High Energy Cosmic Rays
at the Pierre Auger Observatory
after 10 years : results and future

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The Pierre Auger Collaboration

460 collaborators
110 institutions from 17 countries

Argentina – Australia – Brazil – Colombia – Czech Republic – France – Germany – Italy – Mexico – Netherlands – Poland – Portugal – Romania – Slovenia – Spain – United Kingdom – United States

Outline

The Pierre Auger Observatory

- Science case and characteristics

Results, towards the understanding of UHECR's

- Spectrum,
- Anisotropy
- Mass composition
- Hadronic models

Summary and future plans

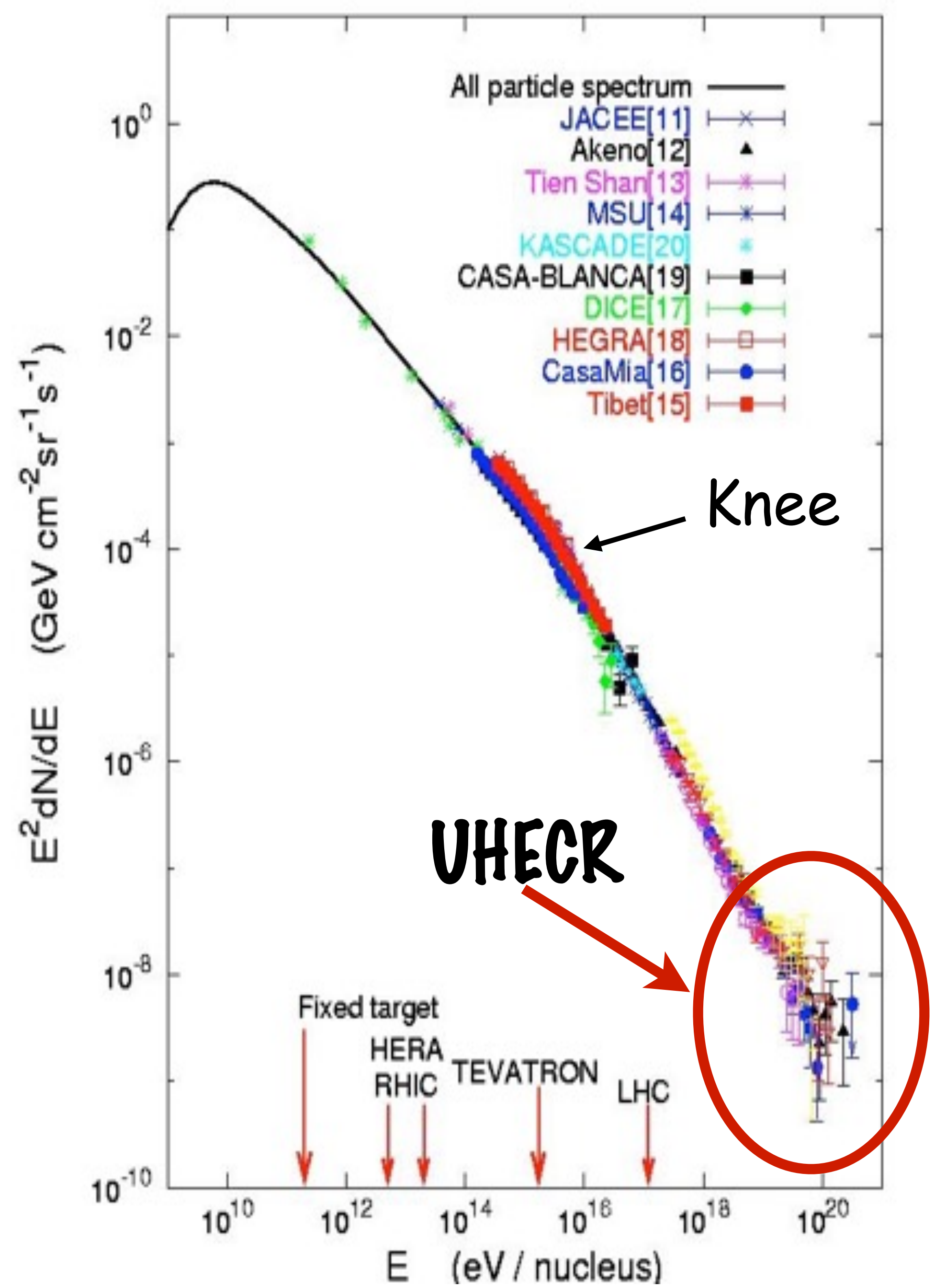
- Auger Prime

Original AUGER Science Case

1. A precise reconstruction of the **energy spectrum**
   Is the GZK cutoff observed or challenged?

2. The **identification of primaries**, even if only **statistical**:
   proton, nuclei , or more exotic particles (gamma, neutrinos ?)
   - Based on the air shower properties,
   - Could give constrain to existing hadronic models

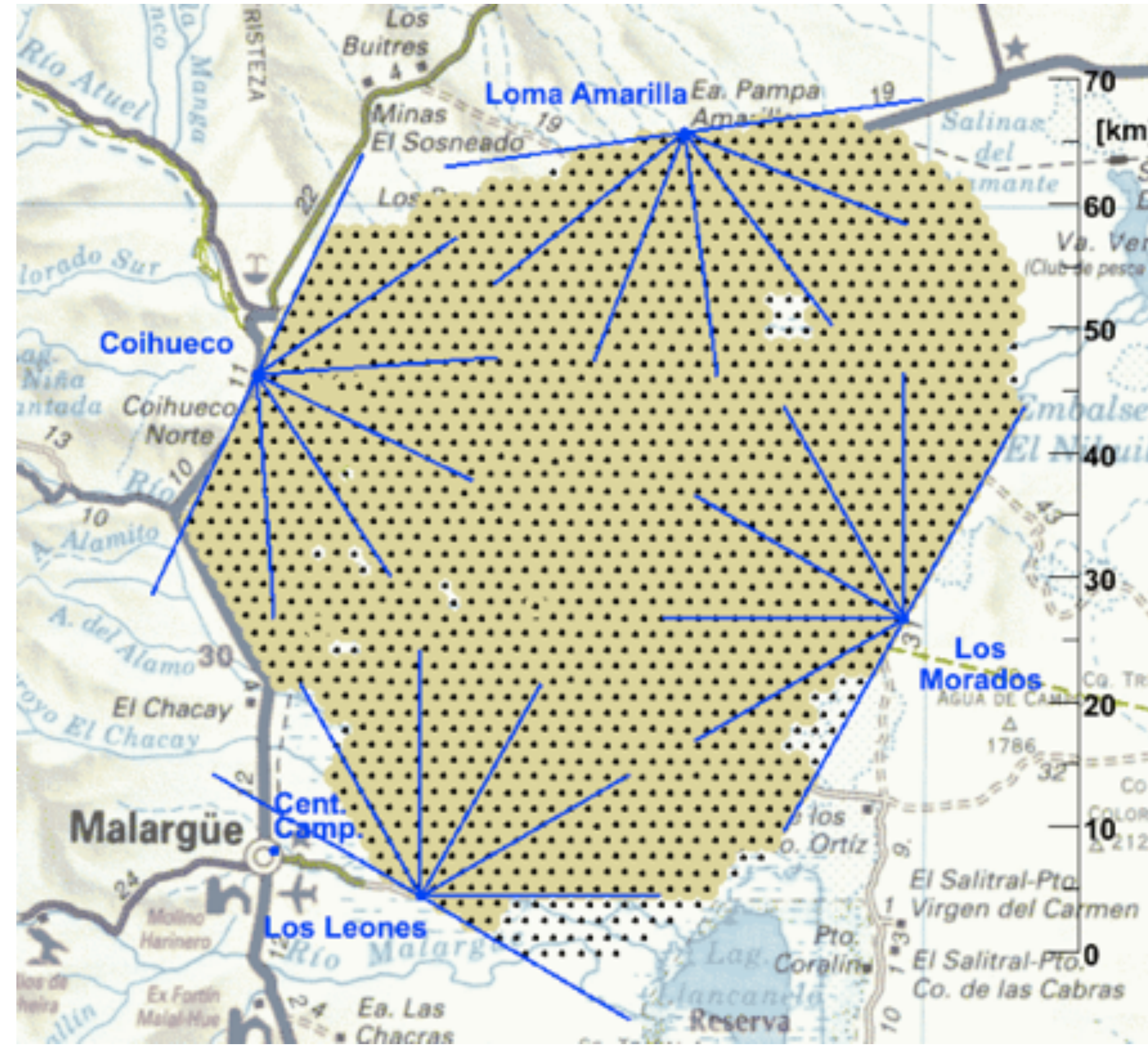
3. A systematic study of arrival directions
   Search for indication of anisotropies
   and existence of point sources



The Pierre Auger Observatory in Argentina

Surface detectors
1680 Cherenkov stations
1.5 Km spaced on a hexagonal grid
Can detect shower up to 90°
100% duty cycle

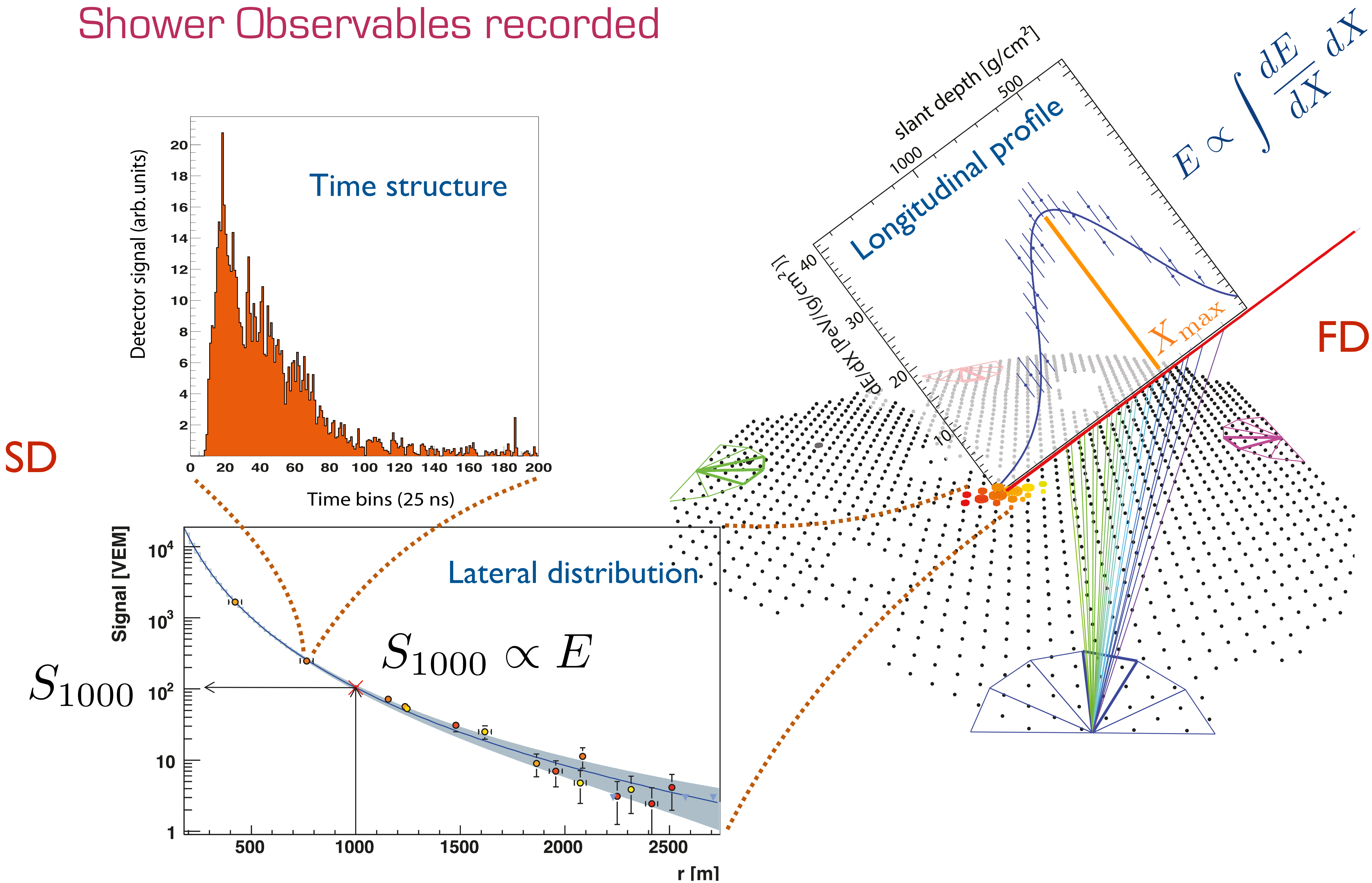
Fluorescence detectors
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30
~15 % duty cycle



Completed in 2008
Progressive data taking starting in 2004

Aiming at understanding the origin of Ultra High Energy Cosmic Rays, the PAO associates the widest detection surface (3000 km^2) together with the highest precision ever achieved

Shower Observables recorded

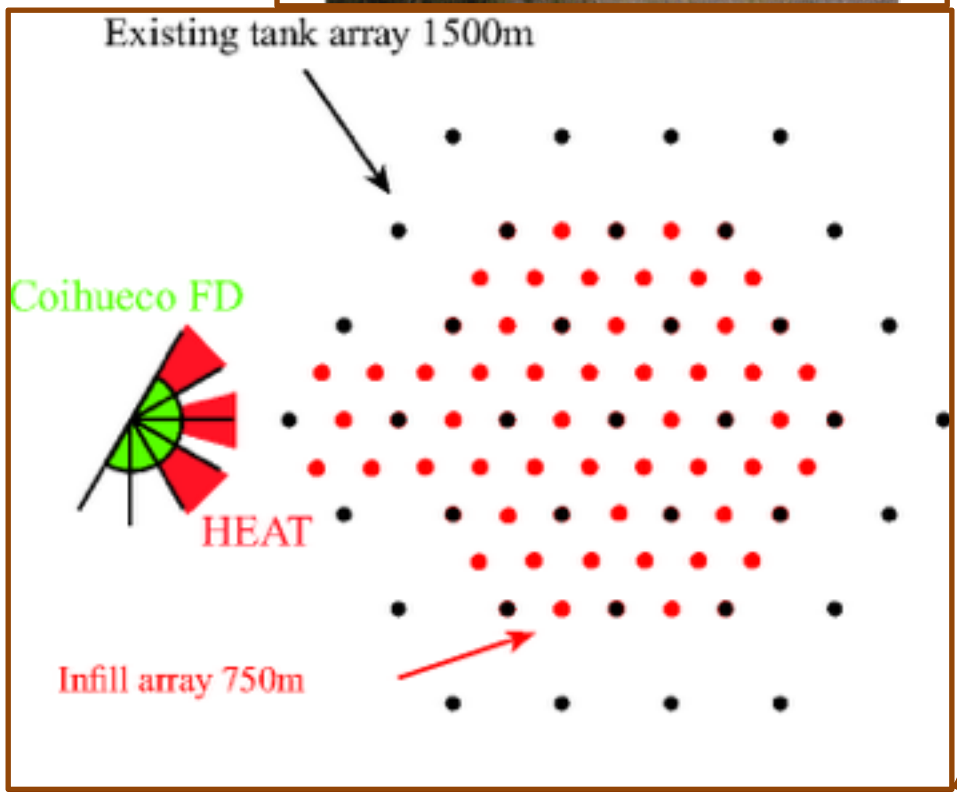


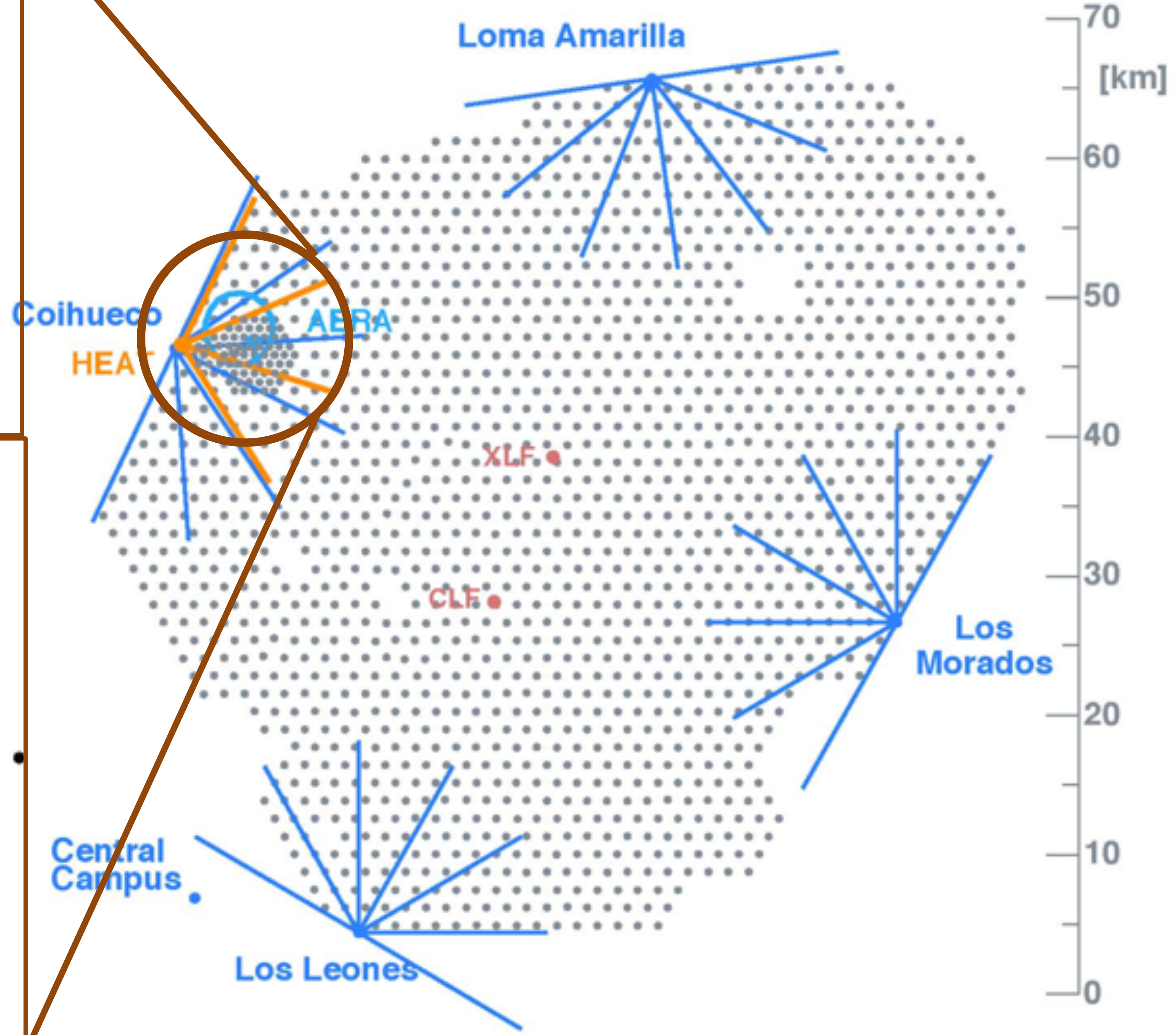
Present status of the Pierre Auger Observatory

LOW ENERGY EXTENSION (10^{17} - 3 10^{18} eV)

