Detection of supernova neutrinos at Super-Kamiokande

M. Nakahata

Kamioka Observatory, ICRR,
Kavli IPMU, Univ. of Tokyo

The sixth Astrophysical Multimessenger Observatory Network(AMON) Workshop
May 22, 2019

Core-collapse supernova

Scenario of the core-collapse supernova

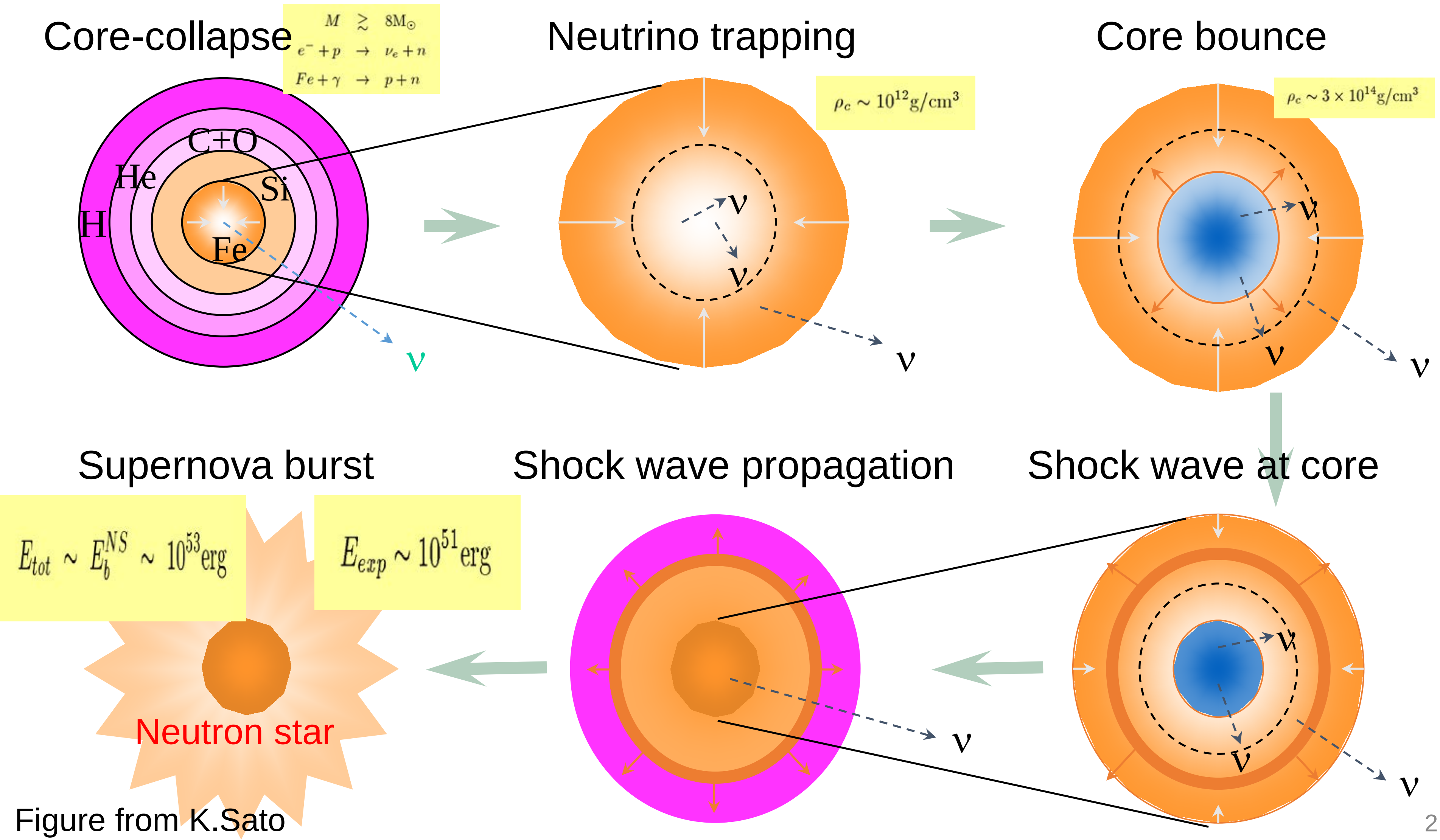


Figure from K.Sato

Expected neutrinos from core-collapse supernova

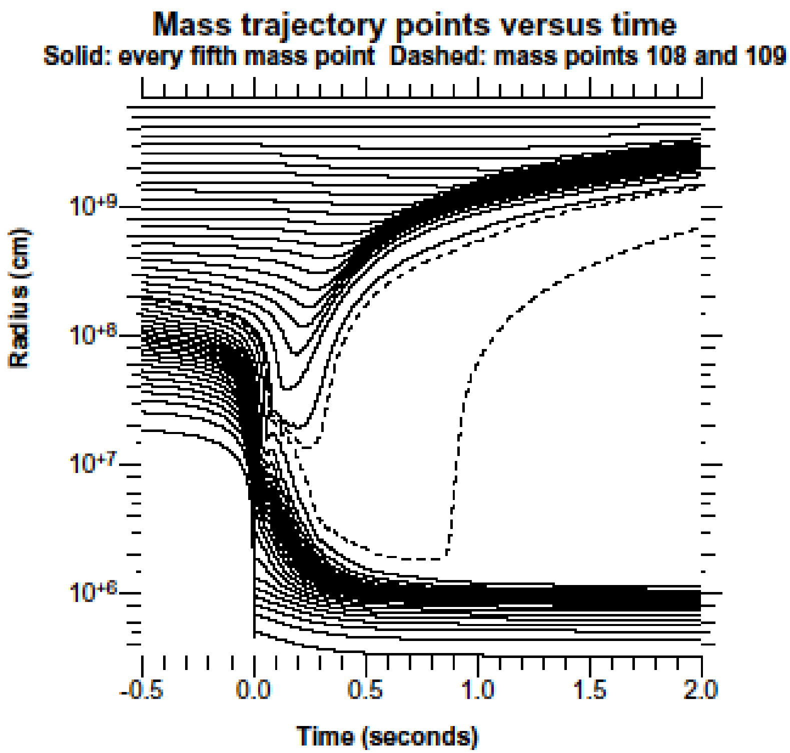
Released total energy: ~3x10^{53} erg (E_{tot})

Neutrinos carry out 99% of the energy

Burst kinetic energy: ~10^{51} erg（1% of E_{tot})

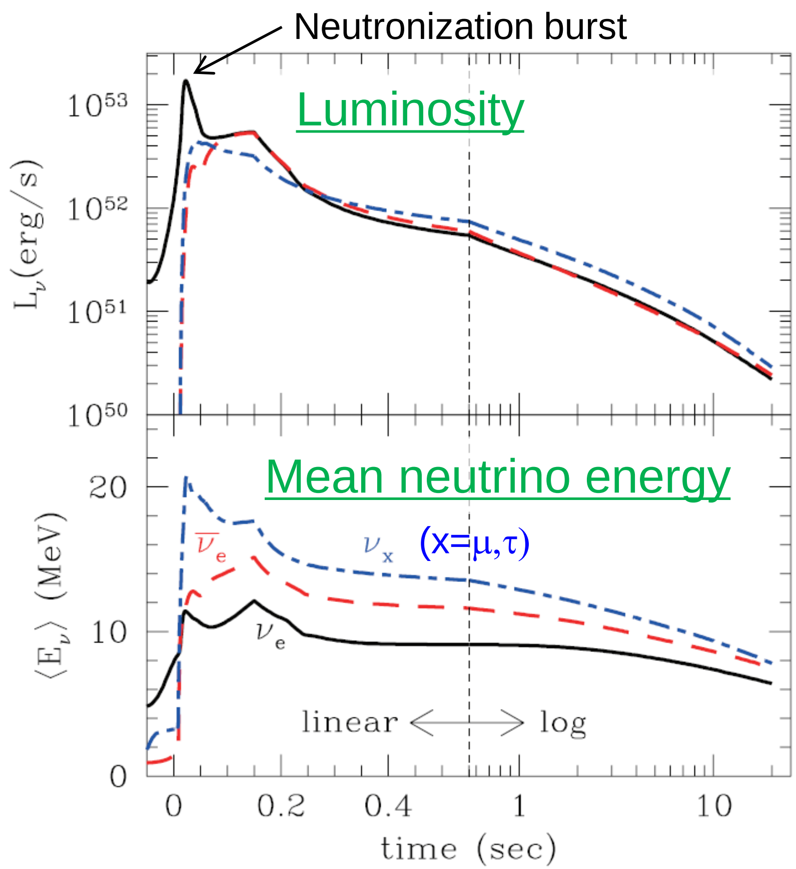
Optical energy: ~10^{49} erg（0.01% of E_{tot})

Iron core → neutron star / black hole



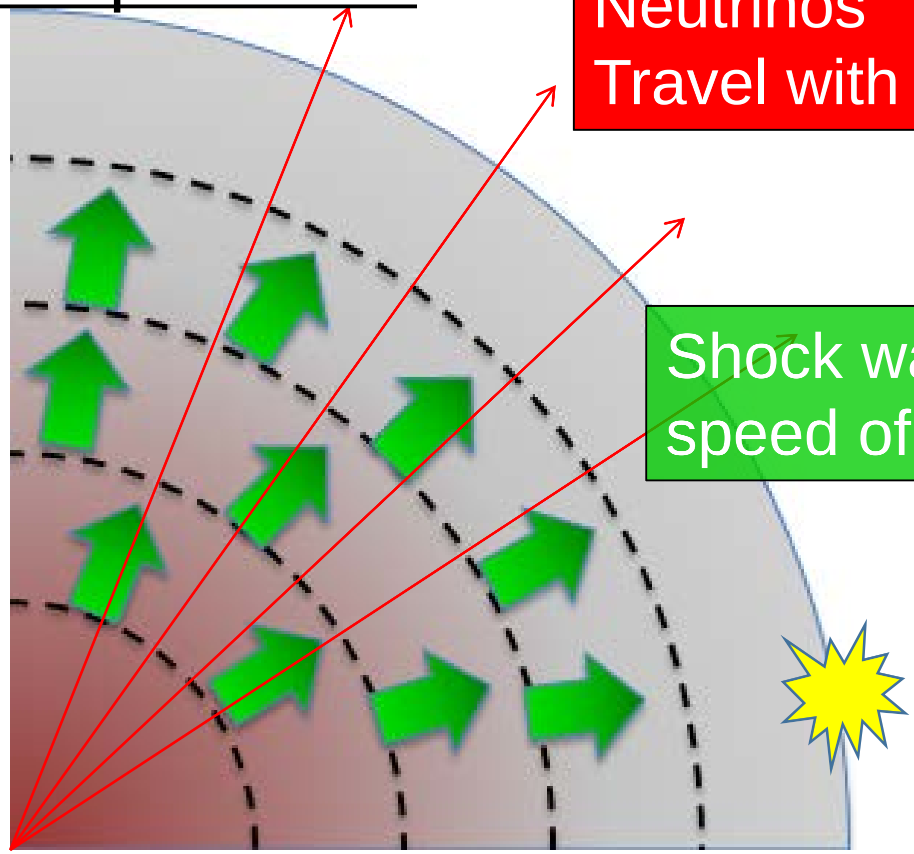
T.Totani et al., ApJ.496,216(1998)

Neutrino emission is
~ several seconds



S. Nakazato et al., APJ supp.205:2(2013)

Neutrino and optical signals in supernova



Neutrinos
Travel with speed of light (3×10^5 km/sec)

Shock wave travels with ~1/30 of speed of light (~10^4 km/sec).

Optical signals are produced when the shock wave arrives at surface.

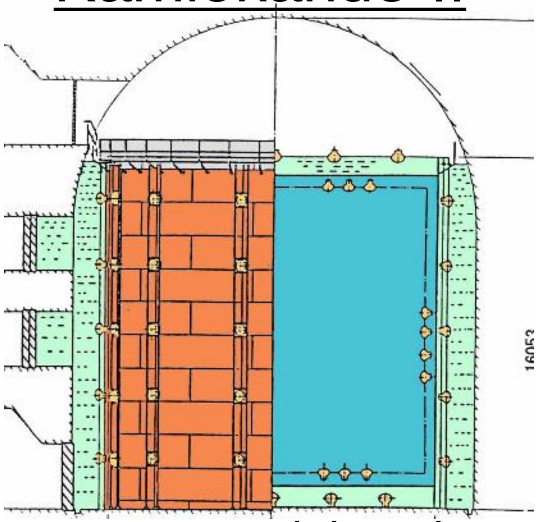
So, neutrinos arrive earlier than optical signals.

