The Pierre Auger Observatory: updated results

F. Arqueros *for the Pierre Auger collaboration*
Universidad Complutense de Madrid
Madrid
Spain

PHYSICS OF THE STANDARD MODEL OF THE UNIVERSE
Colegio de España, Cité Internationale Universitaire de Paris
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OUTLINE

- Ultra high energy cosmic rays. Scientific interest. Measurement techniques

- The Pierre Auger Observatory. The hybrid design concept

- Updated results:
  - The energy spectrum
  - Composition
  - Upper limits on photon flux (>10^{18} eV)
  - Correlation with nearby extragalactic objects

- The future: Auger North, low energy extensions

Scientific interest of UHECR ($E > 5\times10^{18}$ eV)

- John Linsley detects for the first time in 1962 (Volcano Ranch) an extensive air shower initiated by a cosmic ray of energy $\approx 10^{20}$ eV.

- Greisen, and Zatsepin and Kuz'min (1966): Cosmic background radiation (CMBR) makes the Universe opaque for UHECRs.

$$\gamma\, p \rightarrow \Delta^{+} \rightarrow \pi^{0}\, p$$

Attenuation length < 50 Mpc for $E_p > 10^{20}$ eV

Implications:

a) Universal origin of UHECRs $\Rightarrow$ GZK cut expected in the energy spectrum at $E \approx 5\times10^{19}$ eV.

b) UHECRs with $E > E_{GZK}$ would come from (cosmologically) nearby sources $\Rightarrow$ Magnetic fields not sufficient for a significant angular deviation $\Rightarrow$ UHECRs sources could be located $\Rightarrow$

UHECR Astronomy ?

The sources

Bottom-up:

- Astrophysical scenarios

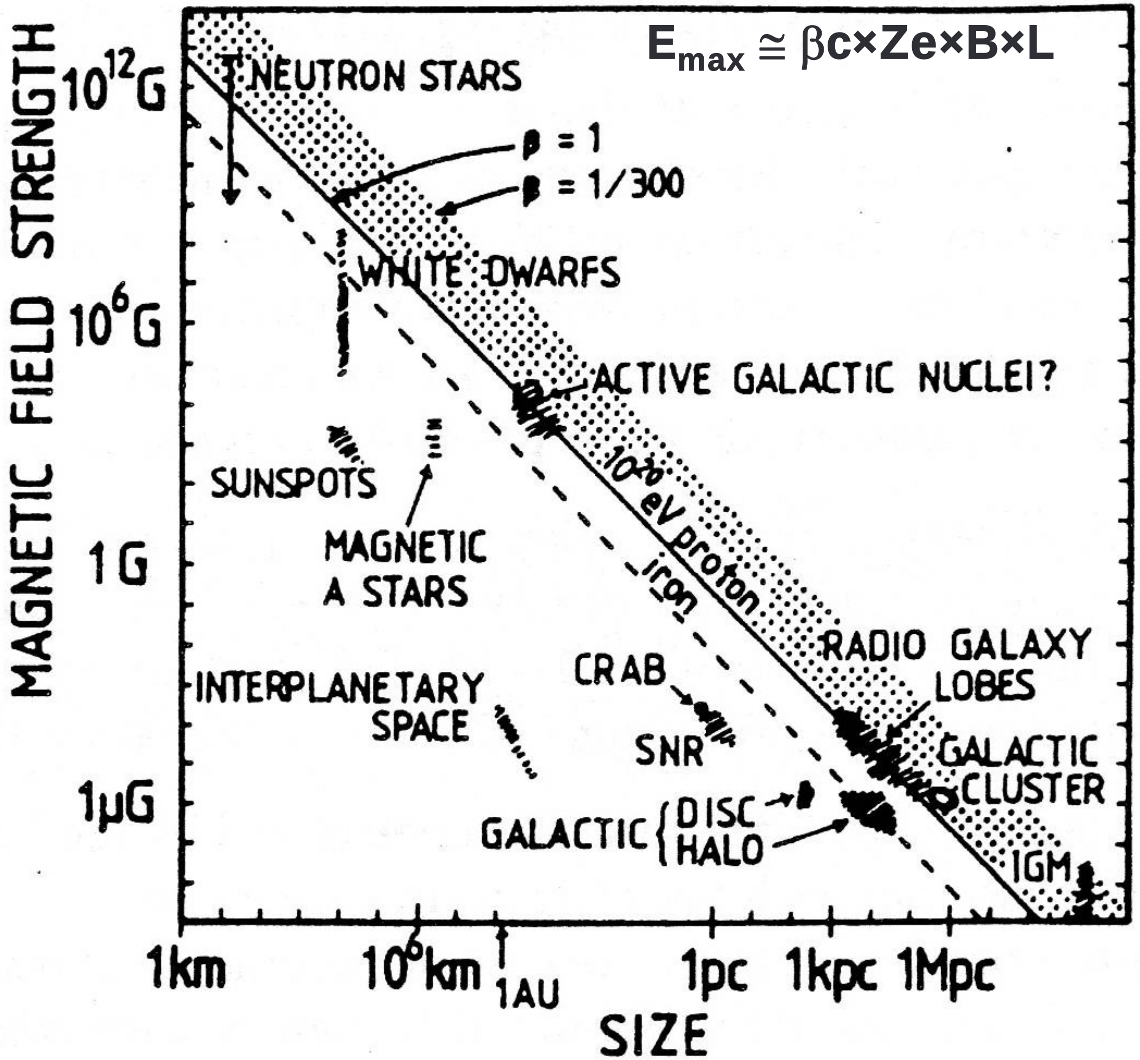
Top-down:

- Super heavy dark matter
- Topological defects
- Z-bursts

- Avoid the GZK cut
- Predict an intense flux of UHE photons

Bottom-up theories: Astrophysical scenarios

The Hillas plot



Objects below the diagonal lines cannot accelerate particles to 10^{20} eV

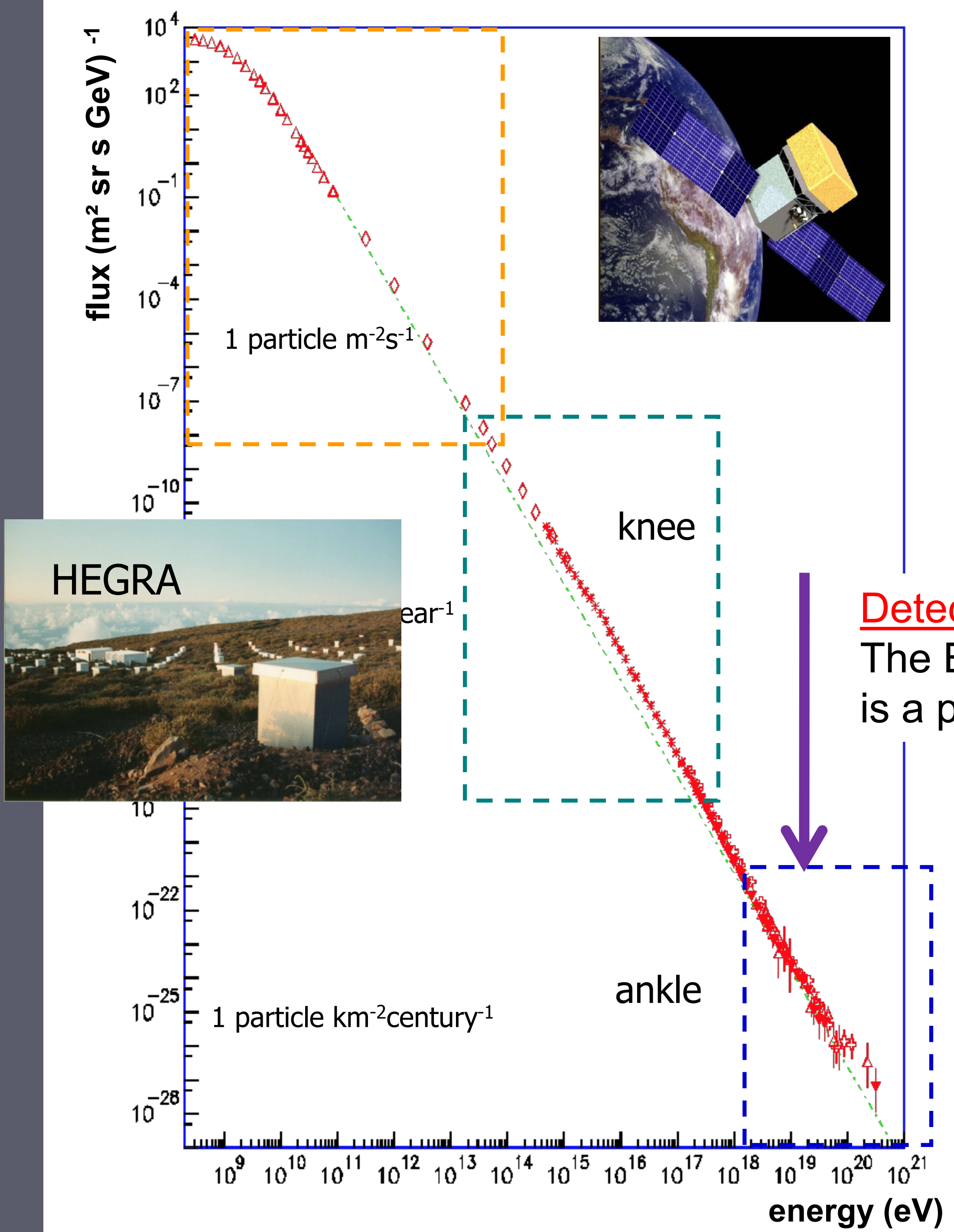
Measurement techniques

Principle:

Reconstruction of the extensive air shower initiated by the cosmic ray

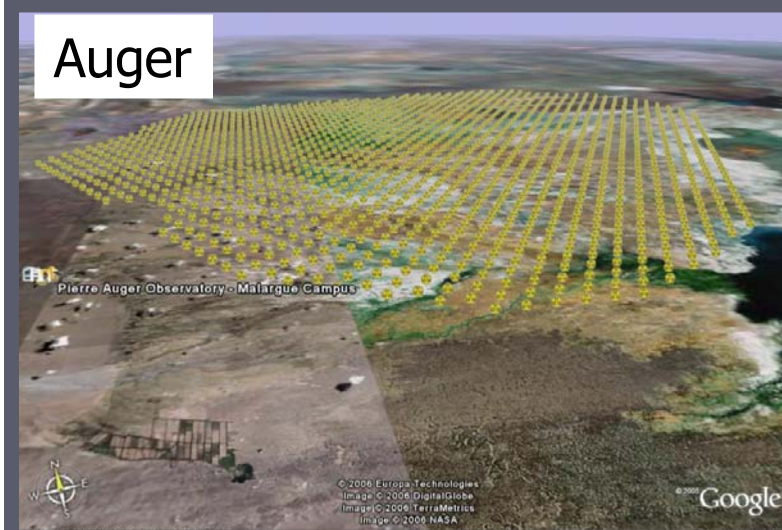
Techniques:

- Arrays of surface detectors for the registration of the shower tail
  - AGASA
  - Pierre Auger Observatory
- Fluorescence telescopes for the registration of the longitudinal development of the air shower.
  - HiRes
  - Pierre Auger Observatory



Detector at ground

The Earth atmosphere is a part of the detector



The cosmic ray develops an atmospheric shower which can be registered by a ground detector

AGASA vs HiRes

Controversial results

Experiment	Technique	Results
AGASA	Surface detector	Super-GZK events Excess near the galactic center
HiRes	Fluorescence telescopes	Spectrum compatible with GZK cut Isotropy

Very low statistics but also
different techniques subjected to different systematic uncertainties

Pierre Auger Observatory:

