High Energy Cosmic Rays: sources and fluxes

Todor Stanev
Bartol Research Institute and Department of Physics and Astronomy, University of Delaware, U.S.A

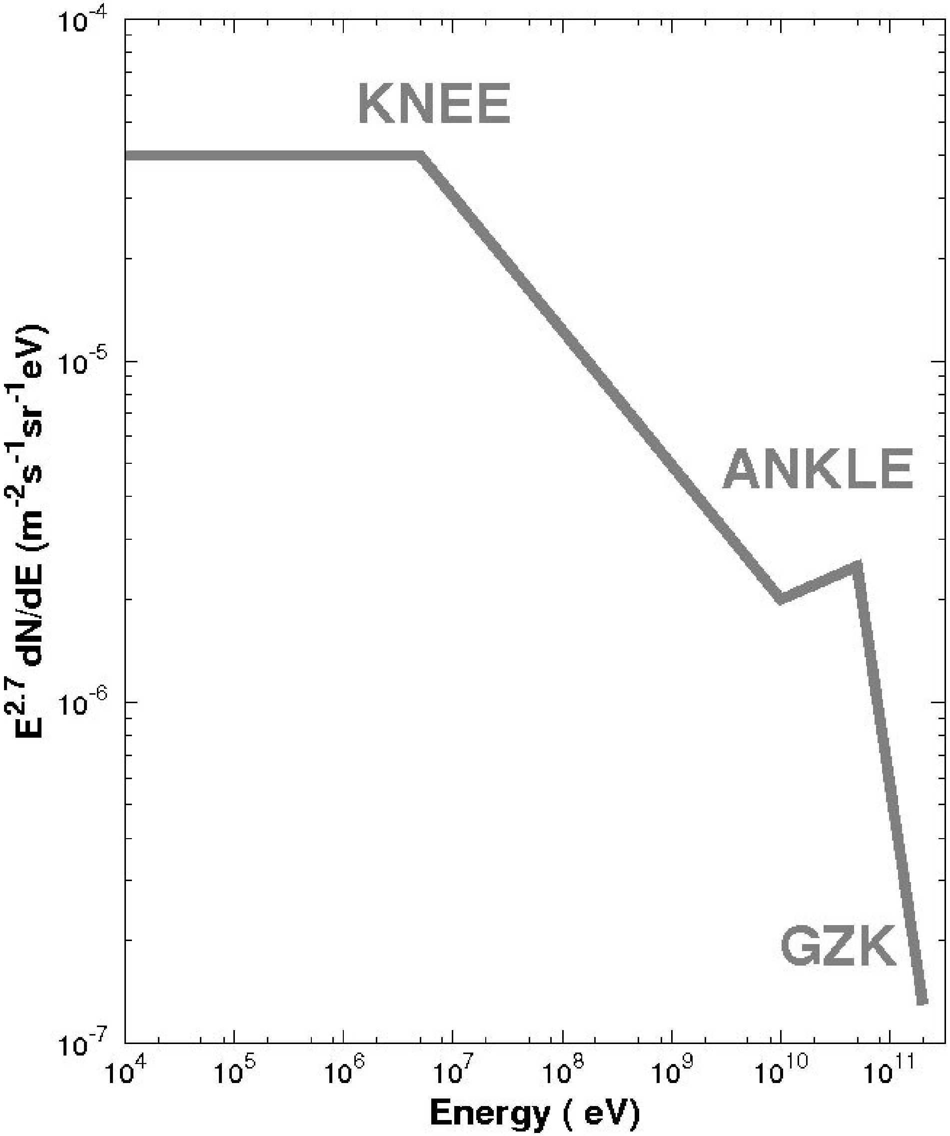
How are High Energy Cosmic Rays measured ?
How is their energy assigned ?
What do the observations during the last 50 years show ?
What can we do to obtain an unique cosmic rays spectrum ?
What does such a spectrum suggest ?

This talk is based on work with Thomas Gaisser and Serap Tilav

At energy above 100 TeV the measurement of the cosmic ray spectrum are impossible in direct experiments. The hope is that AMS 02 will do better working for years on the International Space Station.

What we do is to detect extensive air showers on ground level and use Monte Carlo shower simulations to estimate the energy of the primary particles. This is impossible for individual EAS and depends heavily on the primary particle type (proton or nucleus) and on the hadronic interaction models used in the simulation.

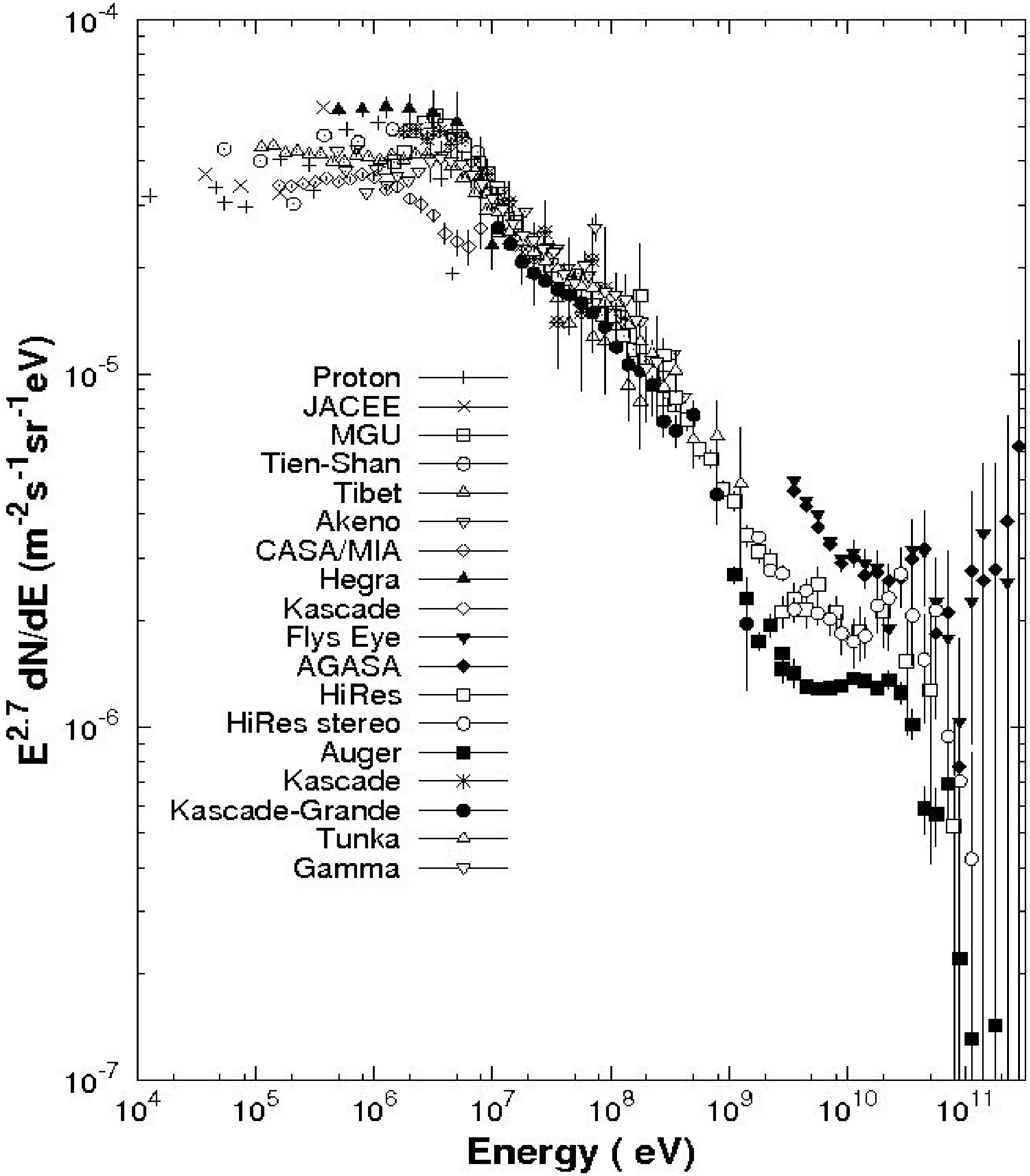
The situation is still more difficult at the highest shower energies where we do not have accelerator measurements to compare the interaction models to. The Lab energy of LHC (14 TeV in cms) is only 10^{17} eV.



