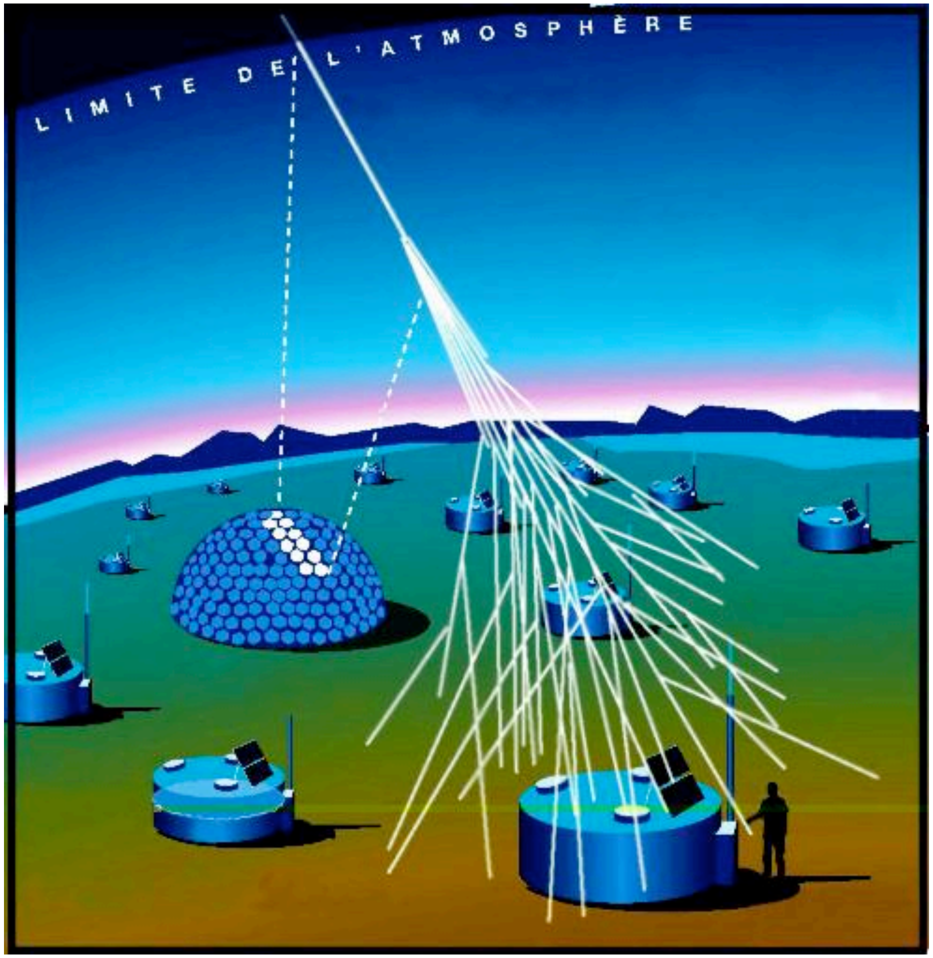
Ultra high energy cosmic rays



Donna Kubik
Spring, 2005

Cosmic accelerators

- Thanks to Angela Olinto for invaluable references and to Jeff Wilkes for getting me into all this in the first place!

Injection, acceleration, propagation in SN1987A

References

1. “Ultra High Energy Cosmic Rays: The theoretical challenge”, A. V. Olinto, Phys.Rept.333 (2000) 329-348
   astro-ph/0002006

2. “Origin and Propagation of Extremely High Energy Cosmic Rays”, Pijushpani Bhattacharjee and Guenter Sigl, Phys.Rept. 327 (2000) 109-247
   astro-ph/9811011

3. *Introduction to Ultrahigh Energy Cosmic Ray Physics*, Pierre Sokolsky, Addison-Wesley, 1989

4. *High Energy Cosmic Rays*, Todor Stanev, Springer, 2004

Cosmic accelerators

- Notice the similar “geometry” of cosmic ray accelerators, like SN1987A, and the manmade accelerator at Fermilab ;) !

Injection, acceleration, propagation
in a manmade accelerator

Injection, acceleration, propagation
in SN1987A

Cosmic accelerators

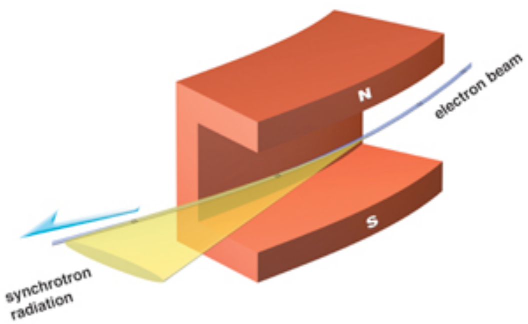
- Energy spectra of cosmic rays have been shaped by a combination of injection, acceleration and propagation

Injection, acceleration, propagation
in a manmade accelerator

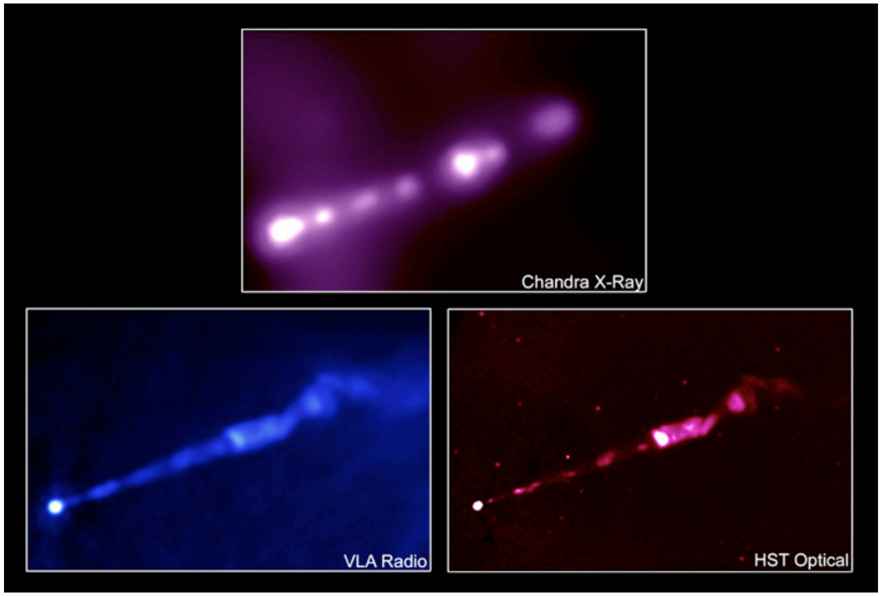
Injection, acceleration, propagation
in SN1987A

Cosmic accelerators

- These processes are modified by energy losses, collisions, and perhaps leakage from the galaxy, and they all depend on particle energies.



