II : Transport

- Interactions of CMB, IR and optical gammas
- Electro-Magnetic showers
- Magnetic fields

Nucleons : GZK cutoff :

Photo pion productions in nucleon gamma (CMB) interactions.

Threshold in the CMB frame :

$$E_{th} \simeq \frac{E_\gamma^{lab} m_p}{2\epsilon} \sim 7 \times 10^{16} (\epsilon/eV)^{-1}\, eV$$

giving about 7×10^{19}eV for interactions with the CMB photons.

[Fig 2.1]

Other processes:

$$p + \gamma \longrightarrow p + e^+ e^-$$

lower threshold $E_{th} \sim 5 \times 10^{14} (\epsilon/eV)^{-1}\, eV$ but much smaller cross-section.

Interaction length :

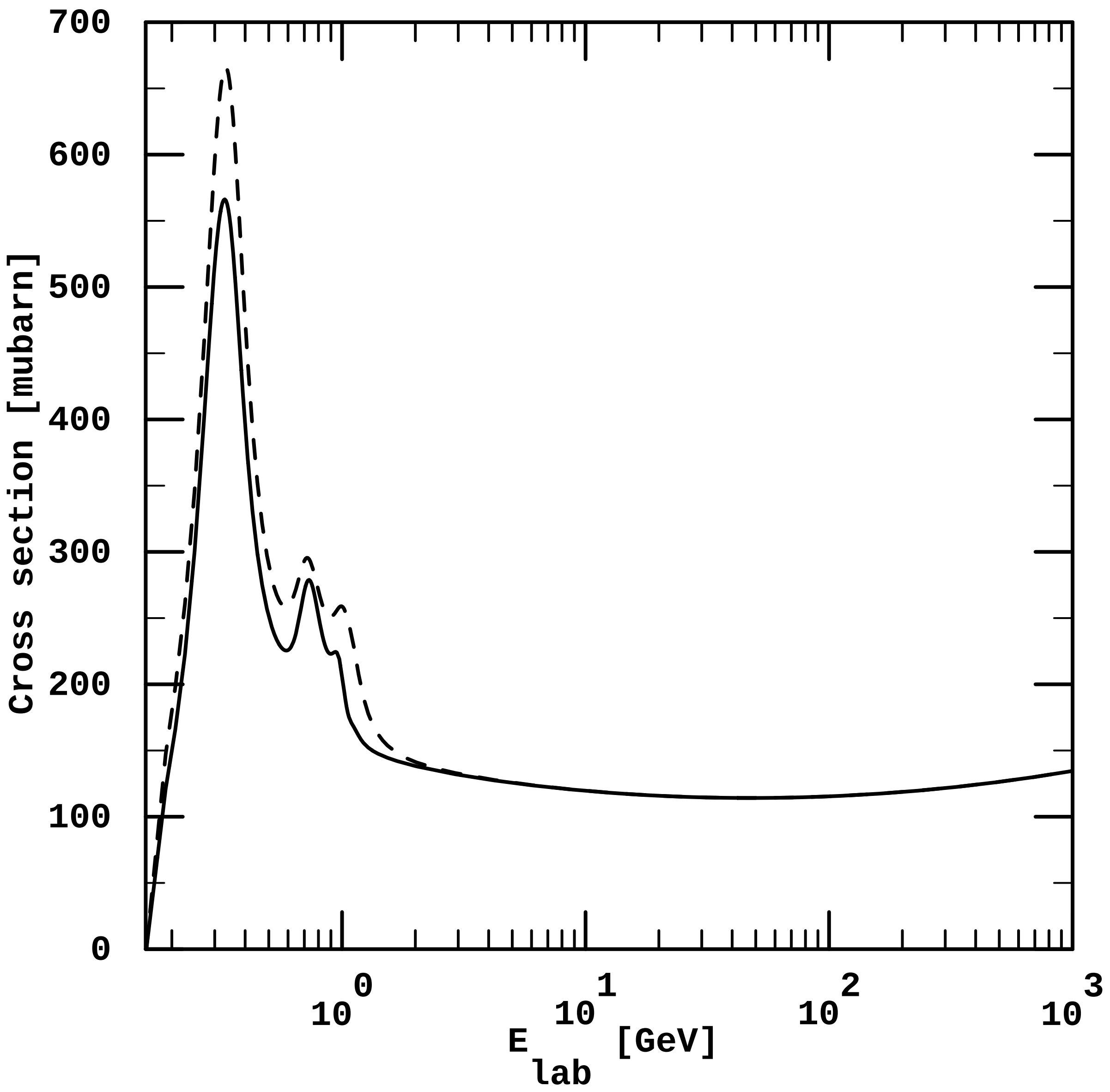
$$\sigma_{p+\gamma}^{N+\pi} \sim 130 \mu b \simeq 0.13 \times 10^{-27} cm^2$$

