The physics of UHECRs: spectra, composition and the transition galactic-extragalactic

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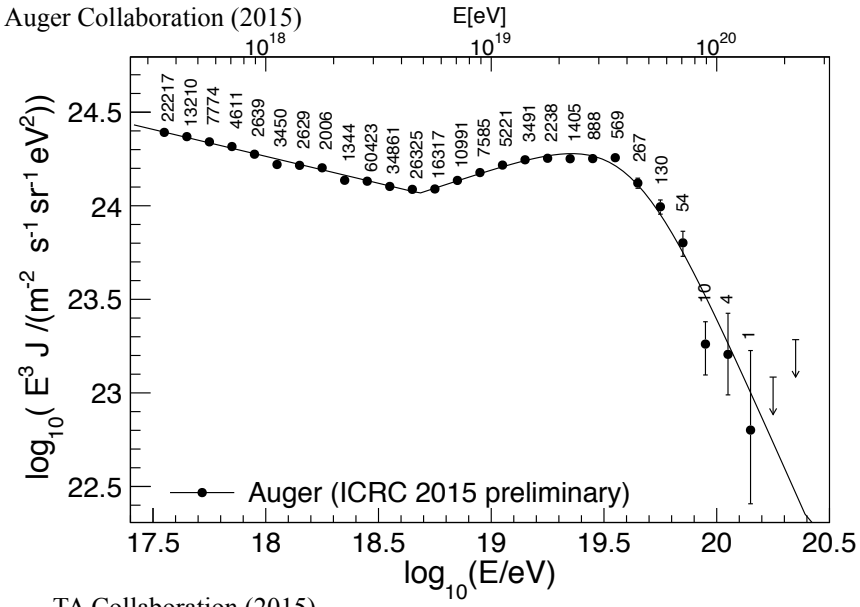
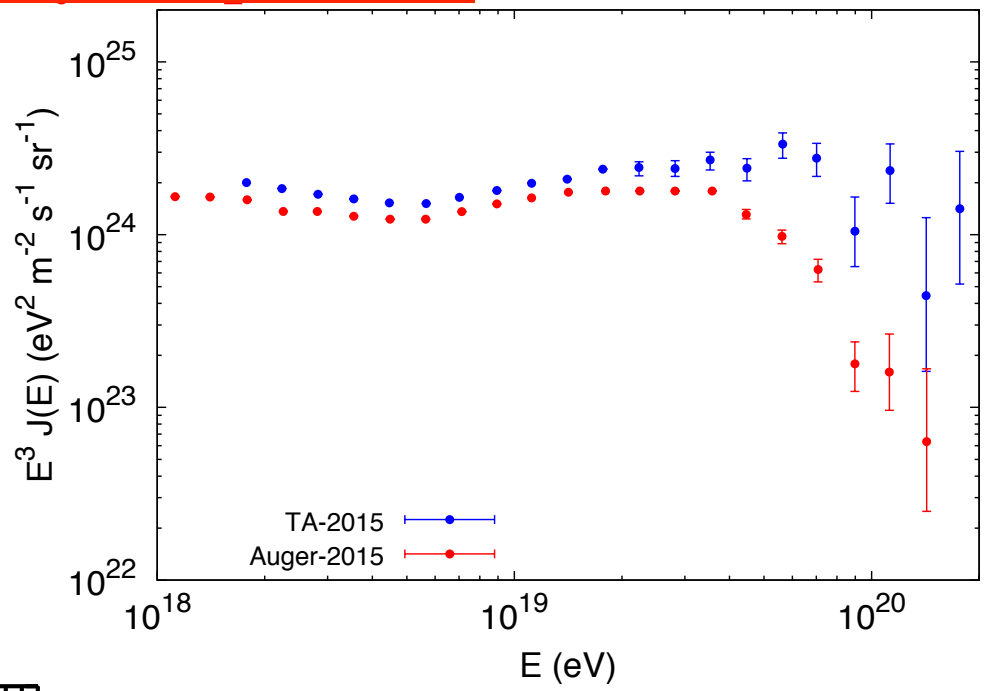
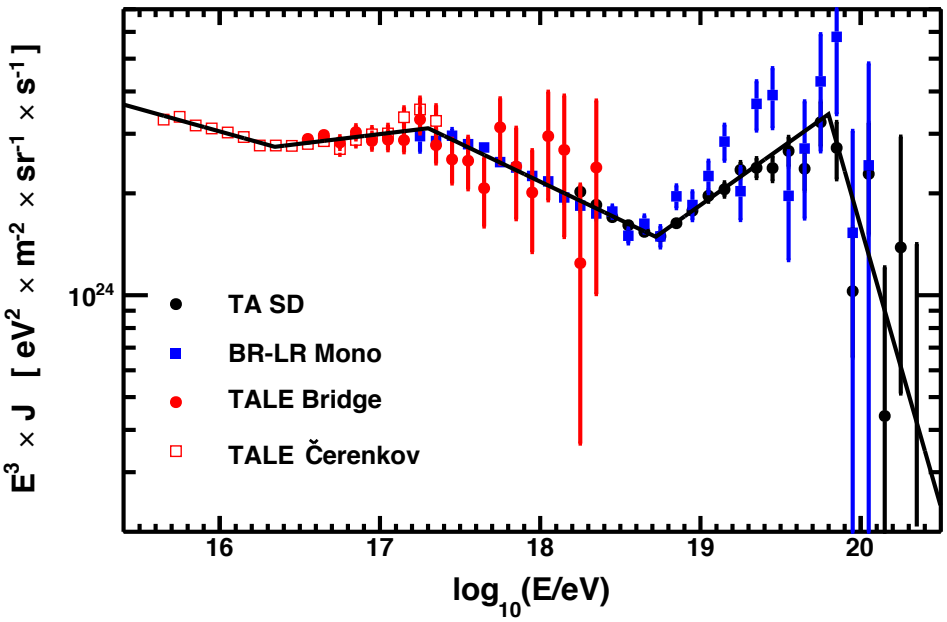
Ultra High Energies Cosmic Rays – Spectrum

Auger Collaboration (2015)





TA Collaboration (2015)

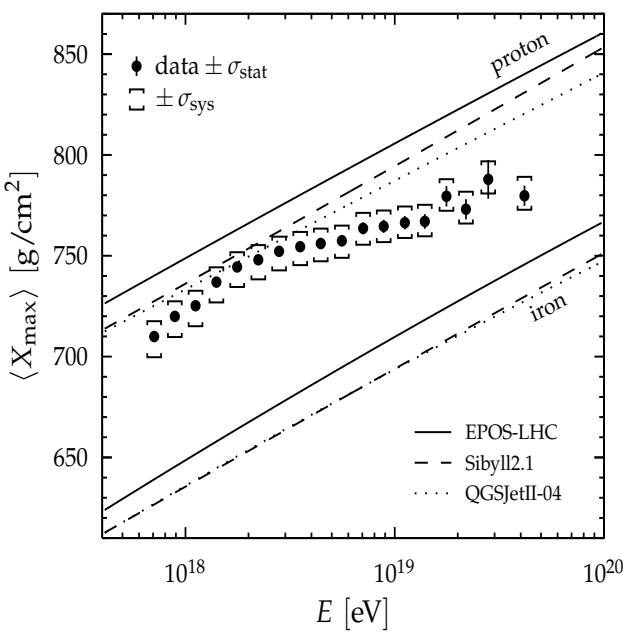


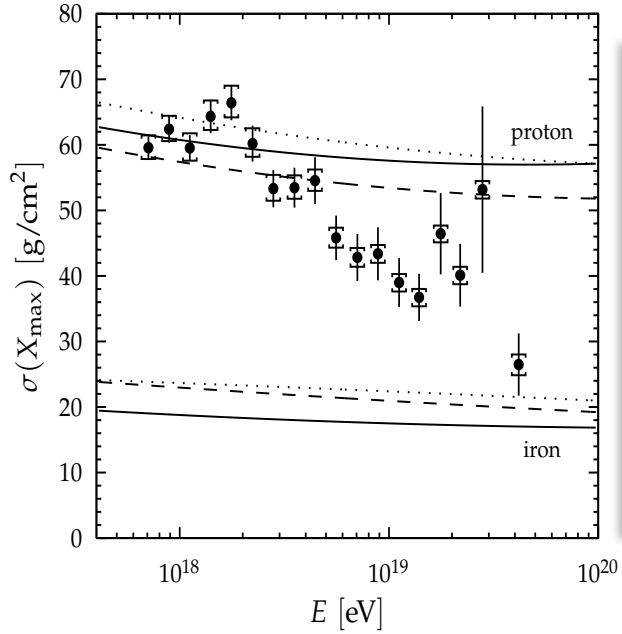
The observations on Earth are the result of the acceleration at the source (injection) and the propagation of particles in the background radiation (CMB & EBL) and possible intergalactic magnetic fields (IMF).