1500 m ARRAY

HEAT



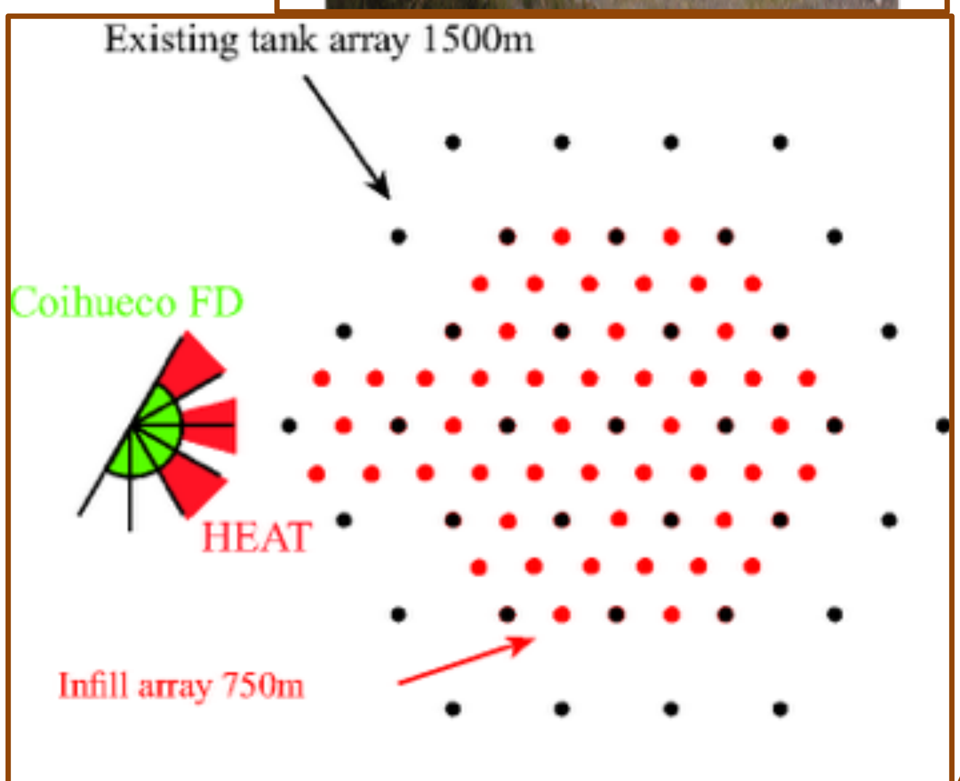


750 m ARRAY

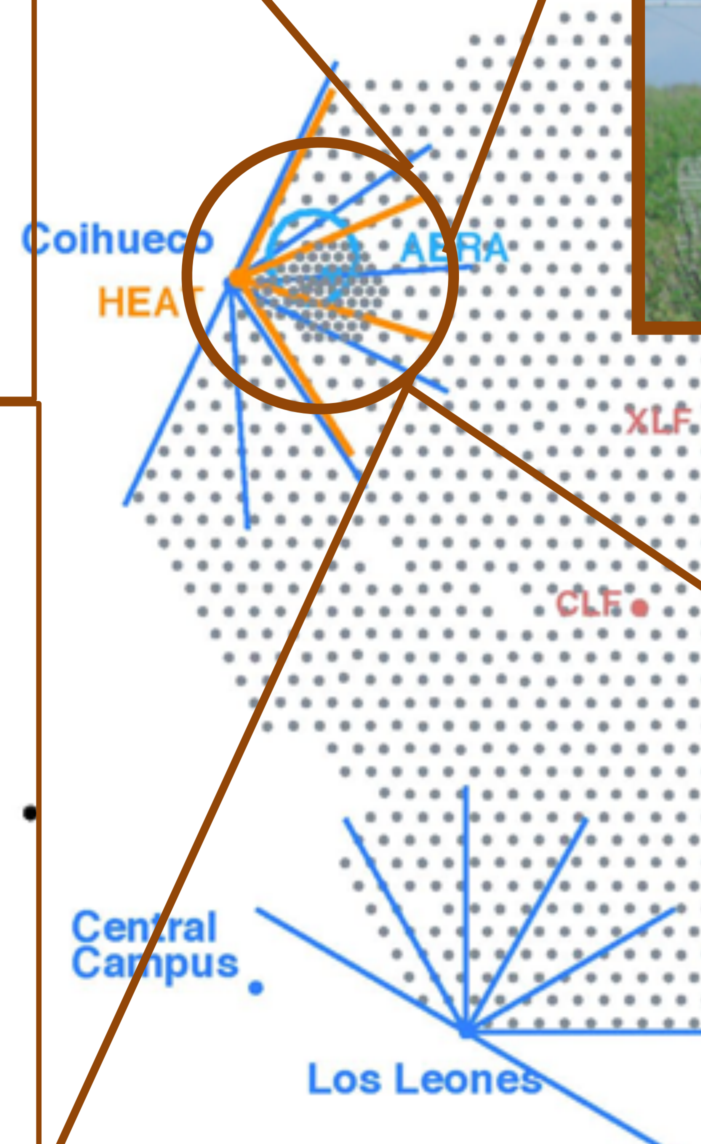
Present status of the Pierre Auger Observatory

LOW ENERGY EXTENSION (10^{17} - 3 10^{18} eV)

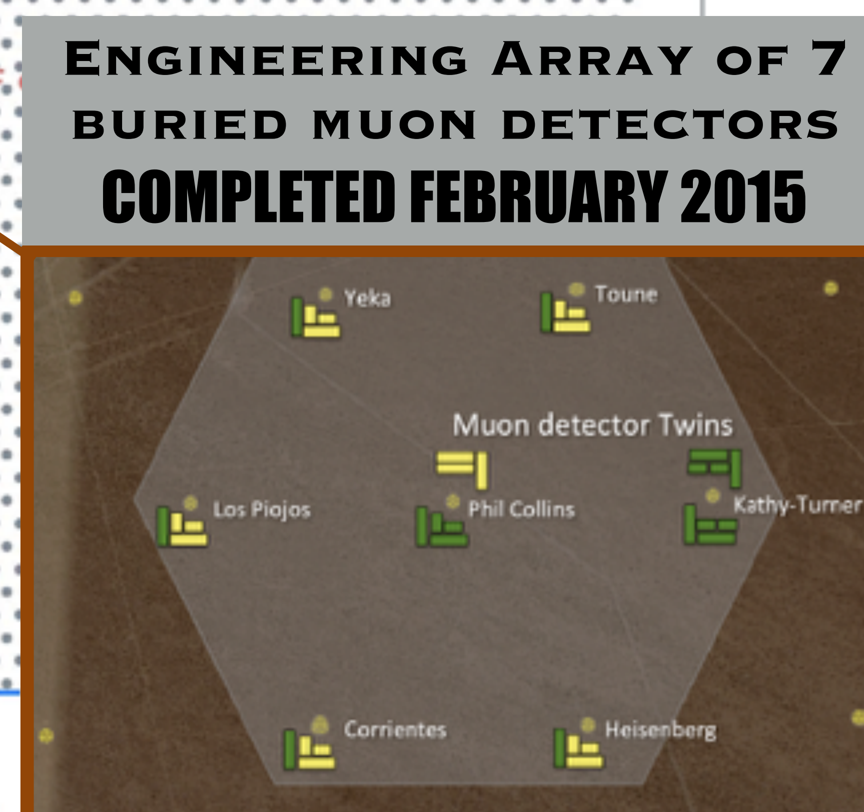
HEAT



750 m ARRAY



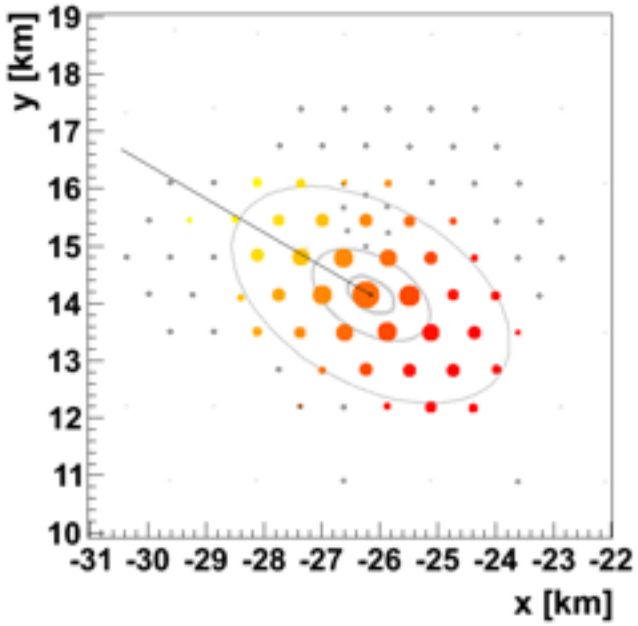
AERA



AMIGA MUON COUNTERS

The different AUGER data sets

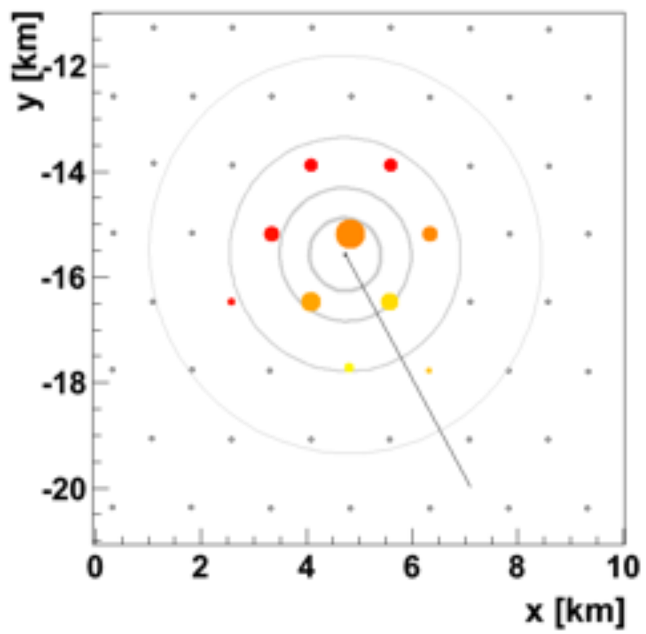
SD-750 m (θ<55°)



fully efficient: E > 3 x 10^{17} eV

energy estimator: S35

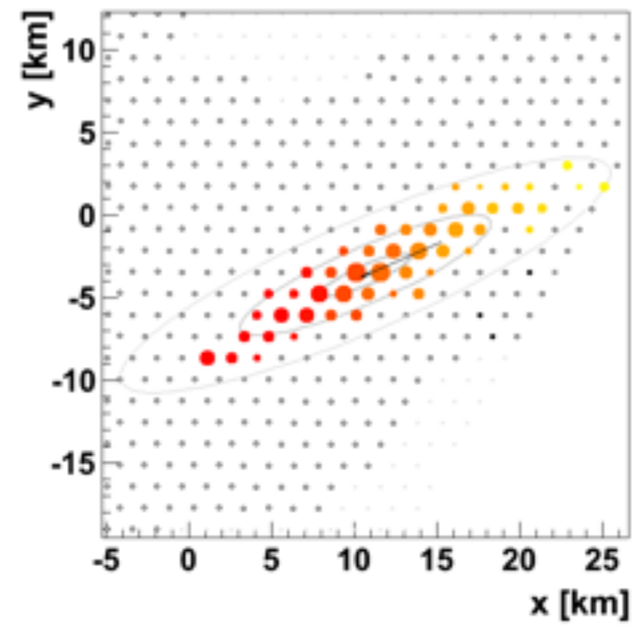
SD-1500 m (θ<60°)



fully efficient: E > 3 x 10^{18} eV

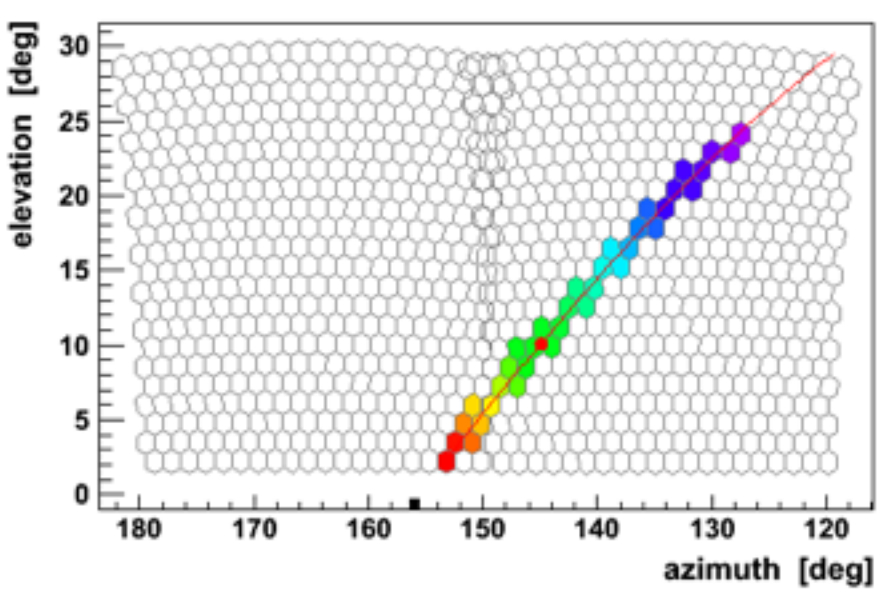
energy estimator: S_{38}

SD-1500 m (62°<θ<80°)



fully efficient: E > 4 x 10^{18} eV

energy estimator: N_{19}



HYBRID

FD + ≥ 1 SD 1500 station Fully efficient: E ≳ 10^{18} eV

HEAT + ≥ 1 SD-750 station Fully efficient E ≳ 10^{17}eV

Energy measurement: E_{FD}

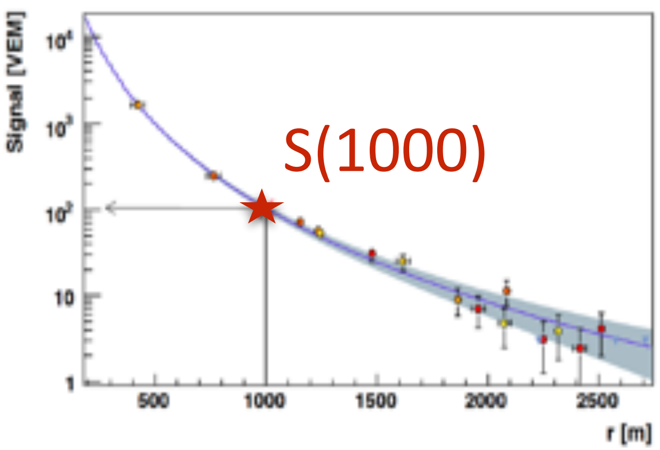
SPECTRUM

Energy Reconstruction of Auger Events

SD vertical ($\theta < 60°$)

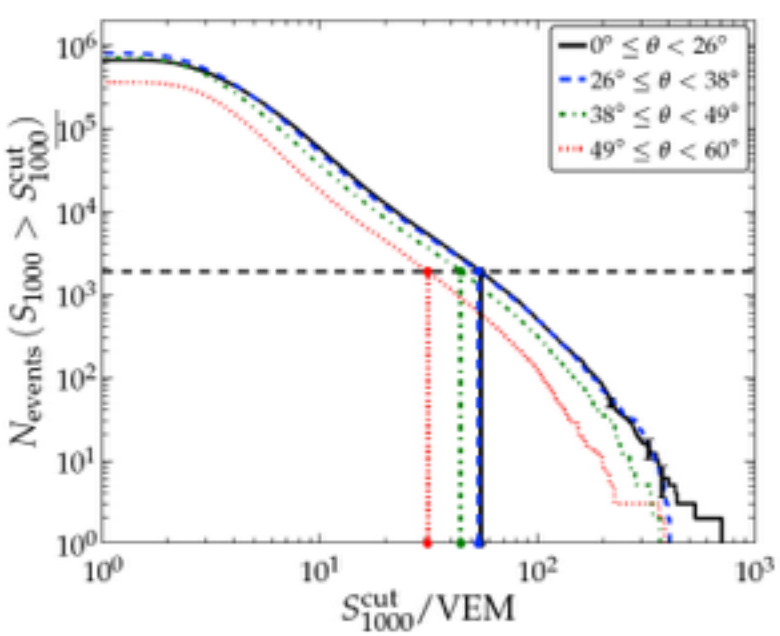
Energy estimator S(1000):

Signal at 1000 m from lateral profile



S(1000) is θ dependent due to attenuation in atmosphere

-> use of Constant Intensity Cut (CIC)



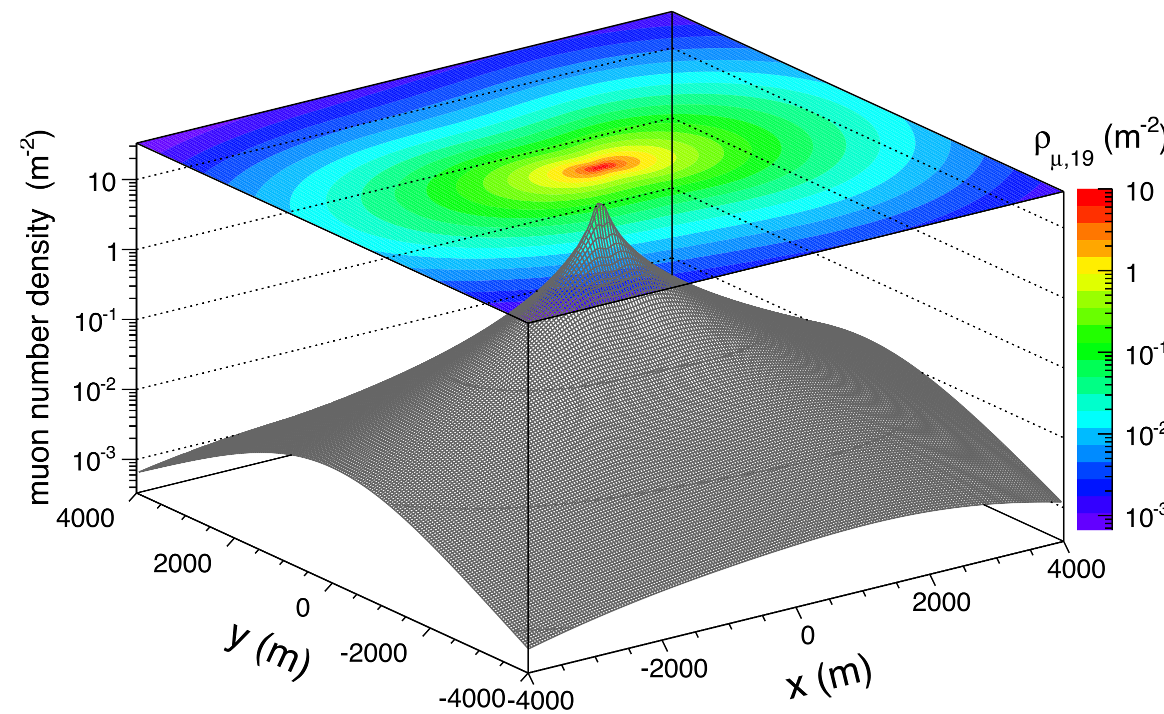
Conversion S(1000) -> S_{38}

In case of SD 750m array: S(450) S_{35}

SD horizontal al ($62 < \theta < 80°$)

Energy estimator : N_{19}

N_{19}: relative number of muons at ground w.r.t. the density of muons of the reference distribution:



$\rho_{\mu,19}$ reference profile from parameterization of muon density at ground (10^{19} eV p QGSJetII-03)