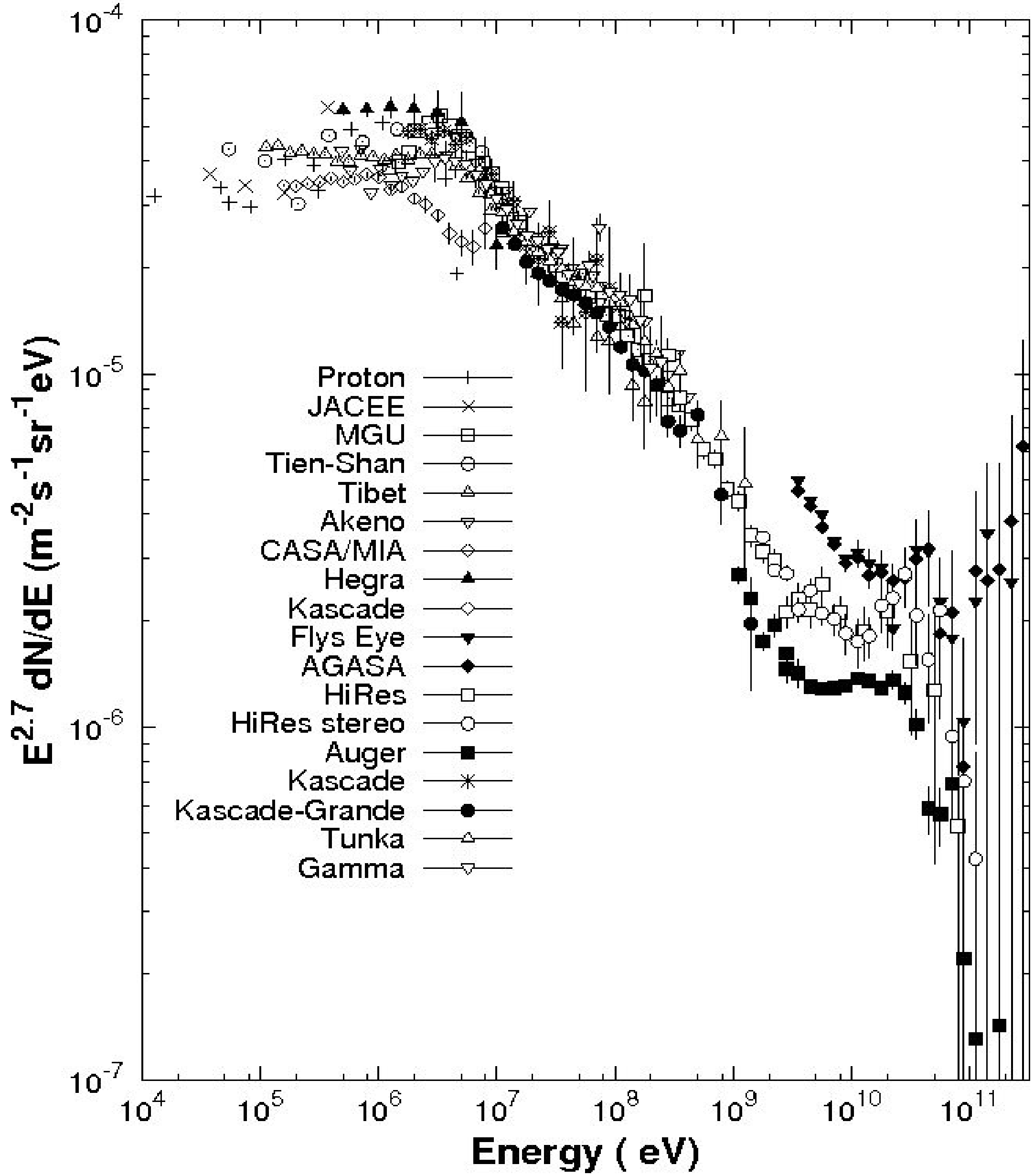
Life used to be easy some time ago when I started studying cosmic rays.

We knew about the `knee' of the cosmic ray spectrum (suggested in 1958) and about the fact that at very high energy the cosmic ray spectrum should dissapear because of the GZK effect (1966).

So we had galactic sources up to the knee and extragalactic sources after the ankle. The knee is either the highest acceleration energy for protons or the beginning of the leakage of the cosmic rays out of the Galaxy.



The measurements, however, showed different features. Here is a collection of spectra published by different experiments. Can we have a better understanding of the spectrum looking carefully at all measurements?



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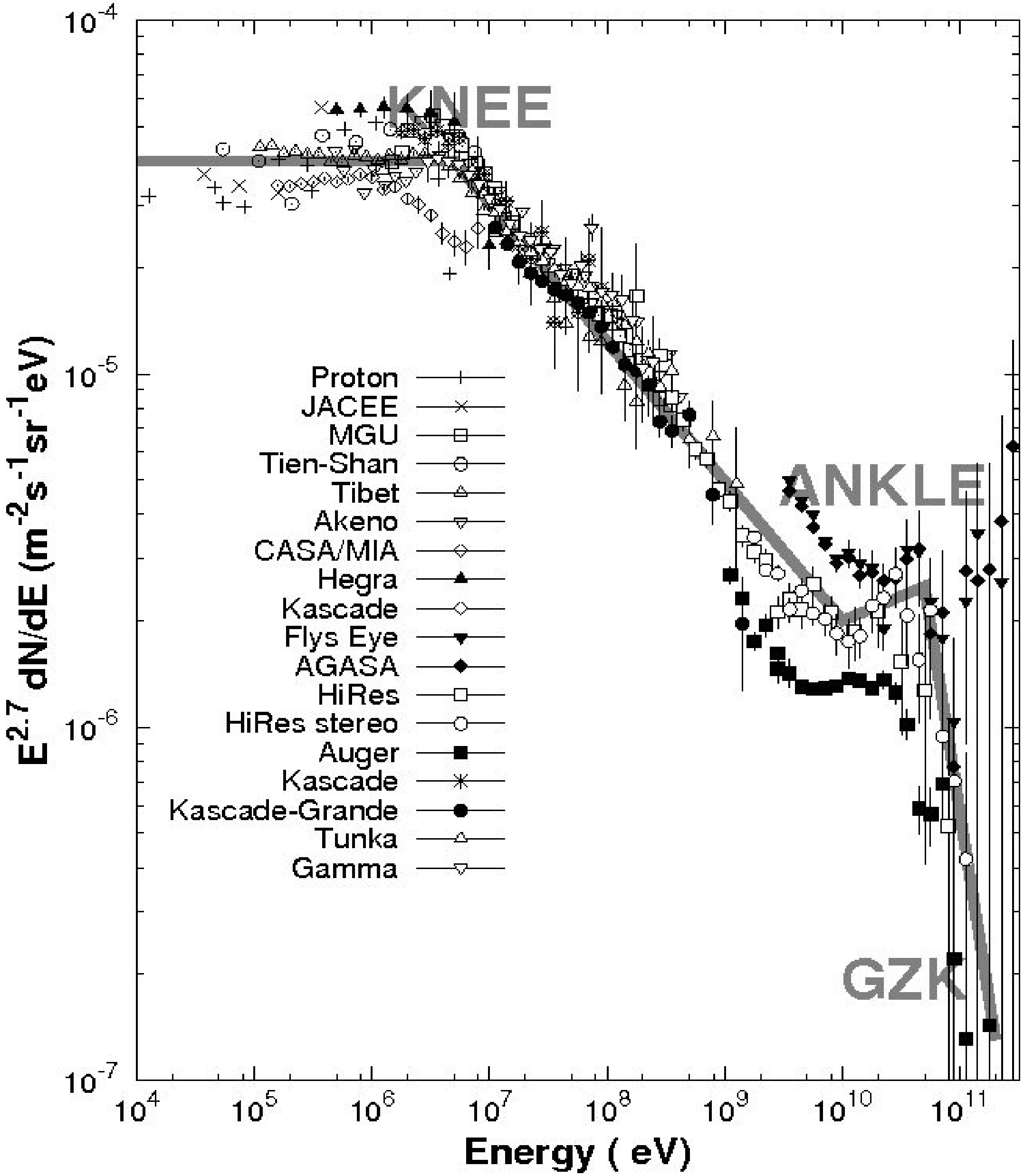
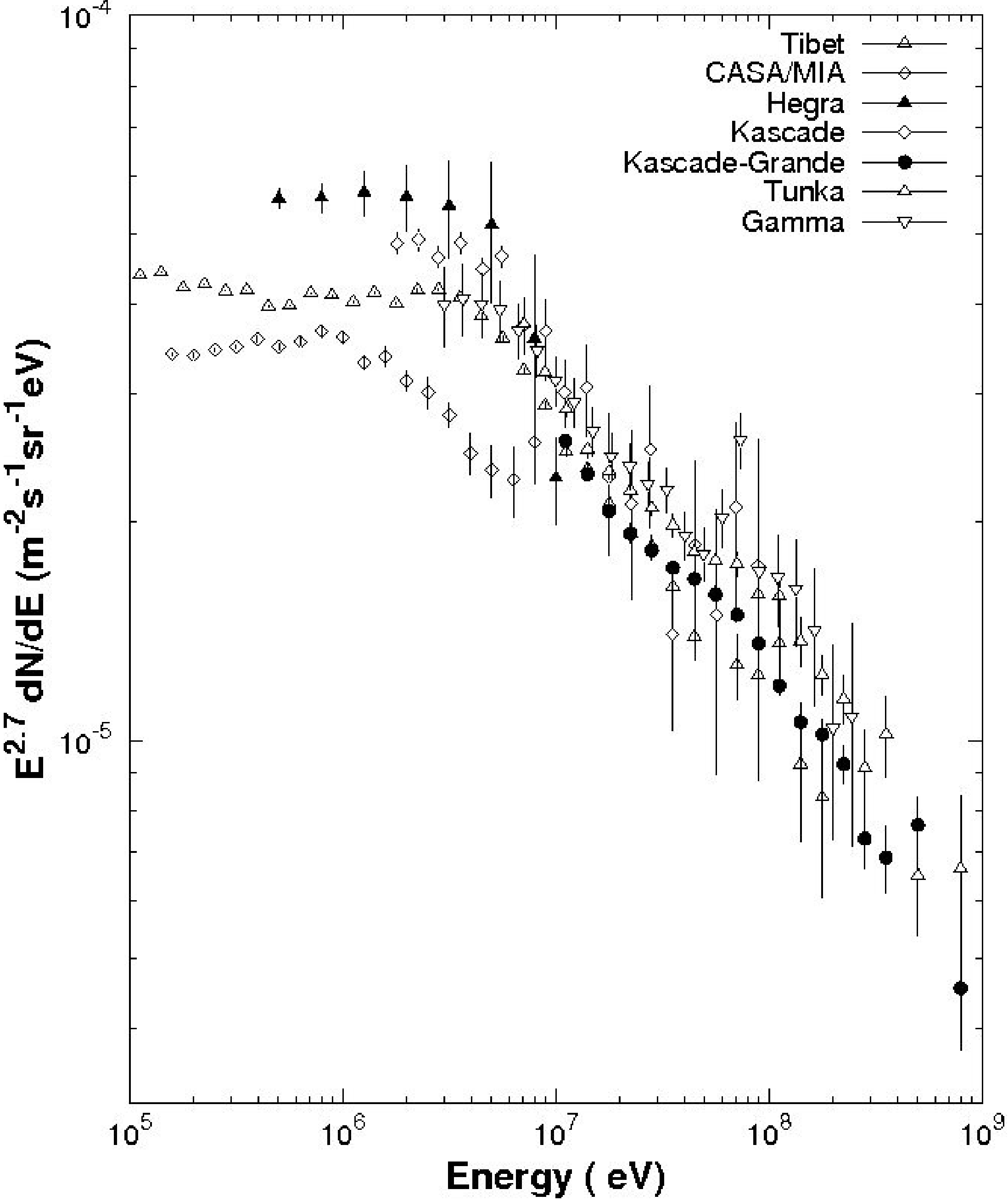


Not that the general features, the knee and the ankle, contradicted the measured spectra.

