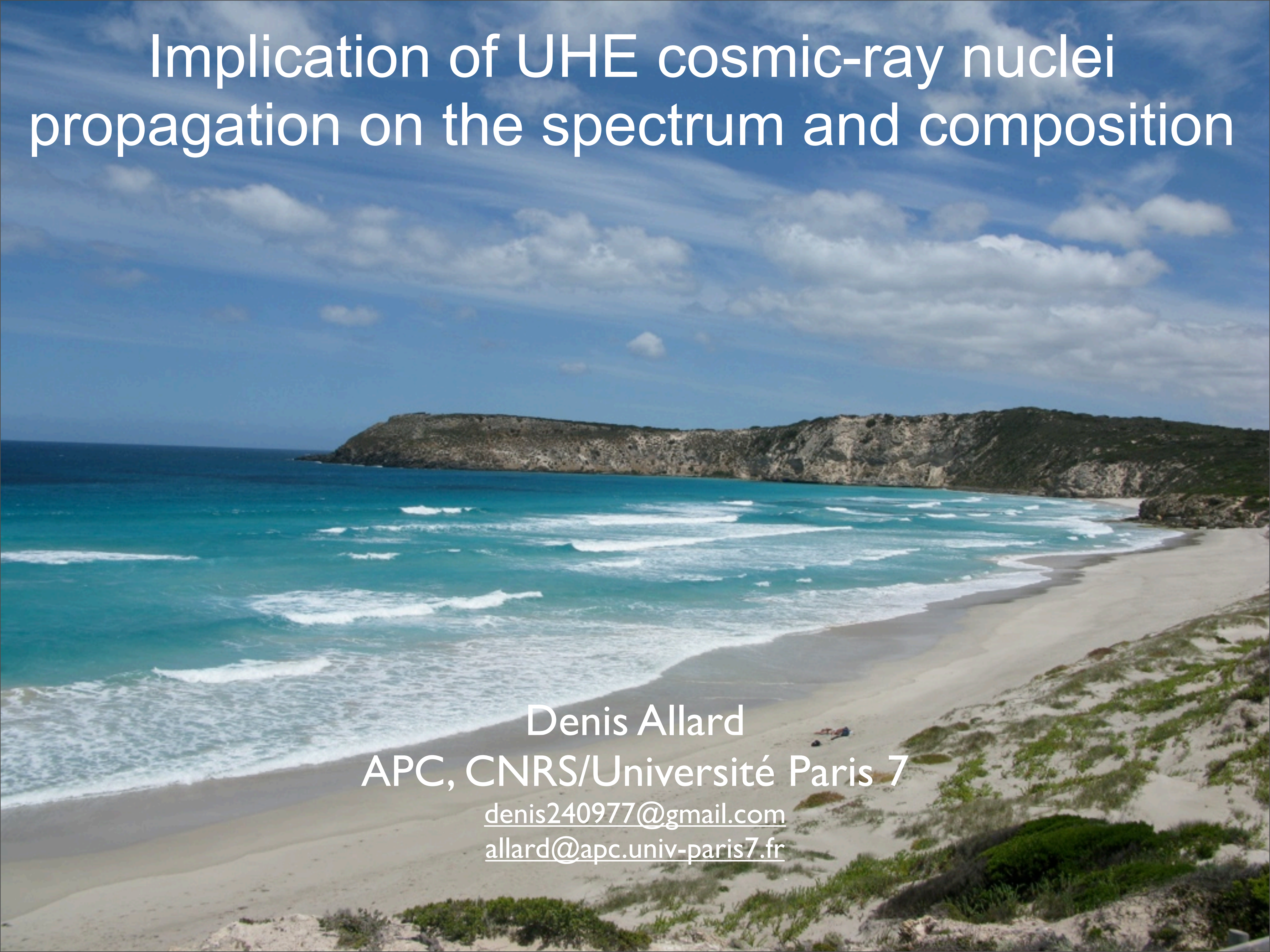
Implication of UHE cosmic-ray nuclei propagation on the spectrum and composition



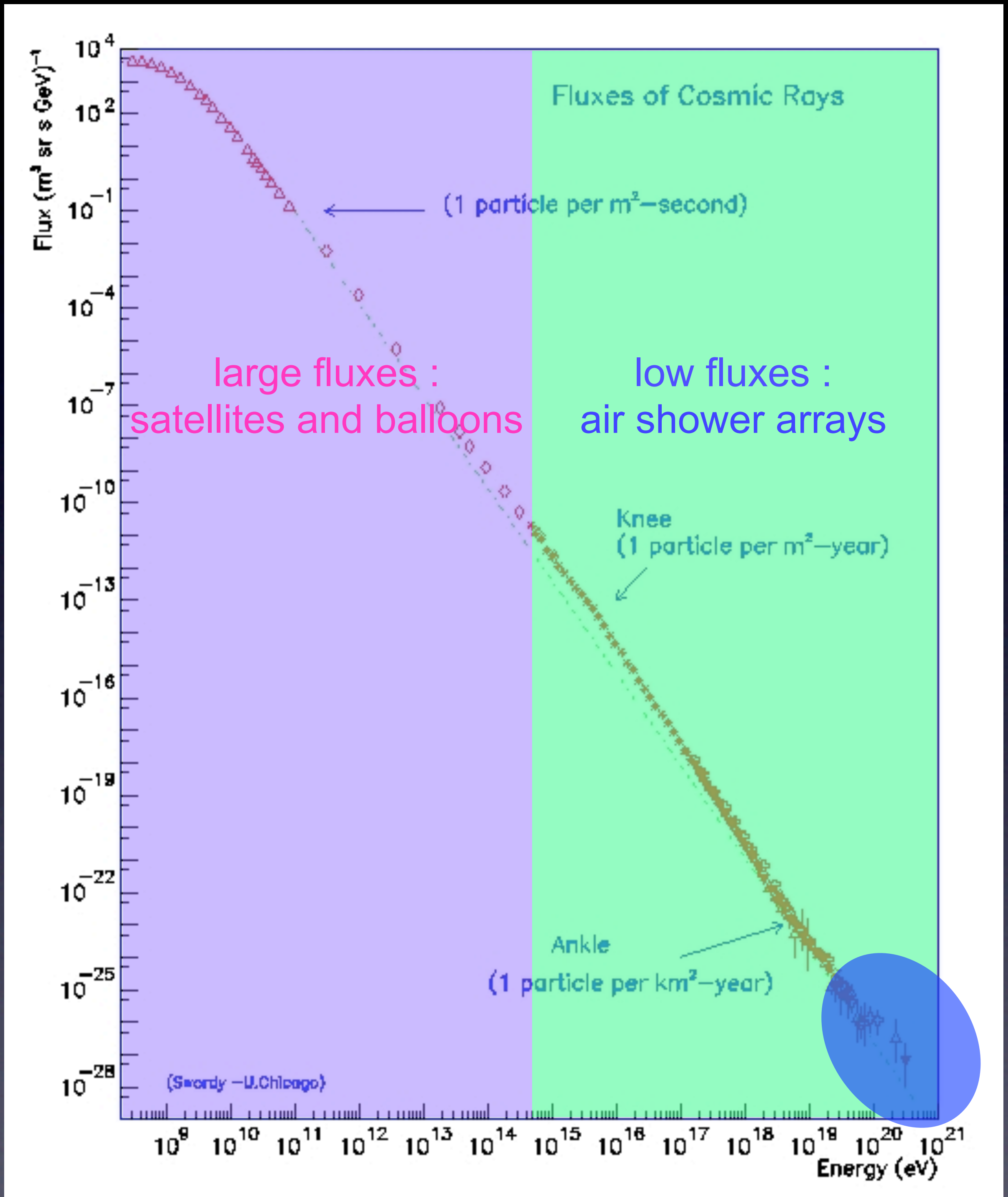
Denis Allard

APC, CNRS/Université Paris 7

denis240977@gmail.com

allard@apc.univ-paris7.fr

The cosmic spectrum : a 50 years old mystery



Spectrum measured on 12 orders of magnitude in energy and 32 in flux

- At low energy ($<10^{14-15}$ eV) the fluxes are large -> domain of satellite and atmospheric balloons
- At high energies (low fluxes) one uses air shower properties to detect cosmic-ray -> domain of air shower arrays and fluorescence detector
- At the highest energies ($\sim 10^{20}$ eV), extremely low fluxes (<1 CR.km^{-2}.century^{-1}) -> domain of giant air shower detectors

CR protons and nuclei interactions

Protons :

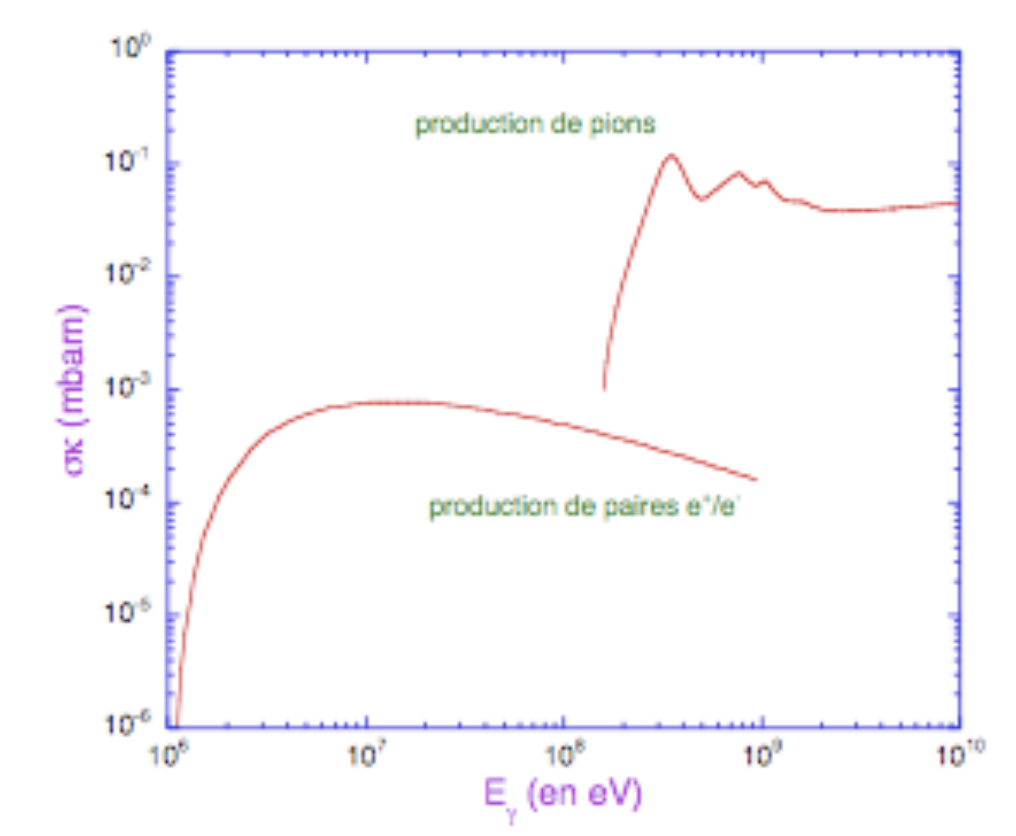
- adiabatic losses
- pair production:
  $P+\gamma \rightarrow p+e^+/e^-$ - low inelasticity process
  Interaction with CMB photons ~ 10^{18} eV
- Pion and meson production :
  $n+\gamma \rightarrow n'+\Pi$ - large inelasticity process (~20%)
  Interaction threshold ~7.10^{19} eV

Neutrinos production channels :

$p + \gamma \rightarrow n + \pi^+ \quad \pi^+ \rightarrow \nu_\mu + \mu^+ \quad \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$

$n \rightarrow p + e^- + \overline{\nu}_e$

$n + \gamma \rightarrow p + \pi^- \quad \pi^- \rightarrow \overline{\nu}_\mu + \mu^- \quad \mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$

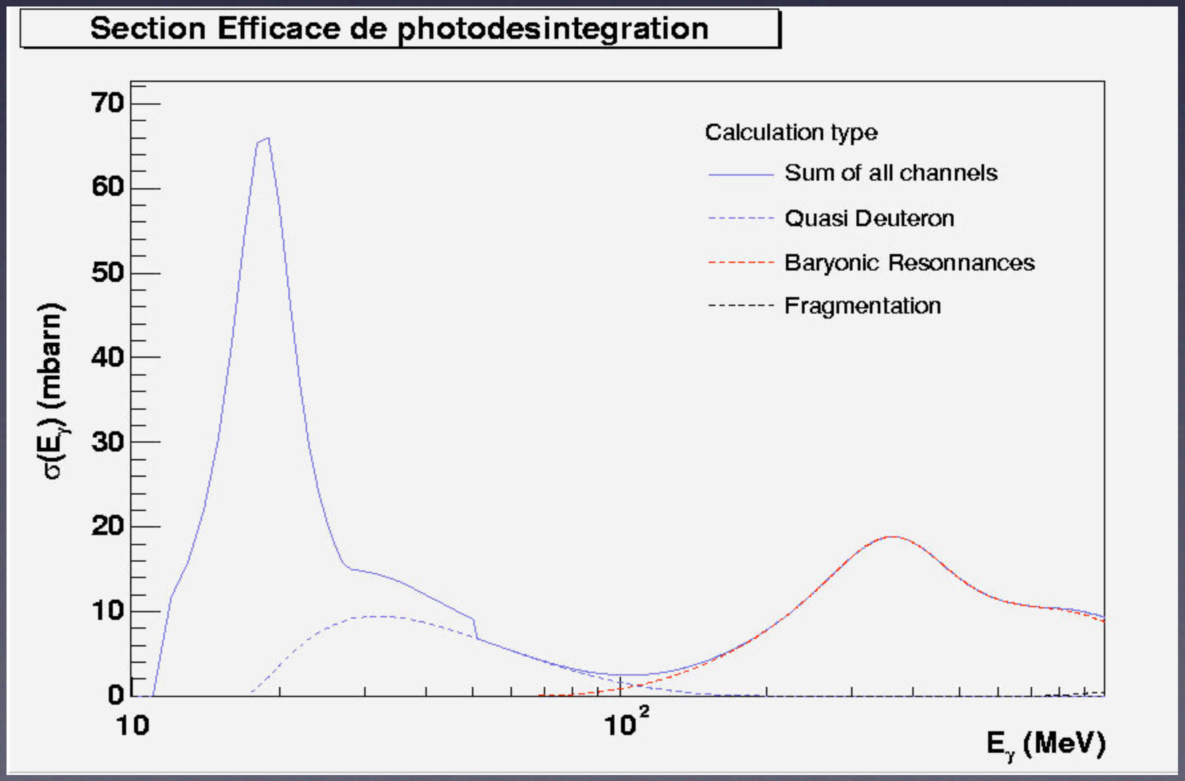


Compound nuclei :

Two types of processes

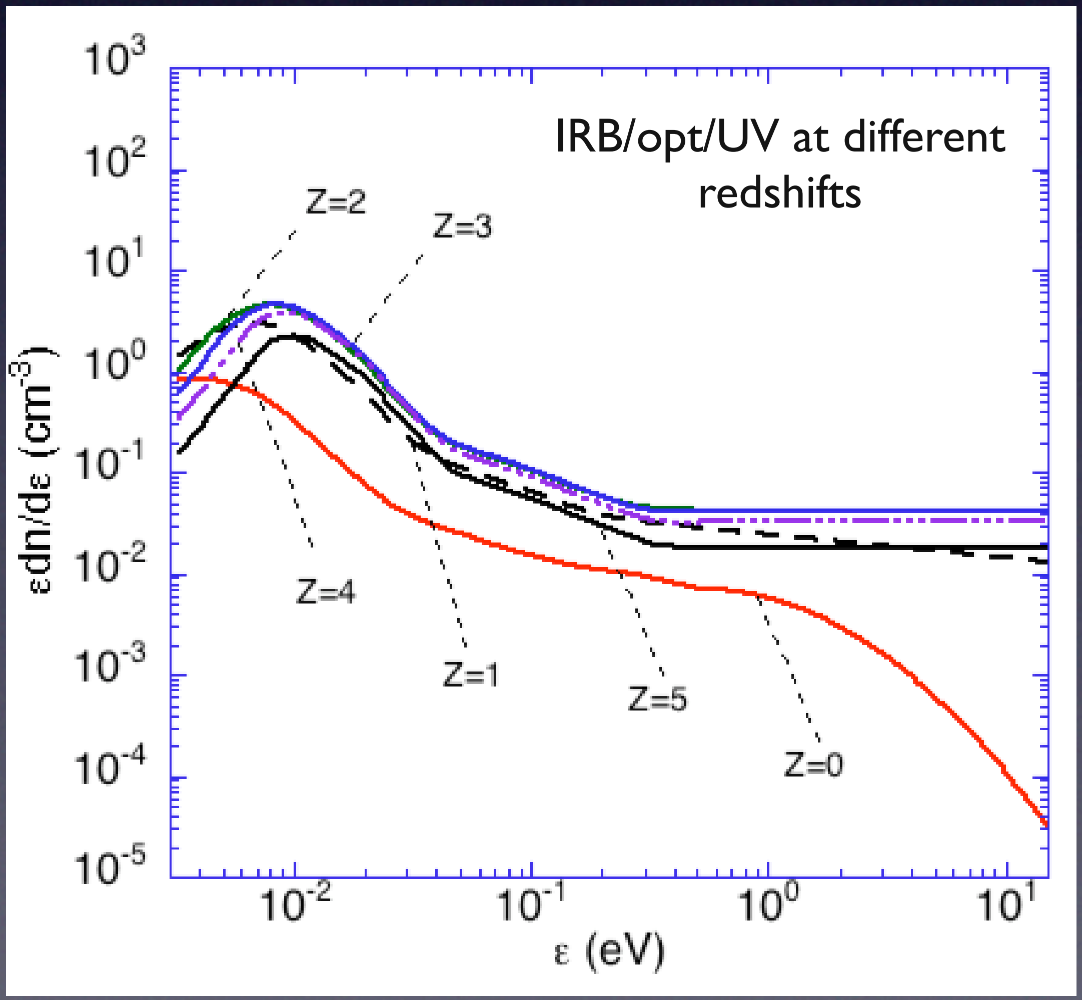
- Processes triggering a decrease of the Lorentz Factor
  - Adiabatic losses
  - Pair production losses (energy threshold ~$A\times10^{18}$ eV)
- Photodisintegration processes
  - Giant Dipole Resonance (GDR); threshold ~ 10 - 20 MeV largest σ and lowest threshold (Khan et al., 2004)
  - Quasi-Deuteron process (QD); threshold ~ 30 MeV (PSB 1976)
  - Pion production (BR); threshold ~ 145 MeV (Rachen 1996)

Neutrinos production channels :
π-prod of secondary p and n; β-decay of secondary n
decay of the π produced during the BR process



