The Origin of Ultrahigh Energy Cosmic Rays and their Spectral Break

Shlomo Dado, Arnon Dar, Alvaro De R’ujula , arXiv:1011.2672

Some Milestones:

1. In 1911 Victor Hess took measuring equipment aloft a balloon and systematically measured the radiation level at altitudes up to 5.3 km. The daring flights were made both at day and during night, at significant risk to himself. He discovered that above 1 km the level of ionizing radiation increased considerably with height and concluded that high energy cosmic rays penetrate the atmosphere from outer space. Hess was awardd the 1936 Nobel Prize in Physics.

2. In the 1930's the French physicist Pierre Auger discovered the extensive air showers created by very high energy cosmic rays.

3. The first observation of a cosmic ray with an energy exceeding 1.0E20 eV (~15 J) was made by J. at the Vulcano Ranch experiment in New Mexico, USA :"Evidence for a Primary Cosmic-Ray Particle with Energy Exceeding 1.0E20 eV". Physical Review Letters 10: 146 (1963).

What can be the origins of UHECRs such as that observed by J. Linsely in 1962 with an energy exceeding 1.0E20 eV !

(QSOs and AGN were discovered much later)

Hillas: Maximum Energy of Fermi Accelerated UHECRs: e Z B R

Cosmic Accelerator	R	B	Emax(p)
Radio Lobes of RLQs	~ kpc	~ 100 μGauss	~100 EeV
Radio Galaxies	~10 kpc	~10 μGauss	~100 EeV
'GRB Fireballs'	?	?	?

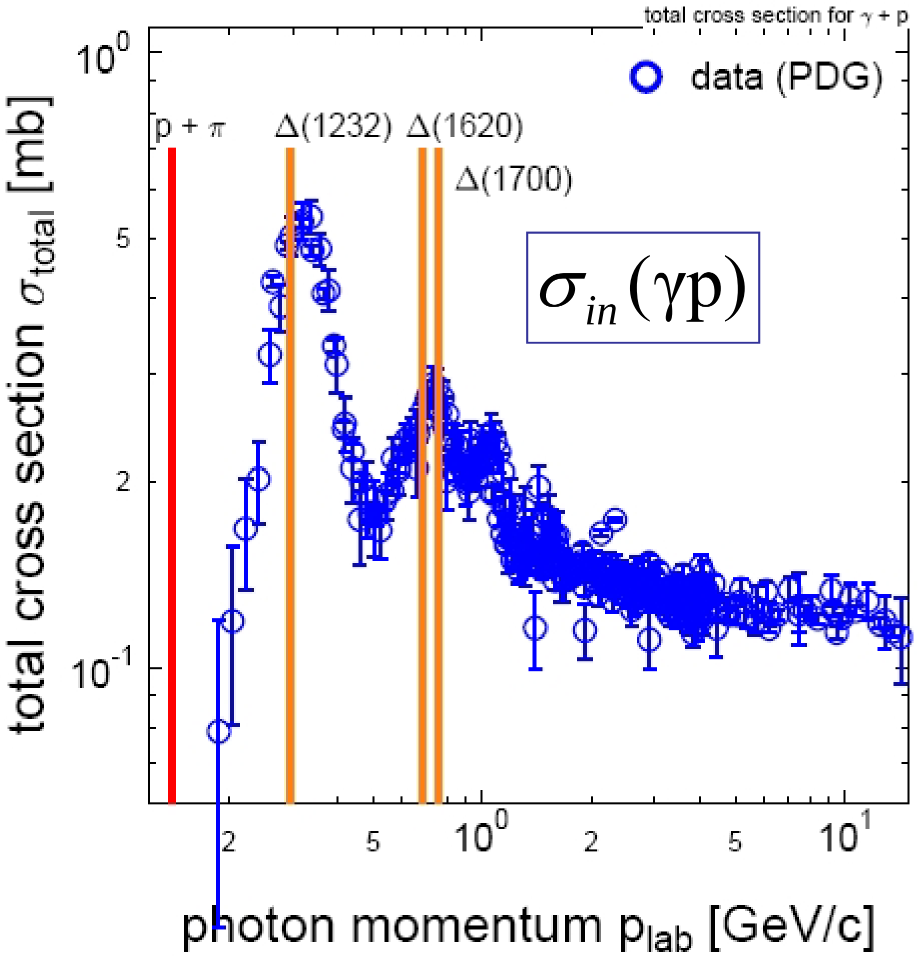
Could the UHECR observed by J. Linsely in 1962 be a heavy nucleus of extragalactic origin ?

GZK Cutoff (1966) :

$$p + \gamma_{CMB} \rightarrow \pi^{+} + n$$
$$p + \gamma_{CMB} \rightarrow \pi^{0} + p$$

Kenneth Greisen and **Georgiy Zatsepin** and Vadim Kuzmin predicted independently in **1966 a cutoff in the spectrum of EGCR**

Exact shape requires knowledge of $\sigma_{in}(\gamma A)$ and CR spectrum and composition as function of redshift.



$$E_{th}(p) \approx \frac{m_\pi^2 + 2m_\pi m_p}{2\,(1 - \cos\theta)\,\varepsilon_\gamma}$$

$$<\varepsilon_{CMB}> = 0.63 \text{ meV}$$

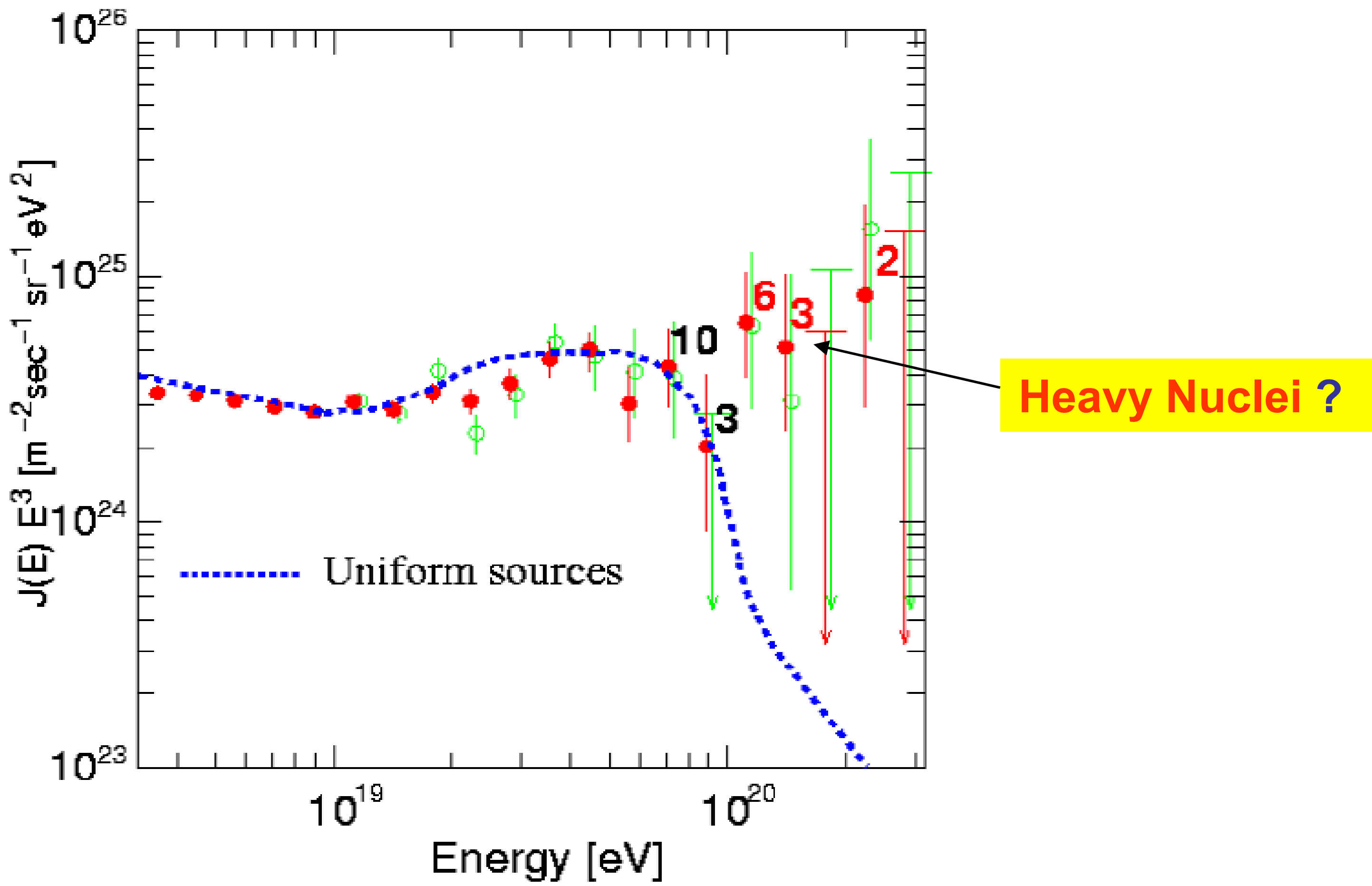
$$\Rightarrow E_{GZK}(p) \approx 5\times10^{19} \text{ eV}$$