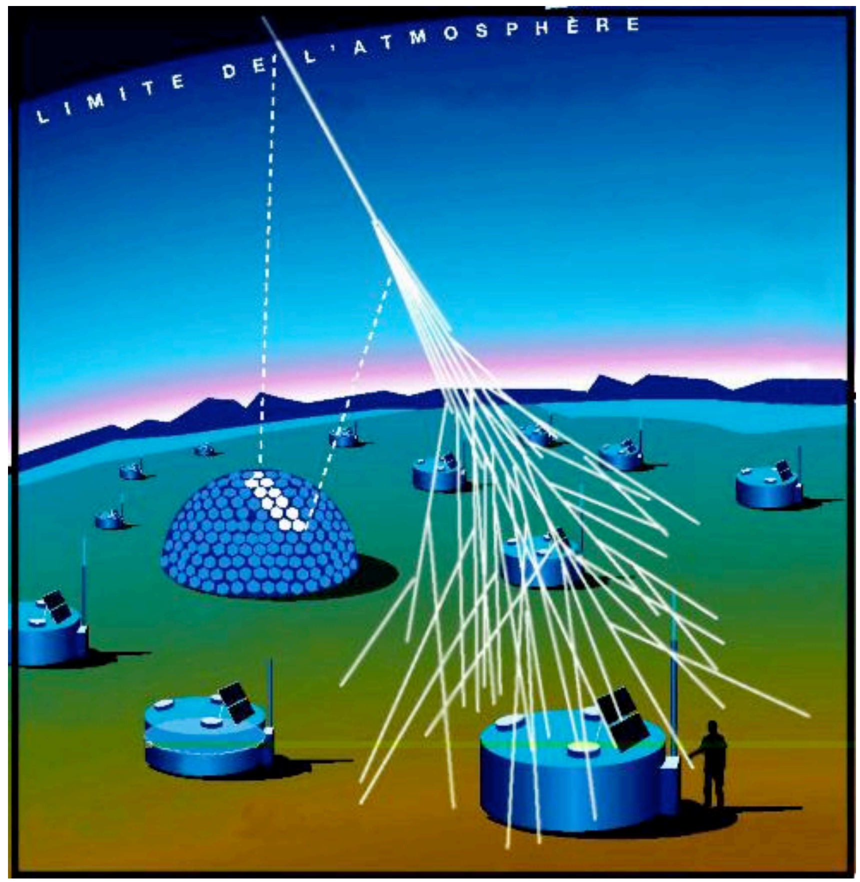
Synchrotron loss in manmade accelerators



Synchrotron emission from high energy electrons in M87

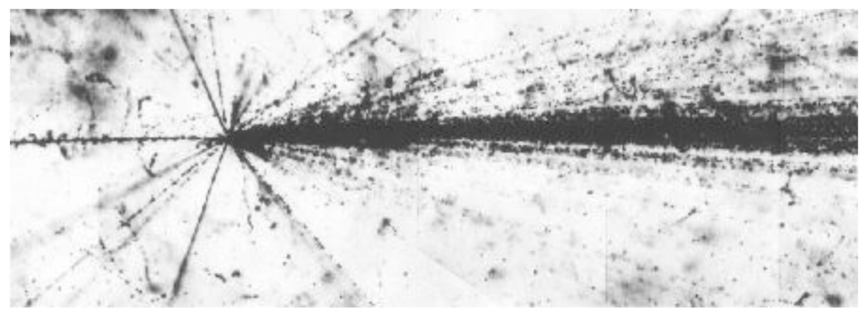
Cosmic ray detection

- The cosmic ray spectrum has been measured over a wide range of energy
- The method of CR detection depends on the energy of the particles



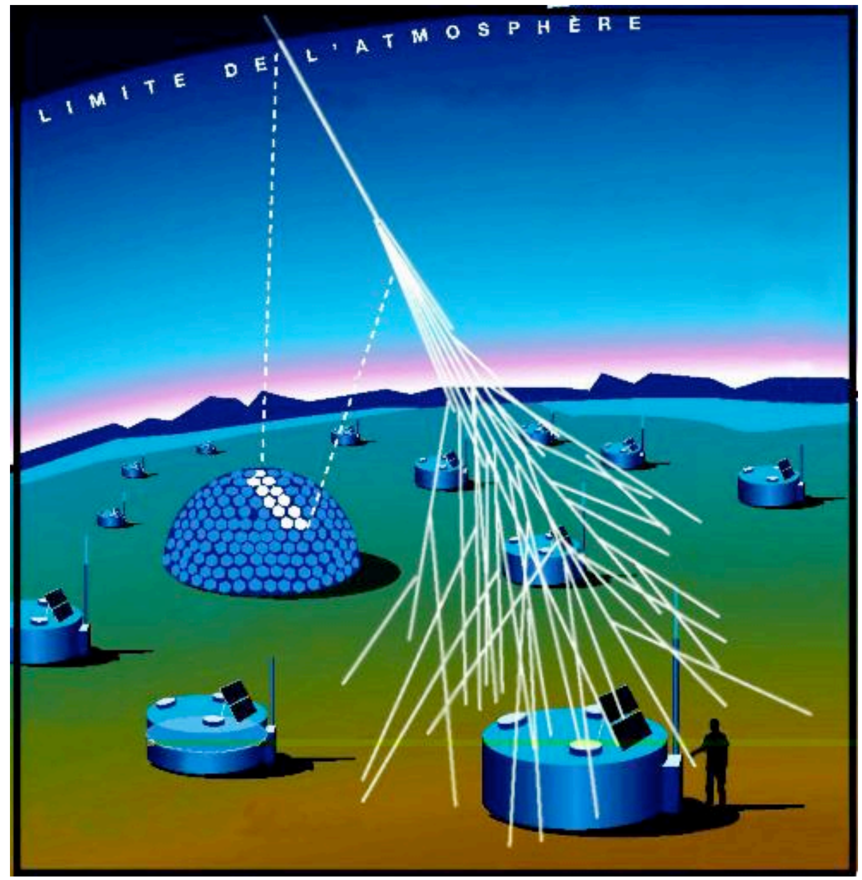
Direct detection

- $<0.1\text{x}10^{15}$ eV
  - Flux is high enough for direct detection
    - Calorimeters, emulsion stacks, TR detectors in balloons, satellites, space station
    - A collision between a high energy cosmic ray and an atom in photographic emulsion viewed through a microscope



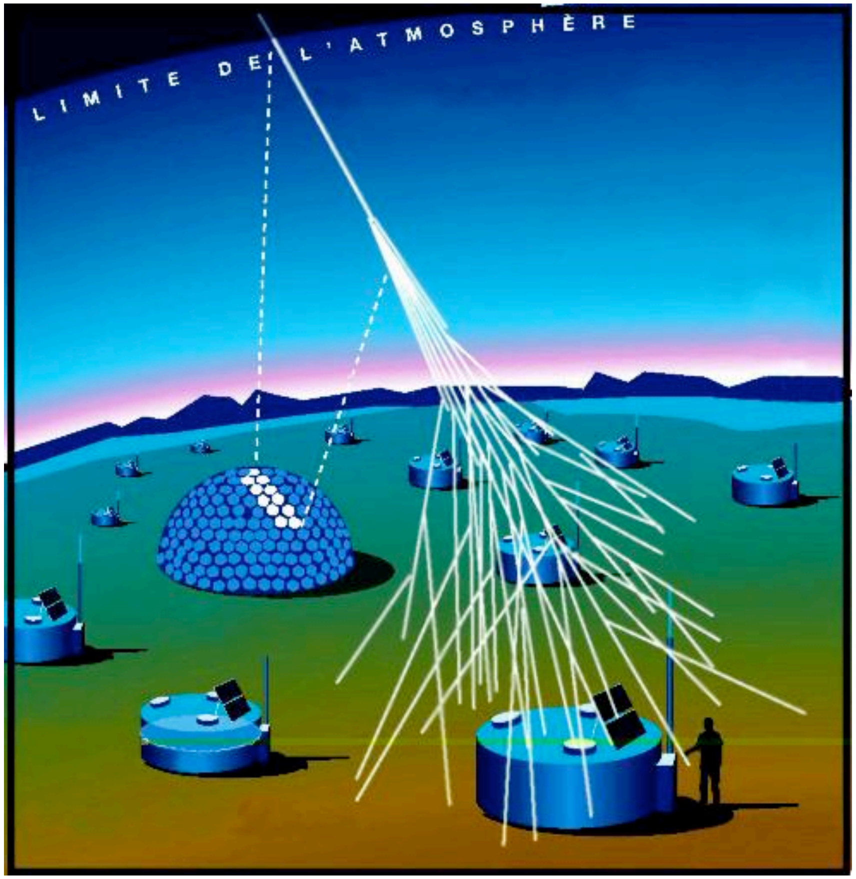
Indirect detection

- $> 0.1 \times 10^{15}$ eV
  - Flux is too low for direct detection
    - Extensive air showers (EAS)
      - Ground arrays
      - Atmospheric light
        - » Cherenkov
        - » Nitrogen scintillation (UV)