Photon backgrounds

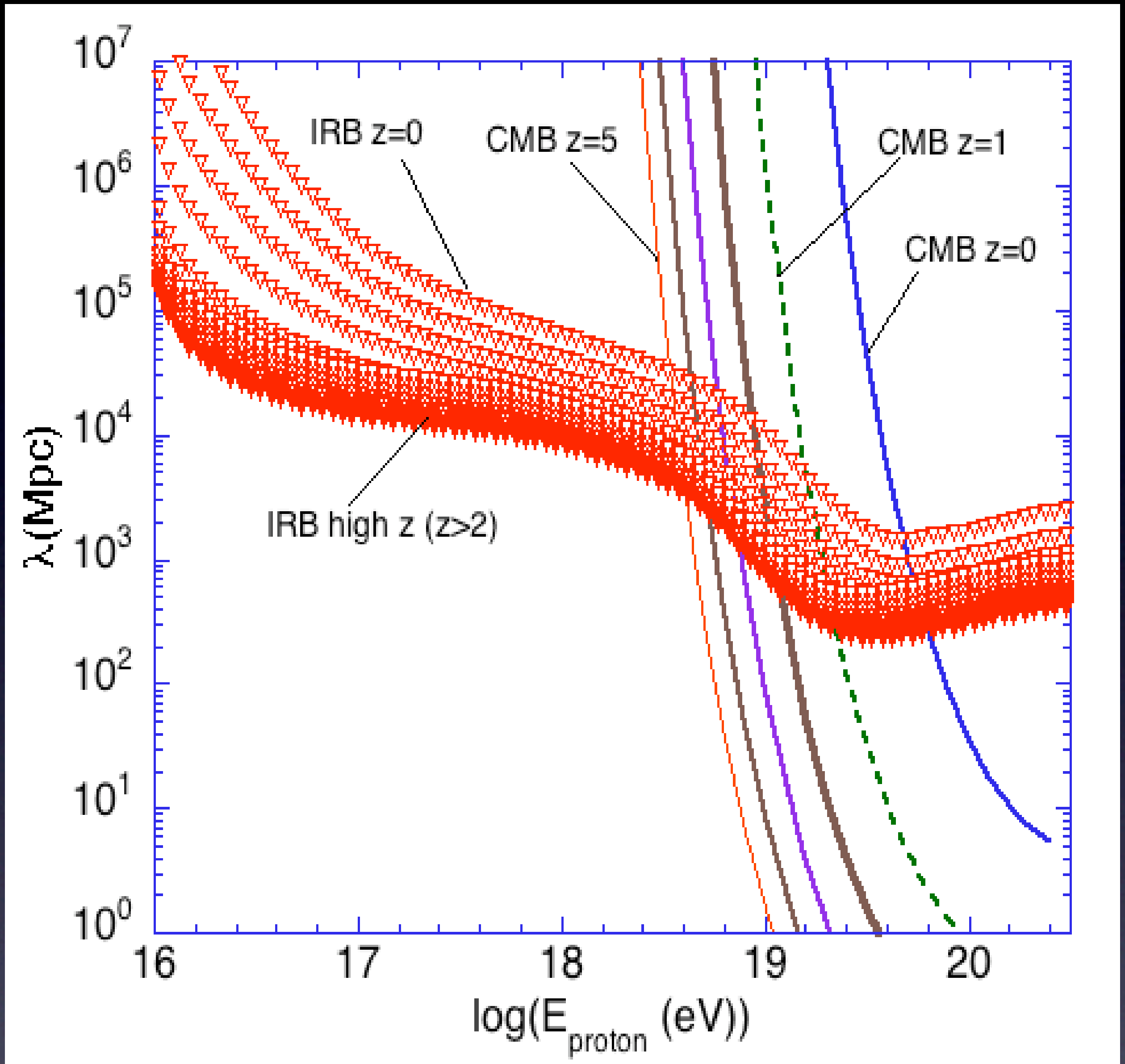
- In the extragalactic medium (very low density), ultra-high energy nuclei mainly interact with photon backgrounds
  - Cosmological Microwave Background, very well known T=2.726K, trivial cosmological (I.e, time) evolution $\lambda_{CR}(E_{CR},z)=\lambda_{CR}(E_{CR}\times(1+z),z=0)/(1+z)^3$ **Densest photon background**
  - Infra-red, optical, ultra violet backgrounds (IR/OPT/UV)
    Time evolution dependent on the Star Formation Rate, stars aging and metalicity (especially the UV background) -> non trivial but recently better constrained by astrophysical data (Spitzer telescope, etc…)



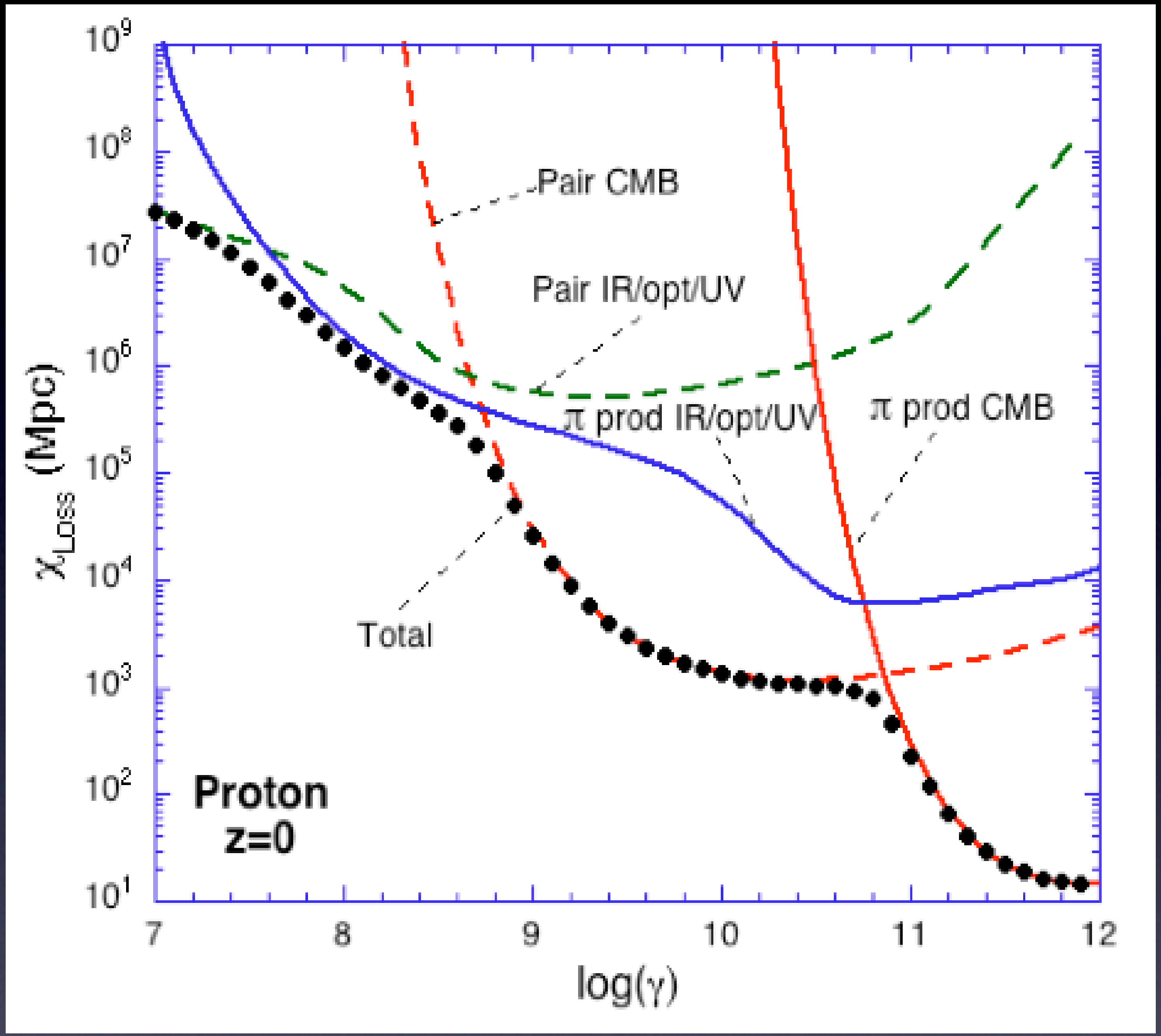
IR/OPT/UV background are very important for nuclei propagation

In the following calculations, we use estimate of IR/OPT/UV background density and time evolution from Stecker, Malkan and Scully 2005

mean free paths and attenuation lengths : protons

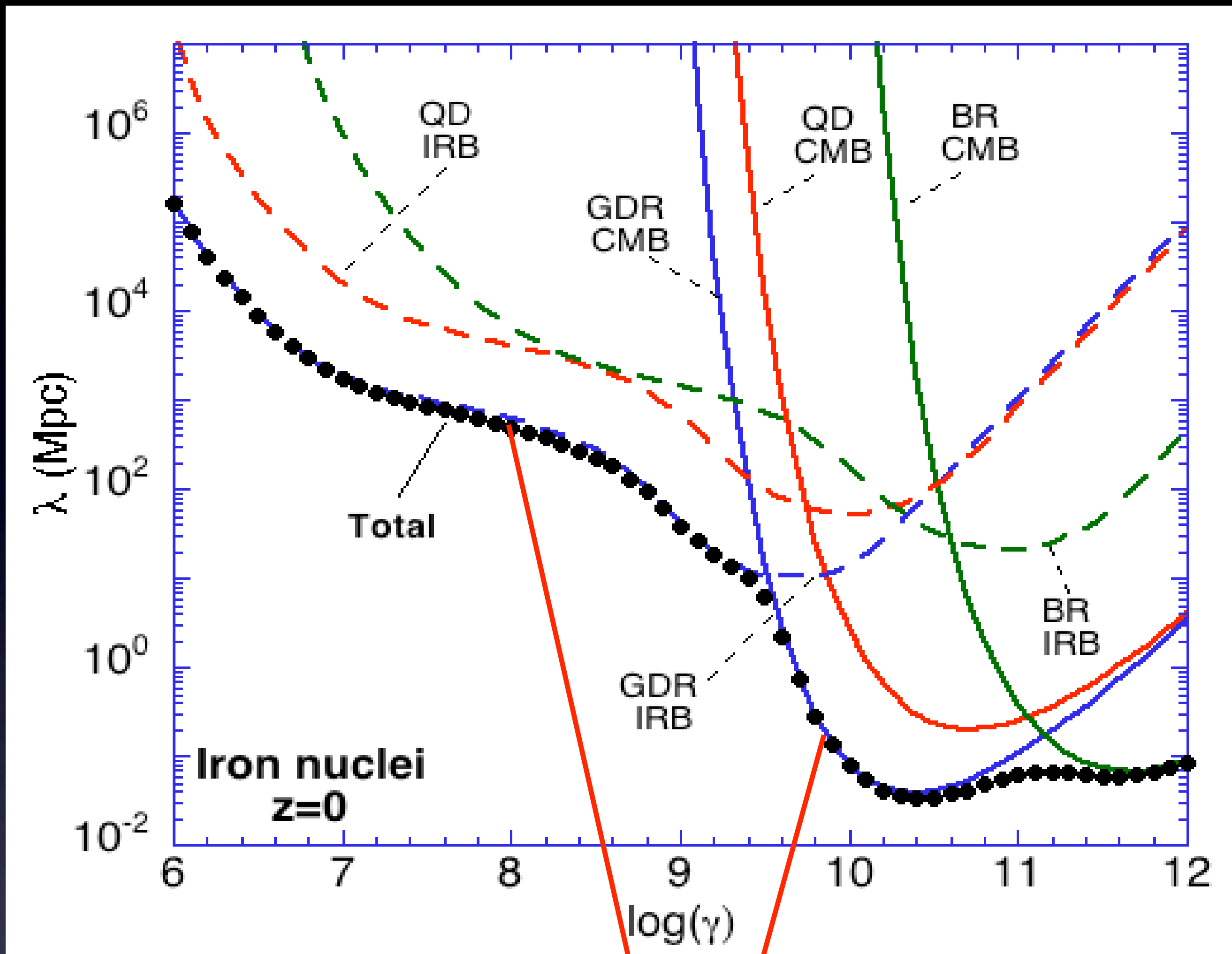


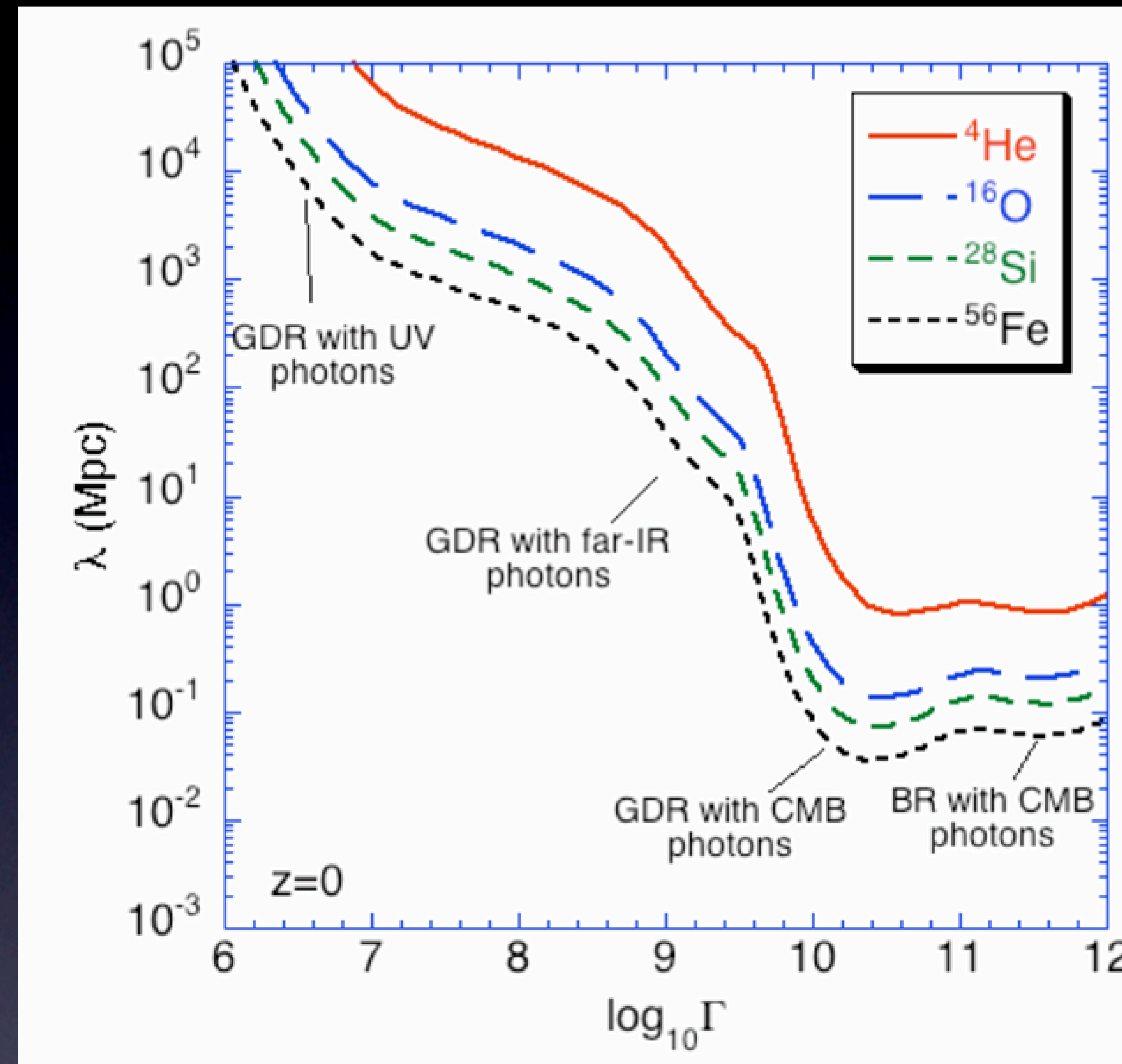
evolution much stronger in the “CMB regime”