- Hybrid detector
- Much larger aperture $\Rightarrow$ Much larger statistics

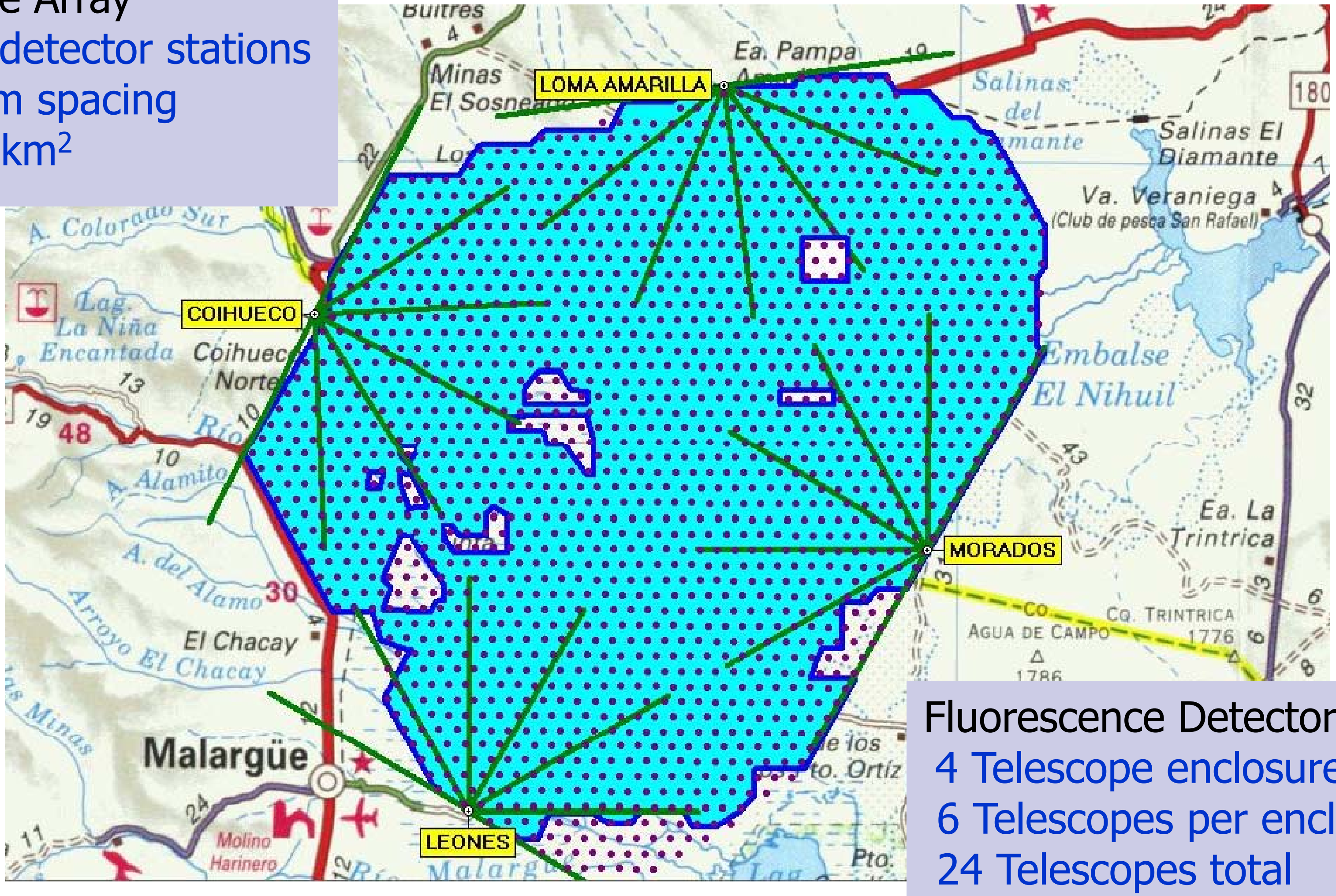
The Pierre Auger Observatory

Auger North
Colorado (USA)
Advanced state of development

Auger South
Mendoza (Argentina)
Complete and fully operative

The South Observatory

Surface Array
- 1660 detector stations
- 1.5 km spacing
- 3000 km²

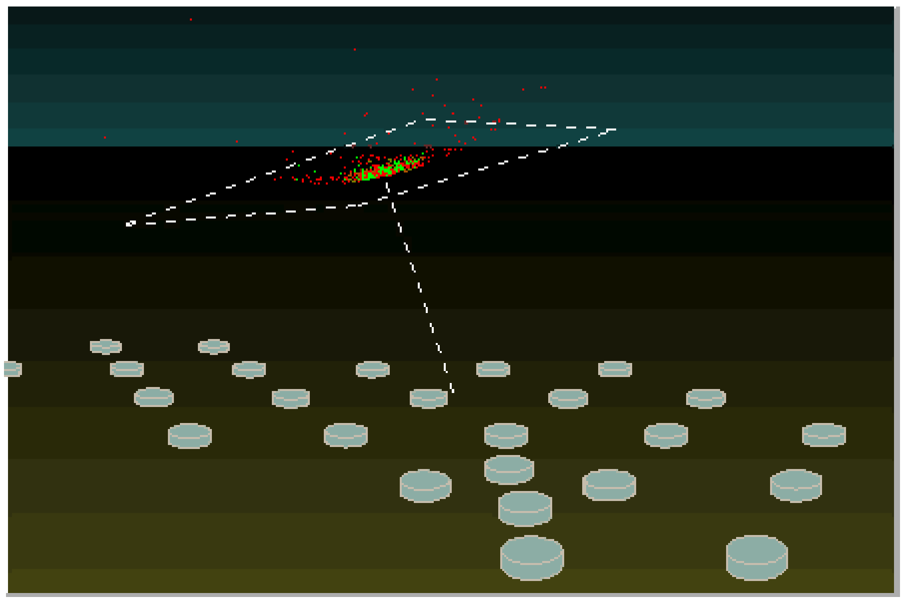


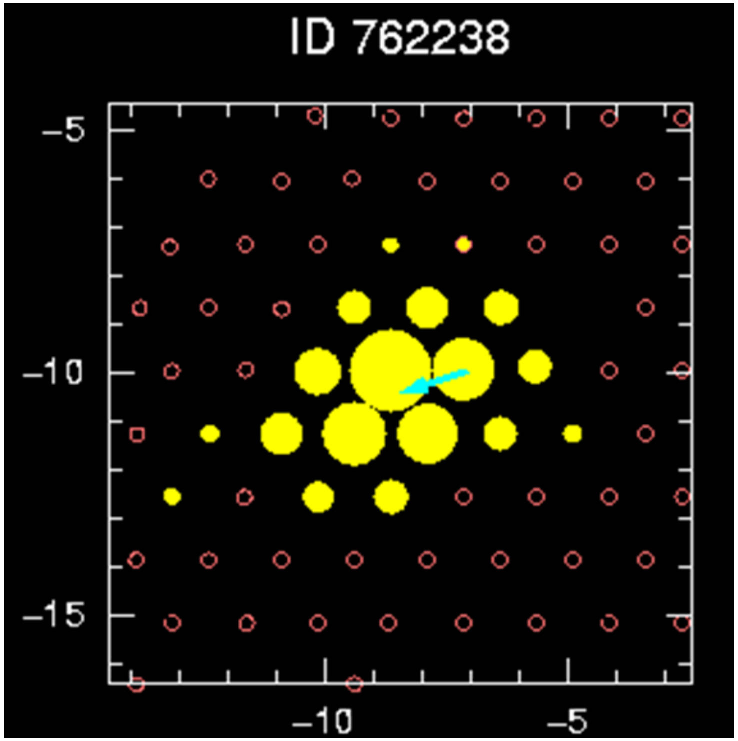
Fluorescence Detectors
- 4 Telescope enclosures
- 6 Telescopes per enclosure
- 24 Telescopes total

The surface detector

Sampling of the shower tail at ground using electron/muon detectors

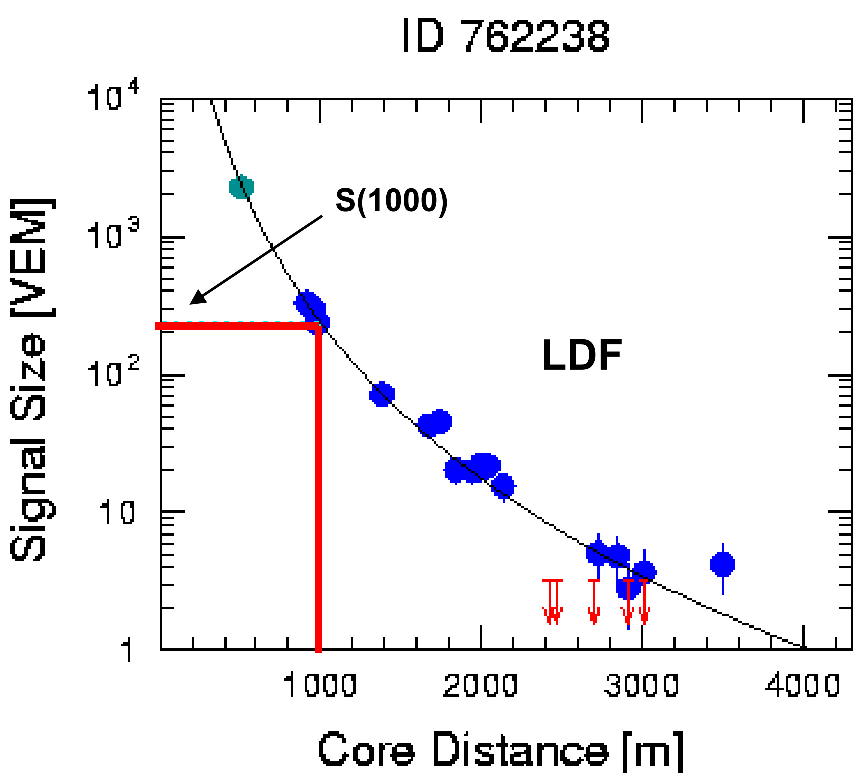
- Arrival times → Reconstruction of the shower front → incidence direction
- Radial distribution of the particle density → primary energy

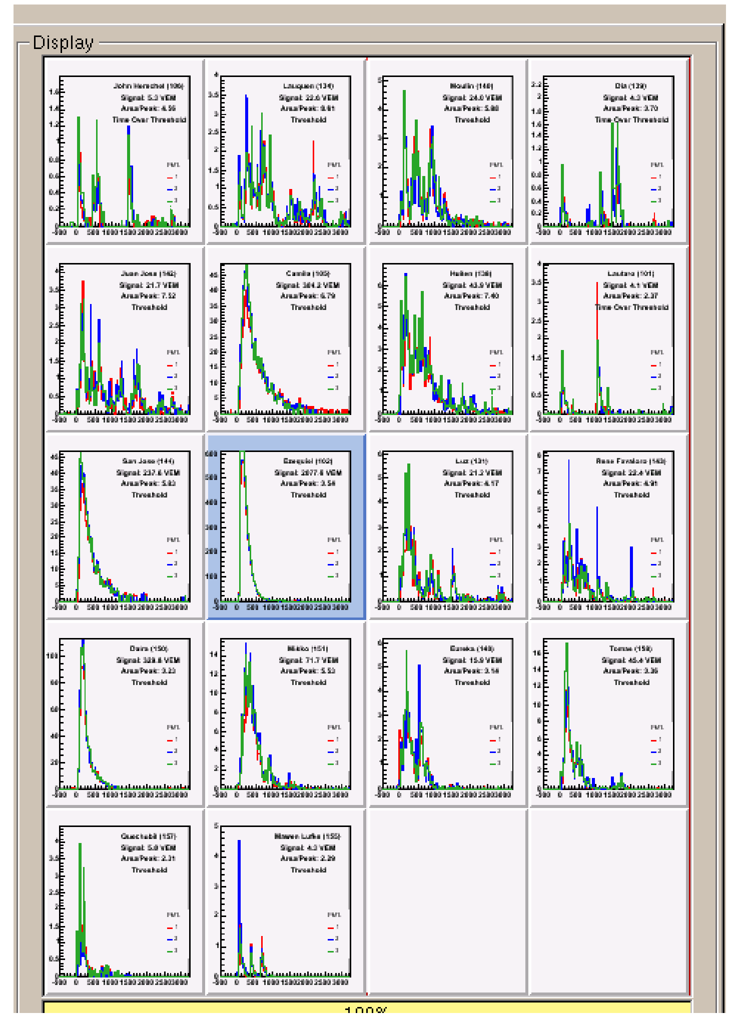




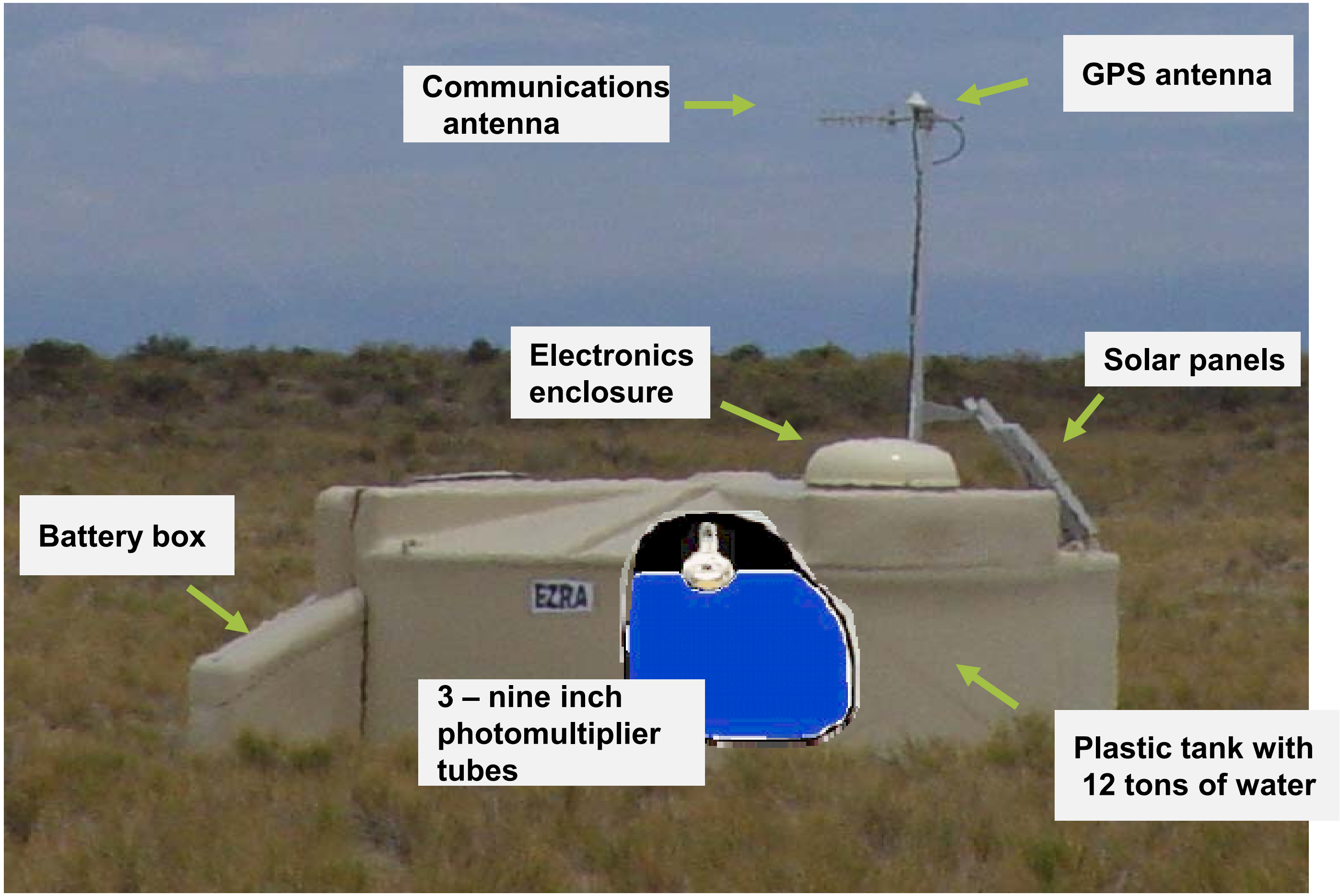
Energy determination with the surface detector

- Signal intensity at 1000 m S(1000) is a good energy estimator; i.e. small fluctuations
- Strongly dependent on the hadronic interaction model and mass composition



