Search for GRB-correlated neutrino events in Borexino

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MeV neutrinos from GRB

**GRB (gamma-ray burst)**
- the most energetic events known in the Universe
- typical energy release of $10^{54}$ erg
- extragalactic events
- source?: massive star collapsing into NS or BH ("long GRB") or binary mergers of NS + NS/BH ("short GRB") [W.H. Lee et al., 2006, P. Meszaros, 2006]

**MeV neutrinos from GRBs**
- Thermal neutrinos from accretion disk: MeV neutrino cooling dominates, still small to be observed
- $10^{10}$ larger energy release than gammas in some models for the origin of GRBs
  [V. Berezinsky et al., 2001, K.S.Cheng et al., 2010]
  i.e. for a typical GRB with gamma energy release of $3 \times 10^{51}$ erg at $z=2$, predicted fluence of
  $\sim 10$ MeV neutrino is $\sim 10^8 - 10^9$ cm$^{-2}$ (compare to solar neutrinos $\sim 6 \times 10^{10}$ cm$^{-2}$ s$^{-1}$ or to geo neutrinos $\sim 5 \times 10^6$ cm$^{-2}$ s$^{-1}$)
  ➡ accessible with existing neutrino detectors’ sensitivity
GRB timing window

to predict neutrino arrival time, things to consider: GRB duration time, time difference of neutrino production to the gamma production, time of flight (tof) delay, ...

GRB duration time: typically <2s ("short GRB") or 10~100s ("long GRB")

⇒ instead of model-dependent analysis, open conservative timing window


Time delay as a function of redshift

For typical GRB z~2, tof-delay ~800s

for highest z in our dataset z~8.2, tof-delay ~900s

Input neutrino mass = 0.0872 eV
The Borexino Experiment

in the Laboratori Nazionali del Gran Sasso (LNGS)
1400m under the Apennine Mountains (3800m water equivalent, $1\mu m^2/h$)
World-cleanest solar neutrino detector with low energy threshold ($E_{th} \sim 200keV$)

Liquid Scintillator in Nylon Vessel with 278t active target

Primary & FADC (Flash ADC) : two DAQ systems
- primary Borexino readout optimized up to a few MeV
- fast waveform digitizer system tuned for above 1 MeV

Buffer volume: 800t, PC+DMP radioactivity shielding

Active volume: 278t, $r=4.25m$, PC+PPO 2212 PMTs (34% photo coverage) light yield $\sim 500p.e./MeV$
GRB neutrino searches in Borexino

Goals: search for time correlations between GRBs and Borexino events

GRB timing information:
Database compiled by the IceCube collaboration - from satellites as SWIFT, Fermi, INTEGRAL, AGILE, Suzaki, Konus/WIND
Period of interest: December 30, 2007 — November 28, 2015
(2350 GRBs in the database)

3 different strategies:
• Search for electron anti-neutrinos via inverse beta-decay(IBD)

• Search for elastic scattering interactions from all neutrinos

• Search for burst events

* all strategies are repeated with both(primary and FADC) DAQ systems
Inverse beta-decay search

**inverse beta-decay on protons in the scintillator**

- 1.8MeV energy threshold
- Coincidence search:
  - spatial info $\Delta R(<1\text{m})$ & timing info $(20\mu\text{s}<\Delta T<1280\mu\text{s})$
  - between prompt & delayed events
- electron anti-neutrino energy reconstruction:
  \[ E_{\bar{\nu}_e} = E_{\text{prompt}} + 0.784\text{ MeV} \]

2302 days of Borexino data (December 2007 - November 2015)

Timing window $\Delta t = 10\times10^3\text{s}(\pm 5\times10^3\text{s})$ around GRB time
- requiring data coverage >80%, 1791 GRBs left for the search
Fluence limit on electron antineutrinos

