Ultra High Energy Cosmic Rays

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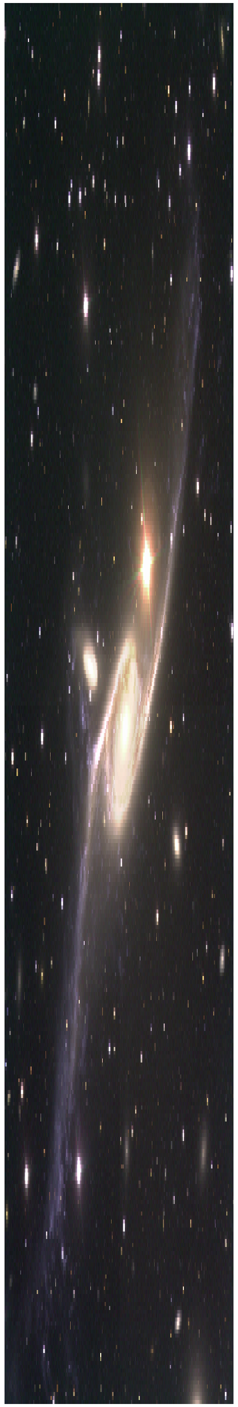
1. The Physics Case
2. Experimental Overview



Outline

- Early History:

➔ Discovery of C.R.'s : Hess, Rossi and Auger

- Low energy regime (E < 1PeV):

➔ Energy Spectrum

➔ Composition

- From Galactic to Extragalactic C.R.'s

  Changes in spectrum and composition: Knees and Ankle (1PeV<E<1EeV)

- UHECR

Units used: length: $pc = parsec = \frac{AU}{(arc\,sec)} = 3.262\,ly = 3.085 \cdot 10^{13}\ Km$

Energy: $PeV = 10^{15} eV \qquad EeV = 10^{18} eV$

First Observations

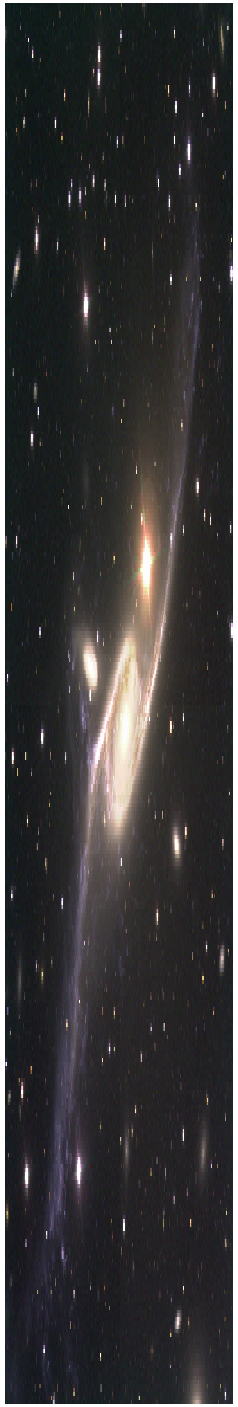
“ The results of present observations seem to be most readily explained by the assumption that a radiation of very high penetrating power enters our atmosphere from above.................”

V. Hess, 1912

“ .... sembra che occasionalmente arrivino sul nostro rivelatore gruppi di particelle che producono coincidenze anche tra rivelatori sufficientemente lontani .... “

B. Rossi, 1936

Systematic studies of CR showers (P.Auger 1938) and evidence for CR of Energy up to 10^{15} eV



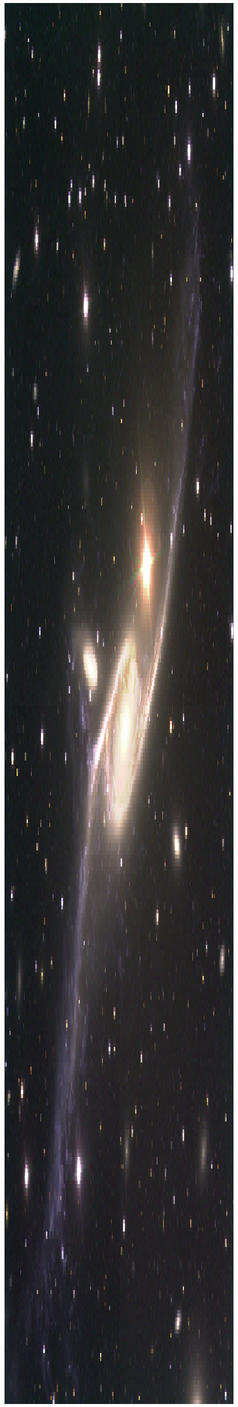
3 Observables:

- Energy Spectrum
- Mass Composition
- Arrival Direction:

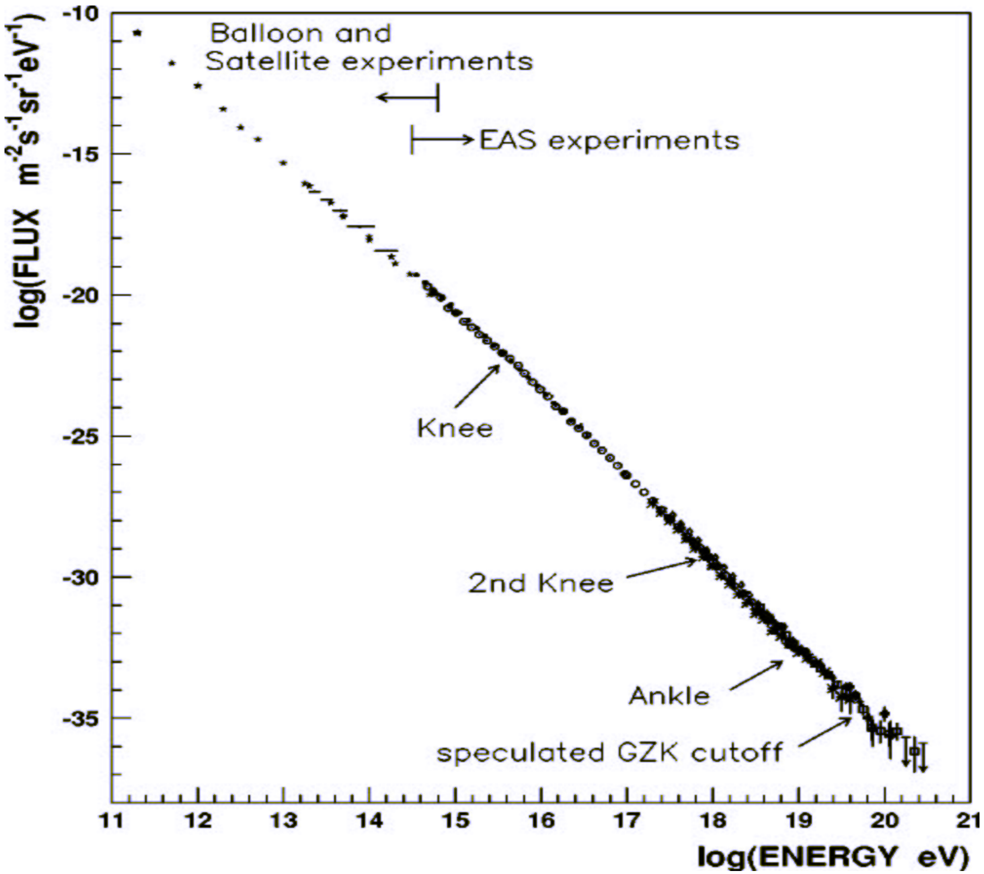
→ Effects of Magnetic Fields

To determine:

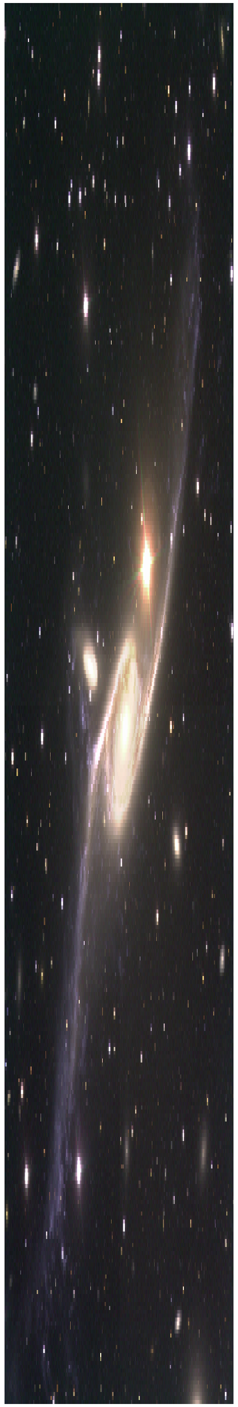
- Source characteristics
- Acceleration Mechanism



Cosmic Rays Spectrum



For E < 3 PeV → $$\frac{dJ(E)}{dE} = K \cdot E^{-2.7}$$



Fermi Acceleration Mechanism

In our galaxy: $$\frac{dE_{CR}}{dV} \approx \frac{1\,eV}{cm^3} \approx \frac{2 \cdot dE_{starlight}}{dV}$$!!!

