Supernova Neutrino Astronomy

John Beacom, Ohio State University
**SN 1987A: Our Rosetta Stone**

**Observation:** Type II supernova progenitors are massive stars

**Observation:** The neutrino precursor is very energetic

**Theory:** This is core collapse with proto-neutron star formation
Astrophysical Neutrino Detections Since 1987

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Importance of Supernova Neutrino Detection

How do core-collapse supernovae explode?
How do they form neutron stars and black holes?
What are the nucleosynthesis products of supernovae?
What are the actions and properties of neutrinos?
What is the cosmic rate of black hole formation?
Which supernova-like events make neutrinos?
What else is out there that makes neutrinos?
...

We cannot solve key problems without detecting supernova neutrinos

Only neutrinos can reveal the interior conditions of collapsing stars
Detecting even a few neutrinos could often give decisive answers
Will open new frontiers in observational neutrino astrophysics
Talk Outline

Introduction to Detection Modes

Theoretical Predictions

Experimental Limits

Detection Strategy

Conclusions
Introduction: Three Detection Modes
Distance Scales and Detection Strategies

- **N >> 1**: Burst
  - Rate $\sim 0.01/yr$
  - High statistics, all flavors

- **N $\sim 1$**: Mini-Burst
  - Rate $\sim 1/yr$
  - Object identity, burst variety

- **N << 1**: DSNB
  - Rate $\sim 10^8/yr$
  - Cosmic rate, average emission

Scale:
- kpc (kiloparsec)
- Mpc (megaparsec)
- Gpc (gigaparsec)
Simple Estimate: Milky Way Burst Yields

Super-Kamiokande (32 kton water)
- $10^4$ inverse beta decay on free protons
- $10^2 - 10^3$ CC and NC with oxygen nuclei
- $10^2$ neutrino-electron elastic scattering (*crude directionality*)

KamLAND, MiniBooNE, Borexino, etc (~ 1 kton oil)
- $10^2$ inverse beta decay on free protons
- $10^2$ neutron-proton elastic scattering
- $10 - 10^2$ CC and NC with carbon nuclei
- $10$ neutrino-electron elastic scattering

IceCube ($10^6$ kton water)
- Burst is significant increase over background rate
- Possibility of precise timing information

Much larger or better detectors are being proposed now
Simple Estimate: Extragalactic Mini-Burst Yields

A 5000-kton detector could see mini-bursts from galaxies within several Mpc, where the supernova rate is above one per year.

New considerations for such a detector as a dense infill for IceCube!

Yield in Super-Kamiokande ~ 1 (Mpc/D)^2

Kistler, Ando, Yuksel, Beacom, Suzuki (2011)
**Simple Estimate: DSNB Event Rate**

Super-Kamiokande rate in every 10 second interval

Kamiokande-II rate in a special 10 second interval $\sim 1 \text{ s}^{-1}$

$$\left[ \frac{dN_\nu}{dt} \right]_{\text{DSNB}} \sim \left[ \frac{dN_\nu}{dt} \right]_{\text{87A}} \left[ \frac{N_{SN} M_{\text{det}}}{4\pi D^2} \right]_{\text{DSNB}} \left[ \frac{N_{SN} M_{\text{det}}}{4\pi D^2} \right]_{\text{87A}}$$

For the DSNB relative to SN 1987A:

- $N_{SN}$ up by $\sim 100$
- $M_{\text{det}}$ up by $\sim 10$
- $1/D^2$ down by $\sim 10^{-10}$

DSNB event rate in Super-Kamiokande is a few per year
Present: Standard Model of Predicted DSNB

See my 2010 article in Annual Reviews of Nuclear and Particle Science
Theoretical Framework

Signal rate spectrum in detector in terms of measured energy

\[
\frac{dN_e}{dE_e}(E_e) = N_p \sigma(E_\nu) \int_0^\infty \left[ (1 + z) \varphi[E_\nu(1 + z)] \right] \left[ R_{SN}(z) \right] \left[ \left| \frac{cdt}{dz} \right| dz \right]
\]

Third ingredient: Detector Capabilities (well understood)

Second ingredient: Supernova Rate (formerly very uncertain, but now known with good precision)

First ingredient: Neutrino spectrum (this is now the unknown)

First Ingredient: Supernova Neutrino Emission

Core collapse releases \( \sim 3 \times 10^{53} \) erg, shared by six flavors of neutrinos

