Neutrinos from GRBs: can they account for the IceCube diffuse neutrino flux?

Silvia Celli
silvia.celli@roma1.infn.it
Plan of the talk

- **Gamma-ray bursts** (GRBs): an introduction.

- GRB and ultra-high energy cosmic-ray (UHECR) connection: the *Waxman-Bahcall (WB) bound*.

- The **diffuse neutrino flux** observed by IceCube (IC).

- ANTARES and IC **searches for neutrinos in coincidence with the prompt emission of GRBs**:
  - Individual source searches (bright GRBs);
  - Population searches (diffuse flux).

- Latest results: **TeV GRBs** and **chocked GRBs**.
Gamma-ray bursts

First serendipitous discovery in 1967 by the (US) Vela satellites, which were operating to ensure the Nuclear Test Ban Treaty was observed.

Transparency of the Earth’s atmosphere for cosmic E-M radiation

Radio  mm  IR  O  UV  X-rays  γ-rays
LE  HE  VHE  UHE  EHE

500 km
100 km
10 km
0 km
An isotropic sky distribution...

2704 BATSE Gamma-Ray Bursts

10 yrs data taking of the CGRO
...namely extra-galactic sources

https://swift.gsfc.nasa.gov/archive/grb table/
Gamma-ray bursts populations

\[ \text{HR} = \frac{F_{50-100 \text{ keV}}}{F_{25-50 \text{ keV}}} \]
Gamma-ray bursts progenitors

- **Long GRBs:**
  - soft emission
  - CC SN progenitor

- **Short GRBs:**
  - hard emission
  - BNS progenitor
A breakthrough: GRB170817A - GW170817

Fermi
Reported 16 seconds after detection

LIGO-Virgo
Reported 27 minutes after detection

INTEGRAL
Reported 66 minutes after detection

Gamma-ray bursts: the fireball model

- **Pre-Burst**
  - $E \sim 10^{51}-10^{54}$ ergs
  - $T = 0 \text{ s}$
  - $R = 10^6 \text{ cm}$

- **Shock Formation**
  - $T \sim 10^2 \text{ s}$
  - $R \sim 3 \times 10^{12} \text{ cm}$

- **Burst**
  - $T \sim 3 \times 10^3 \text{ s}$
  - $R \sim 10^{14} \text{ cm}$

- **Afterglow**
  - $T \sim 10^6 \text{ s}$
  - $R \sim 3 \times 10^{16} \text{ cm}$

- **LOCAL MEDIUM**
- **PHOTOSPHERIC**
- **INTERNAL SHOCK**
Gamma-ray bursts: 
the compactness problem

The short variability time observed in GRB lightcurves (10 ms) indicate a size of the emitting region of

\[ R \approx c t_{\text{var}} \simeq 3 \times 10^8 \text{ cm} \]

implying for the optical depth of $\gamma \gamma \rightarrow e^+e^-$ a value of

\[
\tau_{\gamma\gamma} = \frac{f_{\text{ph}}\sigma_T F_{\gamma} d^2}{R^2 m_e c^2} \simeq 10^{12} f_{\text{ph}} \left( \frac{F_{\gamma}}{10^{-6} \text{ erg/cm}^2} \right) \left( \frac{d}{3 \text{ Gpc}} \right)^2 \left( \frac{t_{\text{var}}}{10 \text{ ms}} \right)^{-2}
\]

namely thick sources to gamma rays, except in the case of a relativistic jet (bulk Lorentz factor $\Gamma$), as

\[
\tau_{\gamma\gamma} = \frac{f_{\text{ph}}\sigma_T F_{\gamma} d^2}{\Gamma^{4+2\alpha} R^2 m_e c^2} \simeq 10^{-3} f_{\text{ph}} \left( \frac{\Gamma}{300} \right)^{4+2\alpha} \left( \frac{F_{\gamma}}{10^{-6} \text{ erg/cm}^2} \right) \left( \frac{d}{3 \text{ Gpc}} \right)^2 \left( \frac{t_{\text{var}}}{10 \text{ ms}} \right)^{-2}
\]
Gamma-ray bursts: the compactness problem
Gamma-ray bursts: the internal shock scenario of the fireball model

Acceleration mechanisms:
- shock acceleration?
- magnetic reconnection?
- other?

Efficiency of particle acceleration?
- energy equipartition among electrons and magnetic fields?