CMB density $\rho \sim 400/cm^3$ giving

$$L = (\sigma\rho)^{-1} \sim 2 \times 10^{25} cm \simeq 6 Mpc$$

[Fig 2.2]

Photo-production cross-section



Total pion-nucleon photo-production cross-section.

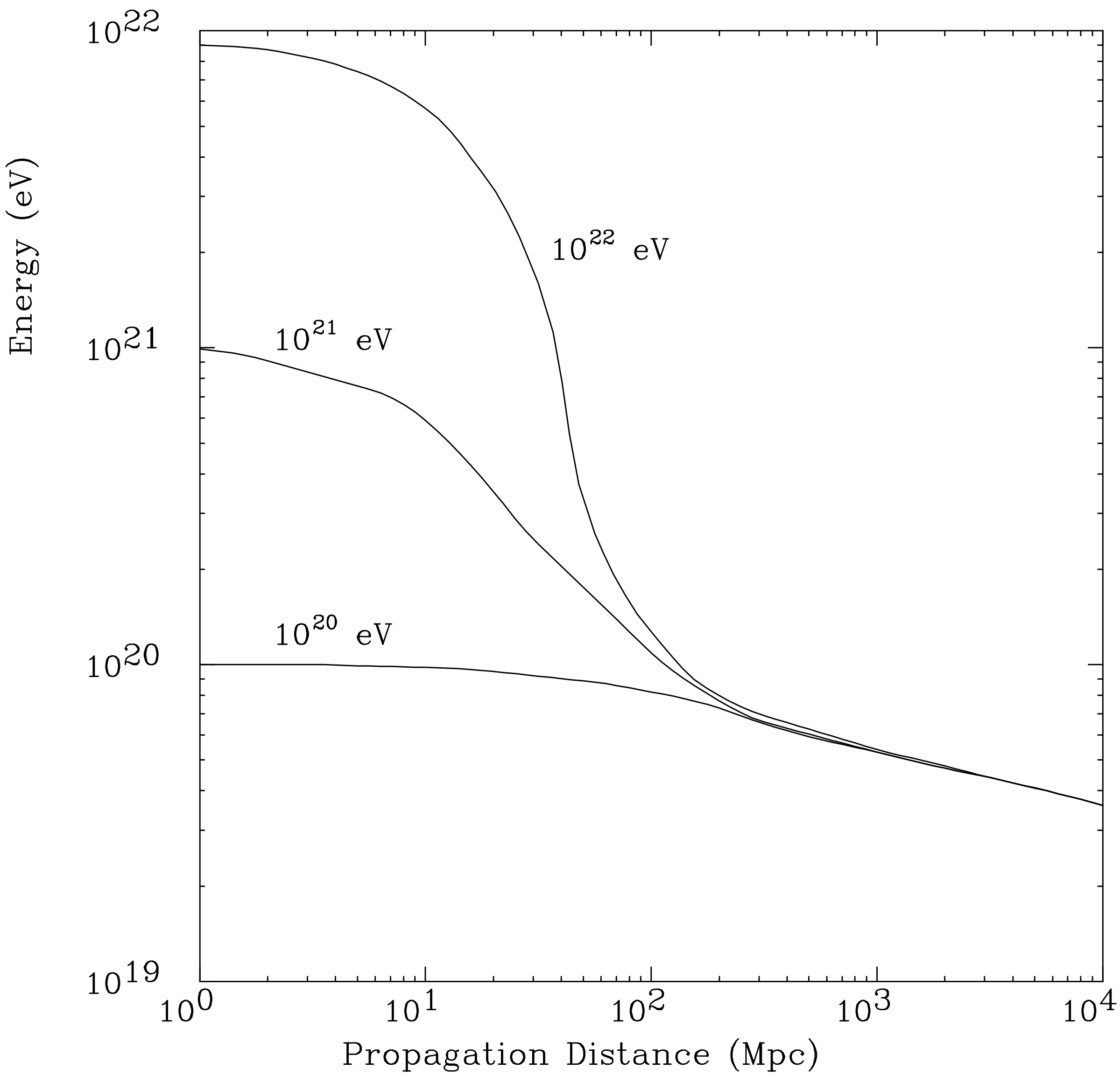
Solid line : protons

Dotted line : neutrons

Δ resonances are clearly visible.

