Cosmic absorption of high energy particles

Gregory Vereshchagin
(joint work with S. Batebi, S. Tizchang, S. Shakeri,
R. Ruffini, S.-S. Xue)

ICRANet

Adriatic Workshop, Pescara

Outline

- Brief overview of UHE observations
- Sources of high energy particles
- Interactions of UHE particles with cosmic backgrounds
- Cosmic horizion of UHE photons, protons and neutrinos
- The photon-photon scattering
- Conclusions

Cosmic rays

Fluxes of Cosmic Rays
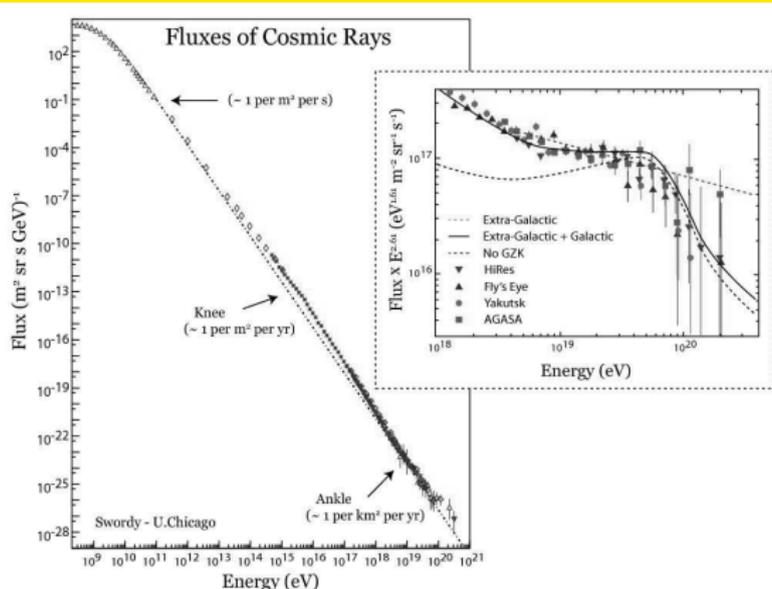
Cosmic rays were discovered in the beginning of the 20th century and studied by Theodor Wulf (first detected), Victor Hess (measured at high altitude in a baloon flight, Nobel prize 1936), Robert Millikan (proved that CR are of extraterrestrial origin, and coined the name "cosmic rays") and Bruno Rossi (proved that most primary CR are positively charged).

Origin of high energy, protons, photons and neutrions

CR composition is: 90 per cent protons, 9 per cent alpha particles, less than 1 per cent in heavier nuclei.

Cosmic rays with energies below 10^{15} eV are considered to originate within our Galaxy in supernova remnants. CR with greater energies are considered to have extragalactic origin. Many possible sources are suggested, including NS-QS transitions, AGNs, radio lobes of powerful radio galaxies, relativistic supernovae, GRBs, dark matter decays...

Sources of high energy CR produce also secondary particles such as photons, neutrinos, electron-positron pairs, muons etc. Only protons (nuclei), photons and neutrinos propagate on cosmological distances.

Highest energy protons, photons and neutrions detected up to date

Observatories of CR: AGASA, HiRes, Pierre Auger Observatory, Telescope Array Project.
Cherenkov observatories of photons: CTA, GT-48, MAGIC, HESS, VERITAS
Neutrino observatories: IceCube, KM3NeT.
Results:

- The Oh-My-God particle (most likely a proton) was detected in 1991 with the energy 3×10^{20} eV.
- Blazar Mrk 501 has so far produced the highest measured energy for a gamma ray of 16 TeV.
- Photons from GRBs have energies up to 100 GeV.
- 28 neutrino events ranging in energy from 30 to 1200 TeV (IceCube).

Processes involving photons

The Breit-Wheeler process (1934) for the photon-photon pair production

$$\gamma_1 + \gamma_2 \longrightarrow e^+ + e^-$$
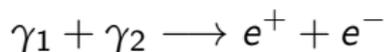
with the cross section

$$\sigma_{\gamma\gamma} = \frac{\pi}{2} \left(\frac{\alpha \hbar}{m_e c} \right)^2 (1 - \beta^2) \left[2\beta(\beta^2 - 2) + (3 - \beta^4) \ln \left(\frac{1 + \beta}{1 - \beta} \right) \right],$$

where

$$\beta = \sqrt{1 - \frac{1}{x}}, \quad x = \frac{E\mathcal{E}}{(m_e c^2)^2}.$$

The characteristic energy of UHE photons interacting with CMB, having temperature today $T_0 \approx 2.725$ K, is given by $E_{BW} = (m_e c^2)/kT_0 \simeq 1.11$ PeV.

