Cosmic horizon for GeV sources and photon-photon scattering

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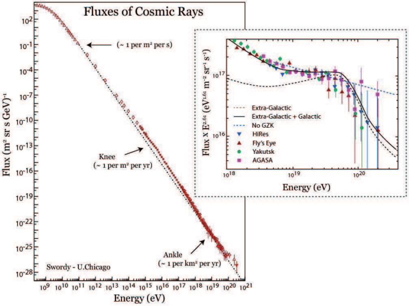
Outline

- 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
- Low energy approximation
- Exact results
- Conclusions

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 neutrinos

CR composition is: 90 per cent protons, 9 per cent α-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

$$p + \gamma \longrightarrow \begin{pmatrix} p \\ n \end{pmatrix} + \pi .$$

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

$$\sigma^R_{\nu\bar{\nu}} \simeq 4\sqrt{2} G_F \frac{m_\nu M_Z^2 \sqrt{\xi} E}{(M_Z^2 - 2Em_\nu)^2 + 4E^2 m_\nu^2 \xi} \text{GeV}^{-2},$$

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 $\sigma^{R\,\max}_{\nu\bar{\nu}} = 2\sqrt{2} G_F M_Z / \Gamma \simeq 0.471 \mu b$. The non-resonant cross-section is adopted as

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

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

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

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

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

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

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

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 (Stecker, 1970)

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

The mean energy loss of UHE protons

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

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

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

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

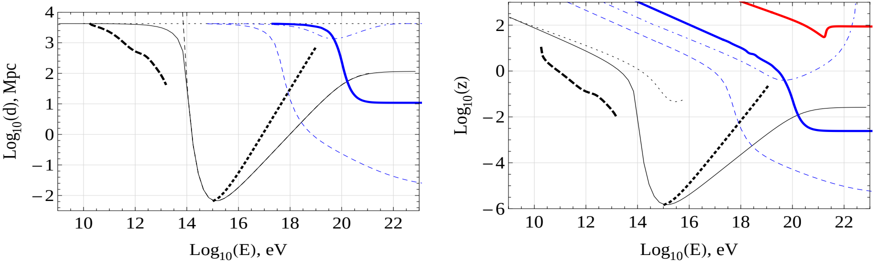
and

$$D = \frac{2}{\pi^2} \alpha^3 \frac{m_e}{m_p} \frac{c}{H_0} \left(\frac{\hbar}{m\, c} \right)^{-1} \left(\frac{k T_0}{m_e c^2} \right)^3 .$$

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

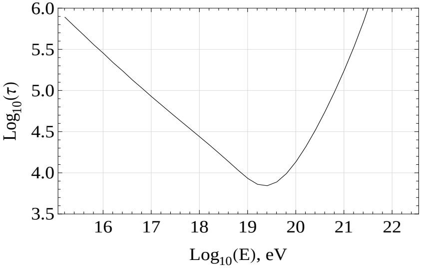
$$\delta \sim \frac{\sqrt{\tau(E)}}{\gamma} .$$

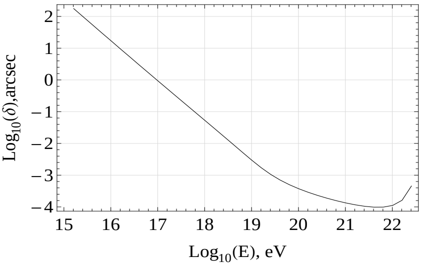
Results



- 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) in the process

$$\gamma_1 + \gamma_2 \rightarrow \gamma_1' + \gamma_2'$$

The influence of this process on propagation of photons at cosmological scales 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

$$\sigma_{EH} = \frac{7 \times 139}{3^4 5^3 \pi} \alpha^4 r_0^2 \varepsilon_{CM}^6,$$

where $\varepsilon_{CM} = \sqrt{E\mathcal{E}\left(1 - \cos\vartheta\right)/2} = \sqrt{x\left(1 - \cos\vartheta\right)/2}$.
This is different from the Breit-Wheeler cross-section: at maximum it is smaller by a factor α^2, but it has no threshold.
At high redshift the crossing between the two curves was obtained for redshift $z_c \simeq 300$.

Cosmic horizon

The computation of the optical depth is straightforward

$$\tau = 4\pi \frac{c}{H_0}\left(\frac{h}{m_e c}\right)^{-3}\left(\frac{kT_0}{m_e c^2}\right)^{3}\int_0^z \frac{dz'}{\left(1+z'\right)^4 H\left(z'\right)}\times$$
$$\int_0^\infty \frac{x^2 dx}{\exp\left(x/y\right)-1}\int_0^\pi \sigma\left(x,y,z',\vartheta\right)\left(1-\cos\vartheta\right)\sin\vartheta d\vartheta,$$

where

$$H(z) = [\Omega_r(1+z)^4 + \Omega_M(1+z)^3 + \Omega_\Lambda]^{1/2}.$$

By equating $\tau = 1$ the cosmic horizon, i.e. $z(E)$, is obtained.

