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

Total 32 pages

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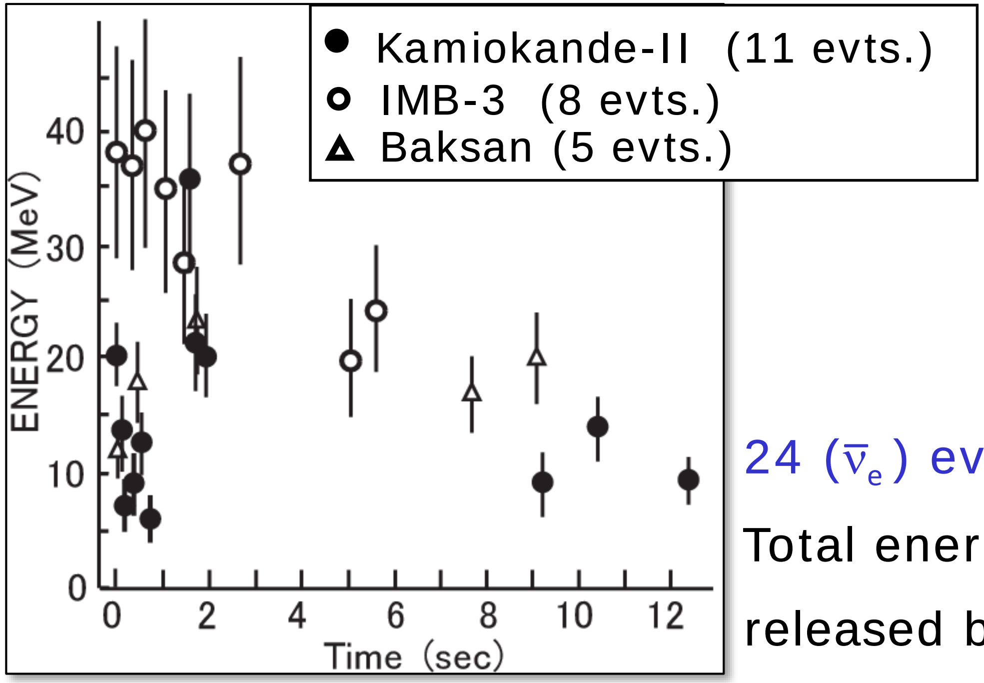
Supernova neutrinos from 1987A

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

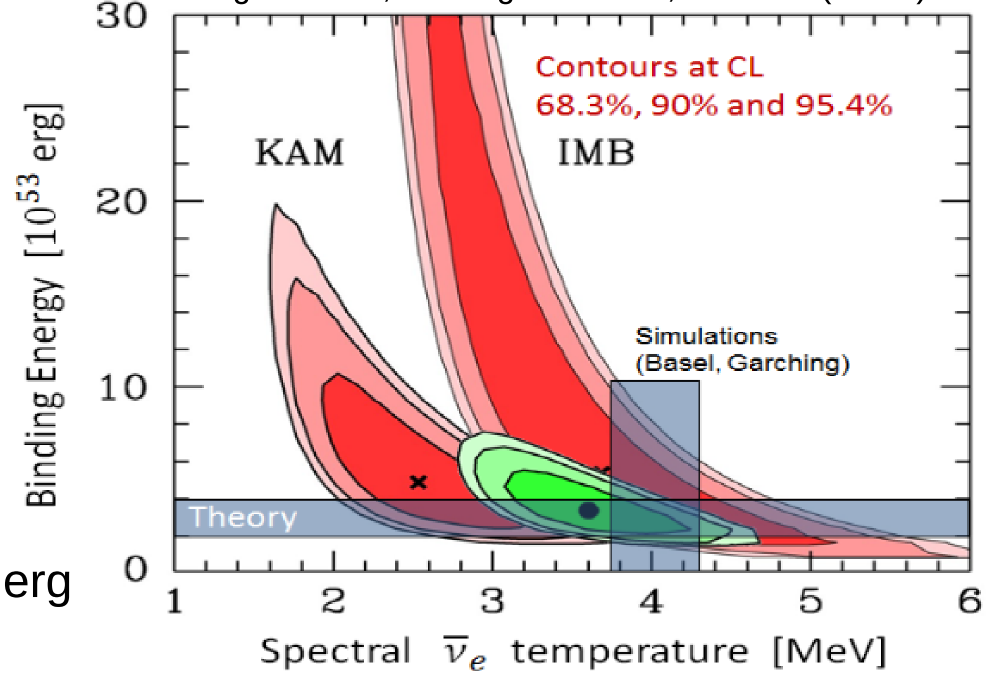


24 ($\bar{\nu}_e$) events in total.

Total energy

released by $\bar{\nu}_e$: ~5x10^{52} erg

Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

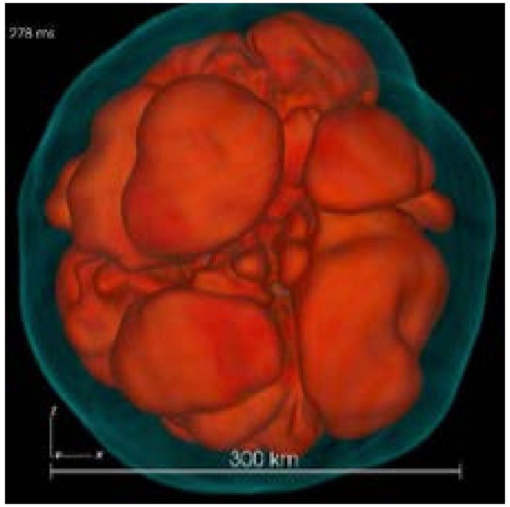


- The obtained binding energy is almost as expected, but large error in neutrino mean energy. No detailed information of burst process.
- We need energy, flavor and time structure.

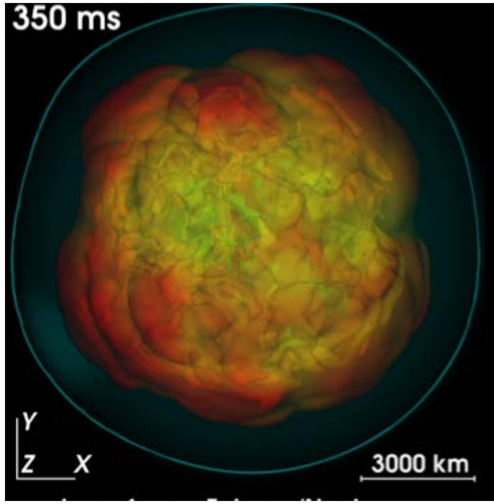
Recent 3D simulations burst

- Mechanism of CCSN needs to be determined by data

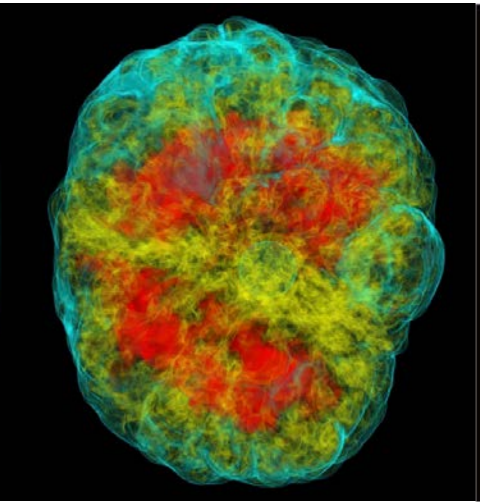
K.Nakamura



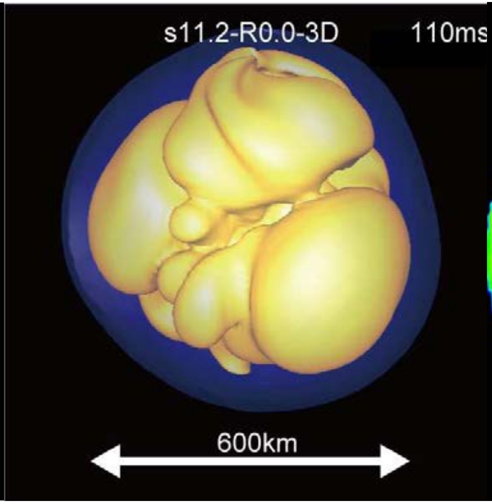
Hanke+'13



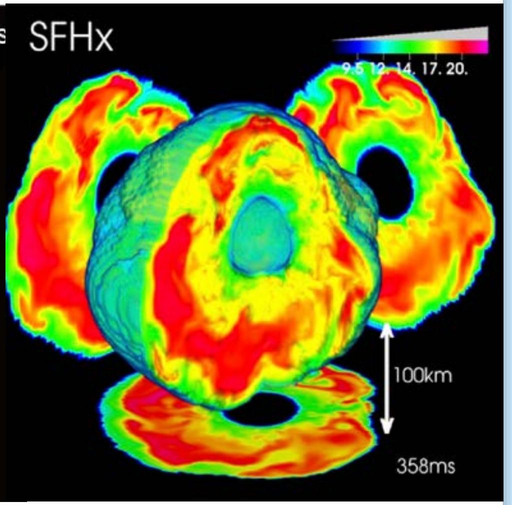
Melson+'15



Roberts+'16



Takiwaki+'16



Kuroda+'16

27 $M_\odot$ (WHW02)
t < ~400 ms
LS220 EoS
1D gravity
+ GR correction

9.6 $M_\odot$ (A. Heger)
t < ~400 ms
LS220 EoS
1D gravity
+ GR correction
Yin-Yang grid

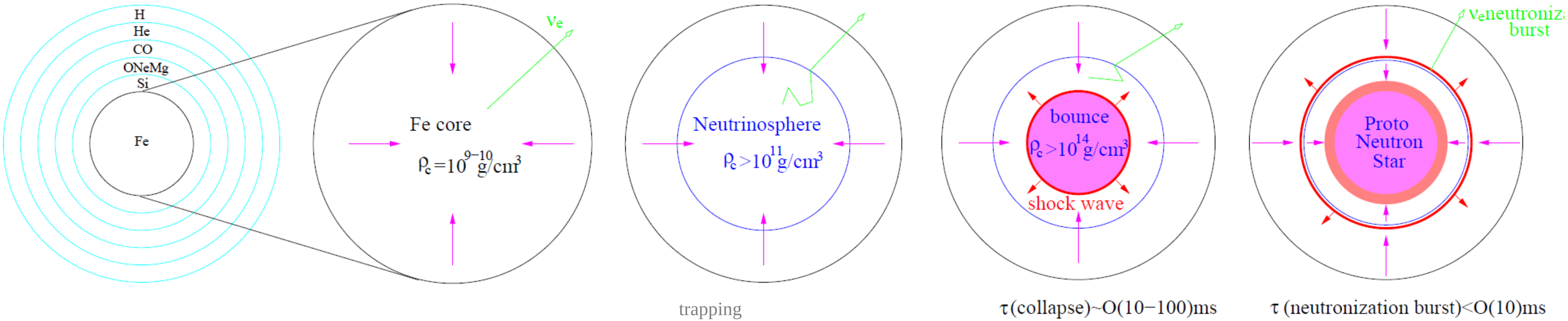
27 $M_\odot$ (WHW02)
t < 380 ms
LS220 EoS
GR
Cartesian AMR

11.2 (&27) $M_\odot$ (WHW02)
t < ~300 (400) ms
LS220 EoS
Newtonian

15 $M_\odot$ (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

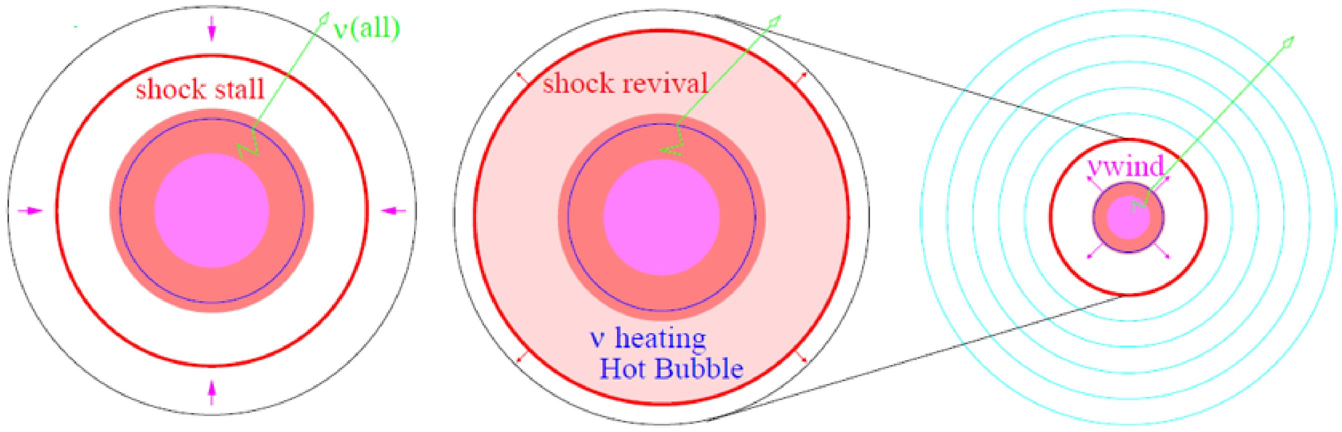
  ν_e emission: EC $e^- \ A(N,Z) \longrightarrow \nu_e \ A'(N+1, Z-1)$
- Neutrino trapping: When core density > 10^{11} g/cm^3, it becomes opaque due to CEνNS $\nu_e \ A \to \nu_e \ A$

  ν_e emission: Only diffuse out from Neutrinosphere
- 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 → p and n $\sigma_{e-cap}(p) > \sigma_{e-cap}(A)$

  ν_e emission: $e^- p \to \nu_e n$ →proto neutron star

Neutrino's significant roles

CCSN overview by H. Suzuki



2. Accretion and Core explosion phase

- Shockwave propagation to outer core

  ν emission: all types of neutrinos (produce by pair creation)are in equilibrium in the neutrino sphere and diffuse out

  Photodissociation and EC

  → Shock wave stalls and accretion occurs → Revival mechanism needed or BH

- Unknown shock revival process (Key of the explosion!)

  neutrino heating via

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

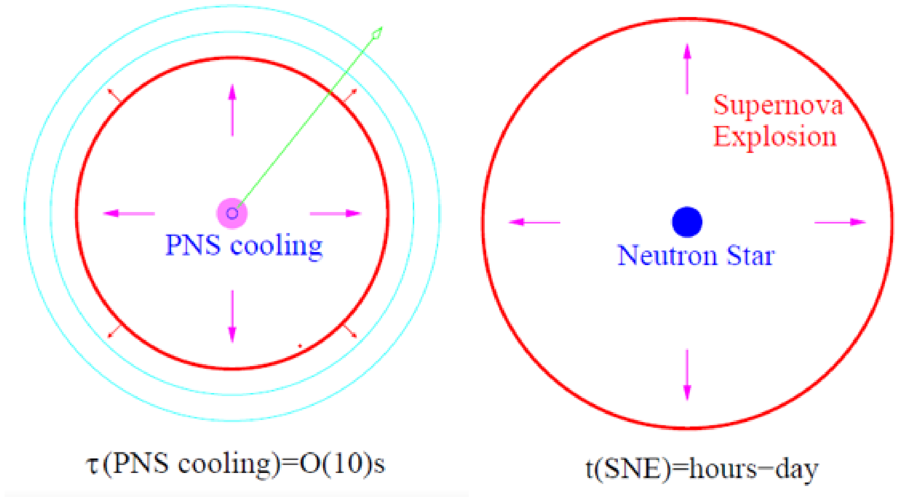
  $\nu_e + n \to e^- + p$?

