Physics 661

Particle Physics Phenomenology

October 9, 2003

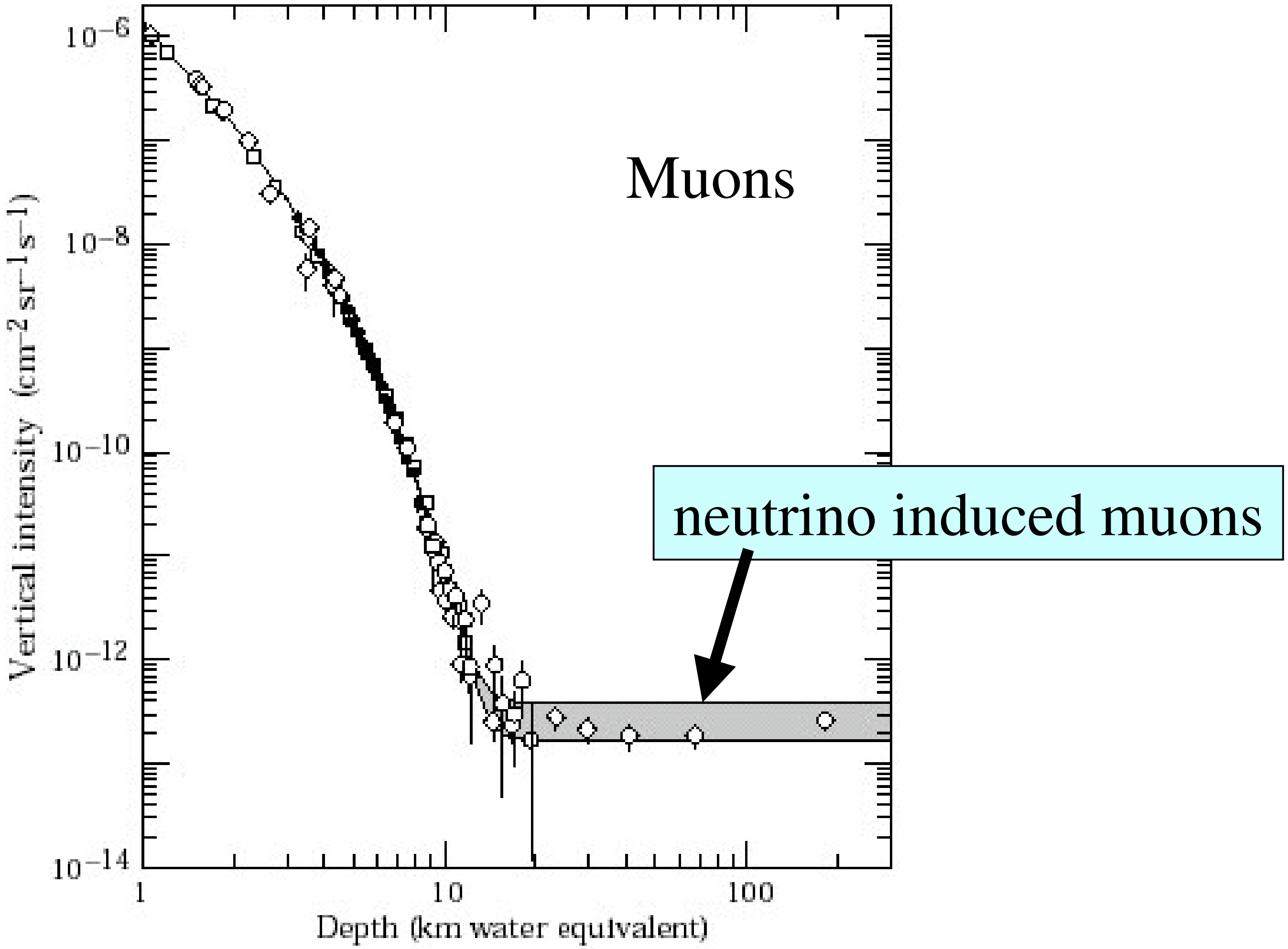
Cosmic Rays

- Outline
  - Primary cosmic ray spectrum and abundances ✓
  - Cosmic rays in the atmosphere ✓
  - Cosmic rays at the Earth's surface ✓
  - Cosmic rays underground **(started)**
  - Air showers
  - Interactions with the CMB
  - Particle acceleration

Cosmic Rays (review)

- Primary cosmic ray spectrum and abundances
  - $dN/dE \sim 1.8\ E^{-\alpha}$ nucleons /cm^2 - s - sr - GeV   (α ~2.7- 3.0)
  - species distribution like composition of Solar System (spallation)
- Cosmic rays in the atmosphere
  - showers alter make-up of particles
- Cosmic rays at the Earth's surface
  - end product of showers
  - dominated by muons
- Cosmic rays underground
  - muons range out
  - deep - irreducible neutrinos

Cosmic Rays Underground



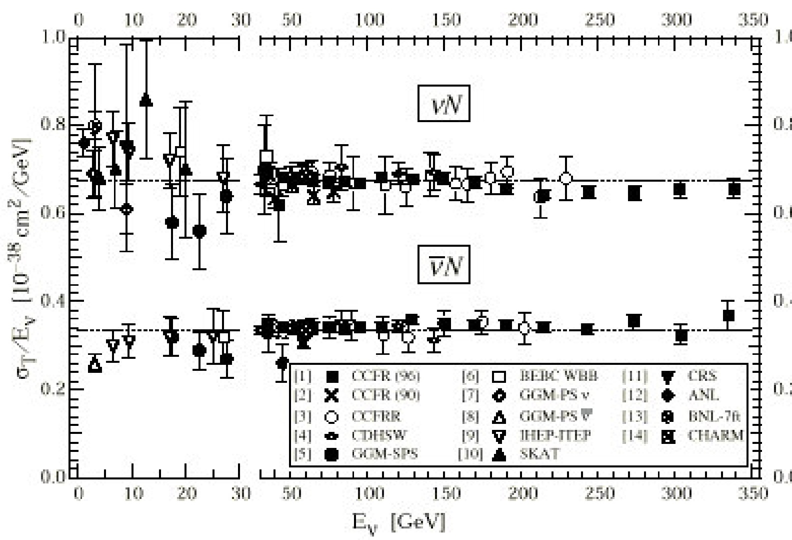
Neutrinos Underground

- $\sigma \approx 0.5 \times 10^{-38}\ \mathrm{cm}^2\ E_\nu/\mathrm{GeV}$

- $\lambda = 1/(\sigma N)$

  $\approx 10^{14}\ \mathrm{cm}\ /(E_\nu/\mathrm{GeV})$

  $\approx 4\mathrm{x}10^{4}\ D_{earth}\ /(E_\nu/\mathrm{GeV}$



- Neutrino components underground
  - Solar neutrinos
    - E ~ MeV
  - Cosmic ray induced in Earth's atmosphere
    - E $\geq$ GeV
  - Other sources