[Fig 2.1]

GZK cut-off



Proton remaining energy as a function of distance from the production point. After 100 Mpc the energy falls below 10^{20}eV regardless of the initial energy.

[Fig 2.2]

Transport (cont.)

photons :

Pair production:

$$\gamma\gamma \longrightarrow e^+e^-$$

Targets are CMB or infra-red (IR) photons and at very high energies the universal radio background (URB). IR and URB densities are not very well known.

Threshold on the CMB : $E_{th} \sim 2.5 \times 10^{14} eV$

[Fig 2.3]

Remarks :

As attenuation lengths strongly depend on the energy, the observed spectra depend a lot on the sources spatial distribution.

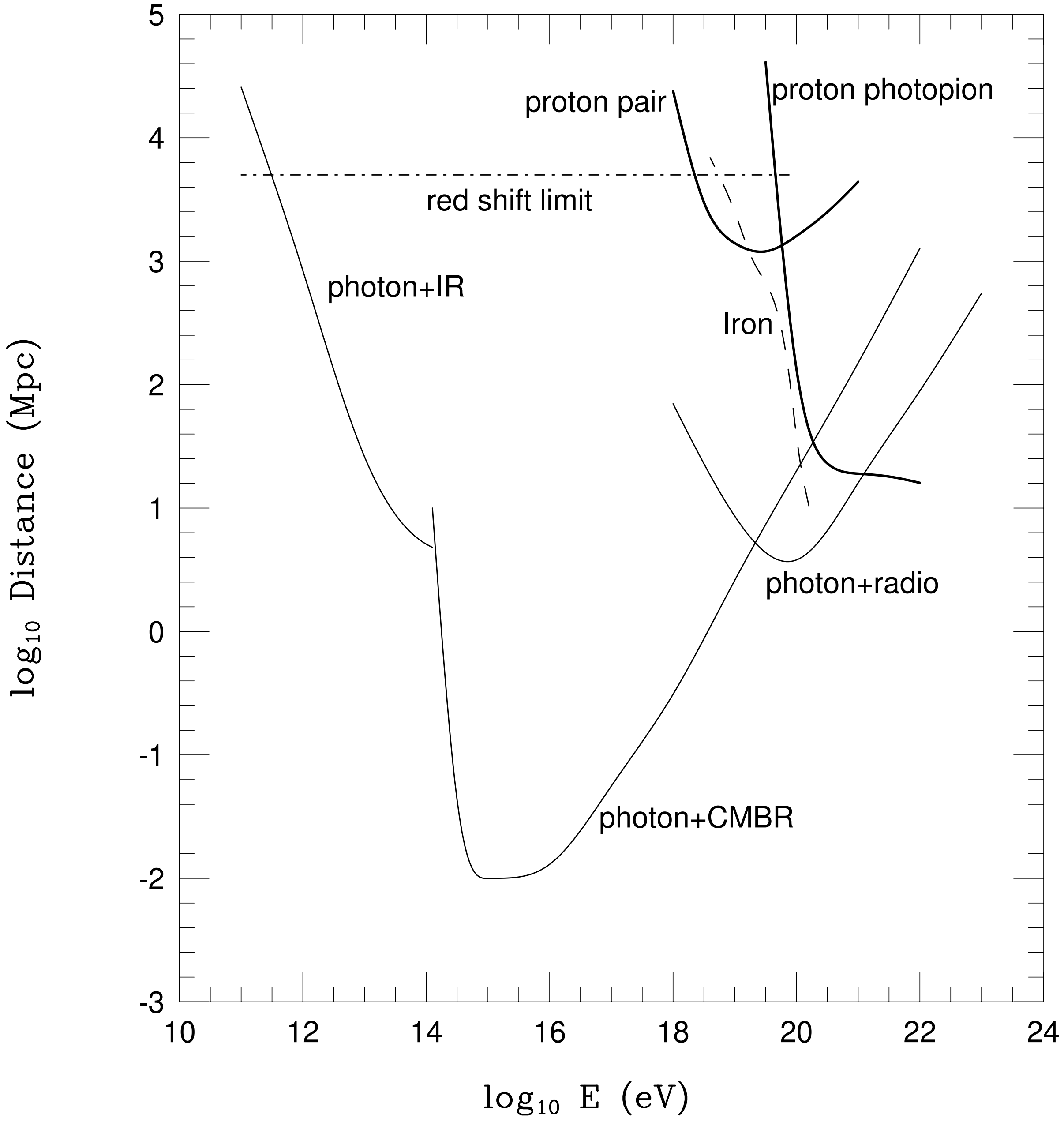
[Fig 2.4]