$$E_{th}(p) \approx \frac{m_\pi^2 + 2m_\pi A m_p}{2\,(1 - \cos\theta)\,\varepsilon_\gamma}$$

$$E_{GZK}(Fe) \approx 2.6\times10^{21} \text{ eV}$$

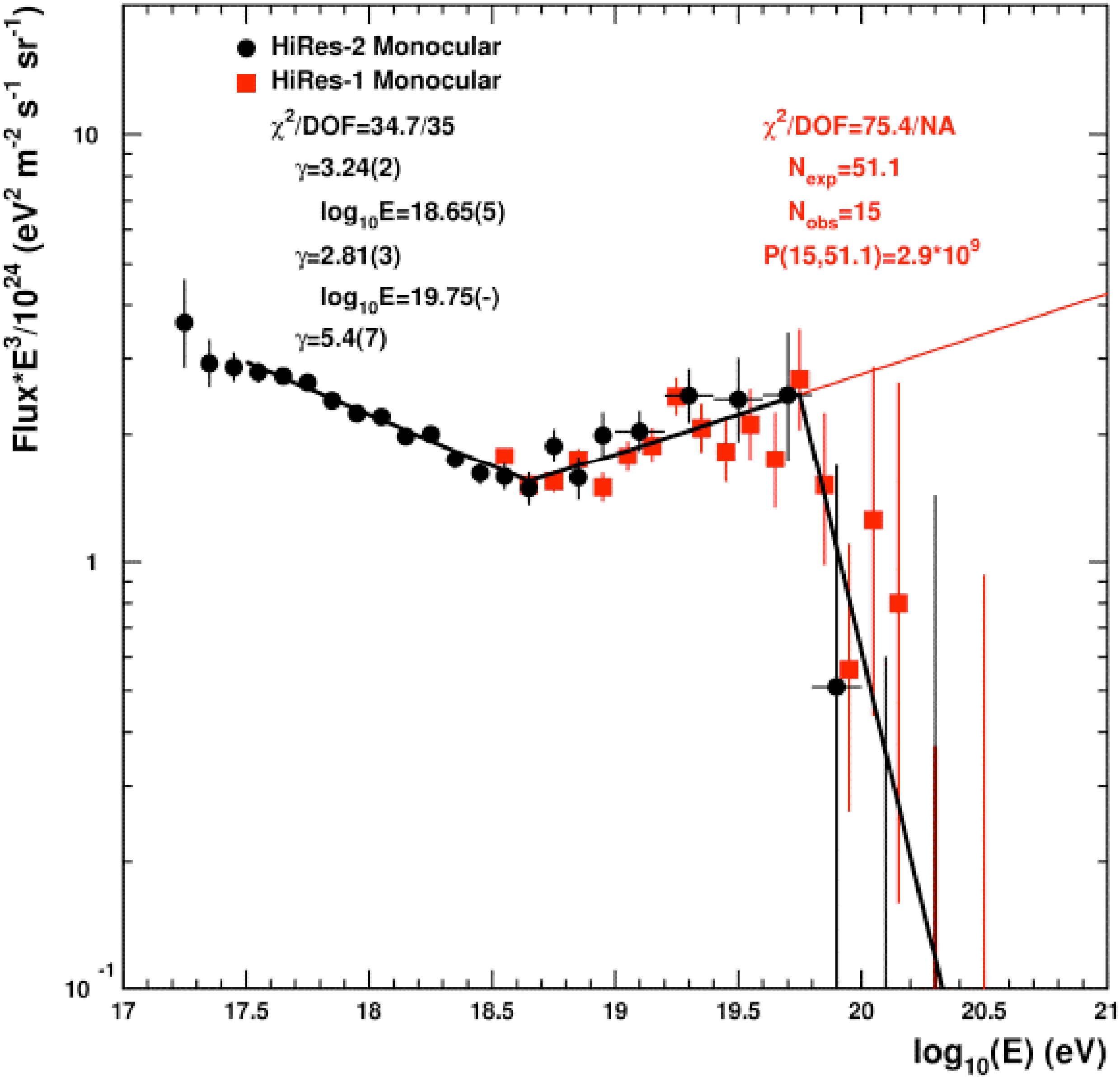
Sensational Results In UHECR Astrophysics

1. Akeno Giant Air Shower Array (AGASA), *Phys*. Rev. *Lett*. 92, 151101 (2004): UHECR spectrum extends beyond the GZK cutoff !!



Phys. Rev. Lett. 100, 101101 (2008).

2. The Discovery of the GZK cutoff by the Fly's Eye HiRes



Pierre Auger Observatory (PAO) confirms: GZK Cutoff Is There !
PAO's and HiReS' spectra agree within their energy uncertainty.

Phys. Rev. Lett. 101 (2008), 061101.

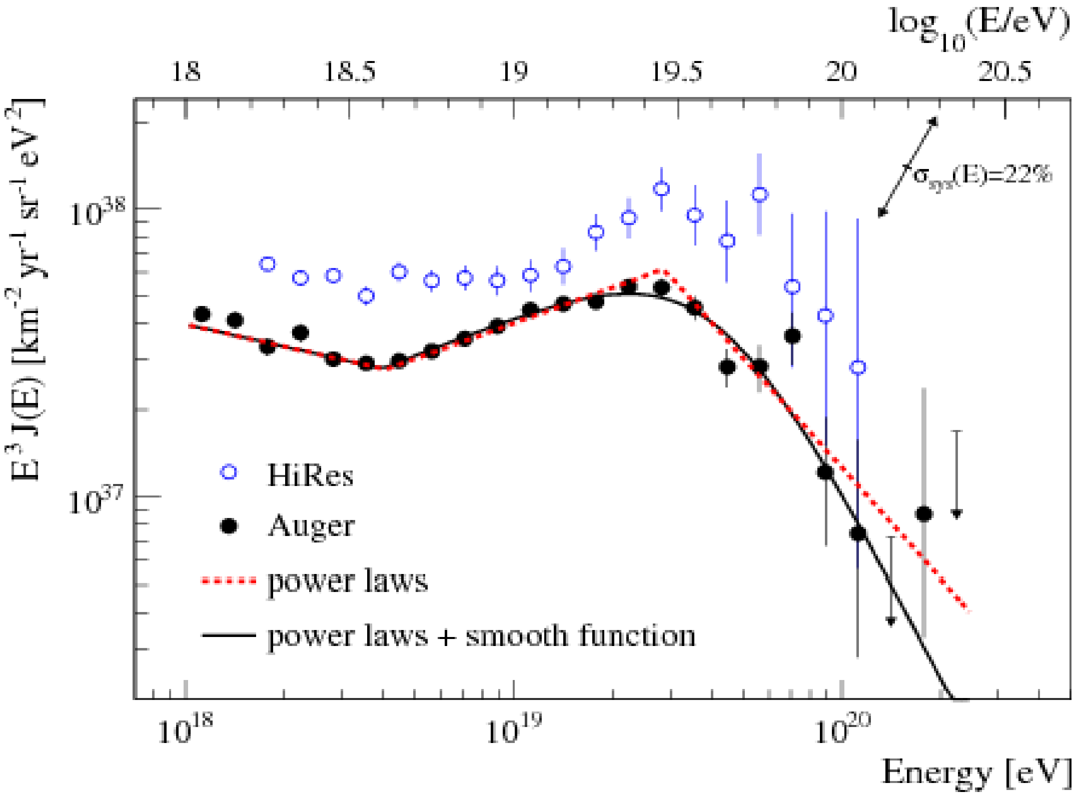


Figure 5: The combined energy spectrum is fitted with two functions (see text) and compared to data from the HiRes instrument [43]. The systematic uncertainty of the flux scaled by E^3 due to the uncertainty of the energy scale of 22% is indicated by arrows. A table with the Auger flux values can be found at [44].

