Status of the SK-Gd Project

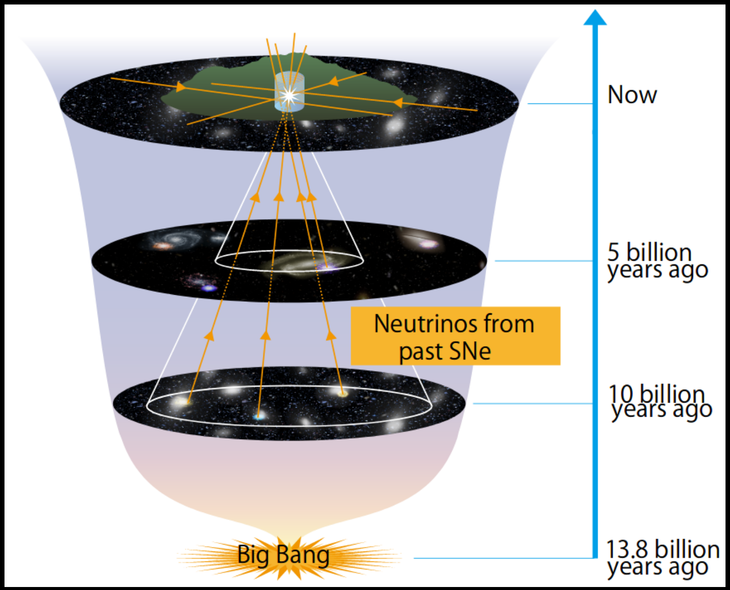
Gd-LOADING ONGOING….

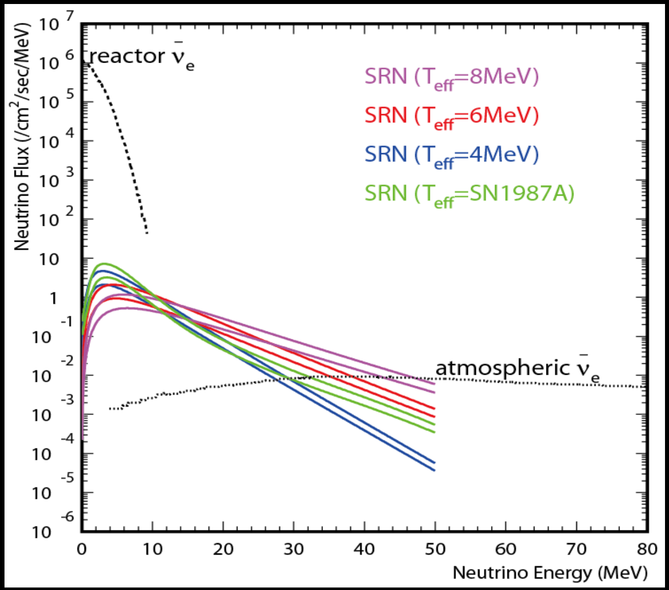
Lluís Martí Magro, ICRR.
on behalf of the Super-Kamiokande Collaboration.

ICHEP July 30th, 2020. Prague, Czech Republic.

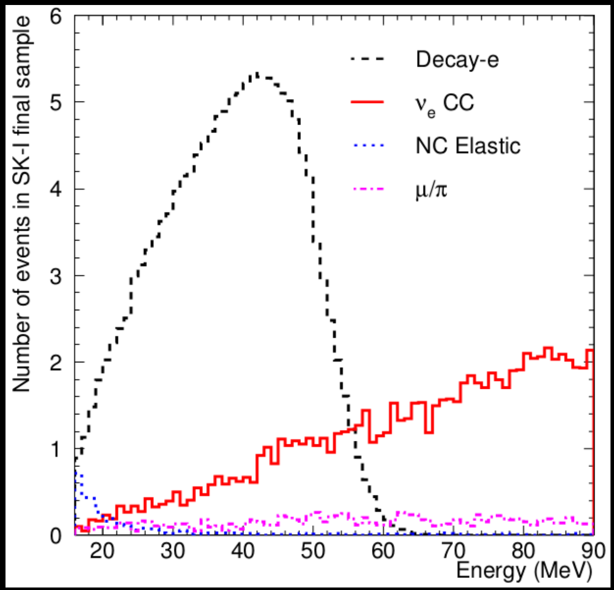
Motivation

Supernova relic neutrinos (SRN): neutrinos from all the past core collapse supernovae in the history of the universe.





Phys.Rev. D 79, 08013 (2009)

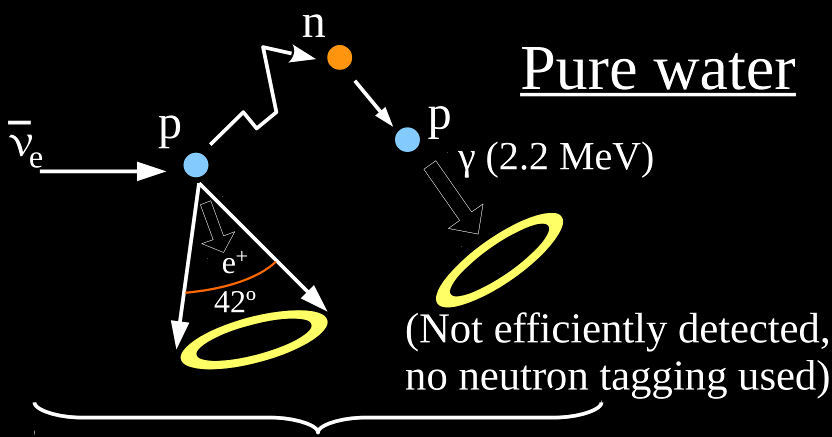


Phys.Rev. D85 (2012) 052007

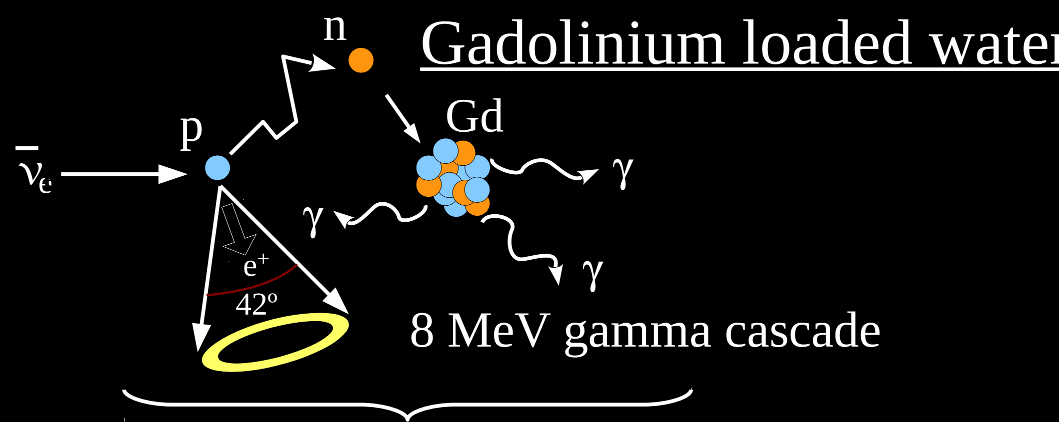
→ From the predictions for the SRN spectrum there should be a discovery window between reactor and atmospheric neutrinos.

→ Without efficient neutron tagging, important backgrounds hinder this analysis.

Efficient neutron tagging in water



ΔT ~ 200 μs



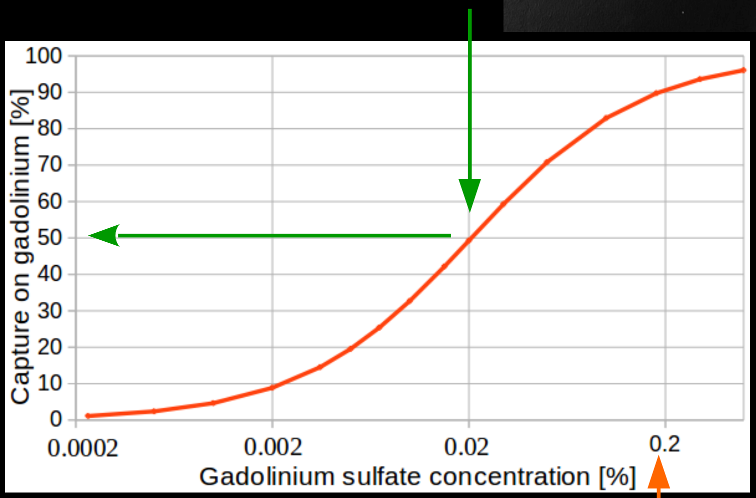
ΔT ~ 30 μs

Idea proposed as GADZOOKS!
by Beacom & Vagins PRL.93, (2004) 171101

With tight time and position coincidence between positron and neutron capture we will be able to tag neutrons with high efficiency

50% neutron capture on Gd

First loading:



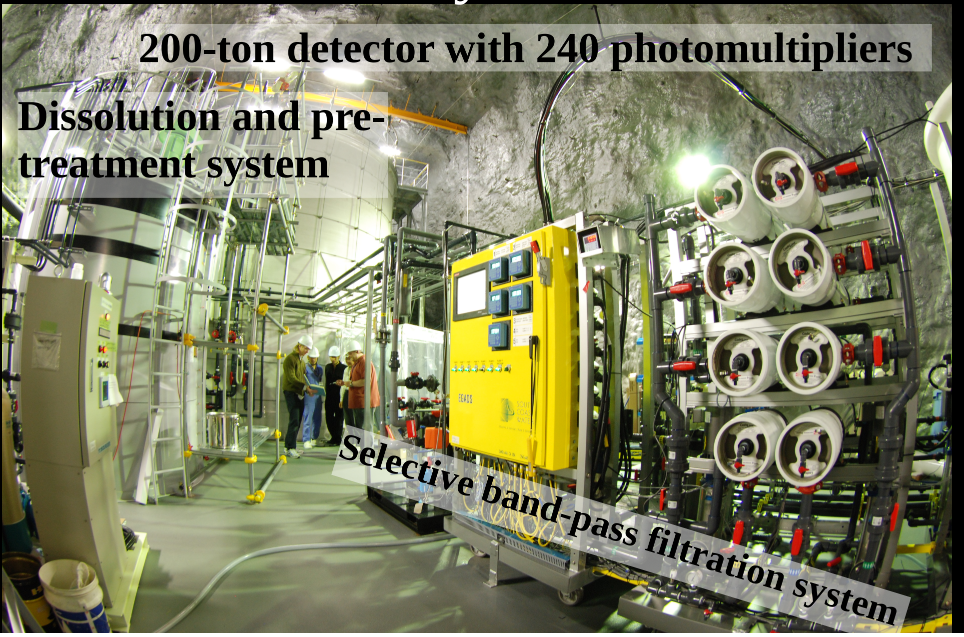
Final target

The road to SK-Gd: EGADS

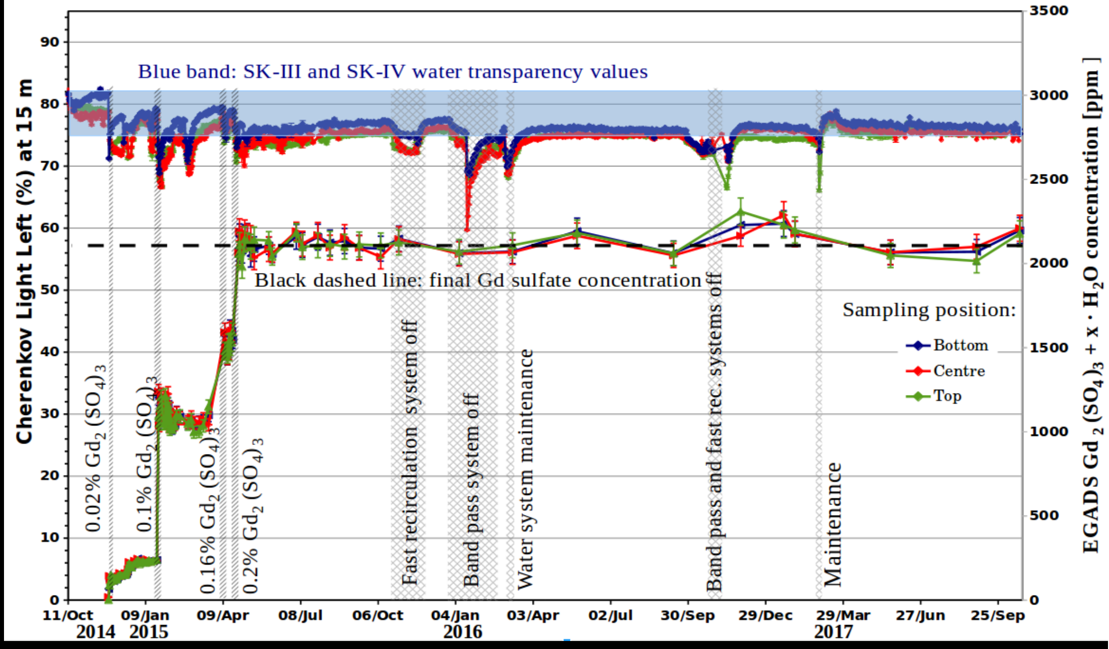
Evaluating Gadolinium's Action on Detector Systems

- New water systems to remove impurities while keeping Gd.
- Study effects of Gd on detector components.
- How to add/remove Gd efficiently.
- Keep neutron background low.