CR interact with nuclei in ISM

$\tau_{nucl} \approx 7 \cdot 10^7\, years \ll 10^{10}\, years$ age of universe

$$dJ_{CR}(t) \propto dt \cdot e^{\frac{-t}{\tau_{nucl}}}$$

Hence continuous creation

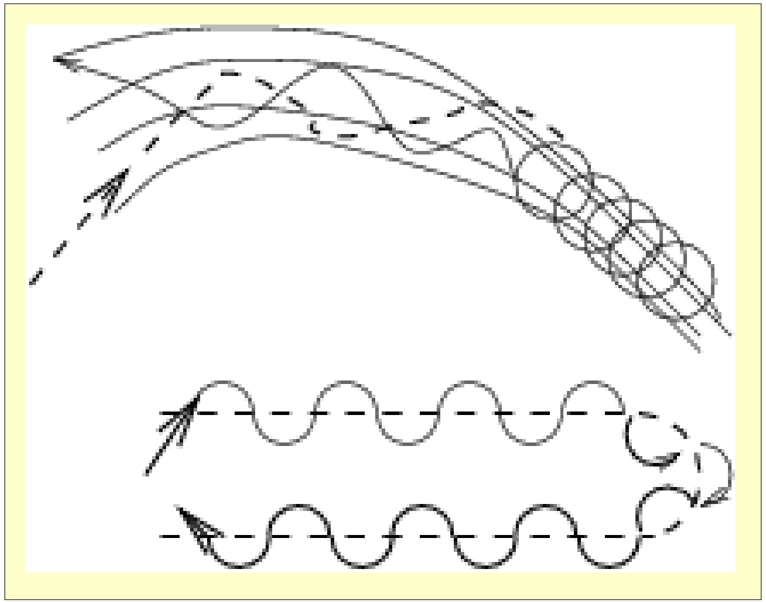
and continuous acceleration

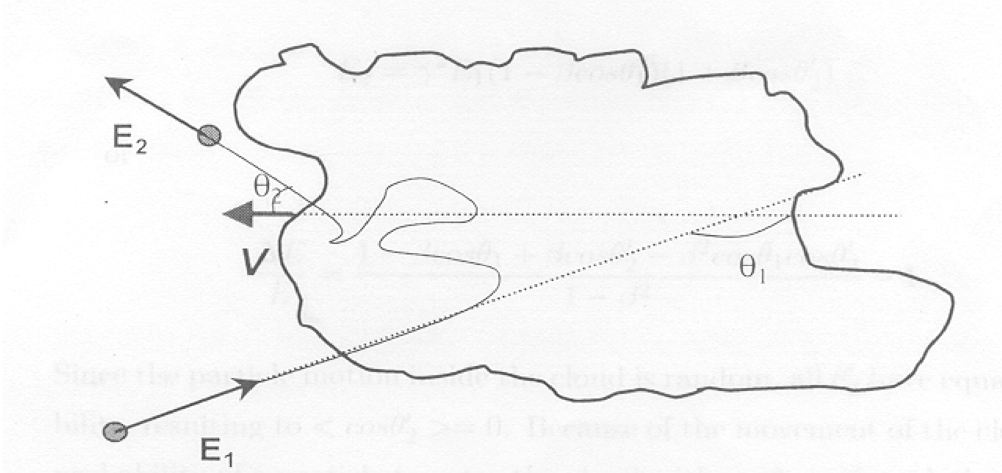
Acceleration in Plasma Clouds several l.y. wide with frozen-in irregular B field

$$\rho_{cloud} \geq 10\, \rho_{ISM}$$

equipartition of energy:

energy that can be reached is only limited by trapping time





$$\beta = \frac{V}{c} = 10^{-4}$$

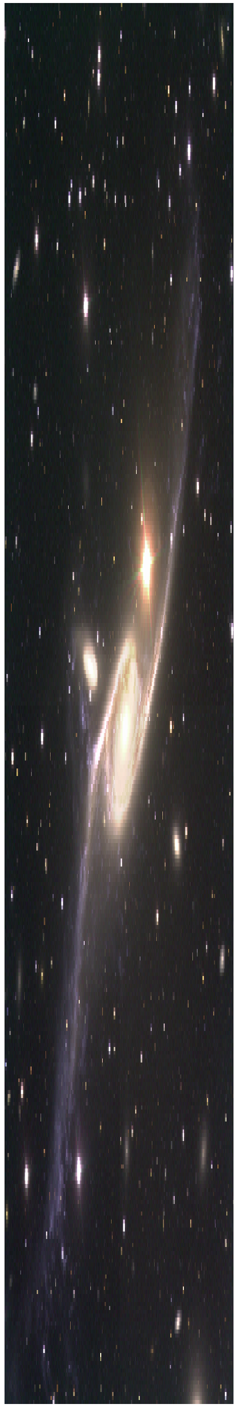
$$E_1^* = E_2^* \qquad P(\cos\theta_1) = \frac{1 - \beta \cdot \cos\theta_1}{2} \qquad P(\cos\theta_2^*) = const$$

$$\frac{\Delta E}{E} = \frac{4}{3} \cdot \beta^2 \qquad E = E_0 \cdot e^{\frac{4}{3}\beta^2} \qquad after \quad n = \frac{t}{\tau_{coll}} \quad collisions \qquad E = E_0 \cdot e^{\frac{4t}{3} \cdot \frac{\beta^2}{\tau_{coll}}}$$

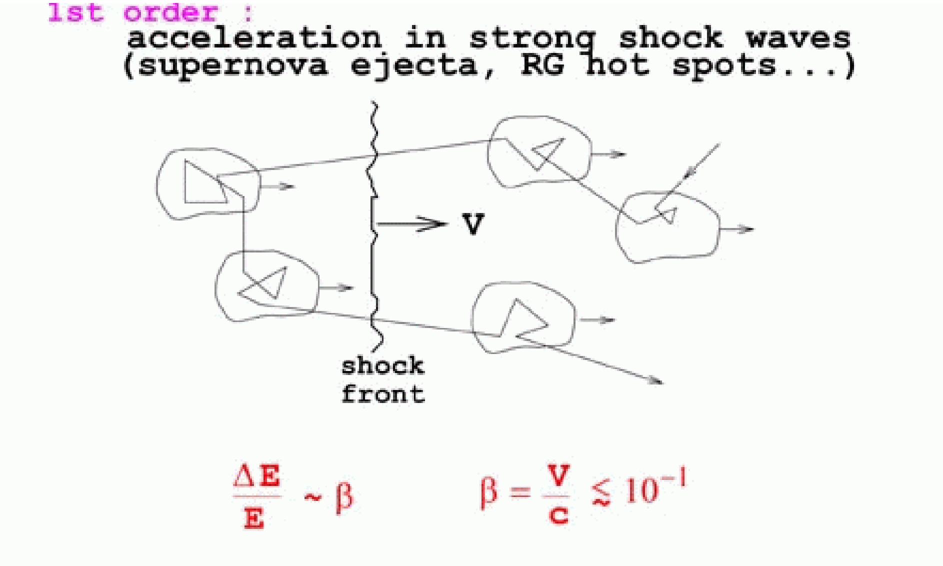
$$a = \frac{4}{3} \cdot \frac{\beta^2}{\tau_{coll}} \qquad E = E_0 \cdot e^{a \cdot t} \qquad t = \ln\left(\frac{E}{E_0}\right)^{\frac{1}{a}} \qquad dt = \frac{1}{a}\frac{dE}{E} \qquad dJ(t) \propto dt \cdot e^{\frac{-t}{\tau_{nucl}}}$$

$$dJ(E) \propto \frac{dE}{E} \cdot \left(\frac{E}{E_0}\right)^{-\frac{1}{(\tau_{nucl} \cdot a)}} \propto E^{-(\gamma+1)}\, dE$$

