2022 夏、
SK-Gdによる超新星ニュートリノ高感度観測開始

池田一得　（ICRR, Kamioka）
他　Super-Kamiokande Collaboration

Contents

- Introduction and history of SK and SK-Gd
- Gd loading in 2022
- Sensitivity
- Summary

Super-Kamiokande Collaboration

Super-K experiment

1000m underground = 2600 m.w.e

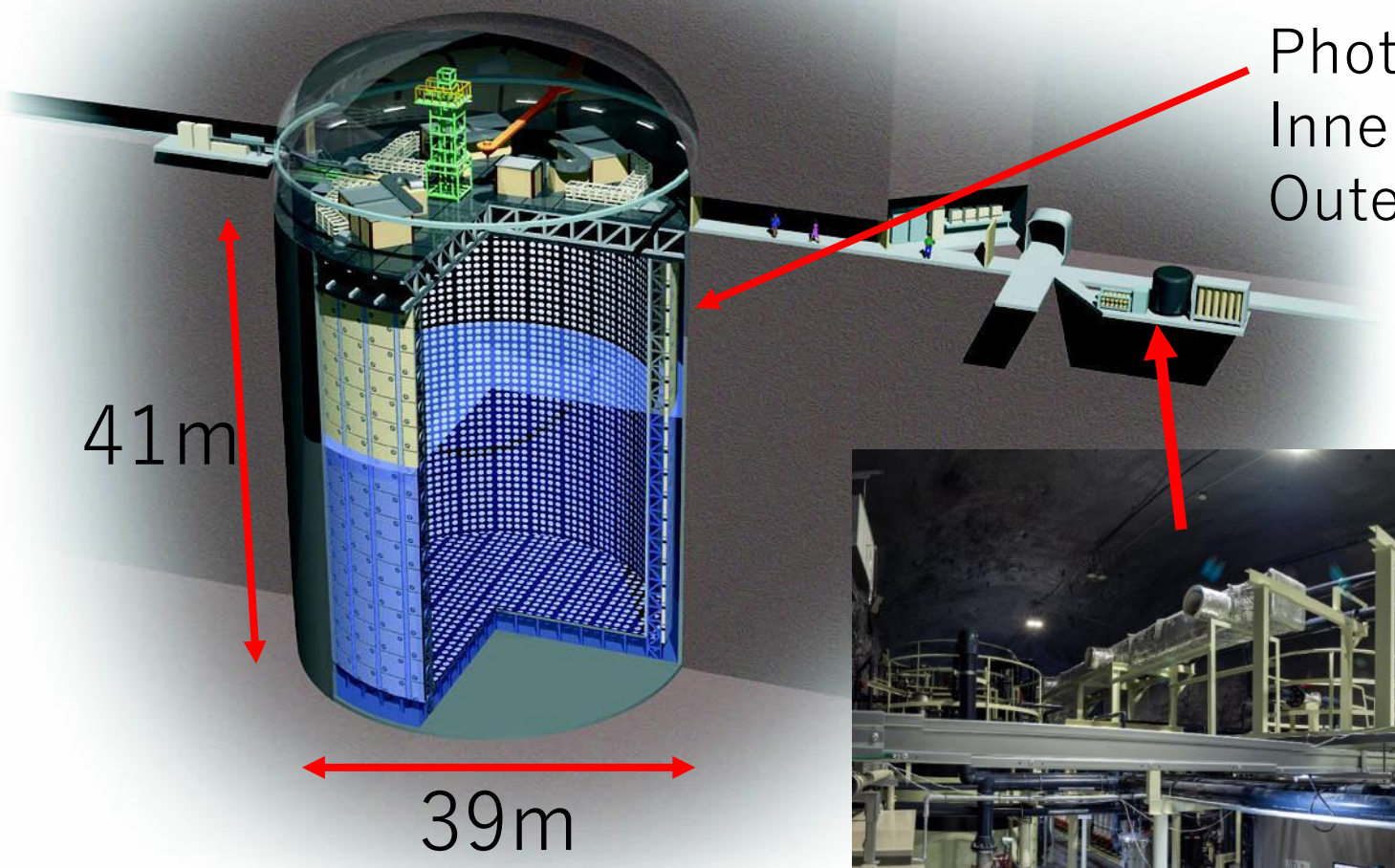


Photo sensors :
Inner detector: 11129 20inch PMTs
Outer detector: 1885 8inch PMTs

Gd water system room

SK-Gd project

Dissolving Gd to enhance detection capability of neutrons from ν interactions

Phys.Rev.Lett. 93 (2004) 171101

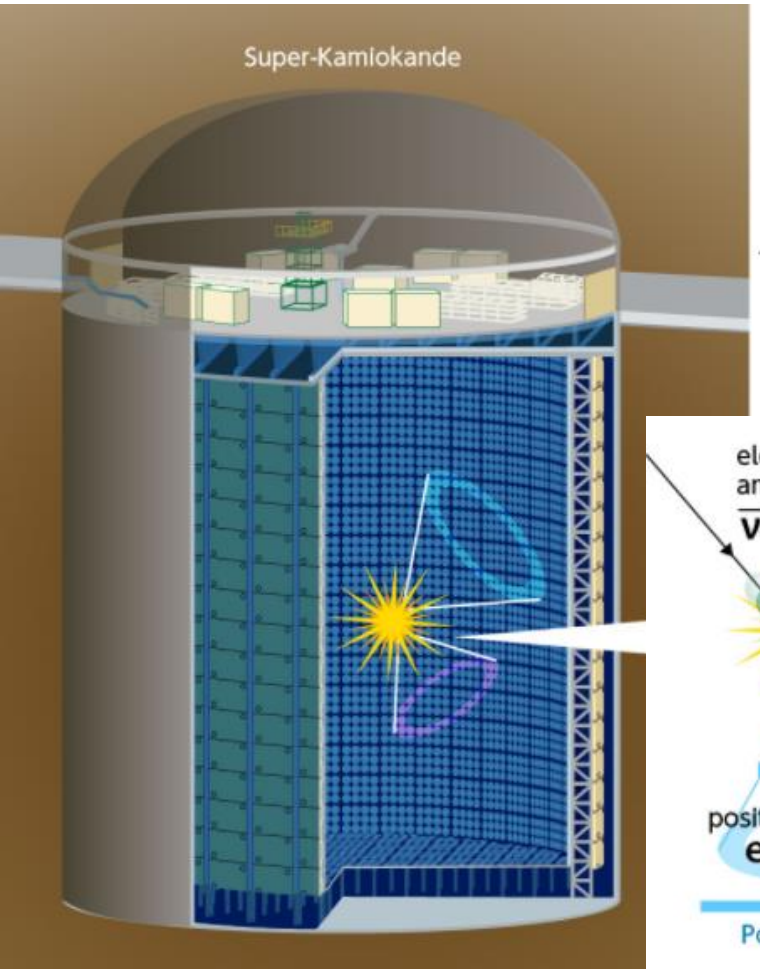
Physics targets:

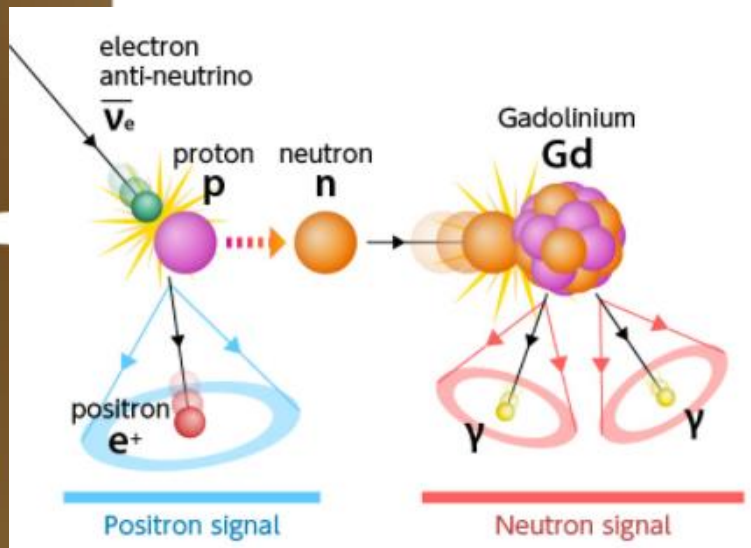
(1) Discovery of Supernova relic neutrino (SRN)

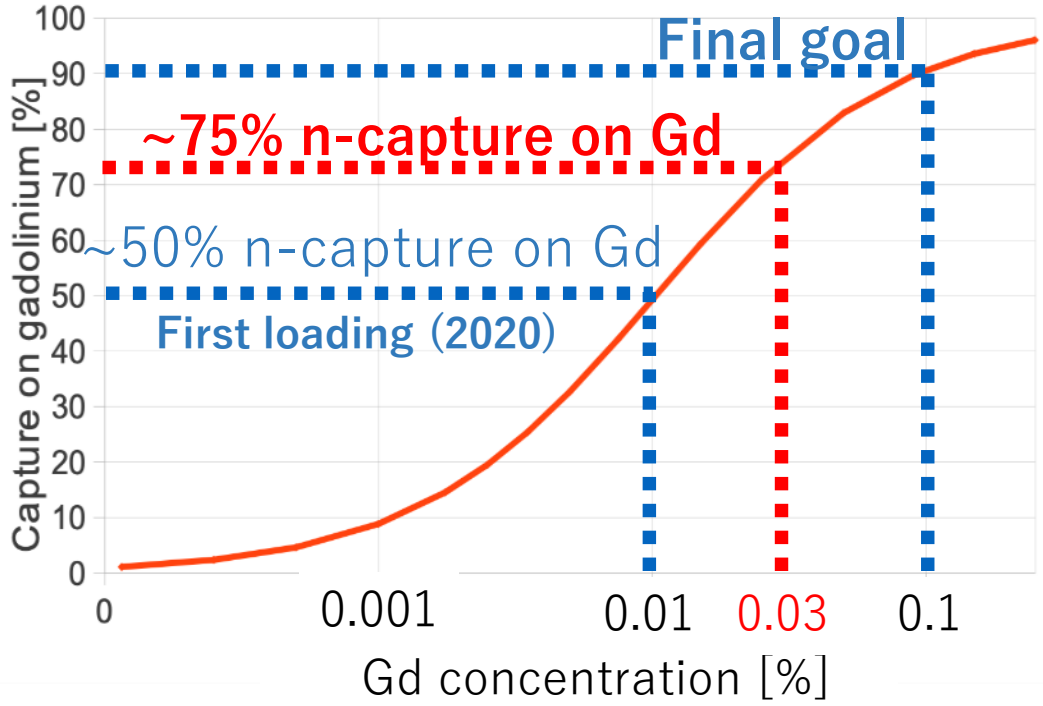
(2) Galactic supernovae (pointing accuracy, and pre-SN ν)

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

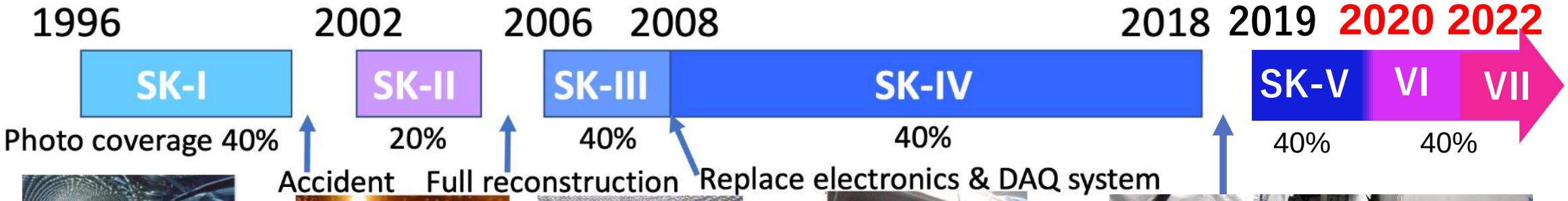
(4) Neutrino/anti-neutrino discrimination