Analytical result

Assuming analytic low energy approximation for σ_{EH} in the Einstein-de-Sitter Universe ($\Omega_\Lambda = 0$, $\Omega_m = 1$) one has

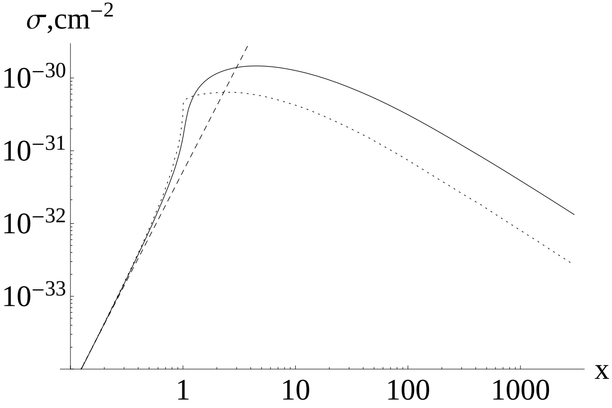
$$z_{EH} = \left(\frac{15}{2\tau_0}\right)^{2/5} \left(\frac{E}{m_e c^2}\right)^{-2/5},$$

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

This results in

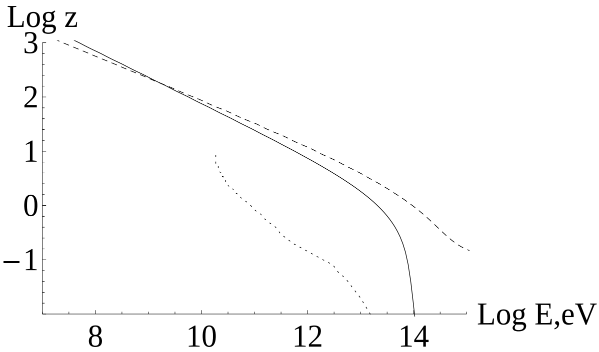
$$z_{EH} = 5.002 \times 10^3\, T_{2.7}^{-4/5} h_{50}^{2/15} \varepsilon_{obs}^{-2/5}.$$

Exact cross section



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

Numerical result



The numerical result is shown for photon-photon scattering (dashed), pair production (solid) on CMB, as function of the variable $y_0 = E/E_{BW}$, where $E_{BW} \simeq 1.11 \times 10^{15}$ eV. Also horizon for pair production on EBL (dotted) is shown.

Low energy (high redshift) approximation

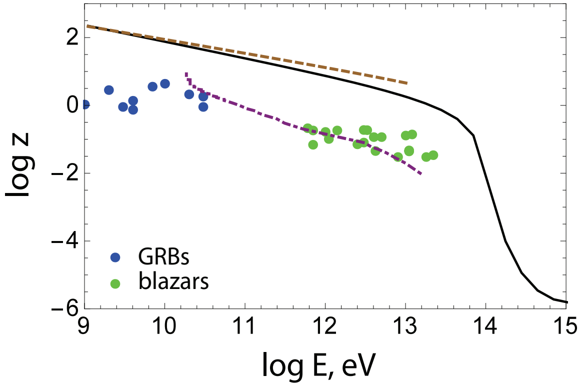
In the Low energy (high redshift) limit the following power laws are recovered:

$$z_{EH} = 0.786 \left(\frac{E}{E_{BW}} \right)^{-0.405}, \quad z_{BW} = 0.257 \left(\frac{E}{E_{BW}} \right)^{-0.488},$$

Crossing of exact curves gives

$$E_{cr} = 1.68 \text{ GeV}, \quad z_{cr} \simeq 180.$$

Observations



Conclusions

- for UHE photons the contribution of CMB photons gives the absolute upper limit on the mean free path.
- 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.

- 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 $z_\lambda \simeq \mathcal{O}(1)\left(\frac{E}{E_c}\right)^{-1/2}$, where E_c is the characteristic threshold energy for a given process.
- The only exception to this rule is the photon-photon scattering with $z_\lambda \simeq \mathcal{O}(1)\left(\frac{E}{E_c}\right)^{-2/5}$.
- Since the exact cross section near the pair production threshold is larger than the approximate one, obtained in the low energy limit, the dominance of the photon-photon scattering over the pair production by two photons occurs at smaller redshift than previously thought, namely the redshift $z_{cr} \simeq 180$. This corresponds to the energy $E_{cr} = 1.68$ GeV.