Astrophysical neutrinos with DUNE, HK and JUNO
(Opportunities with Neutrinos from Supernovae)

Inés Gil Botella

European Neutrino “Town” Meeting and European Strategy Preparation 2019
22-24 October 2018
Scientific motivation

• Supernova neutrino detection is **one of the main goals** included in the physics program of current & future large underground neutrino projects

• Measurement of the neutrino **energy** spectra, **flavor** composition and **time** distributions from supernova will provide information about:
  
  **Supernova physics:**
  • Core collapse mechanism
  • Supernova evolution in time
  • Cooling of the proto-neutron star
  • Nucleosynthesis of heavy nuclei
  • Black hole formation

  **Neutrino (other particle) physics:**
  • Neutrino flavor transformation in SN core and/or in Earth
  • Neutrino absolute mass (not competitive)
  • Other neutrino properties: sterile vs, magnetic moments,…
  • Axions, extra dimensions,…

**Early alert** for astronomers (SNEWS)

First multi-messenger event: *neutrinos and light from SN1987*
Three phases of SN ν emission

**Neutronization burst**
- Shock breakout
- De-leptonization of outer core layers

**Accretion phase**
- Shock stalls ~150 km
- Neutrinos powered by infalling matter

**Cooling phase**
- Cooling on neutrino diffusion time scale
SN neutrino fluxes

\[ \langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle \]

Many theoretical models...

Generic feature

- Burrows et al., arXiv:1611.05859

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**SN ν flavor oscillation physics**

Collective oscillations (r < 200 km) + MSW flavor transformations (r > 200 km) imprint the neutrino signal

Information about the **mass hierarchy** (and SN mechanisms) can be obtained from neutrino time and energy spectra evolution

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**Examples**


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It is important to identify robust, **model-independent observable signatures** of supernova neutrino flavour conversions: self-induced spectral splits, Earth matter effects, neutronization burst, ...
Detection of SN breakout burst

J. Wallace et al., Astrophys. J. 817 (2016), 182

**Robust time signature** during the first few tens of ms after the core bounce

**Strongly dominated by electron neutrinos**

**MSW oscillations**: presence or absence of $\nu_e$ burst allowing to distinguish between different mixing scenarios

- **NH**: strong suppression of $\nu_e$
- **IH**: $\nu_e$ suppressed by $\sin^2 \theta_{12}$

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### Main experimental challenges

<table>
<thead>
<tr>
<th>Detector requirement</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large mass (~ktons)</td>
<td>Enough statistics</td>
</tr>
<tr>
<td>Low energy threshold (few MeV)</td>
<td>Detection of the low E SN neutrino spectra</td>
</tr>
<tr>
<td>Sensitivity to different neutrino flavors</td>
<td>Distinguish different SN effects and neutrino oscillations</td>
</tr>
<tr>
<td>Good knowledge of low-E cross sections and neutrino interactions (particle ID)</td>
<td>Tag different interactions</td>
</tr>
<tr>
<td>Accurate neutrino energy reconstruction</td>
<td>SN features</td>
</tr>
<tr>
<td>Good timing resolution</td>
<td>SN features</td>
</tr>
<tr>
<td>Good angular resolution</td>
<td>SN direction</td>
</tr>
<tr>
<td>Separation from backgrounds</td>
<td>Identification of SN signal</td>
</tr>
<tr>
<td>Good trigger efficiency/DAQ</td>
<td>Large data acquisition in a few seconds</td>
</tr>
</tbody>
</table>
Complementarity

One single detector generally cannot meet all these requirements

- Specially three flavour sensitivity

Different simultaneous observations are needed by multiple detectors
Comparison between technologies

