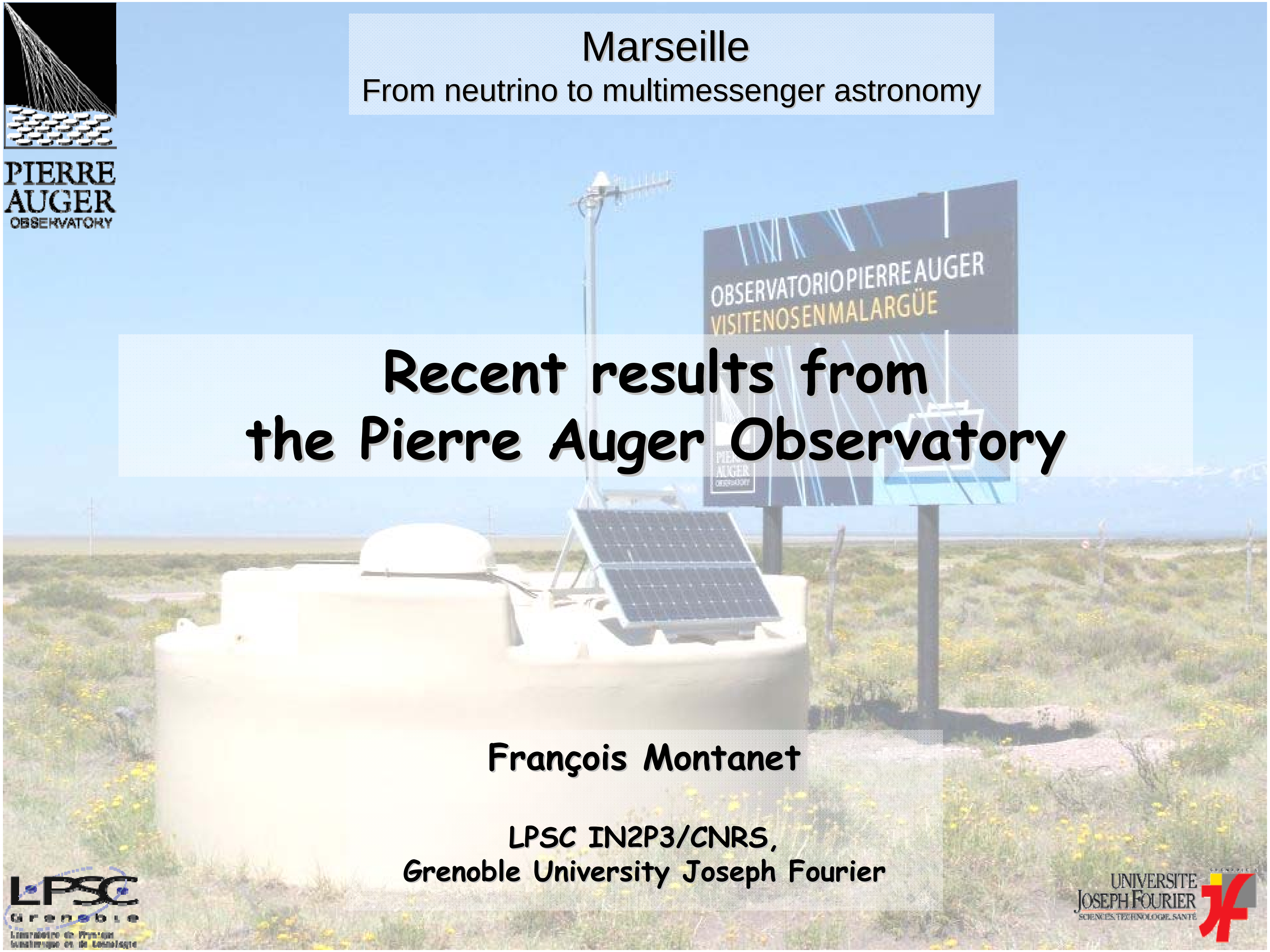
Marseille

From neutrino to multimessenger astronomy

Recent results from the Pierre Auger Observatory



François Montanet

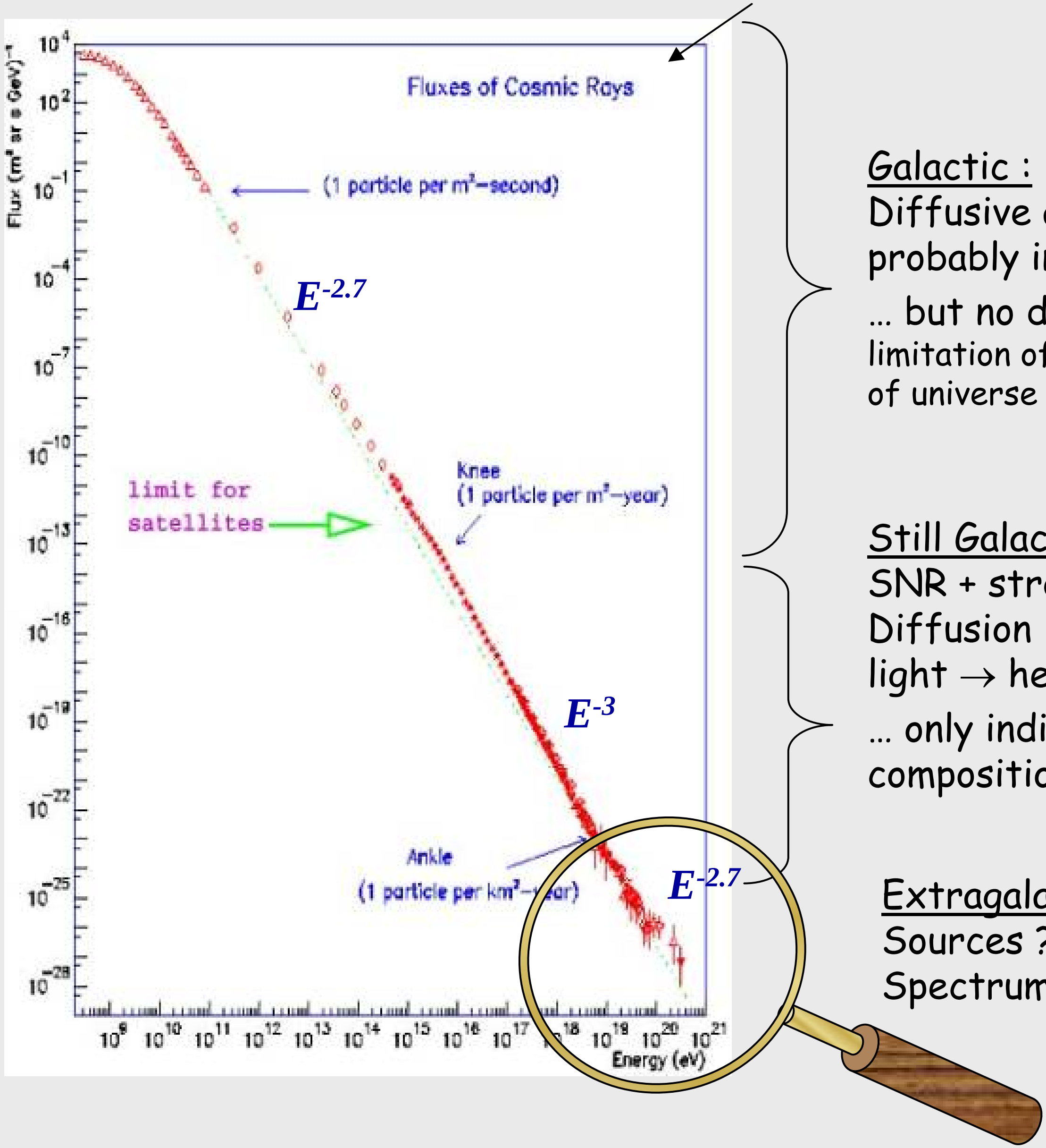
LPSC IN2P3/CNRS,
Grenoble University Joseph Fourier

Outline

- The Pierre Auger Observatory
  - The instrument, status and performance.
- Results, understanding UHECR's
  - Spectrum
  - Anisotropy
  - Mass composition, hadronic interactions
  - Photon and neutrino limits
- Summary

Why UHECR ?

Tribute to Simon Swordy 1954-2010



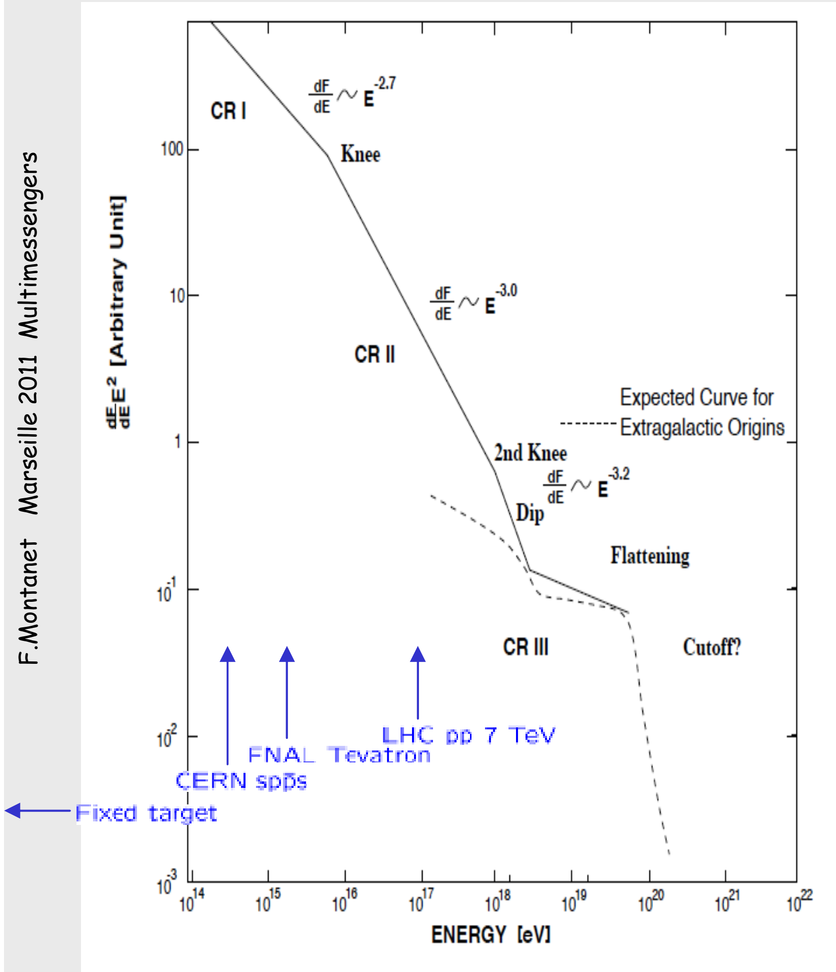
<u>Galactic :</u>
Diffusive acceleration in chocks (Fermi), probably in SuperNovae Remnants
... but no direct evidence so far,
limitation of γ astronomy probing mostly EM nature of universe

<u>Still Galactic</u> ?
SNR + strong B field enhancements ?
Diffusion in the Galaxy, containment limit vs Z, light $\rightarrow$ heavy ?
... only indirect and model dependent mass composition measurements.

<u>Extragalactic</u> ?
Sources ?, Composition ?
Spectrum shaped by propagation.

Where is the transition ?

Why UHECR ?



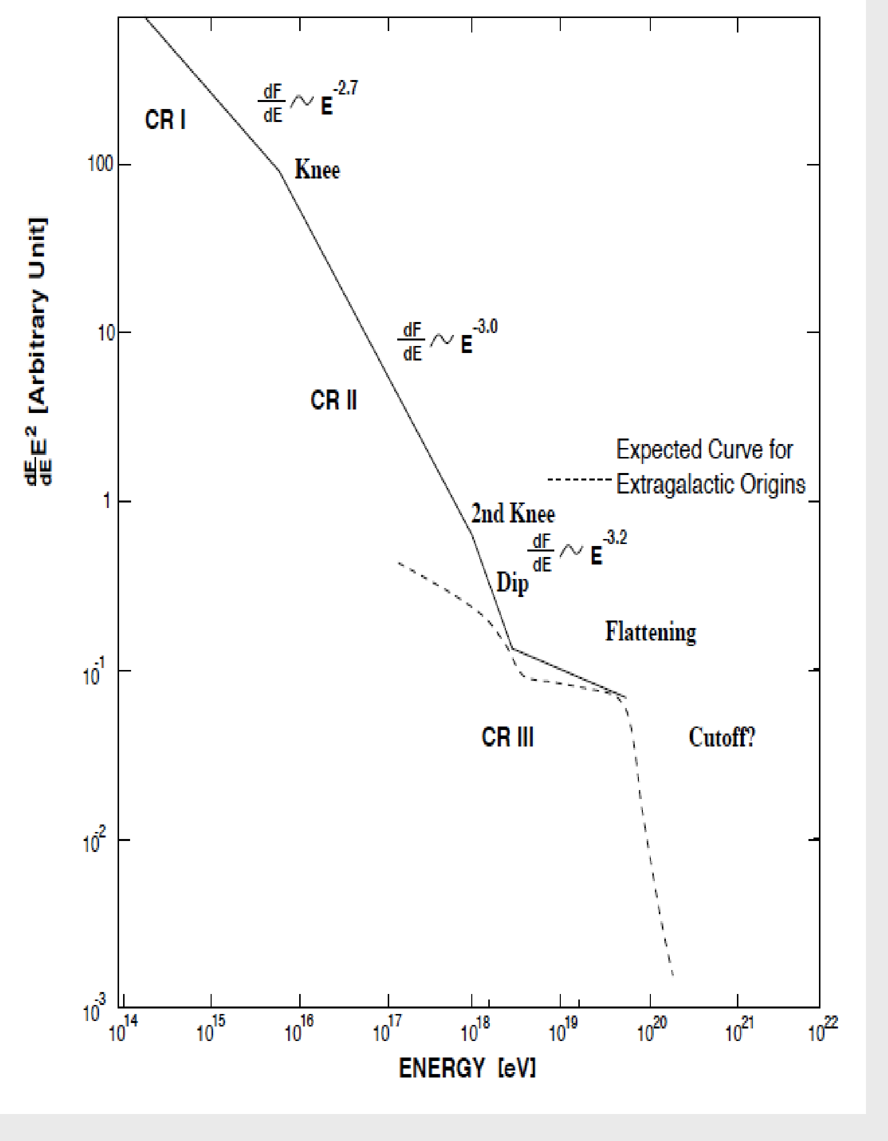
Galactic Magnetic Field can contain CRs up to 10^{17}-10^{18} eV : UHECRs are expected to be extra-galactic: **where is the "transition"**? 2nd knee ? ankle ?

Flux cutoff at extreme energies expected from CR interactions on CMB photons (GZK effect).
Or is there an intrinsic cutoff of the cosmic accelerators ?

