Transition from Galactic to ExtraGalactic Cosmic Rays

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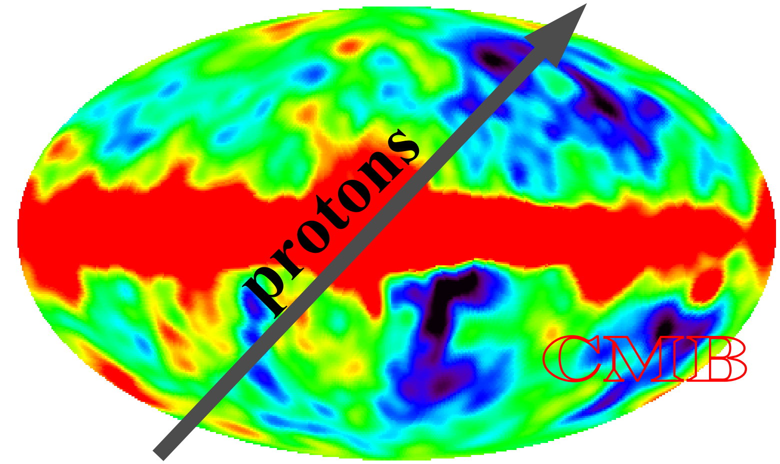
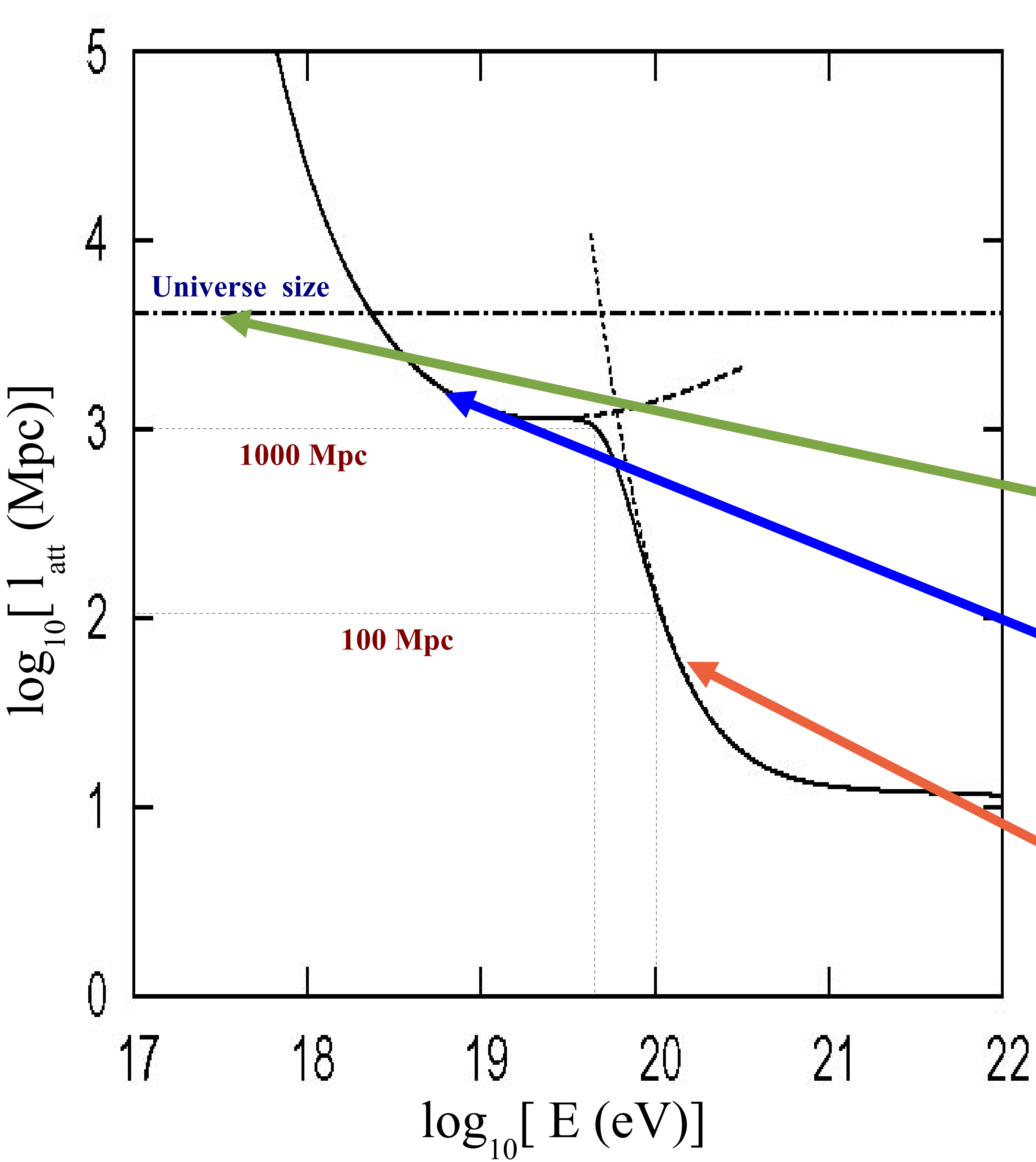
UHE Proton energy losses





Protons propagation in Intergalactic Space

Propagation of UHE protons in intergalactic space leaves its imprints on the spectrum in the form :

GZK $p + \gamma_{CMB} \rightarrow N + \pi$

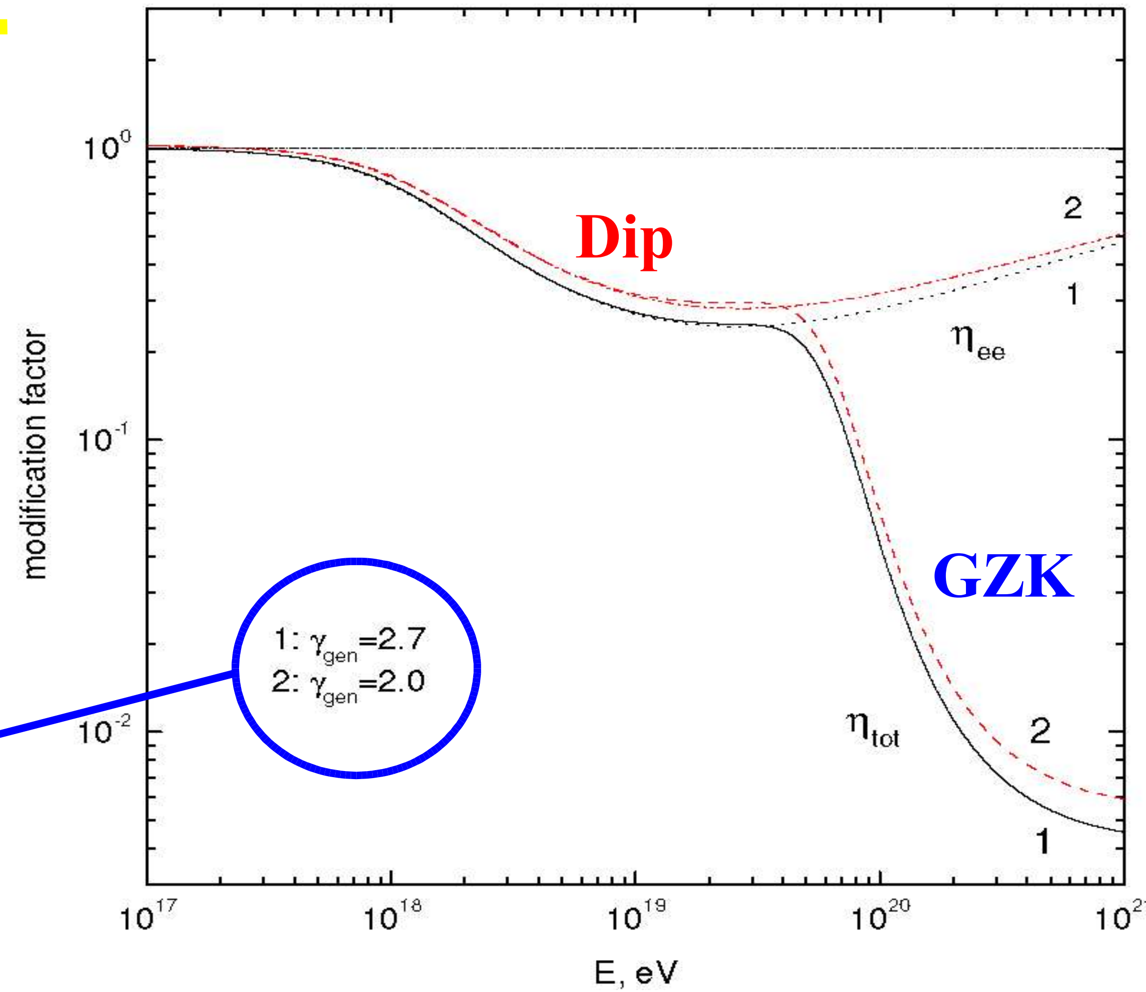
DIP $p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$

These signatures might depend on the distribution of sources and on the way of propagation.

