What are Cosmic Rays?!

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Why do we care about CRs ?

- As humans:
  - Contribution to atmospheric Chemistry: e.g. production of ^{14}C in atmosphere via neutron capture
  - Source of background radiation: when you fly
  - Source of hazard for interplanetary exploration
  - Impact on Earth and space based electronics

- As physicist:
  - Maximum Energy is $\sim 10^{20}$ eV, 10^8 times larger than LHC !
  - High-Energy CRs produce showers in the atmosphere
  - CRs might affect Earth climate (debated)

Why do we care about for Galaxies ?

- Vertical support of ISM in galaxies
- Ionization and heating of ISM through collisions
  - Allows weak ionization in molecular clouds, protoplanetary disks, and the cold neutral medium
  - Impacts chemistry in the ISM and molecular clouds
  - Low energy CRs ($\lesssim$ 10 MeV) are most responsible for this
- Probable driver of galactic winds
- Amplification of magnetic fields
  - Upstream and downstream of shocks

- Modification of astrophysical plasma processes
  - Shocks, dynamos, jets, reconnection

➢ <u>At radio/g-rays in star forming galaxies we are looking at CR emission</u>

Some Questions !

1. How do you accelerate a particle ?

2. If you have a neutron, proton and iron nucleus which gets more energy ?

$$Energy = q_e Z\ V$$

3. If you have a proton with $E=10^{15}$eV which potential drop do you need to accelerate it ?

Discovery

Part of the rise of "modern" physics: early radiation detectors (ionization chambers, electroscopes) showed a ***dark current*** in the absence of sources.

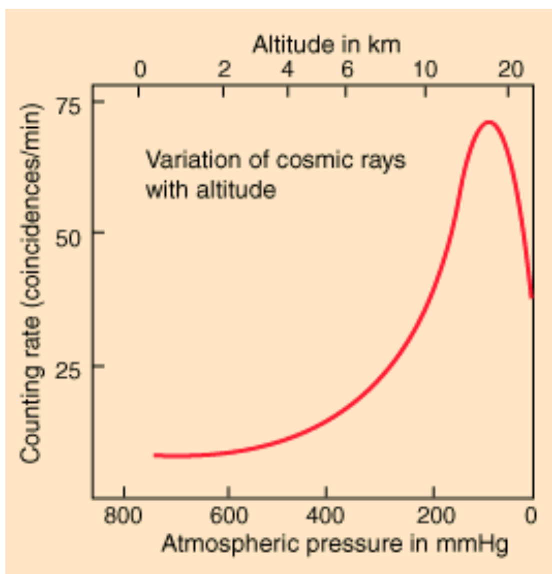
Rutherford (1903): most comes from radioactivity
Wulf (1910): dark current down by 2 at top of Eiffel Tower - could not be gamma rays
Hess (1912): 5 km open-balloon flight showed an *increase*
Hess & Kohlhörster (by 1914): balloon flights to 9 km ...

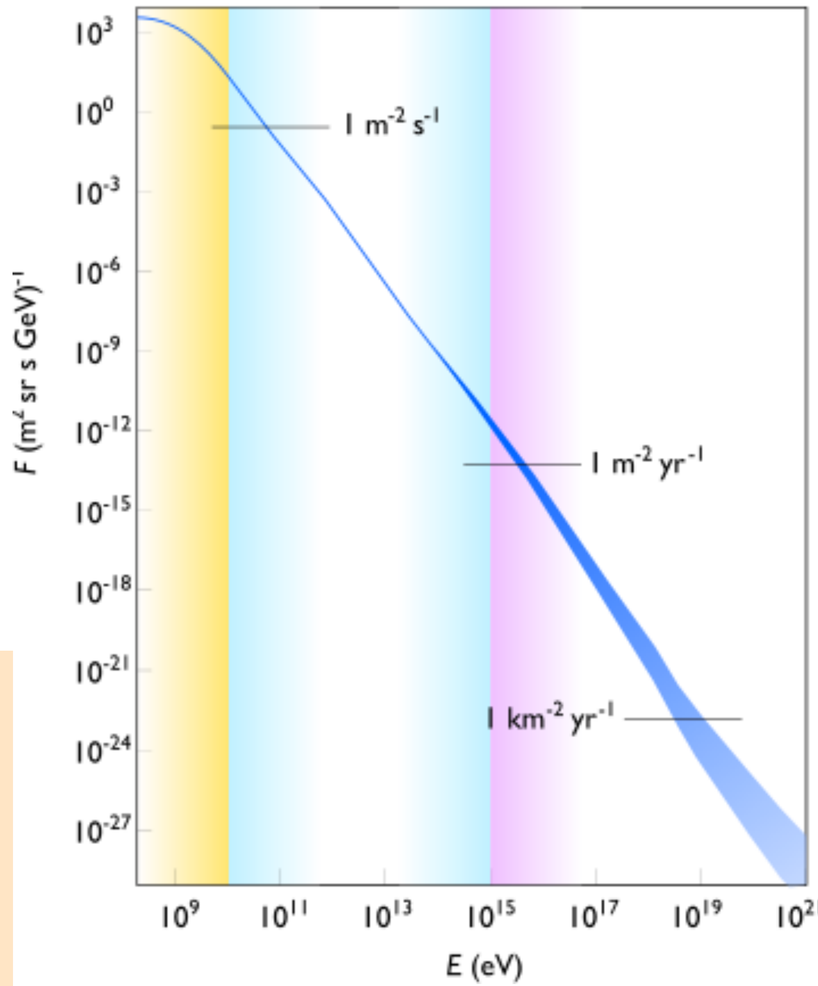
Studies of the variation with height, latitude & longitude confirmed the particle nature of ***cosmic rays*** (Millikan's name) originating above the Earth's atmosphere.

Cosmic Rays

- Hess 1912 experiment showed that ionization increased with height
  - It was coming from the sky
- Charged particles
  - Not clear where they came from, B field deflects them

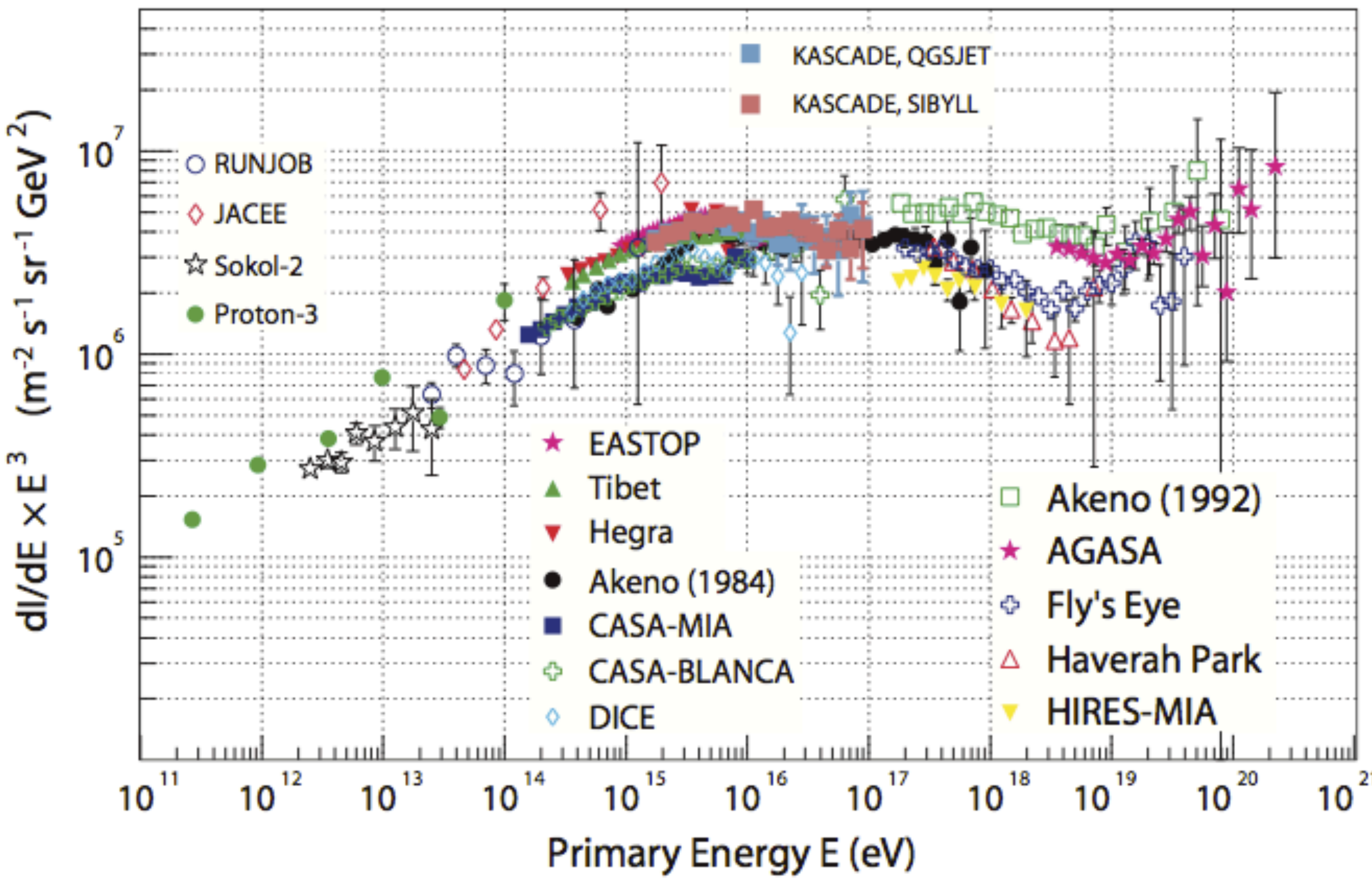
Why the drop ?





