Physics in Collision 2010, Karlsruhe

Ultra High Energy Cosmic Rays

François Montanet
for the
Pierre Auger Collaboration

LPSC IN2P3/CNRS,
Grenoble University Joseph Fourier

Outline

Past and current UHECR observatories,
a fight against flux and a quest for better measurements.

From EAS measurements to UHECR,
Energy, Direction, Composition.

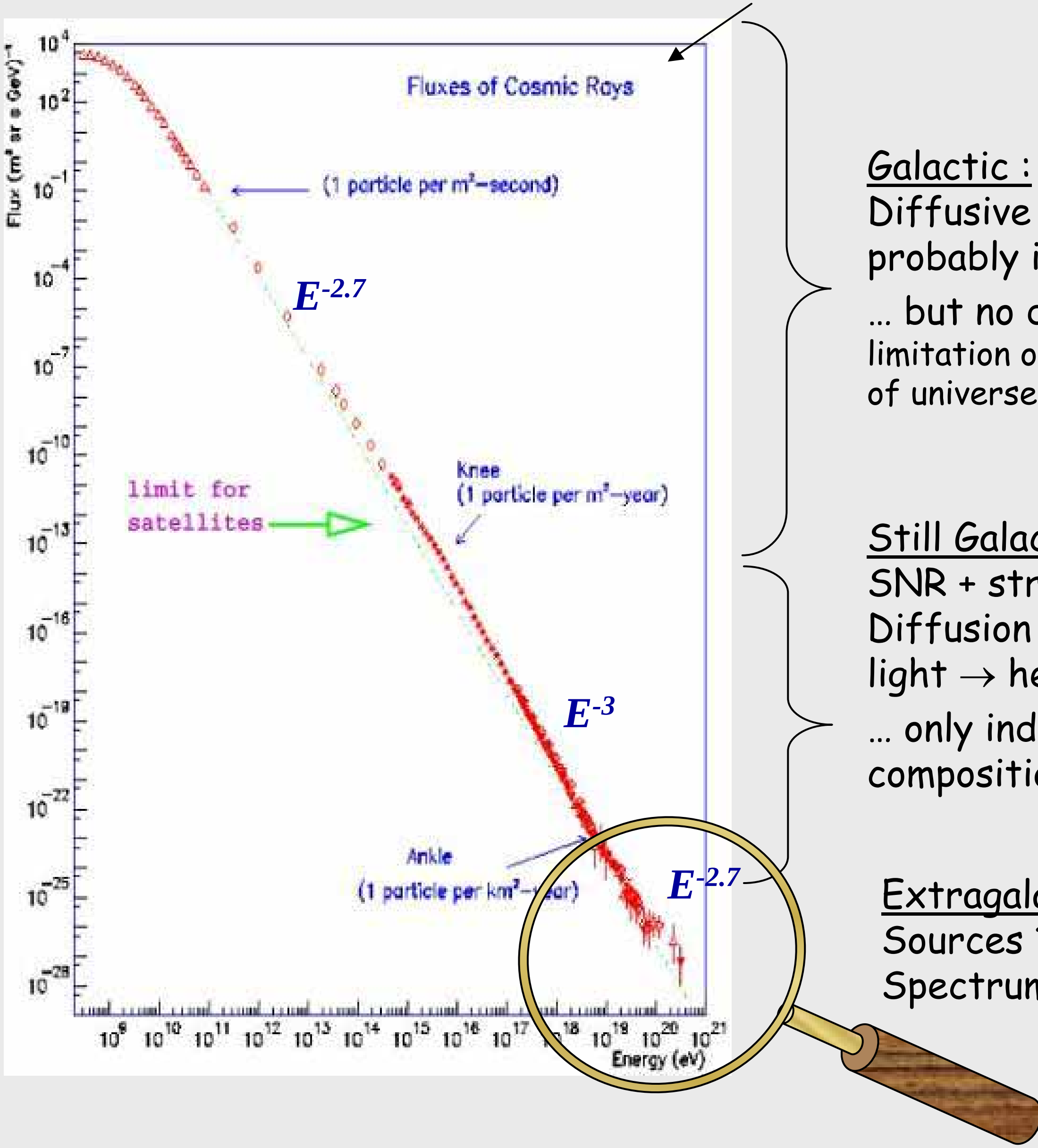
The Experimental Data,
grandeur and weaknesses.

From Astrophysics to High Energy Physics
and vice-versa !.

Perspectives and outlook.

Why UHECR ?

Tribute to Simon Swordy 1954-2010



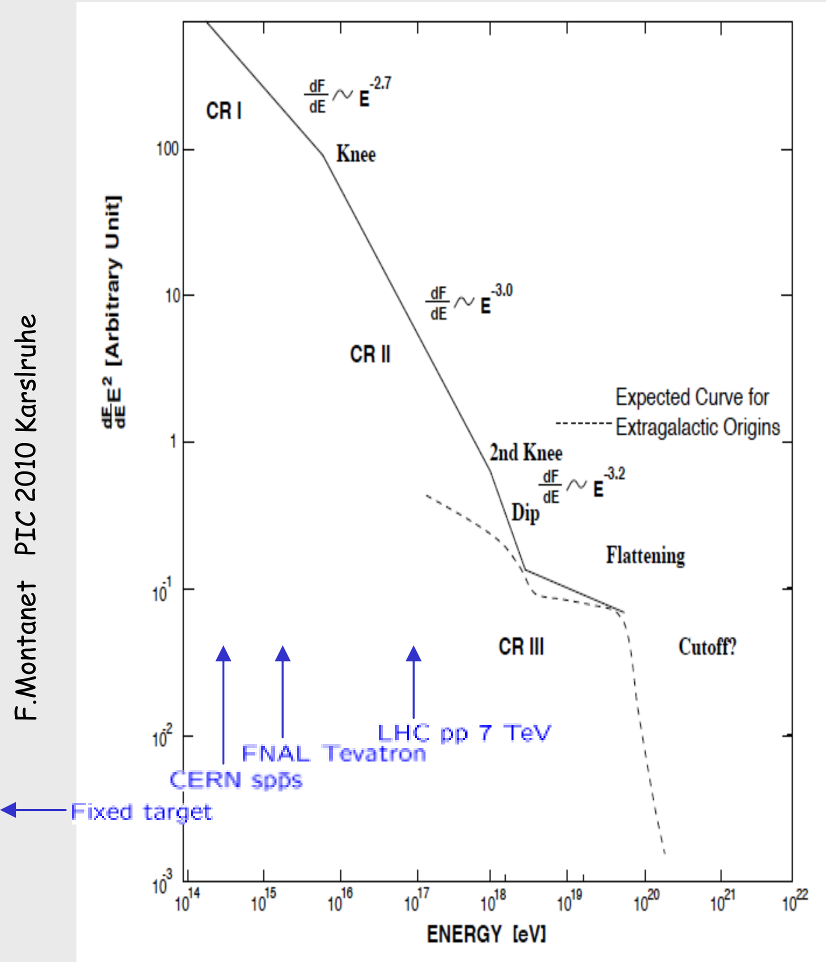
<u>Galactic</u> :
Diffusive acceleration in chocks (Fermi), probably in SuperNovae Remnants
… but no direct evidence so far,
limitation of γ astronomy probing mostly EM nature of universe

<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**

Past and Current UHECR observatories

Increasing the aperture…

Early 60s:
Volcano Ranch
USA, New Mexico, 1800 m a.s.l.
19 scintillators + 1 shielded
Spacing ≈ 450 m
Area:
2 (8) km²

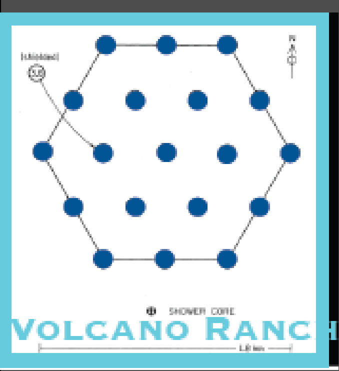
Late 60s - 80s:
Haverah Park
UK, Leeds, 220 m a.s.l.
62 water Cherenkov
Spacing ≈ 500/2000 m
Area: 12 km²

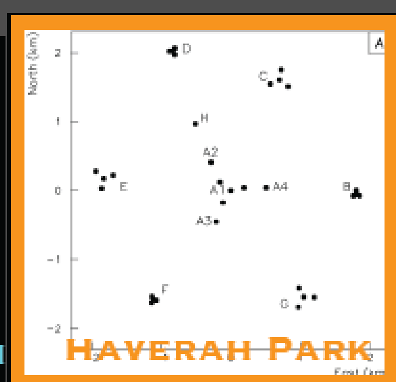
Late 60s - 70s:
SUGAR
Australia, 250 m a.s.l.
54 buried scintillators
Spacing ≈ 1600 m
Area: 55 km²

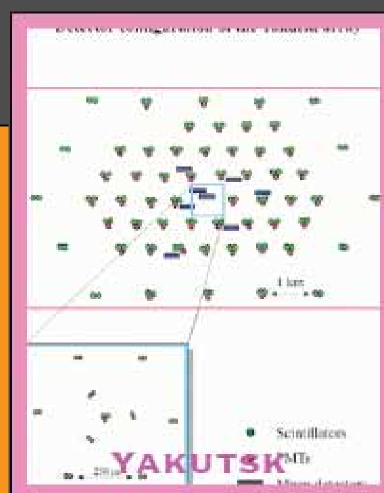
Early 70s - now
Yakutsk
Russia, 100 m a.s.l.
58 scintillators + 6 muon detectors + 45 Cherenkov PMTs
Spacing ≈ 150/500/1000 m
Area: 17 km²

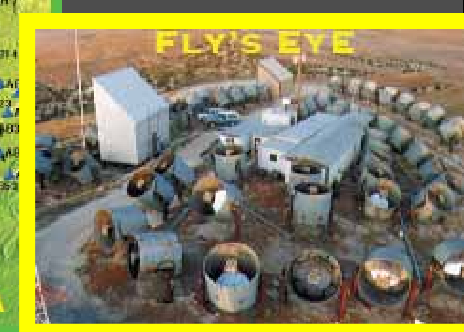
Late 70s - 2004
AGASA
Japan, Akeno, 100 m a.s.l.
111 scintillator detectors + 27 muon detectors
Spacing ≈ 1000 m
Area: 100 km²

Early 80s - 1995
Fly's Eye
USA, Utah, 100 m a.s.l.
2 fluorescence telescopes (67 mirrors & 880 PMTs + 36 mirrors & 464 PMTs)
Spacing ≈ 3.4 km









1960 1970 1980 1990

Taken from P. Ghia ECRS2010

… but also new observables and better measurements

Early 60s:
Volcano Ranch
Pulse amplitude, arrival times
LDF -> Ne -> rough estimate of energy

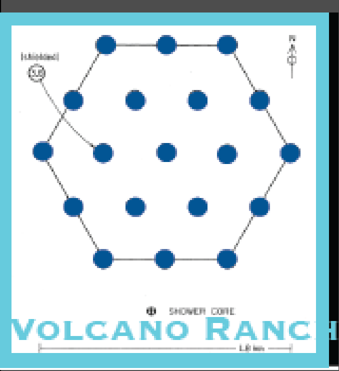
Late 60s - 80s:
Haverah Park
Measurement of EAS photons/electrons/ Muons

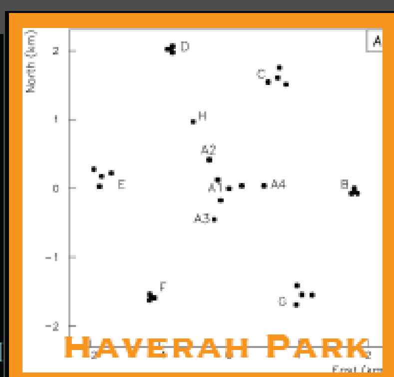
Late 60s - 70s:
SUGAR
Largest array at the time, muon sensitive
Unique in Southern hemisphere

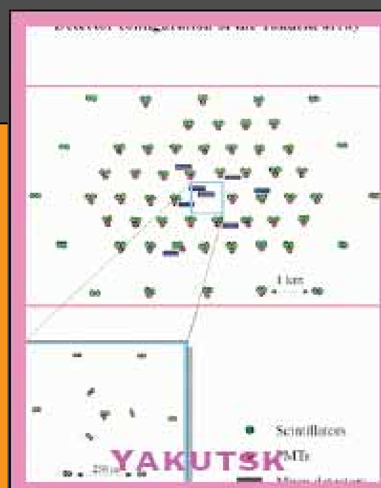
Early 70s - now
Yakutsk
First "complex" detector (multicomponent).
3 nested subarrays, with different spacing.
First calorimetric approach (Cherenkov)

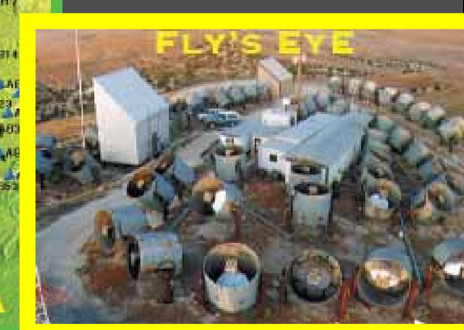
Late 70s- 2004
AGASA
Largest array in the past
Multi-component measurement (e.m. and muonic)

Early 80s-1995
Fly's Eye
First successful use of fluorescence
First "stereo" measurements





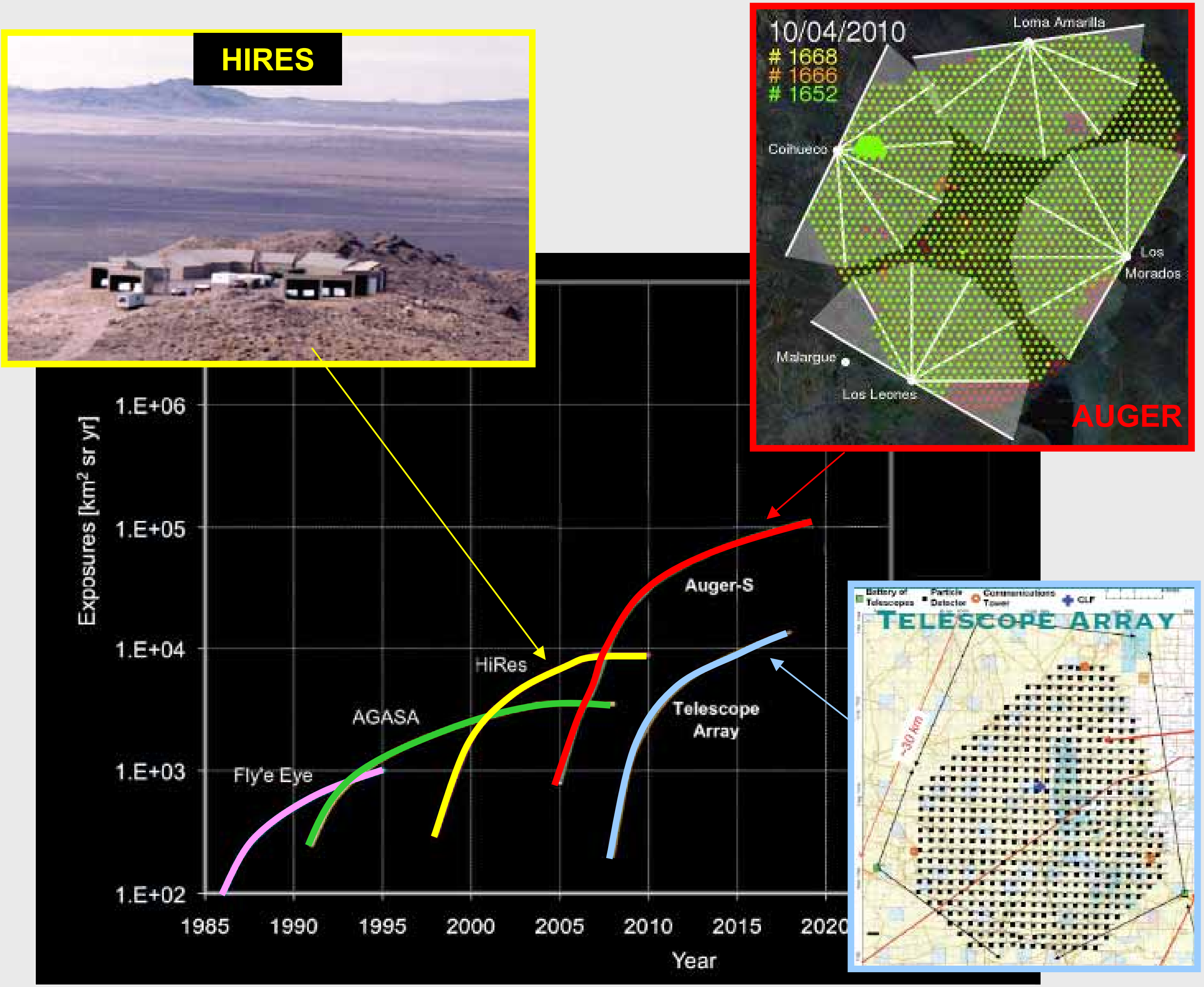




1960 1970 1980 1990

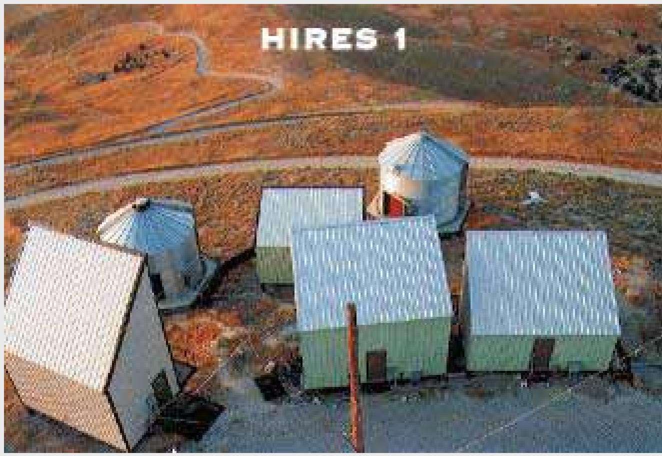
Taken from P. Ghia ECRS2010

Current experiments

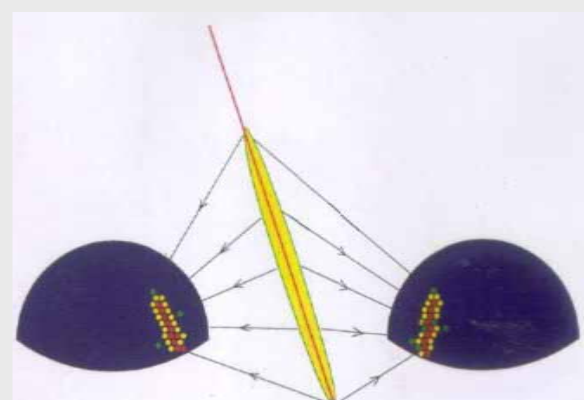


HiRes

1996-2006: The High Resolution Fly's Eye (HiRes I +II)

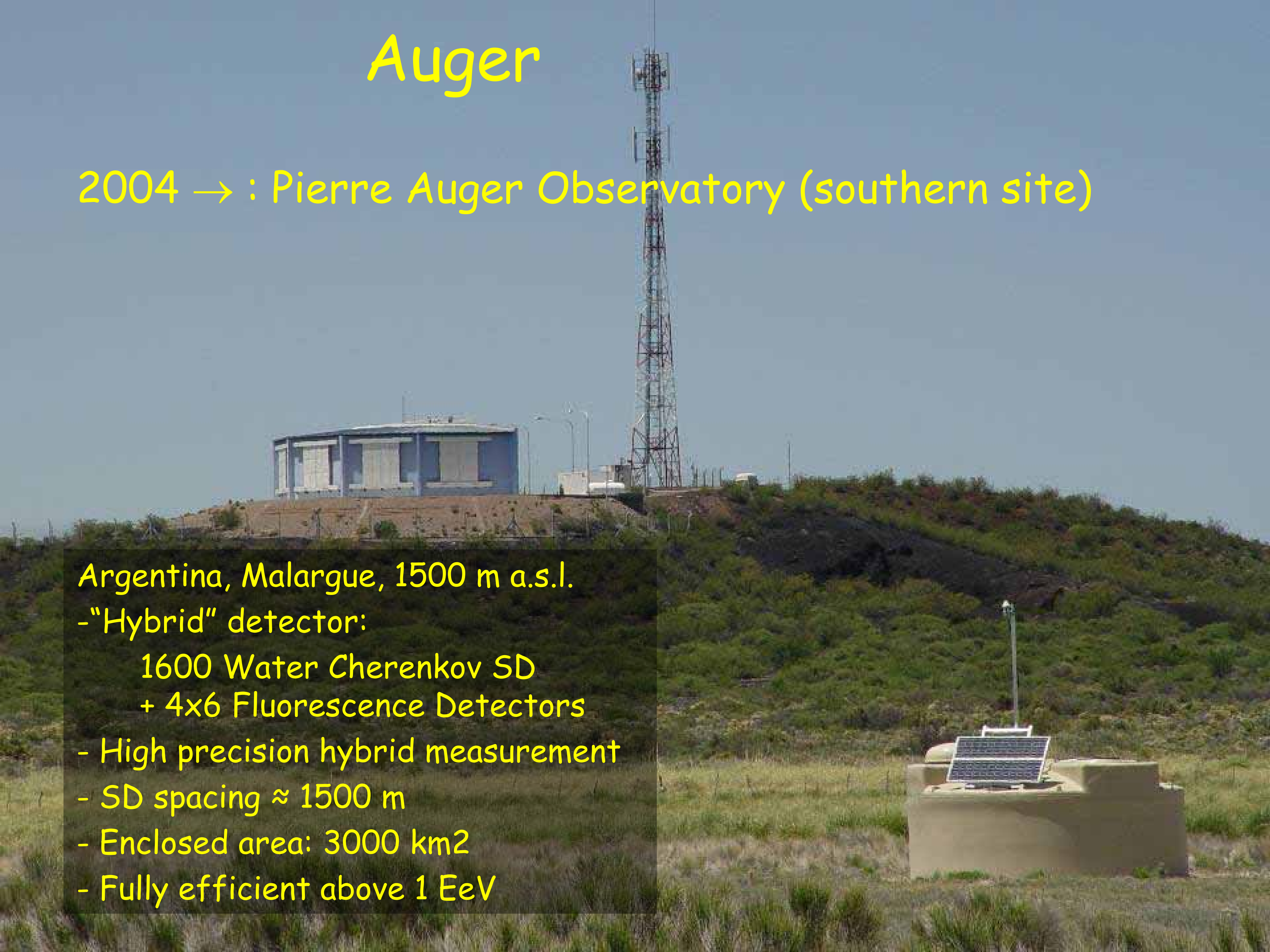


- USA, Utah, 100 m a.s.l.
- 2 fluorescence telescopes (HiRes 1 & 2)
- Larger spacing wrt Fly's Eye ≈ 12.6 km
- HiRes 1: 21 mirrors (alt. 3-17 deg):
  higher statistics, higher energy threshold
- HiRes 2: 42 mirrors (alt. 3-31 deg).
  Lower energy threshold
- High precision stereo measurements



Auger

2004 → : Pierre Auger Observatory (southern site)



