CRIS 2018
Portopalo - Catania

Knee, ankle and GZK in historical perspective

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"Historical perspective refers to understanding a subject in light of its earliest phases and subsequent evolution. This perspective differs from history because its object is to sharpen one's vision of the present, not the past."

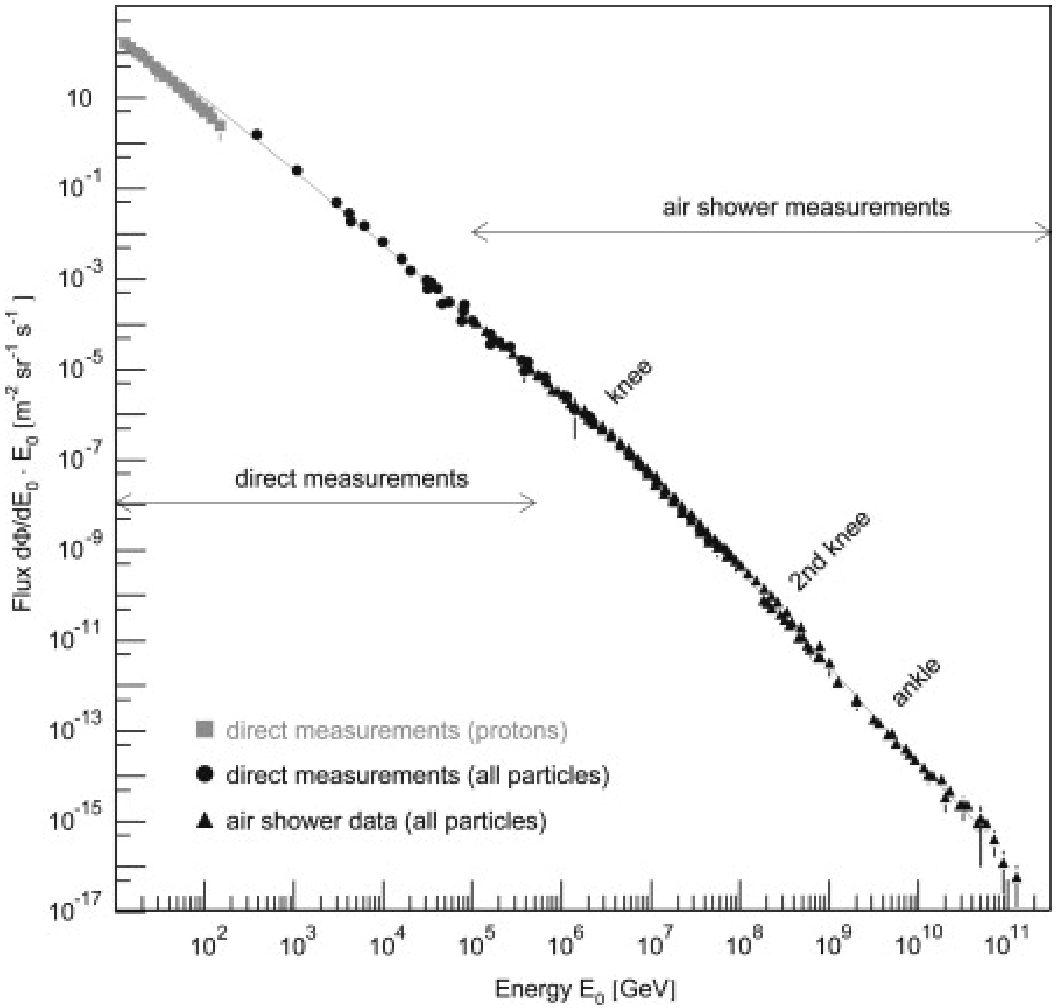
Using the Past to Study the Present

Cosmic rays flux

Energy spectrum

$E^{-\gamma}$

with $\gamma \approx 3$

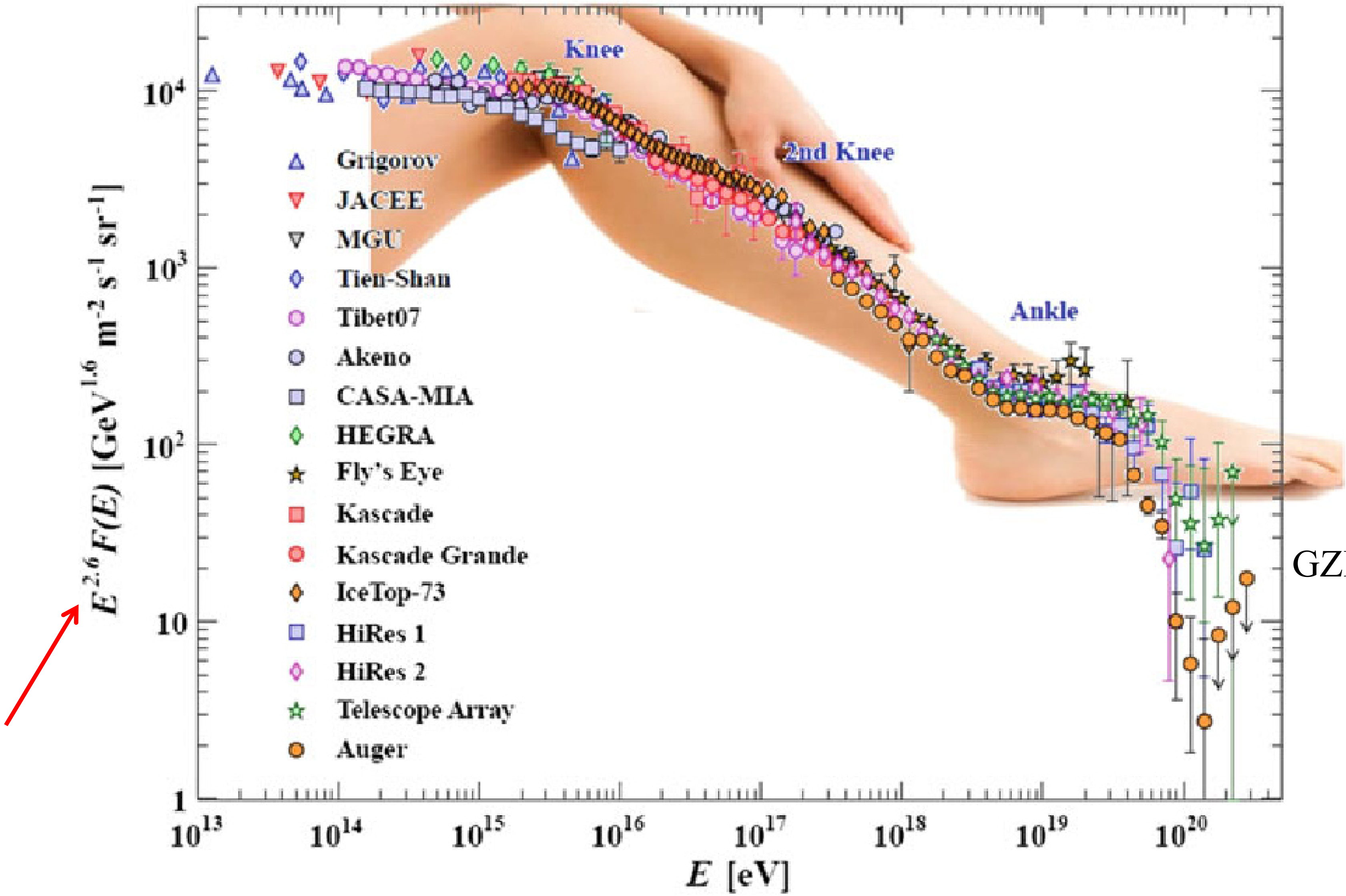


GZK

The knee and second knee, the ankle and the GZK suppression at the end of the spectrum appear as small structures on a power law spectrum extending over ~ 20 orders of magnitude. However, these features are crucial to understand the two basic properties of the cosmic radiation

- **The mechanism of <u>production</u> of the cosmic rays**
- **The <u>propagation</u> of cosmic rays in space**

The cosmic ray leg



GZK

Discovery of the Extensive Air Showers (EAS)

- Bruno Rossi (1934)
- Pierre Auger (1938) Systematic studies. Estimate of the energy, ~ 10^{15} eV

First generation experiments – the pioneering era in the 1950s

Small surface arrays of Geiger and scintillation counters

- Culham – UK , 0.6 km^2
- Institute for Nuclear Studies (INS) –Tokyo

- **Moscow State University (MSU)** Geiger array 800 m^2, s.l.

First observation of the knee (1958)

- **Agassiz Astronomical Station – Harvard** , array liquid scintillators, then replaced by plastic scintillators, 0.2 km^2, s.l. (1952-1058)

MIT group (Bruno Rossi). Important developments.
Instrumental to establish the correlation between shower size (total number of particles observed at ground) and the energy of the primary. Effect of the zenith angle.
Determination of the shower axis – arrival direction of the primary cosmic ray.
Study of fluctuations.

Second generation experiments

Improved instrumentation and much larger aperture (10~100 km^2)

- **Volcano Ranch** , 8 km^2, 820 g/cm^2. John Linsley and Livio Scarsi (1959-1978)
  February 22, 1962 detection of event with size ~ **5x10^{10} particles → ~ 10^{20} eV**
  First evidence flattening of the energy spectrum at few 10^{18} eV ankle

- Haverah park , water tanks, 12 km^2, s.l. (1967-1987)
- EAS-Top , Detailed study of the knee region , 600x200 m^2, 820 g/cm^2 (1987-2000)
- SUGAR , Australia ~ 60 km^2, s.l.
- **Yakutsk ,** Siberia, 18 km^2, s.l., scintillators and Cherenkov air telescopes, Tunka

- **KASCADE - Grande** s.l. (1996-2009) 10^{16} – 10^{18} eV
  complex detector: array plastic scintillator + hadron calorimeters + muon detectors

- **AGASA** array 100 km^2, 930 g/cm^2 (1990-2004) The largest surface array of the second generation experiments. **Claim of extra GZK events (!!!** ???)

Fly's Eye → HiRes , Fluorescence Telescopes, 860 g/cm^2 (1997-2006)
<u>Fluorescence technique developed in Utah</u> , Eugene Loh
First statement on the observation of the GZK cutoff

ARGO, HAWC , high-energy photons but also charged particles

Third generation –The modern era of third Millennium

Hybrid detectors : Surface array of large size + fluorescence telescopes

The atmosphere as a calorimeter → energy of the shower

Large aperture and control of the energy scale.

