Protons or Heavy Nuclei: That is the question

Multi-messenger approach for determination of UHECR composition

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Outline

- Motivation
- Cosmic variance formulae
- Some explicit examples
- Sensitivity of JEM-EUSO to ensemble fluctuations
- Conclusions

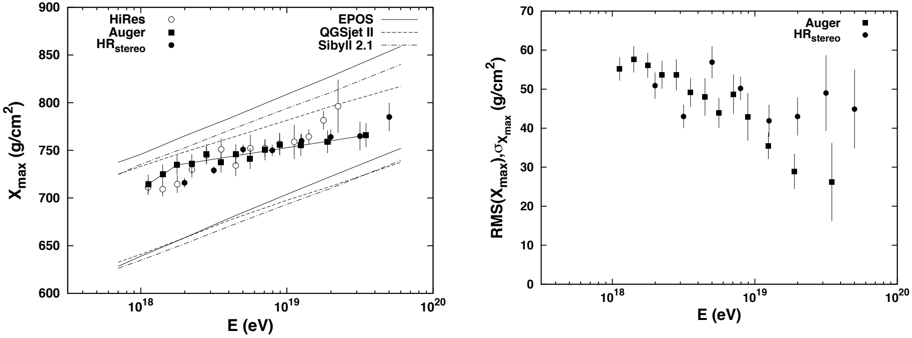
Markus Ahlers, LAA, and Andrew Taylor, arXiv:1209.5427

EAS Observables

- Best indicator of nuclear composition is atmospheric depth at which shower develops its maximum size ☞ $\langle X_{\rm max} \rangle \propto \ln(E/A)$
- Further insight is expected to come from RMS fluctuation of $X_{\rm max}$
- Unfortunately ☞ extracting precise information from EAS has proved to be exceedingly difficult
- Most fundamental problem is that first generations of particles are subject to large inherent fluctuations and this limits event-by-event energy resolution of experiments
- In addition ☞ center-of-mass energy of first few cascade steps is well beyond any reached in collider experiments
- Therefore ☞ one needs to rely on hadronic interaction models that attempt to extrapolate our understanding of particle physics using different mixtures of theory and phenomenology

Collateral Damage

- HiRes has presented evidence that the CR composition remains proton-like up to the highest energies



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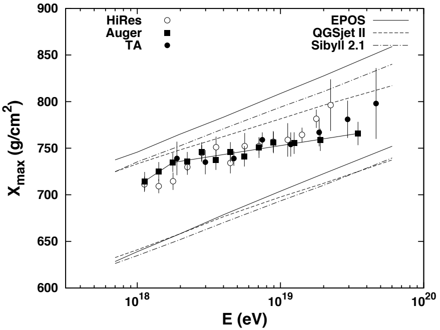

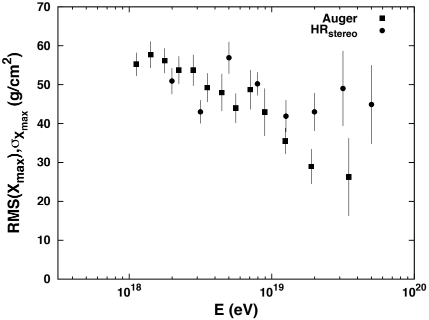

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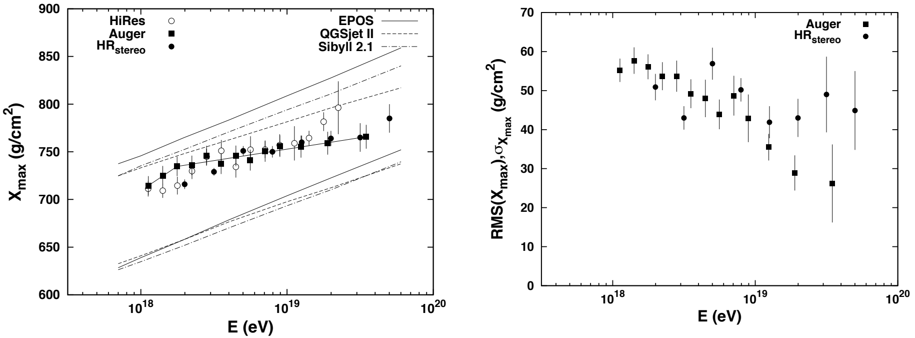
- Auger data on depth of shower maximum and its RMS fluctuation indicate a transition from a light (presumably proton-dominated) towards a heavier composition



