Cosmic ray composition with the Pierre Auger Observatory

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Outline

- Measuring the cosmic ray composition at the highest energies, along with other measurements such as the flux and the arrival direction distribution, is a key to separate the different scenarios of origin and propagation of cosmic rays.
- Composition cannot be determined from direct measurements but must be inferred from measurements of the shower that the primary cosmic ray produces in the atmosphere.
- The most used shower observables to study the composition of UHECR are the mean value of the depth of shower maximum and its dispersion, obtained from hybrid events
- Observables derived from the shower signal measured with the surface detector array of the Pierre Auger Observatory

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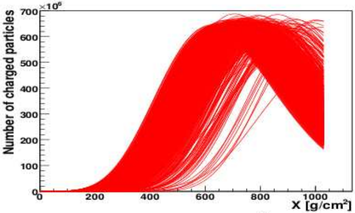
- status of the mass composition measurements with The Pierre Auger Observatory
- method for the interpretation of composition observables
- possible implications in term of interaction models and astrophysical cosmic ray sources

EAS development and composition observables

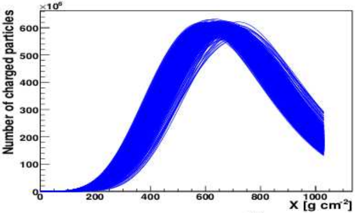
- a UHECR interacting with a nucleus of Nitrogen produces a particle cascade (Extensive Air Shower, EAS)
- the Fluorescence Detector of the PAO measures the profile of the energy deposit of the shower
- simple models illustrates that
  - the number of particles N_{max} at shower maximum is proportional to the primary energy E_0
  - the depth of the shower maximum X_{max} increases logarithmically with energy
- if the primary is a nucleus, from the superposition model:
  - $N^A_{max}(E_0) \sim N_{max}(E_0)$
  - $X^A_{max}(E_0) \sim X_{max}(E_0/A)$

EAS development and composition observables

Depth of shower maximum X_{max}



proton MC longitudinal profile ($E=10^{18}$ eV, $N_{ev}=1000$)



iron MC longitudinal profile ($E=10^{18}$ eV, $N_{ev}=1000$)

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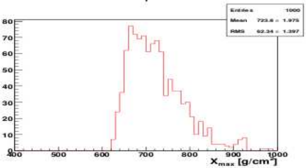

proton MC X_{max} distribution

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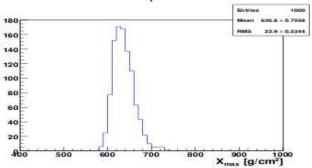


iron MC X_{max} distribution

- Showers of heavier nuclear primaries develop faster that lighter ones
- Shower-to-shower fluctuations smaller for showers of heavier nuclear primaries.

Composition observables - hybrid detection

Hybrid events: showers reconstructed using FD data and that have at least a signal in one of the SD stations measured in coincidence.
Selection cuts $\Rightarrow$ events accepted if:

- geometry selections $\rightarrow$ angle between the shower and the telescope smaller than 20°
- atmosphere selections $\rightarrow$ aerosol content and cloud coverage monitored
- profile selection $\rightarrow$
  - maximum actually observed within the field of view
  - optimal Gaisser-Hillas fit
  - statistical uncertainties in the reconstruction of X_{max} <40 g/cm^2

For data taken between December 2004 and September 2010, 15979 events pass this quality selection.
Another set of cuts is used to ensure that the data sample is unbiased with respect to the cosmic ray composition.
At the end 6744 events (42% of those that pass the quality cuts) remain above 10^{18} eV.

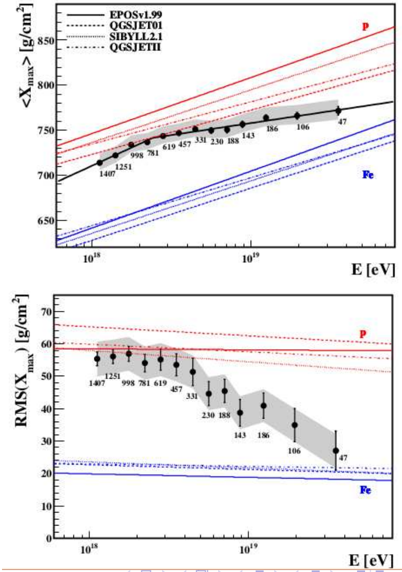
- systematic uncertainty in energy reconstruction of FD: 22%
- resolution in X_{max}: 20 g/cm^2 over the energy range considered