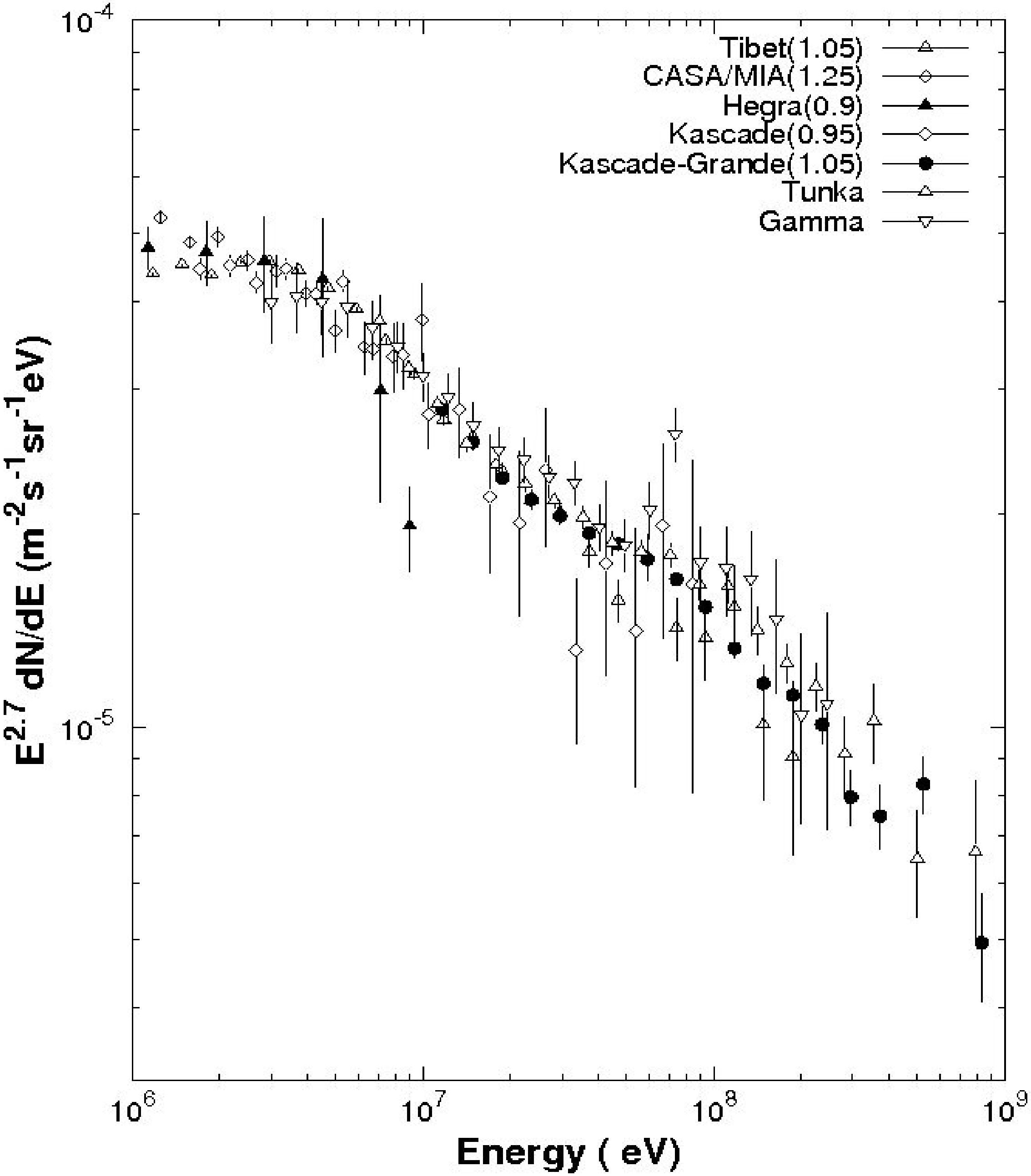
The multiplication of the measured fluxes by a power of the energy was made to make these features better visible.

Below the ankle the fluxes are plotted multiplied by $E^{2.7}$ while at higher energy there were multiplied by E^3.



Here is a smaller data set not reaching the ankle. Can we learn more from it? Can we make the data points agree with each other?

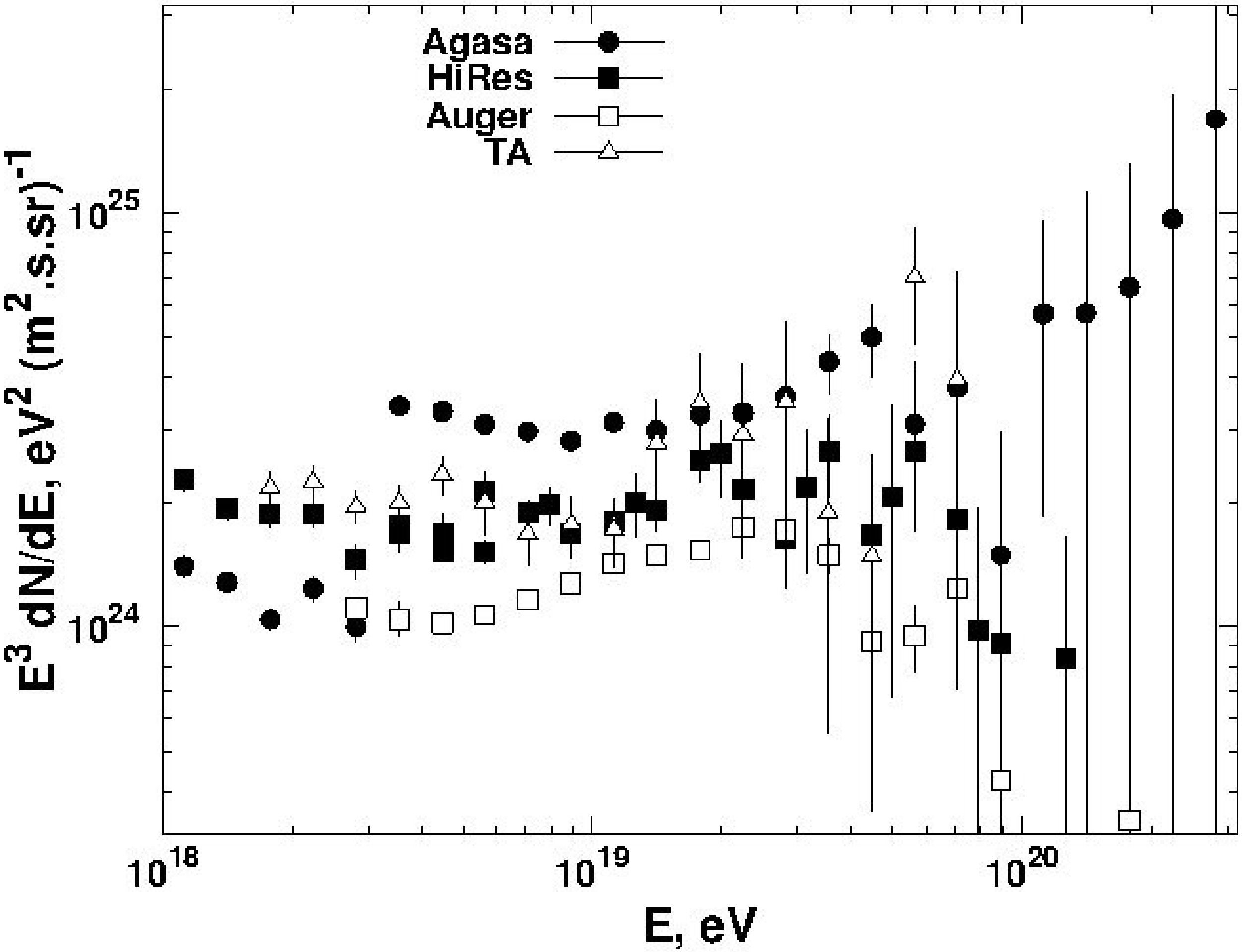
We have to use the trick recommended by Venya Berezinsky or by Arnold Wolfendale and Tolya Erlykin, who used the position of the ankle or of the knee to estimate the energy assignment of the different experiments.



