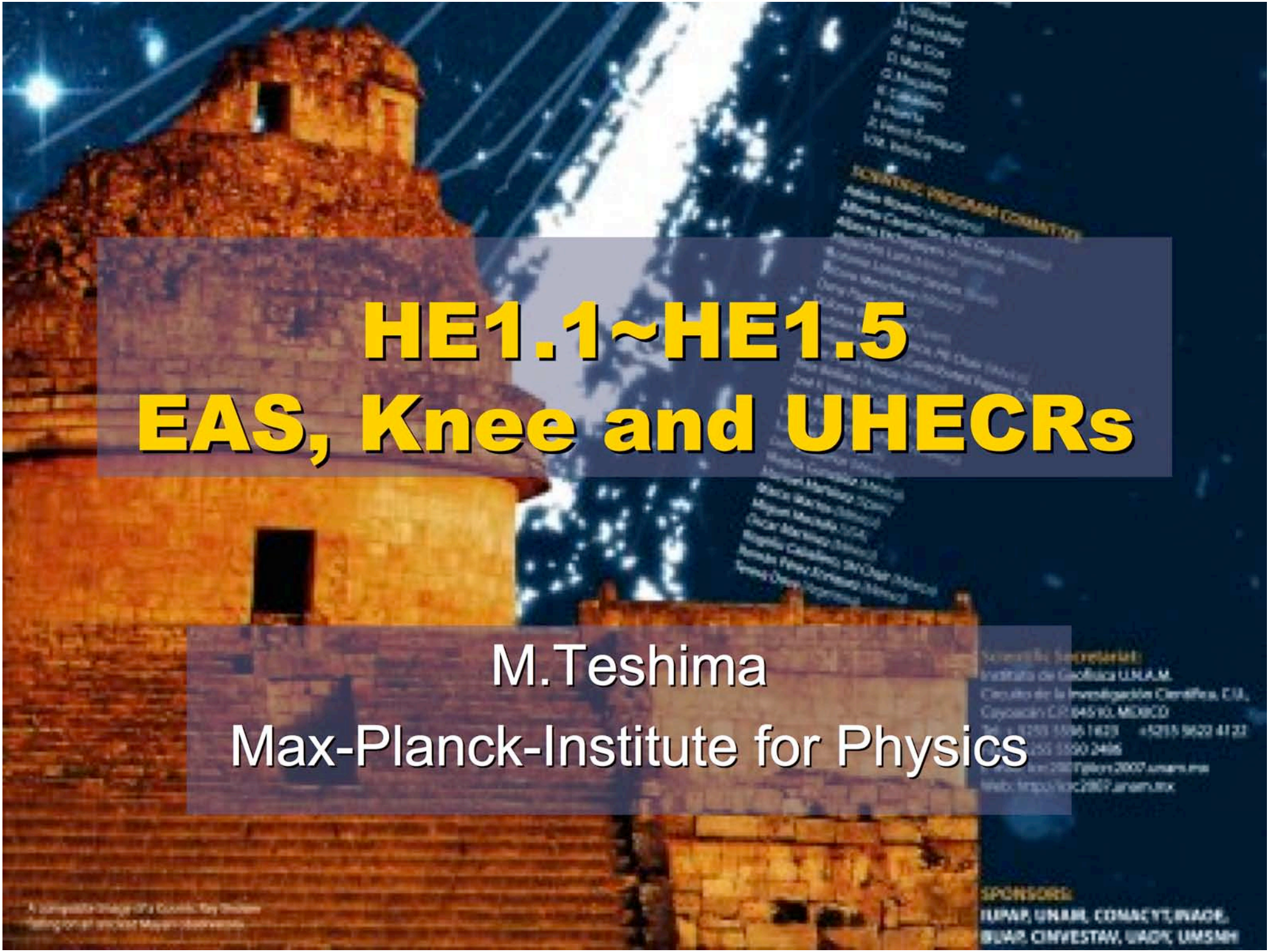

HE1.1~HE1.5
EAS, Knee and UHECRs

M.Teshima
Max-Planck-Institute for Physics

Statistics

- HE1.1 24 papers EAS, Knee region
- HE1.2 26 papers EAS, above knee
- HE1.3 28 papers EAS, UHECR
- HE1.4 78 papers UHECR
- HE1.5 91 papers New experiments
- HE1.6 20 papers M.C. → Dr.Engel

- HE1 total 247 papers 915 pages

Statistics

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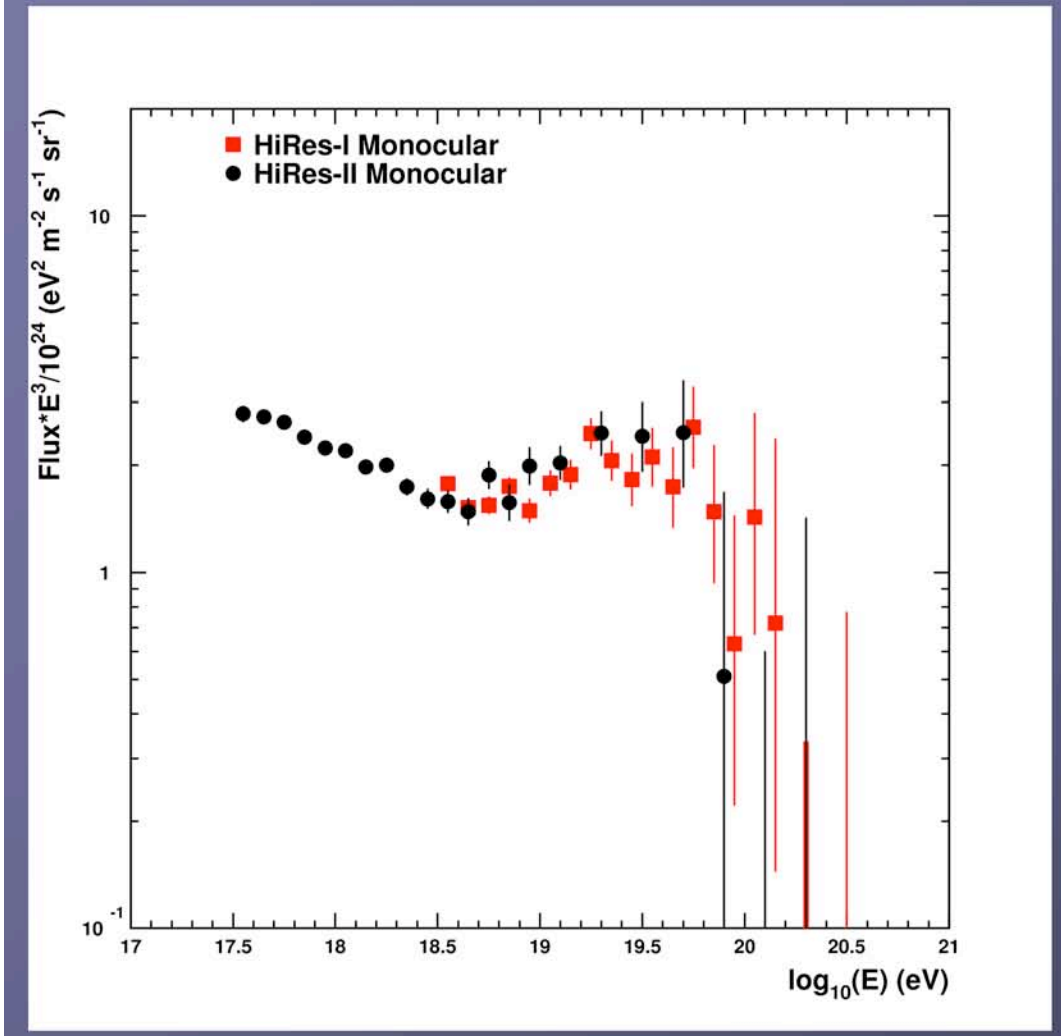
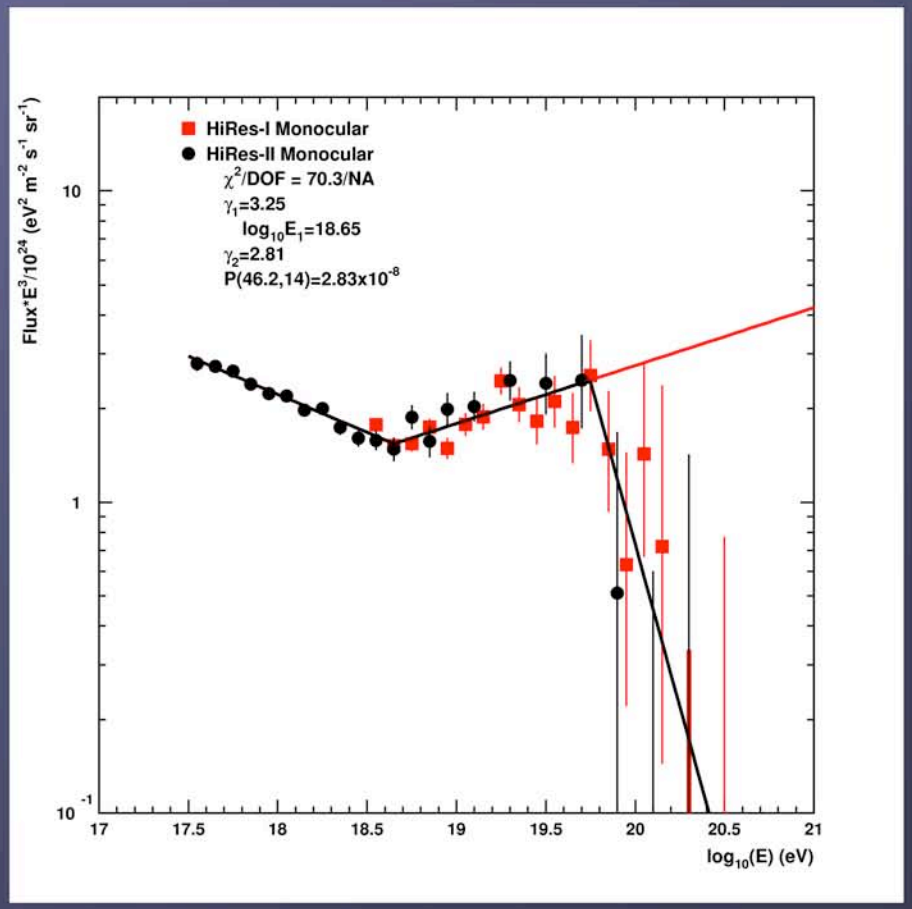
- 14.5 sec/paper → impossible to review all papers
- Will pick up highlights with my biased view; Apologies!!

UHECRs
Energy Spectrum

HiRes Spectrum
Broken power law fits



- Expect 46.2, observe 14
  - $P=7\times10^{-7}$ (4.8σ)

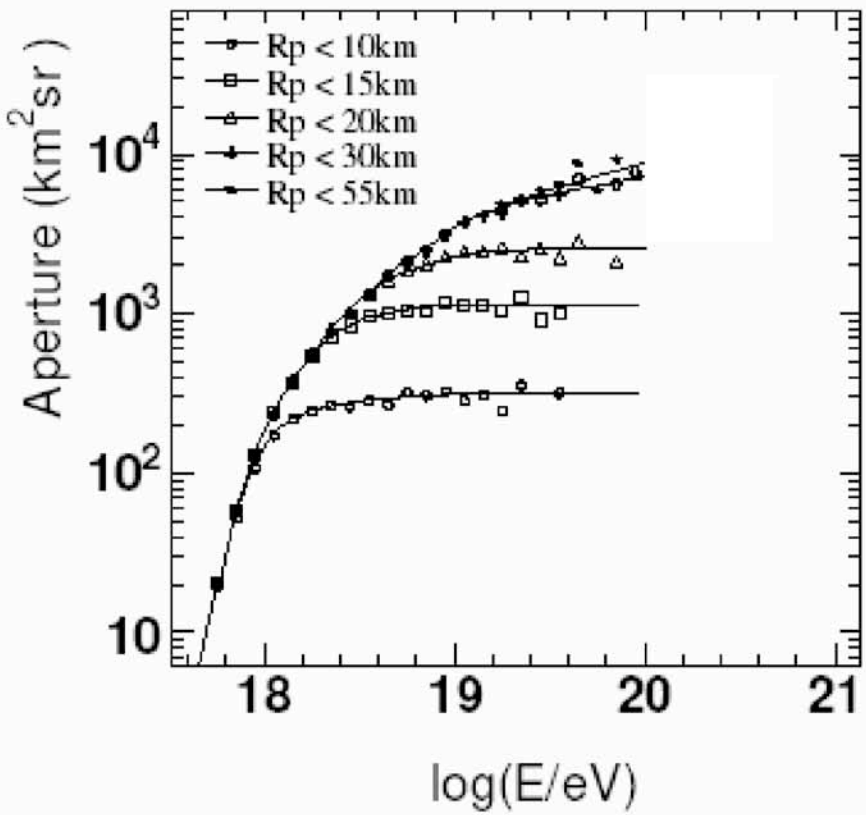


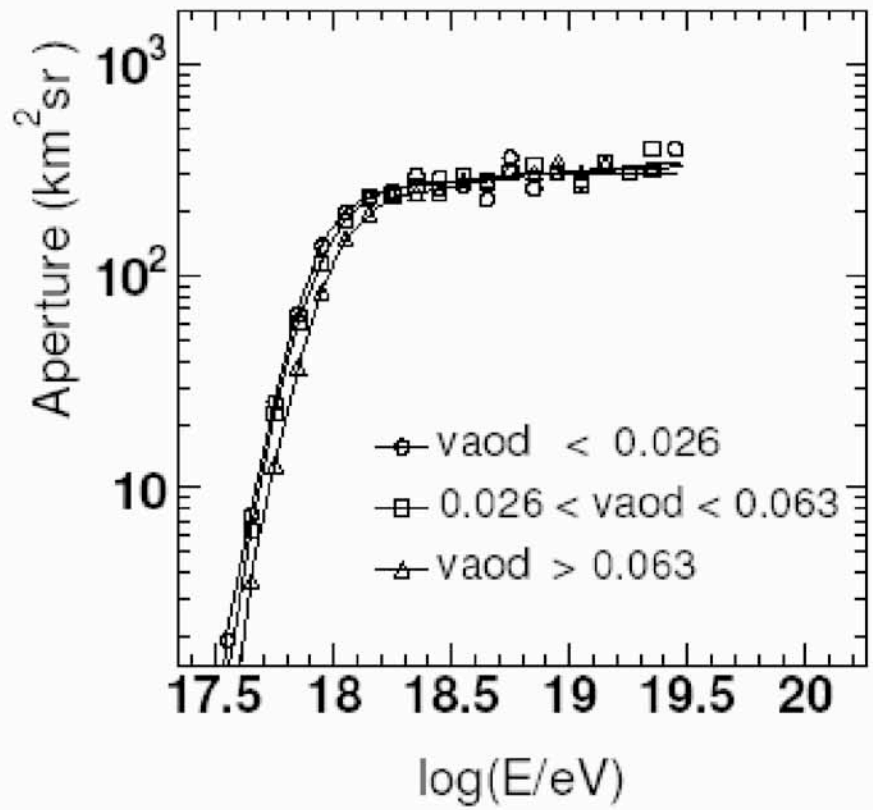
Systematic Error in HiRes Mono Energy Spectrum

- Energy Scale Uncertainties
  - Missing Energy 5%
  - Energy Loss Rate 10%
  - Fluorescence Yield 6%
  - Atmospheric Conditions 4%
  - Photometric Calibration 10%

- Total Energy Scale Uncertainty 17%
  - Flux Uncertainty (with γ=2.8) 30%

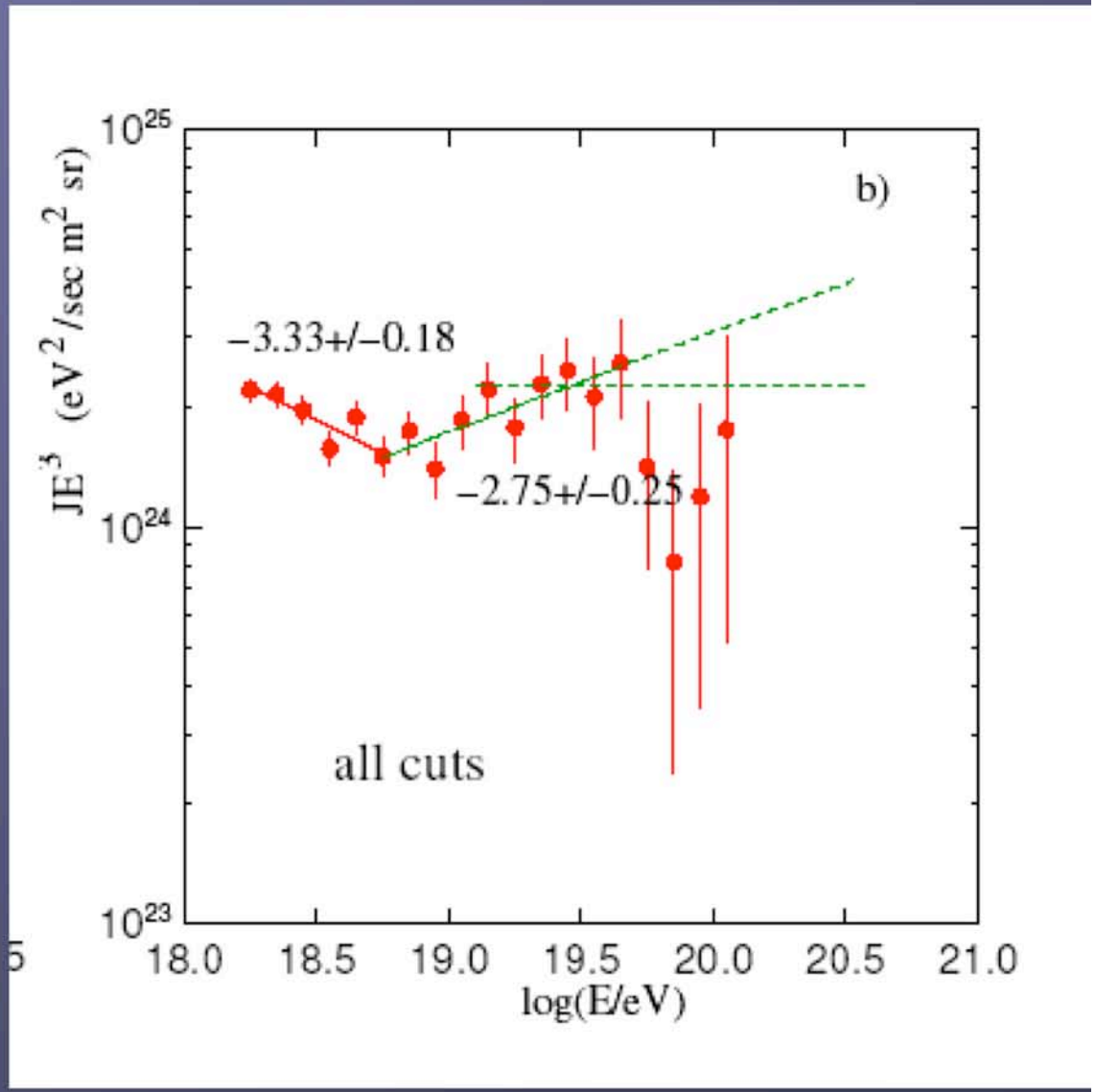
HiRes Stereo Energy Spectrum



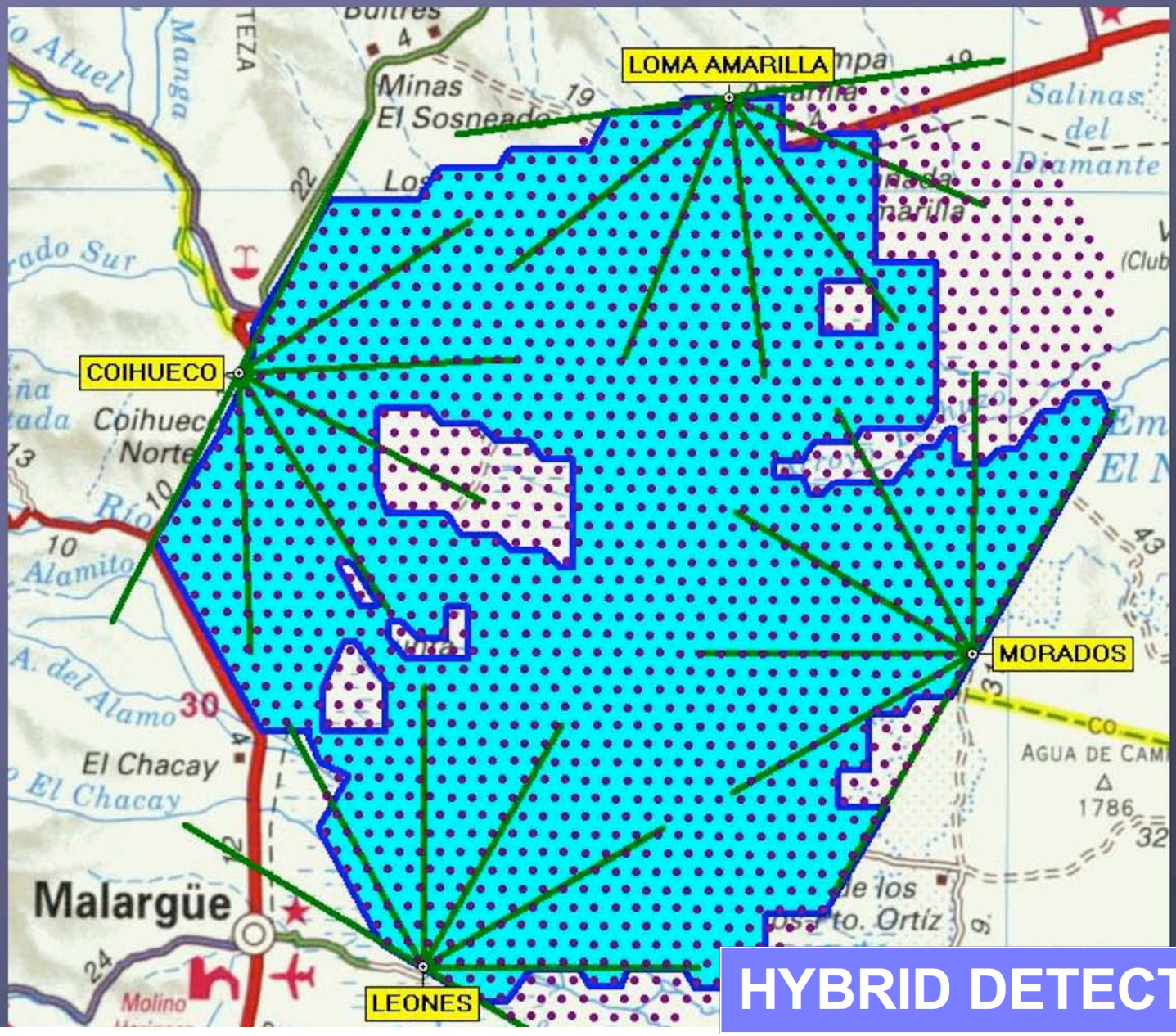


HiRes Stereo Energy Spectrum

- With geometrical constraint
- Consistent with Mono spectrum
- 11 observed, where 37.4 / 29.8 expectation
- -4.3 σ, -3.4 σ deviation

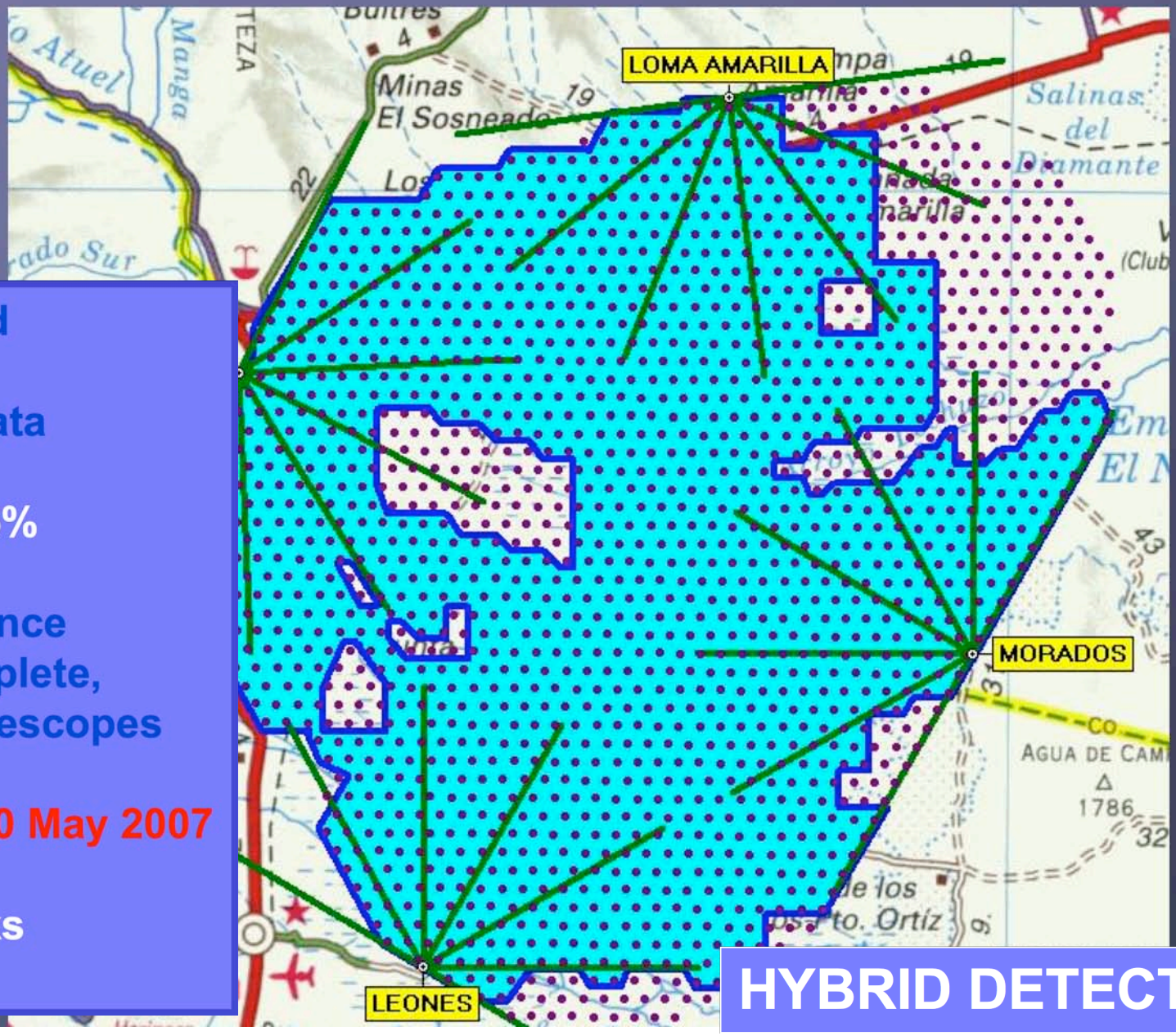


Auger



HYBRID DETECTOR

Auger



1438 deployed
1400 filled
1364 taking data

090707 ~ 85%

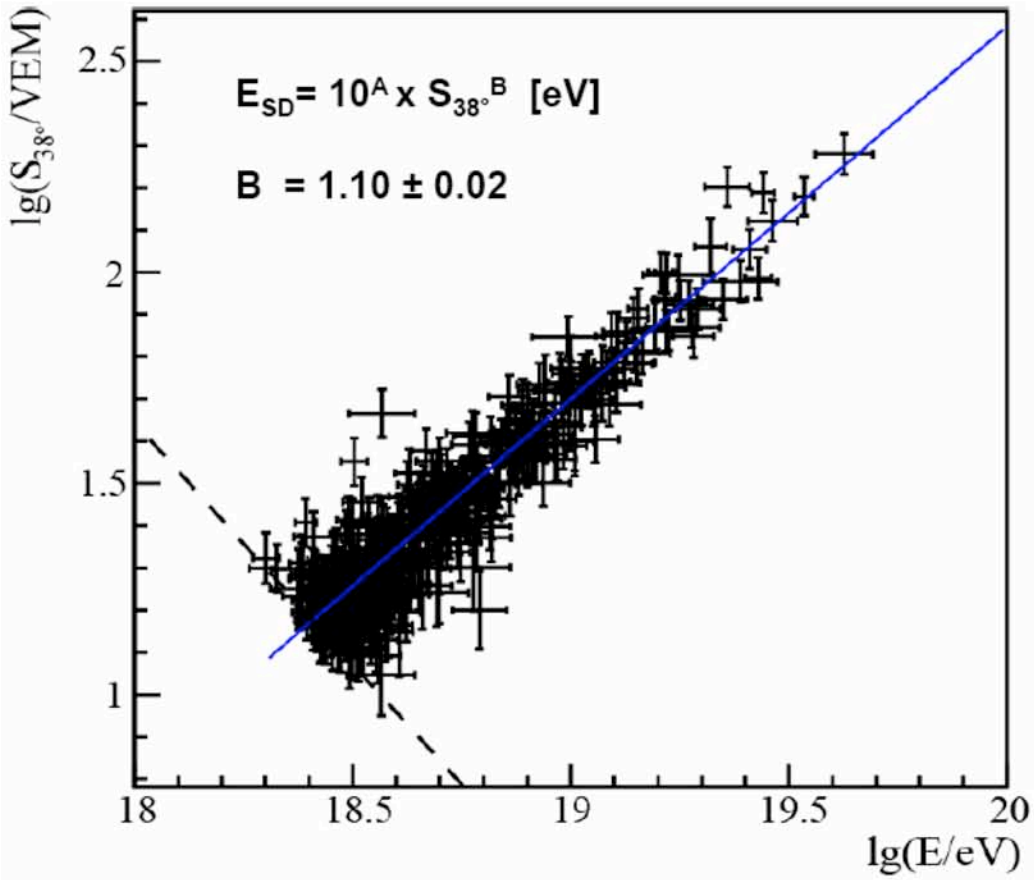
All 4 fluorescence buildings complete, each with 6 telescopes

1st 4-fold on 20 May 2007

AIM: 1600 tanks

HYBRID DETECTOR

Auger: Energy Calibration

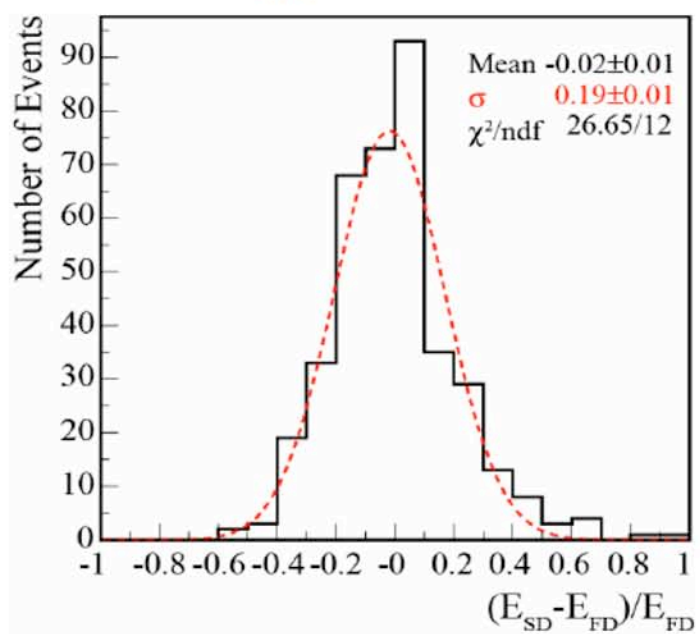


Selection of high quality hybrid data without introducing biases
(talk on elongation rate by M. Unger [Auger Collaboration])

⇨ 387 events

⇨ Correlation of $S_{38°}$ and E_{FD}

Energy resolution



$$\frac{\sigma_E}{E} = \frac{\sigma_{E_{SD}(\sigma_{S_{38°}})}}{E_{SD}} \otimes \frac{\sigma_{E_{FD}}}{E_{FD}} = 18\%$$

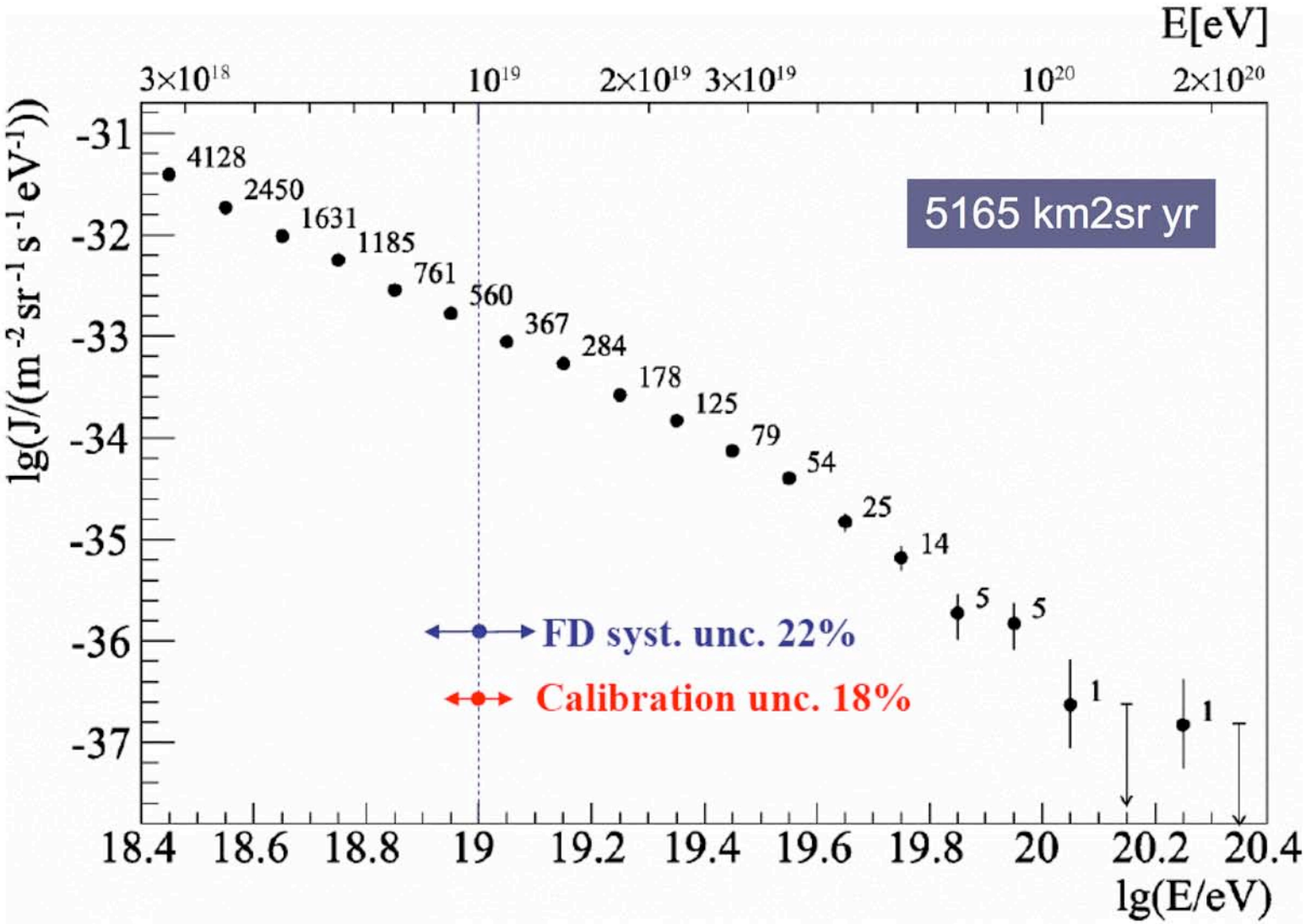
16% 8%

Auger SD Energy Spectrum

Cross-checks:

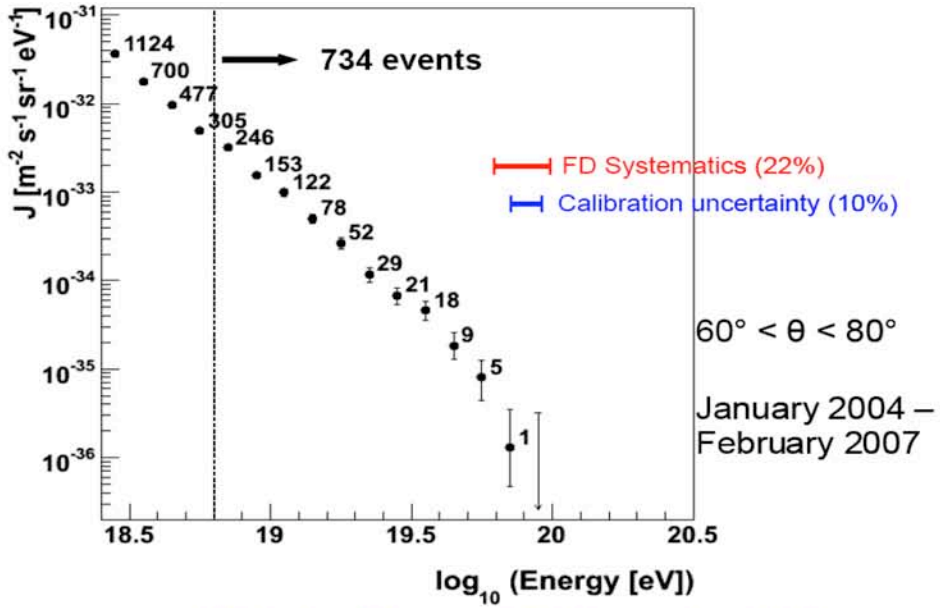
- Different reconst. methods
- $\cos^2\theta$
- Different portions of the array
- Different time periods
- Temperature

⇨ **All compatible within uncert. (few %)**



Auger SD Inclined Energy Spectrum

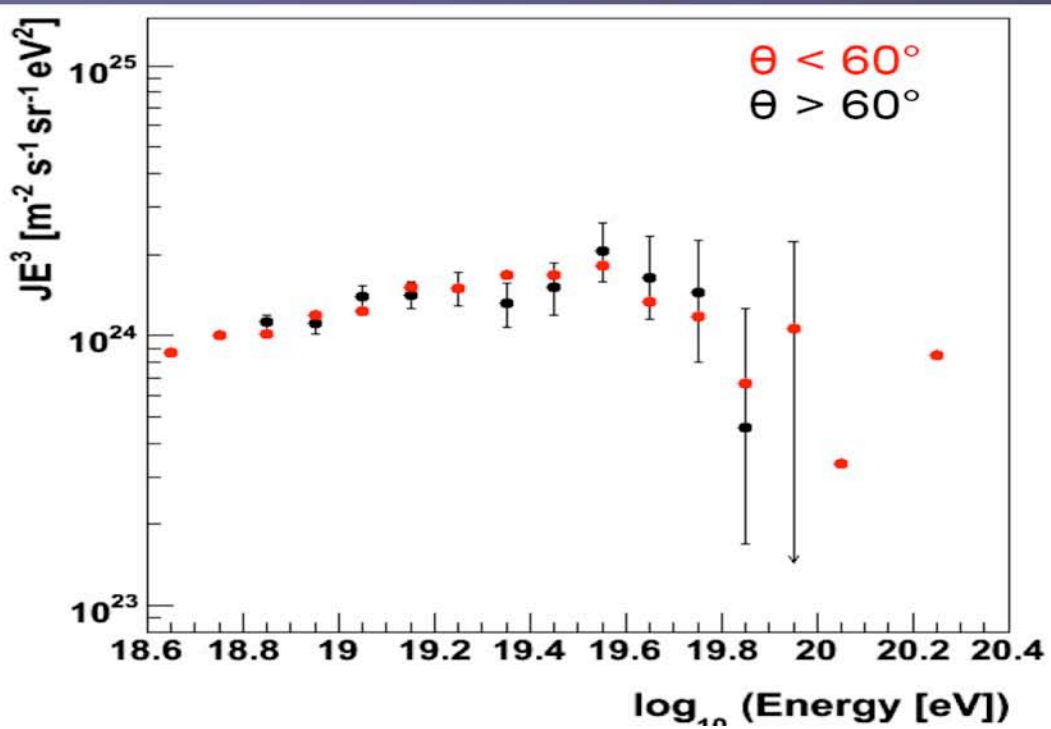
Inclined events energy spectrum



60° < θ < 80°

January 2004 – February 2007

Exposure 1510 km^2 yr sr (29% of θ<60º)

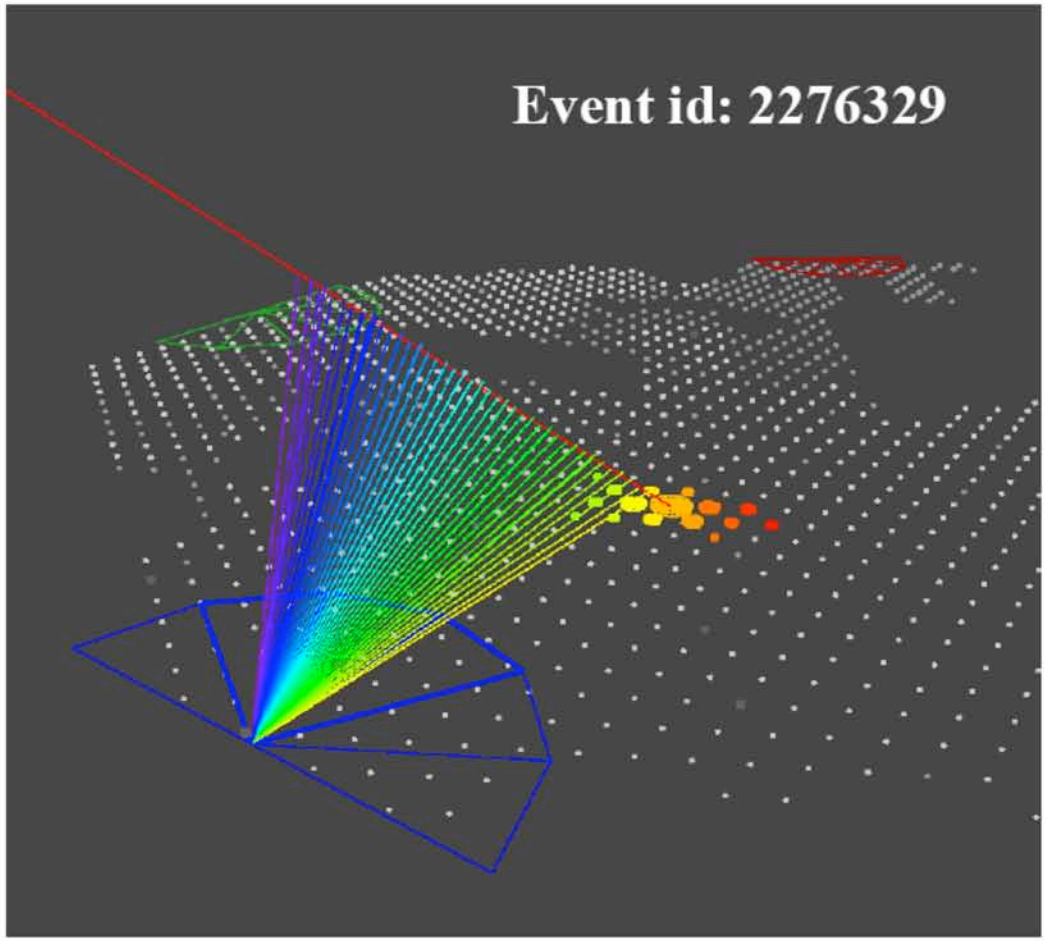


Auger Hybrid Concept

The Auger Observatory combines independent measurement techniques

Surface Detector Array (SD)

Air Fluorescence Detectors (FD)