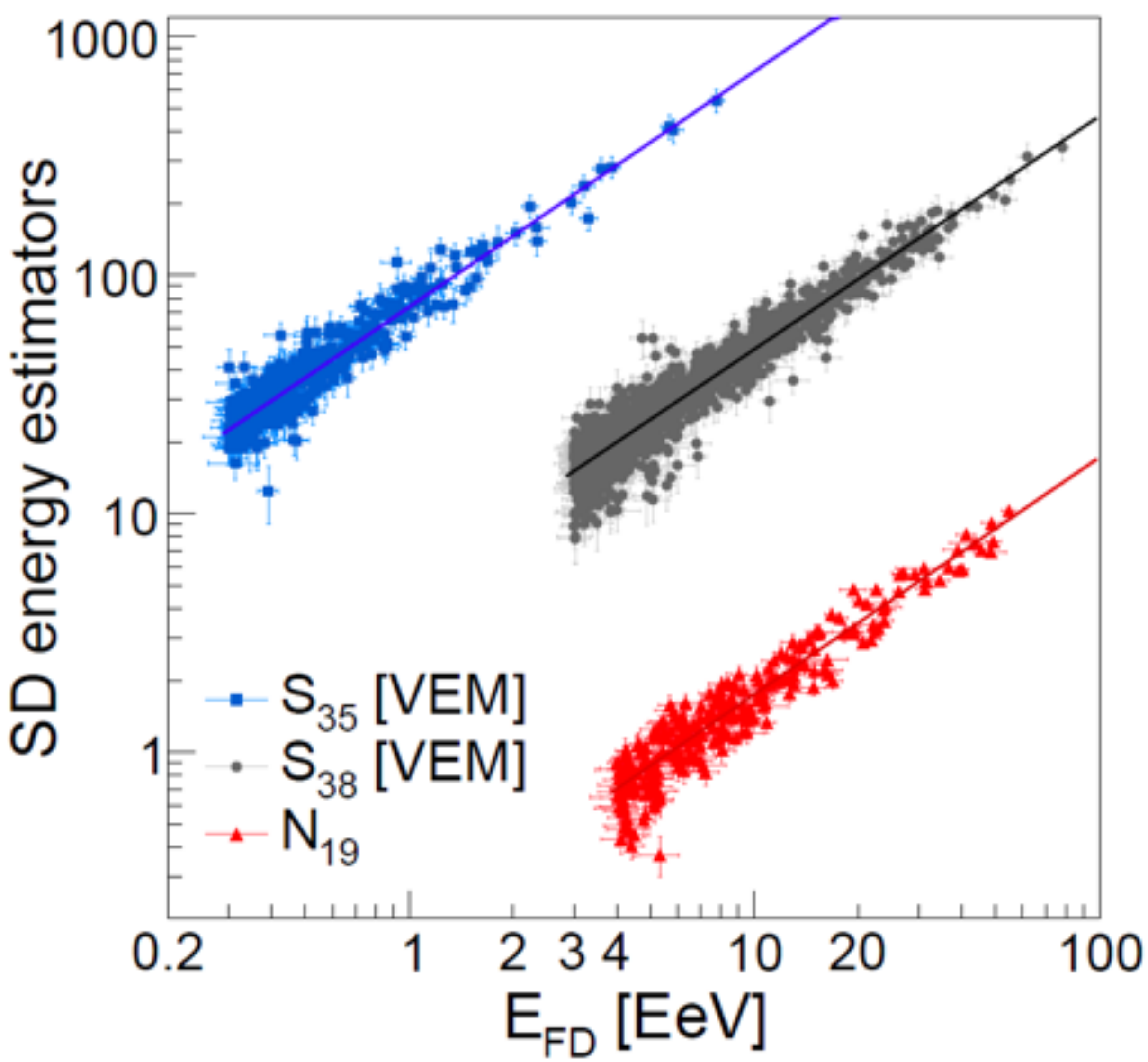
N_{19} is not θ dependent (already included in $\rho_{\mu,19}$)

Calibration of AUGER data sets

For each SD data , the energy estimator is calibrated with FD energy **with hybrid data set**

Cross correlation of the SD energy estimators (S) with the FD energy

$$E_{FD} = A * S^B$$



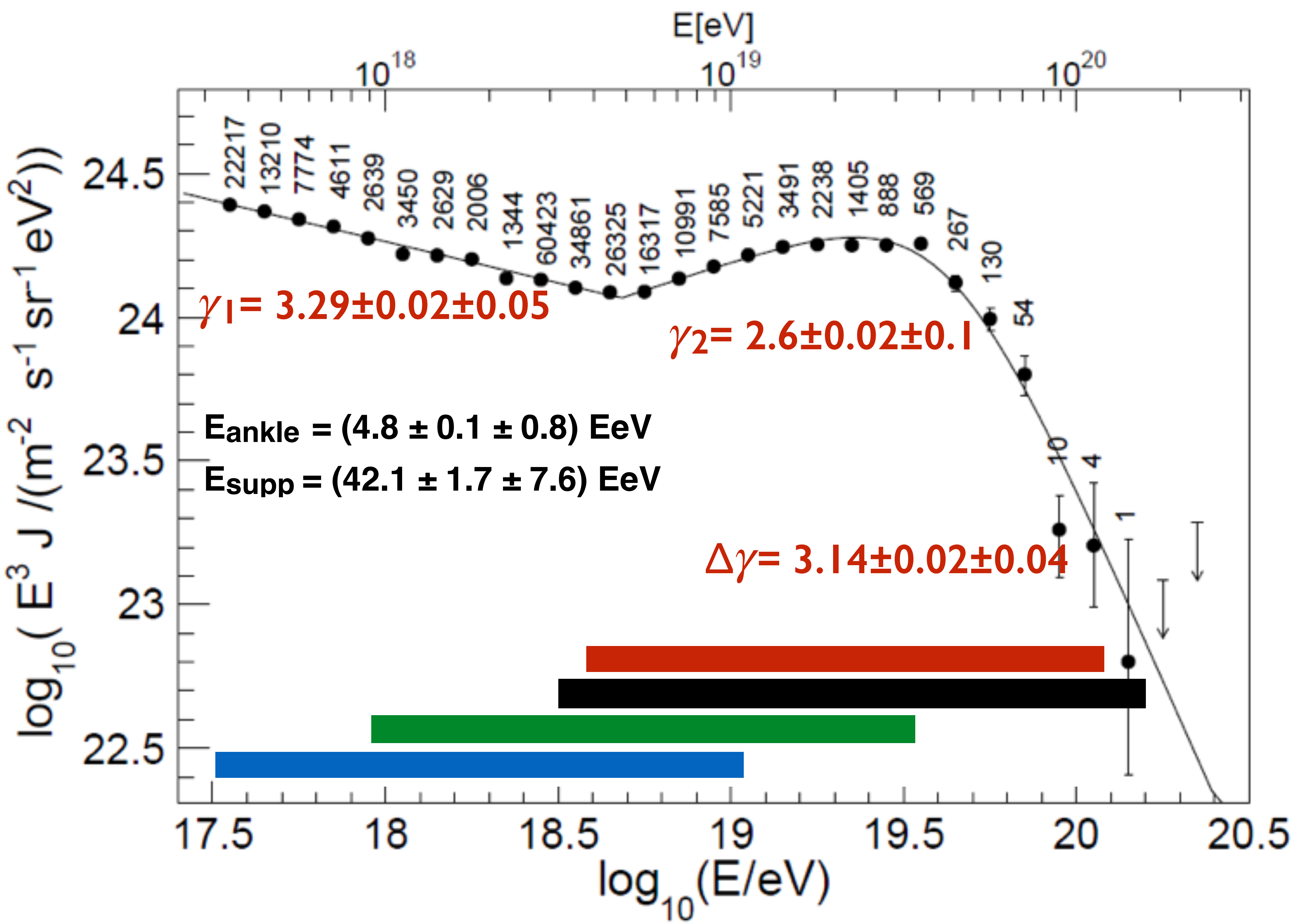
Detector	E	N (E>E
Hybrid FD+SD	1	~10000
SD 1500m (0°-60°)	3	~100000
SD 1500 m (60°-80°)	4	15000
SD 750m (0°-55°)	0.3	6000
HEAT +SD	0.1	60000

The FD defines all energy scales -> systematic uncertainty ~ 14%

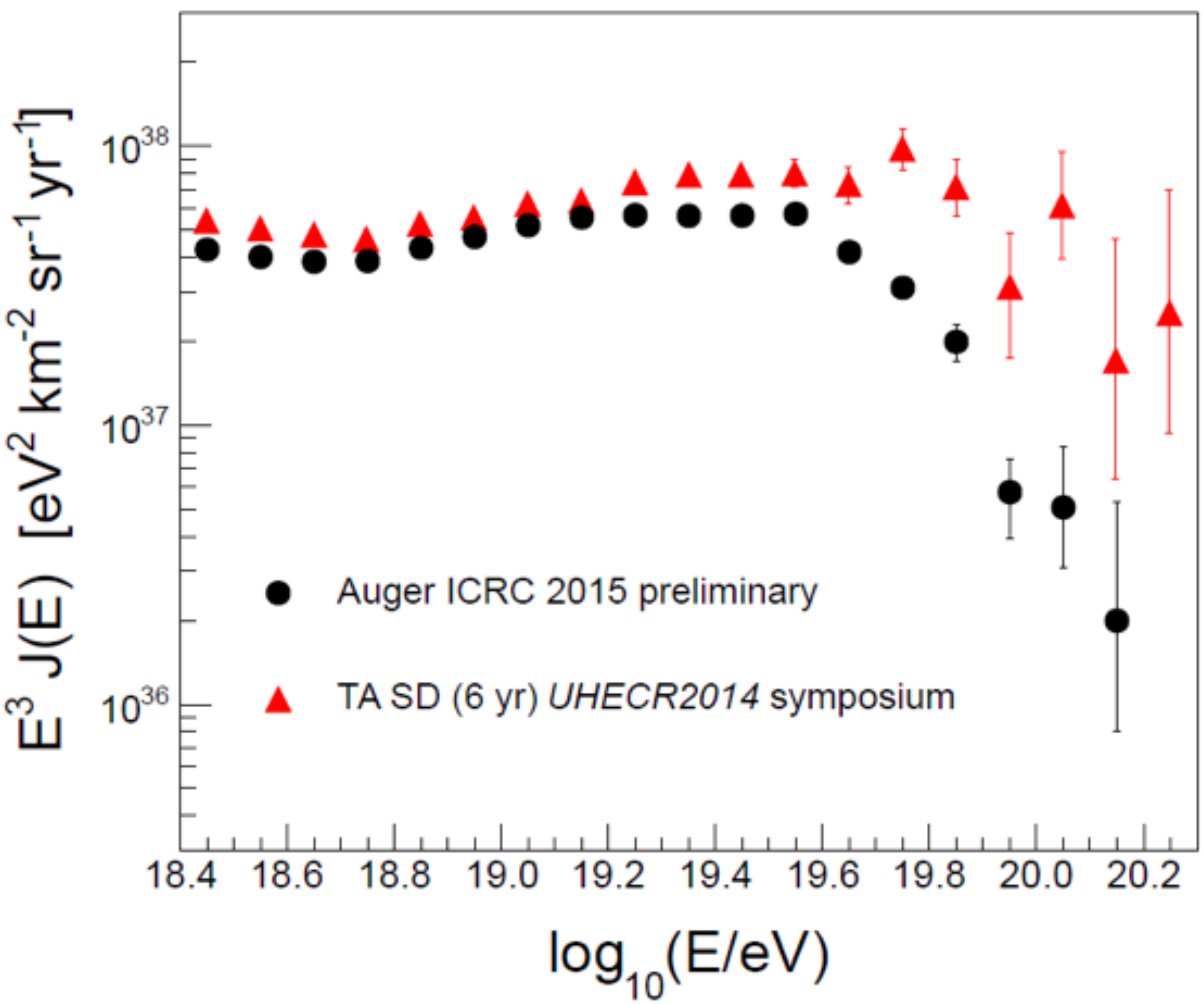
Energy spectrum over 3 decades in energy

4 data sets combined : SD 750 m FD (hybrid) SD 1500 m (0-60°), SD 1500 m (60-80°)

≈ 200 000 events, ≈ 50000 km2 sr yr exposure, FOV: -90°, +25 in δ



AUGER/Telescope Array spectra



Discrepancy can be accommodated within a systematic energy shift , but not at the highest energies

Under study by UHECR spectrum WG(TA/Auger) (I.C Maris, UHECR2014)

ANISOTROPIES

The search for anisotropies to track the origin of cosmic rays

At small and intermediate scale :

For light particles at the largest energies we expect small deviation from magnetic fields (a few degrees) :

- A clear anisotropie would reveal a large fraction of protons in the high energy flux
- Possible CR astronomy ??

-> Intrinsic correlations or correlation with close objects from catalogs

At large scale :

- diffusion & escape of galactic CR below EeV energies can generate dipole pattern

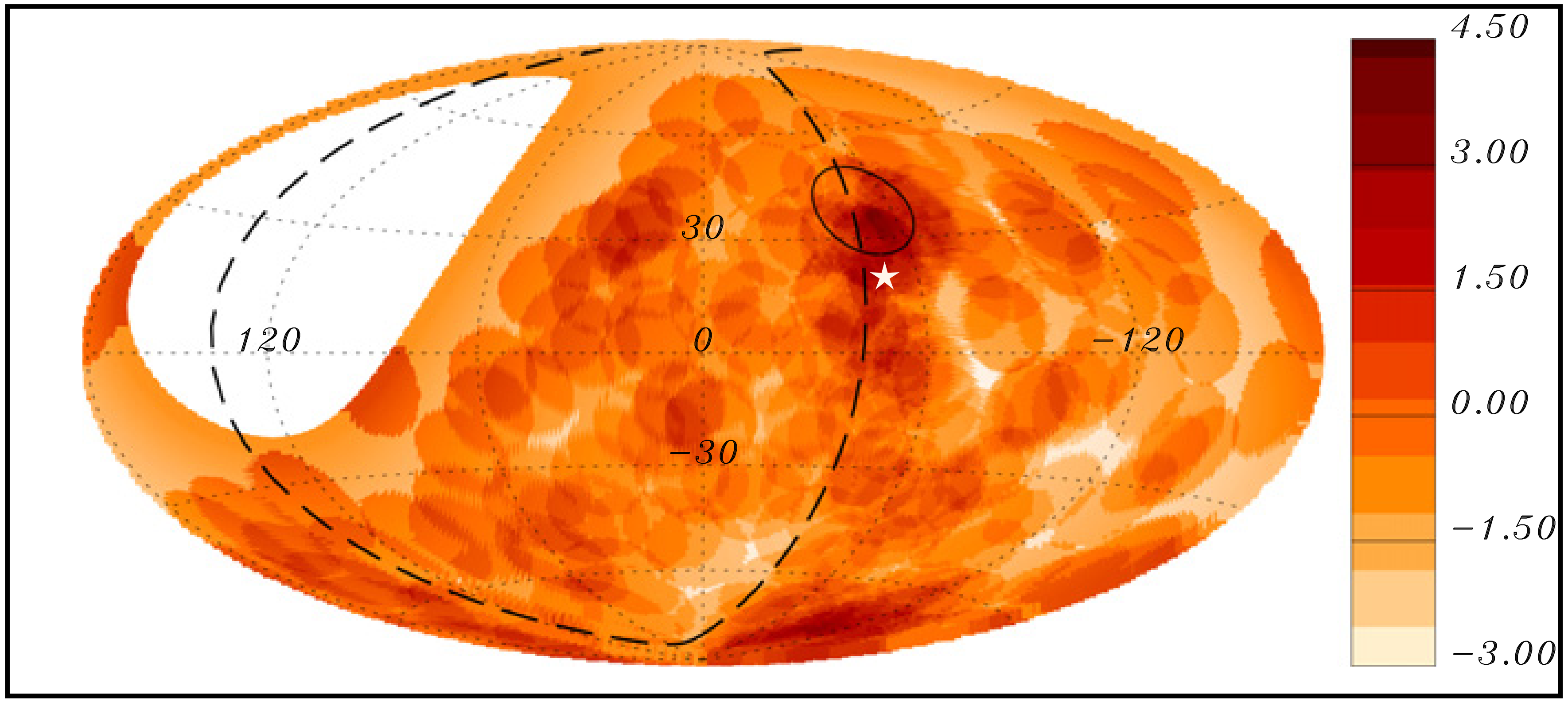
- A change in the large scale anisotropy could sign the galactic/extra galactic transition (at the ankle ?)

-> Search of dipole on different energy ranges

Search of small/intermediate scale anisotropies in the arrival directions of the most energetic cosmic rays < 80°

Blind search for excesses

Scan on parameters: compute the obs./exp number of events in each circular window for:
$E_{th} \in [40;80]$EeV in 1 EeV steps, $\Psi \in [1^\circ; 30^\circ]$) in 1° steps



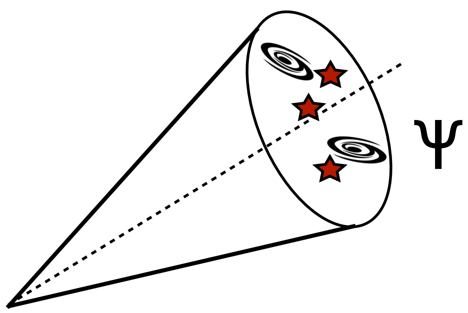
Li-Ma significance map in 12° circles;
largest excess 4.3σ, Ethresh = 54 EeV, 18° from CenA;
Post-trial probability (from simulations) 69%,

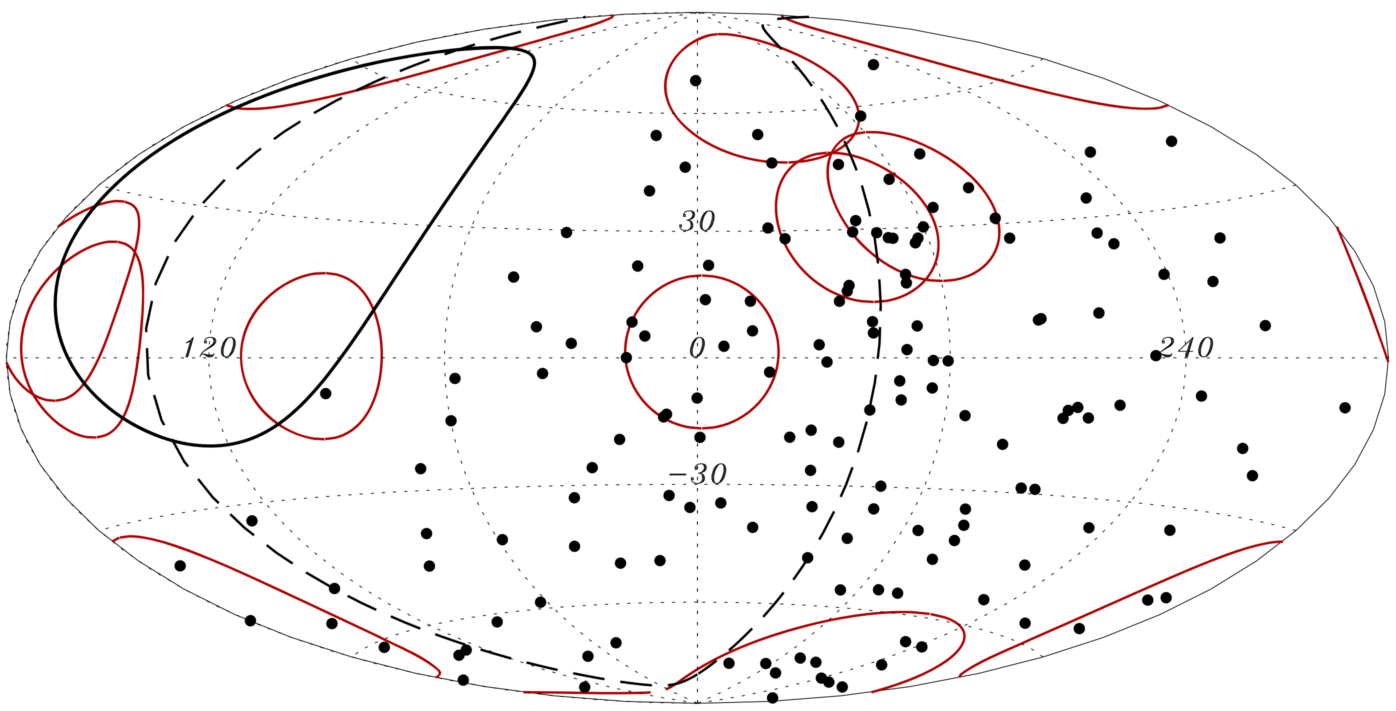
ApJ 804:15 , 2015

All excess found are compatible with isotropy.

Search of small/intermediate scale anisotropies in the arrival directions of the most energetic cosmic rays < 80°

Search of correlations with astrophysical structures Gal-Xgal planes, 2MRS galaxies, Swift-BAT AGNs, jetted radio galaxies, CenA;
Scan over angles, E_{thresh}, luminosity for AGNs and radio galaxies.





Largest excess of pairs for Swift AGNs with
E_{thresh} = 58 EeV, 18° circles,
L > 10^{44} erg/s, closer than 130 Mpc;
post-trial probability 1.3%.