Telescope Array (TA) 860 g/cm^2 North

38 fluorescence telescopes (FD) overlooking the surface array (SD) composed of 507 plastic scintillators deployed on a total area of 700 km^2

Low energy extension TALE: 10 telescopes with higher elevation angle and infill

Energy resolution 21 %. Data from ~ 2x10^{15} eV

Auger Observatory 875 g/cm^2 South

24 fluorescence telescopes, surface array compose of 1600 water Cherenkov tanks covering an area of 3000 km^2

3 higher elevation angle telescopes + infill

Energy resolution 14%, Data from ~ 3x10^{17} eV

Sophisticated methods of analysis

Sociological evolution :

In the ~ 1950s experiments performed by a couple of physicists with help of one or two PhD students

Now, **large international collaborations with complex organizational structure**

5th ICRC in Guanajuato, Mexico (1955) “Introductory Talk “ by G.Cocconi

The spectrum known at that time appears to be smooth, no structures (perhaps because of the poor statistics) but **extends up to about 10^{19} eV**

The Larmor giration radius: R=1.08/Z (E/10^{18} eV) (μGauss/B) kpc

In the energy region 10^{18} – 10^{19} eV the radius of curvature (1 – 10 kpc) is larger than the thickness of the Galaxy (the disk is 50 kpc in diameter, less than1 kpc thick)

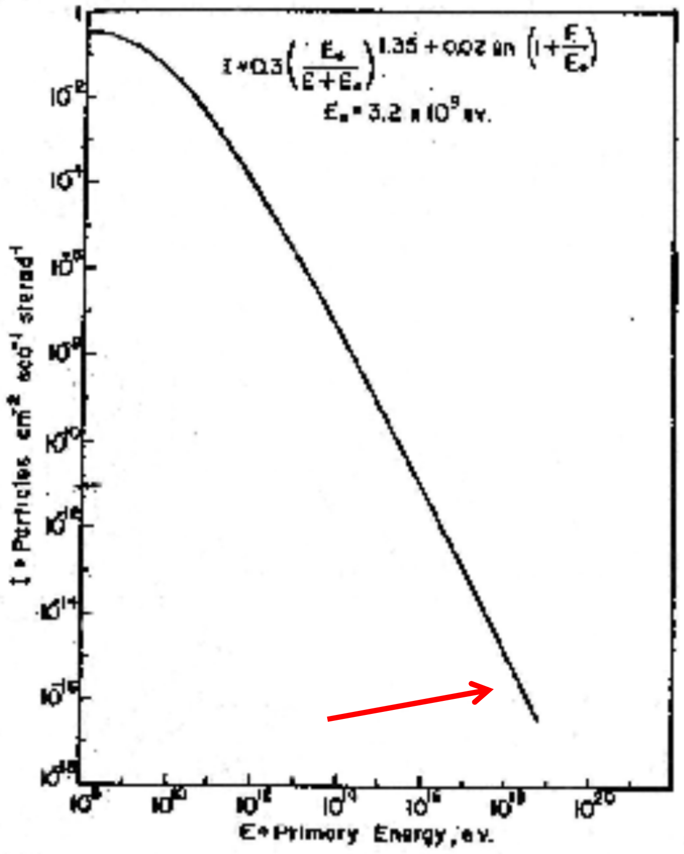
Cocconi concludes that:

“These particles are cosmic , indeed, because even the Galaxy seems too small to contain them“

If no containment, then no acceleration is possible.

At these high energies the acceleration cannot be the result of a single act. It must be a multi step process and without containment no acceleration is possible.

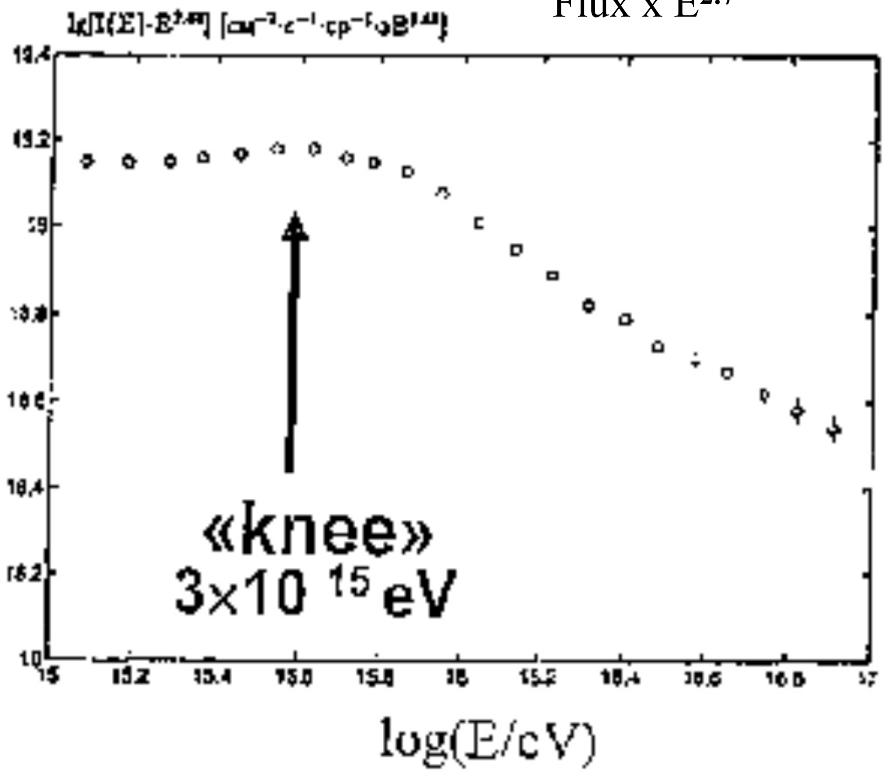
Line drawn through the few data



First observation of the knee, 1958

Kulikov and Khristiansen , JETP 1958
Geiger array of the Moscow State University group

Flux x $E^{2.7}$



Fit with power law spectrum of the form

Flux(E) ~ E$^{-\gamma}$

γ ~ 2.7 before the knee
γ ~ 3.1 after the knee

Soon confirmed by many other experiments (EAS-Top, Yakutsk…)

The knee of the cosmic ray spectrum was discovered more than 50 yr ago. Its underlying physical causes are understood but there is still some debate. A complete, quantitative theory is still missing but there seems to be **general consensus** that **acceleration is due to shock waves in supernova remnants (SNR) with diffusive propagation in the Galactic magnetic field**.
Standard paradigm. Poly-gonate model.
Acceleration is rigidity dependent:

$$\mathbf{E(Z)_{max} = Z \times E(p)_{max}}$$

The sudden change of slope at the knee signals the maximum energy reached by the particles of a given mass.

Each composition of the cosmic rays has its own knee and the superposition of all compositions form the observed knee structure of the energy spectra where the maximum energy is proportional to the atomic number Z.

Protons are accelerated in the sources to a maximum energy
$\mathbf{E(p)_{max} = (4\text{-}5) \times 10^{15}\ eV}$

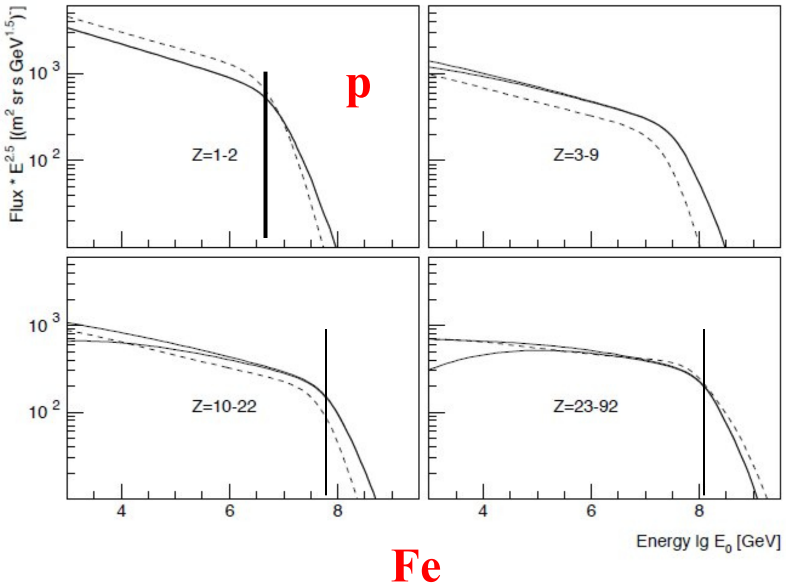
while iron nucleus will be accelerated to
$\mathbf{E(Fe)_{max} = 26\ E(p)_{max} \approx 10^{17}\ eV}$

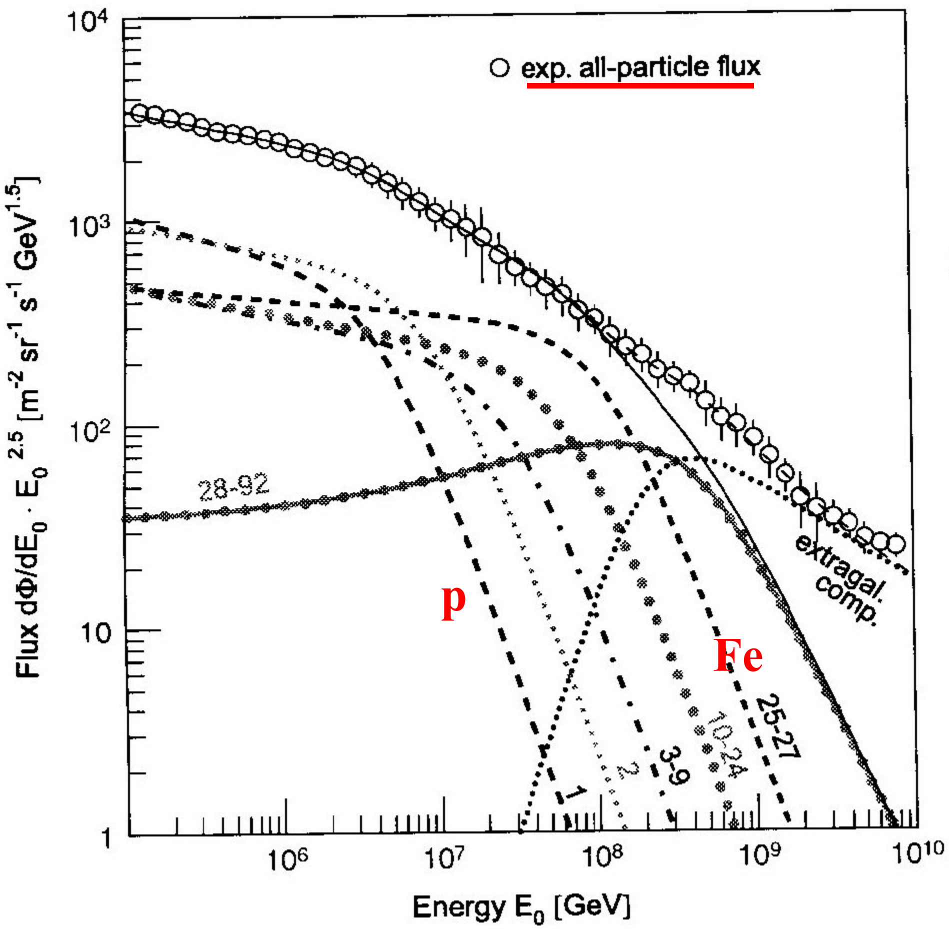
Light nuclei are depressed.

Several reviews: Hörandel 2003…, Berezinsky, Aloisio , Blümer et al… Blasi theoretical 2013 etc.

A model showing how the cutoff energy E_{max} changes with the atomic number Z of the accelerated particle. The "all-particle flux is obtained by summing the individual contributions of accelerated nuclei of different masses.

Addition of extra-galactic component is needed.