Type II: a few hours - several tens of hours earlier

Type Ib/Ic: several minutes earlier

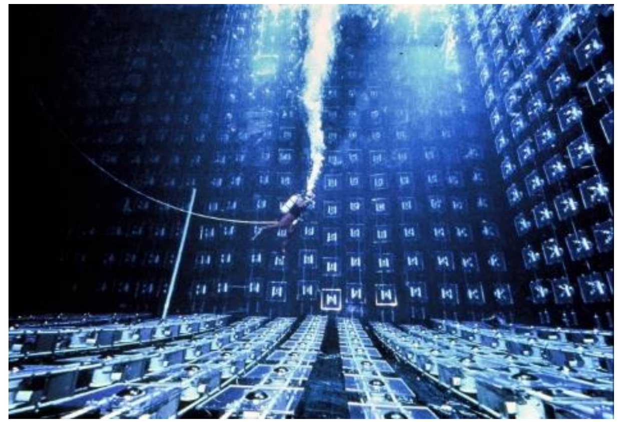
SN1987A: supernova at LMC(50kpc)

Kamiokande-II



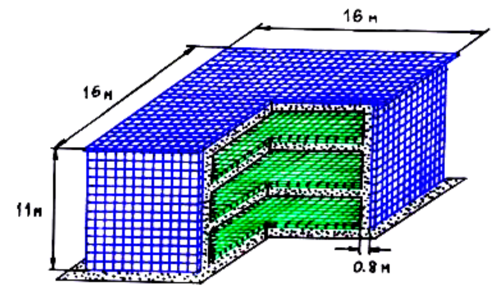
Japan Kamioka mine
2140ton fiducial
Water Cherenkov

IMB-3



USA Ohio state Morton mine
~5000ton Fiducial
Water Charenkov

BAKSAN



Russia Baksan tunnel
330ton in 3150tanks
Liquid scintillator

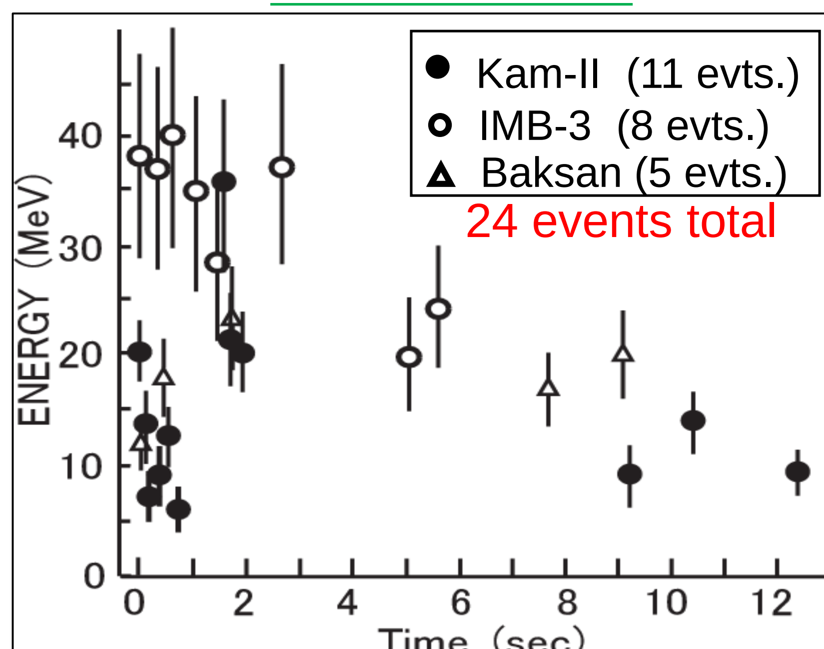
Although the observed number of events was only 24 in total, energy released by $\bar{\nu}_e$ was measured to be ~5x10^{52} erg.

It is consistent with core-collapse scenario.

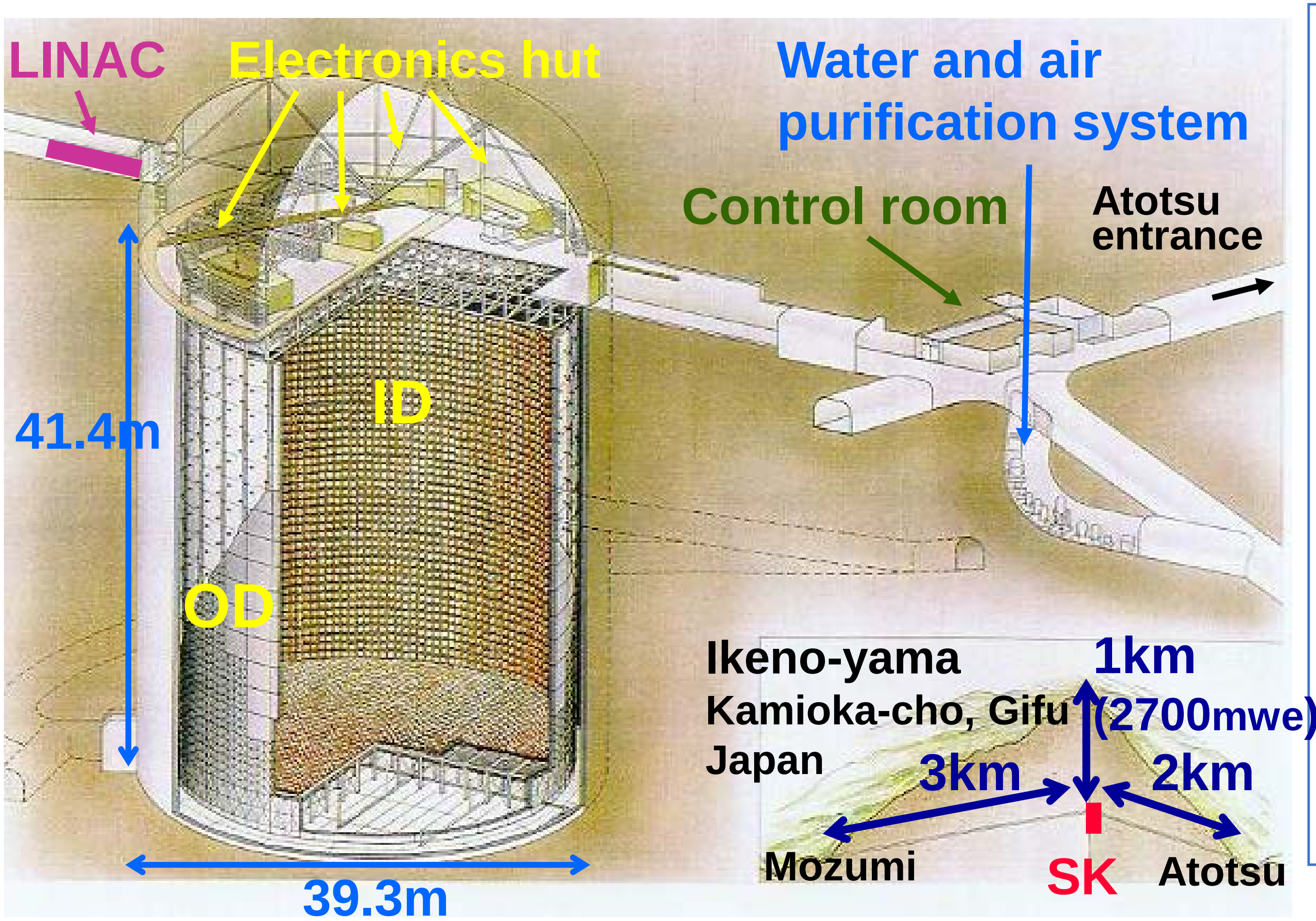
But, no detailed information of burst process was obtained because of the low statistics.

We need next supernova with large number of neutrino events.

Observed events



Super-Kamiokande detector



- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-V is running

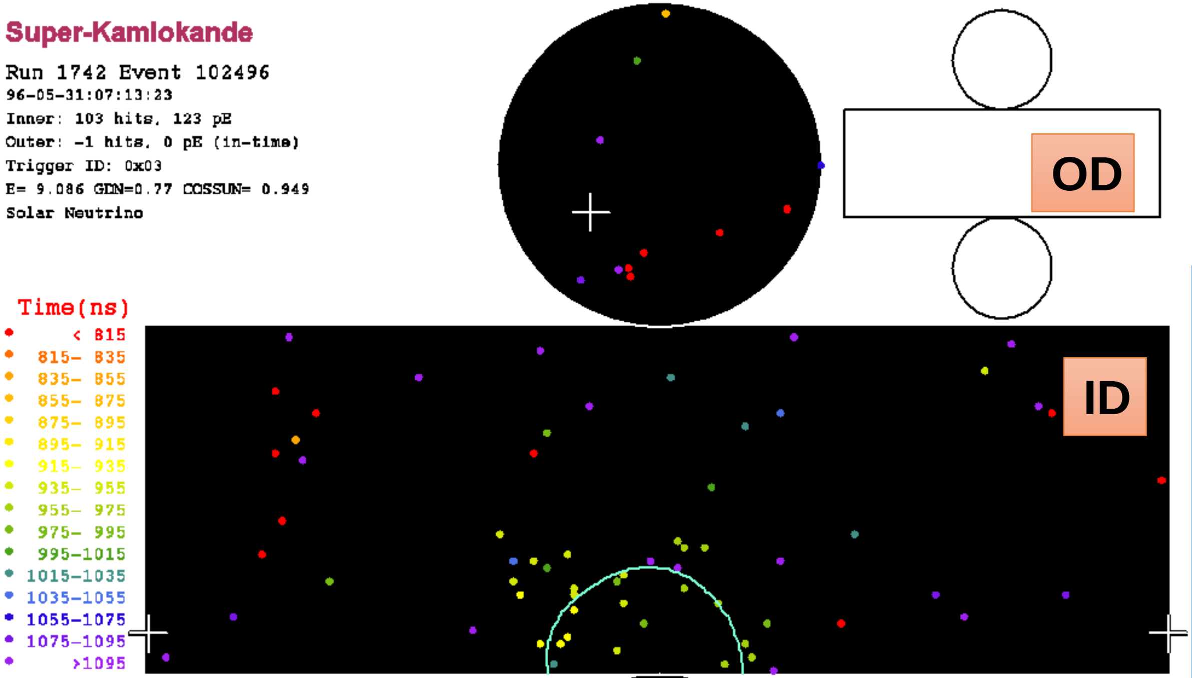
Inner Detector (ID) PMT: ~11,000 20-inch PMTs
Outer Detector (OD) PMT: 1885 8-inch PMTs

The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
Imperial College London, UK
INFN Bari, Italy
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
The University of Winnipeg, Canada
Yokohama National University, Japan

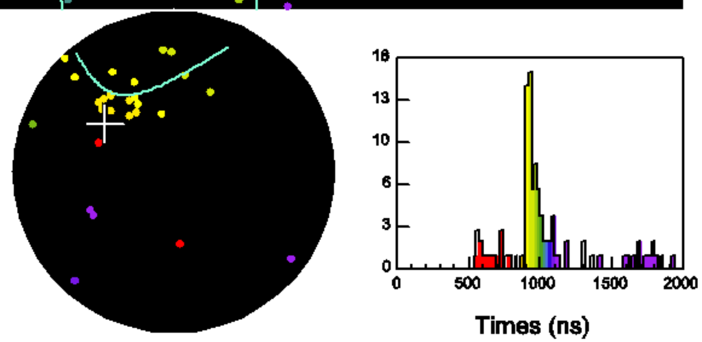
~175 collaborators from 44 institutes in10 countries

Typical low-energy event



(color: time)

$E_{e,total}$ = 9.1 MeV



Electron/positron

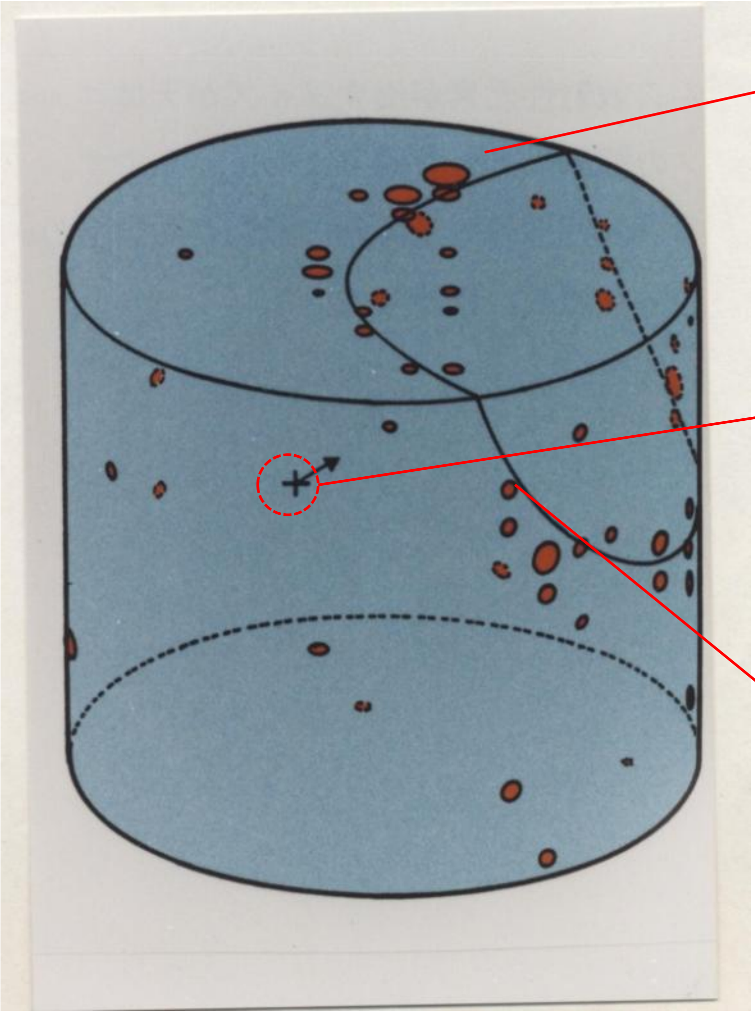
- Timing information
  ➡ vertex position
- Ring pattern
  ➡ direction
- Number of hit PMTs
  ➡ energy

~6 hit / MeV

Resolutions (for 10 MeV electrons)