Instability between shock front and neutrinosphere can drive it

- Neutrino convection?
- Standing Accretion Shock Instability?

Neutrino’s significant roles

CCSN overview by H. Suzuki



Optical burst!

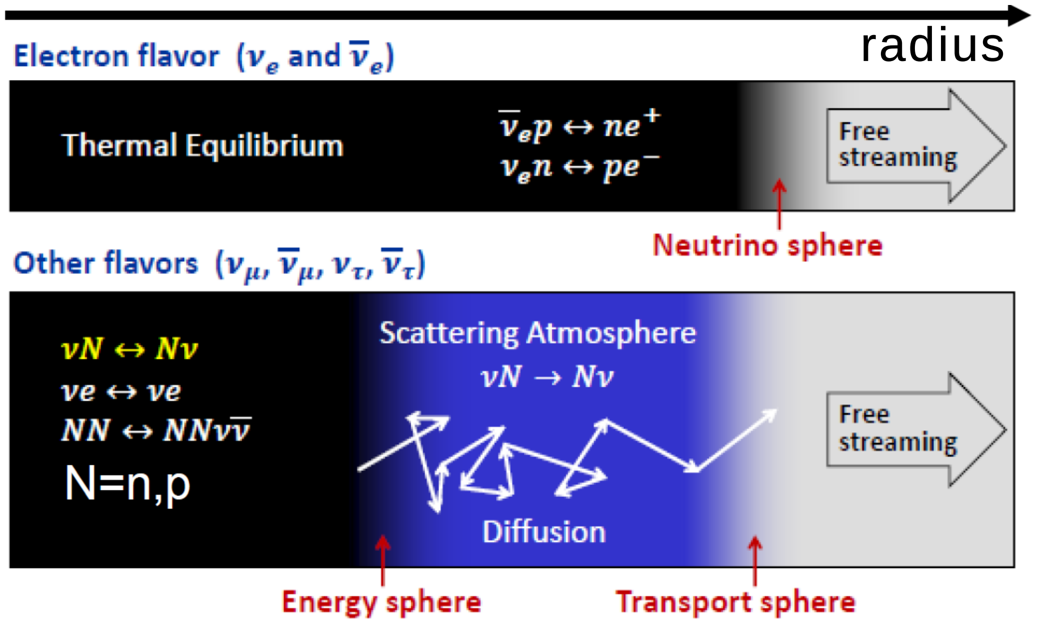
3. Cooling phase

- 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

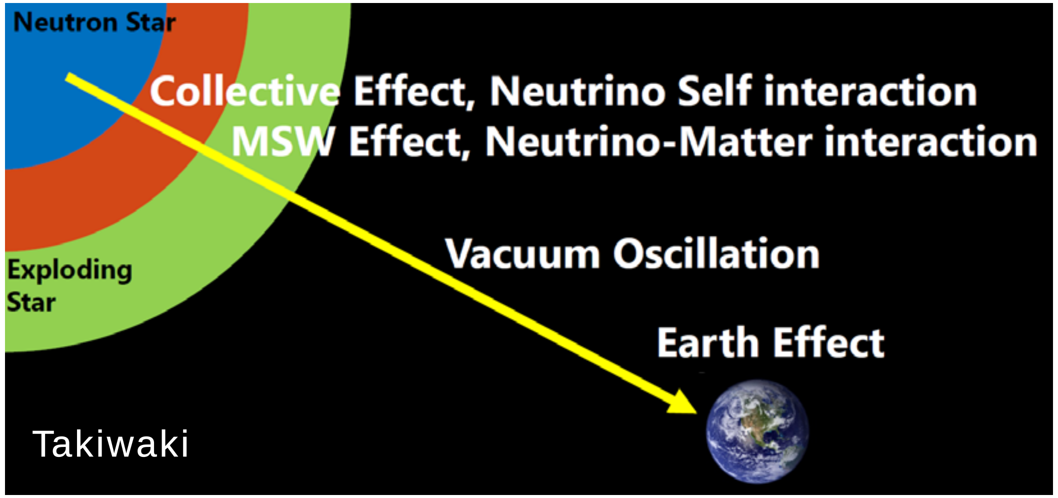
Difficulties

- Neutrino interaction and transportation in high density situation

$e^- p \longleftrightarrow \nu_e n$	$e^+ n \longleftrightarrow \bar{\nu}_e p$	$e^- A \longrightarrow \nu_e A'$	$e^+ A \longrightarrow \bar{\nu}_e A'$
$e^- e^+ \longleftrightarrow \nu\bar{\nu}$	$\text{plasmon} \longleftrightarrow \nu\bar{\nu}$	$NN \longrightarrow NN\nu\bar{\nu}$	$\nu_e\bar{\nu}_e \longleftrightarrow \nu_x\bar{\nu}_x$
$\nu N \longrightarrow \nu N$	$\nu A \longrightarrow \nu A$	$\nu e^\pm \longrightarrow \nu e^\pm$	$\nu\nu' \longrightarrow \nu\nu'$



Janka 2017



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

$t > 1\text{sec}\ r < 10^3\text{km}$, $n_\nu > n_e$

$$\omega \equiv \frac{\Delta m^2}{2E}$$

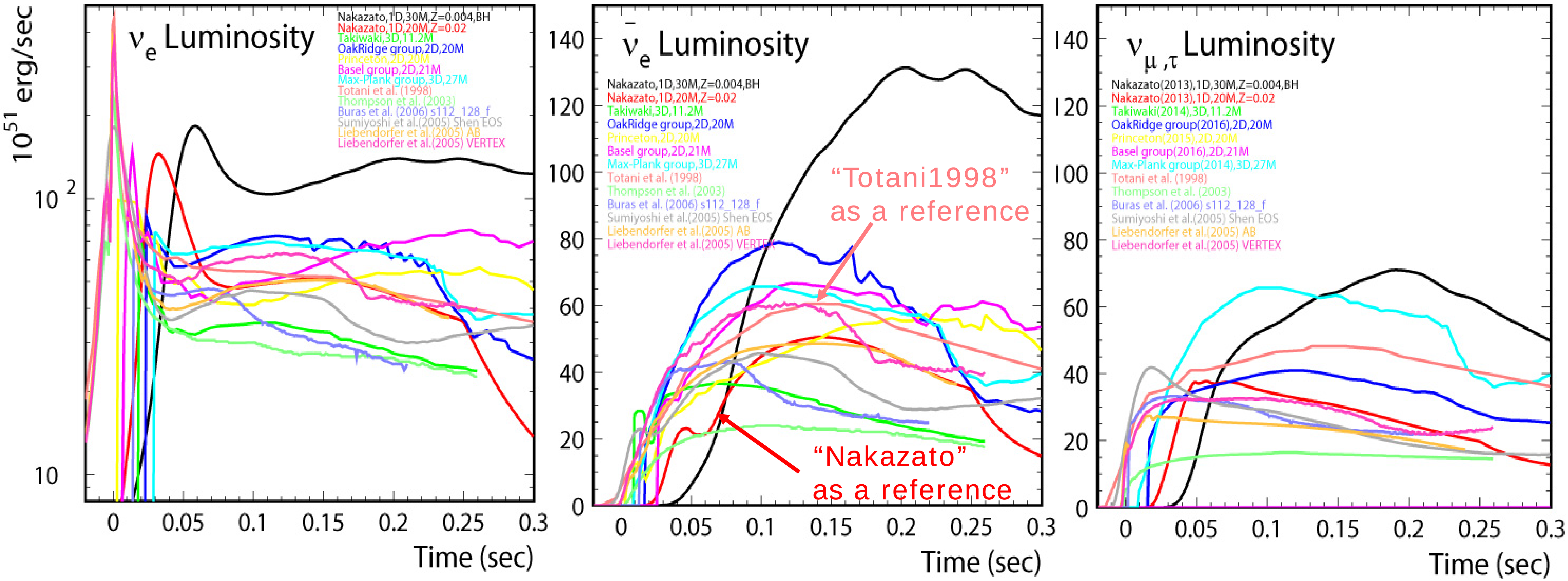
$$\lambda \equiv \sqrt{2} G_F (n_{e^-} - n_{e^+})$$

$$\mu \equiv \sqrt{2} G_F (n_{\bar{\nu}_e} - n_{\bar{\nu}_x}) = \frac{\sqrt{2} G_F}{4\pi r^2} \left(\frac{L_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e} \rangle} - \frac{L_{\bar{\nu}_x}}{\langle E_{\bar{\nu}_x} \rangle} \right)$$

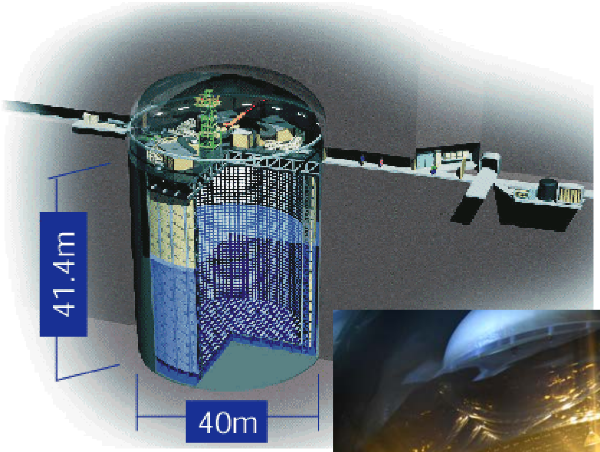
H. Suzuki

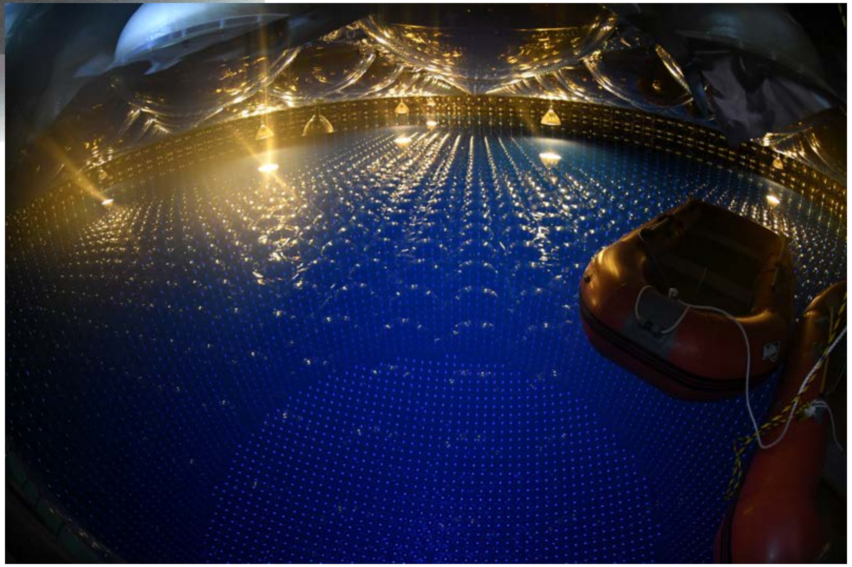
Many models… Need data!

Figures: H.Suzuki, M. Nakahata



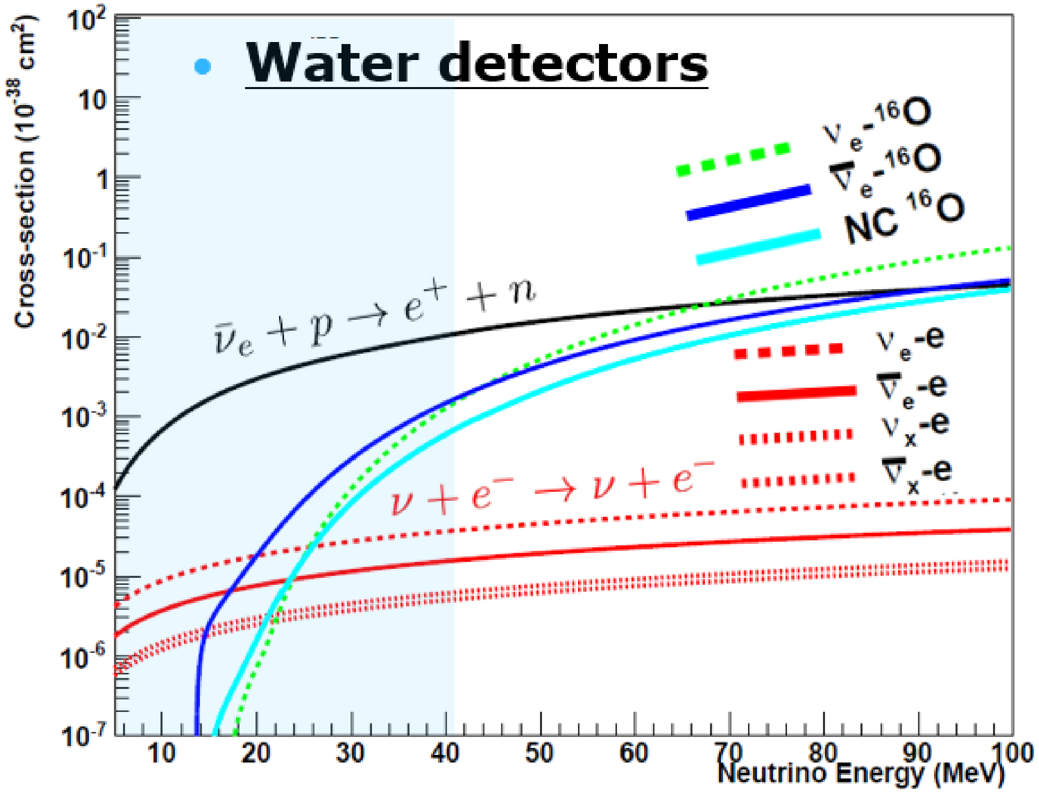
Super Kamiokande V 2019 Jan~2020 Jan.??