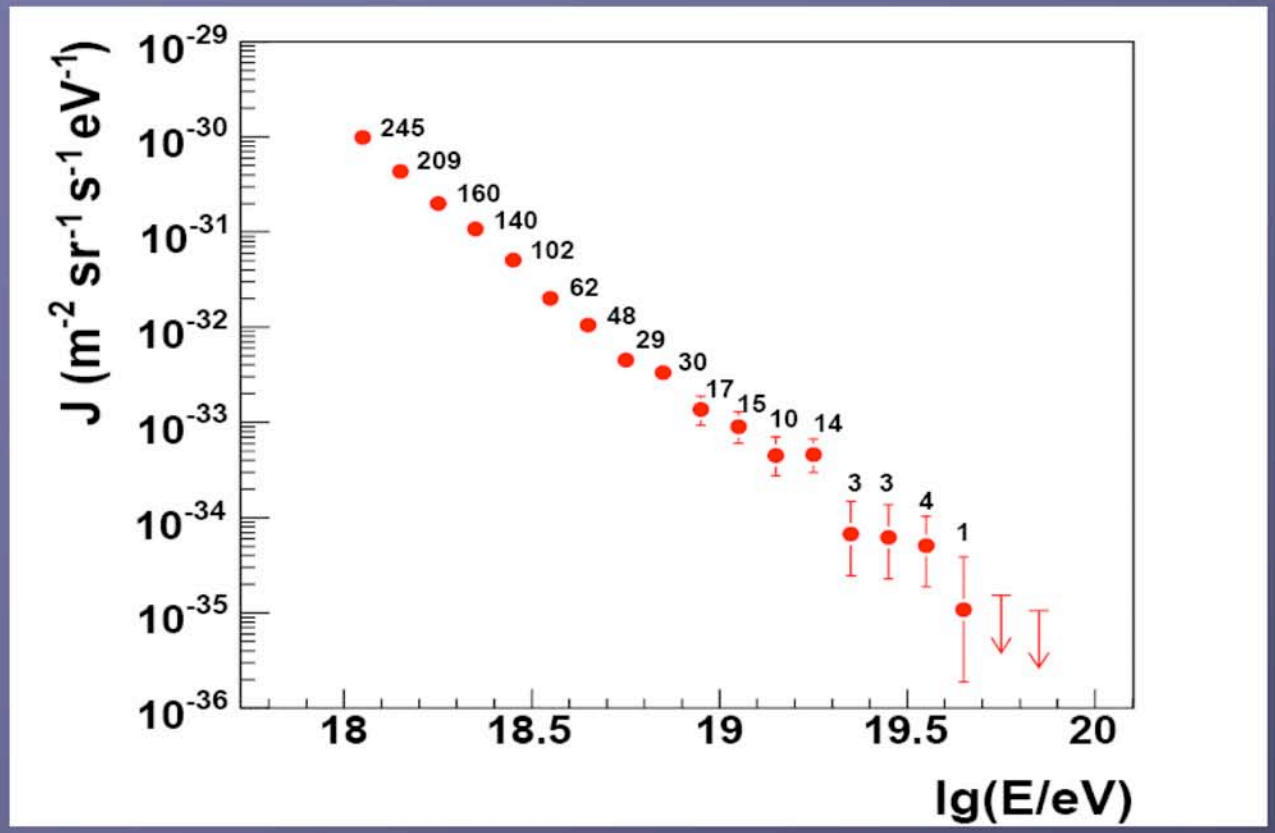


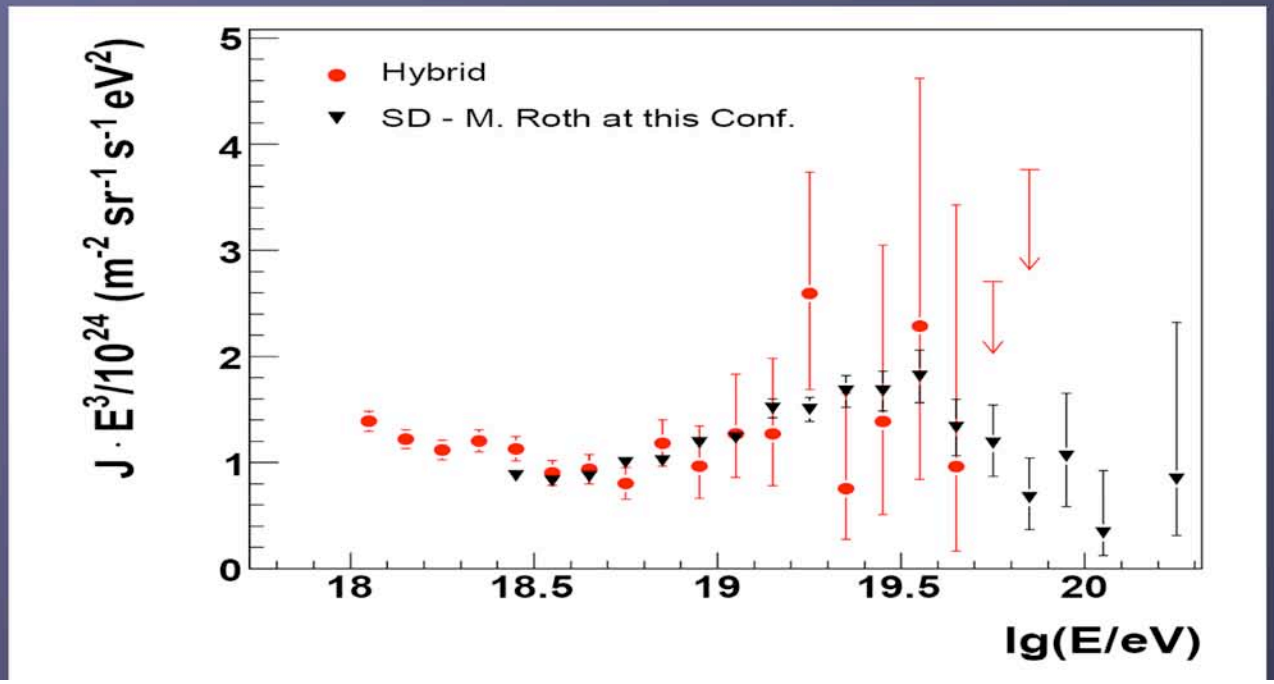
- reliable geometry and energy measurement
- mass composition studies in a complementary way

***Hybrid* data set used for this analysis:**

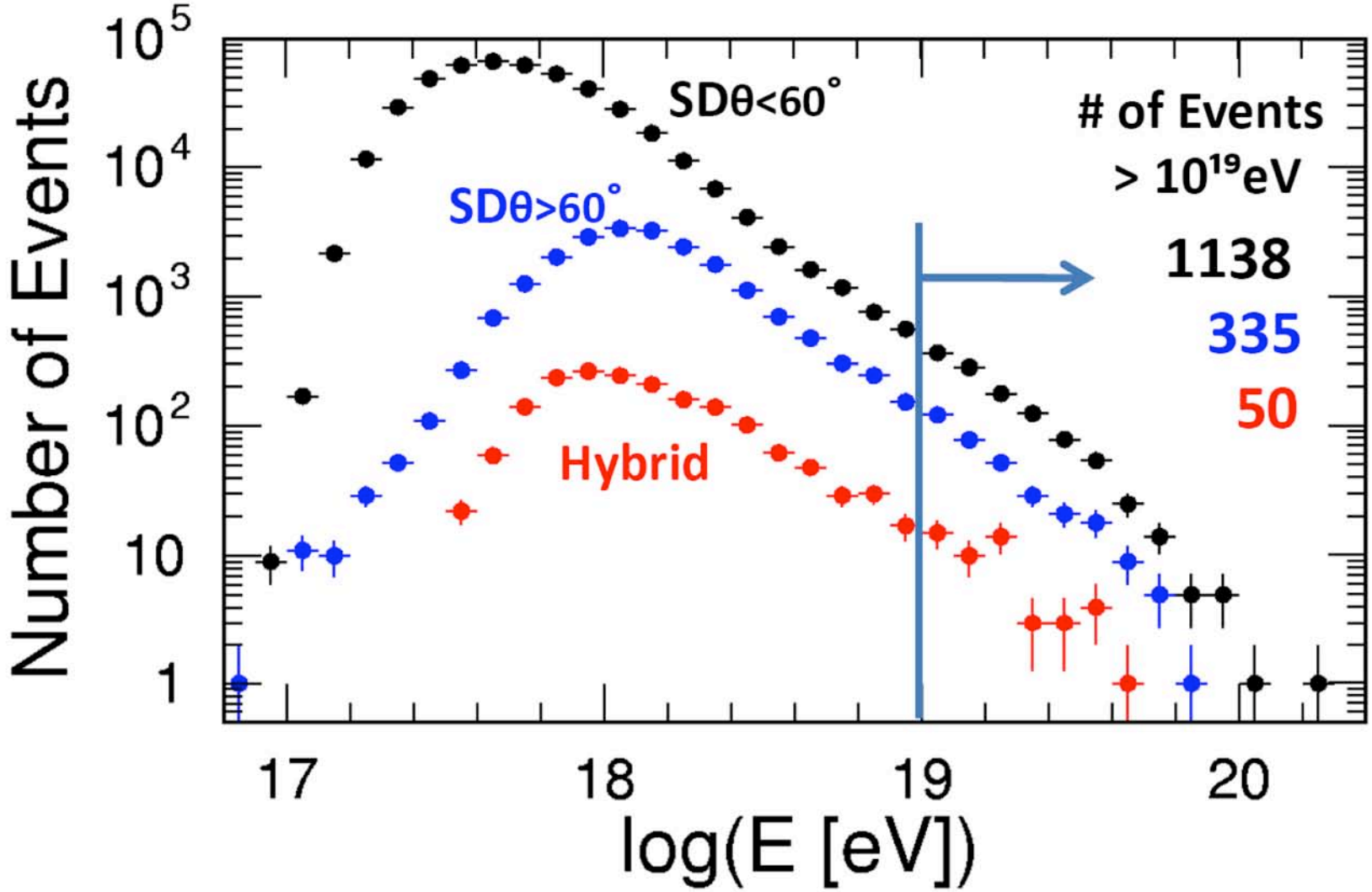
fluorescence events in coincidence with a least one SD station

Auger Hybrid Energy Spectrum





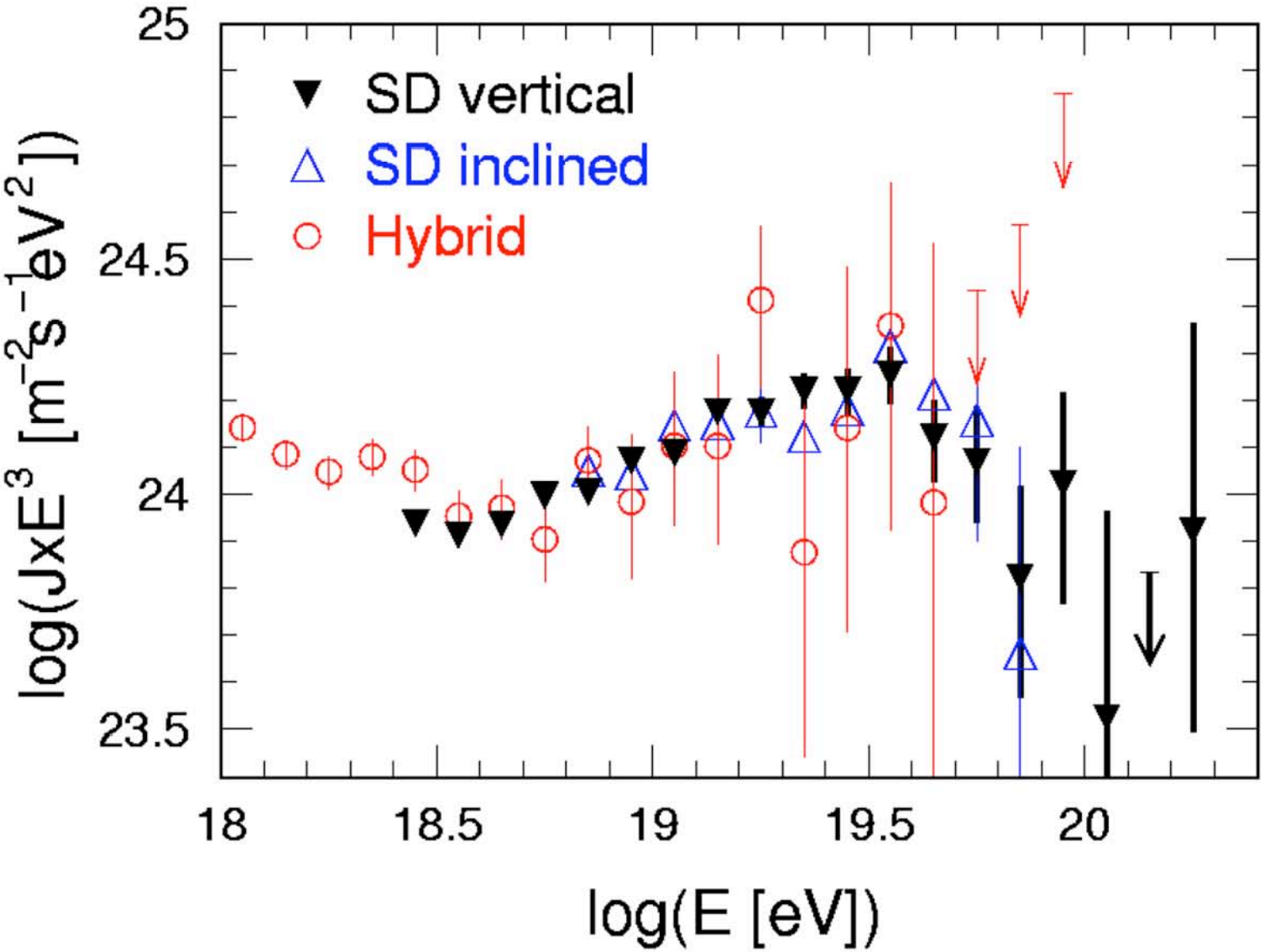
Energy distribution of events in three observation modes



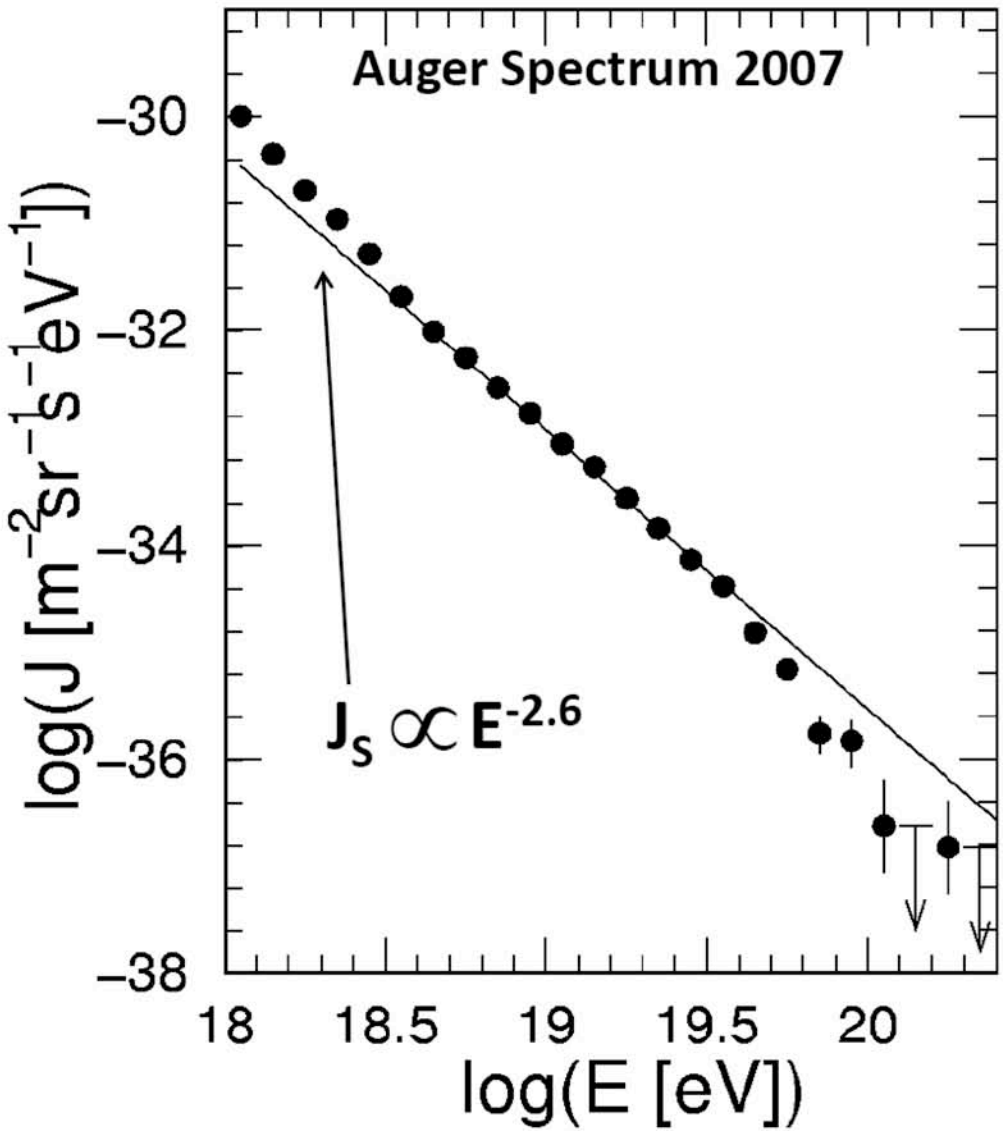
Energy scale is measured with Hybrid Observation

Auger Three Spectra

Good agreement between the three spectra



Auger combined spectrum

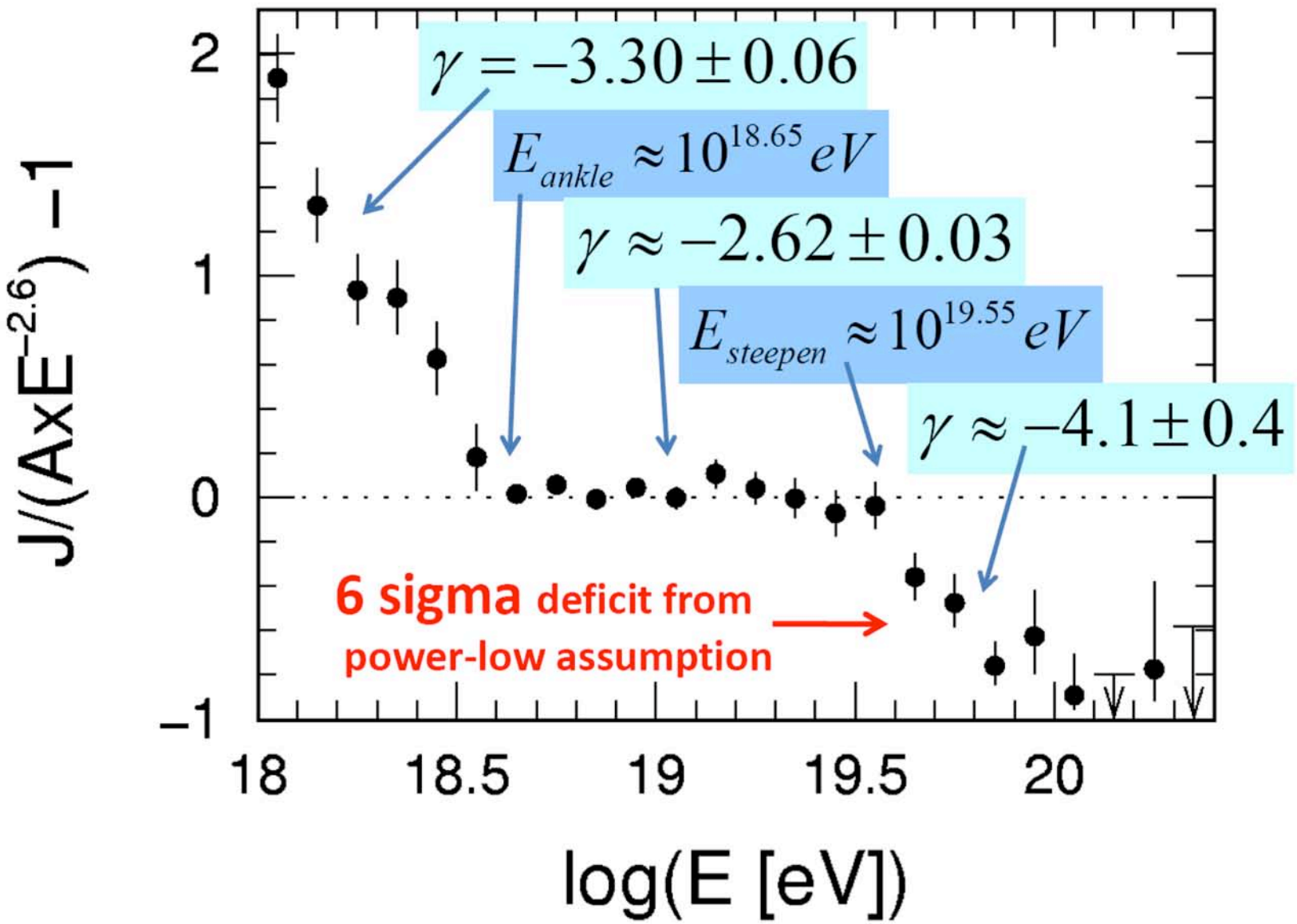


Three spectra combined weighting statistical error in each energy bin.

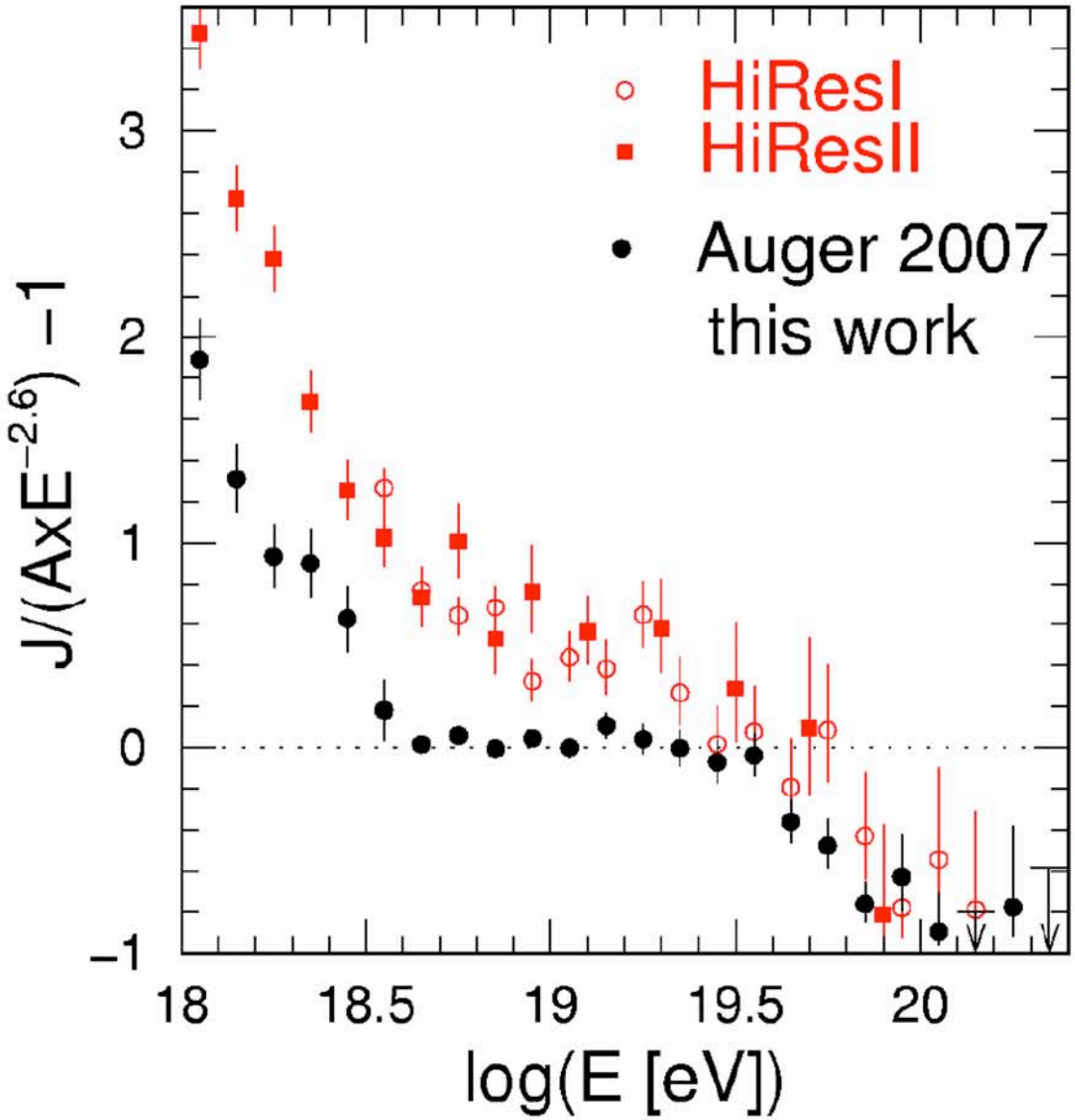
Low energy from Hybrid observation, High energy from SD.

'ankle' and 'steepening' seen in (nearly) model and mass-independent measurement .

Auger Residual plot



HiRes vs. Auger



Uncertainty in Energy scale is achieved to be **22%** and still being reduced.

A significant difference from HiRes spectrum at below 10 EeV.

Slope at Highest End

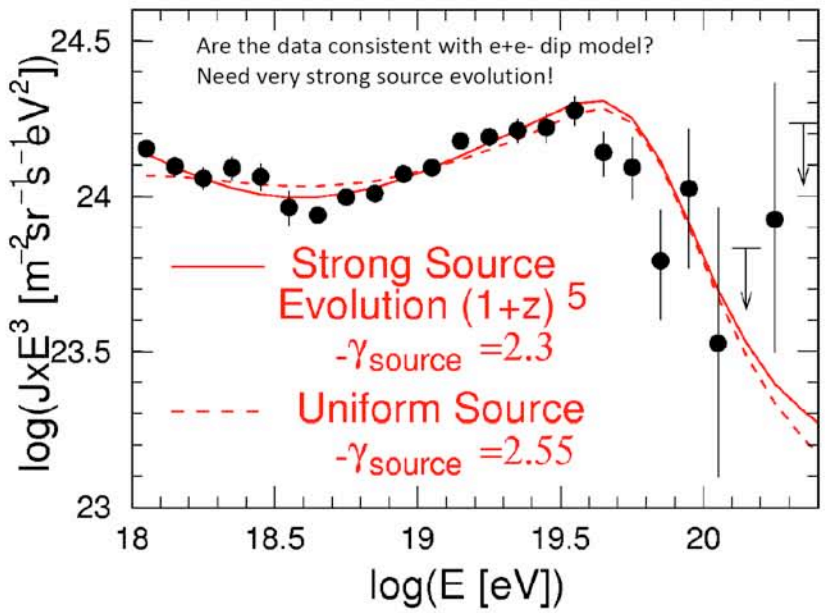
Auger $\gamma = -4.1 \pm 0.4$

HiRes $\gamma = -5.1 \pm 0.7$

Auger Spectrum

comparisons with Proton Model and with Mixed composition model

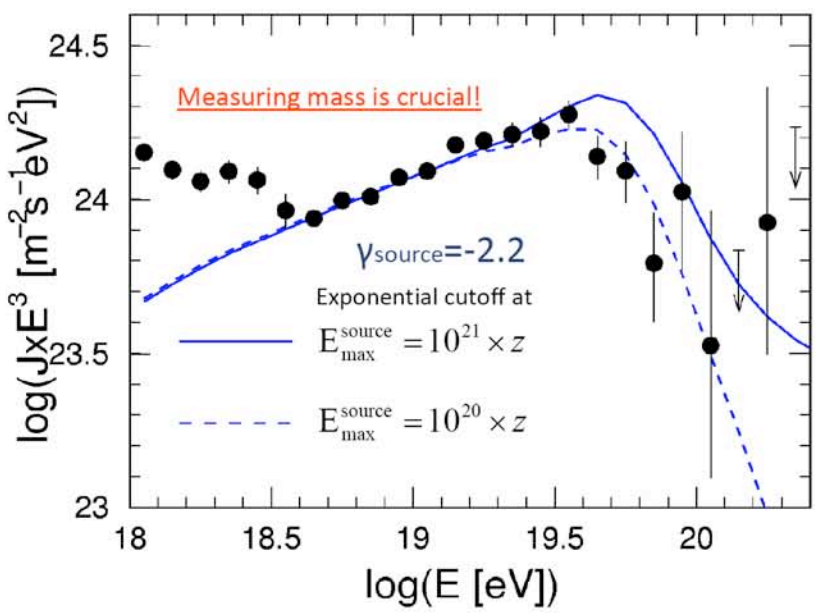
Comparison with Pure Proton Model



(→ Invited talk by Venya Berezinsky)

Nucleus Model

CR abundance is same as low energy Galactic components

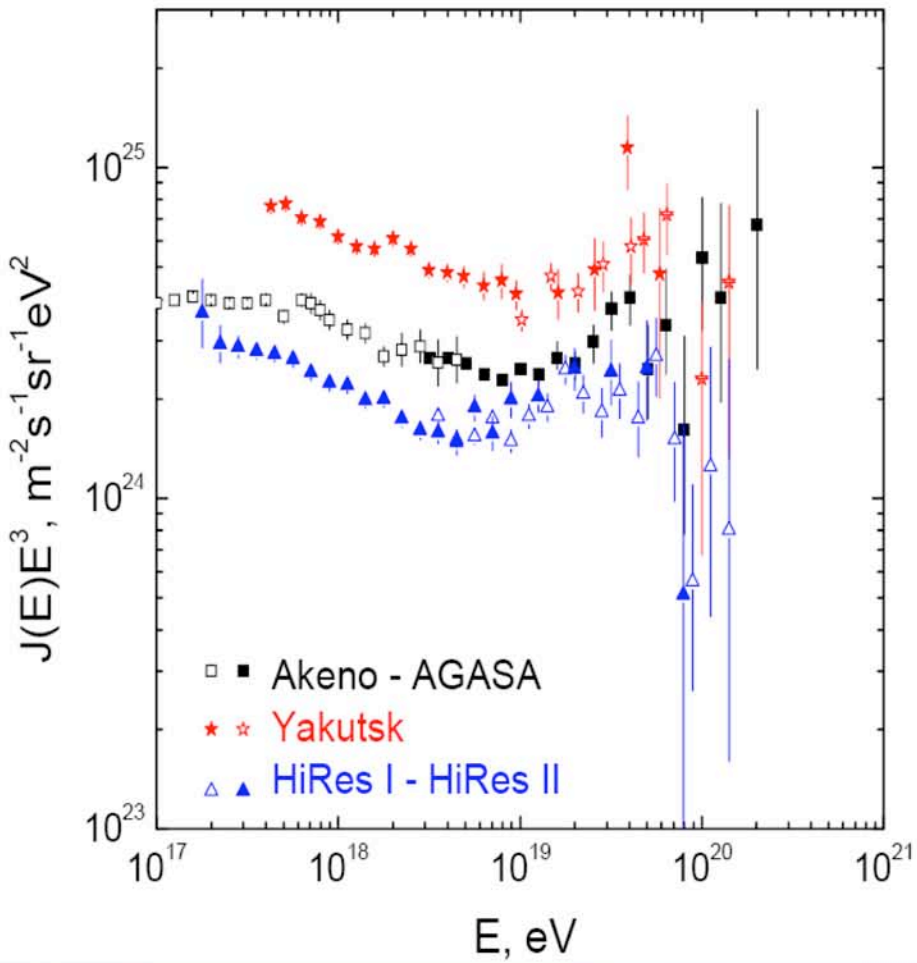


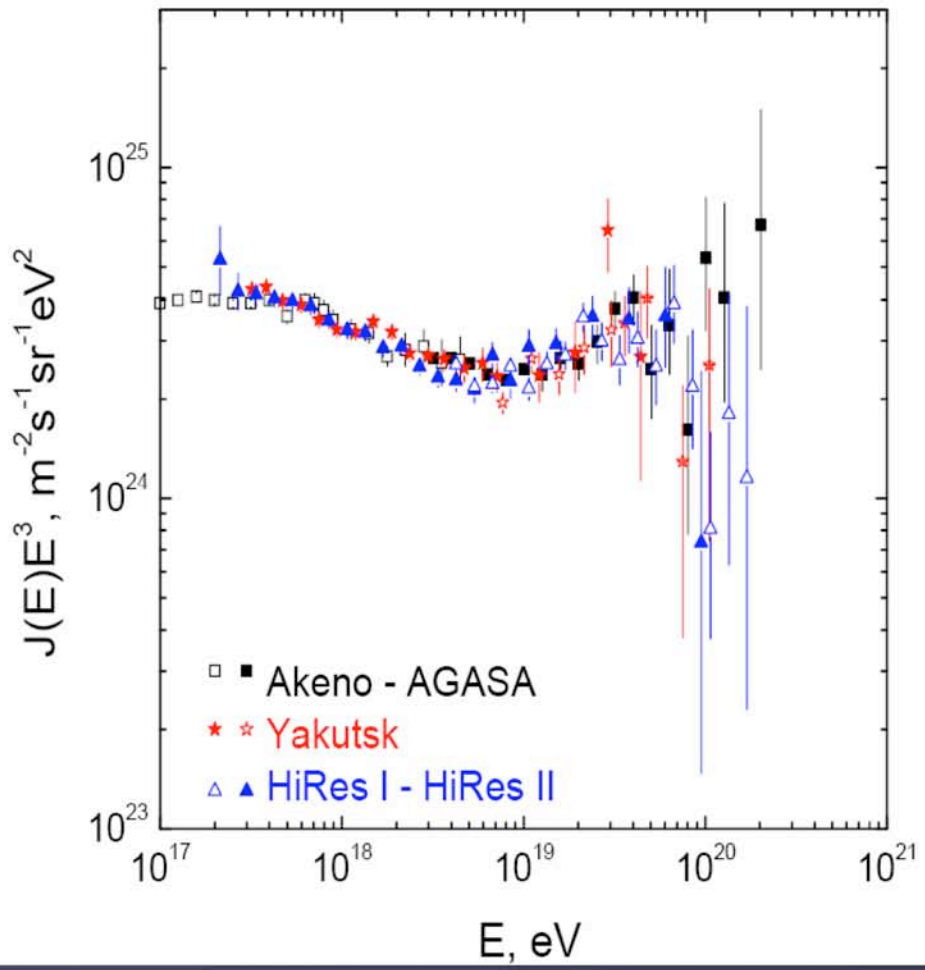
D.Allard, *et al.* Astropart.Phys., **27**, 61, (2007); astro-ph/0512345

