The AUGER Experiment

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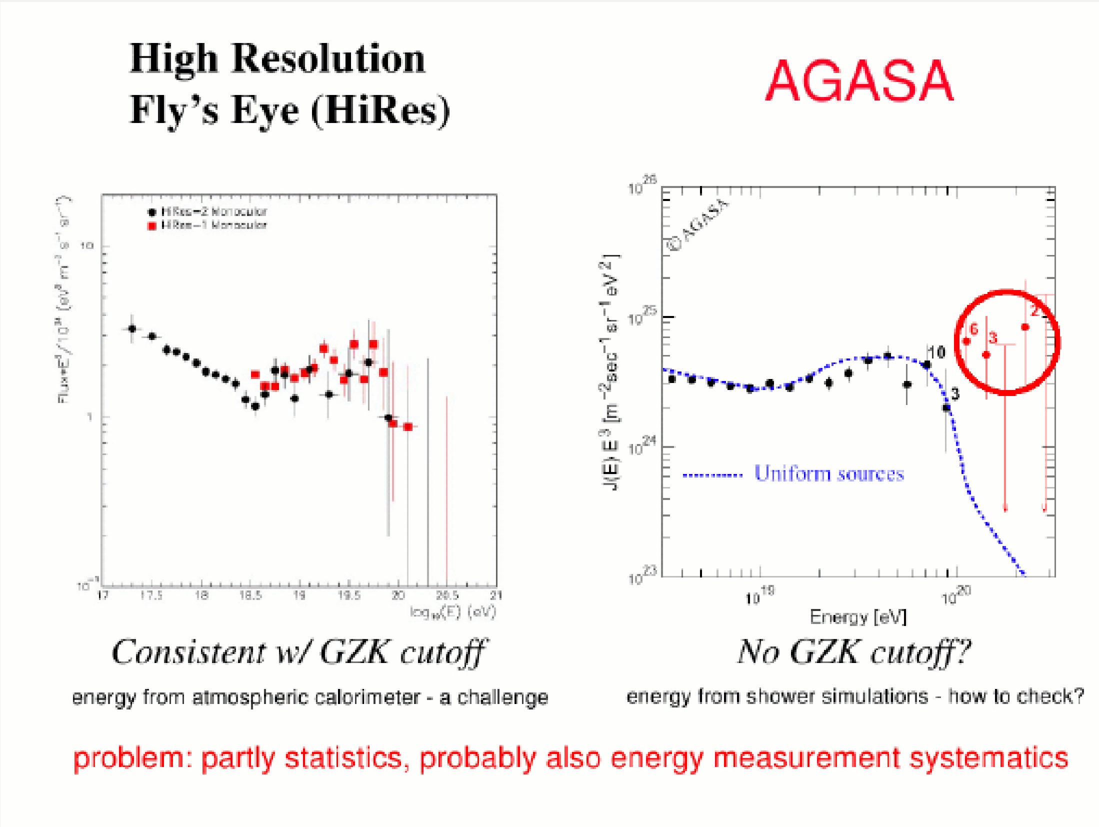
Summary

- Auger Motivations
- The Auger detectors
- Results and Open Issue

History



More than fifty years ago Greisen, Zatsepin and Kuzmin concluded that due to the presence of the Cosmic Microwave Background the universe had to be opaque to charge particle of energy largen than 10^{20} eV.

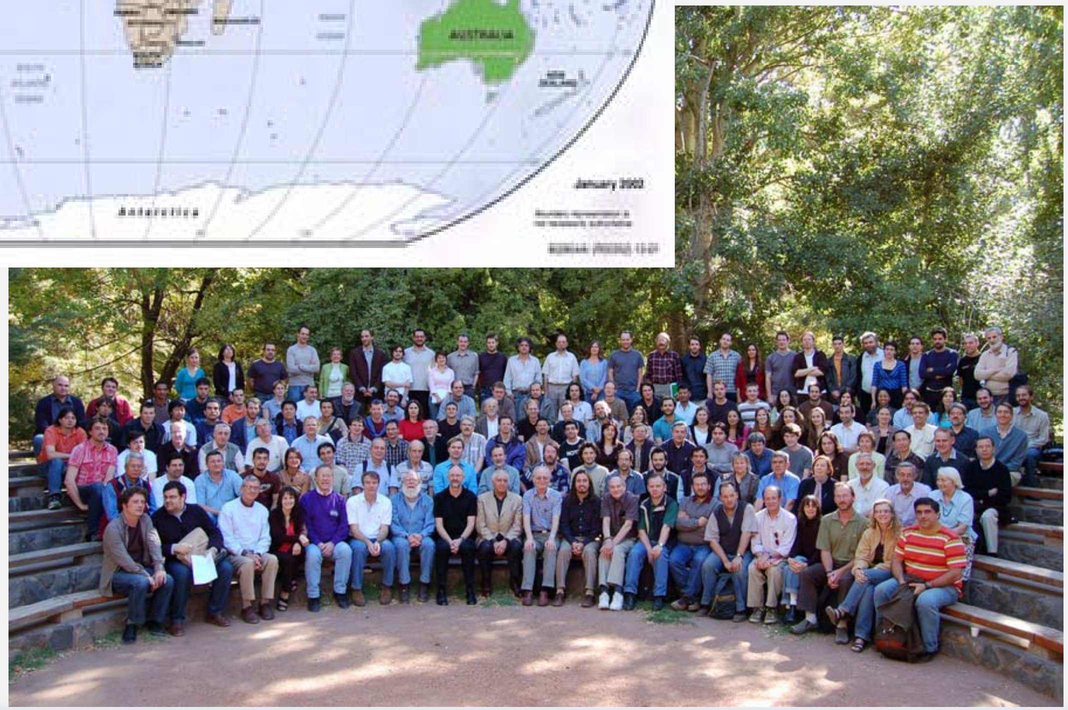
In the 90s the two experiments that could explore this region of energy gave inconsistent results.

The main goal of the AUGER experiment was to verify the existence of the GZK cut-off and study the nature of the highest energy cosmic rays.

The Pierre Auger Collaboration

Argentina
Australia
Bolivia
Brazil
Croatia
Czech Rep.
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Slovenia
Spain
UK
USA
Vietnam

18 Countries
91 Institutions
~ 463 members



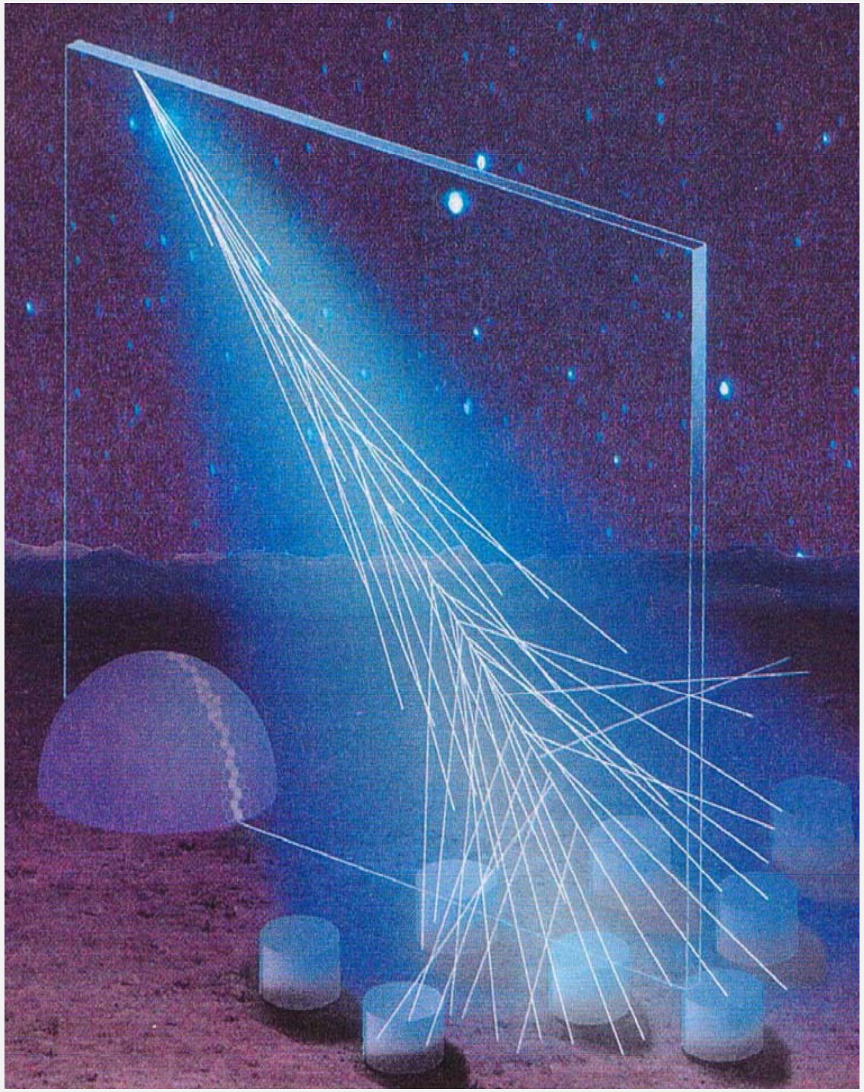
The Pierre Auger Detector

Hybrid Detector:

Array of 1660 water Cherenkov detectors
covering 3000 km^2
duty cycle: 100%

Fluorescence telescopes
27 FDs (30^{o}x30^o each)
duty cycle: 14%

Better geometric reconstruction, cross-calibration, control of systematic.



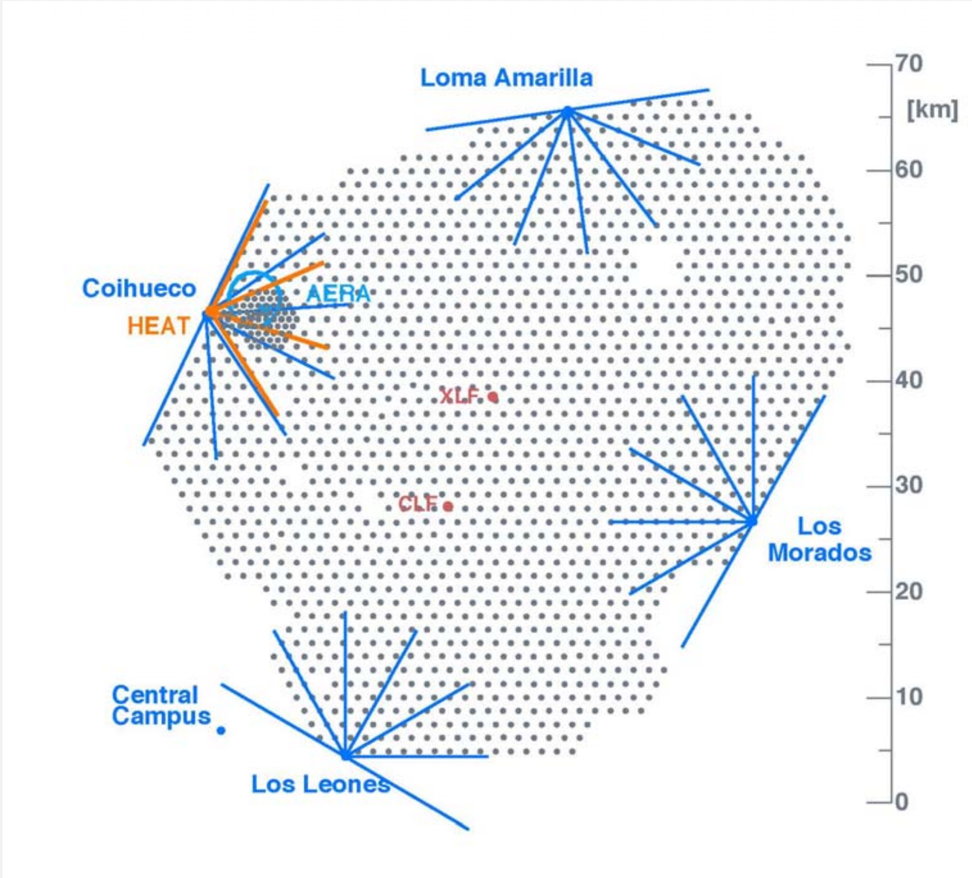
The Pierre Auger Observatory

1660 tanks installed!

27 FD Telescopes (4 positions)!

Completed in 2008 !

