A Search for Correlation of Neutrino Events in the BOREXINO Detector with Transient Astrophysical Phenomena

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Fundamental problems and applications

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Transient Astrophysical Phenomena:

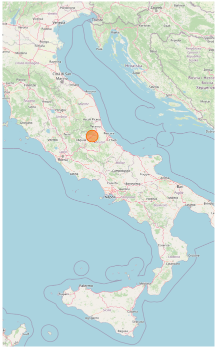
- Singular occurrence
- Short duration: $10^{-3} \sim 10^{2}$ seconds.
- High energy yield $\Rightarrow$ observable from extragalactic ranges.

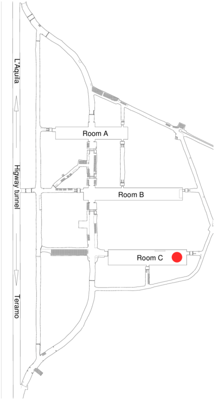
We searched for **correlation** between **neutrino** signals in Borexino and following types of **transients**:

- **GRB** – **G**amma-**R**ay **B**ursts (2016)
- **Solar Flares** (2019)
- **FRB** – **F**ast **R**adio **B**ursts (2022)
- **GW** – **G**ravitational **W**aves (2023)

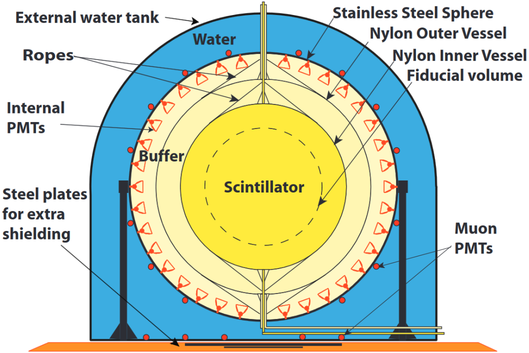
Location: Gran Sasso National Laboratory (INFN) – **3600 m w. e.**

In operation: May 2007 - Oct 2021





The BOREXINO



- **Outer Detector:** 2100 t water, 208 PMTs
- **Inner Detector:** 278 t PC, 2212 PMTs
- **Resolution:** @ 1 MeV:
  $\sigma_E \approx 50$ keV; $\sigma_{pos} \approx 10$ cm
- **Neutrino detection:**
  (ν, e^-) scattering; IBD ($E_\nu > 1.8$ MeV)

Primary electronics: optimized for < 1 MeV (solar neutrino spectroscopy)
Flash ADC system: for energies > 1 MeV

The BOREXINO

Principal background sources:

- Cosmogenic:
  - $\tau \leq 0.3$ s: ^{12}B, ^{8}He, ^{9}C, ^{9}Li...
  - $\tau \geq 0.3$ s: ^{11}Be, ^{10}C, ^{11}C...
- External γ: structural materials, PMTs.
- Nylon vessel surface contamination: ^{210}Pb, U and Th decay chains.
- Organic scintillator: intrinsic ^{14}C + ^{85}Kr, ^{210}Bi, ^{210}Pb

Scintillator purification:

- Ultrafiltration: $> 0.05\ \mu$m particulates
- 80° C distillation: to avoid ^{238}U, ^{232}Th.
- Water extraction: solubles ^{40}K, ^{210}Pb...
- Gas stripping with ultrapure N_2: Ar, Kr, Xe , ^{222}Rn, O_2 (spoils LY).
- ^{14}C: impossible to remove. To minimize: used raw oil from deep and old layers + dedicated pipeline, isotanks.

All detector components had to maintain the **radiopurity** record achieved for the scintillator $\Rightarrow$ custom in-house design, prototyping, assembly, screening...

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Technologies of the Borexino experiment: Introduction

Gianpaolo Bellini *Università degli Studi e INFN* Received 7 April 2014

Gamma-**R**ay **B**urst (GRB)

- Extremely energetic events ($\sim 1 M_{\odot} = 10^{54}$ erg)
- All-sky rate: ≈ 1 event/day
- Duration: $10 - 100$ seconds with possible longer X-ray, optical and radio afterglow
- Short GRB subclass: < 2 s

Possible sources:

- SL Supernovae
- Rotating remnants of massive stars (NS or BH)
- NS+NS, NS+BH mergers