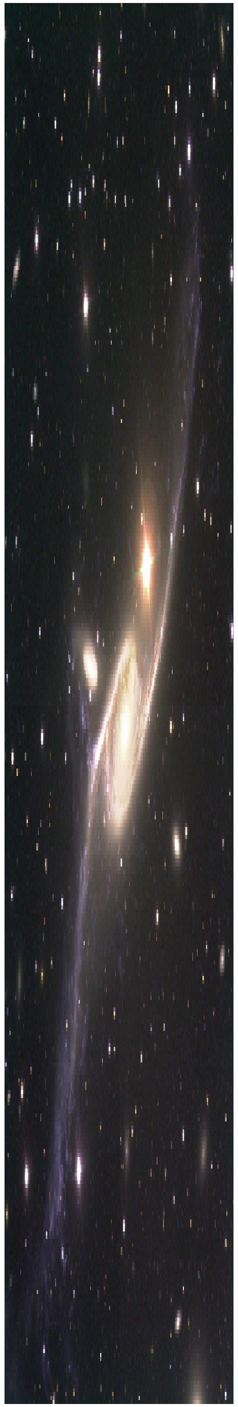
$$\gamma = \frac{3}{4} \cdot \frac{\tau_{coll}}{\tau_{nucl} \cdot \beta^2}$$



Shock wave Acceleration Mechanism (1977)



- Stochastic process:
  Power law Spectrum (1^{st} order Fermi Acceleration)
- Active in Supernova Explosions:
  acceleration up to 0.01 PeV for Protons
  naturally provides Injection Mechanism
- explains Mass Composition
- Interactions with multiple Supernova Remnants to explain energies up to EeV region



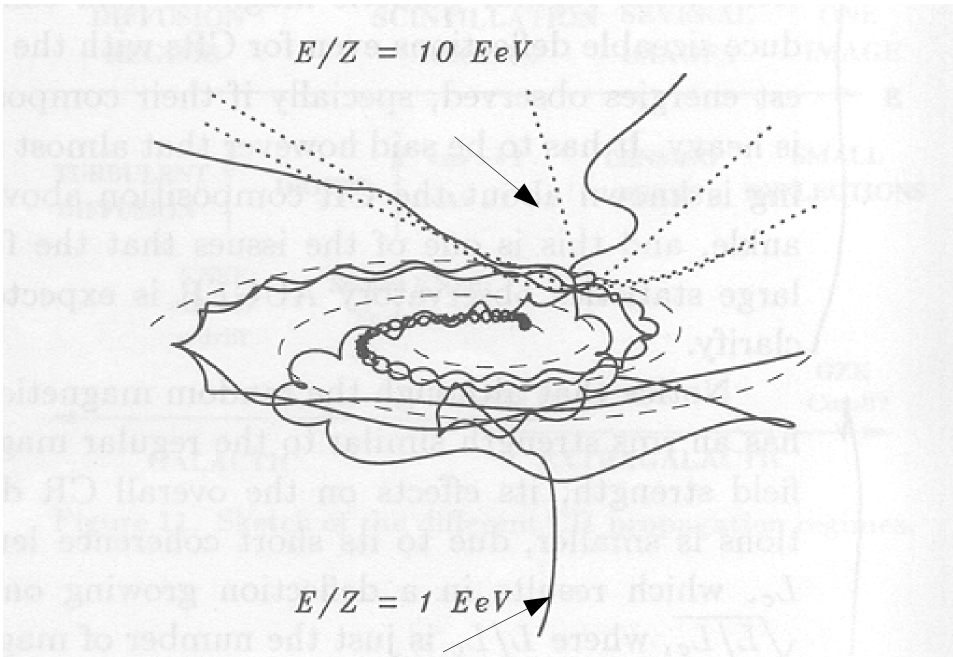
Characteristics and Effects galactic Magnetic Fields

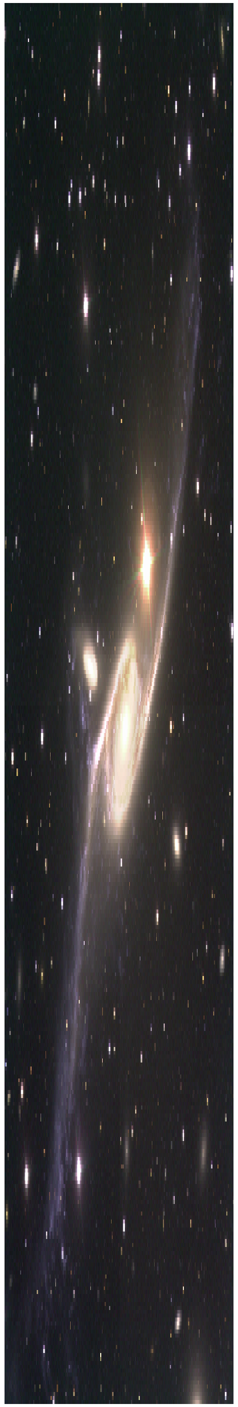
Uniform component along spiral arms: $B_0 = 2\mu G$

Larmor radius: $r_L(pc) = \frac{E(PeV)}{B_0(\mu G)\cdot}$

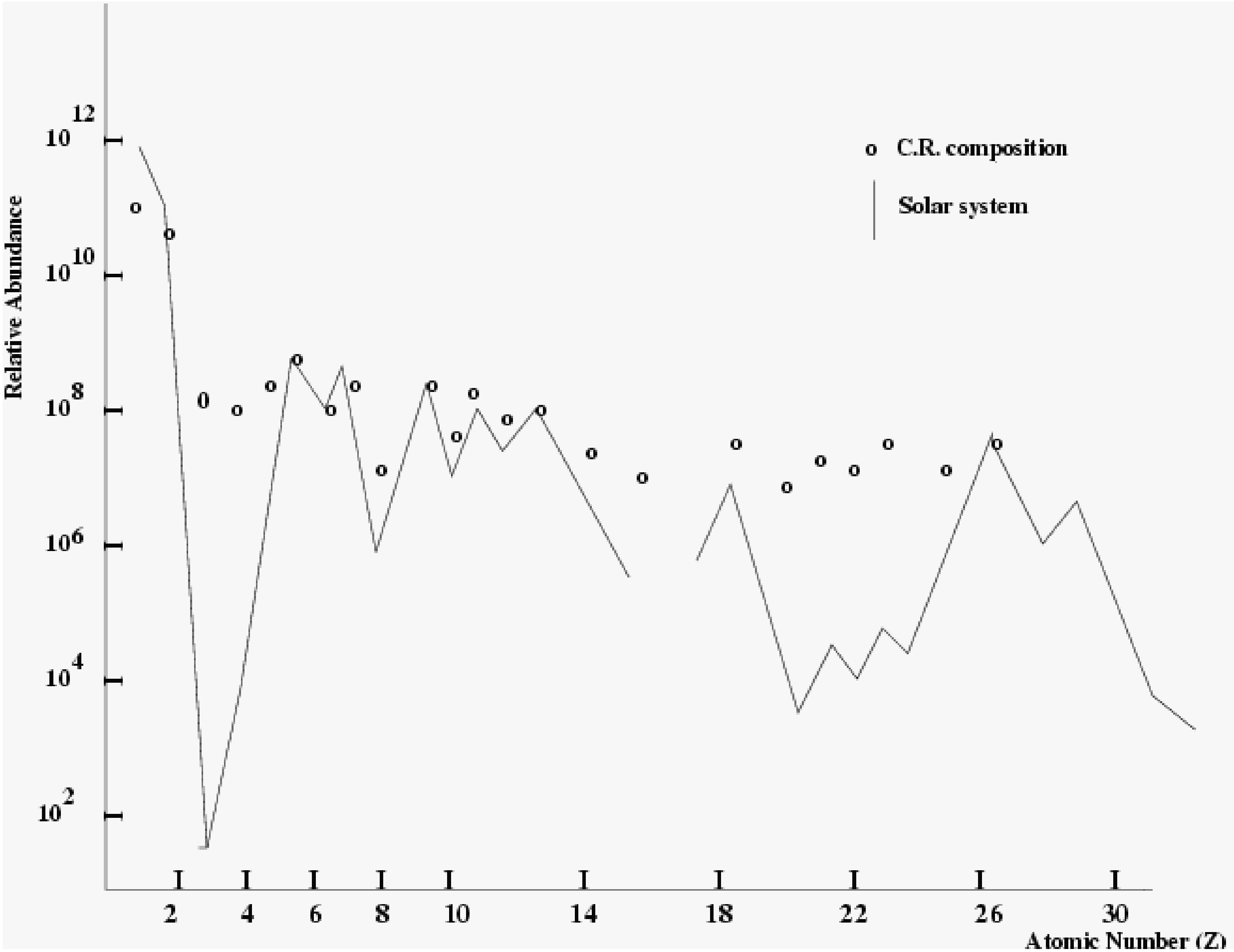
Deflections: $\delta \simeq 3.2^o \frac{10^{20} eV}{E/Z} \cdot \frac{L}{3 kpc} \cdot \frac{B}{2\mu}$ can be large for heavy nuclei