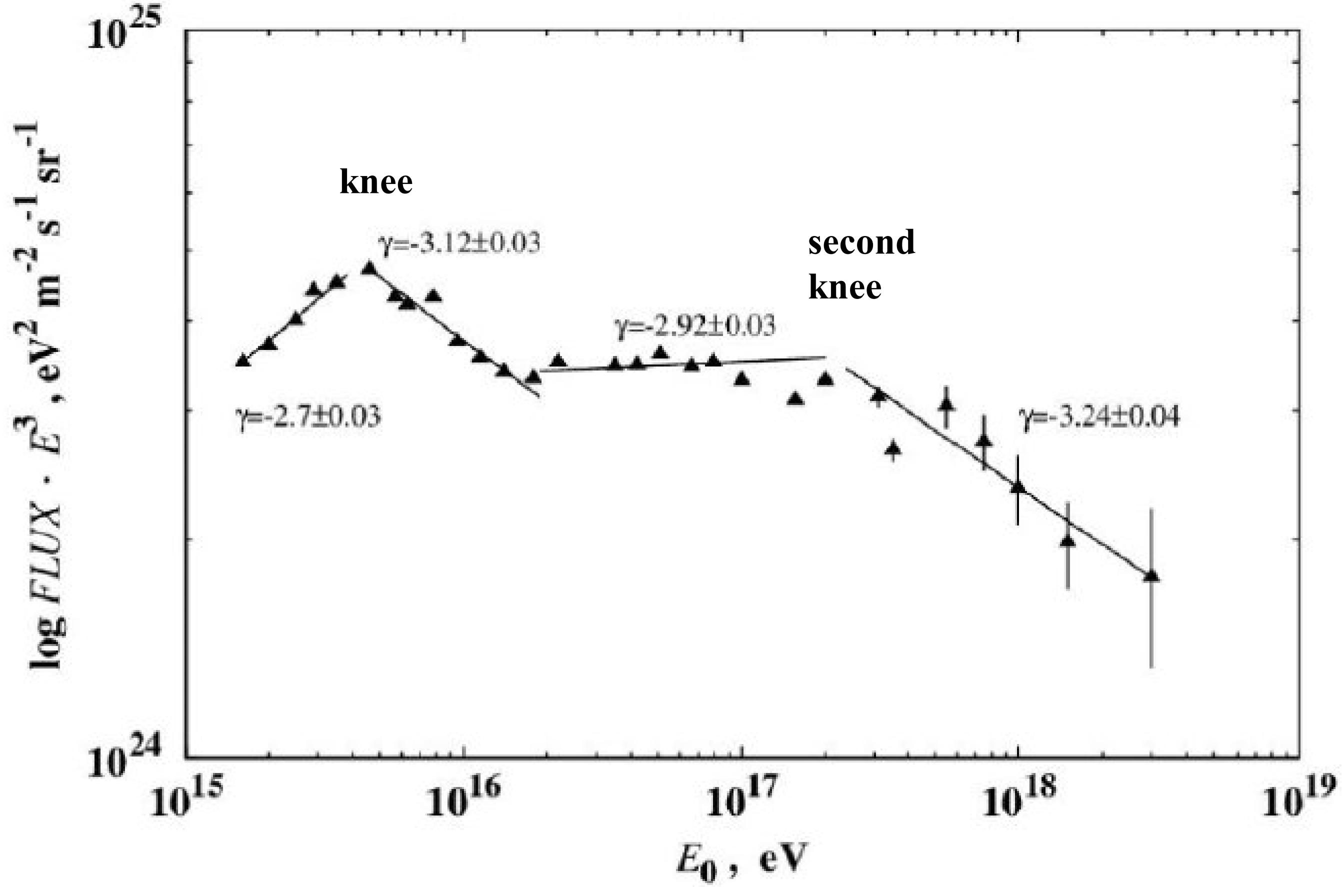




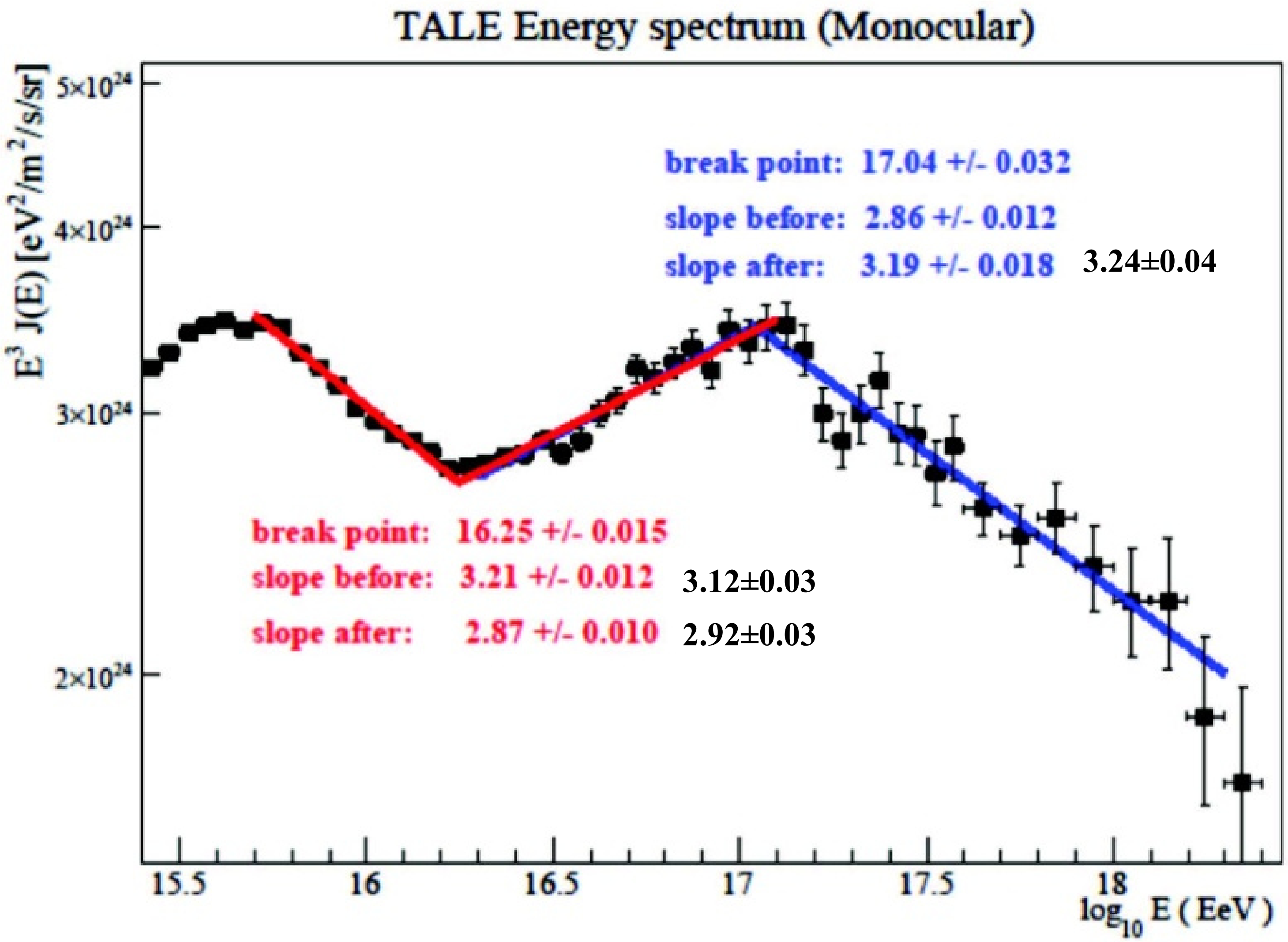
Hörandel 2007. Blümer, Engel, Hörandel, 2009

The structure of the energy spectrum in the region of the knee $3x10^{15}$ eV – $3x10^{17}$ eV

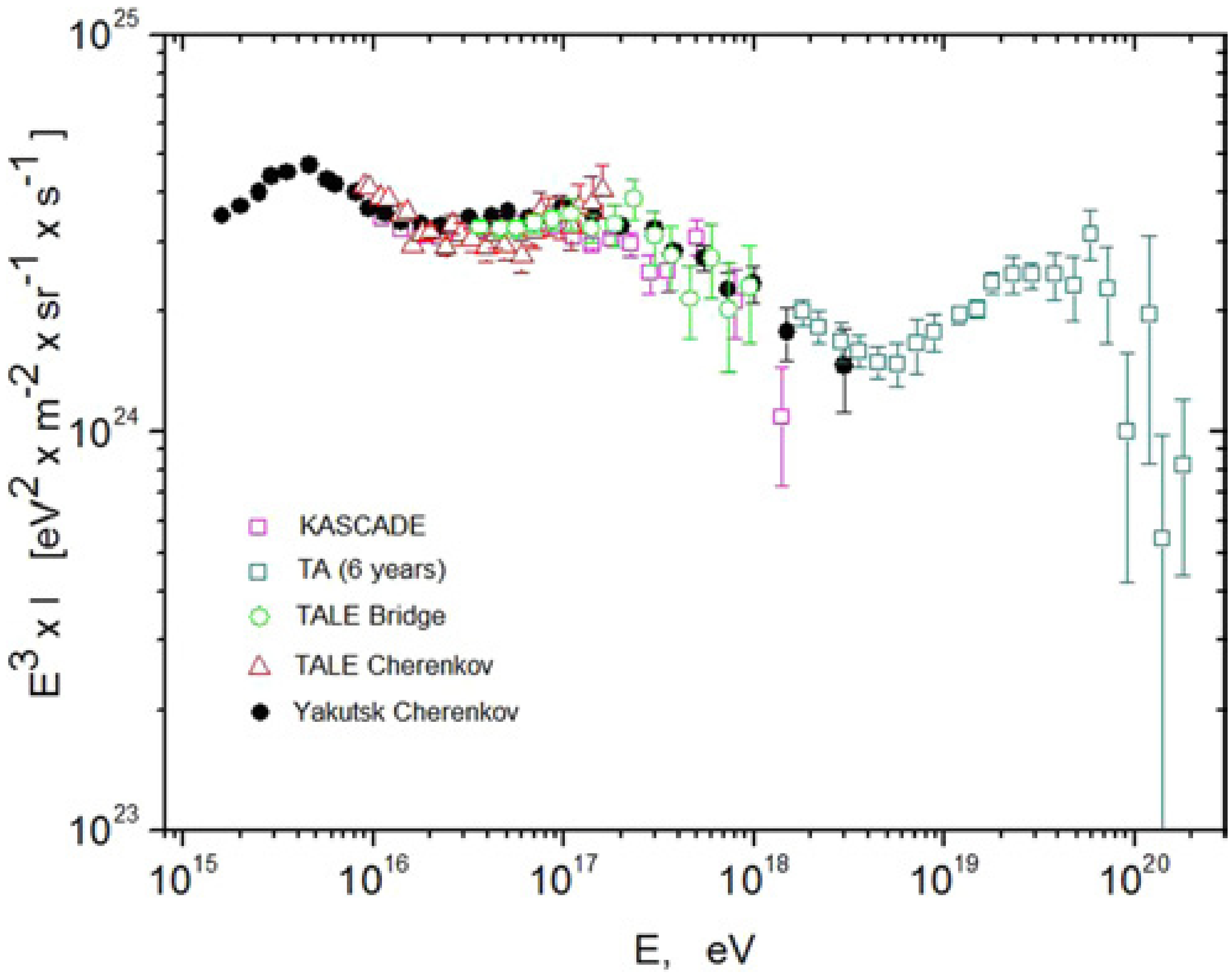
Yakutsk data



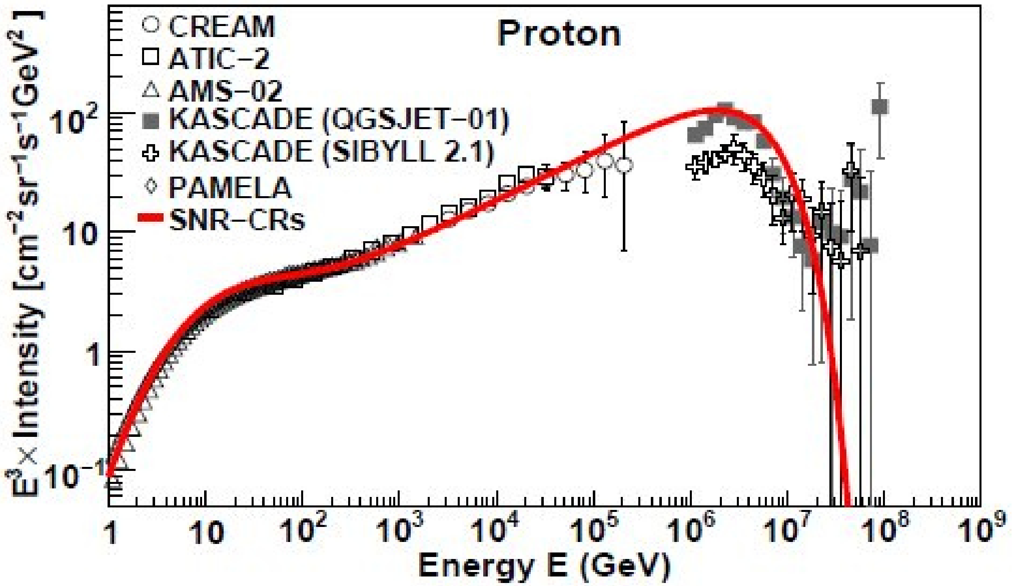
The structure of the energy spectrum in the region of the knee $3x10^{15}$ eV – $3x10^{17}$ eV



Compilation by Yakutsk of the data in the region of the knee
Data from KASCADE, Yakutsk, TA and TALE

