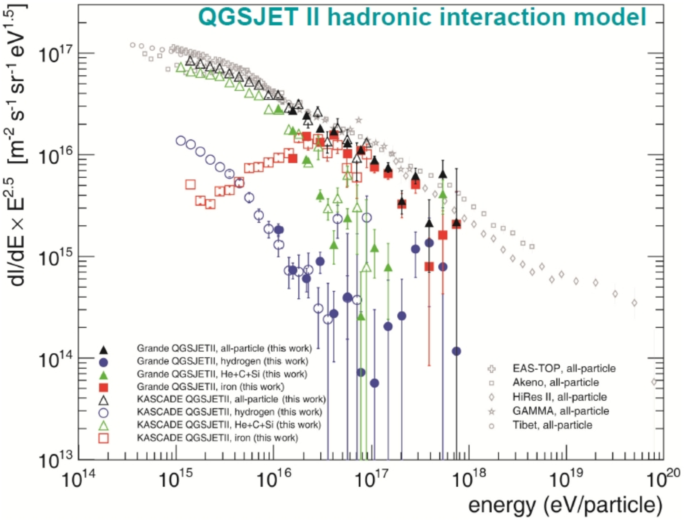
A. Chiavassa [KASCADE-Grande Coll.], icrc504

Evidence for a ’heavy knee’ by KASCADE-Grande



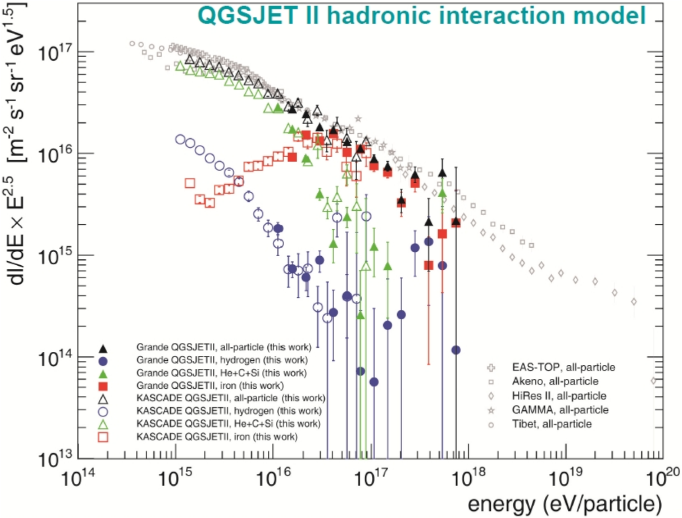
A. Haungs [KASCADE-Grande Coll.], icrc677

Evidence for a 'heavy knee' by KASCADE-Grande



A. Haungs [KASCADE-Grande Coll.], icrc677

Evidence for a ’heavy knee’ by KASCADE-Grande



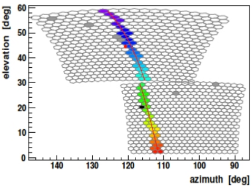
N.B.: add odds with TIBET heavy composition $10^{15} - 10^{16}$

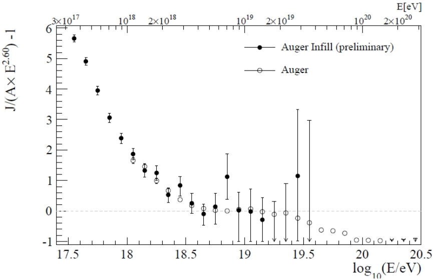
A. Haungs [KASCADE-Grande Coll.], icrc677

'Low energy' Enhancements

Auger towards 10^{17} eV:

- 750 m infill stations
- buried muon counters
- high elevation telescopes





TA towards 10^{17} eV:
start constructing infill and enhanced FD this year

G. Thomson [TA/TALE Coll., icrc1307

B. Wundheiler [Auger Coll.], icrc341

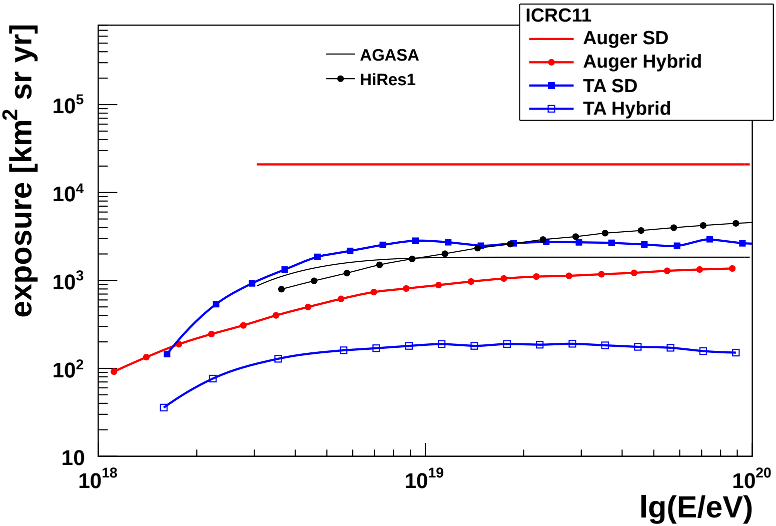
I.C. Maris [Auger Coll.], icrc711

H.J. Mathes [Auger Coll.], icrc761

S. Federico [Auger Coll.], icrc742

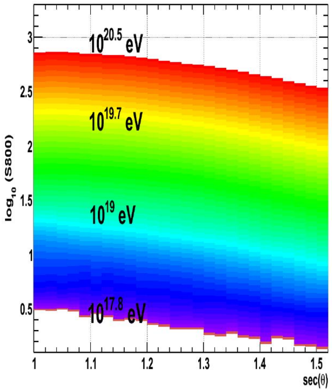
UHECR Energy Spectrum

Comparison of Exposures

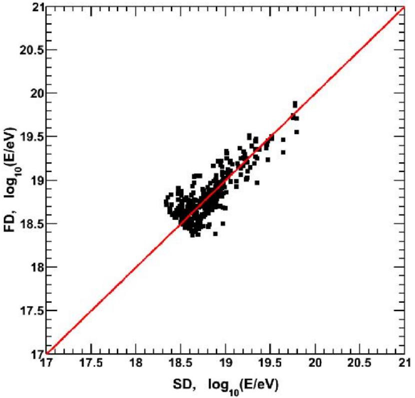


TA Surface Detector Spectrum

shower size to E from MC



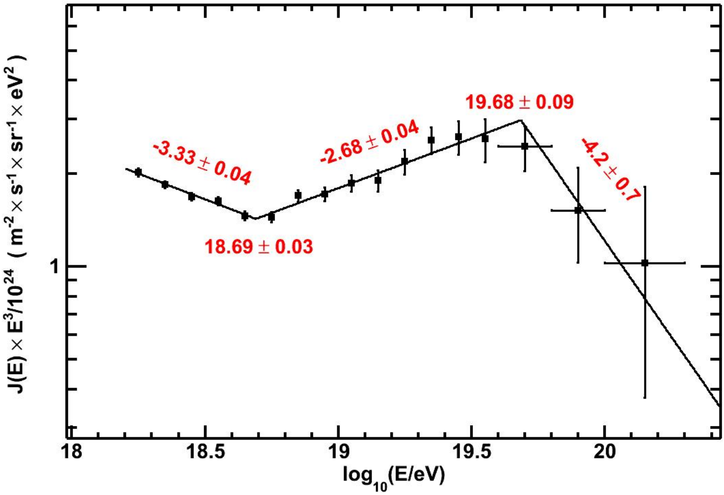
renormalized using FD $(1/1.27)$



acceptance from MC (incl. sub-threshold)

B. Stokes [TA Coll.], icrc1297

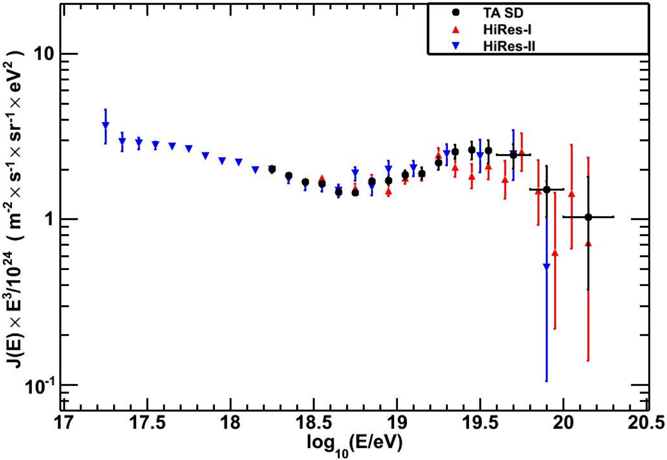
TA Surface Detector Spectrum



B. Stokes [TA Coll.], icrc1297

TA Surface Detector Spectrum

excellent agreement with HiRes (by construction)