History of Super-Kamiokande

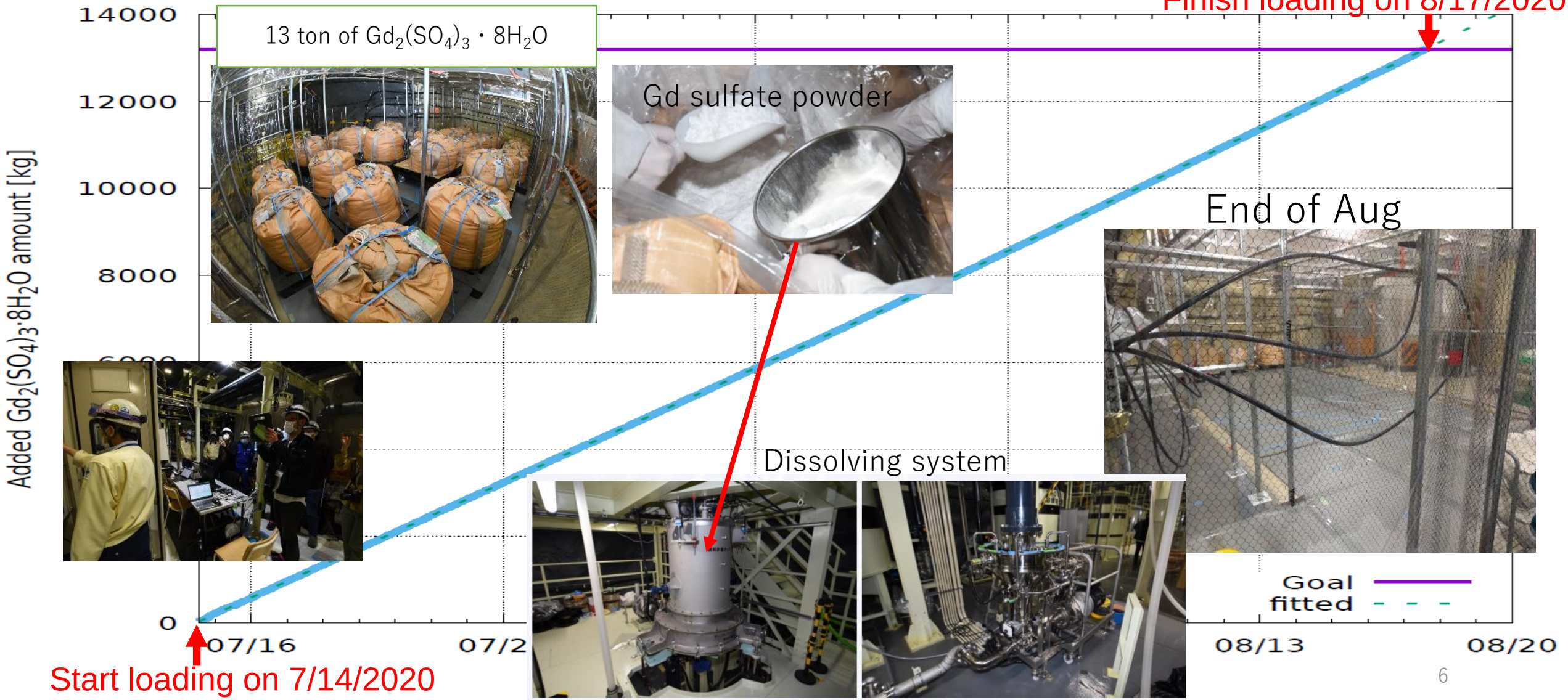


Tank refurbishment

- 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)

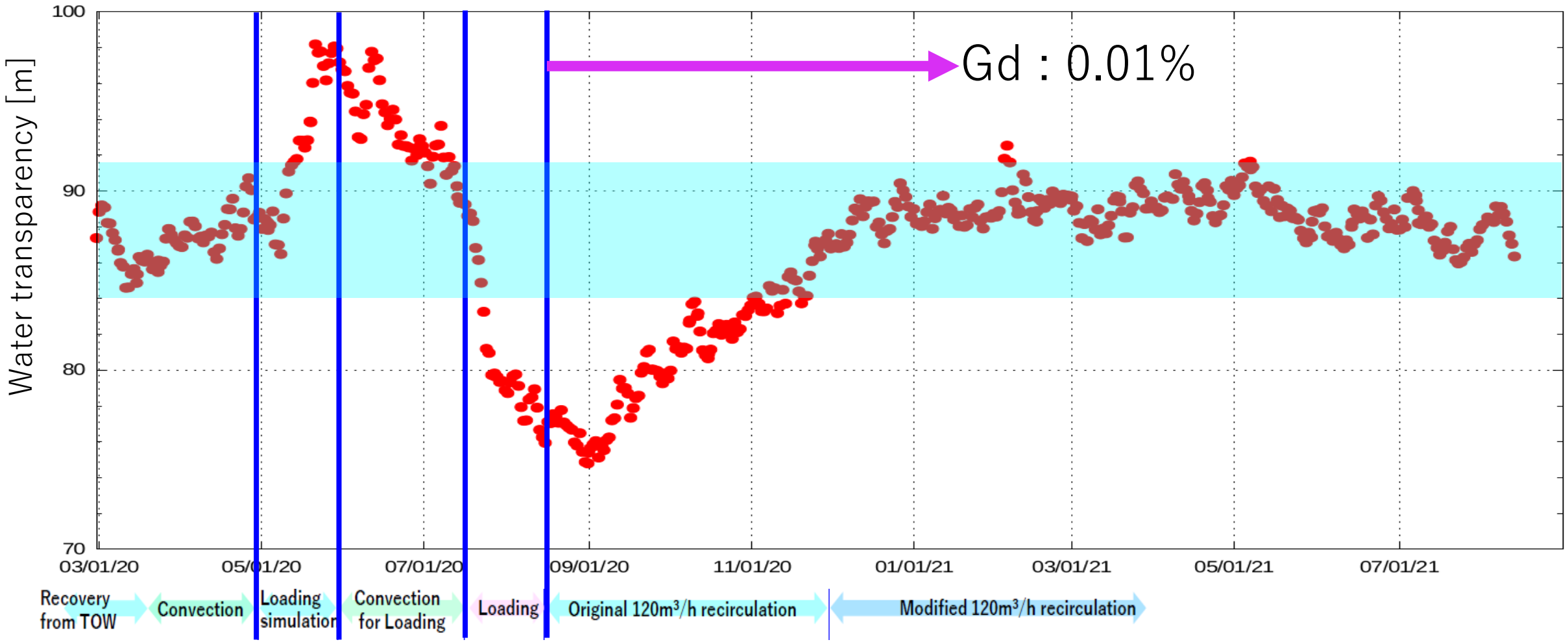
First Gd loading to SK

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



Water transparency after the first loading

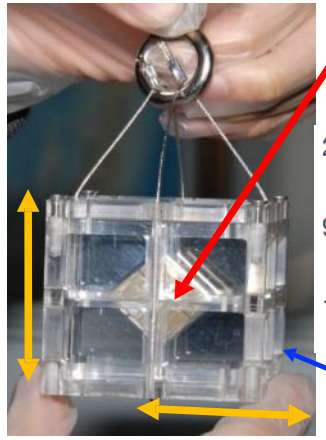
Light attenuation length measured with cosmic muons



Stable water transparency has been recovered few month after the loading

Detector response after the first loading

Neutron source



Am/Be source
100~200 neutrons/s

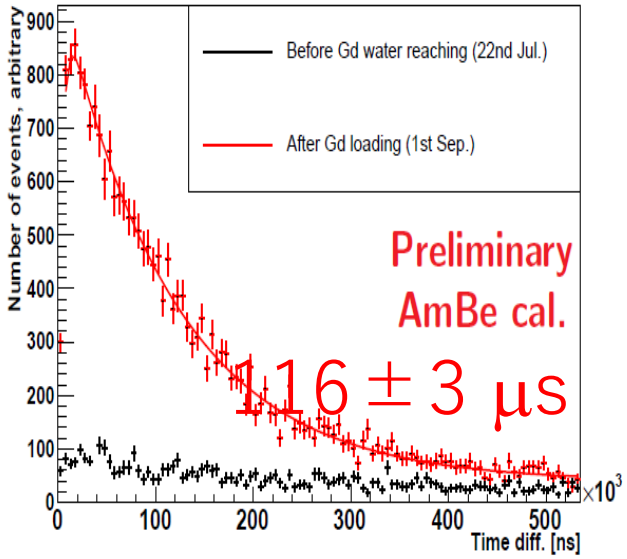
$^{241}Am \rightarrow {}^{237}Np + \alpha$

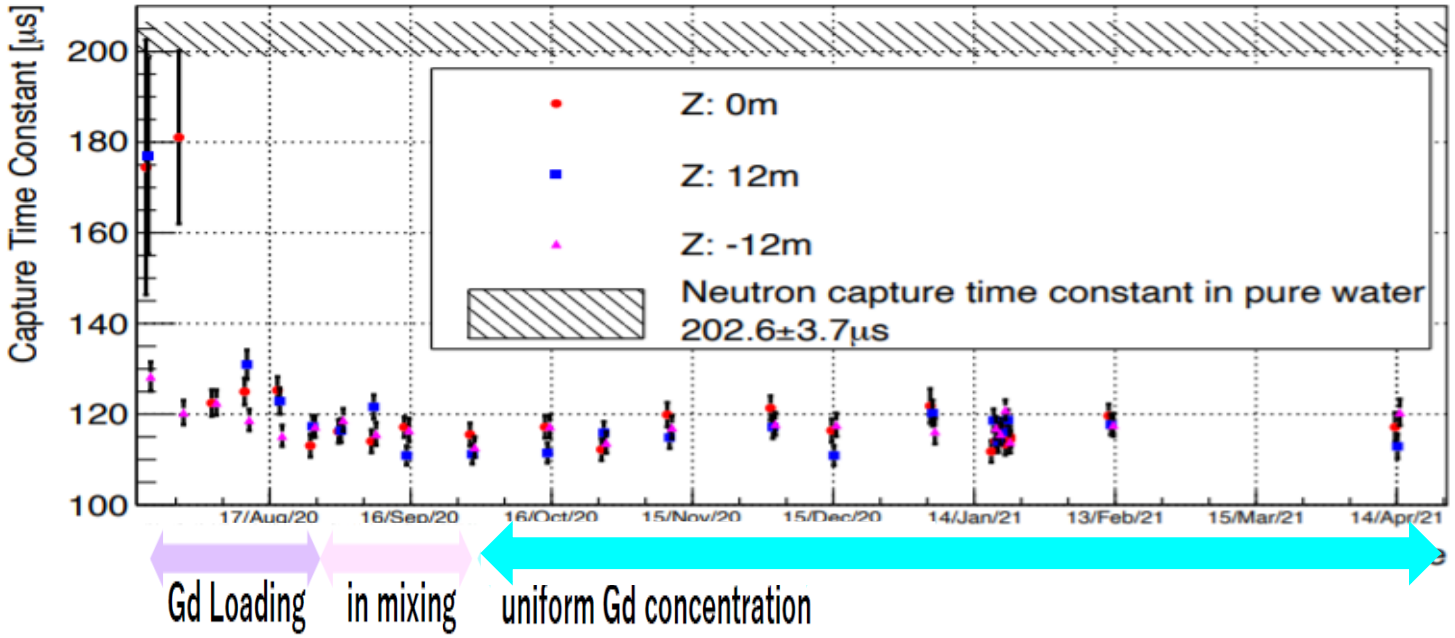
$^{9}Be + \alpha \rightarrow {}^{13}C^{*} + n$ (2-6 MeV)

$^{13}C^{*} \rightarrow {}^{12}C + \gamma$ (4.43 MeV)

