Ultra High Energy Cosmic Rays and Neutrinos

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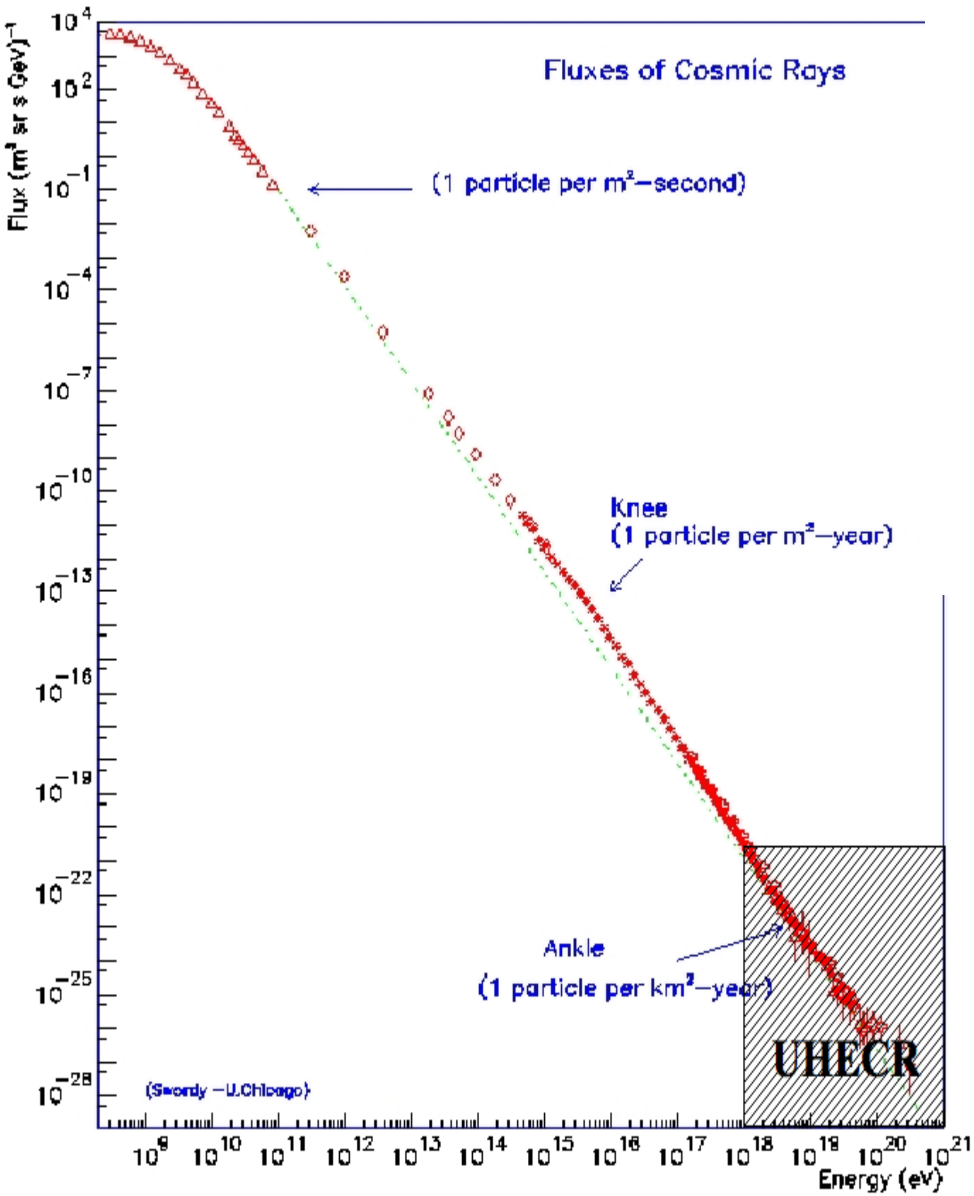
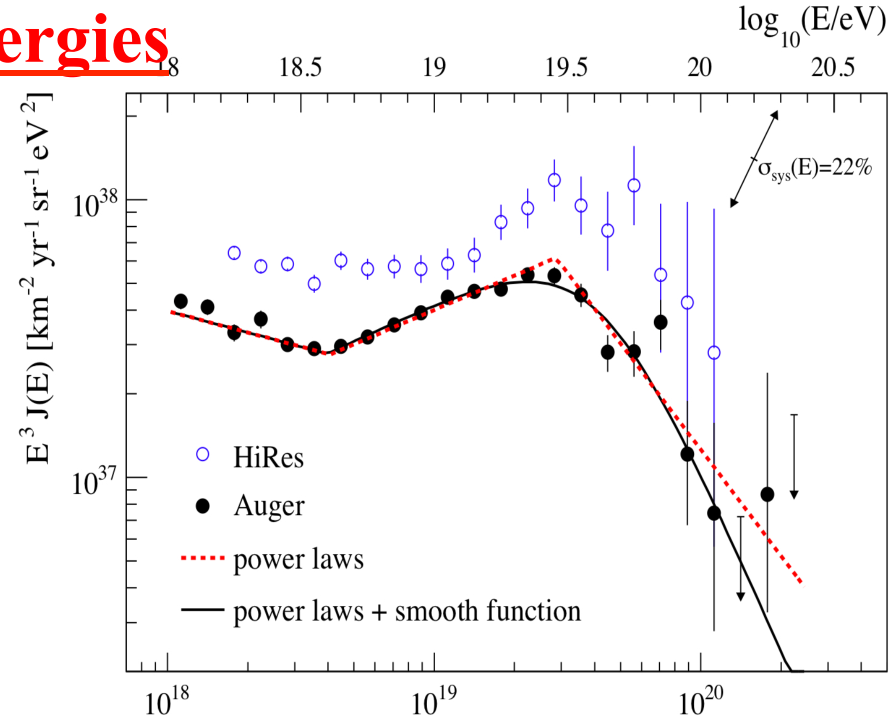
CR spectrum at Ultra High Energies





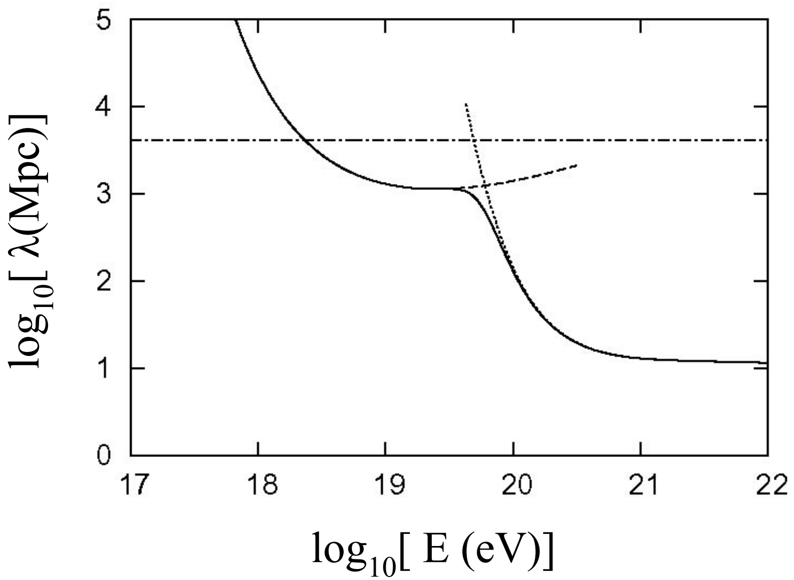
The observations on Earth are the result of the acceleration at the source (injection) and the propagation of particles in the background radiation (CMB & EBL) and possible intergalactic magnetic fields (IMF)

✓ **Spectrum**

✓ **Chemical Composition**

✓ **Anisotropy** (astronomy?)