Taking data since 2004

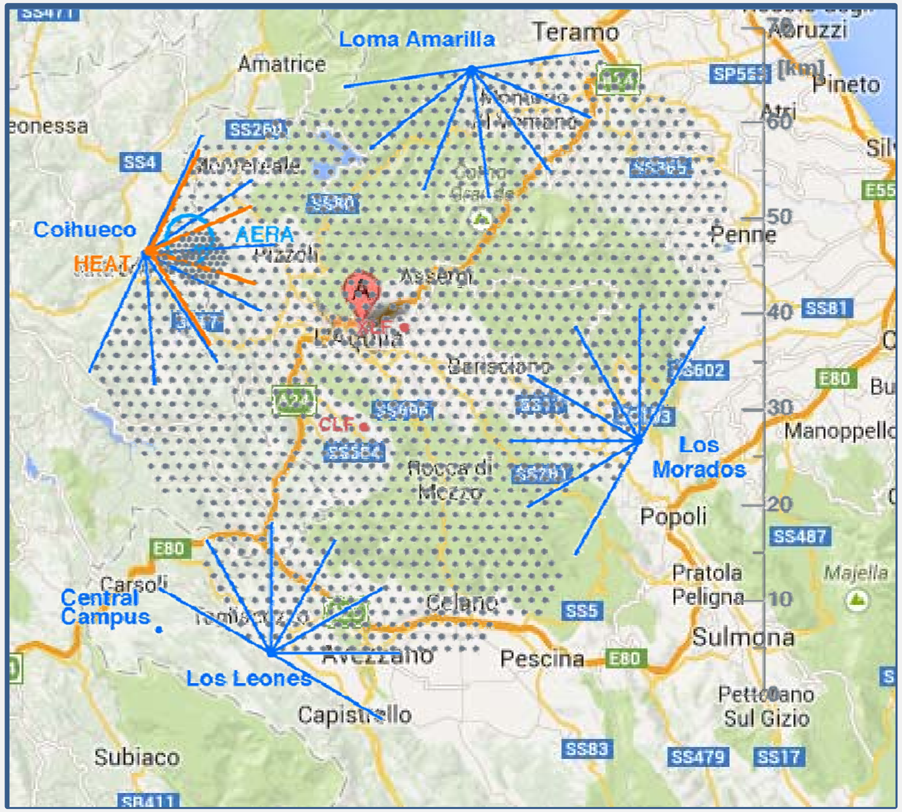


≈ 3000 evts/yr with E > 10^{19} eV

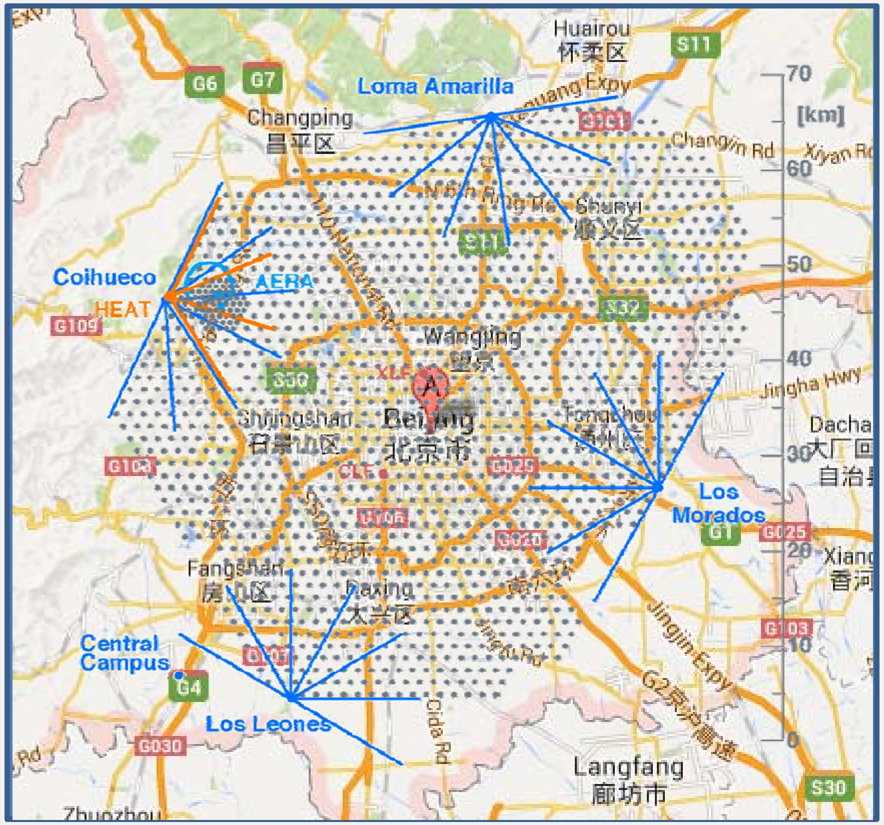
The Pierre Auger Observatory

World largest array! 3000 km^2 area

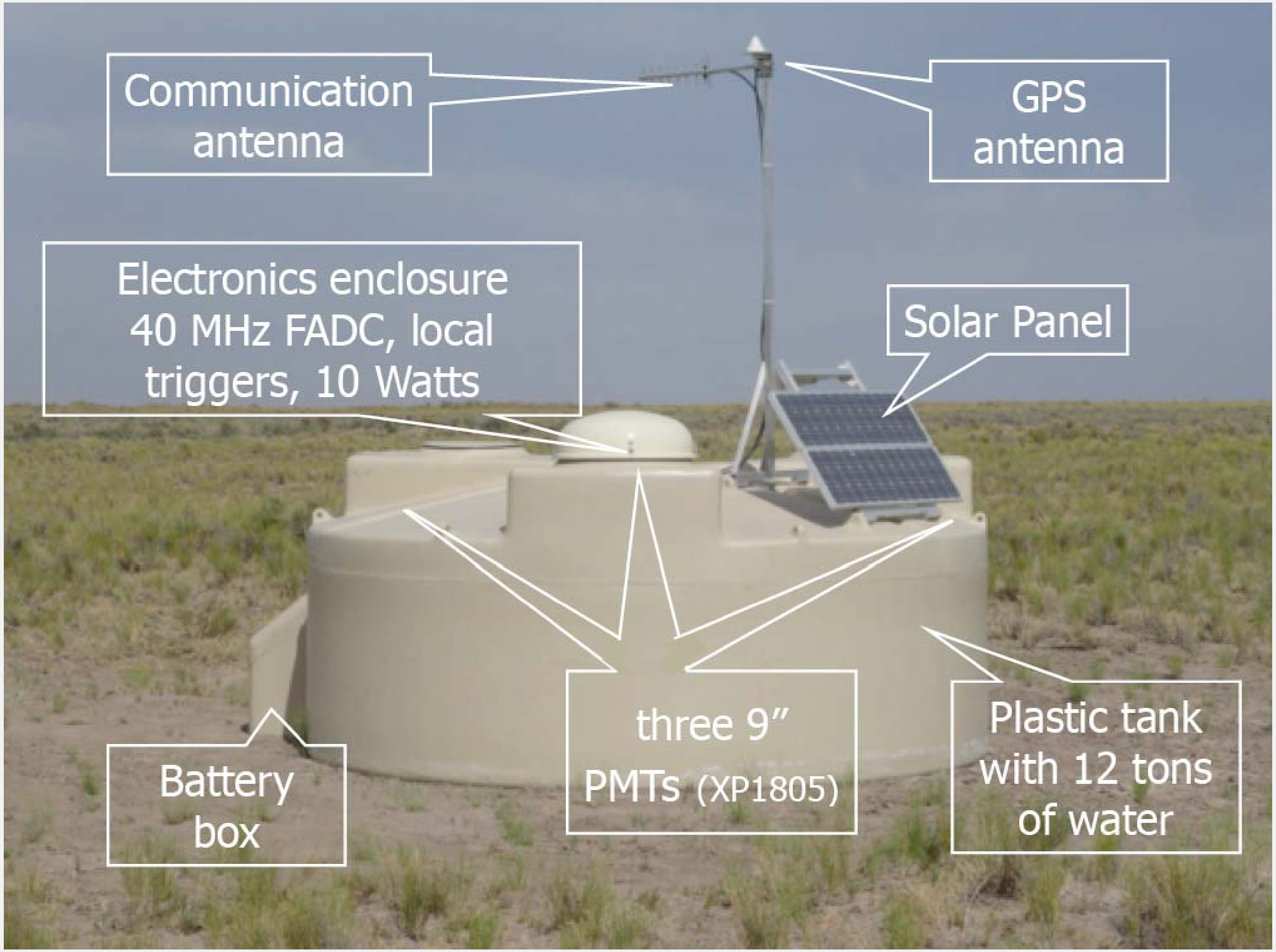
INFN



IHEP



The Surface Detector (SD)



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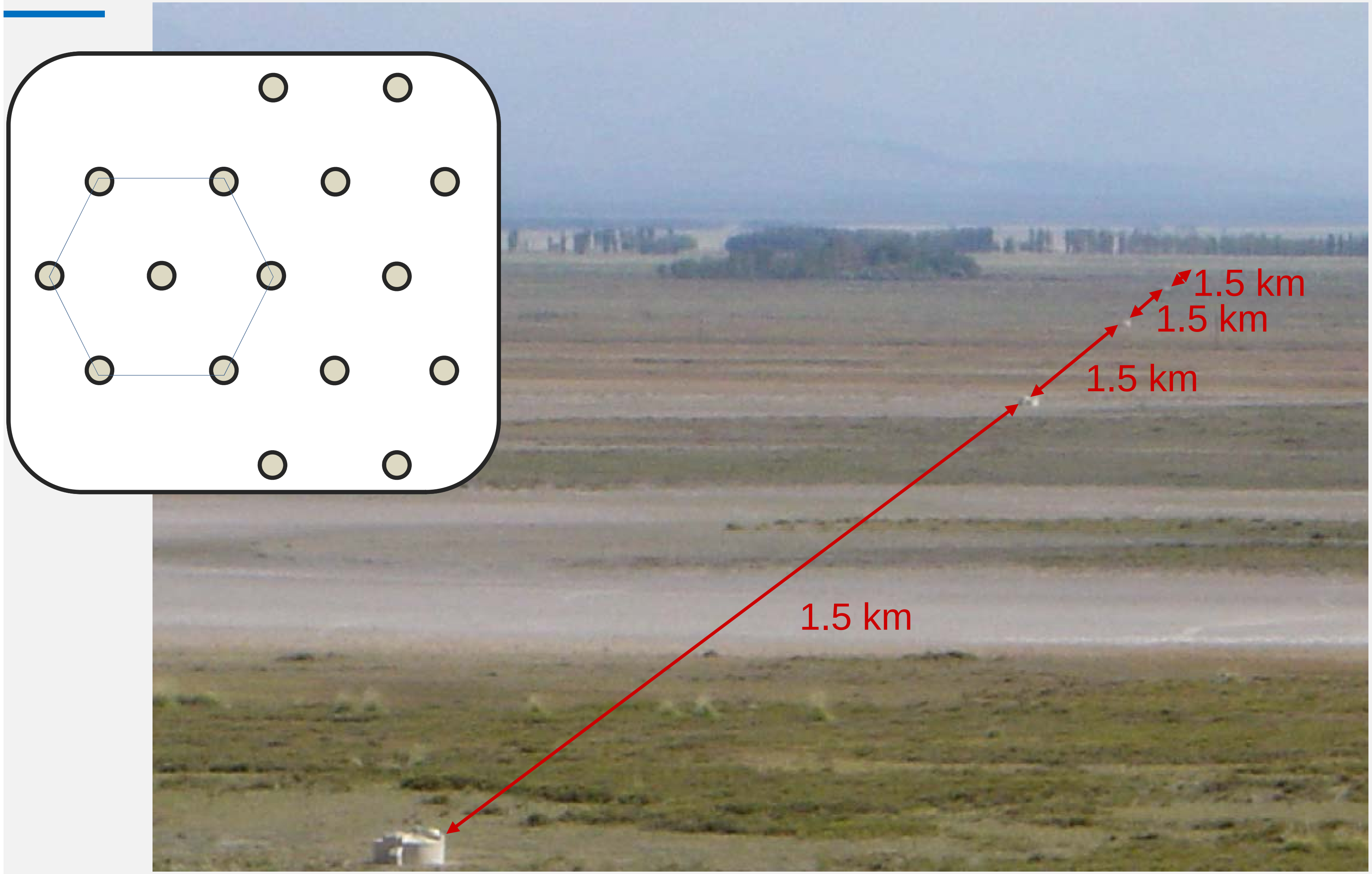
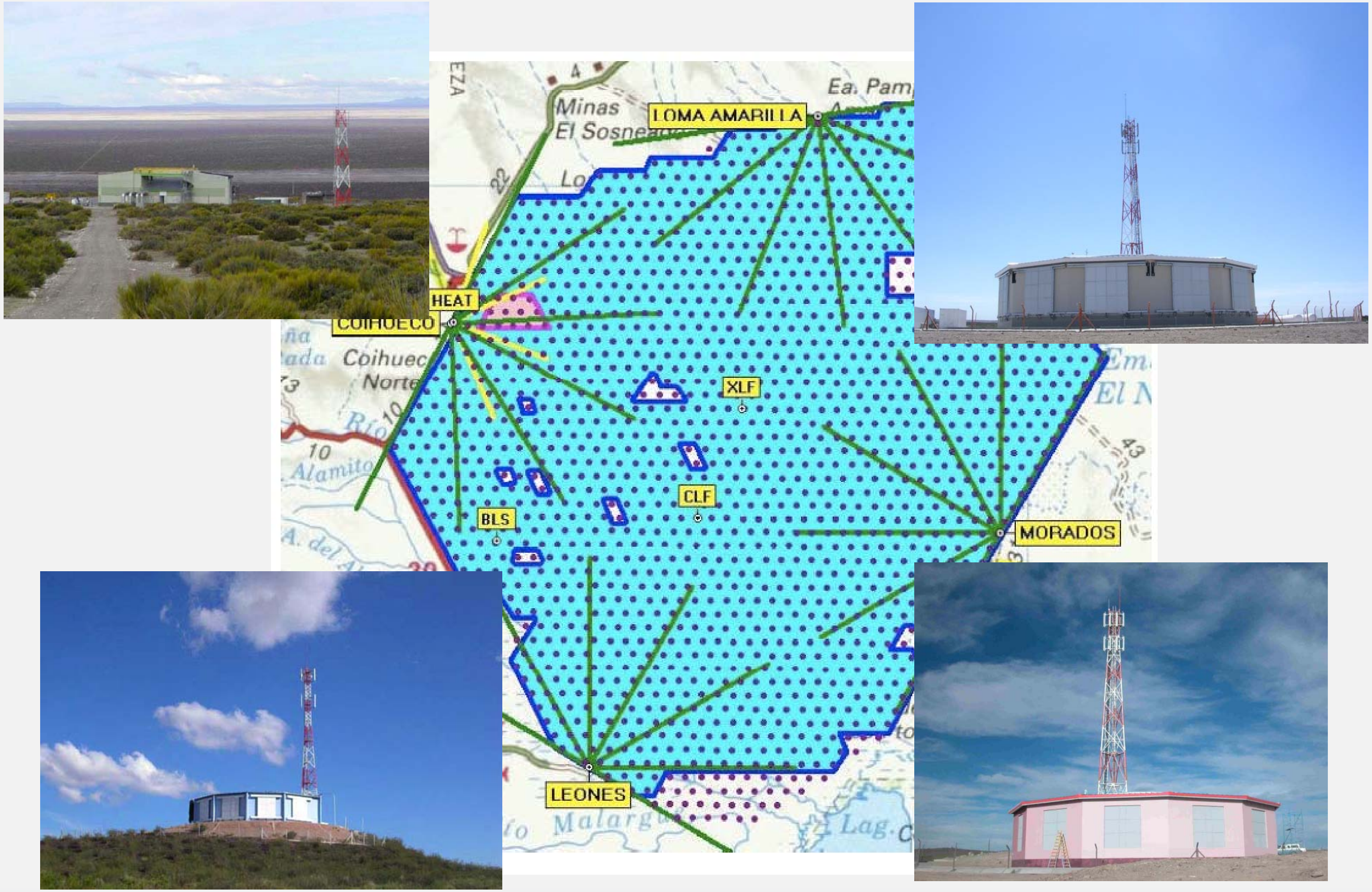


The Fluorescence Detector (FD)



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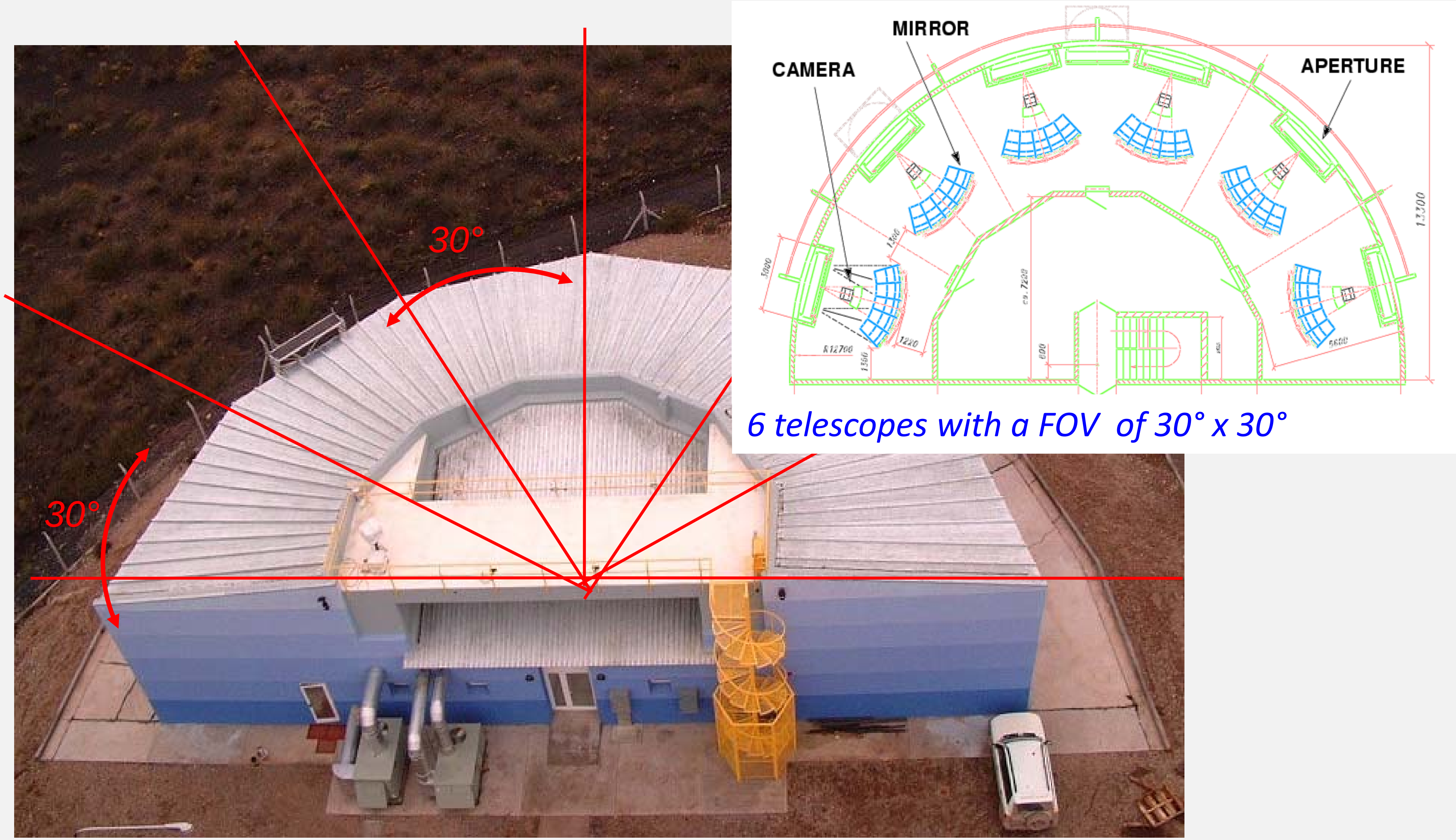
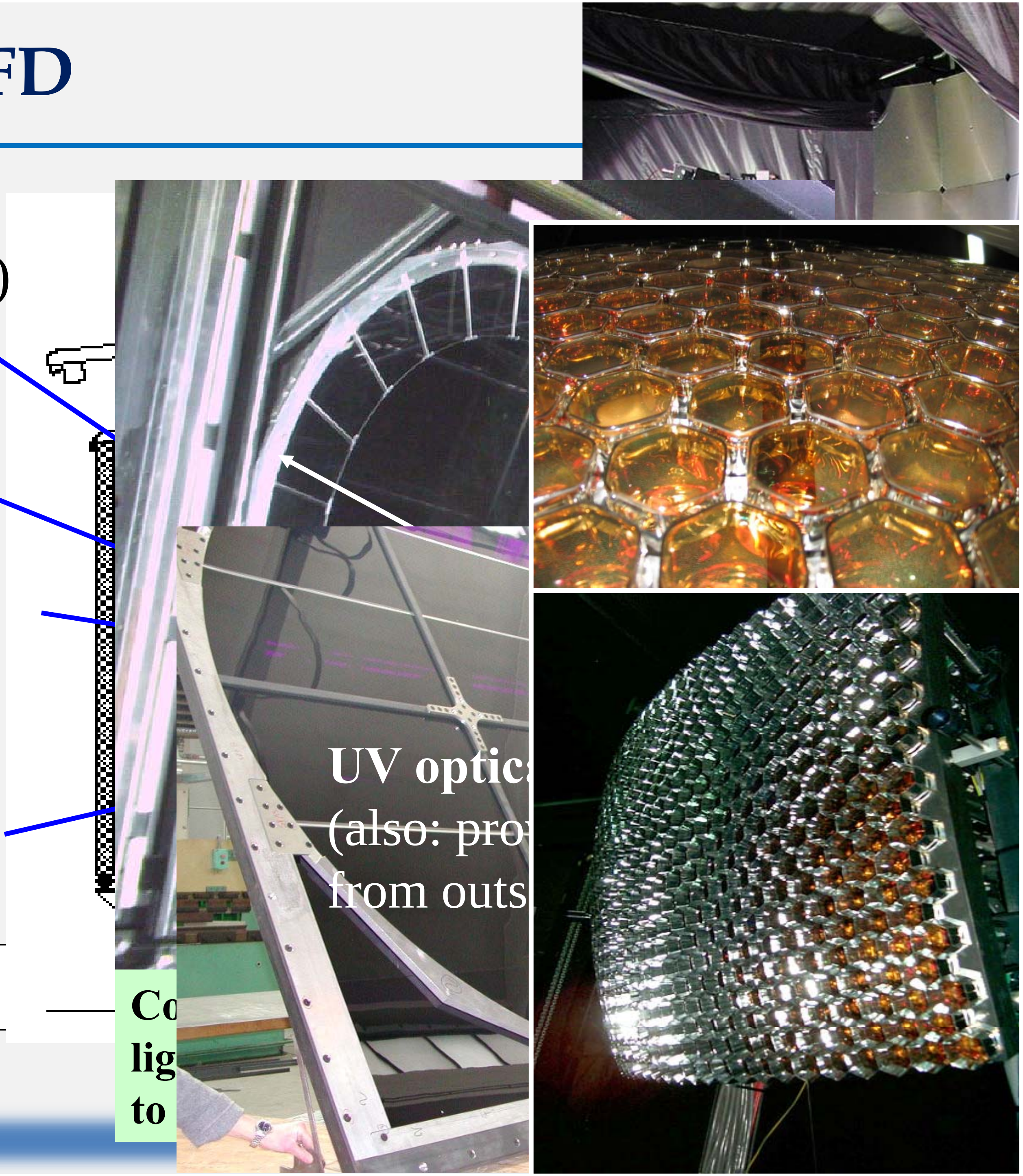


