Recent results on UHECRs from the Pierre Auger Observatory

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on behalf the Pierre Auger Collaboration

LHAASO Workshop, Beijing, Feb. 2011

UHE Detectors

With time, gain not only in detection surface...

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

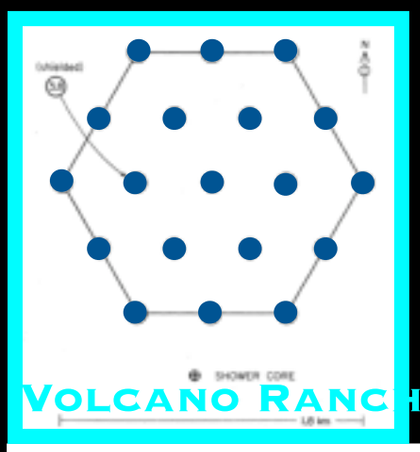
Late 60s-80s:
Haverah Park
UK, Leeds, 220 m a.s.l.
62 water Cherenkov
Spacing ≈ 500/2000 m

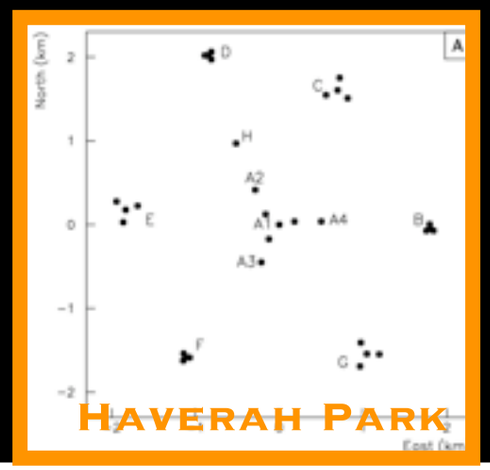
Late 60s-70s:
SUGAR
Australia, 250 m a.s.l.
54 buried scintillators
Spacing ≈ 1600 m
Area: 55 km2

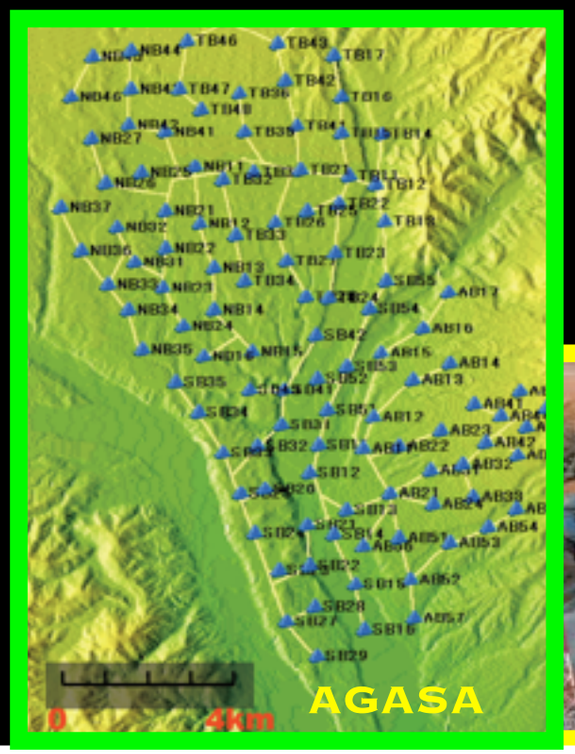
Early 70s - now
Yakutsk
Russia, 100 m a.s.l.
58 scintillators + 6 muon detectors + 45 Cherenkov PMTs
Spacing ≈ 150/500/1000 m
Area: 17 km2

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

...but also in quality/precision

Early 60s:
Volcano Ranch

Pulse amplitude, arrival times

LDF -> Ne -> rough estimation 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 emisphere

Early 70s - now
Yakutsk

First "complex" detector (multi-component).

3 nested subarrays, with different spacing.

First calorimetric approach (Cherenkov)

Late 70s- 2004
AGASA

Largest array in the past

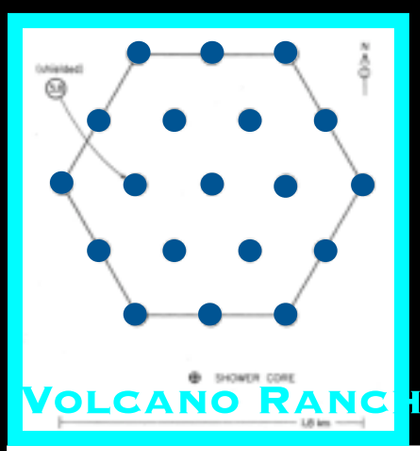
Multi-component measurement

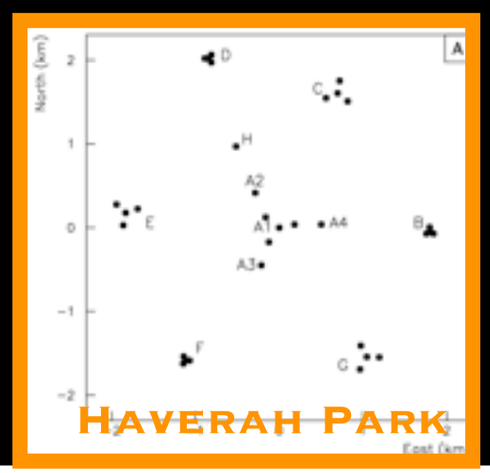
(e.m. and muonic)

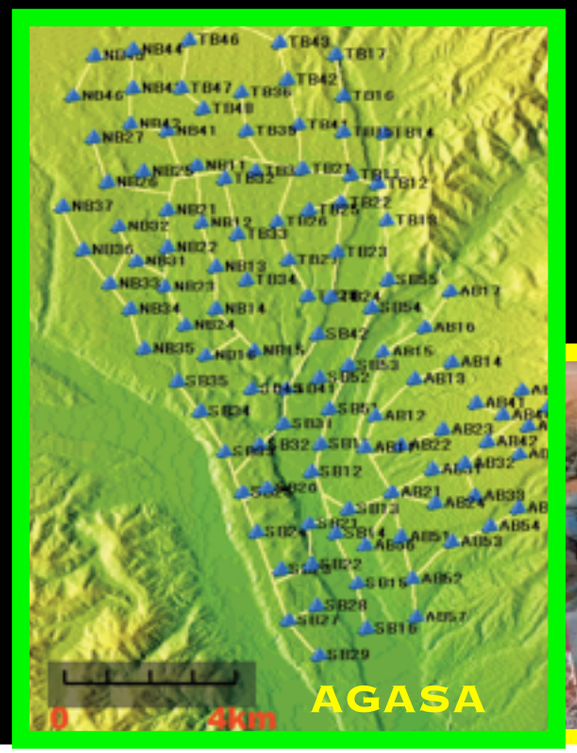
Early 80s-1995
Fly's Eye

First succesful employ of fluorescence

First "stereo"

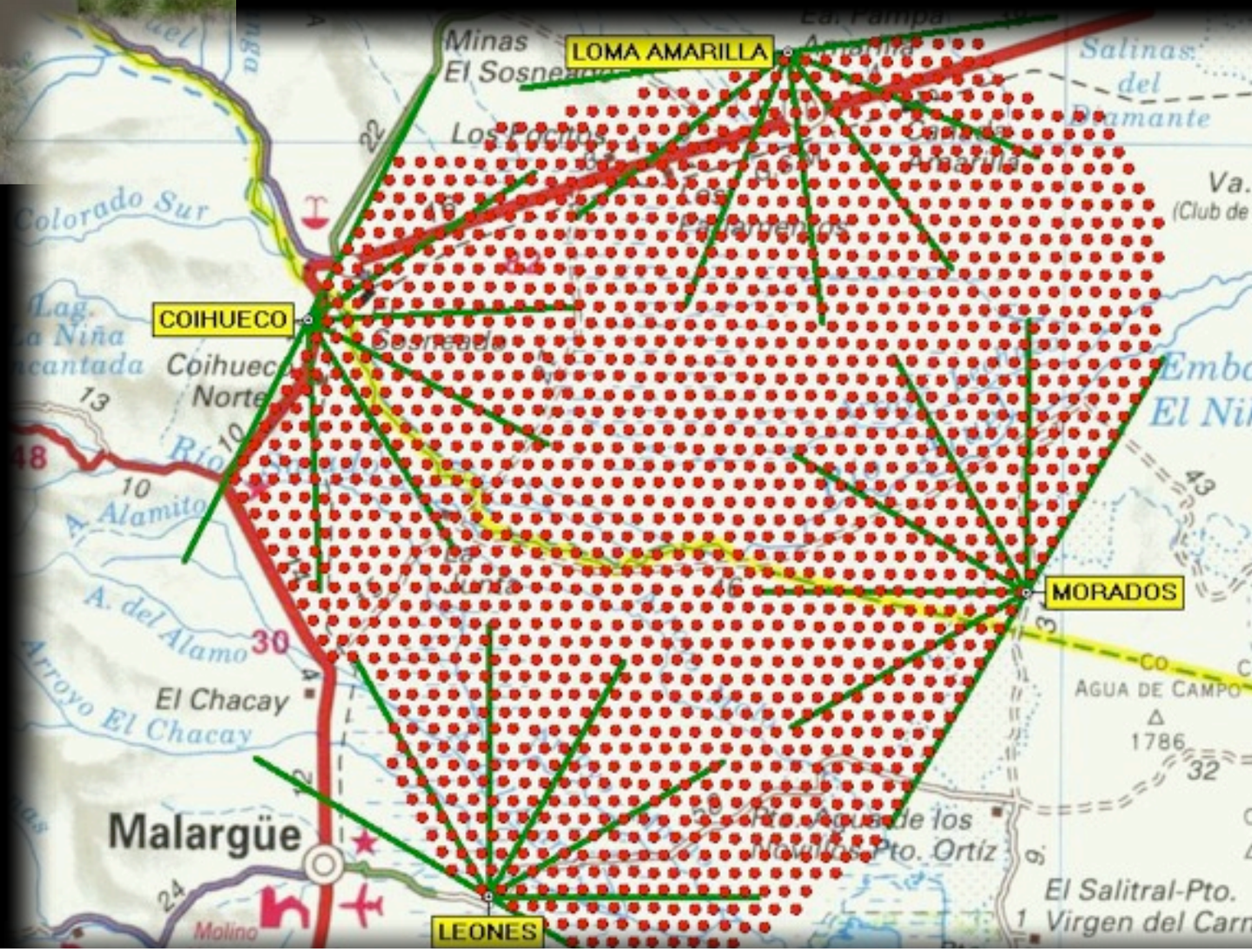






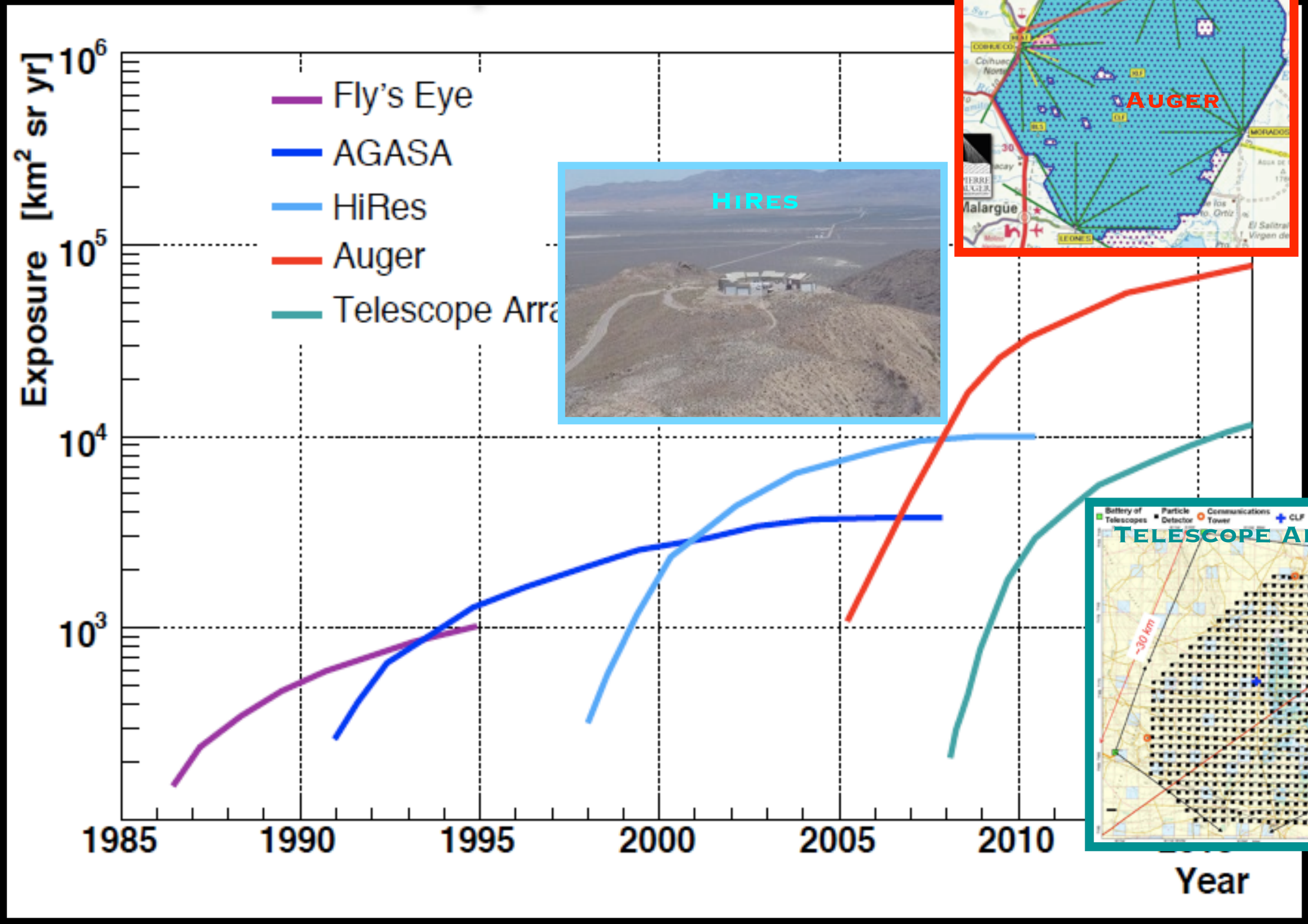
1960 1970 1980 1990

Since 2004: the Pierre Auger Observatory



- Argentina, Malargue, 1500 m a.s.l.
- «hybrid» detector: 1600 water tanks (Cherenkov) + 4x6 fluorescence detectors
- High precision hybrid measurements
- Grid spacing ≈ 1500 m
- Surface: 3000 km^2
- Saturation threshold: ~3 EeV