DP, DD: Maximum Energy of Fermi Accelerated UHECRs by Relativistic Jets*: 2γ e Z B R

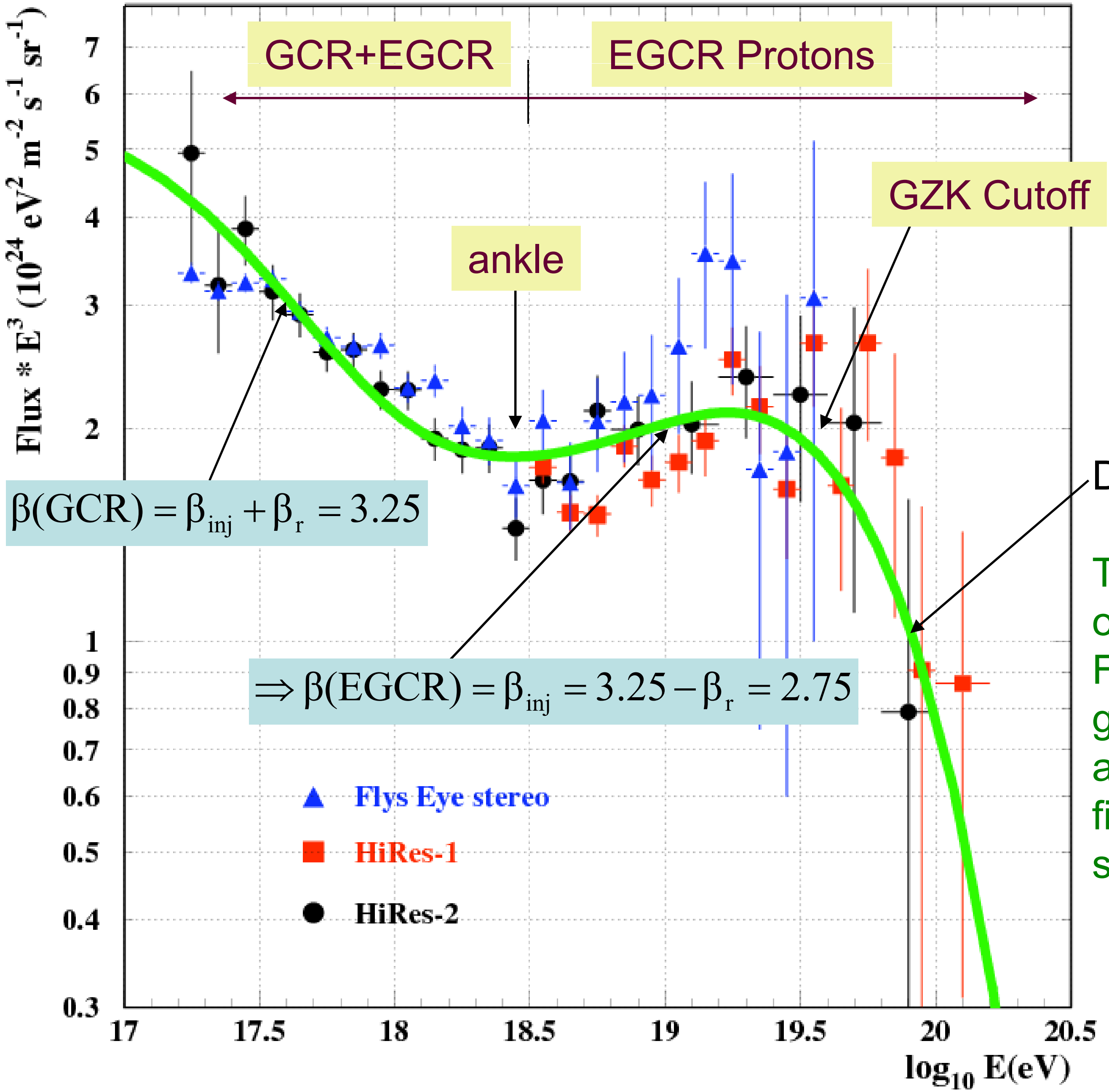
Jet Source	R	B (equipartition)	γ_{max}	Emax(p)
AGN	~ 10 pc	$\sim$ mGauss	~ 100	~ 300 Z EeV
GRB/SHB Sources:				

SNIb,c + SNII?	~ 10 AU	$\sim$ Gauss	~ 1500	~ 150 Z EeV
n* mergers	~ 10 AU	$\sim$ Gauss	~ 1500	~ 150 Z EeV
μQSOs	~ 1000 AU	~ 10 mGauss	~ 20	$\sim$ Z EeV
SGRs ('magnetars')				
Pulsars				
AXPs				
ms Pulsars.				

ULXs				

* All Power-law sources of radio, X-rays and γ-rays are VHECR sources

If the Fly's Eye HiRes p Composition Is Correct:



DD2008 Phys.Rep.

The normalization of the UHECR flux From external galaxies was adjusted to fit the the HiRes spectrum !

3, UHECRs-AGN correlation ?

PAO reported that the arrival directions of 19 UHECRS out of 27 [69 (+11,−13) %] detected between January 2004 and December 2007 with super GZK energy point back within 3.1 degree to AGNs in the VCV catalogue (M.-P. V´eron-Cetty, P. V´eron, Astron. Astrophys. 455 (2006) 773.) **within 75 Mpc with a chance probability of $P < 6\times10^{-7}$ for isotropic distribution.** (Science 318, 938 (2007), Astropart. Phys. 29, 188 (2008). **Most of the UHECRs Originate in AGNs ?**

But:

Fly's Eye HiRes reports that their 11 super GZK events do not show the PAO UHECR-AGN directional correlation at 85% c.l.
(The Astrophysical Journal 713, L64 (2010))

Up-date by PAO: 38 (+7, −6)% in the the entire sample of 69 super GZK events detected between January 2004 and December 2009 to be compared with the 21 % expected to occur by chance.
Astroparticle Physics 2010, (eprint arXiv:1009.1855)

Additional Evidence For Large Scale anisotropy ?

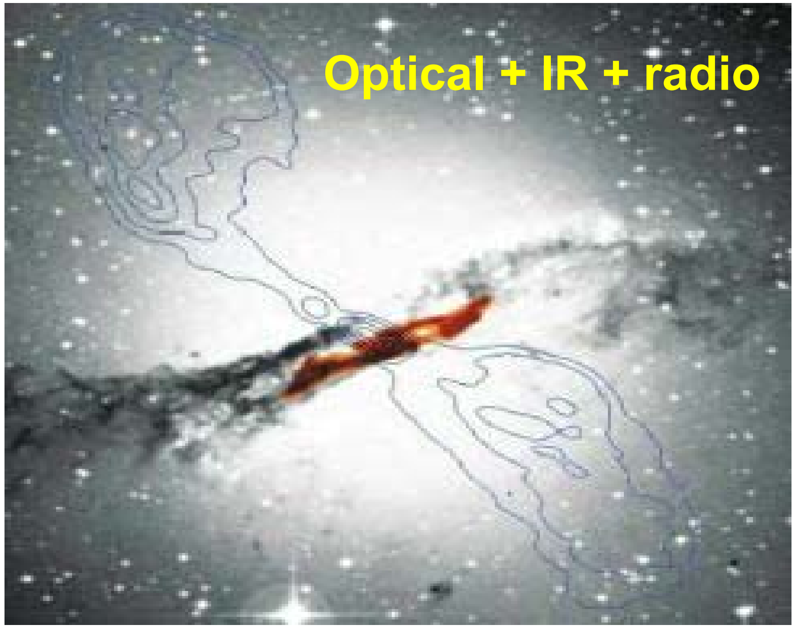
PAO reported: 18.8% of the arrival directions of the 69 UHECRs with E ≥ 55 EeV, lie within 18 deg of Cen A, while 4.7% is the isotropic expectation. (This region is densely populated with different types of nearby extragalactic objects. Flux-weighted models based on 2MRS* galaxies and on Swift-BAT AGNs predict a fraction of UHECRs from this region of 13% and 29% , respectively.) Two arrival directions are very close to the position of the Cen A nucleus. Aside from those two events, the excess is distributed rather broadly.