- Double pair production process

$$\gamma_1 + \gamma_2 \to e^+ + e^- + e^+ + e^-$$
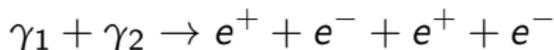
with the cross section at high energies

$$\sigma_{dpp} = \frac{\alpha^2}{36\pi} \left(\frac{\alpha \hbar}{m_e c} \right)^2 [175\zeta(3) - 38] \sim 6.5 \mu b.$$

Processes involving protons

- The pion photoproducton process

$$p + \gamma \longrightarrow \left(\begin{array}{c} p \\ n \end{array} \right) + \pi.$$
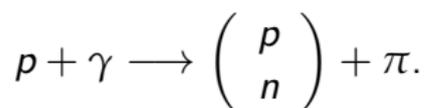
It occurs via production of a resonance e.g.
$p + \gamma \longrightarrow \Delta^+ \longrightarrow p + \pi^0 \longrightarrow p + 2\gamma$ and at high energies has a cross section

$$\sigma_{p\gamma} \simeq 120 \mu b,$$

and the characteristic energy $E_{p\gamma} = 4(m_\pi c^2)^2 / kT_0 \simeq 3 \times 10^5 E_{BW}$.

- The Bethe-Heitler process (1934)

$$p + \gamma \longrightarrow p + e^+ + e^-,$$
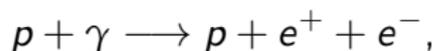
the cross-section is logarithmically increasing above the threshold, and has a characteristic value $\sigma_{BH} \simeq (28/9)\alpha \left[(\alpha \hbar)/(m_e c) \right]^2$. It has the characteristic energy $E_{BH} = m_e m_p c^4 / (2kT_0) \simeq 1$ EeV.

Processes involving neutrinos

The resonant neutrino annihilation occurs in the s-channel:

$$\nu + \bar{\nu} \longrightarrow Z^0 \longrightarrow f + \bar{f},$$

It has a typical Breit-Wigner shape

$$\sigma_{\nu\bar{\nu}}^R \simeq 4\sqrt{2}G_F \frac{m_\nu M_Z^2 \sqrt{\bar{\varsigma}}E}{(M_Z^2 - 2Em_\nu)^2 + 4E^2 m_\nu^2 \bar{\varsigma}} \mathrm{GeV}^{-2},$$

The characteristic energy $E_r = M_Z^2 c^2 / 2m_\nu \simeq 5.2 \times 10^{22} \, (m_\nu/0.08 \text{ eV})$ eV. The amplitude of the resonance $\sigma_{\nu\bar{\nu}}^{R\,\mathrm{max}} = 2\sqrt{2}G_F M_Z/\Gamma \simeq 0.471 \mu b$. The non-resonant cross-section is adopted as

$$\sigma_{\nu\bar{\nu}}^{NR} = \frac{8.3 \times 10^{-4}}{1 + (E/E_r)^{-1}} \mu b.$$

Propagation of high energy particles on large distances

As soon as cosmic microwave background has been detected, and even earlier(Nikishov 1961!), it became clear that CMB imposes limits the distance that high energy particle can travel:

- protons (and cosmic rays): Greisen (1966) Zatsepin and Kuzmin (1966)
- photons: Nikishov (1961), Gould and Schreder (1967)
- neutrinos: (scattering on cosmic neutrino background): Berezinsky (1992).

The optical depth and the mean free path

The optical depth along the light-like world line

$$\tau = \int_{\mathcal{L}} \sigma j_{\mu} dx^{\mu}.$$

Both backrounds have thermal distribution functions

$$f(\mathcal{E}/kT) = \frac{1}{e^{(\mathcal{E}-\mu)/kT} \pm 1}.$$

Then the optical depth is

$$\tau(E, t) = \frac{g_s}{2\pi^2 \hbar^3 c^3} \int_t^0 cdt' \int_{\mathcal{E}_{thr}}^{\infty} \mathcal{E}^2 d\mathcal{E} f(\mathcal{E}) \sigma(E, \mathcal{E}, t'),$$

where $\mathcal{E}_{thr}$ is threshold energy in a given process, $g_s = 2$ is the number of helicity states.

