SUPERNova Neutrino Detection

With present & future detectors

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OUTLINE

- The Core Collapse $\nu$ Signal
- Supernova $\nu$ Detection with Current & Future Detectors
- What Can We Learn from a Galactic SN $\nu$ Signal?
  - $\nu$ physics
  - Core Collapse Physics
  - Early Alert
- SNEWS: the Inter-Experiment Network
- Current Status & Future
SUMMARY OF THE SUPERNova NEUTRINO SIGNAL

\[ \Delta E_b \sim \frac{G M_{\text{core}}^2}{R_{\text{nsstar}}} \sim 2 \times 10^{53} \text{ ergs} \]

\[ \begin{cases} \lesssim 1\% & \text{kinetic energy, em radiation} \\ 99\% & \text{\( \nu \)'s of all flavors} \end{cases} \]

\[ \begin{cases} \nu_e \text{ from 'breakout' } \sim 1\% \\ \nu \bar{\nu} \text{ from cooling } 99\% \end{cases} \]

NEUTRINO ENERGIES

\[ \langle E_{\nu_e} \rangle \sim 12 \text{ MeV} \]
\[ \langle E_{\nu_e} \rangle \sim 15 \text{ MeV} \]
\[ \langle E_{\nu_{\mu,\tau}} \rangle \sim 18 \text{ MeV} \]

DEEPER \( \nu \)-SPHERE \rightarrow HOTTER \( \nu \)'S

TIMESCALE

\[ \Delta t \sim 10\text{'}s \text{ of seconds} \]
\[ \sim 50\% \text{ in first second} \]

PROMPT after core collapse

Possible sharp \( \nu \) cutoff if BH forms
SUPERNova NEUTRINO DETECTORS

- Need $M \sim 1$ kton for $\sim 100$ interactions
- Must have bg rate $\ll$ rate in $\nu$ burst

Also want:  
- timing
- energy resolution
- pointing
- flavor sensitivity (NC)

DETECTOR TYPES:

- scintillator $C_nH_{2n}$
- water Cherenkov $H_2O$
- heavy water $D_2O$
- long string $H_2O$
- “high $Z$” $Pb, Fe$

...
**SCINTILLATION DETECTORS**

Liquid scintillator "CnH2n" volume viewed by PMTs

\[ \bar{\nu}_e + p \rightarrow \nu^+ + n \]
\[ Ee^+ = E_{\bar{\nu}_e} - 1.3 \text{ MeV} \]
\[ 180 \mu s \rightarrow n + p \rightarrow d + \gamma \]
\[ 2.2 \text{ MeV} \]

**INVERSE BETA DECAY**

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

**NC EXCITATION OF }^{12}\text{C**}

\[ \text{NC} \quad \nu_x + ^{12}\text{C} \rightarrow \nu_x + ^{12}\text{C}^* \]
\[ \rightarrow ^{12}\text{C} + \gamma \]
\[ 15.1 \text{ MeV} \]
\[ \sim 5\% \]

**ELASTIC SCATTERING**

\[ \text{NC, CC} \quad \nu_x + e^- \rightarrow \nu_x + e^- \]
\[ \sim \text{few \%} \]

(Almost) **NO POINTING**

Examples: Mont Blanc, Baksan, Palo Verde, Chooz, MACRO, LVD, Borexino, KamLAND
WATER CHERENKOV DETECTORS

Volume of clear water viewed by PMTs

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

Also:

\[
\begin{align*}
&\bar{\nu}_e + ^{16}O \rightarrow ^{16}F + e^- \\
&\bar{\nu}_e + ^{18}O \rightarrow ^{18}F + e^- \\
&\bar{\nu}_e + ^{16}O \rightarrow ^{16}N + e^-
\end{align*}
\]

NC, CC \( \nu_x + e^- \rightarrow \nu_x + e^- \)  
few percent

POINTING \( \Delta \theta \sim 25^\circ \)