contribution of the interaction with IR/Opt/UV background very low

mean free paths : nuclei

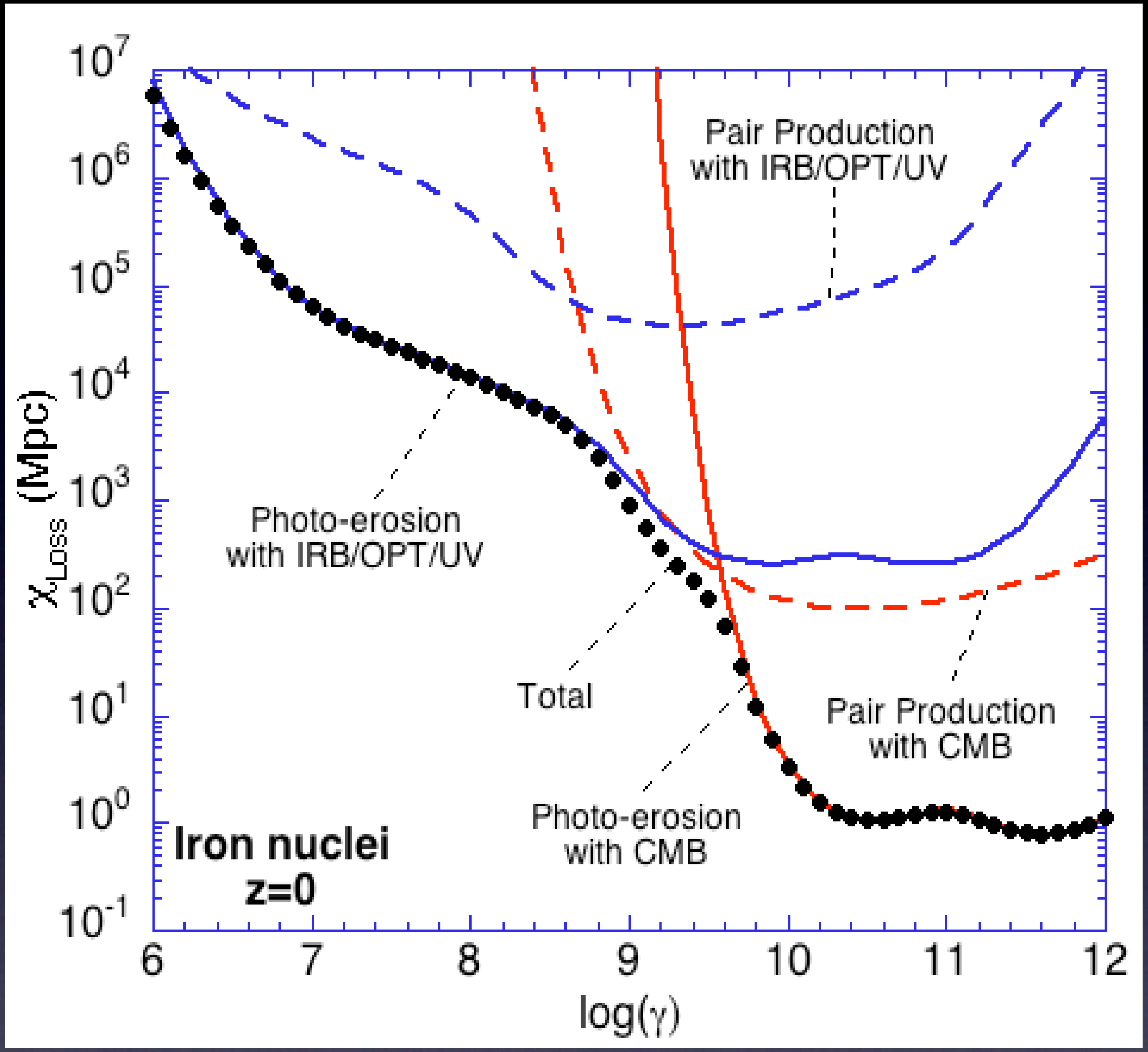


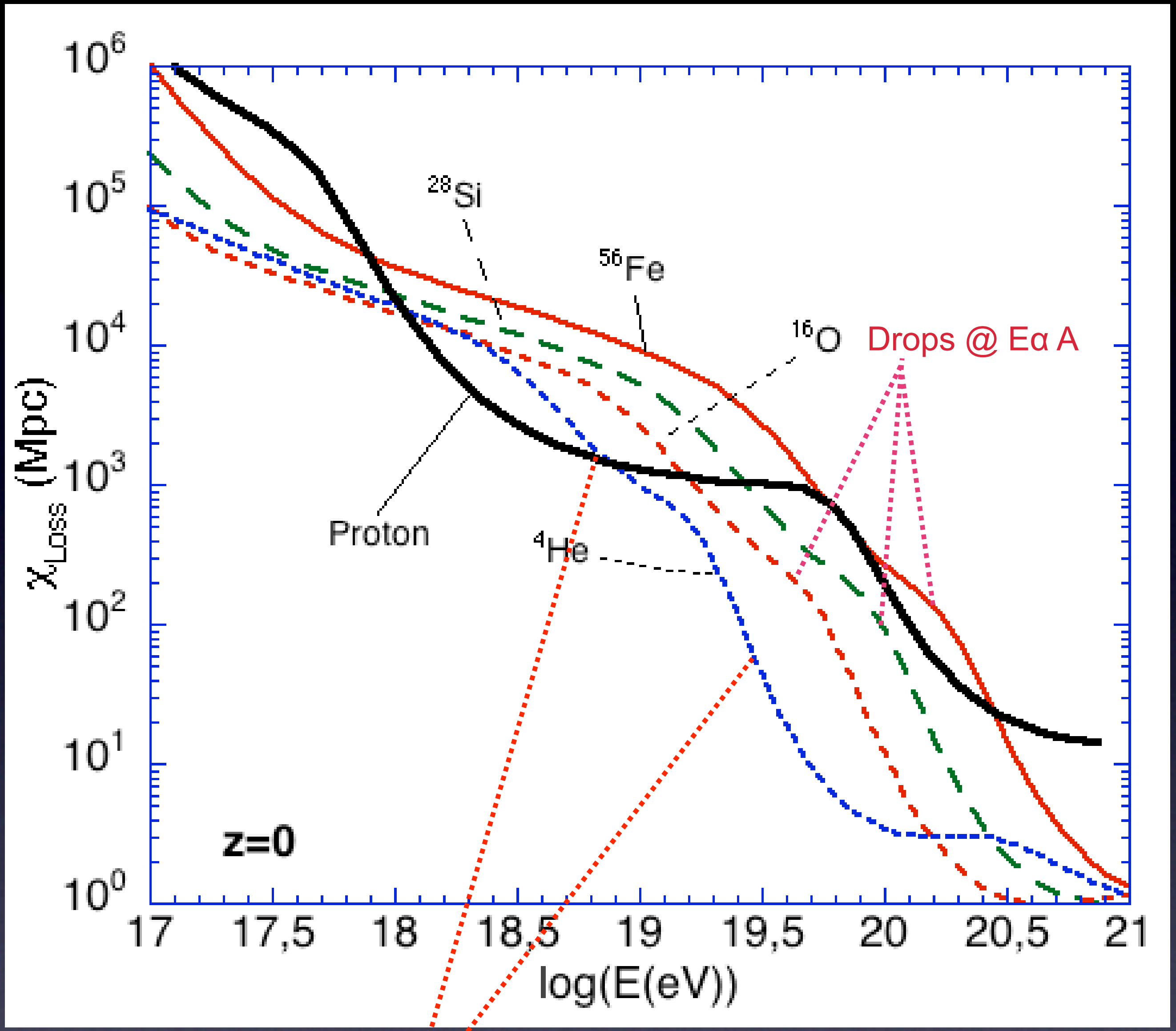


GDR dominant up to $\gamma = 10^{11}$

E_{th} and λ scaling ~ ∝ A

Attenuation lengths : nuclei





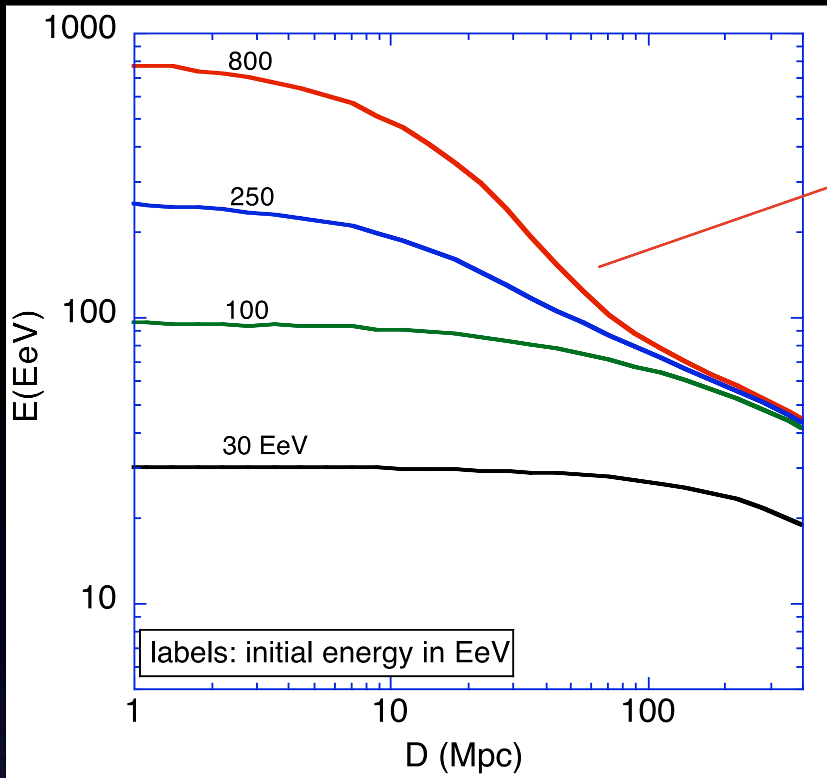
Photodisintegration processes dominant on the whole energy range

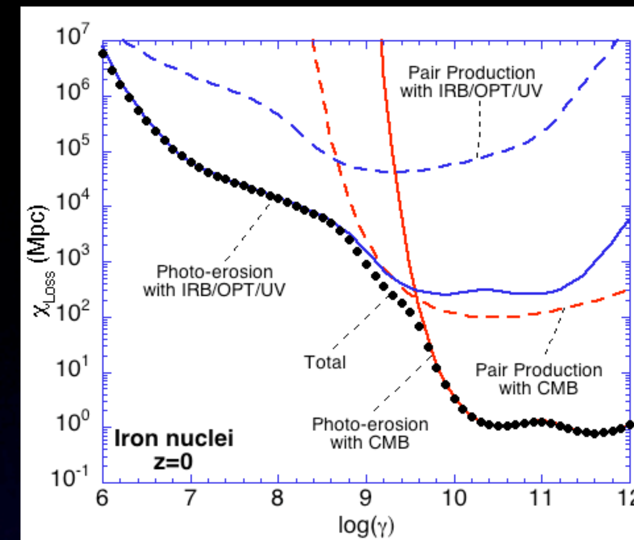
Two drops in the attenuation length :

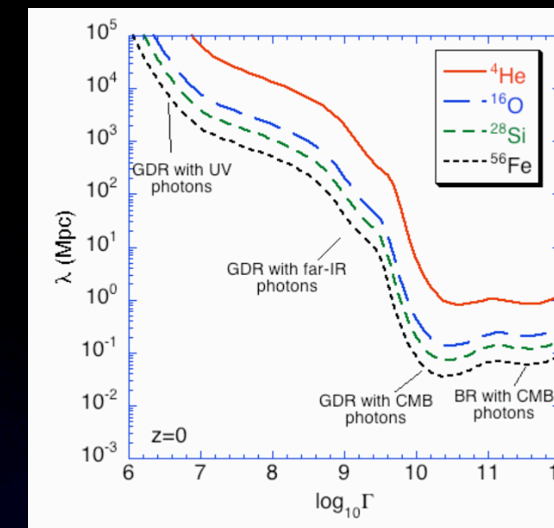
- GDR with IR bump photons
- GDR with CMB photons

Trajectories in the E, A and Γ spaces

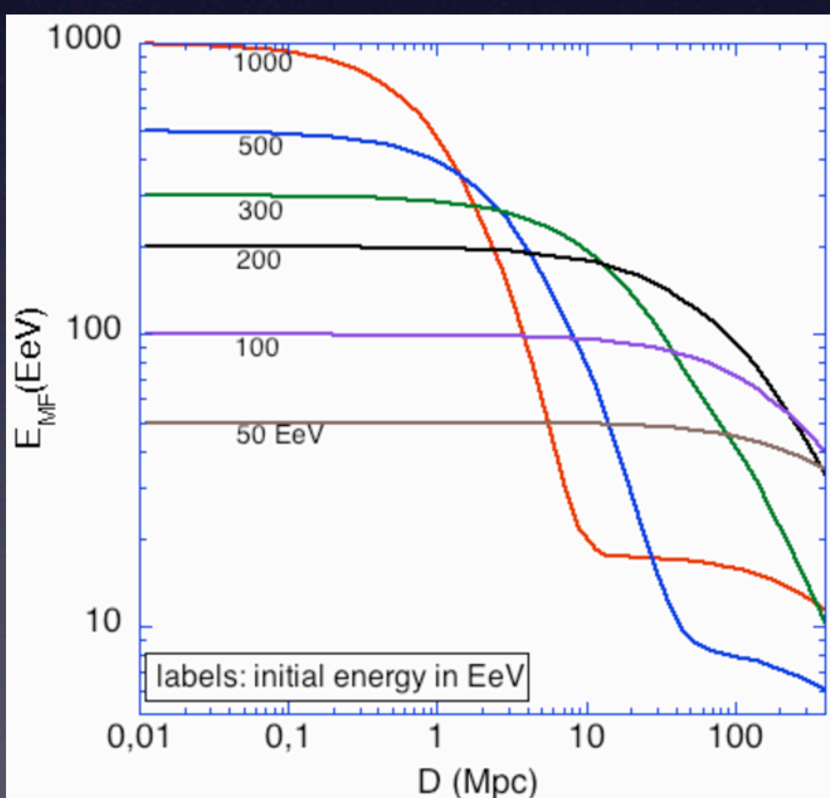
Proton

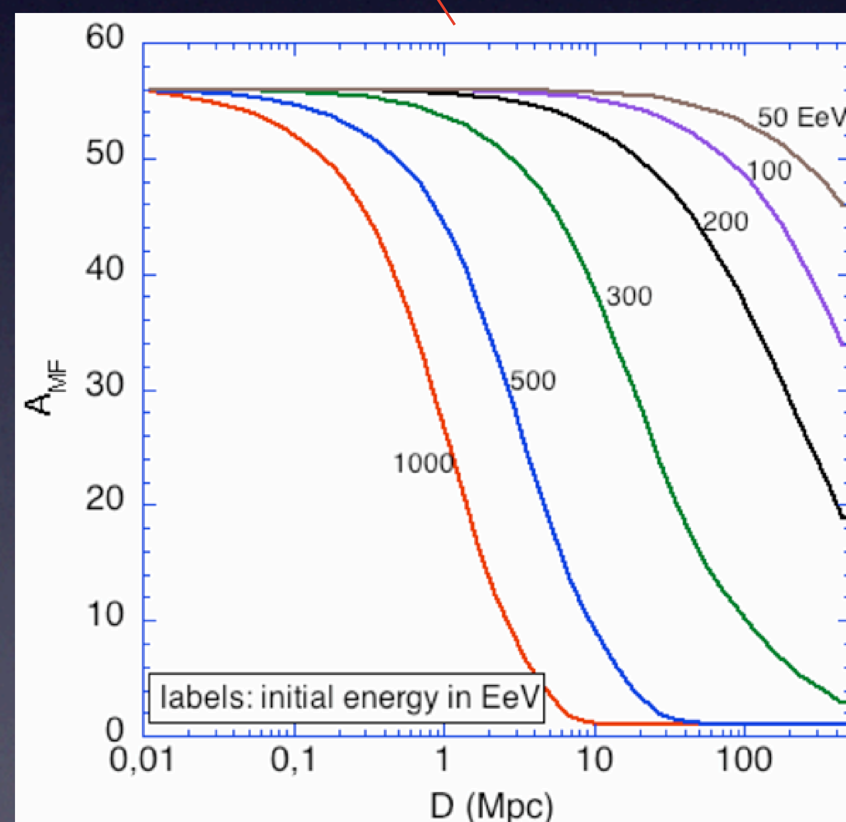


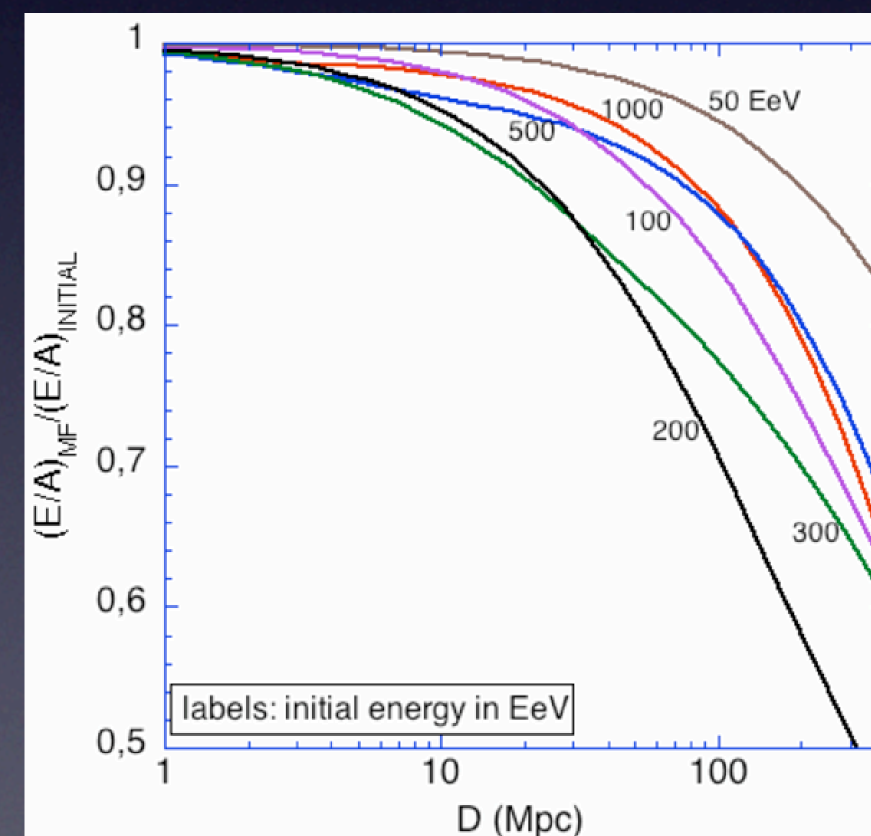




Iron

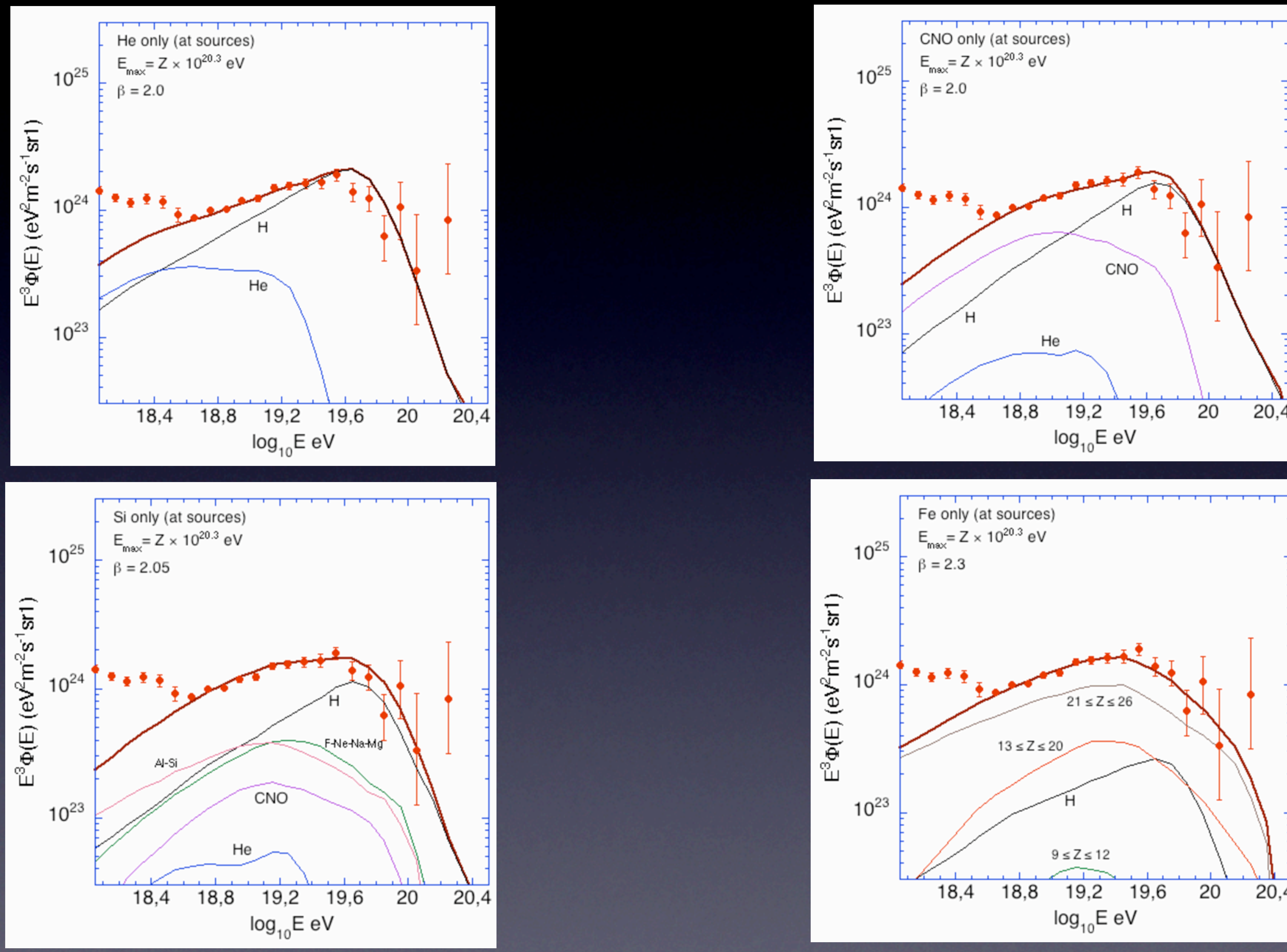






Unlike the in the proton case, energy evolution curves can cross
Lorentz factor evolution depends on the evolution in the (E,A) space
-> a lot more complicated than the proton case