The integral over time is transformed to the integral over redshift

$$\int_t^0 c\,dt' \longrightarrow \frac{c}{H_0} \int_0^z \frac{dz'}{(1+z')\,H(z')},$$
$$H(z) = [\Omega_r(1+z)^4 + \Omega_M(1+z)^3 + \Omega_\Lambda]^{1/2}.$$

Cosmic expansion gives

$$T = (1+z)\,T_0, \quad \mathcal{E} = (1+z)\mathcal{E}_0, \quad E = (1+z)E_0,$$

where temperature $T_{0,\gamma} \simeq 2.725$ K, $T_{0,\nu} = (4/11)^{1/3} \simeq 1.95$ K.

The mean energy loss distance

The mean energy loss distance is

$$\tilde{\lambda}^{-1} = \left(\frac{1}{E} \frac{dE}{cdt} \right).$$

The quantity similar to the optical depth

$$\tilde{\tau} = \int_t^0 \frac{cdt}{\tilde{\lambda}} = \frac{c}{H_0} \int_0^z \tilde{\lambda}^{-1} \frac{dz'}{(1+z') H(z')}.$$

Cosmic horizion of UHE photons

When one considers all possible orientations of CMB photons w.r.t. the high energy photon additional averaging over their angular distribution has to be performed (Nikishov 1961); it results in an averaged cross section

$$\bar{\sigma}_{\gamma\gamma}(x) = \frac{3}{2}\sigma_T \Sigma(x), \qquad \Sigma(x) = \frac{1}{x^2}\left[\left(x + \frac{1}{2}\log x - \frac{1}{6} + \frac{1}{2x}\right) \times\right.$$
$$\left. \times \log\left(\sqrt{x} + \sqrt{x-1}\right) - \left(x + \frac{4}{9} - \frac{1}{9x}\right)\sqrt{1 - \frac{1}{x}}\right].$$

We change variables to

$$y = y_0(1+z)^2; \quad y_0 = \frac{E_0}{E_{BW}} = \frac{E_0}{m_e c^2}\frac{kT_0}{m_e c^2}.$$

The result is

$$\tau_{\gamma\gamma}(E_0, z) = \frac{A}{y_0^3} \int_0^z \frac{1}{(1+z')^4} \frac{dz'}{H(z')} \int_1^\infty \frac{x^2 dx}{\exp(x/y)-1} \Sigma(x),$$

where

$$A = \frac{4\alpha^2}{\pi} \frac{c}{H_0} \left(\frac{\hbar}{mc}\right)^{-1} \left(\frac{kT_0}{m_e c^2}\right)^3 \approx 2.37 \times 10^6.$$

In the low energy $E \ll E_{BW}$ and high redshift $z \gg 1$ limit the integral over x can be evaluated analytically. The redshift corresponding to the mean free path in this limit is

$$z_{\lambda, BW} \simeq 0.21 \left(\frac{E}{E_{BW}}\right)^{-1/2}.$$

The mean energy loss of UHE protons

The mean energy loss distance for protons interacting via the Bethe-Heitler process

$$\tilde{\tau} = \frac{D}{y_0^3} \int_0^z \frac{dz'}{(1+z')^4 \, H(z')} \int_2^\infty \frac{d\bar{x}}{\exp(\frac{\bar{x}}{\bar{y}}) - 1} \phi\left(\bar{x}\right),$$

where the function $\phi\left(\bar{x}\right)$ is given in Blumenthal (1970)

$$\phi\left(\bar{x}\right) = \bar{x} \left[-86.07 + 50.95 \log \bar{x} - 14.45 \left(\log \bar{x}\right)^2 + 2.667 \left(\log \bar{x}\right)^3 \right]$$

and

$$D = \frac{2}{\pi^2} \alpha^3 \frac{m_e}{m_p} \frac{c}{H_0} \left(\frac{\hbar}{m \, c}\right)^{-1} \left(\frac{kT_0}{m_e c^2}\right)^3.$$

From the condition $\tilde{\tau} = 1$ we determine the mean energy loss distance $\tilde{\lambda}$. The average deflection angle is then