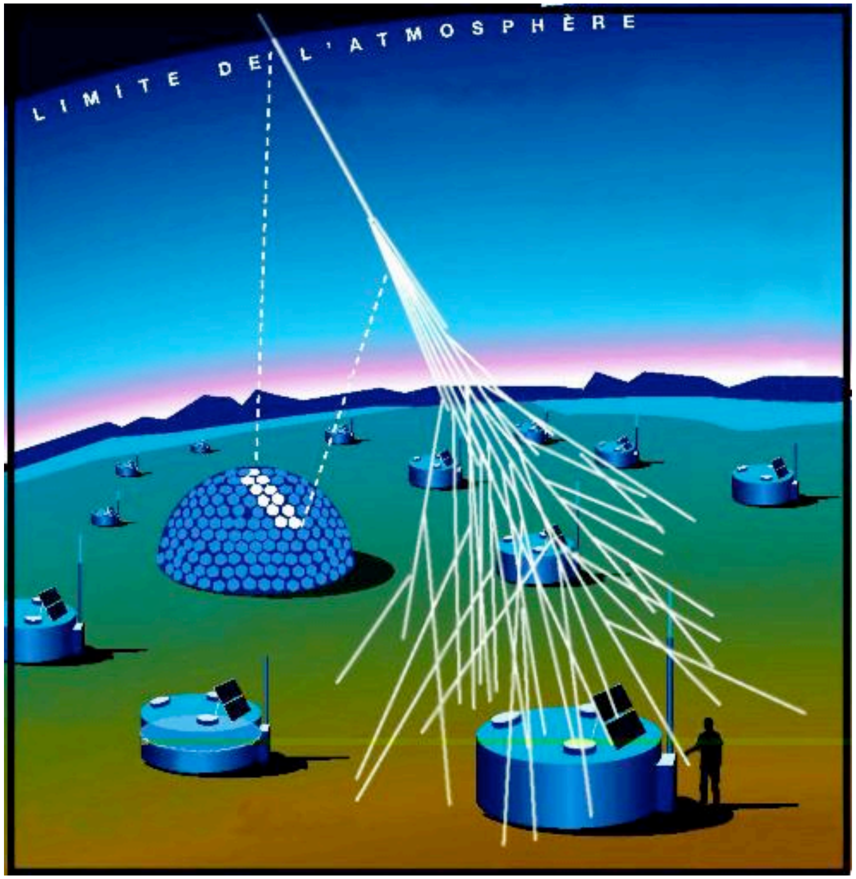
EAS

- The atmosphere above the area of the EAS array serves as a natural transducer and amplifier for the detector.
- The primary energetic cosmic ray collides with a nucleus in the air, creating many secondary particles which share the original energy.



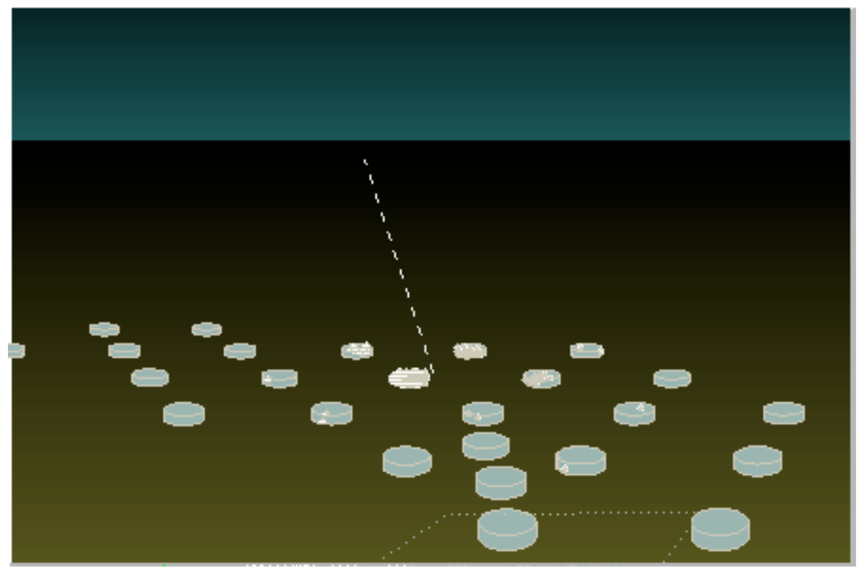
EAS

- The secondary particles also collide with nuclei in the air, creating a new generation of still more particles that continue the process.
- This cascade, called an "extensive air shower", arrives at ground level with billions of energetic particles that can be detected over approximately 10 square kilometers.



Auger Observatory

- Above 10^{19} eV, the arrival rate is only 1 particle per square kilometer per year.
- Cosmic rays with energies above 10^{20} eV have an estimated arrival rate of only $1/km^2$ per century!
- Need huge area
- i.e. Auger Observatory detection area of 3000 square kilometers



Click on image to see EAS animation of Pierre Auger Cosmic Ray Observatory Array
(Must be online to view animation)

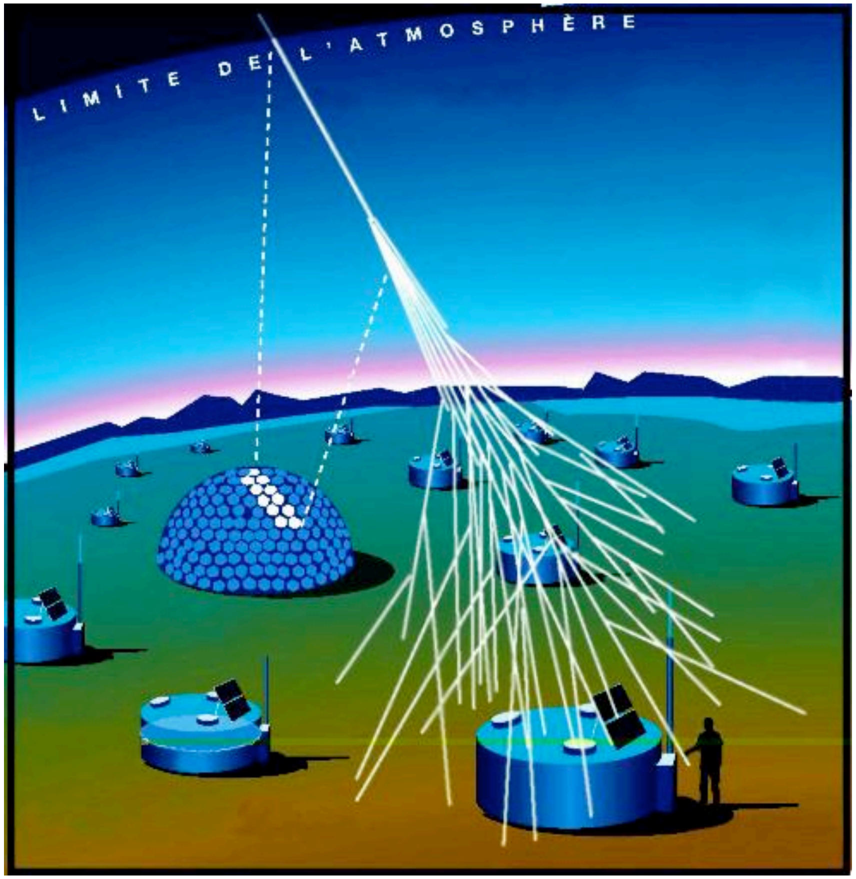
Animation from Auger website http://www.auger.org/photos/AnimGif.html