Exposures at UHE



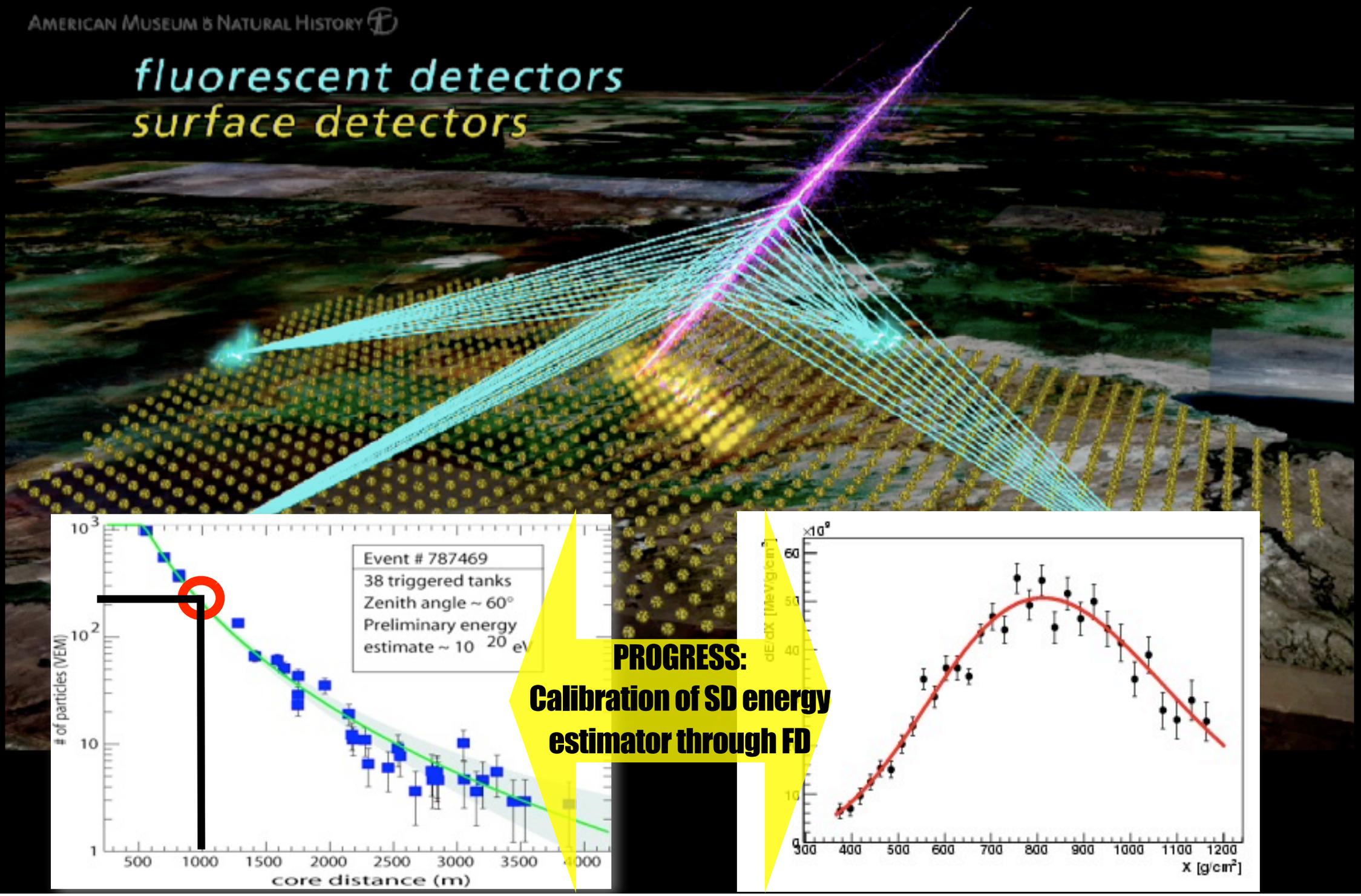
1990 2000 2005 2010

Energy Spectrum

Reference papers:
The Pierre Auger Coll.,
Phys. Letters B 685 (2010) 239-246,
PRL 101 061101 (2008)

Energy measurement

«HYBRID PICTURE» OF THE SAME SHOWER,
ALLOWING THE CALIBRATION OF THE SHOWER SIZE

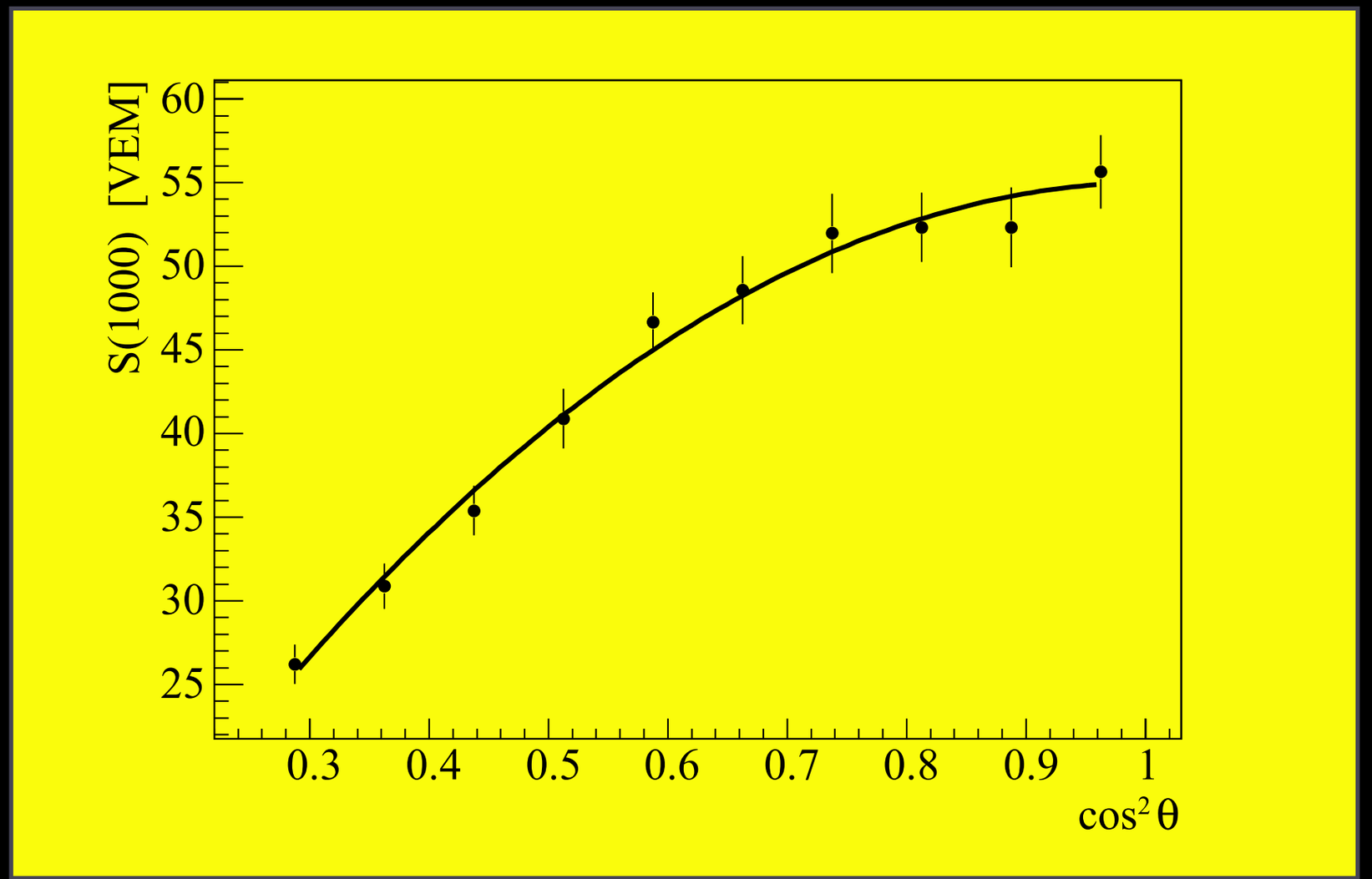


From S(1000) to the shower size : the Constant Intensity Cut method

At a fixed energy, S(1000) decreases with zenith angle (attenuation curve)

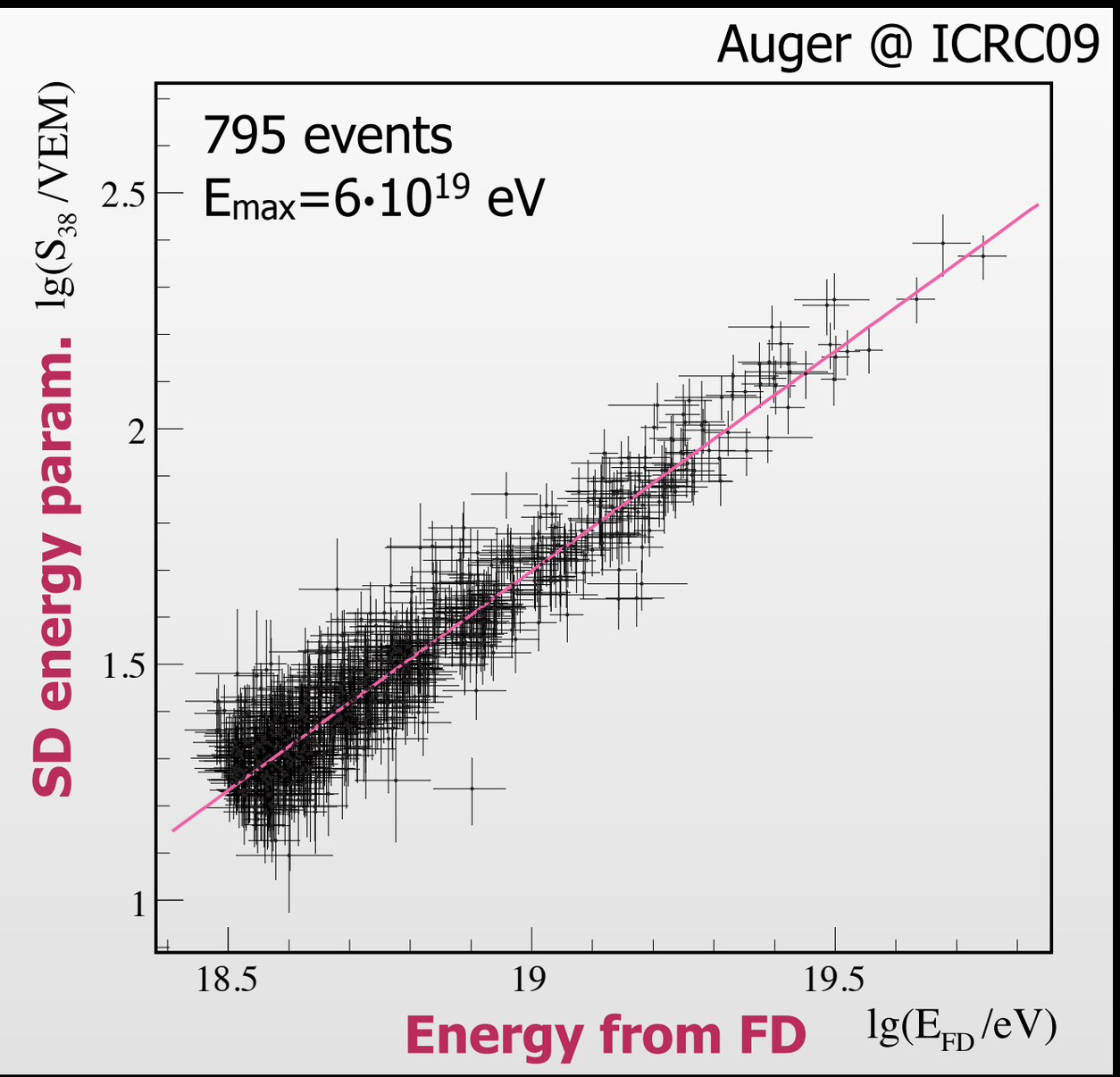
Taking profit of the isotropic distribution of CRs, intensity must be the same in terms of cos^2(th) intervals.

Empirical extraction of the attenuation curve above the saturation energy

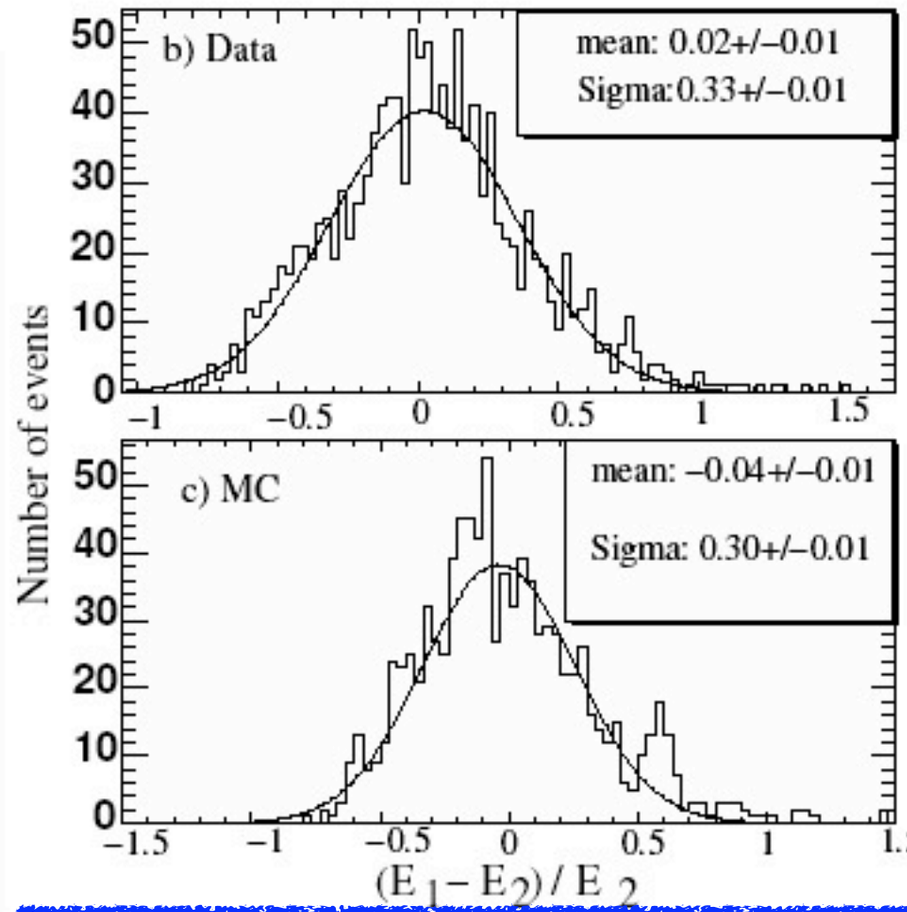


Empirical derivation of the attenuation curve -
No dependence on mass composition a/o hadronic models