Pair creation DIP

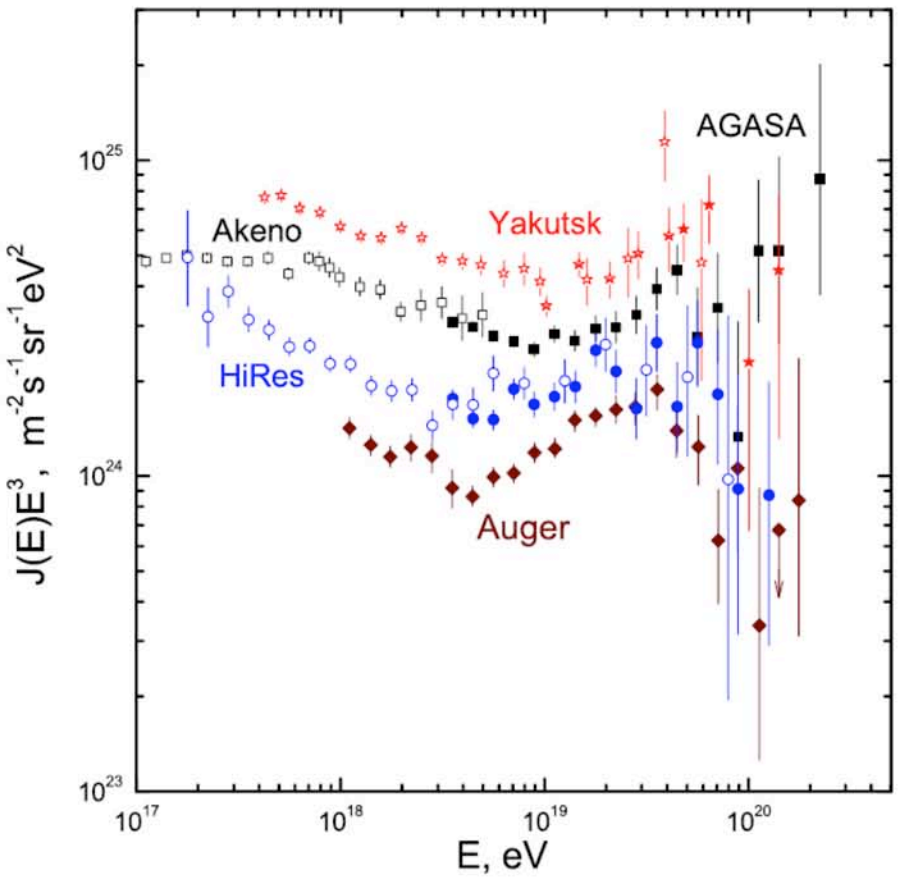
invited talk by V.Berezinsky

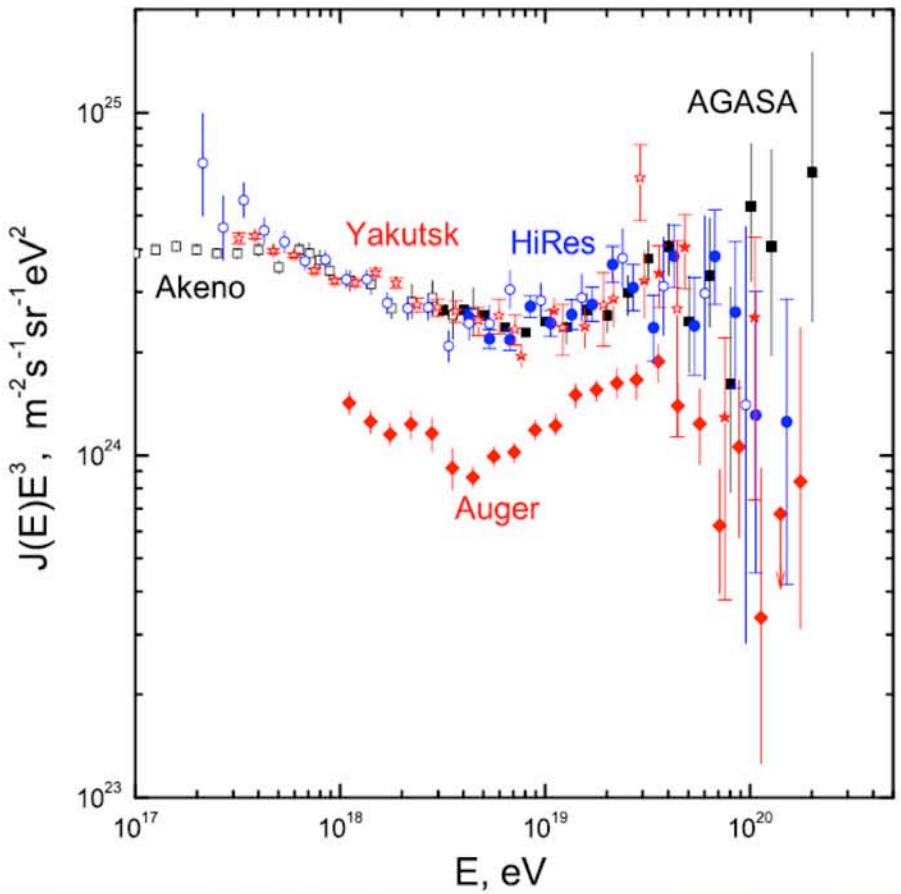
Dip
V.Berezinsky



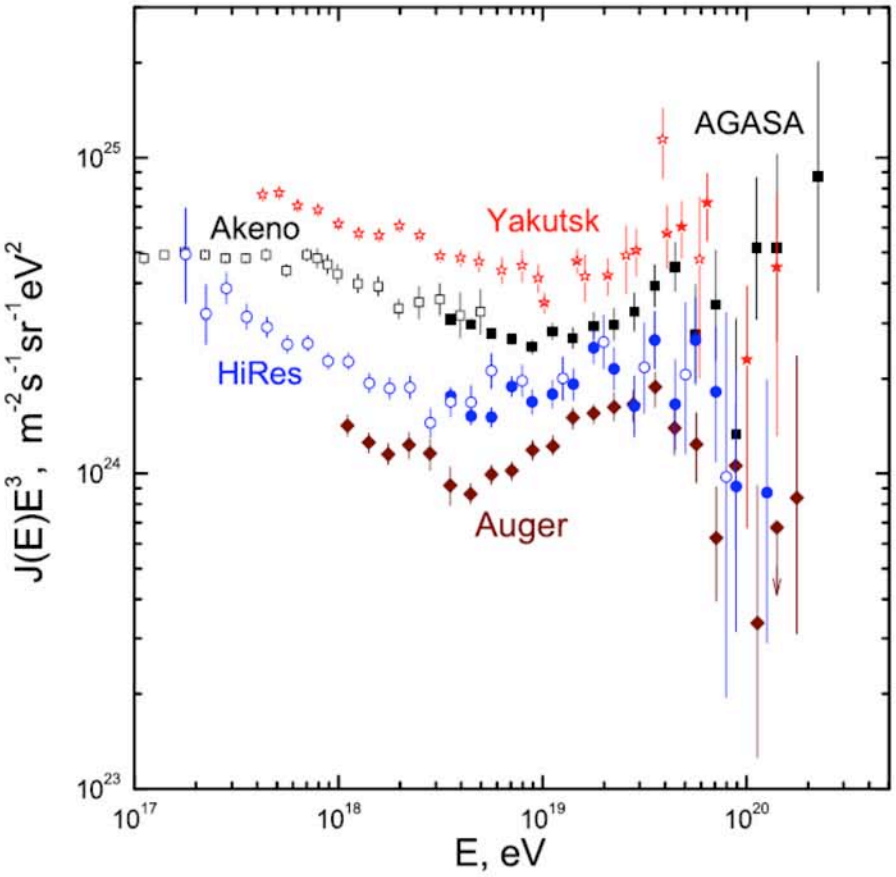


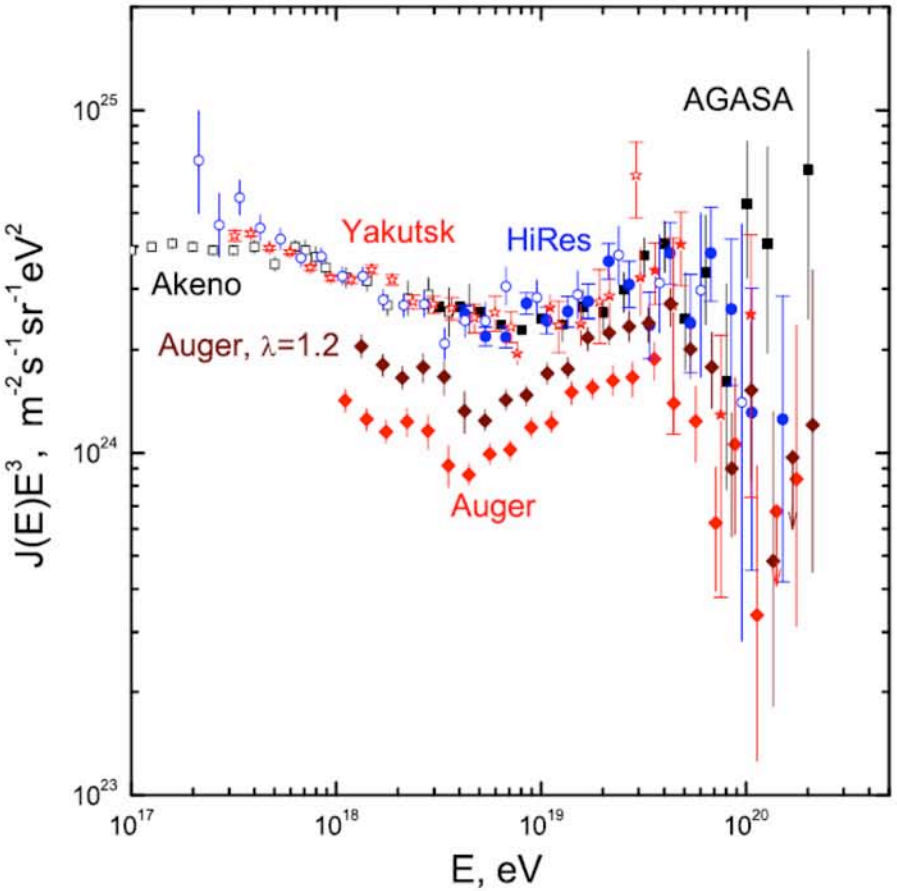
Dip
V.Berezinsky



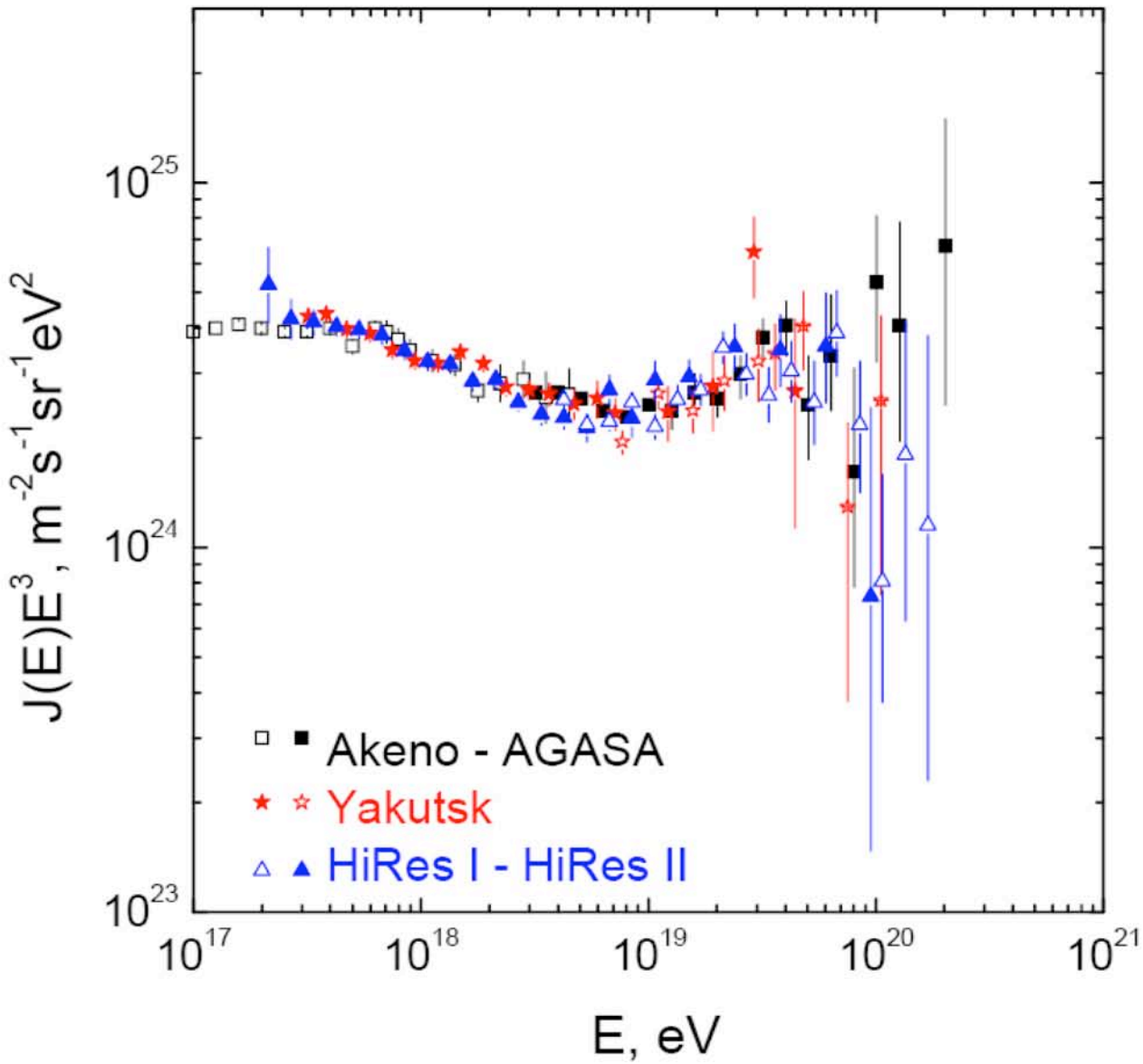


Pair Creation Dip
V.Berezinsky

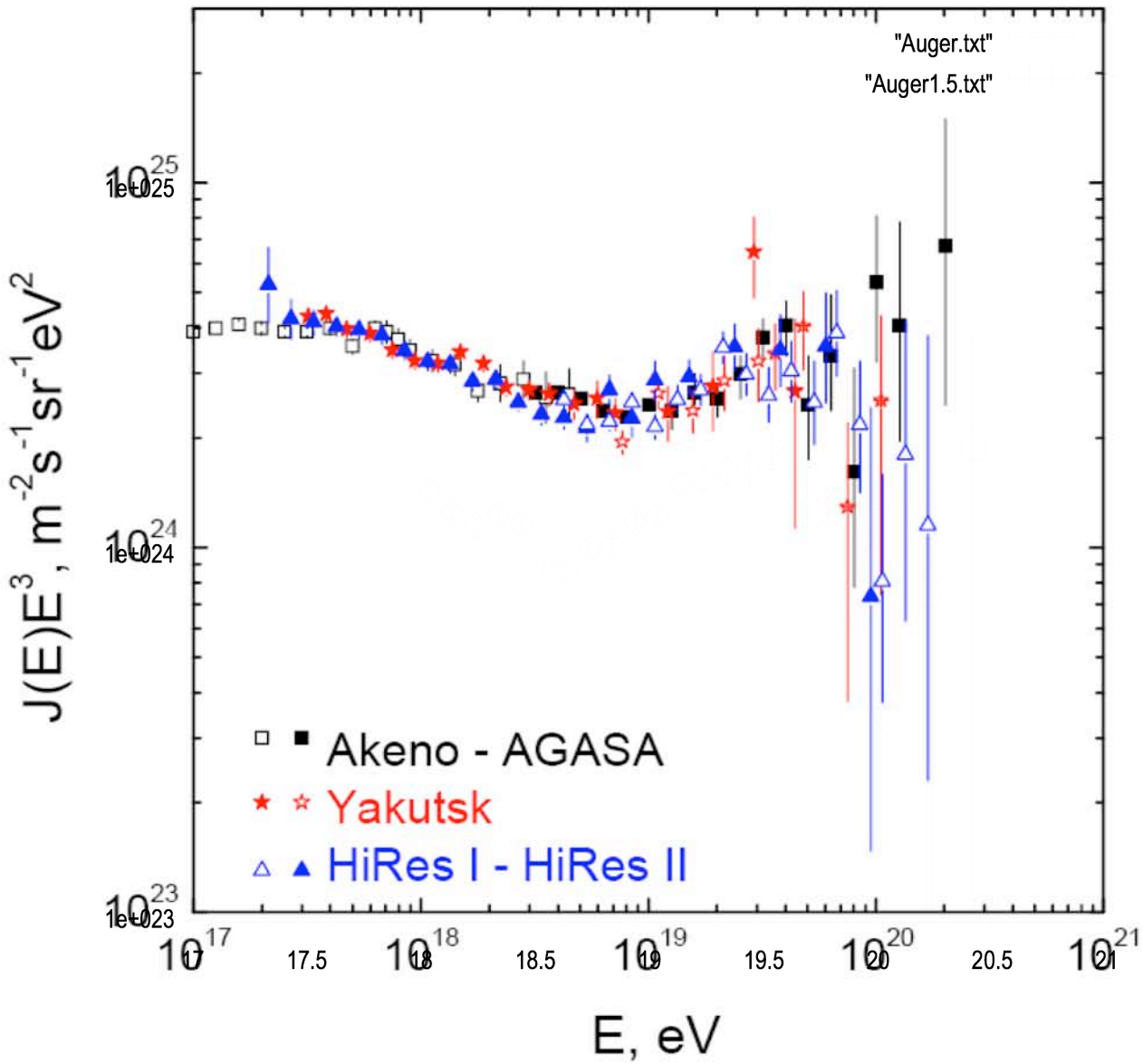




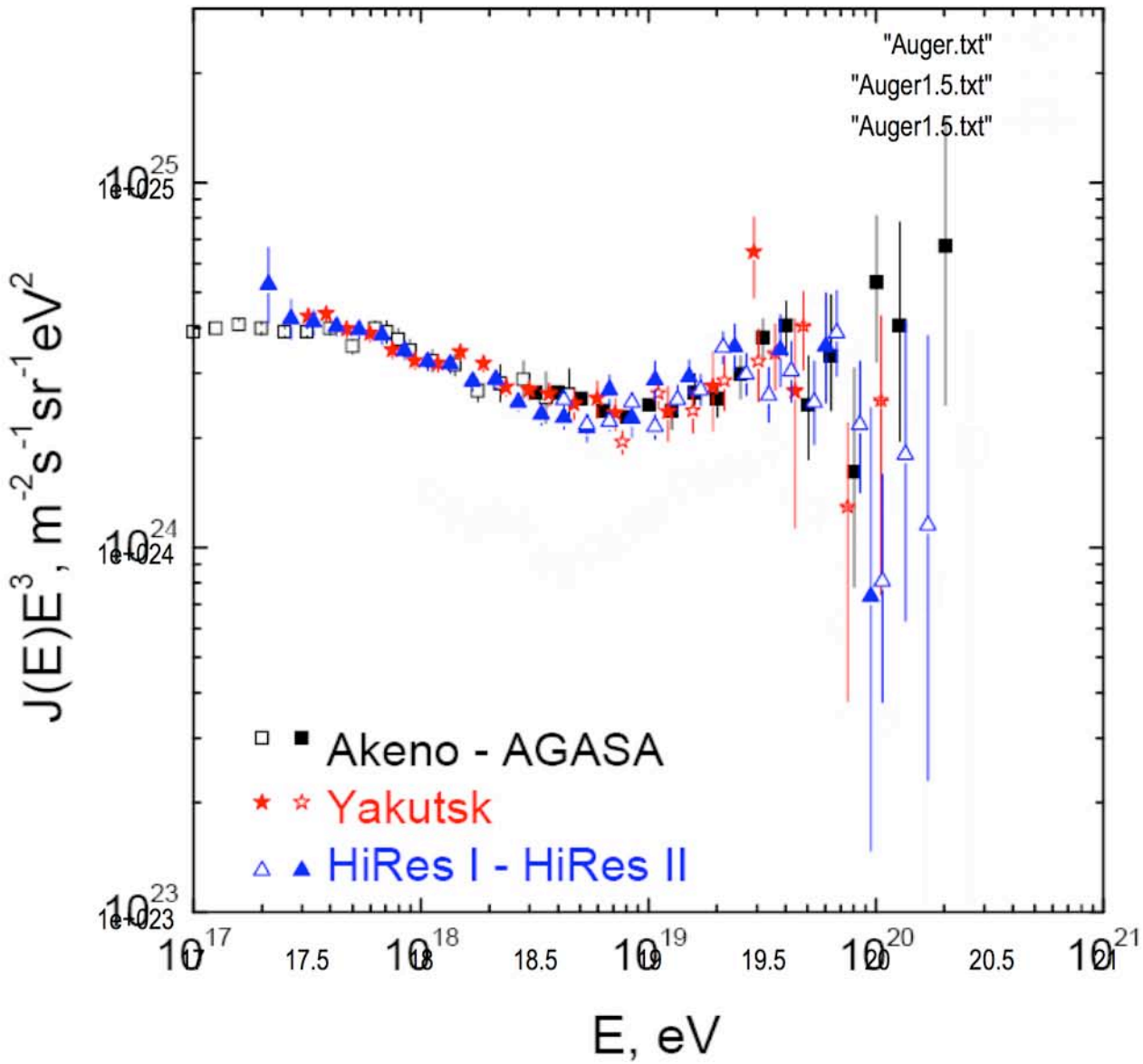
Auger Spectrum x 1.5 +M.Teshima



Auger Spectrum x 1.5 +M.Teshima



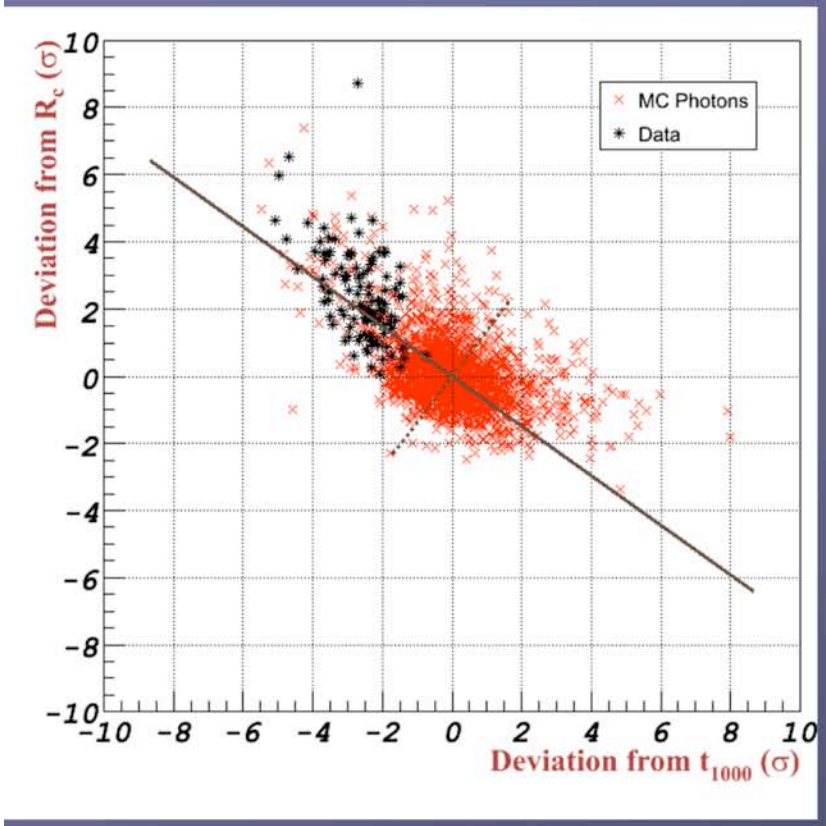
Auger Spectrum x 1.5 +M.Teshima

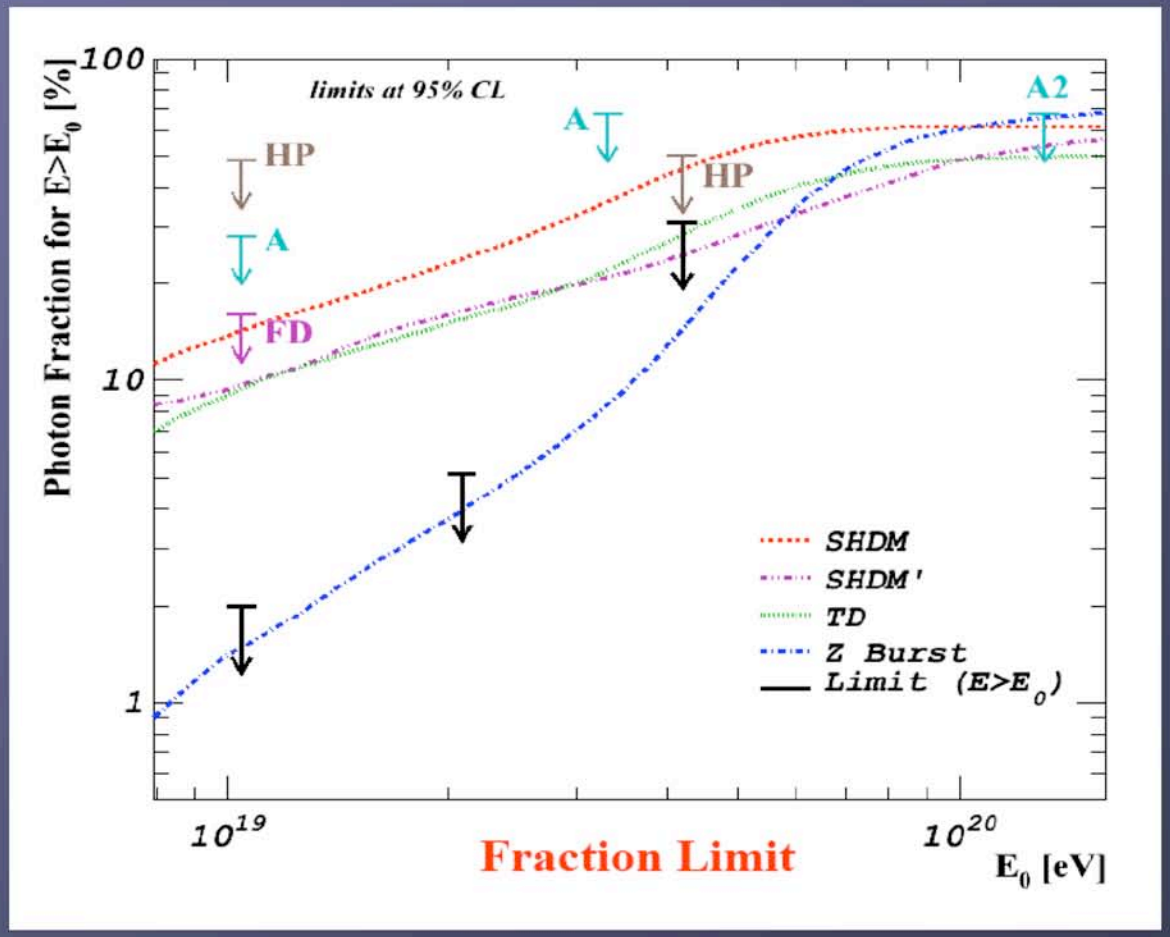


UHECRs
photon limit

Auger: Photon limit

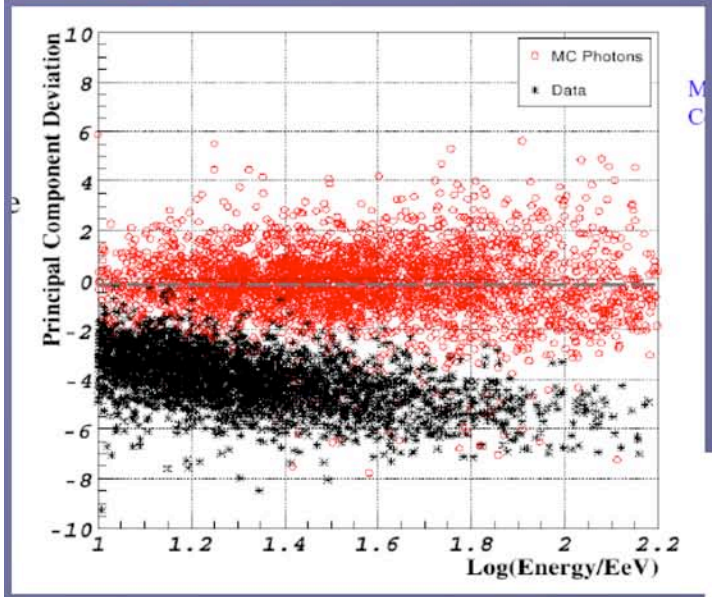
Rise time in shower front
Curvature of shower front



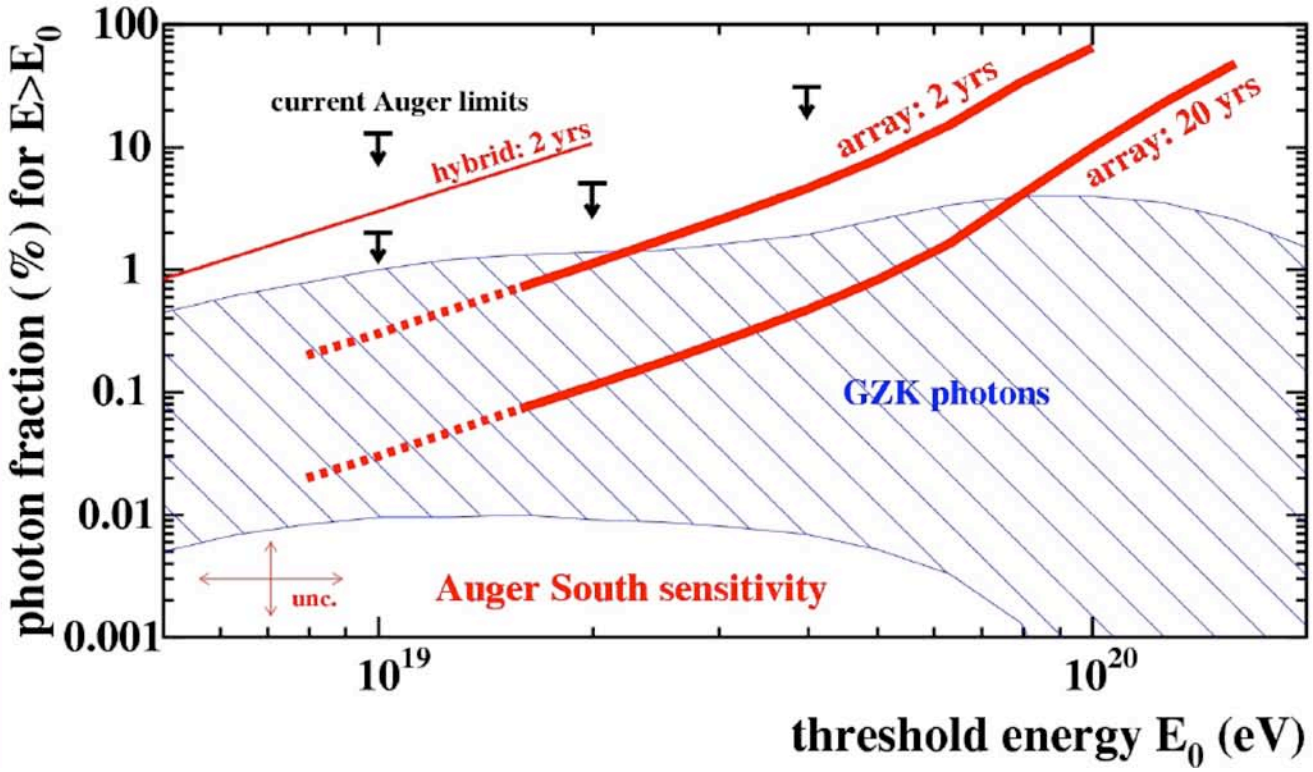


Auger 20years operation will reach to GZK gamma flux of ~0.1%

Auger Sensitivity to GZK photons
M.Risse and P.Homola

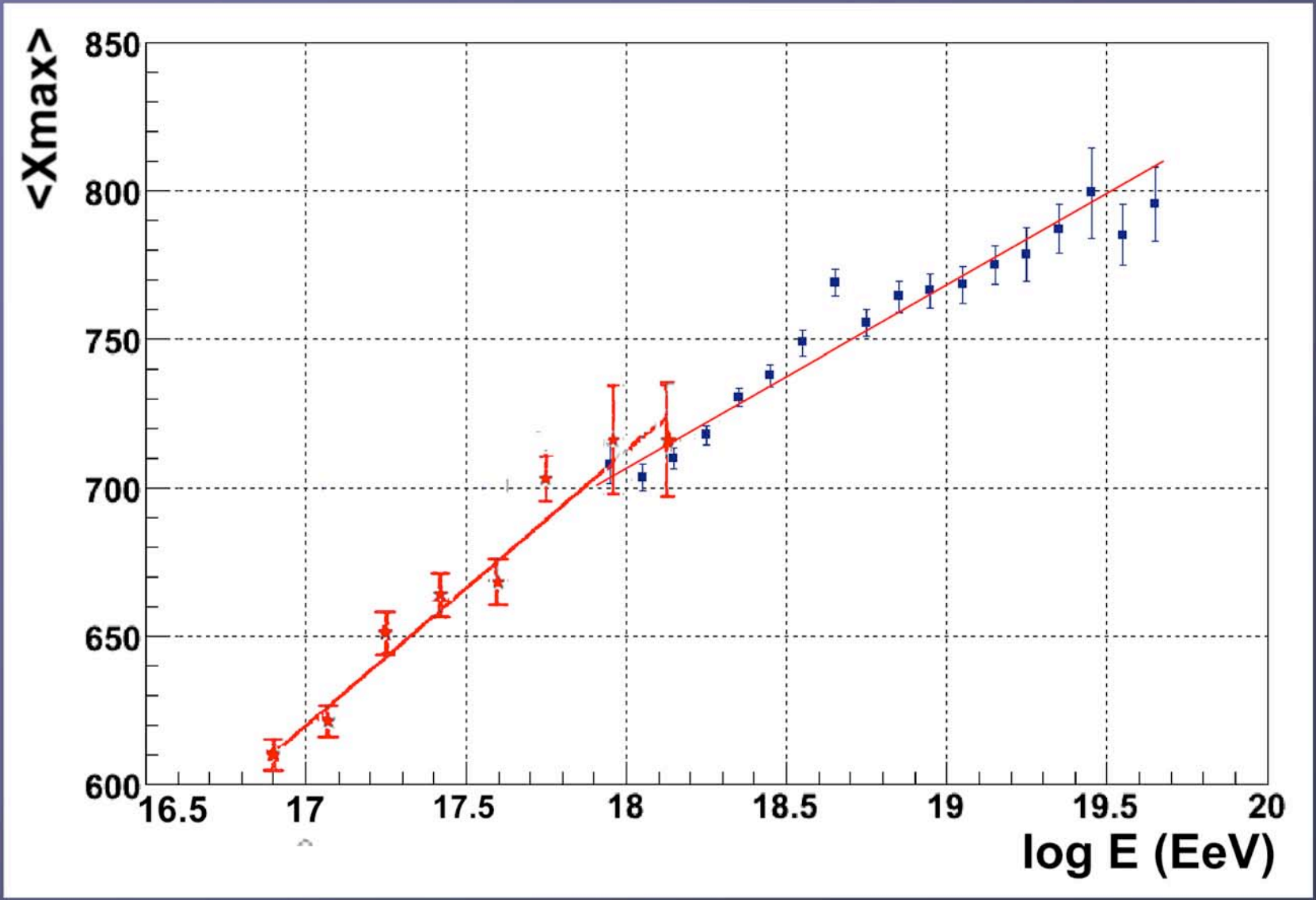


After 20years, we may see GZK photons with Auger

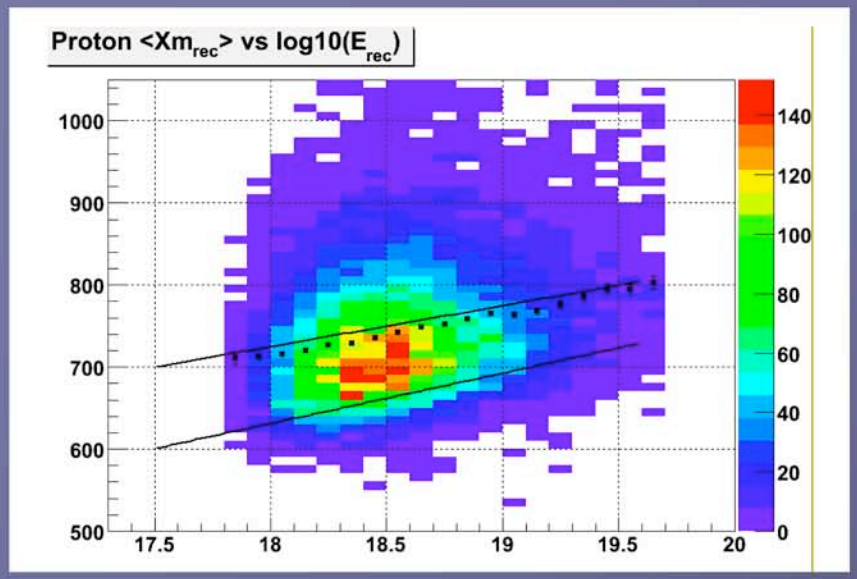


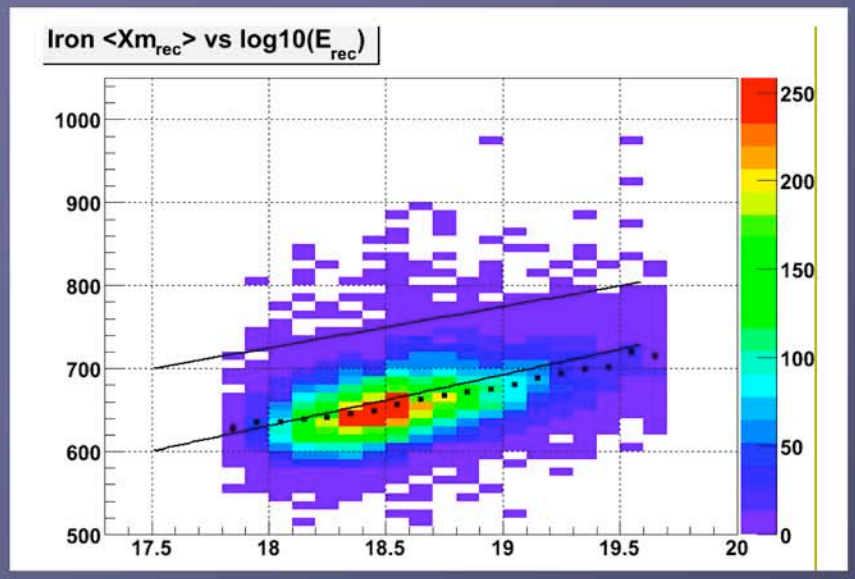
UHECRs
Chemical composition, Xmax

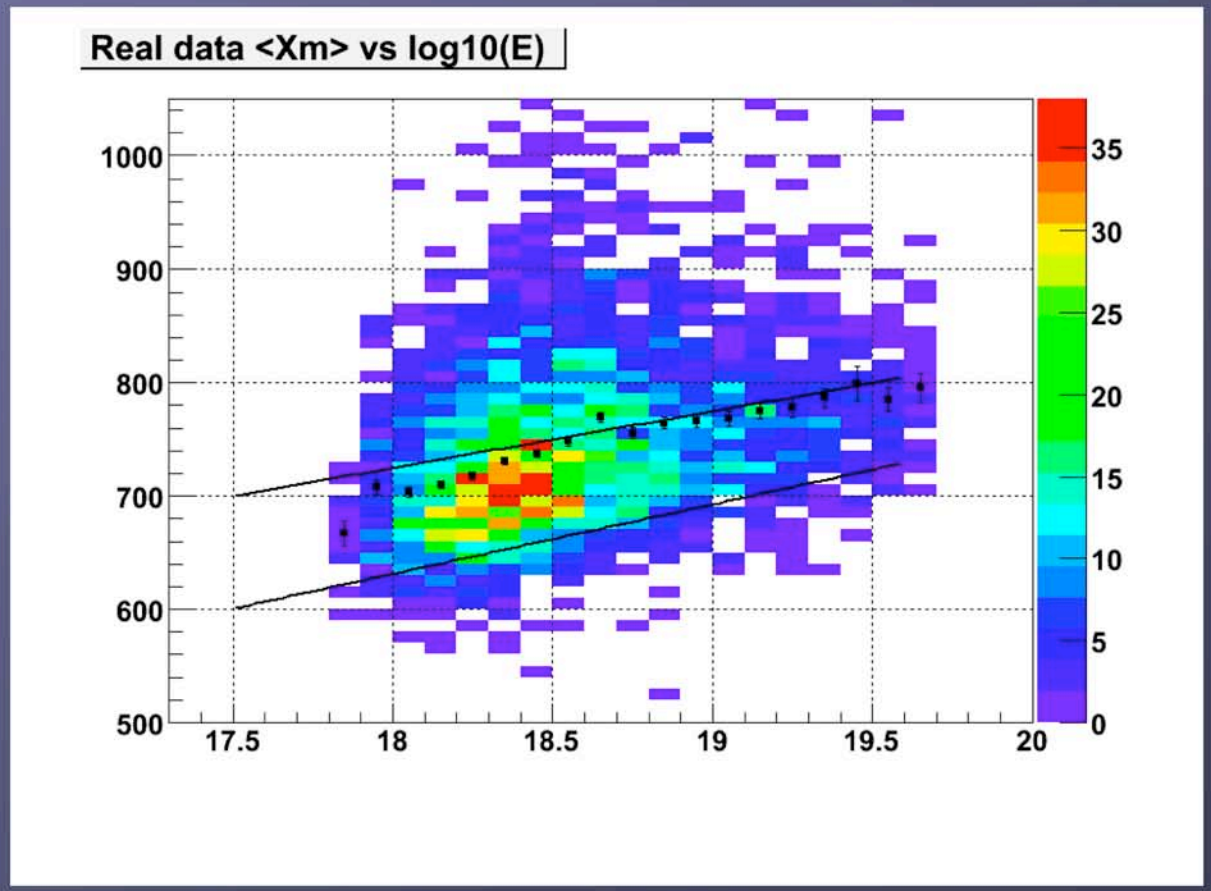
HiRes
Xmax distribution



HiRes Xmax

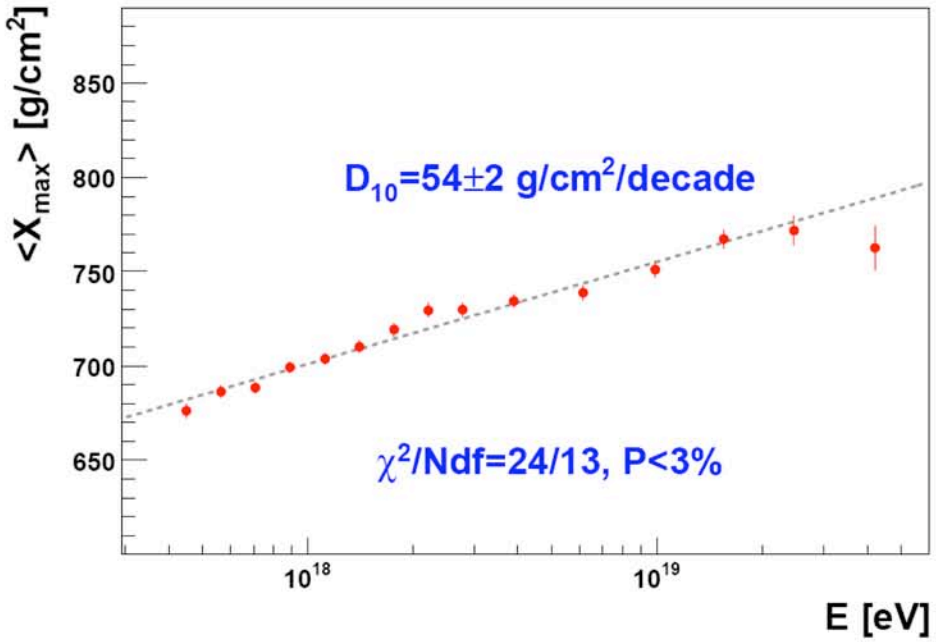

Proton <Xm_rec> vs log10(E_rec)
1000
900
800
700
600
500
17.5
18
18.5
19
19.5
20
140
120
100
80
60
40
20
0


Iron <Xm_rec> vs log10(E_rec)
1000
900
800
700
600
500
17.5
18
18.5
19
19.5
20
250
200
150
100
50
0

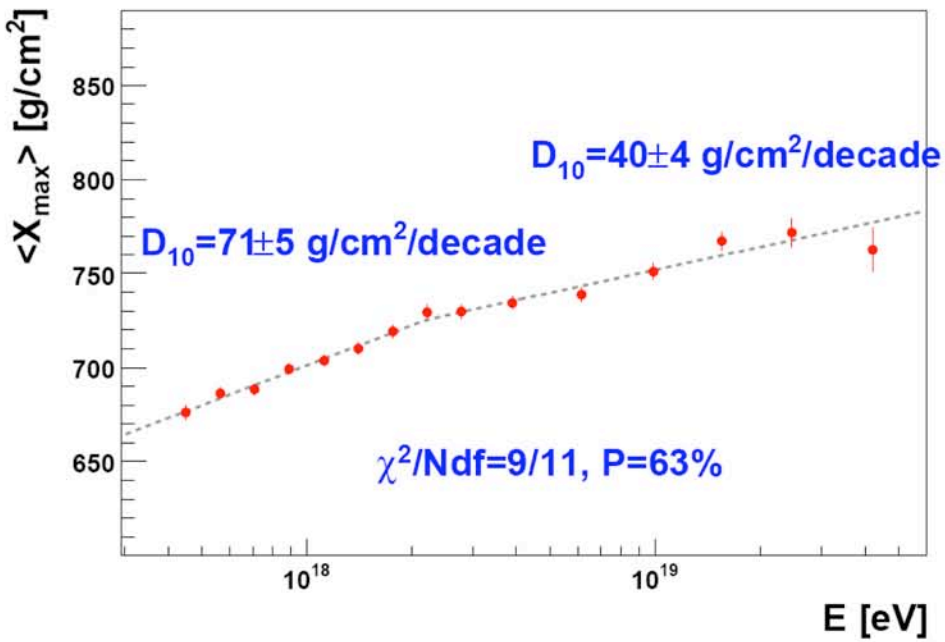

Real data <Xm> vs log10(E)
1000
900
800
700
600
500
17.5
18
18.5
19
19.5
20
35
30
25
20
15
10
5
0

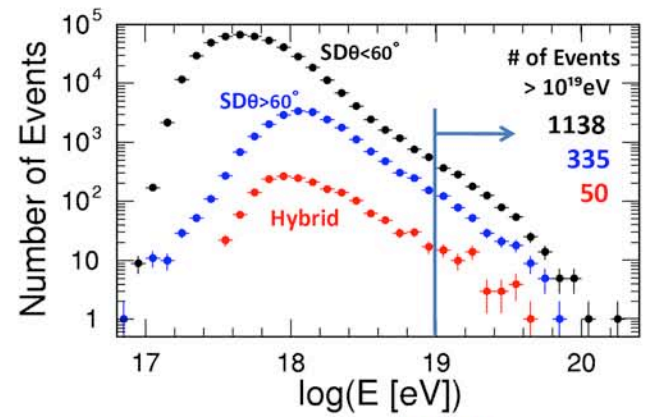
Auger Xmax distribution

Results



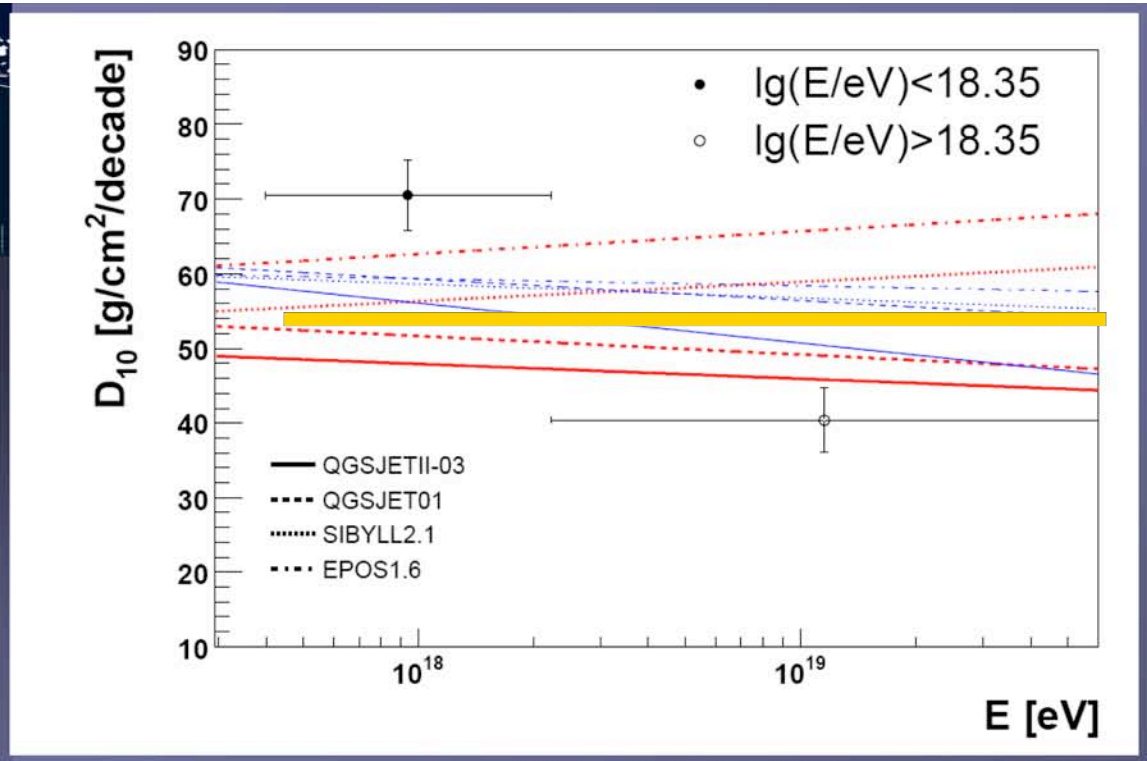
Results





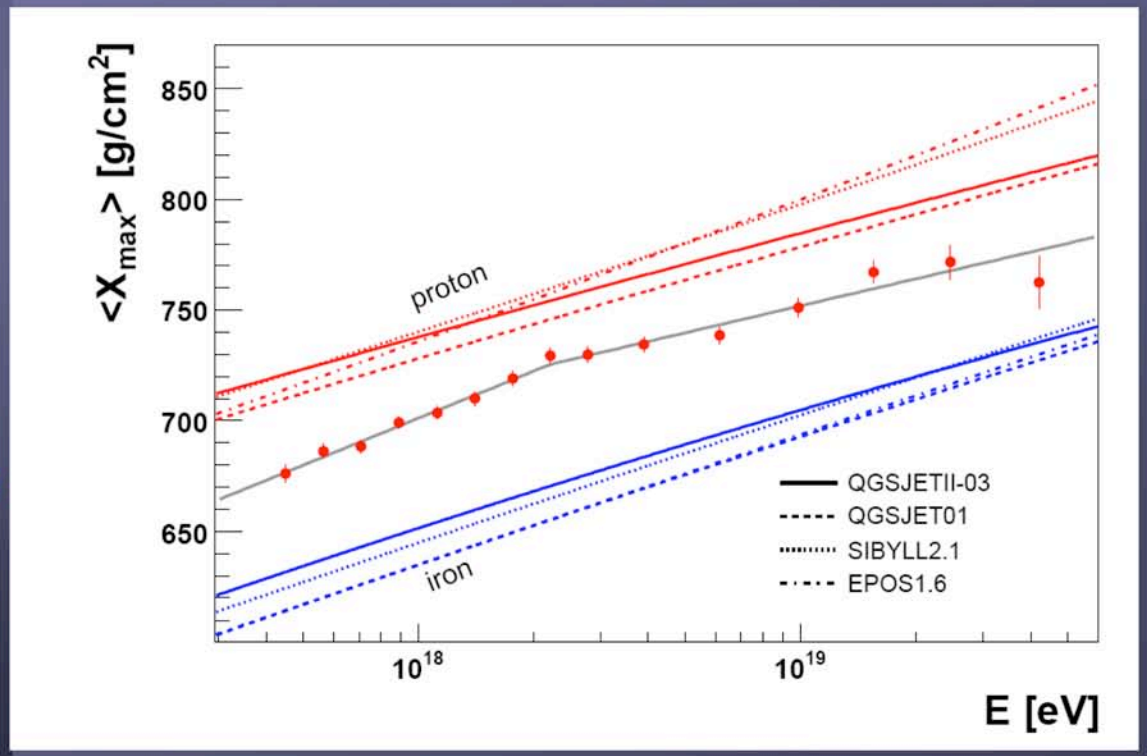
Energy scale is measured with Hybrid Observation

Elongation rate and comparison with M.C.



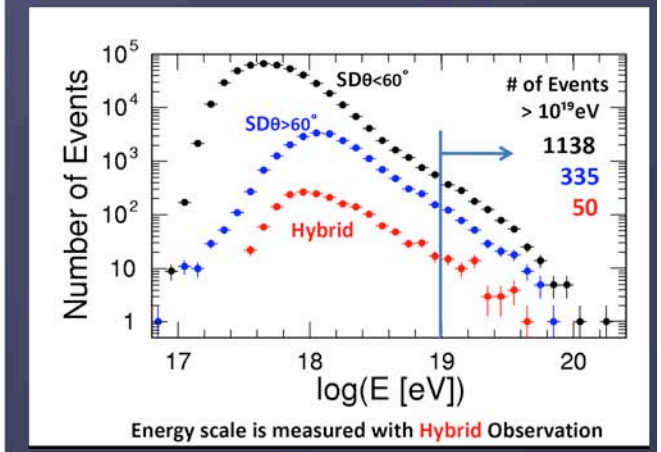
Red: Proton
Blue: Iron

Single line fit gives a better agreement with M.C..

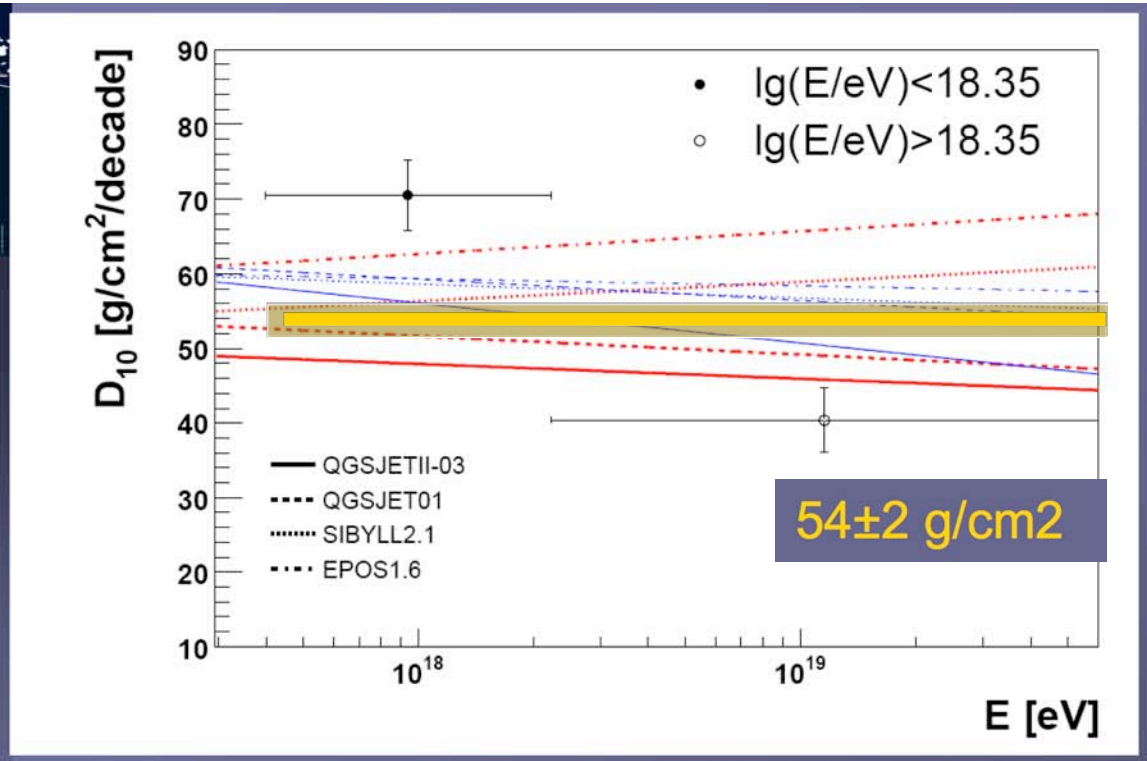


Mixed composition?

Bias in Low energy range?



Elongation rate and comparison with M.C.



