Neutrinos produced by ultra-high-energy photons at high red shift

A diffuse background of "signature" neutrinos with energies $\sim 10^{17}$eV can provide evidence for UHECR generated by photon sources at high red shifts.

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GZK cutoff

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The reaction $p\,\gamma_{\mathrm{CMB}} \to N\pi$ becomes possible for $\sqrt{s} > m_n + m_\pi$

$$\Rightarrow \quad E_p > E_{\mathrm{th}} \simeq 5 \times 10^{19}\ \mathrm{eV}$$

Proton loses approx 20% energy in each reaction. Energy attenuation length:

$$R_{\mathrm{GZK}} \simeq 50\ \mathrm{Mpc}$$

Protons with $E < E_{\mathrm{th}}$: from whole universe
Protons with $E > E_{\mathrm{th}}$: from within 50 Mpc

expect drop in CR flux above E_{th}

Heavy nuclei: photo-disintegrate on IR background
photons: e^+e^--pair production on radio background

Possible solutions for GZK puzzle

bottom-up/acceleration scenario

- AGN, GRB, radio galaxies
- astrophysical sources: small red shift
- protons, charged nuclei

top-down/decay scenario

- topological defects, heavy relic particles
- large red shift
- photons

quantum gravity effects

- violation of Lorentz invariance/equivalence principle

How to distinguish?

high energy photons at high redshift produce neutrino flux

Red shift

<u>small redshift:</u> $z < z_{\mathrm{r}} \sim 5$

γ's absorbed on radio background: $\gamma\gamma_{\mathrm{RB}} \to ee$

Energy lost in EM cascade & synchrotron radiation

<u>large redshift:</u> $z > z_{\mathrm{r}} \sim 5$

- RB and MF negligible
- γ_{CMB} warmer: $T(z) = 2.73\mathrm{K}(1+z)$

  New reactions possible: $\gamma\gamma_{\mathrm{CMB}} \to \mu^+\mu^-$
  $e\gamma_{\mathrm{CMB}} \to e\,\mu^+\mu^-$

  Muons decay in neutrinos, which can reach us today!

Will muons be produced?

Important interactions

Treshold μ production: $E_{\text{th}} \sim 10^{20}/(1+z)$ eV

First reaction

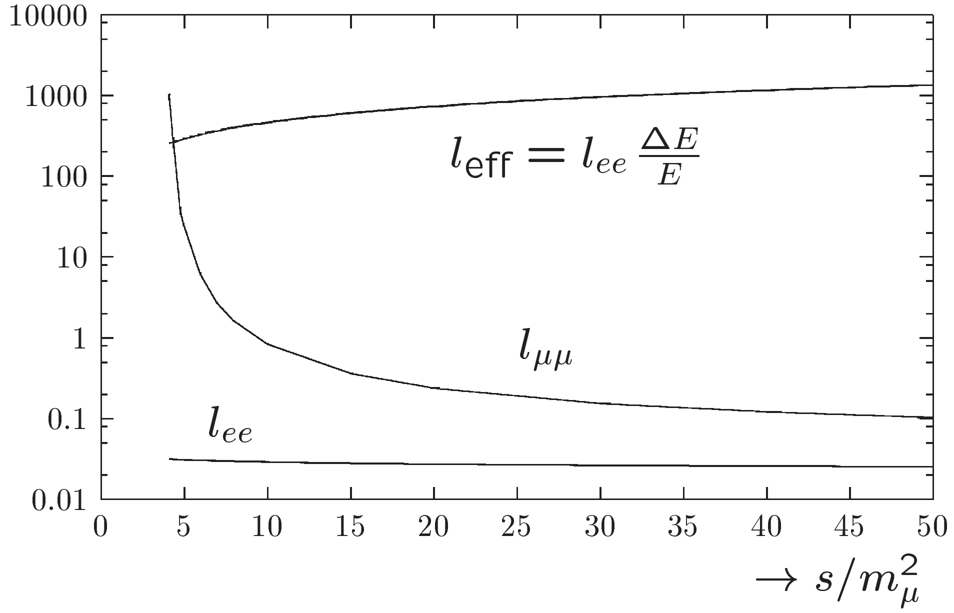
$\gamma\gamma_{\text{CMB}} \to ee$	one e gets all energy
$\to eeee$	$E > 5\times10^{20}/(1+z)$ eV
$\to \mu\mu$	supressed

Following EM cascade

leading particle gets
99.9% of energy

$e\,\gamma_{\text{CMB}} \to eee$	
$\to e\mu\mu$	supressed
$\to e\gamma$	greatly supressed

neutrino production



All electrons above treshold produce muons, which decay into neutrinos right away

$\gamma\gamma_{\text{CMB}} \rightarrow ee$

$e\gamma_{\text{CMB}} \rightarrow e\mu\mu$

$\mu \rightarrow e\nu\nu$

Neutrino flux

Parametrize photon rate of source:

$$\dot{n}_\gamma = \dot{n}_{\gamma,0}\left(\frac{t}{t_0}\right)^m$$

$m = 0$: relic particles, vortons

$m = 3$: ordinary strings, monopolonium, necklaces

$m \geq 4$: superconducting strings

Can relate neutrino flux to UHECR flux:

$$\phi_\nu = \xi\; n_{\gamma,0}\left(E > \frac{10^{20}\,\mathrm{eV}}{1+z_\mathrm{r}}\right)\; \frac{(1+z_\mathrm{r})^a - (1+z_\mathrm{max})^a}{1-(1+z_{\mathrm{GZK},\gamma})^a}$$

ξ: number of neutrinos produced per photon

$a = (3m - 11)/2$

$z > z_\mathrm{r}$: RB & MF negligible $\quad z > z_\mathrm{max}$: universe opaque to UHE neutrinos

Flux estimate

Flux in units of $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$:

$$\phi_\nu \sim \begin{cases} 10^{-20} & m = 0 \qquad \text{too small} \\ 10^{-16} & m = 3 \qquad \text{can be detected soon} \\ > 10^{-13} & m = 4 \qquad \text{ruled out} \end{cases}$$

Typical energy for $m = 3$ source:

$$E_\nu \sim \frac{10^{20}}{(1+z_\mathrm{r})} \times \frac{1}{4} \times \frac{1}{3} \times \frac{1}{(1+z_\mathrm{r})} \sim 10^{17}\mathrm{eV}$$