Combined search of MeV $\nu$ and GWs from astrophysical sources

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Outline

- Sources of low-energy neutrinos bursts and GWs
- Combined search of GWs and neutrinos
  - **Novel Search Method for $\nu$ bursts**
- Results
Core Collapse Supernovae

1. As the massive star nears its end, it takes on an onion-layer structure of chemical elements.

2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.

3. Within a second, the core collapses to form a neutron star. Material rebounds off the neutron star, setting up a shock wave.

4. Neutrinos pouring out of the nascent neutron star propel the shock wave outward, unevenly.

5. The shock sweeps through the entire star, blowing it apart.
Core Collapse Supernovae

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2. Iron does not undergo nuclear fusion, so the core becomes unable to generate heat. The gas pressure drops, and overlying material suddenly rushes in.

“Failed” Supernovae

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Core Collapse Supernovae

“Failed” Supernovae

Quark Novae

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Core Collapse Supernovae

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conversion
Core Collapse Supernovae

“Failed” Supernovae

Quark Novae

Common Signature:
Impulsive Neutrinos Emission

\[ \varepsilon_B = (1 - 5) \cdot 10^{53} \text{ erg} \]

\[ \varepsilon_\nu = 99\% \cdot \varepsilon_B \]

\[ F_{\nu_x} \approx \frac{\varepsilon_B}{6 \langle E_{\nu_x} \rangle} \frac{1}{4\pi D^2} \approx 5 \cdot 10^{10} \left( \frac{20 \text{ kpc}}{D} \right)^2 \frac{10 \text{ MeV}}{\langle E_{\nu_x} \rangle} \frac{\nu_x}{cm^2} \]

\[ \Delta t \approx 10 \text{ sec} \]
Core Collapse Supernovae

“Failed” Supernovae

Quark Novae

Common Signature: Impulsive GWs Emission

\[ \varepsilon_B = (1 - 5) \cdot 10^{53} \text{erg} \]

\[ \varepsilon_{GW} \leq 0.0001\% \cdot \varepsilon_B \]

\[ 10^{-23} < h_{\text{max}} (10 \text{kpc}) < 10^{-20} \]

\[ \Delta t = 10 - 1000 \text{ ms} \]
GWNU overview

**v network:**
- Trigger definition;
- Detection efficiency.

**GW network:**
- Trigger definition;
- Detection efficiency.

Global network
Joint GW-$\nu$ Search

Leonor et al., Class. Quantum Grav. 27 (2010) 084019

- False Alarm Rate
- GW back. Rate
- Neutrino back. Rate
- Time coincidence window

\[ \text{FAR} = R_{GW}(\eta) \cdot R_{\nu}(\xi) \cdot 2w \]

- FAR = 1/1000 years and at least 2 neutrinos in coincidence with a gravitational wave trigger.

- $w = 10$ sec to accommodate most emission models
Joint GW-ν Search

False Alarm Rate  GW back. Rate  Neutrino back. Rate  Time coincidence window

\[ \text{FAR} = R_{GW}(\eta) \]

GW detectors work in a combined way and \( \eta \) is the “Joint coherent statistics” for the search of GWs.

Leonor et al., Class. Quantum Grav. 27 (2010) 084019

Neutrino detectors should work in a more combined way.

**GOAL:** Identify the “Joint coherent statistics” for the search of neutrino bursts
Novel Search Method for $\nu$ bursts

Casentini, Pagliaroli, Vigorito, Fafone,
JCAP 1808 (2018) n.08,010
The observation of an astrophysical burst

Source D=10 kpc

**$E_{\text{vis}} \,[\text{MeV}]$**

LVD

**IBD EVENTS From the source**
The identification of a small statistics signal

$E_{\text{vis}} \ [\text{MeV}]$

Source $D = 65 \ \text{kpc}$

# BACKGROUND EVENTS $\approx$ # SIGNAL EVENTS

SIGNAL OR BACKGROUND FLUCTUATION?
The observation of an astrophysical burst

\[ \xi_i = \frac{m_i}{\Delta t_i} \]

\[ E_{\text{vis}} \text{[MeV]} \]

\[ \Delta t_i (s) \]

LVD 10 kpc
IBD channel

\[ w = 20s \]

\[ m_i \]

Number of events inside the window
Neutrinos Experiments
10 years of background data
3650 injected signals