ApJ 804:15 , 2015

No statistically significant deviation from isotropy

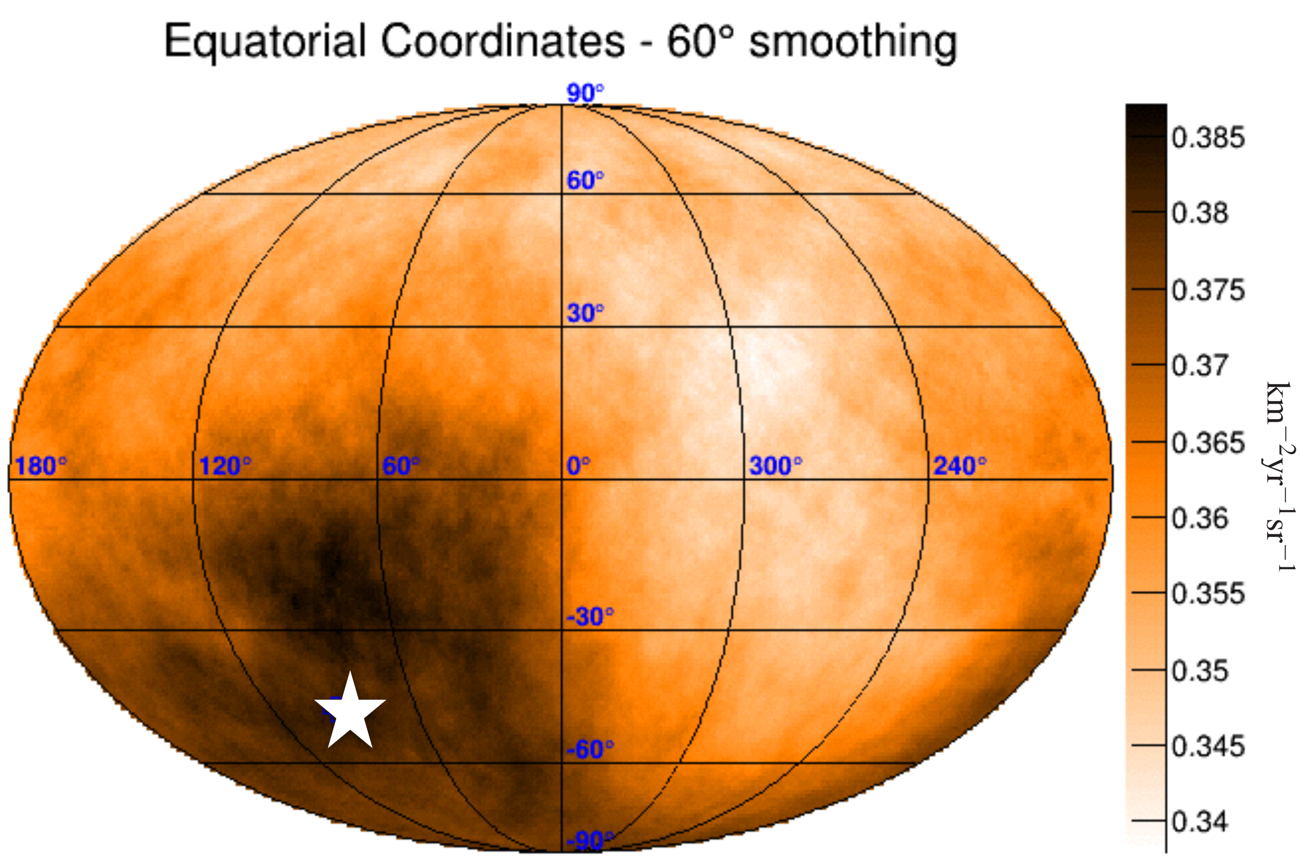
Large scale anisotropies

Auger data set : ≈ 70000 events with E>4 EeV and ϑ < 80° , 85% sky coverage

Modified Raleigh or East-West analysis
on 1500 m and 750 m arrays dataset

Auger/TA : ≈ 17000 Auger events , ≈ 2500 TA events with E>10 EeV , Full sky coverage

Spherical harmonic analysis



AUGER/TA

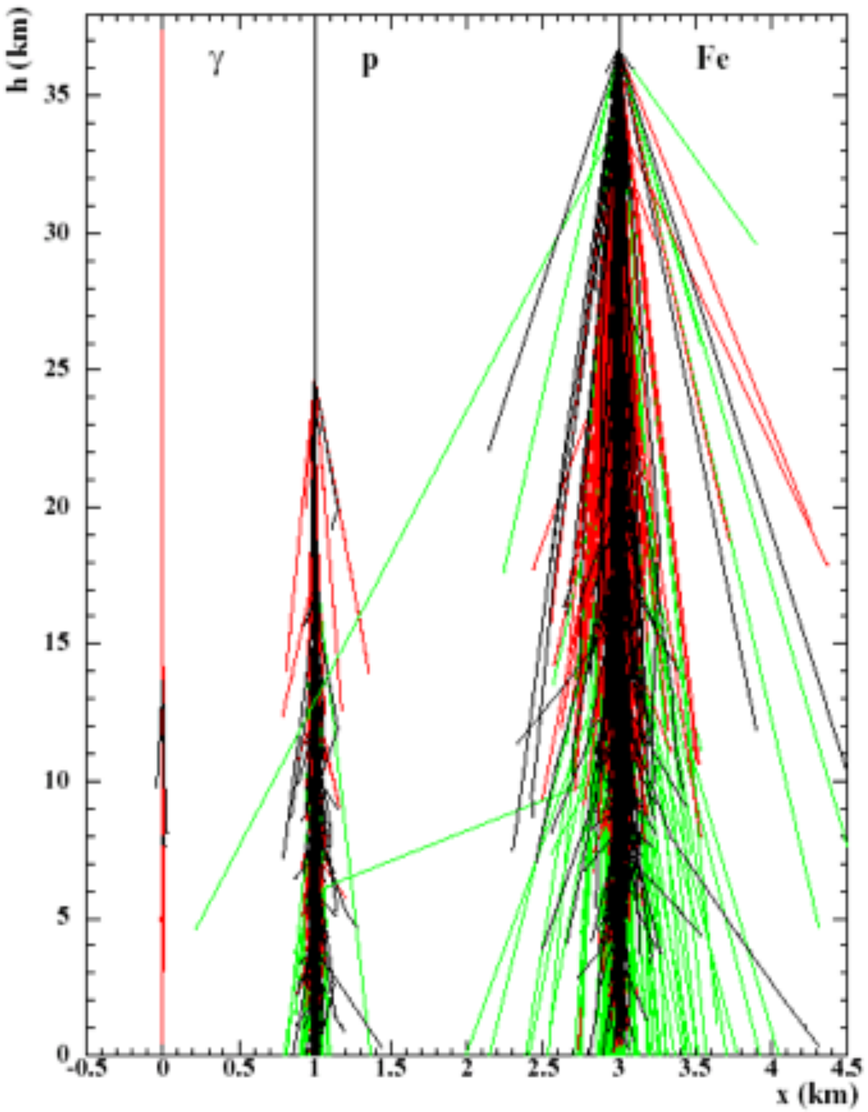
Dipole Amplitude: 6.5 ± 1.9%
(p=5x10^{-3})

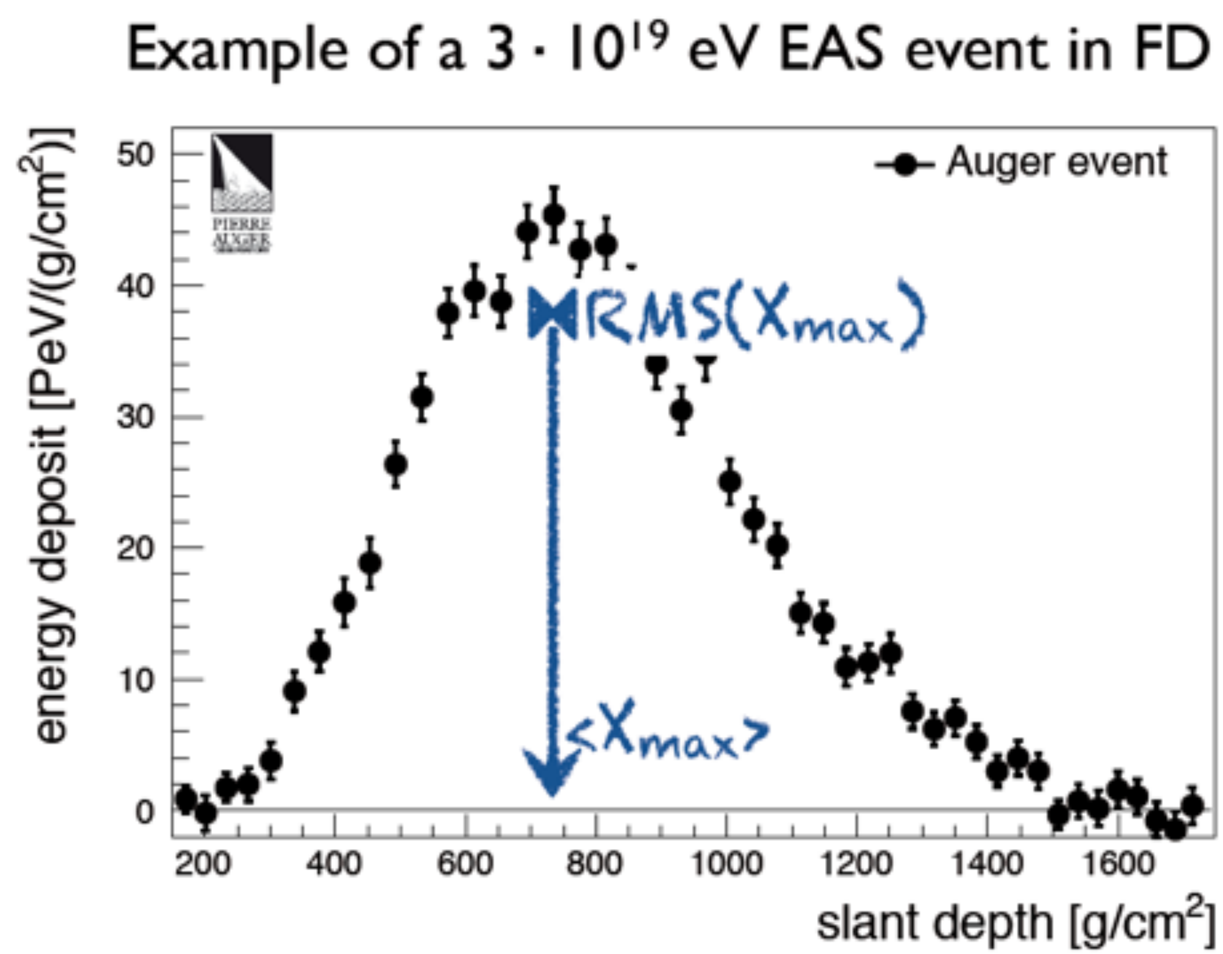
Pointing to (a, d) =
(93°±24°, -46°±18°)

Indications of large-scale anisotropies of CRs at E > 8-10 EeV challenging the original expectations of isotropy at these energies

MASS COMPOSITION

Composition from FD longitudinal profile





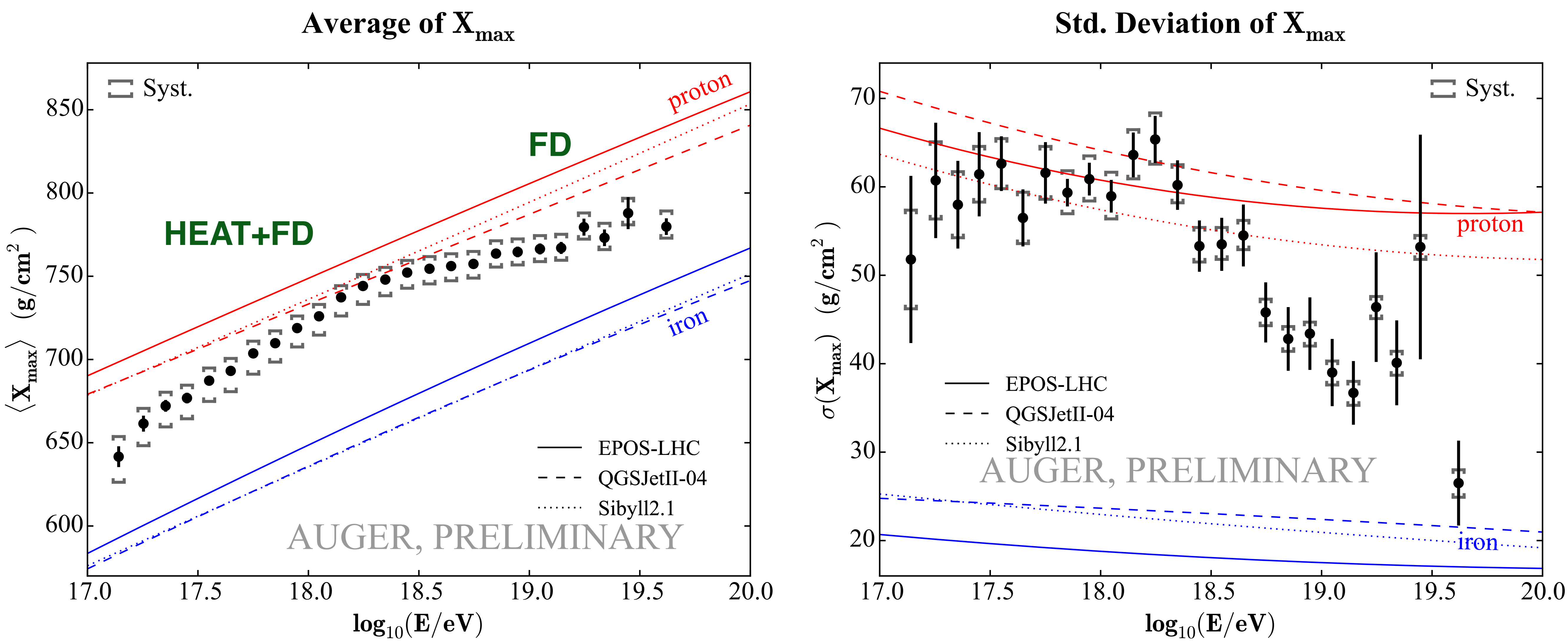
Fe shower develop higher in atmosphere
-> lower Xmax (~100g.cm^{-2} avrg)

Observables sensitive to composition:

- Depth of shower maximum (<Xmax>);
- Elongation rate (d<Xmax>/ dlogE);
- RMS of Xmax distribution at fixed energy:

Mass composition over 3 decades in energy- Xmax

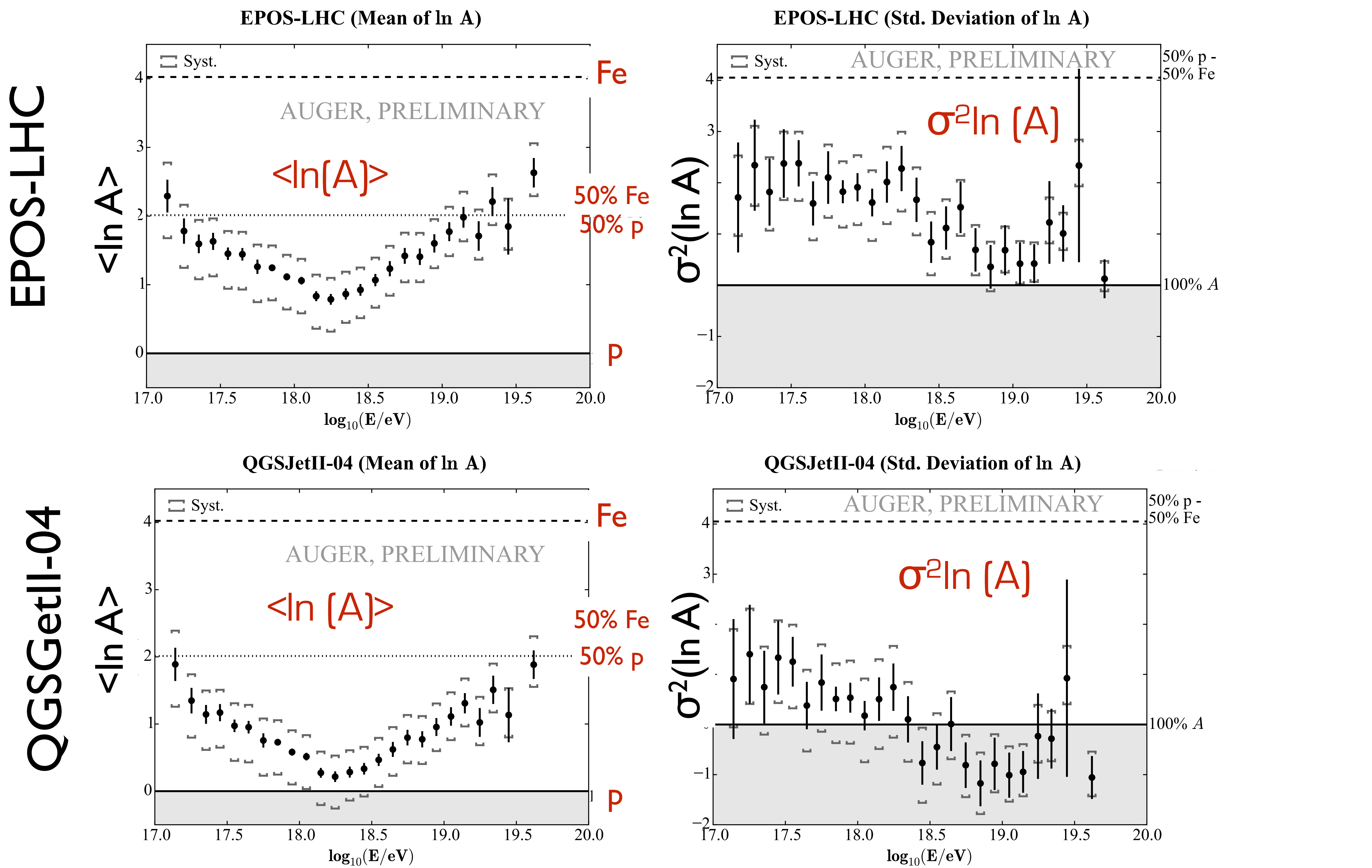
- ✓ From a clean hybrid data set (strong anti-biais cuts), detector independent measurement
- ✓ Lastest Hadronic interaction MCs tuned to 7 EeV LHC data
- ✓ New extended low energy range data down to 10^{17} with HEAT FOV



In agreement with TA when folded from the detector effect (as done in TA)

From X_{max} to primary mass <ln (A)>

$$\langle \ln A \rangle = \ln 56 \frac{X^{p}_{max} - \langle X_{max} \rangle}{X^{p}_{max} - X^{Fe}_{max}}$$



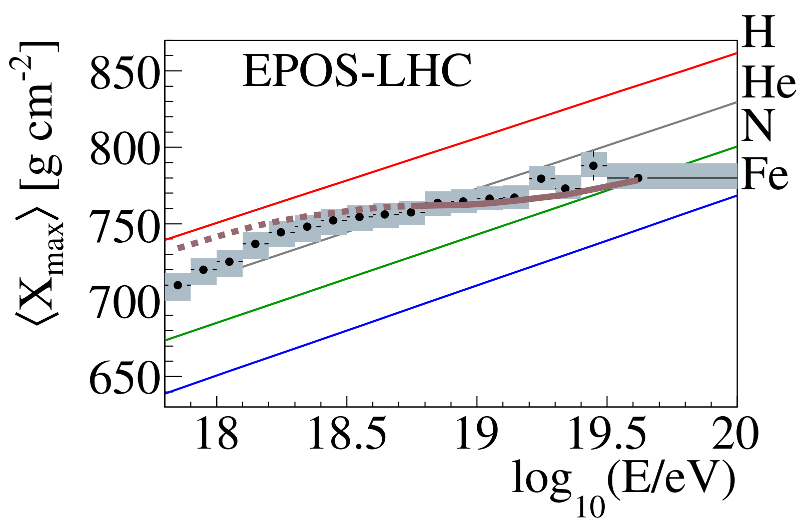
Similar trend with energy for both models : heavy, lighter heavier