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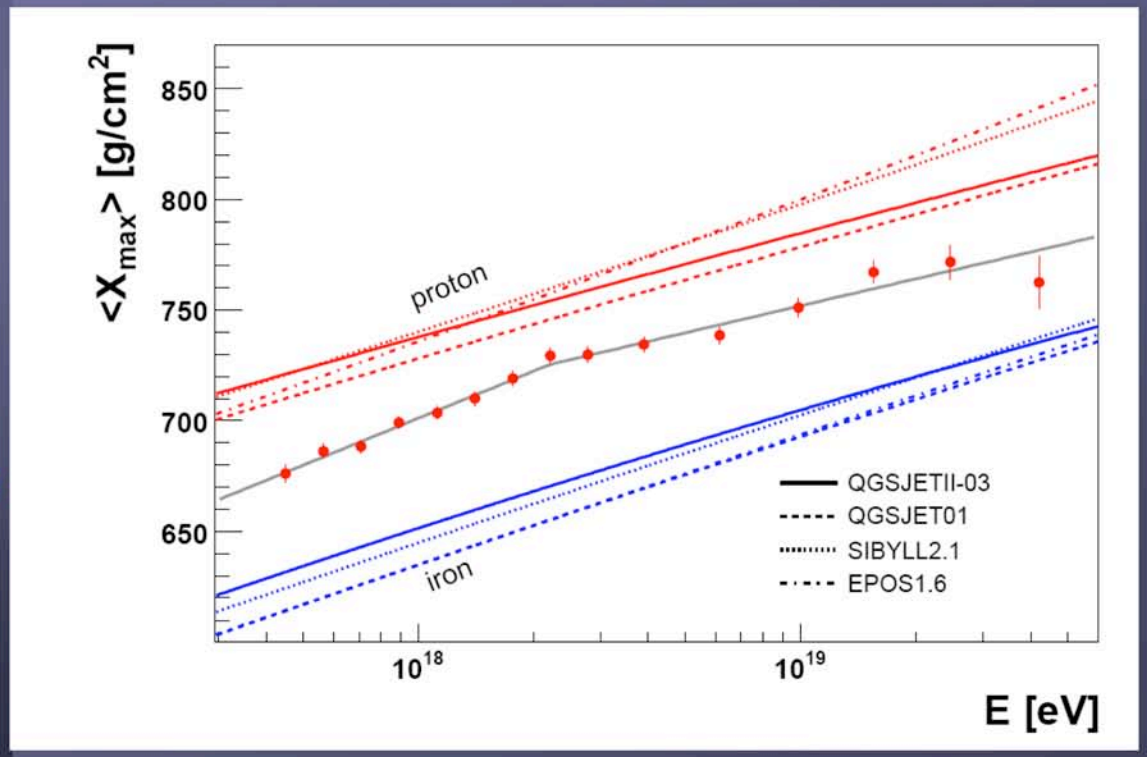
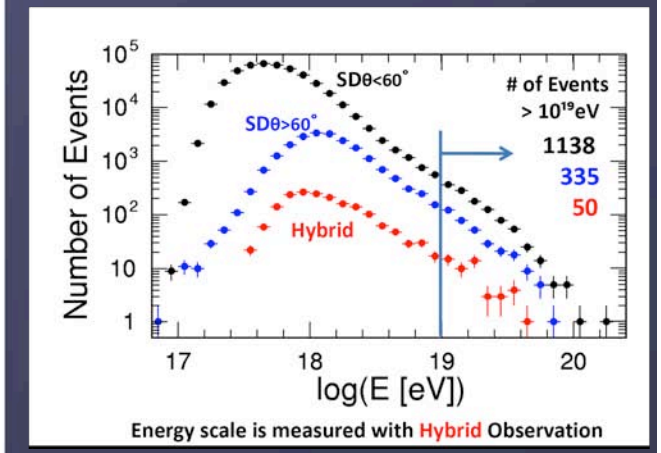
Single line fit gives a better agreement with M.C..

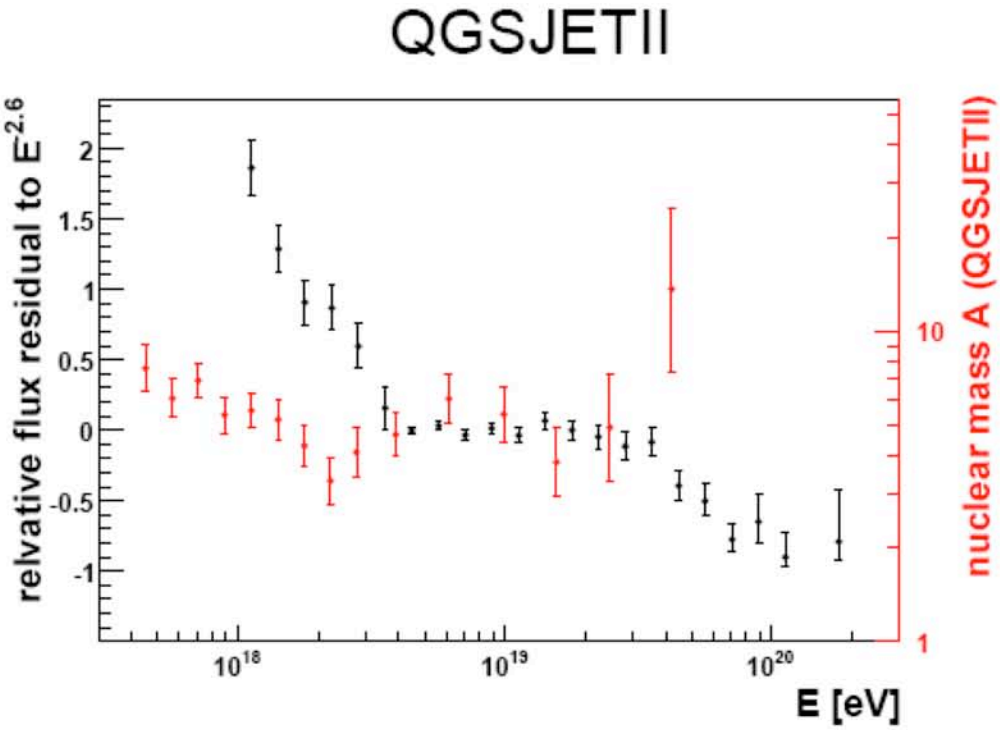


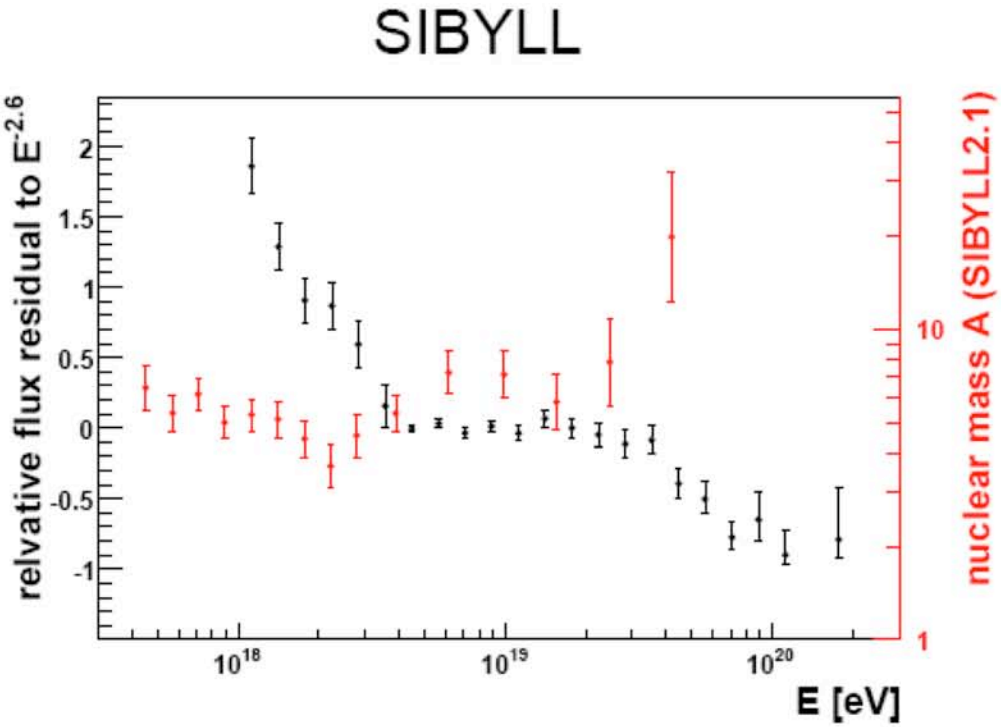
Mixed composition?

Bias in Low energy range?



Auger: Chemical composition Preliminary?

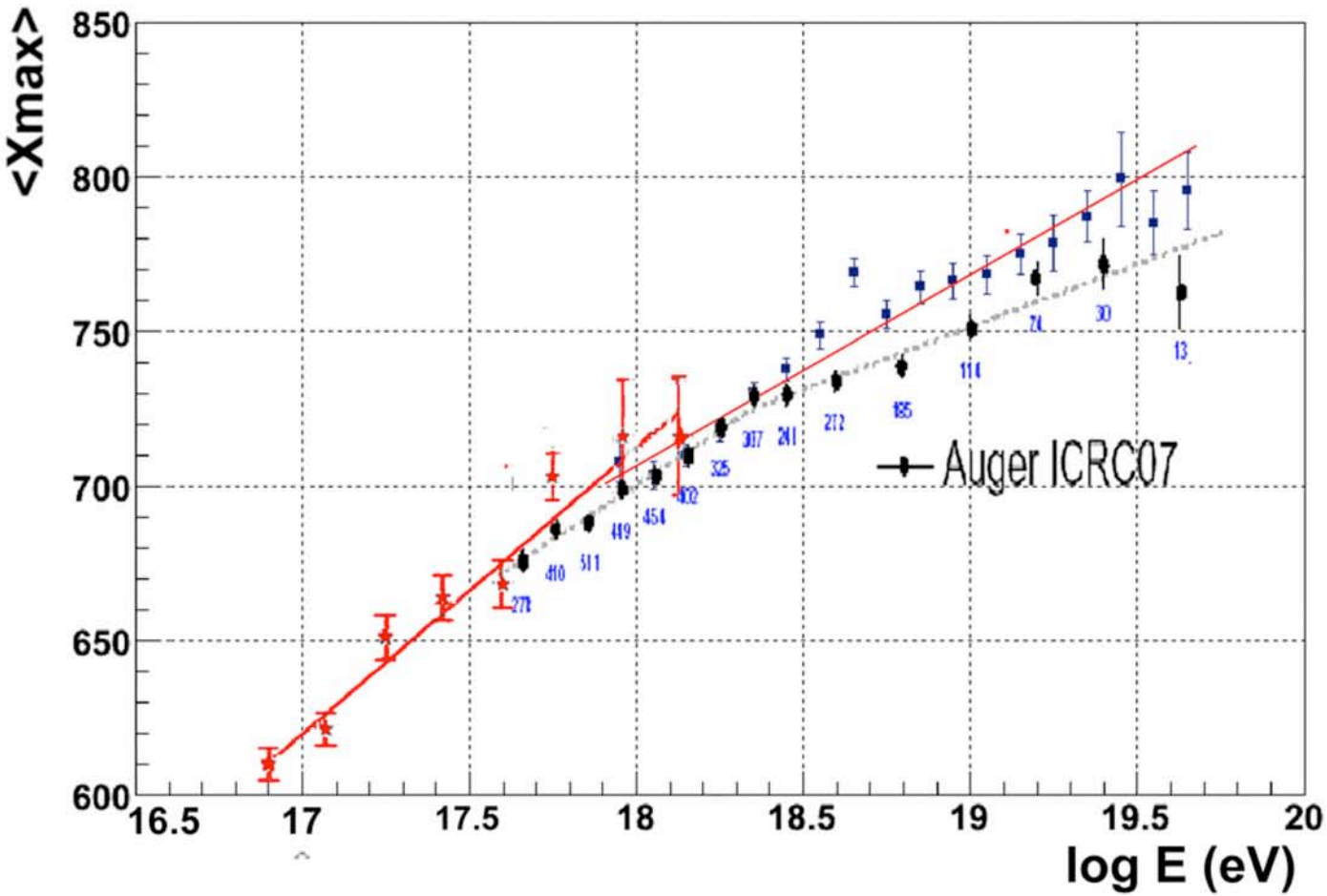




Summary:

- excellent $X_{\max}$ resolution ($\approx$ 20 g/cm^{2}at high energies)
- $X_{\max}$ scale uncertainty $\leq$ 15 g/cm^2
- significantly different D_{10} above and below $10^{18.35}$ eV
- shower simulations $\rightarrow$ mixed composition at all energies

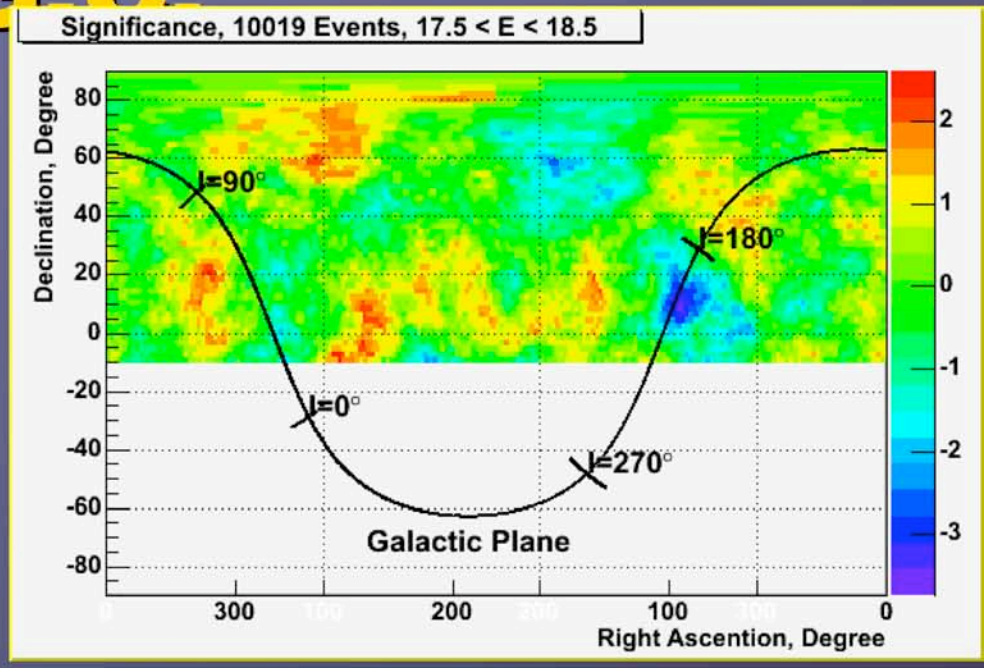
Xmax Auger and HiRes

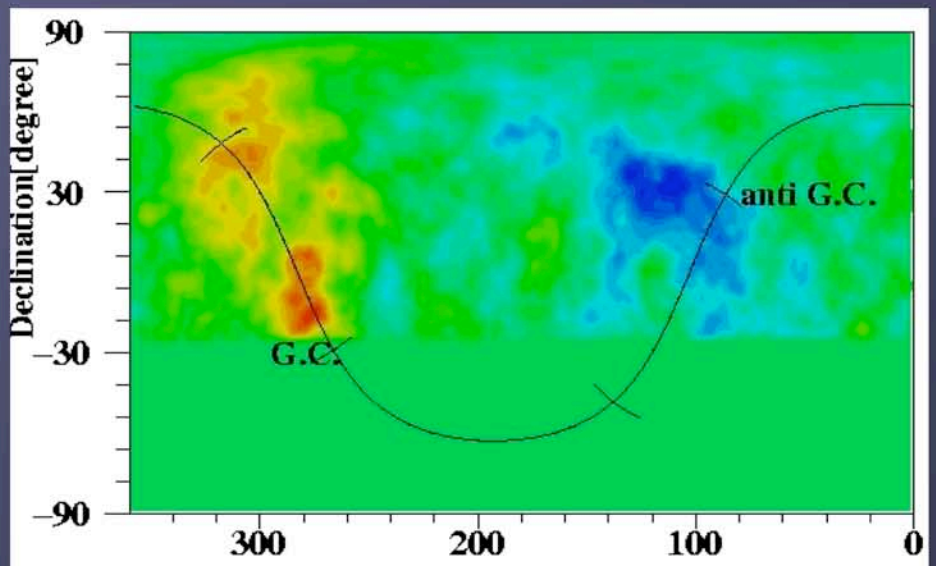


UHECRs Anisotropy

HiRes Anisotropy
Negative excess at Anti-G.C.

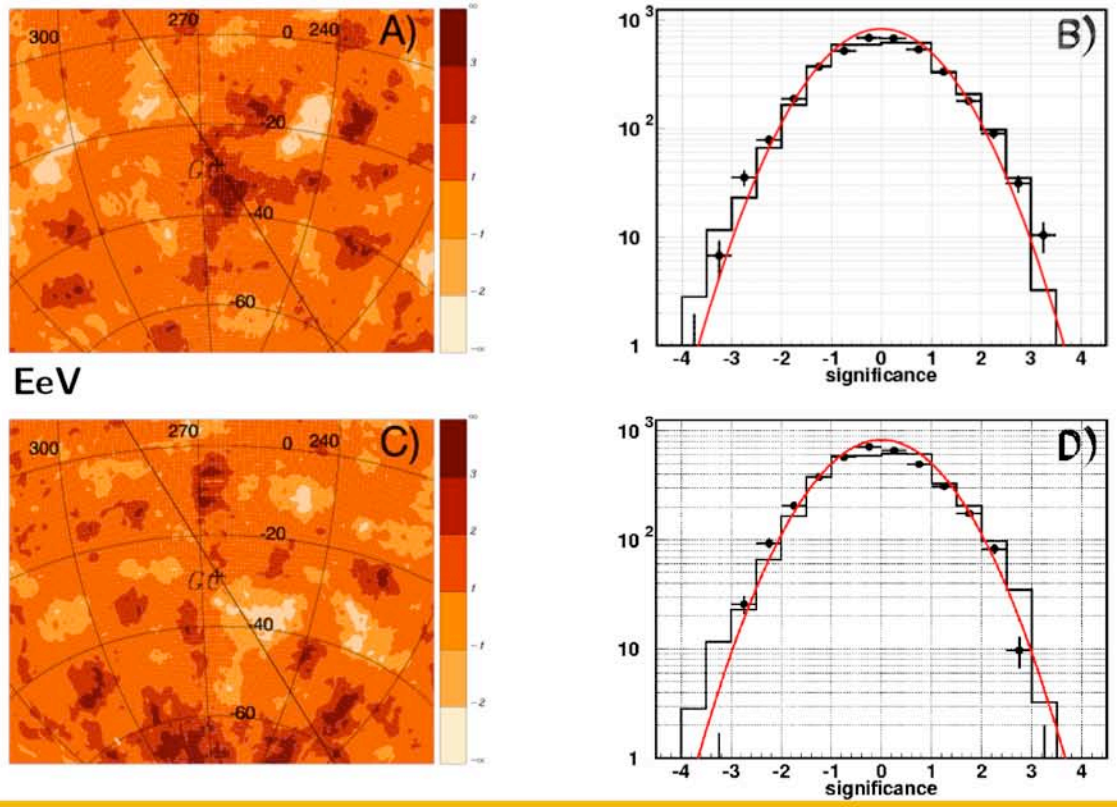
- Integrate over 20º circles
  - Data
  - Significance plot for $10^{17.5} < E < 10^{18.5}$ eV.
  - Akeno/AGASA result





Auger: Galactic Center

$1 < E < 10$ EeV

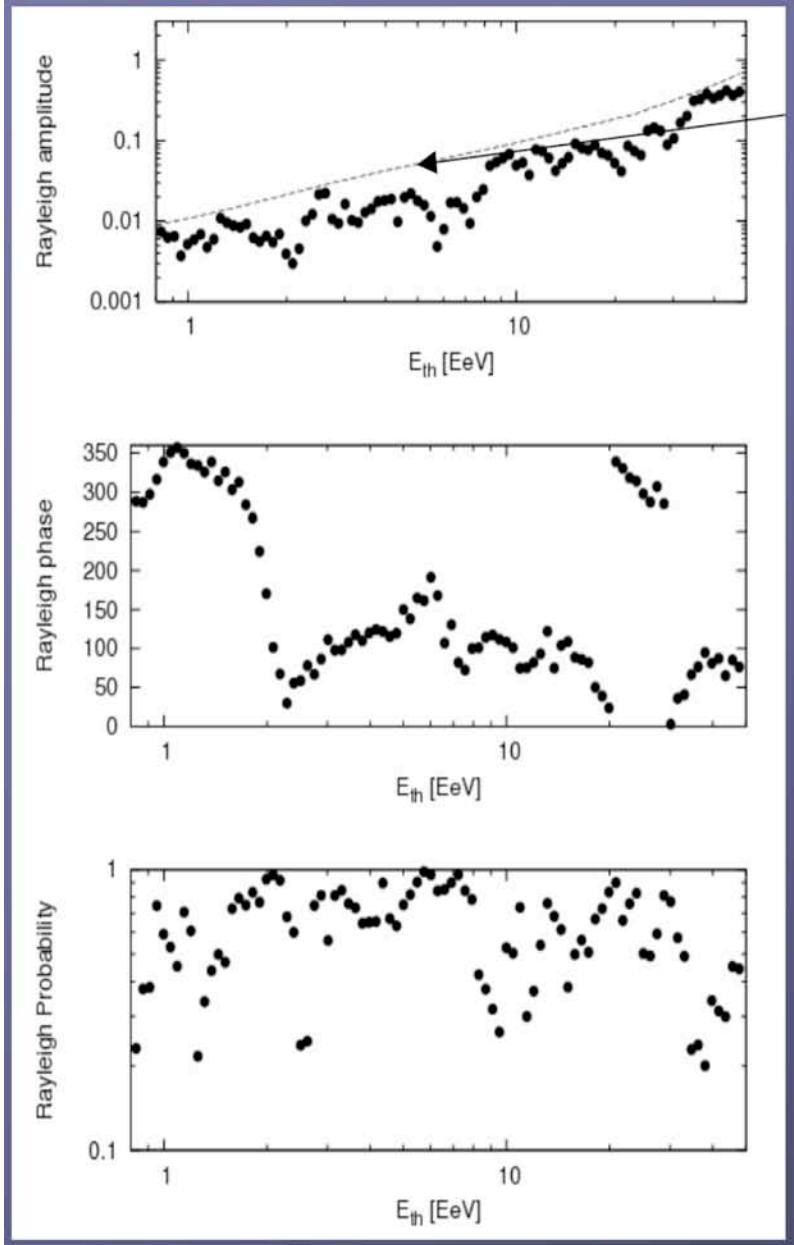


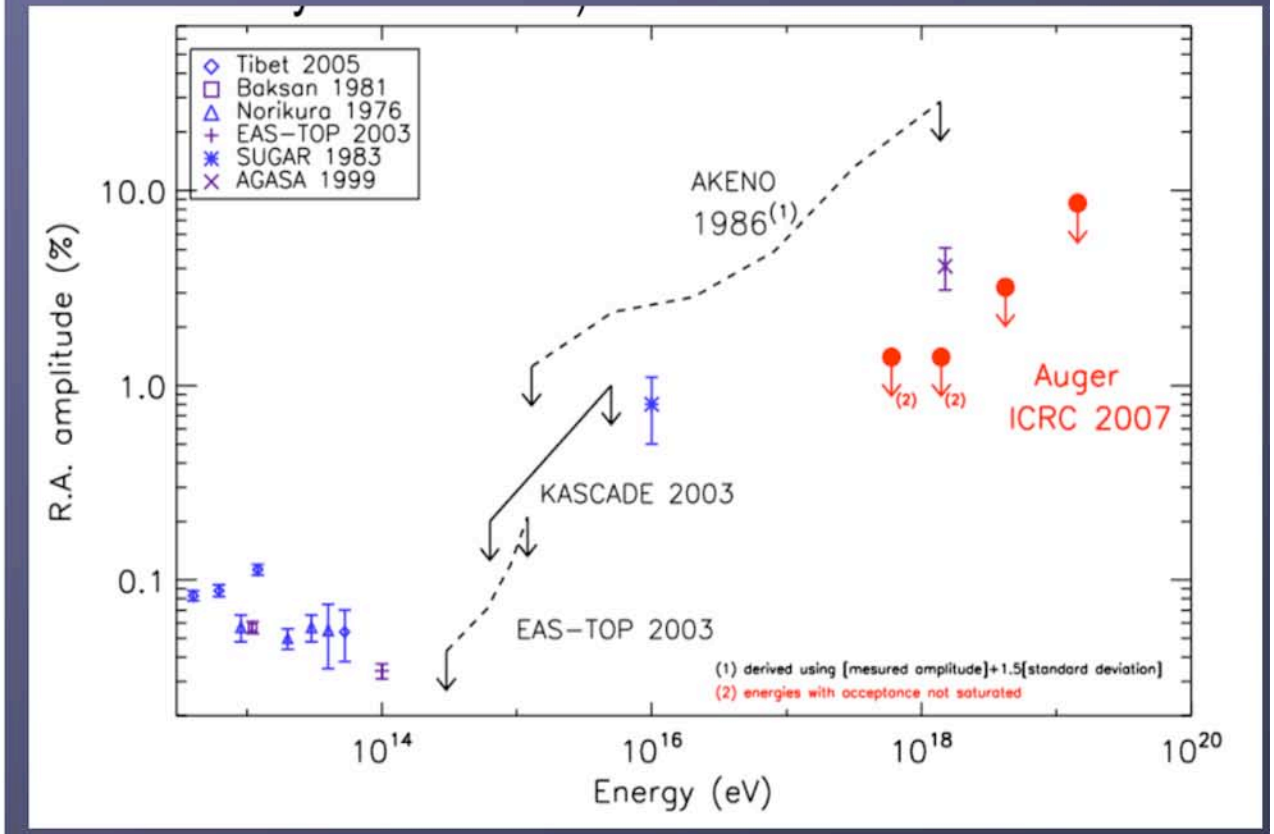
$E < 1$ EeV

$1 < E < 10$ EeV - Search for point-like/extended souces

search	window size	n_{obs}/n_{exp}	n_s^{95}
extended	10° (TH)	$1463/1365 = 1.07 \pm 0.04(\text{stat}) \pm 0.01(\text{syst})$	
	20° (TH)	$5559/5407 = 1.03 \pm 0.02(\text{stat}) \pm 0.01(\text{syst})$	
point-like	0.8° (G)	$16.9/17.0 = 0.95 \pm 0.17(\text{stat}) \pm 0.01(\text{syst})$	5.6

Auger: Harmonic Analysis Upper limits

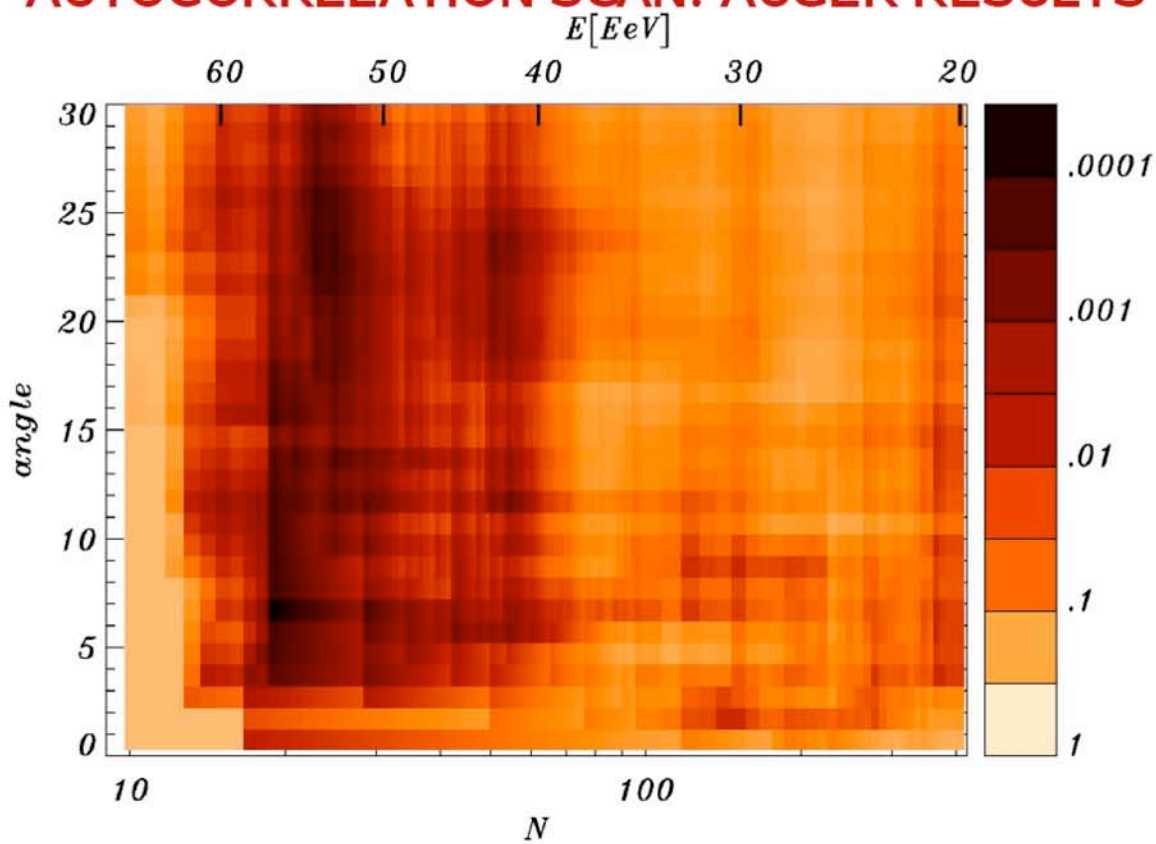




UHECRs
Clusters

Auger: Small & Medium scale anisotropy study

AUTOCORRELATION SCAN: AUGER RESULTS



CORRELATION EXCESS AT INTERMEDIATE ANGLES AND LARGE ENERGIES

MINIMUM: $\theta = 7°$, $E > 57.5$ EeV ($N = 19$), obs/exp = 8/1, $P_{min} = 10^{-4}$

CHANCE PROBABILITY: P = 2%

Auger: Hint of clustering? 6~25 degrees scale

TEST OF SIGNALS FROM PREVIOUS EXPERIMENTS

SMALL SCALE CLUSTERING: $\theta = 2.5^o$ and $E > 40$ EeV

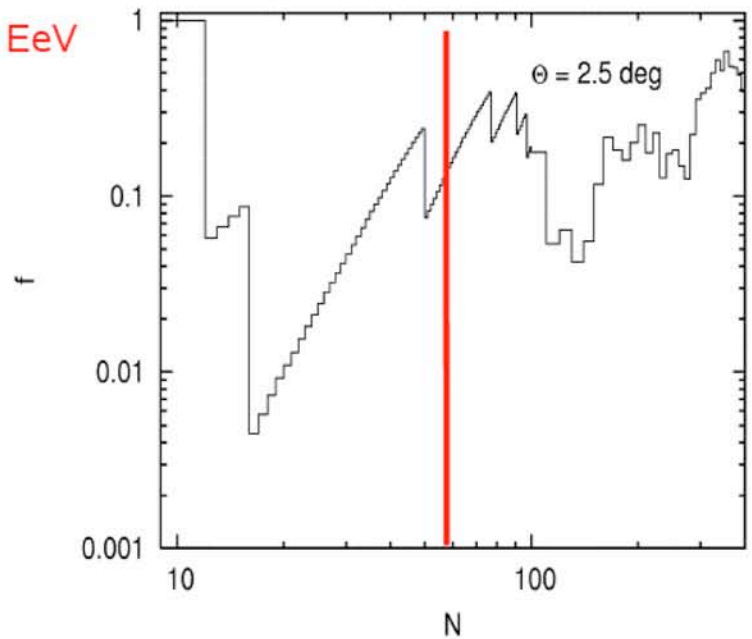
AGASA: obs/exp = 7/1.45 (for N=57)

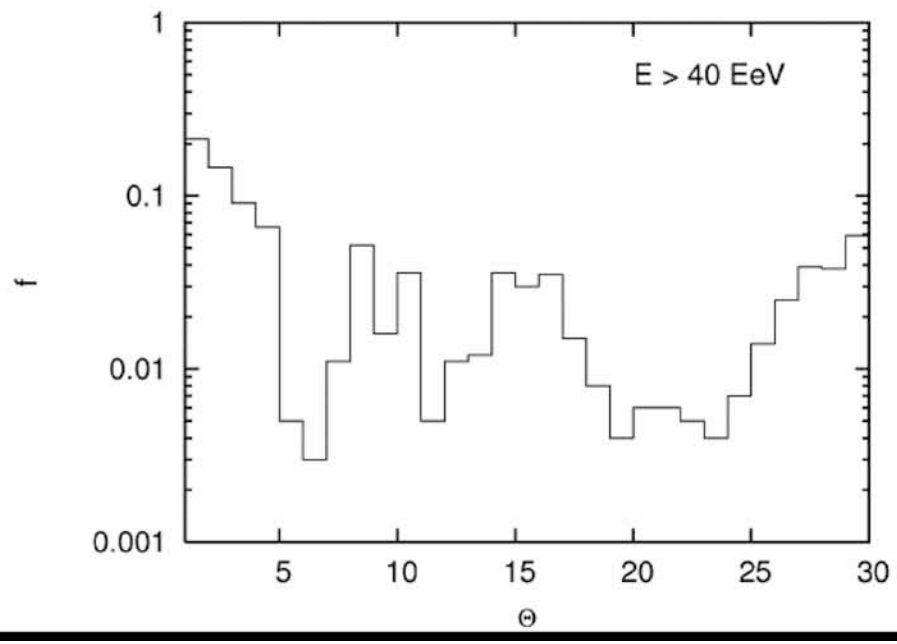
AUGER: obs/exp = 2/1.5

COMPATIBLE WITH ISOTROPIC FLUX

Does a signal appear at a smaller energy?
(possible energy calibration mismatch)

For N =150 events (E > 30 EeV) obs/exp = 14/8.5
No strong excess in the relevant range





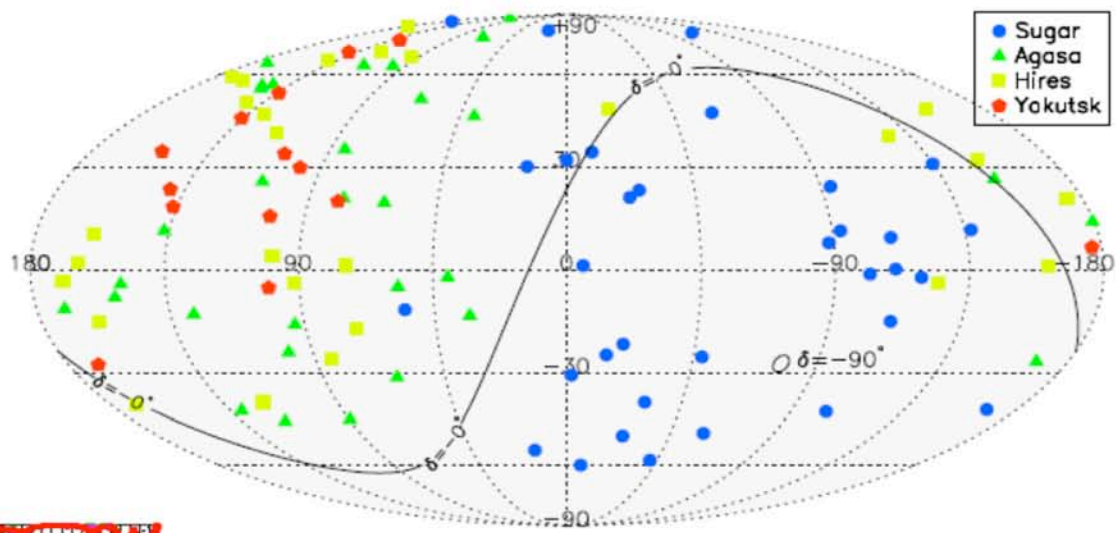
INTERMEDIATE SCALE CLUSTERING:
$\theta = 25^o$ and $E > 40$ EeV

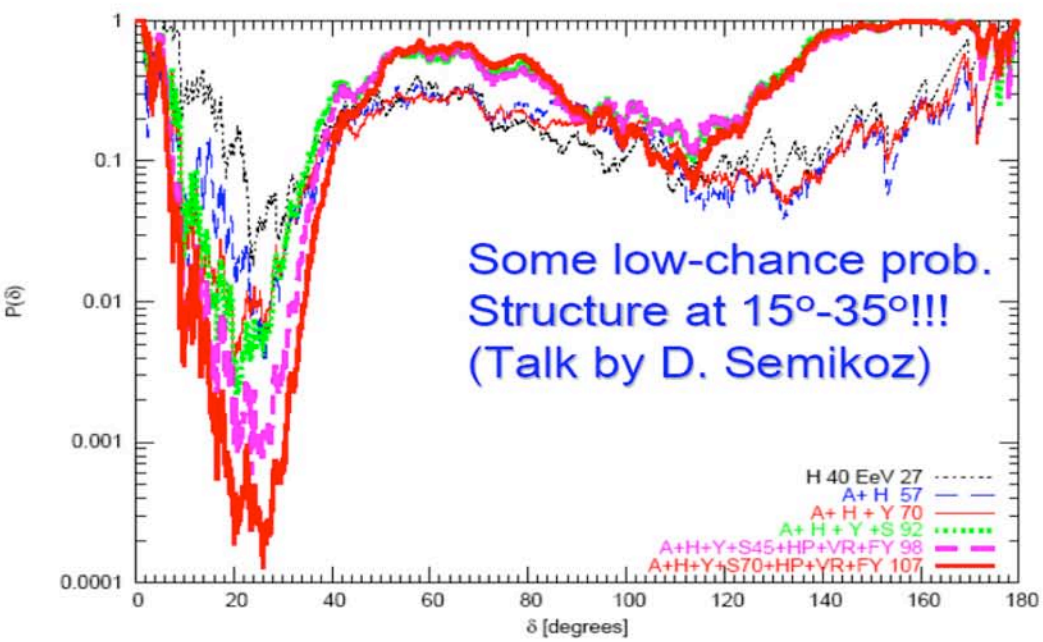
SOME HINT OF CLUSTERING IS PRESENT, ALTHOUGH WEAKER THAN AT HIGHER ENERGIES

Medium scale anisotropy
M.Kachelriess and D.Semikoz

Looking for structures in UHECRs

- ✓ World dataset of O(100) public available UHECRs, above the "rescaled" energy of 4×10^{19} eV (Hires Scale)
- ✓ The rescaling is done a priori, to match the ankle feature in the spectrum





Some low-chance prob. Structure at 15°-35°!!! (Talk by D. Semikoz)

"Both the energy dependence of the signal and its angular scale might be interpreted as first signatures of the large-scale structure of UHECR sources and of intervening magnetic fields"

Can we test that?

M. Kachelrieß & D. Semikoz Astropart. Phys. 26, 10 (2006) [astro-ph/0512498]

Auger: Correlation with BL-Lacs
No correlation

TEST OF PREVIOUS CORRELATION SIGNALS

Test A: 22 BL Lacs m < 18 z > 0.1 or unknown F6 > 0.17 Jy (9th catalog)
(8 in f.o.v.)

Test B: 157 BL Lacs m < 18 (10th catalog)
(76 in f.o.v.)

Test C: 14 BL Lacs selected by possible association with EGRET sources
(3 in f.o.v.)

Test D: 204 BL Lacs m < 18 (10th catalog)
Subclasses: a) 157 BL (76 in f.o.v.) b) 47 HP (30 in f.o.v.)

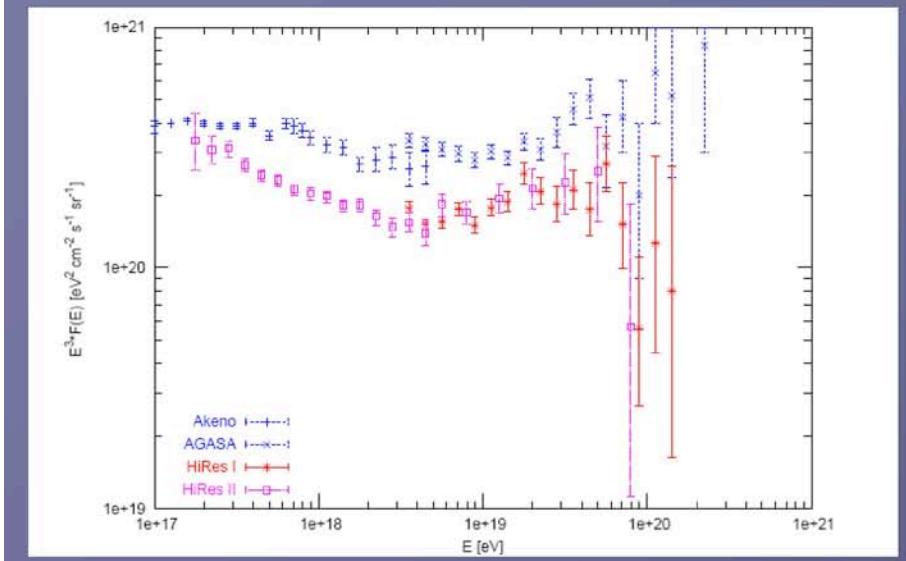
Test	E_{th} (EeV)	Number of events	Angular size	Observed	Expected (isotropic)	Probability
A	24	267	2.5°	1	1.0	0.63
B	40	62	2.5°	2	2.5	0.71
C	24	267	2.9°	1	0.5	0.41
D	10	1672	0.9°	11	12.1	0.66
a)				8	8.9	0.67
b)				3	3.2	0.62

OUR DATA DOES NOT SUPPORT ANY OF THESE PREVIOUSLY REPORTED EXCESSES OF CORRELATION

UHECR Theories

Medium Scale Anisotropy

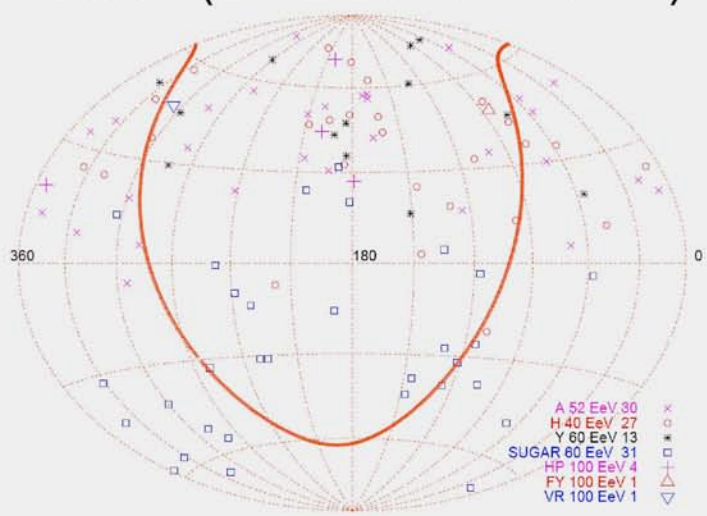
M.Kachelriess & D.Semikoz



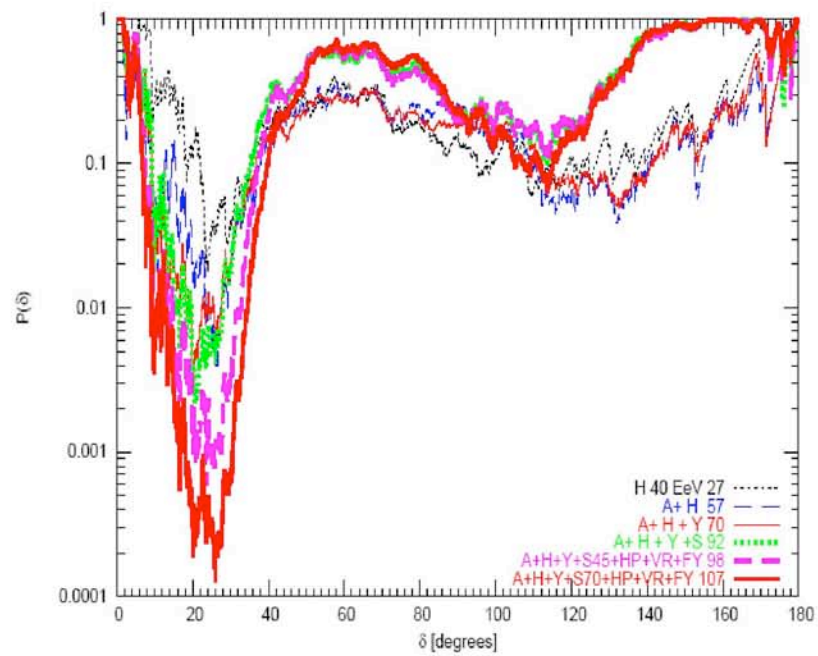
>4x1019eV after Global Energy Scaling

After including penalty ➔ Pch~3×10^{-3}

Arrival directions for E>40 EeV in HiRes (E>52 EeV in AGASA)



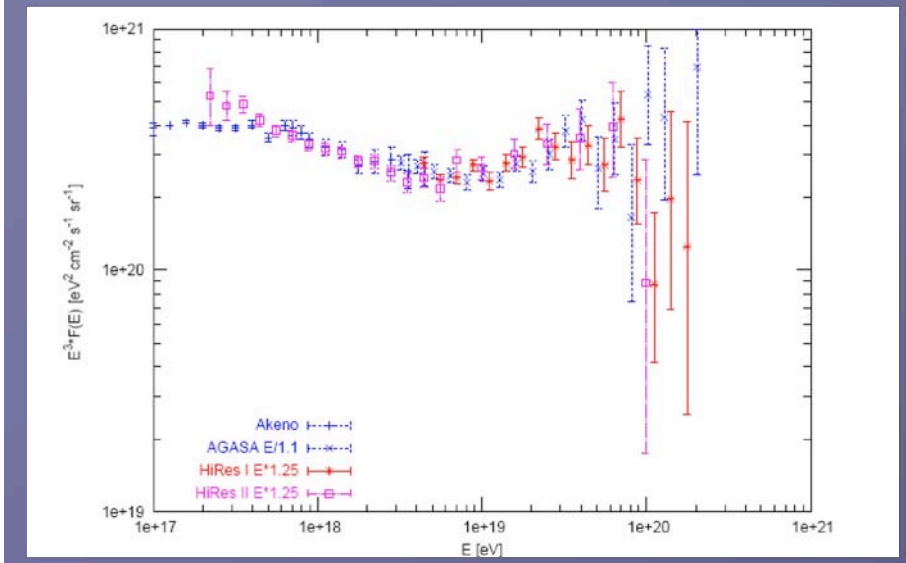
Probability of autocorrelation



M.Kachelriess and D.S., astro-ph/0512498

Medium Scale Anisotropy

M.Kachelriess & D.Semikoz



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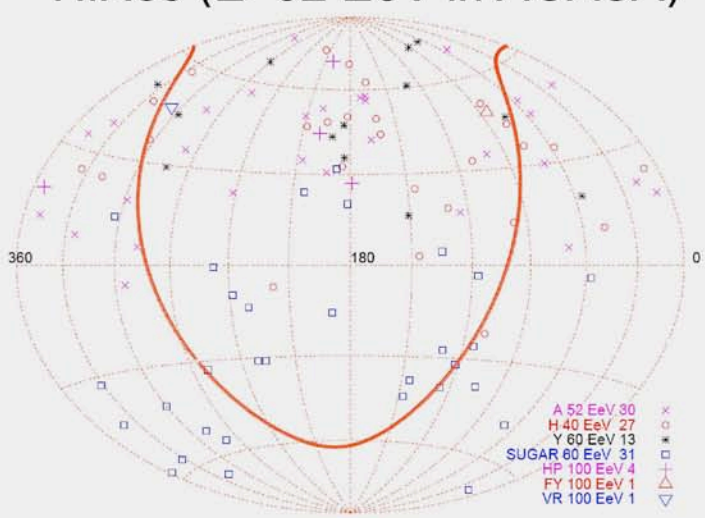