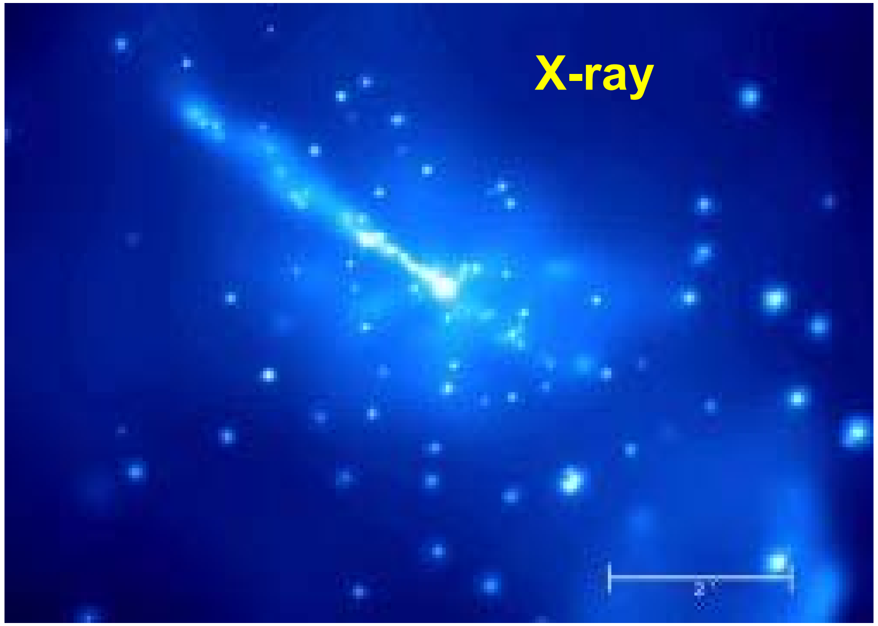
Are the UHECRs that Reach Earth Correlated to Nearby AGNs?

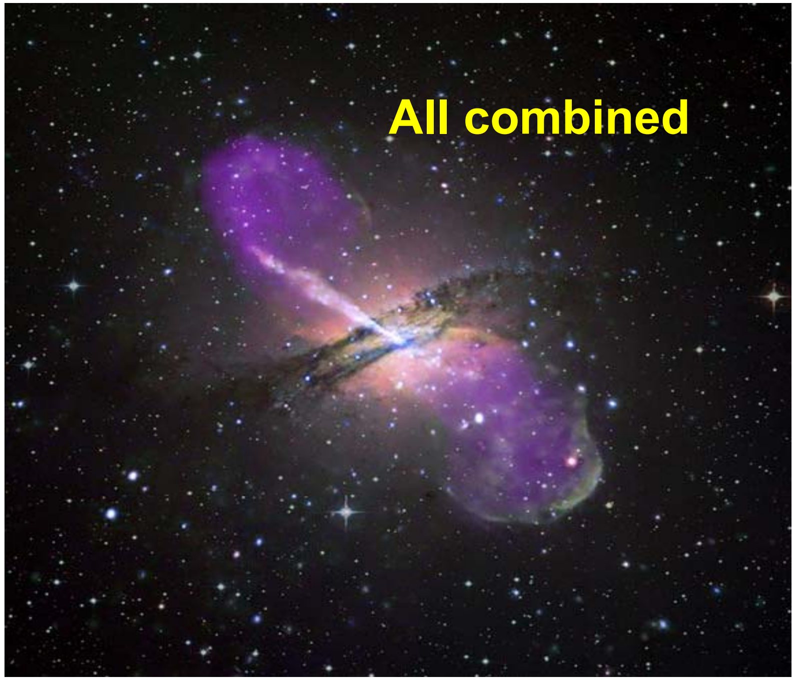
Note :

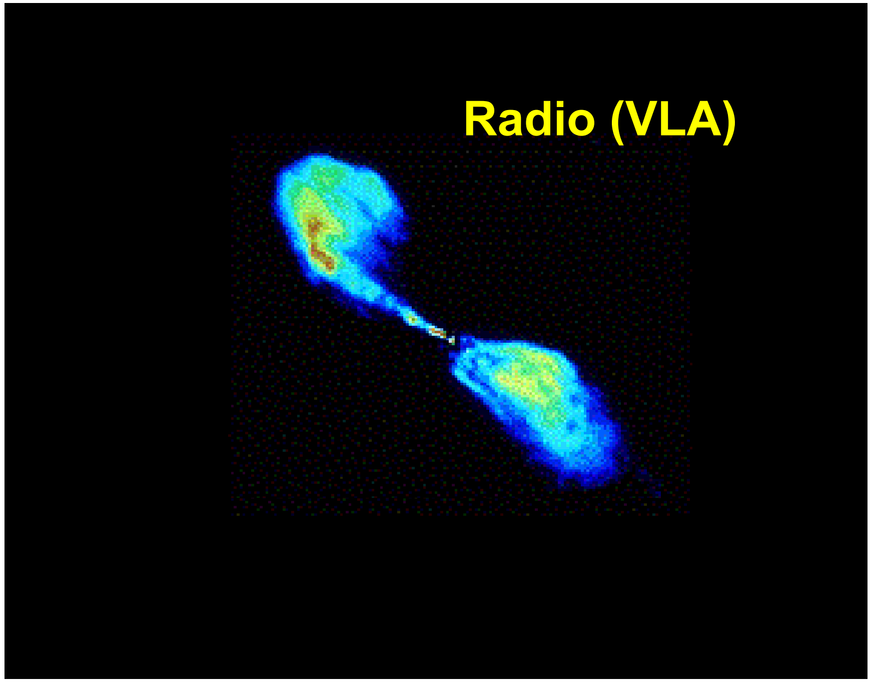
1. Massive black holes in AGNs are believed to be produced by merger of galaxies (Centaurus A itself is an elliptical galaxy with a spiral galaxay at its center). Mergers are correlated with higher densities of galaxies. If the UHECRs - AGN correlation is real, it may be due to a higher density of galaxies around the location of massive black holes, i.e., AGNs.
2. If UHECRs are accelerated by relativistic jets they are relativistically beamed into a narrow cone along the jet axis with an opening angle $\theta \sim 1/\gamma$.
Probably, the UHECR beams from Cen are not pointing towards Earth.

Centaurus A is a giant elliptical galaxy with an active galactic nucleus (AGN) - the closest one to Earth.









PAO: The composition of UHECR change progressively from proton dominated above the CR ankle to iron dominated near the GZK cut-of

Composition above EeV from Measurement of the Depth of Maximum of EAS

Depth of Shower max: $< Xmax > = \alpha(< \ln E > - < \ln A >) + b$

If the nuclear disintegration produces A showers with $E_s \approx E/A$

$\Rightarrow$ Dispersion in $< Xmax >$ decreases like $A^{-1/2}$

[Phys. Rev. Let. 104, 091101 (2010)]:

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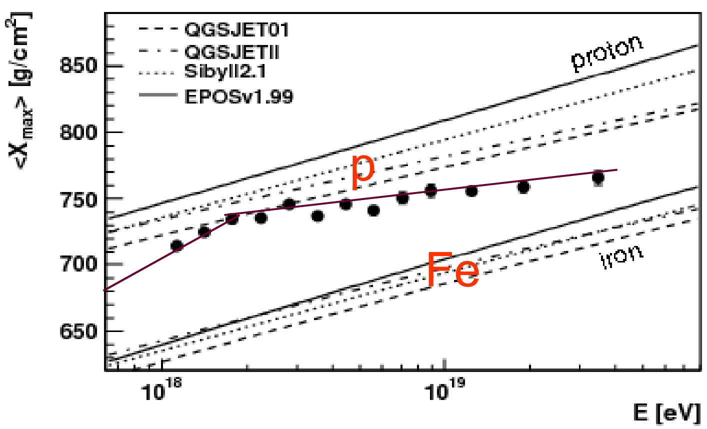
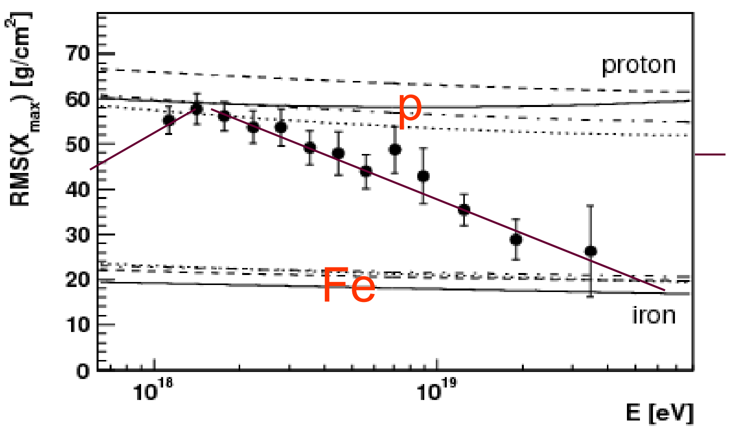




IF THE COMPOSITION BECOMES IRON DOMINATED WHEN E APPROACHES THE GZK CUTOFF, THEN :

1. **The UHE Cutoff Near 50 EeV Is Not The GZK Cutoff because The GZK Cutoff For Nuclei Is at:**

$$E_{GZK}(A) \approx A \times E_{GZK}(p)\,, \quad \text{i.e.,} \quad E_{GZK}(Fe) \approx 2600\text{EeV}\,!$$

2. **The UHECRs Cannot Be Extragalactic In Origin Because Their Mean Free Path For Photo-disintegration In Collisions With The EG Background Radiation Is Much Shorter Than The MPF For Pion Photo Production above the GZK threshold.**

3. **Can UHECR Iron Nuclei With E~100 EeV Point Back to EG Point Sources within 3.1 deg ? If the number of Galactic magnetic domains along the line of sight is** $f \cdot R_{GCRH}/l_c$**, then, because of magnetic eflections by Galactic magnetic fields:**

$$< \vartheta > \approx \left[\frac{f^{1/2}\, R_{GCRH}}{l_c}\right]^{1/2} \left[\frac{l_c}{R_L}\right] = \frac{e\, Z\, B\, [R_{GCRH}\; l_c]^{1/2}}{E} \sim 0.72\, f^{1/2} \text{ rad} = f^{1/2}\, 41^0$$

$$\text{for} \quad R_{GCRH} = 10 \text{ kpc}, \quad l_c = 0.1 \text{ kpc}, \quad B = 3\ \mu\text{Gauss}, \quad E = 100 \text{ EeV}$$

Is there a simple and consistent explanation for the PAO inferred energy spectrum and composition of UHECRs?

