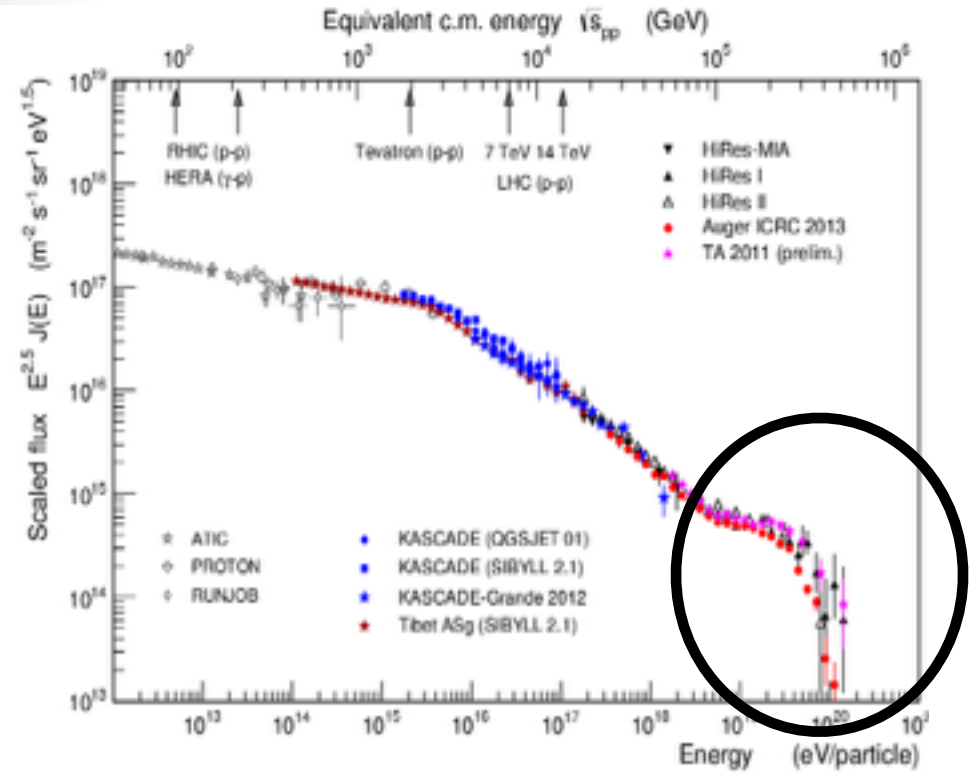
UHECRs and the Pierre Auger Observatory

O. Deligny (CNRS/IN2P3 - IPN Orsay) on behalf of the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

Ultra-High Energy Cosmic Rays

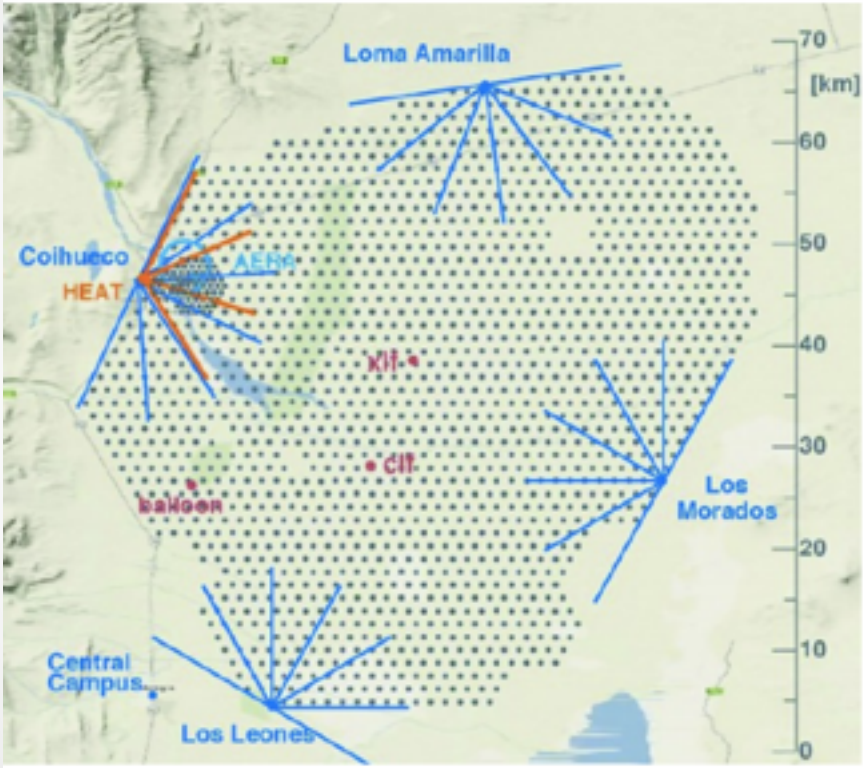


Contemporary questions:

- Gal/XGal transition?
- Origin of the ankle?
- Origin of the UHE steepening?
- Composition at UHE?
- Sources?

NB: From neutrinos/photons upper limits, the bulk of UHECRs are accelerated particles in astrophysical objects

1/ The Pierre Auger Observatory



Hybrid detector:

- Surface detector array (SD):
  - SD-1500:

    1660 spaced by 1.5 km
    ~ 3000 km^2
  - SD-750:

    49 spaced by 750 m
    ~ 24 km^2
- Fluorescence detector (FD):

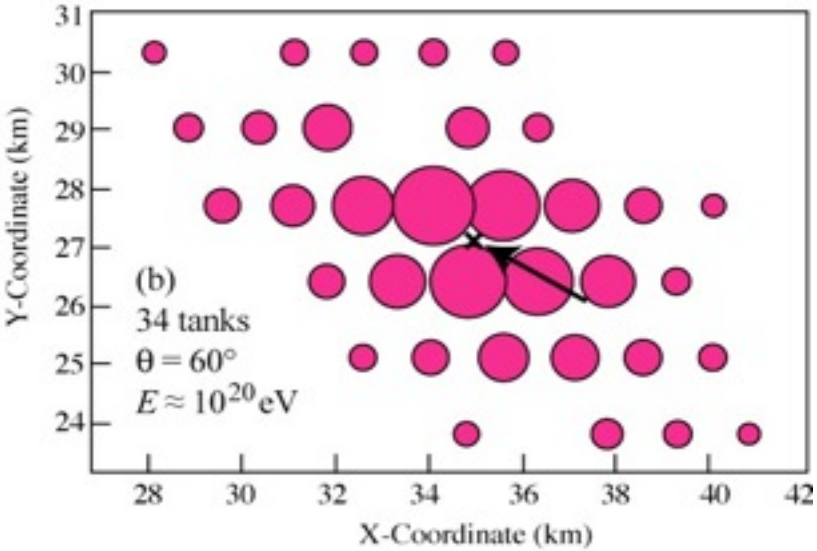
  27 fluorescence telescopes in 5 buildings