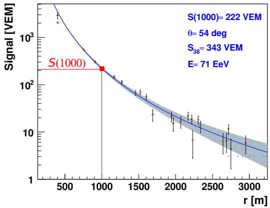


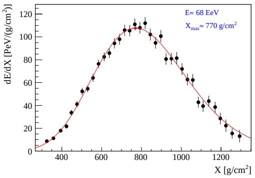
B. Stokes [TA Coll.], icrc1297

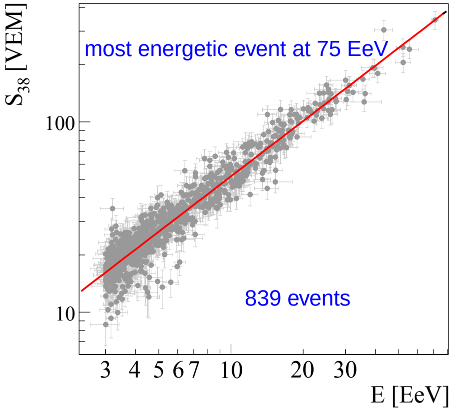
Auger Vertical Spectrum

- constant intensity cut
- FD-SD energy calibration
- SD: geometrical acceptance
- FD: detector MC

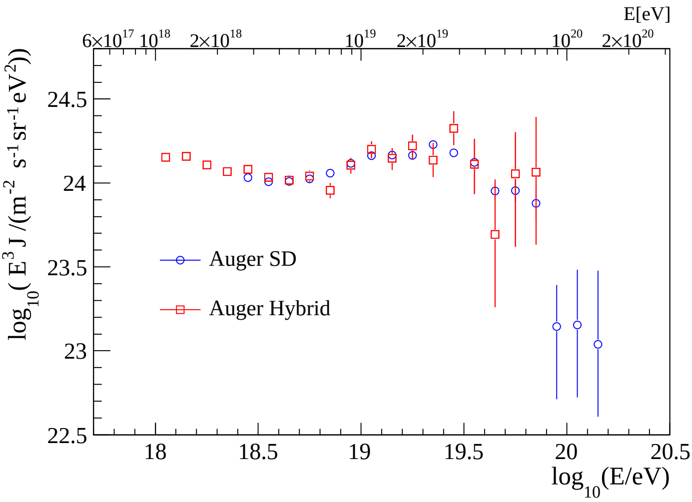
F. Salamida [Auger Coll.], icrc893





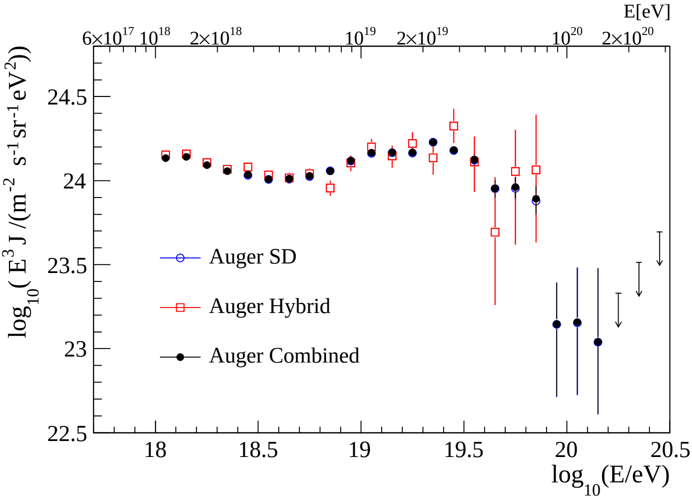


Auger Vertical Spectrum



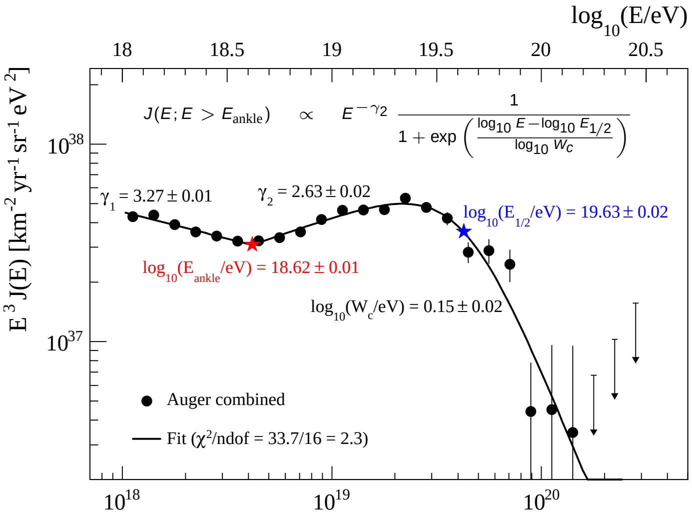
F. Salamida [Auger Coll.], icrc893

Auger Vertical Spectrum



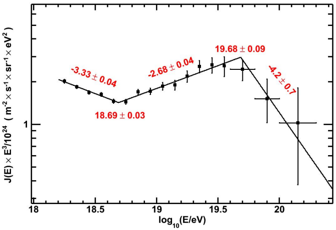
F. Salamida [Auger Coll.], icrc893

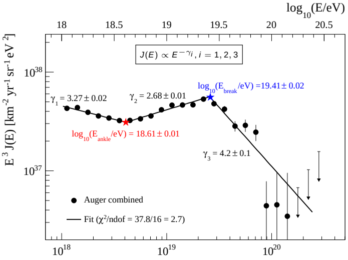
Auger Vertical Spectrum



F. Salamida [Auger Coll.], icrc893

Comparison of spectral features



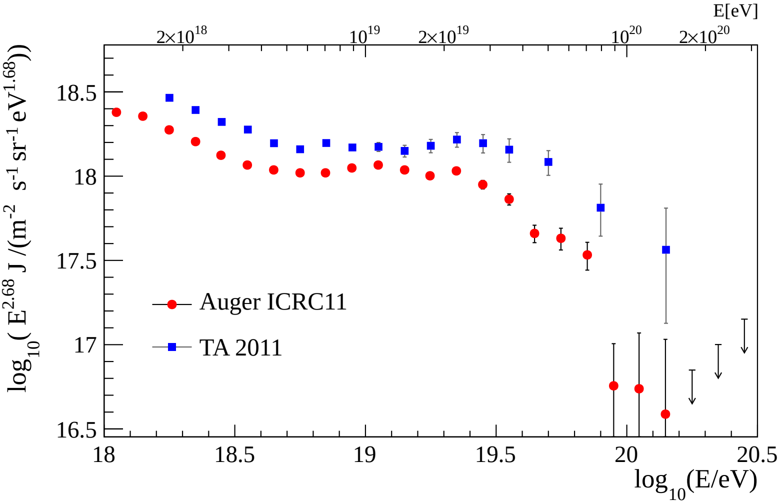


	TA	Auger
γ_1	3.33 ± 0.04	3.27 ± 0.02
γ_2	2.68 ± 0.04	2.68 ± 0.01
γ_3	4.2 ± 0.7	4.2 ± 0.1
$\lg(E_1/\mathrm{eV})$	18.69 ± 0.03	18.61 ± 0.01
$\lg(E_2/\mathrm{eV})$	19.68 ± 0.09	19.41 ± 0.02

B. Stokes [TA Coll.], icrc1297

F. Salamida [Auger Coll.], icrc893

Comparison of Spectra



energy scale difference of ∼ 20%?

