The DIP model in Ultra High Energy Cosmic Ray Physics

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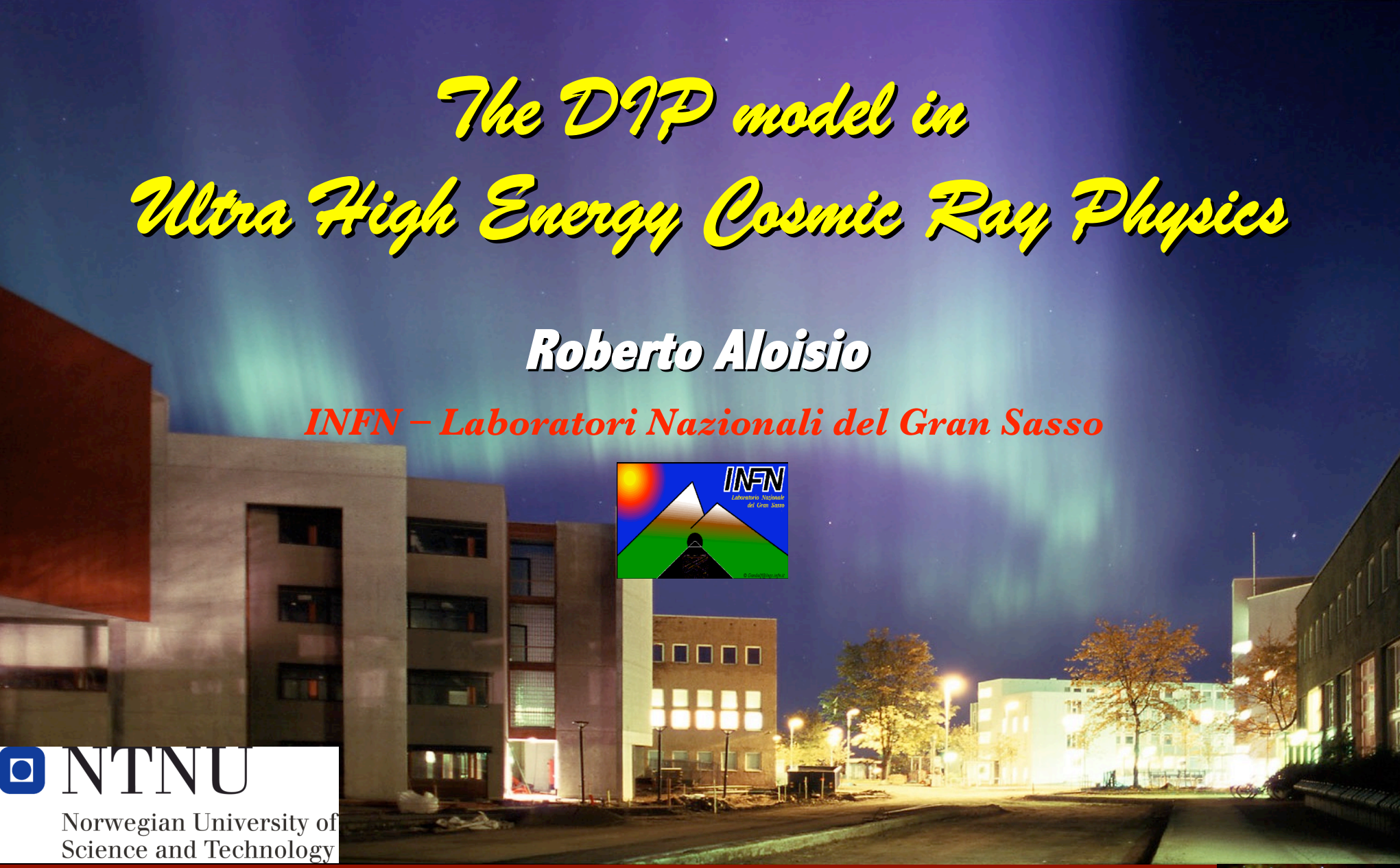
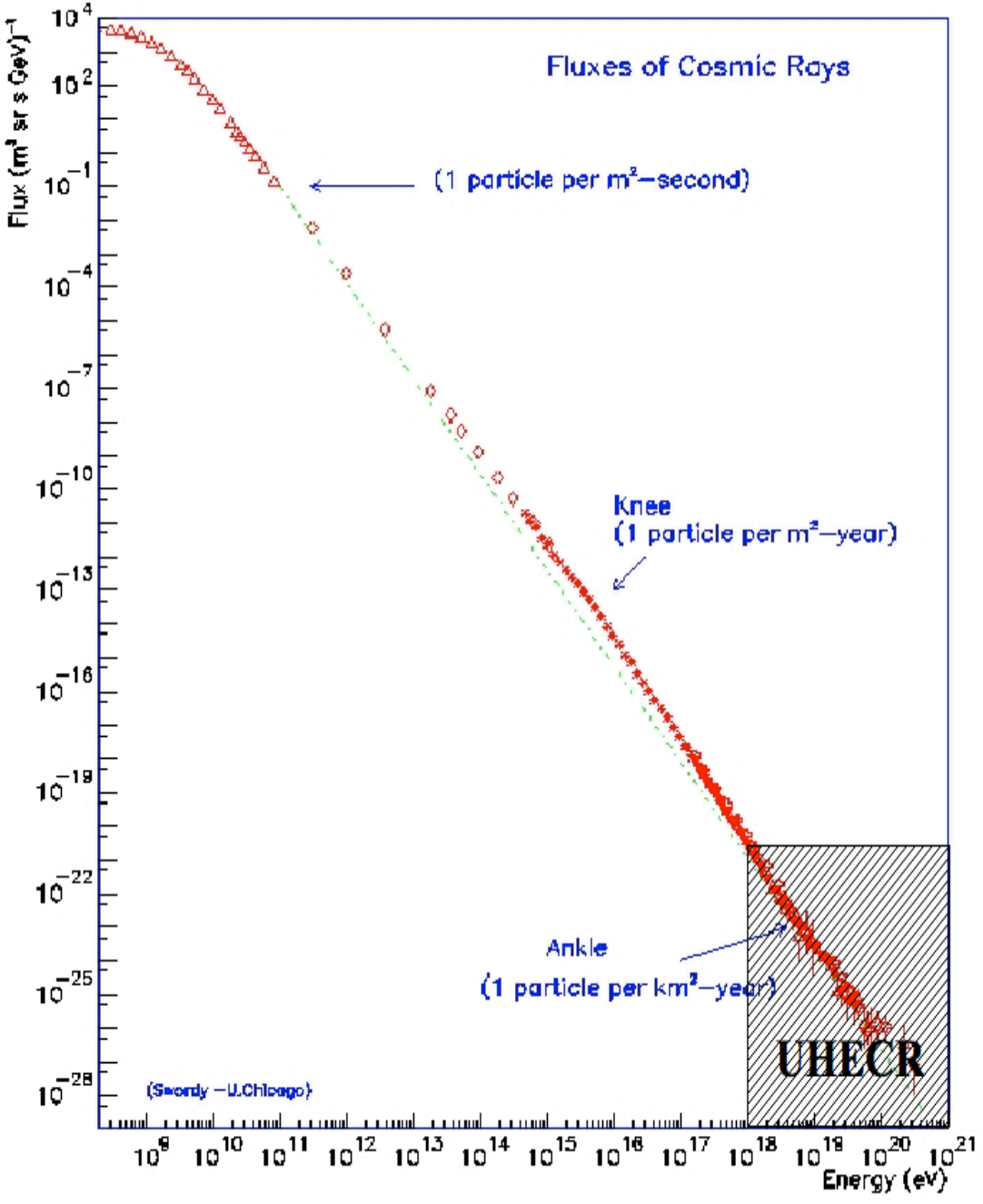


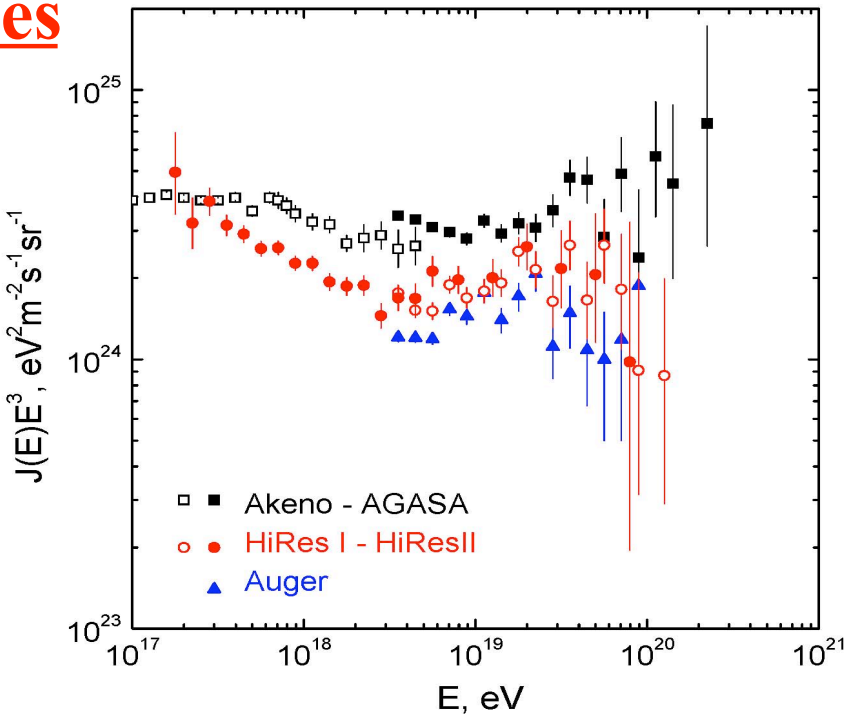
NTNU
Norwegian University of Science and Technology

Searching for the Origins of Cosmic Rays

June 15-19 Trondheim Norway

CR spectrum at Ultra High Energies



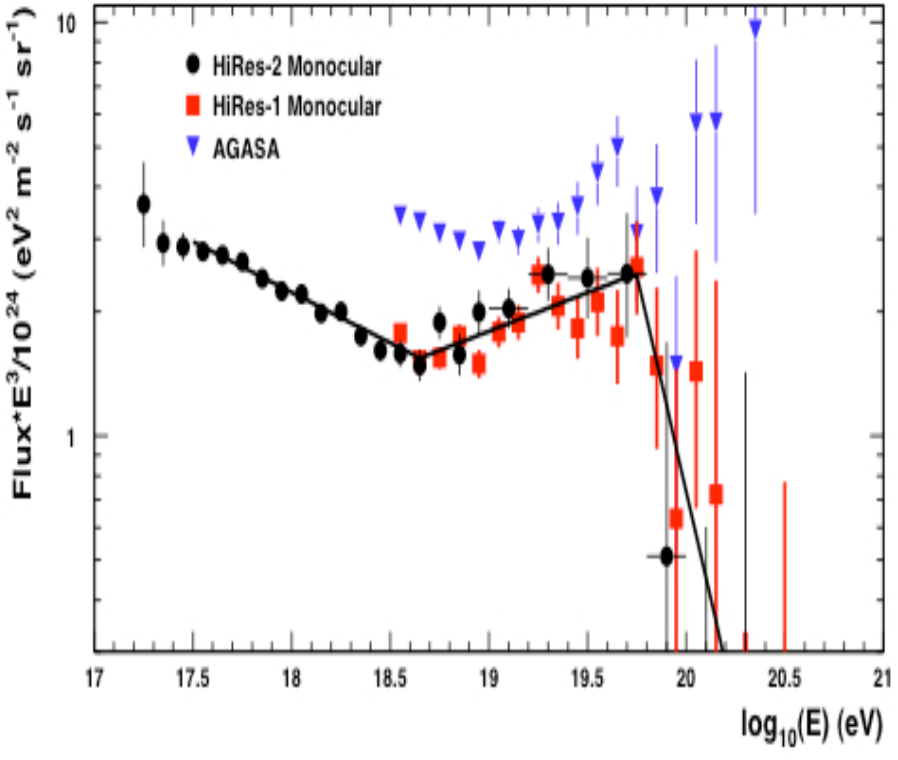


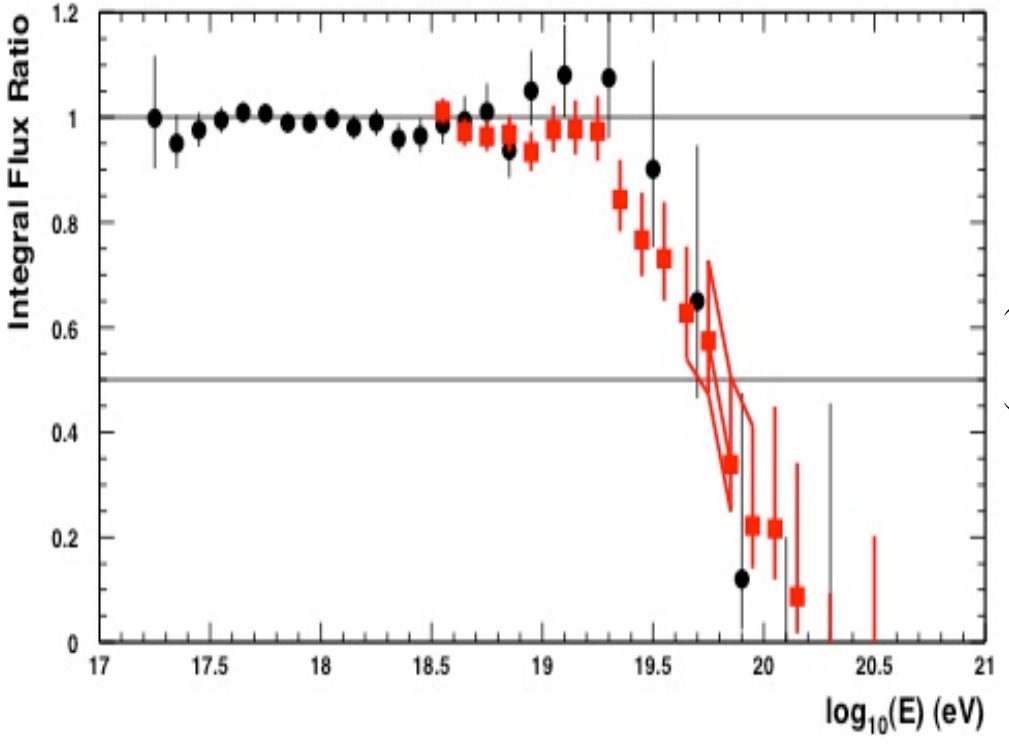
The observations on Earth are the result of the acceleration at the source (injection) and the propagation of particles in the background radiation (CMB & IR) and magnetic fields.