- Inverse beta detector $\bar{\nu}_e$

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



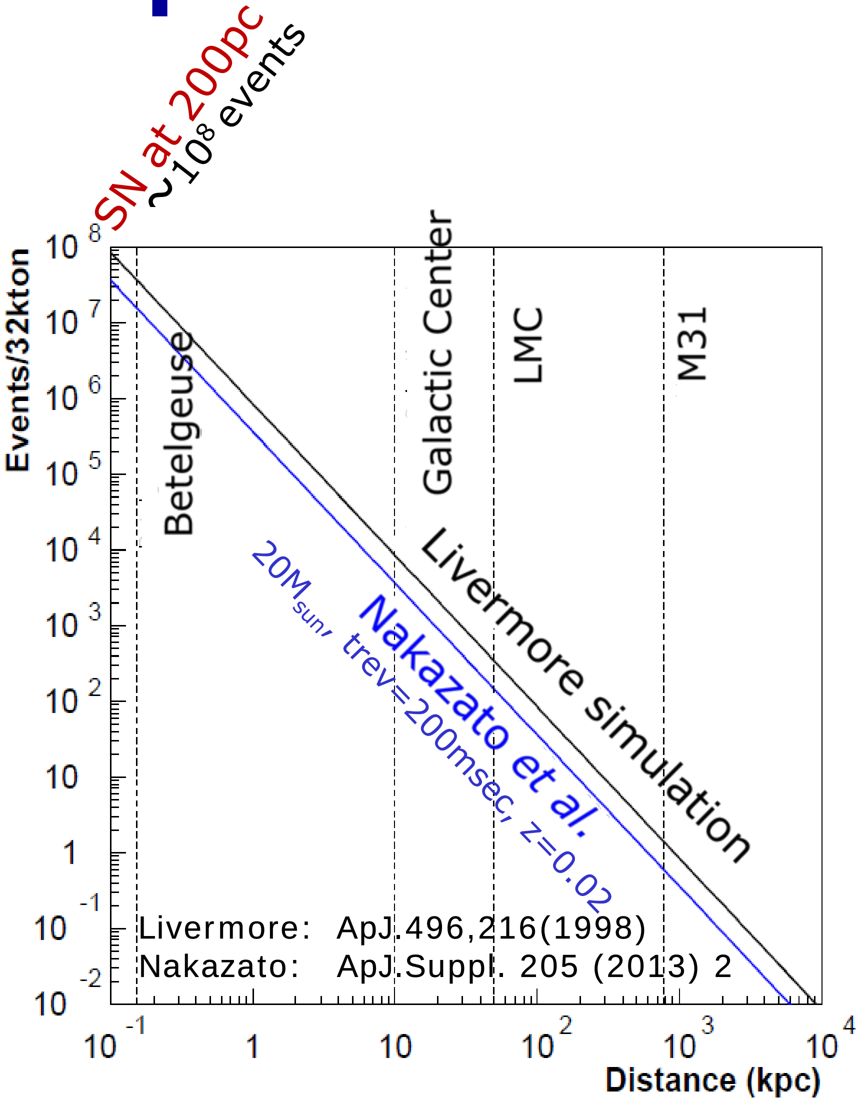
SNOwGLoBES
http://www.phy.duke.edu/~schol/snowglobes/

- Water Cherenkov detector
  - 32k ton FV

Expected events in SK-V

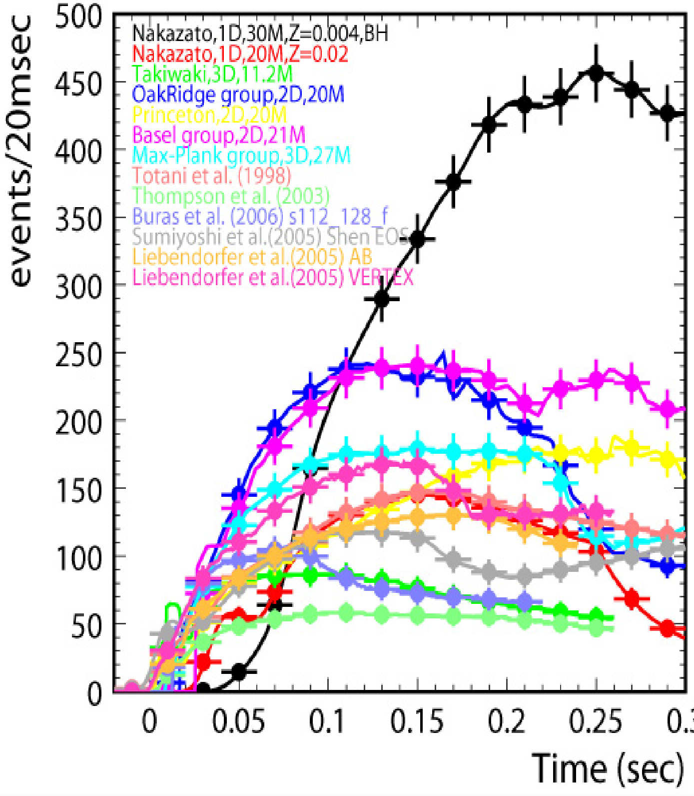
	Totani1998	Nakazato
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

SN at 10 kpc

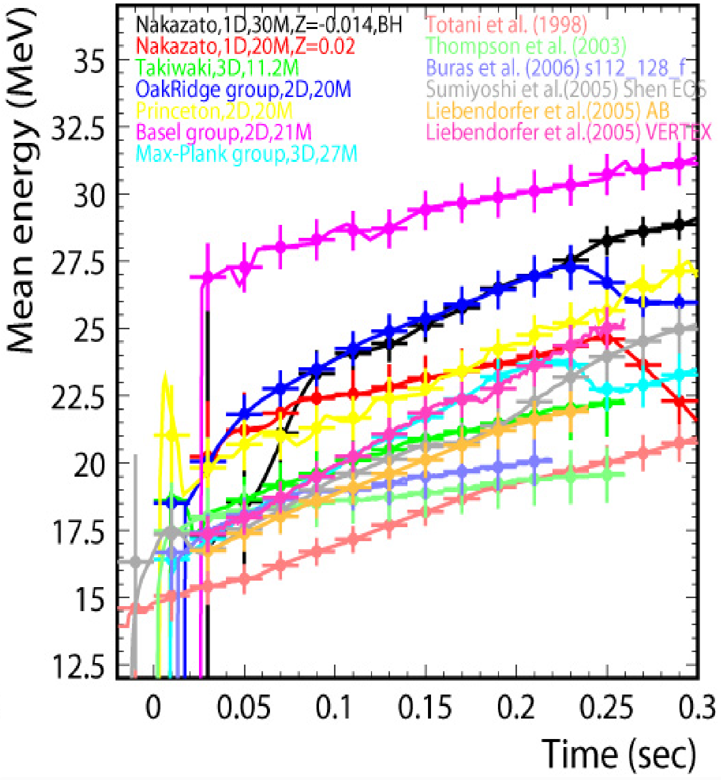


Enough statistics to discriminate models!

Time variation of event rate

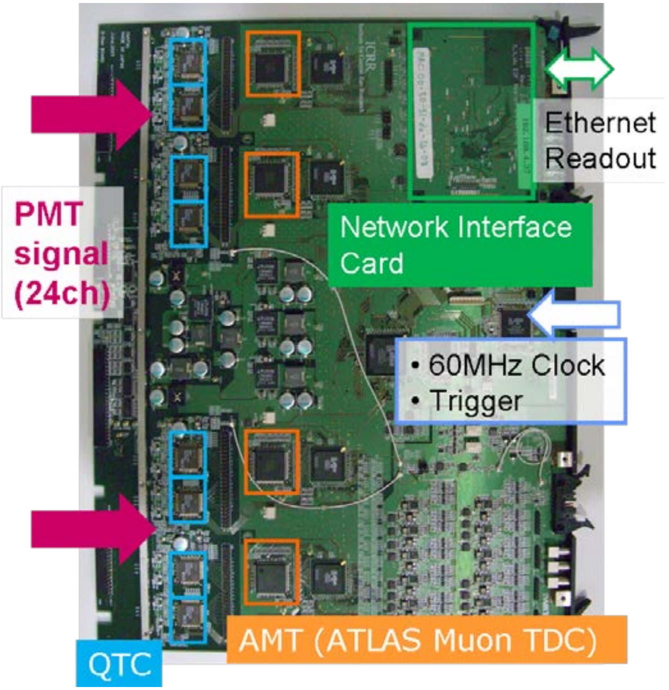


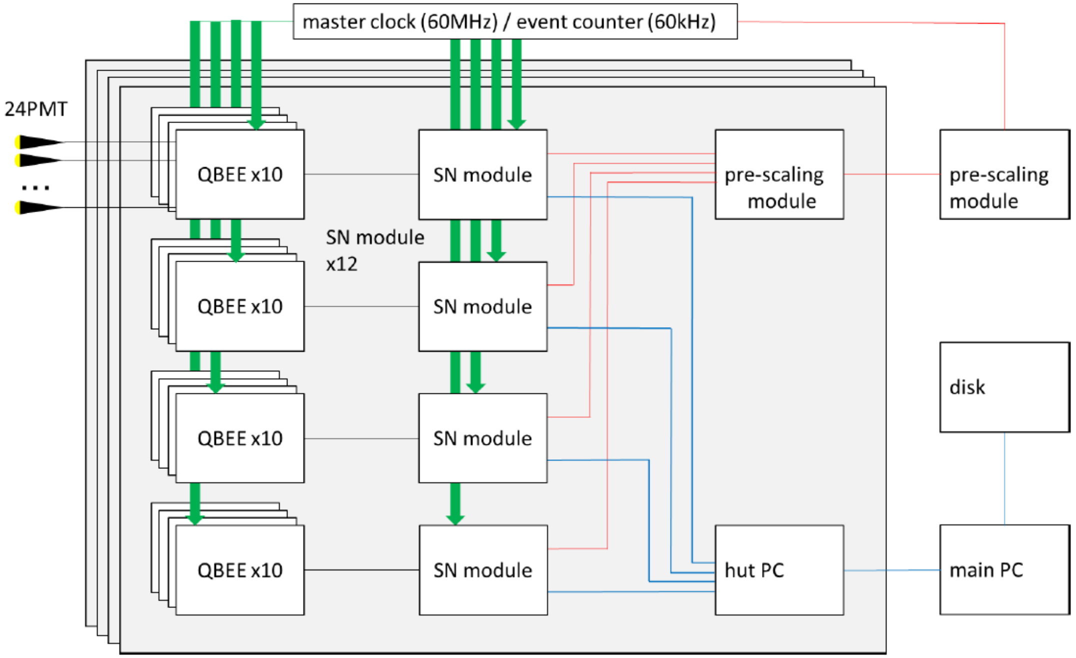
Time variation of mean energy

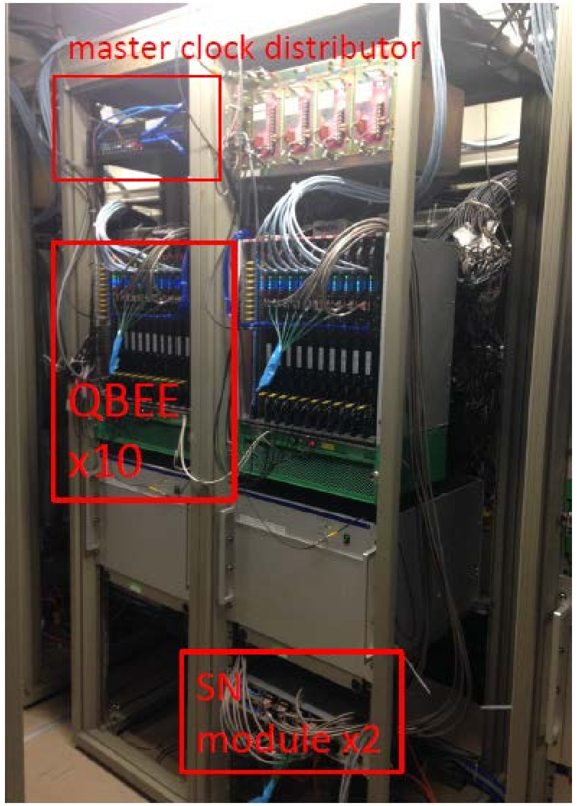


Preparations for too near SNe

- 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





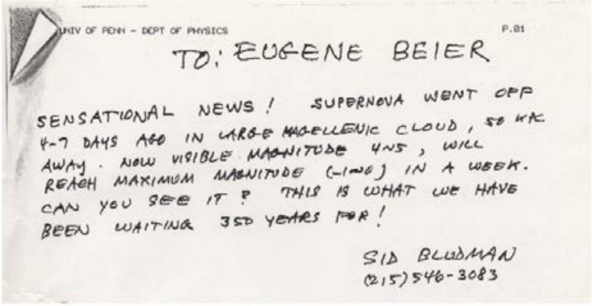


SN1987A@Kamiokande

M. Nakahata@30 years from SN1987A and the future

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

Day 3


UNIV OF PENN – DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4NS, WILL REACH MAXIMUM MAGNITUDE (–1?) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

➡ Totsuka asked Kamioka shift to send recent data tapes.

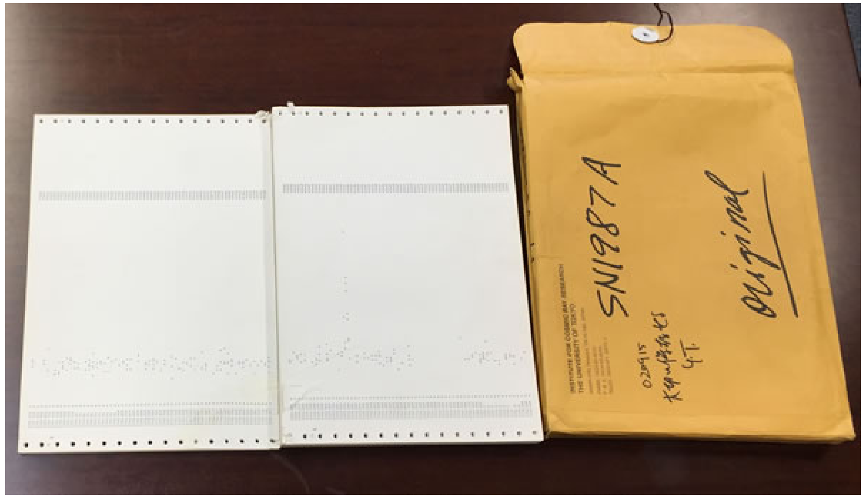
Day 4

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

NHK

Day 5

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



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."

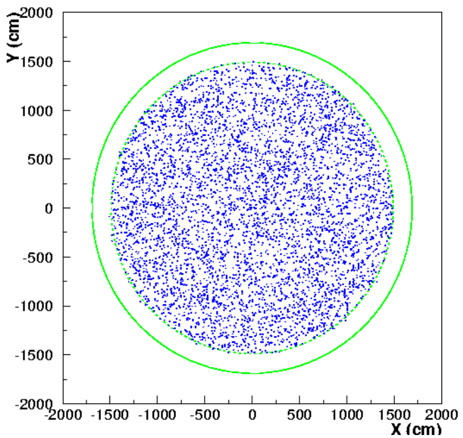
Mar. 2nd – 6th : Data analysis day after day without (enough) sleep

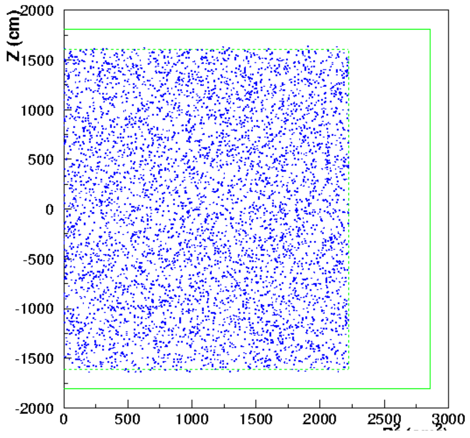
Day 12

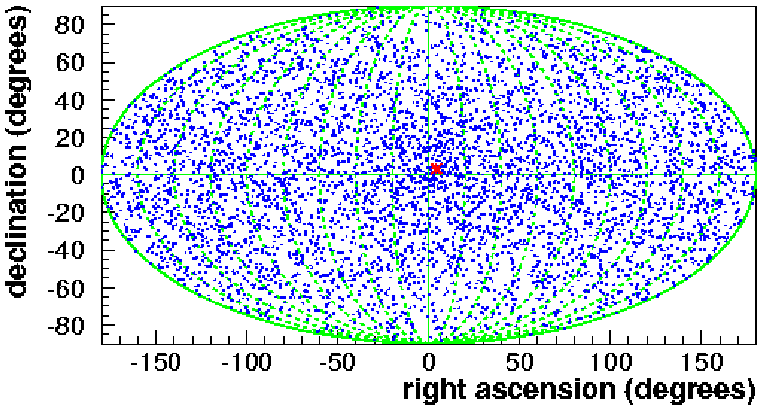
Mar. 7th(Sat): The paper was sent to Physical Review Letters by a postal mail.

