Gd loaded Super-K: status and plan

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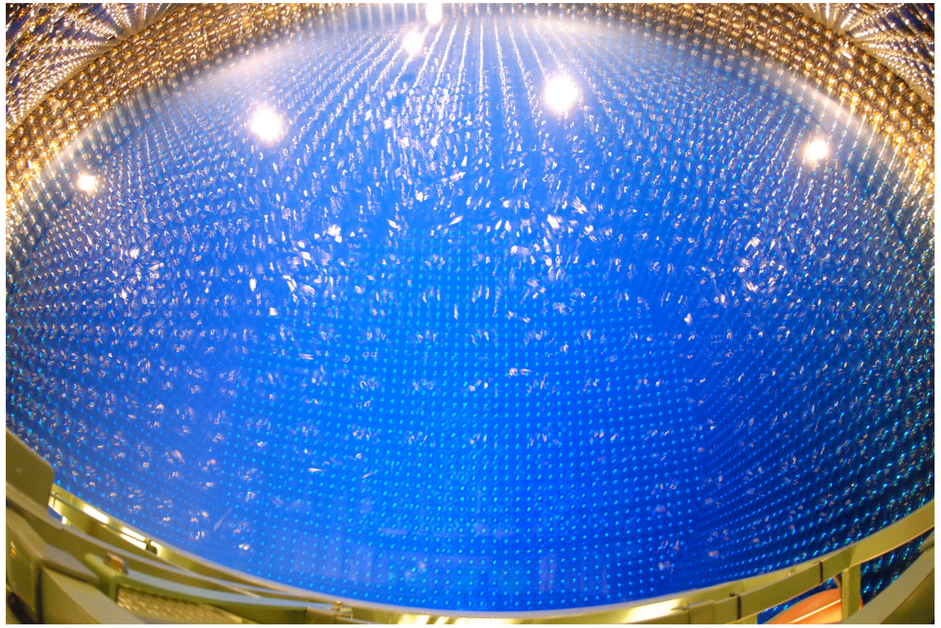
Contents

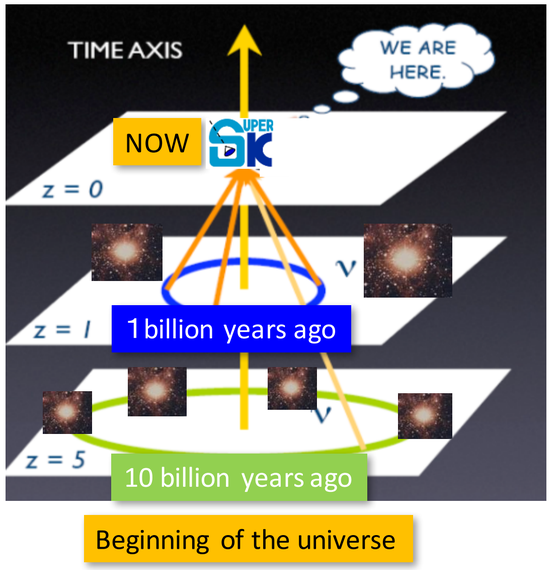
- Diffuse Supernova Neutrino Background
- SK-Gd: Gadolinium loaded Super-K
- R&D and preparation for SK-Gd
- Plan
- Summary



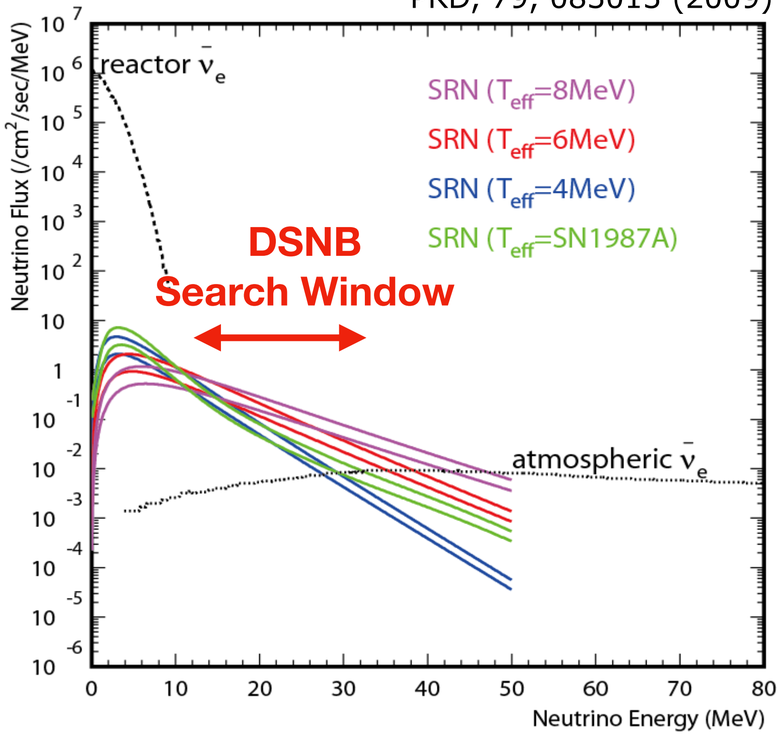
Supernova Neutrinos

- Supernova neutrinos provide a lot of Physics:
  - Mechanism of supernova burst
  - Nature of neutrino
- The only supernova neutrinos we detected so far: SN1987A
- After waiting for 30 years without new burst, we are now *actively* trying to detect supernova neutrinos
- **Diffuse Supernova Neutrino Backgrounds (DSNB)**
  - Neutrinos produced by the past supernova bursts, and now diffused throughout the universe.

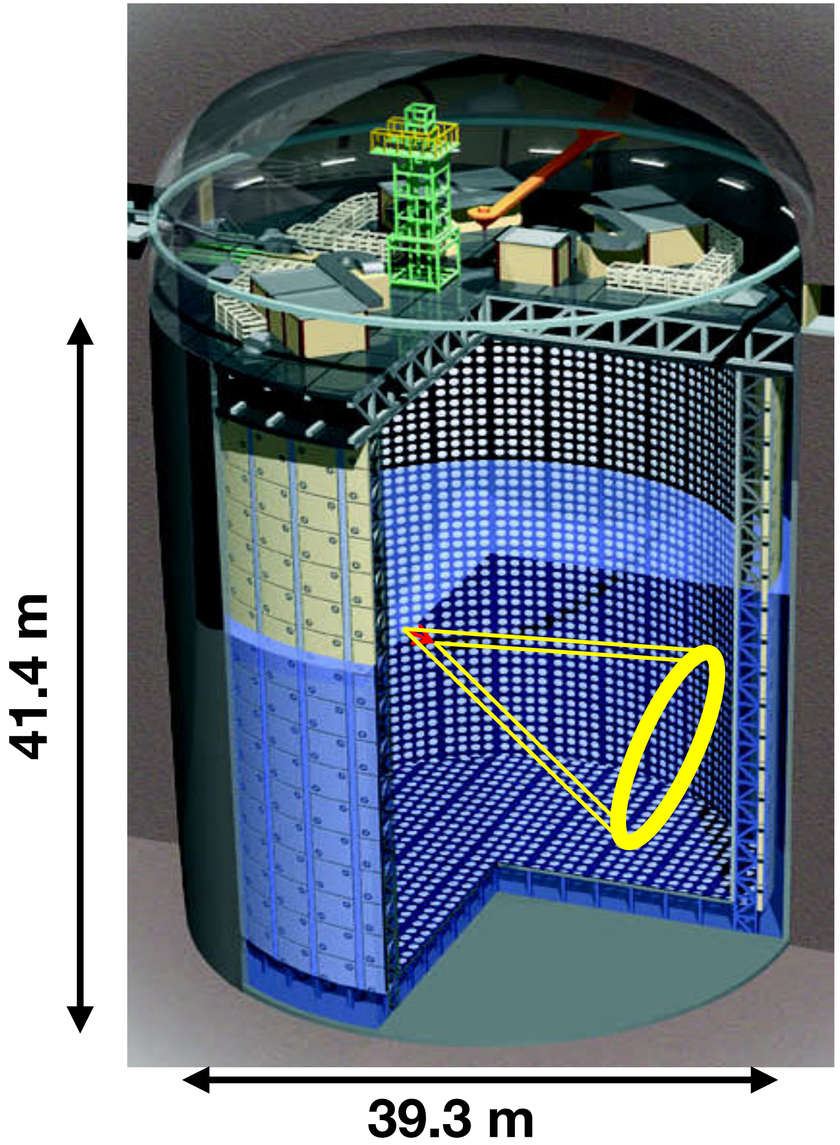
10^{10} stellar/galaxy $\times$ 10^{10} galaxies $\times$ 0.3%(become SNe) ~$O(10^{17})$SNe



