PIERRE AUGER OBSERVATORY

Recent results from the Pierre Auger Observatory

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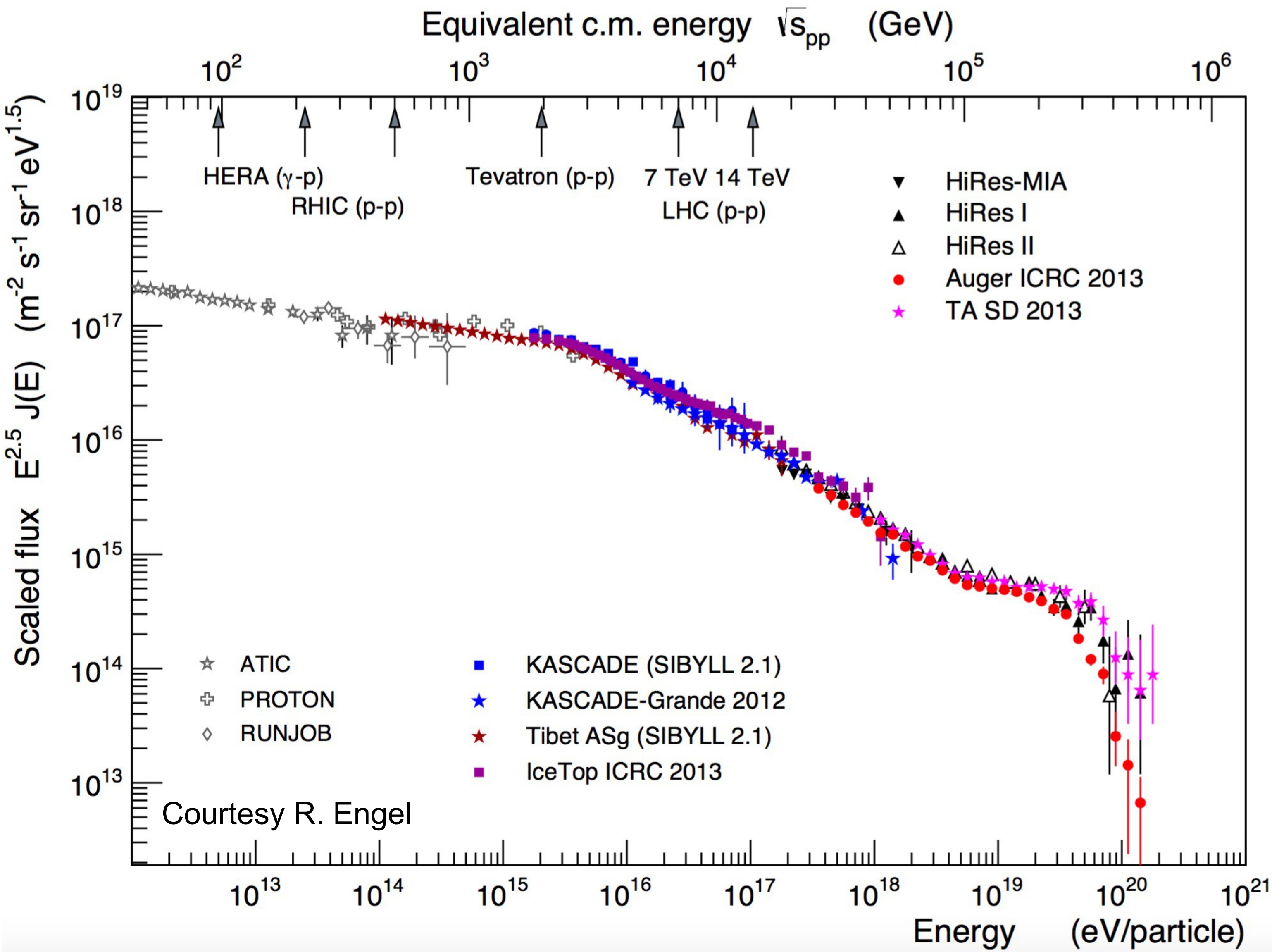
http://www.auger.org/archive/authors_2016_04.html

Workshop on Perspectives on the Extragalactic Frontier: from Astrophysics to Fundamental Physics, ICTP, Trieste, 03.05.2016

UHECR: key problems of astrophysics & fundamental physics



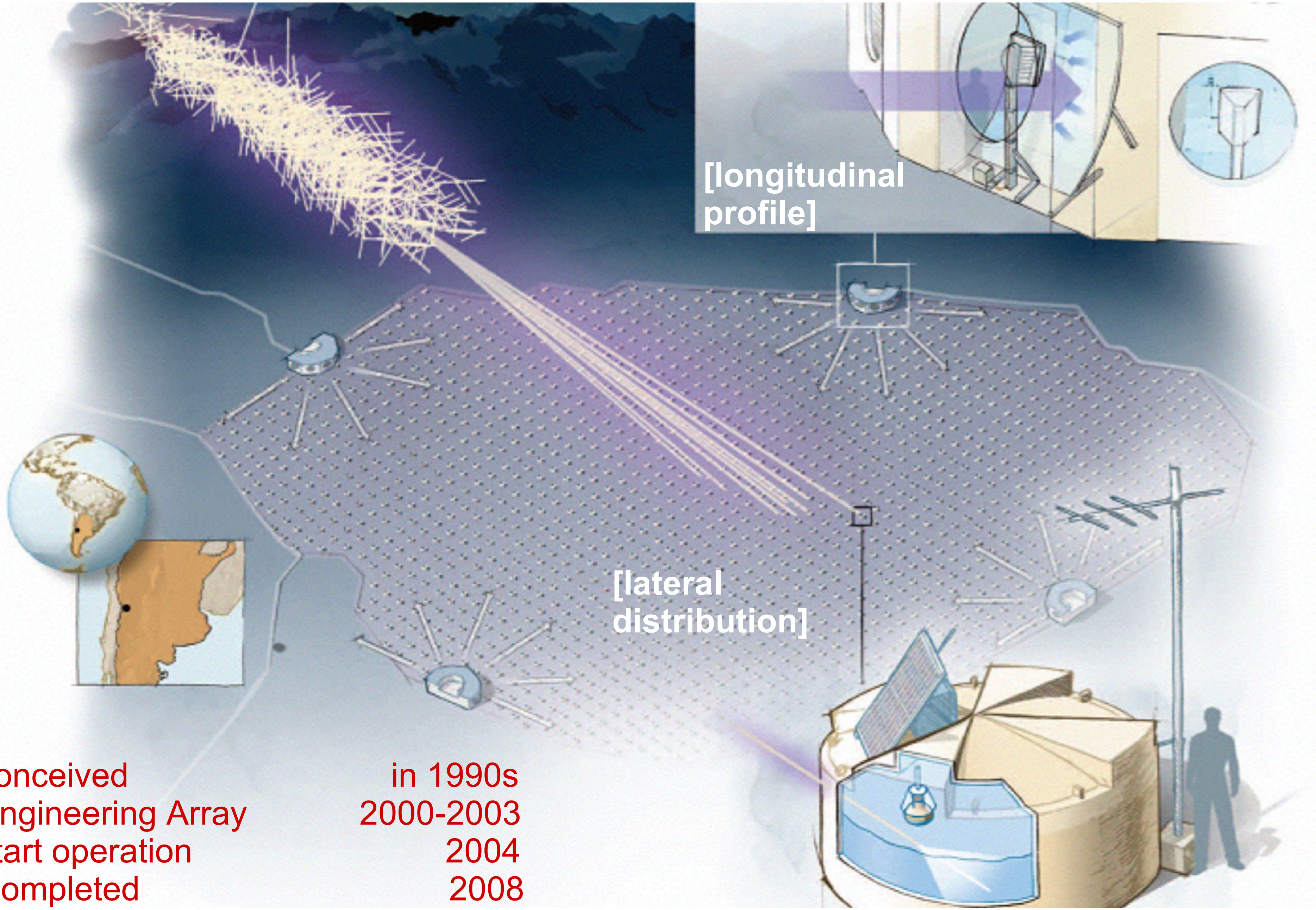
Cosmic particle accelerators

UHECR energy spectrum, mass composition, arrival directions

Particle interactions at the energies inaccessible in laboratory

Validity of interaction models at the extreme CR energies

PAO hybrid design for CR detection above 10^{17} eV

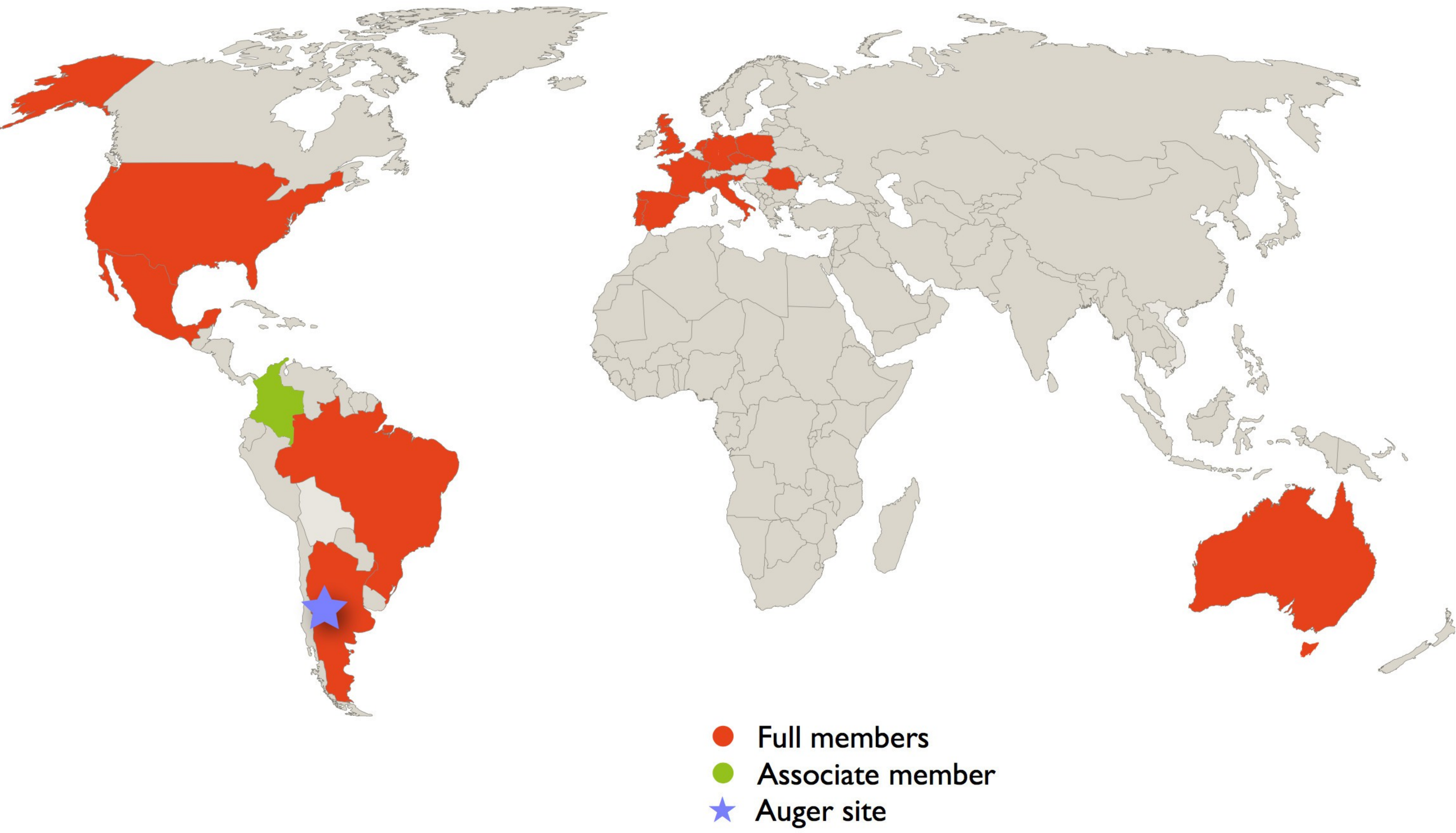


conceived	in 1990s
Engineering Array	2000-2003
start operation	2004
Completed	2008
Upgrade “AugerPrime”	2016-2018
Planned operations	≥ till 2025

+ radio antennas, muon detectors
+ atmospheric monitoring, ...

The Pierre Auger Collaboration

About 450 people from 16 countries and 68 institutions



The Pierre Auger Observatory

Surface detector (SD) duty cycle 100%

SD-1500 m

3000 km^2 area

1600 water-Cherenkov detectors (WCDs)

SD-750 m

23.5 km^2 area

61 WCDs

Fluorescence detector (FD) duty cycle 15%

5 units at 4 locations

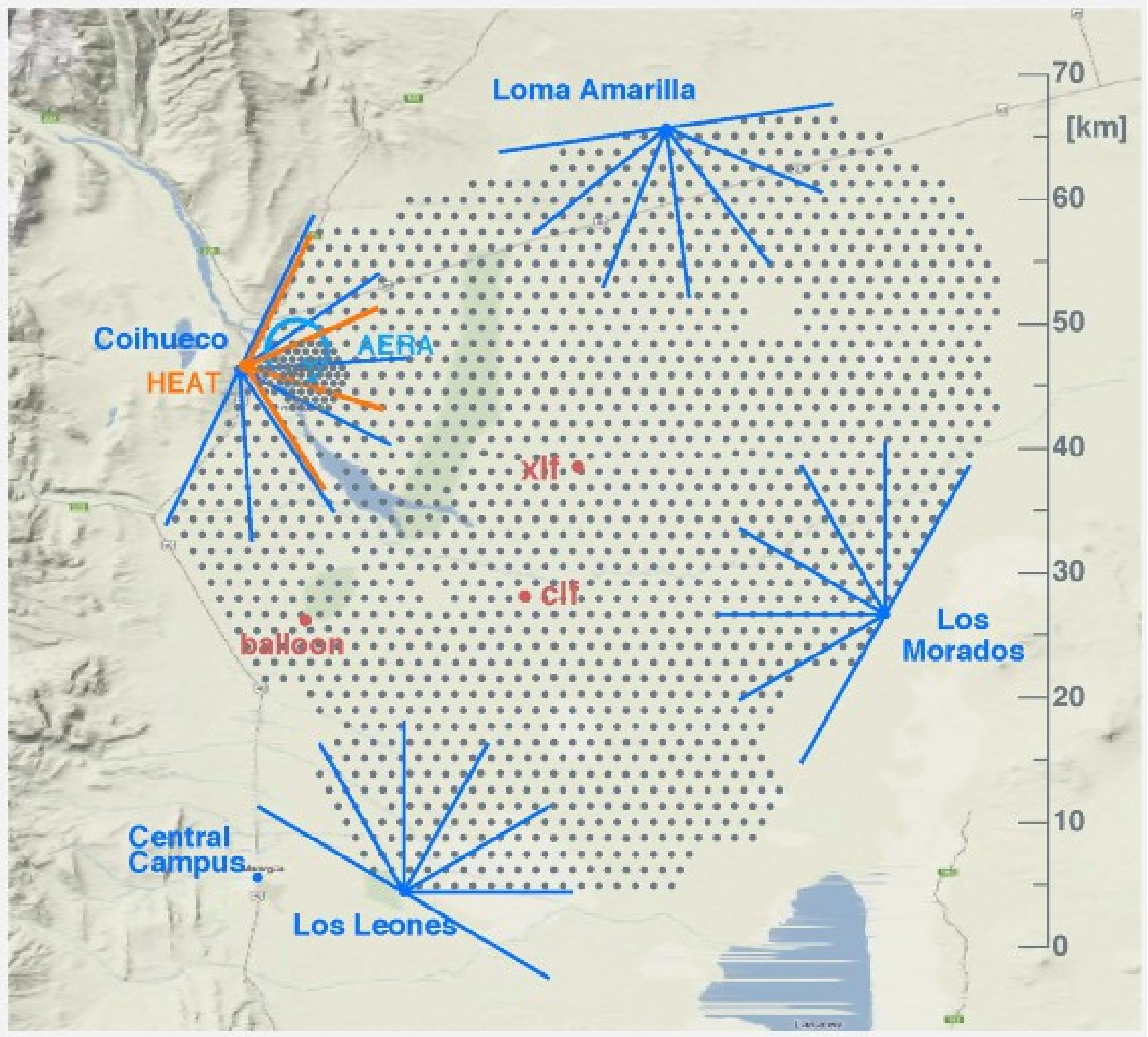
4 units × 6 fluorescence telescopes overlooking SD-1500 m array