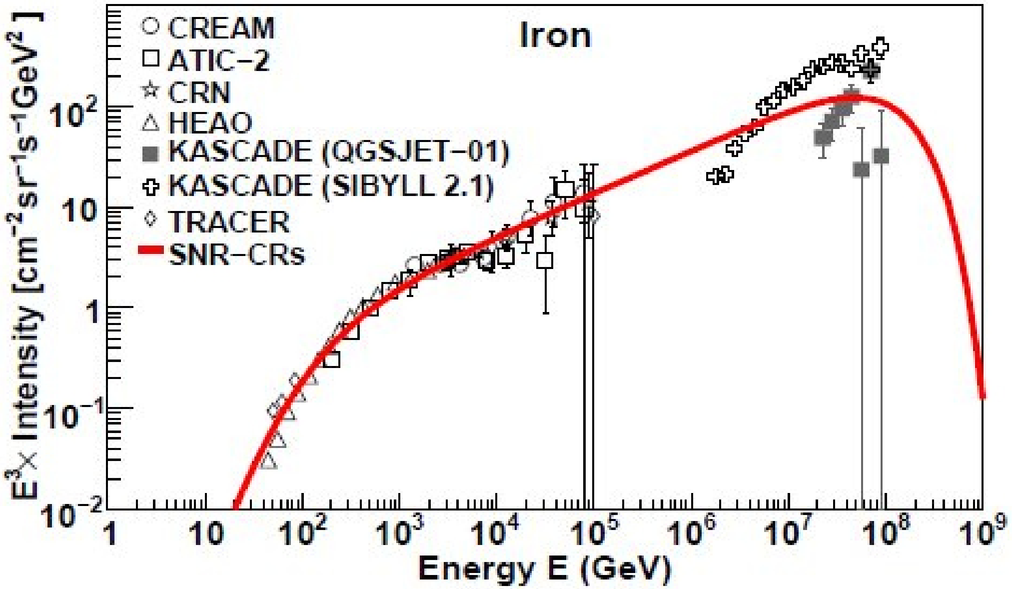


Unfortunately to study the energy spectrum of the individual mass components is <u>very difficult experimentally</u>



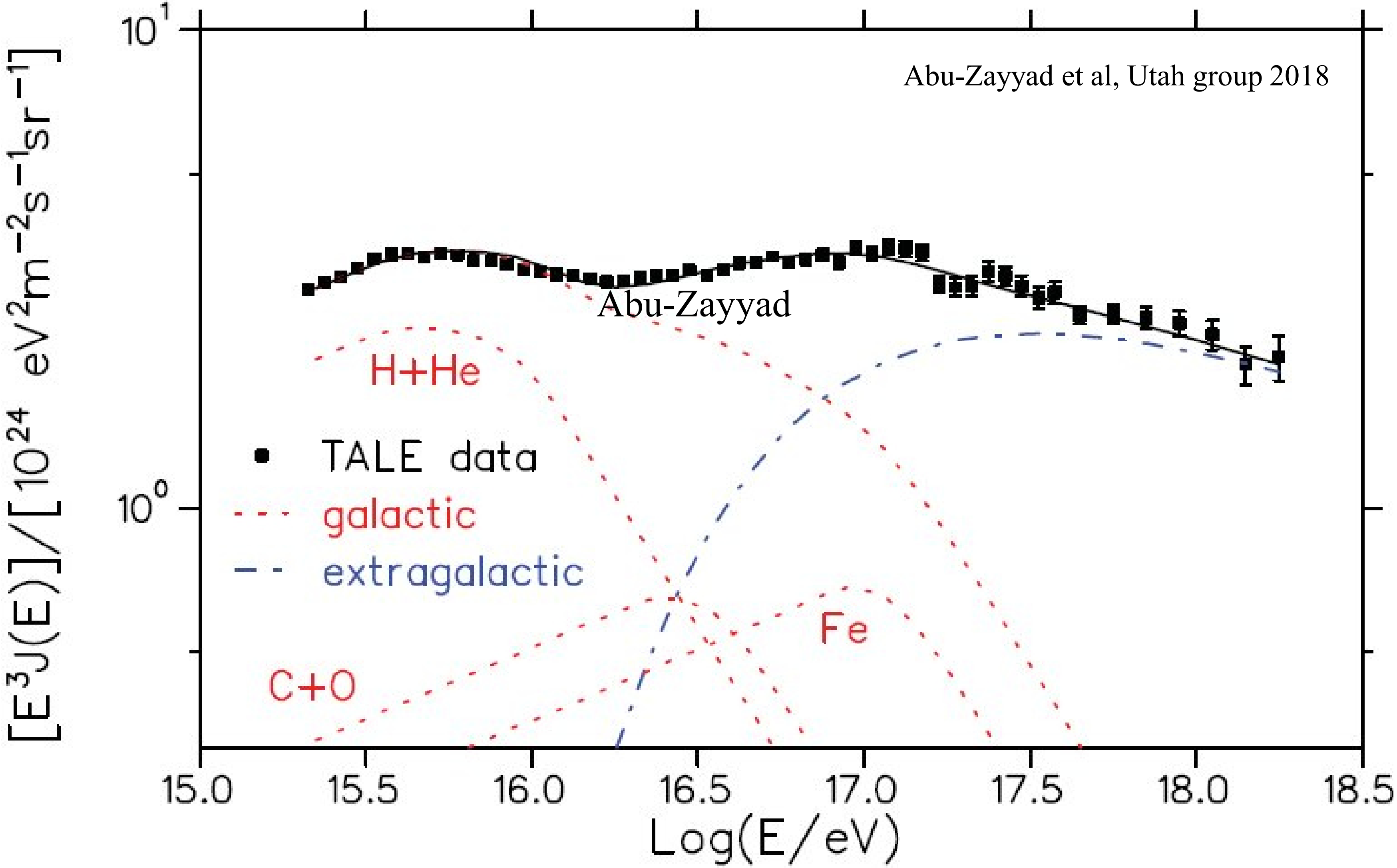
Examples of measured spectra for protons and iron.
Data mainly from KASCADE.

Red lines model from Thoudam et al. 2016

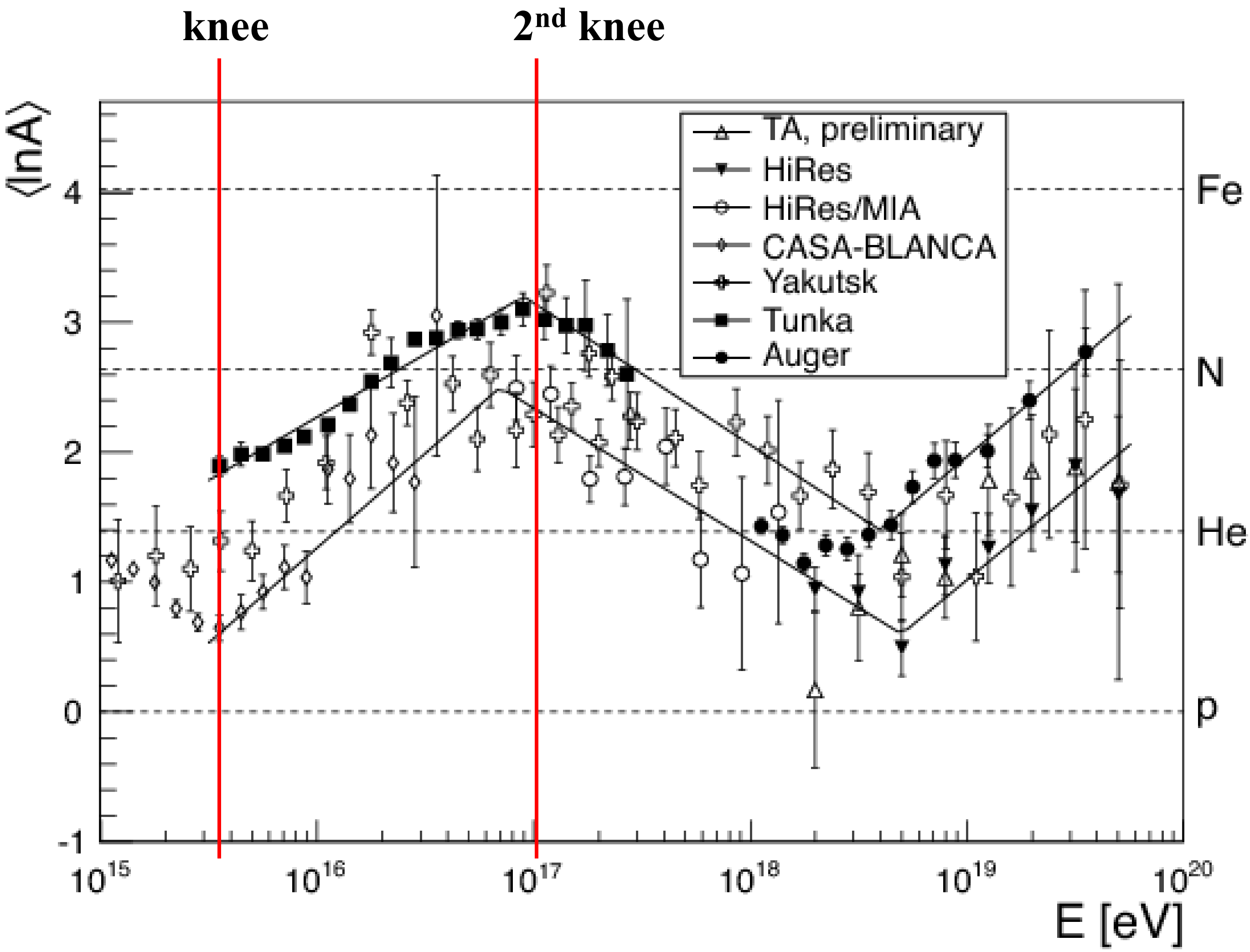


Results of a specific model.

Individual contributions from H+He , Light nuclei C+O, Fe
The overall Galactic and the start of extragalactic components