Hadronic acceleration?
- can GRBs be the main sources of UHECRs?

Bustamante et al., Nature Comm. 6 (2015) 6783
The Hillas plot for CR sources

Particle confinement (aka Hillas) condition:

\[ R > 2r_L / \beta \]

size of accelerator \quad speed of scattering centers

\[ \rightarrow E < 0.5Z\beta BR \]

upstream magnetic field

\[ E_{\text{max}} \approx 10^{20} \text{ eV} \left( \frac{Z}{1} \right) \left( \frac{\beta}{1} \right) \left( \frac{B}{10^5 \text{ G}} \right) \left( \frac{R}{10^8 \text{ km}} \right) \]

The all particle CR spectrum
The all particle CR spectrum
The opaque Universe

\( \gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^- \)

PeV photons interact with microwave photons (411/cm\(^3\)) before reaching our telescopes
Neutrinos? Perfect Messenger

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays
GRB and UHECR connection:  
the Waxman-Bahcall upper bound

UHECR observations indicate an emissivity of

\[ E_{CR}^2 \frac{dN_{CR}}{dE_{CR}} = \frac{\dot{\epsilon}_{[10^{19},10^{21}]} \ln(10^{21}/10^{19})}{10^{44} \text{ erg Mpc}^{-3} \text{yr}^{-1}} \]

hence a maximum \( \nu_\mu + \bar{\nu}_\mu \) intensity as arising from \( p\gamma \) (\( \epsilon=1 \))

\[ I_{\text{max}} \approx 0.25\xi_Z t_H \frac{c}{4\pi} E_{CR}^2 \frac{dN_{CR}}{dE_{CR}} \approx 1.5 \times 10^{-8} \xi_Z \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

cosmological effects, \( O(1) \)

\[ \rightarrow E_{\nu_\mu}^2 \phi_\nu \equiv \frac{c}{4\pi} E_{CR}^2 \frac{dN_{\nu_\mu}}{dE_\nu} = \frac{1}{2} \epsilon I_{\text{max}} \approx 10^{-8} \epsilon \xi_Z \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]
Hadronic acceleration in GRBs?

Protons and gamma rays collisions might be realized in the dense radiation field of the jet, if protons are accelerated at high energies, the interaction proceeds through: $p + \gamma \rightarrow n + \pi^+$, $\pi^0 \rightarrow \gamma + \gamma$, $n \rightarrow p + e^- + \bar{\nu}_e$, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$.

At high energies, the interaction proceeds through: $p + \gamma \rightarrow K^+ + \Lambda/\Sigma$, $K^+ \rightarrow \mu^+ + \nu_\mu$, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$, $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$.

Neutrinos are smoking guns for hadronic processes: $E_\nu \simeq 0.05E_p$. 
Hadronic acceleration in GRBs?

The synchrotron dominated radiation field of the jet represents the photon target of $p\gamma$ interaction. In a simplified scenario of one-zone collision, the optical depth reads as

$$\tau_{p\gamma} = 0.8 \left( \frac{R}{10^{14}\text{cm}} \right)^{-1} \left( \frac{\Gamma}{10^{2.5}} \right)^{-2} \left( \frac{E_\gamma}{1\text{ MeV}} \right)^{-1} \left( \frac{L_{\text{iso}}}{10^{52}\text{erg/s}} \right)$$

If the collision takes place in the photosphere, then

$$R_{\text{PH}} = \frac{L_{\text{iso}} \sigma_T}{8\pi m_p c^3} \Gamma^{-3} \sim 10^{11} \left( \frac{L_{\text{iso}}}{10^{52}\text{erg/s}} \right) \left( \frac{\Gamma}{10^{2.5}} \right)^{-3} \text{cm}$$

while in the internal shock scenario the dissipation radius is

$$R_{\text{IS}} = \frac{c t_{\text{var}}}{1 + z} \Gamma^2 \sim 10^{13} \left( \frac{t_{\text{var}}}{0.01\text{s}} \right) \left( \frac{\Gamma}{10^{2.5}} \right)^2 \left( \frac{1 + 2.15}{1 + z} \right) \text{cm}$$