GZK cutoff is model-dependent feature, which is modified by discreteness in the source distribution and their local overdensity/deficit.

Modification factor

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



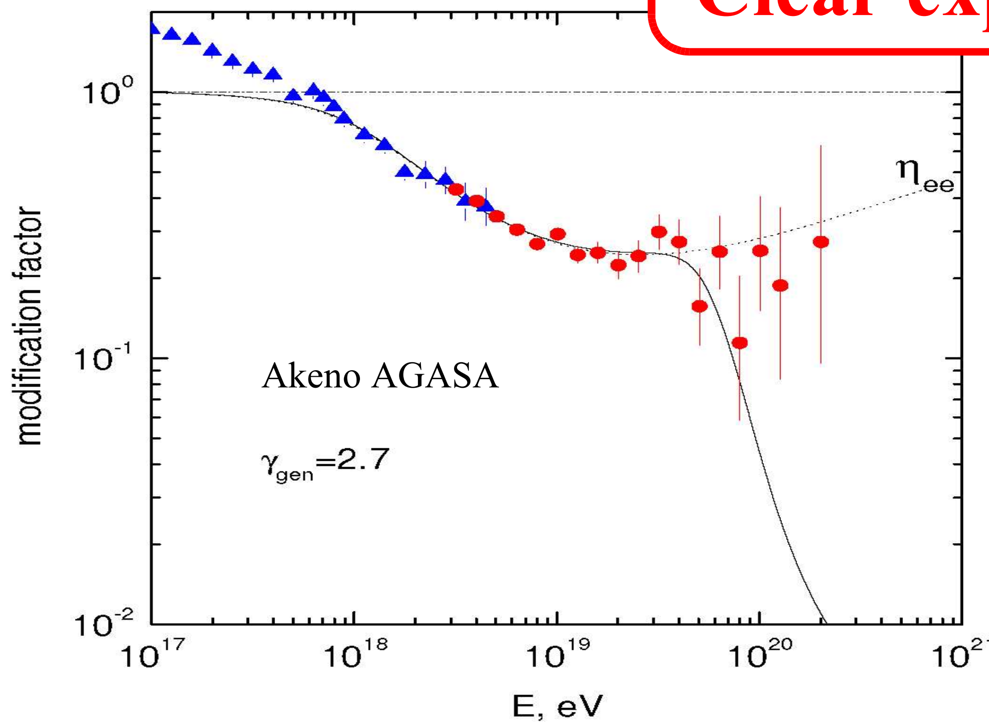
weak dependence on the injection spectrum

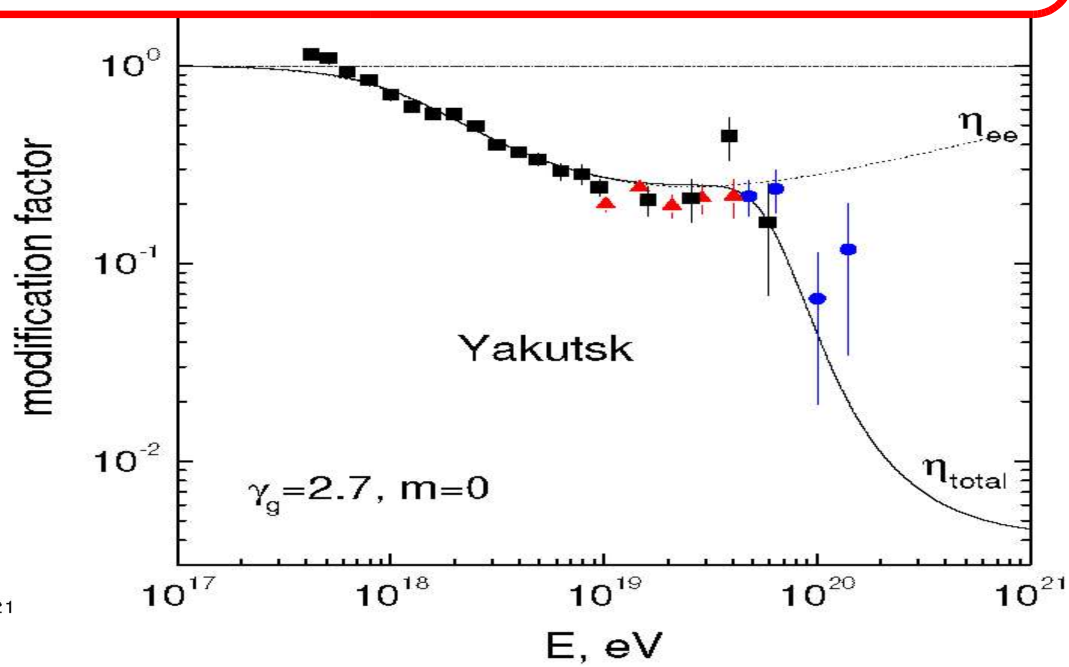
$J_p^{unm}(E)$ includes only adiabatic energy losses (redshift) ,

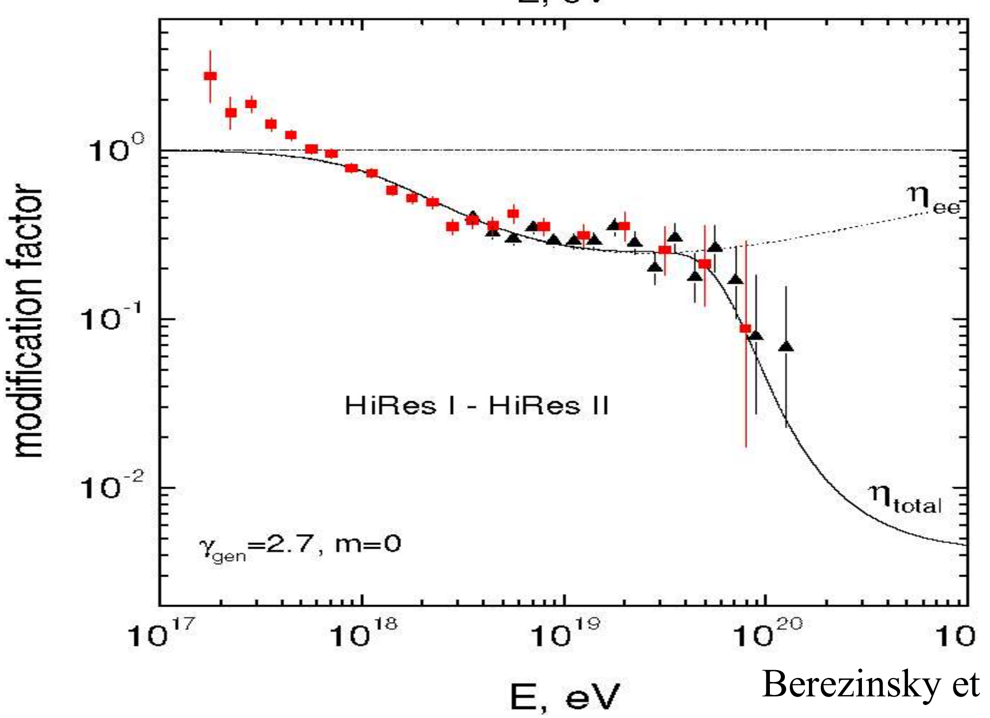
$J_p(E)$ includes total energy losses for $\eta_{tot}(E)$,
or adiabatic and pair - production for $\eta_{ee}(E)$.

