Prospects on SuperNova Neutrinos with SK and HK

Prospects of Neutrino Physics @Kavli IPMU
April 9 2019

Hiroyuki Sekiya
ICRR, University of Tokyo
for the Super-K Collaboration & Hyper-K Proto-Collaboration
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Total 32 pages
Supernova neutrinos from 1987A

- The only detected SN neutrinos are from LMC (50 kpc)

  - Kamiokande-II (11 evts.)
  - IMB-3 (8 evts.)
  - Baksan (5 evts.)

  24 ($\bar{\nu}_e$) events in total.

  Total energy released by $\bar{\nu}_e$: $\sim 5 \times 10^{52}$ erg

- The obtained binding energy is almost as expected, but large error in neutrino mean energy. No detailed information of burst process.

- We need energy, flavor and time structure.
Recent 3D simulations burst

- Mechanism of CCSN needs to be determined by data  
  K.Nakamura

Hanke+'13
27 M☉ (WHW02)
t < ~400 ms
LS220 EoS
1D gravity
+ GR correction
Yin-Yang grid

Melson+'15
9.6 M☉ (A. Heger)
t < ~400 ms
LS220 EoS
1D gravity
+ GR correction

Roberts+'16
27 M☉ (WHW02)
t < 380 ms
LS220 EoS
GR
Cartesian AMR

Takiwaki+'16
11.2 (&27)
M☉ (WHW02)
t < ~300 (400) ms
LS220 EoS
Newtonian

Kuroda+'16
15 M☉ (WW95)
t < ~400 ms
DD2/TM1/SFHx EoS
GR; Cartesian FMR
Neutrino’s significant roles

CCSN overview by H. Suzuki

1. Collapse and Bounce phase
   - Onset of core collapse: transparent for neutrino
     $\nu_e$ emission: EC $e^- A(N, Z) \rightarrow \nu_e A'(N + 1, Z - 1)$
   - Neutrino trapping: When core density $> 10^{11}$ g/cm$^3$, it becomes opaque due to CE$\nu$NS $\nu_e A \rightarrow \nu_e A$
   - Core bounce: When core density $> 10^{14}$ g/cm$^3$, Shockwave produced at the boundary between bounce core and free-falling outer core.
   - Neutronization burst: When shockwave passes the neutrinosphere, $A \rightarrow p$ and $n \sigma_{e-\text{cap}}(p) > \sigma_{e-\text{cap}}(A)$ $\nu_e$ emission: $e^- p \rightarrow \nu_e n$ → proto neutron star
Neutrino’s significant roles

CCSN overview by H. Suzuki

2. Accretion and Core explosion phase
   - Shockwave propagation to outer core
     \( \nu \) emission: all types of neutrinos (produce by pair creation) are in equilibrium in the neutrino sphere and diffuse out
   - Photodissociation and EC
     \( \rightarrow \) Shock wave stalls and accretion occurs \( \rightarrow \) Revival mechanism needed or BH
   - Unknown shock revival process (Key of the explosion!)
     Neutrino heating via
     \[
     \bar{\nu}_e + p \rightarrow e^+ + n
     \nu_e + n \rightarrow e^- + p
     \]
     Instability between shock front and neutrinosphere can drive it
     - Neutrino convection?
     - Standing Accretion Shock Instability?
Neutrino’s significant roles

3. Cooling phase
- Protons and electrons still remains in PNS
- From the reheating layer, neutrino diffuses to the center and to the surface of PNS
- Neutronization and Homogenization through neutrino emission
- Shockwave reaches the surface → Optical burst
Difficulties

- Neutrino interaction and transportation in high density situation

\[
e^{-} p \leftrightarrow \nu_e n, \quad e^{+} n \leftrightarrow \nu_{e} p, \quad e^{-} e^{+} \leftrightarrow \nu \nu, \quad \text{plasmon} \leftrightarrow \nu \nu, \quad \nu N \rightarrow \nu N, \quad \nu A \rightarrow \nu A
\]

- Neutrino oscillation in high density
  - **MSW effect** in much much higher density than in SUN!
  - **Collective oscillation;** neutrino self-interaction near the core

\[
\omega \equiv \frac{\Delta m^2}{2E}, \quad t > 1 \text{sec} \, r < 10^3 \text{km}, \quad n_\nu > n_e
\]

\[
\lambda \equiv \sqrt{2}G_F (n_{e^-} - n_{e^+})
\]

\[
\mu \equiv \sqrt{2}G_F (n_{\nu_e} - n_{\bar{\nu}_e}) = \sqrt{2}G_F \left( \frac{\langle L_{\nu_e} \rangle}{E_{\nu_e}} - \frac{\langle L_{\bar{\nu}_e} \rangle}{E_{\bar{\nu}_e}} \right)
\]