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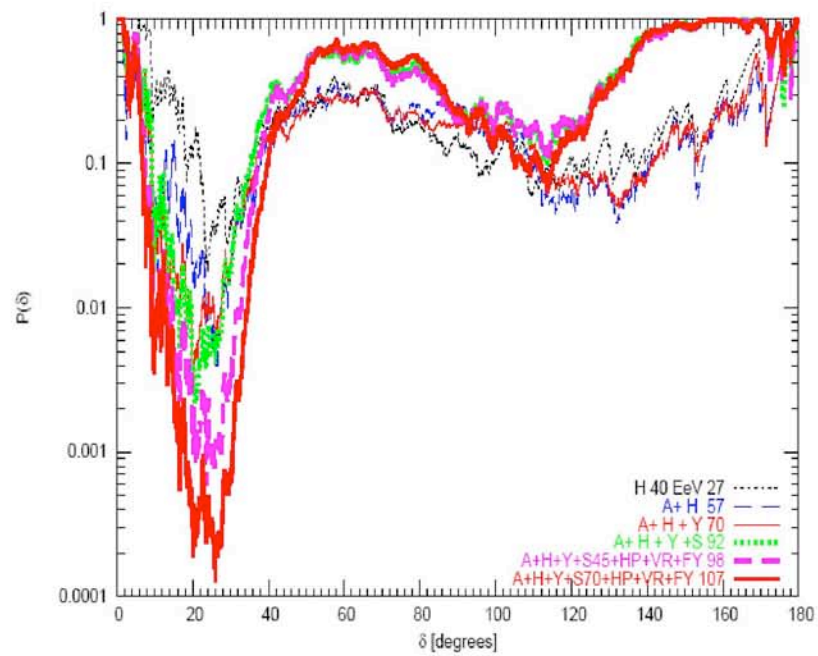

M.Kachelriess and D.S., astro-ph/0512498

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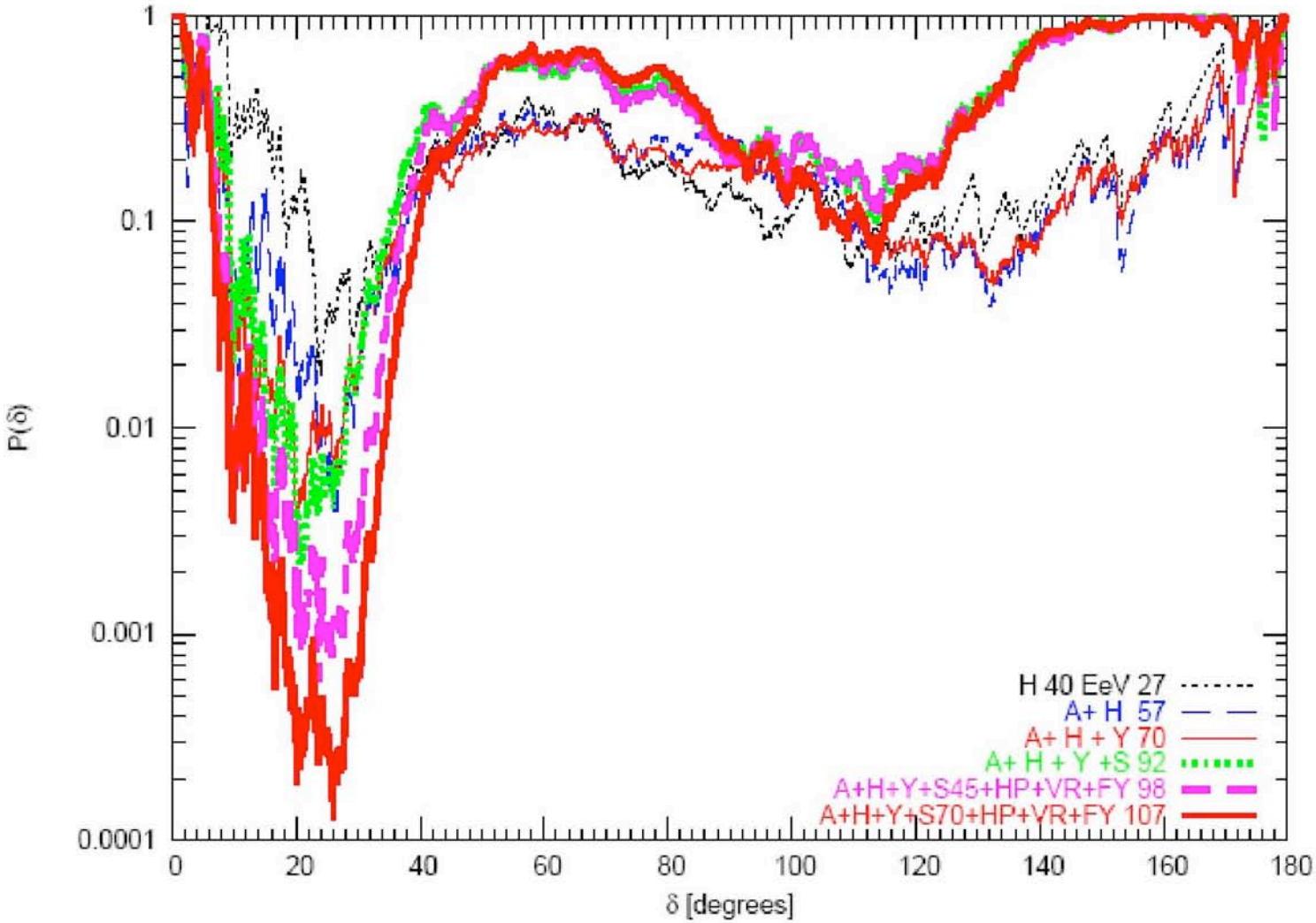

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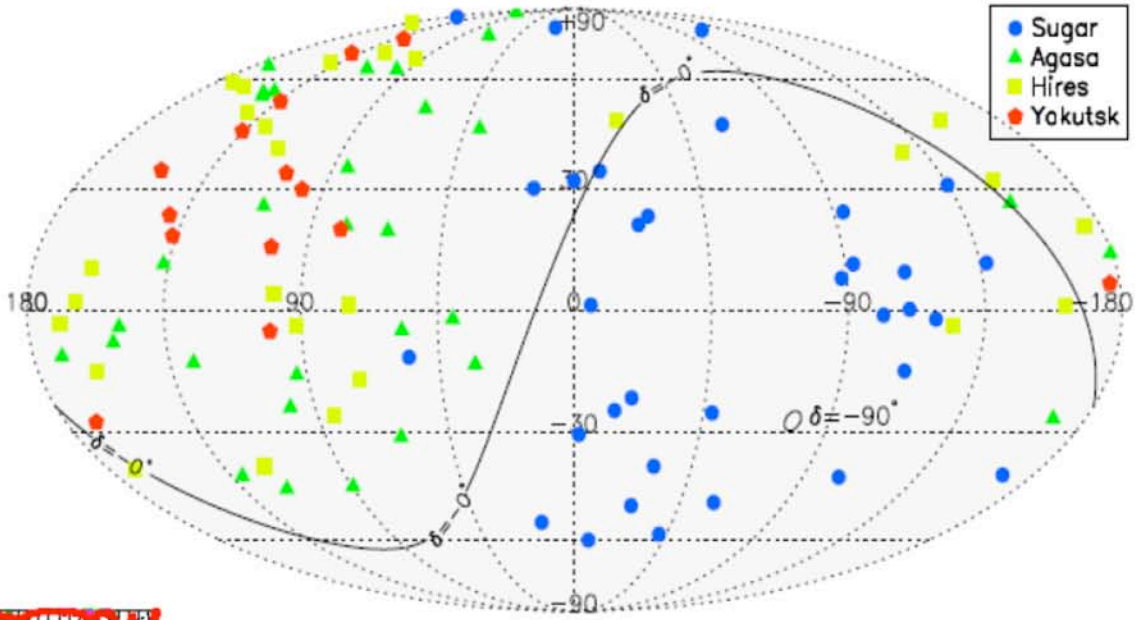

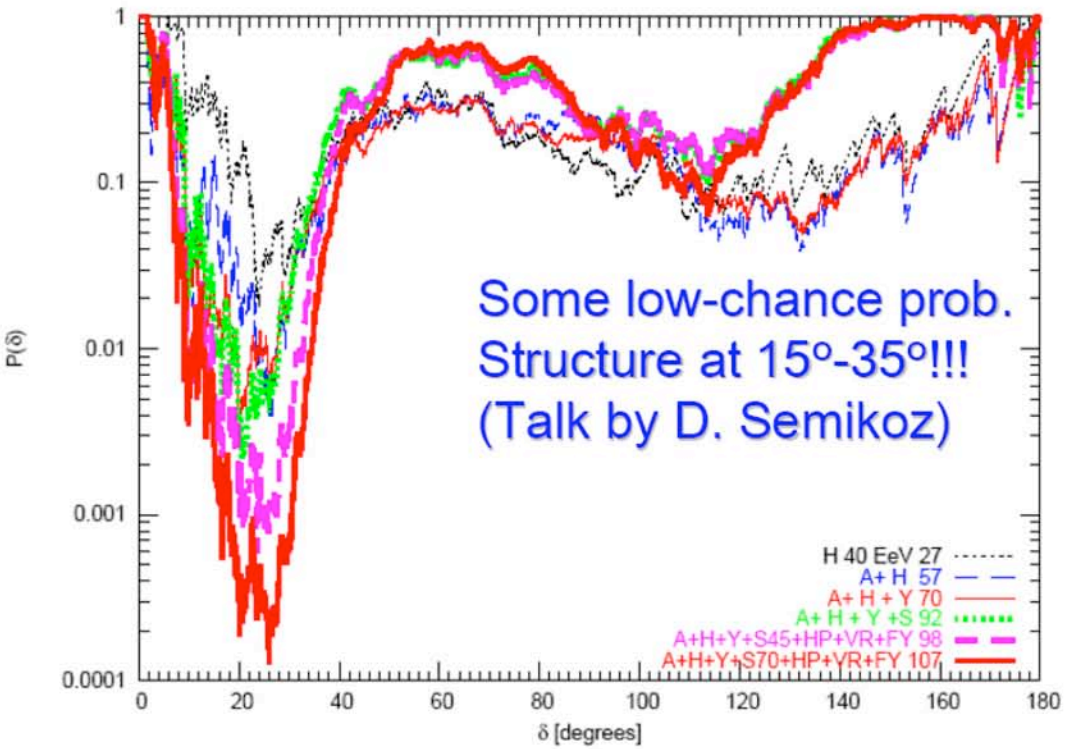

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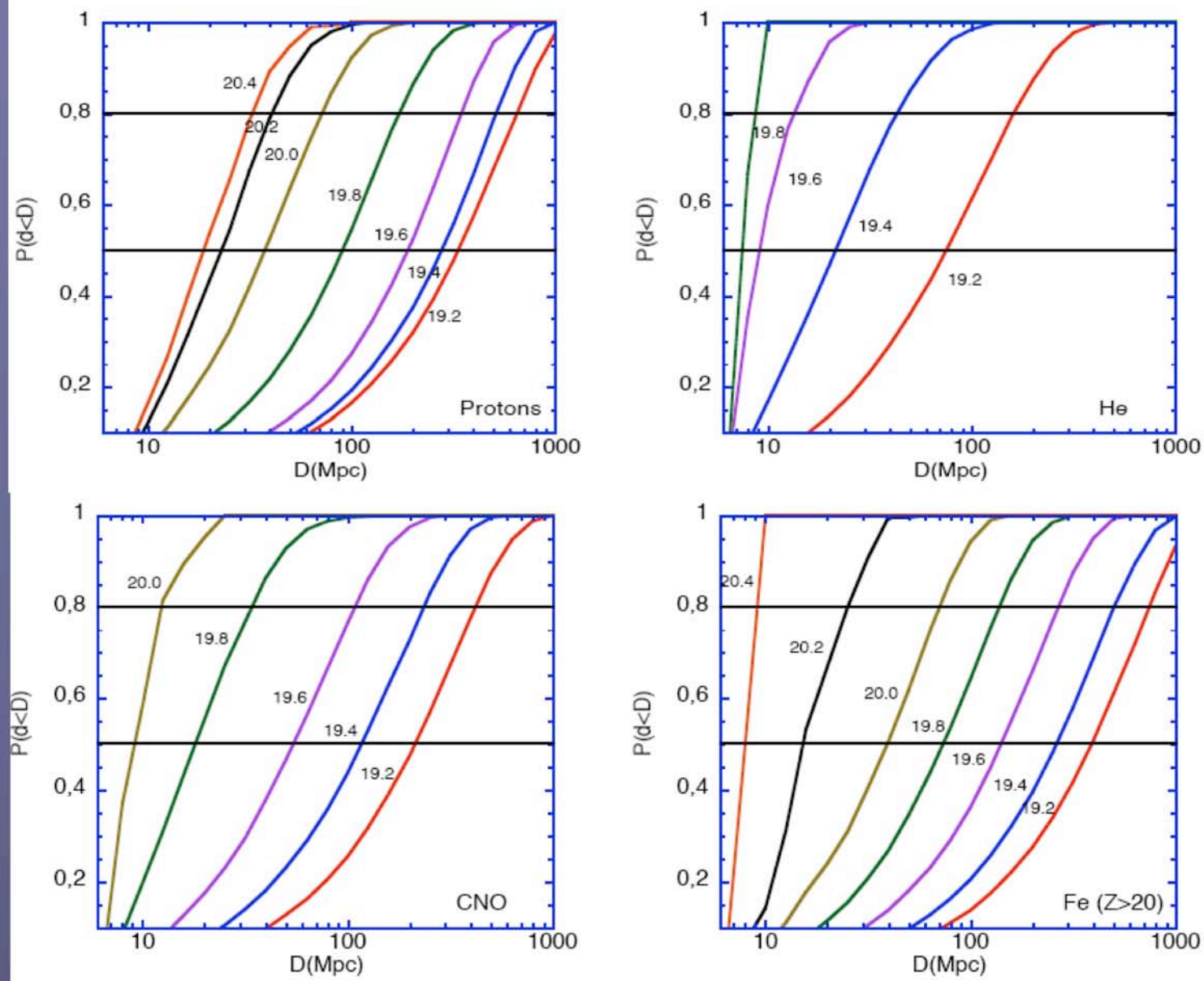
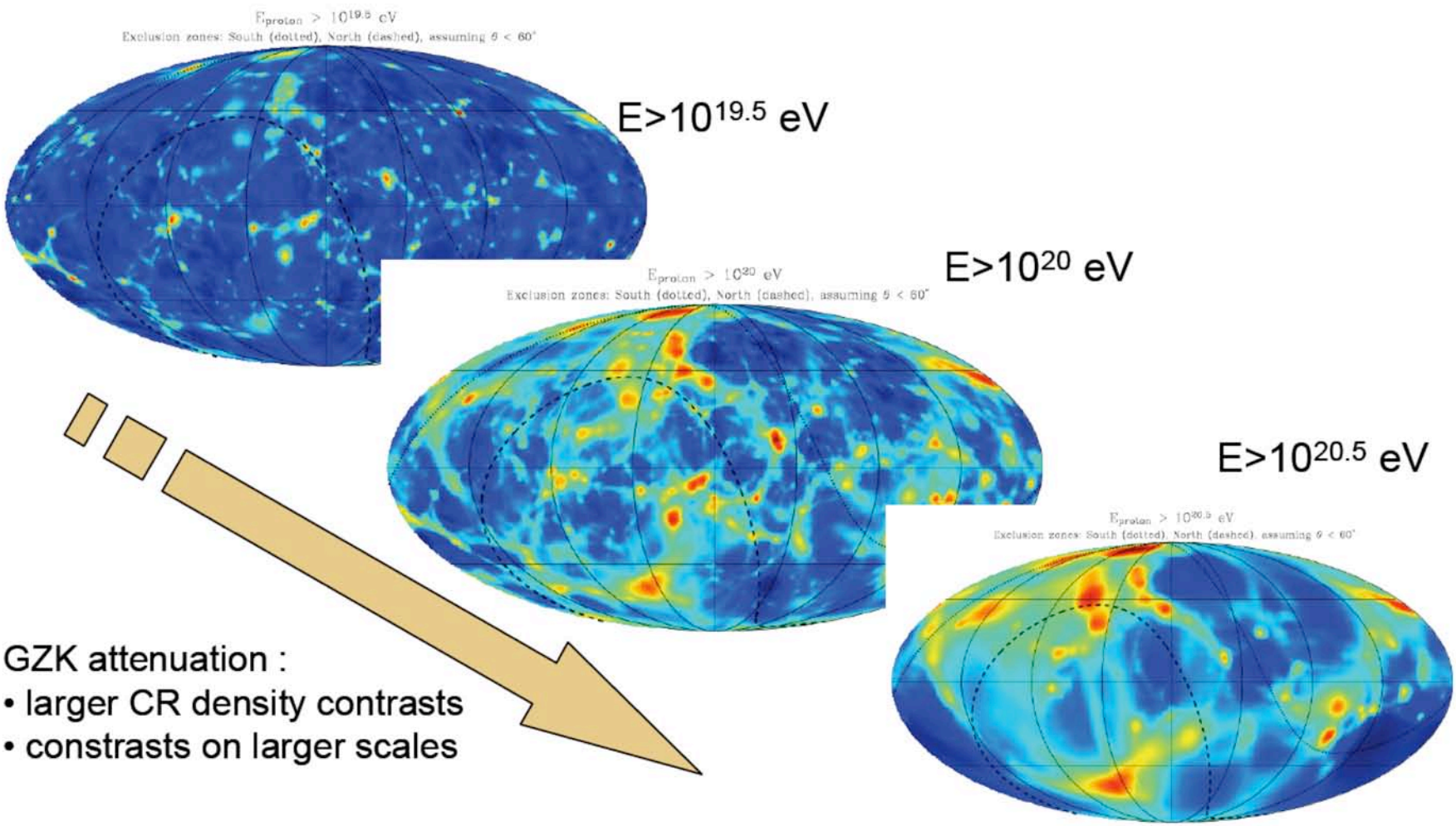
A.Olinto et al.
Horizon of UHECRs



UHECR possible LLS
A.Olinto et al.

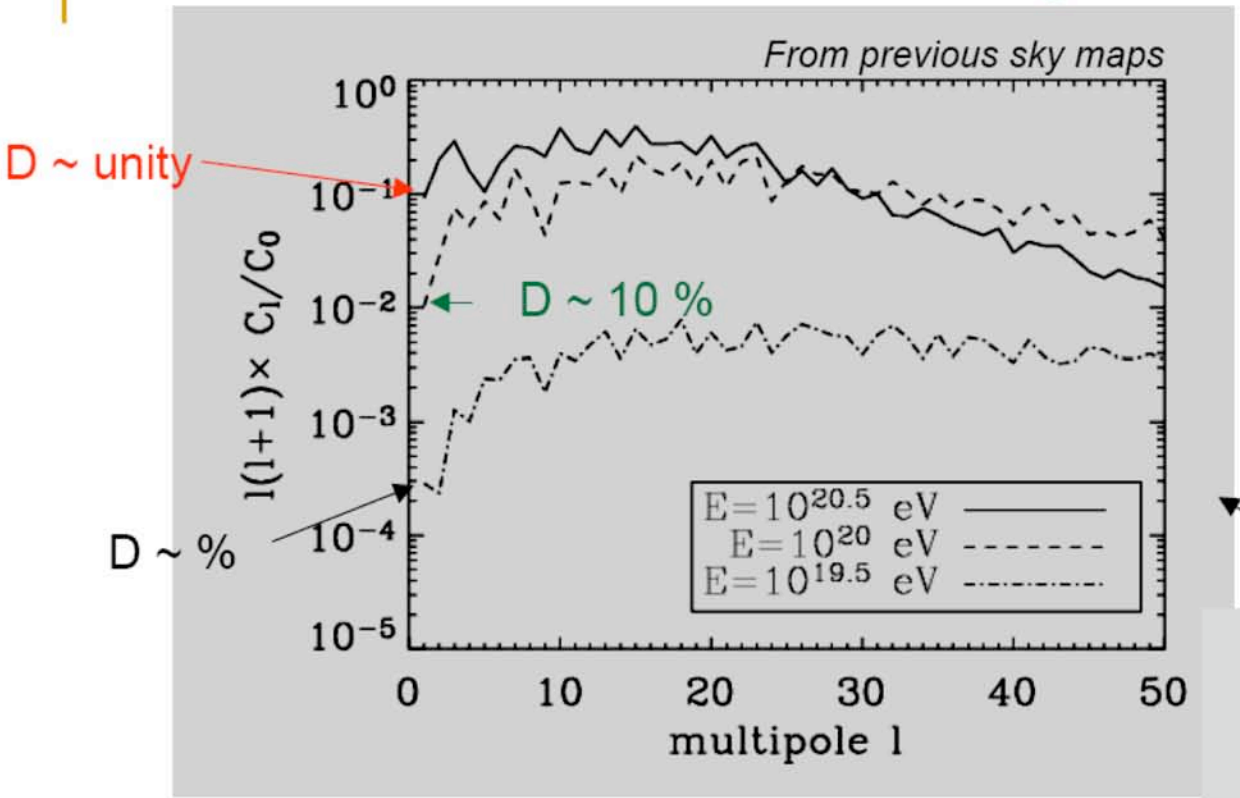


GZK attenuation :

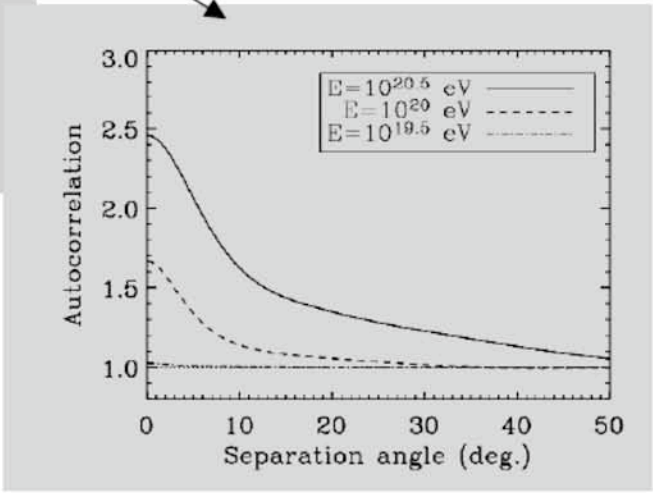
- larger CR density contrasts
- constrasts on larger scales

UHECR LLS
A.Olinto et al.

Continuous source distribution : large scale patterns



(Fourier transform)



- Spectra obtained without drawing events ("infinite statistics")
- Dipole $D \sim \sqrt{(C_1 / C_0)}$ increases with energy

UHECR from cluster accretion shock
S.Inoue

UHECRs from cluster accretion shocks?

Norman, Achterberg & Melrose 95
Kang, Ryu & Jones 96
Kang, Rachen & Biermann 97

particle confinement

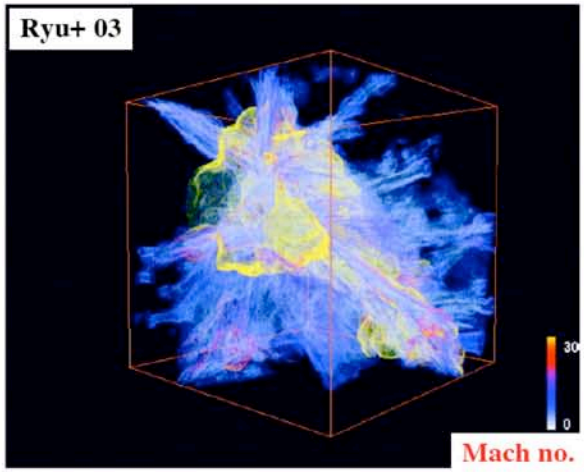
$E \leqq Ze\,B\,R$

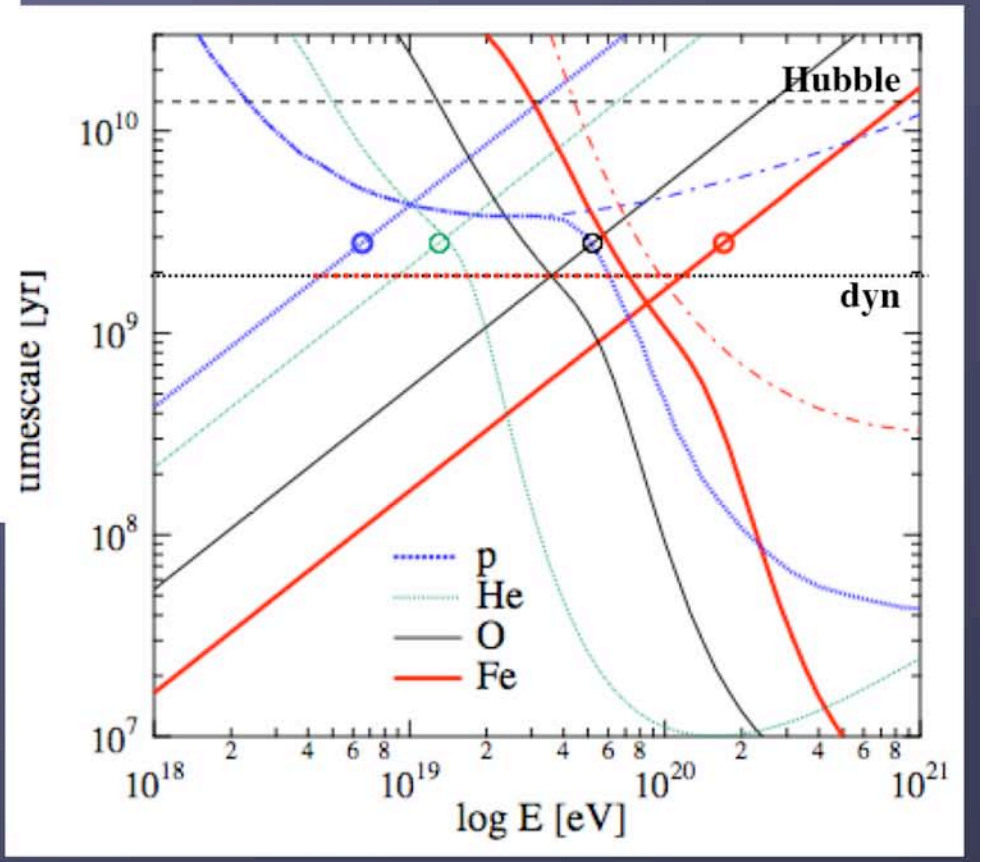
R~Mpc B~μG
10^{20} eV roughly OK

energy budget

(massive clusters ~10^{15} $M_\odot$)
$L_{cluster}$~10^{46} erg/s
$n_{cluster}$~10^{-6} Mpc^{-3}
$P_{cluster}$~~10^{40} erg $s^{-1}Mpc^{-3}$

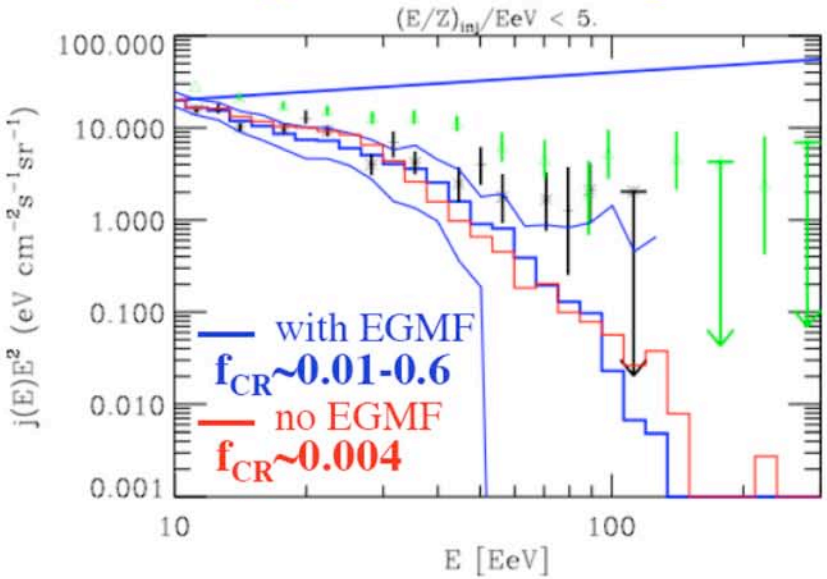
UHECR (>10^{19} eV)
u_{CR} ~3×10^{-19} erg cm^{-3}
τ_{GZK} ~4(10) Gyr for p (Fe)
P_{CR} ~10^{37} erg $s^{-1}Mpc^{-3}$ (no EGMF)

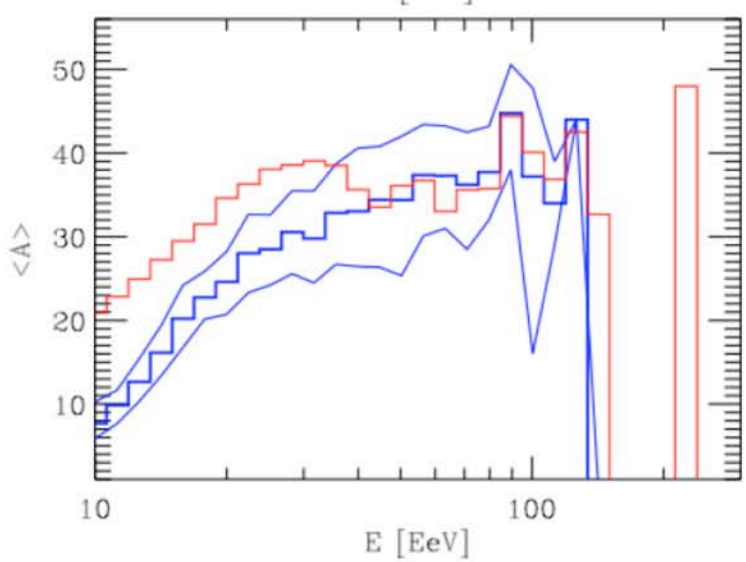




UHECR spectrum and X+Gamma ray emission

results: spectra & composition





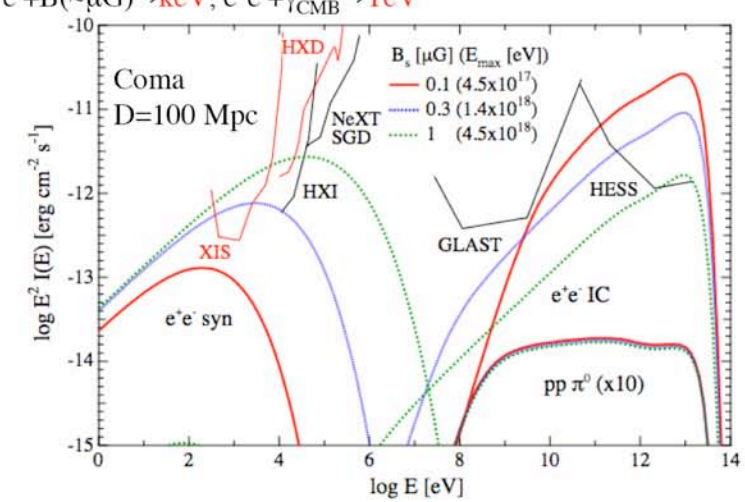
spectra
- consistent with latest HiRes, Auger (AGASA) with "GZK" cutoff
- low f_{CR} generally sufficient
  inefficient escape?

composition
- consistent with previous HiRes light dominant $<10^{19}$ eV
- prediction: heavy dominant $>10^{19}$ eV

UHE proton-induced hard X+γ emission from clusters

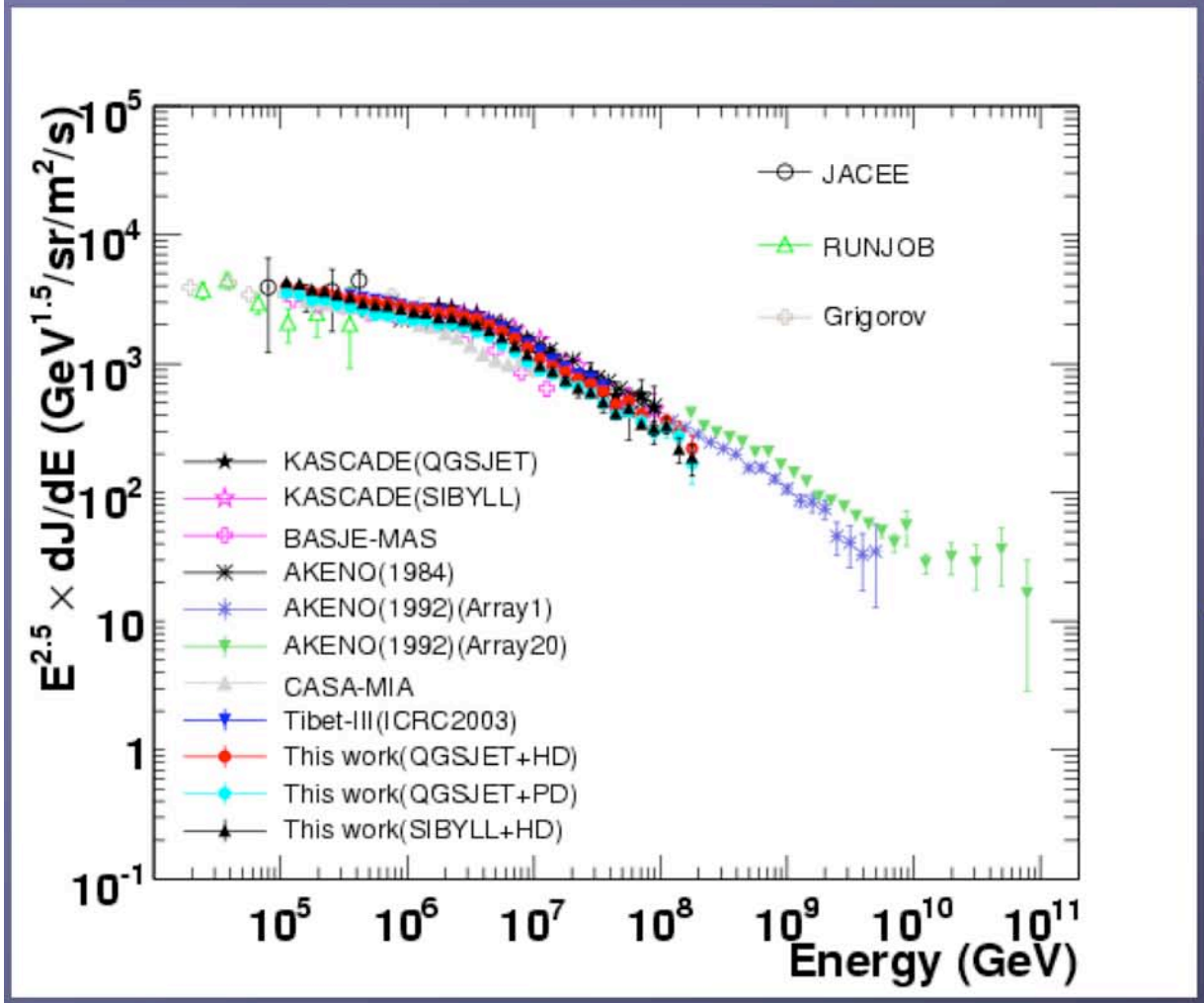
$p(10^{19}\text{eV}) + \gamma_{CMB} \rightarrow p + e^+e^-(10^{16}\text{eV})$ **SI, Aharonian, Sugiyama 0**

$e^+e^- + B(\sim\mu G) \rightarrow$ keV, $e^+e^- + \gamma_{CMB} \rightarrow$ TeV



From Knee to Ankle

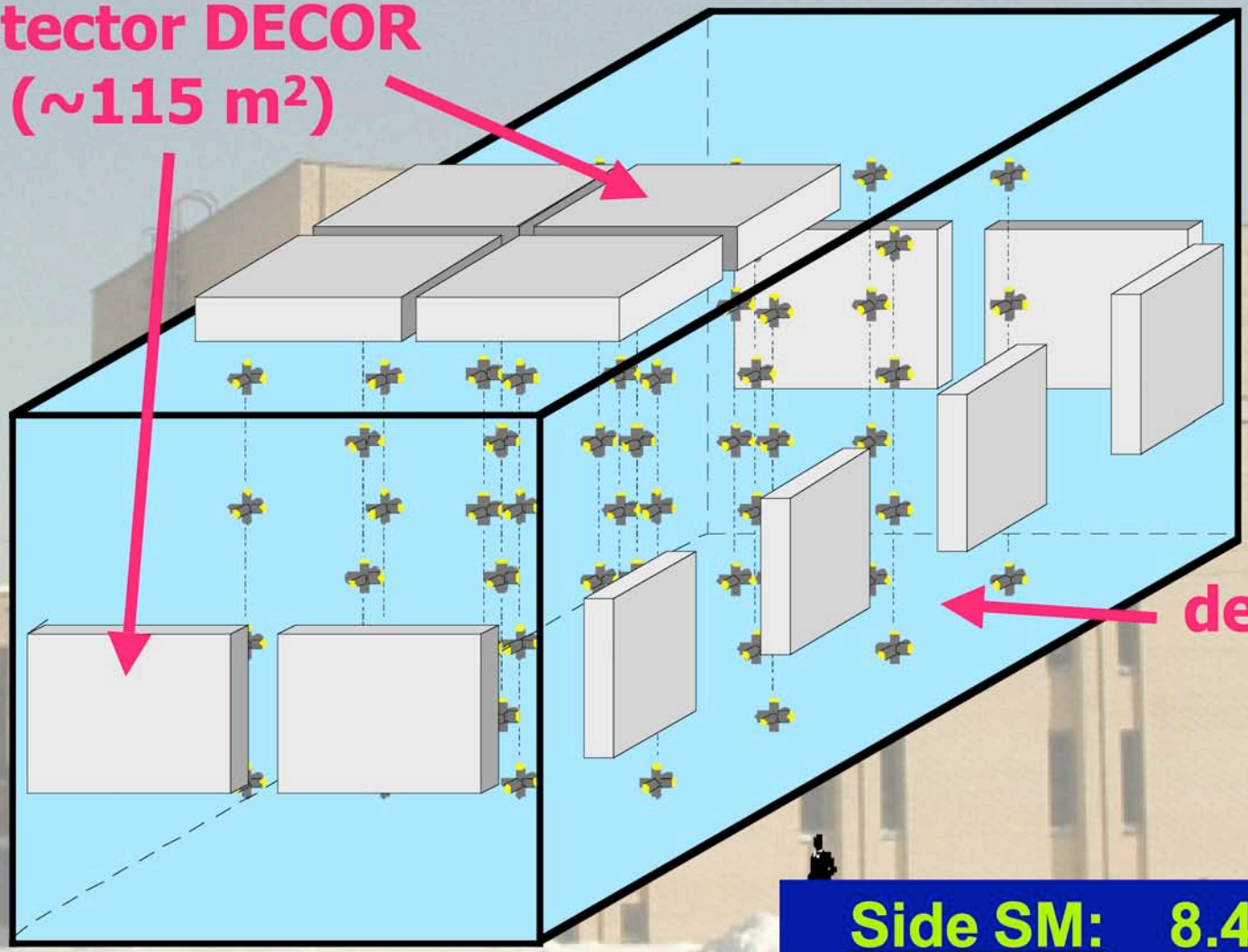
Tibet AS-γ energy spectrum



Model	Index of spectrum	Energy range (eV)
QGSJET+HD	−2.69±0.01	$< 10^{15}$
	−3.13±0.01	$> 4 \times 10^{15}$
QGSJET+PD	−2.64±0.01	$< 10^{15}$
	−3.12±0.01	$> 4 \times 10^{15}$
SIBYLL+HD	−2.68±0.01	$< 10^{15}$
	−3.12±0.01	$> 4 \times 10^{15}$

Model	Knee position (PeV)
QGS+HD	4.0±0.1
QGS+PD	3.3±0.1
SIBY+HD	3.7±0.1

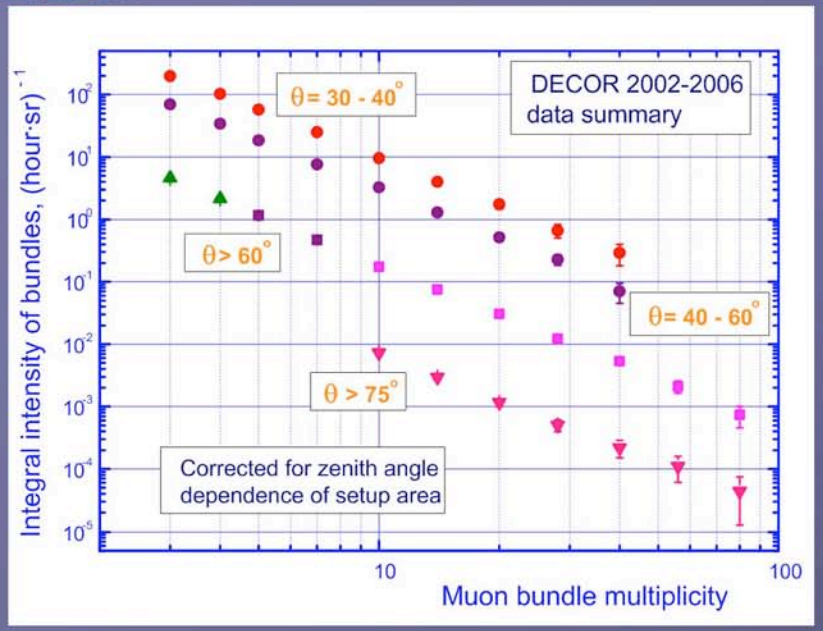
NEVOD-DECOR

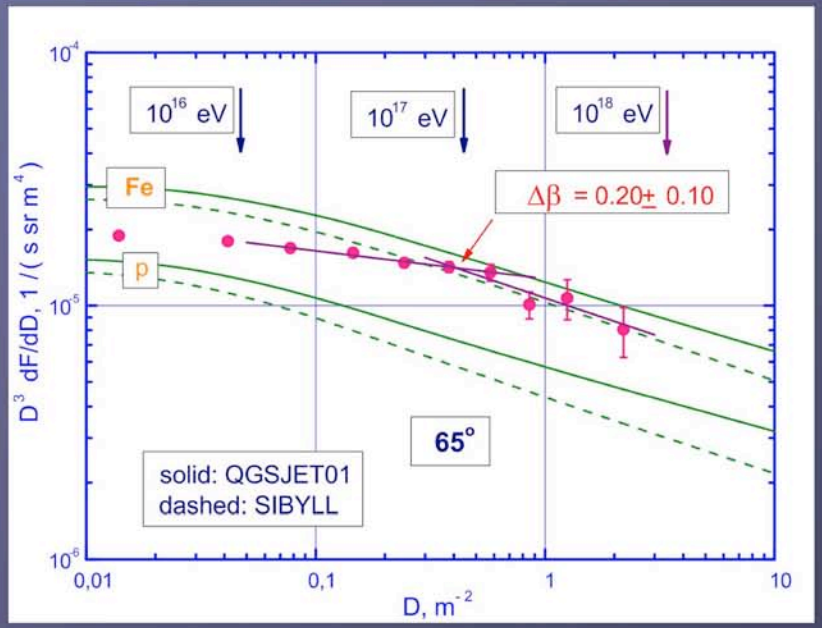


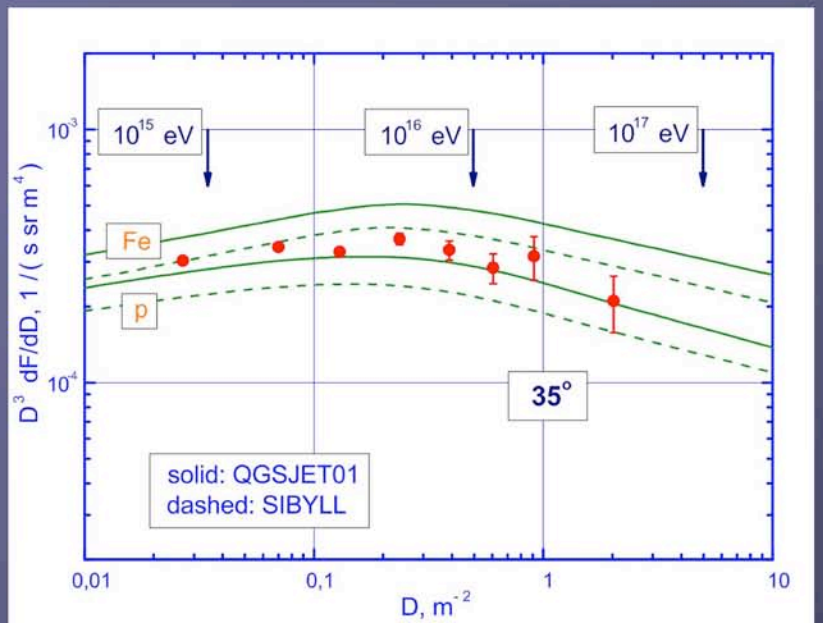
Side SM: 8.4 m² each

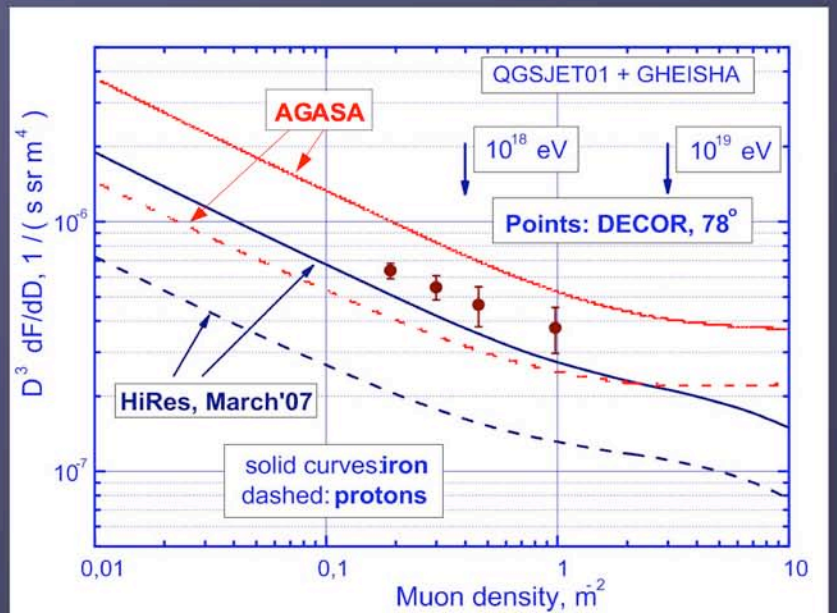
- $\sigma_x \sim 1$ cm; $\sigma_\psi \sim 1°$

