Coherent Scattering and the Flavor Physics and Detection of Supernova Neutrinos

Kate Scholberg, Duke University
CIPANP 2018, Palm Springs
May 31, 2018

https://scitechdaily.com/ten-facts-about-supernovae/supernovae-are-neutrino-factories/
OUTLINE

- Neutrinos from Core-Collapse Supernovae
  - The nature of the signal and what it can tell us
  - Detection of supernova neutrinos

- Coherent elastic neutrino-nucleus scattering (CEvNS)
  - The nature of the process
  - Measurement status and prospects

- CEvNS and Supernovae
  - CEvNS as a supernova process
  - CEvNS as a supernova detection channel
This talk is the union of some of my favorite things...
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Cake and pie
(It’s also about the CIPANPiest topic ever...)
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The core-collapse neutrino signal

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into \( \nu \)'s of all flavors with ~tens-of-MeV energies

(Energy can escape via \( \nu \)'s)

Mostly \( \nu - \bar{\nu} \) pairs from proto-nstar cooling

Timescale: prompt after core collapse, overall \( \Delta t \sim 10 \)’s of seconds
Expected neutrino luminosity and average energy vs time

Vast information in the flavor-energy-time profile

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

(may or may not be robust)
Expected neutrino luminosity and average energy vs time

Vast information in the *flavor-energy-time profile*

[Graph showing neutrino luminosity and average energy vs time]

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

(may or may not be robust)

L. Huedepohl et al., PRL 104 251101
Fluxes as a function of time and energy

\[ \nu_e = \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau \]
The core-collapse supernova explosion is still not fully understood... numerical study ongoing

Neutrinos are intimately involved

Blondin, Mezzacappa, DeMarino

Marek & Janka
What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS

explosion mechanism proto nstar cooling, quark matter black hole formation accretion, SASI nucleosynthesis ....

input from neutrino experiments

from flavor, energy, time structure of burst

NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass (not competitive)
ν mixing from spectra: flavor conversion in SN/Earth (mass hierarchy)
other ν properties: sterile ν's, magnetic moment,...
axions, extra dimensions, FCNC, ...

+ EARLY ALERT

input from photon (GW) observations
Supernova-relevant neutrino interactions

<table>
<thead>
<tr>
<th>Charged current</th>
<th>Neutral current</th>
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- **Charged current**
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- **Neutral current**
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<td><img src="image2" alt="Proton Inverse Beta Decay" /></td>
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<td><img src="image4" alt="Electron Elastic Scattering" /></td>
<td><img src="image5" alt="Proton Elastic Scattering" /></td>
<td><img src="image6" alt="Nuclei Elastic Scattering" /></td>
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Various possible ejecta and deexcitation products |
# Supernova-relevant neutrino interactions

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**Useful for pointing**

**Very low energy recoils**

**Various possible ejecta and deexcitation products**

**IBD (electron antineutrinos) dominates for current detectors**
Neutrino interaction thresholds

Fluence (neutrinos per 0.2 MeV per cm$^2$)

$\nu_x (\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau)$

-$\nu_e$

-$\bar{\nu}_e$

$\nu_e^{16}O$

$\nu_e^{40}Ar$

$\nu_\mu^{CC}$

Require neutral current to see $\nu_{\mu,\tau}$

Neutrino Energy (MeV)
### Supernova neutrino detector types

<table>
<thead>
<tr>
<th>Water</th>
<th>Water, long-string</th>
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<td><img src="image1" alt="Water" /></td>
<td><img src="image2" alt="Water, long-string" /></td>
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<tr>
<td>$\nu_e$</td>
<td>$\nu_x$</td>
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For supernova neutrinos, the more the merrier!
What we want to measure

Neutrino fluxes vs E, t
What we want to measure
Neutrino fluxes vs E, t

What we can measure
Event rates in different interaction channels vs E, t (with imperfect tagging & resolution)

\( \nu_e CC \)
\( \bar{\nu}_e CC \)
NC
Neutrino fluxes vs $E, t$  

Event rates vs $E, t$

---

$\nu_e$

---

LAr

---

$\overline{\nu}_e$

---

Water

---

$\nu_x$

---

Scint
Subdominant channels are in the mix too, and not always easily taggable... may be hard to disentangle!
Neutral-current SN events are especially valuable...