Composition

- The particle identity is determined by the muon content of the shower in ground arrays and the depth of shower max in fluorescence detectors

- But this is difficult analysis at high energies

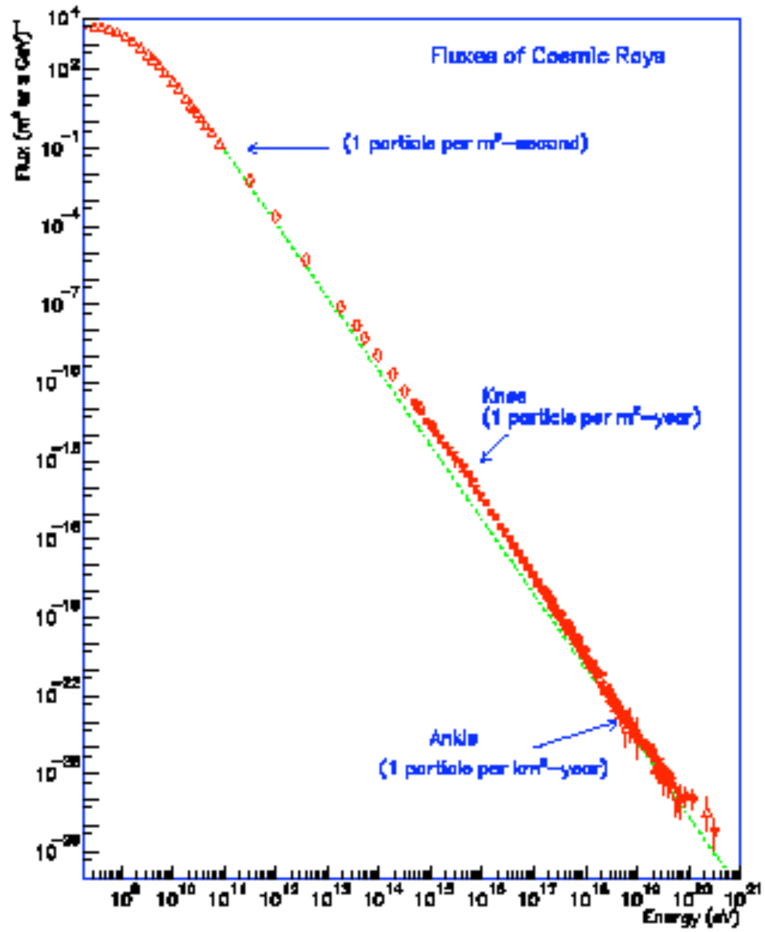
- Need more data



The cosmic ray spectrum Part 1

- < 1 GeV
  - Temporally correlated with solar activity – solar origin
- 1 GeV to Knee
  - Galactic origin (SNR shocks)
- Knee to Ankle
  - Larger shocks (galactic winds) and SN explosions into stellar winds

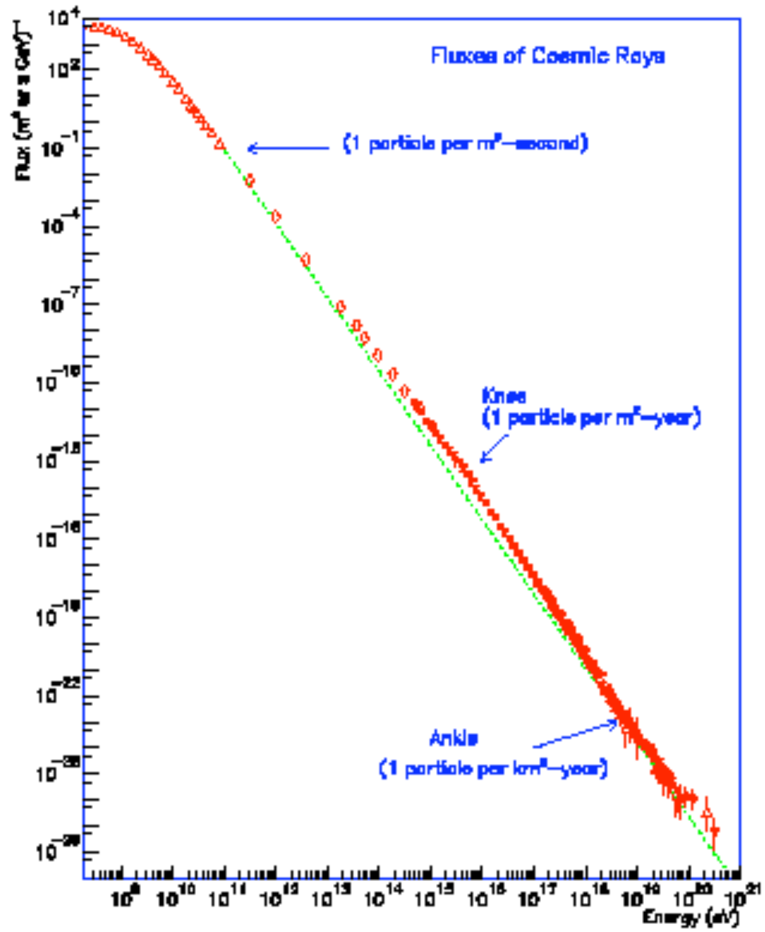
Graph from [2]



The cosmic ray spectrum Part 2

- Ankle (>$10^{19.5}$)
  - Drastic change is slope
  - Crossover from Galactic to extragalactic origin?
  - 100s of events >10^{19} eV
  - 20 events above 10^{20} eV
    - AGASA
    - Fly's Eye
    - HIRES
  - Highest-energy event is $3.2x10^{20}$ eV

Graph from [2]



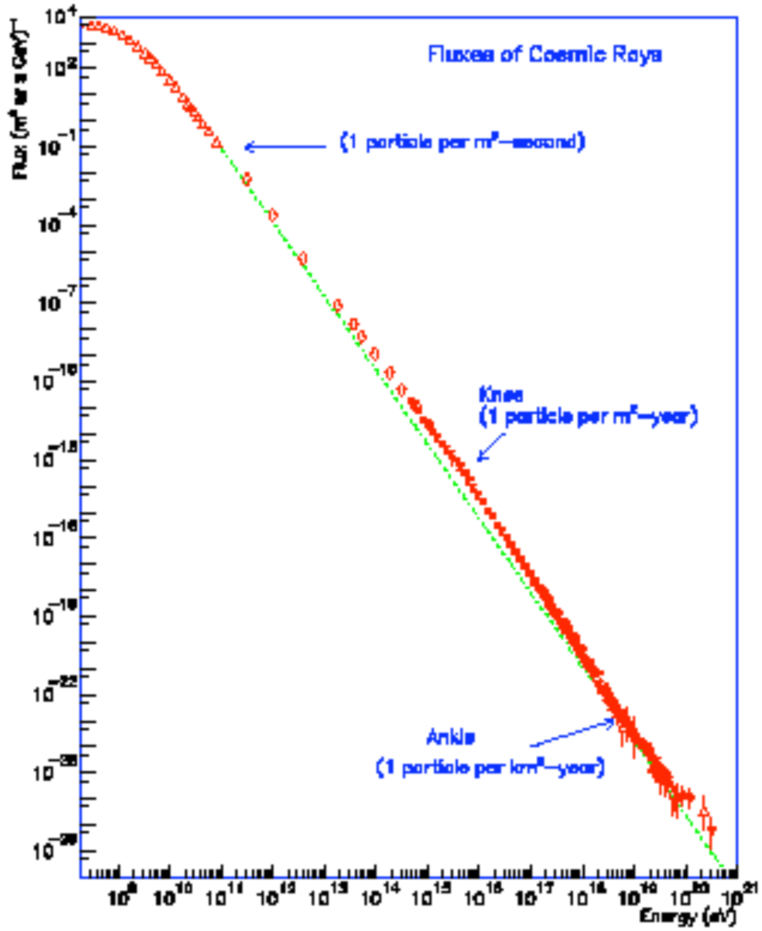
GZK cutoff Part 1

- The many events that have been observed above 7 x 10^{19} eV with no sign of the Greisen-Zatsepin-Kuzmin (GZK) cutoff was not expected

- If the Ultra High Energy Cosmic Rays (UHECRs) are protons, nuclei, or photons from extragalactic sources, an energy cutoff should be present

- Protons with an *initial* E > 10^{20} eV from >100 Mpc should appear at a lower energy due to energy loss to the CMB.