8 BGO Crystals

5cm



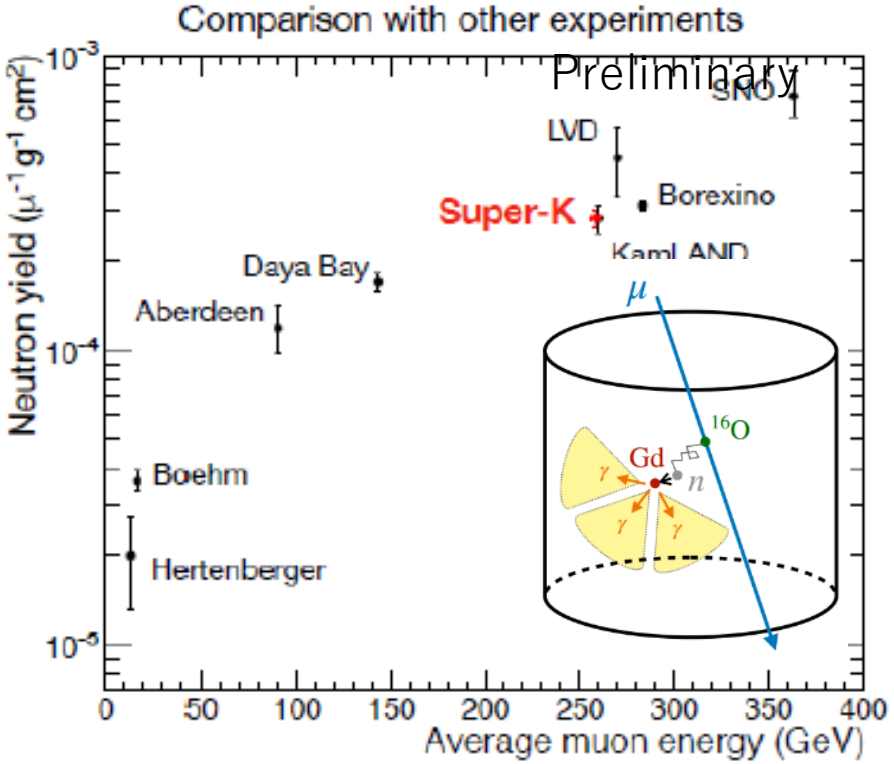


Cosmic μ induced neutrons

講演番号: 7aA125-3 篠木

The result of neutron yield measurement:

$Y_n = (2.81 \pm 0.06\ (stat.) \pm 0.18\ (syst.)) \times 10^{-4}\ \mu^{-1}g^{-1}cm^2$



Second loading toward 0.03% Gd concentration

Achieved 26 tons of ***ultra pure*** Gd sulfate power production

Requirement of RI in Gd powder

Requirements for each isotope are following

Isotope	Before 2015	SRN	Solar
238U	50	< 5	-
226Ra	5	-	< 0.5
232Th	100	-	< 0.05
228Ra	10	-	< 0.05
228Th	100	-	< 0.05
235U	32	-	< 3
227Ac/Th	300	-	< 3

Unit : mBq/kg($Gd_2(SO_4)_3$)

← γ and neutrons from S.F.

←214Bi : β (Q=3.27MeV)

208Tl : γ (=2.6MeV)

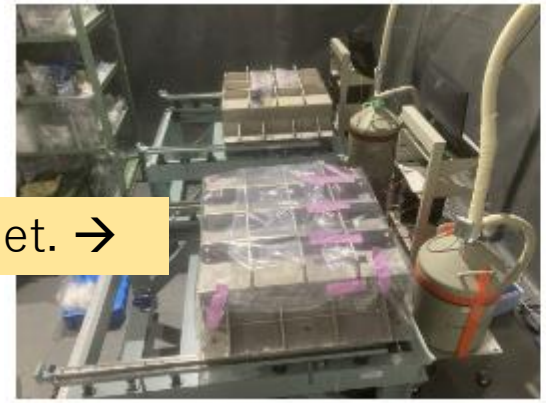
neutrons from decay chain
< solar ν BG level.

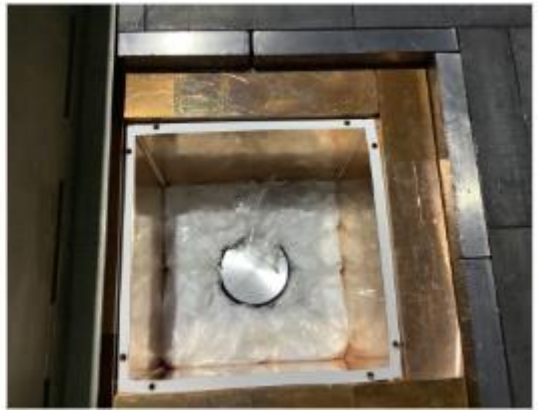
We set requirements so that these will be less than BG levels in pure water phase
= 1/10 ~ 1/1000 reductions have been achieved! (paper in preparation)

Screening of Gd powder

- Ge detectors
  - Easy to make samples
  - Many detectors
    - Spain (Canfranc), UK (Boulby), Korea (IBS), Kamioka
  - Good sensitivity:
    - < 0.5 mBq/kg ($Gd_2(SO_4)_3 \cdot 8H_2O$) for Ra/Th
  - Can check whole decay chain
    講演番号7pA125-12　鈴木さん(横国大)
    （この後の南野さん講演でも紹介）
- ICP-MS
  - Fast measurement (10 lots per measurement)
  - Super high sensitivity
    Th~0.01 mBq/kg($Gd_2(SO_4)_3 \cdot 8H_2O$)
- New methods
  - Ra concentration using resin -> Ge/ICP-MS
    講演番号7aA125-1:細川さん＋筑波大＋岡山大

New Ge det. →





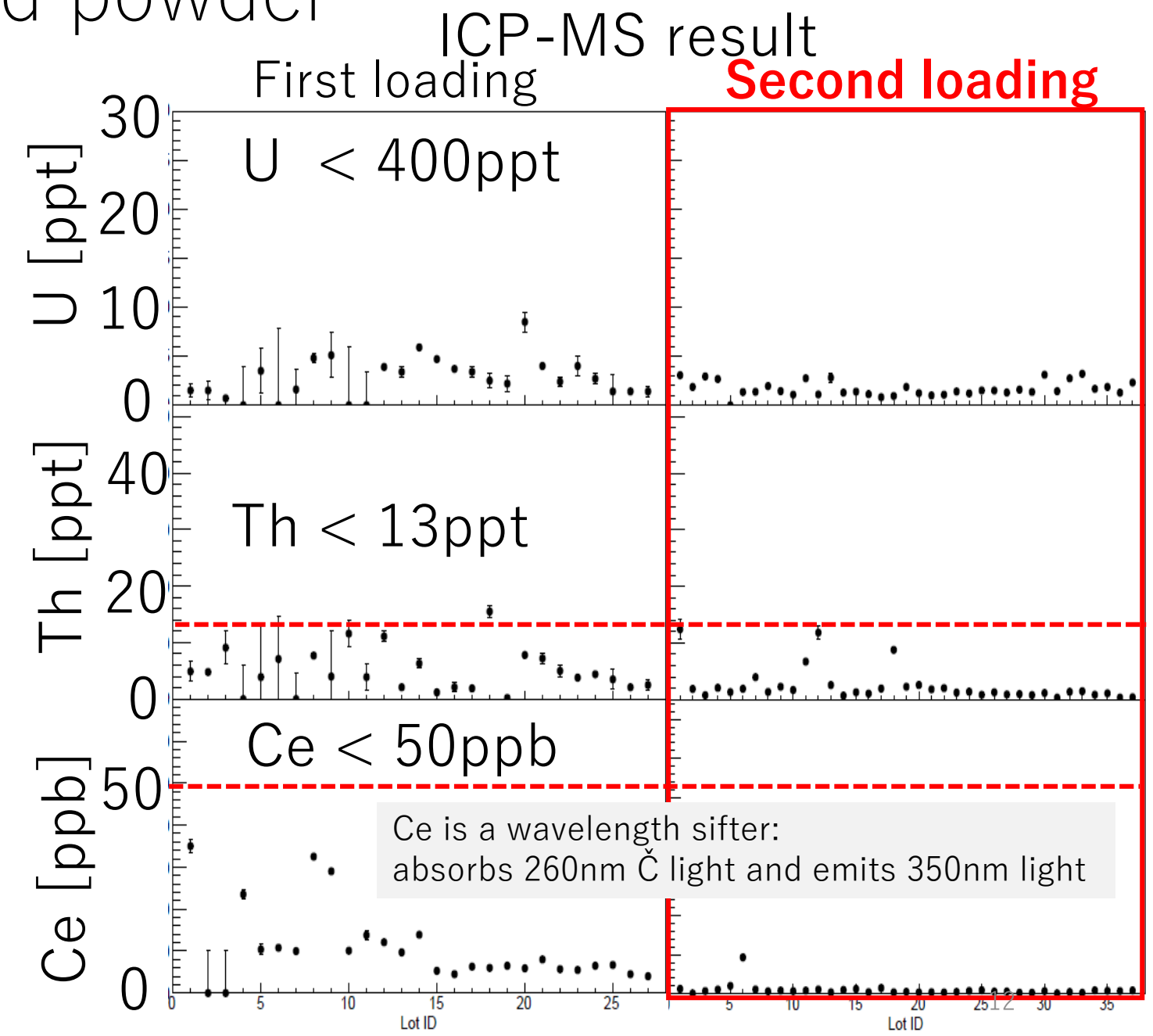
Kamioka Ge detectors

ICPMS in Kamioka

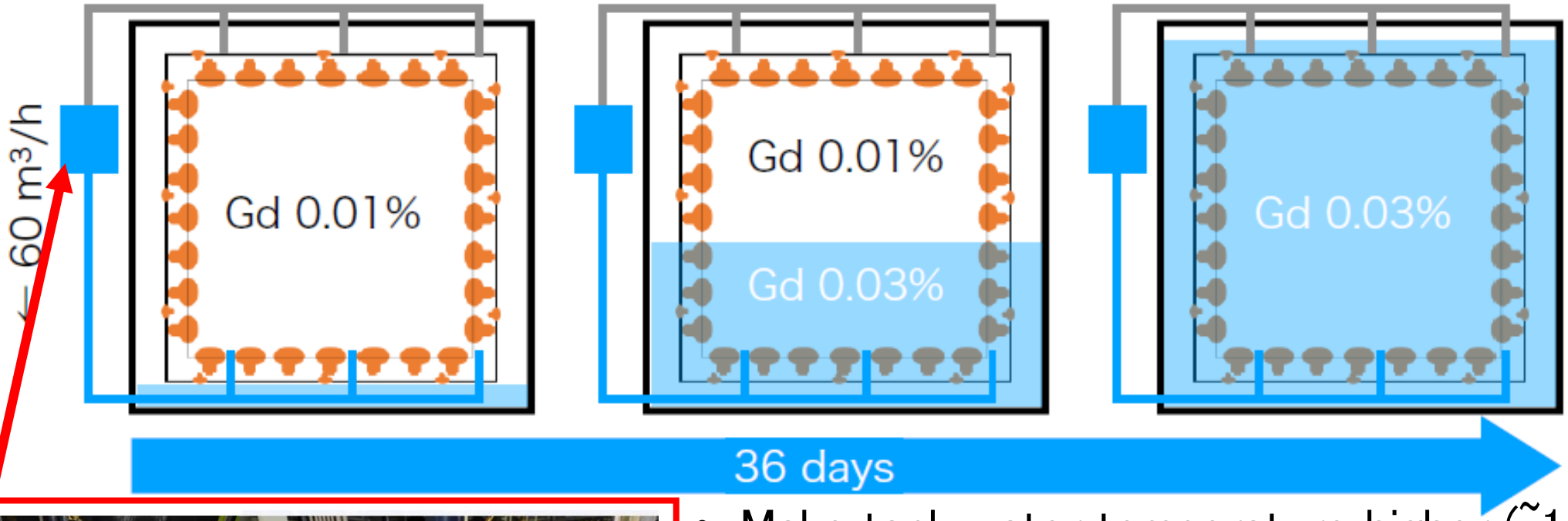
Screening results of Gd powder

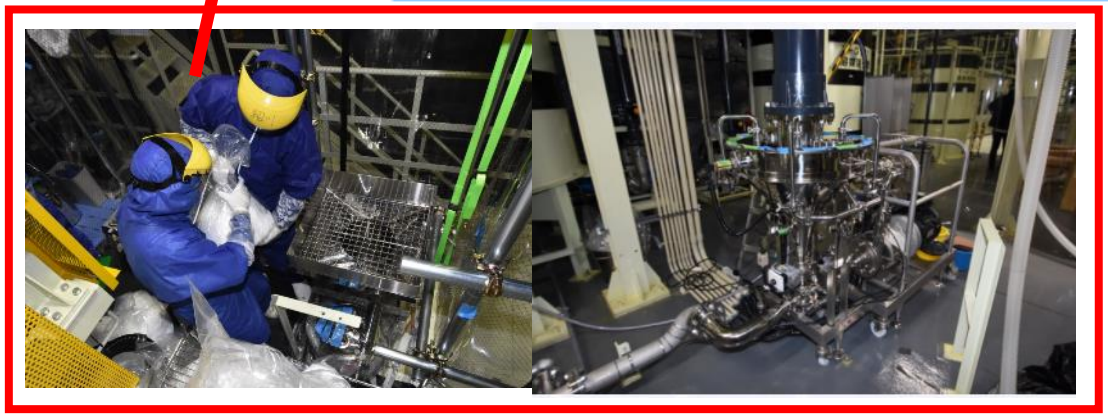
Preliminary

- We checked all 37 lots
- ^{238}U, ^{232}Th,&^{226}Ra meet our requirements
- For ^{228}Ra (Th chain < 0.05mBq/kg), Most Ge measurements could obtain limits;
  ~ 0.15mBq/kg
- Total ^{228}Ra (and lower daughters) activity (Upper limit)
  First loading (2020):
  8.9 Bq / 13ton
  of $Gd_2(SO_4)_3 \cdot 8H_2O$
  Second loading (2022):
  3.9 Bq / 26 ton
  of $Gd_2(SO_4)_3 \cdot 8H_2O$



