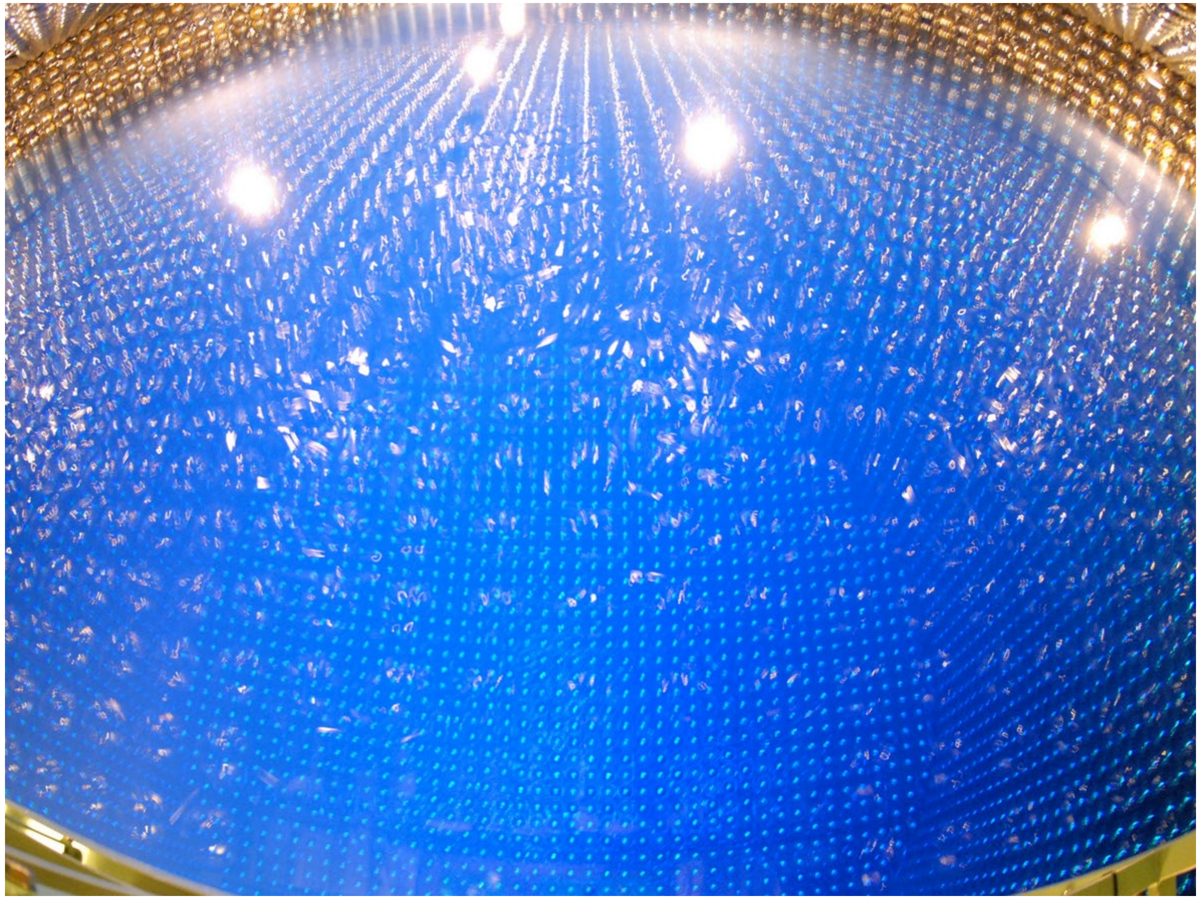
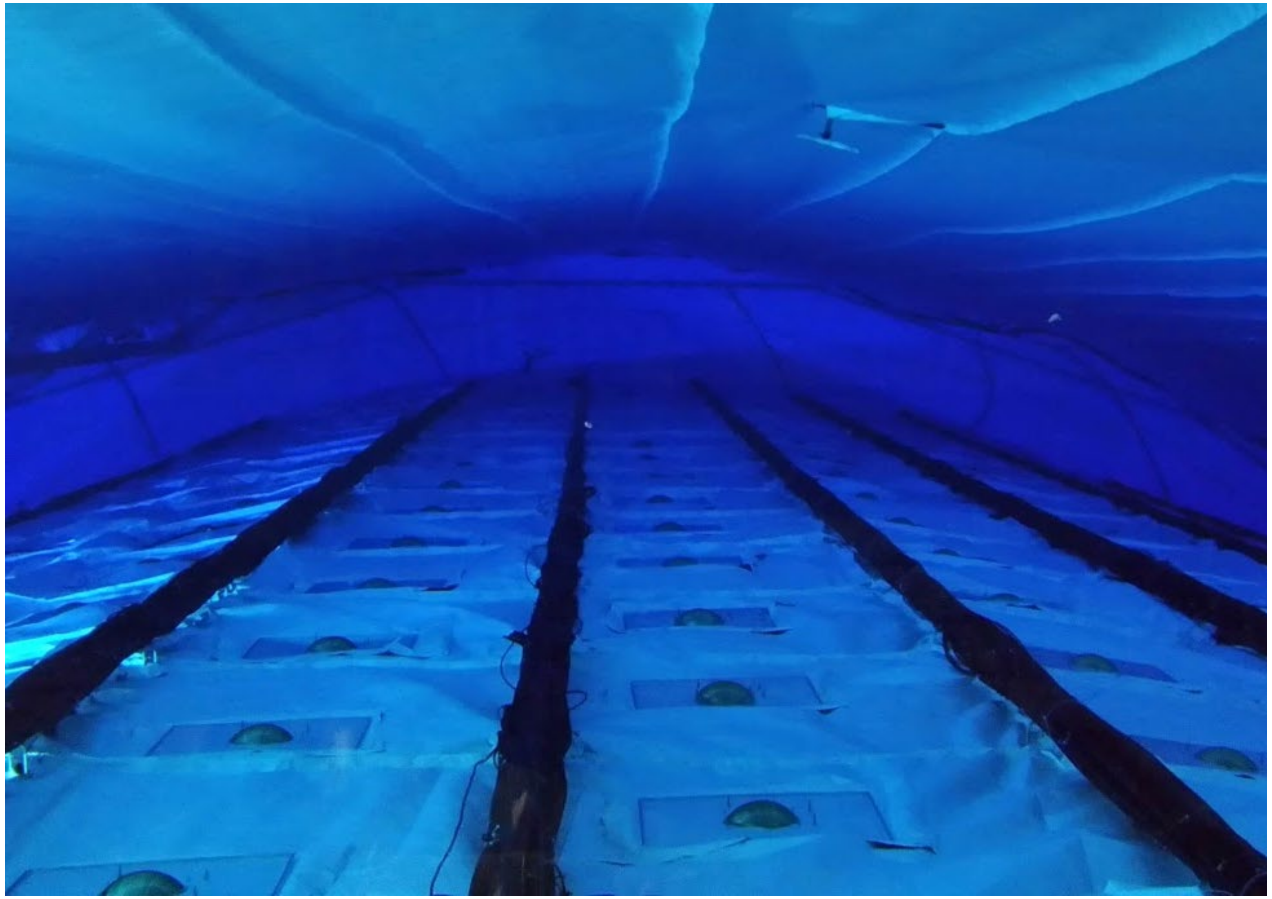




SK-Gd

地下稀事象　領域研究会　2025

25 June 2025

Hiroyuki Sekiya

The Super-Kamiokande Collaboration

~240 collaborators
from 55 institutes
in 11 countries

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
BMCC/CUNY, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France/Japan
INFN Bari, Italyl
INFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Institute of Science Tokyo, Japan
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
University of Minnesota, USA
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
NIT, Numazu college, Japan
Okayama University, Japan
Osaka Electro-Communication Univ.,Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
University of Silesia in Katowice, Poland
Sungkyunkwan University, Korea
Tohoku University, Japan
The University of Tokyo, Japan
Tokyo University of Science, Japan
University of Toyama, Japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

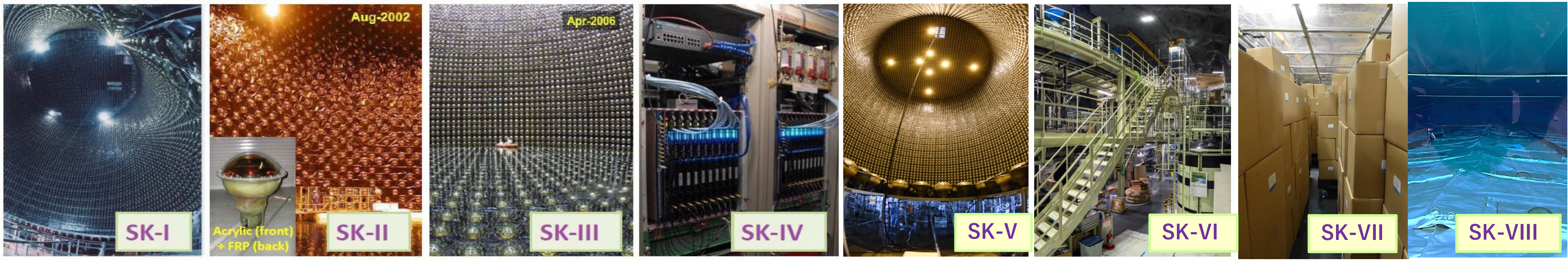
Super-Kamiokande History

SK will celebrate its 30th anniversary in 2026

SK-Gd

1996 2002 2006 2008 2018 2019 2020 2022 2024

SK-I | SK-II | SK-III | SK-IV | SK-V | SK-VI | SK-VII | SK-VIII



0.01%Gd 0.03%Gd

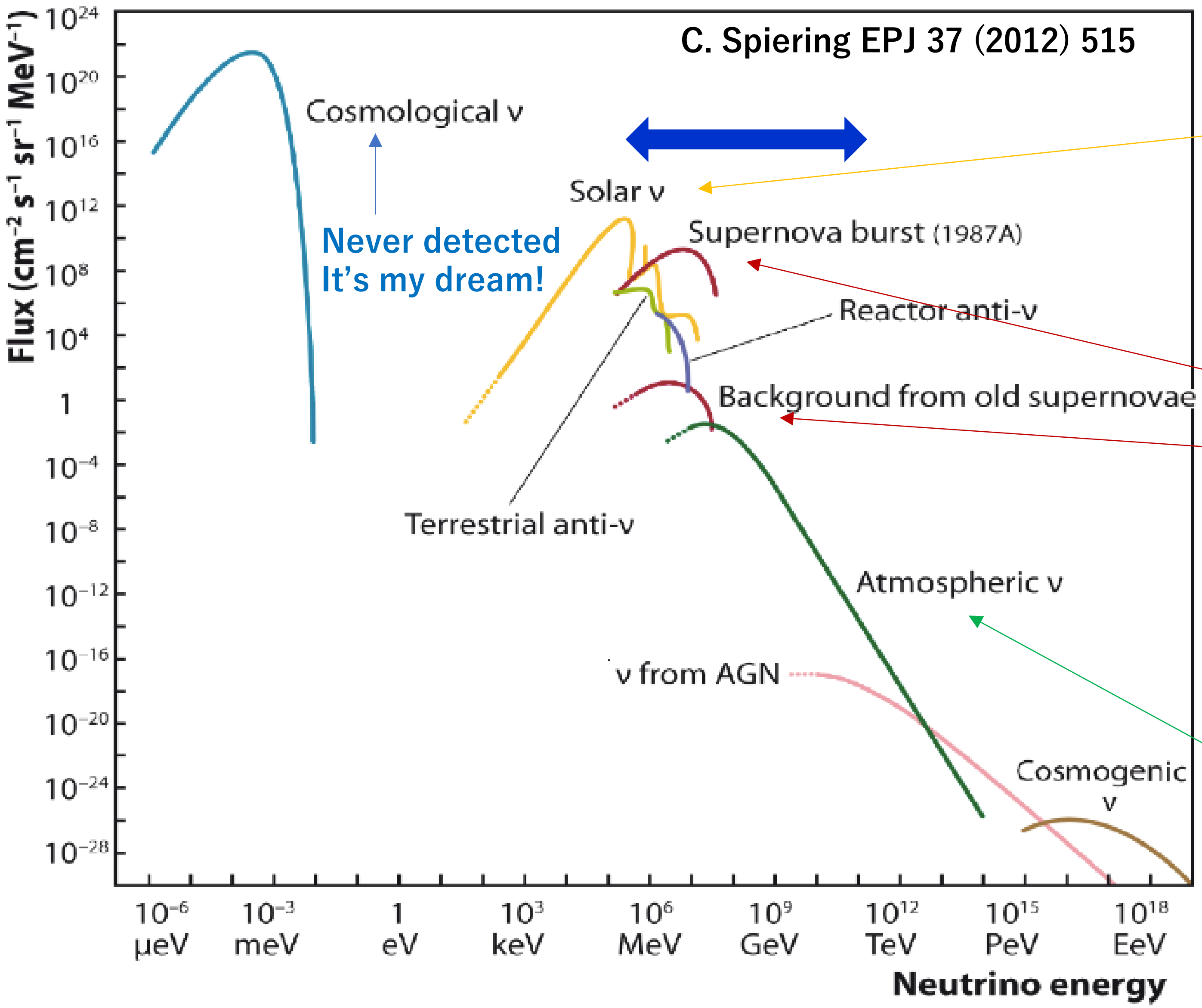
Pure water

Total live time for current oscillation analysis:
5805 days (SK-I~IV, for solar)
6511 days (SK-I~V, for atmospheric)