Operational neutrino telescopes

- **ANTARES**
  - Deep water
  - 0.01 km³
  - 2008 –

- **KM3NeT**
  - Deep water
  - 1 + 0.006 km³
  - Construction

- **IceCube**
  - Deep ice
  - 1 km³
  - 2011 –

- **IceCube-Gen2**
  - Deep ice
  - ~10 km³
  - Projected, 1st phase imminent

- **Baikal/GVD**
  - Deep water
  - ~1 km³
  - Construction
Mediterranean telescopes

ANTARES Complete since 2008

- 25 storeys / line
- 3 PMTs / storey
- 900 PMTs

\[ \lambda_{\text{abs}} = 60 \text{ m} \]
\[ \lambda_{s} = 270 \text{ m} \]

\( \sim 10 \) Mton

230 ARCA + 115 ORCA lines

KM3NeT Under Construction

- 18 storeys / line
- 1 DOM / storey
- \( \sim 200,000 \) PMTs

\( \sim 200 \text{m} / \sim 650 \text{m} \)

- \( \sim 20 \text{m} / 90 \text{m} \)

2 Gton

\( \sim 6 \) Mton

12 lines

First Generation

First line since 10 years


http://www.km3net.org

Compact

• DOM: 31 3” PMTs
• Digital photon counting
• Directional information
• Wide angle of view
• Cost reduction wrt ANTARES

In water
Neutrino event topologies

Isolated neutrinos interacting within the detector

Upgoing muon tracks
Neutrino event topologies

Isolated neutrinos interacting within the detector

Upgoing muon tracks

Calorimetry + all flavors

Astronomy
Atmospheric neutrino background

Cosmic ray

Dominating at < 100 TeV

$p$

$\Pi^{+/0}, K^{+/0}$

Conventional atmospheric neutrinos

$\nu_e : \nu_\mu : \nu_\tau$

$1 : 2 : 0$

$\sim E^{-3.7}$

Cosmic ray

Dominating at > 100 TeV

$D^{+/0}, D_s^{+/0}, \Lambda_c^{+/0}$

Prompt atmospheric neutrinos

$\nu_e : \nu_\mu : \mu$

$1 : 1 : 1$

$\nu_\tau \sim 1/20 \times \nu_\mu$

$\sim E^{-2.7}$
and atmospheric muon background

\[ \nu_\mu N \rightarrow \mu X \]

Search for neutrino induced events, mainly \( \nu_\mu N \rightarrow \mu X \), up-going

Down-going \( \mu \) from atm. showers

\[ \frac{\mu_{\text{upgoing}}}{\mu_{\text{atm}}} \sim 10^{-6} \text{ at 3500m w.e. depth} \]

\[ S/N \sim 10^{-10} \]

Still some background from atmospheric neutrinos
The HESE event sample

“Vetoing the muon produced by the same parent meson decaying in the atmosphere”

\[ \pi \rightarrow \mu^{atmo} + \nu^{atmo}_\mu \]

- Detects penetrating muons
- Reduced effective volume (400 MTon)
- Sensitive to all flavors
- Sensitive to the entire sky

Schonert et al., PRD 79 (2009) 4

\[ E_v \sim 60 \text{ TeV} \] in IceCube
The era of neutrino astronomy
The era of neutrino astronomy

\[
\frac{d\phi}{dE}(\nu_\mu + \bar{\nu}_\mu) = (1.01^{+0.26}_{-0.23}) \left( \frac{E}{100 \text{ TeV}} \right)^{-2.19\pm0.10} \times 10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}
\]

\[
\frac{d\phi}{dE}(\nu + \bar{\nu})_{\text{HESE}} = (2.46 \pm 0.8) \left( \frac{E}{100 \text{ TeV}} \right)^{-2.92} \times 10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}
\]

Tracks
119 TeV - 4.8 PeV
6.7\sigma

HESE
60 TeV - 10 PeV
8\sigma
EXTRAGALACTIC SOURCES APPEAR TODAY
THE MOST REALISTIC CANDIDATES
Identification of ν-sources: open questions

→ SPECTRUM
- Is the IceCube flux an unbroken power law all the way up to 100 PeV? Is there a break or a cut-off?
- Is it a one-component flux?

→ COMPOSITION
- Has the IceCube flux an extra-galactic origin? Which sources contribute it the most? What is the connection with UHECR sources?
- What is the amount of Galactic component?