- ✓ **Spectrum**
- ✓ **Chemical Composition**
- ✓ **Anisotropy**

Ultra High Energies Cosmic Rays – Composition

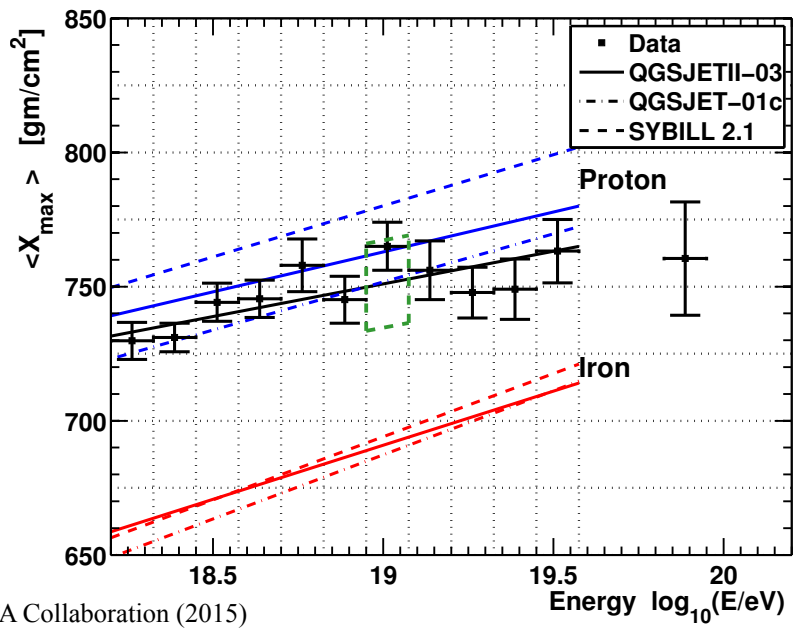
Auger Collaboration (2015)



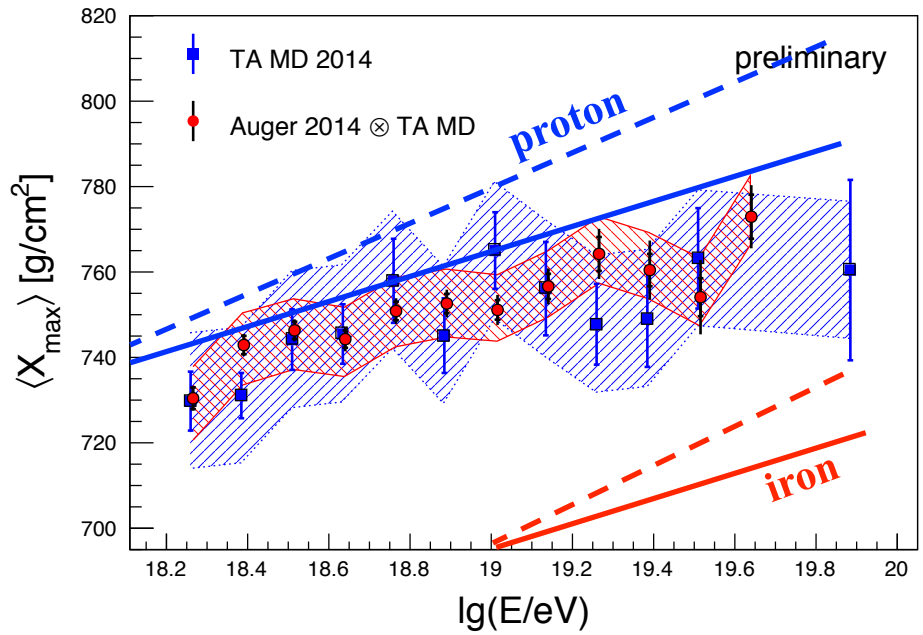


- ✓ **Auger**: protons at low energy and heavier nuclei at high energy.
- ✓ **TA**: protons only.
- ✓ **Strong uncertainties due to the hadronic interaction model.**

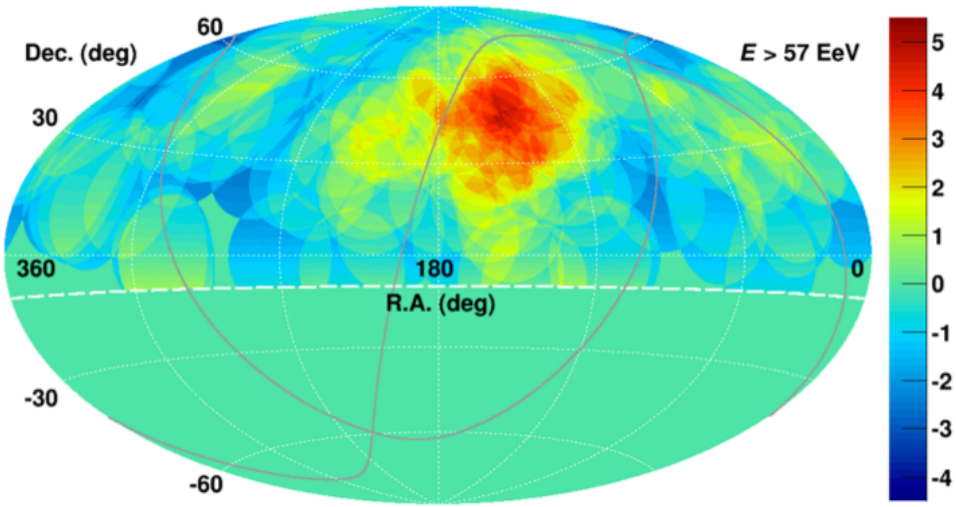
Auger-TA working group (2015)



TA Collaboration (2015)



Ultra High Energies Cosmic Rays – Anistotropy

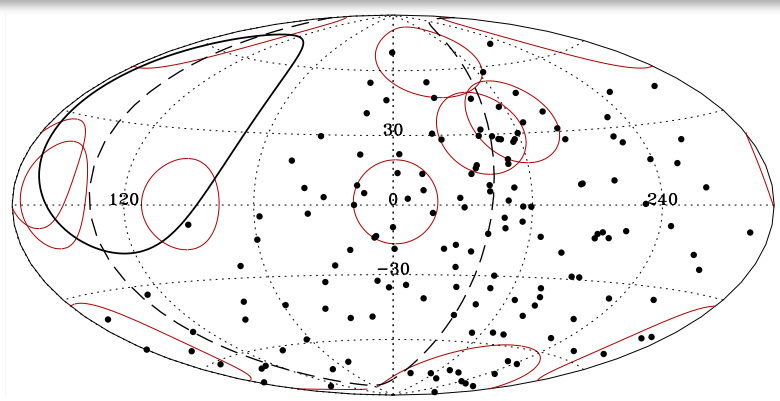


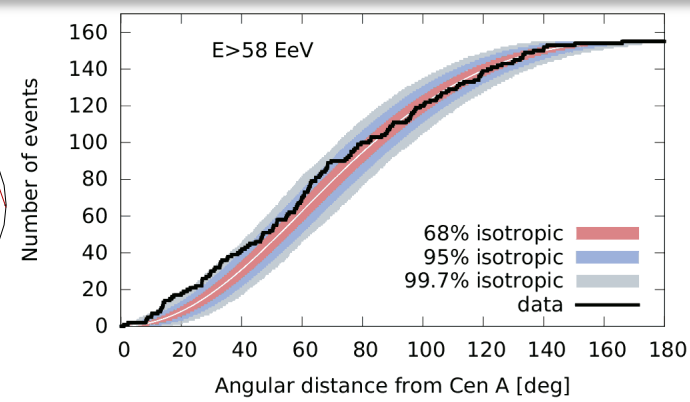
Telescope Array

"hot spot" of radius ~20° events with E > 57 EeV. Seven years of data, with the same significance of the observations collected after five years. Compatible with a pure proton composition at the highest energies.

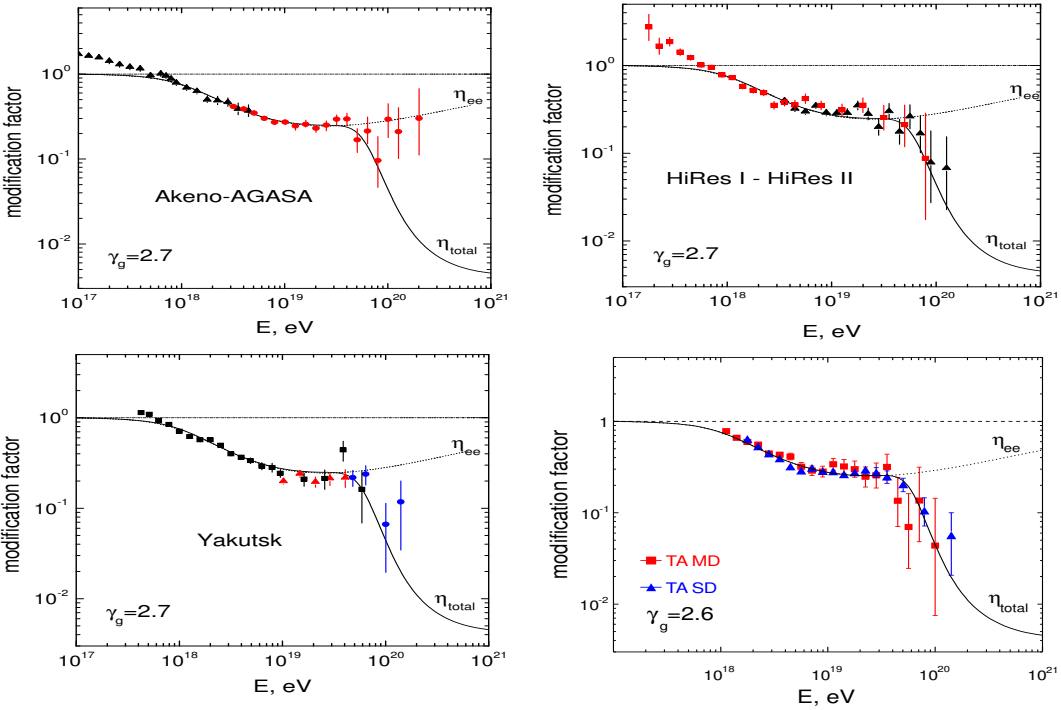
Auger Observatory

No evidences of a statistically significant anisotropy. The two largest departures from isotropy have a post-trial probability ~1.4% for events with E>58 EeV that arrive: (i) within 15° of the direction toward CenA and (ii) within 18° of Swift-BAT AGNs closer than 130 Mpc and brighter than 10^{44} erg/s. If confirmed, this anisotropy is weakly compatible with heavy nuclei at the highest energies, because the μG galactic magnetic field substantially deviates UHE nuclei trajectories.