Total event rates per time bin for 27 and 11 $M_\odot$ SN progenitors

Neutronization burst

## SN neutrino detectors

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kt)</th>
<th>Location</th>
<th>Events</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-Kamiokande</td>
<td>H₂O</td>
<td>32</td>
<td>Japan</td>
<td>7,000</td>
<td>Running</td>
</tr>
<tr>
<td>LVD</td>
<td>C₉H₂n</td>
<td>1</td>
<td>Italy</td>
<td>300</td>
<td>Running</td>
</tr>
<tr>
<td>KamLAND</td>
<td>C₉H₂n</td>
<td>1</td>
<td>Japan</td>
<td>300</td>
<td>Running</td>
</tr>
<tr>
<td>Borexino</td>
<td>C₉H₂n</td>
<td>0.3</td>
<td>Italy</td>
<td>100</td>
<td>Running</td>
</tr>
<tr>
<td>IceCube</td>
<td>Long string</td>
<td>(600)</td>
<td>South Pole</td>
<td>(10⁶)</td>
<td>Running</td>
</tr>
<tr>
<td>Baksan</td>
<td>C₉H₂n</td>
<td>0.33</td>
<td>Russia</td>
<td>50</td>
<td>Running</td>
</tr>
<tr>
<td>HALO</td>
<td>Pb</td>
<td>0.08</td>
<td>Canada</td>
<td>30</td>
<td>Running</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>C₉H₂n</td>
<td>0.33</td>
<td>China</td>
<td>100</td>
<td>Running</td>
</tr>
<tr>
<td>NOνA*</td>
<td>C₉H₂n</td>
<td>15</td>
<td>USA</td>
<td>4,000</td>
<td>Running</td>
</tr>
<tr>
<td>MicroBooNE*</td>
<td>Ar</td>
<td>0.17</td>
<td>USA</td>
<td>17</td>
<td>Running</td>
</tr>
<tr>
<td>SNO+</td>
<td>C₉H₂n</td>
<td>0.8</td>
<td>Canada</td>
<td>300</td>
<td>Near future</td>
</tr>
<tr>
<td>DUNE</td>
<td>Ar</td>
<td>40</td>
<td>USA</td>
<td>3,000</td>
<td>Future</td>
</tr>
<tr>
<td>Hyper-Kamiokande</td>
<td>H₂O</td>
<td>374</td>
<td>Japan</td>
<td>75,000</td>
<td>Future</td>
</tr>
<tr>
<td>JUNO</td>
<td>C₉H₂n</td>
<td>20</td>
<td>China</td>
<td>6000</td>
<td>Future</td>
</tr>
<tr>
<td>RENO-50</td>
<td>C₉H₂n</td>
<td>18</td>
<td>Korea</td>
<td>5400</td>
<td>Future</td>
</tr>
<tr>
<td>PINGU</td>
<td>Long string</td>
<td>(600)</td>
<td>South Pole</td>
<td>(10⁶)</td>
<td>Future</td>
</tr>
</tbody>
</table>

Liquid Scintillator Detectors

Borexino: 0.33 kton
SNO+: 1 kton
KamLAND: 1 kton
JUNO: 20 kton
THEIA: 50 kton
LVD: 1 kton
NOvA: 14 kton
**LSc interaction channels**

- **Main channel**: (few hundred events/kton)
  - **IBD**: $\overline{\nu}_e + p \rightarrow e^+ + n$
  - **Low energy threshold**: 1.8 MeV
  - Good neutron tagging
  - Good energy resolution (7.25% $\sqrt{E}$ KamiLAND)
  - Some pointing capability
  - JCAP08 (2015) 032

- **Other channels**:
  - $\nu_x + e^- \rightarrow \nu_x + e^-$
  - $\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}(*)$
  - $\overline{\nu}_e + ^{12}\text{C} \rightarrow e^+ + ^{12}\text{B}(*)$
  - $\nu_x + ^{12}\text{C} \rightarrow \nu_x + ^{12}\text{C}^*$

- Coherent elastic NC scattering on protons
  - $\nu_x + p \rightarrow \nu_x + p$

**Prompt** signal: $e^+$ scintillation and annihilation

**Delayed** signal: $n$ capture on H (2.2 MeV γ, $\Delta t \sim 200 \mu s$ or Gd (8 MeV γ, $\Delta t \sim 30 \mu s$)

15 MeV de-excitation peak from NC

**GKVM model**

**50 kton @10 kpc**
Current detectors: LVD, Borexino, KamLAND, SNO+, reactors, NOvA (at surface)
• ~300 events (per 1 kton) from a SN at 10 kpc
• Future: JUNO (20 kton)
• ~6000 events for SN @10 kpc

Constrains on absolute neutrino masses via SN neutrino detection in JUNO:
\[ JCAP\ 05\ (2015)\ 044 \]

- \( m_\nu < (0.83 \pm 0.24) \text{ eV} \) at 95% CL for a SN at 10 kpc, assuming nearly-degenerate neutrino mass spectrum and NH

Energy spectra of all flavor SN neutrinos can be extracted by combining IBD, pES and eES

The average energy of SN \( \bar{\nu}_e, \nu_e \) \& \( \nu_x \) can be reconstructed with precision 1%, 10% and 5% respectively.
Water Cherenkov Detectors