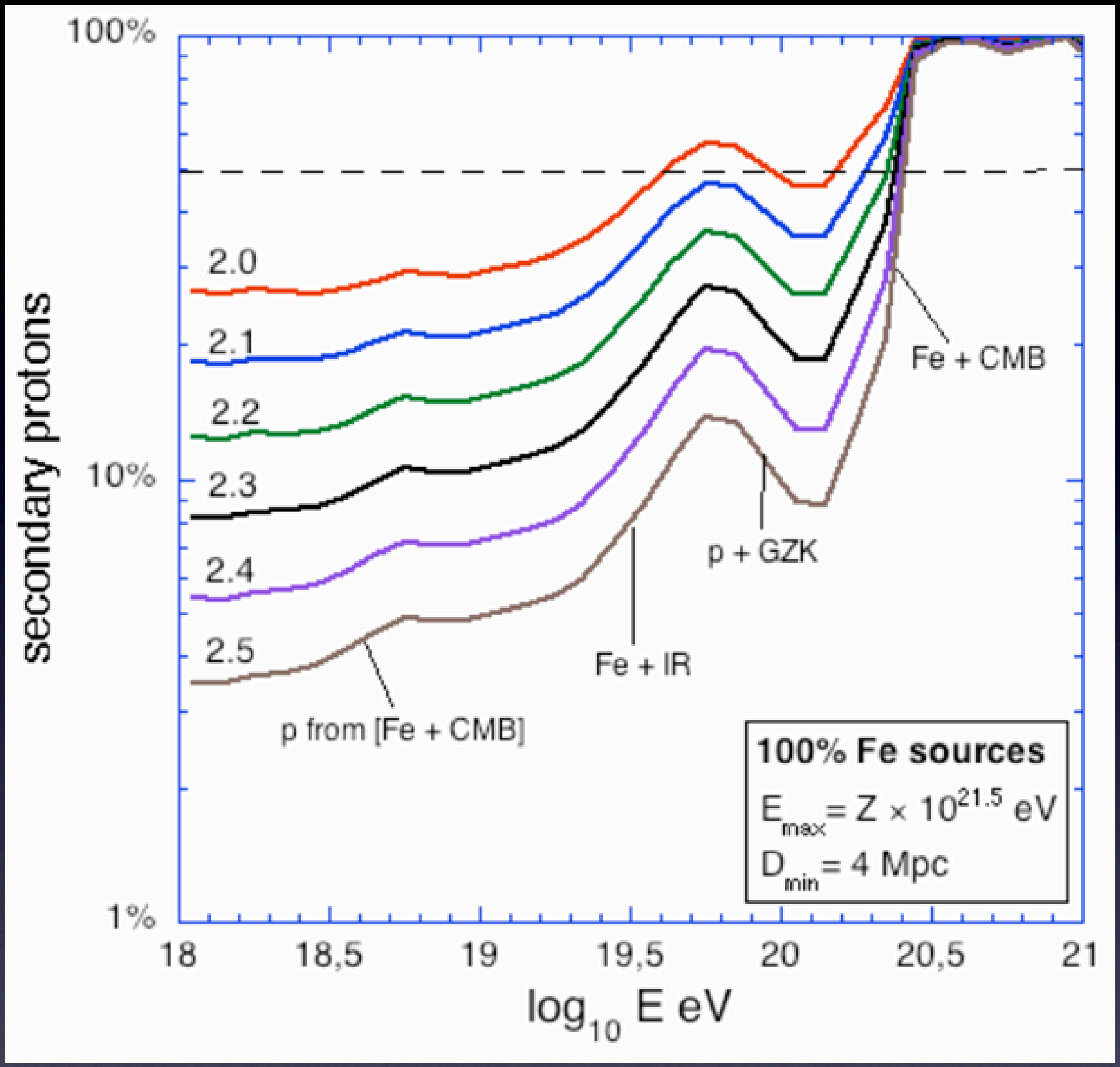
Pure nuclei spectra

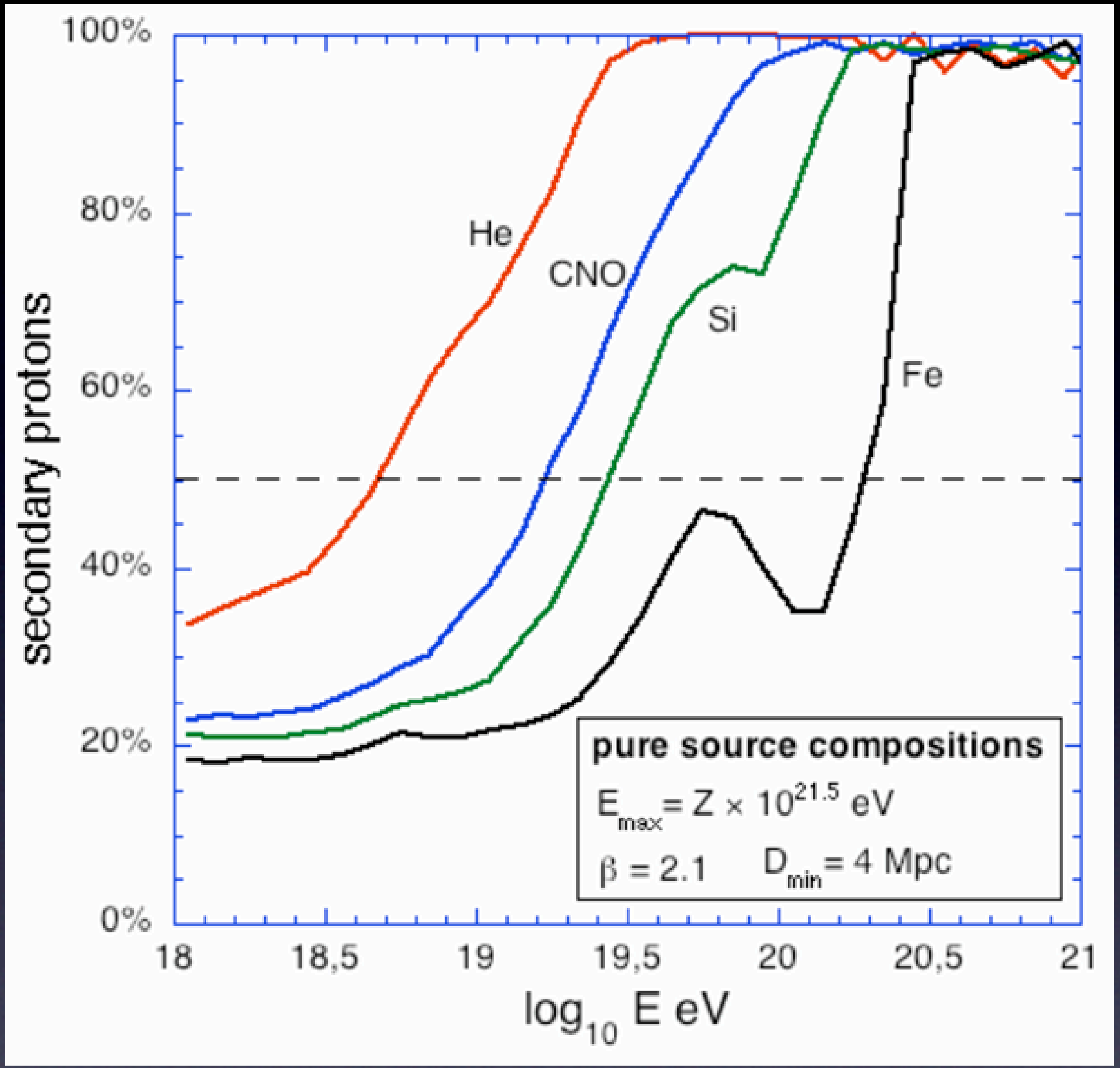


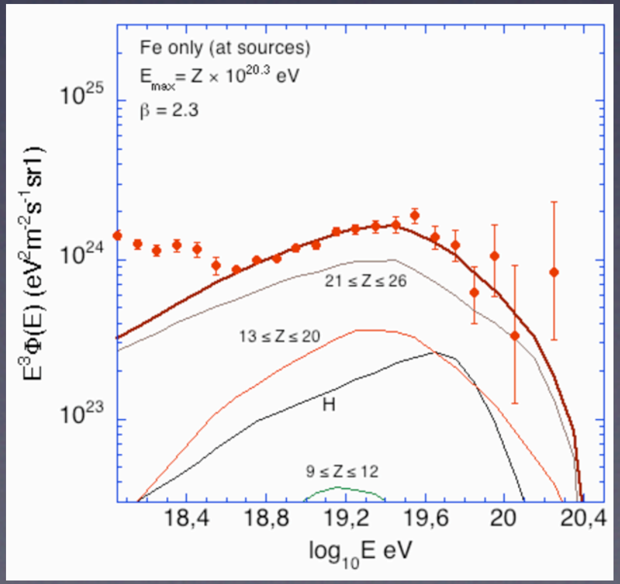
one can fit Auger spectrum with any source composition

at the highest energies the composition should either proton or heavy nuclei

evolution of the secondary protons abundance

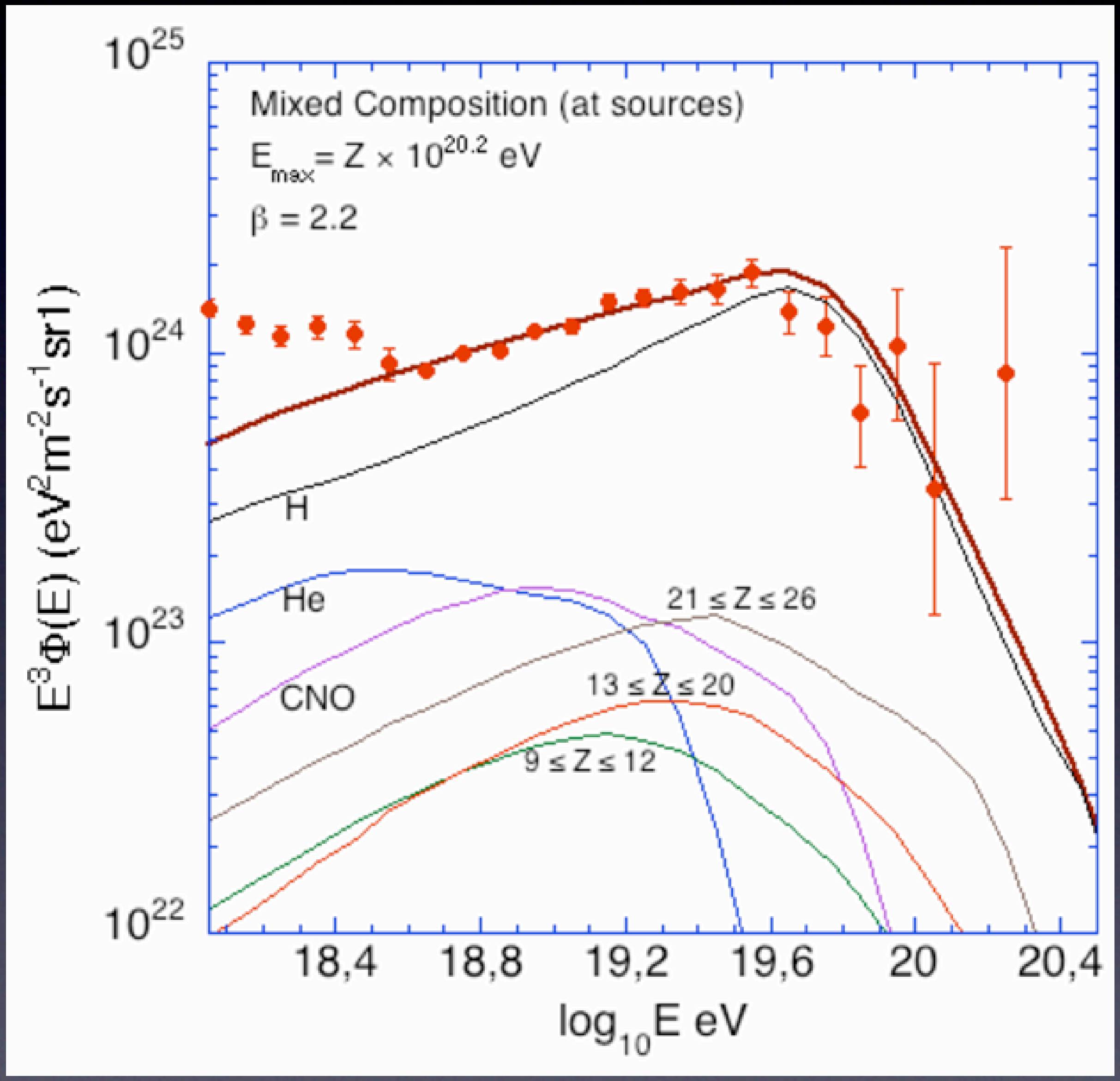






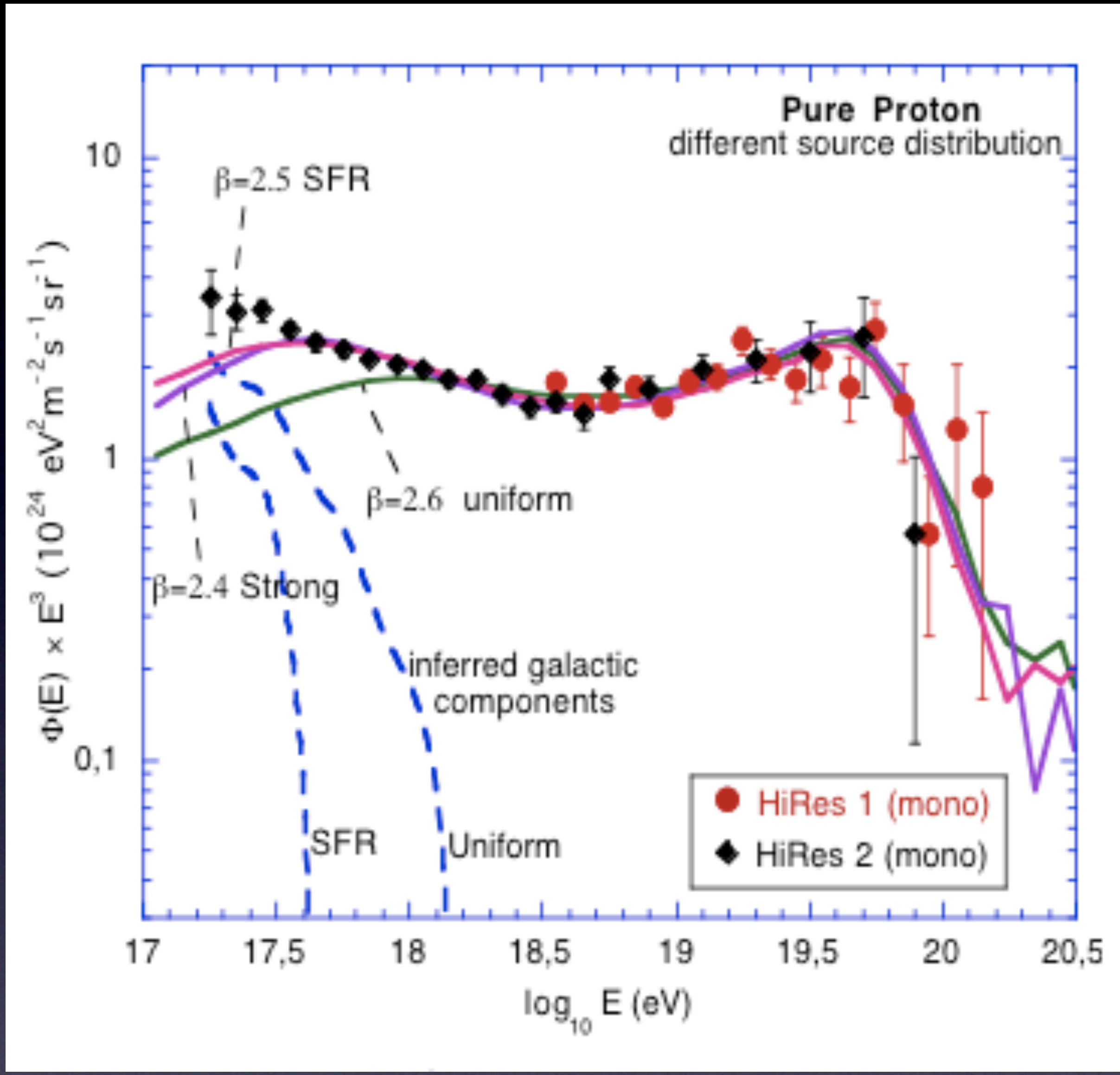
A more realistic composition

We assume a mixed composition at the sources similar to the one reconstructed for low energy Galactic cosmic-rays, protons accelerated above 10^{20} eV, rigidity dependent Emax

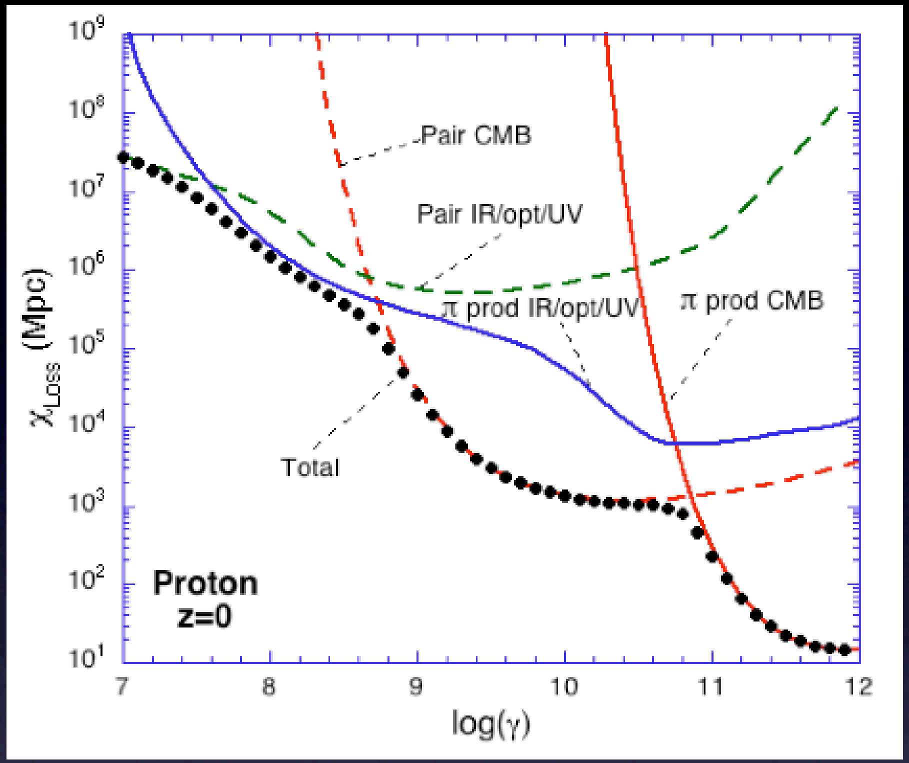


good fit of the data can be found down to the ankle

Why not a pair production dip?