Shower size calibration into energy



E resolution ≈ 15%



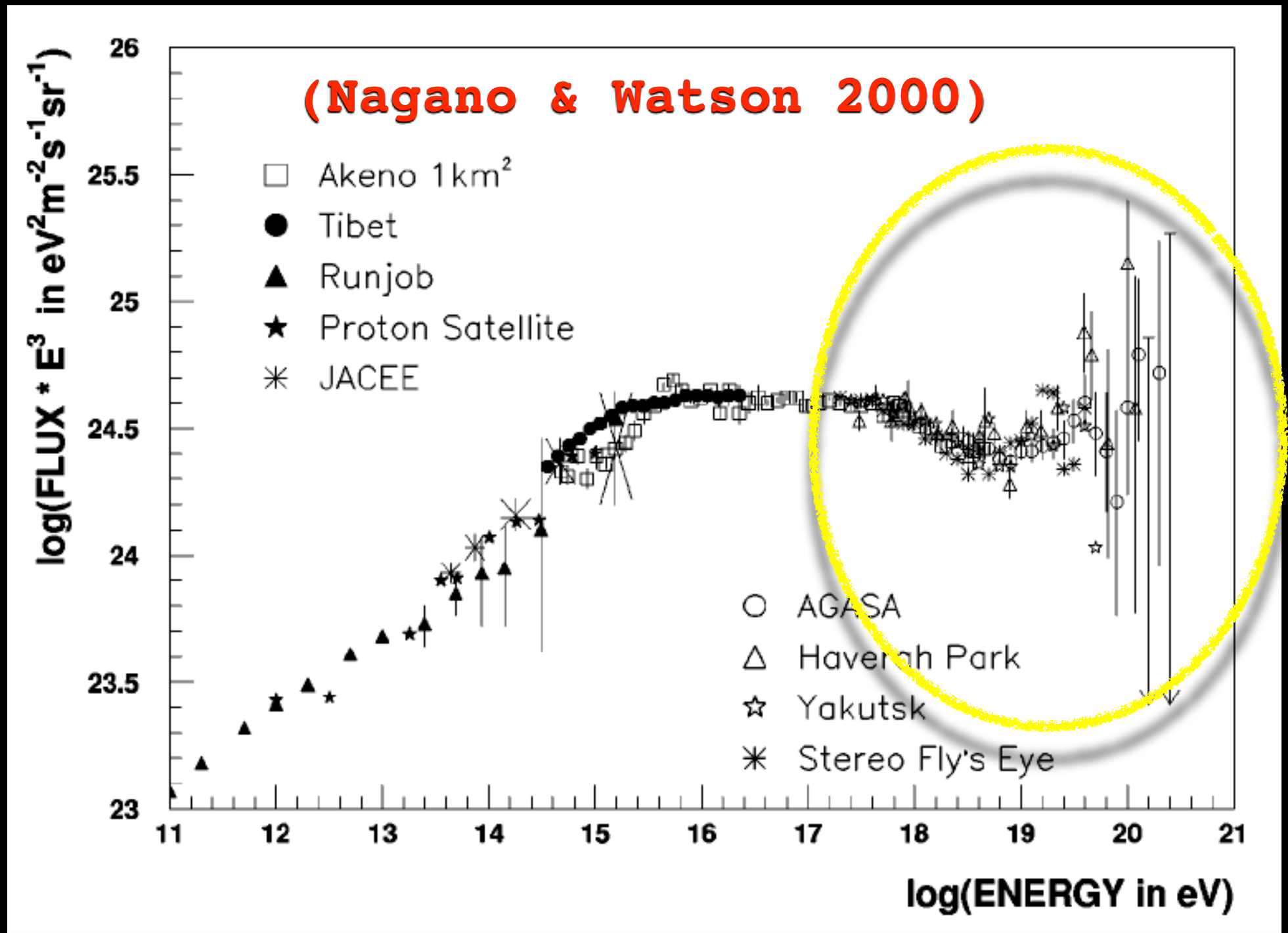
Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

Calorimetric measurement of the energy with the FD.

Calibration of the SD energy through a subset of high quality hybrid events.

No dependence on hadronic models

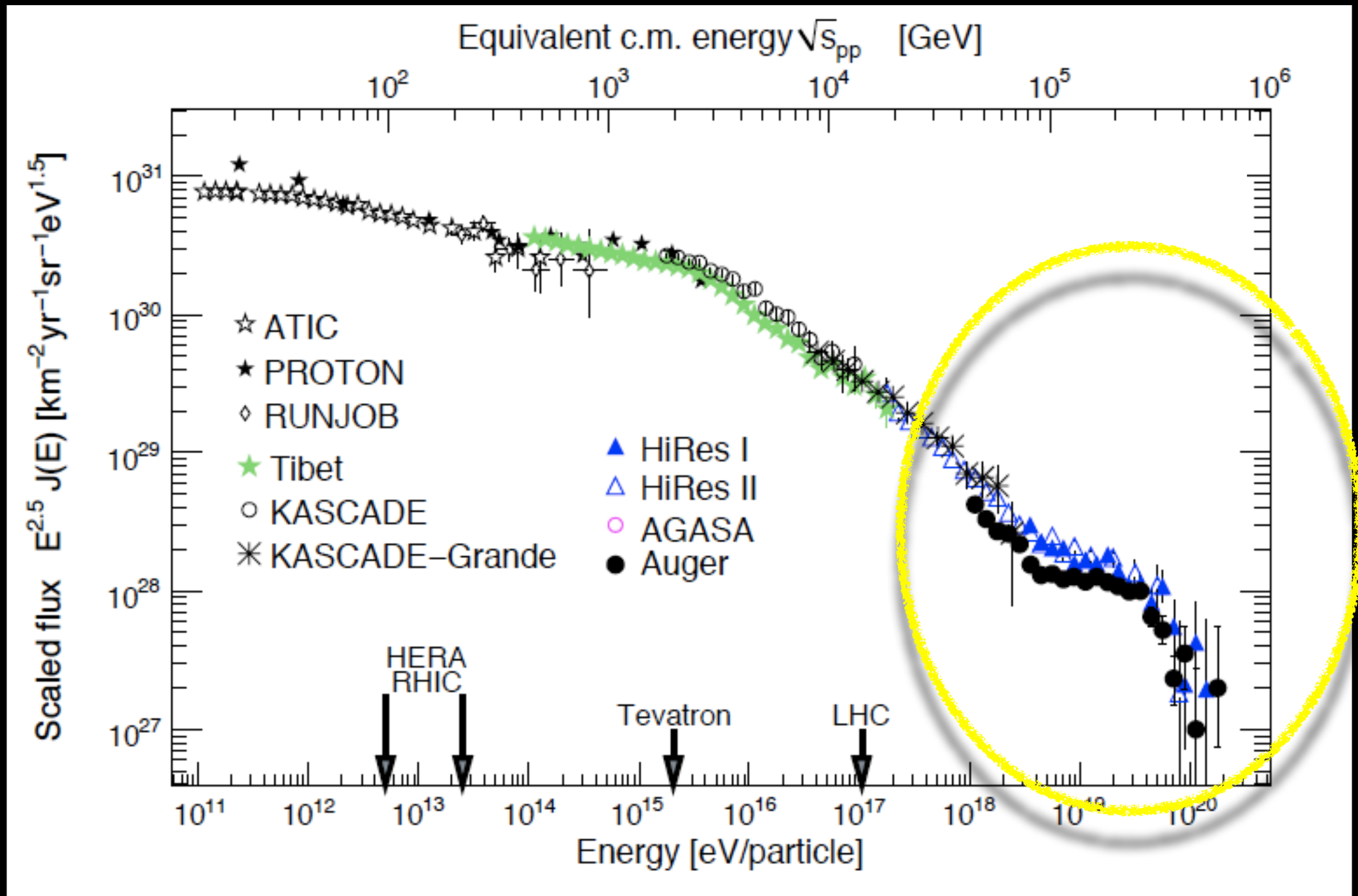
Energy spectrum, 10 years ago...



Smooth ankle at a few EeV (10 EeV?)

Suppression of the flux above ~50 EeV??? (AGASA, HP)

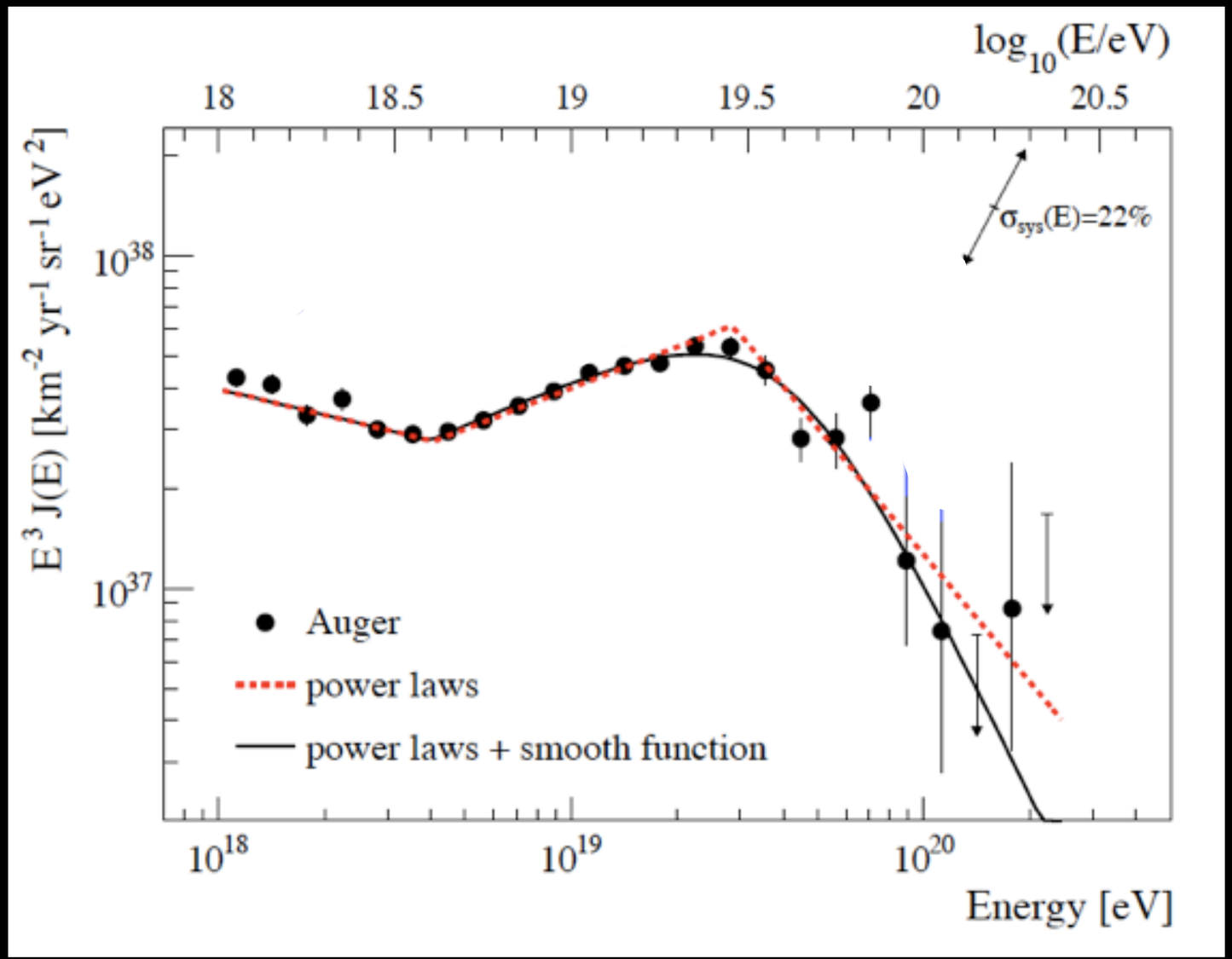
Energy spectrum, today



Sharp ankle at ~4 EeV

Suppression of the flux above ~50 EeV (HiRes, Auger)

Energy Spectrum



Coherent observations of the ankle and of the flux suppression with HIRES, Auger, and TA (modulo systematic uncertainties on the energy scale).

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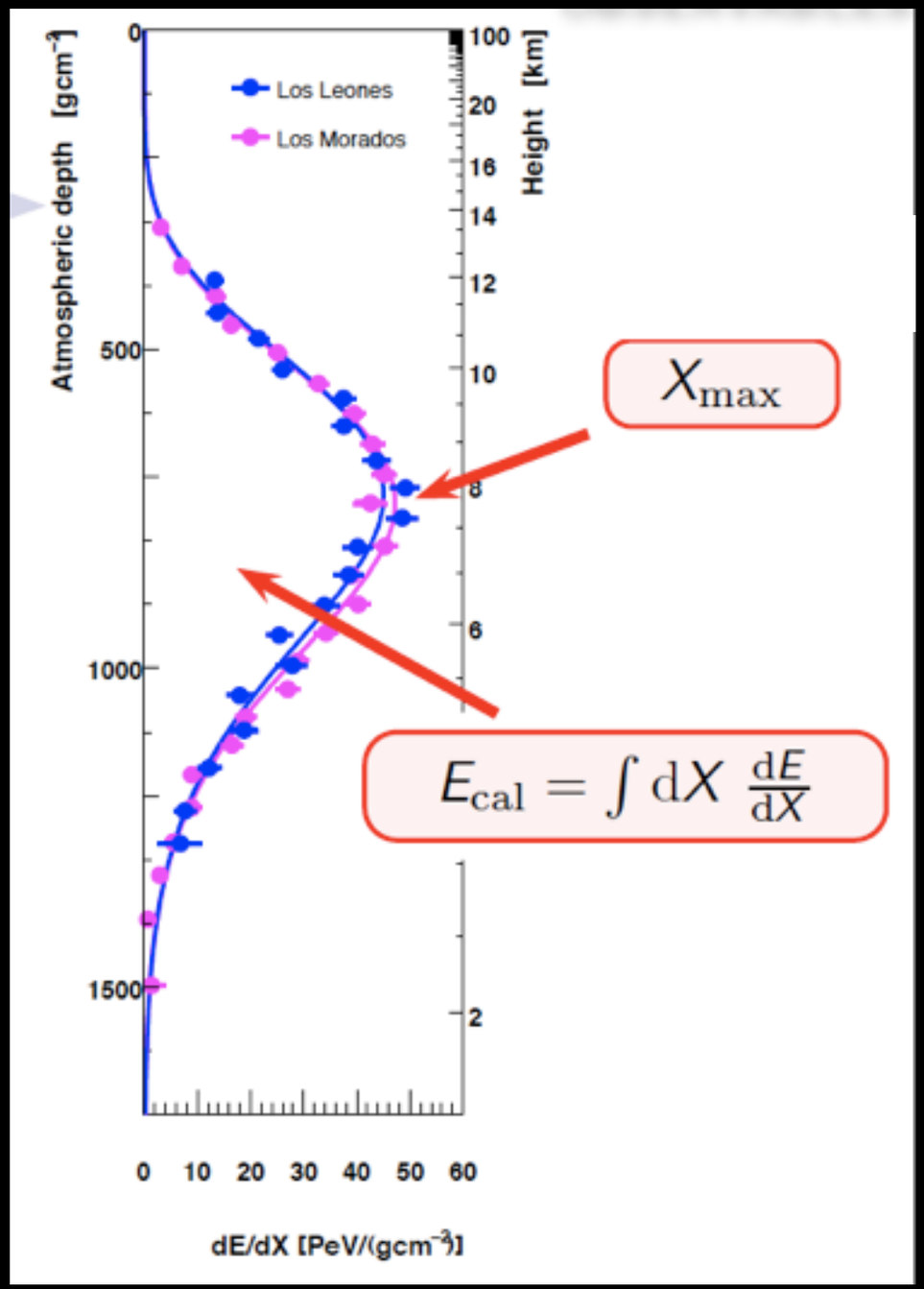
Future Work will profit from the lower energy threshold thanks to the infilled array