Electro-magnetic showers :

- Some UHECR production models (Top-Down) predict that gamma rays dominate at the source.
- Gamma rays and e^+e^- are also secondaries of photo-production products.

One must study the evolution of gamma rays on their way from the source to the observer.

Attenuation Lengths

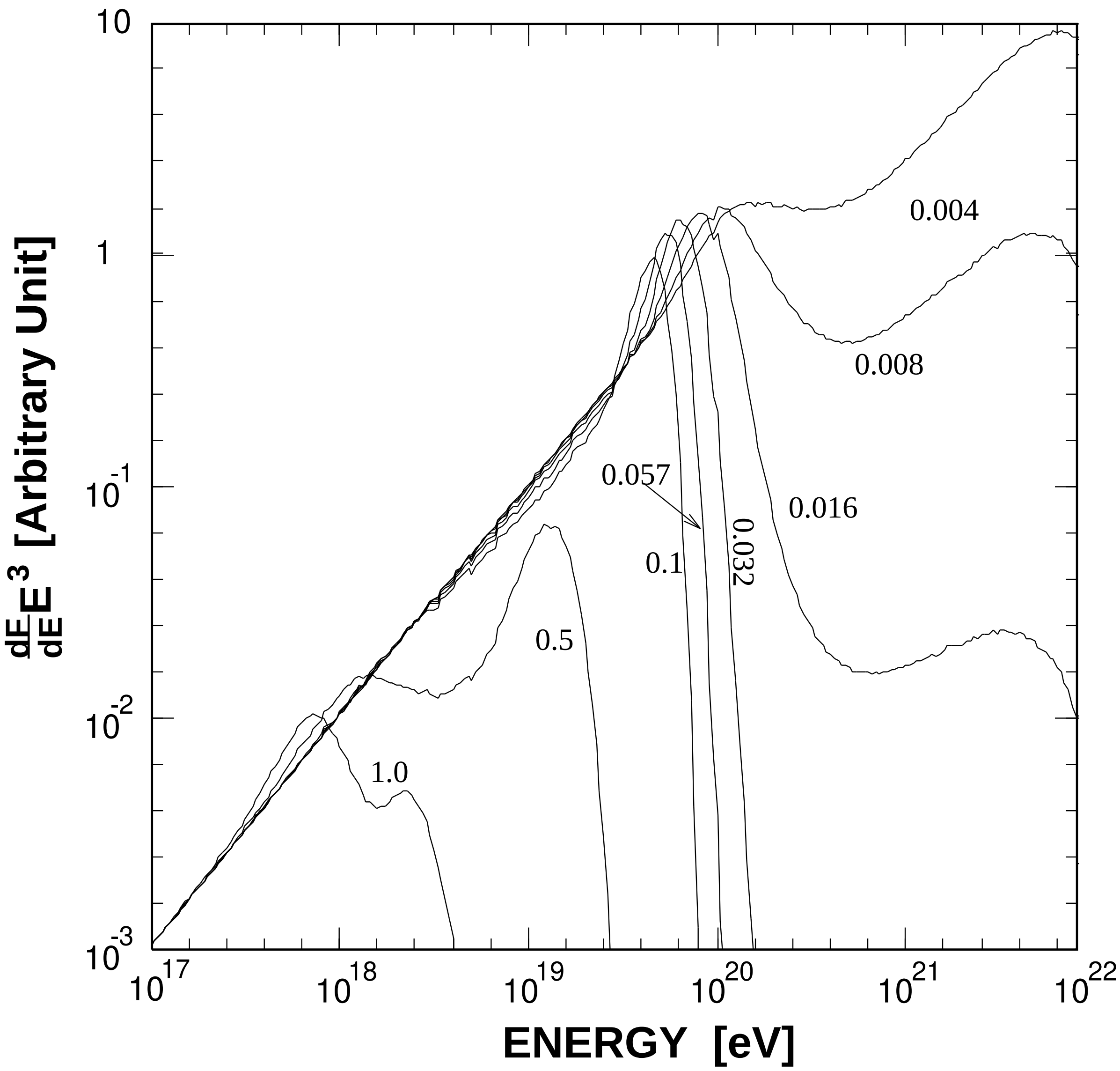


Photons, protons and Iron nuclei interaction length for different radiation backgrounds.

The red-shift limit corresponds to an interaction length equal to the radius of the Universe.

[Fig 2.3]

Spectra deformations



Observed spectra as a function of observed distance from the source (in units of z). The injection spectra is a power law : $dN/dE \propto E^{-2}$.

[Fig 2.4]

Two processes dominate :

- PP : e^+e^- pair production during photon-photon collisions
- ICS : Inverse Compton scattering, (electron scattering of a photon)

No threshold for ICS, PP threshold (as before)

$\sim m_e^2/\epsilon = 2.5 \times 10^{11}(\epsilon/eV)^{-1}\, eV$

At very high energies ($s \gg m_e^2$)

$$\sigma_{pp} \sim 2\sigma_{ICS} = \frac{3}{2}\sigma_T \frac{m_e^2}{s} log\left(\frac{s}{2m_e^2}\right)$$

decreasing with s (therefore E)

$\longrightarrow$ far from threshold shower grow slowly.

$\sigma_T = \frac{8\pi}{3}\frac{\alpha^2}{m_e^2}$ Thomson Xsection for photon diffusion on electron at rest [0.6 b].

For $s \sim m_e^2$ one has

$$\sigma_{ICS} \sim \sigma_T \text{ and } \sigma_{PP} \text{ is resonant}$$

$\longrightarrow$ at threshold shower are growing fast.

At 10^{20}eV the threshold corresponds to $10^{-6}\, eV \simeq 100$MHz (URB).

(Gammas of 10^{20} eV are URB probes)