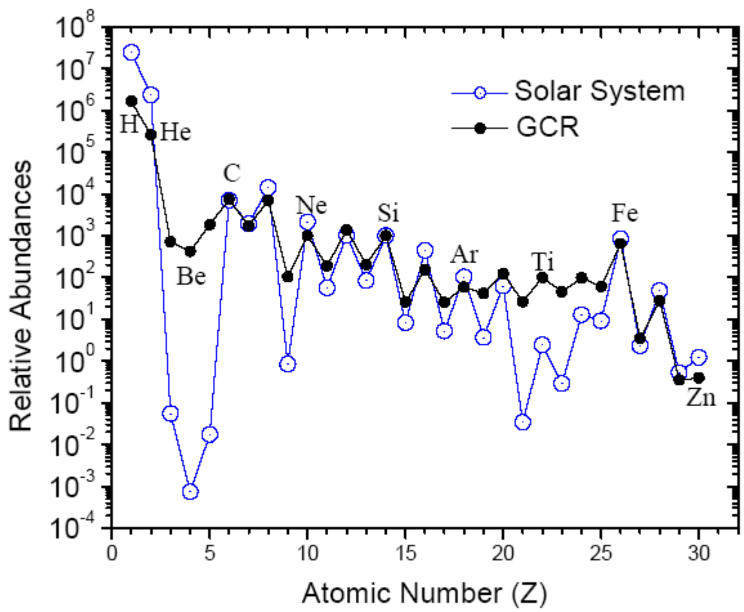
Knee and Ankle might be due to different CR sources or change in the propagation

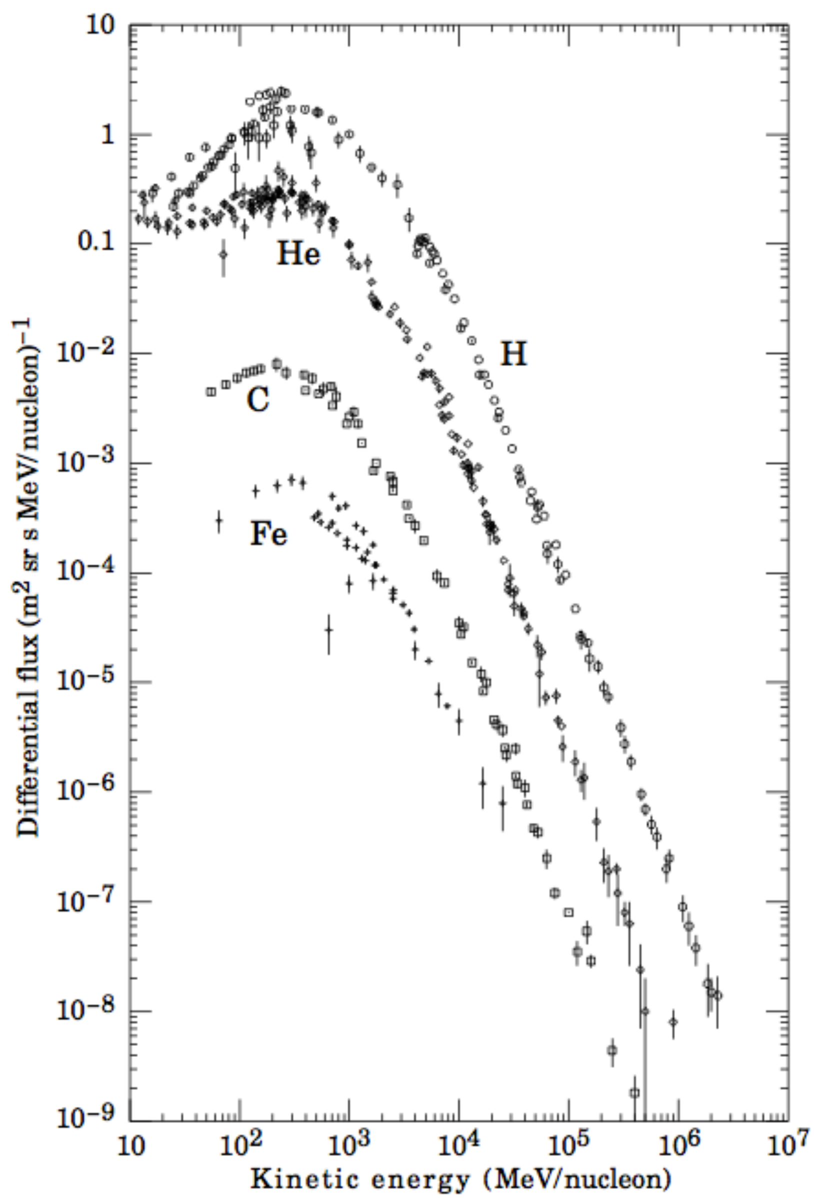
The Knee and the Ankle



CR Composition

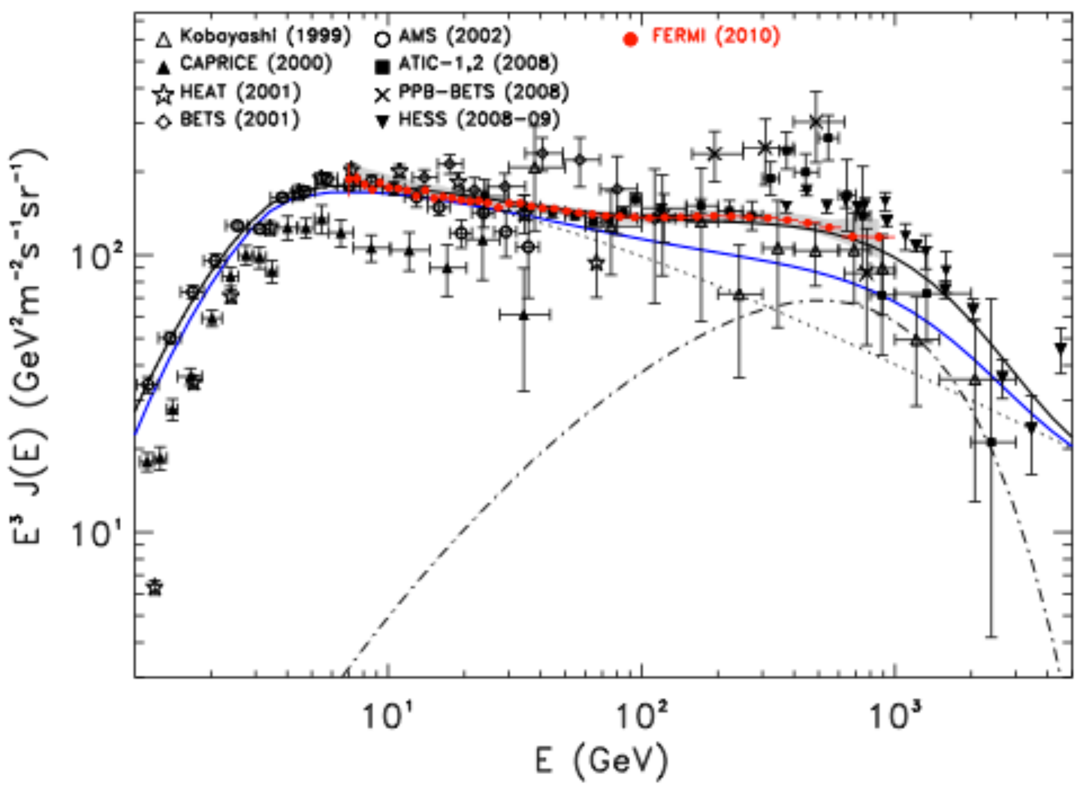
- 90% protons
- 9% He
- 1% electrons
- Only 0.01% is anti-matter
- Isotopic abundance show Be/Ti elements are produced by propagation/spallation





Electron Spectrum

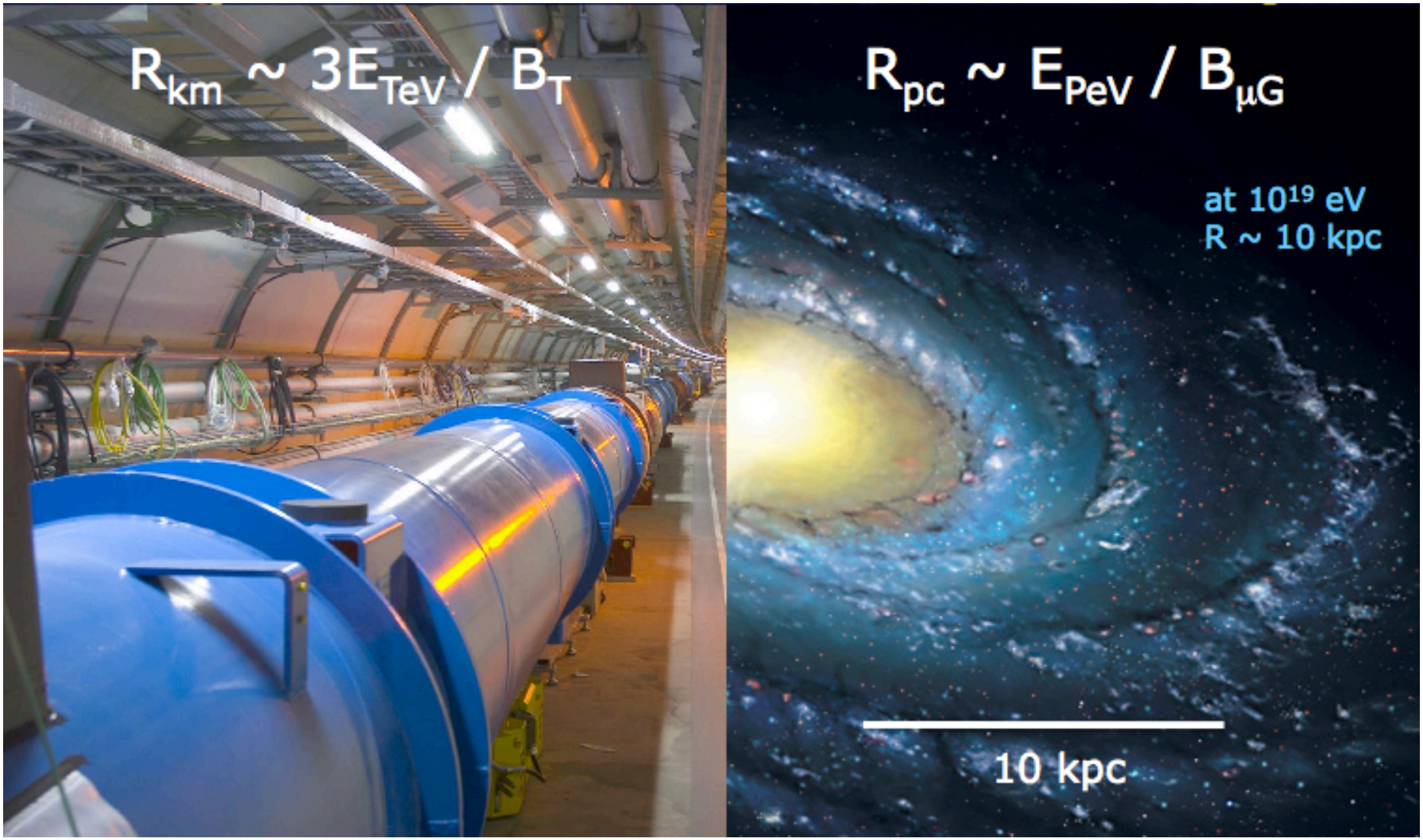
- Electrons ($e^- - e^+$) are only a fraction of protons and have a softer spectrum (slope of ~3.0 w.r.t. 2.76)
- Deviation from propagation (blue line) might indicate additional electron/positron sources
- ATIC bump not confirmed by Fermi