Gd-loaded water

Live time for DSNB search:
956.2 days + the future…

Targets of SK-Gd



(Energy: Kinetic energy)

Solar neutrinos

3.5~ 20 MeV

~15 events/day

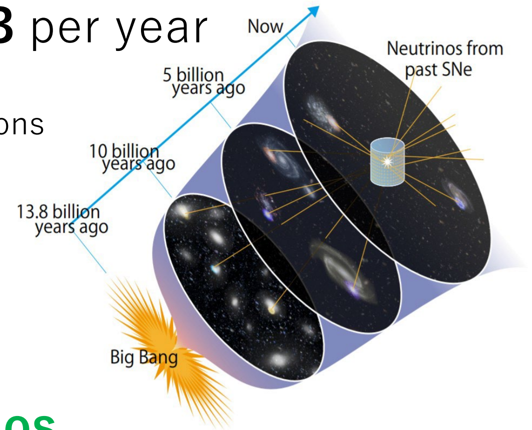
Supernova neutrinos

A few ~ 30 MeV →**Never detected in SK**

Several thousand events (for 10kpc)

Expect a few **DSNB** per year

Neutrinos from
past supernova explosions



Atmospheric neutrinos

100 MeV ~ a few 100 GeV

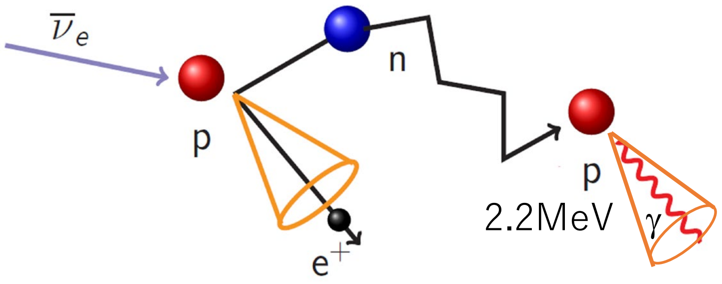
~ 10 events/day

Supernova "signal" in SK

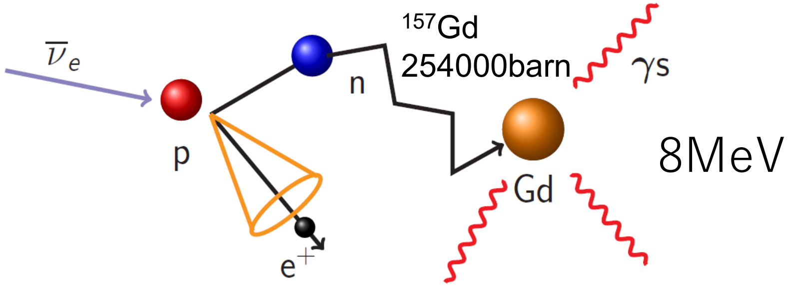
- **Search for inverse-beta decay (IBD)** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Largest cross-section @ DSNB signal range
  - Simple event topology: 1 positron and 1 neutron

→ **Require only one delayed neutrons signal**

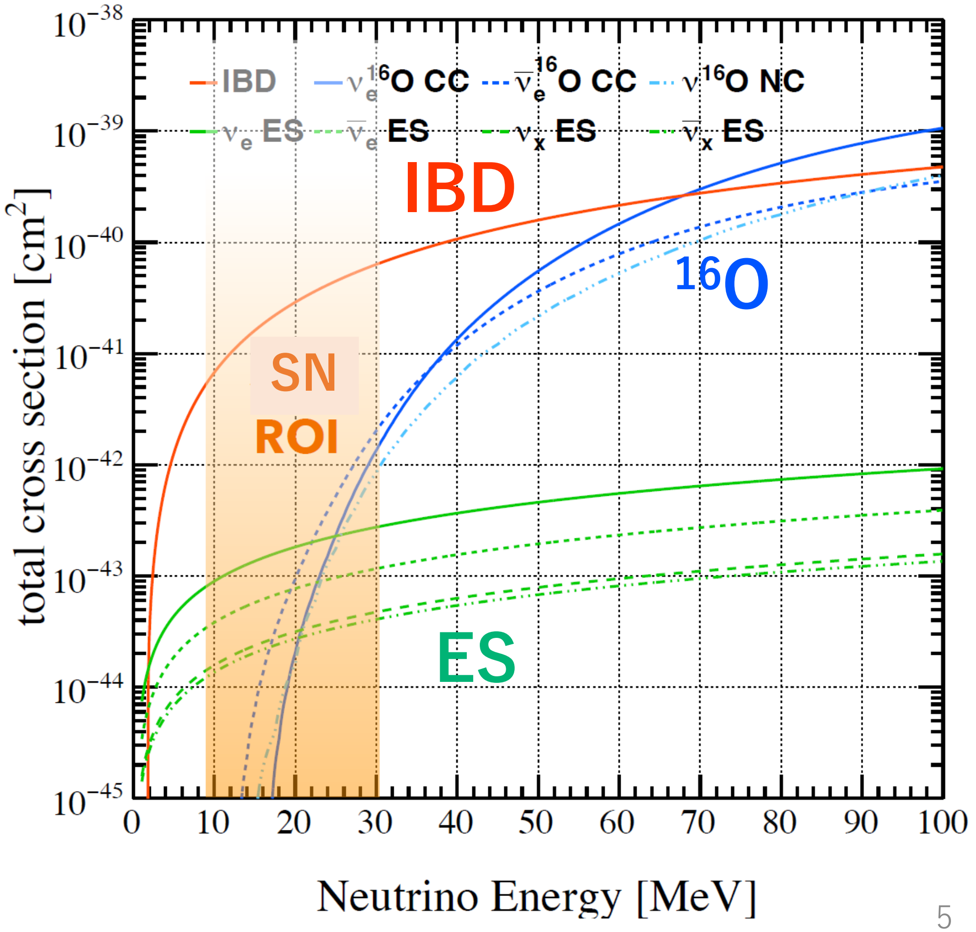
In pure water, the neutron tagging efficiency is low.



Gd-loading improves neutron tagging efficiency.



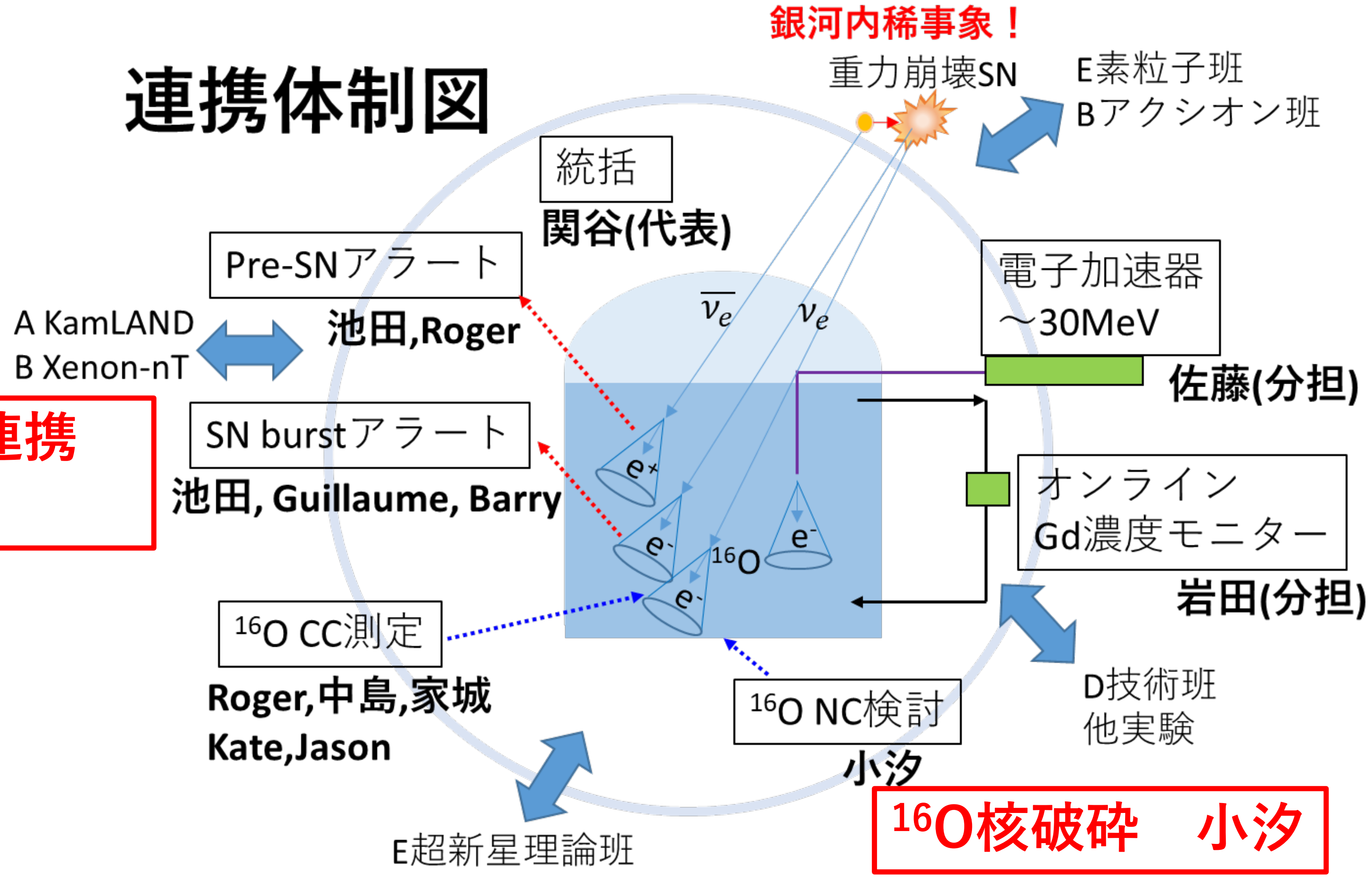
The interaction channels



C01 Group in UGRP

公募研究による体制強化

- Frontier of Rare Events in the Universe: Investigating the Origin of Elements in the Universe with the Universal Supernova Neutrino Detector