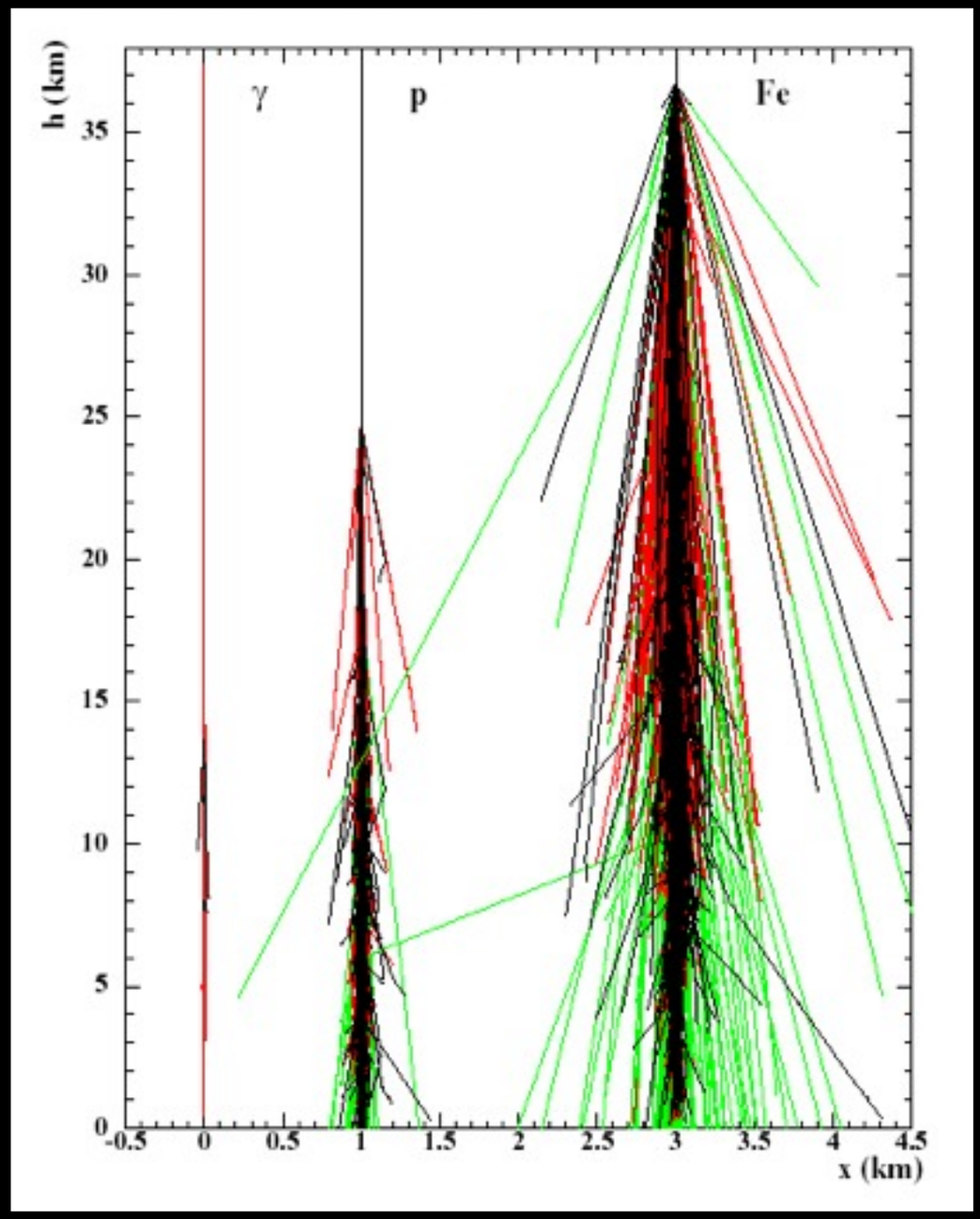
Mass Composition

Reference paper:
The Pierre Auger Coll.,
PRL 104 091101 (2010)

From longitudinal profile to mass composition

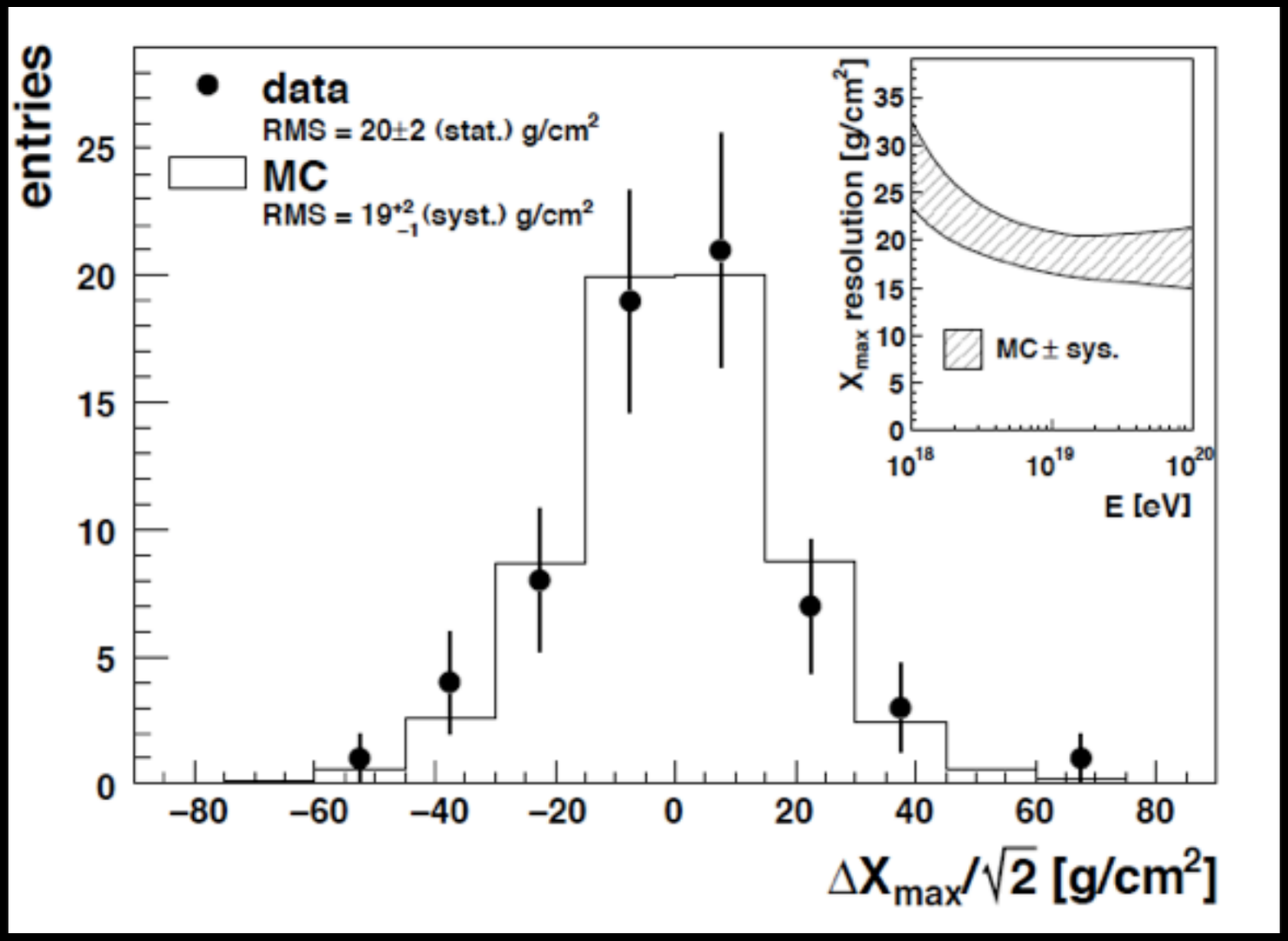
Slant depth of shower maximum (<Xmax>);
Elongation rate (d<Xmax>/dlogE);
RMS of Xmax distribution at fixed energy:
observables sensitive to composition





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

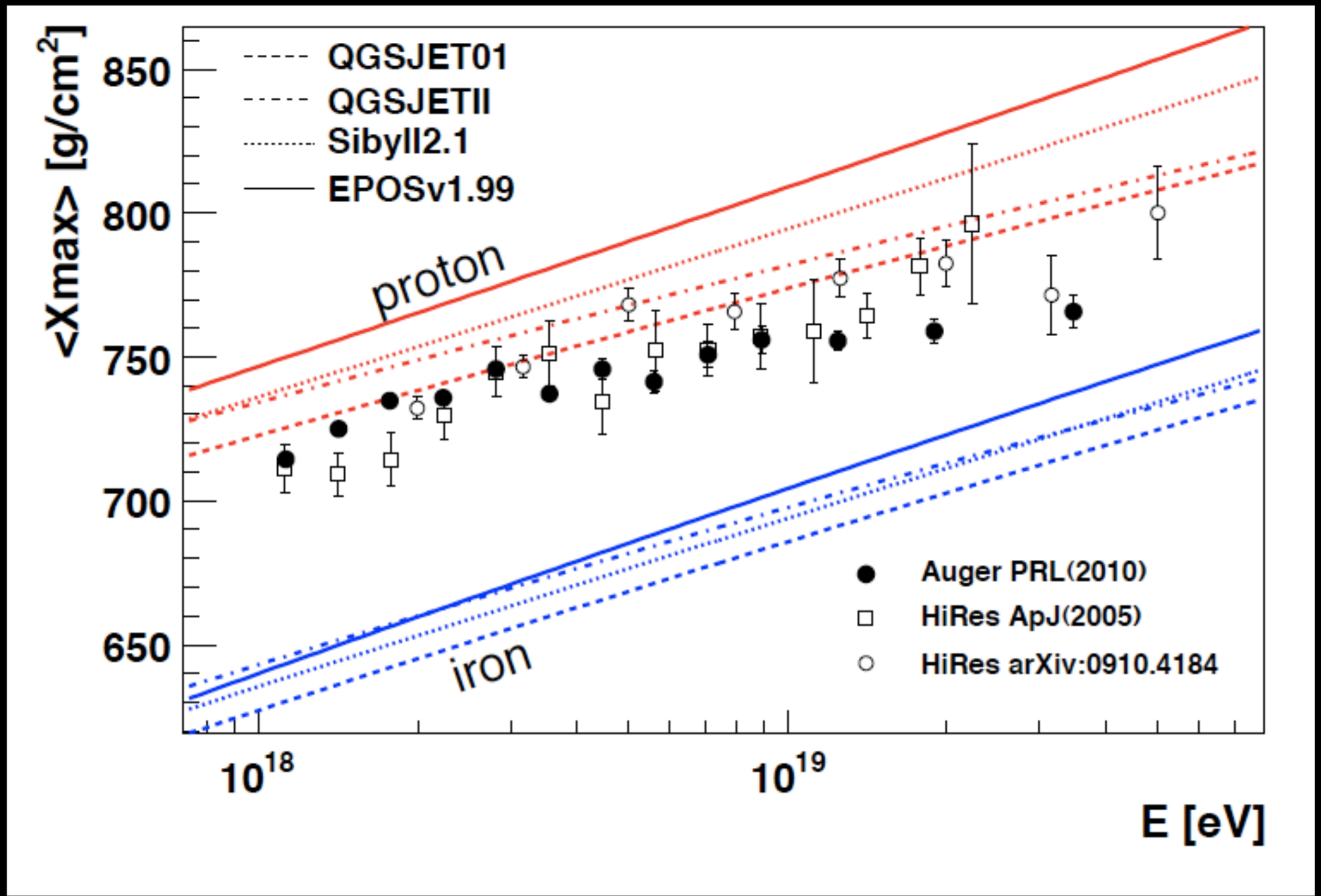
From longitudinal profile to mass composition



Xmax res.: 20 g/cm2

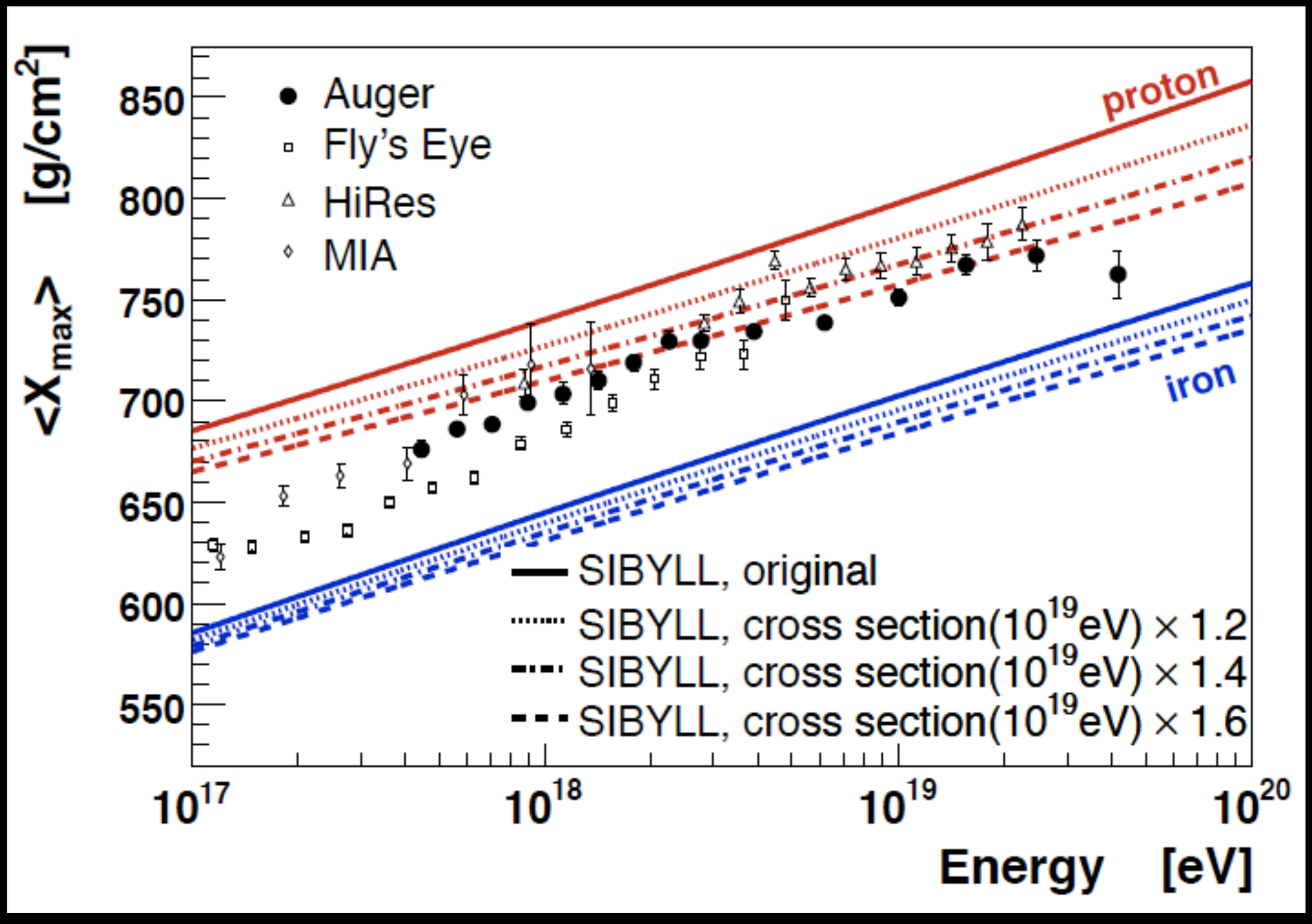
HIGH PRECISION THANKS TO HYBRID AND/OR STEREO MEASUREMENTS
(~ 20-25 G/CM2)