Loading scheme





$Gd_2(SO_4)_3 \cdot 8H_2O$ ~ 800kg / day

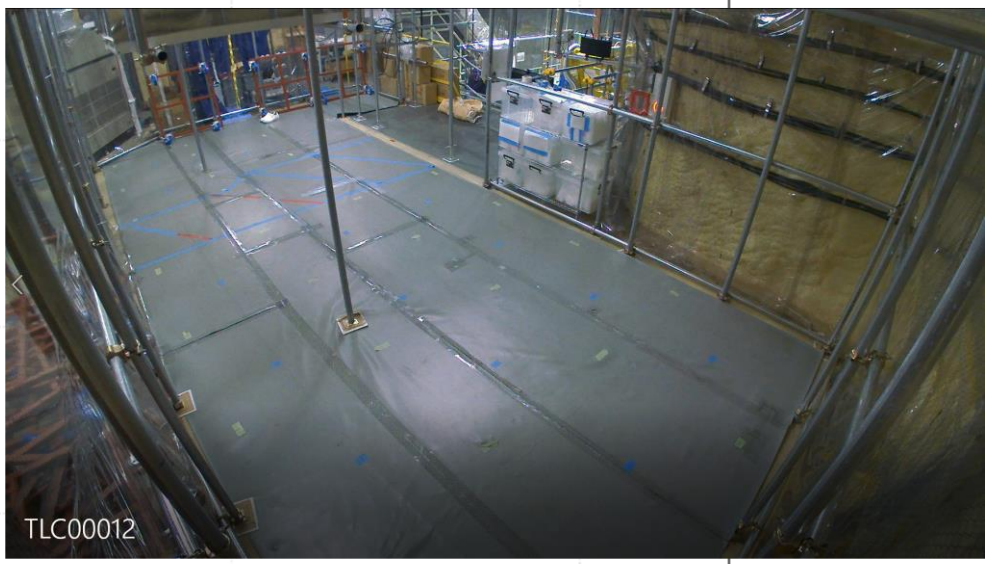
- Make tank water temperature higher (~1month)
  - 13.7℃ at the beginning of the loading
- Dissolve Gd powder to the return water from SK
  - 0.01% Gd-water from the top of SK tank.
- Supply slightly colder water from the bottom
  - Supply water temperature : 13.5℃

Loading profile

Very stable loading has been achieved!

Beginning of the dissolving work

End of the dissolving work

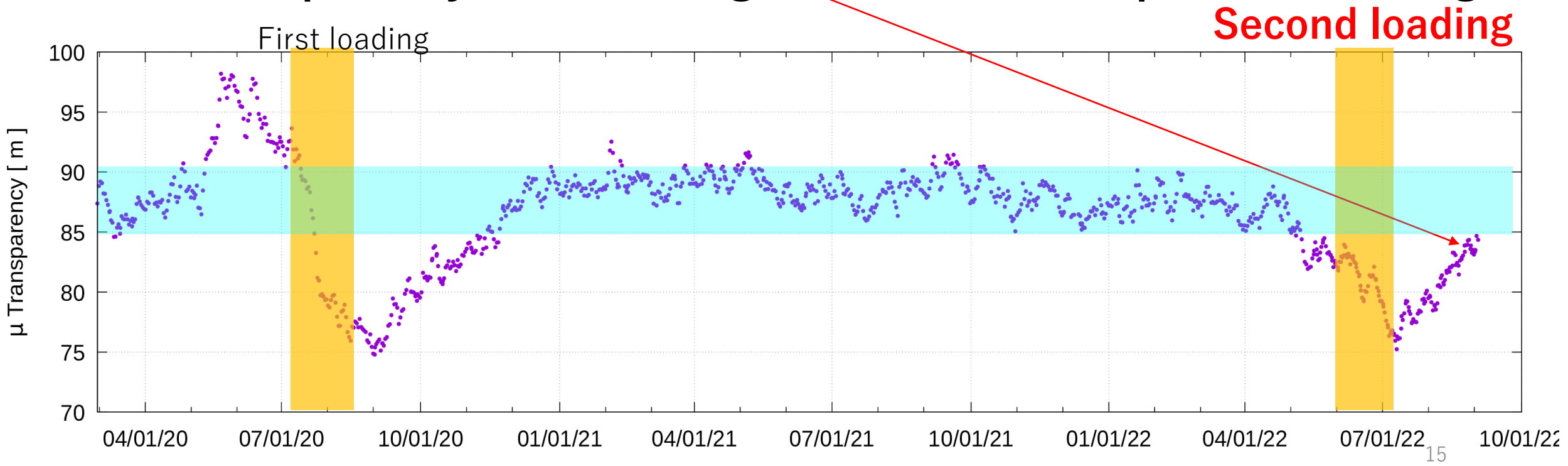


Maintenance

Summary of 2022 loading

- Period: June 1st -> July 4th. 2022
- Weight of $Gd_2(SO_4)_3 \cdot 8H_2O$: 26115 kg
  - In terms of Gd: 10988 kg (Cf. for the first loading : 5426kg)
  - Calculated concentration : 0.033 %

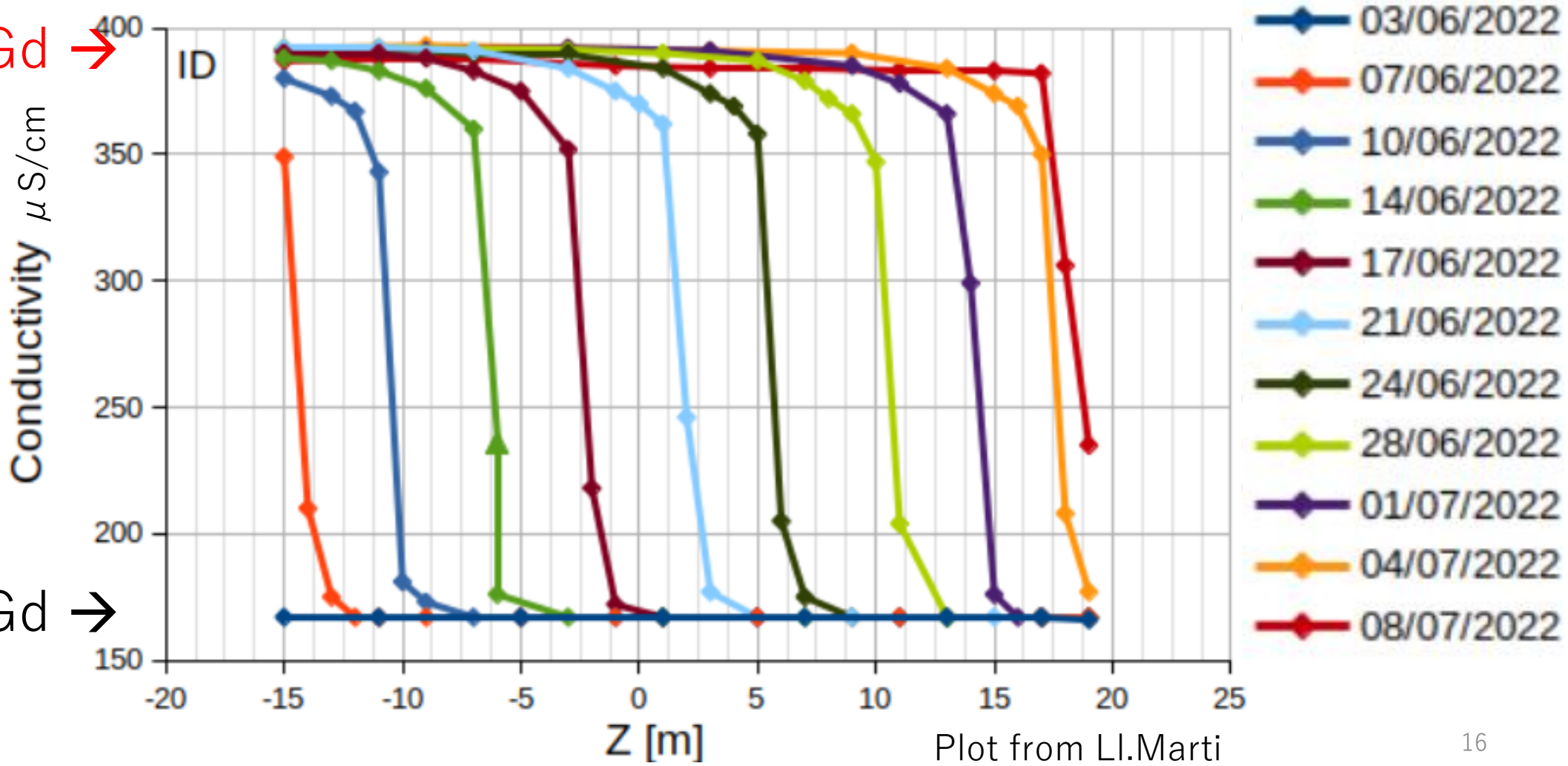
Water transparency is recovering now (reached to pure-water range)