Energy Scale Uncertainties

Auger R. Pesce, icrc1160

calibration	9.5%
reconstruction	10%
atmospheric	8%
fluorescence yield*	14%
invisible energy†	4%
tot. quad. sum	**22%**

Telescope Array D. Ikeda, icrc1264

calibration	10%
reconstruction	10%
atmospheric	11%
fluorescence yield** / invisible energy††	11%
tot. quad. sum	**21%**

total syst. of energy scale difference

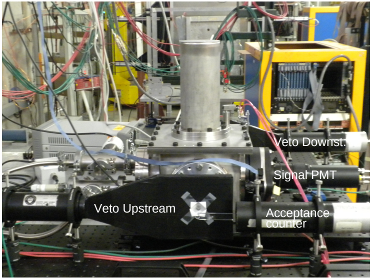
$$\sigma_{\mathrm{sys}}(E_{\mathrm{Auger}} - E_{\mathrm{TA}}) = 30\%$$

without fluorescence yield:

$$\sigma_{\mathrm{sys}}(E_{\mathrm{Auger}} - E_{\mathrm{TA}}) = 24\%$$

* yield: Nagano, spectrum: AIRFLY ** yield: Kakimoto, spectrum: Bunner † QGSJet mixed †† QGSJet proton

Fluorescence Yield Measurement by AIRFLY



normalization:

- method 1: fluorescence to Cherenkov ratio
- method 2: laser + NIST probe

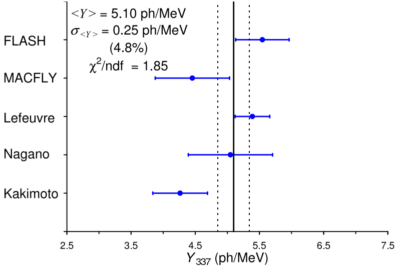
$\rightarrow$ total uncertainty: 4%!

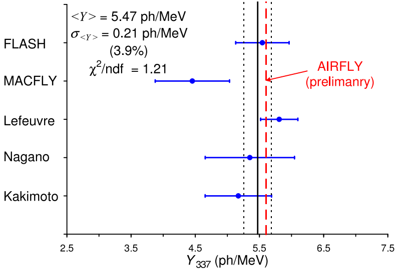
$$Y_{\mathrm{air}} = 5.67 \pm 0.07(\mathrm{stat.}) \pm 0.21(\mathrm{syst.})\ \mathrm{phot}_{337}/\mathrm{MeV}$$

Auger: 5.05 $\mathrm{phot}_{337}/\mathrm{MeV}$, i.e. energy scale goes *down* by 10%

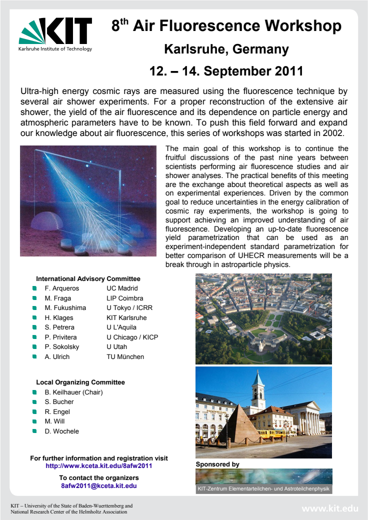
M. Bohacova et al., icrc1159

Fluorescence Yield World Average





F. Arqueros et al., icrc442



KIT
Karlsruhe Institute of Technology

8th Air Fluorescence Workshop

Karlsruhe, Germany

12. – 14. September 2011

Ultra-high energy cosmic rays are measured using the fluorescence technique by several air shower experiments. For a proper reconstruction of the extensive air shower, the yield of the air fluorescence and its dependence on particle energy and atmospheric parameters have to be known. To push this field forward and expand our knowledge about air fluorescence, this series of workshops was started in 2002.

The main goal of this workshop is to continue the fruitful discussions of the past nine years between scientists performing air fluorescence studies and air shower analyses. The practical benefits of this meeting are the exchange about theoretical aspects as well as on experimental experiences. Driven by the common goal to reduce uncertainties in the energy calibration of cosmic ray experiments, the workshop is going to support achieving an improved understanding of air fluorescence. Developing an up-to-date fluorescence yield parametrization that can be used as an experiment-independent standard parametrization for better comparison of UHECR measurements will be a break through in astroparticle physics.

International Advisory Committee

- F. Arqueros — UC Madrid
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- A. Ulrich — TU München

Local Organizing Committee

- B. Keilhauer (Chair)
- S. Bucher
- R. Engel
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For further information and registration visit
http://www.kceta.kit.edu/8afw2011

To contact the organizers
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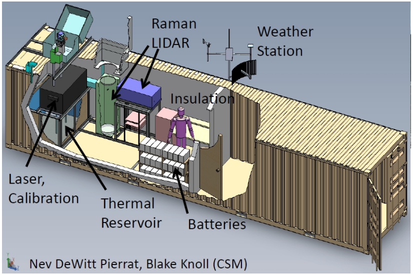
Improved calibration techniques

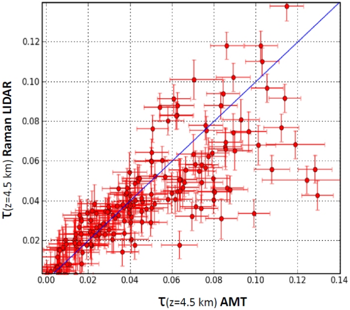


combination of

- stable solid state laser
- automatic laser calibration
- Raman LIDAR

to be installed at Auger in 2012

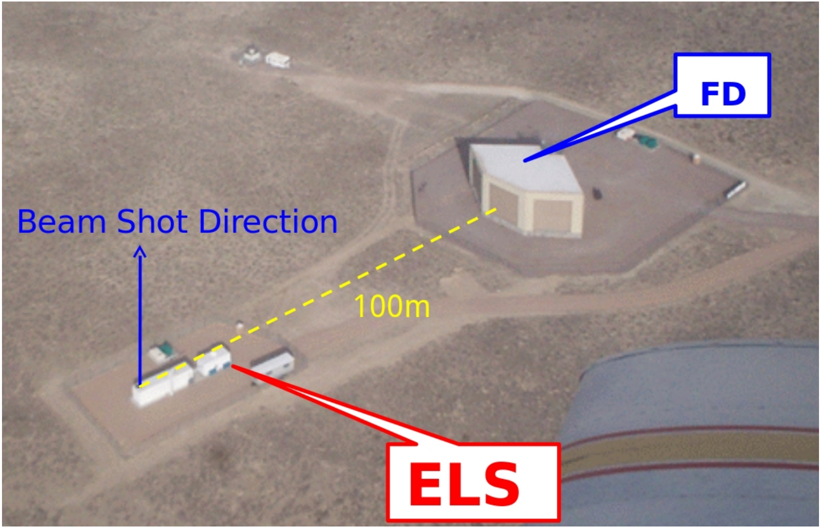
first tests in Colorado:



L. Wiencke [Auger Coll.], icrc741

Improved calibration techniques

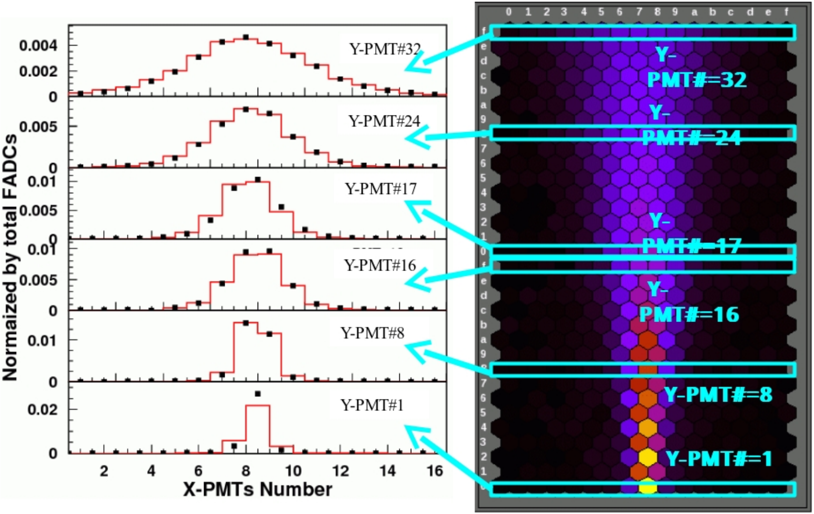
linac, electron light source (ELS) at TA



T. Shibata [TA Coll.], icrc1252

Improved calibration techniques

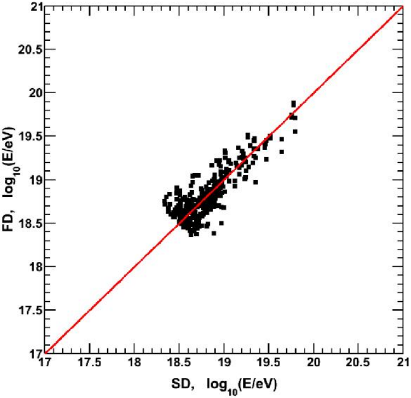
ELS data



T. Shibata [TA Coll.], icrc1252

MC Energy Scale

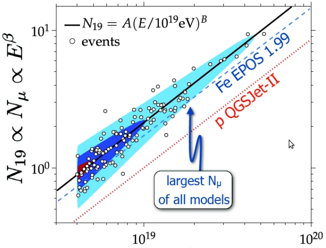
TA: dominated by emag. comp.