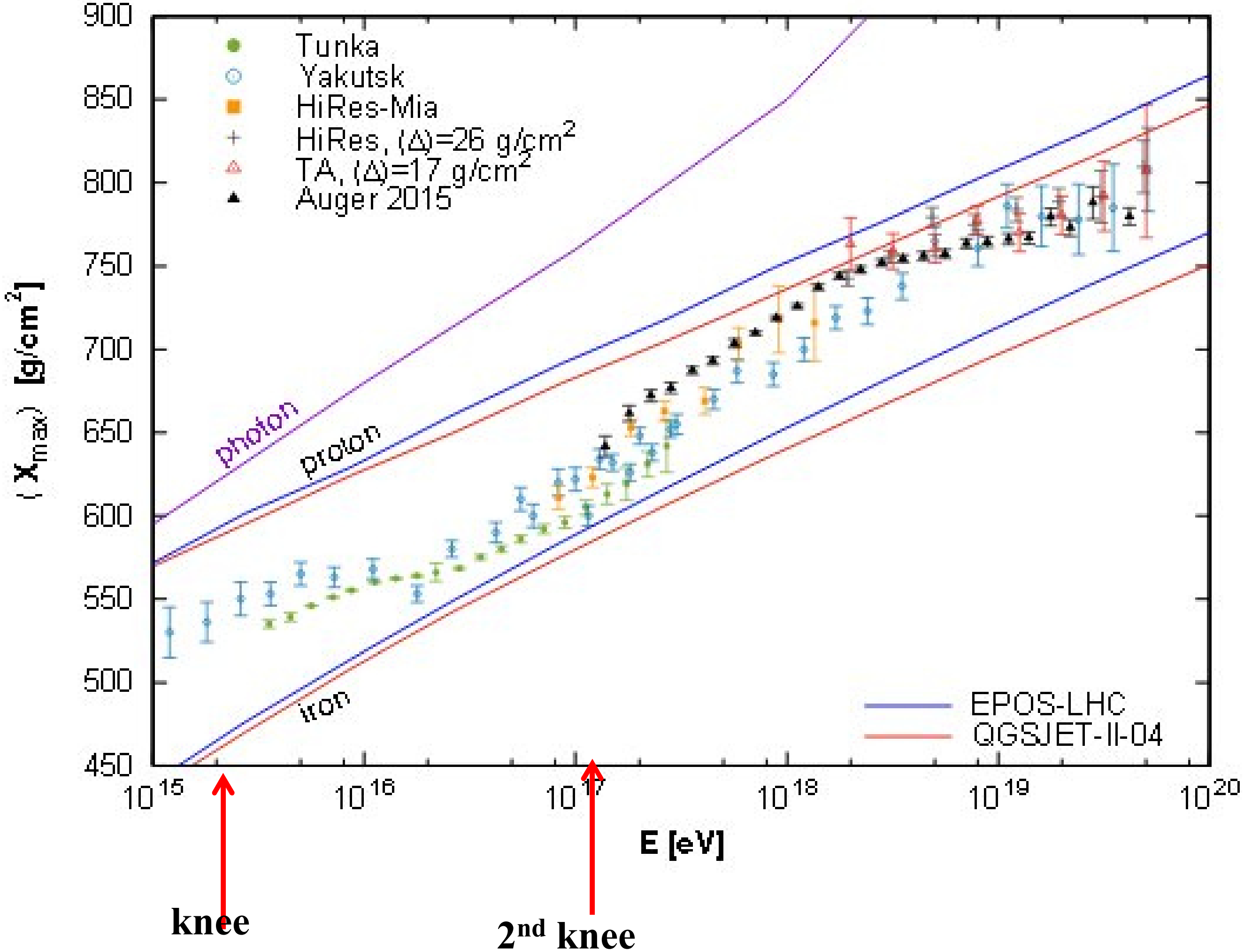


Compilation composition: mean (ln A) as a function of energy



Kampert 2013

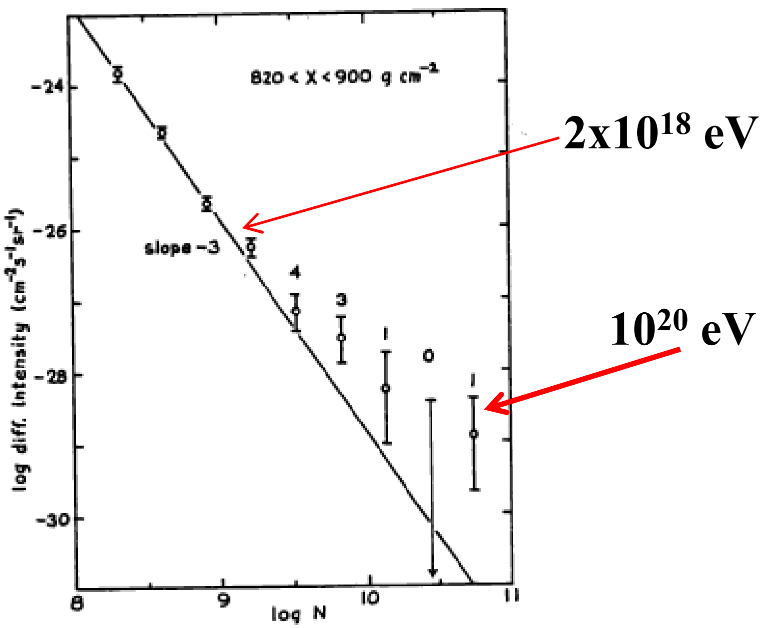
Some selected data



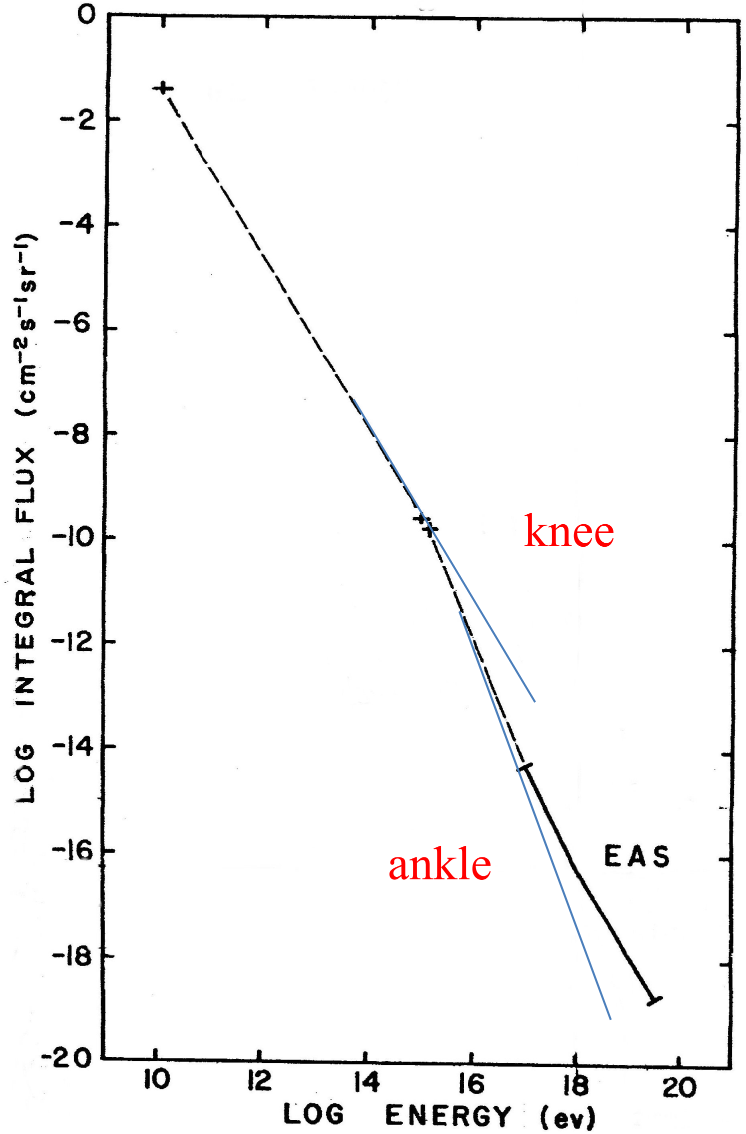
Observation of the ankle

Linsley - 8th ICRC Jaipur, India (1963)

The Primary Energy Spectrum. From examination of zenith angle distributions and other evidence we conclude that all of the showers used in deriving Fig. 4 were essentially at maximum longitudinal development at the level where they were observed. Under that circumstance the primary energy distribution for a given shower size is quite narrow. Thus, Furthermore, in that circumstance one can not err greatly in writing $E \simeq 2x10^9 N$ for the relation between shower size and primary energy in ev. By use of that relation we obtained the integral energy spectrum shown in Fig. 5. Also shown are the results of other measurements at lower energies.



Volcano Ranch



Compilation including previous data

GZK – interaction of protons and nuclei with the photons of CMB

Greisen, PRL 1966

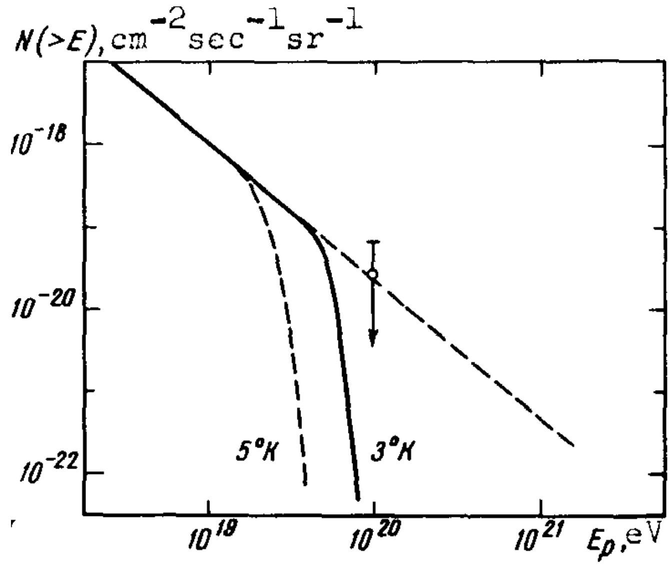
END TO THE COSMIC-RAY SPECTRUM ?

"Therefore, below 3×10^{19}eV the process should have a completely negligible effect on the proton spectrum. As 10^{20} eV is approached, the effect should rise rapidly, and above 2×10^{20} eV it should be a factor of several hundred. At present the data above 10^{19} eV are rather sparse, and the highest energy recorded is represented by a single event at 10^{20} eV."
(Volcano Ranch data, Linsley 1963)

"…. the observed flattening of the primary spectrum in the range 10^{18} -10^{20} eV is quite <u>remarkable.</u> "

Zatsepin and Kuz'min, JETP 1966

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS



The Linsley event of 10^{20}eV at Volcano Ranch quite intriguing !

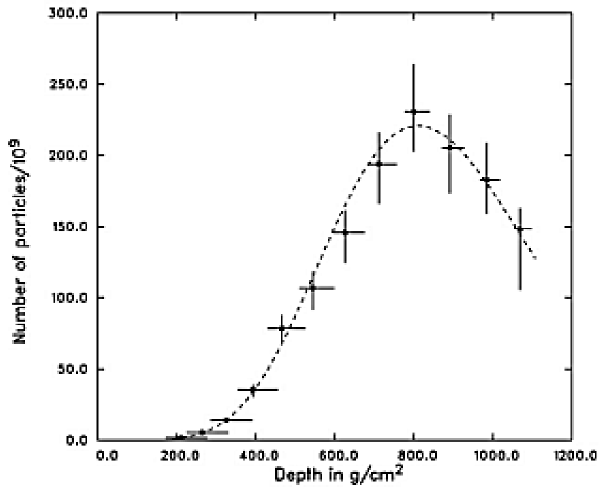
After the announcementof Linsley at the 8th ICRC in Jaipur, India (1963)
of the observation of an event with size N=5x10^{10} particles → 10^{20} eV at Volcano Ranch

The 10^{20} eV struggle

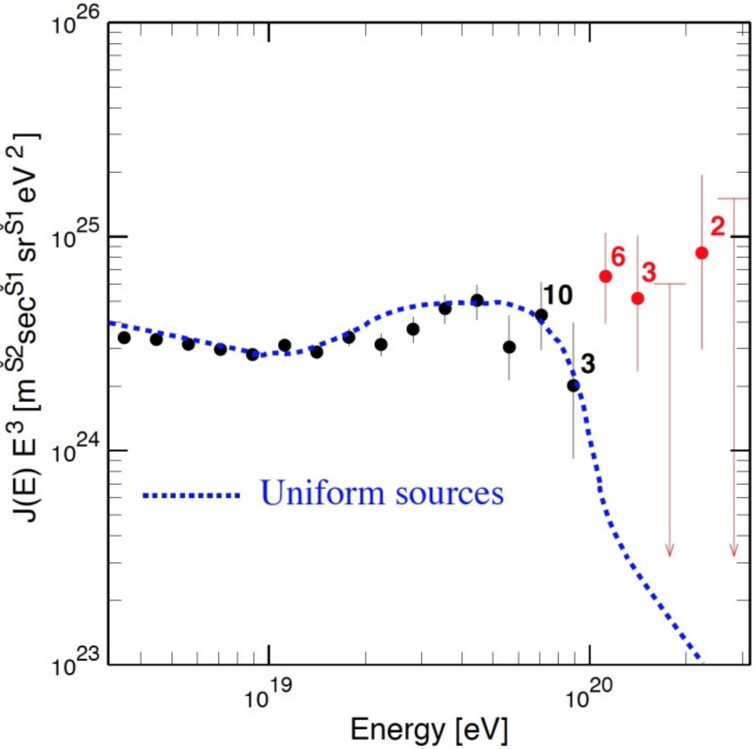
Experiment	Date	Energy 10^{20} eV	Z. angle degrees	RA degrees	Decl. degrees	l degrees	b degrees	Ref. no.
Volcano Ranch	22.04.62	1.4	11.7	306.7	46.8	84.3	4.8	4472
Haverah Park	31.12.70	1.02 ± 0.03	35	353	19	99	-40	8185175
	05.12.71	1.05 ± 0.3	30	199	44	107	73	9160073
	18.04.75	1.2 ± 0.1	29	179	27	212	78	12701723
	12.01.80	1.05 ± 0.05	37	201	71	119	46	17684312
Yakutsk	07.05.89	1.1 ± 0.4	58.9	75.2	45.5	162.2	2.6	
Fly's Eye	15.10.91	$3.2^{+0.36}_{-0.54}$	43.9	85.2	48.0	163.4	9.6	
AGASA	12.01.93	1.01 ± 0.3	33.2	124.3	16.8	206.7	26.4	20957-0382
	03.12.93	2.10 ± 0.5	22.9	18.9	21.1	130.5	-41.4	25400-0296
	06.07.94	1.06 ± 0.32	35.4	281.3	48.3	77.6	20.9	25790-0886
	11.01.96	1.44 ± 0.43	14.1	241.7	23.0	38.9	45.8	00123-3997
	22.10.96	1.05 ± 0.32	33.2	298.5	18.7	56.8	-4.8	00120-4976
	30.03.97	1.50 ± 0.45	44.2	294.6	-5.8	33.1	-13.1	01606-0578
	12.06.98	1.20 ± 0.36	27.3	349.0	12.3	89.5	-44.3	03876-9311