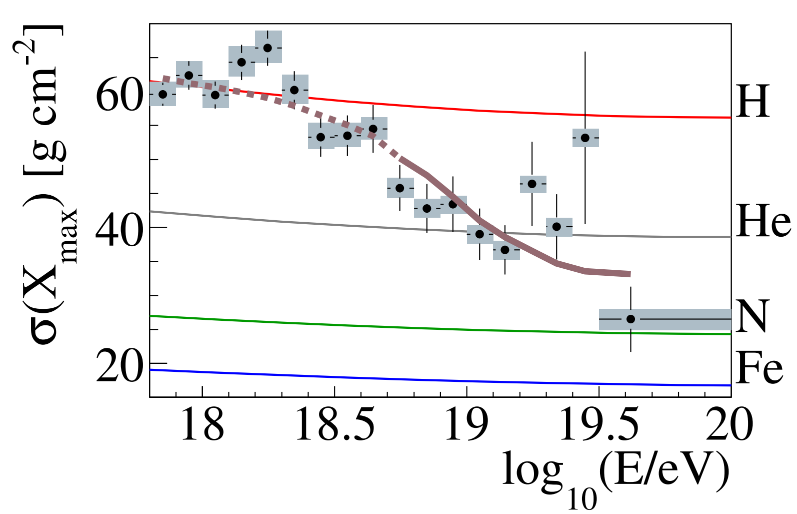
Also tests of models -> QGSJET II yields unphysical results

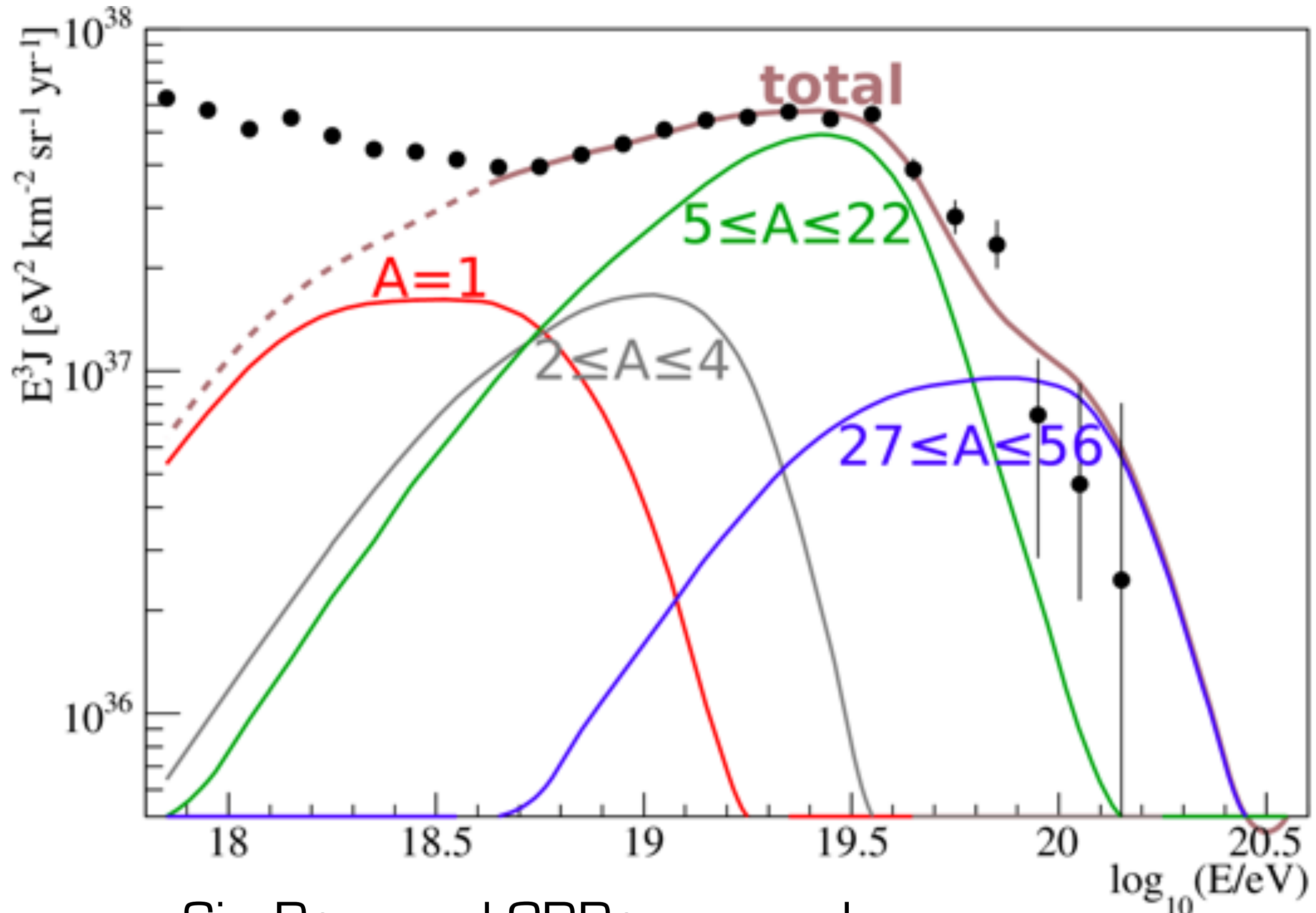
Spectrum and X_{max}

Combined fit of energy spectrum and Xmax using propagation models

Homogenenous distribution of of identical sources of p, He, N and Fe nuclei;
125 data points, 6 fit parameters: injection flux norm. and spec. index γ, cutoff rigidity R_{cut}, p/He/N/Fe fractions;







SimProp and CRPropa used

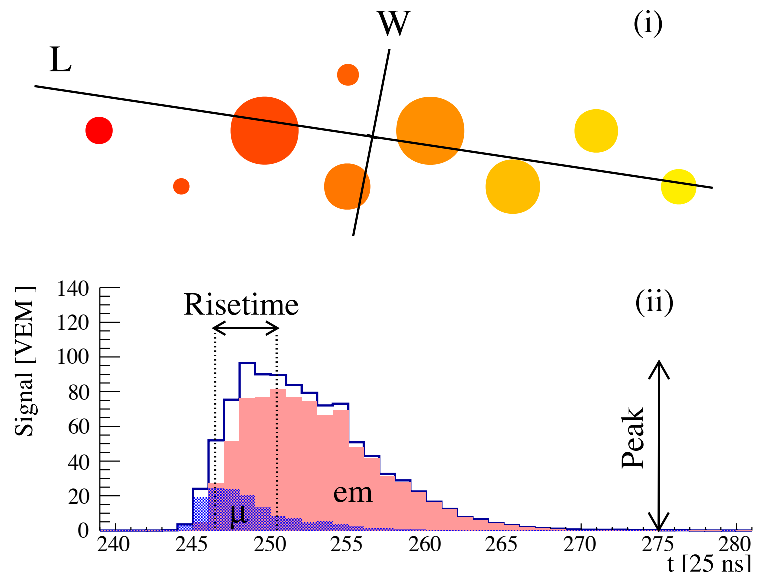
For details, see R. Alves Batista, D. Boncioli, A. di Matteo, A. van Vliet and D. Walz, "“Effects of uncertainties in simulations of extragalactic UHECR propagation, using CRPropa and SimProp, prepared for submission to JCAP” (coming soon on arXiv)

—> Best fit with very hard injection spectra (γ≤1).

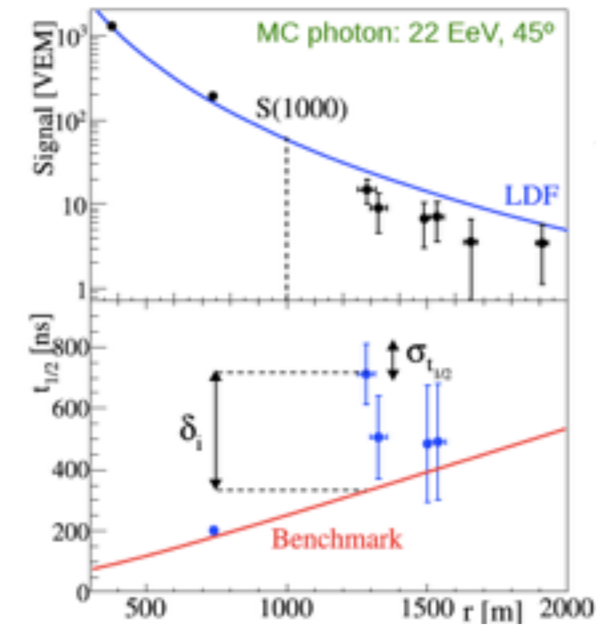
Neutrino and photon at EeV energies ?

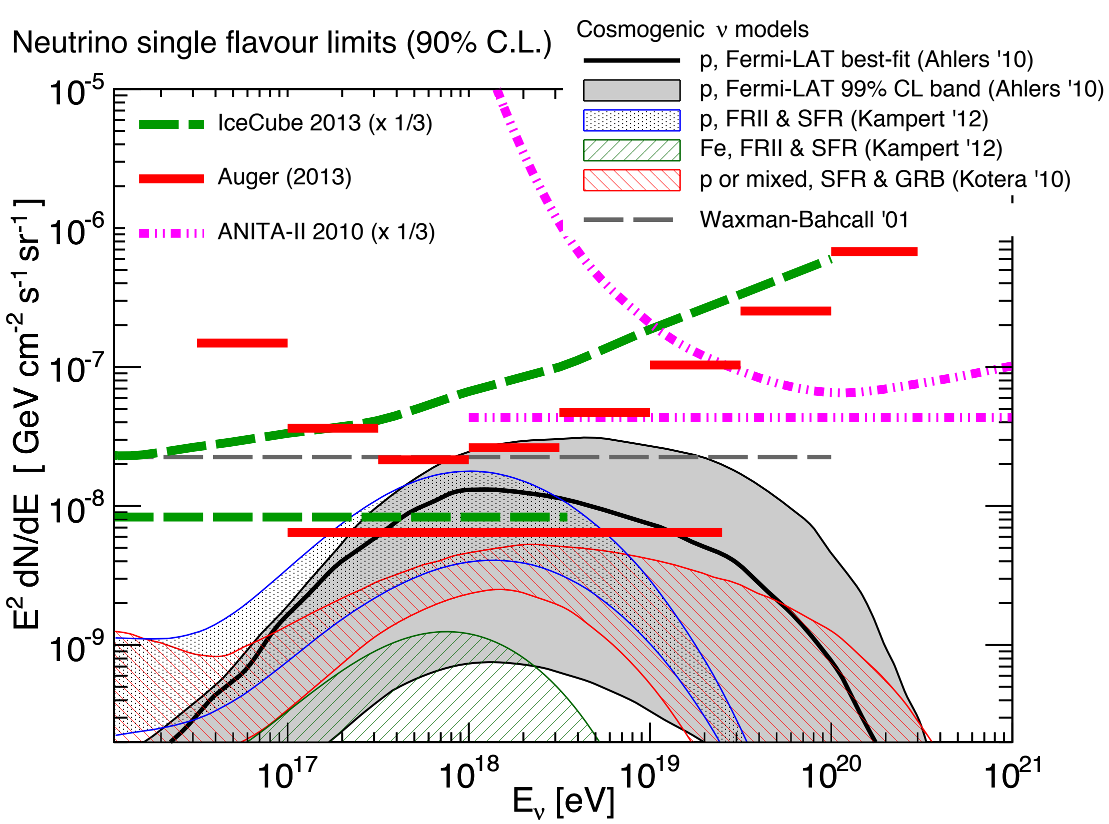
Use observables from SD to select neutrinos or photons

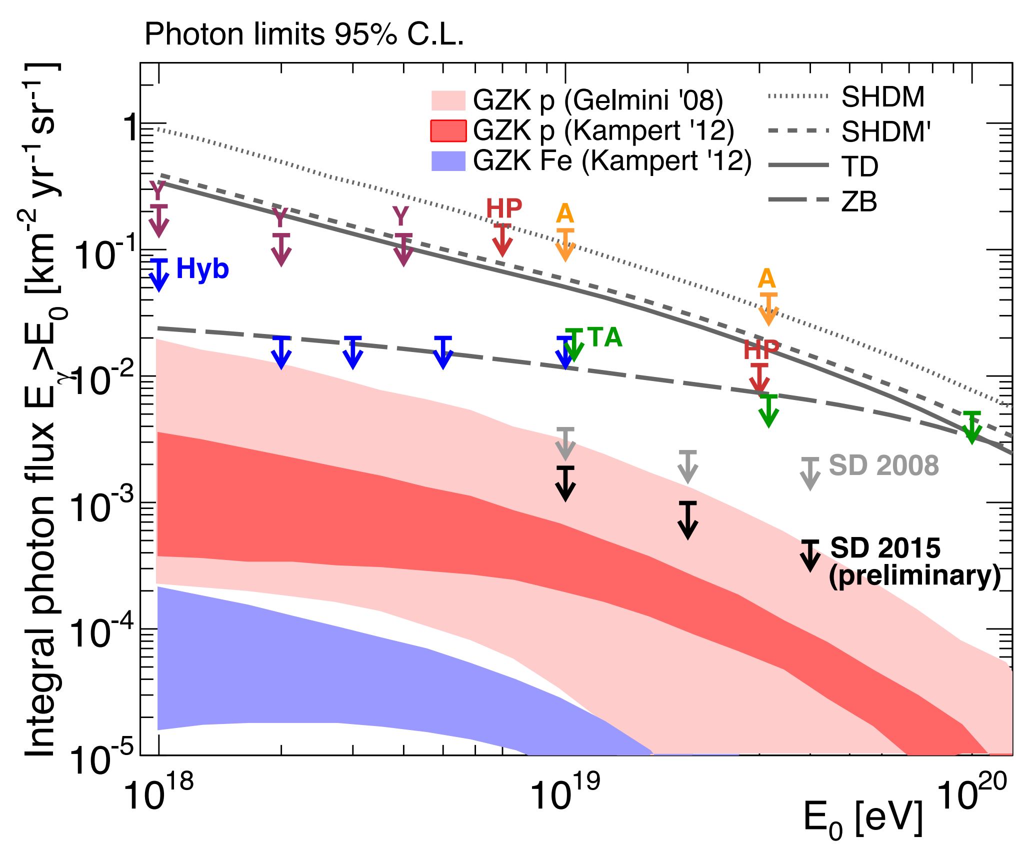
Neutrinos
use footprint of the shower and time structure of the signal



Photons
use later profile of the shower and time structure of the signal







First limit from an EAS array below WB bound

Top-down models strongly disfavoured

MUONS IN SHOWERS
AND
HADRONIC MODELS

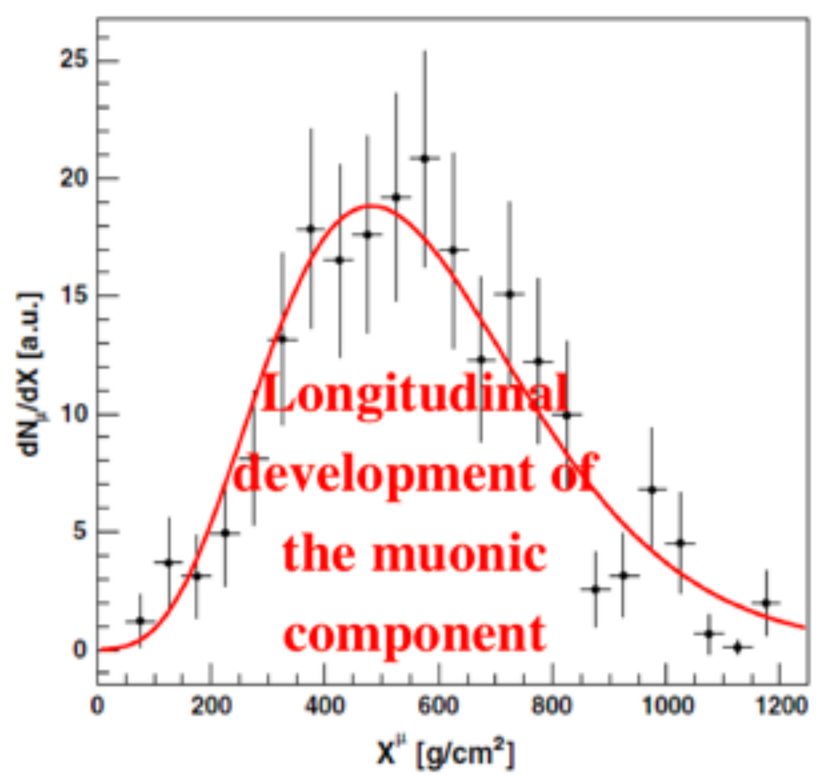
Muon in showers and hadronic models

Composition with SD need reliable hadronic models ->
Comparison of muon number to models with different data using FD and SD

- Measurement of muon number in highly inclined air showers (SD+FD)

  from E-FD and mean muon scale $R_\mu = \frac{N_\mu^{data}}{N_{\mu,19}^{MC}}$

- Measurement of the longitudinal depth of the muon component (SD only)

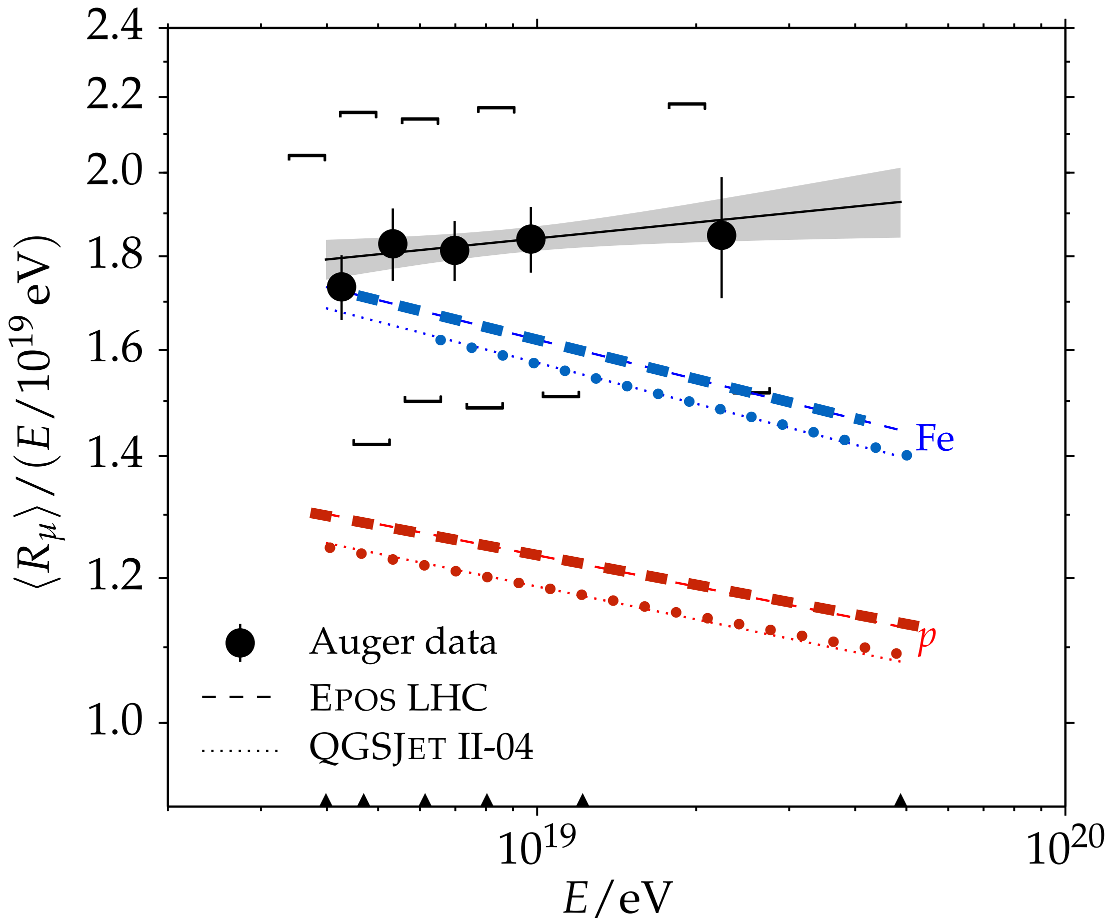


X^μ_{max}

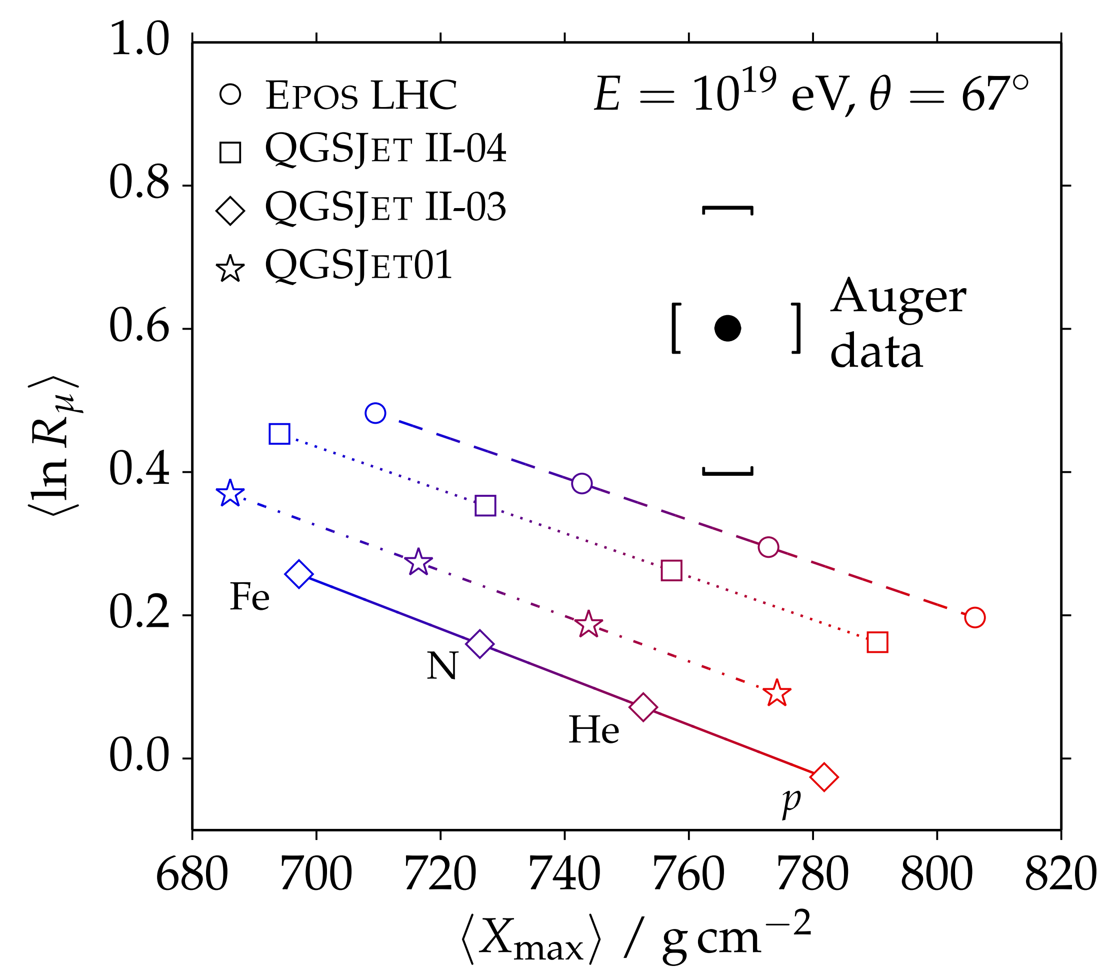
Muon Production Depth inferred from the SD traces for inclined showers

