Multi-messenger physics opportunities from core-collapse supernovae

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Inherently a multi-messenger source

Outline

Review of core-collapse supernovae

Multi-messenger opportunities with Galactic supernovae

Beyond the Milky Way

Concluding remarks
Collapse of massive stars

Massive (>8Msun) star structure

Explosion

R: 8000 km $\rightarrow$ \sim20 km
$\rho$: $\sim10^9$ g cm$^{-3}$ $\rightarrow$ $\sim10^{14}$ g cm$^{-3}$
T: $\sim10^{10}$ K $\rightarrow$ $\sim30$ MeV

Adapted from slides by G. Raffelt
Explosion mechanism

Stalled shock
The bounce shock stalls (photodissociation & neutrino emission). Pressure inside balanced by external ram pressure

\[ p = \rho \Delta v^2 \]

Explosion mechanism
e.g., deposit a fraction of the energy in neutrinos to behind the shock

Bethe & Wilson (1985), Colgate et al (1966), ...

And/or, rotation, magnetic, phase transition, exotic, ...

Mass accretion
VS
Heating
Importance of asphericity

Consensus in the 2000s that 1D doesn’t work.

*e.g., Liebendoerfer et al (2001, 2004)*

Hydrodynamical instabilities aid explosions, *e.g.*, standing accretion shock instability (SASI), convection

*e.g. US, German, Japan, Australian groups*

![Graph showing 1D, 2D, and 3D shock radius over time](chart1)

![Graph showing energy vs. multipole order](chart2)

Shunsaku Horiuchi (VT CNP)  
*Takiwaki et al (2014)*  
*Janka et al (2016)*
Supernova diversity

Systematic studies: thinking in mass looks incomplete

Compactness: a useful indicator

Compactness:
Captures the density structure of the progenitor, which drives mass accretion evolution

$\xi_M = \frac{M/M_\odot}{R(M_{\text{bary}} = M)/1000\, \text{km}}$

$\xi$M = \frac{M/M_\odot}{R(M_{\text{bary}} = M)/1000\, \text{km}}$

O’Connor & Ott (2011)

Mass accretion
Neutrino heating

VS!
Islands of un-explodability

Failed explosions appear in islands, and correspond to stars with large compactness.

- BH formation for $\xi_{2.5} > 0.3$
- Explosions for $\xi_{2.5} < 0.15$
- Mixture in between

1 compactness predicts outcome in at most $\sim 88\%$ of cases
2 parameters successfully predicts in $\sim 97\%$ of cases


Ertl et al (2015), see also Pejcha & Thompson (2015)
Failed fraction could be large

Many circumstantial evidence for a large fraction of failed explosions.

Red supergiant problem
- \( f_{BH} \approx 20-30\% \)
  - Smartt et al (2009)

Black hole mass function
- \( f_{BH} \approx 10-40\% \)

Supernova rate
- \( f_{BH} \approx 10-30\% \)

Survey about nothing
- \( f_{BH} \approx 4-43\% \)

Insights for compactness:
These can be explained by a critical compactness \( \xi_{2.5} \approx 0.2 \)
(i.e., explosions \( \xi_{2.5} < 0.2 \) and fails for \( \xi_{2.5} > 0.2 \))

- e.g., Kochanek (2014), Horiuchi et al (2014)
MULTI-MESSENGER OPPORTUNITIES WITH GALACTIC SUPERNOVAE
Galactic supernova neutrinos: multi-messenger astronomy

Goals:
The next Galactic supernova neutrino signal will
1. Reveal IF one should look – ‘significance’
2. Reveal WHEN one should look – ‘timing resolution’
3. Provide TIMELY alert – ‘TOO’
4. Reveal WHERE one should look – ‘astronomy’