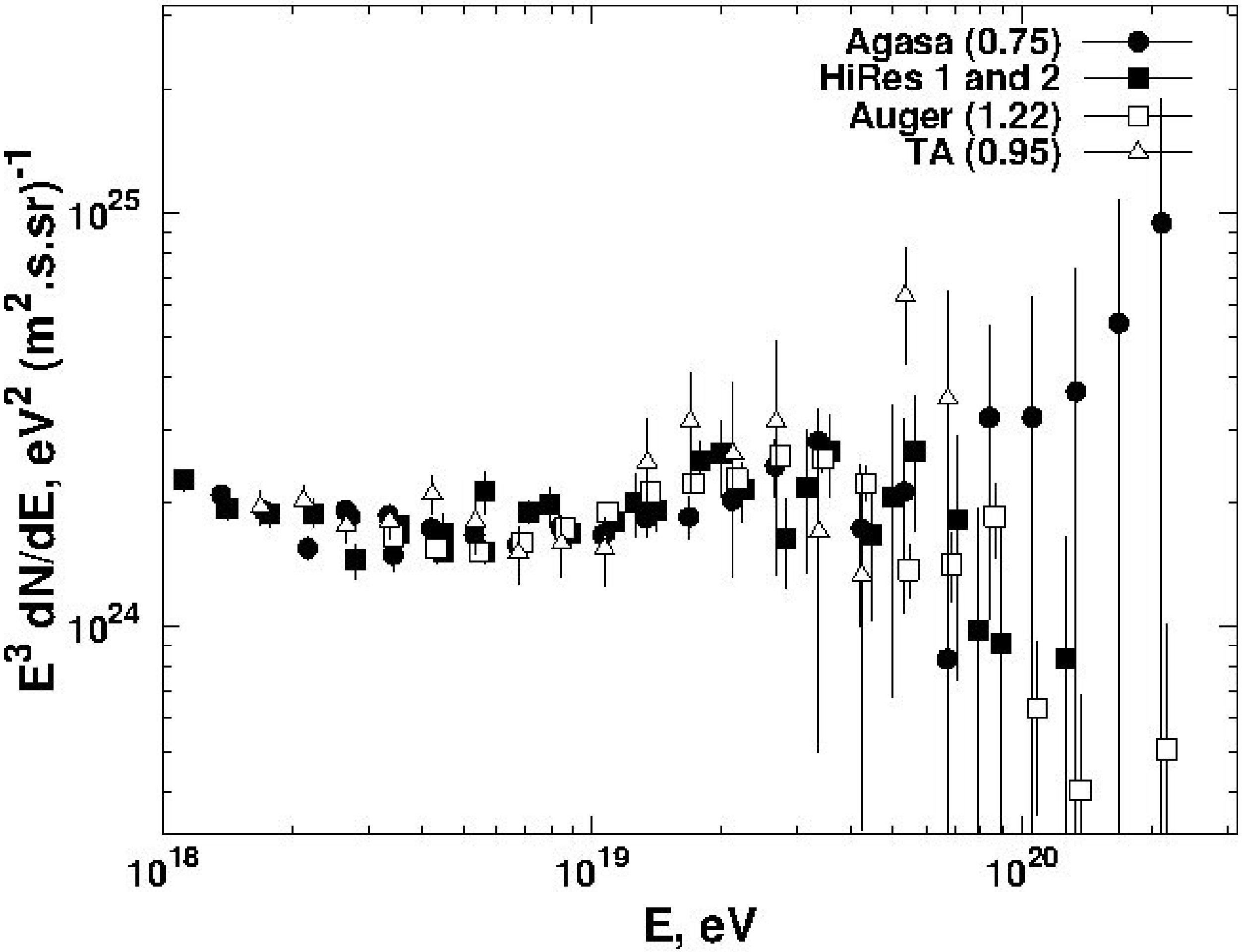
The same features are visible in the IceTop energy spectrum

We did that recently with Tom Gaisser and Serap Tilav. The scaling factors of the different measurements are shown in the graph. The spectra of Tunka and Gamma are not scaled.

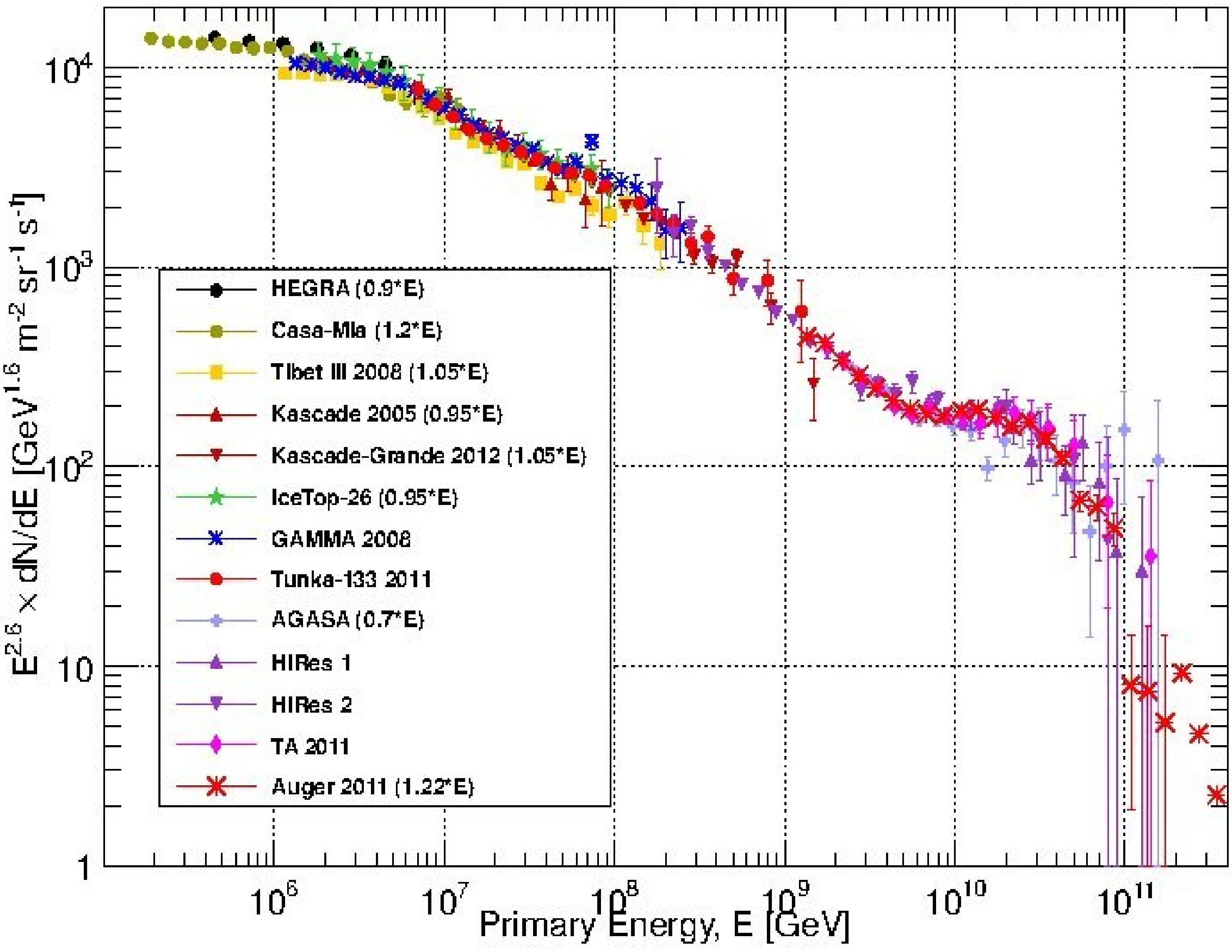
It looks like the spectra combined in this way show more interesting features than the straight lines before and after the knee. **Are these indeed true and what they mean?**



These are the ultrahigh energy cosmic ray spectra including the Agasa experiment. Agasa energy assignment was not made with contemporary hadronic interaction models. The energy assignment with QGSjet was not published.

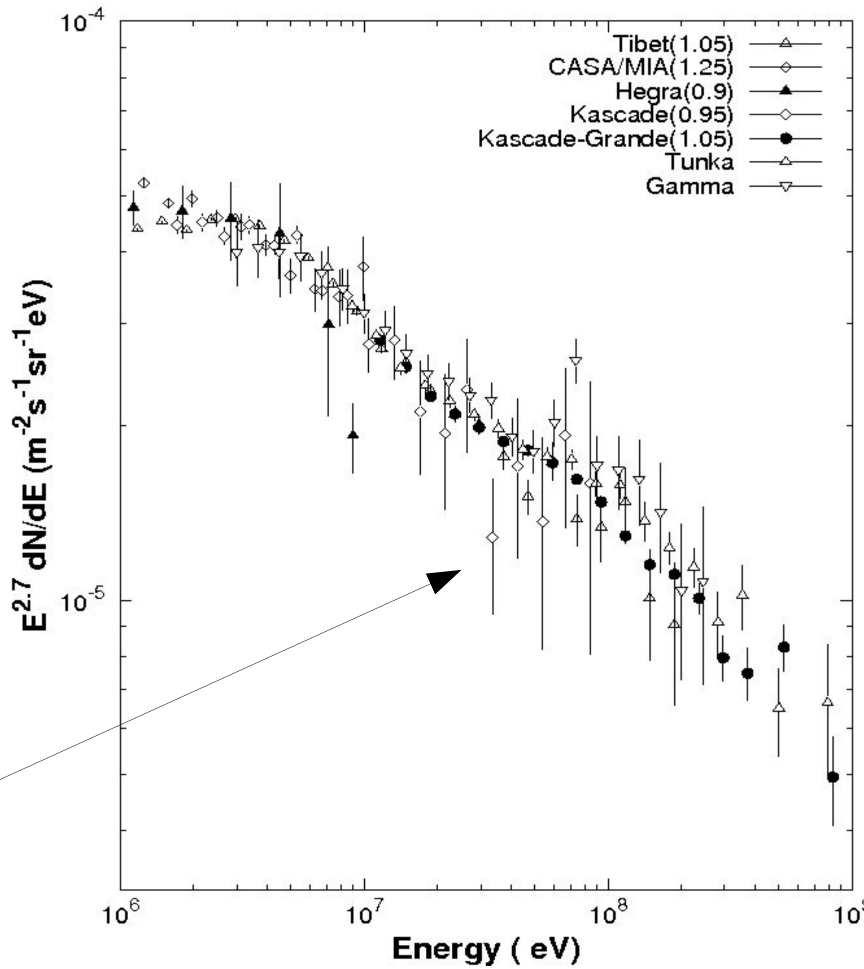


After shifting with indicated amout spectra (even Agasa) seem to agree except the highest energy Agasa events. Note that in this graph we are shifting Auger results up by their whole systematic error. One can do the opposite and shift HiRes and TA down with the same amount.