Larmor (gyro) Radius

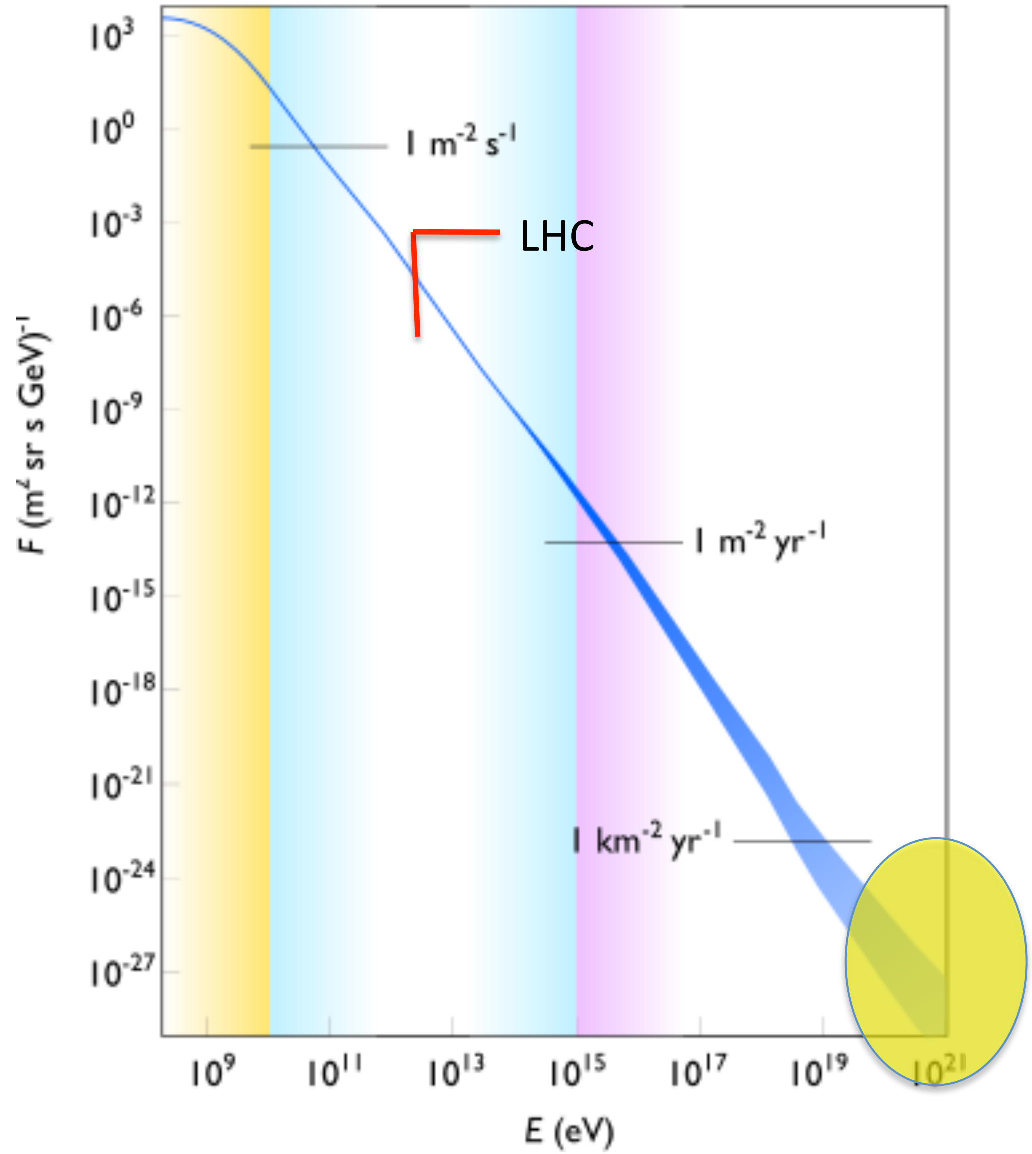
$$r_g = \frac{mv_\perp}{|q|B},$$

Hillas critrerion= the larmor radius must be < size of the accelerator



Ultra high-Energy Cosmic Rays

- UHECRs are a puzzle:
  - Cannot be contained in the Galaxy
  - Cannot be accelerated in SNR
  - Cannot come from very far away:
    - *GZK Cut-off (photo-pion production on CMB)*

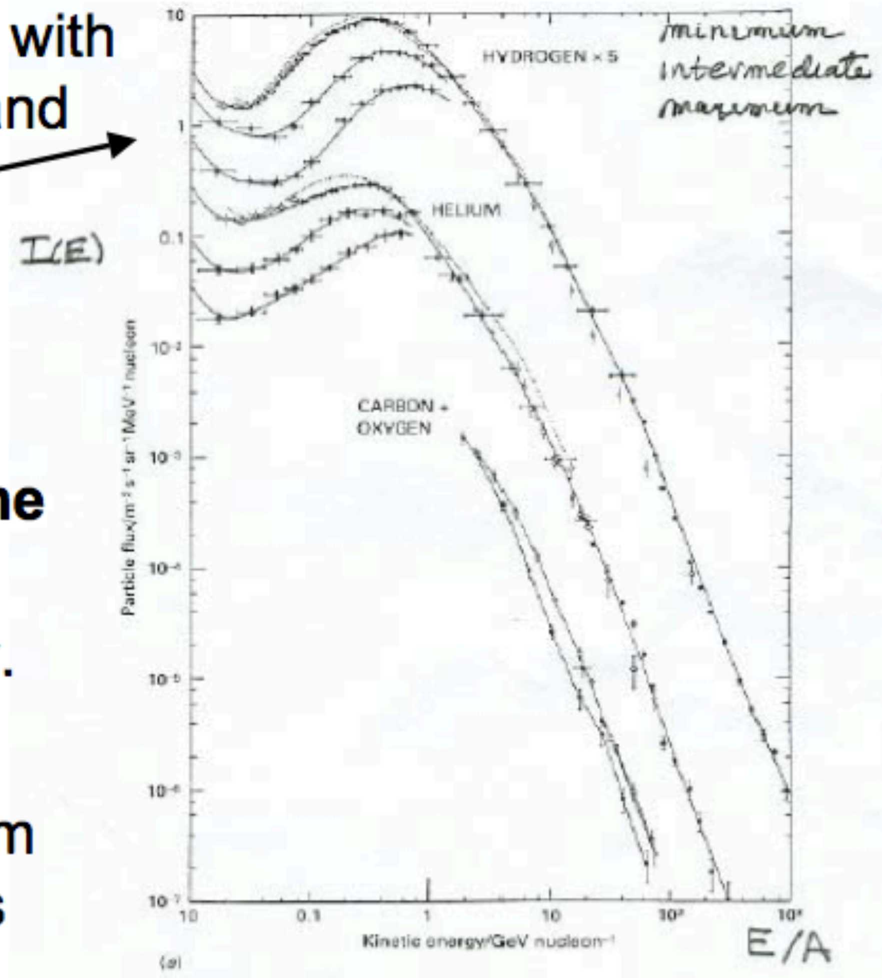


Solar Modulation

With *I(E)* decreasing rapidly with *E*, it is important to understand the low-energy behavior.

The figure shows spectra at three levels of solar activity, indicating that the Sun itself changes the CR intensity: **the solar wind blows the low-energy galactic CRS away**.

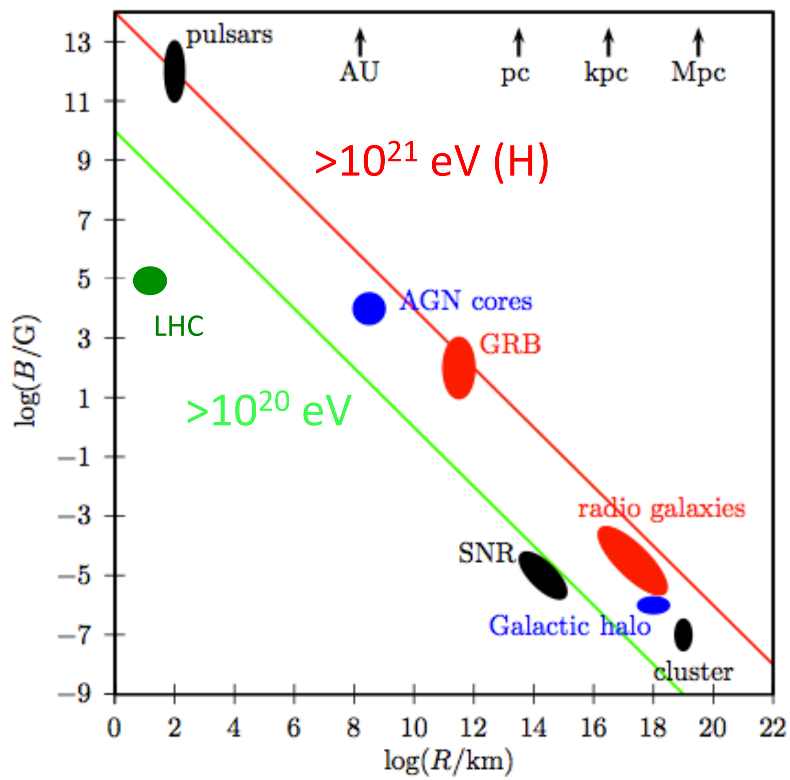
Correcting the observed spectra for such solar system effects, or ***demodulation,*** is required to deduce the CR intensity in the local ISM.