- ✓ **Spectrum**
- ✓ **Chemical Composition**
- ✓ **Anisotropy** (correlations)

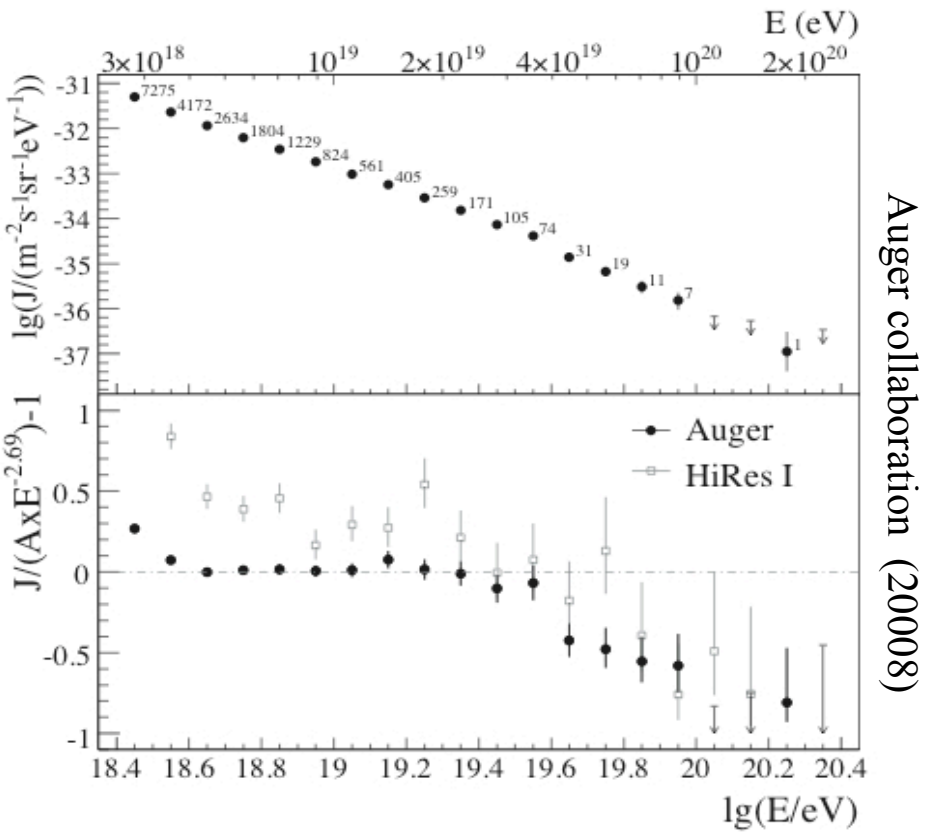
The End of the CR Spectrum?

The last HiReS analysis confirms the expected Greisen Zatzepin Kuzmin suppression in the flux with $E_{1/2}=10^{19.73\pm0.07}$ eV in perfect agreement with the theoretically predicted value for protons $E_{1/2}=10^{19.72}$ (Berezinsky & Grigorieva 1988).



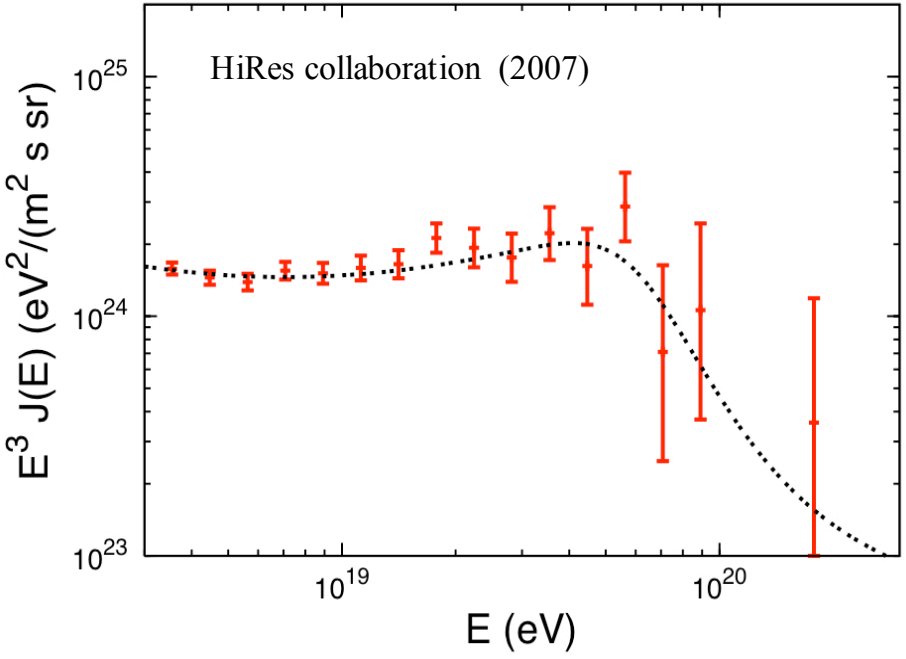


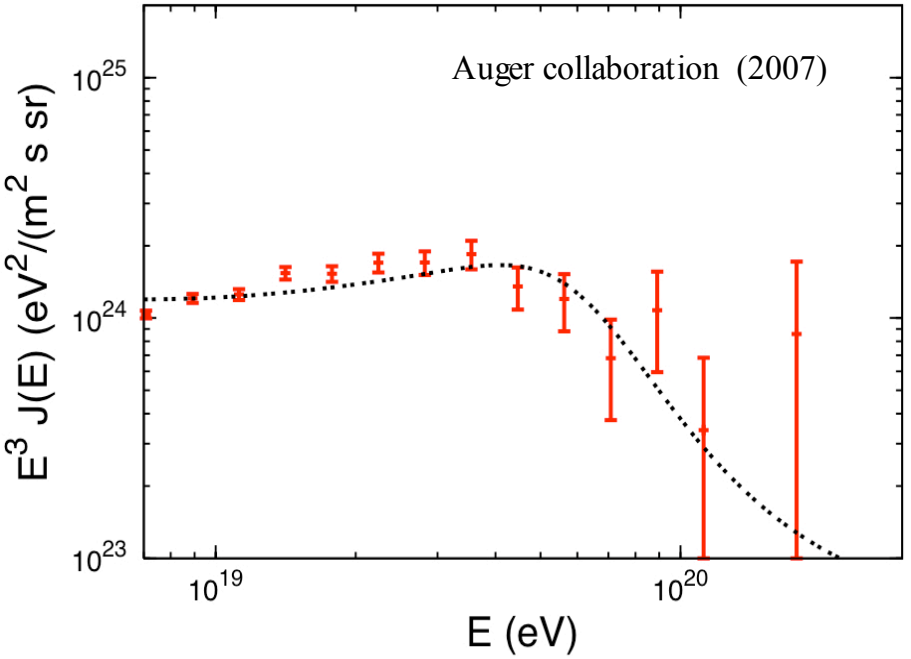
HiRes collaboration (2007)



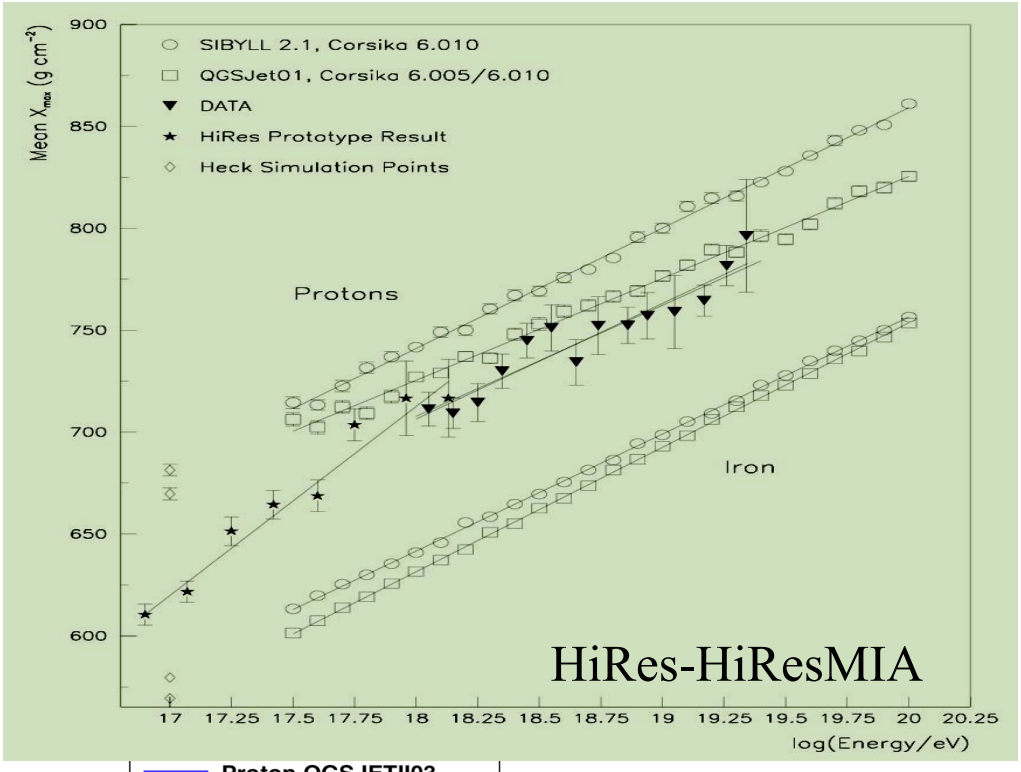
The UHECR spectrum observed by Auger also shows a suppression in the flux at the highest energies compatible with the GZK cut-off.

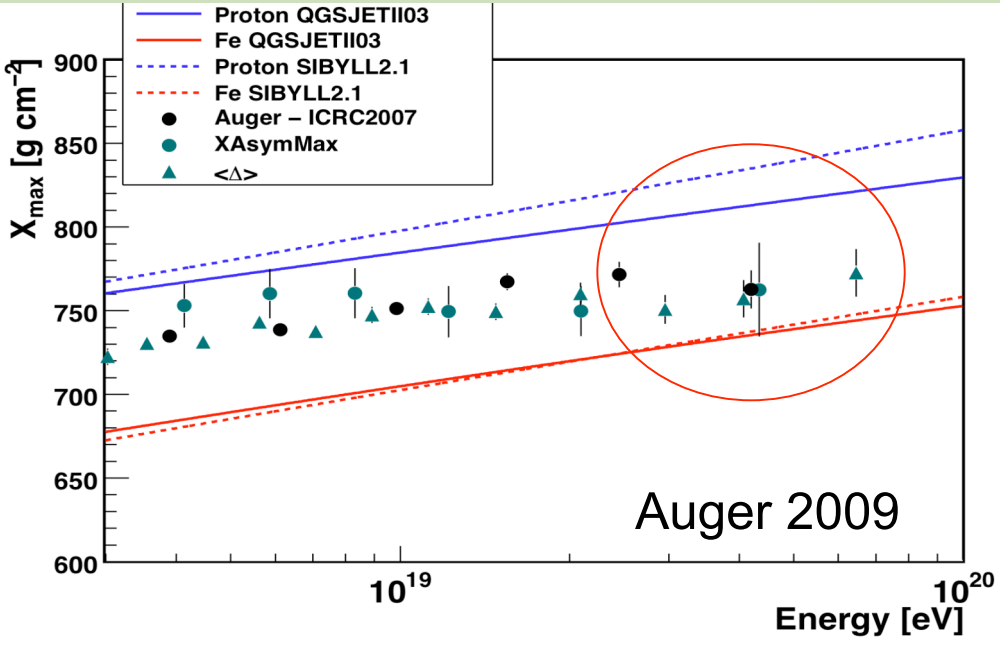
Evidences of an astrophysical proton dominated flux at the highest energies