GZK horizon (<100Mpc)
⇒ UHECRs come from "near by" sources
⇒ marginally deflected by magnetic fields:
CR astronomy possible

Last but not least:
access to **c.m.s. energy much larger than that of LHC**

Essential questions



Essential (and obvious) questions :

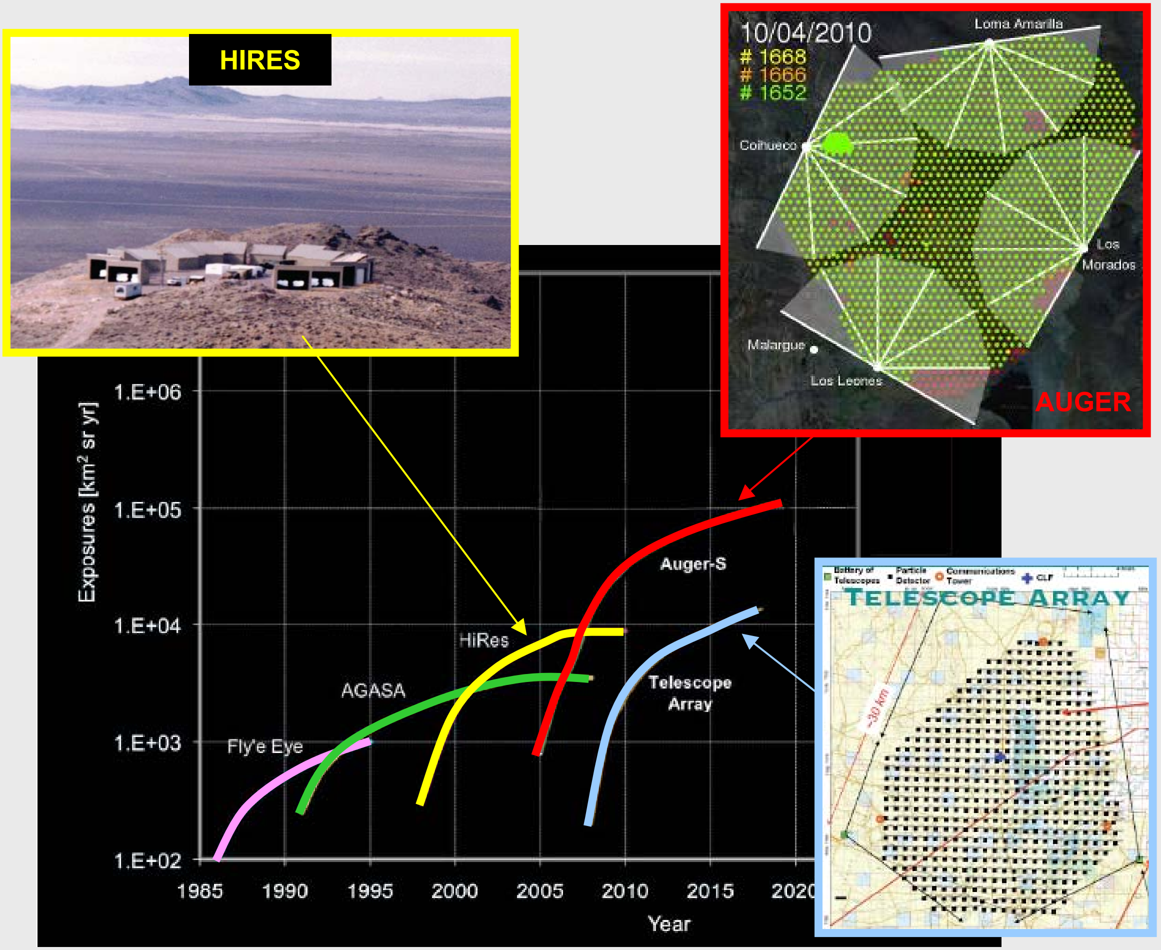
- **Where do they come from?**
- **What are they made of ?**
- **How do they propagate ?**
- **How do they interact ?**

Essential features for astroparticle physics:

- **Galactic/extra-galactic transition:** spectrum shape and composition measurements
- **Flux suppression**: spectrum shape and composition measurements
- **Search for anisotropies and sources**: study of the arrival directions

Current experiments

- Understanding UHECR, a 50 years old challenge
- Not only larger but also better instruments.



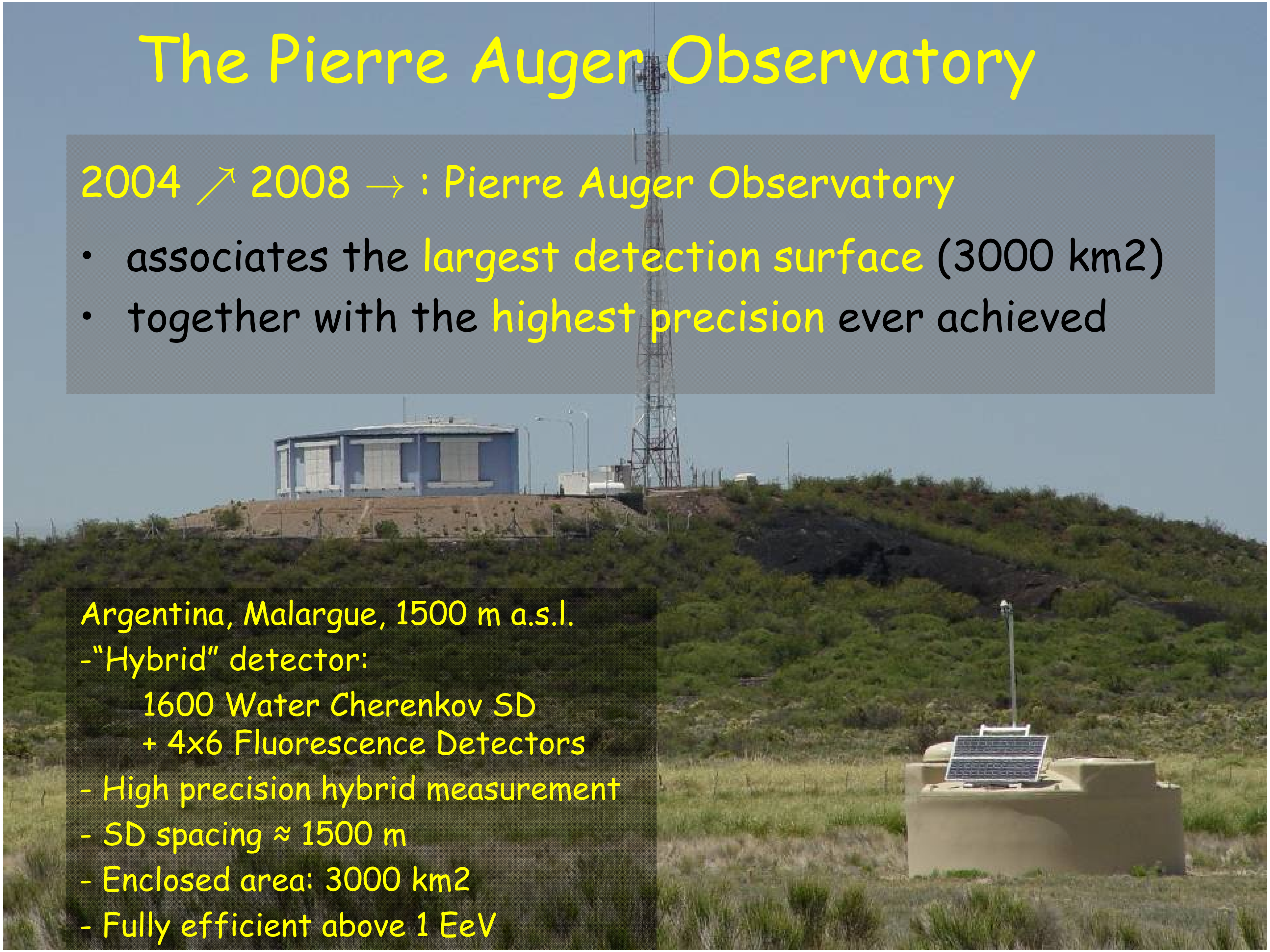
The Pierre Auger Observatory

The instrument

The Pierre Auger Observatory

2004 ↗ 2008 → : Pierre Auger Observatory

- associates the largest detection surface (3000 km2)
- together with the highest precision ever achieved



Argentina, Malargue, 1500 m a.s.l.

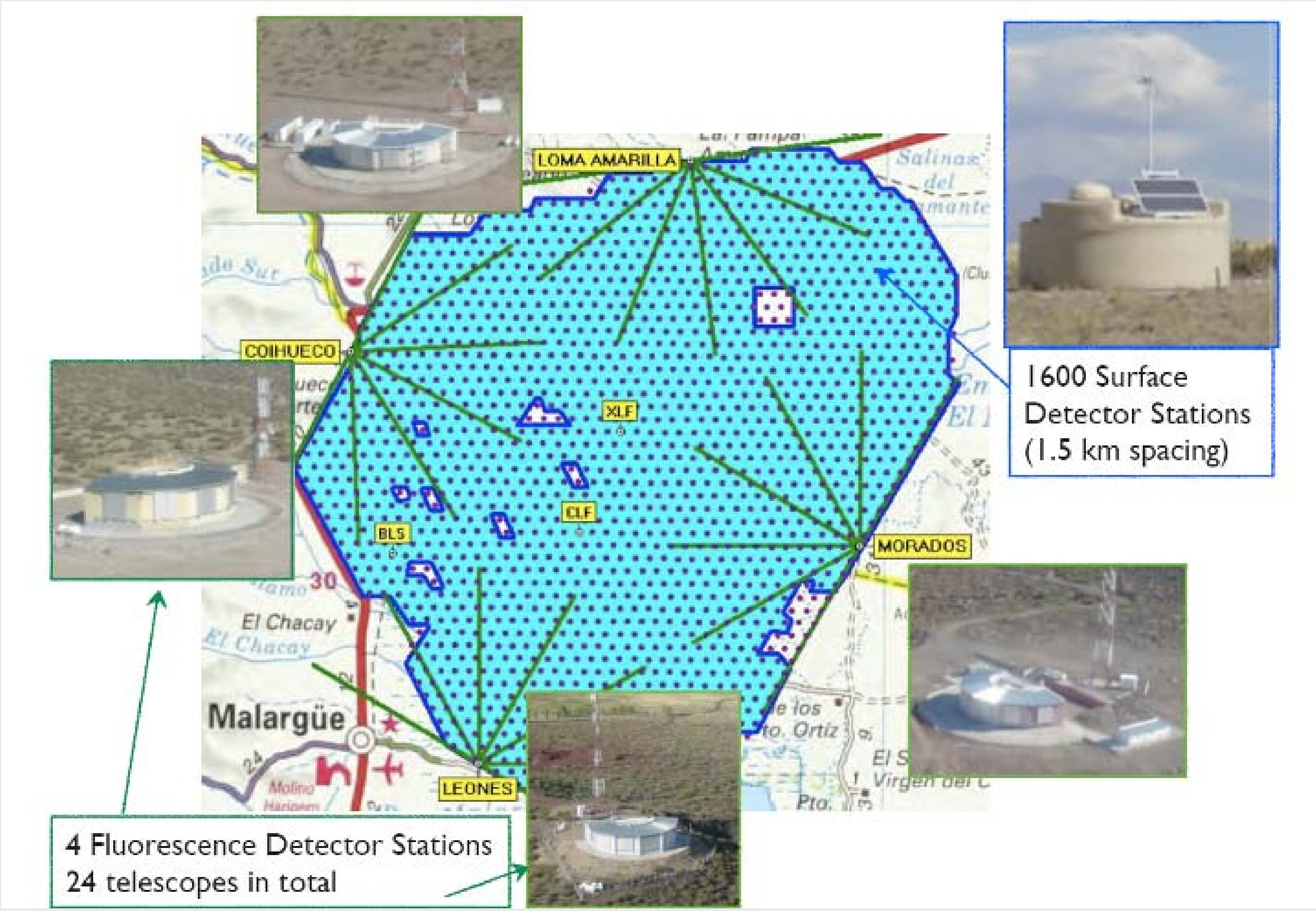
-"Hybrid" detector:

1600 Water Cherenkov SD
+ 4x6 Fluorescence Detectors

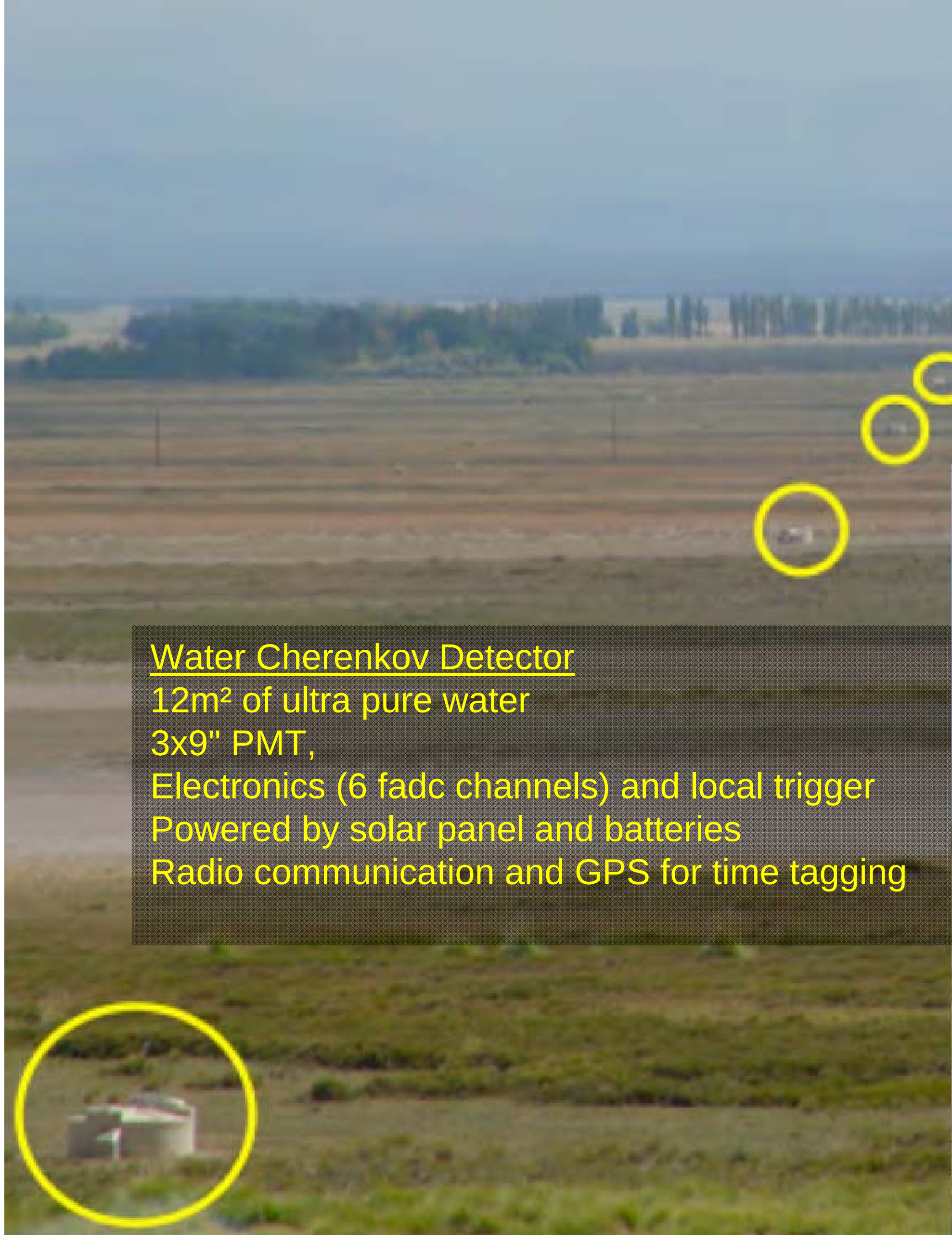
- High precision hybrid measurement
- SD spacing ≈ 1500 m
- Enclosed area: 3000 km2
- Fully efficient above 1 EeV

Auger

A "hybrid" detector :



