Search for Neutrino Emission from Fast Radio Bursts with IceCube

Donglian Xu

Samuel Fahey, Justin Vandenbroucke and Ali Kheirandish

for the IceCube Collaboration
**Fast Radio Bursts - Discovery in 2007**

Lorimer et al., *Science* 318 (5851): 777-780

\[
\Delta t_{\text{delay}} = \frac{e^2}{2\pi m_e c^3} \cdot \text{DM} \cdot w^{-2}
\]

\[
= 1.5 \times 10^{-24} \text{ s} \cdot \text{DM} \cdot w^{-2}
\]

\[
\text{DM} = \int n_e dl = 375 \pm 1 \text{ cm}^{-3} \text{ pc}
\]

“very compact”

“extragalactic”?

\[
\delta t_{\text{width}} = 4.6 \text{ ms} \left(\frac{\omega}{1.4 \text{ GHz}}\right)^{-4.8\pm0.4}
\]

\[
\int dt I_\omega \simeq 150 \pm 50 \text{ Jy ms} @ 1.4 \text{ GHz}
\]

- A total of ~23 FRBs detected to date.
- Estimated FRB event rate is ~1,000/day

Galactic DM: 25 cm\(^{-3}\) pc

SMC

- J0045–7042 (125)
- J0113–7220 (76)
- J0111–7131 (70)
- J0045–7319 (105)
- J0131–7310 (205)
- J0131–7131 (125)
Fast Radio Bursts Emitting Neutrinos?

- **Blitzar “Cataclysmic”**
  

- **Binary neutron star merger**
  

- **Evaporating primordial black holes**
  
  [Halzen et al., PRD 1995]
  
  “MeV neutrinos”

- **Magnetar/SGRs hyperflares**
  

  [Halzen et al. (2005) astro-ph/0503348]

  “TeV neutrinos”? → this work

No concrete neutrino production models yet
**IceCube Detector**

**Goal:** detecting TeV-PeV astrophysical neutrinos

Construction completed in December 2010

**IceCube Laboratory**

Data is collected here and sent by satellite to the data warehouse at UW–Madison

**Digital Optical Module (DOM)**

5,160 DOMs deployed in the ice

86 strings of DOMs, set 125 meters apart

60 DOMs on each string

DOMs are 17 meters apart

Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

Antarctic bedrock
(1) **Track: charged current** $\nu_\mu$
- $<1^\circ$ Angular resolution
- Factor $\sim 2$ energy resolution

(2) **Cascade / Shower:** all neutral current, charged current $\nu_e$, low-E charged current $\nu_\tau$
- $10^\circ$ Angular resolution above 100 TeV
- 15% energy resolution on deposited energy

IceCube has detected a diffuse astrophysical neutrino flux, but **no TeV neutrino point sources** have been identified to date.
Burst times cover IceCube data taking seasons from 2010 to 2015 (6 years)

A total of 29 FRBs (11 unique locations).

Repeated bursts are treated as unique bursts in space & time
Event Samples & Background Modeling

<table>
<thead>
<tr>
<th>North</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>(DEC &gt;= -5°)</td>
<td>(DEC &lt; -5°)</td>
</tr>
<tr>
<td><strong>842,597 events</strong></td>
<td><strong>379,261 events</strong></td>
</tr>
<tr>
<td><em>(collected from 2011-2015)</em></td>
<td><em>(collected from 2010-2014)</em></td>
</tr>
</tbody>
</table>

“dominated by atmospheric neutrinos”  “dominated by atmospheric muons”

A total of 1.2 million events in 6 years

Background PDF derived from off-time data

**Northern sky IC86-1 background PDF**

Integrated Fit / Data vs. Cos(zenith)


Donglian Xu | High-E Neutrinos from Fast Radio Bursts | TeVPA2017, Columbus
The likelihood for observing \( N \) events with properties \( \{x_i\} \) for \((n_s + n_b)\) expected number of events is:

\[
L(N, \{x_i\}; n_s + n_b) = \frac{(n_s + n_b)^N}{N!} \cdot \exp(-(n_s + n_b)) \cdot \prod_{i=1}^{N} P(x_i)
\]

The normalized probability of observing event \( i \) is \( P(x_i) : \)

\[
P(x_i) = \frac{n_s S(x_i) + n_b B(x_i)}{n_s + n_b}
\]

\[
S_i = S_{\text{time}}(t_i) \cdot S_{\text{space}}(\vec{x}_i)
\]

\[
B_i = B_{\text{time}}(t_i) \cdot B_{\text{space}}(\vec{x}_i)
\]