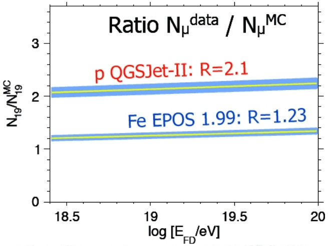


E_{MC} scaled down by 27%

B. Stokes [TA Coll.], icrc1297

Auger Inclined: μ-dominated





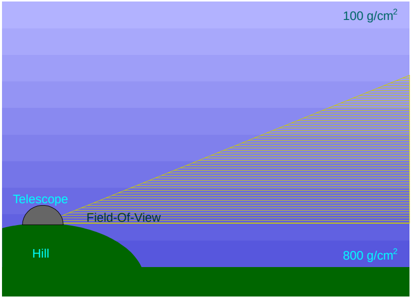
Rodriguez [Auger], 718

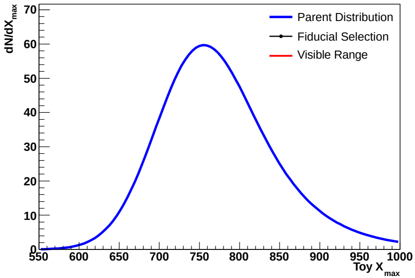
Dembinski [Auger], 724

see also J. Allen [Auger Coll.], icrc703

UHECR Composition

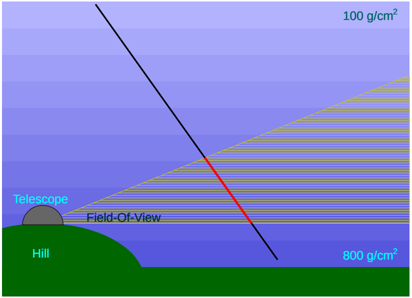
Illustration of FD Acceptance Bias

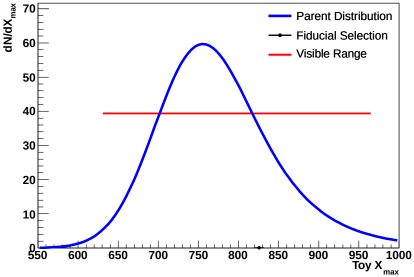




R. Ulrich [Auger Coll.], icrc946

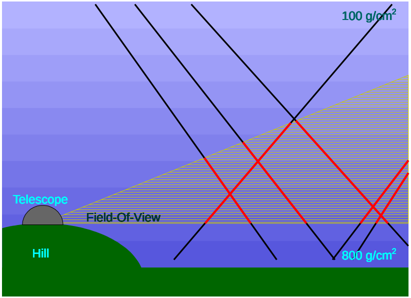
Illustration of FD Acceptance Bias

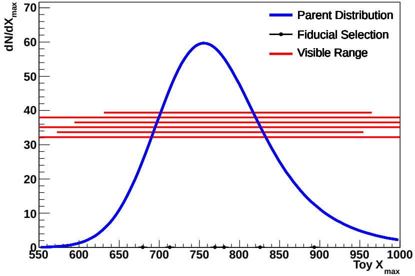




R. Ulrich [Auger Coll.], icrc946

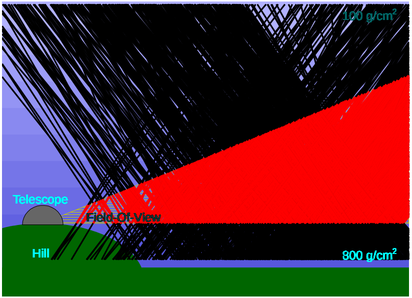
Illustration of FD Acceptance Bias

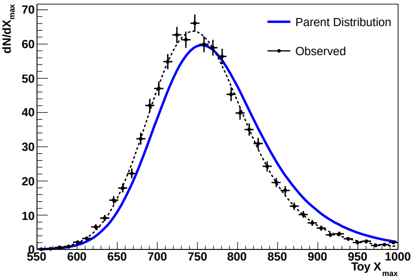




R. Ulrich [Auger Coll.], icrc946

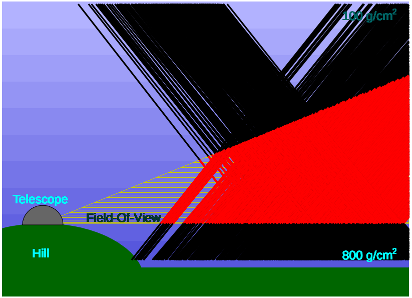
Illustration of FD Acceptance Bias

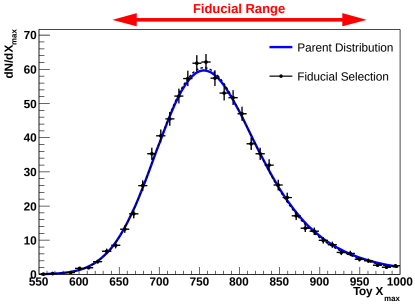




R. Ulrich [Auger Coll.], icrc946

Illustration of FD Acceptance Bias

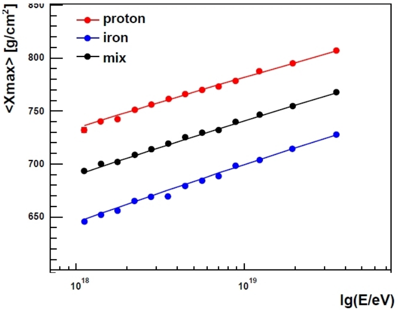




R. Ulrich [Auger Coll.], icrc946

X_{max} Measurement Strategies

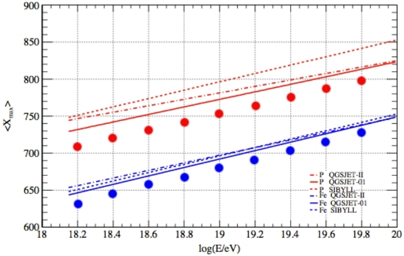
Auger



- correct rec. bias ($\sim 5\ \mathrm{g/cm^2}$)
- apply fiducial volume cuts
- compare unbiased data to simulations at generator level

(J. Bellido [Auger Coll.], ICRC09

TA/HiRes



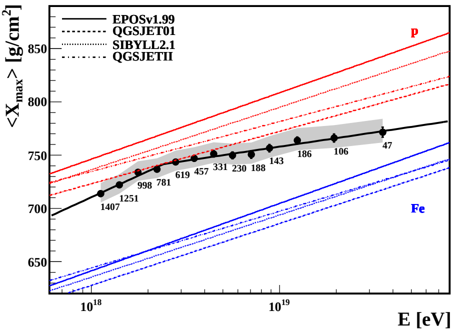
- apply same cuts in data/MC
- compare biased data to biased MC

A. Tameda [TA Coll.], icrc1268

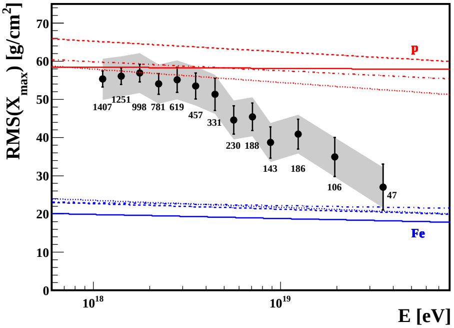
lines: input MC, dots: output after full detector sim. rec. and analysis

Longitudinal EAS Development with Auger FD

average depth

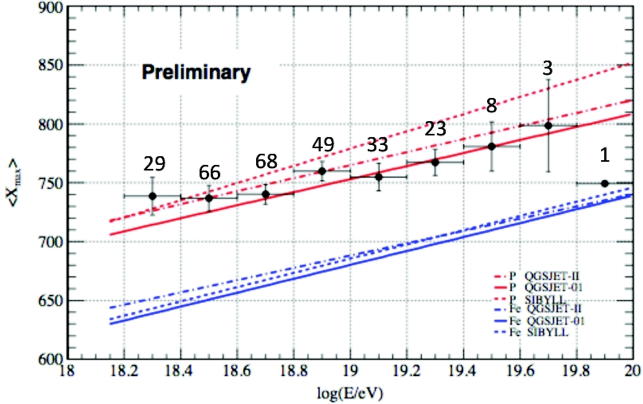


fluctuations



P. Facal [Auger Coll.], icrc725

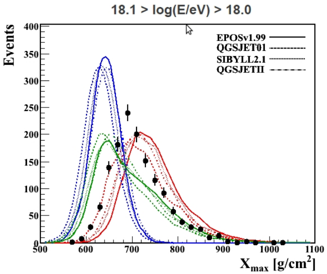
Longitudinal EAS Development with TA Stereo FD

