Supernova Neutrinos

An experimental overview

Alec Habig, Univ. of Minnesota Duluth
Our singular data point (so far...)

- SN1987A
  - Type II
  - In LMC, ~55kpc
- Well studied due to proximity
  - Although a peculiar SN, blue giant progenitor, odd dim light curve
- And close enough so that $1/r^2$ didn’t crush the $\nu$ signal
  - Seen in proton decay detectors (which also had a pesky $\nu$ background)
  - (and not the 4.1 years early the OPERA results would have implied...)
SN1987A $\nu$ observations

Proton Decay experiments see: Water Cherenkov

- **Kamiokande**
  - $E_{\text{th}} = 8.5$ MeV
  - $M = 2.9$ kt
  - Sees 11 $\nu$

- **IMB**
  - $E_{\text{th}} = 29$ MeV
  - $M = 6$ kt
  - Sees 8 $\nu$

- **Baksan**
  - $E_{\text{th}} = 10$ MeV
  - $M = 130$ t
  - Sees 3-5 $\nu$

- **Mont Blanc**
  - $E_{\text{th}} = 7$ MeV
  - $M = 90$ t
  - Sees 5 $\nu$ (?)
Core Collapse Model Confirmed

- Take observed spectra, flux
- Project back to 55kpc
- Generalities of model confirmed!
  - … given the low low statistics
- And time profile is about right too
- Signal also sets mass limit of $m_{\nu_e} < 20$eV
  - No observed dispersion of $\nu$ as a function of $E_\nu$
- For a galactic SN happening tomorrow,
  - $R \sim 10$ kpc
  - Modern detectors, $E_{th} \sim 5$ MeV, $M \sim 10$'s kt
    - 1000's of events would be seen

SN1987A
$
\nu$ event
seen in IMB
Tomorrow?

- Humans haven’t seen a galactic SN since Kepler, why bother looking?

<table>
<thead>
<tr>
<th>Mean interval (yr) per galaxy</th>
<th>Core Collapse</th>
<th>All SNe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historic Visible</td>
<td>?</td>
<td>30-60</td>
</tr>
<tr>
<td>Extragalactic</td>
<td>35-60</td>
<td>30-50</td>
</tr>
<tr>
<td>Radio Remnants</td>
<td>&lt;18-42</td>
<td></td>
</tr>
<tr>
<td>$\gamma$-ray remnants</td>
<td>16-25</td>
<td></td>
</tr>
<tr>
<td>Pulsars</td>
<td>4-120</td>
<td></td>
</tr>
<tr>
<td>Fe abundance</td>
<td>&gt;19</td>
<td>&gt;16</td>
</tr>
<tr>
<td>Stellar death rates</td>
<td>20-125</td>
<td></td>
</tr>
</tbody>
</table>

Overall?

3±1 per century!

Academically – one per career, if Monsieur Poisson cooperates at this rate and given a galactic radius of 15kpc, that’s hundreds of SN-\nu wavefronts already on their way to us here on Earth!
Observational Efficiency

- Perhaps 1/6 would be easily seen optically
  - (Historical SNe map from S&T)

Apparent Brightnesses of Milky Way Supernovae

- 10% will peak brighter than magnitude −3
- 20% will peak between magnitudes −3 and +2
- 20% will peak between magnitudes +2 and +6
- 20% will peak between magnitudes +6 and +11
- 30% will peak fainter than magnitude +11

Progenitor: 12–15 magnitudes fainter
Earliest observations (and non-observations) of SN1987a were fortuitous
- ~hours before/after the actual event
- Chance observations (Shelton, Duhalde, Jones)
- Very careful observer records null-observations to constrain breakout time (Jones)

Extragalactic SNe not so obvious
- Typically days-weeks elapse before someone notices

What goes on between these pictures?
Advance Warning

• Observations from t=0?
  – Sure. Or very nearly so, certainly better than the serendipitous ~hours of SN1987A, and far closer than the ~days which is the best we can get on an extragalactic SN

• How?
  – ν’s exit the SN promptly
  – But stars are opaque to photons
  – EM radiation is not released till the shock wave breaks out through the photosphere – a shock wave travel time over a stellar radius
  – ~hour for compact blue progenitors, ~10 hours for distended red supergiants
Our Telescopes

• Photons should be the easy stuff to work with…

• SN $\nu$ detectors need:
  – Mass ($\sim$100 events/kton)
  – Background rate $\ll$ signal rate

• Bonus items:
  – Timing
  – Energy resolution
  – Pointing
  – Flavor sensitivity (to do all the oscillation physics!)