6 telescopes with a FOV of 30° x 30°

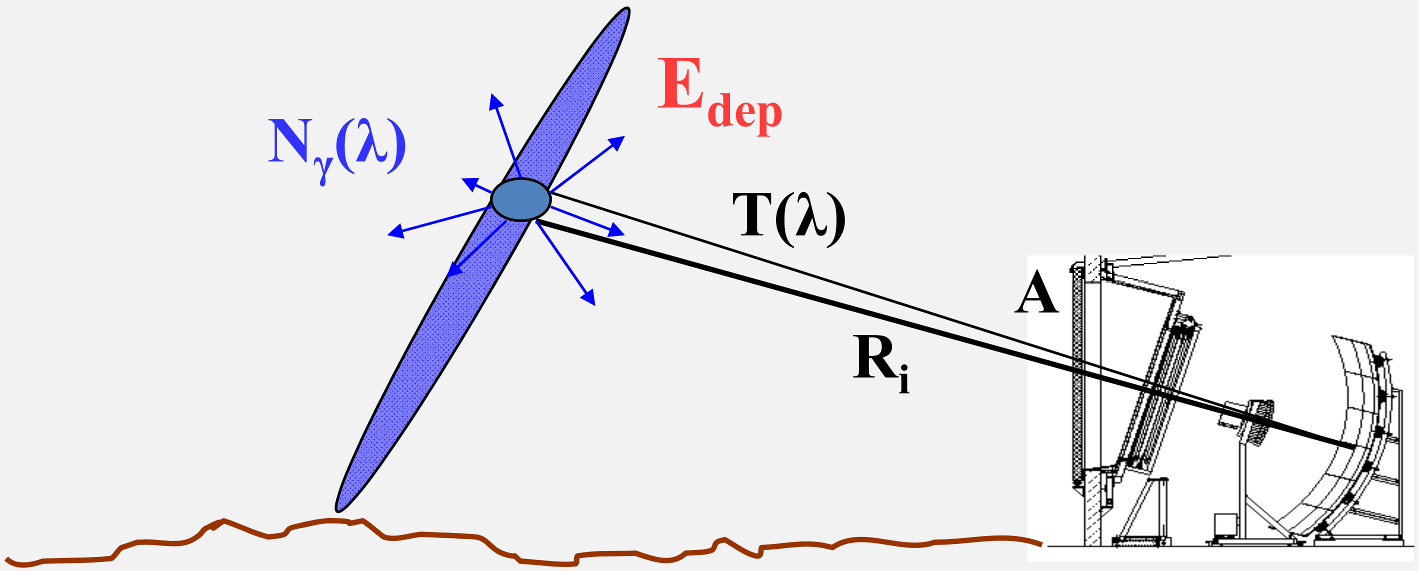
The Telescope FD

- ✓corrector ring (2.2 m)
- ✓UV Filter
- ✓3.4m mirror
- ✓Camera with a FOV 30°x30°



Duty cycle 14%

Detector Performance: the FD Energy Scale



E_{dep} → $N_\gamma(\lambda)$ → Photons in FD FOV → Photons at diaphragm → ADC counts

Fluorescence yield
(from laboratory measurements)

Geometry

$$\frac{A}{R_i^2}$$

Atmosphere
$T(\lambda)$

Detector calibration

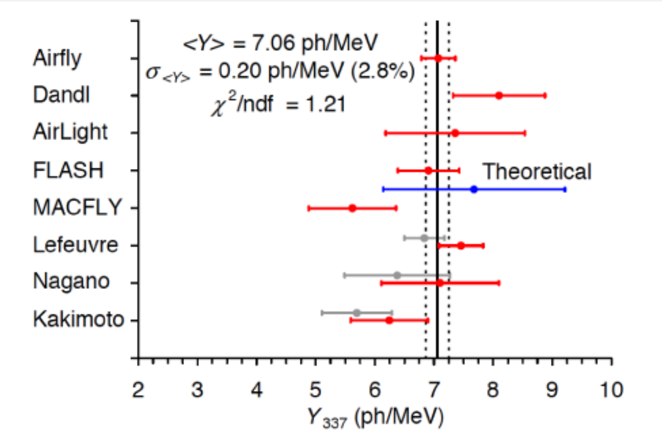
The FD Energy Scale

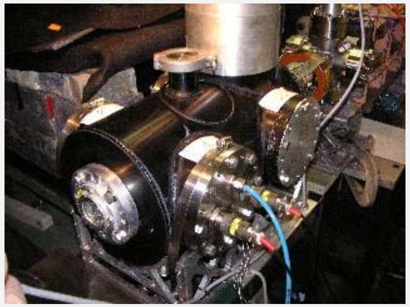
E_{dep} → $N_\gamma(\lambda)$ → Photons in FD FOV → Photons at diaphragm → ADC counts

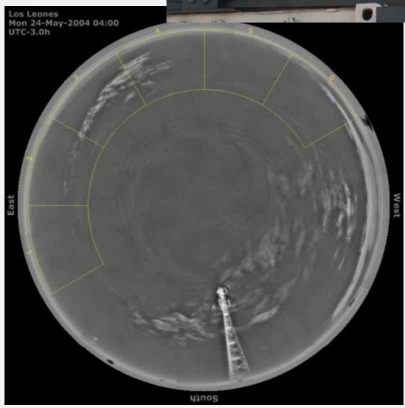
Fluorescence yield

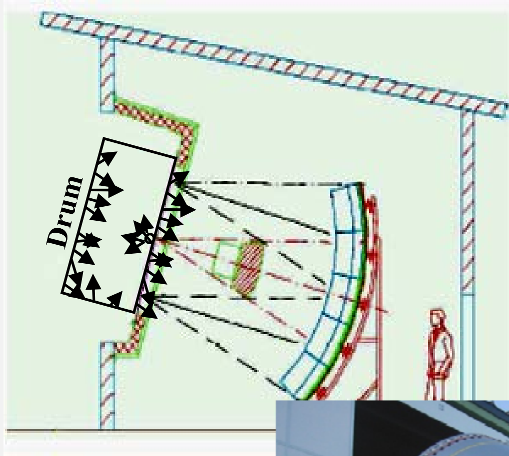
Atmosphere
$T(\lambda)$

Detector calibration









The FD Energy Scale

The new Energy Scale

Absolute fluorescence yield	3.4%		
Fluores. spectrum and quenching param.	1.1%		
Sub total (Fluorescence Yield)	**3.6%**	**14%**	
Aerosol optical depth	3% ÷ 6%		
Aerosol phase function	1%		
Wavelength dependence of aerosol scattering	0.5%		
Atmospheric density profile	1%		
Sub total (Atmosphere)	**3.4% ÷ 6.2%**	**5% ÷ 8%**	
Absolute FD calibration	9%		
Nightly relative calibration	2%		
Optical efficiency	3.5%		
Sub total (FD calibration)	**9.9%**	**9.5%**	
Folding with point spread function	5%		
Multiple scattering model	1%		
Simulation bias	2%		
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%		
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**	**10%**	
Invisible energy	**3% ÷ 1.5%**	**4%**	
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**		
Stability of the energy scale	**5%**		
TOTAL	**14%**	**22%**	⬅

uncertainties on previous energy scale

improvement in each sector with the exception of FD cal. (largest contribution) work in progress to reduce it

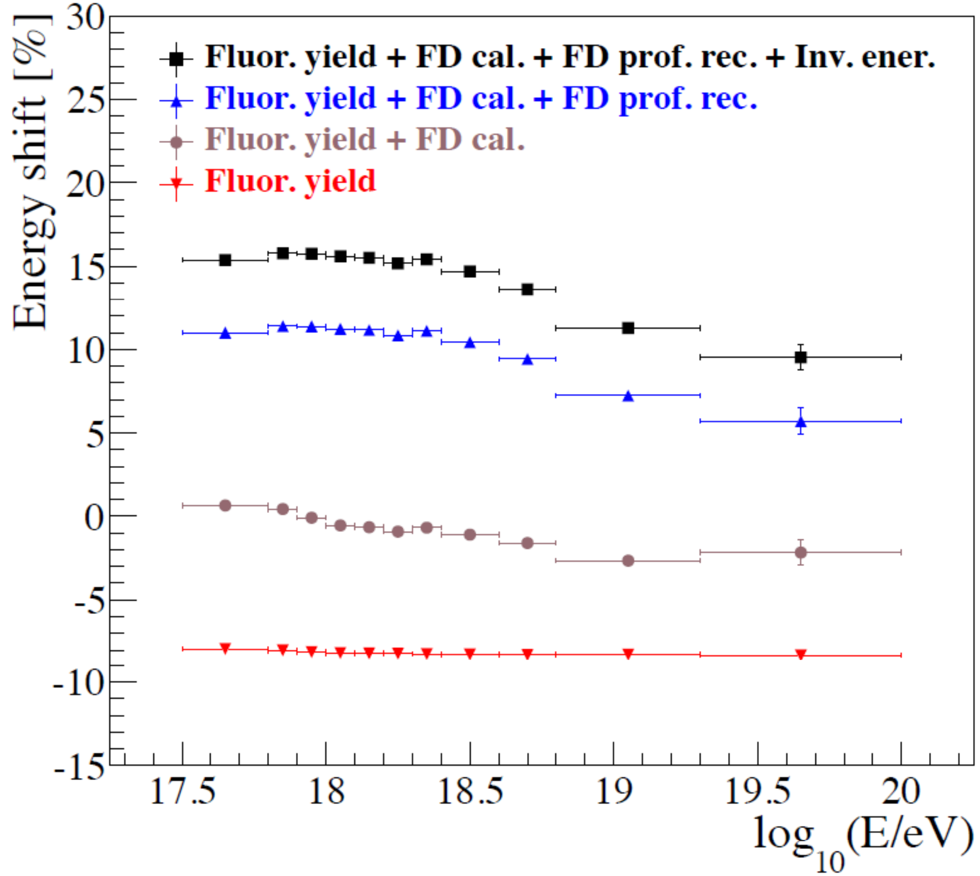
V. Verzi ICRC 2013

The FD Energy Scale

V. Verzi ICRC 2013 maximum change at 10^{18} eV

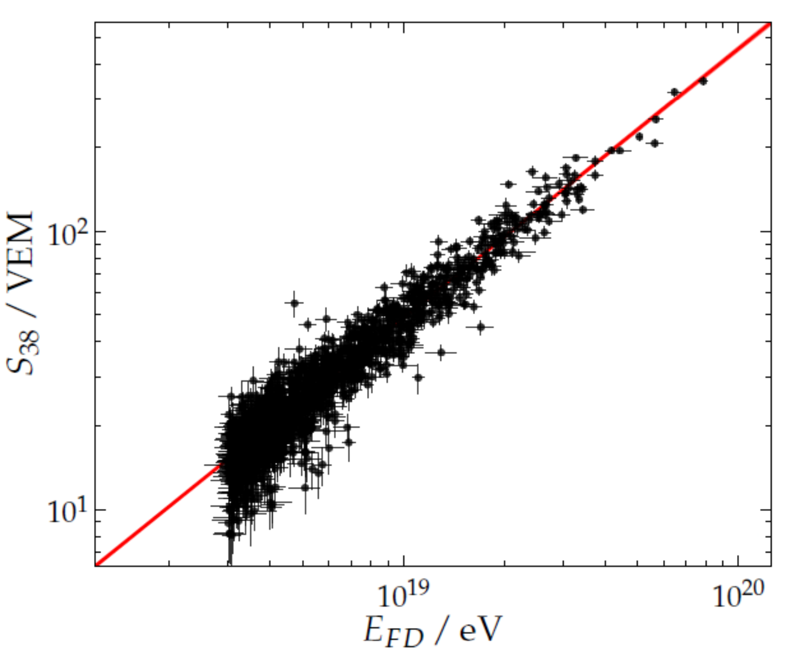
Absolute fluorescence yield	**-8.2%**
New opt. eff.	4.3%
Calibr. database update	3.5%
Sub total (FD cal.)	**7.8%**
Likelihood fit of dE/dX	2.2%
Folding with point. spr. func.	9.4%
Sub total (FD prof. rec.)	**11.6%**
Invisible energy	**4.4%**
Total	**15.6%**

The new Energy Scale

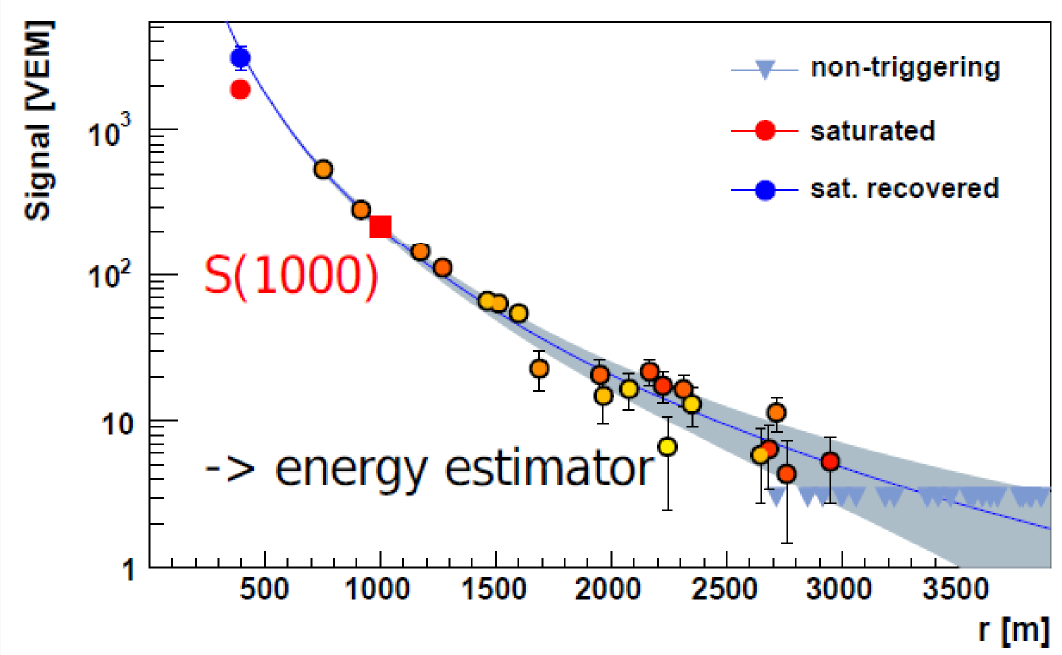


The review of the process of measurement of energy has changed the scale of energy unevenly.

The Energy Calibration



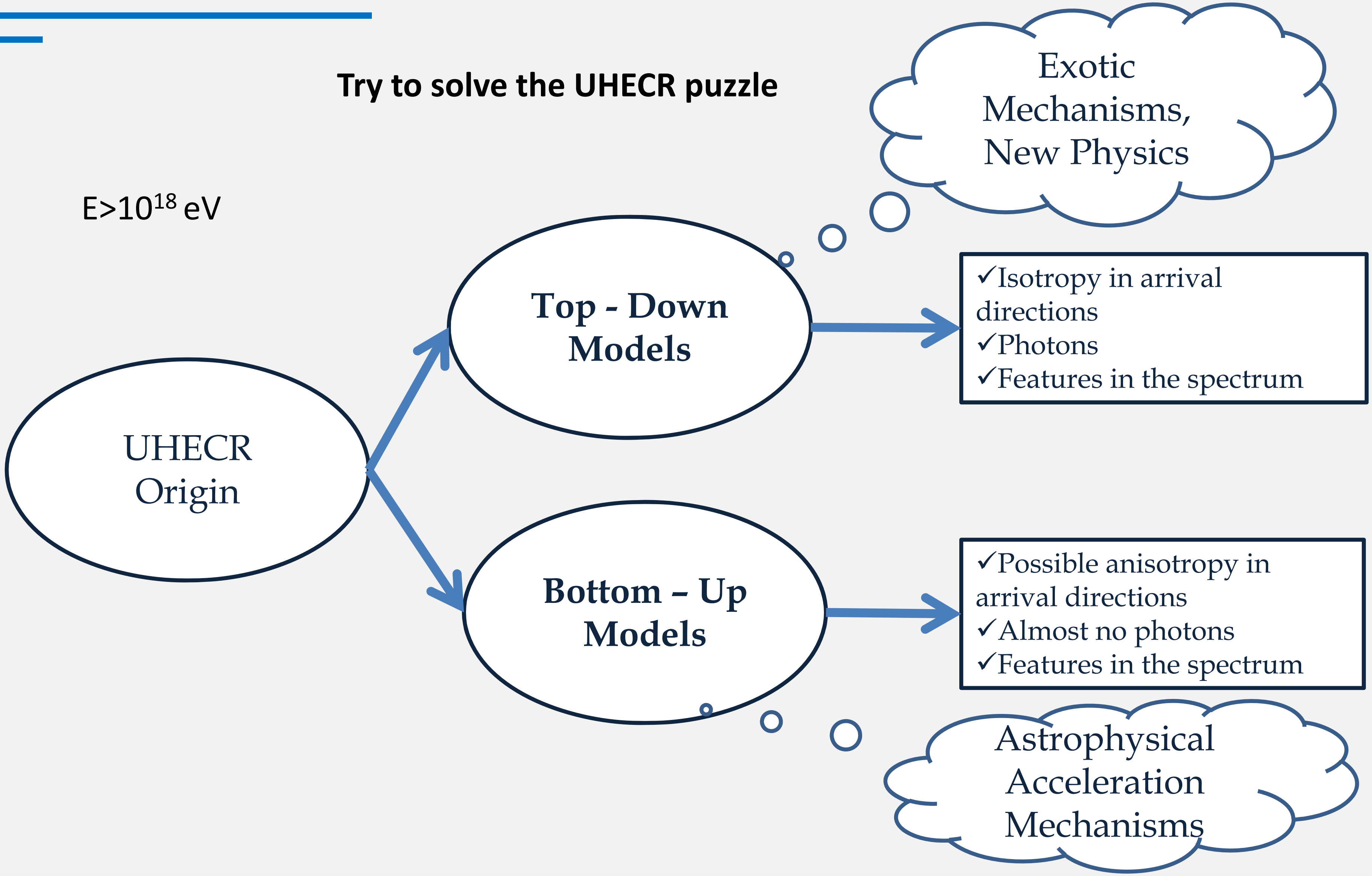
The Sd detector is calibrated using "hybrid" data. No comparison with the MC is required!