→ ANISOTROPY
- Is the IceCube flux truly isotropic?
- Why don’t we see multiplets?
Identification of v-sources: methods

Several strategies to look for v-sources:

1. **Clustering** of neutrino events (all-sky scan);

2. **Catalog search**, i.e. at pre-defined sky positions, as indicated by MM studies (typically bright sources in EM wavelengths): e.g. population & stacking analyses;

3. **MM alerts** for extremely energetic events. So far, only this strategy has lead to positive results:

   → **TXS 0506+056** & **IC170922A** \(^1\) IceCube Coll. et al., Science 361 (2018)

   → **TDE AT2019dsg** & **IC191001A** \(^2\) R. Stein et al., arXiv:2005.05340
Catalog search: transient sources

• GRBs are promising neutrino candidate sources, given their transient nature.

• Background is integrated in a limited time window, which is defined by the T90, assuming coincident neutrino-photon emission during the prompt phase of the burst.

• Still, it is necessary to select sources below the detector’s horizon at the occurrence of the transient event, as to reduce the huge atmospheric muon background.

• Two ANTARES analyses are presented in the following:
  • promising bright GRBs;
  • diffuse search from the GRB population in 2007-2017.
Catalog search: transient sources

We look for muon neutrinos in spatial and temporal coincidence with the GRB occurrence:

- Angular search window around source position:
  \[ \alpha = 10^\circ \]

- Temporal search window around T0:
  \[ T_{\text{search}} = T_{90} \pm 30\% T_{90} \pm 2 \text{ s} \]
Catalog search: transient sources

- Discrimination between signal and background relies upon their different **spatial distribution**, which is obtained through ad-hoc **Monte Carlo simulations** of the detector’s response:

  ![Graph showing signal and background PDFs]

  The spatial PDF is centered in the source position, while the background is considered flat in the search cone angle.

  Albert et al. [ANTARES Coll.], MNRAS 500 (2021) 4

- Optimization is performed individually for each GRB, based on an **extended maximum likelihood ratio**

  \[
  Q = \max_{\mu'_s \in [0; n_{\text{tot}}]} \left( \sum_{i=1}^{n_{\text{tot}}} \log \frac{\mu'_s S(\alpha_i)}{\mu'_b B(\alpha_i)} - \mu'_s \right)
  \]
ANTARES search for $\nu$ from individual bright GRBs

- Source selection:
  - Measured gamma-ray fluence is $F_\gamma > 10^{-4} \text{ erg/cm}^2$;
  - Redshift of the progenitor is measured;
  - GRB observable in 2008-2013, from below the ANTARES horizon at T0.

→ GRB080916C, GRB110918A, GRB130427A, GRB130505A

Adrian-Martinez et al. [ANTARES Coll.], MNRAS 469 (2017) 1

- Search optimization on individual GRBs: pseudo-experiments are run in order to optimize the quality parameter of the reconstructed track, as to yield the maximum discovery potential of the model (MDP)

$$MDP = P(Q \geq Q_p^{\text{th}} | \mu_s) = \int_{Q_p^{\text{th}}}^{\infty} P(Q | \mu_s) dQ = \sum_{n_s=0}^{\infty} P(n_s | \mu_s) \int_{Q_p^{\text{th}}}^{\infty} h_{n_s}(Q) dQ$$
ANTARES search for $\nu$ from individual bright GRBs

Distributions of the test statistics:

- $h_0(Q)$ bkg only
- $h_1(Q)$ 1 signal event + bkg
- $h_2(Q)$ 2 signal events + bkg
- $h_3(Q)$ 3 signal events + bkg

$$p = P(Q \geq Q_p^{\text{thres}} | \mu_b) = \int_{Q_p^{\text{thres}}}^{\infty} h_0(Q) dQ$$
ANTARES search for $\nu$ from individual bright GRBs

**PHOTOSPHERIC SCENARIO**  **INTERNAL SHOCK SCENARIO**

Data unblinding at optimal cuts results in **no neutrino detection**.