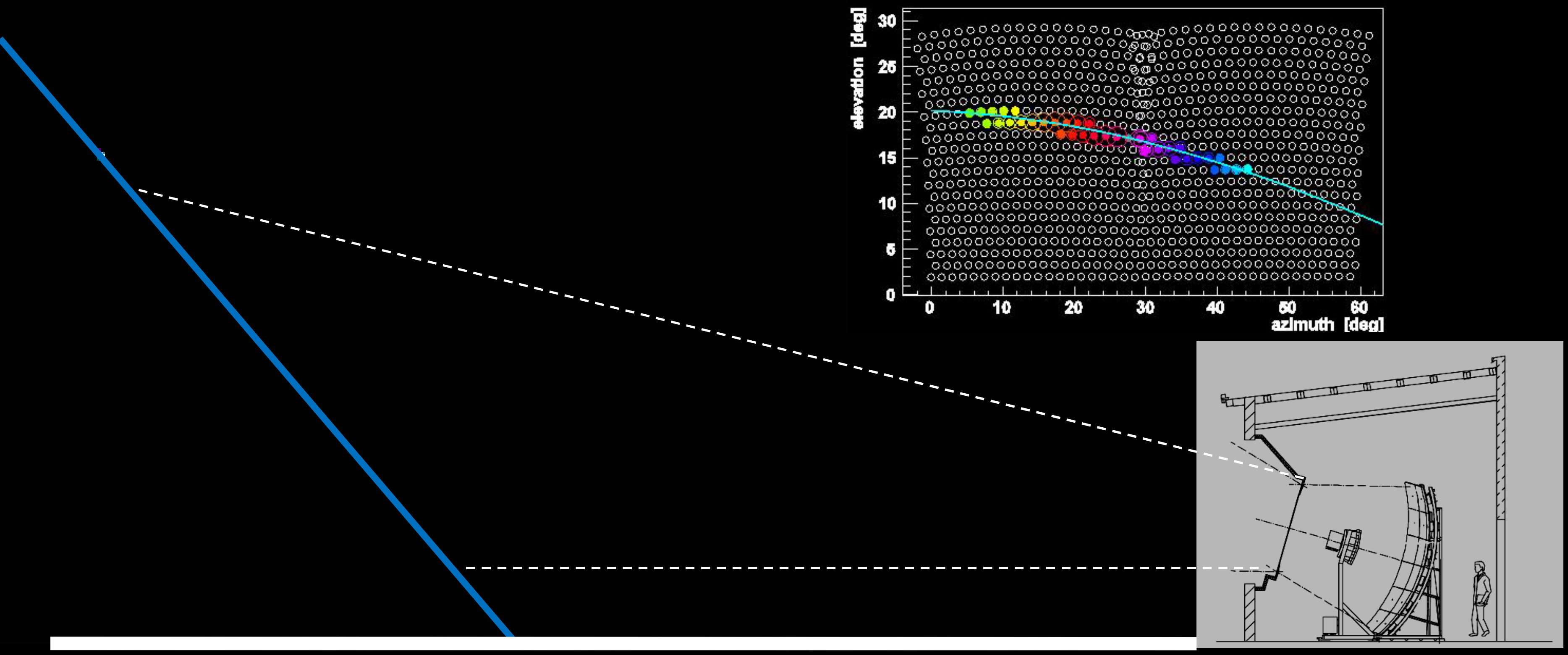


The SD station



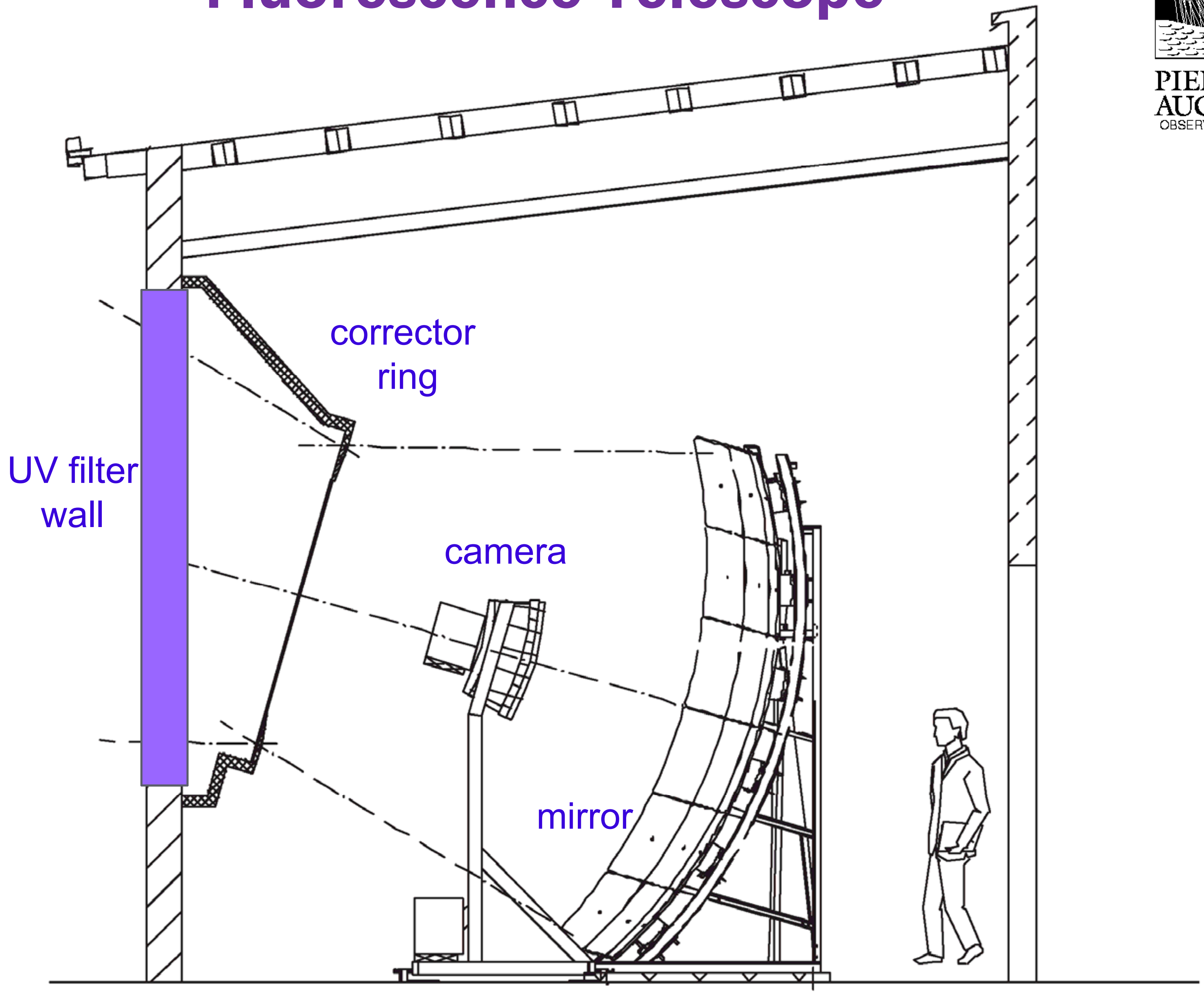
Information on muonic and EM component

Detection of air showers using the fluorescence technique

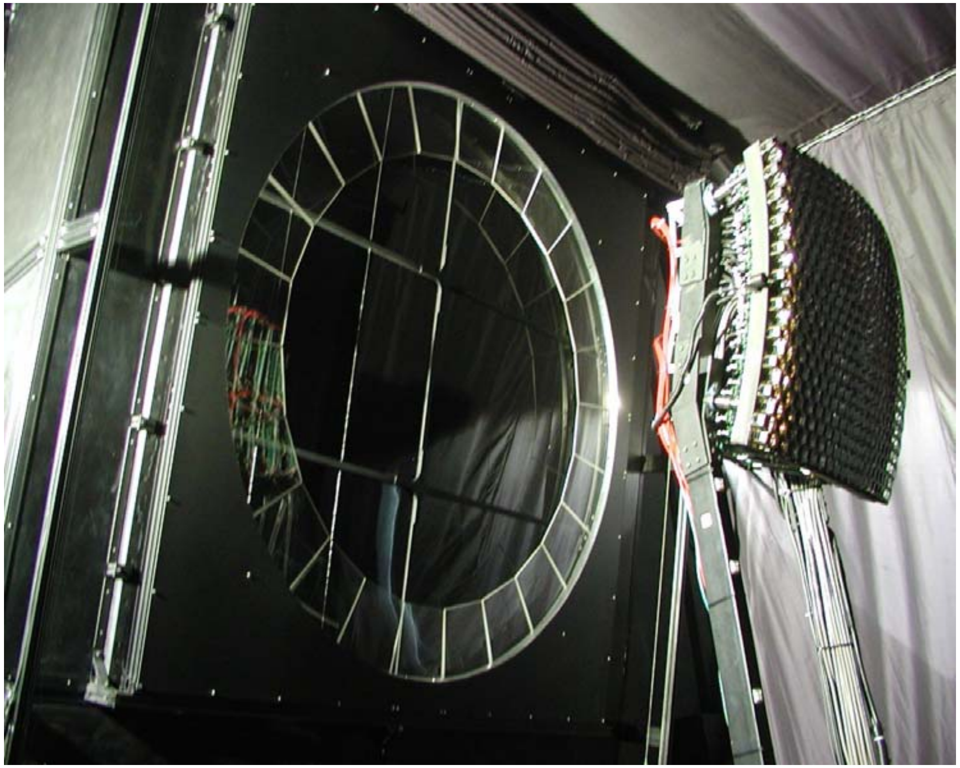


Fluorescence telescopes “see” the UV light emitted by N_2 molecules excited by shower electrons

Fluorescence Telescope

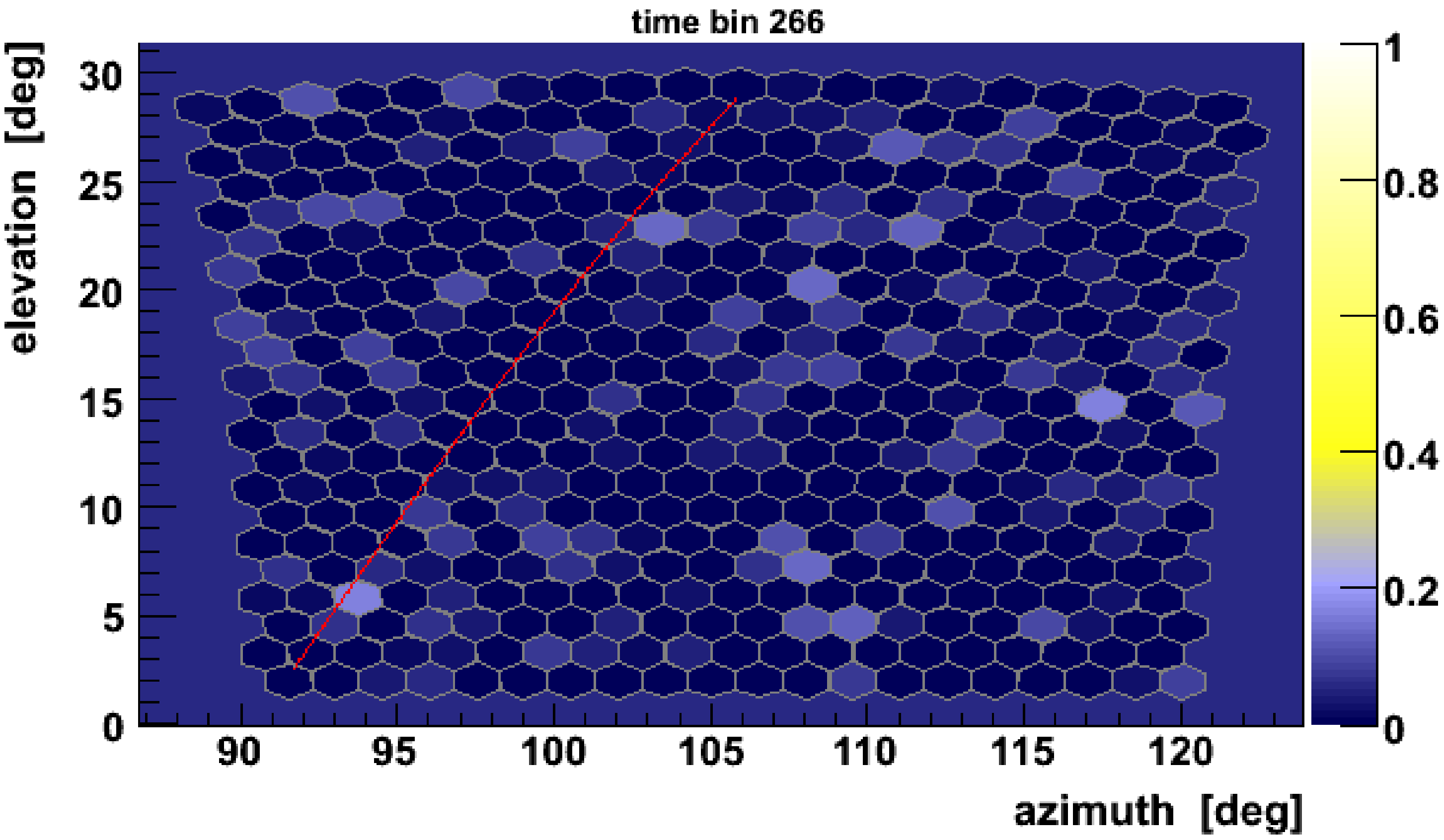


Fluorescence Telescope



- 440 PMT per camera, each 1.5°
- 13% duty cycle
- 100 ns sampling intervals

Fluorescence Telescope



Fluorescence Station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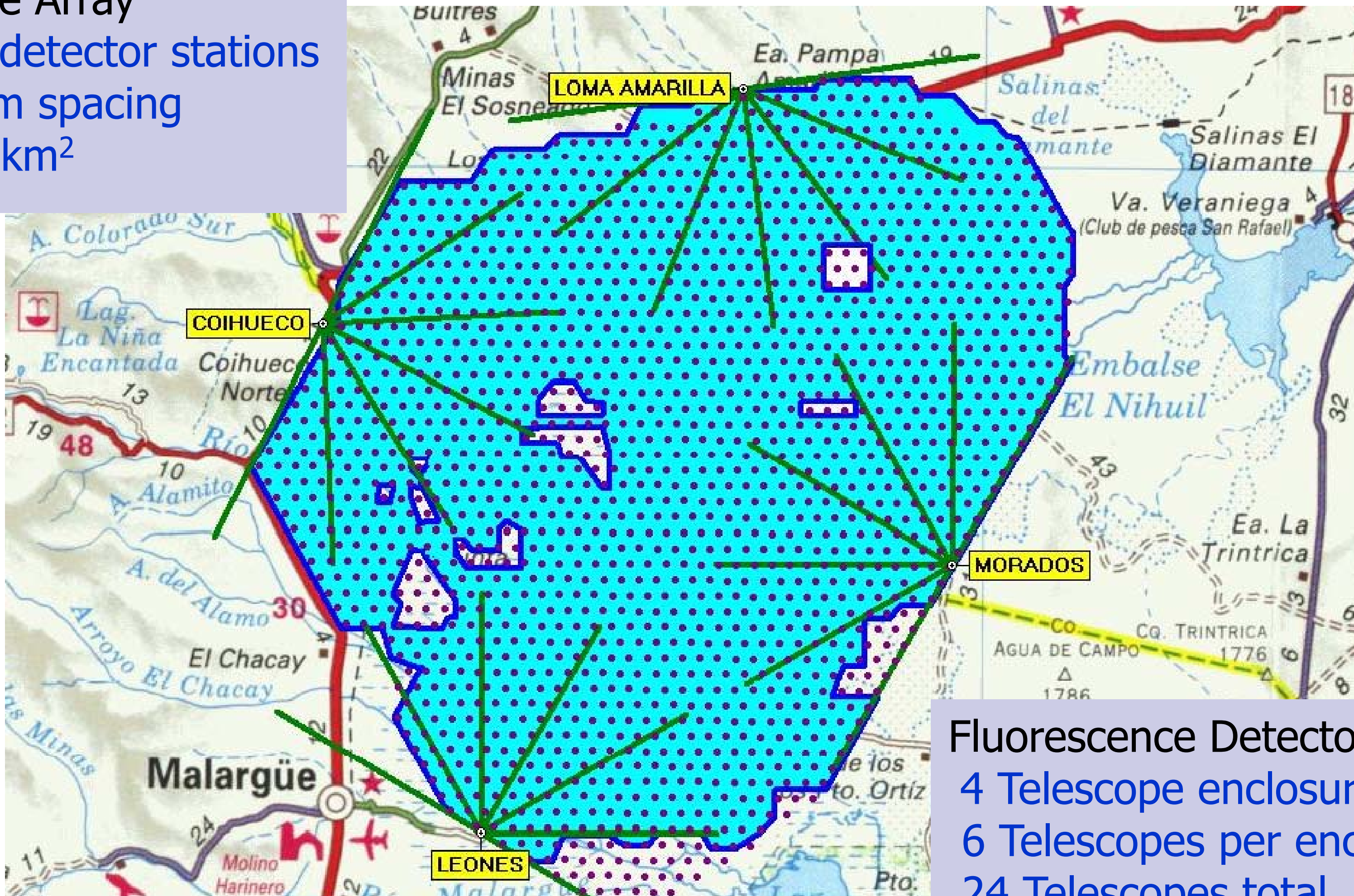
The South Observatory

Surface Array
- 1660 detector stations
- 1.5 km spacing
- 3000 km^2



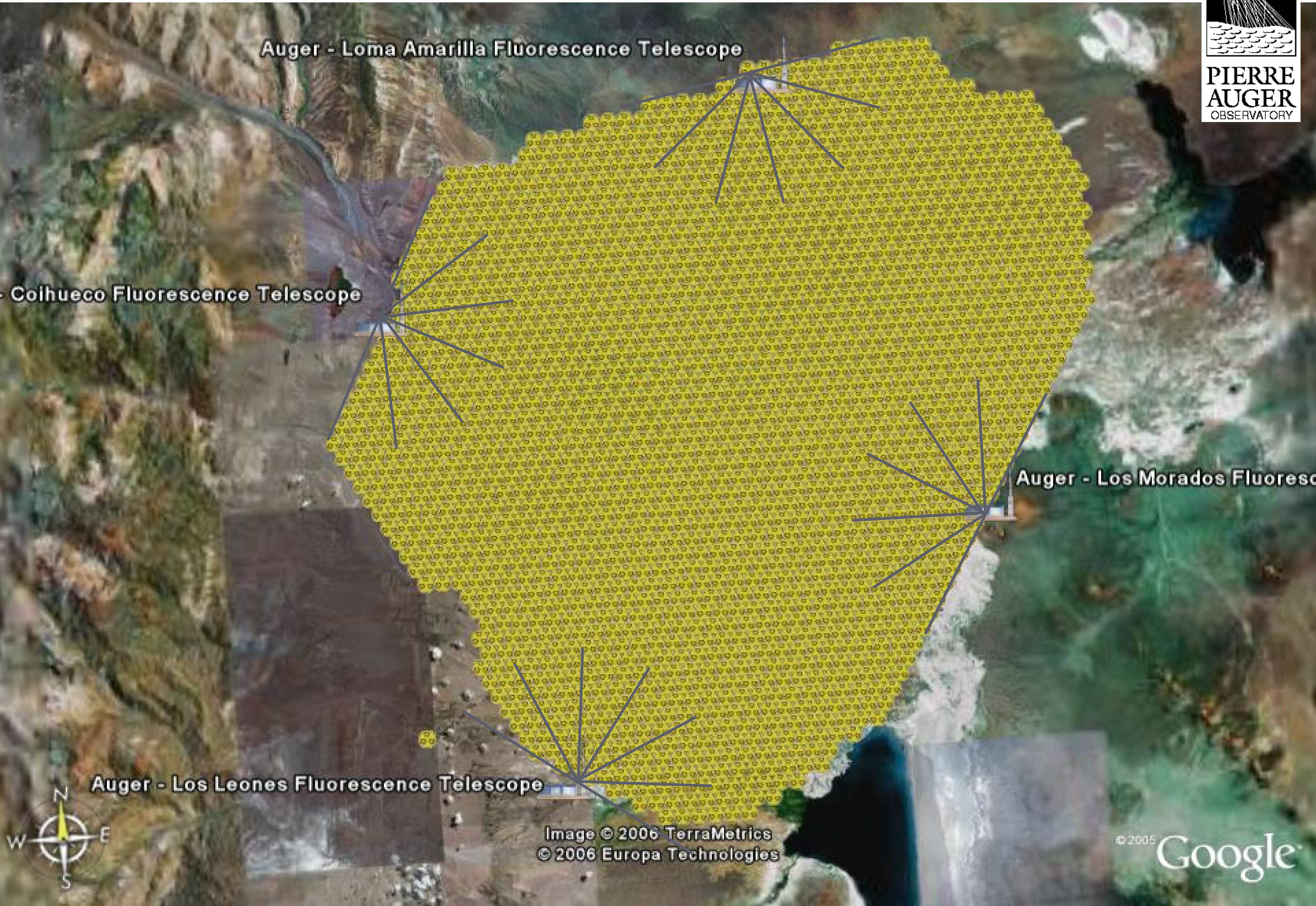
Fluorescence Detectors
- 4 Telescope enclosures
- 6 Telescopes per enclosure
- 24 Telescopes total