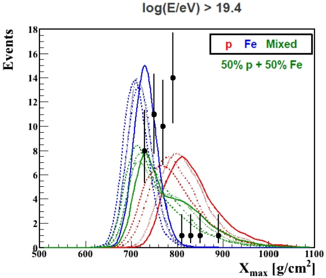


A. Tameda [TA Coll.], icrc1268

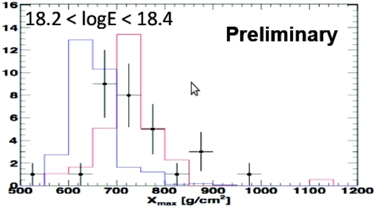
X_{max} Distributions

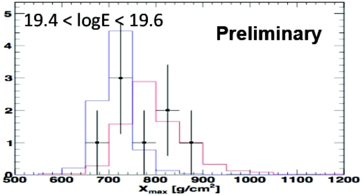
Auger





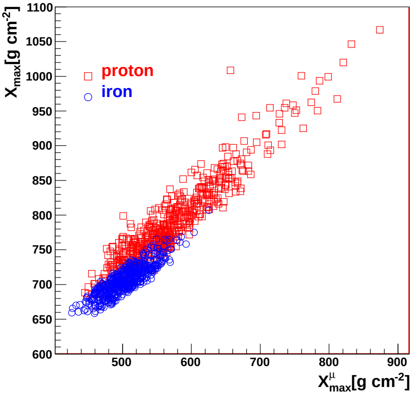
TA





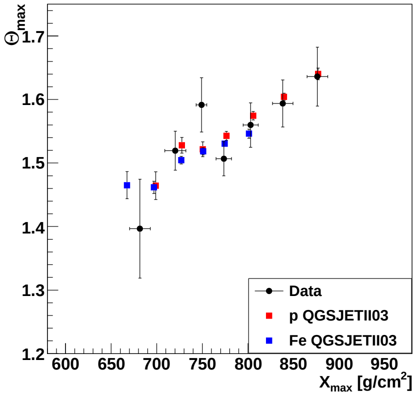
Longitudinal EAS Development with Auger SD

muon production depth



D. Garcia-Gamez [Auger Coll.], icrc735

θ-dep. of risetime asymmetry



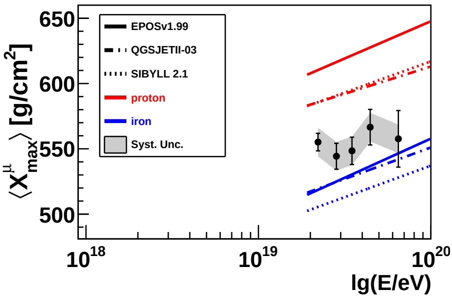
D. Garcia-Pinto [Auger Coll.], icrc709

→ reach to higher energy

→ syst. independent of FD

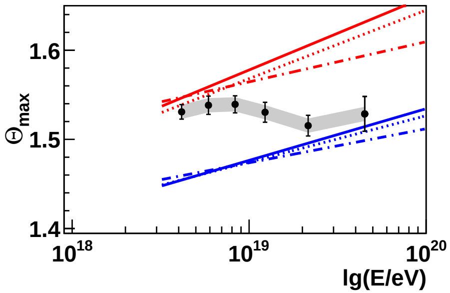
Longitudinal EAS Development with Auger SD

muon production depth



D. Garcia-Gamez [Auger Coll.], icrc735

θ-dep. of risetime asymmetry

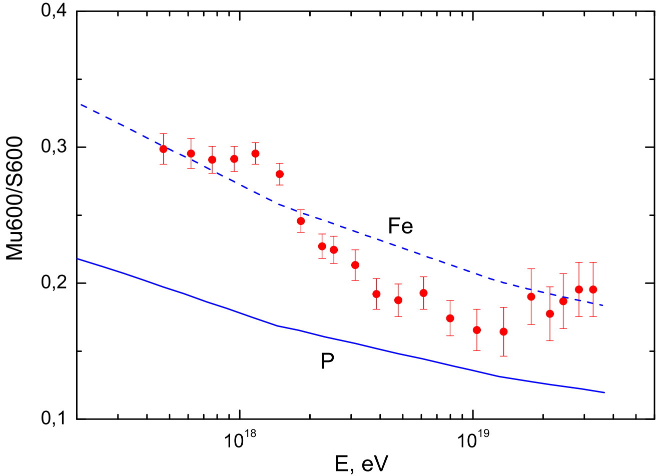


D. Garcia-Pinto [Auger Coll.], icrc709

$\rightarrow$ **reach to higher energy**

$\rightarrow$ **syst. independent of FD**

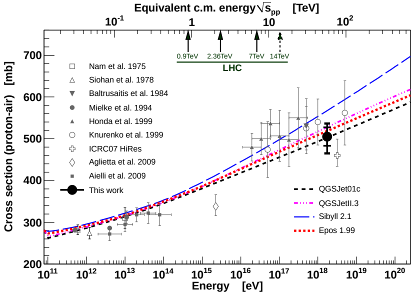
Evolution of muon density by Yakutsk

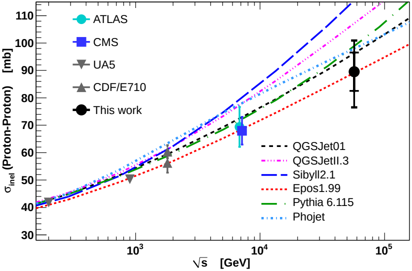


underground μ-density over surface detector scintillator signal at 600 m vs. QGSjetII

A. V. Glushkov et al. [Yaktutsk Coll.], icrc254

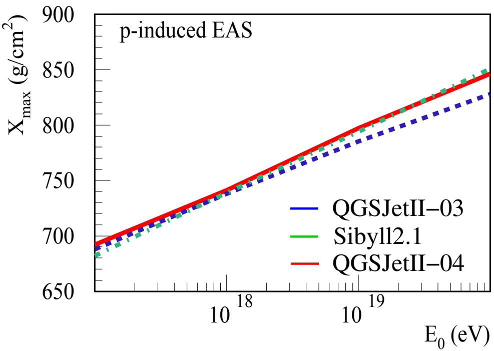
X_{max} predictions





R. Ulrich [Auger Coll.], icrc946

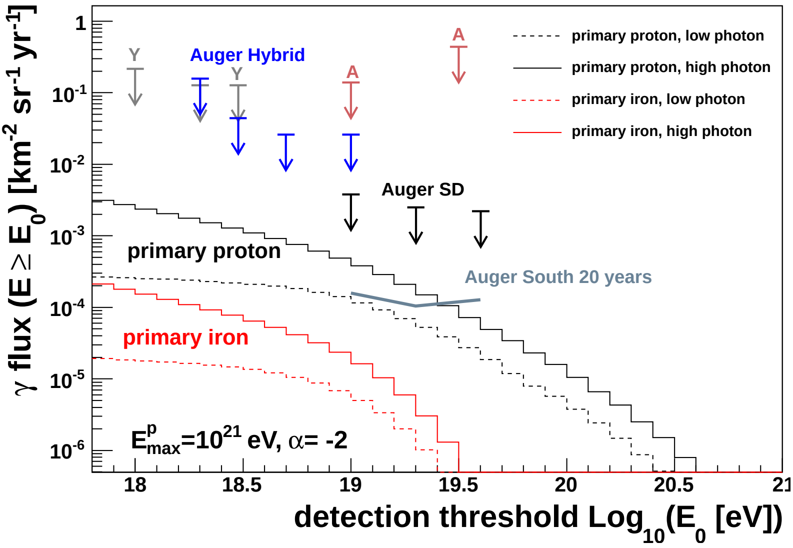
LHC-tune of QGSJetII:



S. Ostapchenko, icrc681

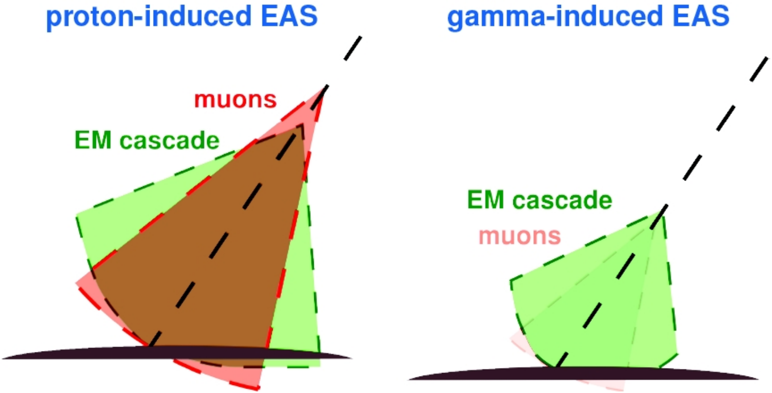
$$\mathrm{RMS}(X_{\mathrm{max}})^2 = \lambda_{\mathrm{int}}^2 + \sigma(\mathrm{sh}-\mathrm{sh})^2$$

UHE Photons



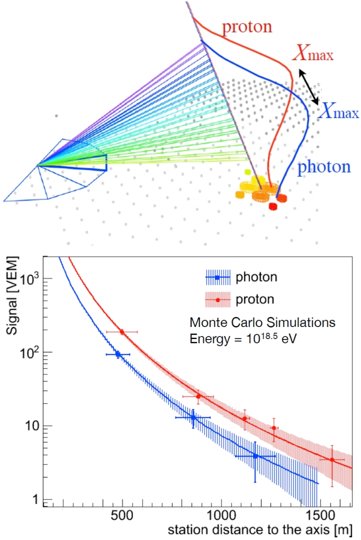
B. Sarkar et al., icrc1087

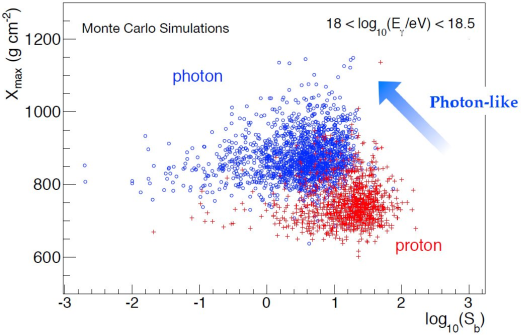
Photon Search with TA (SD)



G.I. Rubtsov [TA Coll.], icrc1266

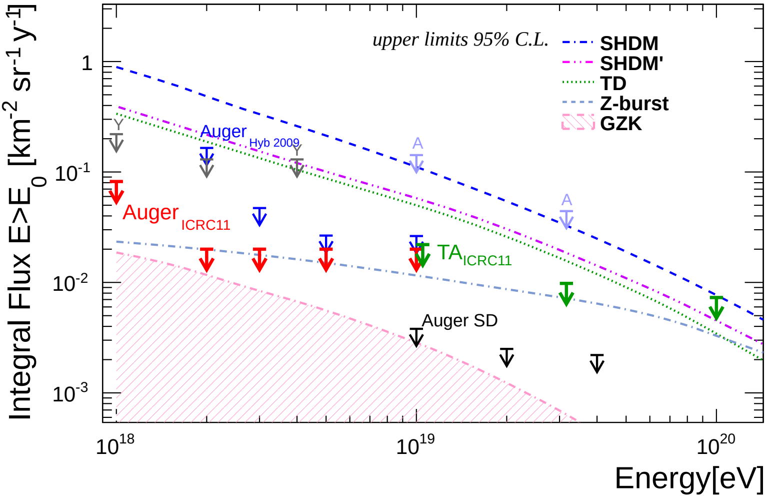
Photon Search with Auger (Hybrid)





M. Settimo [Auger Coll.], icrc393

Photon Search Results



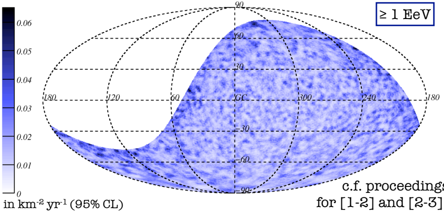
G.I. Rubtsov [TA Coll.], icrc1266

M. Settimo [Auger Coll.], icrc393

Arrival directions

Search for Anisotropies in the EeV range

Galactic neutron sources?



c.f. proceedings
for [1-2] and [2-3] EeV

B. Orfeuil [Auger Coll.], icrc713

Right Ascension Modulation?

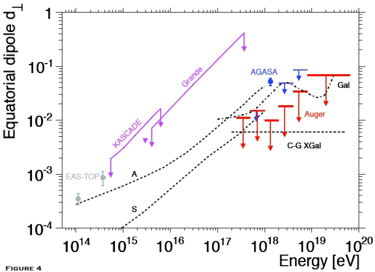
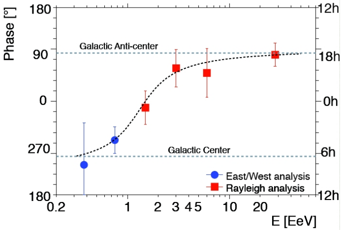


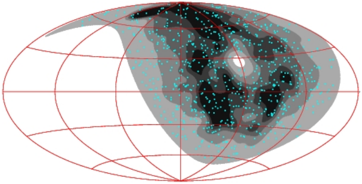
FIGURE 4



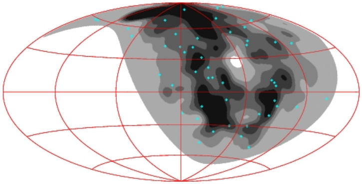
H. Lyberis [Auger Coll.], icrc493

Search for Large Scale Anisotropy with TA

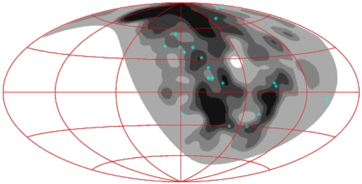
10 EeV

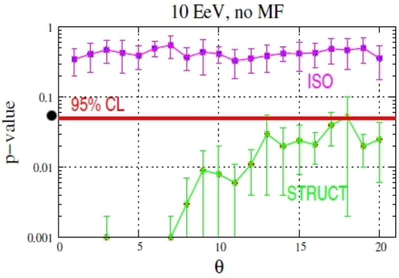


40 EeV



57 EeV





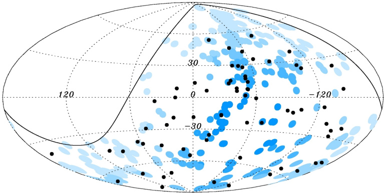
- density map using 2MASS
- incompatible at E>10 EeV
- introduce gal. B-field

P. Tinyakov [TA Coll.], icrc1317

UHE Correlation with AGNs within GZK-sphere?

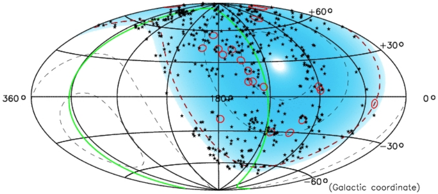
VCV catalogue, E$>$ 57 EeV, z$<$0.018, distance $<$ 3.1 deg.

Auger



28 out of 84 correlate

TA

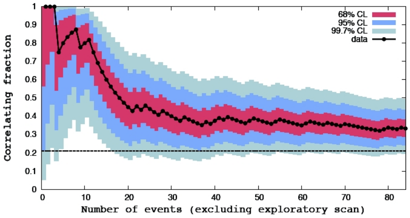


8 out of 20 correlate

UHE Correlation with AGNs within GZK-sphere?

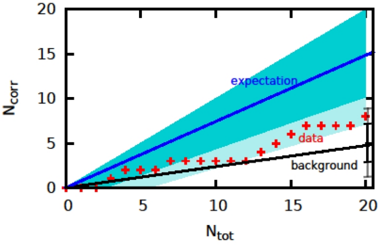
VCV catalogue, E$>$ 57 EeV, z$<$0.018, distance $<$ 3.1 deg.

