The High Energy Neutrino Sky

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Outline

★ Features of high energy neutrino flux detected by IceCube
★ Neutrino emission from hadro-nuclear and photo-hadronic sources
★ Prospects for detection of point sources
★ Conclusions
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 $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

\[7\sigma\] evidence for astrophysical flux

Sky Map of 54 High Energy Starting Events

Distribution of events compatible with an isotropic one.
No evidence of (significant) correlation neither spacial nor temporal with known sources.

* Slide adapted from M. Kowalski @ Neutrino 2016.
The measured astrophysical flux

Assumed equal neutrino flavor ratios \( f_e : f_\mu : f_\tau = 1:1:1 \) at Earth and single unbroken power-law fit

- **IC tracks (6yr)**
- **IC MESE**
- **IC HESE (4yr)**
- **IC combined**
- **IC cascades**
- **IC tracks (2yr)**

**All Sky Cascades \( \nu_e + \nu_\mu + \nu_\tau \) 2yr E>10 TeV**
PoS (ICRC2015) 1109

**Combined fit \( \nu_e + \nu_\mu + \nu_\tau \)**
PoS(ICRC2015) 1066

**All Sky MESE \( \nu_e + \nu_\mu + \nu_\tau \) 2yr E>1 TeV**
PRD 91, 022001 (2015)

**All Sky HESE \( \nu_e + \nu_\mu + \nu_\tau \) 4yr E>60 TeV**
PoS(ICRC2015) 1081

**\( \nu_e \) (Northern Sky only) 2yr**
PRL 115 (2015) 8, 081102

**\( \nu_e \) (Northern Sky only) 6yr**
PoS(ICRC2015) 1079

* Slide adapted from J. Kiryluk @ NOW 2016.
The measured astrophysical flux

Combined spectral index: $\gamma = 2.50 \pm 0.09$
High-energy tracks: $\gamma = 2.13 \pm 0.13$
Prompt component < $1.06 \times$ Enberg et al. (2008)

Are we seeing a spectral flattening of energy spectrum?

Plots adapted from J. Kiryluk’s talk @ NOW 2016.
The measured astrophysical flux

Flavor composition at Earth (combined likelihood analysis).


Not yet possible to pinpoint the production mechanism.
Where are these neutrinos coming from?
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
  - Gamma-ray bursts
  - Active galactic nuclei
  - Low-power or choked sources

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

Neutrino Production Mechanisms

Hadronic interactions

Lepto-hadronic interactions

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

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

Diffuse backgrounds
Diffuse background ingredients

- Gamma and neutrino energy fluxes
- Distribution of sources with redshift
- Comoving volume (cosmology)
Neutrino-Gamma Connection

Confined cosmic rays can make both neutrinos and gamma rays.

Are gamma and neutrino backgrounds explained by the same sources?

* Murase, Ahlers, Lacki, PRD (2013). Plot adapted from Murase’s talk @ Weizmann workshop 2017.
Star-forming galaxies and radio galaxies are among the main contributors to the IGRB.

Star-forming galaxies
Normal galaxies (i.e., Milky Way, Andromeda)

Starburst galaxies (i.e., M82, NGC 253)

Star-forming galaxies

Starbursts efficiently produce neutrinos!

Infrared luminosity function and multi-wavelength luminosity comparison

The numerical calculations we assume with the IR luminosity between 8 and 1000, for a given redshift. Local values of the characteristic luminosity \( \phi_0 \), as well as the values of AGN as gamma-ray sources. The IR population does not evolve all together as a whole, but in general, the IR-galaxy classes evolving differently for different redshifts and constitutes the most direct method for describing the relative number of sources.

\[
I(E_\gamma) = \int_0^{z_{\text{max}}} dz \int_{L_{\gamma,\text{min}}}^{L_{\gamma,\text{max}}} dL_\gamma \frac{dV}{d\Omega dz} \sum_X \Phi_X(L_\gamma, z) \frac{dN_X(L_\gamma, (1+z)E_\gamma)}{dE_\gamma} \Gamma(E_\gamma, z)
\]

gamma-ray flux

comoving volume

luminosity function \( \Phi_X(L_\gamma, z) = d^3N_X/dV dL_\gamma \)

EBL correction

Gamma-ray-IR linear relation from Fermi data:

\[
\log \left( \frac{L_\gamma}{\text{erg s}^{-1}} \right) = \alpha \log \left( \frac{L_{\text{IR}}}{10^{10}L_\odot} \right) + \beta
\]

Diffuse emission from star-forming galaxies

Improved modeling of starburst galaxies may be useful.

* Tamborra, Ando, Murase, JCAP (2014).
Radio Galaxies
Diffuse emission from radio galaxies

Radio galaxies (active galaxies with mis-aligned jets) can also be primary sources of the diffuse neutrino background.

* Hooper, JCAP (2016).
Cross-correlation between GeV gamma rays and galaxy catalogs provide bounds on the neutrino luminosity density up to one order of magnitude tighter than those obtained from the energy spectrum.

Any hadro-nuclear source with a spectrum softer than $E^{-1.1}$ and evolution slower than $(1+z)^3$ is excluded.

Gamma-ray bursts
The smooth curve shown in Fig. 1 was used by us to estimate the cosmic ray flux above $10^{18}$ eV. We also included the adiabatic energy loss due to possible extra-galactic component of lower-energy astrophysical neutrino sources. This very conservative limit is what we shall mean when in the following we refer to the "Waxman-Bahcall bound." The lower solid line is obtained assuming that 100% of the energy of protons is lost to neutrinos. The dotted curve is the maximum contribution of neutrinos to the upper bound corrected for neutrino energy loss due to redshift and expansion of the Universe.