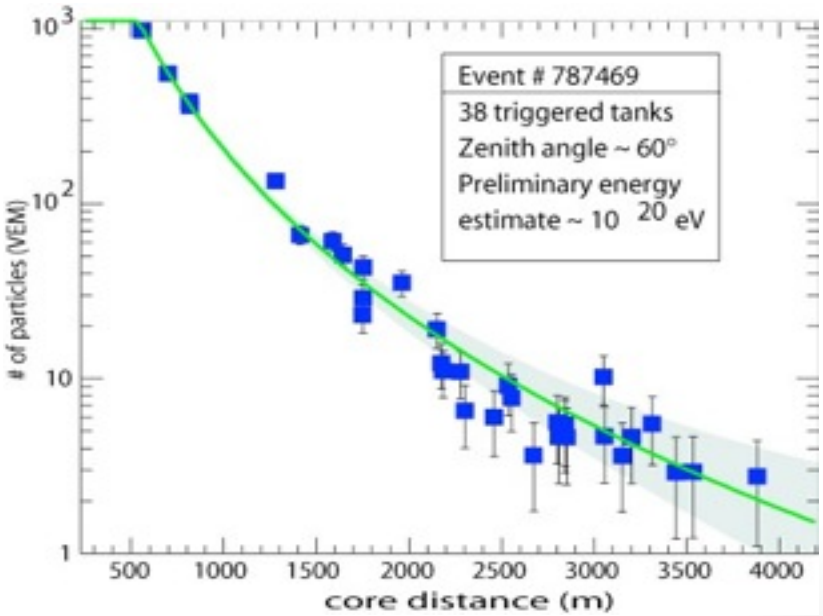
The Pierre Auger Observatory - Surface Detectors