P. Facal San Luis for the Auger Col, ICRC 2011

Composition observables - hybrid detection

- total systematic uncertainties in $\langle X_{max} \rangle$: 10 g/cm^2 at low energy, 13 g/cm^2 at high energy;
- best described using two slopes;
- small elongation rate at highest energies ($D_{10} = 27^{+3}_{-8}$ g/cm^2/decade, $\log_{10}(E/\mathrm{eV}) > 18.38$): change in composition, form light to heavy primaries;
- low energy elongation rate $D_{10} = 82^{+48}_{-8}$ g/cm^2/decade, $\log_{10}(E/\mathrm{eV}) < 18.38$: large stat. uncertainties $\rightarrow$ extension towards low energies with HEAT.

- systematic uncertainties in RMS($\langle X_{max} \rangle$): 5 g/cm^2;
- RMS decreases gradually with energy; decrease with energy becomes steeper around the same point where the two sections of the $\langle X_{max} \rangle$ fit are joined.



The SD provides observables which are related to the longitudinal shower profile.

The higher statistics of showers measured with the SD allows us to reach higher energies than with the FD.

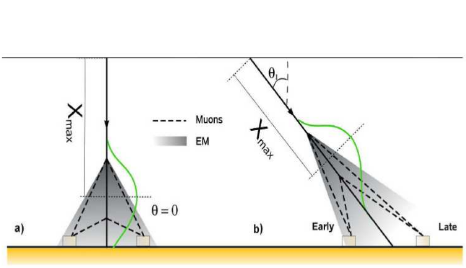
$\rightarrow \langle X_{max} \rangle$ measurements up to 3×10^{19} eV, energy threshold for the correlation signal: 5.7×10^{19} eV...

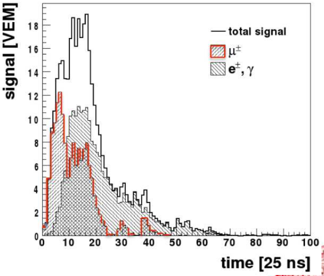
Signal rise time

- Rise time $t_{1/2}$ defined as the time to go from 10% to 50% of the total integrated signal
- it depends on the the distance to the shower maximum, the zenith angle θ and the distance to the core r.

Infact, considering μ in the shower
$\rightarrow$ they travel in straight lines while el-mag component scatters
$\rightarrow$ they dominate beginning of the signal while el-mag component dominates late signal

1. the higher is the production height the narrower is the time pulse $\longleftrightarrow$ μ-rich showers (nuclei) have smaller rise times
2. the larger is the zenith angle the smaller is the time pulse $\longleftrightarrow$ el-mag component strongly absorbed in inclined showers



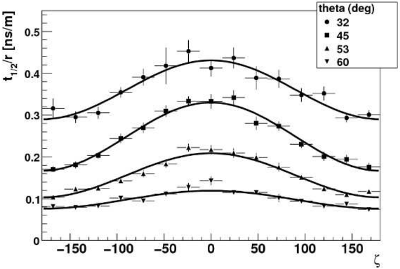


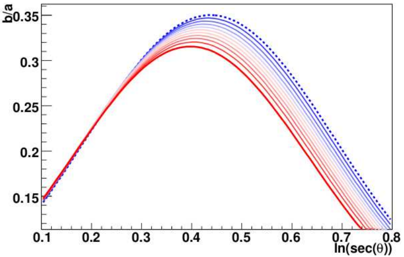
Composition observables - SD

Asimmetry in rise time

- El-mag component more absorbed in late regions $\Rightarrow$ μ dominate
  $\rightarrow$ smaller rise time in late regions than in early: Early-late asimmetry
- El-mag absorption increases with zenith angle, μ component almost asimmetry free
  $\rightarrow$ asimmetry decreases with zenith

1. For each $(E, \sec\theta)$ bin a fit of $\langle t_{1/2}/r \rangle = a + b\cos\zeta$ provides the asymmetry amplitude, b/a.
2. Determination of the position of the maximum Θ_{max} (value of $\sec\theta$ for which b/a is maximum).