➡ EGADS was build using the same materials as in SuperK ⬅



- Very good water transparency can be kept while not losing Gd.
- No harmful effect on detector systems.

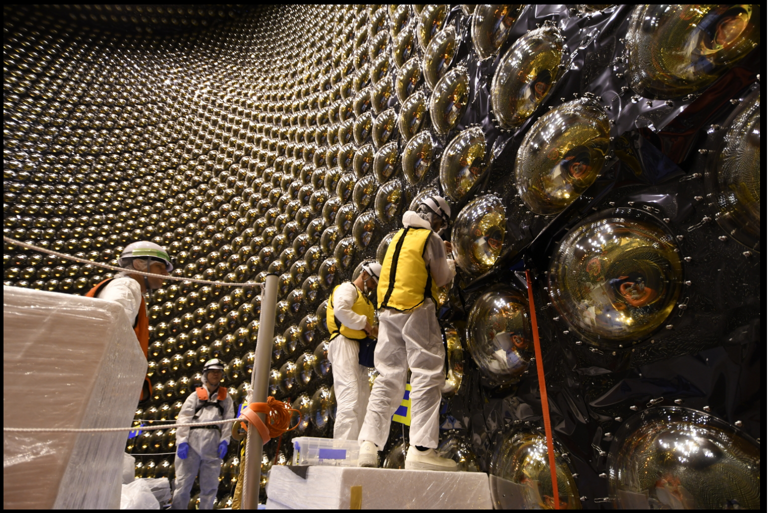


Nucl. Instrum.Meth. A 959 (2020) 163549

Super-Kamiokande upgrade (2018)

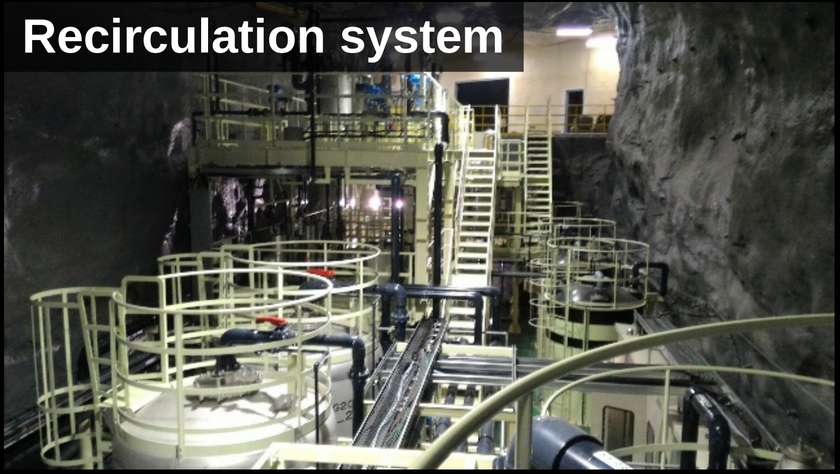
Refurbishment work:

- Cleaned walls and detector structures.
- Replaced faulty ID & OD PMTs.
- Replaced the OD white Tyvek.
- Upgrade in-tank calibration devices.



Upgrade:

- New hall excavated for the new Gd water system and new Gd water purification system.
- Modified the in-tank piping.
- Leak fixed: no leak observed (< 20 L/day).



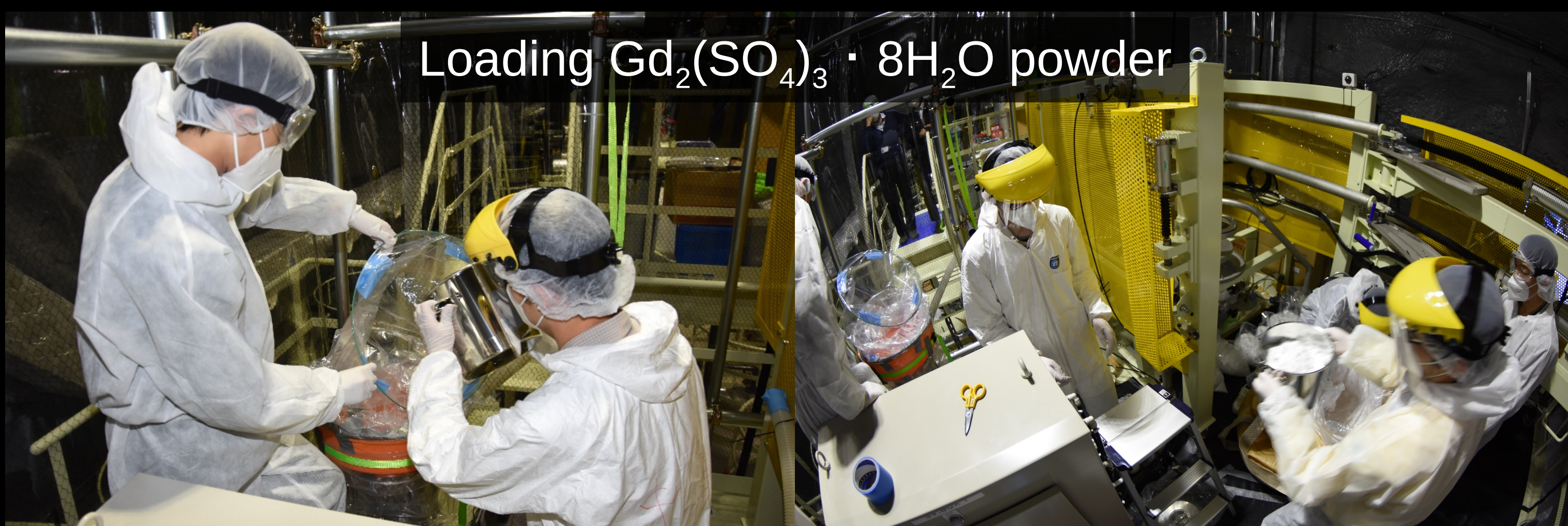
Loading start !!

Gadolinium sulfate loading started on July 14th at 10:29

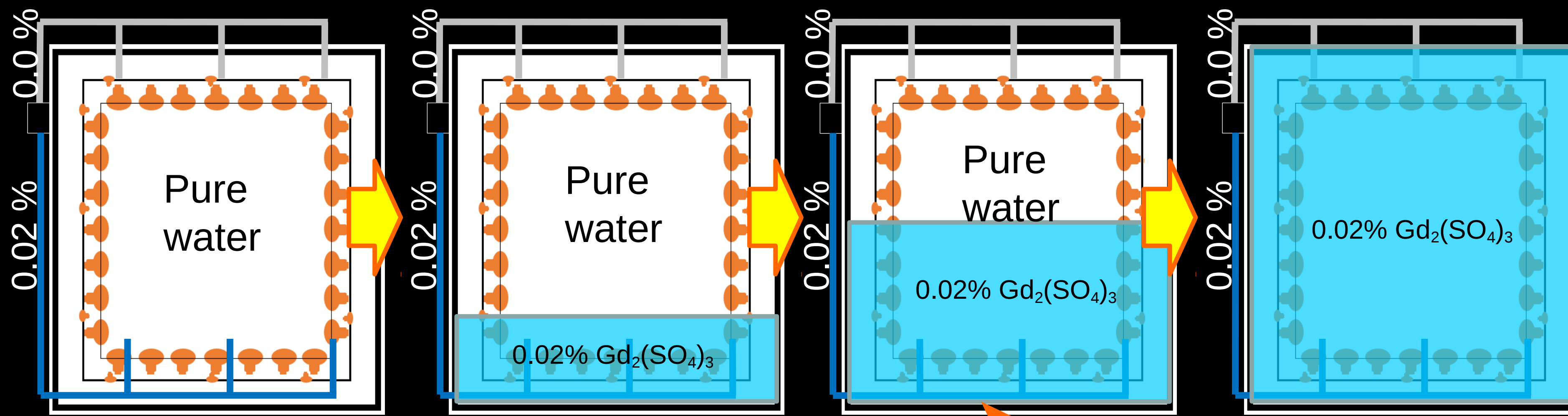
SK-V finished and SK-VI started

Gd-loading system started.

Loading $Gd_2(SO_4)_3$・$8H_2O$ powder

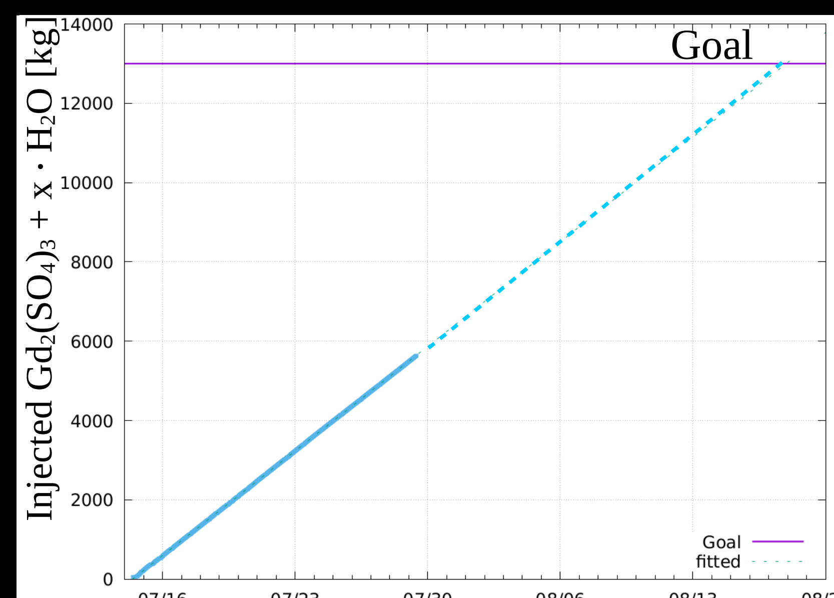


Gd sulfate loading



Almost here!

- Dilute Gd sulfate to 0.02% in mass.
- Supply 0.02% Gd sulfate to the bottom of SK tank.
- Supply flow is 60 tons/hour → about 35 days will be needed to complete Gd loading.
- Pure water return from top of SK tank.

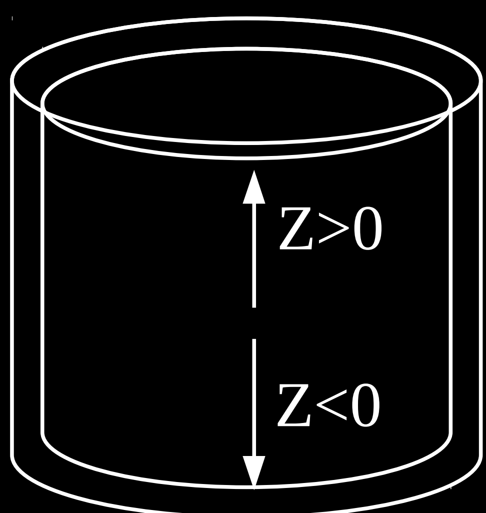


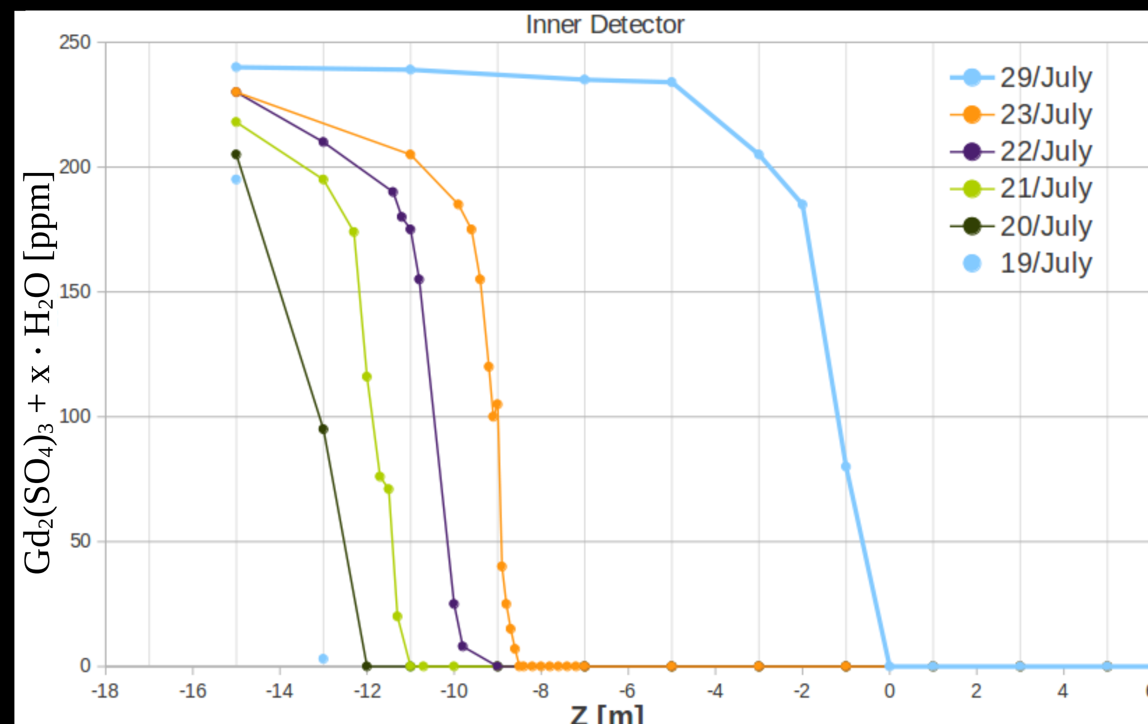
We loaded almost half already!!