Auger Surface Detector



<u>Water Cherenkov Detector</u>

12m² of ultra pure water

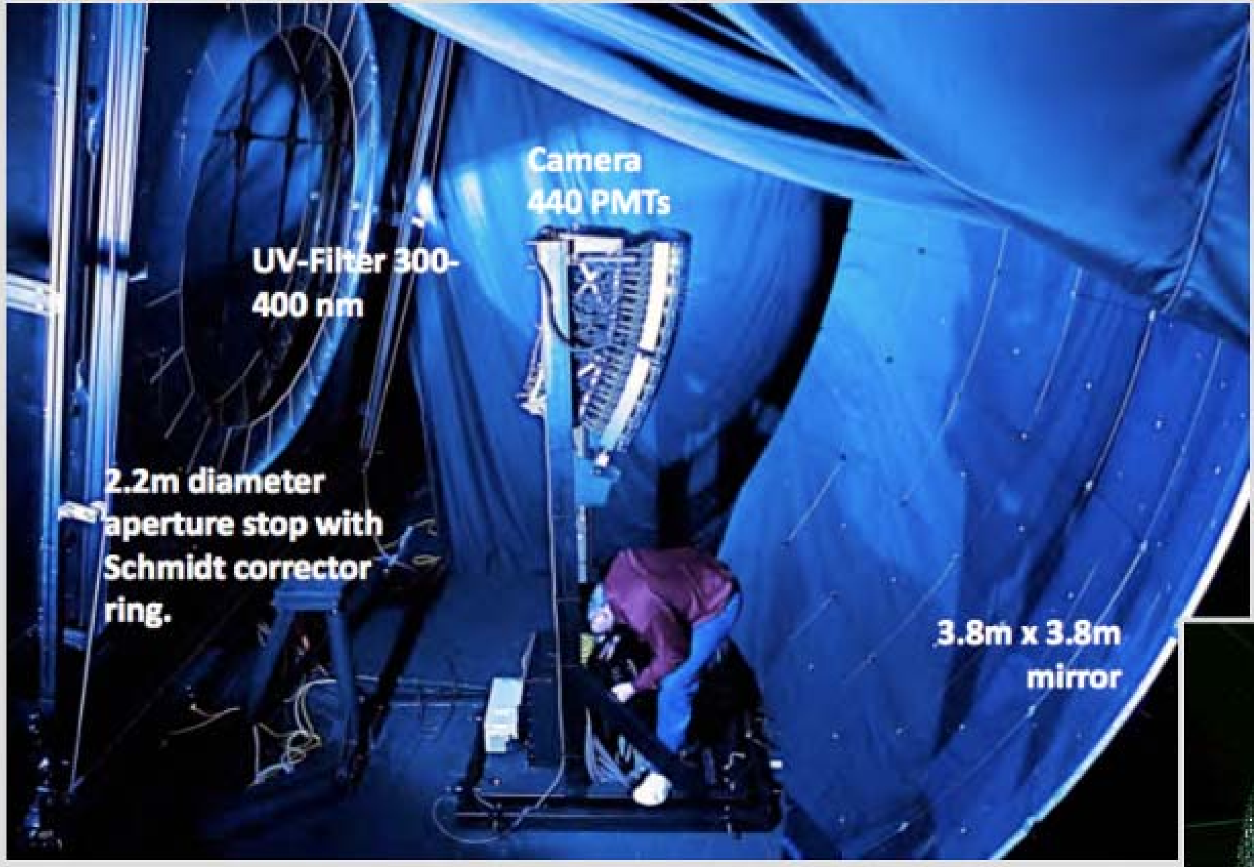
3x9'' PMT,

Electronics (6 fadc channels) and local trigger

Powered by solar panel and batteries

Radio communication and GPS for time tagging

Auger Fluorescence Detector



Fluorescence Detector

✓ Schmidt Telescope (11 m² mirrors)
✓ Camera with 440 PMT (Photonix XP4062)

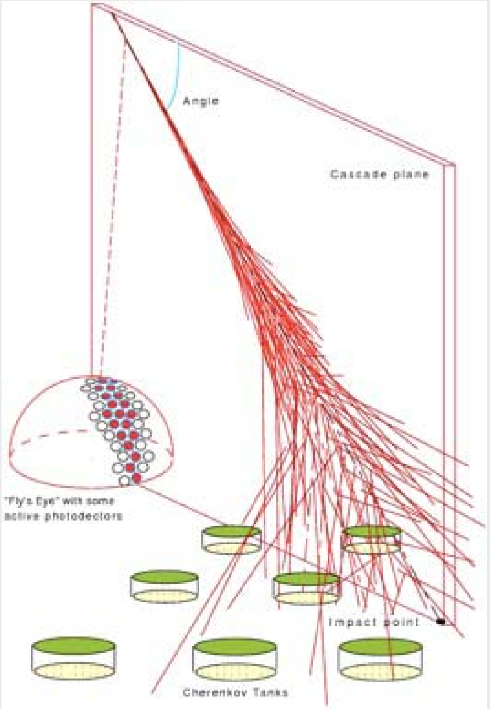
Array deployment

From EAS measurements to UHECR parameters

Energy, Direction, Composition

Improving measurement and observations

The Auger hybrid concept : more than 2 detectors



SD provides:

- Huge aperture (100% duty cycle) easily calculable
- Robust detectors
- Good angular resolution
- Promising Mass composition indicators

FD provides:

- Fluorescence light $\propto$ dE/dx :
  -> Near calorimetric energy measurements
- A direct view of shower maximum (composition)
- Precise directions (hybrid method).
- But duty cycle is only ~10%

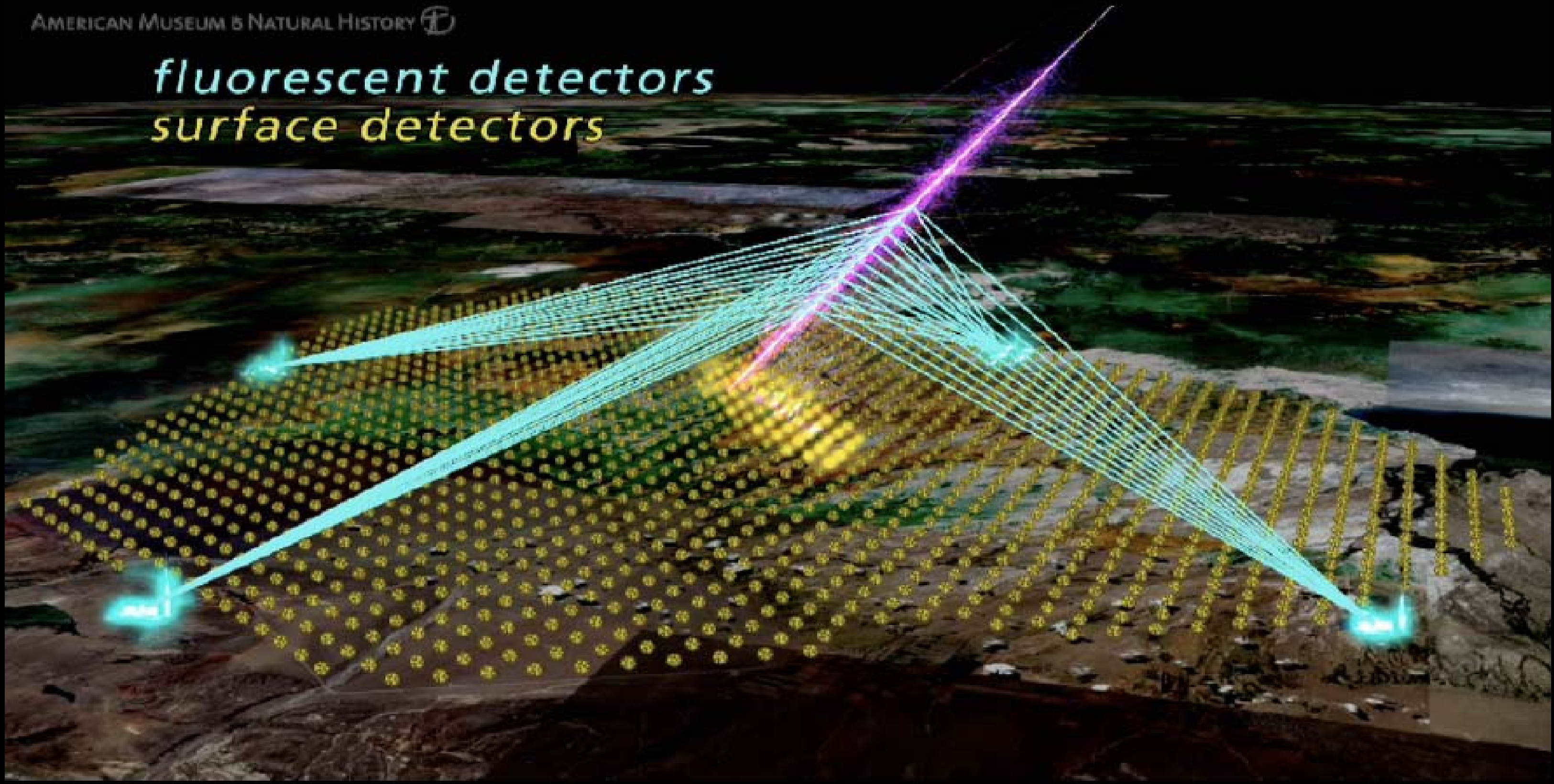
Where possible, minimize use of simulations in the production of key scientific outputs.

- e.g. SD energy spectrum, composition(~ minimal use)

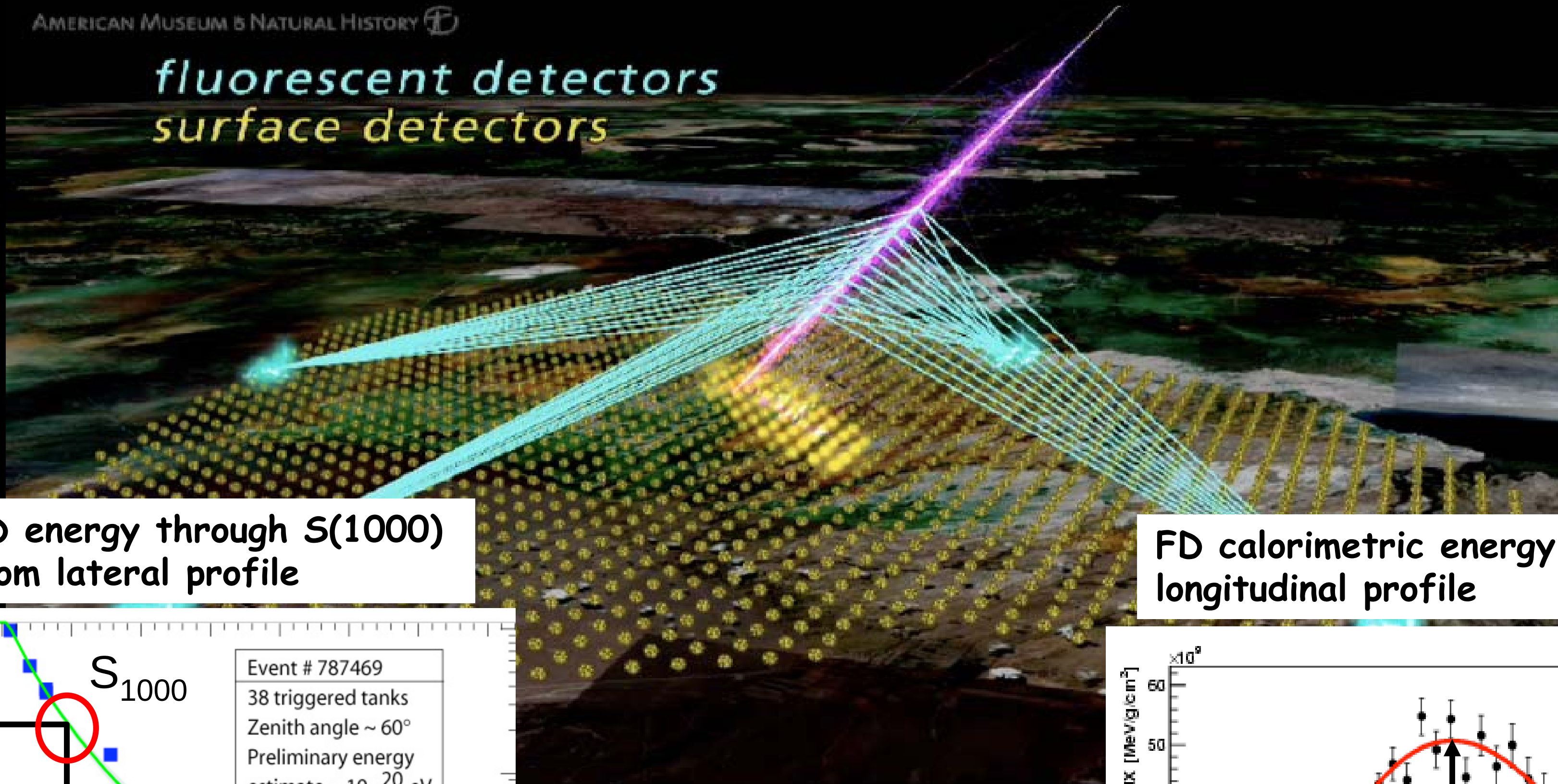
Take advantage of Auger's hybrid nature.

- FD calibrates SD energy scale
- hybrid directions cross-check SD directions
- other SD cross-hecks like exposure FD/SD

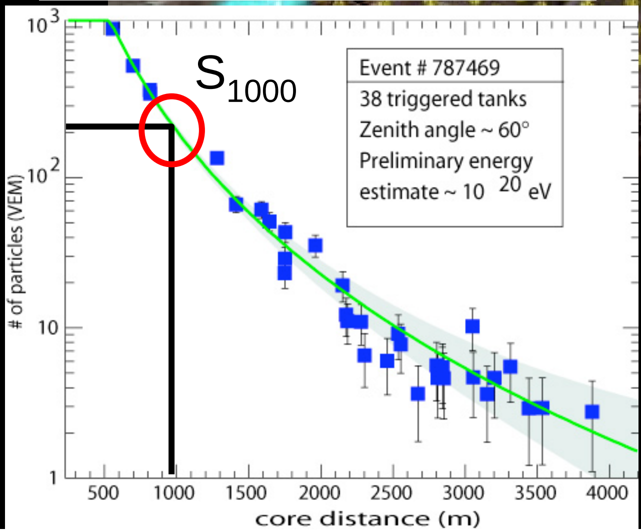
The Auger Hybrid concept: more than 2 detectors !



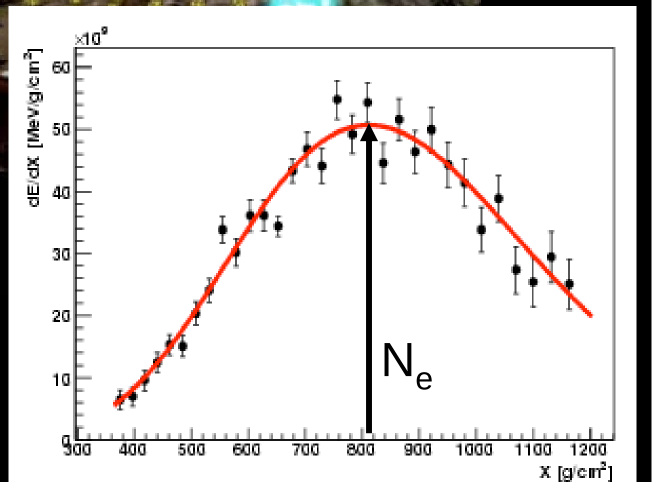
The Auger Hybrid concept: more than 2 detectors !