Muon content of very inclined showers and hadronic models

<Rμ> vs Energy



<Rμ> vs XMax



<Rμ> higher than MC iron predictions

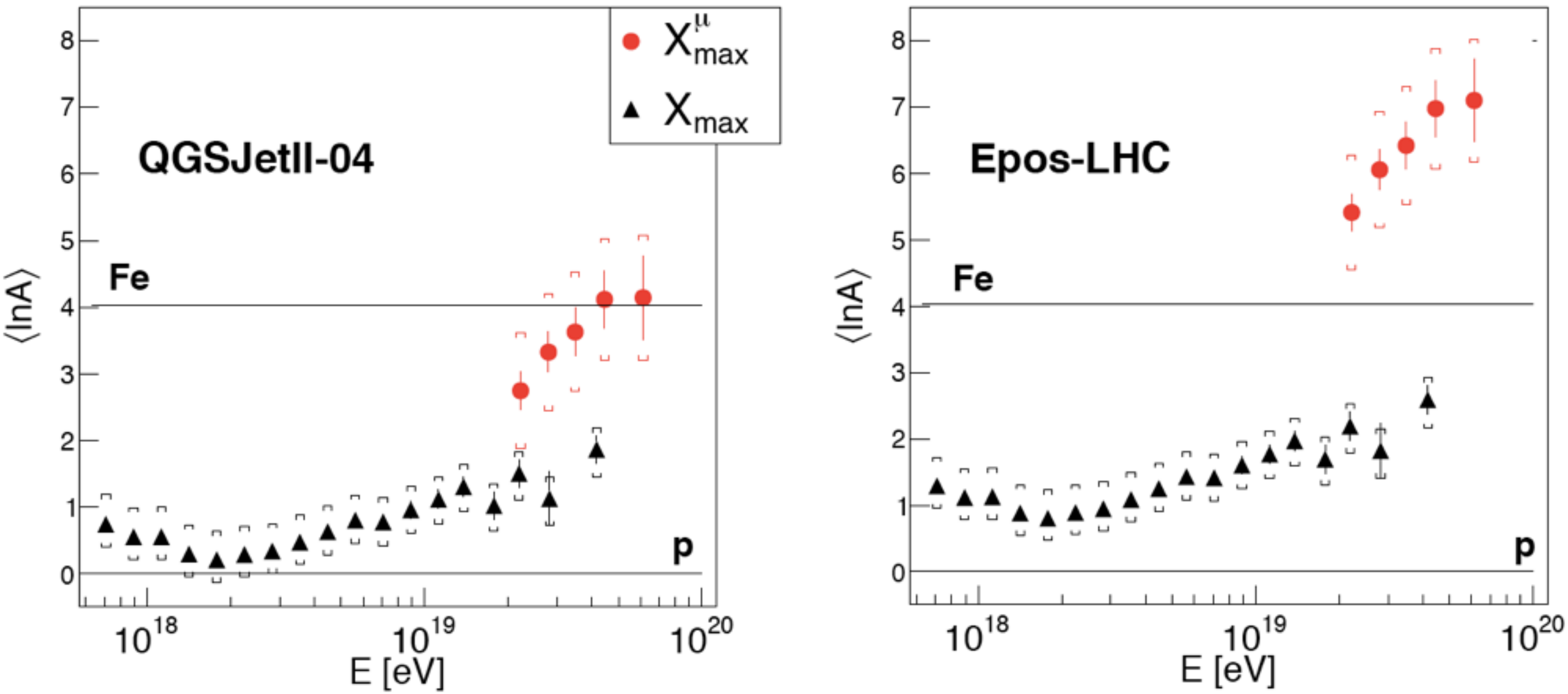
Tension between the Xmax and muon measurements

Deficit of muons in simulations beetween 30% and 80%

PRD91,032003, 059901 (2015)

Muon production depth and hadronic models

Ln(A) deduced from X^{μ}_{max} are compared to ln(A) from X_{max} from FD



Values compatible within 1.5 σ for QGSJetII-04
incompatible at > 6 σ for Epos-LHC

PRD 90, 912012(2014), 019003 (2015)

SUMMARY
AND
FUTURE

Summary and open issues after 10 years of data taking and analysis

✓ Clear flux suppression above 40 EeV(>20 s):

but GZK or end of acceleration power at the sources ?

✓ Towards a heavier mass when going to the highest energies:

but statistics limited by FD only data

and SD composition data in tension with FD and(or) hadronic models

✓ Stringent photon source limit favor astrophysics source but no clear isotropy found at the highest energy : the hypothesis of few sources of light primaries is challenged

Need to select light primaries to do Cosmic ray astronomy

↓

COMPOSITION MEASUREMENTS EVENT BY EVENT, UP TO THE HIGHEST ENERGIES, WITH THE LARGE SD STATISTICS IS ABSOLUTELY NEEDED !

Objective of Auger future upgrade, AUGER- Prime

Primary cosmic **R**ay **I**dentification with **M**uons and **E**lectron

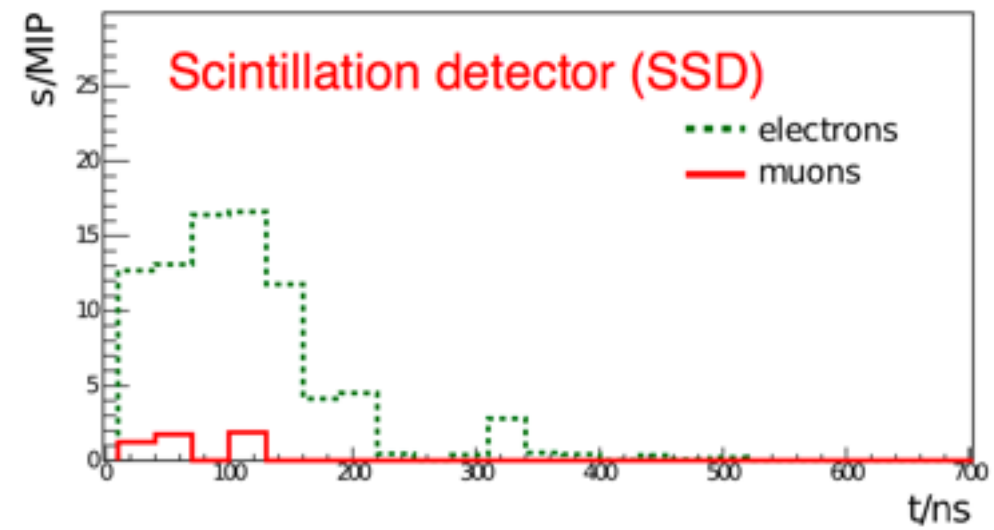
Extended FD duty cycle
Installation of a Scintillator Surface Detector (SSD) on top of each WCD
Upgraded SD Electronics

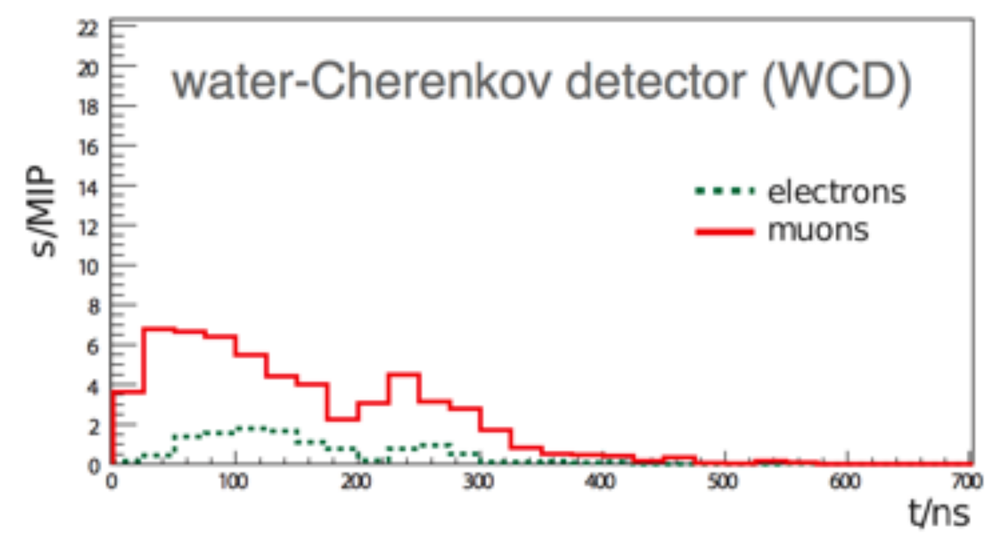
Foreseen schedule

- PDR ready since April 2015
- EA planned for March 2016
- Data taking 2018-2024 (40 000 km^2 sr yr)

The SSD methodology

Sampling of the shower particles with two detectors having different responses to muons and electromagnetic particles.





$$S_{\mu,\mathrm{WCD}} = a S_{\mathrm{WCD}} + b S_{\mathrm{SSD}}$$

AUGER Prime Science Case

1. A precise reconstruction of mass dependant energy spectrum

2. The identification of primaries, event by event , up to the highest energies

3. A systematic study of arrival directions of an enhanced proton data sample

…to access the global picture of the origin of HECR and UHECR

Thank you

BACKUP SLIDES

Galactic neutron searches

Motivation:

- Neutrons of 1 EeV can reach us from ~ 9 kpc (<d> = 9.2 E[EeV] kpc)
- Produced by protons in pion-producing interactions with ambient photons, protons or nuclei, also producing gamma rays
- Travel without deflections
- Air showers indistinguishable from protons

Methods:

Blind search:

NO significant point-like (at the angular resolution) over-density found

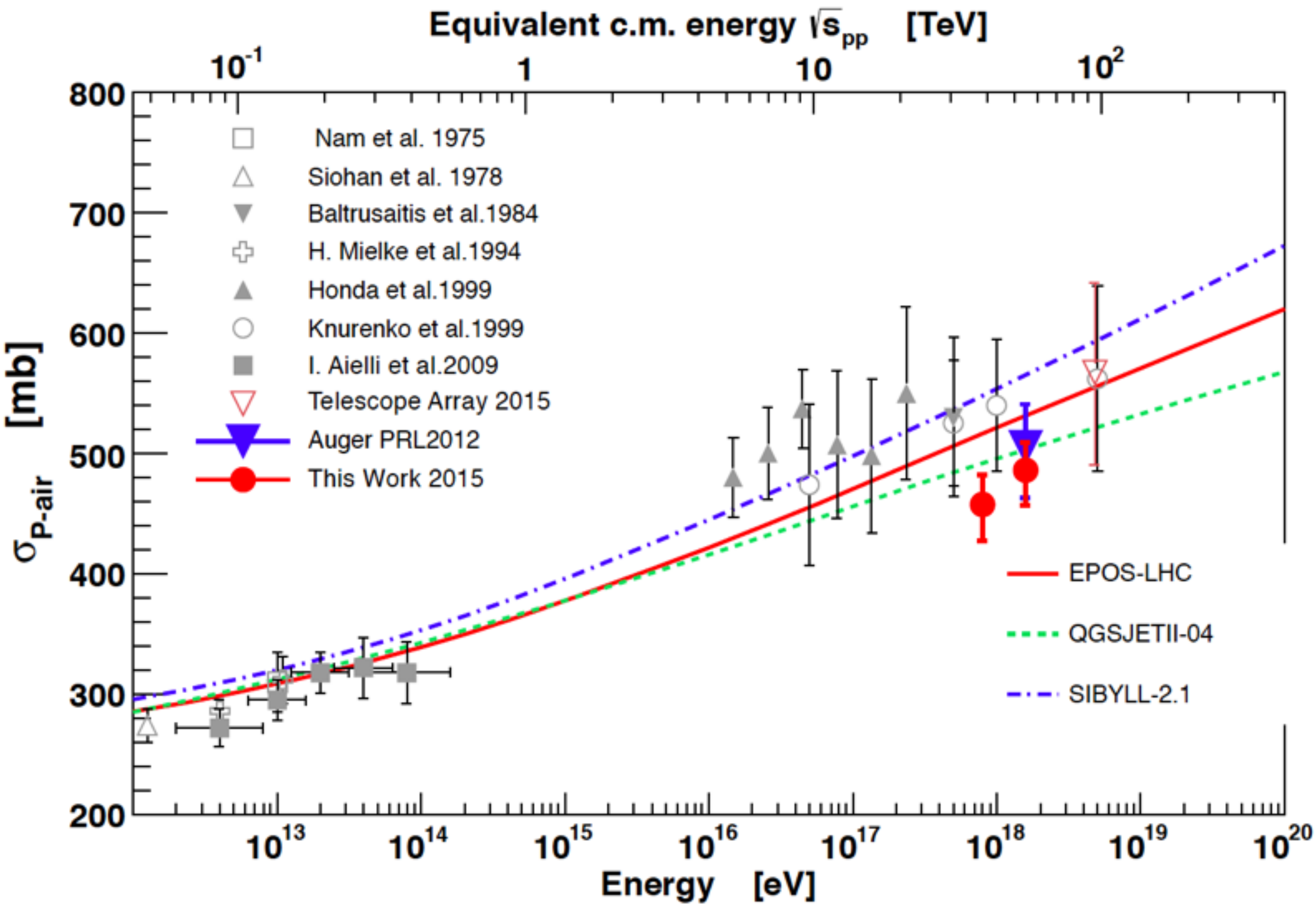
→ sources are extragalactic, or transient, or optically thin to escaping protons, or weak & densely distributed — ApJ 760 (2012)

Search for point-like excess of EeV CRs around different stacked sets of sources (HESS, Fermi sources, X-ray binaries, pulsars, Galactic Plane and Galactic center, magnetars, microquasars, etc.):

NO candidate found with significant excess — ApJL (2014)

→ Flux (>1EeV) < 0.01 $km^{-2}\,yr^{-1}$

σp-air cross-section for deep showers, rising with E, measured at √s ~ 39, 56 TeV.



FLUORESCENCE YIELD

Update of the absolute intensity of the 337 nm band (absolute normalisation of the wavelength spectrum)

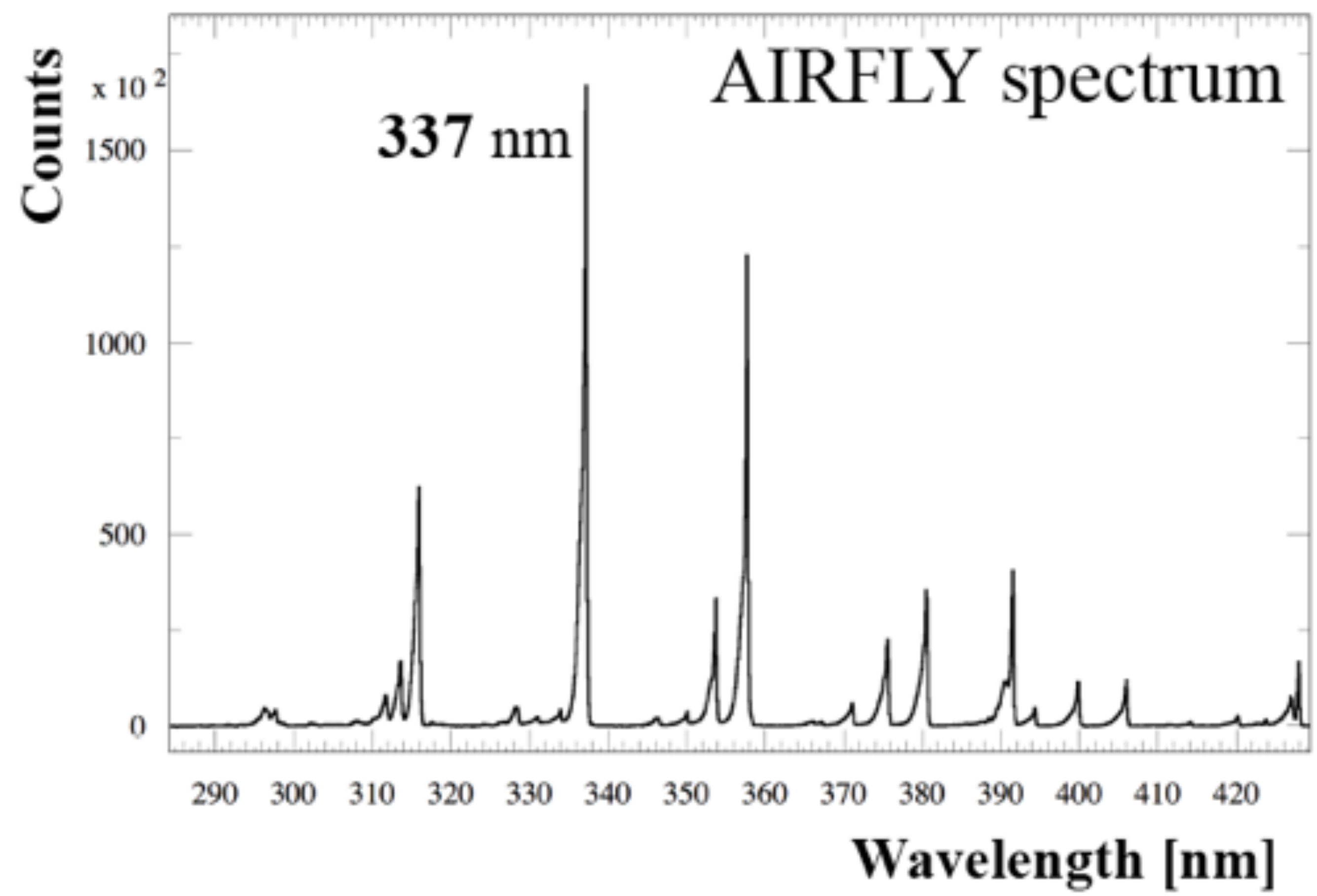
Now AIRFLY: 4% uncertainty
M. Ave et al.,
Astropart. Phys. **42** (2013) 90