90% upper limit on GRB events
• Binned analysis for energy range 2-15 MeV (1 MeV interval)
  Signal: IBD coincident events in timing window in each bin
  Background: IBD coincidence events in off-timing window in each bin
  \( N_{90}^{IBD} = \frac{\mu_{90}}{N_{GRB}} \) : calculated by Feldman-Cousins procedure

model-independent interpretation
• For unknown neutrino spectrum, set fluence limit on mono-energetic neutrinos
  \[ \Phi_{\bar{\nu}_e}(E_{\bar{\nu}_e}) = \frac{N_{90}^{IBD}(E_{\bar{\nu}_e})}{N_p \langle \varepsilon \rangle \sigma(E_{\bar{\nu}_e})} \]

\( N_p = 1.6 \cdot 10^{31} \): number of protons in Borexino
\( \langle \varepsilon \rangle \): the average detection efficiency evaluated by MC simulation
\( \sigma \): IBD cross-section
v-e elastic scattering search

Energy spectrum of recoil electrons:
flat distribution in reconstructed energy range 0-\(T_{\nu}^{\text{max}}\)

\[
T_{\nu}^{\text{max}} = \frac{2E_{\nu}^2}{m_e + 2E_{\nu}}
\]
i.e. \(T_{\nu}^{\text{max}}=4.8\text{MeV}\) for \(E_{\nu}=5\text{MeV}\)

Signal timing window \(\Delta t = 2000\text{s (±1000s)}\)
Back ground time window :
-2000 ~ -1000s & 1000 - 2000s (due to event rate fluctuation)

- Requiring both primary and FADC systems active
- Requiring 95% coverage of the data
→ 980 GRB’s remained in search

data used in 2009/12/06 ~ 2015/10/17 (1279.7 days)

- E\(_{\text{th}}\)=1MeV (for \(E_{\nu}=1.5\text{ to } 3.5\text{ MeV}\))
- E\(_{\text{th}}\)=3MeV (4.0 to 5.0 MeV)
- E\(_{\text{th}}\)=5MeV (6.0 to 15.0 MeV)
Fluence limit on all neutrinos

90% upper limit on GRB events

Binned analysis for neutrino energy 1-15 MeV (different lower energy thresholds were applied)

\[ N_{\text{in}}: \text{events in signal timing window in each bin} \]

\[ N_{\text{bgr}}: \text{events in off-timing window in each bin} \]

\[ N^{\nu_e}_{90} = \left( Q(0.9) \times \sqrt{N_{\text{in}} + N_{\text{bgr}}} \right) / N_{\text{GRB}} \]

model-independent interpretation

For unknown neutrino spectrum, set 90% fluence limit for the mono-energetic neutrinos

\[ \Phi_\nu(E_\nu) = \frac{N^{\nu_e}_{90}(E_\nu)}{N_e \sigma_{\text{eff}}(E_\nu)} \]

\( \sigma_{\text{eff}} \) for electron and other flavours, for neutrino/anti-neutrino respectively, assuming 100% contribution

\[ N_e = 8.8 \cdot 10^{31}: \text{the number of electrons in Borexino} \]

\( \sigma_{\text{eff}} \): effective ES cross section
Burst search

Two kinds of GRBs (“long” and “short”) → two different window sizes
- 40s static window (mean duration of long GRBs)
  event selection: >1MeV
- 2s dynamic window (maximum duration of short GRBs)
  event selection: >5MeV

GRB correlated bursts \((t = ±5000s)\):
- 10 bursts with high multiplicity (>8) found in static approach
- 8 bursts with high multiplicity (>6) found in dynamic approach

→ all consistent with random coincidence (simulated by MC)

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>Date and time (GMT)</th>
<th>Burst’s duration, s</th>
<th>Closest GRB</th>
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<tr>
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<td>1.9</td>
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</tbody>
</table>
Conclusion

- 2302 days (December 2007 ~ November 2015) Borexino data was used for GRB-correlated neutrino searches.
- On the search for GRB correlated anti-neutrinos via IBD, set the best limit in the range of 2-8MeV.
- Set the most stringent bounds for GRB correlated fluence of neutrinos/anti-neutrinos of all species below 7MeV via elastic scattering to electrons (first limit for electron antineutrinos below IBD threshold).
- Bursts of events were looked and no correlation to GRB was found.
- First Borexino analysis using FADC data - good agreement between primary-FADC DAQ system was checked.