Detector status during/after the loading- 1

- Conductivity of the tank water: concentration of Gd

0.03% Gd →

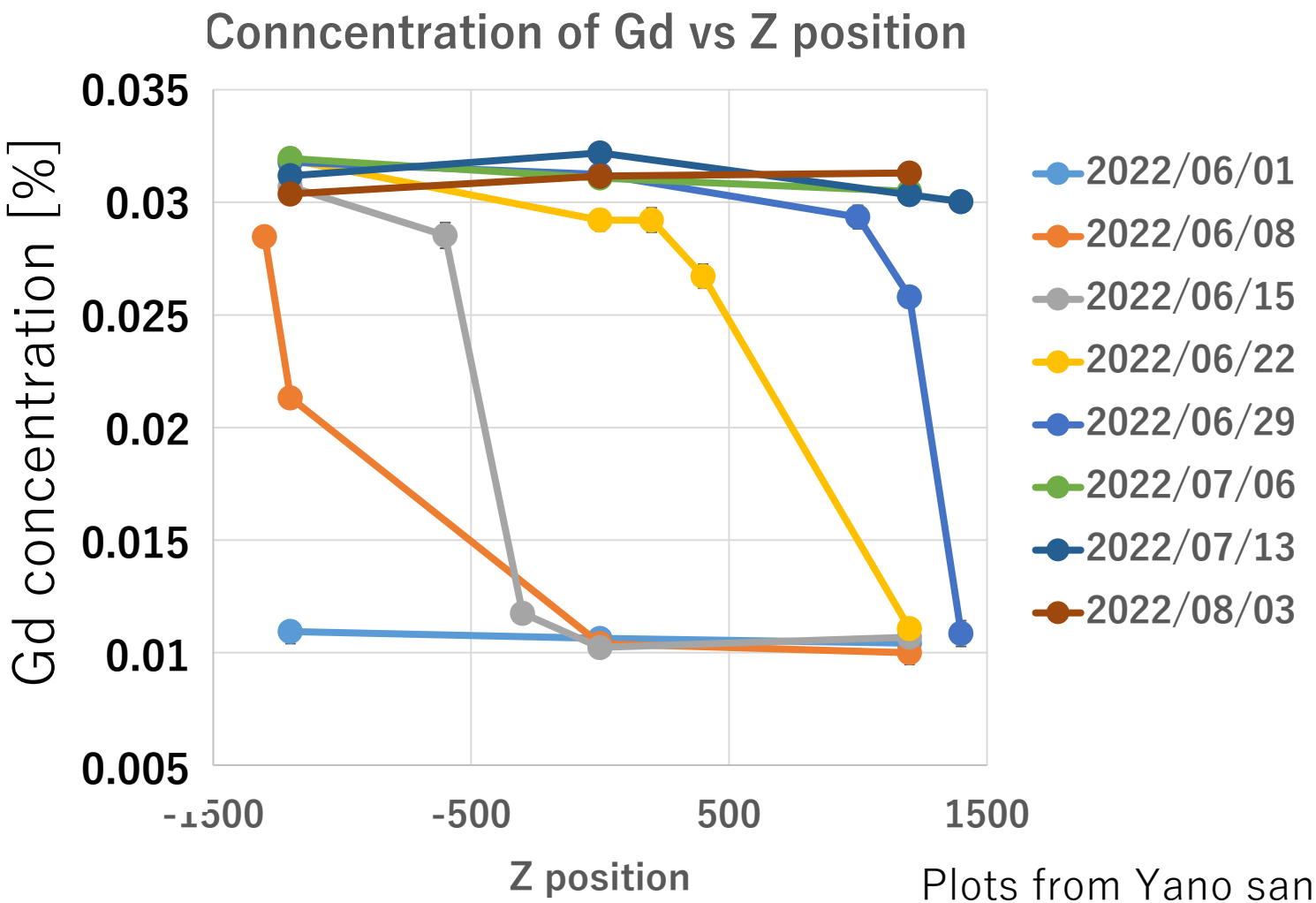


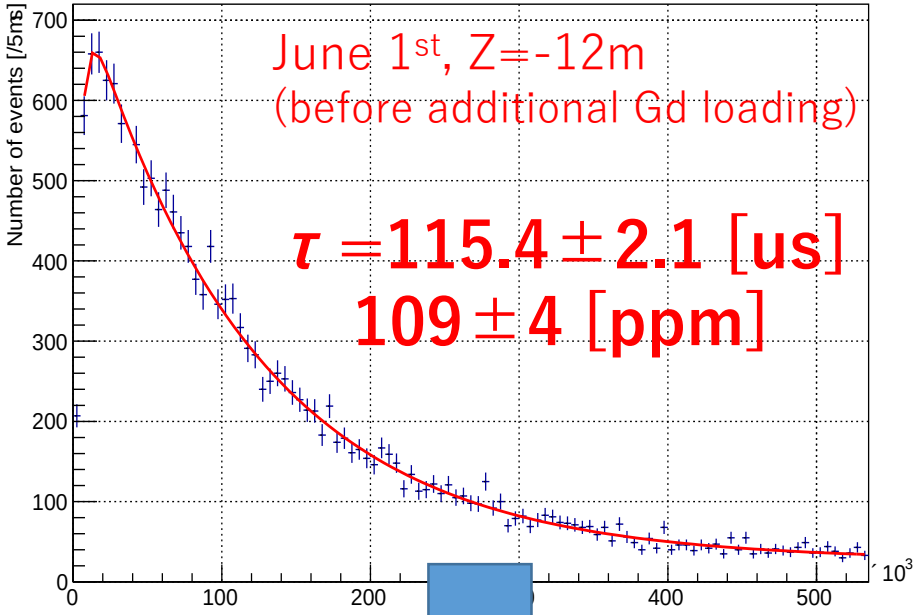
0.01% Gd →

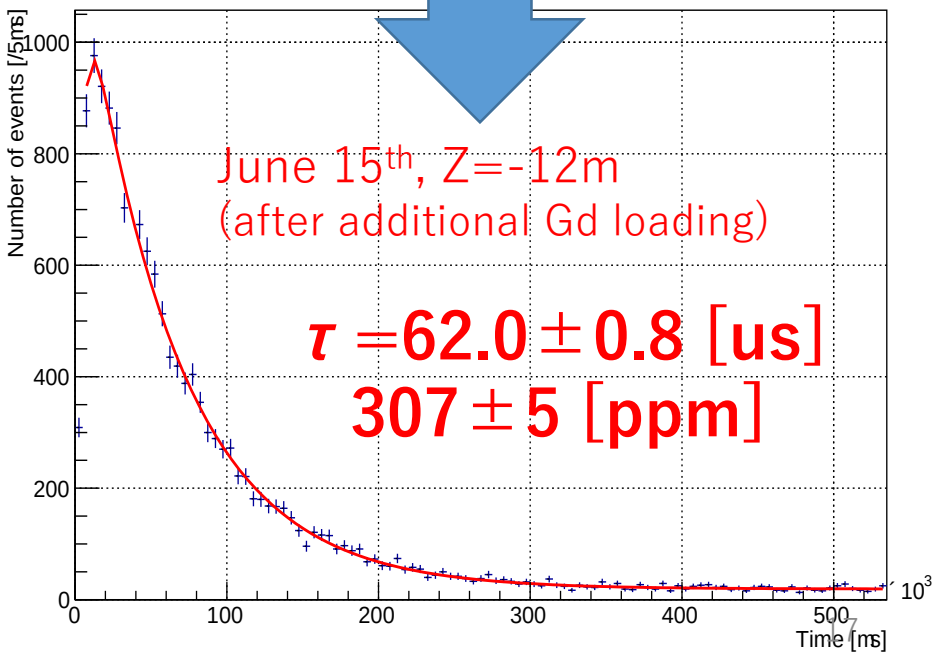
Plot from Ll.Marti

Detector status during/after the loading- 2

AmBe neutron source





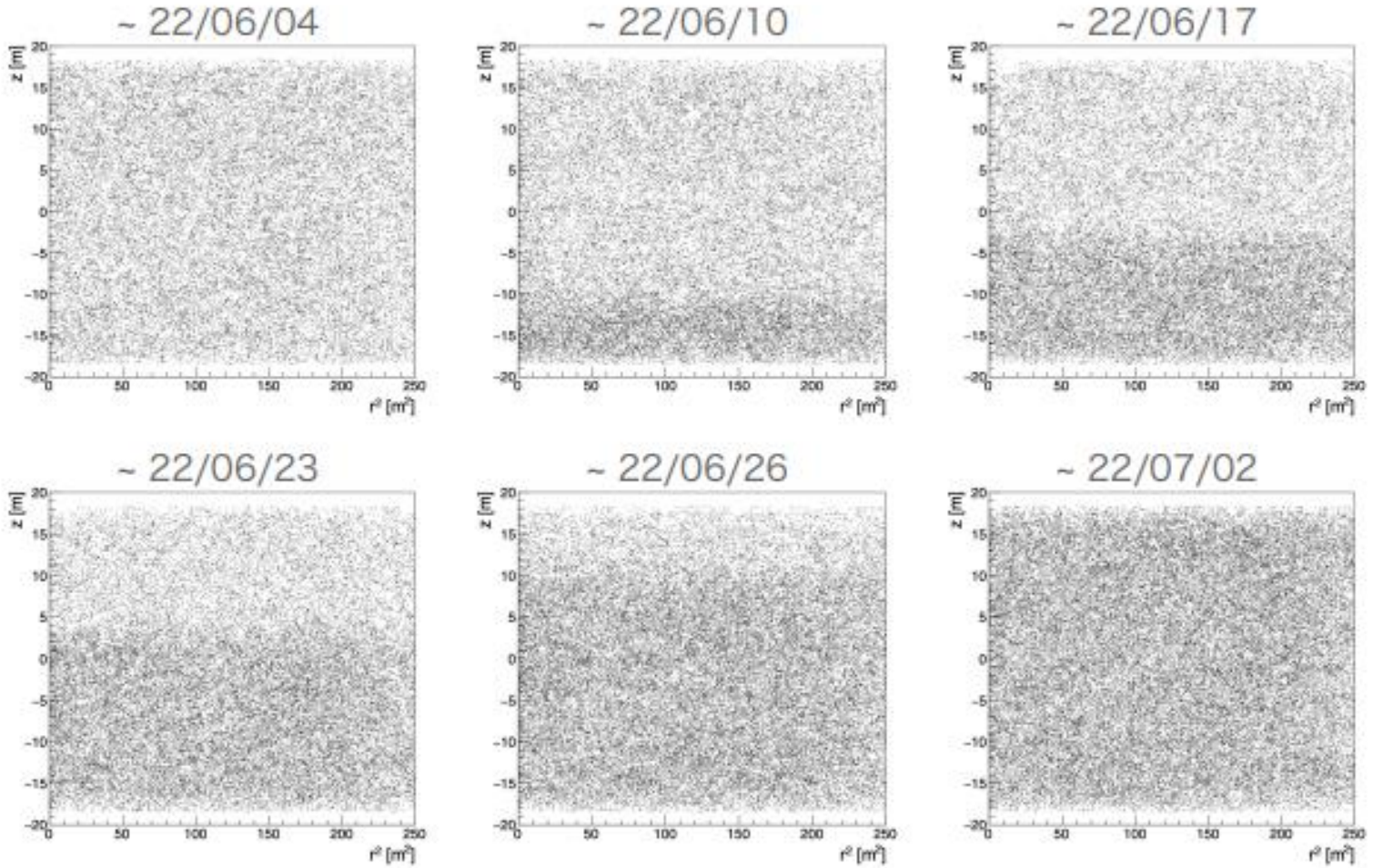


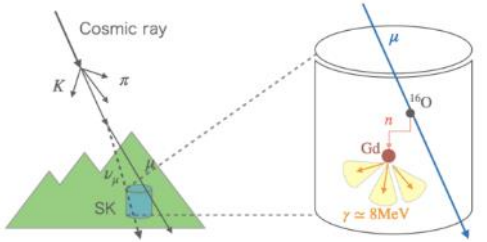
Plots from Yano san

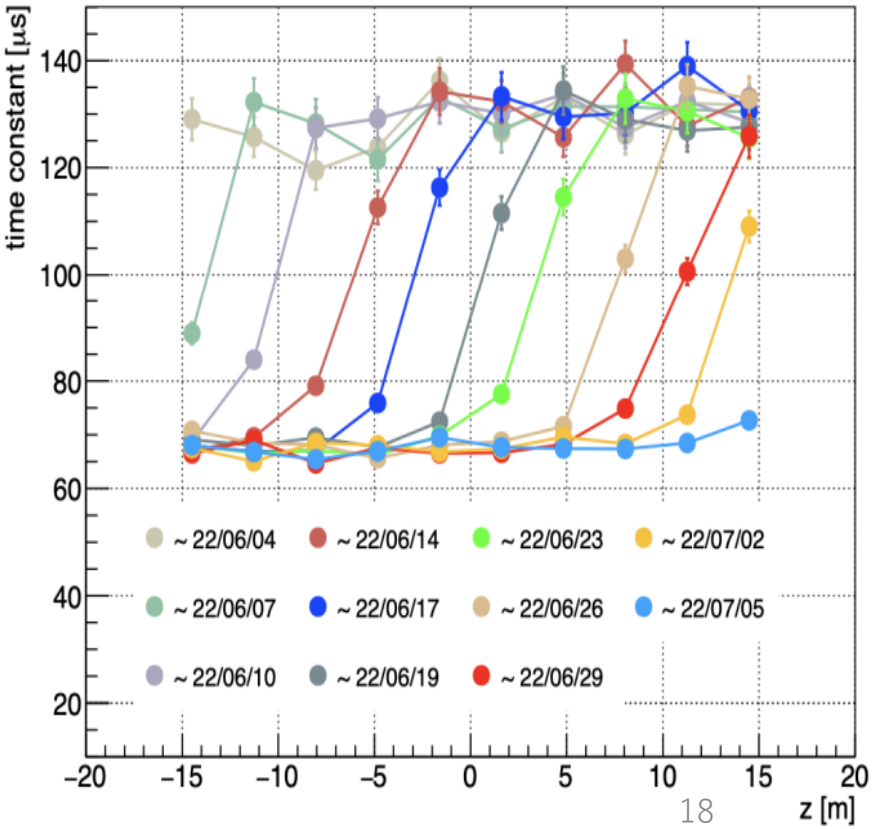
Detector status during/after the loading- 3