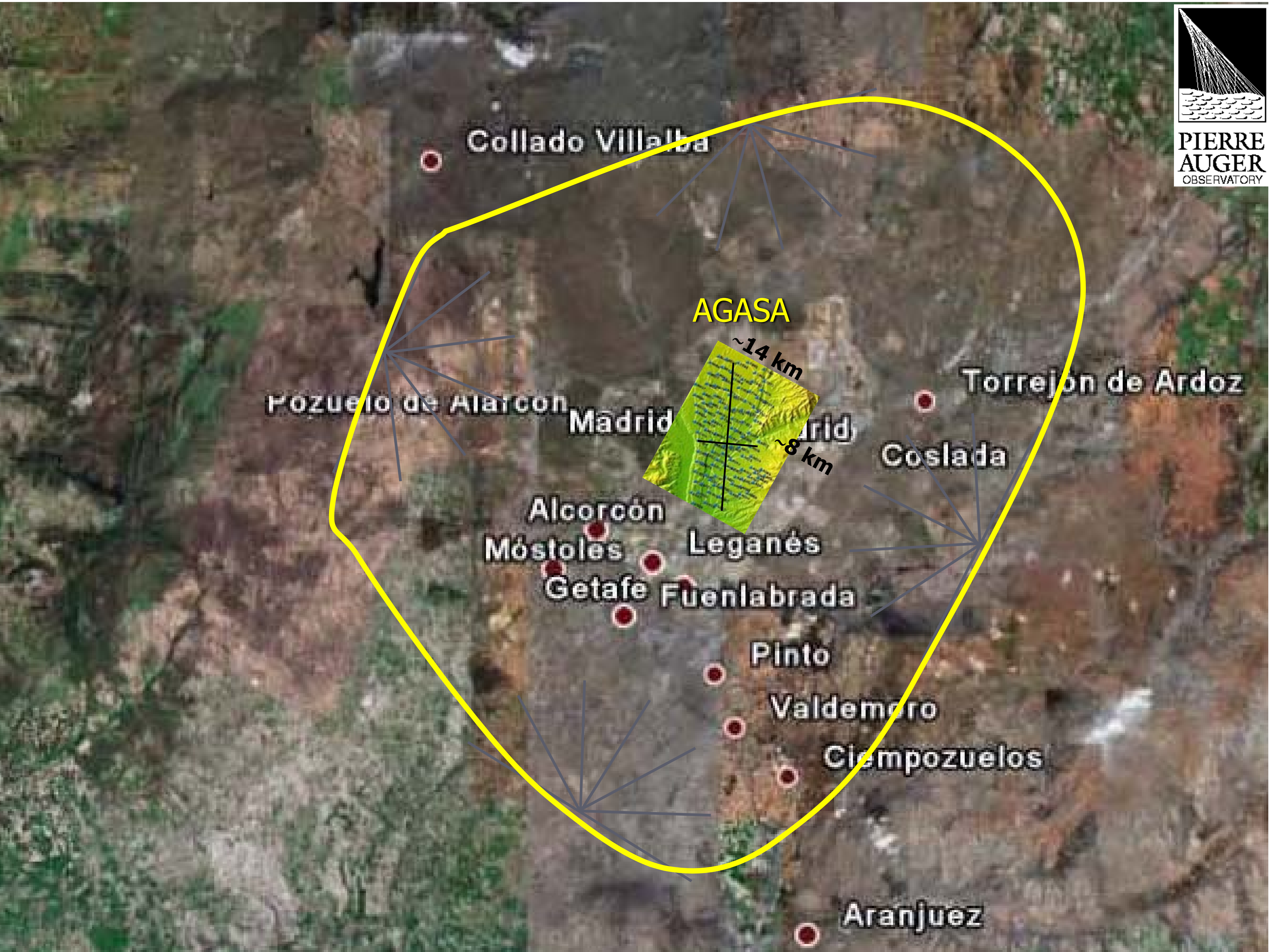
April 2006

April 2006


April 2006

Southern Observatory (Argentina)




PIERRE AUGER OBSERVATORY
Collado Villalba
AGASA
~14 km
Torrejón de Ardoz
Pozuelo de Alarcón
Madrid
~8 km
Coslada
Alcorcón
Móstoles
Leganés
Getafe
Fuenlabrada
Pinto
Valdemoro
Ciempozuelos
Aranjuez

The Hybrid Design

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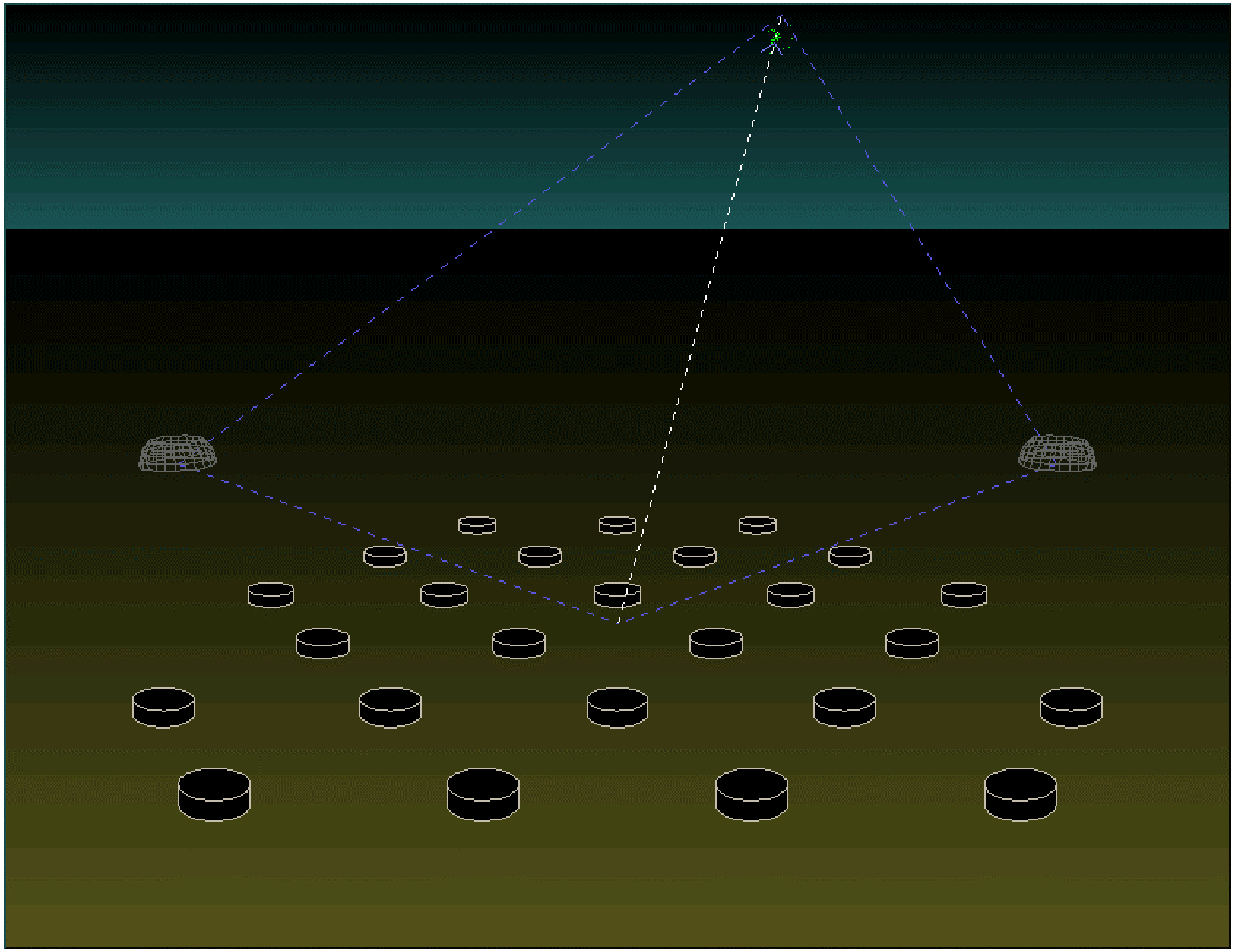
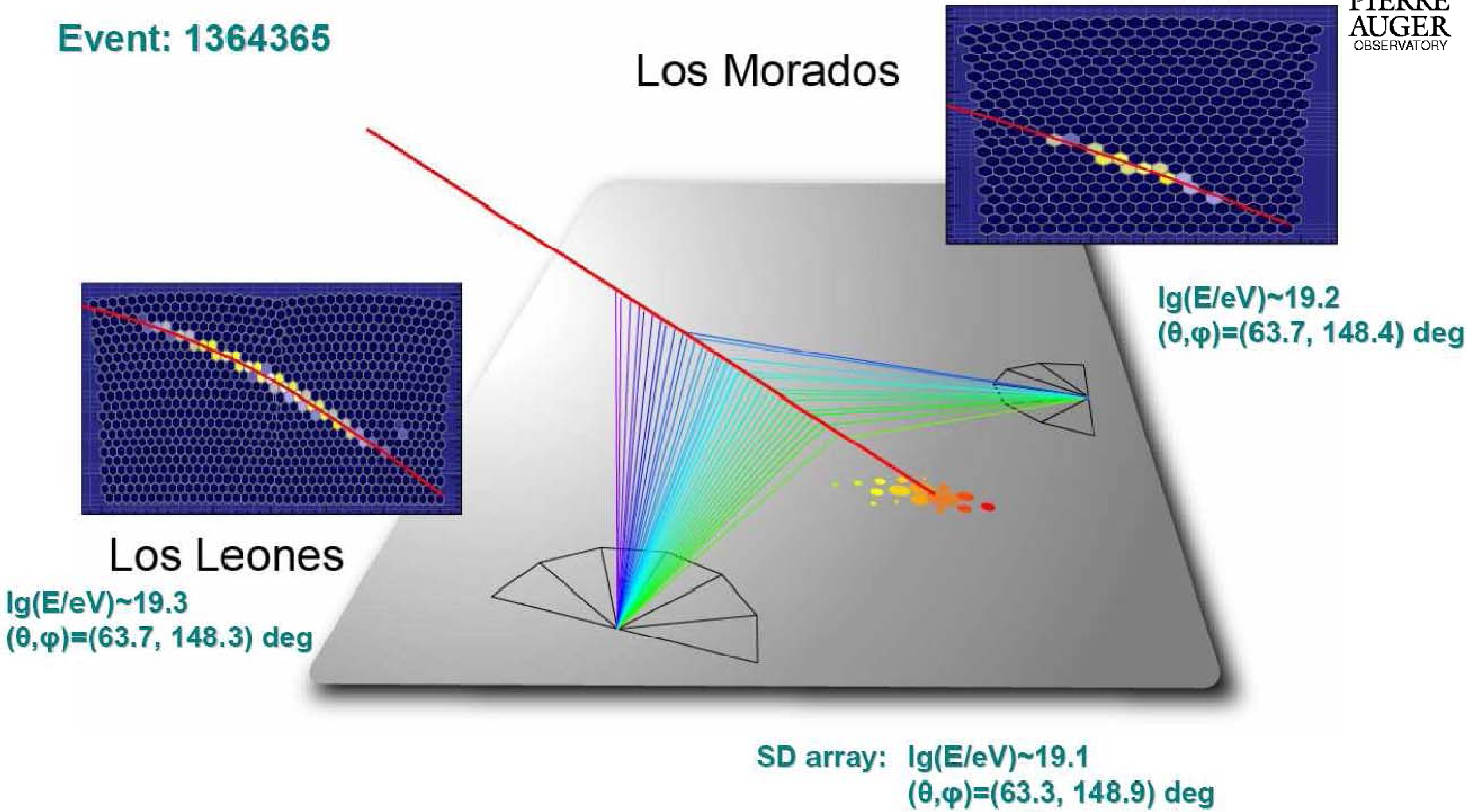


Stereo Hybrid Event - E = 1.6×10^{19} eV ; θ = 64°



The measurement of the energy spectrum of UHECRs

Measurement of the energy spectrum with a hybrid detector

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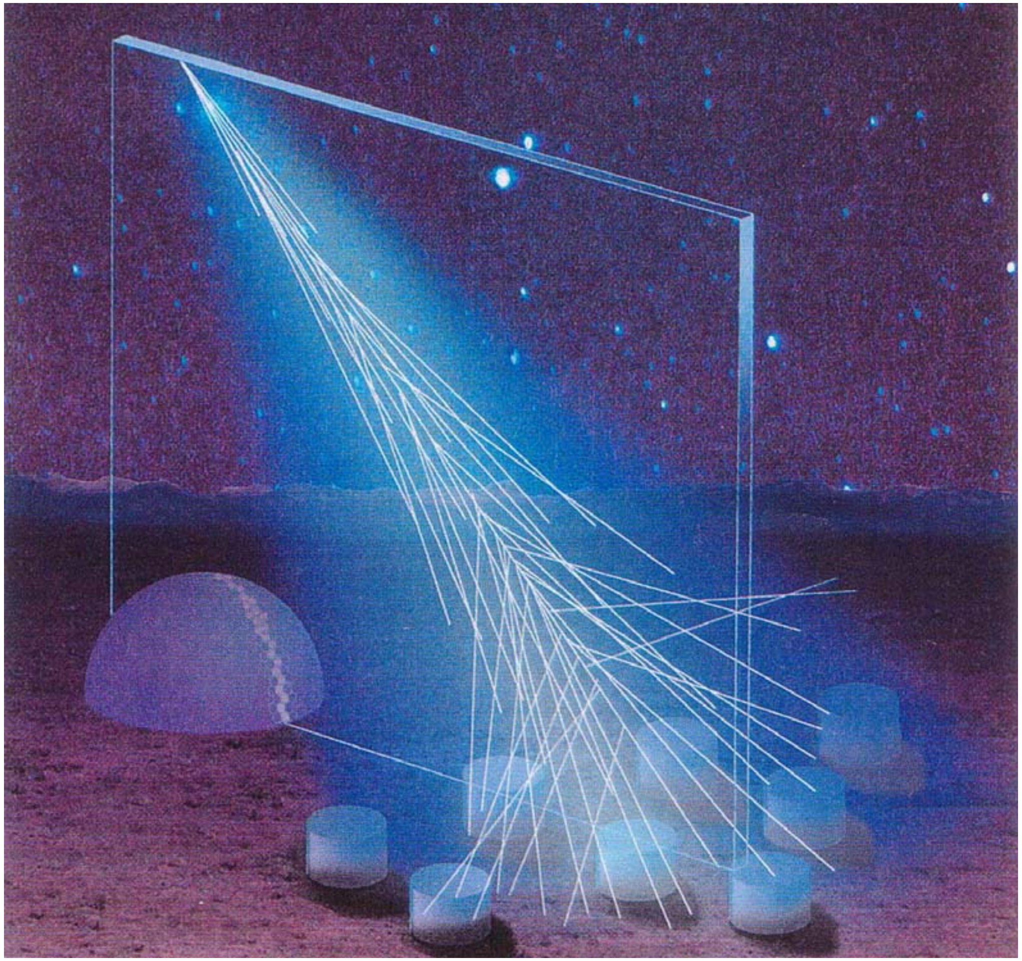


Surface Detector

- Acceptance: Geometric
- Energy: Mass and Model dependent
- Duty cycle ≈ 100%

Fluorescence Detector

- Acceptance: E, γ, A, M dependent
- Energy: nearly calorimetric
- Duty cycle ≈ 13%

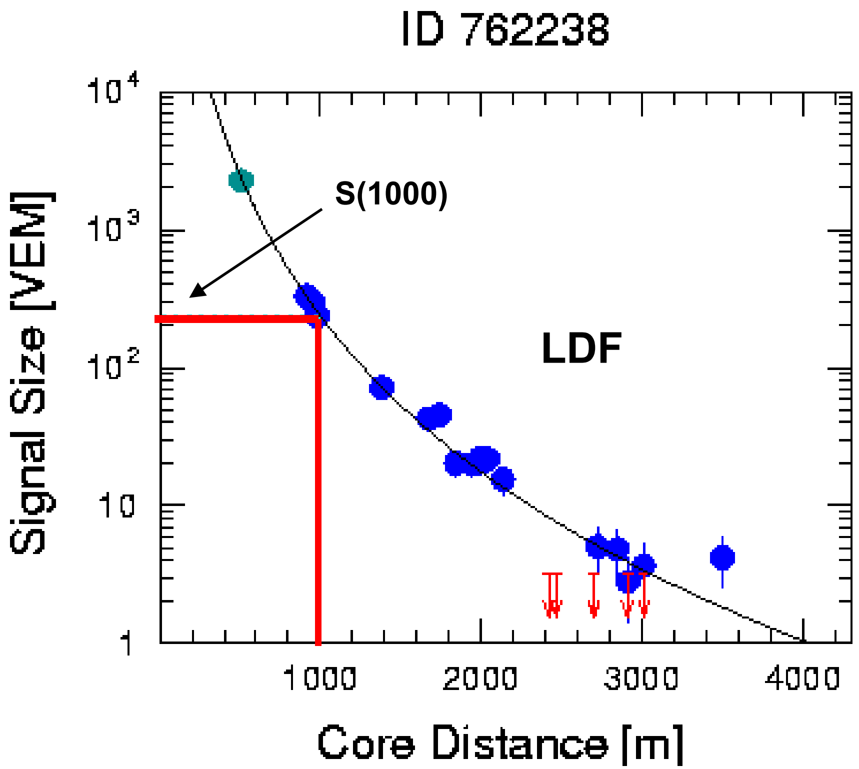
Energy reconstruction

SD

Lateral (radial) distribution of particles at ground

Energy estimator S(1000)