Now they’re detectors studying aspects of neutrino oscillations, since protons apparently don’t decay…
Basic Types

- Scintillator ($C_nH_{2n}$)
- Imaging Water Cherenkov ($H_2O$)
- Long String Water Cherenkov ($H_2O$)
- Nobel Liquids ($Ar, Xe$)
- High Z ($Fe, Pb$)
- Gravitational waves
  - Well, not neutrinos, but gravitons would also provide a prompt SN signal if SN was asymmetric
Scintillator

- Volume of hydrocarbons (usually liquid) laced with scintillation compound observed by phototubes
  - Mostly inv. β decay (CC): $\bar{\nu}_e + p^+ \rightarrow e^+ + n$
  - ~5% $^{12}$C excitation (NC): $\nu_x + ^{12}$C $\rightarrow \nu_x + ^{12}$C$^*$
  - ~1% elastic scattering (NC+CC): $\nu_x + e^- \rightarrow \nu_x + e^-$
  - Low E proton scattering (NC): $\nu_x + p^+ \rightarrow \nu_x + p^+$

Mont Blanc, Baksan, MACRO, LVD, Borexino, KamLAND, MiniBooNE, DoubleCHOOZ, Daya Bay, SNO+, NO$\nu$A, JUNO, RENO50, LENA

Little pointing capability
Scintillator Expts.

KamLAND (Japan)
1 kton
~300 $\overline{\nu}_e$
at 8.5 kpc

Borexino (Italy)
0.3 kton
~100 $\overline{\nu}_e$

LVD (Italy)
1 kton
~200 $\overline{\nu}_e$

Daya Bay (China)
8x {20ton w/ Gd + 22ton plain scint}
~100 $\overline{\nu}_e$
The NO$\nu$A Experiment

- Far Detector at Ash River
- Near Detector near beam source
  - Establishes pre-oscillation expectations
- Both same “highly active” construction: scintillator is 60% of mass
- PVC Cells in alternating directions filled with liquid scintillator provide stereo readout

SEE TALK BY JUSTIN VASEL
Water Cherenkov

- $\text{H}_2\text{O}$ viewed with phototubes, Cherenkov radiation observed
  - Mostly inv. $\beta$ decay (CC): $\nu_e + p^+ \rightarrow e^+ + n$ (seen)
  - $\sim\%$ elastic scattering (NC+CC): $\nu_x + e^- \rightarrow \nu_x + e^-$
  - $^{16}\text{O}$ excitation (NC): $\nu_x + ^{16}\text{O} \rightarrow \nu_x + ^{16}\text{O}^*$
  - $^{16}\text{O}$ CC channels: $\nu_e + ^{16}\text{O} \rightarrow ^{16}\text{F} + e^- ; \bar{\nu}_e + ^{16}\text{O} \rightarrow ^{16}\text{N} + e^+$

Pointing!

$\delta\theta \sim \frac{25^\circ}{\sqrt{n}}$

IMB, Kamiokande, Super-K, EGADS, outer part of SNO
Imaging Water Cherenkov

Super-Kamiokande (Japan) 50kton

- Events expected for SN@8.5 kpc > 5MeV
  - $\text{inv} \beta$ decay: 7000
  - $^{16}\text{O}$ excitation: 300
  - $^{16}\text{O}$ CC channels: 110
  - elastic scattering: 200
    - 4° pointing
  
  - Addition of gadolinium will allow lowering of IBD threshold by looking for neutron captures, tags IBDs
Long String Water Cherenkov

- Dangle PMT’s on long (~km) strings in clear ice or water
- High-E $\nu$ telescopes with $E_{th} \sim 100 \text{ GeV}$
- But singles rates around PMT’s raised by SNe $\bar{\nu}_e$
  - $M_{eff} = 0.4\text{kton}/\text{PMT}$

AMANDA, Ice Cube, Baikal, Nestor, Antares, Km3Net…
Long String Ice Cherenkov

- Ice-based expts. have low enough background rate to work
  - Sea based have $^{40}\text{K}$, squid, etc.
- $16\sigma$ S/N @8.5kpc
  - But little $\nu$ by $\nu$ info such as energy
- AMANDA:
  - Special SN trigger was operational till experiment was retired
- IceCube’s new electronics do it even better
• Argon sees $O(10 \text{ MeV}) \nu$ via the leptons and de-excitation gammas from:

Charged-current absorption

$\nu_e + ^{40}\text{Ar} \rightarrow e^+ + ^{40}\text{Cl}^*$

$\bar{\nu}_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^*$

Neutral-current excitation

$\nu_x + ^{40}\text{Ar} \rightarrow \nu_x + ^{40}\text{Ar}^*$

Elastic scattering: *(points back!)*

$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$

Look for electrons and de-excitation gammas
Nobel Liquids

- DUNE: 4 staged 10 kt LArTPC modules at Homestake

DUNE: 4 staged 10 kt LArTPC modules at Homestake

~3000 events

Gaining LArTPC experience with LARIAT, MicroBoone, CAPTAIN, SBND at FNAL
Xenon1t

• Dark Matter detectors are now so huge they can see $\nu$
• $\sim$10 events over no background via NC $\nu$-nucleon coherent scattering at low energy
• Pb’s neutron excess Pauli-blocks the usual SN ν detection channel of:
  – $\overline{\nu}_e + p^+ \rightarrow e^+ + n$
  – allowing: $\nu_e + n \rightarrow e^- + p^+$
• An 18 MeV $\nu_e$ will result in an excited Bi nucleus with high cross-section due to the Gamow-Teller giant resonance
  – Bi emits thermal neutrons, to which the surrounding Pb is fairly transparent
• So: instrument a big pile of lead with neutron counters, watch for SN-sized burst of neutrons