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

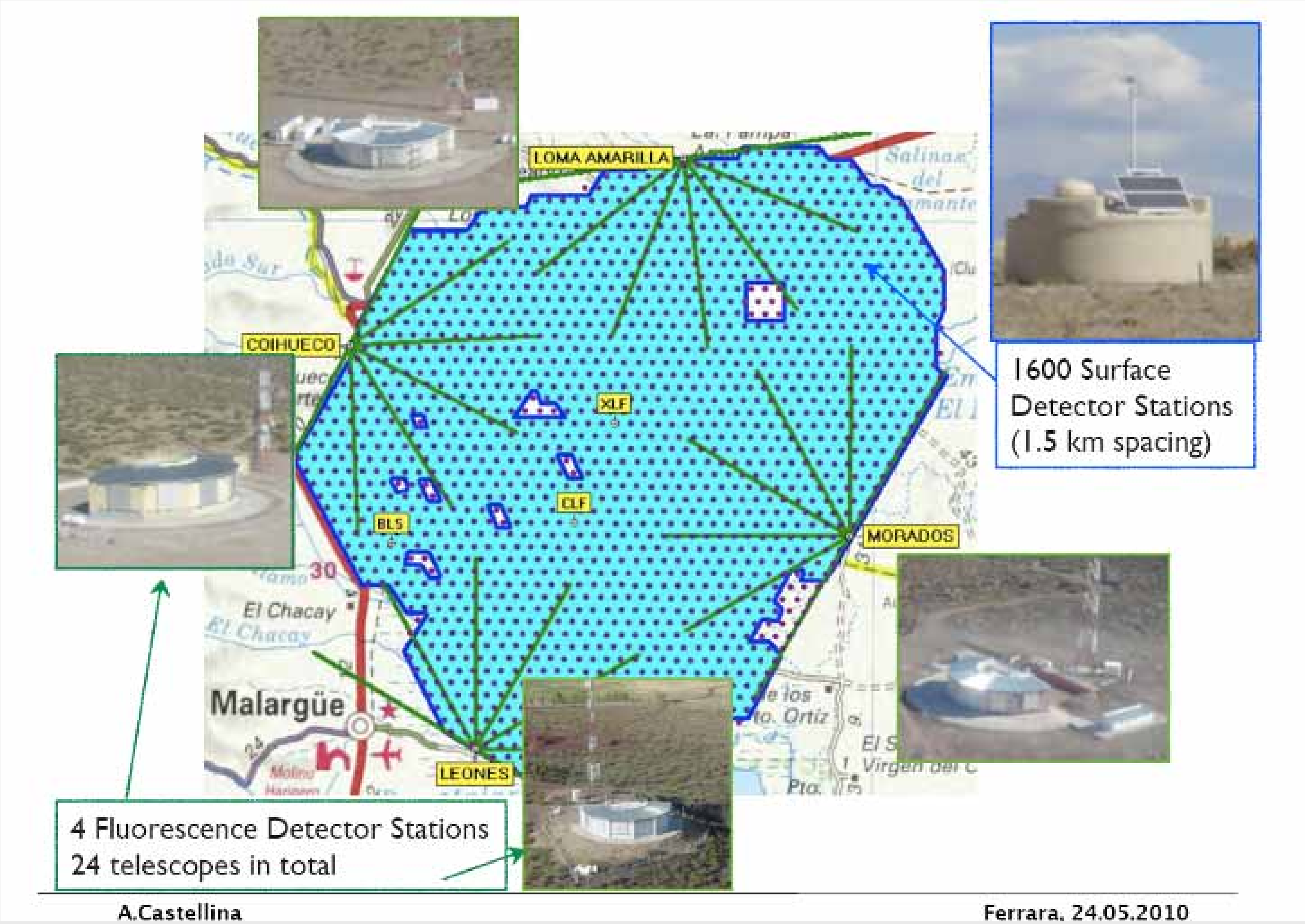
-"Hybrid" detector:

    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

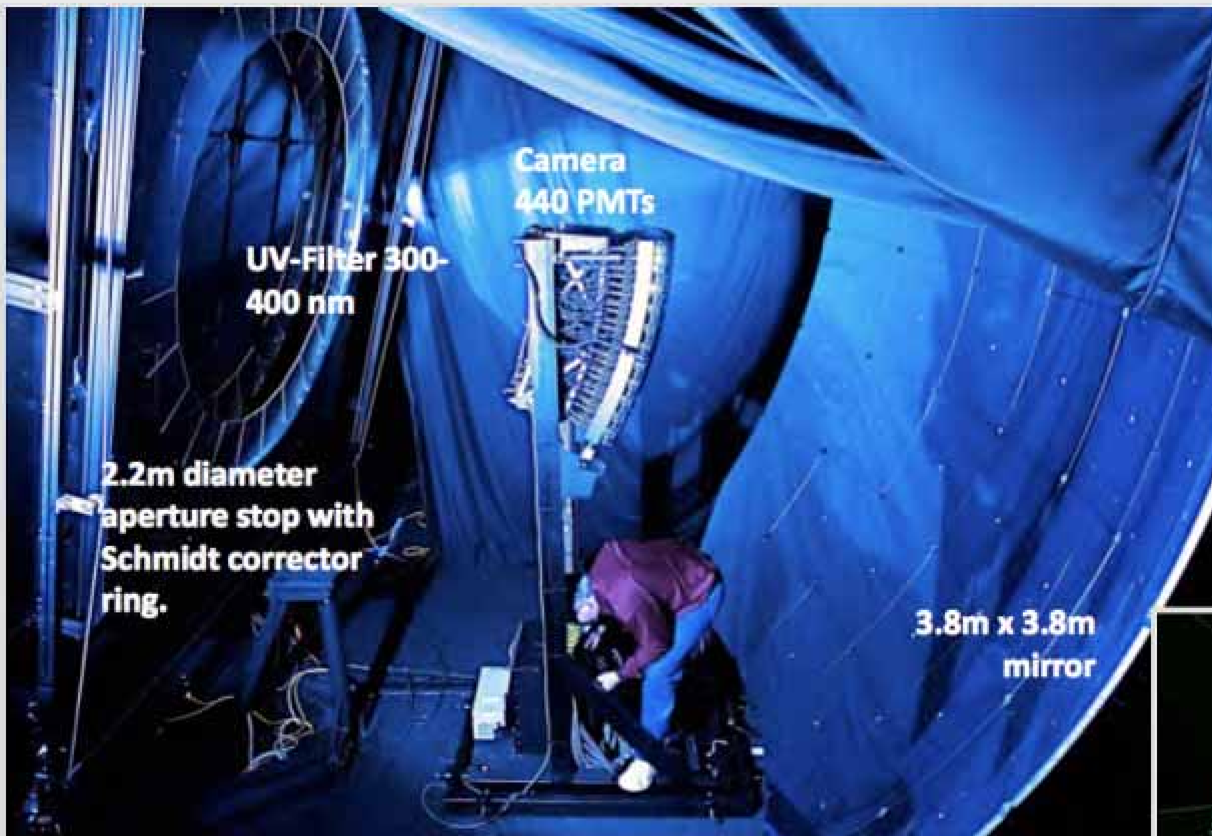
A "hybrid" detector :

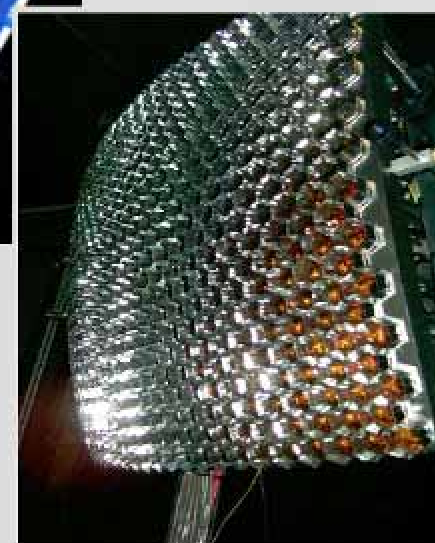


Auger Surface Detector

Water Cherenkov Detector
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 m^2 mirrors)
- ✓ Camera with 440 PMT (Photonix XP4062)

Telescope Array

- 2008 → : Telescope Array

USA, Utah, 1400 m a.s.l.

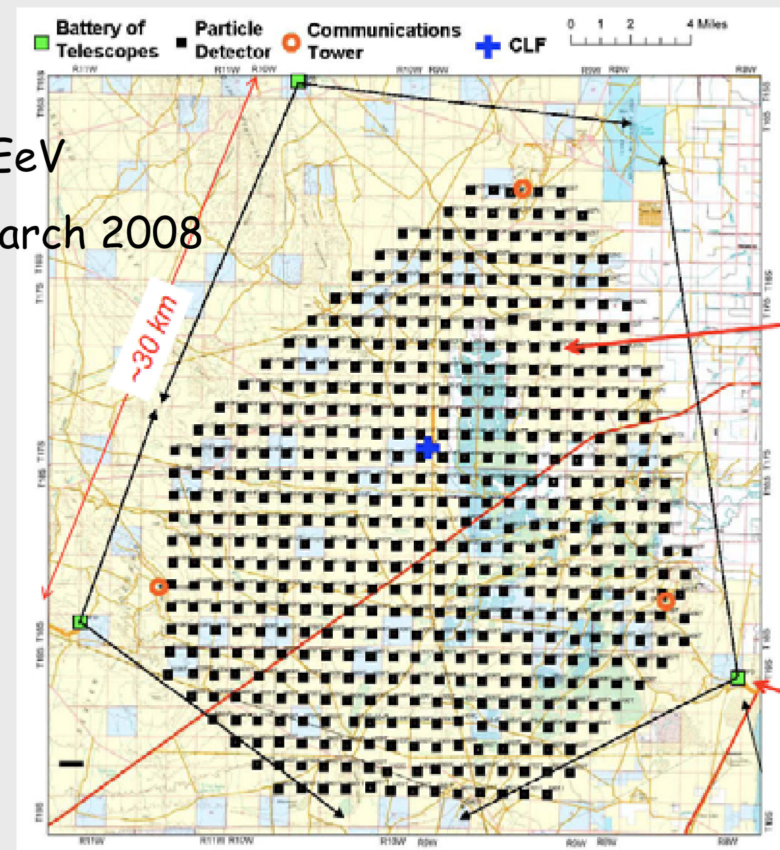
- Hybrid detector: 507 scintillators SD array
+ 3 fluorescence sites

- SD Spacing ≈ 1200 m

- Enclosed area: 700 km^2

-Fully efficient above 0.1 EeV

- Data taking started in March 2008



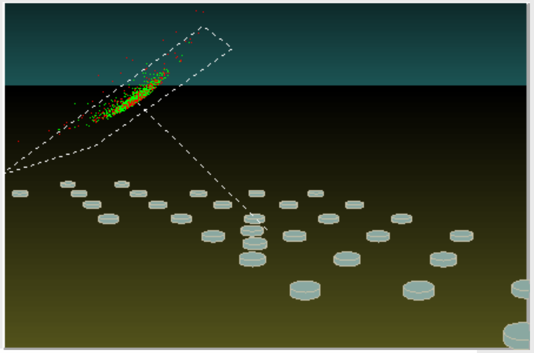
From EAS measurements to UHECR parameters

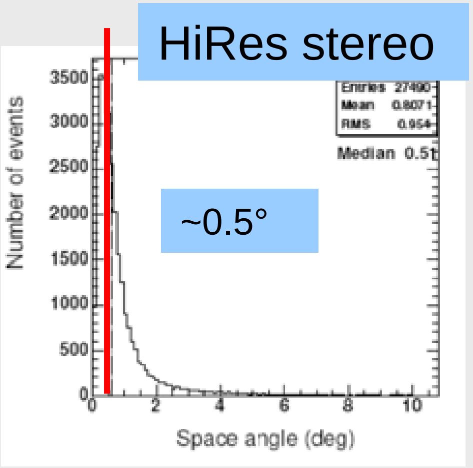
Energy, Direction, Composition

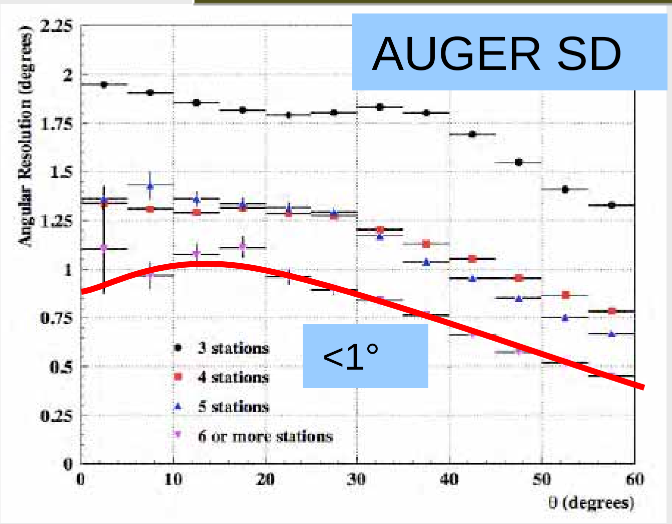
Improving measurement and observations

From EAS particles (light) arrival times to primary CR arrival direction

- CR arrival direction: from relative arrival times of signals at ground detectors, or from the time sequence of hit PMTs at fluorescence detectors





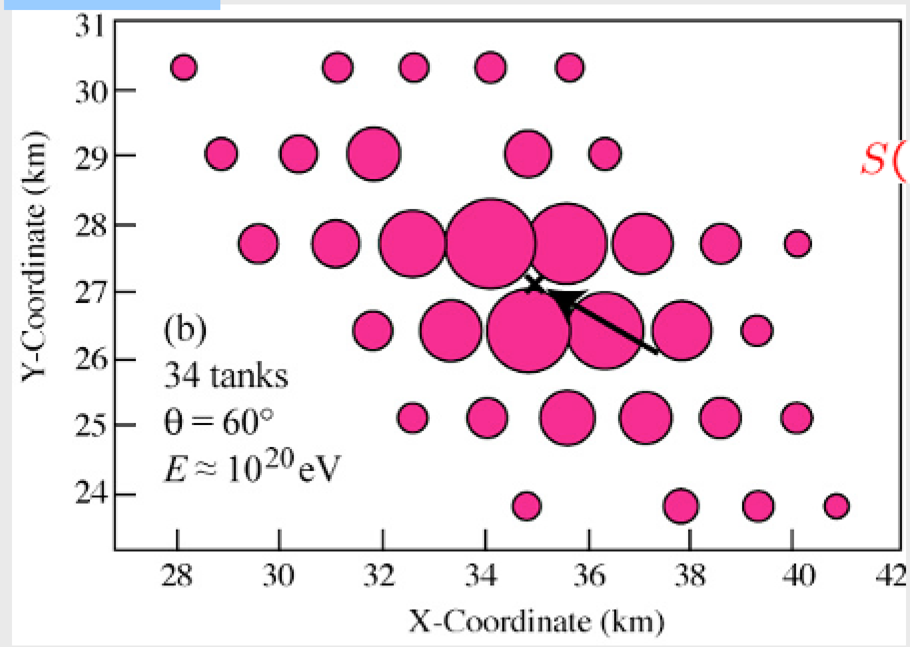


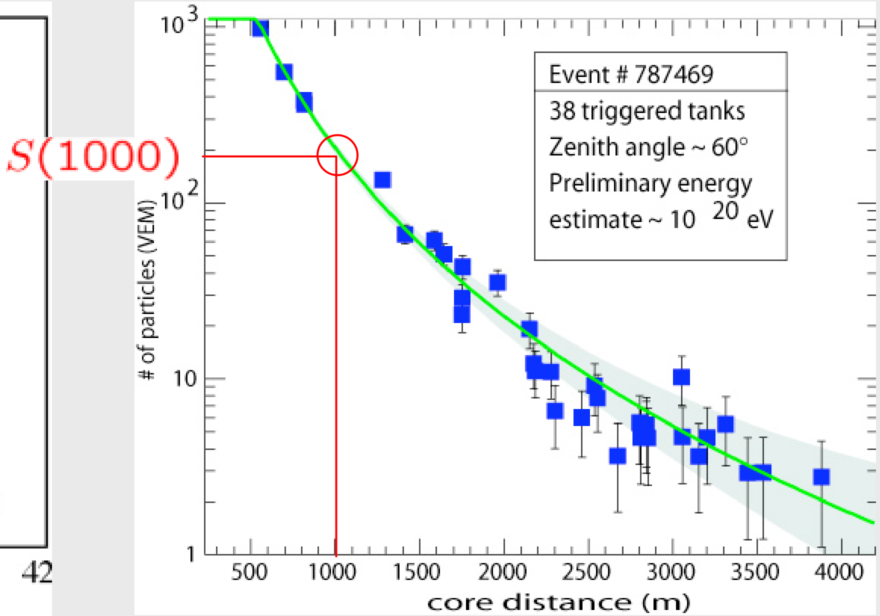
Large improvement wrt earlier detectors :

- Larger area single detector
- Better electronics (fadc traces)
- Precise geometry (stereo fluorescence / hybrid)

From EAS footprint and LDF to primary CR energy estimator

AUGER

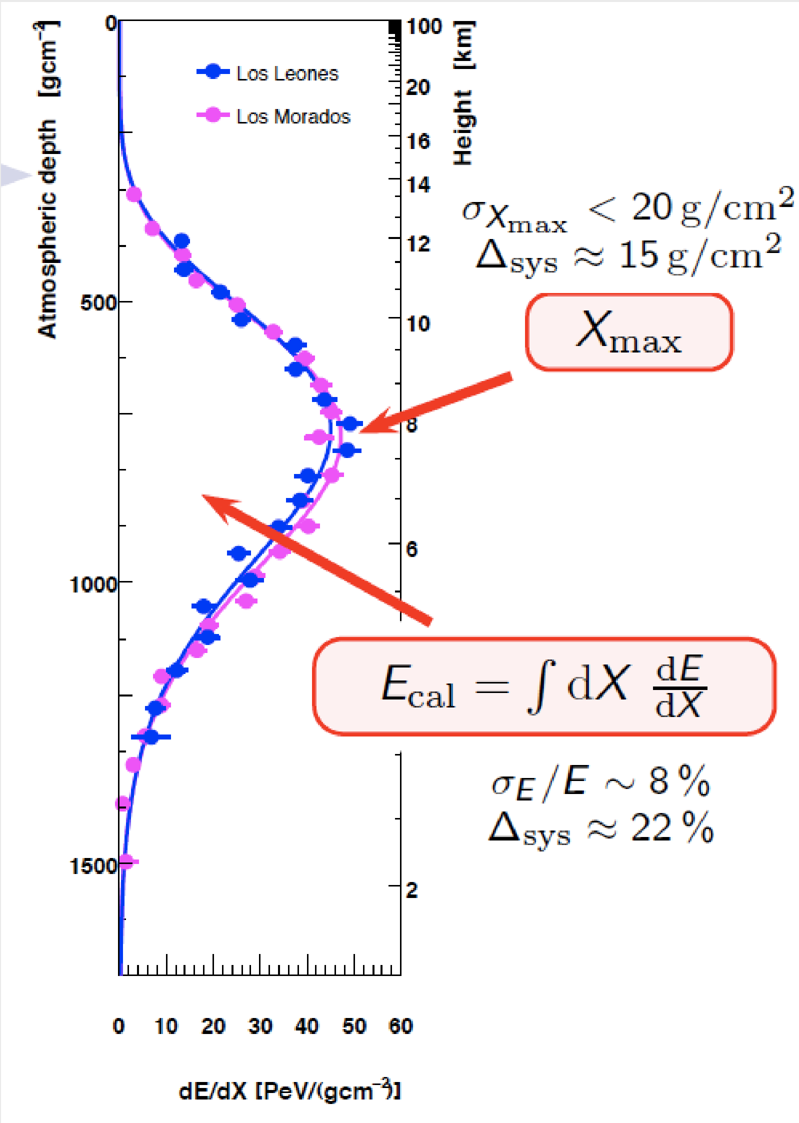




Idea from Hillas 1970 (pioneered by Haverah Park and Agasa)

- energy estimator: signal @ fixed (large) core distance S(R)
- small shower-to-shower fluctuations, depends on primary E only
- Determination of particle density -> LDF -> S(R)
- Largest uncertainty: converting estimator to energy (see later)

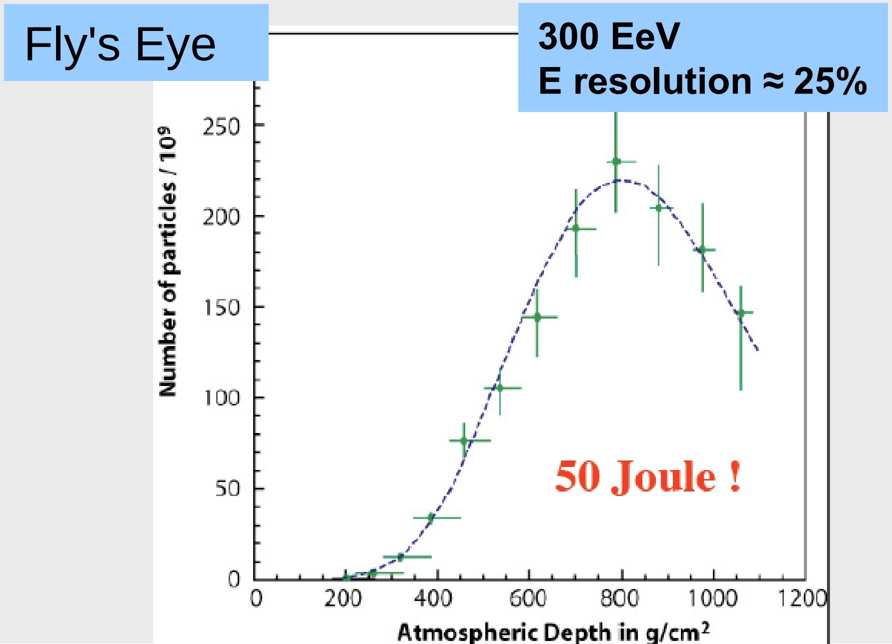
From EAS longitudinal profile to primary CR energy



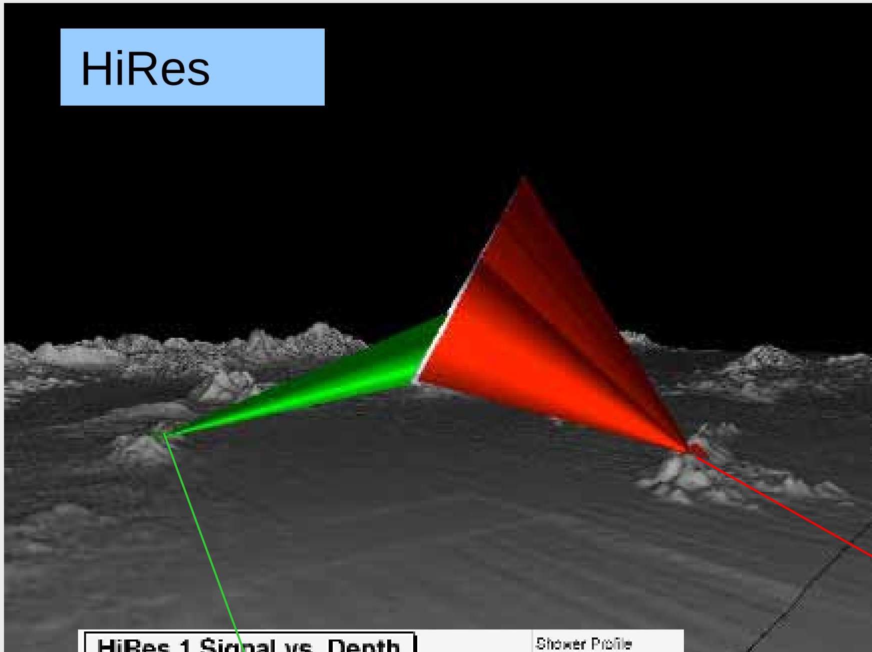
PROGRESS:

Calorimetric measurement of E with :

- Fluorescence technique
- Validated by Fly's Eye
- Largest uncertainty: fluorescence yield,
- Atmosphere, "missing" energy
- No hadronic model dependence

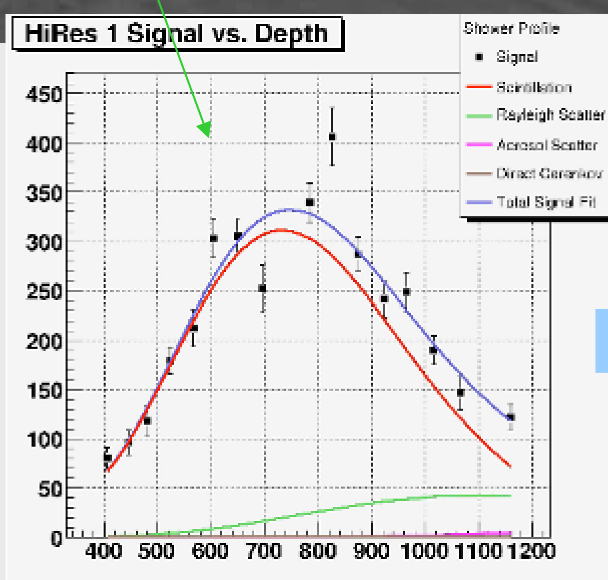


From EAS longitudinal profile to primary CR energy

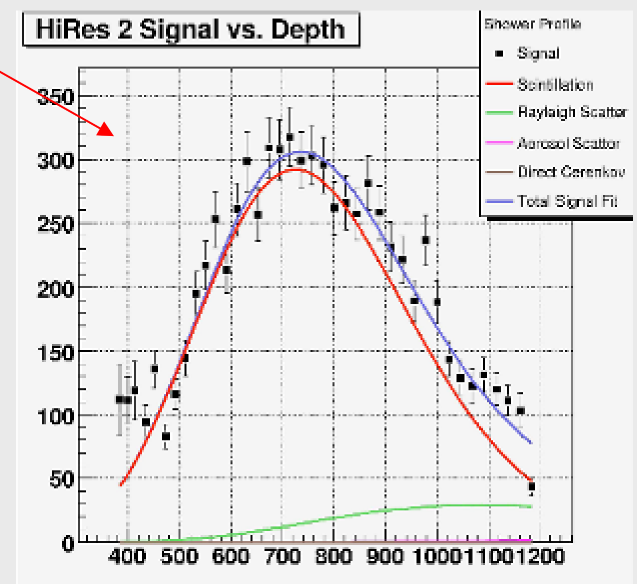


PROGRESS:

The stereo "image" of the same shower together with improved resolution and electronics increases the accuracy of the measurement pioneered by Fly's EyE

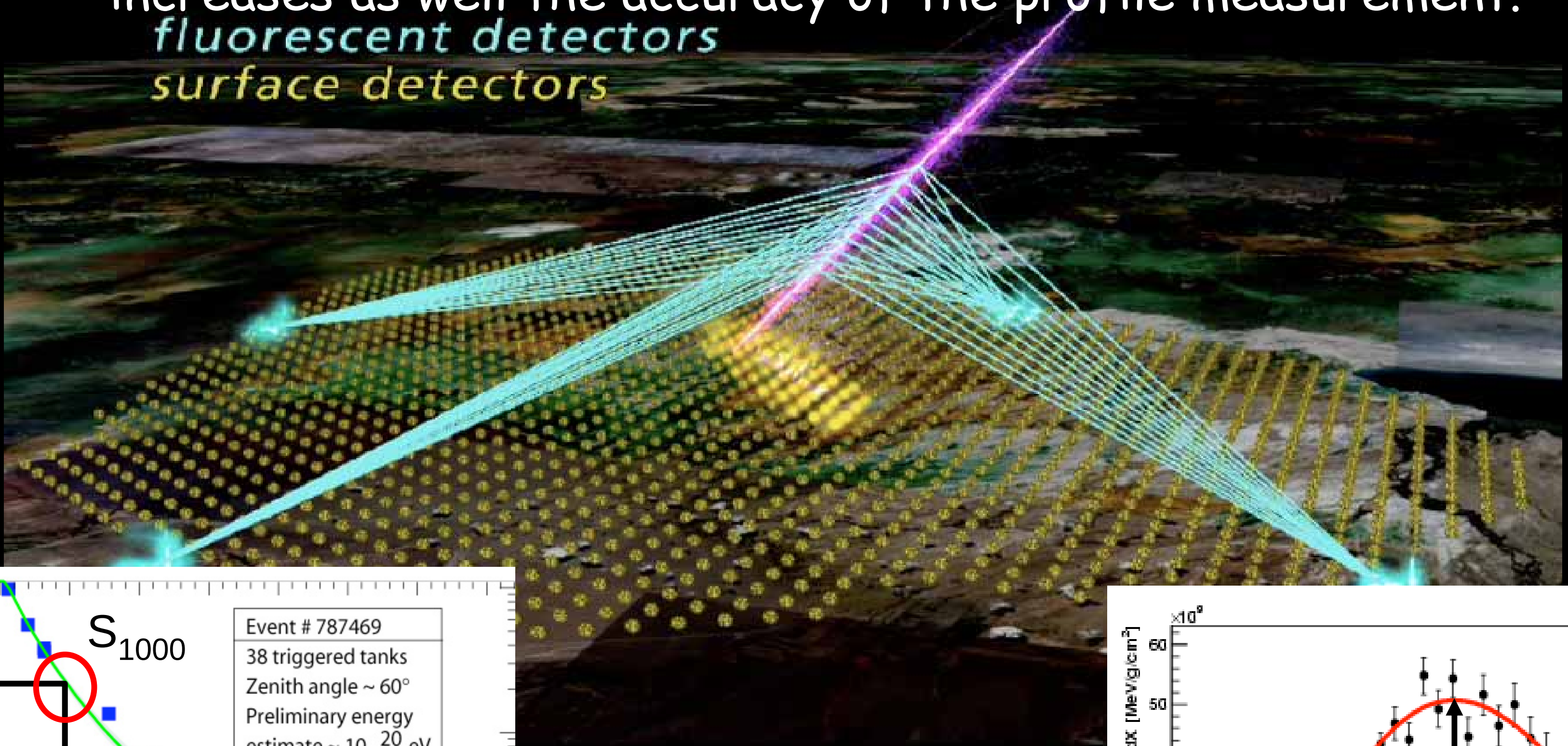


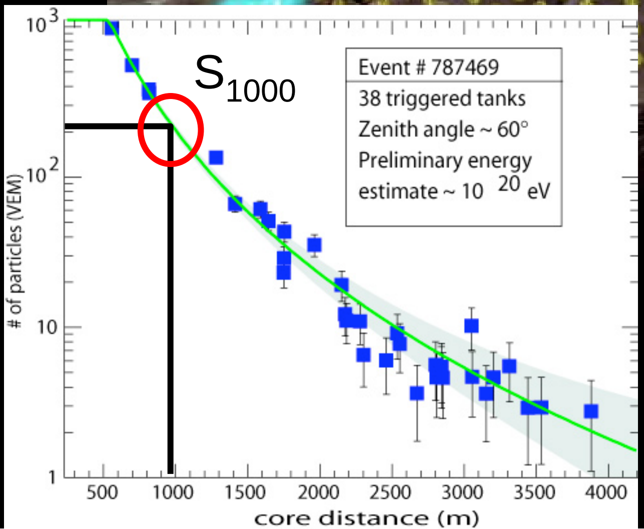
E resolution ≈ 15%



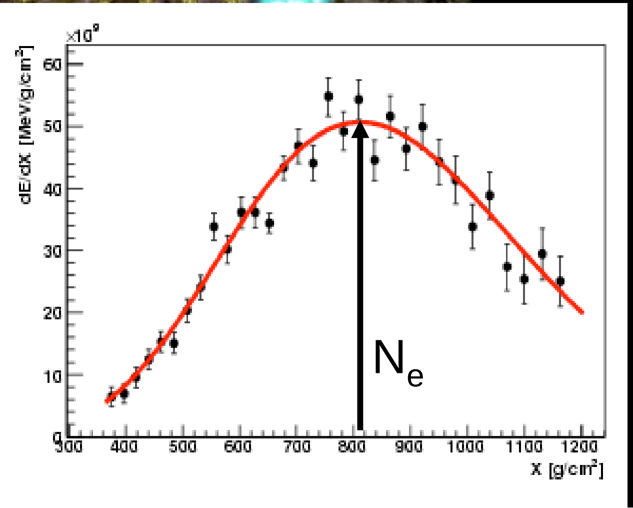
From EAS longitudinal profile to primary CR energy

The Hybrid "image" of the same shower, pioneered by Auger, increases as well the accuracy of the profile measurement.





PROGRESS:
Calibration of SD energy estimator through FD



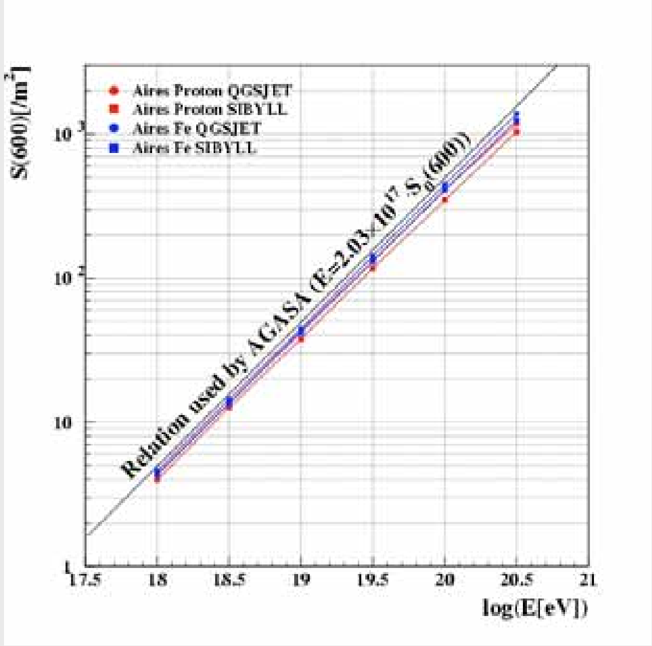
From EAS energy estimator to primary CR energy

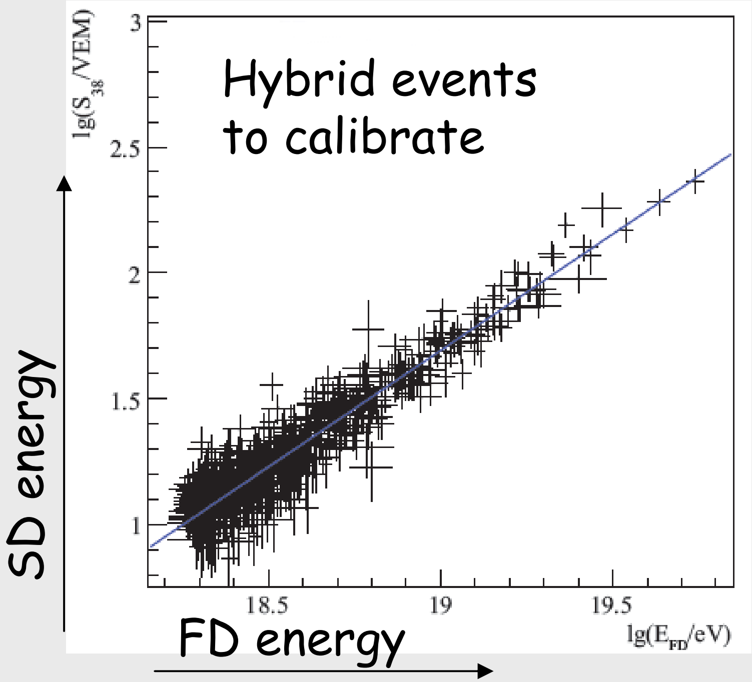
AGASA

- Measure particle density at 600 m "S(600)" and correct for attenuation.
- Use simulations to convert S(600) to E
- Largest source of uncertainty: extrapolation of hadronic interactions from low-energies and model dependences

AUGER

- Measure particle density at 1000 m "S(1000)" and correct for attenuation using CIC cuts (no simulation used).
- Calibrate with FD measurements to convert S(1000) to E.
- Largest source of uncertainty: fluorescence technique uncertainties





From EAS energy estimator to primary CR energy

AGASA

Detector	
▪ Detector Absolute gain	± 0.7%
▪ Detector Linearity	± 7%
▪ Detector response(box, housing)	± 5%
Energy Estimator S(600)	
▪ Interaction model, P/Fe, Height	±15%
Air shower phenomenology	
▪ Lateral distribution function	± 7%
▪ S(600) attenuation	± 5%
▪ Shower front structure	± 5%
▪ Delayed particle(neutron)	± 5%
Total	± 20%

... but "possible over-estimation of energy by 10% (15%) @ 10 EeV (100 EeV)" (Teshima, 2006)

Auger

Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

HiRes

HiRes total energy uncertainty $\approx$ 17%

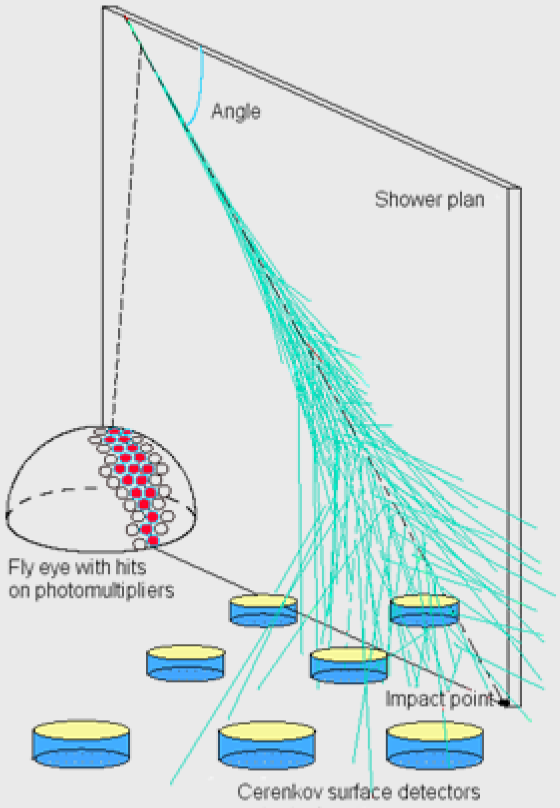
Energy scale measurements are much more robust now.

Lab measurements of fluorescence yield may reduce the uncertainties

Improving measurements

Fluorescence vs Hybrid techniques :

	Hybrid	SD only	FD only
Angular resolution	0.2°	1-2°	3-5° (0.5° stereo)
Aperture	**Independent on E, mass, models.**	**Independent on E, mass, models.**	**Dependent on E, mass, models, spectral shape.**
Energy	**Independent on mass, models.**	**Dependent on mass, models.**	**Independent on mass, models.**

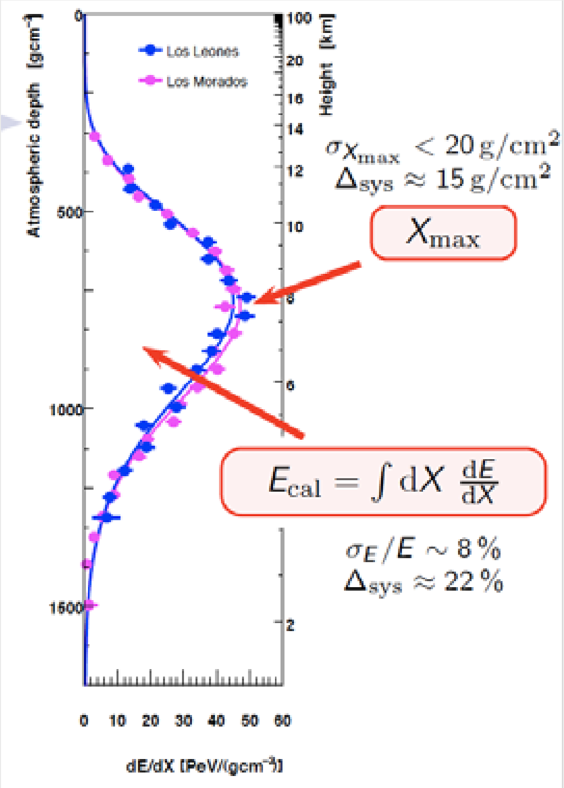


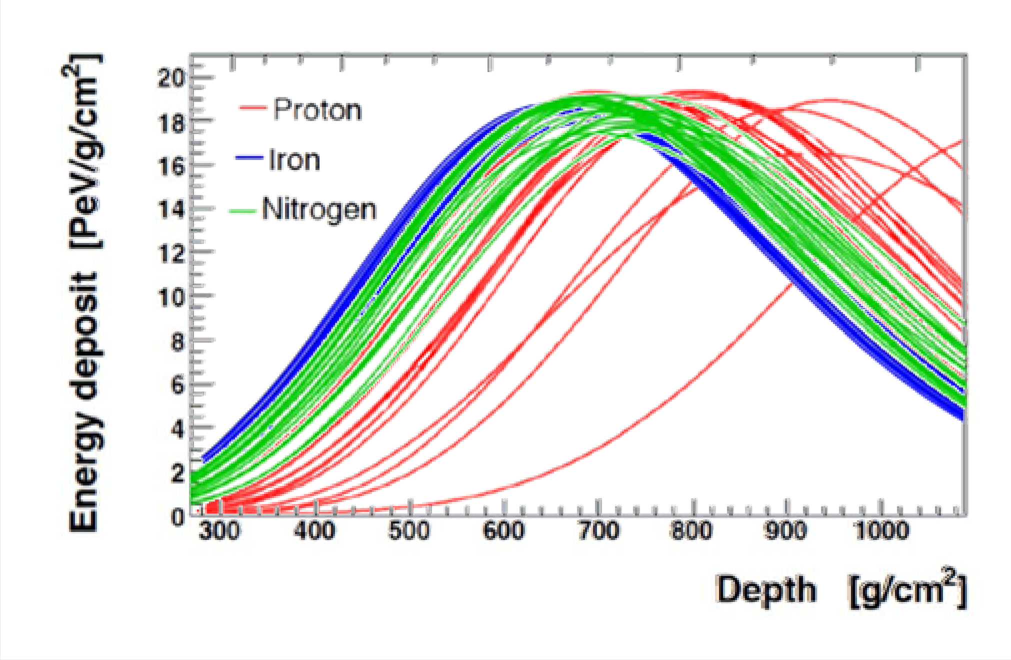
From EAS longitudinal profile to primary CR mass composition

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

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

sensitive to <u>primary composition</u>

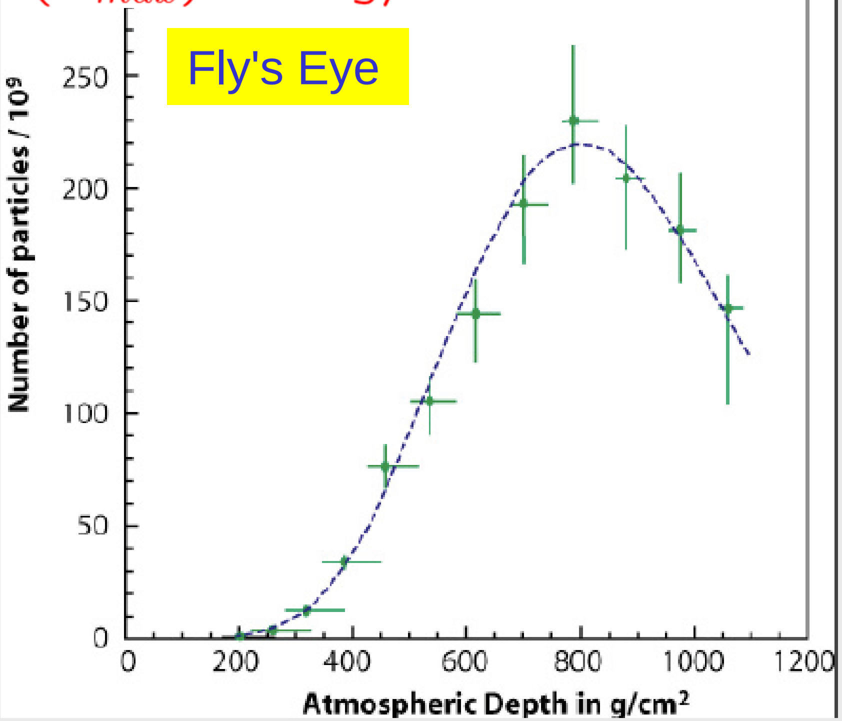




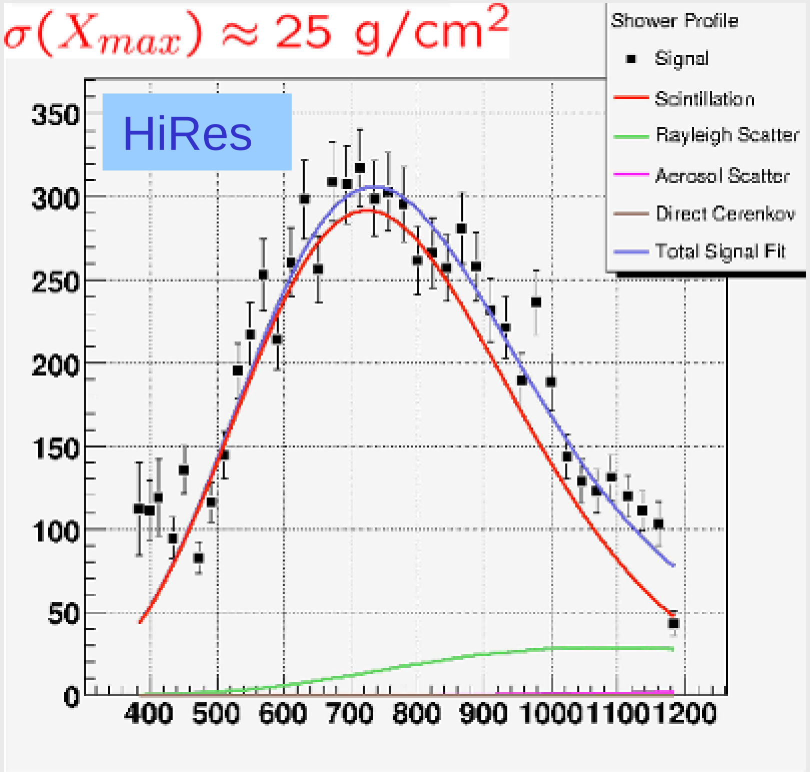
$$X_{max} \propto ln(E_0) - ln(A)$$ (MC Sim.)