- Footprint of the shower at ground = lateral sampling

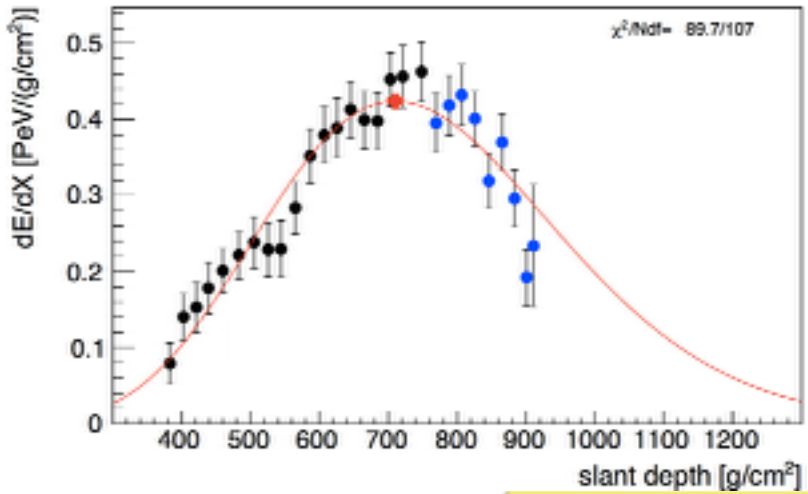
✦ 100% duty cycle

- arrival direction + size of the shower

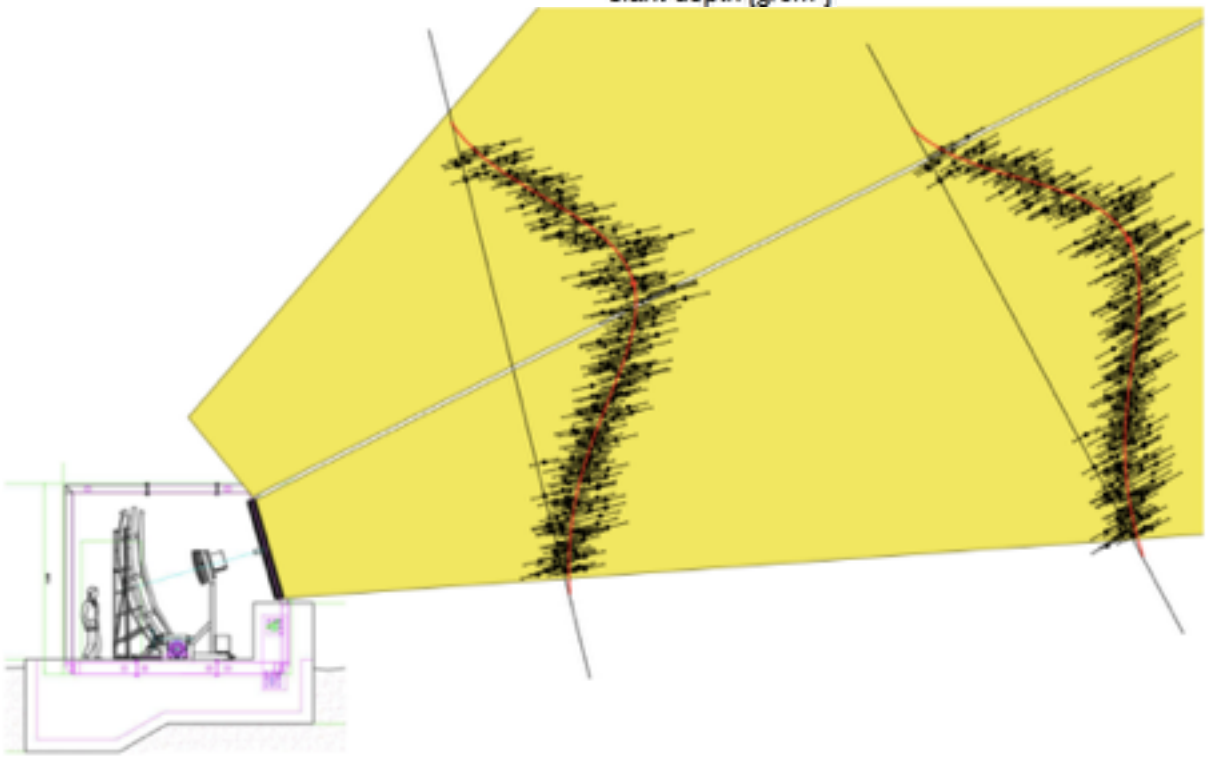




The Pierre Auger Observatory - Fluorescence Detectors

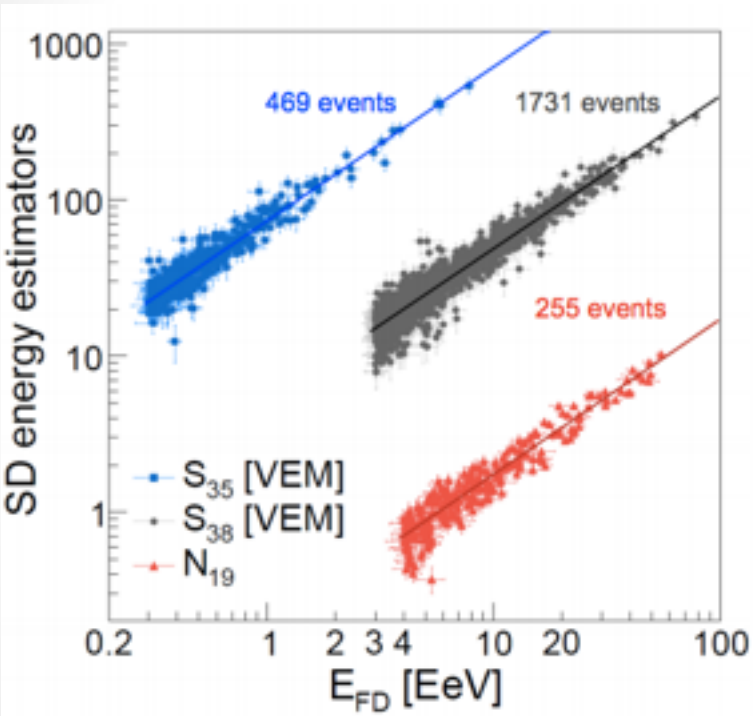


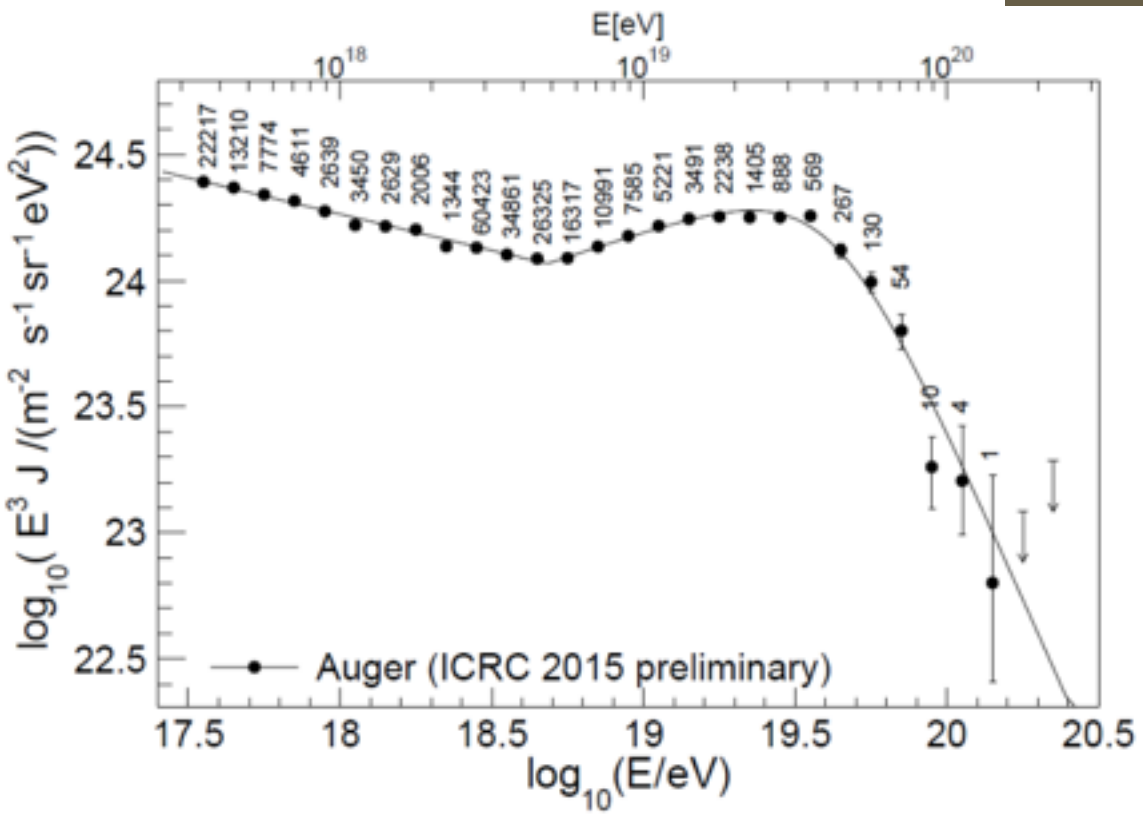
- longitudinal sampling
- calorimetric energy measurement
- X_{max} measurement
  - ✦ 13% duty cycle



2/ Tracking the Origin of UHECRs

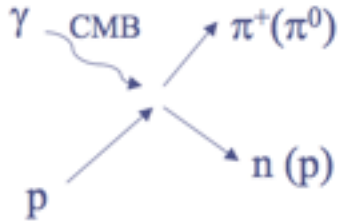
Energy Spectrum at UHE





Two features: ankle and flux suppression at UHE

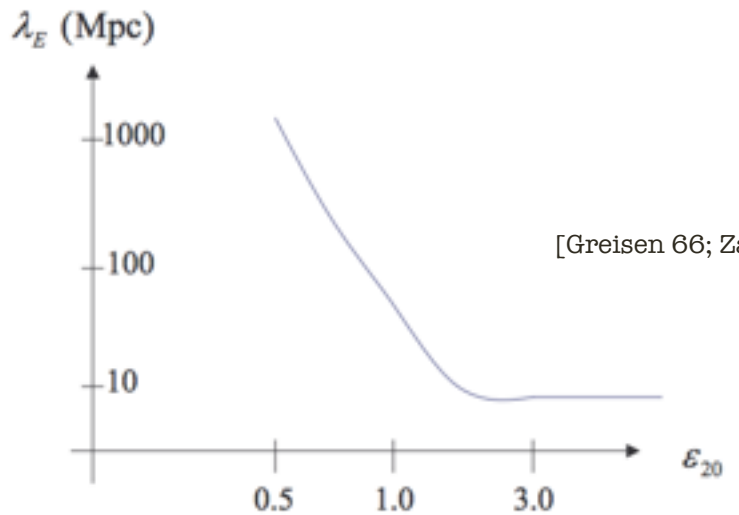
The GZK Paradigm



$$\varepsilon_\gamma > \frac{m_\pi m_p}{\varepsilon_p} \sim 10^{-3}\varepsilon_{20}^{-1}\ \text{eV} \Rightarrow \quad n_\gamma \sim \frac{400}{\text{cm}^3}\exp\left[1-\frac{3}{\varepsilon_{20}}\right]$$

$$\lambda_E \sim \frac{m_p}{m_\pi}\frac{1}{n_\gamma \sigma_{\gamma p}}$$

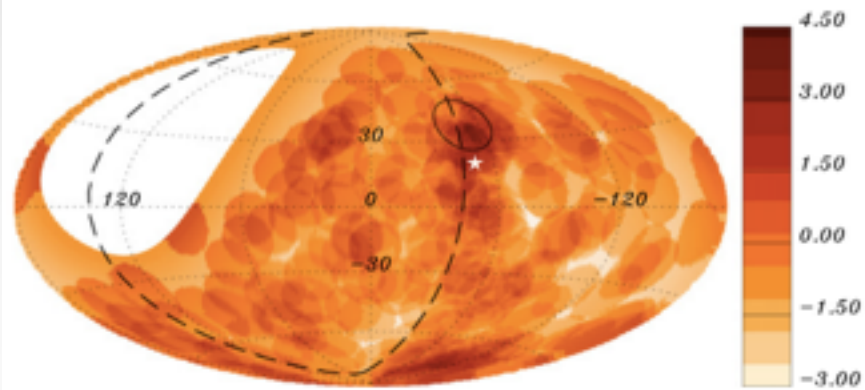
$$\sim 11\exp\left[\frac{3}{\varepsilon_{20}}-1\right] \quad \text{Mpc}$$