Random component: $B_r = 2\mu G$



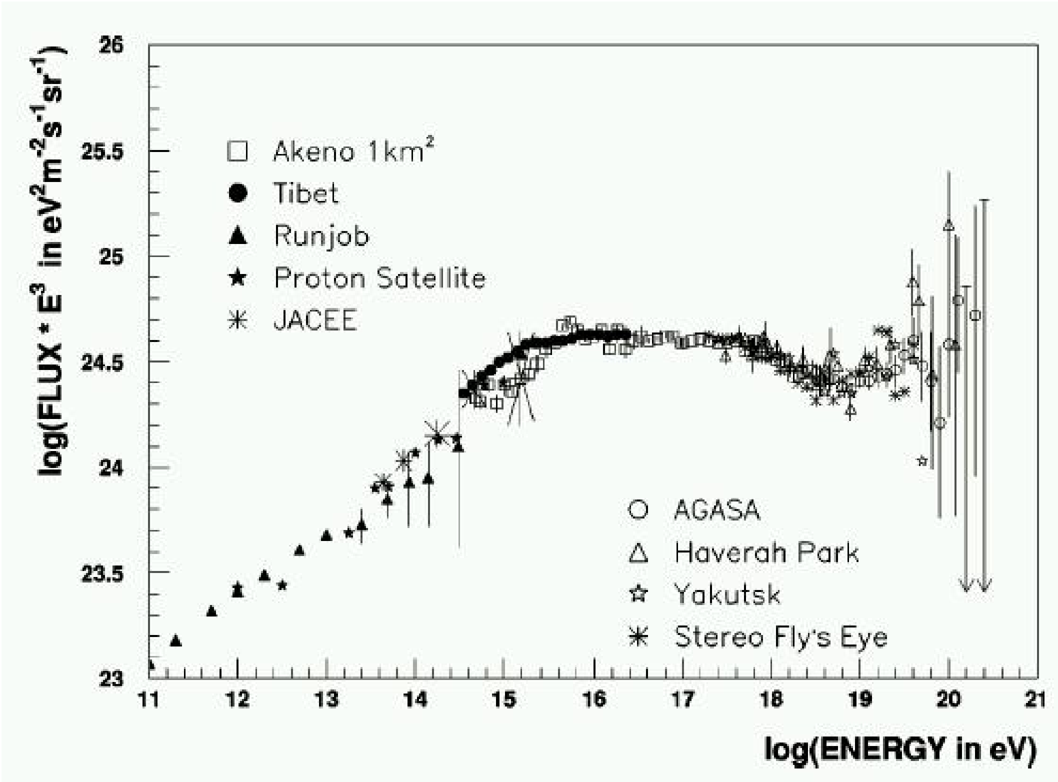


Composition



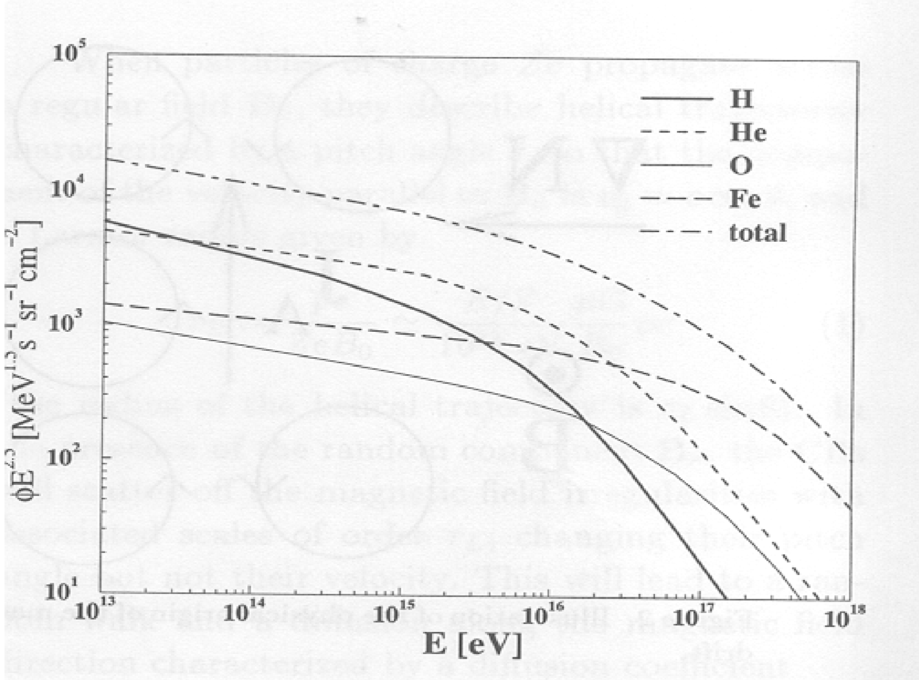
For E < 1 PeV ⟶ 2<Z<4 and 19<Z<25 CR excess