From EAS longitudinal profile to primary CR mass composition

$\sigma(X_{max}) \approx 60$ g/cm^2



$\sigma(X_{max}) \approx 25$ g/cm^2



PROGRESS:

Fly's Eye showed experimental access to X_{max} through fluorescence

High precision now possible through higher resolution + stereo and hybrid measurements (around 20-25 g/cm^2)

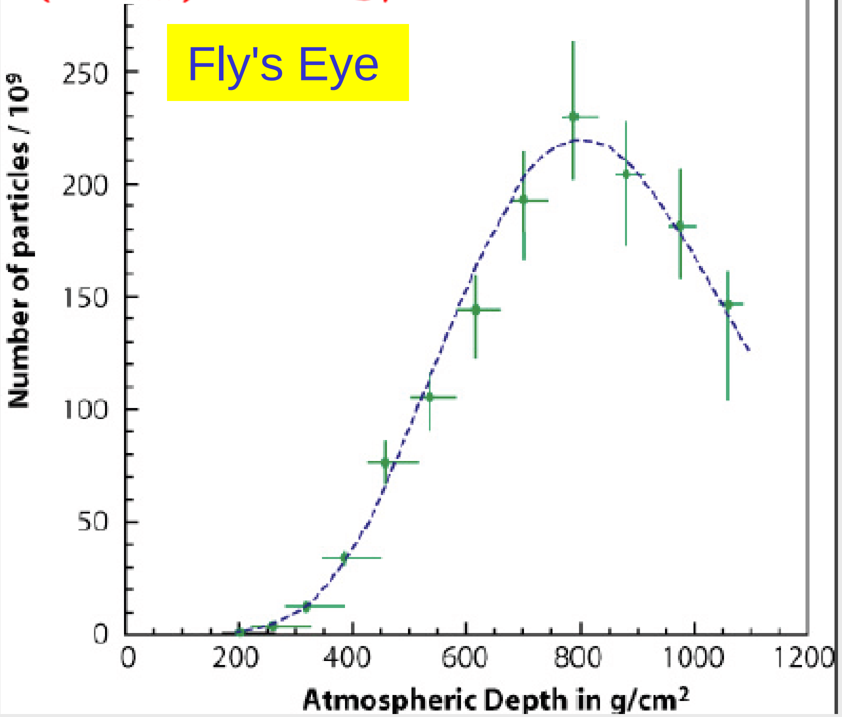
N.B. : $< X_{max} >_{proton} - < X_{max} >_{iron} \approx 150$ g/cm^2

Delicate issues: great care in event selection (possible biases)

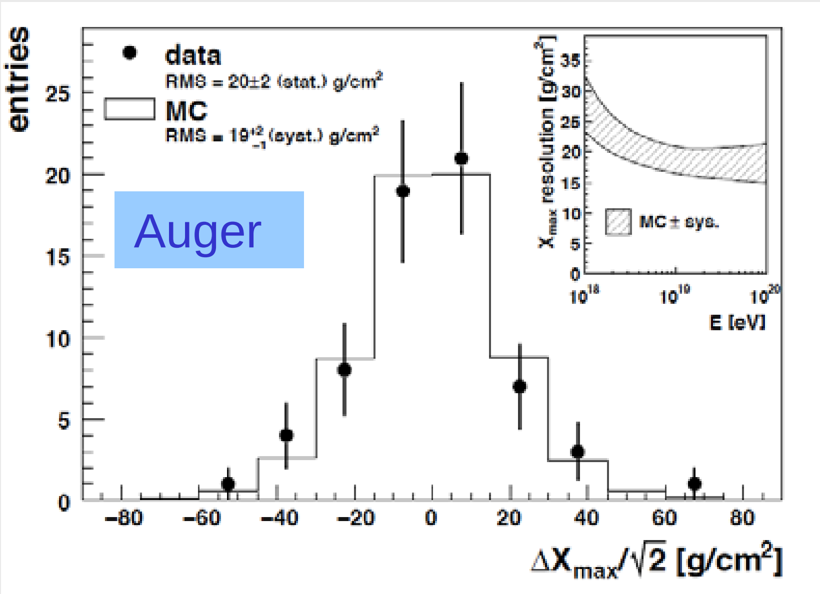
Important drawback: strong need for models in the interpretation

From EAS longitudinal profile to primary CR mass

$\sigma(X_{max}) \approx 60$ g/cm^2



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



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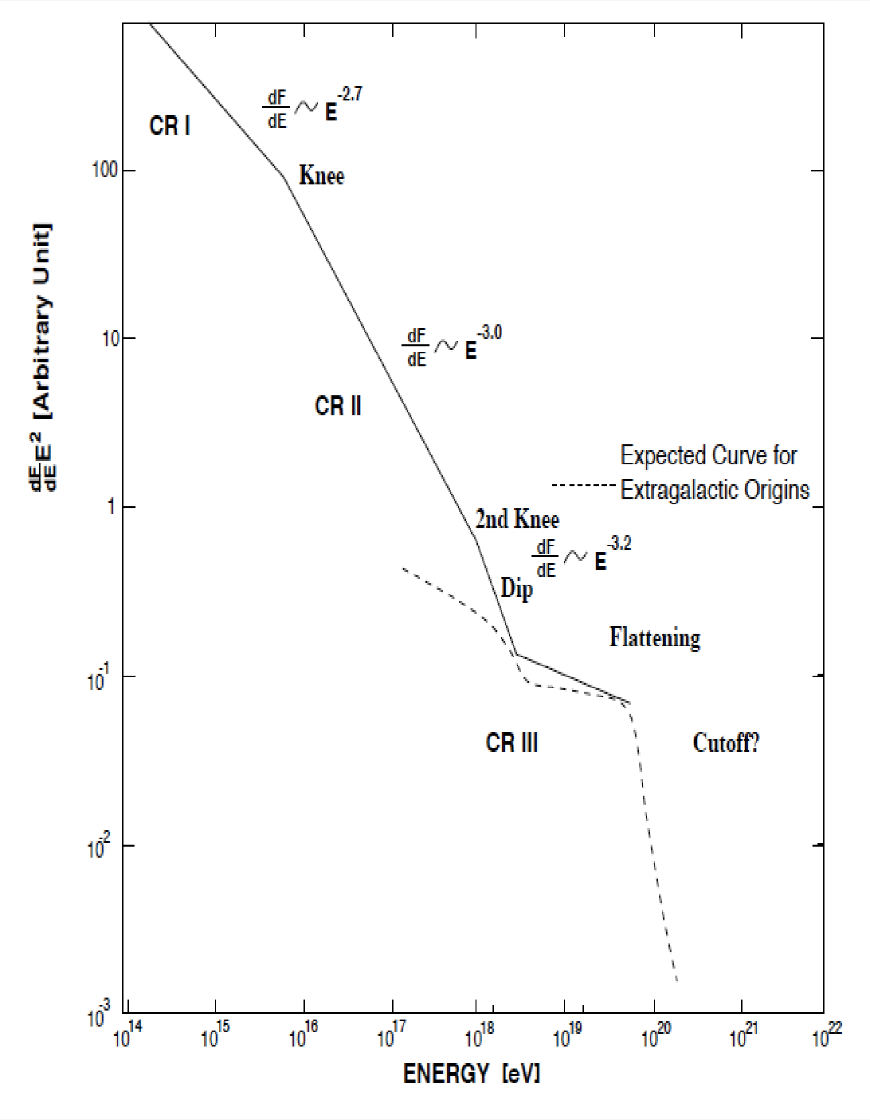
The Experimental Data

Virtues and Imperfections

Essential questions



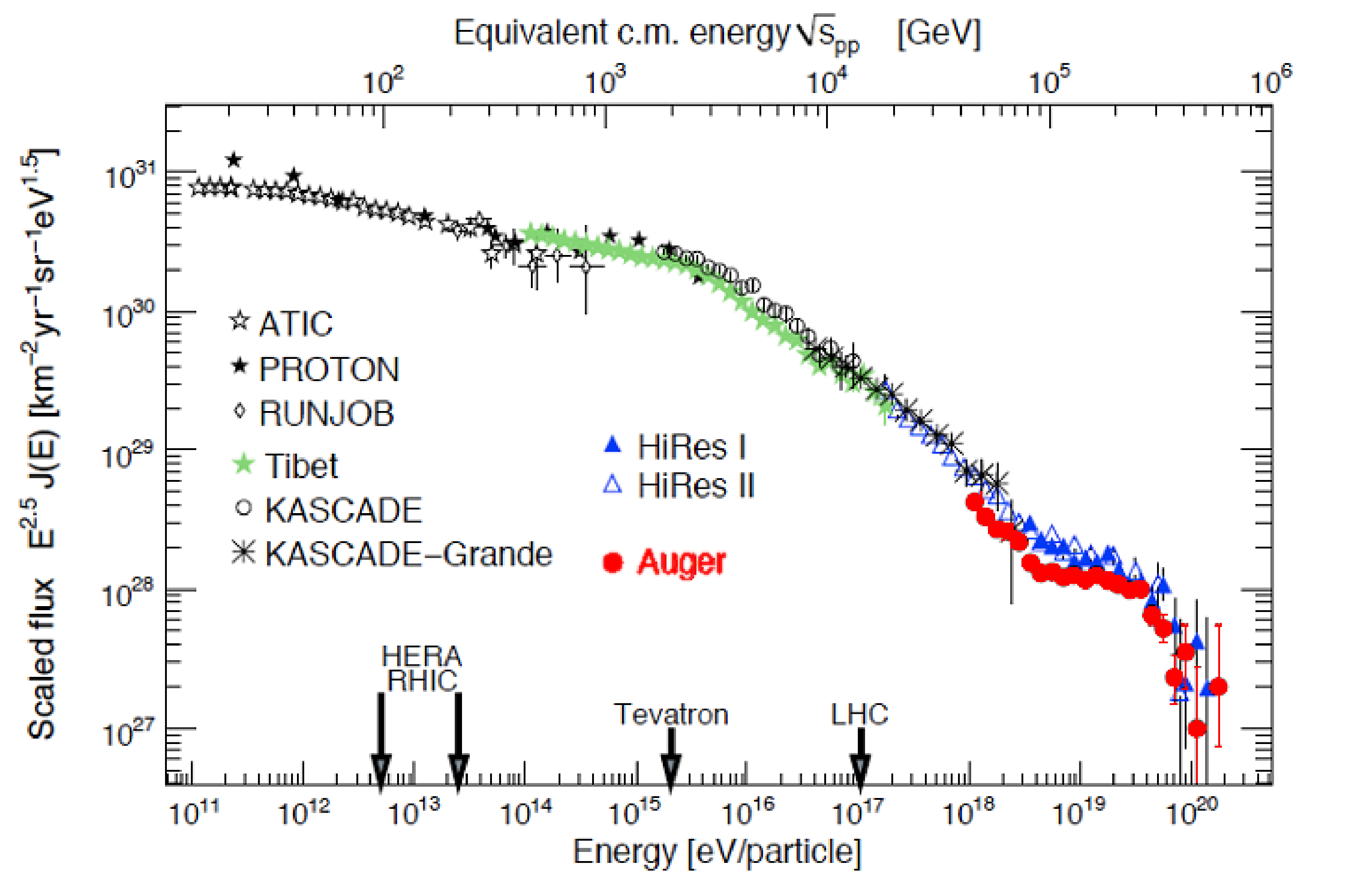
<u>**Essential (and obvious) questions**</u> **:**

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

<u>**Essential features for astroparticle physics:**</u>

- **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

CR Spectrum

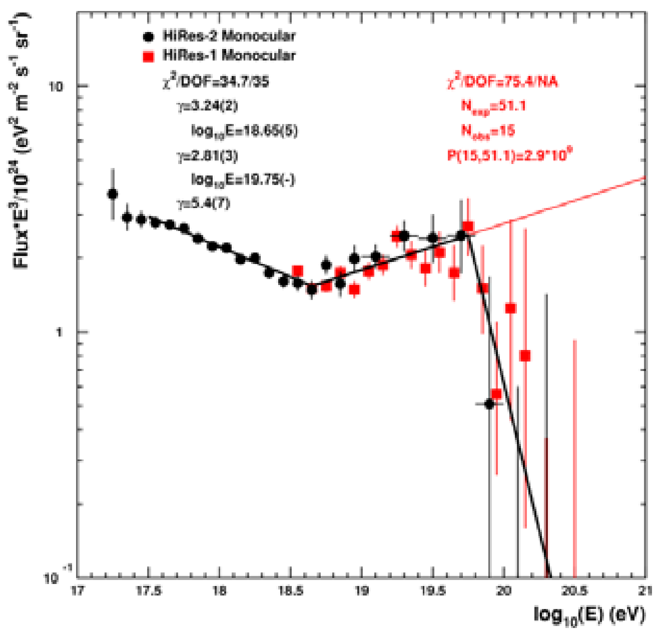


Confirmation of an "ankle" at few EeV
Flux suppression above 50 EeV (HiRes, Auger)

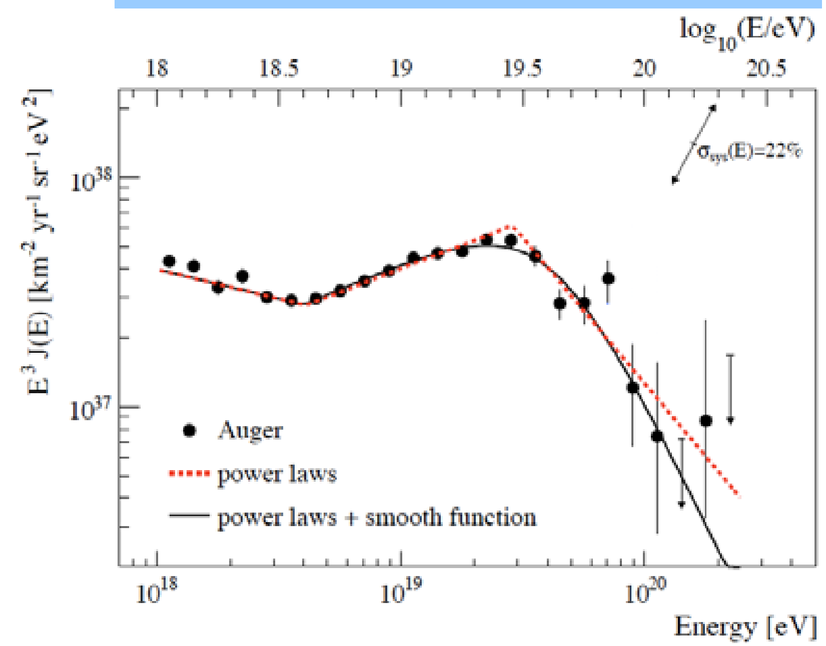
Auger :
Phys, Rev. Lett. 101 (2008) 061101
Phys. Lett. B 685 (2010) 239-246
HiRes:
Astropart. Phys. 32 (2009) 53.

CR Spectrum

HiRes spectrum (mono)



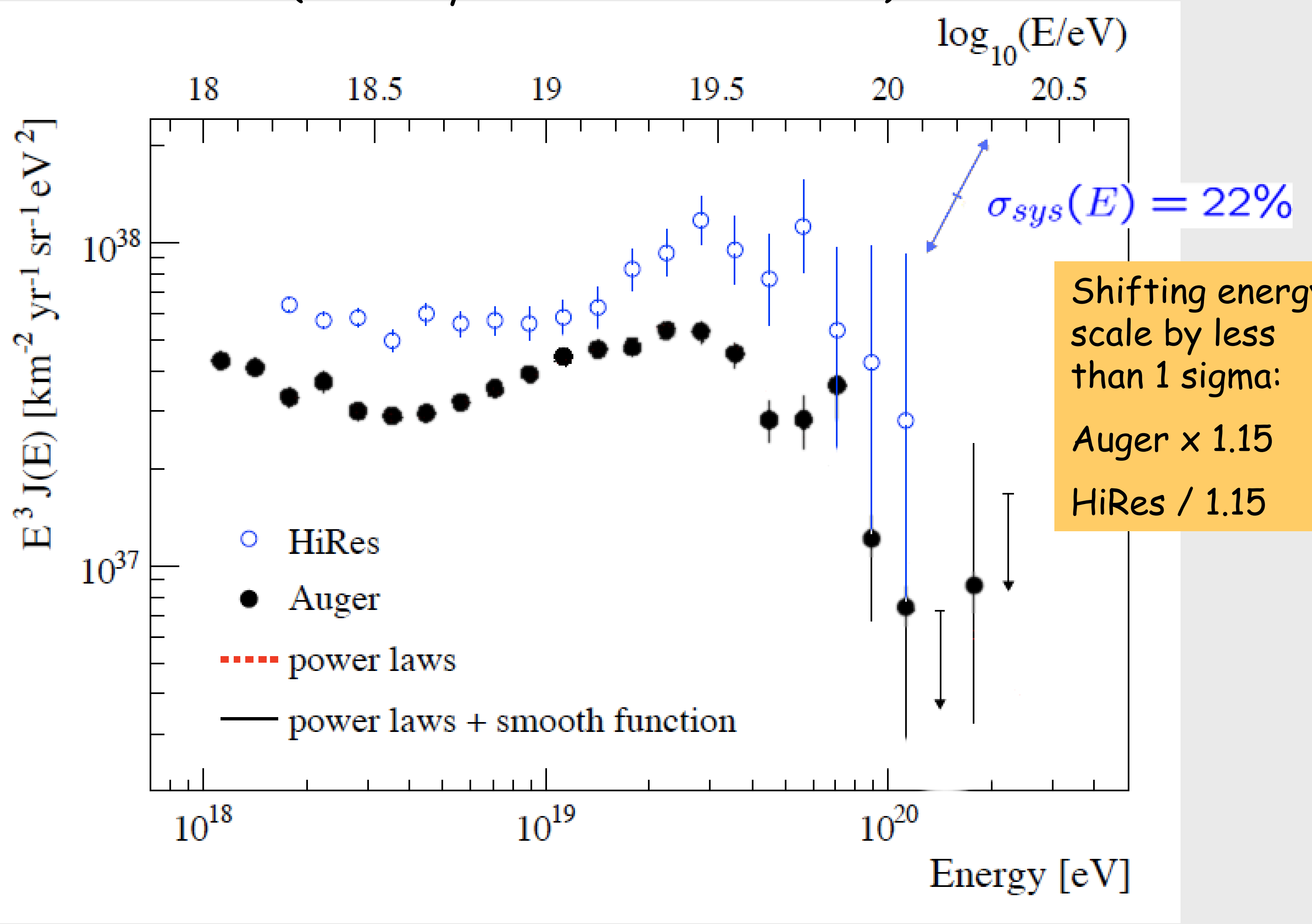
Auger "combined" spectrum (hybrid+SD)



Coherent observation of ankle and suppression in HiRes and Auger

CR Spectrum

Good agreement between HiRes and Auger
(within systematic uncertainties)



Shifting energy scale by less than 1 sigma:

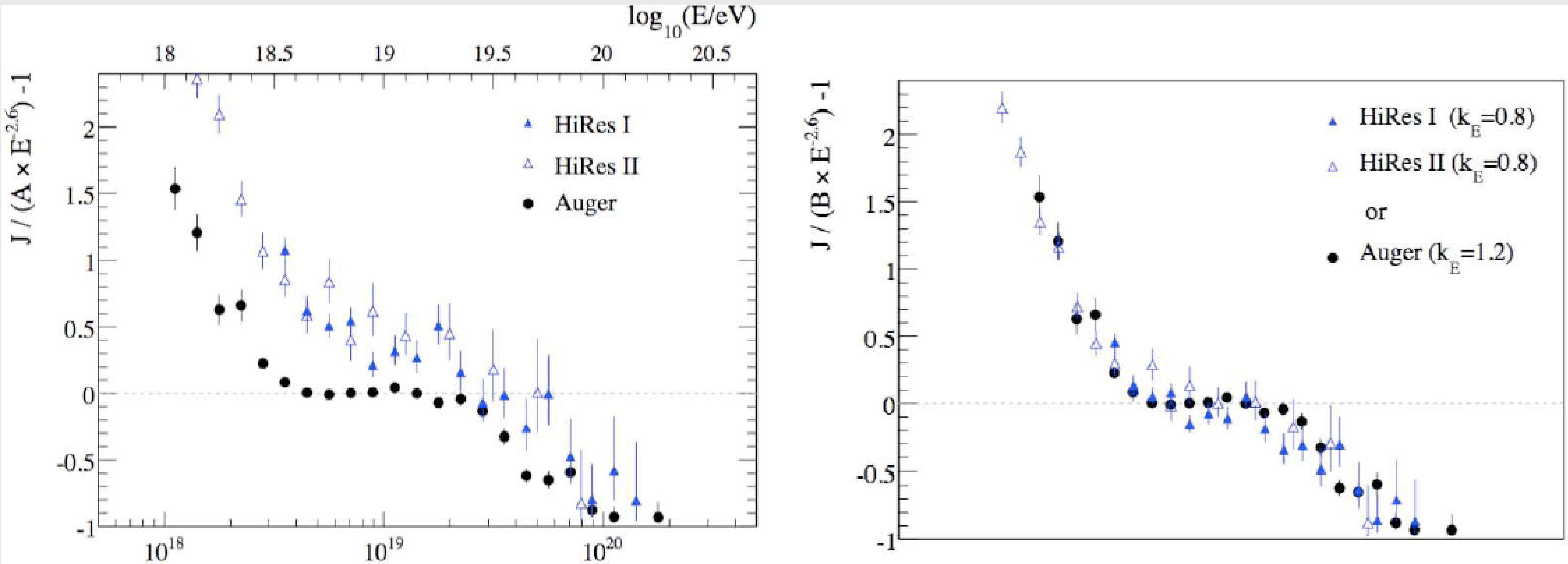
Auger x 1.15

HiRes / 1.15

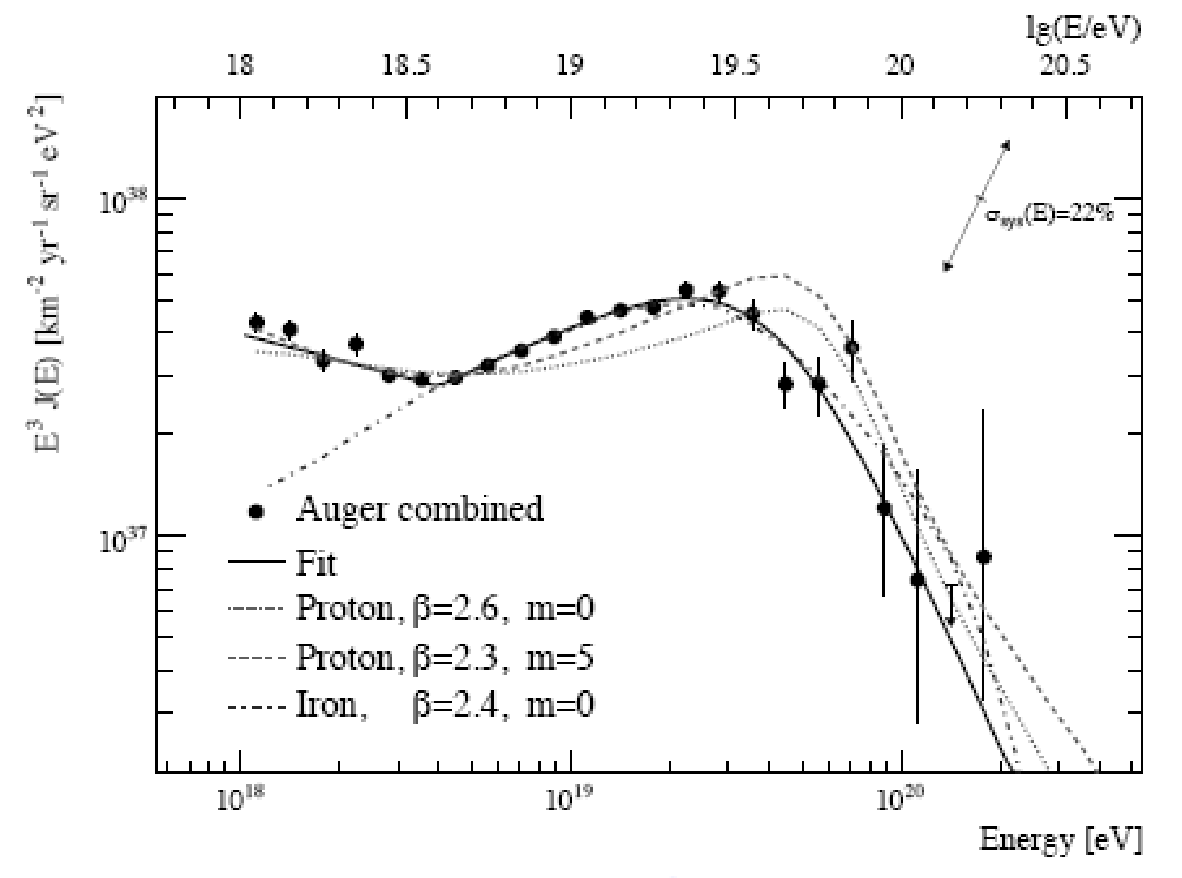
CR Spectrum

Good agreement between HiRes and Auger
(within systematic uncertainties)

A other unusual way to see it: power laws on linear scales !