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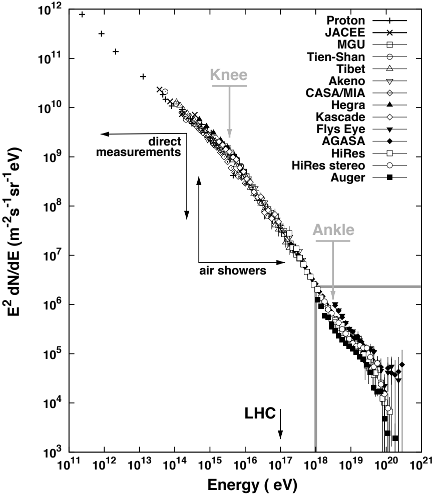
- Auger data on depth of shower maximum and its RMS fluctuation indicate a transition from a light (presumably proton-dominated) towards a heavier composition
- Apparent contradictory results reported by HiRes, TA, and Auger suggest that known and/or unknown systematic uncertainties may still affect the interpretation of EAS data

Postcards from oases in the desert

- Various features in the CR spectrum can also provide *indirect* evidence for the nuclear composition of UHECRs

E.g. ☞ The *ankle* hardening of spectrum at $10^{18.5}$ eV naturally arises by superposition of two power-law fluxes and serves as a candidate of transition between galactic heavy nuclei and extra-galactic cosmic ray protons



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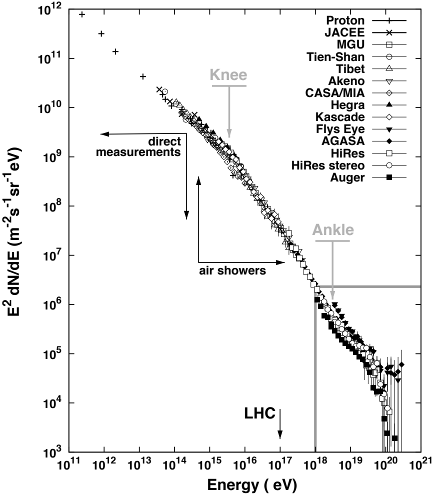
Proton-dominance beyond ankle is ultimately limited by the onset of photopion production on the cosmic microwave background while dominance of heavy stuff is restricted by photodisintegration through the giant dipole resonance the so called *GZK-suppression* at around $10^{19.7}$ eV



What Really Lies at the End of the CR Rainbow

- In this talk ☞ I will elaborate on the question as to what extent spectral information in GZK region can be used to discriminate between different CR source composition models

- Due to strength of GZK mechanism ☞ spectrum in this region is dominated by (and requires the presence of) local sources

- In this case the flux from a few CR sources can significantly fluctuate from a homogeneous distribution that is typically assumed in CR flux predictions

- In contrast to Poisson fluctuations in the GZK region –see De Marco, Blasi and Olinto, Astropart. Phys. **20**, 53 (2003)– manifestations of ensemble fluctuations ☞ persist in the limit of large event statistics

Cosmic Ray Propagation

Mean (ensemble-averaged) flux ☞ described by Boltzmann equation

$$\begin{aligned} \frac{1}{r^2}\partial_r(r^2 F_{A,i}) &\simeq \frac{\delta(r)}{4\pi r^2} Q_{A,i} \\ &- \sum_{B<A} \Gamma_{(A,i)\to(B,i)} F_{A,i} + \sum_{B>A} \Gamma_{(B,i)\to(A,i)} F_{B,i} \\ &+ \Gamma^{\rm CEL}_{A,i+1} F_{A,i+1} - \Gamma^{\rm CEL}_{A,i} F_{A,i} \end{aligned}$$