- Small fluctuations
- Energy calibration depends on composition and model



Energy reconstruction

SD Lateral (radial) distribution of particles at ground

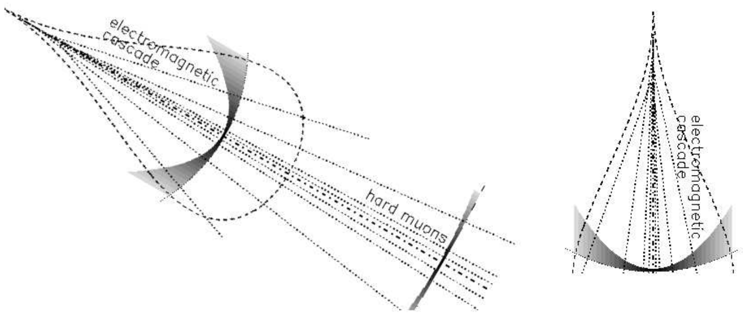
Energy estimator S(1000)

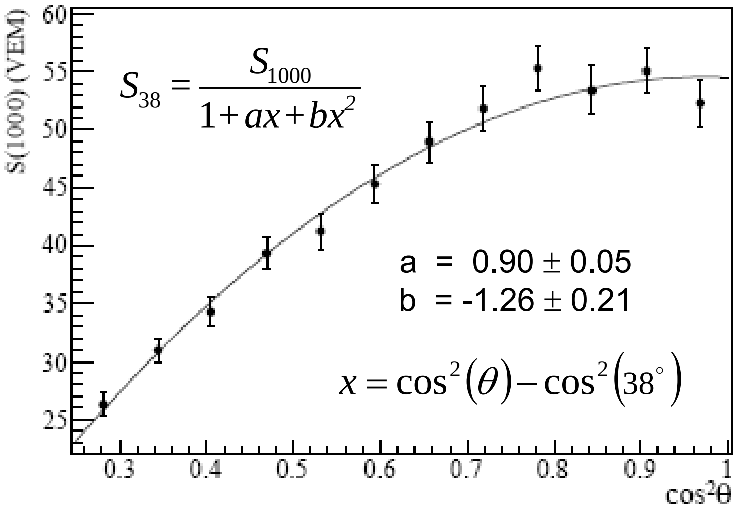
- Small fluctuations
- Energy calibration depends on composition and model

Constant Intensity Cut

S(1000) depends on incoming direction

S_{38}





Energy reconstruction

SD Lateral (radial) distribution of particles at ground

↓

Energy estimator S(1000)

- Small fluctuations
- Energy calibration depends on composition and model

Constant Intensity Cut ↓

S(1000) depends on incoming direction

S_{38}

FD

"Golden" hybrid events ↓

Calorimetric energy calibration

Energy of SD events

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Measure of the EM energy of an air-shower using the fluorescence technique

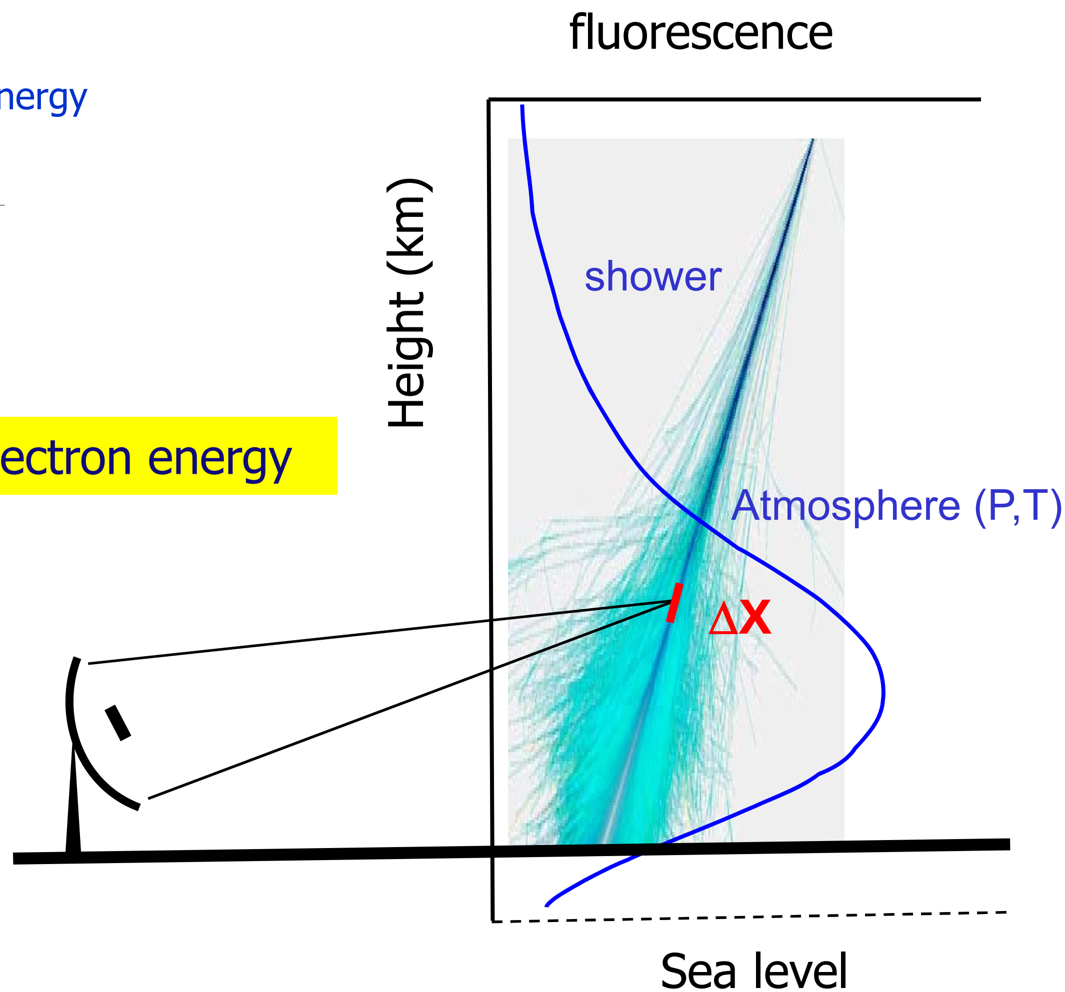
Fluorescence photons — Deposited energy

$$\frac{dN_\gamma}{dX} = Y(P,T,h)\ \frac{dE_{dep}}{dX}$$

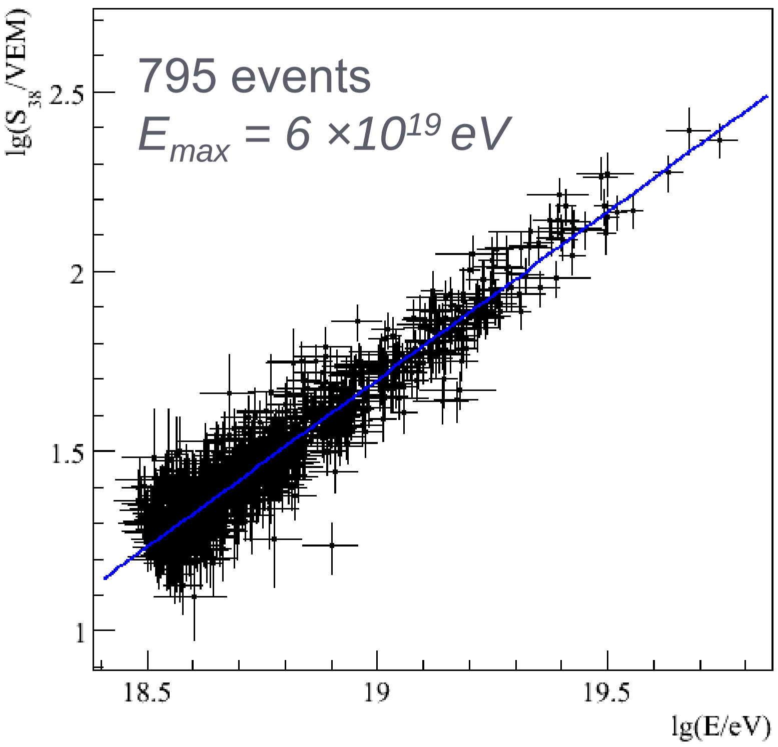
Fluorescence yield (photons / MeV)

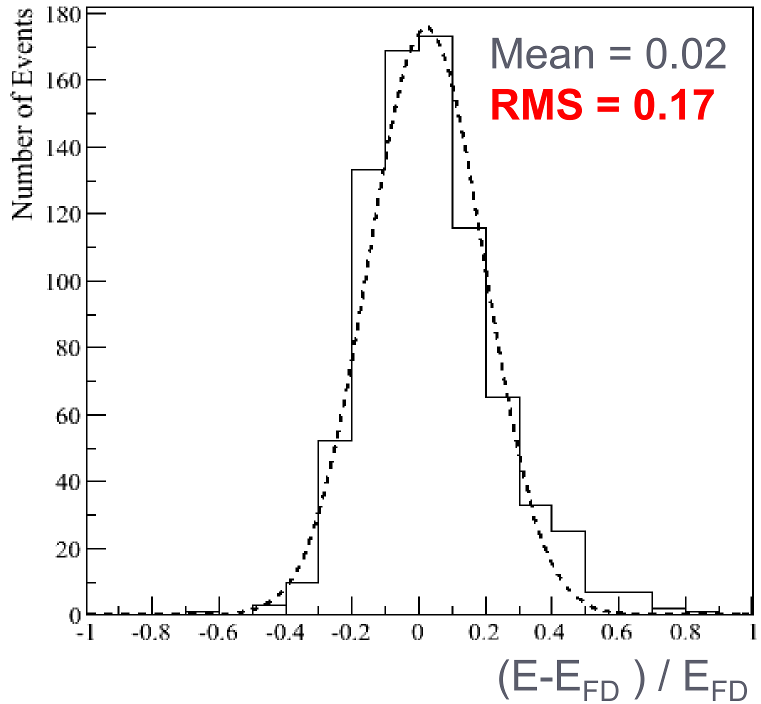
Assumption: FY independent on electron energy

$$E_{dep} = \int dX\ \frac{1}{Y(P,T,h)}\frac{dN_\gamma}{dX}$$



Energy calibration





<u>Systematic uncertainties:</u>
7% (10^{19} eV)
15% (10^{20} eV)

Systematic uncertainties in the FD energy

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FD absolute optical calibration	9 %
FD wavelength dependence response	3 %
Absolute Fluorescence Yield	**14 %**
Quenching effect on F.Y.	5 %
Molecular Attenuation	1 %
Aerosol Attenuation	7 %
Multiple scattering Models	1 %
FD reconstruction method	10 %
Invisible energy	4 %
TOTAL SYST.	**~22 %**

Exposure

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Trigger efficiency

> 90% (E> 2.5 $\times 10^{18}$ eV)

> 99% (E> 3.0 $\times 10^{18}$ eV)

Data

01/2004 – 12/2008

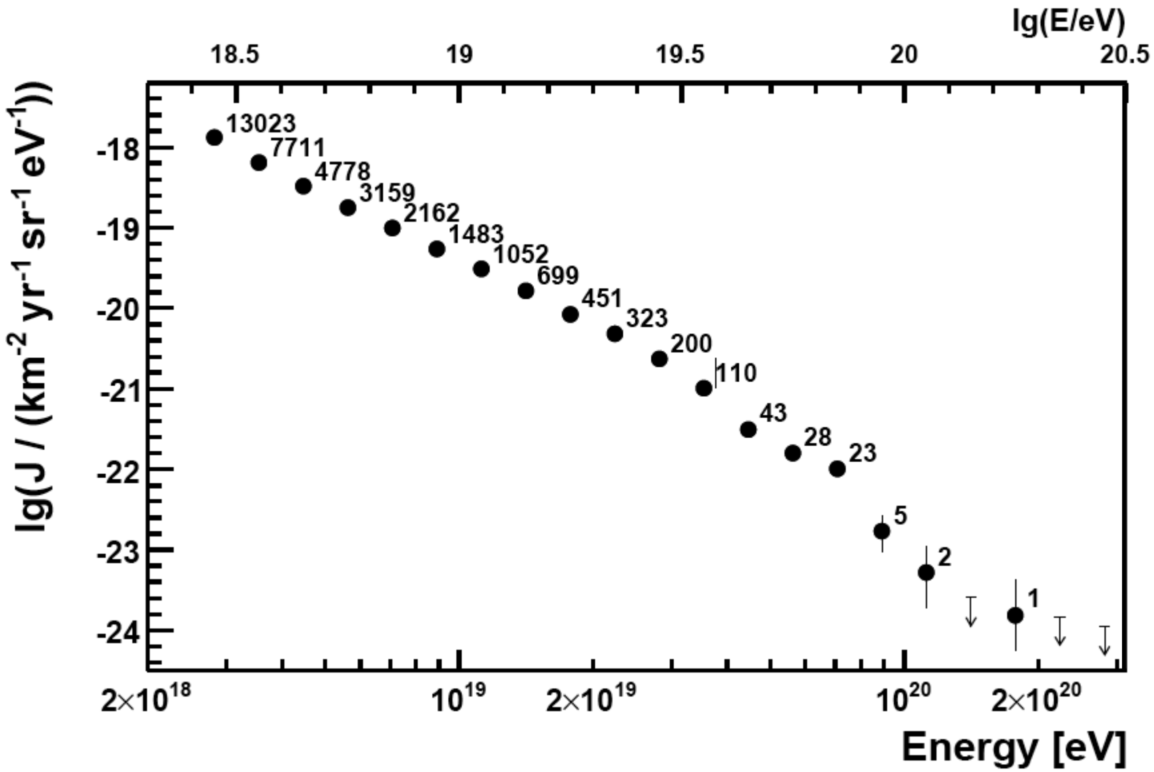
$\approx$ 35000 events (< 60°)

Integrated exposure

12790 (± 3%) km^2 sr yr

growing at about 350 km^2 sr yr / month

The Auger energy spectrum from SD calibrated with FD



Flux uncertainties:

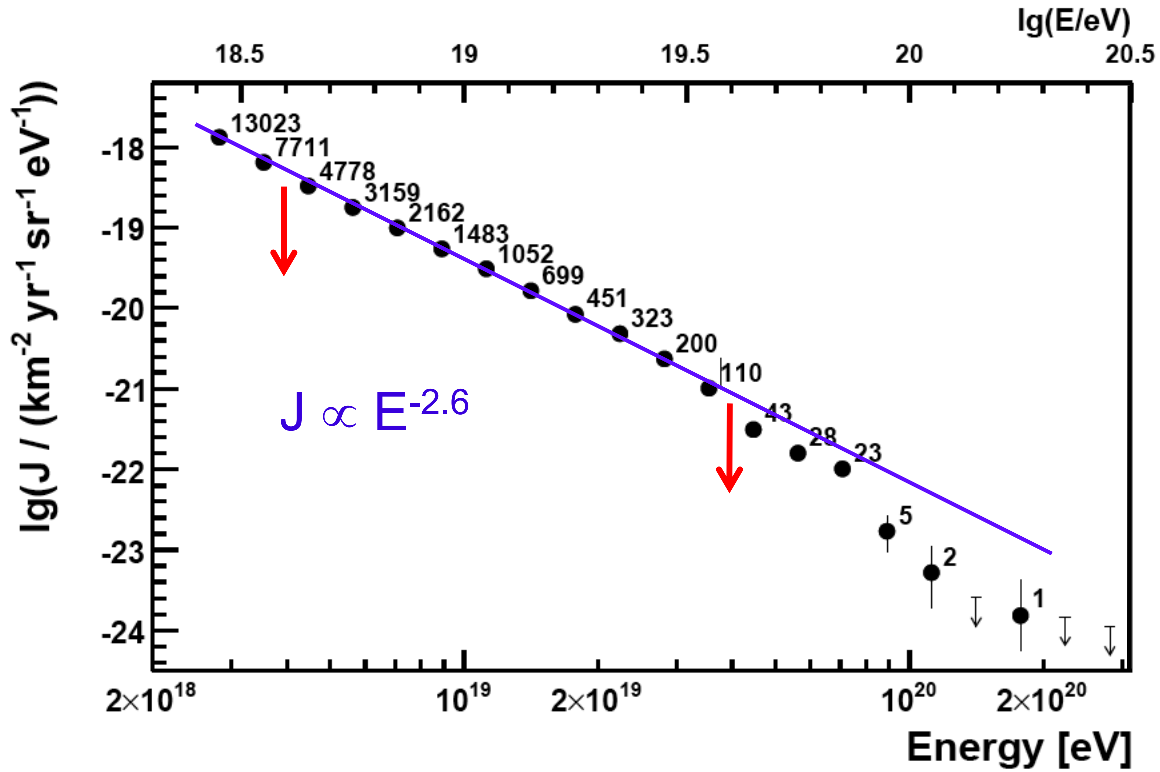
Systematic ≈ 6 % (3% exposure + 5% unfolding)