$$\delta \sim \frac{\sqrt{\tau\left(E\right)}}{\gamma}.$$

Results
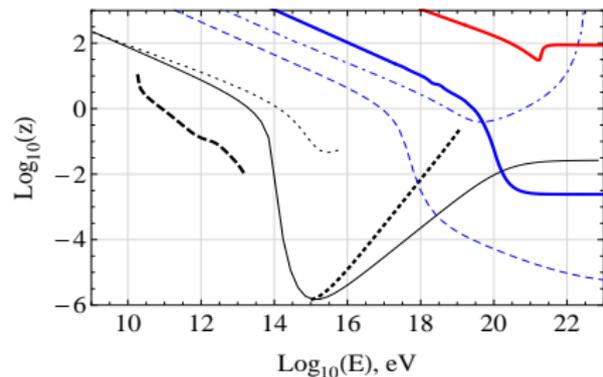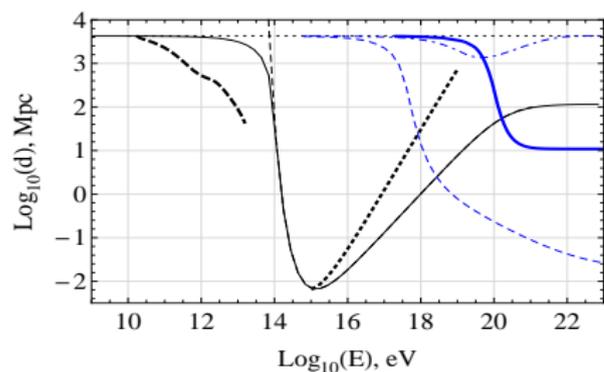
- Ruffini, Xue, Vereshchagin, Ap&SS 361 (2016) 82.

Bethe-Heitler deflection of protons
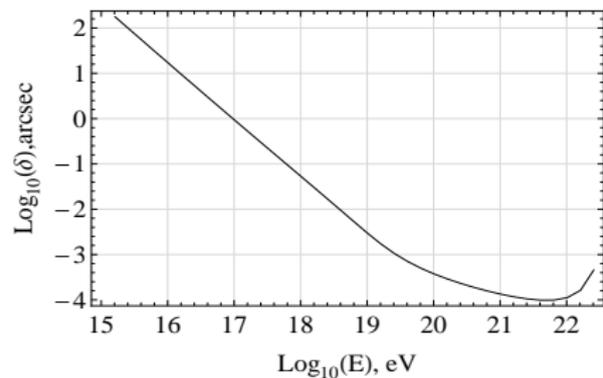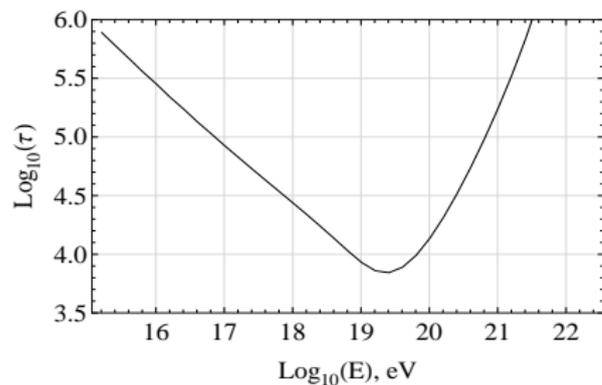
Photon-photon scattering

According to QED, in addition to pair creation, photons can scatter on photons: Euler (1931). The influence of this process for cosmological propagation of photons has been considered by Zdziarski and Svensson (1989) and Svensson and Zdziarski (1990). They used the low energy approximation of the scattering cross section with $\sigma \propto x^3$.
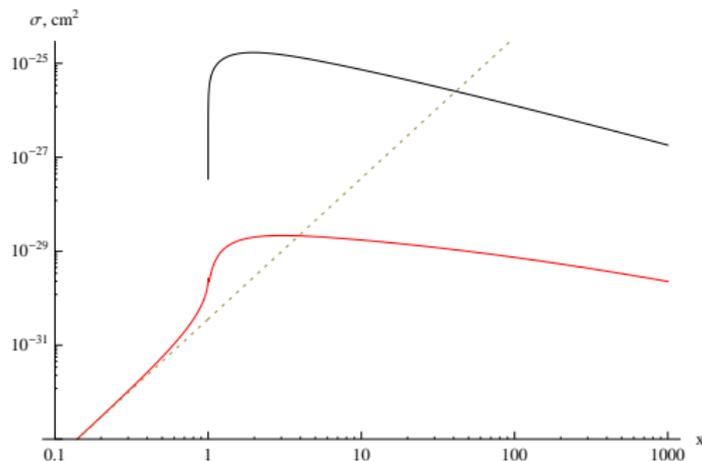
Results
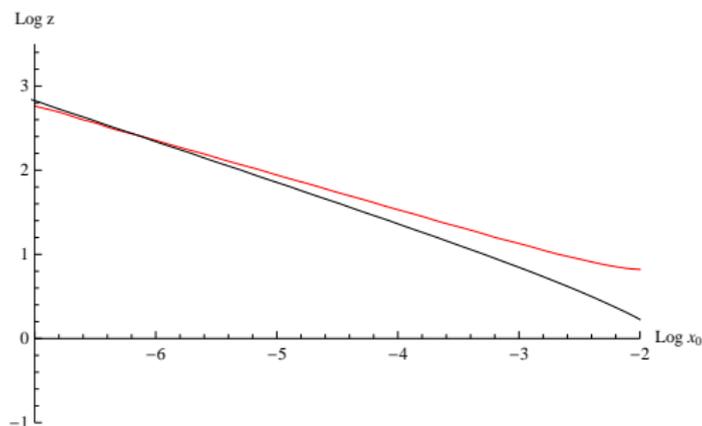
$$z_{EH} = \left(\frac{15}{2\tau_0}\right)^{2/5} \left(\frac{E}{m_e c^2}\right)^{-2/5},$$

