Core-collapse Supernova Model Discrimination with Hyper-Kamiokande

Jost Migenda (they/them)
For the Hyper-Kamiokande Collaboration

Based on arXiv:2002.01649 & 2101.05269
Hyper-Kamiokande

Kamiokande
1983–1996

Super-Kamiokande
1996–today (and beyond)

Hyper-Kamiokande
~2027–???

Koshiba, 2002

Kajita, 2015

To be determined ...

3 kton

20×

50 kton
(22.5 kton FV)

8.4×

260 kton
(188 kton FV)
Physics goals:

- $\delta_{CP}$ & other $\nu$ oscillation parameters
- Proton decay (reaching $\sim 10^{35}$ years)
- Solar $\&$ supernova neutrinos
- ... and much more!


- Funding approved $&$ excavation started in 2020

- 350+ members from 19 countries

Now is a great time to join!
HK offers both large statistics and event-by-event energy information

- Order of magnitude larger than Super-K, DUNE, JUNO
- IceCube: more events, but no energy information for individual events

- 54k–90k events for SN at 10 kpc
  - ~3k events for SN in LMC

- Directionality: ~1° (via $\nu_e$-scattering)

- Most sensitive to $\bar{\nu}_e$
Modern cross-sections for main interaction channels

- Inverse beta decay full result from arXiv:astro-ph/0302055
- $^{16}\text{O }\text{CC}$ arXiv:1809.08398,1807.02367

- Modular & easily extensible (e.g. LS, WbLS & THEIA)
- Open source: https://github.com/JostMigenda/sntools
- Accepted by JOSS (to be published as DOI:10.21105/joss.2877 soon)
• Used sntools to generate 1000 data sets each for
  • 5 different SN models
  • Normal & inverted mass ordering
  • N=100, 300 events per data set

• Consider 20–520 ms post bounce only
  • Accretion phase is most interesting physically
    (late times: PNS cooling, similar across models)
  • Can include advanced 3D models, where computing
    time limitations only allow simulating <1 s
Models by different groups, using various approximations → telling models apart can help understand the explosion mechanism

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass</th>
<th>events at 10 kpc*</th>
<th>N=100</th>
<th>N=300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Totani</td>
<td>20 M⊙</td>
<td>1D</td>
<td>19716</td>
<td>140 kpc</td>
</tr>
<tr>
<td>Nakazato</td>
<td>20 M⊙</td>
<td>1D</td>
<td>17978</td>
<td>134 kpc</td>
</tr>
<tr>
<td>Couch</td>
<td>20 M⊙</td>
<td>1D</td>
<td>27539</td>
<td>166 kpc</td>
</tr>
<tr>
<td>Vartanyan</td>
<td>9 M⊙</td>
<td>2D</td>
<td>10372</td>
<td>102 kpc</td>
</tr>
<tr>
<td>Tamborra</td>
<td>27 M⊙</td>
<td>3D</td>
<td>25021</td>
<td>158 kpc</td>
</tr>
</tbody>
</table>

* during 20–520ms after core bounce, assuming Normal Ordering
• Performed full detector simulation & reconstruction for all data sets

• Applied cuts:
  • $E_{\text{reco}} > 5$ MeV (eliminate low-E backgrounds)
  • Vertex inside fiducial volume (avoid higher backgrounds & worse reconstruction near walls)

→ Effectively background-free in 500 ms interval

• Each data set contains 100 (300) events originally
→ typically over 80% remaining after trigger and cuts
Each data set contains events \((t_i, E_i)\)

Per data set: calculate unbinned likelihood \(L\) for each SN model


Extended to include multiple interaction channels

Use \(\Delta L = L_A - L_B\) to determine whether model A or B better describes any given data set

\[
L = \ln \mathcal{L} = \sum_{\text{evt } i} \ln \left( \frac{d^2N(t_i, E_i)}{dt \ dE} \right)
\]
Good model separation with just $N=100$ events
Pairwise Comparison of SN Models

Vertical line indicates $\Delta L = 0$

Normal ordering
$N=100$ events/data set
Tamborra model similar to Couch (Vartanyan) model in Normal (Inverted) Ordering. Other models are separated well!
## Model Identification, N=300

