First DSNB search at SK-Gd and SN related topics SK/HK

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2023.12.3

DBD23

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- First DSNB search result from SK-Gd
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- Summary

Super-K experiment

1000m underground = 2600 m.w.e

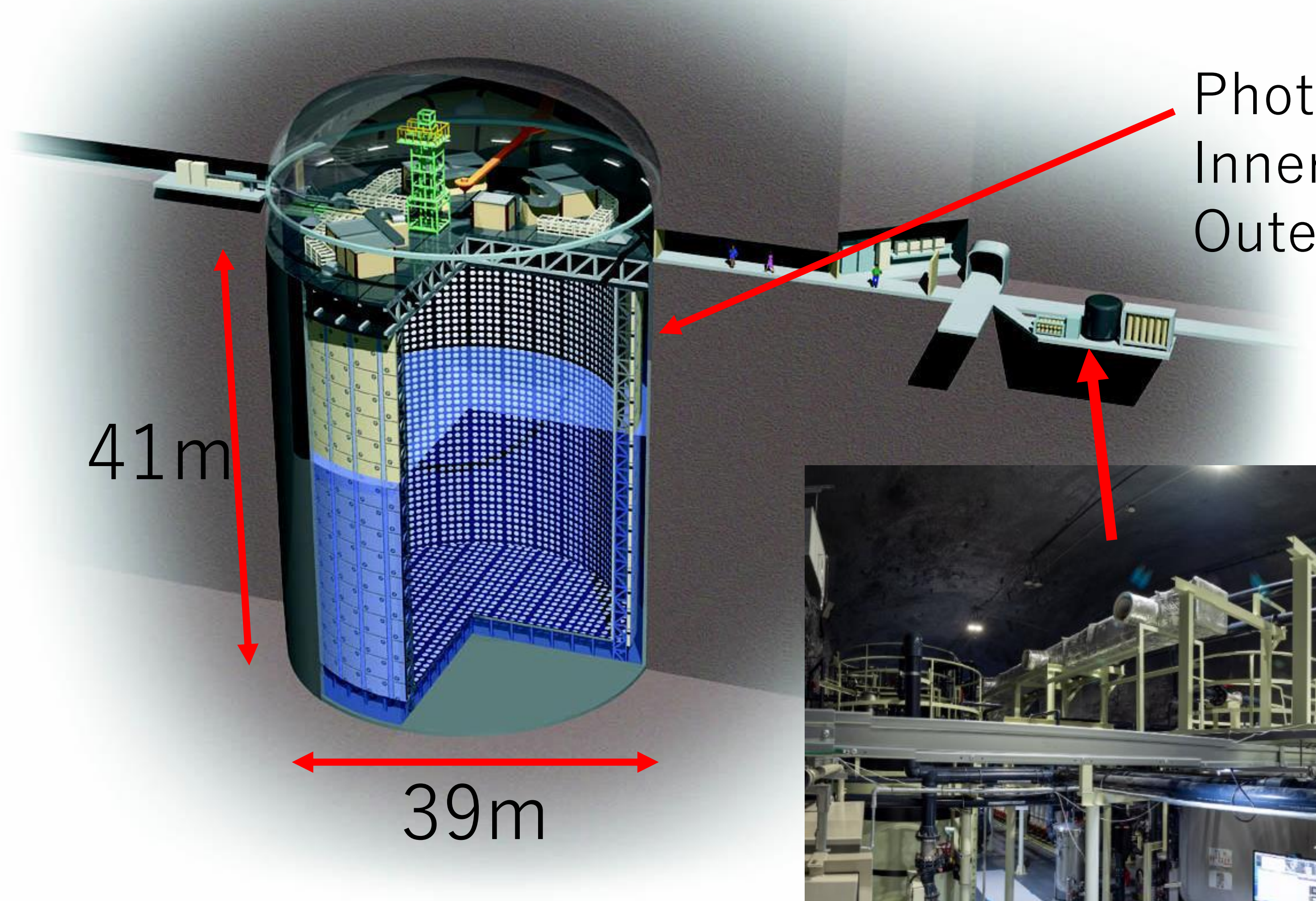


Photo sensors :
Inner detector: 11129 20inch PMTs
Outer detector: 1885 8inch PMTs

Gd water system room

SK-Gd project

Dissolving Gd to enhance detection capability of neutrons from ν interactions

Phys.Rev.Lett. 93 (2004) 171101

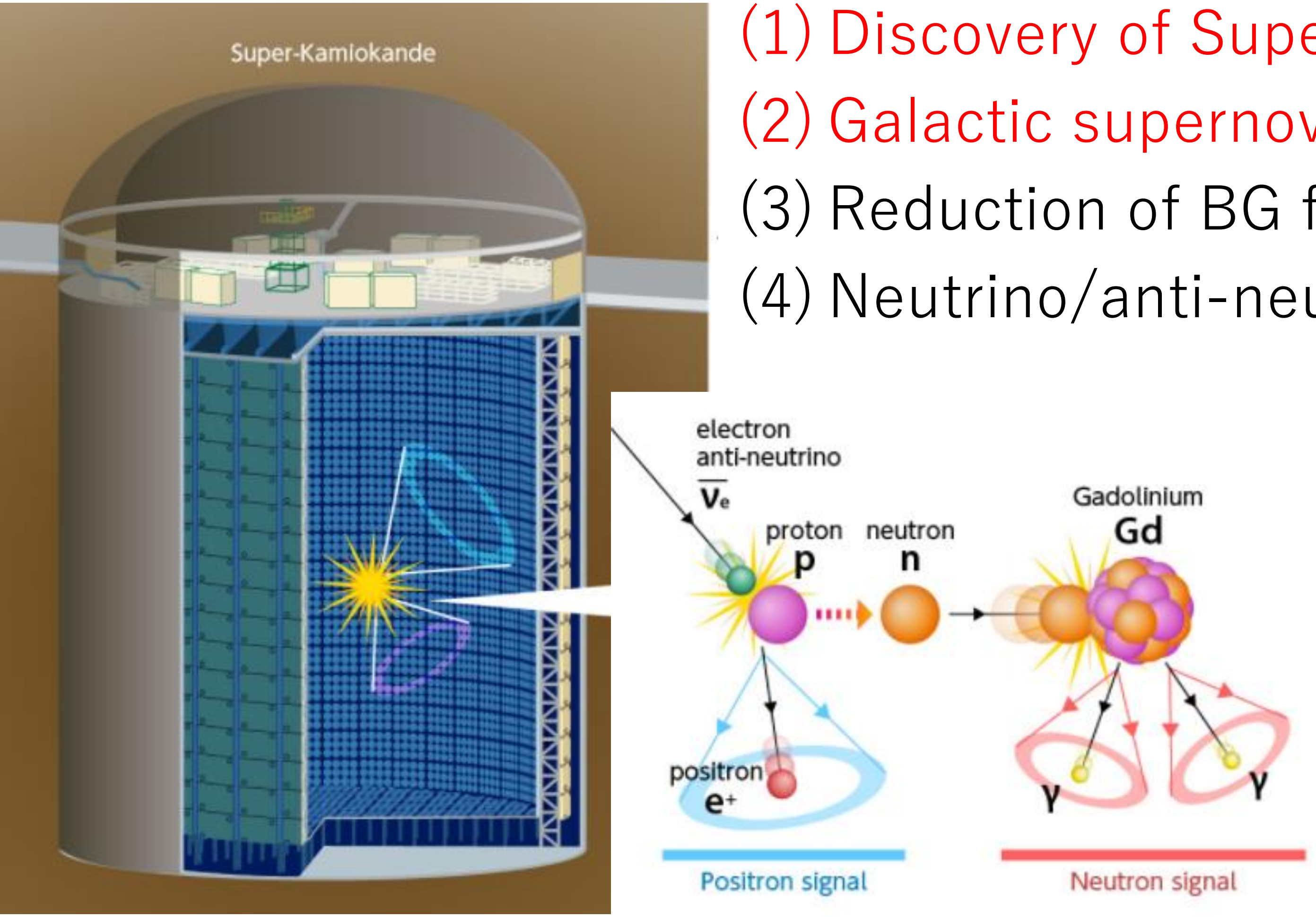
Physics targets:

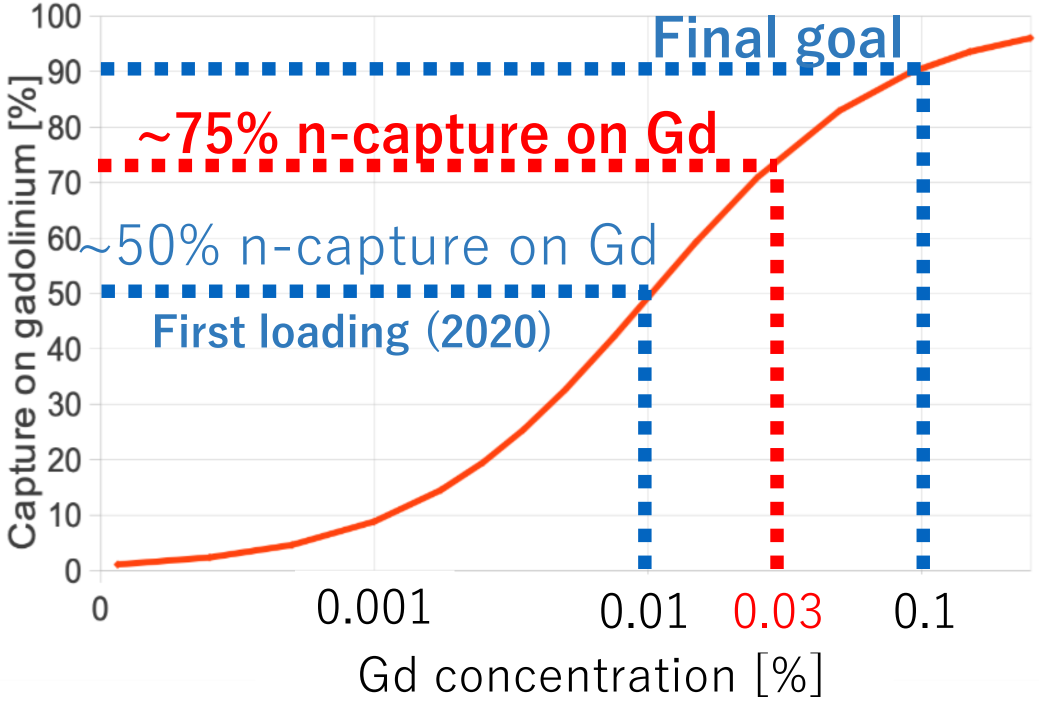
(1) Discovery of Supernova relic neutrino (or DSNB)

(2) Galactic supernovae (pointing accuracy, and pre-SN ν)

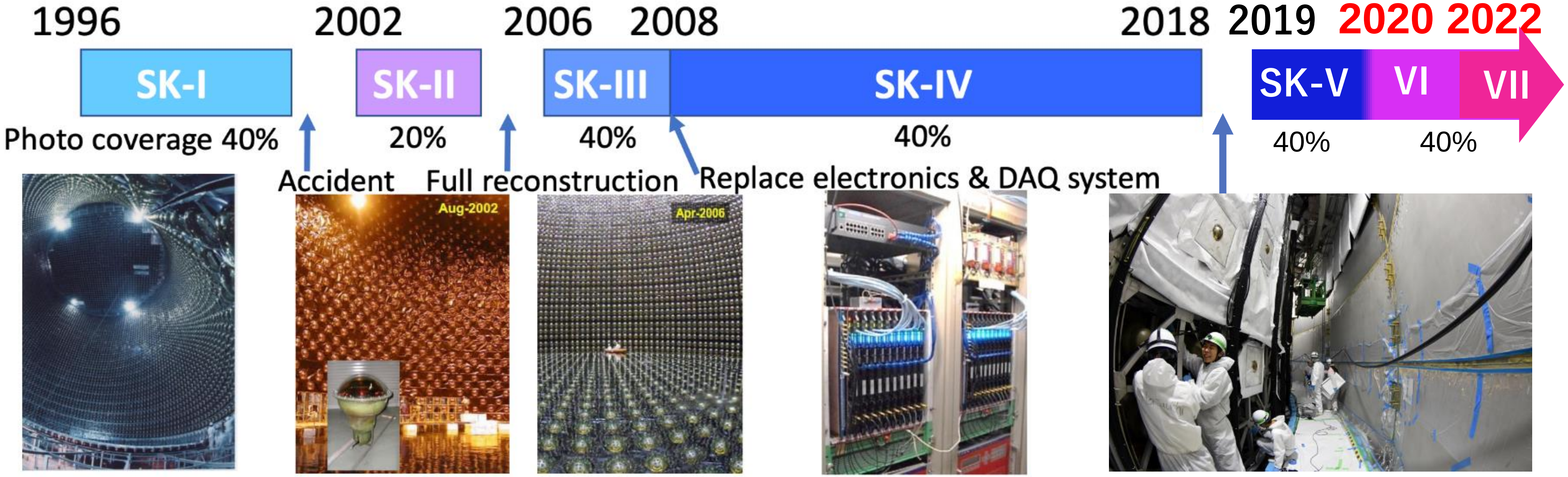
(3) Reduction of BG for proton decay, solar ν , or reactor ν

(4) Neutrino/anti-neutrino discrimination





History of Super-Kamiokande

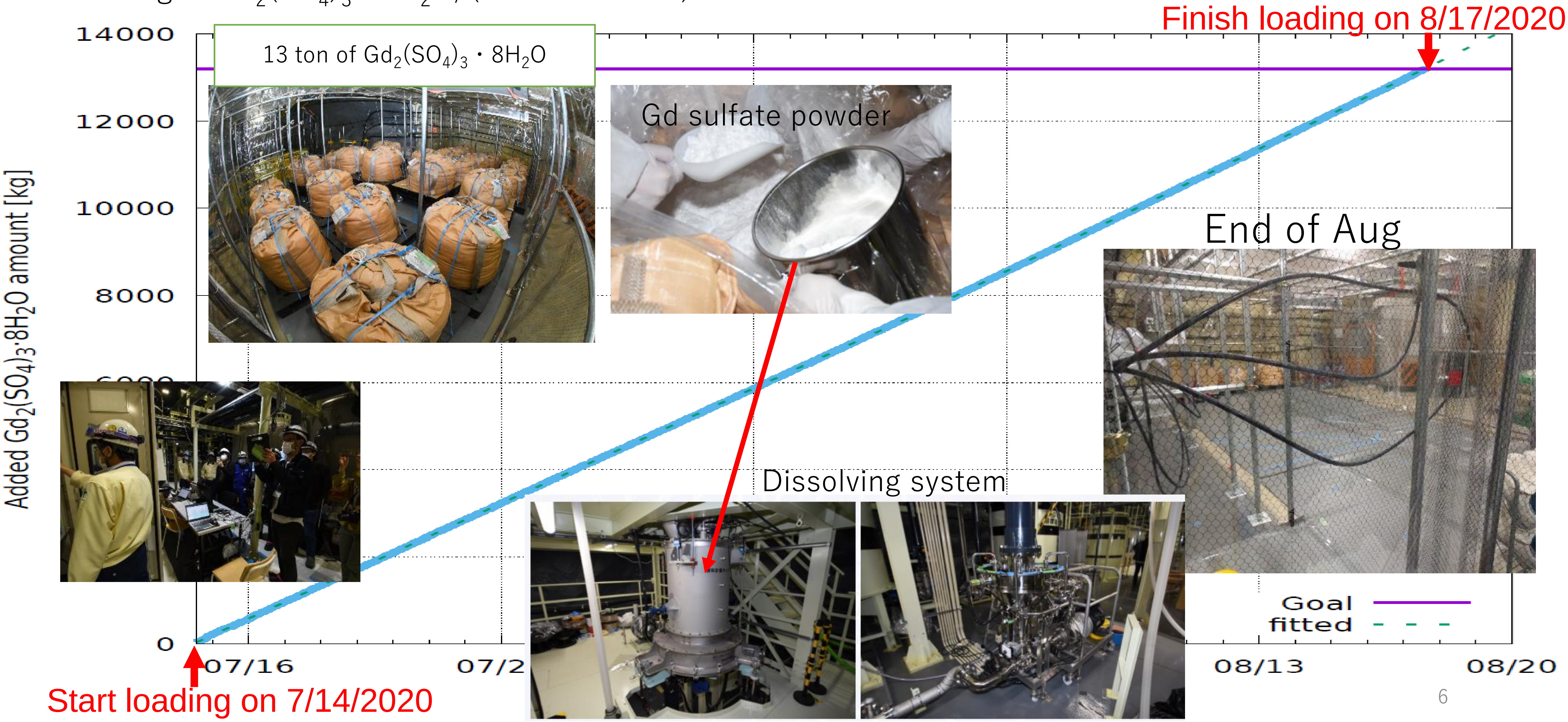


Tank refurbishment

- 1996 Start observation
- 1998 Discovery of the neutrino oscillation by atmospheric neutrino observation
- 2001 Discovery of the solar neutrino oscillation (together with SNO result)
- 2011 Discovery of electron neutrino appearance (T2K)
- 2015 Nobel prize
- 2016 Breakthrough prize
- 2020 Constraint on neutrino CP phase (T2K)

