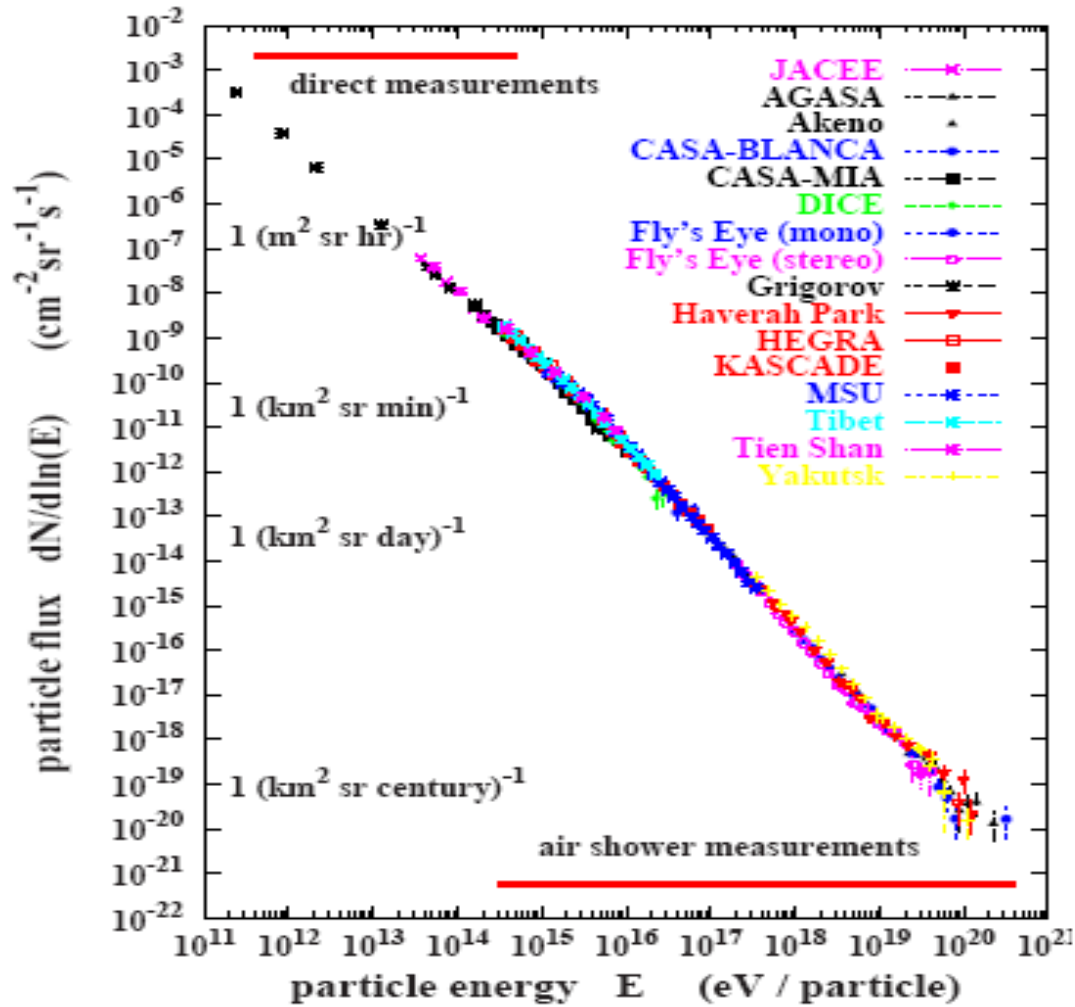


# Quest for origin of ultra-high energy cosmic rays

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# Cosmic ray energy spectrum



# Ultra-high energy cosmic rays

Sources of ultra high energy cosmic rays remain unclear:

Acceleration in known astrophysical objects (bottom-up)?

radio galaxies, AGN,...

Large Z nuclei easier to accelerate

Only secondary neutral particles

Exotic processes (top-down)?

topological defects, relic particles,...

Photon/neutrino dominance

No heavy nuclei

„Hybrid“ scenarios, e.g. new properties of known particles?

new particles, Lorentz invariance violation,...

Need measurements of

arrival directions

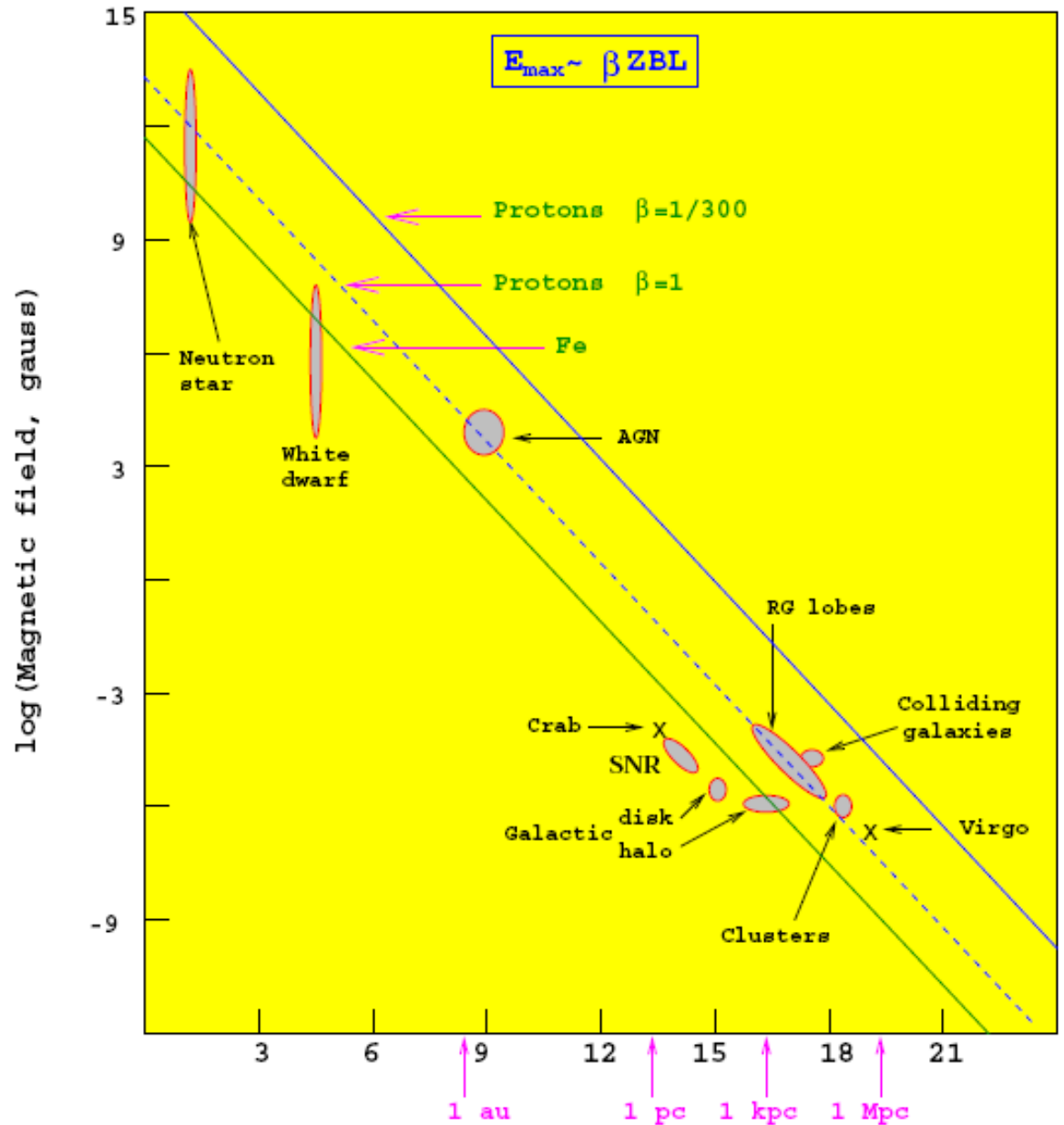
energy spectrum

composition

# Hillas plot

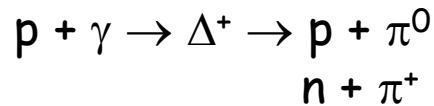
Candidate sites of particle acceleration to  $10^{20}$  eV