Longair Vol.1, Fig 10.3a

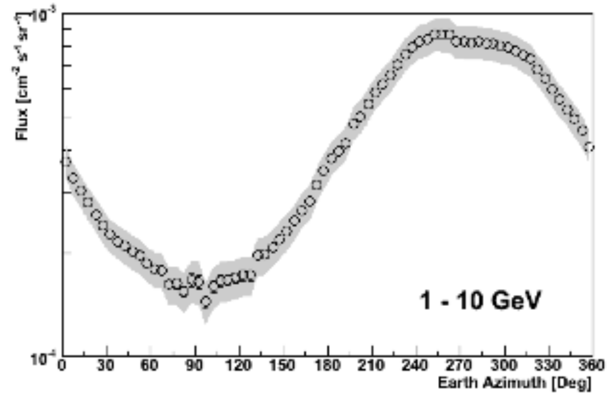
Sources of Cosmic Rays

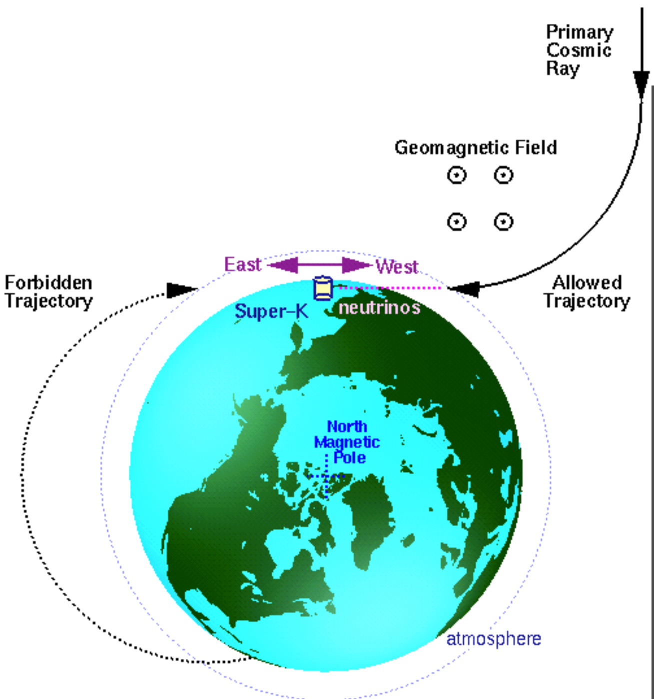
- Change in slope of the CR spectrum suggests there are 2 kinds of CR sources
  - Galactic: dominate the low energy spectrum till E<1e15 eV
  - Extra-Galactic: dominate about E>1e15 EV
    - *At these energies CRs are not contained in our Galaxy: Larmor Radius > kpc*
    - *The observed sky isotropy suggests these are coming from everywhere and accelerated by galaxies more powerful than our own*
  - Galactic sources must match the CR luminosity
    - *SN require only a ~1% efficiency in accelerating CRs*
    - *Derive it on the black board*
- Hillas Criterion:
  - The Larmor Radius < Accelerator

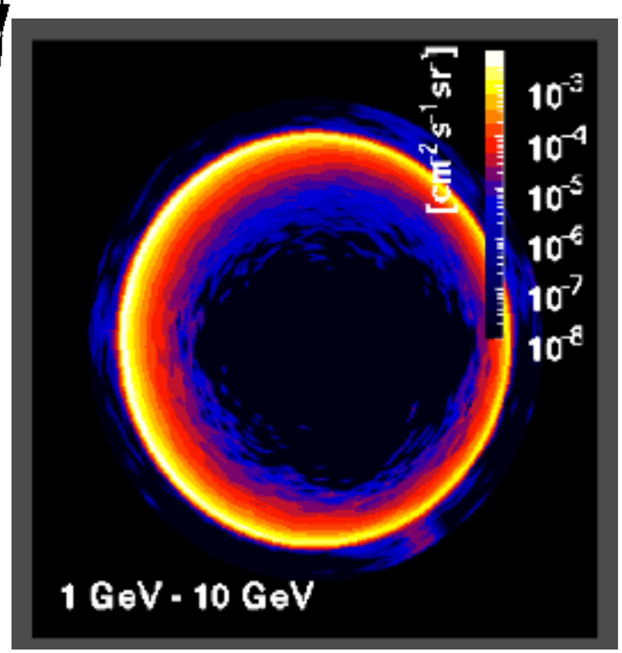


East West Effect

- In 1930, Bruno Rossi predicted that the Earth's B field should introduce a modulation in the intensity of CRs
- Clearly seen also at gamma-rays (by product of CRs)



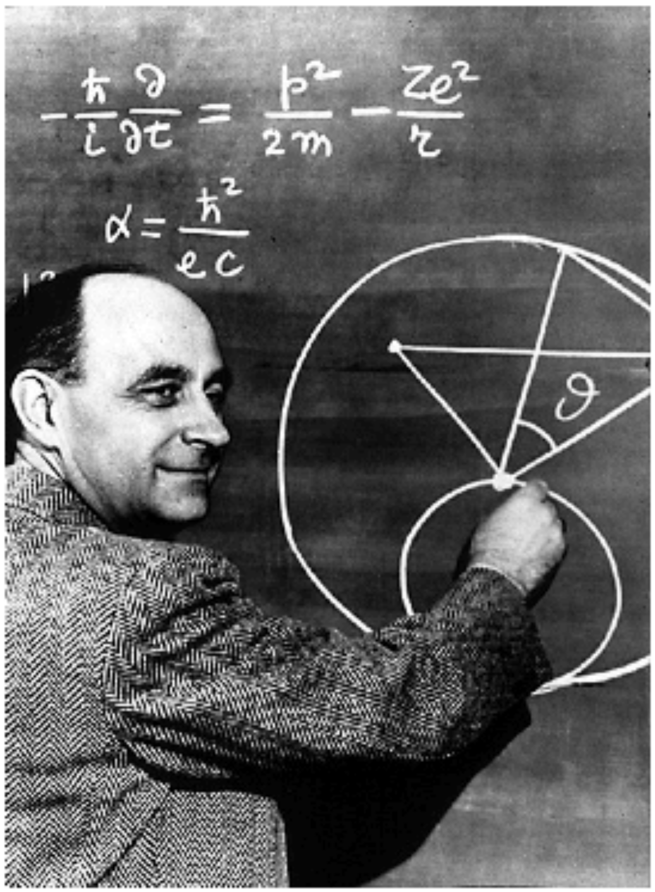




Fermi

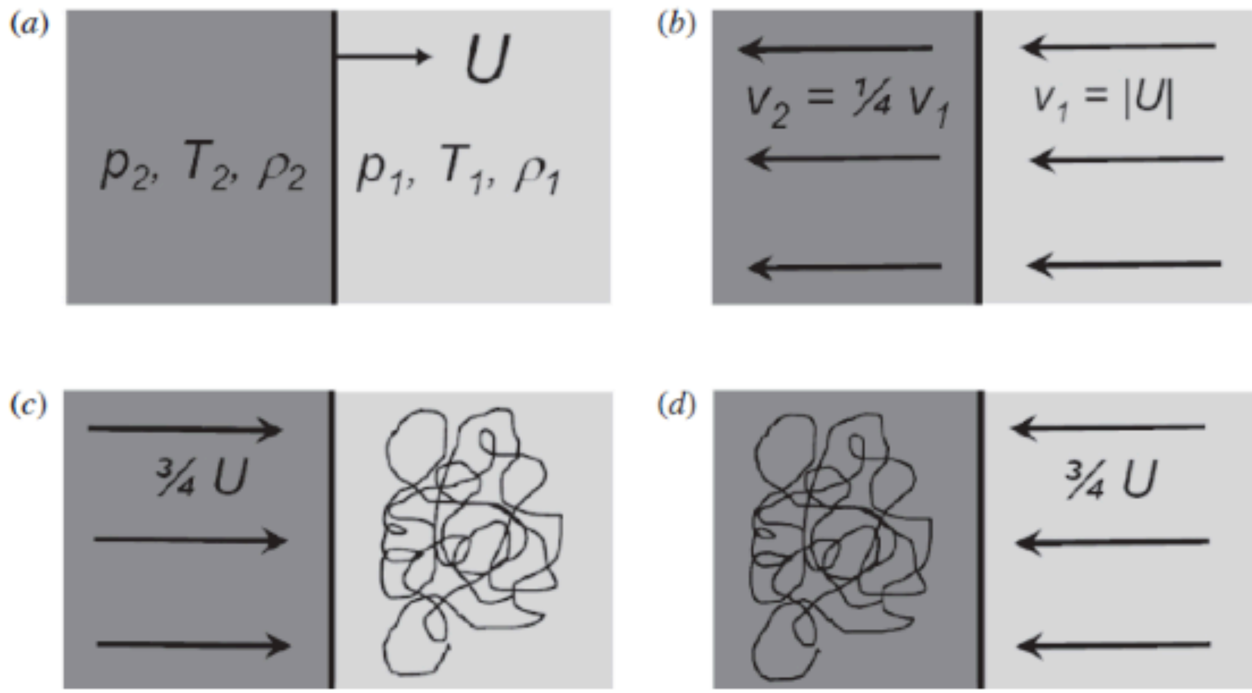
CR acceleration

Enrico Fermi



Never underestimate the joy people derive from hearing something they already know.

1^{st} Order Fermi: Cross Shocking



- (a) Observer's frame, (b) reference frame of shock, (c) upstream frame, (d) downstream frame
- When crossing the shock from either side, the particle sees plasma moving toward it at a velocity of $V \equiv \frac{3}{4}U$

$r = V_1/V_2 \approx 4$ for strong shocks

Fractional Energy Increase

- A particle with energy $\mathcal{E}$ on the upstream side sees plasma approaching it at a velocity V from the downstream side
- The particle's energy in the downstream frame is

$$\mathcal{E}' = \gamma_V(\mathcal{E} + p_x V)$$

- Assume shock is non-relativistic so $\gamma_V = 1$
- The particles are relativistic so $p_x = \frac{E}{c}\cos\theta$ and therefore

$$\Delta\mathcal{E} = pV\cos\theta$$

$$\frac{\Delta\mathcal{E}}{\mathcal{E}} = \frac{V}{c}\cos\theta \qquad \text{Eq. 1}$$

where we use that $\mathcal{E} = pc$

For a simulations of the shock

https://www.cfa.harvard.edu/~lsironi/Site/Research.html

What is the probability for an angle theta ?