Dip Model

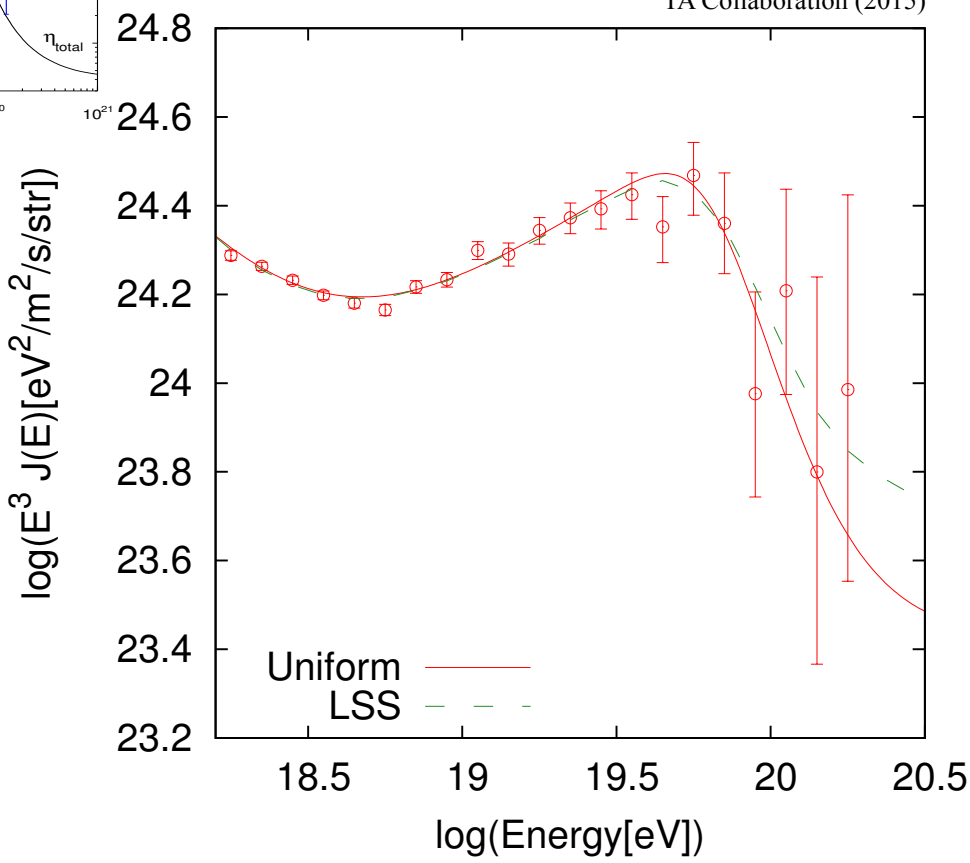


Berezinsky et al (2002-2007)

Protons footprint

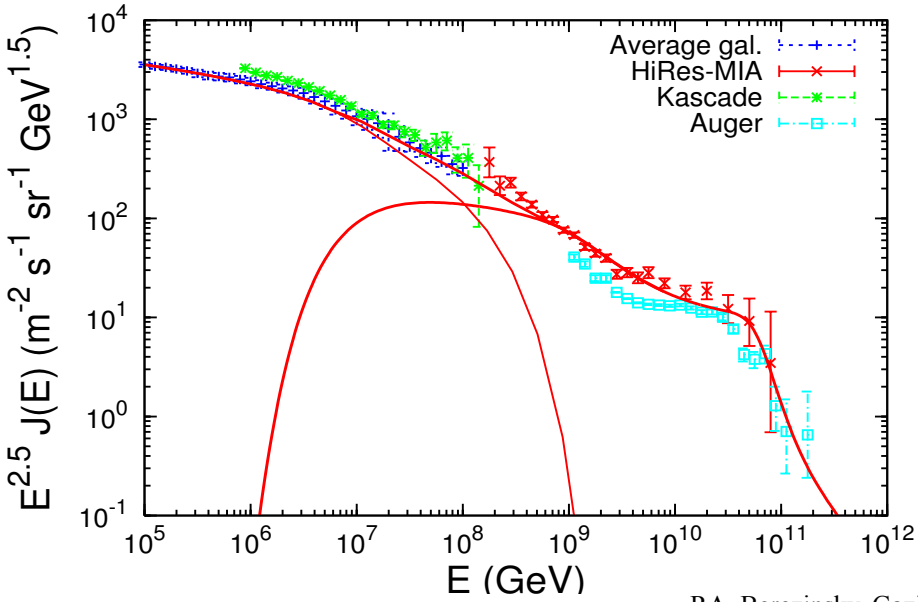
In the energy range 10^{18} - $5x10^{19}$ eV the spectrum behavior is a signature of the pair production process of UHE protons on the CMB radiation field.

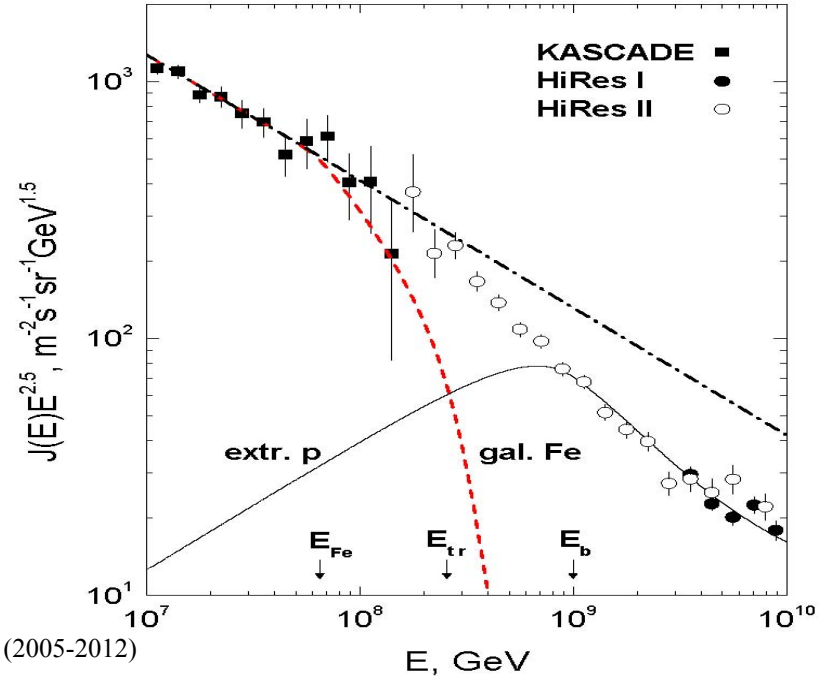
TA Collaboration (2015)



✓ TA surface detector events compared with theoretical expectation of the dip model, with uniformly distributed sources and with sources distributed according to large scale structures (LSS).