Energy: 14% Vertex: 55cm Direction: 23°

Event reconstruction in water Cherenkov detector



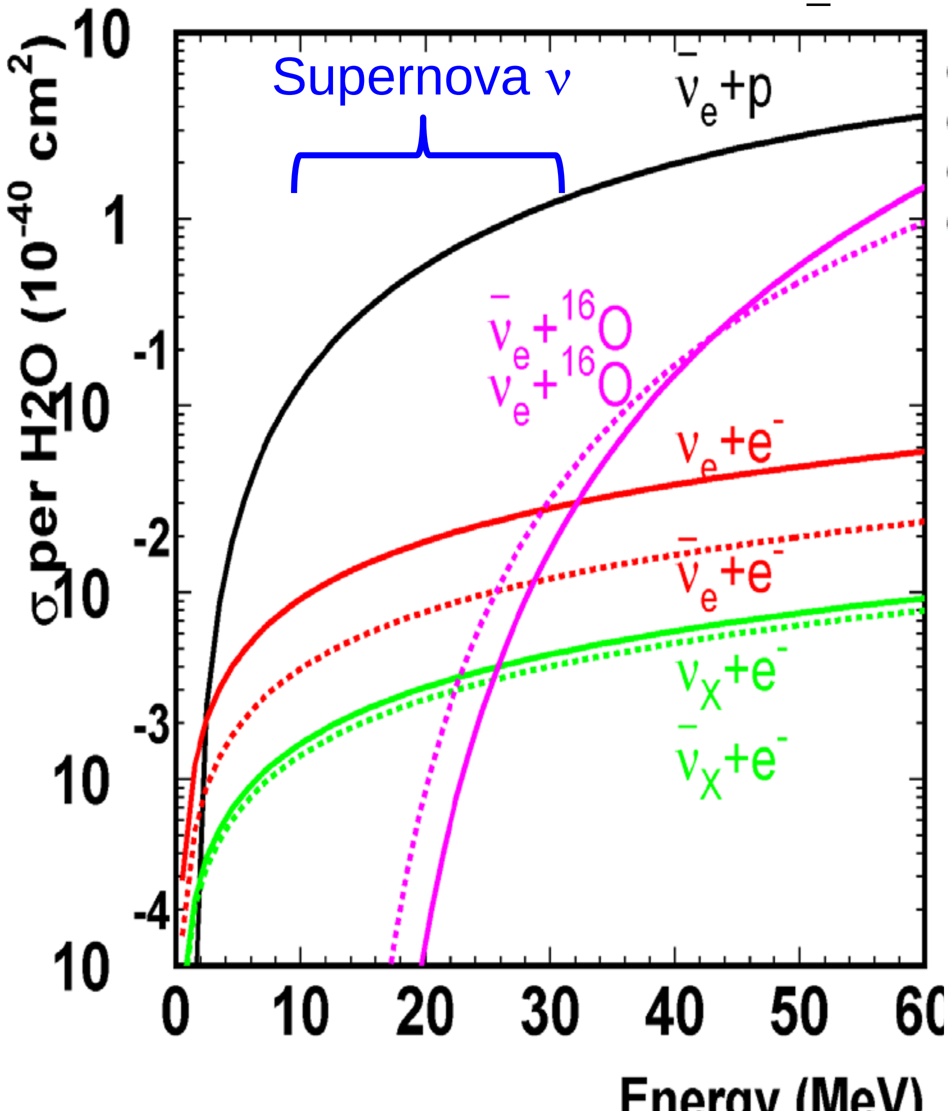
Timing and pulse height of each PMT are recorded.

Reconstruct vertex position (i.e. interaction position) using timing information of PMTs

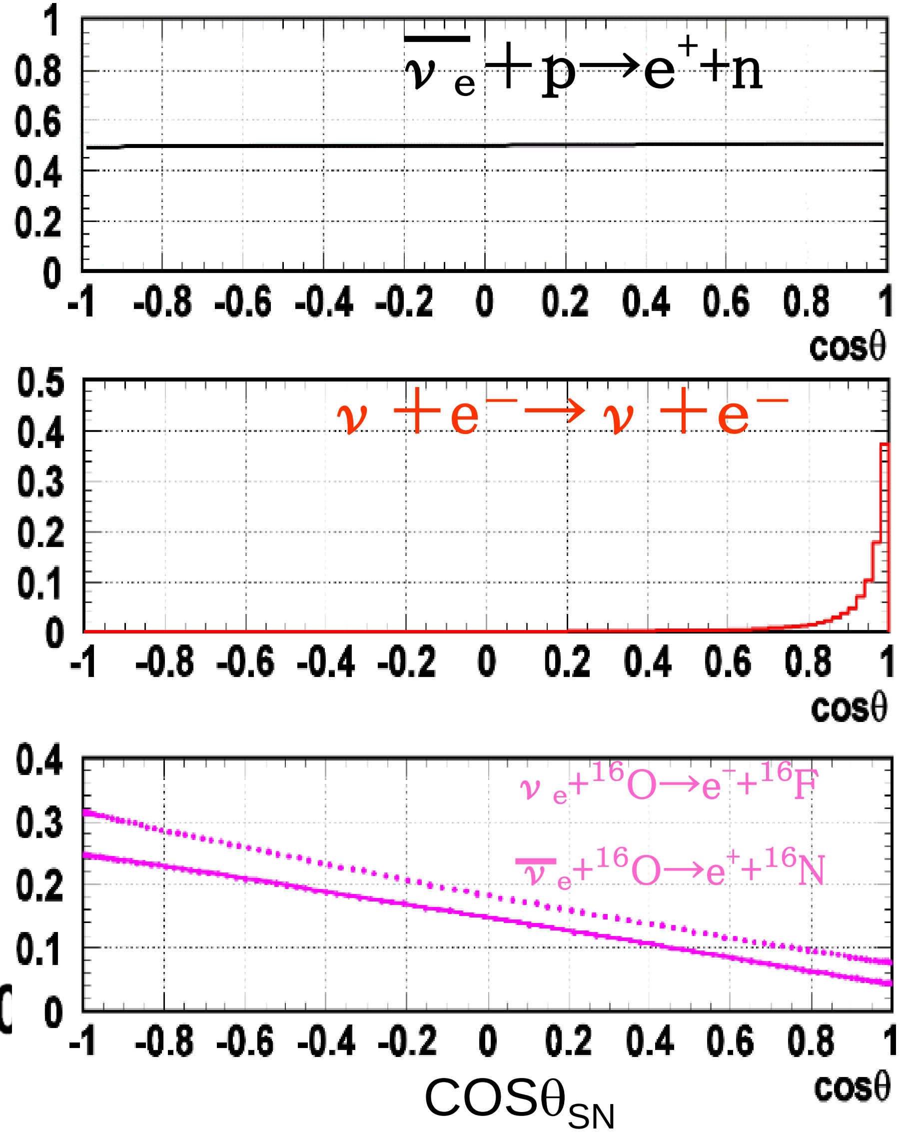
Reconstruct particle direction using the Chrenkov pattern (ring pattern with 42 deg. opening angle) .

Neutrino interaction in water

Cross section (for H_2O)

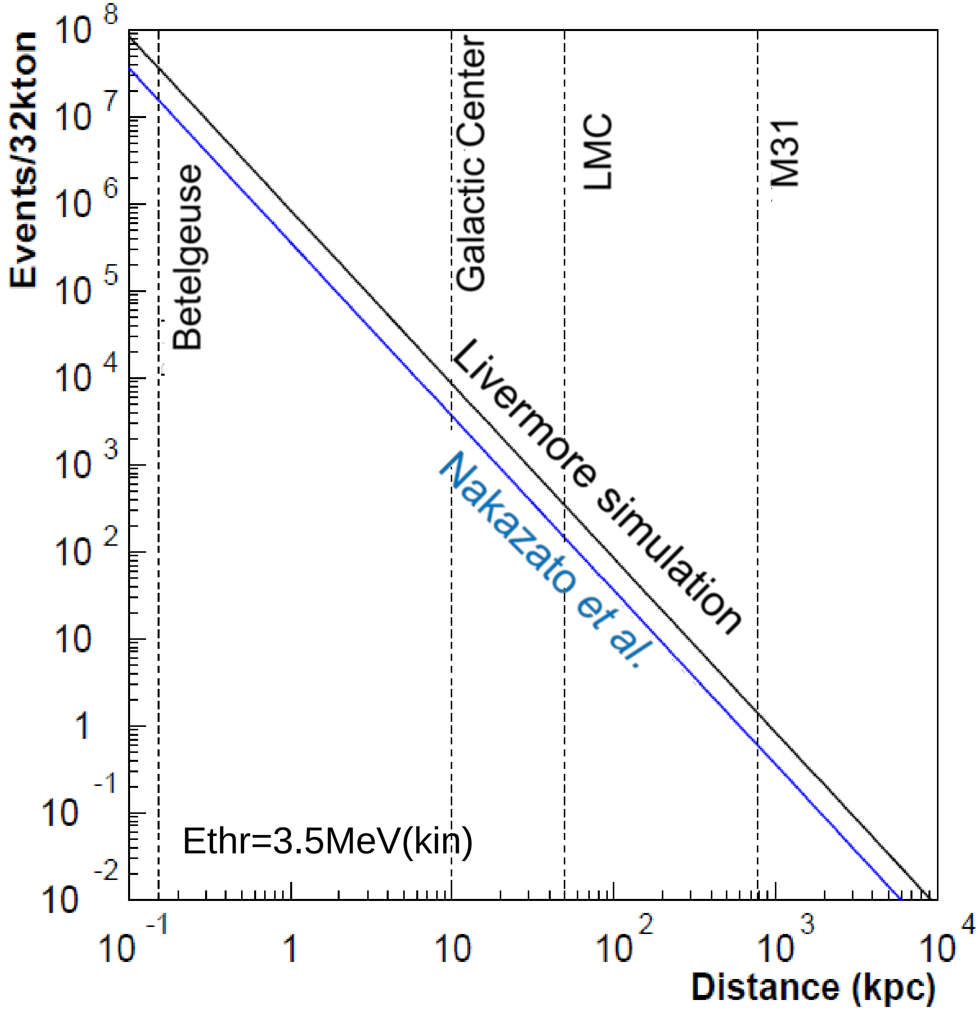


Angular distributions

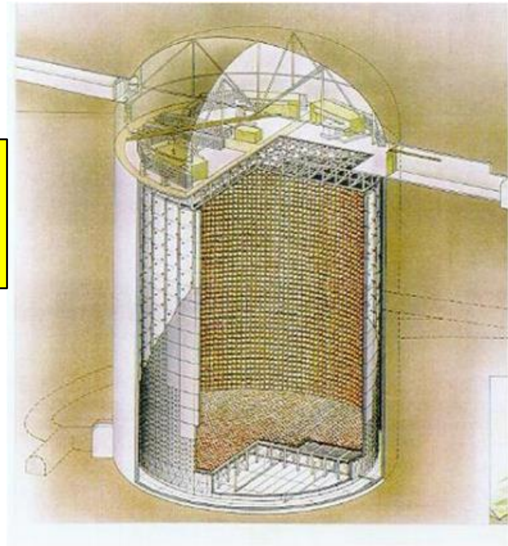


Super-K: Number of events

Number of events vs. distance



32kton water Cherenkov



For each interaction

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

Directional info.

Supernova at 10 kpc
32kton SK volume
4.5MeV(kin) threshold
No oscillation case.

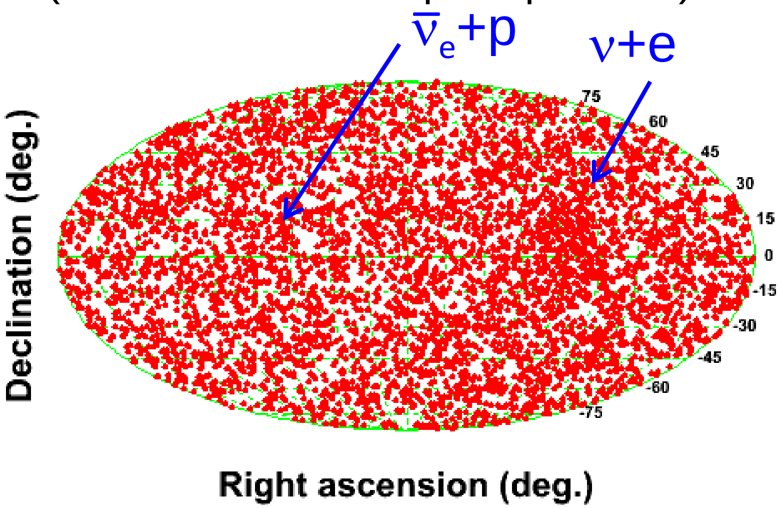
Livermore simulation T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

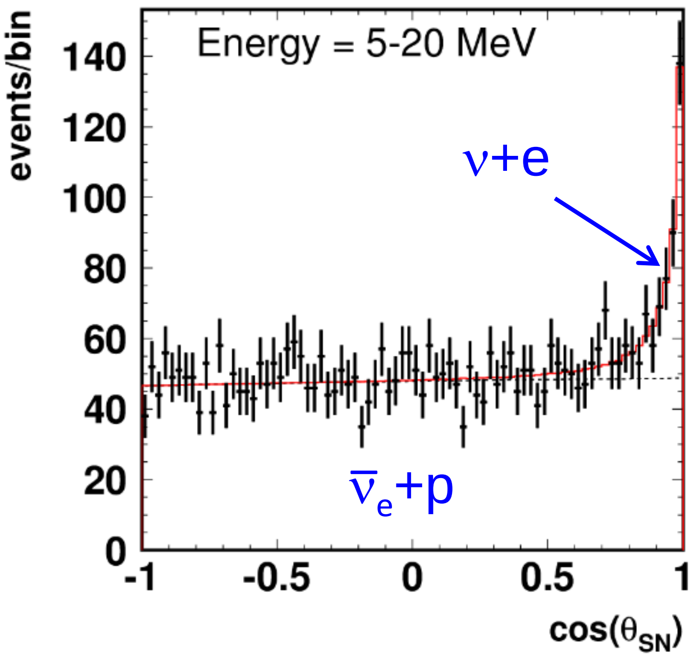
Nakazato et al. K.Nakazato, K.Sumiyoshi, H.Suzuki, T.Totani, H.Umeda, and S.Yamada, ApJ.Suppl. 205 (2013) 2, ($20M_{sun}$, trev=200msec, z=0.02 case)