Consequences : The photon energy gets degraded down to the lowest threshold of pair production given the various cosmological photon spectra, i.e. the threshold on Optical/IR photons. Photons pile up below $E_\gamma = 100\ GeV$ with a power law spectrum. ($dN/dE \propto E^{-1.5}$)

The diffuse astronomical background of gamma rays between 0.1 and 100 GeV as measured by EGRET put constraints on the production models of UHECR with large gamma production.

Magnetic fields

Magnetic fields modify E.M. shower developments and charged particles trajectories.

1 Shower developments, synchrotron radiation of e^+e^- pair :

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T \frac{B^2}{8\pi}\left(\frac{qm_e}{M}\right)^4 \left(\frac{E}{m_e}\right)^4$$

Dominant process for e^+e^- pair above :

$$E_{th} \sim 10^{20}\left(\frac{B}{10^{-10}G}\right)^{-1}$$

Consequently at those energy, observed photons must be primaries and their flux is given by :

$$j_\gamma(E) = \frac{1}{4\pi} l(E)\phi(E)$$

Gammas from the synchrotron radiation have a mean energy of

$$E_{synch} = 6.3 \times 10^{13}\left(\frac{E_e}{10^{21}eV}\right)\left(\frac{B}{10^{-9}G}\right) eV$$

Again constraints on the flux of diffuse gamma rays may be applied (EGRET $\sim$ 1-100 GeV, HEGRA $\sim$ 50-100TeV, CASA-MIA $\sim$ 0.6-60 PeV)

2 Bending and delay of hadrons :

RMS of deflection angle :

$$\theta \simeq 0.5^o Z \left(\frac{E}{10^{20} eV}\right)^{-1} \left(\frac{d}{10Mpc}\right)^{1/2} \left(\frac{l_c}{1Mpc}\right)^{1/2} \left(\frac{B}{10^{-9}G}\right)$$

where l_c is the coherence length and d the range. This formula gives a few degrees for $d \sim 100$ Mpc. Since $l(E = 10^{20} eV) \sim 10Mpc$ one can do astronomy with UHECR.