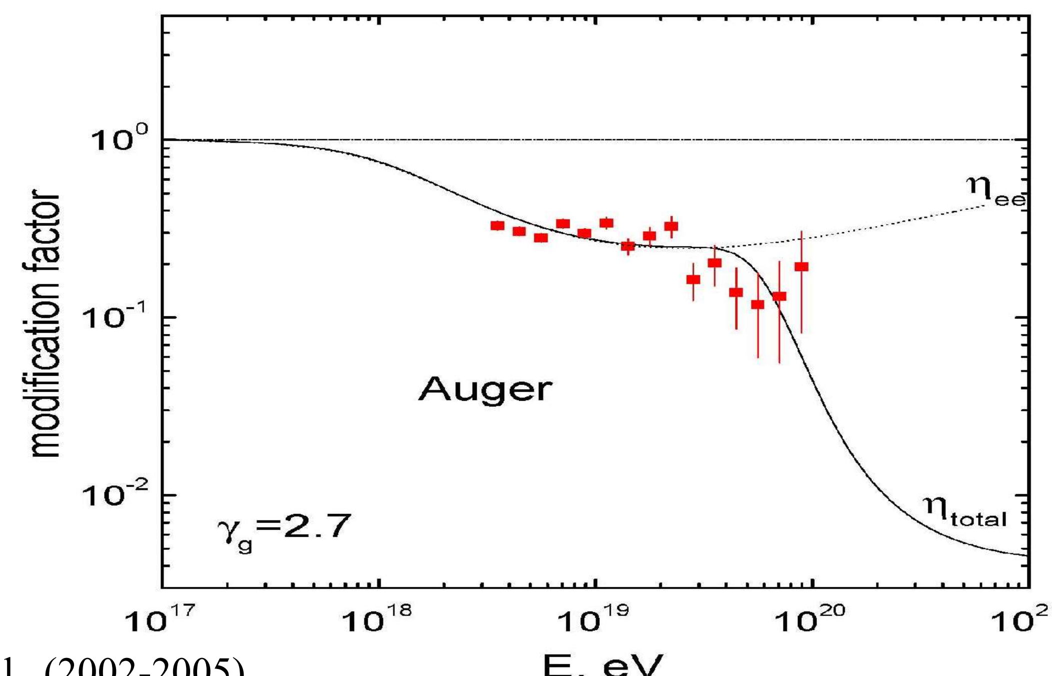
Proton Dip

Clear experimental evidence of the Dip









Berezinsky et al. (2002-2005)

Injection Spectrum

$$Q_{inj}(E) = \frac{L_p(\gamma_g - 2)}{E_{min}^2} \left(\frac{E}{E_{min}} \right)^{-\gamma_g}$$

Number of particles injected at the source per unit time and energy

model parameters

L_p source luminosity

$\gamma_g > 2$ injection power law

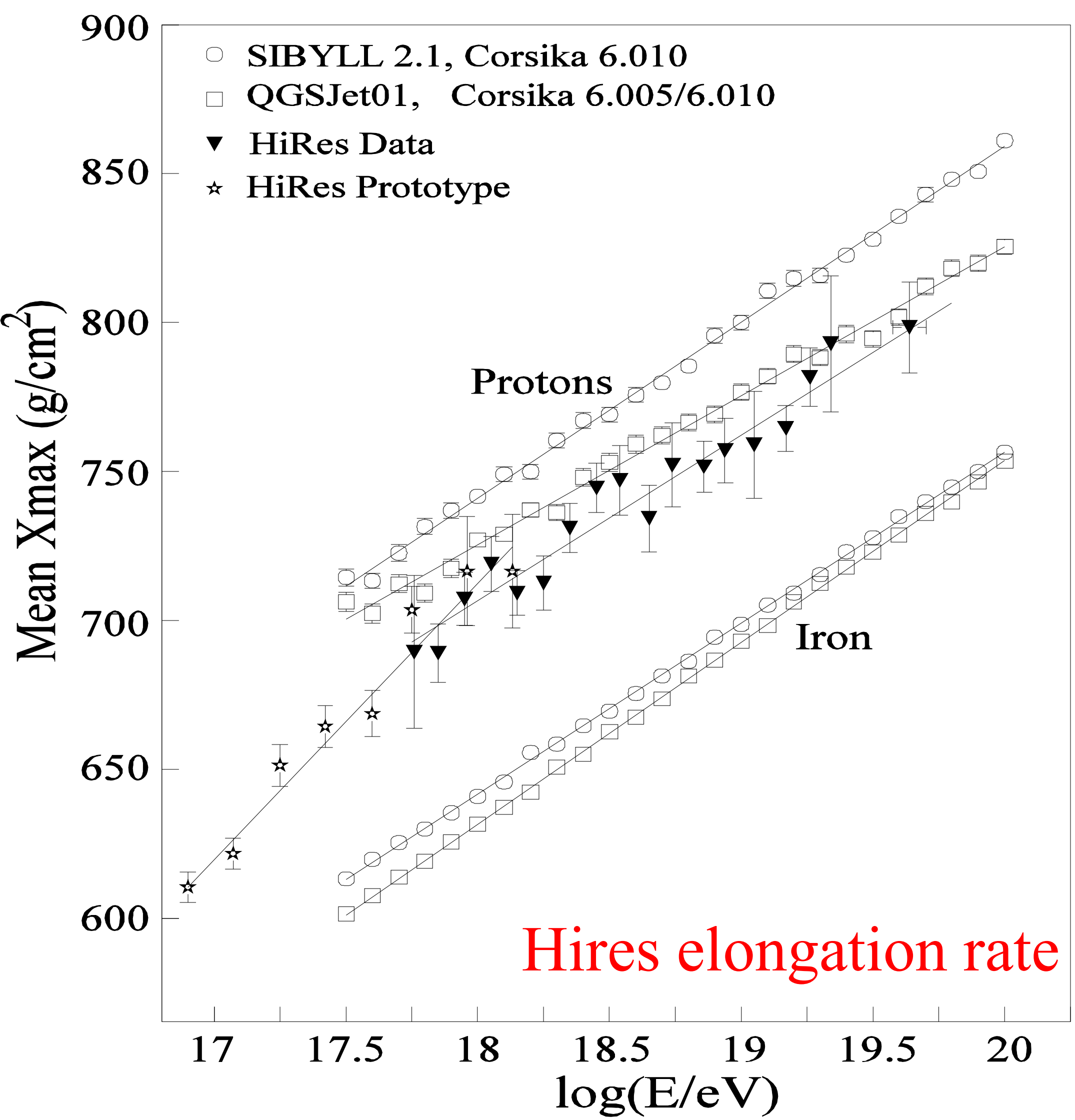
$E_{min} = m_p$ minimum energy

$\gamma_g = 2.7$ **is the only free parameter**

Observation of the Dip can be understood in terms of Extragalactic proton composition at $E > 10^{18}$ eV

Composition in Experimental Data

Hires, HiresMIA, Yakutsk : favor proton composition
Fly's Eye, Haverah Park, Akeno : mixed composition



Fly's Eye [Dawson et al. 98]

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% can be Iron above 10^{19} eV
No more than 50% can be photons above 4 10^{19} eV

Similar limits from AGASA

Proton composition at E>10^{18} eV **not disfavored** by experimental observations

Intergalactic Magnetic Fields

Very poor experimental evidences

Cosmological origin
Faraday rotation
→
Large Scale Structures are characterized by magnetic field produced from compression and twisting of the primordial field