[Greisen 66; Zatsepin & Kuzmin 66]

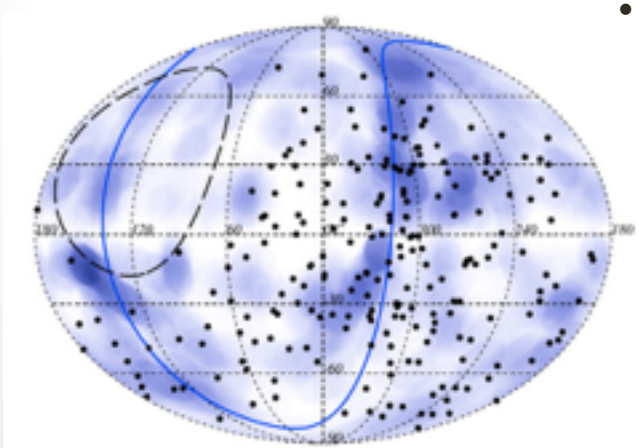
- Rapid reduction of the horizon ⇒ Flux suppression at UHE
- Anisotropy of extragalactic local matter + small magnetic deflection for 10^{20} eV protons ⇒ possibility of UHECR astronomy

Sky Maps at UHE



Significance map for Ψ=12° and E>54 EeV

- Scan on energy threshold E and circular window radius Ψ to compute the obs/exp number of events
- 4.3 σ for E>54 EeV and Ψ=12°
- Post-trial p-value: 69%



Map for E>52 EeV and 2MRS objects < 90 Mpc

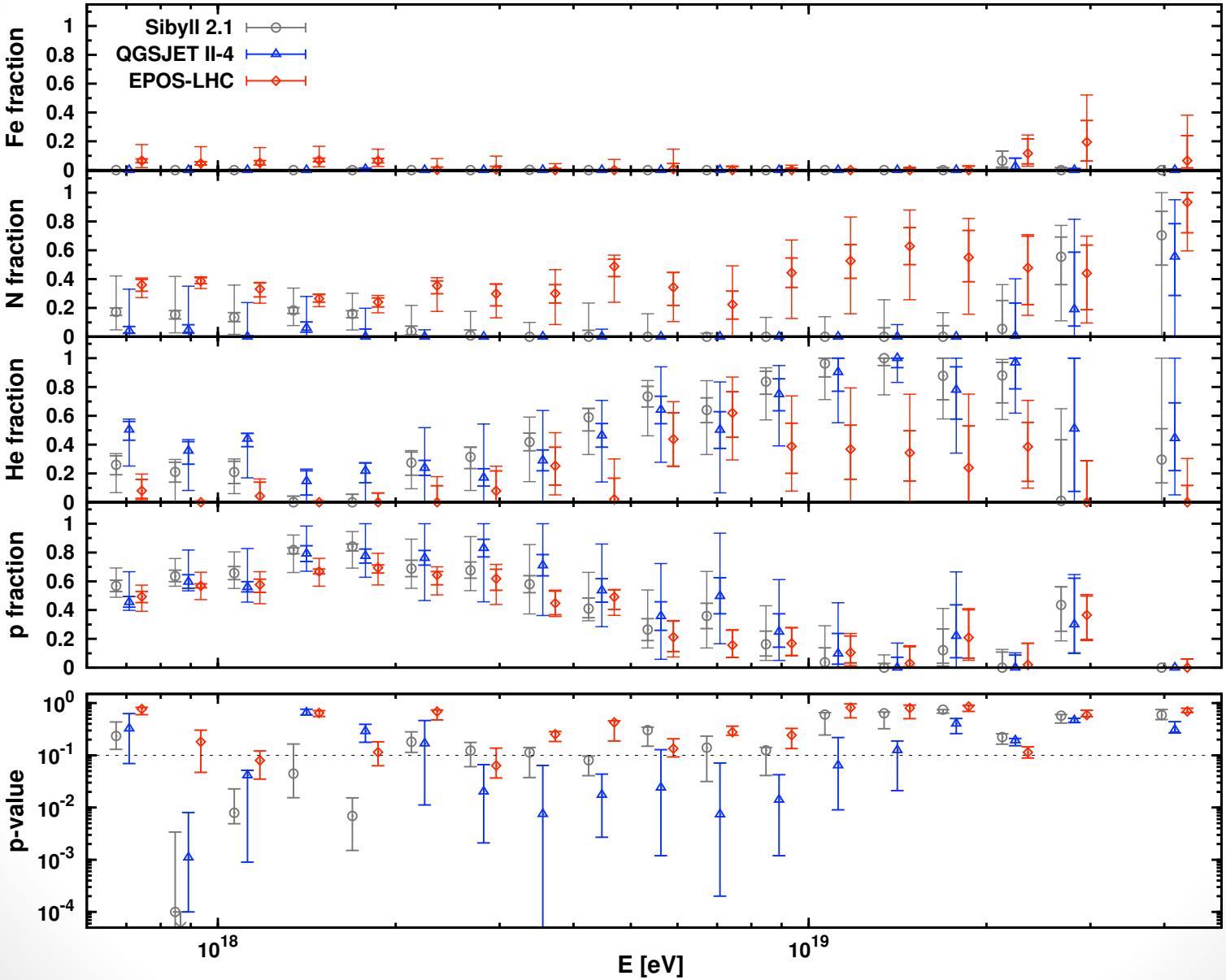
- Cross-correlation with catalogs of extragalactic matter:

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	f_{min}	$\mathscr{P}$
2MRS Galaxies	52	9	90	1.5×10^{-3}	24%
Swift AGNs	58	1	80	6×10^{-5}	6%
Radio galaxies	72	4.75	90	2×10^{-4}	8%

Objects	E_{th} [EeV]	Ψ [°]	D [Mpc]	$\mathscr{L}_{min}$ [erg/s]	f_{min}	$\mathscr{P}$
Swift AGNs	58	18	130	10^{44}	2×10^{-6}	1.3%
Radio galaxies	72	4.75	90	$10^{39.33}$	5.1×10^{-5}	11%

➡ No significant indication of anisotropy

From X_{max} to the Mass



Energy Loss vs Max. Acceleration Energy

✦ The Xmax measurements suggest a scenario with a rigidity-dependent maximum acceleration energy at the sources