- **Measure total flux, all flavors**
  - total energy in neutrinos
  - improves flavor transition knowledge
- **All-flavor spectral information** also valuable
Neutral-current SN events are especially valuable...

- Measure total flux, all flavors
  - total energy in neutrinos
  - improves flavor transition knowledge
- All-flavor spectral information also valuable

Example: suppression of the neutronization burst $\nu_e$ is a robust mass ordering signature; knowing total flux via tagged NC will help to interpret
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A neutrino smacks a nucleus via exchange of a $Z$, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV

\[
\nu + A \rightarrow \nu + A
\]
Coherent elastic neutrino-nucleus scattering (CEvNS)

\[ \nu + A \rightarrow \nu + A \]

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; coherent up to \( E_\nu \sim 50 \text{ MeV} \)

For \( QR \ll 1 \),

\[ [\text{total xscn}] \sim A^2 \times [\text{single constituent xscn}] \]

A: no. of constituents

Nucleon wavefunctions in the target nucleus are in phase with each other at low momentum transfer

See also J. Newstead slides, NMNM 3
\begin{aside}

Literature has CNS, CNNS, CENNS, ...

- I prefer including “E” for “elastic”… otherwise it gets frequently confused with coherent pion production at \sim GeV neutrino energies
- I’m told “NN” means “nucleon-nucleon” to nuclear types
- CE\nuNS is a possibility but those internal Greek letters are annoying

\rightarrow {\text{CE\nuNS}}, pronounced “sevens”…

spread the meme!

\end{aside}
The cross-section is large

\( \sigma \propto Q_W^2 \propto (N - (1 - 4 \sin^2 \theta_W) Z)^2 \)

\[ \implies \sigma \propto N^2 \]
Large cross section (by neutrino standards) but hard to observe due to tiny nuclear recoil energies:

\[
\frac{d\sigma}{dT} \sim \frac{G_F^2 M}{2\pi} \frac{Q_W^2}{4} F^2(Q) \left( 2 - \frac{MT}{E_{\nu}^2} \right)
\]

Max recoil energy is \( \sim 2E_{\nu}^2/M \) (25 keV for Ge)
The only experimental signature:

tiny energy deposited by nuclear recoils in the target material

⇒ **WIMP dark matter detectors** developed over the last ~decade are sensitive to ~ keV to 10’s of keV recoils
Now, *detecting* the tiny kick of the neutrino...

This is just like the tiny thump of a WIMP; we benefit from the last few decades of low-energy nuclear recoil detectors.

http://dmrc.snu.ac.kr/english/intro/intro1.html
The COHERENT collaboration

http://sites.duke.edu/coherent

~80 members, 19 institutions, 4 countries

arXiv:1509.08702
Free supernova-like, pulsed neutrinos!

Spallation Neutron Source

Prompt $\nu_e$ from $\pi$ decay in time with the proton pulse

Delayed anti-$\nu_\mu$, $\nu_\mu$ on $\mu$ decay timescale
Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!
(or 0.2 microsupernovae per pulse, 60 Hz of pulses)
## COHERENT CEvNS Detectors

<table>
<thead>
<tr>
<th>Nuclear Target</th>
<th>Technology</th>
<th>Mass (kg)</th>
<th>Distance from source (m)</th>
<th>Recoil threshold (keVr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI[Na]</td>
<td>Scintillating crystal</td>
<td>14.6</td>
<td>19.3</td>
<td>6.5</td>
</tr>
<tr>
<td>Ge</td>
<td>HPGe PPC</td>
<td>10</td>
<td>22</td>
<td>5</td>
</tr>
<tr>
<td>LAr</td>
<td>Single-phase</td>
<td>22</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>NaI[Tl]</td>
<td>Scintillating crystal</td>
<td>185*/2000</td>
<td>28</td>
<td>13</td>
</tr>
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</table>