The UHECR Puzzle

Try to solve the UHECR puzzle

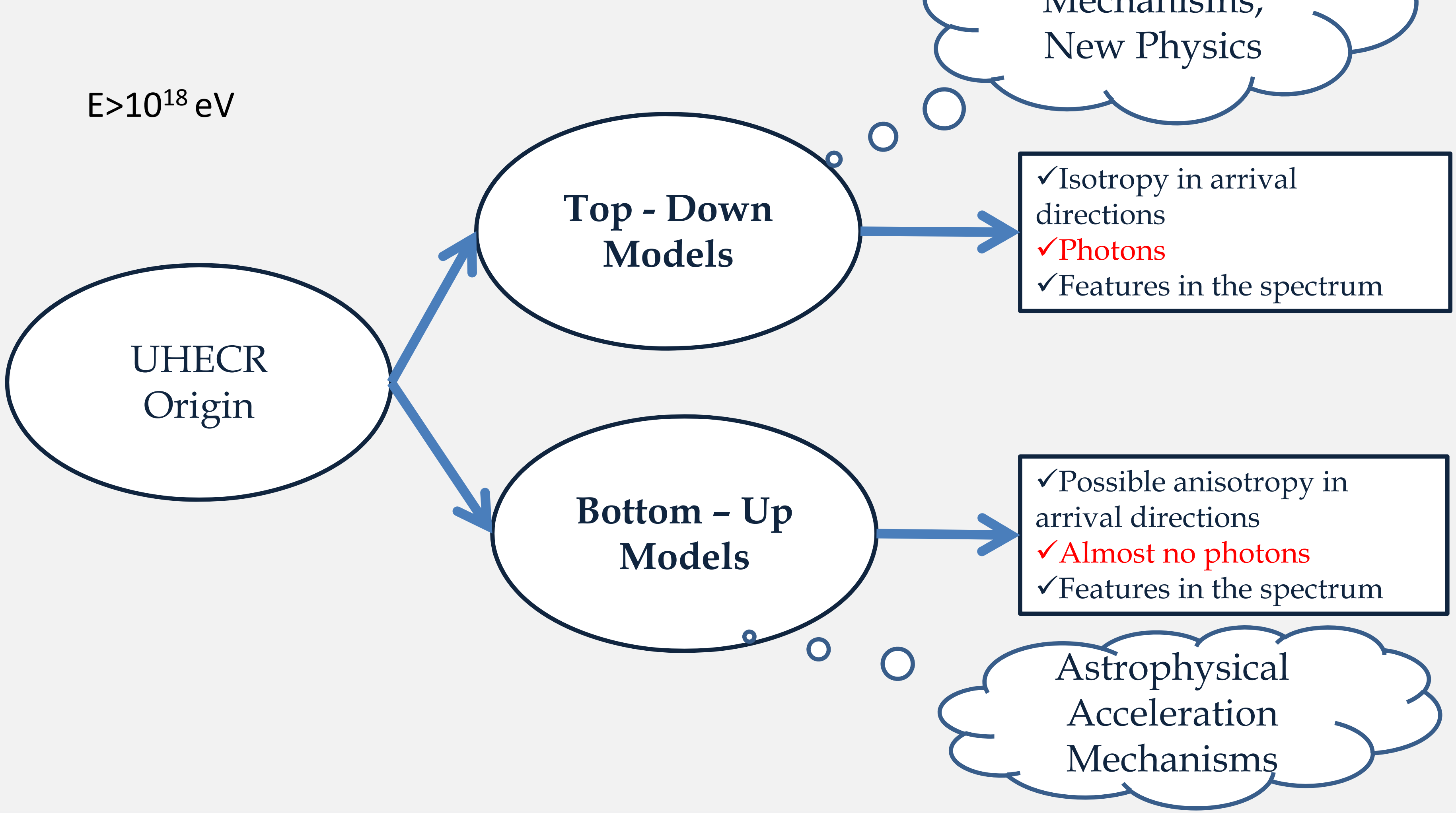
E>10^{18} eV



The UHECR Puzzle

Try to solve the UHECR puzzle

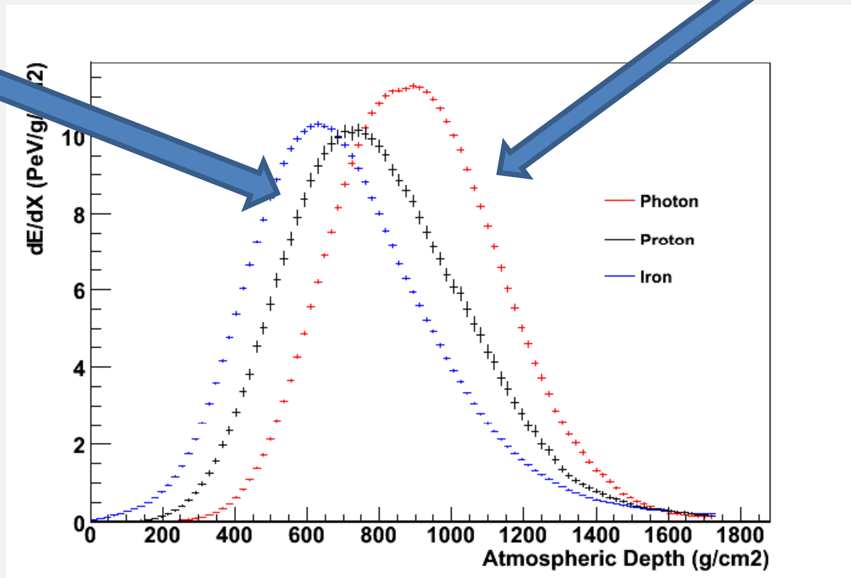
$E > 10^{18}$ eV



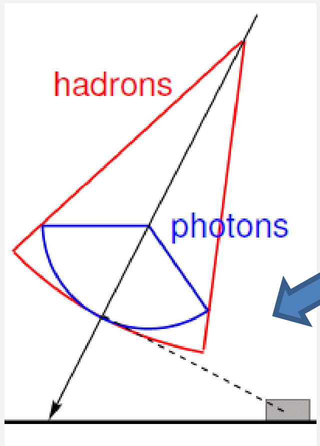
Photons

Photons

hadrons

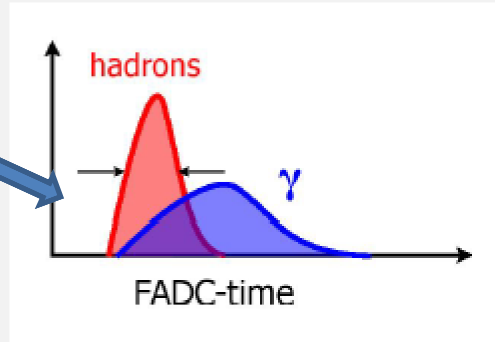


FD photons search based on X_{max} distribution



Deeper showers larger curvature

Slower signal, longer risetime

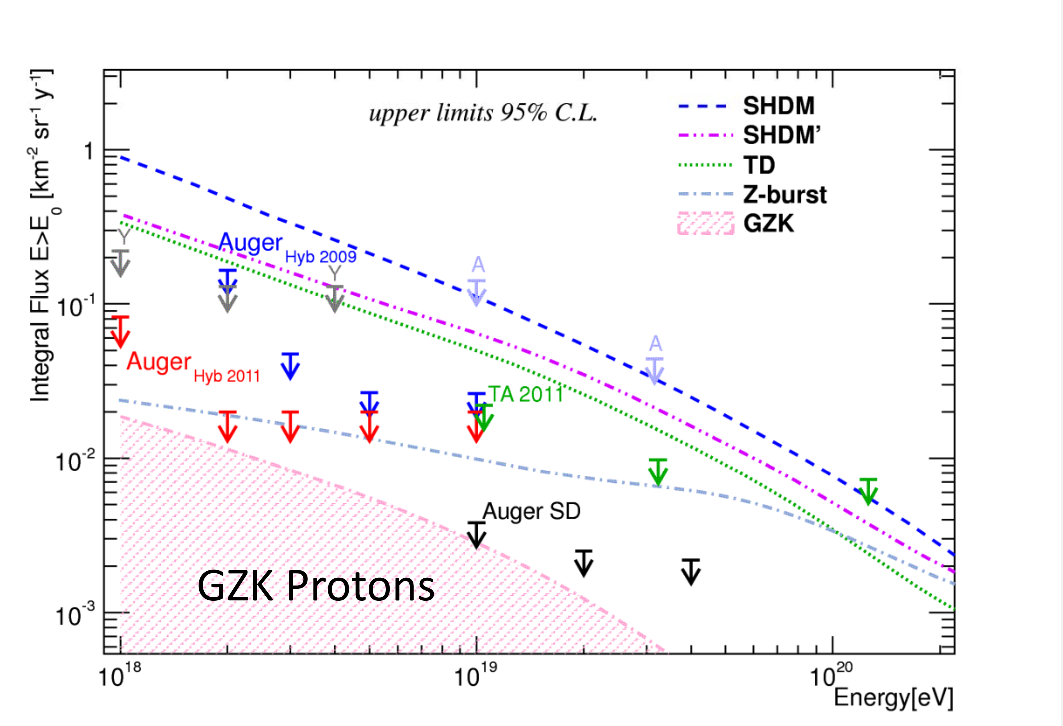


SD photons search based on signal structure

Photons

Exotic Mechanisms
- ✓ Decay of topological defects
- ✓ Relic monopoles
- ✓ Etc.

New Physics
- ✓ Supersymmetric particles
- ✓ Strongly interacting neutrinos
- ✓ Decay of massive new long lived particles
- ✓ Etc.



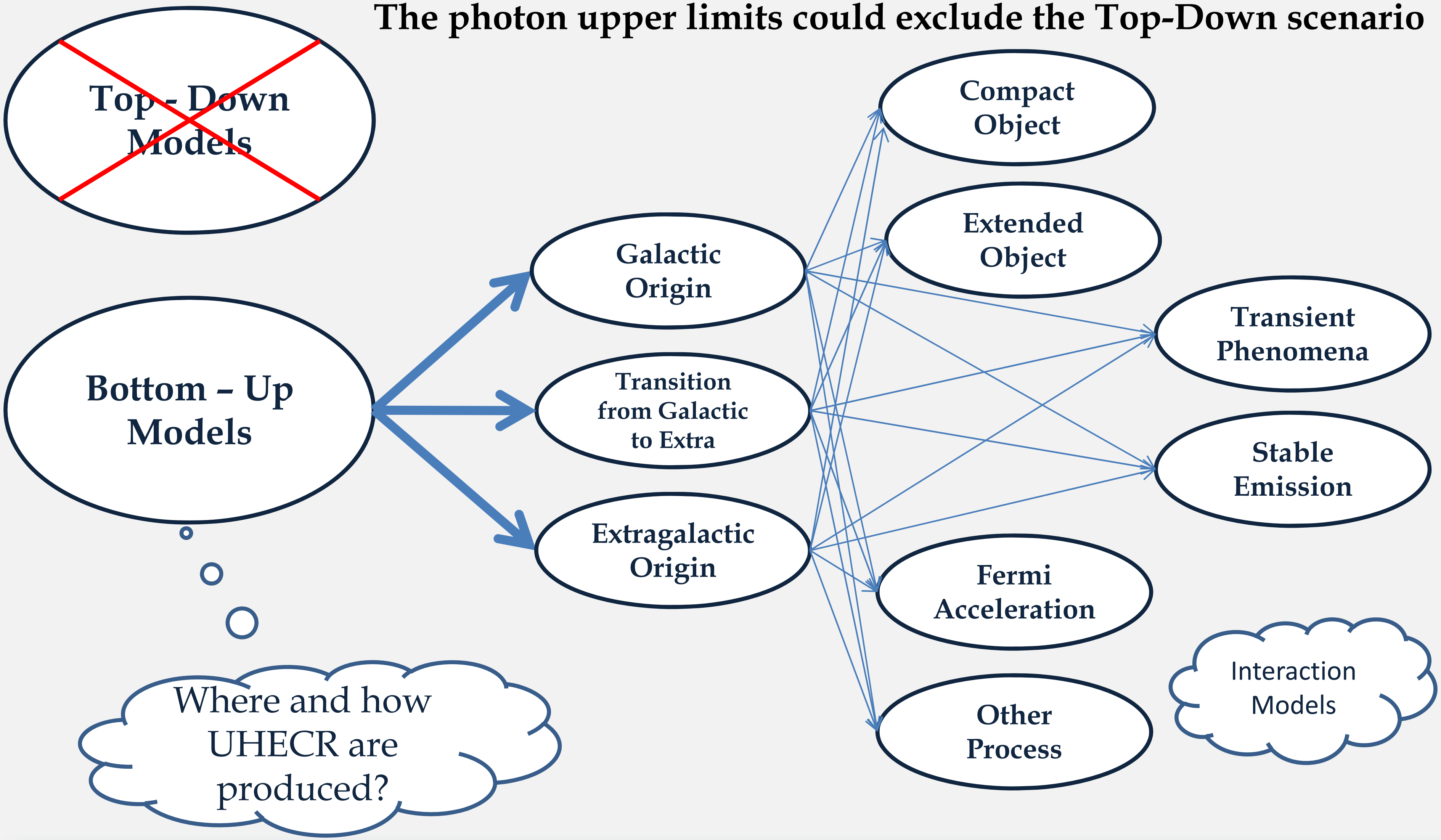
GZK region within reach in the next years

Top-down models severely constrained

Favor astrophysical origin of UHECR

Photons: implications

The photon upper limits could exclude the Top-Down scenario



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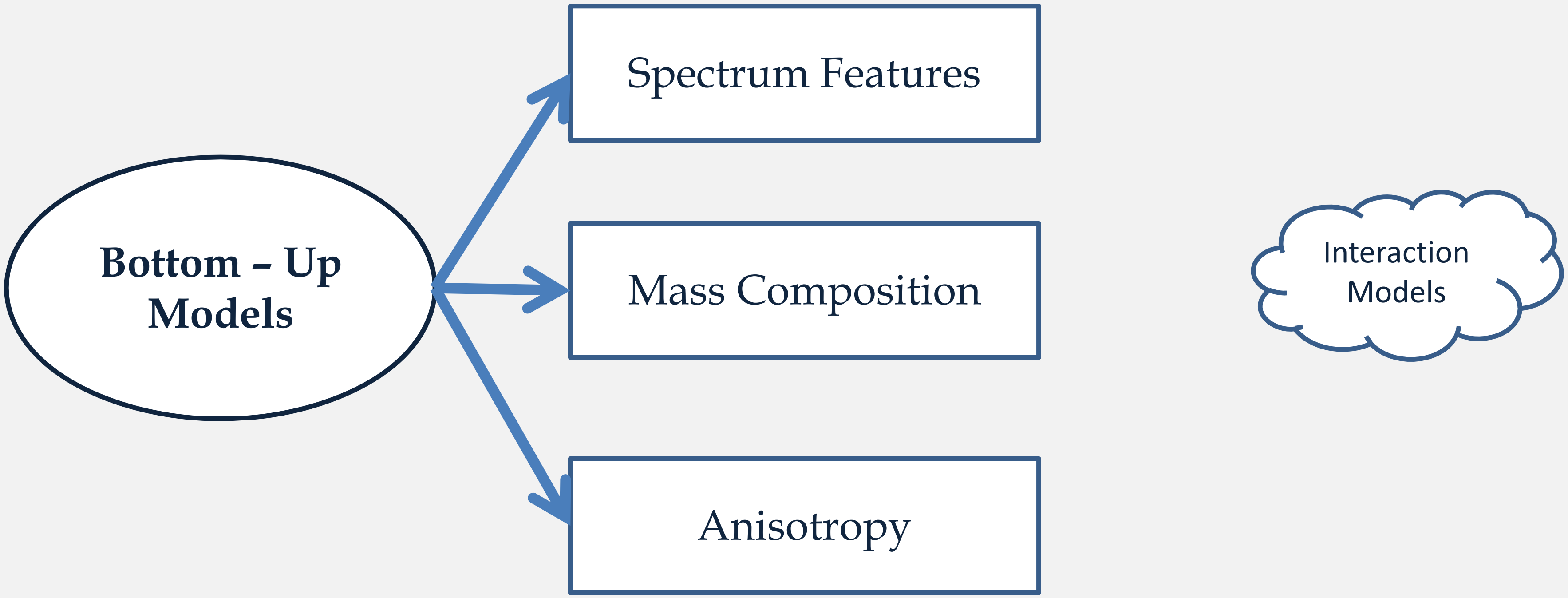
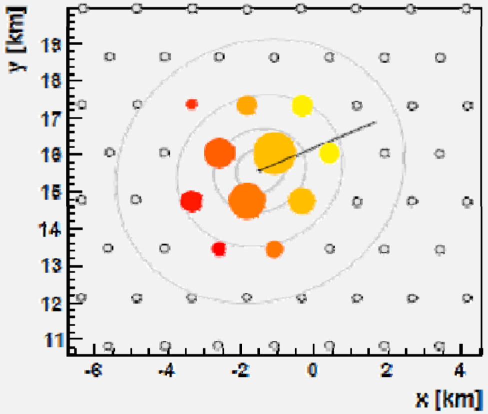