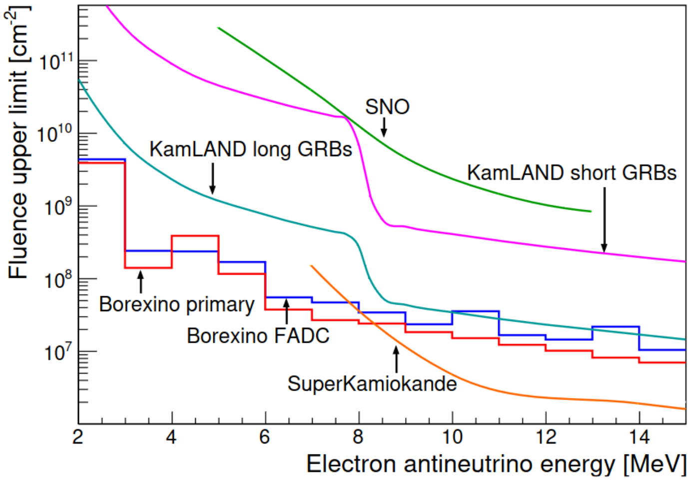
GRB Data & Time Window Selection

IceCube GRB database: satellite data from SWIFT, Fermi, INTEGRAL, AGILE, Suzaki, Konus/WIND.
Contains GRB position, t_{det}, duration, energy spectrum, intensity and redshift (available only for $\sim$ 10% of registered GRBs)

Time Window: for $z \sim 2$ and assuming $m_\nu \leq 87$ meV $\Rightarrow t_{delay} = 800$ s.
$\Delta t_{SIG} = \pm 1000$ s for (ν, e^-) scattering channel
$\Delta t_{SIG} = \pm 5000$ s for IBD channel

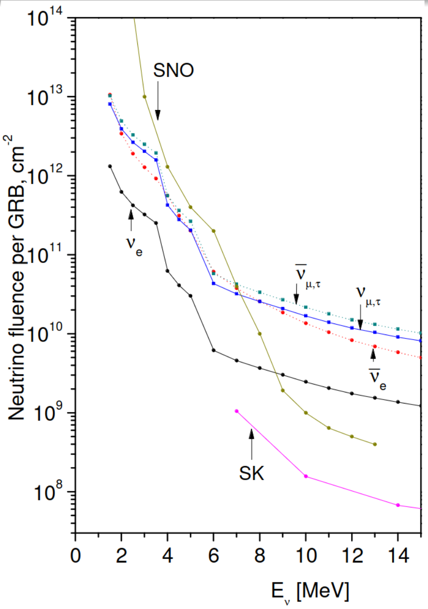
DAQ system	Primary	FADC	Primary + FADC
Period Observed GRBs	Dec 2007 - Nov 2015 2350	Dec 2009 - Nov 2015 1813	Dec 2009 - Nov 2015 1813
Livetime [days]	2302.0	1388.1	1279.7
Used GRBs	1791	1114	980

GRB Limits from IBD



$E_{\bar{\nu}_e}$ [MeV]	$\Phi_{\bar{\nu}_e}$ primary DAQ [cm^{-2}]	$\Phi_{\bar{\nu}_e}$ FADC [cm^{-2}]
2	4.36×10^9	4.87×10^9
3	1.13×10^8	2.64×10^8
4	4.00×10^8	2.49×10^8
6	3.81×10^7	5.67×10^7
10	1.50×10^7	3.57×10^7
14	6.96×10^6	1.04×10^7

GRB Limits from (ν, e^-) scattering



E_ν [MeV]	Φ_{ν_e} [cm^{-2}]	$\Phi_{\bar{\nu}_e}$ [cm^{-2}]	$\Phi_{\nu_{\mu,\tau}}$ [cm^{-2}]	$\Phi_{\bar{\nu}_{\mu,\tau}}$ [cm^{-2}]
1.5	1.31×10^{12}	1.06×10^{13}	8.10×10^{12}	1.03×10^{13}
2	6.25×10^{11}	3.42×10^{12}	3.93×10^{12}	4.93×10^{12}
3	3.23×10^{11}	1.28×10^{12}	2.03×10^{12}	2.50×10^{12}
4	6.24×10^{10}	5.60×10^{11}	4.26×10^{11}	5.60×10^{11}
6	6.18×10^{9}	6.12×10^{10}	4.33×10^{10}	5.77×10^{10}
10	2.46×10^{9}	1.36×10^{10}	1.69×10^{10}	2.17×10^{10}
14	1.37×10^{9}	5.82×10^{9}	9.12×10^{9}	1.15×10^{10}

Fast **R**adio **B**urst (FRB)