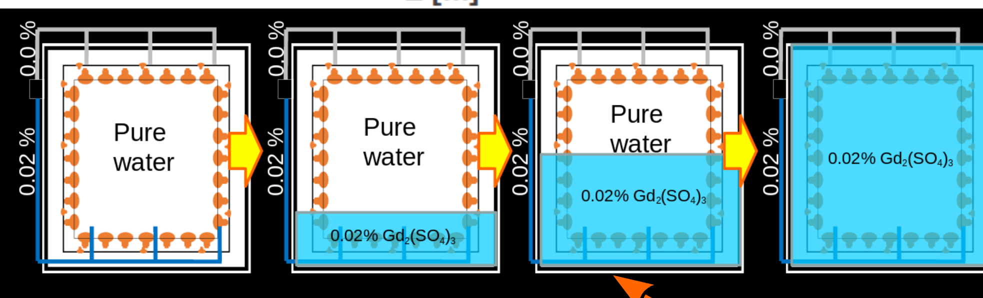
First Gd loading is expected to be completed around Aug 17th-18th !!

First days of Gd sulfate loading

- There is a sharp Gd front of ~2 m .
- Gd front advances ~1.5 m/day.
- The Gd loaded region still in the process of becoming homogeneous.
- Lower half of SK tank is loaded with Gd sulfate → search for neutrons!







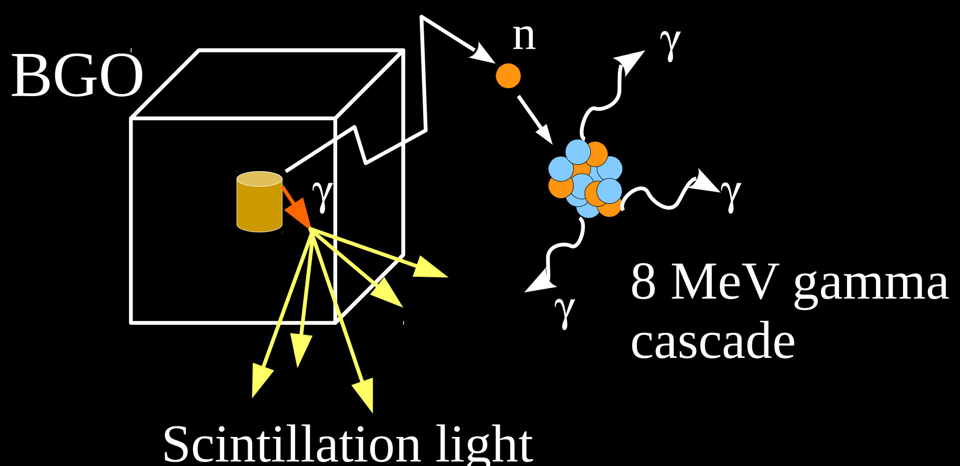
Almost here!

Am/Be source + BGO crystal

- ^{241}Am is an α source: $^{241}\mathrm{Am} \rightarrow {}^{237}\mathrm{Np} + \alpha$

$$\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + \gamma\,(4.4\ \mathrm{MeV}) + n$$

- The Am/Be source is inside a BGO crystal: γ (4.4 MeV) produces scintillation light that triggers a prompt event.
- Neutron candidates are then searched.



Am/Be source + BGO cristal

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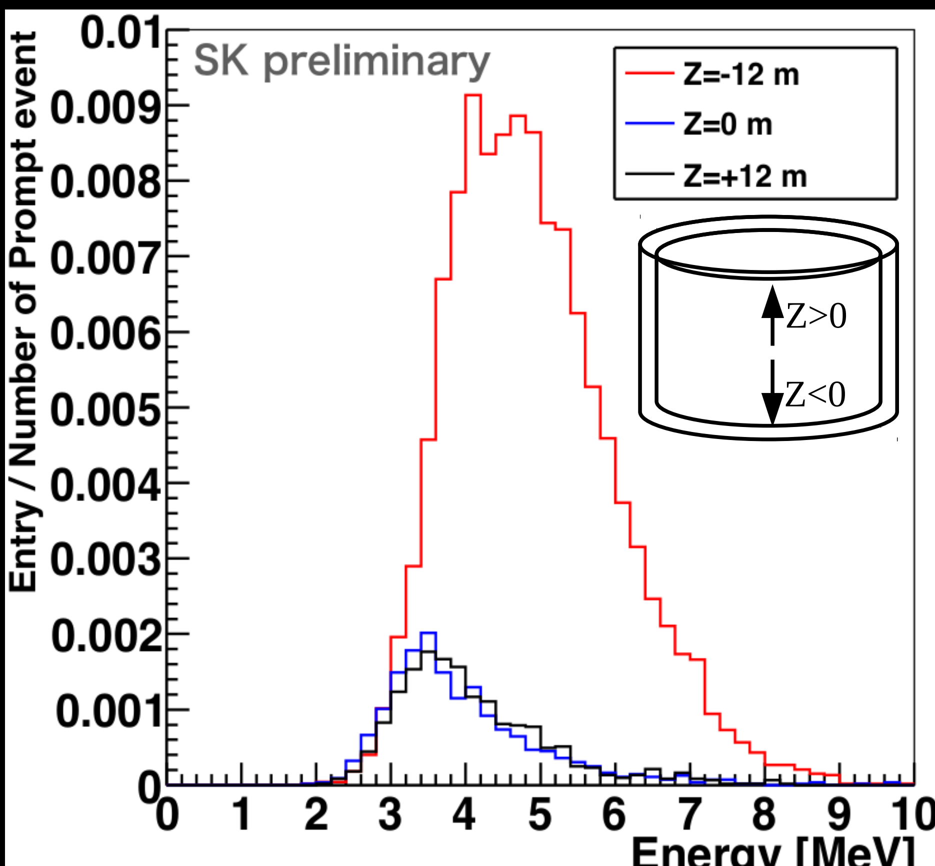
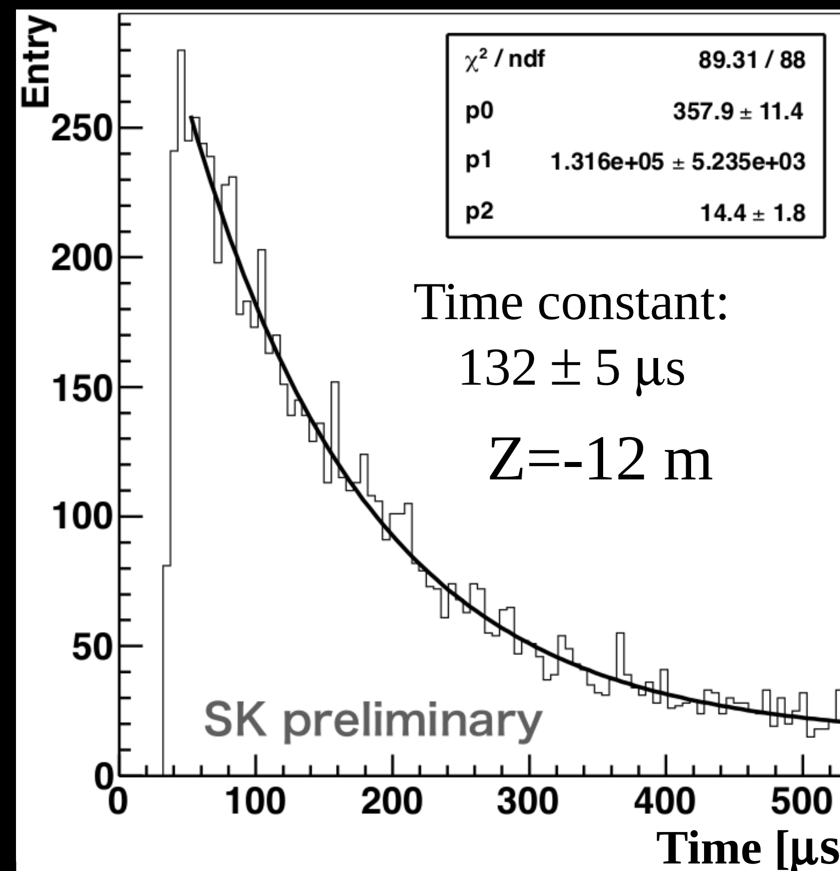
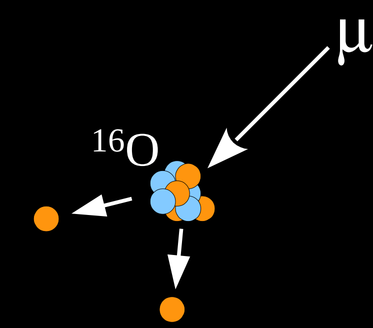