Composition: Xmax vs E

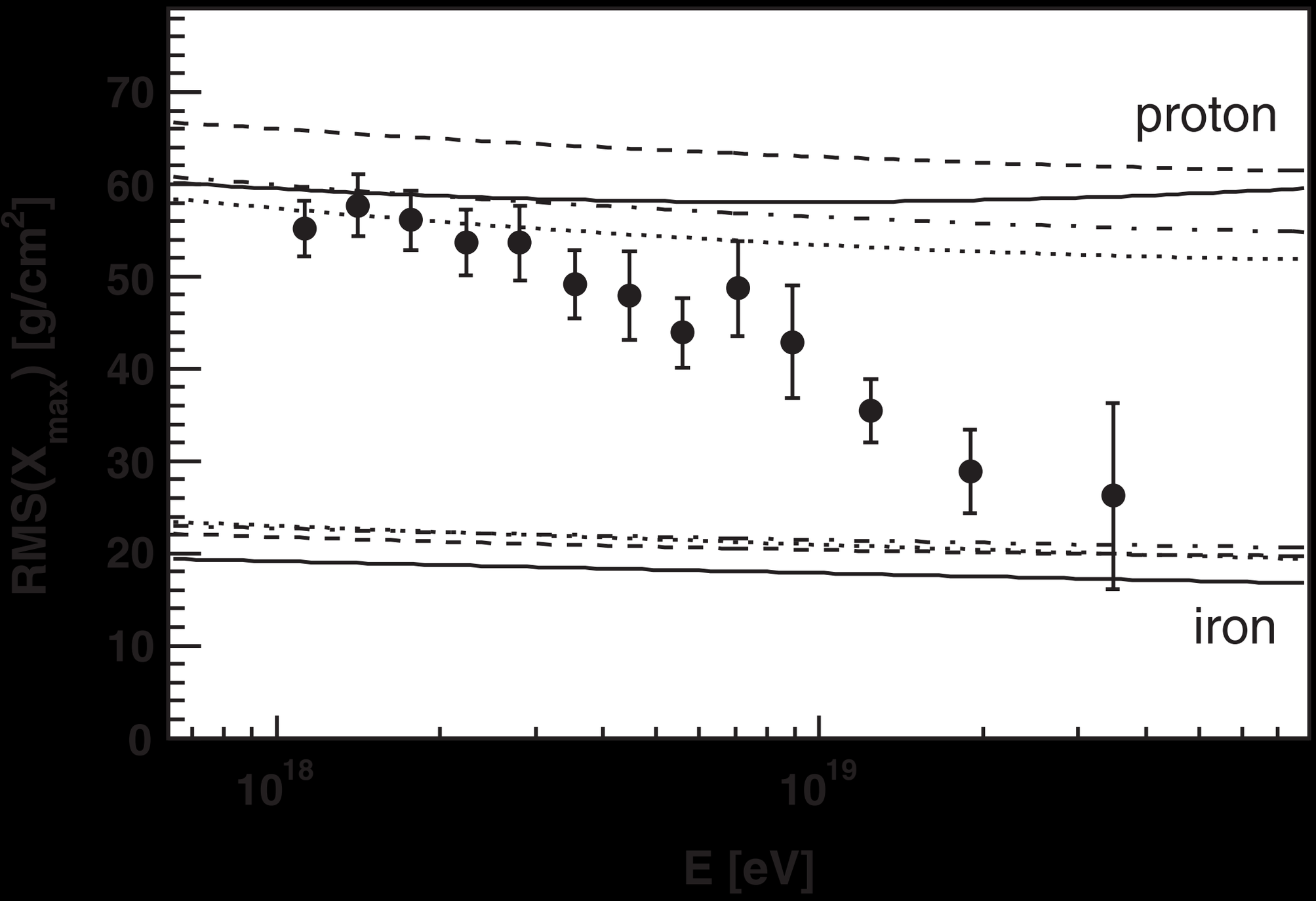


INCREASE OF THE AVERAGE MASS WITH ENERGY

Composition: Xmax vs E – caveat: hadronic interaction models



Composition: RMS(Xmax) vs E



More evidence of the increase of the average mass with energy

Angular distributions

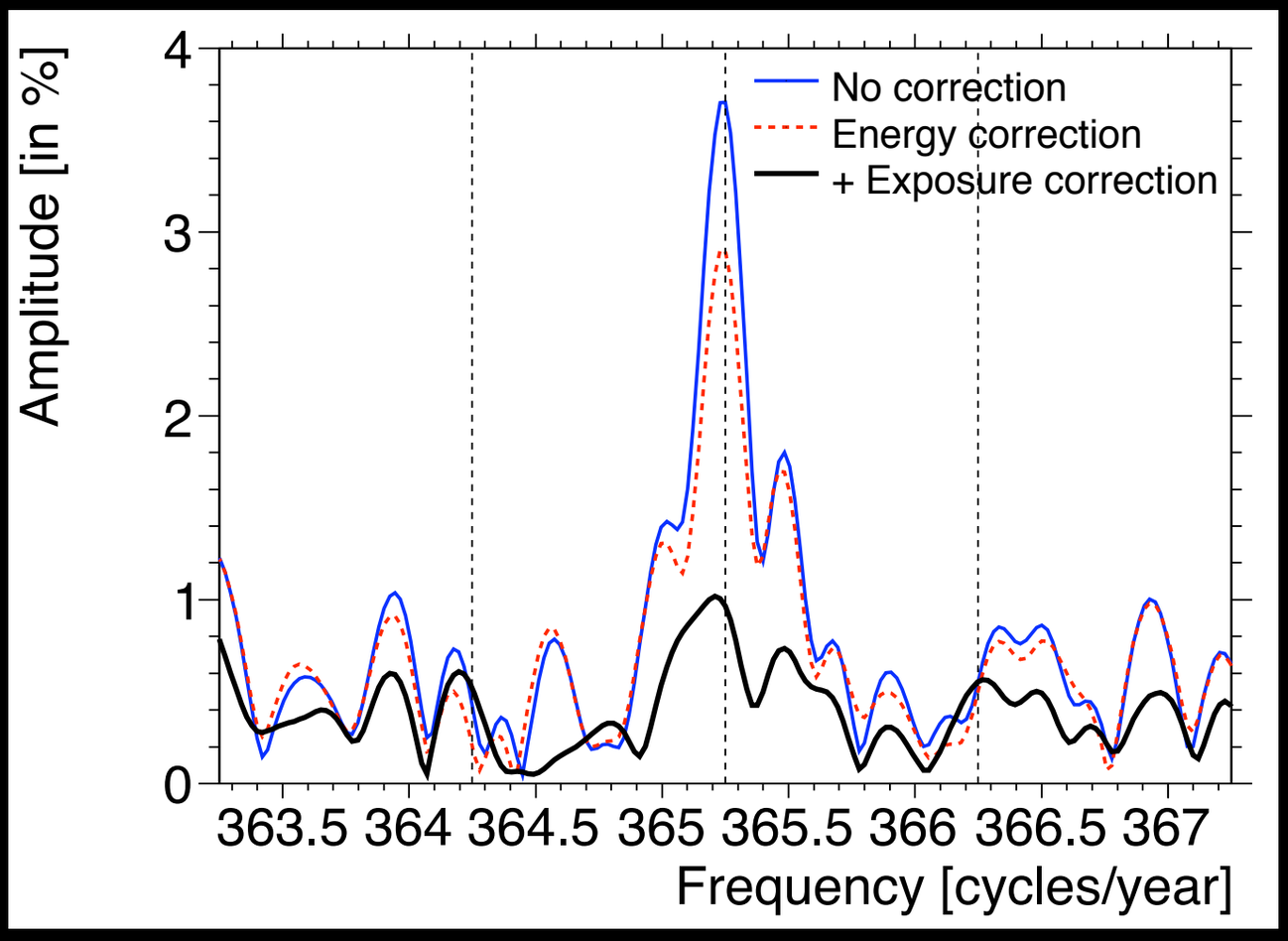
Reference paper:
The Pierre Auger Coll.,
Astropart. Phys. 34 (2011) 627-639

Large scale anisotropies : Search for first harmonic modulations

Challenge: estimation of the exposure with high accuracy

1- Monitoring of the number of elementar cells => geometrical exposure calculation in each direction

2- Shower size corrections as a function of atmospheric pressure and density

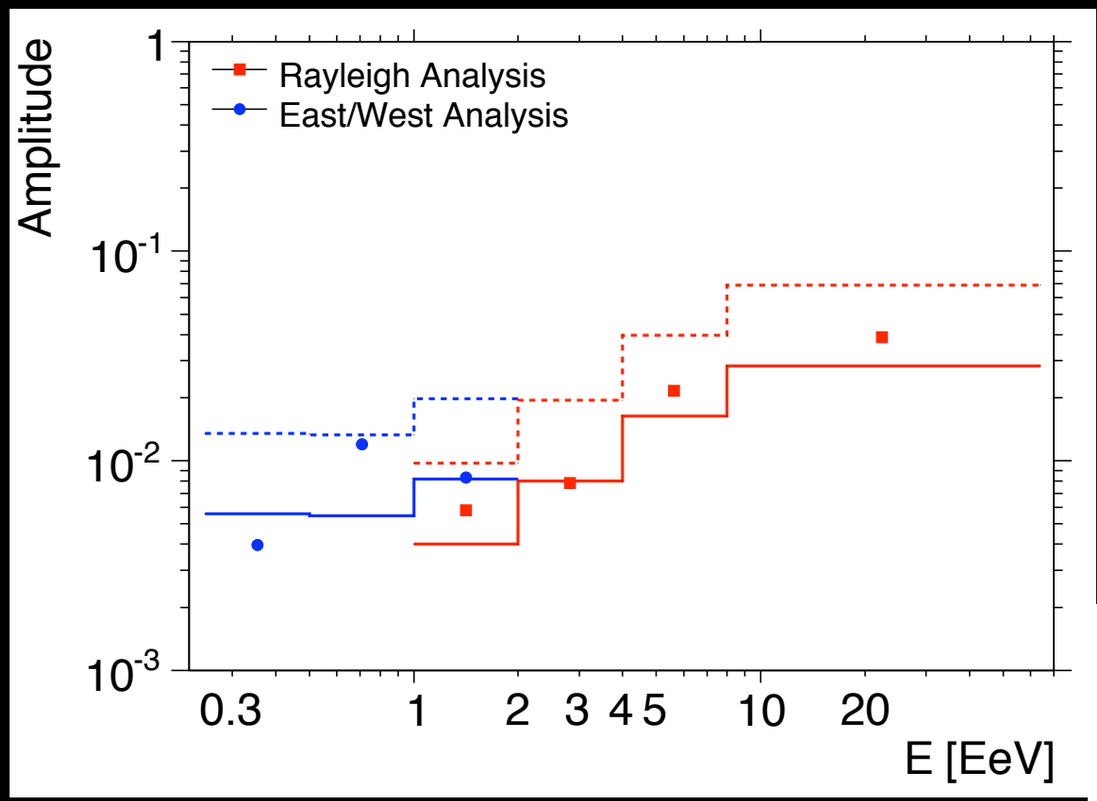


2 possible sources of spurious modulations at the sidereal frequency:

1- Pollution by the solar frequency (=> canceled by the 6-yrs exposure time)