Dar & Plaga, A & A, 349, 259 (1999): The UHECRs that are observed near Earth are Galactic in origin. They are accelerated by the highly relativistic jets that produce Galactic GRBs, most of which are beamed away from Earth.

DDD 2010: 1. The ankle is the energy when free escape of Galactic cosmic ray nuclei from the Galactic magnetic field begins:

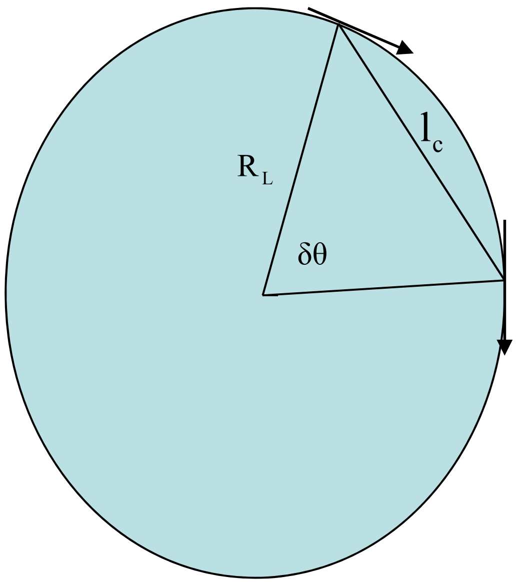
Is the UHE break the Fe escape break ?

$$R_L = \frac{E}{e\,Z\,B} \approx 0.36 \left[\frac{E}{EeV}\right] \frac{1}{Z} \left[\frac{3\,\mu Gauss}{B}\right] \text{kpc} >> l_c$$

(Larmor radius much larger than the coherence length of the random Galactic B field)

$R_L >> l_c \Rightarrow$

$\delta\theta \approx l_c/R_L$



'Free Escape' when :

$$\vartheta \approx \sqrt{N}\,\delta\theta \approx \left[\frac{R_{GCRH}}{l_c}\right]^{1/2} \left[\frac{l_c}{R_L}\right] = \frac{e\,Z\,B\,[R_{GCRH}\;l_c]^{1/2}}{E} \leq \frac{\pi}{2}$$

for $R_{GCRH} = 10$ kpc, $l_c = 0.1$ kpc, $B = 3\ \mu$Gauss, $E = 100$ EeV $\Rightarrow$

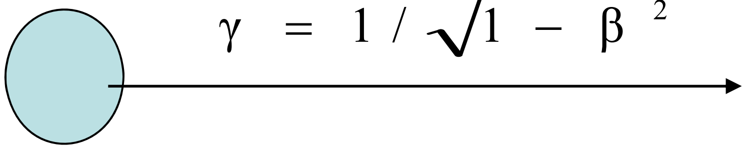
Eescape(p)=1.8 EeV Eescape(He)=3.6 EeV Eescape(Fe)= 46.8 EeV

when $E >>$ Eescape, $\tau_r \approx R_{GCRH}/c \sim 30{,}000$ y

Fermi Acceleration By Relativistic Cannonballs

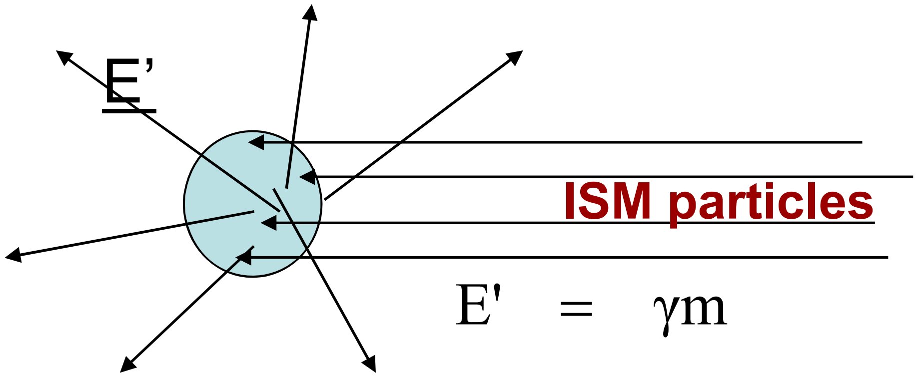
CB

$$\gamma = 1/\sqrt{1-\beta^2}$$



ISM

Lab Frame



$$E' = \gamma m$$

CB's Rest Frame

After Isotropization in the CB By
Magnetic Elastic Scatterings

$$E = \gamma E'(1+\beta^2 \cdot \cos\vartheta')$$

$$E_{max} \approx (2\gamma^2 - 1)\cdot m$$

$$\frac{dn}{dE} \approx \frac{n}{(2\gamma^2 - 1)\cdot m} \qquad m \le E \le E_{max}$$

DD2008: CR Spectrum & Composition Due To Fermi Acceleration By Relativistic Jets, Modified By Galactic Residence Time

Universal power-law:

$$\frac{dn_A^{inj}}{d\gamma} = X(A,Z)\frac{dn_p^{inj}}{d\gamma} \qquad X(A,Z) \equiv \left.\frac{n_A}{n_p}\right|_{source}$$

$$\frac{dn_p}{d\gamma} = n_p(\beta_{inj}-1)\gamma^{-\beta_{inj}} \quad , \qquad \beta inj = 13/6 \approx 2.17,$$

Injection spectrum :

$$d\gamma = \frac{dE}{A\, m_p} \Rightarrow \frac{dn_A^{inj}}{dE} = X(A,Z)A^{\beta inj\text{-}1}\frac{dn_p^{inj}}{dE}$$

Residence time:

$$\tau_r(E,Z) \propto \left[\frac{E}{e\,B\,Z}\right]^{-\beta_r} \quad , \qquad \beta_r \approx 0.5 \quad (\text{empirical})$$