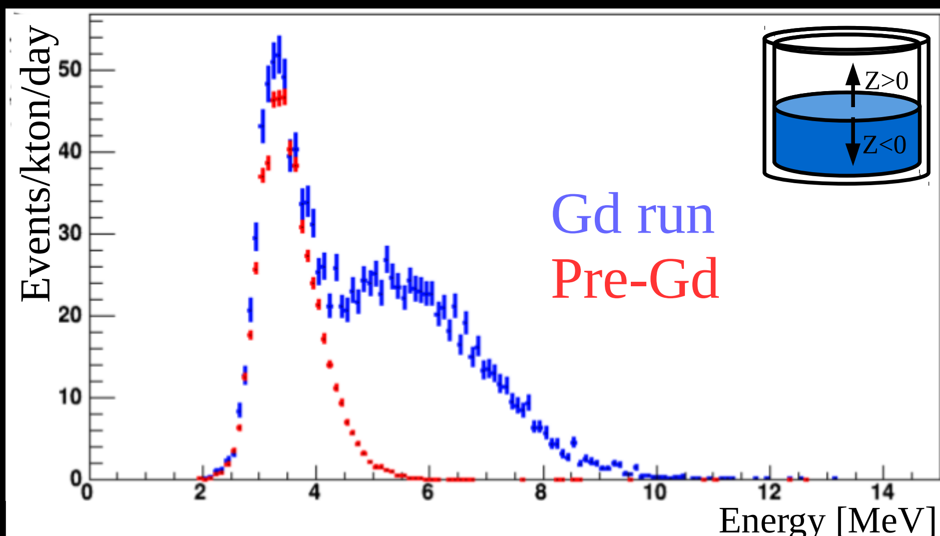


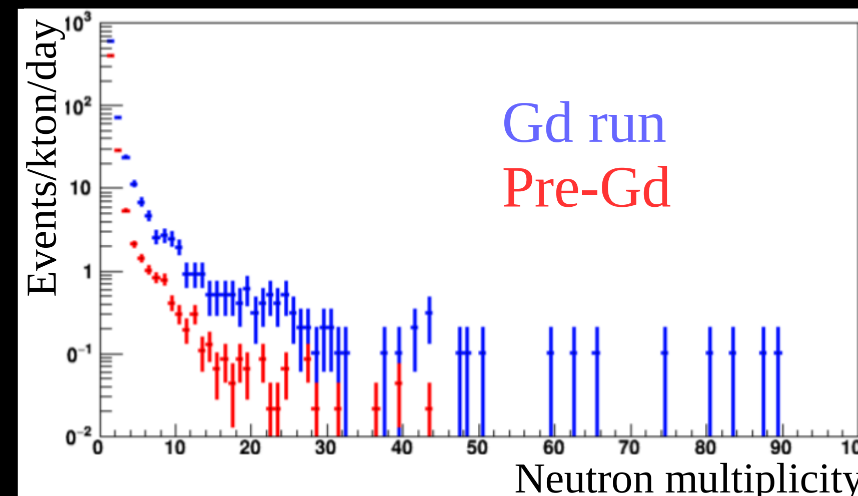
Spallation neutrons

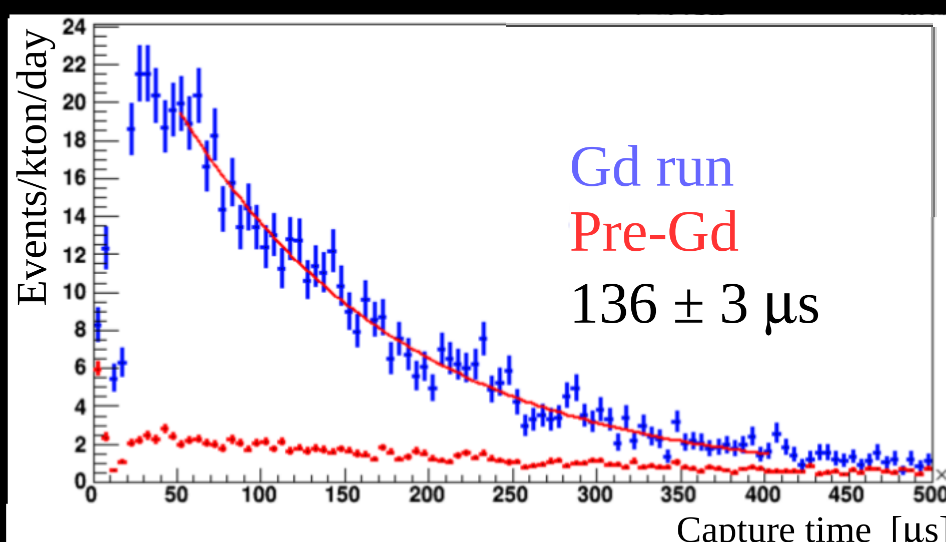
- Cosmic ray muon rate ~2 Hz
- O(10000) spallation neutrons per day produced.



Search for neutron candidates near the parent muon in the Z<0 region where the Gd concentration is increasing :







Neutron captures on Gd clearly seen and in the expected energy range.

Time constant close to the expected MC value.

We can see now many neutrons!

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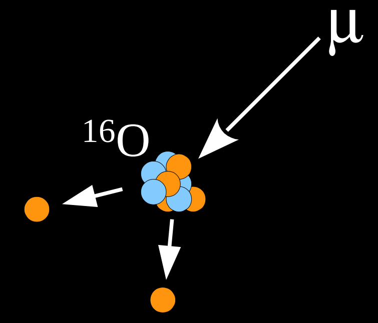
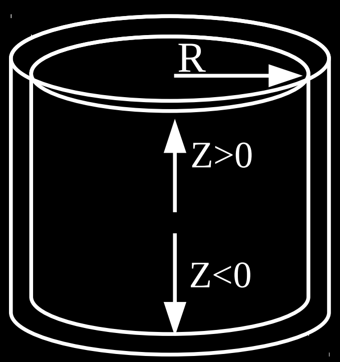
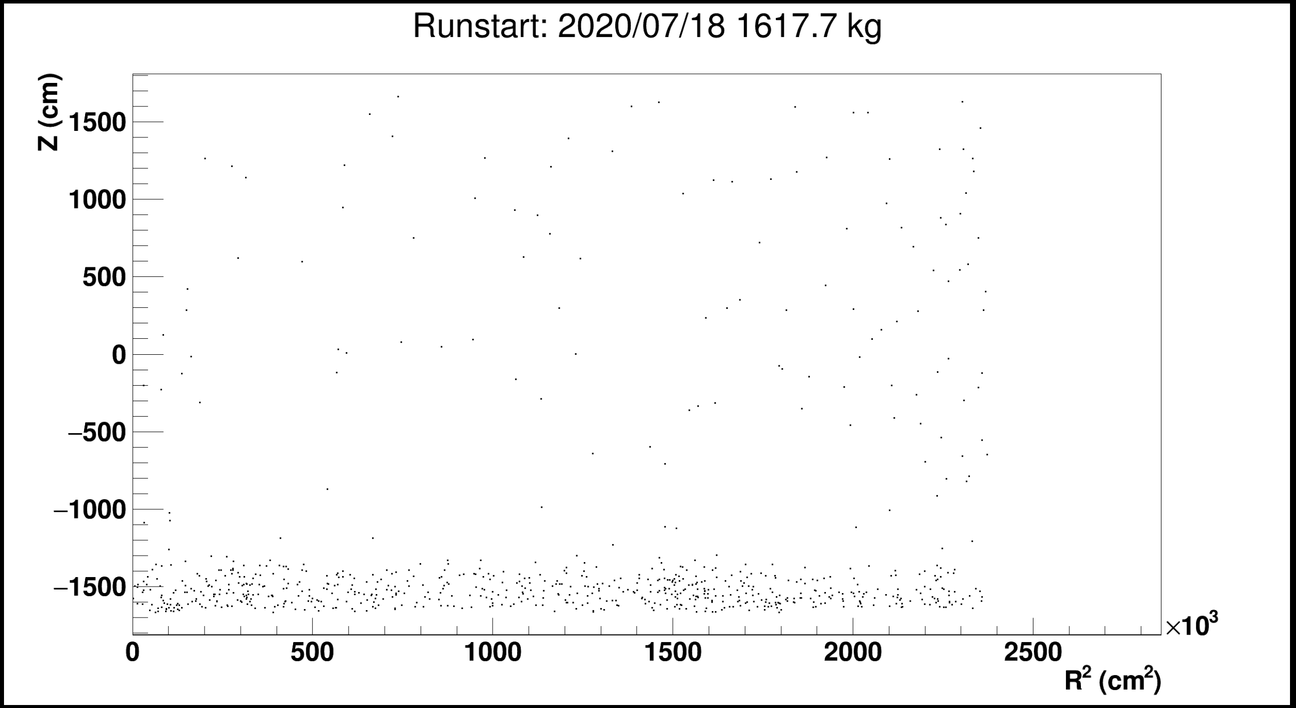


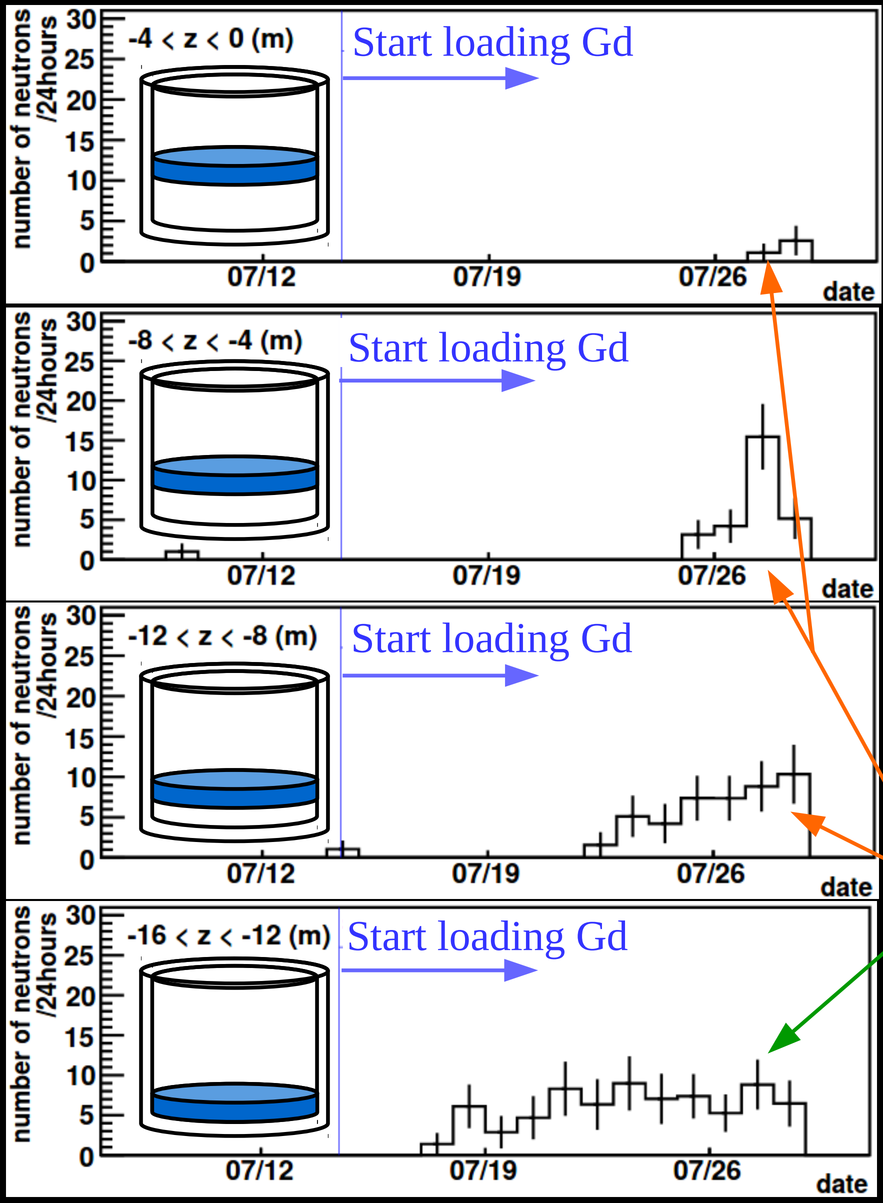
Search for neutron candidates near the parent muon in the Z region where the Gd concentration is increasing :

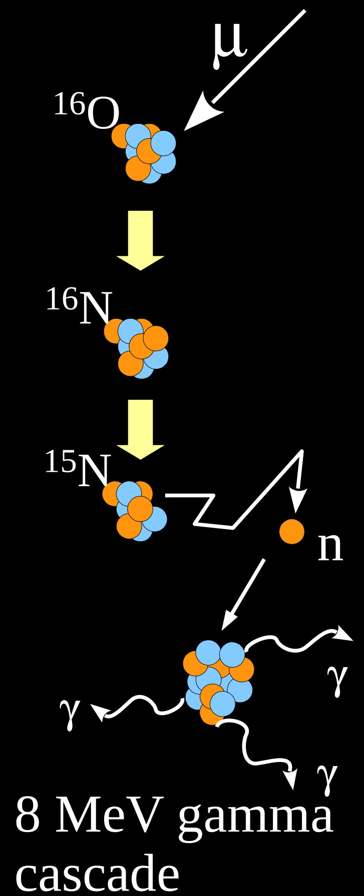




Stopping muons

- Neutrons from stopping-μ captured on ^{16}O
- Search for stopping muons and search for related neutron capture candidates on Gd.

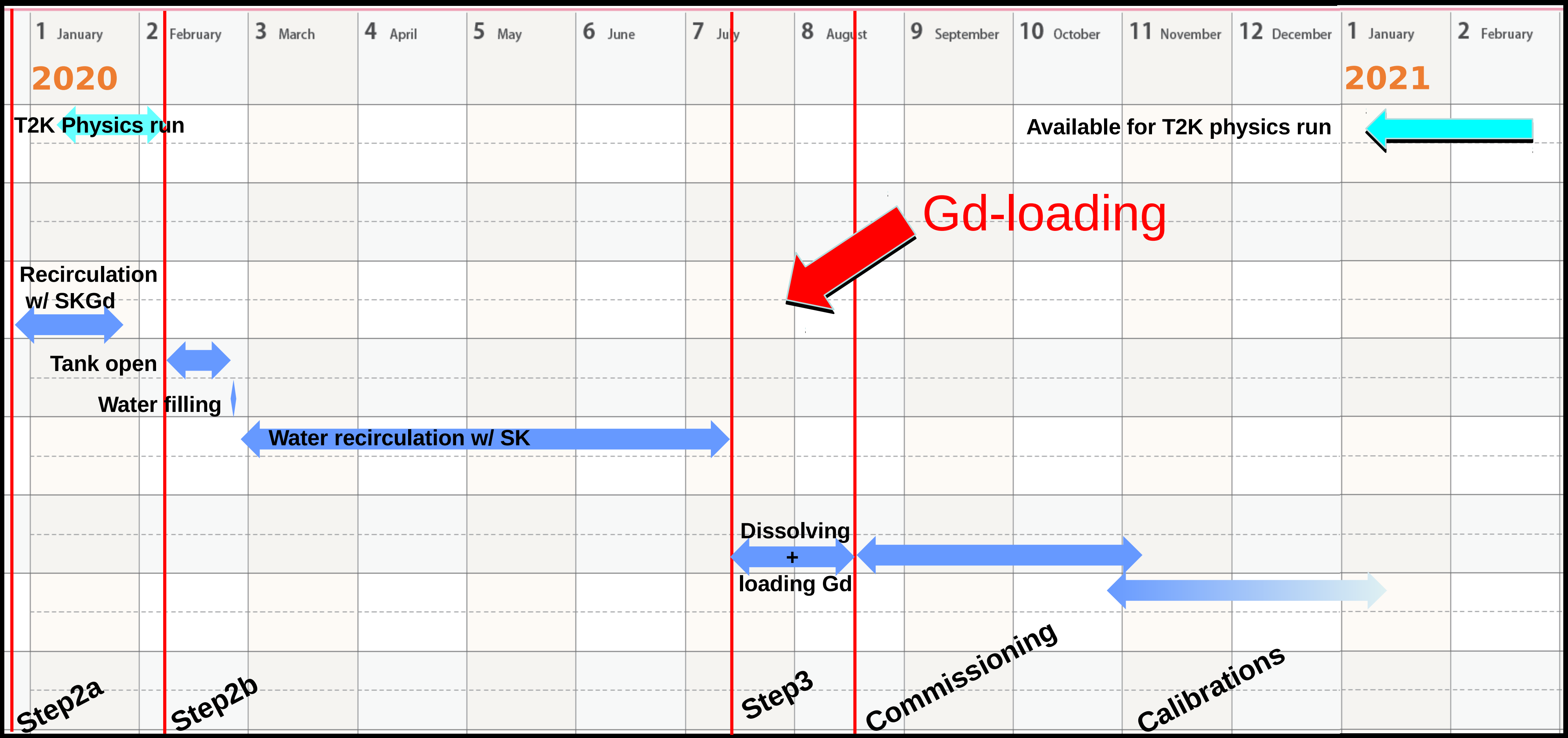




Neutron candidates start to appear in the lower regions first.