Voids are characterized by an appreciable magnetic field

Astrophysical sources
Synchrotron and ICS emission
→
Magnetic field concentrated around sources, i.e. in Large Scale Structures

No appreciable field in most part of the universe volume

Effect of IMF on UHECR

→ **deflection** → **diffusion** → **isotropization**

favored scenario

Quasi-rectilinear propagation of protons at $E>4\times10^{19}$ eV

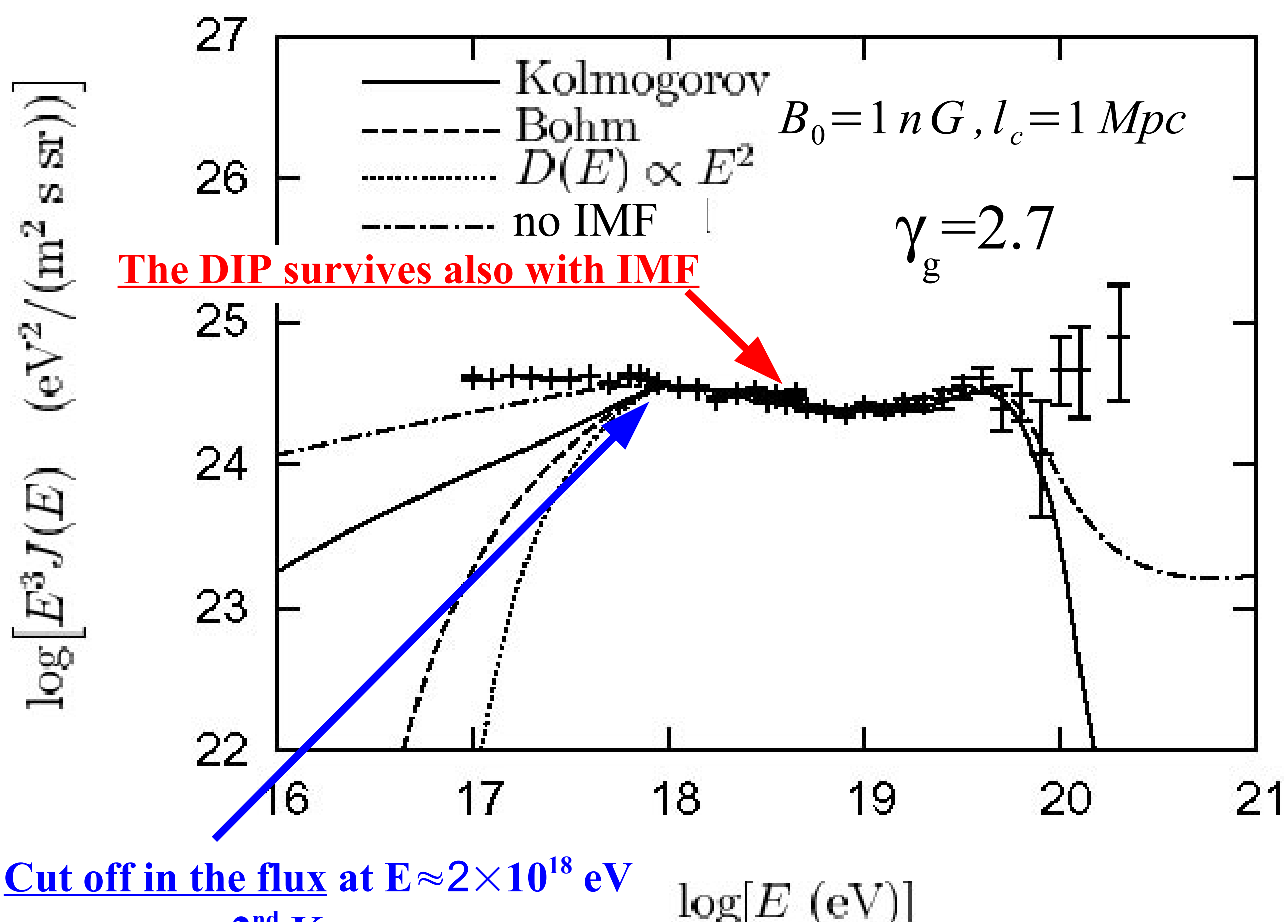
The IMF effect on the UHE proton spectrum

Maximal distance (magnetic horizon)

The diffusive flux presents an exponential suppression if the source is placed at

$$r > r_{max} = 2\sqrt{\lambda(E, E_{max})} \qquad \lambda(E, E_{max}) = \int_E^{E_{max}} d\epsilon \frac{D(\epsilon)}{b(\epsilon)} \qquad E_{max} = min[E_g(E, L_{uni}), E_{max}^{acc}]$$

At low energy ($E \leqslant 10^{18}$ eV) the maximal distance of the contributing sources r_{max} is suppressed by the E_{max} behavior (fixed only by energy losses).



Cut off in the flux at $E \approx 2 \times 10^{18}$ eV
2^{nd} Knee

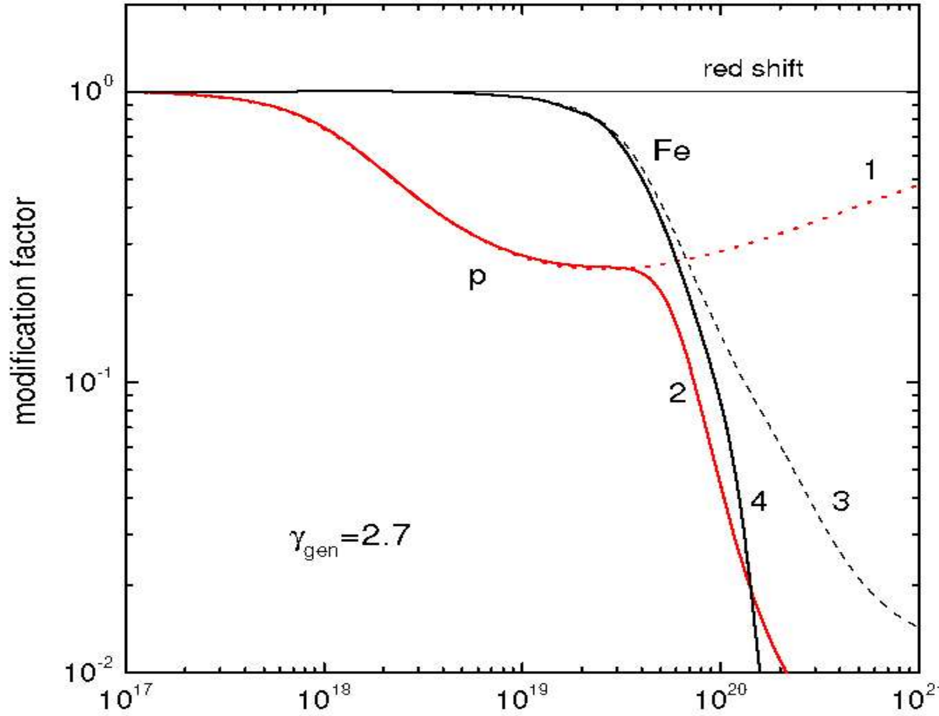
- **The suppression in the maximal contributing distance produces a low energy cut-off in the spectrum.**
- **The position of the cut-off is independent of the IMF, it depends only on the proton energy losses and coincides with the observed 2^{nd} Knee.**
- **The low energy behavior depends on the diffusive regime.**

RA & Berezinsky (2005)
Lemoine (2005)

Robustness and Caveats

Protons in the Dip come from large distances: up to 10^3 Mpc. The Dip does not depend on:

- **local source overdensity/deficit**
- **inhomogeneities**
- **maximum energy at the source**
- **discreteness of the source distribution**
- **intergalactic magnetic fields**