Horiuchi, Beacom and Dwek, PRD, 79, 083013 (2009)



The Super-Kamiokande detector



- 50-kton water Cherenkov detector located at Kamioka, Japan
- Overburden: 2700 mwe
- Inner Detector covered by > 11000 20-inch PMTs
- Can detect neutrinos for wide energy rage
  - Solar neutrinos
  - **Supernova neutrinos**
  - Atmospheric/Accelerator neutrinos

~ MeV

~ GeV

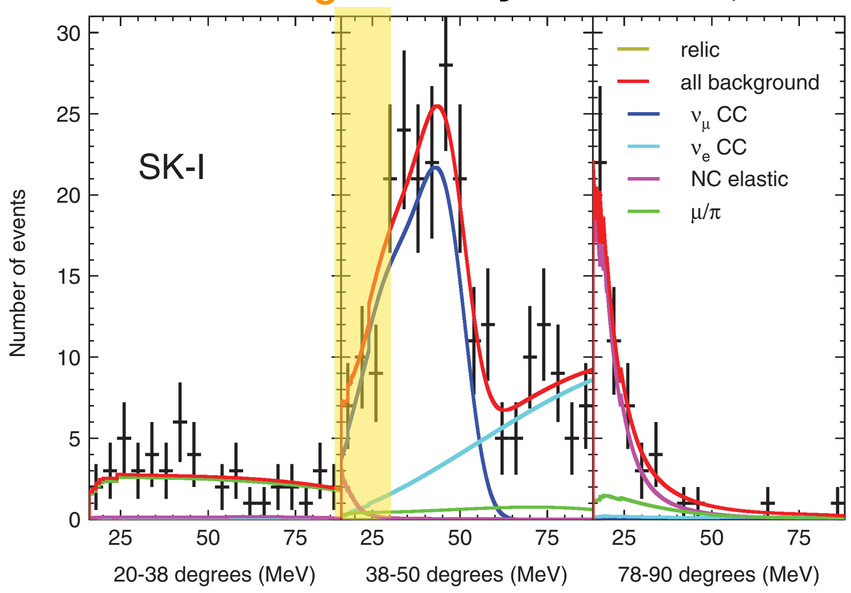
- Operational since 1996

DSNB search at Super-Kamiokande

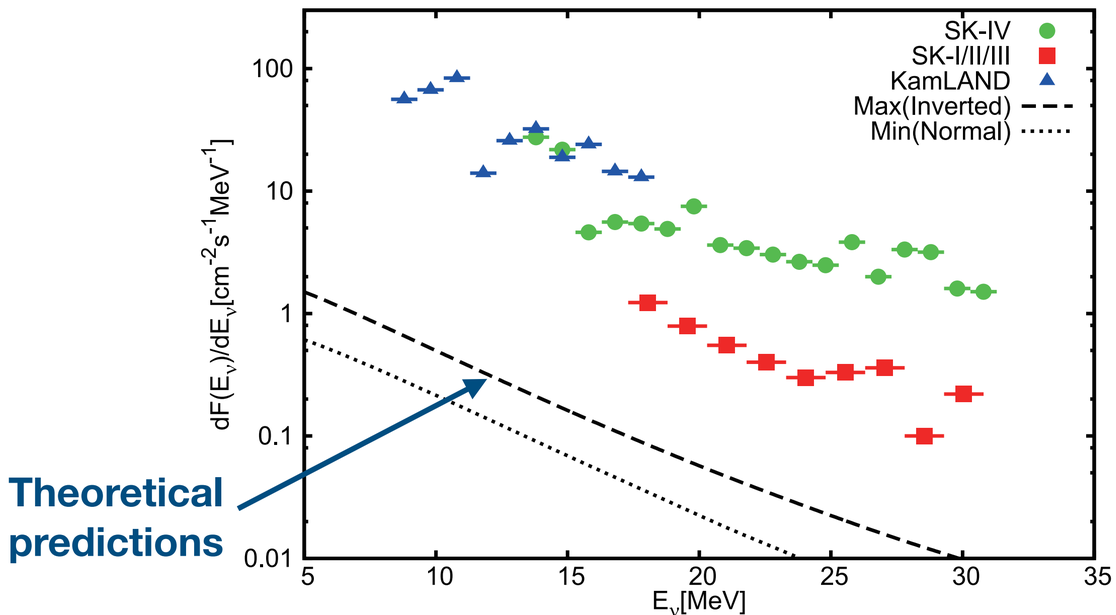
- Super-K holds the current best limits for the DSNB flux
- Sensitivity limited by backgrounds
- However, only one order magnitude above theoretical predictions.
- Should be within Super-K's reach once we were able to reduce backgrounds!

DSNB Region

Phys. Rev. D85, 052007 (2012)



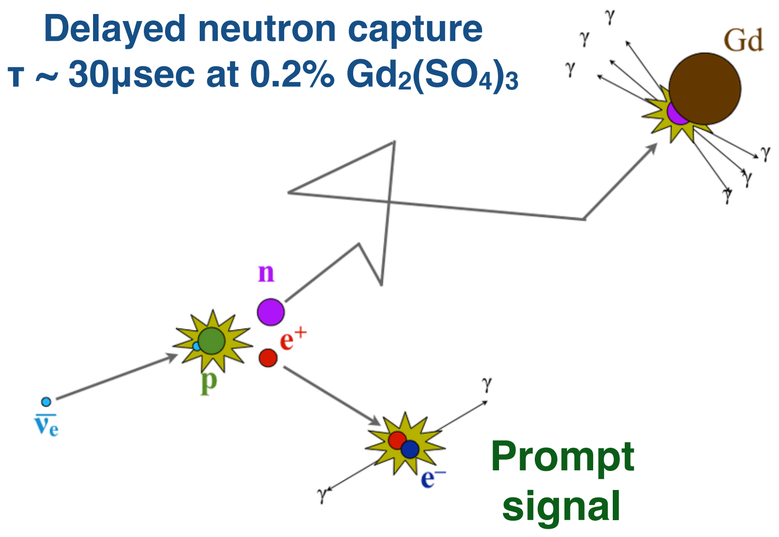
Astrophys. J. **804**, 75 (2015)



