## Neutrino astrophysics of compact objects

Fermi acceleration of electrons responsible for the observed **GRB** $\gamma$-ray, X-ray and optical photons is likely also to accelerate protons, either in internal shocks [1] or external shocks [2, 5]. The extreme electromagnetic brightness implies a high intra-source density of photons, and a high optical depth to $p\gamma$ photomeson interactions. Interactions between protons of $E_p \gtrsim 10^{16}$ eV and photons of $\epsilon_\gamma$ leads to neutrinos whose energy in the observer frame is $E_{\nu,\,\mathrm{GeV}} \sim 10^{-2}\Gamma^2/\epsilon_{\gamma,\,\mathrm{GeV}} \sim 100$ TeV for a GRB emitting MeV photons from a jet of Lorentz factor $\Gamma \sim 10^2$. For a GRB with a typical photon spectrum $dN_\gamma/d\epsilon_\gamma$ of slope $-1$ and $-2$ below and above the photon peak energy $\epsilon_{\gamma_p} \sim$ MeV, the neutrino spectrum has an $E_\nu^2(dN/dE_\nu)$ spectrum with slopes $+1$ and 0 below and above a neutrino break energy $E_{\nu,p} \sim 100$ TeV [3]. A comprehensive discussion of Fermi acceleration and photomeson neutrino production in both GRB and AGNs was given in [4], indicating that electromagnetic cooling of pions and muons leads to a second spectral break at neutrino energies $E_{\nu,c}$ above which the cooling time is shorter than the lepton decay time.

A different mechanism for neutrino production in GRB [7] is inelastic $p, n$ collisions in the early relativistic outflow, caused by the relative drift between the entrained neutrons and protons when they decouple. These neutrinos have lower energies $E_\nu \sim 40 - 50$ GeV. Another neutrino component [8] is expected from "long" GRB arising from massive stellar core collapses, when internal shocks can arise while the jet is still inside the stellar envelope. Photomeson and $pp$ neutrinos at $E_\nu \sim 1$ TeV would arise as precursors, $\sim 10 - 100$ s before the $\gamma$-rays from shocks outside the star. In addition to such GRB, there may be an even larger number of 'failed' GRB, where **choked jets** did not emerge, leading to an orphan neutrino burst [8] without a corresponding electromagnetic signal. Part of the motivation for the current deployment of the *Deep Core* sub-array of IceCube, sensitive in the 10 GeV$-$ TeV range is to look for such objects. Neutrinos would serve as 'tomographical' probes of the stellar structure of the GRB progenitors, as well as of those stars leading to choked, electromagnetically dark GRBs [9].

The shocks in the jets of **AGNs** (active galactic nuclei) may also be photo-meson neutrino sources. However, there are many more AGNs with modest or no jets, and the cores of such 'radio-quiet' AGNs may be promising neutrino sources. This is due to shocks between blobs in the dense inner accretion flow near the central black hole [10].

**Magnetars**, ultra-high magnetic field ($\gtrsim 10^{14}$ Gauss) neutron stars, are another type of potential neutrino source. Magnetars give rise to soft-gamma repeaters (SGRs), burst-like events thought to be due to magnetic reconnection leading to a fireball where shocks will Fermi accelerate electrons and protons leading to photomeson effects [11]. A novel mechanism arises in non-bursting magnetars, where for fields $\gtrsim 10^{15}$ Gauss the equivalent of curvature radiation can lead directly to pions and neutrinos [12]. In newly formed magnetars, wake-field acceleration can lead to ultra-high energy proton acceleration, which interact with the ejected supernova shell targets leading to significant neutrino fluxes [13].

# References

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