Spectra quasi-thermal with average energies of \( \sim 15 \) MeV

Neutrino mixing surely important but actual effects unknown

Goal is to measure the received spectrum

Yuksel, Beacom (2007)
Importance of the Spectrum

Experiment

SN 1987A data

Experiment

DSNB data

Theory

Supernova simulations
(initial spectra)
Several groups

+ Neutrino flavor change
(effects of mixing)
Several groups

Experiment

SN 201? data
Second Ingredient: Cosmic Supernova Rate

Number of massive stars unchanging due to short lifetimes

\[
\left( \frac{dN}{dt} \right) = 0 = + \left( \frac{dN}{dt} \right)_{\text{star birth}} - \left( \frac{dN}{dt} \right)_{\text{bright collapse}} - \left( \frac{dN}{dt} \right)_{\text{dark collapse}}
\]

- Measured from \( N/\tau \) using luminosity and spectrum of galaxies (now high precision)
- Measured from the core collapse supernova rate (precision will improve rapidly)
- Inferred from mismatch; can be measured by star disappearance; can be measured by DSNB (frontier research area)
**Predictions from Cosmic Star Formation Rate**

Total star formation rate deduced from massive stars using initial mass function (IMF)

Impressive agreement among results from different groups, techniques, and wavelengths

Integral of $R_{SF}$ agrees with EBL

$R_{SN}(z) \approx \frac{R_{SF}(z)}{143M_\odot}$

IMF uncertainty on $R_{SN}$ small
Measured Cosmic Supernova Rate

Measured cosmic supernova rate is **half as big as expected**, a greater deviation than allowed by uncertainties.

Why?

There must be missing supernovae – are they faint, obscured, not looked for, or truly dark?

Preliminary Dahlen (2010) points near solid line, below preliminary Dahlen (2008)

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Horiuchi et al. (2011);
see also Hopkins, Beacom (2006), Botticella et al. (2008)
What About the Supernova Rate Nearby?

Within ~ 10 Mpc, *more* supernovae than expected are found

Lots of faint supernovae

And Botticella et al. (2011) find *an excess* in $R_{SN}/R_{SF}$ in 11 Mpc

Matches progenitor studies

Minimum mass for core collapse $(8 \pm 1) M_{\odot}$

**Catalog SNRs:**
- Total
- Luminous ($M < -15$)
- Dim ($M > -15$)

**Prediction from cosmic SFR**

**Cosmic SNR measurements**

**Distance [Mpc]**

**SNR [yr$^{-1}$ Mpc$^{-3}$]**

**Horiuchi et al. (2011)**

**Botticella et al. (2011)**

John Beacom, Ohio State University

Royal Society Transients Workshop, April 2012
Third Ingredient: Neutrino Detection Capabilities

Only Super-Kamiokande has large enough mass AND (nearly) low enough backgrounds.

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Free proton targets only
Cross section grows as \( \sigma \sim E_\nu^2 \)
Kinematics good, \( E_e \sim E_\nu \)
Directionality isotropic

Vogel, Beacom (1999); Strumia, Vissani (2003)
**Predicted Flux and Event Rate Spectra**

Horiuchi, Beacom, Dwek (2009)

Bands show full uncertainty range arising from cosmic supernova rate
When core collapse fails (no optical supernova), the neutrino emission can be larger in total and average energy.

The collapse goes farther and faster, but must shed its thermal energy by neutrino emission.


**DSNB spectrum would be more detectable**

\[
\Phi / \text{cm}^{-2} \text{MeV}^{-1} \text{s}^{-1}
\]

<table>
<thead>
<tr>
<th>E/MeV</th>
<th>NS</th>
<th>BH</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;19.3</td>
<td>0.33</td>
<td>0.56</td>
<td>0.89</td>
</tr>
<tr>
<td>&gt;11.3</td>
<td>1.9</td>
<td>1.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Lunardini (2009)
Limits on the Black Hole Formation Rate

Low visible supernova rate would require large black hole fraction, up to \( \sim 50\% \)

Standard models predict at least \( \sim 10\% \) black holes

This can be resolved soon

“Survey About Nothing” (Kochanek et al., 2008) can see massive stars disappear

Large DSNB a crucial test

Lien, Fields, Beacom (2010)
Present: Limits from Super-Kamiokande
Amazing background rejection: nothing but neutrinos despite huge ambient backgrounds

Amazing sensitivity: factor \( \sim 100 \) over Kamiokande-II limit and first in realistic DSNB range

No terrible surprises

**Challenges:** Decrease backgrounds and energy threshold and *increase* efficiency and particle ID

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**Measured Spectrum Including Backgrounds**

- **Visible Energy** \( E_e \) [MeV]
- **dN / dE_e** [(22.5 kton yr)\(^{-1}\) MeV\(^{-1}\)]

**Graph Details:**
- Atm. \( \nu_\mu + \nu_\mu \)
- Atm. \( \nu_e + \nu_e \)

**Note:**
- Malek et al. [Super-Kamiokande] (2003); energy units changed in Beacom (2011) – use with care
Limits on Supernova Neutrino Emission

2003 Super-Kamiokande limit: \( \Phi < 1.2 \text{ cm}^{-2} \text{ s}^{-1} \) (90% CL) for nuebar with \( E_\nu > 19.3 \text{ MeV} \)

Supernova rate uncertainty is now subdominant; this limits the effective nuebar spectrum that includes mixing effects

Within range of expectations from theory and SN 1987A!