**Kamland**
- Liquid Scintillator
- Energy & NC
- M = 1 kton

**Borexino**
- Liquid Scintillator
- Energy & NC
- M = 0.3 kton

**SuperK**
- Water Cerenkov
- Energy & NC
- M ≈ 22 kton

**LVD**
- Liquid Scintillator
- Energy & NC
- M = 1 kton
Background-Signal separation

\[ \xi_i = \frac{m_i}{\Delta t_i} \]

CLUSTERS WITH \( \xi_i < \bar{\xi} \) ARE ELIMINATED

Pure Background Clusters

PDF

SuperKamiokande

\( BKG \)

65 kpc

140 kpc

300 kpc

500 kpc

Cutting value for the \( \xi \) parameter providing Maximum of the signal to noise ratio
Results for SuperKamiokande

$\eta(D)$ Detection efficiency = Survived signals/Injected signals

$\zeta(D)$ Misidentification probability = Background clusters/Survived clusters

![Graph showing detection efficiency and misidentification probability vs. D(kpc)]
Results for SuperKamiokande

$\eta(D)$ Detection efficiency = Survived signals/Injected signals

$\zeta(D)$ Misidentification probability = Background clusters/Survived clusters

![Graph showing $\eta$ and $\zeta$ as functions of $D(kpc)$]
Results for SuperKamiokande

$\eta(D)$  Detection efficiency = Survived signals/Injected signals

$\zeta(D)$  Misidentification probability = Background clusters/Survived clusters
Results for SuperKamiokande

No Efficiency loss for

\[ D \leq \bar{D} = 200(\text{kpc}) \]

Gain factor on the misidentification probability

Gain = \( \frac{\zeta}{\zeta'} \)

Gain = 8.9

\[ \zeta = 23\% \]

\[ \zeta' = 3\% \]
Gain Factors

<table>
<thead>
<tr>
<th>Detector</th>
<th>M(kton)</th>
<th>$E_{thr}$(MeV)</th>
<th>$f_{bkg}$ (Hz)</th>
<th>$\bar{\xi}$ (Hz)</th>
<th>$D$(kpc)</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borexino</td>
<td>0.3</td>
<td>1</td>
<td>0.048</td>
<td>0.65</td>
<td>20</td>
<td>6.9</td>
</tr>
<tr>
<td>SuperK</td>
<td>22.5</td>
<td>7</td>
<td>0.012</td>
<td>0.72</td>
<td>200</td>
<td>8.9</td>
</tr>
<tr>
<td>KamLAND</td>
<td>1</td>
<td>1</td>
<td>0.015</td>
<td>0.77</td>
<td>50</td>
<td>13.4</td>
</tr>
<tr>
<td>LVD</td>
<td>1</td>
<td>10</td>
<td>0.028</td>
<td>0.72</td>
<td>40</td>
<td>14.0</td>
</tr>
</tbody>
</table>

Table 1: Columns in order show: sensitive detector mass in kton; energy threshold considered for the analysis in MeV; average background frequency in Hz; value for the $\bar{\xi}$ parameter that maximize the signal to noise ratio, as described in the text; maximal distance $\bar{D}$ without efficiency loss after the new cut; gain factor obtained by using the new proposed method.
Clusters Selection for Networks

\[ \sqrt{\xi_L \times \xi_K} > \sqrt{\bar{\xi}_L \times \bar{\xi}_K} \]

The product of the \( \xi \) values bigger than:

\[ \bar{\xi}^* = Net \sqrt{\prod_i Net \bar{\xi}_i} \]

\( wc = 10 \)s

E\(_{\text{vis}}\) [MeV]

LVD

Kamland
The network LVD+Kamland

\[ \eta^*(D) \] Detection efficiency = Survived coincidences/Injected signals

\[ \zeta^*(D) \] Misidentification probability = Background coincidences/Total

Standard Procedure

07/09/18 Giulia Pagliaroli
**The network LVD+Kamland**

\[ \eta^* (D) \quad \text{Detection efficiency} = \frac{\text{Survived coincidences}}{\text{Injected signals}} \]

\[ \zeta^* (D) \quad \text{Misidentification probability} = \frac{\text{Background coincidences}}{\text{Total}} \]

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![Graph showing \( \eta^* \) and \( \zeta^* \) as functions of \( D \) (kpc)]

**New Procedure**

07/09/18

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Results for a network
LVD+Kamland

No Efficiency loss for

\[ D < \bar{D} = 75\text{kpc} \]

Gain factor on the misidentification probability

\[ \zeta^* = 4\% \]
\[ \zeta^* = 0.2\% \]

Gain = 20

07/09/18

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Conclusions

The novel proposed method:

- Exploits the temporal structure of a burst emission
- Applies to different detectors or networks of detectors
- Allows to decrease the misidentification probability between a factor 10-20 without loosing on detection efficiency
- Can be considered as the “joint statistic” for the neutrino network

\[ \text{FAR} = R_{GW}(\eta) \cdot R_\nu(\xi) \cdot 2\omega \]
$\text{FAR} = R_{GW}(\eta) \cdot R_{\nu}(\xi) \cdot 2\omega$
Backup Slides
Optimal cut value for blind search

The distance of the source is unknown and the search is optimized to the larger distance allowed by the proposed method.

\[ \bar{\xi} = 0.72 \]

CLUSTERS WITH \( \xi_i \) ARE ELIMINATED \( \xi_i < \bar{\xi} \)
Neutrinos Burst

\[ f(t) = (1 - \exp(-t/\tau_1)) \exp(-t/\tau_2) \]

\[ \tau_1 = (10 - 100) \text{ms} \]

\[ \tau_2 \geq 1 \text{s} \]

\[ \langle E_{\nu_e} \rangle = 9 \text{ MeV} \quad \langle E_{\bar{\nu}_x} \rangle = 15.6 \text{ MeV} \]

\[ \langle E_{\bar{\nu}_e} \rangle = 12 \text{ MeV} \]
SNEWS comparison

SNEWS threshold
FAR* = 1/1000 years

EQUIVALENT
FAR = 0.365/year
\( \bar{\xi}^{*} \) cut

Increasing the detection probability of faint signals 57% -> 75%

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Clusters Selection

- **Standard Procedure**

  \[ f_i^{im} = N \sum_{k=m_i}^{\infty} \frac{(f_{bkg}w)^k e^{-f_{bkg}w}}{k!} \text{day}^{-1} \]

  Statistical cut on the imitation frequency
  \[ f^{im} \leq 1/\text{day} \quad m_i \geq 4 \]

- **New Procedure**

  - Standard cut
  - The new selection criteria

  \[ \xi_i > \bar{\xi} \]

\[ \eta(D) \] Detection efficiency = Survived signals/Injected signals

\[ \zeta(D) \] Misidentification probability = Background clusters/Survived clusters
Clusters Selection for Networks

- **Standard Procedure:**
  - Coincidences in time
  
  \[ w_c = 10s \]
  - Statistical cut on the global false alarm rate
  
  \[ \text{FAR} = 2w_c^{N-1} \prod_{X=1}^{N} f_{im} \]

- **New Procedure**
  - Standard cuts
  - The new selection criteria: the product of the \( x_i \) values bigger than:

\[
\bar{\xi}^* = \sqrt[Net]{\prod_{i}^{Net} \bar{\xi}_i} 
\]

- \( \eta^* (D) \) Detection efficiency = Survived coincidences/Injected signals

- \( \zeta^* (D) \) Misidentification probability = Background coincidences/Total
Time Integrated Features

Total energy budget

\[ E_b = 3 \cdot 10^{53} \text{ erg} \]

Equipartition Hypothesis

\[ \epsilon_i = E_b \cdot f_i \]
\[ f_i = 1/6 \]

Fluence at the Earth

\[ \Phi_i = \frac{\epsilon_i}{4\pi D^2} \times \frac{E^\alpha e^{-E/T_i}}{T_i^{\alpha+2} \Gamma(\alpha + 2)} \]

Pinched spectra with \( \alpha = 3 \)
\[ T_i = \langle E_i \rangle / (\alpha + 1) \]
Supernova Neutrinos Detection

**EMISSION**

- $\langle E_{\nu_e} \rangle = 9.5\text{MeV}$
- $\langle E_{\bar{\nu}_e} \rangle = 12\text{MeV}$
- $\langle E_{\nu_x} \rangle = 15.6\text{MeV}$

**DETECTION**

- $\langle E_{\nu_e} \rangle = 15.6\text{MeV}$
- $\langle E_{\bar{\nu}_e} \rangle = 13\text{MeV}$
- $\langle E_{\nu_x} \rangle = 13\text{MeV}$
- $\langle E_{\bar{\nu}_x} \rangle = 14\text{MeV}$

Neutrinos Fluences

$$N_{ev} \propto N_t \int_{E_{thr}}^{\infty} dE_{vis} \sigma_{Int}(E_{\nu}) F_{\nu}(E_{\nu})$$

Number of targets

Detector Energy Threshold

Cross Section

Kinematic threshold