(see Adams et al 2013)
1. Reveals IF to look

Reveal IF: High number statistics expected from a Galactic core collapse

<table>
<thead>
<tr>
<th>Detector</th>
<th>Type</th>
<th>Mass (kt)</th>
<th>Location</th>
<th>Events</th>
<th>Flavors</th>
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<tbody>
<tr>
<td>Super-Kamiokande</td>
<td>H\textsubscript{2}O</td>
<td>32</td>
<td>Japan</td>
<td>7,000</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>LVD</td>
<td>C\textsubscript{n}H\textsubscript{2n}</td>
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<td>Italy</td>
<td>300</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
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<td>C\textsubscript{n}H\textsubscript{2n}</td>
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<td>Japan</td>
<td>300</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>Borexino</td>
<td>C\textsubscript{n}H\textsubscript{2n}</td>
<td>0.3</td>
<td>Italy</td>
<td>100</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>IceCube</td>
<td>Long string</td>
<td>(600)</td>
<td>South Pole</td>
<td>$10^6$</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>Baksan</td>
<td>C\textsubscript{n}H\textsubscript{2n}</td>
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<td>Russia</td>
<td>50</td>
<td>$\bar{\nu}_e$</td>
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<tr>
<td>MiniBooNE*</td>
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<td>USA</td>
<td>200</td>
<td>$\bar{\nu}_e$</td>
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<td>HALO</td>
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<td>Canada</td>
<td>30</td>
<td>$\nu_e, \nu_x$</td>
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<tr>
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<td>China</td>
<td>100</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>NO\nuA*</td>
<td>C\textsubscript{n}H\textsubscript{2n}</td>
<td>15</td>
<td>USA</td>
<td>4,000</td>
<td>$\bar{\nu}_e$</td>
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<tr>
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<td>MicroBooNE*</td>
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<td>17</td>
<td>$\nu_e$</td>
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<tr>
<td>DUNE</td>
<td>Ar</td>
<td>34</td>
<td>USA</td>
<td>3,000</td>
<td>$\nu_e$</td>
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<tr>
<td>Hyper-Kamiokande</td>
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<td>Japan</td>
<td>110,000</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>JUNO</td>
<td>C\textsubscript{n}H\textsubscript{2n}</td>
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<td>China</td>
<td>6000</td>
<td>$\bar{\nu}_e$</td>
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<tr>
<td>RENO-50</td>
<td>C\textsubscript{n}H\textsubscript{2n}</td>
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<td>Korea</td>
<td>5400</td>
<td>$\bar{\nu}_e$</td>
</tr>
<tr>
<td>LENA</td>
<td>C\textsubscript{n}H\textsubscript{2n}</td>
<td>50</td>
<td>Europe</td>
<td>15,000</td>
<td>$\bar{\nu}_e$</td>
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<td>Long string</td>
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2. Reveals WHEN to look

WHEN one should look: from reconstruction of the core bounce time

- $E_\nu > 100$ GeV

- Neutrinos can determine the bounce time to $O(10)$ ms

Halzen & Raffelt (2009)

Shunsaku Horiuchi (VT CNP)  
Abbasi et al. (2011)
**Multi-messenger: gravitational wave**

Without neutrino timing
Maximum signal-to-noise ratio is \(\sim 3.5\) occurring at \(\sim 200\text{Hz}\): but no strong detection (using H-L-V-K network)

With neutrino timing
Narrowing window to 60 ms and freq [50, 500] Hz: SNR \(\sim 7 \rightarrow \) `correlated’ detection

\(\rightarrow\) Pagliaroli talk

\(\rightarrow\) Timing of core bounce helps GW detection

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3. TIMELY alerts

TIMELY alert: rapid sharing of core collapse occurrence

✓ SNEWS:
  - Borexino
  - DayaBay
  - HALO
  - IceCube
  - KamLAND
  - LVD
  - Super-K

Coincidence server (@BNL)

http://snews.bnl.gov
astro-ph/0406214

✓ Individual detectors

  - Super-K will release alert within ~ 1 hour of neutrino burst
    (info: time, duration, total events, pointing)
  - EGADS to automate and release alert within ~ 1 sec

Adams et al (2013)

E-mail ALERT

Rapid alerts!

IAU, ATel alerts

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Multi-messenger: electromagnetic

Shock breakout
- Among the first EM signatures of a supernova
- Helpful for early light curve modeling, revealing progenitor radius and envelope properties ($R$, $M_{\text{ej}}$), as well as explosion energetics ($E_{\text{exp}}$).