Before: 14% uncertainty
M. Nagano et al.,
Astropart. Phys. **22** (2004) 235

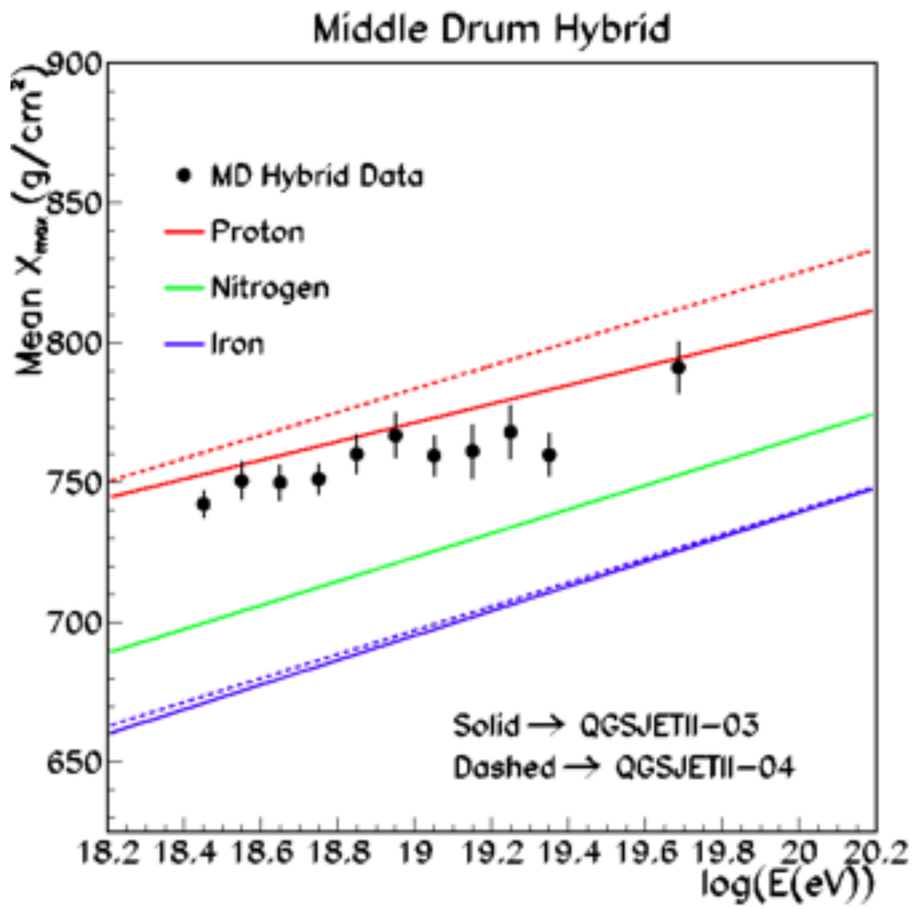
E lowered by 8%

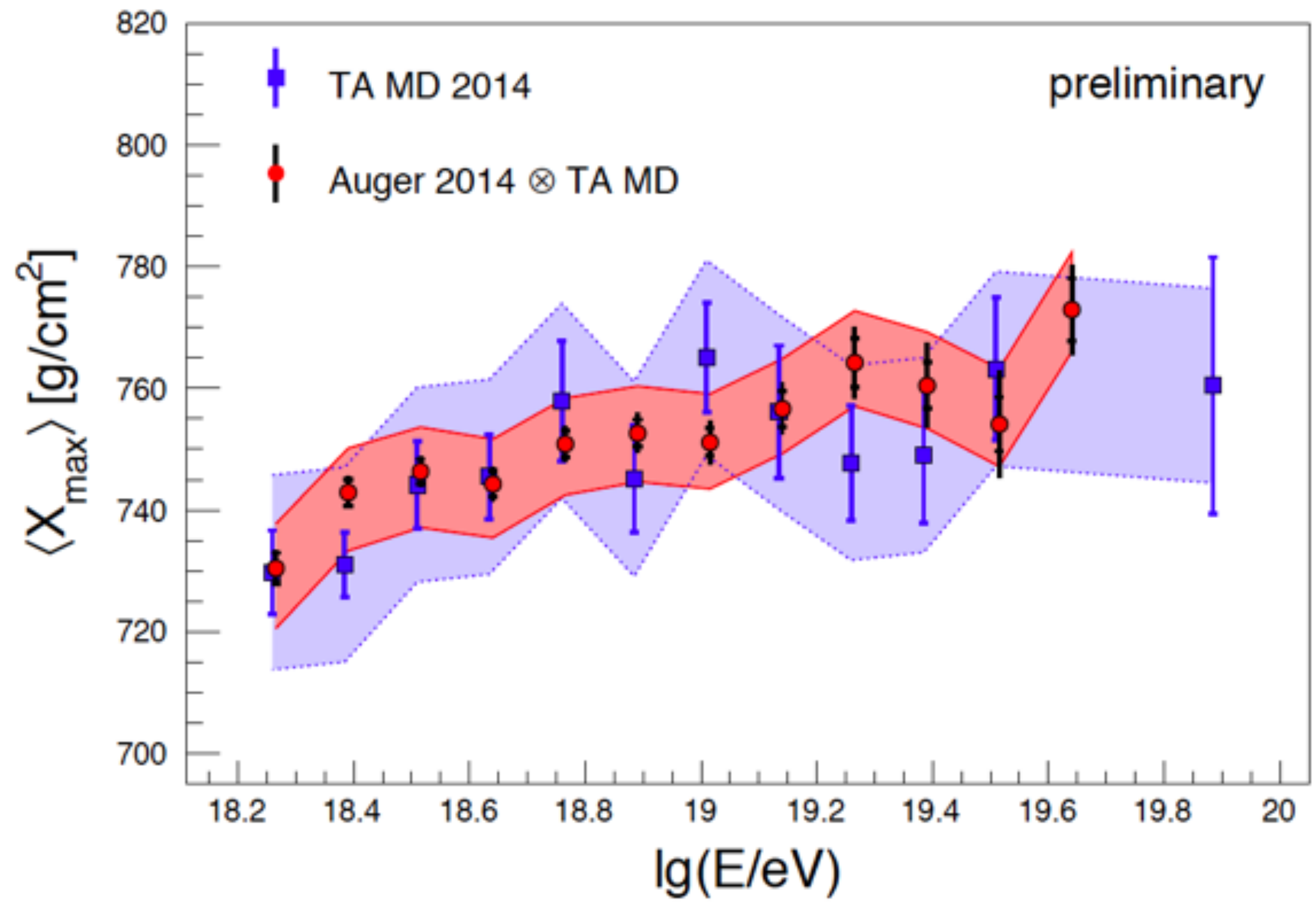
$\Delta E/E \approx 3.4\%$
(before we had 14%)

M. Ave et al., Astropart. Phys. **28** (2007) 41



Mass composition - Xmax



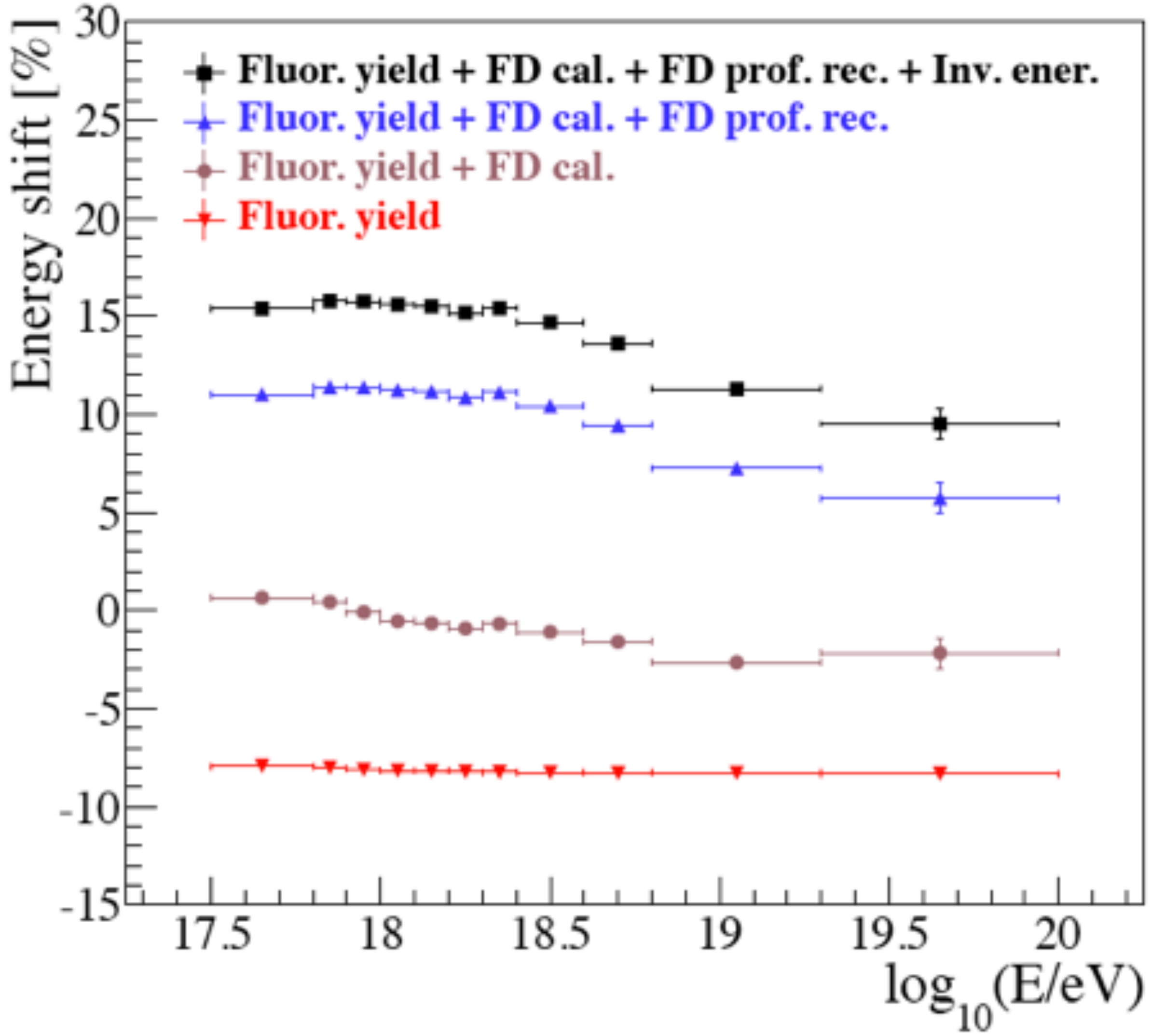


Change from a mixed/light composition to a heavier one

Changes in : Atmosphere, fluorescence yield, invisible energy, FD calibration
Longitudinal profile fit (at ICRC2013)

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%**



Still compatible with former uncertainty (22%)

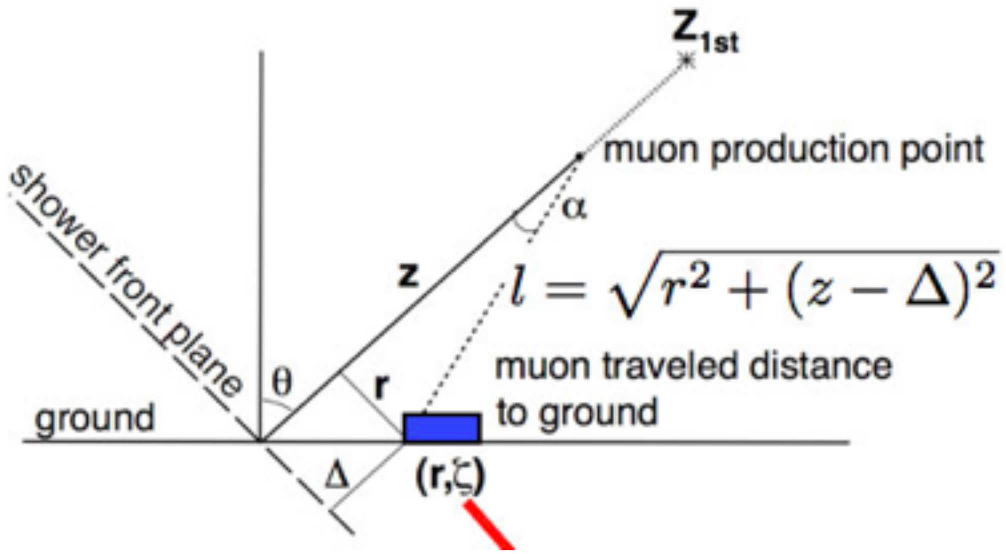
Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**9.9%**
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%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

FD uncertainties propagate to the SD energies

TOTAL ≈ 14%

~ independent of energy

Mass composition from SD - MPD (Muon Production Depth)

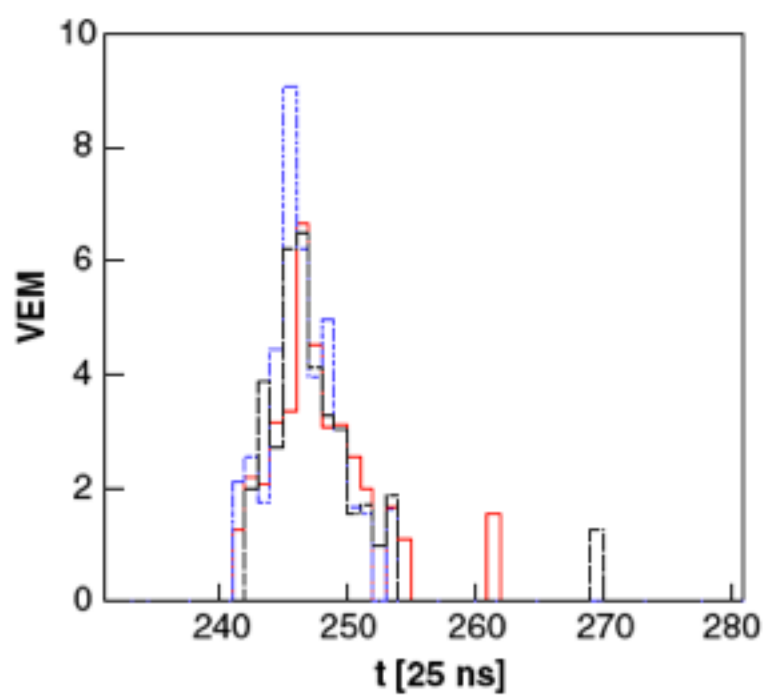


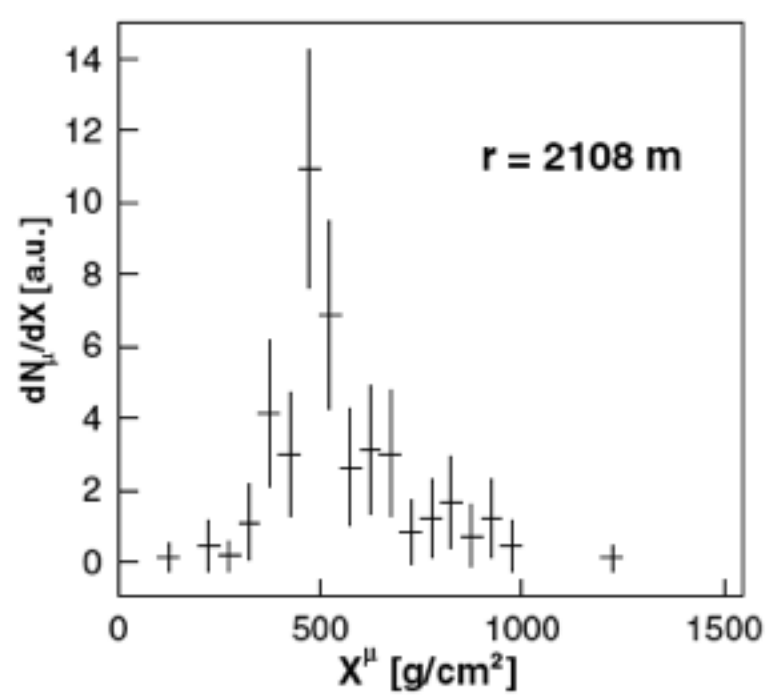
$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

$$X^{\mu} = \int_z^{\infty} \rho(z')dz'$$

$$t_g \simeq t - \langle t_\varepsilon \rangle$$

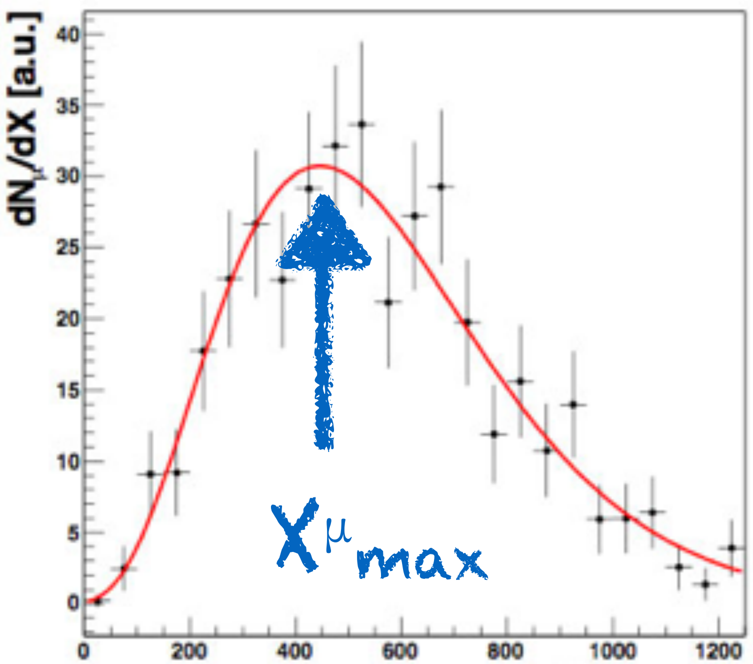
Data selection: θ>55 ° , traces from tanks between 1700 and 4000m only to avoid EM contamination