The Spectrum

SD 1500 m, $\theta < 60°$

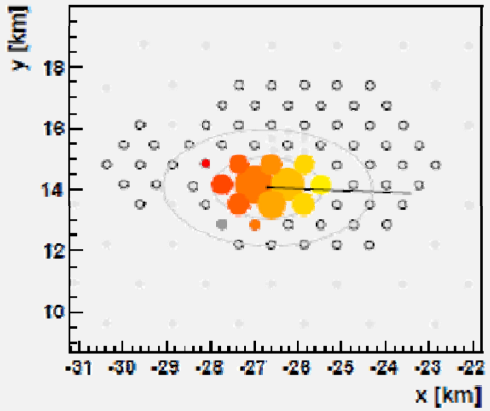


Vertical events

fully efficient:
$E \geq 3$ EeV

energy estimator:
S_{38}

SD 750 m, $\theta < 55°$

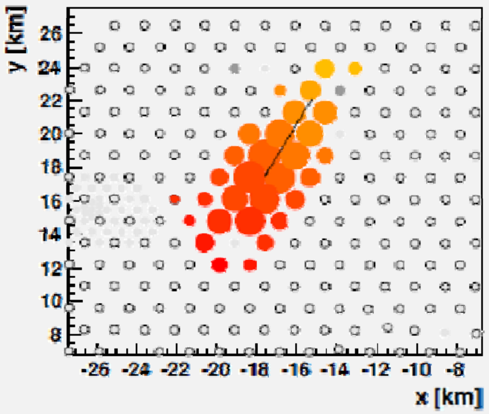


750 m events

fully efficient:
$E \geq 0.3$ EeV

energy estimator:
S_{35}

SD 1500 m, $62° < \theta < 80°$

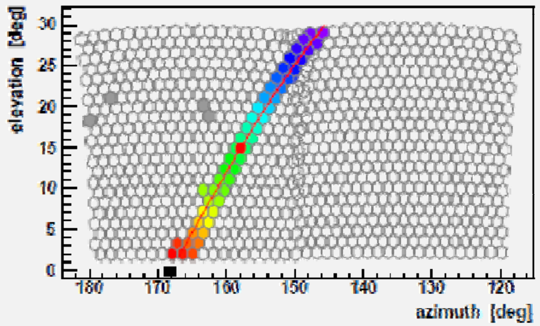


Inclined events

fully efficient:
$E \geq 4$ EeV

energy estimator:
N_{19}

Hybrid (FD + 1 SD), $\theta < 60°$



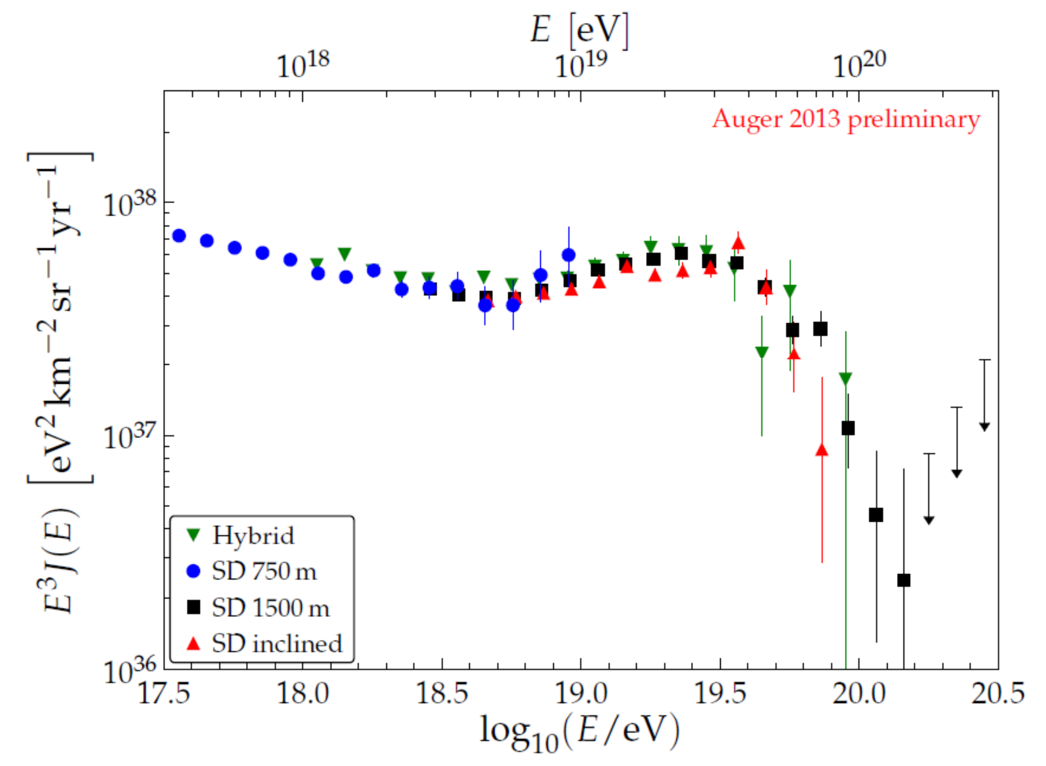
Hybrid events

fully efficient:
$E \geq 1$ EeV

energy meas.:
E_{FD}

The Spectrum

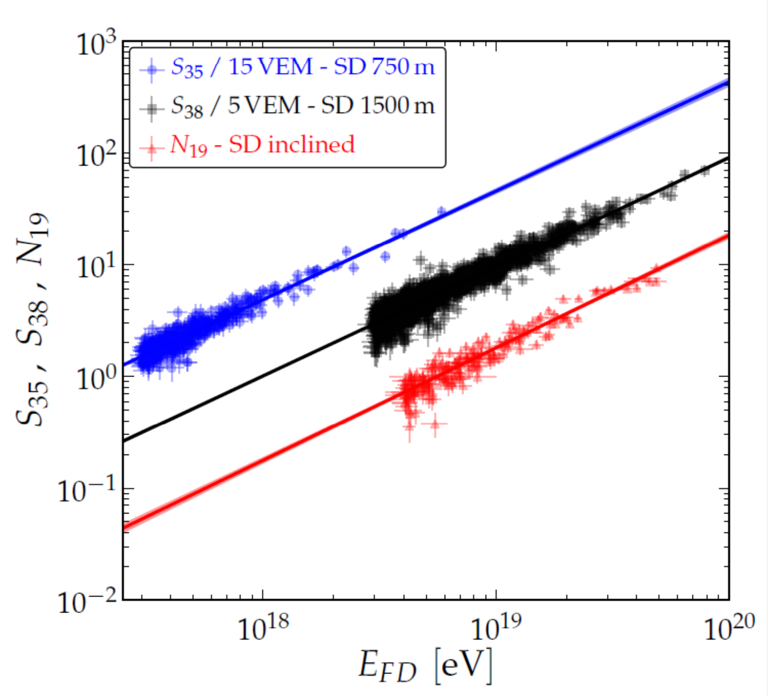
Perfect agreement between the different samples.



Exposures at 10 EeV:

[km^2 sr yr]

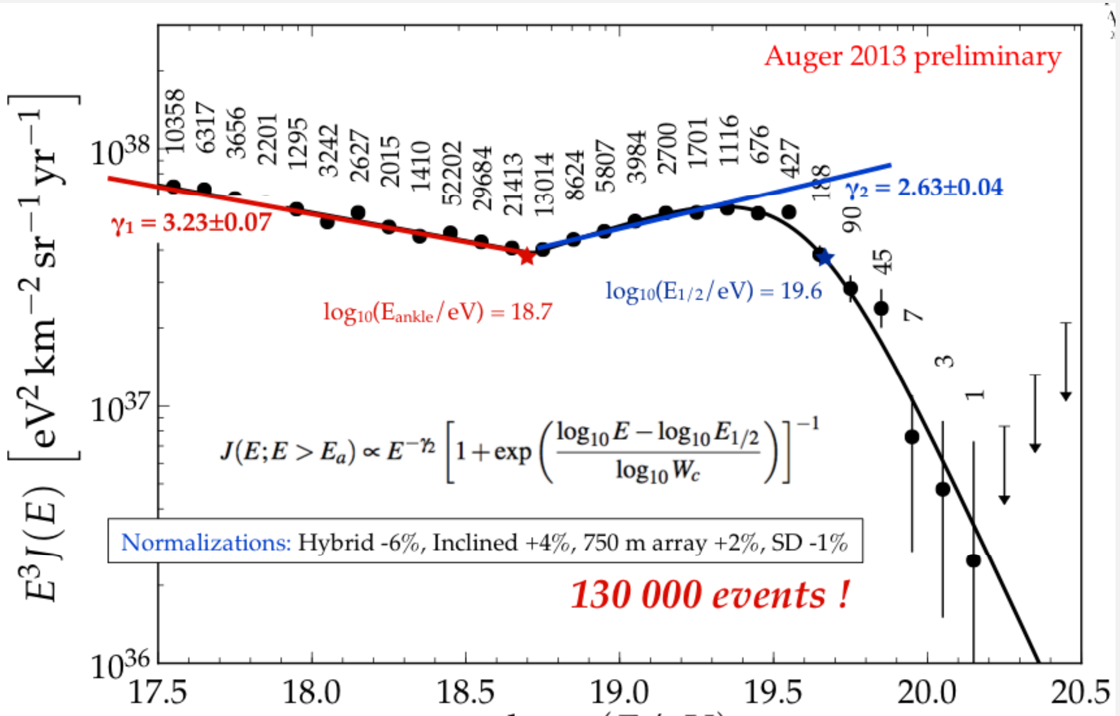
- SD vertical: 31645 ± 950
- SD inclined: 8027 ± 240
- Hybrid: 1496 ± 25
- SD 750 m: 79 ± 4



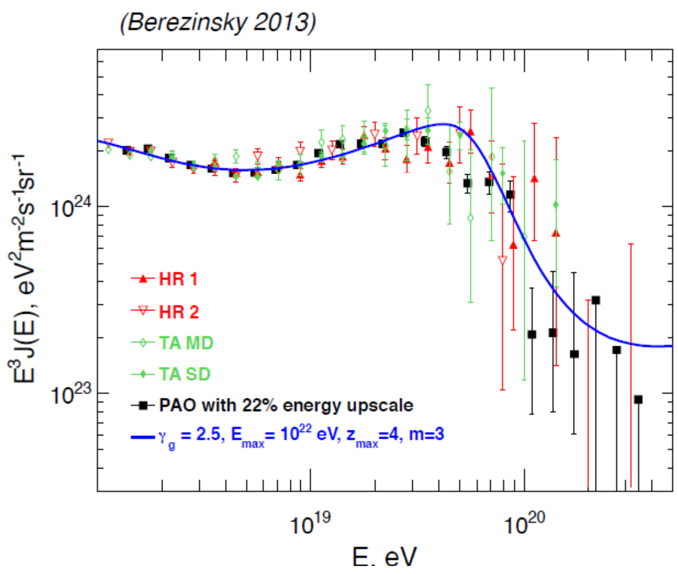
A. Schulz ICRC 2013

The Spectrum

Combined spectrum. It is unquestioned the presence of an "ankle" and of a cut-off



A. Schulz ICRC 2013



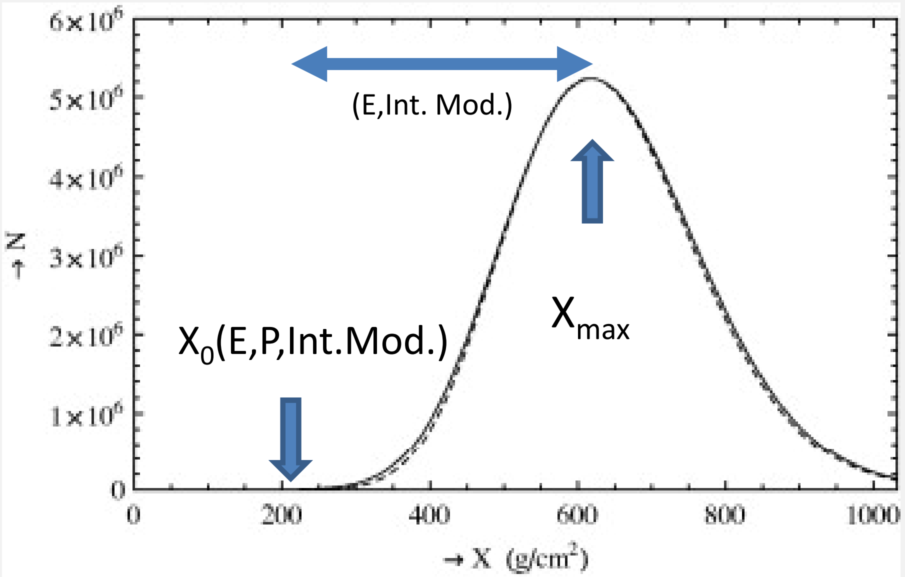
The visible cut-off is due to the GZK effect?

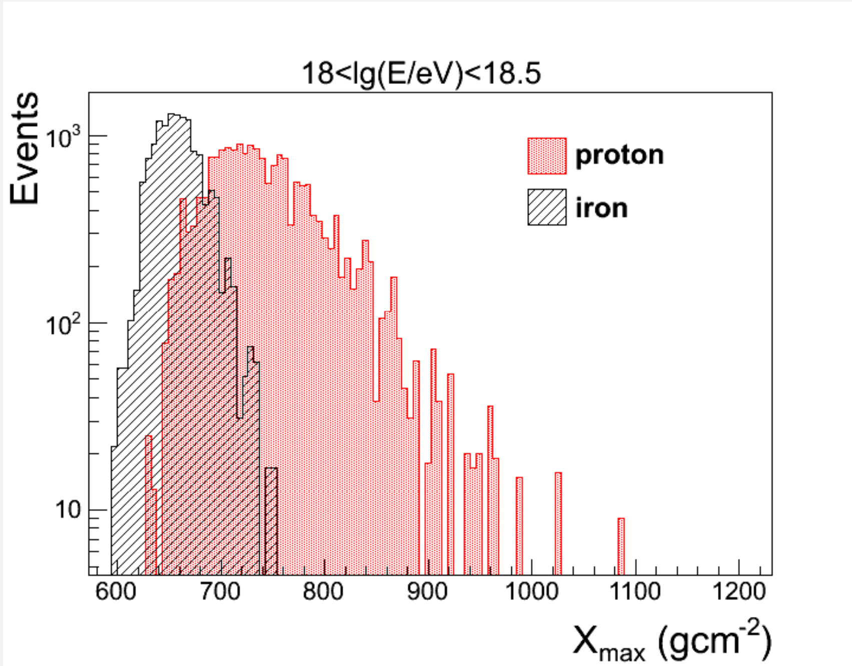
Where and how the UHECR are accelerated?

The most natural explanation.
A stream of pure protons can reproduce the measured spectrum by Auger. The ankle is a natural consequence of the process of interaction P-γ.

Mass Composition

The main instrument of analysis is the Fluorescence Detector, but also the Surface Array can be used.