SK: 32 kton fid. volume

HK: 374 kton fid. volume

IceCube: 1 km$^3$
WC interaction channels

- **Main channel (IBD):**
  \[ \bar{\nu}_e + p \to e^+ + n \]

- **Elastic scattering (ES):**
  \[ \nu_X + e^- \to \nu_X + e^- \]
  - Pointing to the supernova

- **Other channels**

  \[ \nu_e + ^{16}O \to e^- + ^{16}F(\ast) \]
  \[ \bar{\nu}_e + ^{16}O \to e^+ + ^{16}N(\ast) \]
  \[ \nu_x + ^{16}O \to \nu_x + ^{16}O^* \]

**Detection:**
- Cherenkov light emission
- Neutron tagging: observation of \( \gamma \)-Compton scatters
  (SK-IV 20% n tagging efficiency)

**Advantages:**
- Huge size detectors
- Mainly sensitive to electron antineutrinos
- Pointing information

**Events vs observed energy (SNOwGLoBES)**

GKVM model

30% PMT coverage

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Super-K/Super-K Gd

- **Super-K rates**: ~8000 evts (5 MeV thr.) for Livermore model and no-osc.
- **Possibility to improve neutron tagging with Gd** (0.1% Gd gives >90% efficiency for n-capture)

Hyper-K

- High-statistics (x10 Super-K fiducial mass) keeping low energy threshold
- Aiming to start observation in 2027
- **Expected #events (@10 kpc):**
  - 49-68 kevts (IBD)
  - 2.1-2.5 kevts (ES) (6-40 neutronization)
  - 80-4100 evts (nue CC)
  - 650-3900 evts (anti-nue CC)


Thanks to Yusuke Koshio & Takatomi Yano
Heavy-nuclei detectors
HALO (Helium and Lead Observatory)

• Lead-based SN detector at SNOLAB: SNO $^3$He counters + 79 tons of Pb

• CC: $\nu_e + ^{208}\text{Pb} \rightarrow e^- + ^{208}\text{Bi}^*$
  \[ (1n, 2n) + \gamma \]

• NC: $\nu_x + ^{208}\text{Pb} \rightarrow \nu_x + ^{208}\text{Pb}^*$
  \[ (1n, 2n) + \gamma \]

• Running since 2013

• Integrated in SNEWS in 2015

Detection:
- Neutron tagging
  \[ ^3\text{He} + n \rightarrow ^3\text{H} + p + 764 \text{ keV} \]
- Low neutron capture cross section
- Not possible to distinguish between CC & NC

Large neutrino capture cross sections
1-40 evts @10 kpc

HALO-1kT at Gran Sasso: 1 kton lead detector
(from OPERA decommissioning):
~300 interactions for a SN @10 kpc
LAr TPC detectors

- MicroBooNE: 89 ton
- protoDUNE-DP: 300 ton
- protoDUNE-SP: 300 ton
- ICARUS: 476 ton
- DUNE: 40 kton
SN neutrino signal in LAr

- Elastic scattering (ES) on electrons
  \[ \nu + e^- \rightarrow \nu + e^- \]

- Charged-current (CC) interactions on Ar
  \[ \nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K}^* + e^- \quad E_{\nu_e} > 1.5 \text{ MeV} \]
  \[ \bar{\nu}_e + ^{40}\text{Ar} \rightarrow ^{40}\text{Cl}^* + e^+ \quad E_{\bar{\nu}_e} > 7.48 \text{ MeV} \]

- Neutral current (NC) interactions on Ar
  \[ \nu + ^{40}\text{Ar} \rightarrow \nu + ^{40}\text{Ar}^* \quad E_{\nu} > 1.46 \text{ MeV} \]

Possibility to separate the different channels by a classification of the associated photons from the K, Cl or Ar de-excitation (specific spectral lines for CC and NC) or by the absence of photons (ES)
**Deep Underground Neutrino Experiment**: 40 kton LAr TPC detector at 1480 m depth (4300 mwe)

- 4 x 10 kton (single/dual-phase) LAr TPCs with ability to detect SN burst neutrinos (+ nucleon decay, LBL osc., atmospheric neutrinos)
- First module installation begins in 2022

- Unique sensitivity to *electron neutrinos*
- Event rates in DUNE for a core-collapse SN at 10 kpc

