The Super-Kamiokande Supernova Alert

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The Quest to Watch a Supernova in Real Time

By Susanna Kohler on 26 August 2024 FEATURES Share:

An artist's illustration shows a core-collapse supernova radiating into its surroundings. Scientists hope to study these explosions in detail using key messengers: neutrinos. [**Melissa Weiss/CfA**]

Barry Pointon for the **Super-Kamiokande Collaboration**

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BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY

BCIT

The Next Nearby Core-Collapse Supernova (CCSN)

Next galactic CCSN promises abundance of multi-messenger info

Differences from other multi-messenger alerts/events:

- SN → galactic/nearby only (MW, LMC, SMC)
- Neutrinos → detected burst of 1's to 1000's of neutrinos
- Neutrino energies → O(10's) MeV
- Burst duration → ~10 sec

- Observed SN neutrino bursts → 1
- Last known burst → 1987
- Estimated burst rate → 3 ± ? /100 yr

SN1987A – early image

Galactic CCSN science yield → priceless

Supernova Neutrino Detection

CCSN produces $O(10^{58})$ neutrinos

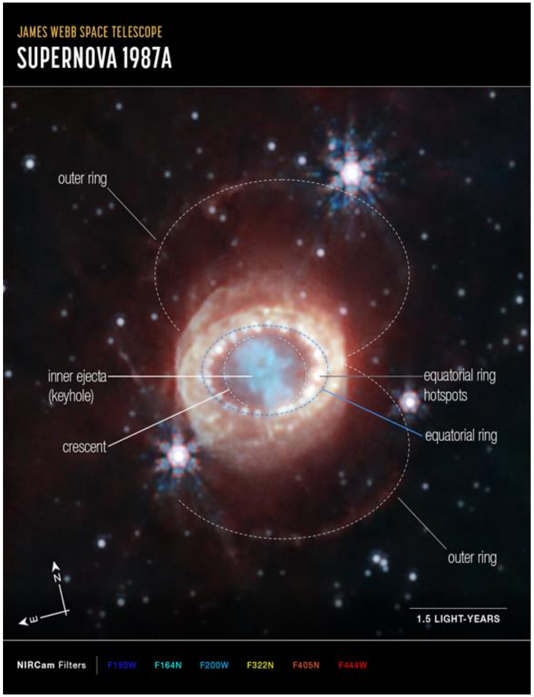
- > 99% of energy from gravitational collapse
- neutrino flavors have different fluxes
- different stages of production
- neutrinos stream from stellar envelope before shock breakout

Challenges to SN neutrino detection

- flux decreases as 1/distance^2
- small reaction cross sections

Opportunity

- SN early warning alert before first EM radiation arrives at earth
- SN pointing direction

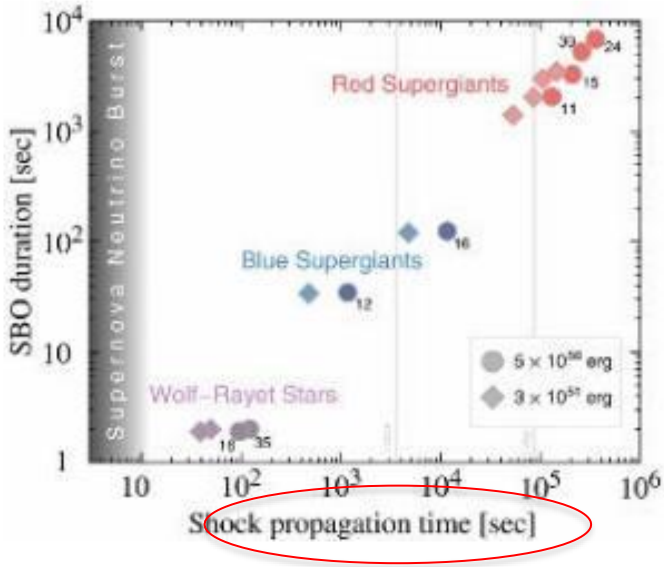


Credits:
Science - NASA, ESA, CSA, Mikako Matsuura (Cardiff University), Richard Arendt (NASA-GSFC, UMBC), Claes Fransson (Stockholm University), Josefin Larsson (KTH)
Image Processing - Alyssa Pagan (STScI)

Science Goals of CCSN Early Warning Alerts

Observe first shock breakout (SBO) radiation:

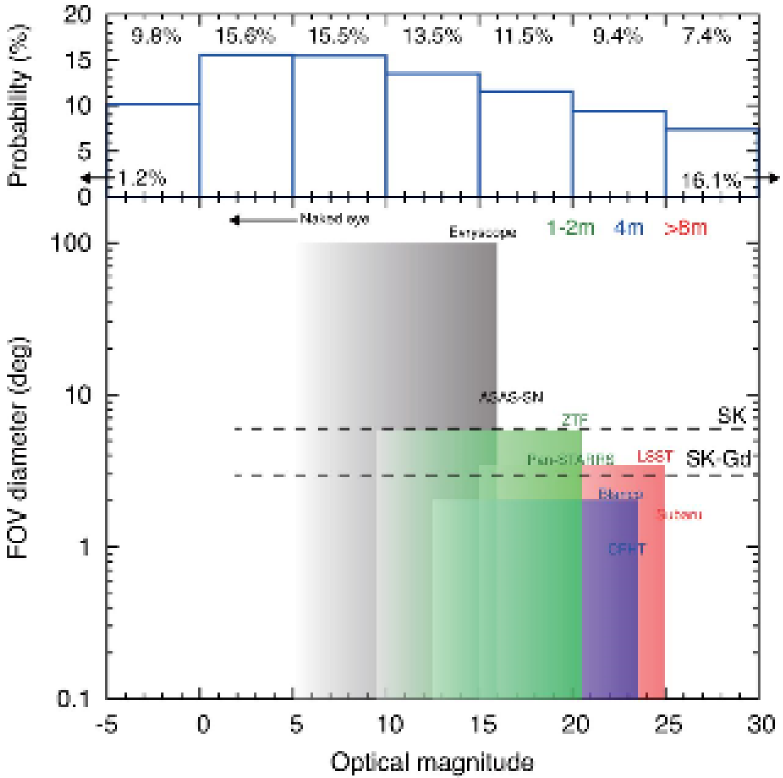
- Fully characterize the SBO at multi-wavelengths
- Measure neutrino burst-to-SBO time for tomographic snapshot of progenitor.



From Kistler, et al. Tomography of Massive Stars from Core Collapse to Shock Breakout. The Astrophysical Journal, Vol. 778, Issue 1, article id. 81, 9 pp. (2013). Arxiv:1211.6770

- Alert requires low latency and accurate pointing info

Challenges in MM Observation following SN Alert



(top) Estimated probability of a galactic CCSN for ranges of optical magnitude.