Phyisics at the end of the CR spectrum



Protons (CMB)

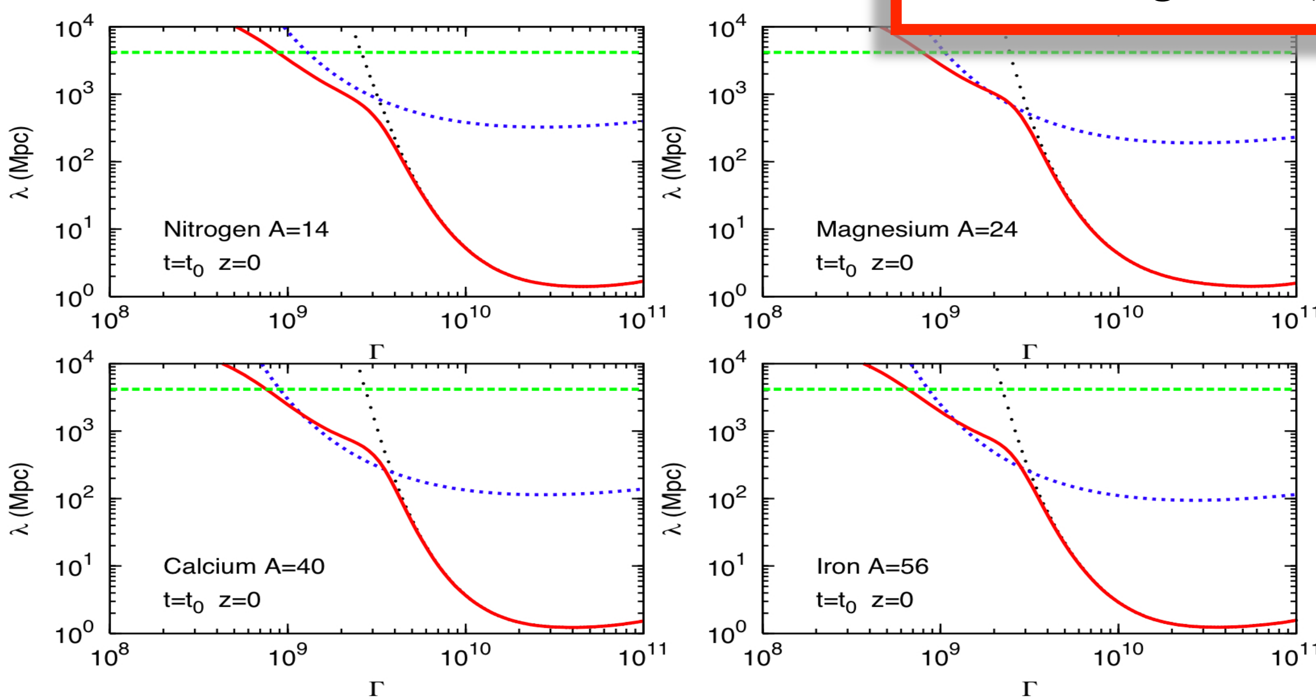
Pair production $p\,\gamma \rightarrow p\,e^+\,e^-$

Photopion production $p\,\gamma \rightarrow p\,\pi^0 \rightarrow \gamma$
(GZK-cutof) $\rightarrow n\,\pi^+ \rightarrow \nu$

Nuclei (CMB+EBL)

Pair production (CMB only) $A\,\gamma \rightarrow A\,e^+\,e^-$

Photodisintegration (CMB+EBL) $A\,\gamma \rightarrow (A\text{-}1)\,N$

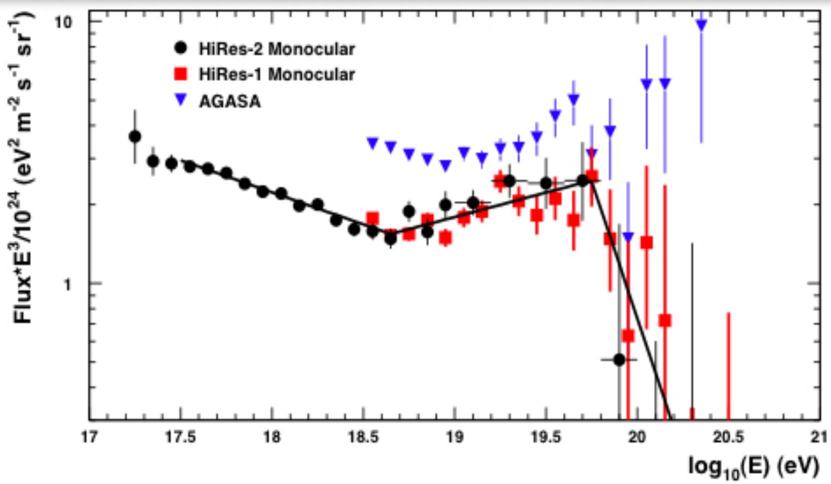


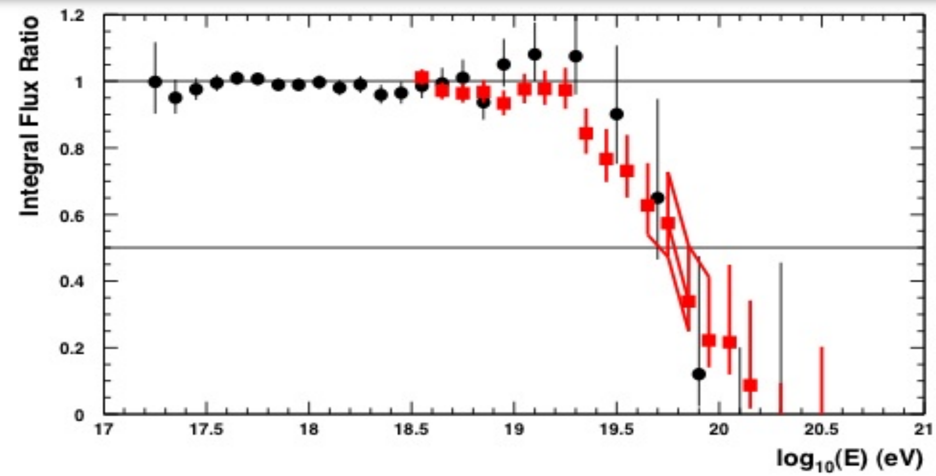
$E<10^{20}$ eV

cosmological distances
adiabatic energy losses
due to universe expansion

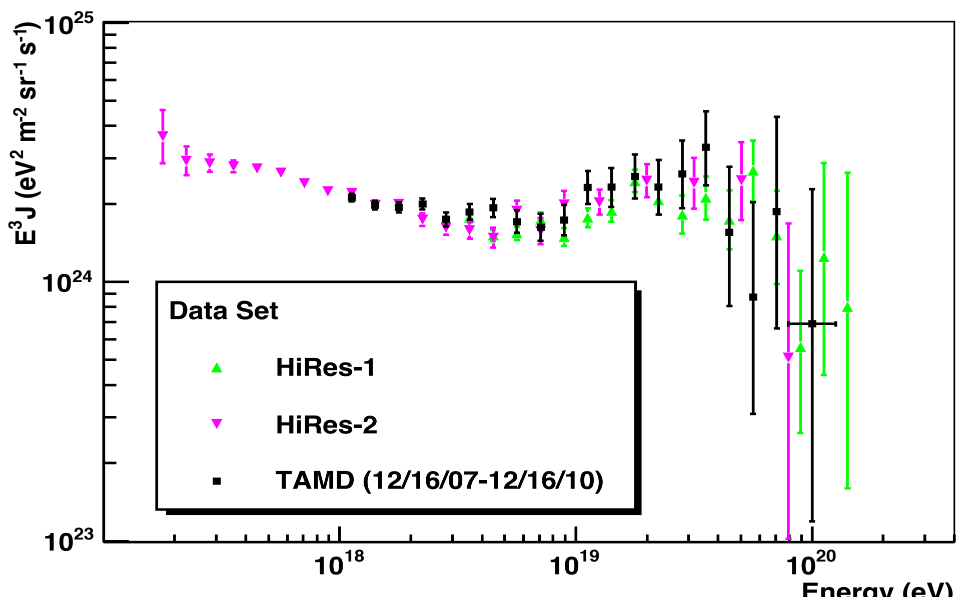
HiRes & Telescope Array

The HiReS analysis confirms the expected Greisen Zatzepin Kuzmin suppression for protons with $E_{1/2}=10^{19.73\pm0.07}$ eV in fairly good agreement with the theoretically predicted value $E_{1/2}=10^{19.72}$ eV.





HiRes collaboration (2007)

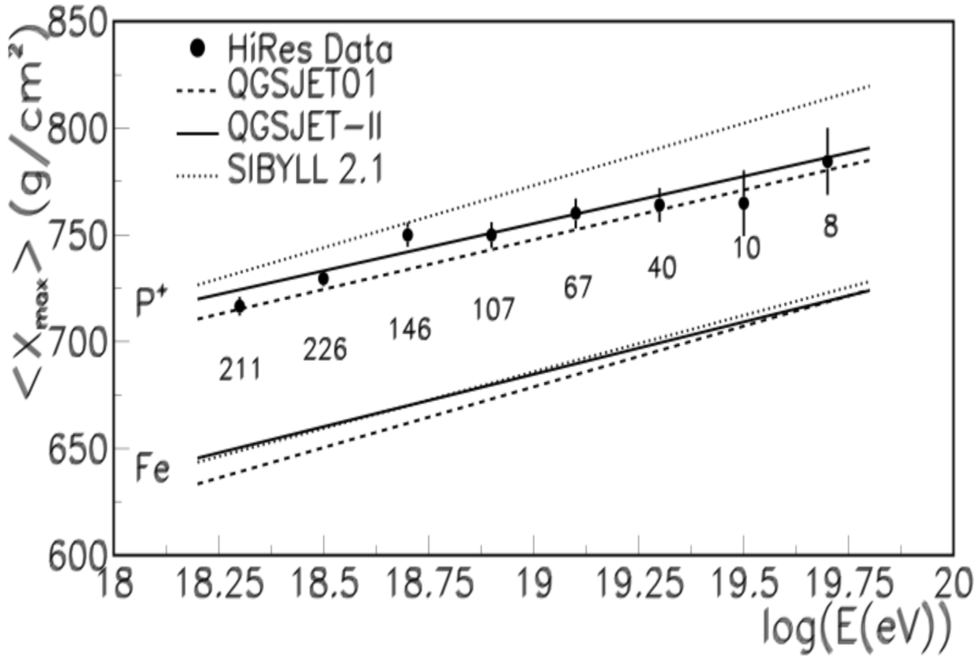


TA collaboration (2012)