Galactic and ExtraGalactic Dip Model

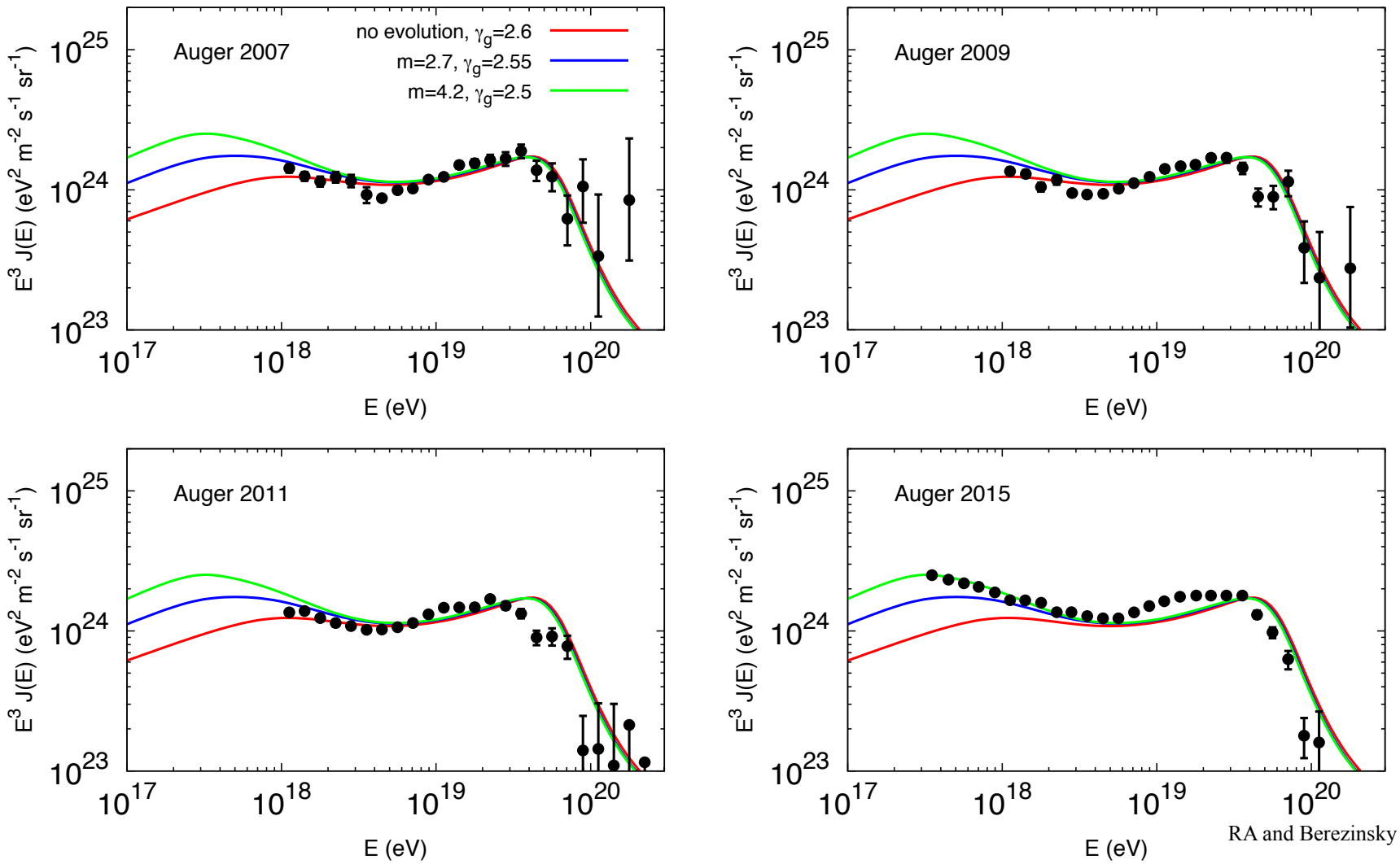




RA, Berezinsky, Gazizov (2005-2012)

- ✓ The Galactic CR spectrum ends in the energy range 10^{17} eV, 10^{18} eV.
- ✓ The transition corresponds to a change from a galactic heavy composition to an extragalactic light composition.

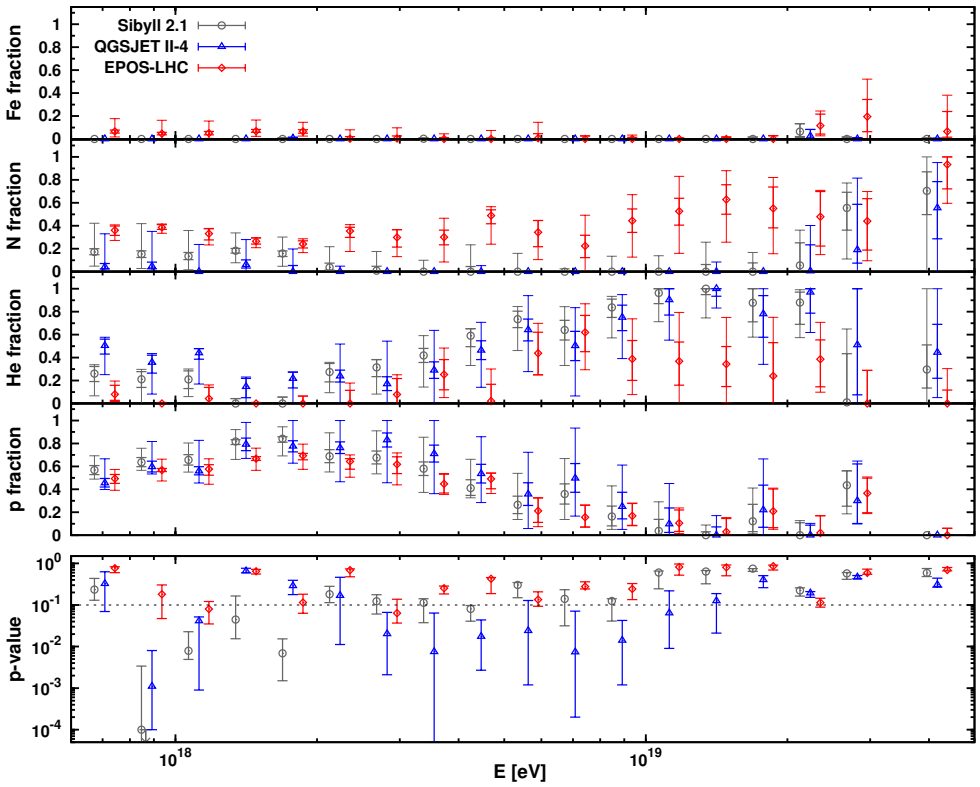
Auger Observatory – Energy Spectrum

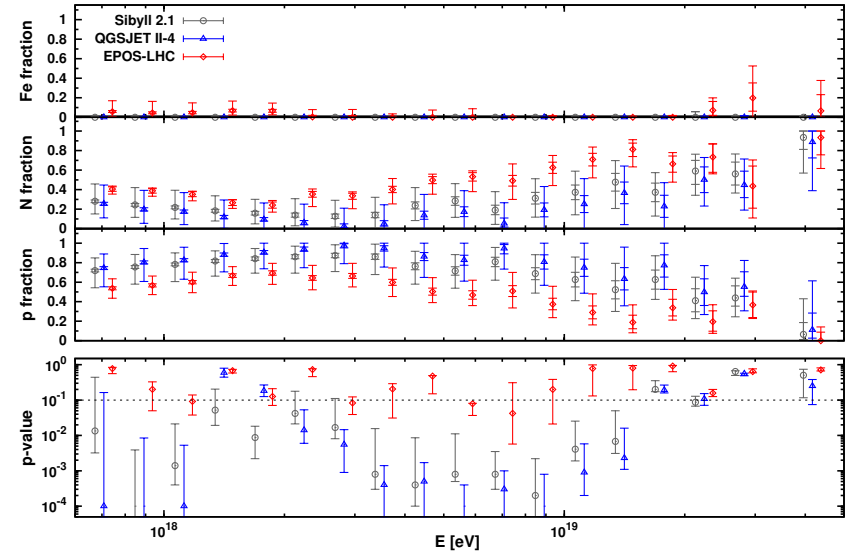


RA and Berezinsky (2016)

At the ankle energies it seems difficult to explain the Auger flux in the framework of the dip model. At the highest energies the flux suppression seems not compatible with the suppression of the proton flux (GZK). Signals of a mixed composition.

Auger Observatory – Composition





Auger Collaboration (2014)

Mixed Composition

Auger Collaboration (2016)

The hybrid events recorded by Auger enable the study of the correlation between depth of shower maximum and number of muons in the cascade. These correlations, in the energy range of the ankle log(E/eV)=18.5 – 19, seem to exclude a light composition made up of protons and helium nuclei.

Auger data at the ankle can be well explained only assuming a mixed composition with nuclei heavier than helium (A>4). **The dip model seems disfavored by this analysis**.

Caveat

Composition

It is impossible to observe at the Earth a pure heavy nuclei spectrum, even if sources inject only heavy nuclei of a fixed specie at the Earth we will observe all secondaries (protons too) produced by photo-disintegration.