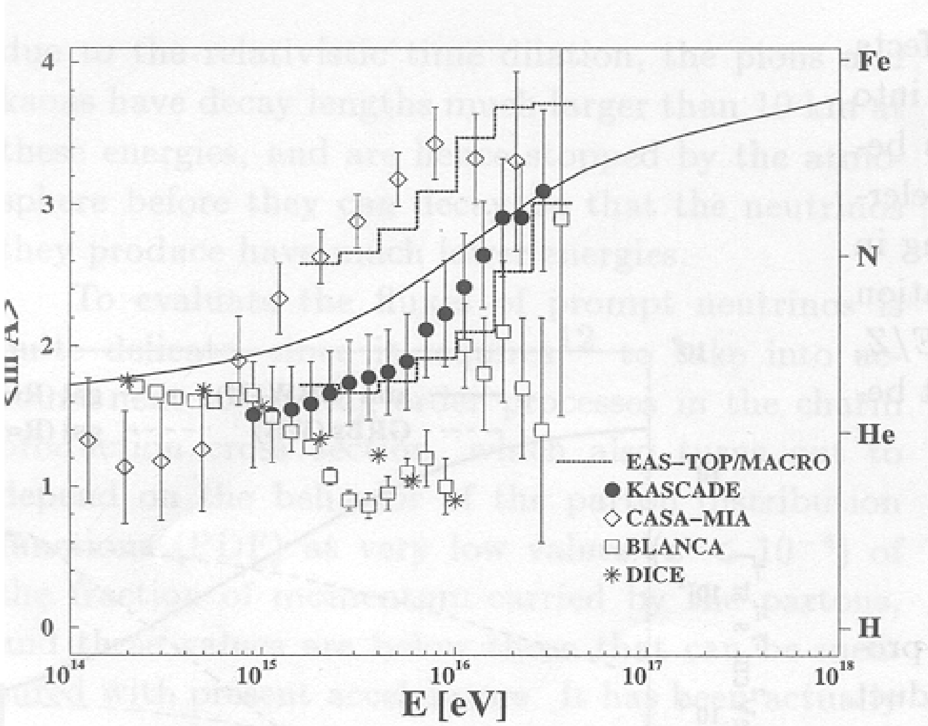
From Galactic to Extra-Galactic CR



CR s start escaping when $E_{CR} \simeq 1\,PeV$

The Knee Structure





1st Knee

E = 3 10^{15} = 3 PeV

J(E) = K E $^{-3.1}$

2nd Knee

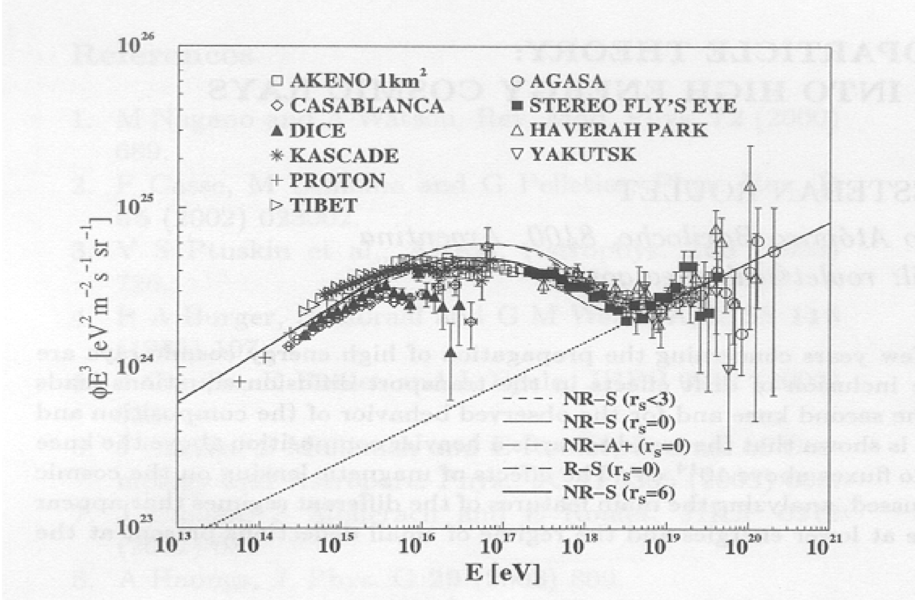
E = 3 10^{17}= 300 PeV

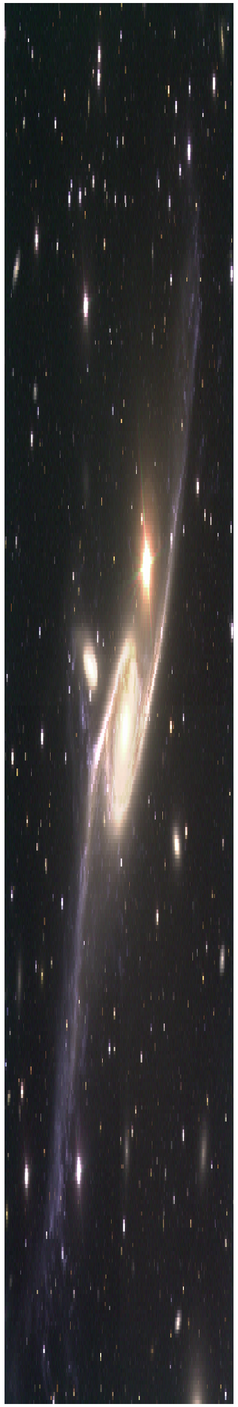
J(E) = K E – $^{3.25}$

Onset of Extra-Galactic Component

E = 5 10^{18} = 5 EeV

J(E) = K E $^{-2.7}$





Ankle Region: 5 EeV < E < 50 EeV

Energy Spectrum: $J(E) \propto E^{-2.7}$

Possible sources:

- Extra-Galactic:

➔ Composition: Protons, g

➔ Acceleration: 1st order Fermi Mechanism in catastrofic events › power-law spectrum

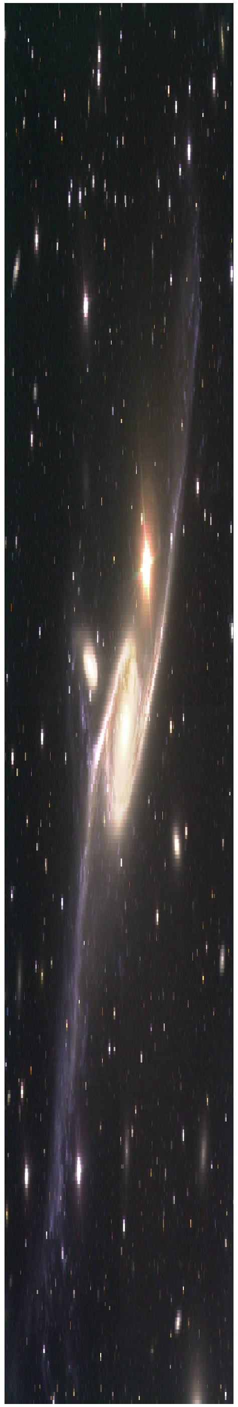
➔ Direction: CRs direction: Effect of Galactic B-Field vs Energy

- Galactic: Rotating Strong-Magnetic Neutron Stars

➔ Composition: Heavy Nuclei

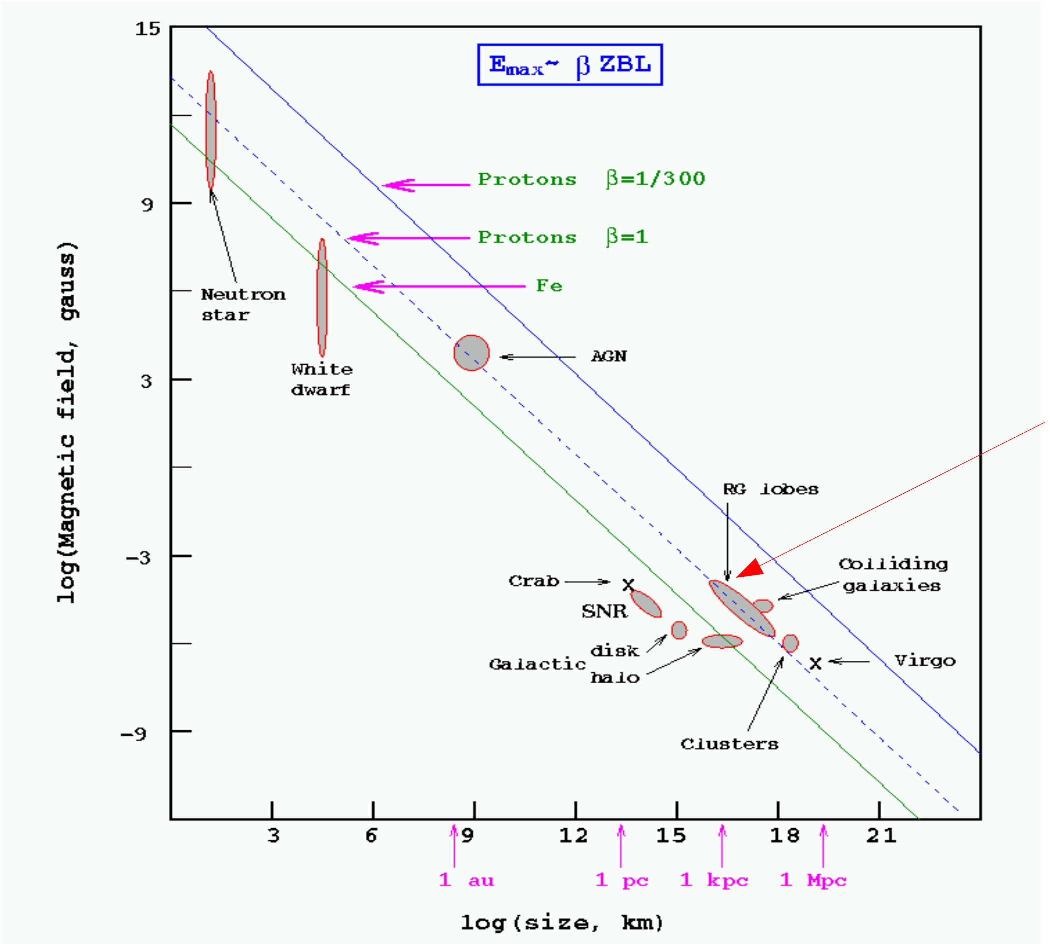
➔ Acceleration: Electric Field – difficult to generate power law spectrum