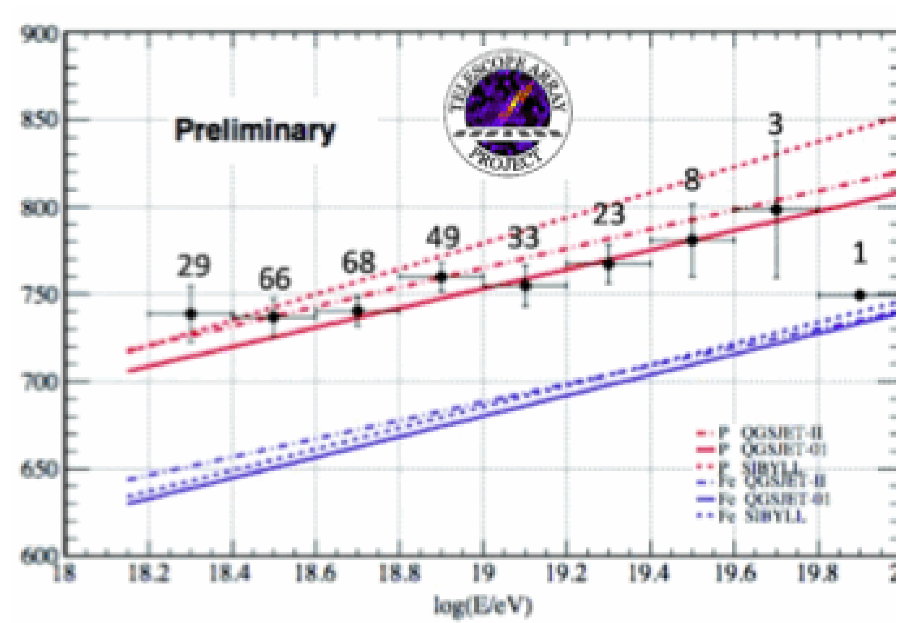
The new Telescope Array results, in agreement with HiRes, show a suppression in the spectrum compatible with the GZK feature

Chemical Composition

HiRes and Telescope Array favor a proton dominated spectrum at $E>10^{18}$ eV.