Neutrinos Underground

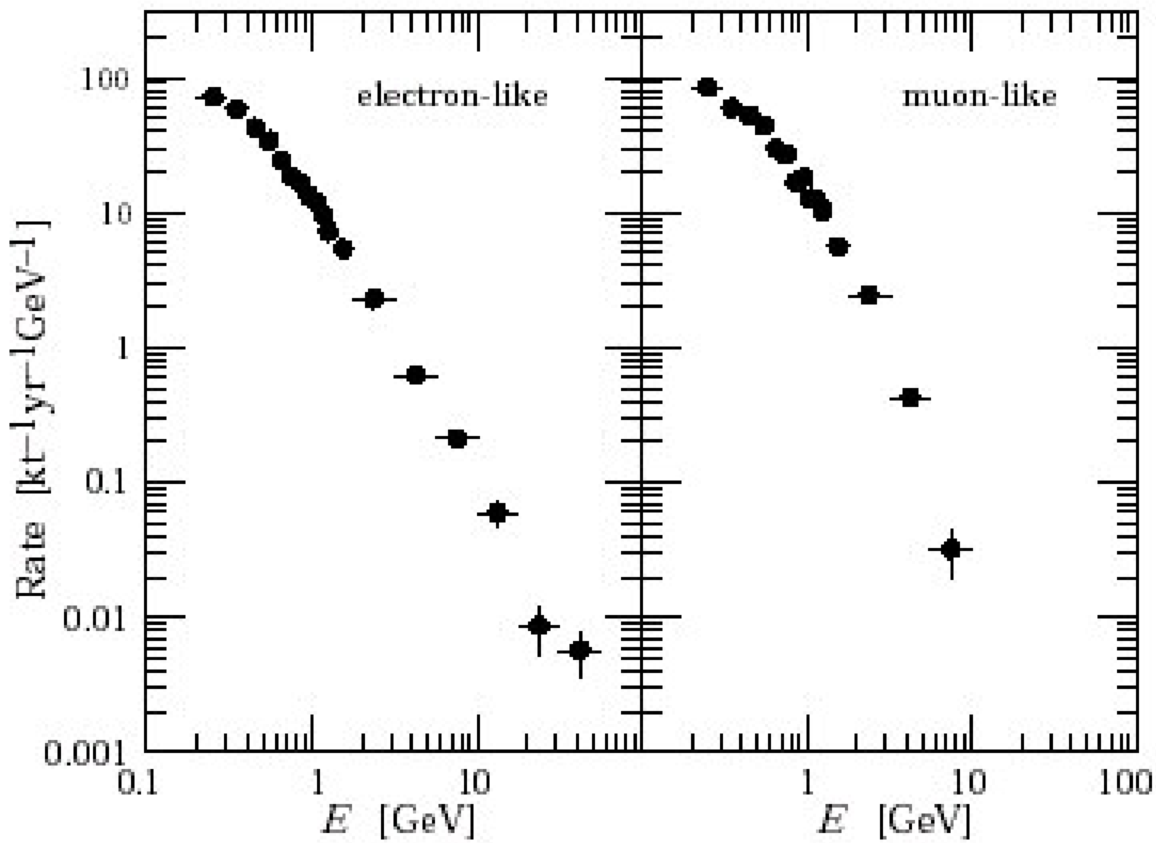
- Cosmic Ray induced neutrinos should be in the ratio $\nu_\mu/\nu_e \approx 2$
  - pions are produced in atmosphere
    - $\pi \to \mu\ \nu_\mu$
    - $\mu \to e\ \nu_e\ \nu_\mu$

Neutrinos Underground

- Contrary to the expected ratio $\nu_\mu/\nu_e \approx 2$, the two types of neutrinos have similar spectra

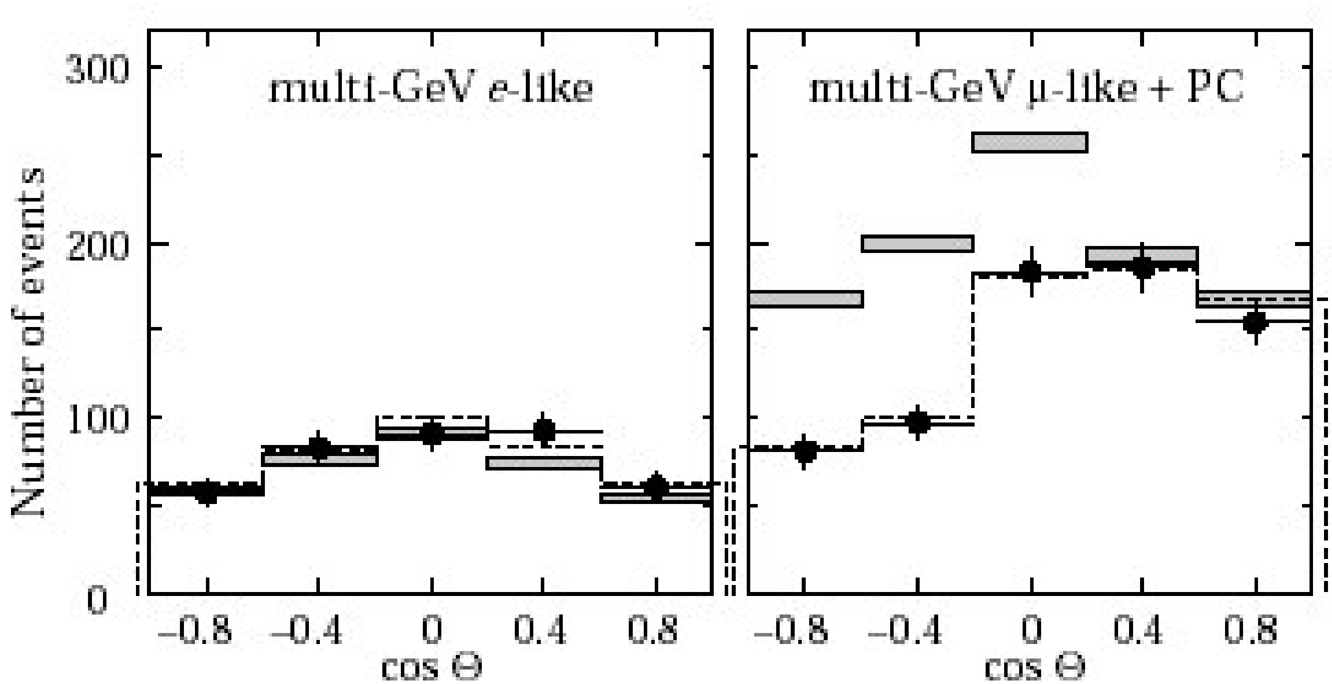
- Some new physics is coming into play?