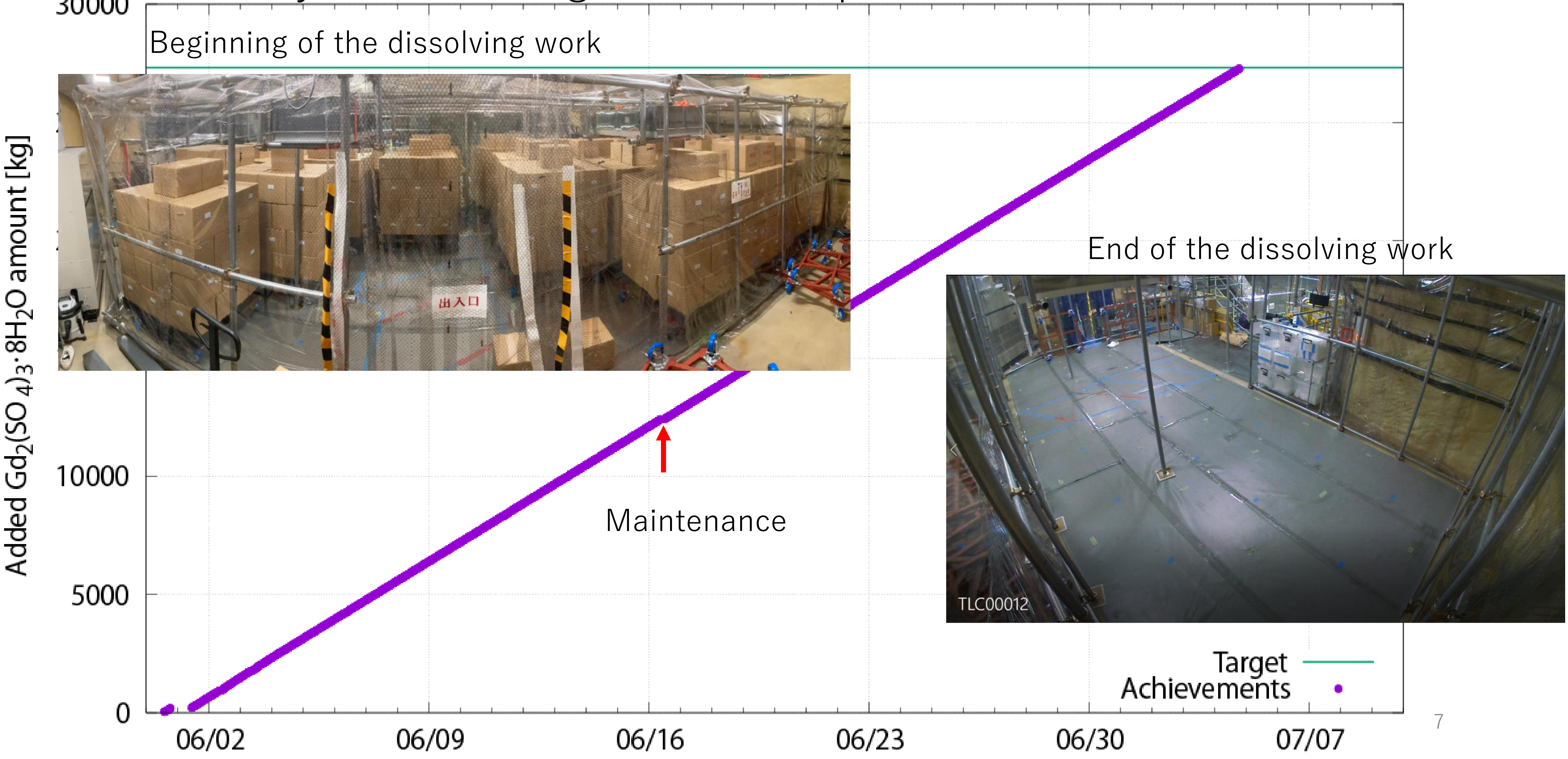
First Gd loading in 2020

- 12884 kg of $Gd_2(SO_4)_3 \cdot 8H_2O$, (=0.011% of Gd) was dissolved into SK water



Second Gd loading in 2022

Very stable loading of 27304 Gd powder has been achieved!



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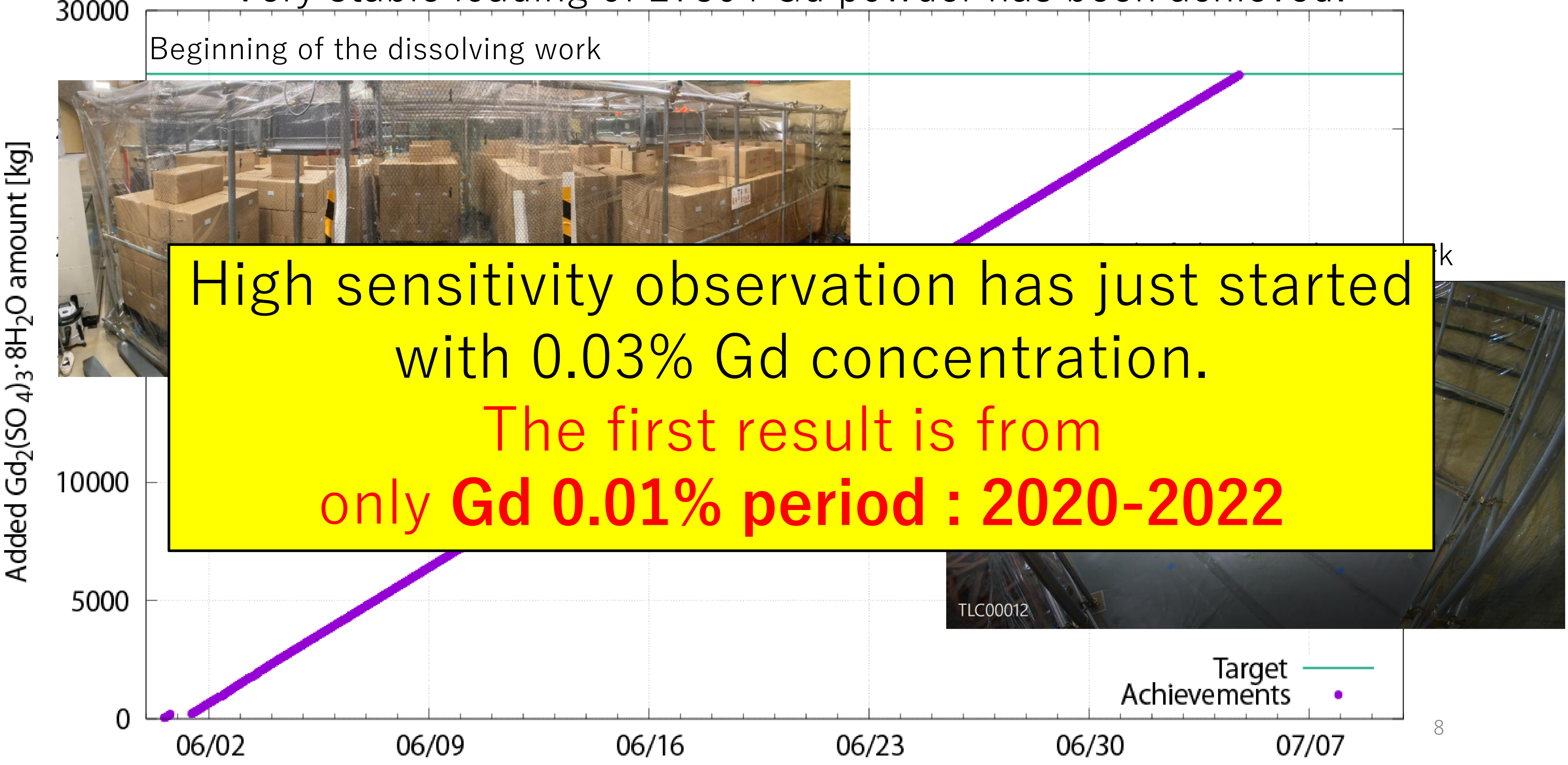
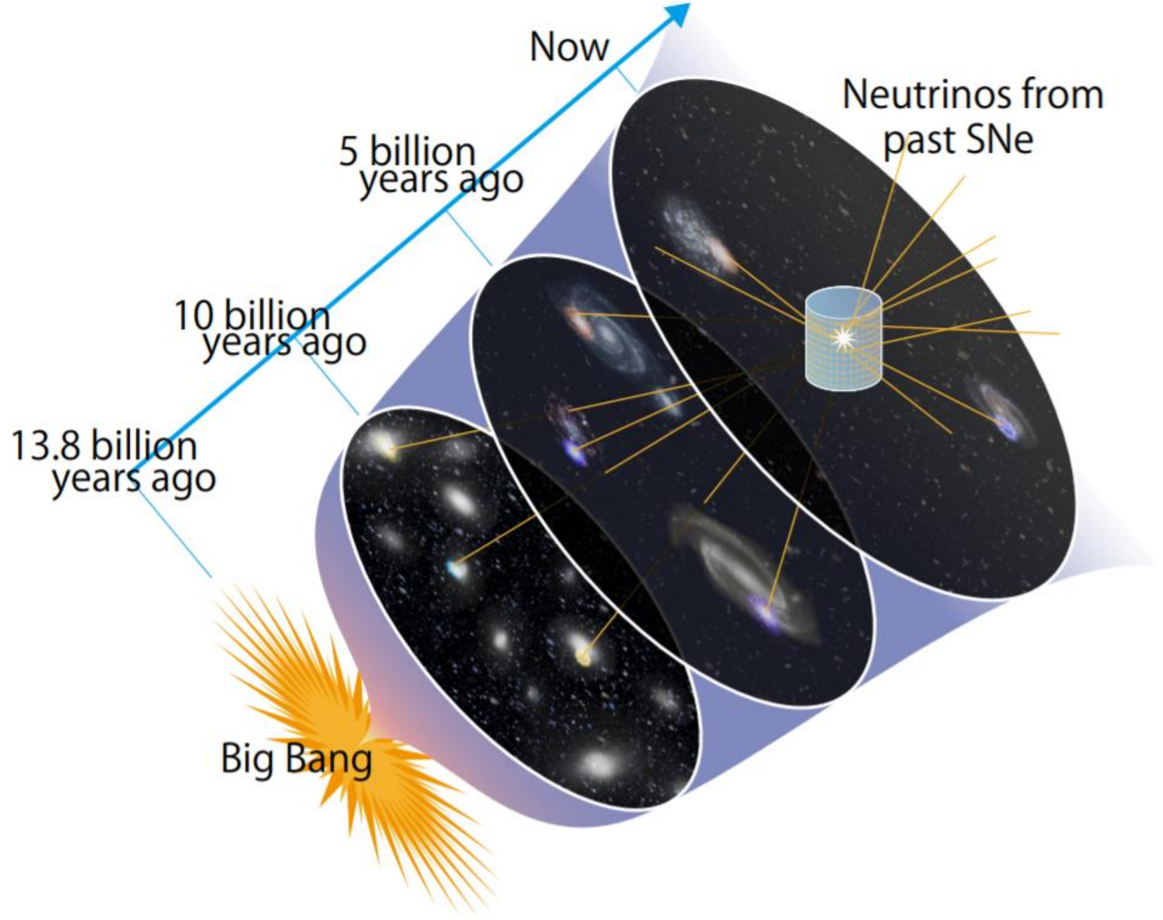


High sensitivity observation has just started with 0.03% Gd concentration.