Later, these start to be seen later at always increasing Z positions.

Loading schedule



- This first Gd loading is expected to be completed around August 17th-18th.
- SK-Gd will be ready for T2K beam by January 2021.

Summary

Neutron tagging is a useful tool for most SK analyses and adding Gd sulfate will give us this capability.

We have proven with EGADS that Gd sulfate is safe to use in SK and developed the techniques needed to do it.

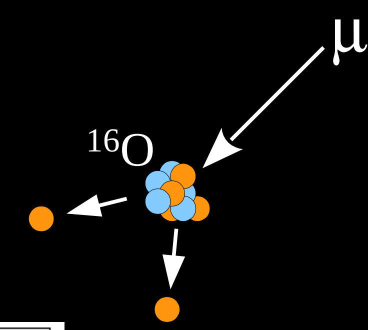
The SK tank has been thoroughly refurbished → **Since July 14th we are loading Gd**:

- Laminar flow seen while loading **Gd: front moving at ~1.5 m/day**. **Mixing layer mostly contained within ~2 m**.
- Gd loaded region can be seen too through the newly acquired efficient neutron tagging capability (for now for Z<0): neutron candidates seen in muon spallation events, stopping muons and from Am/Be source.

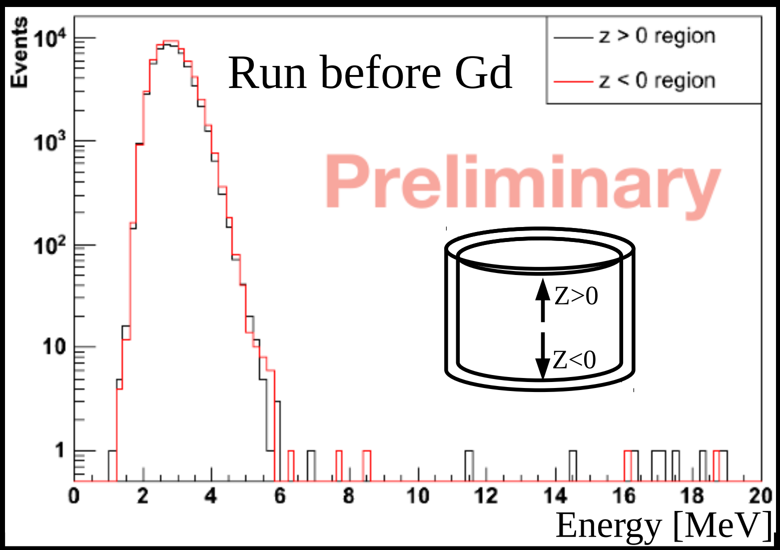
Exciting physics days ahead with neutron tagging at SuperK-Gd !!

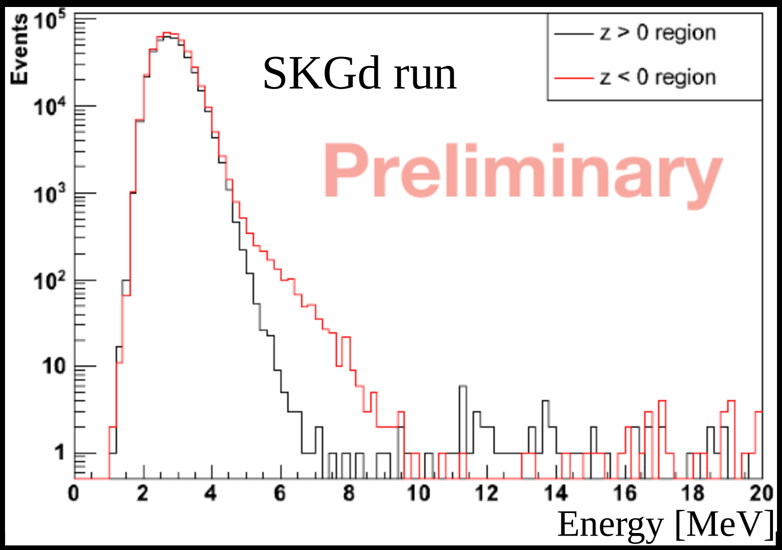
Spallation neutrons

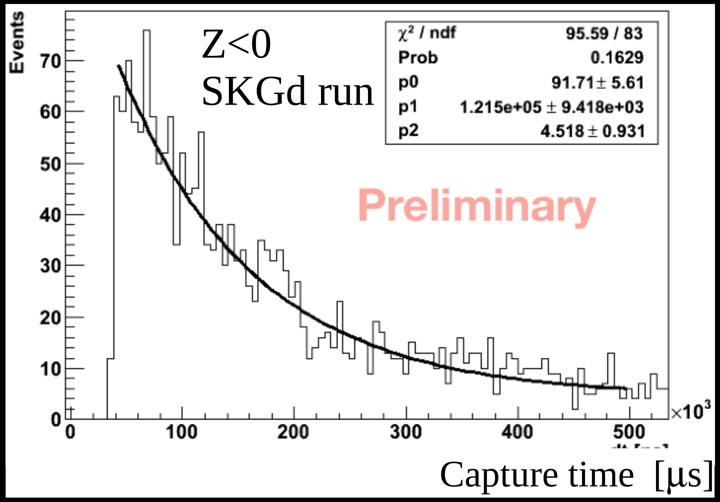
- Cosmic ray muon rate ~2 Hz
- O(10000) spallation neutrons per day produced.



Search for neutron candidates:







Clear excess seen in the Z<0 region where the Gd concentration is increasing

Time constant 121 ± 9 μs

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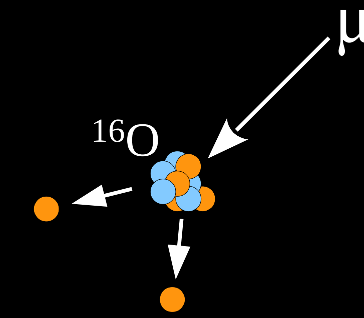
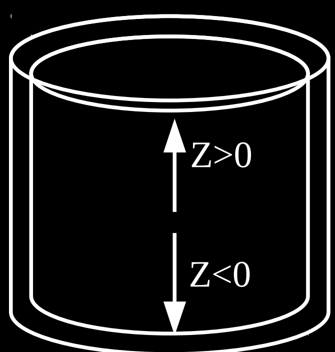
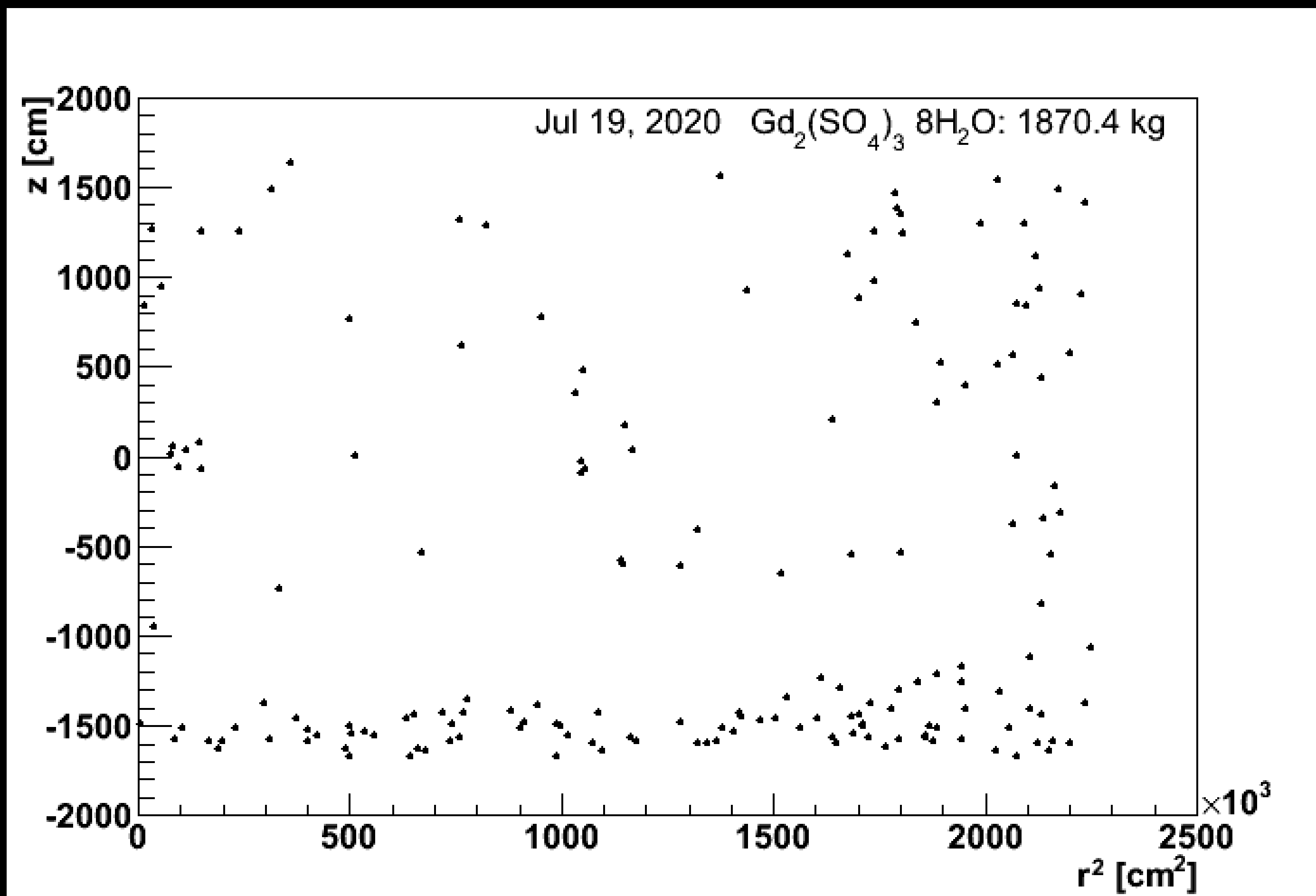


Search for neutron candidates:



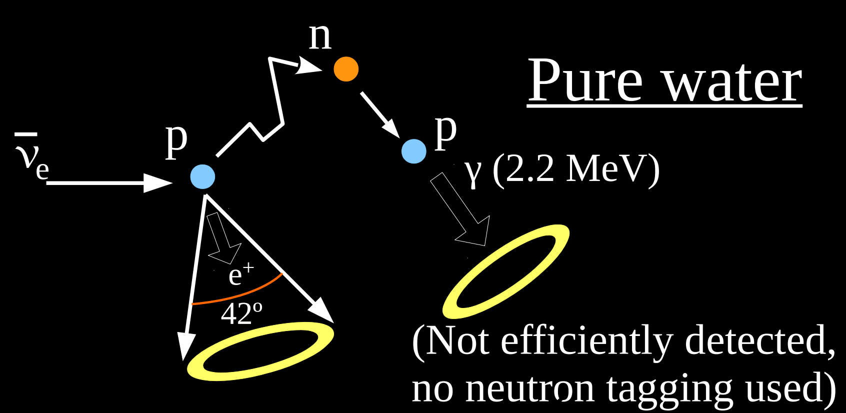


More about spallation @SK: see talk by Laura Bernard, July 29th 18:30 (CET)

Benefits of neutron tagging

Supernova relic neutrinos (SRN): neutrinos from all the past core collapse supernovae in the history of the universe.