Charged particles:  
heavy nuclei?  
neutrals only as secondary



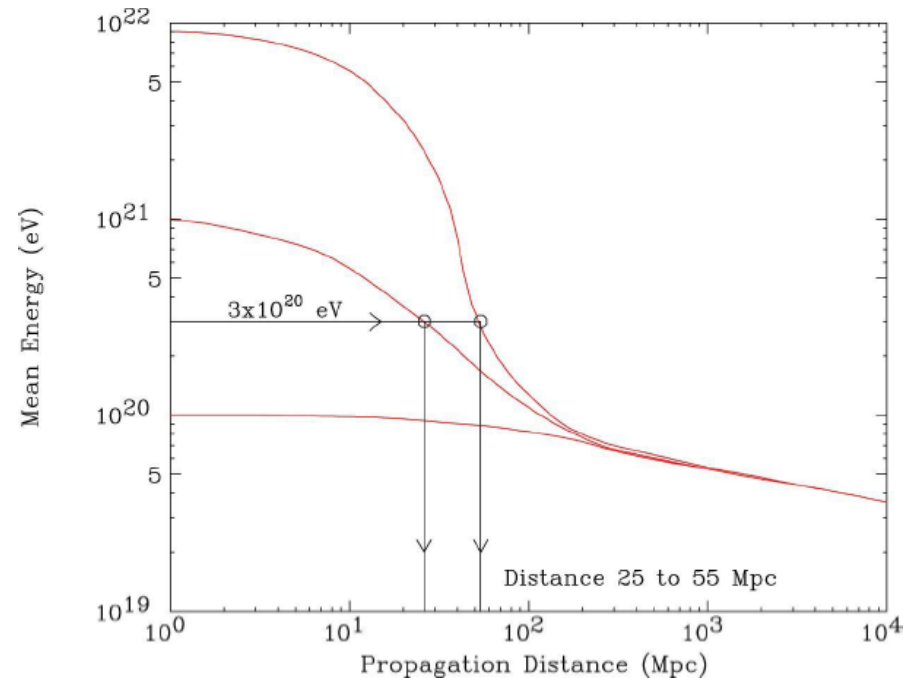
# GZK effect

Greisen-Zatsepin-Kuzmin effect  
interactions with CMB photons  
at  $E > \sim 5 \times 10^{19}$  eV:



- reduction of proton energy
- spectrum steepening

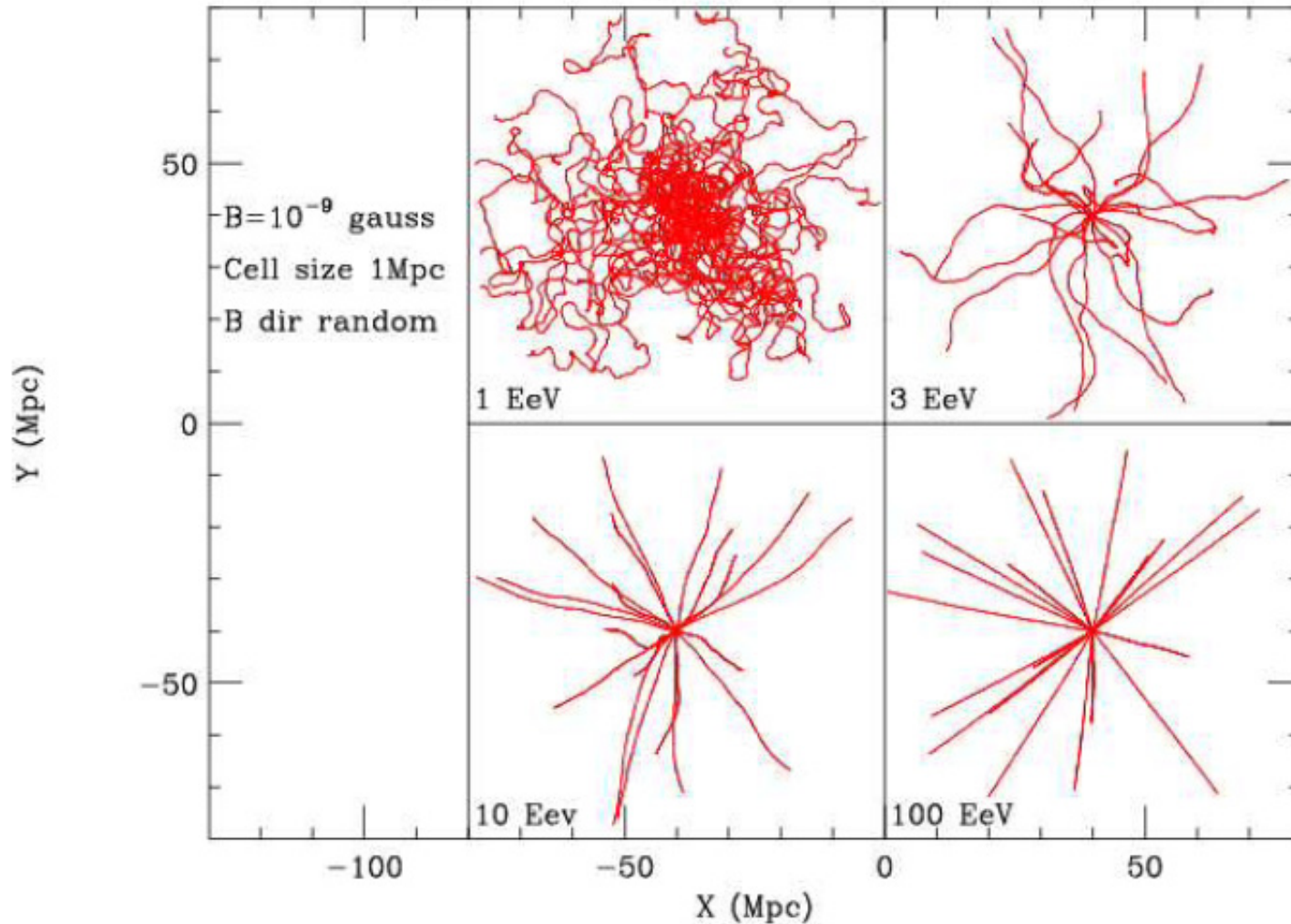
For  $E > 10^{20}$  eV the source must be  
within  $\sim 50$  Mpc  
source identification should be easy??