Auger



$P = 0.006$, $f = 33 \pm 5\%$

TA

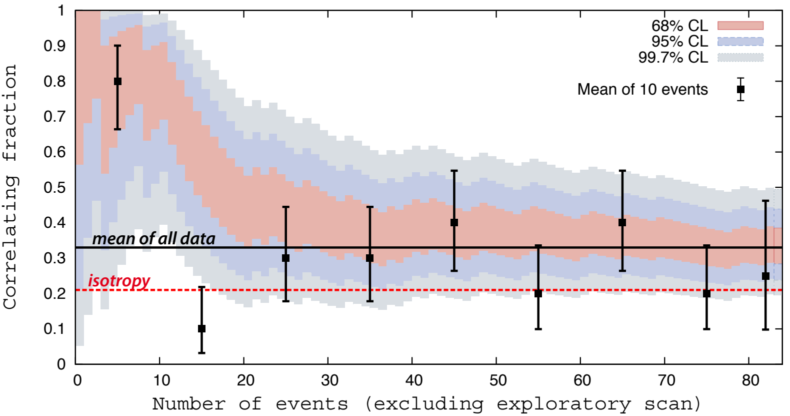


compatible with isotropy and updated (!) Auger

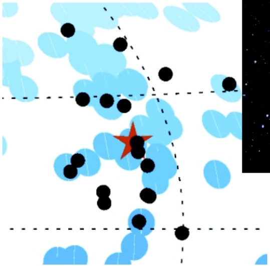
UHE Correlation with AGNs within GZK-sphere?

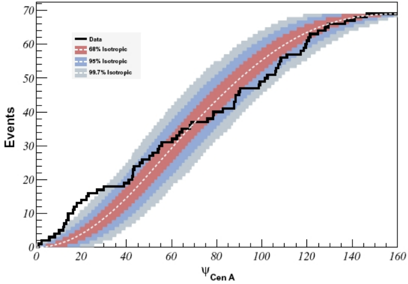
VCV catalogue, E$>$ 57 EeV, z$<$0.018, distance $<$ 3.1 deg.

Differential Auger Signal



UHERs from CenA?



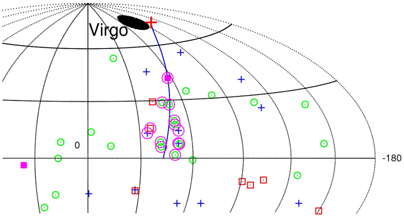


13/62 within 18 deg., expect 3.2

limits on source composition?

E.M. Santos [Auger Coll.], icrc868

... or Virgo?

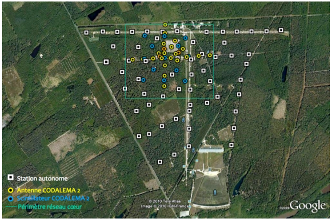


Giacinti&Semikoz, icrc171

New Techniques
R&D Projects
Future Experiments

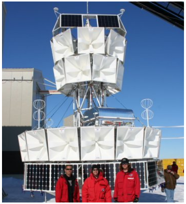
Radio-Detection of EAS

F. Schröder [LOPES Coll.], icrc313



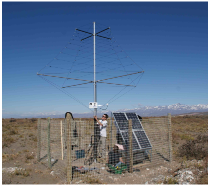
A. Belletoile [CODALEMA Coll.], icrc299

T. Saugrin [TREND Coll.], icrc1177



P. Gorham [ANITA Coll.]

J. Kelley [LOFAR Coll.], icrc916



J. Kelley [Auger Coll.], icrc556

B. Revenu [Auger Coll.], icrc845

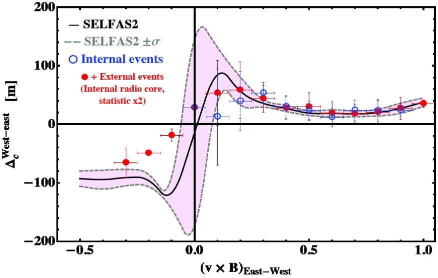
Radio-Detection of EAS

Main production mechanism: geomagnetic effect, $\vec{n} \times \vec{B}$

'Second order" effects:

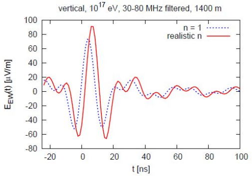
charge excess:

core shifts in CODALEMA

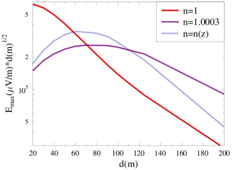


V. Marin [CODALEMA Coll.], icrc942

refractive index, Cherenkov

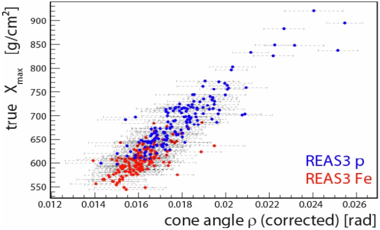


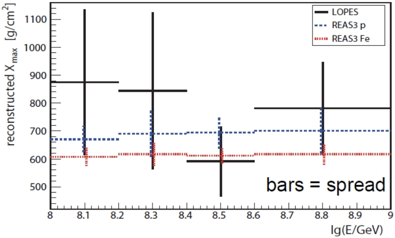
M. Ludwig et al. icrc149



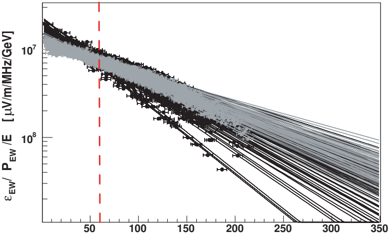
K. de Vries et al. icrc139

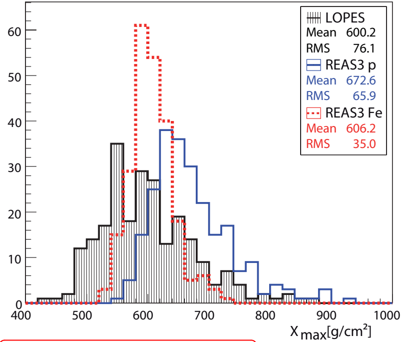
First MHz Composition Sensitivity Studies





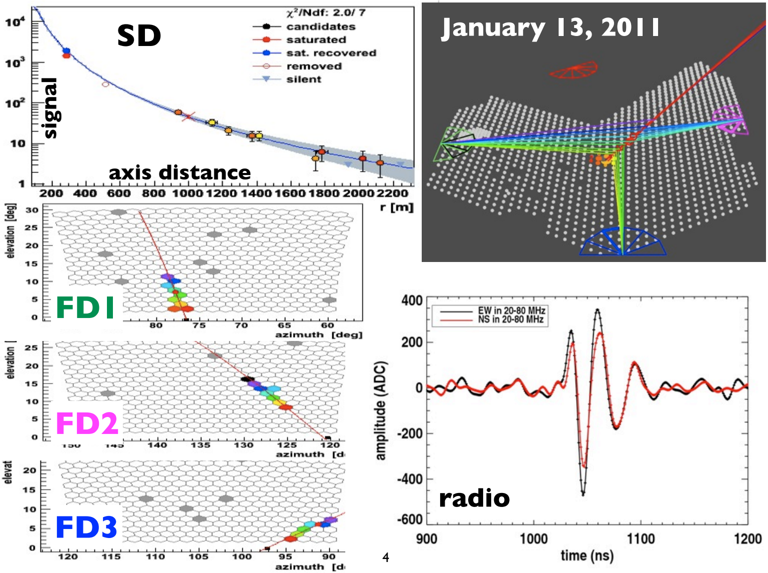
F. Schröder [LOPES Coll.], icrc313





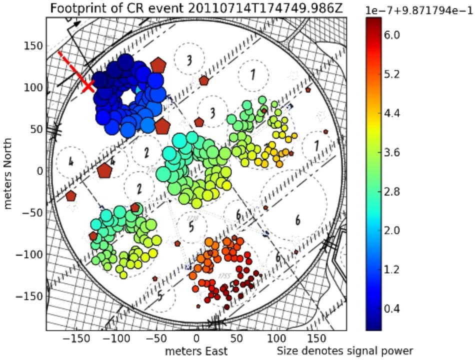
N. Palmieri [LOPES Coll.], icrc309

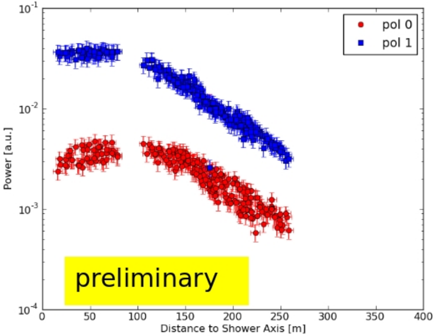
Auger 'Super Hybrid' (radio self-triggered!)