SD energy through S(1000) from lateral profile



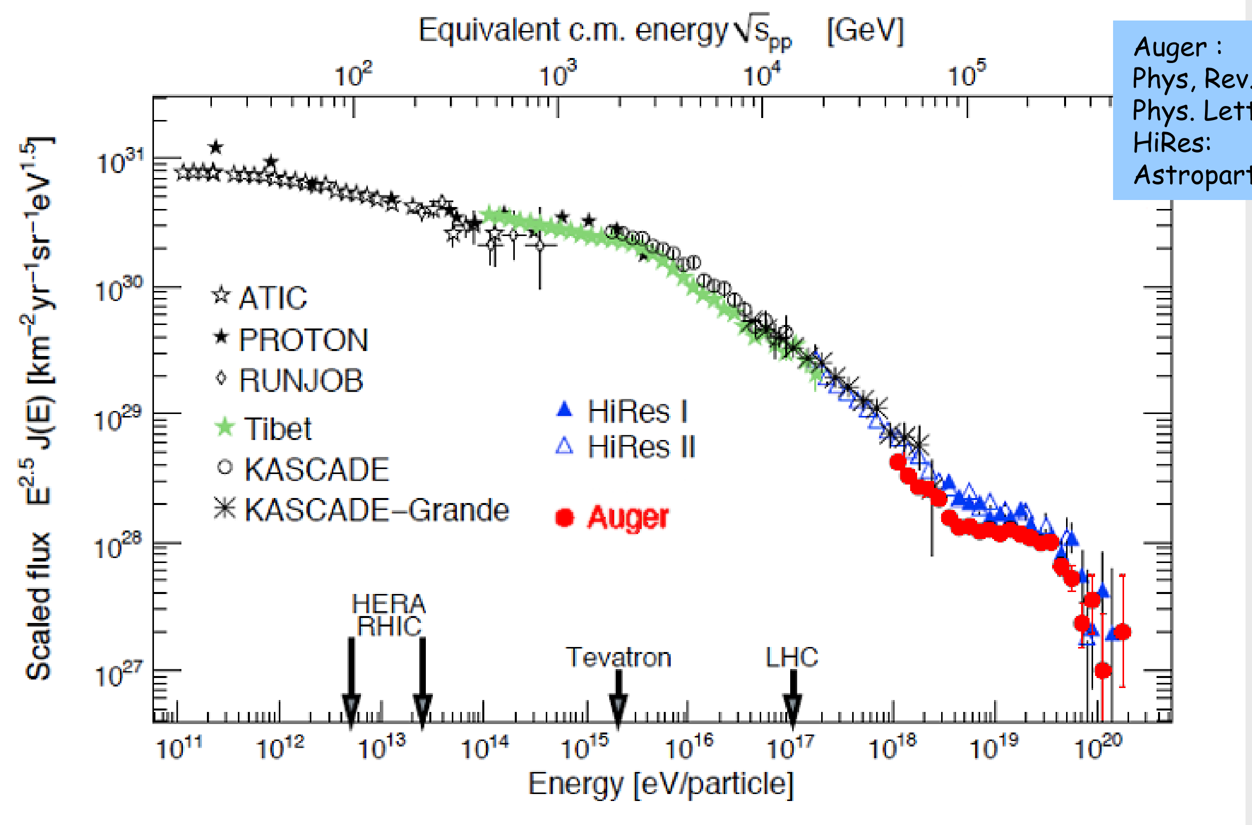
FD calorimetric energy from longitudinal profile



Calibration of SD energy estimator through FD

Spectrum

CR Spectrum



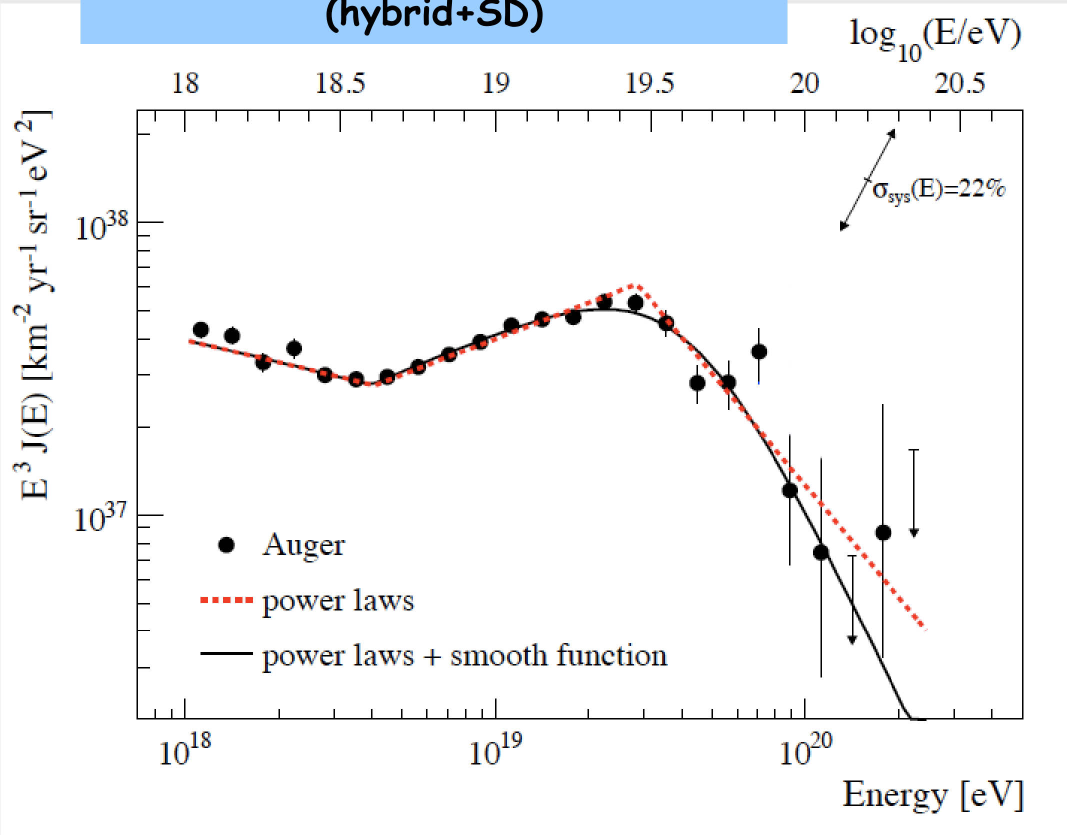
Auger :
Phys, Rev. Lett. 101 (2008) 061101
Phys. Lett. B 685 (2010) 239-246
HiRes:
Astropart. Phys. 32 (2009) 53.

The spectrum measurement has improved a lot in 10 years !

- Sharp ankle at ~4 EeV
- Clear suppression of the flux above ~50 EeV (HiRes, Auger)
- flux drop to 50% at logE =19.6, significance ~20σ.
- Consistent with GZK suppression.

CR Spectrum

Auger "combined" spectrum (hybrid+SD)



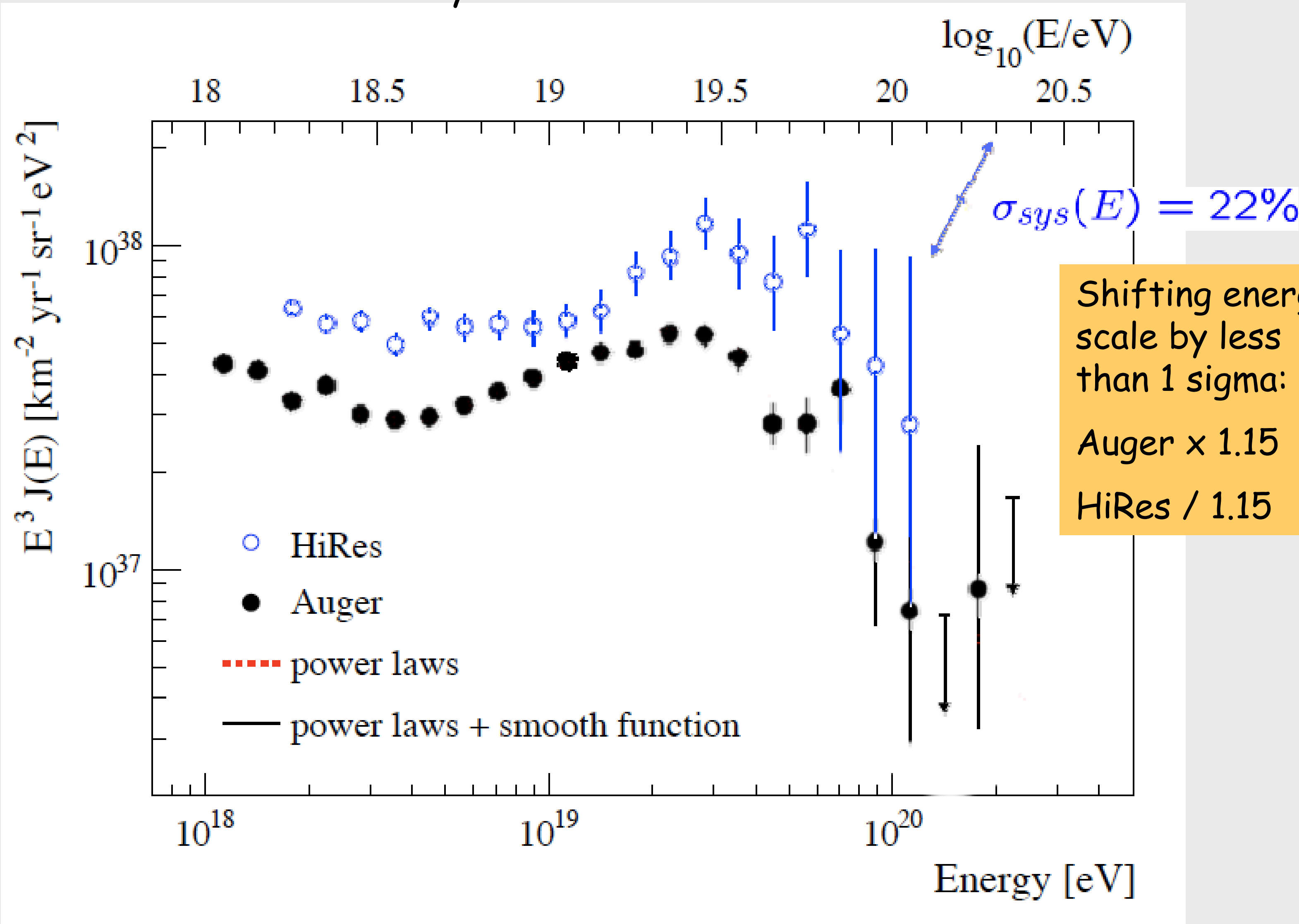
Phys.Lett.B 685 (2010) 239-246

Parameter	Power Laws	Power Laws + smooth function
$\gamma_1(E < E_{ankle})$	3.26 ± 0.04	3.26 ± 0.04
$\log_{10}(E_{ankle}/eV)$	18.61 ± 0.01	18.60 ± 0.01
$\gamma_2(E < E_{ankle})$	2.59 ± 0.02	2.55 ± 0.04
$\log_{10}(E_{break}/eV)$	19.46 ± 0.03	
$\gamma_3(E > E_{break})$	4.3 ± 0.2	
$\log_{10}(E_{1/2}/eV)$		19.61 ± 0.03
$\log_{10}(W_c/eV)$		0.16 ± 0.03
χ^2/ndof	38.5/16	29.1/16

- Sharp ankle at ~4 EeV
- Clear suppression of the flux above ~50 EeV (HiRes, Auger)
- flux drop to 50% at logE =19.6, significance ~20σ.
- Consistent with GZK suppression.

CR Spectrum

Consistent spectral shapes and fluxes between HiRes and Auger within systematic uncertainties

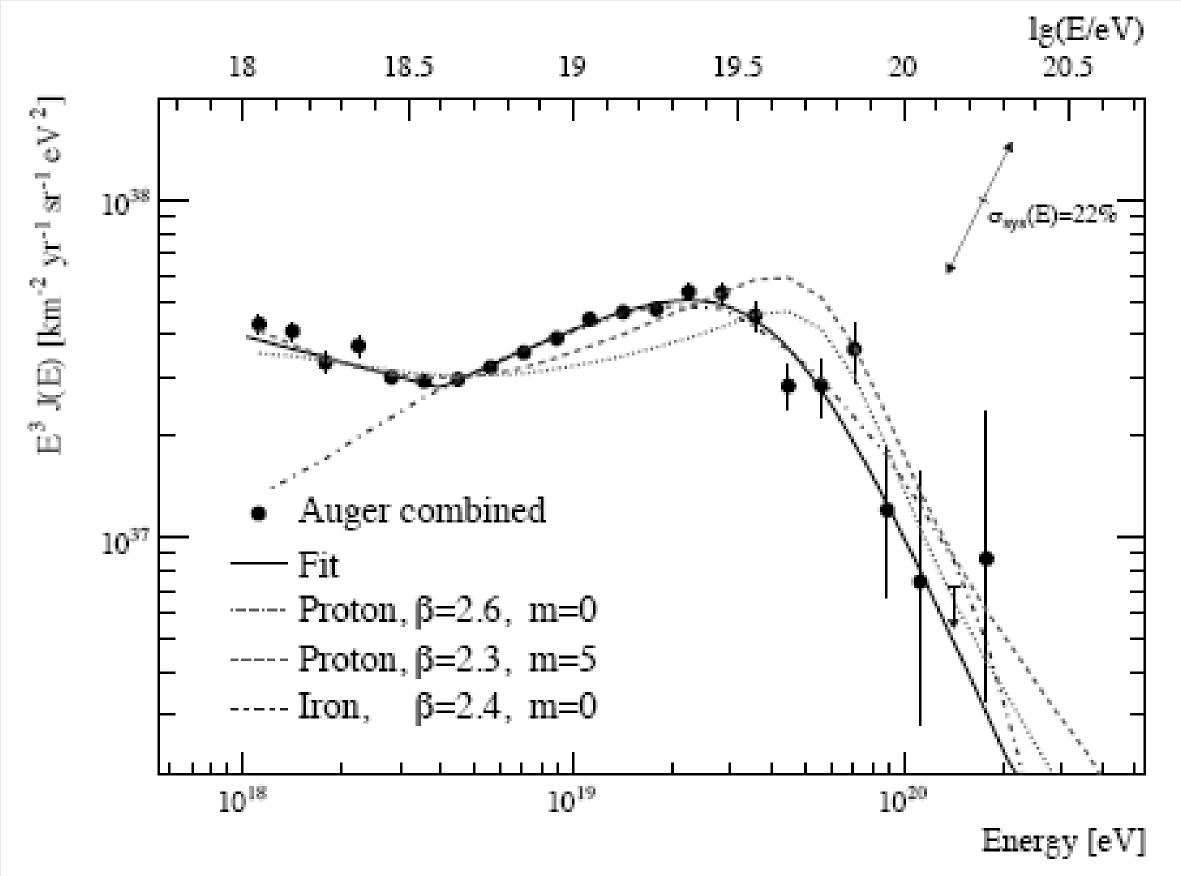


Shifting energy scale by less than 1 sigma:

Auger x 1.15

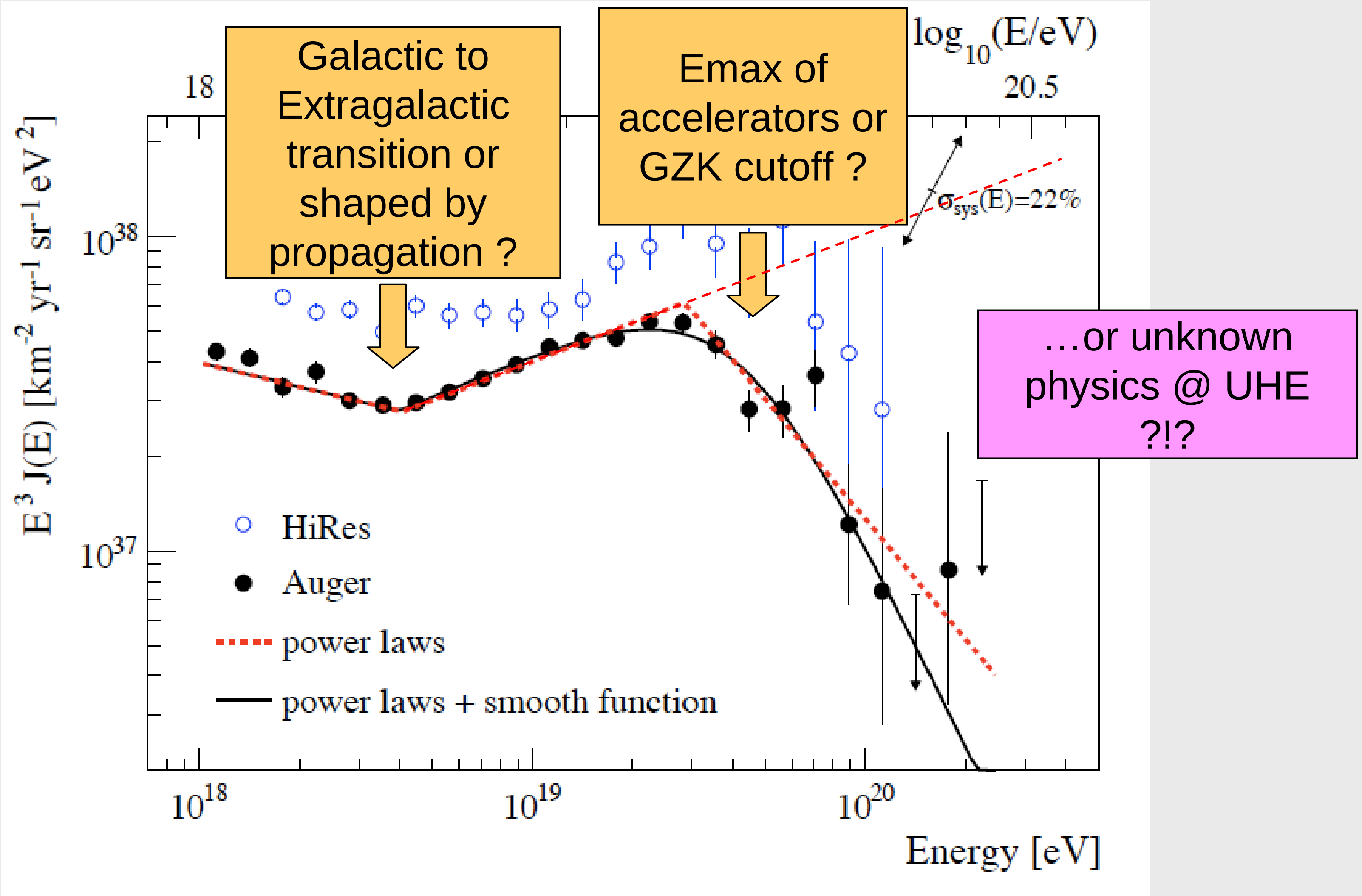
HiRes / 1.15

CR Spectrum



Constraints from spectral shape on mass composition models
and on sources distributions