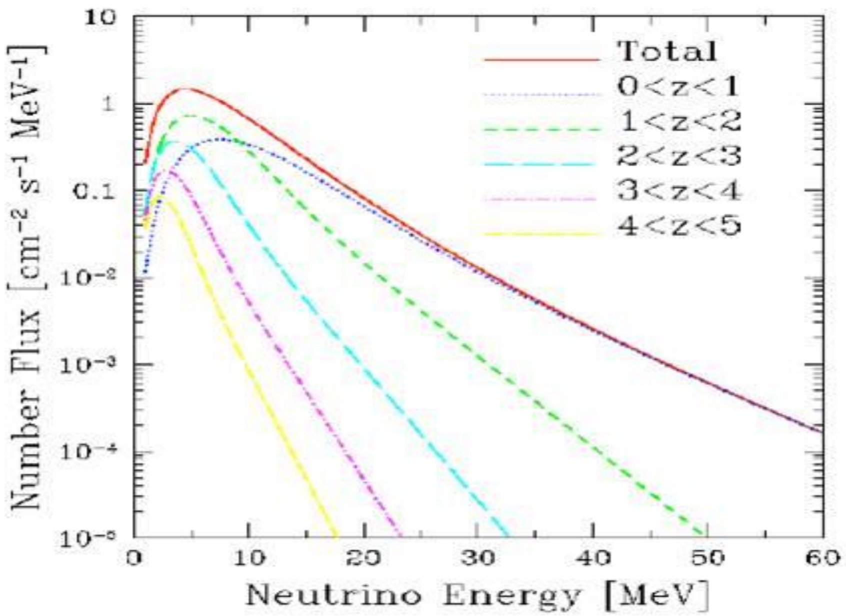
The first result is from only **Gd 0.01% period : 2020-2022**

Diffuse supernova neutrino background (DSNB)

Discovery of DSNB is the first goal



S.Ando, Astrophys.J. 607, 20(2004)



Spectrum also depends on:

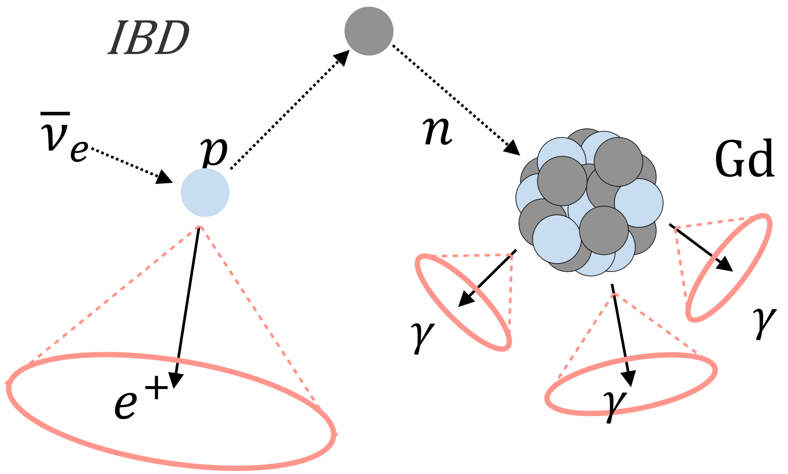
- Supernova rate
- History of massive star formation
- Mean neutrino energy at explosion

Theoretical flux prediction : 0.1~2 /cm2/s (17.3MeV threshold)

Background reduction using neutron

Signal

Only one neutron



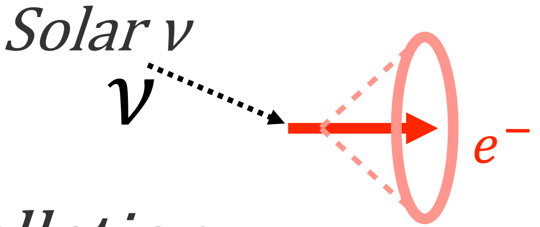
Selection using neutron:

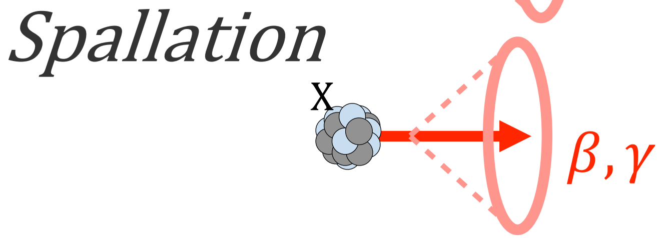
Require only one neutron

after prompt positron event

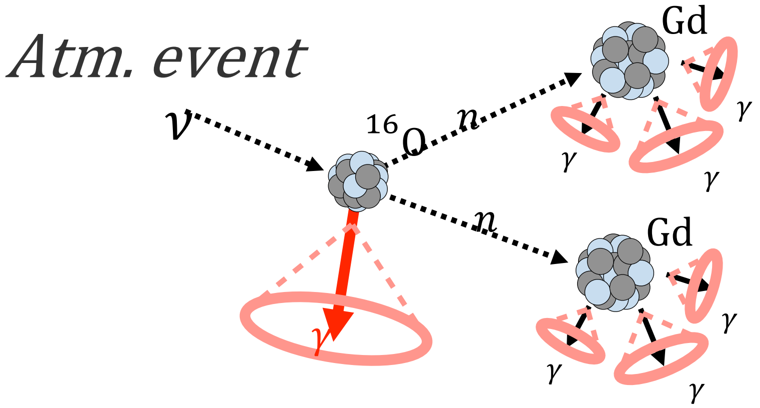
Background

Without neutron





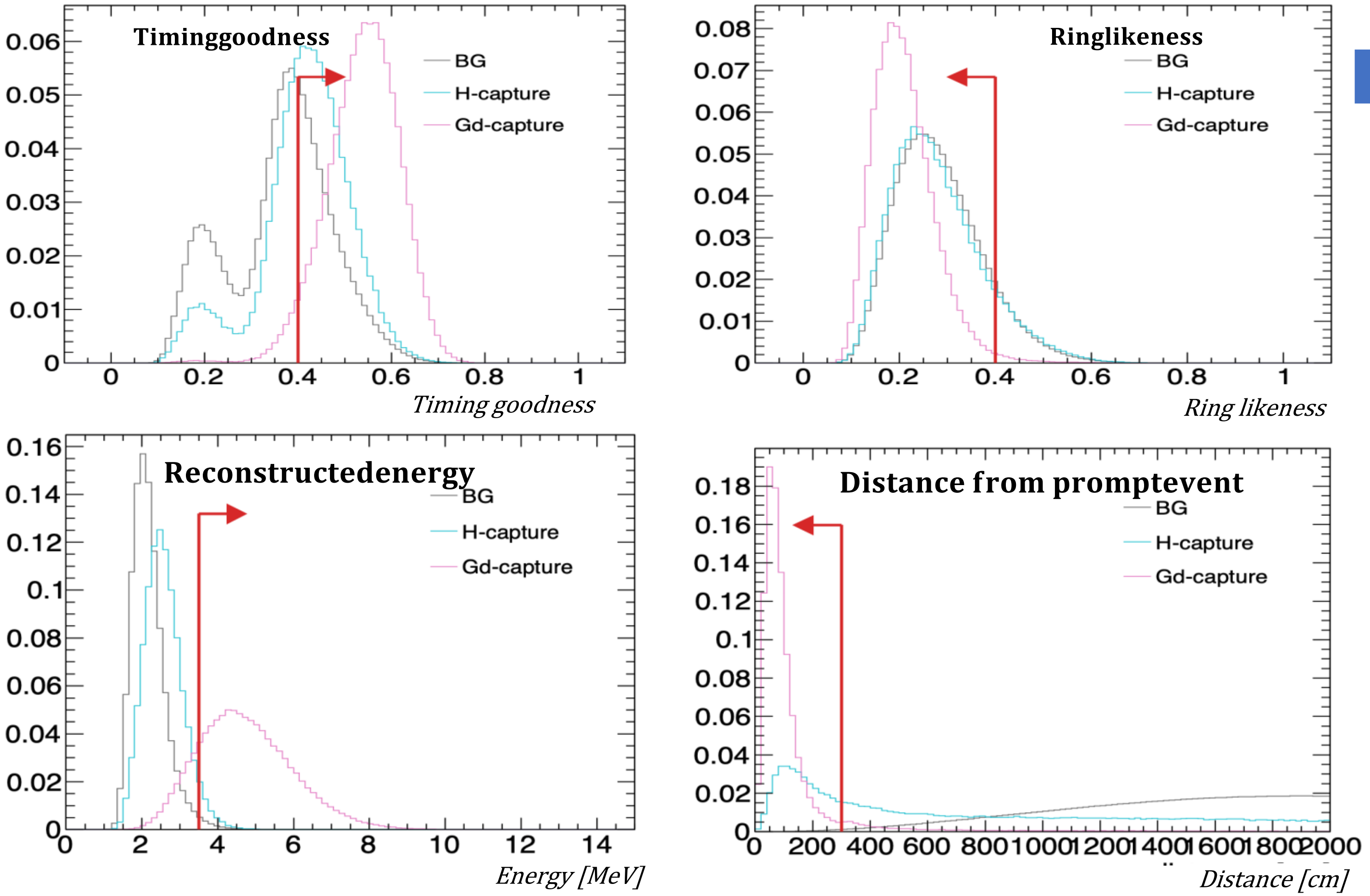
Multiple neutron

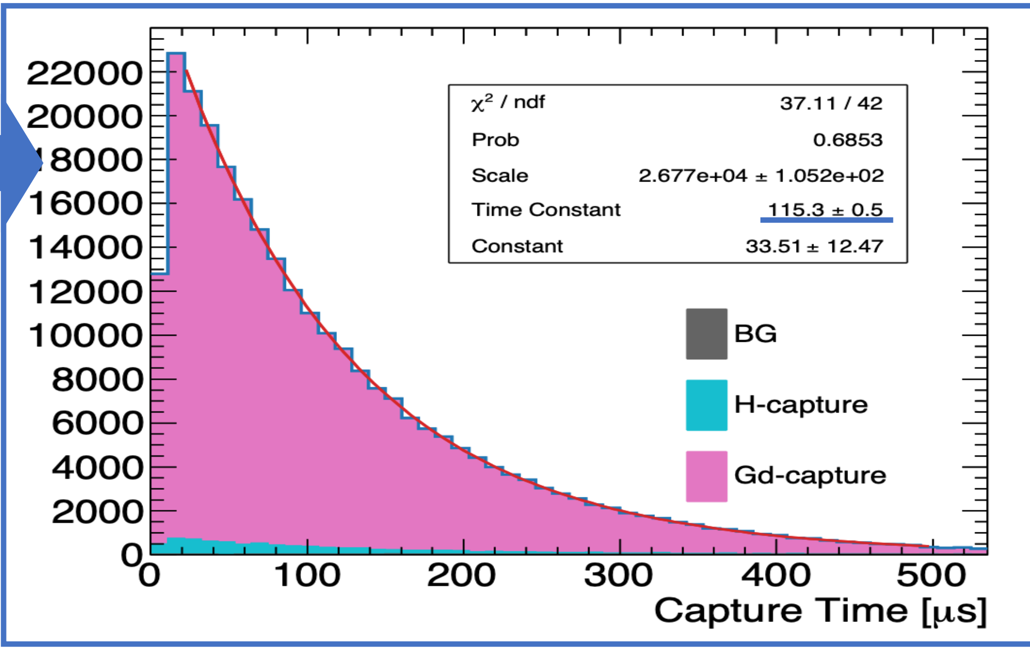


Neutron search in SK-Gd

- **pure-water: ML method to select 2.2 MeV gamma-ray (~ 20%)**
- **This analysis: Simple rectangular cut to select Gd gamma-rays**
- **The neutron tag performance is confirmed by AmBe source calibration.**

Delayed Event Selections





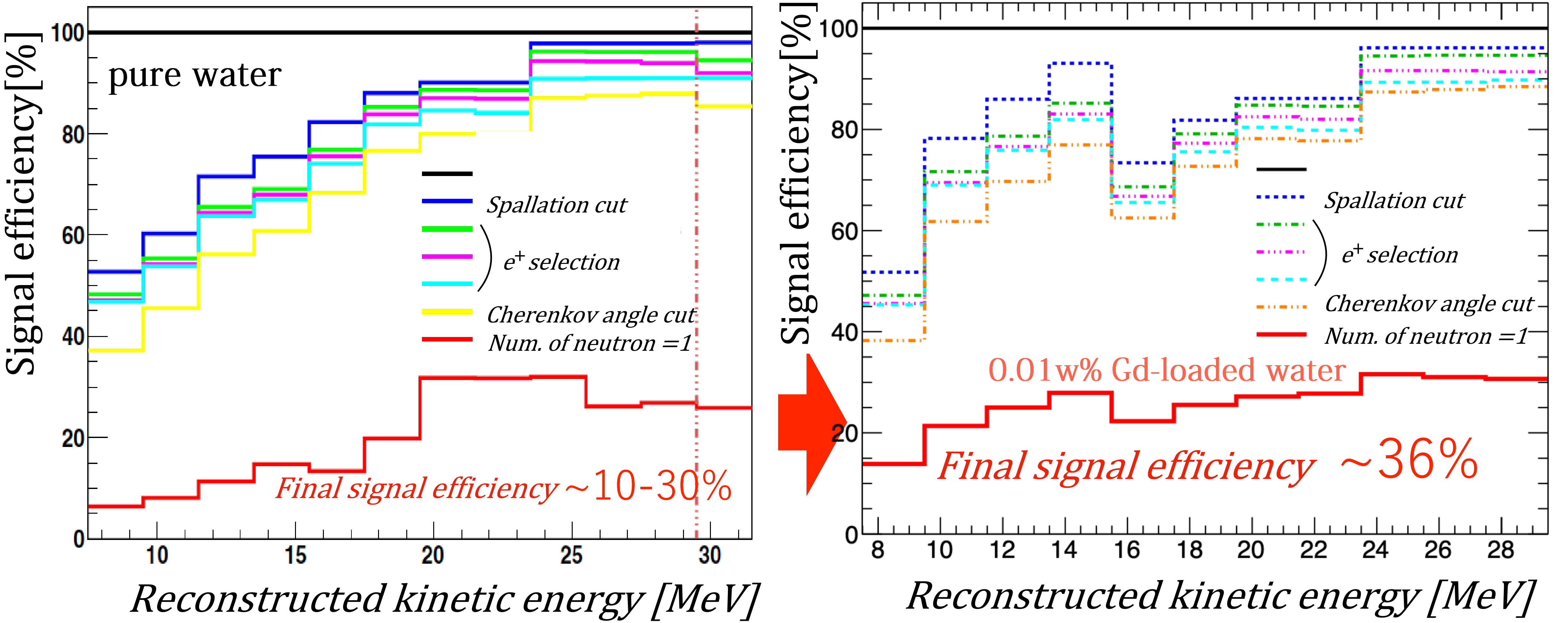
- ~70% of Gd is identified

  →Totally ~35% of n
- Mis-ID rate: 2.8×10^{-2}%

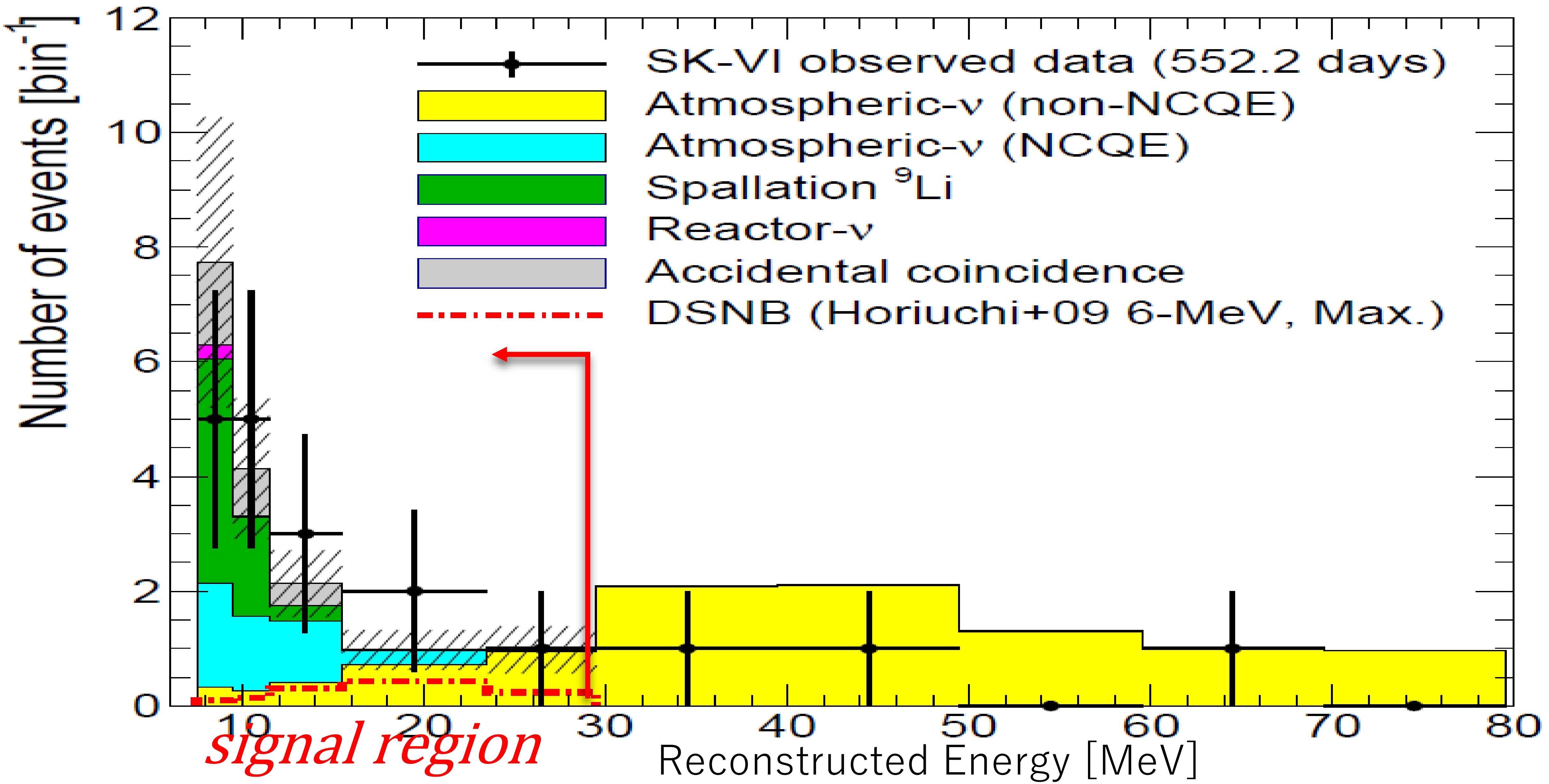
Signal efficiency

- Spallation cut reduces signal efficiency at low-energy side
- Atm. Neutrino reduction well conserve signal efficiency
- 2-3 times higher efficiency thanks to neutron tagging!!