Statistical = error bars

Energy scale uncertainty

Systematic ≈ 22%

The Auger energy spectrum from SD calibrated with FD



Flux uncertainties:

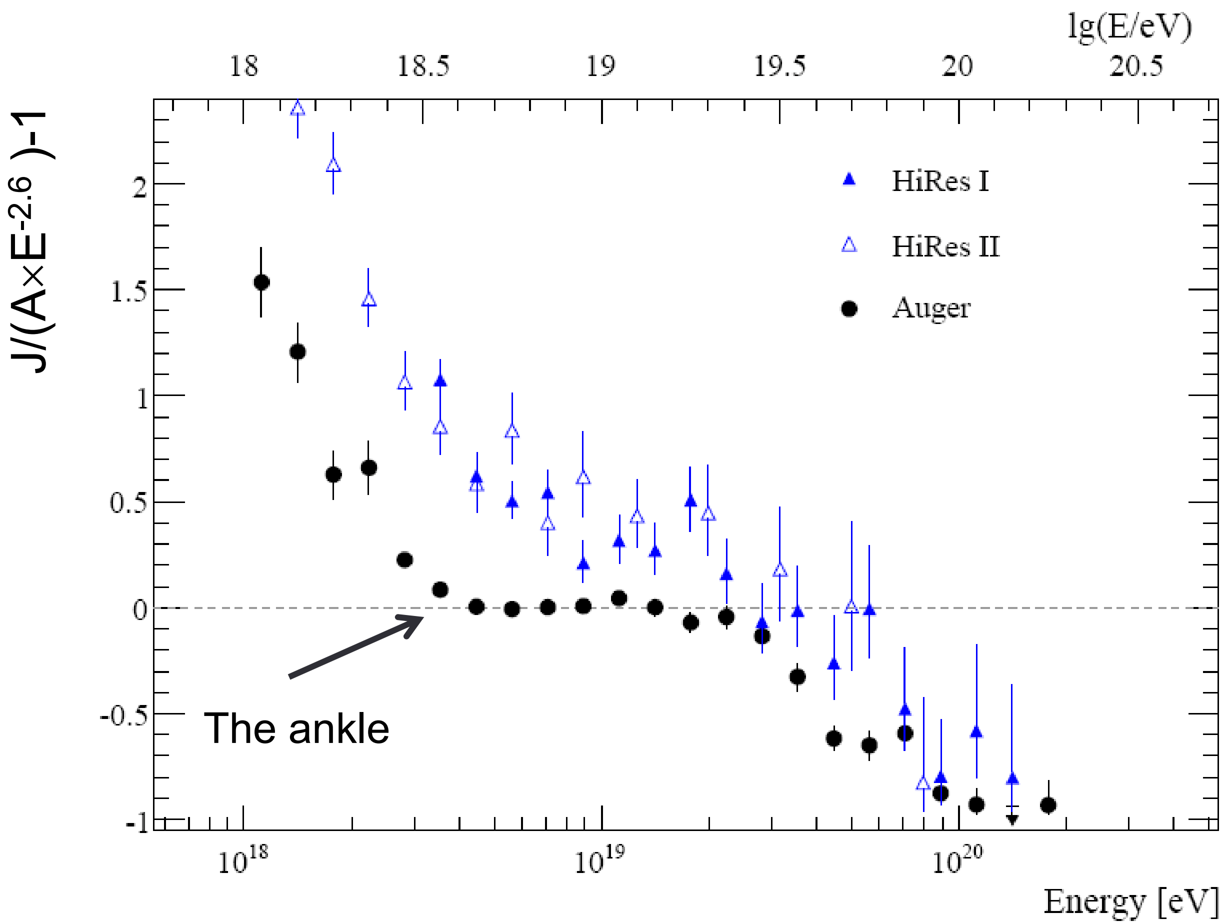
Systematic ≈ 6 % (3% exposure + 5% unfolding)

Statistical = error bars

Energy scale uncertainty

Systematic ≈ 22%

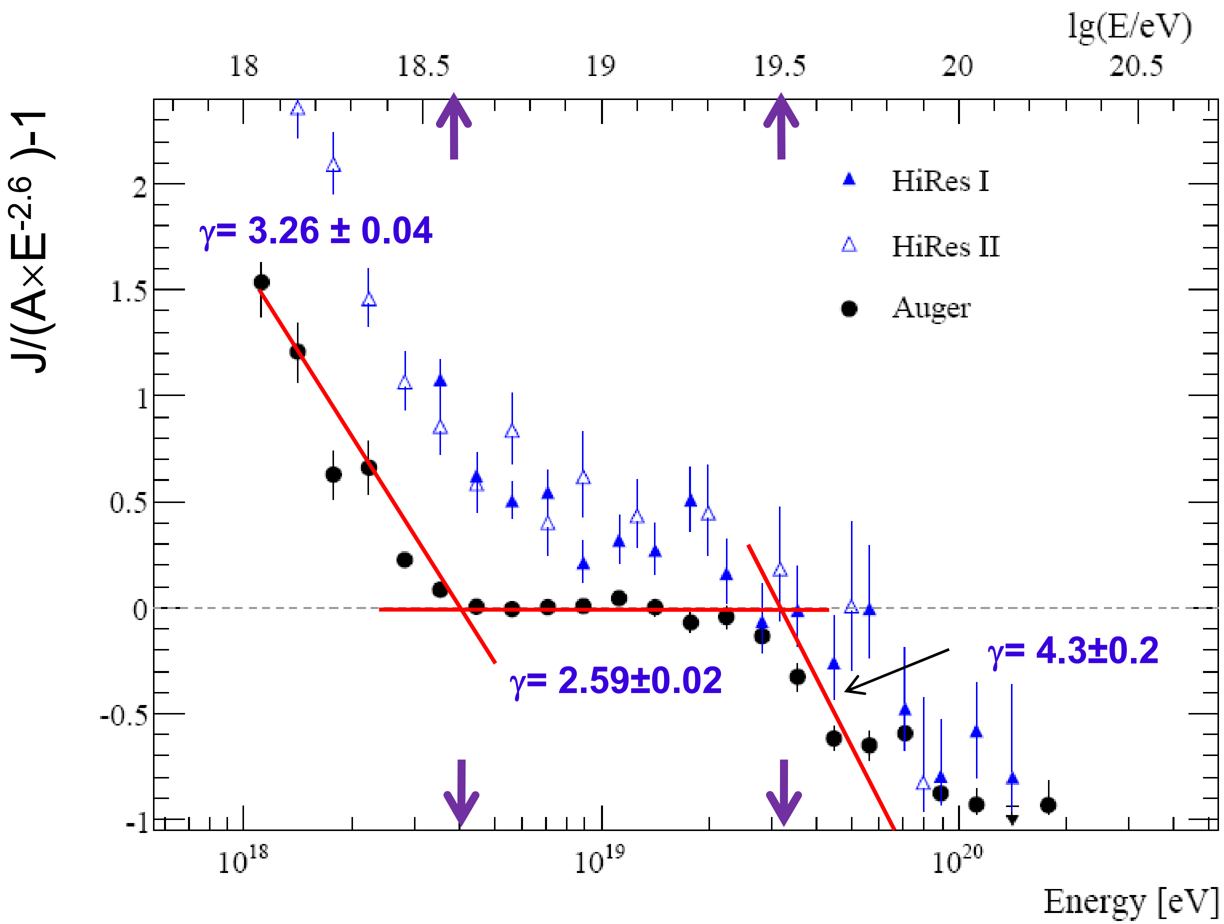
Combined (SD – hybrid) energy spectrum - E > 10^{18} eV



Flux systematic uncertainty = 4%

Systematic uncertainty in the Energy scale ≈ 22%

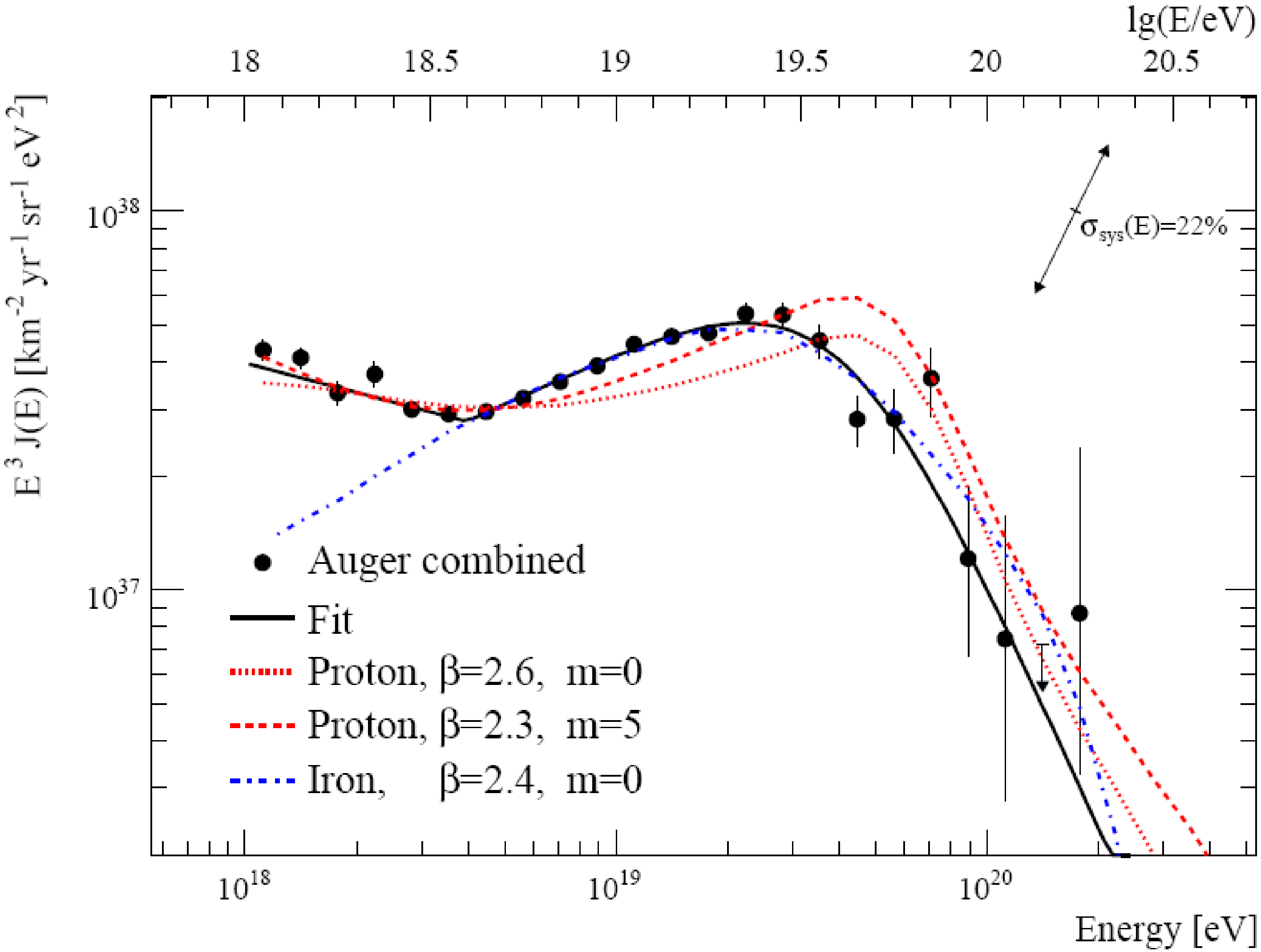
Combined (SD – hybrid) energy spectrum - E > 10^{18} eV



Flux systematic uncertainty = 4%

Systematic uncertainty in the Energy scale ≈ 22%

The Auger combined spectrum vs models



Source flux $\propto E^{-\beta}$

Cosmological evolution of the source luminosity $(z+1)^m$

The energy spectrum

Conclusions

- The energy spectrum of cosmic rays above 10^{18} eV has been measured with unprecedented precision.
- The combined spectrum enables a precise measurement on both the ankle and the flux suppression.
- Comparison with astrophysical models can be performed.

Composition

Composition of UHECRs

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- Interpretation of the features of the energy spectrum
  - Flux suppression at the highest energies
  - The ankle (transition galactic – extragalactic)
- Interpretation of anisotropies
- Hadronic interactions at the highest energies

Measurement of the UHECR composition

Fluorescence detector:

Shower maximum depth X_{max}
Proton showers penetrate deeper in the atmosphere and have a wider distribution of X_{max} than heavy nuclei

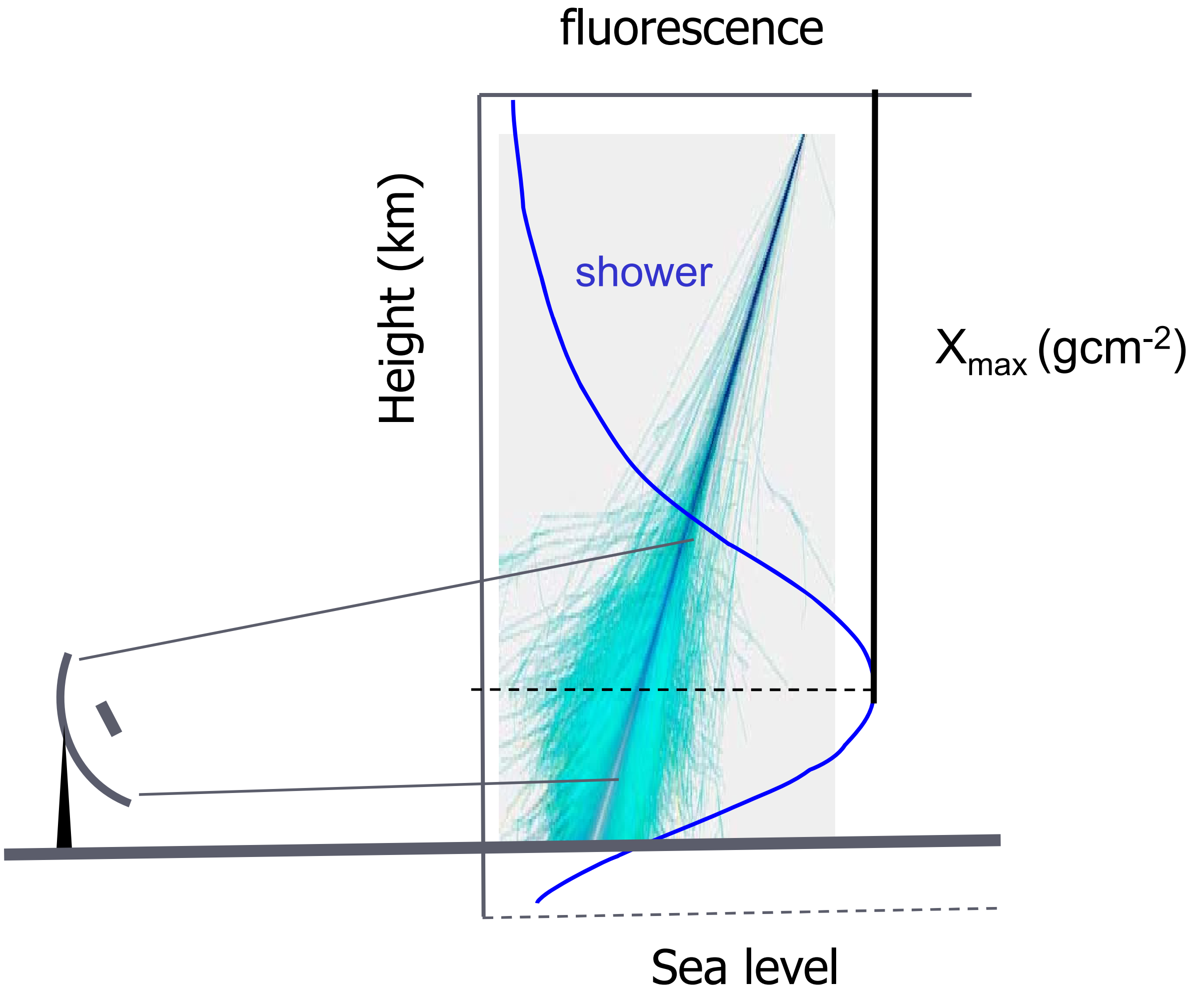
- $\langle X_{max} \rangle$
- RMS of X_{max} distribution