Table from Nagano and Watson, RMP 2000
14 events with E > 10^{20} eV

The famous Fly's Eye event
of ~ 3.2 x10^{20} eV
Recorded 15 October 1991



AGASA
Final data



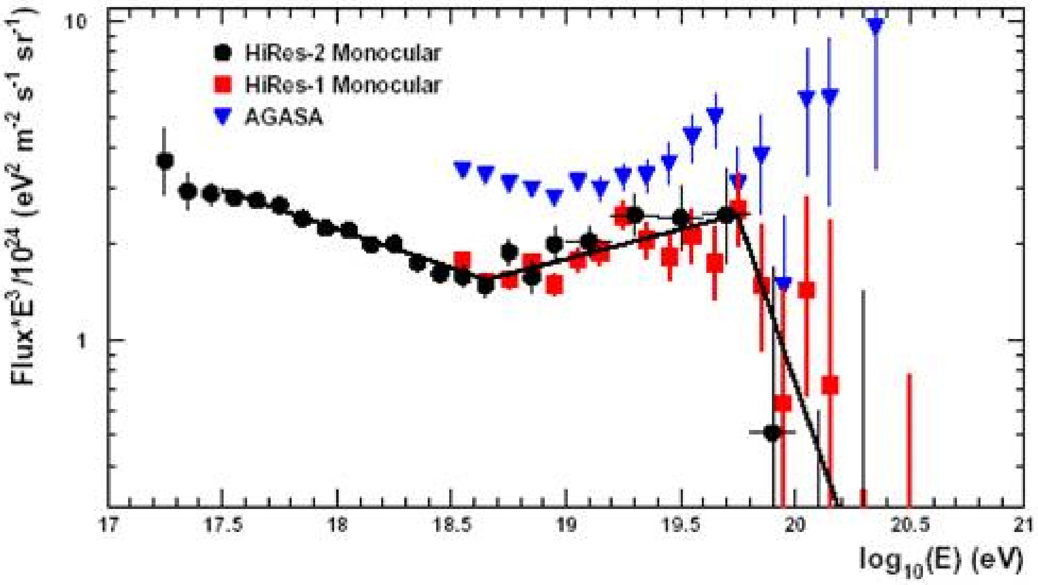
K.Shinozaki – NP B (2006)
Energy scale error 18%

In the 1990s discussion on the presence and effectiveness of the GZK suppression.
Many speculations……

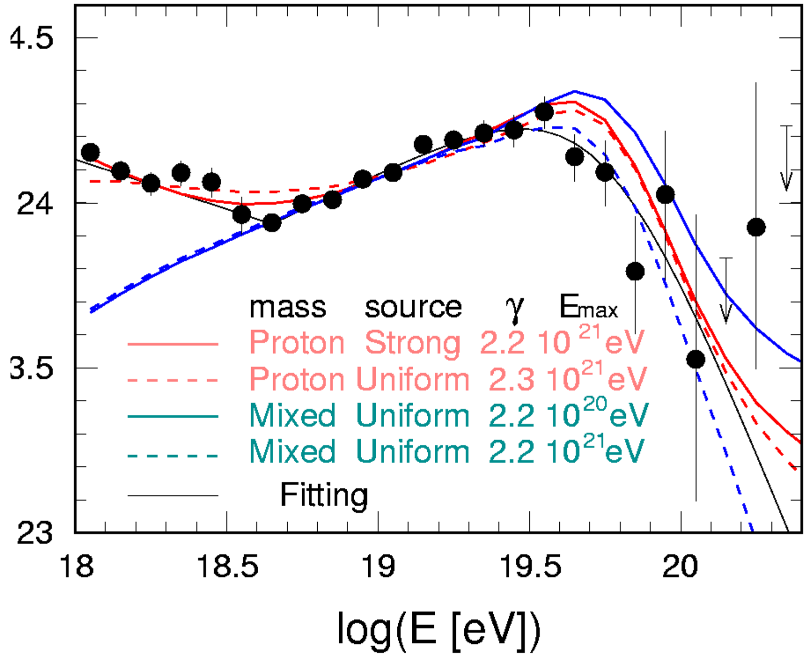
"This cutoff is not seen; in fact,
no cutoff is seen at any energy, up to the limit of data, at 3x10^{20} eV, or 300 EeV.
This is one of the most serious problems facing cosmic ray physics today."
Biermann and Sigl – UHECR2000 Meudon

Claim of "superGZK" events !

HiRes



Auger Observatory



HiRes arXiv astro-ph/0703099v1 6 Mar2007
"Observation of the GZK Cutoff by the HiRes Experiment"

Auger arXiv astroph/0707.2638v3 13Aug2007
Yamamoto 30 th ICRC, Mérida, México (2007)

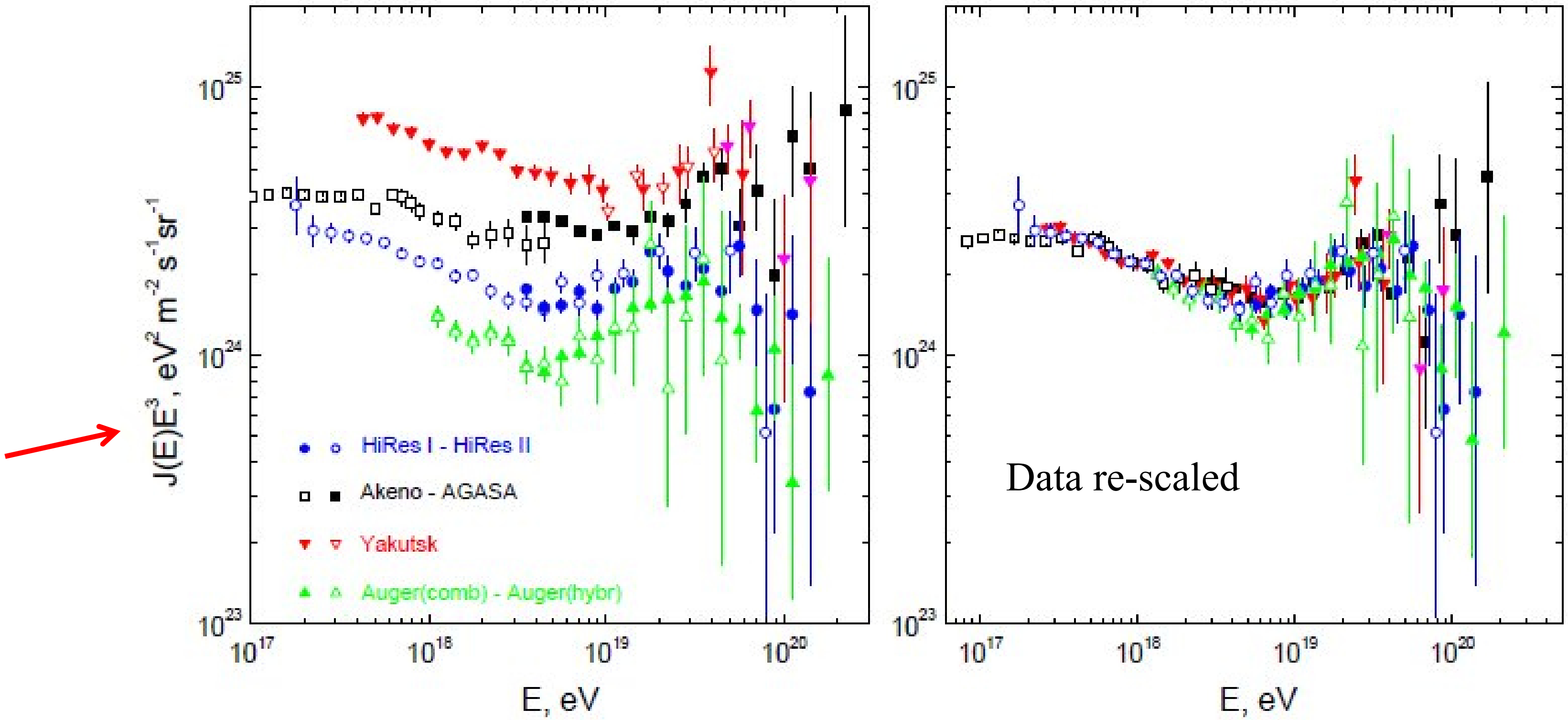
The HiRes and Auger data point to an error in the energy scale of AGASA

No "super GZK events" **("What cannot happen, does not happen")**

Confirmation of GZK prediction had to wait 40 years !!
(quite remarkable)

The problem of the energy assignment – the absolute energy scale

In the plot of Flux x E^3 the change of slope at the ankle appears as a "dip"
The position of the "dip" in the plot of the **Flux x E^3** used to compare the energy scale of different experiments.

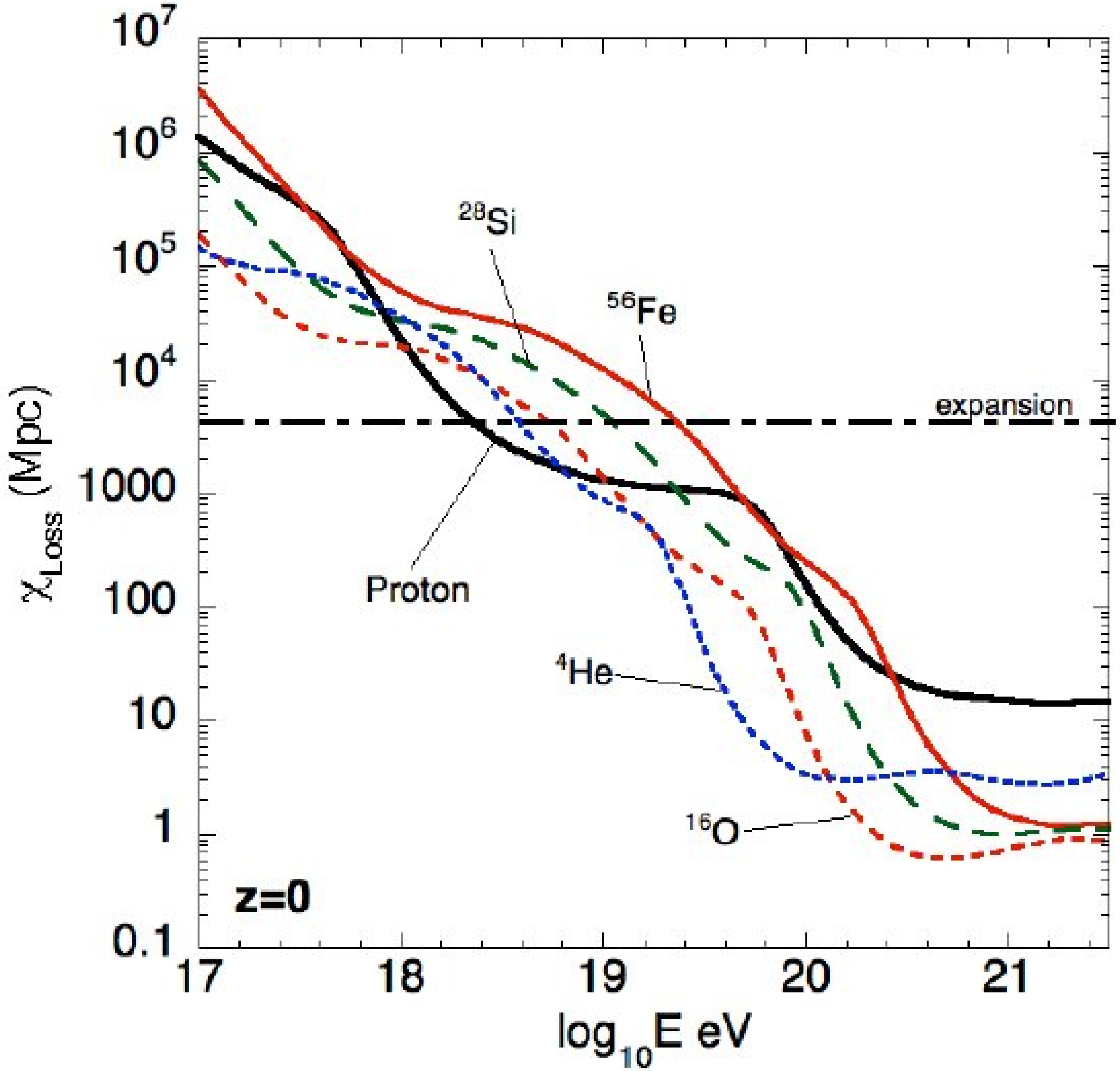


Energy shift: $\lambda = 1$ for HiRes, $\lambda = 1.2$ for Auger, $\lambda = 0.75$ for AGASA, $\lambda = 0.83$ for Akeno and $\lambda = 0.625$ for Yakutsk.