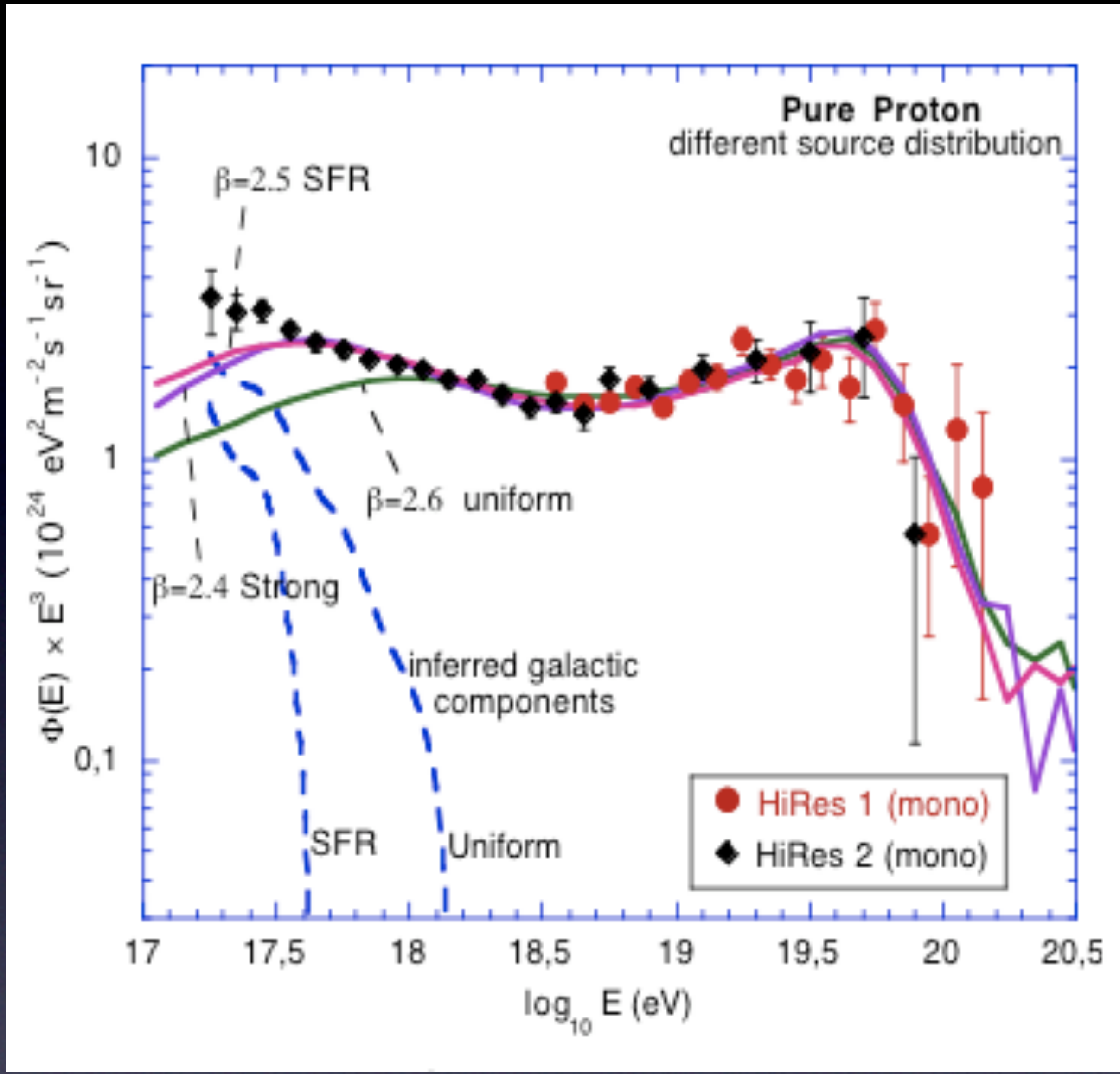


The ankle can be fitted by the extragalactic component itself : pair production dip->the ankle feature has nothing to do with the transition (model developed by Berezinsky et al., 2002-2007)



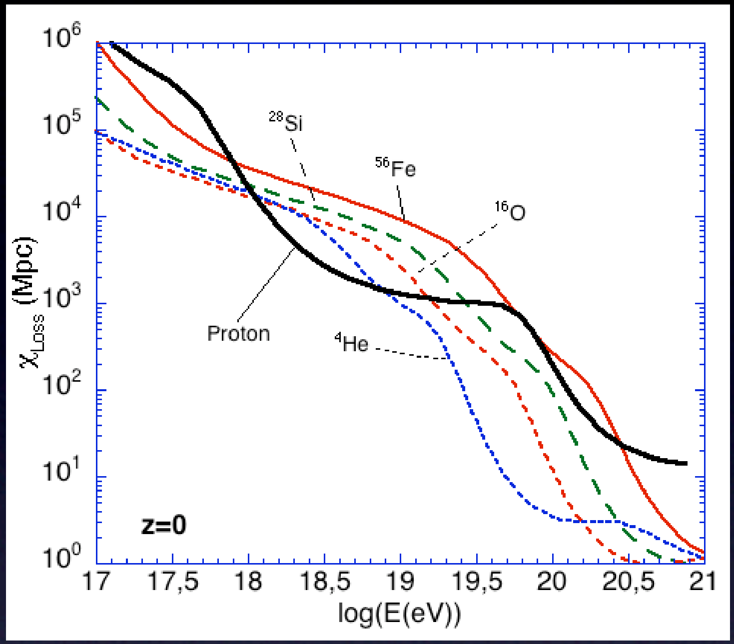
The existence of the pair production dip is due to the energy evolution of the proton attenuation length

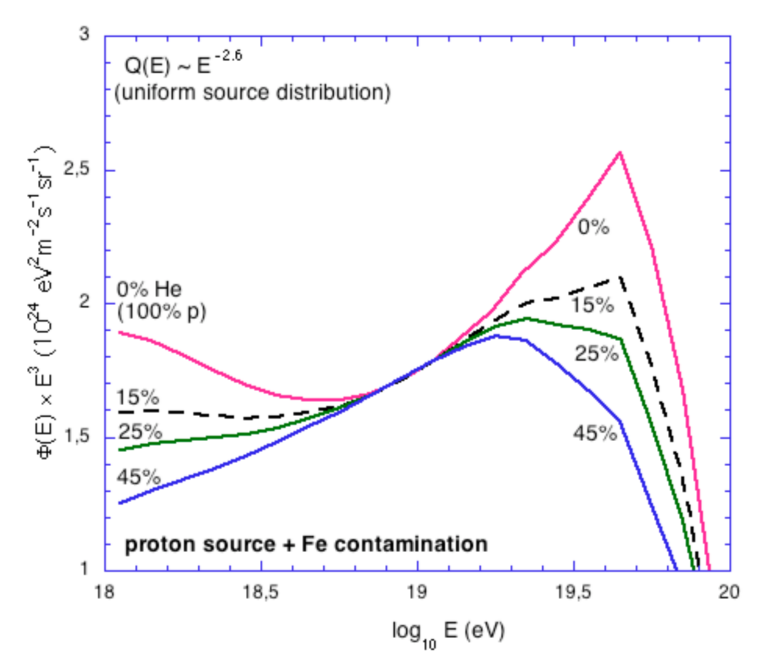
Why not a pair production dip?



The ankle can be fitted by the extragalactic component itself : pair production dip->the ankle feature has nothing to do with the transition (model developed by Berezinsky et al., 2002-2007)

BUT

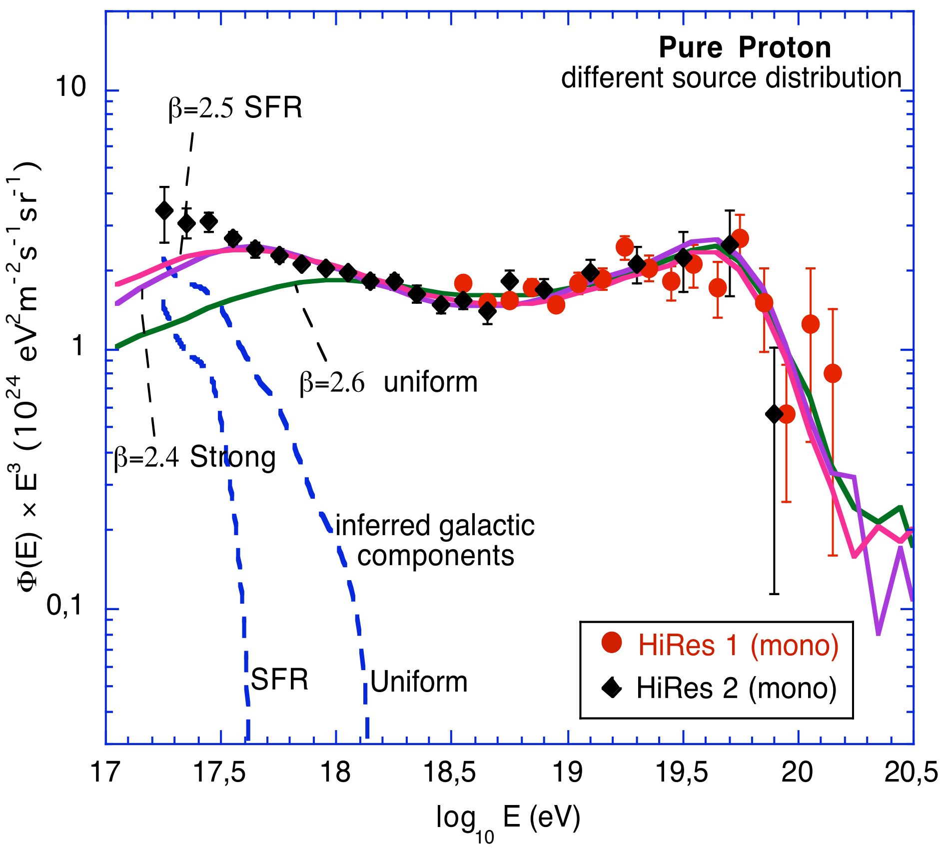


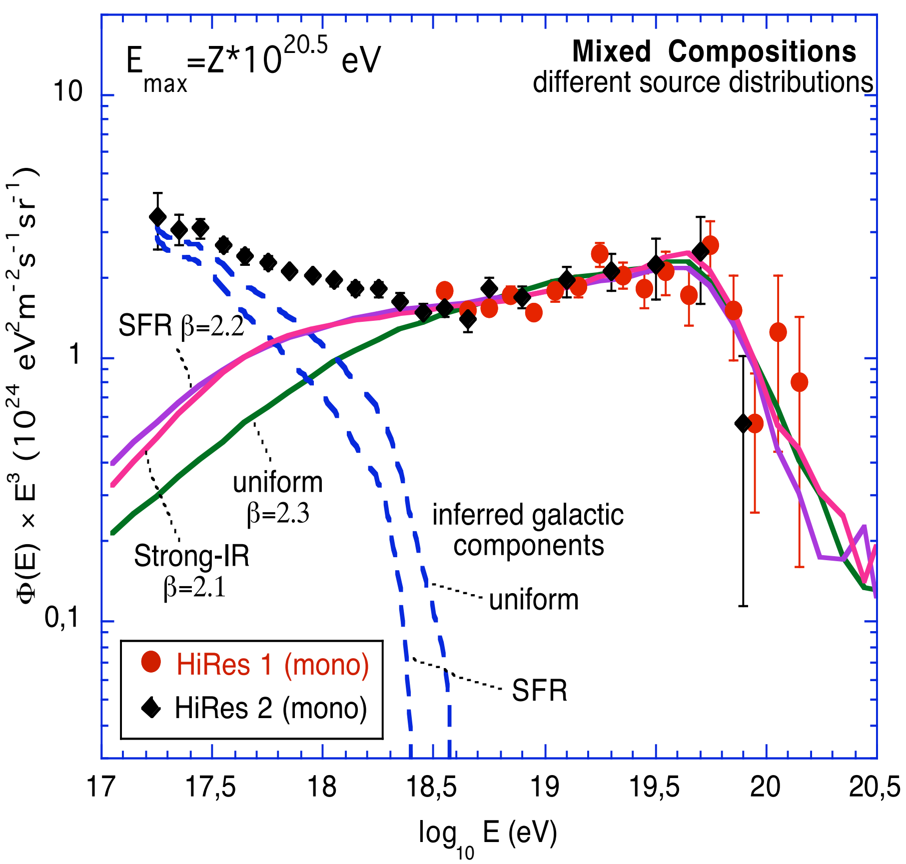


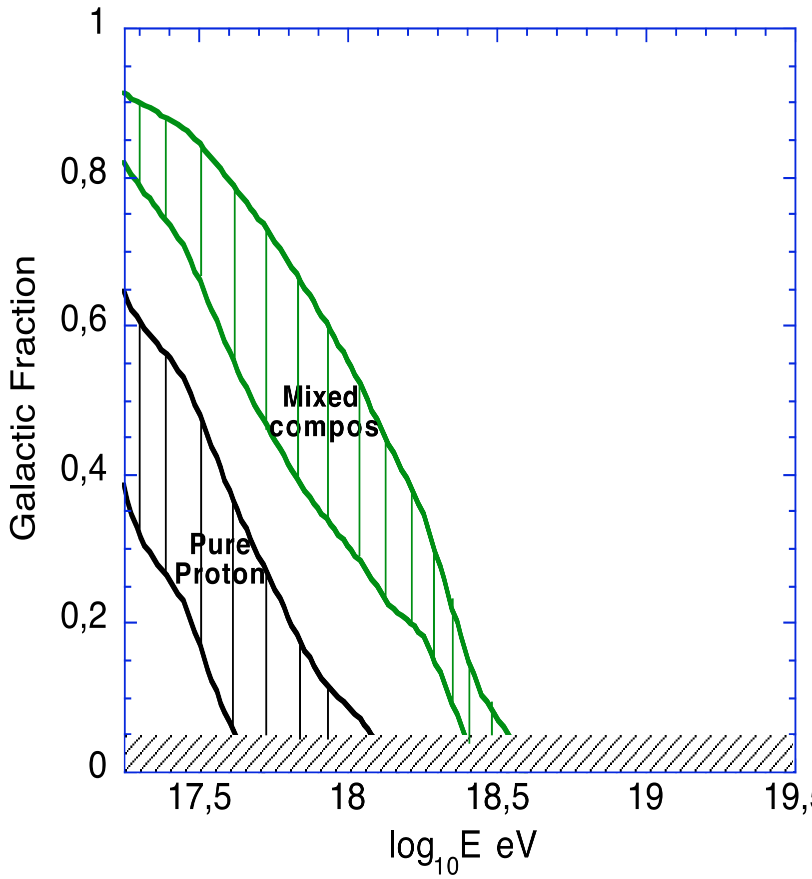
The attenuation length evolution is different for nuclei

A small admixture of nuclei erase the dip

Comparison between pure proton and mixed composition models







Different energy scales for the transition (finishes earlier for the pure proton model)

Different interpretations for the ankle (transition Vs proton interaction)

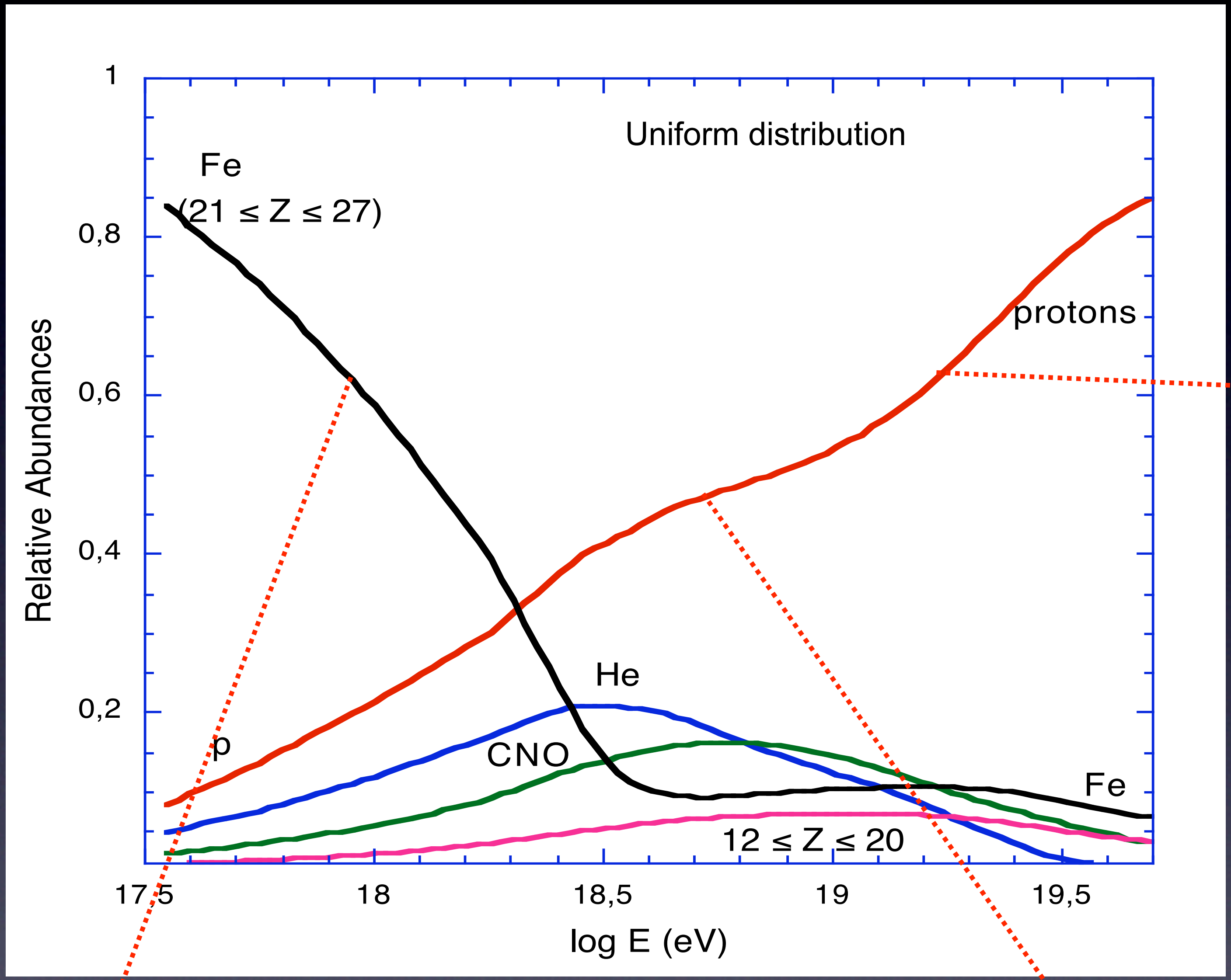
Impressive agreement of the pair production dip with the ankle but the scheme of the transition for the mixed composition model looks more natural