Chemical Composition





mixed composition at $10^{18.5}$ eV

Fly's Eye-Akeno-AGASA
[Hayashida et al. 95,Dawson et al. 98, Teshima et al 2003]

transition from heavy (at $10^{17.5}$ eV) to light composition (at 10^{19} eV)

Haverah Park [Ave et al. 2001]

no more than 54% Iron above 10^{19} eV
no more than 50% photons above 4 10^{19} eV

Auger [Wahlberg et al. 2009]]

mixed composition at all energies with an heavier composition at the highest energies

proton composition at $10^{18.5}$ eV

HiRes-HiResMIA [Sokolsky et al 2005]

Transition from heavy (at $10^{17.5}$ eV) to light composition (at $10^{18.5}$ eV)

Yakutsk [Glushkov et al. 2006]]

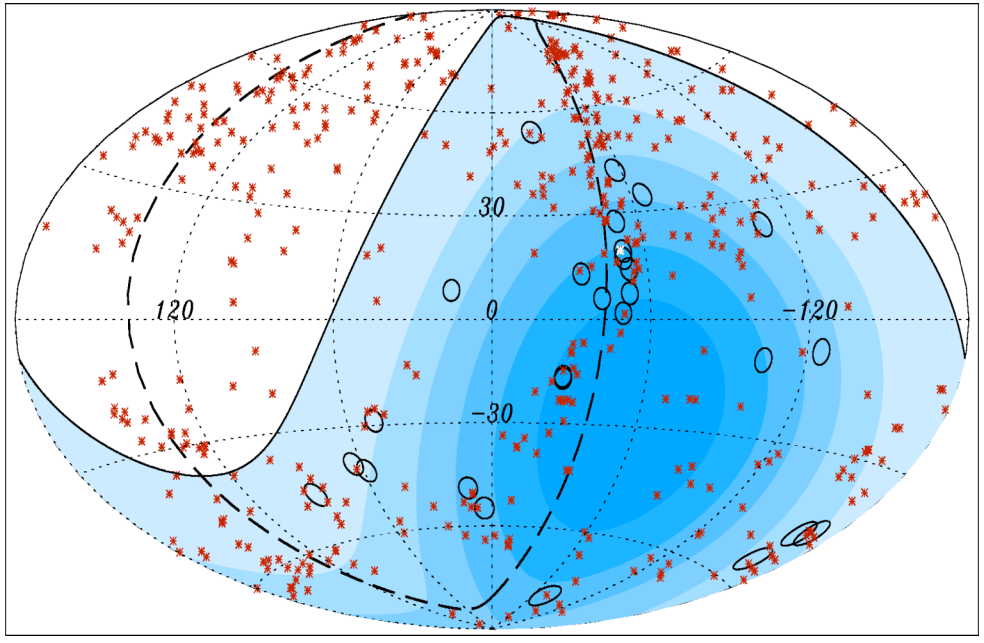
Transition from heavy to light composition at 10^{18} eV

Puzzling Situation

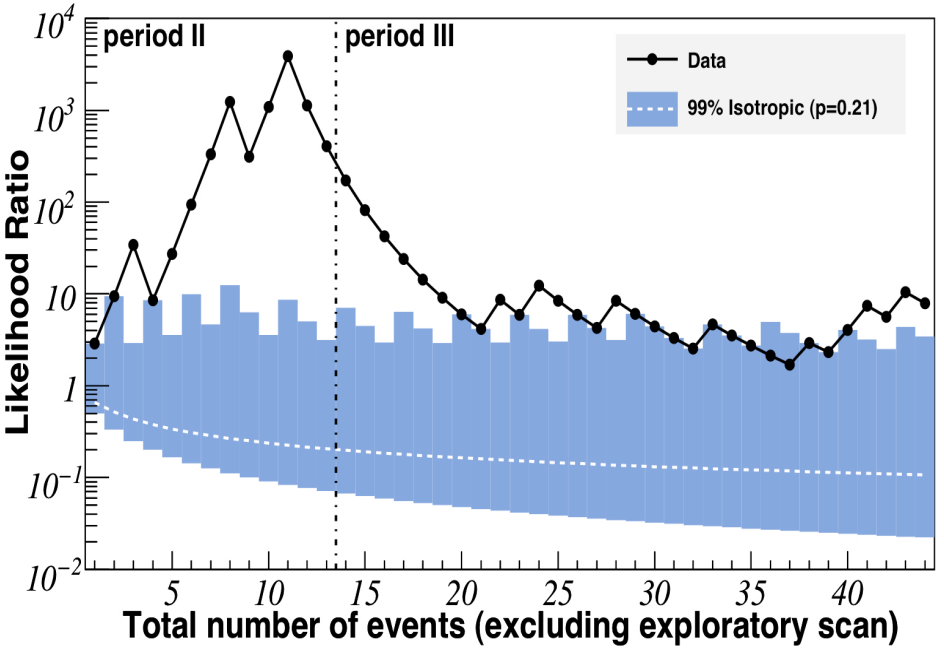
chemical composition at $E>10^{18}$ eV
not conclusively observed

Correlation with AGNs

The Auger collaboration claims a correlation between the highest energies events $E>5.7\times10^{19}$ eV and several nearby AGNs



Auger collaboration (2007)



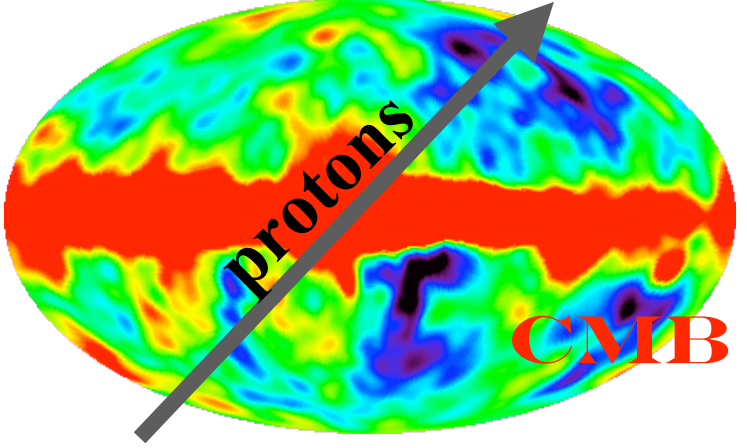
Auger collaboration (2009)

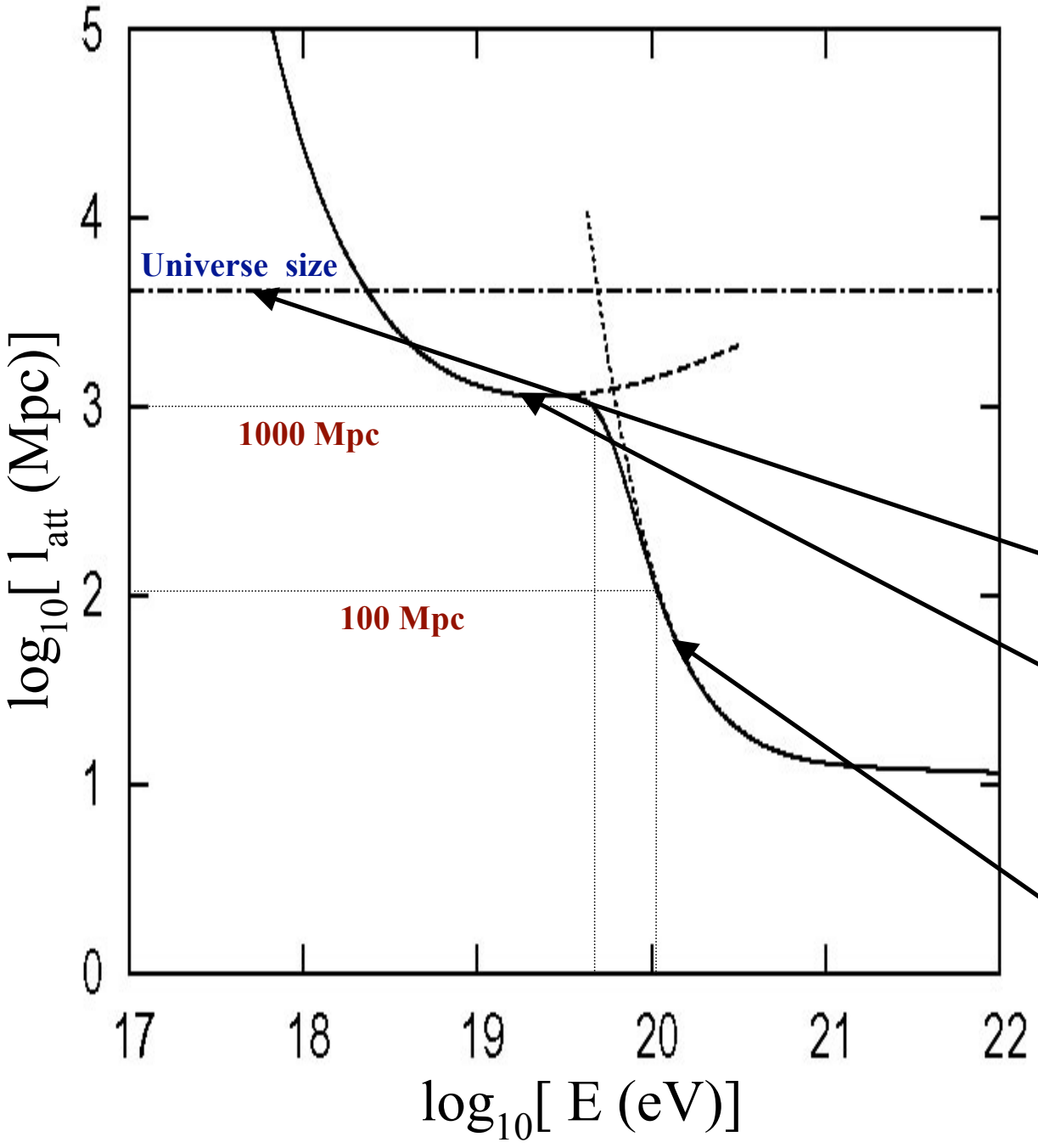
The latest analysis of the Auger data still shows a correlation with the closest AGN but with a lower statistical significance respect to the data of 2007

(see the talk by Letessier-Selvon)

UHE protons could show a correlation with sources
UHE nuclei couldn't (deflection by galactic magnetic field)

UHE Proton energy losses





proton propagation is affected only by CMB

Adiabatic losses
Universe expansion

Pair production

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

Photopion production

$p\,\gamma \rightarrow p\,\pi^0$

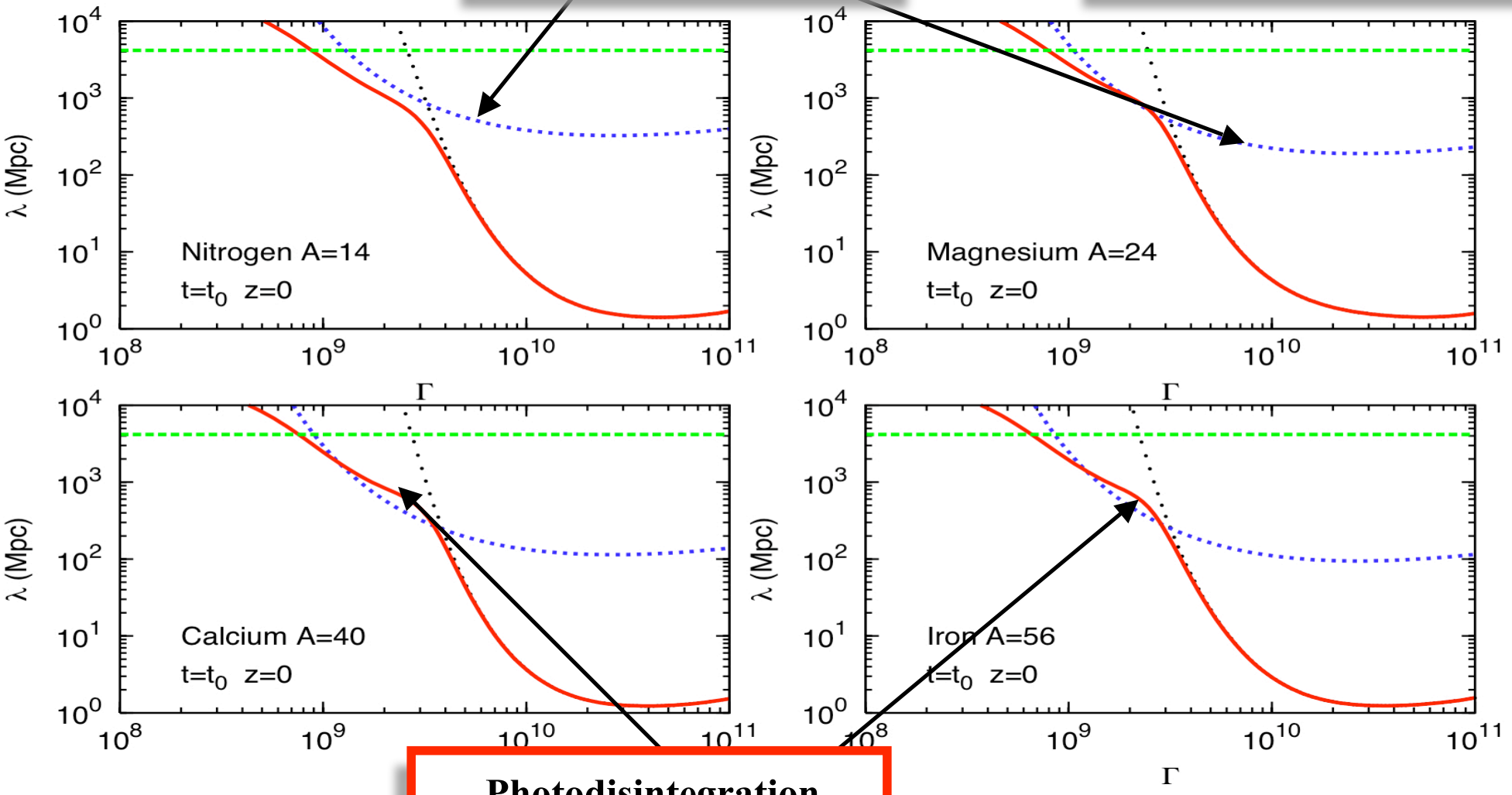
$\rightarrow n\,\pi^+$

UHE Nuclei energy losses

Pair production (CMB)

$A\,\gamma \rightarrow A\,e^+\,e^-$

Nuclei propagation is affected also by IR/V/UV



Photodisintegration (CMB+IR/V/UV)

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

$E_{Fe} \approx 10^{20}$ eV

Protons propagation in Intergalactic Space

Continuum Energy Losses

Protons lose energy but do not disappear. Fluctuations in the pγ interaction start to be important only at $E>5\times10^{19}$ eV.