(neutrino oscillations)



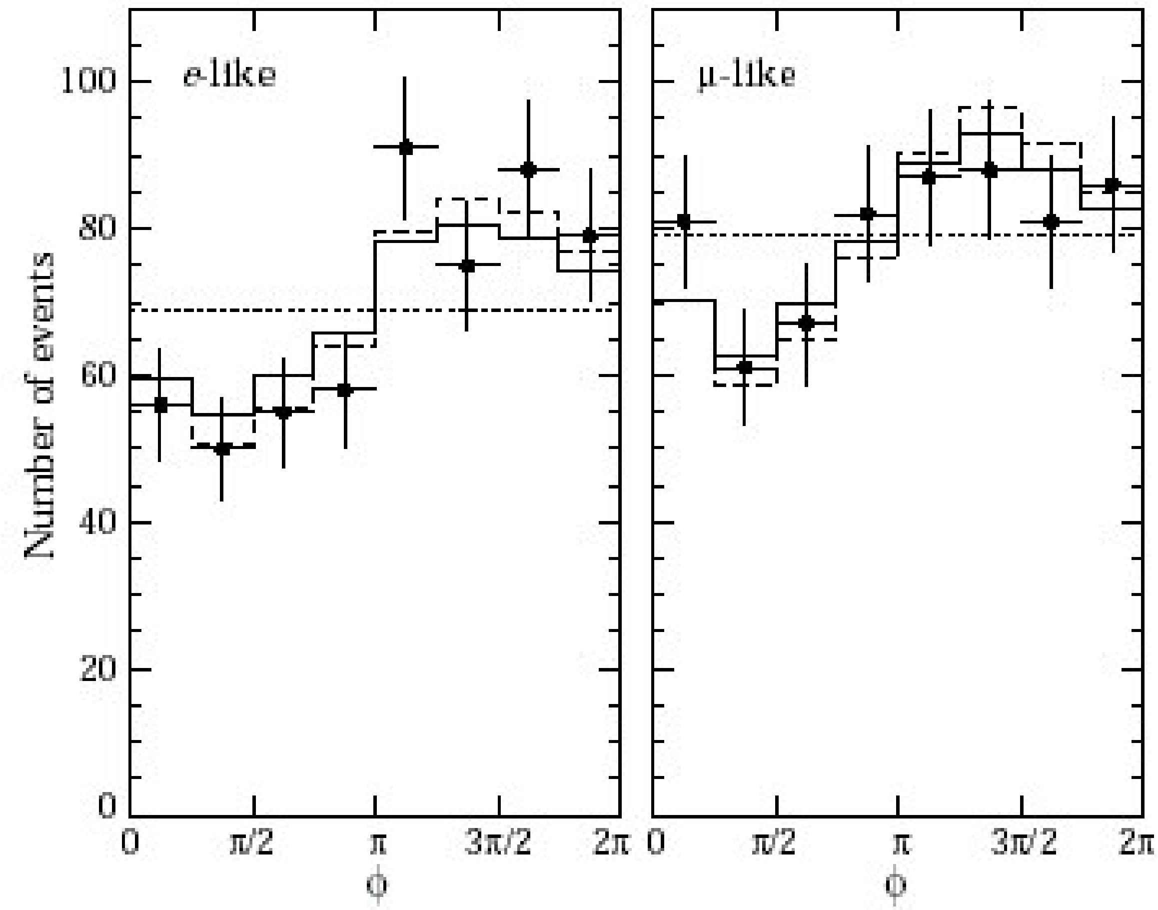
Neutrinos Underground (Zenith angle dependence)

- Evidence for neutrino oscillations ($\nu_1 \rightarrow \nu_2$)



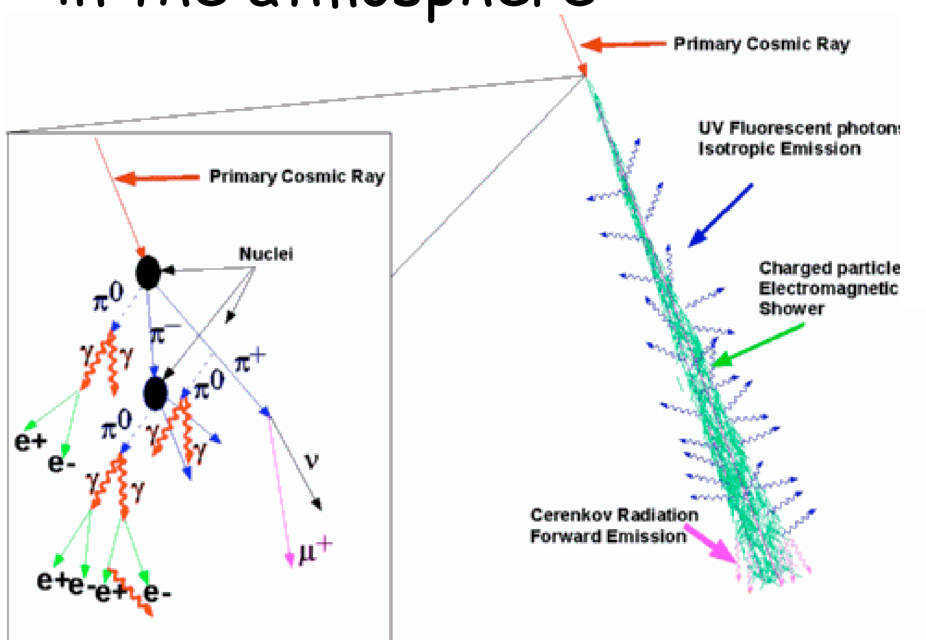
Shaded boxes show the expectation. The dashed lines show the expectation in the presence of derived oscillation parameters.