The cosmic ray spectrum after shifting all air shower data energy assignment.

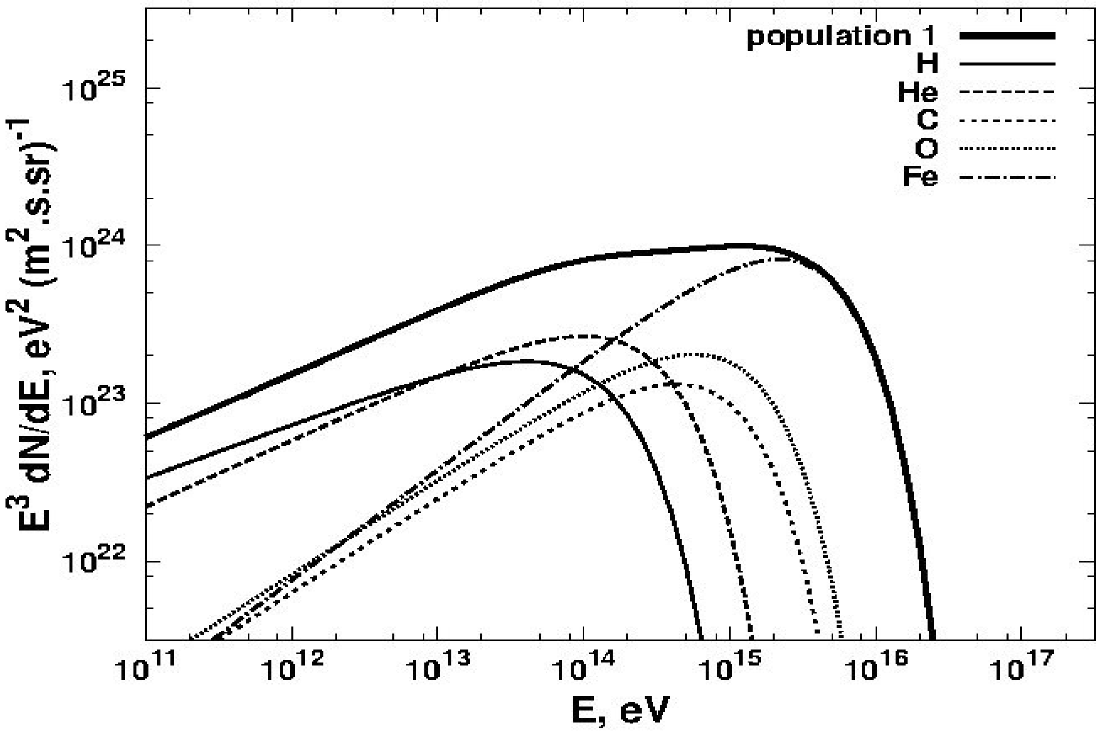
The appearance of a `second knee' at about logE = 7.8 reminds us of an idea of A. Michael Hillas (2005) who felt the need of a second generation of galactic sources that peak just below the ankle.

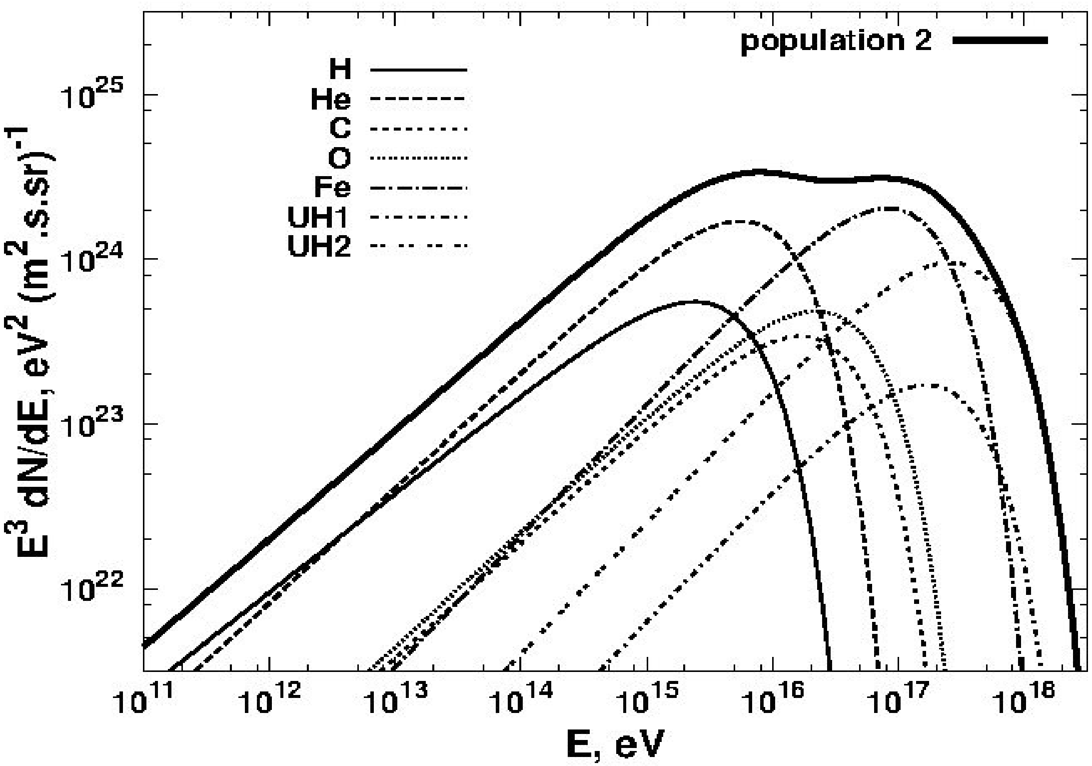


The second knee suggested by the Gamma and Tunka experiments

It is easy to re-implement the idea thinking of the 1961 paper of Bernard Peters stating that both cosmic ray acceleration and propagation in the Galaxy have to be discussed in terms of rigidity ($R = p/Z$). If a proton can be accelerated up to energy E_{max} then a nucleus of charge Z could achieve Z times higher energy.

We did use the Peters cycle trying to fit the shifted air shower spectra. There was no restriction on the number of *populations* of cosmic rays (presumably due to different types of sources) in the fit. The fitting procedure came up with four population where the fourth one describes the extragalactic cosmic rays. It is highly uncertain because the differences in the UHECR composition derived by HiRes (and TA) and Auger.

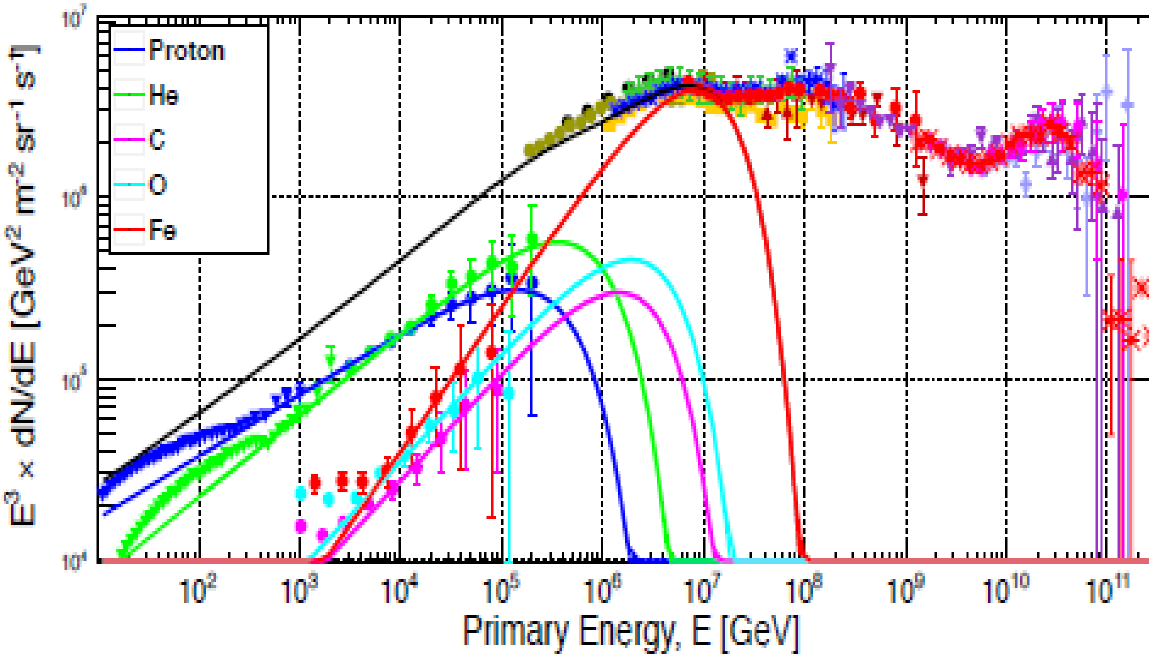




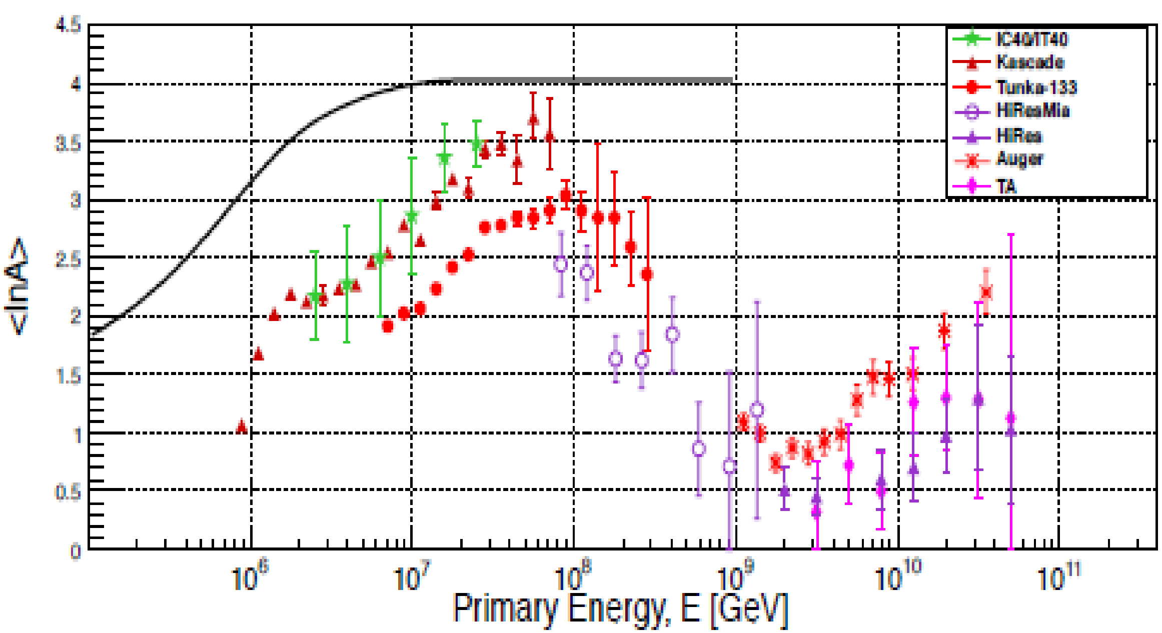
These are the first two *populations* that came out of the `global fit' performed by Serap Tilav.