Uniform distribution of sources

the UHECR sources are continuously distributed with a density n_s.

$$J(E) = \frac{c}{4\pi} n_s \int_0^{z_{max}} dz \left|\frac{dt}{dz}\right| Q_{inj}(E_g(E,z)) \frac{dE_g}{dE}$$

Discrete sources

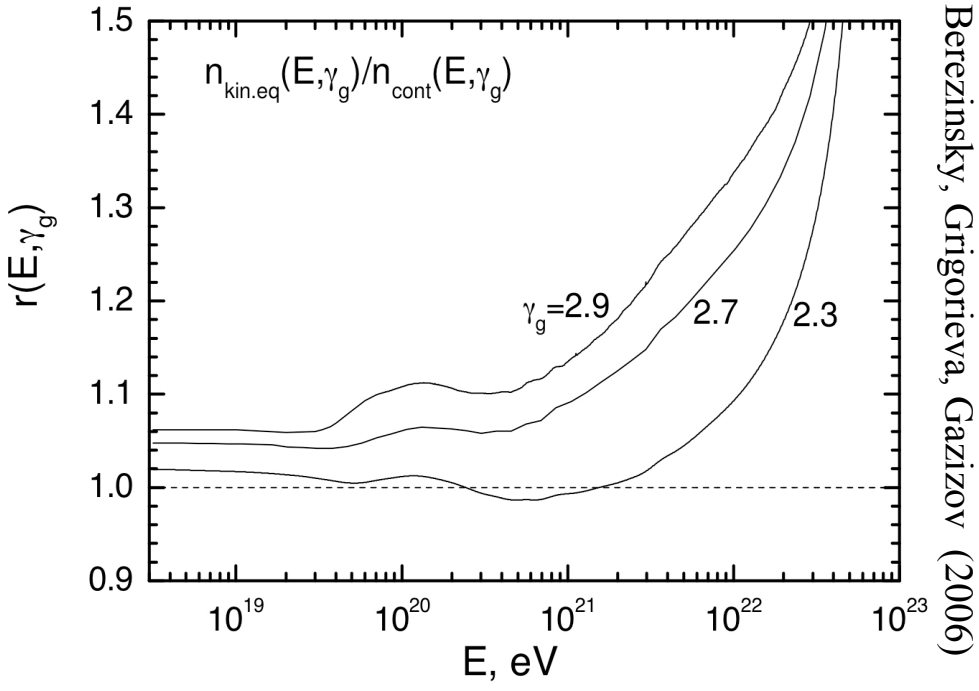
the UHECR sources are discretely distributed with a spacing d.

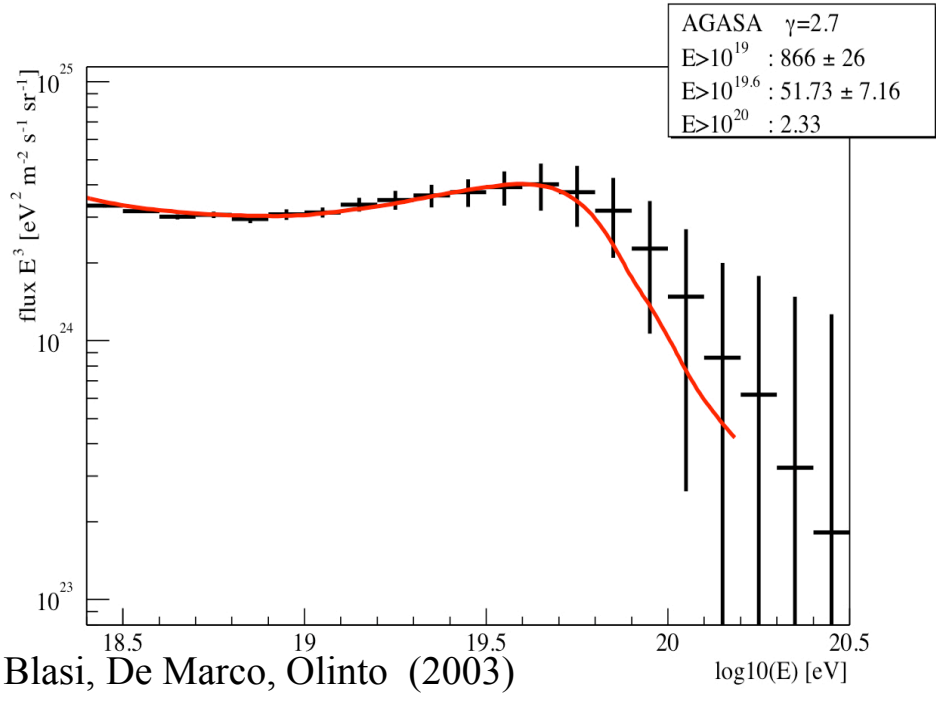
$$J(E) = \frac{1}{4\pi} \sum_i \frac{Q_{inj}(E_g(E,z_i))}{r_i^2(1+z_i)} \frac{dE_g(E,z_i)}{dE}$$

Injection spectrum number of particles injected at the source per unit time and energy

$$Q_{inj} = \frac{L_p(\gamma-2)}{E_C^2}\left(\frac{E}{E_C}\right)^{-\gamma} \qquad \gamma > 2$$

$J_p = L_p\, n_S$





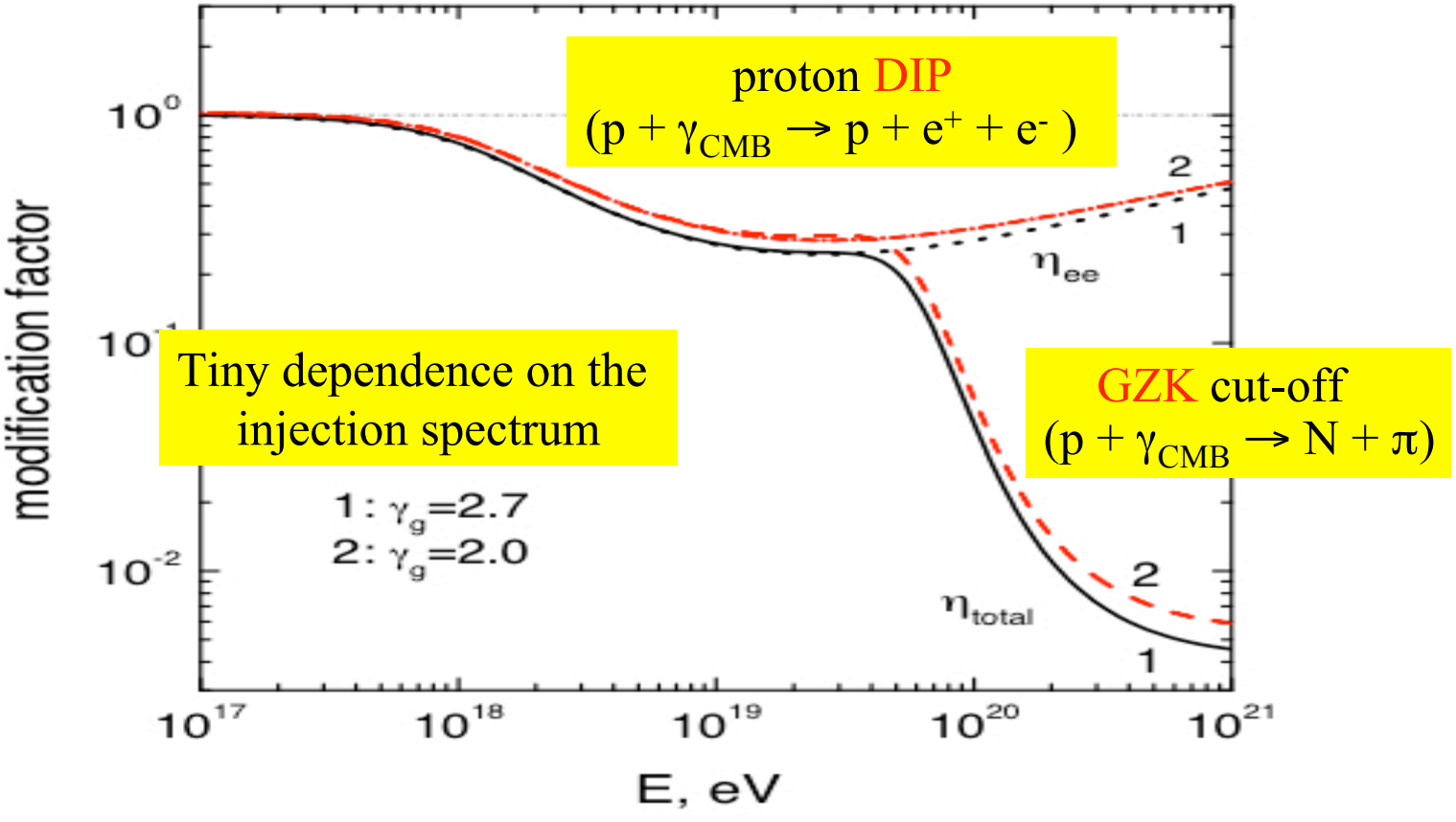
Modification Factor

Assuming a proton dominated spectrum the modification factor is a good theoretical tool