Graph from [2]



GZK cutoff Part 2

- The CMB has a blackbody spectrum with T=2.7 K corresponding to mean energy of 6.34×10^{-4} eV [4]. A proton of high enough energy (> 7×10^{19} eV) will interact inelastically with CMB photons producing pions via

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

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

GZK cutoff Part 3

- With each collision, the proton would lose roughly 20% of its energy
- This only happens for cosmic rays that have at least 6×10^{19} eV of energy, and this is the predicted GZK cutoff.
- So if cosmic rays were given an initial energy greater than that, they would lose energy in repeated collisions with the cosmic microwave background until their energy fell below this cutoff.
- However, if the source of the cosmic ray is close enough, then it will not have made very many collisions with microwave photons, and its energy could be greater than the GZK cutoff.
- This distance is about 150 million light years.

Calculation of the required UHECR proton energy for pion photoproduction

- The approach is to calculate the proton energy, E_p, required for pion photoproduction using conservation of 4-momenta, P.
- Considering the left hand side in the lab frame and the right hand side in the center-of-mass frame, where
  - E_p = UHECR proton energy (the unknown)
  - $E\gamma$ = average CMB photon energy = 6.34x10-4 eV [4]
  - m_p = 938.27 MeV/c2
  - $m_{\pi 0}$ = 134.97 MeV/c2
  - P = 4-momentum
- Conclusion: $E_p \sim 2\mathrm{x}10^{20}$ eV
- See Ref 4 p221 (Stanev)

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

$$\text{Lab} \rightarrow \text{Center of mass}$$

$$(P_{p\mu} + P_{\gamma\mu})^2 = P_{TOT\mu} P^{\mu}_{TOT}$$

$$P_{p\mu} P^{\mu}_{p} + 2P_{p\mu} P^{\mu}_{\gamma} + P_{\gamma\mu} P^{\mu}_{\gamma} = P_{TOT\mu} P^{\mu}_{TOT}$$

$$(m_p c^2)^2 + (2E_p E_\gamma) + (m_\gamma c^2)^2 = \left((m_p + m_{\pi^0})c^2\right)^2$$

$$m_\gamma c^2 = 0, \text{because it's a photon}$$

$$E_p = \frac{m_{\pi^0}}{2E_\gamma}\left(2m_p + m_{\pi^0}\right)$$

$$E_p = \frac{(134.97MeV/c^2)c^2}{2(6.34x10^{-4}eV)}\left(\frac{(2*938.27MeV) + 134.97MeV)}{c^2}c^2\right)$$

$$E_p \approx 2x10^{20}eV$$

Calculation of the gamma wall energy

- The approach is to calculate the photon energy, E_γ, required for e+e- production on the CMB using conservation of 4-momenta, P.
- Considering the left hand side in the lab frame and the right hand side in the center-of-mass frame, where
  - E_γ = gamma ray (gamma wall) photon energy
  - E_{cmb} = average CMB photon energy = 6.34x10-4 eV [4]
  - m_{e+} = m_{e-} = 0.511 MeV/c^2
  - P = 4-momentum
- Conclusion: E_γ~8.2x10^{14} eV
- See Ref 4 page 264 (Stanev)

$$\gamma_{cmb} + \gamma_{wall} \rightarrow e^+ e^-$$
$$\text{Lab} \rightarrow \text{Center of mass}$$

$$(P_{cmb\mu} + P_{\gamma\mu})^2 = P_{TOT\mu} P^{\mu}_{TOT}$$
$$P_{cmb\mu} P^{\mu}_{\gamma} + 2P_{cmb\mu} P^{\mu}_{\gamma} + P_{\gamma\mu} P^{\mu}_{\gamma} = P_{TOT\mu} P^{\mu}_{TOT}$$
$$(m_{cmb}c^2)^2 + (2E_{cmb}E_\gamma) + (m_\gamma c^2)^2 = \left((m_{e+} + m_{e-})c^2\right)^2$$
$$m_{cmb}c^2 \ and \ m_\gamma c^2 = 0, \text{ because they're photons}$$
$$E_\gamma = \frac{\left((m_{e+} + m_{e-})c^2\right)^2}{2E_{cmb}}$$
$$E_\gamma = \frac{\left[(0.511 MeV/c^2 + 0.511 MeV/c^2)c^2\right]^2}{2(6.34x10^{-4} eV)}$$

$$E_\gamma \approx 8.2x10^{14} eV$$

GZK cutoff Part 4

- Above the threshold, multiple pion production becomes important. The π^+ will decay via

$$\pi^+ \rightarrow \nu_\mu \mu^+ \rightarrow \nu_\mu \bar{\nu}_\mu \nu_e e^+$$

- Thus, for each such interaction there will be three neutrinos, as well as gamma rays from the decay of the π^o:

$$\pi^0 \rightarrow \gamma\gamma$$

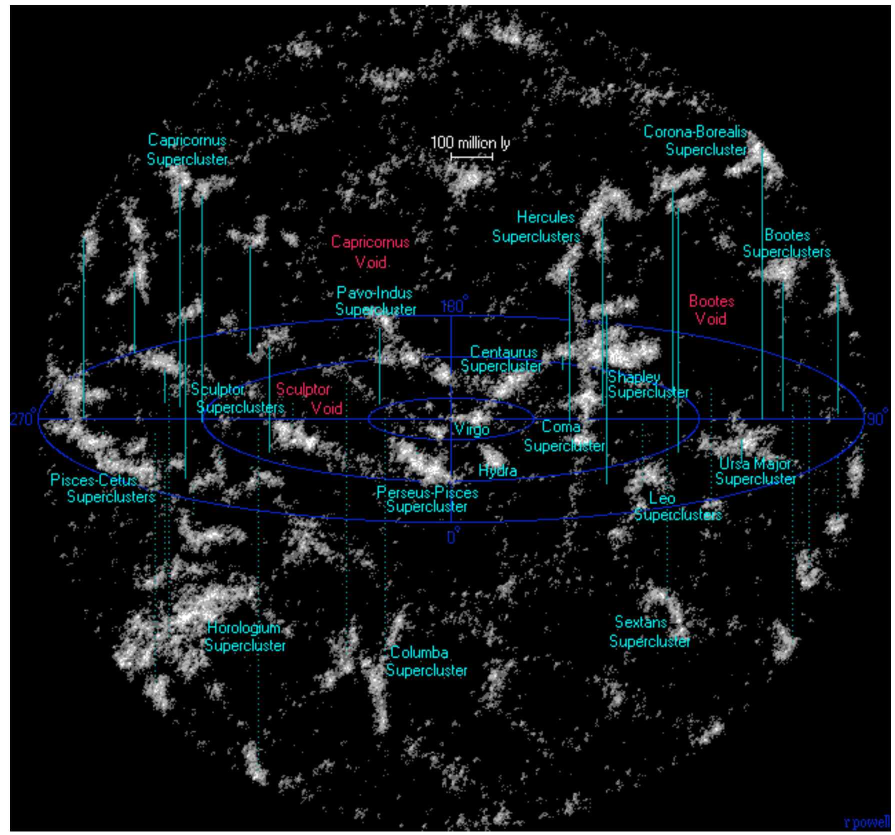
GZK cutoff Part 5

- The presence or absence of the GZK cutoff is fundamental to understanding the sources and nature of the propagation of UHECR