(bottom) The capabilities of several instruments with size of FOV compared to SK pointing accuracy. (outdated)

From Nakamura, et al Multimessenger signals of long-term core-collapse supernova simulations, Mon. Not. Roy. Astron. Soc. Vol. 461, Issue 3, (2016)

Super-Kamiokande Supernova Alert

Early warning alert from SN neutrino burst detection provided by:

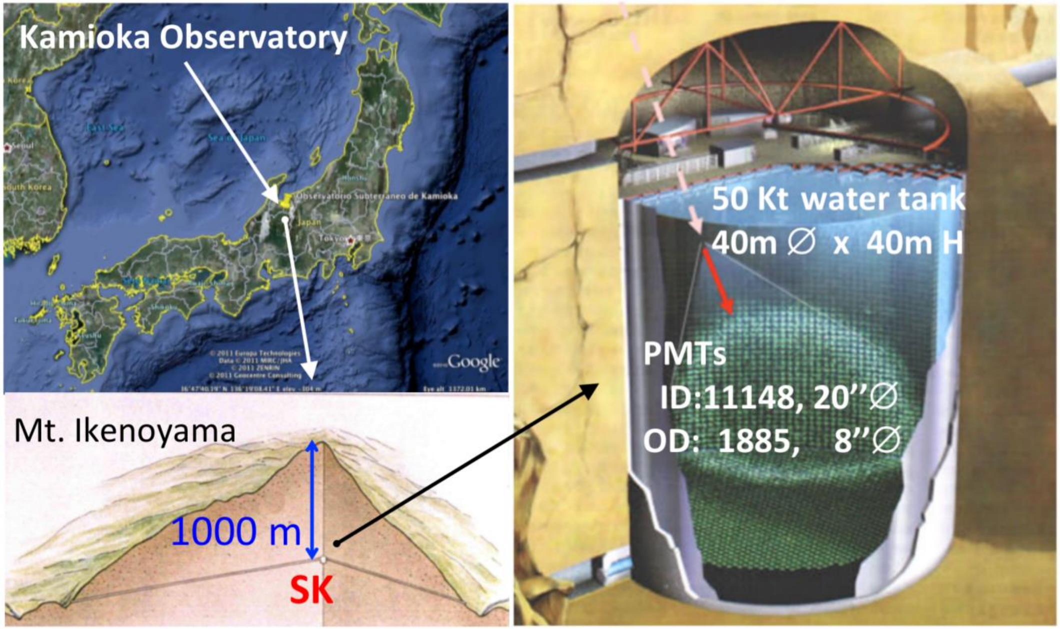
- individual detectors (e.g., Super-Kamiokande)
- combined detectors (SNEWS)

- **Super-Kamiokande** recently upgraded SNWatch system.
  - improved burst detection (from Gd added to water)
  - improved SN pointing
  - lower latency from SN burst detection to alert
  - new SK_SN automated alert → GCN*

"Performance of SK-Gd's Upgraded Real-time Supernova Monitoring System," Y. Kashiwagi et al 2024 *ApJ* **970** 93. doi:10.3847/1538-4357/ad4d8e

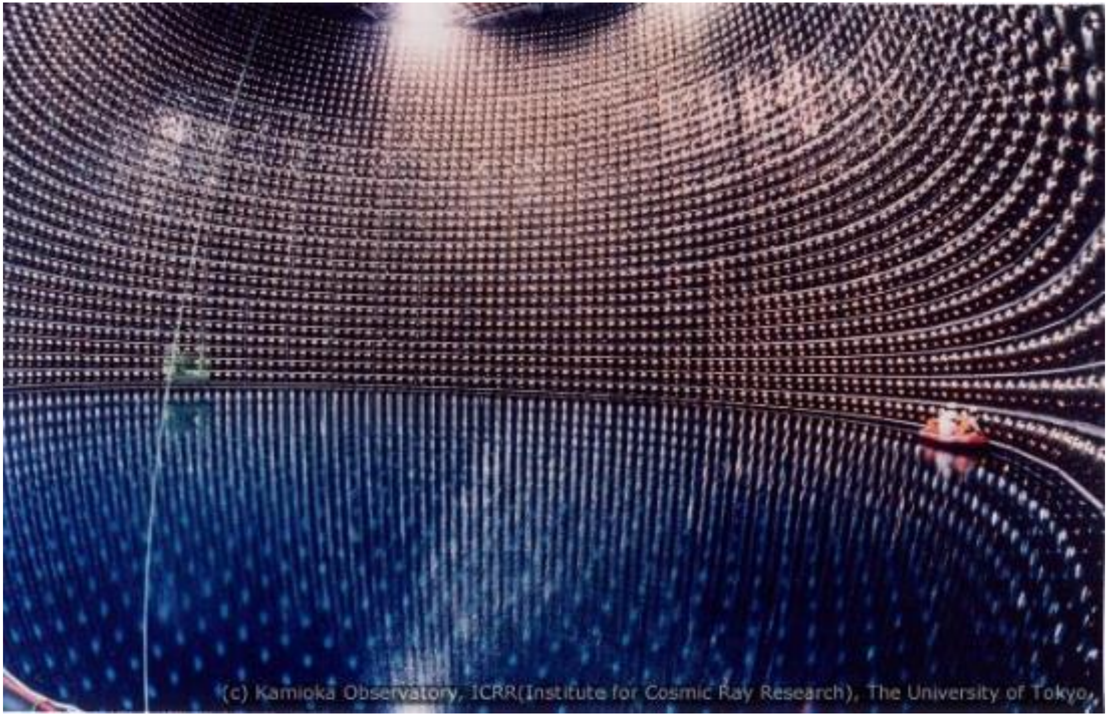
* SK_SN Notice information at https://gcn.nasa.gov/missions/sksn

The Super-Kamiokande Detector



- Largest water-Cherenkov detector with multiple physics experiments
  - 50 kt water volume.
  - Outer detector (active shield)
  - Inner detector (ID) 22.5 kt fiducial volume with ~11148 PMTs.
- Dissolved Gd added to water to improve reaction channel identification.

Super-Kamiokande – Water Tank and ID PMTs



Super-K tank (half-drained)

Super-K entrance

Reaction Channels in WC Detector (H_2O)

Dominant reaction channels for 0 – 80 MeV neutrinos in water + Gd:

1. inverse beta decay (IBD): $\bar{\nu}_e + p \to e^+ + n$

- largest cross section, outgoing e^+ directions nearly isotropic
  - neutron absorbed by Gd, delayed γ emission → tag IBD

2. electron elastic scatter (ES): $\nu_{all} + e^- \to \nu_{\mathrm{all}} + e^-$

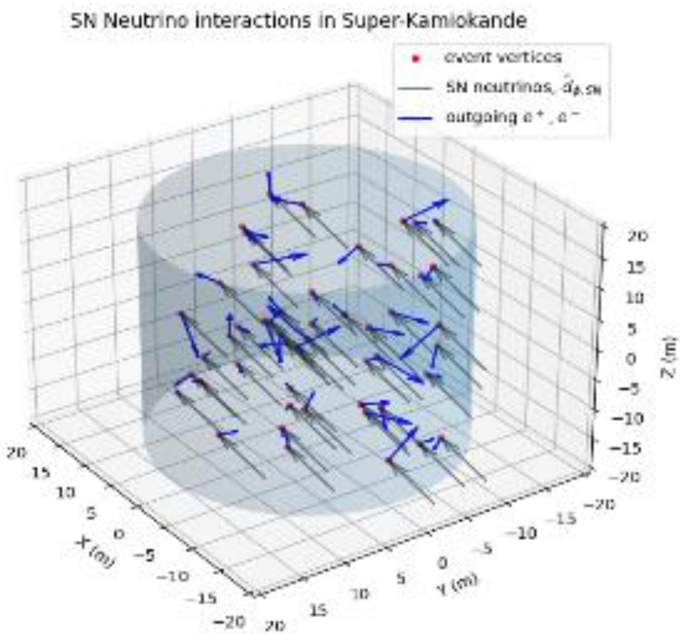
- smaller cross section, outgoing e^- forward scattered in direction of flux