CR Spectrum

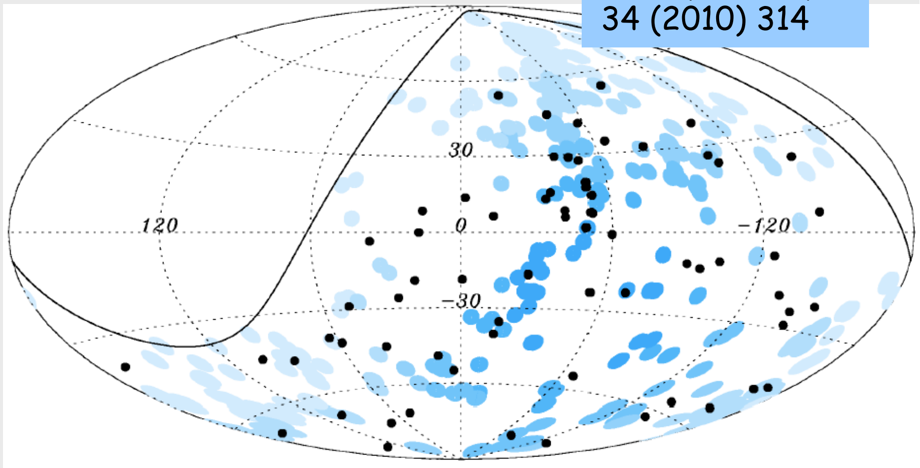


Answering these questions requires
anisotropy and composition studies up to 10^{20}eV

Anisotropies

Anisotropies at UHE

Astropart. Phys. 34 (2010) 314



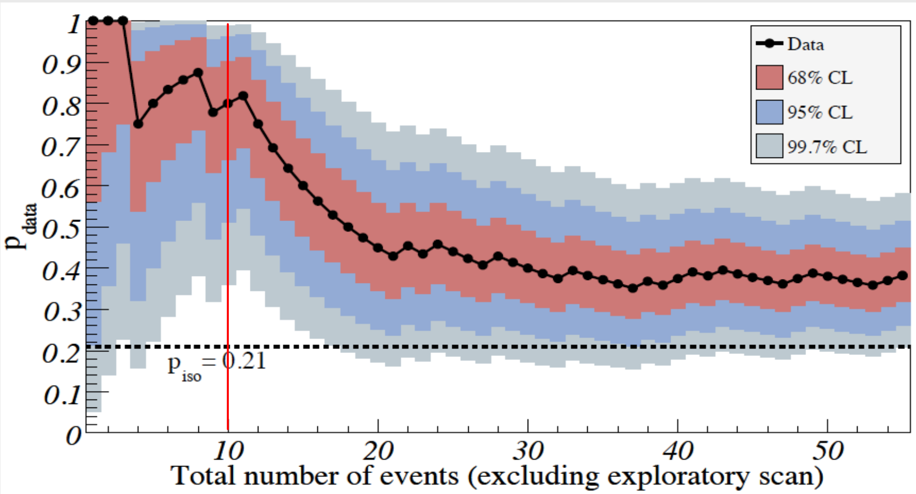
Prescription: used early dataset to define energy and angle cuts, catalog and redshift cut (12th VCV).

First published November 2007 in *Science*

AGN correlation now weaker but still present (38 +/- 6 % compared with 21% for isotropy).

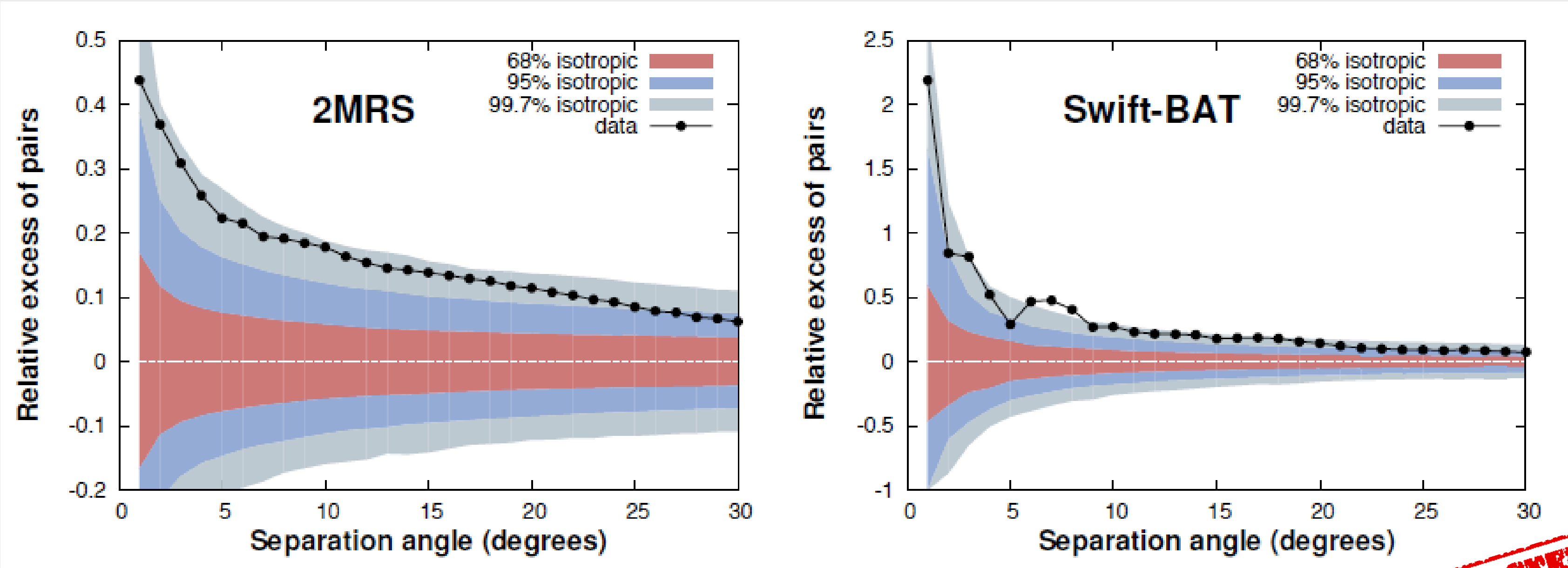
5 years of observation
Integrated exposure: 20400 km^2 sr y

Degree of correlation P_{data}=k/N



21/55 events now correlate
0.3% chance of finding this degree of correlation from an isotropic distribution

Where do they come from ?



A POSTERIORI ANALYSIS

A posteriori searches:

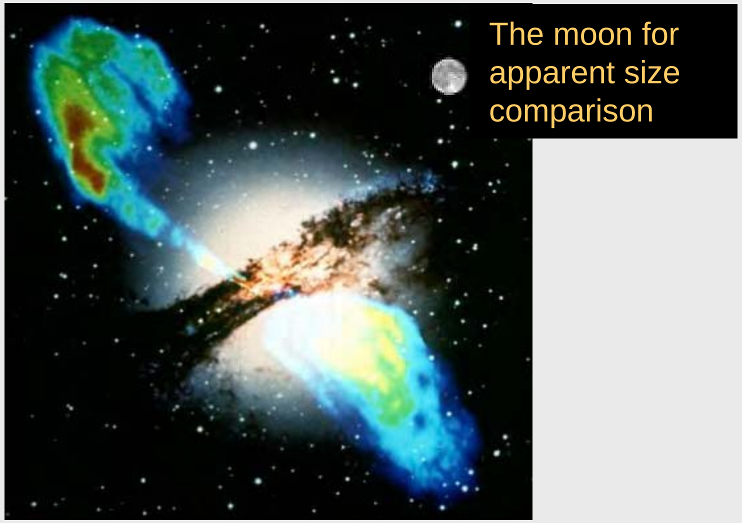
- Form pairs between each CR with E>55 EeV (69 Auger events) and each object from catalogues with d< 200 Mpc.
- Plot fractional excess of pairs (event+catalog object) in data vs isotropic distribution.
- Less than 1% of isotropic samples yield more pairs.
- Expectation 2MRS → (1.5°, 64%); Swift → (7.8°, 56%)

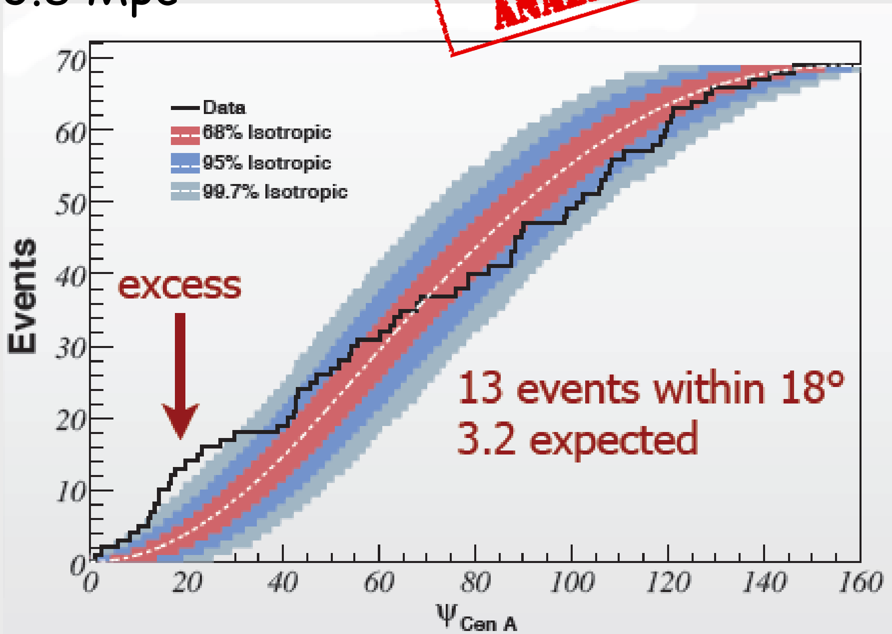
Large isotropic fraction favoured but correlating component required.

Where do they come from ?

A POSTERIORI ANALYSIS

Centaurus-A, nearest AGN (FR-I) at 3.8 Mpc
(→ no GZK attenuation expected)





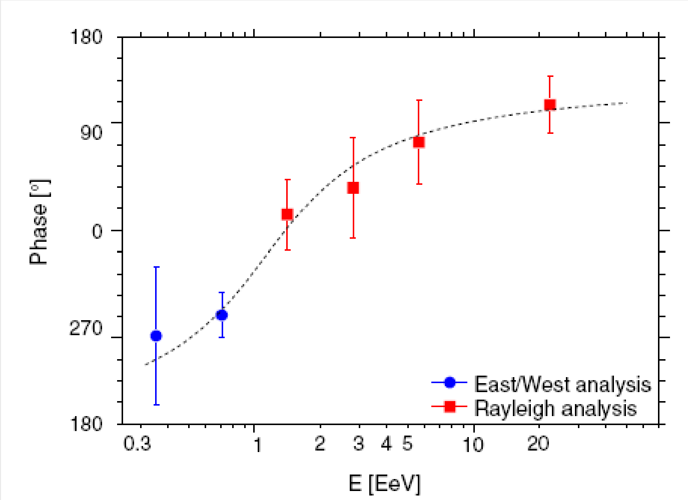
Excess from 18° circular window around Cen A of 12/58 events vs 2.7 expected.
Kolmogorov-Smirnov test: max departure from isotropy > max departure for observed events only in 2% of isotropic realizations

Virgo cluster

0/58 events in a 20° circular window vs 1.2 expected low exposure region for the Pierre Auger Observatory dominated by low luminosity AGN.

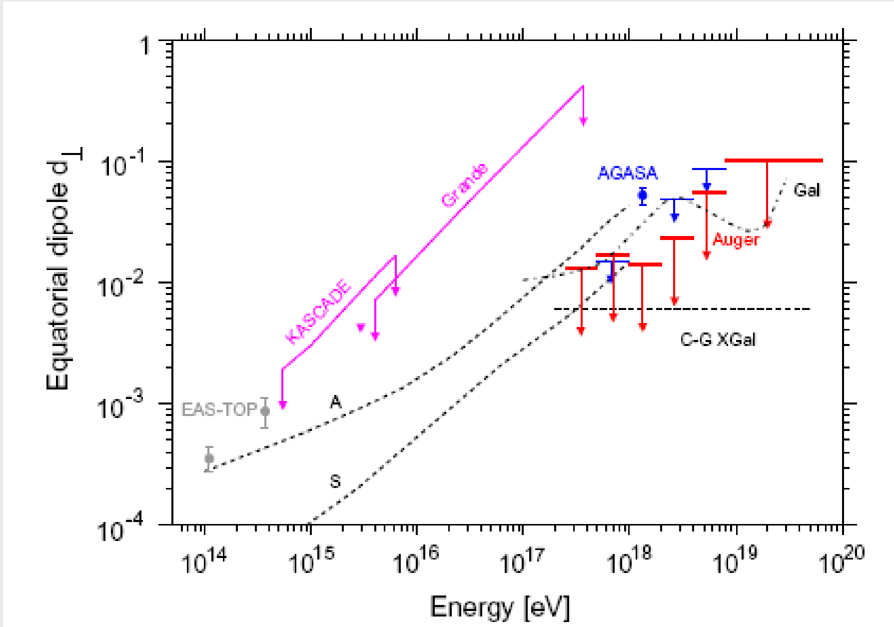
A POSTERIORI ANALYSIS

Large scale anisotropies



Anisotropies above 10^{17} eV.
Measure both phase and amplitude of the first harmonic modulation in the right-ascension distribution are measured.
Rayleigh analysis + East-West asymmetry

Upper limits on amplitudes below 2% at 99% C.L., excluding the dipolar anisotropy as reported previously by AGASA.