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 Astropart. Phys. 81(2016)39
  - In several minutes plots are generated automatically and auto-emails+ auto-phone calls follow







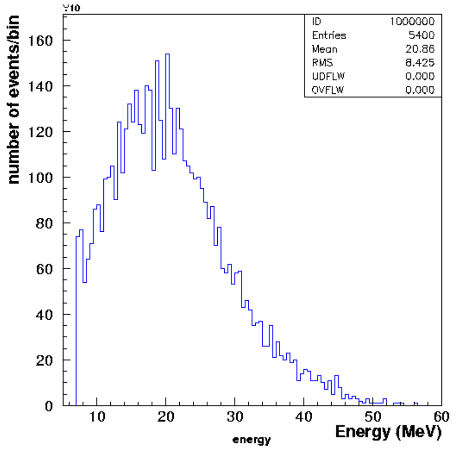
Subject: DRILL!: SNwatch GOLDEN alarm of all info.: run=074132 srun=000434
Date: Sat, 24 Oct 2015 23:25:08 +0900

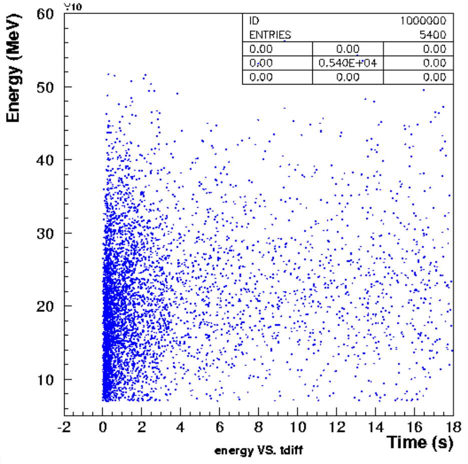
```
*********** event cluster information ***********

The followings are information of the SN candidate.

Time Information:
------------------------------------------------------------
Fst evt info.: evtno=1028040 time= 2015/Oct/24 23:20:42 (JST)
Lst evt info.: evtno=1036600 time= 2015/Oct/24 23:20:59 (JST)
------------------------------------------------------------
Fst evt GPS time = 2015/Oct/24 14:20:42 2838[us] (UT)
Lst evt GPS time = 2015/Oct/24 14:20:59 889838[us] (UT)
------------------------------------------------------------
Time range (sec.)        | 17.8870
------------------------------------------------------------

Basic Information:
------------------------------------------------------------
Run number               | 74132
------------------------------------------------------------
Subrun number            | 434
------------------------------------------------------------
Number of events         | 5227
 in the cluster          |
------------------------------------------------------------
Estimated distance       | 7.55 to 10.36 (kpc)
for +-1 sigma range      |
```

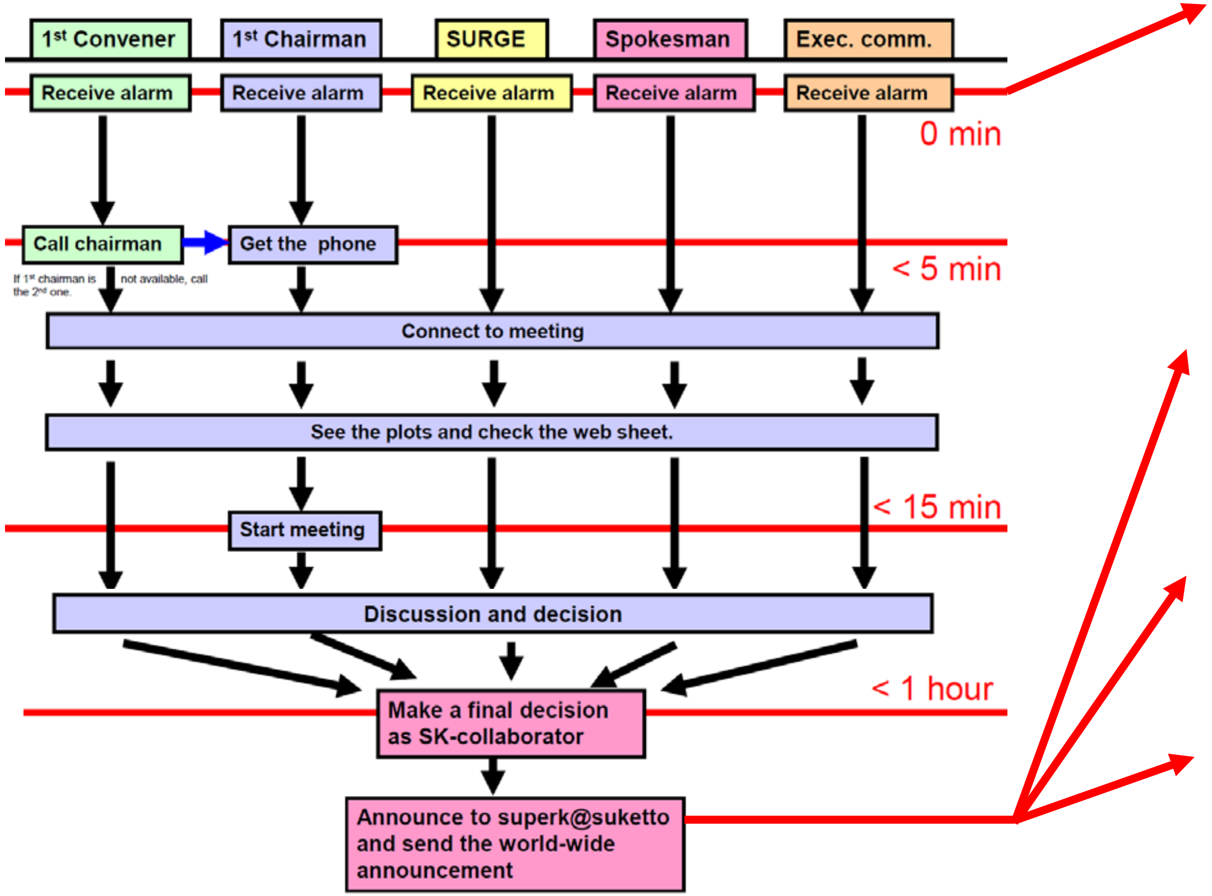




- Golden Alarm:
  - 60 events in 20sec
- The process time depends on the events
  - It takes about 10minutes for the process of 10k events
  - After processing first 1000 events, 1st alarm issued
  - 2nd alarm after finishing all the process

Announcements

SURGE:
Supernova Urgent Response Group of Experts



SNEWS level "0"

SNEWS:
SuperNova Early Warning System

http://snews.bnl.gov/

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

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

  http://www.cbat.eps.harvard.edu/

- ATEL: The Astronomer's telegram

  http://www.astronomerstelegram.org/

- GCN: The Gamma-ray Coordinates Network

  https://gcn.gsfc.nasa.gov/

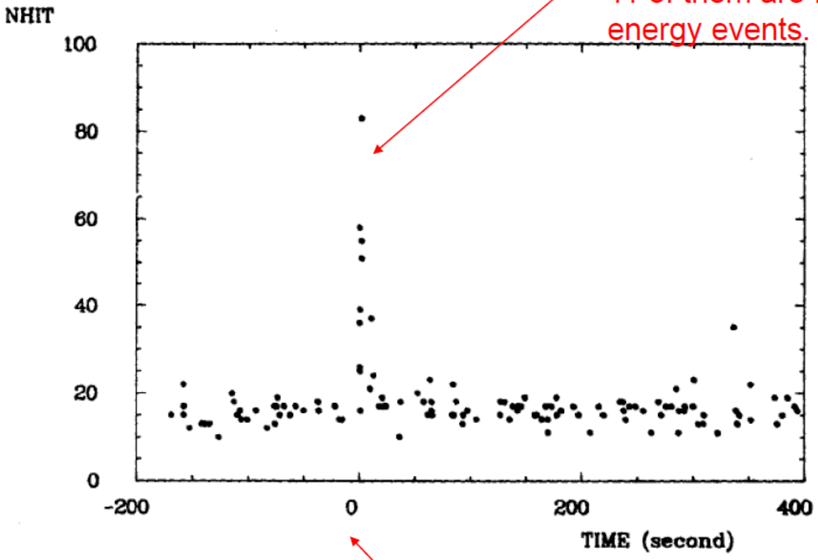
1 hour delay is ok?

- 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 13sec.
11 of them are higher
energy events.



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

$\Delta T \sim$ 3 hours

http://www.cbat.eps.harvard.edu/iauc/04300/04316.html

Circular No. 4316

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 710-320-6842 ASTROGRAM CAM Telephone 617-495-7244/7440/7444

SUPERNOVA 1987A IN THE LARGE MAGELLANIC CLOUD

W. Kunkel and B. 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. = 5h35m.4, 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 4.5 by Feb. 24.33.

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. = 5h35m.8, Decl. = -69 18', equinox 1950.0) at mag 6.5-7.0 (in clouds); he estimated mv = 5.1 on Feb. 24.46. B. Moreno and S. Walker, Auckland Observatory, obtained V = 4.81, B-V = +0.085, U-B = -0.836 on Feb. 24.454 UT.

R. H. McNaught, Siding Spring Observatory, communicates the following visual magnitude estimates by G. Garradd (G) and himself (M): Feb. 24.455, 4.8 (M); 24.472, 4.8 (M); 24.635, 4.4 (G); 24.679, 4.5 (M); 24.717, 4.4 (M). McNaught obtained the following precise position with the University of Aston Hewitt Satellite Schmidt camera: R.A. = 5h35m50s.22, Decl. = -69 17'59".2 (equinox 1950.0, uncertainty 2"). The object appears on films from the previous night: Feb. 23.443, 6.0; 23.445, 6.2. He also notes the position of a blue star, of mv about 12 and not obviously variable during the past century (through Feb. 22.4): R.A. = 5h35m50s.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. Menzies on Feb. 24.9 UT with the 1.9-m reflector at the South African Astronomical Observatory shows the 615-nm dip, indicating that the object may be a supernova of type I.

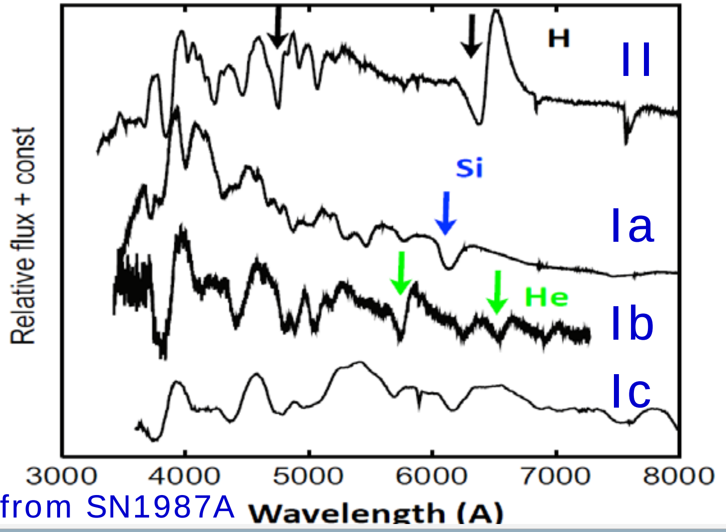
$T_{optical}$ = 23.44 UTC

Categories of SNe

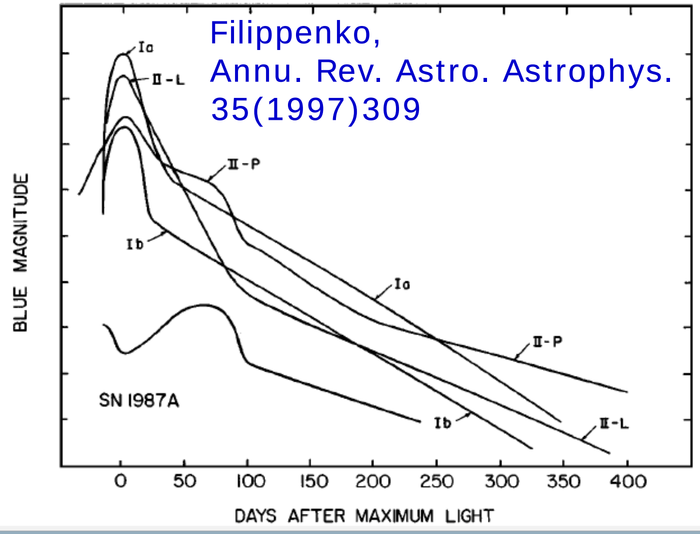
Types		Spectrum			Light Curve	Explosion mechanism	
		H	Si	He		runaway reaction of NF	Core-collapse
Type I	Ia	×	○			○	
	Ib	×	×	○			○
	Ic	×	×	×			○
Type II	IIP	○			Plateau		○
	IIL	○			Linear		○
	IIn	○(nallow)					○

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

Outer layer remains
in PLbc order



M. Tanaka
@30 years from SN1987A



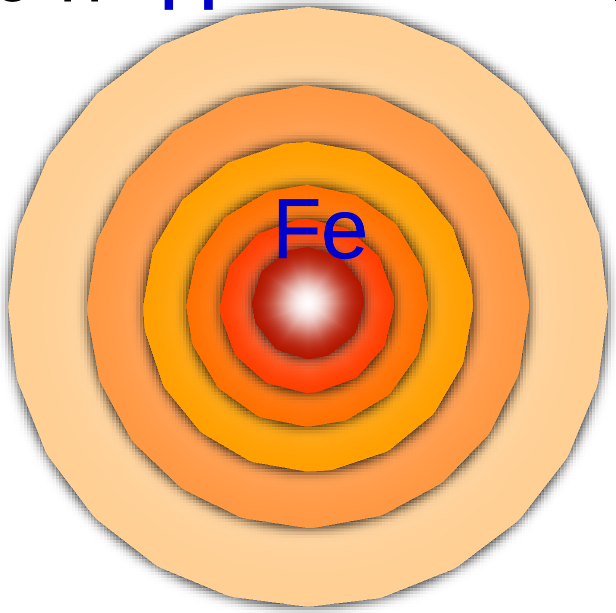
Filippenko,
Annu. Rev. Astro. Astrophys.
35(1997)309