The first one is based on the direct measurements of Pamela and CREAM. All nuclei have a flatter acceleration spectrum.

The second one is amazing because of the very flat acceleration spectra of all nuclei. The final spectrum is determined by the acce-leration spectra and the corresponding cutoff R.



This is how fitting goes
If we stop after the first population all cosmic rays above 10^5 GeV are Fe nuclei. We have to add another population to have correct lnA.



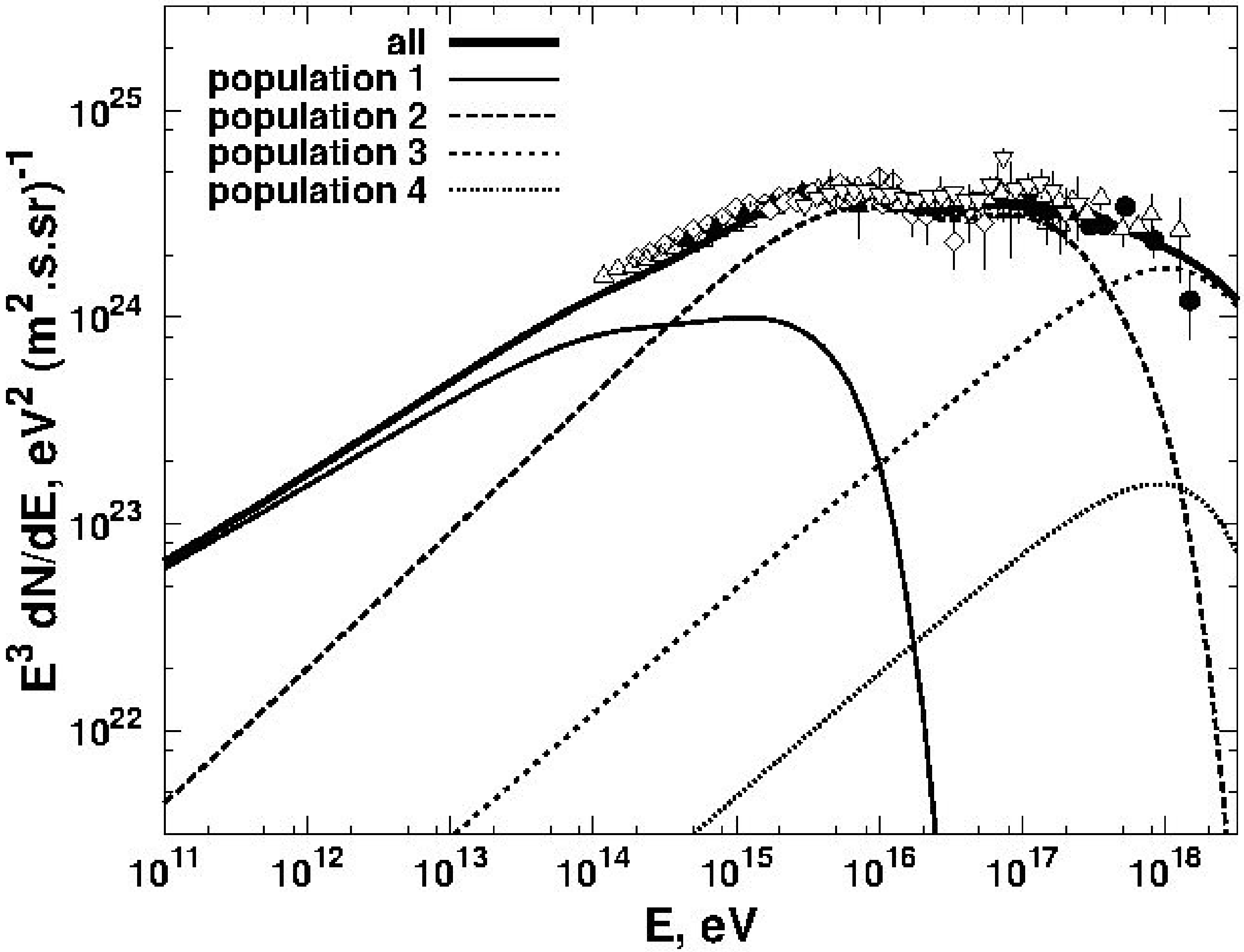
source: Serap Tilav

Here are the major features of the four populations

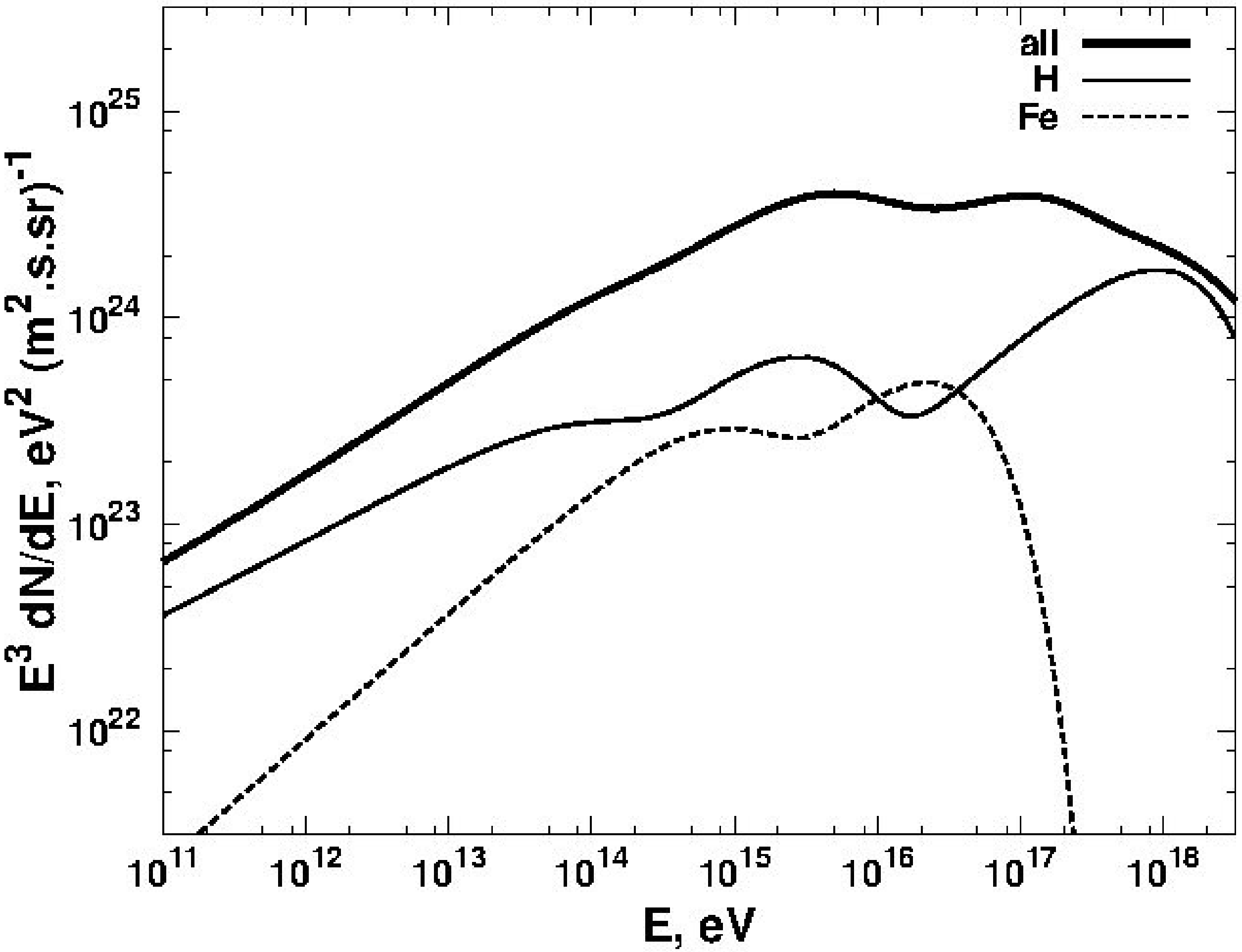
	Cutoff	γ	H	He	C	O	Fe	53	60
1	1.2E5		1.66	1.58	1.4	1.4	1.3		
2	4.0E6		1.4	1.3	1.3	1.3	1.2	1.2	1.2
3	1.5E9		1.4				1.2		
4*	4.0E10		1.4						