FOV 30° × 30° in azimuth and elevation

minimum elevation of 1.5°

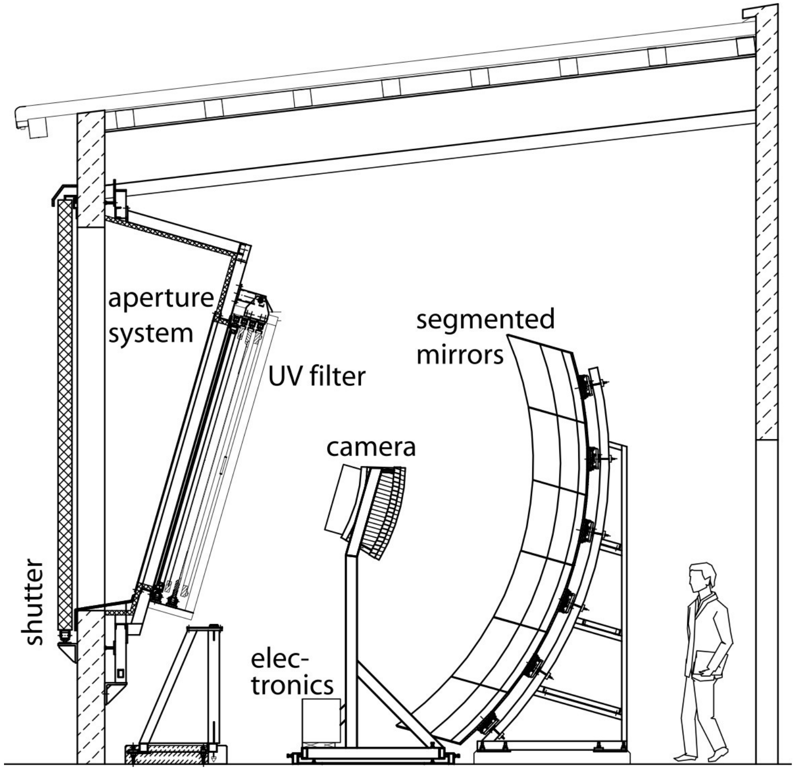
1 unit × 3 fluorescence telescopes (HEAT) overlooking SD-750 m array

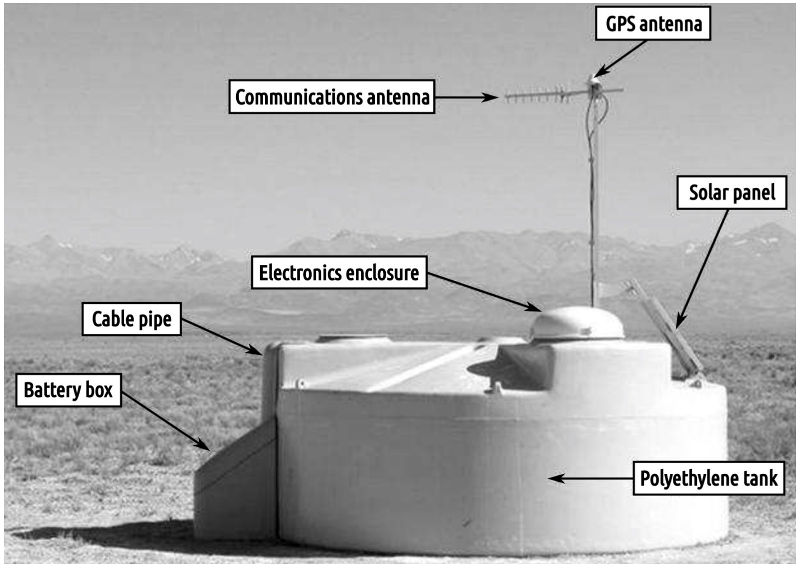
FOV [30°, 60°] in elevation



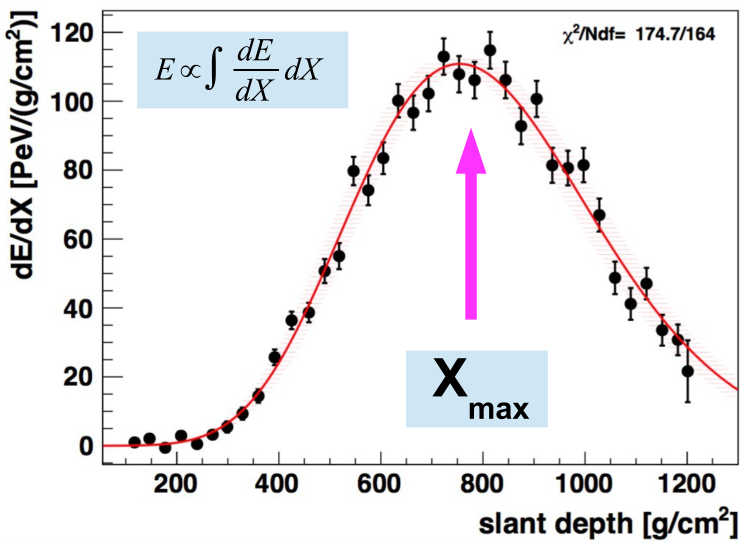
Auger Coll., Nucl. Instrum. Meth. A798 (2015) 172

The Pierre Auger Observatory

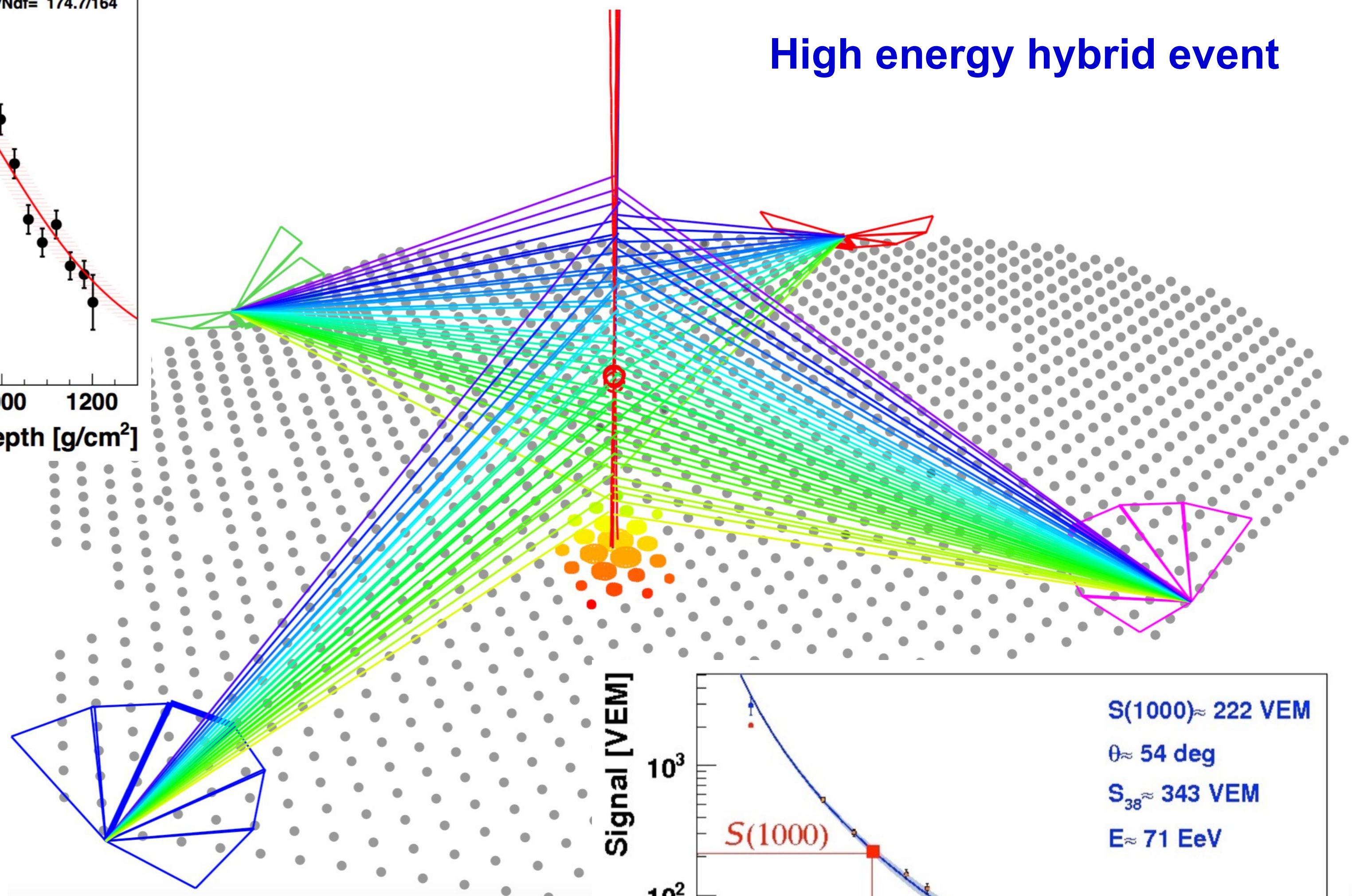




Primary CR reconstruction

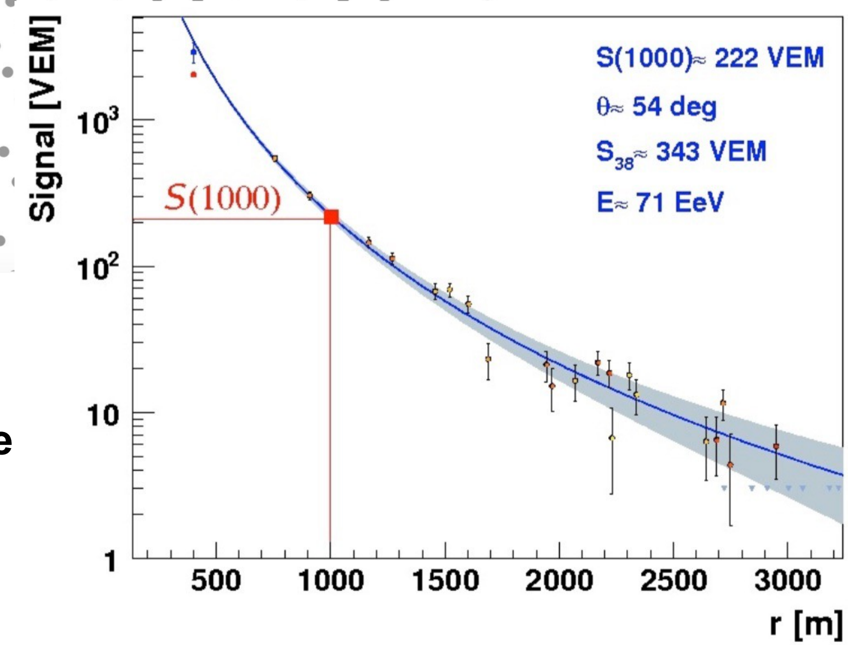


High energy hybrid event



FD energy: integral of the longitudinal profile

FD: position Xmax of the shower maximum => information on the primary mass

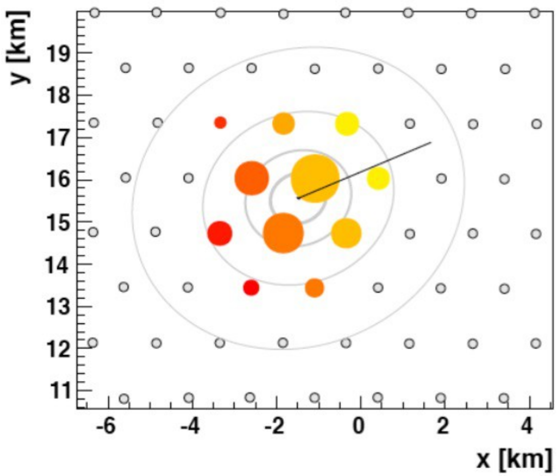


SD energy: ∝ signal S(1000) at 1 km from the shower core

SD: shower geometry (core position and arrival direction)

Auger events

SD-1500 m, θ < 60°



Vertical events

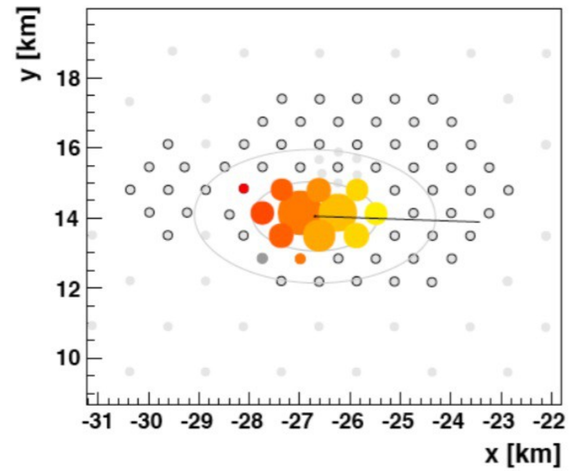
fully efficient:

E > 3 EeV

energy estimator:

S38

SD-750 m, θ < 55°



“Infill” events

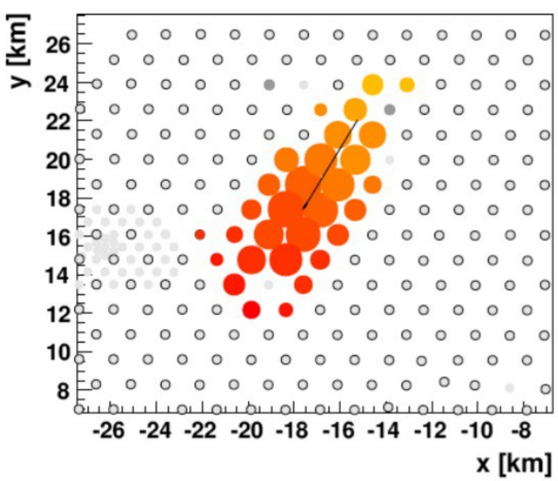
fully efficient:

E > 0.3 EeV

energy estimator:

S35

SD-1500 m, 60° < θ < 80°



Inclined events

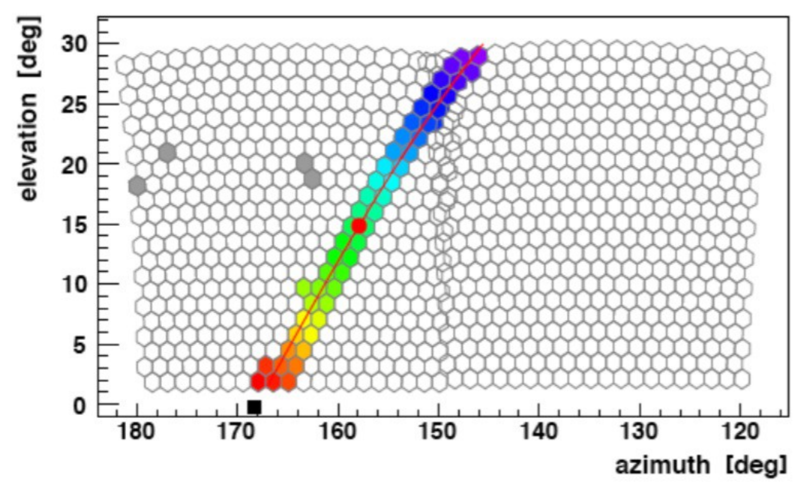
fully efficient:

E > 4 EeV

energy estimator:

N19

Hybrid (FD + ≥ 1 SD), θ < 60°



Hybrid events

fully efficient:

E > 1 EeV

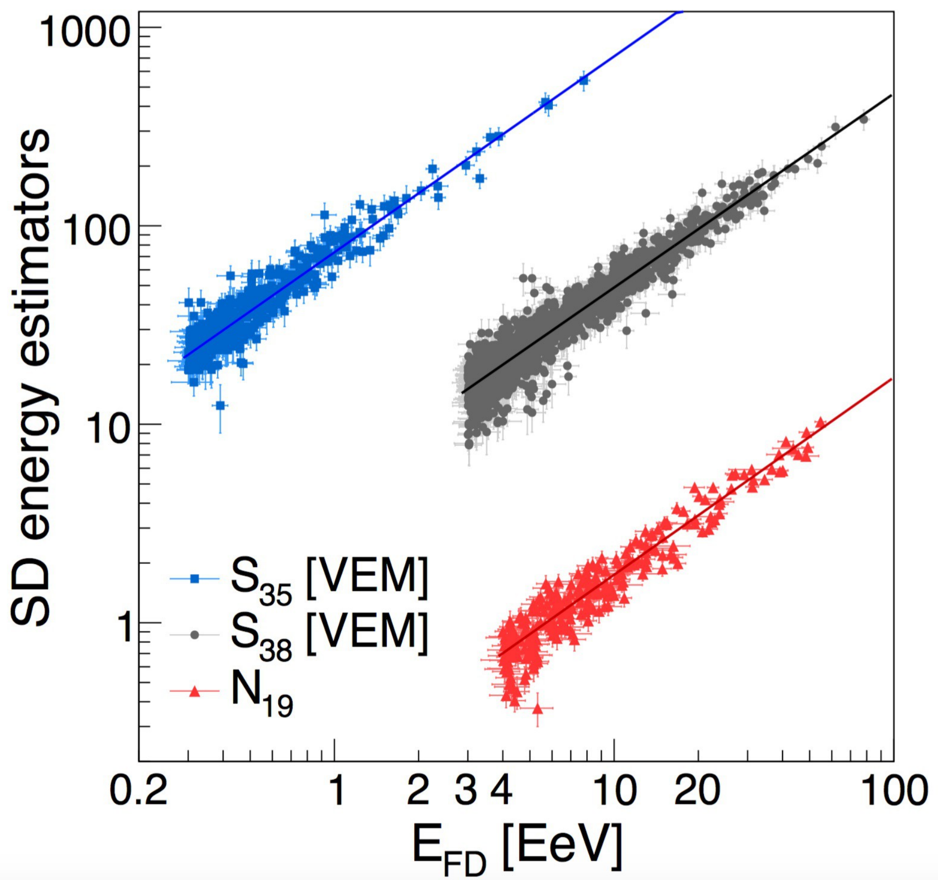
energy measured

Combined measurement allows to cover 3 decades in energy

Auger energy calibration & systematics

FD: the common energy scale

free of SD-related uncertainties (cascade simulation + hadronic interaction models)



Energy systematic uncertainties:

FD calibration: 9.9%

FD profile reconstruction 6.5-5.6%

Atmospheric conditions: 3-6%

Stability of the energy scale 5%

Fluorescence yield: 3.6%

Invisible energy 3-1.5%

Statistical error of SD calibration fit 0.7-1.8%

FD energy scale: 14%

SD resolutions for energy reconstruction:

S(1000): 22% (@3 EeV) to 12% (highest E)

Energy: 16% (@3 EeV) to 12% (highest E)

Hybrids (FD + at least 1 SD station):

Energy resolution 8%

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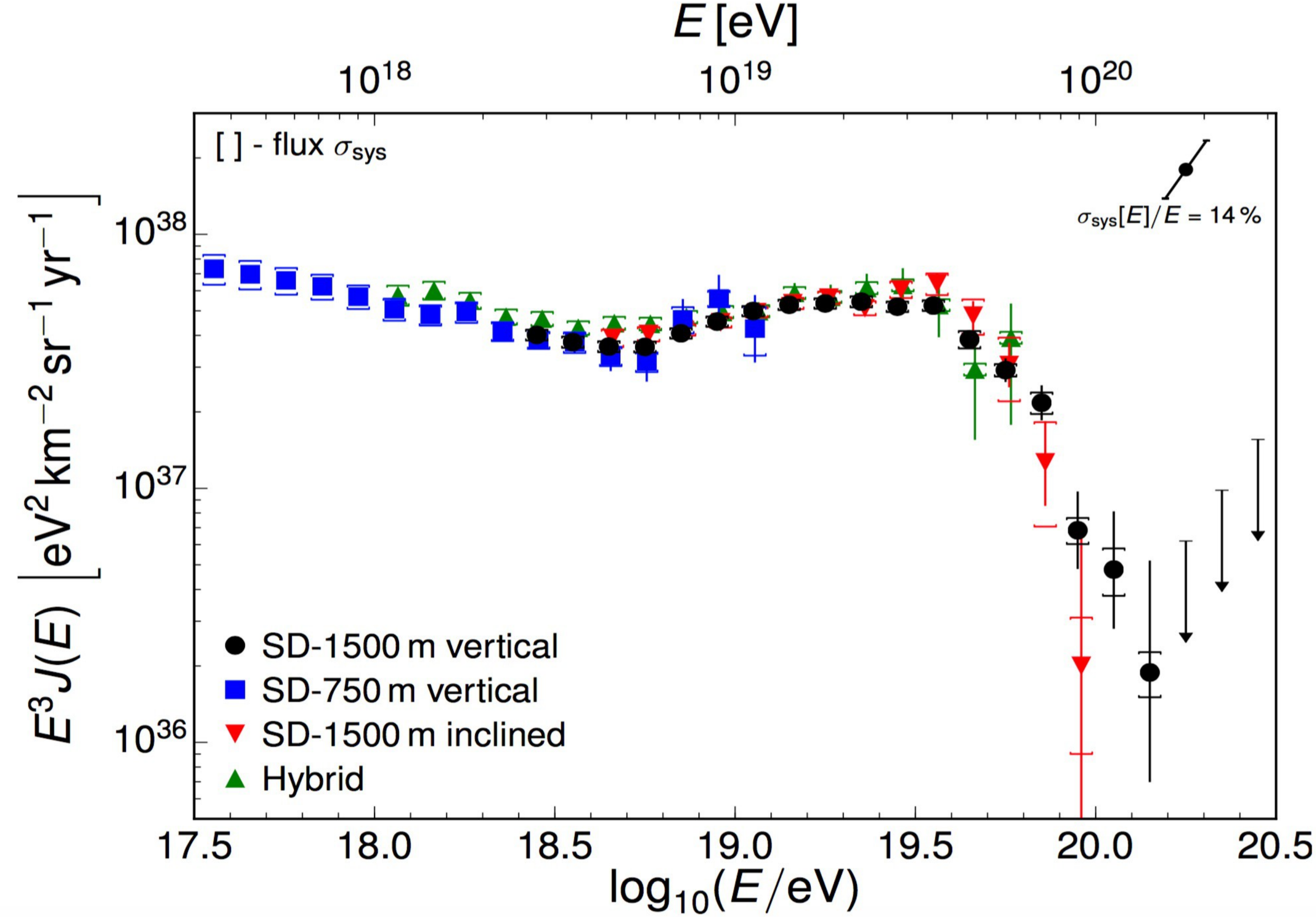
Energy spectra from SD and hybrid data



	SD-1500 m		SD-750 m	Hybrid
	vertical	inclined		
Data-taking period	01/2004–12/2014	01/2004–12/2013	08/2008–12/2014	11/2005–12/2013
Exposure [km^2 sr yr]	42500±1300	10900±300	150±5	1500±20 at 10^{19} eV
Number of events	**102901**	**15614**	**61130**	**9346**

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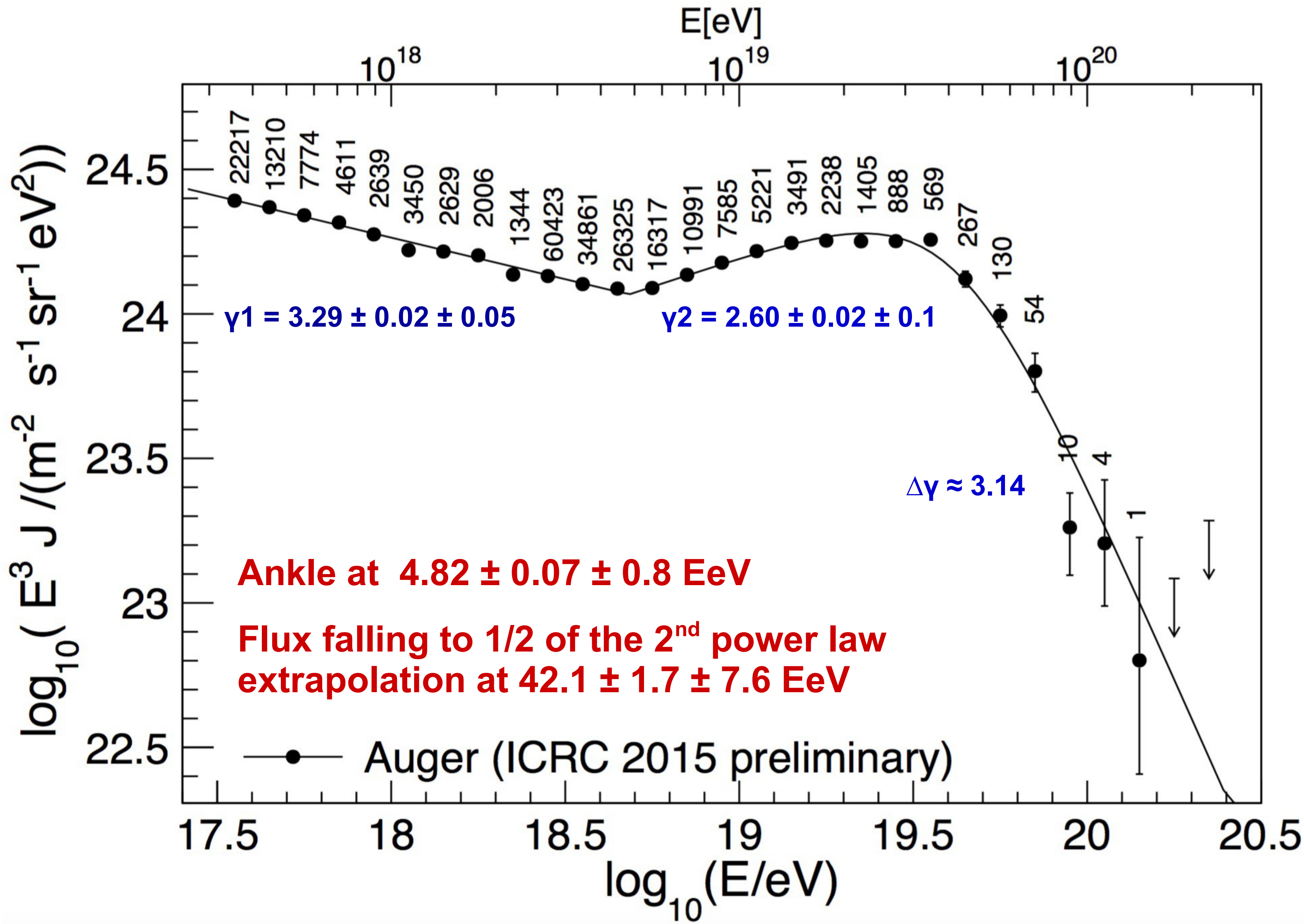
Auger all-particle CR spectrum

Combined maximum-likelihood fit, the normalisations of the different spectra are allowed to vary within the corresponding uncertainties



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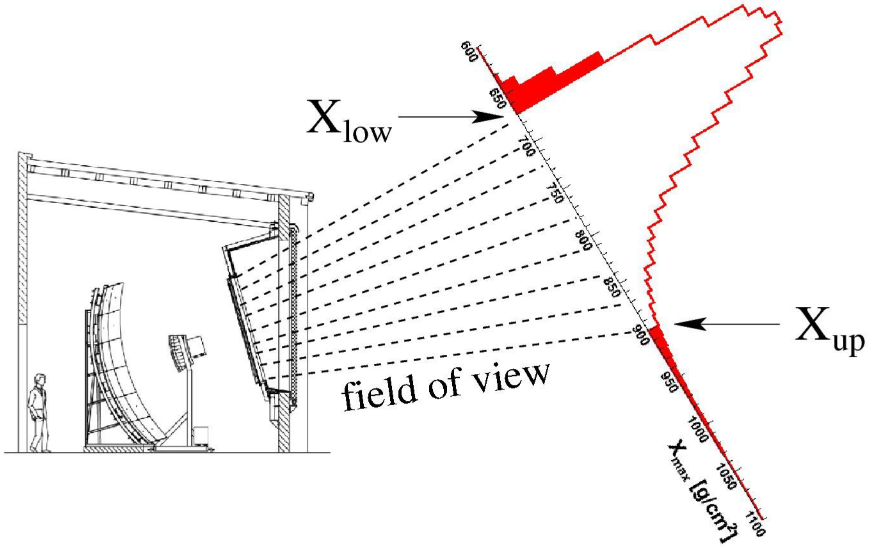
Update on X_{max} measurements