HiRes

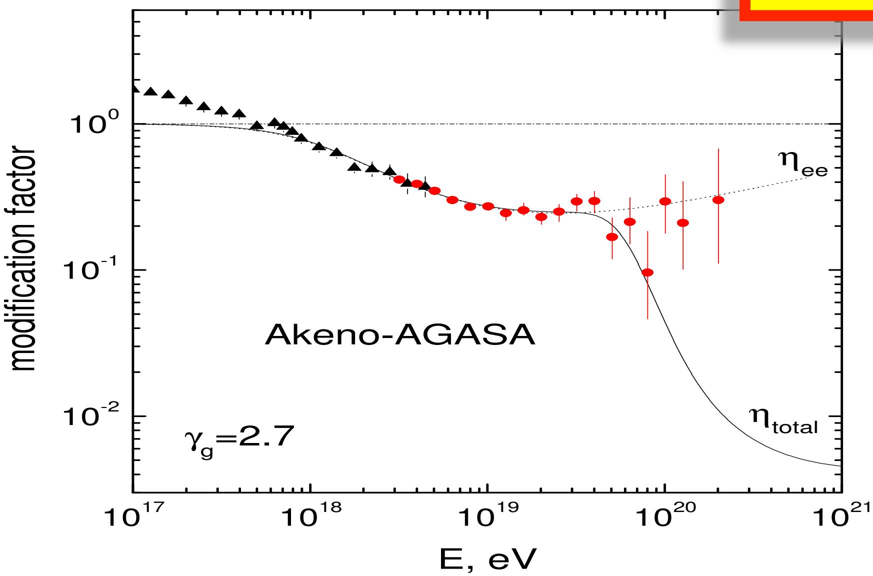


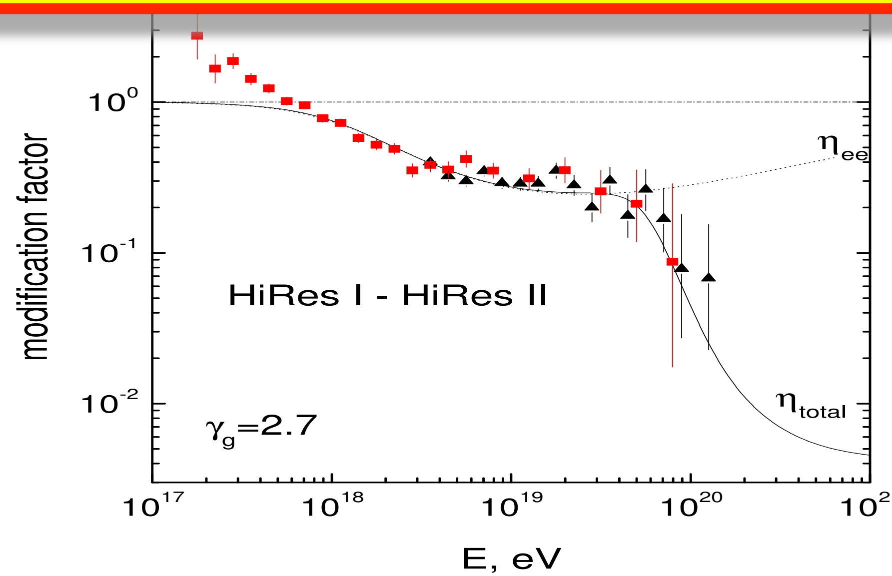
TA

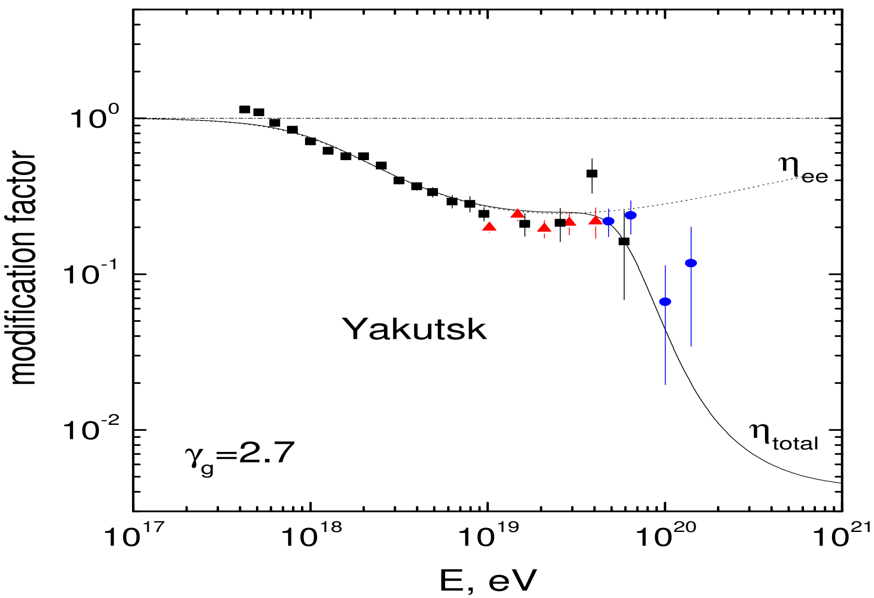
Dip Model

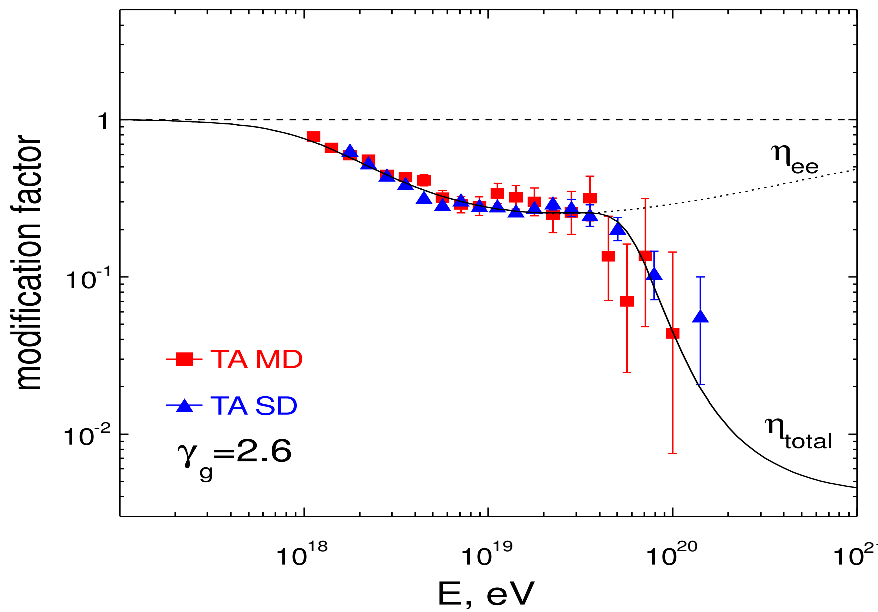
the protons footprint

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



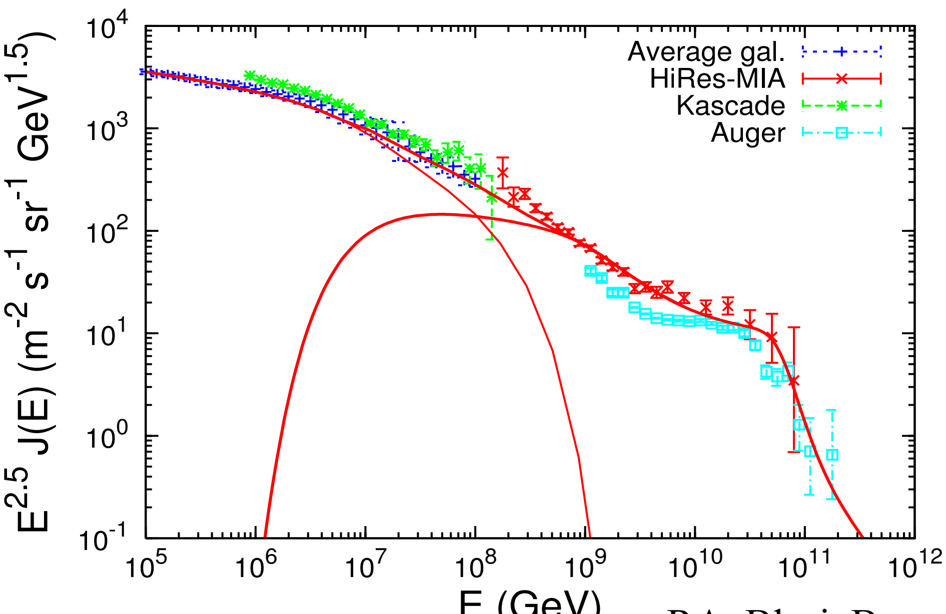




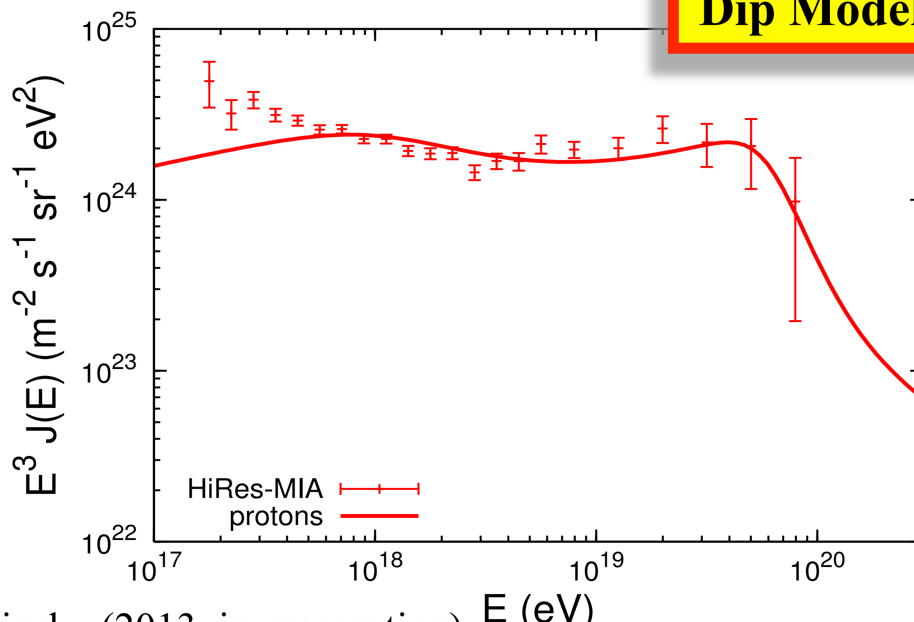


Berezinsky et al (2002) - RA et al. (2007-2012)