Super-K: directional information

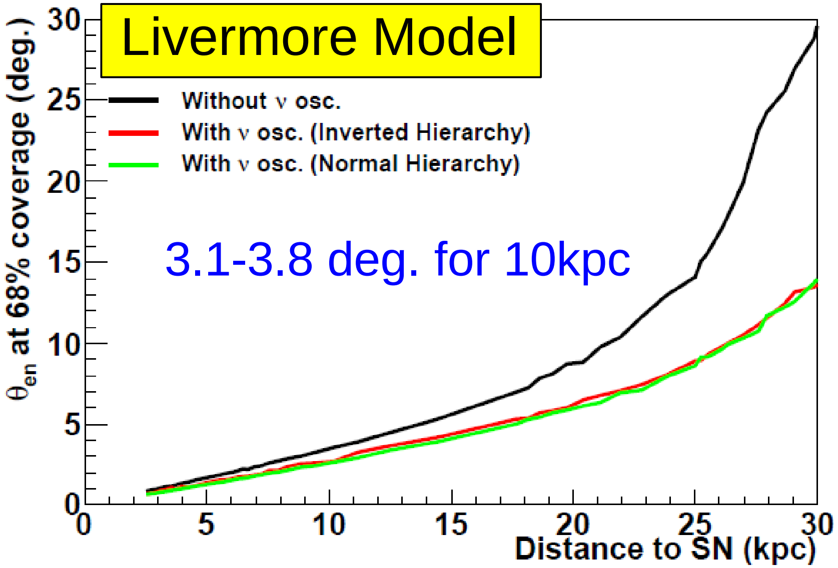
Reconstructed direction

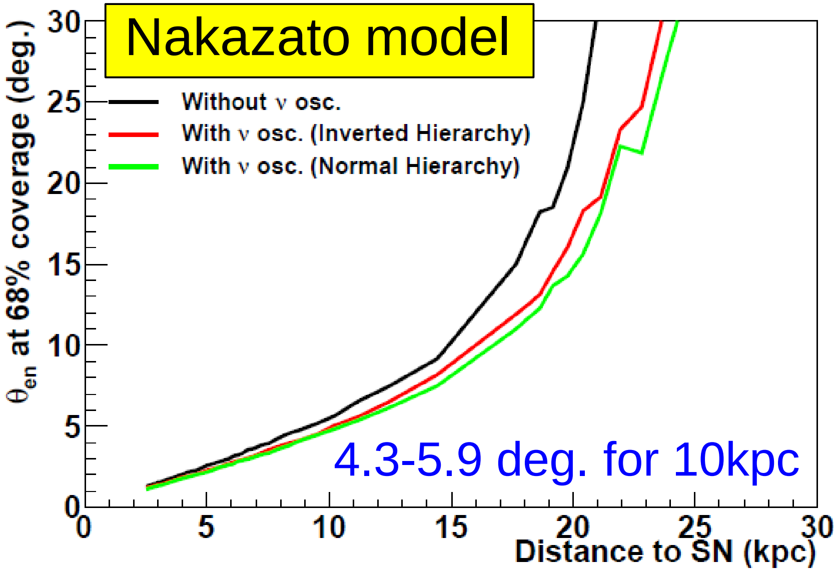
(Simulation of a 10kpc supernova)





Distance vs. pointing accuracy

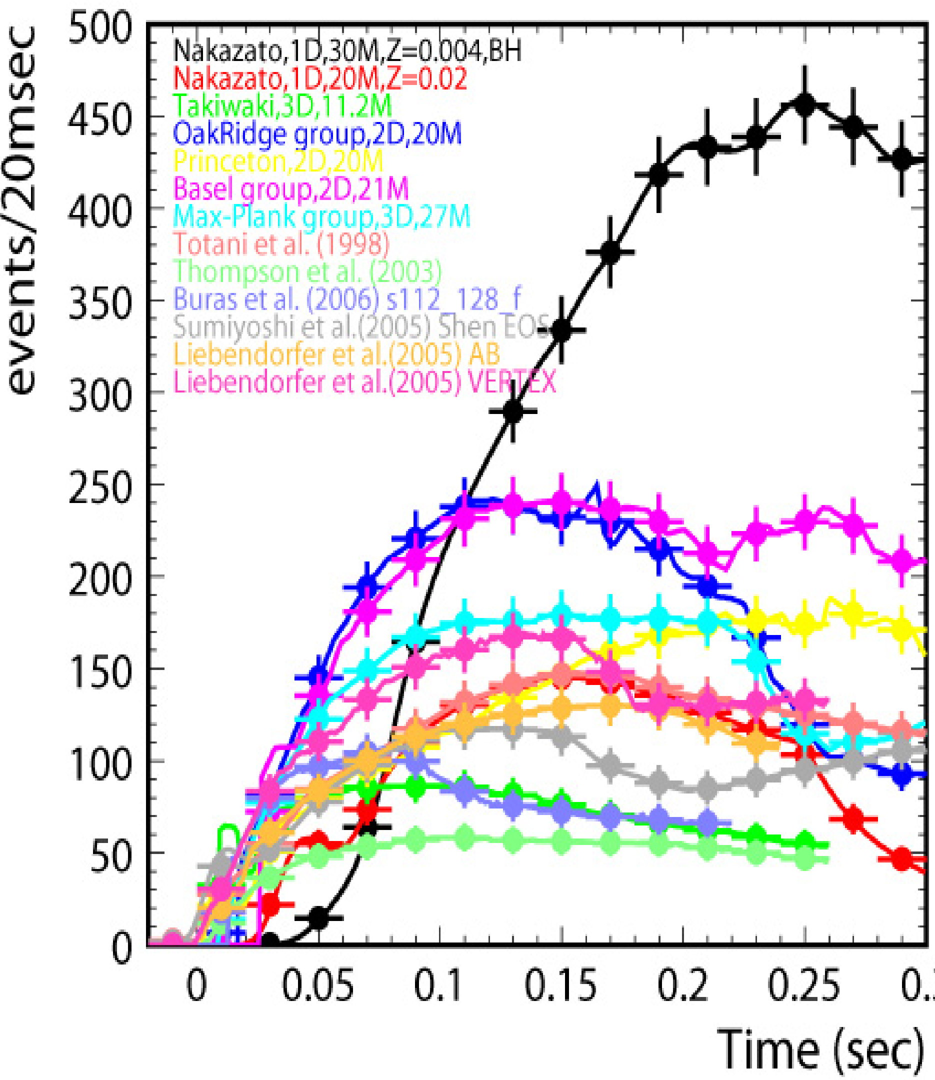




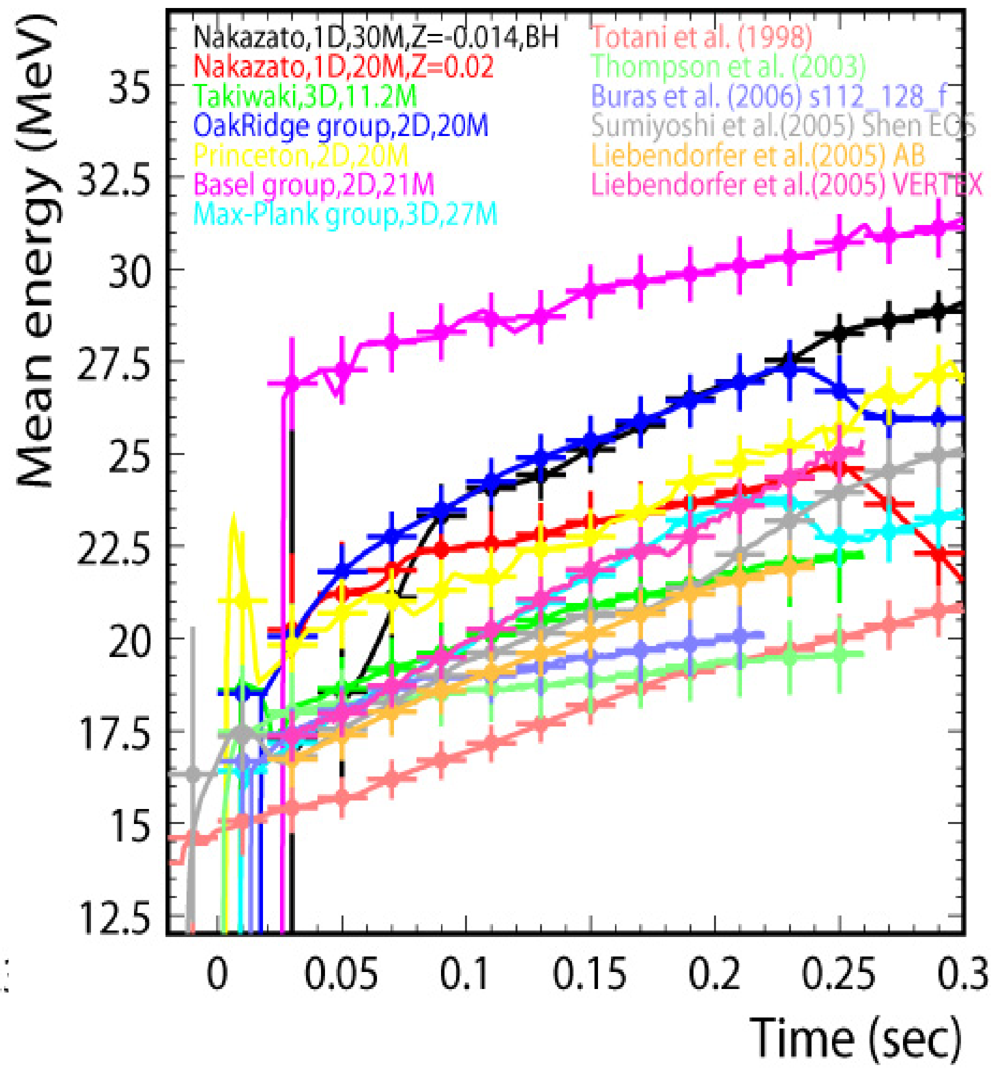
Sensitivity of Super-K for the model discrimination

10kpc supernova

Time variation of event rate



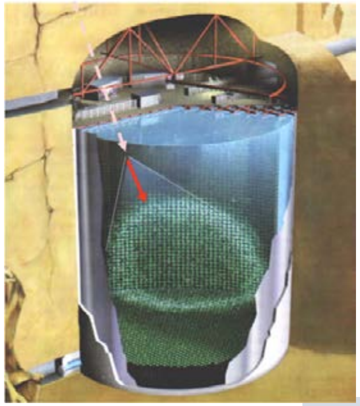
Time variation of mean energy

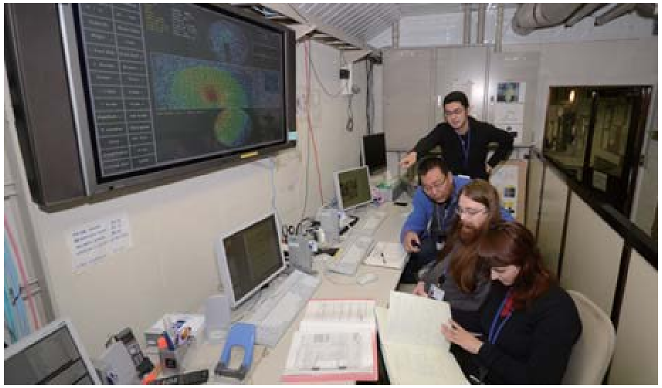


High statistics enough to discriminate models

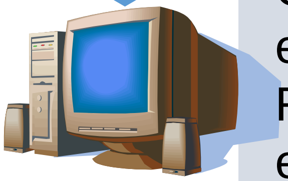
Cooperation: H. Suzuki

Real time supernova monitor in Super-K





Raw data

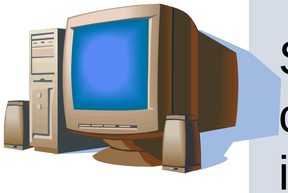


Real Time Process

Quickly analyze events.
Reconstruct vertex, energy and direction.

SK shift people always keep watch whether the processes are running.

Processed data



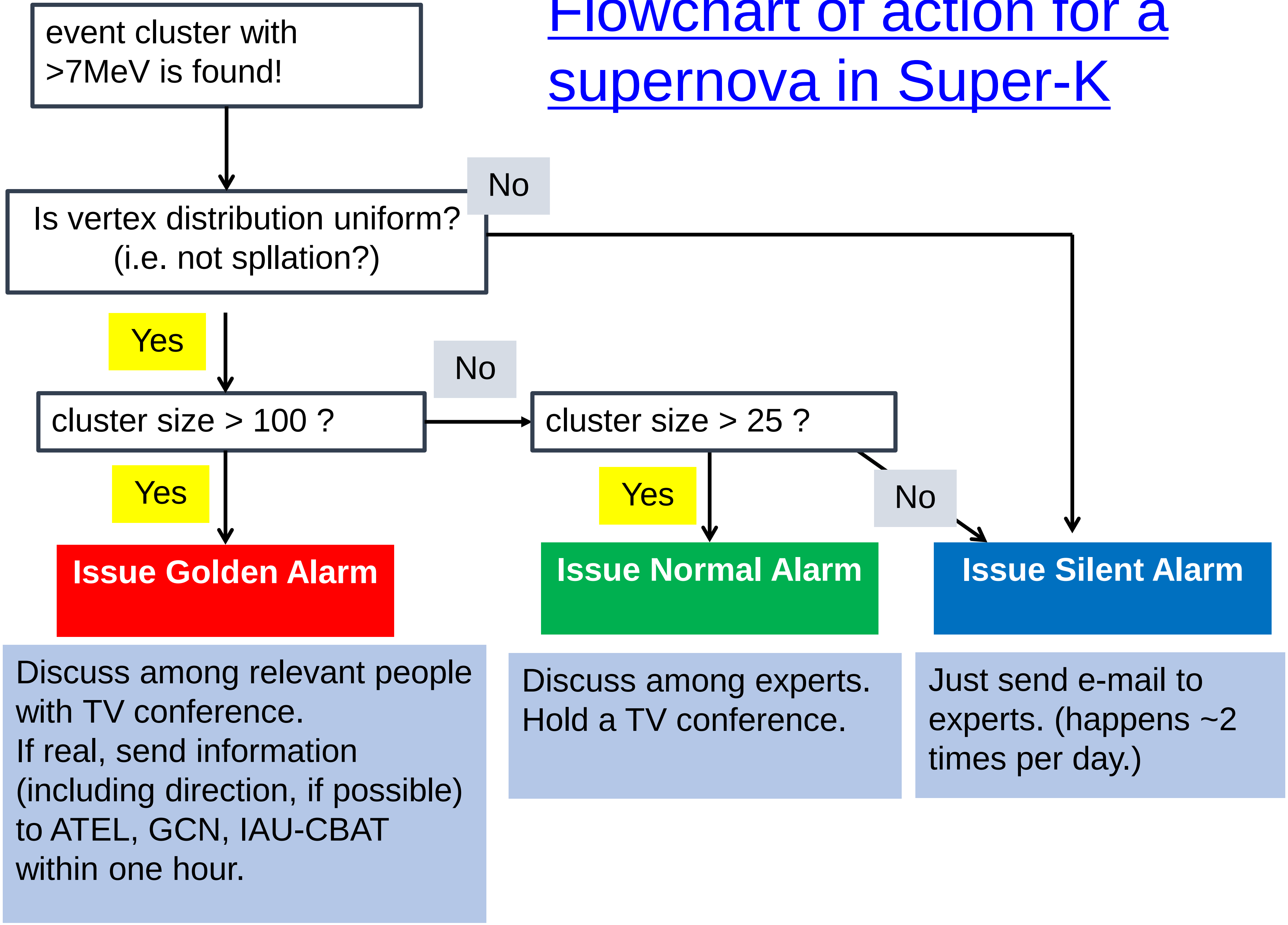
Supernova Watch

Search for time-clustered events. Get initial result within 200 sec after a burst.