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events “Livermore” model</th>
<th>Events “GKVM” model</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e + ^{40}$ Ar $\rightarrow e^- + ^{40}$ K*</td>
<td>2720</td>
<td>3350</td>
</tr>
<tr>
<td>$\bar{\nu}_e + ^{40}$ Ar $\rightarrow e^+ + ^{40}$ Cl*</td>
<td>230</td>
<td>160</td>
</tr>
<tr>
<td>$\nu_x + e^- \rightarrow \nu_x + e^-$</td>
<td>350</td>
<td>260</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3300</strong></td>
<td><strong>3770</strong></td>
</tr>
</tbody>
</table>

*no oscillations*  
*collective effects*
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DUNE: 40 kton LAr (SN @10 kpc)

Time-dependent signal

Expected event spectrum integrated over time

no oscillations

Garching model
Neutronization burst

DUNE will provide unique information about the early breakout pulse thanks to its sensitivity to electron neutrinos.

40 kton argon, 10 kpc

Events per bin

Time (seconds)

Robust mass ordering signature

Garching model, MSW transitions only, total events (mostly $\nu_e$)
## Pros & cons

<table>
<thead>
<tr>
<th>Liquid scintillators</th>
<th>Water Cerenkov</th>
<th>Liquid Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Electron antineutrino sensitivity</td>
<td>• Poor directionality</td>
<td>• Electron neutrino sensitivity</td>
</tr>
<tr>
<td>• Good n tagging</td>
<td>• Low energy vulnerable to backgrounds</td>
<td>• Some other flavours</td>
</tr>
<tr>
<td>• Low energy threshold</td>
<td>• Electron antineutrino sensitivity</td>
<td>• Potentially good tagging</td>
</tr>
<tr>
<td>• Good energy resolution</td>
<td>• Potentially good n tagging with Gd</td>
<td></td>
</tr>
<tr>
<td>• Very well known IBD int.</td>
<td>• Directionality</td>
<td>• Potential good reconstruction</td>
</tr>
<tr>
<td></td>
<td>• Very large mass</td>
<td>• Some directionality</td>
</tr>
<tr>
<td></td>
<td>• Good energy resolution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Very well known</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IBD int.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Water Cerenkov</th>
<th>Liquid Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cherenkov threshold limits reconstruction</td>
<td>• Technology under development</td>
</tr>
<tr>
<td>• Relatively high energy threshold</td>
<td>• Capabilities still unknown</td>
</tr>
<tr>
<td>• Difficult to disentangle channels</td>
<td>• Statistics limited</td>
</tr>
<tr>
<td>• No event-by-event reconstruction (long-strings)</td>
<td></td>
</tr>
</tbody>
</table>

Complementarity
Diffuse Supernova Neutrino Background

- Diffuse SN neutrino background (DSNB) from all the SN explosions in the Universe → **guaranteed steady source of SN neutrinos**
- **Not detected yet** (same detection interactions as for burst vs)
- Main experimental issue: **backgrounds**

Different theoretical DSNB models

*C. Lunardini, Astropart. Phys. 79 (2016) 49-77*
DSNB in WC

DSNB flux:

• It depends on typical/actual SN emission spectrum

Expected total BG
$T_{\nu} = 6\, \text{MeV}$
$T_{\nu} = 4\, \text{MeV}$
$T_{\nu} = 1987a$

Hyper-K aims to measure the spectrum of DSNB

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Thanks to Yusuke Koshio & Takatomi Yano

HBD models & DSNB events number with 10 years observation

<table>
<thead>
<tr>
<th>HBD models</th>
<th>10-16MeV (evts/10yrs)</th>
<th>16-28MeV (evts/10yrs)</th>
<th>Total (10-28MeV)</th>
<th>significance (2 energy bin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{eff}}, 8, \text{MeV}$</td>
<td>11.3</td>
<td>19.9</td>
<td>31.2</td>
<td>5.3 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}, 6, \text{MeV}$</td>
<td>11.3</td>
<td>13.5</td>
<td>24.8</td>
<td>4.3 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}, 4, \text{MeV}$</td>
<td>7.7</td>
<td>4.8</td>
<td>12.5</td>
<td>2.5 $\sigma$</td>
</tr>
<tr>
<td>$T_{\text{eff}}, \text{SN1987a}$</td>
<td>5.1</td>
<td>6.8</td>
<td>11.9</td>
<td>2.1 $\sigma$</td>
</tr>
<tr>
<td>BG</td>
<td>10</td>
<td>24</td>
<td>34</td>
<td>----</td>
</tr>
</tbody>
</table>