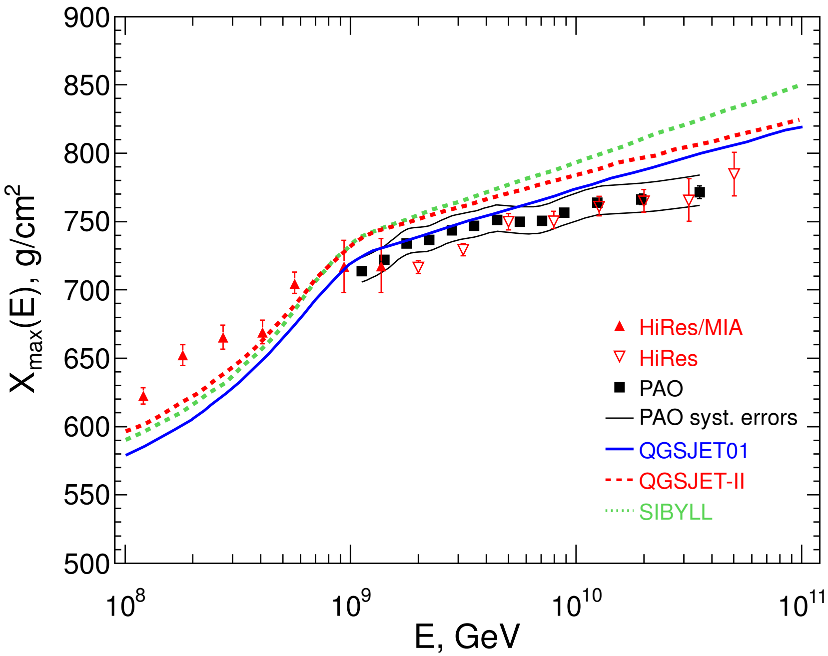
Galactic and ExtraGalactic HiRes-TA



Dip Model

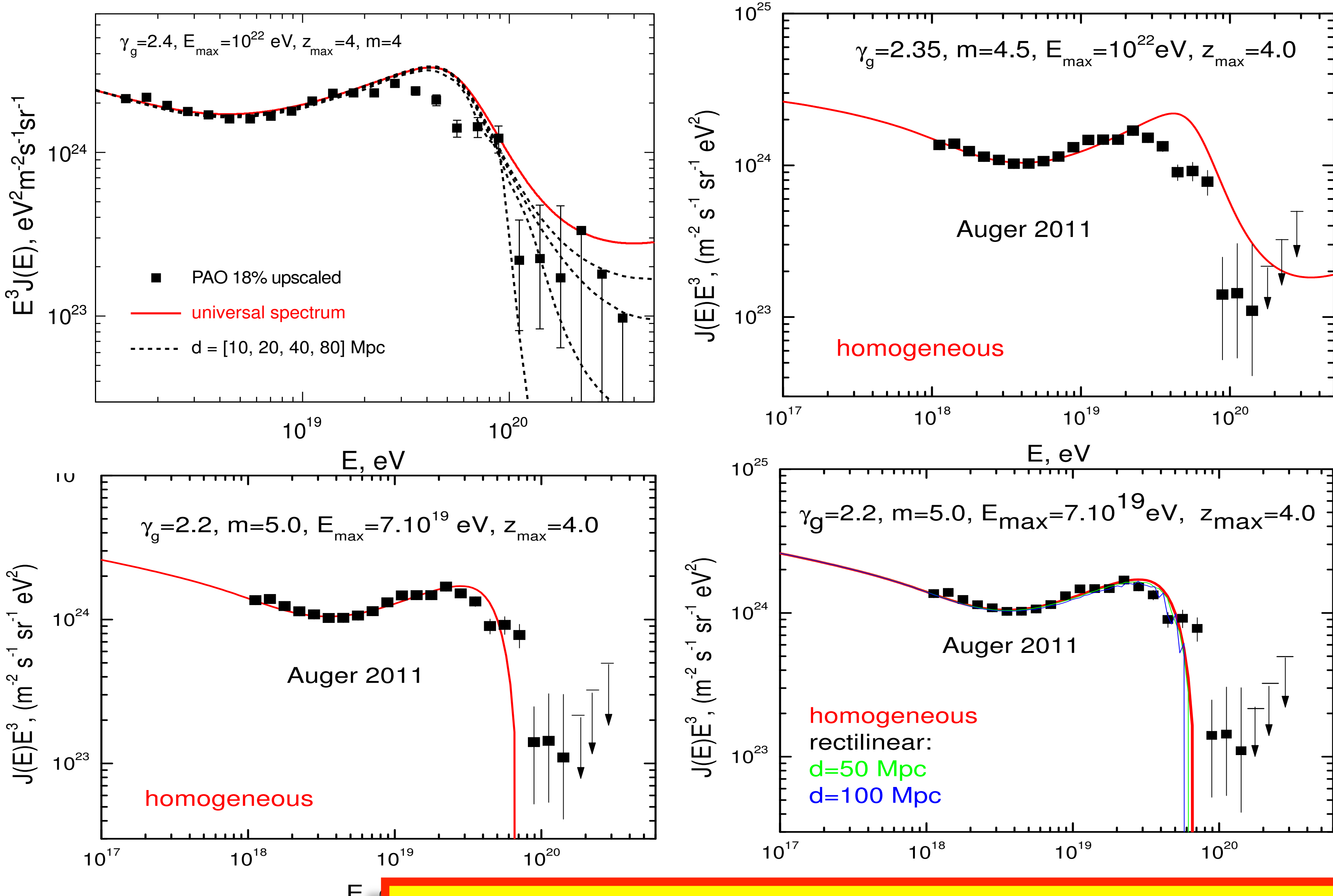


RA, Blasi, Berezinsky (2013, in preparation)



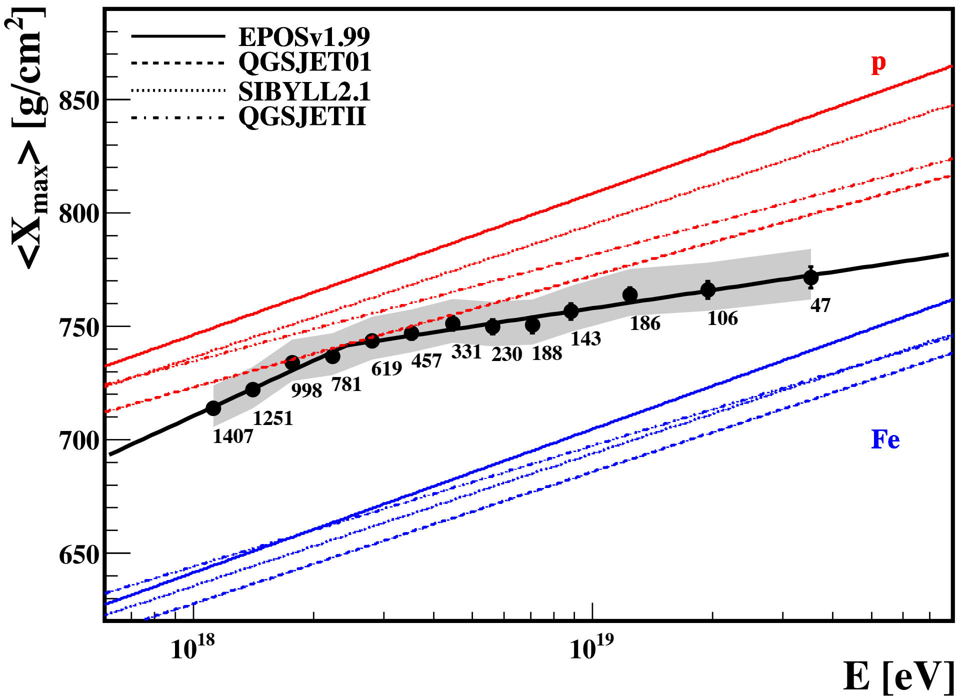
- The Galactic CR spectrum ends in the energy range 10^{17} eV, 10^{18} eV.
- 2^{nd} Knee appears naturally as the steepening energy corresponding to the transition from adiabatic to pair production energy losses $E_{2K} \approx 10^{18}$ eV.

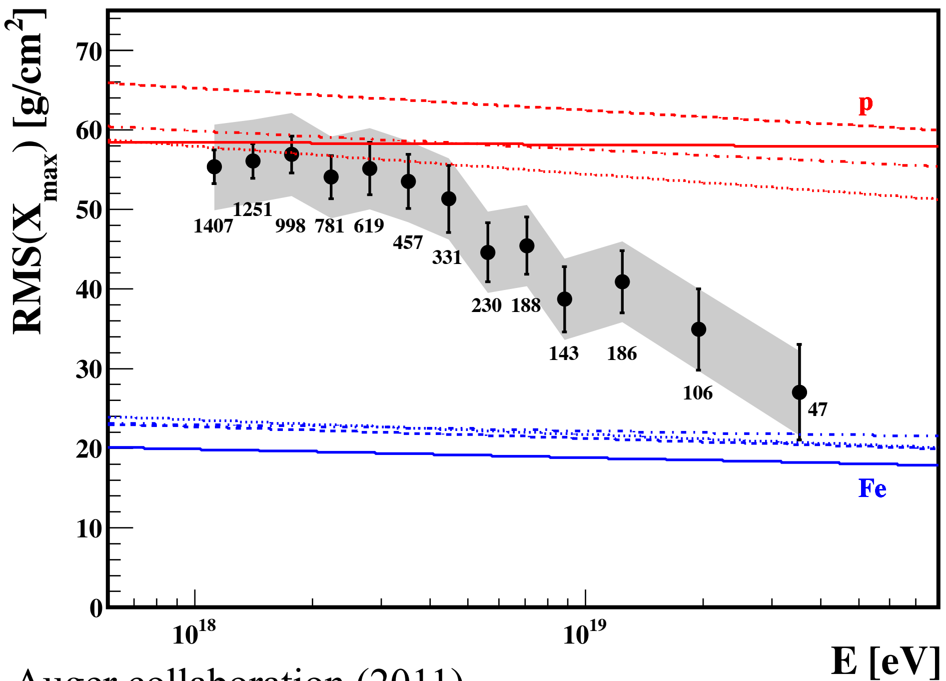
Auger Observatory



it is very difficult to explain the Auger flux in the framework of the dip model . <u>Signal of heavy nuclei</u>.

Auger chemical composition



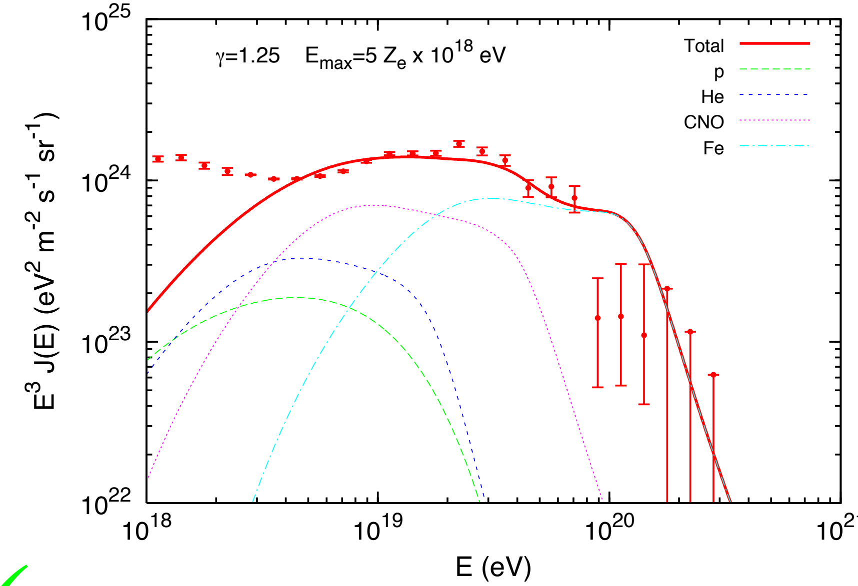


Auger collaboration (2011)

The latest Auger results on chemical composition show the tendency for a nuclei dominated flux at the highest energies.

Mixed Compositions

Models with an heavy nuclei dominance at the highest energies, constructed to fit the observations of Auger on flux and chemical composition.