- Duration: $\sim 10^{-3}$ seconds
- All-sky rate: $\approx 2 \times 10^3$ events/day (fluence$>$ 2 Jy ms)

Possible sources:

- Repeating: magnetar activity
- Single:
  - Supernova evolution
  - NS/BH Mergers
  - NS collapse

BX Data selection

Transient Approach

- Search for temporal correlation between the most intense FRBs and BX events with $E > 0.25$ MeV
- Generic background reduction:
  - 0.3 s muon veto + PSD
  - $E > 250$ keV vs C^{14}
  - FV 75 cm from the IV nylon sphere (Bi, Tl) = 145 t of PC
- Use complete BX dataset (2007 - 2021)

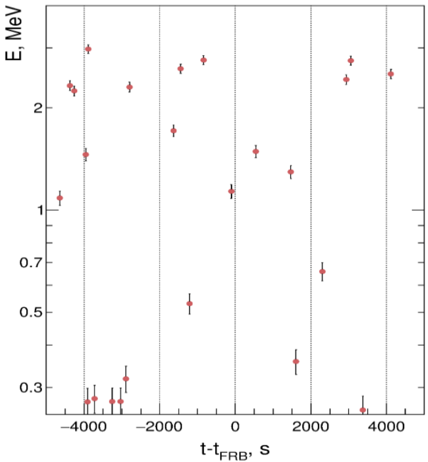
Spectral Approach

- Search for characteristic spectral shape of (ν, e)-scattering.
- Use the most radio-pure dataset (2013 - 2020).
- Advanced cosmogenic veto:
  - 120 s veto after muon in ID > 20 neutron daughters within 1.6 ms trigger gate.
  - 20-s 0.8 m cylindrical veto around muon track.
  - 120 s 1.3 m spherical veto on each neutron within 1.6 post-muon. trigger

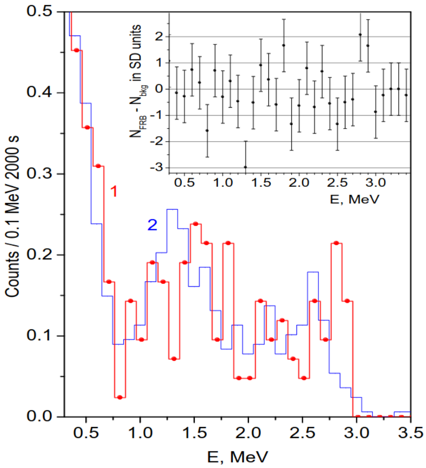
Transient Approach - FRB Data

- **FRB dadasets:**
  - `chime-frb.ca` database by CHIME Radio Telescope
  - `frbcat.org` database: Parkes, Arecibo, Green Bank, UTMOST, ASKAP, FAST, Apertif, VLA. DSA-19, Pushchino.
- **42 FRBs** with $\Phi_{FRBi} > 40$ Jy ms for temporal correlation search.
- $F_{all} = \Phi_{all} N_{all} / T$ s^{-1}
- Excess neutrino events ratio:
  $r = \Phi_{40} / (\Delta t \ F_{all})$ $\Phi_{all} = 7.0$ (Jy ms) per FRB $\Rightarrow r = 0.2$ for time window $\Delta t = 2000$ s