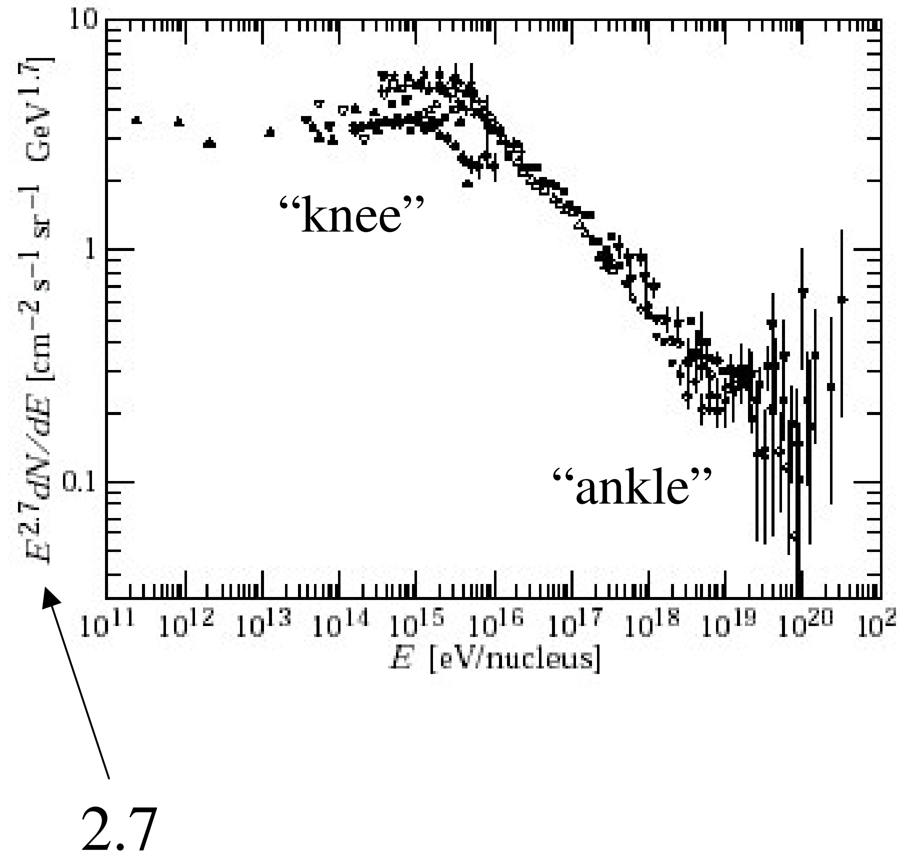
Neutrinos Underground



Air Showers

Very High Energy cosmic rays will produce air showers when they interact in the atmosphere