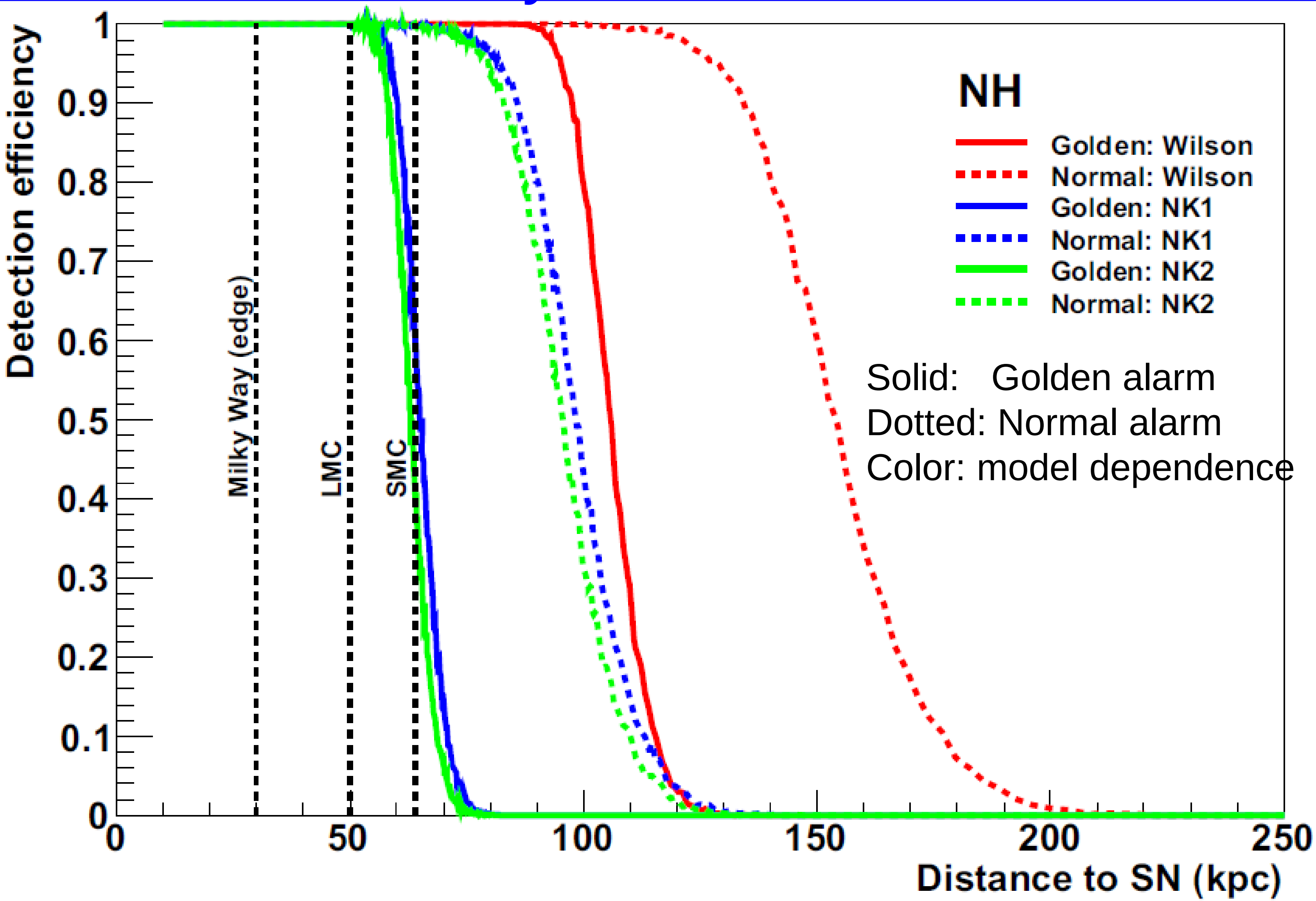
If significant time-clustered events are found, send e-mails to experts (PC and portable phone e-mails.)
Also, send signal to SNEWS.

Details in K. Abe et al., Astropart. Phys. 81 (2016) 39-48

Flowchart of action for a supernova in Super-K



Detection efficiency of the real time SN monitor



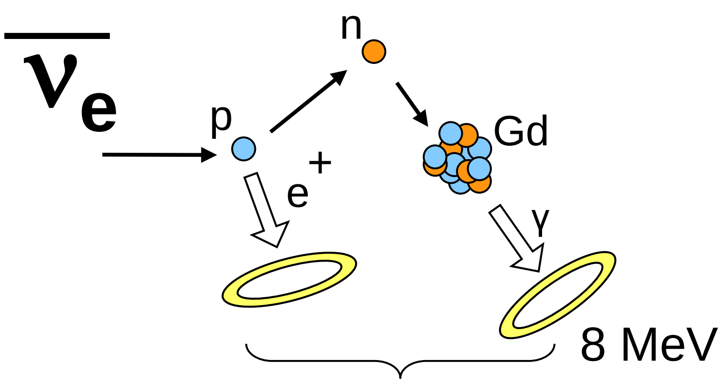
100% efficient for our galaxy and LMC for various models.

K. Abe et al., Astropart. Phys. 81 (2016) 39-48

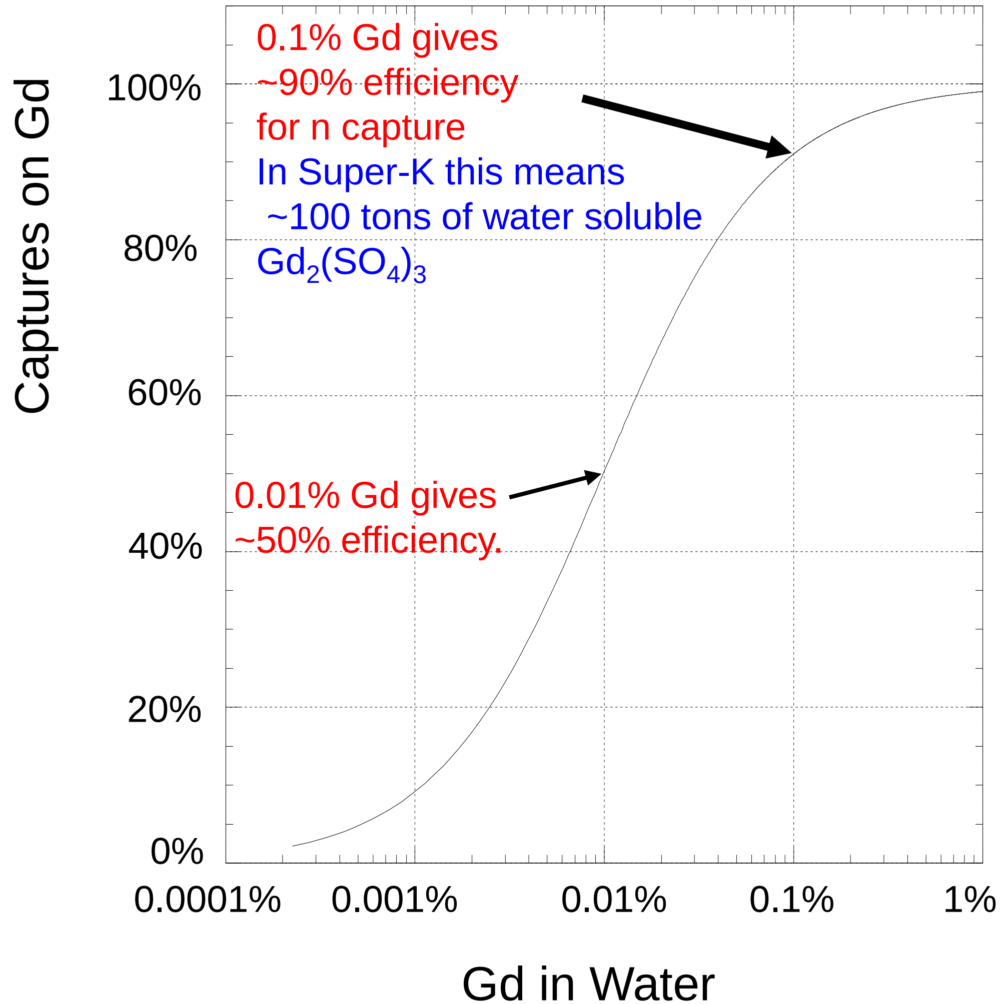
Gadolinium project at Super-K: SK-Gd

Identify $\overline{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.



ΔT~30μs
Vertices within 50cm

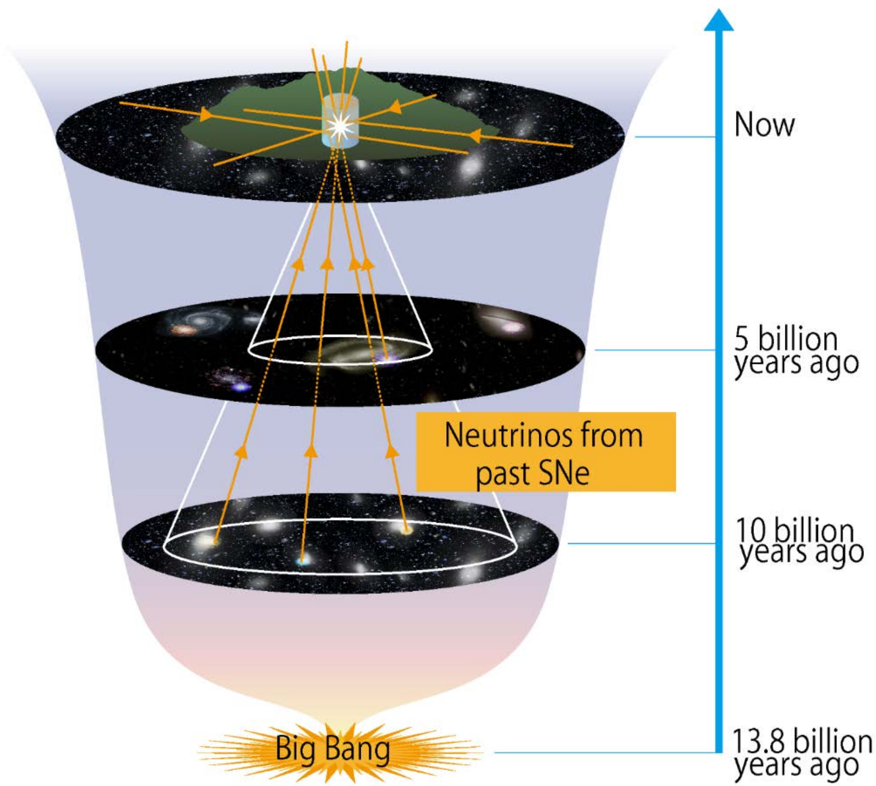


Physics with SK-Gd project

- Observation of Supernova Relic Neutrinos (SRN)
  - (also called Diffuse Supernova Neutrino Background (DSNB))
  - First observation is expected at SK-Gd
- Improve observation of supernova burst neutrinos
  - Improve pointing accuracy
  - $\nu_e(+\nu_x)$ spectrum measurement
  - Possible detection of neutrinos from Si burning.
- Reduce neutrino background for proton decays
  - Anti-tag neutrons to reduce atmospheric neutrino background
- Discriminate neutrino and anti-neutrino events for T2K
  - Using neutron multiplicity
- Reactor neutrinos
  - precise determination of θ_{12} and Δm^2_{12} with high statistics measurement, if Japanese reactors restart

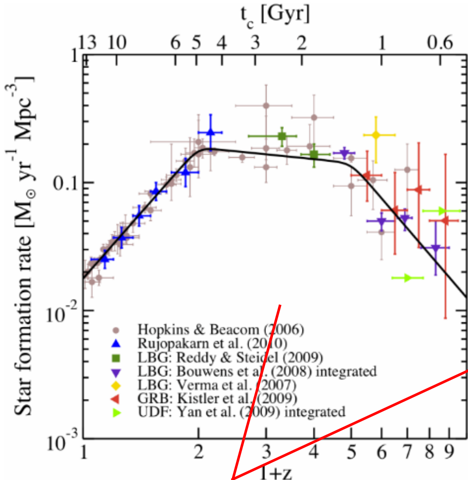
Supernova Relic Neutrinos (SRN)

$10^{22\text{-}23}$ stars in the universe (∼10^{11} galaxies, ~$10^{11\text{-}12}$ stars/galaxy)
At present, we are getting neutrinos from 10^8 supernovae every year.