H. Suzuki
Many models... Need data!

Figures: H. Suzuki, M. Nakahata

"Totani1998" as a reference

"Nakazato" as a reference
Super Kamiokande V

2019 Jan~2020 Jan.??

- Inverse beta detector
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- Water detectors

- Water Cherenkov detector
  - 32k ton FV

SNOwGLoBES
http://www.phy.duke.edu/~schol/snowglobes/
Expected events in SK-V

SN at 200 pc

- $10^8$ events

- $\bar{\nu}_e p \rightarrow e^+ n$
  - 7300

- $\nu + e^- \rightarrow \nu + e^-$
  - 320

- $^{16}O$ CC
  - 110

SN at 10 kpc

- Time variation of event rate
- Time variation of mean energy

Enough statistics to discriminate models!
Preparations for too near SNe

- Betelgeuse: 300M events/10sec
- SK DAQ (QBEE) can deal with up to 6MHz (buffer full)
- With new SN module, number of PMT Hits are retained even for 30MHz burst events
SN1987A@Kamiokande

Feb. 25th, 1987: A fax was sent to Univ. of Tokyo

Day 3

Totsuka asked Kamioka shift to send recent data tapes.

Day 4

Feb. 27th (Fri): The data tapes arrived at Univ. of Tokyo and Nakahata analyzed the data.

Day 5

Feb. 28th (Sat): Hirata and Nakahata found the neutrino signals and made plots with Totsuka and Ovama.

Day 6

Mar. 1st (Sun): Totsuka tried to report this discovery to Koshiba but it was not possible because Koshiba was at the Hakone hot spring.... Totsuka went to Kamioka for a work.

Day 7

Mar. 2nd (Mon): Nakahata reported the discovery to Koshiba. Koshiba said “You must analyze all Kamiokande data and demonstrate that this is the only signal.”

Mar. 2nd – 6th: Data analysis day after day without (enough) sleep.

Day 12

Mar. 7th (Sat): The paper was sent to Physical Review Letters by a postal mail.
What if SN happens now? @Super-K

- SN simulation @10kpc (RA=0, decl=0), generated by Wilson model
- SNwatch: Real-time supernova neutrino burst monitor
  - In several minutes plots are generated automatically and auto-emails+ auto-phone calls follow

Golden Alarm:
- 60 events in 20sec
- The process time depends on the events
  - It takes about 10 minutes for the process of 10k events
  - After processing first 1000 events, 1st alarm issued
  - 2nd alarm after finishing all the process
Announcements

SURGE: Supernova Urgent Response Group of Experts

- **Super-K** (Japan), **LVD** (Italy), **Ice Cube** (South Pole), **KamLAND** (Japan), **Borexino** (Italy), **Daya Bay** (China), and **HALO** (Canada).

**SNEWS**: SuperNova Early Warning System


**IAU CBAT**: International Astronomical Union Central Bureau for Astronomical Telegrams

- [http://www.cbat.eps.harvard.edu/](http://www.cbat.eps.harvard.edu/)

**ATEL**: The Astronomer's telegram


**GCN**: The Gamma-ray Coordinates Network

- [https://gcn.gsfc.nasa.gov/](https://gcn.gsfc.nasa.gov/)
1 hour delay is ok?

SN1987A

M. Nakahata@30 years from SN1987A

Vertical axis:
Number of hit PMTs for each event,
which is almost proportional to energy

12 events within 13 sec,
11 of them are higher energy events.

$T_{\text{neutrono}} = 23.31 \text{ UTC}$
at 16:35:35 on Feb. 23, 1987

$\Delta T \approx 3 \text{ hours}$

http://www.cbateps.harvard.edu/iauc/04300/04316.html

Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION
Postal Address: Central Bureau for Astronomical Telegrams:
Smithsonian Astrophysical Observatory, Cambridge, MA 02138, U.S.A.
TWX 710-320-0842 ASTROGRAM CAM "Telephone 617-486-7444/7440/7444

SUPERNOVA 1987A IN THE LARGE MAGELLANIC CLOUD

W. Kurek and D. Madore, Las Campanas Observatory, report the
discovery by Ian Shelton, University of Toronto Las Campanas
Station, of a mag 5 object, ostensibly a supernova, in the Large
Magellanic Cloud at R.A. = 5h35m4, Decl. = -69°16' (equinox 1987.2), 18°
west and 10° south of 30 Dor and possibly involved with the
association NGC 2044. The discovery was made around Feb. 24.23 UT on
a 3-hr exposure with a 0.25-m astrograph beginning on Feb. 24.06,
and the object had evidently brightened by at least about 8 mag since
the previous night. An independent suspected sighting was made
visually by Oscar Duhalde, also at Las Campanas, around Feb. 24.2.
The object had brightened to about mag 4.8 by Feb. 24.35.