Kamiokande, IMB, Super-Kamiokande, part of SNO

\( \gtrsim 5000 \) events  
@ 8.5 kpc
HEAVY WATER DETECTORS

$D_2O$ viewed by PMTs + neutron detection

$$\begin{align*}
CC & \begin{cases} 
\nu_e + d \rightarrow p + p + e^- \\
\bar{\nu}_e + d \rightarrow n + n + e^+
\end{cases} \\
NC & \begin{cases} 
\nu_x + d \rightarrow n + p + \nu_x \\
\bar{\nu}_x + d \rightarrow n + p + \bar{\nu}_x
\end{cases}
\end{align*}$$

VERY GOOD NC SENSITIVITY.
⇒ sensitivity to $\nu$ mass, osc

SNO: 1 kton $D_2O$ , few hundred each of $\overline{\nu}_e p$, NC, CC breakup for collapse @ 8.5 kpc
LONG STRING WATER CHERENKOV DETECTORS

\~ km long strings of PMTs in very clear ice or water

Nominally multi-GeV energy threshold

\[ \bar{\nu}_e \]

burst of Cherenkov photons from \( \bar{\nu}_e \)-induced positrons

BUT: may see burst of low energy \( \bar{\nu}_e \)'s (\cite{Hamaguchi2009}) as COINCIDENT INCREASE in PMT singles rates!

\[ M_{\text{eff}} \sim 0.4/\text{pmt} \] (No pointing, energy resolution)

AMANDA, Antares, Baikal, Nestor

low noise promising (\( \sim 10 \) kpc sensitivity)
OTHER SN $\nu$ DETECTORS

- HIGH $Z$/NEUTRON DETECTORS
  
  Large quantity of high $Z$ material + neutron counters

  NC  \[ \nu_x + (A,Z) \rightarrow (A-1,Z) + n + \nu_x \]

  CC  \[ \begin{align*}
  \nu_e + (A,Z) & \rightarrow (A-1,Z+1) + n + e^- \\
  \overline{\nu}_e + (A,Z) & \rightarrow (A-1,Z-1) + n + e^+
  \end{align*} \]

  e.g. OMNIS, LAND (Fe/Pb) (Pb)

- LIQUID ARGON
  
  CC  $\nu_e + {}^{40}\text{Ar} \rightarrow {}^{40}\text{K}^* + e^-$

  e.g. Icanoe

- RADIOCHEMICAL
  
  Homestake  $\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$

  Gallium  $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$

  NOT REAL TIME, but may register counts

  $\Rightarrow$ perform prompt extractions

  $+\$ gravitational radiation from asymmetric explosions ($\sim$ unknown signal)
# Summary of SN Neutrino Detector Types

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Material</th>
<th>Energy</th>
<th>Time</th>
<th>Point</th>
<th>Flavor</th>
</tr>
</thead>
<tbody>
<tr>
<td>scintillator</td>
<td>C,H</td>
<td>y</td>
<td>y</td>
<td>n</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>water Čerenkov</td>
<td>H$_2$O</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>heavy water</td>
<td>D$_2$O</td>
<td>NC: n</td>
<td>y</td>
<td>n</td>
<td>all</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CC: y</td>
<td>y</td>
<td>y</td>
<td>$\nu_e, \bar{\nu}_e$</td>
</tr>
<tr>
<td>long string water Čerenkov</td>
<td>H$_2$O</td>
<td>n</td>
<td>y</td>
<td>n</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>liquid argon</td>
<td>Ar</td>
<td>y</td>
<td>y</td>
<td>y</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>high Z/neutron</td>
<td>Fe, Pb</td>
<td>n</td>
<td>y</td>
<td>n</td>
<td>all</td>
</tr>
<tr>
<td>radio-chemical</td>
<td>$^{37}$Cl, $^{127}$I, $^{71}$Ga</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>$\nu_e$</td>
</tr>
</tbody>
</table>

- primary sensitivity to $\bar{\nu}_e$
- NC for heavy water, neutron
- pointing for water Ch., heavy water, argon
- all real-time except radio-chemical
- all have energy resolution except long string neutron, radio-chemical
## SUMMARY OF SPECIFIC SN NEUTRINO DETECTORS