Charged particle astronomy should be possible

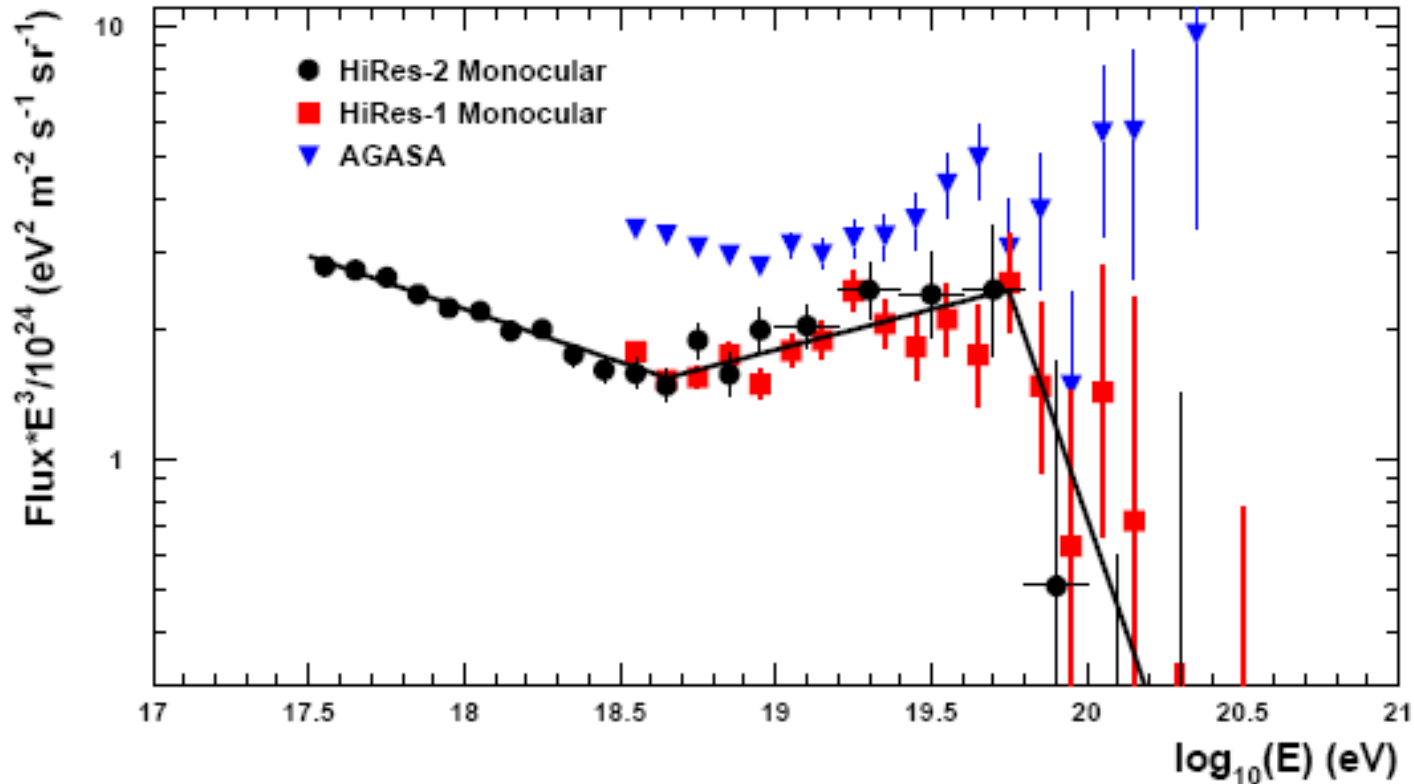
# Cosmic ray propagation

3D trajectories projected on X-Y plane



Pointing to sources at  $E > 100$  EeV?

# UHECR spectrum 2007

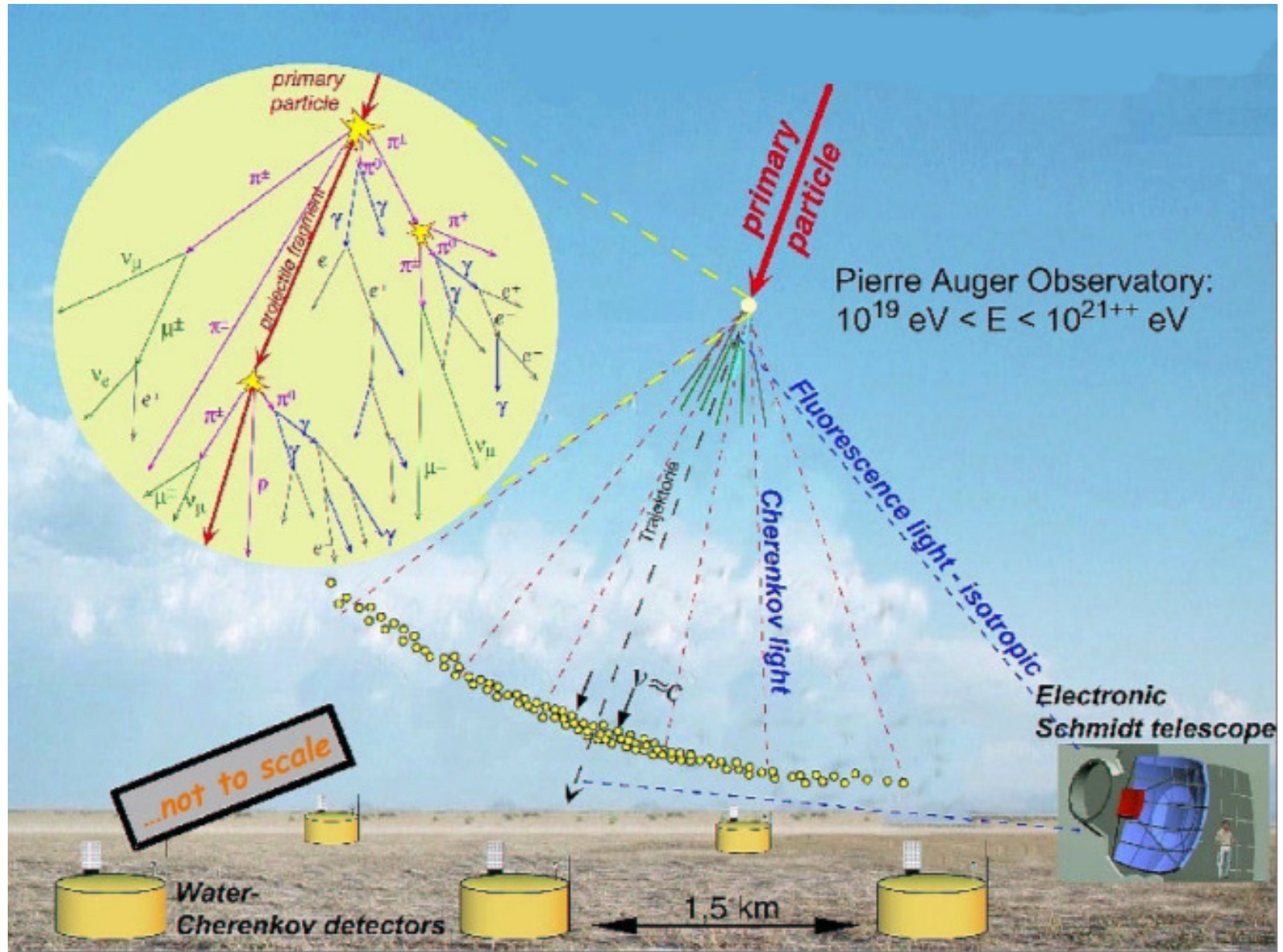


Is there the GZK cutoff?

Different experimental techniques used;

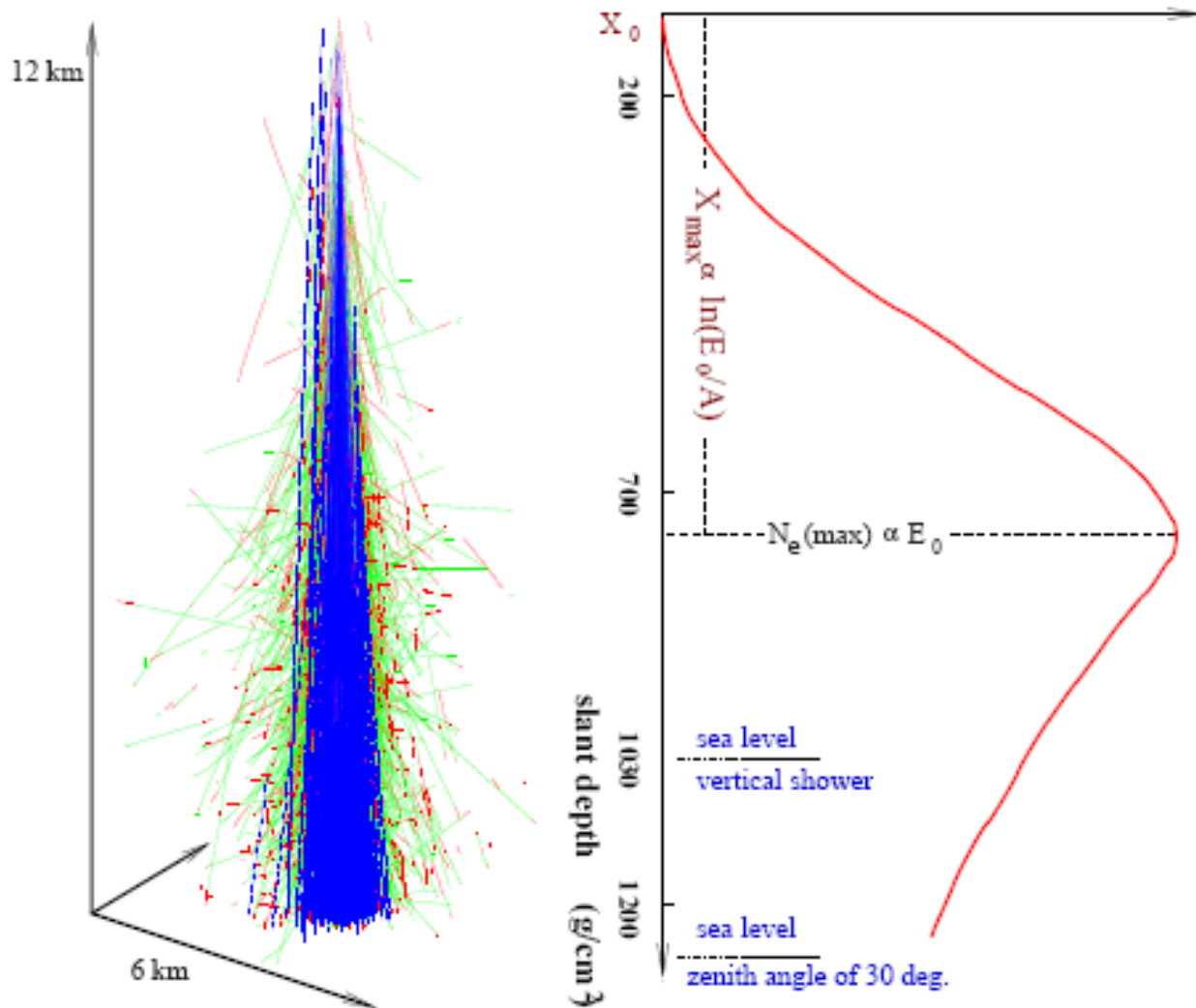
Is the discrepancy due to shower development modelling?