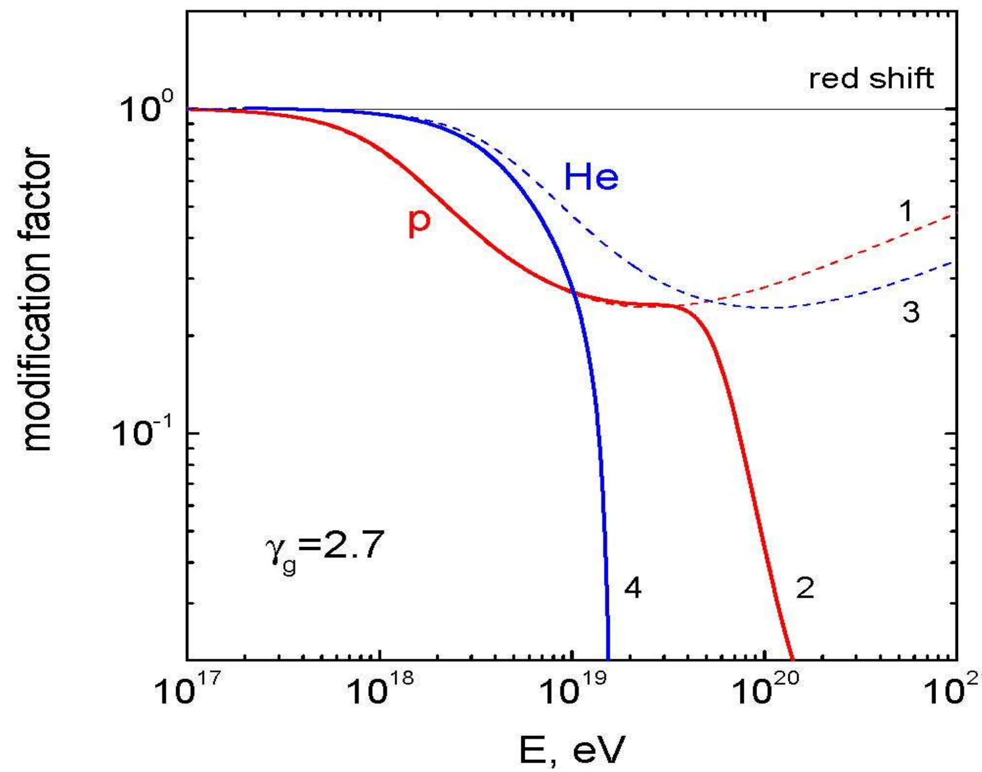
RA et al. (2006)

the interpretation of the DIP in terms of protons pair-production FAILS if:

heavy nuclei fraction 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)

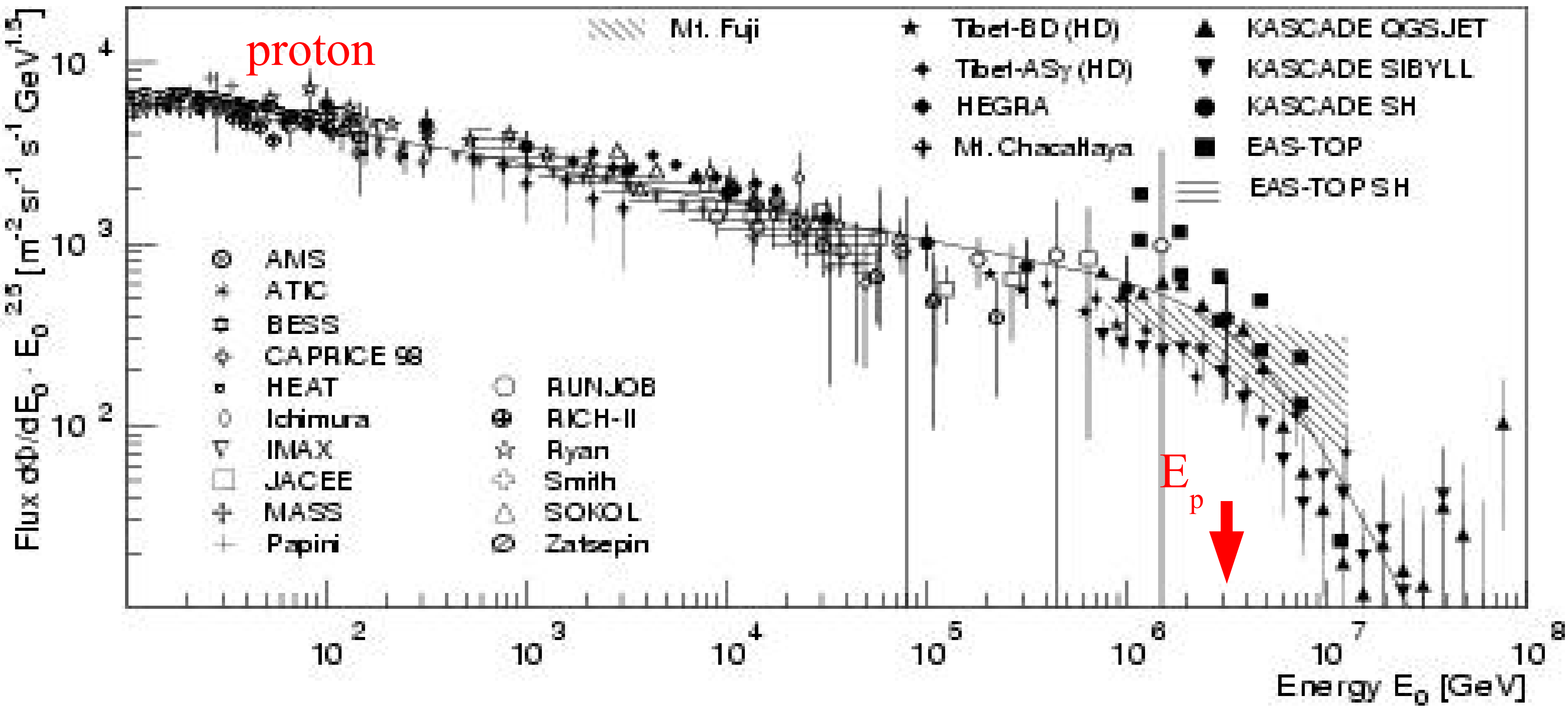
the injection spectrum has $\gamma_g < 2.4$