NEVOR-DECOR Energy Spectrum

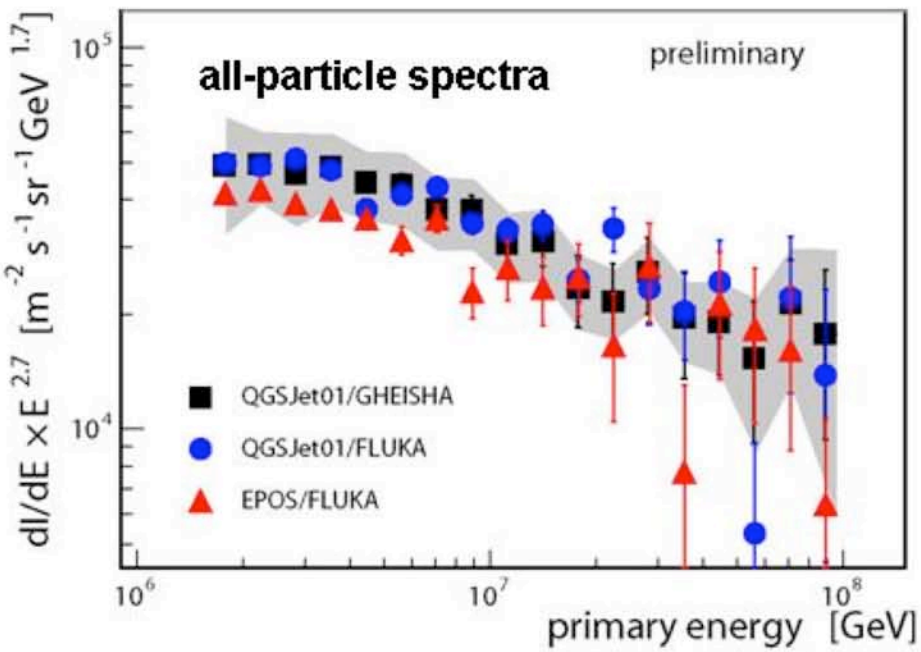


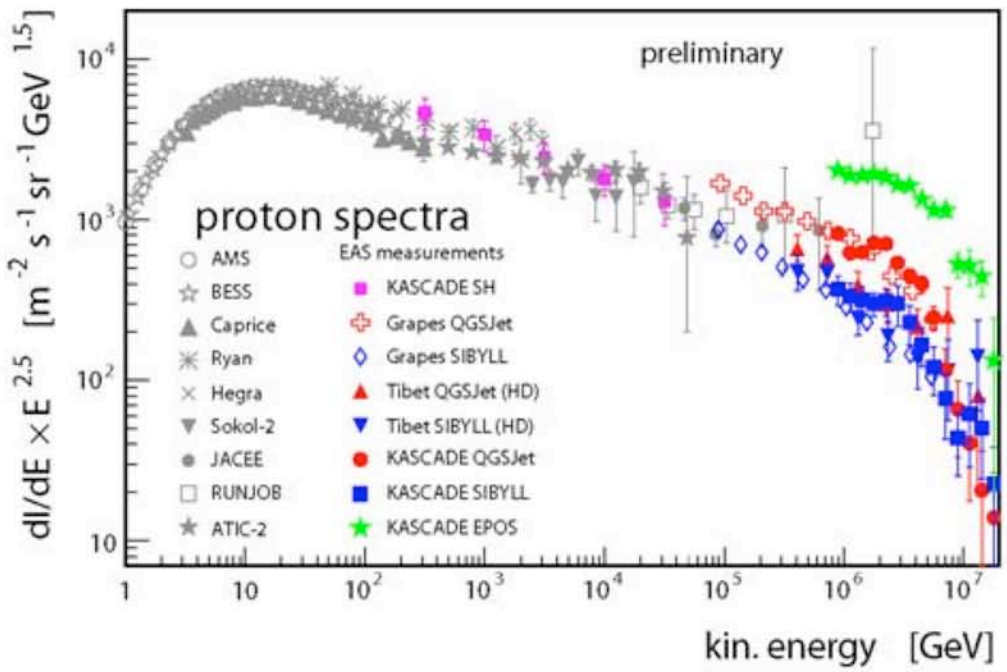






KASCADE Unfolding: Summary



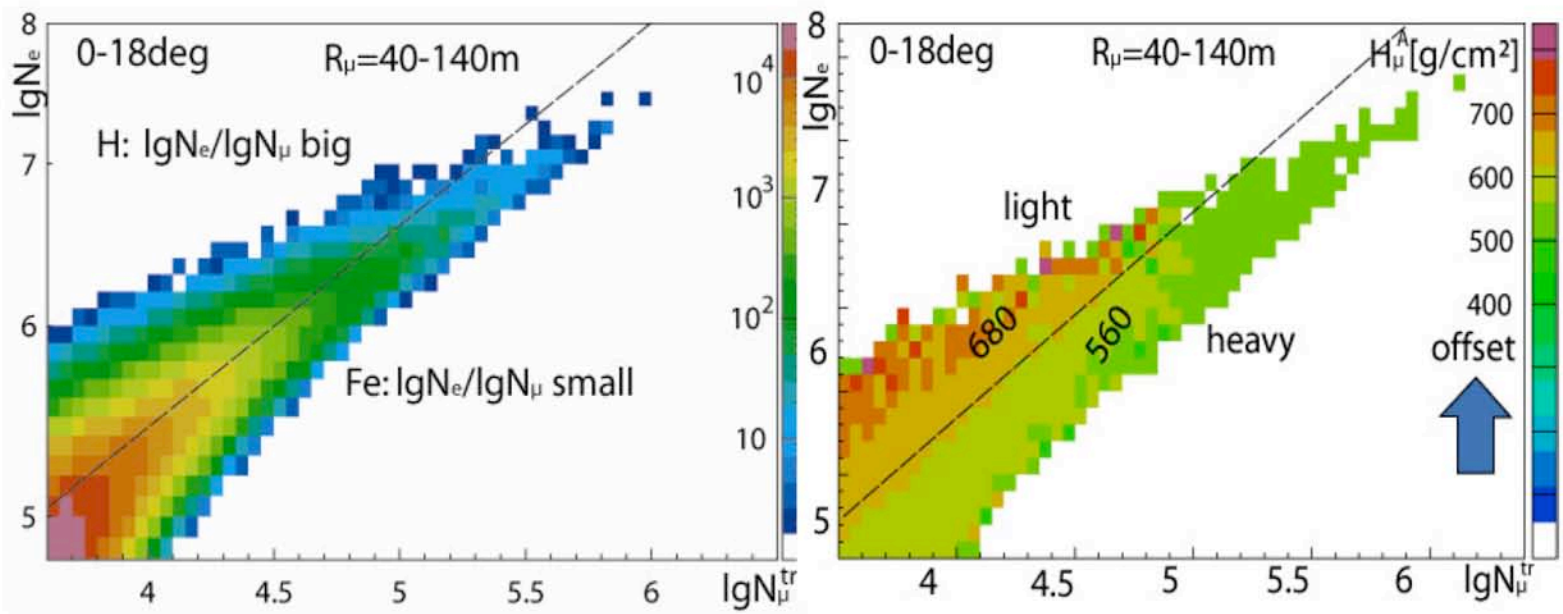


-) knee visible in data structure
-) knee caused by light primaries ➔ composition gets heavier across knee
-) positions of knee vary with primary elemental group
-) relative abundancies depend strongly on high energy interaction model
-) result only weakly dependent on low energy interaction model
-) result consistent for different data sets
-) no (interaction) model can describe the data consistently
-) all-particle spectra agree inside uncertainties (EPOS a bit lower)

KASCADE: Muon production height

Muon Production Height $H_{\mu A}$ versus lgN_e/lgN_μ

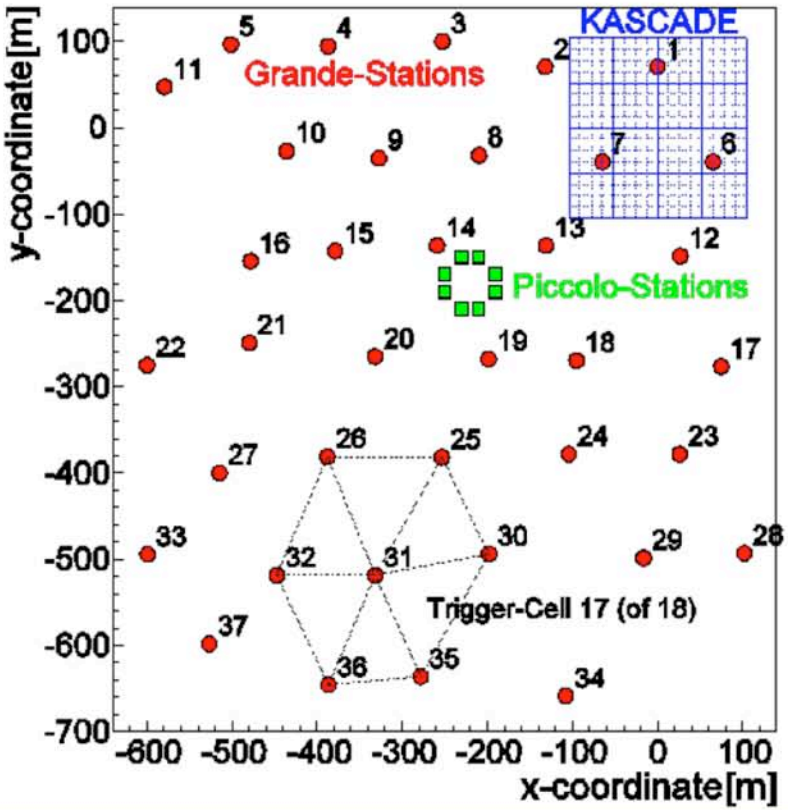
The muon production height $H_{\mu A}$ can be calculated for each muon track in a shower. After correction for elongation rate as function of lgN_μ and lgN_e the resulting $H_{\mu A}$ distribution exhibits regions of distinct $H_{\mu A}$ in a colour code with 40g/cm² step size.



KASCADE-Grande

KASCADE-Grande: the experimental set-up

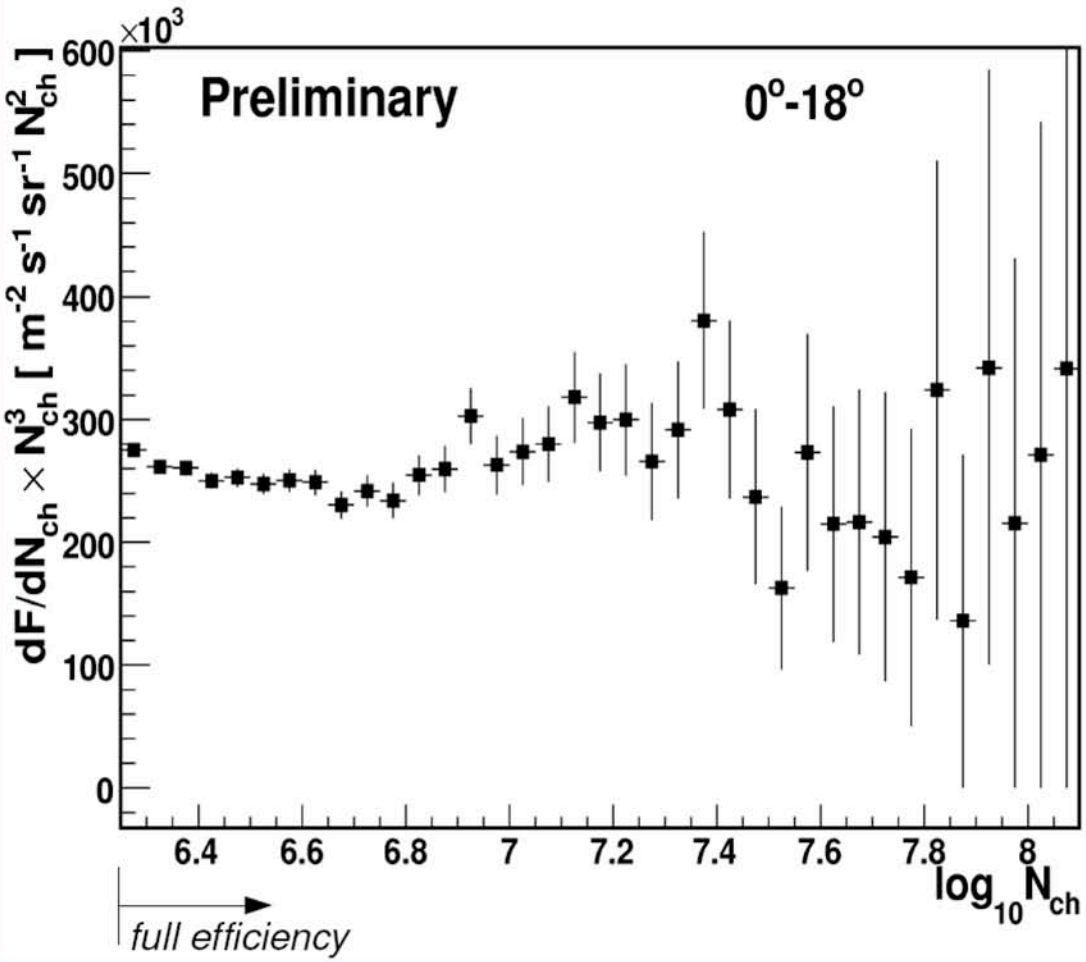
- Forschungszentrum Karlsruhe, 48.1 N, 8.4 E, 110 m
- Energy range: 10^{16} -10^{18} eV
- Multi-observables (charged particles, muons at different thresholds)
- 2 different arrays overlapping each other



Detector	Detected EAS component	Sensitive area (m2)
Grande	Charged particles	37x10
Piccolo	Charged particles	8x10
KASCADE array e/γ	Electrons, γ	490
KASCADE array μ	Muons ($E\mu^{th}$=230 MeV)	622
MTD	Muons (Tracking) ($E\mu^{th}$=800 MeV)	3x128
MWPCs/LSTs	Muons ($E\mu^{th}$=2.4 GeV)	3x129
LOPES 30	Radio	
Trigger Plane	*Muons ($E\mu^{th}$=490 MeV)*	*208*
Calorimeter	*Hadrons*	*9x304*

KASCADE-GRANDE Size spectrum

Shower size spectrum



- vertical events
- 290 days of data taking
- fiducial area 0.3 km^2
- flux multiplied by N_{ch}^3

- ...not deconvoluted for reconstruction uncertainties!

- ...low statistics to see spectral features!

KASCADE-GRANDE
Inclined muon spectrum

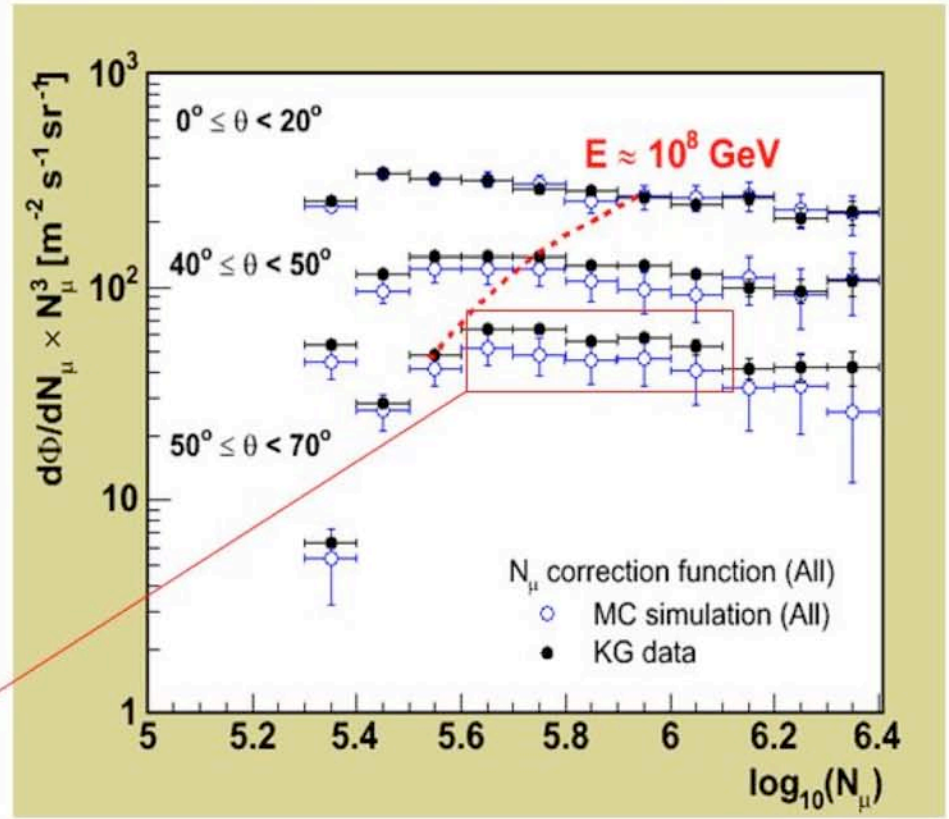
4) Confronting MC and KG data

Differences between MC and KG data increase with θ.

- Shower simulations:

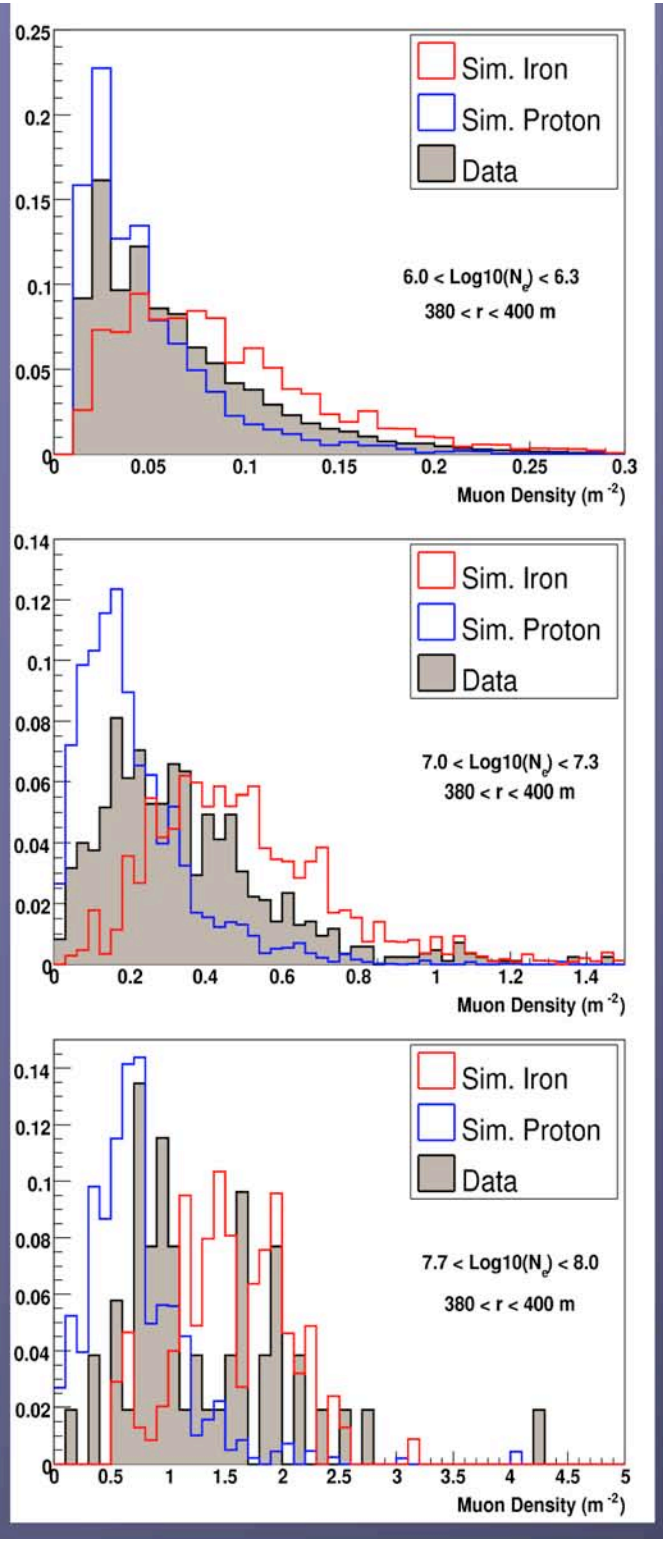
  More muons/harder secondary μ spectrum in MC are needed?

- Detector simulation?

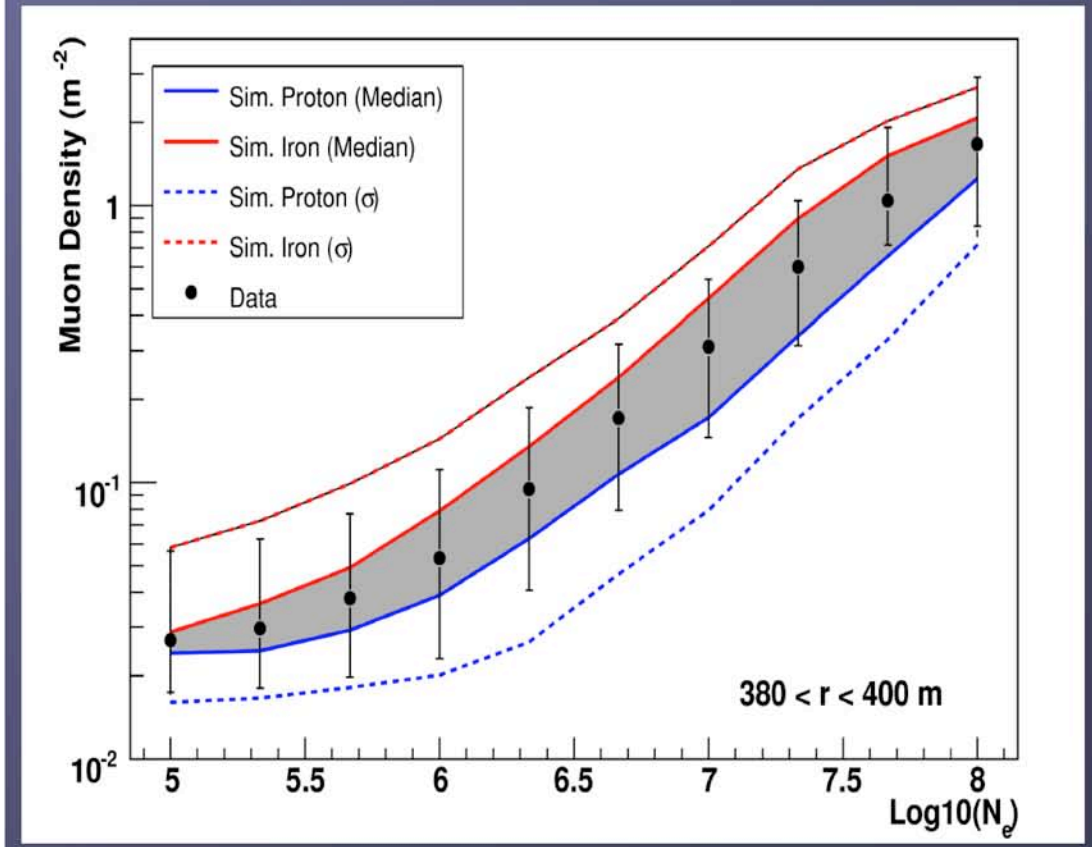


For $50° \leq \theta \leq 70°$:
$\Delta\Phi_\mu \sim 20$ %

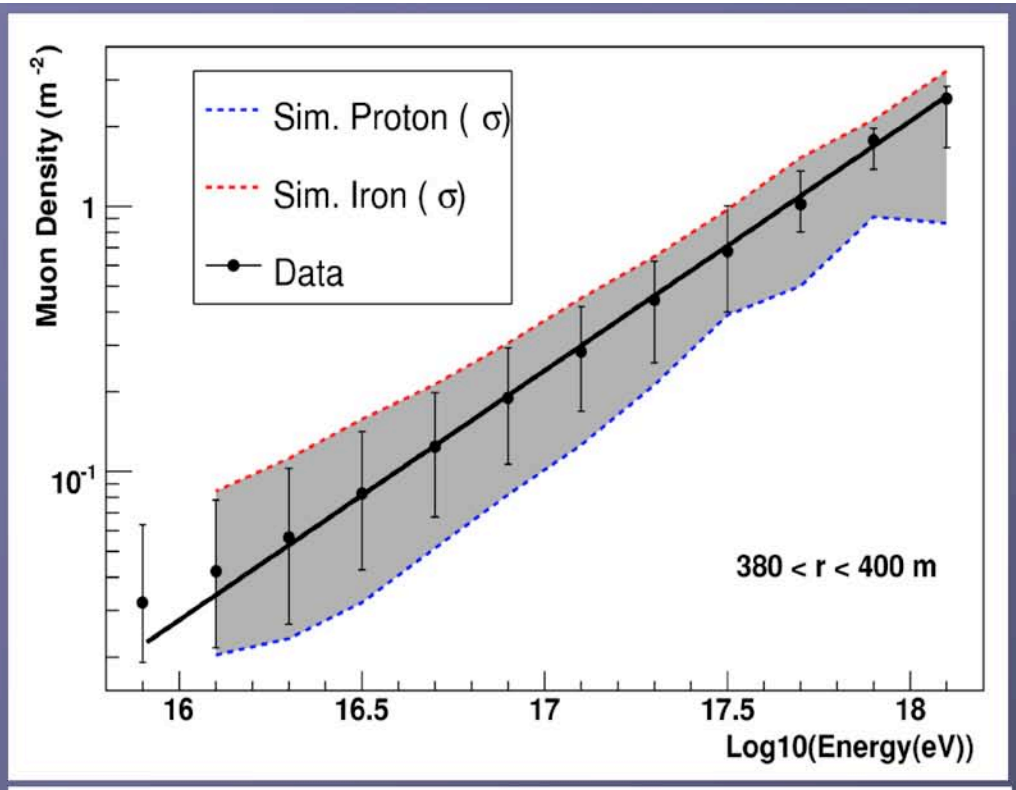
KASCADE-GRANDE
Chemical composition

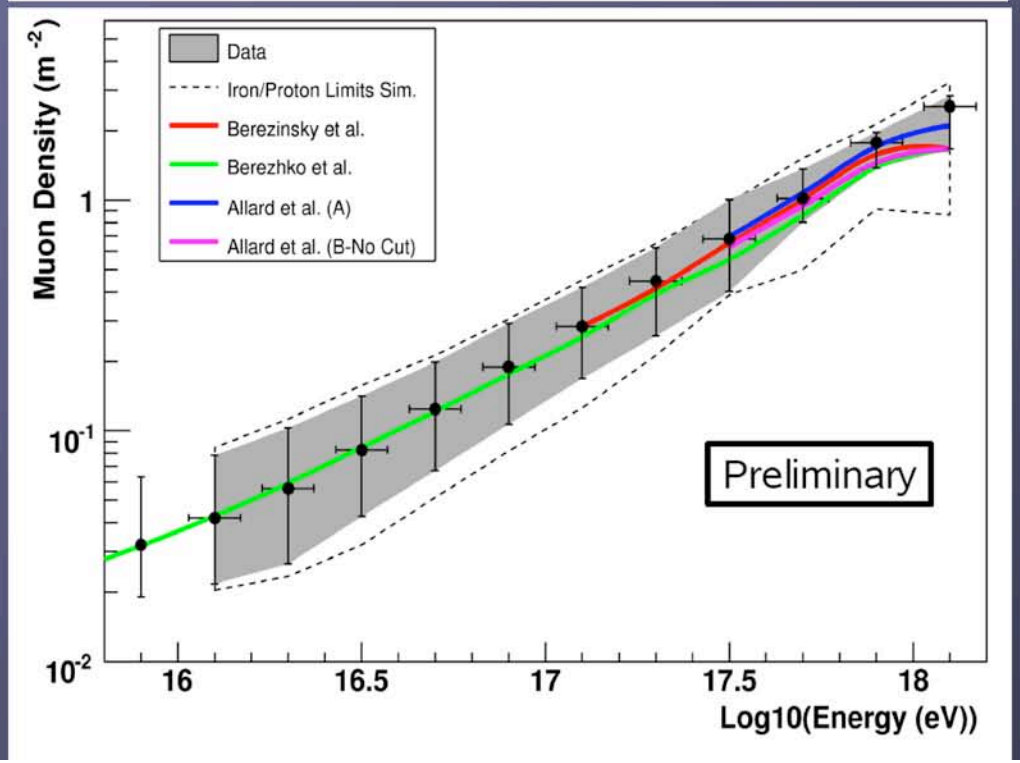


CORISKA QGS-JET II

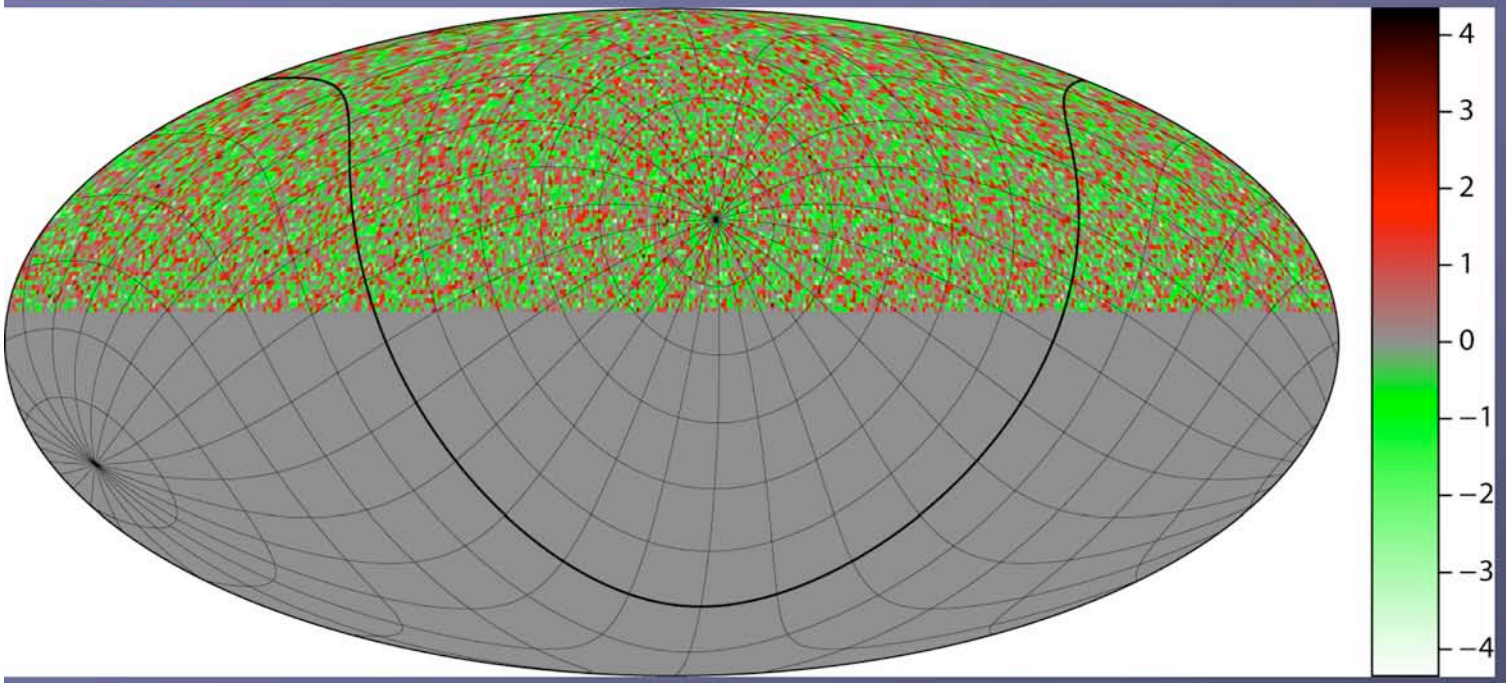


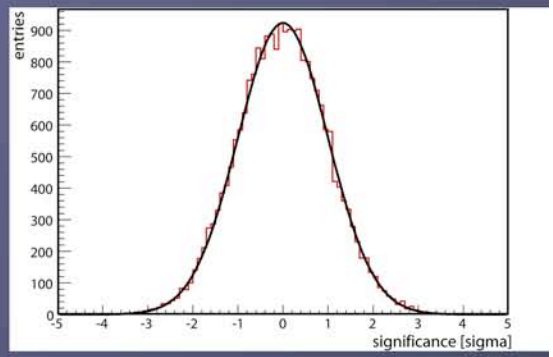
KASCADE-GRANDE
Chemical Composition

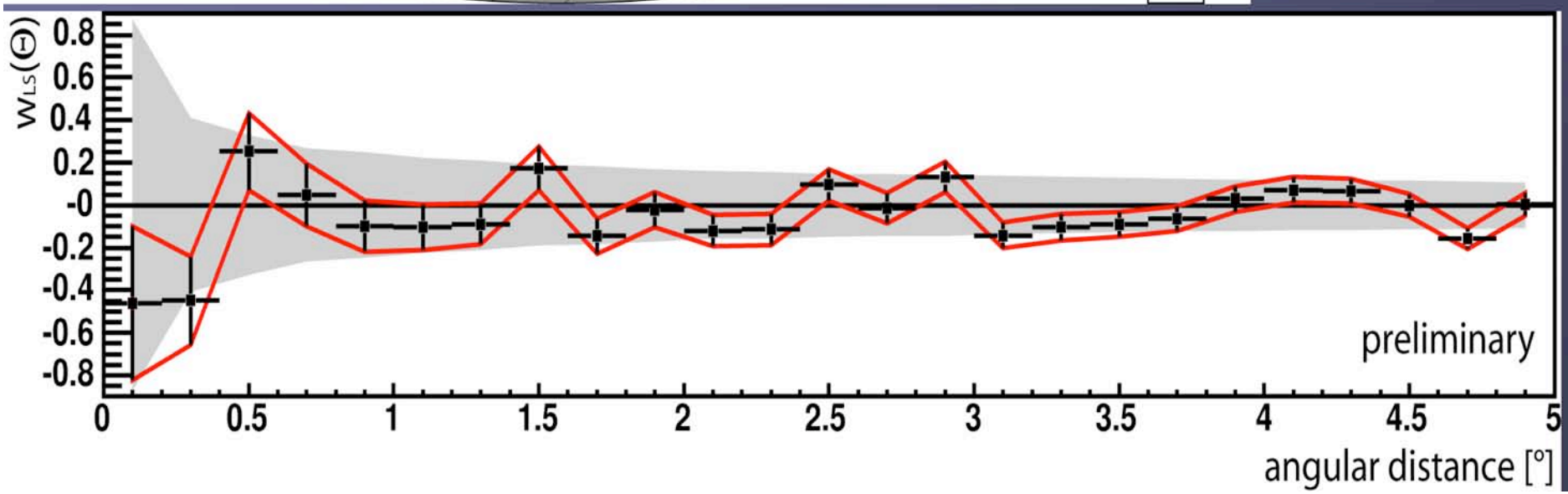




KASCADE-GRANDE
No point sources

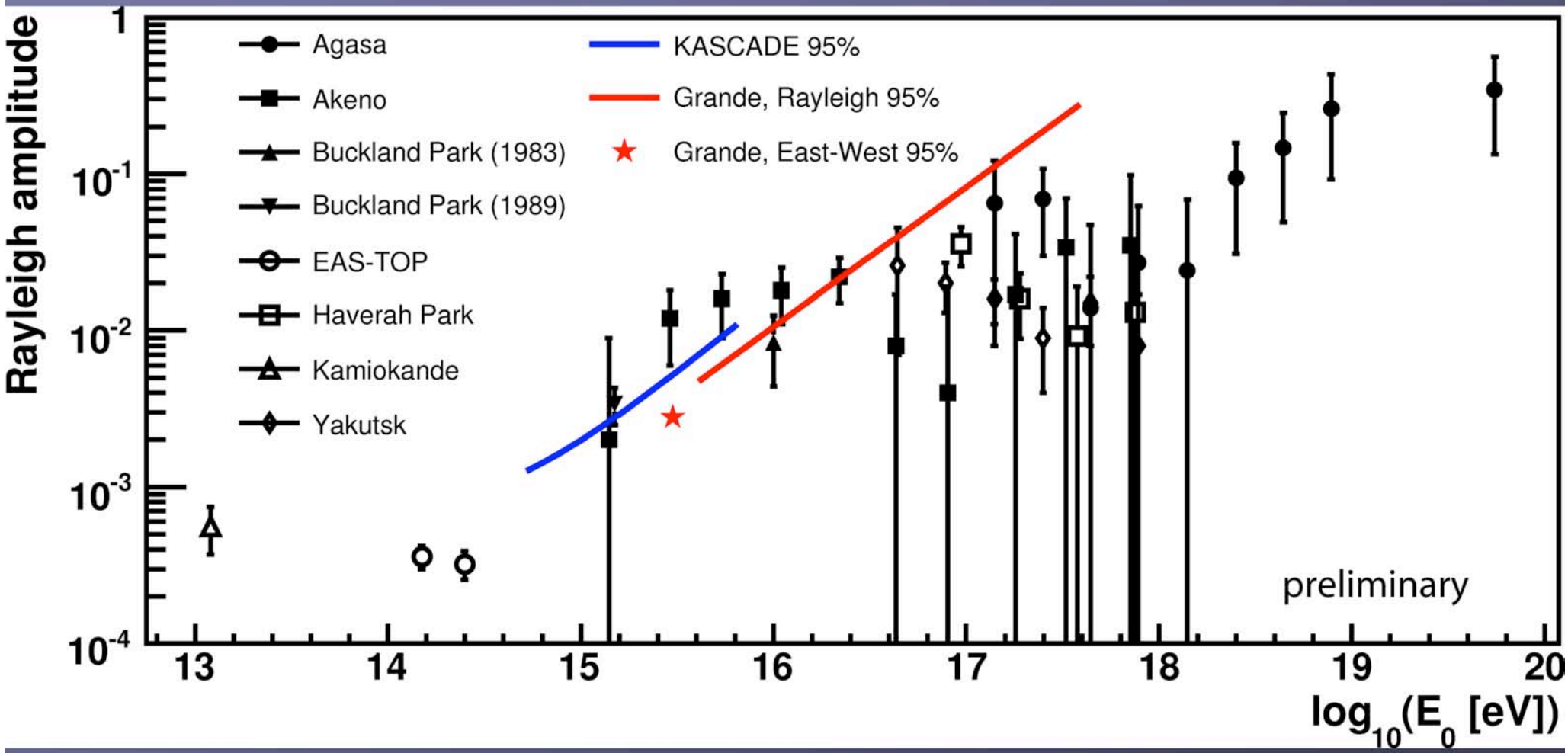






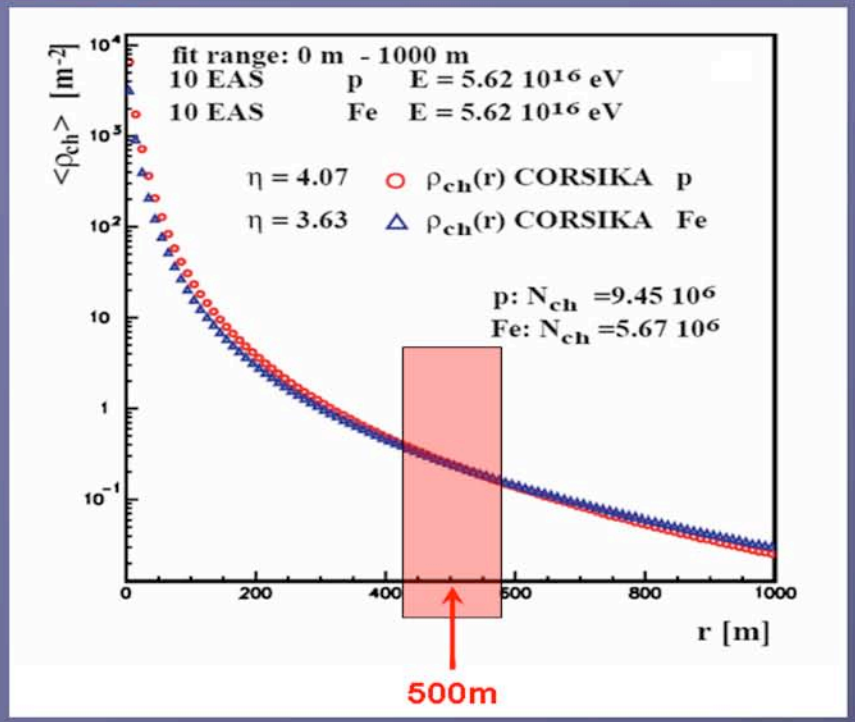
KASCADE-GRANDE

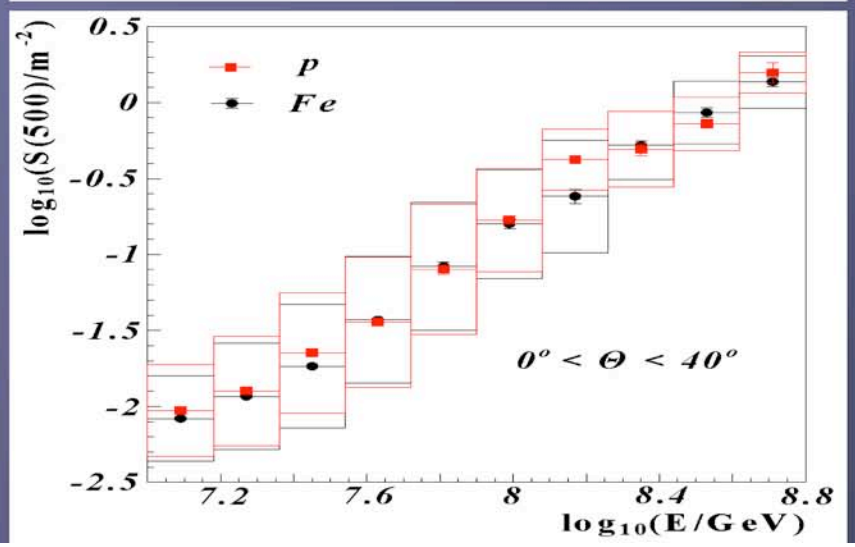
Upper limit for Large scale ansiotropy

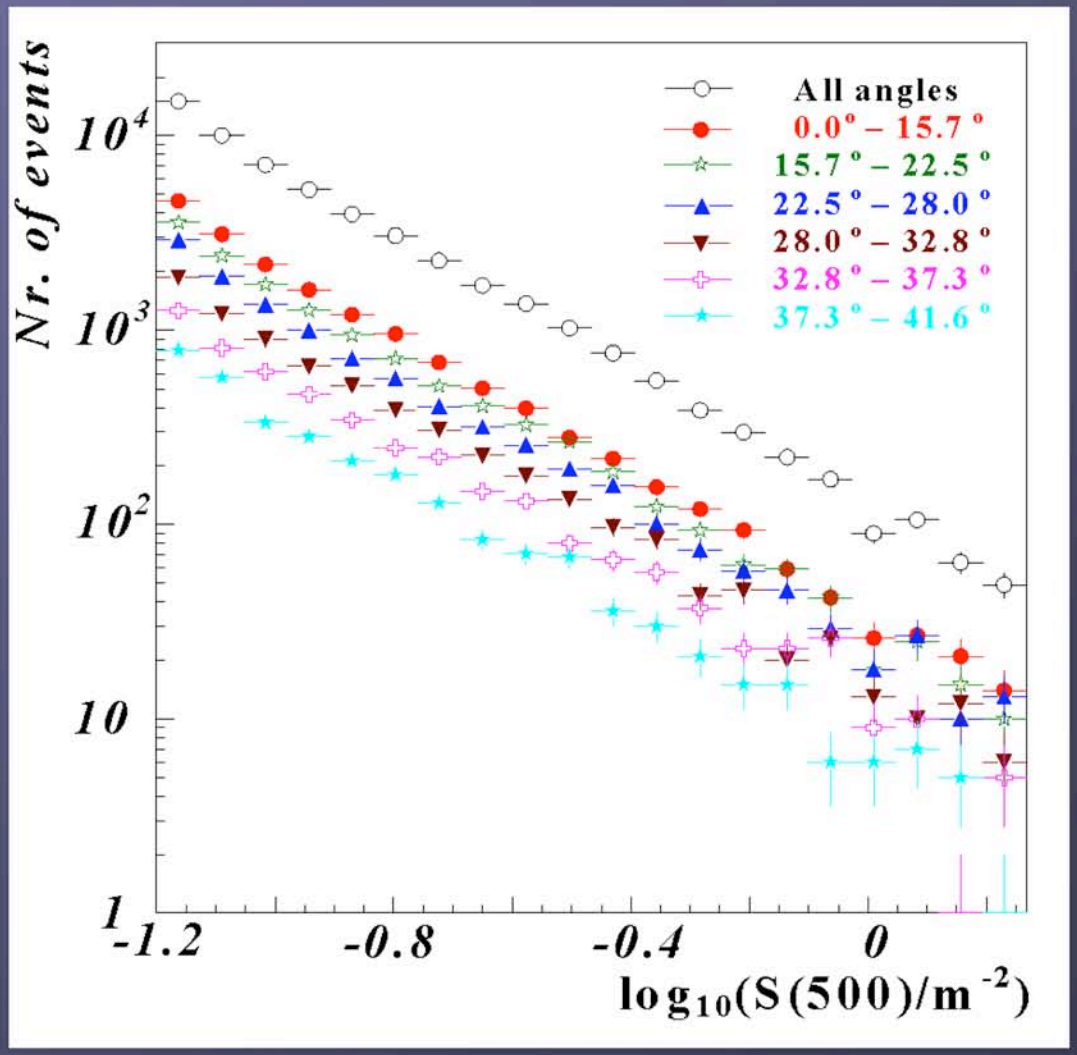


KASCADE-GRANDE

New Energy Estimator S(500)