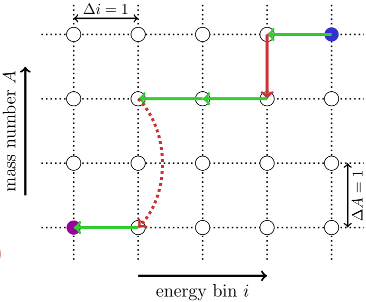
binned flux ☞ $F_{A,i} \equiv \Delta E_i A \, \mathrm{d}F_A(AE_i)/\mathrm{d}E$

emission rates ☞ $Q_{A,i} \equiv A \Delta E_i \mathcal{Q}_A(AE_i)$

interaction rates ☞

$$\Gamma^{\rm CEL}_{A,i} \equiv \frac{b_A(AE_i)}{A\Delta E_i}$$

$$\Gamma_{(A,i)\to(B,i)} \equiv \Gamma_{A\to B}(AE_i)$$



Ensemble Average

- For local ($r/H_0 \ll 1$) sources
  probability distribution function (PDF) ☞ is flat in Euclidean space
- Consider n_s sources distributed between redshift $r_{\rm min}$ and $r_{\rm max}$
  ☞ # of sources can be expressed via (local) source density $\mathcal{H}_0$ as:
  $$n_s = \mathcal{H}_0(4\pi/3)(r_{\rm max}^3 - r_{\rm min}^3)$$
- PDF of a single source is ☞ $p(r) = \frac{\mathcal{H}_0}{n_s} 4\pi r^2 \Theta(r - r_{\rm min})\Theta(r_{\rm max} - r)$
- Ensemble-average of a quantity $A(r_1, \dots, r_{n_s})$
  (depending on the distance of the n_s sources)
  can be expressed as ☞ $\langle A \rangle = \int {\rm d}r_1 \cdot \dots \cdot {\rm d}r_{n_s} p(r_1) \cdot \dots \cdot p(r_{n_s}) A$
- Ensemble-average of local flux ☞ $\sum_{n_s} F_{A,i}(r_s)$ is simply

$$\langle N_{A,i} \rangle \equiv \mathcal{H}_0 \int_{r_{\rm min}}^{r_{\rm max}} {\rm d}r' 4\pi r'^2 F_{A,i}(r')$$

Fux Variation

Mean total flux

$$\langle N_{\rm tot}(E)\rangle \equiv \sum_A \langle N_A(E)\rangle$$

together with

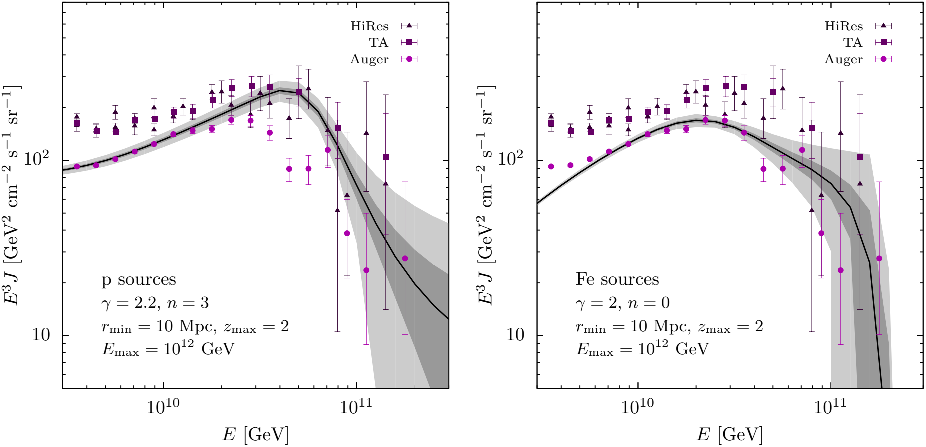
cross variance between relative flux of two particle species

$$\langle \delta N_{A,i}\delta N_{B,j}\rangle \equiv \langle N_{A,i}N_{B,j}\rangle - \langle N_{A,i}\rangle\langle N_{B,j}\rangle$$

enables us to express relative variation of total flux
via two-point density perturbations as