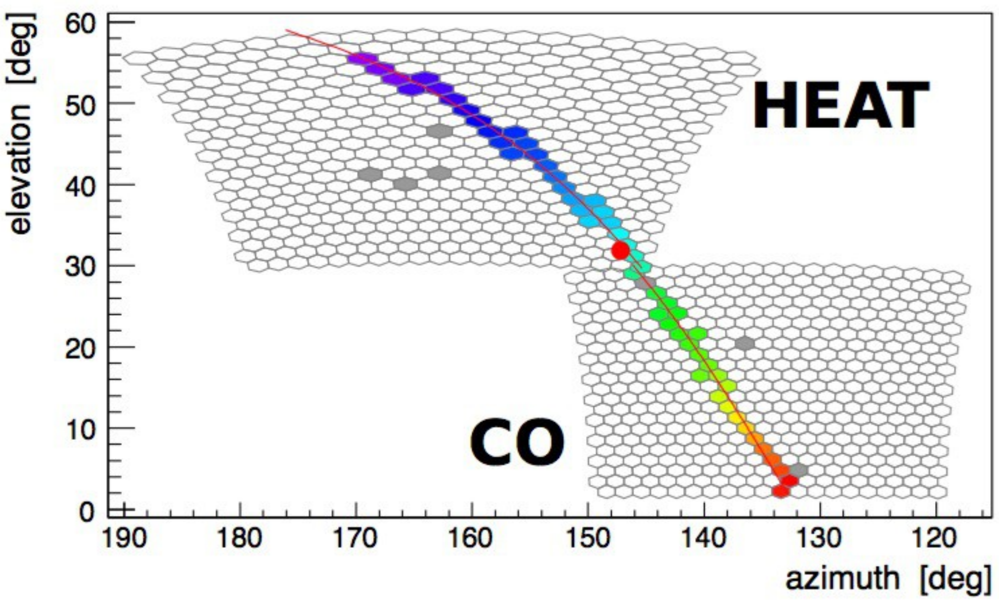
robust mass-sensitive EAS observable

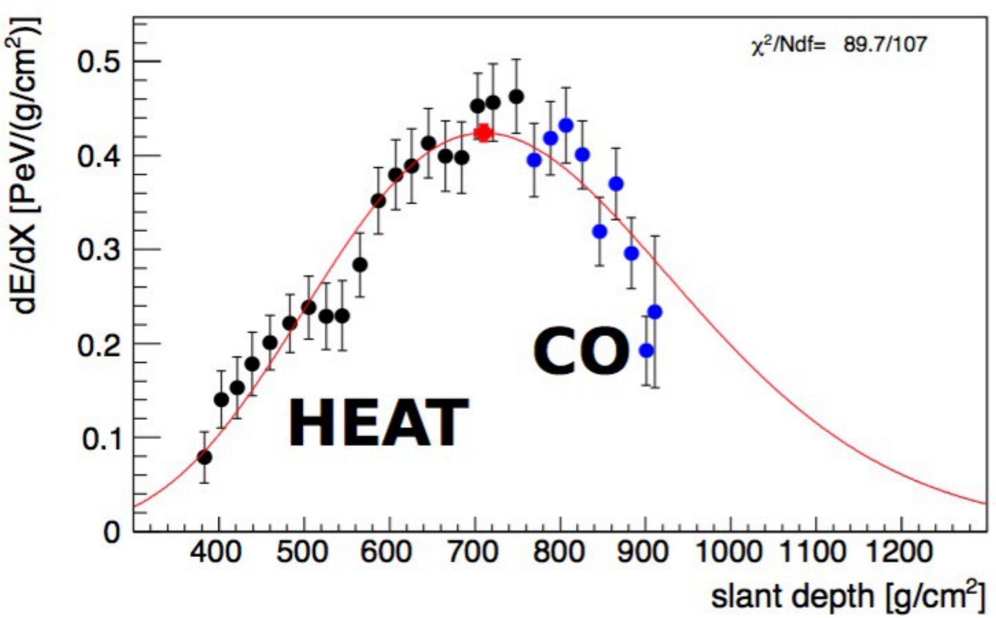
uncertainties due to models << difference proton-iron

Extending analysis down to 0.1 EeV using HEAT

hybrid events used

Xmax resolution < 30 (20) g/cm^2 above 0.1 (0.63) EeV





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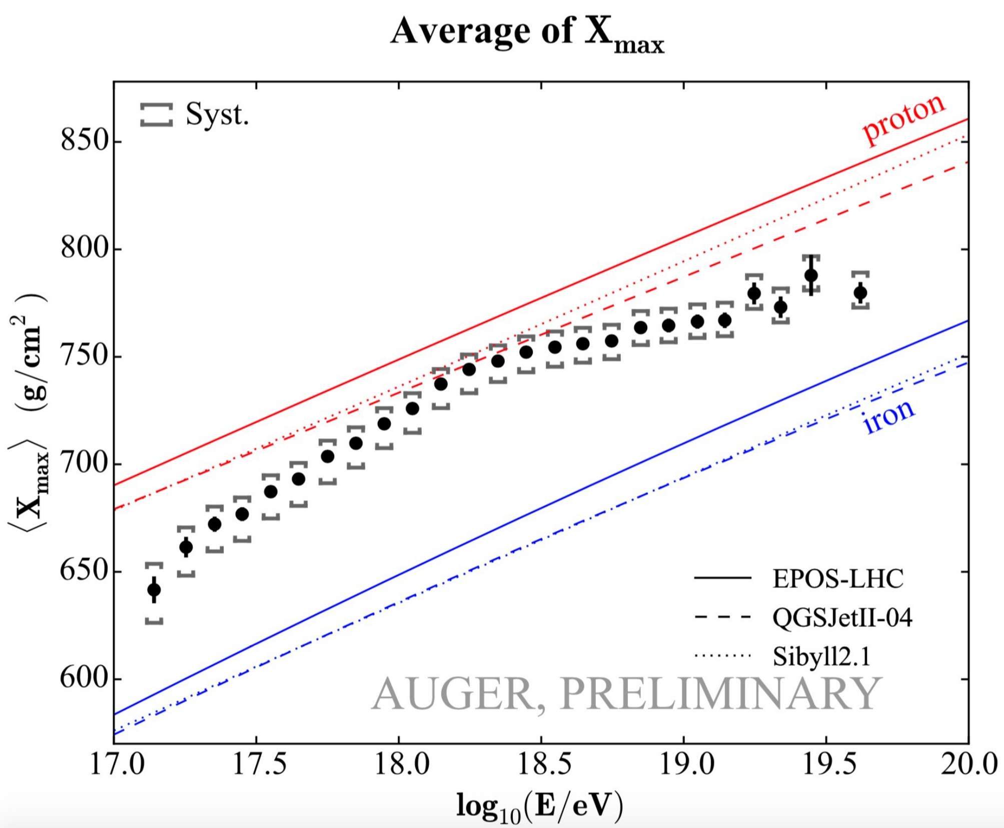
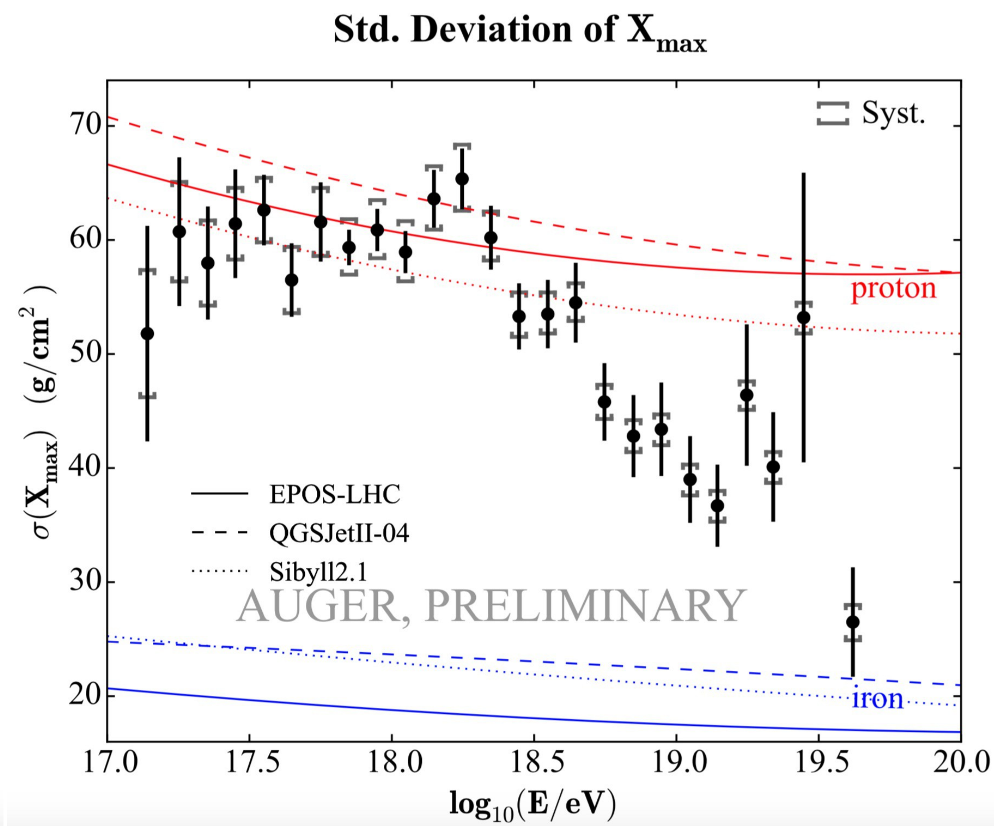
First two moments of X_{max} distributions





Below ≈ 2 EeV, <Xmax> increases by ≈ 85 g cm^{-2} per energy decade

Above this energy, <Xmax> decreases by ≈ 26 g cm^{-2} per energy decade

=> the composition is getting lighter (heavier) below (above) ≈ half of the ankle energy

Auger Coll., PRD 90 (2014) 122005

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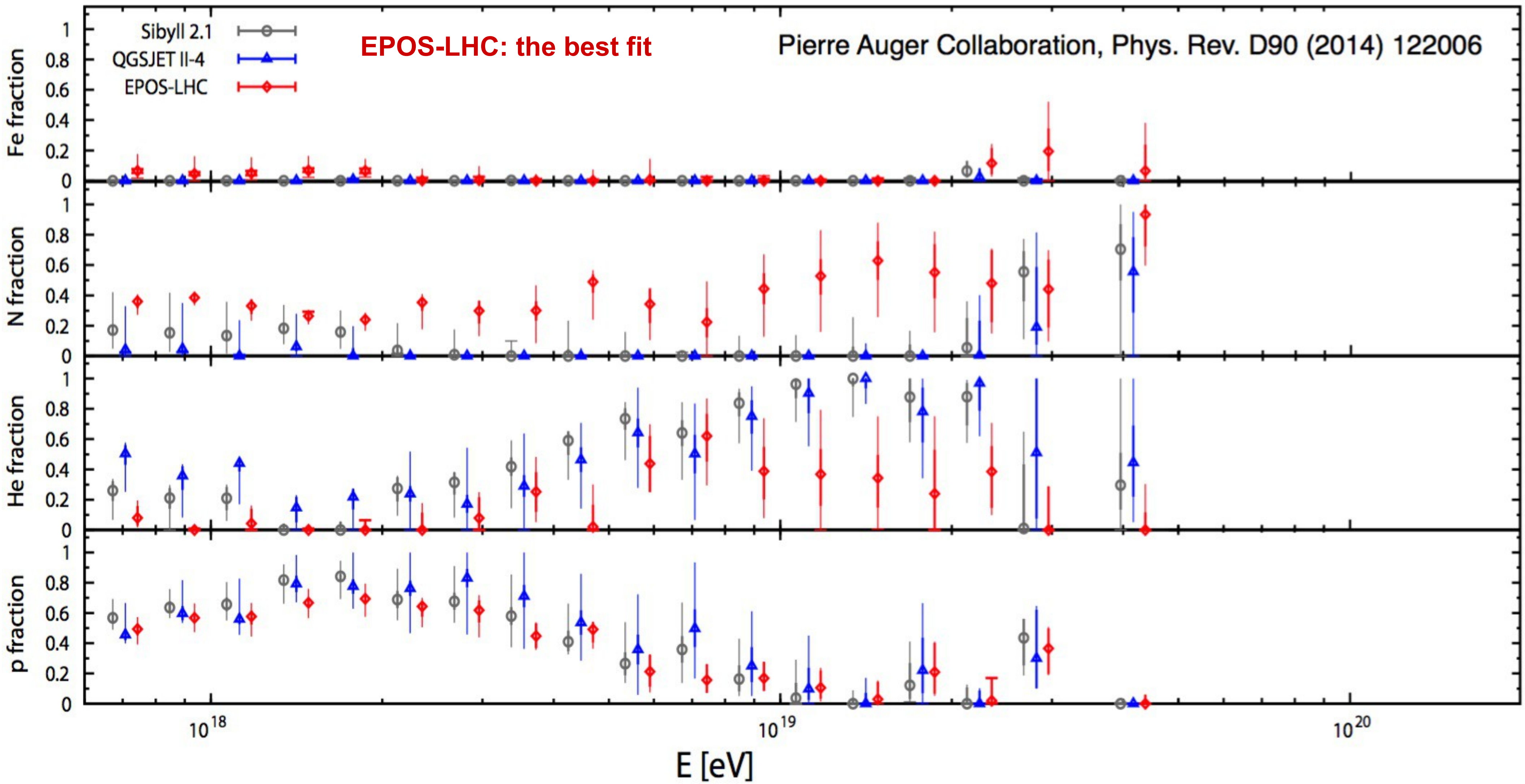
Elemental primary CR fractions from X_{max} fits

Three hadronic models used to fit the data with 2, 3 or 4 (p, He, N, Fe) elemental groups



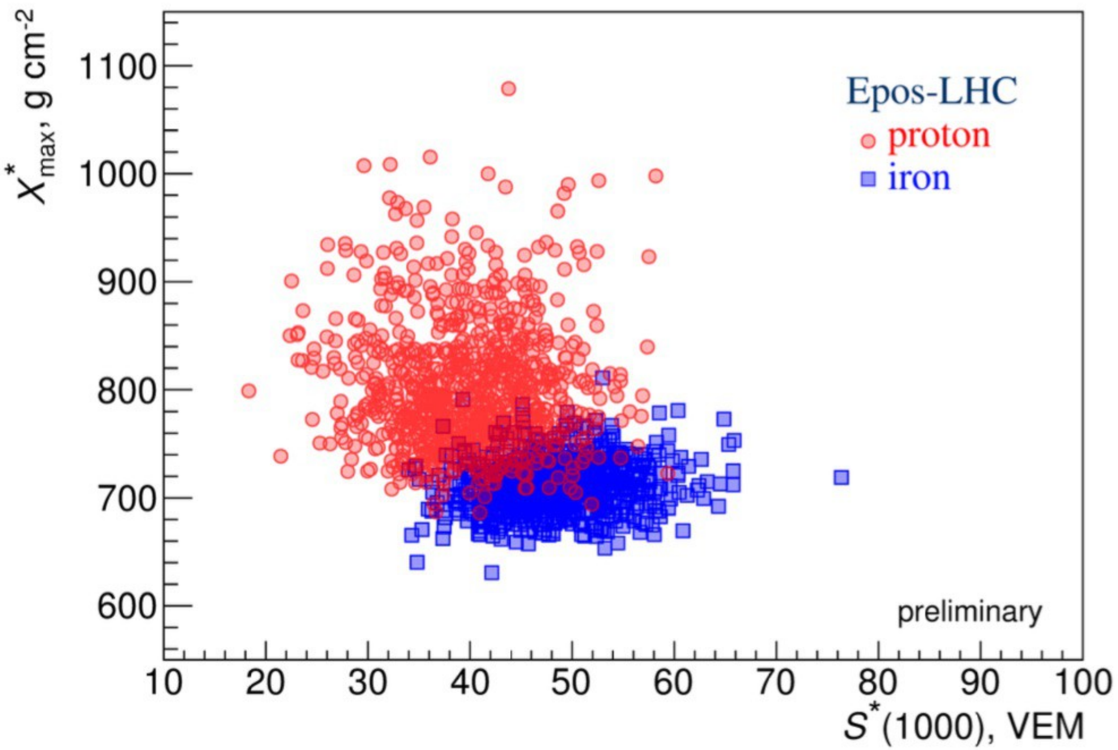
Iron fraction is almost absent, fractions of p and He change strongly with energy

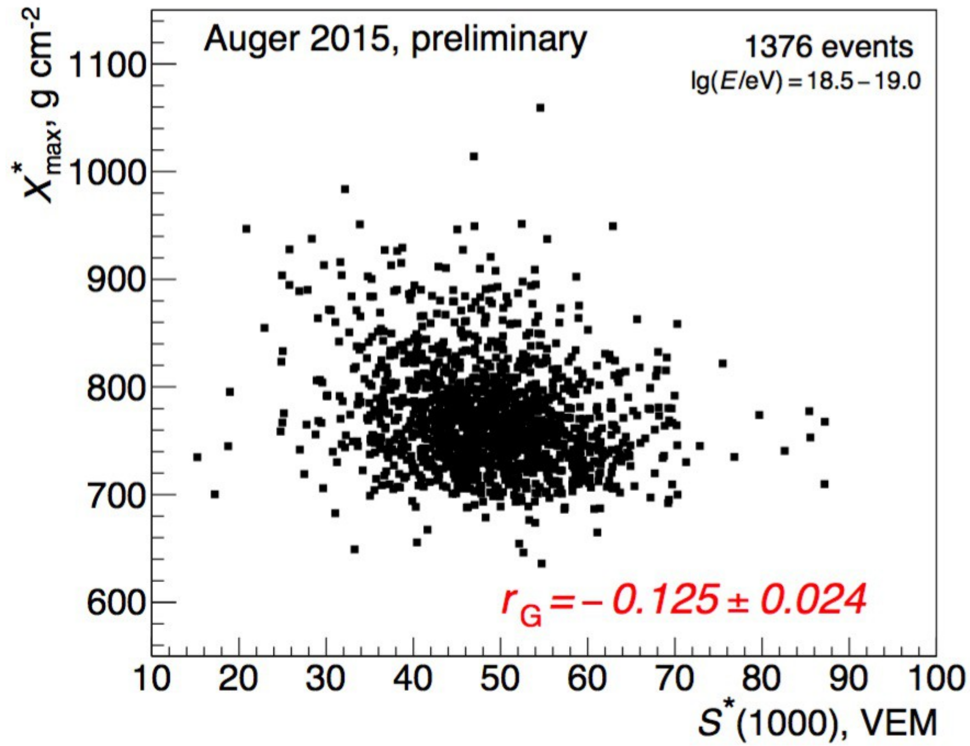
Proton fraction present at 30 EeV ?!