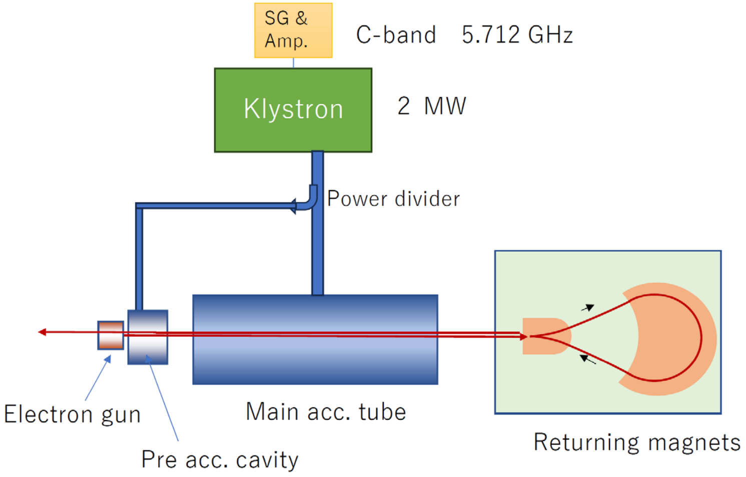


XRISM連携
内田

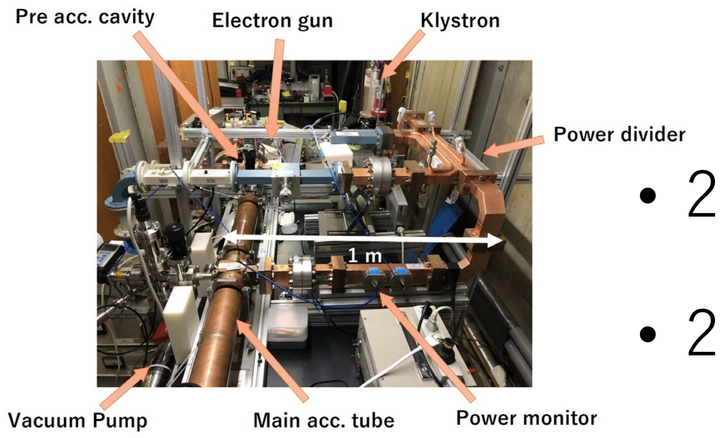
^{16}O核破砕　小汐

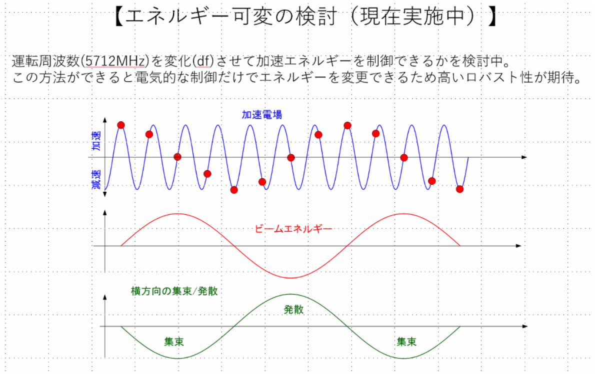
Development of Linac 佐藤、鈴木@AIST

Developed electron accelerator



Developed electron accelerator

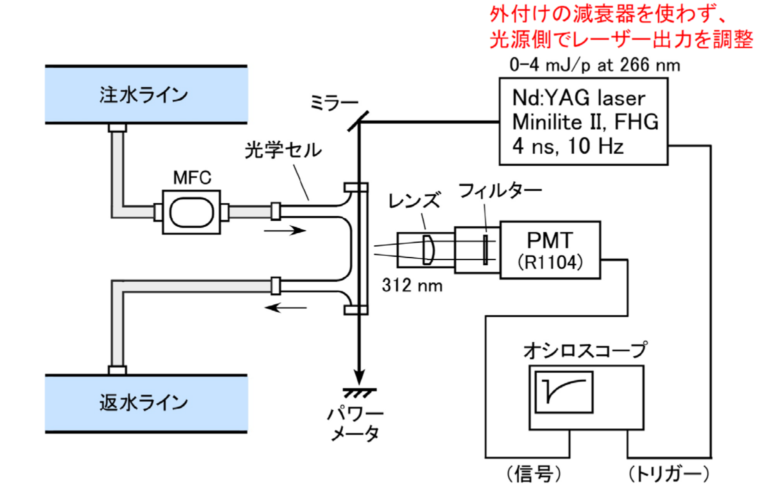




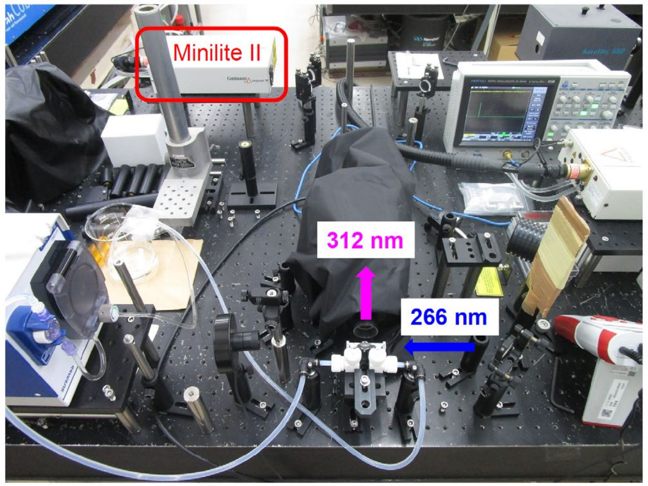
- 20MeV→30MeV
  - Improve the acc. tube efficiency
- 2MeV~ 30MeV
  - Variable acc. energy by changing the operation frequency.

Gd concentration monitoring 岩田@JAEA

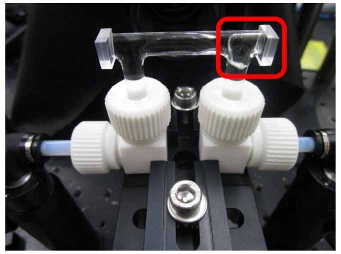
SK注水ライン～MFC～光学セル～SK返水ライン



ビーカーに0.03% Gd を150 mL（1/28作製を再使用）

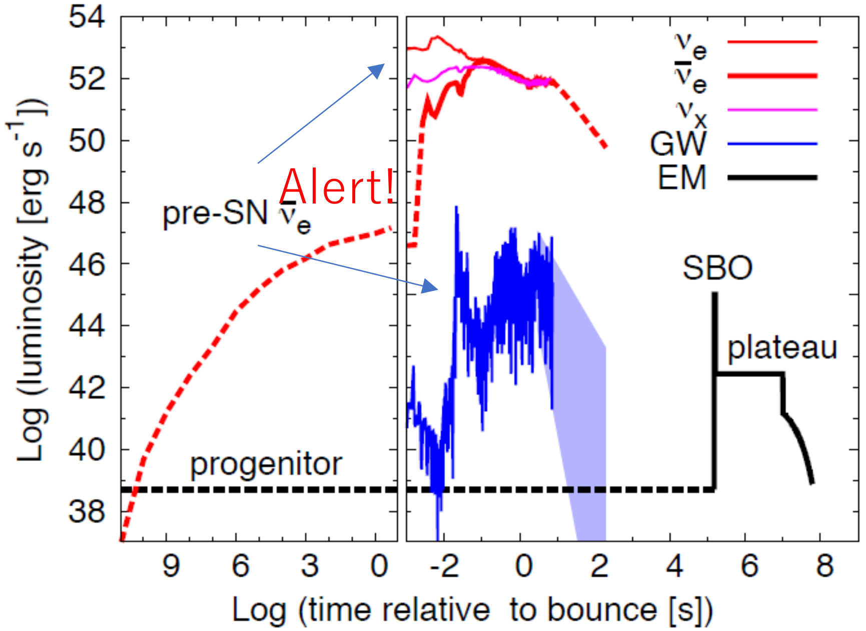


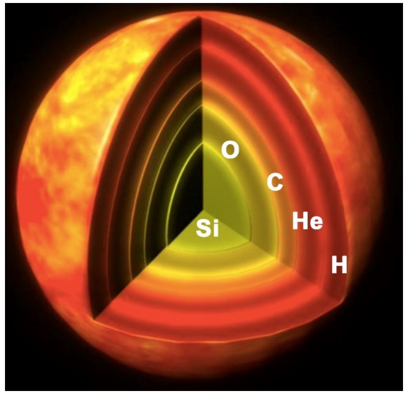
超純水を左→右に10 mL/min



- Portable system
- Wider dynamic range for Gd collection monitoring

Pre-SN alarm for nearby SNe (<400pc)





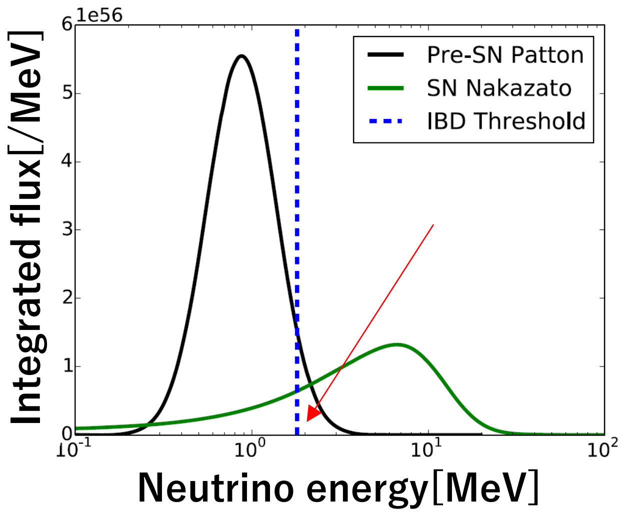
Burning Stage	Duration	Average ν energy
C	300 years	0.71 MeV
Ne	140 days	0.99 MeV
O	180 days	1.13 MeV
Si	**2 days**	**1.85 MeV**

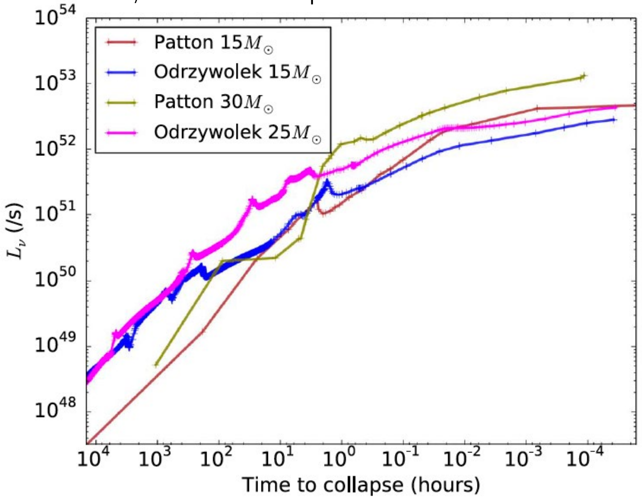
Duration of burning stages and the fraction and average energy of electron neutrinos emitted by **pair-annihilation** for a 20 M⊙ star (**Astropart.Phys. 21 (2004) 303-313**)

- and many Models･･･

Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611
Patton, et al 2017 ApJ 851 6