- The probability that a particle will cross the shock with an angle of incidence between θ and $\theta + \mathrm{d}\theta$ is proportional to $\sin\theta\,\mathrm{d}\theta$
- The rate at which they approach the shock front is proportional to $v_x = c\cos\theta$
- For $\theta \in [0, \pi/2]$, the probability function for θ is

$$p(\theta) = 2\sin\theta\,\cos\theta\,\mathrm{d}\theta$$

- Eq. 1 then averages to

$$\begin{aligned}\left\langle \frac{\Delta\mathcal{E}}{\mathcal{E}} \right\rangle &= \frac{V}{c}\int_0^{\pi/2} 2\cos^2\theta\sin\theta\,\mathrm{d}\theta \\ &= \frac{2}{3}\frac{V}{c}\end{aligned}$$

which gives the energy increase for one shock crossing

Escape Probability per Cycle

- The rate of particles crossing the shock from either direction is $\frac{1}{4}nc$, where n is the number density of energetic particles and we average over velocities/angles
- Upstream particles are swept into the shock, so few losses
- Particles removed from downstream region at a rate of $nV = \frac{1}{4}nU$
- The fraction of particles lost is then $\frac{1}{4}nU/\frac{1}{4}nc = U/c$ so that the fraction of particles remaining after one cycle is

$$P = 1 - \frac{U}{c} \tag{40}$$

Since $U \ll c$, few particles are lost per cycle

Spectrum of Accelerated Particles

- Notes on blackboard

To Remember

- There are no configurations that lead to losses
- The acceleration depends on shock velocity/strength
- The energy gain is basically independent of any detail on how the particles scatter back and forth

Maximum Energy

- The magnetic field must be able to confine energetic particles
- For interstellar magnetic field strengths $\sim 1\mu$G, the proton Larmor radius is ~ 1 pc
- Supernova remnants could then not confine particles with energies $\gtrsim 10^{14}$ eV
- But what if there are mechanisms to amplify the magnetic field?

Amplified B fields are present because CRs are accelerated efficiently

Propagation of Cosmic Rays

- Continuity eq. + Fick's Law = diffusion equation

$$\frac{\partial n}{\partial t} - \nabla(D\nabla n) = Q - losses$$

- In the `leaky box model': CR inside a volume have a constant escape prob. ~n/τ

$$\frac{\partial n}{\partial t} = \nabla(D\nabla n) = -\frac{n}{\tau_{esc}}$$

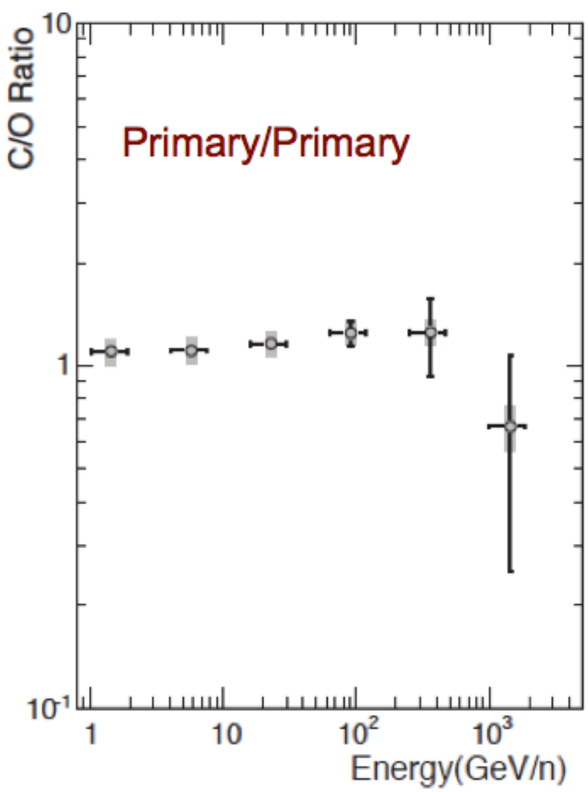
- At steady state (dn/dt=0) and neglecting losses: $n = Q\ \tau_{esc}$
- τ_{esc} depends on Energy: $\tau_{esc} \sim E^{-b}$ with b~0.7

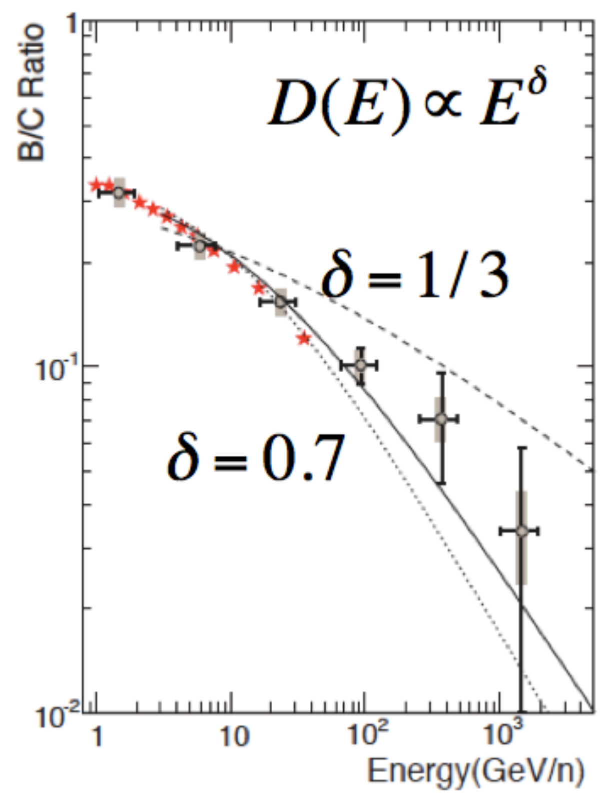
- $Q \sim E^{-2}$ -> spectrum of CRs $\sim E^{-2.7}$ like we observe at Earth

- Radioactive elements used to infer how much matter CR traverse : $X \sim 0.3\ cm^{-3}$: -> CR spend part of their life in the Halo

Boron to Carbon Ratio

- Secondaries/primaries ratios as function of Energy are used to constrain the path length (e.g. tau_esc) for CRs
- Most famous one is Boron/Carbon (B/C) ratio
  - Boron has Z=5 - Carbon Z= 6





Observation of the pion decay bump in a supernova remnant by *Fermi* (Ackermann et al. 2013)