Multiple detectors for $N^2$ dependence of the cross section
Siting for deployment in SNS basement
(measured neutron backgrounds low, 
~ 8 mwe overburden)

Isotropic $\nu$ glow from Hg SNS target
Expected recoil energy distribution

Lighter targets: less rate per mass, but kicked to higher energy
First light at the SNS with 14.6-kg CsI[Na] detector

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov, J. B. Albert, P. An, C. Awe, P. S. Barbeau, B. Becker, V. Belov, A. Brown, A. Bolozdy...

See all authors and affiliations

D. Akimov et al., Science, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990
What’s Next for COHERENT?

One measurement so far! Want to map out $N^2$ dependence

See talk by I. Tolstukhin
Parallel 5, NMNM
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CEvNS in the supernova itself

Recognized early as a key process in the core collapse and explosion
Supernova detection with CEvNS: any detector sensitive to WIMP recoils will be sensitive to a burst of supernova neutrinos as well and neutrinos
• WIMP DM detectors tend to be low background, low threshold (10’s of keV or less)
• Scalability to large mass is desirable
Supernova neutrinos in tonne-scale DM detectors

10 kpc
$L = 10^{52} \text{ erg/s per flavor} \times 10 \text{ s}$
$E_{\text{avg}} = (10, 14, 15) \text{ MeV}$
$\alpha = (3, 3, 2.5)$ for
$(\nu_e, \bar{\nu}_e, \nu_x)$

~ handful of events per tonne
@ 10 kpc: sensitive to
all flavor components of the flux
Information on the **all-flavor neutrino flux**, and on the **all-flavor neutrino spectrum**, in both integrated counts and recoil spectrum.

Recoil energy distribution and counts vs time for some specific models.

Detector example: **XMASS**

- tonne-scale single-phase xenon

Detector example: **XENON/LZ/DARWIN**

- dual-phase xenon time projection chambers

What will be learned?

Example: **PICO-500**

- tonne-scale superheated-fluid bubble chamber
- \(<\sim 10\) keV threshold, high recoil event sample purity
- could see multiple bubbles if detector kept superheated over seconds

S. Fallows, T. Kozynets, C. Krauss, in preparation
The so-called "neutrino floor" for DM experiments


Coherent $\nu$
Background

7Be $\nu$
8B $\nu$
solar $\nu$'s

diffuse bg SN $\nu$'s

atmospheric $\nu$'s

SN burst flux @ 10 kpc is 9-10 orders of magnitude greater than DSNB flux
Think of a SN burst as “the ν floor coming up to meet you”


L. Strigari

Cross section [cm$^2$] (normalised to nucleon)

Mass [GeV/c$^2$]

- 7Be
- 8B
- Coherent ν Background
- Atmospheric and DSNB

XENON1T
LUX
PandaX
DAMIC
SuperCDMS
Darkside 50
EDELWEISS-III
CRESST-II

Think of a SN burst as “the ν floor coming up to meet you”

L. Strigari
Summary

• **Core-collapse supernova neutrinos:**
  - vast information in flavor-energy-time profile
  - **NC info is especially valuable!** total energy, all-flavor profile

• **CEvNS:**
  - large cross section, but tiny recoils, $\alpha N^2$
  - accessible w/low-energy threshold detectors, plus extra oomph of stopped-pion neutrino source
  - **First light** from COHERENT at the SNS

• **Supernova neutrinos and CEvNS:**
  - CEvNS is an important process inside the SN
  - CEvNS is a **supernova neutrino burst detection channel** w/ NC spectral info, tonne-scale DM detectors can exploit