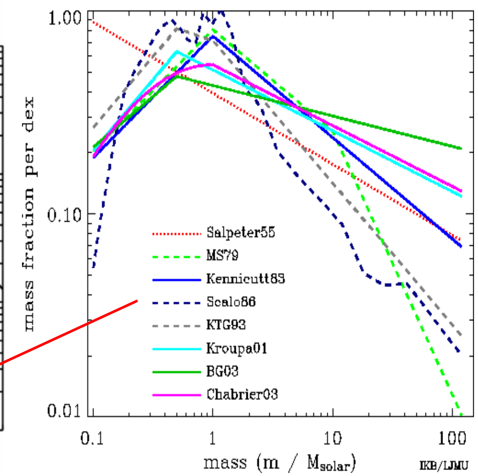


Horiuchi,Beacom(2010)

Star Formation Rate

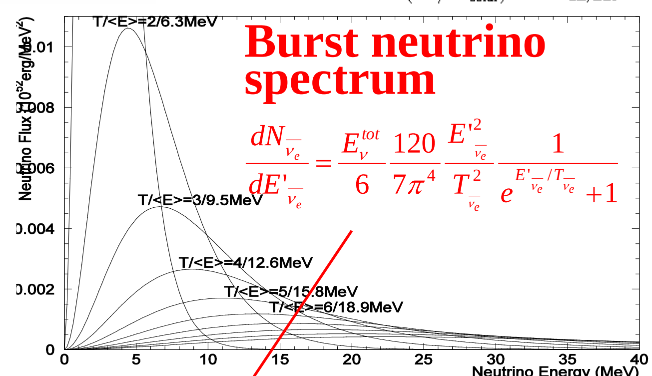


Initial Mass Function



Burst neutrino spectrum

$$\frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}} = \frac{E_\nu^{tot}}{6}\frac{120}{7\pi^4}\frac{E'^2_{\bar{\nu}_e}}{T^2_{\bar{\nu}_e}}\frac{1}{e^{E'_{\bar{\nu}_e}/T_{\bar{\nu}_e}}+1}$$

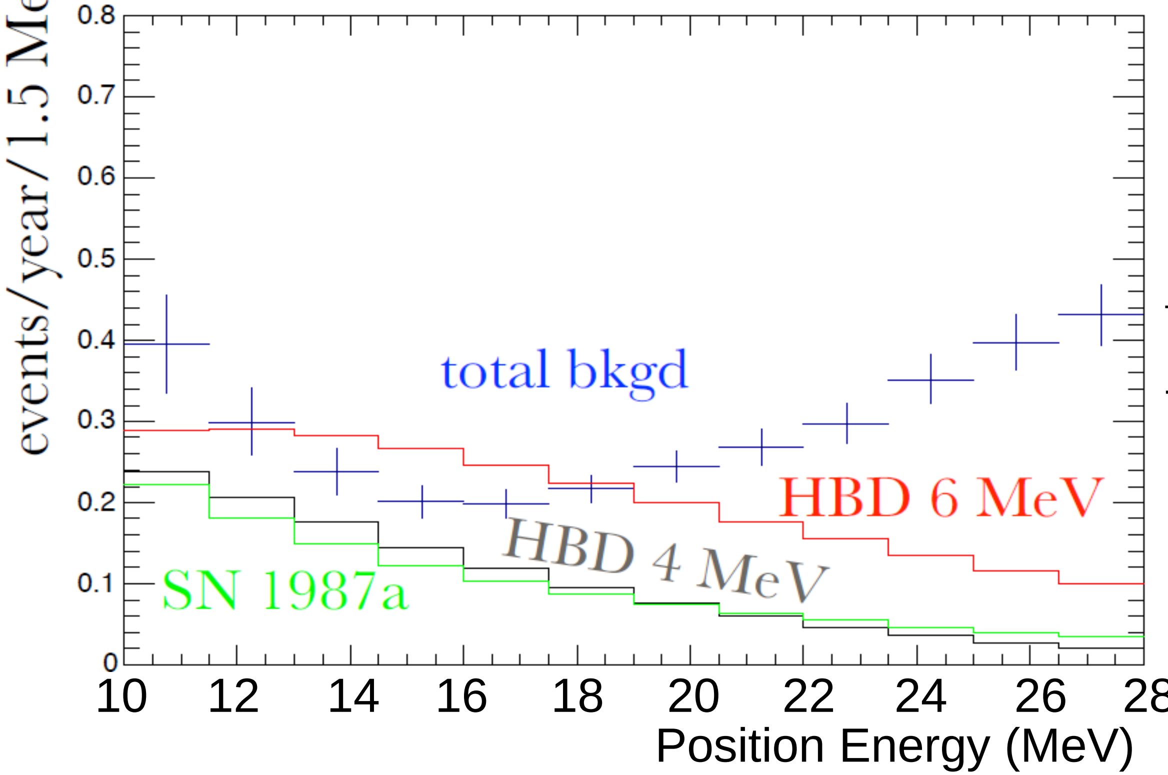


We can study
star formation history and
averaged neutrino spectrum.

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

SK-Gd: Expected SRN signal and its significance

preliminary



SRN flux from
Horiuchi, Beacom and Dwek,
PRD, 79, 083013 (2009)

<u>BG assumption</u>

BG can be reduced by neutron tagging as follows

- ν_μ CC BG 1/4
- ν_e CC BG 2/3
- NC elastic BG 1/3（require only one neutron)

Model	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV) (/10yrs)	Significance (2 energy bin)
HBD 8MeV	11.3	19.9	31.2	5.3 σ
HBD 6MeV	11.3	13.5	24.8	4.3 σ
HBD 4MeV	7.7	4.8	12.5	2.5 σ
HBD SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

In case of Galactic supernova

Improve pointing accuracy

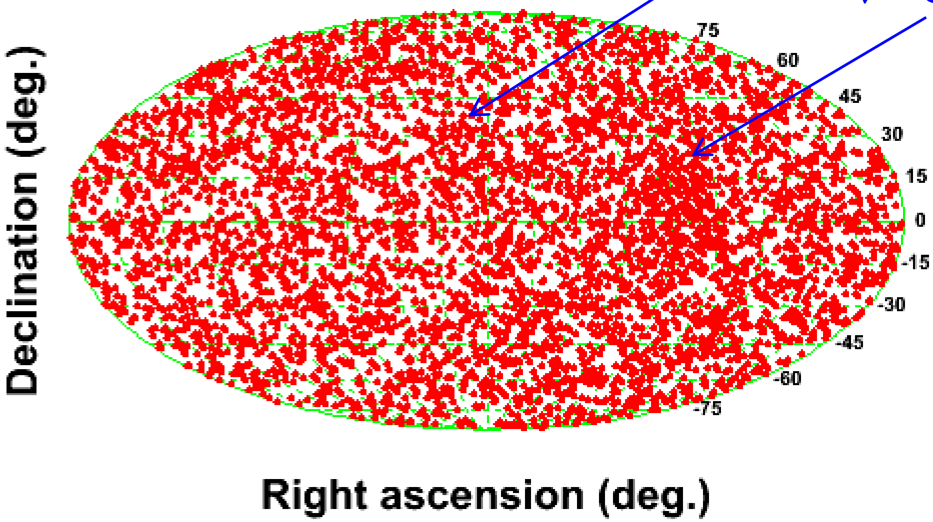
(10kpc SN simulation)

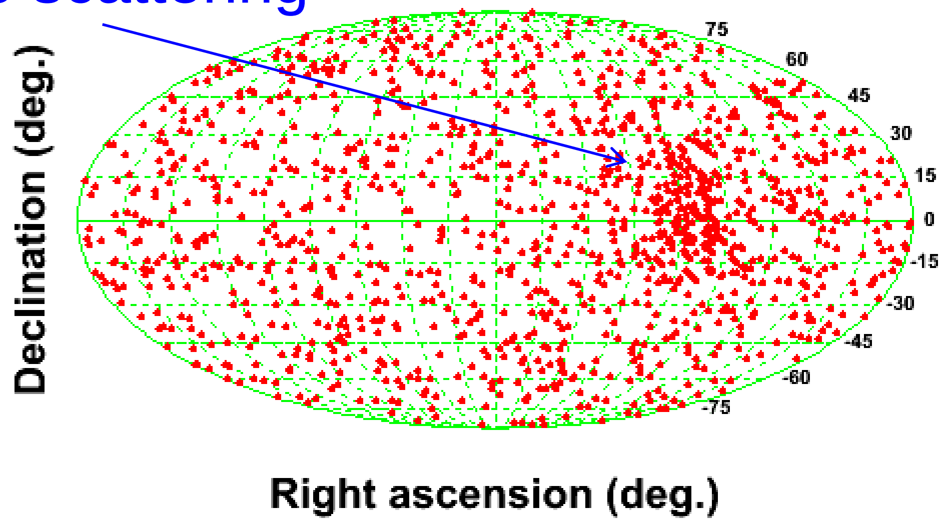
$\bar{\nu}_e$ w/o tagging

$\bar{\nu}_e$+p

$\bar{\nu}_e$ tagged with 80% eff.