2- Sideband mechanism due to any annual variation of the daily modulation

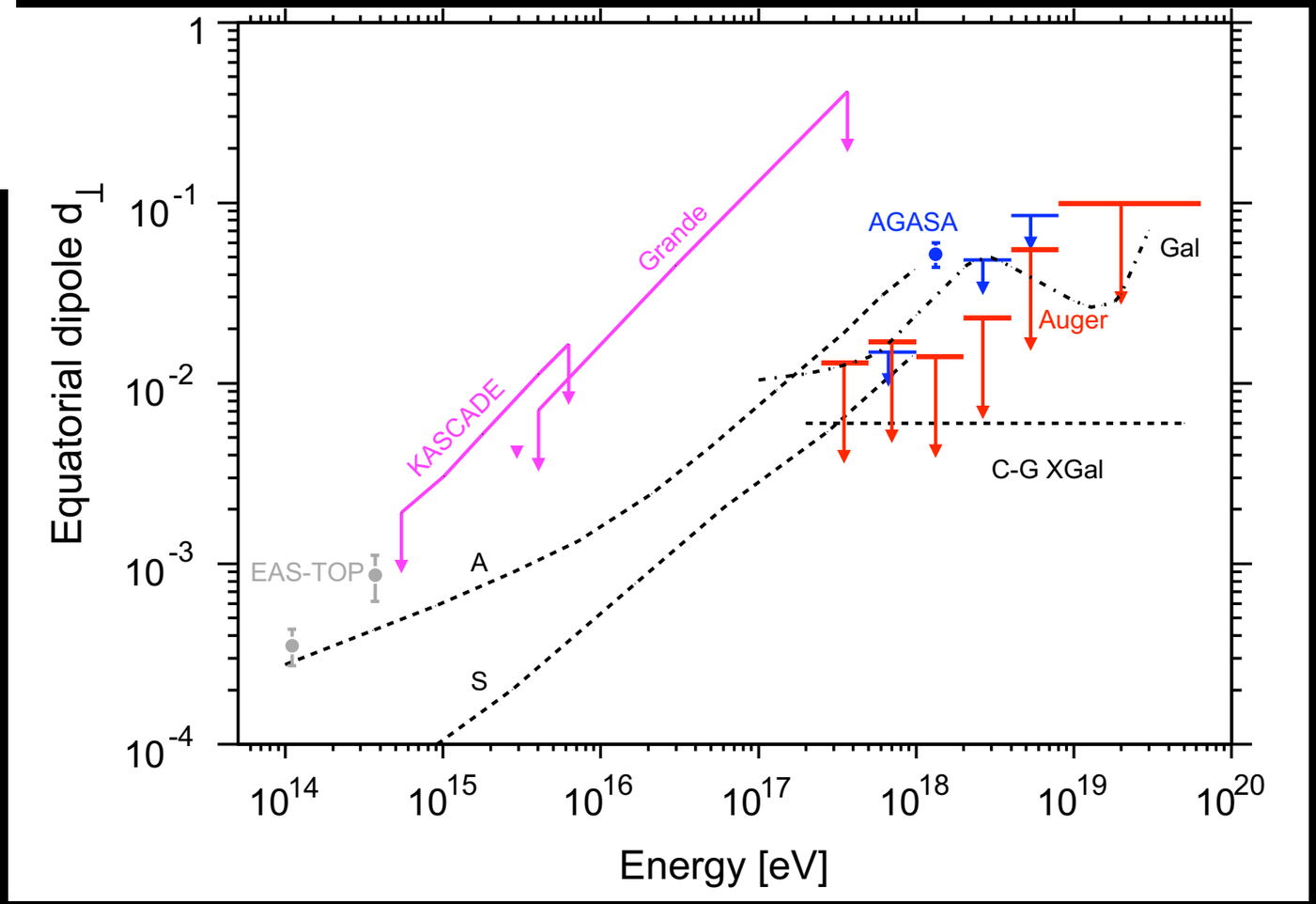
Search for first harmonic modulations



NO SIGNIFICANT AMPLITUDES

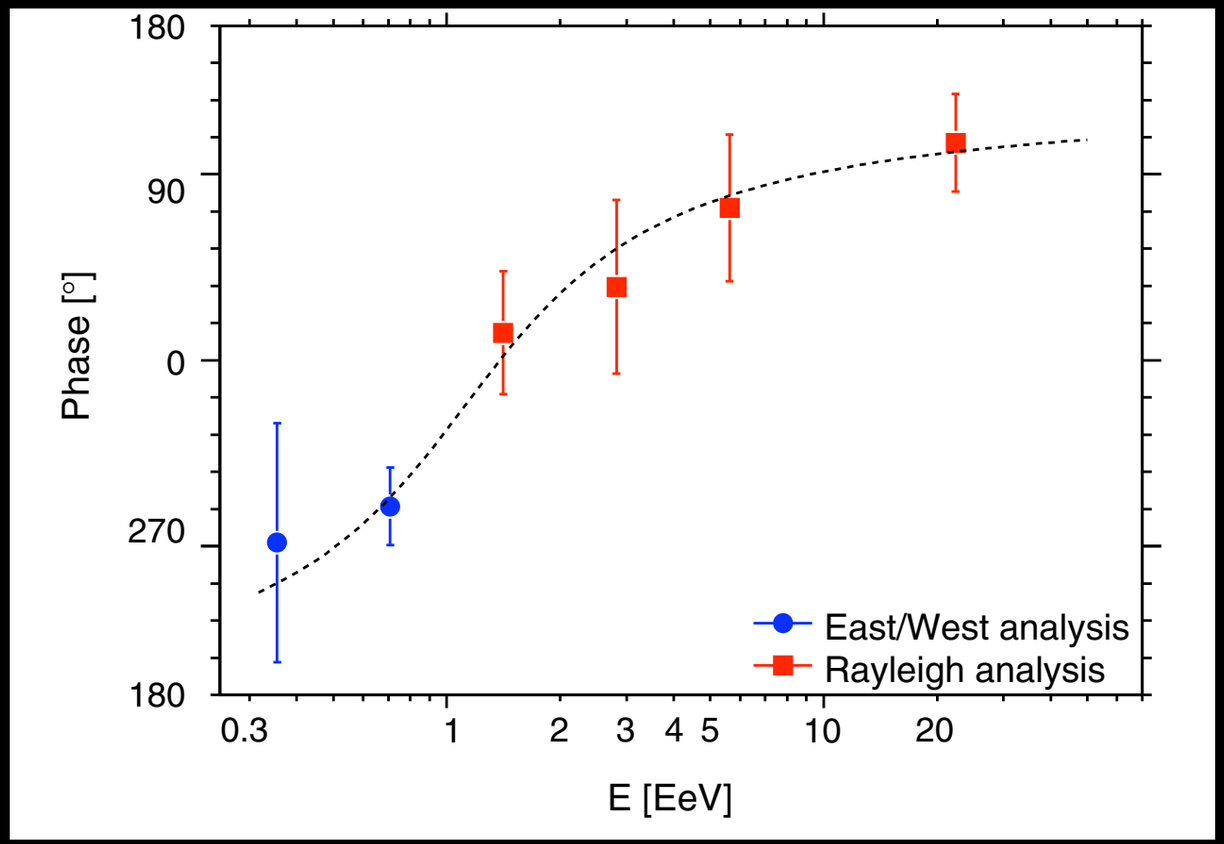
=>

UPPER LIMITS

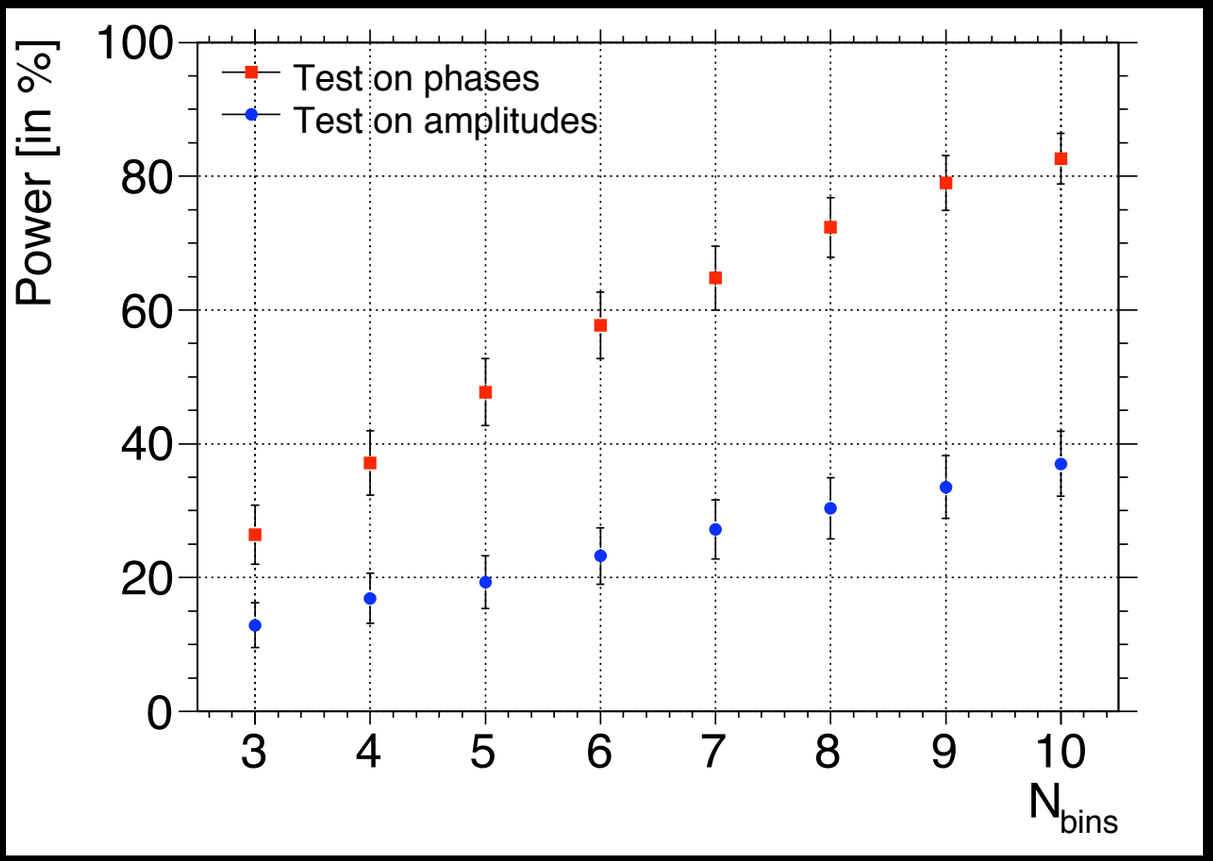


FUTURE WORK WILL PROFIT FROM THE LOWER ENERGY THRESHOLD THANKS TO THE INFILLED ARRAY

What about the phases ?



Not random... Suggestive of a smooth transition around 1 EeV
Posterior significance: ~0.002



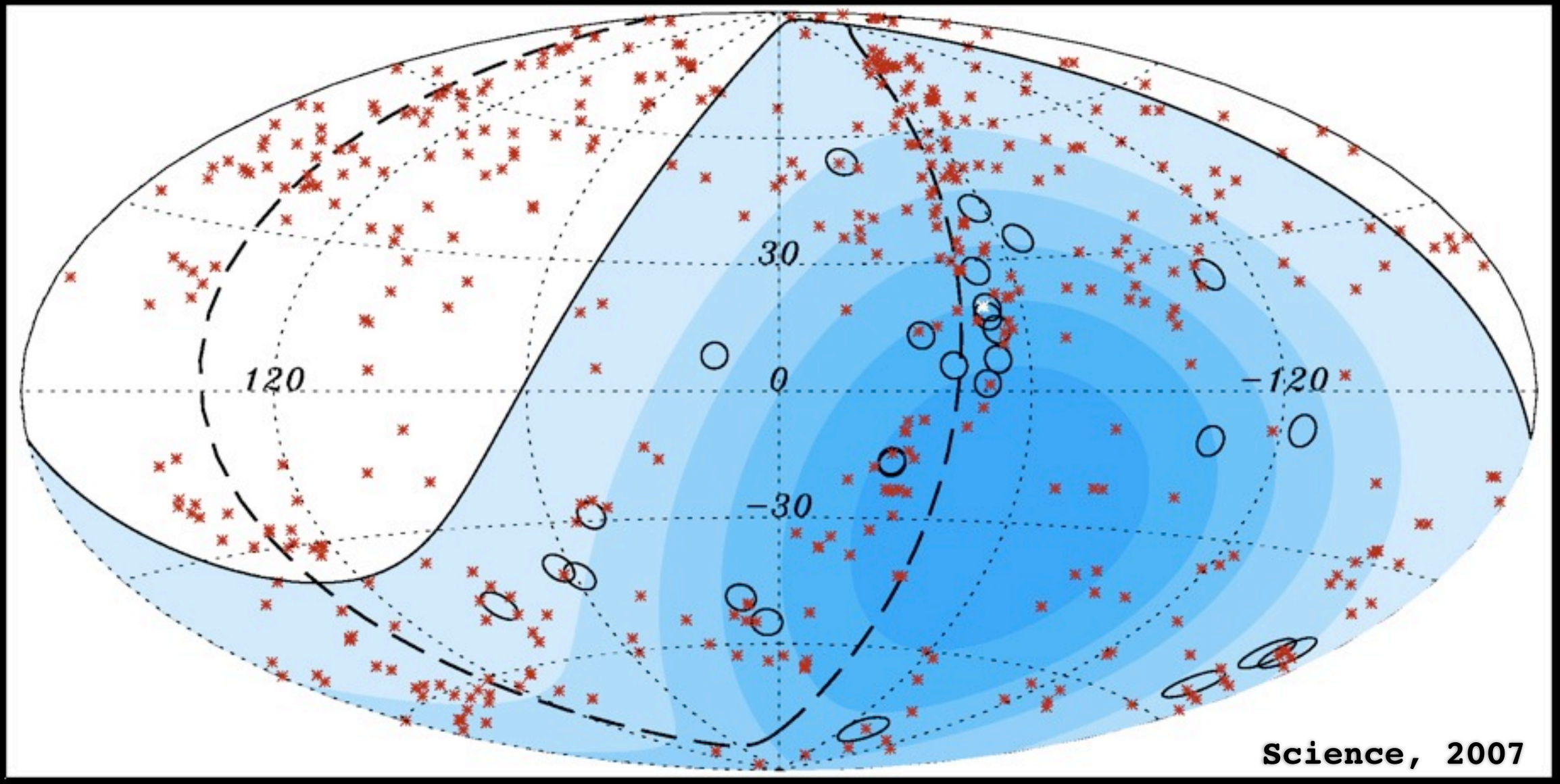
Phase is ~2.5 more sensitive than amplitude to a genuine signal diluted within the background noise

Future work will profit from the lower energy threshold thanks to the infilled array

Angular distributions at UHE

Reference papers:
The Pierre Auger Coll.,
Science 318 938 (2007),
Astropart. Phys. 29 (2008) 188-204,
Astropart. Phys. 34 (2010) 314-326

Angular distributions at UHE



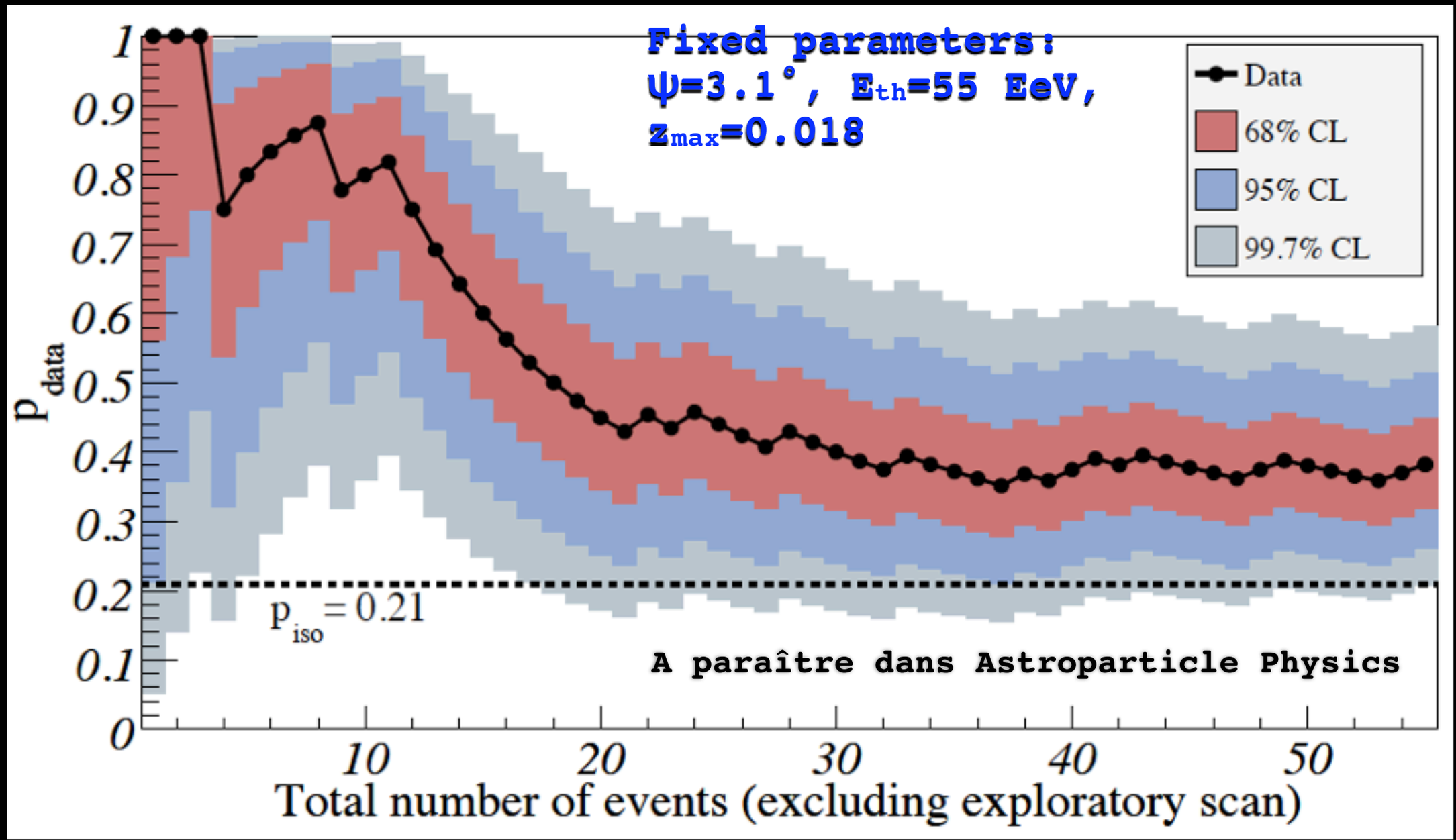
Auger: using 27 CR above 56 EeV collected through 31 August 2007 -> correlation with the positions of nearby quasars and AGNs (12TH VCV)

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 of doing it incorrectly: test passed (9/13 correlated events)

--> Isotropy rejected at 99% c.l.