# Extensive air shower

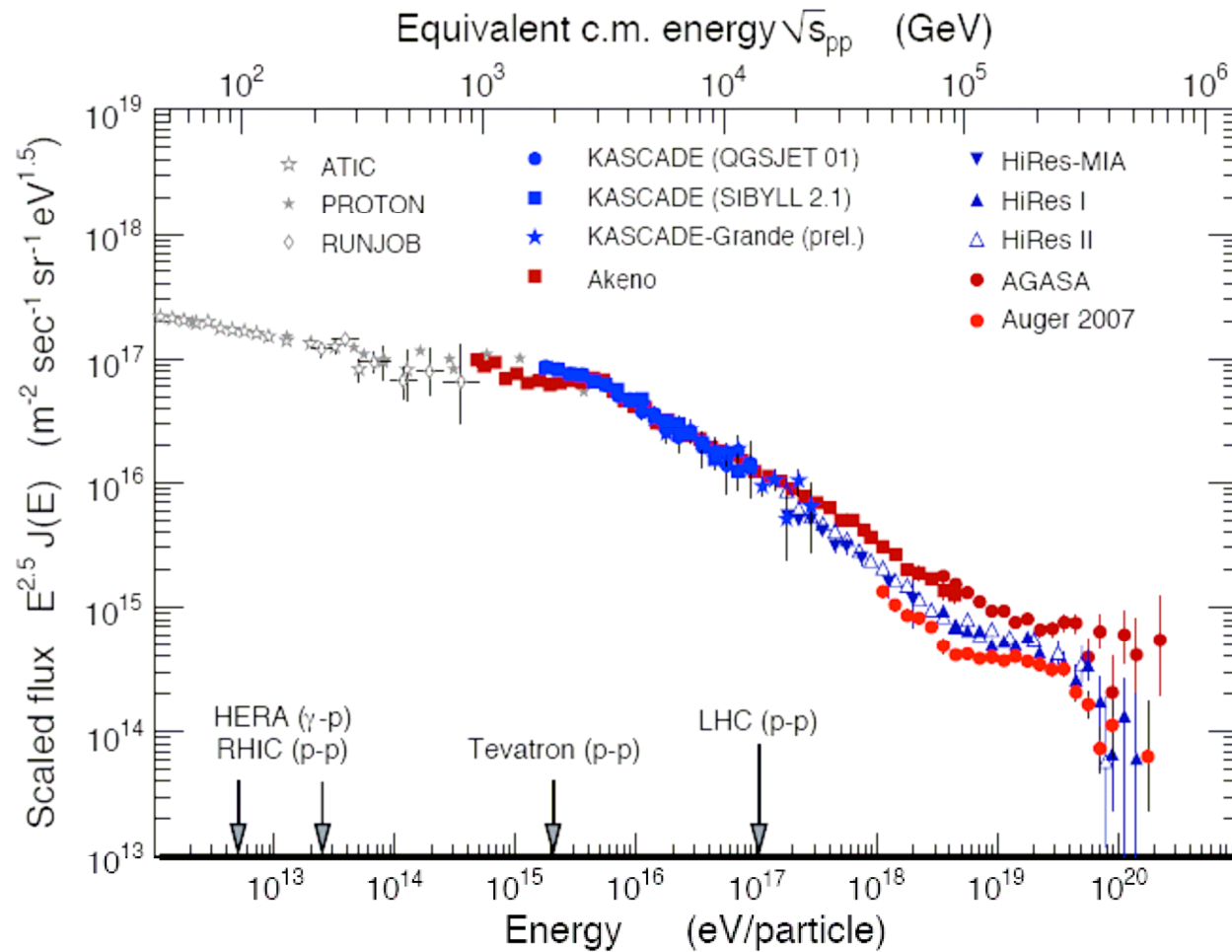




# Air shower development

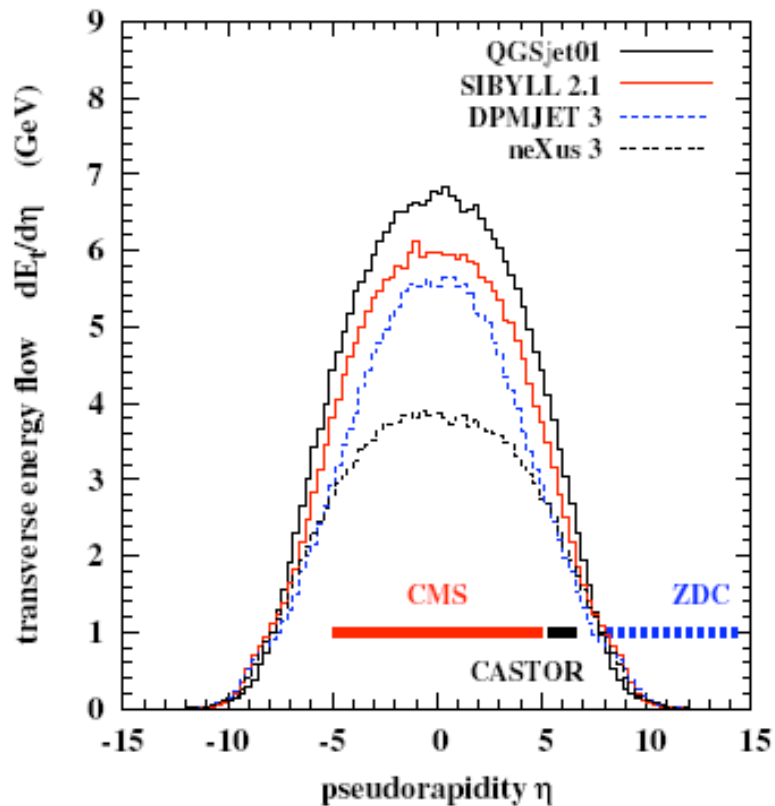


# C.M. Energy scale

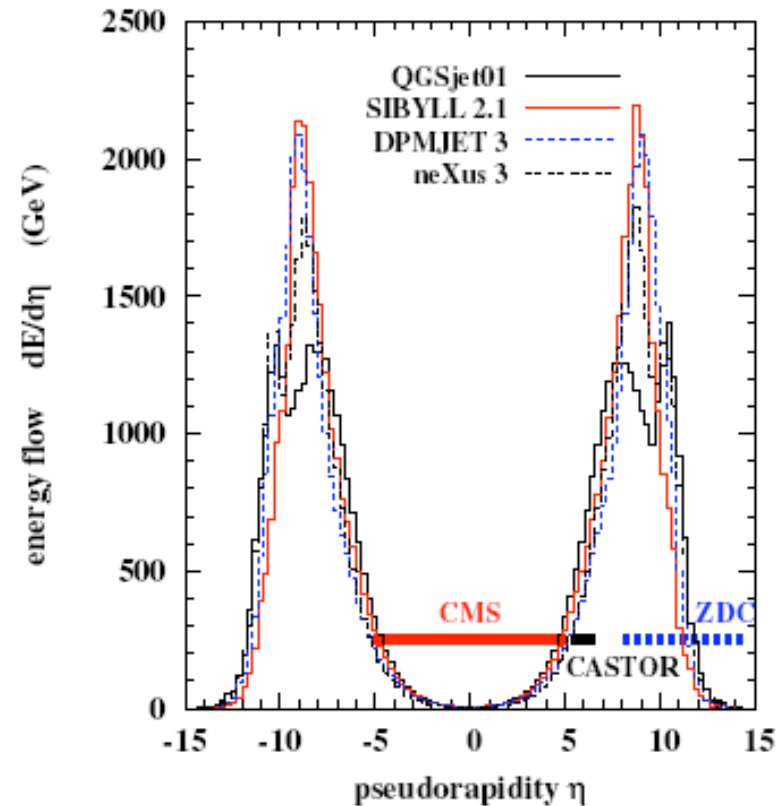


# Particle production

transverse energy



total energy

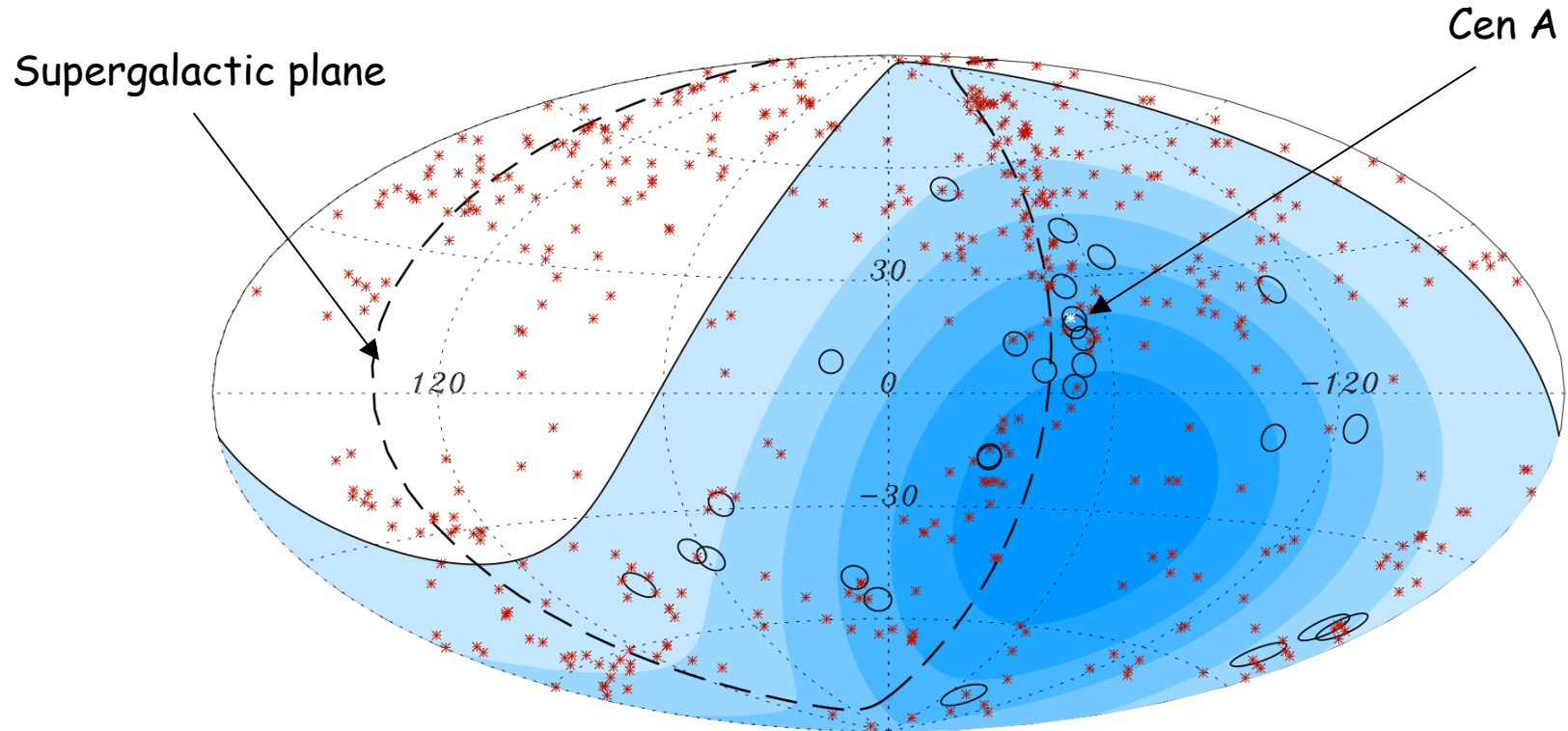