3. charged-current reactions with ^{16}O nuclei:

$$\nu_e + {}^{16}O \to {}^{16}F + e^-, \qquad \bar{\nu}_e + {}^{16}O \to 16N + e^+$$

- higher energy threshold, outgoing e^+, e^- nearly isotropic

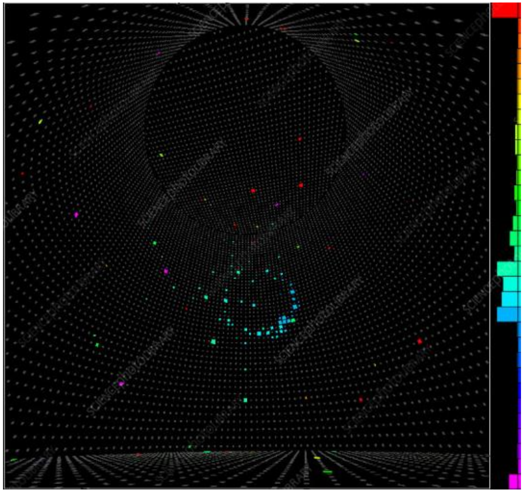
Supernova Neutrino Detection at Super-K



neutrinos interact in water:

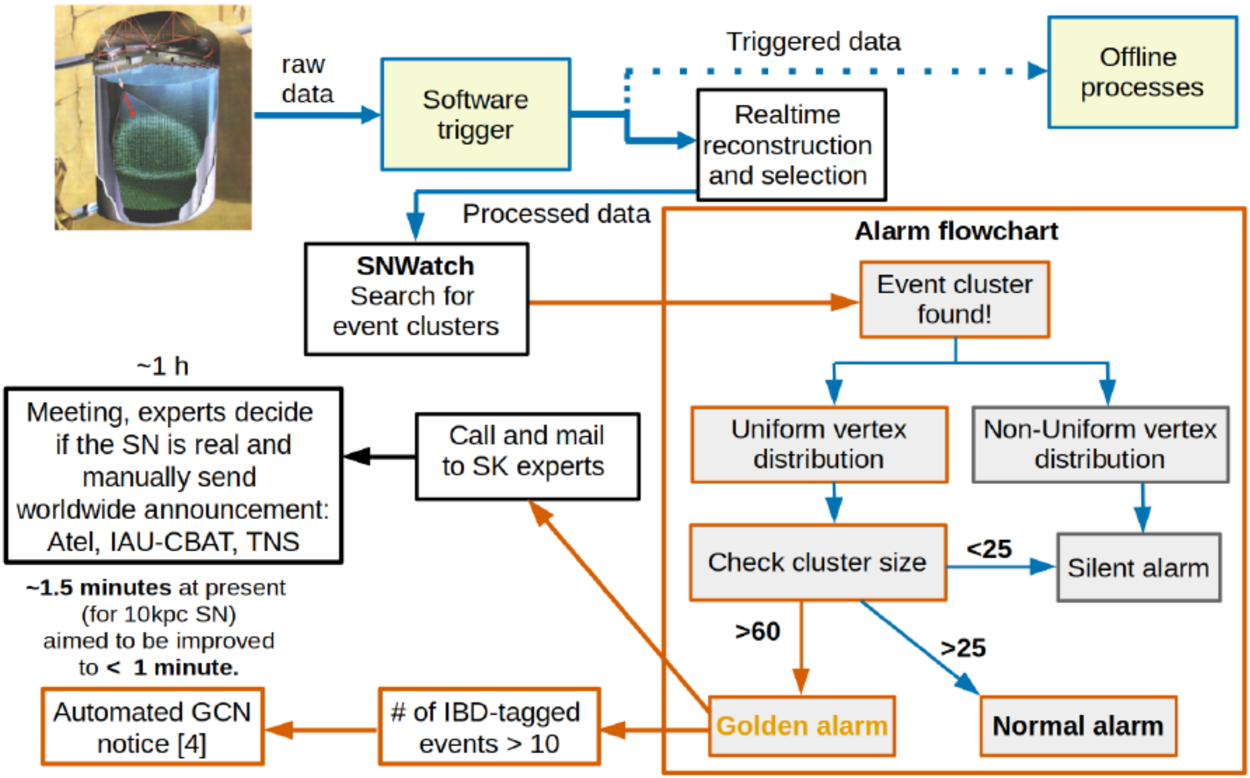
- SN @10 kpc, ~2500 neutrino events /burst.

Cherenkov ring from single low energy event



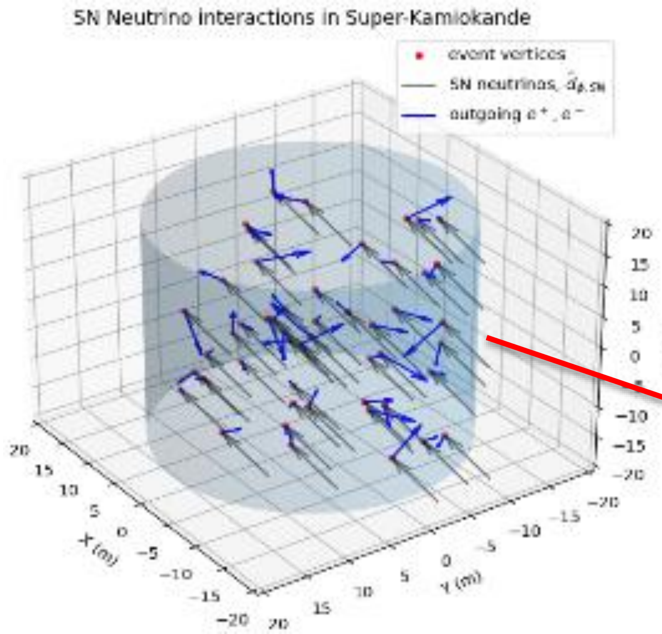
Each event reconstructed for vertex, and outgoing e^-/e^+ energy and direction

Super-K Realtime Burst Monitoring - SNWatch



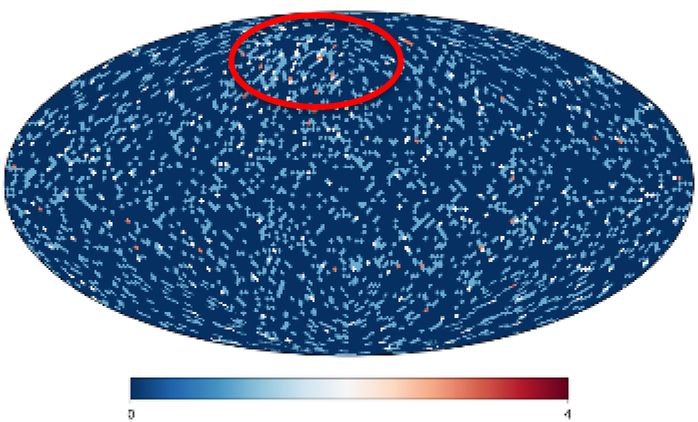
SN Direction Reconstruction

Upgraded direction reconstruction includes **novel HEALPix-based method**



SN burst events on HEALPix sphere

- pixel location = 3-d direction.
- pixel counts = number of events in direction.