Gd-loaded Super-K: SK-Gd

- Dissolving Gd to Super-Kamiokande to significantly enhance detection capability of neutrons from ν interactions
- Idea first proposed in:

  J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. 93 (2004) 17110



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

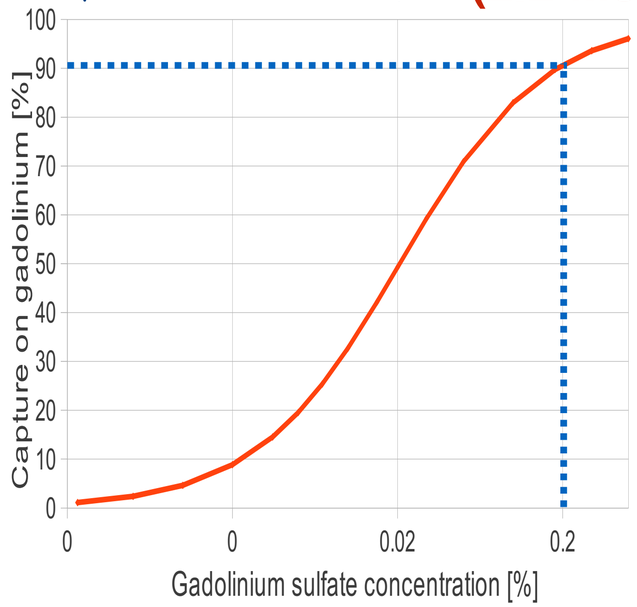
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma(s) \quad \text{(8 MeV)}$$

$$n + H \rightarrow D + \gamma \quad \text{(2.2 MeV)}$$

Advantage of Gd:

- Large n-capture cross section:
  - 90% of Gd capture efficiency at 0.2% loading of $Gd_2(SO_4)_3$ (corresponds to 100 ton/SK)
- Large released energy of ~8MeV
  - Well above most of natural radioactivity and the SK trigger threshold

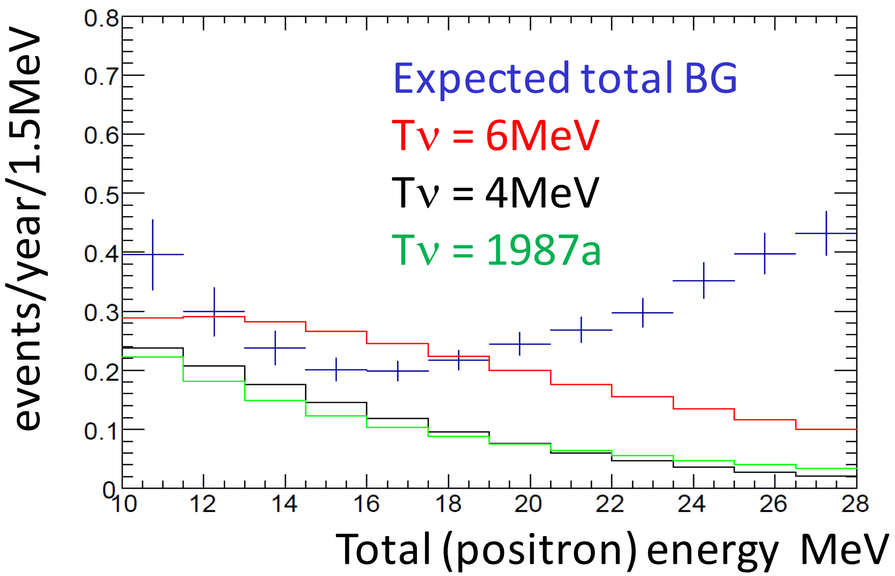
Strongly tag electron antineutrinos by prompt (e^+) and delayed (n-Gd) coincidences

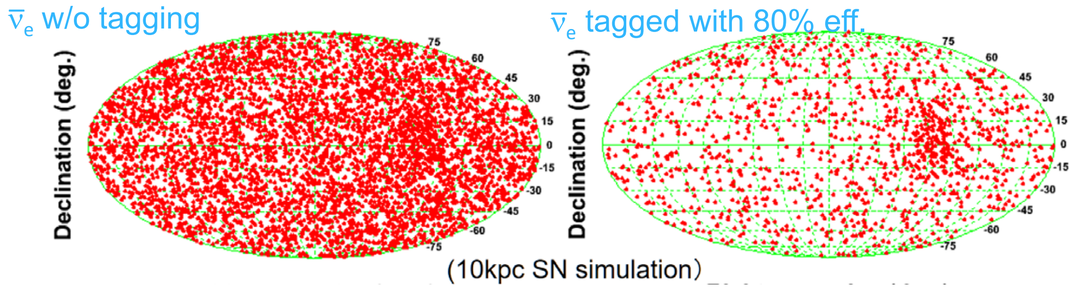


Goals of SK-Gd

- **First observation of DSNB**
  - Expect several events / year
  - Opens the door for “new” astrophysical observables
- Improve pointing accuracy for galactic supernova
- Precursor of nearby supernova by Si-burning neutrinos
- Reduce proton decay background
- Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)
- Reactor neutrinos

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





Enhance directional events (ν+e scattering) by tagging $\bar{\nu}_e$ inverse beta decay

Overview of R&D and preparation

Environmental safety

Minimize negative impacts to current physics programs at SK

Further investigate physics capability with n-tagging

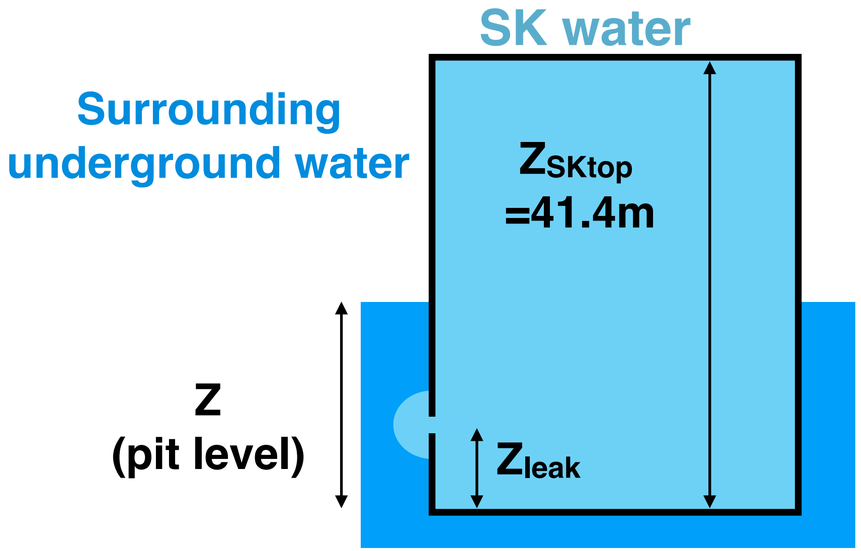
- **Stopping water leak from the SK**
  - Estimation of the leak location
  - Development of leak-fixing method
- **Reduction of RIs from $Gd_2(SO_4)_3$ powder**
  - Test of Ra removal raisins
  - Material screening with HP-Ge detectors
  - High sensitivity measurement with ICP-MS
- **Test with the EGADS demonstrator**
  - Continuous monitoring of the water quality and Gd concentration
  - Upgrading the DAQ system
- **Construction of the new water system**
- **Improved simulation of Gd capture in SK**