Core-collapse SN bursts: with neutron tagging we can clearly identify the dominant IBD events (88% of the events).



$\Delta T \sim 200\ \mu s$

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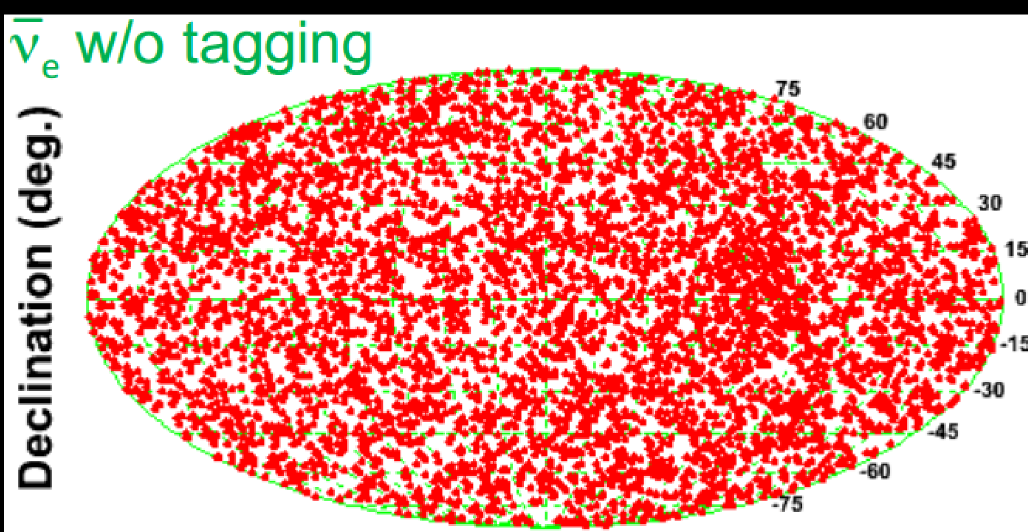
Core-collapse SN bursts: with neutron tagging we can clearly identify the dominant IBD events (88% of the events):

- Prompt recognition of a SN.
- This would outline the ν_x elastic scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ and hence, greatly improves the pointing accuracy to the SN.



Right ascension (deg.)

Right ascension (deg.)

Benefits of neutron tagging

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- Prompt recognition of a SN.
- This would outline the ν_x elastic scattering: $\nu_x + e^- \rightarrow \nu_x + e^-$ and hence, greatly improves the pointing accuracy to the SN.
- Measure $\bar{\nu}_e$ and ν_e spectra.
- Late black hole formation.
- Pre-supernova warning: stellar neutrinos from silicon fusion in nearby stars (< 1kpc and M > 13 $M_\odot$).

Others:

- Reduce proton decay backgrounds.
- Reactor antineutrinos.

Gadolinium sulfate radio purity

Radio impurity limits to keep neutron backgrounds low for solar and SRN neutrinos.

Partnered with several companies :
→ Multiple screening campaigns:
- In Kamioka (Japan), Canfranc (Spain) and Boulby (UK).
- ICP-MS and HPGe detectors.

Chain	Part of the chain	SRN (mBq/Kg)	Solar (mBq/Kg)
^{238}U	^{238}U	< 5	-
	^{226}Ra	-	< 0.5
^{232}Th	^{232}Th	-	< 0.05
	^{228}Th	-	< 0.05
^{235}U	^{235}U	-	< 30
	^{227}Ac/^{227}Th	-	< 30

→ Requirements were met. Now loading!!

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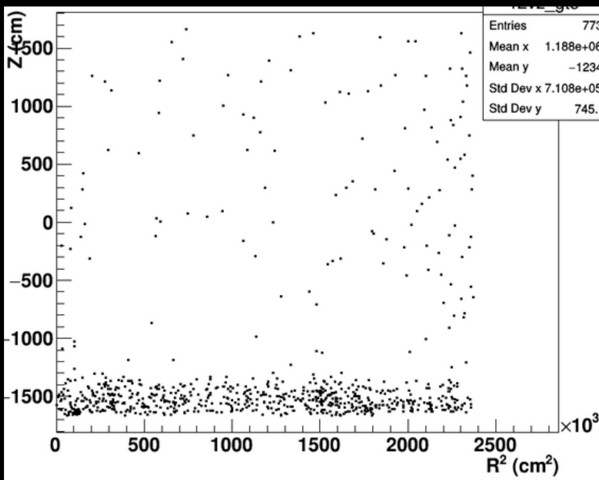
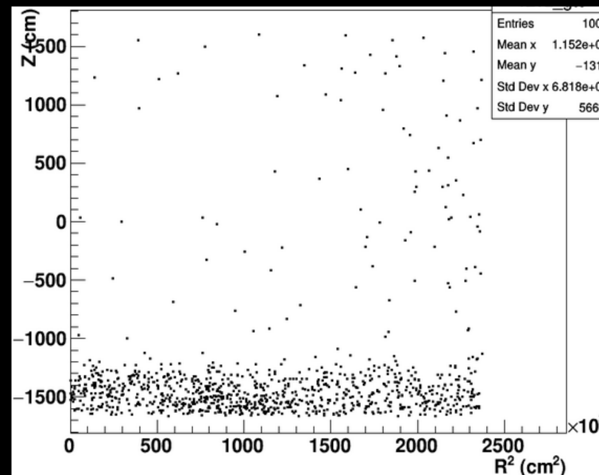
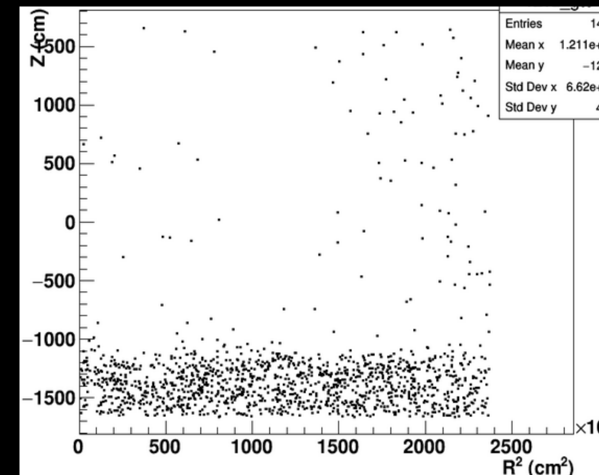
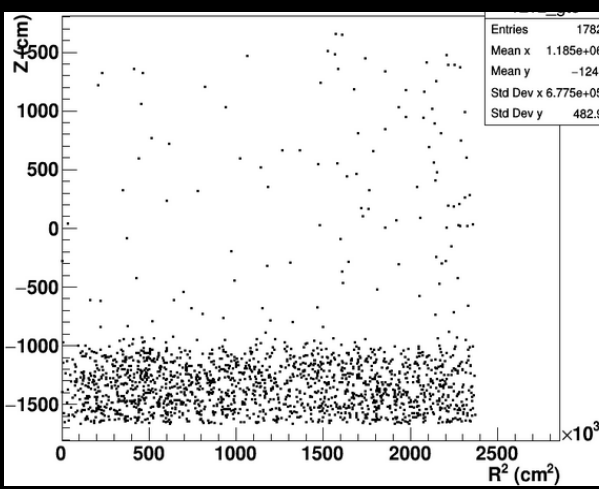
Neutrons from spallation muons

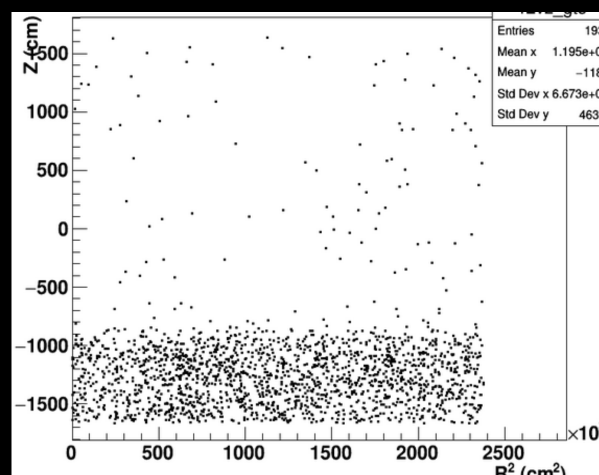
- Cosmic ray muon rate ~2 Hz
- O(10000) of spallation muons per day produced.

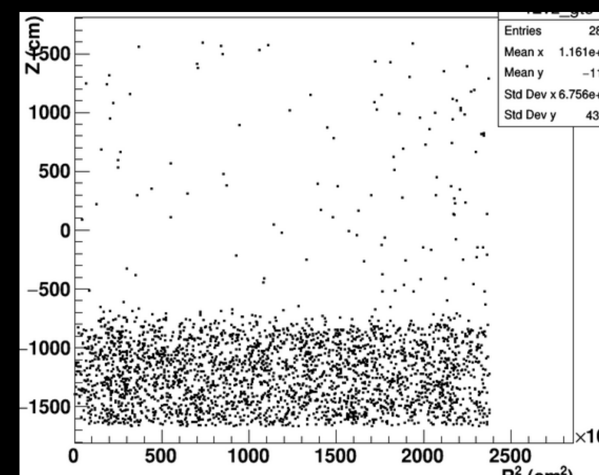










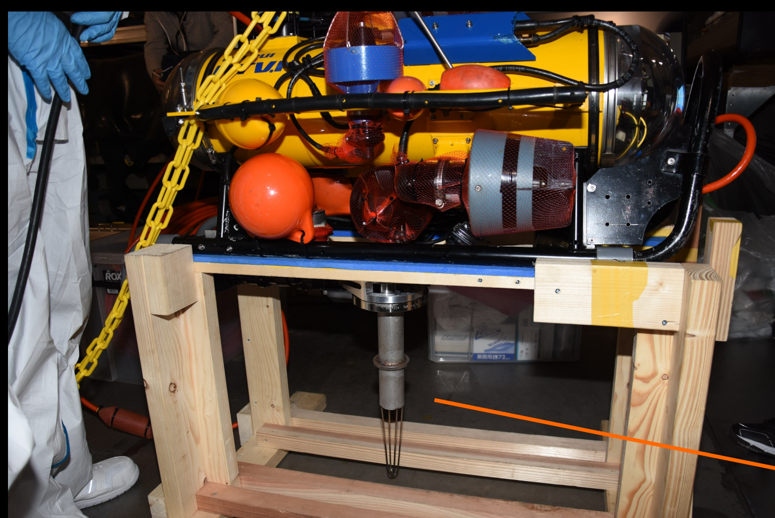


Brief tank open work February 2020

In SK laminar flow helps to suppress diffusion of radon from PMTs and walls into the fiducial volume.

Goal: install caps on water outlets.

