Z-Bursts: A Zombie Model for Cosmic Rays

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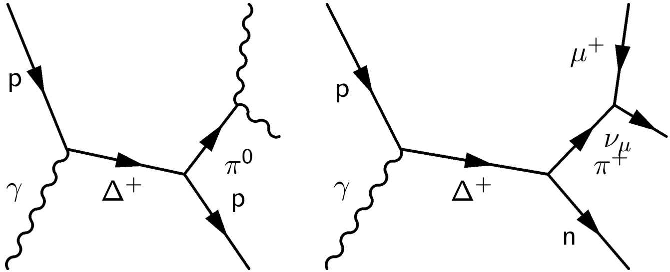
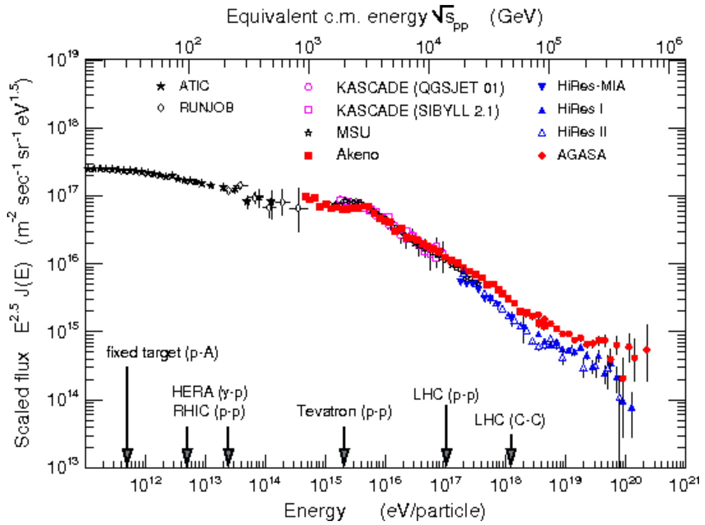
The GZK Cut-Off

Due to photo-pion production at the Δ resonance, cosmic ray protons at the highest energies ($10^{19}eV = 1J$) should not be able to propagate more than ≈ 50 megaparsecs due to strong absorption on the cosmic microwave background.

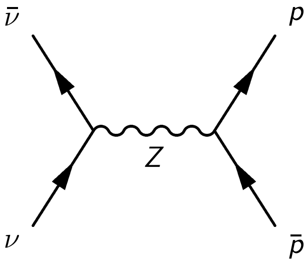


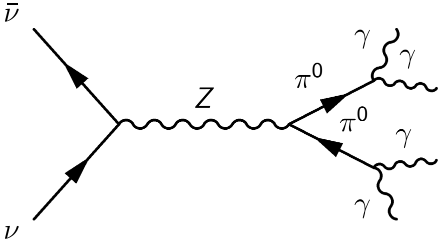
GZK Spectrum - AGASA



Z-Burst

The Z-Burst model is analogous to the GZK cut-off, but for extremely high-energy neutrinos (10^{21} eV = 100 J) annihilating on the cosmic neutrino background. Because there is no charge, and they are neutrinos, only neutral current Z-exchange processes are allowed.





Z production cross section

s-channel ν, $\bar{\nu}$ annihilation to $f\bar{f}$ via the Z^0 is is just like any other $f\bar{f}$ pair

$$\mathscr{M} = \left(\frac{-i}{4} \bar{u}_2 \frac{g}{\cos\theta_W} \gamma^\mu (1 - \gamma^5) u_1 \right) \left(\frac{-ig_{\mu\nu} - p_\mu p_\nu / M_z^2}{p^2 - M_z^2} \right)$$

$$\left(\bar{u}_3 \frac{-ig}{2\cos\theta_W} \gamma^\nu (c_v^f - c_A^f \gamma^5) u_4 \right)$$

Z production cross section

This looks very much like neutrino-quark scattering, except with a different propagator and phase space differences.

$$\sigma = \frac{G^2 s}{\pi} \frac{1}{4} \frac{M_Z^4}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} f(s)$$

where $f(s)$ is a phase space factor. The $s - M_Z^2$ is carried through from the $p^2 - M_z^2$ in the propagator, since the propagator has to hold all the momentum available. At the resonance, $\sigma = 315$ nb for hadronic decays ($\Gamma = 69$ %)

Kinematics

The reaction is peaked at $\sqrt{s} = M_Z = 91$ GeV.

$$s = (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2p_1 \cdot p_2 = 2(m_\nu^2 + p_1 \cdot p_2) \approx 2p_1 \cdot p_2$$

Letting p_2 correspond to the $C\nu B$ momentum:

$$\begin{aligned} p_1 \cdot p_2 &= E_1 E_2 - p_1 p_2 = E_1 E_2 - \sqrt{E_1^2 E_2^2 - m_\nu E_1 + \ldots} \\ &= E_1 E_2 (1 - \sqrt{1 - m_\nu / E_2}) = E_1 E_2 (1 - 1 + \frac{1}{2} m_\nu / E_2) \\ &= \frac{1}{2} m_\nu E_1 \end{aligned}$$

$$s = m_\nu E_1 \Rightarrow E_1 = \frac{M_Z^2}{m_\nu} \approx 8 \times 10^{21} eV$$

UHE Neutrino Horizon

Like GZK cut-off, if this high energy flux exists, it should be suppressed at the resonance energy.

$$\lambda = 1/(\rho_{C\nu B}\sigma) \approx 8 Gpc$$

This is comparable to the Hubble radius, and much larger than the GZK horizon of 50 Mpc.

Observable effects of Z-Bursts

The Z has primarily hadronic decay modes, but should give a characteristic composition signature in the ratio of high-energy γ from π^0 decay and hadrons.

The emitted protons and photons should also have a very characteristic spectrum, as the Z decay is well-understood. This has been searched for, and is not observed. Similarly, the high-energy neutrino flux has also not been observed.

Back from the Dead?

While the post-GZK excess turns out not to exist, and the fluxes required to create it are too large, this theory has been reanimated to explain pointing of cosmic rays over large distances.