Air shower development determined by the very forward particles

# Anisotropy of UHECR

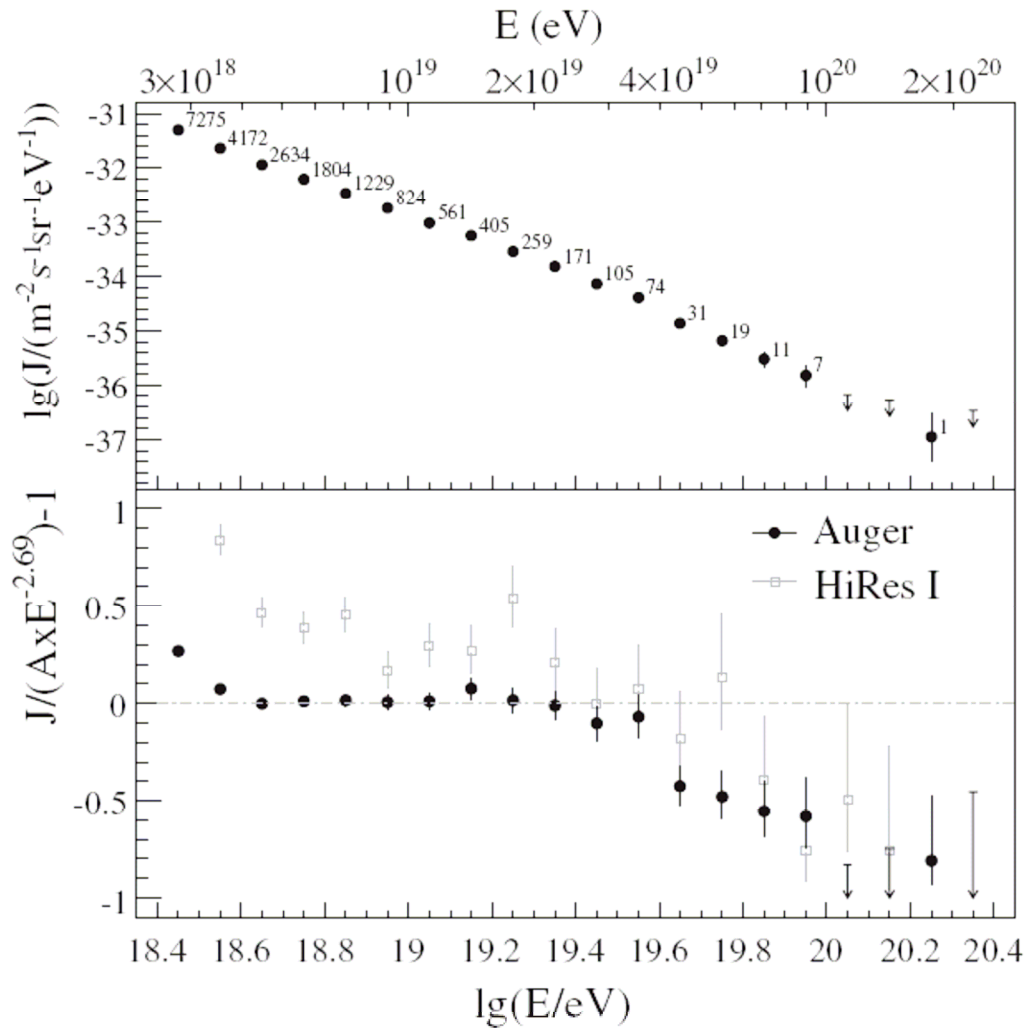
\* 472 AGN  $d < 75$  Mpc  
(318 in Auger field of view)

○ events  $E > 57$  EeV



Are AGN (subclass of them) the sources of UHECR?  
Are AGN tracers of the sources?