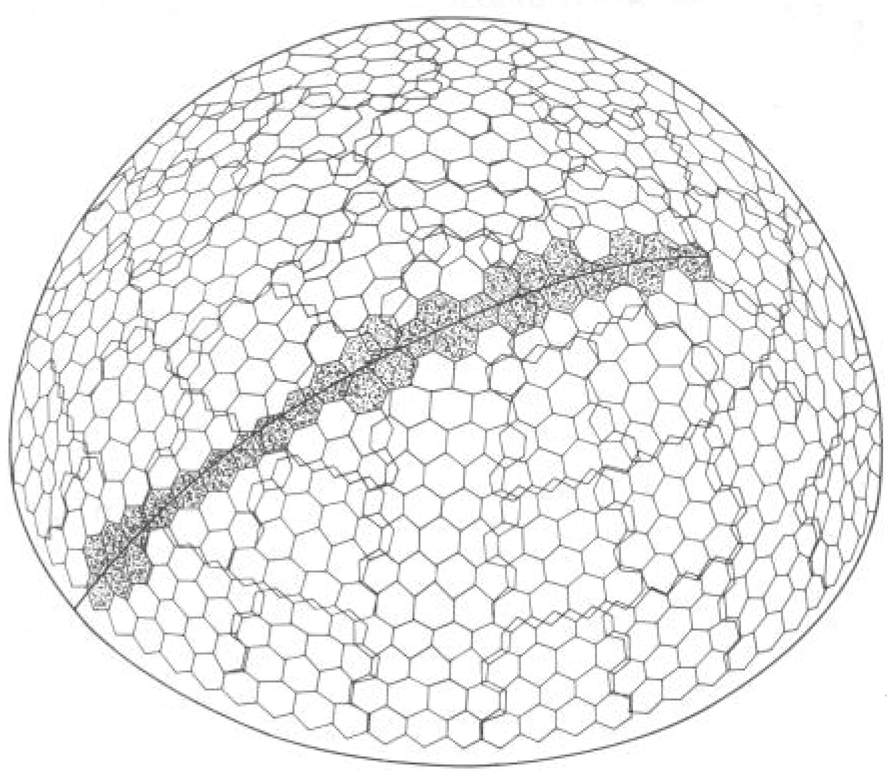


Air Showers

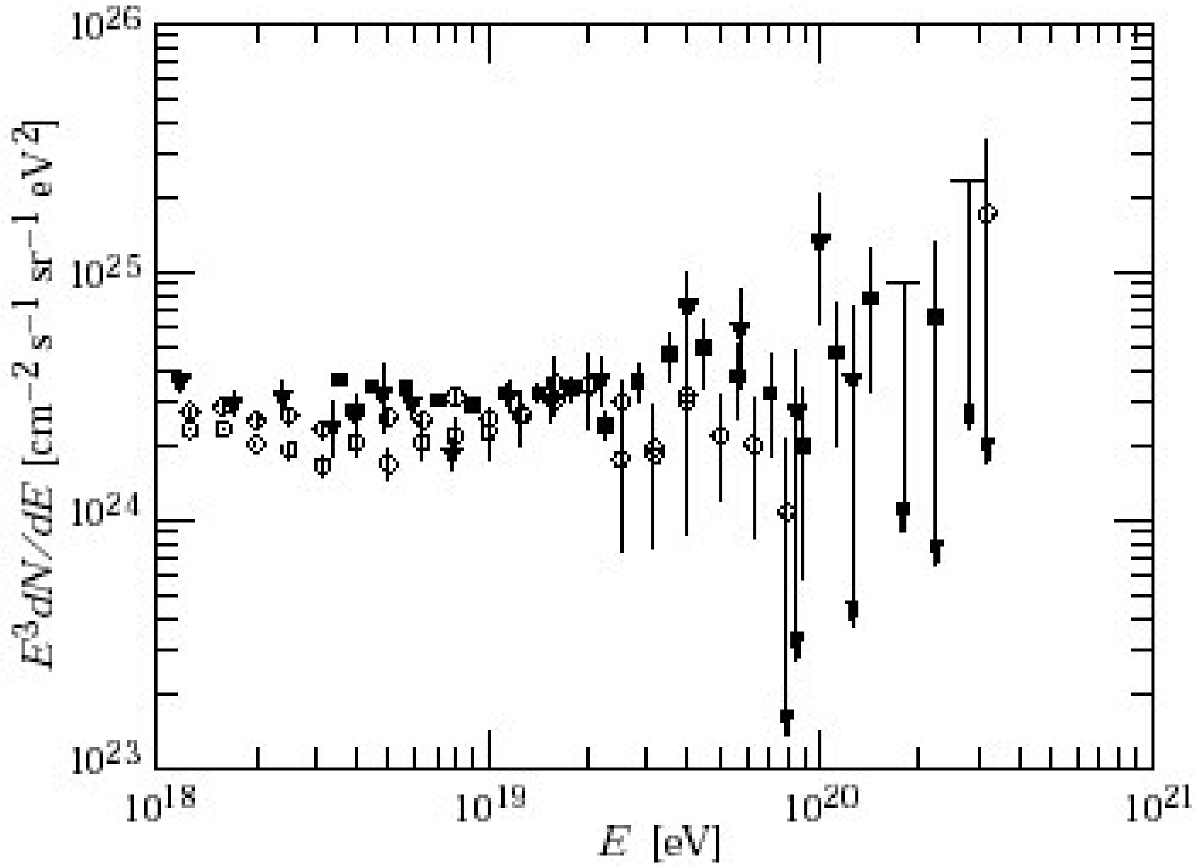
- High energy showers (say > 100 TeV) require arrays of detectors observing large areas
- eg. HiRes
  Fly's Eye

Air Showers

- Each detector monitors a different portion of the sky



Air Showers



10^{26}
10^{25}
10^{24}
10^{23}
$E^3 dN/dE$ [cm^{-2} s^{-1} sr^{-1} eV^2]
10^{18}
10^{19}
10^{20}
10^{21}
E [eV]

Lifetimes of cosmic rays

- The interstellar magnetic field is about 10^{-11} Tesla. The diameter of the Milky Way's disk is about 100,000 light-years. How high an energy cosmic ray will be trapped in this field?
- 10^5 ly = 10^5 (3×10^{10} cm/sec) ($\pi \times 10^7$ sec/yr)

  $= 10^{23}$ cm
- p (GeV/c) = 0.3 B(Tesla) ρ(meters) q

  $= 0.3\,(10^{-11})(5\times10^{22}) = 1.5 \times 10^{11}$ GeV/c

  $= 1.5 \times 10^{20}$ eV

Lifetimes of cosmic rays

- The cosmic rays can travel through roughly 5 gm/cm^2 before interacting
- The disk of the Milky Way has a density of about $1/cm^3 = 1.67 \times 10^{-24}$ gm/cm^3
- Therefore, the lifetime of cosmic rays trapped in the Milky Way is

$$t = 5 \; gm/cm^2 \quad / \quad N\,c$$

$$= 5 \,/\, (1.67 \times 10^{-24} \; 3 \times 10^{10}) \qquad \text{seconds}$$

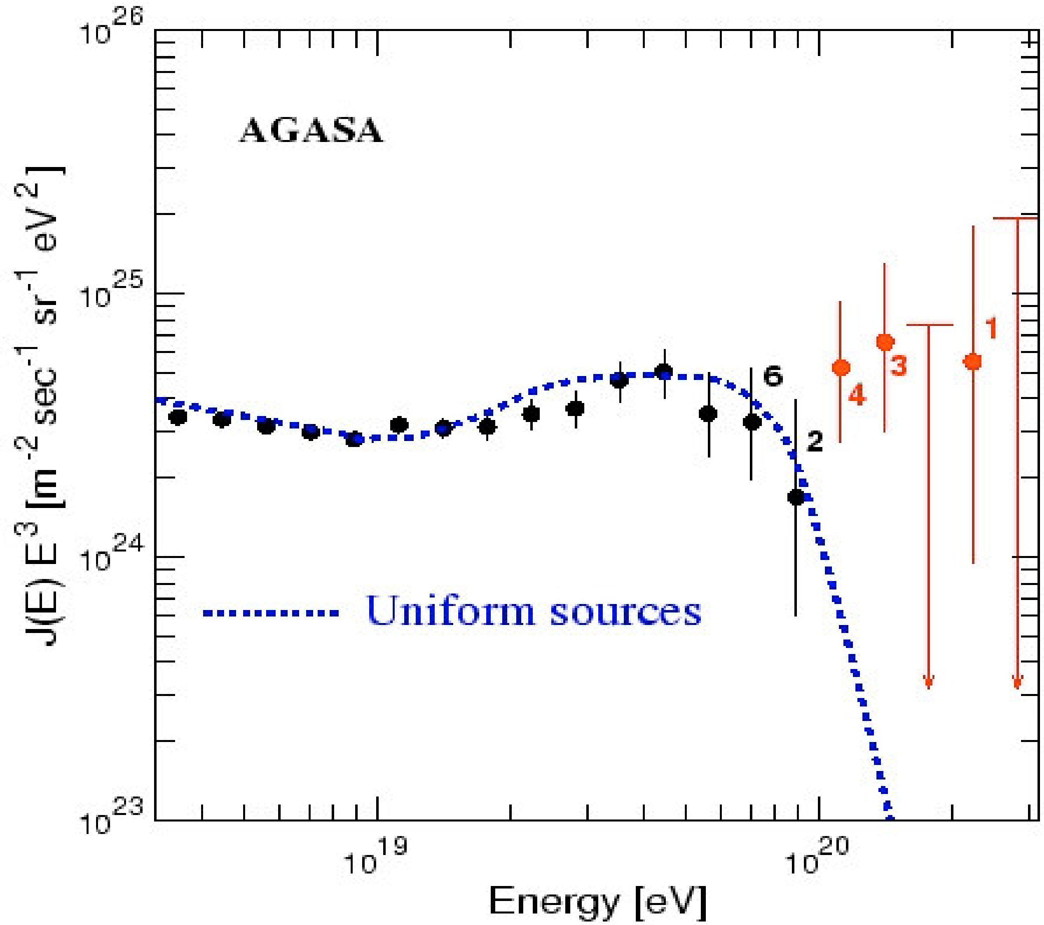
$$= 10^{14} \text{ seconds} = 3 \times 10^{6} \text{ years}$$