HP-sphere 12,288 pixels, ~2600 events, SN @10 kpc.

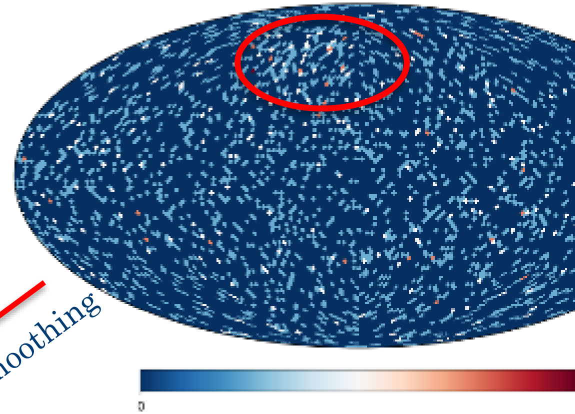
paper in preparation.

SN Direction Reconstruction

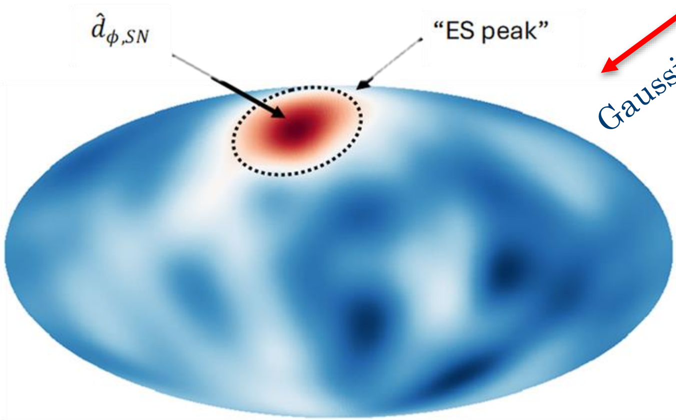
Upgraded direction reconstruction includes **novel HEALPix-based method**

- distribution nearly uniform.
- area of higher density (circled) from ES.
- centroid of ES events at $\hat{d}_{\phi,SN}$.
  - difficult to find b/c low event density

HP-sphere 12,288 pixels, ~2600 events, SN @10 kpc.



Gaussian smoothing



- smoothing produces well defined ES-peak.
- ES-peak centroid at max pixel
- direction of max pixel = $\hat{d}_{\phi,SN}$.
- SN pointing direction $\hat{d}_{SN} = -\hat{d}_{\phi,SN}$.

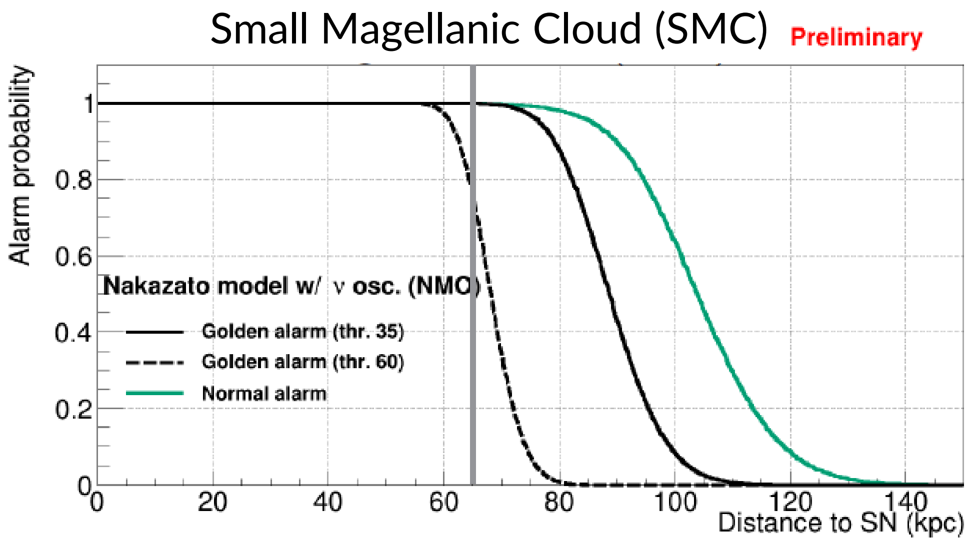
Recon time ~ **1sec** (vs. previous 5-10 min)

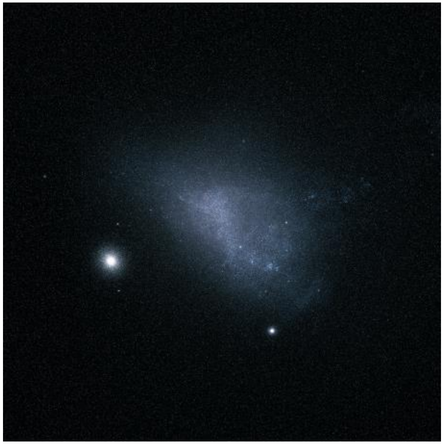
paper in preparation.

SK_SN Alarm Performance

- SNWatch **reduced latency** between burst detection and GCN notice (with pointing) to ~90 sec.
  - improvements to reduce < 60 sec.

- Golden alarm with lower threshold (35 events) allows coverage of SMC

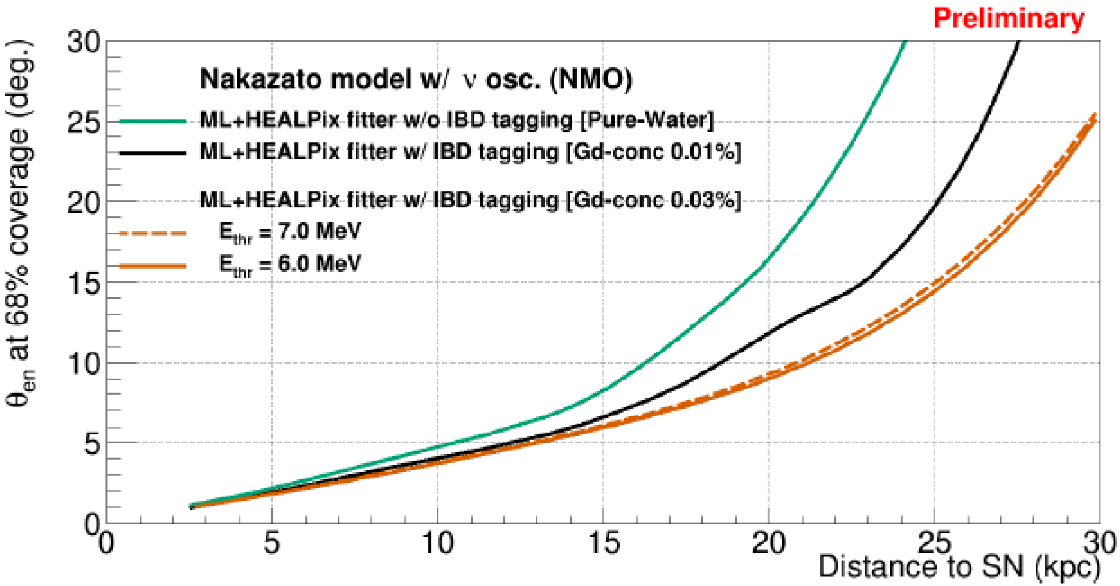




Acknowledgement: Gaia Data Processing and Analysis Consortium (DPAC); A. Moitinho / A. F. Silva / M. Barros / C. Barata, University of Lisbon, Portugal; H. Savietto, Fork Research, Portugal.