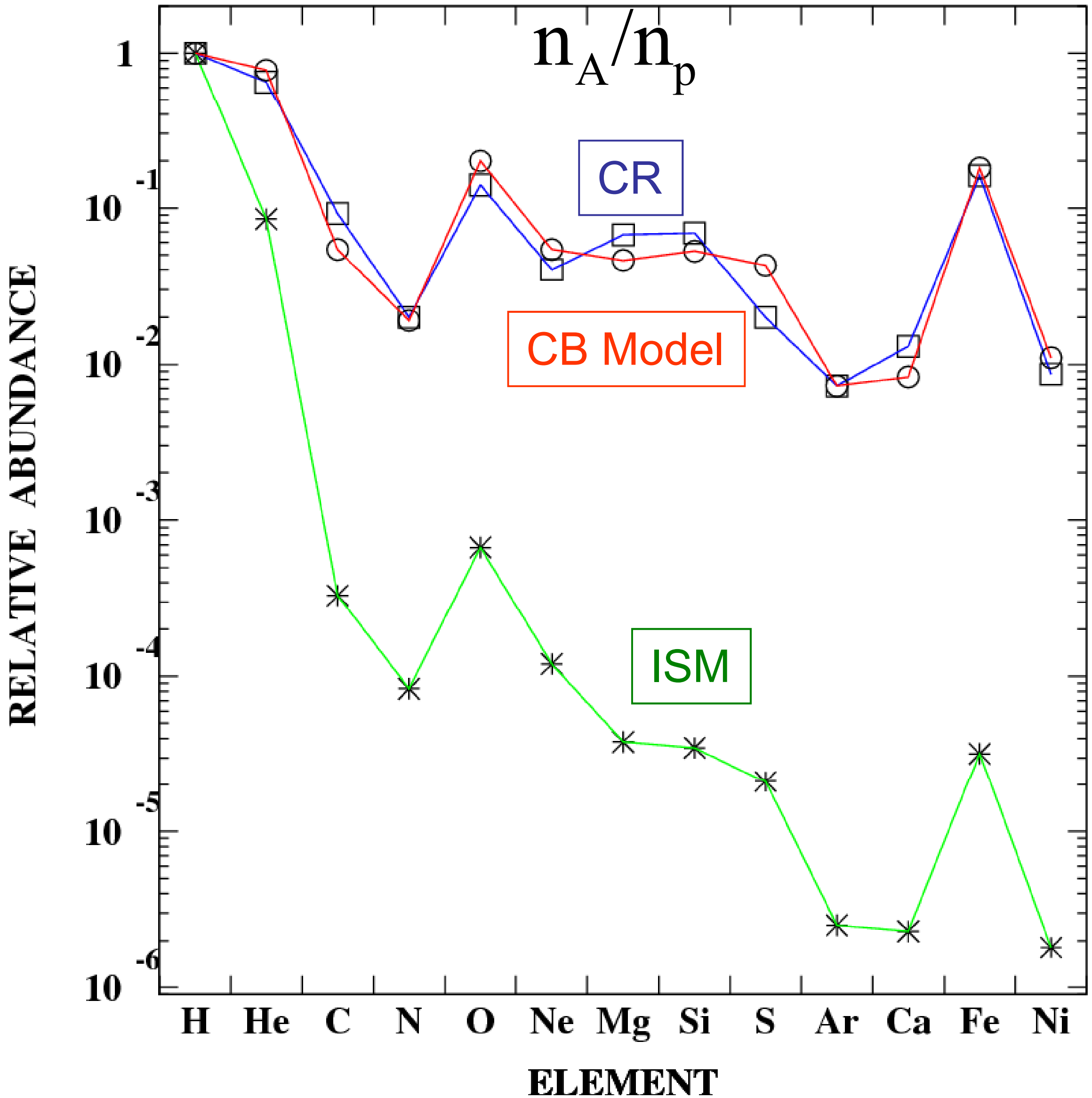
Residence time modification :

$$\frac{dn_A}{dE} = \tau_r(E,Z)\frac{dn_A^{inj}}{dE}$$

$$\Rightarrow \frac{dn_A}{dE} = X(A,Z)\,A^{\beta inj\text{-}1}Z^{\beta_r}\frac{dn_p}{dE} \propto X(A,Z)\,A^{\beta inj\text{-}1}Z^{\beta_r}E^{-(\beta_{inj}+\beta_r)}$$

The abundance of iron nuclei (A=56, Z=26) in CRs
is the abundance in the source enhanced by a factor 566
If, e.g., Xsfr (Fe) ~ 4 Xism(Fe) ➔ n(Fe) =0.08 n(p) .

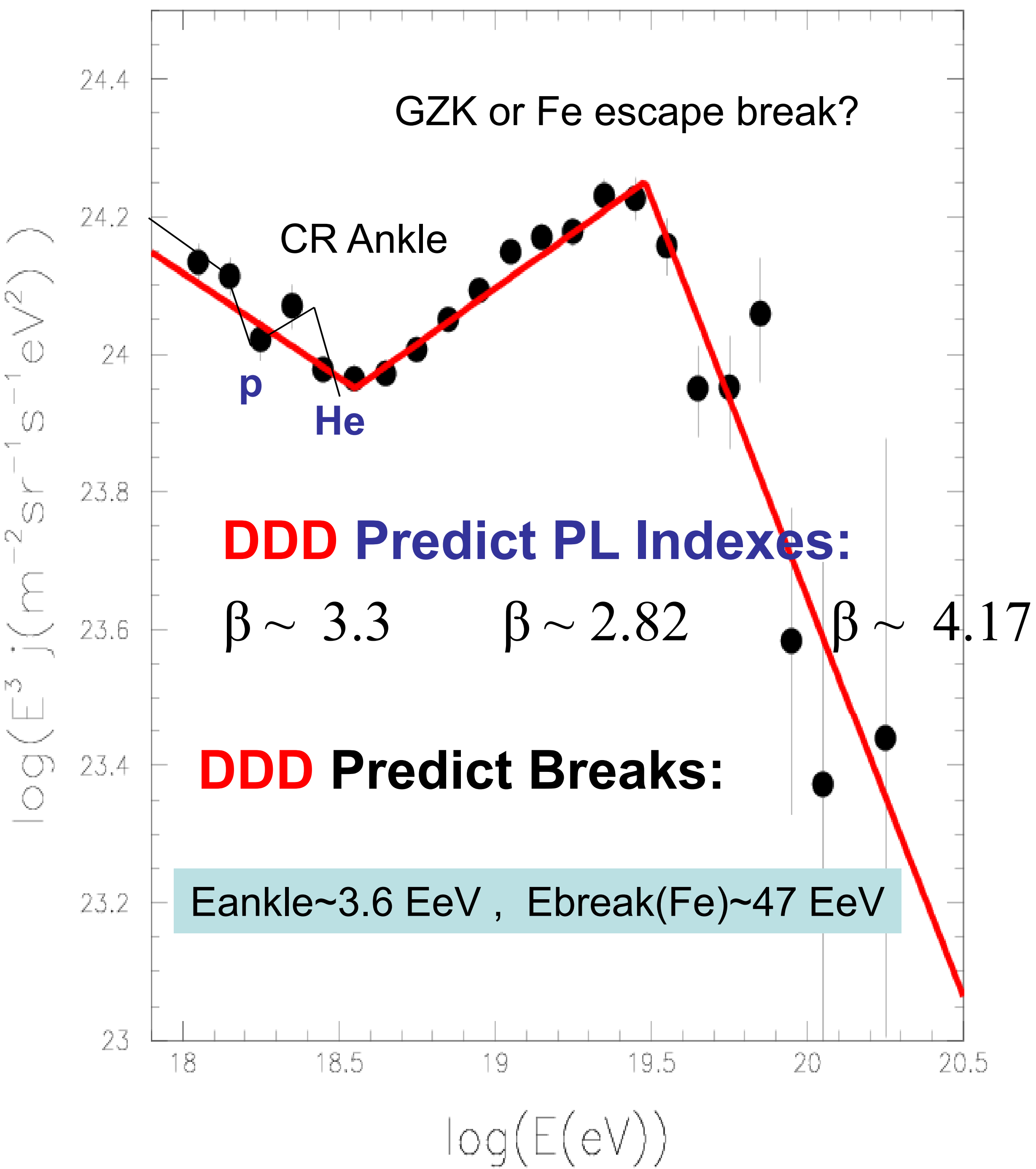
The relative abundances of primary CR nuclei, from H to Ni around 1 TeV . The stars (green line) are ISM abundances.The circles (red line) are the prediction for an initial Super-bubble abundances. The squares (joined in black) are the CR observations.



$$\frac{dn_A}{dE} = X(A,Z)\, A^{\beta inj\text{-}1} Z^{\beta_r} \frac{dn_p}{dE}$$

$$\Rightarrow X_{CR}(A,Z) = X_{source}(A,Z)\, A^{\beta inj\text{-}1} Z^{\beta_r}$$

(Before Spallation)



DDD: arXiv:1011.2672

If the PAO composition is correct, the breaks and power-law indexes of broken power-law spectrum of the UHECRs measured by PAO (multiplied by E^3 for clarity) can be predicted from general considerations provided there is no UHECR - AGN correlation

The Spectral Index Above The Second Knee

The Second knee is the energy threshold for nuclear photodisintegration in the IGM by the giant dipole resonance with peak strength around photon energy of ~15 MeV in the nucleus rest frame. The disintegration in collisions with the FIR BKG, Lorentz boosted to the threshold energy in the nucleus rest frame begins with He4 and ends with Fe56, a factor of 14 in energy . Removal of the nuclei from the CR flux reduces the total flux by a factor, $1/(1+\sum X(A,Z)) \approx 1/2.4$ **.**

This increases the spectral index above the 2'nd knee to the value :

$$\beta = 2.9 + \log(2.4)/\log(14) = 3.23 \quad .$$

The Spectral Index Above The CR ankle

Removal of the Galactic CR nuclei by escape from p up to Fe56 reduces the Galactic CR flux by a factor ~8.4 over a factor 26 in energy (Eescape(Fe)/Eescape(p)=26) yielding

$$\beta \approx \beta_{inj} + \log 8.4/\log 26 = 2.82$$

The Spectral Index Above The Escape energy

Magnetic deflections spread the UHECRs into a solid angle:

$$\pi\vartheta^2 = \pi\left[\frac{R_{GCRH}}{l_c}\right]\left[\frac{l_c}{R_L}\right]^2 = \frac{e^2 Z^2 B^2 [R_{GCRH}\, l_c]}{E^2} << 4\pi$$

and their arrival times by $\tau_d \approx R_{GCRH}\vartheta^2/2c$

The probability that CRs from a source are beamed towards Earth is thus

$\vartheta^2/4 \propto E^{-2}$ **and for** $\dot{N}_s \tau_d \vartheta^2/4 << 1$ **the spectral index becomes**

$$\boxed{\beta = \beta_{inj} + 2 = 13/6 + 2 = 4.17}$$

Large Scale Isotropy :Many potential CR jet sources (whose non-thermal radio, X-ray and gamma-ray emissions indicate that they are cosmic accelerators) such as pulsars, millisecond pulsars, and in particular SHBs, are NOT distributed like the stars. They are distributed over a large halo like super star-clusters (globular clusters, etc). Fong et al. ApJ 708, 9-25 (2010) finds that the PROJECTED offsets of SHBs relative to their host centers range from about 1 kpc to 64 kpc, with a large median value. They fire very often, once every ~10 years.