Cosmic μ induced neutrons

講演番号：7aA125-7 志摩さん





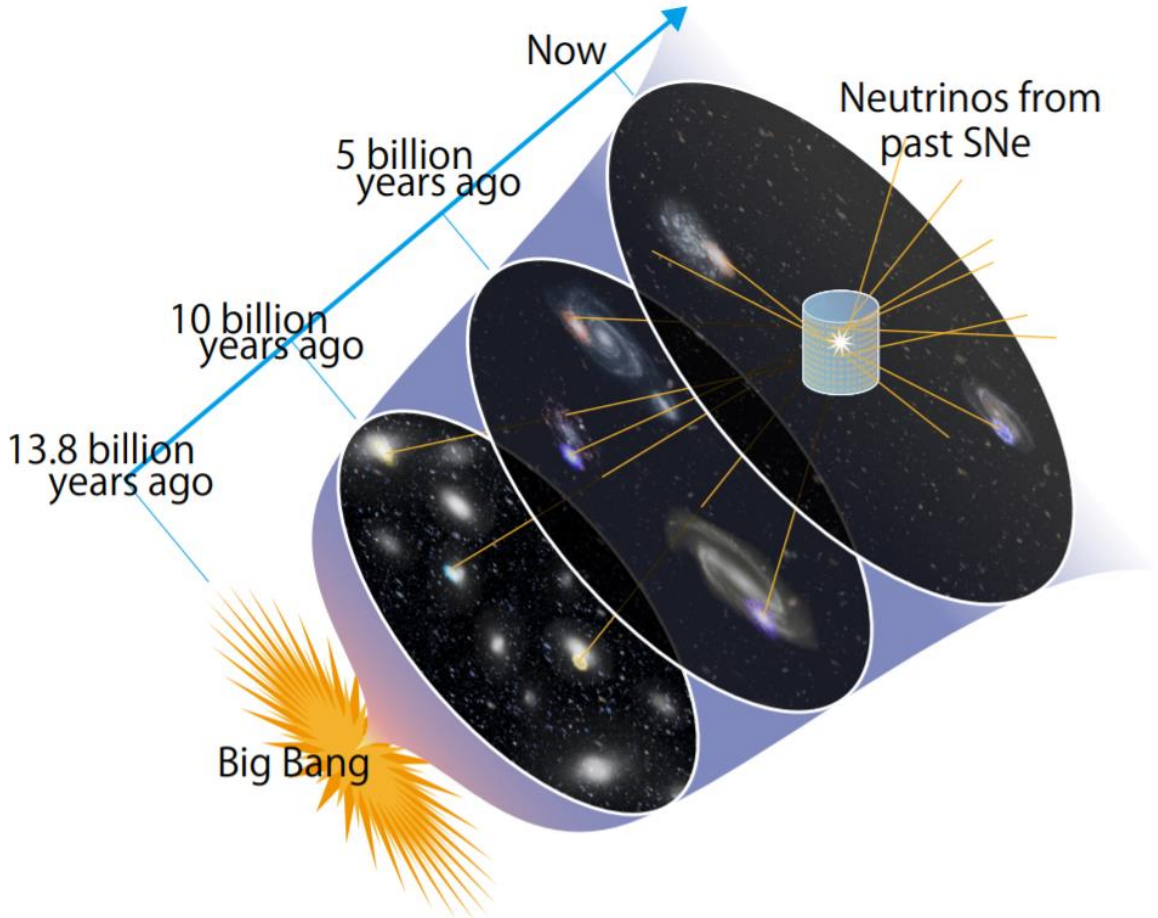


Physics sensitivity to supernova neutrinos

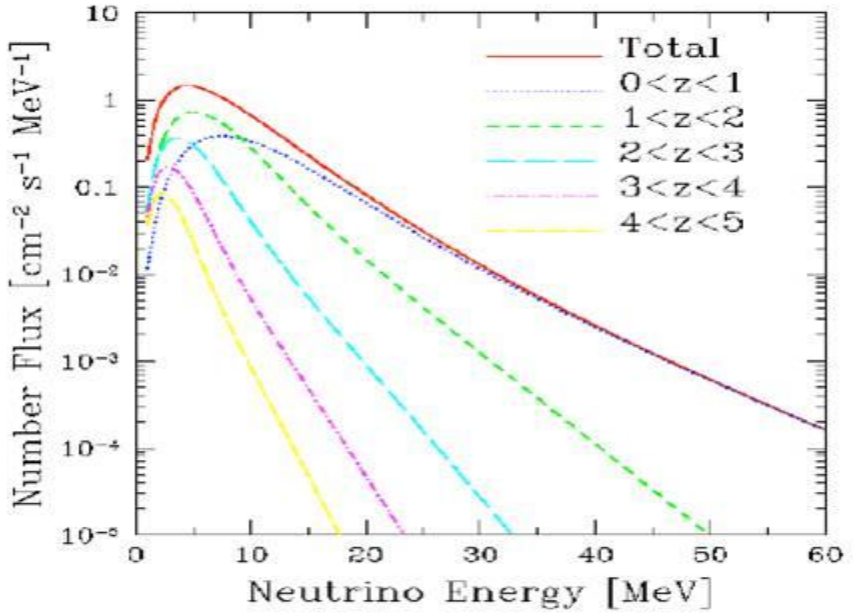
- SRN
- Galactic supernova burst
- Pre-SN neutrinos

Supernova Relic Neutrino (SRN)

Discovery of SRN 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)

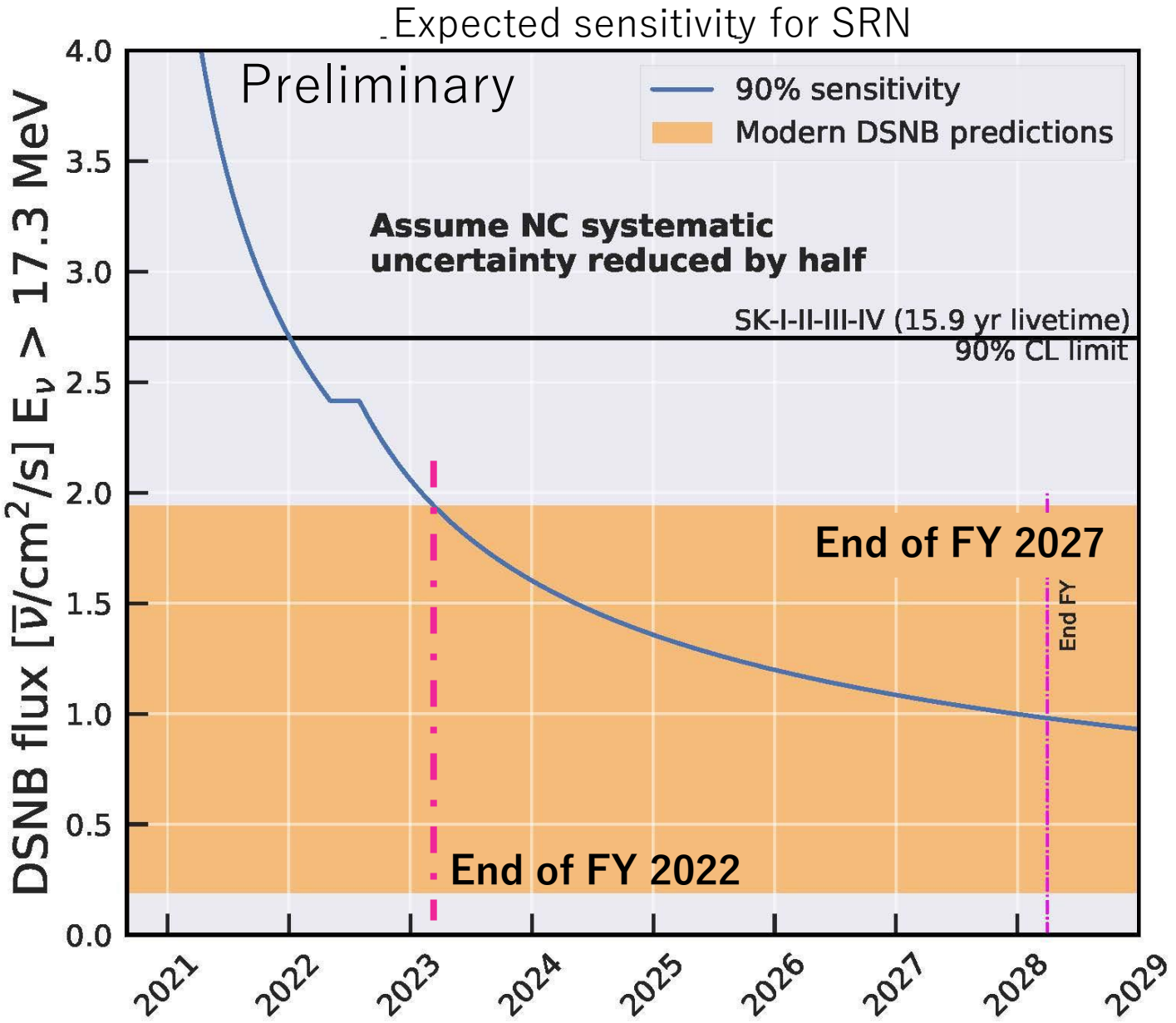
Search for SRN

Many studies are on going.

Ex. Talks at this JPS

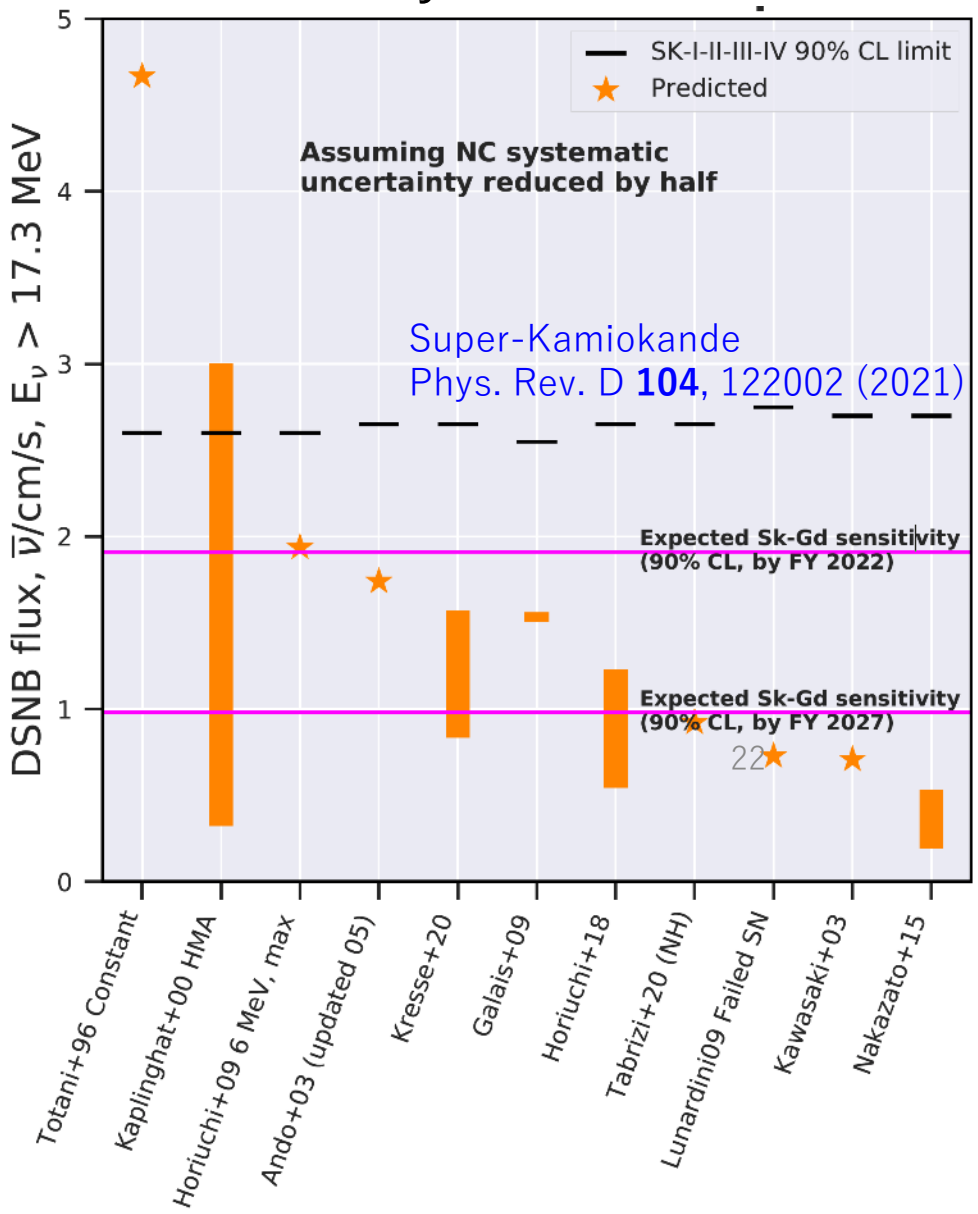
BG study
- PMT noise : 6aA422-4 前川さん(慶大)
- Spallation：7pA125-8 原田さん（岡大）