ApJ 885:133, 2019



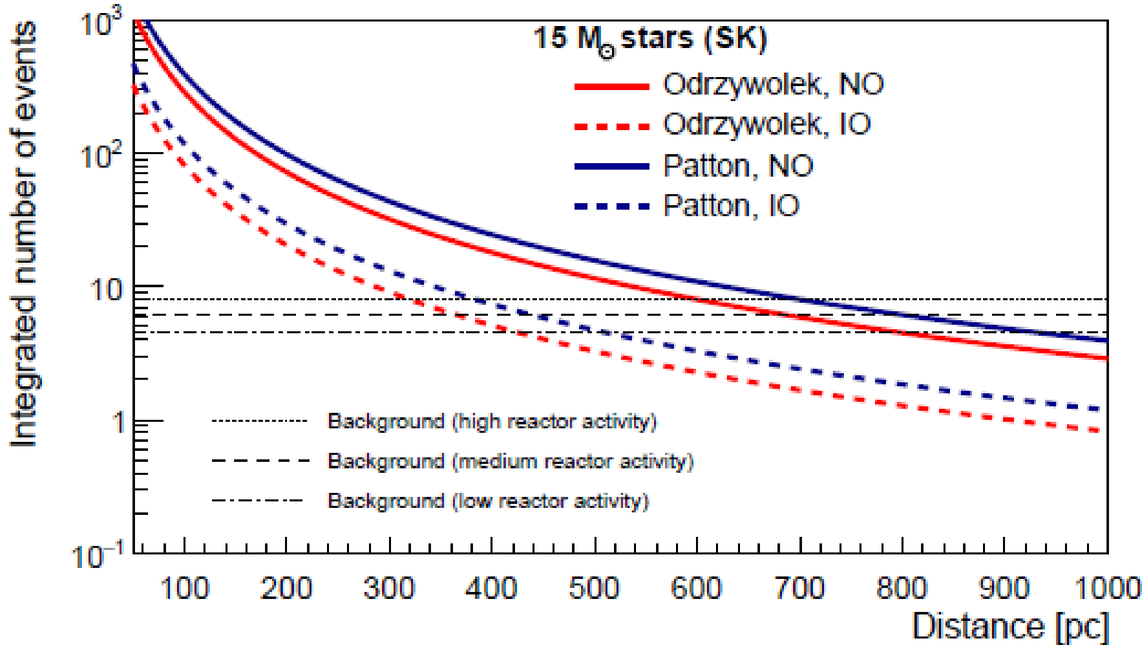


- IBD is the main channel
  - The energy threshold for IBD is 1.8 MeV
- Low-BG low-threshold required

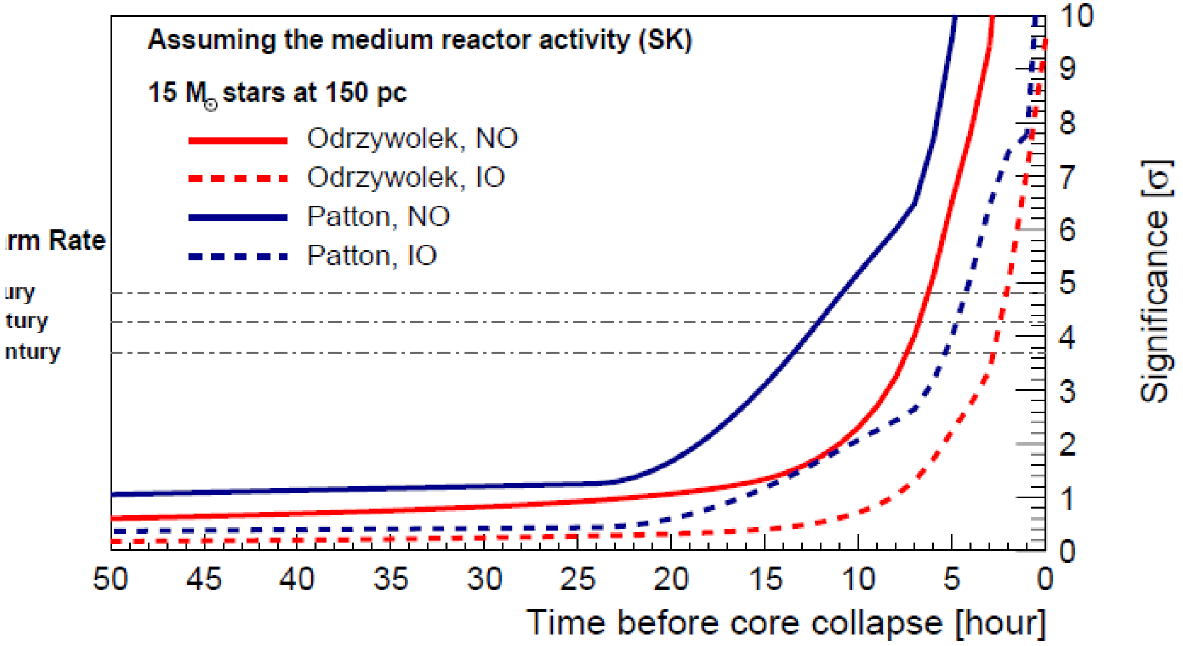
Pre-SN alarm

- **During the KamLAND offline period, SK's role is important.**
  - SK only GCN_circular?
  - Faster alarm system (like GCN_notice) will be tried.
    - Secure the reliability

Number of events in past 12 hours



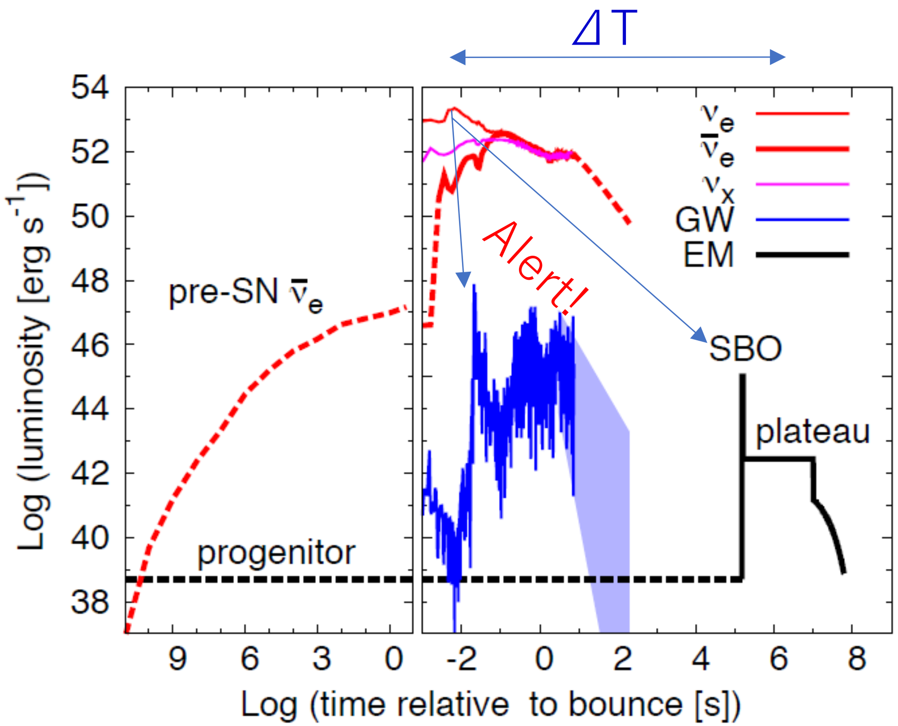
Warning significance for 150pc SN



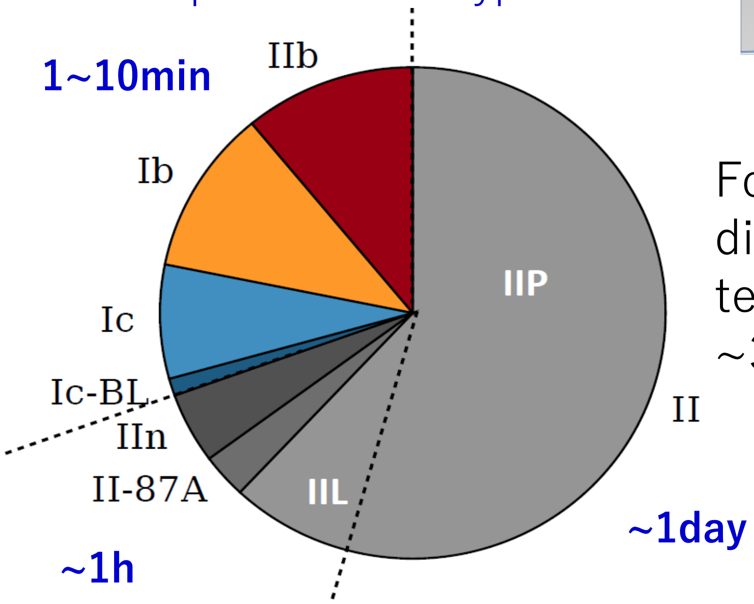
For Betelgeuse (-Ori) we can send a warning ~10 hours before the core-collapse (NMO).
The rate+shape method will be implemented.
Of course, once KamLAND comes back, the coincidence alert is a critical tool for the astro community

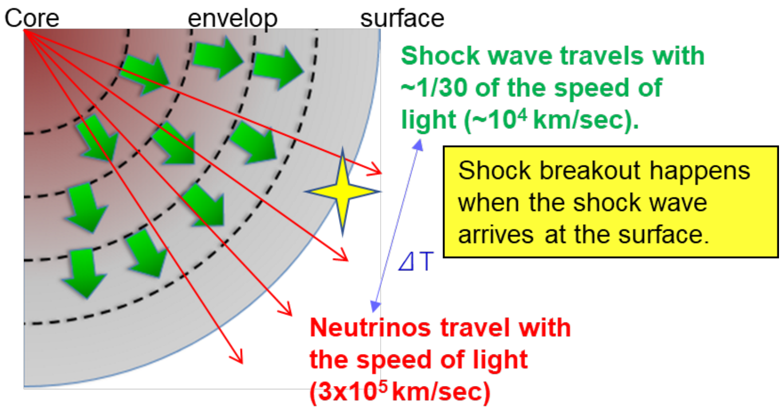
The neutrino burst alarm

The vital role for Super-Kamiokande



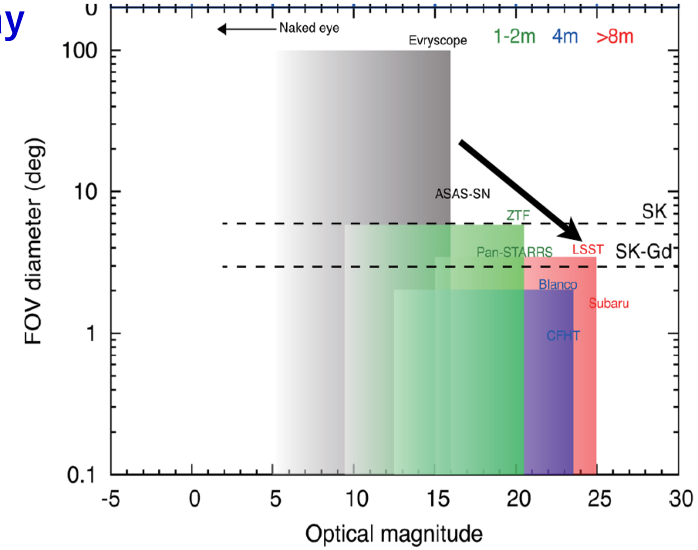
⊿T depends on the type of SN



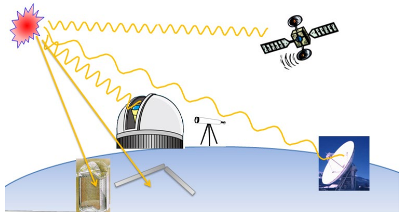


For ~70% of SNe, the time difference is several hours to tens of hours. For the remaining ~30%, that is several minutes.