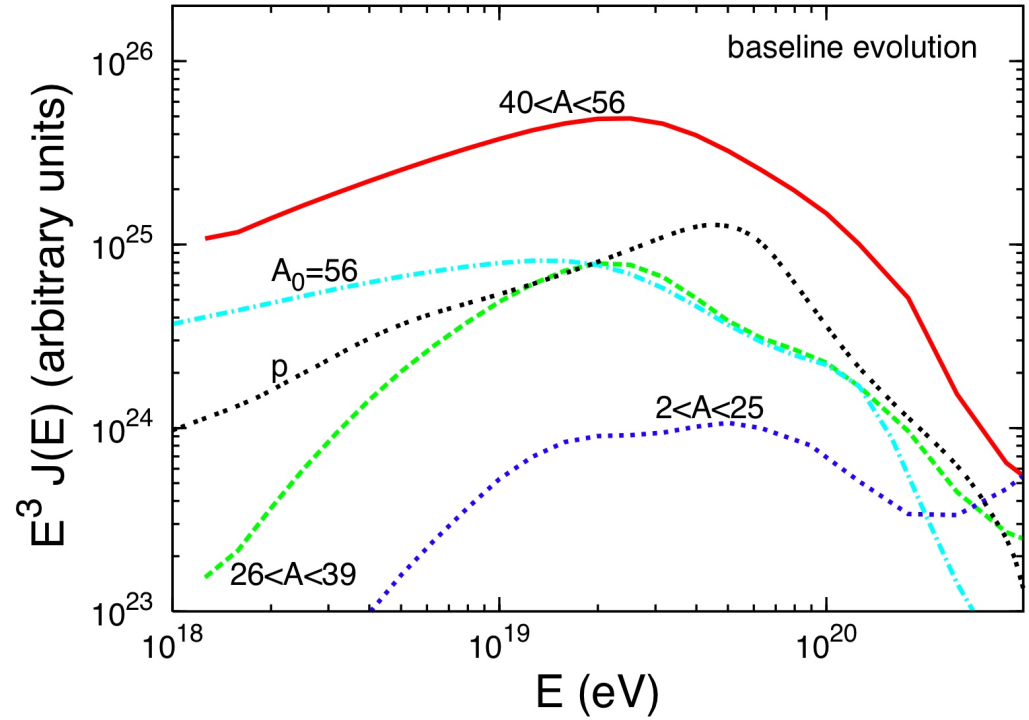
Critical Lorentz factor

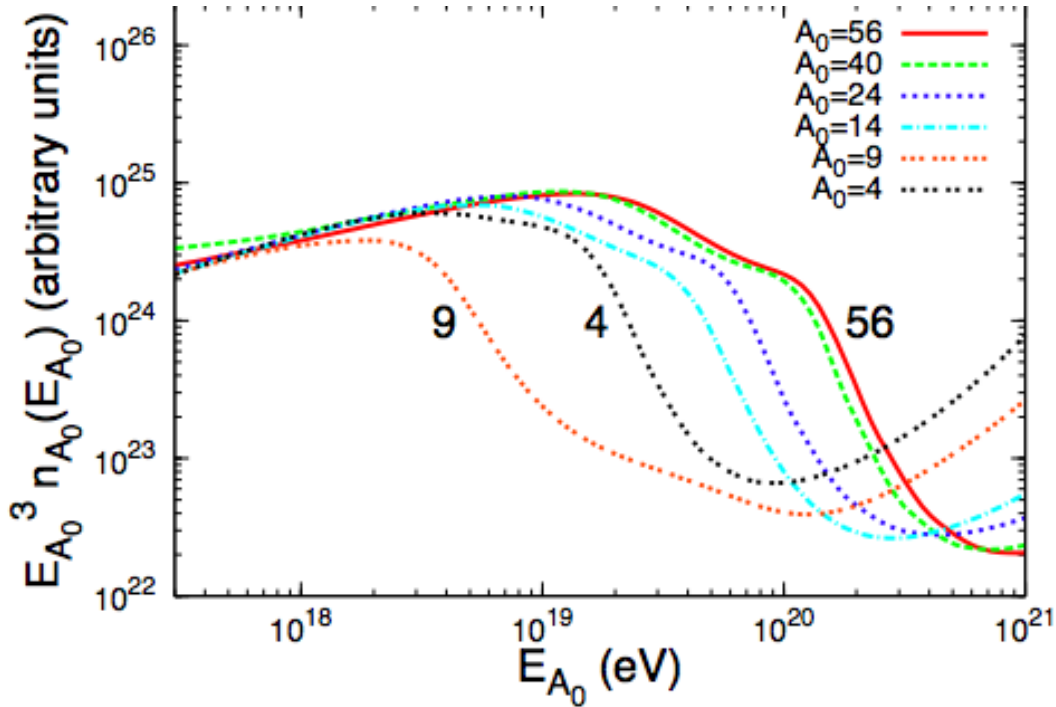
The critical Lorentz factor fixes the scale at which photo-disintegration becomes relevant, for heavy nuclei it is almost independent of the nuclei specie

$$\beta^{A}_{e^+e^-}(\Gamma,t) + H_0(t) = \beta^{\Gamma}_{dis}(A,t)$$

$$E_{cut}(A) = A m_N \Gamma_c$$

$$\Gamma_c \simeq 2 \times 10^9$$





RA, Berezinsky, Grigorieva (2009-2013)

Interaction vs maximum energy

The highest energy behavior of the fluxes is dominated by particles interaction with backgrounds (nuclei photo-disintegration or protons photo-pion) depending on the maximum acceleration energy at the sources.

✓ **Protons**

$$E^p_{max} > E_{GZK} \simeq 10^{20} eV$$

✓ **Nuclei**

$$E_{max}(A) = Z E^p_{max}$$

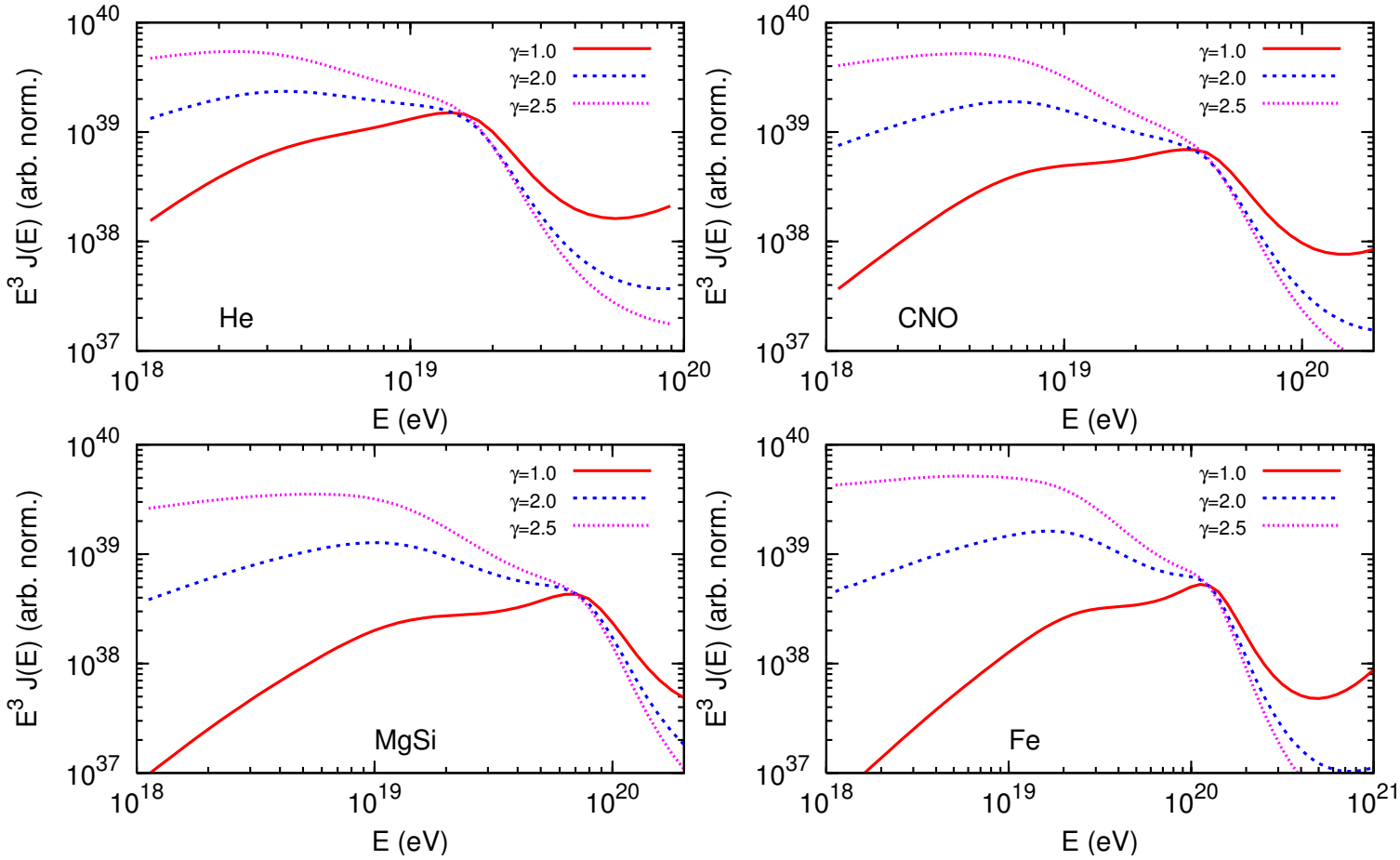
$$E_{max}(A) > E_{cut}(A)$$

$$E^p_{max} > \frac{A}{Z} m_N \Gamma_c \simeq 4 \times 10^{18} eV$$

✓ Only under these conditions the high energy flux is shaped by the protons photo-pion production process (GZK) or by the nuclei photo-disintegration process.