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kton)</th>
<th>Location</th>
<th>No. of events @8.5 kpc</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K</td>
<td>water Čeren.</td>
<td>32</td>
<td>Japan</td>
<td>5000</td>
<td>running</td>
</tr>
<tr>
<td>SNO</td>
<td>H₂O, D₂O</td>
<td>1.4</td>
<td>Canada</td>
<td>300</td>
<td>running</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>MACRO</td>
<td>scint.</td>
<td>0.6</td>
<td>Italy</td>
<td>150</td>
<td>running</td>
</tr>
<tr>
<td>LVD</td>
<td>scint.</td>
<td>0.7 (1 σ)</td>
<td>Italy</td>
<td>170</td>
<td>running</td>
</tr>
<tr>
<td>KamLAND</td>
<td>scint.</td>
<td>1</td>
<td>Japan</td>
<td>300</td>
<td>2001</td>
</tr>
<tr>
<td>Borexino</td>
<td>scint.</td>
<td>0.3</td>
<td>Italy</td>
<td>100</td>
<td>2000</td>
</tr>
<tr>
<td>Baksan</td>
<td>scint.</td>
<td>0.33</td>
<td>Russia</td>
<td>50</td>
<td>running</td>
</tr>
<tr>
<td>AMANDA</td>
<td>long string</td>
<td>Meff ~ 0.4/pmt</td>
<td>Antarctic</td>
<td></td>
<td>running</td>
</tr>
<tr>
<td>OMNIS</td>
<td>high Z Pb/Fe</td>
<td>10(Fe) +4(Pb)</td>
<td>USA</td>
<td>~1000</td>
<td>proposed</td>
</tr>
<tr>
<td>LAND</td>
<td>high Z Pb</td>
<td></td>
<td>Canada</td>
<td></td>
<td>proposed</td>
</tr>
<tr>
<td>Icanoe</td>
<td>liquid argon</td>
<td>9</td>
<td>Italy</td>
<td></td>
<td>2005</td>
</tr>
</tbody>
</table>

~ Galactic sensitivity
WHAT CAN WE LEARN FROM A GALACTIC SN $\nu$ SIGNAL?

- NEUTRINO PHYSICS
  - $\nu$ absolute mass from t.o.f. delay
  - $\nu$ oscillations from spectra

- CORE COLLAPSE PHYSICS
  - explosion mechanism
  - proto n star cooling
  - black hole formation

- ASTRONOMY FROM EARLY ALERT
  - hours of warning before visible SN
  - some pointing w/$\nu$'s
  - progenitor & environment info
  - unknown early effects?
NEUTRINO PHYSICS with SN NEUTRINOS

\( \nu \) ABSOLUTE : time of flight delay
\( \nu \) MASS

Look for:
\[
\begin{align*}
&\text{energy-dependent time spread} \\
&\text{flavor-dependent delay}
\end{align*}
\]

\( \nu \) OSCILLATION : distortion of energy spectra
\( \nu \) (hot \( \nu_e, \bar{\nu}_e \))

(in core)

Look for: NC vs. CC detected rates
\[ \begin{align*}
\text{e.g., Fuller et al., astro-ph/9809169} \\
\text{Dighe & Smirnov, hep-ph/9907223}
\end{align*} \]

Also:
\( \nu \) lifetime
\( \nu \) charge
No of \( \nu \) flavors
\( \nu \) magnetic moment

CAVEAT : Always at least some core-collapse model-dependence
MEASURING ABSOLUTE $\nu$ MASS WITH A SN BURST

Time of flight $\Delta t(E) = 0.515 \left( \frac{m}{E} \right)^2 D$

$[m:\text{eV}, E:\text{MeV}, D:\text{10 kpc}]$

Spread in arrival time & correlation with energy $\Rightarrow$ non-zero $\nu$ mass

But: due to finite emission $\Delta t$ $\Rightarrow$ only get upper limit on $m_{\nu}$

SN1987A $m_{\nu_e} \lesssim 20 \text{ eV}$ w/ reasonable assumptions

Next SN in Galaxy: will get $m_{\nu_e} \lesssim 3 \text{ eV}$ e.g. T. Totani astro-ph/9801104

NOT BETTER THAN LAB!