[Fig 2.5]

Time delays:

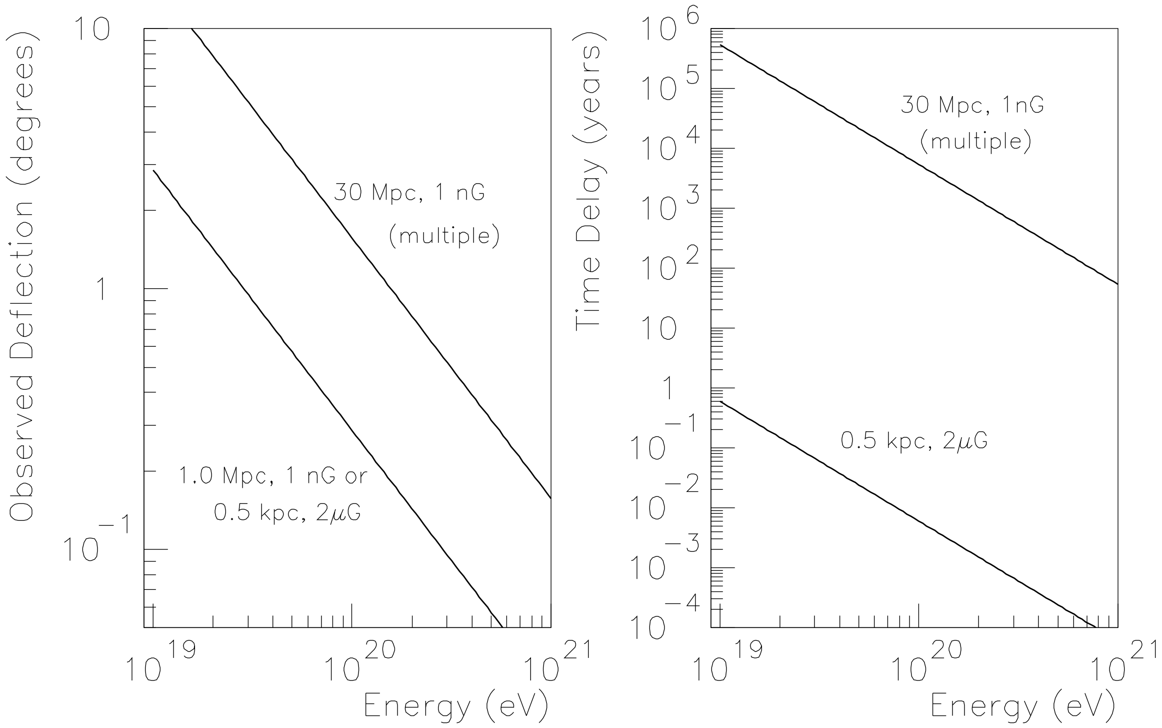
$$\tau \simeq 0.6Z^2 \left(\frac{d}{10Mpc}\right)^2 \left(\frac{l_c}{1Mpc}\right) \left(\frac{B}{10^{-9}G}\right)^2 \left(\frac{E}{10^{20}eV}\right)^{-2} 10^3 yr$$

Assuming that a pair of CR come from the same source one can derive informations about the magnetic filed with those variables.

Examples :

- $E >$10^{20}eV $\quad \delta\theta \sim 2.1^o \quad (\sqrt{50} \times 0.3^o)$
  Auger (2 sites x 3 years) = 180 RC, 2.1^o of angular resolution gives 20 accidental doublets, 3.5^o gives 70.
- $E >$ $4\times$10^{19}eV $\quad \delta\theta \sim 10^o \quad (\sqrt{200} \times 0.7^o)$
  Auger (2 sites x 3 years) = 1000RC. [Fig 2.6]
- $E >$10^{19}eV, Auger (2 sites x 3 years) = 18000 RC but $\delta\theta \sim 90^o \quad (L \sim 4Gpc)$. Galactic Iron sources could be visible.