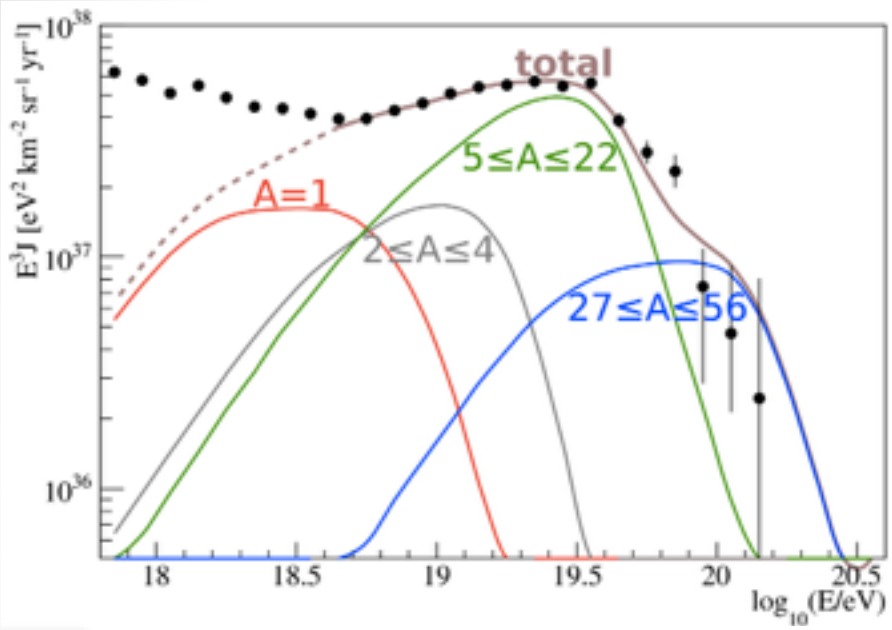
➡ Fit > $10^{18.7}$ eV both the energy spectrum and the Xmax measurements following a simple astrophysical scenario:

- Identical sources homogeneously distributed in a comoving volume
- Injection consisting only of ^{1}H, ^{4}He, ^{14}N, ^{56}Fe (approximately equally spaced in lnA)
- Power-law spectrum at the sources with rigidity-dependent broken exponential cutoff:

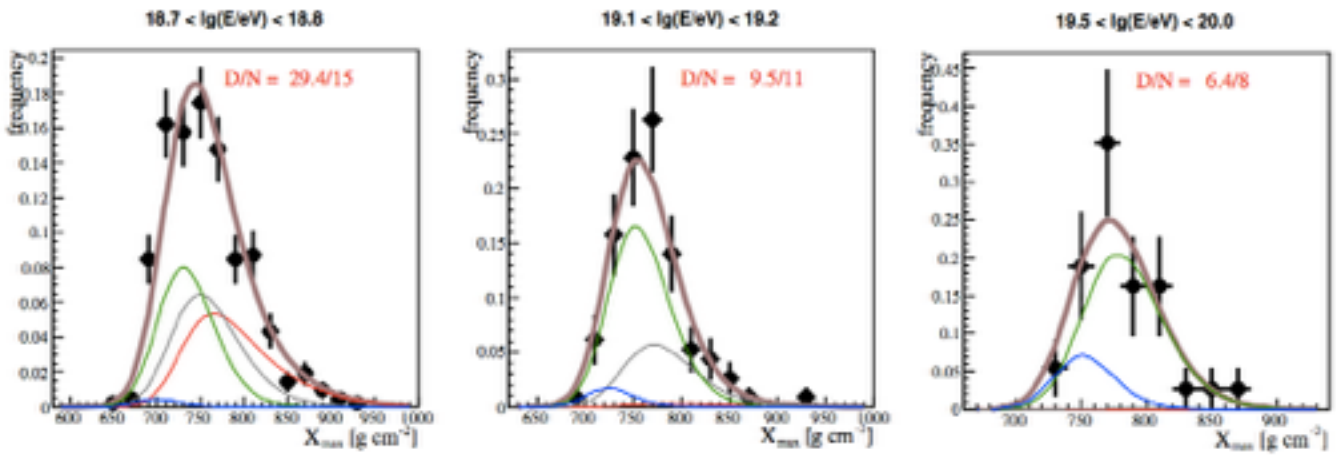
$$\frac{dN_{\mathrm{inj},i}}{dE} = \begin{cases} J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma}, & E/Z_i < R_{\mathrm{cut}} \\ J_0 p_i \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(1 - \frac{E}{Z_i R_{\mathrm{cut}}}\right), & E/Z_i > R_{\mathrm{cut}} \end{cases}$$

➡ 6 free parameters: $(J_0, \gamma, R_{\mathrm{cut}}, p_{\mathrm{H}}, p_{\mathrm{He}}, p_{\mathrm{N}})$; $p_{\mathrm{Fe}} = 1 - p_{\mathrm{H}} - p_{\mathrm{He}} - p_{\mathrm{N}}$