K. Nakamura MNRAS, 461, 3296 (2016)

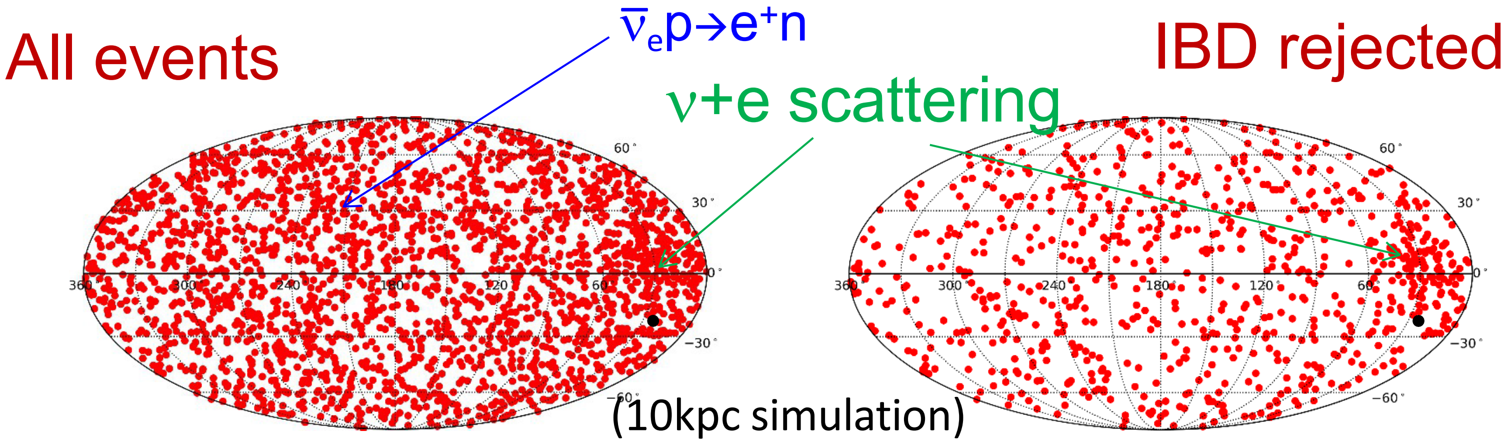


- **Neutrino burst alarm <~1 min. with the DIRECTION INFORMATION <~3^o must help the pointing of EM telescopes**



Realtime supernova monitoring of SK-Gd

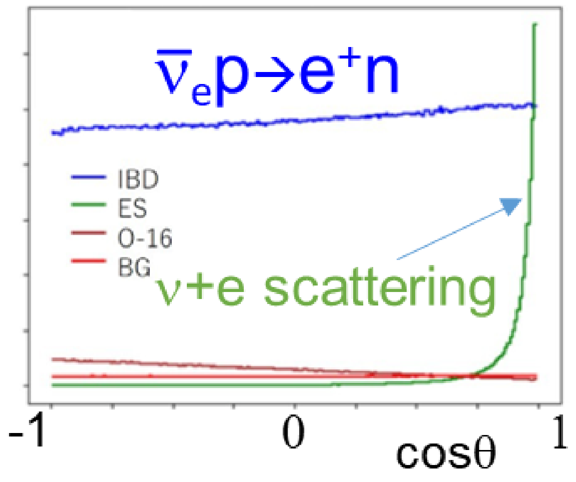
Pointing accuracy has been improved with Gd

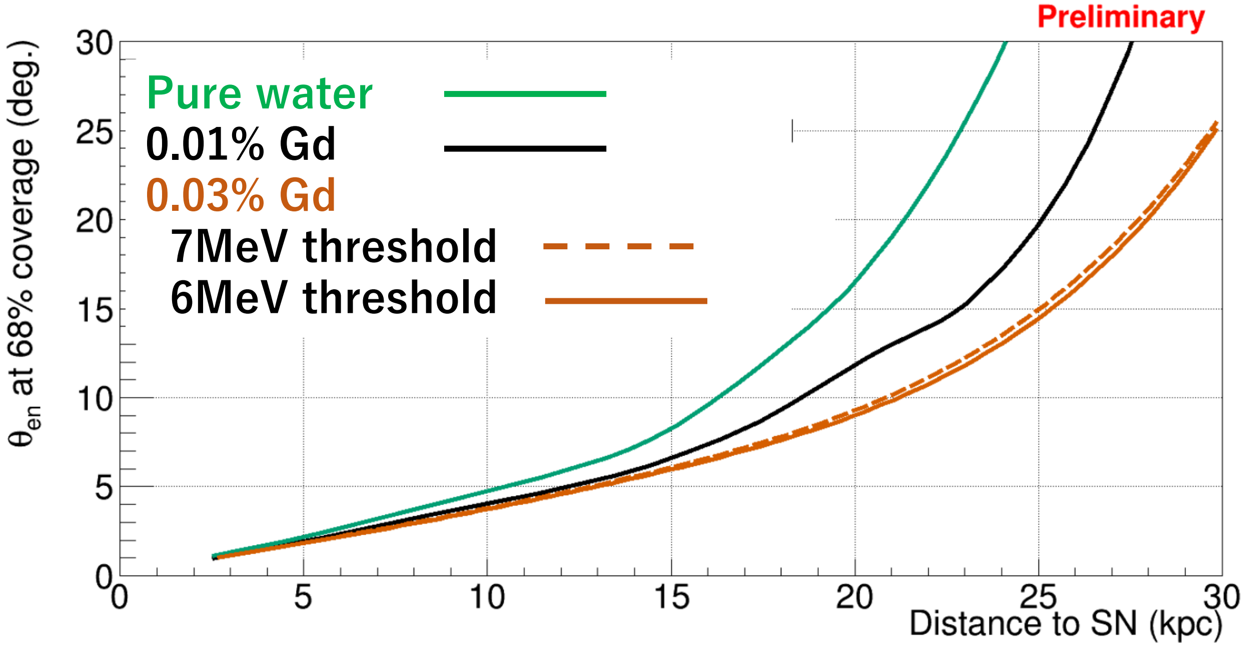


SN burst events w/o IBD tagging

SN burst events w/ 72% IBD events tagged/removed

Angular distribution of each interaction





Nakazato 20M$_\odot$

z=0.02, 200ms (NMO)

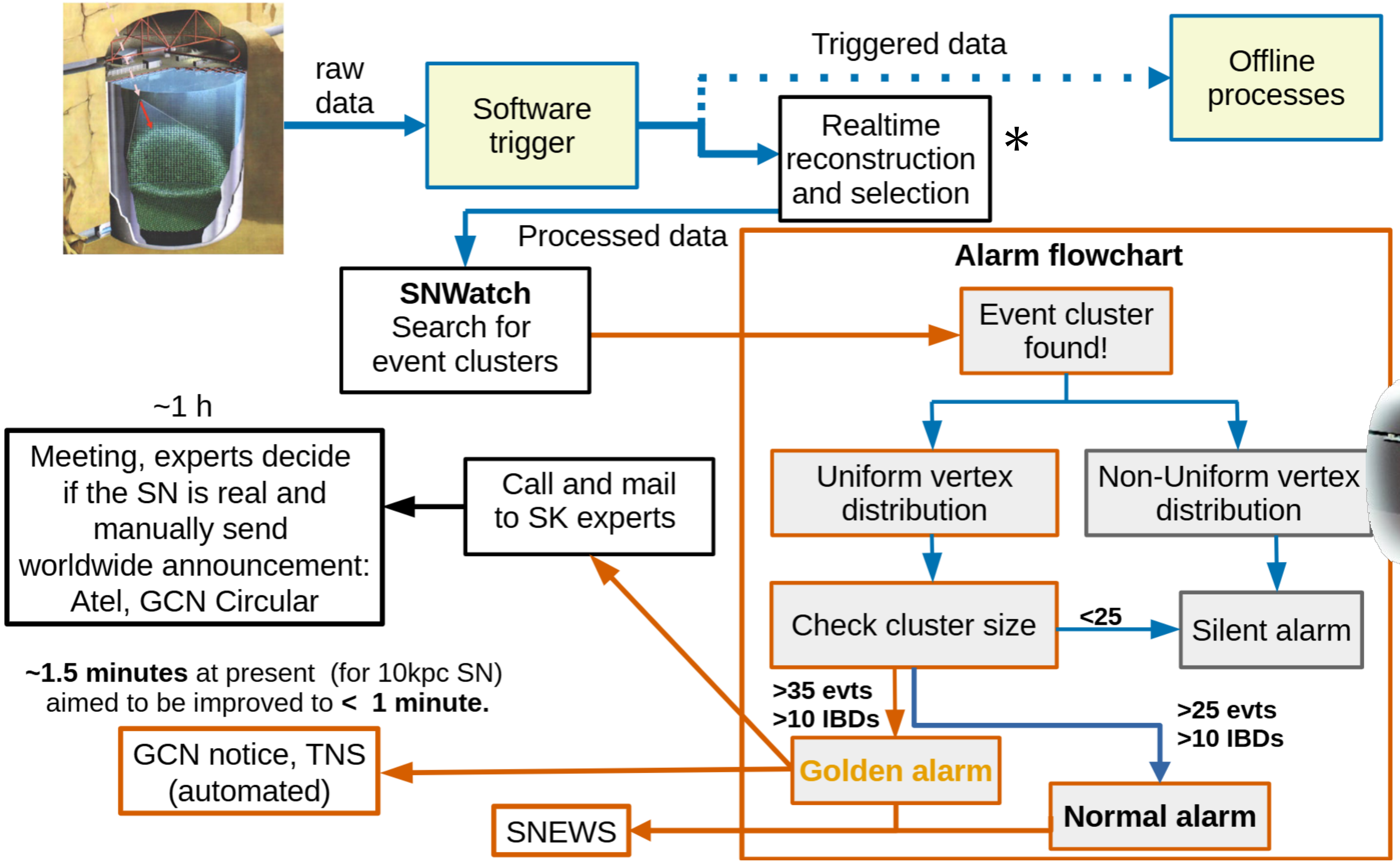
Current status

With 0.03% Gd (46% IBD tagging efficiency), the supernova direction pointing accuracy is **~3.7 degrees at 10 kpc.**

Realtime supernova monitoring of SK-Gd

“SNWatch.” will send automatic alarms within 1.5 min for a 10kpc SN

Golden alarm to GCN Notice and TNS <u>with direction info</u>.
Normal+Golden alarm to SNEWS <u>without direction info</u>.

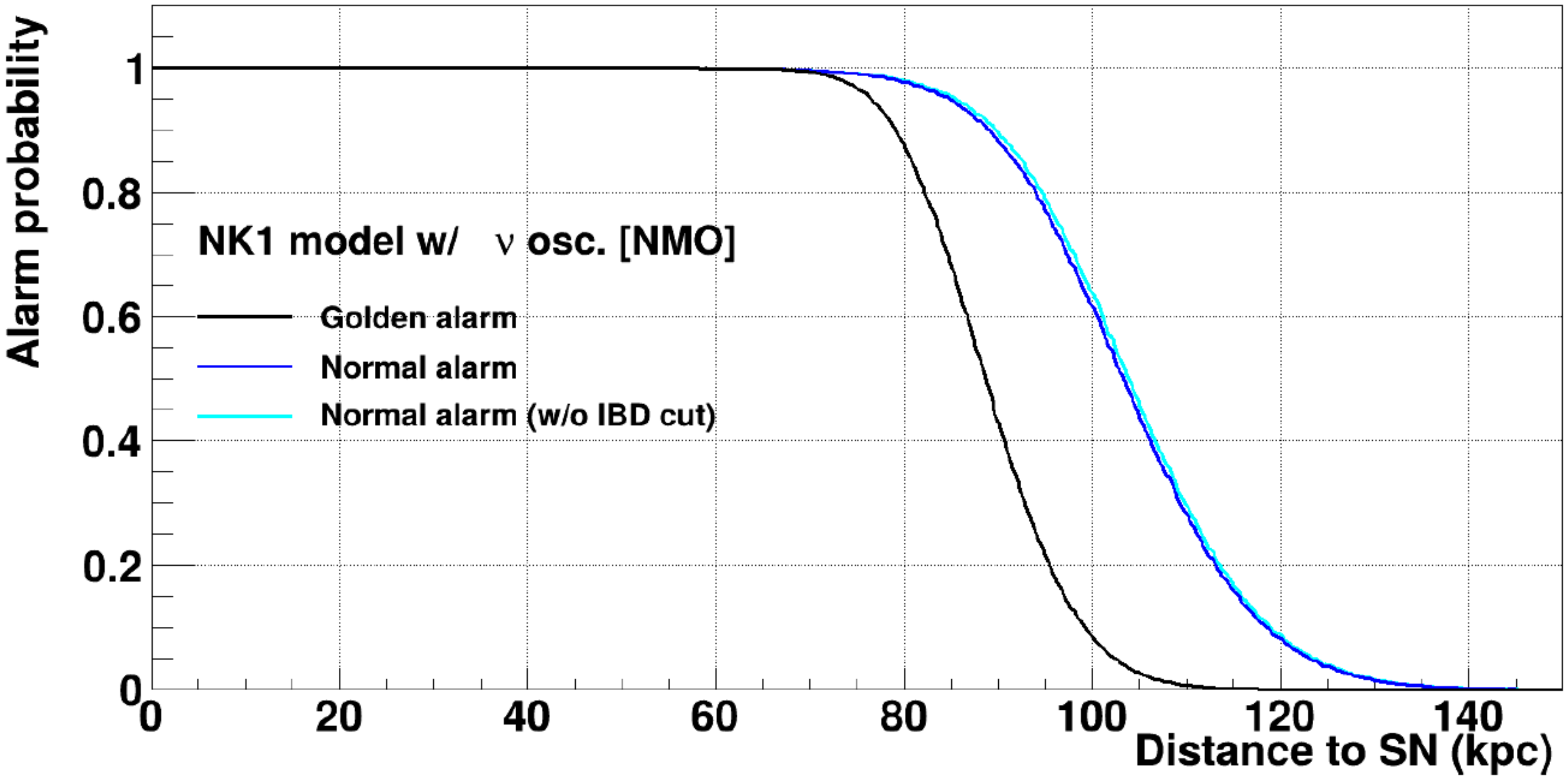


* **Fast analysis:**
- vertex reconstruction
- direction reconstruction
- energy reconstruction
- **Inverse Beta Decay candidates selection**