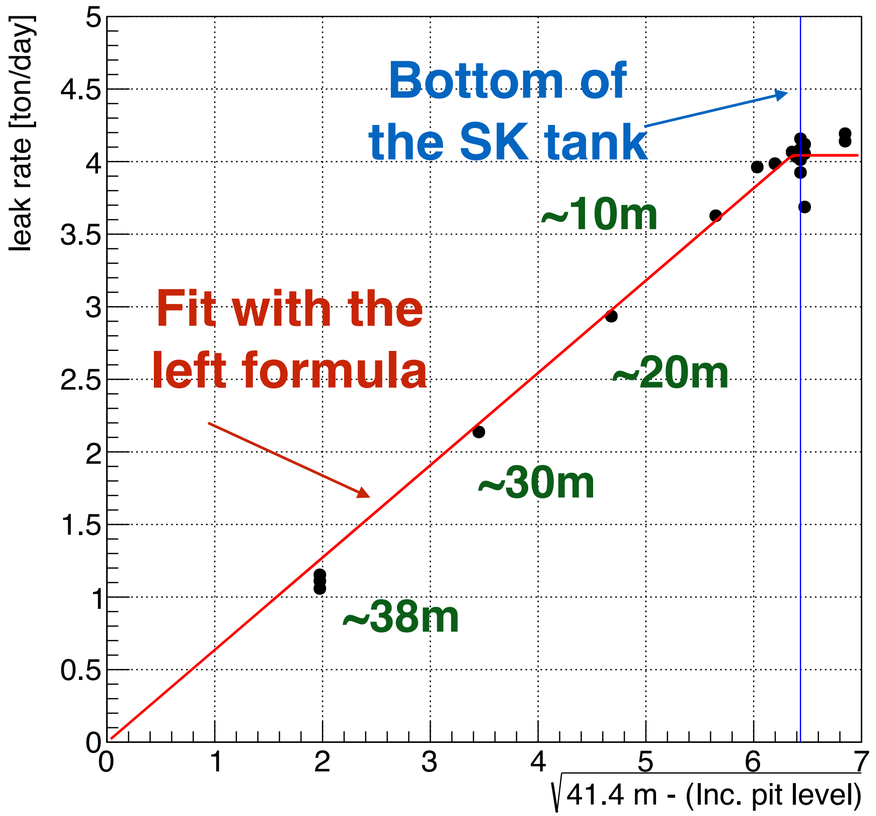
SK water leakage

- Currently, SK water is leaking at ~1 ton/day
- To investigate the leak location, measured the leak rate for different levels of surrounding underground water.
  - Done by draining water from the inclined pit which leads to the bottom of the SK tank
  - Changes water pressure applied to the tank
- Leak rate from a single hole can be described as:

$$\Phi_{leak}(z) = \begin{cases} a \times \sqrt{z_{SKtop} - z} & (z > z_{leak}) \\ a \times \sqrt{z_{SKtop} - z_{leak}} & (z < z_{leak}) \end{cases}$$

Data indicates that the leak location is near the bottom of SK detector





Leak-fixing method

- Paint all the welding lines with sealing materials
  - **Bio-seal 197**: Fill pinholes and cracks in steel plates
  - **Poly-urea based sealant**: Newly-developed, flexible and low-background material.
- Test of the new poly-urea based sealant:
  - Mechanical strength
    - No problem after applying 5 atm pressure in Gd-loaded water for months so far
    - Passed the JIS standard for attachment strength
  - TOC elusion
    - Effect in light yield less than 2.4%
  - Radon emanation
    - ~0.3 mBq/m^2, less than the 20 inch PMTs
    - No problem for solar neutrino measurement
  - Test at more realistic environment ongoing

Most suspicious part: Anchors of the PMT frame

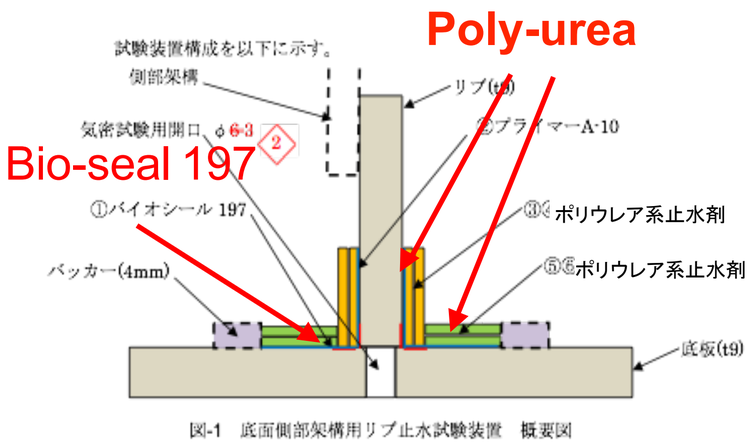


図-1 底面側部架構用リブ止水試験装置 概要図

Test at realistic (humid) environment

Mock-up test

Development of pure Gd powder

- U and Th/Ra contamination in Gd powder becomes backgrounds for solar neutrino measurements
- Intensively developing pure Gd powder with several companies
- Radio impurity measured w/ two methods:

Ge detector: Sensitive to ~1 mBq/kg (Canfranc, Boulby and Kamioka)

ICPMS: For isotopes w/ long life (Kamioka) [arXiv:1709.03417 (accepted by PTEP)]

*** Goal for 0.2% Gd-sulfate loading**

Chain	Isotope	Typical	Goal*	Company A		Company B		Company C	
				Ge	ICPMS	Ge	ICPMS	Ge	ICPMS
^{238}U	^{238}U	50	< 5	< 13	~ 0.7	< 20	~ 0.2	< 9	~ 0.1
	^{226}Ra	5	< 0.5	0.7 ± 0.4	—	< 0.6	—	< 0.3	—
^{232}Th	^{232}Th	100	< 0.05	—	~ 0.3	—	~ 0.2	—	~ 0.2
	^{228}Ra	10	< 0.05	< 0.4	—	< 0.7	—	< 0.3	—
	^{228}Th	100	< 0.05	1.7 ± 0.4	—	0.5 ± 0.2	—	< 0.4	—
^{235}U	^{235}U	30	< 3	< 1.3	—	< 0.7	—	< 0.6	—
	^{227}Ac/Th	300	< 3	< 3.1	—	< 2.3	—	< 1.9	—

Unit: [mBq/kg $(Gd_2SO_4)_3$]