New Super-Kamiokande Limits

Much improved analysis and more data
To be conservative, new limits are a factor ~ 2 worse than before

Must further decrease detector backgrounds and energy threshold

Bays et al. [Super-Kamiokande] (2012)
Emerging: Gadolinium in Super-Kamiokande?

See talk by Mark Vagins at HAvSE 2011
The signal reaction produces a neutron, but most backgrounds do not.

Beacom and Vagins (2004): First proposal to use dissolved gadolinium in large light water detectors showing it could be practical and effective.

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Neutron capture on protons
Gamma-ray energy 2.2 MeV
Generally not detectable

Neutron capture on gadolinium
Gamma-ray energy $\sim 8$ MeV
Easily detectable coincidence separated by $\sim 4$ cm and $\sim 20$ $\mu$s

New general tool for particle ID
Benefits of Neutron Tagging for DSNB

Solar neutrinos: eliminated

Spallation daughter decays: essentially eliminated

Reactor neutrinos: now a visible signal

Atmospheric neutrinos: significantly reduced

DSNB: More signal, less background!

Research and Development Efforts

Over the last seven years there have been a large number of Gd-related R&D studies carried out in the US and Japan:
EGADS Proposal

EGADS Facility

In June of 2009 we received full funding (390,000,000 yen = ~$4,300,000) for this effort.
EGADS Detector

Hall E and EGADS

12/2009

2/2010

6/2010

12/2010
Adding 383 grams $\text{Gd}_2(\text{SO}_4)_3$ to 191 liters of $\text{H}_2\text{O}$; January 5th, 2011
**Recent News from Vagins**

**Plain Water Purification System:**
Transparency of purified plain water in EGADS exceeds that in SK

**Gadolinium Removal System:**
Demonstrated factor $10^6$ removal of gadolinium in a single pass

**Gadolinium Water Small-Batch Brew System:**
Gadolinium dissolved with no problems in 15-ton holding tank

**Gadolinium Water Purification:**
Gadolinium water circulation already has 99.97% efficient return

**Gadolinium Water Transparency:**
Transparency for gadolinium water is already high

On track for full test of EGADS with gadolinium water
Concluding Perspectives


Prospects for First Detection of the DSNB

Guaranteed signal:  
SK has a few DSNB nuebar signal interactions per year  
Astrophysical uncertainties are small and shrinking quickly

Super-Kamiokande upgrade:  
Possibility of adding gadolinium is seriously considered  
Research and development work very promising so far

Supernova implications:  
New measurement of cosmic core-collapse rate (and more?)  
Direct test of the average neutrino emission per supernova

Broader context:  
Possible first detections besides Sun and SN 1987A  
Non-observation of a signal would require a big surprise
### Summary of Three Detection Modes

<table>
<thead>
<tr>
<th>Milky Way</th>
<th>Nearby Galaxies</th>
<th>DSNB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mostly ready</td>
<td>Need new detectors</td>
<td>Need an upgrade</td>
</tr>
<tr>
<td>Lifetime events</td>
<td>Annual events</td>
<td>Steady detections</td>
</tr>
<tr>
<td>Only way to measure</td>
<td>Only way to check</td>
<td></td>
</tr>
<tr>
<td>precise details,</td>
<td>neutrino presence,</td>
<td></td>
</tr>
<tr>
<td>time structure,</td>
<td>burst variation,</td>
<td></td>
</tr>
<tr>
<td>all flavors,</td>
<td>etc.</td>
<td></td>
</tr>
<tr>
<td>etc.</td>
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</tbody>
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We cannot solve key problems without detecting supernova neutrinos
Broader Vision for Core-Collapse Science

Core-collapse paradigm          Optical supernova types
Core-collapse simulations       Supernova explosions
Failed collapses                Disappearing stars
Extreme stellar outbursts      Supernova “impostors”
Exact collapse time             Gravitational wave searches
Nuclear matter theory           Neutron star properties
Conditions above core          Nucleosynthesis yields
Massive star fates              Missing supernova problem
Variety in collapse             Variety in neutron stars
New particle physics            Extreme conditions

Multiple SN neutrino detection modes
Postdoctoral Fellowship applications welcomed in Fall

ccapp.osu.edu

Some rough statistics that may surprise

**Columbus, Ohio:** 0.8 million people (city), 1.8 million people (metro)

**Ohio State University:** 56,000 students on Columbus campus

**Physics:** ~ 60 faculty, **Astronomy:** ~ 20 faculty

**CCAPP:** 20 faculty, 10 postdocs from both departments