PROMISING APPROACH FOR $\nu_{\mu,\tau}$

Use detectors with NC sensitivity $\Rightarrow$ look for relative delay of $\nu_{\mu,\tau}$ wrt $\nu_e$
STRATEGY: tag NC & CC events
and measure relative delay

e.g. Beacom & Vogel hep-ph/9806311

Delay of SNO NC wrt SK $\bar{\nu}_e$

MC Simulation of $10^4$ SN'S

10 kpc

Limit 30 ev for no observed delay

Get $\sim 30-50$ ev limits ($\nu_{\mu, \tau}$) with SK+SNO
Better than lab! \{ $m_{\nu_{\mu}} < 0.17$ MeV, $m_{\nu_{\tau}} < 18$ MeV \}
Core collapse resulting in black hole formation (fraction: 50%?) $\Rightarrow$ sharp cutoff of $\nu_x$ luminosity

$t = 0$ for tof delay measure

Use $\nu$ energy info e.g. SK $\bar{\nu}_e p$

$\Rightarrow$ limit on $\bar{\nu}_e$ mass: $\sim 1.8$ eV

Using NC in OMNIS-like detector:

$\sim 6$ eV for $\bar{\nu}_\mu, \bar{\nu}_e$ mass limit
AN EARLY ALERT for astronomers

~ hours of warning (depends on stellar envelope)

Early light actually not helpful for SN explosion theory (ν's are)

BUT:  
- environment near progenitor probed by initial stages
- UV/soft x-ray flash @ shock breakout predicted

+ possible unknown early effects!

Early light observations very rare for extragalactic

⇒ Supernova Early Warning System

Computer(s) receive 'blind' alert messages from ν detectors;
automated alert if coincidence
SNEWS IMPLEMENTATION

Alarm datagrams sent by individual experiments to server(s)
Now running @ Super-K site

SERVER
on central machine
10 second coincidence by UT time stamp

CLIENT Super-K
Alarm datagram

CLIENT SNO

CLIENT MACRO
Alarm datagram: (experiment UT time)

CLIENT LVD

alert to astronomical community
{ optical satellites HST amateurs

MACRO, LVD, Super-K: automated alarms

Next: SNO, Amanda
New server @ LNGS

Automated alerts to astronomers within the year
**POINTING with ν's**

Beacom & Vogel  astro-ph/9811350

**ASYMMETRIC REACTIONS** in a single detector may be the best bet

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

few % of SK events

\[ \Delta \Theta \sim 25^\circ \]

\[ \frac{\delta \Theta}{\sqrt{N}} \sim \frac{25^\circ}{\sqrt{N}} \]

\{ correction factor of \sim 2 - 4 due to centroiding on isotropic bg

SK \sim 5^\circ, SNO \sim 20^\circ for SN @ Galactic center

**TRIANGULATION** using relative timing of signals

2 exp'ts: circle on sky
3 exp'ts: 2 blobs
4 exp'ts: point to spot

\[ \cos \alpha = \frac{c \Delta T}{d} \]

\[ \delta(\cos \alpha) = \frac{c \delta(\Delta T)}{d} \]

(registration error)

Statistics for current detectors poor...

SK-SNO \[ \delta(\cos \alpha) \sim 0.5 \@ 10 \text{ kpc} \]

for realistic pulse shapes (\+
practical problems for prompt answer)

Still worth a try...
SUMMARY

• Several \( \nu \) detectors with Galactic sensitivity online now

  Super-K
  SNO
  MACRO
  LVD
  AMANDA
  Borexino
  KamLAND
  OMNIS

• Core collapse will yield a bonanza of information!

  \( \nu \) physics: absolute mass limits
  \[ \bar{\nu}_e \leq 3 \text{ eV} \]
  \[ \bar{\nu}_\mu,\tau \leq 30 \text{ eV} \]
  better for BH collapse?
  • oscillation info
  • etc.
  \( \Rightarrow \) Core collapse models
  \( \Rightarrow \) SNEWS: early alert from coincidence

Hoping for SN2XXX soon!