Progenitors of CCSNe

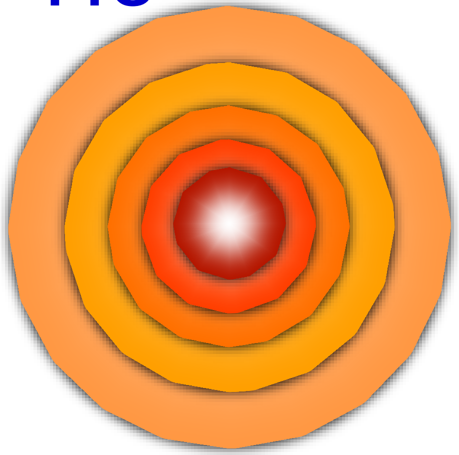
M. Tanaka
@30 years from SN1987A

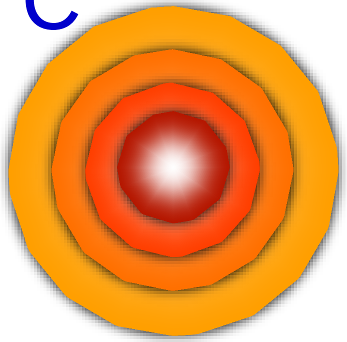
- Type II
- Type Ib
- Type Ic

N.B. scale is arbitrary



Red supergiants
$R \sim 1000 R_{\odot}$





Wolf-Rayet stars
$R \sim 1\text{-}10 R_{\odot}$

Average shock speed inside of the star
$v \sim 10{,}000\ \mathrm{km\ s^{-1}} = 10^{9}\ \mathrm{cm\ s^{-1}}$

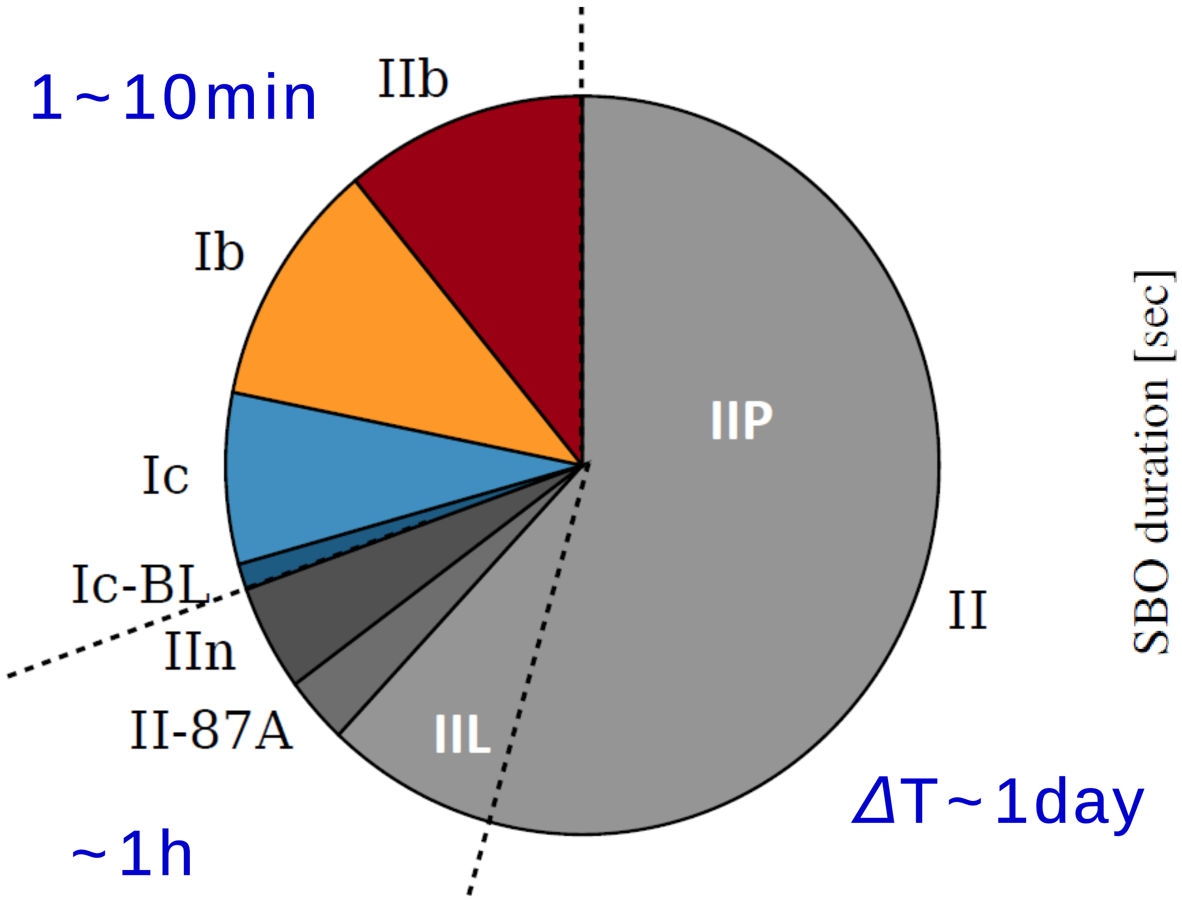
$R_{\odot} \sim 7 \times 10^{10}\mathrm{cm}$

$\Delta T \sim R/v \sim$ 1day

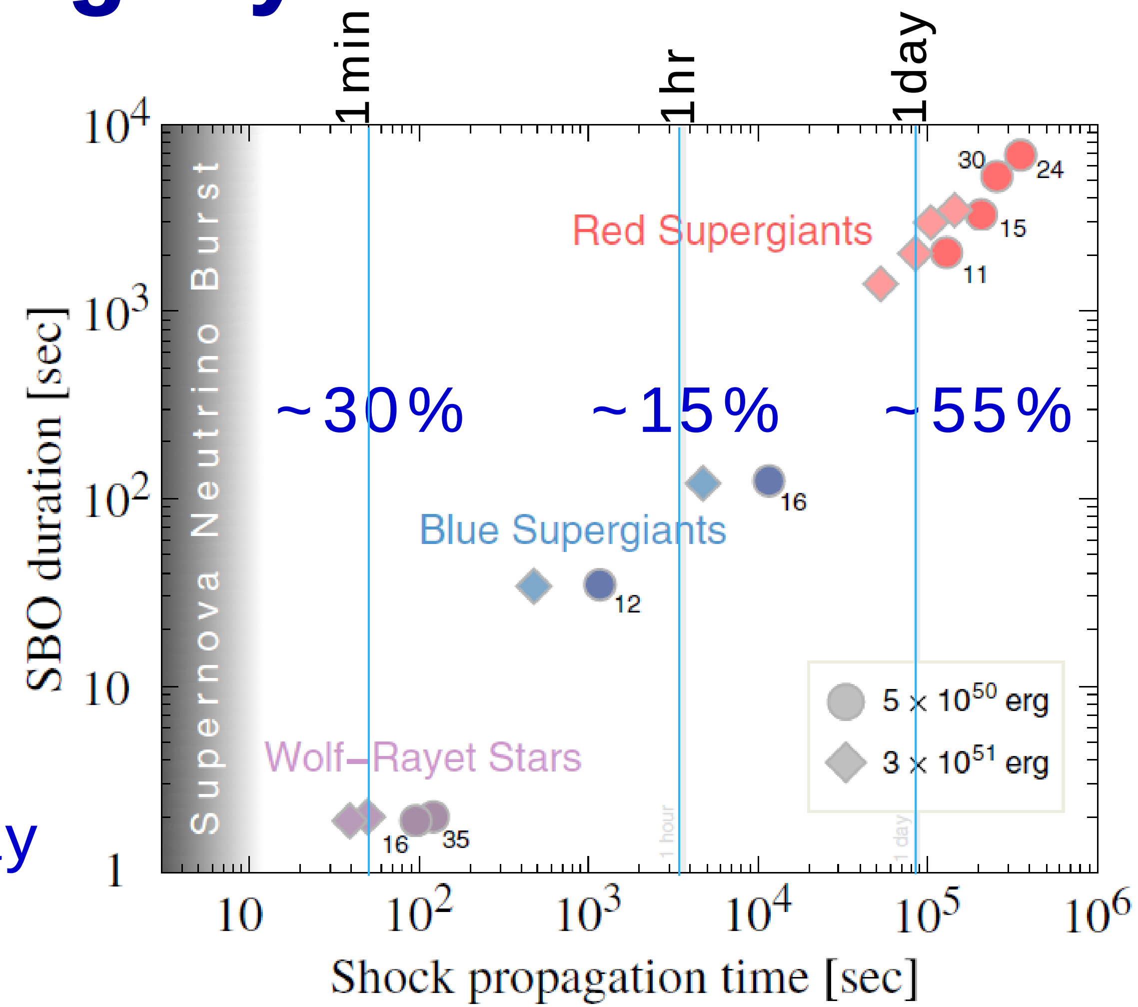
$\Delta T \sim R/v \sim$ 1-10min

M. Tanaka
@30 years from SN1987A

The ratio of each category



I. Shivvers et al., 2017 PASP



M Kistler et al.,ApJ 778 (2013) 81

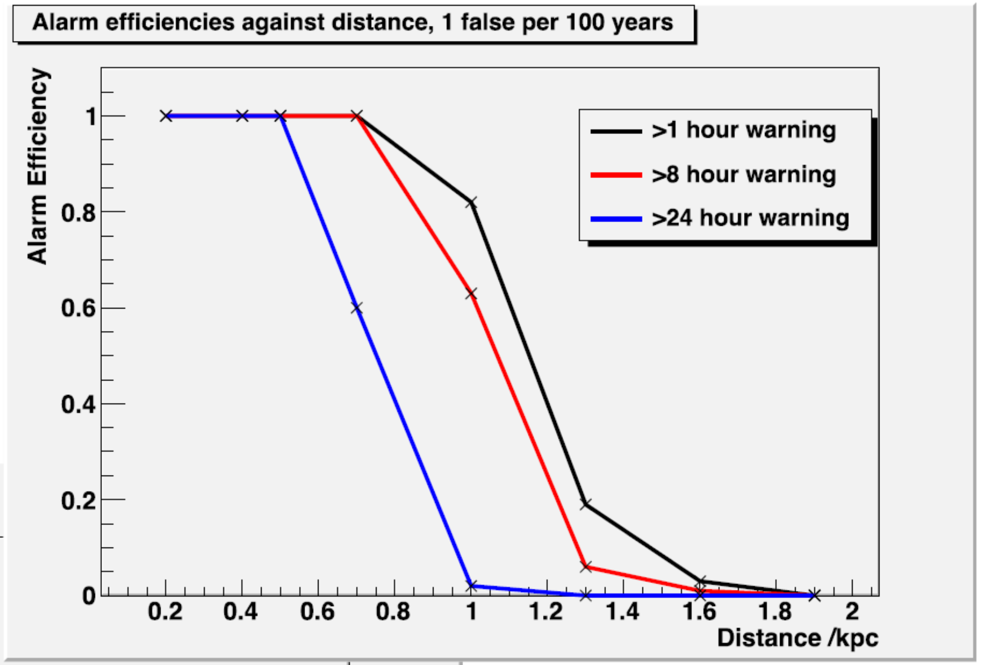
- 1 hour is too late.. quicker warning system needed

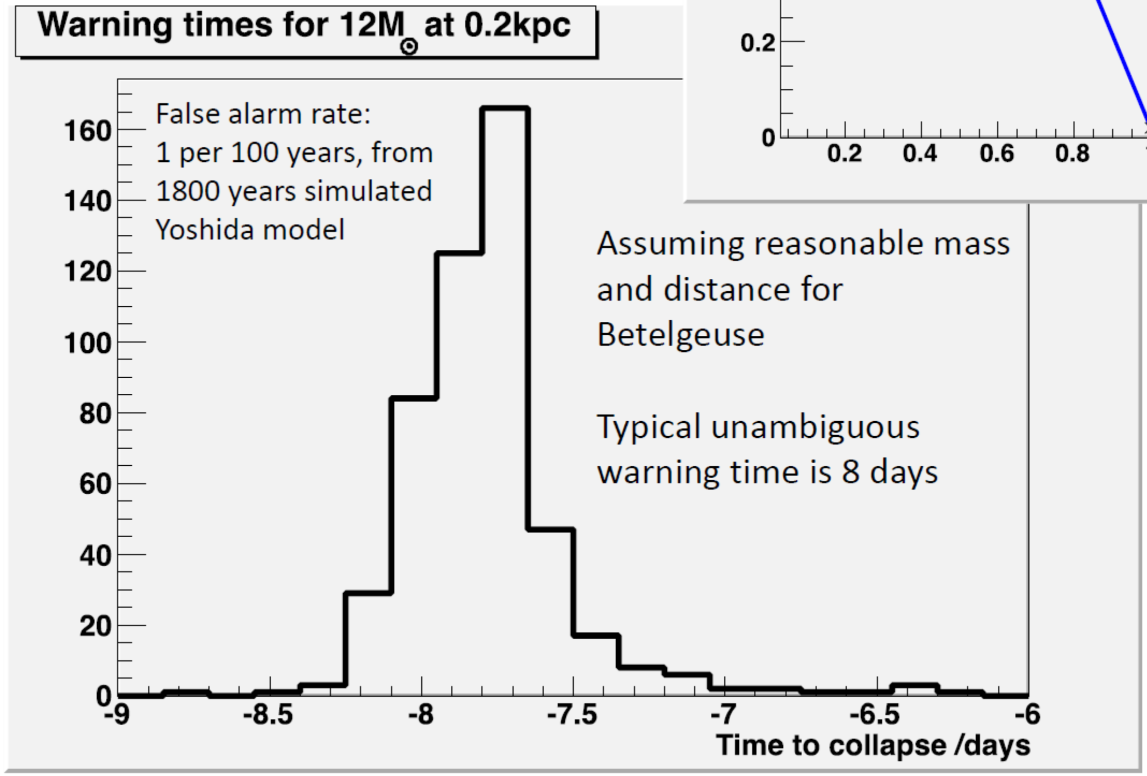
SK-Gd

- Will provide early warnings.