From the sole point of view of the spectrum the two models are degenerated

Other observables needed to distinguish them

Evolution of the composition

• We assume the remaining galactic components are made of iron nuclei above $10^{17.5}$ eV (certainly not completely true but likely to be accurate enough)



Above ~10^{19} eV, intermediates and then heavies start to photodisintegrate faster (IR bump) -> fast increase of the proton relative abundance

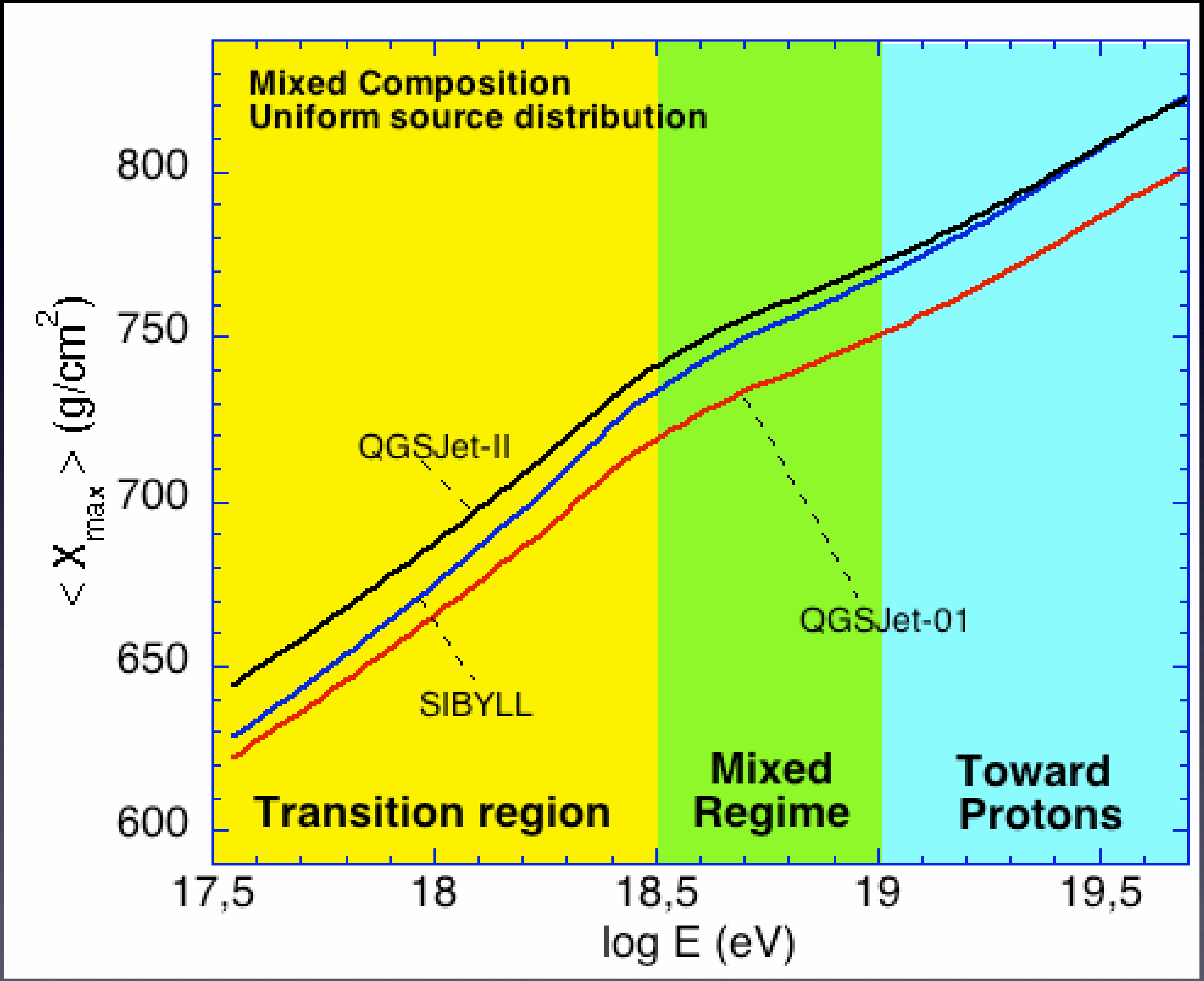
Below the ankle, sharp decrease of the heavy galactic CR

Beetween the ankle and ~ 10^{19} eV

Ratio light (P/He) to intermediate/heavy ~ constant

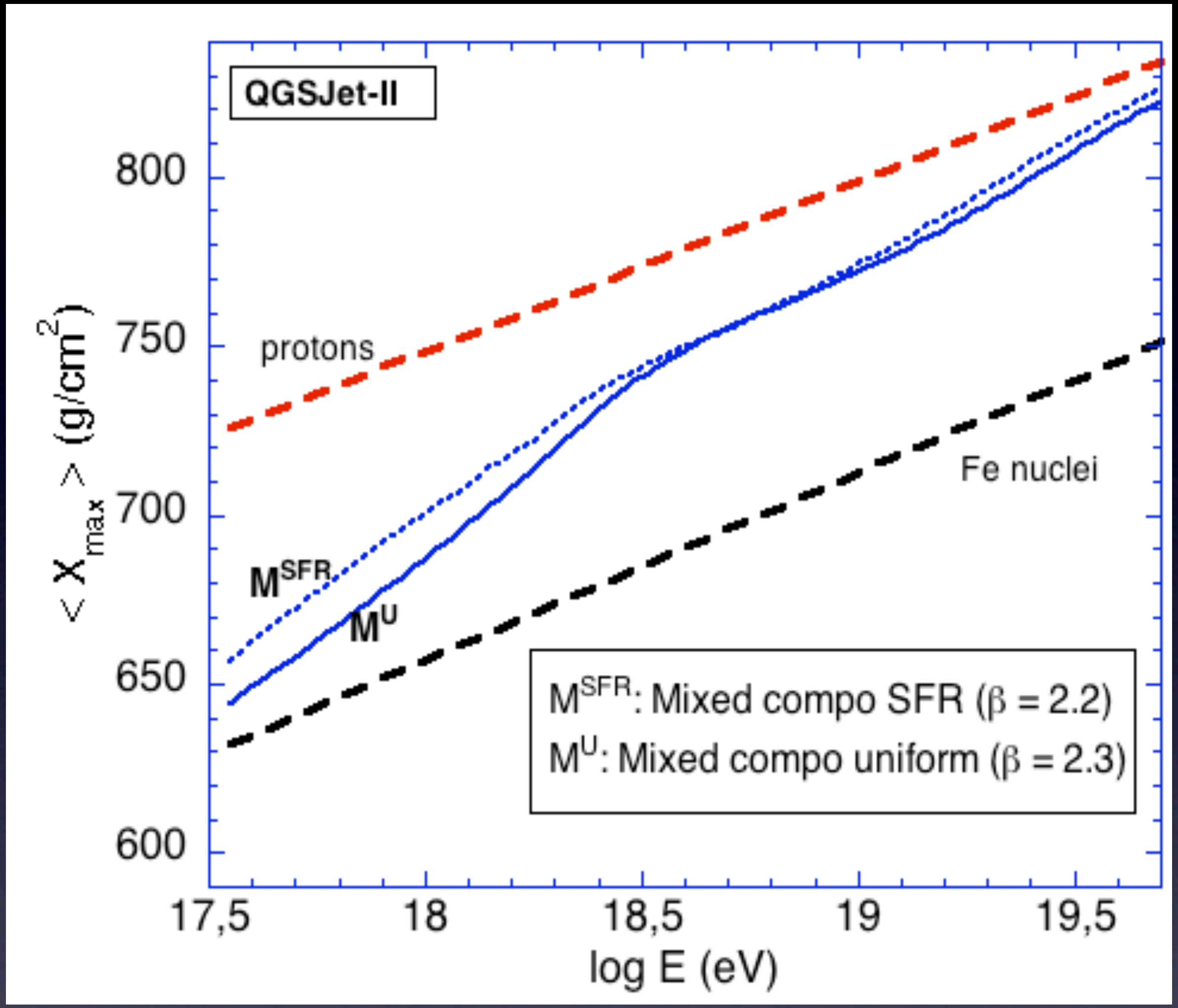
Xmax evolution

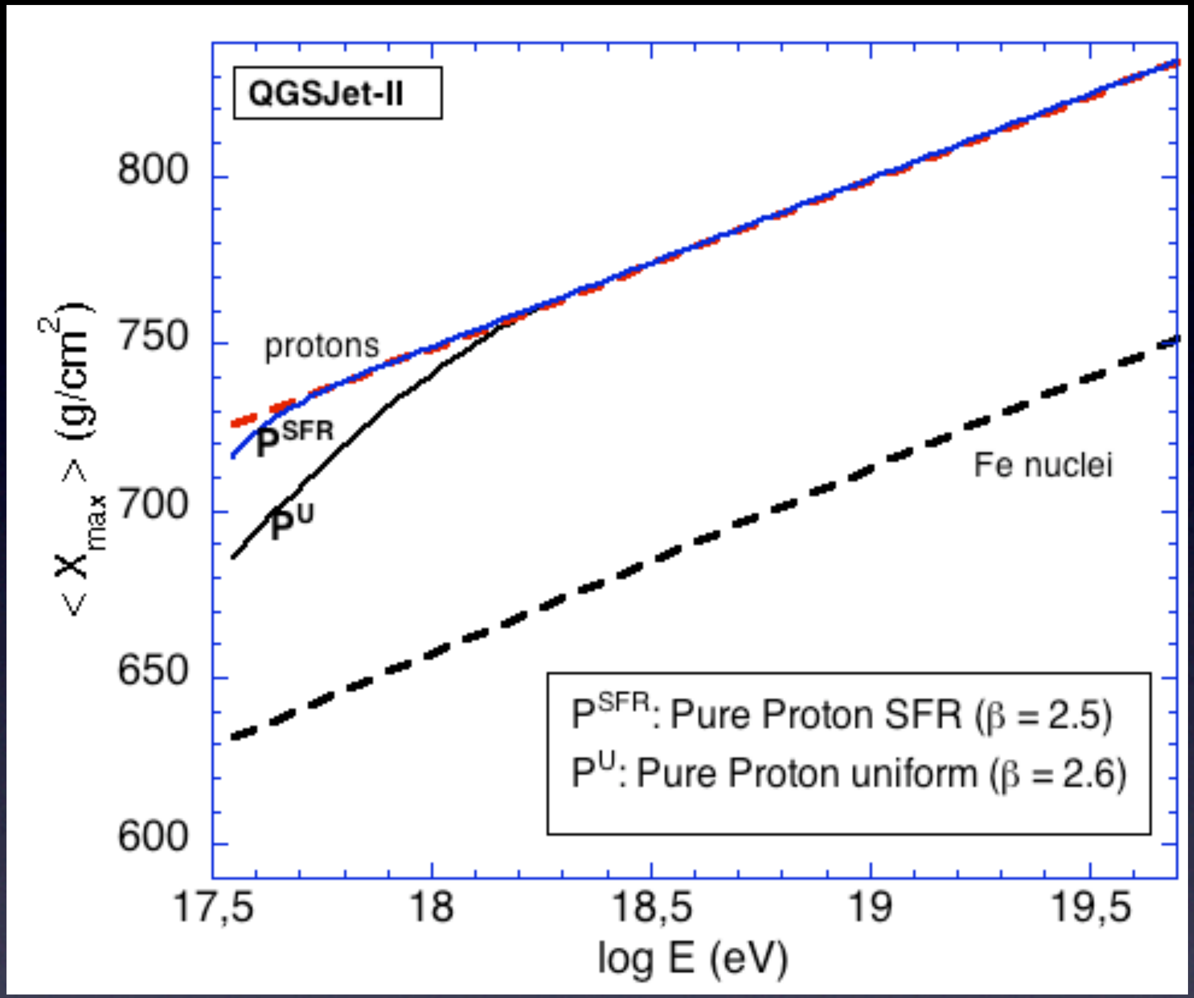
- From the relative abundances one can derive a predicted X_{max} evolution



The three regimes seen in the evolution of the relative abundances are present in the X_{max} evolution

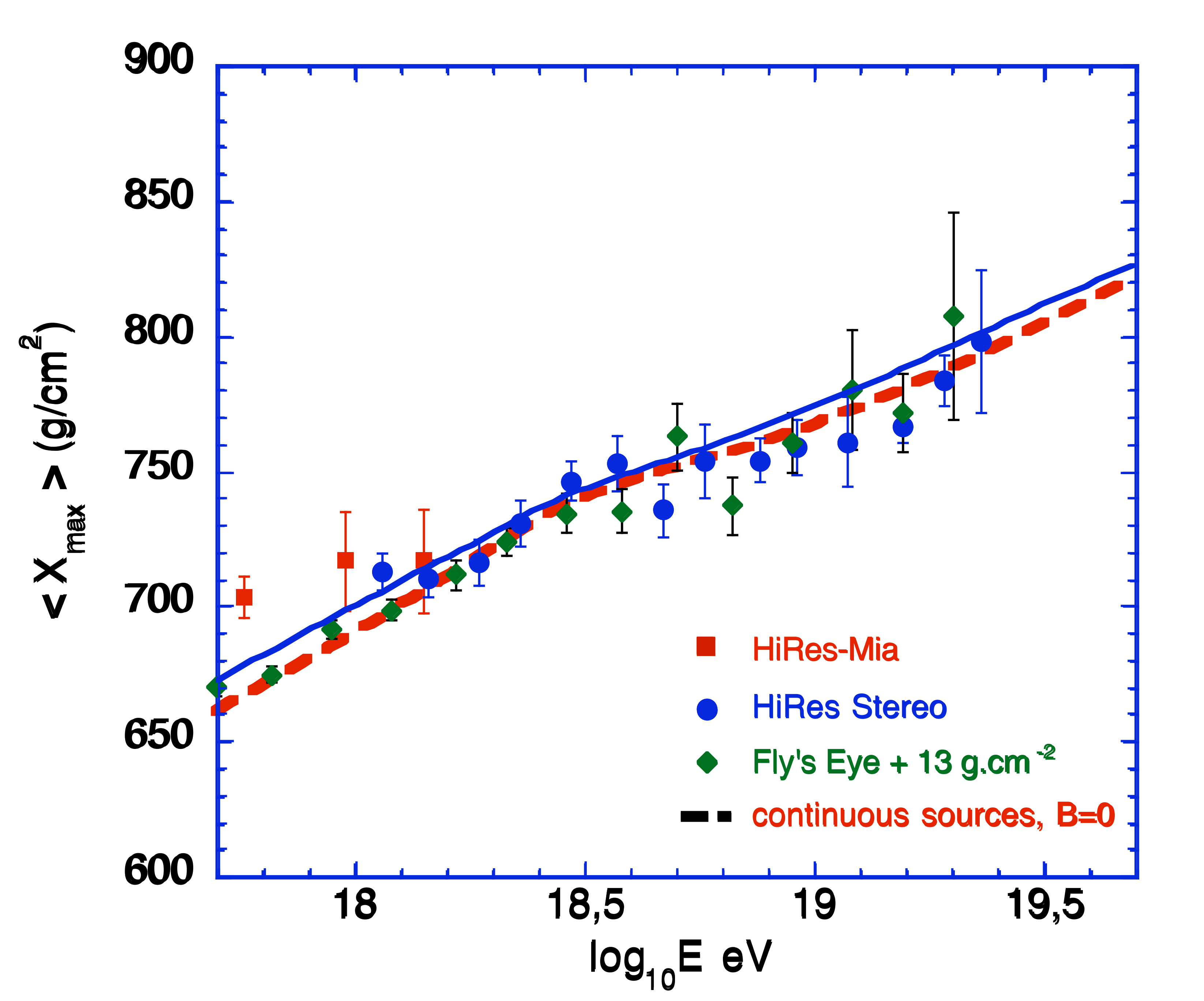
Xmax evolution : comparison with the pure proton model





Shapes and break points are unambigously different for the different models -> signatures of the transition models