Interactions with the CMB

The CMB provides a source of collisions which cuts off high energy CRs

$$E_p \longrightarrow \qquad \longleftarrow E_\gamma$$

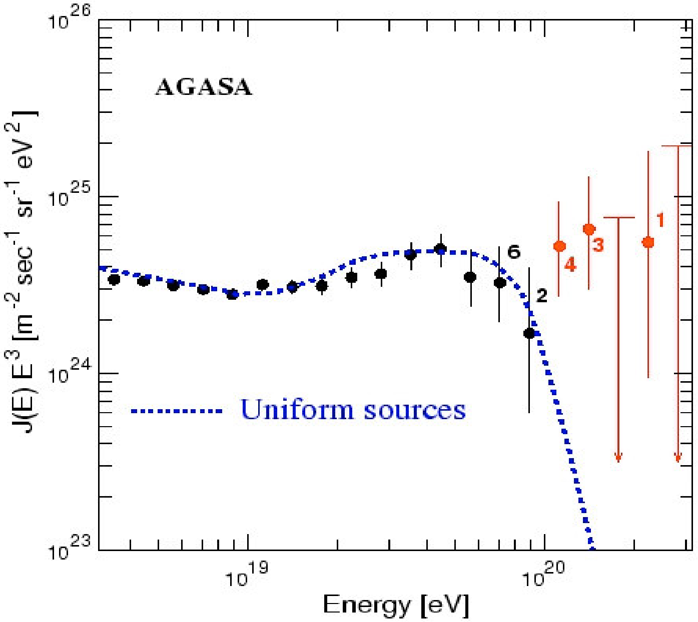
When the cosmic ray energy exceeds 10^{20} eV, pion production is possible, the cross section is large, and there is a cut-off



Interactions with the CMB

Existence of cosmic rays above Greisen-Zatsepin-Kuzmin limit suggest

- possibly propagation of exotic particle
- and/or decays of topological defects
- or ultra-massive relic particles



- <u>More data is needed</u>

Has the GZK cutoff been seen?

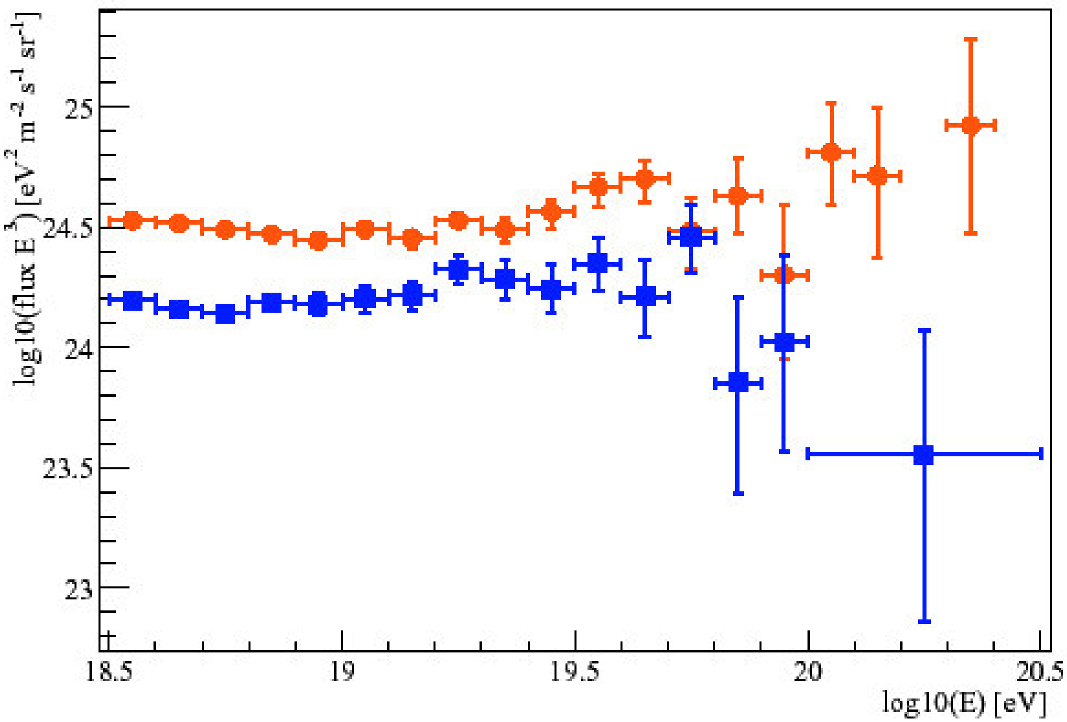


Fig. 5. Circles show the AGASA spectrum from [6] while squares show the HiResI spectrum from [9].