M. Vagins' talk

Gd-loaded
Super-Kamiokande's
Sensitivity to pre-SN ν's
(Super-K internal study)

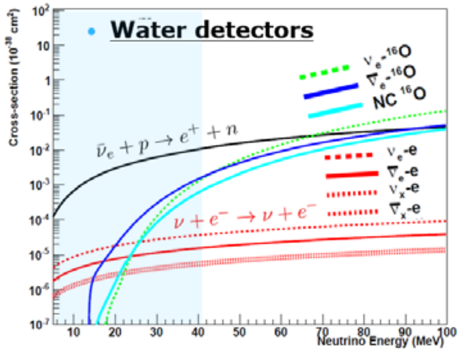


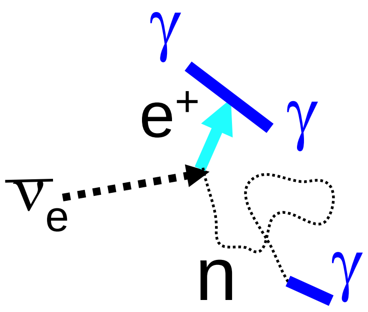


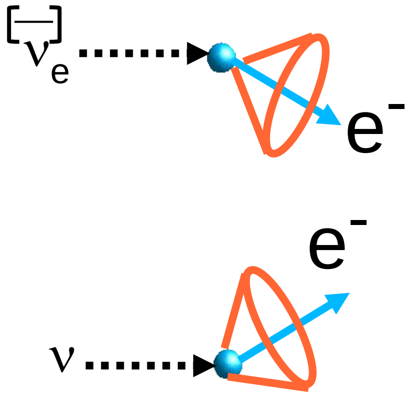
[C. Simpson]

Pointing accuracy

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



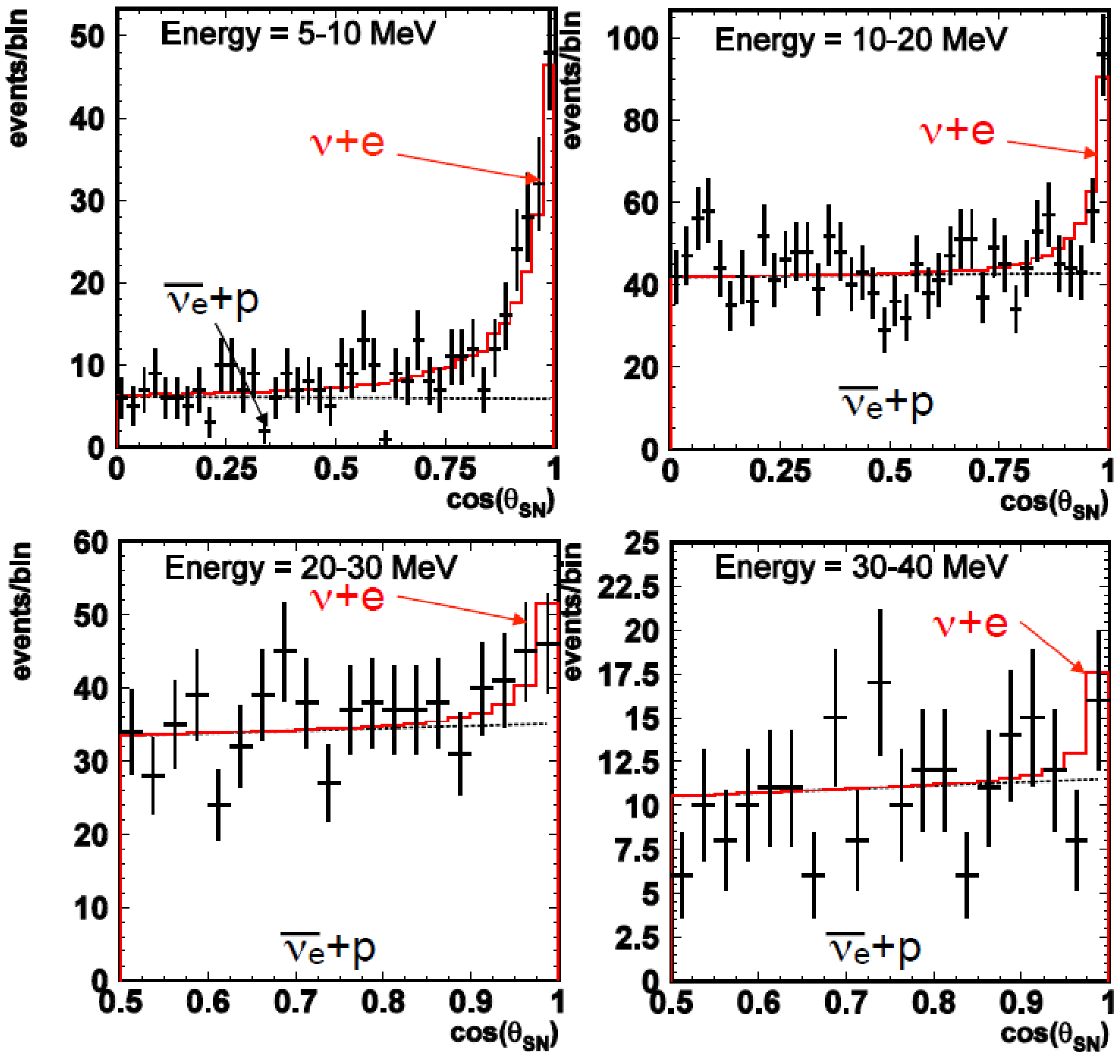




$\bar{\nu}_e p \to e^+ n$	7300
$\nu + e^- \to \nu + e^-$	320
^{16}O CC	110

- BG reduction by neutron tagging
  - → SK-Gd

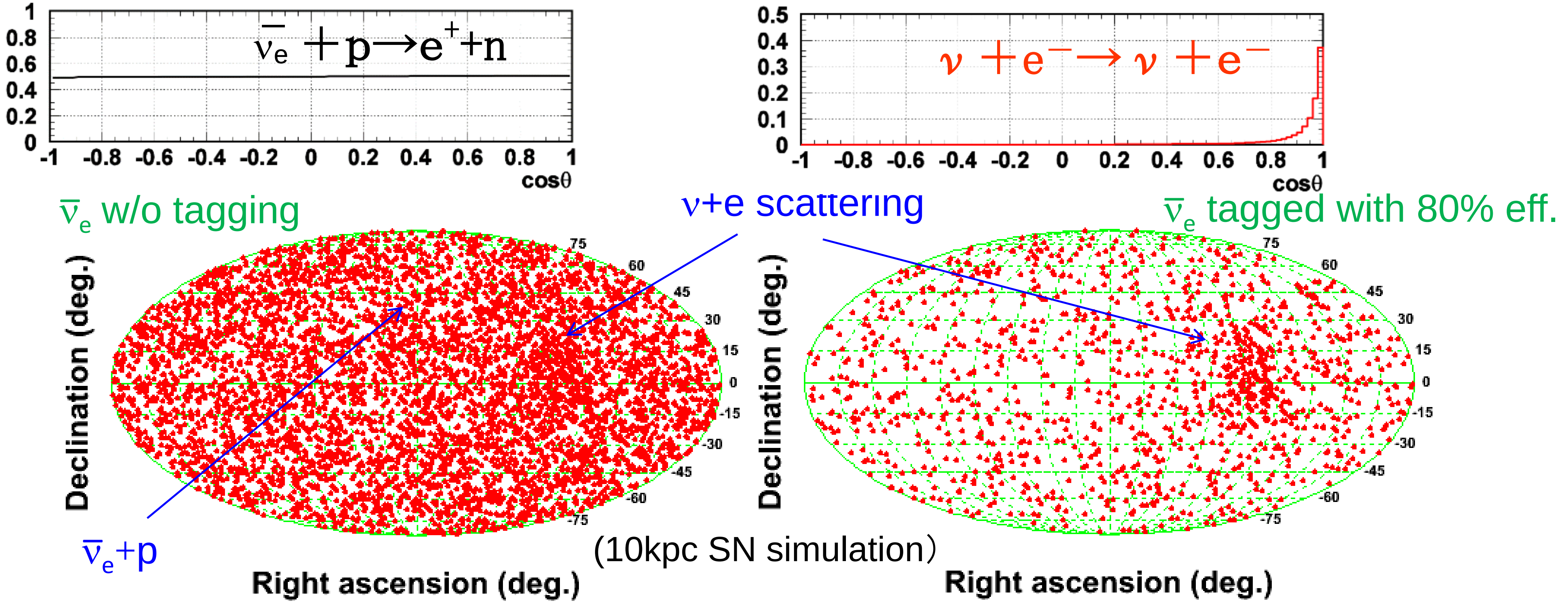
Pointing accuracy ~5° @10kpc SN



SK-Gd pointing accuracy

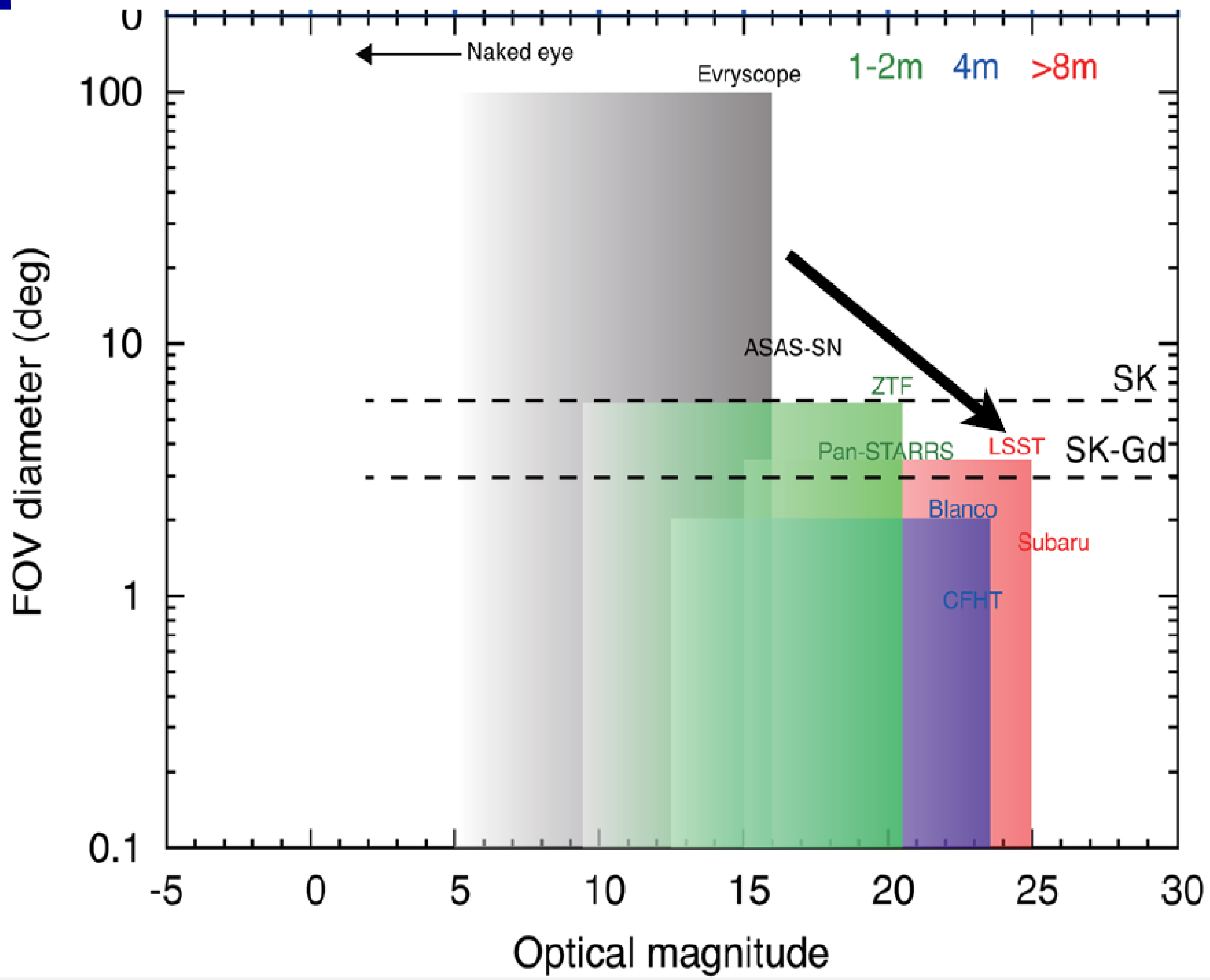
- If $\bar{\nu}_e$ can be tagged, directional events (ν+e scattering events) are enhanced.

  For 10kpc SN ~5° → ~3° (@90%C.L.)