Xmax evolution : comparison with pre-Auger data



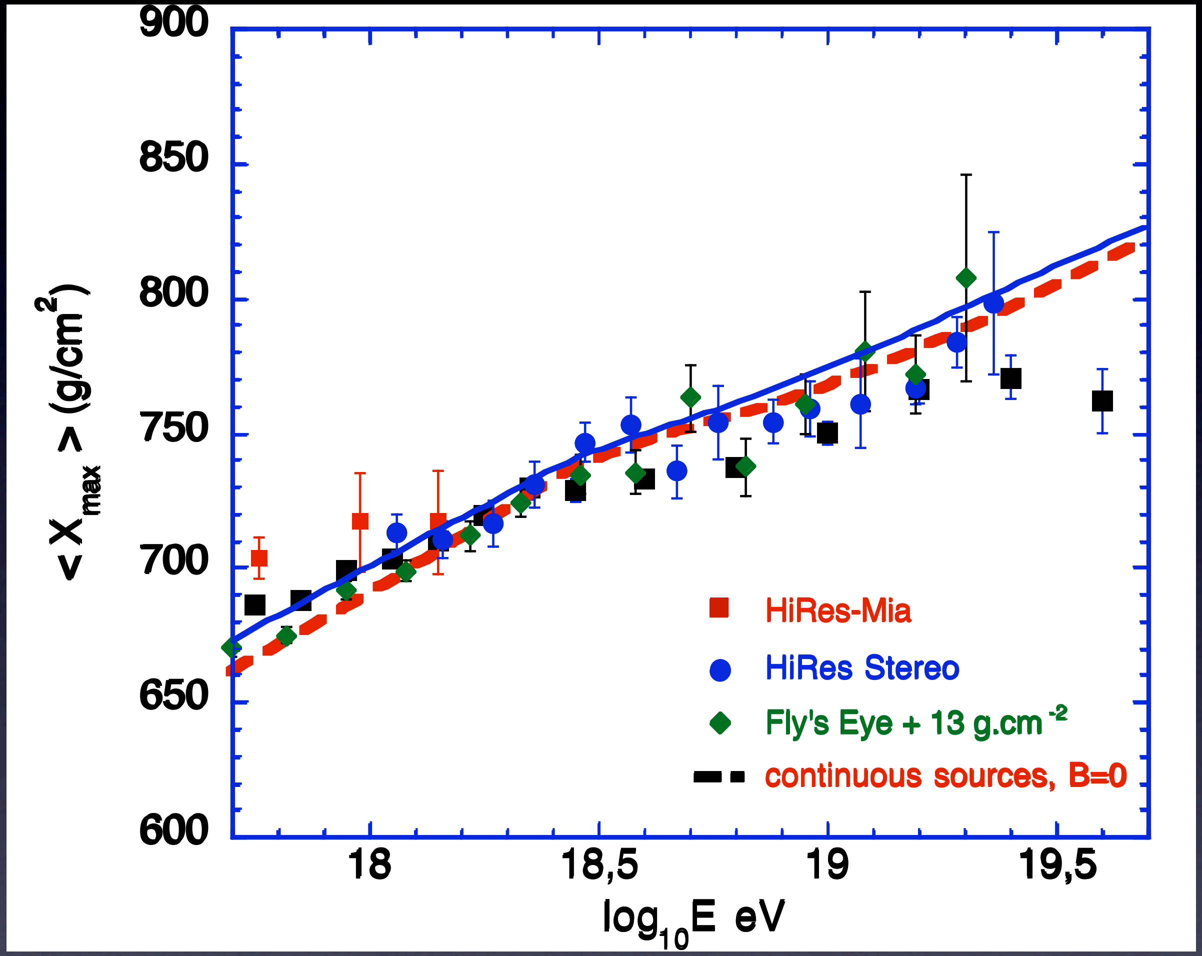
Good agreement above $10^{17.5}$ eV

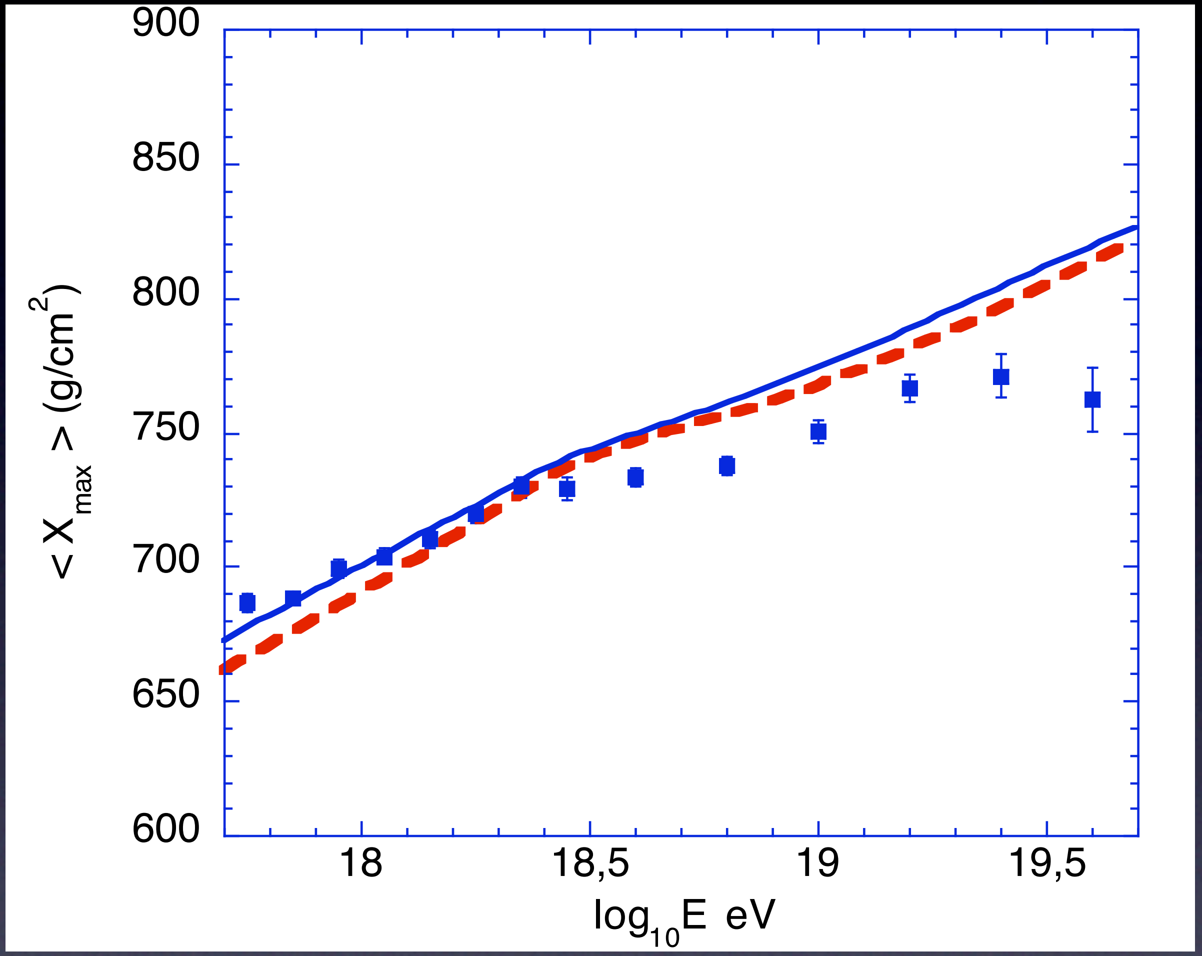
Fly's eye and HiRes compatible with the features expected for mixed composition model

HiRes-Mia only significantly disagrees in 1 point

More data are needed however

Adding Auger data... It does not work anymore

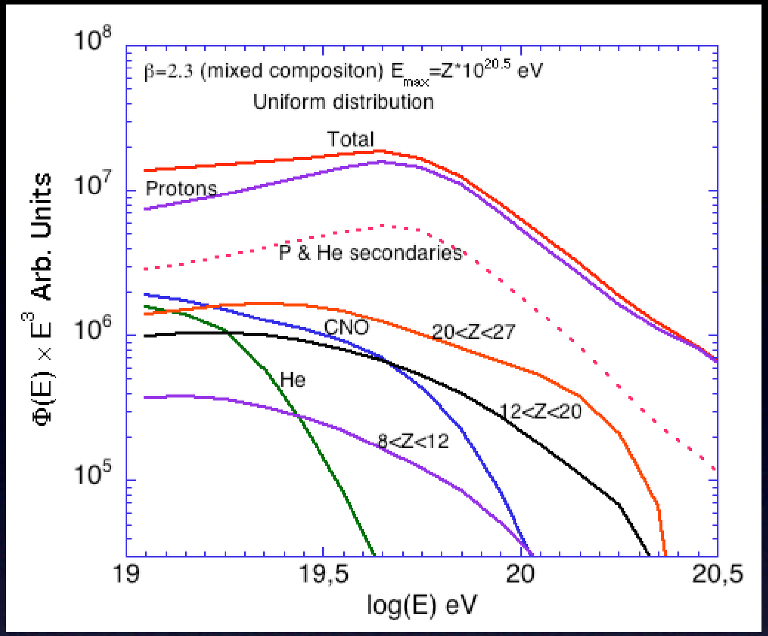


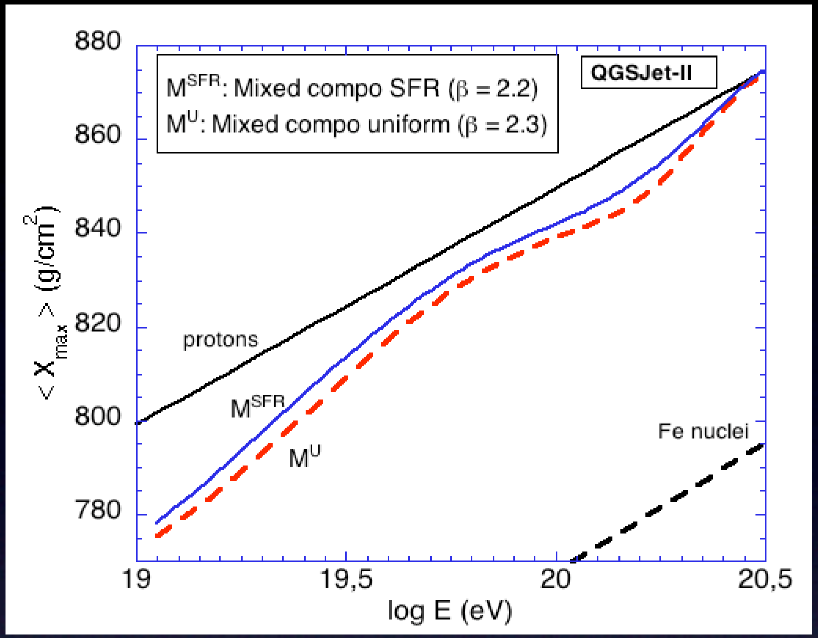


Break in the evolution compatible with the energy of the ankle
(very difficult to handle for pure proton models)
But the composition seems to get heavier at the highest energies
Latest Auger data seem to confirm this trend

What could it be?

High energy feature?





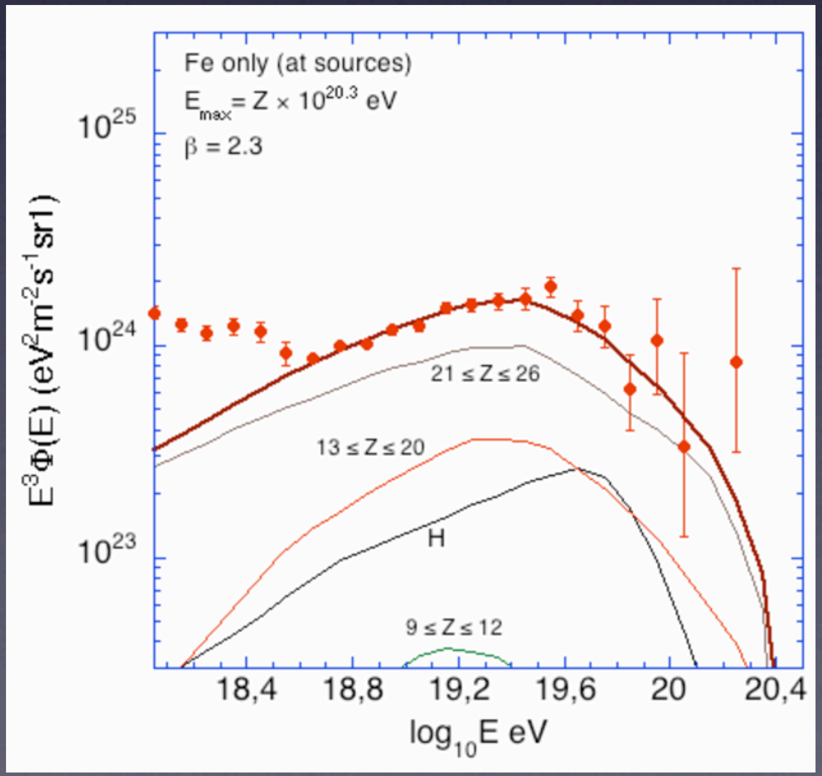
Above E~$10^{19.7}$ eV protons experience GZK effect -> proton spectrum falls more steeply than the heavy component up to the GDR threshold with CMB

The composition could get heavier in this short energy range and then go to pure proton

Effect is visible in the elongation even with low iron abundance at the source

not at the good energy !

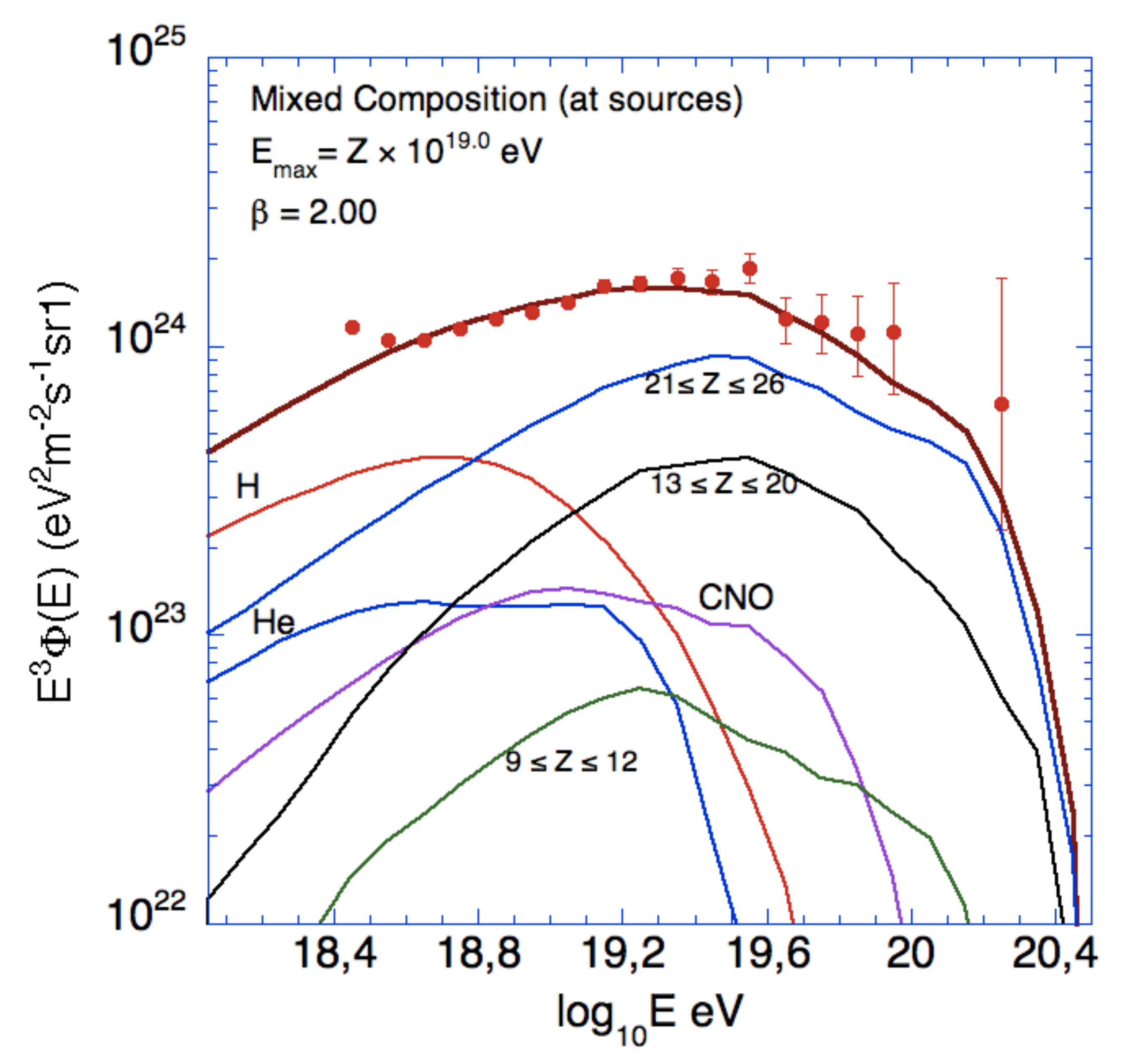
Pure iron composition?



No, the composition would be heavy all the way and we “know” the composition is quite light at the ankle

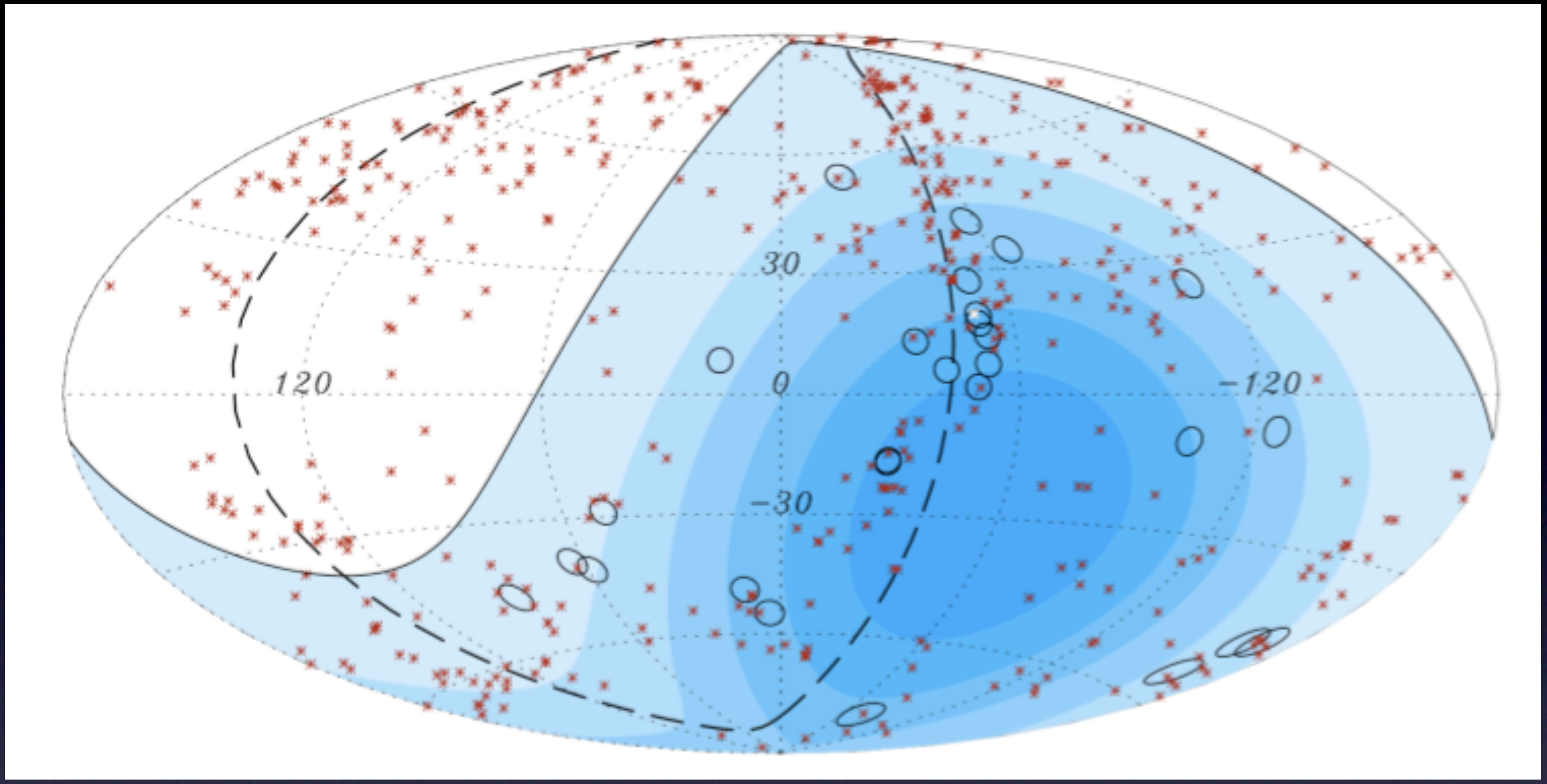
What could it be?