Detection efficiency is not considered

Number of SRN events in FV

- HK
- SK-Gd
- JUNO

- HK (BH 30%)
- SK-Gd (BH 30%)
- JUNO (BH 30%)

Year

2020 2025 2030 2035 2040 2045

Total (positron) energy  MeV

5.1

6.8

11.9

2.1 $\sigma$
DSNB in LSc

KamLAND best limit (90% CL):
\[ f(\nu_e) < 3.7 \times 10^2 \text{ cm}^{-2}\text{s}^{-1} \text{ for } 8.3 < E_\nu < 14.8 \text{ MeV} \]

- Few events per year are expected in JUNO
- **Main backgrounds**: atmospheric and reactor $\nu_e$
  - atm NC & fast neutrons can be identified and reduced
- Discovery potential: $3\sigma$ level for 17 kton x 10 y (syst uncertainty on BG: 5%)

\[ \text{JUNO} \]

**10 Years' sensitivity**

<table>
<thead>
<tr>
<th>Syst. uncertainty BG</th>
<th>Rate only</th>
<th>Spectral fit</th>
<th>Rate only</th>
<th>Spectral fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle E_{\nu_e} \rangle$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 MeV</td>
<td>2.3 $\sigma$</td>
<td>2.5 $\sigma$</td>
<td>2.0 $\sigma$</td>
<td>2.3 $\sigma$</td>
</tr>
<tr>
<td>15 MeV</td>
<td>3.5 $\sigma$</td>
<td>3.7 $\sigma$</td>
<td>3.2 $\sigma$</td>
<td>3.3 $\sigma$</td>
</tr>
<tr>
<td>18 MeV</td>
<td>4.6 $\sigma$</td>
<td>4.8 $\sigma$</td>
<td>4.1 $\sigma$</td>
<td>4.3 $\sigma$</td>
</tr>
<tr>
<td>21 MeV</td>
<td>5.5 $\sigma$</td>
<td>5.8 $\sigma$</td>
<td>4.9 $\sigma$</td>
<td>5.1 $\sigma$</td>
</tr>
</tbody>
</table>
DSNB in LAr

- LAr TPCs can detect relic neutrinos through $\nu_e$CC interactions
- **Main background**: solar and atmospheric neutrinos
- **DUNE**, in 10 years, n.h.
  $N_{\text{DSNB}} = 46 \pm 10 \ (16 \text{ MeV} \leq E_e \leq 40 \text{ MeV})$

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DSNB flux prediction based on Strigari et al., JCAP03 (2004) 007

3 kton, 5y, n.h.

$N_{\text{DSNB}} = 1.7 \pm 1.6 \ 	ext{evts} \ (16 \leq E_e \leq 40 \text{ MeV})$

$f(\nu_e) < 1.6 \ 	ext{cm}^{-2}\text{s}^{-1} \ (90\% \ 	ext{CL})$

100 kton, 5y, n.h.

$N_{\text{DSNB}} = 57 \pm 12 \ 	ext{evts} \ (16 \leq E_e \leq 40 \text{ MeV})$

4$\sigma$ measurement
Comparison between technologies

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Exposure</th>
<th>Energy Window</th>
<th>Signal/Bkgd</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLACIER</td>
<td>0.5 Mton year 5 years</td>
<td>[16 - 40] MeV</td>
<td>(40-60)/30</td>
</tr>
<tr>
<td>LENA at Pyhasalmi</td>
<td>0.4 Mton year 10 years</td>
<td>[9.5 - 30] MeV</td>
<td>(20-230)/8</td>
</tr>
<tr>
<td>MEMPHYS module + 0.2% Gd (with bkgd at Kamioka)</td>
<td>0.7 Mton year 5 years</td>
<td>[15 - 30] MeV</td>
<td>(43-109)/47</td>
</tr>
</tbody>
</table>

Expected DSNB interaction rates

Conclusions

• Detection of SN neutrino events is one of the main goals of current and future large underground detectors

• SN neutrinos can provide information about fundamental processes related to SN physics and neutrino properties

• The understanding of the SN explosion mechanism and the neutrino flavor transformations is still in progress (spectacular advance of theoretical models) but new experimental inputs are needed

• Important to understand the different SN ν detection channels (cross-sections, signatures, directionality, reconstruction, timing, etc.) and a good detector response in terms of time, flavor and energy

• Complementarity between different detector technologies will be crucial