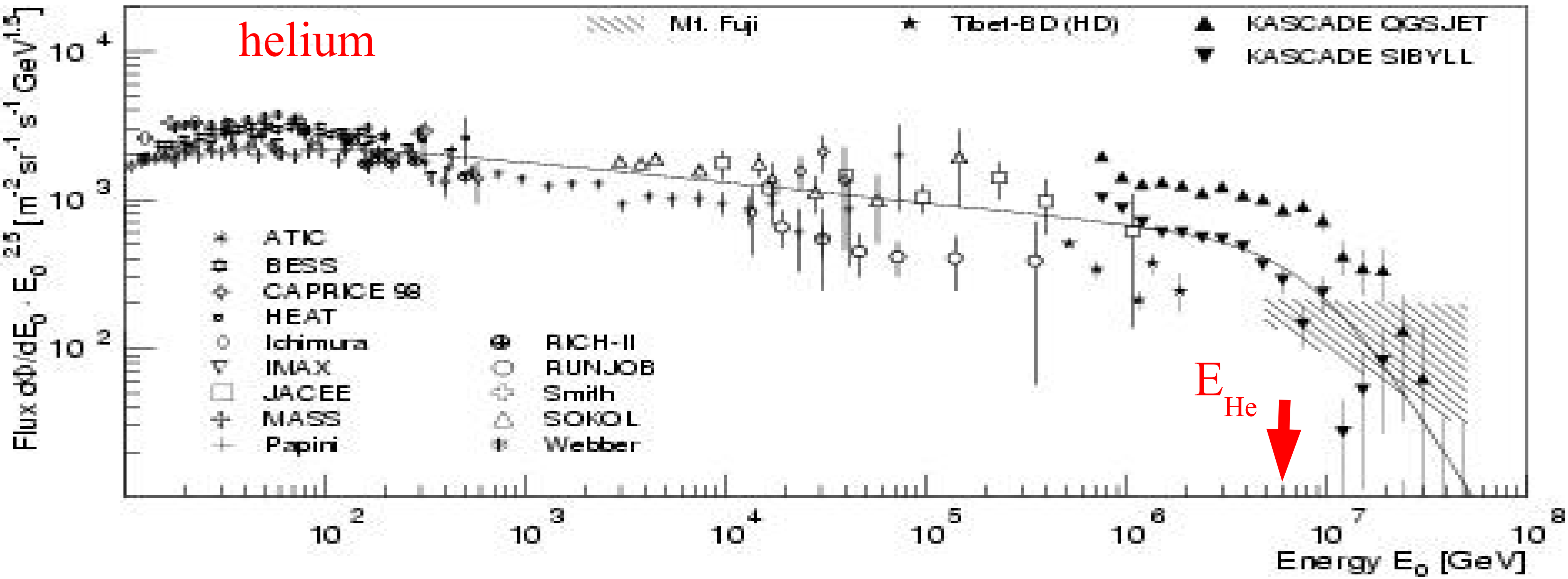


Galactic Component - Trans Knee particles

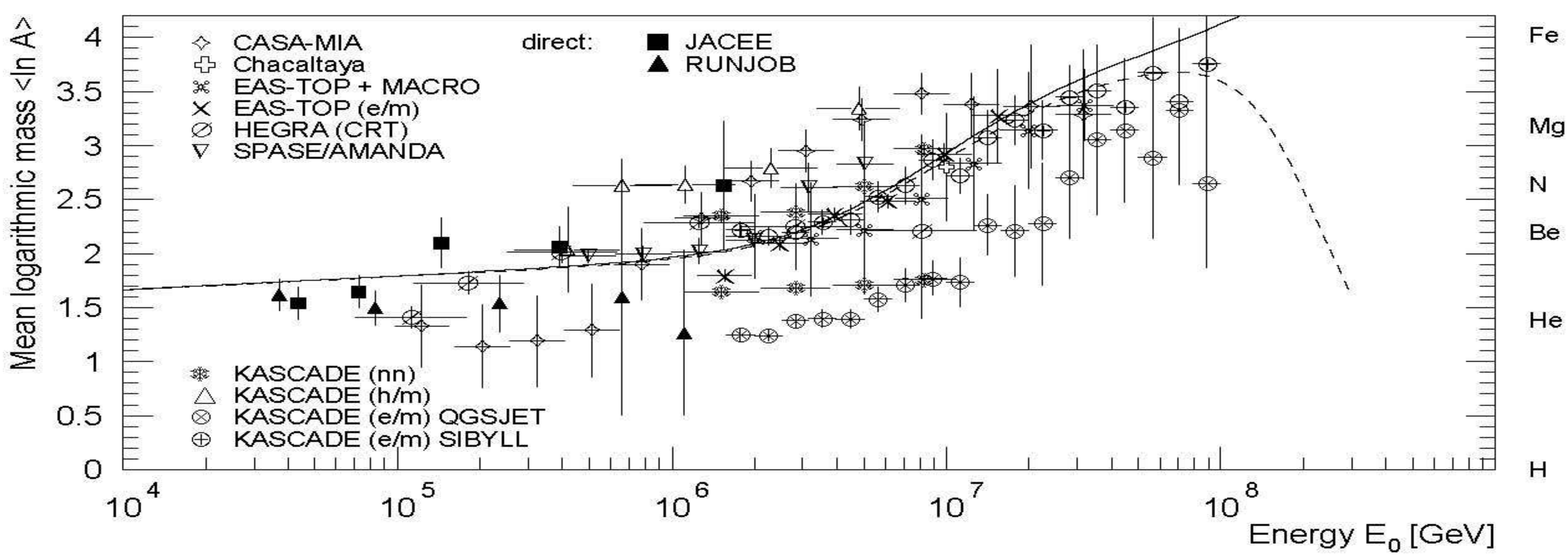
- Rigidity models can be rigidity-confinement models or rigidity-acceleration models.

- The energy of spectrum bending (knee) for nuclei Z is $E_z = Z\,E_p$, where $E_p \approx 3\times10^{15}$ eV is the proton knee. For Iron $E_{Fe} \approx 8\times10^{16}$ eV.



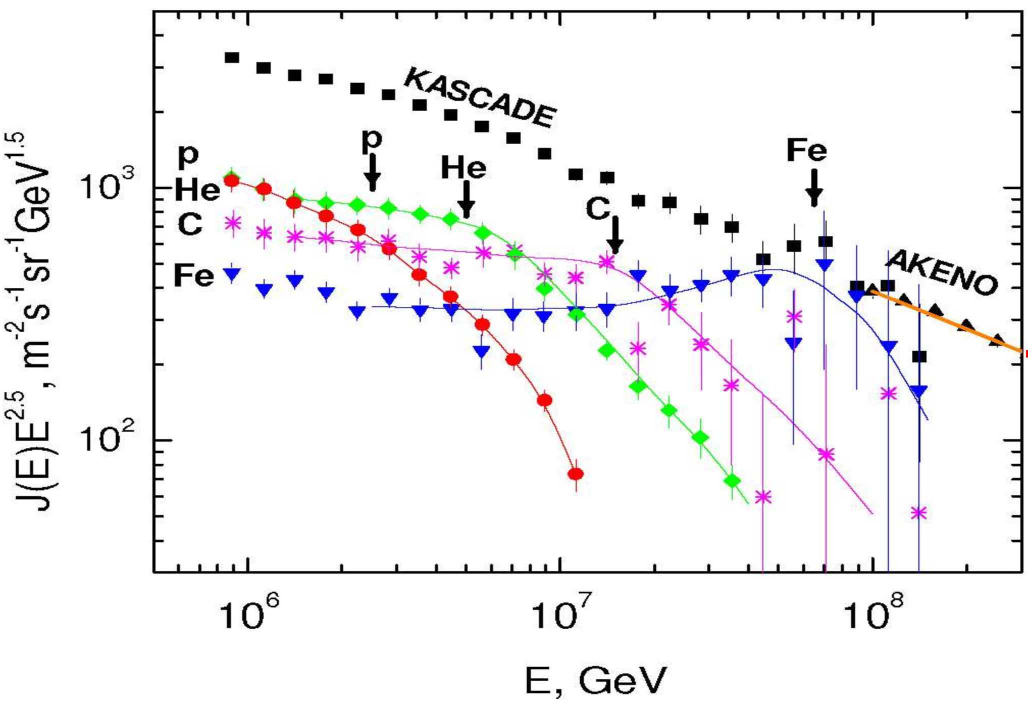


helium
Mt. Fuji
Tibet-BD (HD)
KASCADE QGSJET
KASCADE SIBYLL
ATIC
BESS
CAPRICE 98
HEAT
Ichimura
IMAX
JACEE
MASS
Papini
RICH-II
RUNJOB
Smith
SOKOL
Webber
E_{He}
Flux $d\Phi/dE_0 \cdot E_0^{2.5}$ [$m^{-2} sr^{-1} s^{-1} GeV^{1.5}$]
Energy E_0 [GeV]



CASA-MIA
Chacaltaya
EAS-TOP + MACRO
EAS-TOP (e/m)
HEGRA (CRT)
SPASE/AMANDA
direct:
JACEE
RUNJOB
KASCADE (nn)
KASCADE (h/m)
KASCADE (e/m) QGSJET
KASCADE (e/m) SIBYLL
Mean logarithmic mass <ln A>
Energy E_0 [GeV]
Fe
Mg
N
Be
He
H