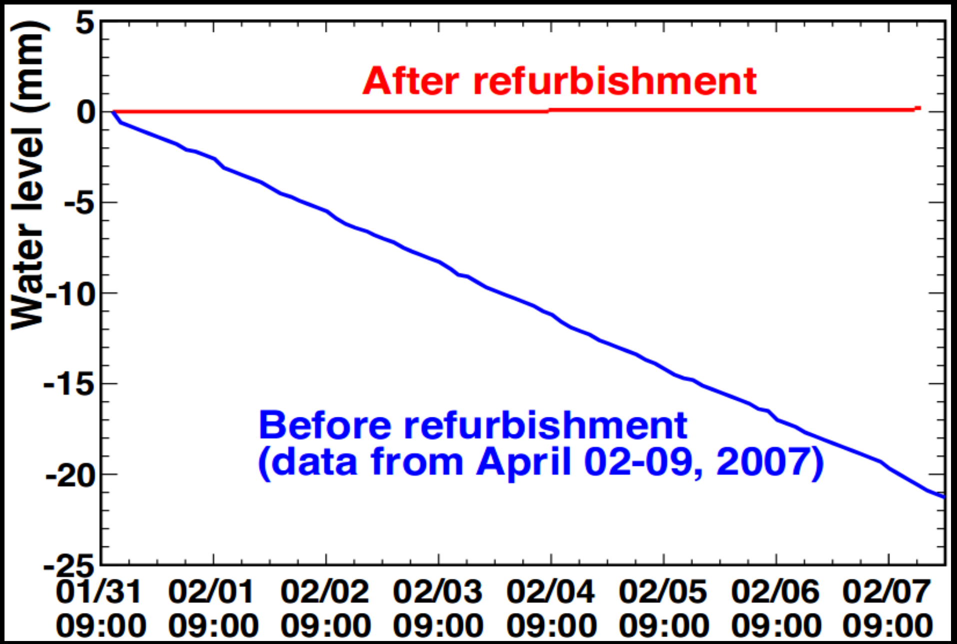
How to: Use a robotic submarine

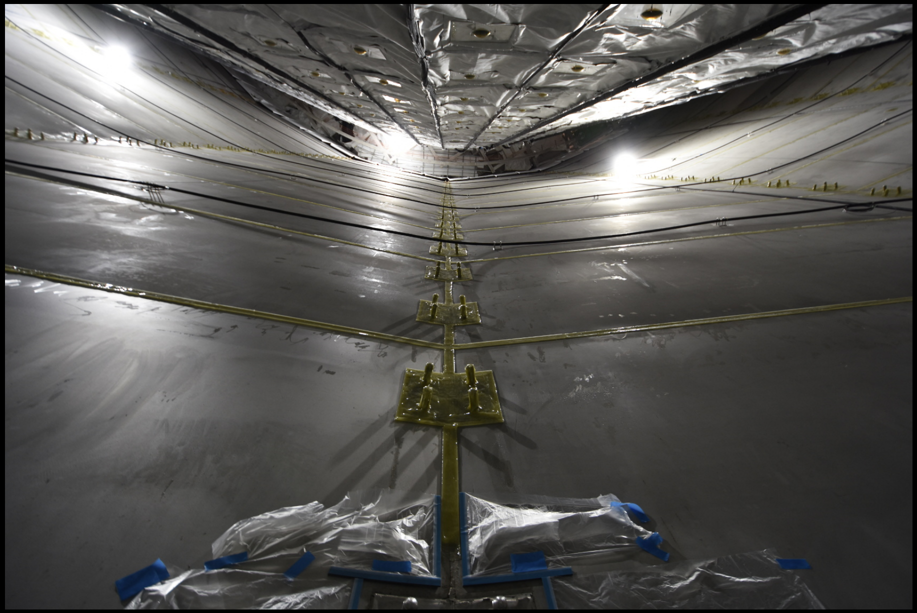


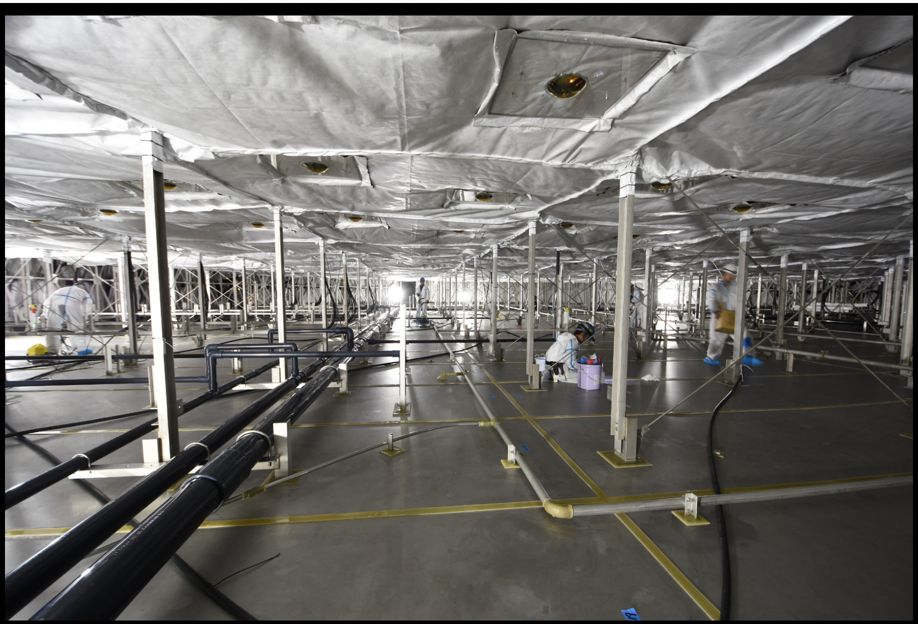
→ 12 caps installed in the ID and 8 in the OD between Feb 15th and 19th.

Super-Kamiokande refurbishment

We do not observe any water leak 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 2018/9 tank refurbishment.

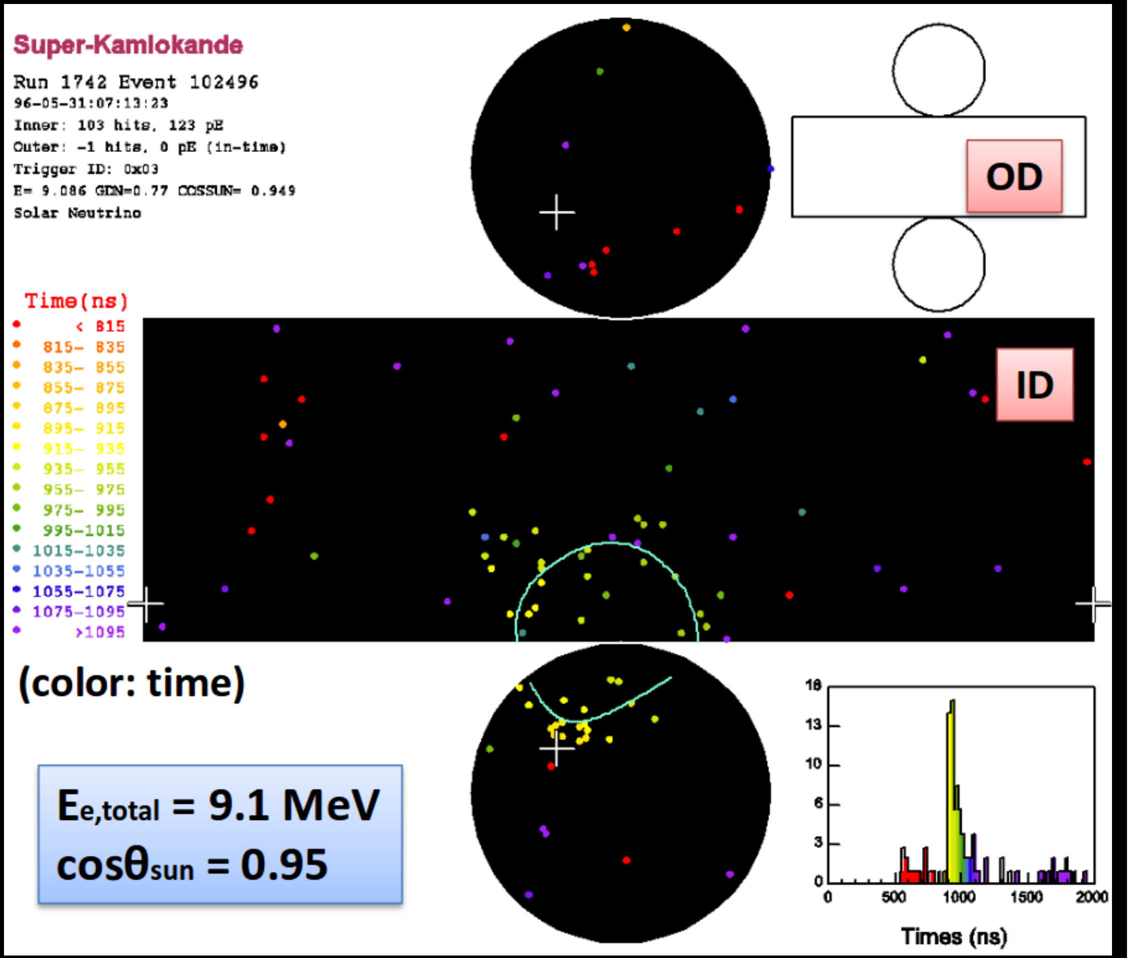






Low energy event reconstruction

Solar neutrino: $\nu + e^- \rightarrow \nu + e^-$



<u>Reconstruction:</u>

- <u>**Interaction vertex:**</u>
  ⇨ Timing information

- <u>**Electron direction:**</u>
  ⇨ Cherenkov Ring pattern

- <u>**Electron energy:**</u>
  ⇨ Number of hit PMTs, N_{eff} (~6 hit/MeV @ SK-I, III and IV)

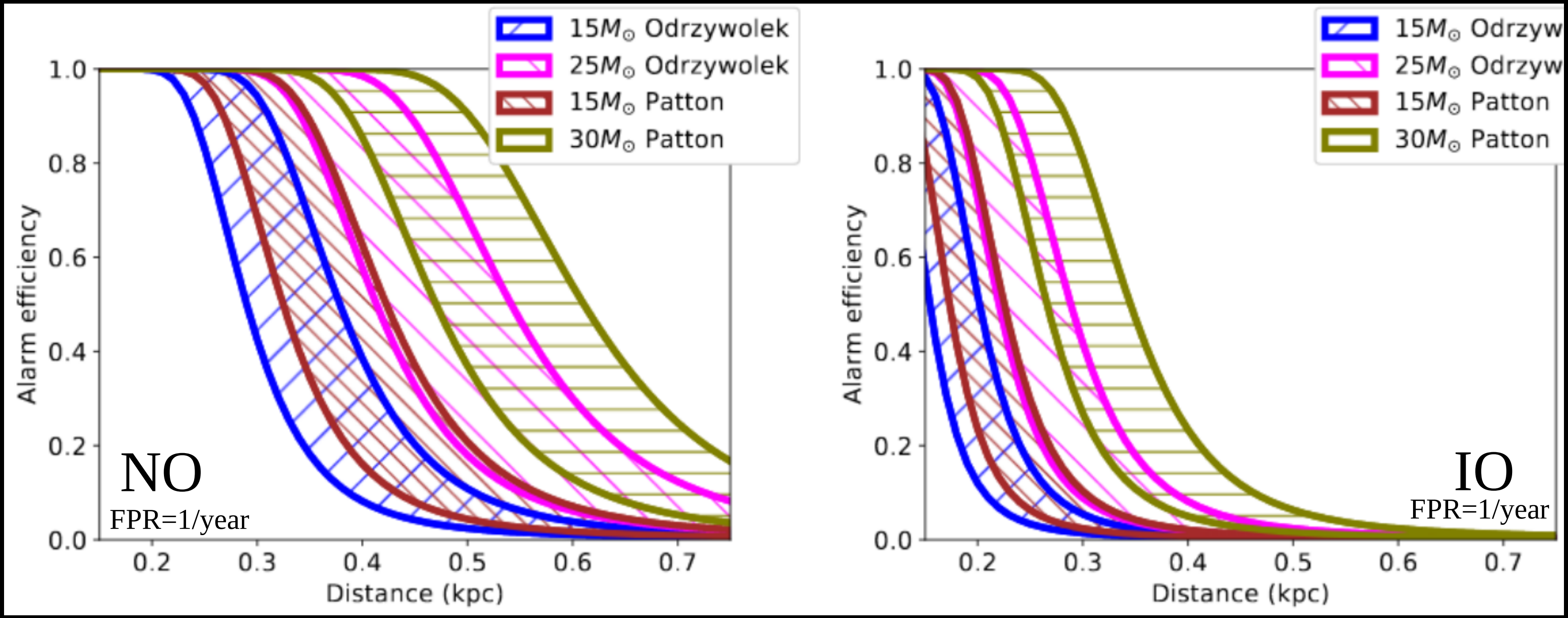
Resolution (10 MeV electron case):

→ Energy 14% Vertex: 87 cm Direction: 26° ⟸ SK-I

→ Energy 14% Vertex: 55 cm Direction: 23° ⟸ Software improvement for SK-III & SK-IV