F. M. Bateson, Royal Astronomical Society of New Zealand,
informs us that the object was discovered independently by Albert
Jones, Nelson, on Feb. 24.37 UT (position R.A. = 5h35m0.8, Decl. = -69°18',
equinox 1980.0) at mag 6.5-7.0 (in clouds); he estimated $m_v = 5.1$
on Feb. 24.48. B. Moreno and S. Walker, Auckland Observatory,
obtained $V = 4.81, B-V = 0.005, U-B = -0.008$ on Feb. 24.45 UT.

R. H. McNaught, Siding Spring Observatory, communicated
the following visual-magnitude estimates by G. Garradd (G) and himself
(M): Feb. 24.45, 4.8 (M); 24.47, 4.8 (M); 24.65, 4.4 (G);
24.67, 4.5 (M); 24.71, 4.4 (M). McNaught obtained the following
precise position with the University of Aston Hewitt Satellite
Schmidt camera: R.A. = 5h35m60s.22, Decl. = -69°17'59.2" (equinox
1950.0, uncertainty 2'). The object appears on films from the
previous night: Feb. 22.440; R.A. = 5h35m60s.12, Decl. =
-69°17'58.0" (equinox 1950.0, x = 15447, y = 9261 in the Harvard
LMC system). Films by Garradd confirm that the field was
identical down to mag 14.5 on Jan. 24 and Feb. 22.

B. Warner, University of Texas, reports that a spectroscopic
observation by J. Mereles on Feb. 24.9 UT with the 1.0-m reflector
at the South African Astronomical Observatory shows the 015-m
line, indicating that the object may be a supernova of type I.
### Categories of SNe

<table>
<thead>
<tr>
<th>Types</th>
<th>Spectrum</th>
<th>Light Curve</th>
<th>Explosion mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
<td>Si</td>
<td>He</td>
</tr>
<tr>
<td>Type I</td>
<td>Ia</td>
<td>×</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Ib</td>
<td>×  ×</td>
<td>〇</td>
</tr>
<tr>
<td></td>
<td>Ic</td>
<td>×  ×  ×</td>
<td>〇</td>
</tr>
<tr>
<td>Type II</td>
<td>IIP</td>
<td>〇</td>
<td>Plateau</td>
</tr>
<tr>
<td></td>
<td>IIL</td>
<td>〇</td>
<td>Linear</td>
</tr>
<tr>
<td></td>
<td>IIIn</td>
<td>〇(nallow)</td>
<td></td>
</tr>
</tbody>
</table>

- I or II : H line or not
- small: feature in spectrum
- Capital: feature in LC

Outer layer remains in PLbc order

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*M. Tanaka @30 years from SN1987A*

Progenitors of CCSNe

- Type II
  - Red supergiants
    - $R \sim 1000 R_\odot$
    - Average shock speed inside of the star
      $v \sim 10,000 \text{ km s}^{-1} = 10^9 \text{ cm s}^{-1}$
      $R_\odot \sim 7 \times 10^{10} \text{ cm}$
      $\Delta T \sim R/v \sim 1\text{ day}$

- Type Ib
  - Wolf-Rayet stars
    - $R \sim 1-10 R_\odot$
      $\Delta T \sim R/v \sim 1-10\text{ min}$

- Type Ic
  - N.B. scale is arbitrary

M. Tanaka
@30 years from SN1987A
The ratio of each category

- 1~10 min
- Ib
- Ic
- Ic-BL
- II
- II-87A
- IIP

ΔT~1 day

~1 h

I. Shivvers et al., 2017 PASP

\[ \Delta T \sim 1 \text{day} \]

M. Tanaka @30 years from SN1987A

\[ \sim 30\% \quad \sim 15\% \quad \sim 55\% \]

- Red Supergiants
- Blue Supergiants
- Wolf–Rayet Stars

\[ 5 \times 10^{50} \text{ erg} \quad 3 \times 10^{51} \text{ erg} \]

- 1 hour is too late.. quicker warning system needed


Hiroyuki Sekiya

Prospects of Neutrino Physics

Kavli IPMU

Apr. 9 2019
SK-Gd

- Will provide early warnings.