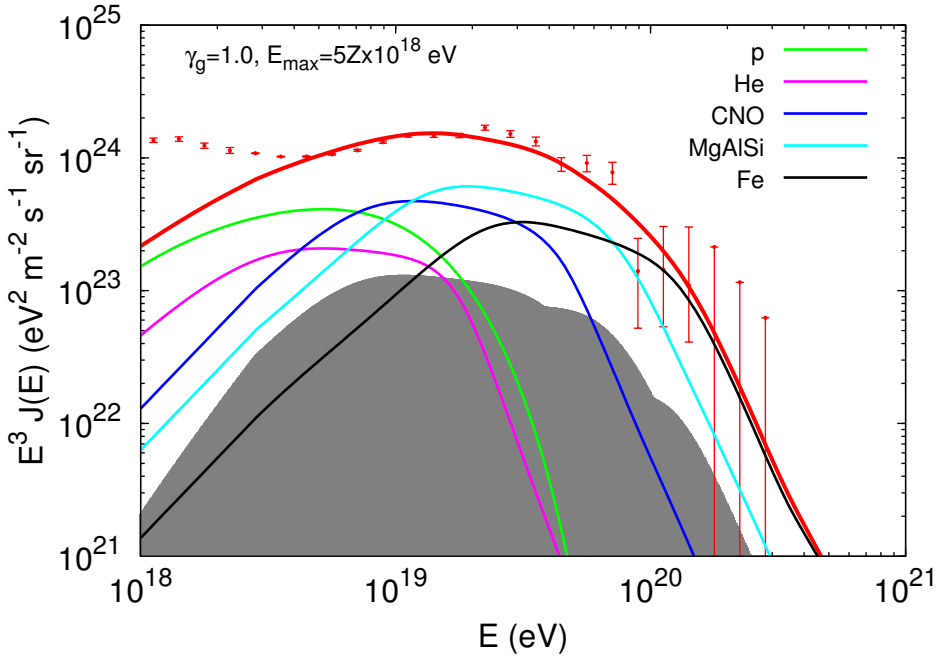
Injection of nuclei flat vs steep

$$Q_A(\Gamma) = Q_0 e^{-\Gamma/\Gamma_{max}} \left(\frac{\Gamma}{\Gamma_0}\right)^{-\gamma_g} \qquad \mathcal{L}_0 = n_{UHE} L_{UHE} = A m_N \int_1^{\Gamma_{max}} d\Gamma \Gamma Q_A(\Gamma)$$



The combined effect of nuclei energy losses, mainly photo-disintegration, and injection implies that a steep injection increases the low energy weight of the mass composition

What we can learn from Auger data

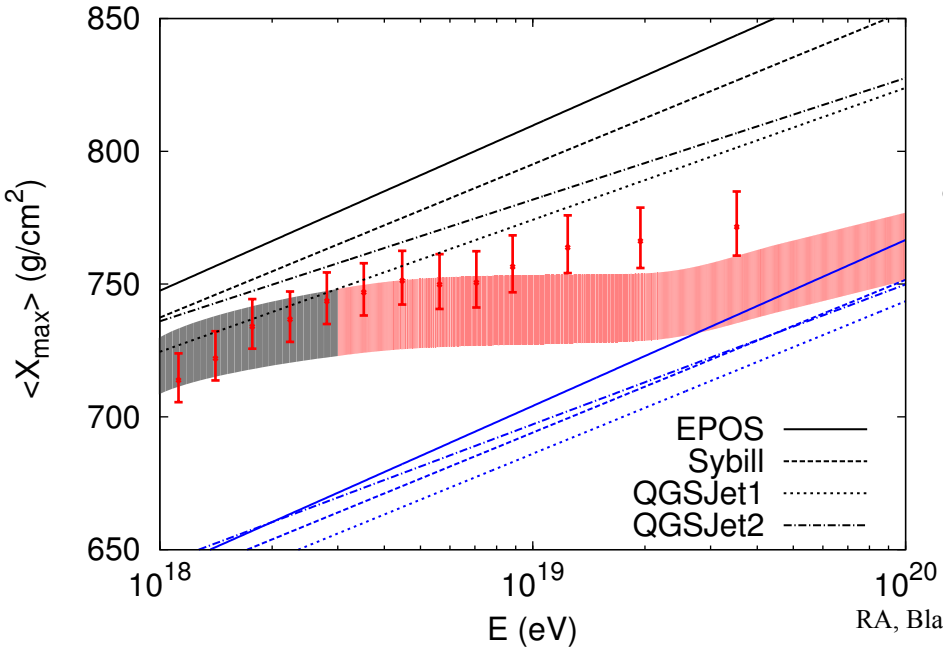


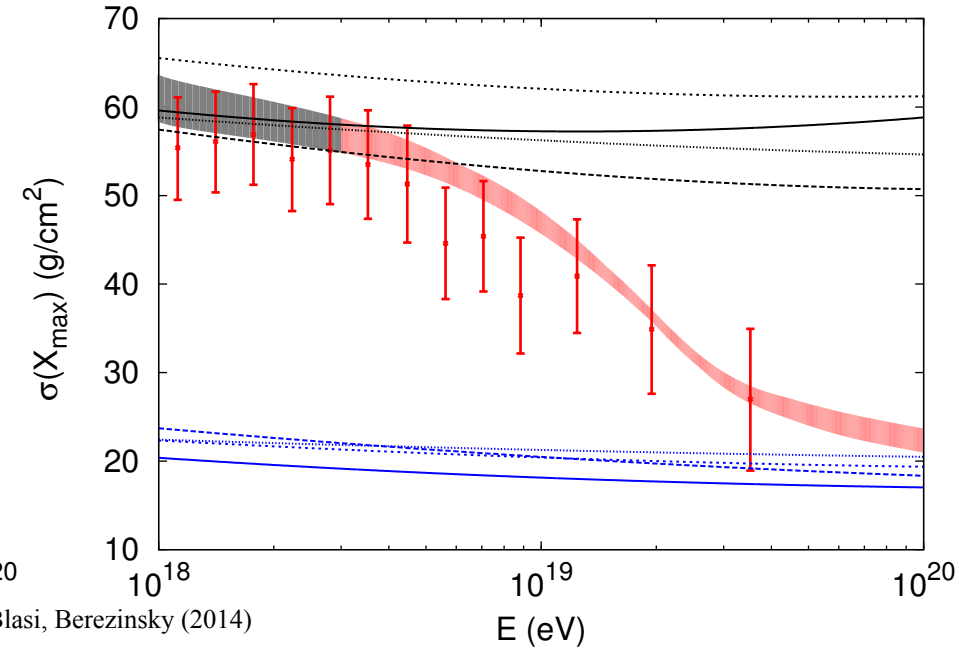
Auger chemical composition can be reproduced only assuming a very flat injection of primary nuclei

$$\gamma_g = 1.0 \div 1.5$$

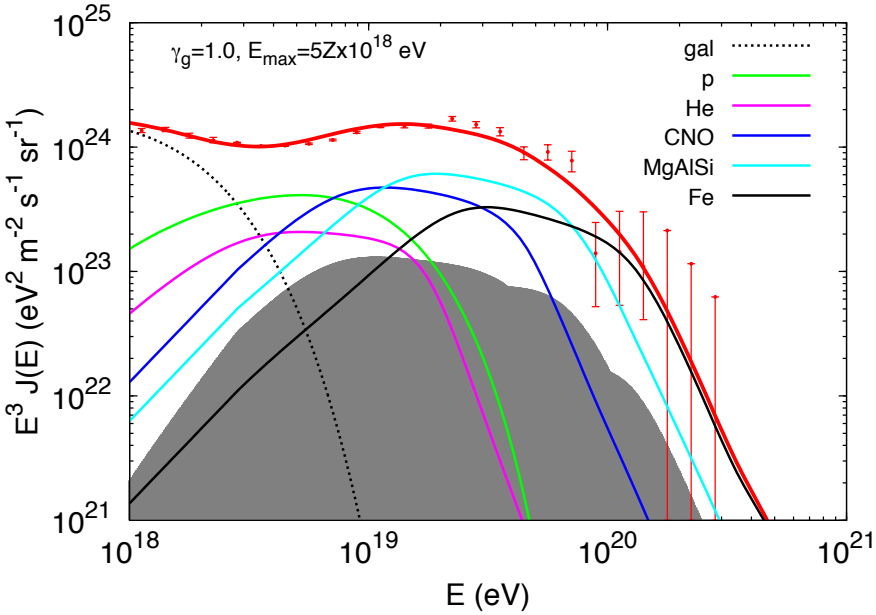
$$\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3 \mathrm{y}}$$

75% p, 15% He, 5% CNO,
3% MgAlSi, 1% Fe.