M. Harada et al., ApJL 951, L27 (2023)



Search Result (Energy Spectrum)



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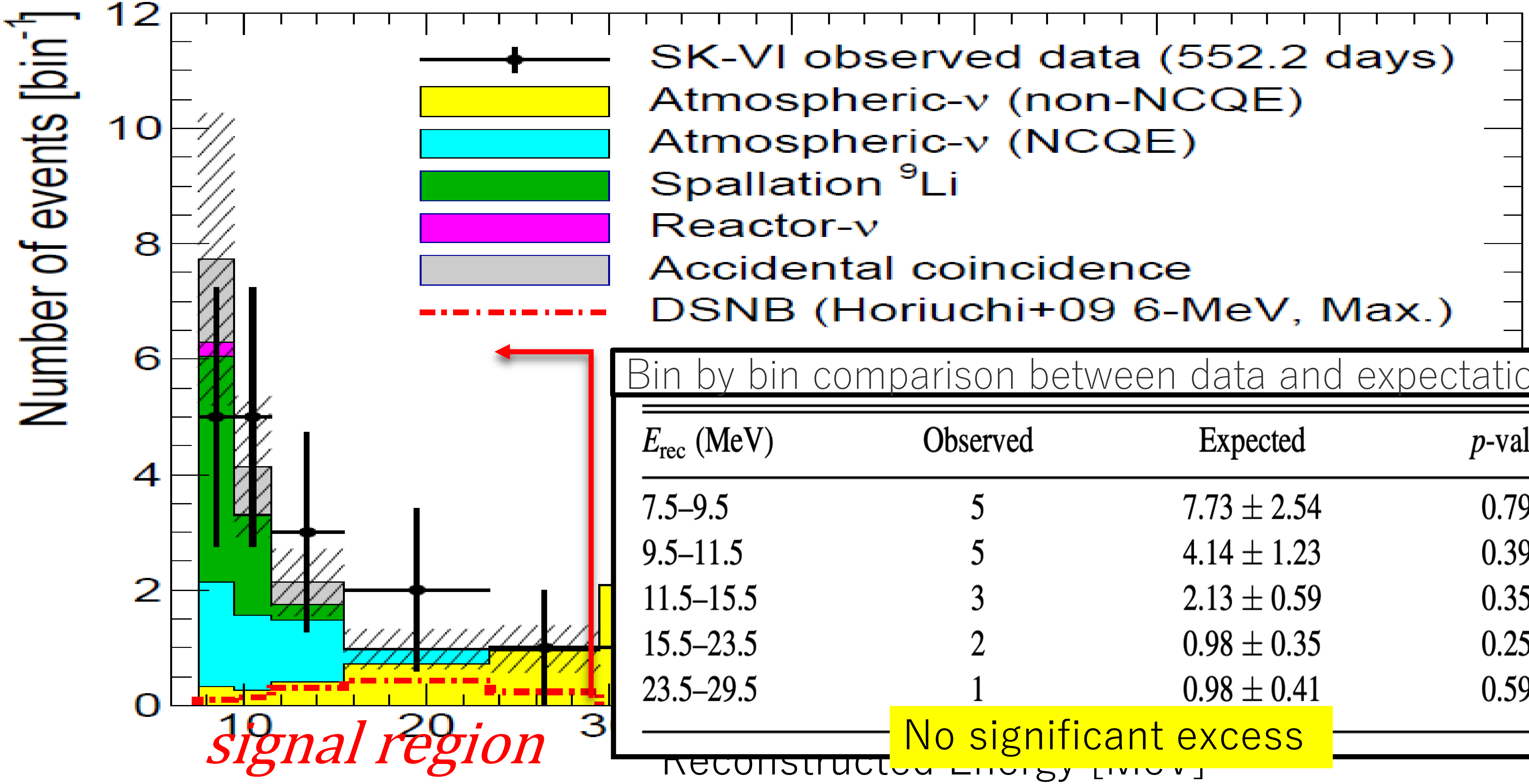


Bin by bin comparison between data and expectation

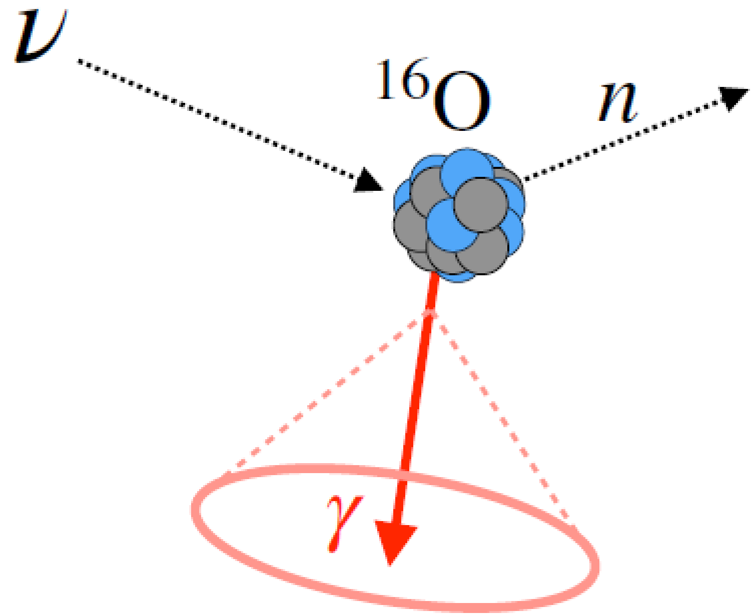
E_{rec} (MeV)	Observed	Expected	*p*-value
7.5–9.5	5	7.73 ± 2.54	0.798
9.5–11.5	5	4.14 ± 1.23	0.398
11.5–15.5	3	2.13 ± 0.59	0.359
15.5–23.5	2	0.98 ± 0.35	0.258
23.5–29.5	1	0.98 ± 0.41	0.597

No significant excess

NCQE background

Main BG uncertainty comes from NCQE uncertainty

NC quasi-elastic (NCQE)



T2K cross-section	44%
Atmospheric neutrino flux	15%
Flux difference	7%
Reductions	2%
Neutron tagging efficiency	9%
Neutron multiplicity	30%
Spectral shape	37%
Total	68%

This uncertainty is included in the limit calculation

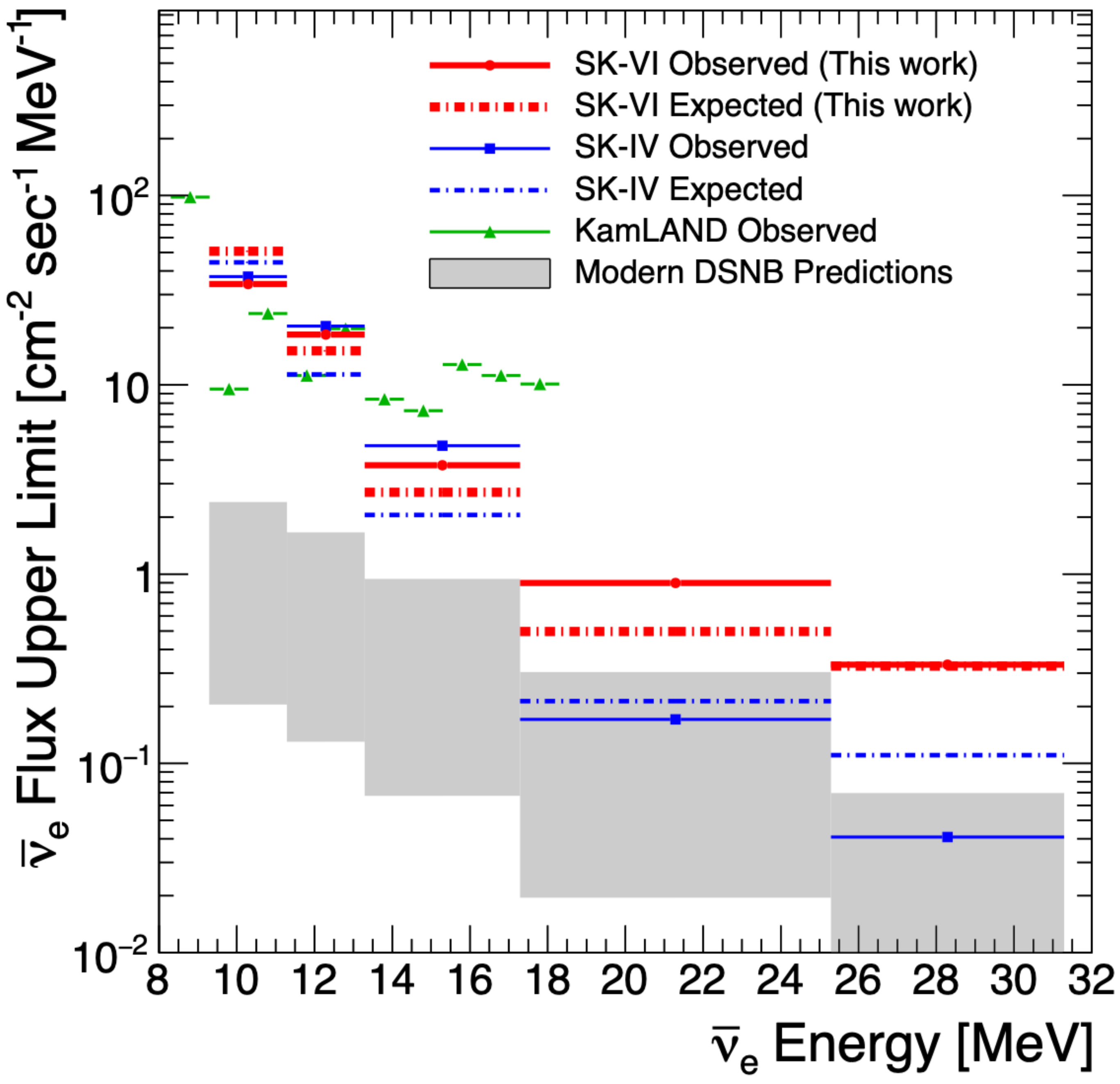
(We need reduce this uncertainty in future)

Flux upper limit

$$\phi_{90}^{\text{limit}}\ [\text{cm}^{-2}\,\text{sec}^{-1}\,\text{MeV}^{-1}] = \frac{N_{90}^{\text{limit}}}{N_p \cdot T \cdot \bar{\sigma}_{\text{IBD}} \cdot \varepsilon_{\text{sig}} \cdot dE}$$

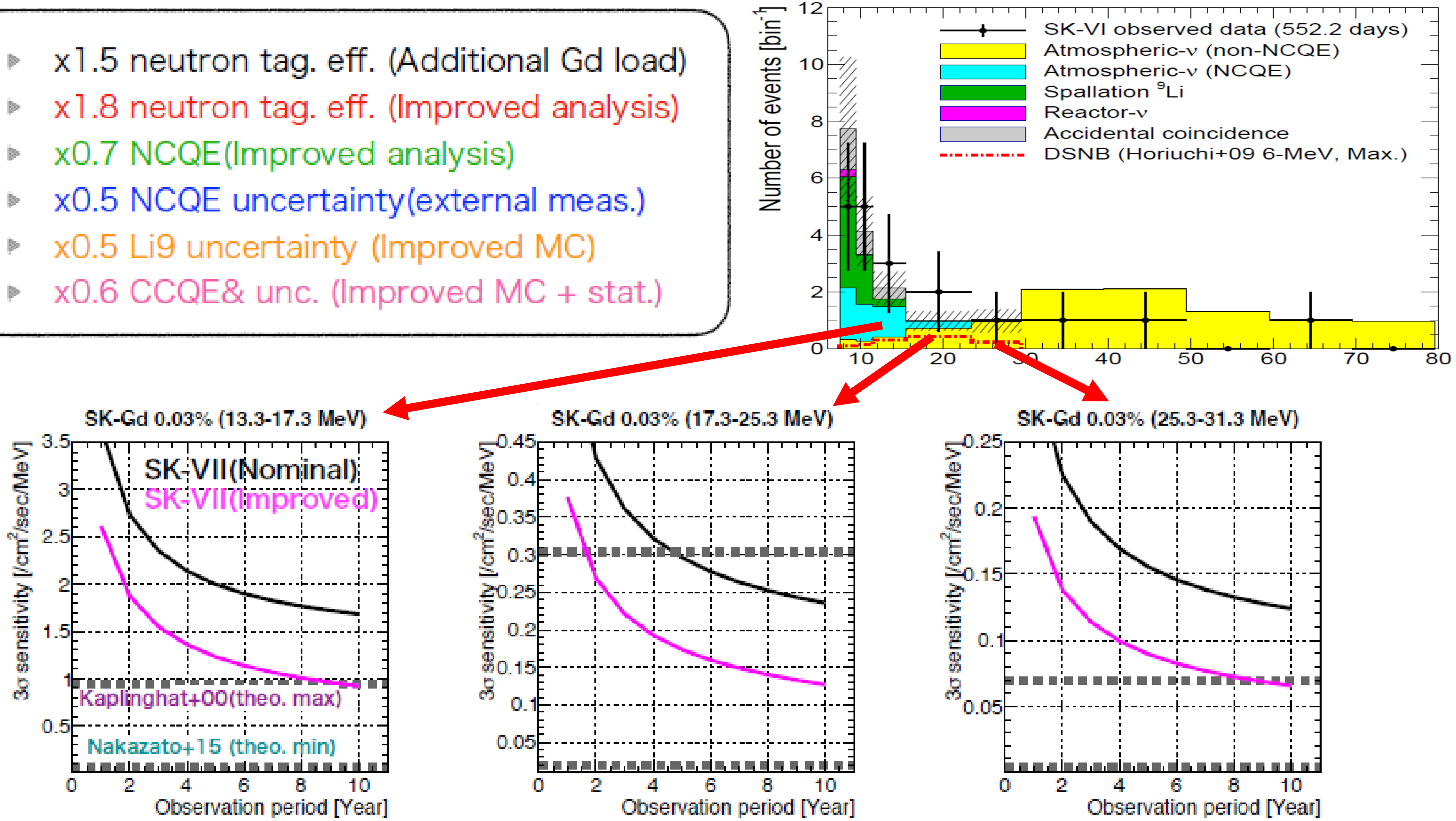
N_{90}^{limit} :90% C.L upper limit
from Nobs, BG and their uncertainty