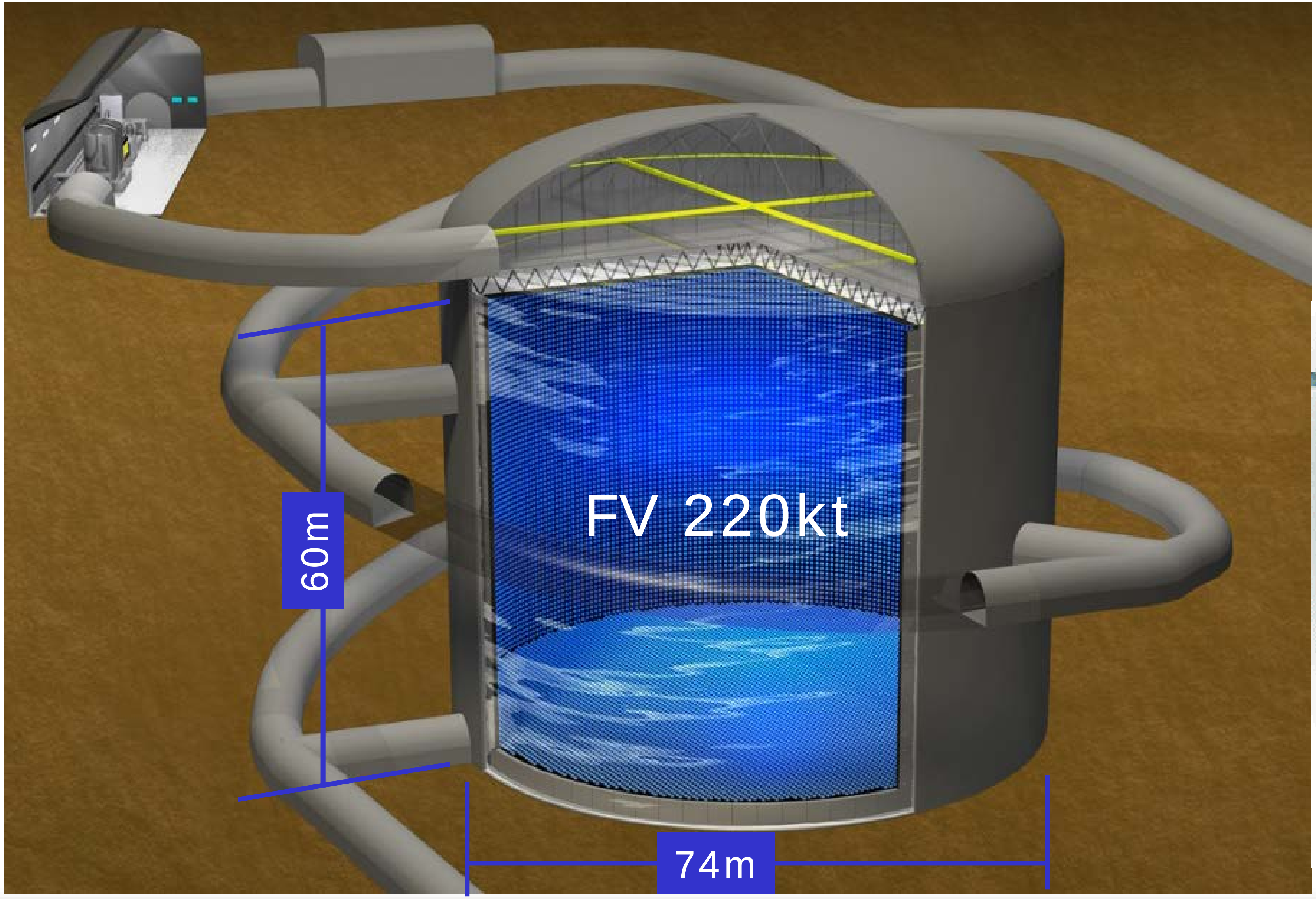
Impact of SK-Gd

- Pointing in 3° accuracy will allow the follow-up with large telescopes

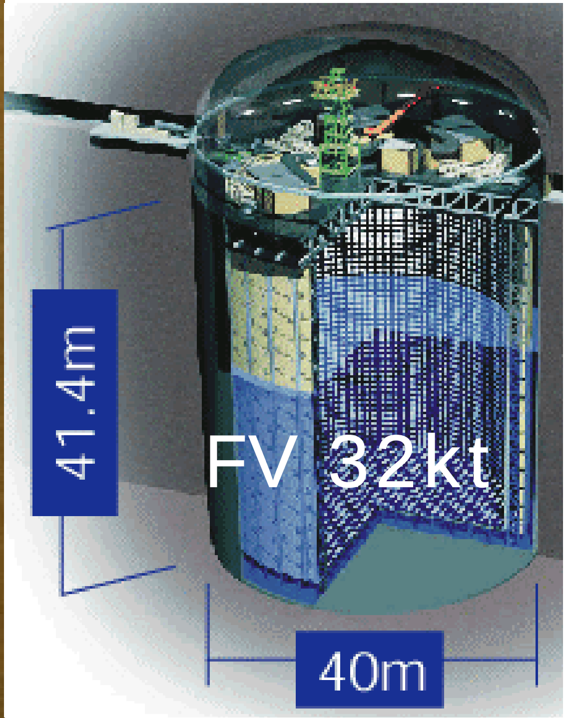


K. Nakamura MNRAS, 461, 3296 (2016)

Hyper Kamiokande

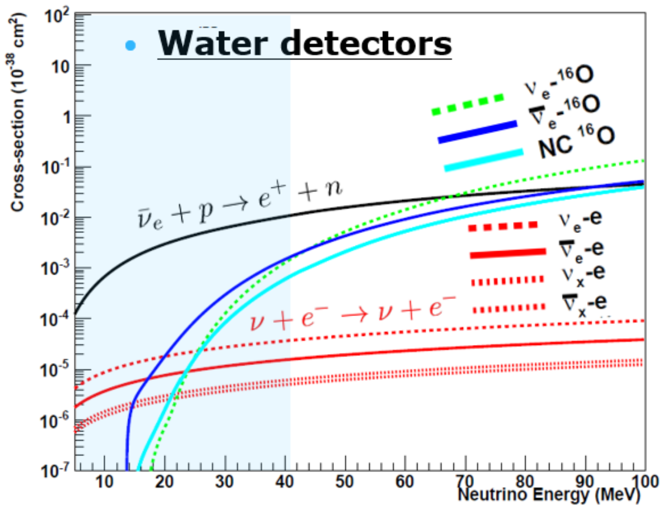


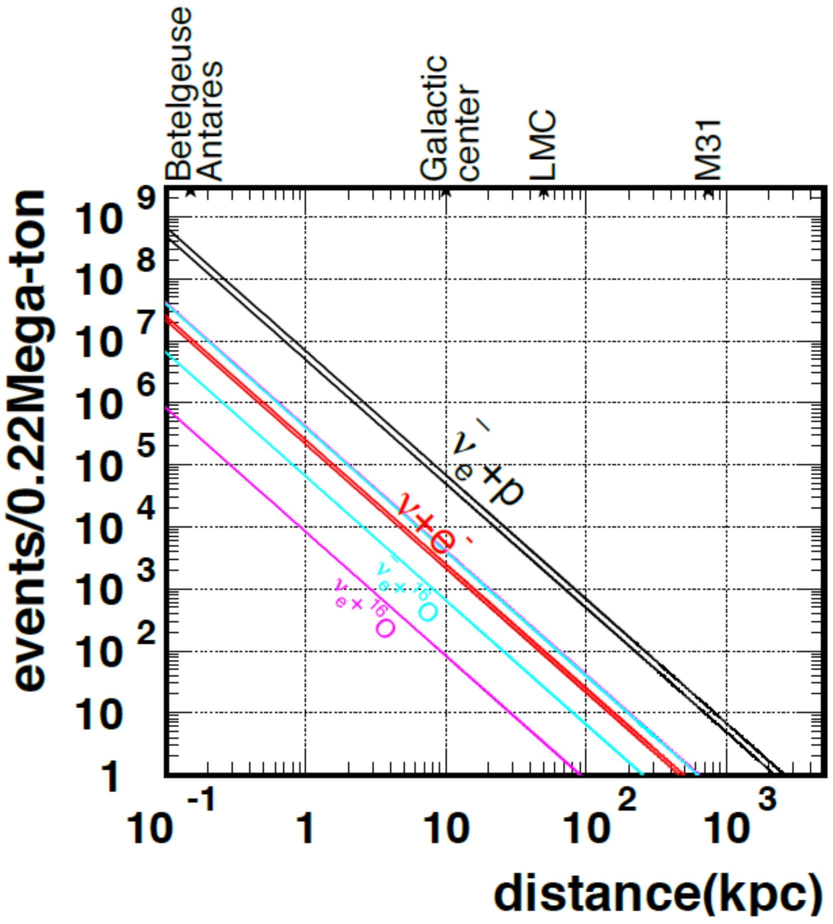
Construction will start at 2020.
Observation will be ready by 2027



Expected events in HK

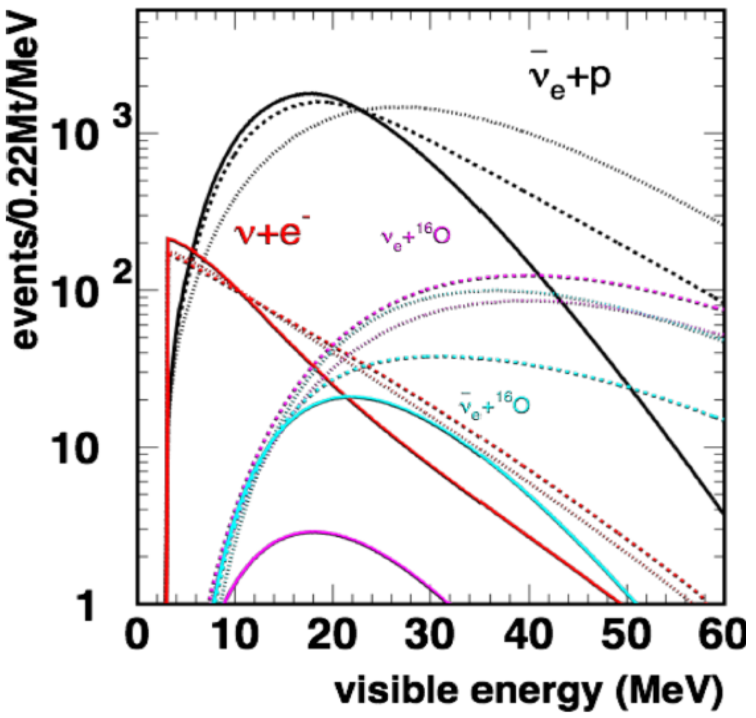
- SK 32kt → HK 220kt
  - Not only inverse beta decay!
- 54000-90000 events are expected for the galactic SN





SN at 10 kpc

Totani1998
Total Energy spectra

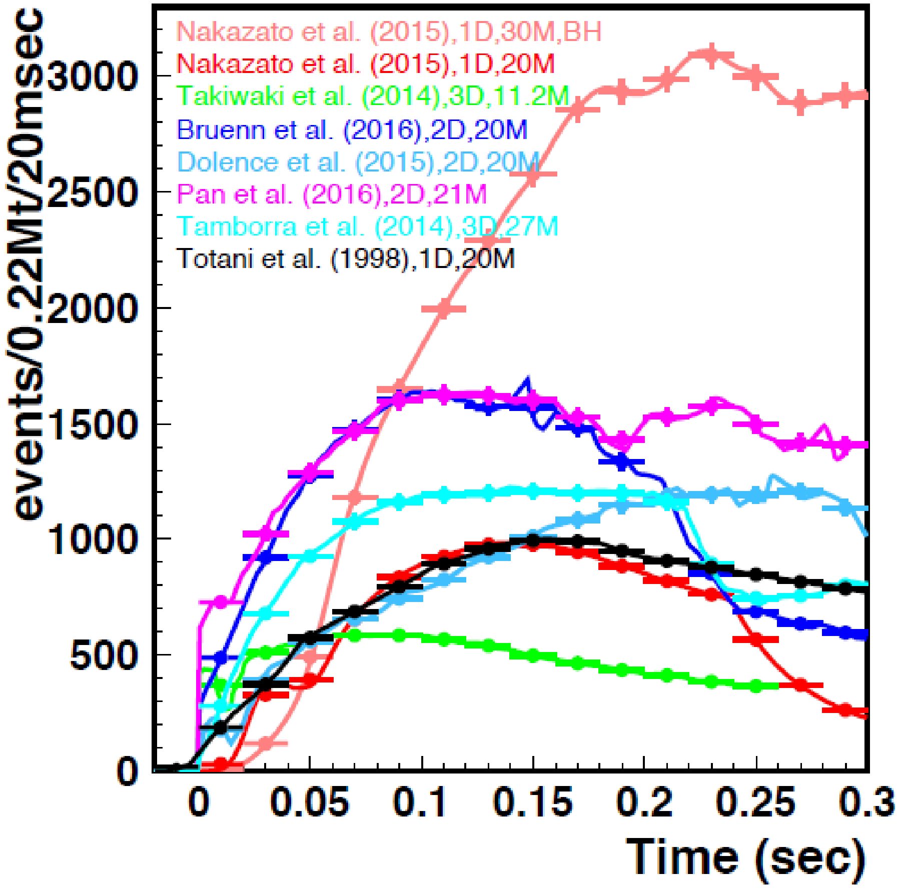


Expected events in HK

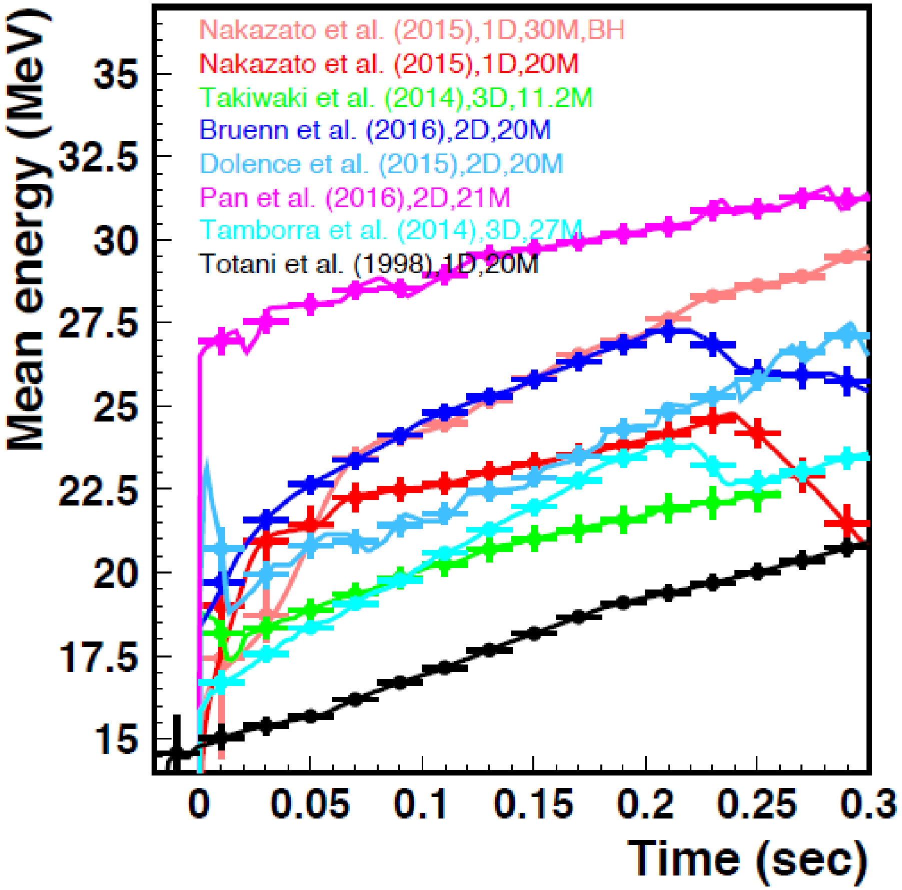
- SK 32kt → HK 220kt
  - Inverse beta decay events

Easier to discriminate models!

Time variation of event rate



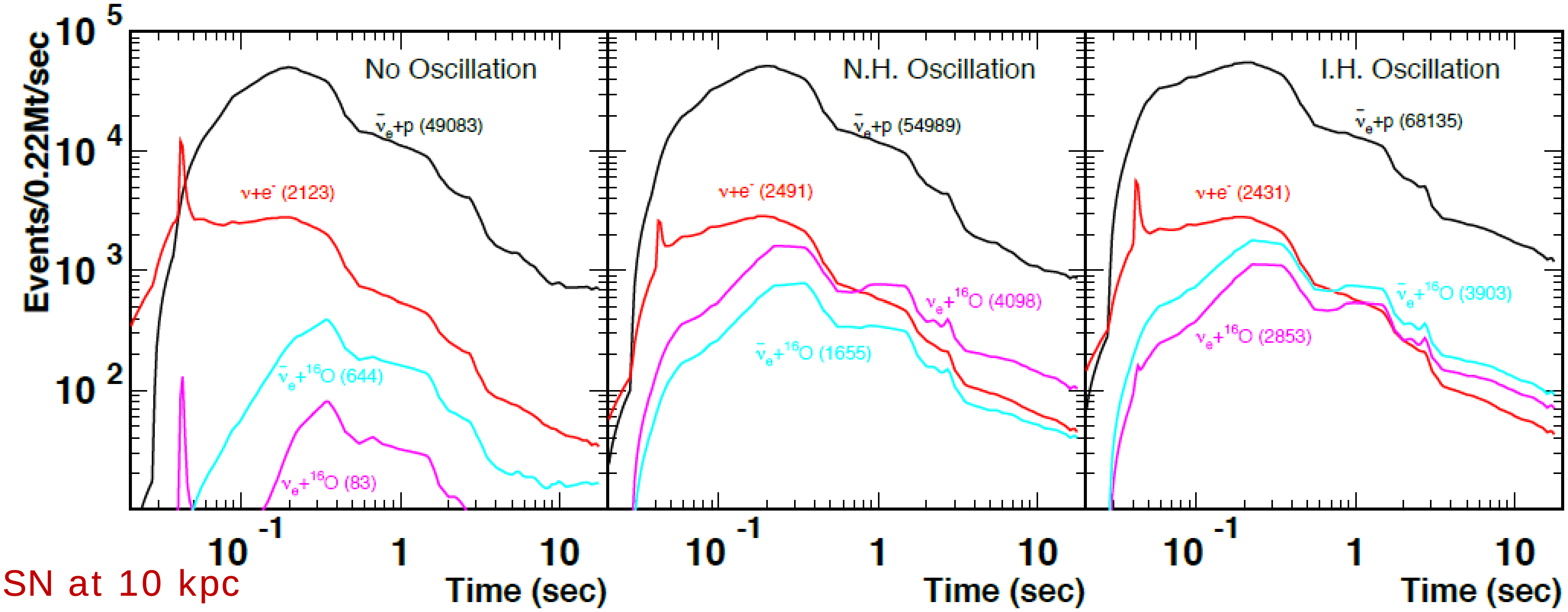
Time variation of mean energy



SN at 10 kpc

Non trivial Neutrino Oscillation!