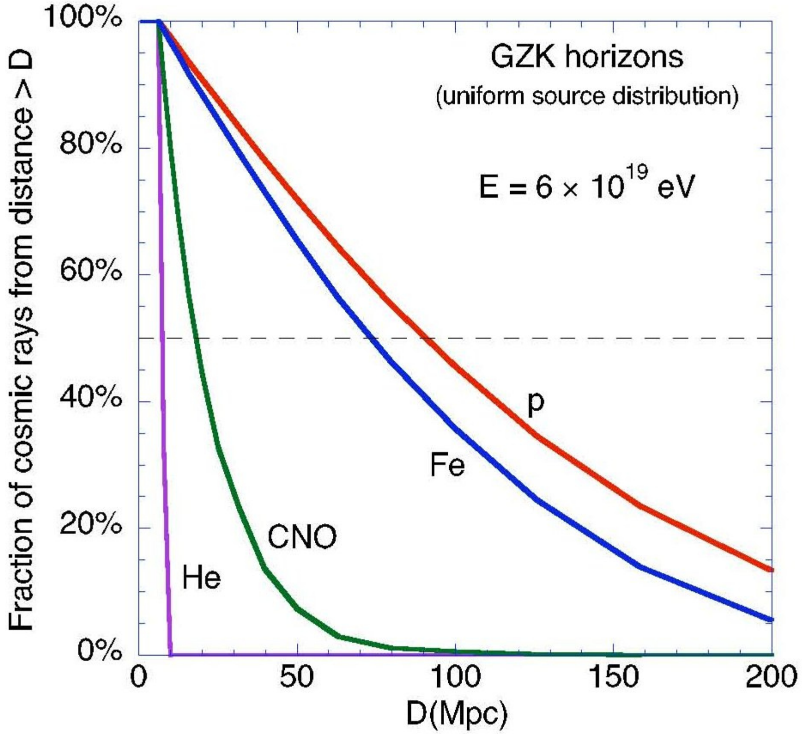
Berezinsky , TAUP Conference 2007

GZK effect on protons and nuclei

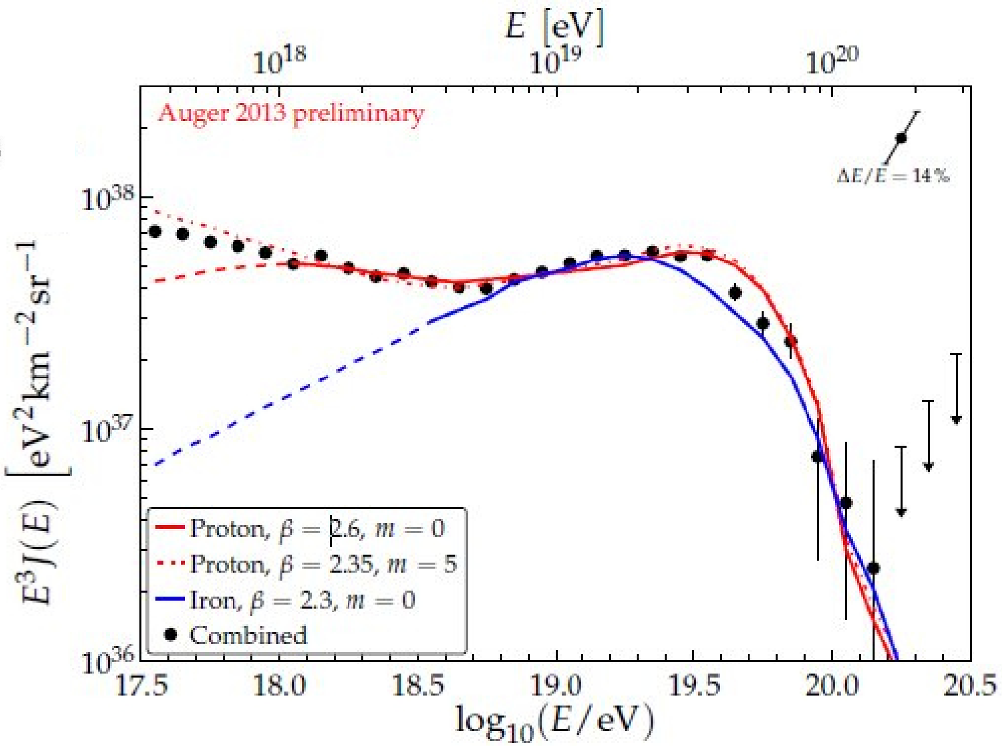
Interaction length



Allard 2012

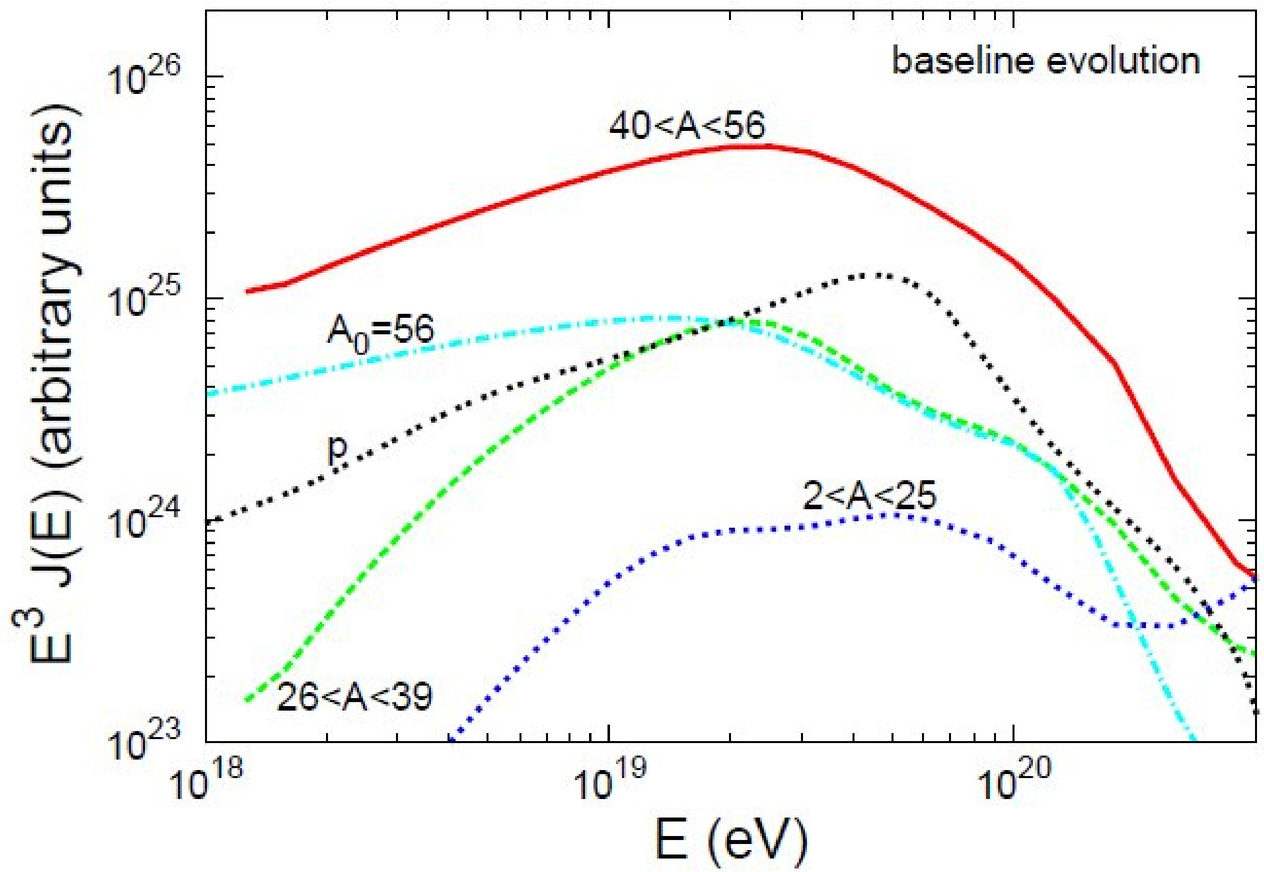


- **Light nuclei easily destroyed**
- **Only p and Fe can survive**



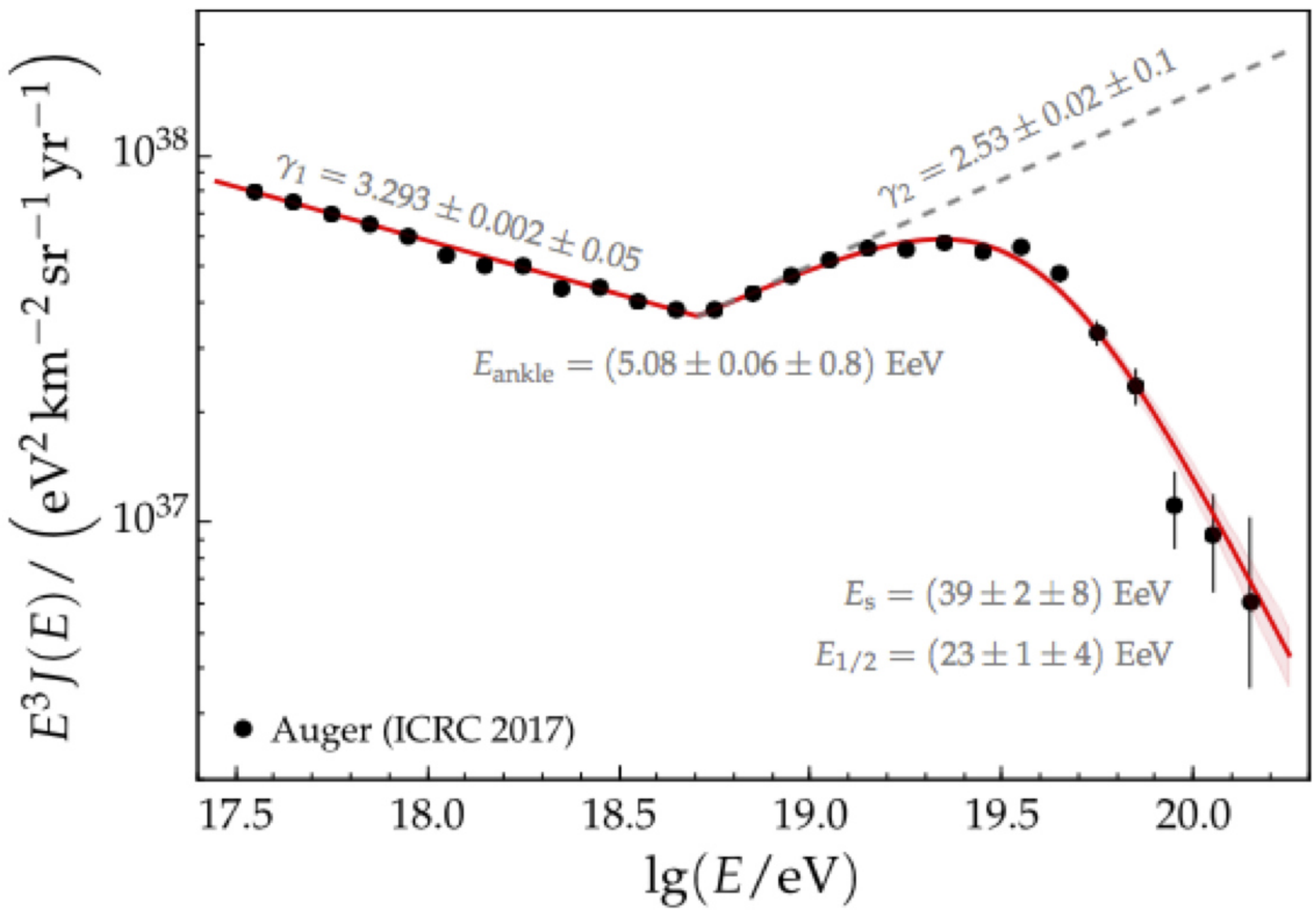
Interpretation of observed chemical composition on Earth requires great care