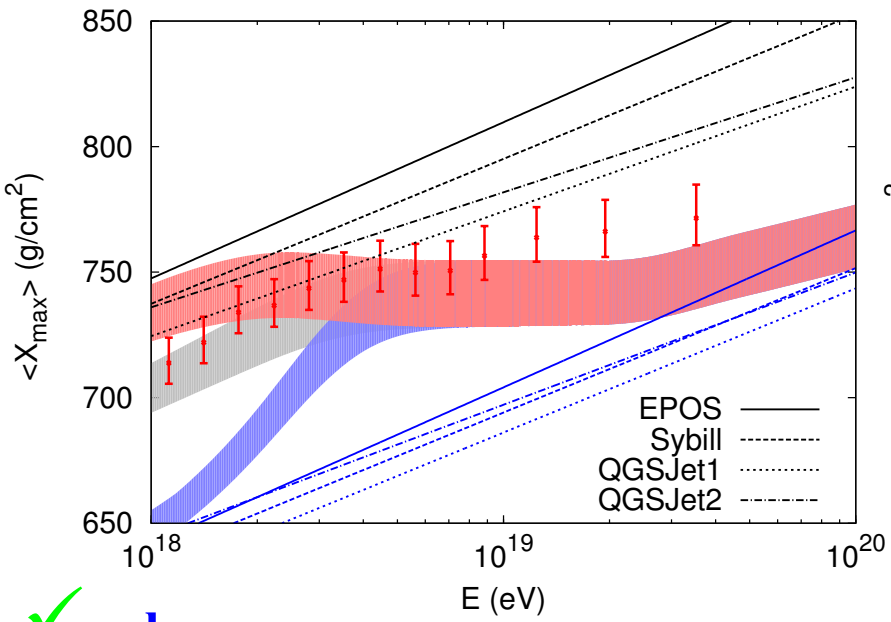


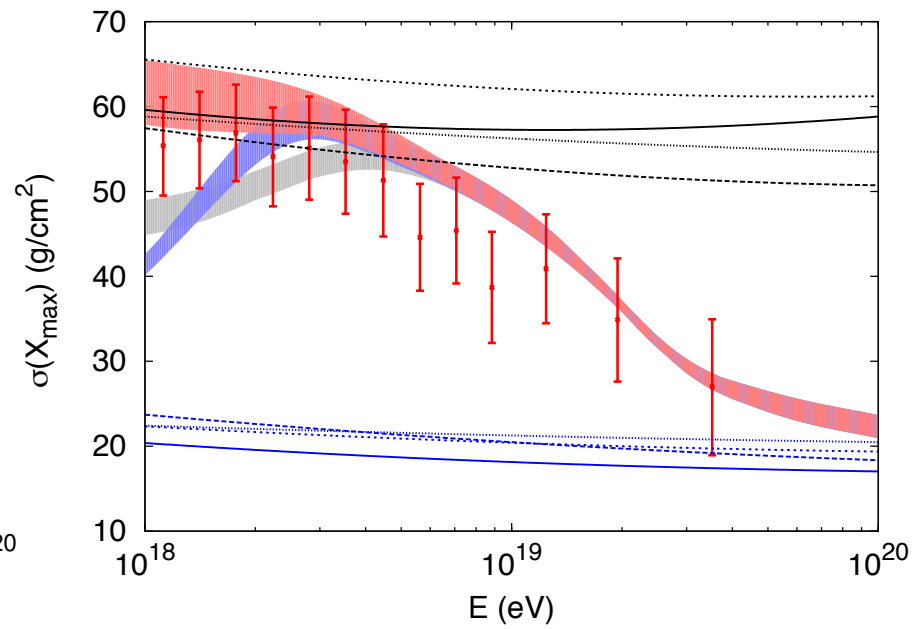
RA, Blasi, Berezinsky (2014)



An additional galactic component can fill the gap in the spectrum.

Composition issue. Mixture of 80% p and 20% He to reproduce Auger observations. Difficult to reconcile with galactic CR physics and anisotropy observations.



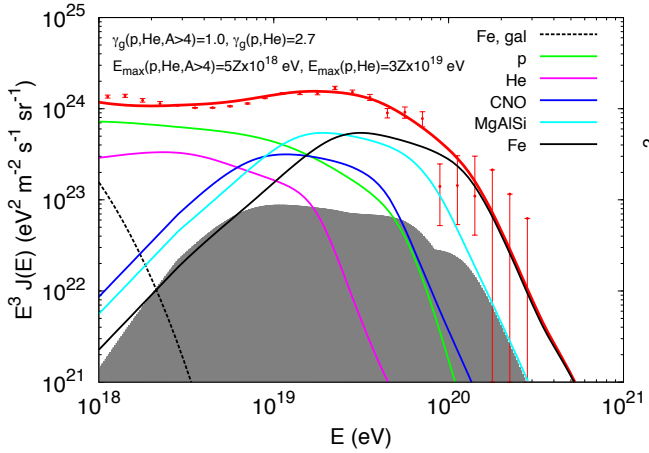


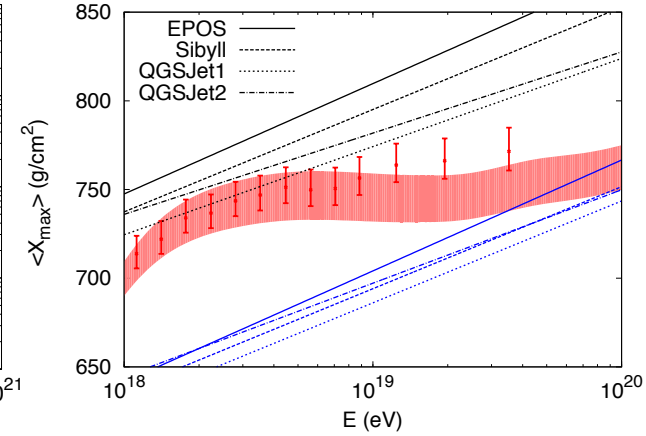
RA, Blasi, Berezinsky (2014)

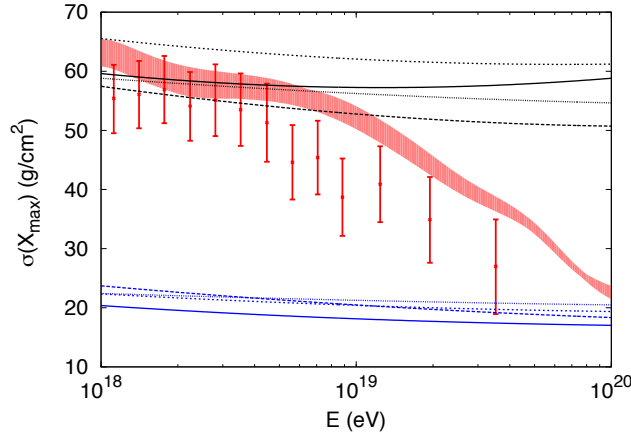
✓ **pulsars**

flat component from galactic pulsars fills the gap, flat injection, correct emissivity, problems with chemical composition and anisotropy.

Fang, Kotera, Olinto (2013)



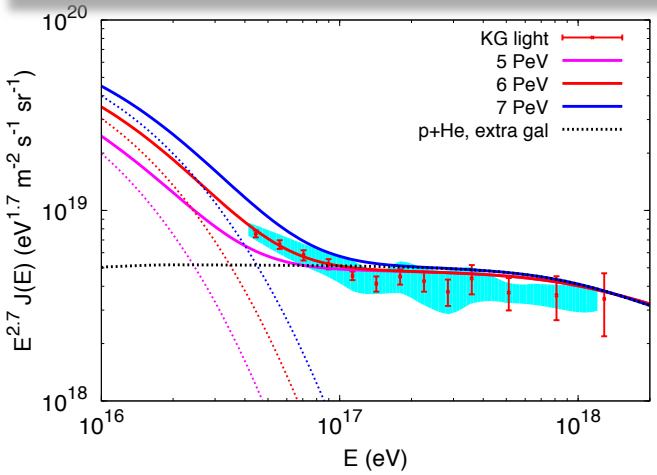




Two types of extra-galactic sources:

- ✓ light component steep injection (γ_g>2.5) $\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{47} \frac{\mathrm{erg}}{\mathrm{Mpc}^3\mathrm{y}}$
- ✓ heavy component flat injection (γ_g<1.5) $\mathcal{L}_0 = n_{UHE} L_{UHE} \simeq 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3\mathrm{y}}$

RA, Blasi, Berezinsky (2014)

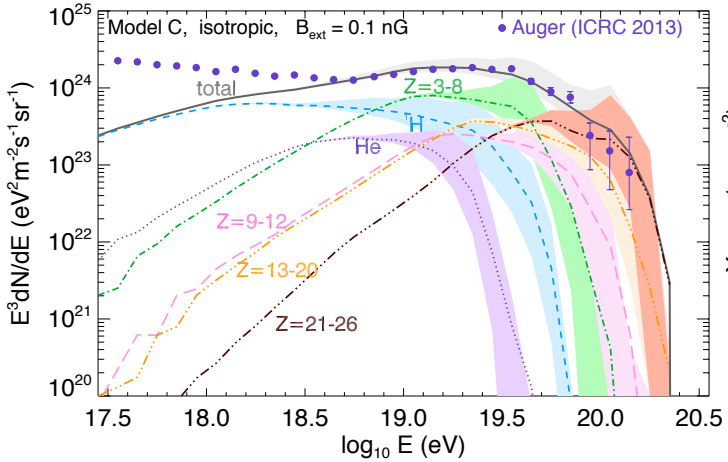


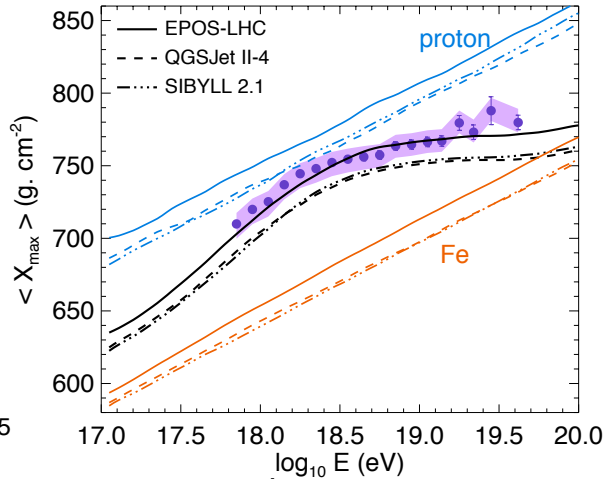
The Kascade-Grande observations seem to confirm the presence of an extragalactic light component with a steep injection spectrum.