Magnetic bending



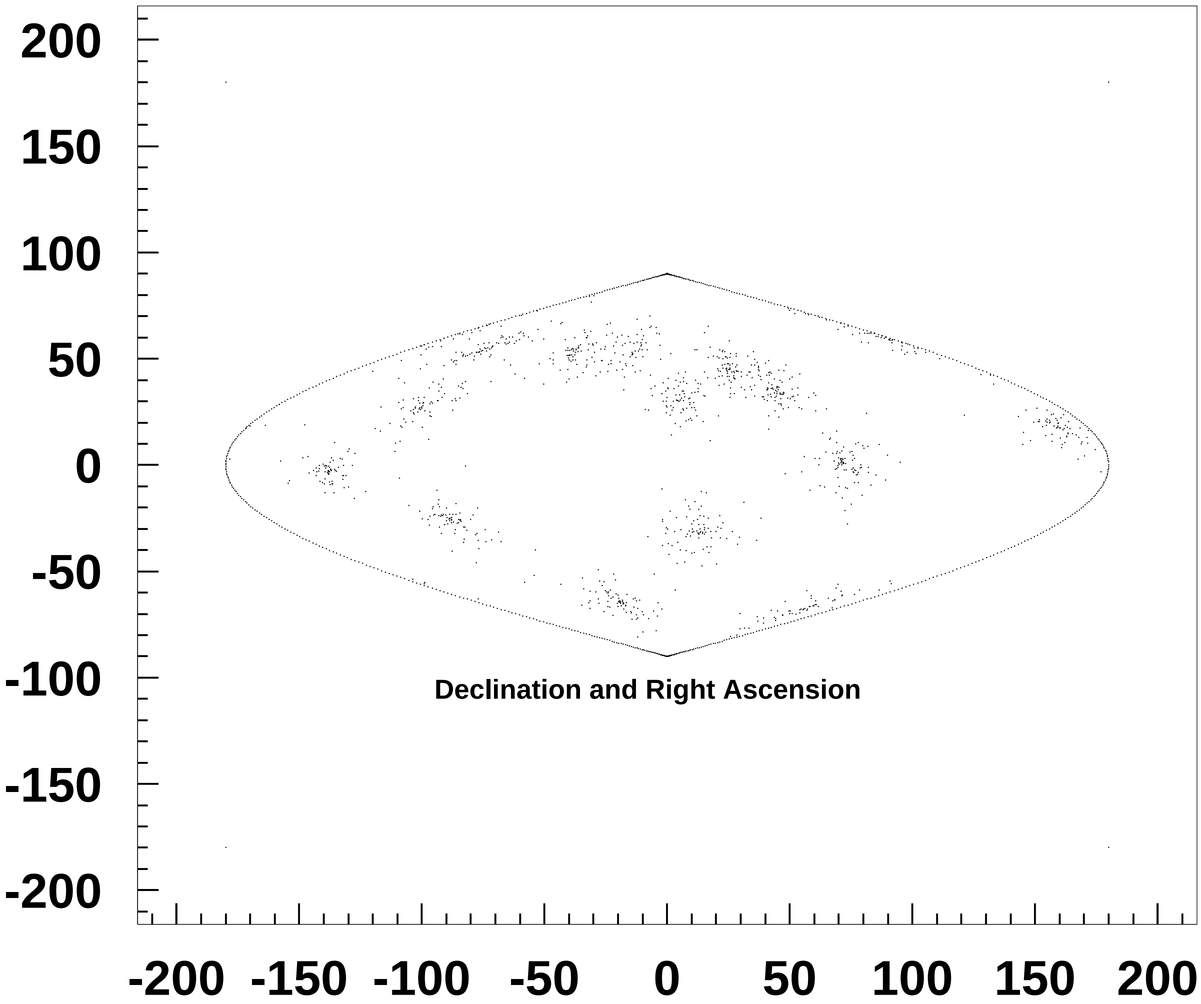
Protons.

Left trajectories of 0.5 kpc in the galactic disk or of 1 Mpc in the inter-galactic medium and random walk of 30 Mpc (coherence length 1 Mpc).

Right : Time delay in the same conditions.

[Fig 2.5]

Auger's sky



Sky above $4{\times}10^{19}$eV .

Conditions : 3 years of data (1165 events) with 15 sources of equal intensities randomly distributed, $\delta\theta \sim 10^o$.

[Fig 2.6]