→GCN Notice via Kafka
https://kafka.apache.org/
open-source streaming platform

Realtime supernova monitoring of SK-Gd

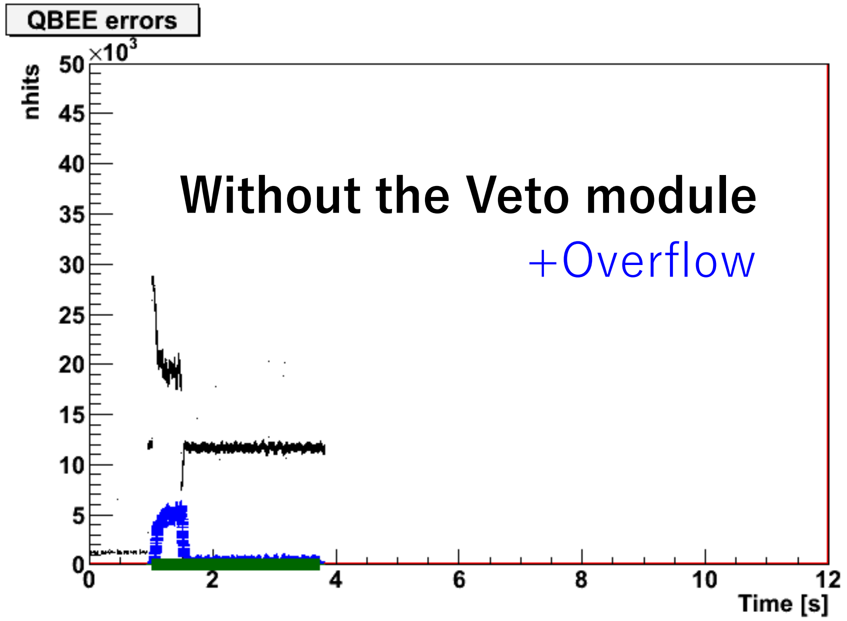
In case of supernova, SK would detect a burst of events for SN happening up to >100kpc (depending on the models assumed), and send **Golden alarms** (automated) and **Normal alarms** (non-automated)
▷Both LMC and SMC are covered by the Golden alarm

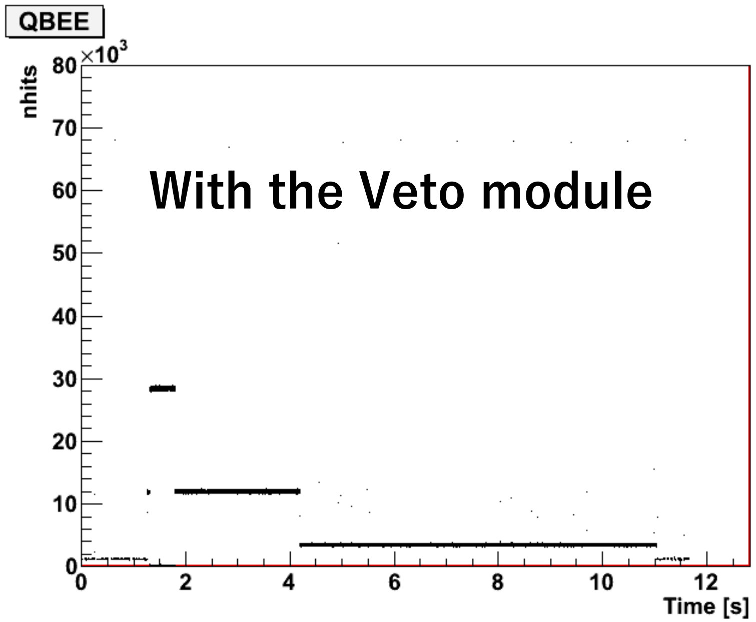


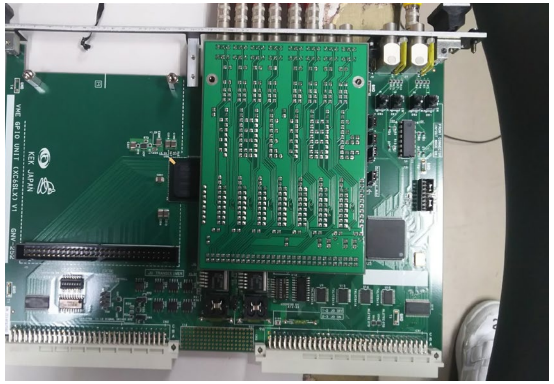
Close supernova detection

Mori et al. PTEP 2024 103H01

- In case of very close supernova bursts, the amount of neutrino interactions may be too high for the Super-Kamiokande electronics system, causing overflow.
- We have developed two modules to prevent this issue
  - A “SN module” which records the number of PMT hits over time
  - A “veto module” which **prescales** the number of PMT hits to prevent overflow, enabled when a pre-SN alert is detected

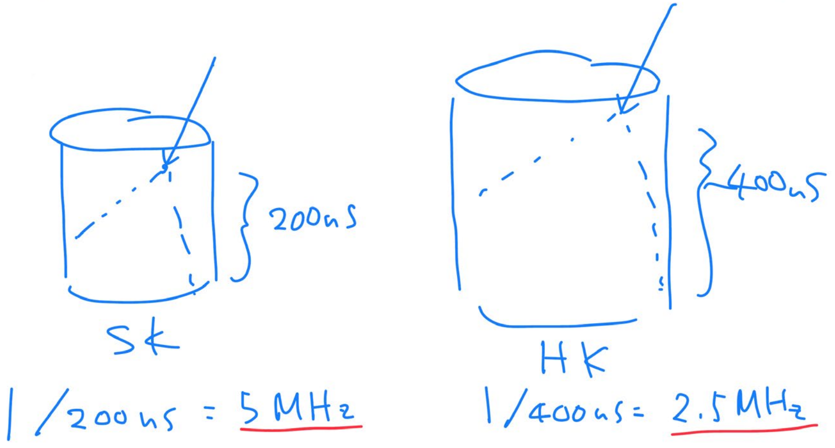




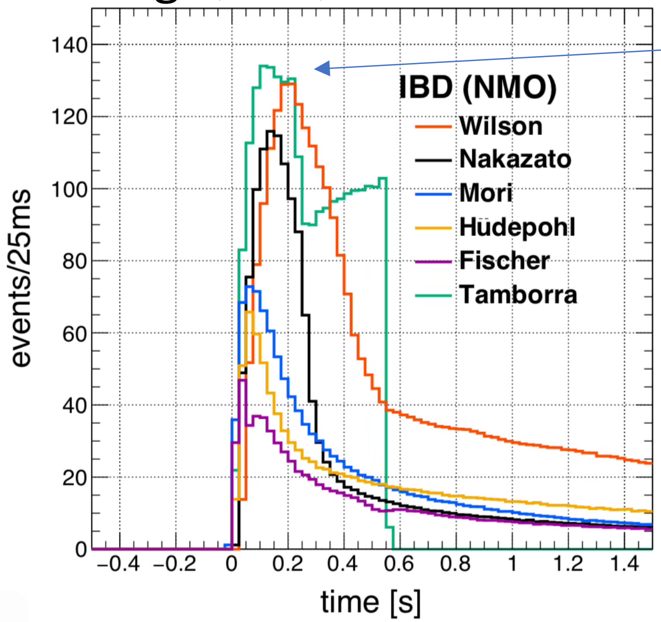


SK(HK) Coverage of the SN Burst Monitor

- Pile-up issue
  - overlapping events in the detector

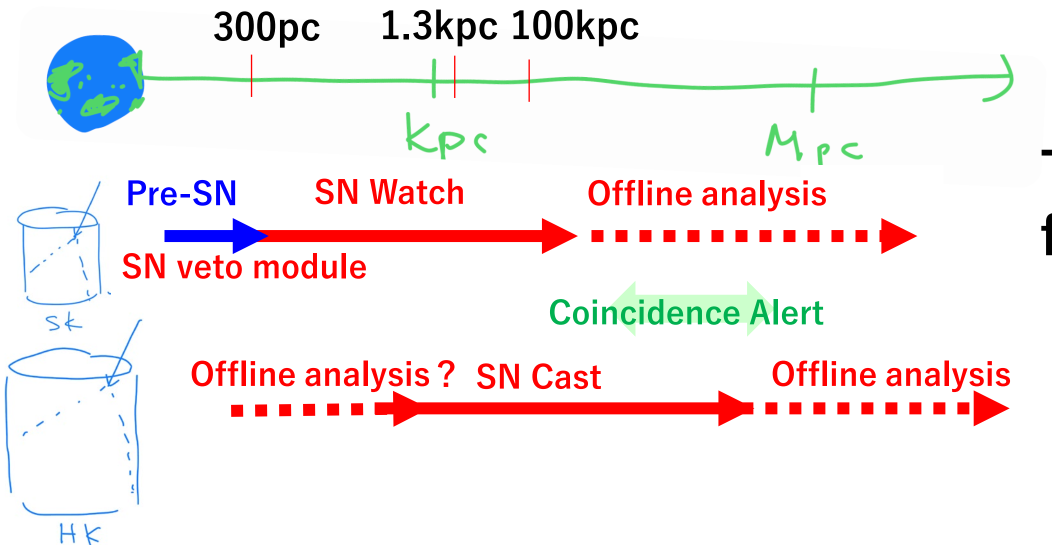


Expected Number of Events in SK
for a Supernova at 10 kpc
Kashiwagi (2024)



SK Threshold Distance for Pile-up
5kHz@10kpc
~5MHz@300pc

HK Threshold Distance for Pile-up
40kHz@10kpc
~2.5MHz@1.3kpc



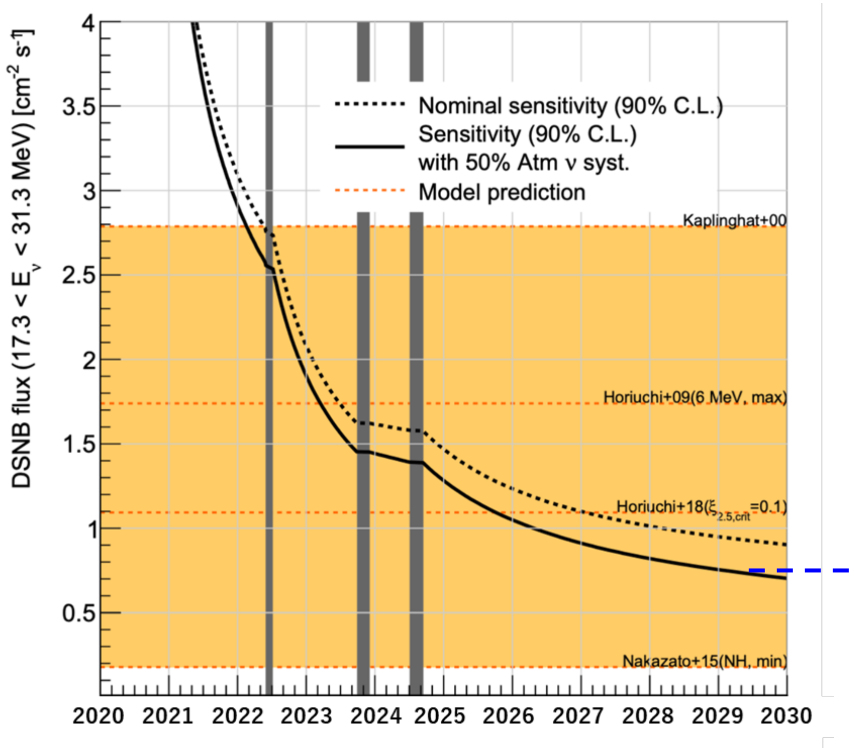
The alarm (angular resolution) is advantageous for SK up to a distance of 1.3 kpc

Of course, if SK/HK coincidence could be achieved, it would be ideal.

