High-Energy Neutrinos from Gamma-Ray Burst Fireballs

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TAUP 2015
Turin, September 9, 2015
Outline

★ IceCube detection of high-energy neutrinos
★ Neutrinos from gamma-ray burst fireballs
★ Diffuse emission from gamma-ray bursts
★ Conclusions

This talk is based on work in collaboration with Shin'ichiro Ando, arXiv: 1504.00107, JCAP (2015, in press).
High-energy neutrino astronomy is happening!

- IceCube observed 54 events over four years in the 25 TeV-2.8 PeV range.
- Zenith Distribution compatible with isotropic flux.
- Flavor distribution consistent with \( \nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1 \).

7σ evidence for astrophysical flux

Where are these neutrinos coming from?

★ New physics?
★ Galactic origin [sub-dominant contribution or new unknown sources?]
★ Extragalactic origin [flux compatible with Waxman&Bahcall bound]
   • Star-forming galaxies
   • Active galactic nuclei
   • Gamma-ray bursts

Warning: More statistics needed! No strong preference so far.

* Anchordoqui et al., JHEAp 1-2 (2014) 1.
Sizable emission of high-energy neutrinos from gamma-ray bursts expected.

Neutrinos from gamma-ray bursts

Dedicated stacking searches on GRBs unsuccessful up to now. Existing detectors are achieving relevant sensitivity.

Does the diffuse emission from ALL GRB families contribute to the IceCube flux?

Neutrino emission from gamma-ray bursts

High energy neutrinos are produced through the following reactions:

\[ p + \gamma \rightarrow \Delta \rightarrow n + \pi^+, p + p^0 \]
\[ p + \gamma \rightarrow K^+ + \Lambda/\Sigma . \]

\[ \pi^+ \rightarrow \mu^+ \nu_\mu , \]
\[ \mu^+ \rightarrow \bar{\nu}_\mu + e^+ , \]
\[ \pi^- \rightarrow \mu^- \nu_\mu , \]
\[ \mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^- , \]
\[ K^+ \rightarrow \mu^+ + \nu_\mu , \]
\[ n \rightarrow p + e^- + \bar{\nu}_e . \]

Neutrinos emission from gamma-ray bursts

Short-duration bursts (t < 2s)
\[ \dot{L}_{\text{iso}} = 10^{51} \text{erg/s}, \Gamma = 650, t_v = 0.01s \]

Long-duration bursts (t > 2s)

High-luminosity GRBs
\[ \dot{L}_{\text{iso}} = 10^{52} \text{erg/s}, \Gamma = 500, t_v = 0.1s \]

Low-luminosity GRBs
\[ \dot{L}_{\text{iso}} = 10^{49} \text{erg/s}, \Gamma = 5, t_v = 100s \]

Neutrino emission from gamma-ray bursts

We revisited the analytical modeling of prompt emission from fireballs, including pion and kaon decays as well as adiabatic, radiative and hadronic cooling processes. Neutrino spectrum normalized in terms of the photon fluence:

\[
\int_0^\infty dE_p E_p \left( \frac{dN_{\nu}}{dE_{\nu}} \right)_{\text{iso}} = N_{\gamma} \frac{h_{\gamma}}{h_{\nu}} (1 - (1 - (\epsilon_p)) \gamma) \int_0^\infty dE_p E_p \left( \frac{dN_{\nu}}{dE_{\nu}} \right)_{\text{iso}}
\]

Example of predicted HL-GRB flux w/o flavor oscillations at z=1.


Diffuse background ingredients

- Gamma and neutrino energy fluxes
- Distribution of sources with redshift
- Comoving volume (cosmology)
Diffuse emission from gamma-ray bursts

\[ I_X(E_\nu) = \int_{z_{\text{min}}}^{z_{\text{max}}} dz \int_{E_{\text{min}}}^{E_{\text{max}}} dE \frac{1}{\Omega_M (1 + z)^3 + \Omega_R} \frac{c}{4\pi H_0} \frac{d}{dE} L_{\text{iso}}(1 + z)^\Gamma \frac{dN_{\nu}}{dE} \]

GRB redshift distribution

Recent work based on BATSE, Fermi and Swift data.

Analytical modeling of the prompt emission from fireballs.

GRBs can make up to few % of the high-energy IceCube flux in the sub-PeV region. LL-GRBs can be main sources of the IceCube flux in the PeV range.

Diffuse emission from gamma-ray bursts

Conclusions robust with respect to variation of model parameters.

GRBs cannot explain the IceCube flux for sub-PeV energies, but could contribute around PeV energies for certain choices of the model parameters.