Conclusions

1. The observed spectrum of UHECRs measured from extensive air showers cannot distinguish alone between Extra Galactic UHECR protons and Galactic Nuclei (A sawteeth GCR nuclei spectrum is smoothed by the imprecise inherent energy measurement).

2. Conflicting results were reorted by the PAO and Fly's Eye on small scale anisotropy of the arrival directions of UHECRs above the UHE break:

PAO: The degree of the observed correlation with AGN has decreased from (69+11,−13)% to (38 +7,−6)%, to be compared with the 21% expected to occur by chance if the flux were isotropic. 18.8% of the CR events with E ≥ 55 EeV, lie within 18 deg of Cen A, while 4.7% is the isotropic expectation. Flux-weighted models based on 2MRS galaxies and on Swift-BAT AGNs predict a fraction of 13% and 29% respectively CRs from this region.

Fly's Eye: Neither a correlation with AGN nor with large scale structure at 95% C.I. (based on much smaller statistics: only 13 super GZK events).

3. Conflicting results were reported by the PAO and Fly's Eye on the composition of the UHECRs;

Measurements by the PAO of the depth of shower maximum and its fluctuations show a transition toward heavy nuclei with increasing energy. Although the measurements available now are only up to about 55 EeV, the trend suggests that primary CRs are likely to be dominated by heavy nuclei at higher energies.

4. If the UHECR composition near the GZK cutoff is dominated by heavy nuclei then the spectral break near 50 EeV is not the GZK cutoff.

5. If the composition near the GZK cutoff is dominated by heavy Nuclei, the UHECRs must be Galactic in origin since extragalactic UHECR nuclei are photo-disintegrated in collisions with the FIR and CMB radiations.

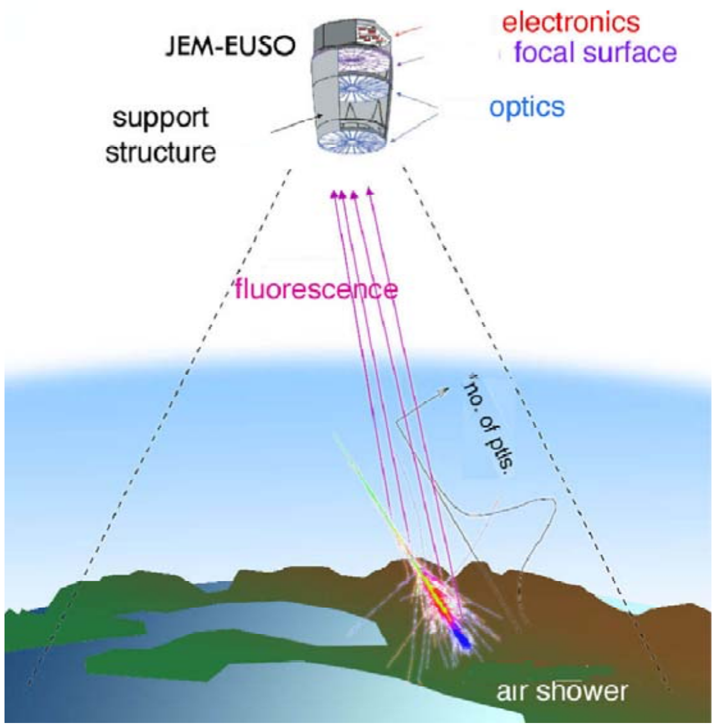
However, the interpretation of the shower depths relies on shower simulations that use hadronic interaction models to extrapolate observed particle interaction properties two orders of magnitude in center-of-mass energy beyond the regime where they have been tested experimentally (LHC).

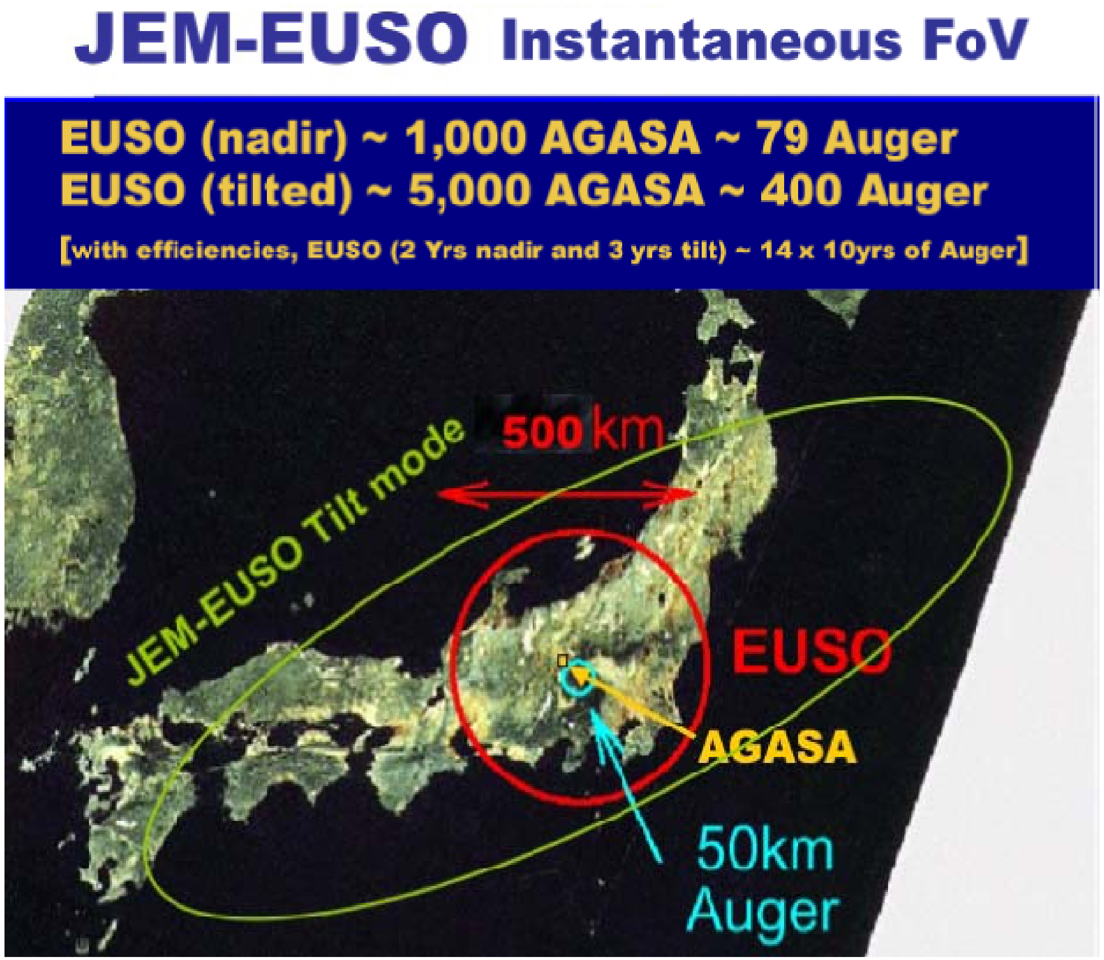
Moreover, the composition measured with the Fly's Eye HiRes does not confirm the PAO trend towards heavy nuclei with increasing energy

Will EUSO Resolve The discrepancies?