MC simulation
- Water parameters :
  7pA125-7 多田さん（岡大）、
  7aA125-4 清水さん（東大）
- Trigger efficiency etc.:
  7p125-9 泉山さん（TIT）
- Oxgen interaction：
  7pA125-6 中西さん（岡大）



Sensitivity to SRN

Preliminary



Milestones

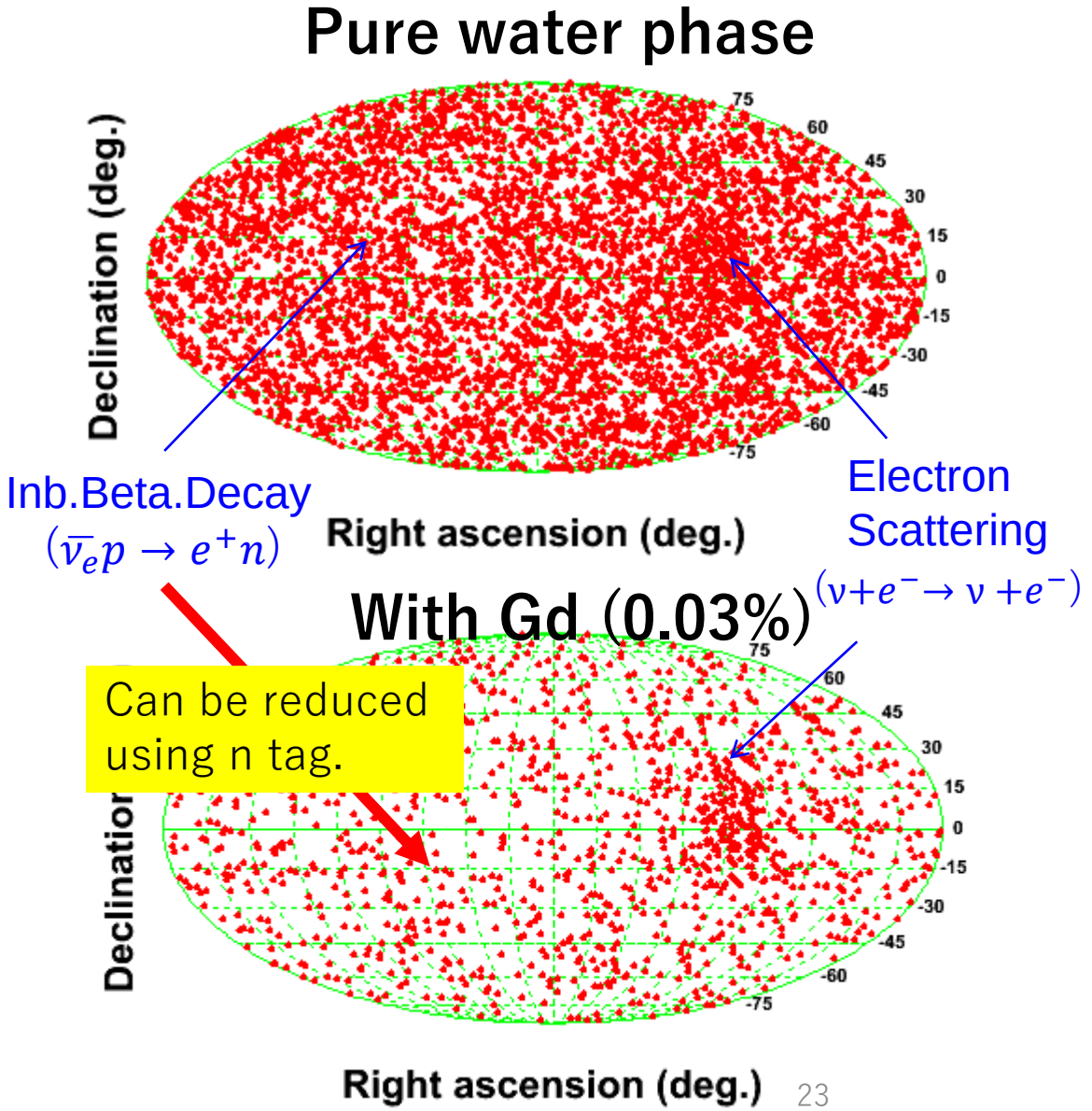
- Improved S/N ratio by Gd neutron tag.
- Reduce systematic uncertainties related to atm. *ν*
  - T 2 K measurement
  - External nuclear experiments

← **FY2022** **Better than SK pure water phase**

← **FY2027** **Can reach most of model prediction**

Galactic supernova burst observation

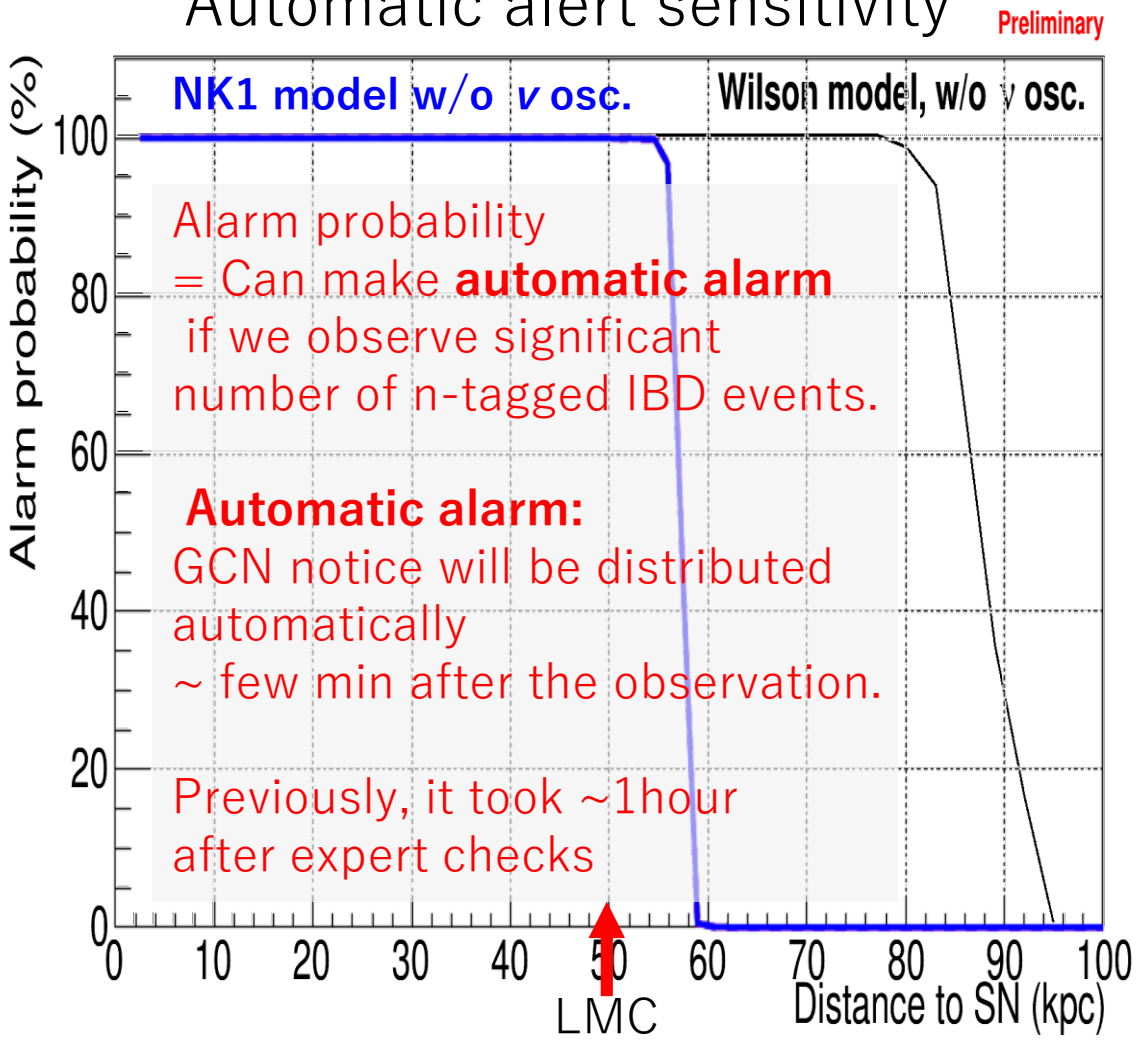
- Neutrinos can escape from a supernova earlier than photons.
  - Neutrinos arrive few min ~ hours before photons
  - Observation of the neutrino burst can inform telescopes.
    - SK can detect the direction of SN by itself
- Improvements in SK-Gd
  - Significance of SN is enhanced if we observe many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