- N_p : N of target proton 1.5 × 10^33
- T : Livetime
- $\bar{\sigma}_{\text{IBD}}$: IBD cross section
- ε_{sig} : Signal efficiency
- dE : Energy bin width



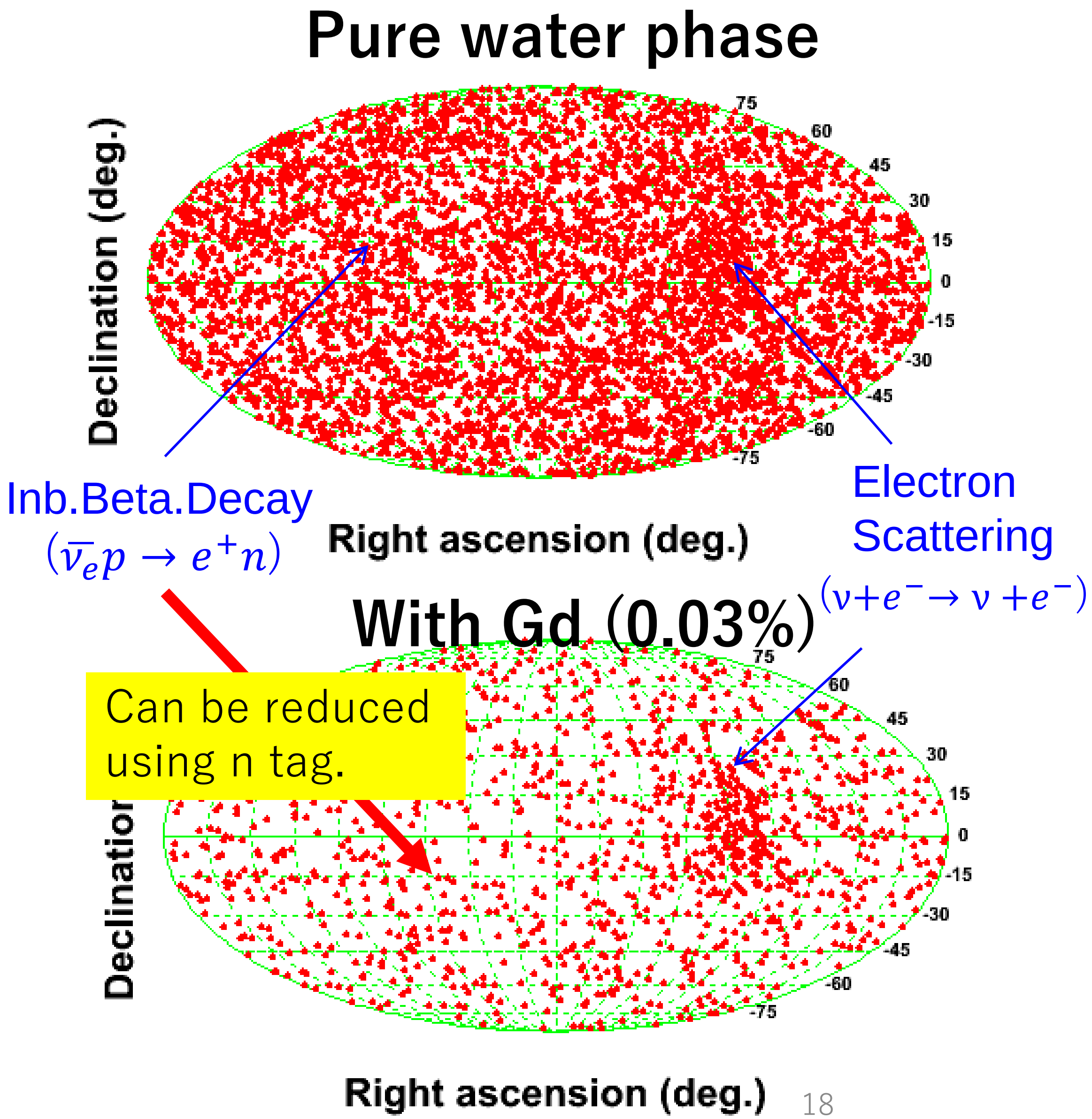
Expected sensitivity in 10years

- x1.5 neutron tag. eff. (Additional Gd load)
- x1.8 neutron tag. eff. (Improved analysis)
- x0.7 NCQE(Improved analysis)
- x0.5 NCQE uncertainty(external meas.)
- x0.5 Li9 uncertainty (Improved MC)
- x0.6 CCQE& unc. (Improved MC + stat.)



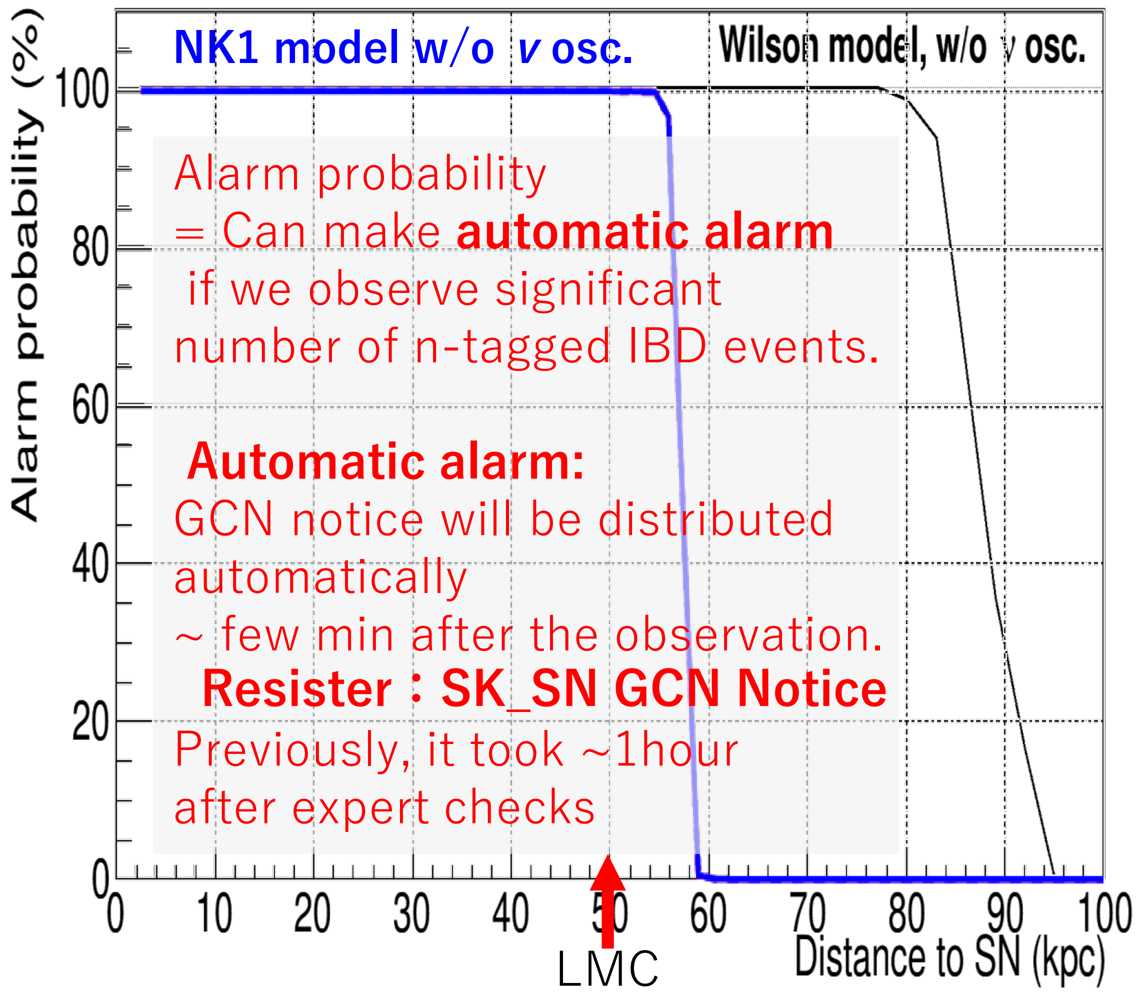
Galactic supernova burst detection

- Neutrinos can escape from a supernova earlier than photons.
  - Neutrinos arrive few min ~ hours before photons
  - Observation of the neutrino burst can inform telescopes.
    - SK can detect the direction of SN by itself
- Improvements in SK-Gd
  - Significance of SN is enhanced if we observe many IBD events.
    - Automatic alert
  - the pointing accuracy has been improved.