Improvement in direction reconstruction

- Angular resolution for SN @10 kpc:
  - 3.78 ± 0.04° (7 MeV thresh.)
  - 3.68 ± 0.04° (6 MeV thresh.)
- Much faster than previous, *O(secs)* vs *O(mins)*



Summary and Action Points

- Improvements to SNWatch
  - improved burst detection
  - faster and more accurate pointing information
  - automated alert (SK_SN) to GCN*

→ Improved opportunity for MM SBO observations

→ SN alert response plans should be reviewed and revised

- Other progress:
  - Super-K + KamLAND has combined **pre-SN alarm****
    - neutrinos from Si-burning stage
    - for nearby stars *O*(100 pc)
  - Hyper-Kamiokande under construction (8X)

* SK_SN Notice information at https://gcn.nasa.gov/missions/sksn

**https://www.lowbg.org/presnalarm/

Strategies for SN Alert Follow-up

For discussion:

Optimizing MM strategies for SN Alert follow-up:

- response strategy? pointing vs survey instrument
- response time:
  - alert → action (ToO? priority?)
  - slewing time
- instrument properties:
  - FOV and tiling
  - limiting magnitude and saturation
- observability constraints and observer patience
  - may need to point for several hours

Backup slides

Super-K Realtime Burst Detection - SNWatch

During data acquisition:

- Realtime event analysis and reconstruction
- identify IBD events from coincident prompt and delayed events
- Search for cluster of events in 20 s time window

When cluster found:

- characterize event vertex distribution as uniform or non-uniform
- check number of events in cluster
  - If vertices not uniform or events < 25, on "silent" alarm issued
- SN direction reconstructed from all burst events.

Golden or Normal alert based on number of events in cluster.

- Golden: > 60 events (lowered to 35), Normal: > 25 events

- If alarm criteria met:
  - SK_SN notice issued on GCN
  - Automatic alert of burst sent to SNEWS
  - SK experts manually send notice to TNS, IAU-CBAT and ATEL.

Super-Kamiokande

- located in mine, deep **under mountain**
  - ~ 1 km rock overburden, passive shielding of atmospheric muons

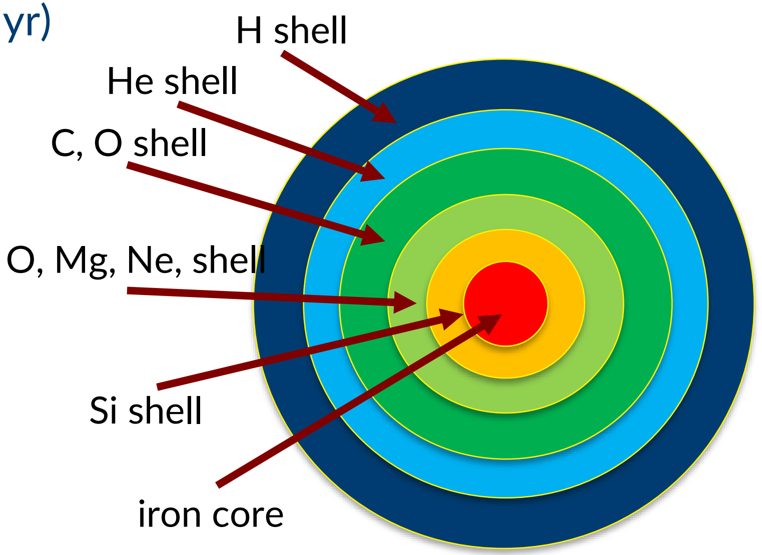
- large volume water-Cherenkov detector
  - cylindrical tank (d = 39.1 m, h = 41.4 m)
  - ultra-pure water, total mass = 50 kt

- water volume divided into inner detector (I.D.) and outer detector (O.D.)
  - **O.D**. active shielding of atmospheric muons
    - 1885 - 8” PMTs
    - mass = 18 kt
  - **I.D.** is the active detector
    - 11146 - 20” (50 cm) PMTs
    - mass = 32 kt
    - fiducial volume > 200 cm from walls
      - outer water volume acts as passive shielding
      - Final fiducial mass = 22.5 kt

Core-Collapse Supernovae

High mass stars (M > 8$M_\odot$) undergo successive stages of nuclear fusion (e.g., 25 $M_\odot$.)

- H burning → He (7 Myr) – Main Sequence
- He burning → C, O, … (500,000 yr)
- C burning → O, Ne, Mg, (600 yr)
- Ne, O burning → Si, … (1 yr)
- Si burning → Fe, … (1 day)
- Fe burning ?



Cores of highly evolved massive stars have overlying shells of the fusion products from earlier burning stages with an iron core

- fusion not possible an Fe core - no “Fe burning”.
  - cannot generate energy to sustain hydrostatic equilibrium.

Core-Collapse SNe

- When Fe core > 1.4 $M_{\odot}$,
  - degeneracy pressure cannot sustain
  - Fe core (r ~ 6000 km) collapses to PNS (r ~ 30 km) in < 1 s.
  - CC mechanism essentially releases gravitational PE

- Peak energy output ~10^{53} erg s^{-1} (~10^{46} J s^{-1})
  - > output of visible universe
    - visible light (~0.01%
    - explosive kinetic energy (~1%)
    - neutrinos (~99%)

- Emission ~10^{58} neutrinos
  - energies ~10's MeV
  - mixed neutrino flavour content
  - time dependent energies and luminosities

Stages of SN Neutrino Production During CCSN

Hot dense environment

- ~10^{11} - 10^{14} g cm^3
- endothermic and reversable reactions possible

Breakout Burst / Neutronization (10's ms)

- Out-going shock wave causes nuclei to dissociate
  - ν_e production by electron capture $e^- + p \rightarrow n + \nu_e$