Transient Approach



BX events ($E > 0.25$ MeV) within ±5000 s of FRB 200428 detection time

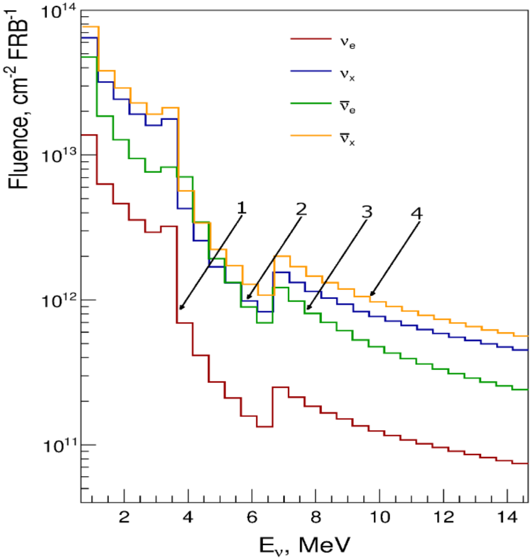


BX events within ±1000 s time window

Normalized BG

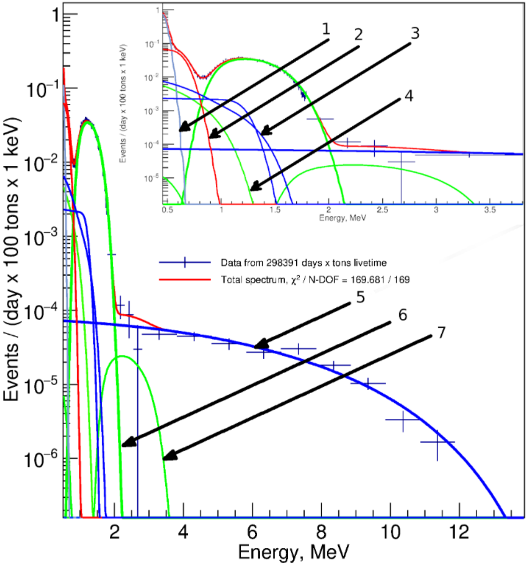
$[-5000 \ldots -1000] \cup [1000 \ldots 5000]$ s

Transient Approach - Limits



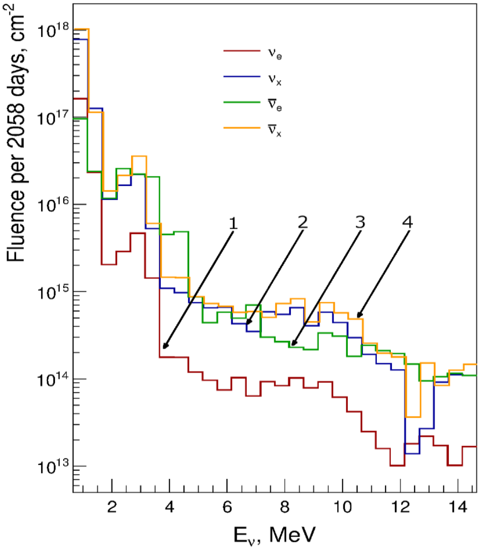
- 90% C.L. upper limits on mono-energetic neutrino fluences for 42 FRBs with $\Phi_{FRB} \geq 40$ Jy ms
- Total electron neutrino fluence per single FRB: $\Phi(\nu_e) \leq 3.69 \times 10^{10}$ cm^{-2}

Spectral Approach - Spectral Fit



- 2058 days live time (298.39 kt · day)
- Spectral fit:
  1. ^{210}Po α-peak
  2. ^{7}Be
  3. CNO + pep
  4. ^{210}Bi β-spectrum
  5. ^{8}B
  6. ^{11}C β^{+}-decay
  7. ^{10}C β^{+}-decay

Spectral Approach - Limits



- 90% C.L. upper limits on mono-energetic neutrino fluences from spectral fit.
- Total electron neutrino fluence per single FRB: $\Phi(\nu_e) \leq 3.69 \times 10^{10}$ cm^{-2}

BX vs. GW

Gravitational **W**aves (GW)

- Continuous
- Spiral
- Stochastic

Possible sources:

- Supernovae
- Binary systems
- Merger events (BH and/or NS)

GRB170817A & GW170817 – 1.7 s delay

GW Data Selection

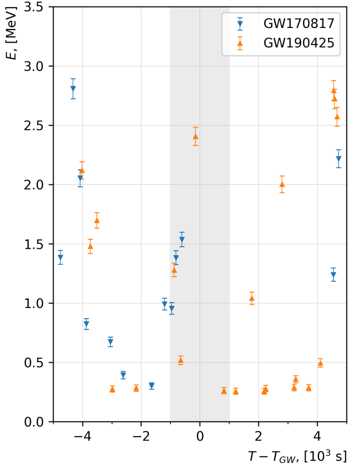
GWTC-3 database: compiled by LIGO and VIRGO (includes 3 observing runs).

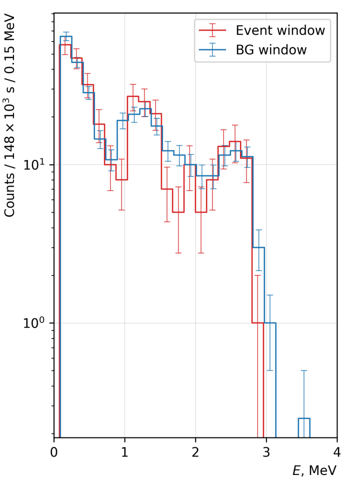
Contains time of event, object masses M_1, M_2, chirp mass δM, final mass, redshift, distance

Sep 2015 - March 2020 93 GW events:

- 87 BH + BH events
- 2 NS + NS events
- 4 NS + BH events

GW Temporal Correlation

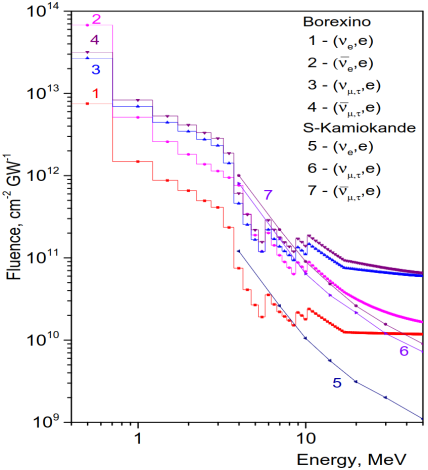




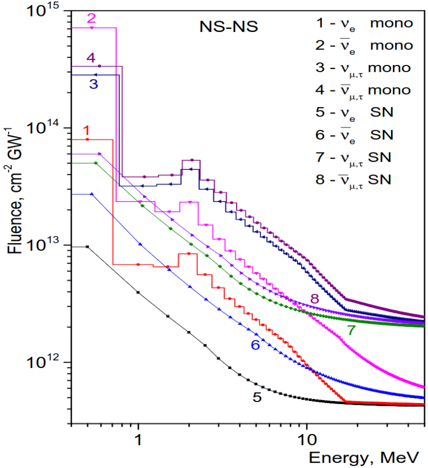
BX events ($E > 0.25$) MeV within ± 5000 s
GW detection time

BX events ($E > 0.25$) MeV within ± 1000 s
Normalized BG
$[-5000 \ldots -1000] \cup [1000 \ldots 5000]$ s

GW Limits from (ν, e^-) scattering

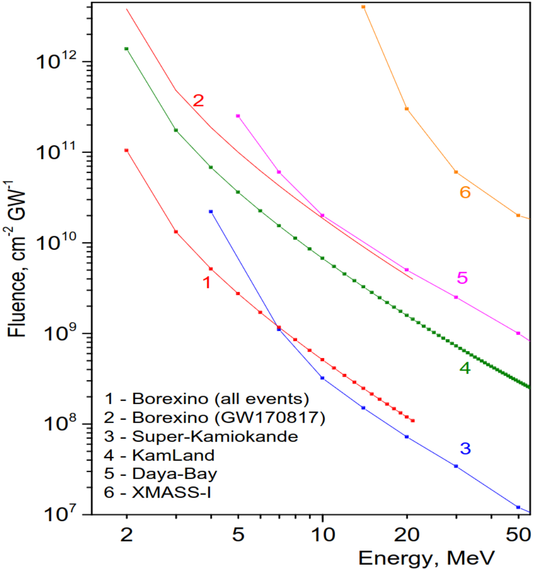


74 GW events



GW170817

GW Limits from IBD



Upper limits on ν_e fluence from IBD reaction:

1. all 74 GW events
2. GW 170817 NS-merger

Conclusions

- **GRB:** searched for temporal correlation. 2350 GRBs within 2007 - 2015 period. No statistically significant correlation $\Rightarrow$ set new limits on GRB correlated ν_x fluences in $1.5 - 15$ MeV energy range.
- **FRB:** searched for temporal correlation + spectral shape contribution. FRB data 2007 - 2021, including 42 with $\Phi_{FRBi} > 40$ Jy ms. No statistically significant excess of events $\Rightarrow$ new limits on ν_x fluences in $0.5 - 15$ MeV energy range from temporal correlation + new limits in $0.5 - 50$ MeV from spectral shape approach.
- **GW:** searched for temporal correlation. 74 GW events from 2015 - 2020 data. No statistically significant excess of events $\Rightarrow$ set new limits on ν_x fluences in $0.5 - 50$ MeV range.

References

Astroparticle Physics 86 (2017) 11–17

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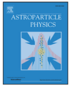

Borexino's search for low-energy neutrino and antineutrino signals correlated with gamma-ray bursts

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Eur. Phys. J. C (2022) 82:278
https://doi.org/10.1140/epjc/s10052-022-10197-0

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Regular Article - Experimental Physics

Search for low-energy signals from fast radio bursts with the Borexino detector

Borexino Collaboration

Eur. Phys. J. C (2023) 83:538
https://doi.org/10.1140/epjc/s10052-023-11688-4

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Borexino's search for low-energy neutrinos associated with gravitational wave events from GWTC-3 database

Borexino Collaboration