Energy Loss vs Max. Acceleration Energy

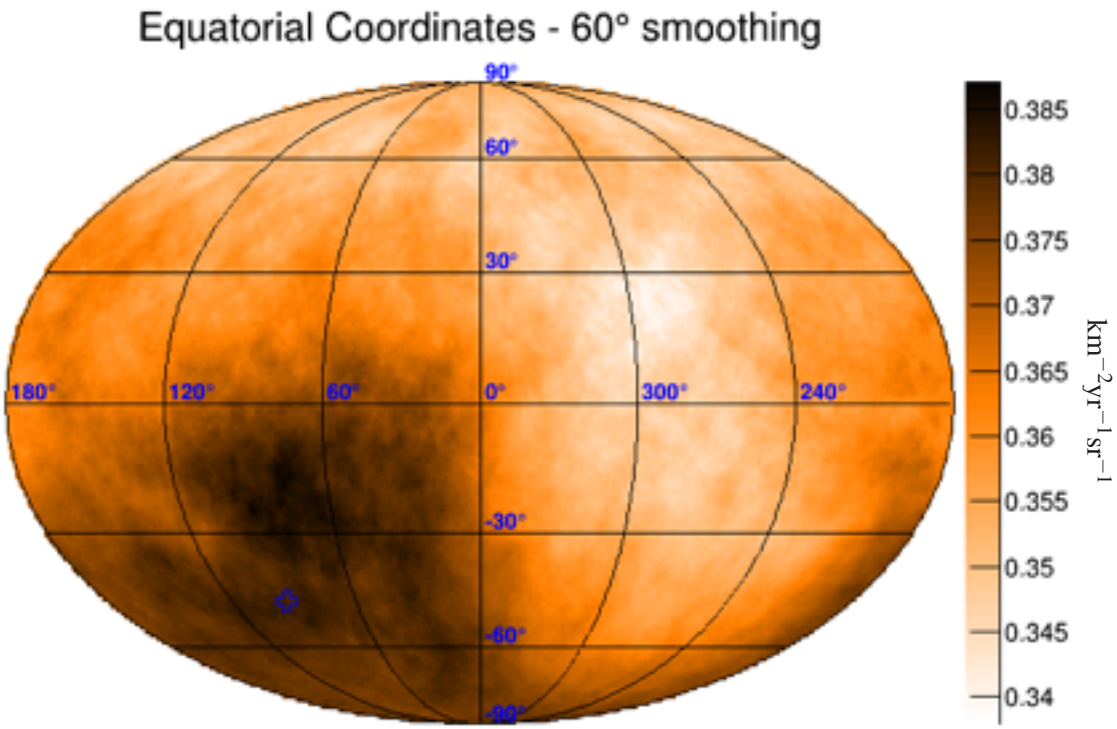


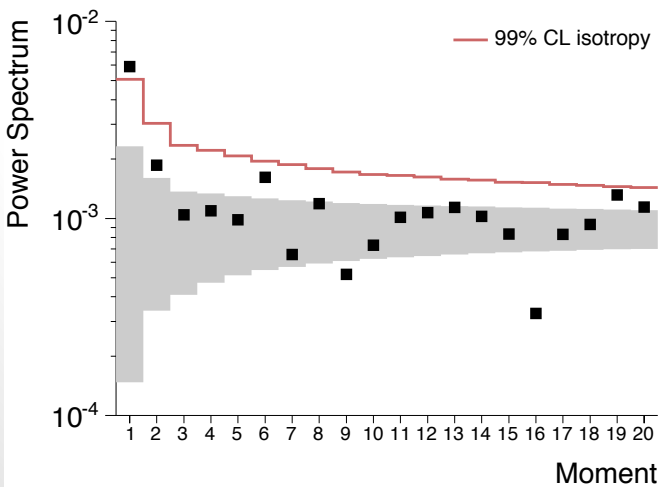
- ➡ Hard, meal-rich injection, low cutoff (R_{cut}<$10^{18.7}$ V)!
- Mainly due to narrow X_{max} distributions (little mixing of different masses at the same energy)
- **NB: Relies on extrapolations of the mass at UHE**



- red: $A = 1$
- gray: $2 \leq A \leq 4$
- green: $5 \leq A \leq 22$
- blue: $A \geq 23$
- thick brown: total
- black dots: Auger data

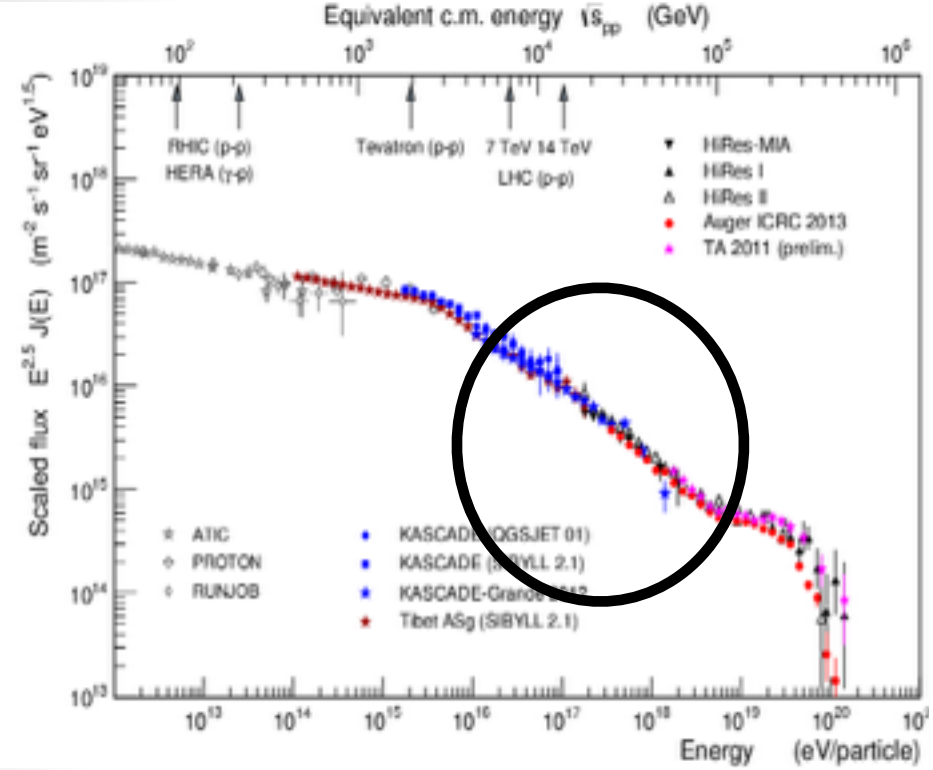
Full-Sky Map > 10 EeV (with Telescope Array)





- Interesting dipole effect to monitor
- No strong destruction of a dipole pattern by the GMF
- Dipole direction related to the anisotropy contrast of the local sources

3/ The Ankle - End of Galactic CRs?



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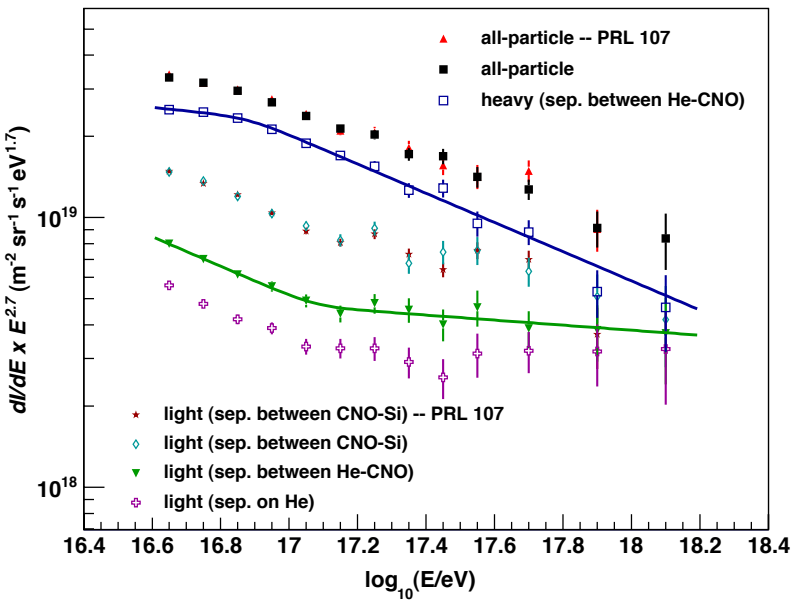
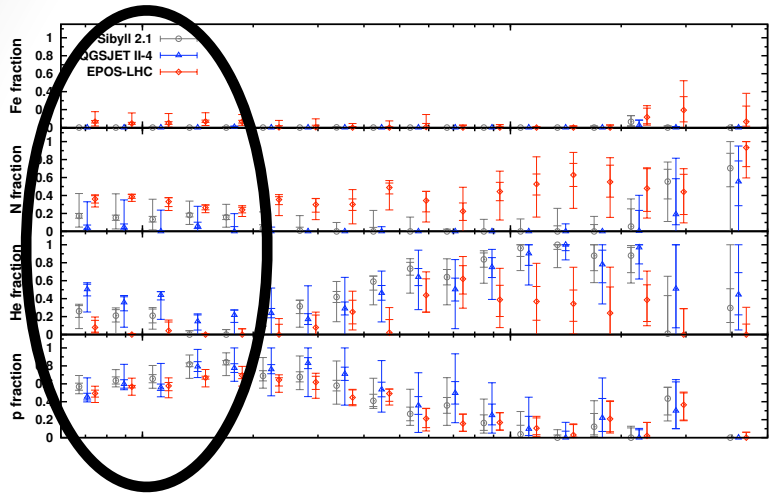