“temporal” + “spatial”

\[
T := \ln \frac{L(N, \{x_i\}; n_s + n_b)}{L_0(N, \{x_i\}; n_b)}
\]

\[
T := -\hat{n}_s + \sum_{i=1}^{N} \ln(1 + \frac{\hat{n}_s S_i}{<n_b>B_i})
\]
Search Strategy

• **Stacking**

  “Distributed fluence test”

  - Model independent

  - Expanding time windows centered at burst times

  - 25 time windows from 10 ms to 2 days, expanding as $2^i \times 10$ ms ($i = 0, \ldots, 24$)

• **Max-burst**

  “Single bright neutrino source test”

  - Model independent

  - Expanding time windows centered at burst times

  - 25 time windows from 10 ms to 2 days, expanding as $2^i \times 10$ ms ($i = 0, \ldots, 24$)
25 time windows from 10 ms to 2 days, expanding as $2^i \times 10 \text{ ms (i =0, ..., 24)}$

One coincident event can be discovery in the short time windows
25 time windows from 10 ms to 2 days, expanding as $2^i \times 10$ ms ($i = 0, \ldots, 24$)

One coincident event can be discovery in the short time windows
Results - Most Significant Bursts & Events

North Max-burst

Most optimal time window:
\[ \Delta T = 655.36 \text{s} \]

South Max-burst

Most optimal time window:
\[ \Delta T = 167772.16 \text{s} \]
Results - Upper Limits

North Stacking

\[ \Delta T = 655.36 \text{ s} \]

North Max-burst

\[ \Delta T = 655.36 \text{ s} \]
Results - Upper Limits

South Stacking

- $E^{-2}$ sensitivity
- $E^{-2.5}$ sensitivity
- $E^{-3}$ sensitivity

IceCube Preliminary

South Max-burst

- $E^{-2}$ sensitivity
- $E^{-2.5}$ sensitivity
- $E^{-3}$ sensitivity

IceCube Preliminary

$E^2 F @ 100 \text{ TeV (GeV cm}^{-2})$

$\Delta T (s)$

$10^{-2}$ $10^{-1}$ $10^0$ $10^1$ $10^2$ $10^3$ $10^4$ $10^5$
Conclusion & Outlook

- Fast radio bursts (FRBs) could emit high energy neutrinos

- A maximum likelihood analysis has been established to search for spatial and temporal coincidence between IceCube neutrinos and FRBs

- No significant correlations between IceCube neutrinos and FRBs were found in 6 years of data.

- Most stringent limits on neutrino fluence from FRBs have been set to be \(~0.04\, \text{GeV cm}^{-2}\). Publication is in preparation.

- IceCube can now quickly follow up on the FRBs to be detected in the forthcoming future, adding a multi-messenger window to help untangle the FRB mystery
Back up slides
Assume the same escape time $t_0$:

$$\Delta t = D \cdot \left| \frac{1}{c} - \frac{1}{v_\nu} \right| = D \cdot \left( \frac{1}{\sqrt{1 - \frac{1}{\gamma^2}}} - 1 \right) \text{ s}$$

$$\gamma = \frac{E_\nu}{m_\nu}, \ c = 1$$

$$\Delta t \simeq \frac{1}{2} \cdot D \cdot \left( \frac{m_\nu}{E_\nu} \right)^2$$

$$\Delta t \simeq \frac{1}{2} \cdot \left( \frac{m_\nu}{\text{eV}} \right)^2 \cdot \left( \frac{\text{MeV}}{E_\nu} \right)^2 \cdot \left( \frac{D}{10 \text{ kpc}} \right)$$
Neutrino vs Photon Arrival Times

For $z \simeq 0.5$, $D_{\text{light}} \simeq 2$ Gpc

For 10 MeV neutrinos:

$$\Delta t \simeq \frac{1}{2} \cdot \left( \frac{1 \text{ eV}}{\text{eV}} \right)^2 \cdot \left( \frac{\text{MeV}}{10 \text{ MeV}} \right)^2 \cdot \left( \frac{2 \text{ Gpc}}{10 \text{ kpc}} \right) \simeq 1000 \text{ s}$$

For 1 TeV neutrinos:

$$\Delta t \simeq \frac{1}{2} \cdot \left( \frac{1 \text{ eV}}{\text{eV}} \right)^2 \cdot \left( \frac{\text{MeV}}{1 \text{ TeV}} \right)^2 \cdot \left( \frac{2 \text{ Gpc}}{10 \text{ kpc}} \right) \simeq 1.0 \times 10^{-7} \text{ s}$$

Photon trapped time unknown