- For RSG (type IIP): 1000 Rsun, 10 Msun $\rightarrow$ \textit{hours} duration arriving \textit{days} delay
- For WR (type Ibc): 1 Rsun, 1-10 Msun $\rightarrow$ \textit{seconds} duration arriving with \textit{minutes} delay

$\rightarrow$ Rapid alert will help chase the shock breakout signal

\textit{Kistler et al} (2013)

\textit{based on Matzner & McKee} (1999)

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4. Reveals WHERE to look

WHERE one should look
Use $e^-$ scattering in the forward cone:
$\sim300$ events at SK

$$\nu + e^- \rightarrow \nu + e^-$$

Background to be reduced by neutron tagging with Gd ($\sim90\%$ efficiency):

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

Remaining background is the $\sim10\%$ of IBD and $\nu_e$ absorption on $^{16}O$ ($\sim20$-$80$ events)

$\rightarrow$ Pointing accuracy of several degrees

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<td>Water only</td>
<td>$\sim6$ deg</td>
<td>$\sim1.4$ deg</td>
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Input 3: Super-K with Gadolinium

Background rejection:
In water Cherenkov the signal produces a neutron, while backgrounds typically do not

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


Capture on protons, signal mostly lost (~18% tagging)
Capture on Gadolinium, yields a coincidence signal (~90% tagging)

After many R&D tests and studies, approved in 2015 and begun in June 2018!
4. Reveals WHERE to look

WHERE one should look
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<td>$\sim6$ deg</td>
<td>$\sim1.4$ deg</td>
</tr>
<tr>
<td>Water + Gd (90% tag)</td>
<td>$\sim3$ deg</td>
<td>$\sim0.6$ deg</td>
</tr>
</tbody>
</table>

**Multi-messenger: electromagnetic**

**Magnitude of optical signal:**

- ~35% are within reach of large FOV <1m class telescopes
- ~20% will need >1m class telescopes
- ~20% may be too bright
- ~25% of CCSNe are hard to reach even with modern 8m telescopes

**Importance of pointing!**

*Nakamura et al (2016)*

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Q: was the explosion SASI-driven?

Signatures:
SASI’s time variations (~10-20 ms) in the neutrino luminosity and energy can be measured with the excellent neutrino event statistics expected.

Multiple SASI episodes + convection

Single SASI episode + convection

No SASI episode, only convection

see also Lund et al (2010, 2012)
Q: was the progenitor rotating?

Signatures

- Rotation leaves signatures in neutrinos and gravitational waves
  - Lighthouse effect of spiral flows
  - Complementary viewing angle by gravitational wave
- Frequency matching can help confirm peak

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Takiwaki & Kotake (2018); Ott et al (2005)
Q: what was the progenitor?

Did a black hole form?
Neutrinos directly reveal the moment of black hole formation

*Beacom et al (2001)*

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Progenitor compactness
The neutrino emission reflects the progenitor compactness

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**Black hole case (40Msun)**

**NS case (13Msun)**
BEYOND THE MILKY WAY
Reach to our neighbors

With Super-K (32 kton):

- Approximately $10^4$ events from the Galactic center
- Approximately 400 events from LMC
- Approximately 1 event from M 31

With Hyper-K (~x10 SK):

- Approximately $10^5$ events from GC
- Approximately 4000 events from LMC
- Approximately 10 events from M 31
- Approximately 1 event from a few Mpc away

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The challenge: beating background

Two approaches:

1. Neutrino trigger: look for doublets or higher multiplets, depending on bkg rate:
   - Atmospheric neutrinos
   - Invisible muon decays
   - Spallation daughter decays
e.g., doublets in 10 sec occurs once per ~10 years (scaling SK-II to 0.56 Mton)

2. EM trigger: use SBO or early SN light curve to model constrain the bounce time
e.g., Cowen et al (2009)
e.g., background rate in signal region is ~0.8 /day/0.56Mton (scaling from SK-II)
→ maybe even can use neutrino singlets