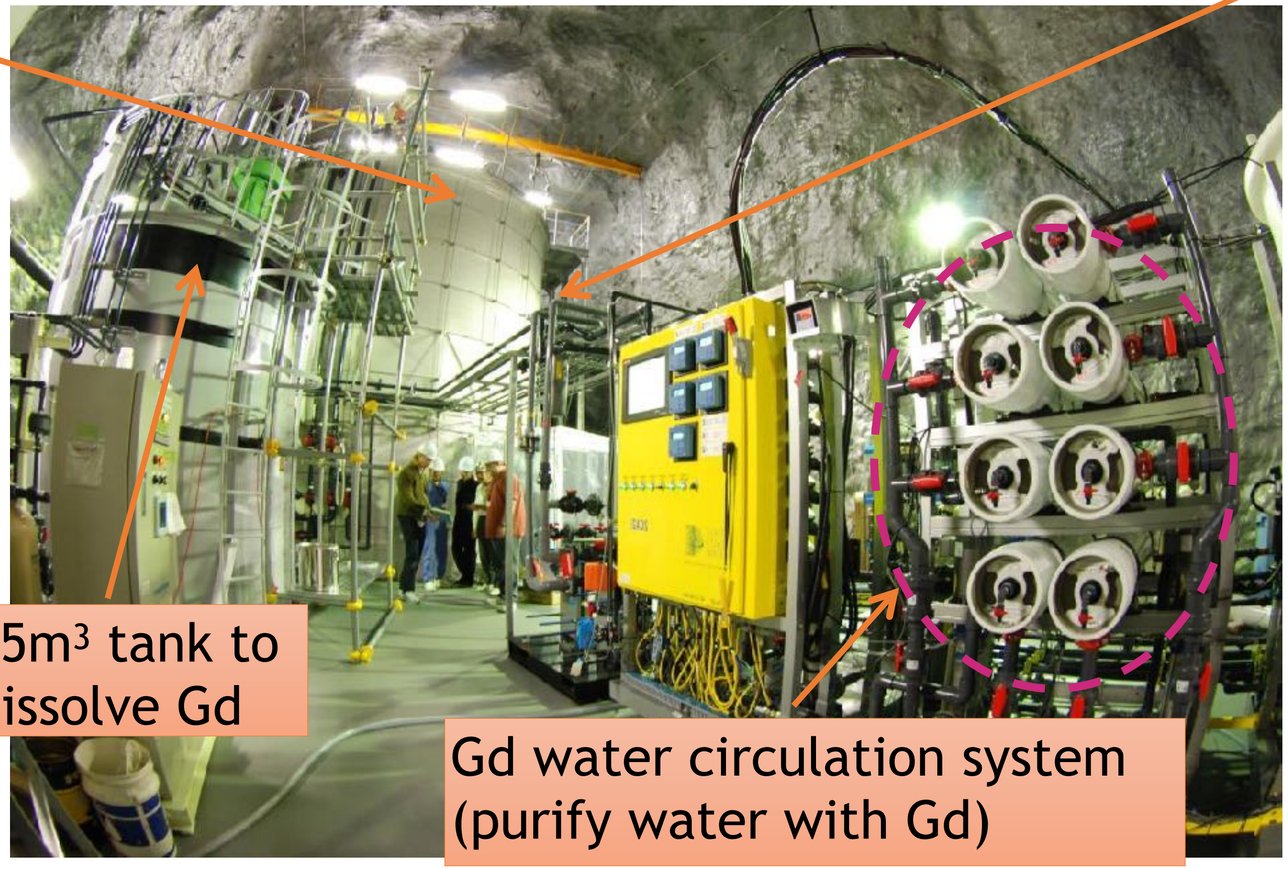
U: Achieved our goal, Th/Ra: Close to our goal

Each company is still making rapid progress on reducing radio impurity

EGADS

Evaluating Gadolinium's Action on Detector Systems

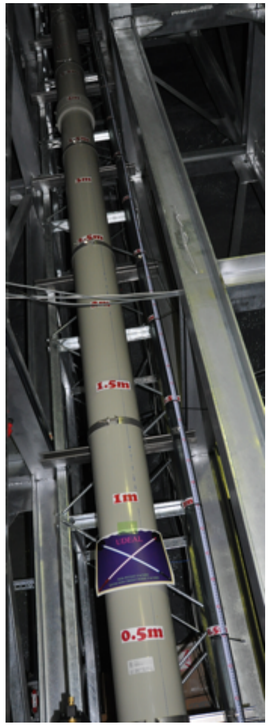
200 m³ tank with 240 PMTs

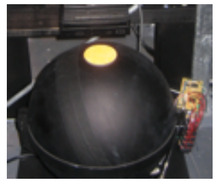


15m³ tank to dissolve Gd

Gd water circulation system (purify water with Gd)

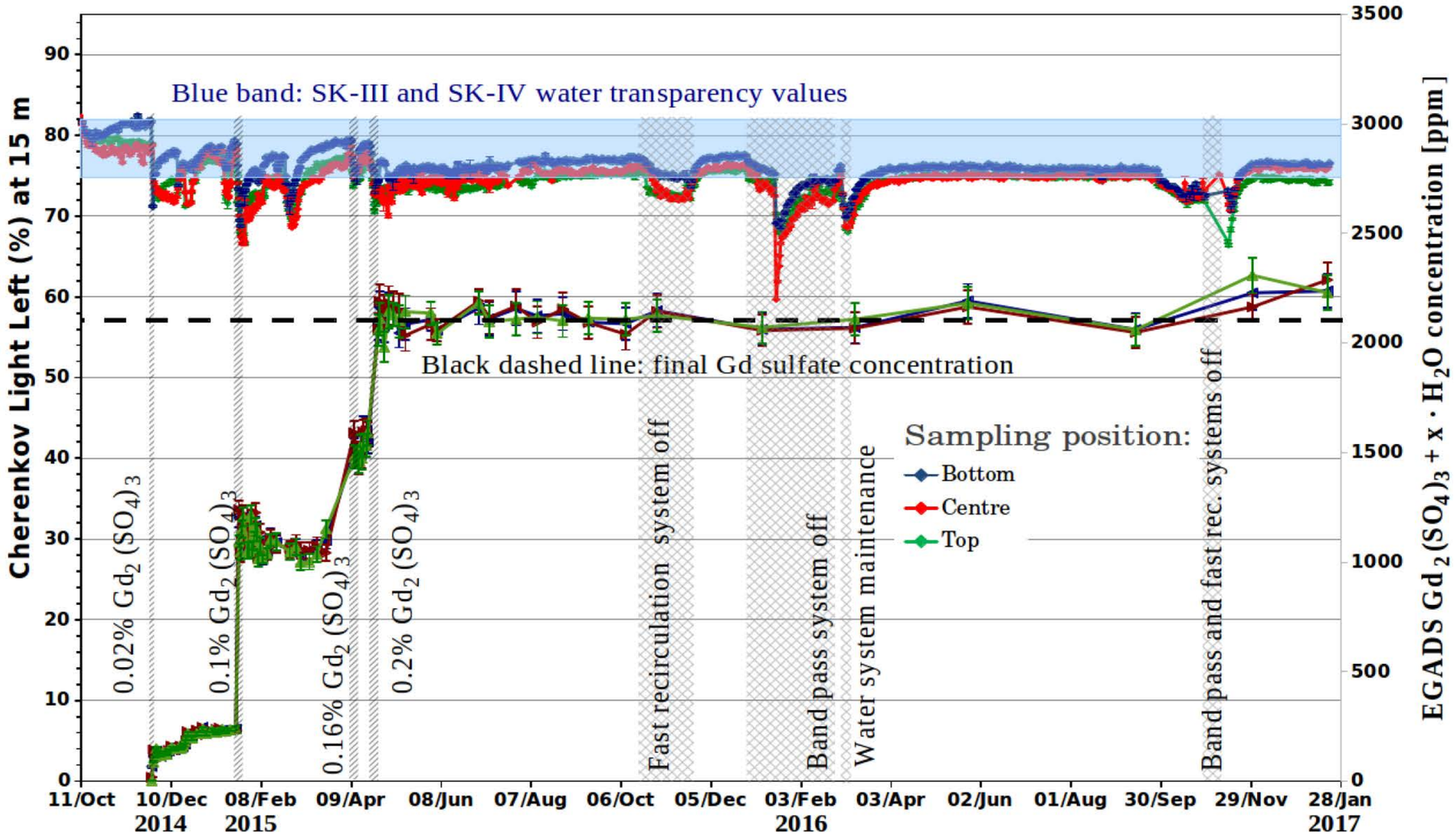
Transparency measurement (UDEAL)