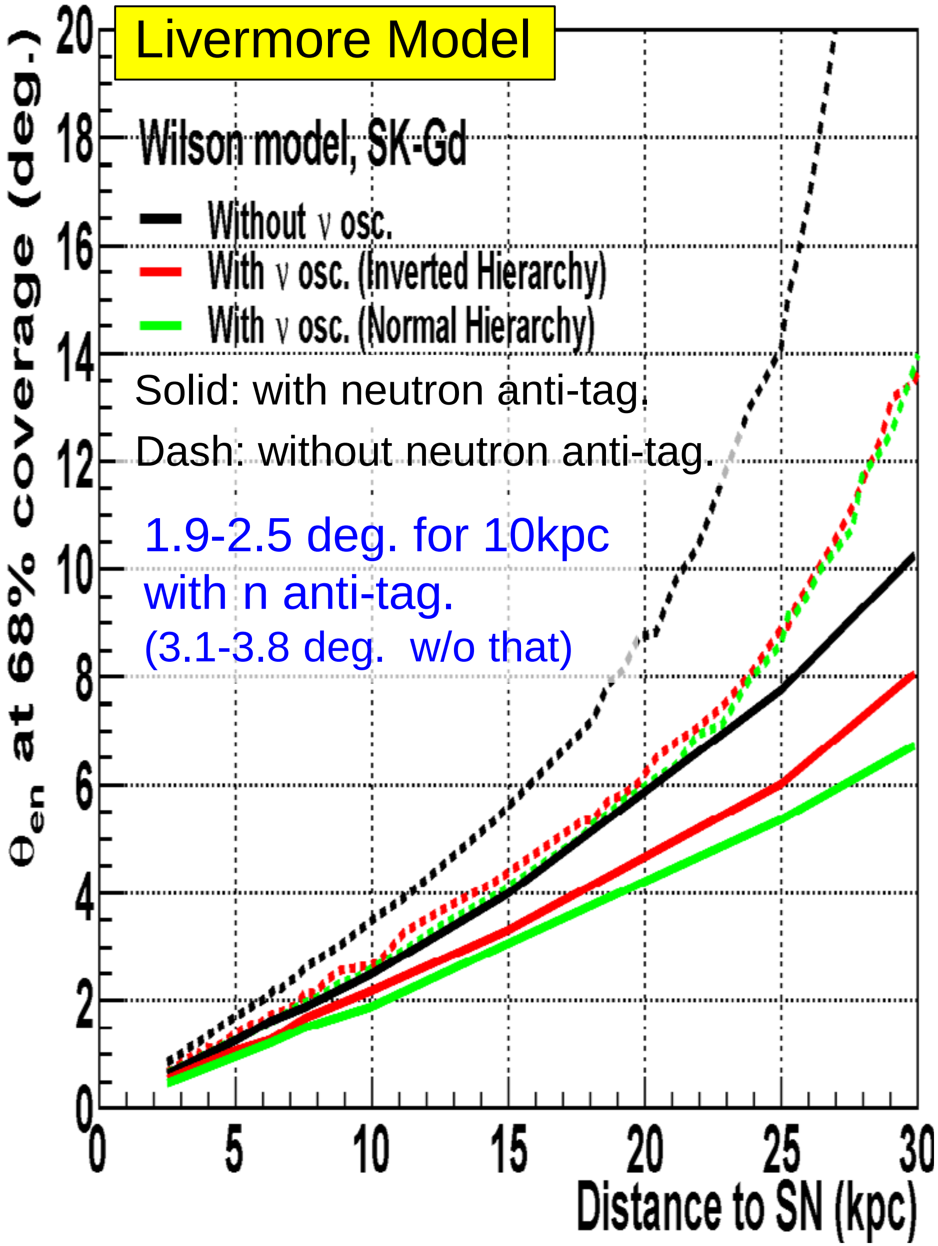
ν+e scattering

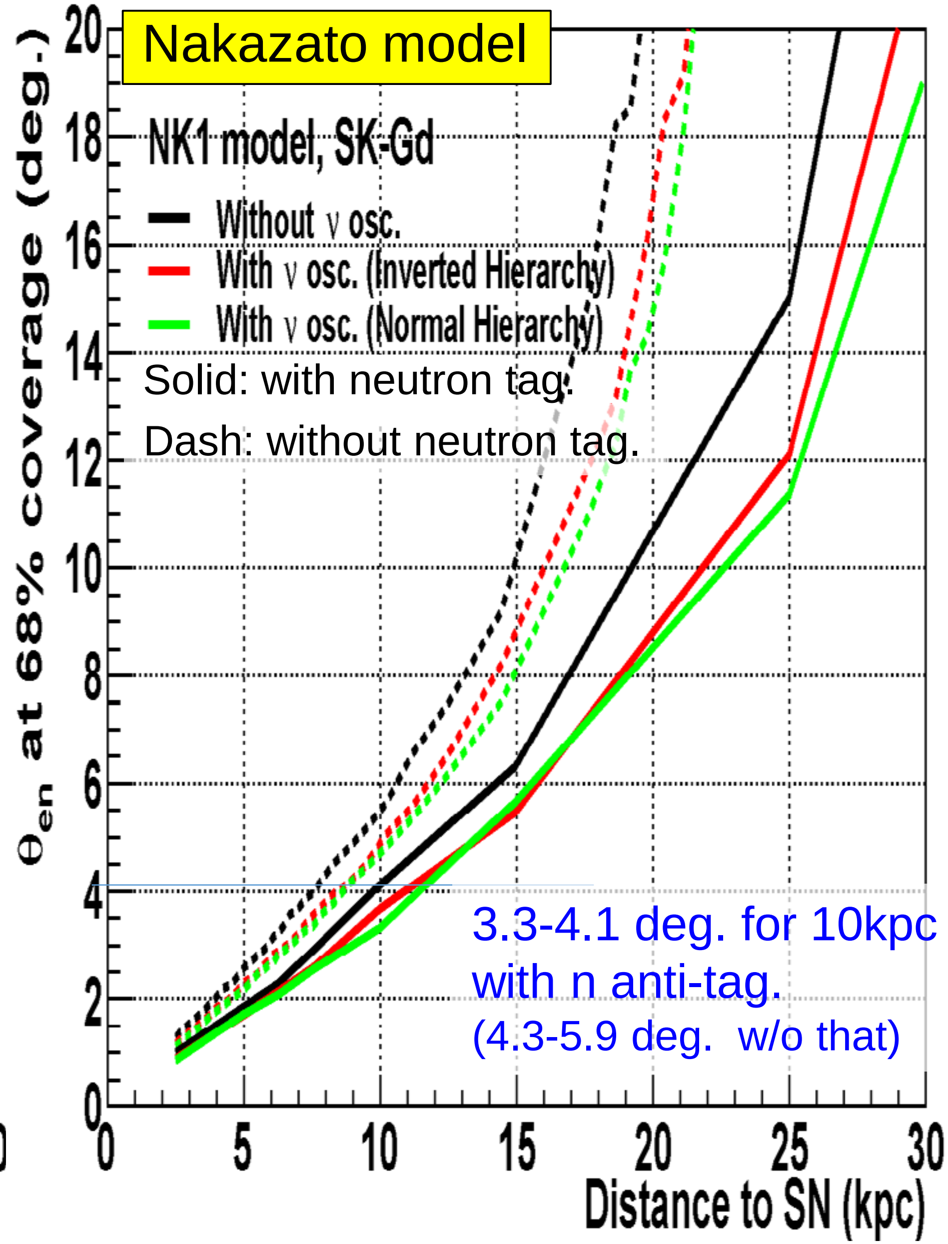




If $\bar{\nu}_e$ can be tagged and subtracted from the plot, directional events (ν+e scattering events) can be enhanced and pointing accuracy can be improved.

Pointing accuracy with neutron information

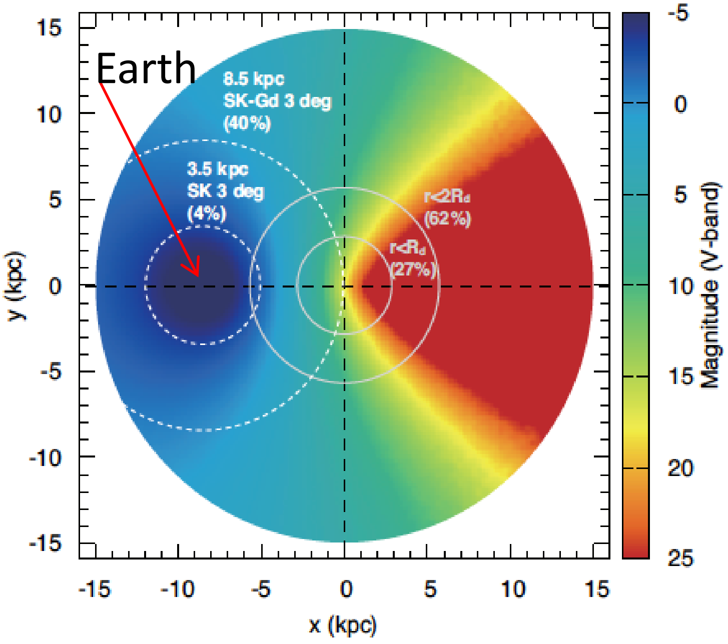




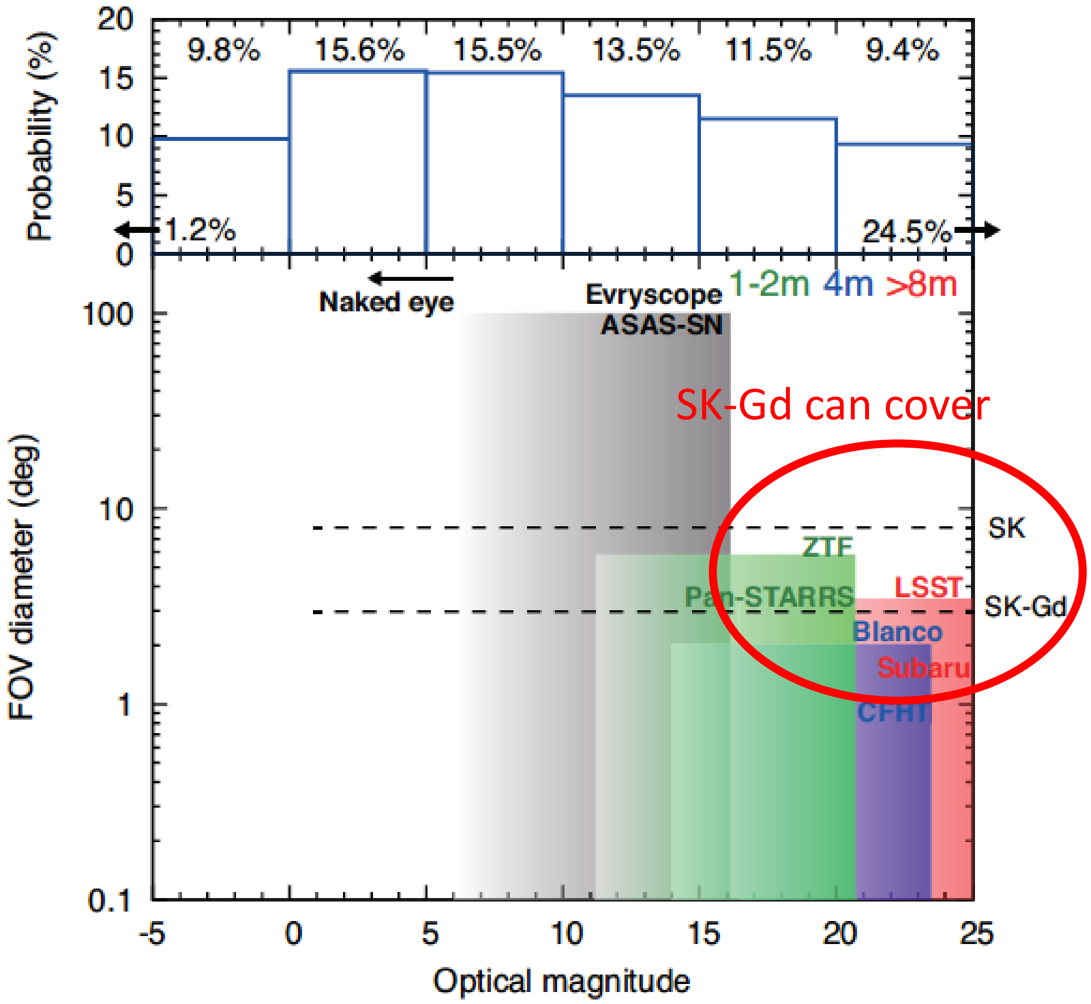
Pointing accuracy can be improved by neutron anti-tagging.

Electromagnetic follow up

Optical magnitude



Nakamura, Horiuchi, Tanaka, Hayama, Takiwaki, Kotake,MNRAS 461 (3): 3296-3313, http://arxiv.org/abs/1602.03028

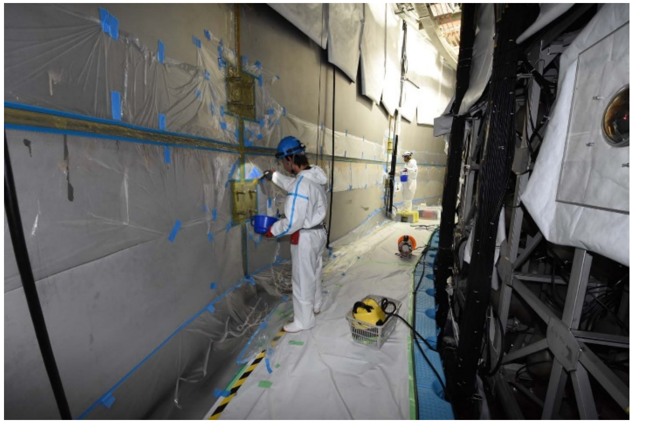


SK detector refurbishment in 2018

Purpose of the refurbishiment

◆Fix water leak from the tank

About 1 ton per day of pure water leaked from the SK detector until 2018. We have sealed all welding joints of the stainless steel panels that make up the tank.



◆Improvement of tank piping

Ultra-pure water in the tank was circulated at a flow rate of 60 tons per hour before. We improved the water piping and water systems so that they can process and circulate water at 120 tons per hour. (17days per one circulation).

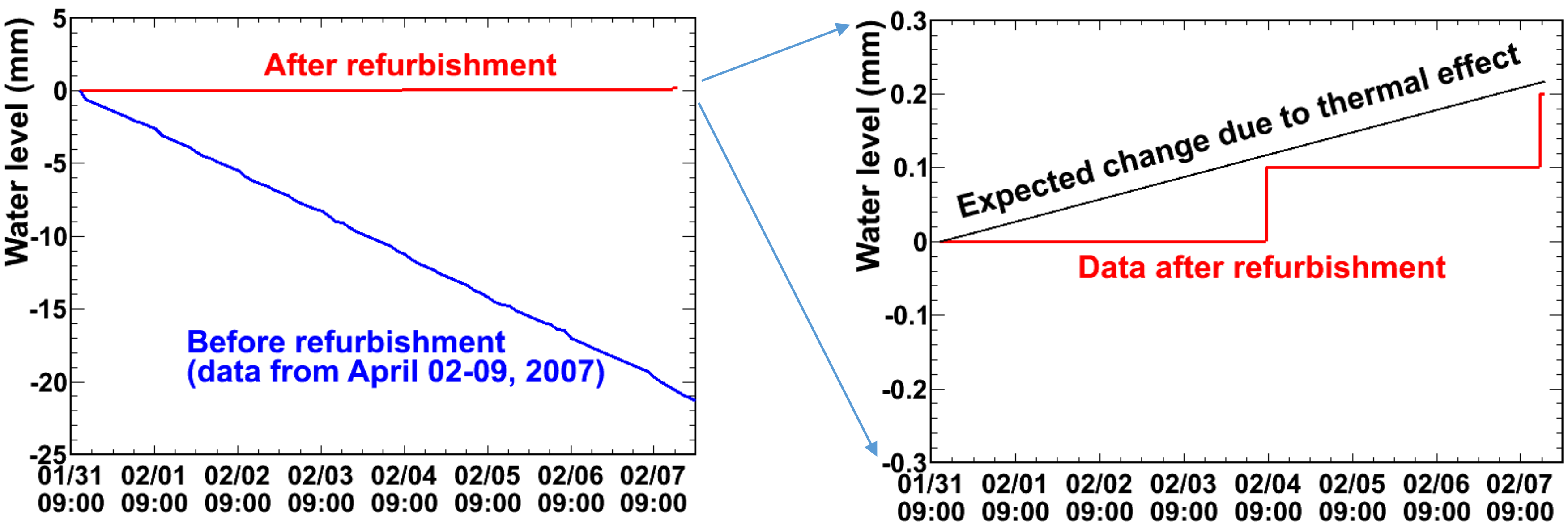
◆Replacement of faulty photomultiplier tubes

Since the last in-tank SK maintenance during 2005-2006, some photomultipliers became faulty. We have replaced a few hundred PMTs.

The refurbish started from May 2018 and completed by January 2019.

Water Leakage check after refurbishment

After filling the tank completely with water, we started the water leakage measurement from 11:30 on 31st January to 15:52 on 7th February, 2019. (7 days 4 hours 22 minutes in total)

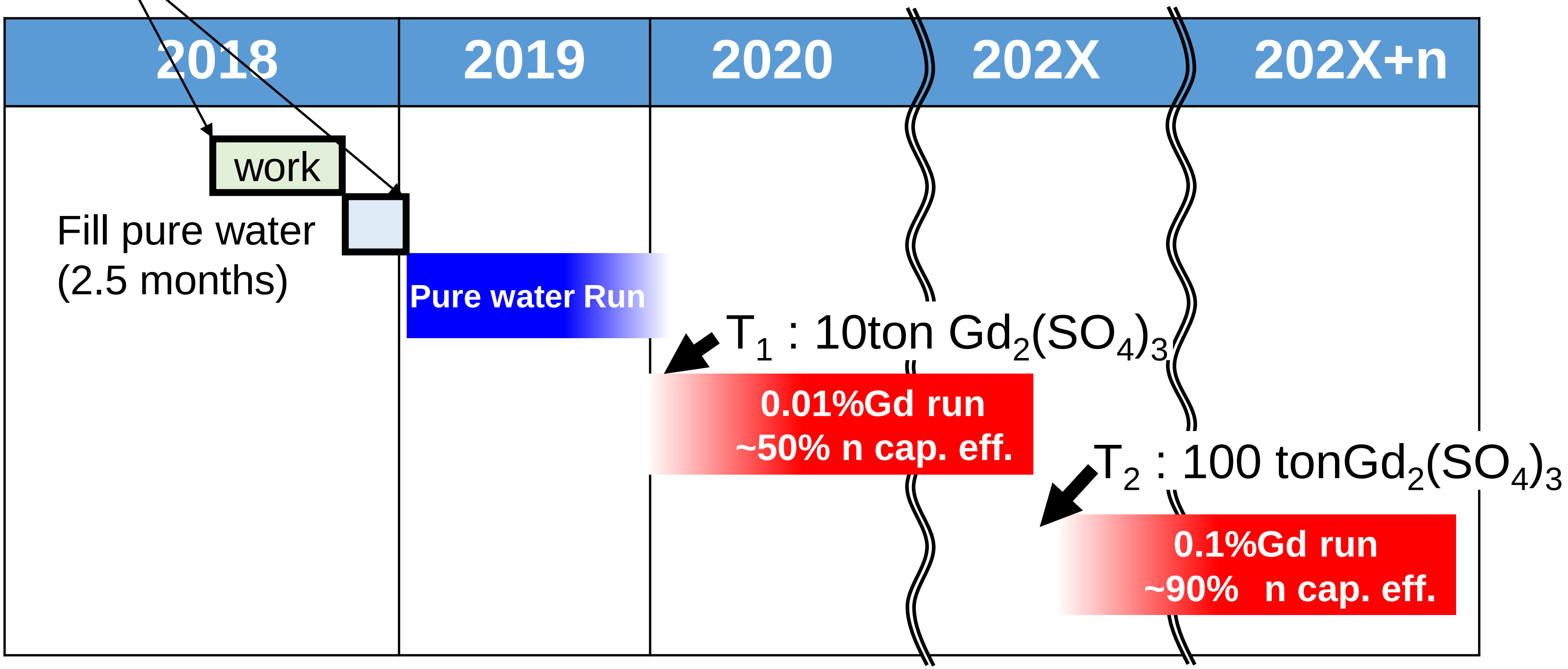


Conclusion

- Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day.
- This is less than 1/200th of the leak rate observed before the 2018/2019 tank refurbishment.