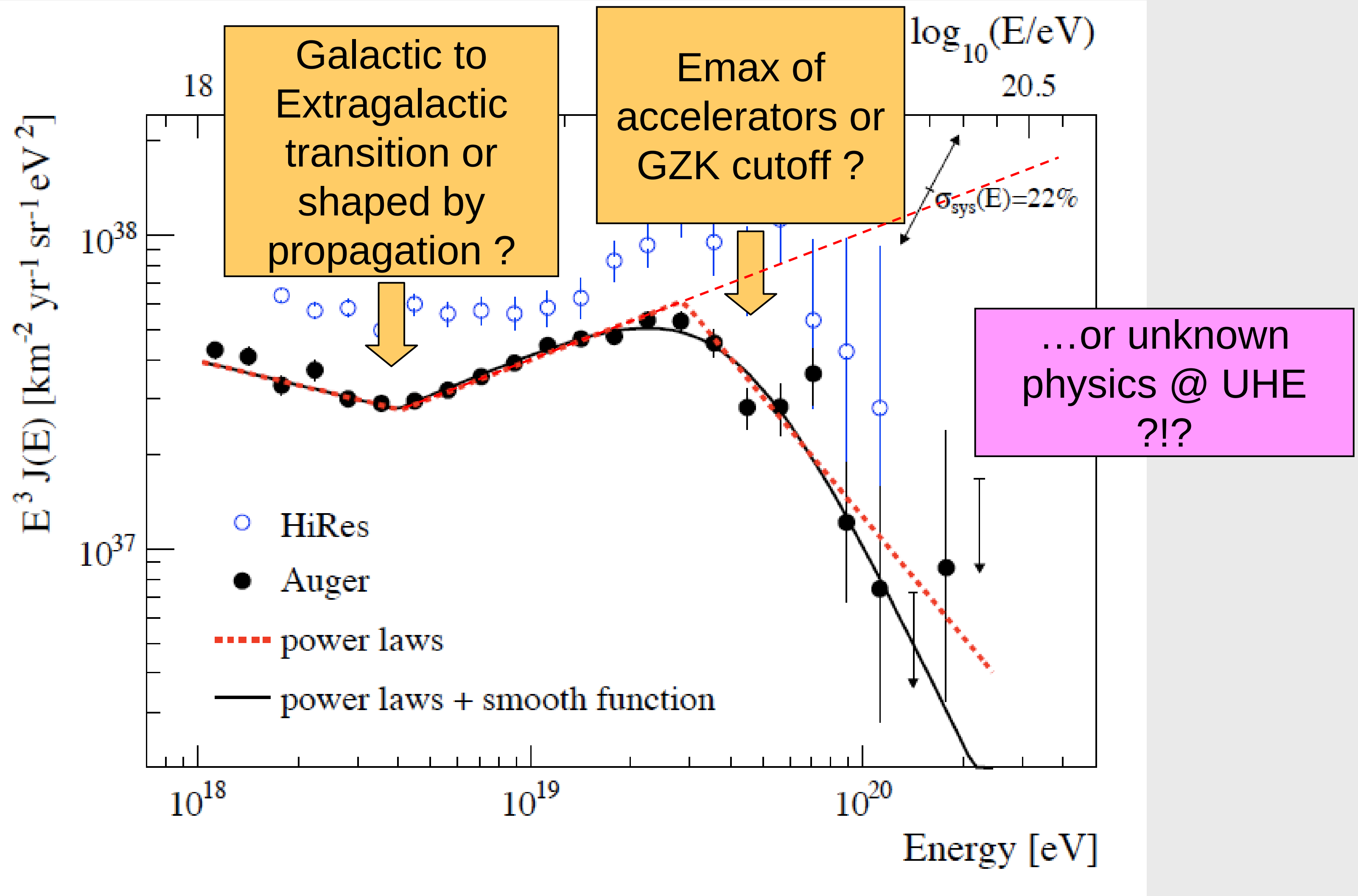


CR Spectrum



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

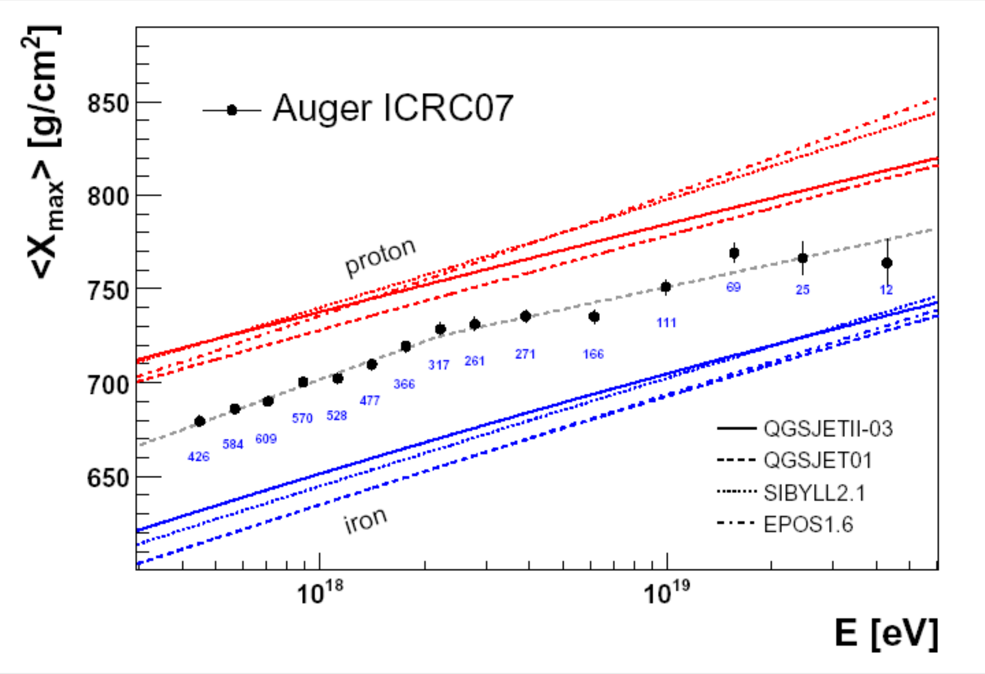
CR Spectrum

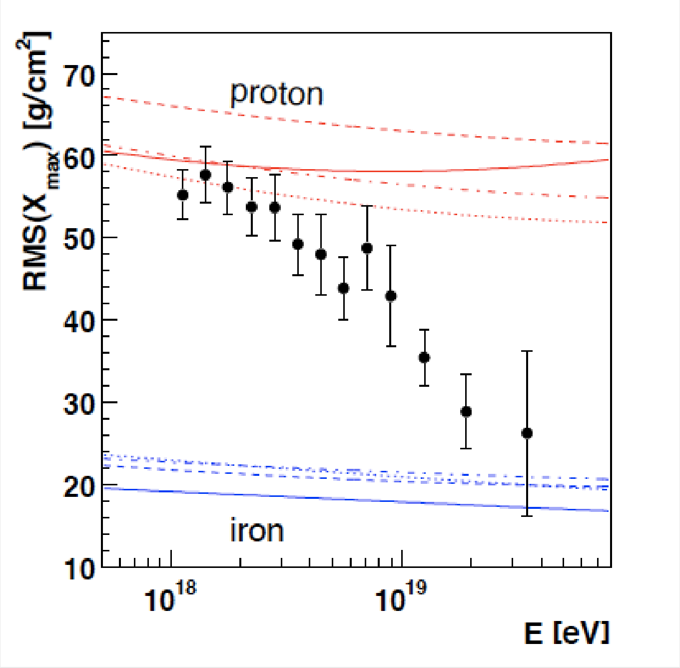


Part of the answers to these questions
may come from composition anisotropy studies.

Composition

Average depth of maximum $<X_{max}>$ as a composition sensitive observable.
Distribution width $RMS(X_{max})$ as a composition sensitive observable

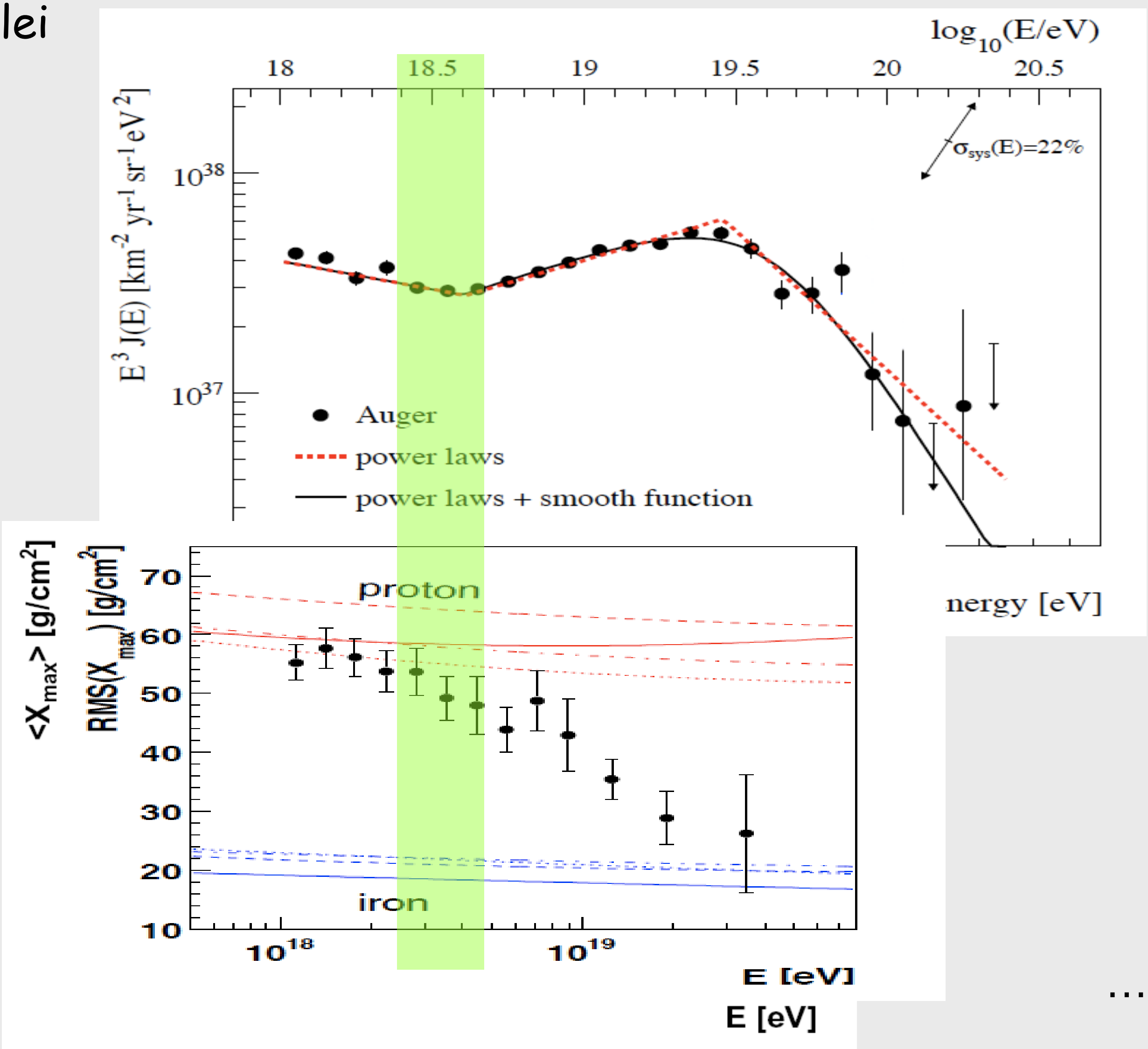




Models dispersion makes the interpretation still difficult

Composition

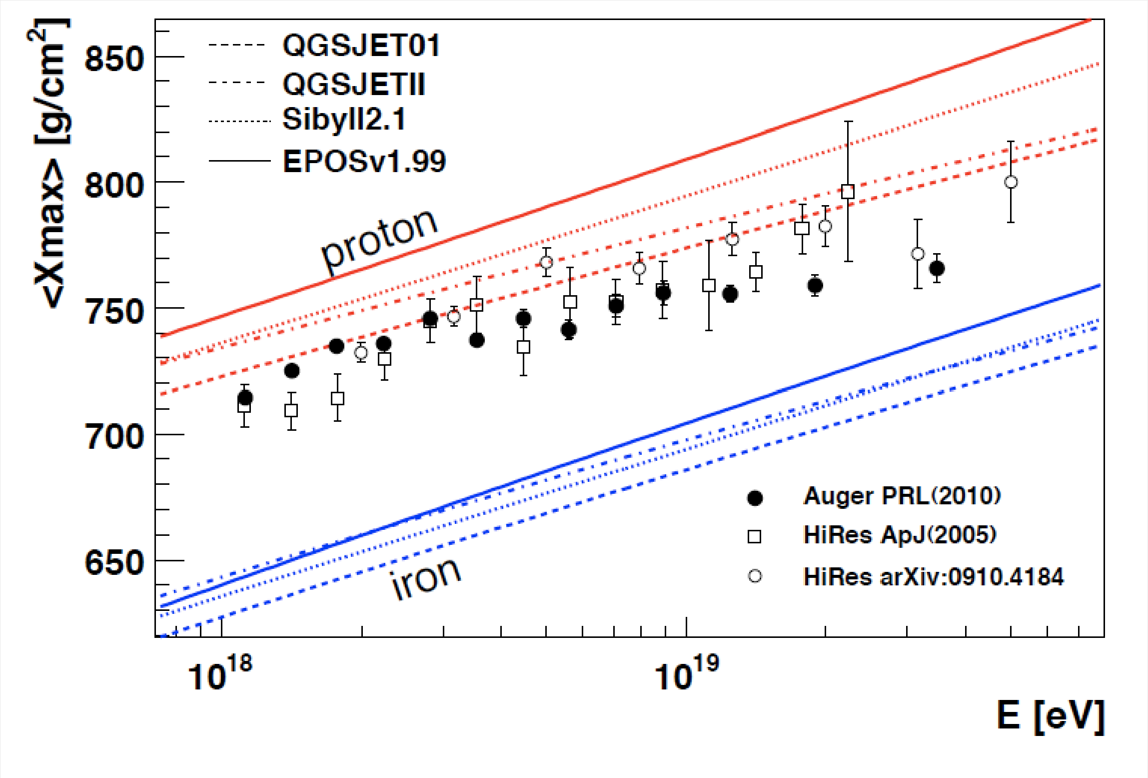
The Ankle seems to coincides with a change in composition from lighter to heavier nuclei



… But …

Composition

Average depth of maximum $<X_{max}>$ as a composition sensitive observable.



Discrepant results

(in spite of apparent agreement within systematic errors):

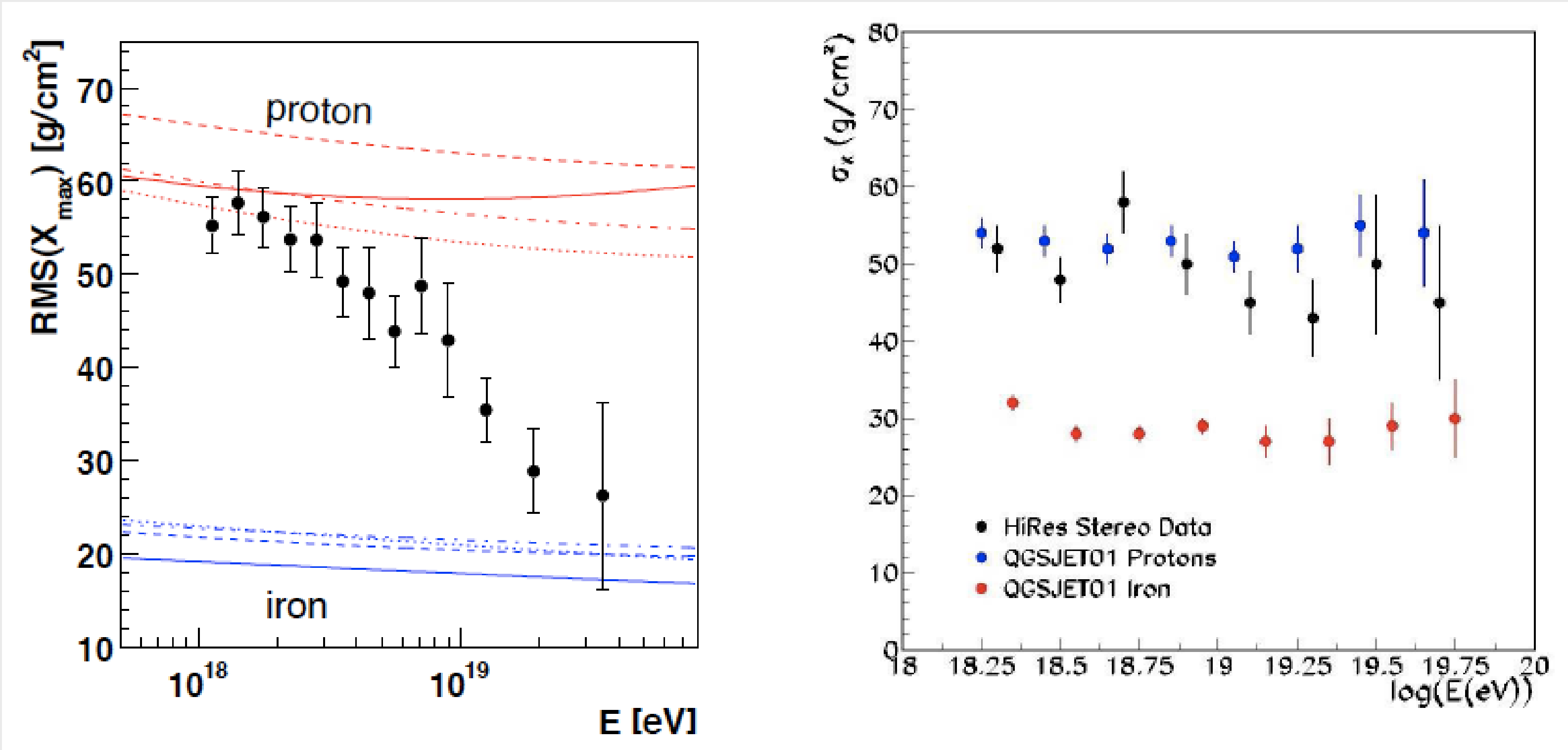
Constant elongation rate from HiRes

↔

Change of elongation rate at the ankle from Auger

Composition

Distribution width RMS<X_{max}> as a composition sensitive observable



Even more discrepant results :

Constant RMS from HiRes (Suggesting Protons)

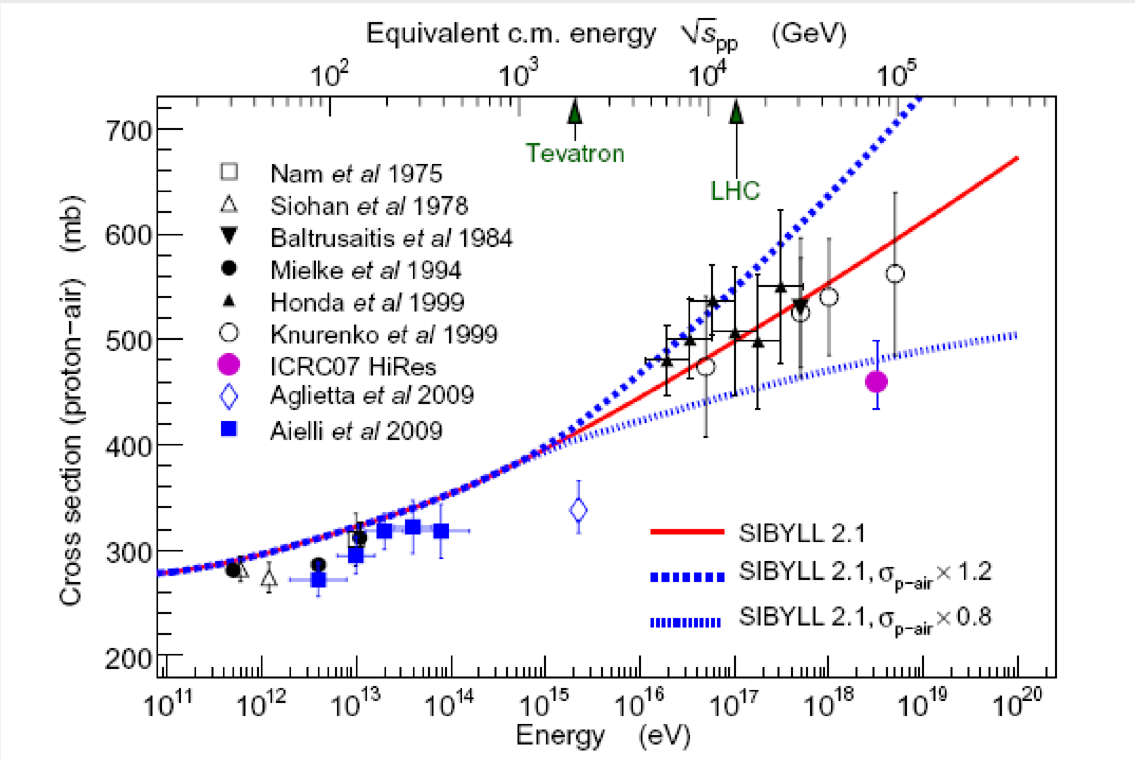
↔

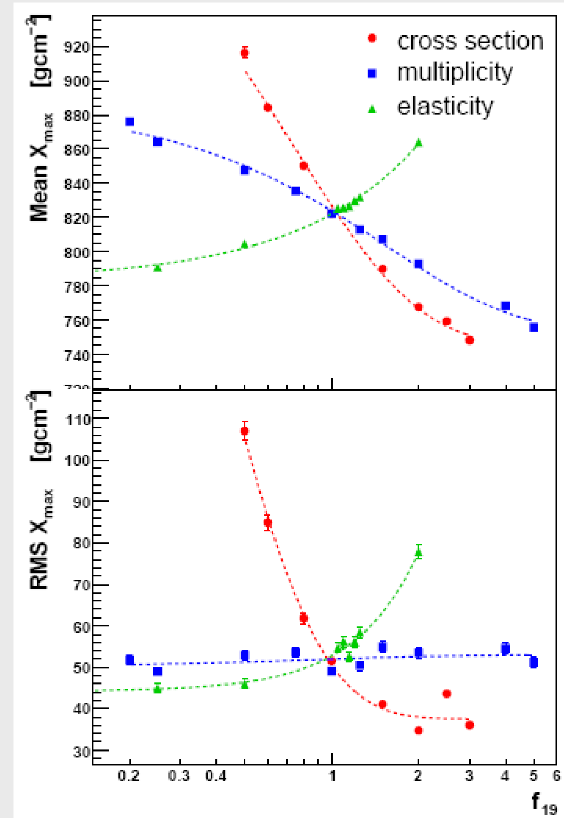
Decrease of RMS from Auger (suggesting increasing average mass)

N.B. Different data treatment: HiRes RMS from gaussian fit truncated at 2 RMS, no correction for detector resolution; Auger: no truncation, correction for detector resolution.