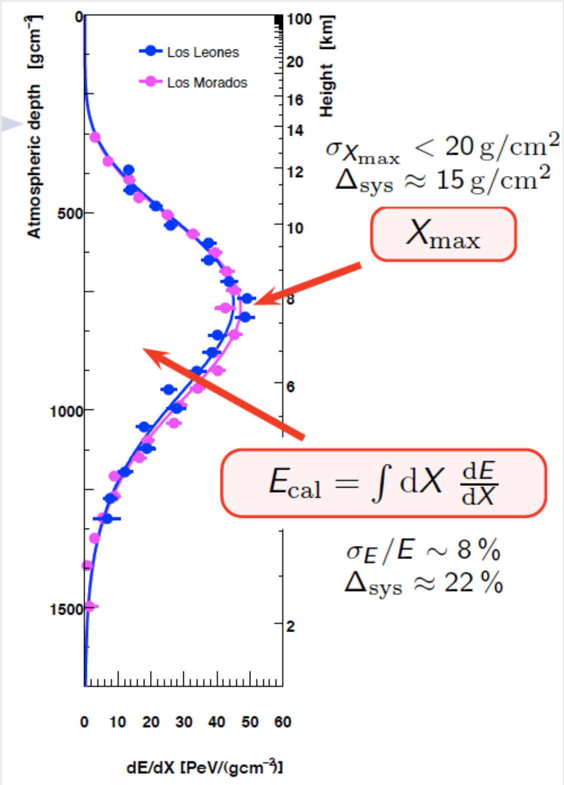
Composition

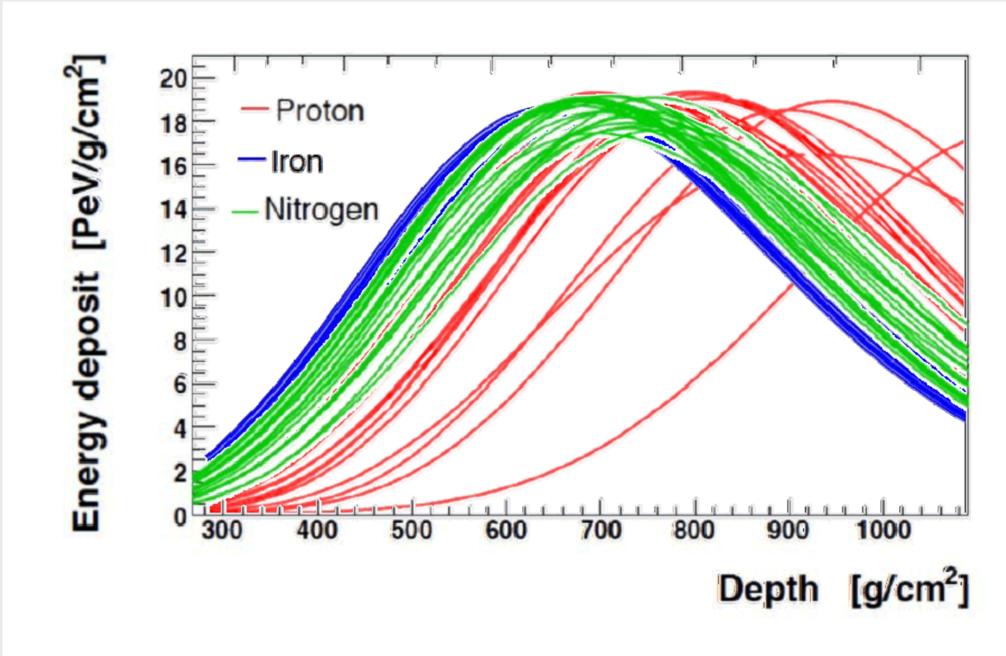
From EAS longitudinal profile to primary CR mass composition

Average depth of shower maximum $<X_{max}>$;

Width of distribution $RMS(X_{max})$ at a certain E

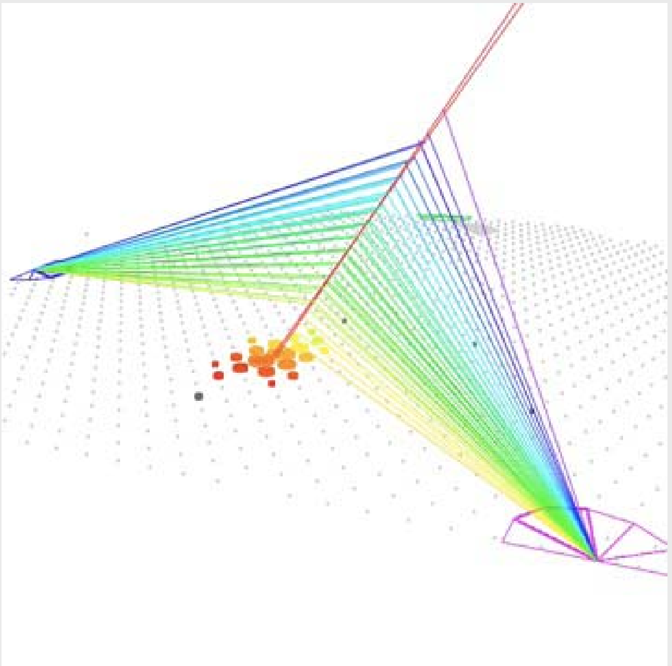
sensitive to <u>primary composition</u>

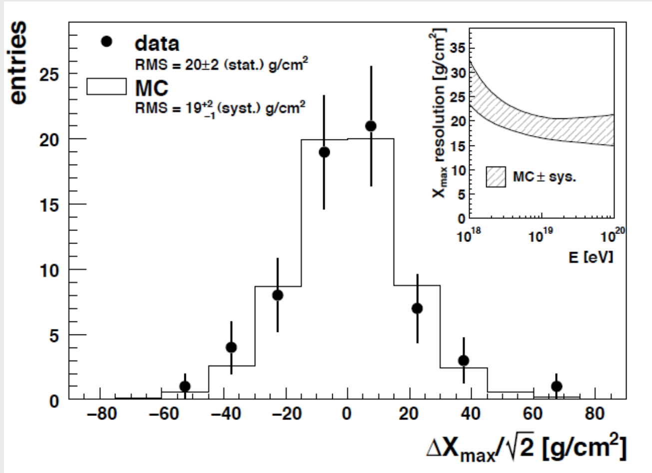




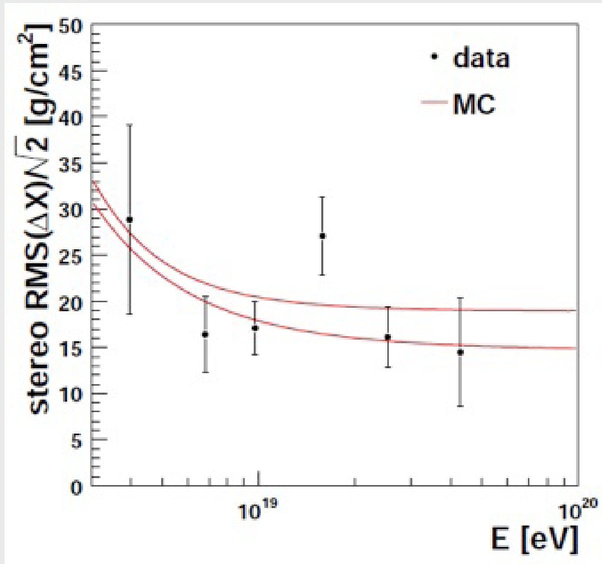
$X_{max} \propto ln(E_0) - ln(A)$ (MC Sim.)

EAS longitudinal profile measurement



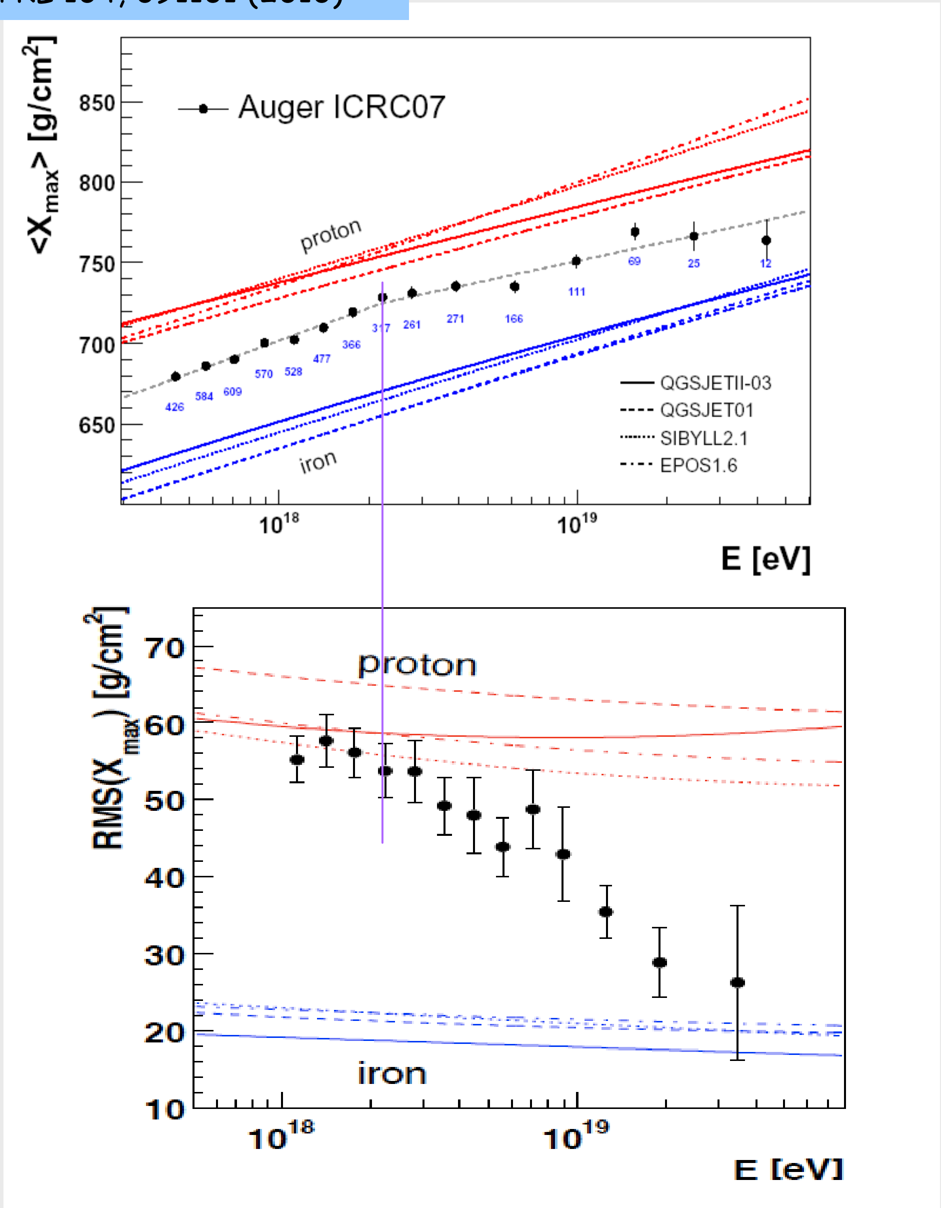


$$\sigma(X_{max}) \approx 20 \text{ g/cm}^2$$



Mass composition

PRL 104, 091101 (2010)



Data favor a break in the Xmax vs energy curve at :
E_b = $10^{18.25\pm0.05}$ eV ~E_{ankle}

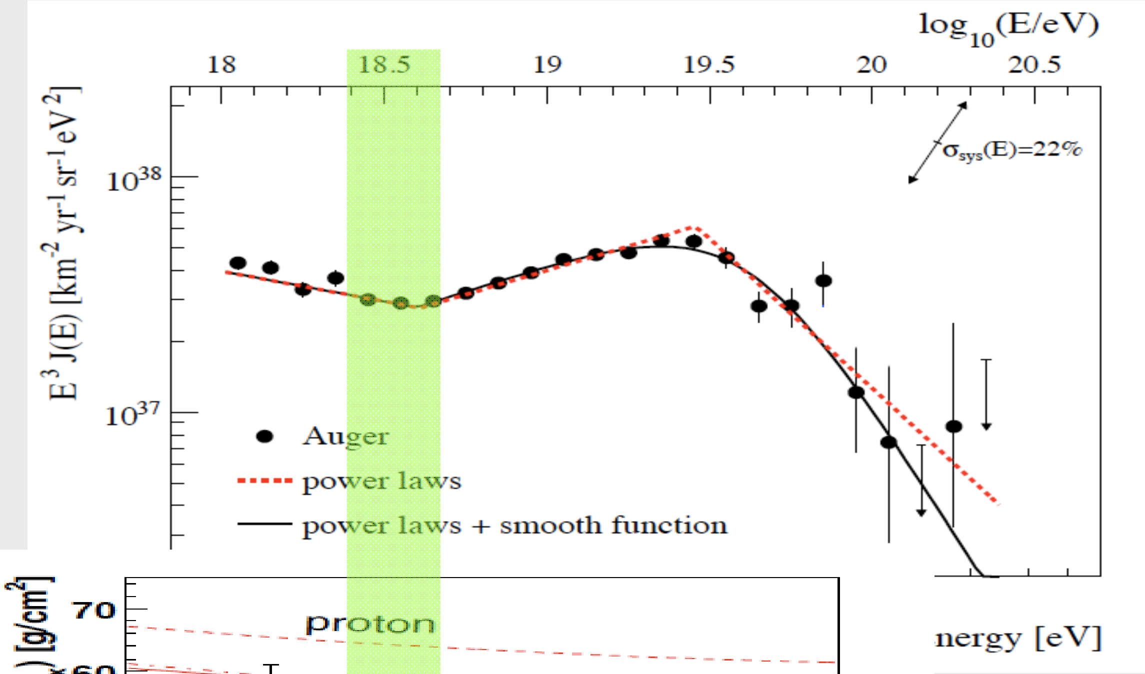
At energies above
E = 2 x10^{18} eV,
small elongation rate and decreasing RMS(Xmax) suggest a composition change towards a heavier composition

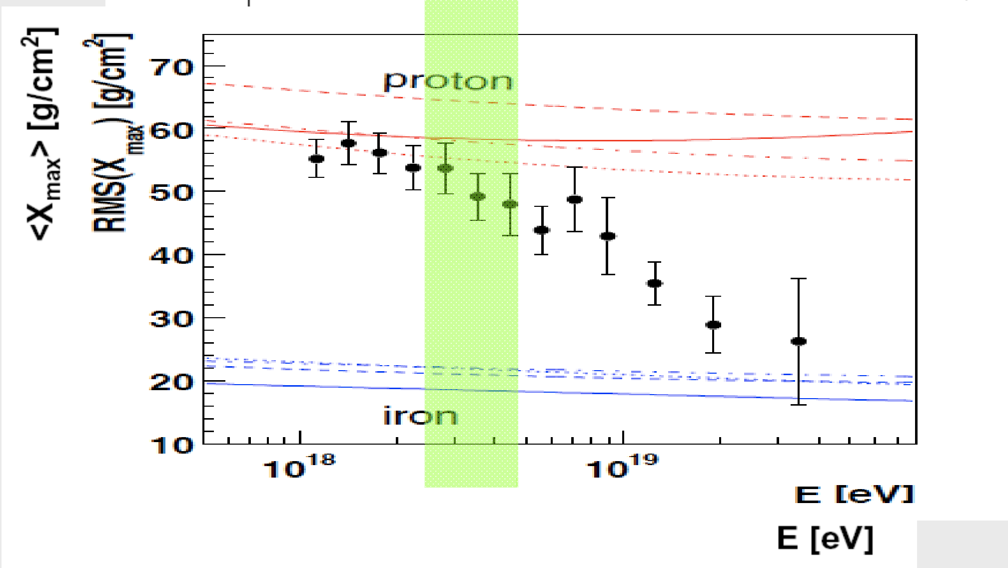
Tension with anisotropies results?
Need statistics above 50 EeV (need SD)

Models dispersion makes the interpretation still difficult

Composition and origin ?