Schedule of SK-Gd

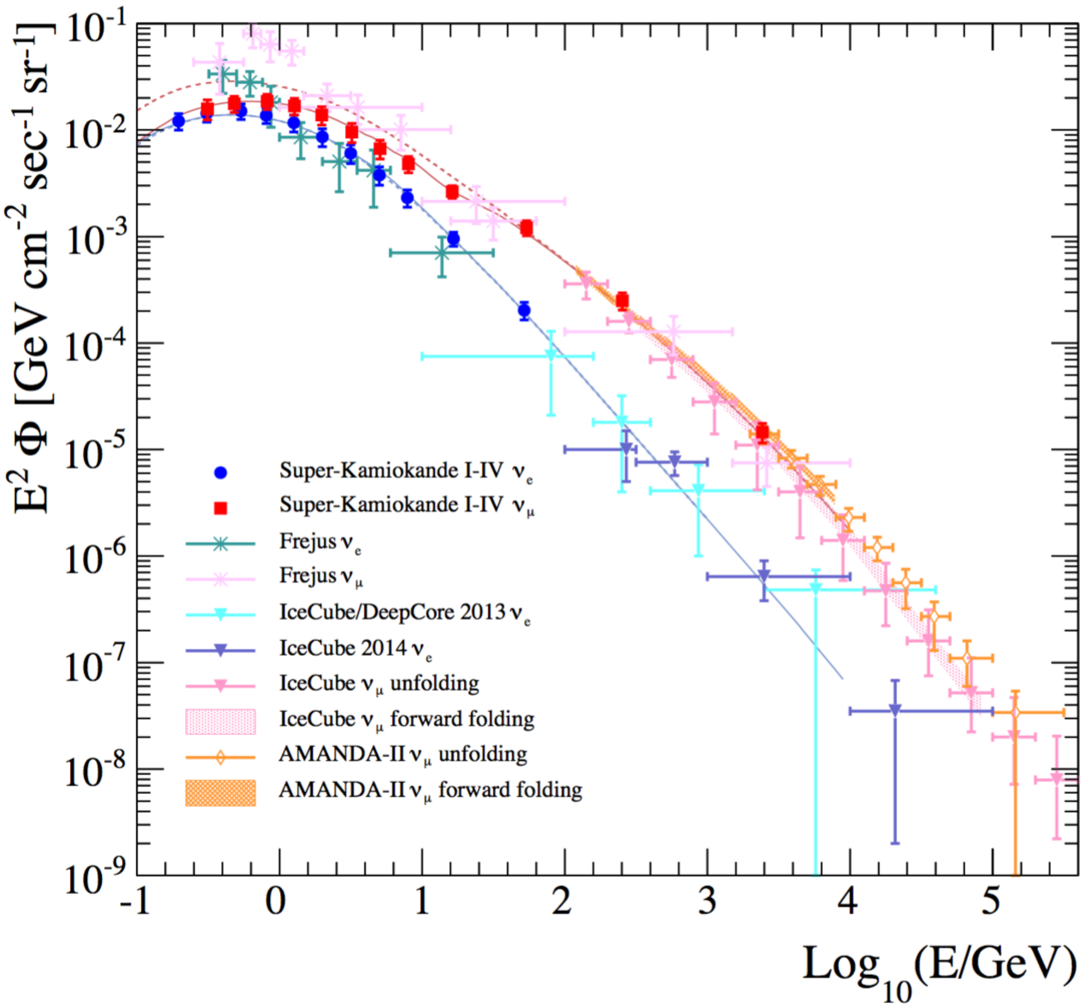
Refurbishment: Water filling was completed in January 2019.



Plan to start 0.01% Gd run in early 2020.
(Adjusting schedule with T2K)

High energy neutrinos at SK

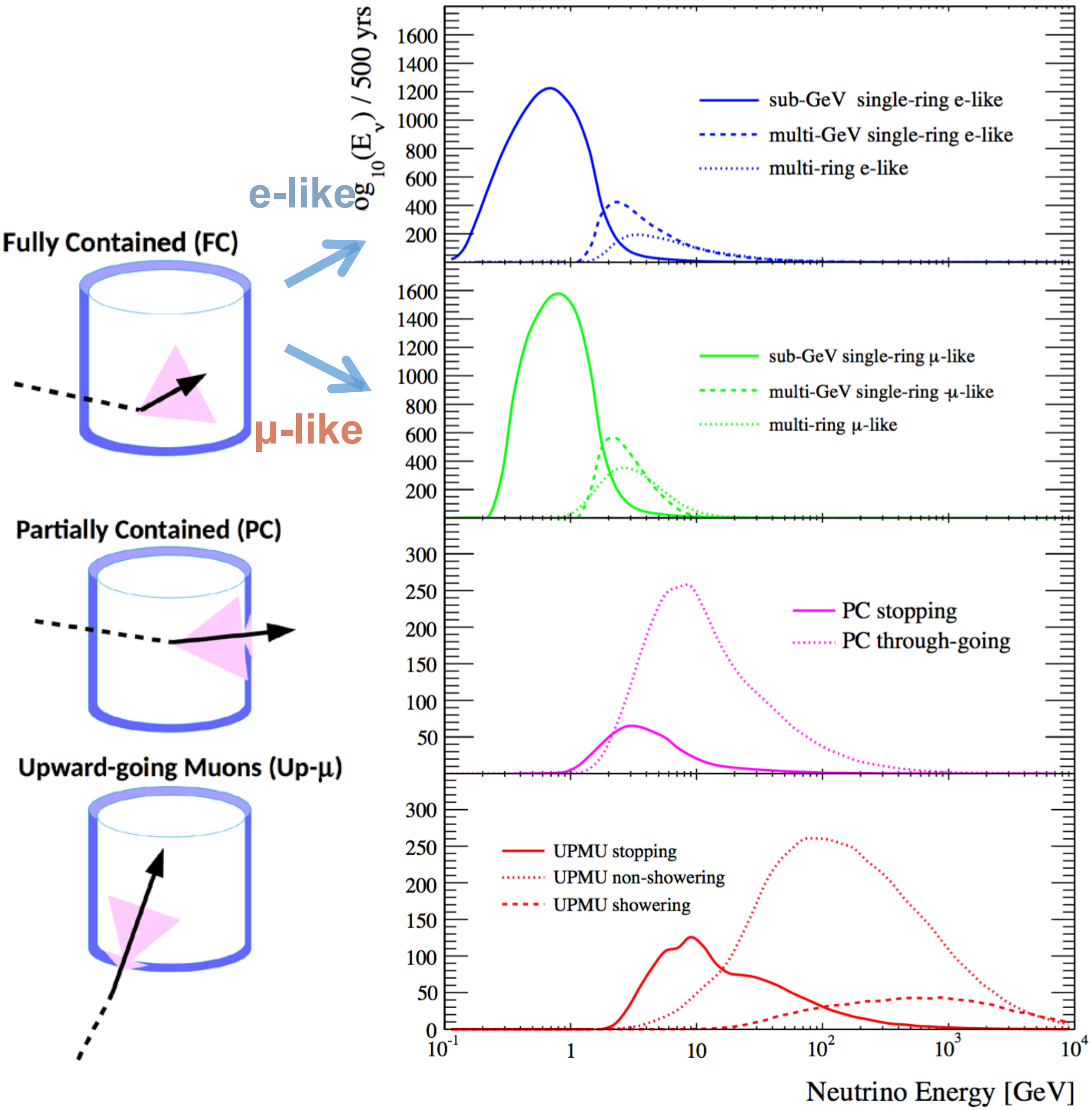
Atmospheric neutrino spectrum



- Super-K measures atmospheric neutrinos in a wide energy range from 100 MeV to several TeV
- Overlap in high energy with AMANDA and IceCube regions

SK has the world largest sensitivity for <10GeV neutrinos.

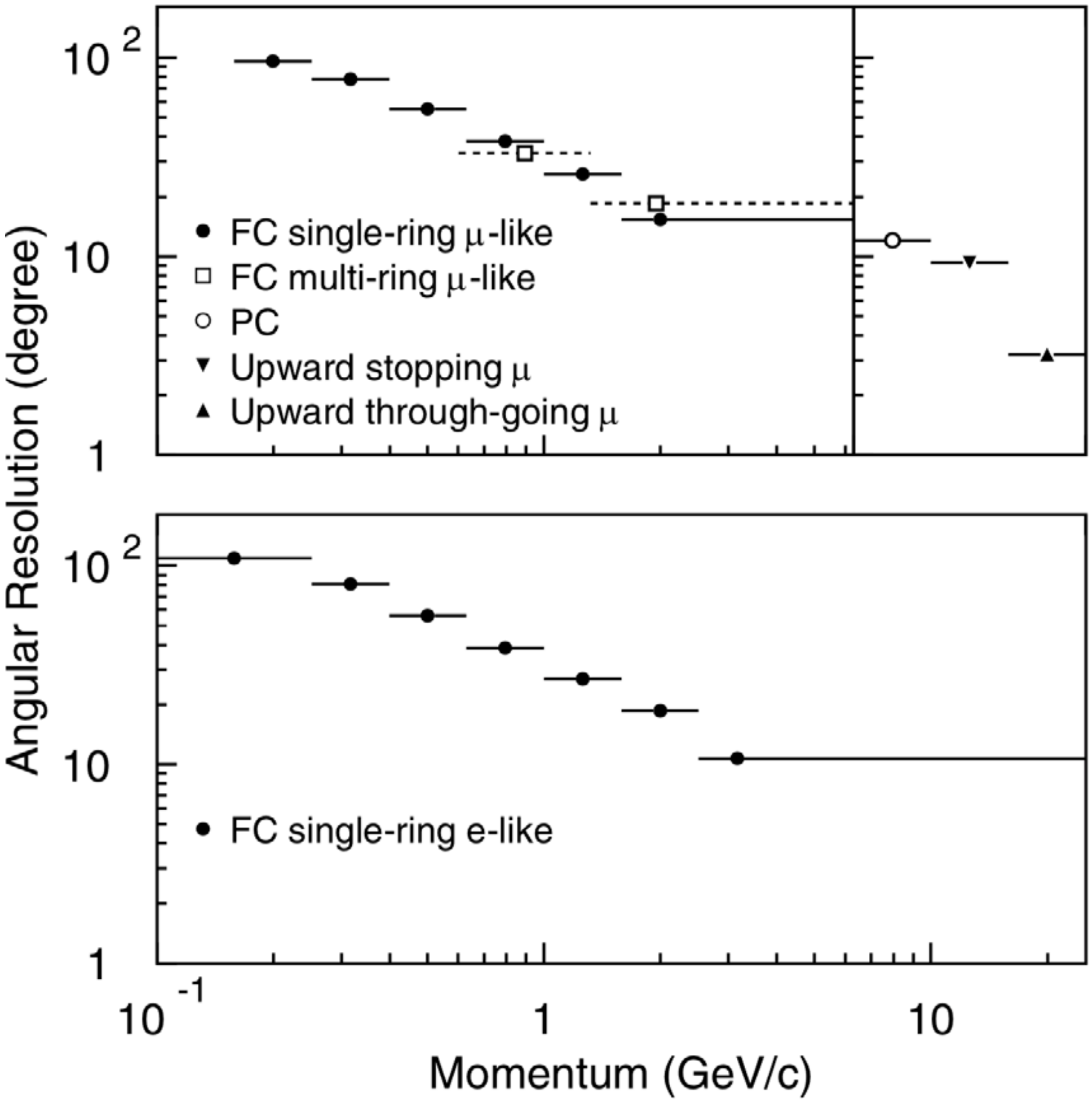
High energy neutrino data samples



- Three event topologies: FC, PC, UPMU
- Sub-divided by particle ID, number of rings, stopping/thru-going
- Different sub-sample provides different energy response
- Covers from sub-GeV up to 100 GeV (10 TeV) for ν_e (ν_μ) by combination of these samples

Angular Resolution

PRD 71, 112005 (2005)



- Roughly tens of degrees on average for less than several GeV
- Better resolution (2~3 degrees) for UPMU sample in >10GeV due to high Lorentz boost
- Directional search is possible for high energy events above 10 GeV in <10 degree circle

Conclusions

- Large number of neutrino events is expected for a galactic supernova and they will tell us detailed information to reveal explosion mechanism.
- SK-Gd phase is being prepared. Main physics target is the detection of supernova relic neutrinos.
- SK-Gd will improve pointing accuracy for galactic supernova.
- The tank open work in 2018 stopped the water leak.
- The SK-Gd phase should start within one year.
- SK has the world largest sensitivity for <10GeV neutrinos.