Surface detector:

Risetime of the SD signals is correlated with μ/EM $\Rightarrow$ primary-mass dependent

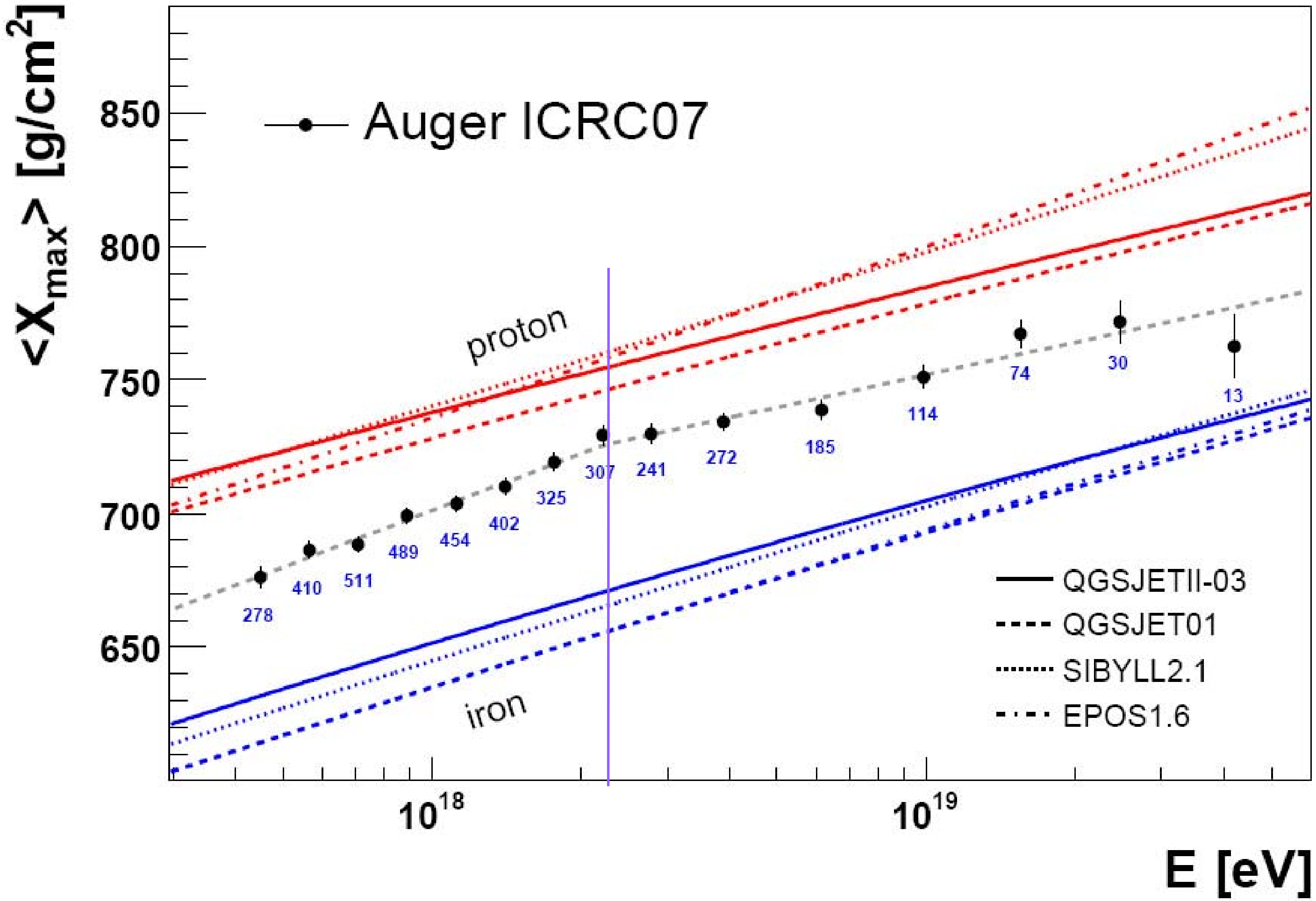
- Deviation from a benchmark
- Azimuthal time asymmetry

Shower maximum depth

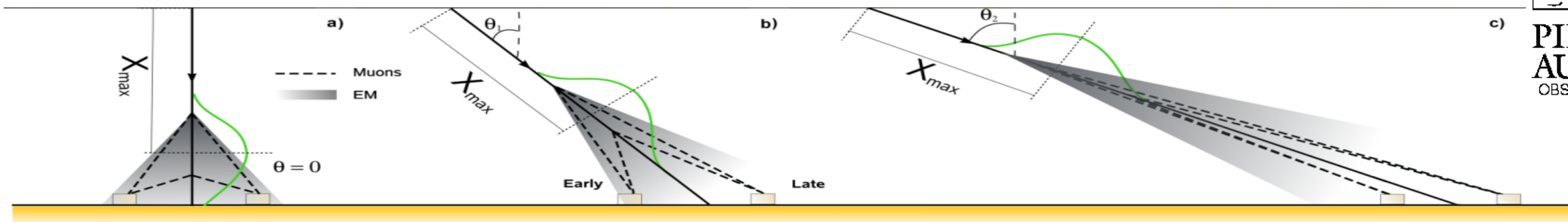


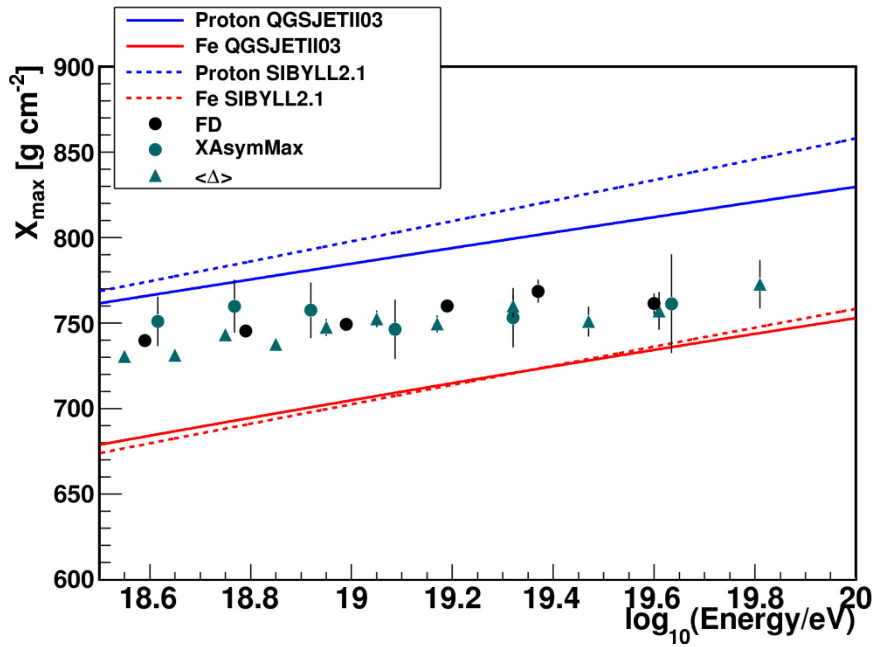
Elongation rate and composition

$$<X_{\max}>= D_p\left[\ln\left(E/E_0\right) - <\ln A>\right] + c_p$$



Time asymmetry of risetime





- The circular asymmetry in azimuth (shower front) is broken in inclined showers due to the μ/EM ratio. In inclined showers the EM component is absorbed in the late region.
- This asymmetry depends on the primary mass
- Asymmetry is well correlated with X_{max}

Composition

Conclusions

- Experimental results favors a mixed composition
- Both elongation rate and risetime measurements suggest that the mean mass increases with energy.
- Uncertainties in the hadronic interaction models still make any conclusion ambiguous.

Upper limits on UHE photons

Upper limits on UHE photons

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Upper limits on photon flux ($\geq 10^{19}$ eV)

Measurement relies in SD observables sensitive to the longitudinal shower development

- signal risetime
- curvature of the shower front

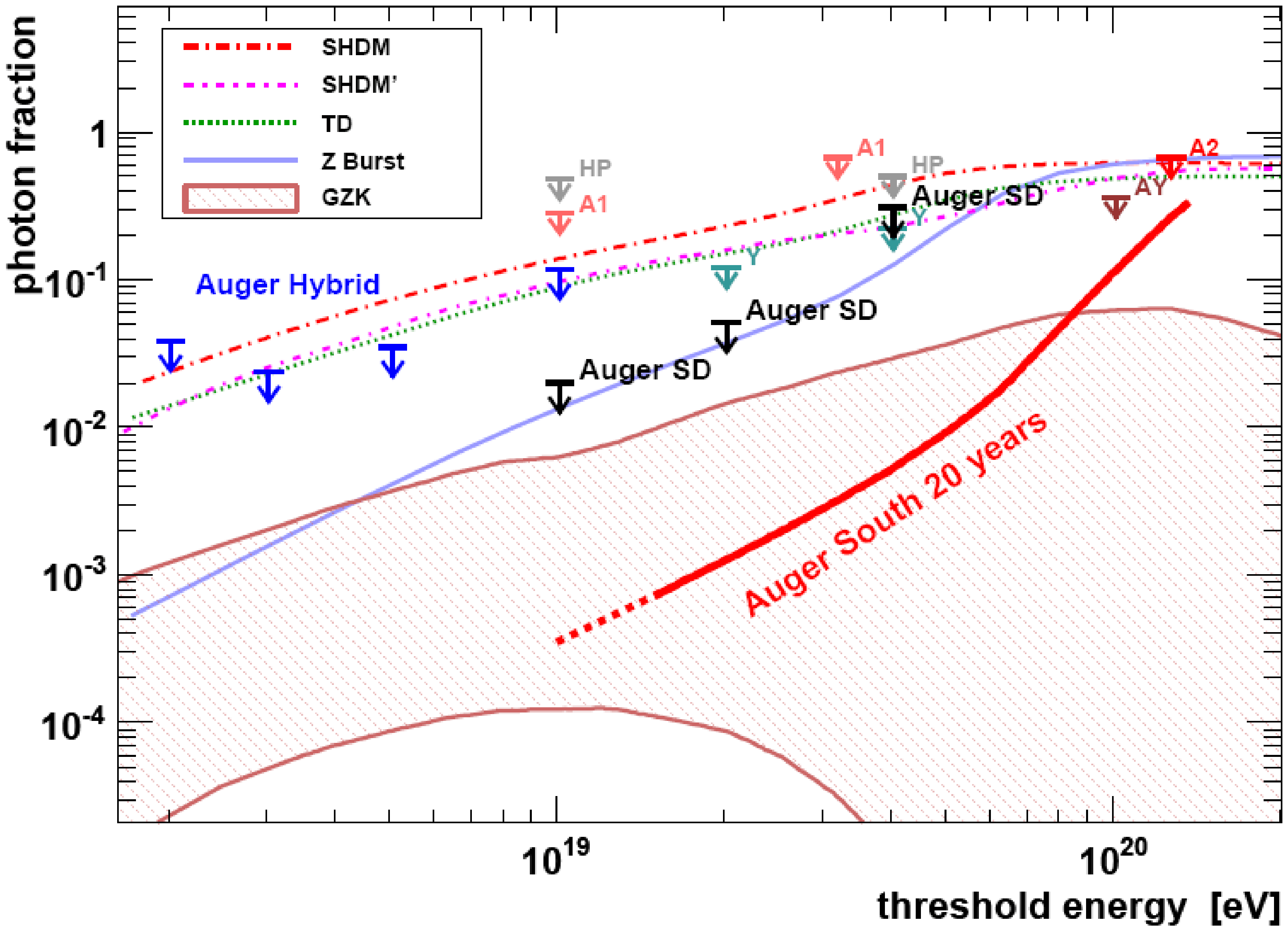
Astroparticle Physics 29 (2008) 243–256

Upper limits on photon flux at EeV (10^{18} eV) energies

Measured from hybrid events

- X_{max}

UHE photons - Comparison with predictions



UHE photons

Conclusions

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- These results improve significantly upper bounds from other experiments.
- First experimental limits at EeV energies.
- They disfavor top-down models.

The search for correlations with nearby extragalactic objects

Sources of UHECR

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- Cosmic rays with E > 6 x 10^{19} eV $\Rightarrow$ sources < about 200 Mpc (GZK)
- Extra-galactic nearby objects identified as possible candidates (Hillas plot)
- Nearby sources not uniformly distributed $\Rightarrow$ arrival directions of cosmic rays anisotropic.
- Angular windows (few deg.) around AGNs (< 100 Mpc) cover a (not big) fraction of the sky

The Sources

Véron-Cetty / Véron Catalogue (12th edition, 2006):

- Large collection of quasars, BL Lacs and active galaxies
- Not an unbiased statistical sample because it's incomplete around the galactic plane and for objects distances >> 100 Mpc

Not an obstacle to demonstrate anisotropy although affects our sensitivity to identify sources unambiguously.

Search method

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Scan over

ψ	angular distance CR - AGN
D_{max}	maximum distance of the source
E_{th}	minimum CR energy

Cumulative binomial probability P for k/N correlations with individual chance probability p_{iso} (ψ,D_{max}); i.e. probability for a CR from an isotropic flux to arrive within ψ deg. around an AGN with D < D_{max}

$$P = \sum_{j=k}^{N} \binom{N}{j} p_{iso}^{j} \left(1 - p_{iso}\right)^{N-j}$$

exposure-weighted fraction of the sky accessible to the Pierre Auger Observatory

p_{iso} = 0.21

Data set

I) Exploratory period
1 January 2004 – 26 May 2006
Exposure = 4390 km^2 sr yr

II)
27 May 2006 – 31 August 2007
Exposure = 4500 km^2 sr yr

Science 318 (2007) 938

III)
1 September 2007 – 31 March 2009
Exposure = 8150 km^2 sr yr

Angular resolution
AR ≈ 0.9° (68 %)

Energy
Systematic uncertainty ≈ 22%
Resolution ≈ 17%

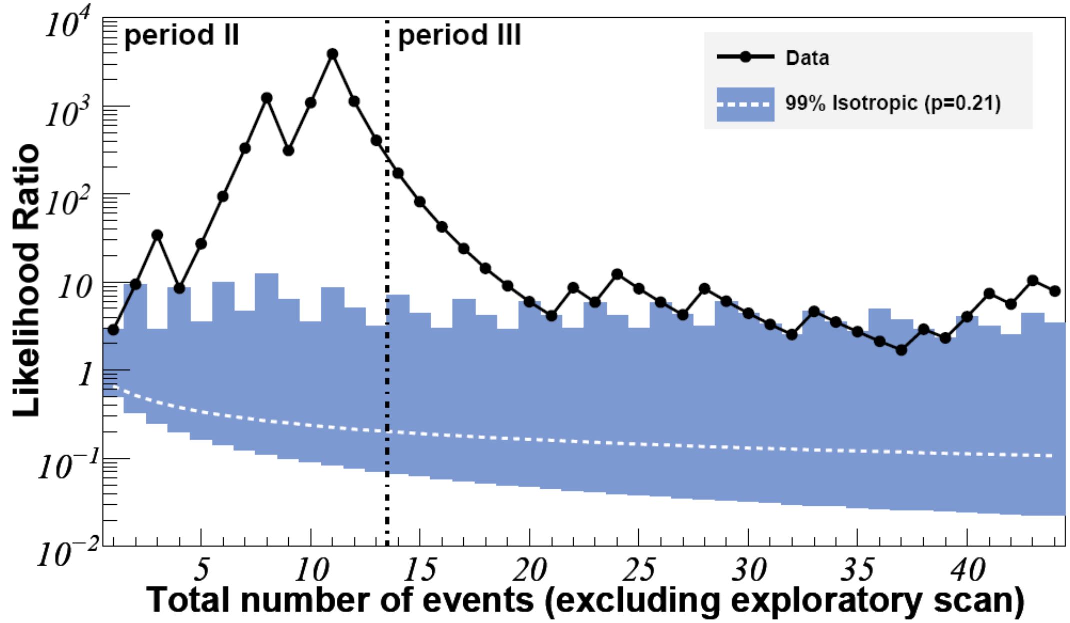
Prescription

- E_{th} = 55 EeV , D_{max}= 75 Mpc (z_{max} = 0.018), ψ = 3.1° (from exploratory scan)
- Data set independent from exploratory scan (from 27 May 2006)
- α=1% → probability to incorrectly reject isotropy
- β=5% → probability to incorrectly reject correlation