* if HiRes composition is correct

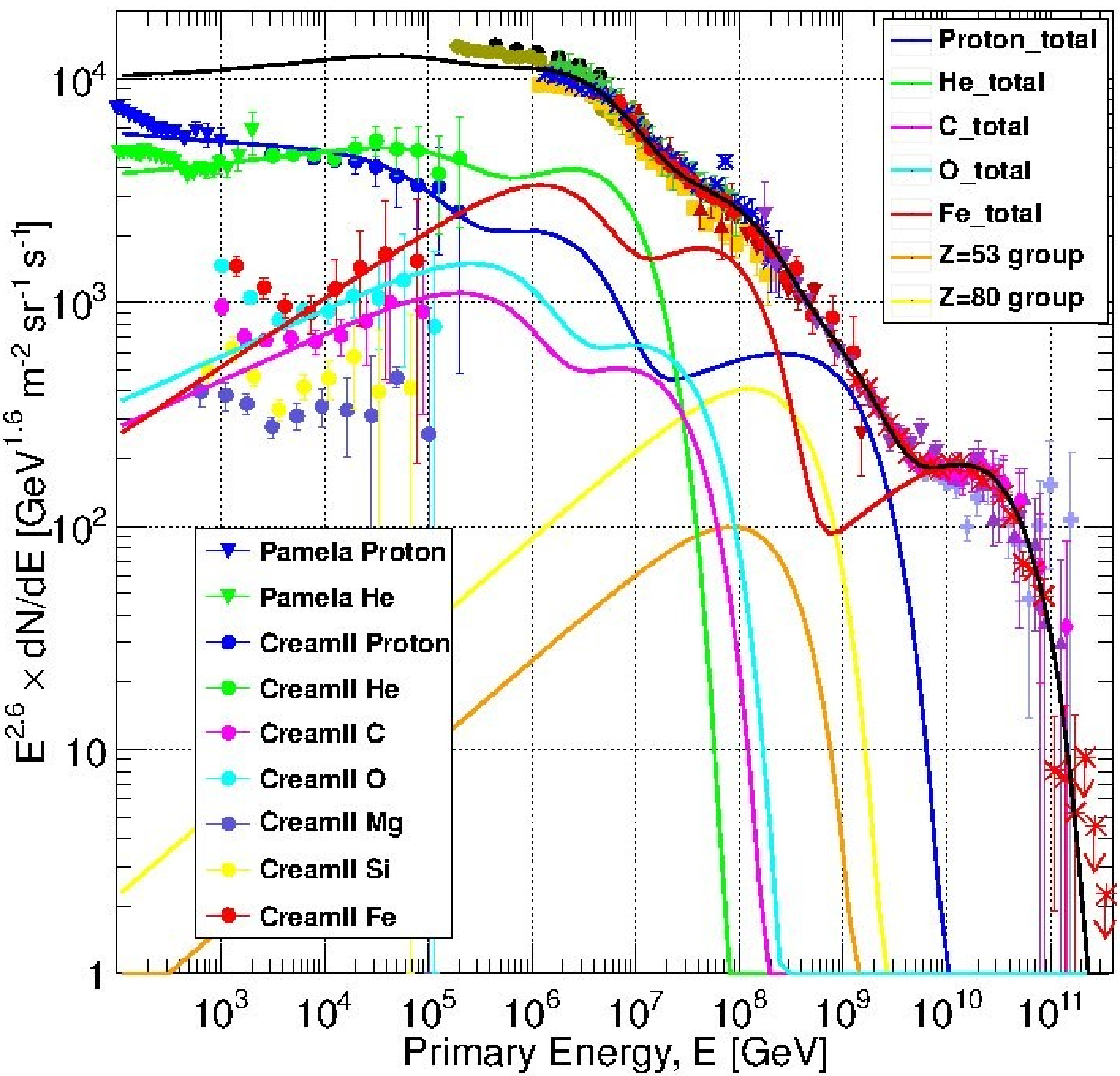
It is very interesting that the cutoff of population 1 corresponds of the early calculation of Lagage & Cesarsky (1983). One could start thinking of supernova remnants having the same parameters that they assumed.



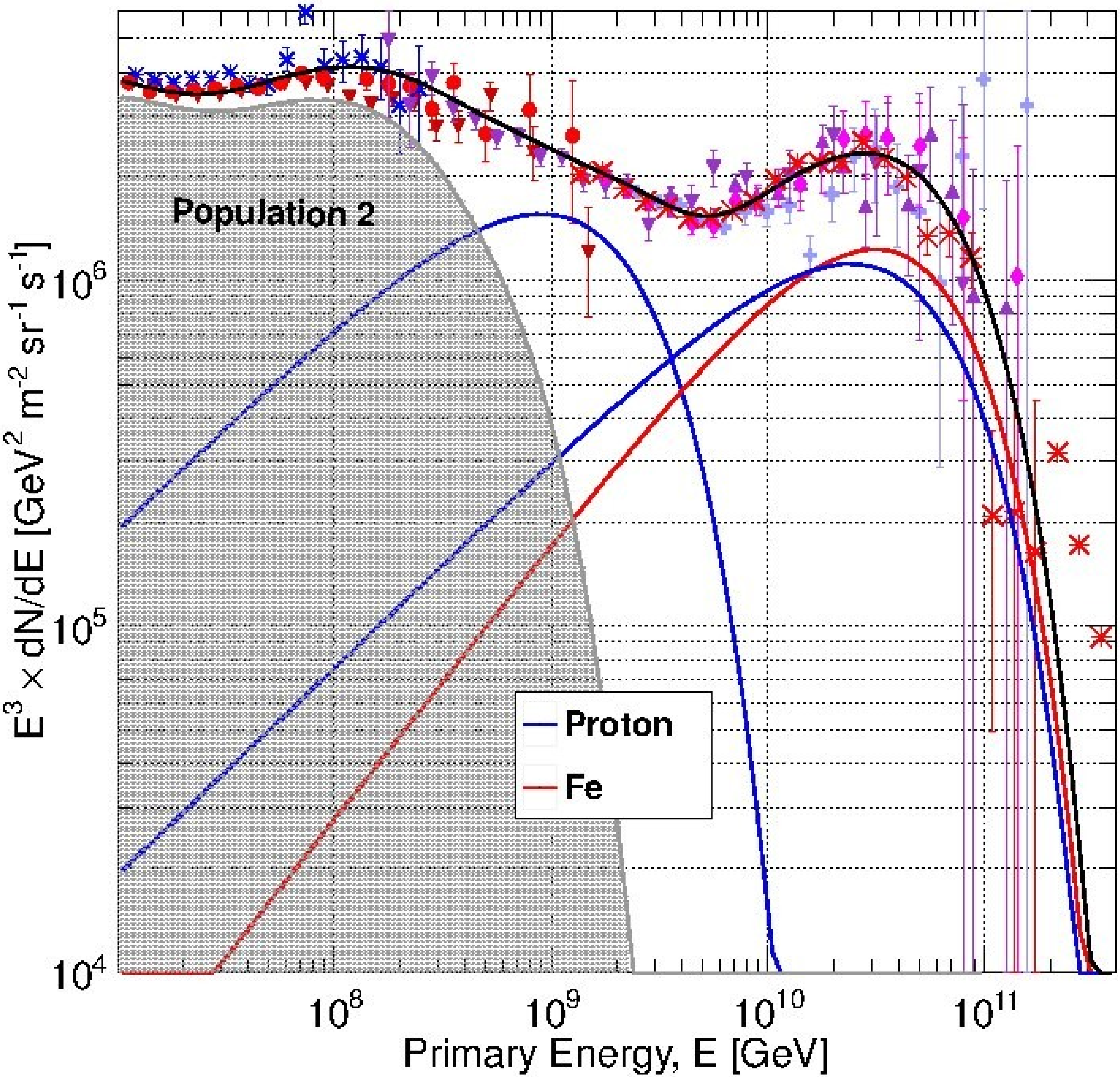
Here is the contributions of the four populations to the final cosmic ray spectrum fit. A comparison with all spectrum data will be shown later.



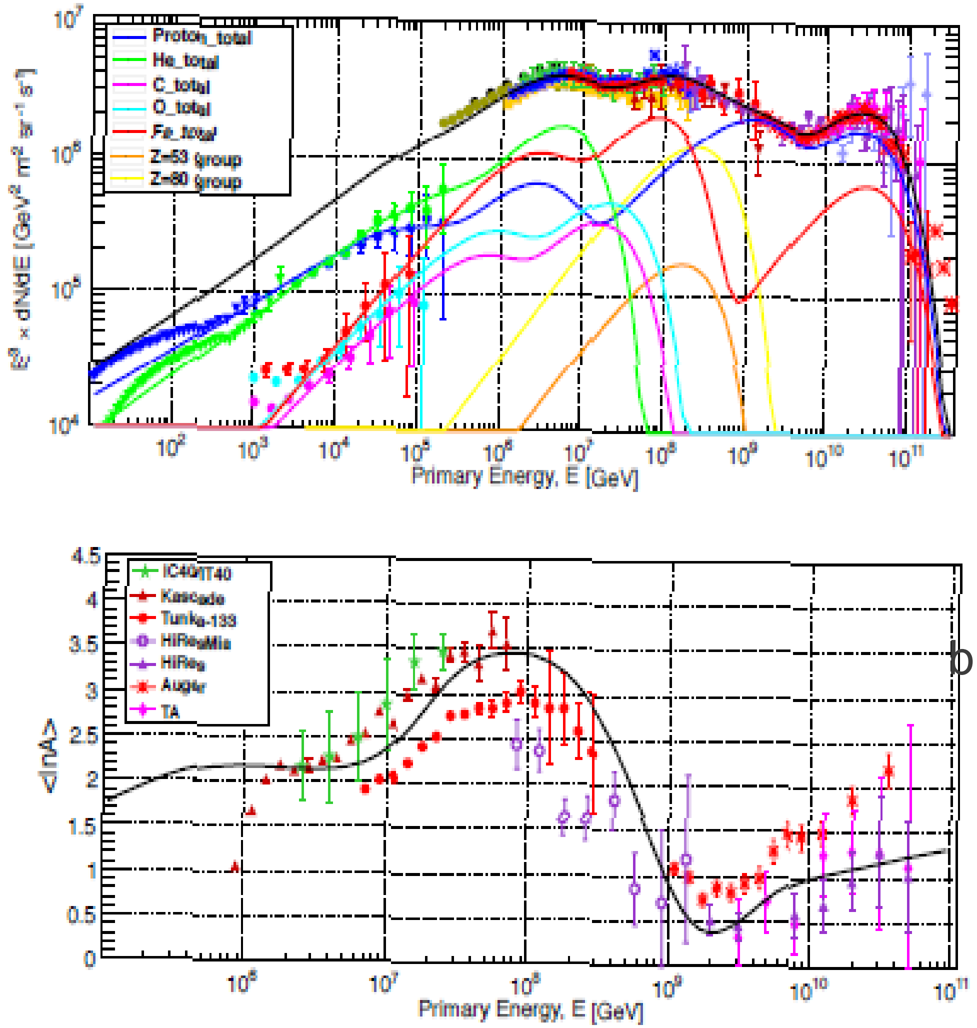
The graph shows the contribution of protons and of Fe nuclei to the final all particles spectra. Ultraheavy nuclei do not contribute a lot to the final spectrum. The fits of the highest energy are uncertain because of the different composition in HiRes and Auger.