Composition observables - SD detection - Asimmetry

Asimmetry in rise time

Data taken between Jan 2004 and Dec 2010:
18581 surviving these cuts:

- $E > 3 \times 10^{18}$ eV and $\theta < 60°$
- signal in detectors $>$ 10 VEM
- core distances between 500 m and 2000 m

Systematic uncertainties $<$ 10% of the proton-iron separation predicted by the models

Composition observables - SD

Depth profile of muon production points

- reconstruction of the Muon Production Depth (MPD), i.e. the depth at which a given muon is produced measured parallel to the shower axis: $\rightarrow$ is populated with surviving muons, so its shape depends on the zenith angle
- the MPD technique allows us to convert the time distribution of the signal recorded by the SD detectors into muon production distances using an relation between production distance, transverse distance and time delay with respect the shower front plane.
- definition of $\langle X^{\mu}_{max} \rangle$: depth along the shower axis where the number of produced muons reaches a maximum

Data taken between Jan 2004 and Dec 2010: 244 surviving these cuts:

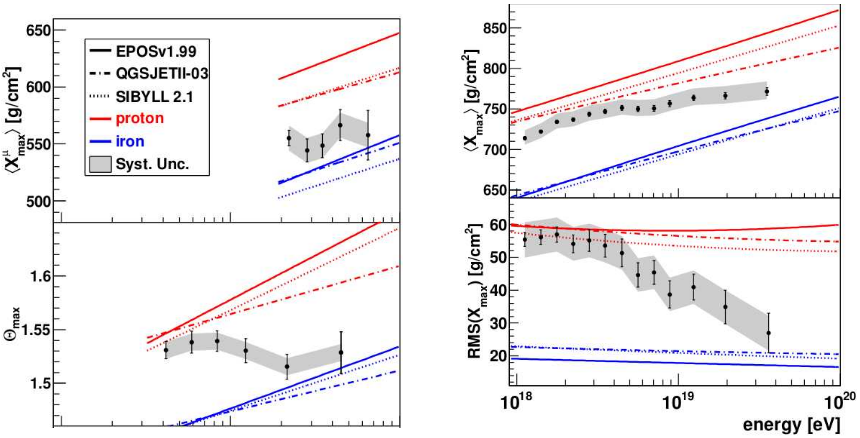
- zenith angles between 55° and 65°
- distance to the core: $>$ 1800 m
- Selection cuts: energy cut $E > 20$ EeV, fit quality, curvature

Systematic uncertainties: 11 g/cm^2, corresponding to 14% of the proton-iron separation predicted by models

Auger Composition results

P. Facal San Luis for the Auger Col, ICRC 2011

D. Garcia-Pinto for the Auger Col, ICRC 2011



Comparison of the results obtained with FD on the depth of shower maximum with complementary information derived from asymmetry properties of the particle signal in the SD stations and the depth profile of muon production points

Auger Composition results

- What these results are trying to say us?
  Although all methods presented are independent from each other and present different systematic uncertainties, the data interpretation yields similar results: gradual increase of the average mass composition of cosmic rays at higher energies.
- Moreover, from $\sigma(X_{max})$ we have the additional information of the decrease of fluctuations with energy

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- Moreover, from $\sigma(X_{max})$ we have the additional information of the decrease of fluctuations with energy
- **Our aim is to use shower observables to infer parameters related to the sources**
- Consider the most commonly used observables $\langle X_{max} \rangle$ and $\sigma(X_{max})$:
  - what is their different role with respect to mass composition?
  - their conversion to mass relies on the use of shower simulation codes that assume a hadronic interaction model
  - how they can be used to interpret mass composition even in the presence of uncertainties in the hadronic interaction modeling?

A method to interpret $\langle X_{max} \rangle$ and $\sigma(X_{max})$

- use analysis method based on the generalized Heitler model of EAS:

$$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f_E \langle \ln A \rangle$$

$\Rightarrow$ $\langle \ln A \rangle$ actually measures composition

$$\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f_E^2 \sigma^2_{\ln A}$$

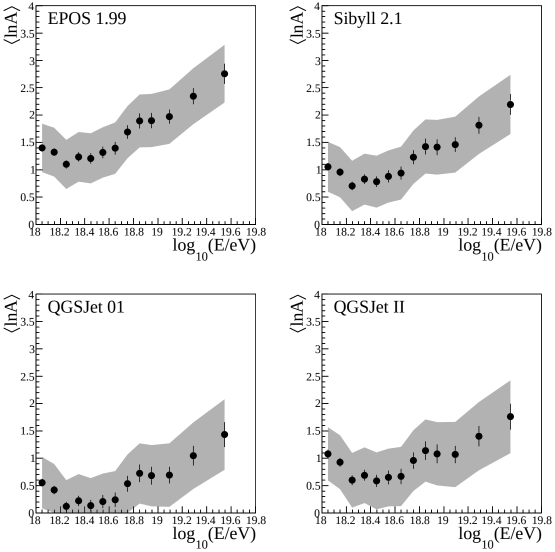
$\Rightarrow$ more complex behaviour: it depends on