Composition at the ankle: a joint X^*_{max} & S*(1000) analysis

lighter nuclei produce deeper showers with smaller signal (less muons) => S*(1000)

general air shower properties, minor model dependence P. Younk, M. Risse, APh 35 (2012) 807





correlation in the data with lg(E/eV) = 18.5-19.0 compared with simulated primary beams

Correlation coefficient r_G (X^*_{max}, S*(1000)) **≥ 0** for pure beams, EPOS-LHC: 0 (**p**), +0.08 (**Fe**)

r_G (X^*_{max}, S*(1000)) **minimal (negative)** for the **0.5 p – 0.5 Fe** mixture (-0.37 for EPOS-LHC)

In data, r_G = −0.125 ± 0.024 => primary CR composition near the ankle is mixed

X^*_{max} : X_{max} scaled to 10 EeV; S^*(1000): S(1000) scaled to 10 EeV, 38°
r_G : rank correlation coefficient, see R. Gideon, R. Hollister, JASA 82 (1987) 656

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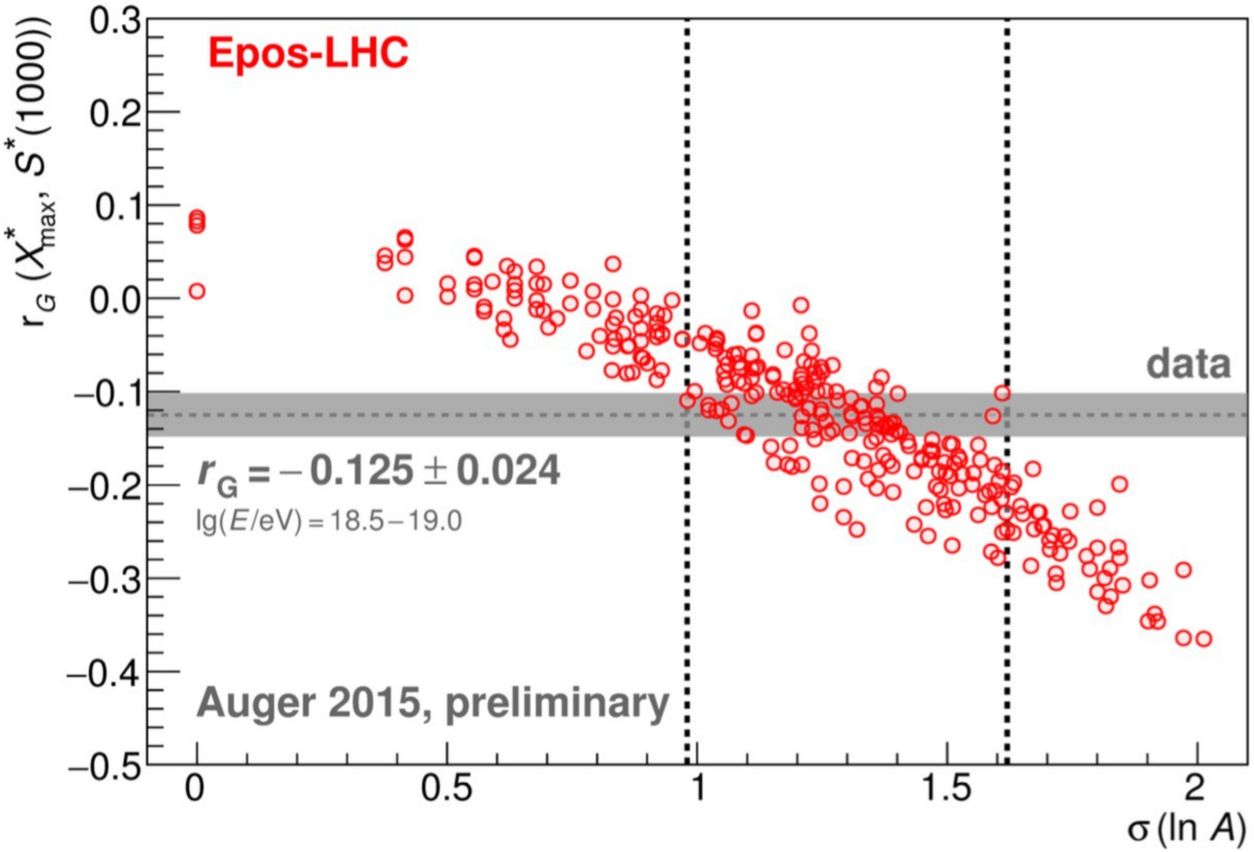
Dispersion of primary CR masses in data

Conversion of Xmax moments to ln A moments applied



Data near the ankle are consistent with 1.0 ≤ σ(ln A) ≤ 1.7 for the three models

Results are robust against modifications of hadronic models

“Dip” model of the ankle is disfavoured

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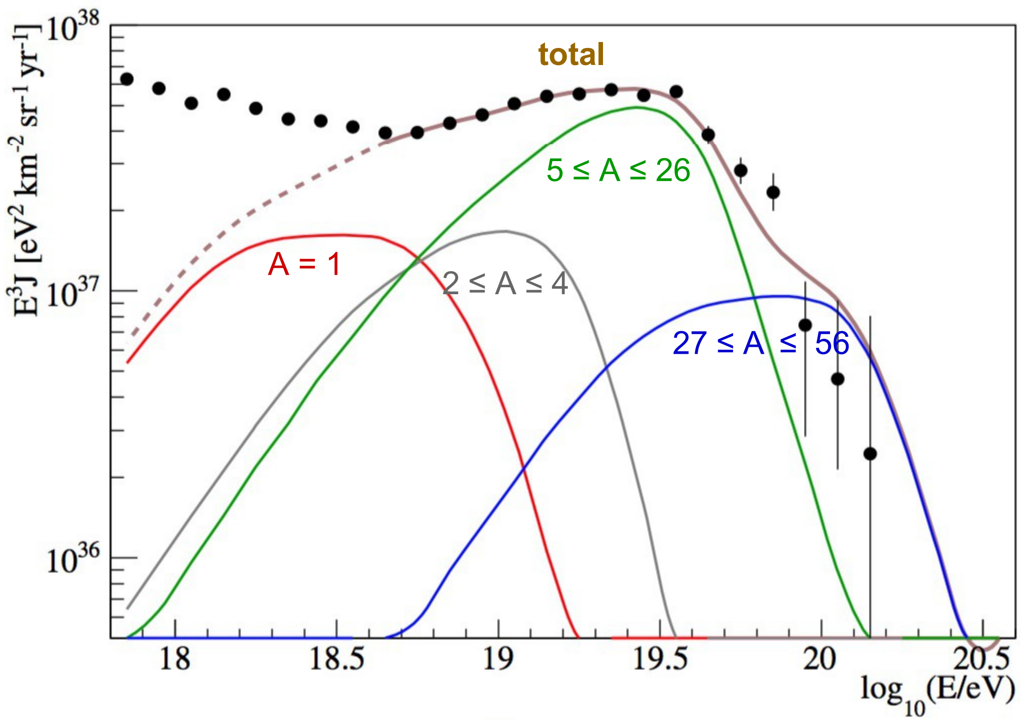
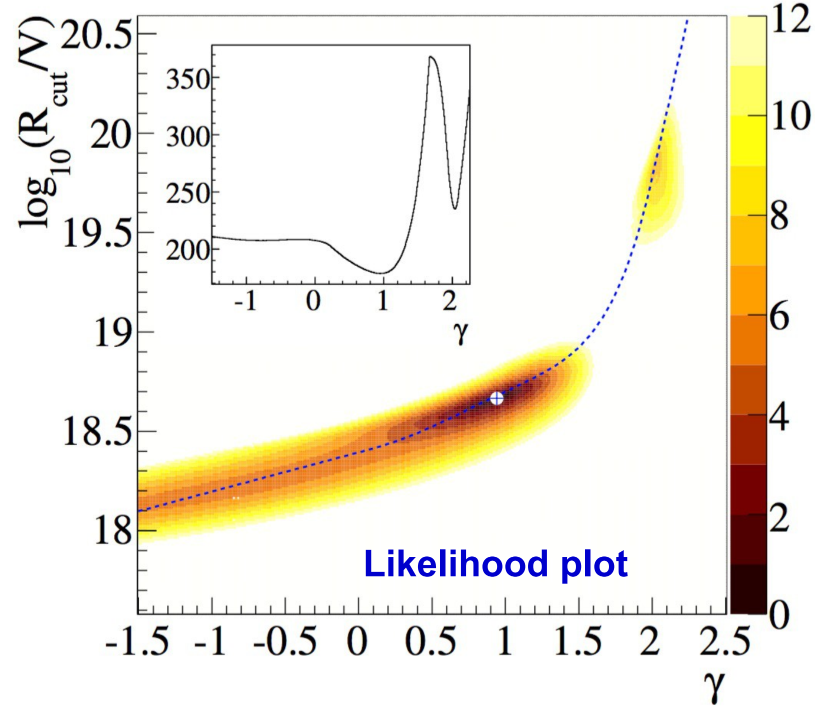
Combined fit of spectrum and composition data

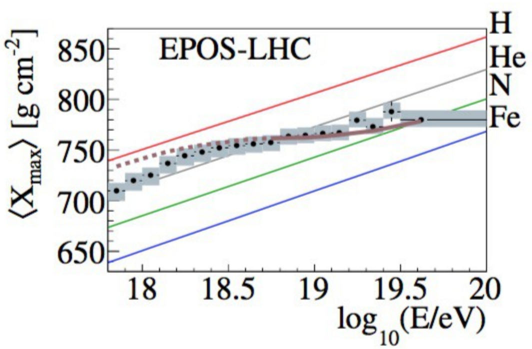
Identical uniformly distributed sources with a rigidity-dependent injection of nuclei

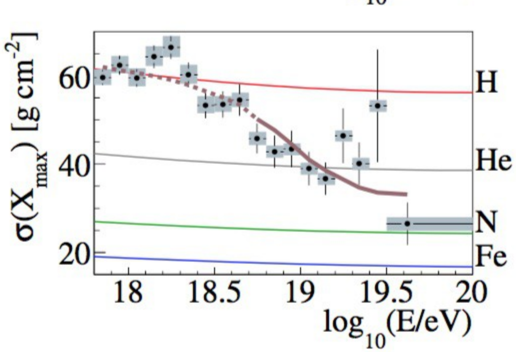
Several CR propagation models cross sections for photo-disintegration and for EBL spectrum

LHC-tuned models for air-shower particle interactions the atmosphere









Best fit: flux limited by max. energy @ sources

Hard injection spectral index γ~1 preferred, with low cutoff energy E ~ Z x 4.7 EeV

Second scenario γ~2, R~70 EV disfavored (~7.5σ): wider mass dispersion than in the data

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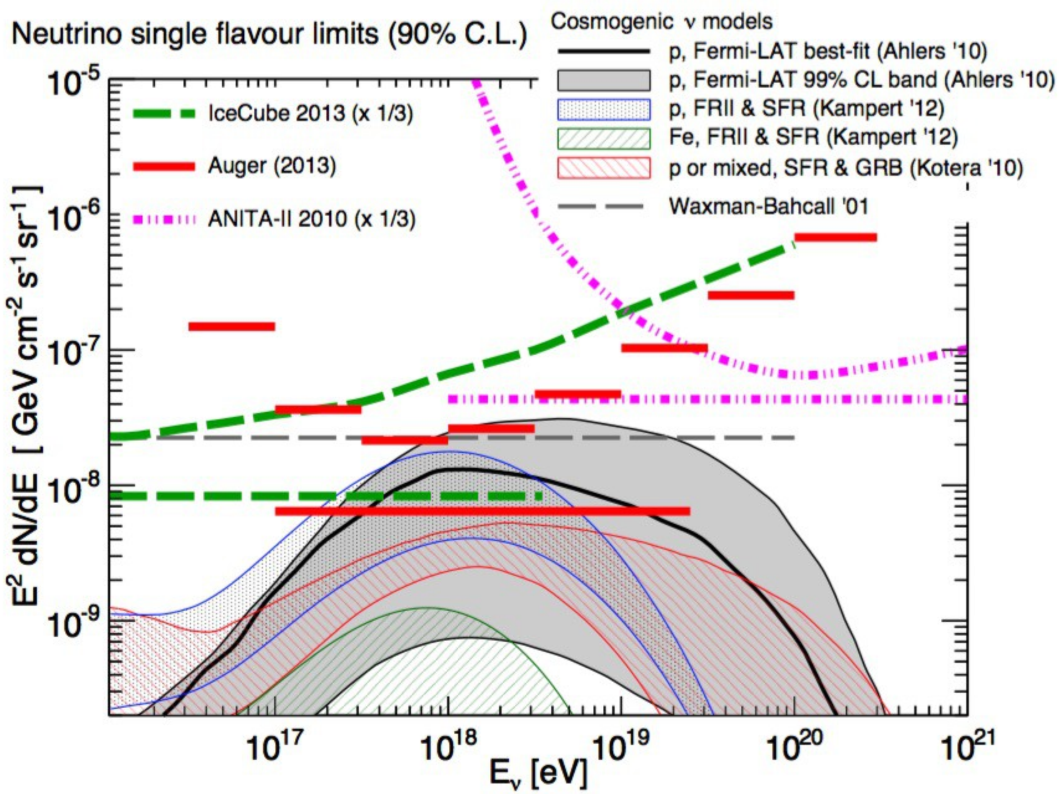
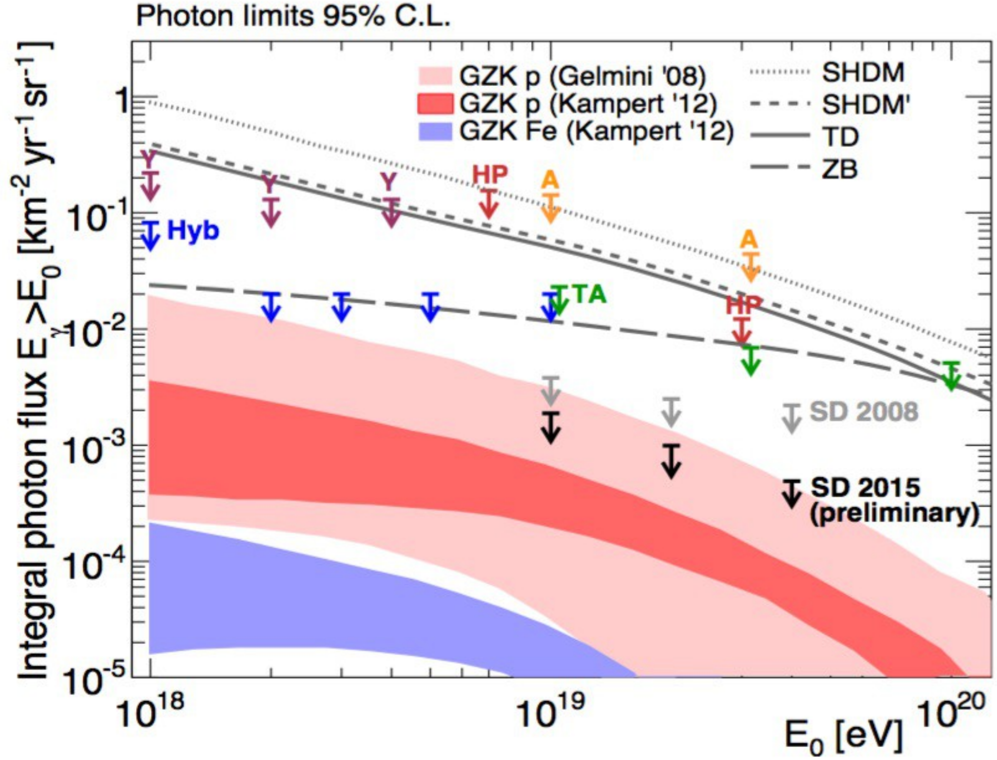
Auger neutrino and photon limits