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



SN at 10 kpc

Totani1998

Even though, Power of the statistics

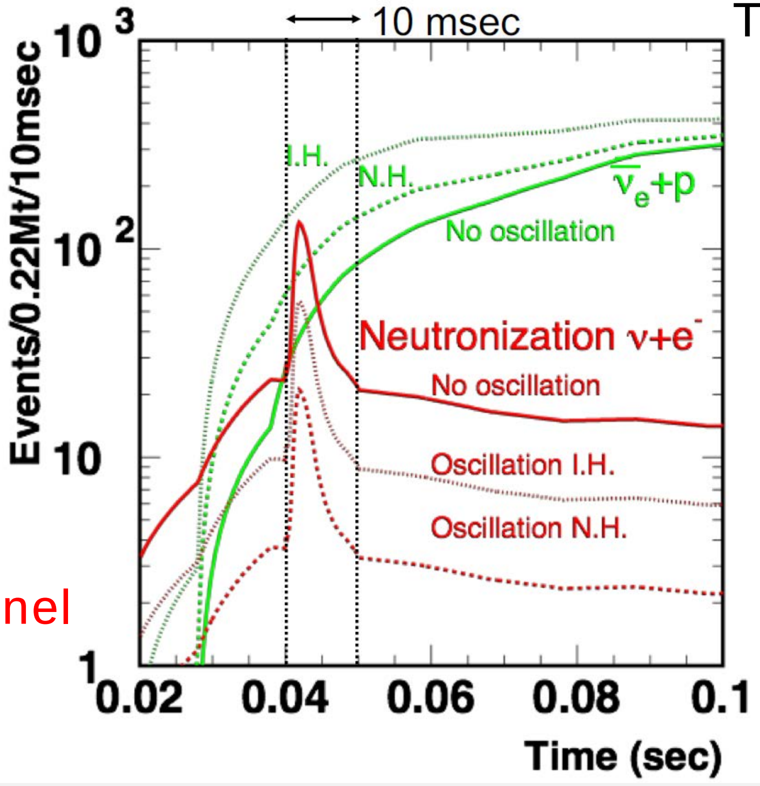
- Direct observation of key features of SN mechanism

Neutronization burst

When shockwave pass through the neutrino sphere

SN at 10 kpc

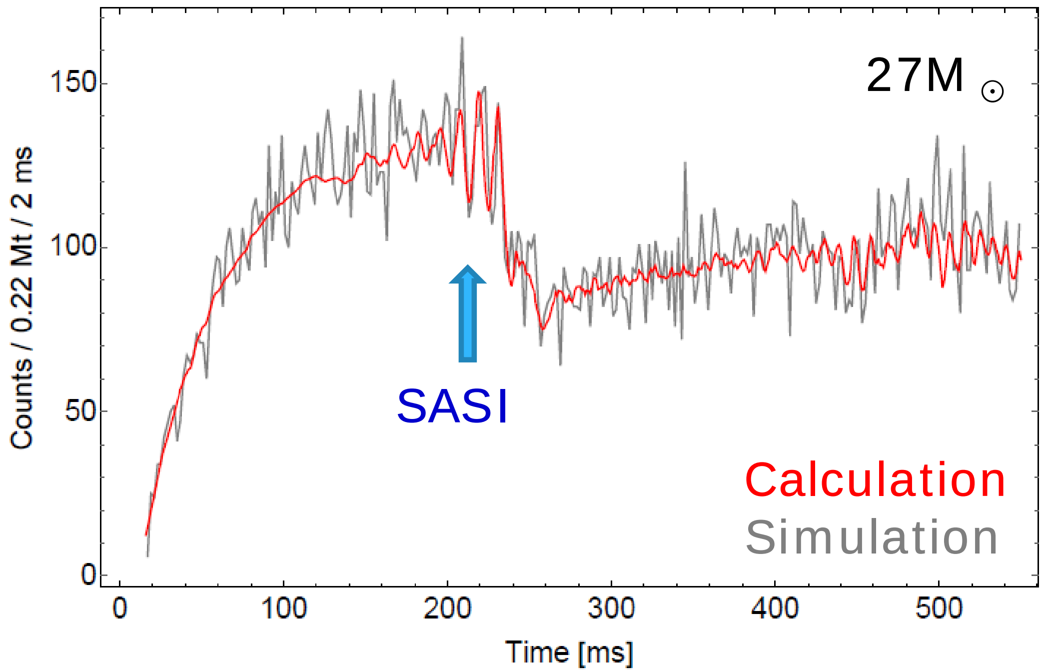
Totani2018



ES channel

SASI? Convection?

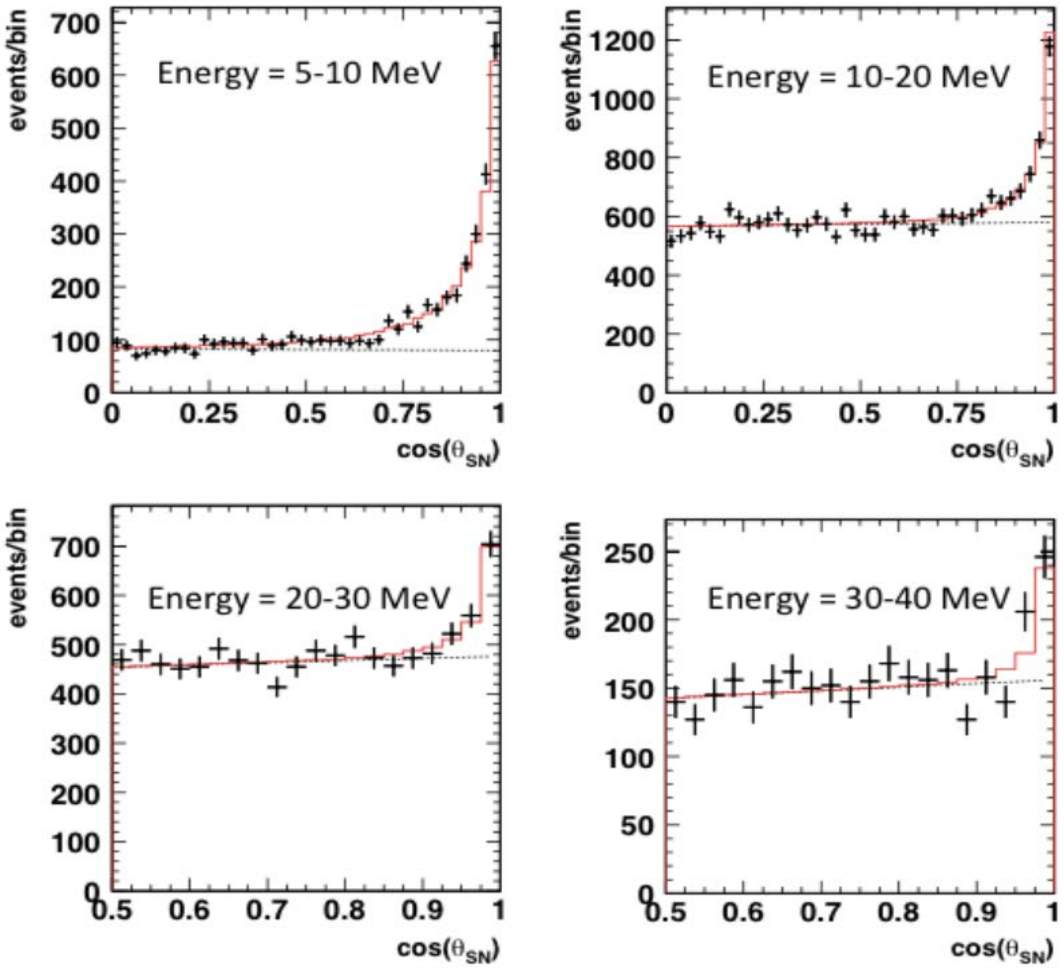
Shock revival by neutrino heating?
Key phenomenon of the burst!

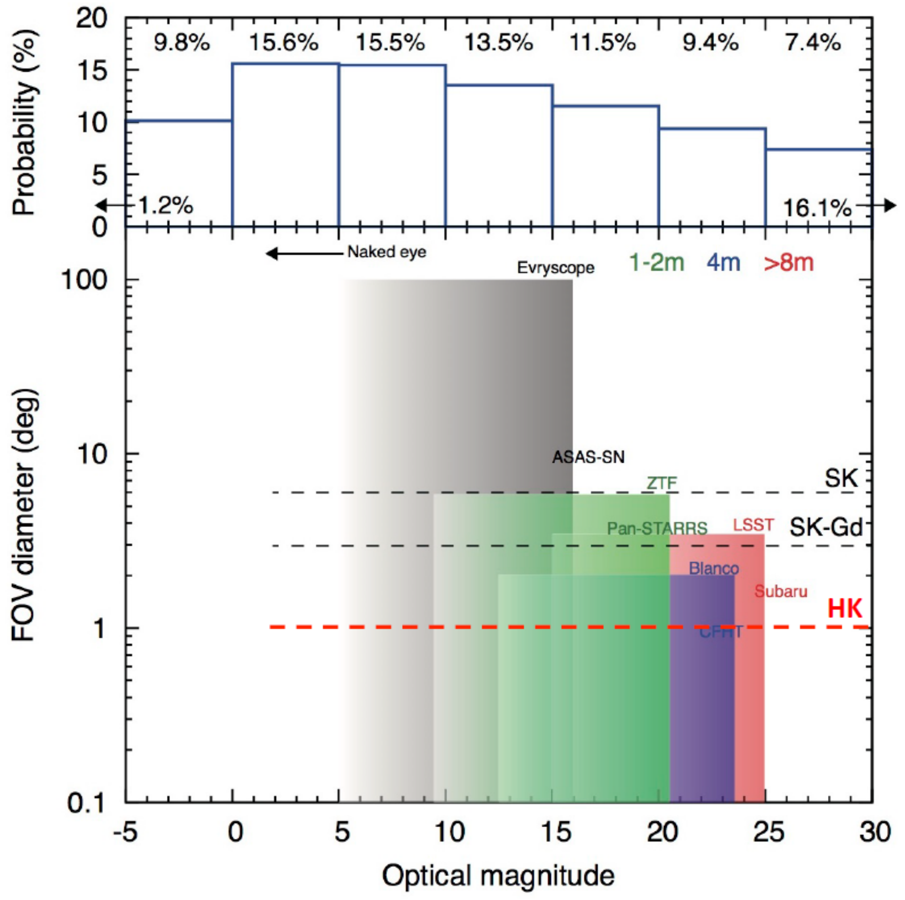


Pointing accuracy of HK

- Further help for Multi-messenger observation

Livermore 10kpc





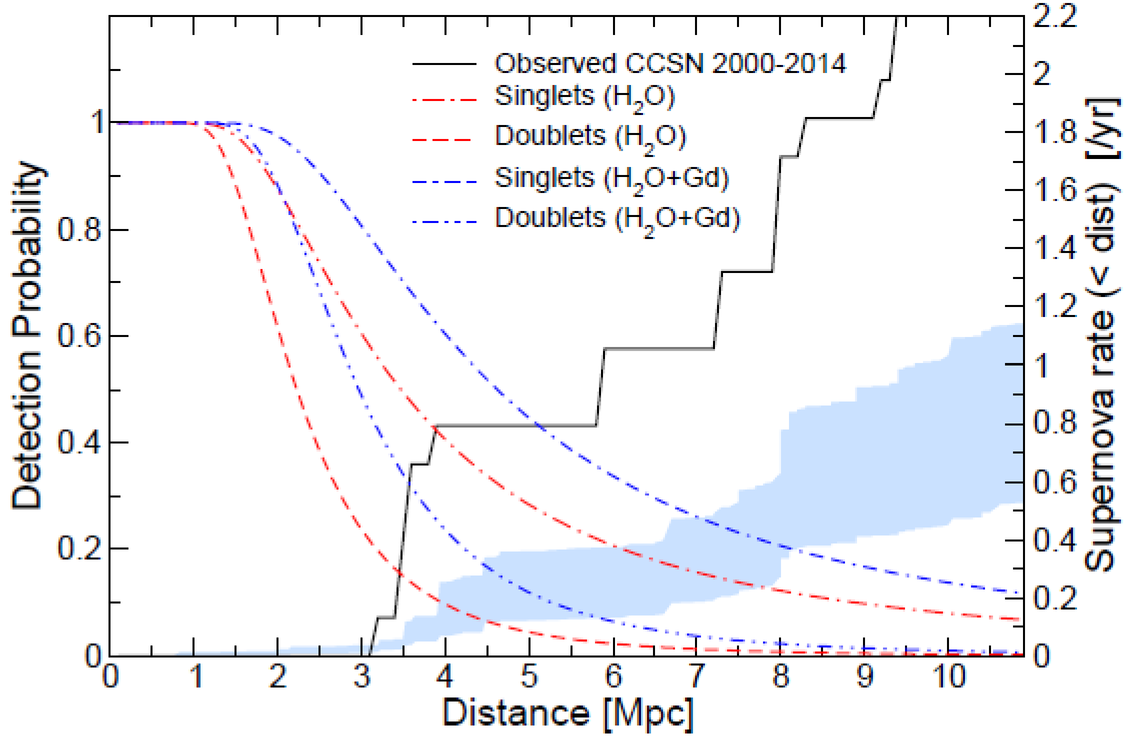
1～2° @10kpc SN

SN detection probability of HK

- Doublet(N=2)

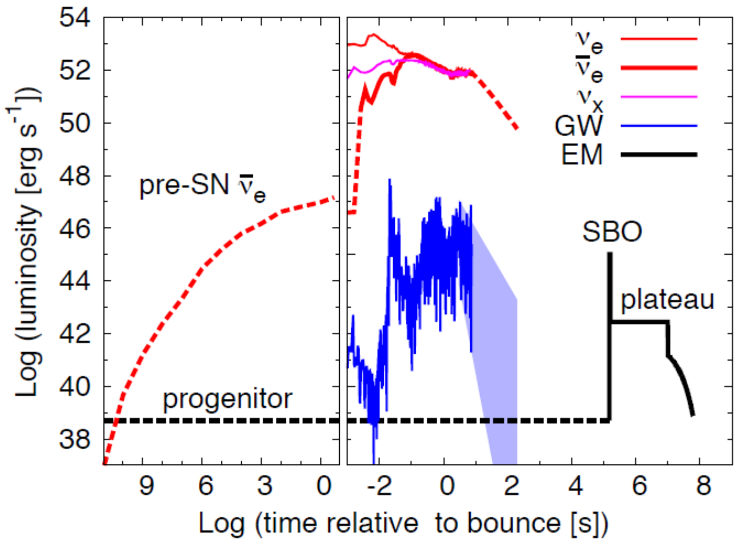
  0.8x0.1x20years$_{x0.22/0.56}$=0.7 (<4Mpc)

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



K. Nakamura MNRAS, 461, 3296 (2016)

- GW(+EM) coincidence enables singlet(N=1) events
  - 0.8x0.4$_{x0.22/0.56}$=0.17/year (<4Mpc)



The Astrophysical Journal Letters, 830:L11 (6pp), 2016 October 10
doi:10.3847/2041-8205/830/1/L11

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 2.4×10^4 to 7.0×10^9 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.