  - shower fluctuations (mass and energy dependence via hadronic interaction models)
  - mass dispersion (generated by mixed composition at injection and propagation of CR's from source to Earth)

- using measurements of $\langle X_{max} \rangle$ and $\sigma(X_{max})$ these two equations can be inverted to get the first two moments of $\ln A$ distribution

The Auger Collaboration, JCAP 1302 (2013) 026

A method to interpret $\langle X_{max} \rangle$ and $\sigma(X_{max})$



$\rightarrow$ increasing $\langle \ln A \rangle$ above $10^{18.3}$ from light to intermediate masses

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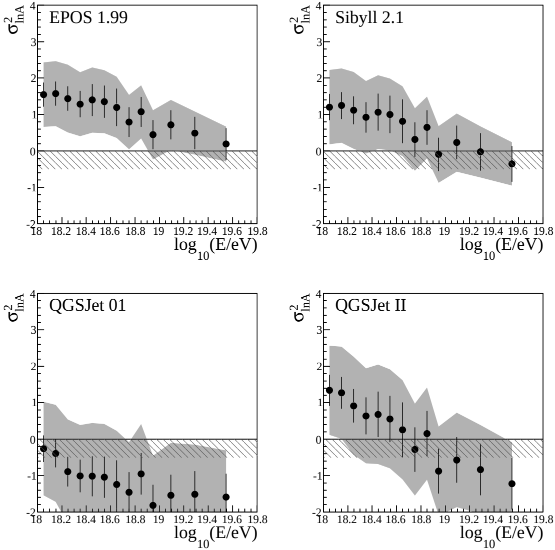

$\rightarrow$ decreasing $\sigma^2_{\ln A}$ over the whole energy range, tendency to pure composition

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A method to interpret $\langle X_{max} \rangle$ and $\sigma(X_{max})$

- What we observe:
  - increasing $\langle \ln A \rangle$ above $10^{18.3}$ from light to intermediate masses;
  - decreasing $\sigma^2_{\ln A}$ over the whole energy range, tendency to pure composition
- $\langle \ln A \rangle$ always has valid values
- wide regions where $\sigma^2_{\ln A} < 0$.

$$\sigma^2_{\ln A} \propto (\sigma^2(X_{max}) - \langle \sigma^2_{sh} \rangle)$$

$\Rightarrow$ negative values occurs for energies where the shower fluctuations corresponding to $\langle \ln A \rangle$ exceed the measured X_{max} fluctuations

$\rightarrow$ $\sigma^2_{\ln A}$ points are within the allowed physical region only for EPOS 1.99 and Sibyll 2.1.

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- the model presented also shows that the Auger data can confront hadronic physics models, provided that future developments in the shower data analysis reduce systematics

A method to interpret $\langle X_{max} \rangle$ and $\sigma(X_{max})$

- Energy evolution common $\Rightarrow$ average mass increases with decreasing $\ln A$ dispersion
- For some models, Auger data outside allowed region
- Systematic uncertainties are large $\Rightarrow$ no definite conclusions

$\Rightarrow$ What could be the astrophysical implications? How the composition observables can be related to source characteristics?

From detection to source:

- Atmospheric showering $\rightarrow$ once a nucleus reaches the Earth it produces an extensive air shower by interacting with the atmosphere.
- Propagation from source to Earth: interactions (with photon backgrounds) suffered by particles form the source to the top of the atmosphere $\rightarrow$ energy losses and secondary production
- Source injection $\rightarrow$ distribution of sources, parameters of the injection spectrum (power law index, maximum acceleration energy), particle species, magnetic fields...

What are the possibilities for extragalactic sources to produce composition with the observed behaviour?

- only primary protons: propagation without mass dispersion
  $\rightarrow$ excluded by composition data at highest energies
- nuclei from nearby sources ($<$ 100 Mpc) might be detected with small mass dispersion...
  but, if sources are distributed uniformly, distant sources induce natural mass dispersion...
- Moreover, the superposition of p+Fe gives the largest variance

A method to interpret $\langle X_{max} \rangle$ and $\sigma(X_{max})$

- Protons (primary or originating by photodisintegration of nuclei): main source of mass dispersion
- End of the spectrum based on a rigidity-dependent mechanism can reduce the proton component at the highest energies
- Moreover, the tendency to “pure composition” seen in $\sigma^2_{\ln A}$ suggests a minimal mixing between masses (transition from a pure composition to the next one $\rightarrow$ minimum variation of $\sigma^2_{\ln A}$).