Neutrino flux computation assuming $f_p=10$ and $\Gamma=316$:

**PH analytical model** from Zhang & Kumar, Phys. Rept. 561 (2015) 1

**IS numerical model** from Hummer et al., ApJ 721 (2010) 630 (NeuCosmA)

Adrian-Martinez et al. [ANTARES Coll.], MNRAS 469 (2017) 1
ANTARES search for $\nu$ from individual bright GRBs

For each GRB, the parameter space of the models was investigated:

\[
\int_{0}^{\infty} E_\nu F_\nu(E_\nu) dE_\nu = \frac{1}{8} f_p [1 - (1 - \langle x_{p \rightarrow \pi} \rangle) \tau_{p\gamma}] \int_{E_{\min}}^{E_{\max}} E_\gamma F_\gamma(E_\gamma) dE_\gamma
\]
1. GRB selection for the years from 2007 to 2017

GRBs from Fermi, Swift, and Konus-Wind satisfying the following conditions are selected:

- T90 (~ duration) measured and > 2s (long GRBs);
- Gamma-ray spectrum is measured;
- Position measured and satellite angular uncertainty <10°;
- One among fluence and redshift is measured;
- Below ANTARES horizon at trigger time (up-going events);

→ sample of 784 GRBs
1. GRB selection for the years from 2007 to 2017

equatorial coordinates
ANTARES diffuse search for $\nu$ from GRBs in 2007-2017

2. Analysis features

- We explore the selected GRB sample by assuming the one-zone internal shock scenario of the fireball model.
- We investigate the uncertainties connected to the lack of knowledge of some model parameters on neutrino expected flux.

- 89% of the sample has unknown $z$;
- 68% of the sample has unknown $t_{\text{var}}$;
- $\Gamma$ is unknown for the entire sample.

Instead of assuming a fixed value for these unknowns, we randomly extract their values from distributions obtained by satellites with large statistics.
ANTARES diffuse search for $\nu$ from GRBs in 2007-2017

2. Analysis features

For each GRB of the sample, **1000 extractions** are realized:


**https://swift.gsfc.nasa.gov/archive/grb table/**

assumed in previous stacking analyses
2. Analysis features

From extracted redshift, \( \Gamma \) is derived thanks to correlation with \( L_{\text{iso}} \):

\[
\Gamma = 249 \left( \frac{L_{\text{iso}}}{10^{52} \text{ erg/s}} \right)^{0.30}
\]

for each GRB, we can compute \( \langle E^2 \nu F_\nu \rangle \pm 2\sigma \)
ANTARES diffuse search for $\nu$ from GRBs in 2007-2017

2. Analysis features

$$\langle E_{\nu}^2 F_{\nu} \rangle \pm 2\sigma$$
2. Analysis features

The stacking technique allows to derive the GRB sub-sample that is able to provide the highest discovery potential of the model. In order to do so, two strategies are possible:

- Introduce a weight factor according to $\nu$ flux: would highly depend on the signal modelling;

- Consider the individual source contribution to the overall MDP, while accounting for a trial factor in the definition of the $p$-value in order to have the same overall probability of false discovery:

$$p = 1 - \sigma \quad \rightarrow \quad p' = \frac{1 - \sigma}{TF}$$
2. Analysis features

The search is optimized in the stacking MDP:

\[ MDP(N_{\text{GRB}}) = 1 - \prod_{i=1}^{N_{\text{GRB}}} (1 - MDP_i) \]

Maximum values:

- MDP(N=82) = 0.010
- MDP(N=430) = 0.028
- MDP(N=482) = 0.14

Selecting entire sample:

- MDP(N=784) = 0.09
- MDP(N=784) = 0.027
- MDP(N=784) = 0.14
2. Analysis features

Hence, **stacking the entire GRB sample**, we obtain:

1. cumulative neutrino fluence:

\[
E_{\nu_\mu}^2 F_{\nu_\mu} = \sum_{i=1}^{N_{GRB}} (E_{\nu_\mu}^2 F_{\nu_\mu})^i
\]

2. stacking neutrino flux (quasi-diffuse):

\[
E_{\nu_\mu}^2 \phi_{\nu_\mu} = \sum_{i=1}^{N_{GRB}} (E_{\nu_\mu}^2 F_{\nu_\mu})^i \frac{1}{4\pi} \frac{1}{N_{GRB}} 667 \text{yr}^{-1}
\]
After data unblinding, **no event** passed the selection criteria: hence, we derived an upper limit given the expected signal events

\[ n_s(N_{GRB} = 784) = 0.03^{+0.14}_{-0.02} \]

![Graph showing E^2*phi_{ν_μ} vs. E_{ν_μ} (GeV) with data points and error bars](image-url)
IceCube search for $\nu$ from GRBs

The latest IceCube search refers to:

- **All flavor** (tracks+cascades);
- **All sky** (upgoing+dowgoing);
- Sample of **1172 GRBs**, looking for neutrino spatial and temporal coincidences with the prompt phase of gamma-ray emission.
Latest results: TeV GRBs

A major advancement has been recently achieved with the detection of TeV emission from GRBs by IACTs:

http://tevcat2.uchicago.edu
ANTARES search for $\nu$ from TeV GRBs

No neutrinos were observed in ANTARES in coincidence with the prompt and afterglow of the bursts:

- **Real time alert** with upgoing muon tracks
  - GCN 25582 for GRB190829A
- **Tailored offline analysis** with tracks and cascades

<table>
<thead>
<tr>
<th>Event</th>
<th>$\delta t_{\text{total}}$</th>
<th>$\delta t_{\text{up}}$</th>
<th>$\delta t_{\text{down}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 180720B</td>
<td>12.1 h</td>
<td>7.7 h</td>
<td>4.4 h</td>
</tr>
<tr>
<td>GRB 190114C</td>
<td>2805 s</td>
<td>-</td>
<td>2805 s</td>
</tr>
<tr>
<td>GRB 190829A</td>
<td>8.1 h</td>
<td>2.85 h</td>
<td>5.25 h</td>
</tr>
</tbody>
</table>

Albert et al. [ANTARES Coll.], arXiv:2011.11411

<table>
<thead>
<tr>
<th>GRB 180720B</th>
<th>GRB 190114C</th>
<th>GRB 190829A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{0,\uparrow}^{90%}$ (GeV·cm$^{-2}$)</td>
<td>$\lesssim 1.5$</td>
<td>-</td>
</tr>
<tr>
<td>$\phi_{0,\downarrow}^{90%}$ (GeV·cm$^{-2}$)</td>
<td>$\lesssim 10$</td>
<td>$\lesssim 1.6$</td>
</tr>
<tr>
<td>$E_{5-95%}^{\uparrow}$ (2.5 TeV – 4.0 PeV)</td>
<td>-</td>
<td>$\lesssim 2 \times 10^{53}$</td>
</tr>
<tr>
<td>$E_{\nu,\text{iso}}^{90%}$ upgoing (erg)</td>
<td>$\lesssim 2 \times 10^{55}$</td>
<td>-</td>
</tr>
<tr>
<td>($\frac{I_{\pi}}{f_{\nu}}$)$_{\uparrow}$</td>
<td>$\lesssim 80$</td>
<td>-</td>
</tr>
<tr>
<td>$E_{5-95%}^{\downarrow}$ (20 TeV – 30 PeV)</td>
<td>7 TeV – 20 PeV</td>
<td>15 TeV – 25 PeV</td>
</tr>
<tr>
<td>$E_{\nu,\text{iso}}^{90%}$ downgoing (erg)</td>
<td>$\lesssim 1 \times 10^{56}$</td>
<td>$\lesssim 8 \times 10^{54}$</td>
</tr>
<tr>
<td>($\frac{I_{\pi}}{f_{\nu}}$)$_{\downarrow}$</td>
<td>$\lesssim 600$</td>
<td>$\lesssim 2 \times 10^{3}$</td>
</tr>
<tr>
<td>$E_{\gamma,\text{iso}}$ (erg)</td>
<td>$6 \times 10^{53}$ [50; 300 keV]</td>
<td>2.5$\times 10^{53}$ [1 keV; 10 MeV]</td>
</tr>
<tr>
<td>[2 \times 10^{52} [300 \text{ GeV; 1 TeV}]]</td>
<td>[2 \times 10^{50} [50 \text{ keV; 300 keV}]]</td>
<td>2$\times 10^{50}$ [50 keV; 300 keV]</td>
</tr>
</tbody>
</table>
Neutrinos from chocked GRBs

Unsuccessful GRBs might have unique signatures in neutrinos

Thermalized photons in the reverse shock have typical temperatures of

\[ kT_\gamma \approx 741 \text{ eV} \ L_{\text{iso}}^{1/8} \epsilon_e^{-1/4} t_{\text{jet}}^{-1/4} \rho_H^{-7/8} \]

From the forward shock region, they’re energy reads as

\[ E_{\gamma, \text{IS}}^{\text{max}} = \Gamma E_{\gamma, \text{RS}}^{\text{max}} \approx 210 \text{ keV} \]
Neutrinos from chocked GRBs