$$\eta = \left(\frac{J_p(E)}{J_p^{unm}(E)} \right)$$

$J_p^{unm}(E)$ only adiabatic losses

$J_p(E)$ total energy losses

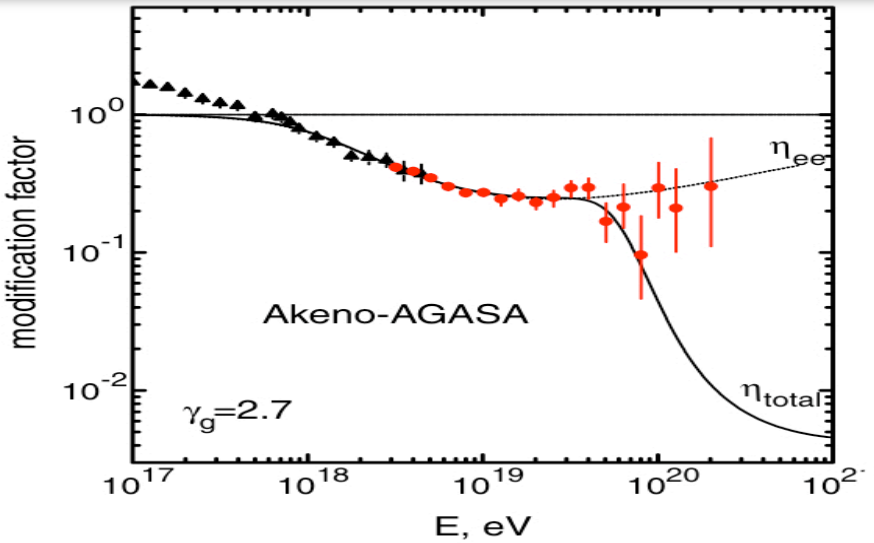


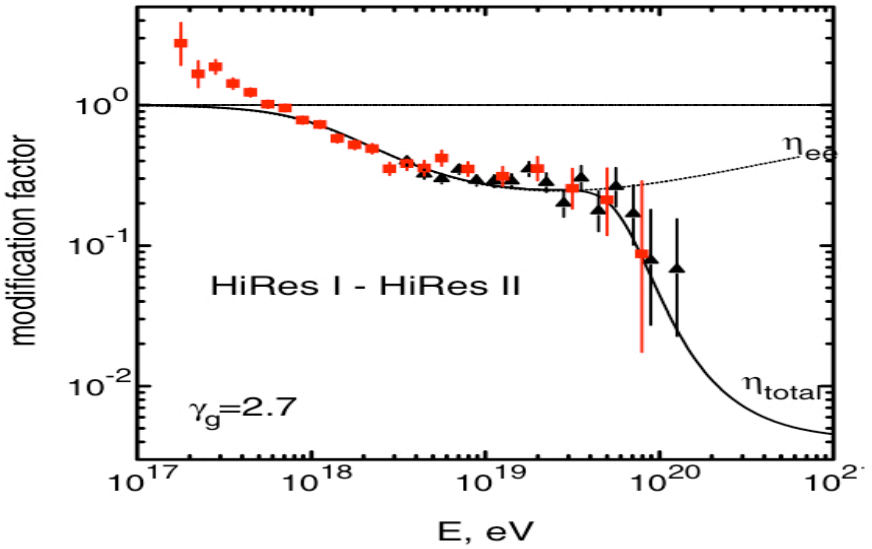
Dip Model

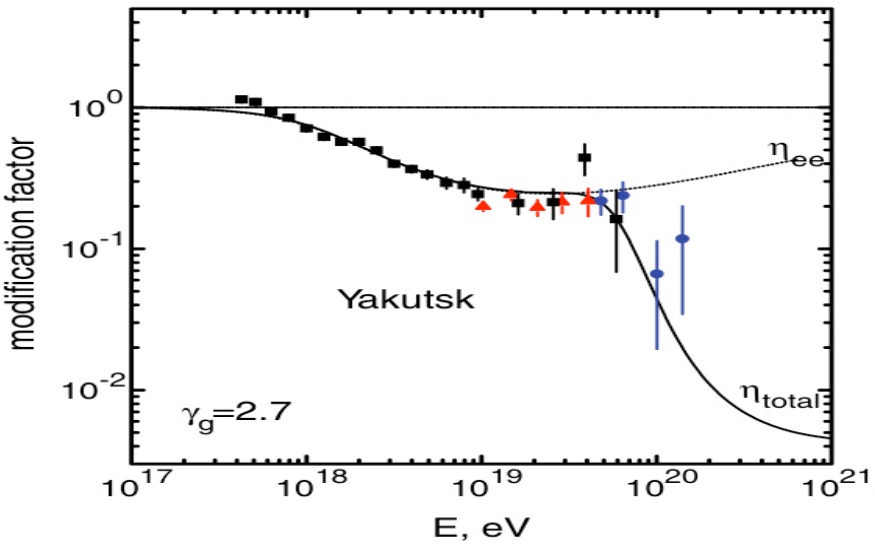
In the energy range 10^{18} - $5x10^{19}$ eV the spectrum behavior is a signature of the pair production process of UHE protons on the CMB radiation field.

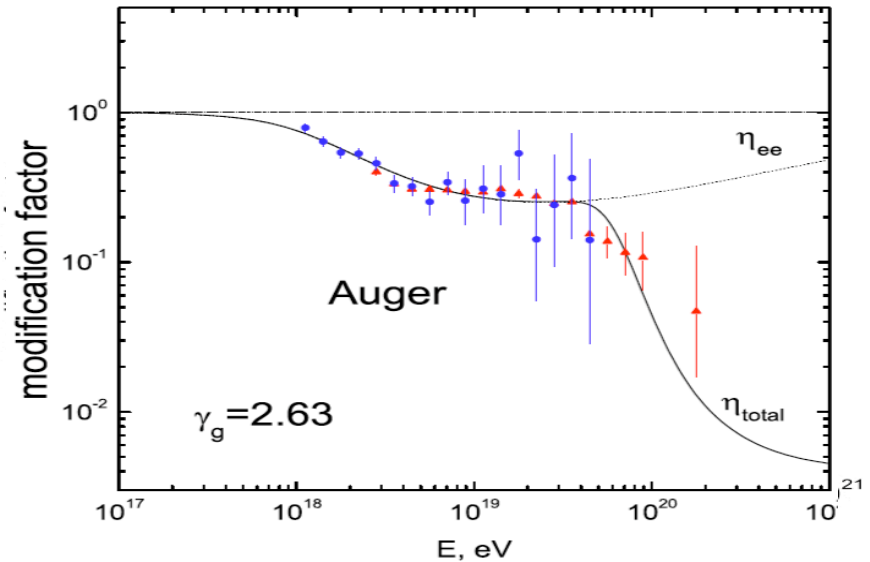
Best fit values

$\gamma = 2.7$ $J_p = O(10^{40})$ erg $s^{-1}Mpc^{-3}$





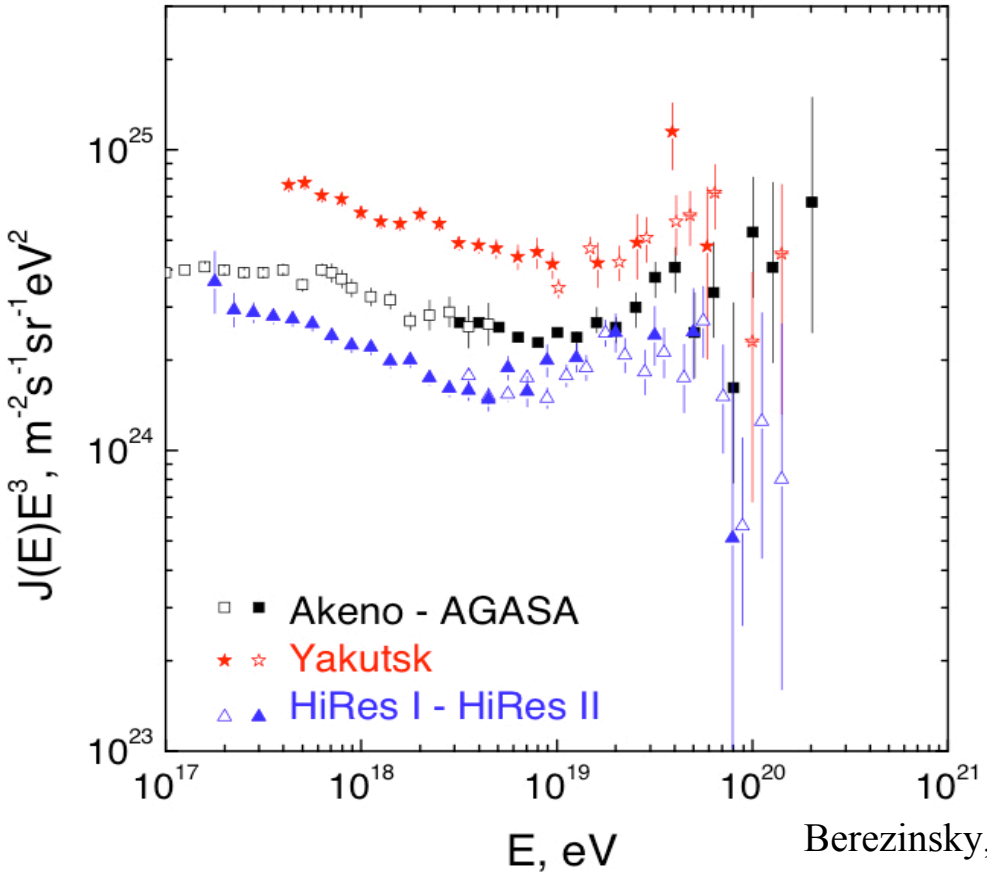


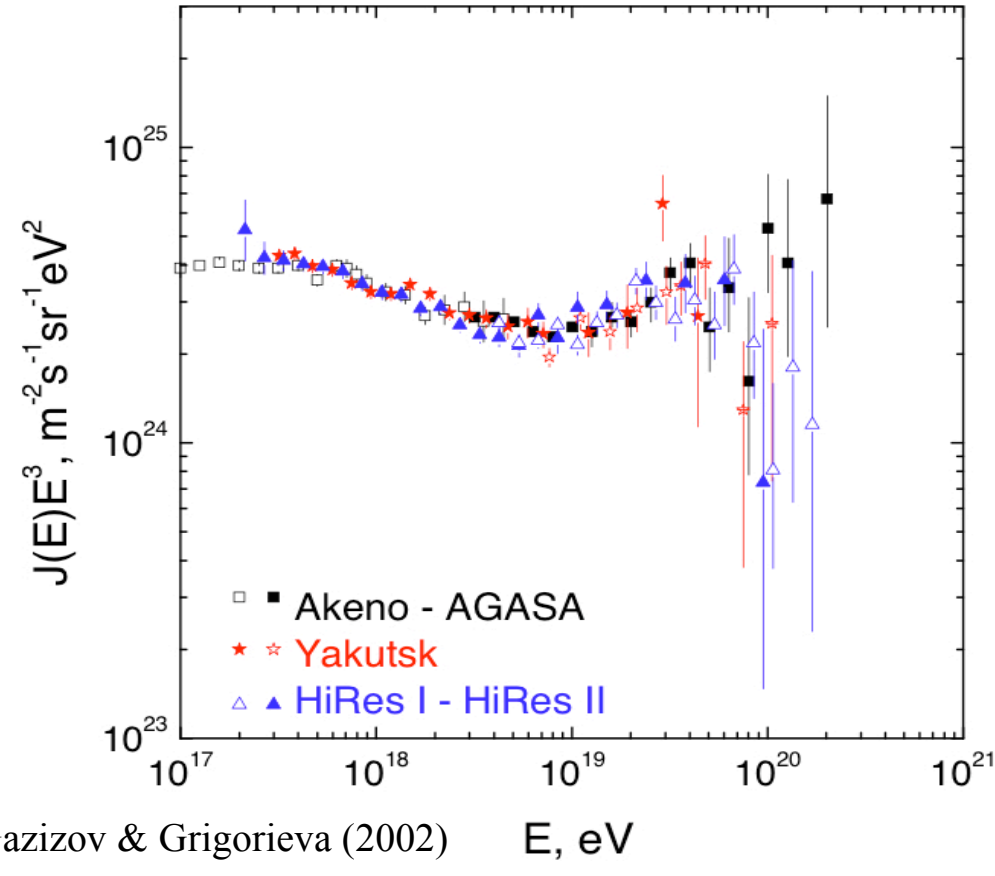


Berezinsky et al (2002) - RA, Berezinsky, Blasi, Ostapchenko (2007)

Energy calibration by the Dip

Different experiments show different systematic in energy determination





Berezinsky, Gazizov & Grigorieva (2002)

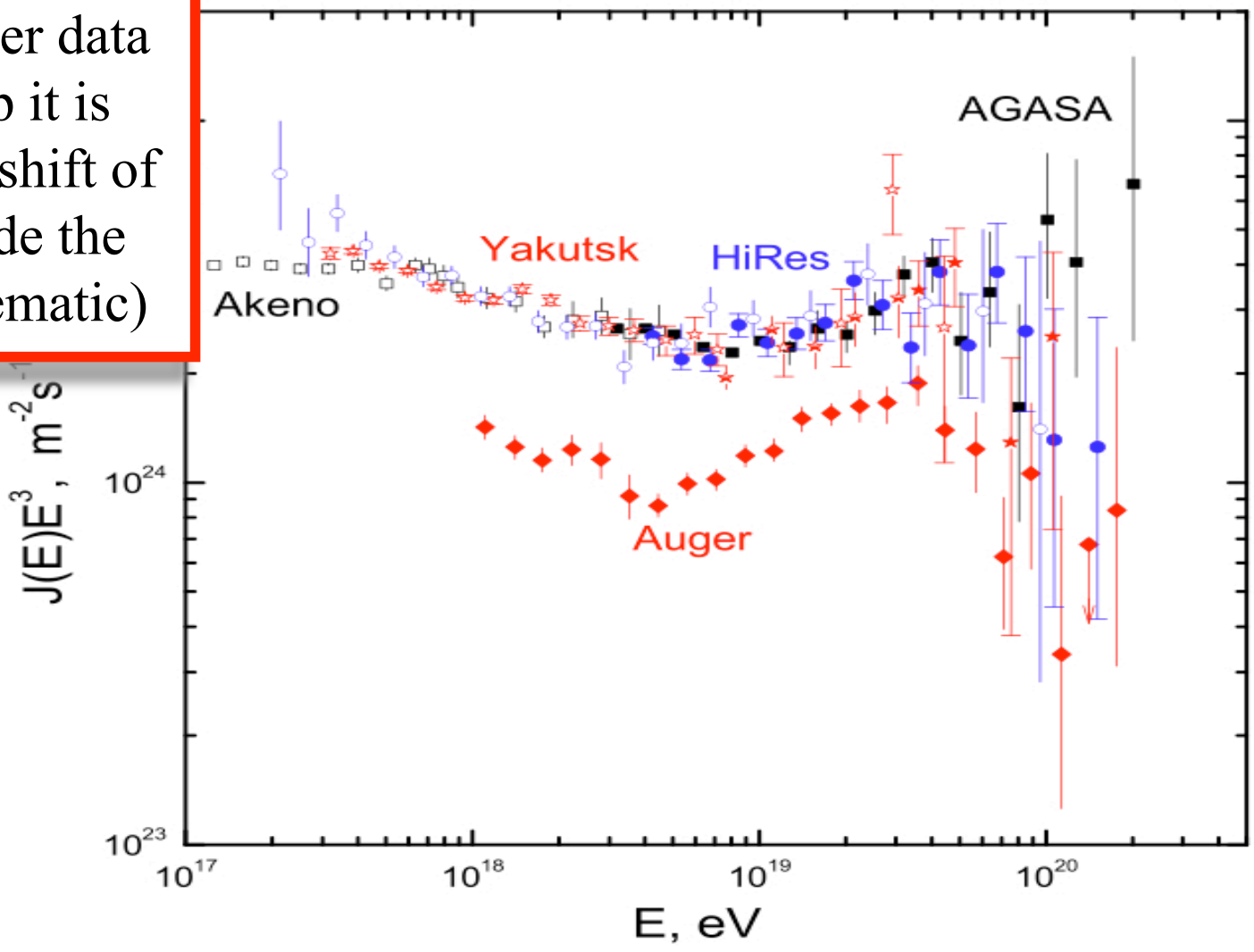
Calibrating the energy through the Dip gives an energy shift $E \rightarrow \lambda E$ (with λ fixed by minimum χ^2)

$$\lambda_{AGASA} = 0.90 \qquad \lambda_{HiRes} = 1.21 \qquad \lambda_{Yakutsk} = 0.75$$