B. Revenu [Auger Coll.], icrc845

LOFAR CR event



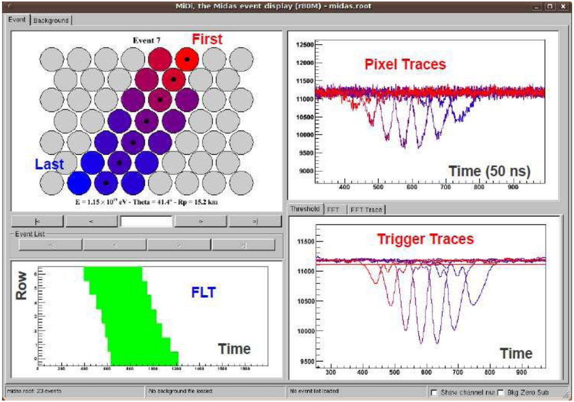


J. Kelley [LOFAR Coll.], icrc916

Microwave-Detection of EAS

isotropic emission of molecular bremsstrahlung

$\rightarrow$'FD' with 100% duty cycle?



MIDAS event display (simulation!)

based on SLAC measurement Gorham et al., Phys.Rev.D 78 (2008)

Microwave-Detection of EAS

Auger

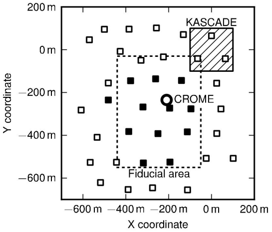
AMBER

MIDAS

EASIER

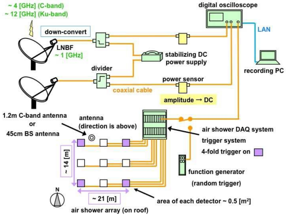
KASCADE Grande

CROME



Konan Univ.

Osaka Univ.



R. Smida [CROME Coll.], icrc1177

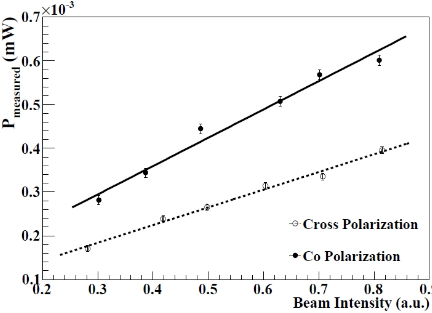
P. Allison [Auger Coll.], icrc733

T. Yamamoto et al. icrc998

K. Kuramoto et al. icrc808

Microwave-Detection of EAS

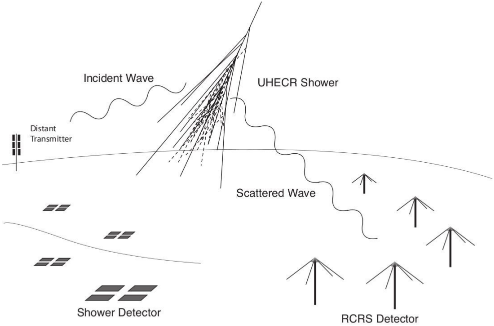
MAYBE (Microwave Air Yield Beam Experiment) at ANL



- 3 MeV beam (sub-Cherenkov)
- anechoic chamber

M. Monasor [MAYBE Coll.], icrc917

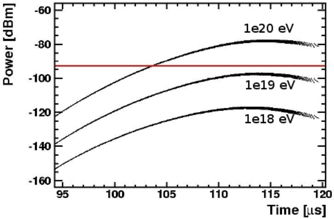
Radar Detection of EAS at TA



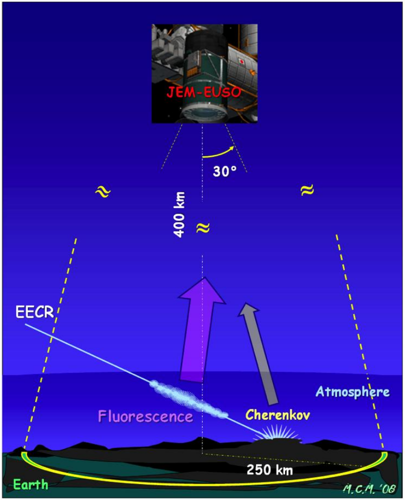
J. Belz [TARA Coll.], icrc1314

H. Takai [TARA Coll.], icrc1315

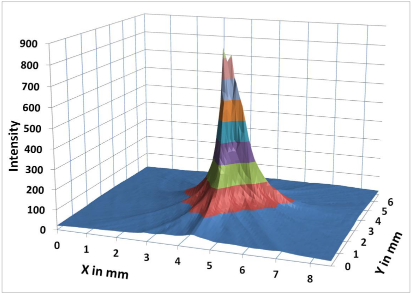
Signal-to-Noise, 20 kW TX



JEM-EUSO Optics Prototype



J.H. Adams [JEM-EUSO Coll.], icrc1100



JEM-EUSO Exposure

using Universitetsky Tatiana satellite data

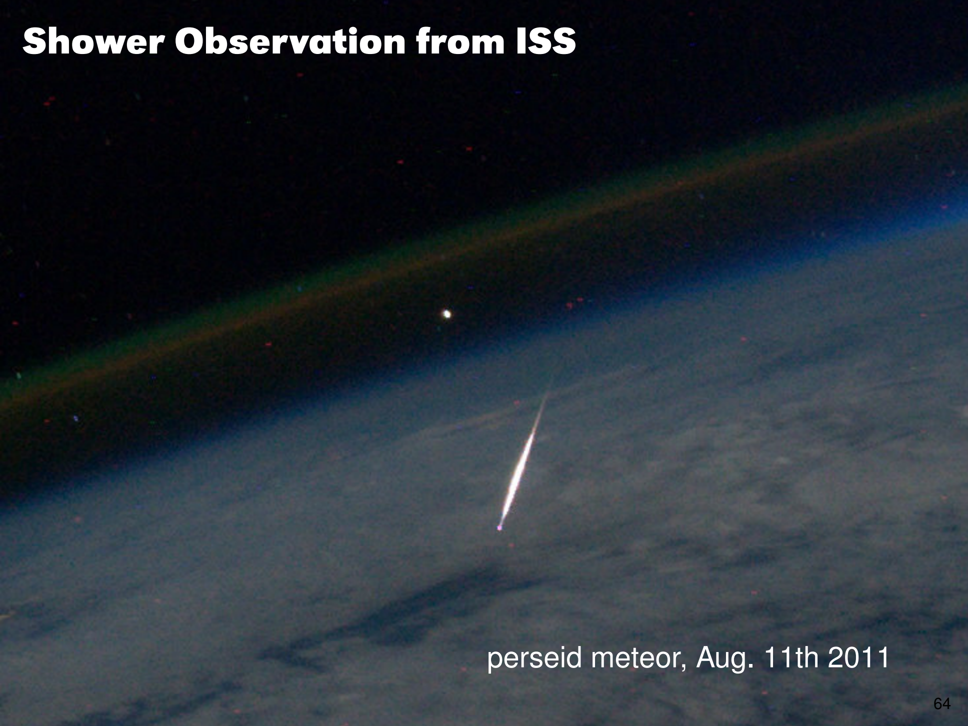
Observatory	Aperture km^2 sr	Status	Start	Lifetime	Duty cycle	Annual Exposure km^2 sr yr	Relative to Auger
Auger	7,000	Operations	2006	4 (16)	1	7000	1
TA	1,200	Operations	2008	2 (14)	1	1,200	0.2
TUS	30,000	Developed	2012	5	0.14	4,200	0.6
JEM-EUSO ($E \approx 10^{20}$ eV)	430,000	Design	2017	5	0.14	60,000	9
JEM-EUSO (highest energies) Tilted mode 35°	1,500,000	Design	2017	5	0.14	200,000	28

- 2013: launch JEM-EUSO balloon from Kiruna
- 2017: launch to ISS using Japanese HII Transfer Vehicle (HTV)?

T. Ebisuzaki [JEM-EUSO Coll.], icrc120

Shower Observation from ISS

Shower Observation from ISS



perseid meteor, Aug. 11th 2011

Pre-Announcement

UHECR 2012

International Symposium on Future Directions in UHECR Physics

CERN
February 13-17, 2012

Follow-up of Nagoya Symposium 2010
Scope: Discuss **science case for next generation UHECR observations**, ground based Giant Detector and Space Observatory, **technological challenges, related R&D works**

Contacts: M. Fukushima (fukushim@icrr.u-tokyo.ac.jp)
K.-H. Kampert (kampert@uni-wuppertal.de)

Conclusions

my subjective highlights :

- evidence for a 'heavy knee' by KASCADE-Grande
- high quality data from Telescope Array
- refinement of Auger measurements with larger statistics and new methods

situation at ultra-high energies :

- good agreement on spectral features of spectrum
- persistent Auger anisotropy in UHE arrival directions
- new data on composition, but still inconclusive
  $\rightarrow$ need to find a way for direct comparison of measurements from different experiments to judge level of (dis-)agreement.