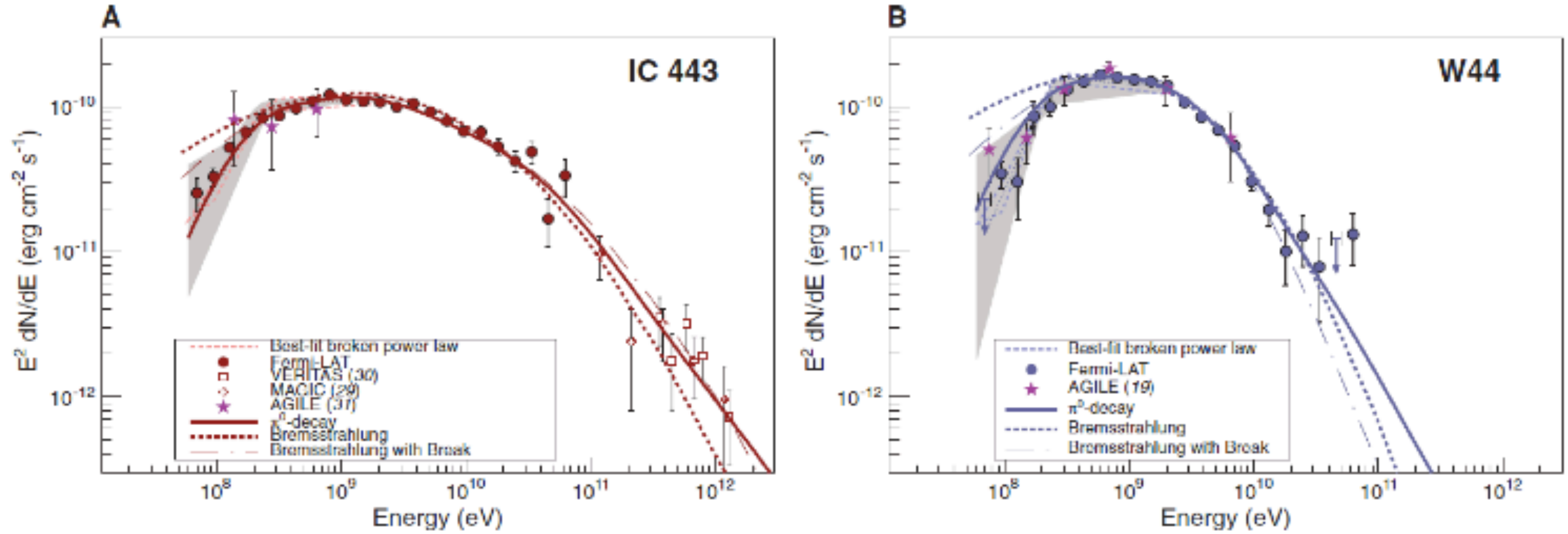


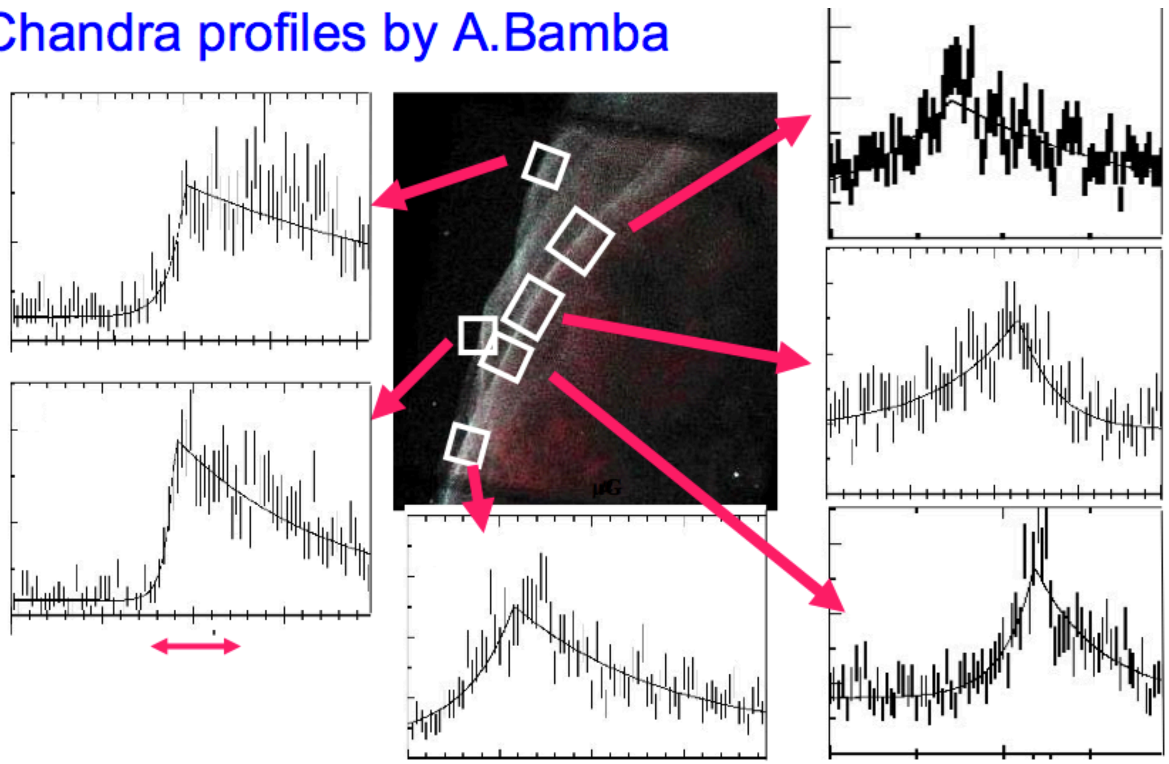
Fig. 2. (**A** and **B**) Gamma-ray spectra of IC 443 (A) and W44 (B) as measured with the Fermi LAT. Color-shaded areas bound by dashed lines denote the best-fit broadband smooth broken power law (60 MeV to 2 GeV); gray-shaded bands show systematic errors below 2 GeV due mainly to imperfect modeling of the galactic diffuse emission. At the high-energy end, TeV spectral data points for IC 443 from MAGIC (*29*) and VERITAS (*30*) are shown. Solid lines denote the best-fit pion-decay gamma-ray spectra, dashed lines denote the best-fit bremsstrahlung spectra, and dash-dotted lines denote the best-fit bremsstrahlung spectra when including an ad hoc low-energy break at 300 MeV c^{-1} in the electron spectrum. These fits were done to the Fermi LAT data alone (not taking the TeV data points into account). Magenta stars denote measurements from the AGILE satellite for these two SNRs, taken from (*31*) and (*19*), respectively.

- 67.5 MeV in rest frame of π^0
- Detection difficult because energetic electrons also emit gamma rays through bremsstrahlung and inverse Compton scattering

Magnetic Field Amplification

- Larmor radius of ~1pc for E~10^{14} eV
  - SNR with μG fields cannot accelerate CRs to such energy
- Evidence from X-ray images of larger fields

Chandra profiles by A.Bamba



CRs create magnetic turbulence in the shock region

measurements of the width of synchrotron X-ray filaments ~ 0.01pc
STRONG MAGNETIC FIELD AMPLIFICATION > 20 μG
Electron energies >> 1 TeV

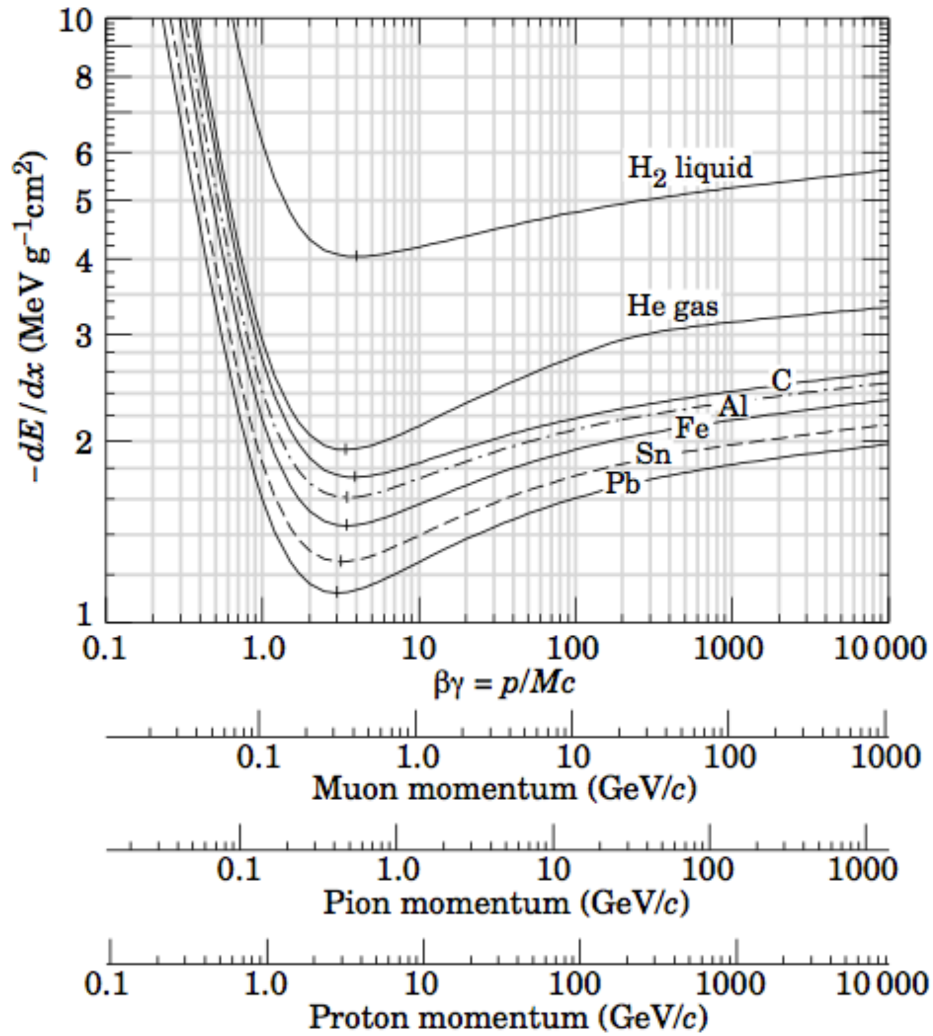
CR Ionization rate

- Protons of 1-10 GeV are like MIPS: e.g. loose energy by ionization (governed by Bethe's cross section)

$$\sigma_i = \frac{1.23 \times 10^{-20} Z^2}{\beta^2}\left(6.20 + \log\frac{\beta^2}{1-\beta^2} - 0.43\beta^2\right),$$

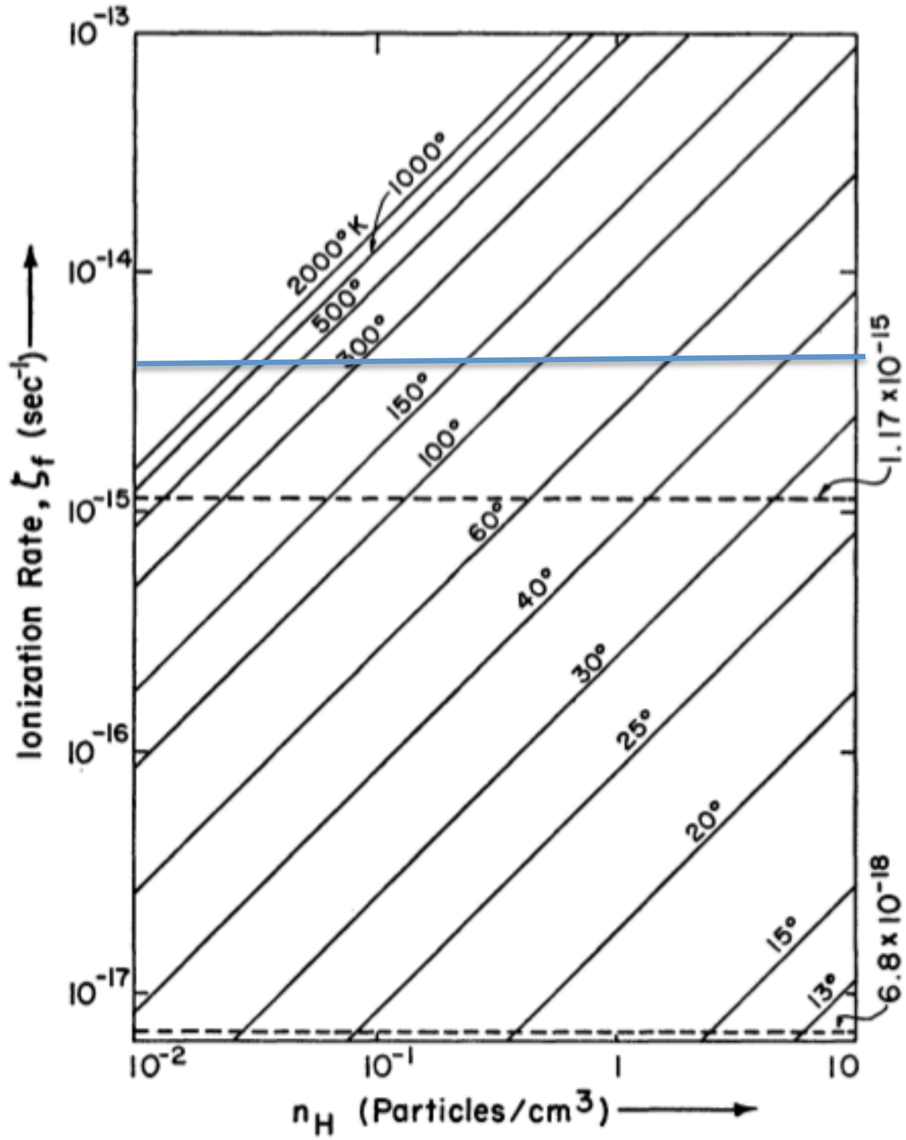
- The ionization rate comes:
  - $\zeta_{CR} = f_h \, f_{sec} \, \zeta_p$
  - Where f_h=5, f_{sec}=5/
  - ζ_{CR}=5e-17 s