Possible sources

- Sources of high energy CR are thought to be powerful radio galaxies
- But they are located >>150 Mpc from Earth
- This is a major problem if the particles are conventional particles as nucleons or heavy nuclei
- They should lose energy via the GZK effect

100 MLY
30.6 Mpc

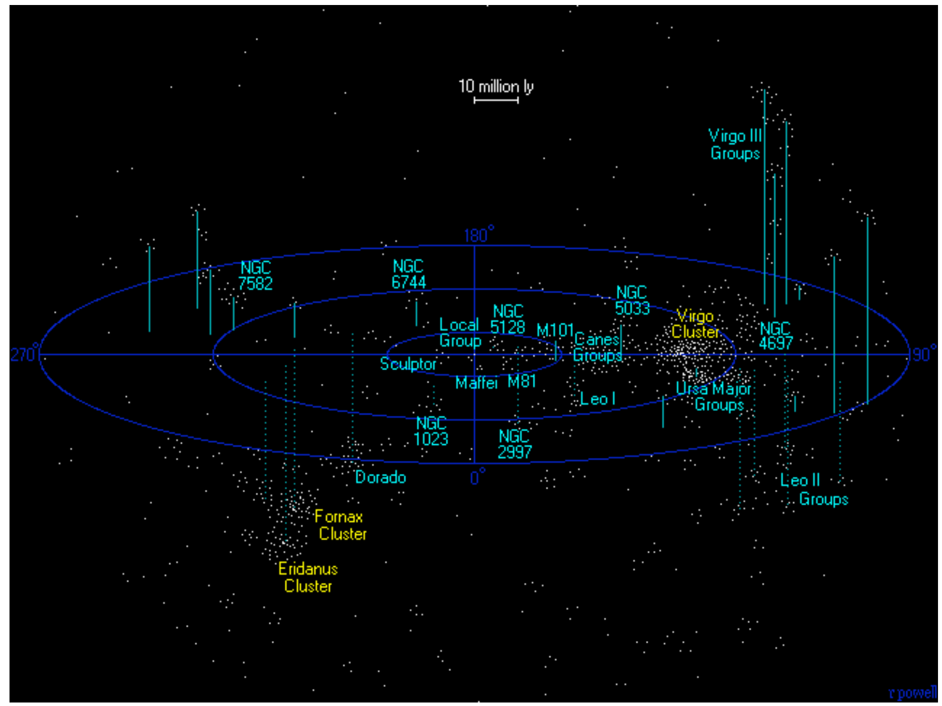


The neighboring superclusters
(Earth is at center of image,
in the Virgo Supercluster)

Possible sources

- Mean free path ~ few Mpc
- This process limits CR sources to <150 Mpc
- But then what is accelerating the cosmic rays?

10 MLY
3.06 Mpc

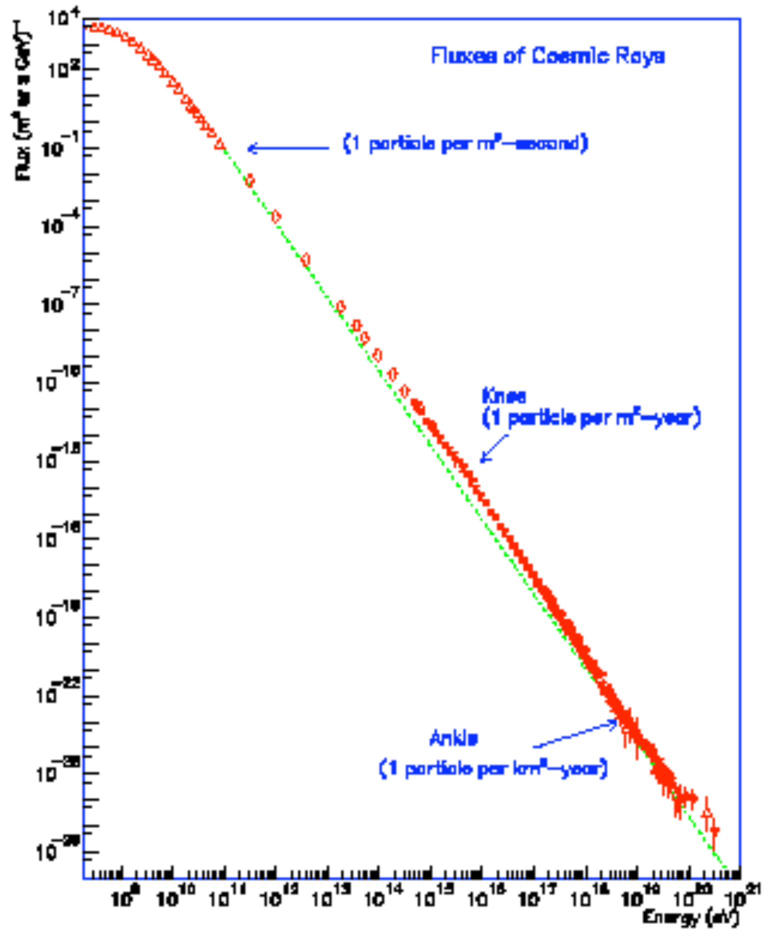


Virgo Supercluster
(Earth is at center of image, in Local Group)

Isotropy

- Regardless of whether the source of the UHECR is Galactic or extragalactic, at these high energies, the particle paths should not be significantly affected by magnetic fields, so their arrival direction should point back to their source
- But the arrival directions are isotropic
- Note, B= uG in Galaxy, <<uG extragalactic

Graph from [2]



The Challenge

- The absence of a GZK cutoff and the isotropy of arrival directions are two of the main challenges that models for the origin of UHECRs face
- Maybe the source resides in an extended Galactic halo
- That eases the difficulty of the lack of GZK cutoff but is a challenge to acceleration mechanisms
- There are 2 scenarios popularly proposed for the origin of UHECRs:
  - Bottom-up
  - Top-down

Two scenarios Part 1

- Bottom-up
  - Astrophysical acceleration
- Top-down
  - Physics beyond the standard model

Two scenarios Part 2

- Bottom-up
  - Main hurdle is the need to find a way to produce the high energies
- Top-down
  - Main hurdle is to account for the high flux

Two scenarios Part 3

- Bottom-up
  - Pro: The highest energy event (3.2×10^{20} eV) argues for the existence of Zevatrons (ZeV=10^{21} eV),
  - Con: But even the most powerful astrophysical objects, as radio galaxies and AGNs, can barely accelerate charged particles to 10^{20} eV

- Top-down
  - Pro: Decay of very high mass relics from the early universe; no acceleration mechanism needed
  - Con: The dynamics of topological defect generation and evolution generally selects the present horizon scale as the typical distance between defects which implies a very low flux

Two scenarios Part 4

- Bottom-up

- Statistical acceleration
  - Fermi acceleration
    - Acceleration in shocks associated with SN remnants, AGNs, radio galaxies

- Direct acceleration
  - Assumes existence of a strong electromagnetic field
    - Acceleration in strong E fields generated by rotating neutron stars with high surface B fields