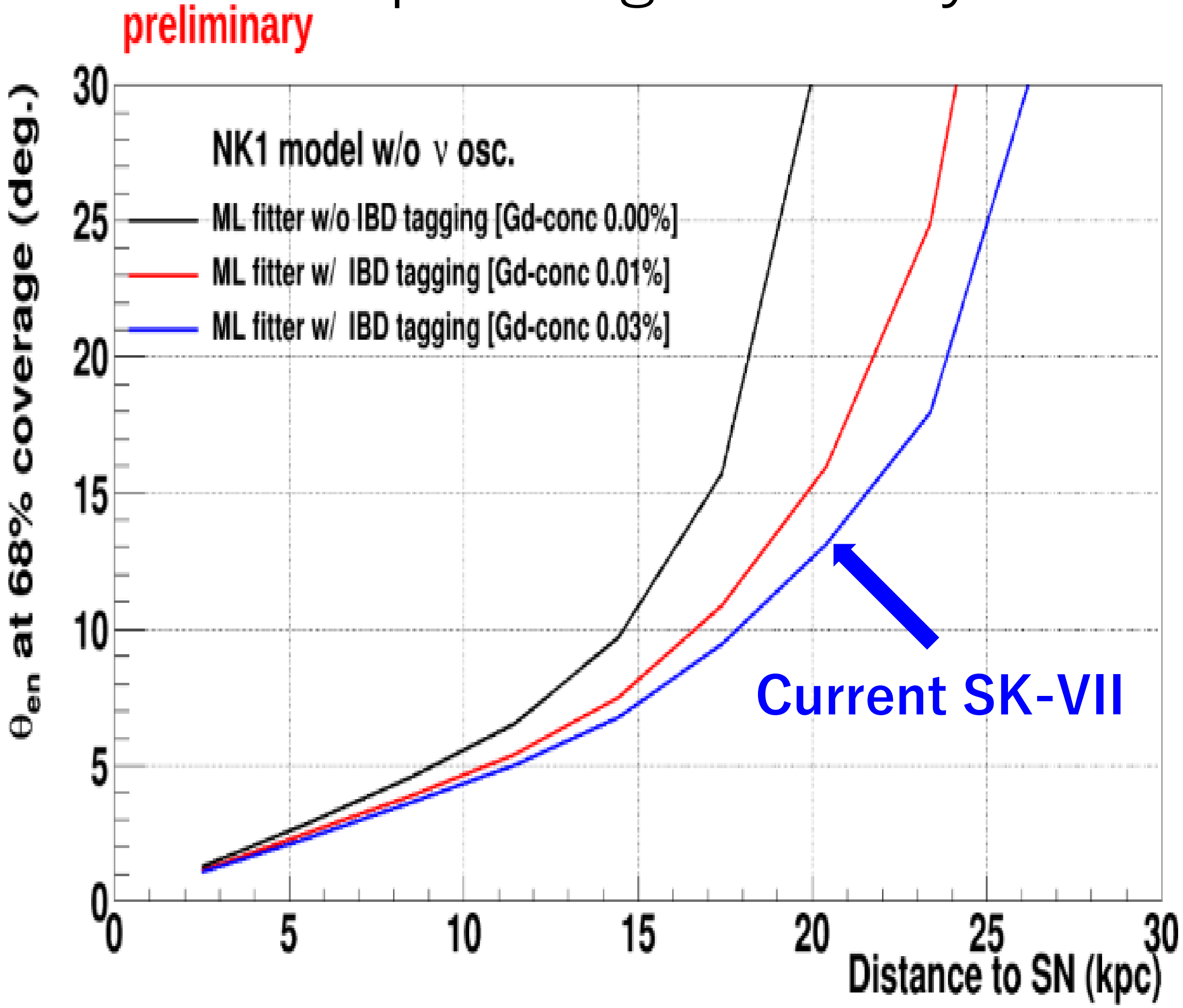


Sensitivity to Galactic supernova burst

Automatic alert sensitivity



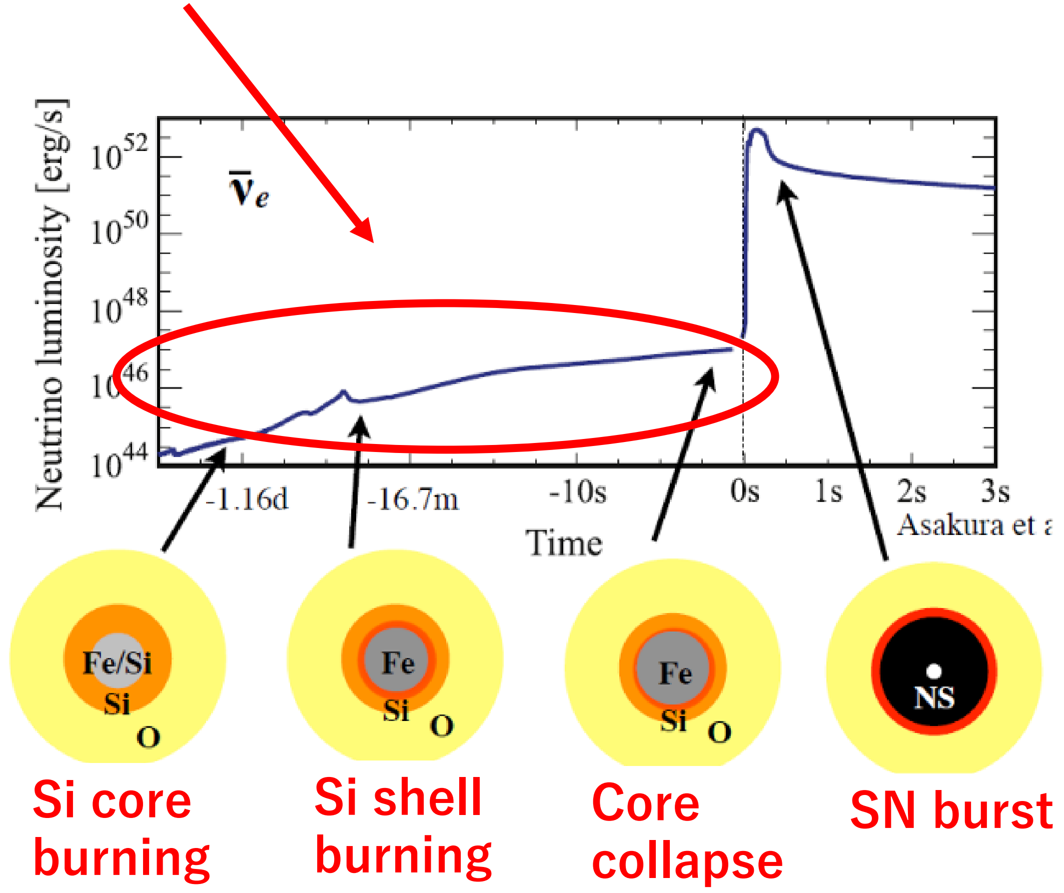
SN pointing accuracy



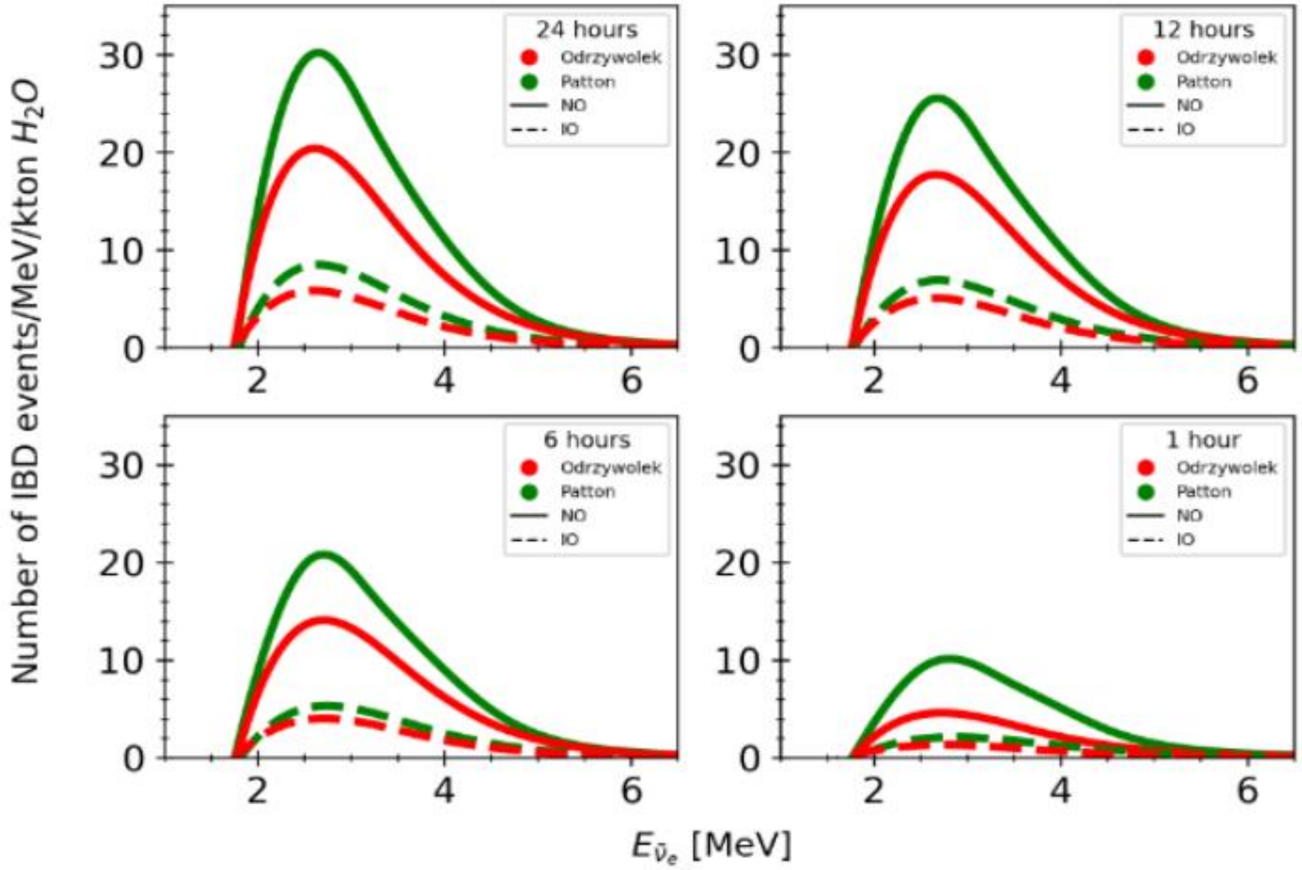
We want to shorten the latency below 1min in future

Sensitivity to very close supernova burst

Pre-SN neutrino detection



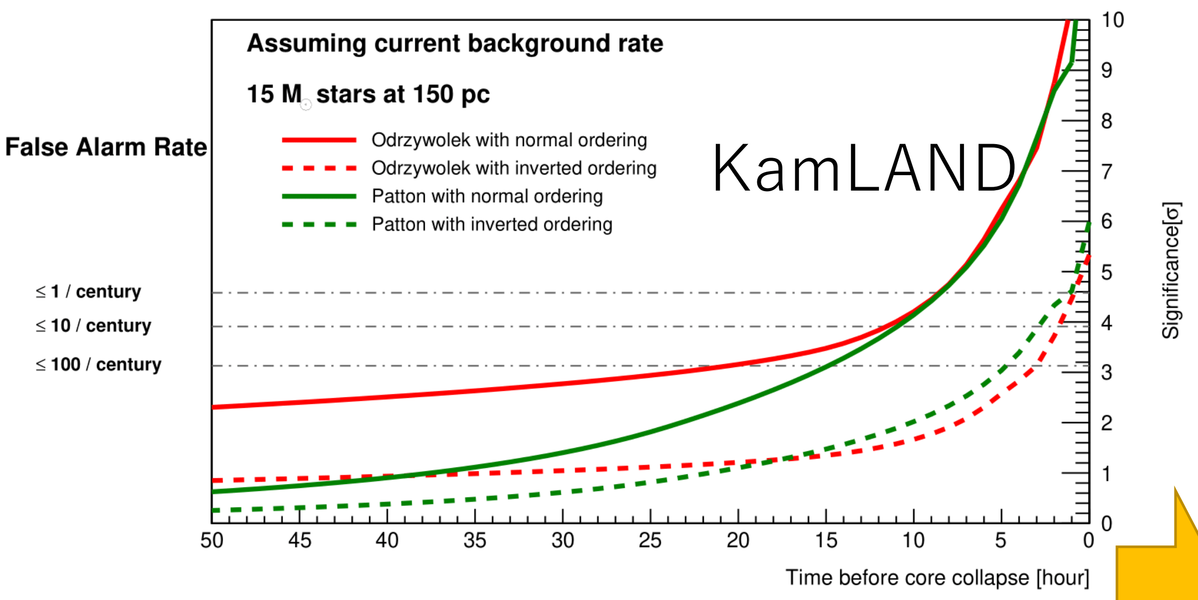
15M⊙, 150pc (~ Betelgeuse)

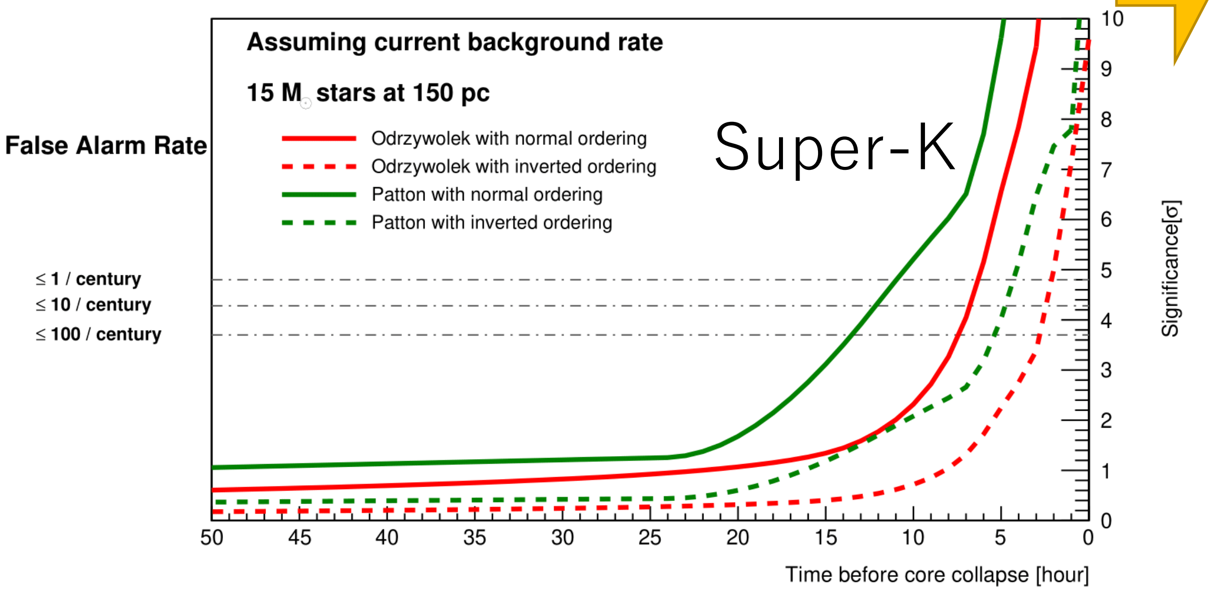


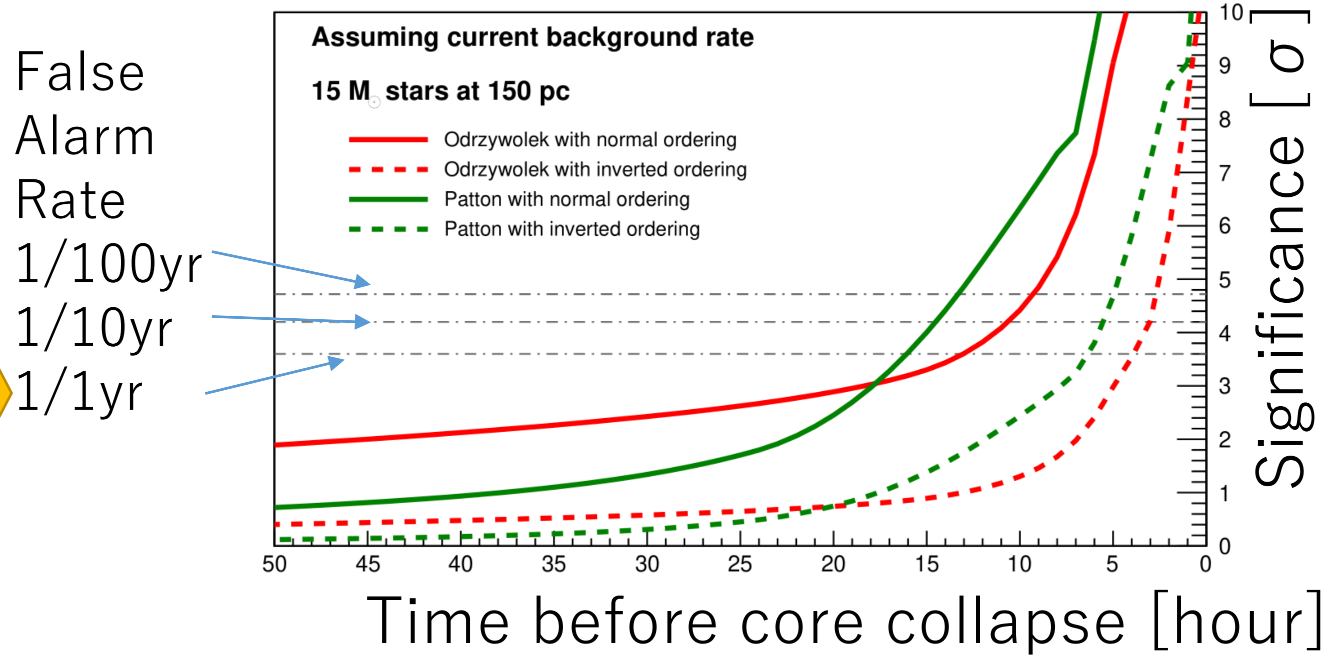
Not only KamLAND but also SK-Gd can detect pre-SN neutrinos now!
Thanks to neutron tag by Gd and a intelligent trigger system (2~3 MeV threshold) ,

→ Collaboration with KamLAND can give higher sensitivity

SK-Gd&KamLAND Combined Sensitivity

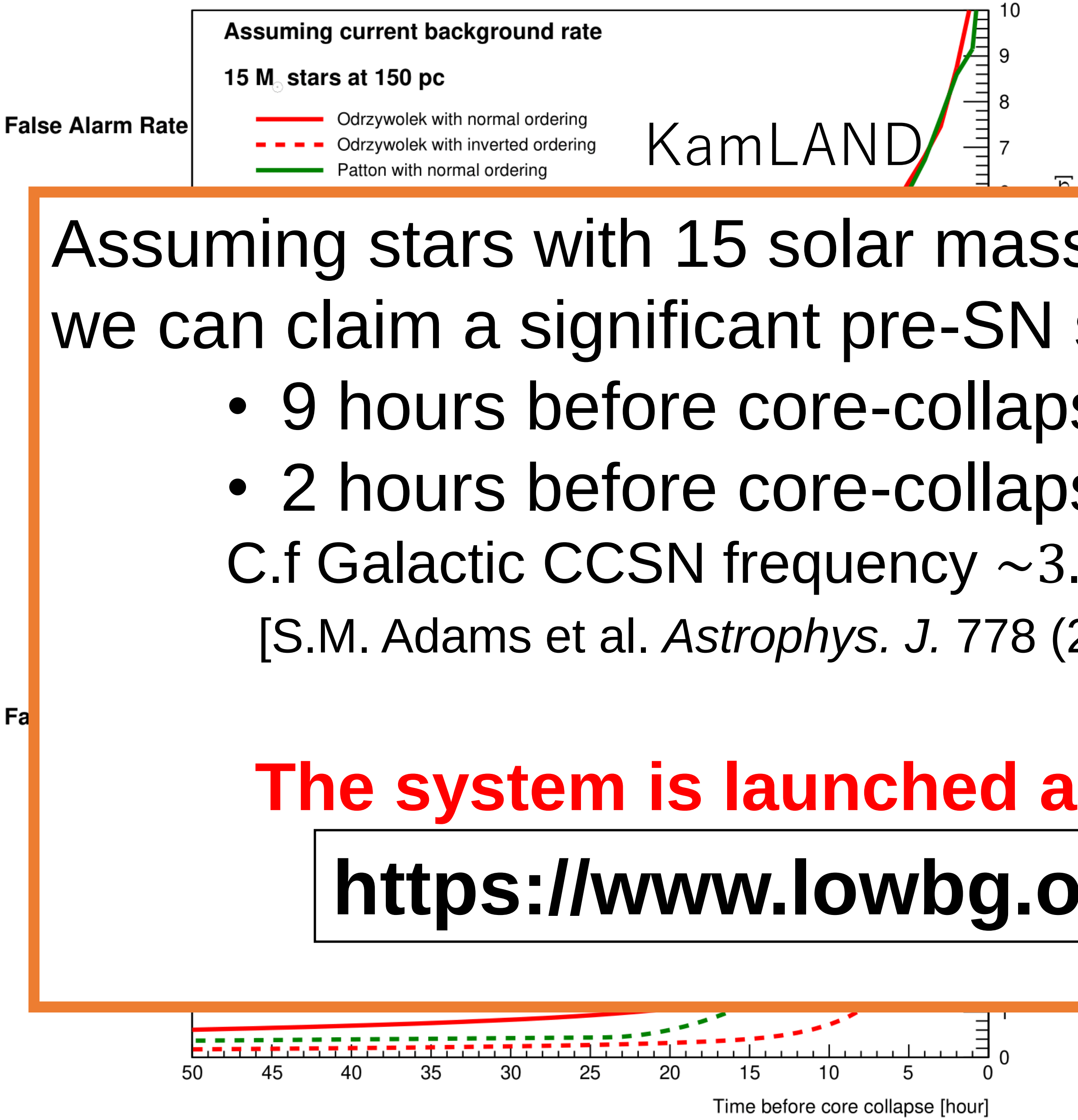






- KamLAND can resolve a signal early because of low background rate.
- Super-K's large size help increasing significance.
- **Combined**: Taking advantages from KL ＆SK