NOTE: $\lambda<1$ for on-ground detectors and $\lambda>1$ for fluorescence light detectors

(these shifts are all inside the systematic errors of the experiments)

to calibrate the Auger data by the protons dip it is required an energy shift of about 50% (outside the experimental systematic)



the possibility of an energy calibration by the dip could represent an indication of a proton dominated spectrum

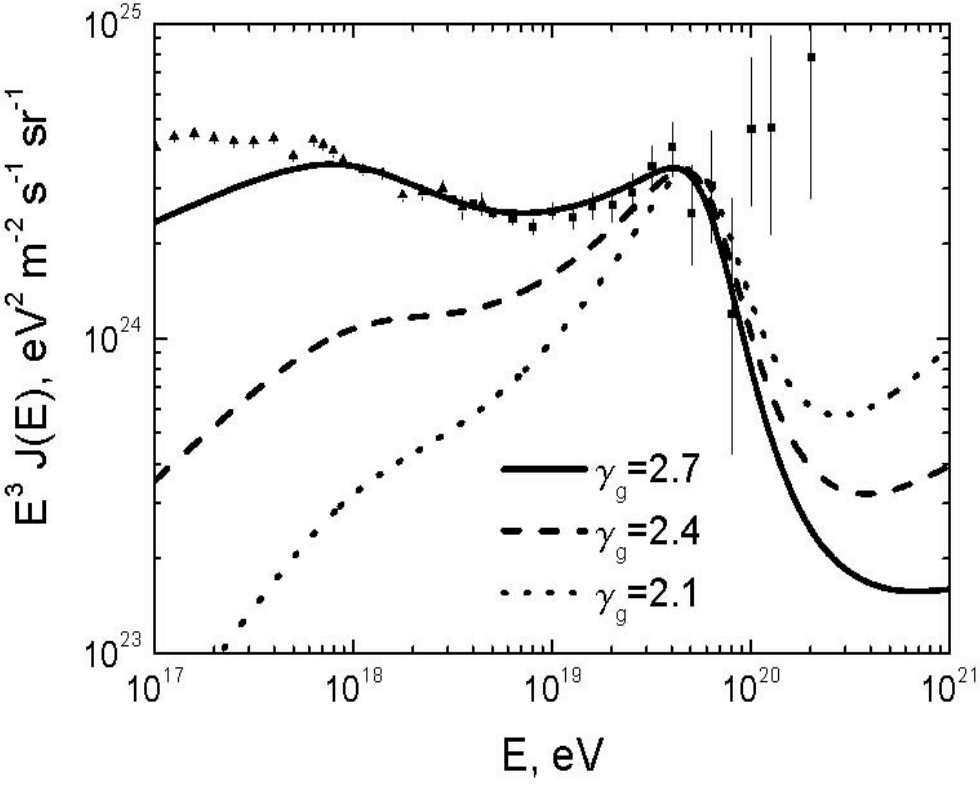
Caveats

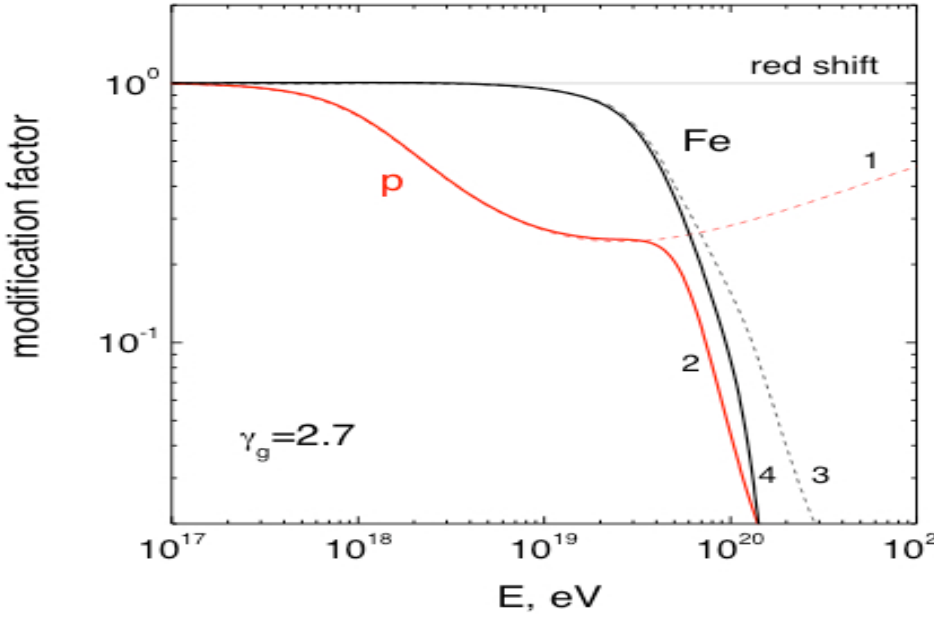
The interpretation of the observed spectrum in terms of protons pair-production losses FAILS if:

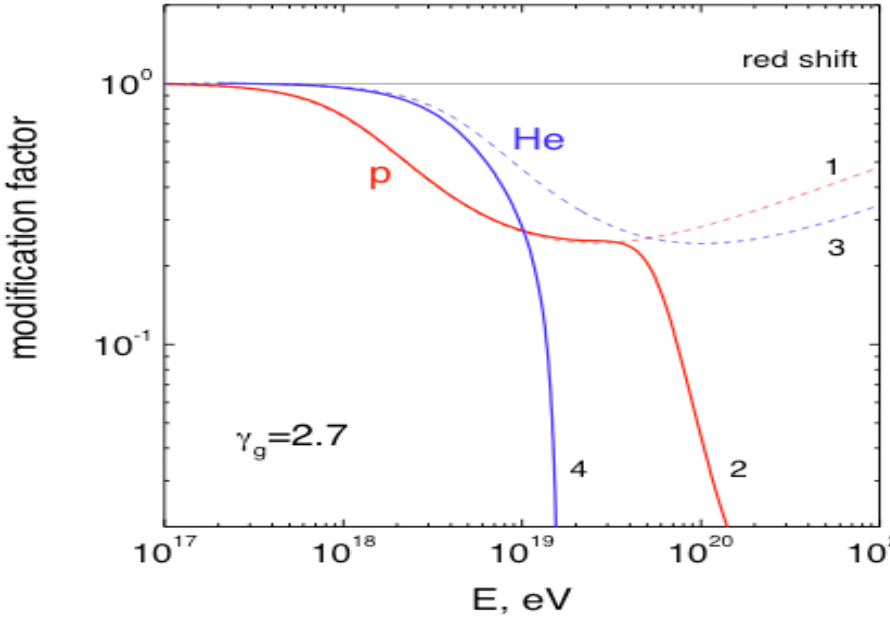
- ✓ the injection spectrum has $\gamma < 2.4$
- ✓ heavy nuclei fraction injected at $E>10^{18}$ eV larger than 15%

(primordial He has $n_{He}/n_H \approx 0.08$)

Berezinsky et al. (2004) Allard et al. (2005) RA et al. (2006)







RA, Berezinsky, Grigorieva (2008)

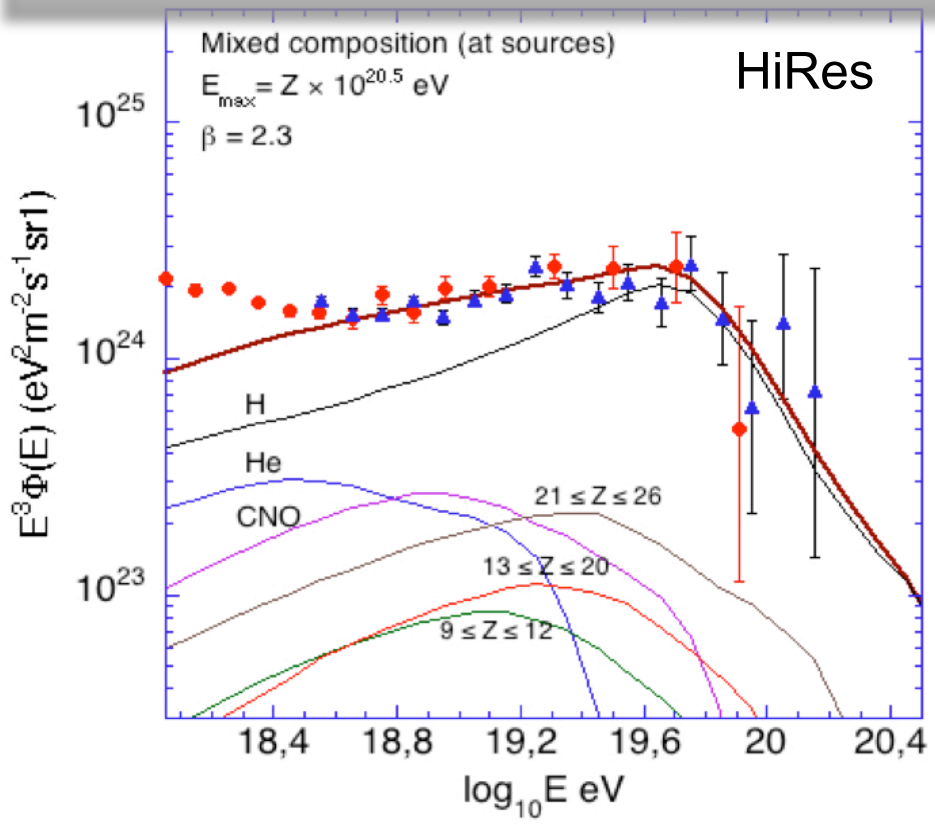
Mixed Composition Model

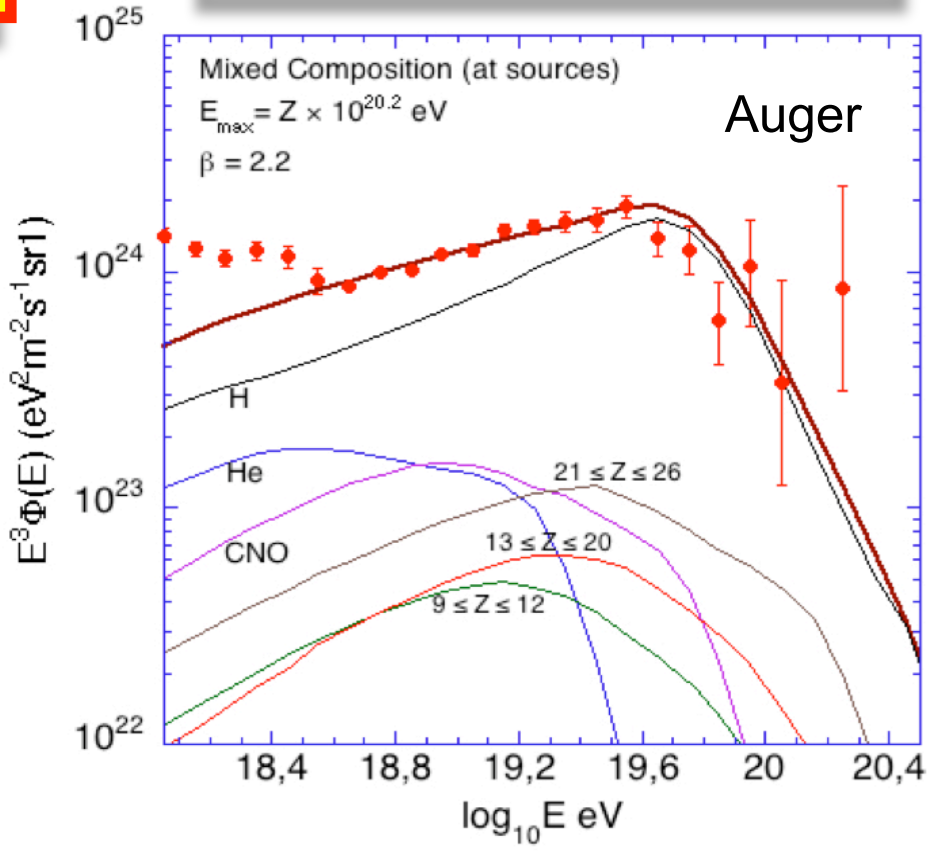
The mixed composition model is based on two assumptions