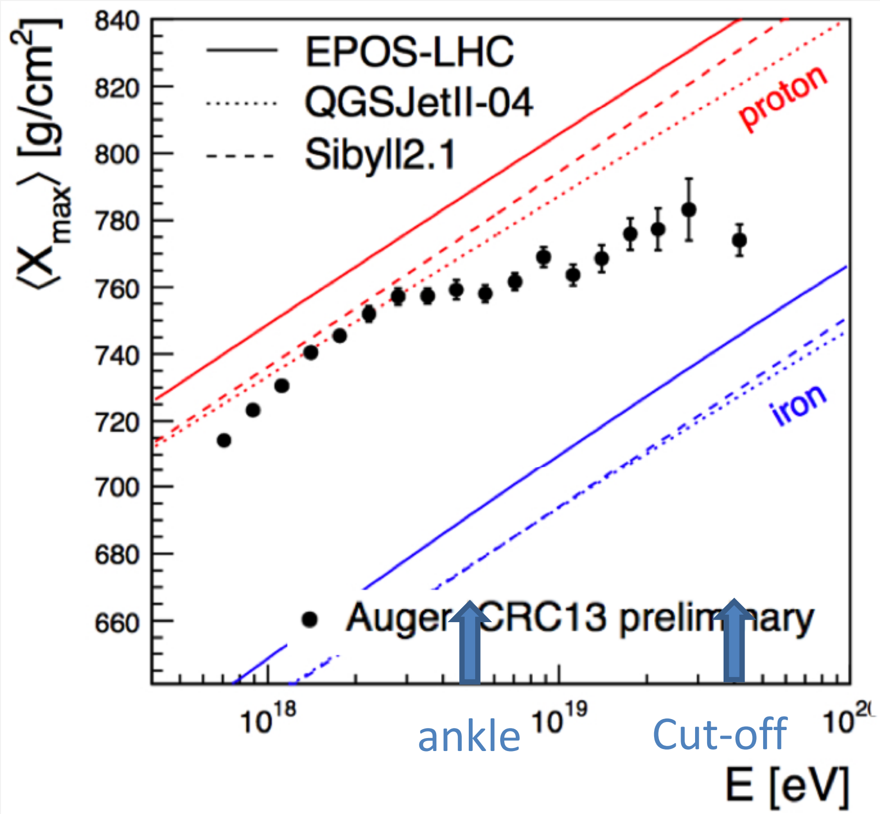


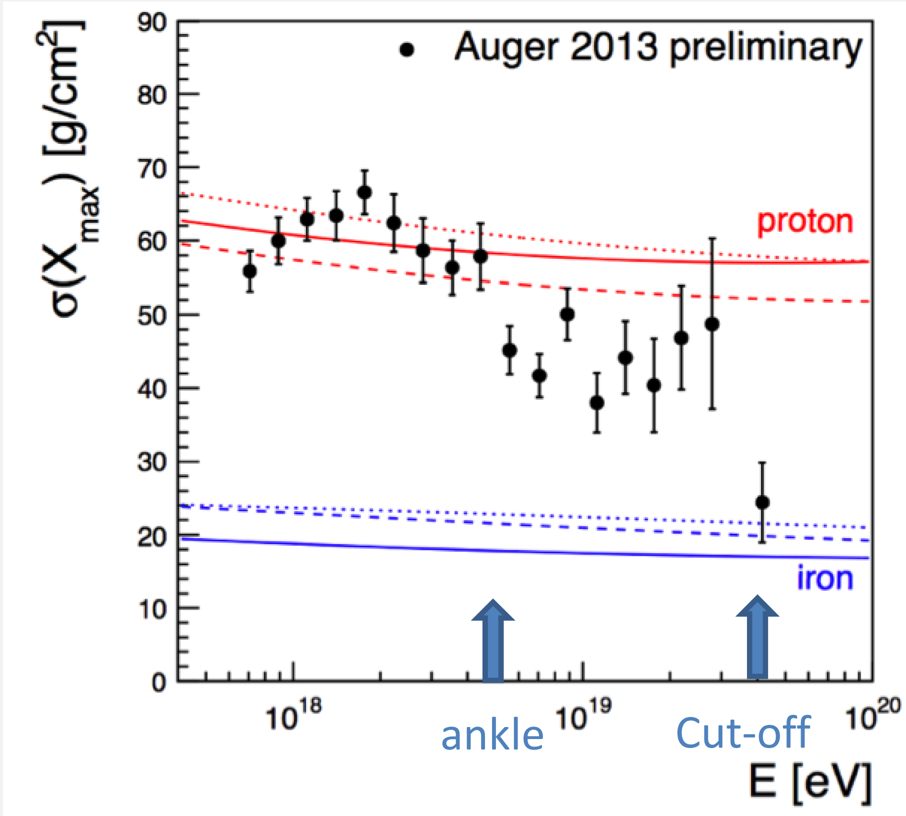


The X_{max} position is related to the primary mass.
The fluctuation of the first interaction point are related to the primary mass.

<X_{max}> and its RMS sensitive to mass composition
Key observables for composition studies

Mass Composition



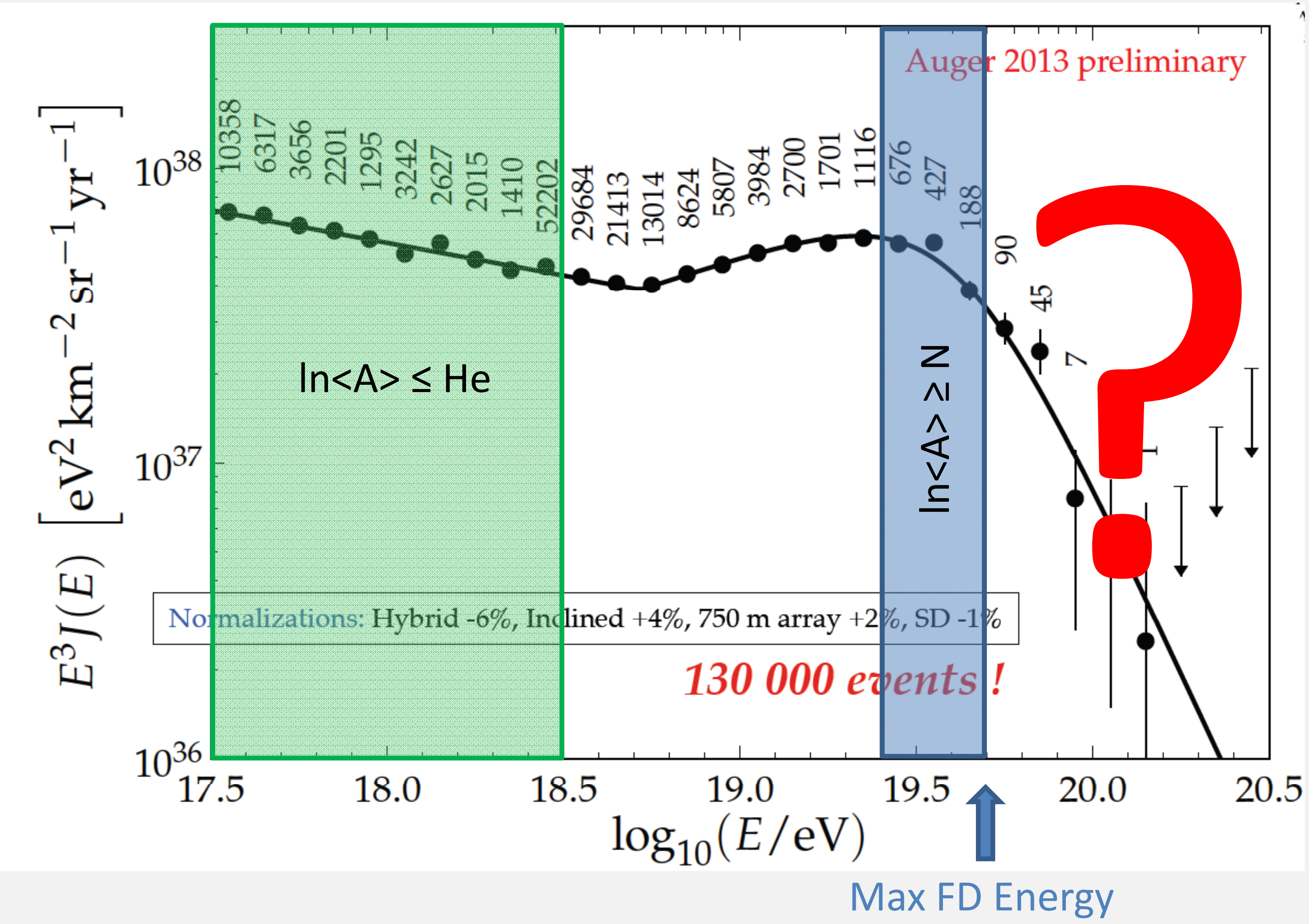


$<X_{max}>$ became lower with energy

X_{max} distributions become narrower with energy

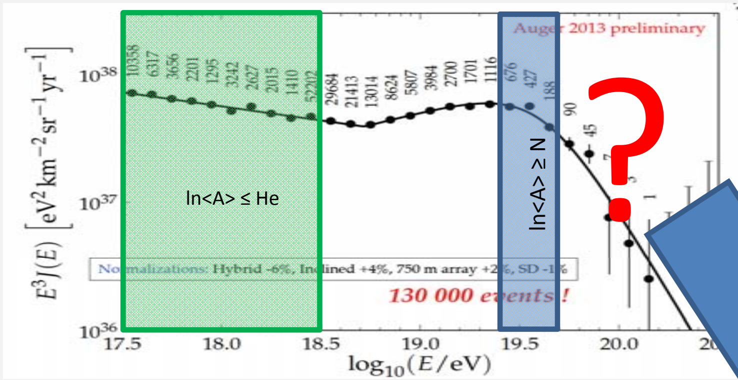
Increase of the mean mass with the energy? Inadequate interaction models?

Mass Composition

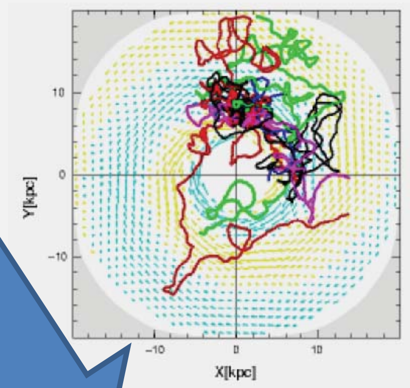


What is it happening? What is the origin of the cut-off and of the ankle?

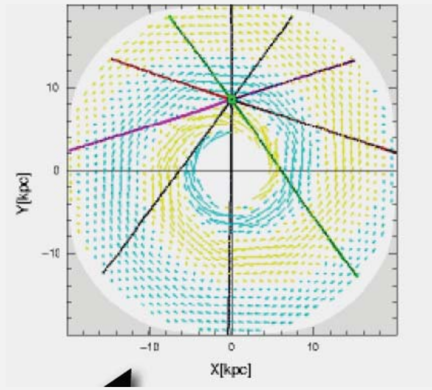
Anisotropy



Proton 10^{18} eV



Proton 10^{20} eV

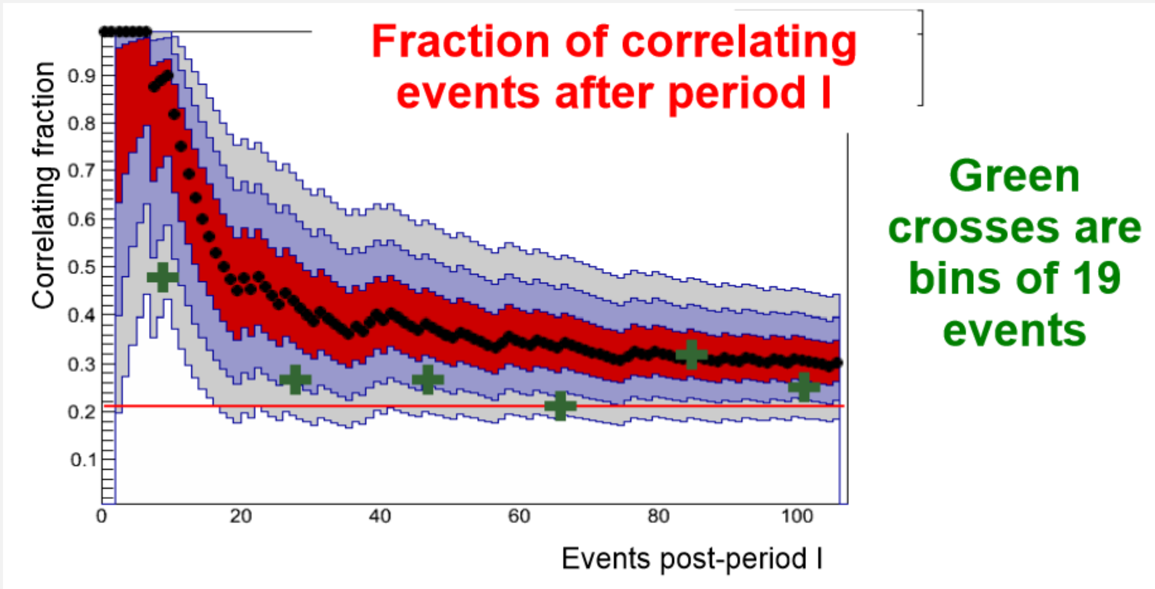


Events with energy larger than 54.8 EeV. Selection angle 3.1°. Reference catalog VCV.

Results not compatible with an isotropic flux.

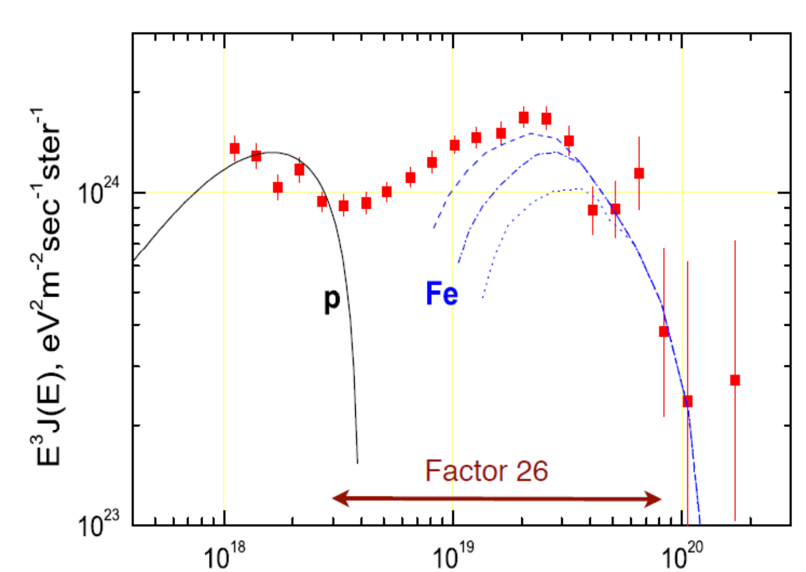
How we can explain? Few near sources plus an isotropic flux? Similar results obtained by TA.

Deflection P <3° ; Deflection Fe 15°-20°

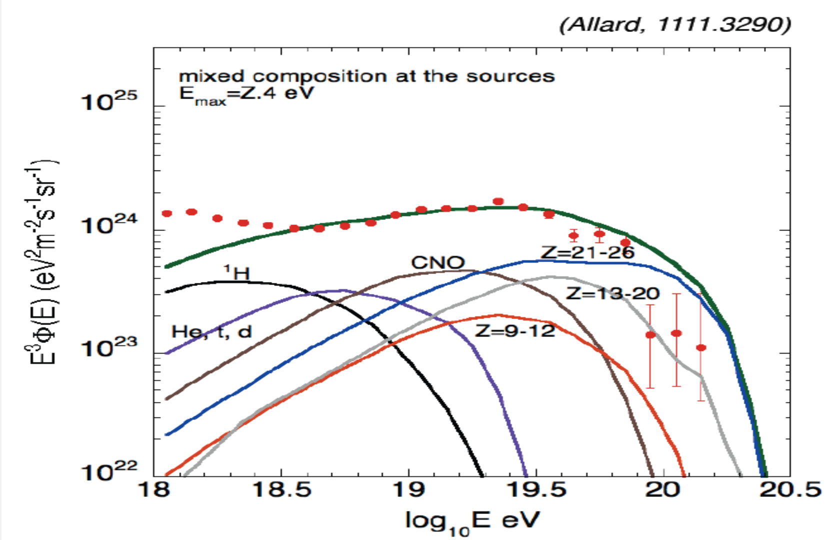


UHECR

How we can explain this results



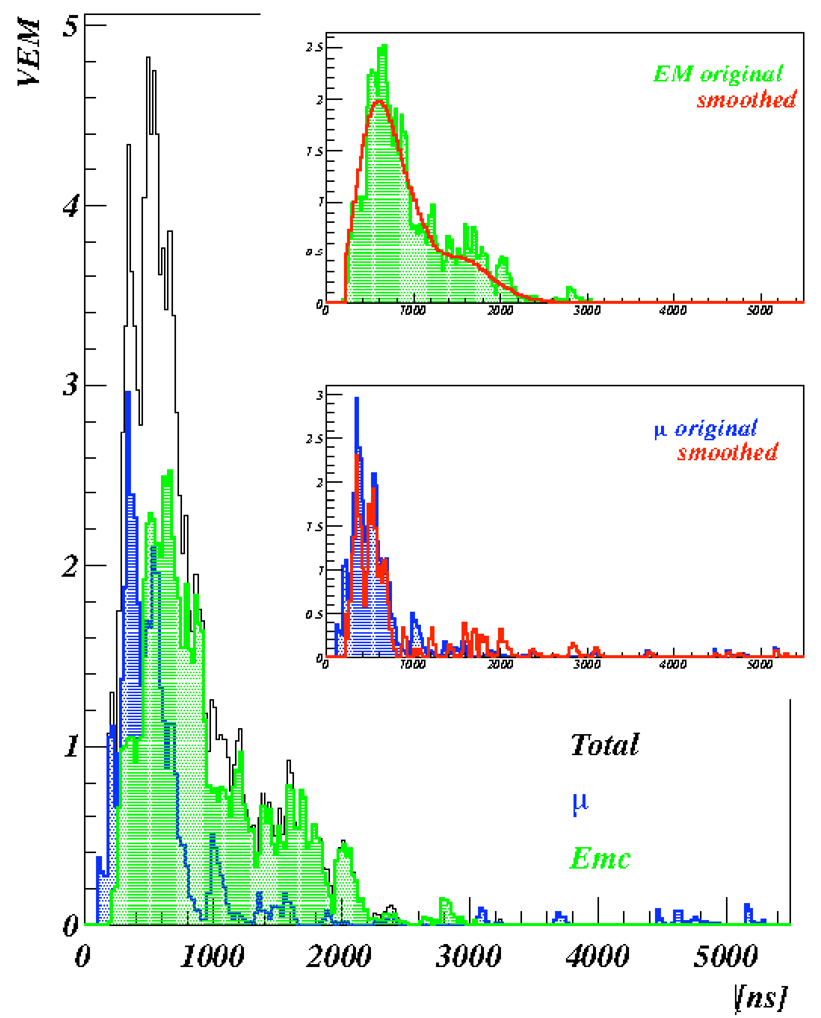
(Aloisio et al. 2011)

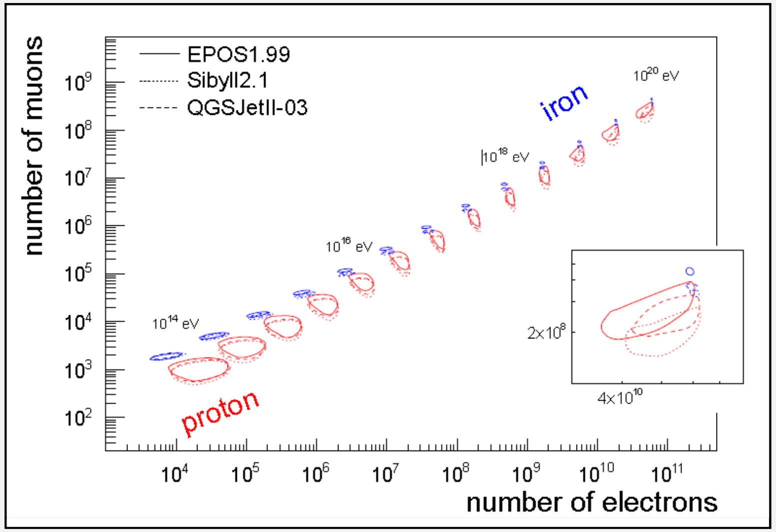


✓UHECR Rigidity dependent composition of Extragalactic origin
✓GZK effect not needed
✓ Transition from galactic to extragalactic at lower energy (2nd knee)

✓UHECR Mixed composition at the sources (Extragalactic origin)
✓GZK effect but for Heavy Elements
✓ Ankle due to transition between Galactic and Extragalactic spectrum.