RA, Berezinsky, Gazizov (2010)

✓ **flat injection** $\gamma_g = 1.1 \div 1.3$

low injection power law index, hints of pulsars as UHECR sources (Blasi, Epstein, Olinto 2000)

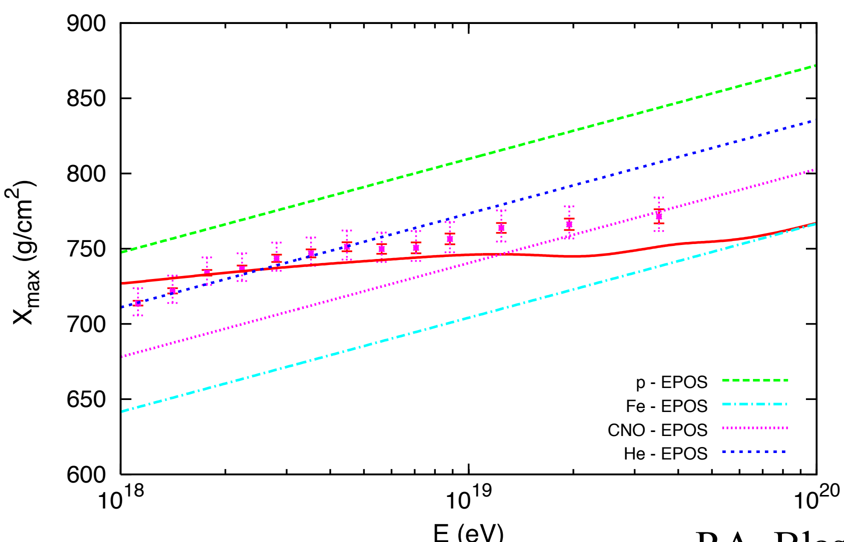
✓ **steep injection**

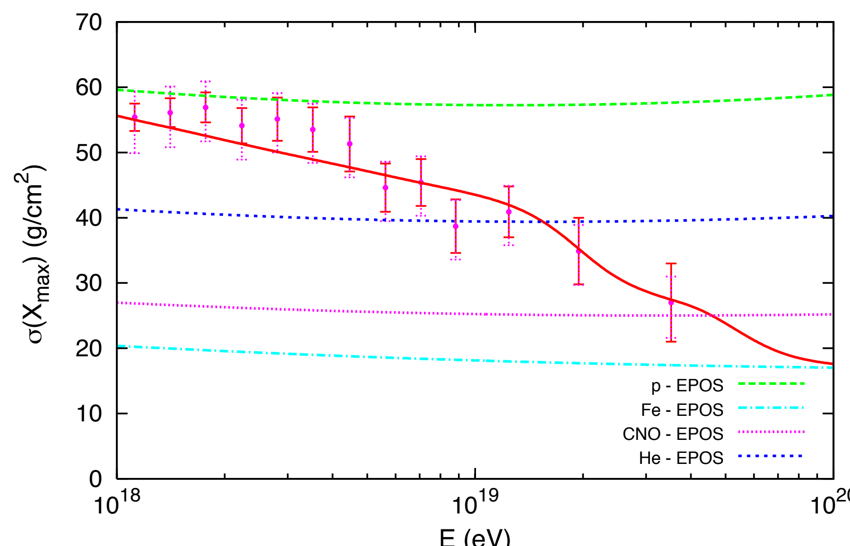
steep injection can be recovered if assuming low rigidity cut-off (RA, Blasi, Berezinsky 2013, in preparation)

✓ **no correlation with sources**

The μG galactic magnetic field substantially deviates particles trajectories:

$$\theta = \frac{Z}{2\pi} \frac{l_{Kpc} B_\mu}{E_{20}}$$

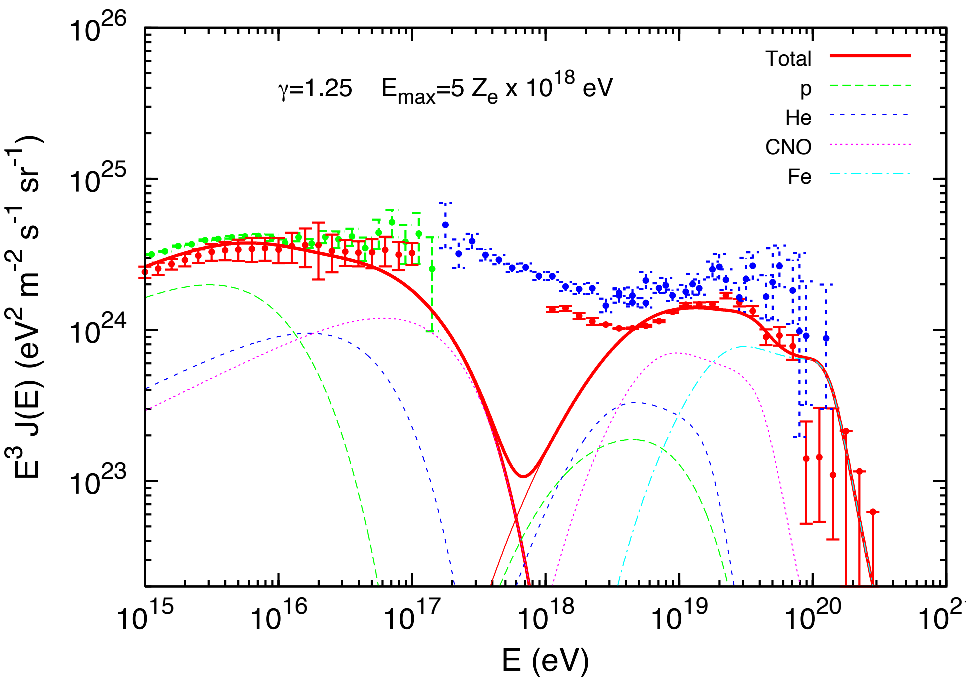


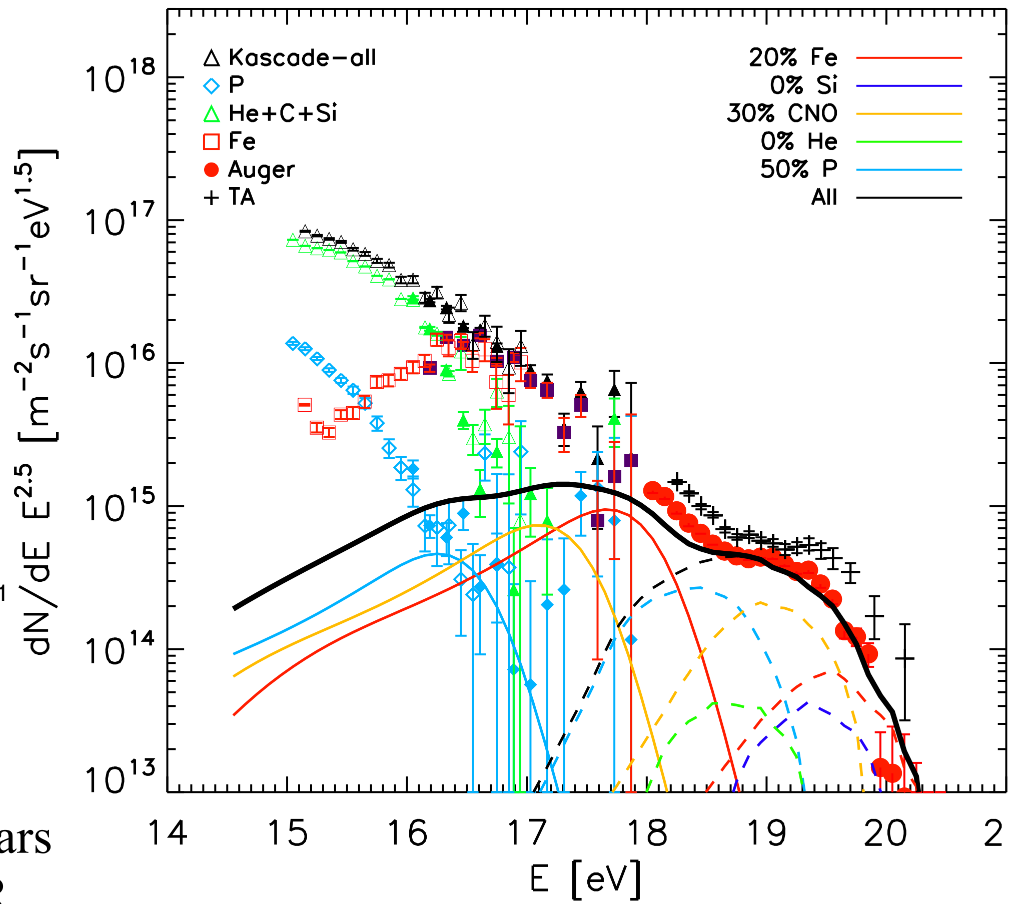


RA, Blasi, Berezinsky (2013, in preparation)

Galactic and ExtraGalactic Auger

Fang, Kotera, Olinto (2013)





✓ **galactic pulsars**

an additional component from galactic pulsars fills the gap, evidence of pulsars as UHECR sources (Fang, Kotera, Olinto (2013))

✓ **scenarios with steep injection**

scenarios with $\gamma > 2.5$ do not produce any gap at the transition, a behavior of the transition as in the dip model can be recovered assuming low cut-off rigidities (RA, Blasi, Berezinsky (2013) in preparation)

Data vs Data

If compared with theoretical models a very puzzling scenario emerges from HiRes and Auger data:

HiRes -TA

- ✓Protons dominate the UHECR flux
- ✓Transition Galactic/ExtraGalactic CR at $E<10^{18}$ eV
- ✓Steep injection spectra at the sources $\gamma_g>2.5$
- ✓High maximum energy at the source $E_{max}>10^{20}$ eV
- ✓Correlation with sources (UHECR astronomy is feasible)

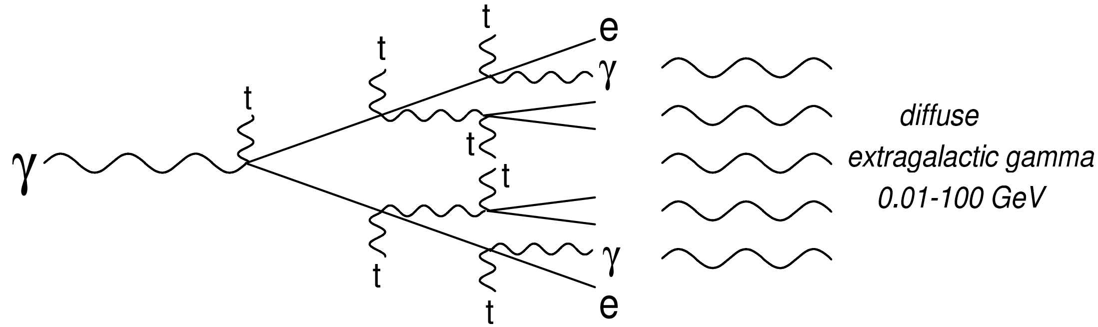
Auger

- ✓Heavy nuclei dominate the UHECR flux at $E>4\times10^{18}$ eV
- ✓Transition Gal/Ext at $E>10^{18}$ eV, need for a new HE Gal component (pulsars)
- ✓Flat injection spectra at the sources $\gamma_g<2.0$
- ✓Low maximum energy for protons at the source $E_{max}<10^{19}$ eV
- ✓No correlation with sources (deflections due to galactic magnetic field)

Neutrinos from UHECR

Cascade upper limit

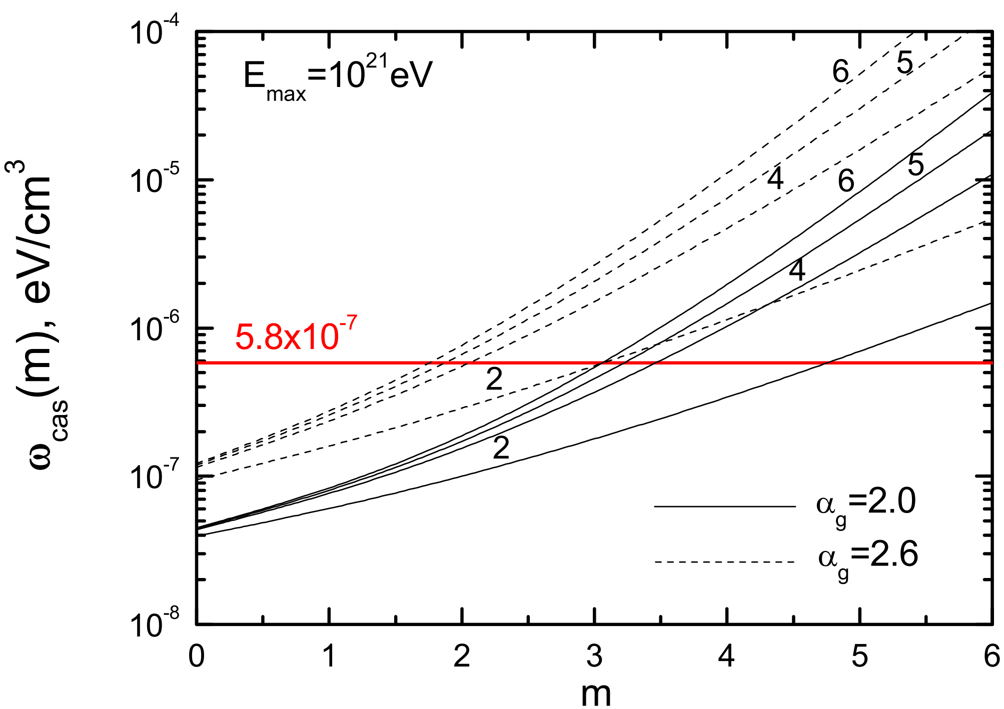
$$p\gamma \to \pi^0 \to \gamma$$
$$p\gamma \to \pi^{\pm} \to e^{\pm}$$
$$p\gamma \to \pi^{\pm} \to \nu$$



Berezinsky, Smirnov (1975)

Fermi-LAT data
$\omega_{cas} = 5.8\text{x}10^{-7}$ eV/cm^3

$$\omega_{cas}^{max} > \omega_{cas}^{\pi} > \frac{4\pi}{c}\int_E^{\infty} E' J_\nu(E') dE' > \frac{4\pi}{c} E_\nu J_\nu(>E)$$



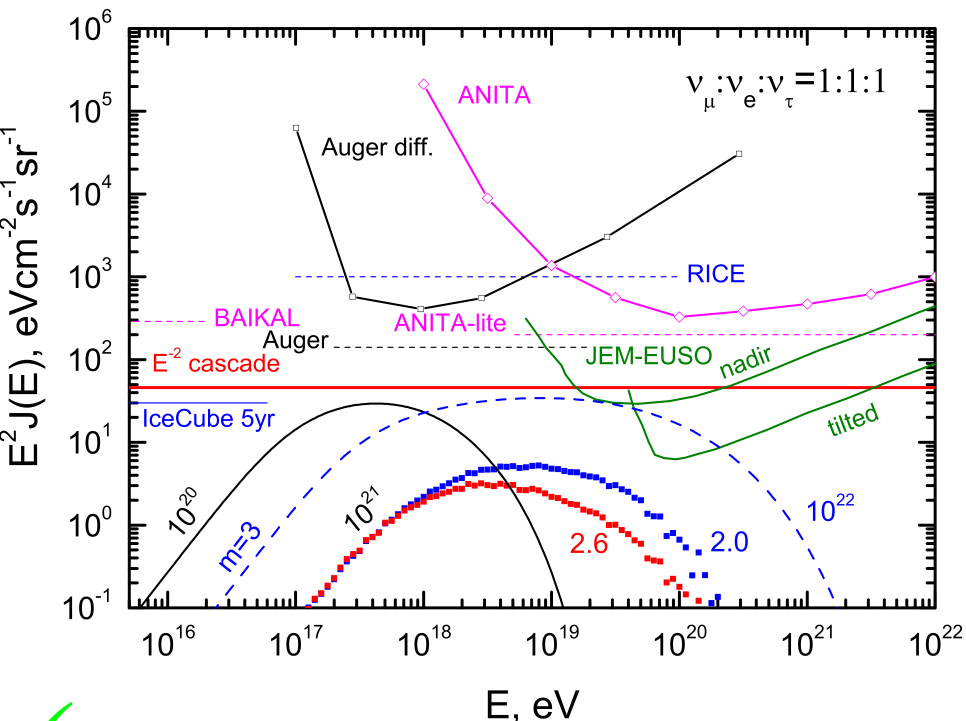
Berezinsky, Gazizov, Kachelriess, Ostapchenko (2010)

Assuming an E^{-2} neutrino flux , the cascade limit can be expressed in terms of the energy densities of pions and e^+e^- pairs initiated cascades

$$E^2 J_\nu(E) \le \frac{c}{4\pi}\frac{\omega_{cas}^{max}}{\ln(E_{max}/E_{min})}\frac{1}{1+\omega_{cas}^{e^+e^-}/\omega_{cas}^{\pi}}$$

The cascade upper limit constrains the source parameters mainly in terms of their allowed cosmological evolution, injection power law and maximum acceleration energy.

Berezinsky, Gazizov, Kachelriess, Ostapchenko (2010)



✓ EeV neutrinos in the dip model

Fermi-LAT observations constrain cosmogenic neutrino fluxes. Detectability only for high maximum energies (>10^{20} eV) and strong cosmological evolution of the sources (m>2)

✓ PeV neutrinos in the dip model

PeV neutrinos can be produced by protons photopion interactions on the EBL. Fluxes (≈ 10^{-9} GeV/cm^s s sr) below the Ice Cube detection capabilities.