The Ankle seems to coincides with a change in composition from lighter to heavier nuclei

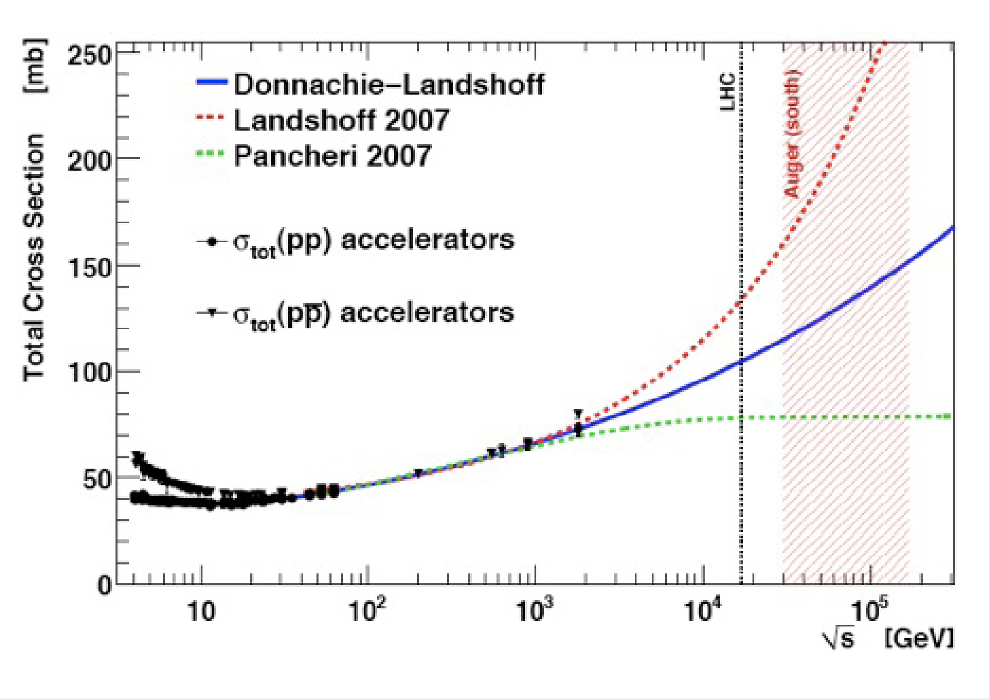


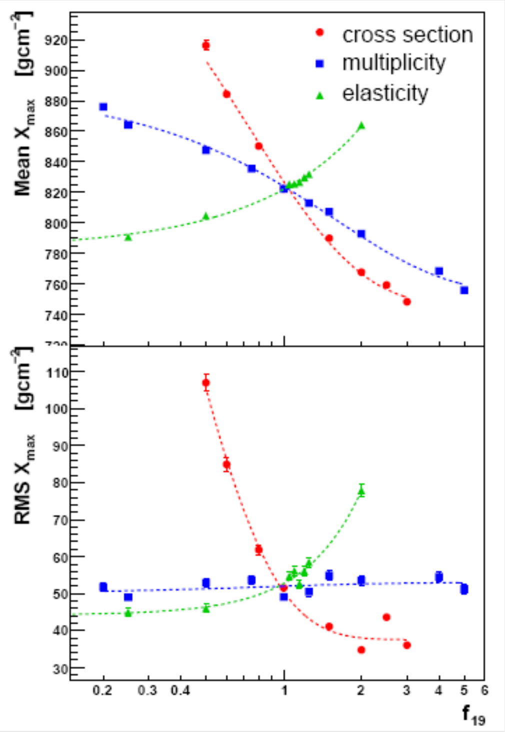


… But …

Composition hadronic interactions

Extrapolations of hadronic interactions and cross sections

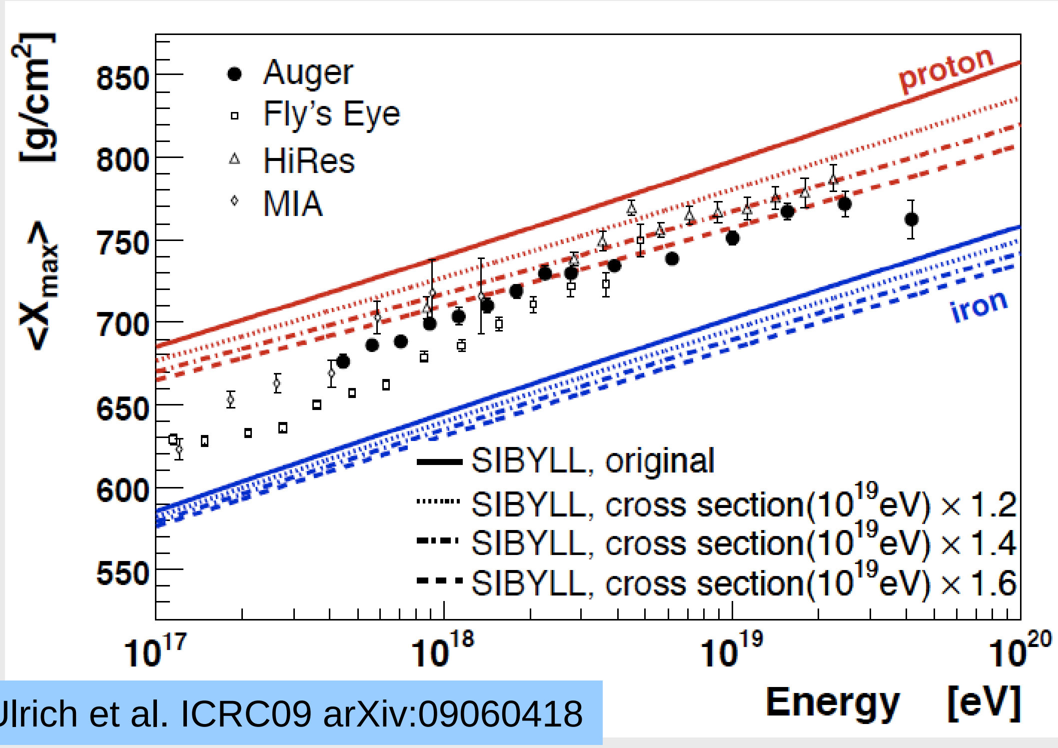




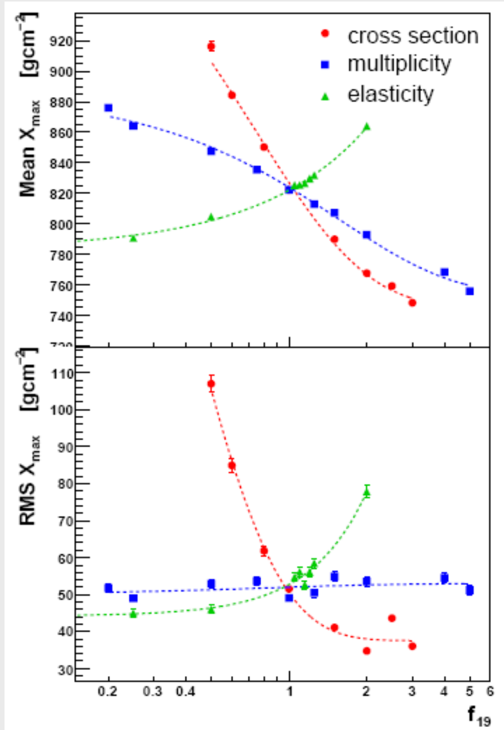
Hadronic interactions extrapolations (p-air cross section, multiplicity, elasticity) are crucial for composition measurements (and vice-versa).
Larger cross section imply smaller $<X_{max}>$ and $RMS(X_{max})$
$<X_{max}>$is easier to influence than the RMS
Dramatic change to cross-section required and quite a fine tuning...

Composition hadronic interactions

Extrapolations of hadronic interactions and cross sections



R. Ulrich et al. ICRC09 arXiv:09060418



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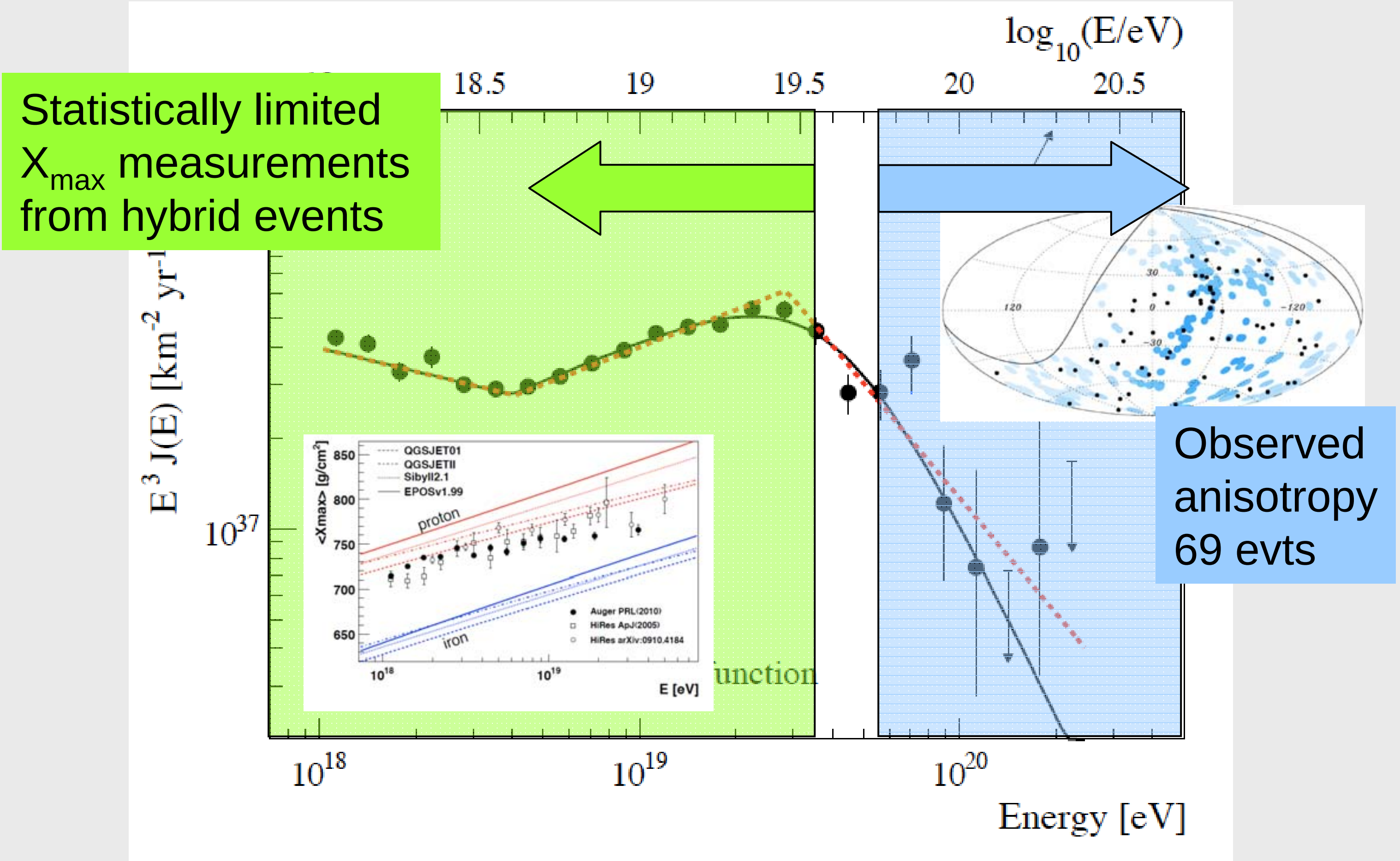
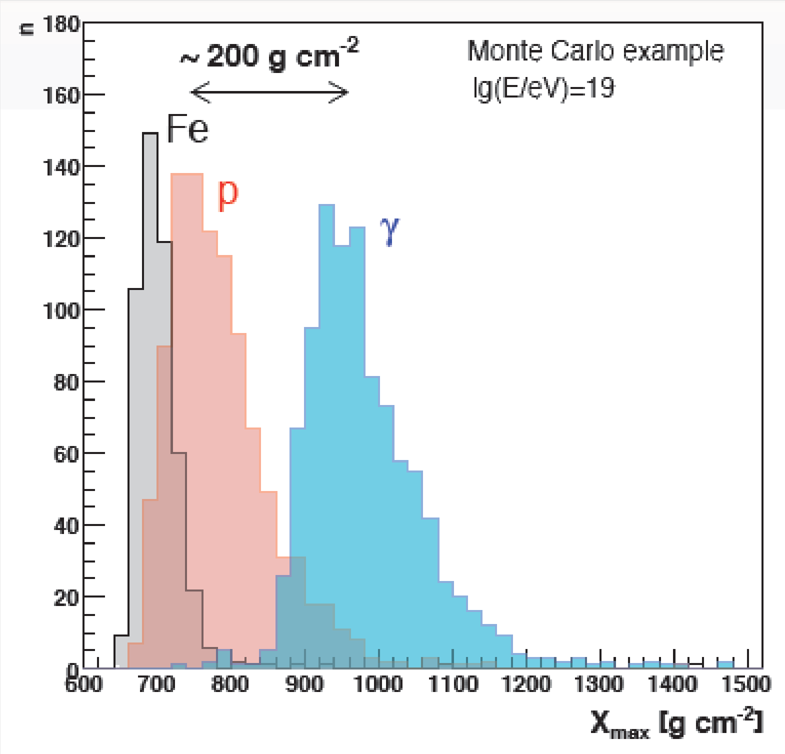
Composition and Anisotropy

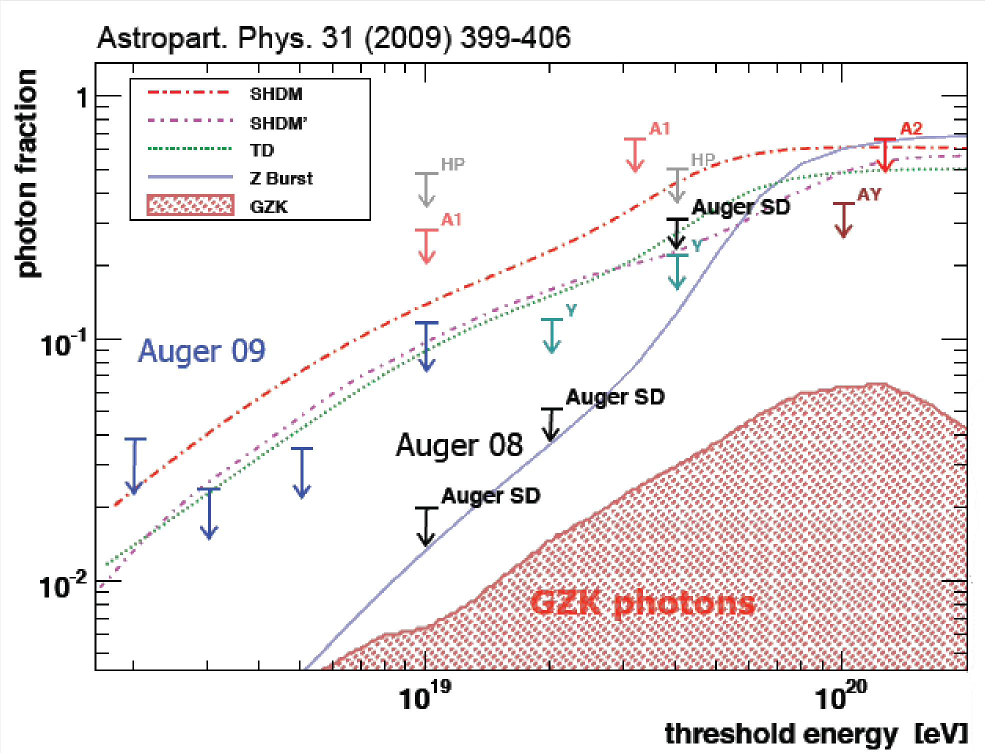


Need for higher statistics higher energy composition measurements
→ Auger North? Radio Detection ?

Composition: what they are not !