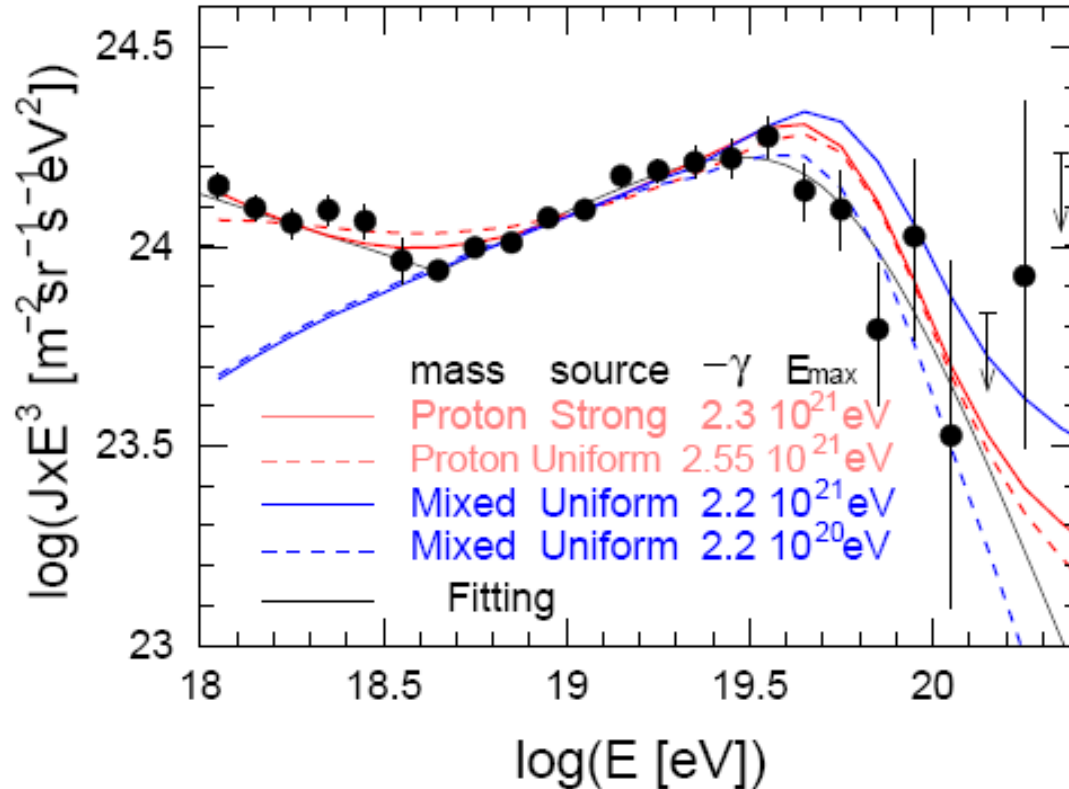
# Spectrum from Auger 2008



GZK steepening?

# Spectrum vs composition

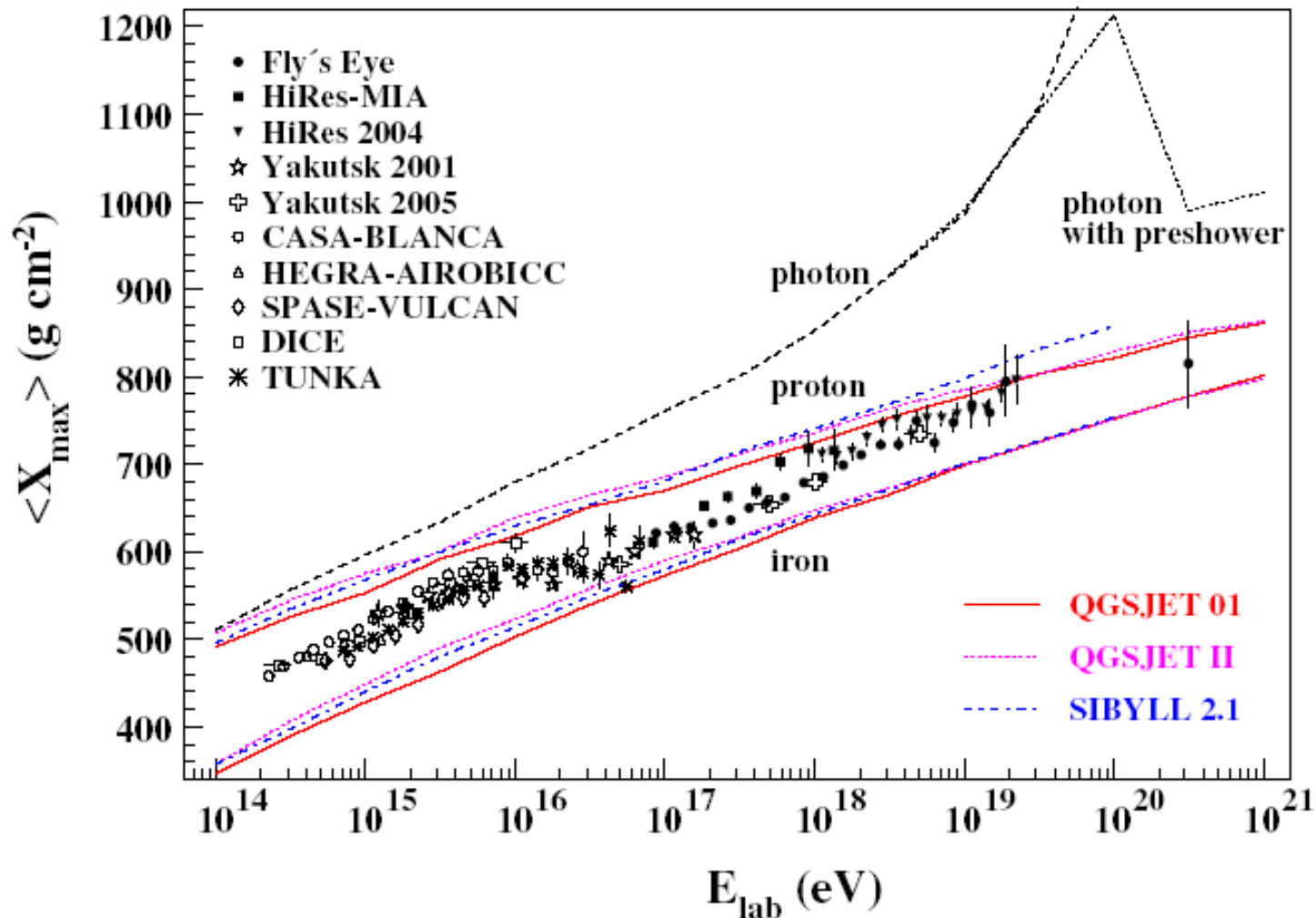
Auger 2007



Composition measurement is crucial

# CR composition based on $X_{\max}$

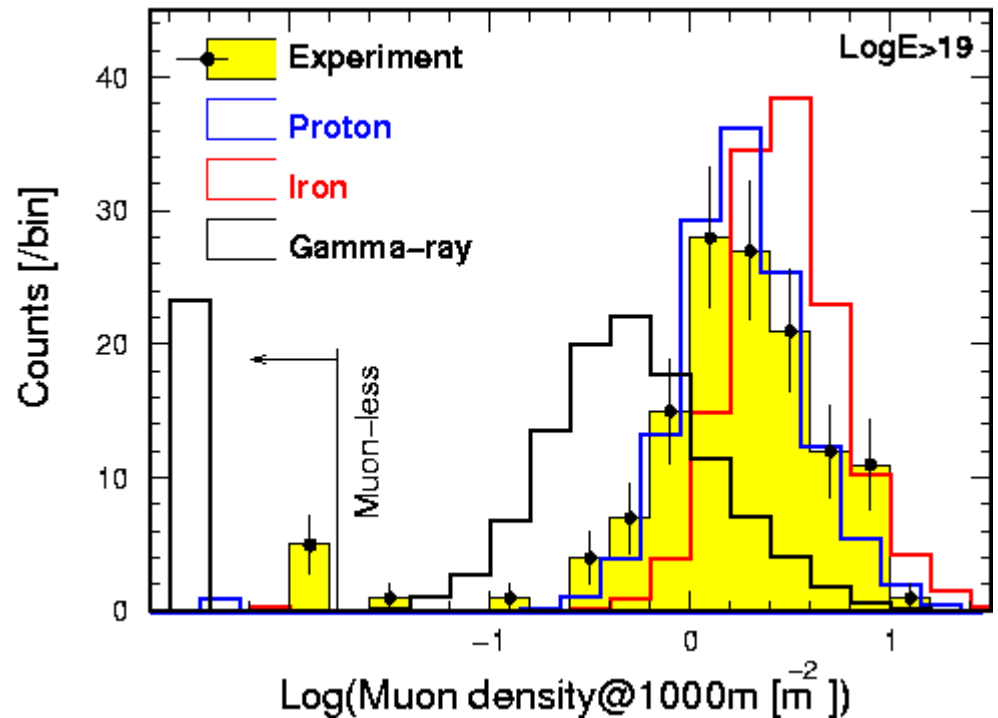
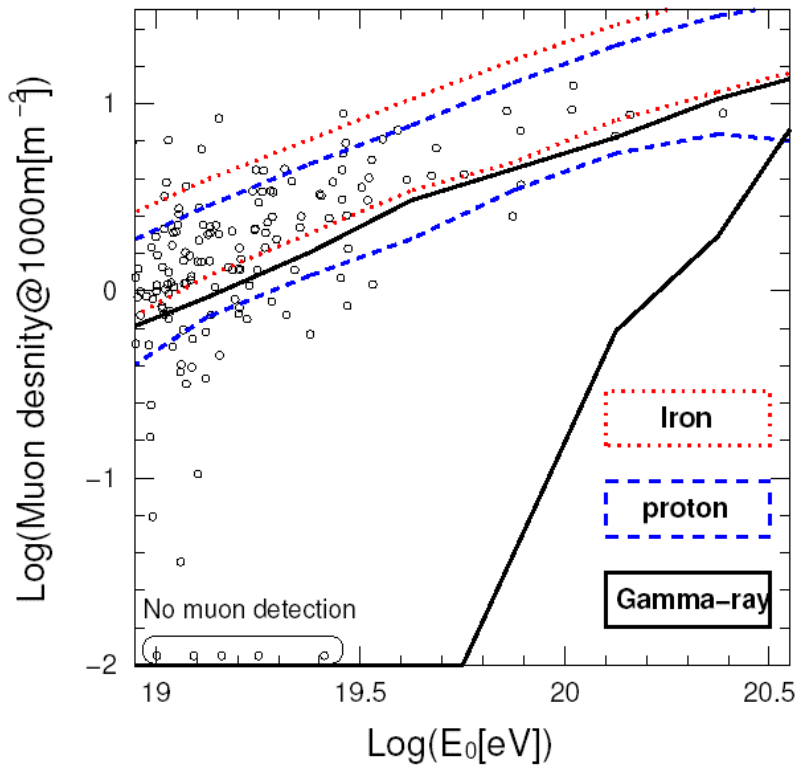
Elongation rate:  $X_{\max}$  vs Energy