SD Mass Composition



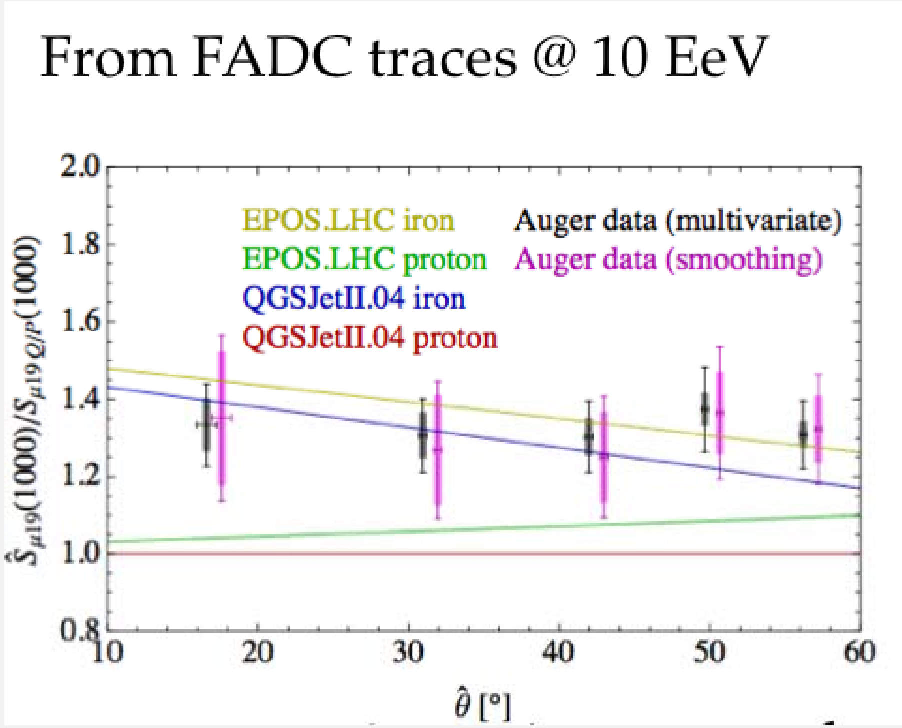


FD has limited statistic. It "sees" only the e.m. component of the shower.

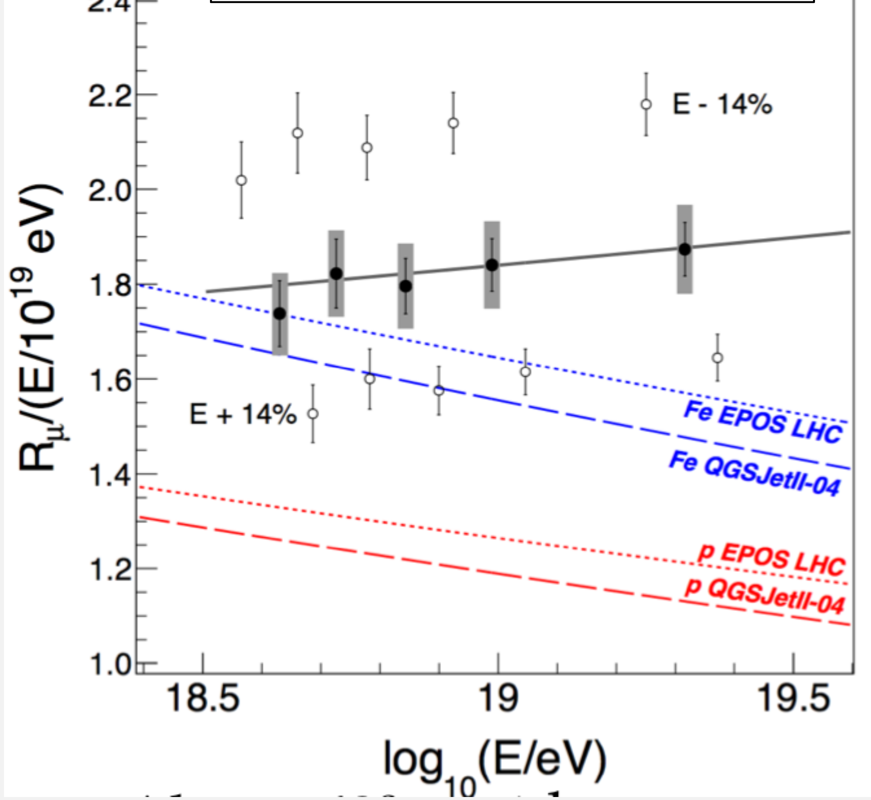
SD has not been optimized to make mass composition studies, but has the possibility to estimate (with large uncertainty) the number of muons. Muons provide information on the mass of the primary.
Combined with FD can put constraints on the interaction models.

SD Mass Composition

Different methodologies developed.



Inclined events θ>60°

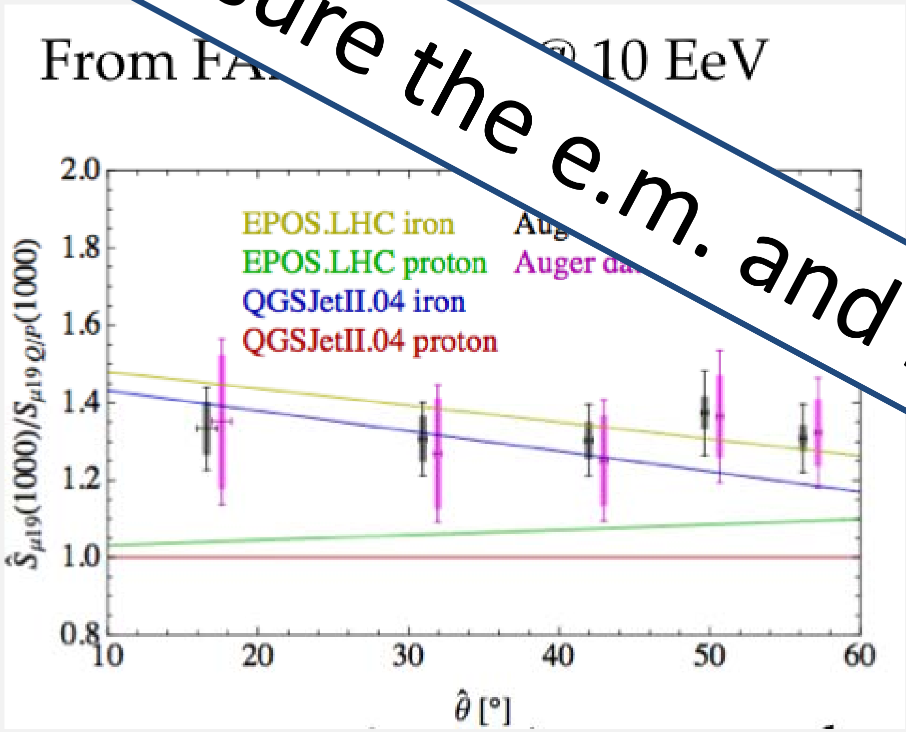


Measurements and Monte Carlo expectations not in agreement.
Other types of measures have also contradictions more pronounced.

SD Mass Composition

Measure the e.m. and muonic components!

…t methodologies developed.



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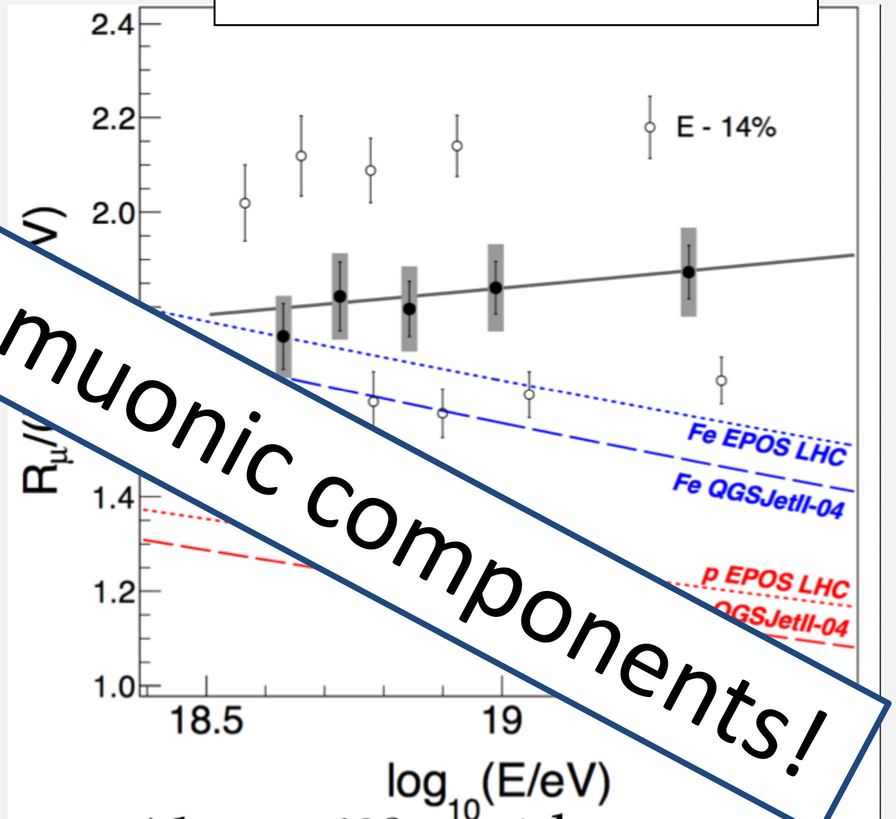

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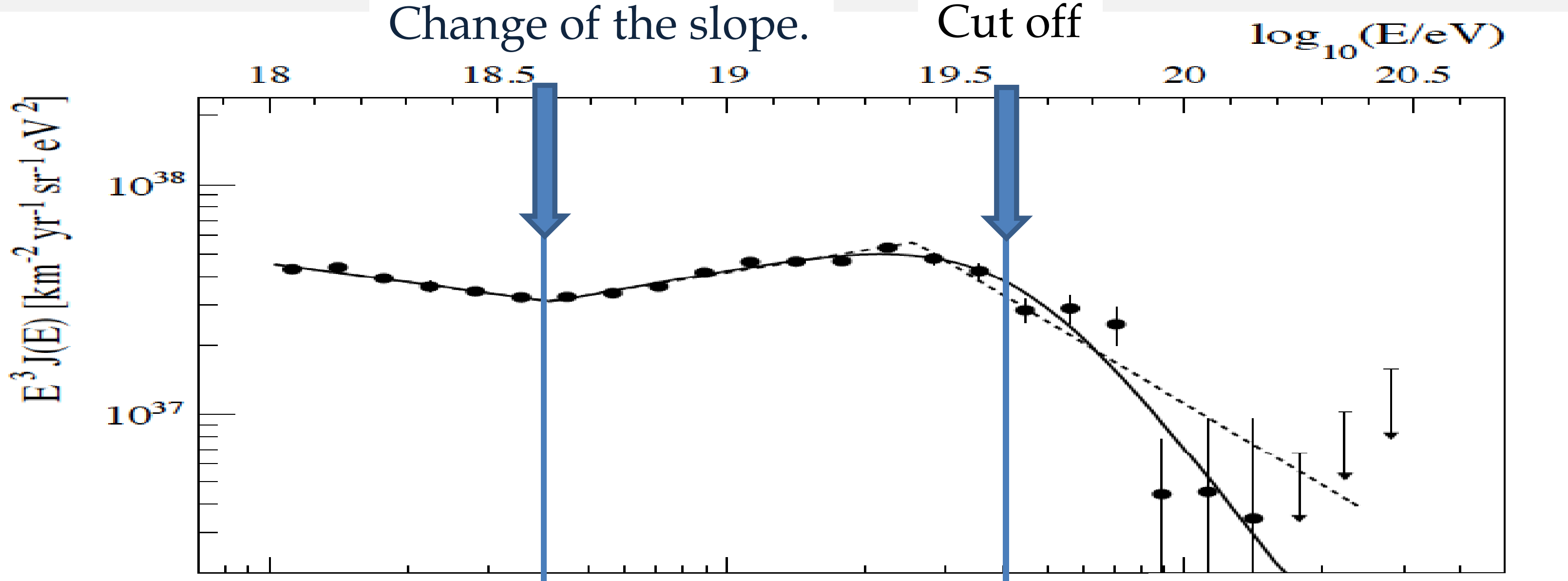
AUGER: A Summary



Light composition.
Weak or none anisotropy
(no galactic protons).

The composition
became heavy.
No galactic
neutrons.

Anisotropy present
but weak.
Not only GZK
protons.

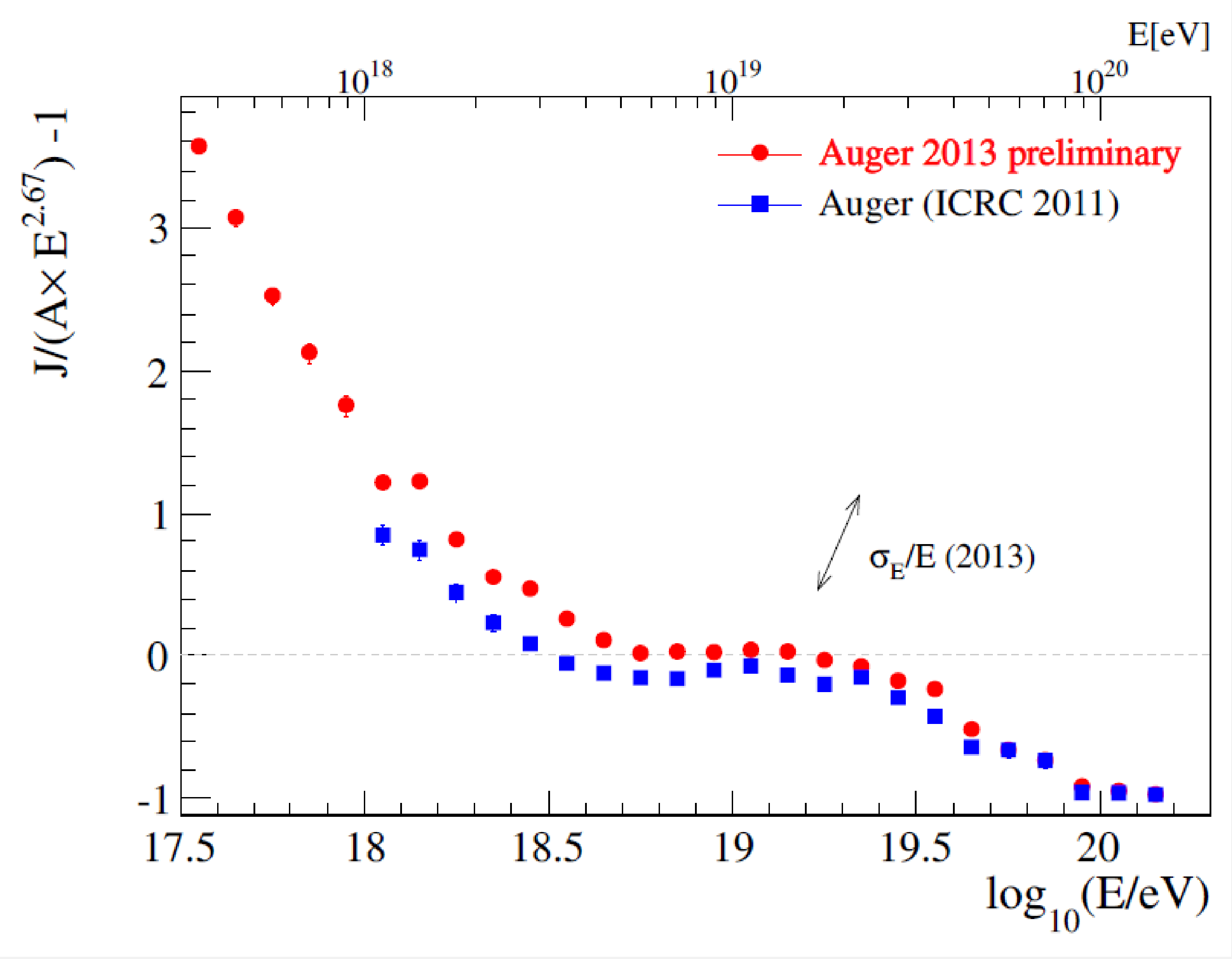
Muons: Problems with the interaction models? New physics?