SK-Gd&KamLAND Combined Sensitivity



Assuming stars with 15 solar mass at 150 pc,
we can claim a significant pre-SN signal with false alarm ≤ 1/century,

- 9 hours before core-collapse, for all models with NMO
- 2 hours before core-collapse, for all models with IMO

C.f Galactic CCSN frequency ~3.2 per century

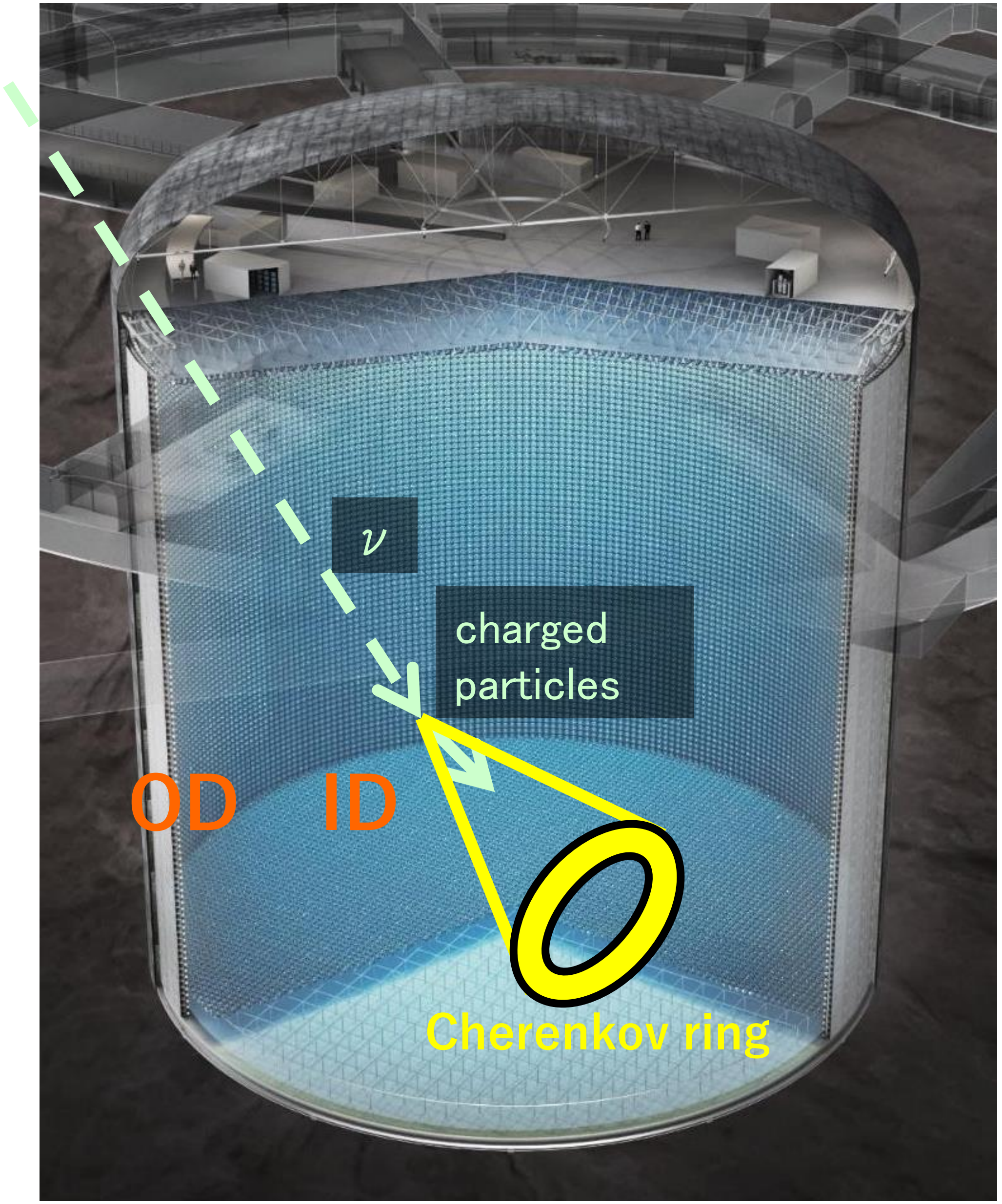
[S.M. Adams et al. *Astrophys. J.* 778 (2013)]

The system is launched and open to public!

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

- **Combined**: Taking advantages from KL &SK

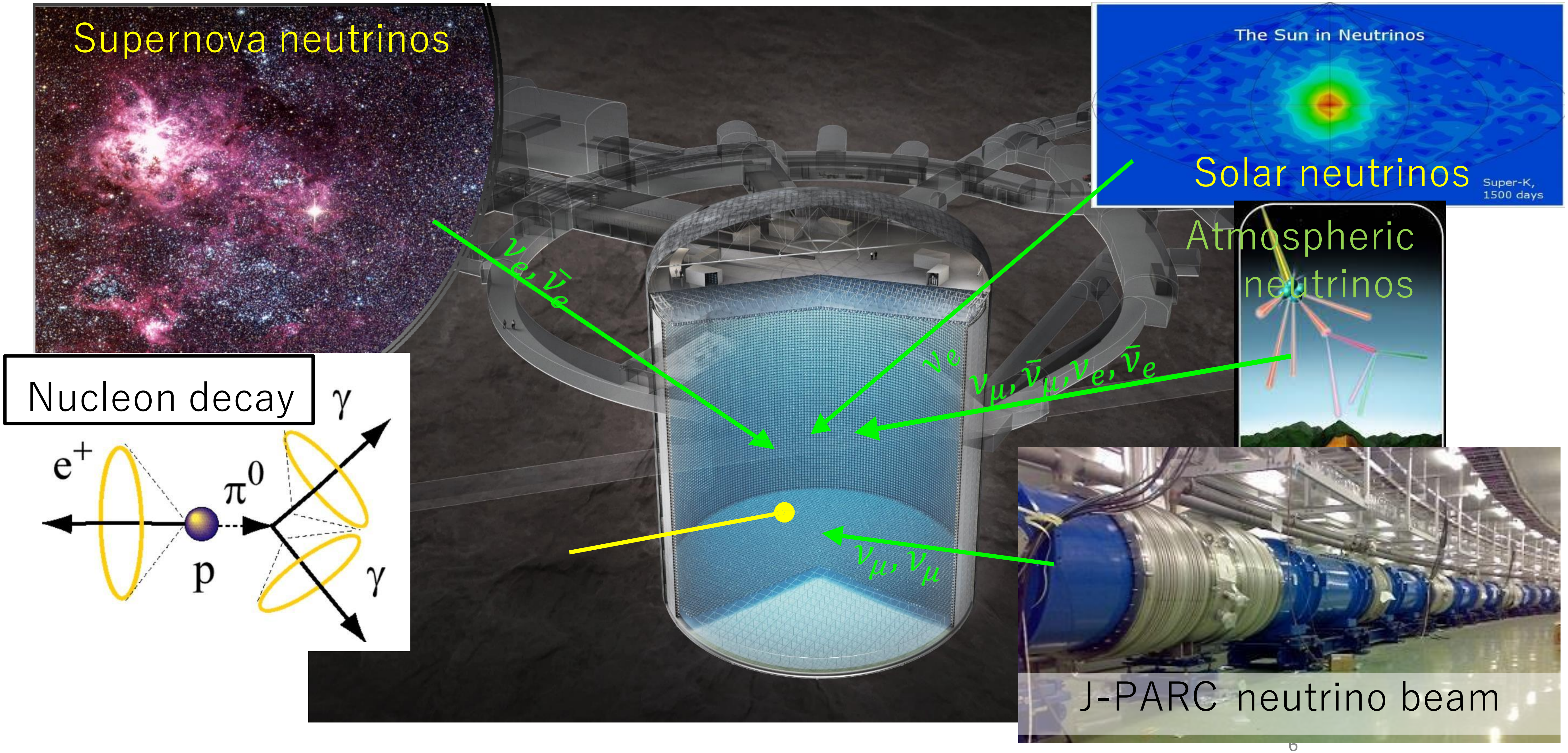
Hyper-Kamiokande



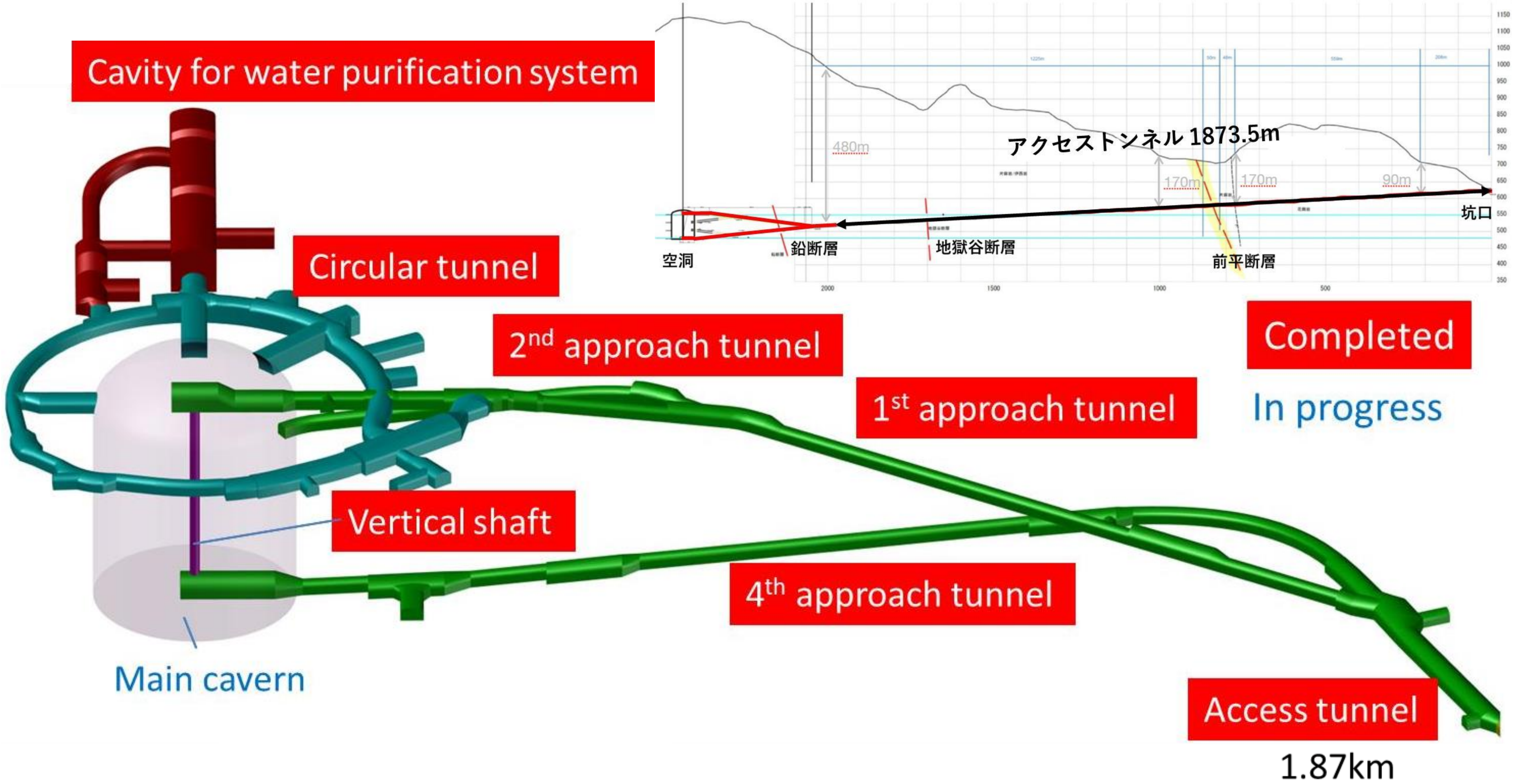
- **258 kt tank, providing 188 kt fiducial vol.**
  - Including J-PARC neutrino beamline at Ibaraki, Japan.
  - It will be constructed **600 m** under the Nijyugo-yama mountain at Kamioka, Gifu, Japan (**1600 m.w.e.**).
  - **The operation will start in 2027.**
- The detailed detector design is now being settled.
  - **Inner detector (ID)**
    - **40,000 of 20" PMT**
      - 40% photocathode coverage (PC40%)

    or
    - **20,000 of 20" PMT** & **thousands of multi-PMT** modules
      - 20% and more photocathode coverage
  - **Outer detector (OD)**
    - **3" PMT and wavelength shifting plates**

Hyper-K Observation Target



Overview of the HK Cavern Excavation



- Excavation of all tunnels completed.
- Excavation of the water system cavity was completed in May 2023.
- Excavation of the dome section of the main cavern has been completed in Oct. 2023.