# Cosmic ray composition

muon density: *AGASA* (Shinozaki et al.)

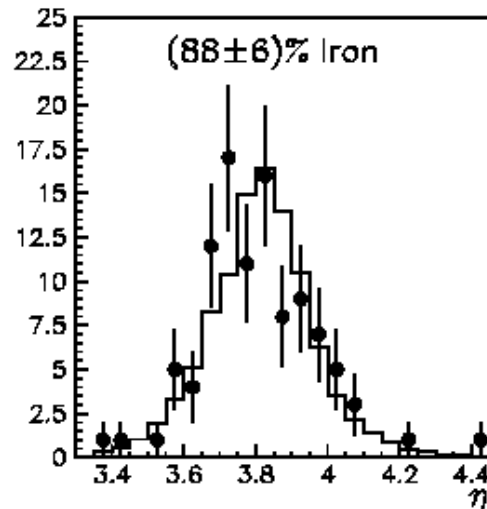
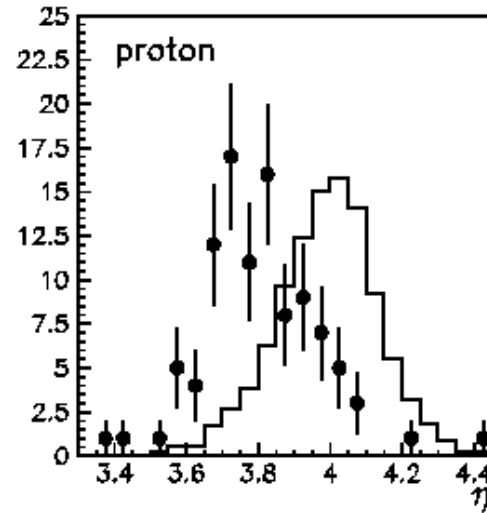
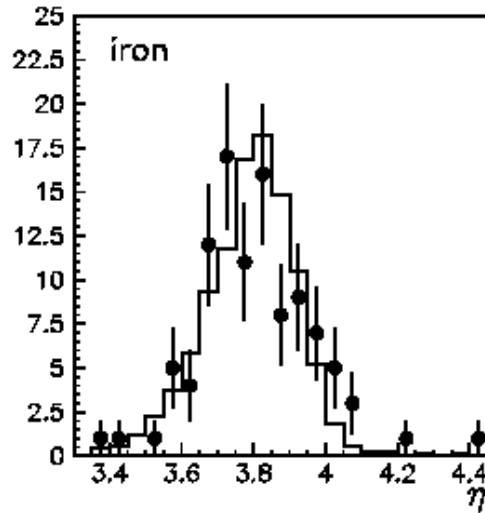
consistent with proton-dominant composition?





# Cosmic ray composition

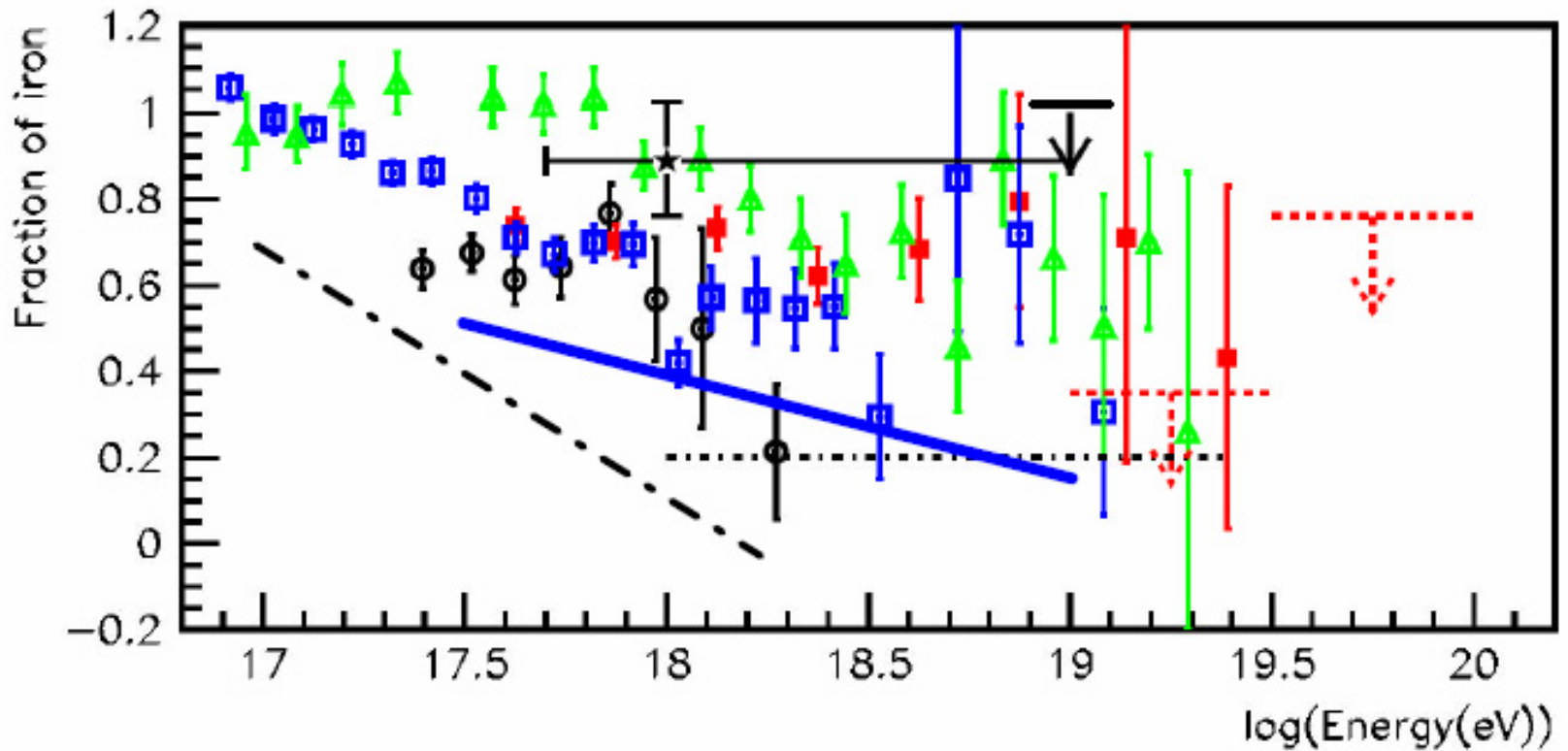
Lateral distribution function: Volcano Ranch (Dova et al.)