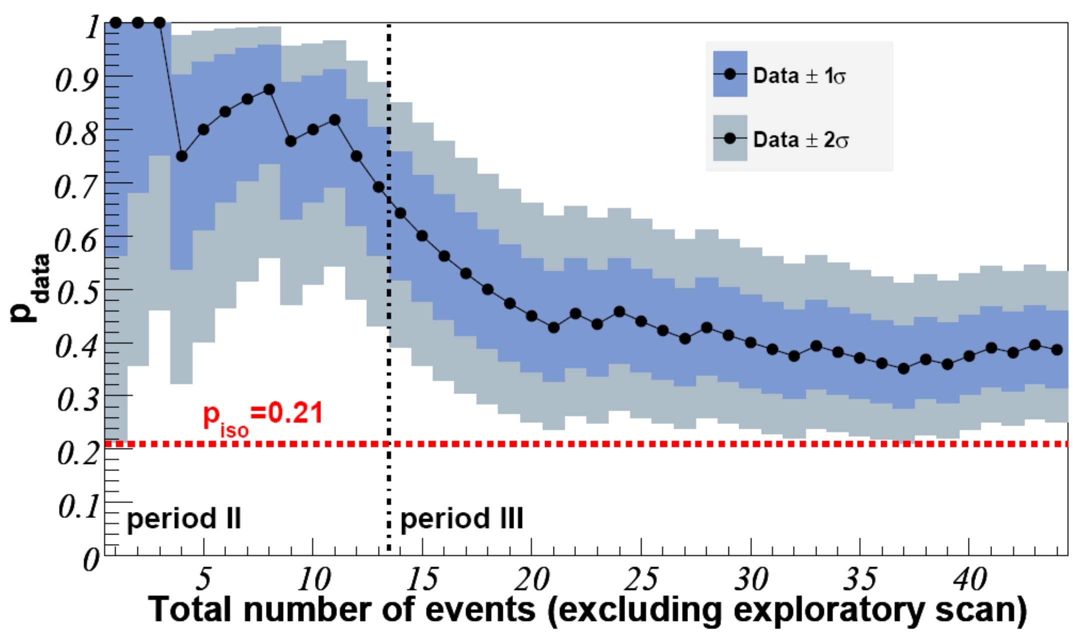
N	4	6	8	10	12	....	31	33	34
k_{min}	4	5	6	7	8	....	14	15	15

The prescription was fulfilled on May 25th 2007

CL = 99%; P = 1.7×10^{-3}



Best estimate of $p_{data} = k/N$



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Numerical summary of results for events $E \geq 55$ EeV

Period	**Exposure** km^2 sr yr	**GP**	**N** Total # events	**k** Correlated events	**k_{iso}** Expected from isotropy	**P** Cumulative binomial P
I	4390	UM M	14 10	9 8	2.9 2.5	
II	4500	UM M	13 11	9 9	2.7 2.8	2×10^{-4} 2×10^{-4}
III	8150	UM M	31 24	8 8	6.5 6.0	0.33 0.32
II+III	12650	**UM** M	**44** 35	**17** 17	**9.2** 8.8	$\mathbf{6\times10^{-3}}$ 2×10^{-3}
I+II	8890	UM M	27 21	18 17	5.7 5.3	
I+II+II	17040	UM M	58 45	26 25	12.2 11.3	

M masked (12º from the galactic plane; |b| < 12º)
UM umasked

Correlations with nearby extragalactic objects

Conclusions

- Evidence for anisotropy has not strengthened since the analysis published in *Science*. Departure from isotropy remains at the 1% level.

- The degree of correlations with objects of the VCV catalog appears to be weaker than suggested by the earliest data.

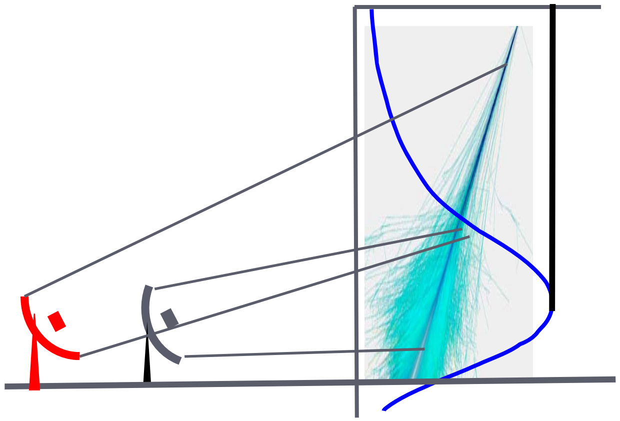
- Excess of events in the Cen A region. It warrants further study.

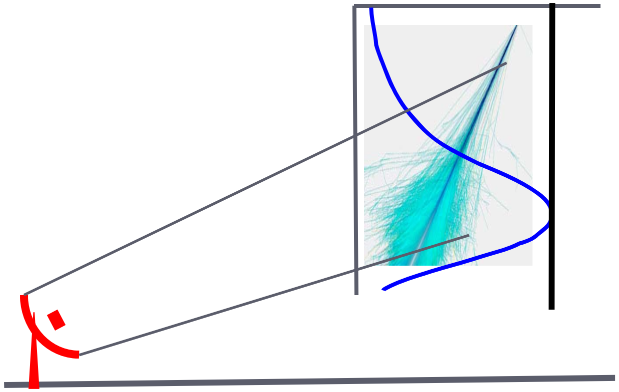
- More statistics is needed.

The Future

Enhancements of Auger South: HEAT

High Elevation Auger Telescopes





A system of tilted telescopes allows enlarging upwards the observation height of the fluorescence detector.

It provides access to a lower energy range.

Enhancements of Auger South: HEAT

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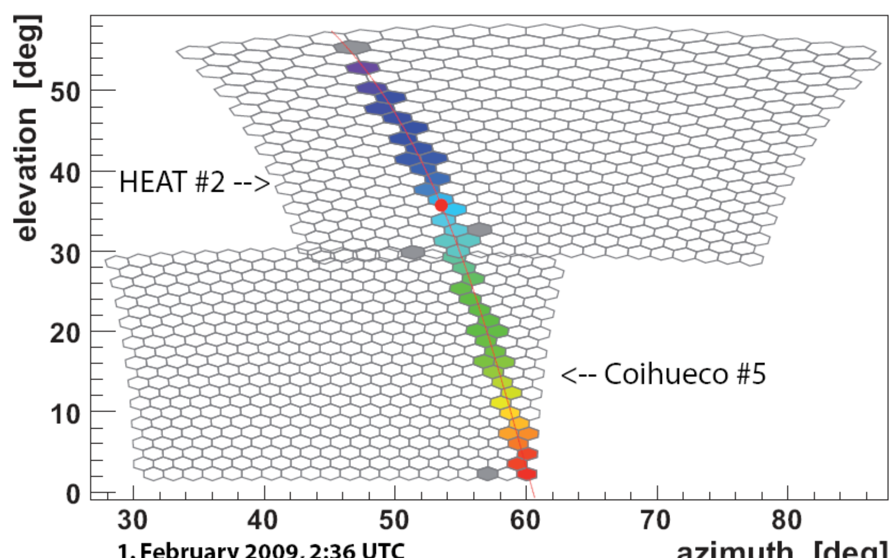
High Elevation Auger Telescopes

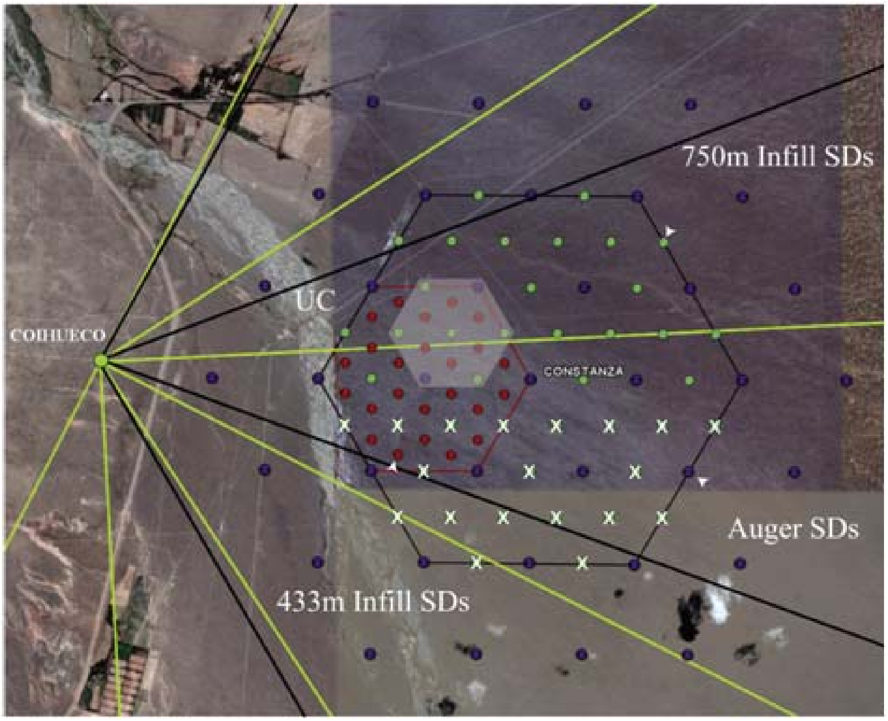


A system of tilted telescopes allows enlarging upwards the observation height of the fluorescence detector.

It provides access to a lower energy range.

Enhancements of Auger South: AMIGA

Auger Muons and Infill for the Ground Array



85 pairs of water-Cherenkov detector plus muon counter.

It aims at a detailed study of the $10^{17} - 10^{19}$ eV region

Auger North

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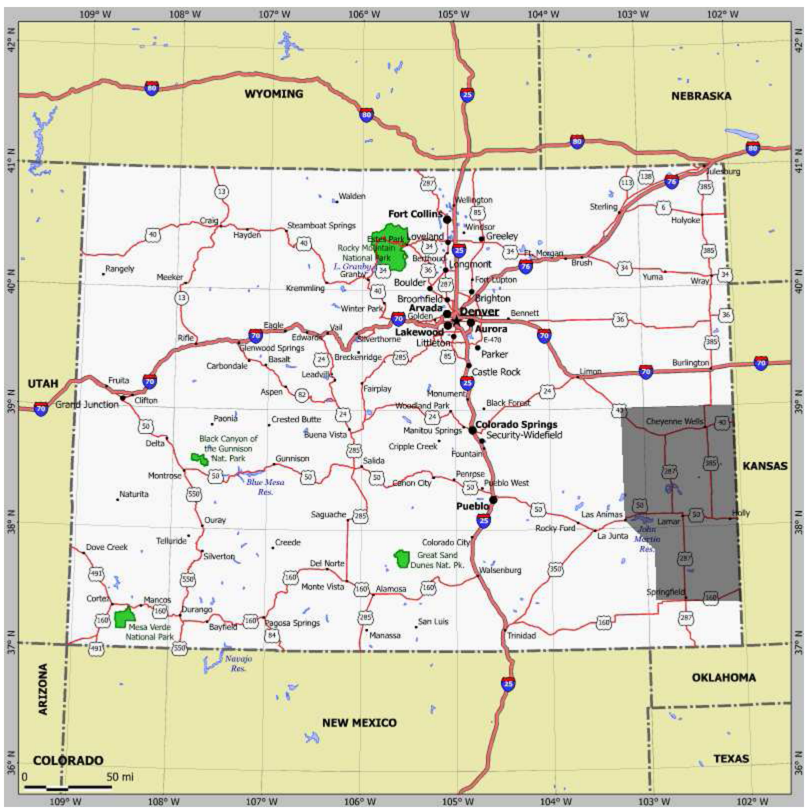
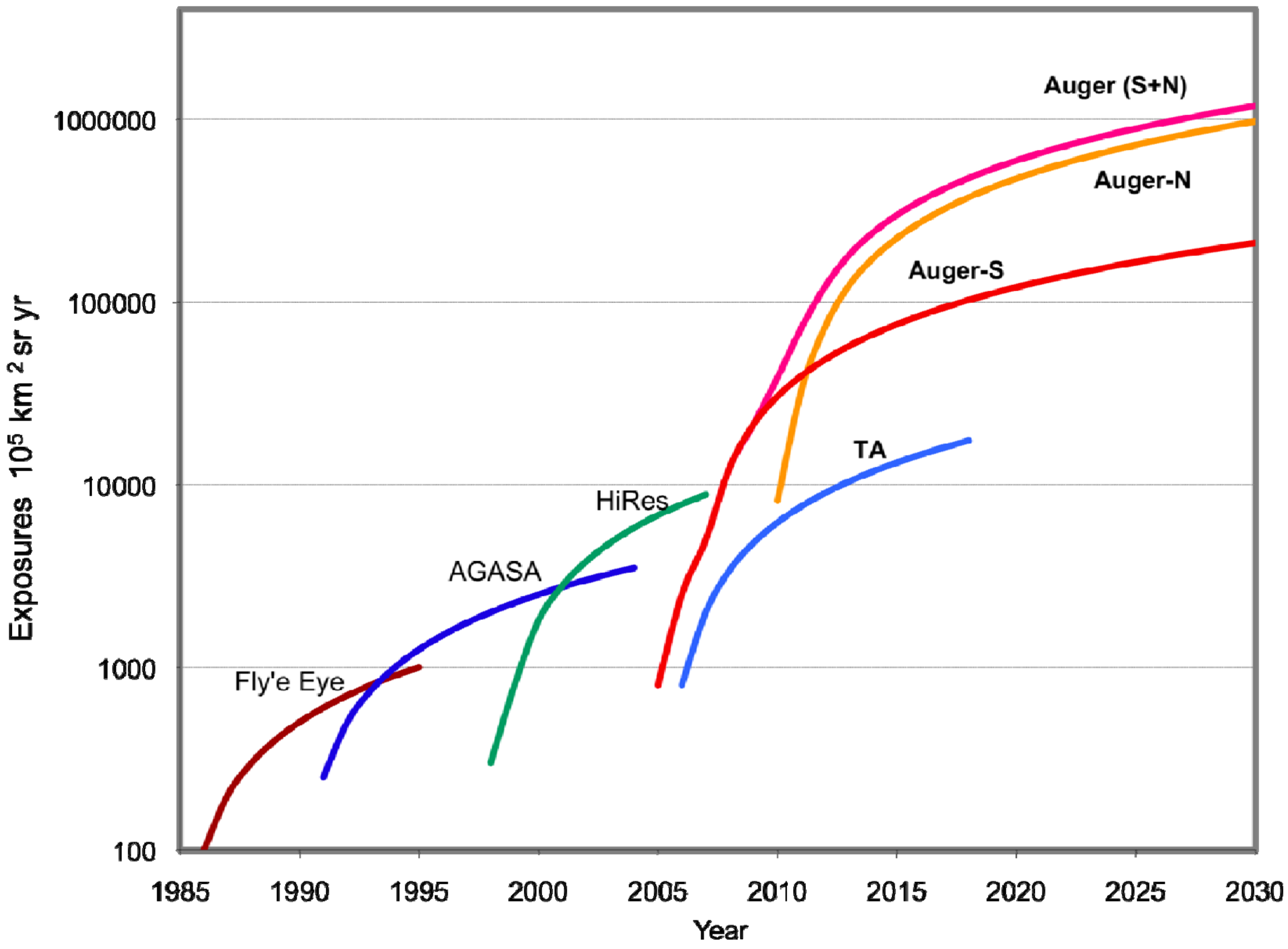
- Much larger acceptance necessary to achieve enough statistics at energies above a few times 10^{19} eV.

- The plan for Auger North is to cover an area greater than 20,000 km^2



The Future



Auger (S+N)
Auger-N
Auger-S
TA
HiRes
AGASA
Fly'e Eye
1000000
100000
10000
1000
100
Exposures 10^5 km ^{2} sr yr
1985
1990
1995
2000
2005
2010
2015
2020
2025
2030
Year

In summary

- Energy spectrum with unprecedented accuracy confirms GZK feature.
- Composition on UHECRs still under study with some indications that CRs become heavier at higher energies.
- Limits on the flux of UHE photons impose more strict restrictions to exotic models.
- Correlations with extragalactic sources weaker than suggested by the earliest data although evidence of anisotropy remains.
- Much more statistics needed. Auger North.

THANKS

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