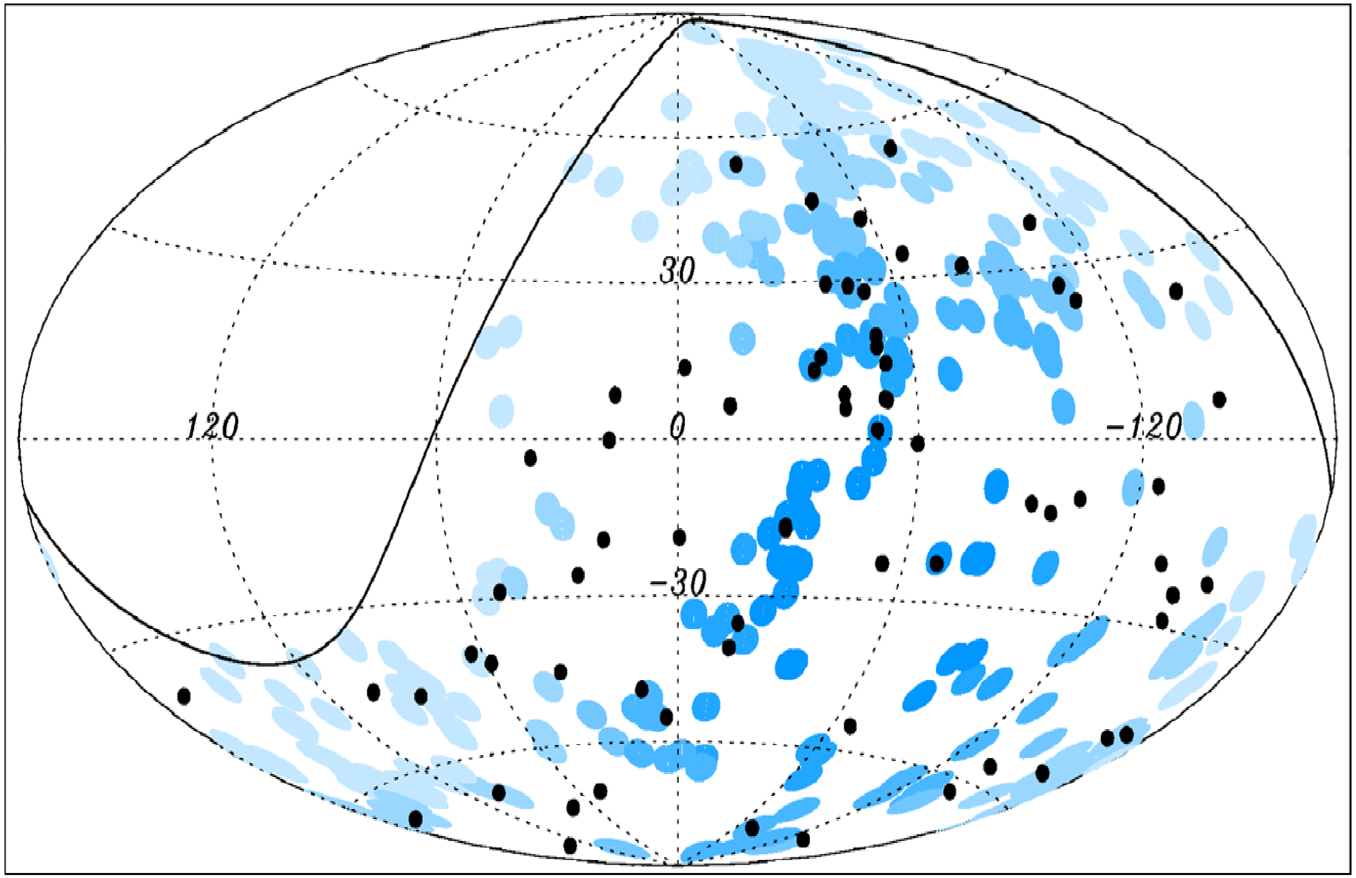
Extreme Universe Space Observatory (EUSO) on (2013?) the intl. space station

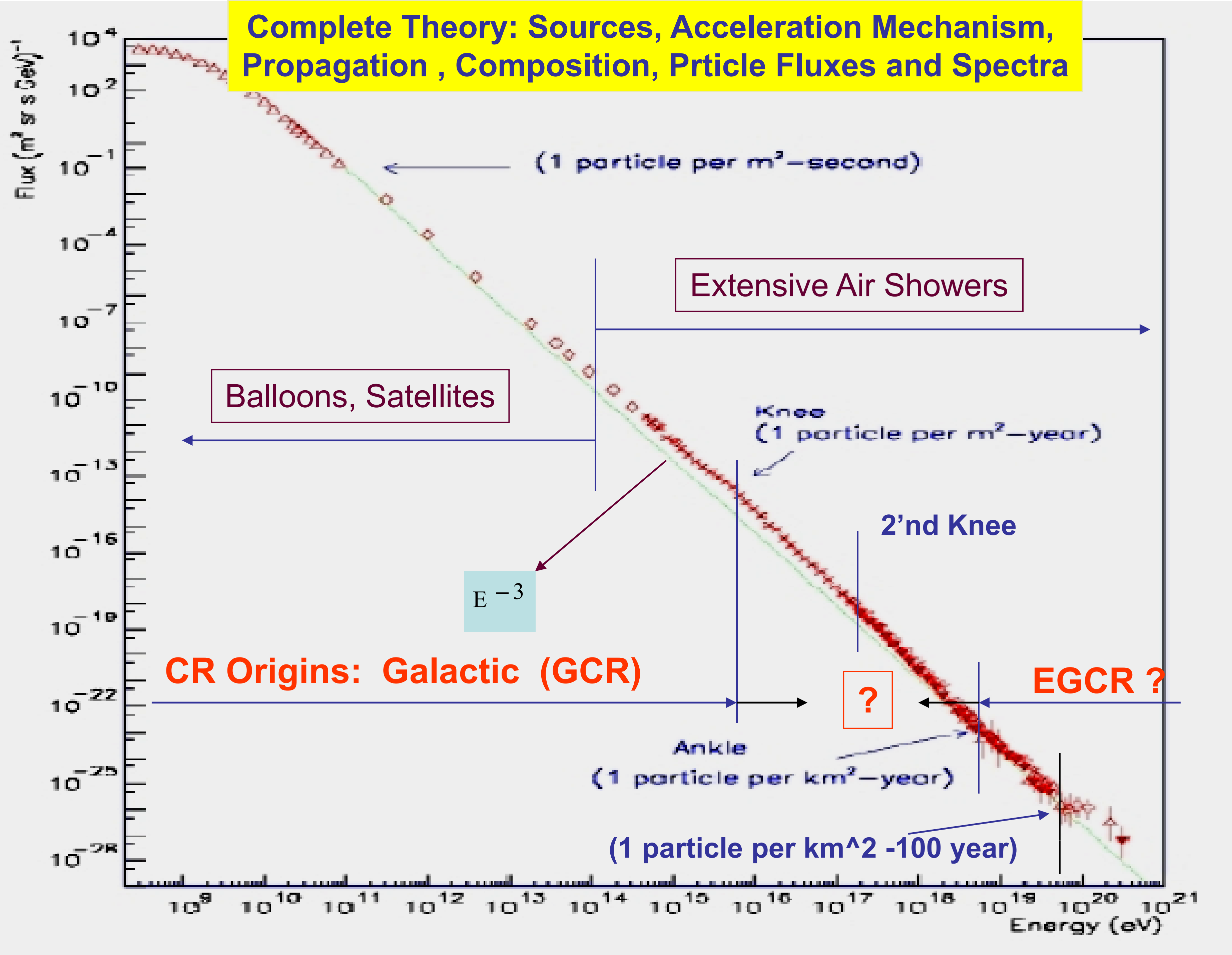
EUSO will detect in 5 years at least 1000 super GZK events with E>70 EeV





The 69 arrival directions of CRs with energy E ≥ 55 EeV detected by PAO up to 31 December 2009 are plotted as black dots projection on the sky in galactic coordinates. The solid line represents the field of view of PAO for zenith angles smaller than 60 deg. Blue circles of radius 3.1 deg. are centred at the positions of the 318 AGNs in the VCV catalog that lie within 75 Mpc and that are within the field of view of PAO. Darker blue indicates larger relative exposure. The exposure-weighted fraction of the sky covered by the blue circles is 21%. Total PAO Exposure 20370 km^2/ sr y.




Complete Theory: Sources, Acceleration Mechanism, Propagation , Composition, Prticle Fluxes and Spectra
Flux (m² sr s GeV)⁻¹
(1 particle per m²–second)
Extensive Air Showers
Balloons, Satellites
Knee
(1 particle per m²–year)
2'nd Knee
E ⁻³
CR Origins: Galactic (GCR)
?
EGCR ?
Ankle
(1 particle per km²–year)
(1 particle per km^2 -100 year)
Energy (eV)