Composition

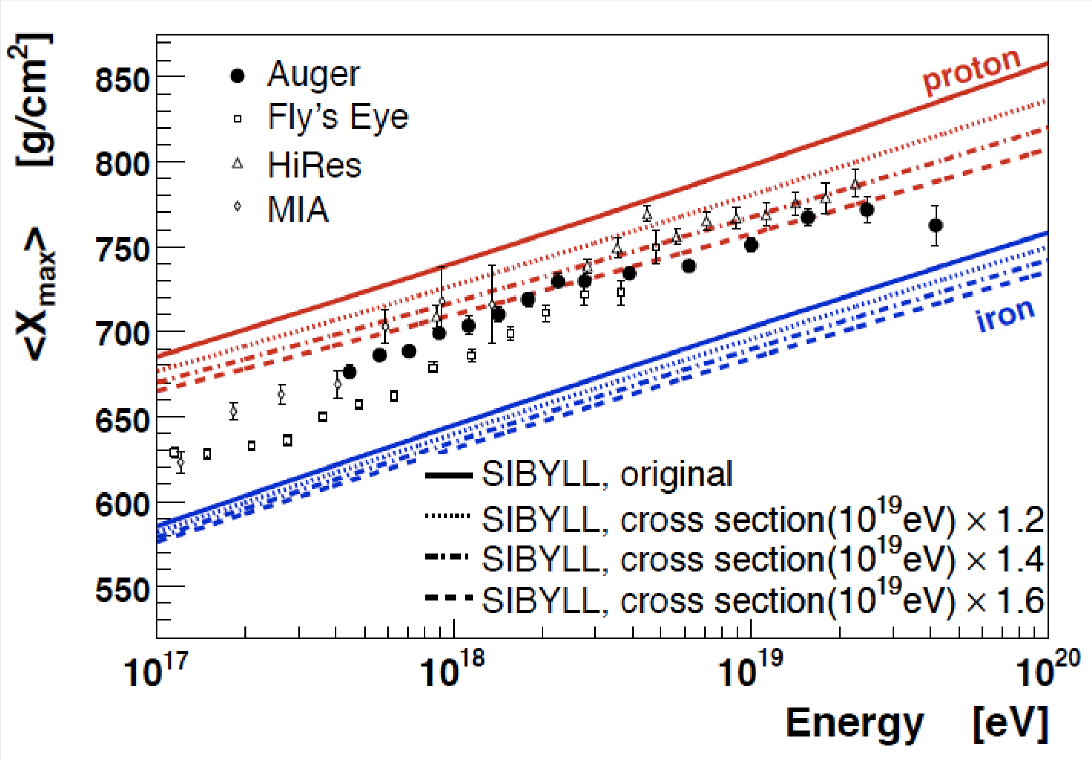
Extrapolations of hadronic interactions and cross sections





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}) … but this requires quite a fine tuning.

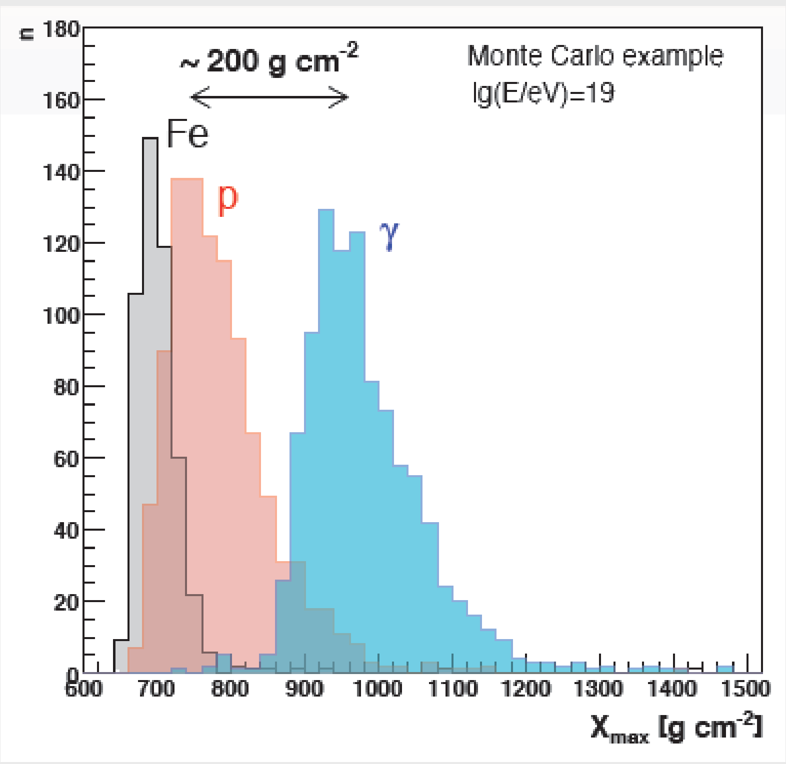
Composition and hadronic interactions

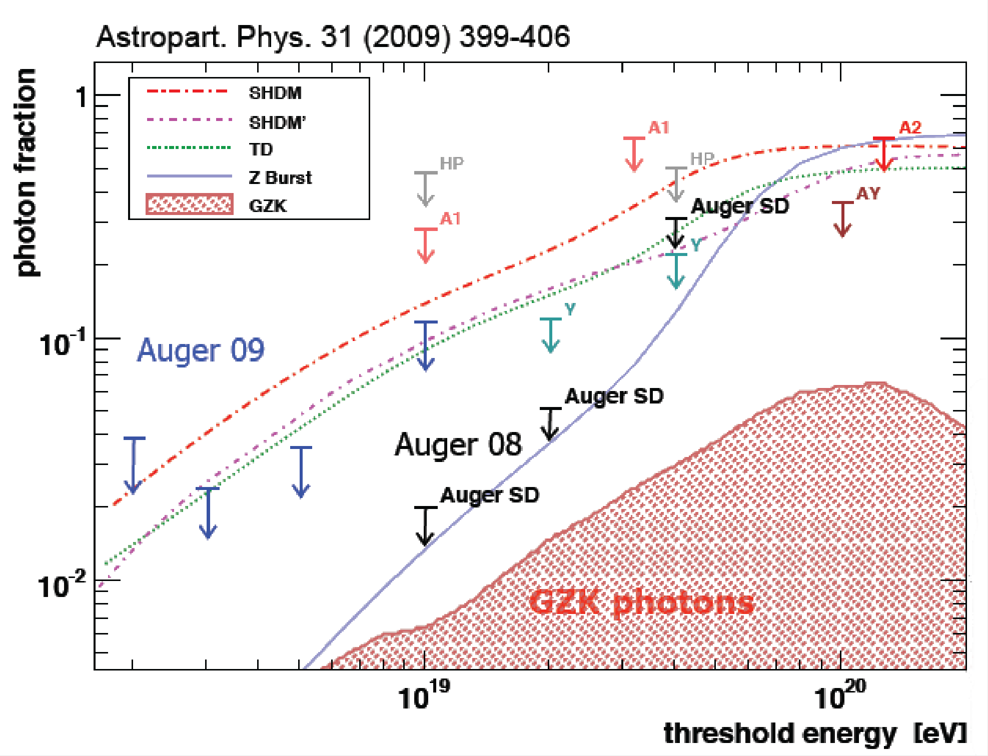


Hadronic interactions extrapolations (p-air cross section, multiplicity, elasticity) are crucial for composition measurements (and vice-versa). Larger cross section imply smaller $<X_{max}>$ and RMS(X_{max}) … but this requires quite a fine tuning.

Composition: what they are not !

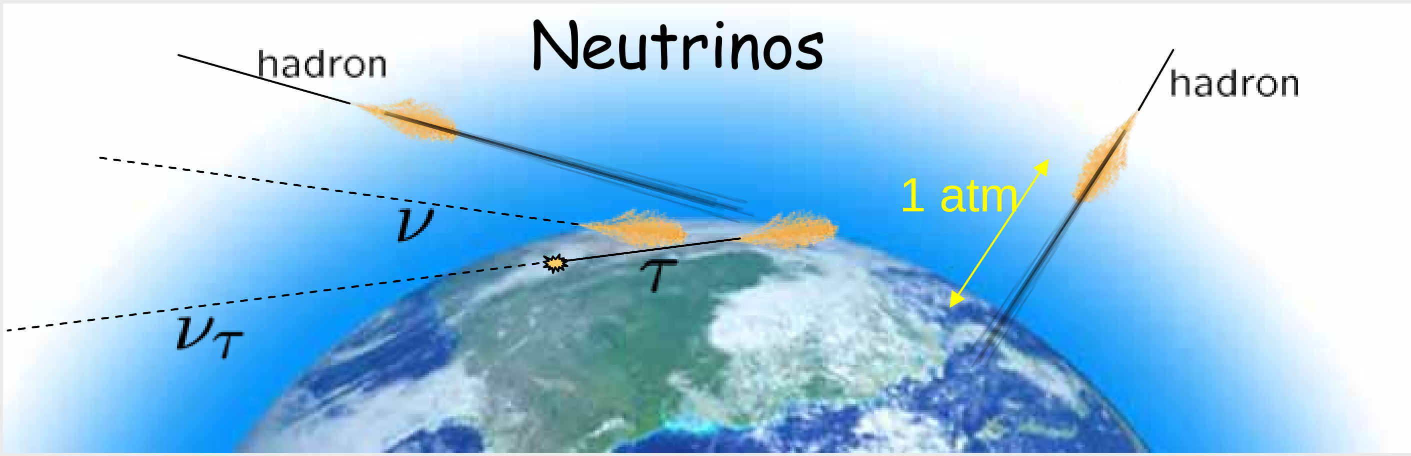
Very good γ-Hadron Discrimination by X_{max} Measurements γ-induced showers less sensitive to EAS modeling

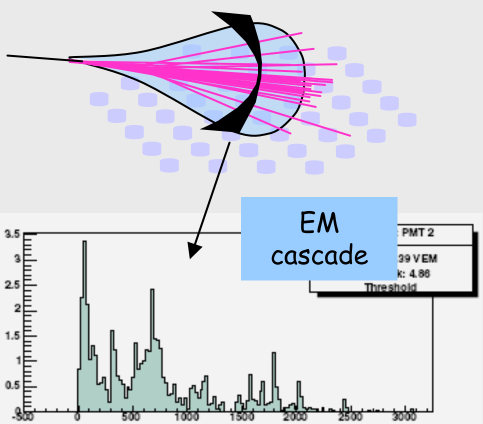


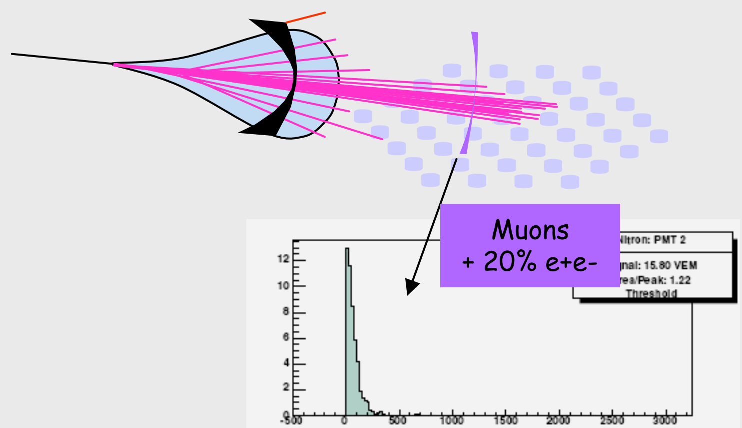


Top-Down models are largely disfavoured (if not dead!).

Composition: what they are not !





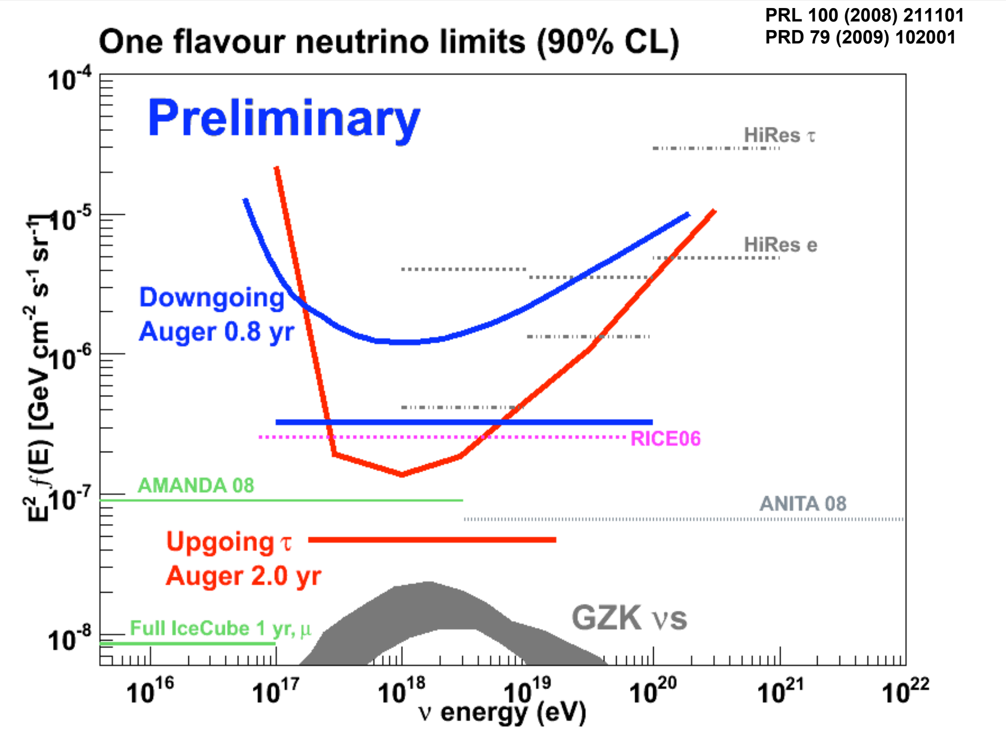


'young' showers (ν)
- Wide time distribution
- Strong curvature
- Steep lateral distribution

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

Composition: what they are not !

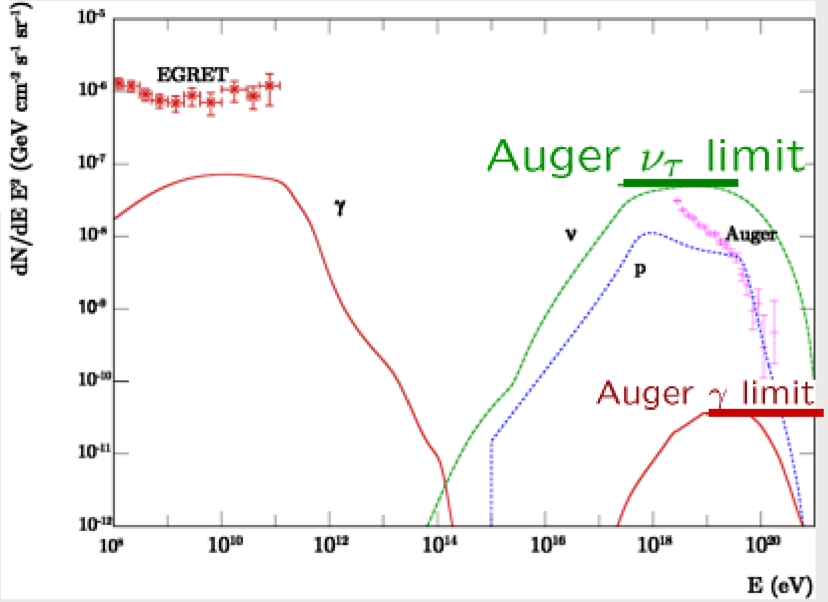
Neutrinos



Several astrophysical models excluded

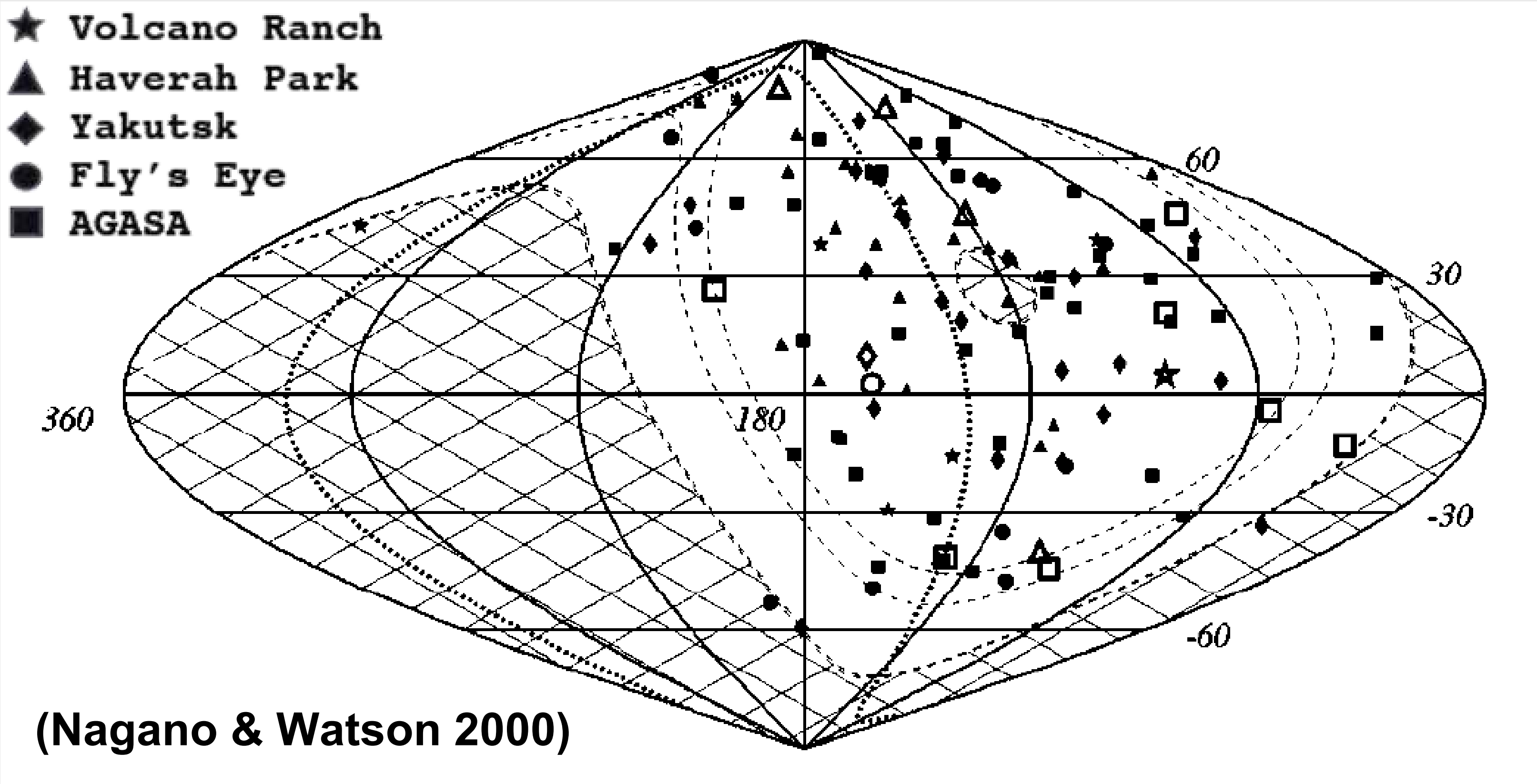
Cosmogenic (GZK) neutrinos in reach !

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



Where do they come from ?