Studying Gd water quality with actual detector materials used in SK
Also testing 13 HPDs for Hyper-K
Have been operating with full (0.2%) $Gd_2(SO_4)_3$ loading since 2015

EGADS water quality

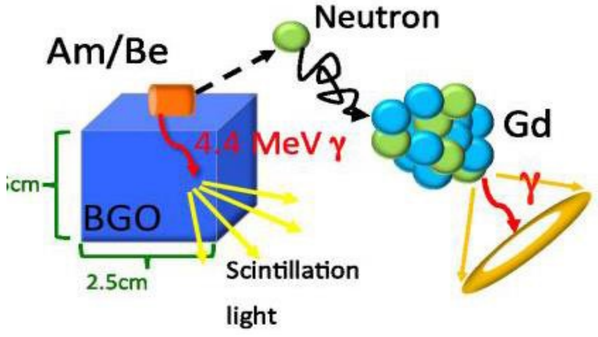


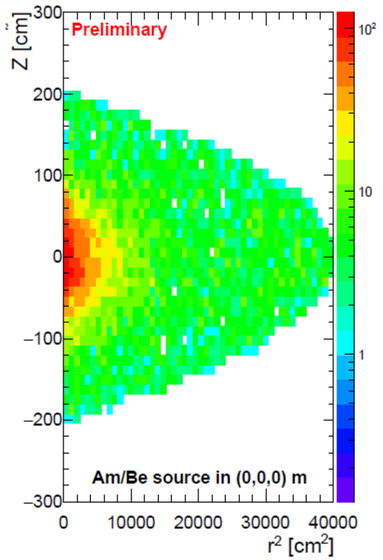
The light left at 15 m has been stable at ~75% for 0.2% $Gd_2(SO_4)_3$, corresponds to ~92% of SK-IV average.

No loss of Gd: >99.99% of Gd remains after circulating the water system for more than 350 times

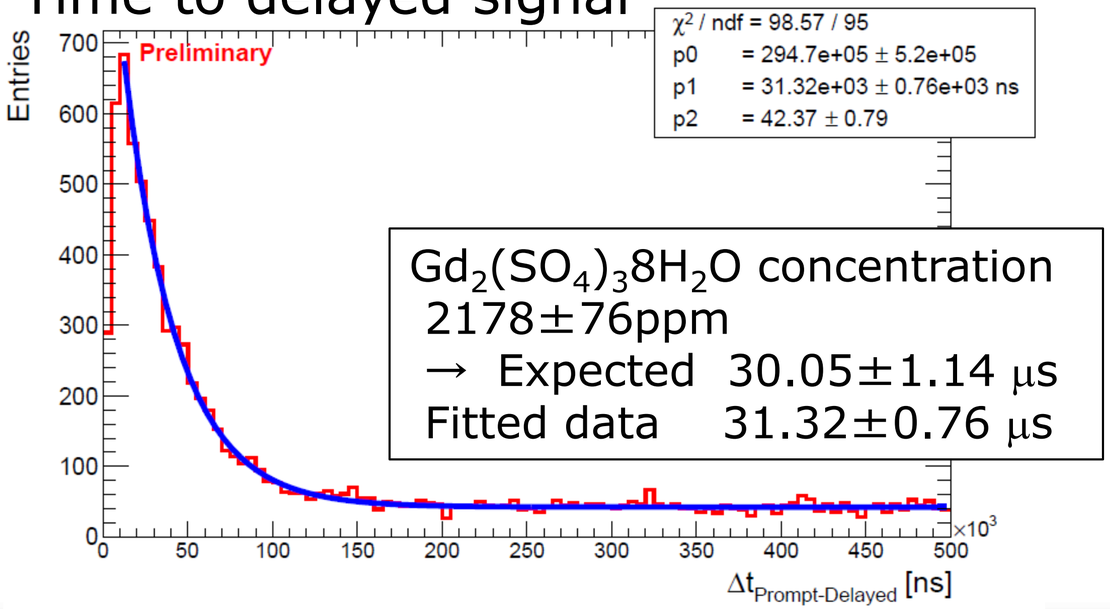
Neutron calibration in EGADS

- Calibration done w/ AmBe neutron source
- BGO crystal used to detect 4.4 MeV “prompt” γ signal
- Decay time constant consistent w/ expectation
- Energy distribution well reproduced by MC



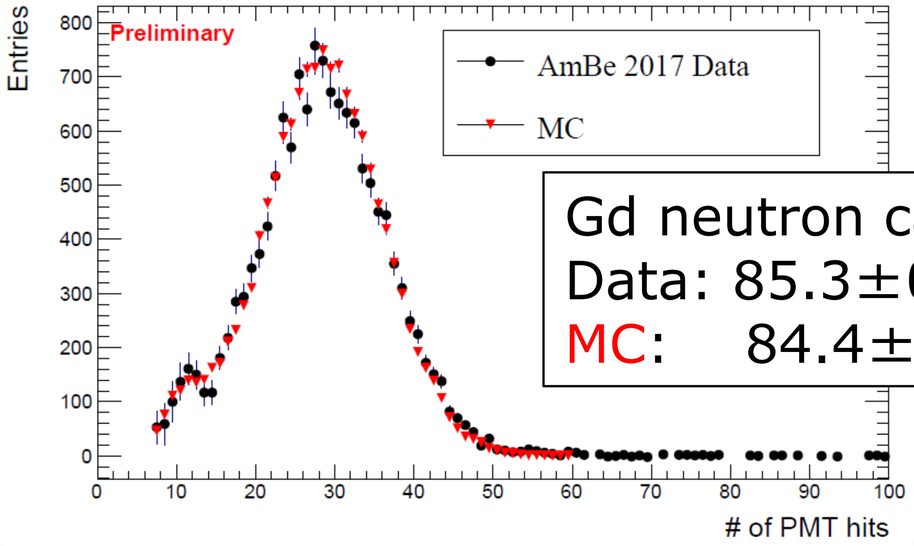


Time to delayed signal



$Gd_2(SO_4)_3 8H_2O$ concentration
2178±76ppm
→ Expected 30.05±1.14 μs
Fitted data 31.32±0.76 μs