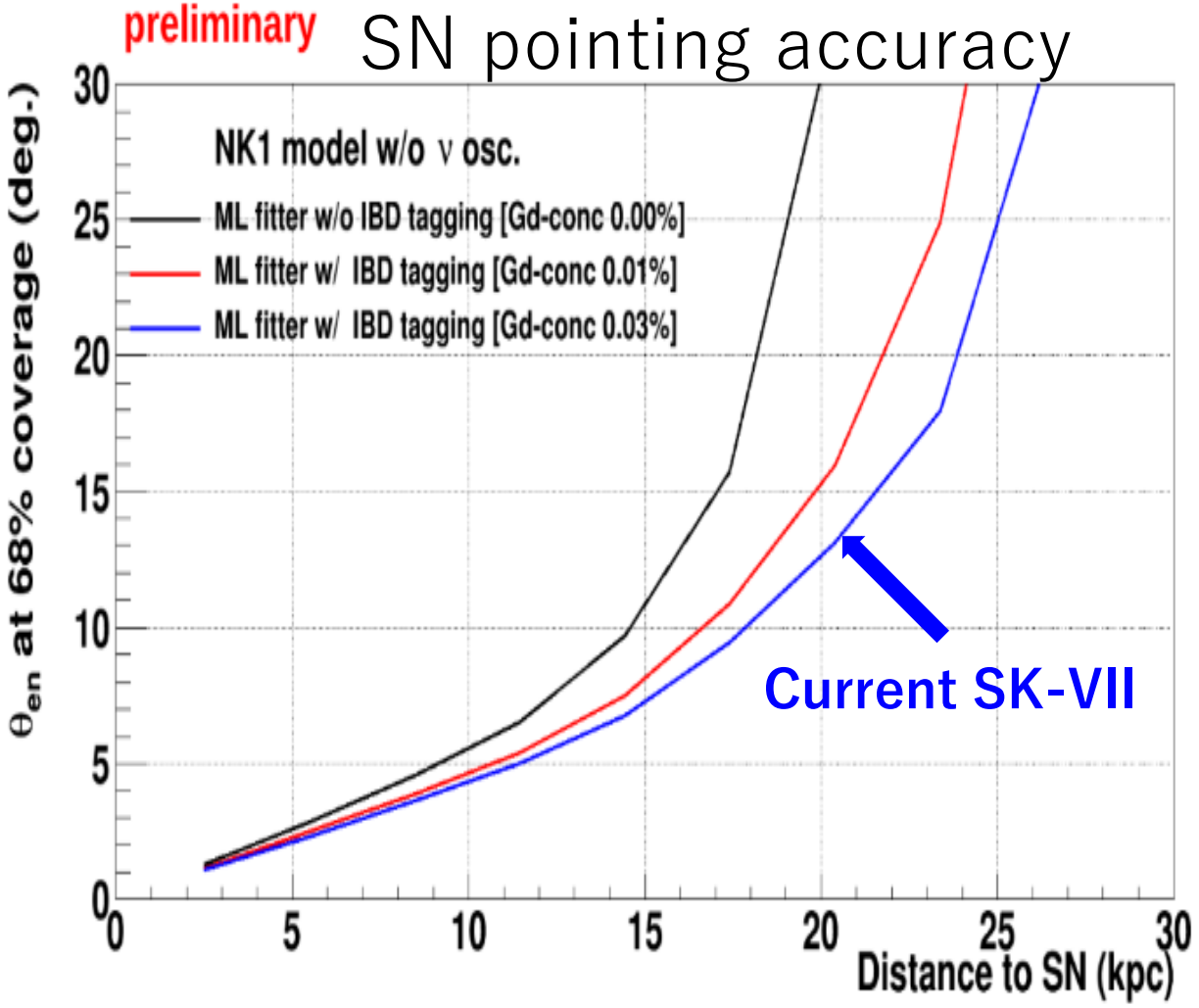
Sensitivity to Galactic supernova burst

System upgrade: 7pA125- 4　Guillaume さん
Model dependence; 7pA125-5　柏木さん

Automatic alert sensitivity



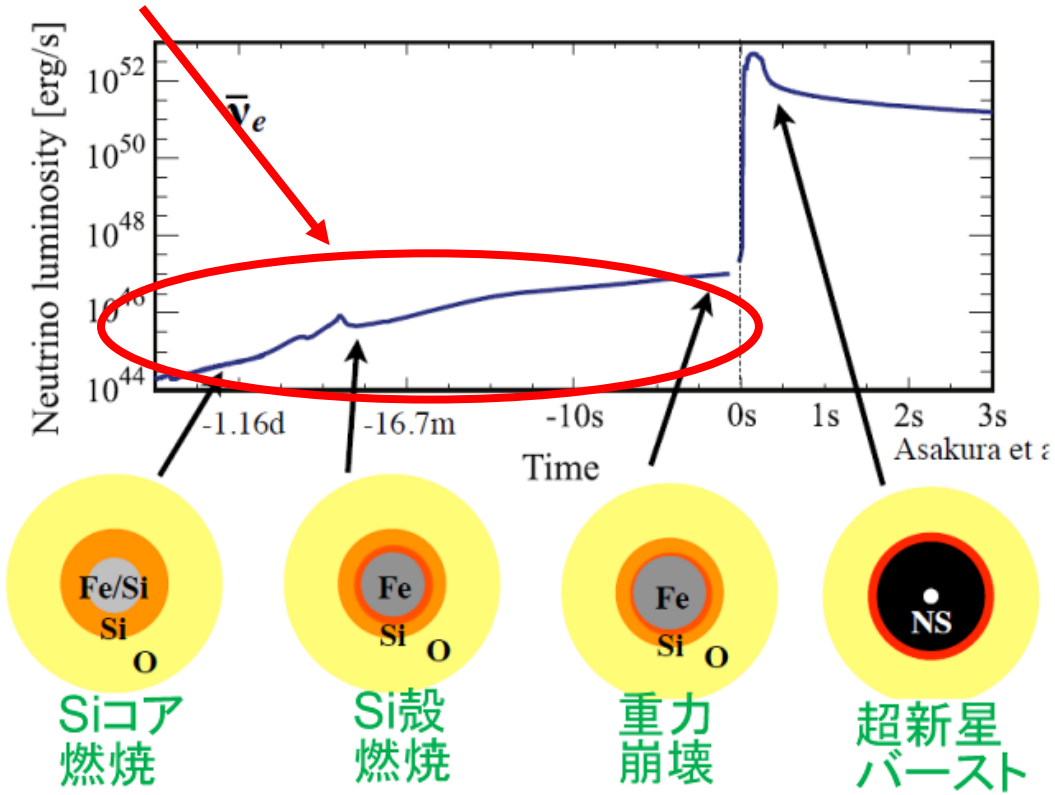
SN pointing accuracy



We want to shorten the latency below 1min in future

Sensitivity to very close supernova burst

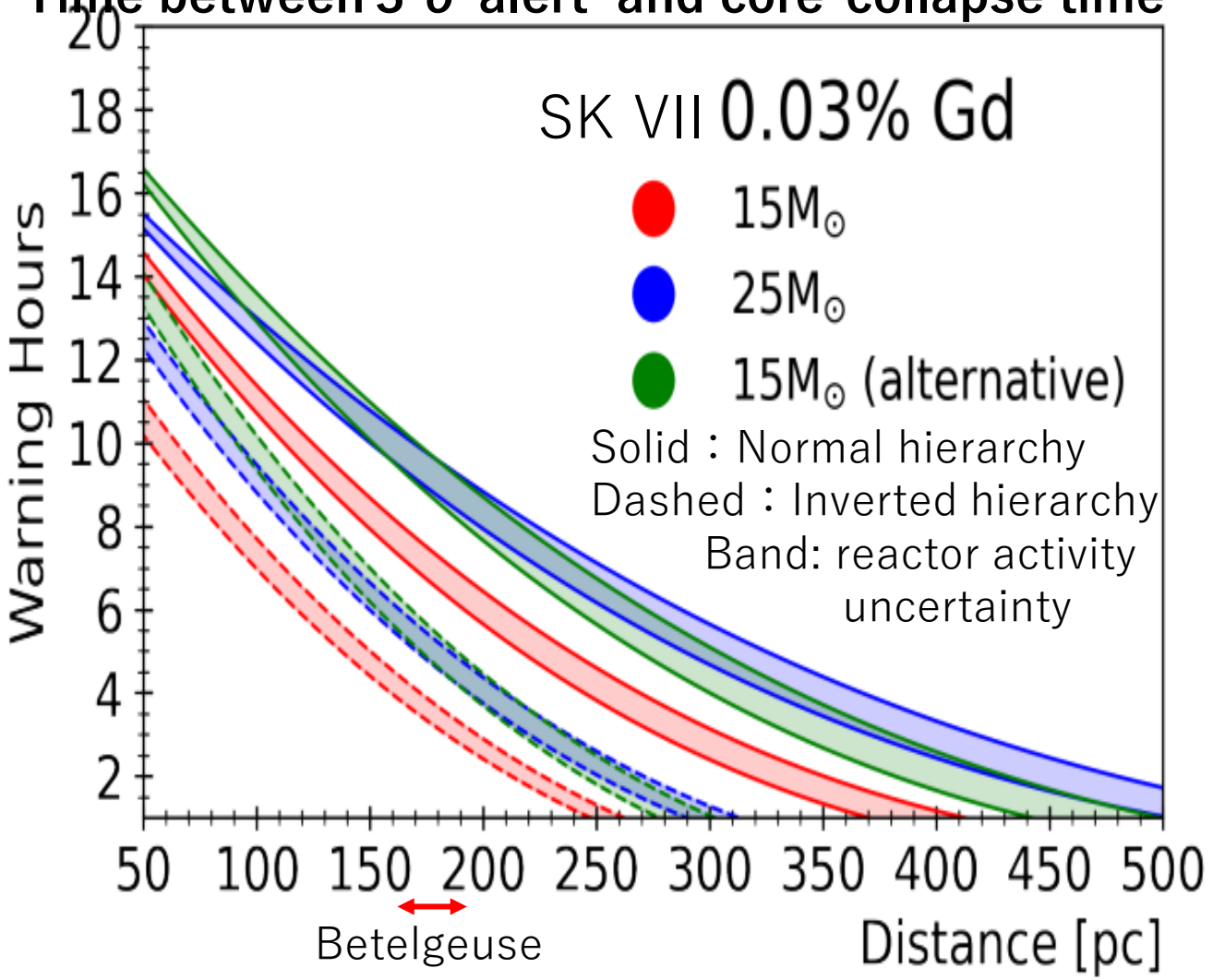
Pre-SN neutrino detection



Using neutron tag by Gd and a intelligent trigger system (2~3 MeV threshold) ,
SK-Gd can detect pre-SN neutrinos.

The Astrophysical Journal, Volume 935, Number 1 (2022)

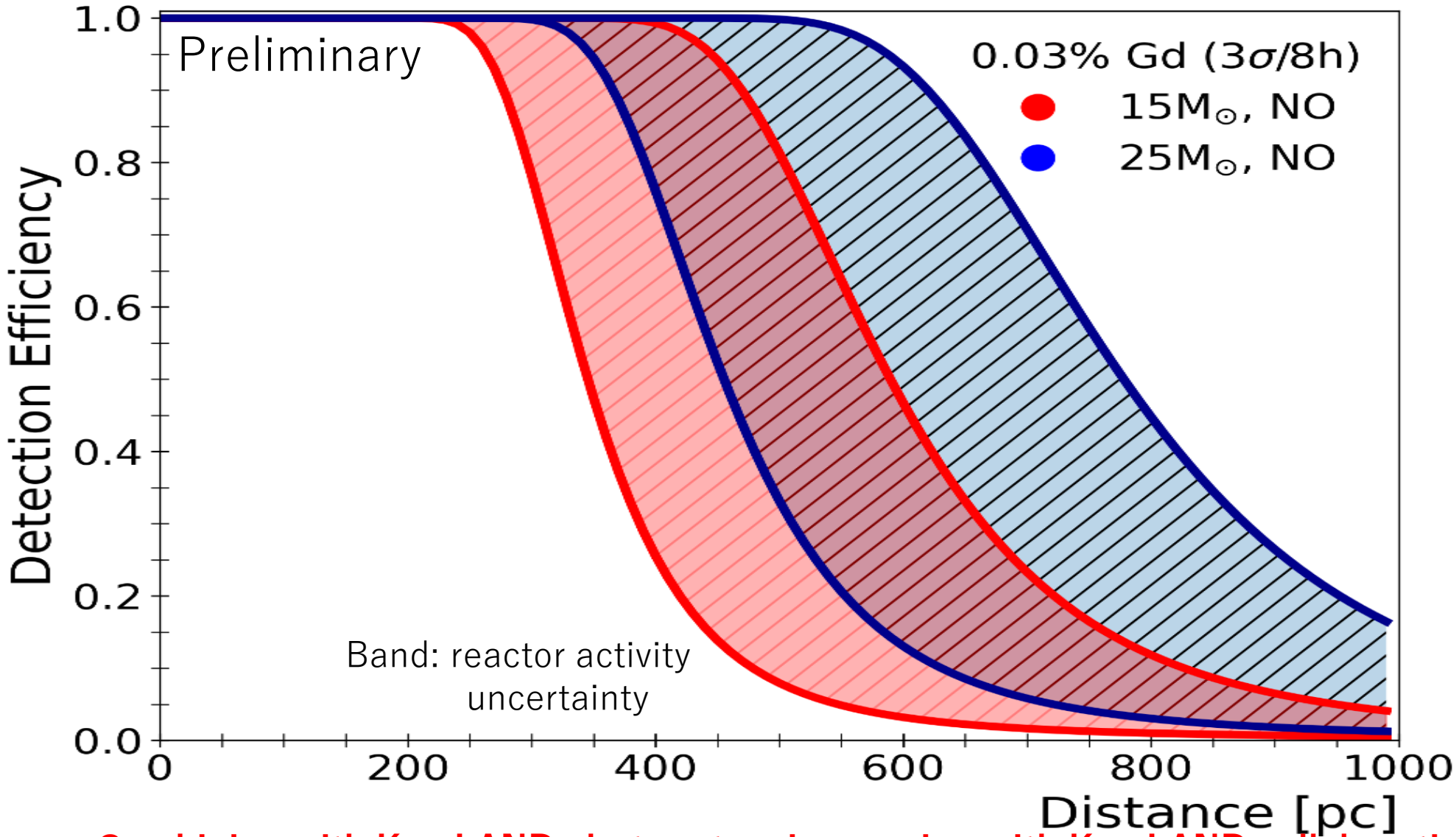
Time between 3 σ alert and core-collapse time



For Betelgeuse, we can get 3 σ alert 5 to 10 hours in advance of its core-collapse

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

Summary

- SK-Gd project:
  - Better quality of 26 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ compared to 2020
  - In July, 2022 : 0.03% Gd has been achieved
  - Water transparency recovering(we are now in the pure-water range)
- Higher sensitivities to supernova neutrino observations
  - SRN : By the end of FY2027, we can reach most of model predictions
  - Galactic SN burst:
    - Aiming to achieve better than 3° resolution@10kpc
    - Automatic alert system : ~5min latency @ 10kpc
      (We will upgrade the system so that the latency will be ~ 1min)
  - Pre-SN burst
    - 3 σ detection sensitivity up to 500pc
    - For Betelgeuse, we can get 3 σ alert 5 to 10 hours in advance of its core-collapse
    - Combined alert system with KamLAND will come soon!