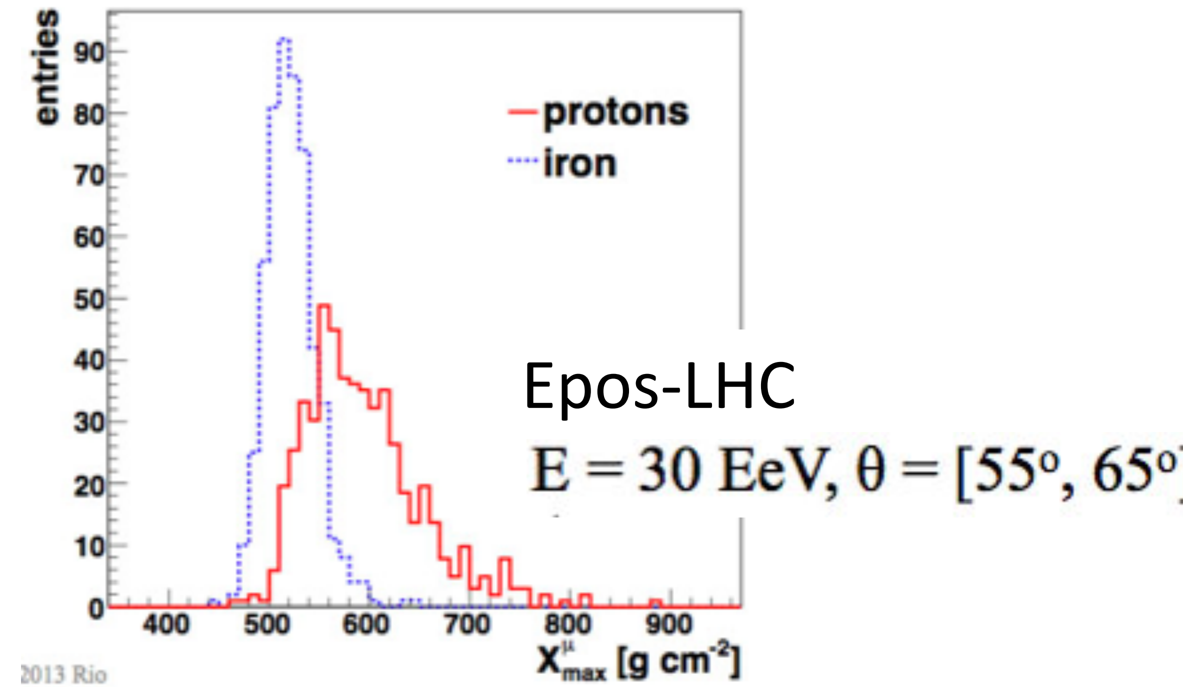


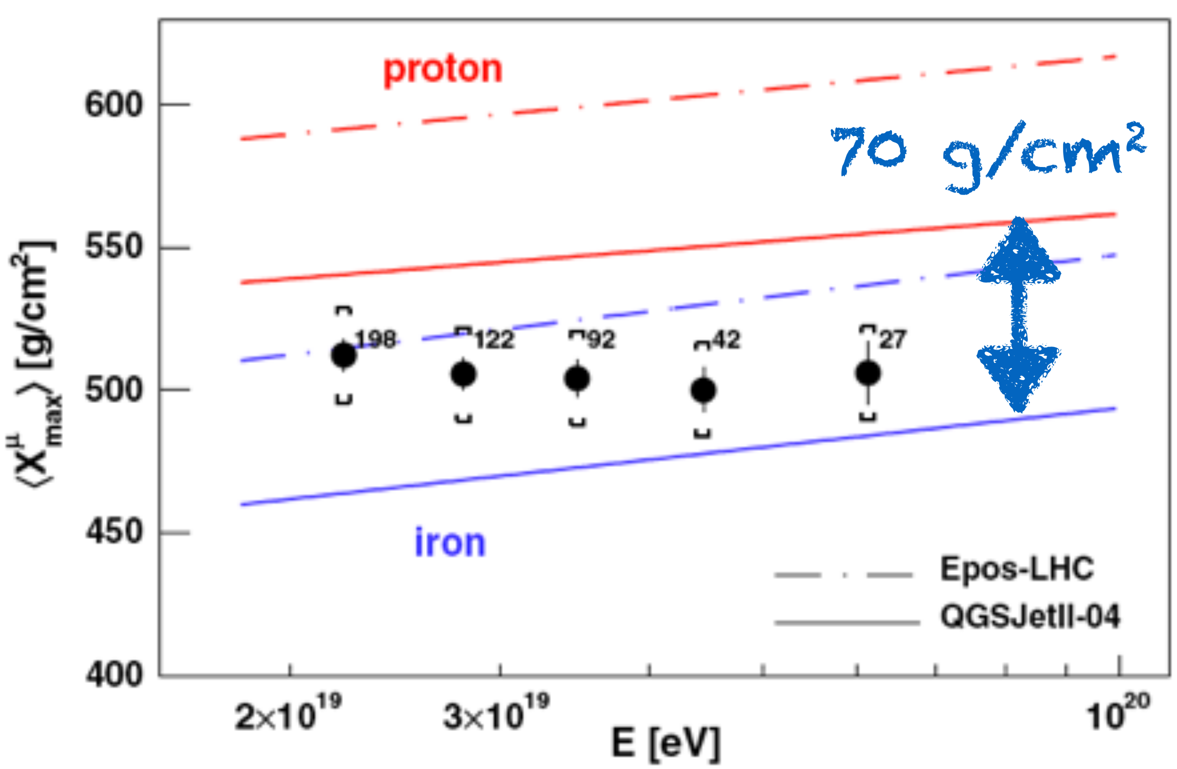


Mass composition from SD - MPD

Gaisser Hillas profile $\rightarrow X^{\mu}_{\max}$





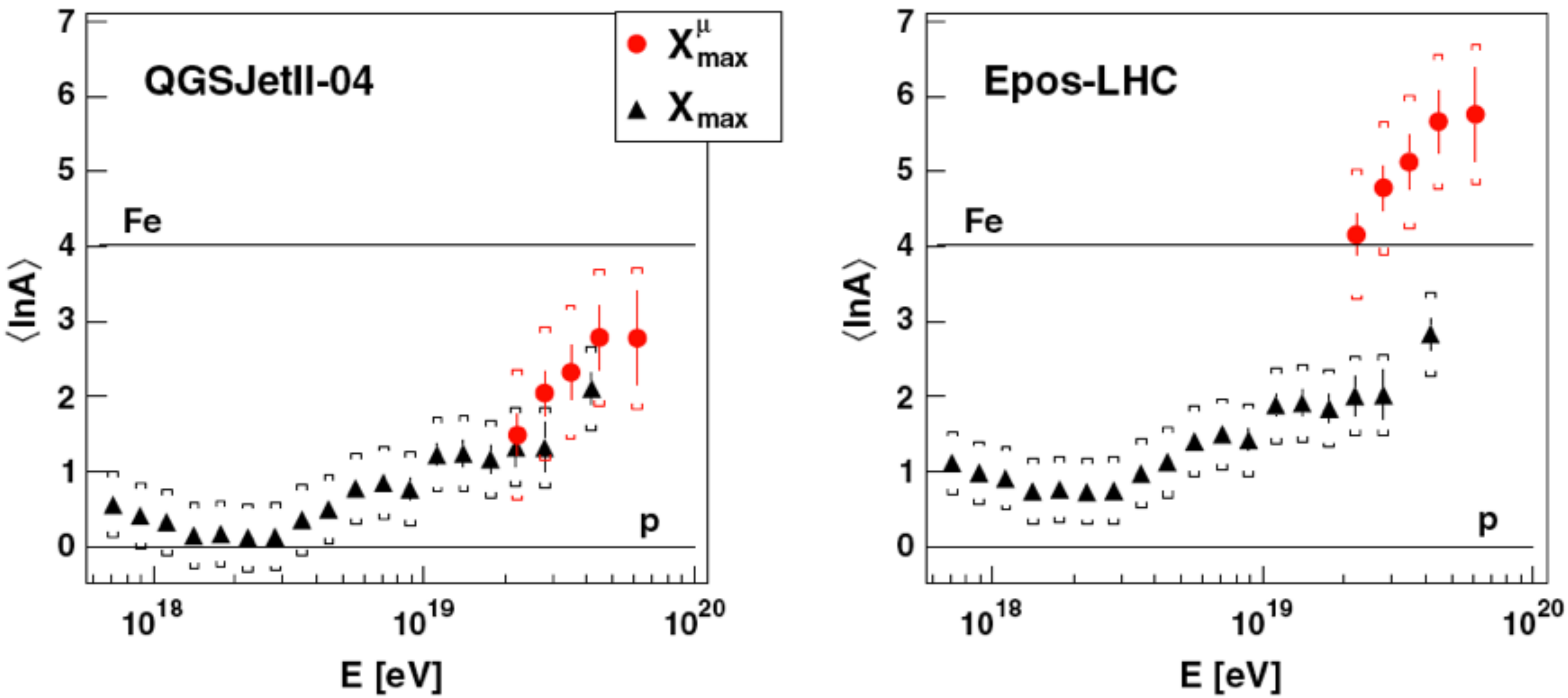


- Novel approach to study longitudinal profile
- Agree with conclusion of Xmax
  (but compatible with constant composition)
- Needs to be extended to more data
  (find methods to measure muons directly)

Interpreting X_{max} and X^{μ}_{max}

$$\langle \ln A \rangle = \ln 56 \frac{X^{p}_{max} - \langle X_{max} \rangle}{X^{p}_{max} - X^{Fe}_{max}} \qquad \langle \ln A \rangle^{\mu} = \ln 56 \frac{X^{\mu p}{}_{max} - \langle X^{\mu}{}_{max} \rangle}{X^{\mu p}{}_{max} - X^{\mu Fe}{}_{max}}$$

lnA



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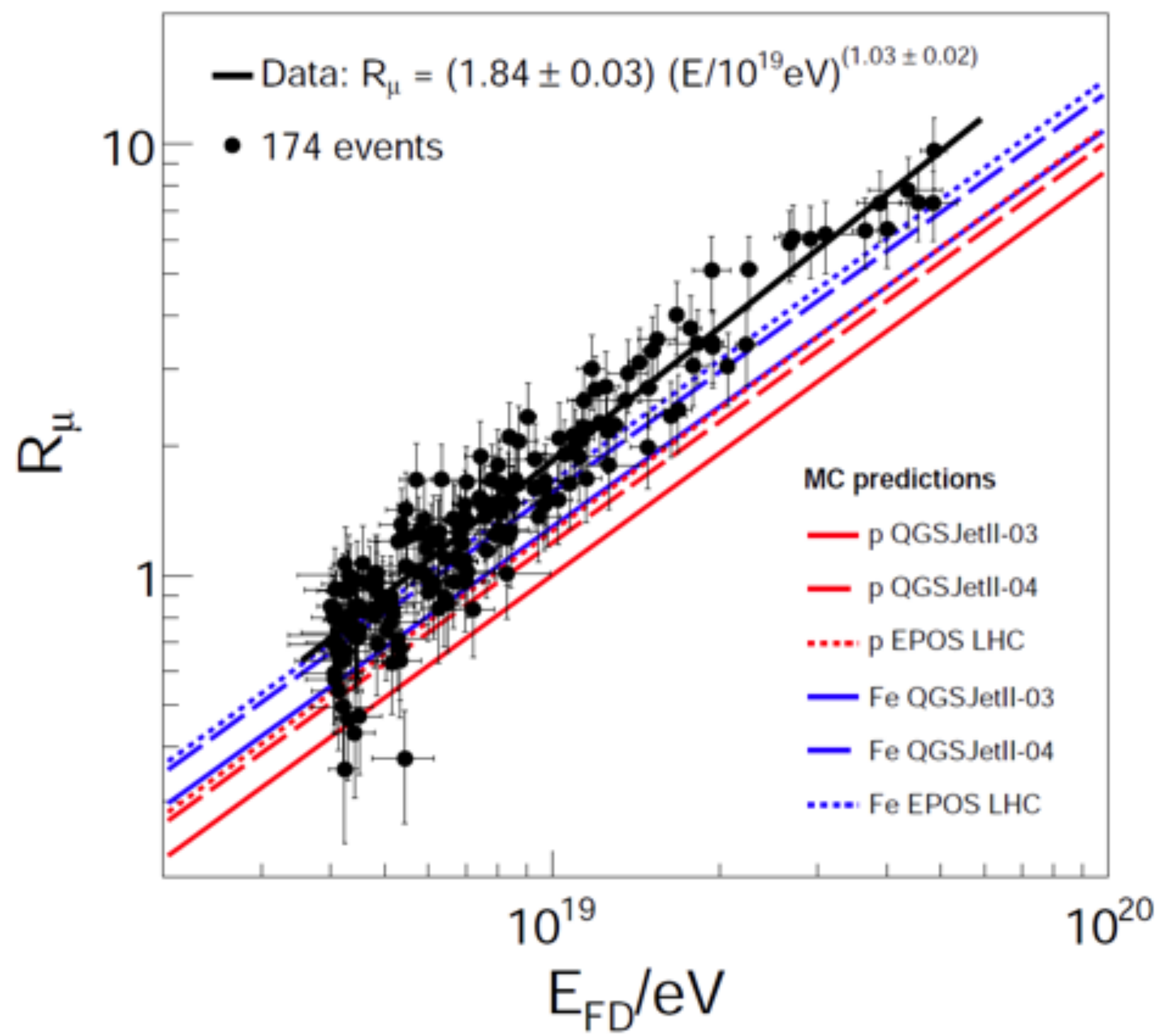
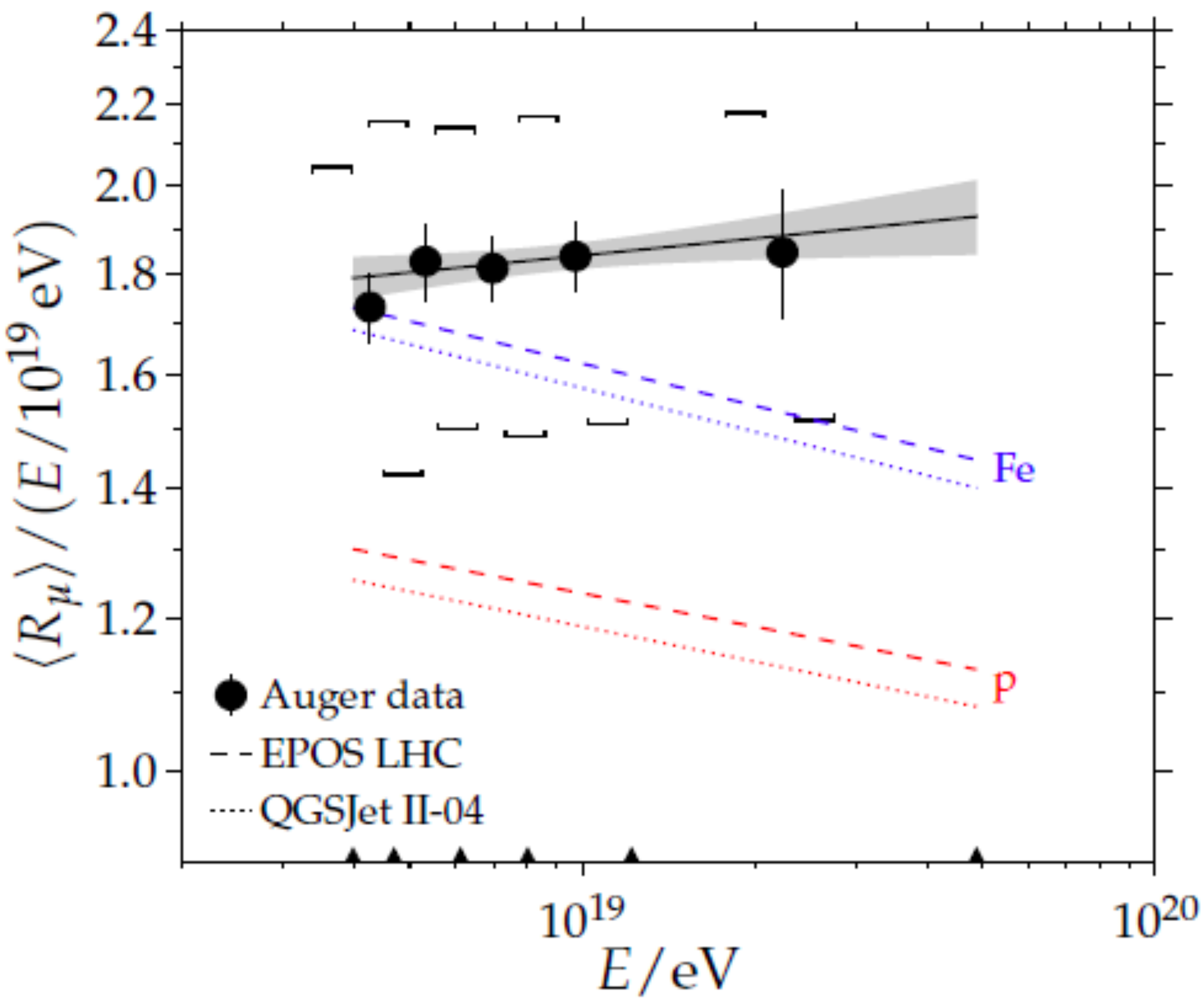
Data are not consistently reproduced by models

Muon deficit in inclined showers

Rμ is N_{19}, the estimated number of muons, corrected from hadronic model dependency (<3%)





Muon numbers predicted by models are under-estimated by 30 to 80% (20%systematic)

arXiv:1408.1421v2

Mass composition - from Xmax to lnA

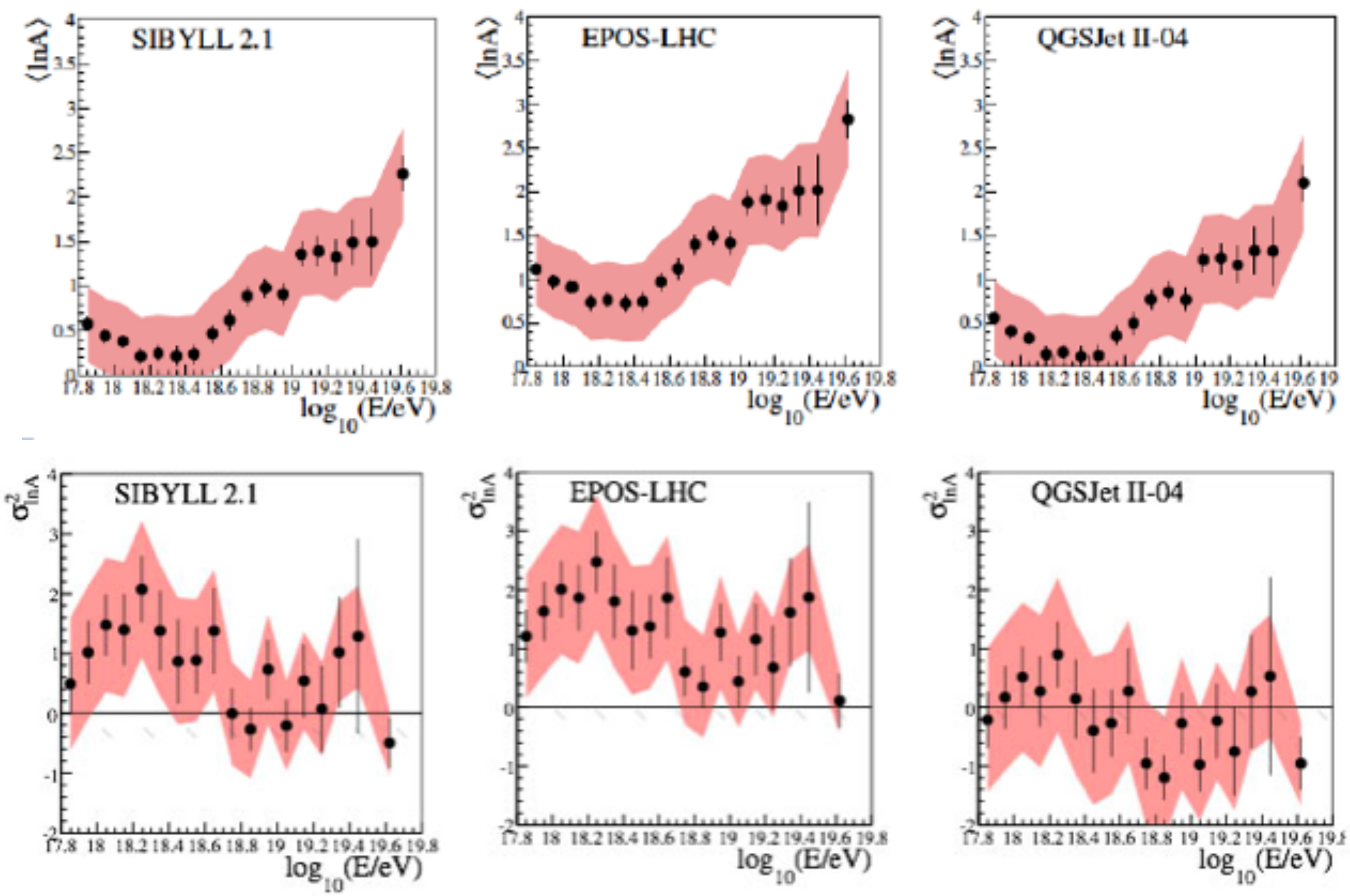
$$\langle X_{max}\rangle \simeq \langle X^{p}_{max}\rangle - D_p \langle \ln A\rangle \qquad \langle \ln A\rangle = \sum f_i \ln A_i$$

$$\sigma(X_{max})^2 \simeq \langle \sigma_i^2\rangle + D_p^2\, \sigma(\ln A)^2 \qquad \sigma(\ln A)^2 = \langle(\ln A)^2\rangle - \langle \ln A\rangle^2$$

D_p elongation rate <σi> mass-averaged fluctuations

lnA

σ(lnA)2



Average composition

<lnA> = 4 pure Fe

<lnA> ~ 2 50%Fe 50% p

<lnA>=0 pure p

Dispersion of masses at ground (source or propagation)

σ(lnA)=0 pure p or Fe

σ(lnA) ~ 4 50%Fe 50% p

- <ln A > minimum in ankle region
- Energy evolution common to all models <lnA> increasing from light to medium
- The mix include intermediates species