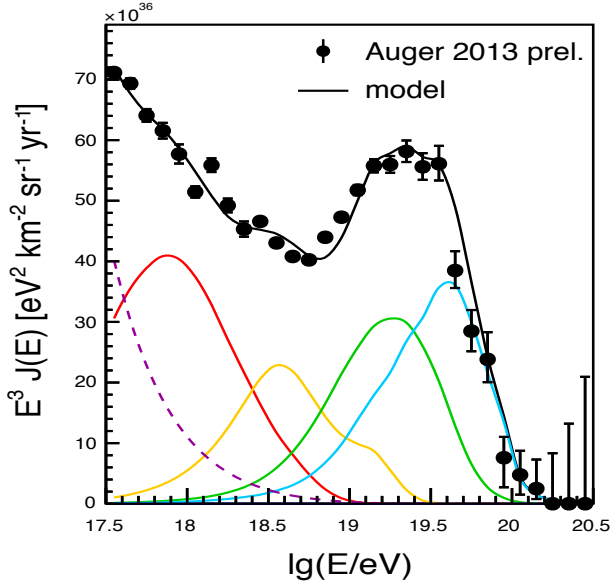
✓ **active galactic nuclei**
can easily provide steep injection, correct emissivity.

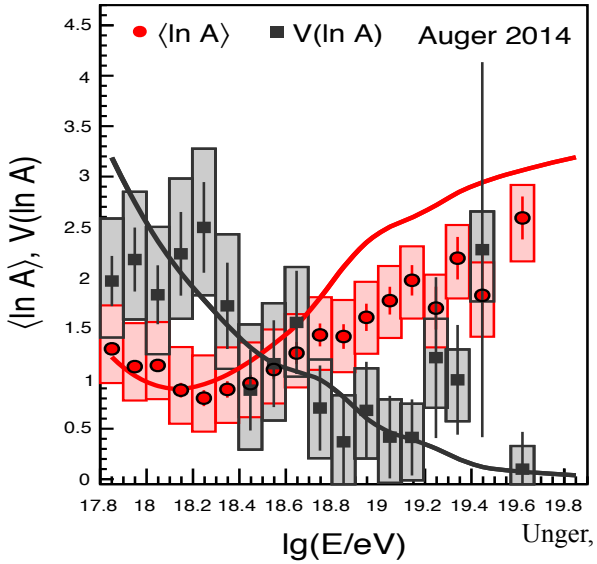
GRB and Galactic CR (pushed at high energies)

Globus, Allard, Parizot (2014-2015)







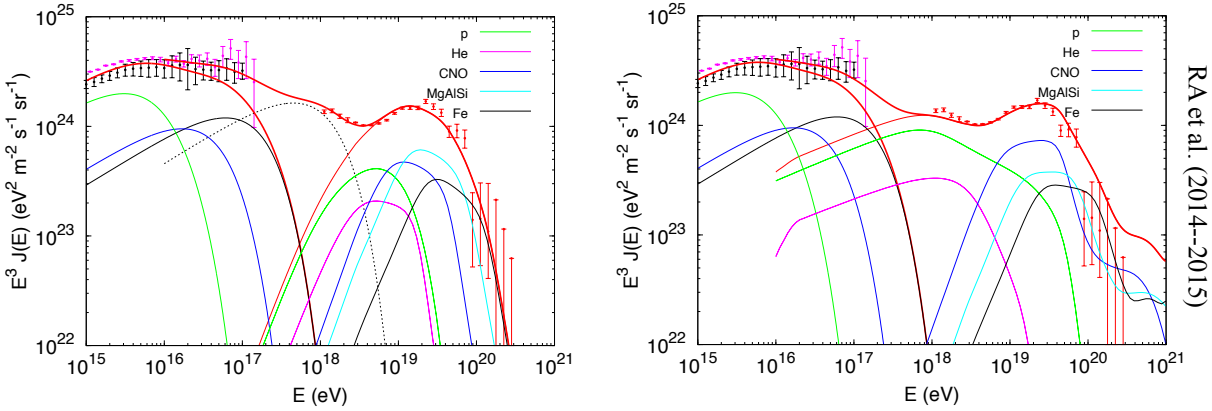


Unger, Farrar, Anchordoqui (2015)

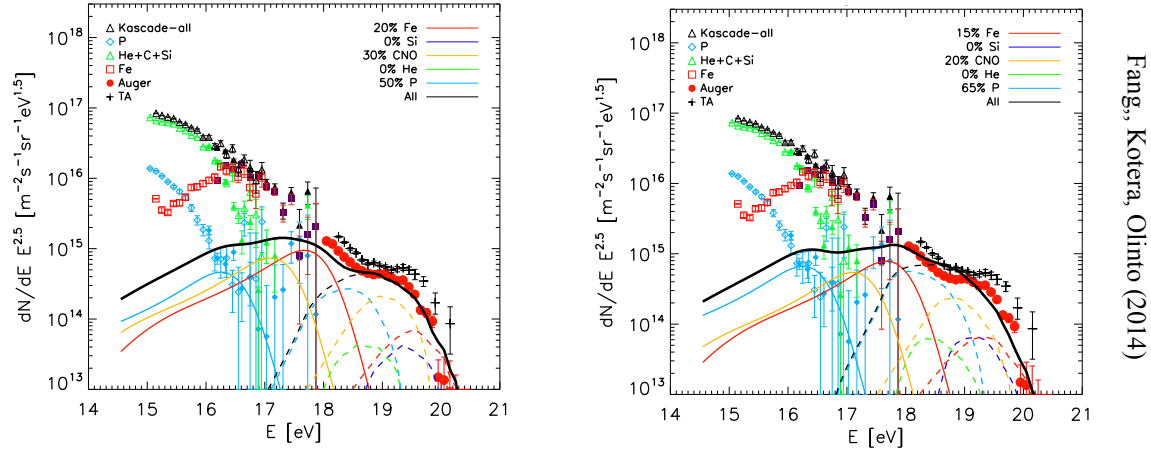
- ✓ Single class of extragalactic sources: Mildly relativistic shocks in GRBs.
- ✓ Photodisintegration at the source. Flat injection for nuclei ($\gamma \approx 1$) and steep for protons ($\gamma > 2$).
- ✓ Agreement with Kascade-Grande.

Galactic CR maximum acceleration energy larger than 10^{16} eV
difficult to reconcile with standard DSA in SNR.

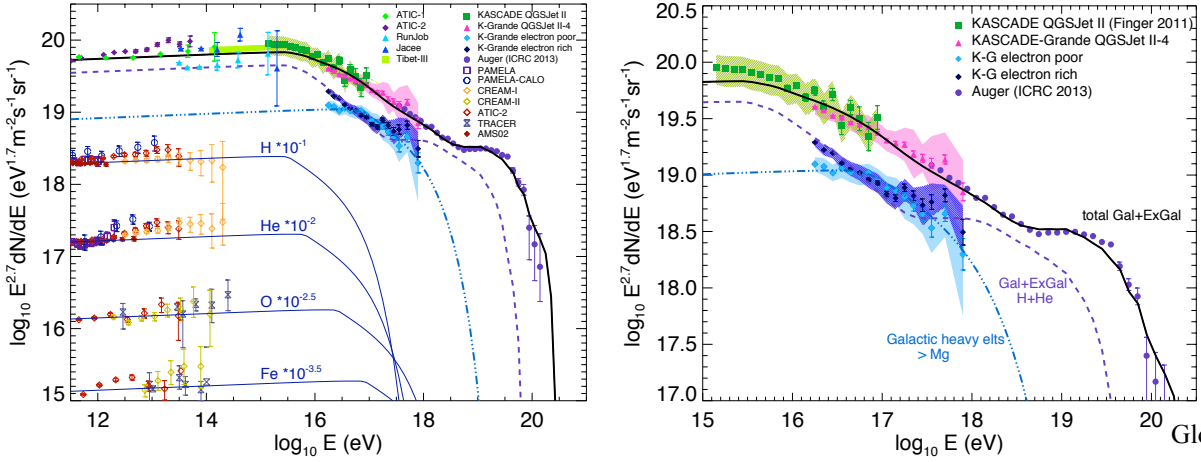
Galactic and ExtraGalactic Mixed Composition



RA et al. (2014--2015)



Fang, Kotera, Olinto (2014)



Transition strictly linked with the source model invoked to fill the gap between 10^{18} eV and $5x10^{18}$ eV.

- ✓ Different extragalactic sources. Transition below 10^{18} eV as in the dip model.
- ✓ Pulsars. Transition at the ankle energies, contribution of galactic pulsars below the ankle.
- ✓ GRB. Transition at the ankle energies, galactic CR pushed to higher energies.

Transition at $E \geq 10^{18}$ eV challenges galactic CR models and observations.

Globus, Allard, Parizot (2014-2015)

Conclusions

Composition of UHECR is a fundamental observable:

- ✓ To identify possible sources.
- ✓ To tag galactic-extragalactic transition.

A pure proton composition (dip model) seems strongly disfavored by Auger while still possible according to TA data:

- ✓ Steep injection ($\gamma_g > 2.5$). High maximum acceleration energies ($\sim 10^{20}$ eV).
- ✓ AGNs are strong candidate as UHECR source.
- ✓ Transition galactic-extragalactic below 10^{18} eV.

Mixed composition, with nuclei heavier than He, imply a rich phenomenology:

- ✓ Flat injection ($\gamma_g < 1.5$). Dynamics at the source, non-shock acceleration.
- ✓ Low maximum acceleration energies $E_{max}(Z) < 5Z \times 10^{18}$ eV.
- ✓ At low energies ($E < 5 \times 10^{18}$ eV) the light component observed can be of extra-galactic origin (different kind of sources) or galactic origin, in this case new galactic acceleration frameworks needed and some tensions arise with anisotropy observations and DSA acceleration models.