Photohadronic processes

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Three fundamental photohadronic processes:

each involves high-energy protons or ions N with atomic charge Z and atomic mass A interacting with target photons.

$$N + \gamma \rightarrow N + \pi \text{ (denoted } \phi\pi\text{)}, \quad \text{photopion or photomeson production}$$

$$N + \gamma \rightarrow N + e^+ + e^-, \quad \text{photopair } (\phi\text{e}) \text{ production}$$

$$N + \gamma \rightarrow N' + N'', \quad \text{photodisintegration, forions}$$

particles in intergalactic space lose energy adiabatically as the universe expands

Charged pions formed by the photopion process decay into leptons and neutrinos, and neutral pions decay into γ rays. The secondary neutrino flavor ratio from $\phi\pi$ processes at production is

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

decay products of charged pions

$$\pi^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu,$$

$$\pi^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu,$$