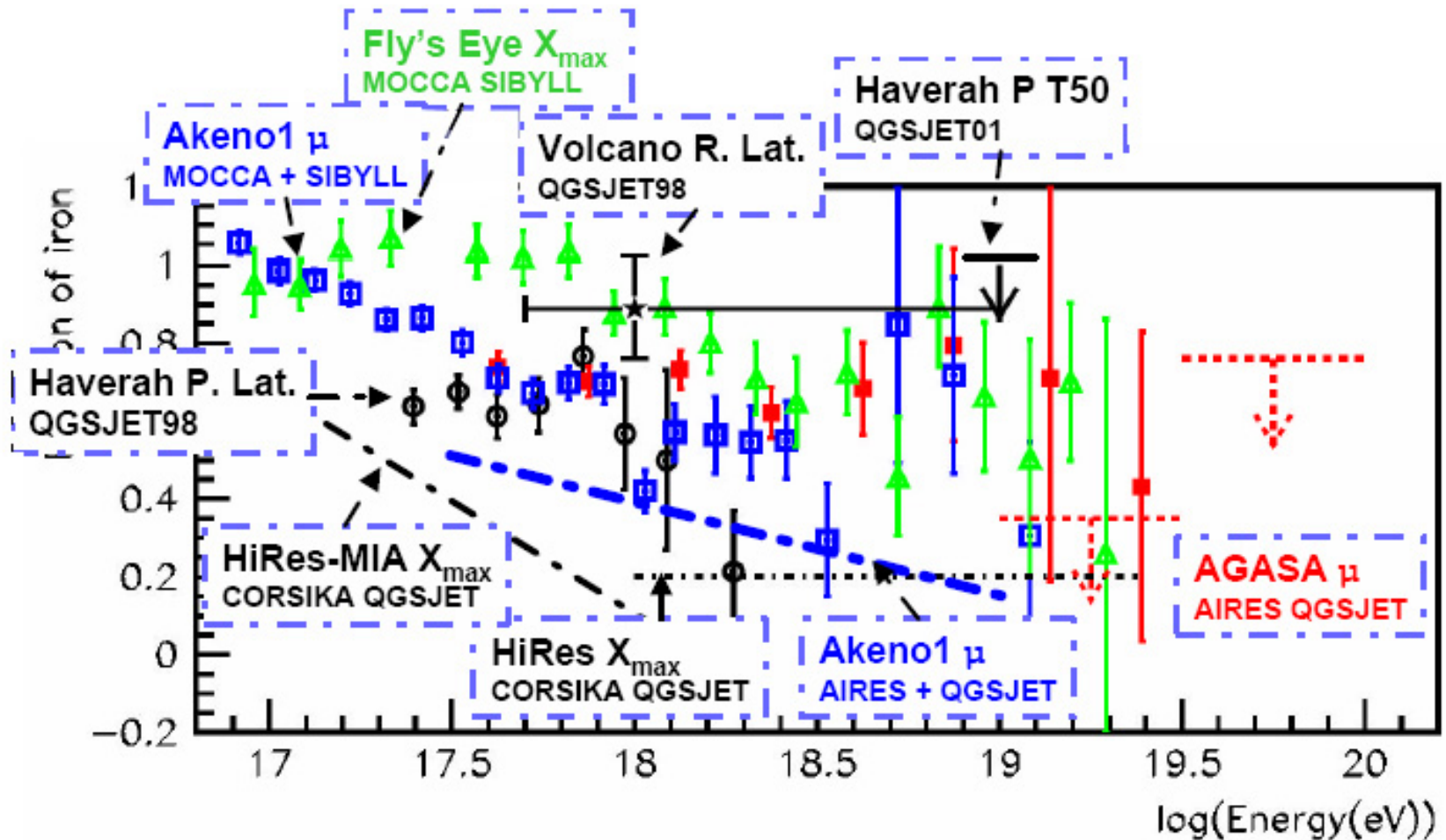
90% iron?

# Composition - summary 2004

Are interaction models correct?

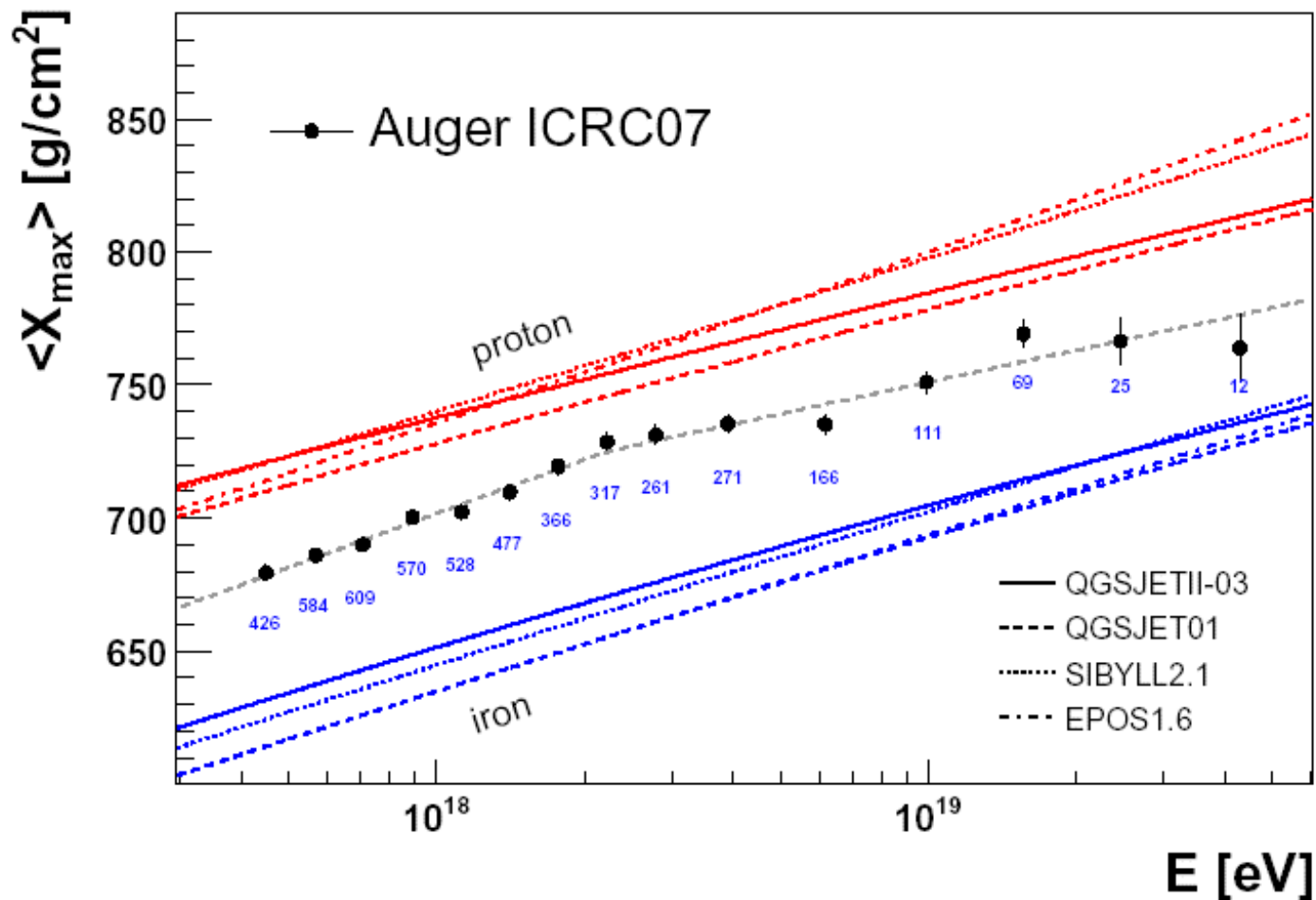


# Composition - summary 2004



# Composition from Auger

mixed composition at highest energies?  
are interaction models correct?



# Summary

The CR spectrum steepens at the GZK threshold energy

The AGN correlation suggests that the steepening is a propagation effect (the sources are extragalactic):

It is not due to the sources “running out of steam” at that energy

If interaction model is correct:

CR composition measurement → study of sources and propagation

If CR composition known otherwise:

„composition measurement“ → test of interaction models

(The angular scale of the AGN correlation is characteristic for protons)