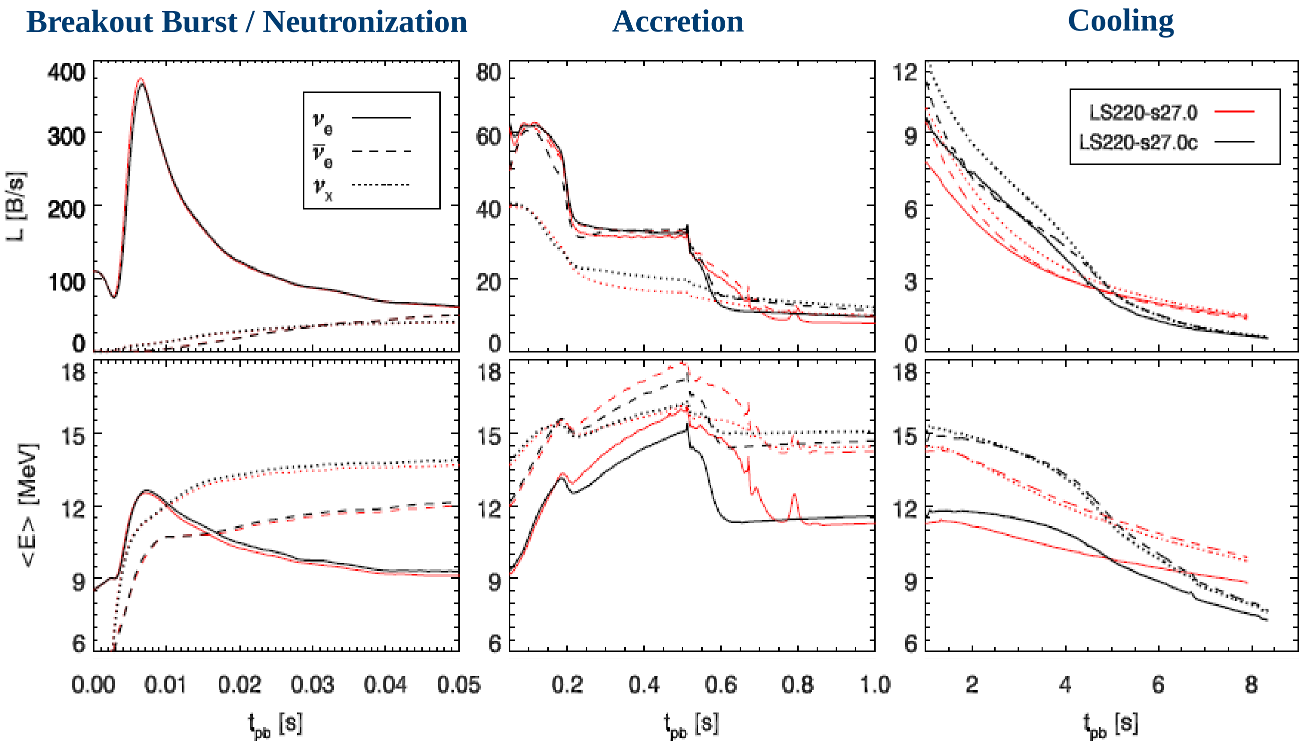
Accretion (10's – 100's ms)

- powered by gravitational PE of matter accreting onto PNS
  - may have complex time structure (SASI)
  - $\nu_e,\ \bar{\nu}_e$ production dominates, but flavours produced.

Cooling (10's s)

- PNS shrinks, sheds gravitational PE and thermal energy
  - positron annihilation, $e^+ + e^- \rightarrow \nu + \bar{\nu}$
  - all neutrino flavours produced in equal abundance

Supernova Neutrino Production – Light Curves



1 B = 10^{51} erg = 1 foe

A. Mirizzi, et. al Supernova Neutrinos: Production, Oscillations and Detection. Riv Nuovo Cim. 39 (2016) no.1-2, 1 arXiv: 1508.00785

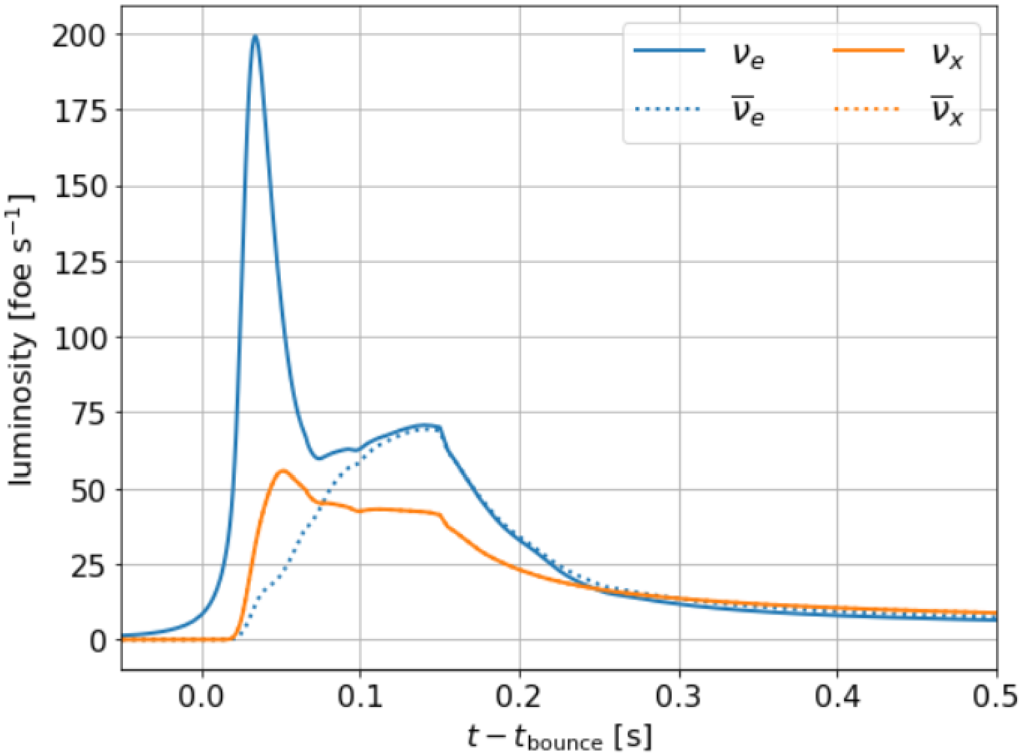
$$\nu_x = \nu_\mu , \nu_\tau , \bar{\nu}_\mu , \bar{\nu}_\tau$$