**Pb σ & SN $\nu_e$ flux**
S. Elliot,

**Pb & Bi nuclear levels**
Bacrania et al, NIM A492, 43 (2002)
HALO

SEE TALKS BY CLARENCE VIRTUE AND STAN YEN
Flavor Sensitivities

Water Cherenkov (w/o Gd)

Lead

\[
\begin{align*}
\nu_e + ^{208}_{\text{Pb}} & \rightarrow ^{207}_{\text{Bi}} + n + e^- \\
\nu_e + ^{208}_{\text{Pb}} & \rightarrow ^{206}_{\text{Bi}} + 2n + e^- \\
\nu_x + ^{208}_{\text{Pb}} & \rightarrow ^{207}_{\text{Pb}} + n \\
\nu_x + ^{208}_{\text{Pb}} & \rightarrow ^{206}_{\text{Pb}} + 2n
\end{align*}
\]

Strong threshold dependence

Liquid Scintillator

\[\overline{\nu}_e \text{ CC} \quad \text{NC}\]

Iron

\[\overline{\nu}_e \text{ CC} \quad \text{NC}\]

Low thresholds see NC coherent scattering

… but no Fe experiments exist
SNEWS

- SNEWS
  - Supernova Early Warning System

- Any single experiment has many sources of noise and few SNe
  - Flashing PMTs, light leaks
  - Electronic noise
  - Spallation
  - Coincident radioactivity

- Most can be eliminated by human examination (takes time)
  - No experiment would want to make an automated SN announcement alone!

- None will simultaneously occur in some other experiment
The Experiments

- **Currently:**
  - Super-K
  - LVD
  - IceCube
  - Borexino
  - Daya Bay
  - Kamland
  - HALO

- **Alumni:**
  - MACRO, SNO, AMANDA

- **Operational but not SNEWS contributors:**
  - Baksan, SBND

- **Near-Future participants**
  - NOvA, EGADS, SNO+
A Global Coincidence Trigger

- Experiments send blind TCP/IP packets to central coincidence server
- Secure, stable hosting at Brookhaven
  - Backup server at Bologna
- Other benefits such as down time coordination, working relationship between SN teams, etc

Server
10s coincidence window

SSL sockets

PGP signed email

Email alarms to astronomers

Alarm packets to trigger LIGO, NOvA, GCN

Daya Bay
Borexino
LVD
Kamland
IceCube
SK
HALO
Where will we see?

- All these experiments sensitive to all or most of the Milky way and all but the smallest also the Magellenic clouds
  - But even Super-K would see only one interaction from a SN in Andromeda: $1/r^2$ is murderous when combined with weak interaction cross-sections
- Super-K could point back to within $\sim 4^\circ$ using the sub-dominant electron elastic scatters
  - And do this even better once Gd captures tag IBD interactions
Elastic Scattering

• This is the reaction that lets Super-K identify solar neutrinos

• Problem – each pixel in this picture is about 0.5°
  – Diameter of full moon

• Resolution dominated by neutrino/lepton scattering angle not experimental resolution
  – Can’t upgrade that

The core of the Sun as seen with $\nu$ (Super-K)
What flavors will we see?

- High statistics anti-electron neutrino "light curve" from Ice Cube and Super-K
  - Smaller experiments will add statistics, redundancy, and each has its own slightly different set of sensitivities
  - All also have microsecond or better timing resolution
- Electron-neutrinos only available with low statistics until DUNE comes online
  - HALO, SK elastic scatters
- All have some NC sensitivity at low stats that need disentangled
  - Xenon1t is nearly pure NC but low stats
Summary

- A core-collapse SN will occur in our galaxy sooner or later
  - It will produce a $\nu$ signal $\sim$hours in advance of the light
- Many experiments are online now, more coming soon
  - Each brings a different set of strengths to the table
  - Combining their signals will be very useful (mandatory?) to deconvolute neutrino flavor
- Pointing not great until someone sees it with photons
- SNEWS has been online ready to form a quick alarm for more than a decade now, and will continue into the future
Acknowledgements

• SNEWS supported by NSF collaborative grant #1505960
  – Alec Habig @ UofM Duluth
  – Kate Scholberg @ Duke

• SNEWS only functions with the cooperation of member experiments and their SN teams, plus Sky & Telescope, Brookhaven, and INFN Bologna

• HALO thanks go to SNOLAB, NSERC, and NSF (again via Duke & UMD)

• See http://snews.bnl.gov for more info and to sign up for the alert list