Angular distributions at UHE



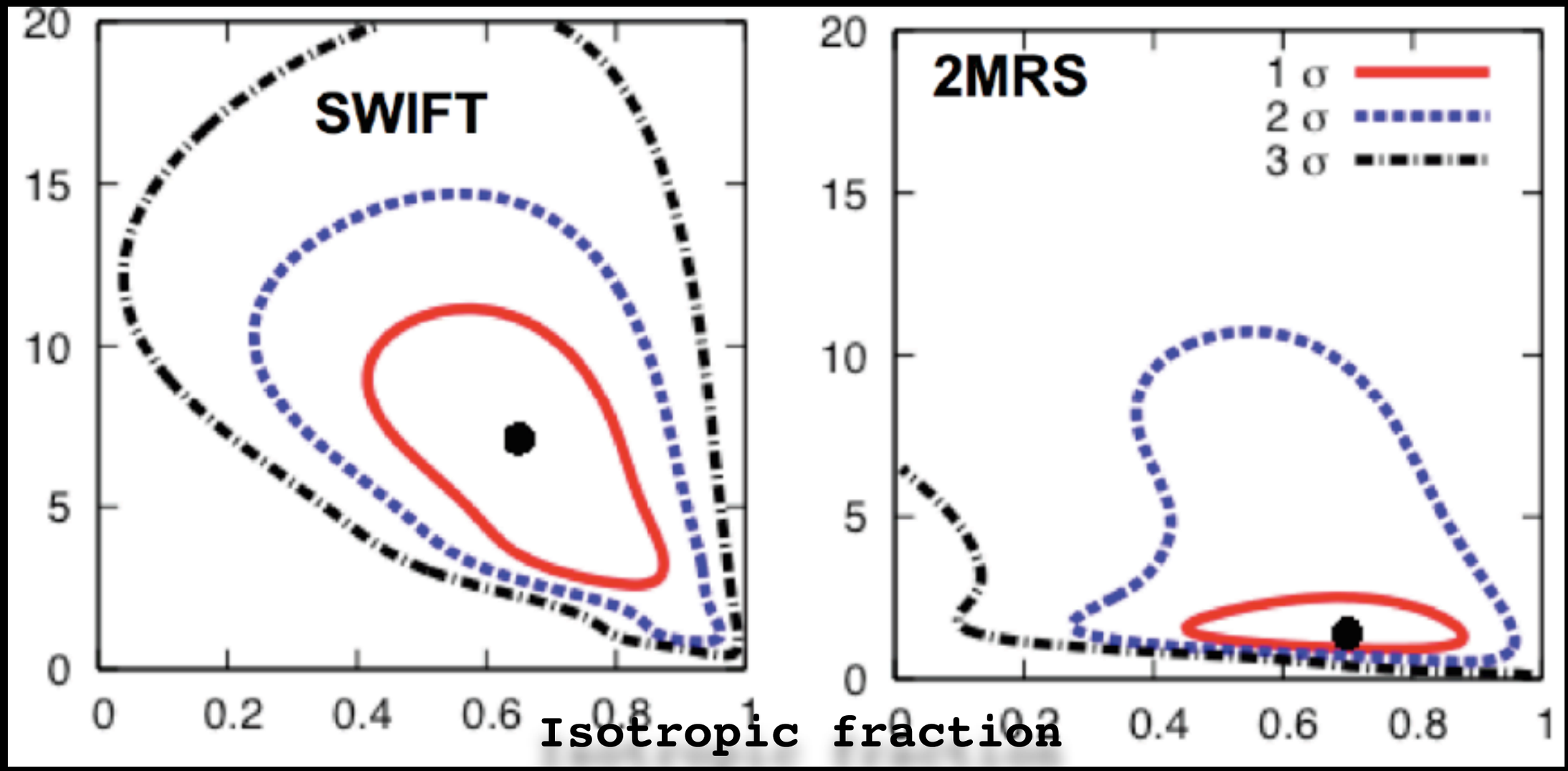
Since the «SCIENCE» publication

Correlation down: from (69±12)% to (38±7)%

(21% of random correlation from isotropic expectations)

Corresponding probability P=0.003

Angular distributions at UHE

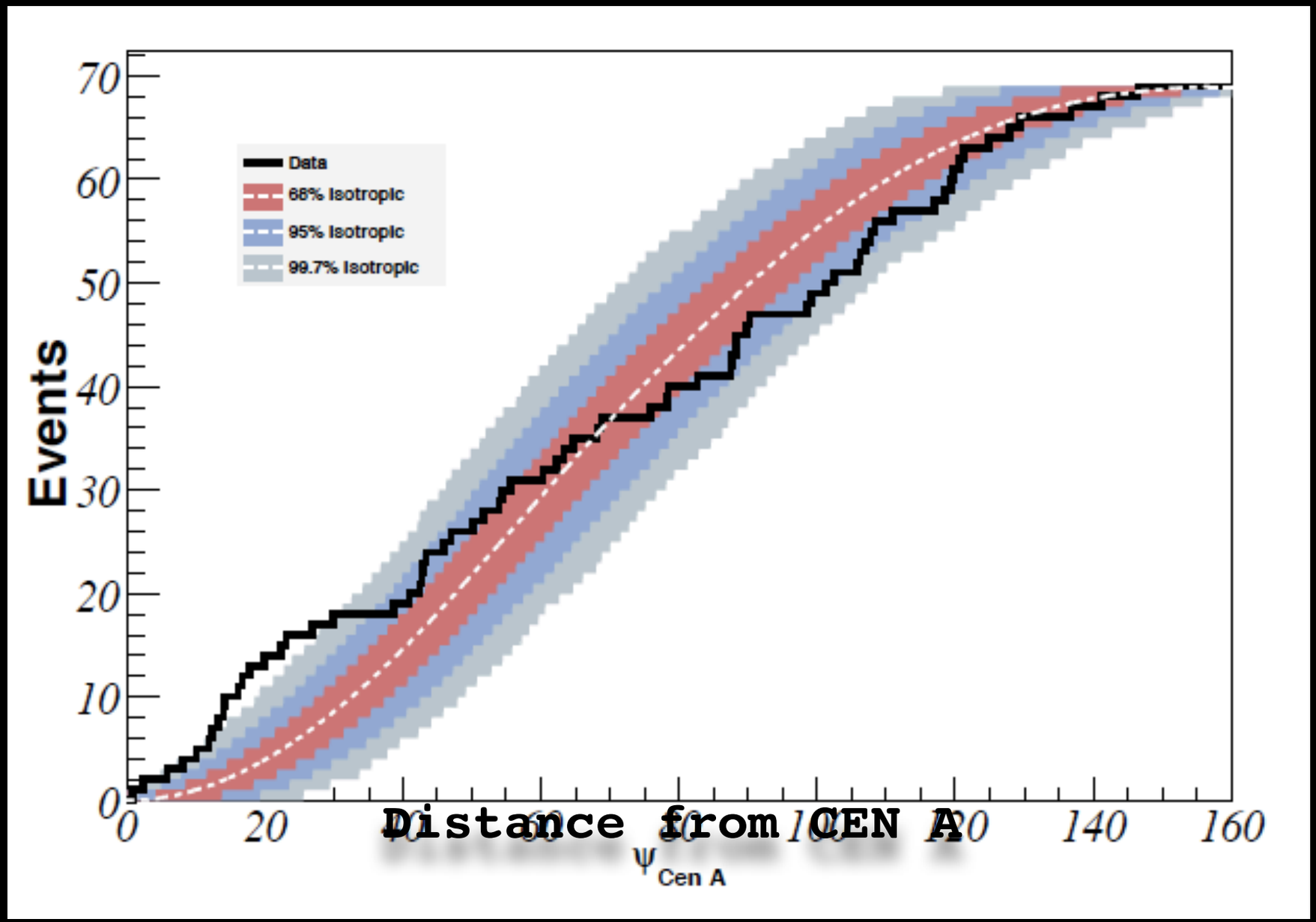


Search for correlations with other (more complete) catalogs of extra-galactic objects

Fitting the 69 events on map densities built from source models based on 2MRS and Swift-BAT catalogs and including the GZK effect
2 free parameters : deflection angle (magnetic field) and «isotropic fraction» (incompleteness, heavier elements, ...)

2MRS -> (1.5°, 64%); Swift -> (7.8°, 56%)

Angular distributions at UHE

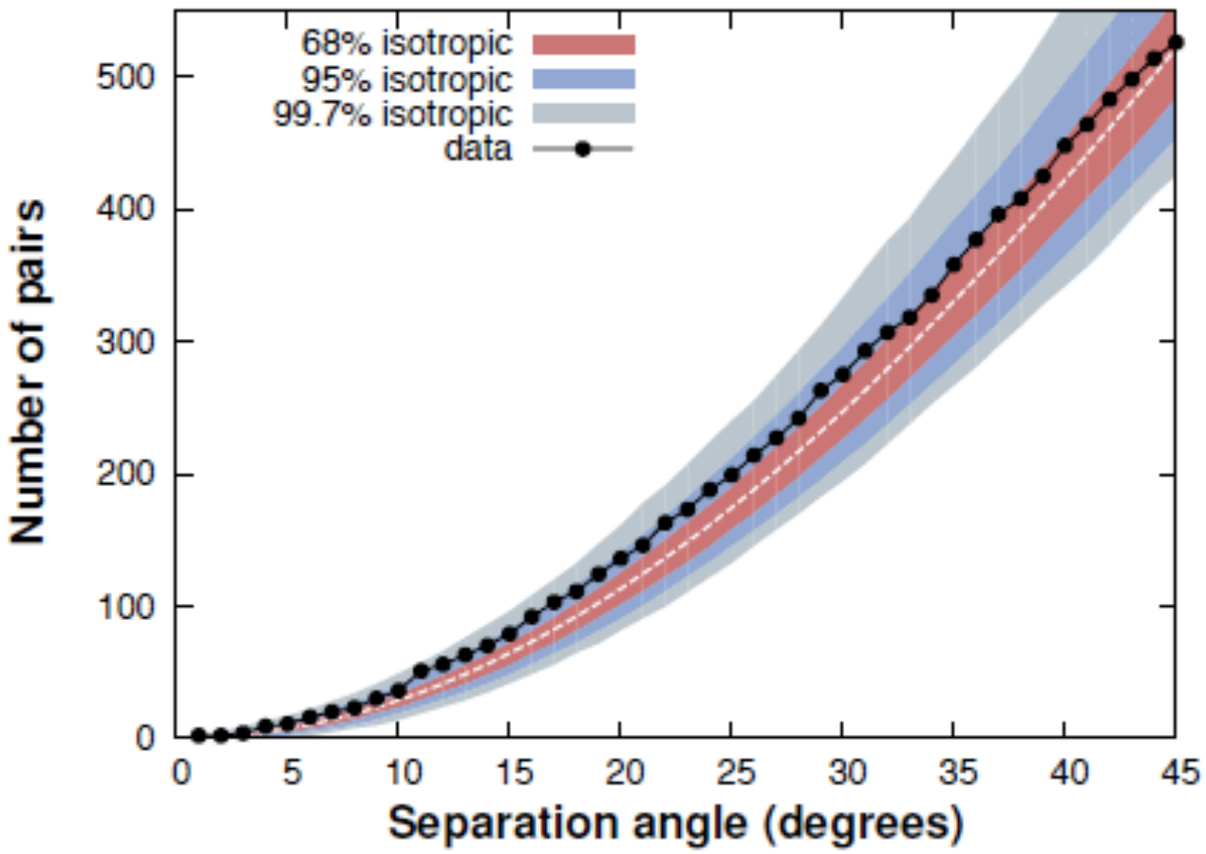


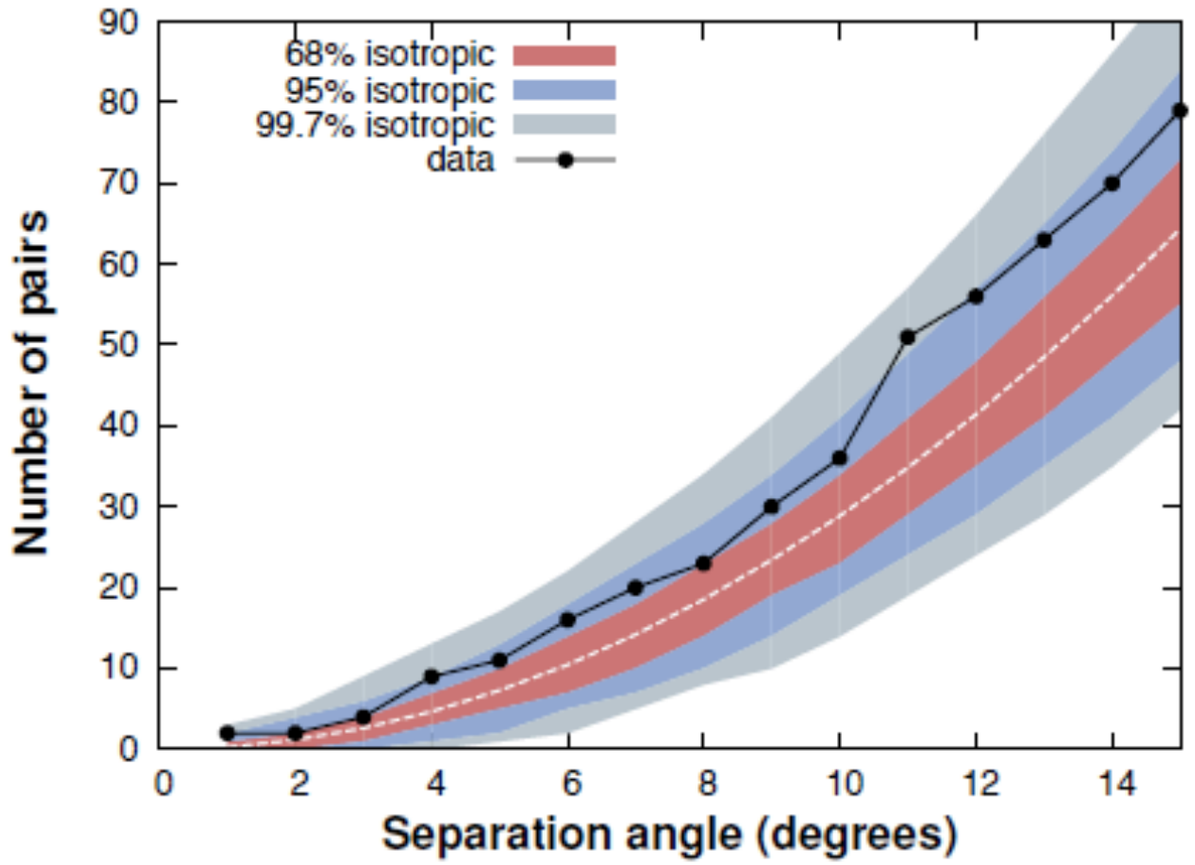
Auger: search for the largest excess (above 57 EeV):