M. Vagins’ talk

[C. Simpson]
Pointing accuracy

- Advantage of WC detectors
  - Inverse beta events are useless
  - Excess of elastic scattering events

- BG reduction by neutron tagging
  - $\bar{\nu}_e p \rightarrow e^+ n$: 7300
  - $\nu + e^- \rightarrow \nu + e^-$: 320
  - $^{16}\text{O}$ CC: 110

Pointing accuracy $\sim 5^\circ$ @10kpc SN
SK-Gd pointing accuracy

- If $\bar{\nu}_e$ can be tagged, directional events ($\nu$+e scattering events) are enhanced.
- For 10kpc SN $\sim 5^\circ \rightarrow \sim 3^\circ$ (@90% C.L.)

If $\bar{\nu}_e$ can be tagged, directional events ($\nu$+e scattering events) are enhanced. For 10kpc SN, the angle changes from $\sim 5^\circ$ to $\sim 3^\circ$ with 90% confidence level.
Impact of SK-Gd

- Pointing in $3^\circ$ accuracy will allow the follow-up with large telescopes

Hyper Kamiokande

Construction will start at 2020. Observation will be ready by 2027.
**Expected events in HK**

- SK 32kt → HK 220kt
  - Not only inverse beta decay!
- 54000-90000 events are expected for the galactic SN

---

**SN at 10 kpc**

**Totani1998**

**Total Energy spectra**

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**Water detectors**

- $\bar{\nu}_e + p \rightarrow e^+ + n$
- $\nu + e^- \rightarrow \nu + e^-$
Expected events in HK

- SK 32kt → HK 220kt
- Inverse beta decay events

Easier to discriminate models!

SN at 10 kpc

Time variation of event rate

Time variation of mean energy

Nakazato et al. (2015), 1D, 30M, BH
Nakazato et al. (2015), 1D, 20M
Takizawa et al. (2014), 3D, 11.2M
Bruenn et al. (2016), 2D, 20M
Dolence et al. (2015), 2D, 20M
Pan et al. (2016), 2D, 21M
Tamborra et al. (2014), 3D, 27M
Totani et al. (1998), 1D, 20M
Non trivial Neutrino Oscillation!

- MSW and Collective oscillation
  - Observed spectrum should be between these 3 patterns..

SN at 10 kpc
Totani1998
Even though, Power of the statistics

- Direct observation of key features of SN mechanism

**Neutronization burst**
When shockwave pass through the neutrino sphere

**SASI? Convection?**
Shock revival by neutrino heating?
Key phenomenon of the burst!

SN at 10 kpc
Totani2018

[Graph showing neutronization burst and SASI simulation]

ES channel
Pointing accuracy of HK

- Further help for Multi-messenger observation

Livermore 10kpc

1～2° @10kpc SN
SN detection probability of HK

- Doublet (N=2)
  \[0.8 \times 0.1 \times 2 \text{years} \times 0.22 / 0.56 = 0.7\ (<4\text{Mpc})\]

- GW (+EM) coincidence enables singlet (N=1) events
  \[0.8 \times 0.4 \times 0.22 / 0.56 = 0.17 / \text{year}\ (<4\text{Mpc})\]

Black Observed CCSN for 15 years
Cyan band Expected from star formation rate
Red HK detection prob \times 0.56\text{Mt}/0.22\text{Mt}
Blue HK-Gd case

SEARCH FOR NEUTRINOS IN SUPER-KAMIOKANDE ASSOCIATED WITH
GRAVITATIONAL-WAVE EVENTS GW150914 AND GW151226

ABSTRACT

We report the results from a search in Super-Kamiokande for neutrino signals coincident with the first detected gravitational-wave events, GW150914 and GW151226, as well as LVT151012, using a neutrino energy range from 3.5 MeV to 100 PeV. We searched for coincident neutrino events within a time window of ±500 s around the gravitational-wave detection time. Four neutrino candidates are found for GW150914, and no candidates are found for GW151226. The remaining neutrino candidates are consistent with the expected background events. We calculated the 90% confidence level upper limits on the combined neutrino fluence for both gravitational-wave events, which depends on event energy and topologies. Considering the upward-going muon data set (1.6 GeV–100 PeV), the neutrino fluence limit for each gravitational-wave event is 14–37 (19–50) cm⁻² for muon neutrinos (muon antineutrinos), depending on the zenith angle of the event. In the other data sets, the combined fluence limits for both gravitational-wave events range from 2.4 × 10⁴ to 7.0 × 10⁹ cm⁻².

Key words: astroparticle physics – gravitational waves – neutrinos
Prospects

- 2019- SK-V
- 2020- SK-Gd
- 2027- HK-I

Next time CCSN occurs in the Galaxy, SK and/or HK will assess the mechanism of CCSN.
Even if CCSN does not occur for the next 10 years in nearby Galaxies, SK-Gd and/or HK+GW will assess the mechanism of CCSN.