Cosmogenic ("GZK") photon and neutrino emission, flux depends on CR mass distribution

Difference in air shower development w.r.t. nuclei => difference in WCD signal time structure





10-year Auger SD data set analysed, 0 neutrino candidates & 4 photon candidates found

Upper limits on photon and neutrino fluxed derived, assuming differential flux $dN(E) = k \cdot E^{-2}$

Photon limits: top-down models clearly disfavored, astrophysical UHECR scenarios preferred

Both limits reach predictions for cases of a pure proton composition at the UHECR sources

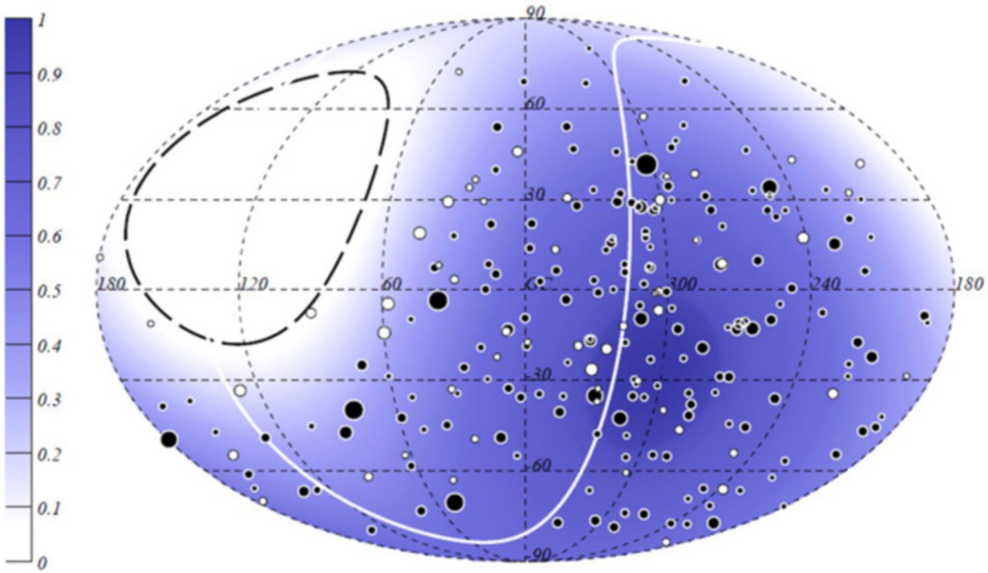
see today's talk on neutrino analyses by Lili Yang

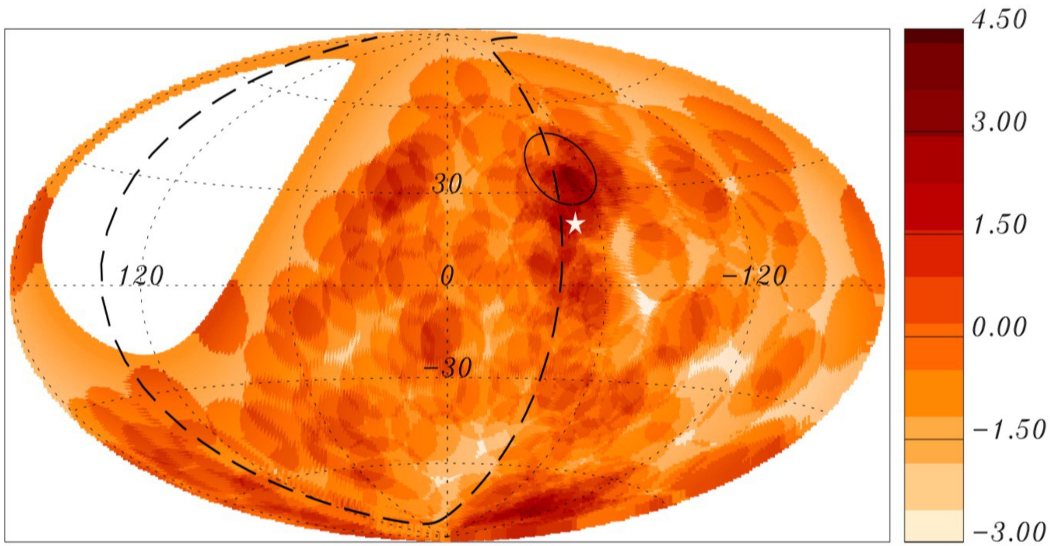
C. Bleve for the Auger Coll. PoS (ICRC2015) 1103

Arrival directions of the highest energy Auger events

UHECR sources within GZK sphere => anisotropy at small or intermediate angular scales?

602 events above 40 EeV collected in 10 years, −90° to +45° in declination (< 80° in zenith angle)





Search in circles 1-30°, E_{thresh} up to 80 EeV for

1) intrinsic anisotropies 2) correlations with astrophysical structures (e.g. GP, SGP, GC) and plausible UHECR candidates: Cen A; catalogs: galaxies, X-ray emitting AGN, jetted radiogalaxies: +scan distance & luminosity

No significant anisotropy found. Two largest excesses are above 58 EeV (post-trial p ≈ 1.4%):

a) UHECR within 18° of Swift-BAT AGNs closer than 130 Mpc and brighter than 10^{44} erg/s

b) UHECR within 15° of Cen A (consistent with the largest overdensity found, see the right plot)

Large number of low luminosity sources or large-Z nuclei ? CR mass information is crucial !

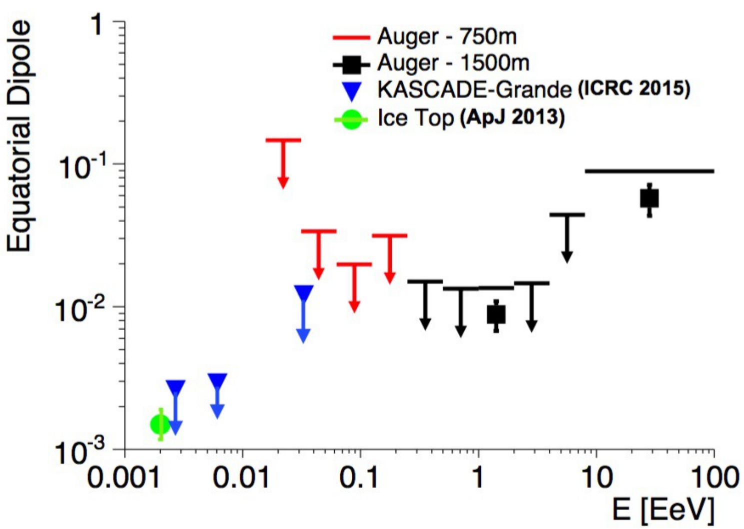
Auger Coll., ApJ 804 (2015) 15

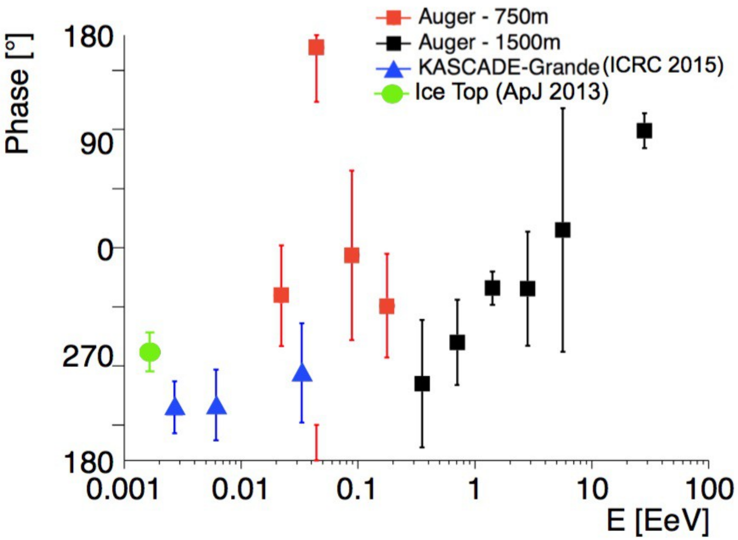
J. Aublin for the Auger Coll. PoS (ICRC2015) 310

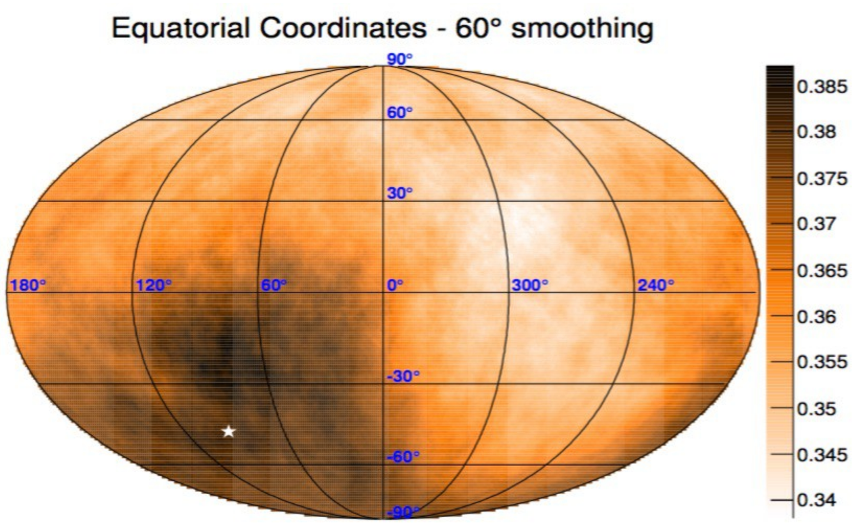
Large scale anisotropy at the highest energies?

May be indicative of the collective CR motion and/or of the CR sources distribution

Rayleigh analysis in right ascension and azimuth







Dipole amplitude at E > 8 EeV

Auger (7.3 ± 1.5)% (p=6.4 10^{-5})

Auger and TA (6.5 ± 1.9)% (p=5 10^{-3})

Dipole directions are compatible between 2 analyses

Phase changes from ≈270° (< 1 EeV) to ≈100° (> 8 EeV)

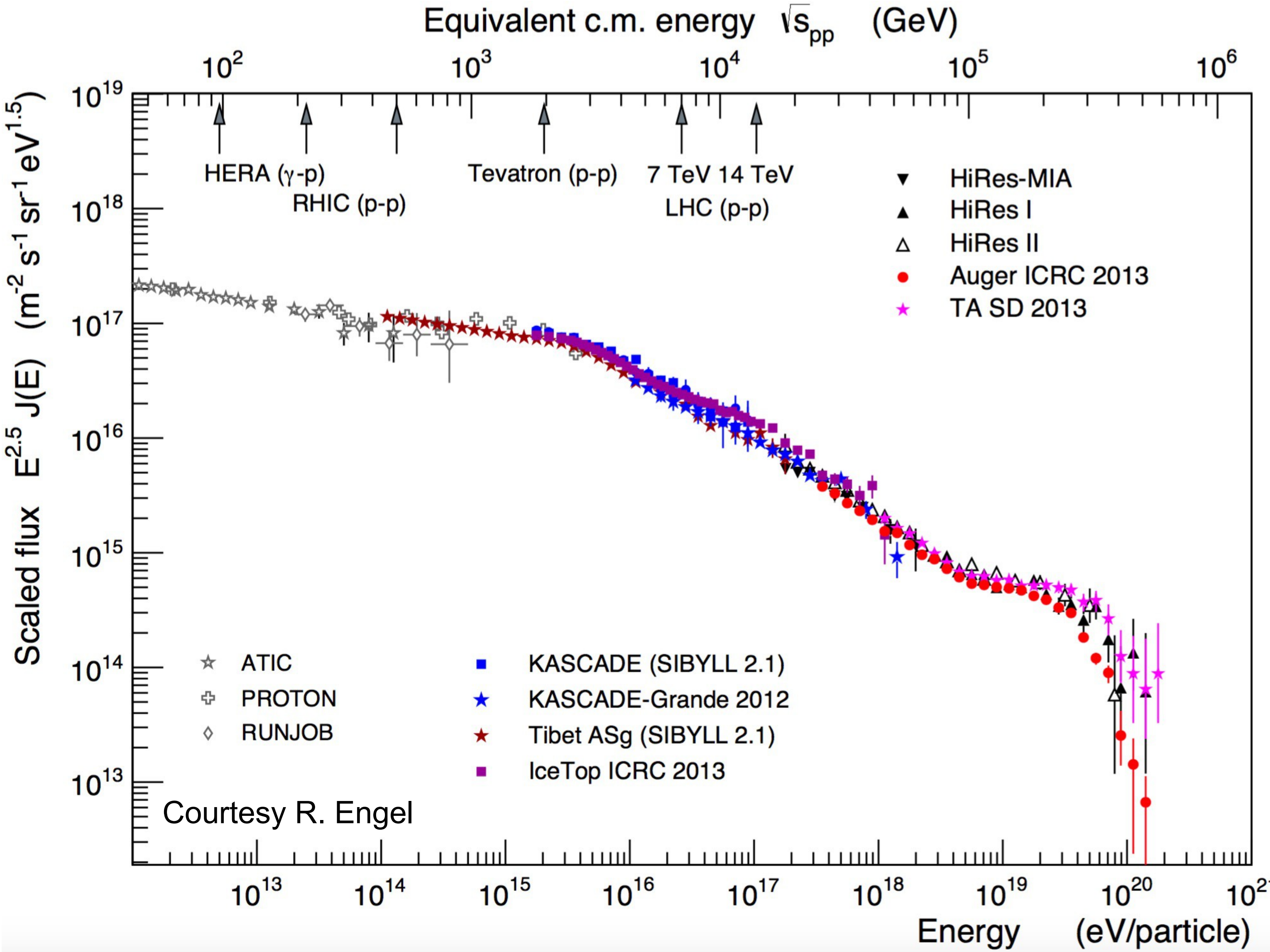
Transition from galactic to extragalactic CR ?