- ✓ injection spectrum $\gamma \approx 2.2 \div 2.3$
- ✓ Chemical composition as in the case of galactic CR (with an heavy nuclei fraction larger than 30%)

Allard, Parizot, Olinto (2005-2008)

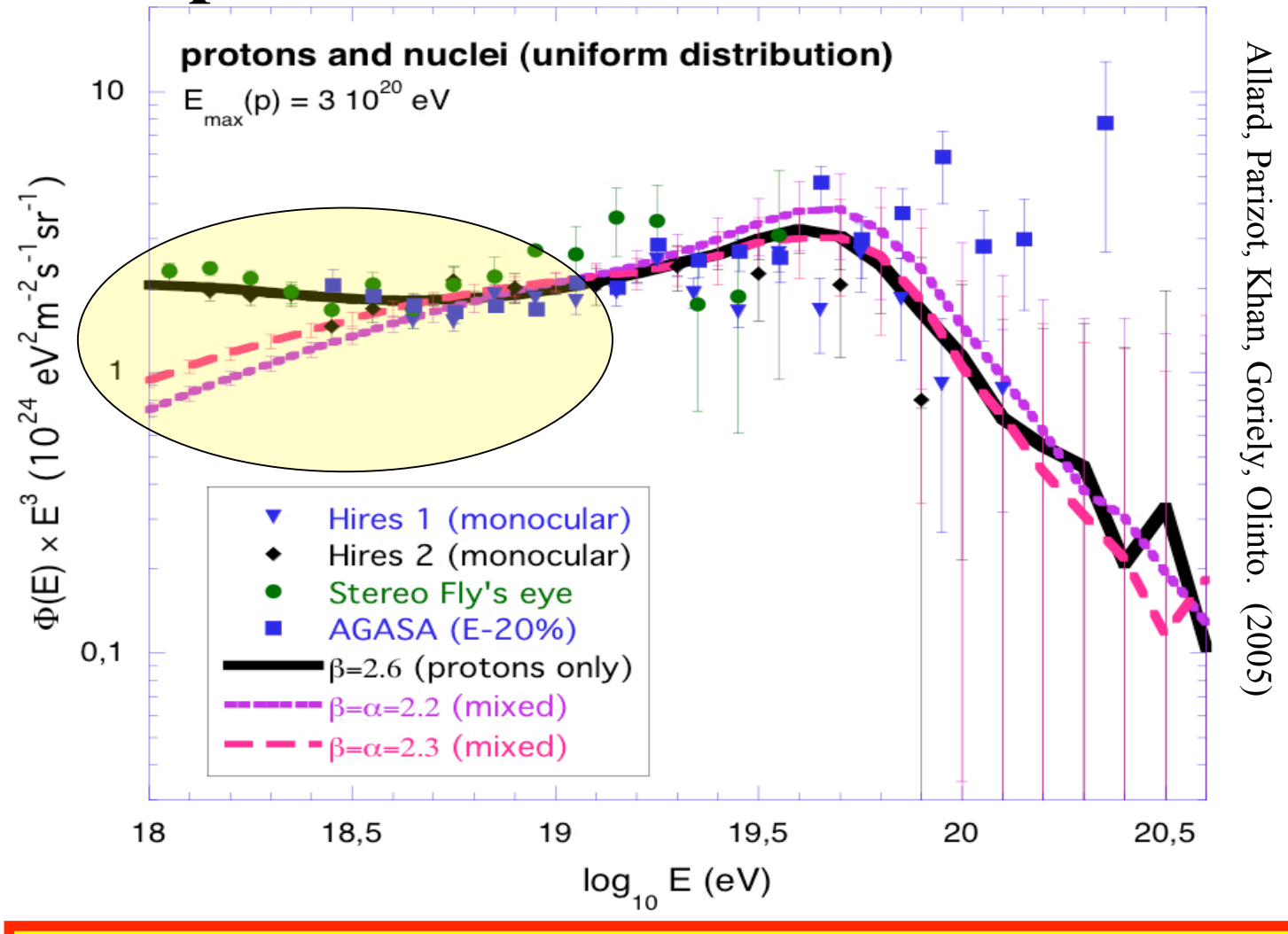
At the ankle energies a substantial fraction of extra-galactic UHE nuclei contributes to the flux. At the highest energies protons still dominate.





Allard, Parizot, Olinto (2005)

Mixed vs Dip

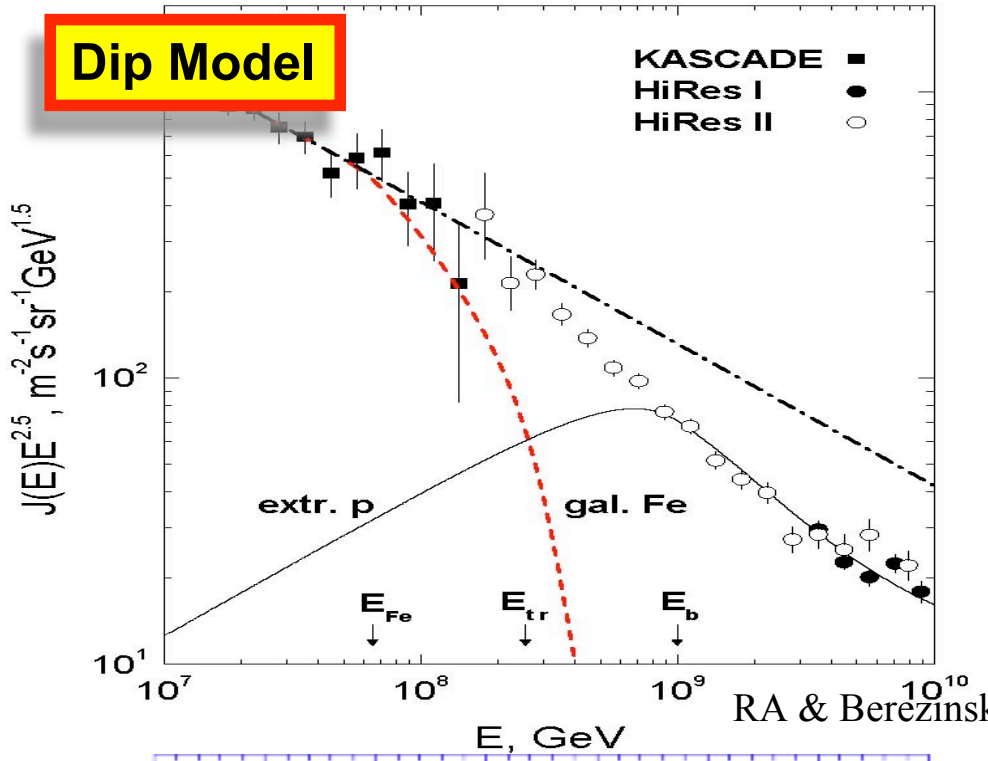


Basic differences among the two models

✓ Transition Galactic-Extragalactic Cosmic Rays

✓ Chemical composition in the energy range $10^{18} \div 10^{19}$ eV

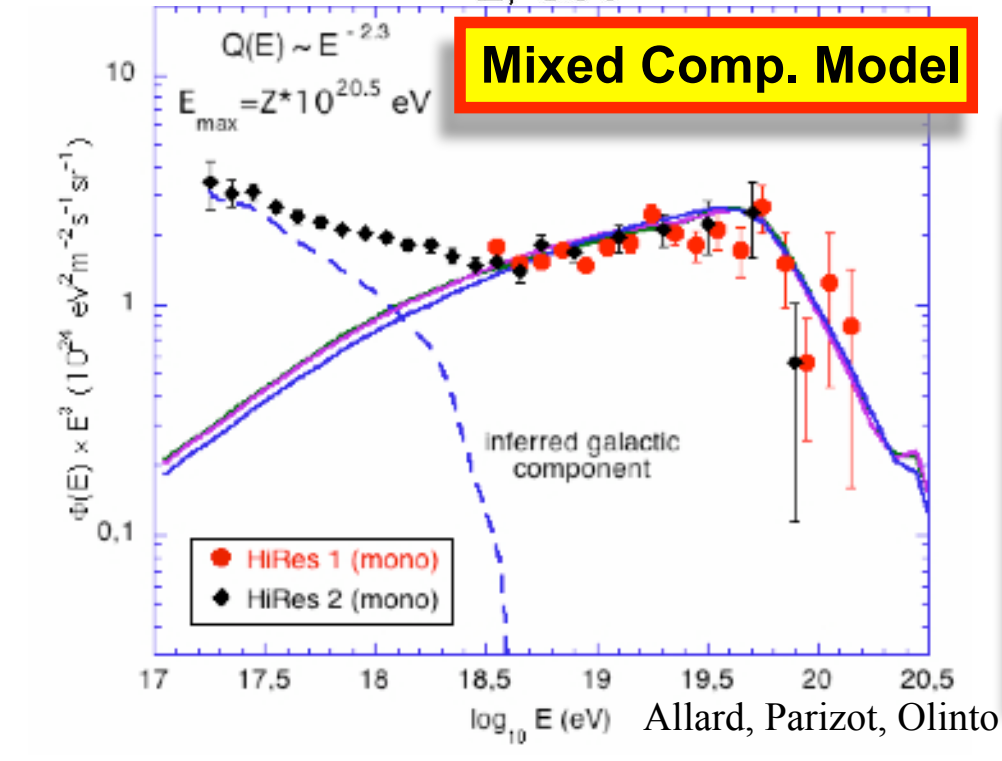
Dip Model



RA & Berezinsky (2004)

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

Mixed Comp. Model

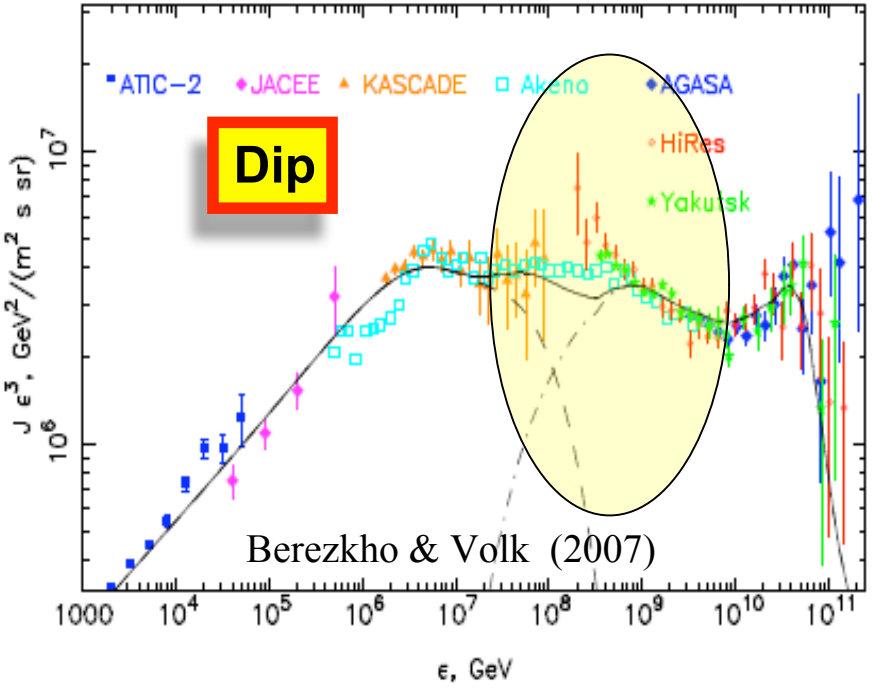


Allard, Parizot, Olinto (2005)

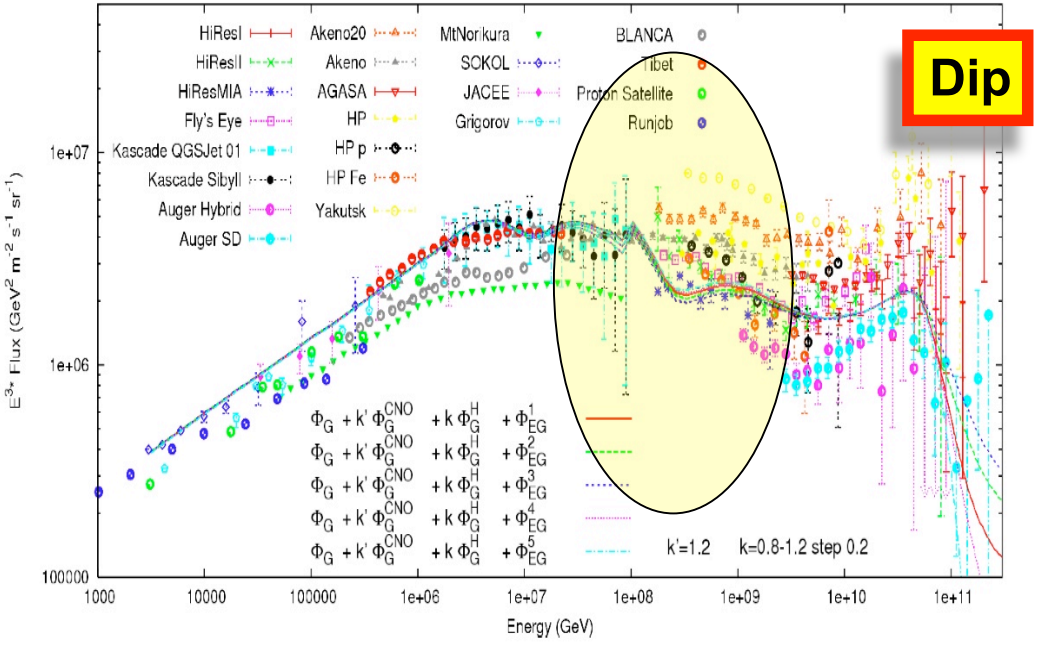
- The Galactic CR spectrum ends at energies larger than 10^{18} eV ($E_{tr} \approx 3 \times 10^{18}$ eV).
- Composition dominated by Galactic nuclei below E_{tr}, and Extra-Galactic nuclei above E_{tr} (difficult to detect).