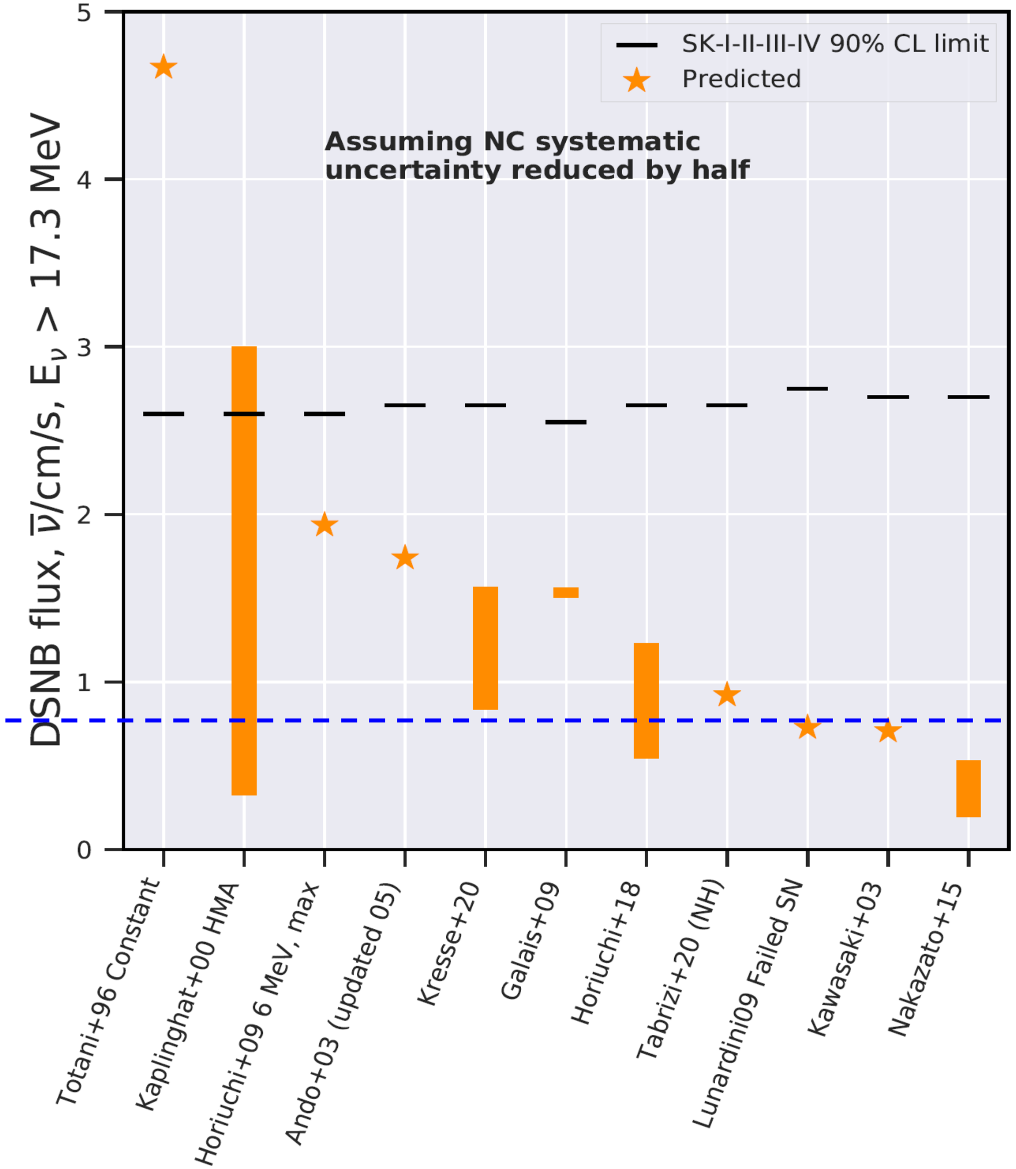
SK's DSNB search prospects

Sensitivity 90%CL

M. Harada



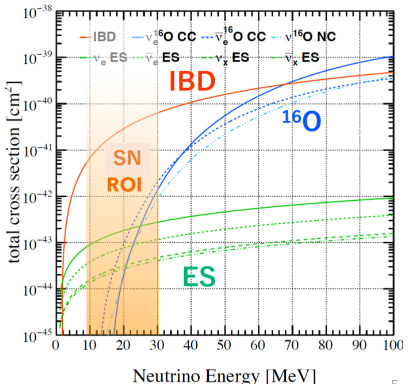
The period of malfunction in the geomagnetic compensation coil: 'SK7.5' phase lasted for 216 days (150 days live time), assuming the same efficiency as SK6.



Super-Kamiokande
Phys. Rev. D **104**, 122002 (2021)

March 2029

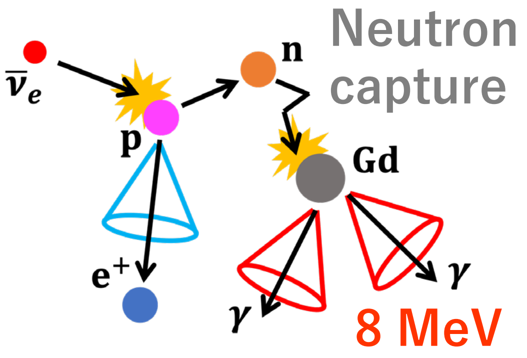
Make use of ^{16}O channel in SK



- They are more complicated topologies than IBD's and ES's.
- All final state particles should be investigated.

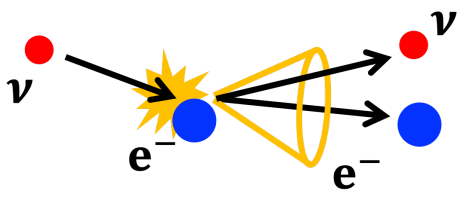
Inverse Beta Decay (IBD)

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



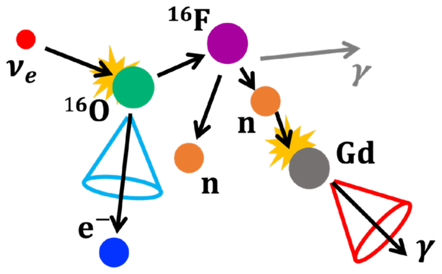
Elastic Scattering (ES)

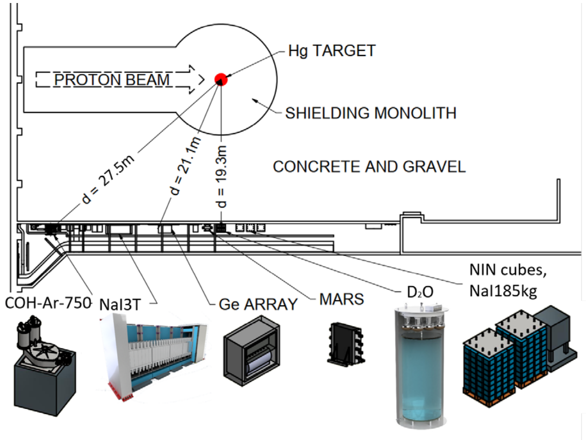
$$\nu + e^- \rightarrow \nu + e^-$$



^{16}O interactions

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

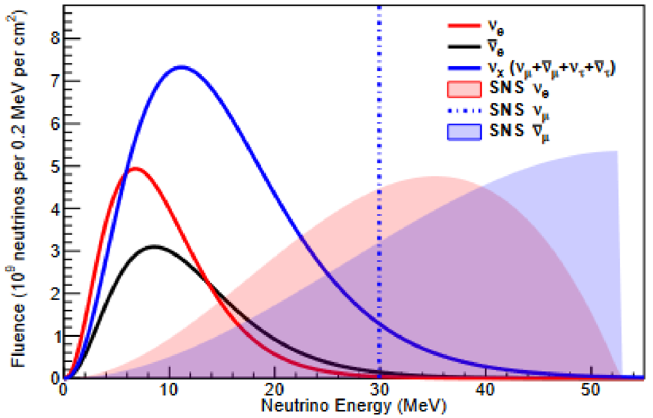




Neutrino interaction measurement at ORNL SNS

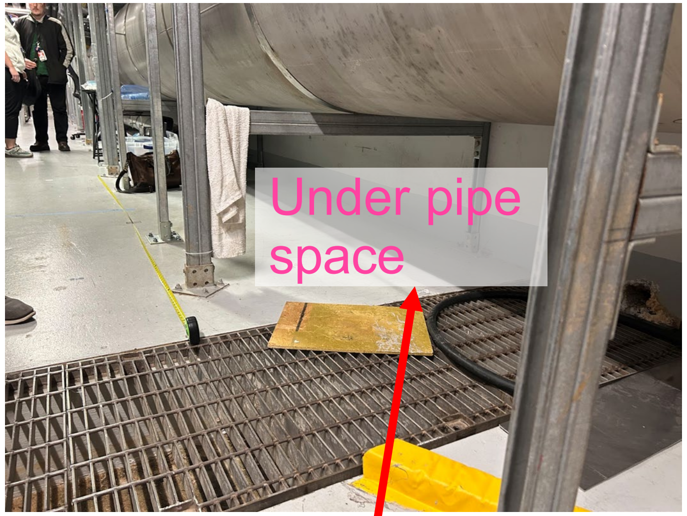
- ORNL SNS is an ideal place to measure these interactions!
- High intensity neutrino available that matches supernova neutrino energy range
- Ongoing D2O detector measurement for precise flux normalization