✓ PeV neutrinos from popIII stars

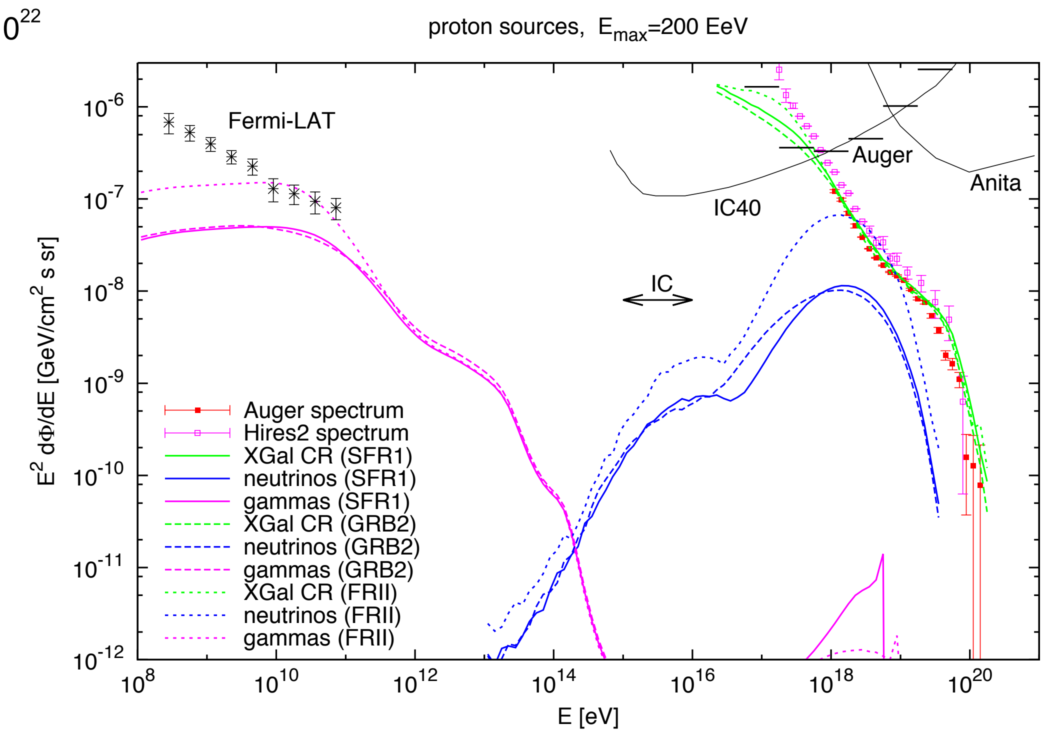
- massive stars (100 M_{sol}) at z ≈ 10 ÷ 15
- protons acceleration with γ_g =2.0 ÷ 2.3
- E_{max} = 10^{21} eV

$$E_\nu = \frac{1}{20}\frac{E_{p\gamma\to\pi}}{(1+z_b)^2} \simeq 7.5\times 10^{15}\left(\frac{20}{1+z_b}\right)^2 \; eV$$

$$E_\nu^2 J_\nu(E_\nu) = 0.1\frac{c}{4\pi}\frac{\omega_p(z_b)}{(1+z_b)^4}\frac{1}{\ln(E_{max}/E_{min})}$$

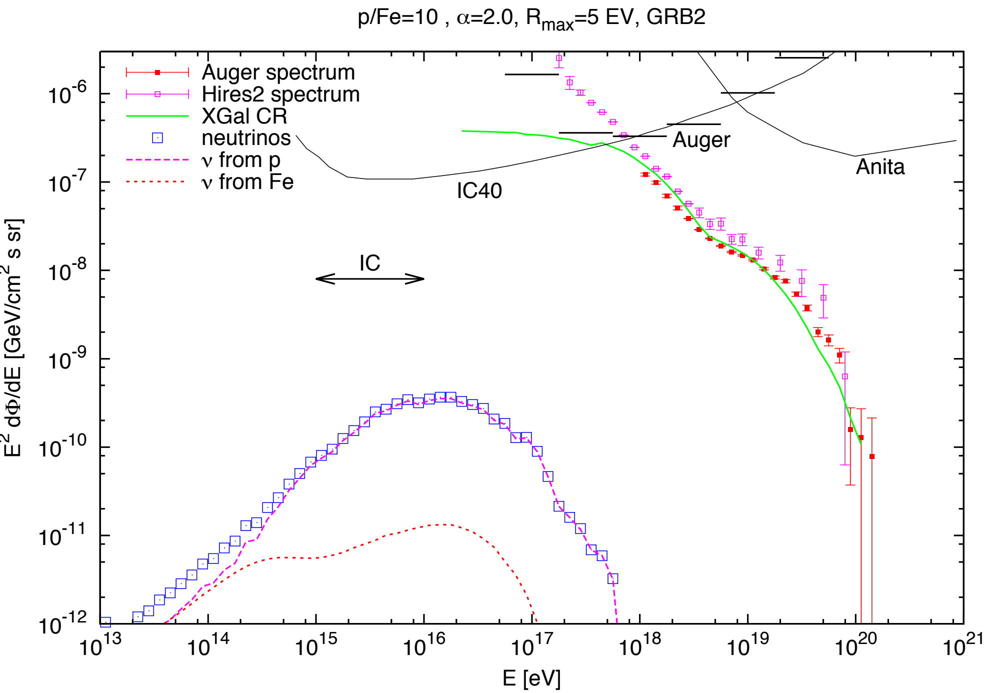
$\omega_p \gtrsim 10^{-6}\mathrm{eV/cm^3}$ Ice Cube detectable

Berezinsky and Blasi (2012)



Roulet, Sigl, van Vliet, Mollerach (2013)

Roulet, Sigl, van Vliet, Mollerach (2013)



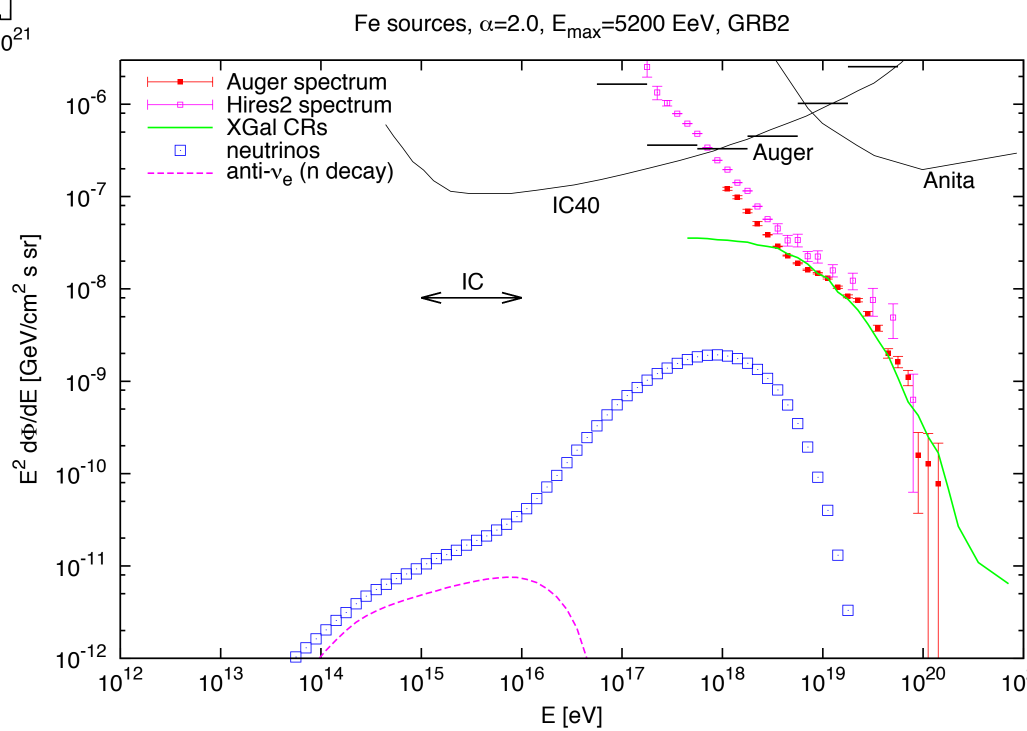
✓ EeV neutrinos from UHE nuclei

UHE nuclei suffer photo-pion production on CMB only for energies above AE_{GZK}. The production of EeV neutrinos strongly depends on the nuclei maximum energy. UHE neutrino production practically disappears in models with maximum nuclei acceleration energy $E_{max} < 10^{21}$ eV.

✓ PeV neutrinos from UHE nuclei

PeV neutrinos produced in the photo-pion production process of nuclei on the EBL radiation field well below the Ice Cube Detection capabilities

UHECR Disappointing Model
models with an heavy nuclei composition at the highest energies: no correlation with sources, no detectable neutrino production.



Roulet, Sigl, van Vliet, Mollerach (2013)

Conclusions

- ✓ The experimental observation of the UHECR chemical composition has a paramount importance in choosing among different source models.

- ✓ Observations of UHECR are still unclear, with different experiments claiming different results. A renewed experimental effort is needed in order to asses the nature of UHECR.

- ✓ Cosmogenic neutrino production strongly dependent on the UHECR chemical composition. Only in protons dominated scenarios a detectable flux is expected.

- ✓ PeV neutrinos observed by Ice Cube can be of cosmogenic origin only if produced by UHE protons from popIII stars.

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