In order to establish a conservative upper limit, we assumed that the local rate given in Eq. (3) is a conservative upper bound on the high energy neutrino flux.

What is the neutrino bound that results from the observed cosmic ray flux? Figure 2 shows the numerical limit that is implied by the cosmic ray observations. The upper horizontal curve is computed by assuming that the cosmic ray sources evolve as rapidly as the most rapidly evolving known astronomical population, i.e., the evolutionary rate exhibited by the quasar population.

The dash-dot curve shows the experimental upper bound on diffuse neutrino flux recently established by the AMANDA experiment. The dash-dot-dot curve shows the "most extragalactic p" that may in units of $10^{-21}$ erg cm$^{-2}$ s$^{-1}$ for small optical depths.

The theoretical curve in Fig. 1 shows the predicted decrease above $5 \times 10^{17}$ eV, protons as first discussed in Bahcall bound. The lower curve is computed assuming that the cosmic ray sources evolve with redshift at the maximum rate observed for any astronomical objects.

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?**

Diffuse emission from gamma-ray bursts

\[ I_X(E_\nu) = \int_{z_{\text{min}}}^{z_{\text{max}}} \frac{dE}{dL_{\text{iso}}} \frac{1}{4\pi R^2_0 \sqrt{1 + z}} \int_{L_{\text{min}}}^{L_X(z)} \frac{dN_{\nu}}{dE_{\nu}} \text{d}L \]

Recent work based on BATSE, Fermi and Swift data.

Analytical modeling of the prompt emission from fireballs, involving pion and kaon decays.

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

Figure 7. Diffuse high-energy neutrino intensity as a function of the neutrino energy after flavor oscillations for the HL-GRB (blue band), LL-GRB (violet band) and sGRB (orange band) families. The bands represent uncertainties related to the luminosity functions and local rates (Table 1), whereas all the other GRB parameters are fixed to the canonical values. The best fit estimation of the high-energy diffuse neutrino flux as in [43] is plotted in light blue, while the blue dot (IC-GRB) marks the upper limit of the GRB diffuse neutrino flux from the IceCube Collaboration [20]. The diffuse neutrino background from GRB fireballs is smaller than the observed high-energy IceCube neutrino flux in the sub-PeV energy range and it scales differently as a function of the neutrino energy.

For each population X, we implement the analytical recipe described in Sec. 3 and automatically define the neutrino energy spectrum according to the specific hierarchy among the different cooling processes for each ($\tilde{L}_{iso}, z$). Note as for luminosities and redshifts different than the ones adopted in Figs. 2, 3 and 4, the hierarchy among cooling times changes. For example, we find that the adiabatic cooling becomes relevant for pions and kaons when $\tilde{L}_{iso}$ is on the lower tail of the studied luminosity interval for all three GRB families. We do not include HL-GRBs and sGRBs whose parameters ($\tilde{L}_{iso}, z$) violate the condition $\tau_{\gamma\gamma} \leq 1$ (Eq. 3.22) in our calculations. However, for the input parameters, $\tau_{\gamma\gamma} > 1$ is realized only for sources with $z > 7$ and with luminosities at the upper extremes of their interval. Therefore, our computation might underestimate the expected diffuse flux only by a few% since the diffuse neutrino flux is not affected from sources at $z > 7$.

Blazars
Blazars cannot explain the flux observed by IceCube. Few PeV events may be associated with distant blazars (still low significance).

Choked or low-power sources
Hidden cosmic ray accelerators

Latest data may point toward a population of CR accelerators hidden in GeV-TeV gamma-ray range. Future searches in the X-ray and MeV bands may address with issue.

Dark GRBs are especially poorly understood because scarcely (or not) visible in photons.

Constraints on SN-GRB connection

Redshift evolution:

\[ R(z) \propto \left[ (1 + z)^{\alpha_k} + \left( \frac{1 + z}{5000} \right)^{\beta_k} + \left( \frac{1 + z}{9} \right)^{\gamma_k} \right]^{1/2} \]

Rate evolution with the Lorentz boost factor:

\[
\int_{1}^{10^{3}} d\Gamma_b \Gamma_b^{\alpha_b} \beta_T = R_{\text{SN}}(0) \frac{\theta_{\text{SN}}}{2} \\
\int_{200}^{10^{3}} d\Gamma_b \Gamma_b^{\alpha_b} \beta_T = \rho_{0, \text{HL-GRB}} \cdot
\]

Local Evolution Rate

* Tamborra & Ando, PRD (2016).
Neutrinos from luminous and dark GRBs

Constraints on the SN-GRB connection

IceCube flux can put indirect constraints on the fraction of SNe evolving in choked bursts and their jet energy.

Point Source Detection
Anisotropies of the Local Universe


IceCube (7 years)

- PS limit (MC)
- correlation sensitivity (MC)
- PS limit (analytical)
- correlation sensitivity (analytical)

No evolution
SFR evolution

PS sensitivity (analytical)
correlation sensitivity (analytical)

IceCube (7 years)

\[ \log_{10}(L_{\nu} [\text{erg s}^{-1}]) \]

[\text{au}/\text{Mpc}^3]
Anisotropies of the Local Universe

IceCube-Gen2 (10 years)

Conclusions

- Origin of the IceCube high-energy neutrino flux not yet clear.
- Multi-messenger approach useful to pinpoint the origin of the IceCube events.
- Diffuse neutrino flux from starburst-like galaxies is one natural possibility. Improved modeling required.
- Low-luminosity gamma-ray bursts (and blazars) may dominate the PeV energy region.
- Correlation studies with IceCube and IceCube-Gen2 will allow to place constraints on certain kind of sources provided they have the right local density and luminosity.
Thank you for your attention!