➔ Direction: pointing to galactic plane

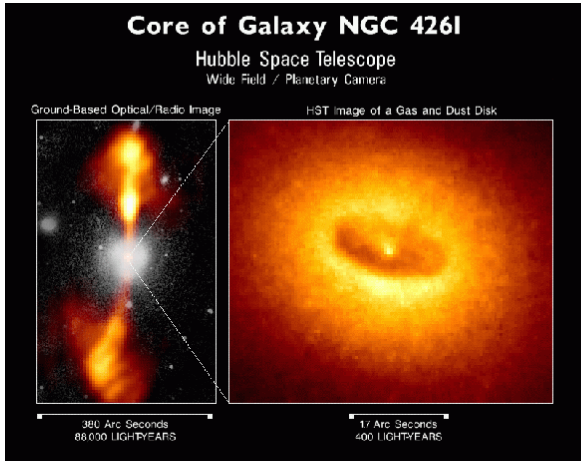


Ultra-high Energy CR's (E > 50 EeV)

Astronomical Sources (Bottom-Up Scenario)



E_{max} = bZBL

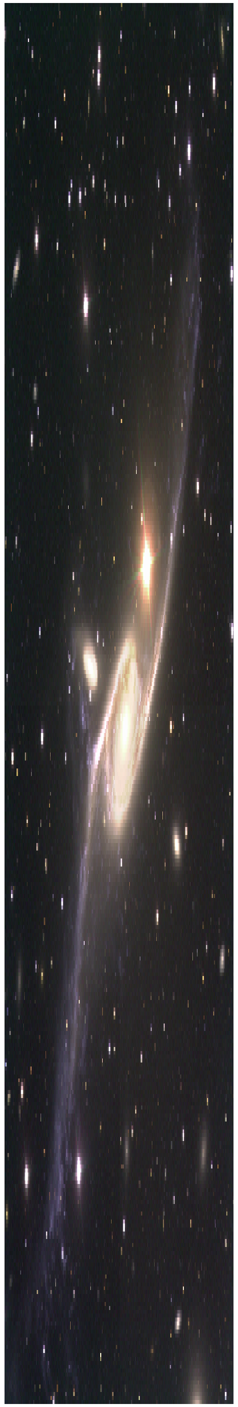


Hillas Plot

Assumes continuous acceleration;
bis velocity of scattering centers

Total magnetic energy of source:

$$W = \frac{B^2}{(4\pi)} \cdot \frac{4}{3} \cdot \pi L^3$$



Astronomical Sources (Bottom-Up Scenario)

- Nearby Galaxies: Possibility that in galaxies with higher activity and rates of star formation B field be higher

Density higher within 50 Mpc radius

- Radio-Galaxies Lobes: gigantic shock waves injected by jets emanating from a central active galactic nucleus at relativistic speeds (L ~ kpc; B ~ 100 μG)

Limited number within 50 Mpc, no correlation with high energy CR

- Colliding Galaxies: converging flows contain shock fronts that could accelerate particles to 100 EeV

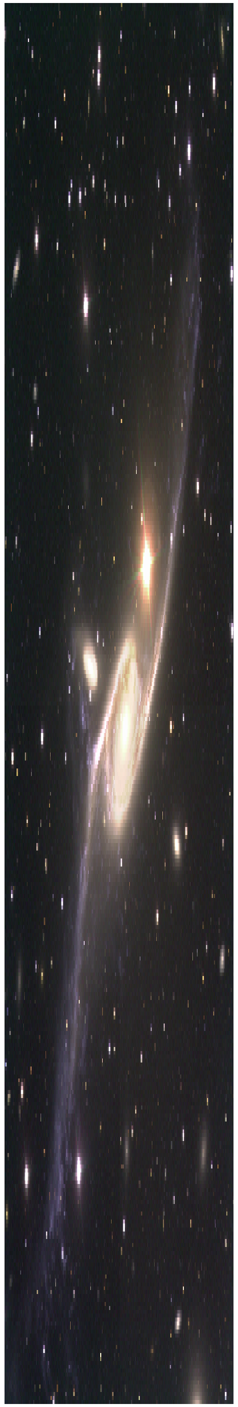
Possible correlation with observed doublets

- Clusters (Virgo): Particles could be accelerated to high energy by accretion shocks formed by the infalling flow toward clusters of galaxies

Nuclei could reach energy above GZK cutoff

- Cosmological Gamma Ray Bursts: at the moment favorite hypothesis

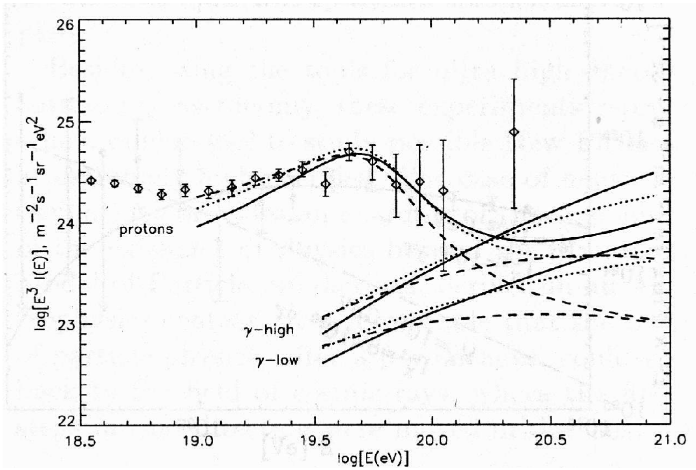
Energy budget and rate of events compatible.

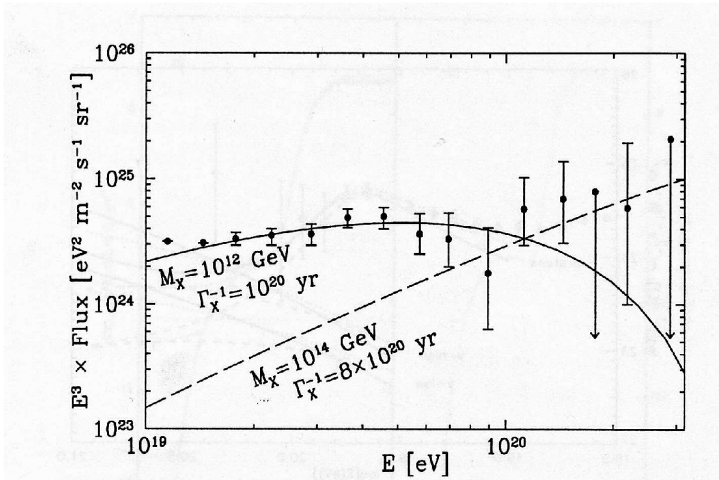


Heavy Particles Decay Mechanism (Top-Down models)

Particles are not accelerated, but get their energy as products of the decay of very massive objects:

- Topological defects relics of phase transitions in early stages of universe
- Dark matter particles clustering in galaxy halo

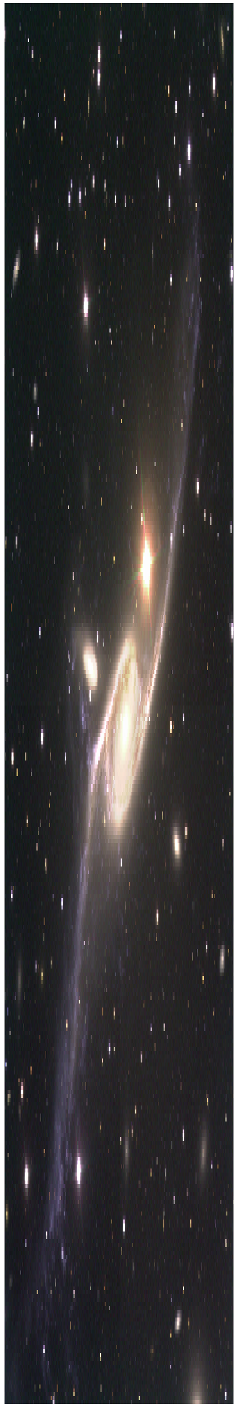




Strong signatures:

γ rays as dominant component

no anisotropy



The Greisen – Zatsepin - Kuzmin (GZK) effect

- Discovery of CMB (Penzias and Wilson 1965)
- GZK (1966):

Extra-Galactic Crs interact with photons of CMB (black body spectrum with peak enegy $E_{CMB} = 6.10^{-4}$ eV and number density $N_g = 400$ per cm^3) and their energy is degraded in the reactions:

$$p + \gamma \rightarrow n + \pi^{+}$$

$$p + \gamma \rightarrow p + \pi^{0}$$

E_{thresh} = 40 EeV l =6Mpc

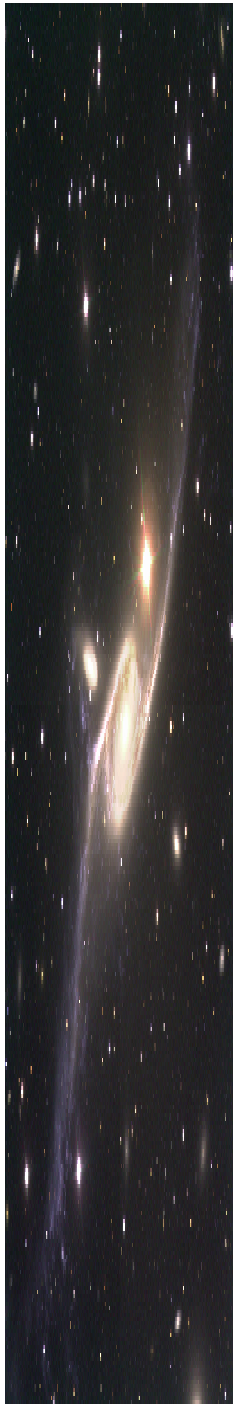
energy loss per interaction: 20 %

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

E_{thresh} = 1EeV l =1Mpc

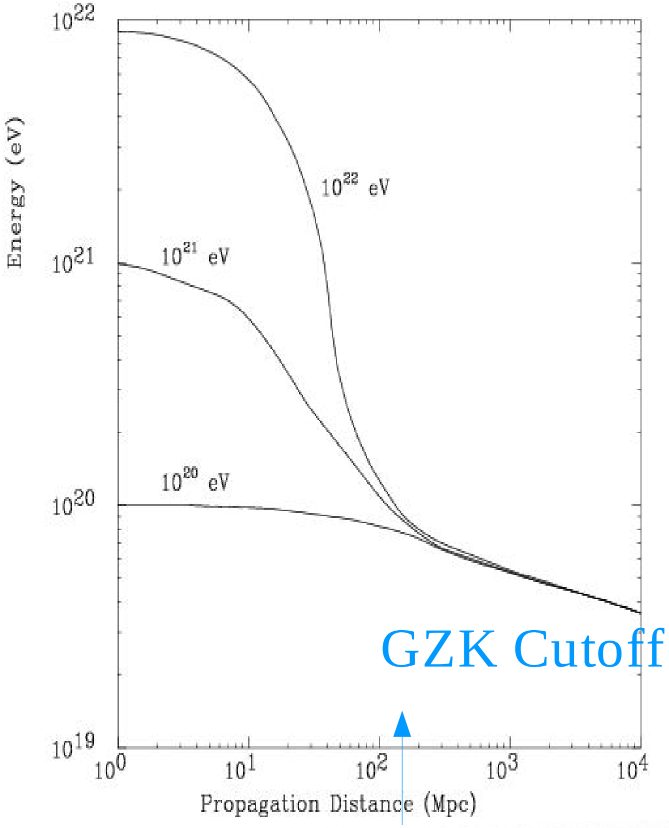
energy loss per interaction: 0.1%

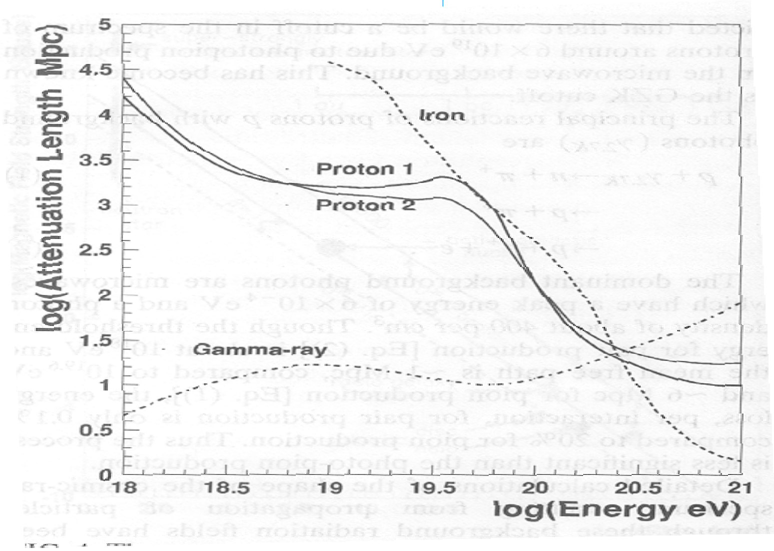
$$A + \gamma \rightarrow (A - 1) + N$$

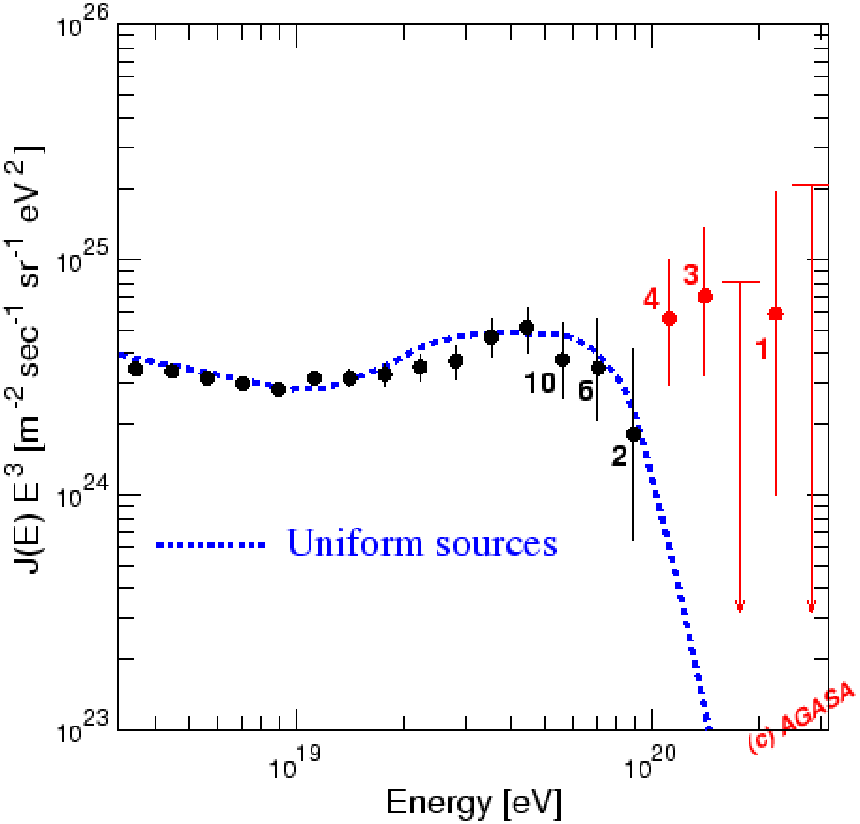


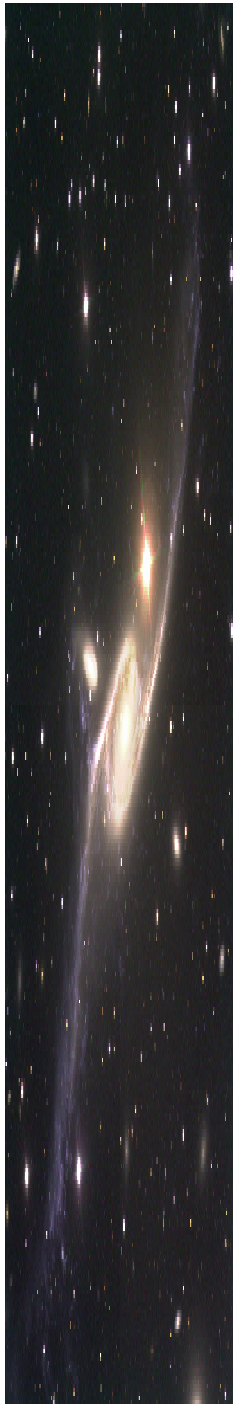
GZK Cutoff

If sources homogeneusly distributed









Review of existing data

- Observed events above 100 EeV:

11 from Agasa
1 from Volcano Ranch (1962 !)
2 from Yakutsk
1 from Fly's Eye
? from HiRes

- Observed events above 40 EeV:

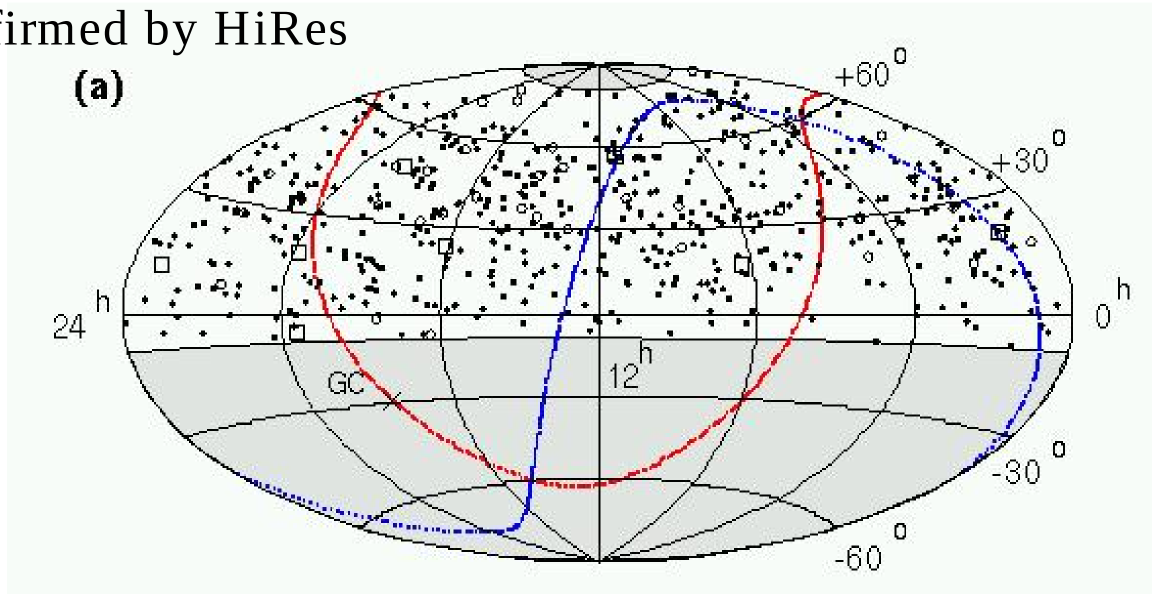
50 from Agasa
1 from Volcano Ranch
2 from Yakutsk
24 from Fly's Eye
? from Hires

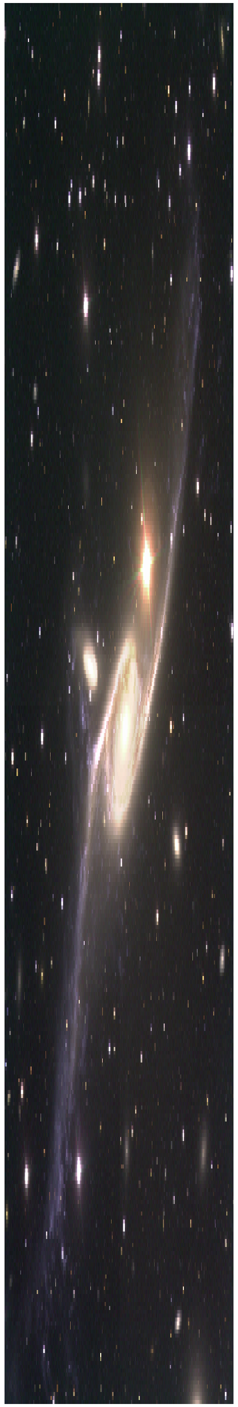
Composition: No evidence so far of a γ (< 30%) or ν component; < 40% Fe

- Observed multiplets:

2 douplets and 1 triplet from Agasa
1 douplet from Haverah Park
Not confirmed by HiRes

- No evidence of broad anisotropy





Has GZK cutoff been seen ?

No agreement between experiments **but events above 100 EeV seen by several groups.**

Second knee could be evidence of

$$p + \gamma \rightarrow p + e^{+} + e^{-}$$

➔ **Structure of cutoff could be complicated:**

Are sources uniformly distributed?

Is age (Z) of source relevant? (Hillas)

Does the GZK cutoff exsist?

Yes

No

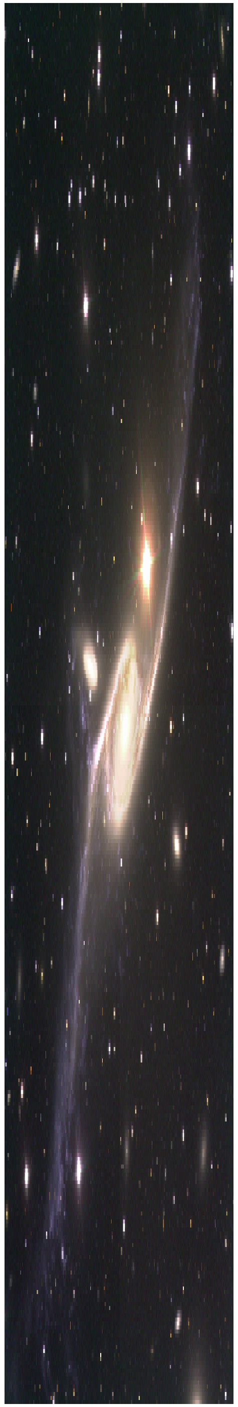
Why events with E > 100 EeV?

- Excess of Sources at d < 50 Mpc
- n primaries
- Decays of Dark Matter
- ....

Possible explanations:

- n primaries: n + n_{relic} = Z0 > > hadrons > nucleons + g + ...
- Decays of Dark Matter
- Violation of special relativity
- ....

....



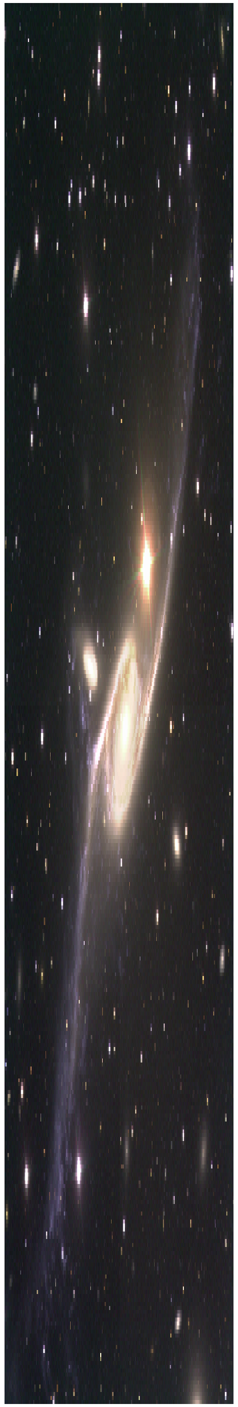
Does the GZK cutoff exsist?

Yes

No

When you carry out an experiment ther are two possibilities: either you confirm the theoretical expectation, and in this case you made a measurement, or you don't, and in this case you made a discovery

(E.Fermi)



Future experiments: what is the legacy ?

- Increase Statistics by large factor !!!!!!
- Hybrid techniques to improve systematics in energy measurements
- Cover large energy range in a single experiment
- Anisotropy studies over full sky including Southern Hemisphere
- ....