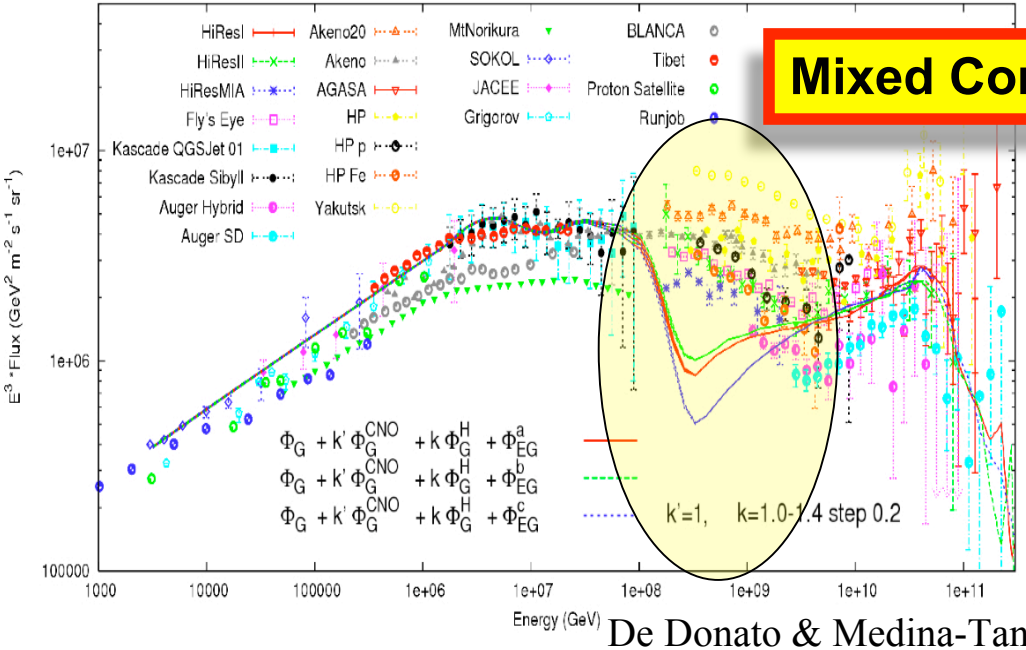
Mixed vs Dip: Spectrum

De Donato & Medina-Tanco (2007)



Berezkho & Volk (2007)





De Donato & Medina-Tanco (2007)

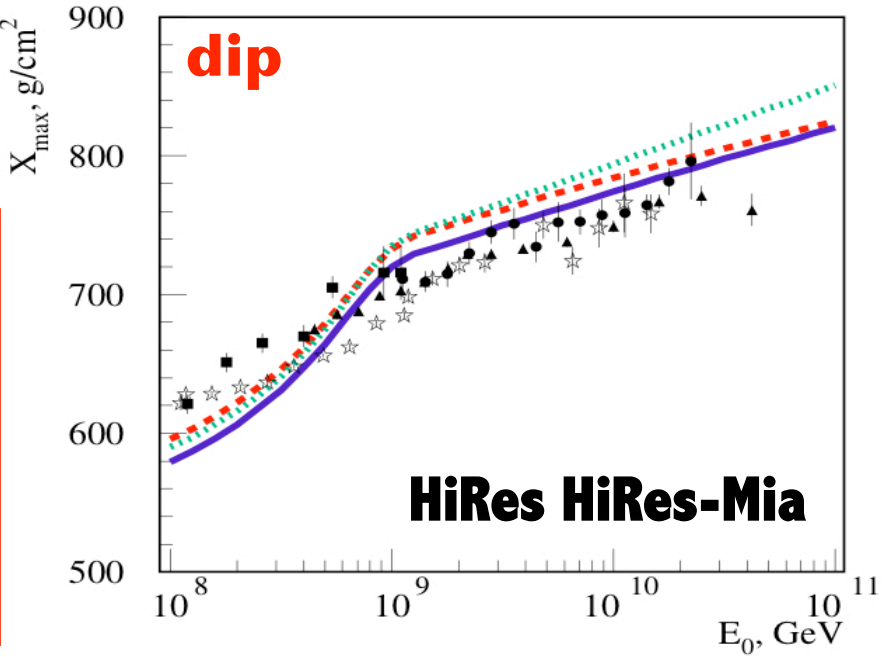
In the transition region, the Dip and Mixed Composition models show different features in the spectrum.

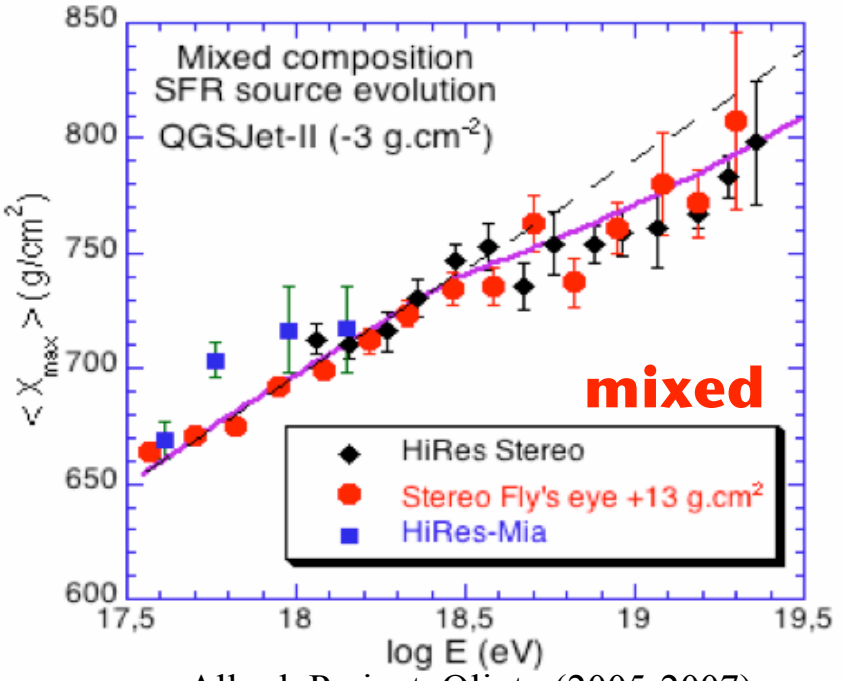
Mixed vs Dip: Chemical Composition

The fundamental observable that can be used to distinguish among Dip and Mixed Composition models is the UHECR chemical composition at the ankle energies.

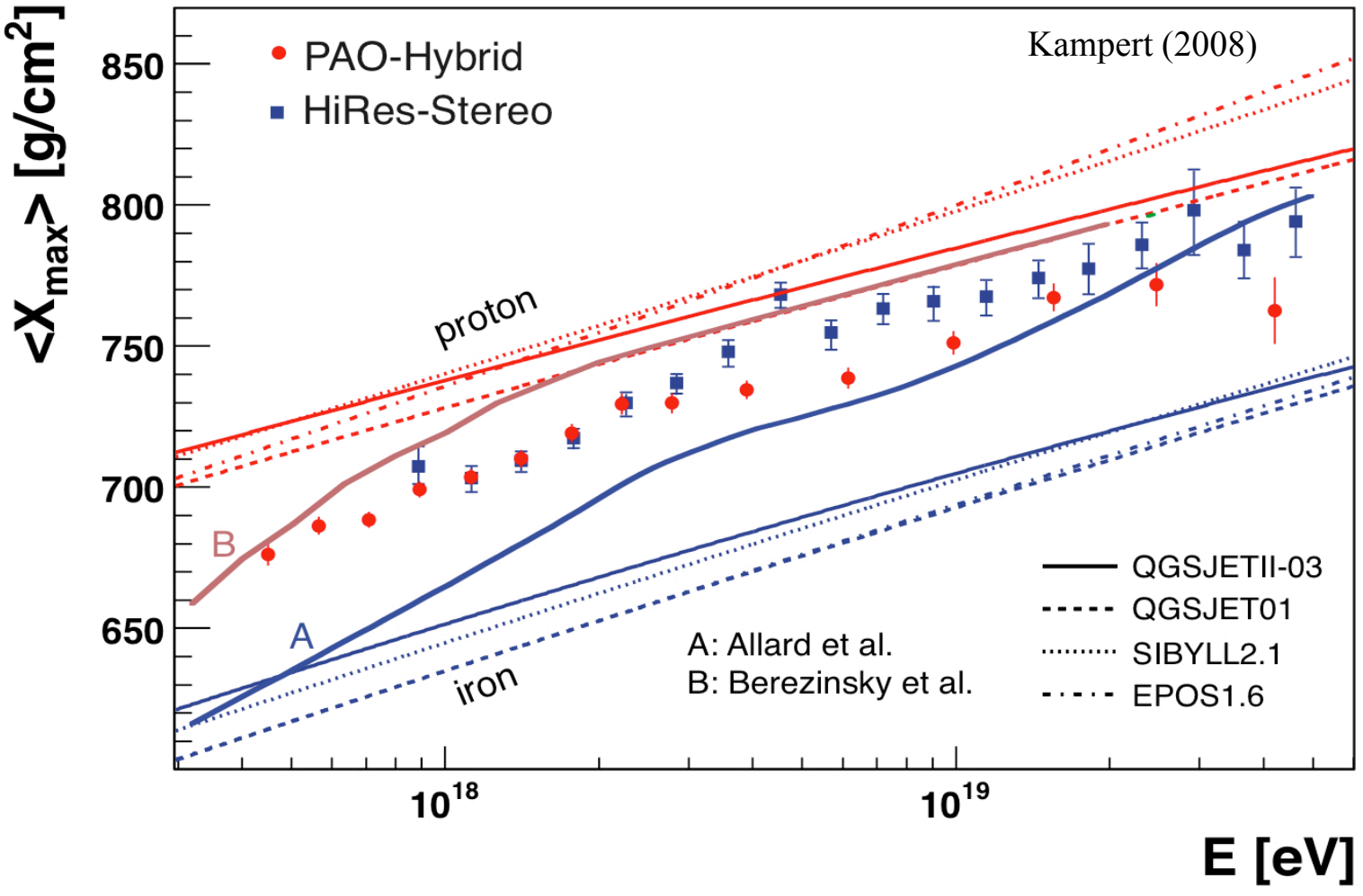
- Dip or mixed composition scenarios are not ruled out by the available observations of HiRes and HiRes-Mia

RA, Blasi, Berezinsky & Ostapchenko (2007)





Allard, Parizot, Olinto (2005-2007)



A mixed comp.

B dip

Auger observations on chemical composition are not conclusive in order to distinguish among mixed composition and dip models.

Conclusions I

UHECR observations can be accommodated in two alternative models with different implications on the sources and their characteristics.

Mixed Composition Model

- Flat injection $\gamma_g \leq 2.5$

- ✓ Protons dominate the spectrum only at the highest energies $E>10^{19}$ eV.
- ✓ An Extragalactic heavier component is needed at energies $E<10^{19}$ eV (mixed composition).
- ✓ The transition Galactic-Extragalactic is expected at energies $E>3x10^{18}$ eV.
- ✓ The model critically depends on the composition at the source (many parameters to fit the data).

Dip Model

- Steep injection $\gamma_g \geq 2.5$

- ✓ Elegant explanation of the observed spectrum in terms of the energy losses channels on the CMB radiation field.
- ✓ Enables the calibration of the energy observed by different experiments, reaching a very good agreement among different measurements.
- ✓ Transition Galactic-Extragalactic is expected at energy $E\sim10^{18}$ eV (second knee).

Observations

Conclusions II

- GZK cut off (HiRes & Auger) at energies $E_{GZK} \approx 5 \times 10^{19}$ eV
- Correlation with astrophysical sources (Auger) at $E \geq E_{GZK}$
- Proton dominated spectrum at energy $E > 10^{18}$ eV (HiRes)
- Nuclei dominated spectrum at energy $E > 10^{19}$ eV (Auger)

controversial observations on chemical composition and correlations

a firm experimental determination of the chemical composition of the observed UHE events is a key information in understanding the genesis of Ultra High Energy Cosmic Rays