- Top-down

- Relics of the very early universe (topological defects or superheavy relics) produced after the end of inflation can decay today and generate UHECR

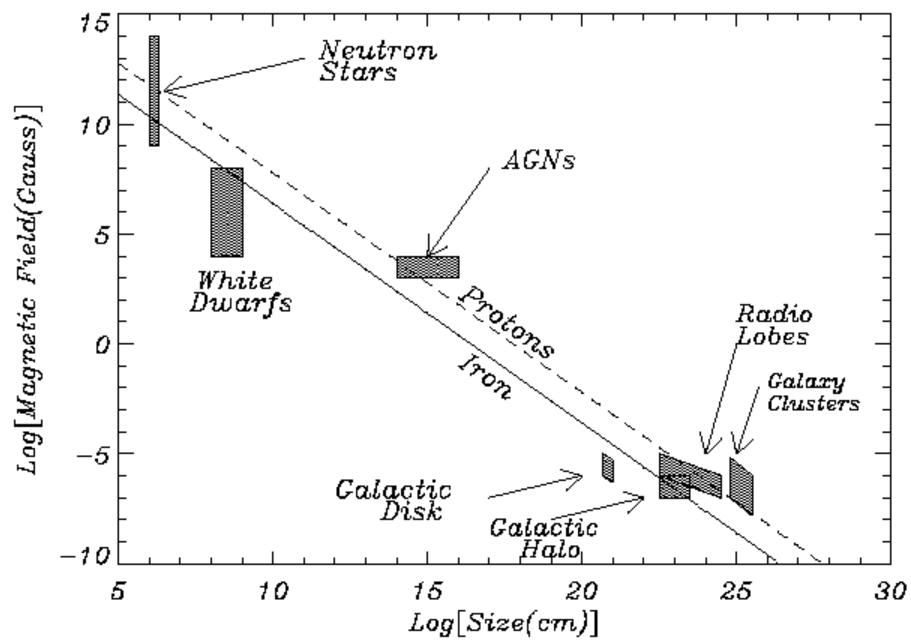
- ZeV energies are not a challenge since symmetry-breaking scales at the end of inflation are >> 10^{21} eV (typical particle masses between 10^{22} - 10^{25} eV)

Hillas plot Part 1

- Acceleration of UHECR in astrophyiscal plasmas occurs when large-scale macroscopic motion, such as shocks ad turbulent flows, is transferred to individual particles

- The max energy can be estimated by the gyroradius of the particles contained in the acceleration region

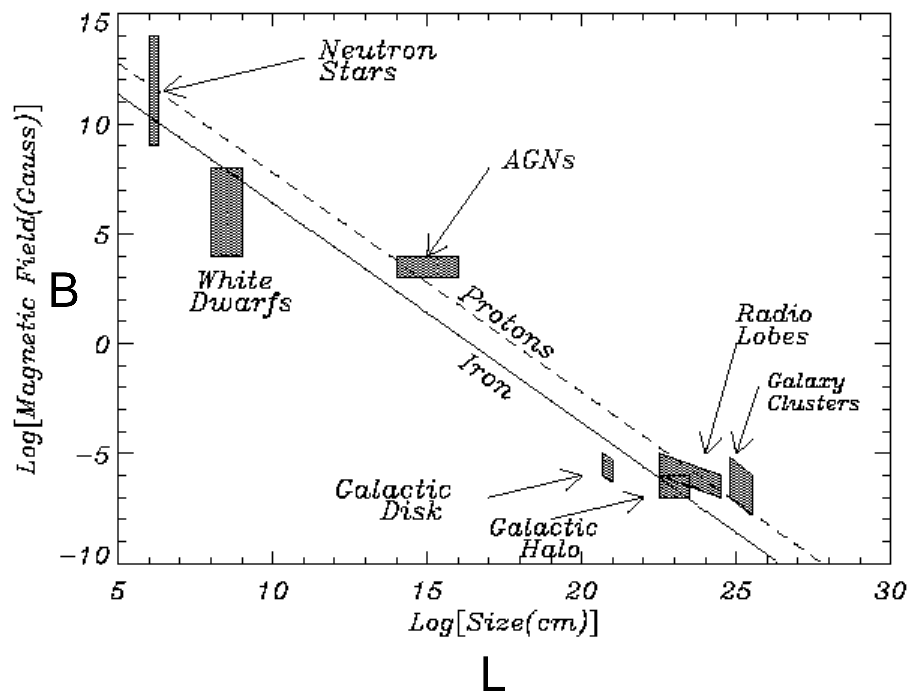
Graph from [1]



Hillas plot Part 2

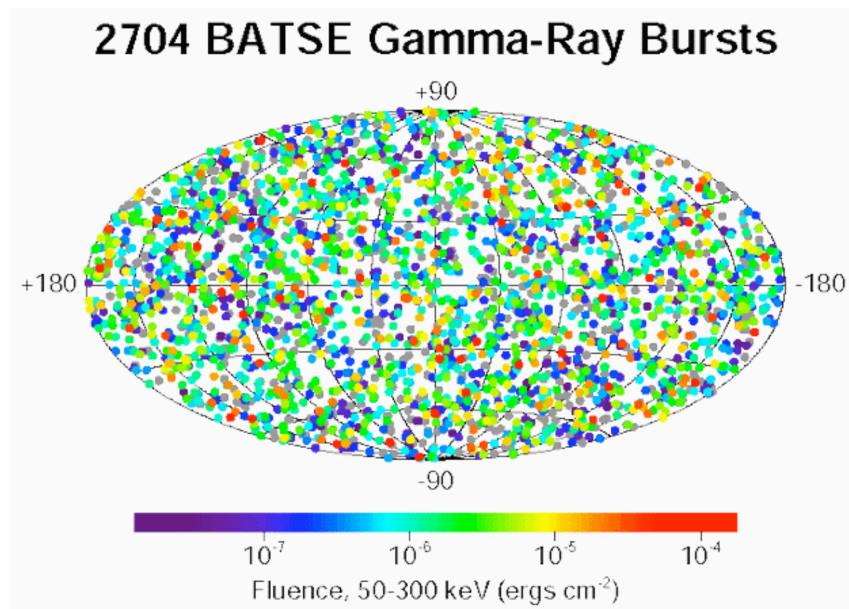
- For a given strength, B, and coherence length L, of the field embedded in the plasma, E_{max}=ZeBL
- Hillas plot shows known astrophysical sources with reasonable BL

Graph from [1]



GRB

- Can GRBs be a source of UHECR?
- GRB and UHECR are both distributed isotropically in the sky
- Average rate of gamma ray energy emitted by GRBs is comparable to the energy generation rate of UHECR of energy > 10^{19} eV
- GZK still a problem



Isotropic distribution of GRB

Hybrid Models

- Uses physics beyond the standard model in a bottom-up approach, hence termed “Hybrid”

- Uses Zevatrons to generate UHECR that are particles other than protons, nuclei, and photons,