Model of 27 $M_\odot$ progenitor

Supernova Neutrino Production – Light Curves

Neutrino light curve, first 500 ms: Breakout and Accretion

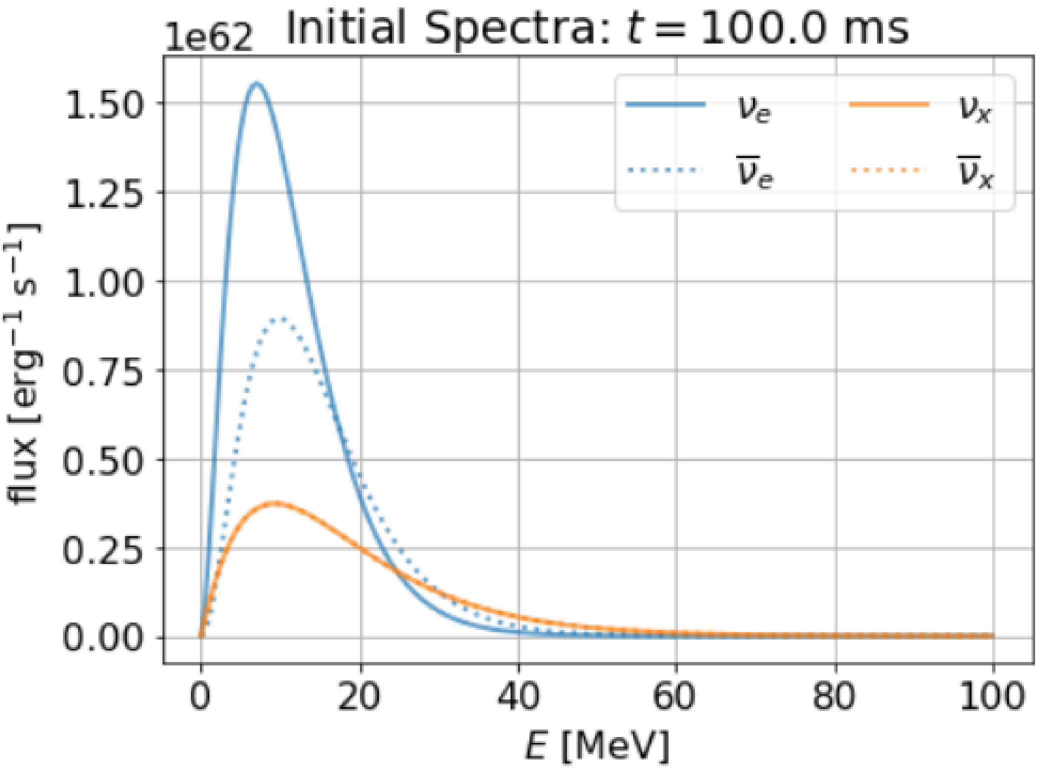
Nakazato 2013 Model: 20 $M_\odot$, Shen EOS, 100 ms revival time, Metallicity 0.004.



Source: SNEWPY Github Repo
L. Baxter *et al.* (SNEWS Collaboration): "SNEWPY: A Data Pipeline from Supernova Simulations to Neutrino Signals". Journal of Open Source Software 6 (2021) 67, 3772.
arXiv: 2109.08188,

Supernova Neutrino Production – Energy Spectrum

Energy spectrum at t = 100 ms. (Nakazato 2013)



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Supernova Neutrino Production – Neutrino Oscillations

- Flavour content of energy spectrum changes when neutrinos undergo "flavour-swapping" MSW oscillations as they travel through stellar envelope

- Oscillations depend on "ordering" or "hierarchy" of the neutrino mass eigenstates (m_1, m_2, m_3)