<table>
<thead>
<tr>
<th>True model</th>
<th>Identified as</th>
<th>Couch</th>
<th>Nakazato</th>
<th>Tamborra</th>
<th>Totani</th>
<th>Vartanyan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Normal</strong></td>
<td>Couch</td>
<td>982</td>
<td>2</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Nakazato</td>
<td>1</td>
<td>999</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Tamborra</td>
<td>16</td>
<td>0</td>
<td>980</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Totani</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Vartanyan</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Inverted</strong></td>
<td>Couch</td>
<td>999</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Nakazato</td>
<td>0</td>
<td>1000</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Tamborra</td>
<td>0</td>
<td>0</td>
<td>974</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Totani</td>
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<td>0</td>
<td>0</td>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Vartanyan</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>992</td>
</tr>
</tbody>
</table>

Higher statistics reduce random fluctuations & improve accuracy.
• Hyper-K is still ~6 years away & SN simulations will make progress in the meantime

• Can we use this approach to determine progenitor properties?

• Use different Nakazato models
  - 13, 20, 30 $M_{\odot}$ with solar metallicity ($z=0.02$)
  - 20 $M_{\odot}$ with SMC metallicity ($z=0.004$)

Figure from arXiv:1210.6841
### Progenitor Properties, N=300

#### Identified as

<table>
<thead>
<tr>
<th>True model</th>
<th>13 $M_{\text{sol}}$</th>
<th>20 $M_{\text{sol}}$</th>
<th>20 $M_{\text{sol}}^*$</th>
<th>30 $M_{\text{sol}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 $M_{\text{sol}}$</td>
<td>878</td>
<td>61</td>
<td>61</td>
<td>0</td>
</tr>
<tr>
<td>20 $M_{\text{sol}}$</td>
<td>17</td>
<td>944</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>20 $M_{\text{sol}}^*$</td>
<td>74</td>
<td>75</td>
<td>850</td>
<td>1</td>
</tr>
<tr>
<td>30 $M_{\text{sol}}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1000</td>
</tr>
<tr>
<td>Inverted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 $M_{\text{sol}}$</td>
<td>866</td>
<td>78</td>
<td>56</td>
<td>0</td>
</tr>
<tr>
<td>20 $M_{\text{sol}}$</td>
<td>64</td>
<td>848</td>
<td>88</td>
<td>0</td>
</tr>
<tr>
<td>20 $M_{\text{sol}}^*$</td>
<td>53</td>
<td>88</td>
<td>859</td>
<td>0</td>
</tr>
<tr>
<td>30 $M_{\text{sol}}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1000</td>
</tr>
</tbody>
</table>

* lower metallicity ($z=0.004$)

Different progenitors simulated with the same code.
If SN simulations converge, HK can be used to study the progenitor!
Hyper-Kamiokande has unique capabilities for detecting supernova neutrinos

- High event rate and event-by-event energy information
- Can tell SN models apart even at ~100 kpc distance
  - ≥80% able to identify true model with 100 evts
  - ≥97% accuracy with 300 evts
  - If mis-ID: only by very narrow margin ➔ can at least narrow down list of possible models
- Chance to identify progenitor properties

Conclusions

Other HK talks at NeuTel 2021:
- Long-baseline sensitivities (T. Dealtry, 24/02)
- mPMT modules (A. Ruggeri, 25/02)
- Overview (F. Di Lodovico, 25/02)
N=100, Normal Ordering

Vartanyan

Totani

Tamborra

Nakazato

Couch

Nakazato

Tamborra

Totani
N=300, Normal Ordering

Vartanyan

Totani

Tamborra

Nakazato

Number of data sets

Delta Log-Likelihood

Couch

Nakazato

Tamborra

Totani

Number of data sets

Delta Log-Likelihood

Couch

Nakazato

Tamborra

Totani

Number of data sets

Delta Log-Likelihood

Couch

Nakazato

Tamborra

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N=100, Inverted Ordering

Vartanyan

Totani

Tamborra

Nakazato

Couch

Nakazato

Tamborra

Totani
N=300, Inverted Ordering

Vartanyan

Totani

Tamborra

Nakazato

Couch

Nakazato

Tamborra

Totani
Event Rate & Mean Energy of 5 Models

NMO: Tamborra & Couch most similar

IMO: Tamborra & Vartanyan most similar