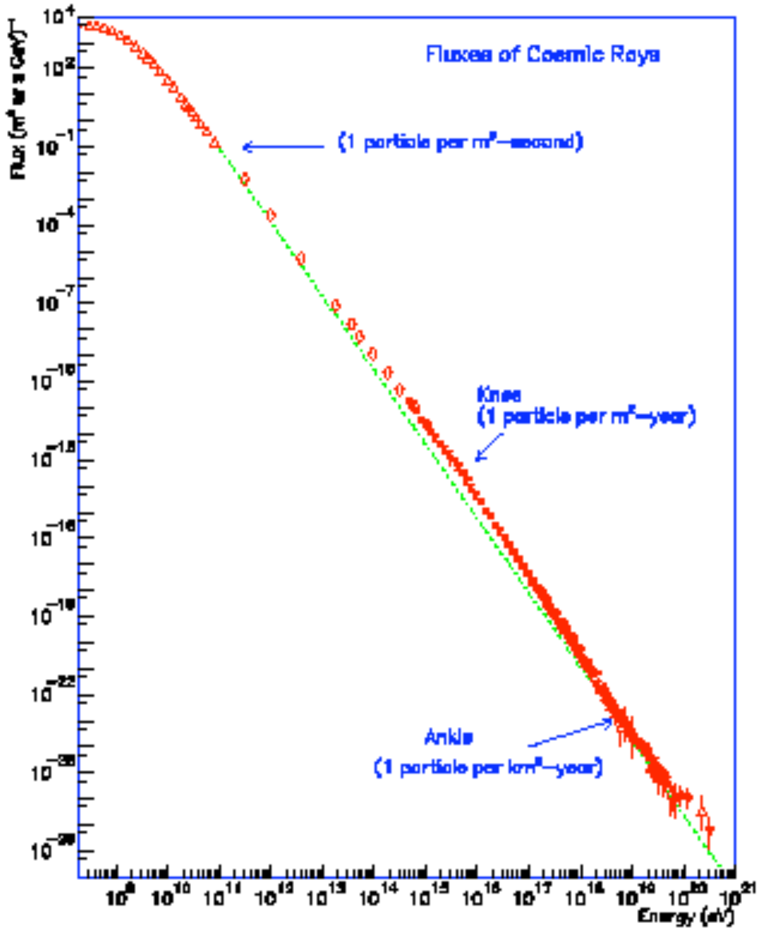
- One example: Neutrino masses ~ 1eV, the relic neutrino background will cluster in halos of galaxies and clusters of galaxies. High energy neutrinos accelerated in Zevatrons can annihilate on the neutrino background and form UEHCR through the hadronic Z decay.

- Neutrinos do not suffer from GZK losses, so the Zevatrons can be located much farther away

Power law

- Power law exists over many decades
- Source must generate a power law spectrum

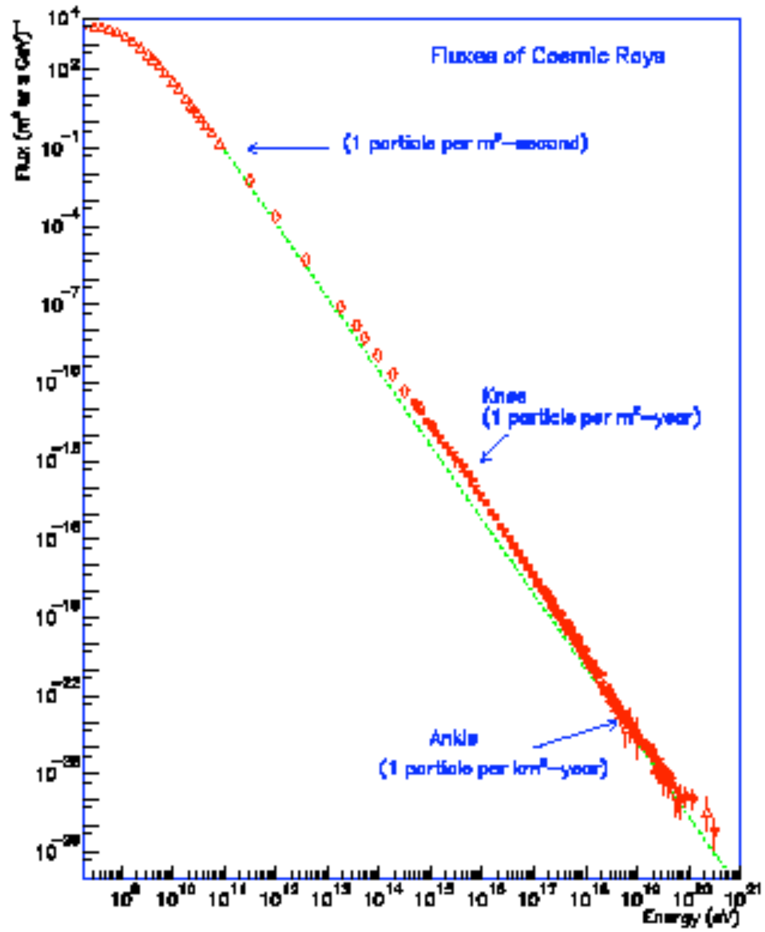
Graph from [2]



Composition

- The composition of the UHECR could help discriminate between proposed sources
- Galactic disk models need to invoke heavier nuclei (Fe) to be consistent with the isotropic distribution
- Extragalactic models favor proton primaries
- Photon primaries more common among top-down scenarios

Graph from [2]

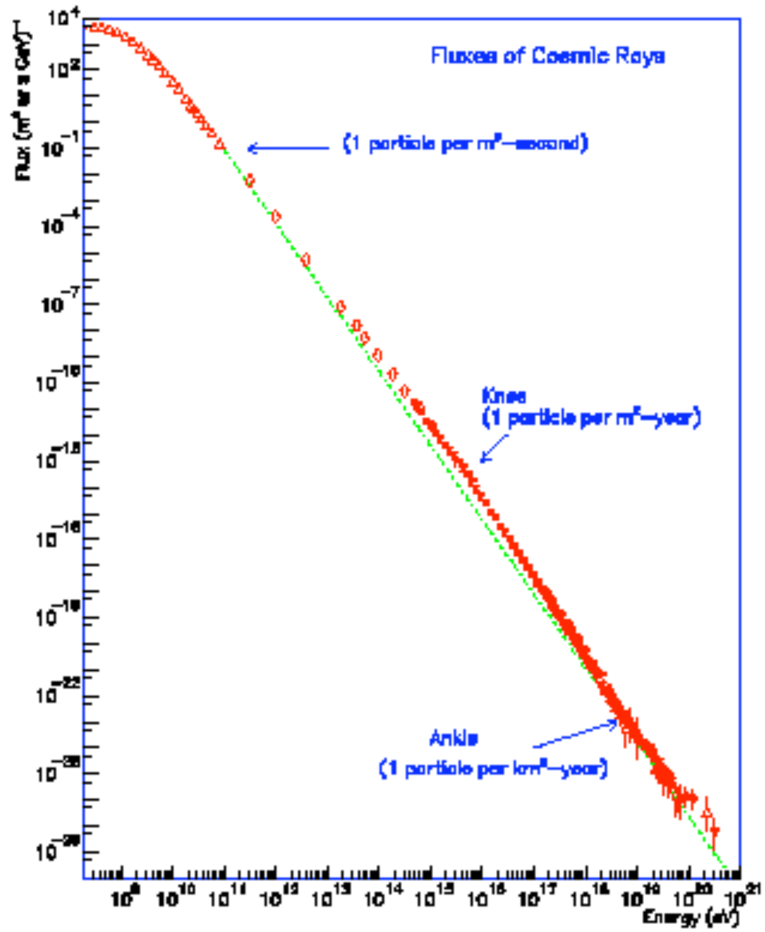


The future

- The new experiments, HIRES, the Auger Observatory, and the OWL-Airwatch satellite will improve data on the spectrum and spatial distribution, and composition of UHECR.

- The lack of a GZK cutoff should become apparent with Auger and, if so, most extragalactic Zevatrons may be ruled out.

Graph from [2]



The future

- The observed spectrum will distinguish Zevatrons or top-down model by testing power las vs. QCD fragmentation fits
- The correlation of arrival directions of UHECR with some known structure as the Galaxy, Galactic halo, Local Group, or Local Supercluster would be key in differentiating between different models

Graph from [2]