12 events in a 13° cell (1.7 expected): It lies at 4° from CEN A

Centering on CEN A: largest excess within 18° (13 events vs 3.2 expected)

Angular distributions at UHE





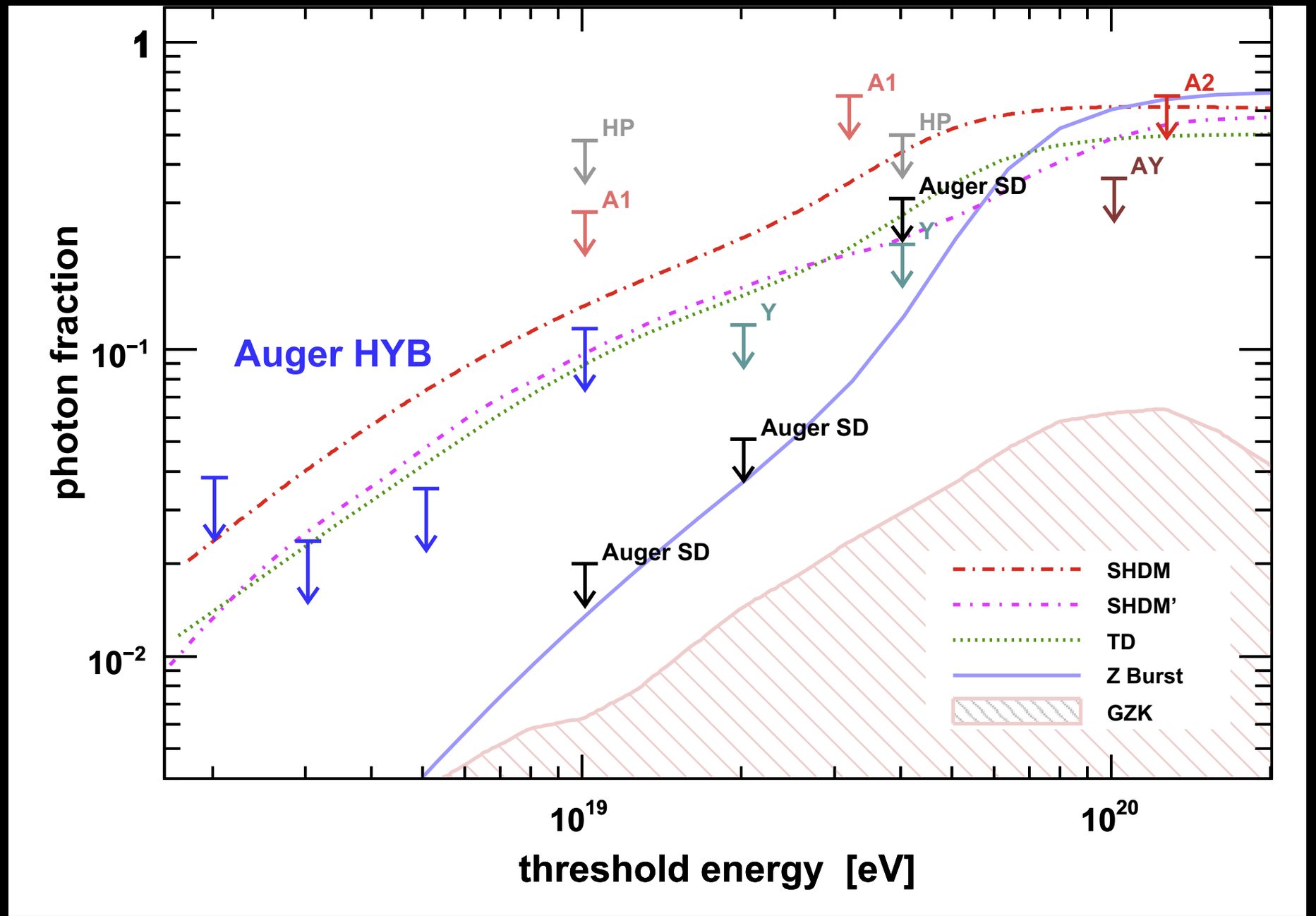
Search for auto-correlation :

NO SIGNIFICANT CLUSTERING

Photons/Neutrinos ?

Reference papers:
The Pierre Auger Coll.,
Astropart. Phys. 27 (2007) 155-168,
Astropart. Phys. 29 (2008) 243-256,
PRL 100 211101 (2008),
PRD 79 102001 (2009),
Astropart. Phys. 31 (2009) 399-406

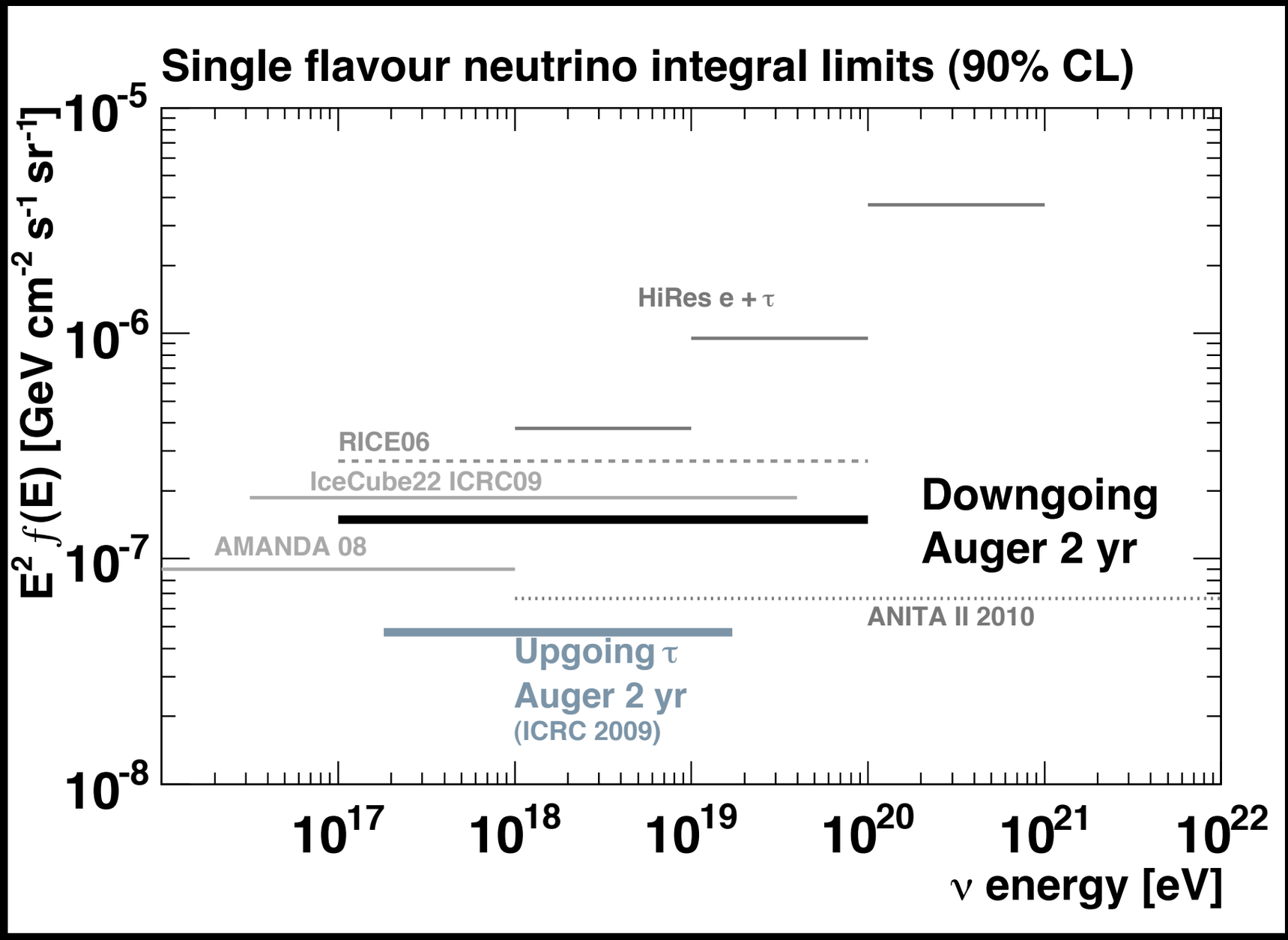
Photon limits



BOTTOM IS UP

TOP IS DOWN

Neutrino limits



BOTTOM IS UP

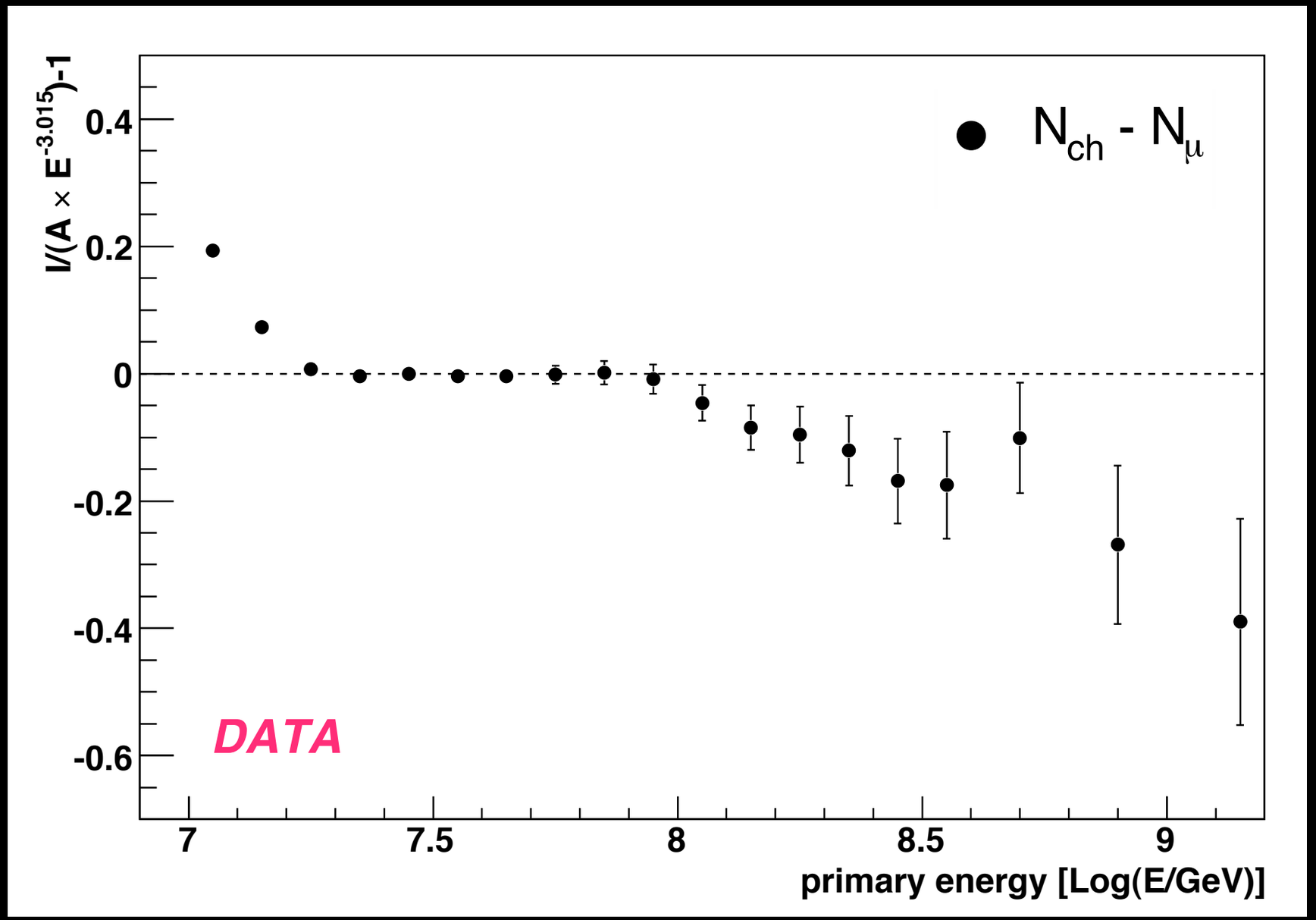
TOP IS DOWN

Outlook

- **Observation of a sharp ankle and of the flux suppression at UHE**
  - Sharpness of the ankle unnatural with a gal/Xgal transition
  - Spectral features between 0.1 and 1 EeV ?
  - Origin of the suppression still uncertain
- **Mass composition**
  - Rather unexpected lightening of the composition at EeV energies (iron knee at 0.1 EeV)
  - Dedicated measurements needed to understand the end (?) of the galactic component
  - Increase of the average mass above ~1.5 EeV (but quid of the hadronic interaction models ?)
- **Angular distributions**
  - Correlations at UHE, but large isotropic component (mixing of masses ?, ...)
  - Suggestion of a dipolar modulation over a large energy range through the phase alignment
  - If Xgal, very low anisotropies are expected between ~3 and ~50 EeV. Gal.

UHECRs understanding requires better knowledge of any spectral features, mass composition and angular distributions of CRs between ~0.01 and 1 EeV

Spectre en énergie, maintenant



KASCADE-Grande, ECRS 2010

«SECOND GENOU»: GENOU DE FER VERS 0.1 EEV

«MÉNISQUE» À ~10 PEV !