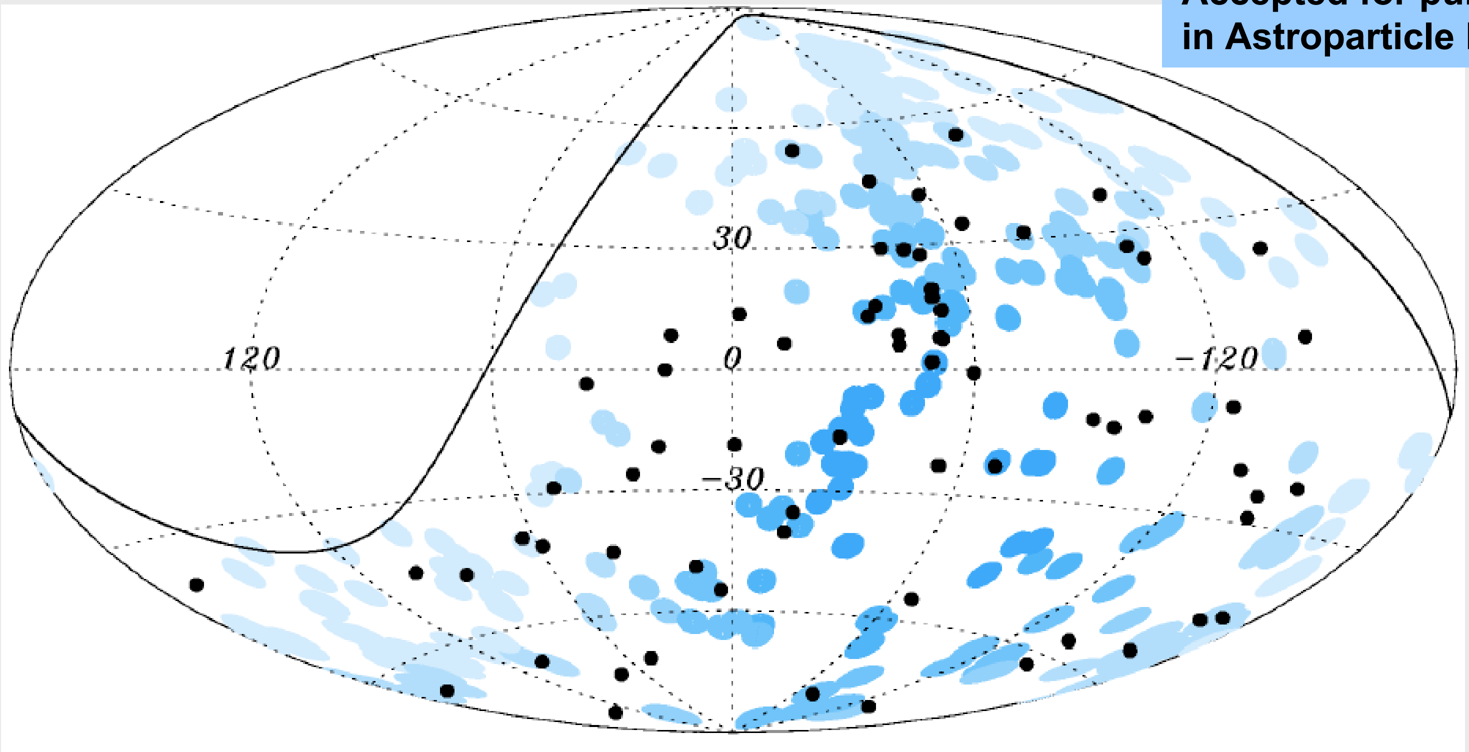
40 years of observation, 5 different experiments: 114 events above 40 EeV
Angular resolution: 2.5-5° (N.B.: difficult to be analyzed together)



Observations:
No significant deviation from isotropy in galactic and super-galactic coordinates
No correlation with nearby matter distribution
Possible clusters? (Doublets/triplets)

Where do they come from ?

Accepted for publication in Astroparticle Physics



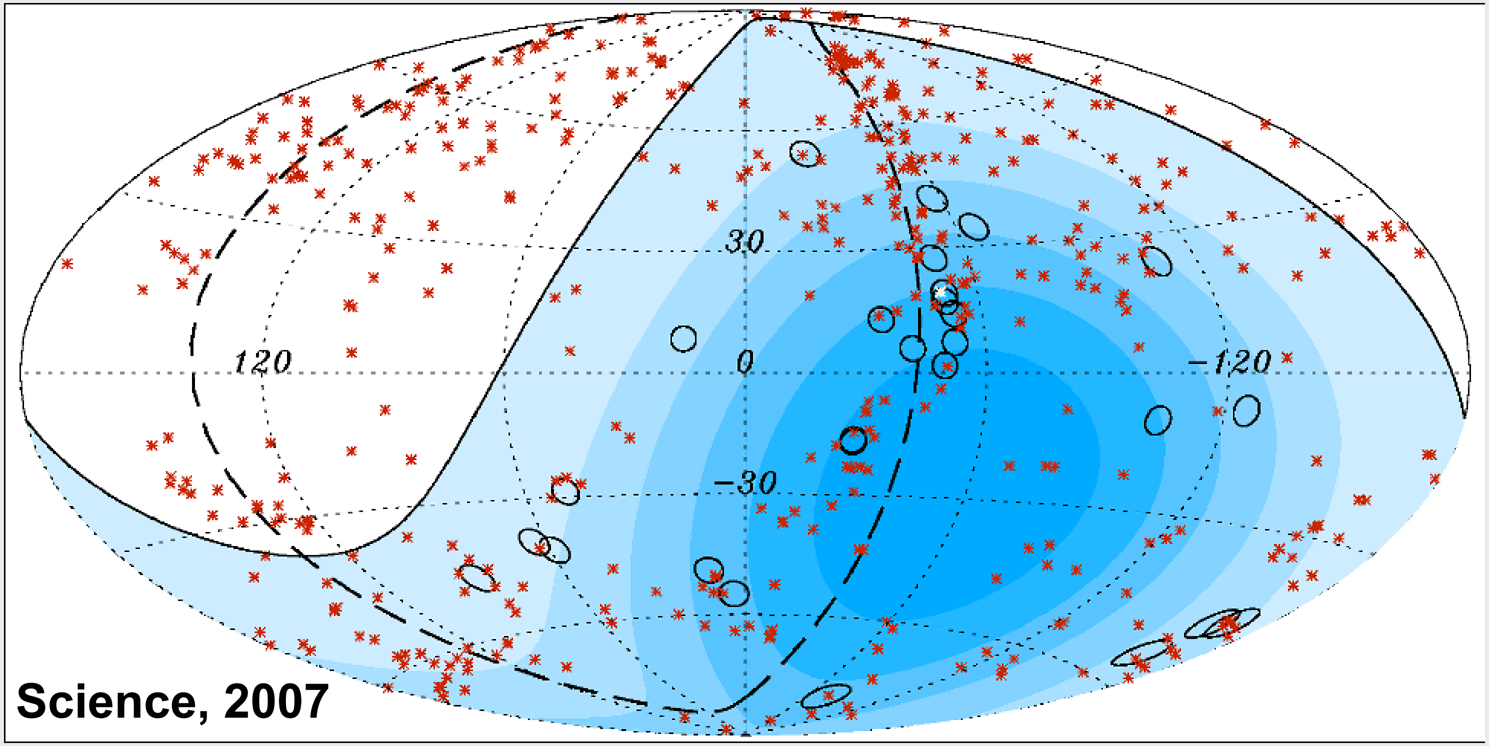
5 years of observation, one experiment: 69 events above 55 EeV

The largest UHECR statistics in the Southern hemisphere

Angular resolution < 1°

Integrated exposure: 20400 km^2 sr y

Where do they come from ?



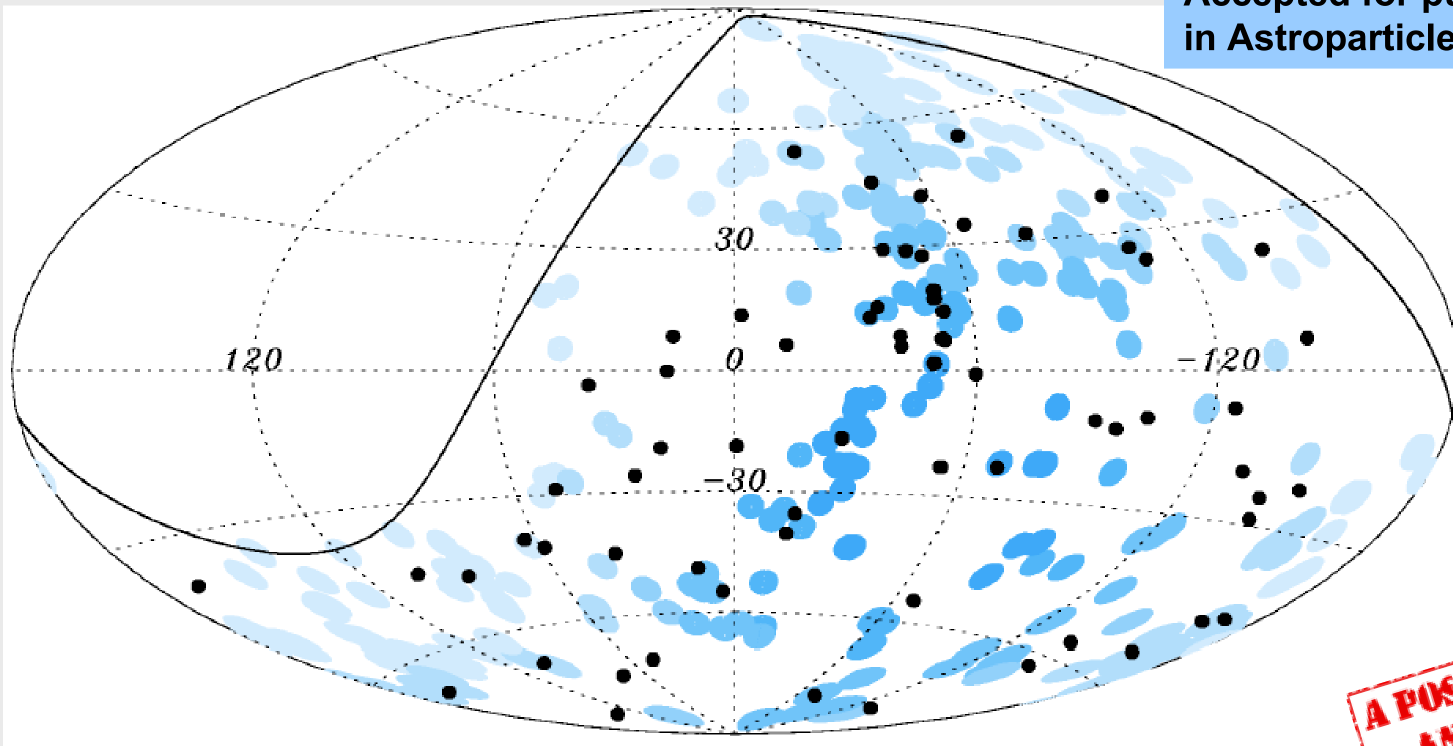
Auger: using 27 CR above 56 EeV collected through 31 August 2007 →
correlation with the positions of nearby quasars and AGNs (12th VCV)

Correlation parameters: energy (55 EeV), angular separation (3.1°), distance
(75 Mpc) fixed with early data

Test with later data, built to reject isotropy with 1% probability being wrong:
test passed (9/13 correlated events)
→ **Isotropy rejected at 99% C.L.**

Where do they come from ?

Accepted for publication in Astroparticle Physics



A POSTERIORI ANALYSIS

<u>Update of Correlations results by Auger</u> (paper to appear in Astrop. Phys):

Updated estimate of the degree of correlation (69 events above 55 EeV)

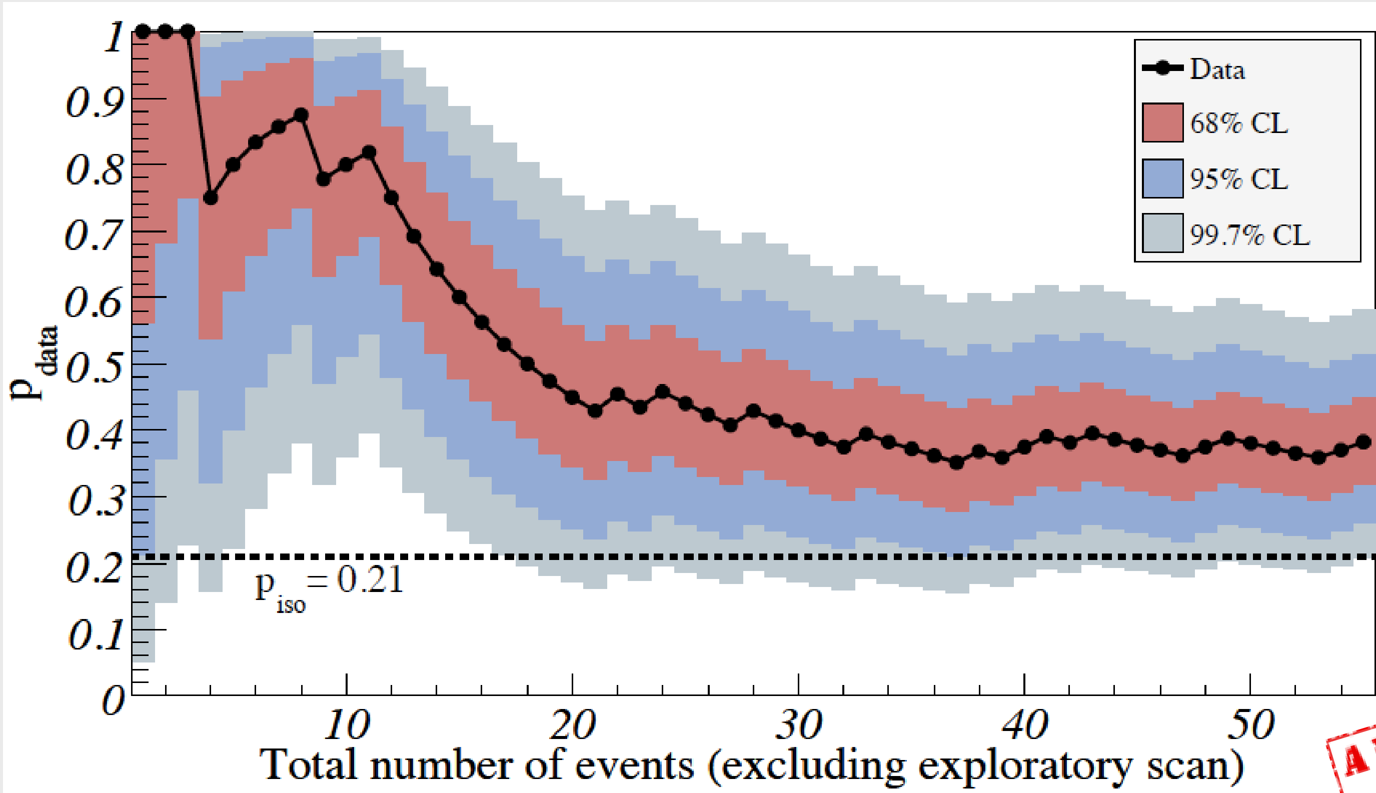
Correlation decreased from (69±12)% to (38±7)% (21/55 correlated events)

Fraction expected under isotropic hypothesis: 21%

Cumulative binomial probability P=0.003

Cannot derive a CL

Where do they come from ?



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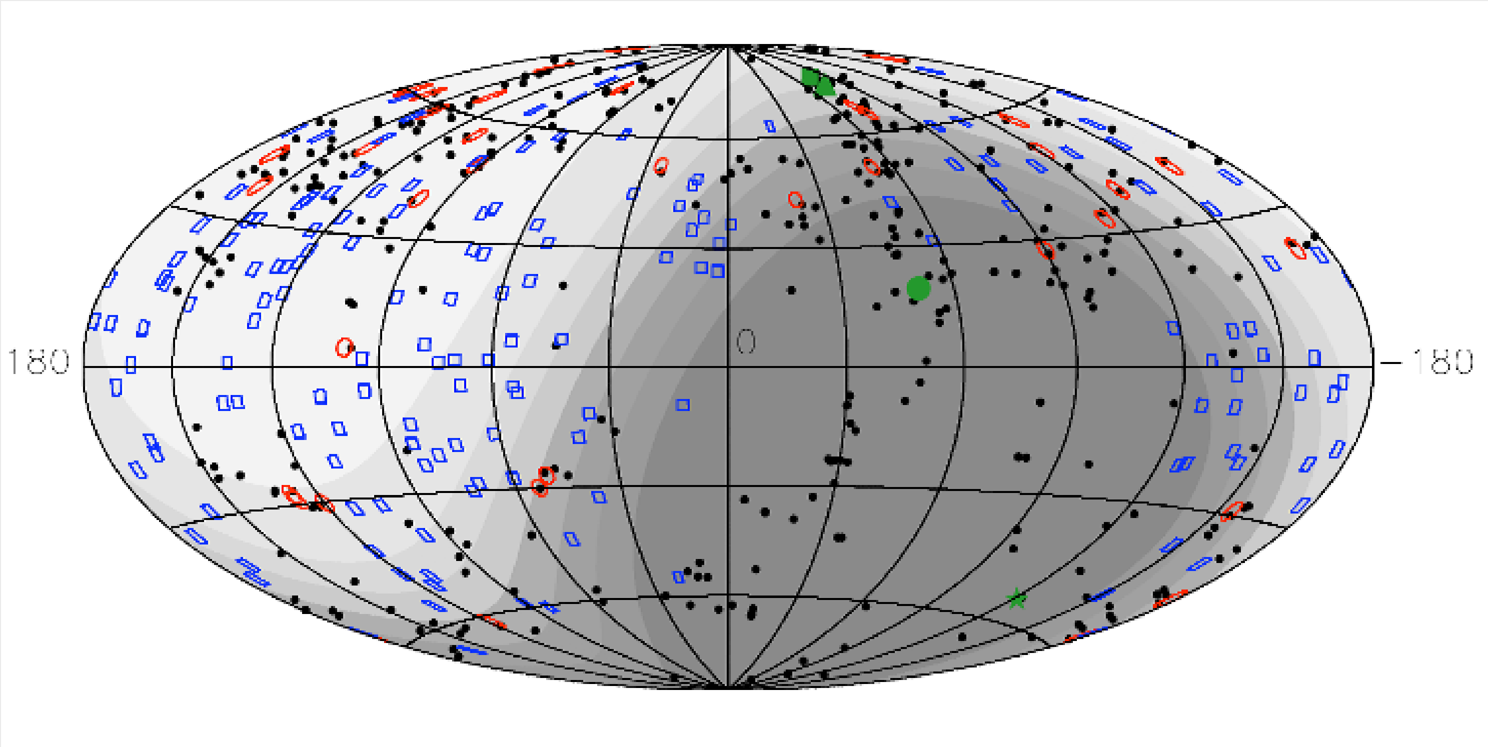
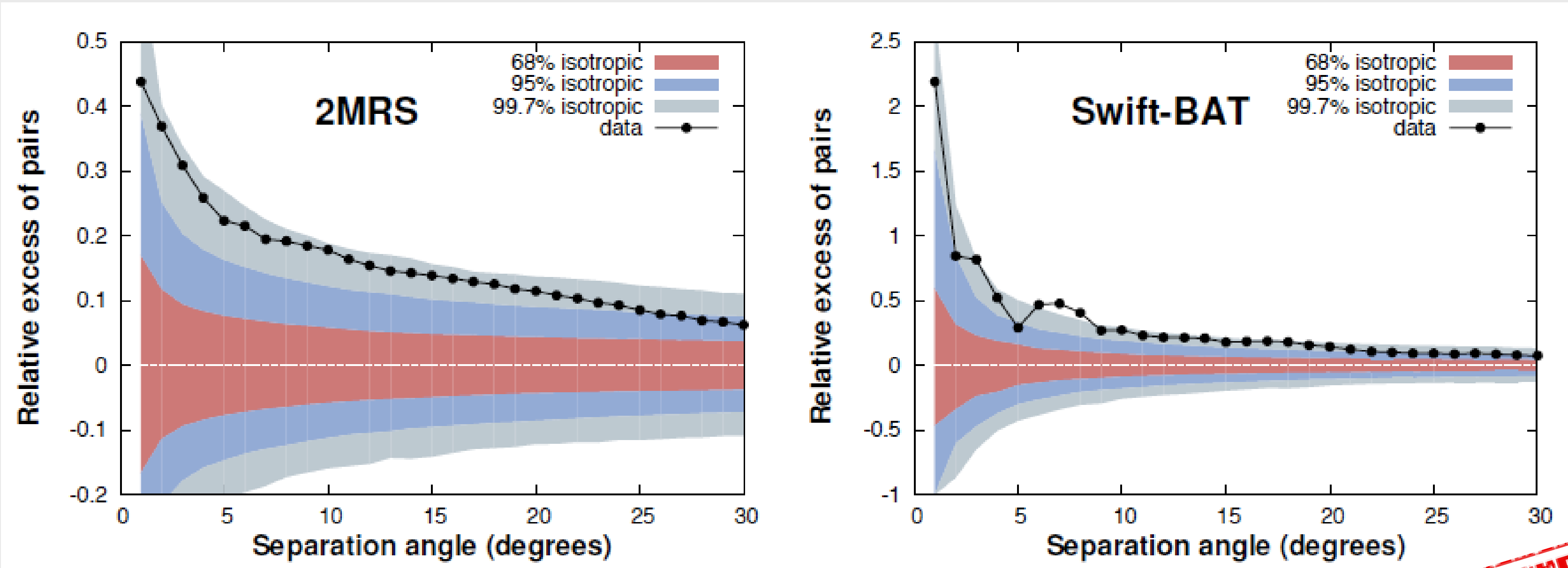


HiRes: correlation with VCV (same parameters as Auger):
2/13 correlated events (3.2 expected by chance)
not incompatible with 38% Auger correlation
Moreover, north and south hemispheres may be different
(AGN distribution and ≠ incompleteness of the catalogue)
Possibly "different" energy scales (very steep spectrum)

Where do they come from ?



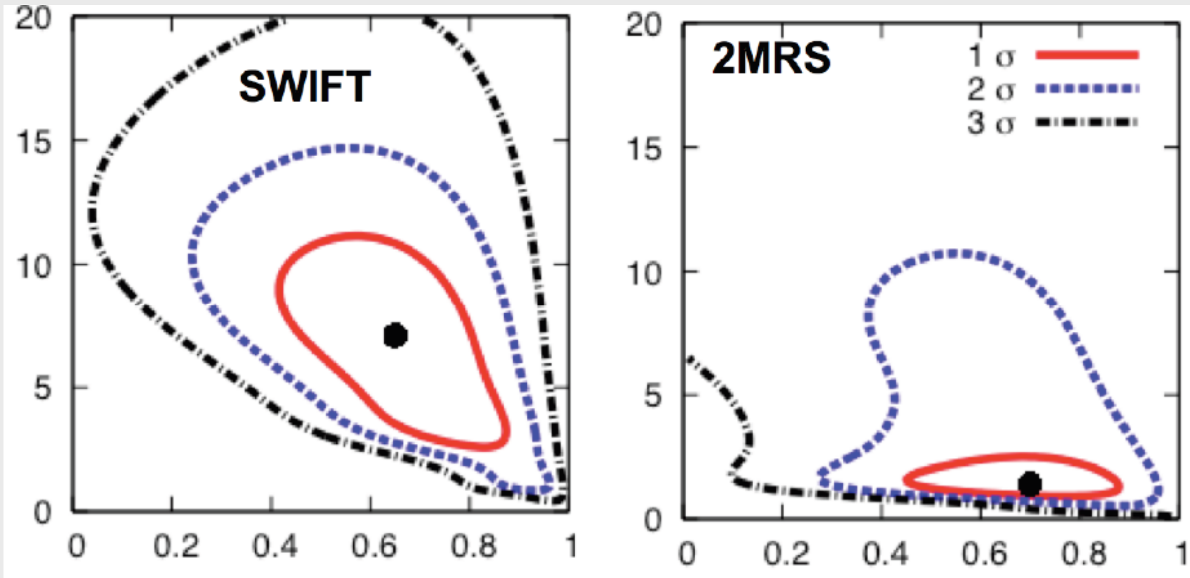
A POSTERIORI ANALYSIS

Other 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 in data vs isotropic distribution
Less than 1% of isotropic samples yield more pairs

Where do they come from ?

smoothing angle (deflection)



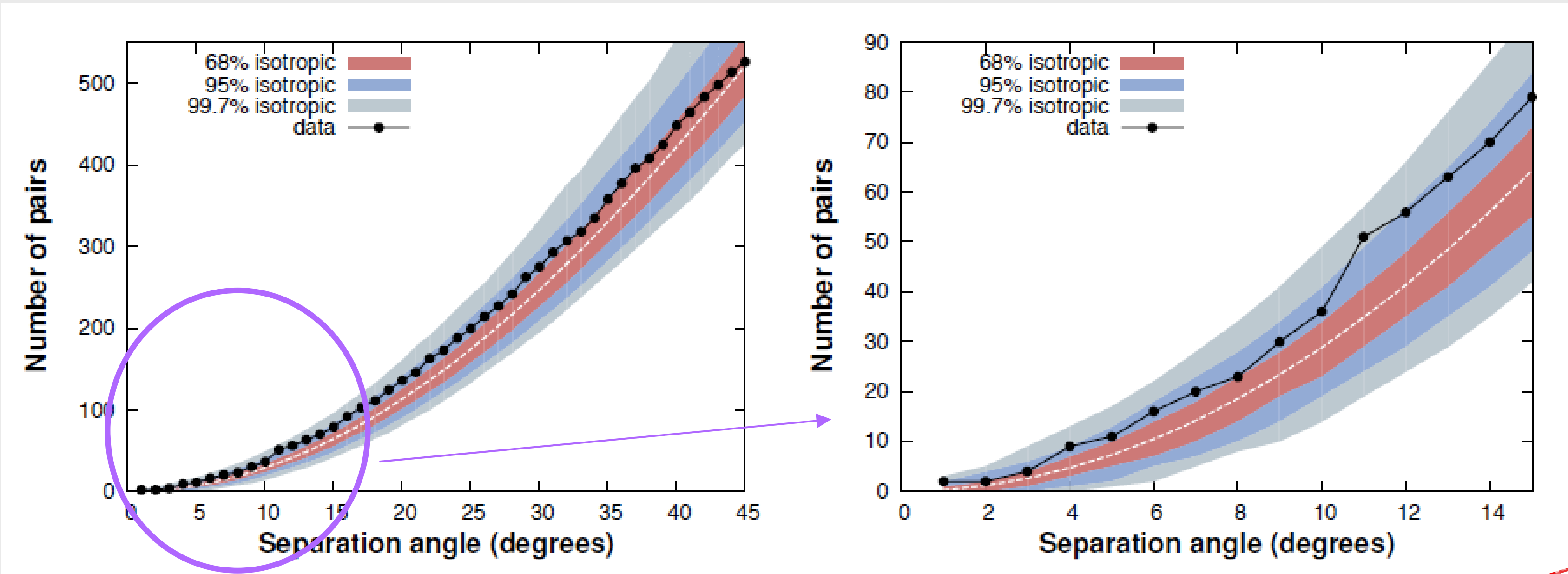
isotropic fraction (incompleteness),

A POSTERIORI ANALYSIS

<u>Other a posteriori searches:</u>

Statistical tests of the 69 Auger events with density maps weighting each object (2MRS and Swift-BAT) by their flux and distance (GZK effect)
Two free parameters:
smoothing angle (deflection) and isotropic fraction (incompleteness),
Best fit: 2MRS -> (1.5°, 64%); Swift -> (7.8°, 56%)
Large isotropic fraction favoured

Where do they come from ?