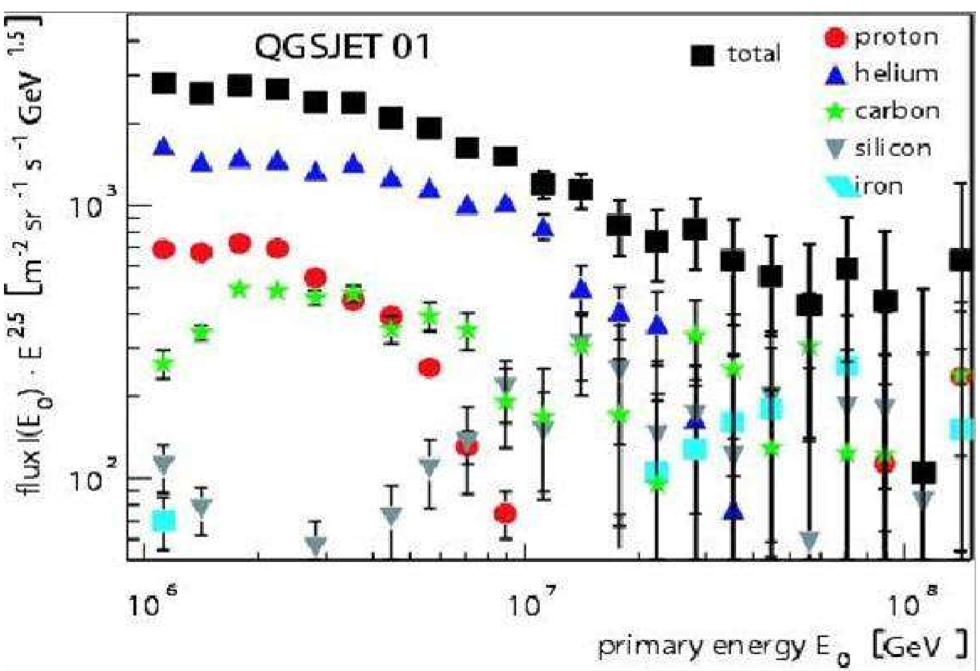
Kascade data

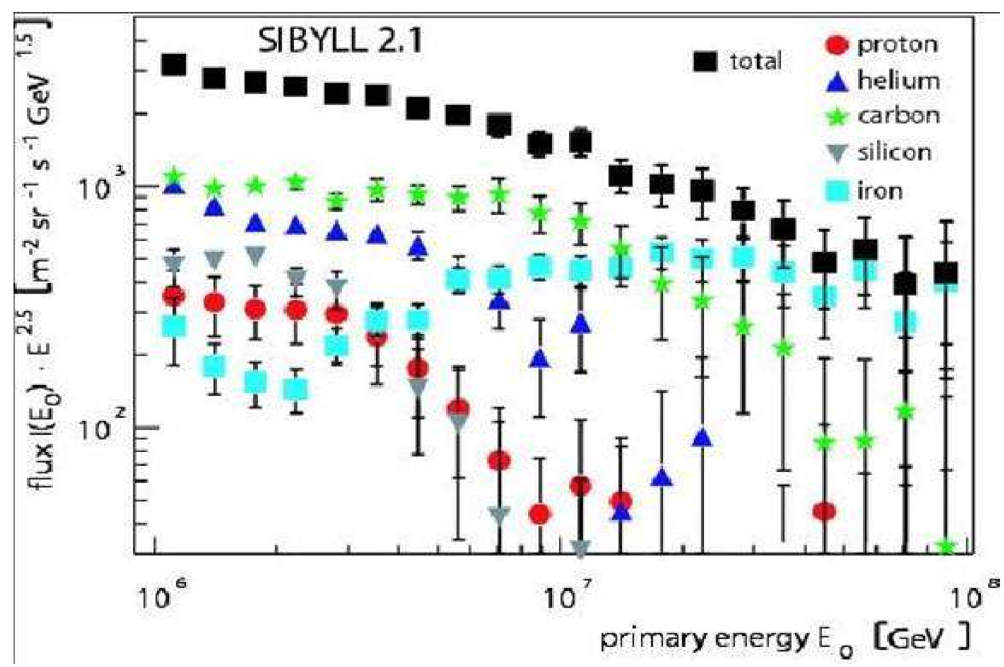


Kascade data 2003:
seem to confirm the rigidity model.

BUT

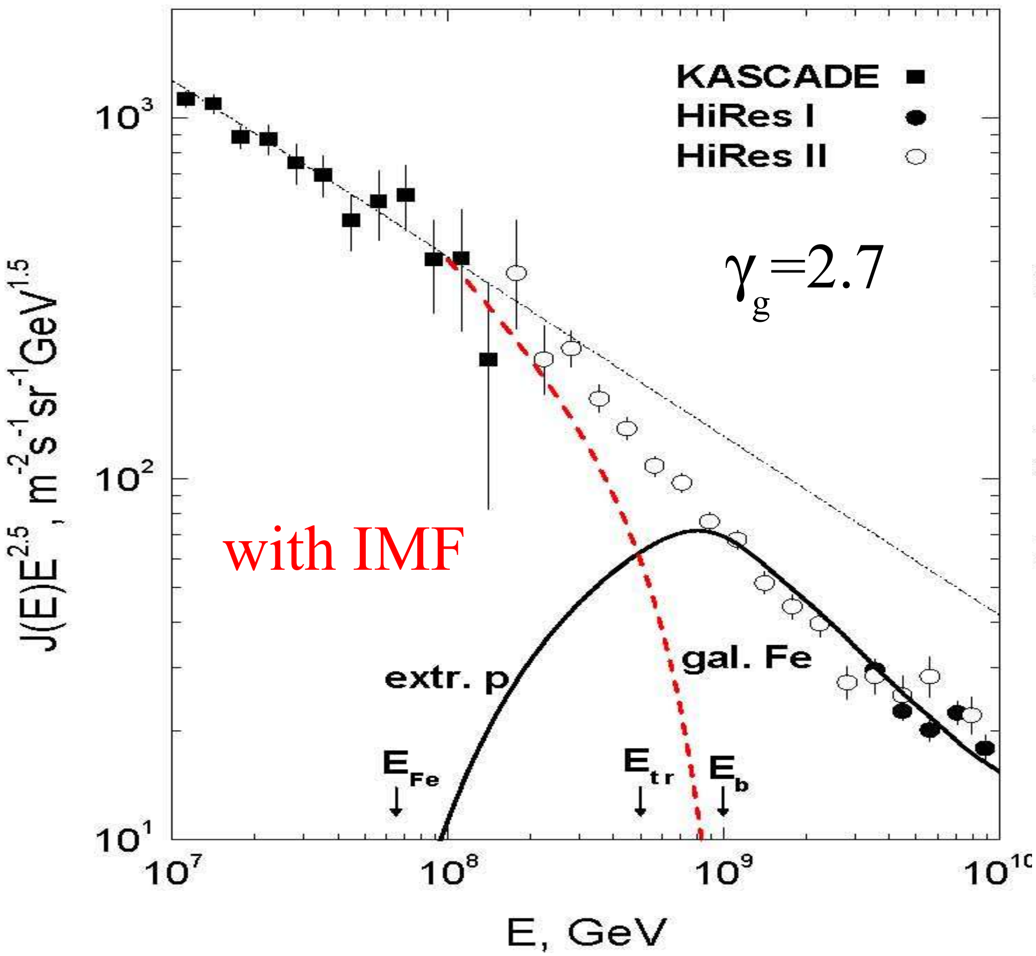
Kascade data 2005:
different results with different Monte Carlo approaches in data reconstruction.
Rigidity scenario not confirmed.