Conclusions

★ Gamma-ray bursts account up to few % of the observed IceCube flux for E< 1 PeV. Low-luminosity gamma-ray bursts dominate the diffuse emission in the PeV range.

★ High-luminosity and low-luminosity GRBs have comparable intensities, while the contribution from the short-duration component is small.

★ Our findings confirm the most-recent IceCube results on GRB searches. Larger exposure is mandatory to detect neutrinos from high-luminosity GRBs.
Thank you for your attention!
Back-up slides
Neutrino emission from gamma-ray bursts

Cooling times in the jet comoving frame for HL-GRBs.

Figure 2. Top panel: Muon and pion lifetimes and cooling times in the jet comoving frame as a function of the neutrino energy $E_\nu$ for a typical HL-GRB with $\tilde{L}_{\text{iso}} = 10^{52}$ erg/s and $z = 1$. Bottom panel: Muon and kaon lifetimes and cooling times for the same HL-GRB. For the assumed HL-GRB parameters, the radiative cooling is always important, while the hadronic cooling is negligible and the adiabatic cooling is relevant for muons.

3.2 Neutrino production from kaon decay

Yet another contribution to the total neutrino spectrum from GRB originate from kaon decays. The resultant neutrino spectrum will have a first break energy coming from the...
Neutrino emission from gamma-ray bursts

Predicted GRB flux for HL-GRB at \( z=1 \) and without flavor oscillations.

Figure 5. Predicted \( E^2\nu F_\nu(E_\nu) \) for a typical HL-GRB (\( \tilde{L}_{\text{iso}}=10^{52} \text{erg s}^{-1} \), \( z=1 \)) without flavor oscillations. Top: Neutrino fluence from \( \pi \) (blue line) and \( K \) (magenta line) decays as well as from \( \mu \) from pion decay (\( \mu_{\pi} \), dashed blue line) and \( \mu \) from kaon decay (\( \mu_{K} \), dashed magenta line). Bottom: \( E^2\nu F_\nu(\nu_e) \) (black line) and \( E^2\nu F_\nu(\nu_\mu) \) (red line) for a typical HL-GRB and without flavor oscillations.

As by adopting the analytical prescription developed in Sec. 3, we find that estimation of the neutrino flux from GRBs gave results close to the ones obtained adopting numerical routines in [10, 20, 74], by adopting their same GRB inputs.

Neutrino emission from gamma-ray bursts

Figure 6. Predicted $E_\nu F_\nu$ for a typical HL-GRB ($\tilde{L}_{iso} = 10^{52}$ erg s$^{-1}$), LL-GRB ($\tilde{L}_{iso} = 10^{48}$ erg s$^{-1}$), and sGRB ($\tilde{L}_{iso} = 10^{51}$ erg s$^{-1}$) at $z = 1$ with flavor oscillations included. The HL-GRBs exhibit the highest flux and the kaon contribution affects the high-energy tail of the spectra in all cases.

In this section, we present our results on the high-energy diffuse neutrino background from GRB fireballs. We first discuss the expected neutrino background within the canonical model in terms of the astrophysical uncertainties on the local GRB rates and luminosity functions (see Table 1), then we study the dependence of the high-energy diffuse neutrino flux from the model parameters for each GRB family (see Table 2).

4.1 Expected diffuse background and uncertainties on the local rate and luminosity function of each GRB family

The diffuse neutrino intensity from each GRB component (X) can be defined in terms of the gamma-ray luminosity function, through

$$ I_X(E_\nu) = \int_{z_{min}}^{z_{max}} \int_{\tilde{L}_{iso,min}}^{\tilde{L}_{iso,max}} d\tilde{L}_{iso} \frac{4\pi H_0 \Gamma}{\sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}} R_X(z) \Phi_X(\tilde{L}_{iso}) (dN_\nu dE_\nu' \delta_{osc}). $$

In the numerical computation of the neutrino background, we assume $z_{min} = 0$ and $z_{max} = 11$, $\tilde{L}_{iso} \in [\tilde{L}_{min}, \tilde{L}_{max}]$ with $\tilde{L}_{min}$ and $\tilde{L}_{max}$ defined as in Table 1 for each family X, and $E_\nu' = E_\nu (1 + z)/\Gamma$. Note that the chosen values for $\nu$ and $\Gamma$ (Table 1) should guarantee an average description of the whole GRB population. However, our estimation of the diffuse neutrino emission from GRBs also depends on parameters such as $\epsilon_e$, $\epsilon_B$, $\Gamma$, and $h_\gamma$ that are currently poorly constrained from observations (see discussion in Sec. 4.2) and should therefore be considered with caution.