<table>
<thead>
<tr>
<th></th>
<th>H₂O only</th>
<th>H₂O + Gd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search energy window [MeV]</td>
<td>18-30</td>
<td>12-38</td>
</tr>
<tr>
<td>Signal ν (in 10 sec, d = 1 Mpc, 0.56Mton)</td>
<td>~5</td>
<td>~10</td>
</tr>
<tr>
<td>Background ν (over 1 day, 0.56Mton)</td>
<td>~0.8</td>
<td>~1.1</td>
</tr>
</tbody>
</table>

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Ando et al (2005)
The nearby supernova rate

Over-dense region of the Universe
→ high rates: one every few years

Detection probability for $P(N=1)$, $P(N\geq2)$, w/ and w/out Gd

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Nakamura et al (2016); see also Ando et al (2005)
**Diffuse supernova neutrino background**

Average neutrino emission
- Use $>100$ simulations to characterize progenitor dependence of neutrinos
- Include collapse to black holes, characterized by critical compactness

Event rate predictions
Hyper-K sensitive to small compactness ($\xi_{2.5} < 0.2$, or $f_{BH} > 0.2$)

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>SK + Gd ($&gt;10\text{MeV}$) [#/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 MeV</td>
<td>1.8 +/- 0.5</td>
</tr>
<tr>
<td>4 MeV+BH</td>
<td>&lt; 2.5</td>
</tr>
<tr>
<td>SN1987A</td>
<td>1.7 +/- 0.5</td>
</tr>
</tbody>
</table>

**Graphs and Diagrams**
- Graph showing $dN/dE$ vs $E$ for different $\xi_{2.5,\text{crit}}$ values.
- More BH events at lower compactness.
- Event rate predictions for Hyper-K.

**References**
- Reviews by Beacom (2010), Lunardini (2010)

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High-energy phenomena

GRB connection:

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu \]
\[ \mu^\pm \rightarrow e^\pm + \nu_e + \nu_\mu \]

High-luminosity GRB jets are constrained by null results from stacked searches.

Low-luminosity/choked jets remain possible.

Prompt <1% of IceCube diffuse.
Ultra-high energy phenomena

Ultra-high energy cosmic rays
High-luminosity and low-luminosity jets capable of accelerating CRs to ultra-high energies (~$10^{20}$ eV).

Possible sites for sourcing nuclei UHECR
- Initial loading
- Entrainment
- In-situ nucleosynthesis

Simple loading model + propagation (CRPropa3) can describe the spectrum & composition measurements by Auger


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Concluding remarks

Supernova is a multi-messenger phenomenon

- The whole range: photons, neutrinos, gravitational waves, cosmic rays

Galactic multi-messenger opportunities

- Neutrinos will reveal IF, WHEN, and WHERE to look – in RAPID alert
- Neutrinos will help detect GW and photon counterparts

Beyond Milky Way

- Photon-neutrino synergy nearby
- Source candidates of HE neutrino & UHE cosmic rays

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#4: Searches of failed explosions: Survey about nothing

Survey About Nothing
Look for the disappearance of red-supergiants in nearby galaxies caused by core collapse to black holes

Monitor 27 galaxies with the Large Binocular Telescope

- Survey $\sim 10^6$ red supergiants with luminosity sensitivity $> 10^4$ Lsun
- expect $\sim 1$ core collapse /yr
- In 10 years, sensitive to 20 – 30% failed fraction at 90% CL

Kochanek et al. (2008)
Results so far:

In 7 years running,

- 6 luminous CC supernovae (SN2009dh, SN2011dh, SN2012fh, SN2013ej, SN203em, SN2014bc)
- 1 candidate failed supernova: NGC6946-BH1 (@~6Mpc); SED well fit by 25Msun RSG

→ Failed fraction 4 – 43% (90%CL)
The NGC6946-BH1 candidate

False positive?
New search will have new false positive $\rightarrow$ multi-wavelength follow-up is needed to vet failed SN candidates and determine whether the star survived or disappeared.

Constant $L_{bol}$, SED well fit by a 25Msun RSG

Star didn’t survive?
Significant dimming compared to pre-burst; $L_{bol} \sim t^{-1.3}$

Optical outburst consistent with Lovegrove & Woosley (2014)

Late-time IR due to fallback onto BH behind dust?

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Adams et al (2016)