Proton_total
He_total
C_total
O_total
Fe_total
Z=53 group
Z=80 group
Pamela Proton
Pamela He
CreamII Proton
CreamII He
CreamII C
CreamII O
CreamII Mg
CreamII Si
CreamII Fe
$E^{2.6} \times dN/dE$ [$GeV^{1.6}$ m^{-2} sr^{-1} s^{-1}]
Primary Energy, E [GeV]

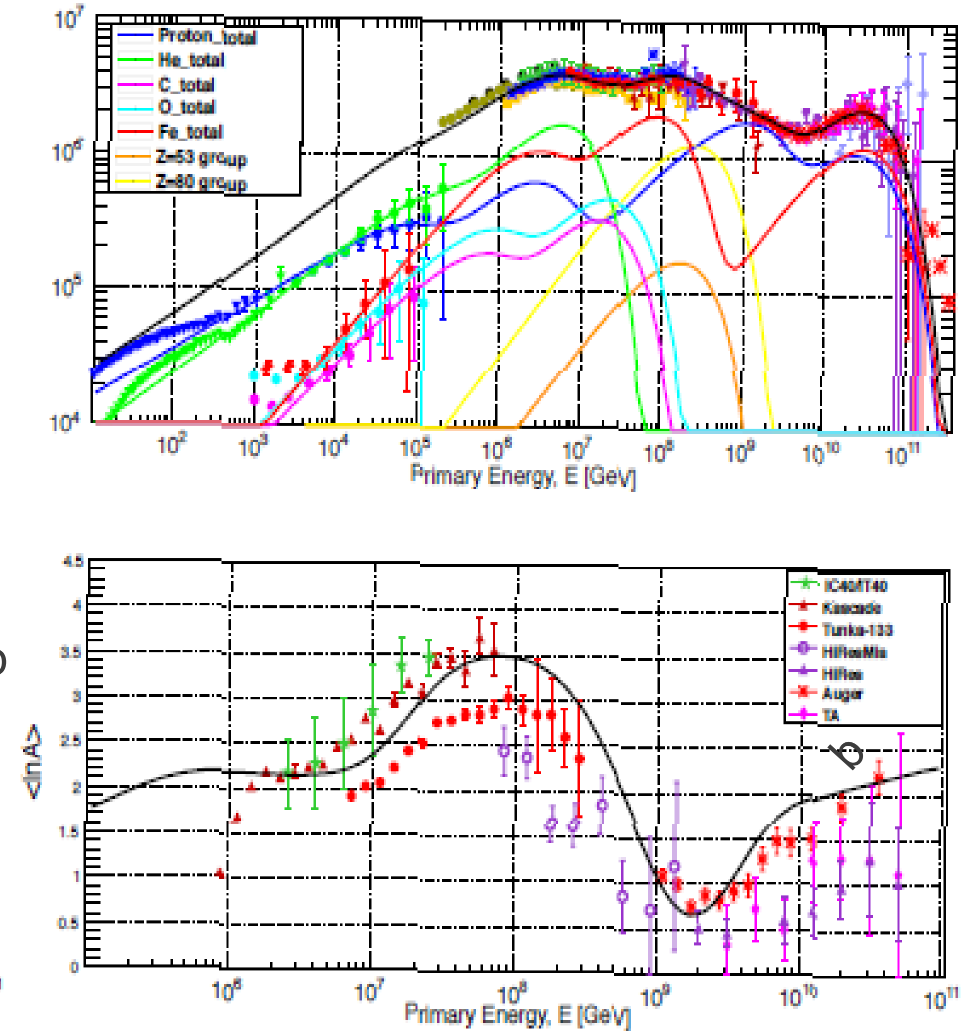


Population 2
Proton
Fe
$E^3 \times dN/dE$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
Primary Energy, E [GeV]
10^4
10^5
10^6
10^8
10^9
10^{10}
10^{11}



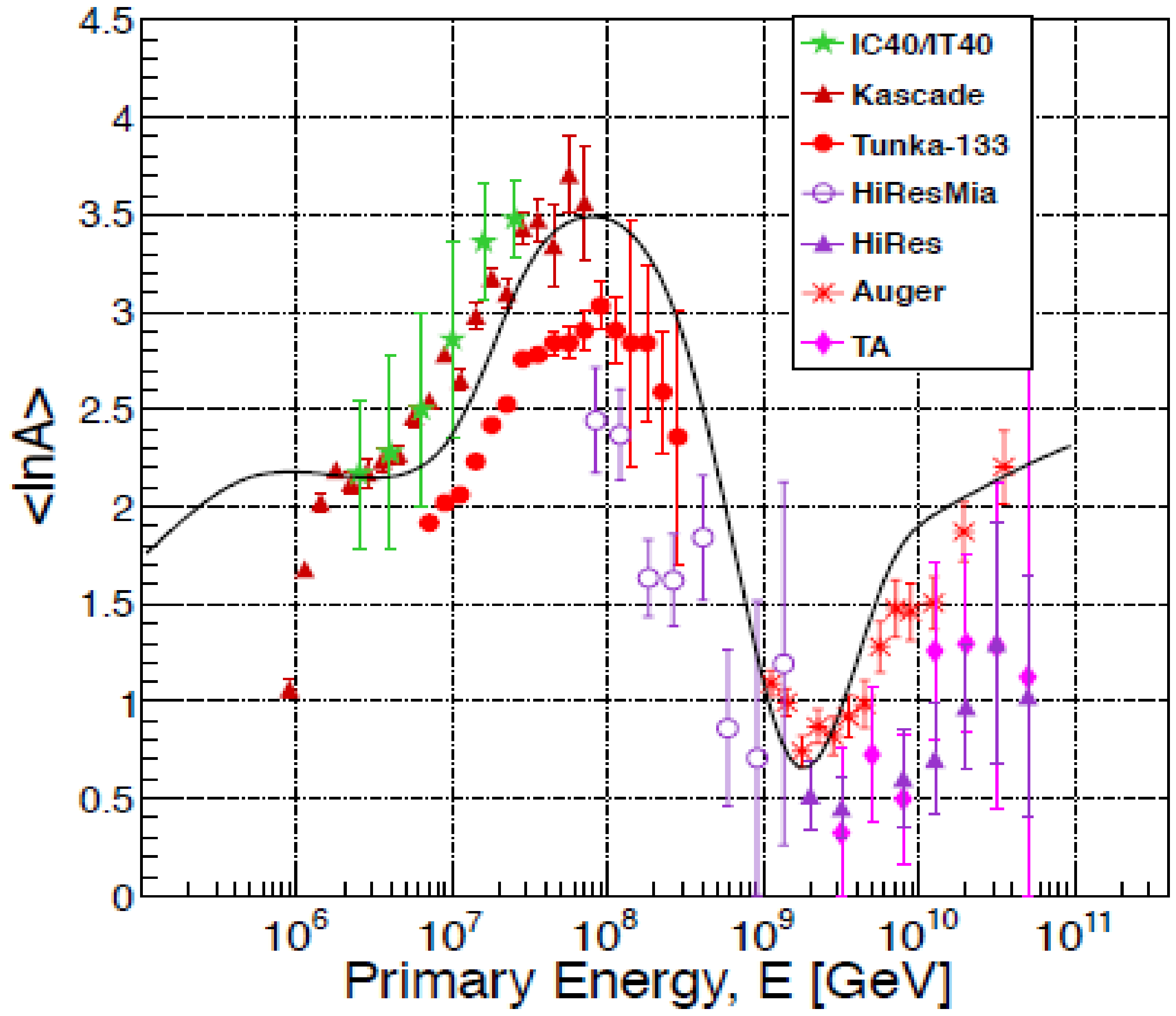
Pop3 for TA/HiRes

Pop4 Proton makes up most of the bump.



Pop3 for Auger

Pop3 Fe + Pop4 Proton make up the bump.



The chemical composition of cosmic rays of the global fit compared to data from air shower experiments. The fit in this case uses the Auger heavy composition

What does this exersize mean ?
Do we really have three different sources for galactic Cosmic rays ?   **Why not.**

If the first population is due to SNR with the Lagage&Cesarsky features expanding in the interstellar space, we can have young SNR that expand with higher velocity.

We can also have SNR that expand in the highly magnetized stellar winds of the pre-supernova star thus expanding in higher magnetic field.

The magnetic field at the supernova shock could be much higher (a factor up to 100) than the average magnetic field in the Galaxy (Bell).