- See Spitzer&Tomasko 1969



ISM temperature

- Balancing heating=cooling, the equilibrium temperature can be measured
  - Cooling = radiative recombination, cooling due to inelastic scattering etc.
- See Spitzer&Tomasko 1969



Summary up to now

- CRs are important for a number of reasons
  - Most energetic particles ever -> study of accelerator
  - Propagating through the galaxy they support the ISM, ionize it, create products by spallation, create observable radiation (bright at radio and gamma-rays)
  - Amplify magnetic fields in

- SNe can, on energetic ground, accelerate CRs with $E<10^{15}$ eV

- Acceleration happens via 1st order Fermi acceleration with amplification of magnetic fields in upstream/downstream shock regions
  - Reproduces the power law distribution of the energy of Cosmic rays

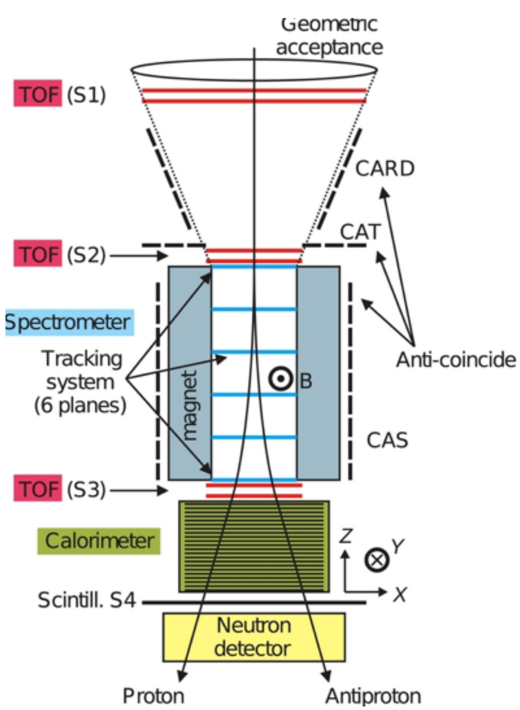
- Pion bump in SNRs as expected for CR accelerators

- Propagation of CRs (leaky box model) soften the spectrum (e.g. the high-E CRs leave sooner)

- CRs heat up the ISM via ionization

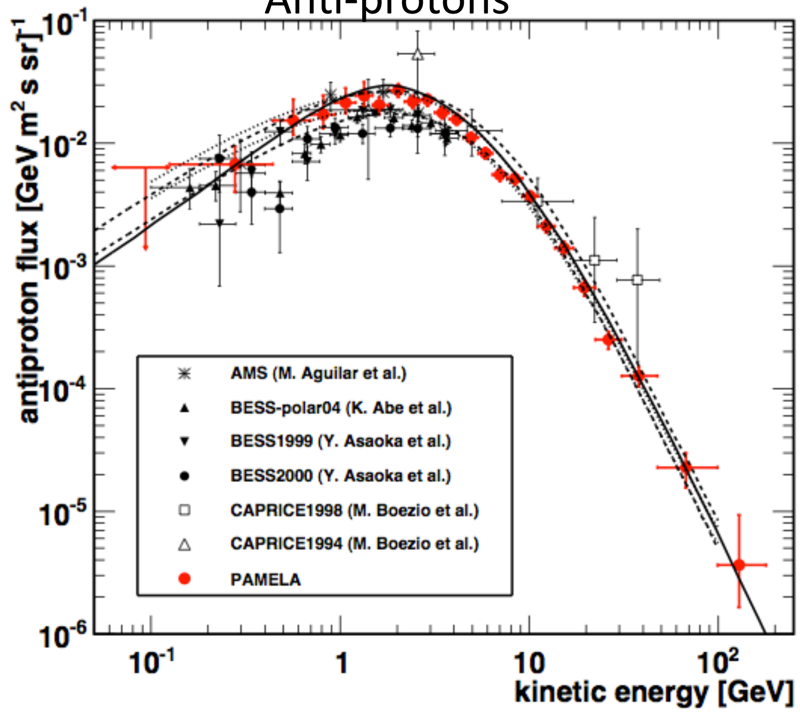
Anti-matter CRs (DM!)

- The search for anti-matter is mainly of interest for two reasons:
  - accelerated anti-matter could be the result of acceleration of anti-nuclei in a anti-matter galaxy ☺
  - anti-protons (as well as positrons) are produced in cosmic- ray interactions with gas and provide insights into the cosmic-ray transport. Deviations from the anti-proton flux expected from secondary production may lead us to conclude that additional, primary anti-proton-production is necessary as e.g. suggested in models of evaporating black holes as well as from self-annihilating dark matter (e.g. WIMP-dark matter).



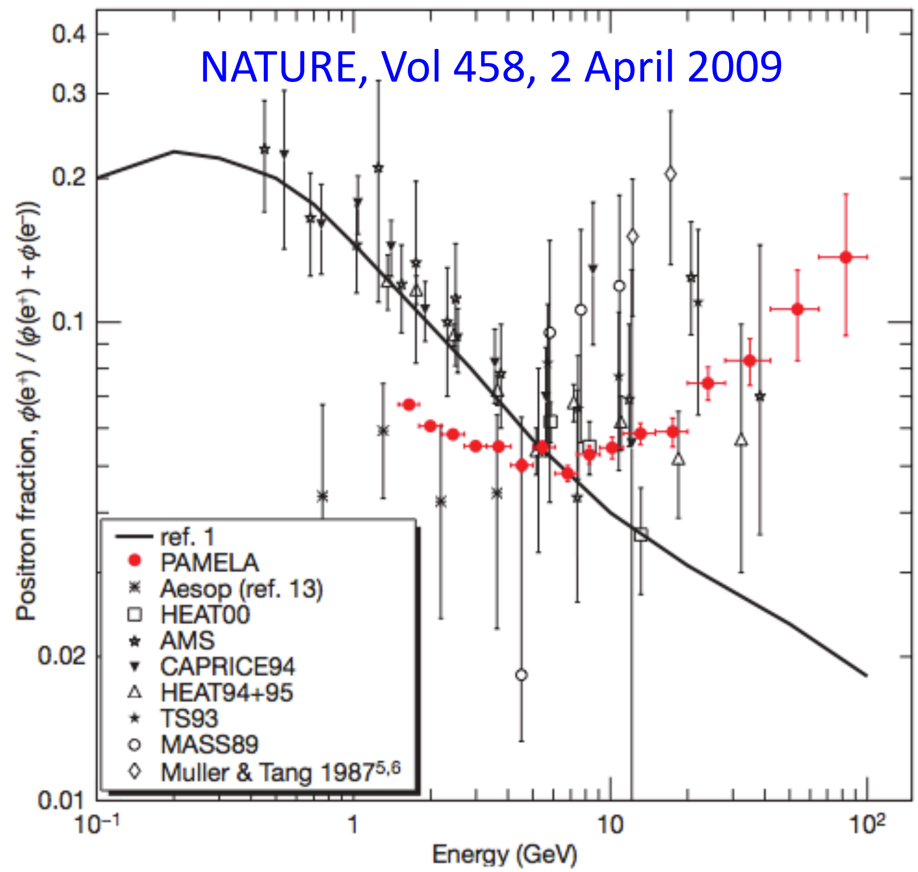
PAMELA experiment

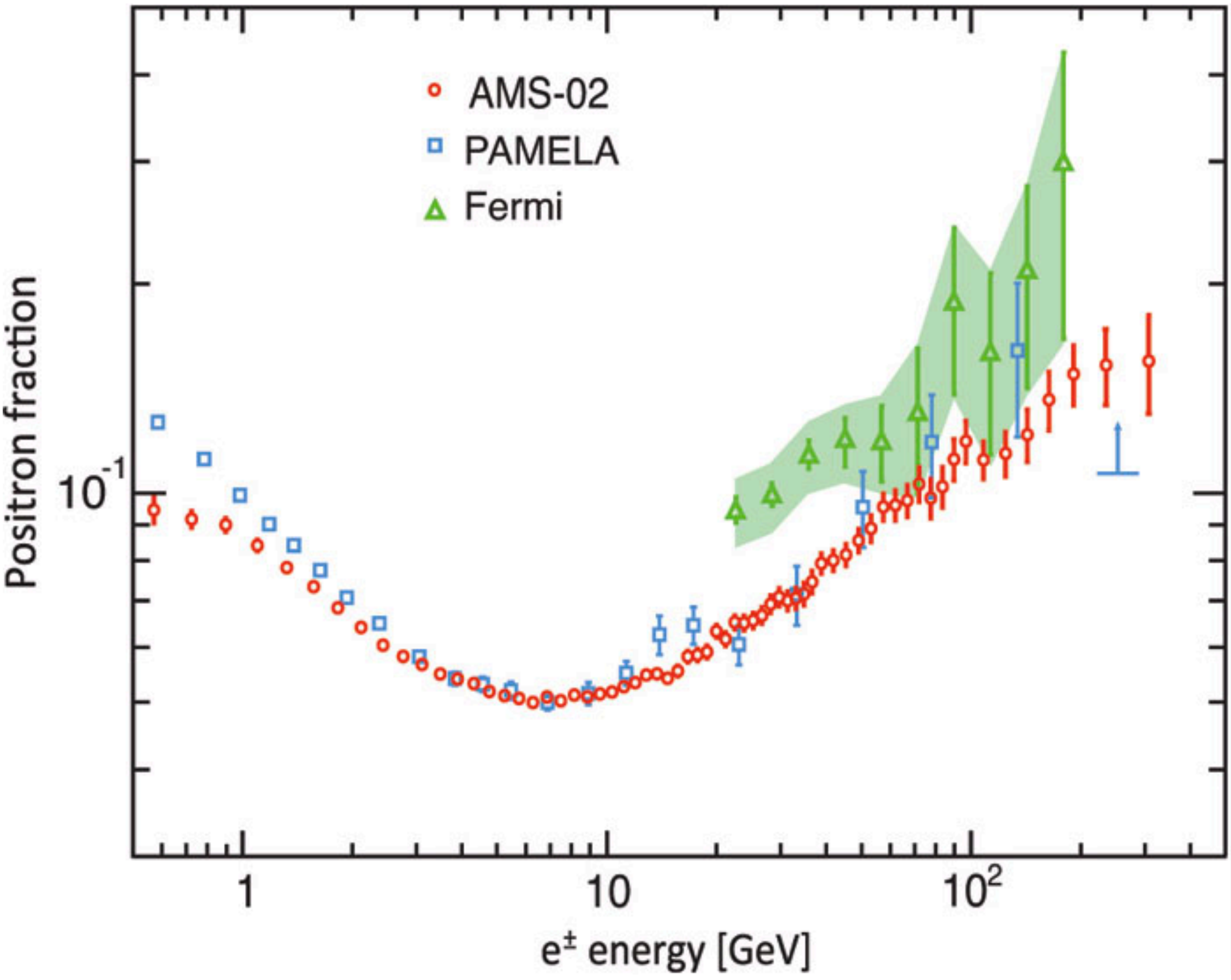
Anti-protons



Positron Fraction

- Pamela found a positron excess w.r.t. the level of positrons generated by secondaries
  - Positron fraction increases with energy!
  - DM or nearby pulsars ?!