Pure iron injection at the sources



Aloisio 2013, Allard…

The Auger data in the region of the ankle and GZK suppression



Comparison energy spectrum Auger - TA

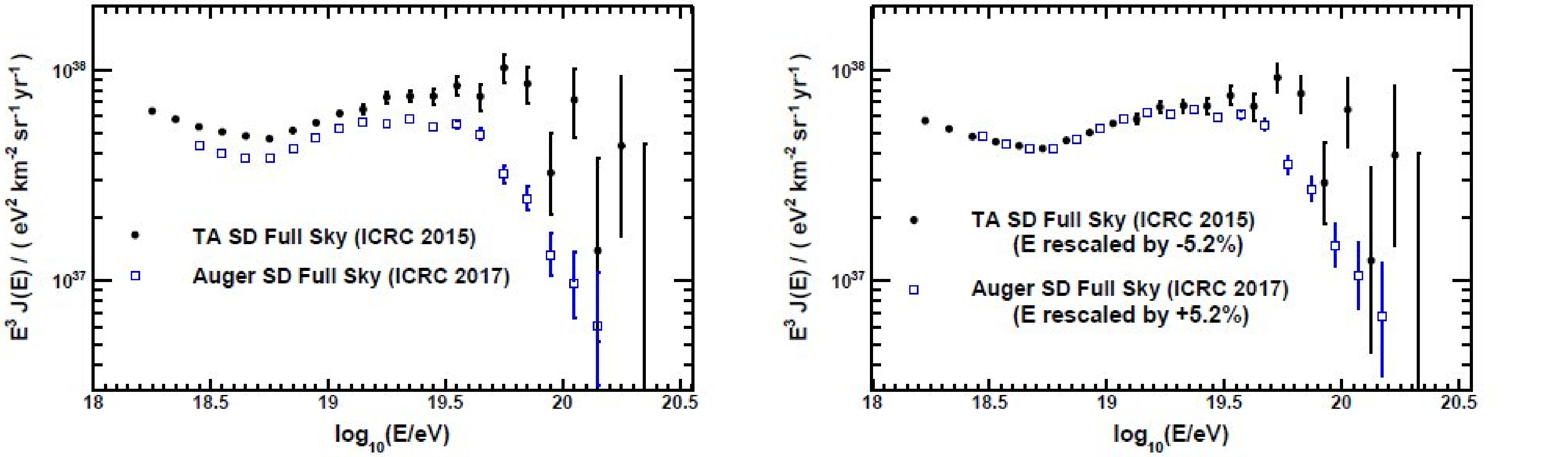


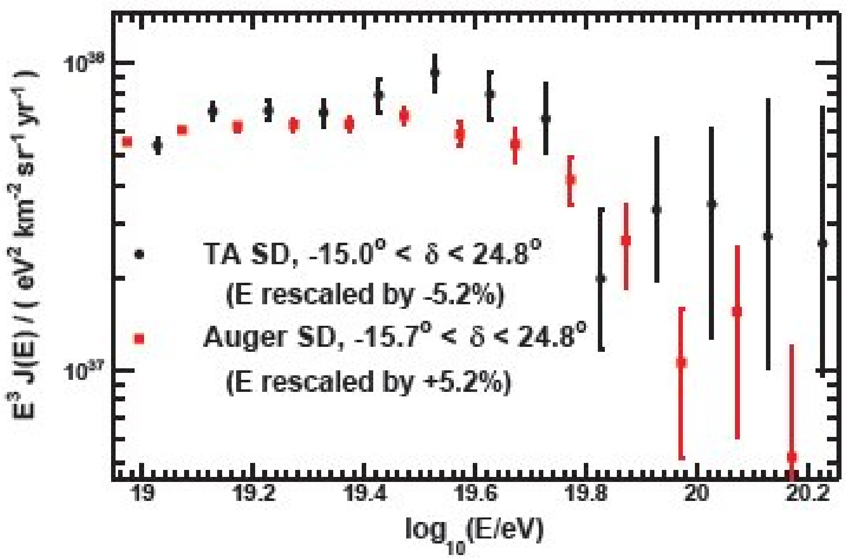
Figure 1: Energy spectrum measurements by the Auger [8] and TA [9] surface detectors. Left: Using energy scales of Auger and TA. Right: TA energy scale is reduced by 5.2% while Auger energy scale is increased by 5.2%.

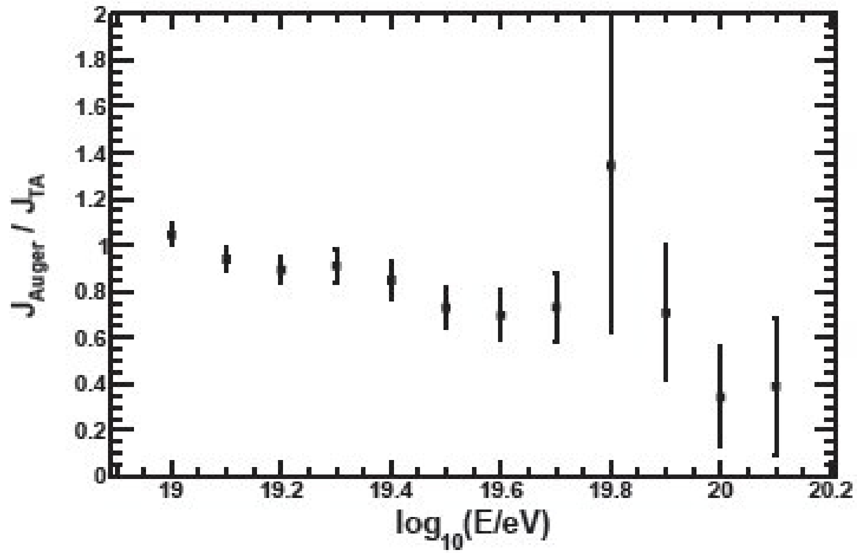
The energy scales differ by about 10% (well within systematic uncertainties !)
Auger + 5.2% and TA - 5.2% (Solomonic decision !) brings the data in **perfect agreement in the region of the ankle.**

However, difference remains in the GZK region.

Auger/TA Working Group Report – ICRC 2017 POS498

The difference persists in the subset of data of the common declination band ..
It is not a difference in the Sky, North vs South.
Seems to be an ***instrumental problem****.*





Auger vs TA in the common declination band of the sky

There is **general consensus** **that the**

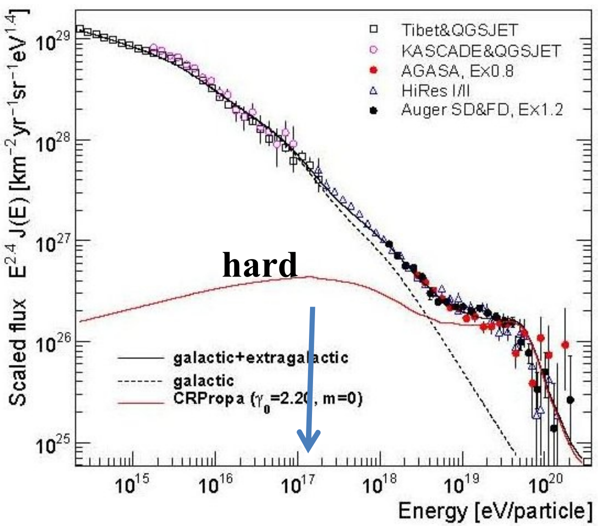
- **The observed structure in the region of the knee and second knee signals the end of the galactic component.**
- **The ankle is extra-galactic with a cutoff due to the GZK mechanism**

Now, the main question is on

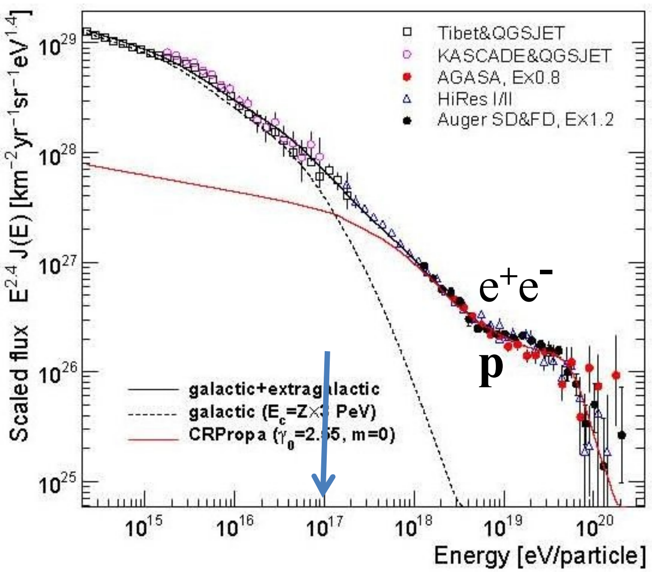
the transition from Galactic to extra-galactic components.

At least three different models

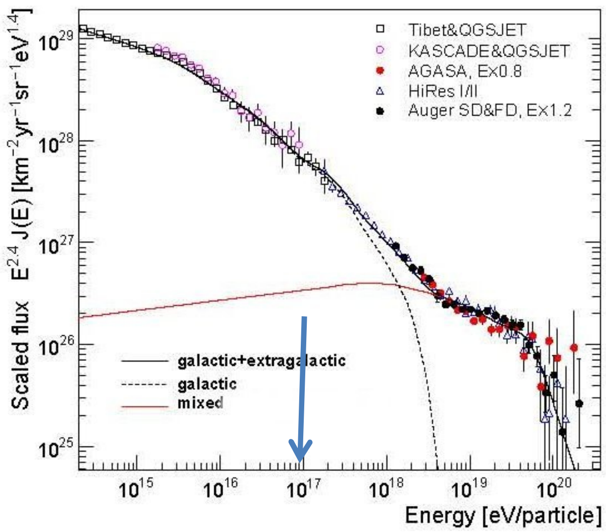
Ankle model



Dip model



Mixed composition



Unger 2008

Future plans – first Century of Third Millennium

Auger: > 300.000 events with E > $3x10^{17}$ eV, ~14 years
HiRes – TA: ……… E > $2x10^{15}$ eV ~18 years
Increase statistics always usefull but eventually systematics dominates

Important improvement on measurement of mass composition is expected.
Better understanding of the transition from Galactic to extra-galactic and of the GZK suppression.

Auger Observatory upgrade plastic scintillators on top of the water Cherenkov tanks to measure mass composition up to the highest energies
(now limited by the low duty cycle of the FD)

TA Electron linear accelerator with vertical beam.
End-to-end absolute calibration of the fluorescence telescopes.
Reduce uncertainty on the energy scale

TA extension TAx4 : from 700 km^2 to about 3000 km^2, same as Auger

Auger large radio array on the site of the Observatory

The great hope

Clear identification of the extra-galactic sources of the VHECR