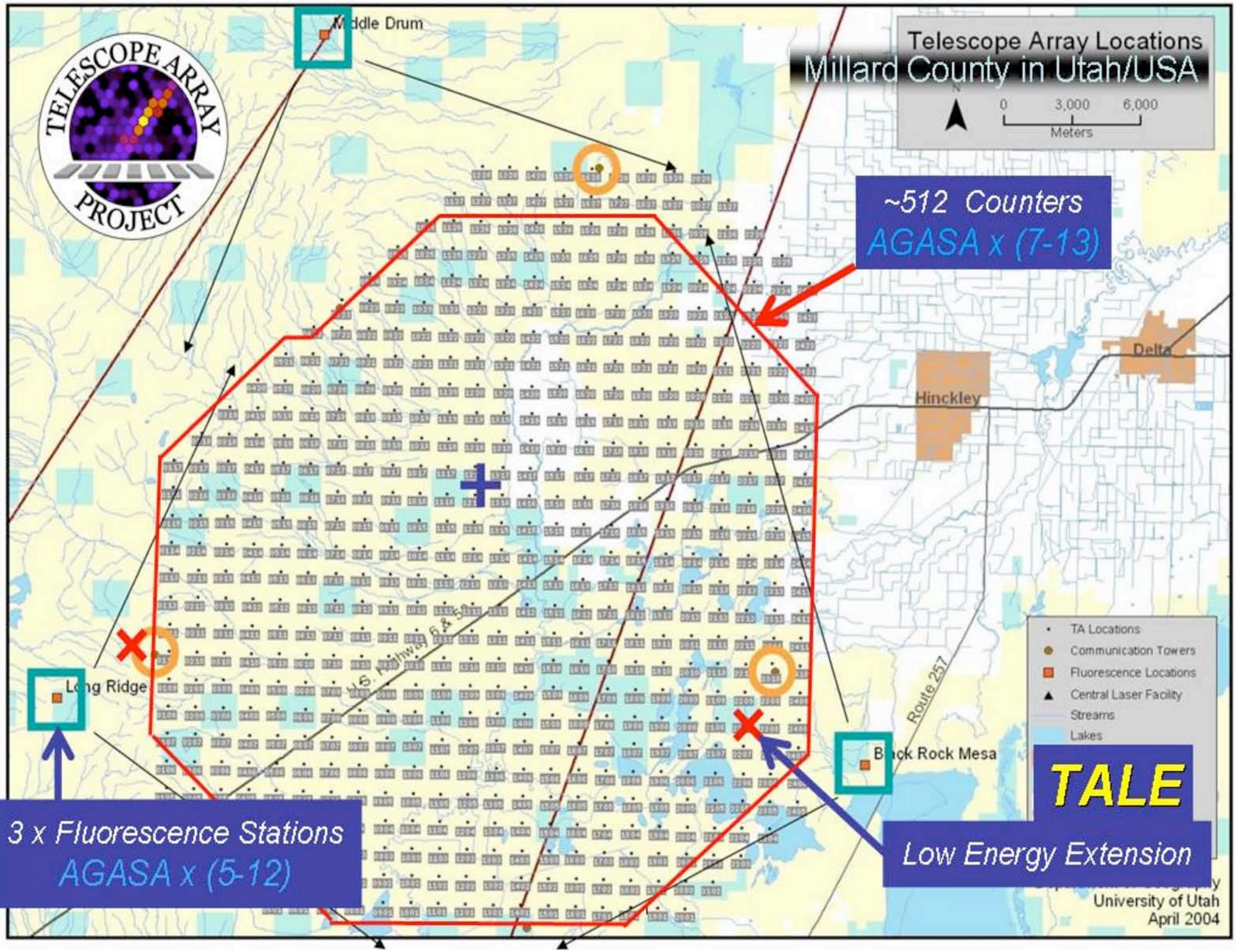


New Projects

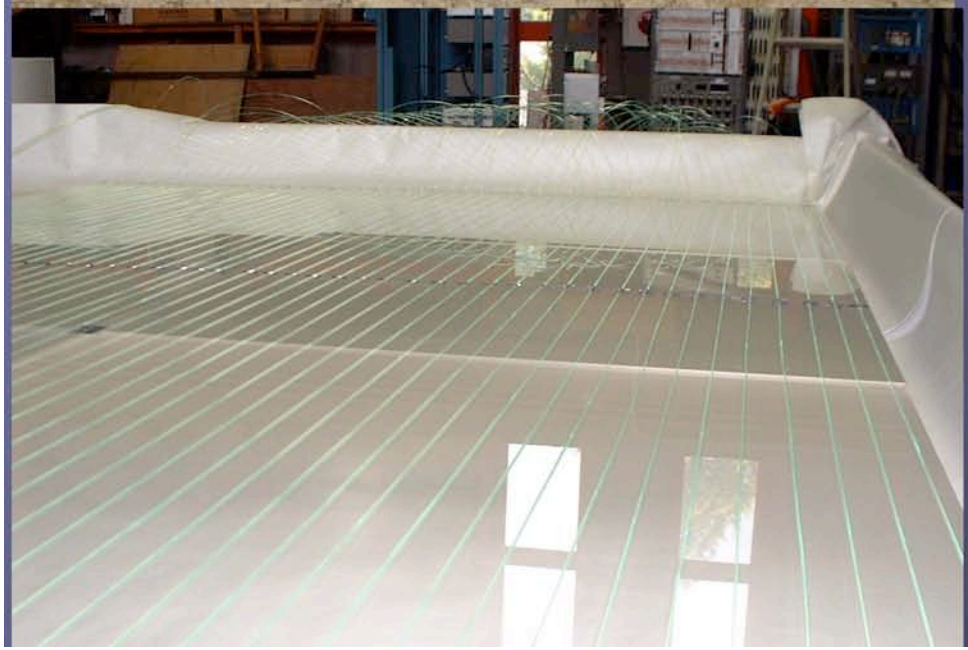
Towards Bright Future

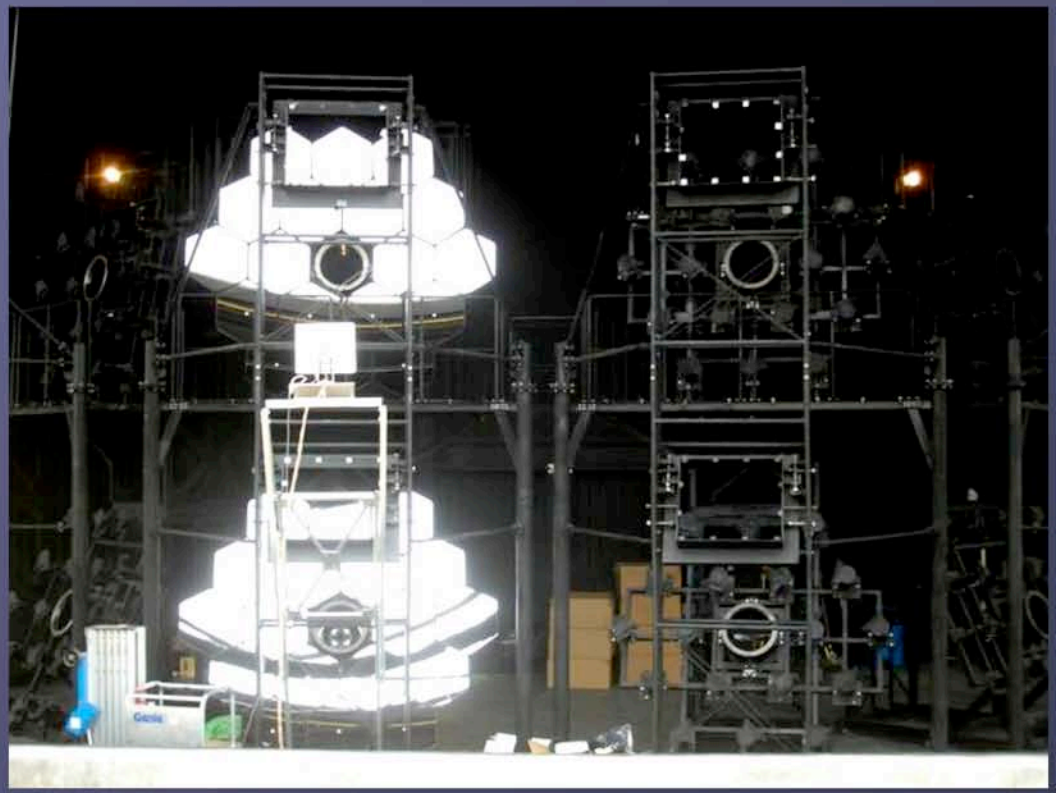
New commissioning Projects, New Projects and R&D

- TA is in commissioning phase
  - Full operation from autumn 2007
  - TALE will follow to extend coverage toward lower energies (Transition from galactic to extragalactic)
- ARGO-YBJ
  - In full operation
  - Moon shadow, Crab, Mrk421 detection
- Auger North (200,000 km2 sr yr at 2014)
- From Space
  - TUS, JEM-EUSO, Super-EUSO
  - ~M km2 sr yr(L)
- R&D for radio detection ➔ H. Falcke's talk
  - LOPES, CODALEMA
  - Looks very promising
- New photodetector
  - SiPM ➔ Improve HEAP experiments
- Air Florescence yield measurements
  - Flash, Airfly
  - Final results will come soon

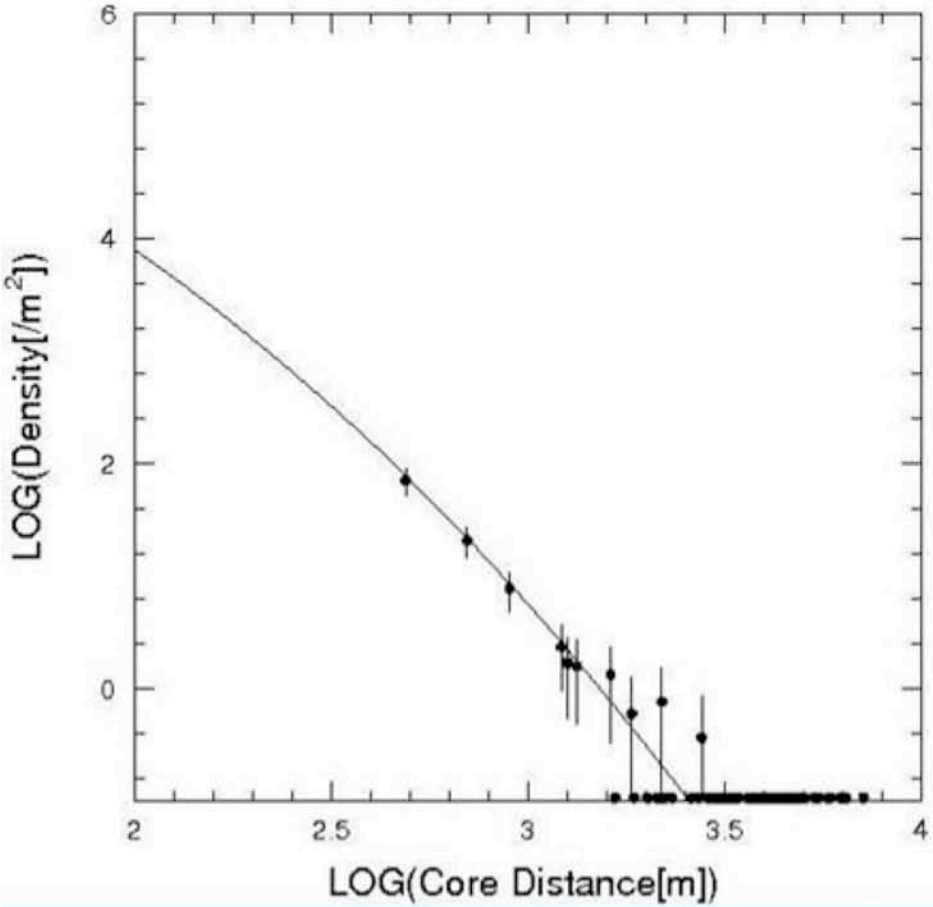

TELESCOPE ARRAY PROJECT
Telescope Array Locations
Millard County in Utah/USA
0 3,000 6,000
Meters
Middle Drum
~512 Counters
AGASA x (7-13)
Delta
Hinckley
Long Ridge
Black Rock Mesa
Route 257
TA Locations
Communication Towers
Fluorescence Locations
Central Laser Facility
Streams
Lakes
TALE
Low Energy Extension
3 x Fluorescence Stations
AGASA x (5-12)
University of Utah
April 2004

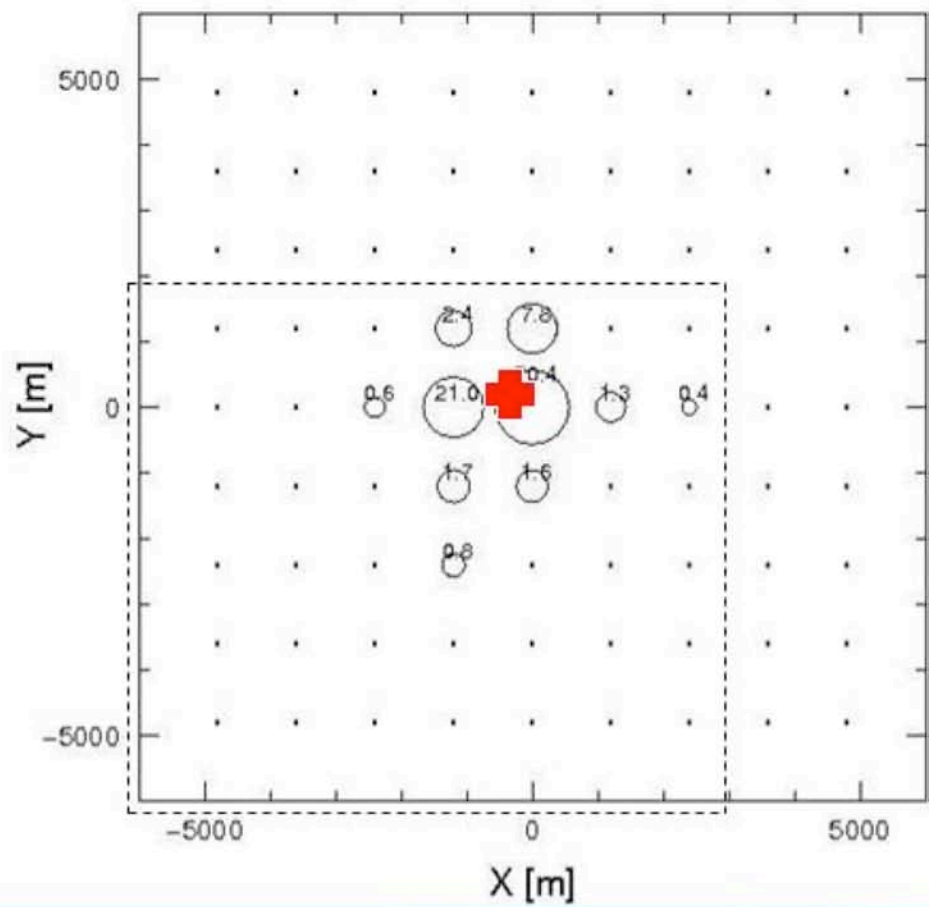
TA Scintillators and Florescence detectors





A shower event recorded by TA-SD





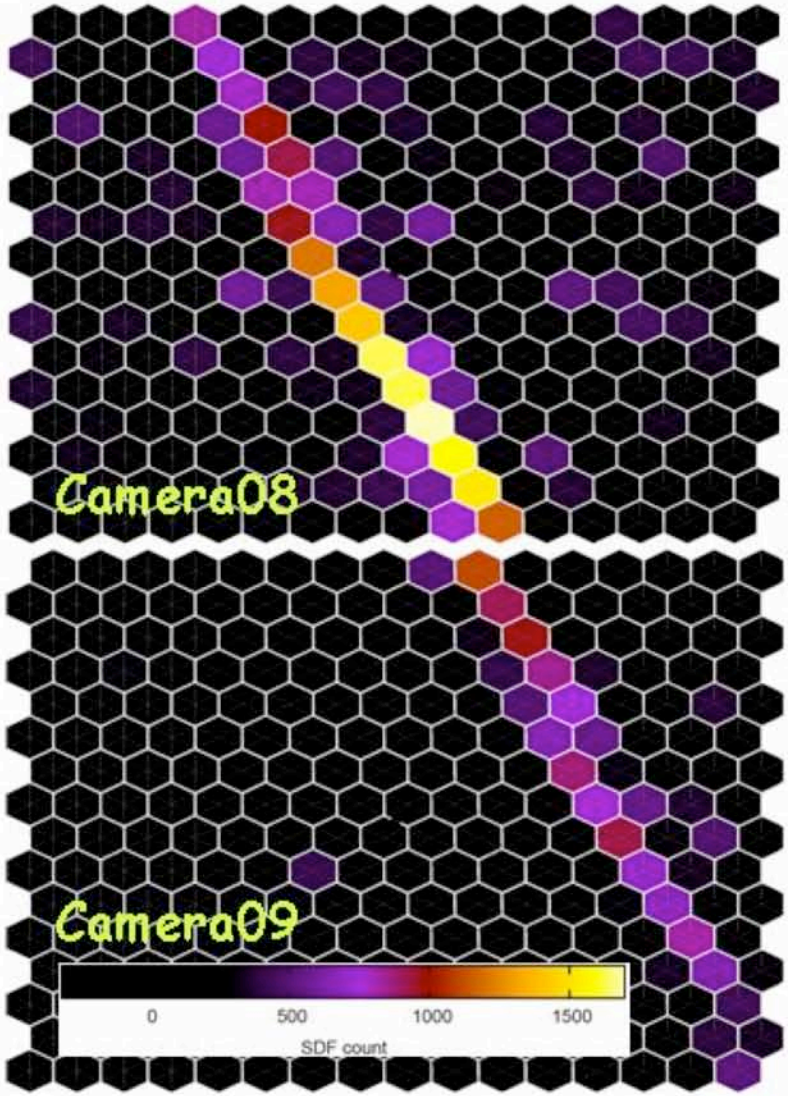
Trigger>3MIPs

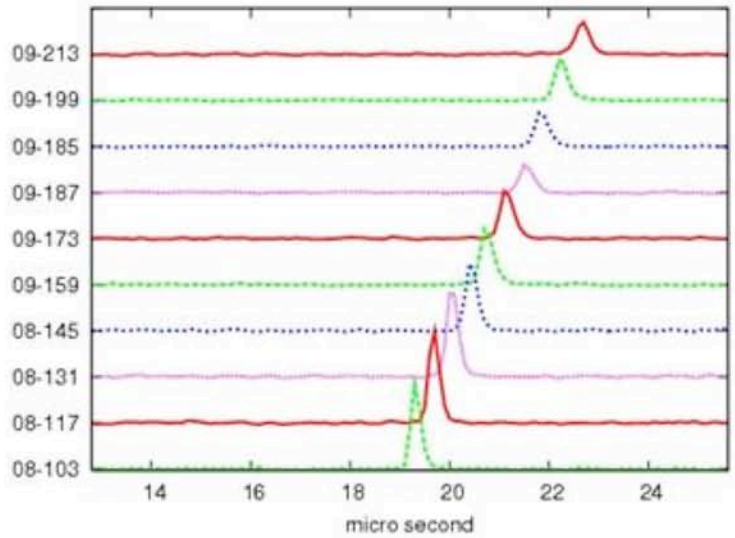
Very preliminary

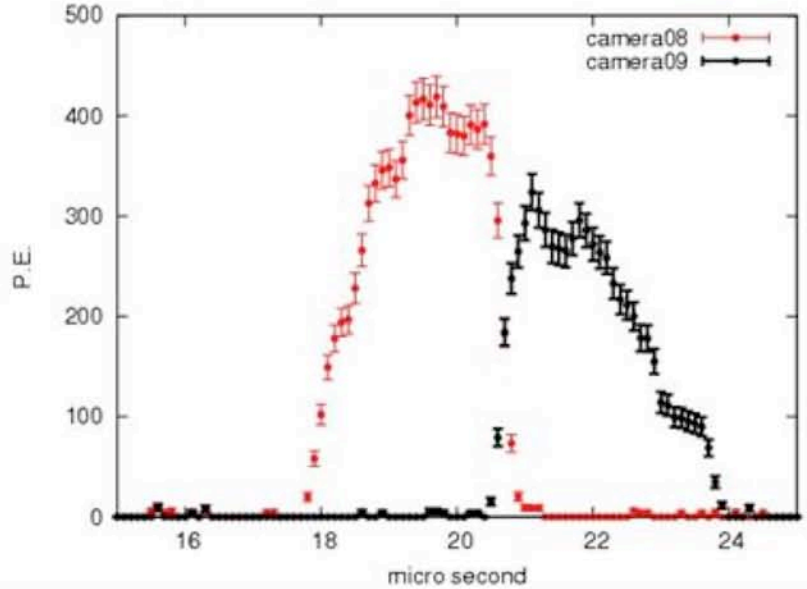
Log(E[eV])=19.1
Zenith=36.3[deg]
Azimuth=241.2[deg]

Example: shower event

June 20, 08:18:21(UTC), trigger ID 0000169





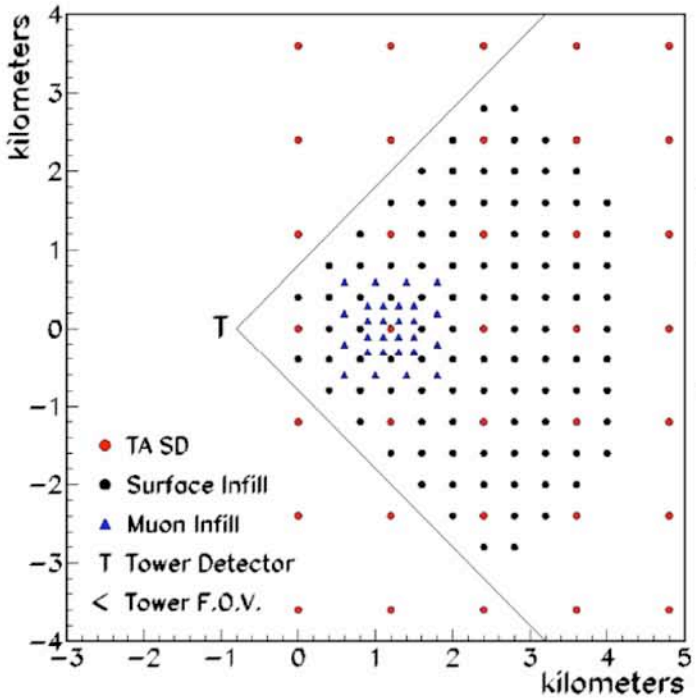


Telescope Array

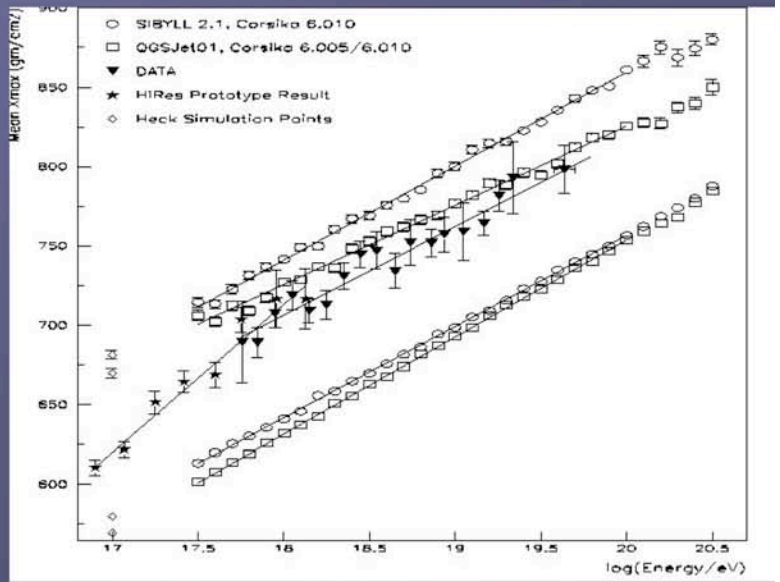
- Balanced SD ~ FD hybrid for UHECRs
- Aperture = AGASA x (12 ~ 23)
- Complimentary to Auger South
- Energy spectrum: by SD and FD independently
  - both are from EM component measurements
- GZK cutoff, Cluster in North ?
- Construction ~95% completed, commissioning phase
- Autumn 2007, Full Data Collection starts.
- Low Energy extension TALE planned.

TALE $10^{16.5}$eV~$10^{18.5}$eV

TALE Infill Array



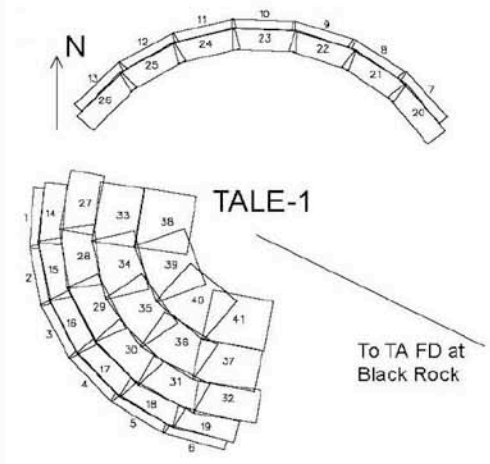
- Standard TA: 1.2 km grid
- Surface Infill: ~100 detectors on 0.4 km grid
- Muon stations: 16 on 0.2 km grid, additional detectors on larger grid



Galactic/Extragalactic Transition:
HiRes/MIA hybrid experiment, and HiRes Stereo, results show transition from heavier to lighter composition, complete by about 1018 eV.

TALE Florescence detector and Muon detector

Tower Fluorescence Detector:



3 additional rings of mirrors, 31° – 72°

Each mirror 3x HiRes mirror area

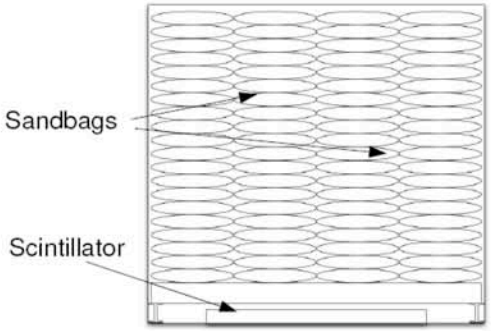
(See D. Bergman poster)

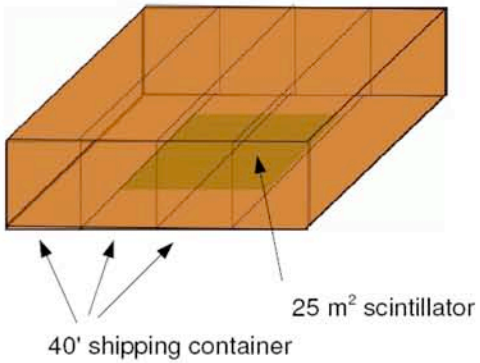
Left: TALE-1 site, showing 3rd 4th and 5th rings

Right: Prototype 4th ring detector

TALE μ Prototype

- "Sand Box" muon detectors
- Shield 25 m^2 scintillator from EAS electromagnetics





See also J. Belz poster

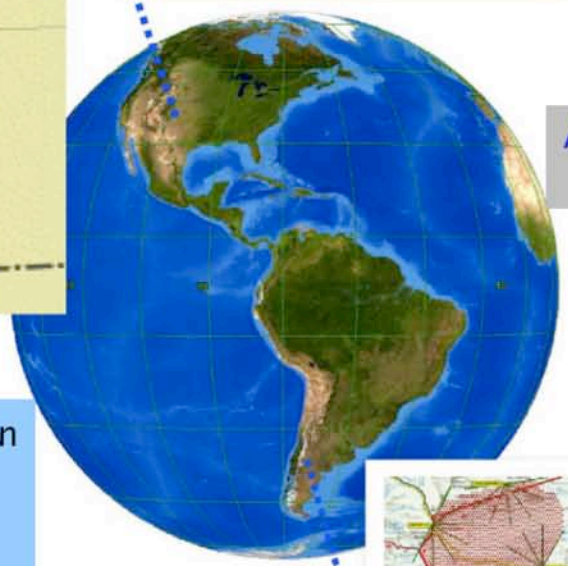
Auger North

The Pierre Auger Observatory – 2 Sites

Need for 2 sites realized since beginning of project

Northern Site: Colorado

- Retain features & functionality of Southern Site
  - Hybrid detection & energy calibration
  - Water Cherenkov surface array
    - 4000 stations, 10,370 km^2
    - Square mile grid



Altitude and latitude are similar

Southern and Northern sites are shown at the same scale

Southern Site: Mendoza

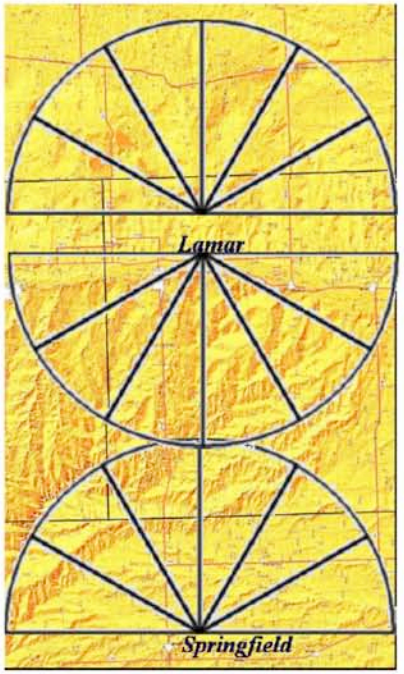
- Hybrid detection & energy calibration
- Water Cherenkov surface array
  - 1600 stations, 3000 km^2
  - 1.5 km triangular grid
- Completion end 2007
- Science flowing – 38 papers here

Auger South upgraded by HEAT & AMIGA

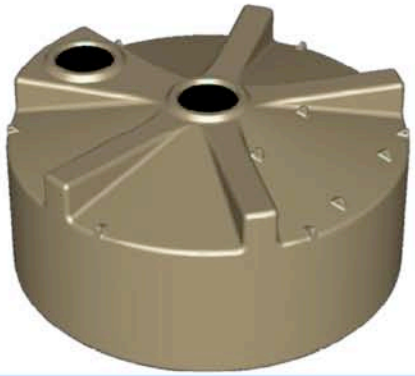
Auger North

FD Layout

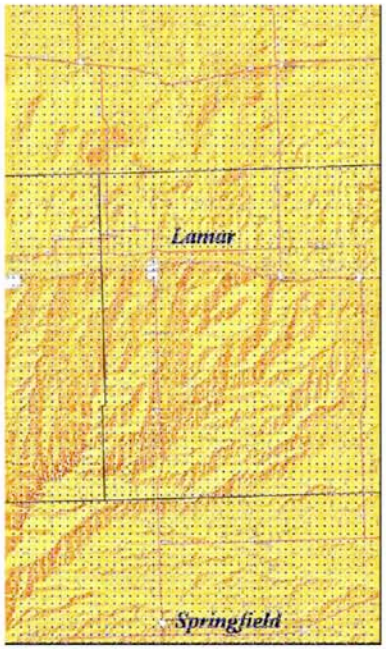
- FD layout optimized to provide maximum hybrid coverage per telescope
- 18 30° field of view telescopes organized in 3 eyes
- Telescope design similar to Auger South design, incorporating HEAT (paper #65) enhancement updates (new electronics, cost optimized enclosure)



Surface Array



- Tank with internal rotationally molded polyethylene foam insulation
  - Northern site is colder
- Central hatch for single large PMT
  - Cost reduction refinement
- 2nd hatch for assembly access



Dots indicate positions of 4032 tanks

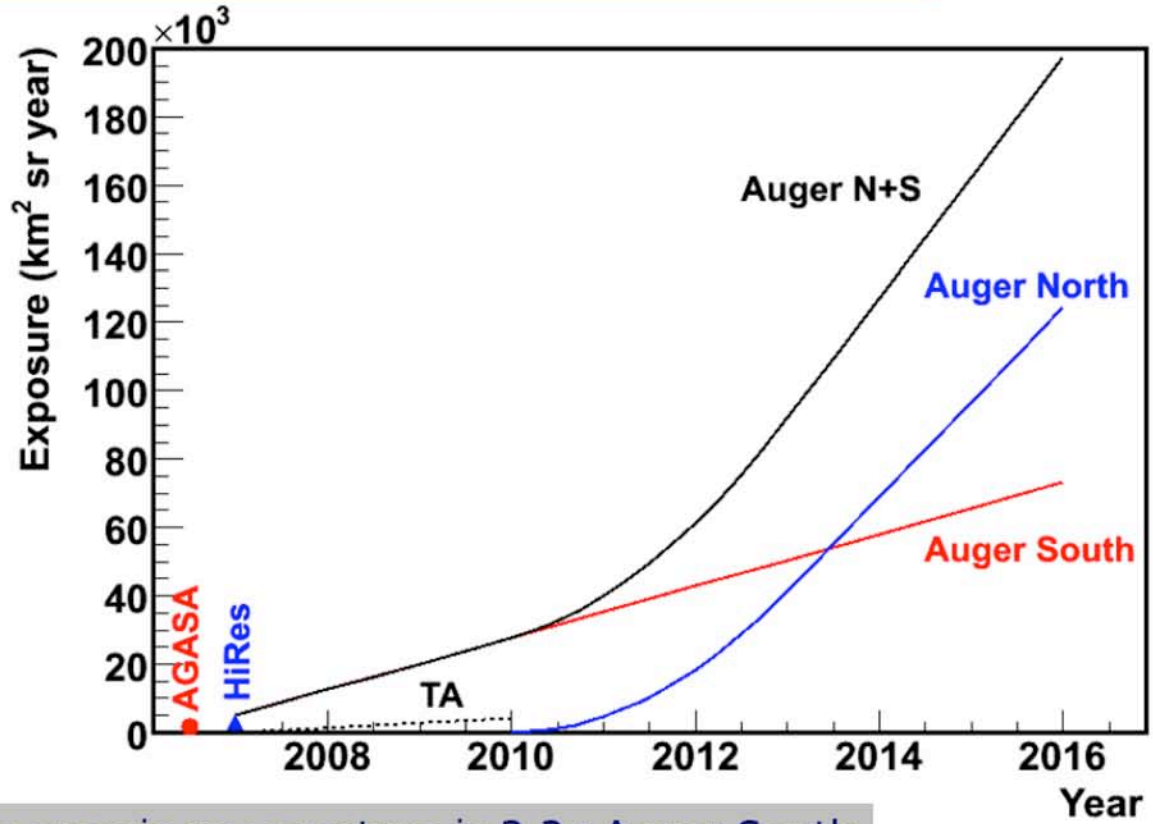
Auger North

PIERRE AUGER OBSERVATORY

Exposure

- It is time to design the Northern Site
- Build upon lessons learned in the South

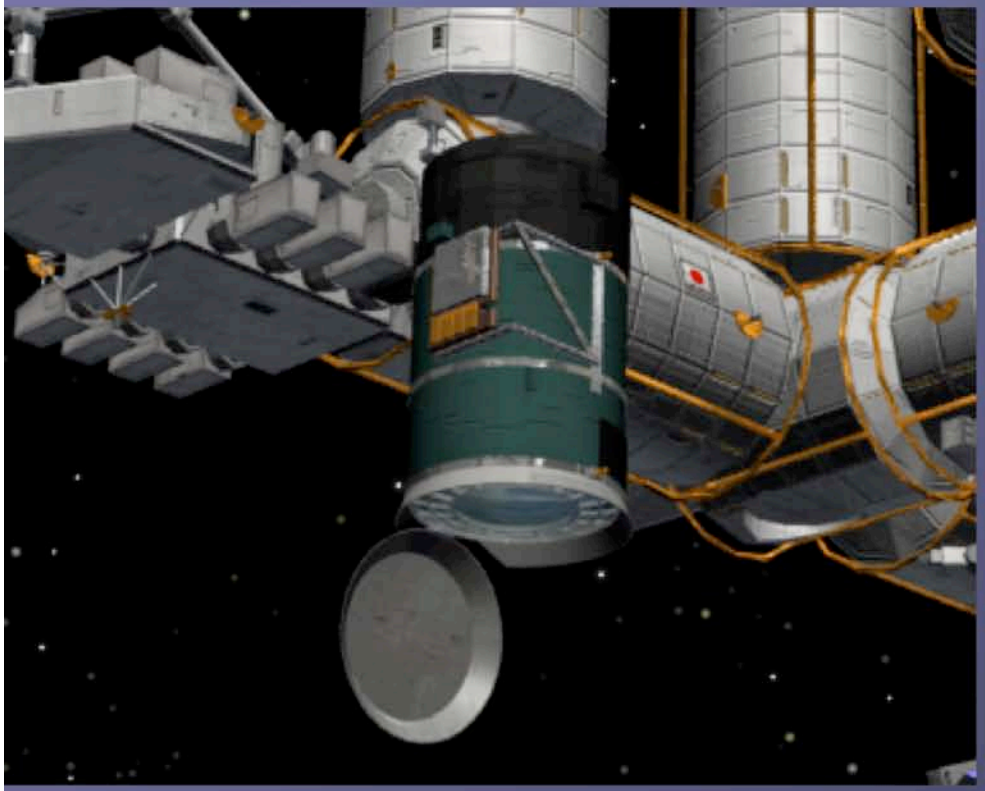
- Assumes:
  - Auger South finished end of 2007
  - Auger North construction starts 2009
  - Auger North construction finished 2012



- Auger North cosmic ray aperture is 3.3x Auger South
- Auger North neutrino aperture 2x Auger South

JEM-EUSO Telescope on ISS

JEM-EUSO Telescope will be attached to Exposure Facility of Japanese Experiment Module (JEM/EF) of ISS in 2013

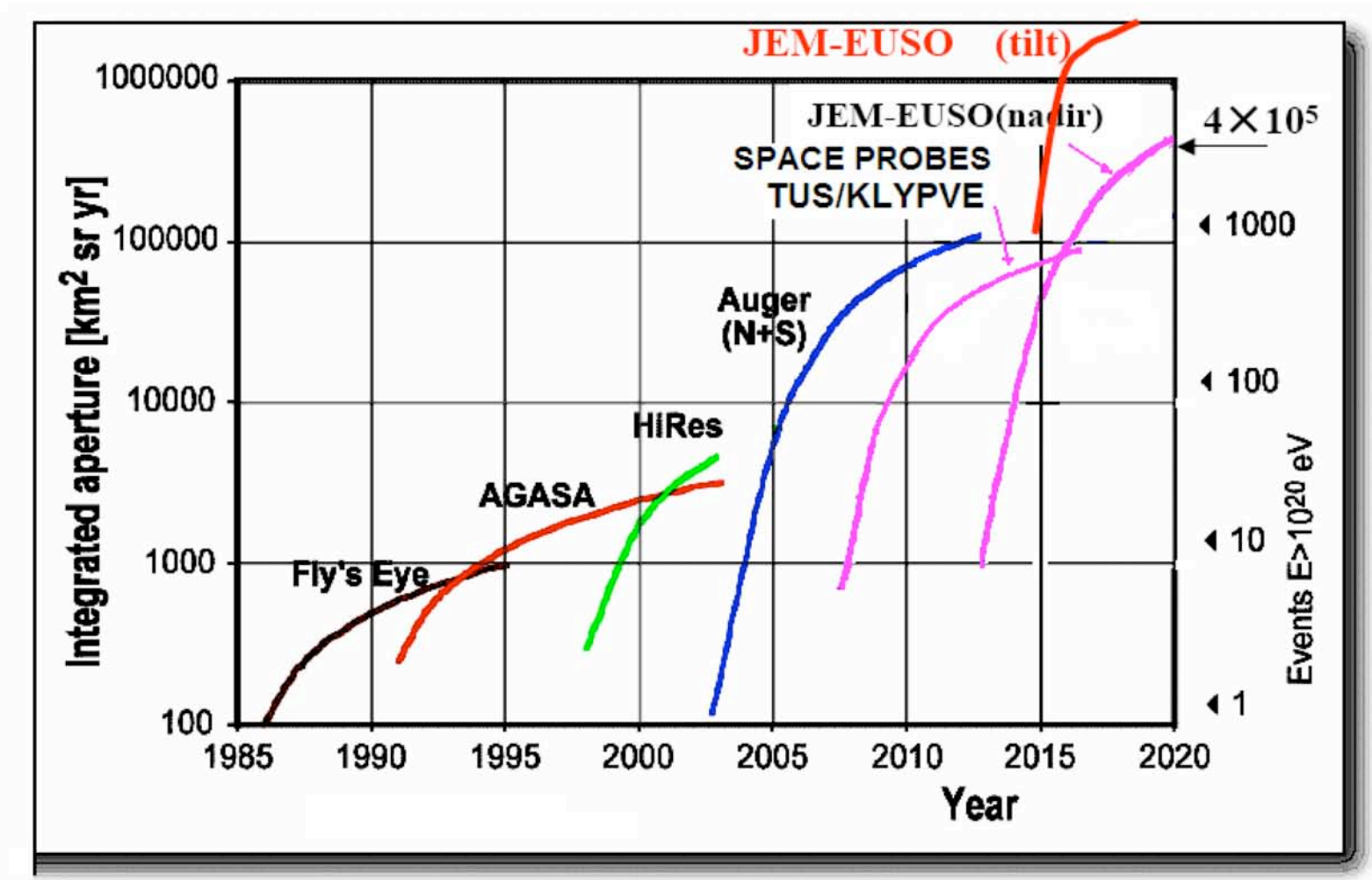


Vertical Mode

Tilted Mode

Larger effective area (x5) with ~35°tilt

Progress of the study of EECR expected in the near future:

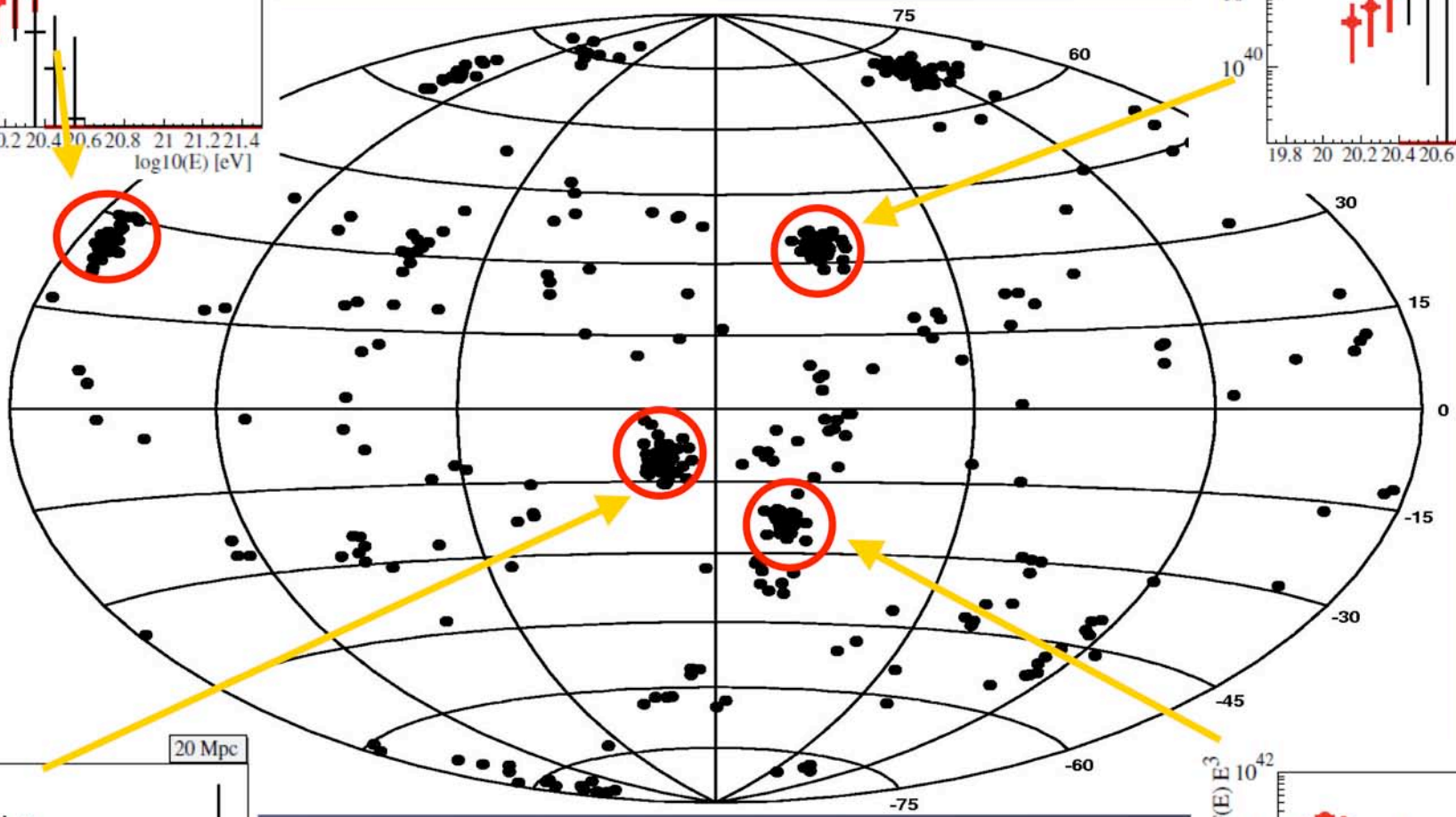


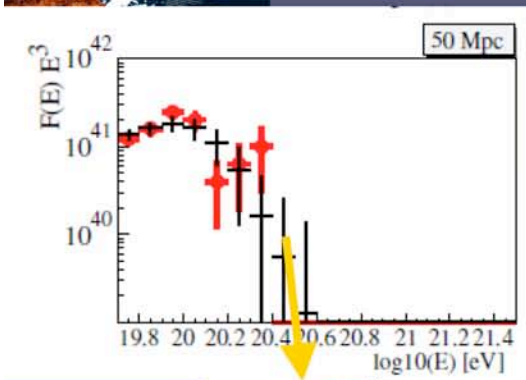
by Boris Khrenov 2006

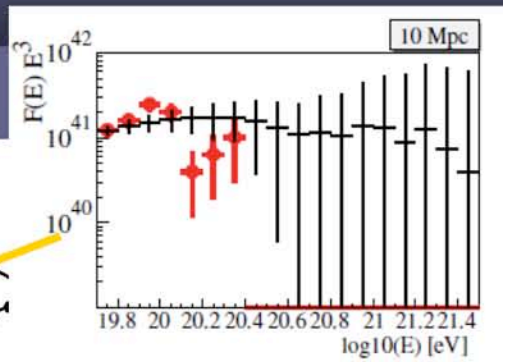
JEM-EUSO ~1M km^2 sr yr, >1000events above 6x10^{19}eV

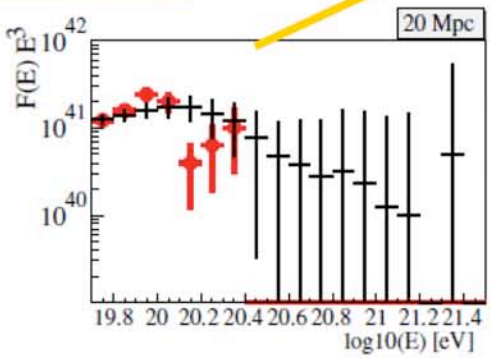
Particle Astronomy

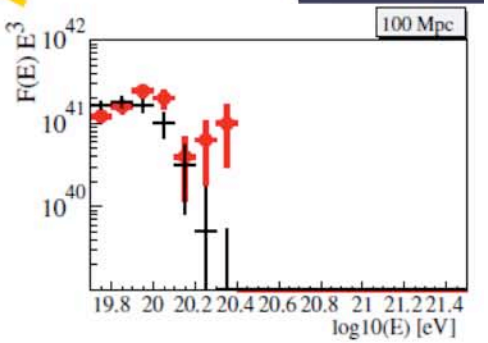
If we get >1,000 events,











- 1,000 events : $E>7\times10^{19}$eV
- Several dozen clusters are expected
- All sky coverage

Summary

- Energy Spectrum of UHECRs
  - HiRes and Auger saw the steepening of the spectrum above 4×10^{19}eV with 5 sigma and 6 sigma
  - GZK cutoff?
- Chemical compostion of UHECRs
  - Auger Xmax suggests mixed composition
  - HiRes claimed proton dominance above10^{18}eV
- Anisotropies
  - No galactic center excess was found with Auger around 10^{18}eV
  - HiRes: deficit in the direction of anti-galactic center
  - Small scale anisotropy was not found with Auger
    - The effect of galactic magnetic field must be considered
  - Hint of medium scale anisotropy with Auger
  - World data also shows medium scale anisotropy
    - Relating with large scale structure?