AMS-02
PAMELA
Fermi
Positron fraction
10^{-1}
1
10
10^2
$e^{\pm}$ energy [GeV]

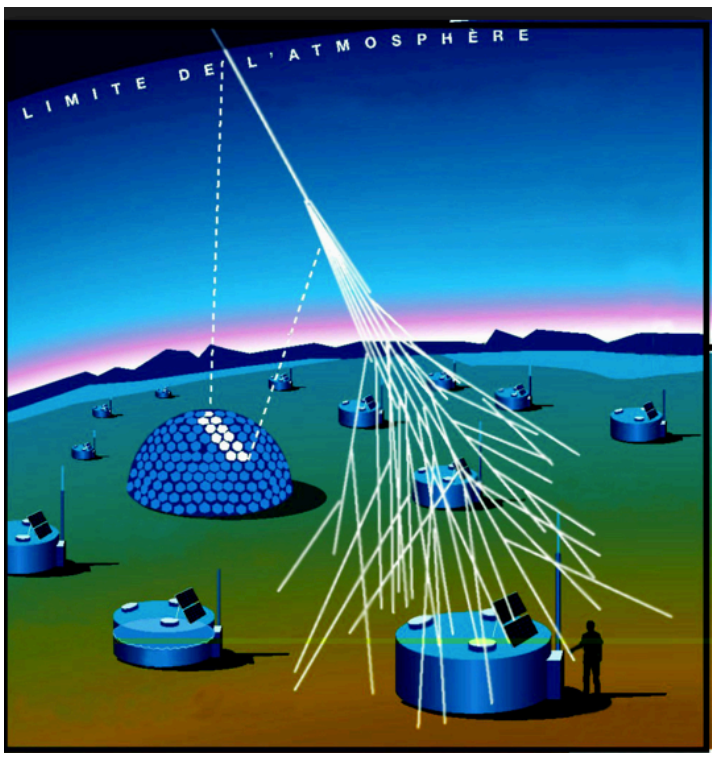
UHECRs

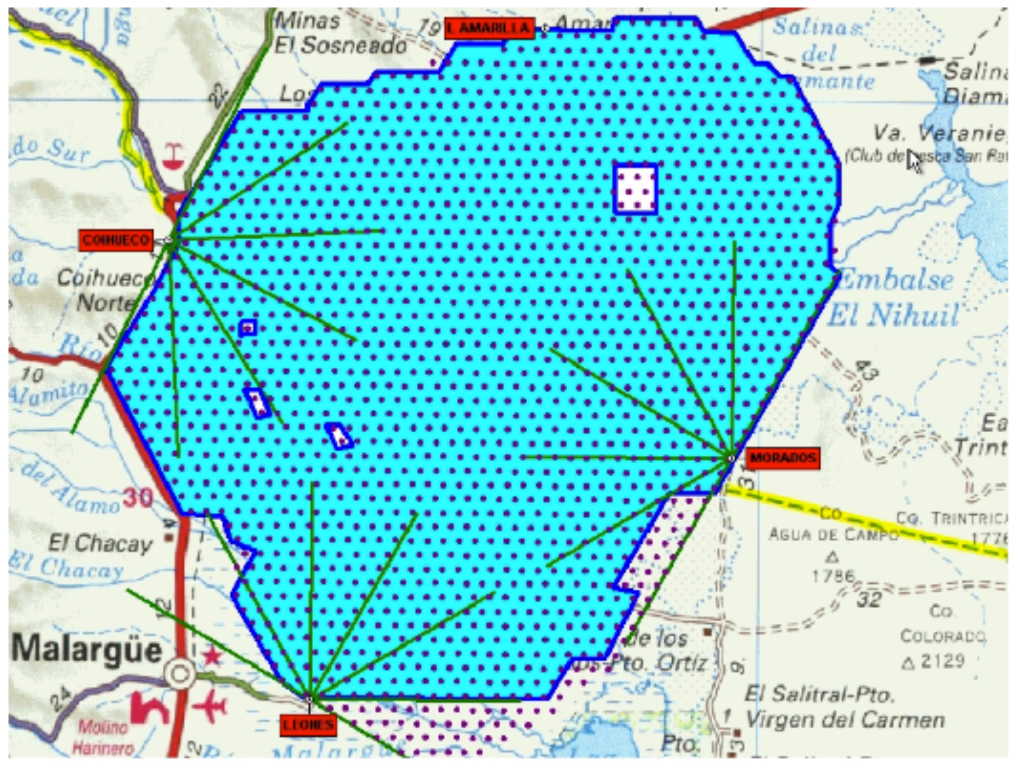
- E>5e19 eV
  - Above the GZK (Greisen–Zatsepin–Kuzmin) limit, photo-pion production over the CMB
  - Protons travel <50 Mpc (z<0.01)

$$\gamma_{\rm CMB} + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0},$$

or

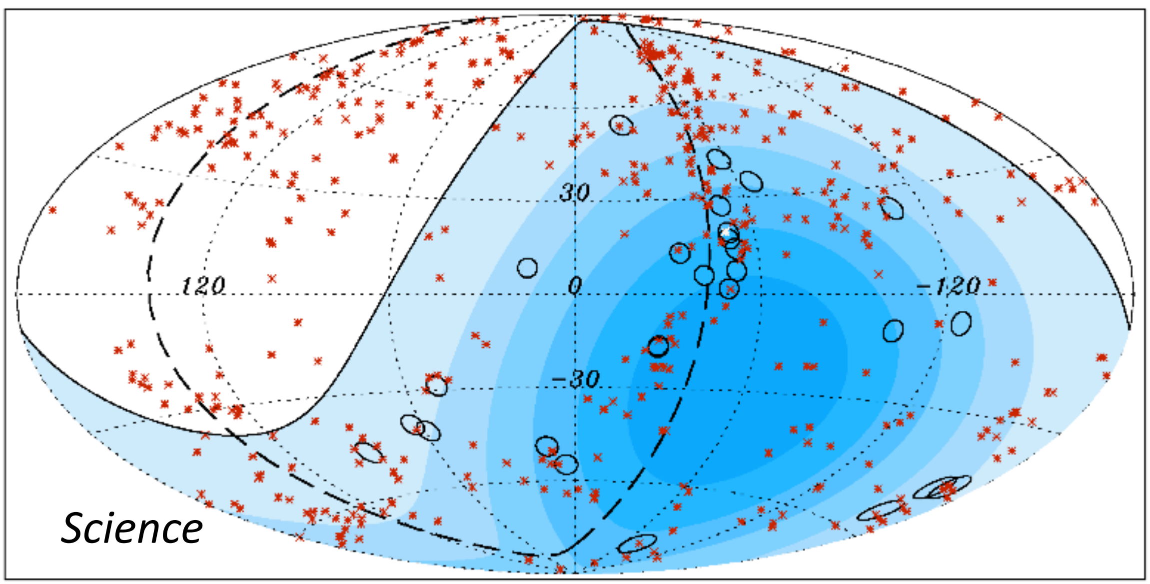
$$\gamma_{\rm CMB} + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}.$$

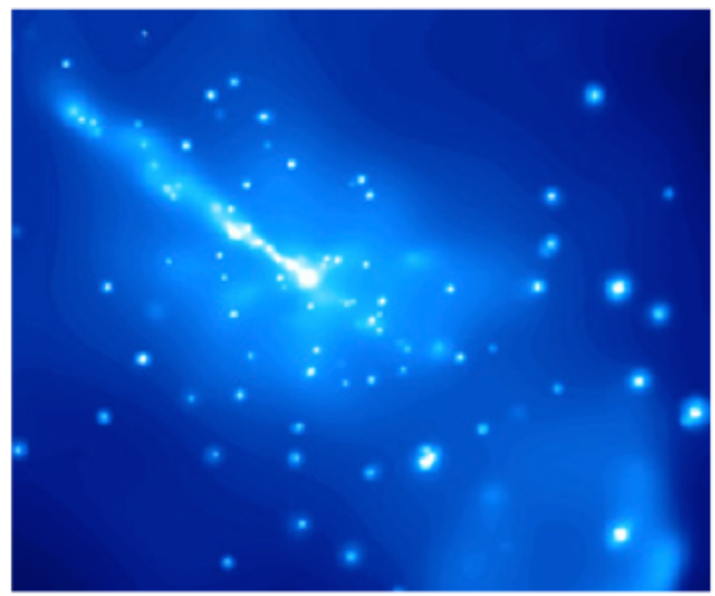




Sources of UHECRs

- Because of the GZK they have to be nearby
- Correlation found with AGN within the GZK cut-off along the super-galactic plane
  - 27 CRs – 99% C.L. e.g. < 3sigma
- Several CRs from around the position of Cen-A
  - Bright nearby (5 Mpc) radio galaxy





Mystery Over ? Not yet….

- Subsequent analyses did not confirm the results
  - 69 CRs, no significant correlation