Demarco-2003

Propagation

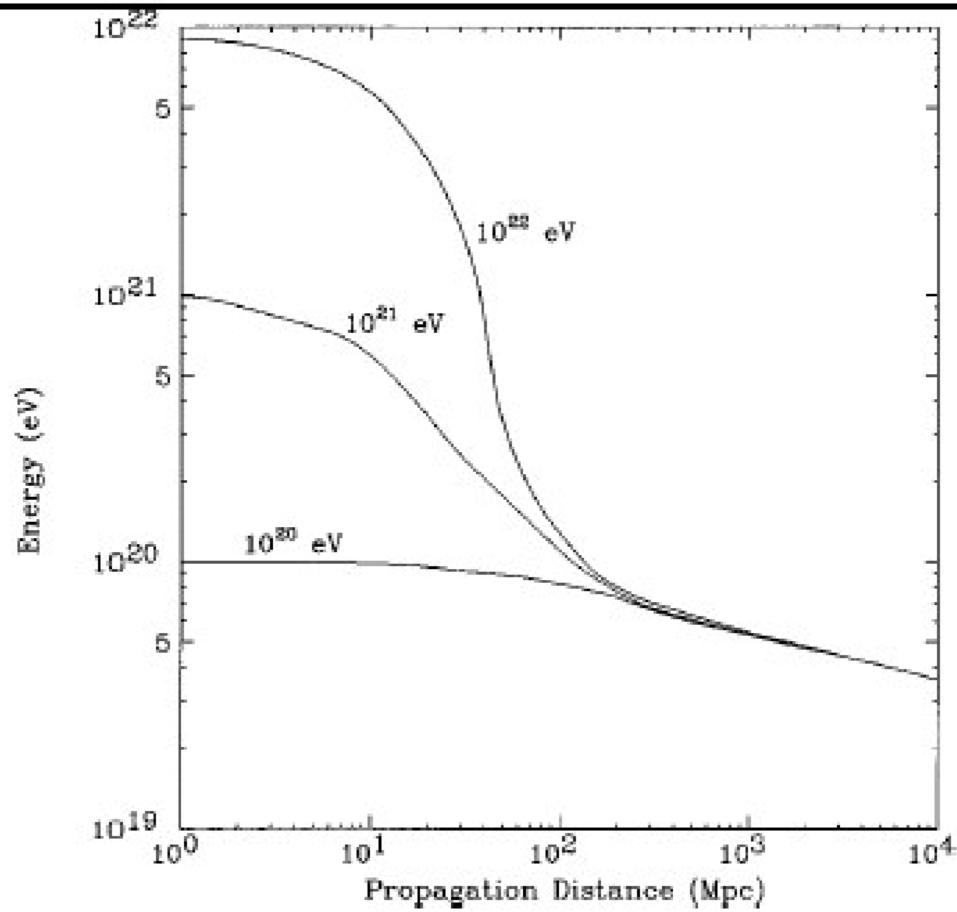


FIG. 4. Proton energy as a function of propagation distance through the 2.7-K cosmic background radiation for the indicated initial energies.

Cronin-1999

Particle Acceleration

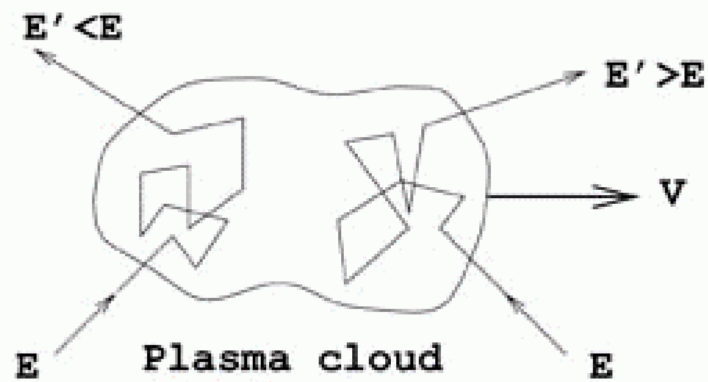
- Mechanism is an open question
- Conventional scenario:
  - all high energy charged particles are accelerated in magnetized astrophysical shocks, whose size and typical magnetic field strength determines the maximal achievable energy, similarly to man-made particle accelerators.
- Most likely astrophysical accelerators for cosmic rays up to the "knee," and possibly up to the "ankle"
  - shocks associated with remnants of past Galactic supernova explosions
- Extragalactic component
  - powerful objects such as active galactic nuclei are assumed

Particle Acceleration

Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

2nd order :
randomly distributed magnetic mirrors

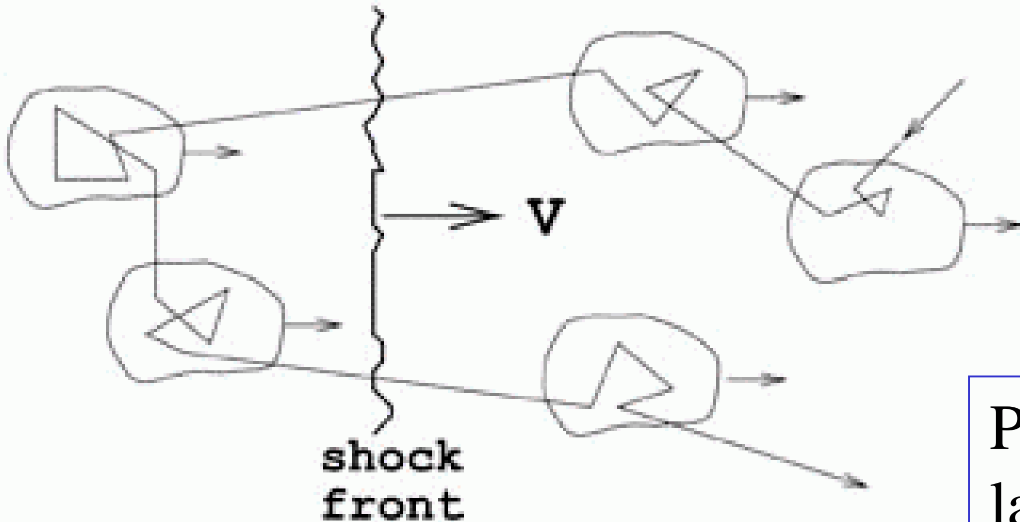


$$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$$

[Slow and inefficient]

Particle Acceleration

1st order :
acceleration in strong shock waves
(supernova ejecta, RG hot spots...)