A POSTERIORI ANALYSIS

Autocorrelations:

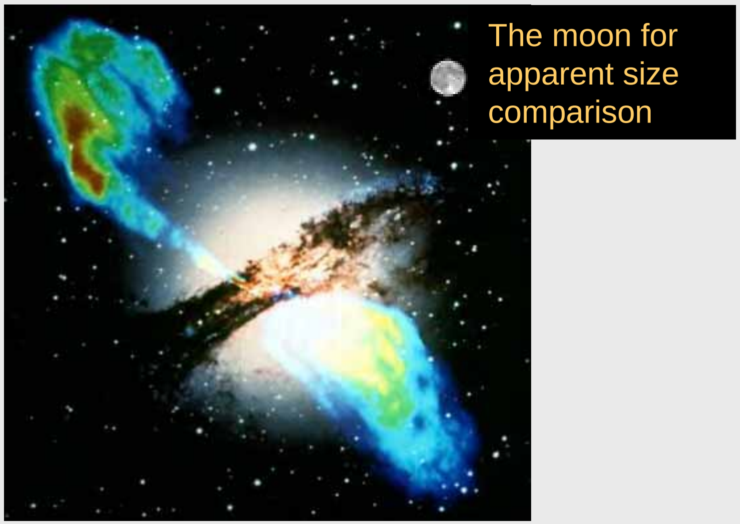
Auger: Search for UHECR clusters (above 57 EeV):

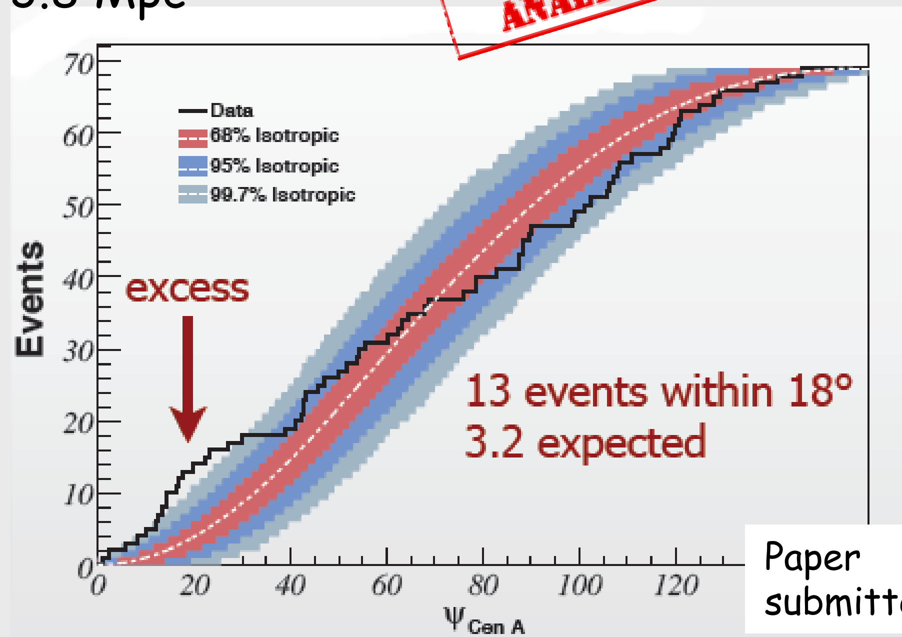
Largest deviation from isotropic expectations @ 11° (P=0.10)
Small scale clustering (à la AGASA) not supported by Auger
(even changing the energy threshold)
neither by HiRes

Where do they come from ?

A POSTERIORI ANALYSIS

<u>**Centaurus-A**</u>, nearest AGN (FR-I) at 3.8 Mpc
(→ no GZK attenuation expected)





Paper submitted

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

<u>**Virgo cluster**</u>

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

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.

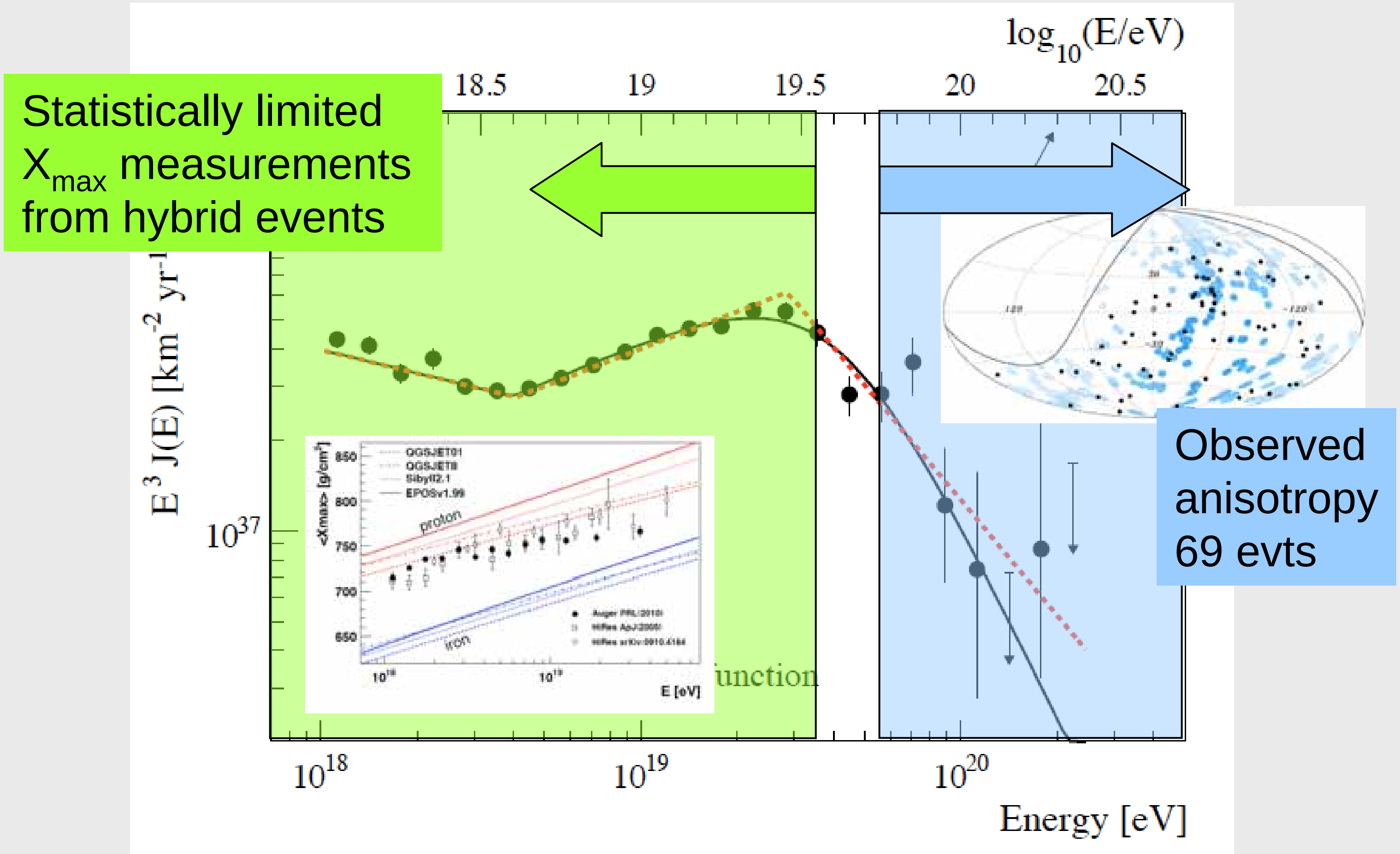
Anisotropies and correlations:

- 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 ($\rightarrow$Fe).

Composition measurements:

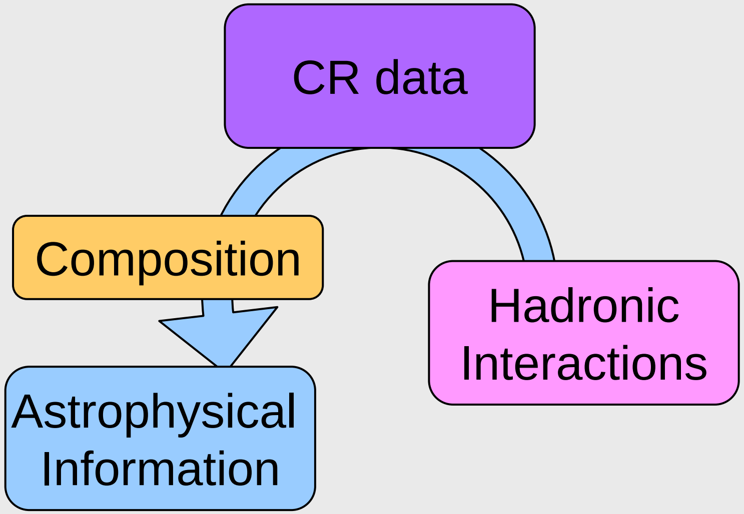
- Now more precise than ever but still challenging.
- Trend towards higher masses above 10^{19}eV (Auger <Xmax> and RMS(Xmax)), but contradicted by HiRes results.
- Important role of hadronic interactions extrapolations: change in composition, or cross-section higher ? Muon excess in data wrt models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

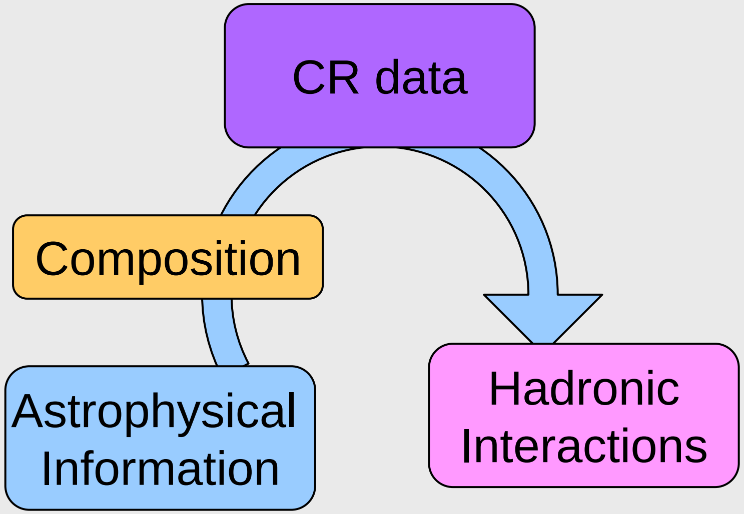
Composition and Anisotropy



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

Astroparticle Physics and HEP an essential interplay





- To study **hadronic interactions at UHE**, some knowledge on the "CRbeam" is essential: knowledge on **mass composition.**
- Reversely understanding the **sources** of UHECR, studies on cosmic **magnetic fields**, etc, requires **mass composition knowledge**: control on **hadronic interaction models is needed** for CR data interpretation.
- **Astrophysical information on composition may come from high stat and high precision measurements on:**
  - spectral shapes (propagation of CR),
  - Point sources and B fields used as cosmic magnetic spectrometer

Summing it up

- **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)

- **Composition measurements are more precise but still challenging**
  - 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

- **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?)
  - Comparing different experiments observing different skies is complicate

What 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?)

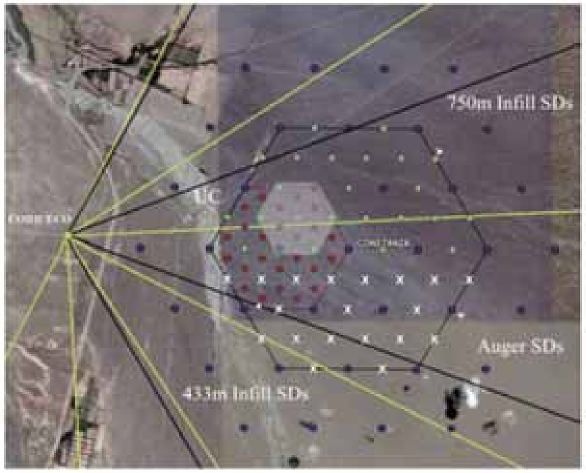
What next ?

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

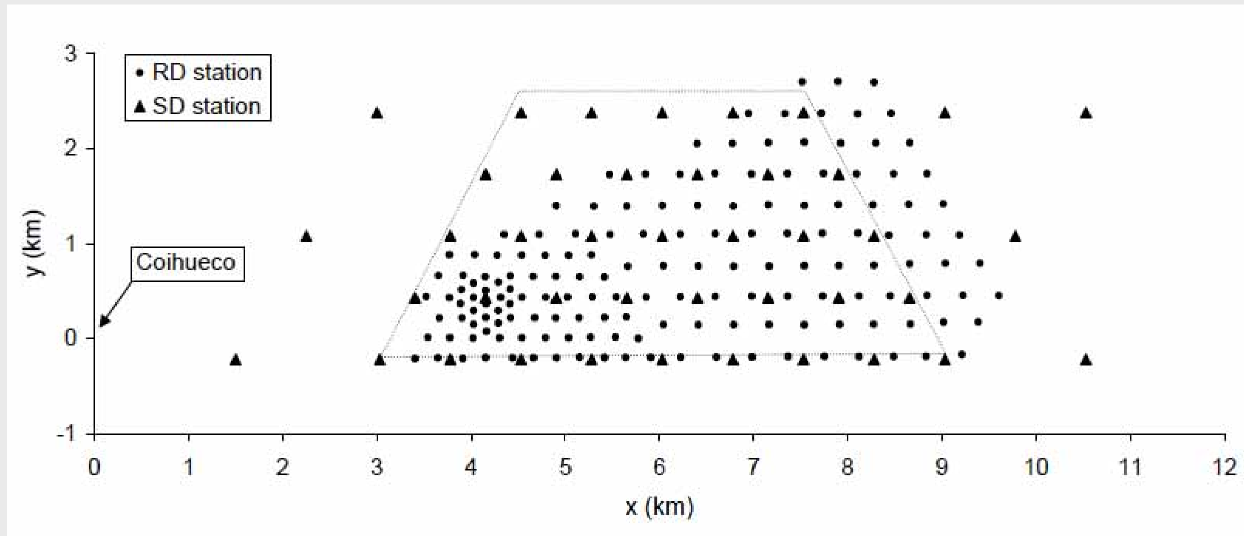
Multi-Hybrid detector fully efficient at 0.1 EeV (100 PeV)

Same kind of enhancement within Telescope Array :
TALE-FD: 24 telescopes viewing up to 31° + 15 "towers" viewing up to 73°
+ TALE-Infill: 111 scintillators + 25 muon counters (400 m spacing)
Hybrid detector fully efficient at 0.03 EeV (30 PeV)

What next ?

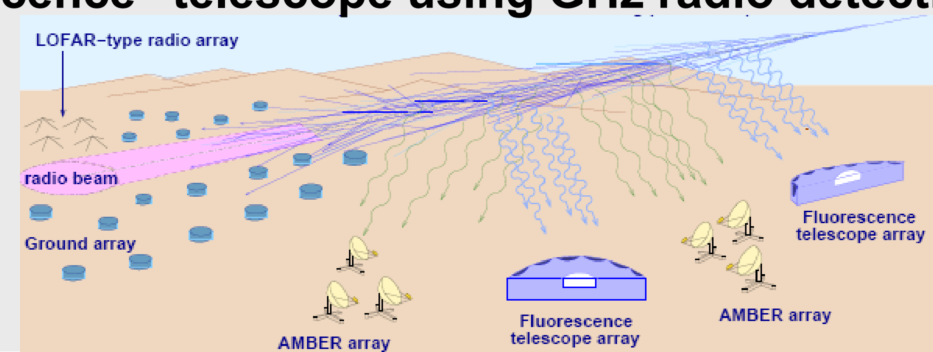
New observables

AERA @ Auger 150 VHF radio-detectors on 20 km²



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

AMBER @ Auger "Fluorescence" telescope using GHz radio detection.

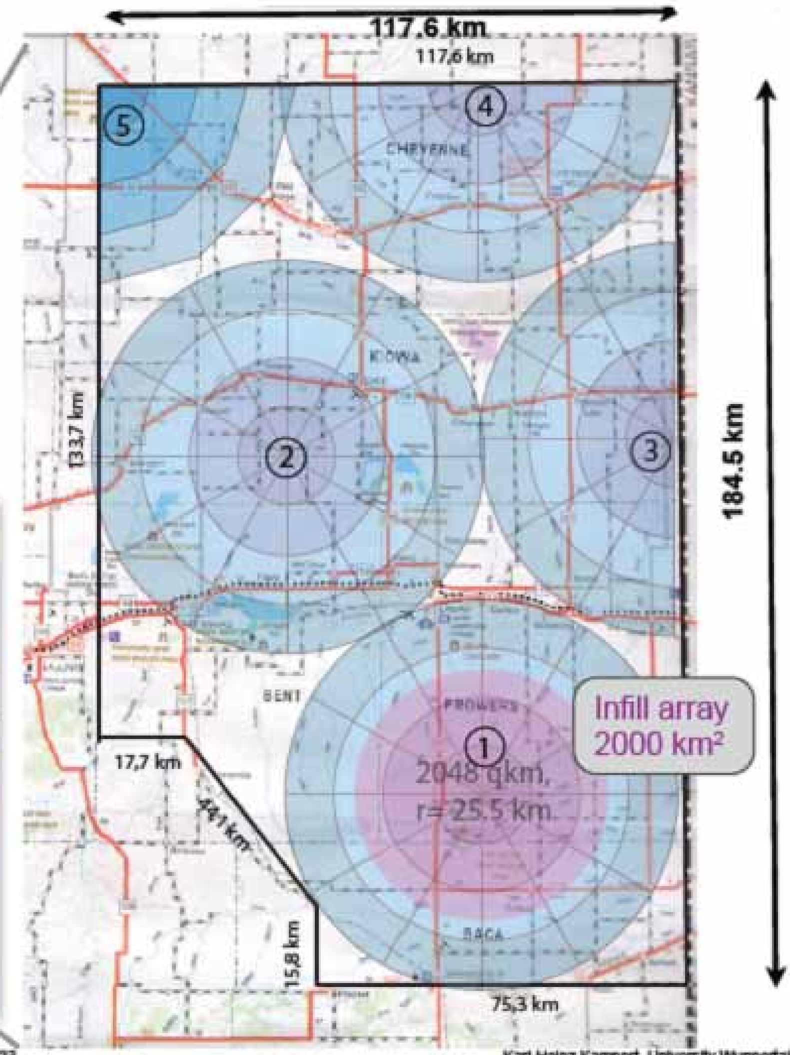


What next ?

Make it bigger ! high statistics hybrid detector for point sources searches and mass composition at super-GZK energies

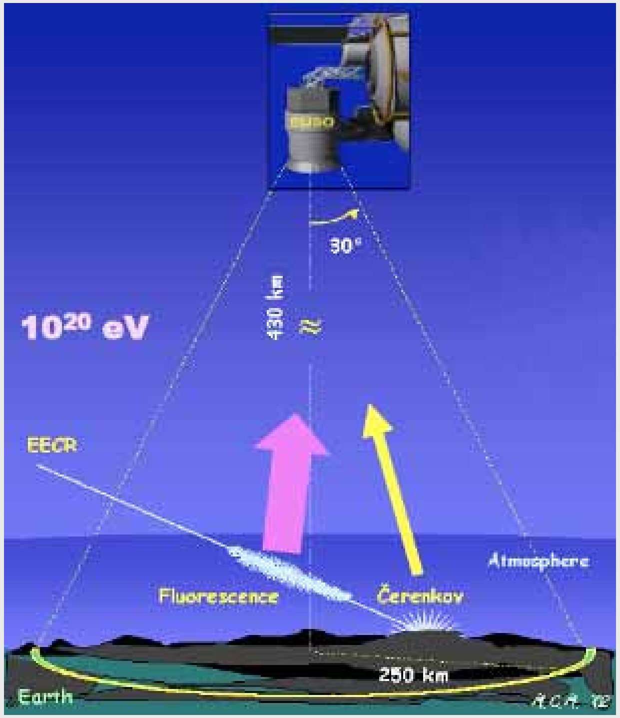
Auger North

- **Optimized for science and costs**
- **Surface array with 4000 stations:**
  20,000 km² with
  √2-mile = 2.3 km grid
- **Infill array with 400 stations:**
  2,000 km² with
  1-mile = 1.6 km grid
- **39 fluorescence telescopes**



What next ?

Much much bigger…



<u>Observing fluorescence and Cherenkov from space</u>
Less accurate than ground experiments (>2° angle, 30% energy, 100 g/cm² X_{max})
+ ever changing acceptance and higher energy threshold
… but very large aperture (30-150xAuger) and full-sky coverage

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