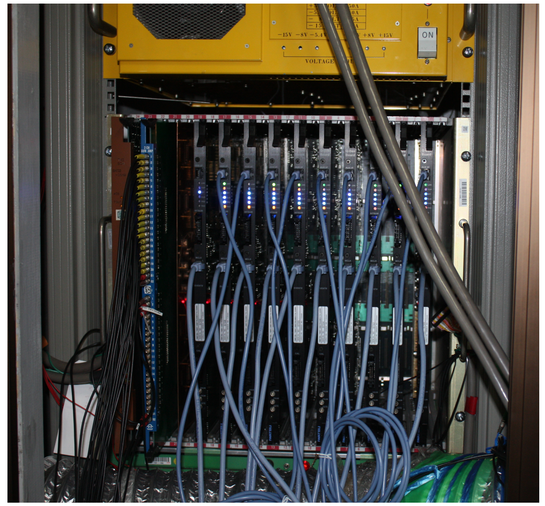
Delayed signal spectrum

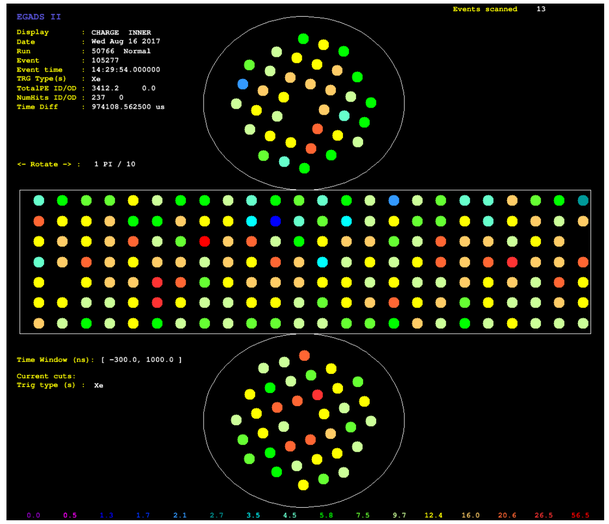


Gd neutron capture efficiency
Data: 85.3±0.9% (stat)
MC: 84.4± 0.3% (stat)

Recent progresses on EGADS

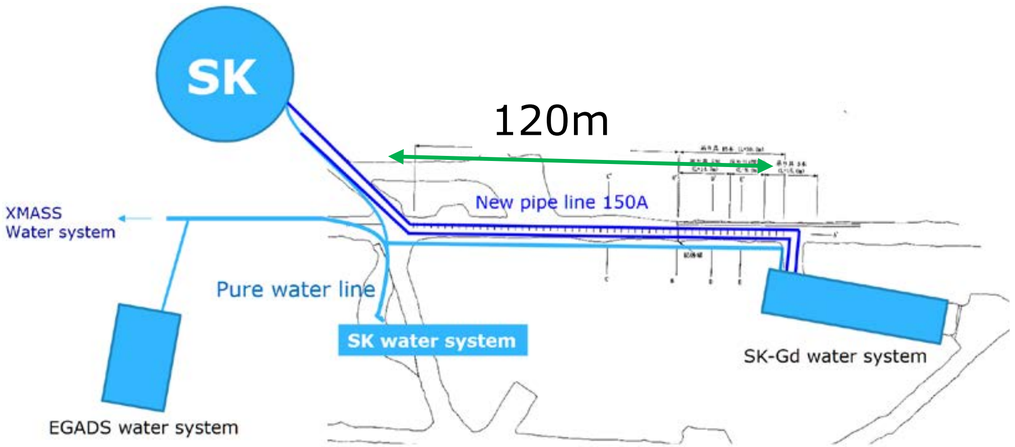
- DAQ electronics upgraded with the same type of modules as SK-IV (June 2017)
  - To be served as a supernova monitor while SK refurbishment
- Top part inspection (May 2017)
  - Opened the tank after more than 2 years of operation with 0.2% $Gd_2(SO_4)_3$ water
  - No visible change!
- Draining water completely from EGADS for full inspection of inside the tank (happening as I speak!)