Prescription running for Auger to set confidence level

O. Deligny for the Auger & TA Coll. PoS (ICRC2015) 395

I. Al Samarai for the Auger Coll. PoS (ICRC2015) 372

UHECR: key problems of astrophysics & fundamental physics



Cosmic particle accelerators

UHECR energy spectrum, mass composition, arrival directions

Particle interactions at the energies inaccessible in laboratory

Validity of interaction models at the extreme CR energies

Conversion of X_{max} moments to *ln A* moments

One-to-one relation between $X_{\max}$ and $\ln A$ moments

$$\langle X_{\max} \rangle \approx \langle X^{p}_{\max} \rangle - D_p \langle \ln A \rangle$$

$$\sigma^2(X_{\max}) \approx \langle \sigma^2_{\rm sh} \rangle + D_p^2\, \sigma^2(\ln A)$$

$\langle \sigma^2_{\rm sh} \rangle$ — shower-to-shower fluctuations for $\langle \ln A \rangle$;
$D_p = d\langle X^{p}_{\max} \rangle / d \ln E$ (elongation rate for protons).

$\langle \ln A \rangle = \sum_i f_i \ln A_i$, ($f_i$ — relative fractions of masses $A_i = 1, \ldots, 56$)
$\langle \ln A \rangle(\text{proton}) \approx 0; \quad \langle \ln A \rangle(\text{Fe}) \approx 4$

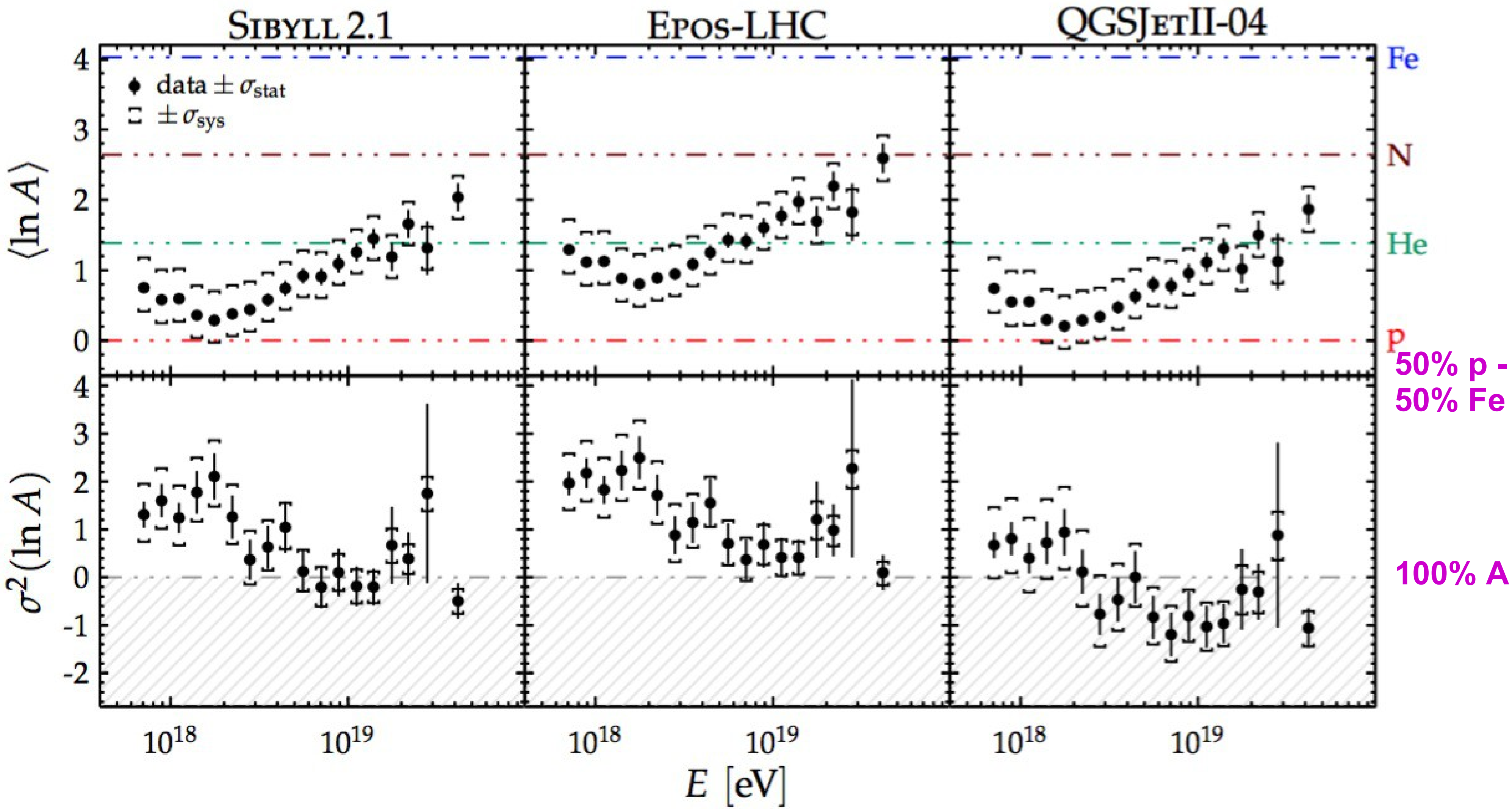
purity of the primary beam

$$\sigma^2(\ln A) = \langle \ln^2 A \rangle - \langle \ln A \rangle^2$$

for pure beams $\sigma^2(\ln A) = 0$; maximal mixing 0.5 p – 0.5 Fe $\sigma^2(\ln A) \approx 4$

Auger Coll., JCAP 02 (2013) 026, PRD 90 (2014) 122005

ln A moments from X_{max} measurements



transition from lighter to heavier composition above 2 EeV

dispersion of masses decreases with energy

QGSJetII-04: σ^2(ln A) < 0 (within 2σ), too large shower-to-shower fluctuations?

Auger Coll., PRD 90 (2014) 122005

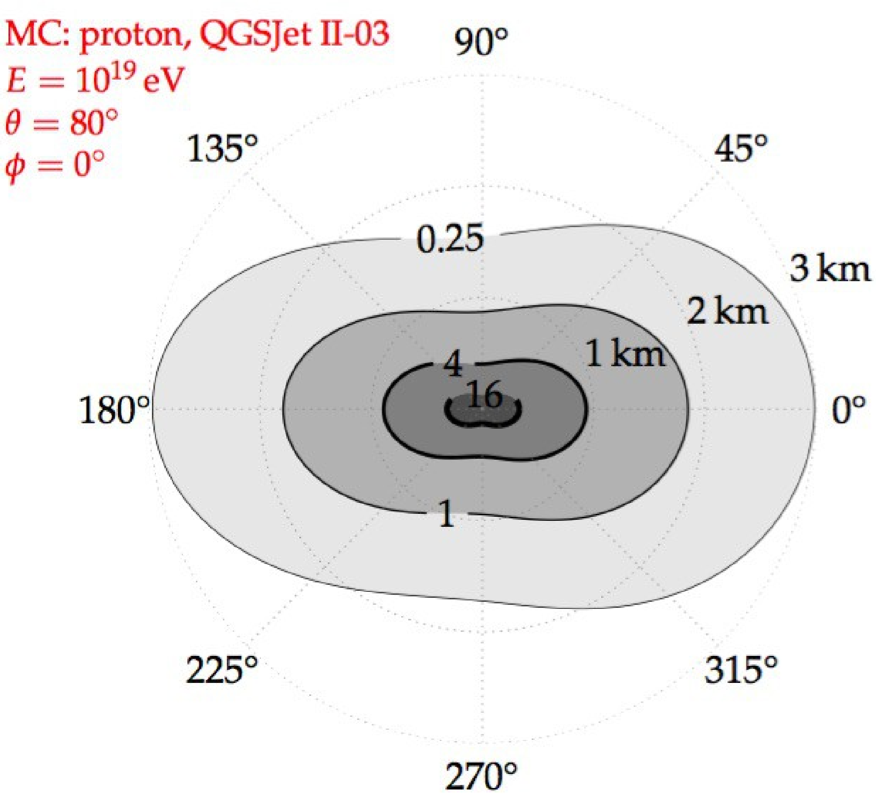
Muons in highly inclined events

Muon density profiles in highly inclined events:
- depend strongly on azimuth (geomagnetic deflection) and zenith (atmospheric absorption)
- depend weakly on energy, mass, model for showers with θ > 60°

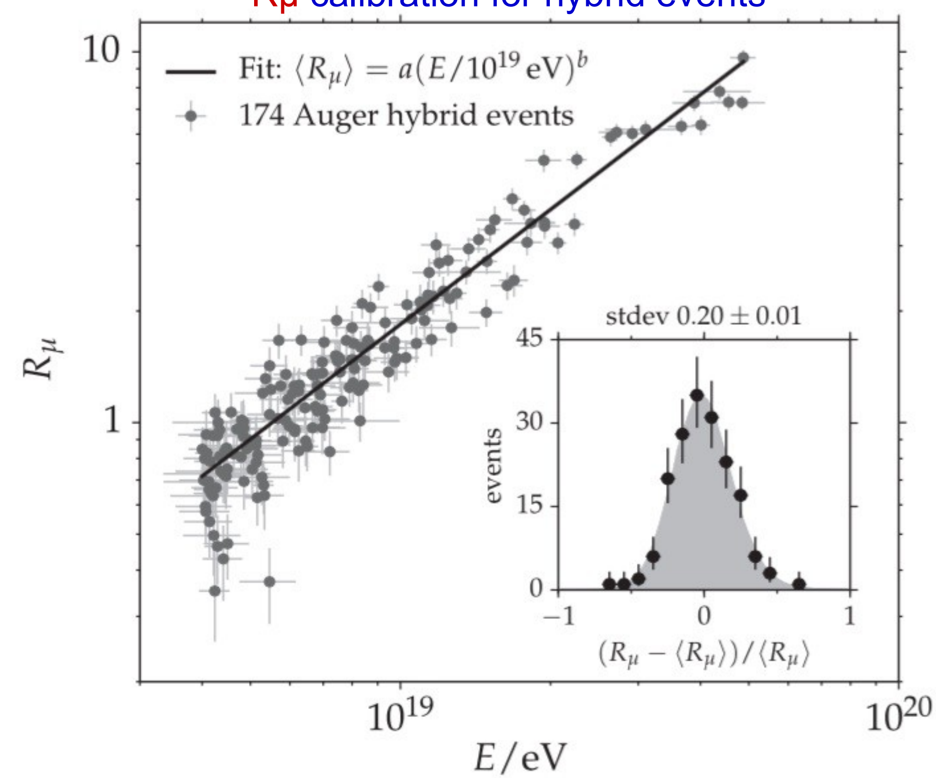
=> factorization is possible using ratio N19 of measured/reference density: $\rho_\mu(\vec{r}) = N_{19}\rho_{\mu,19}(\vec{r};\theta,\phi)$

Muon content R is the ratio data/MC : $R_\mu = N_{19}^{\mathrm{data}}/N_{19}^{\mathrm{MC}}$

Reference density profile $\rho_{\mu,19}$ [hits/station]



Rμ calibration for hybrid events



Auger Coll., PRD 91 (2015) 032003

Average muon content

data 01/2004 – 12/2012

zenith angles [62°; 80°]

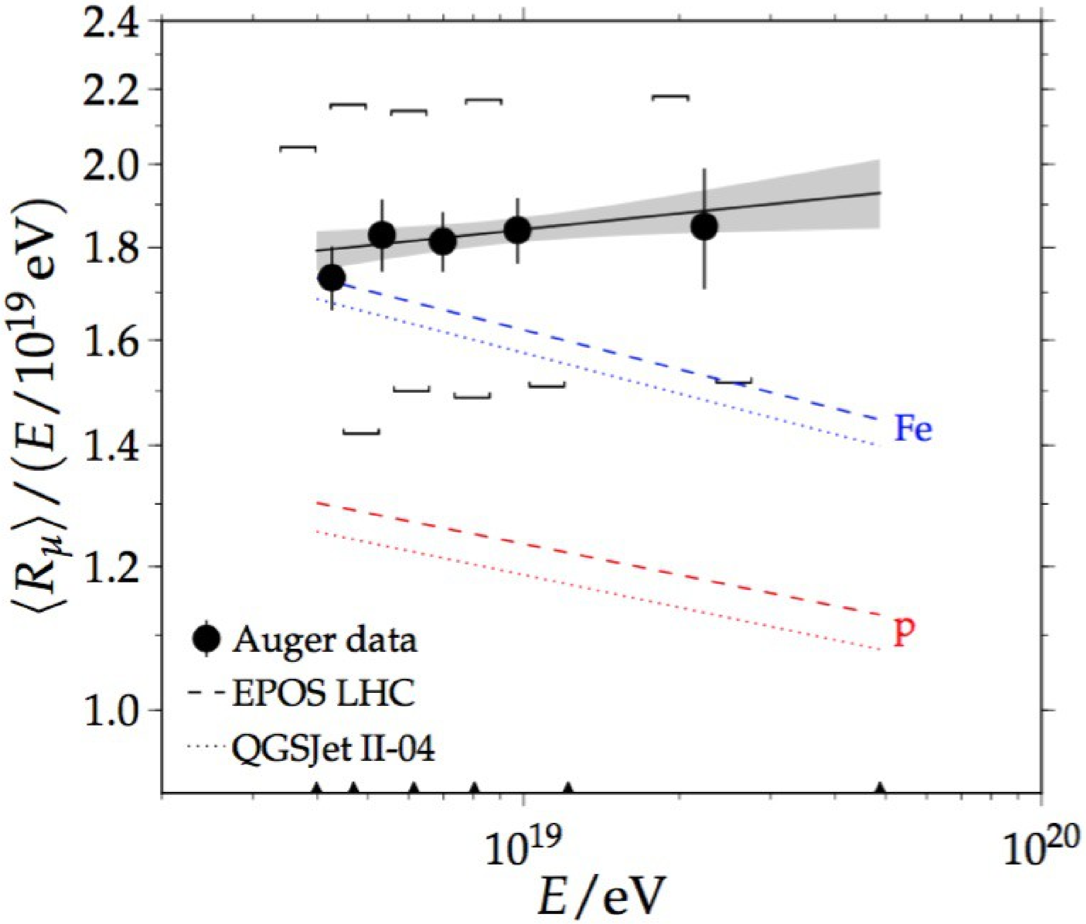
low EM contamination

E > 4 EeV

SD array fully efficient

174 events after selection

systematic uncertainty 18%



$\langle R_\mu^{data} \rangle$ is larger than MC values for iron, in conflict with <ln A> from Xmax

$d\langle \ln R_\mu^{data} \rangle / d \ln E$ deviates from pure proton (iron) by 2.2σ (2.6σ),

and is positive in agreement with the $\langle X_{max} \rangle$ evolution (transition from lighter to heavier elements)