We performed a **Monte Carlo** simulation of py interactions with

1. accelerated protons:

\[
\frac{dN_p}{dE_p} = k_{MC} E_p^{-2}
\]

2. target photons

\[
\frac{dN_\gamma}{dE_\gamma} = 2 \sqrt{\frac{E_\gamma}{\pi}} \left( \frac{1}{kT_\gamma} \right)^{\frac{3}{2}} e^{-\frac{E_\gamma}{kT_\gamma}}
\]

---

Fasano et al., arXiv:2021:03502
Neutrinos from choked GRBs

studying both the region of the $\Delta^+$ resonance, as well as the out-of-resonance region

\[ p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \smallskip \\ n + \pi^+ \end{cases} \]

Fasano et al., arXiv:2021:03502
Neutrinos from choked GRBs

1. EXPECTED EVENT RATES

\[ k_{MC} \int_{E_{\text{min}}}^{E_{\text{max}}} E_p \frac{dN_p}{dE_p} dE_p = E_{\text{iso}} \implies \Phi_{\nu_\mu}^{\text{Earth}} = k_{MC} \frac{\Omega}{4\pi D(z)^2} F_{\nu_\mu}(E_{\nu_\mu}) \]

Benchmark of the model:
\( z = 1, E_{\text{iso}} = 10^{53} \text{ erg}, t_{\text{jet}} = 100 \text{ s}, \Gamma = 100, \Omega = 0.13 \text{ sr} (\alpha = 0.2 \text{ rad}) \)

<table>
<thead>
<tr>
<th>Detector</th>
<th>( \delta )</th>
<th>( N_{\text{events}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANTARES</td>
<td>( 0^\circ &lt; \delta &lt; 45^\circ )</td>
<td>0.011</td>
</tr>
<tr>
<td></td>
<td>( -45^\circ &lt; \delta &lt; 0^\circ )</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>( -90^\circ &lt; \delta &lt; -45^\circ )</td>
<td>0.025</td>
</tr>
<tr>
<td>KM3NeT</td>
<td>Mean ( \delta )</td>
<td>2.57</td>
</tr>
<tr>
<td>IceCube</td>
<td>( 0^\circ &lt; \delta &lt; 90^\circ )</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
<td>( 0^\circ &lt; \delta &lt; 30^\circ )</td>
<td>2.45</td>
</tr>
</tbody>
</table>

Fasano et al., arXiv:2021:03502
Neutrinos from chocked GRBs

2. CONTRIBUTION TO THE DIFFUSE NEUTRINO FLUX

Assuming chocked GRBs follow the SRF, \( \rho(z) = \frac{(1 + z)^{2.7}}{1 + [(1 + z)/2.9]^{5.6}} \)

\[
\frac{E_{\nu_{\mu}}}{dE_{\nu_{\mu}}^{\text{obs}}} \left( \frac{dN_{\nu_{\mu}}^{\text{obs}}}{dE_{\nu_{\mu}}^{\text{obs}}} \right) = \frac{c}{4\pi H_0} \int_0^8 E_{\nu_{\mu}} \frac{dN_{\nu_{\mu}}}{dE_{\nu_{\mu}}} ((1 + z)E_{\nu_{\mu}}) \frac{\frac{\Omega}{4\pi} R_0 \rho(z) dz}{(1 + z) \sqrt{\Omega_\Lambda + \Omega_M (1 + z)^3}}
\]

Implying a local rate of chocked GRBs of \( R_0 = (0.3 \pm 0.1) \) Gpc\(^{-3}\) yr\(^{-1}\) consistent with standard GRBs

Fasano et al., arXiv:2021:03502

Conclusions

• The origin of IC neutrinos remains so far elusive, though overall a major contribution from EG sources appears preferable;

• ANTARES has performed neutrino searches from 4 bright GRBs and from the population of long GRBs occurred in the years 2007-2017 through upgoing muons in spatial and temporal coincidence with the gamma-ray emission. No event satisfied the optimized cuts and limits were derived, as well as constraints in the parameter space of the models;

• Upper limits derived in the stacking search of ANTARES disfavor GRBs as major contributors of the IC diffuse flux (<10% below 100 TeV), consistently with IC results;

• Choked GRBs appear a viable alternative, possibly dominating the IC flux if their local rate is of the order of standard GRBs.
THANKS FOR YOUR KIND ATTENTION