  - $m_1^2 \approx m_2^2 < m_3^2$ normal mass ordering (NMO) or NH

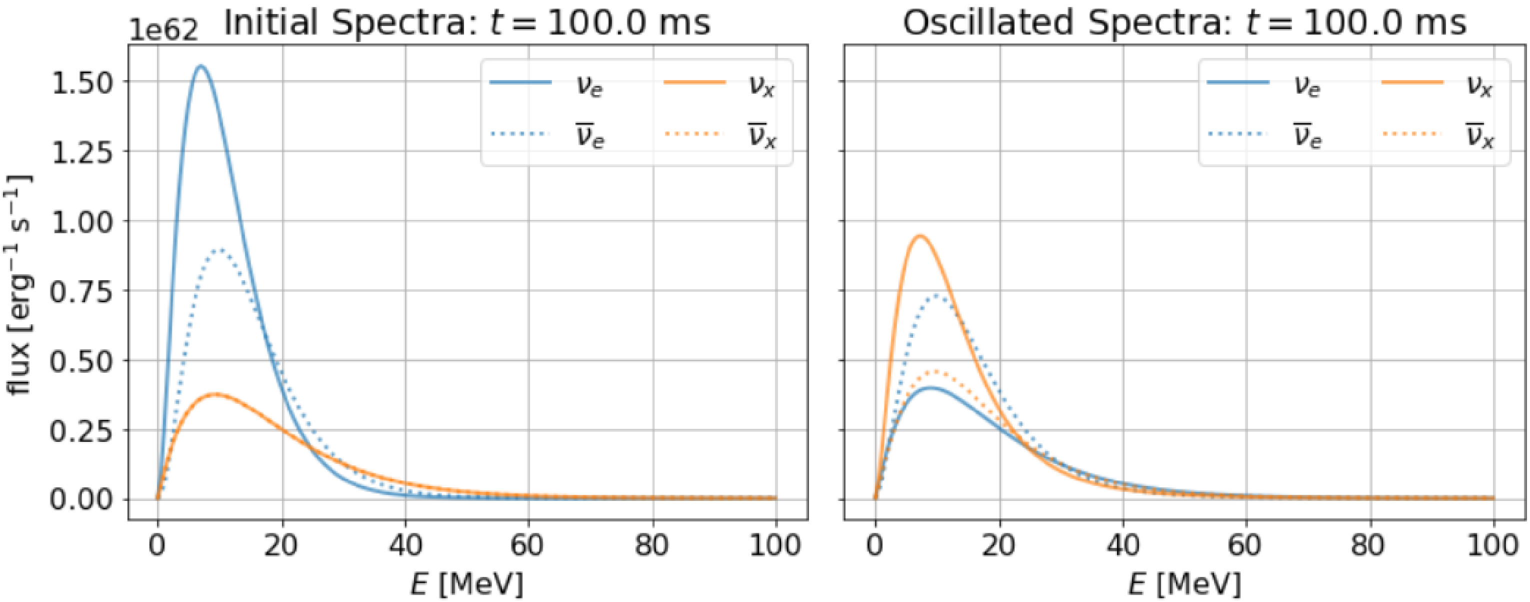
    or

  - $m_3^2 < m_1^2 \approx m_2^2$ inverted mass ordering (IMO) or IH

Supernova Neutrino Production – Flavour Swapping

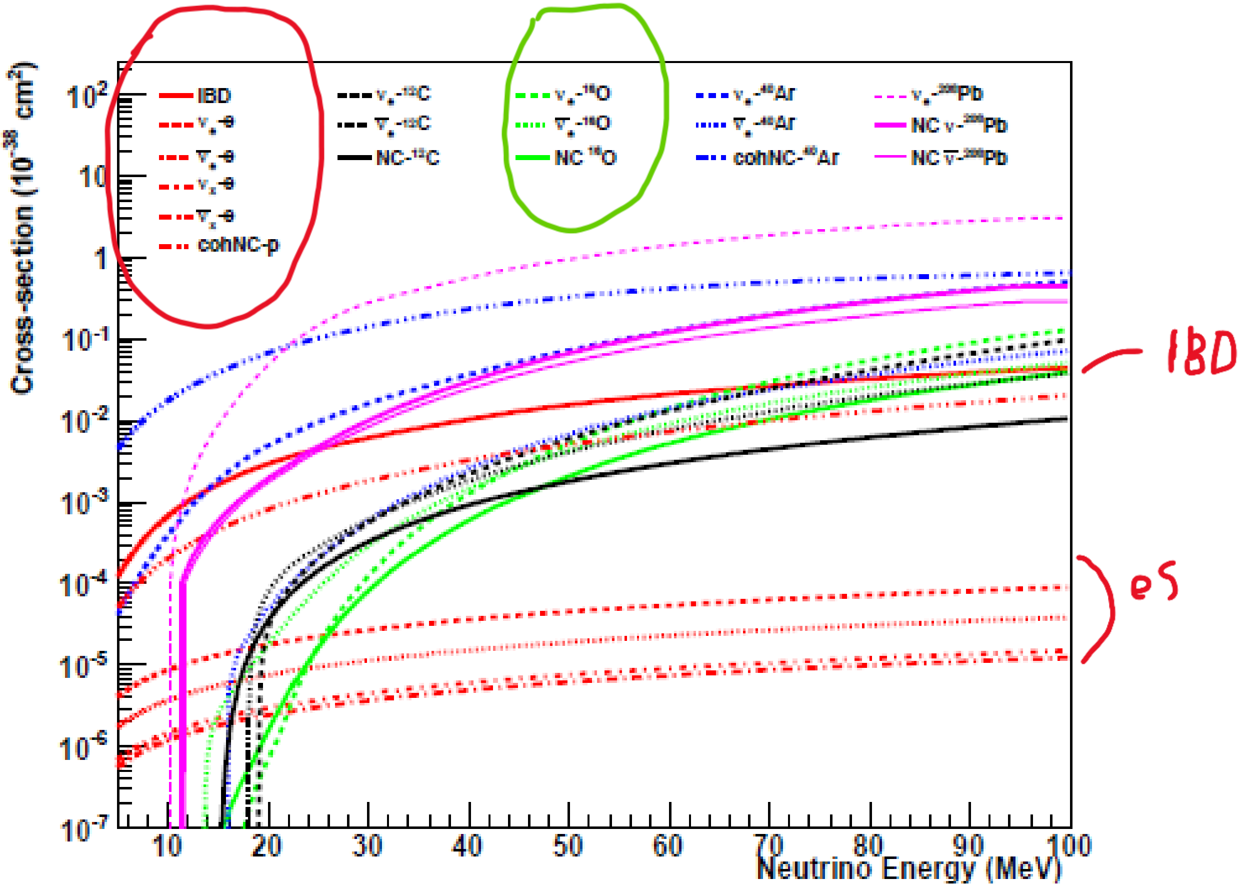
t = 100 ms, (Nakazato 2013 Model) with MSW oscillations with NMO

$$\nu_e \rightleftarrows \nu_x, \qquad \bar{\nu}_e \rightleftarrows \bar{\nu}_x$$



Source: SNEWPY Github

WC Neutrino Reaction Channels Cross Sections



Predicted SN Neutrino Events for Super-K

- E.g., with two SN models, Wilson (Livermore) and Nakazato1
  - Different progenitor mass, nuclear EOS, hydrodynamics
- simulated neutrino oscillations for NMO and IMO
- fiducial SN distance of 10 kpc (~centre of galaxy).
  - integrated over 18 s

- NK1 (2013): 20 $M_{\odot}$, Shen EOS, 200 ms revival time, Metallicity 0.02.
  - NH = NMO

	Wilson			NK1			NK2		
	no osc.	NH	IH	no osc.	NH	IH	no osc.	NH	IH
$\bar{\nu}_e + p \rightarrow e^+ + n$	4923	5667	7587	2076	2399	2745	1878	2252	2652
$\nu_e + e^- \rightarrow \nu_e + e^-$	74	130	114	43	56	56	39	54	54
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	25	29	37	10	12	14	9	11	13
$\nu_x + e^- \rightarrow \nu_x + e^-$	41	33	34	17	19	18	17	17	17
$\bar{\nu}_x + e^- \rightarrow \bar{\nu}_x + e^-$	34	33	29	14	14	14	13	13	14
$\nu_e + ^{16}\mathrm{O} \rightarrow e^- + X$	8	662	479	22	78	74	16	72	68
$\bar{\nu}_e + ^{16}\mathrm{O} \rightarrow e^+ + X$	64	196	531	27	48	70	20	41	64
total	5169	6750	8811	2209	2626	2991	1992	2460	2882

from "Real-Time Supernova Neutrino Burst Monitor at Super-Kamiokande"

Predicted SN Neutrino Events for Super-K

Example of directional signal for NH:

Total – 2626 events

Background - IBD (2399) + O-16 (128) = 2525 events (96.2%)

	Wilson			NK1			NK2		
	no osc.	NH	IH	no osc.	NH	IH	no osc.	NH	IH
$\bar{\nu}_e + p \rightarrow e^+ + n$	4923	5667	7587	2076	2399	2745	1878	2252	2652
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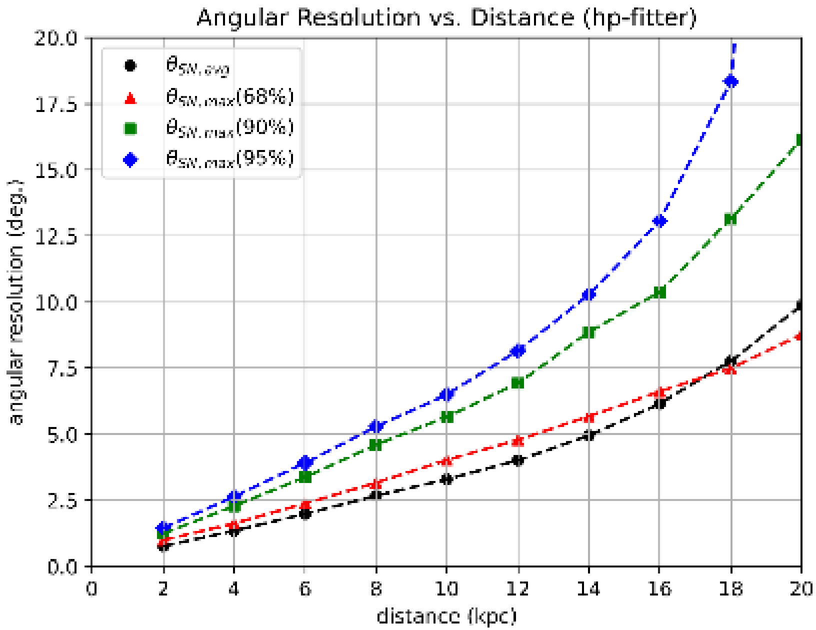
Signal - ES: 101 events (3.8%)


Angular Resolution vs. Distance (hp-fitter)
$\theta_{SN,avg}$
$\theta_{SN,max}(68\%)$
$\theta_{SN,max}(90\%)$
$\theta_{SN,max}(95\%)$
angular resolution (deg.)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
0
2
4
6
8
10
12
14
16
18
20
distance (kpc)

Supernova Neutrinos – SN1987A

February 24, 1987, 07:35 UT

- 168,000 yrs ago, Sanduleak-69 202 undergoes CC
  - blue supergiant
  - naked eye visibility

- in LMC, distance 51.4 kpc
- recent evidence of NS

- 25 SN neutrinos detected
- proved basic theory of CCSN

2002 Nobel Prize in Physics
Masatoshi Koshiba, Kamiokande II, Japan (1/4) "Observation of a Neutrino Burst from the Supernova SN1987a"