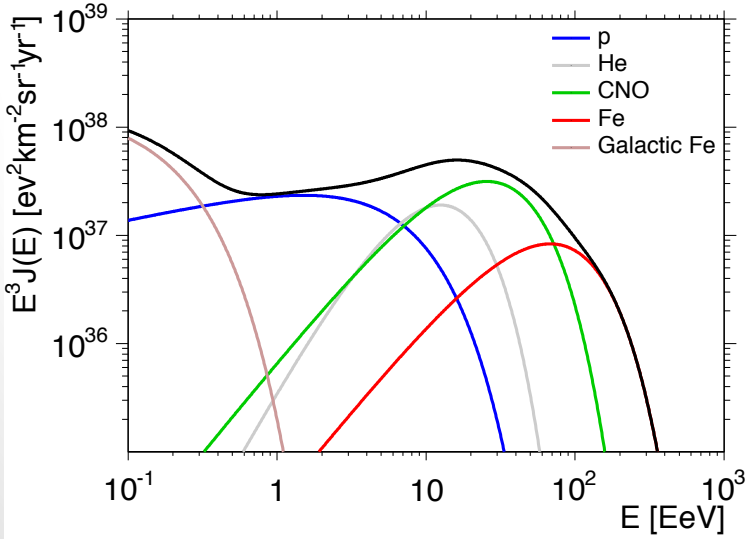
- Rigidity-dependent scenario for GCRs
- « Knees » = maximum acceleration energies
- Extragalactic protons entering progressively

The Ankle - End of Galactic CRs?

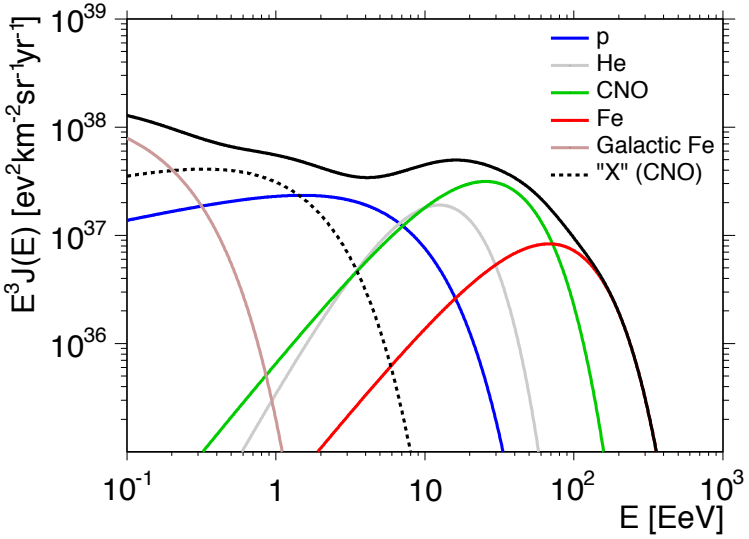


➡ In addition to (extragalactic) protons, EeV CRs are from the CNO group, not Fe!

Gal/xGal scenario:

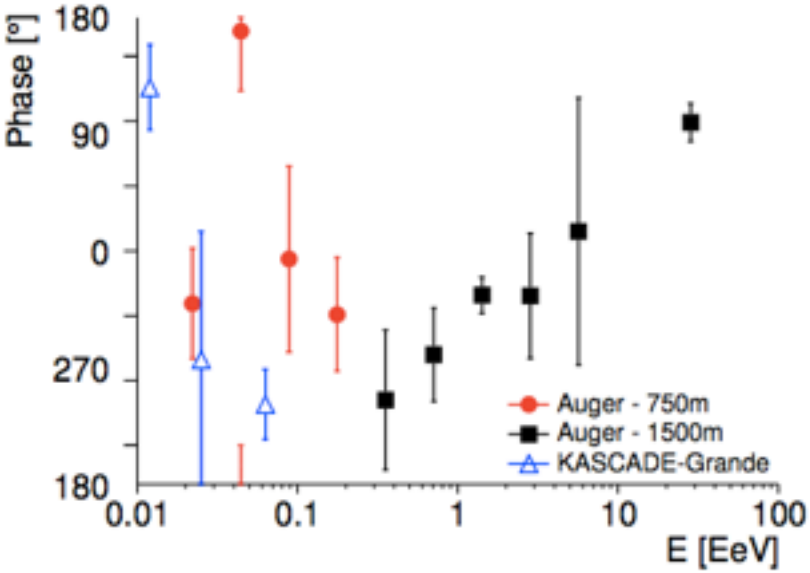


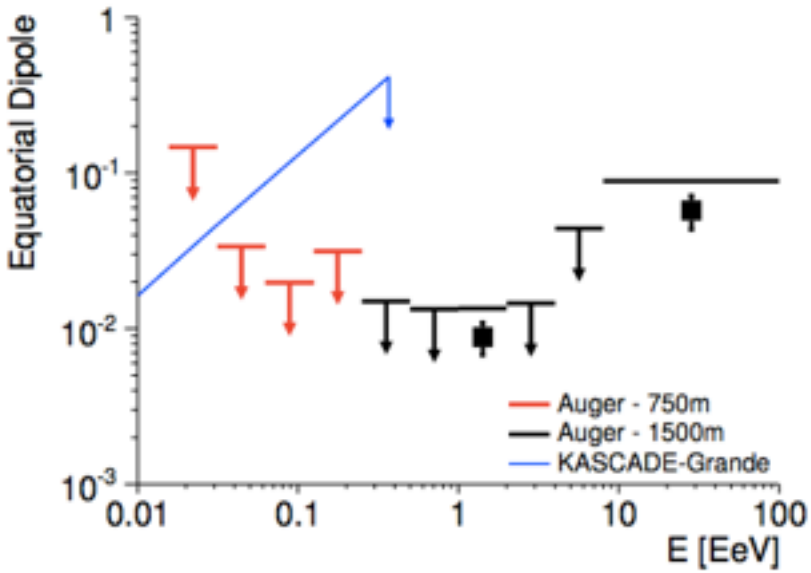
Observed scenario:



Origin of the Ankle?

direction/amplitude of the dipole in right ascension:



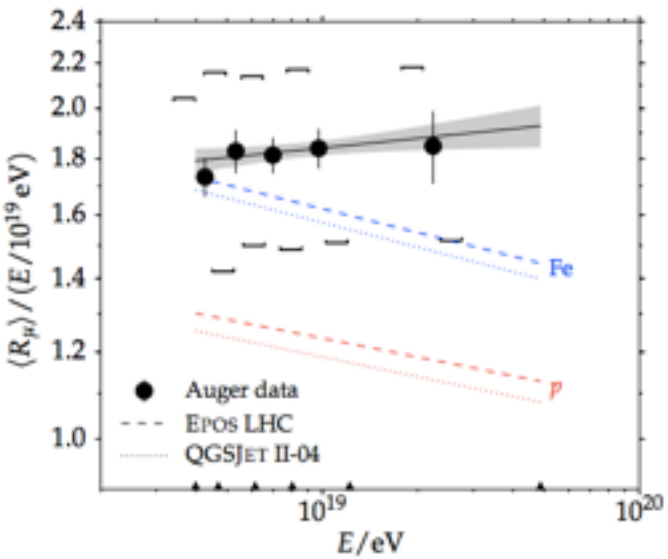


➡ Phase roughly in the direction of the Galactic center

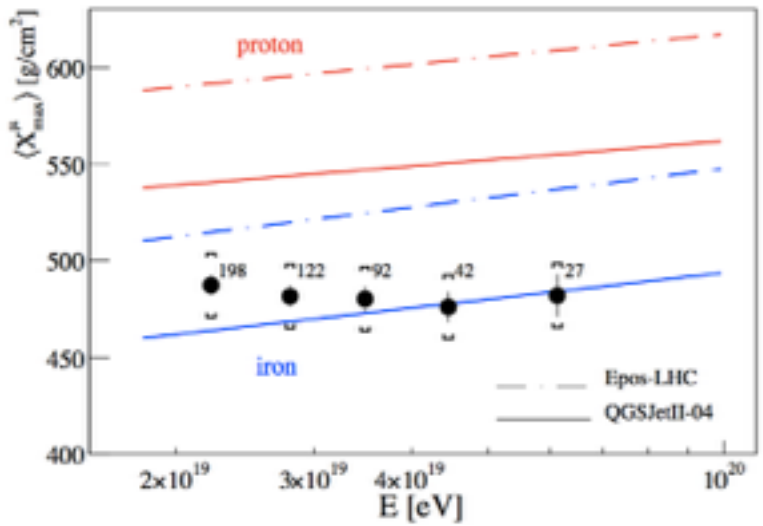
- CNO elements as the high-energy tail of the bulk of GCRs: breakdown of the rigidity-dependent paradigm?
- CNO: additional component?

4/ Particle Interactions - Muon Content of EAS

Mean Muon Scale <R_μ>



X^{μ}_{max} vs. energy



- Deficit of muons in simulations, between 30% and 80%
- Systematic uncertainty inherited from energy scale

➤ QGSJetII-04: data bracketed by predictions
➤ EPOS-LHC: predictions above data

➡ Constraints on hadronic interaction models (inelasticity, multiplicity)

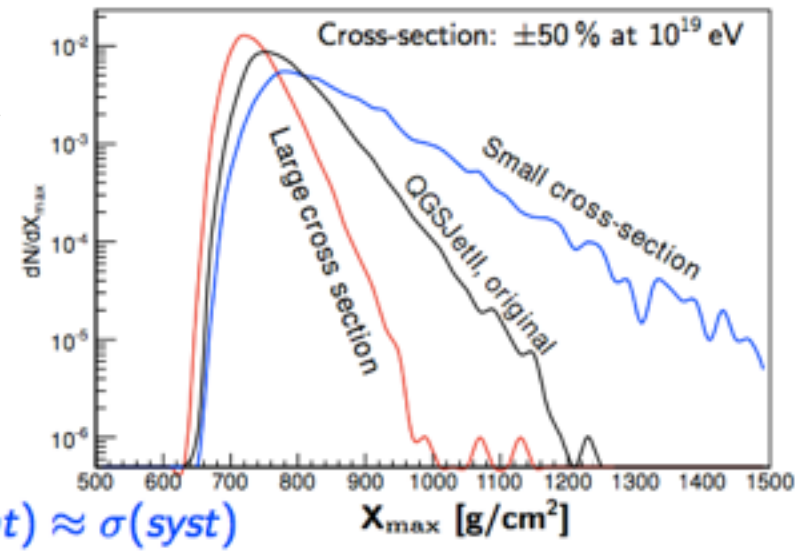
➡ Currently, tension between muon and e.m. contents of EAS in simulations

Proton-Air Cross-Section

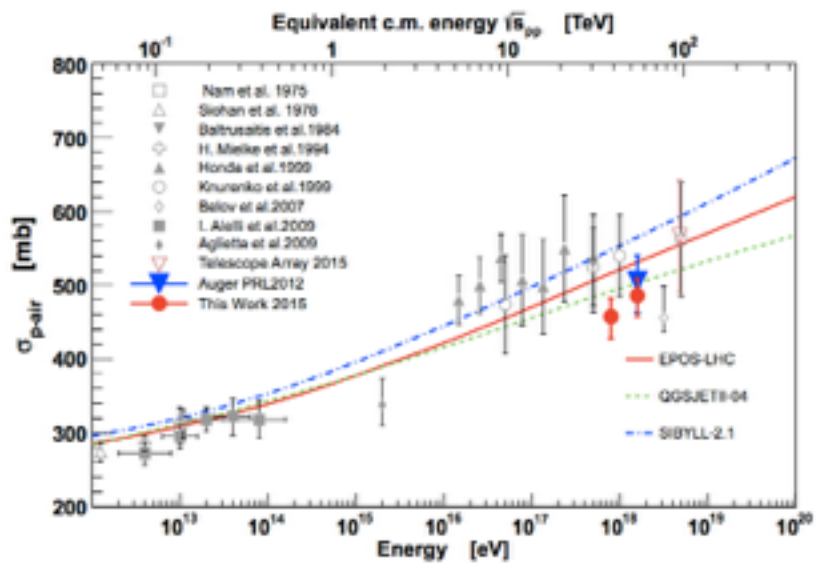
- Tail of X_{max} distribution sensitive to p-air cross-section

$$dN/dX_{max} \propto \exp(-X_{max}/\Lambda_\eta)$$

- Measurement of Λ_η around 1 EeV, where a significant proton fraction is seen



- Choose $\eta = 0.2$ to achieve $\sigma(stat) \approx \sigma(syst)$



➡ Extended Glauber conversion with inelastic screening + propagation of modeling uncertainties:

- Lower energy point
  76.95±5.4(stat)+5.2/-7.2(syst)±7(glauber)
  at $\sqrt{s_{pp}} = 38.7 \pm 2.5$ TeV

- Higher energy point
  85.62±5(stat)+5.5/-7.4(syst)±7.1(glauber)
  at $\sqrt{s_{pp}} = 55.5 \pm 3.6$ TeV

Summary

- Quest of UHECR origin more difficult than expected 10 years ago
  - Unexpected scenario for UHECR production
  - Unexpected scenario at EeV energies: ankle origin?
- Hadronic interaction models can benefit from muon content measurements
- Need for composition measurements at UHE: Upgrade of the Observatory designed to provide complementary measurements allowing better constraints on the muon content of EAS
  - Need for (much) larger exposure keeping similar resolutions…