$$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$$

Predicts power law:
$dN/dE \sim E^{-2}$

Curvature in B Field

- Curvature of a relativistic charged particle in a magnetic field
- Lorentz force: $\vec{F} = q\,\vec{v}/c \times \vec{B}$
- Motion: $d\vec{p}/dt = \vec{F}$
- Radius of curvature (ρ): $F_n = pv / \rho$

  so $q\,(v/c)\,B = pv / \rho$ or $\rho = cp/qB$

  $p\,(\mathrm{GeV}/c) = 0.3\,B(\mathrm{Tesla})\,\rho(\mathrm{meters})\,q$

Particle Acceleration

p (GeV/c) = 0.3 B(Tesla) ρ(meters) q

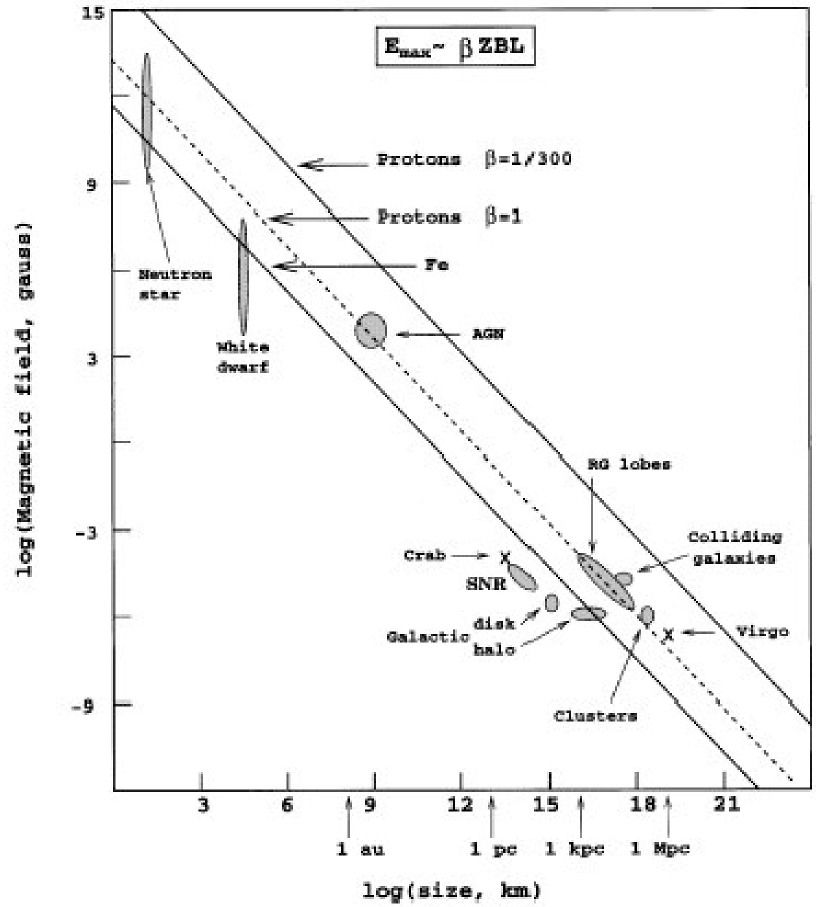
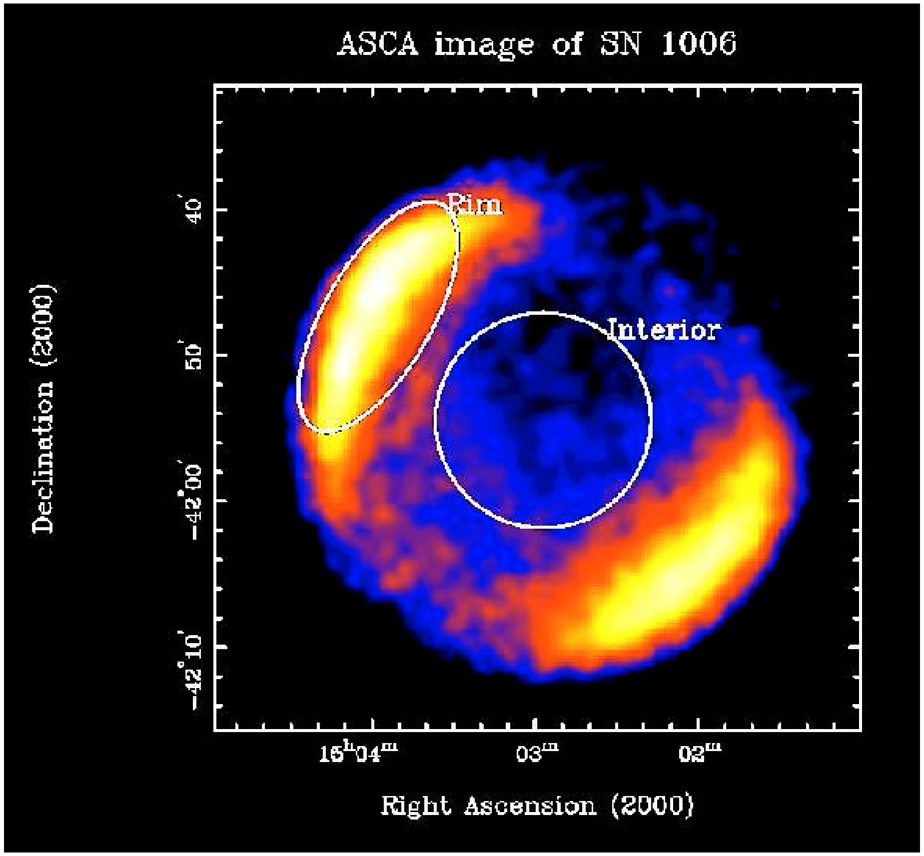


FIG. 3. Modified Hillas plot (Hillas, 1984). Size and magnetic field of possible sites of acceleration. Objects below the dashed line cannot accelerate protons to 10^{20} eV.

Cronin-1999

Source of UHE CRs

- Large, energetic structures, where shock waves are likely (eg. Supernovae, colliding galaxies, AGNs)
- SN 1006
  - non-thermal X-rays
- SNs can probably only go up to 10^{15} eV ("knee")



Source of UHE CRs

- Colliding Galaxies
- Active Galactic Nuclei