$$\tau_0 = \frac{4448\pi^2}{455625}\alpha^4 \frac{c}{H_0} \frac{1}{\lambda_C} \left(\frac{kT}{m_e c^2}\right)^6.$$

Results II

We used exact cross section for photon-photon forward scattering.
Fits:

$$z_{BW} \simeq 0.21 \left(\frac{E}{E_{BW}} \right)^{-1/2}, \qquad z_{BW} \simeq 0.270 \left(\frac{E}{E_{BW}} \right)^{-0.485},$$

$$z_{EH} \simeq 0.92 \left(\frac{E}{E_{BW}} \right)^{-2/5}, \qquad z_{EH} \simeq 0.770 \left(\frac{E}{E_{BW}} \right)^{-0.411}.$$

Crossing of "analytic" curves gives

$$E_{cr} \simeq 0.470 \text{ GeV}, \ z_{cr} \simeq 318.$$

Crossing of "numerical" curves gives

$$E_{cr} \simeq 0.792 \text{ GeV}, \ z_{cr} \simeq 259.$$

Observations
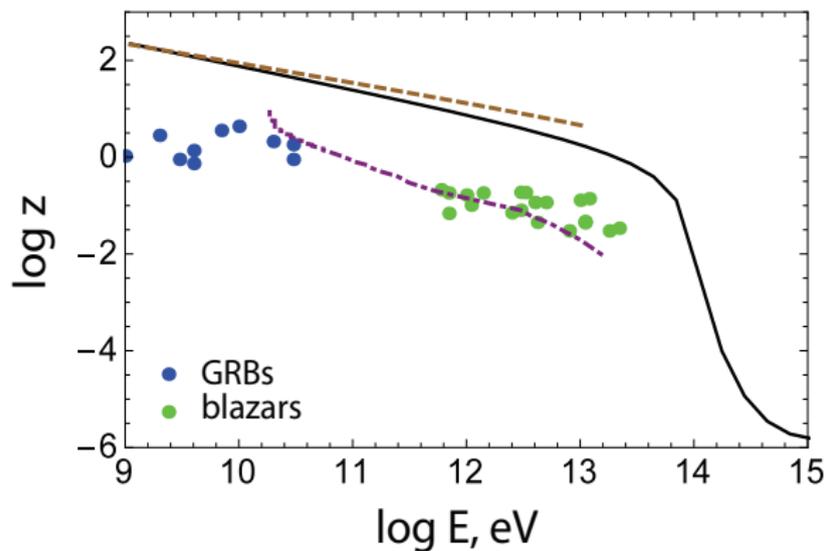
Conclusions

- for UHE photons the contribution of CMB photons gives the absolute upper limit on the mean free path. At high redshift, where other radiation backgrounds, such as EBL are absent, the CMB radiation limits the propagation of UHE photons at energies above GeV.

- for UHE protons the mean free path due to Bethe-Heitler process appears to be much shorter than the mean energy loss distance. This results in multiple deflections suffered by UHE protons, before they start to lose energy in the energy range $10^{16} - 10^{20}$ eV. Such deflections result in dimming of point sources of UHE protons, which makes it more difficult to detect them.

- for UHE neutrinos for the first time we compute the horizon as a function of redshift. We found that the Universe is transparent of UHE neutrinos at redshifts $z < 30$, near the Breit-Wigner resonance at $E_r \simeq 5.2 \times 10^{22} \left(m_\nu / 0.08 \text{ eV} \right)^{-1}$ eV, and it is transparent at redshifts $z < 87$ at higher energies.

- Remarkably, in the low energy and high redshift limit, the redshift corresponding to the mean free path depends on particle energy in the same way for all particles, and it is given by a universal expression $z_\lambda \simeq \mathcal{O}\left(1\right) \left(\frac{E}{E_c} \right)^{-1/2}$, where E_c is the characteristic threshold energy for a given process.

- The only exception to this rule is the photon-photon scattering with $z_\lambda \simeq \mathcal{O}\left(1\right) \left(\frac{E}{E_c} \right)^{-2/5}$.