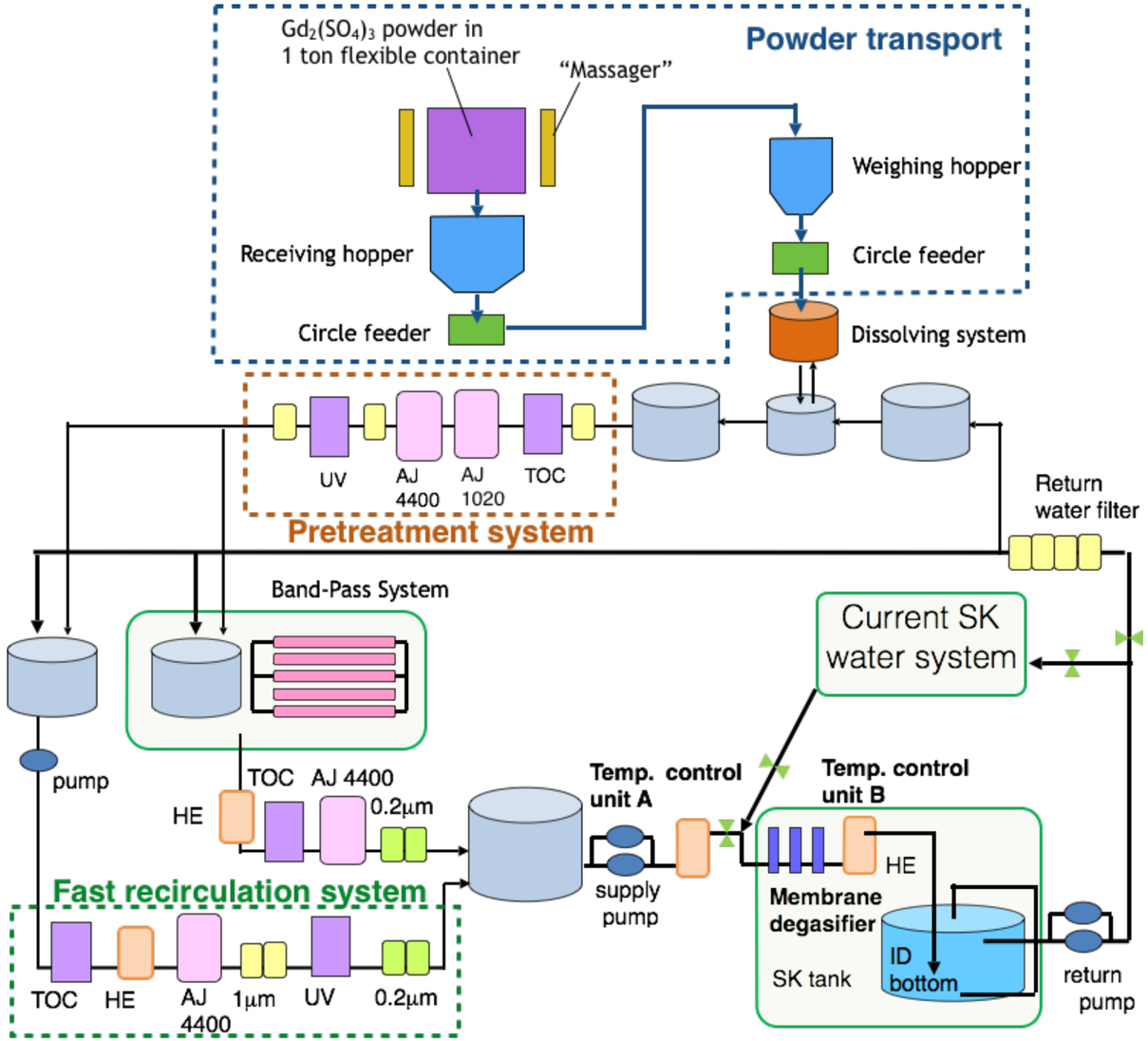




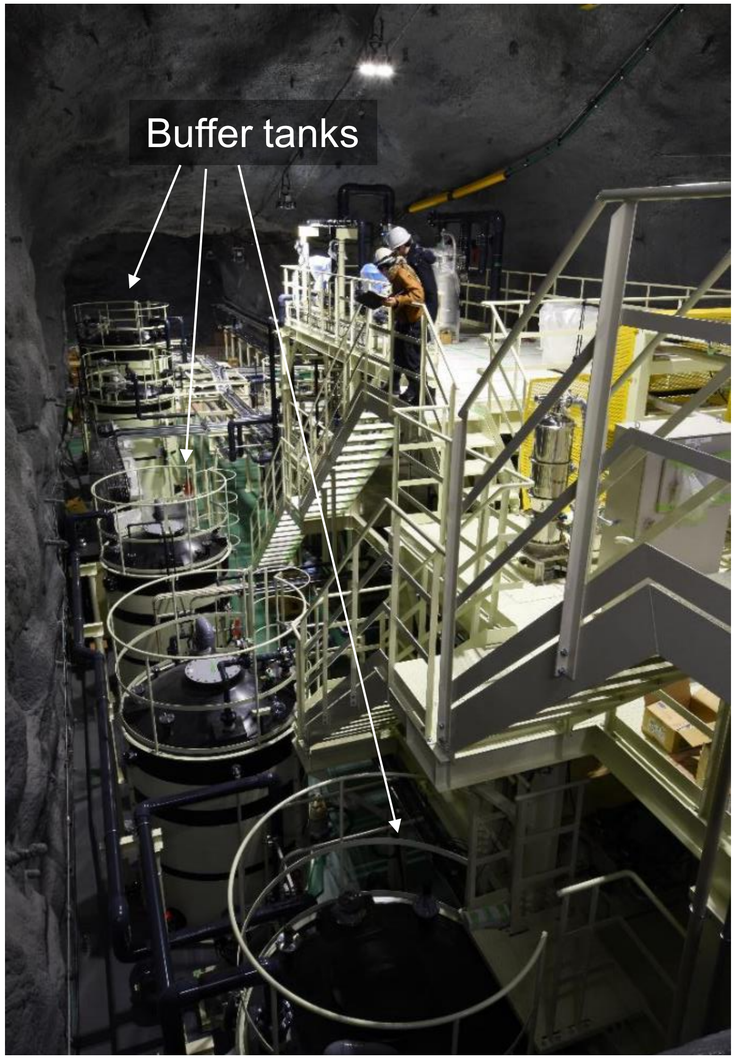
SK-Gd water system

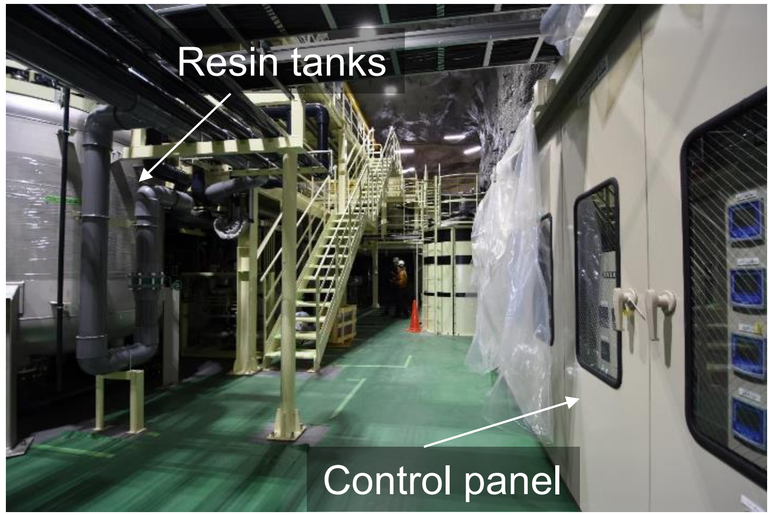
- Designed based on EGADS experience
- Consists of:
  - Dissolving system
  - Pretreatment system
  - Recirculation system





Status of water system

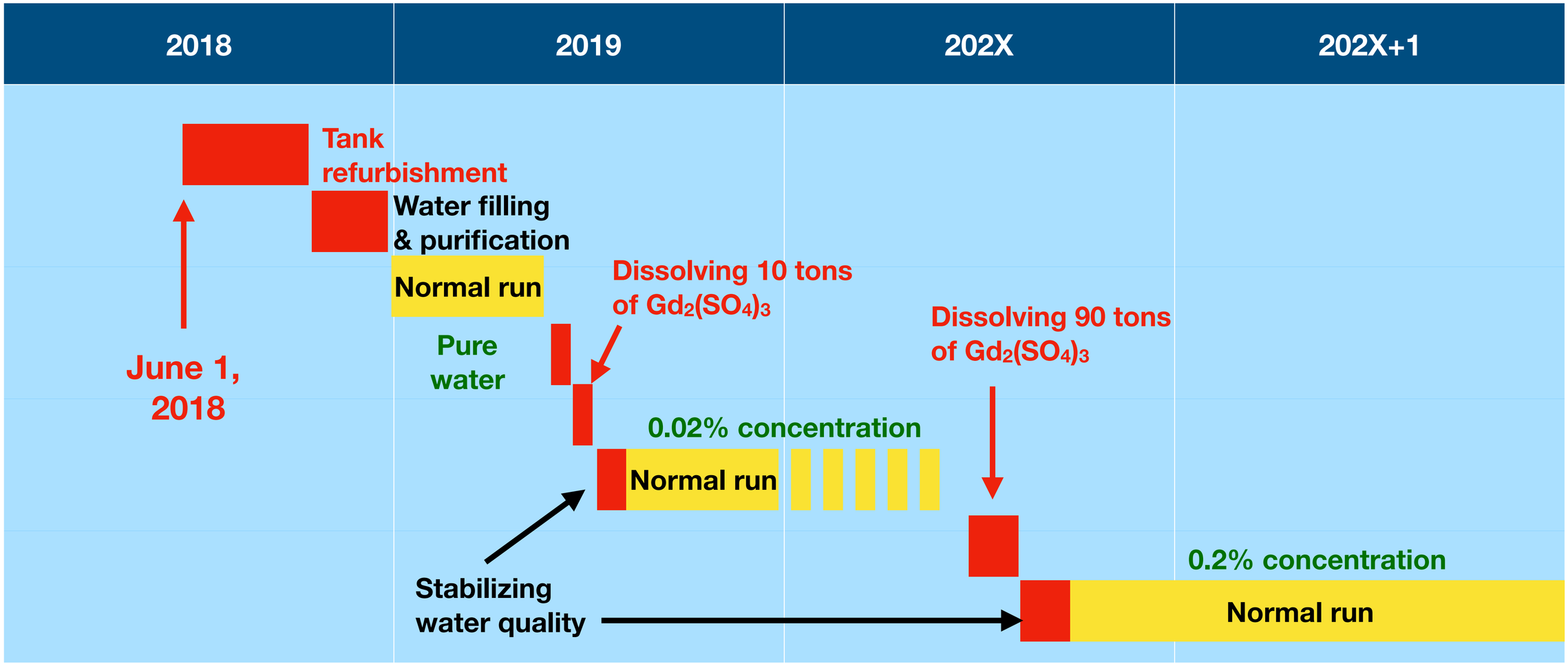




Getting ready to receive Gd!

Plan

We will open the tank and start the refurbishment work on June 1, 2018



Summary

- SK-Gd: Gadolinium loaded Super-K
  - Neutron tagging efficiency significantly enhanced with Gd
  - Aiming for the first detection of DSNB
  - Many other physics benefits also expected
- Many R&D and preparation works in progress
- SK-Gd will start very soon!
  - Open the tank for the refurbishments in 2018
  - First Gd loading planned to be in 2019