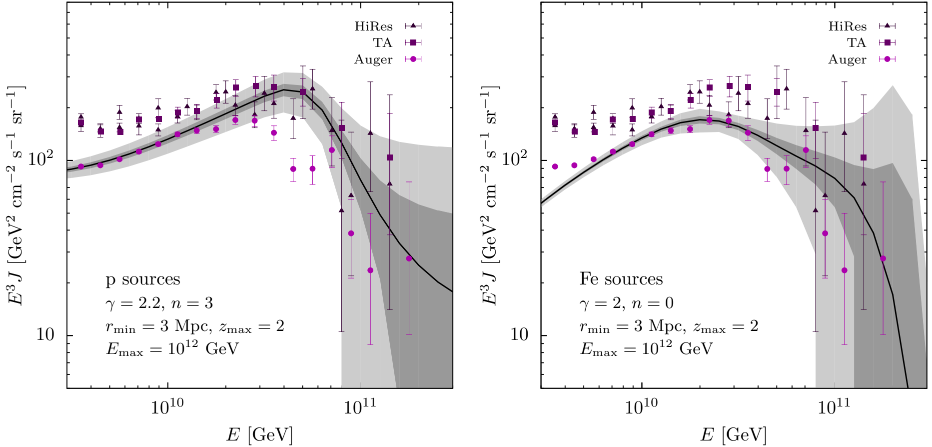
$$\sigma^2_{\rm loc} = \sum_{A,B} \frac{\langle \delta N_A(E)\delta N_B(E)\rangle}{\langle N_{\rm tot}(E)\rangle^2}$$

$r_{\min} = 10$ Mpc



Approximate variation of the flux assuming a local source distribution:
$\mathcal{H}_0 = 10^{-5}$ Mpc^{-3} (dark gray band)
$\mathcal{H}_0 = 10^{-6}$ Mpc^{-3} (light gray band)

$r_{\min} = 3$ Mpc



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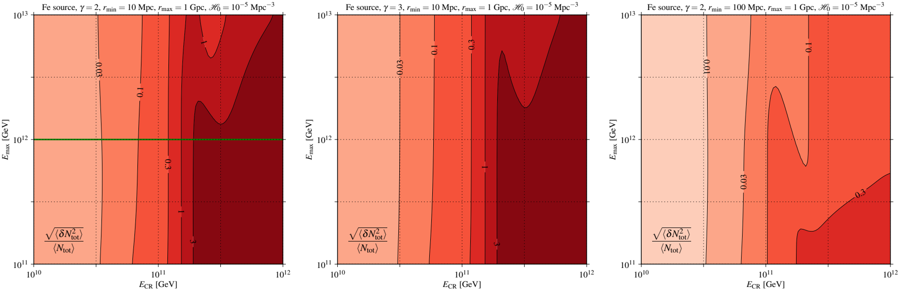
Ensemble Fluctuations



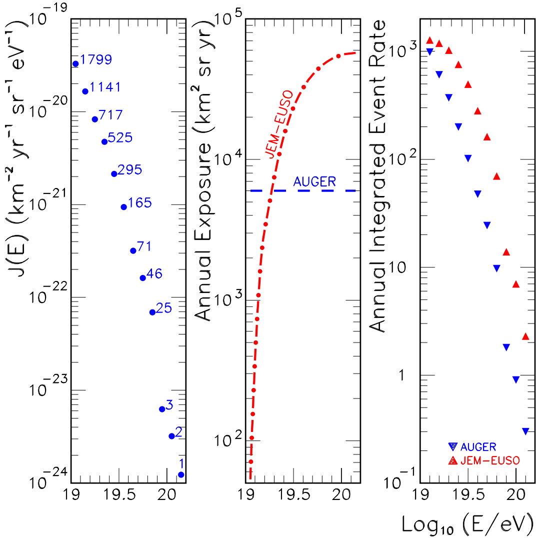
Local relative error of the flux for a distribution of iron sources