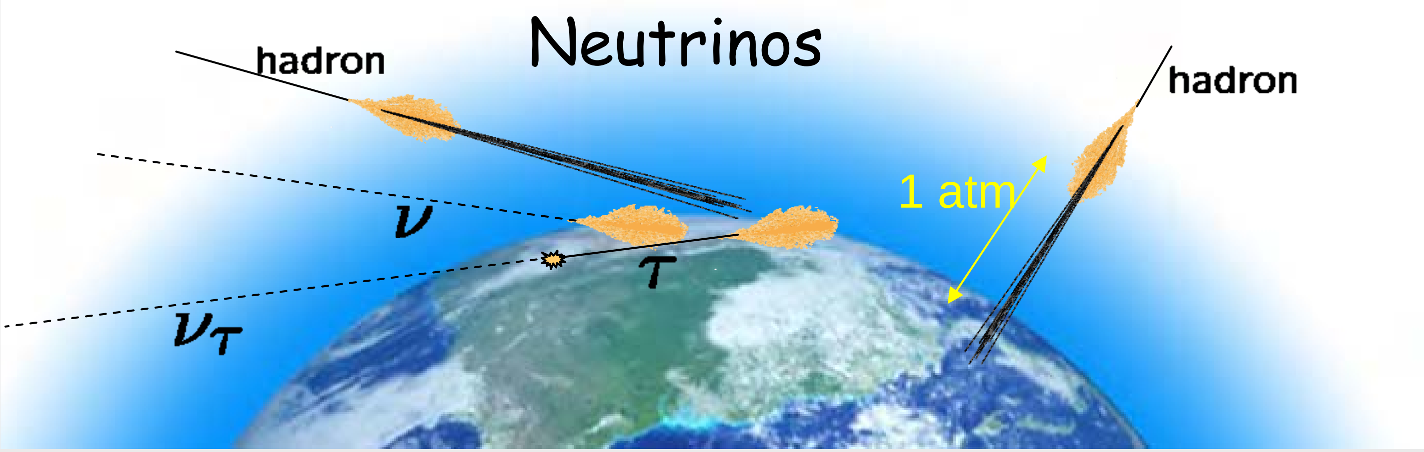
Very good γ-Hadron Discrimination by X_{max} Measurements
γ-induced showers less sensitive to EAS modeling

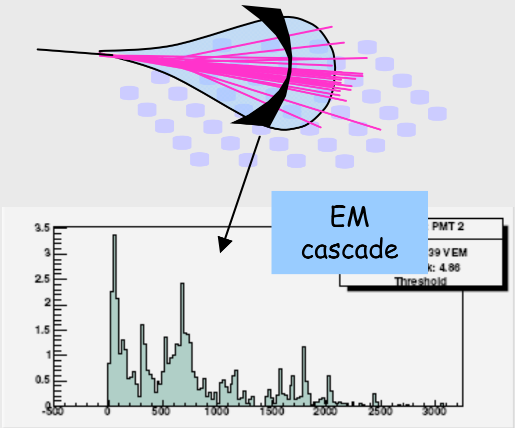


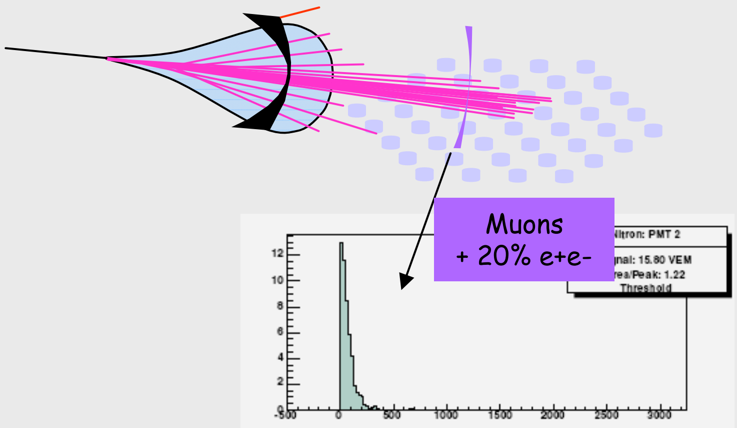


Top-Down models are largely disfavoured (if not dead!).

Composition: what they are not !





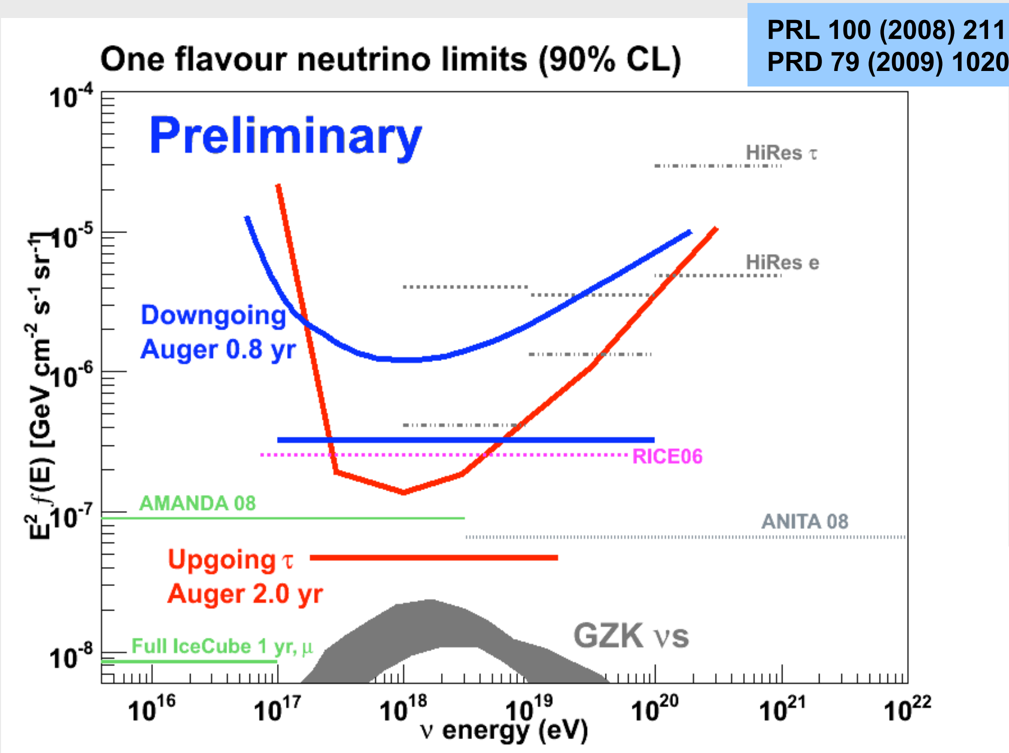


'young' showers (ν)
- Wide time distribution
- Strong curvature
- Steep lateral distribution

'old' showers (h)
- Narrow time distribution
- Weak curvature
- Flat lateral distribution

Composition: what they are not !

Neutrinos

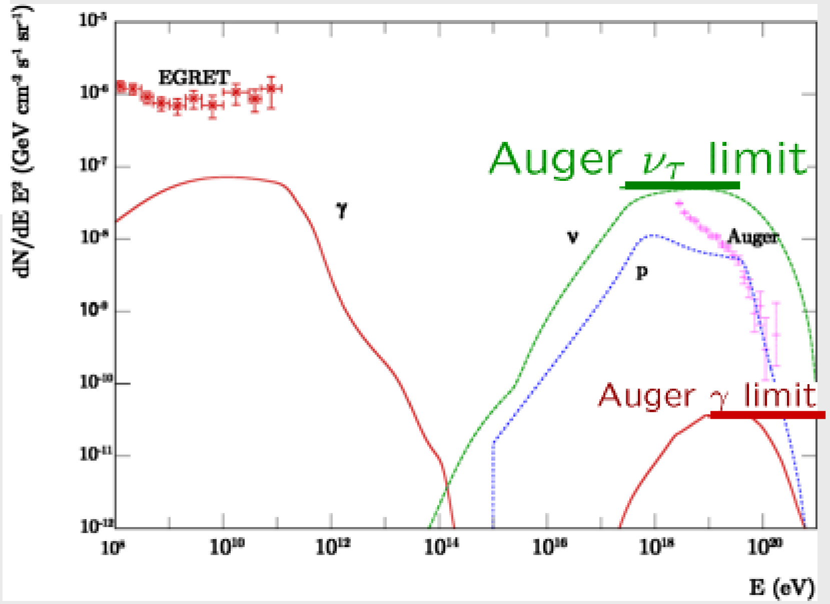


PRL 100 (2008) 211101
PRD 79 (2009) 102001

Several astrophysical models excluded

Cosmogenic (GZK) neutrinos in reach !

Neutrino limits are competitive with photon limits to exclude top-down models



Trying to make the picture clear…

Spectrum:

- Flux measurements at UHE: coherent observation of a suppression above 10^{19}eV, that can be interpreted as GZK cut off.

Anisotropies and correlations:

- Correlation with the direction of nearby sources (<75Mpc) at small angular scale (3.1°). This favors protons (higher charges would dilute the correlation).
- Still, a large isotropic contribution is needed: catalogues incompleteness or a contribution from higher masses (→Fe).

Composition measurements:

- Now more precise than ever but still challenging.
- Trend towards higher masses above 10^{19}eV (Auger <Xmax> and RMS(Xmax)), but contradicted by HiRes results.
- Important role of hadronic interactions extrapolations: change in composition, or cross-section higher ? Muon excess in data wrt models (1.3÷1.5) to be understood.
- Composition and anisotropies observed in disjoint spectral regions, larger hybrid aperture or new observables needed.
- Close connection with high-energy particle physics.

What did we learn from PAO

- **Flux measurements at UHE: observation of an ankle and a suppression (coherently between different detectors and with the same detector)**
  - thanks to extended range of operation AND higher statistics AND higher measurement precision
  - extensions at lower energies needed (to study the second knee with the same detectors)

- **UHECR sources are still mysterious:**
  - UHECR are anisotropic, but no clear association with sources
  - Large isotropic fraction and spread in the angular scales when correlating with nearby extragalactic matter (high Z CR?)

- **Composition measurements are more precise but still challenging:**
  - A change in shower development with E
    - Mass increase or change in hadronic physics ?
    - Tension with anisotropy ?
  - Relevant to understand the nature of the suppression (GZK effect/sources), of the ankle and of the second knee (galactic/extra-galactic transition)
  - Relevant to find UHECR sources?
  - Close connection with high-energy particle physics

- **No photons nor neutrinos so far:**
  - Exotic "top-down" models in serious trouble !
  - GZK photons and neutrinos fluxes at reach

And many other things…

What did we learn from PAO

Some of the subjects I did not cover that will be presented at ICRC2011.

- The Cosmic Ray Spectrum above 4 EeV as measured with inclined showers recorded at the Pierre Auger Observatory
- Measurement of Muon Atmospheric Production Depths with the Pierre Auger Observatory
- Comparison of showers at 10^19 eV observed with the Pierre Auger Observatory to models
- Measurement of the proton-air cross section with the Pierre Auger Observatory
- Anisotropies and chemical composition of ultra-high energy cosmic rays using arrival directions measured with the Pierre Auger Observatory
- First harmonic analyses of the right-ascension distribution of cosmic rays detected at the Pierre Auger Observatory
- Search for ultra-high energy cosmic ray multiplets in the Pierre Auger Influence of geomagnetic effects on large scale anisotropy searches
- Search for Galactic point-sources of EeV neutrons
- Bounds on the density of sources of ultra high energy cosmic rays from the Pierre Auger Observatory data
- Measurement of Energy-Energy-Correlations with the Pierre Auger Observatory
- Constraints on the Galactic Magnetic Field from the Pierre Auger Observatory
- Low Energy Radiation Measurements with the Water Cherenkov Detector Array of the Pierre Auger Observatory
- Thunderstorms And Atmospheric Effects In The Electromagnetic Component Of Secondary Cosmic Rays Observed With The Pierre Auger Surface Detector

...

and what's next ?

- **Extension of flux measurements down to lower energies**
  - more complete (and complex) detectors
  - keeping the accuracy of the measurements (i.e., multi-component)
- **Enhance composition measurements**
  - larger statistics above the GZK energy
  - keeping the same (or better?) precision (trying to learn about hadronic interaction physics at UHE)
- **UHECR sources are still to be found**
  - larger aperture detectors needed (more statistics!!!)
  - full sky coverage needed with a unique detector
  - possibly increase precision (e.g., event-by-event composition estimator?)

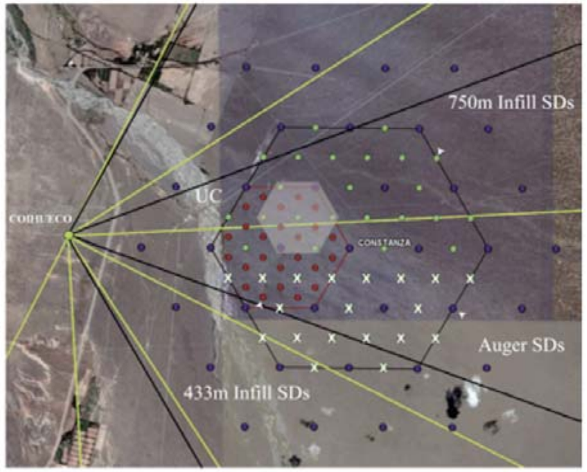
What next ?

Enhancements at Auger :

High Elevation Telescopes (HEAT)

HEAT: 3 additional FD telescopes with field of view 30°-58° detect lower energy EAS

Infill and muon detectors (AMIGA)



AMIGA: denser array (750 and 433 m spacing) of water Cherenkov + buried muon detectors

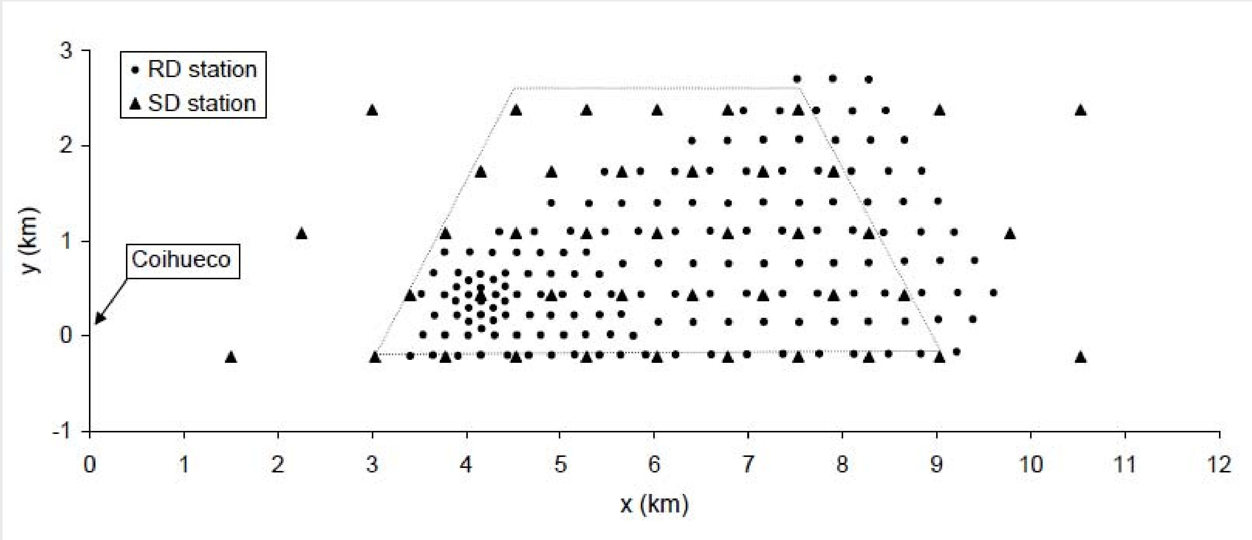
Multi-Hybrid detector fully efficient at 0.1 EeV (100 PeV)

EASIER: reading out the EM content of the showers and their profile with antennas used in slave mode on each SD tank ⇒ New observable for composition measurements up to the highest energies.

What next ?

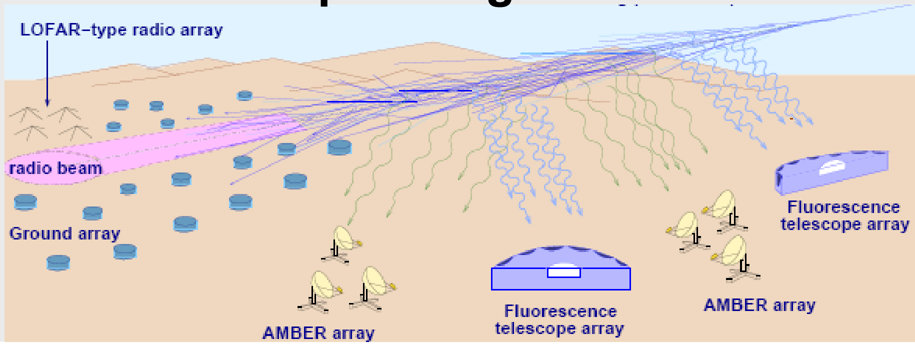
New observables

AERA @ Auger 150 VHF radio-detectors on 20 km²



- R&D (for a future revolution à la Fly's Eye ?)

MIDAS , AMBER "Fluorescence" telescope using GHz radio detection.



Conclusions

Great recent experimental achievements:

- Single-experiment comprehensive measurements over a large energy range successful.
- Larger detectors but more important more accurate and model independent measurements (stereo, hybrid).
- The E spectrum of UHECR is now well measured up to few 10^{20}eV. Ankle @ 4×10^{18}eVand flux suppression above 10^{19}eV are clearly seen.

  Interpretation of suppression in terms of GZK effect still premature (depends on composition).
- Composition and anisotropy measurements still "critical": lacking statistics at the highest energies.
- Essential interplay between hadronic interactions measurements at accelerators and UHECR measurements to improve interaction models.

Wishes for future: not only bigger but better…

- larger aperture, higher precision "multi-hybrid" detectors
- large energy range coverage with single detectors
- full sky coverage


Thanks