Mixed composition but with a low Emax for protons?



Fits well but requires more iron than the typical Galactic composition
quite light at the ankle, heavy at the highest energies

Auger anisotropy

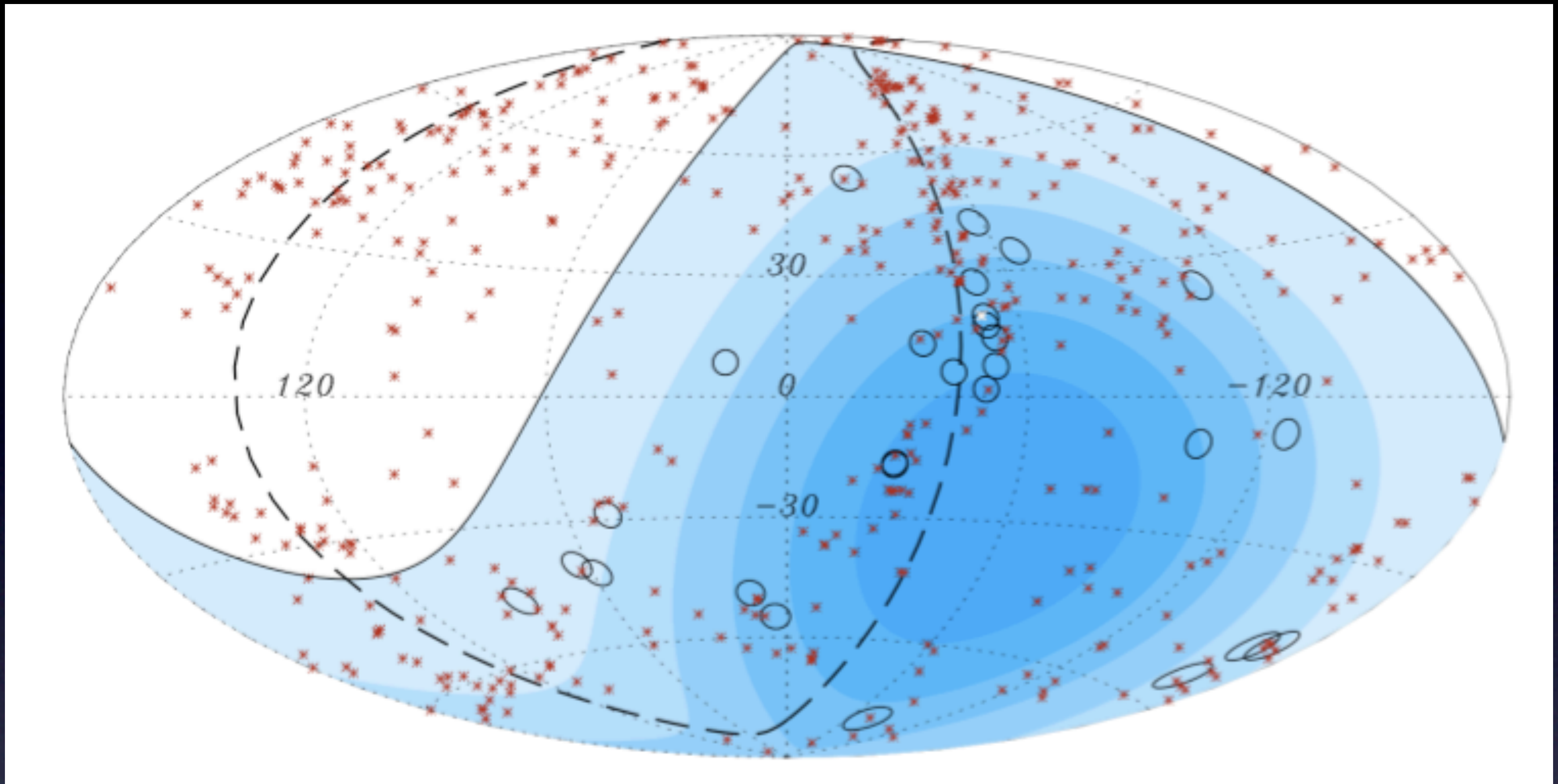


Nov 2007 : the Auger collaboration published results showing the correlation between the arrival direction of the 27th highest energy events and the direction of nearby AGN

Result obtained after a prescription placed on the Energy of the events, the maximum distance of the correlating objects and the angular scale of the correlation

Parameter of the correlation : E_{min}=57 EeV, D_{max}=75 Mpc, θ=3.1 deg
21/27 correlating events (19/21 outside galactic plane)

Auger anisotropy



What does it tell us?

the sky is anisotropic at the highest energies : isotropy rejected at 99% C.L

-> extragalactic origin

-> promise of cosmic-ray astrophysics

But it does not tell :

what the sources are

what the composition is

whether the correlation parameters are physical or not

Protons coming from AGNs?

The AGN that correlate could be the sources and the correlation parameters could be physically relevant
-> small deflexions
-> most likely protons

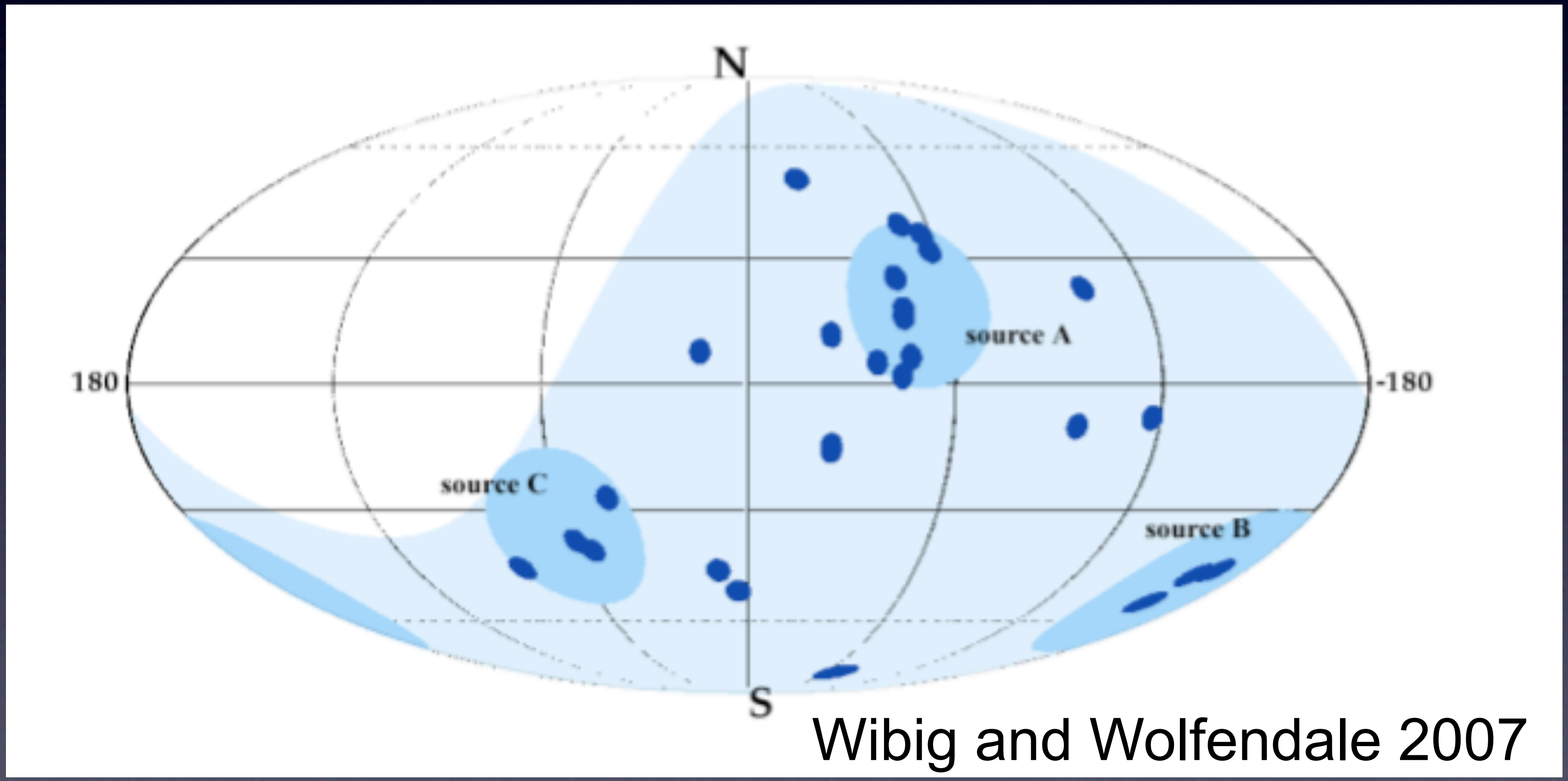
Parameter of the correlation : E_{min}=57 EeV, D_{max}=75 Mpc, θ=3.1 deg
21/27 correlating events (19/21 outside galactic plane)
Assuming sources distributed like AGN
From propagation studies one would expect D_{max} between 160 and 200 Mpc
-> either an energy or a horizon crisis (one would have to increase Auger energy scale by ~40% to reconcile E_{min} and D_{max})
-> one can actually show "simulating" the scan and prescription procedure that the correlation parameters are not trivially related to the physical parameters (N.G Busca et al., 2008)

We have a correlation with an imcomplete and inhomogenous catalogue
Most of the AGN that correlate are not especially strong objects for non thermal radiations

Arrival directions might just point toward the last (magnetic) scattering center and not the source (hypothesis quantitatively studied by Kotera and Lemoine (2007))

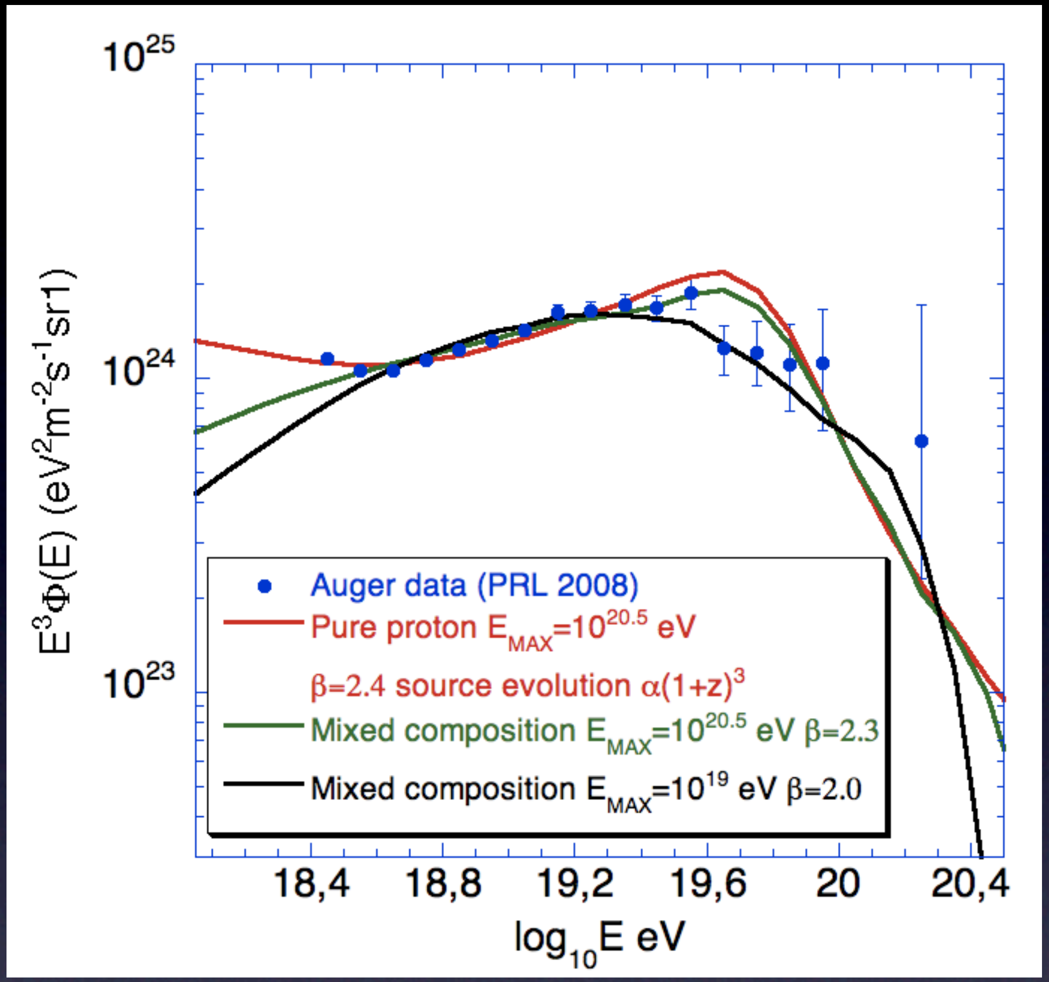
Does a composition getting heavy contradict Auger anisotropy result?

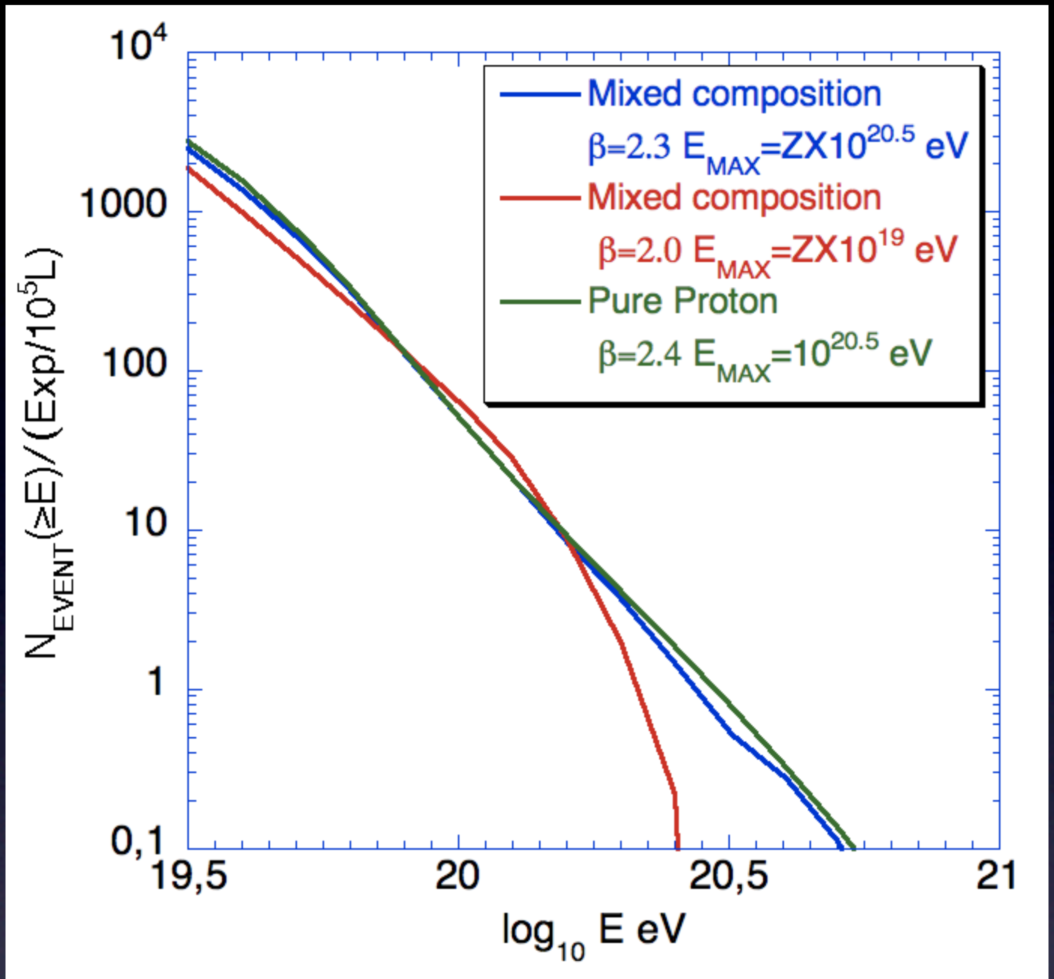
Not at the current level of statistics : Anisotropy depends on the source density, the magnetic fields and the composition. An anisotropic sky does not imply protons (neither do protons imply anisotropy).
Significant small scale clustering would be difficult to handle but is not seen so far



Wibig and Wolfendale 2007 : a few dominant sources of heavy nuclei reproduce most of the correlation

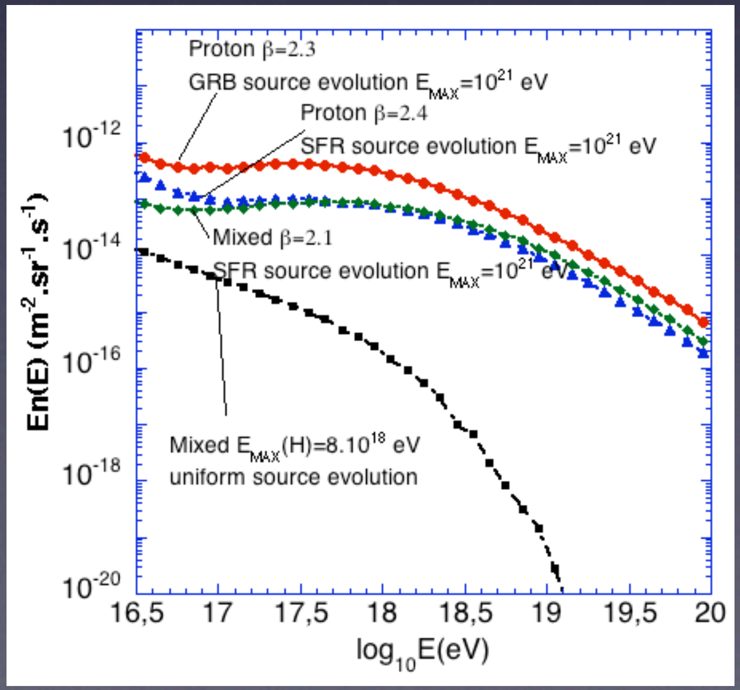
Implications and collateral damages





Basically 0 event expected for Auger North above 3.10^{20} eV

Cosmogenic neutrino flux should be highly depleted at high energy




Thank you!