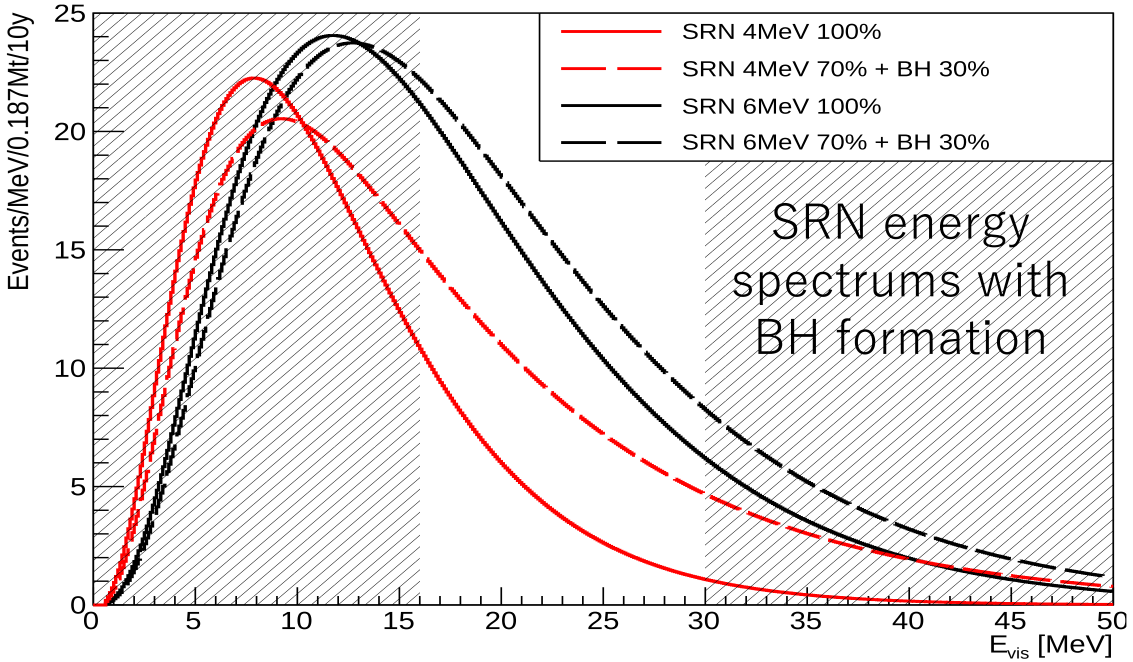
2023.10.03 Completion of the Dome Section

Huge underground space excavated: Diameter = 69m, Height = 21m
The dome section supporting 600m ground pressure is a key to the cavern stability.

https://www-sk.icrr.u-tokyo.ac.jp/news/detail/1299/

DSNB with HK

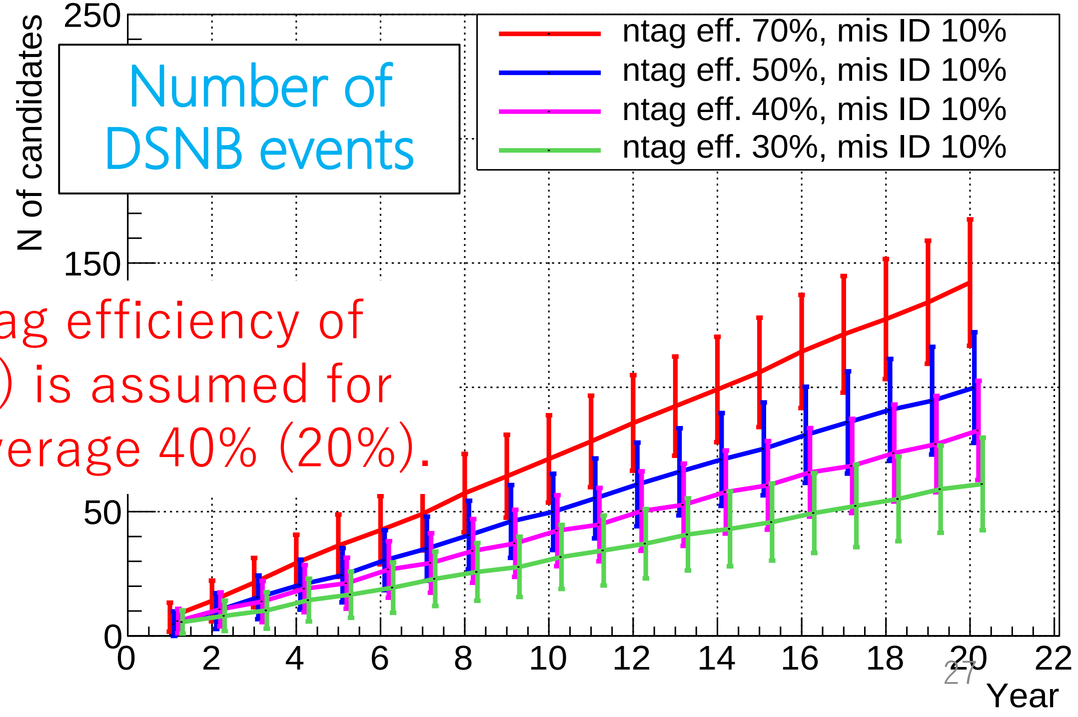
- DSNB can be observed by HK in 10y
  - **~40±13** events and 3σ for PC20%.



We will go beyond the discovery and aim to measurement of DSNB:

- Test of star formation rate
- Energy spectrum of supernova burst neutrinos
  Temperature inside the SN
- Extraordinary SN
  BH formation, dim supernova.

Neutron tag efficiency of 70% (40%) is assumed for photo-coverage 40% (20%).



Summary

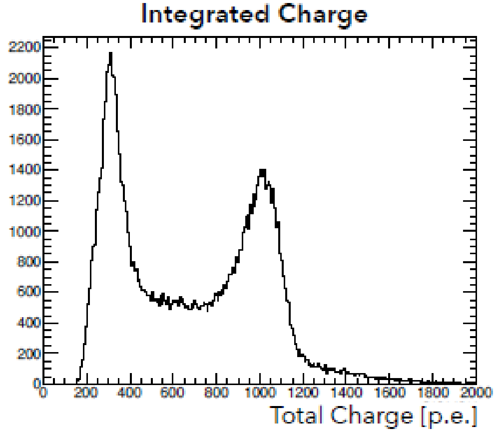
- First result from SK-Gd
  - Only ~1year observation with 0.01% Gd concentration gave comparable limit of 20 year of pure water observation
  - Now SK-Gd has been running with 0.03% with 0.03% Gd concentration.
  - 3 σ discovery of DSNB is achievable after 10 years of observation
- Supernova burst at SK-Gd
  - Detection of Galactic SN will be announce automatically with the direction (few degree precision) ~1min after the observation
  - Nearby SN (< few 100 pc) can be detected and announced before the core collapse by observing pre-SN neutrinos.
  - We have developed an alert system with KamLAND for pre-SN neutrinos.
    - The system has been running since May 2023.
- Hyper-K
  - Cavern excavation is ongoing without delay, expecting the observation starting in 2027.
  - HK can obtain more information on SN through DSNB observations.

Select prompt events by BGO scintillation and accompanying Gd-capture signal

Prompt event

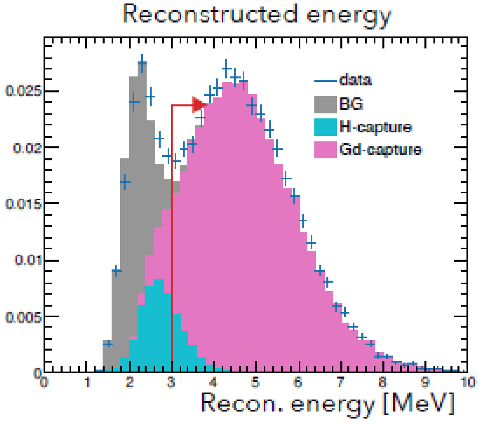
Selection criteria

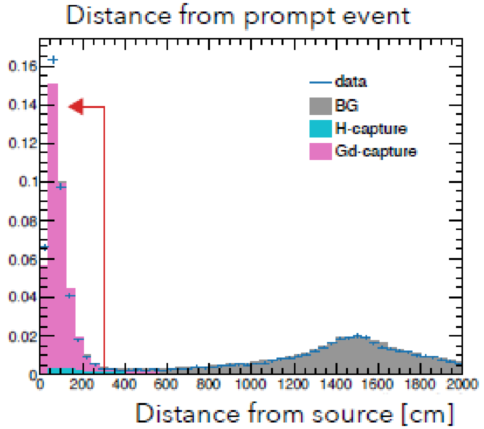
- Time diff. of events
- Small OD PMT hits
- Total charge of event

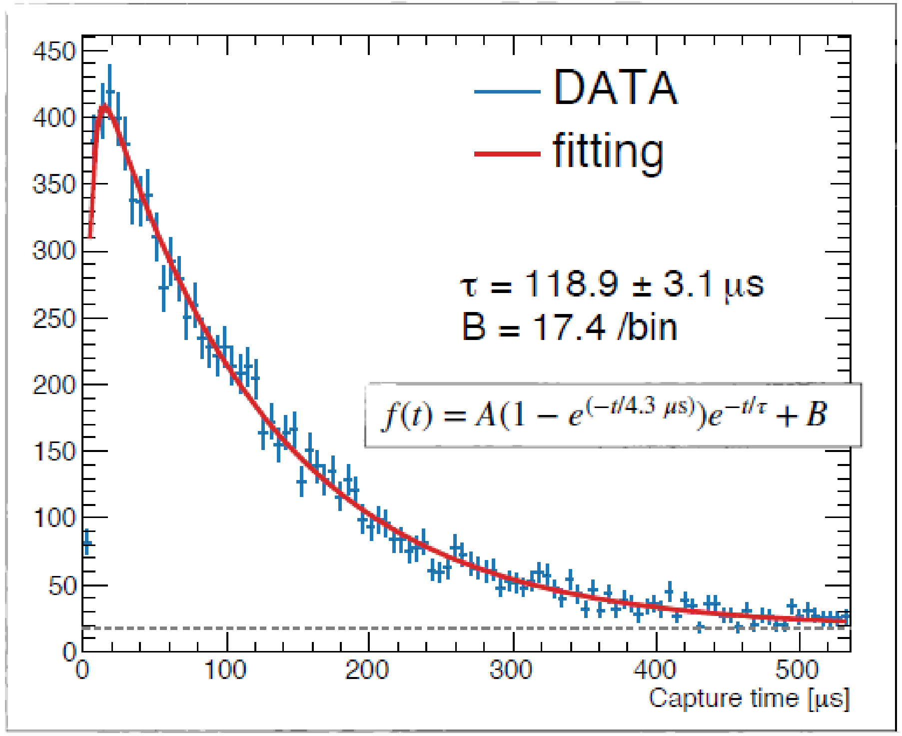


Delayed signal

- Selection using reconstructed information







Selection uncertainty

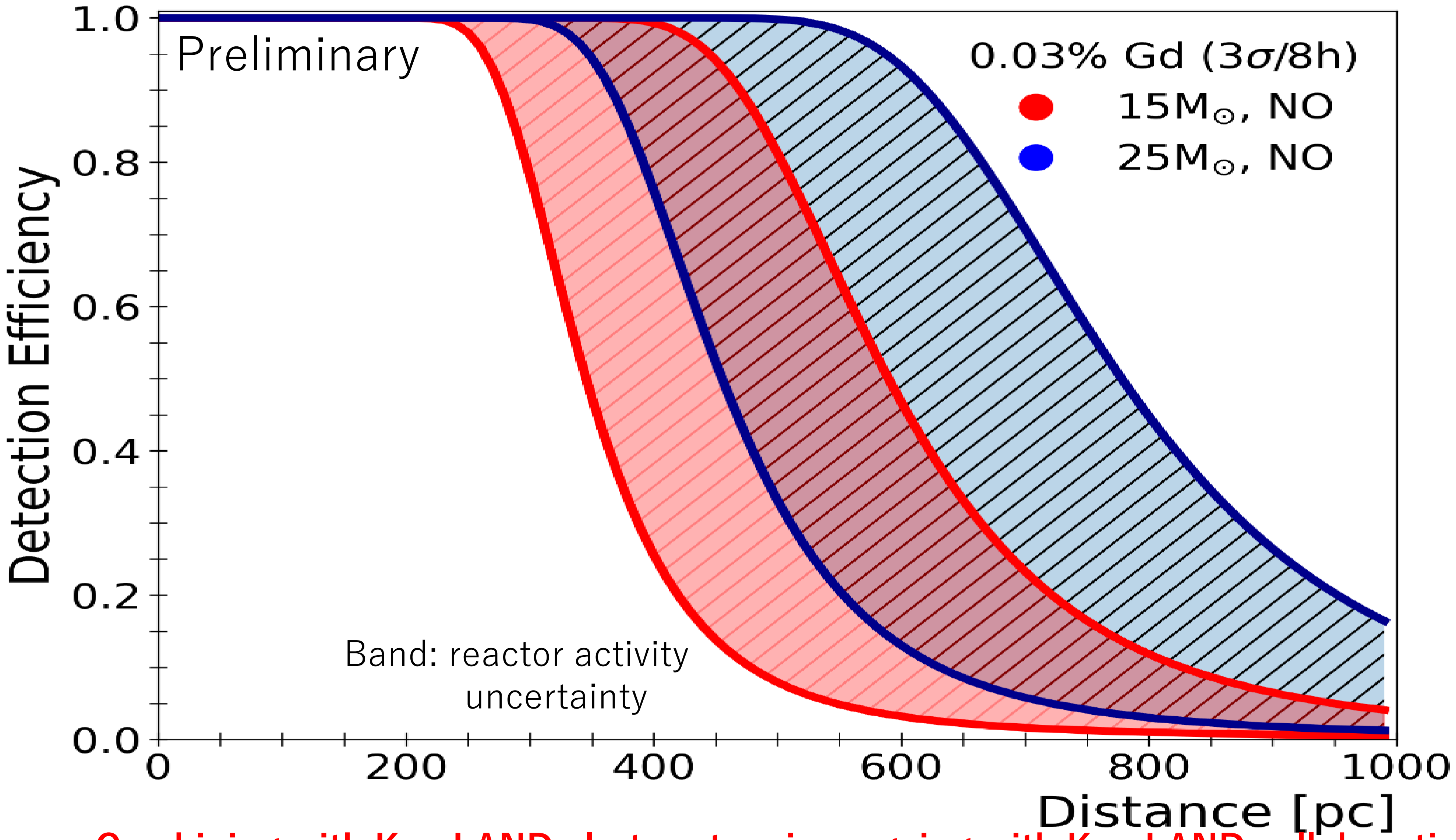
Content	Systematic uncertainty	
Prompt event selection	0.47%	0.47%
Timing goodness g_{vtx}	0.94%	
Direction goodness g_{dir}	0.03%	1.06%
Reconstructed energy	0.23%	
Vertex resolution	0.44%	
Gd concentration	0.17%	
$\mathrm{Gd}(\mathrm{n},\gamma)\mathrm{Gd}$ model	1.70%	1.83%
Neutron excitation state	0.39%	
Neutron energy spectrum	0.53%	
Position dependence	0.47%	0.47%
Total	2.22%	

BG unceratinty

E_{rec} bin [MeV]	7.49–9.49	9.49–11.49	11.49–15.49	15.49–23.49	23.49–29.49
non-NCQE background	0.32 ± 0.12	0.27 ± 0.10	0.41 ± 0.15	0.71 ± 0.26	0.94 ± 0.34
NCQE background	1.81 ± 0.90	1.30 ± 0.64	1.06 ± 0.53	0.26 ± 0.13	0.03 ± 0.02
^{9}Li background	3.92 ± 2.16	1.73 ± 0.95	0.28 ± 0.15	0.00 ± 0.00	0.00 ± 0.00
Reactor background	0.25 ± 0.25	0.01 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Accidental background	1.43 ± 0.07	0.83 ± 0.04	0.38 ± 0.02	0.01 ± 0.00	0.00 ± 0.00
Total	7.73 ± 2.35	4.14 ± 1.15	2.13 ± 0.57	0.98 ± 0.29	0.98 ± 0.34

Pre-NS detection efficiency vs. distance

SK-Gd has sensitivity up to ～500pc : about 20 candidate stars including Betelgeuse.



Combining with KamLAND alert system is on going with KamLAND collaboration