Auger Coll., PRD 91 (2015) 032003

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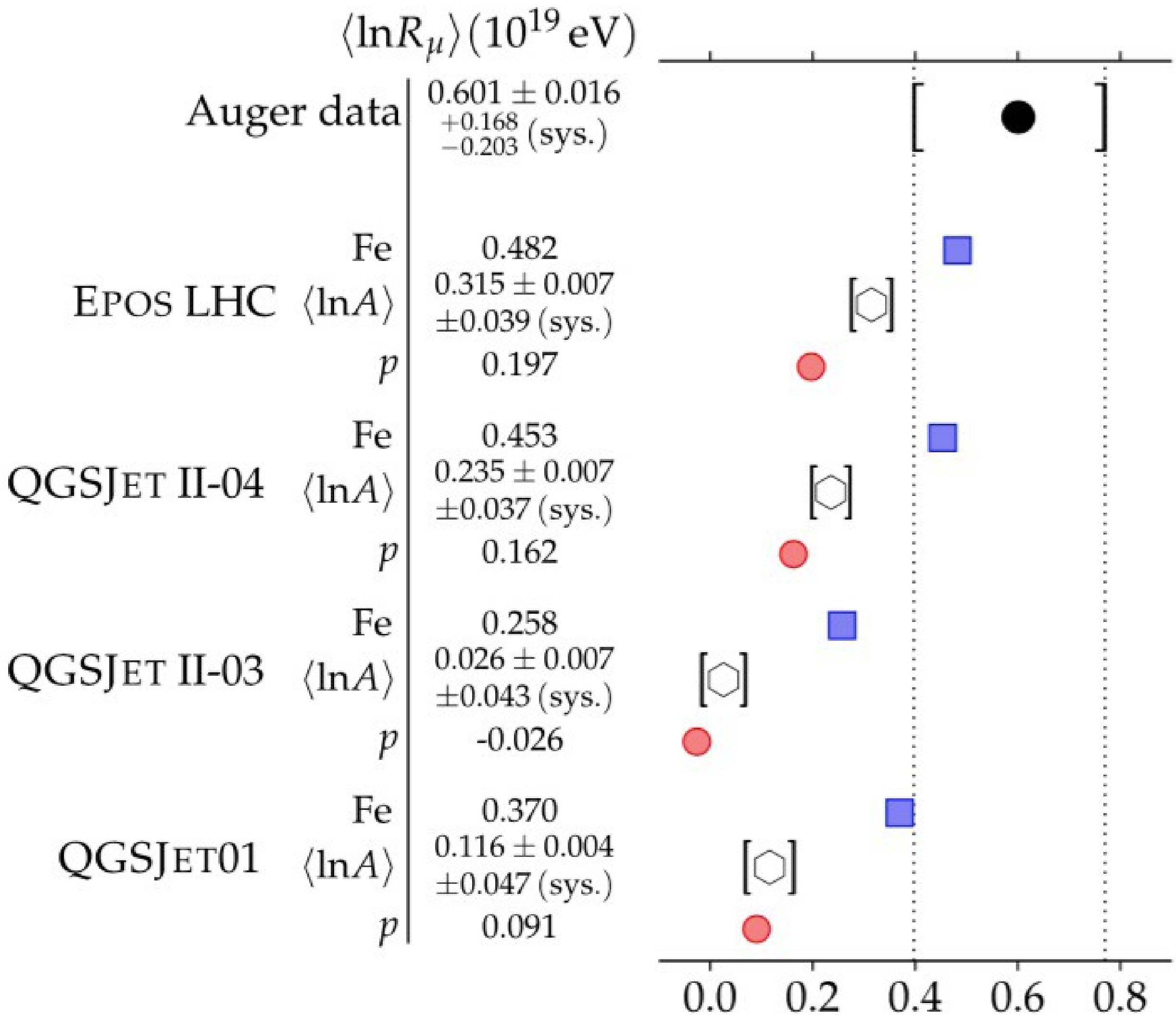
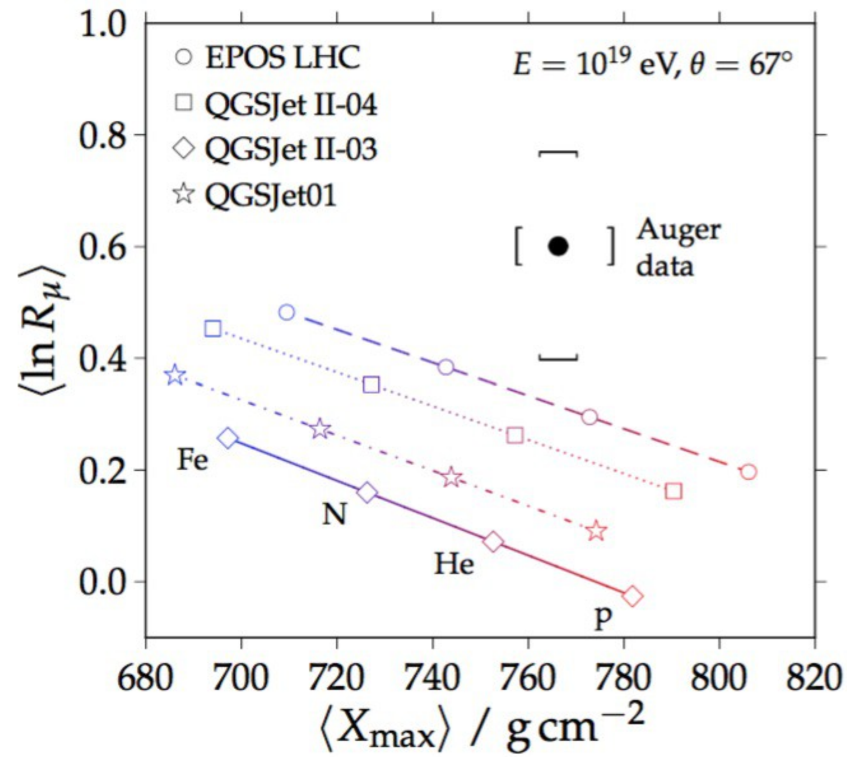
Average log muon content





muon content in MC (for <ln A> from X_{max}) is (30 − 80)% smaller than in data, minimal difference is 1.4 $\sigma_{(sys)}$ with EPOS-LHC

Auger Coll., PRD 91 (2015) 032003

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Summary

Spectrum	Combined measurements over 3 decades in E, ankle observed at about 5 EeV, flux suppression above 40 EeV
Composition	Gets heavier (lighter) with increasing energy in the region above (below) ~ 2 EeV, half the ankle energy
	Spectrum and composition together favor the “source extinction” scenario
Photons & Neutrinos	Photon limits above 1 EeV strongly disfavor top-down models. Absence of GZK neutrinos disfavors pure proton composition
Arrival directions	Compatible with isotropy at small and intermediate scales. Hints on a dipole anisotropy above 10 EeV
Hadronic interactions	Great potential of mass-sensitive observables. Muon content is larger in data w.r.t. simulations (by a model-dependent factor)

Open science case at the highest energies

- lack of composition data in the suppression region
- need to better understand hadronic interaction models
- need to separate a light component to identify UHECR sources

Perspectives: detector upgrade "AugerPrime"

Goal: improve on the sensitivity to mass composition in the suppression region

Timeline:

July 2016: Engineering Array, 12 stations equipped with scintillators

end of 2016: evaluation

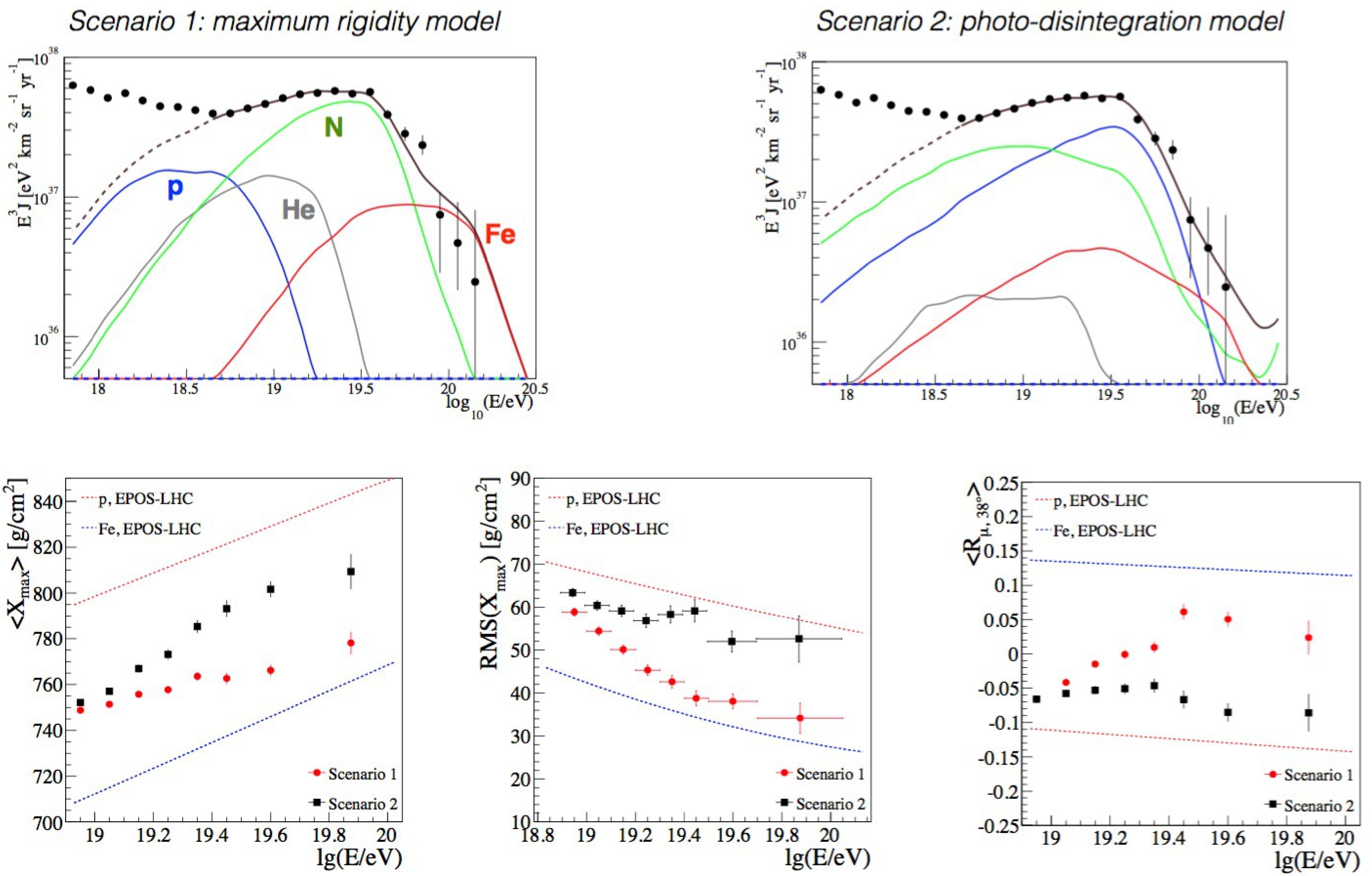
2017-2018: deployment of 1600 SSD

until 2025: data-taking

Equip each WSD with scintillator layer on top => Scintillators sensitive to the electromagnetic content of the shower => muon component estimate

In addition:
- **Upgraded and faster electronics**
- **Extension of the dynamic range**
- **Cross check with underground buried AMIGA detectors**
- **Extension of the FD duty cycle**

AugerPrime: discrimination of scenarios



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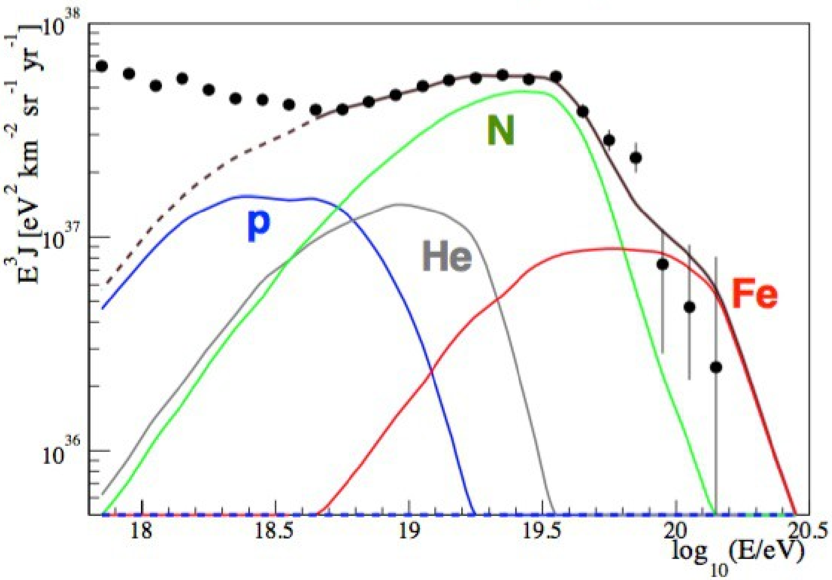
AugerPrime: discrimination of scenarios

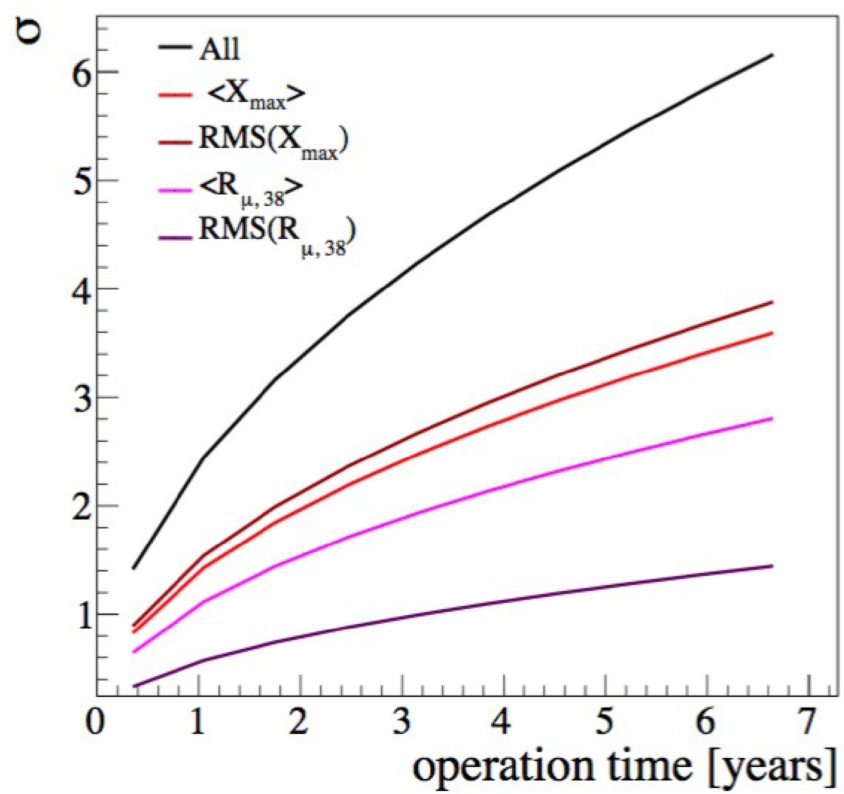
Reference: maximum rigidity model



- Standard scenario 1 (almost no protons)
- Scenario 1 with 10% protons added

Significance of distinguishing scenarios with and without 10% protons

(ideal case for knowing proton predictions without uncertainty due to had. int. models)



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