A complete study of source models is required to study source parameters that limit the mass dispersion.

Conclusions

- Different composition sensitive variables can be evaluated by the Fluorencence and Surface Detector; methods are independent to each other and present different systematic uncertainties, but data interpretation yields similar results $\rightarrow$ Auger data are consistent with a gradual increase of the average mass composition of cosmic rays at higher energies.

- Inferring mass composition from these measurements is subject to uncertainties due to hadronic interaction modeling.
- The different role of $\langle X_{max} \rangle$ and $\sigma(X_{max})$ with respect to the mass composition has been discussed

- Method to convert observables to the first moments of the log mass distribution has been presented
- Combined analysis of $\ln A$ and $\sigma^2_{\ln A}$ can provide a useful representation of the mass transition to be found in shower profile data.
- Possible implications of these dependences in term of interaction models and astrophysical cosmic ray sources have been discussed

BACKUP

The Auger Collaboration, JCAP 1302 (2013) 026

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$\Rightarrow$ more complex behaviour: it depends on

  - shower fluctuations (mass and energy dependence via hadronic interaction models)
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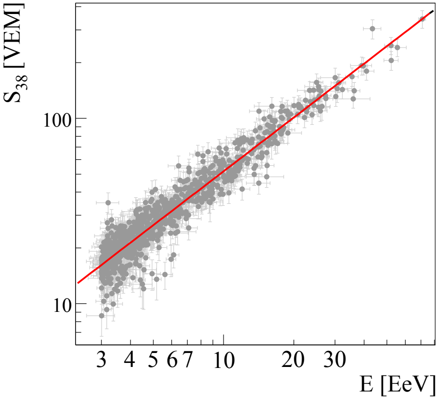
f_E (energy dependent parameter) contains 3 parameters that depend on the specific hadronic interaction model. In this work they are obtained from shower simulation with CONEX

Hybrid detection - Energy calibration

Event footprint ⇒ sequence of hit PMTs forming a track in the camera + triggered tanks at ground
→ Events used to relate the energy reconstructed with the FD E_{FD} to the SD energy estimator $S(1000)$
→ energy scale applied to all showers detected by the SD array



R. Pesce for the Auger Col, ICRC 2011

Resolutions:

- Energy $\sim 7\%$
- $X_{max} \sim 20$ g cm^{-2}

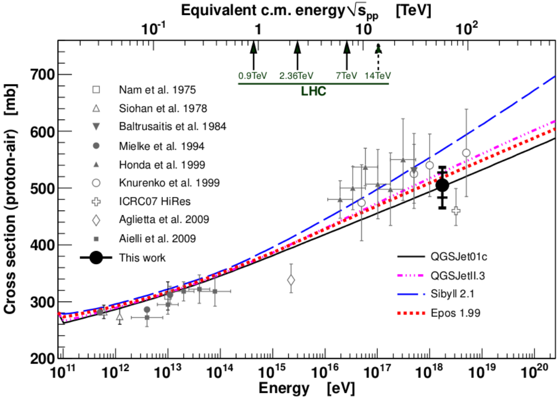
Energy systematics: 22%

- fluorescence yield 14%
- FD absolute calibration 9.5%
- invisible energy 4%
- reconstruction 10%
- atmospheric effects 8%