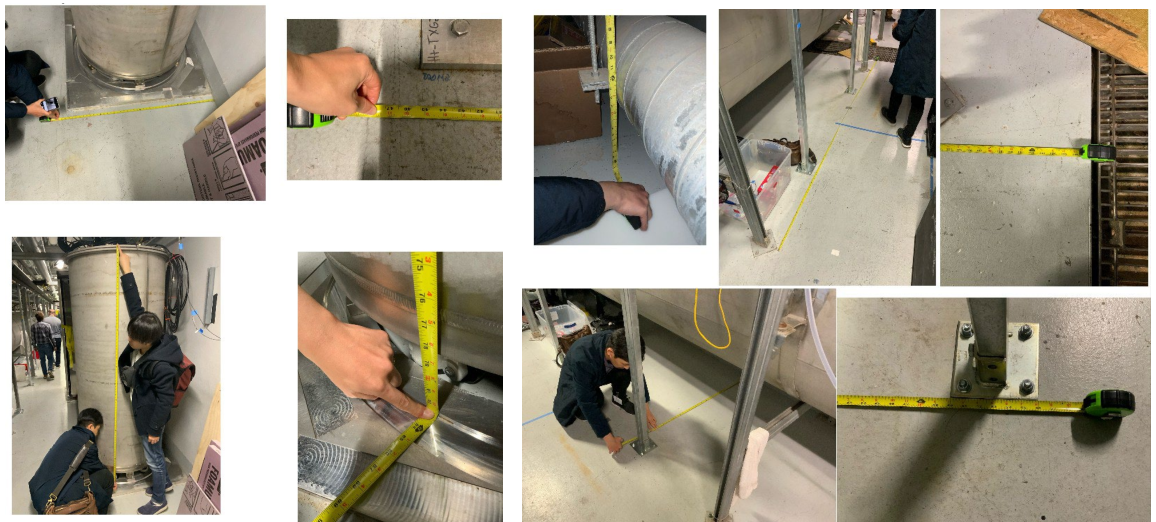
ORNL SNS neutrino spectra

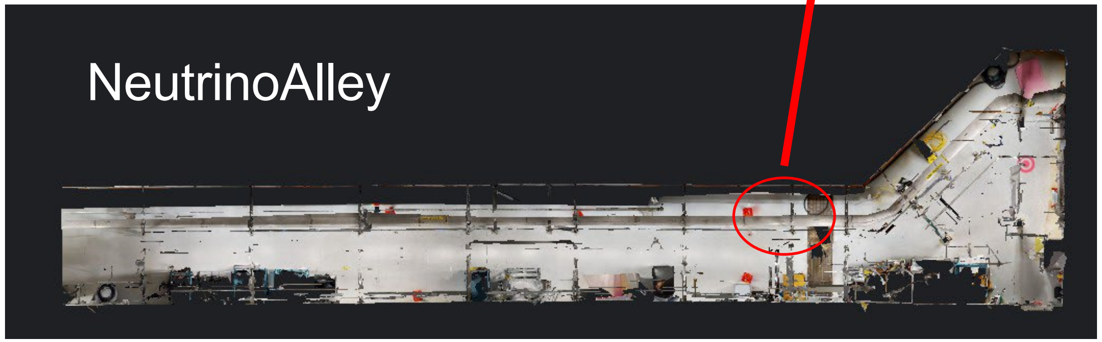


Place to mount our detector

- Visited Neutrino Alley to explore potential detector locations and discuss placement.
- Preferably, the detector should be installed in Neutrino Alley for easy access.
- However, the usual installation area is already occupied, so alternative locations need to be considered.
- One possible option is a low and narrow space beneath the pipe, on the opposite side of the existing detectors.



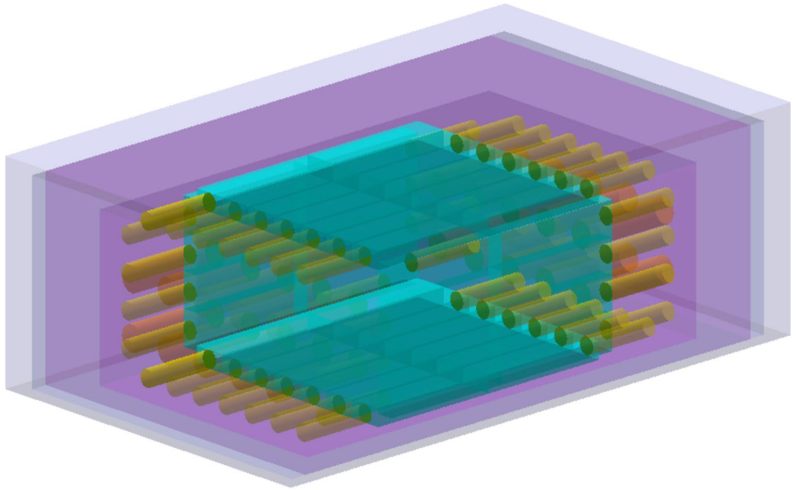


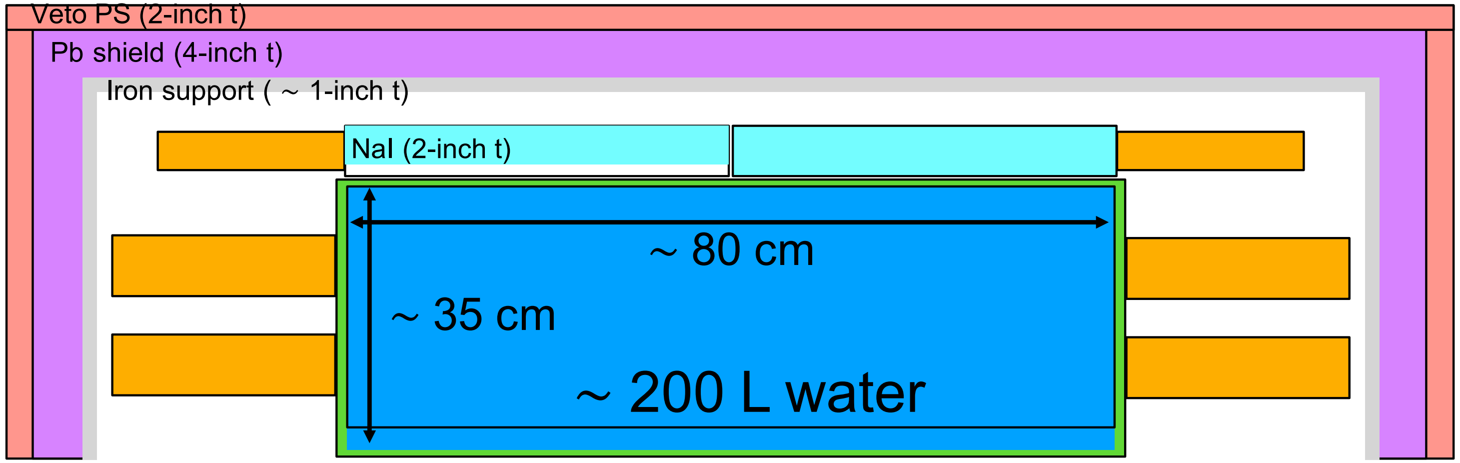


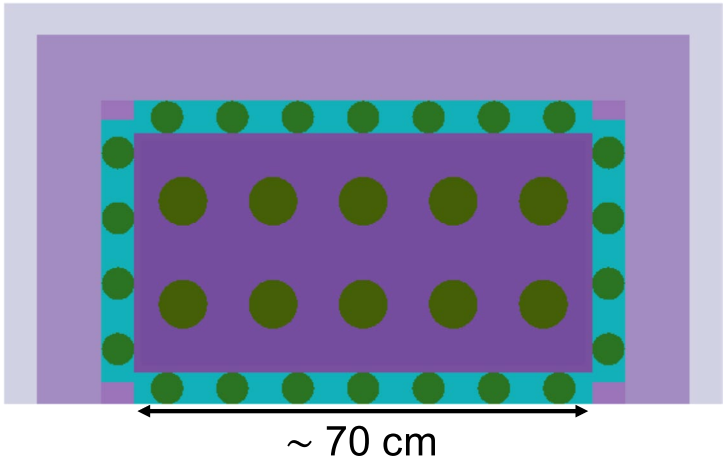
New Design: 200L cuboid detector

Detector Placement and Feasibility Study

- The detector configuration needs to be modified to fit under the pipe.
  - Available space: approximately 2 ft (H) × 4 ft (L) × 11 ft (W).
  - NaI requires 80 cm height clearance; depending on the situation, we may divide the detector into two modules.
- MC feasibility study has been initiated.
  - Geometry construction completed
  - Basic sensitivity study completed

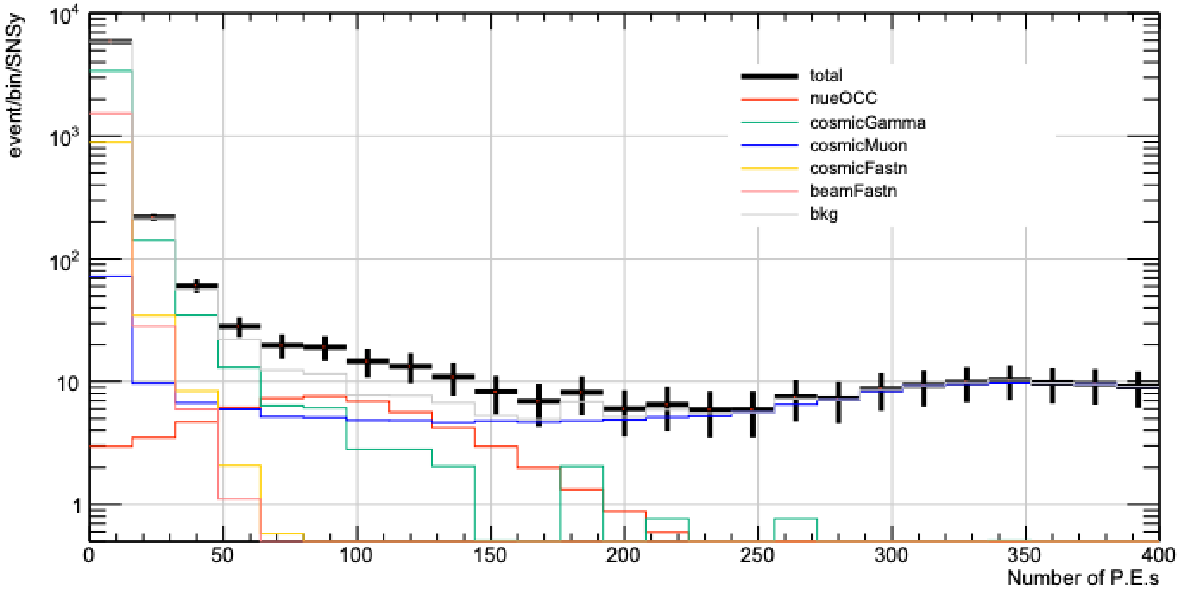


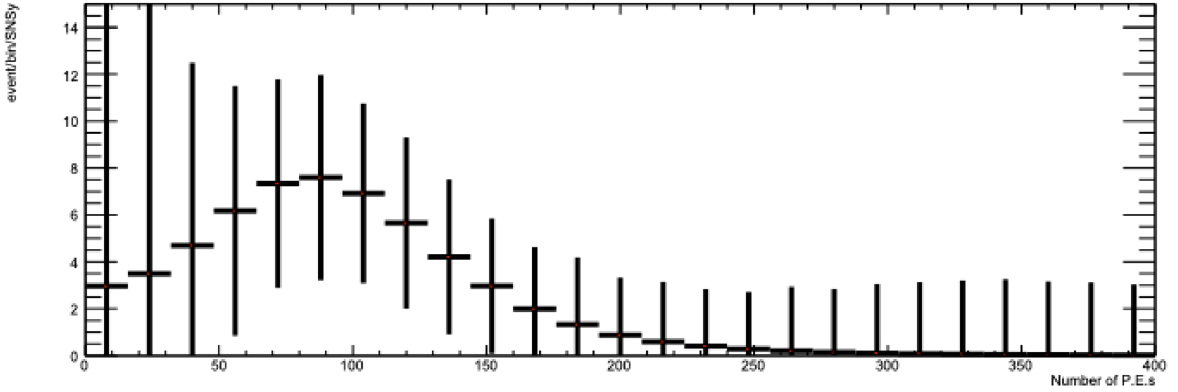




Expected sensitivity

Expected number of photoelectrons compared with the background





- Require energy deposit at veto plastic scintillator (PS) to be < 5 MeV
- Beam-related event rates based on ORNL measurements
- Cosmic-ray induced backgrounds are dominant
  - NaI(Tl) scintillator information not used → Potential to further reduce cosmic backgrounds

~36 ν_e–^{16}O CC events expected (~20% statistical uncertainty)

1 SNS-year exposure

If two detectors can be installed, may reduce exposure time to ~0.5 year

Status of SK for SNe

C01 framework has been strengthened through 公募研究

Pre-supernova

- Continued collaboration with KamLAND even while KamLAND is offline.

Supernova Pointing

- Improved angular resolution with a lowered 6 MeV energy threshold.
- Automated alert issuance to the TNS (Transient Name Server).
- Faster GCN Notice delivery through GCN Kafka upgrade.

DSNB (Diffuse Supernova Neutrino Background)

- Increasing statistics.
- Reducing NCQE background using CNN.
- Reducing systematic uncertainties via improved understanding of T2K NCQE events and spallation.