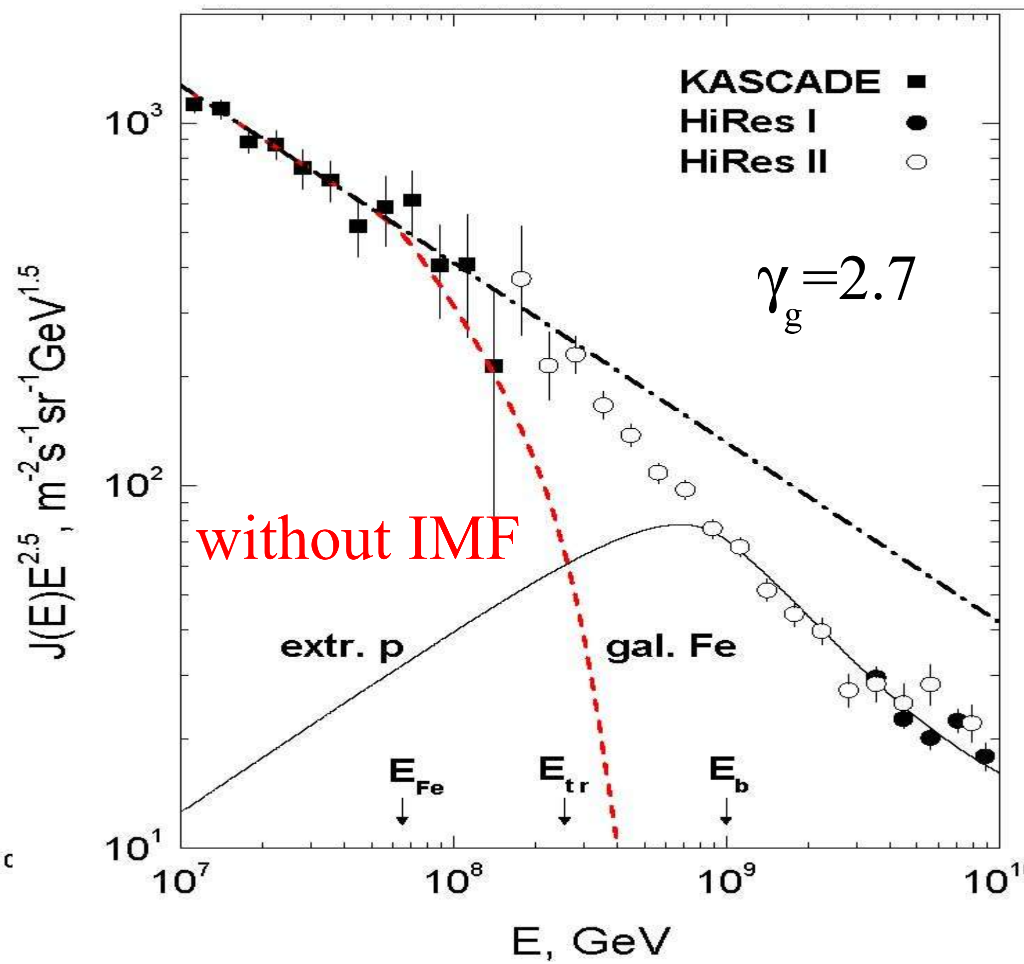




Galactic and ExtraGalactic CR

- The Galactic CR spectrum ends in the energy range 10^{17} eV, 10^{18} eV.
- 2^{nd} Knee appears naturally in the extragalactic proton spectrum as the steepening energy corresponding to the transition from adiabatic energy losses to pair production energy losses. This energy is universal for all propagation modes (rectilinear or diffusive): $E_{2K} \approx 10^{18}$ eV.





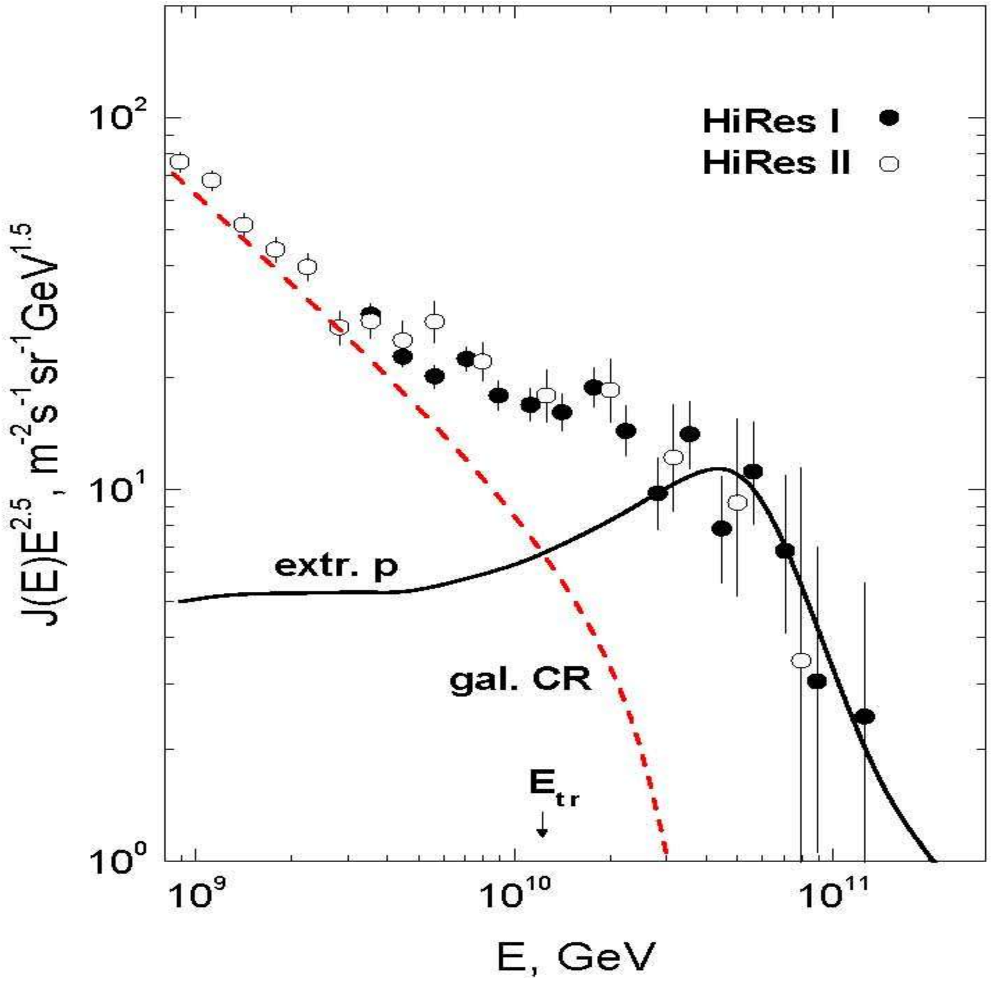
RA & Berezinsky (2005)

Traditional Approach

- Traditionally (since 70s) the transition Galactic-ExtraGalactic CR was placed at the ankle ($\approx 10^{19}$ eV).
- In this context ExtraGalactic protons start to dominate the spectrum only at the ankle energy with a more conservative injection spectrum $\gamma_g \approx 2$.

Problems for the Galactic component:

- Galactic acceleration:
  Maximum acceleration energy required is very high $E_{max} \approx 10^{19}$eV
- Composition:
  How the gap between Iron knee $E_{Fe} \approx 10^{17}$eV and ankle is filled



Conclusions

1. Experimentally confirmed Dip can be understood as a signature of the interaction of extragalactic protons with CMB. It can be considered as independent evidence of proton composition in the energy range $1\times10^{18} \le E \le 4\times10^{19}$ eV.

2. Dip gives a natural explanation of the second knee: below the low-energy end of the Dip ($E_c \approx 1\times10^{18}$ eV) extragalactic proton spectrum becomes flatter than the measured one, providing the transition from galactic to extragalactic cosmic rays. This mechanism works for both rectilinear and diffusive propagation under the assumption of an unbroken power-law generation spectrum (with γ_g>2.4).

3. Transition energy $E_c \approx 1\times10^{18}$ eV is a universal value, independent of the propagation mode, including different diffusion regimes.

4. Experimentally a transition to a proton dominated flux at 10^{18} eV seems confirmed by Hires Hires-MIA and Yakutsk it does not contradict Haverah Park and it contradicts Akeno and Fly's Eye data.

5. Transition at the ankle remains a possible alternative.

Firm experimental results on the chemical composition in the energy range 10^{17} eV ÷ 10^{19} eV are needed in order to confirm or falsify the model.