Many open questions are popped up

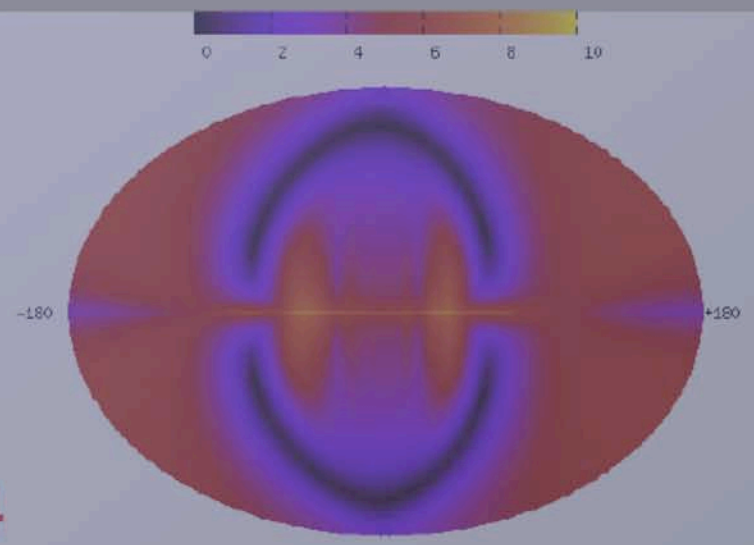
- Energy scale problem
  - 1.2~1.5 factor difference between Auger and other experiments
  - FD energy (FY) ←→ SD energy (MC-Calibration energy)
- What is ankle?
  - Pair creation dip → V.Berezinsky; Beautiful results
  - Transition from galactic to extragalactic
- Chemical composition at UHE
  - Proton dominance ? → support pair creation dip hypothesis
  - Mixed composition → photodisintegration energy (Eth ~A) → small elongation ratio D10 → Support Auger Xmax?
- Break in energy spectrum at 4×10^{19}eV
  - GZK Cutoff?
  - Acceleration limit?
  - Drop off of lighter elements?
- Medium scale anisotropy
  - Relating with large scale structure?
  - Deflected images of point sources (North-South asymmetry)

Thanks

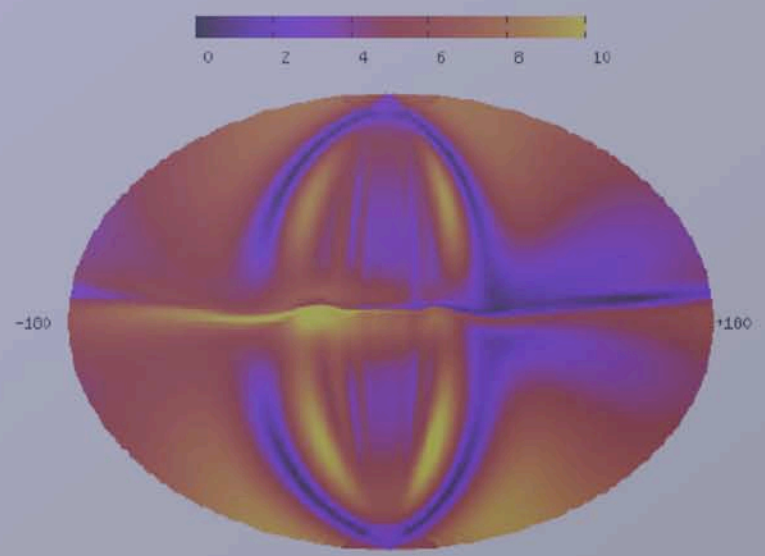
Uncertainty of GMF models

Deflection in degrees in galactic magnetic field models for protons with energy 4 x10^{19} eV

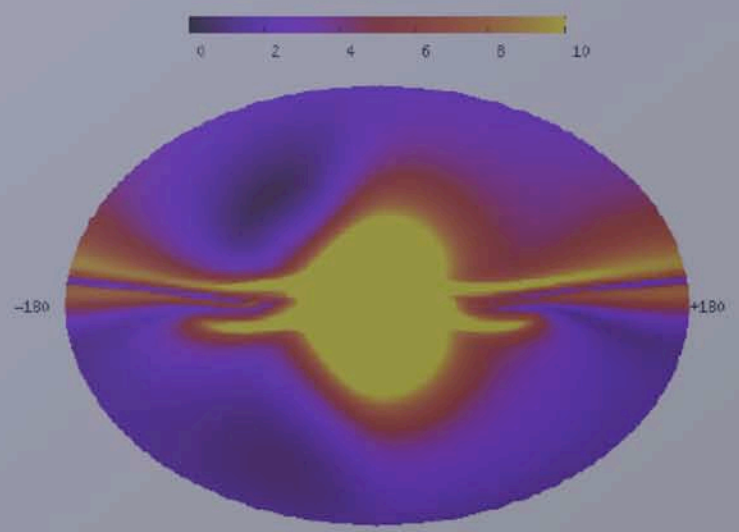
M.Kachelriess et al. astro-ph/0510444



TT model

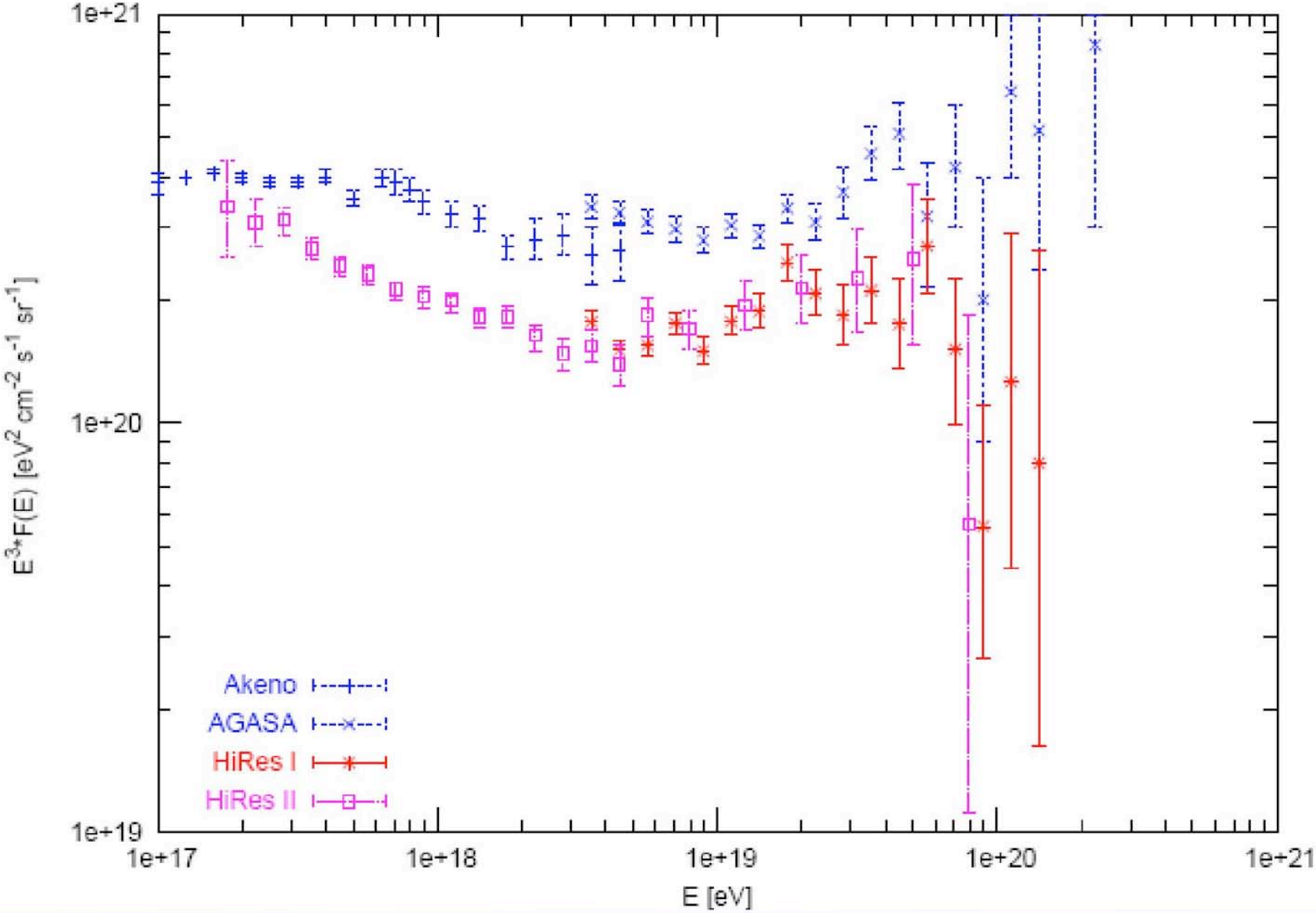


HMR model

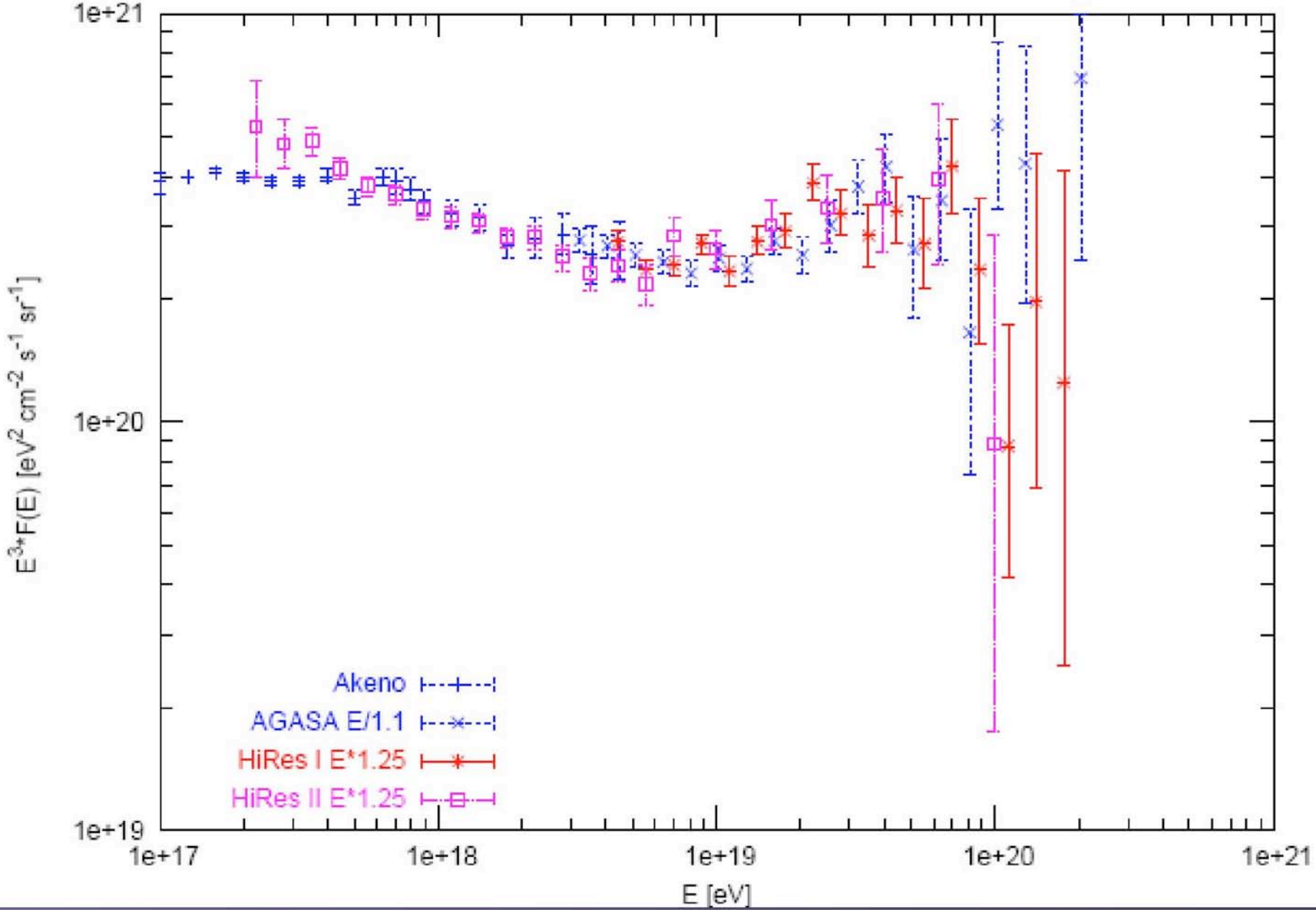


PS model

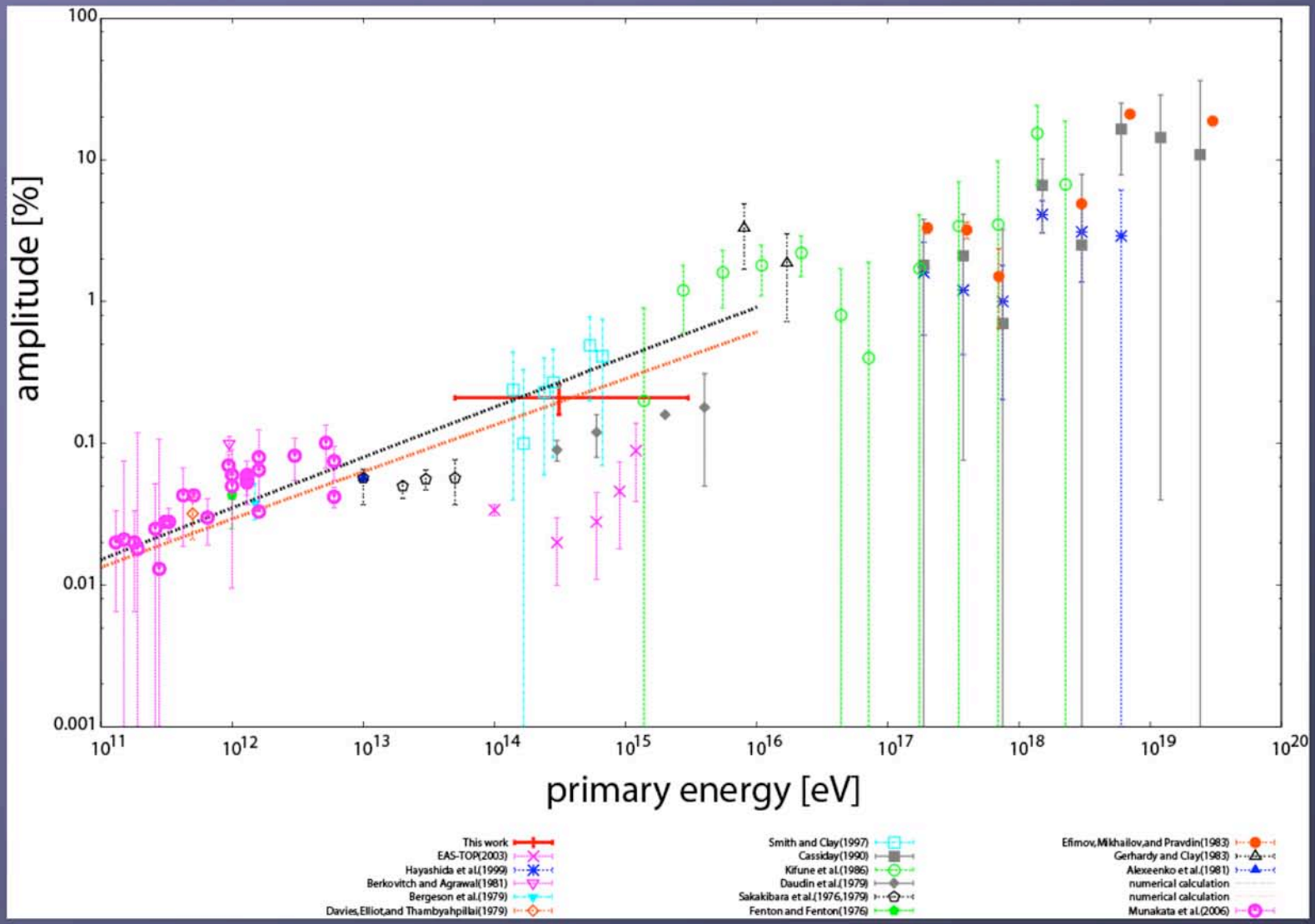
Global energy rescaling



Global energy rescaling



Anisotropy measurement by LAAS
A.Iyono et al.



Anisotropy measurement by LAAS
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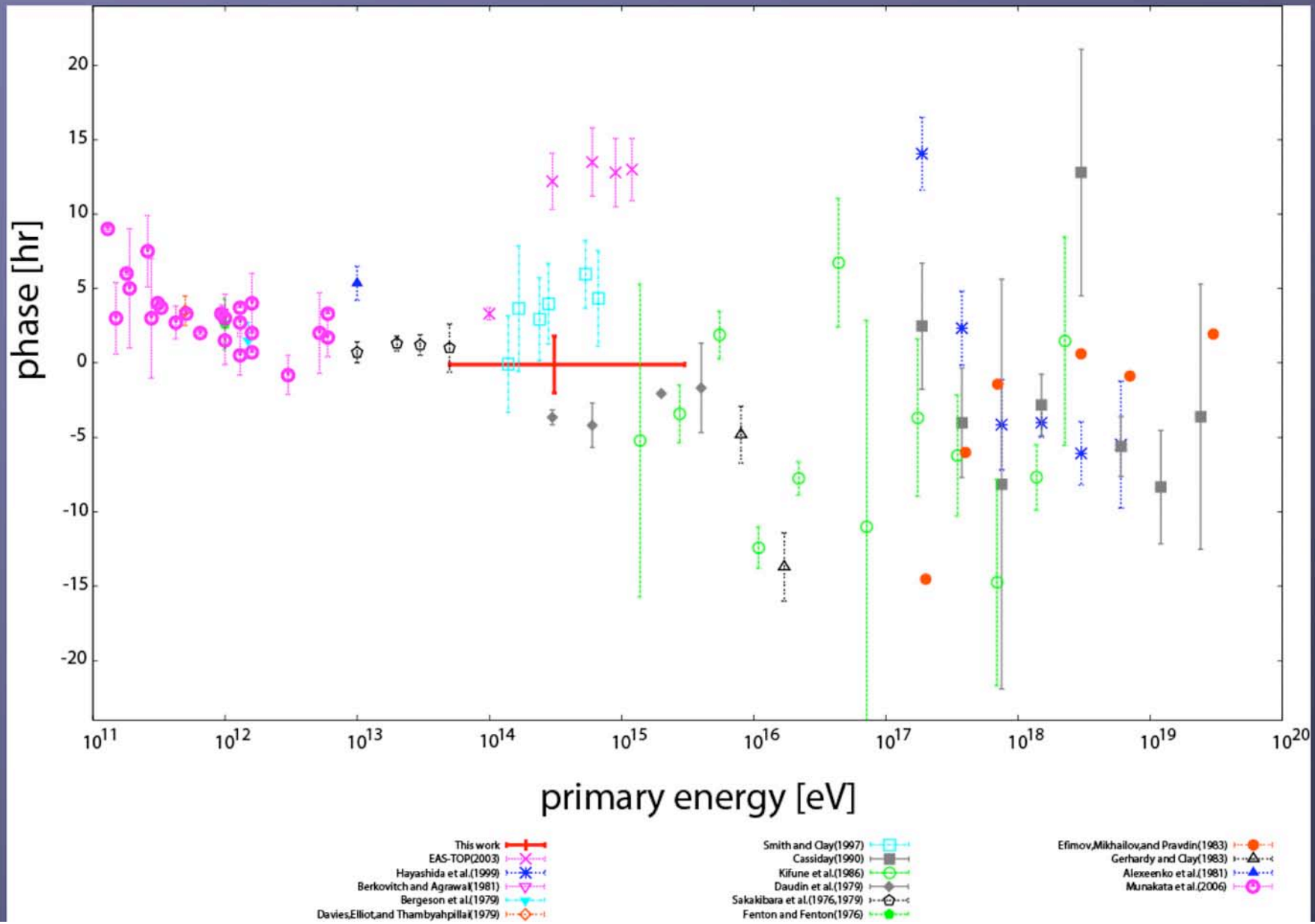
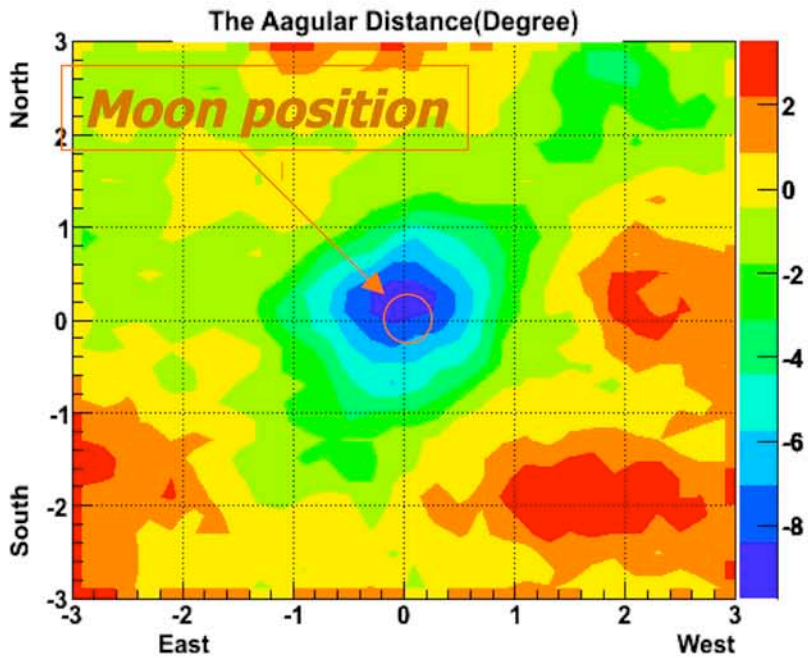
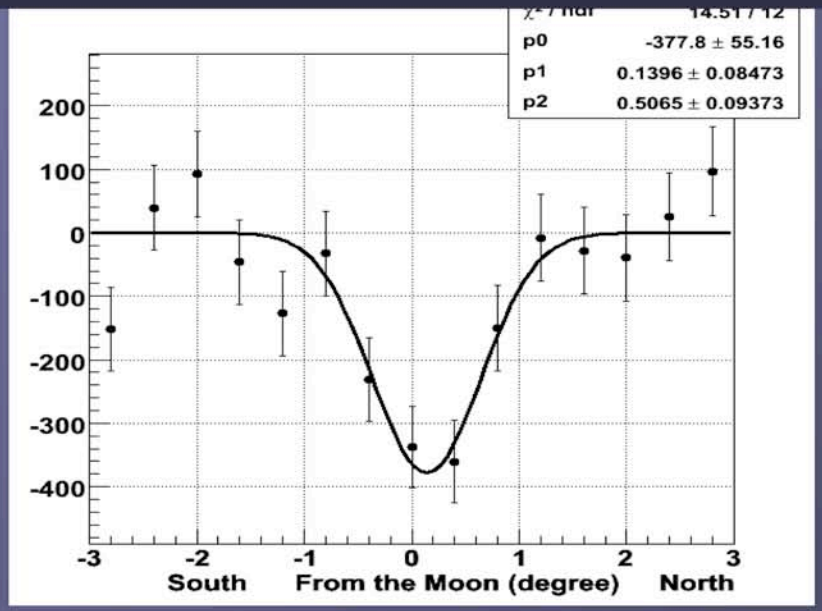
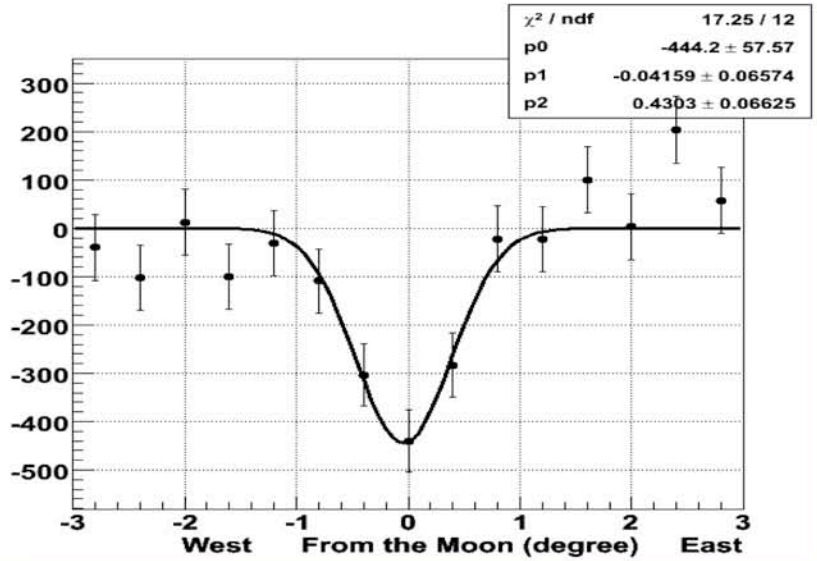


ARGO-YBJ: Moon Shadow

-10 sigma in 558hrs, $\triangle\theta$= 0.51 degrees







- *The max significance:* ***~ 10*** *standard deviations, shifted by* ***0.04*** *toward the West and* ***0.14*** *toward the North with respect to the nominal Moon position.*
- *the distribution of the observed deficit events projected along the W-E and N-S axes. The Gauss width:*

σ_{E-W}= 0.43±0.07, σ_{N-S}= 0.51 ±0.09.

TUS Mission Launched 2009-2010

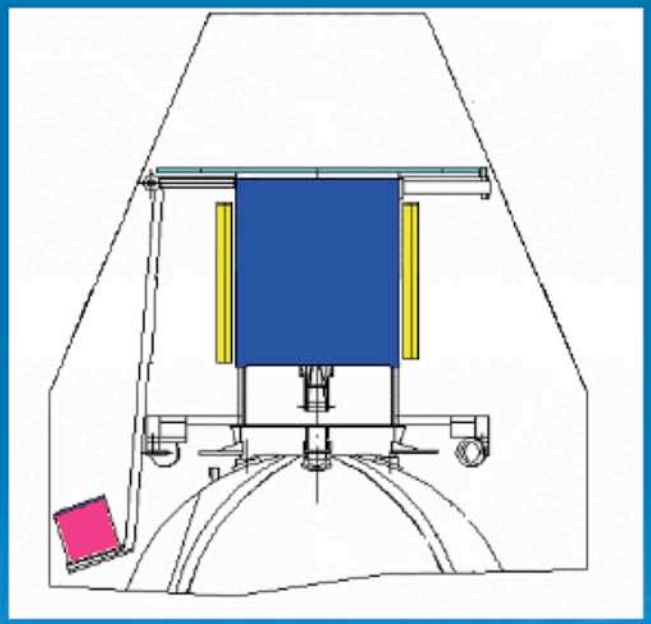
The TUS detector will be launched on a new platform separated from the main body of the "Foton" satellite (RosCosmos project, Samara enterprise, launching in 2009-2010).

Satellite limits for the scientific instrument are:

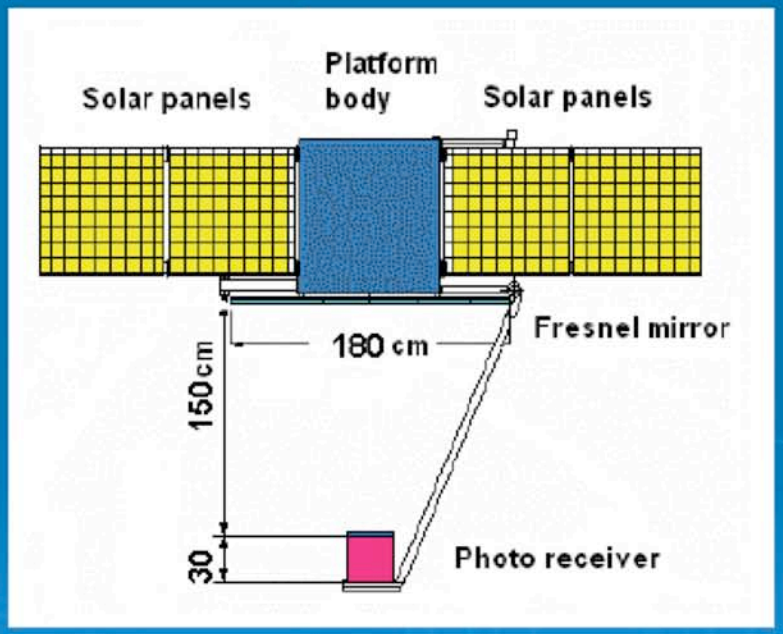
mass 60 kg, electric power 60 Wt, orientation to nadir ±3° .

Preliminary TUS design:

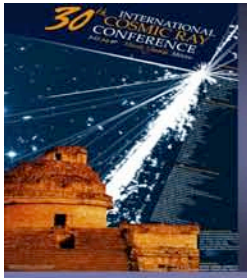
1- in the transportation mode,



2 – in operation.



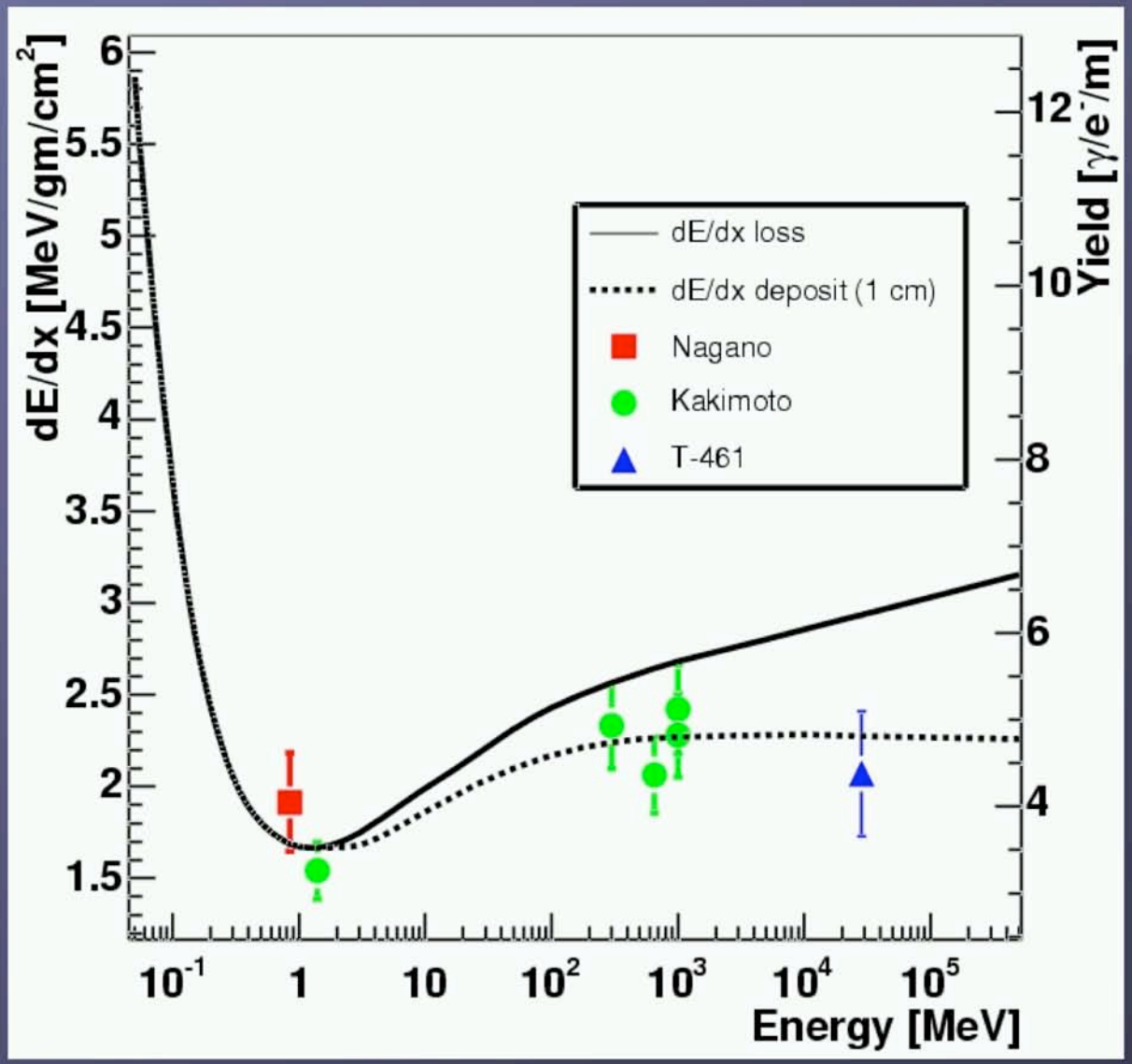
Mirror area is up to 2 m^2, pixels cover 4000 km^2 of the atmosphere (orbit height 400 km).


30th INTERNATIONAL
COSMIC RAY
CONFERENCE

Flash

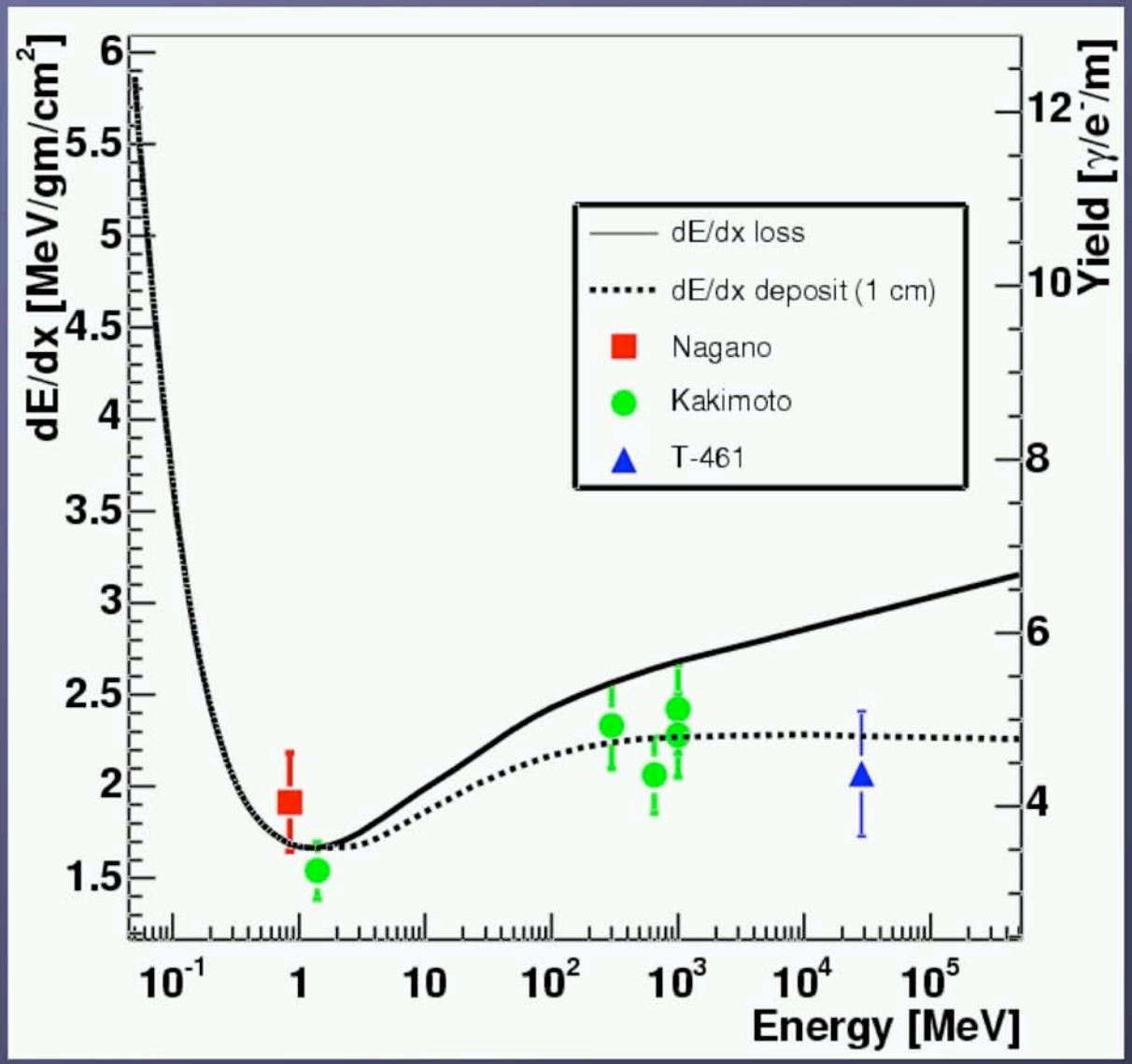
- Sampling of Previous Results: Kakimoto *et al*., Nagano *et al*., and T461 (FLASH test run).
- Ratio of fit to (Kakimoto, Nagano, and T461) to fit to Kakimoto

  = 1.00 ± 0.06
- FLASH result will be shown at the air fluorescence conference at El Escorial in Sept.



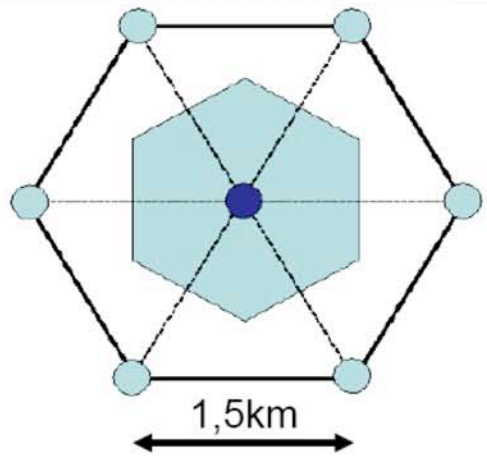
Previous Measurement of the Absolute Fluorescence Yield

- Sampling of Previous Results: Kakimoto *et al*., Nagano *et al*., and T461 (FLASH test run).
- Ratio of fit to (Kakimoto, Nagano, and T461) to fit to Kakimoto
  = 1.00 ± 0.06
- FLASH result will be shown at the air fluorescence conference at El Escorial in Sept.



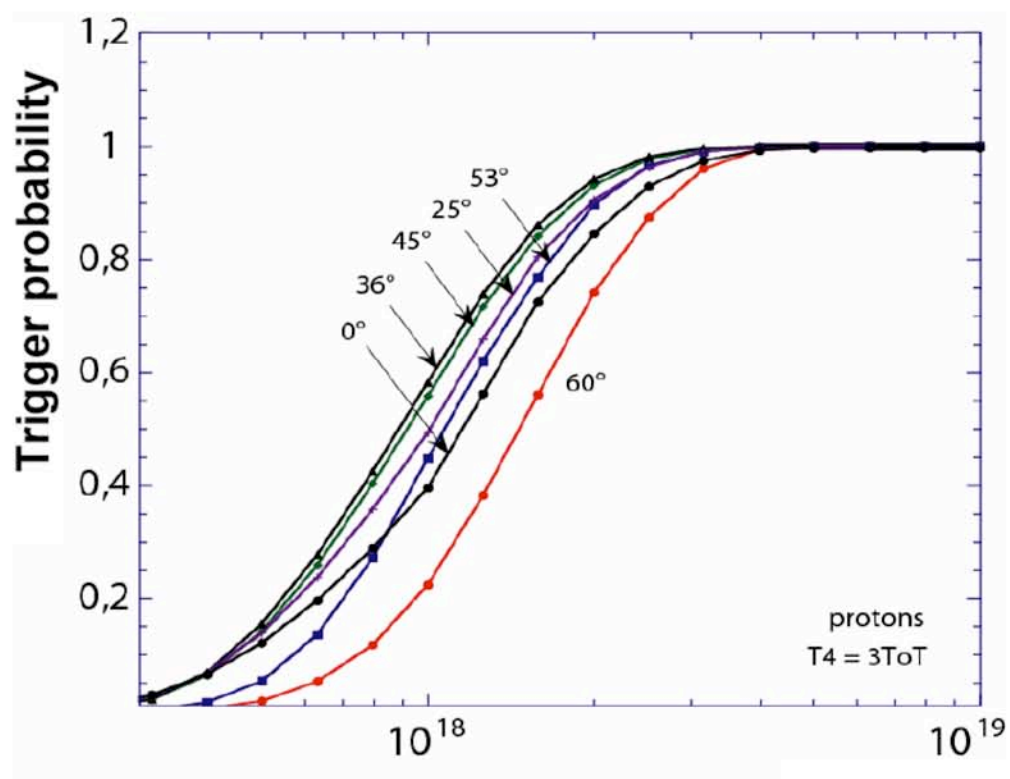
Auger: Event selection for Energy spectrum study

- **Physics trigger:**
  3 stations (equilateral △, ToTs)
- **Full efficiency:**
  E ~ 3×10^{18} eV
- **Quality trigger:**
  Hottest tank surrounded by 6 active stations
- **[0,60°]**
- **1.1.2004 – 28.2.2007**
- **Exposure: 5165 km² sr yr**
  (uncertainty 3%)



Aperture:
# of elementary cells;
A_C=1.95 km²

Exposure:
Integr. of array evolution



Auger SD Energy Spectrum Residual plot