Direct measurement of muons and mass composition up to 10^{20} eV needed.
Challenging (open) science case at the highest energy

The End

Backup

The Spectrum



Correction & Systematics

(1) Based on TA-FY model = Kakimoto modified + FLASH

Measured FY/TA-FY = 1.18 ± 0.01(stat) ± 0.18(syst)

TA-FY = 16.4 ph/MeV@300-420nm,1013hPa,293K
4.29ph/MeV@337nm,1013hPa,293K
TA-FY has ~10% systematic uncertainty

(2) Based on Common Model FY 2012 (Absolute Yield is AirFly)

Measured FY/CM-FY2012 = 0.96 ± 0.01(stat) ± 0.15(syst)

337nm FY of CM-FY2012 = 5.61 ph/MeV@ 1013 hPa,293K

CM-FY2012has ~4% systematic uncertainty

Total Correction = −3 %
- Correction of Beam charge/pulse which measured by Faraday Cup
- Contribution of background photons from the ELS container
- Contribution of Cerenkov photons

Systematic Uncertainties = 15 %(*)	
Fluorescence Detector	10%
ELS	< 11%
Charge measurement	< 10%
Shower geometry and Telescope optics	5%

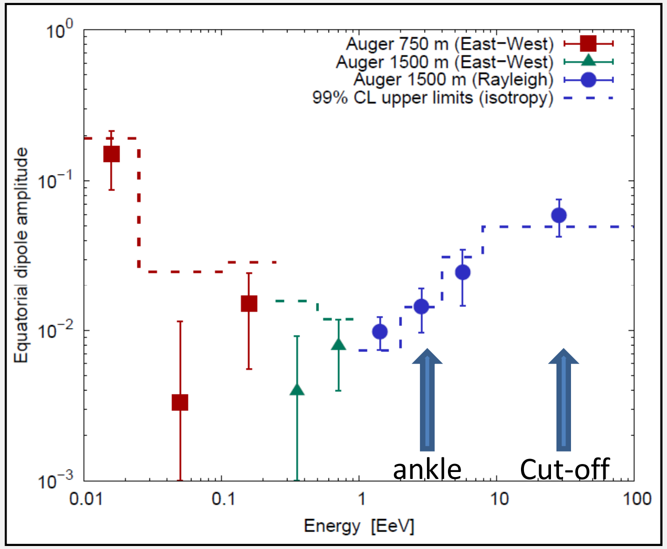
(*)15% of DATA/MC value before correction

FD vs SD

	SD-only	FD-only	Hybrid
Duty-cycle	~100%	~10%	~10%
Angular resolution	1-2 deg	3-5 deg	0.2 deg
Energy	C & M depend	independent	independent
Aperture	independent	E, C, M depend	independent
Energy Thr.	~$10^{18.5}$ eV	~$10^{17,5}$ eV	~10^{18} eV

E = Energy, M = Interaction Model, C = Composition

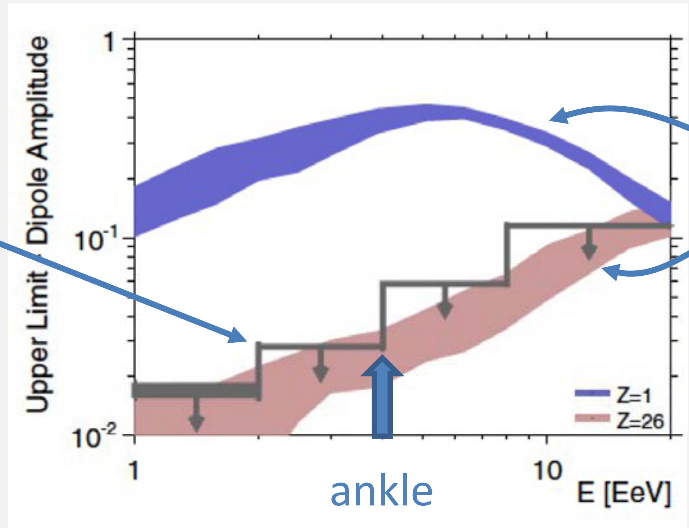
Anisotropy



Above 1 EeV anisotropies could be imprinted in the distribution of arrival directions as the result of the escape of UHECRs from the Galaxy up to the ankle energy.

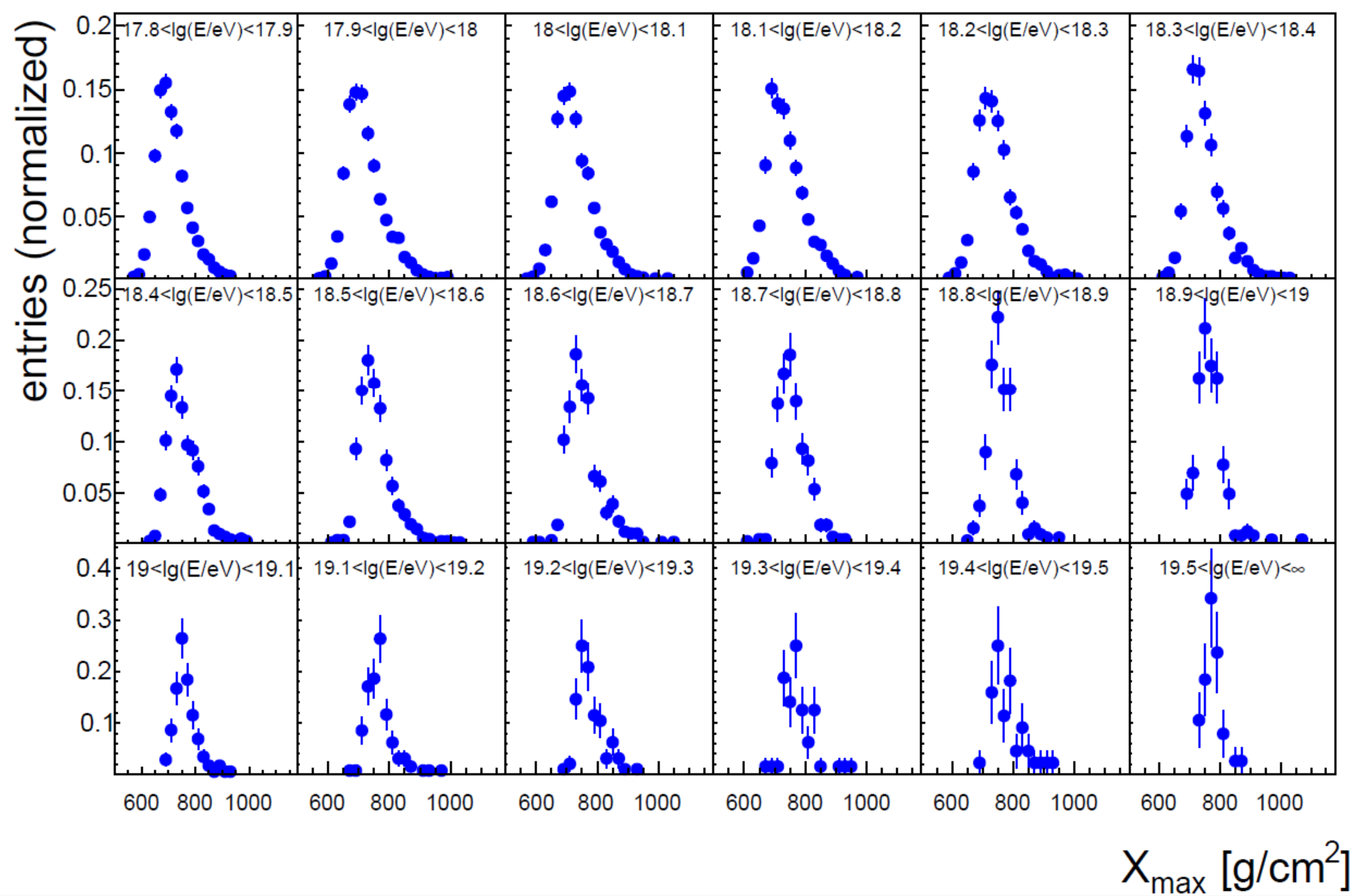
If UHECRs have already a predominant extragalactic origin their angular distribution is expected to be isotropic to a high level.

99% C.L. upper limits



Model prediction for an uniform distribution of sources in the galaxy and different compositions

Mass Composition



Anisotropy

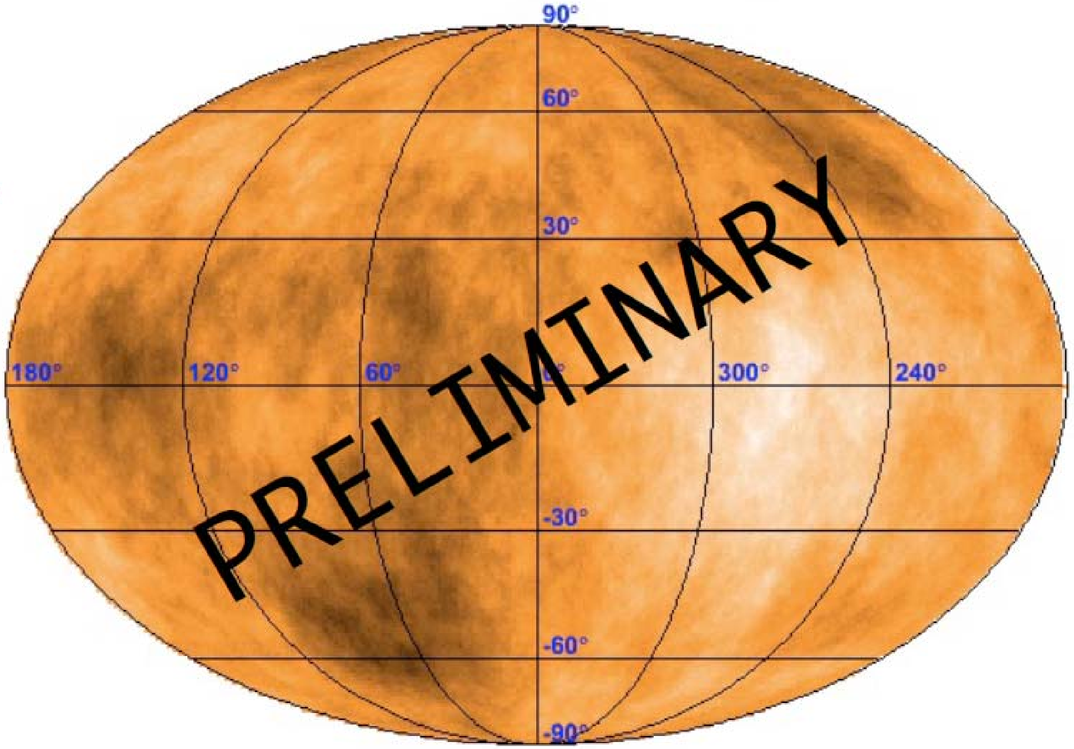
Full-Sky Map >10 EeV
(30° smoothing)

N_{TA}~1800

(~5200 km^2 sr yr)

N_{Auger}~10900

(~32000 km^2 sr yr)



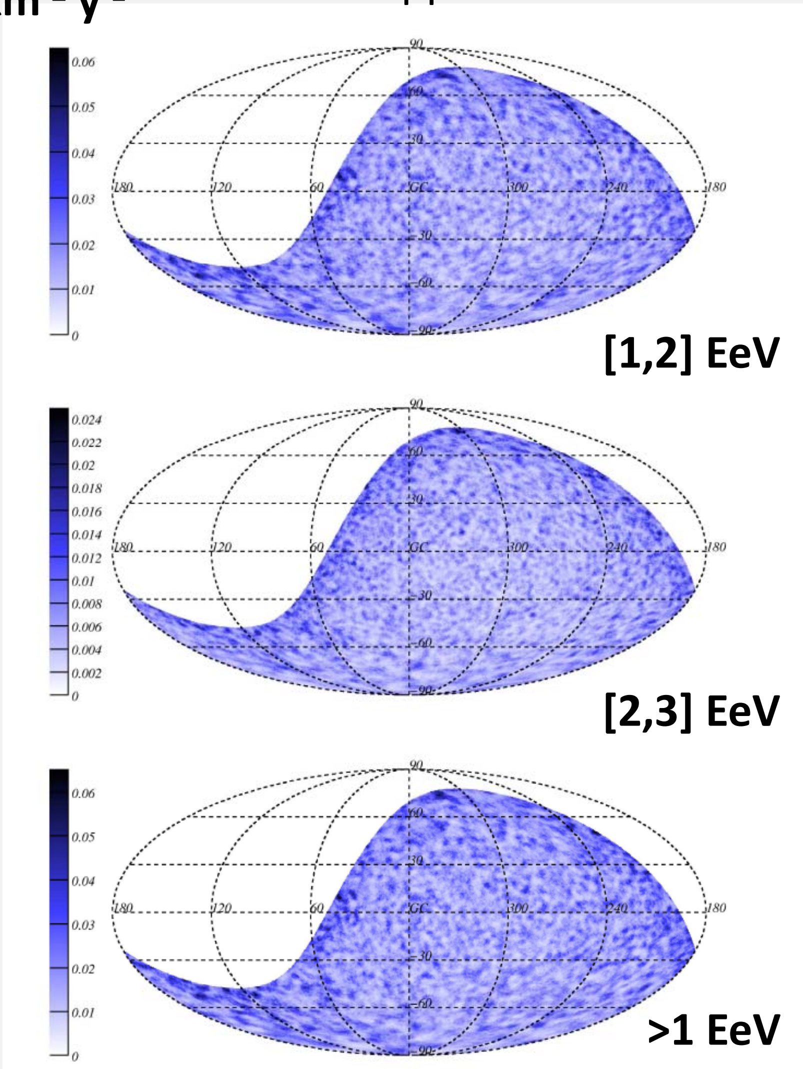
In the overlap :

N_{TA}~650

N_{Auger}~3400

Anisotropy: Neutrons

km^{-2} y^{-1} 95% C.L. upper limit



AUGER has sensitivity to galactic neutron sources

✓ Neutrons are undeflected by galactic magnetic fields!

✓ Flux of neutrons from discrete source would cause an excess of CR events in the direction of the source!

✓ 1 EeV neutron emitted by Galactic center could be seen!

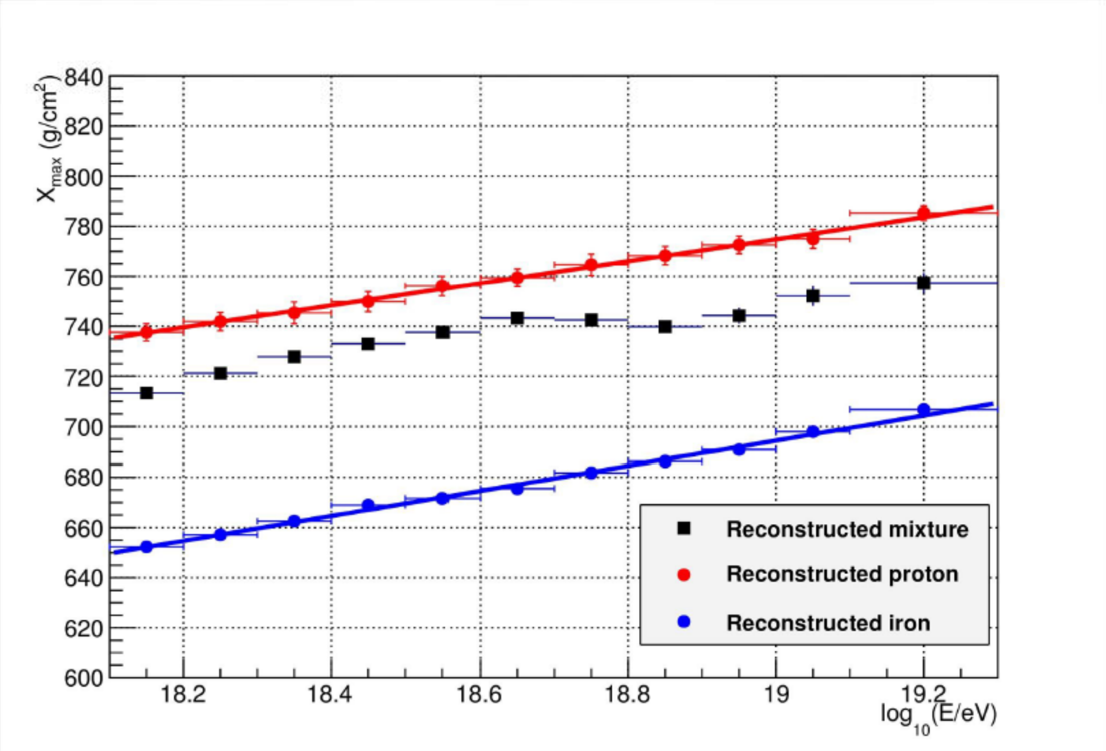
✓ Flux of gammas rays from some sources in the galaxy, could be associated to neutron fluxes detectable by Auger!

✓ Select SD events with θ≤600, good event reconstruction!

✓ Exposure of 24,880 km^2 sr yr, with 429,138 events with energy ≥ 1 EeV!

No excess found

Mass Composition



We now have a testable hypothesis: TA claims it sees a light composition as energy increases, Auger claims to see composition increasing in mass as energy increases. TA can reconstruct pure proton, helium, nitrogen, etc. and test, including all detector resolution effects and biases, does TA see what Auger sees?

Total bias TA sees in reconstructing pure protons is 12 g/cm^2. (Note this bias is calculated against unbiased thrown proton distribution).

TA reconstructed $<X_{max}>$ for the Auger composition mix does not look like TA reconstructed $<X_{max}>$ for pure protons.