Green line indicates relative error for previously shown example

All calculations assume a local source density of $\mathcal{H}_0 = 10^{-5}$ Mpc^{-3}

which scale as $\mathcal{H}_0^{-1/2}$

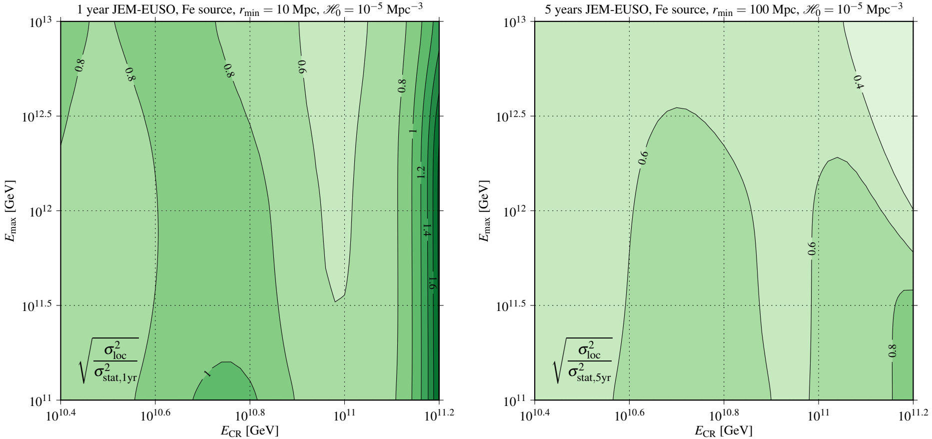
JEM-EUSO pathfinder mission



JEM-EUSO mission
will orbit the Earth
on board the ISS

Instrument will monitor
$\approx 1.3 \times 10^5$ km^2
and will observe annually
$\approx 6 \times 10^4$ km^2 sr yr
a factor of 10 above Auger

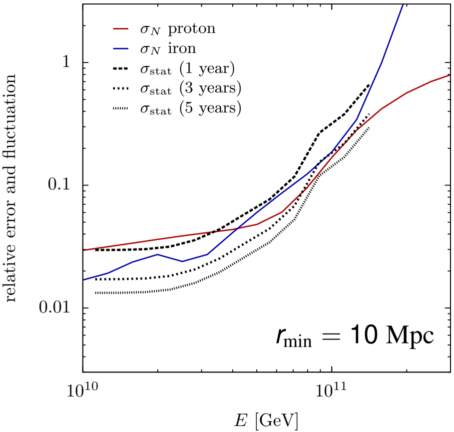
Ensemble Fluctuations vs. Statistical Fluctuations

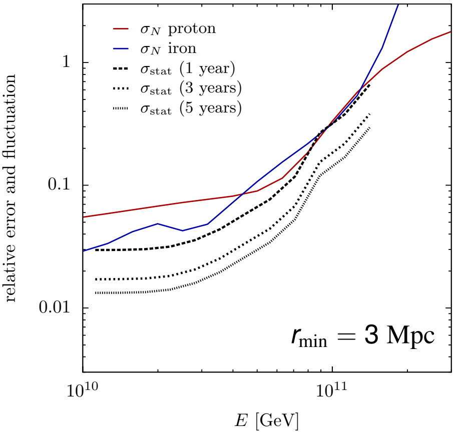


Contour plots for previously shown iron contours
divided by the statistical uncertainty of JEM-EUSO

Contour 1 means that the statistical error equals the ensemble fluctuation and for larger values the statistics is sufficient to see the ”spectral wiggles”

JEM-EUSO Integrated Exposure





Since ensemble fluctuations are systematic errors
whereas statistical fluctuations are random errors
we can study cosmic variance by dividing the data sample in two halves
Systematic errors would be the same in both halves
but the random errors would be different

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- This will naturally complement current *direct* measurements through extensive air shower observables