Hadronic interactions

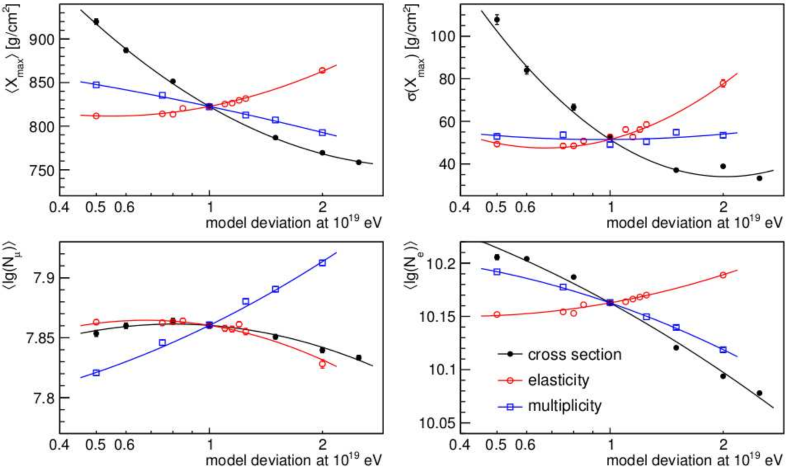
R. Ulrich for the Auger Col, ICRC 2011

- hadronic showers $\rightarrow$ lack of theoretical and experimental knowledge of the characteristics of hadronic interactions
- At ultra- high energies, the center of mass energies of the first nucleus-air interactions are beyond accelerator energies and correspondingly the models rely on extrapolations.
- At its maximum center of mass energy of 14 TeV the LHC will eventually reach the equivalent of 10^{17} eV in the laboratory system



Hadronic interactions

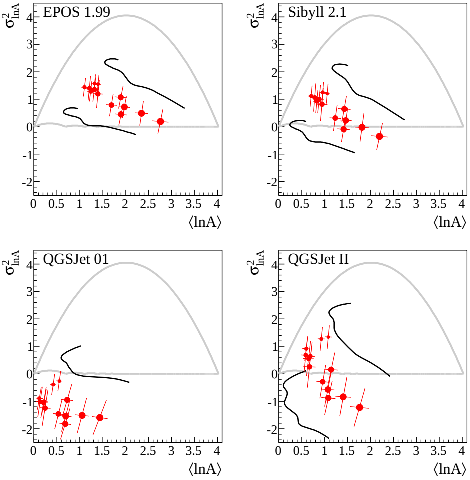
Effect of uncertainties in hadronic interaction characteristics on air shower observables



- muon number and X_{max} very sensitive to the multiplicity
- X_{max} and $\sigma(X_{max})$ sensitive to λ, not so for muon number

A method to interpret $\langle X_{max} \rangle$ and $\sigma(X_{max})$

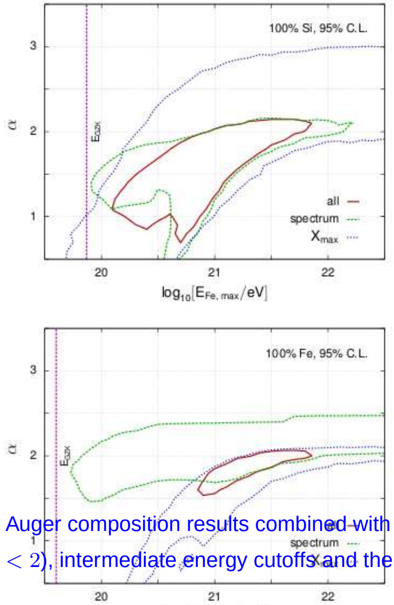
Converting X_{max} data to $\ln A$ variables one can plot data in the ($\langle \ln A \rangle$,$\sigma^2_{\ln A}$) plane →
each mixing is an arch shaped line in the ($\langle \ln A \rangle$,$\sigma^2_{\ln A}$) plane.



Possible transitions are constrained to a limited region.

Other independent analyses

A.M. Taylor, M.Ahlers and F.A. Aharonian, Phys.Rev.D84:105007,2011 and arXiv:1107.2055



Following the motivation that UHE CRs consist of heavy nuclei, whose sources have been suggested to be local [27, 28], we have here looked closer at the requirements on their source distribution. In this work we obtained concrete quantitative constraints on the UHE CR source population. Making explicit use of the recently provided Auger spectral and shower composition results, along with detailed UHE CR nuclei modeling, we investigated whether consistency may be found with this data using single source composition models.

For the case of negligible extragalactic magnetic fields, we demonstrated that a simplified analytic description agrees well with the spectrum and composition results obtained from the complete Monte Carlo description. Utilising this analytic description, we made a scan over the source spectral index and exponential energy cutoff, for a given source composition, to obtain the goodness-of-fit contours. We found that hard ($\alpha < 2$) source spectral indices and intermediate cutoff energies ($E_{\rm Fe,max} \sim 10^{20.5} - 10^{21}$ eV) for intermediate-to-heavy nuclei could provide a good fit to the full set of Auger UHE CR measurements above 10^{19} eV.

Auger composition results combined with energy spectrum require hard injection spectra (index < 2), intermediate energy cutoffs and the possible presence of local sources