Other benefits from Gd

Pre-burst (nearby) signal: for M > 13 $M_\odot$ during Si burning



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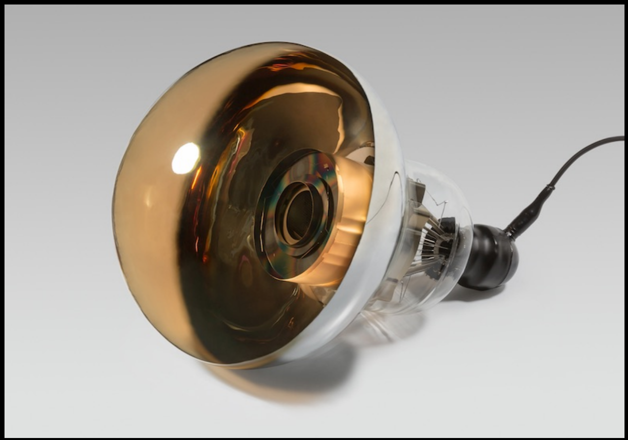
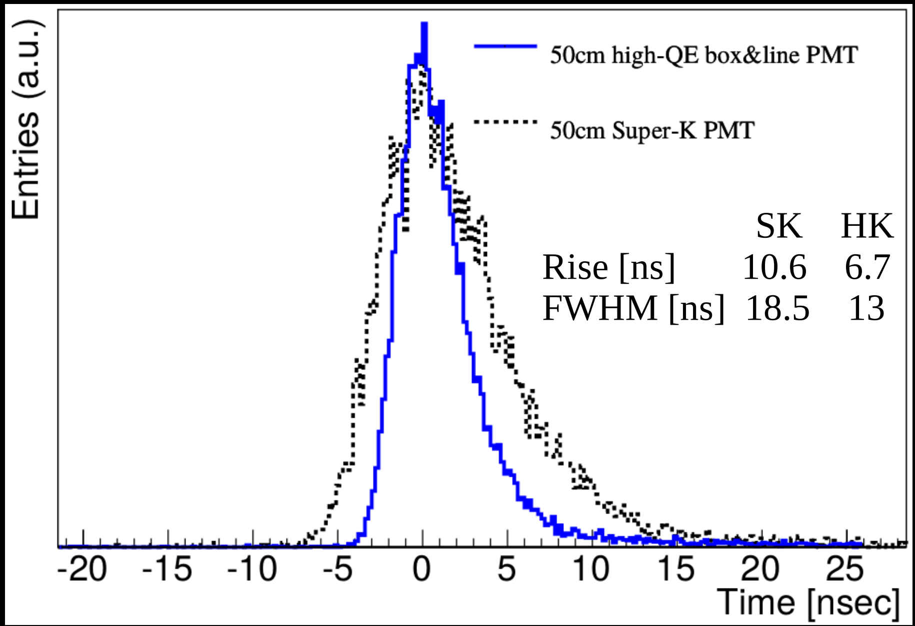
Hyper-Kamiokande ID photo-sensors

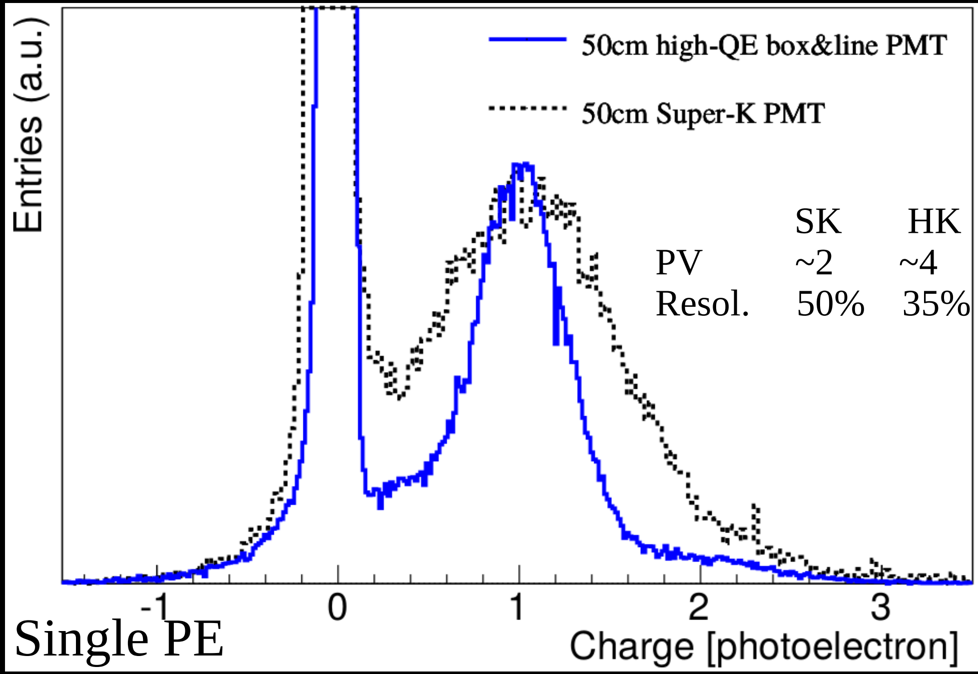
- Newly developed Hamamatsu HQE B&L PMT with high QE
- x2 better single photon efficiency as compared to the SuperK PMTs
- Improved charge and timing resolutions



50-cm HQE B&L R12860



	SK	HK
Rise [ns]	10.6	6.7
FWHM [ns]	18.5	13

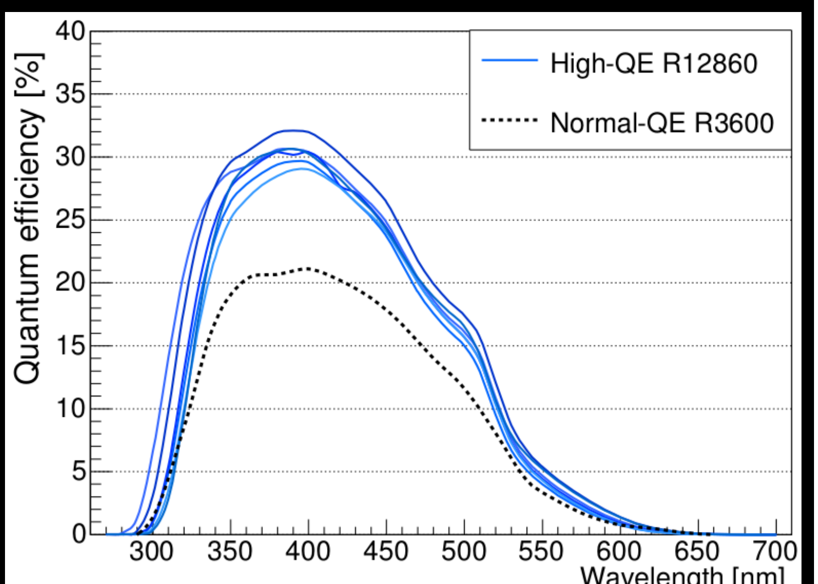


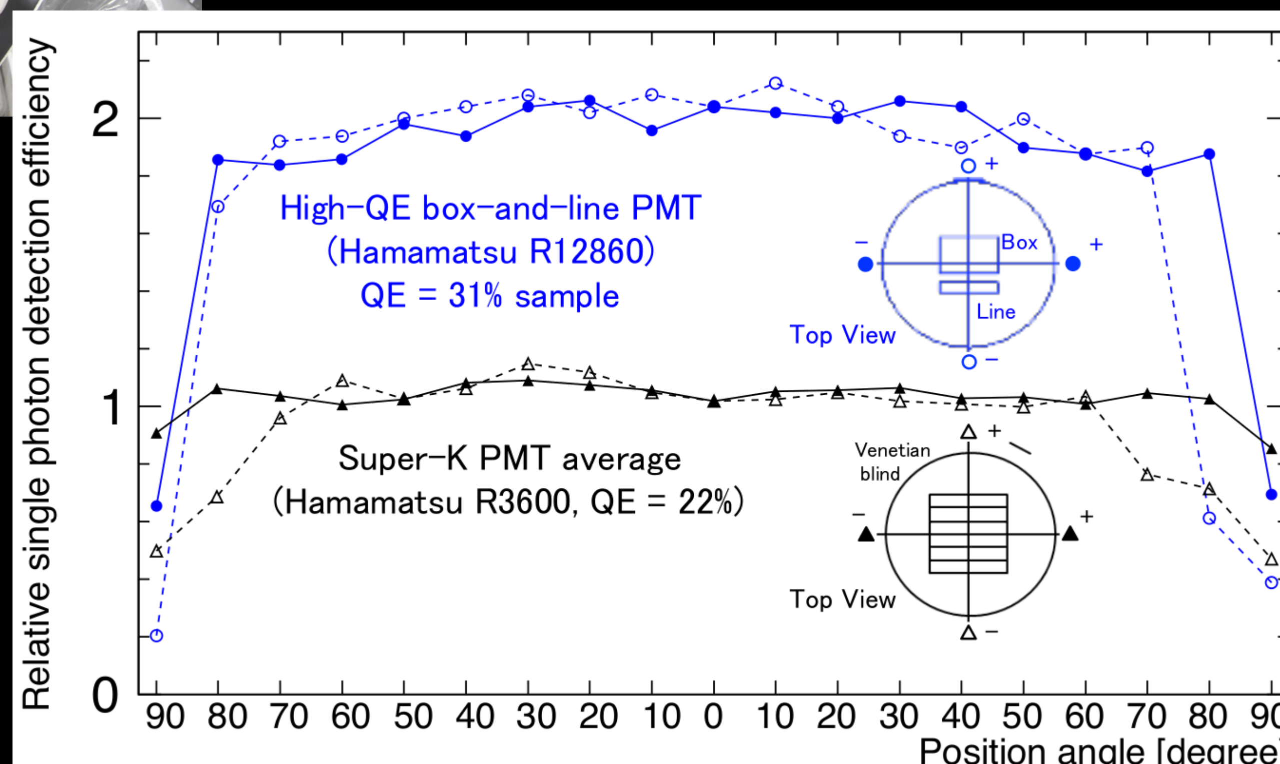
	SK	HK
PV	~2	~4
Resol.	50%	35%

Single PE

Super-Kamiokande ID PMT refurbishment

- Newly developed Hamamatsu HQE B&L PMT with high QE
- x2 better single photon efficiency as compared to the SuperK PMTs

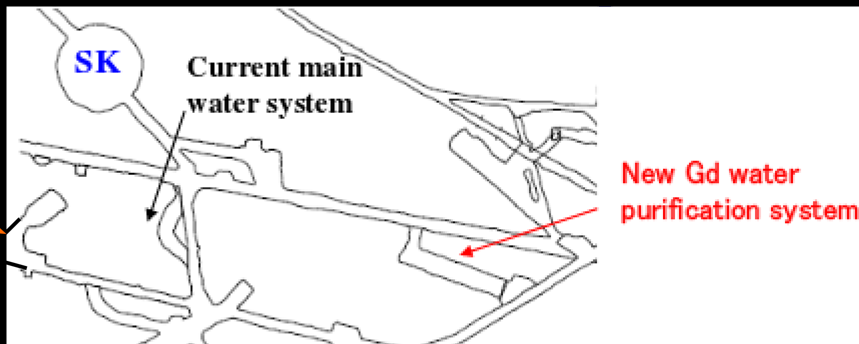




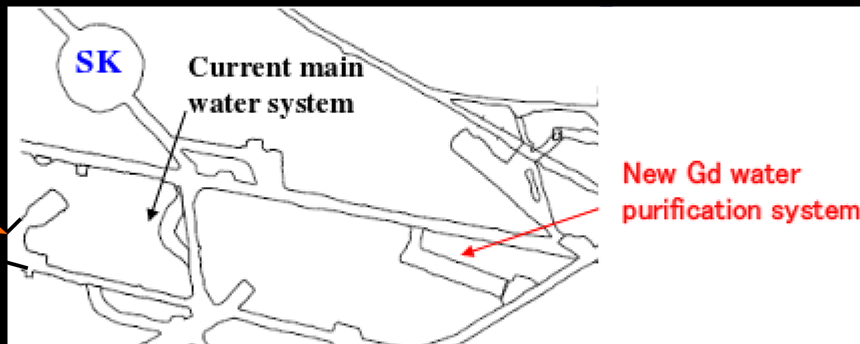
Improved charge and timing resolutions (see backup)

New Water System for SuperK-Gd

EGADS



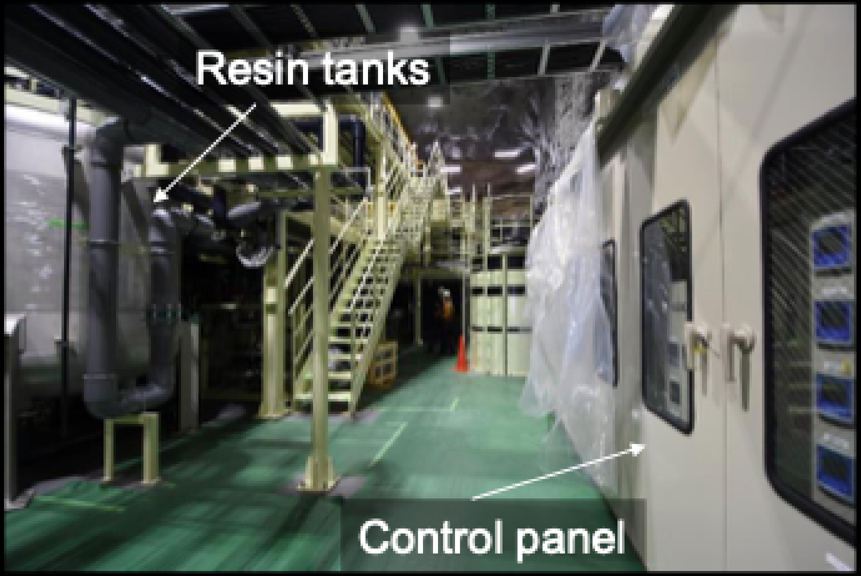
New Water System for SuperK-Gd



Cavern for the new water system has been excavated

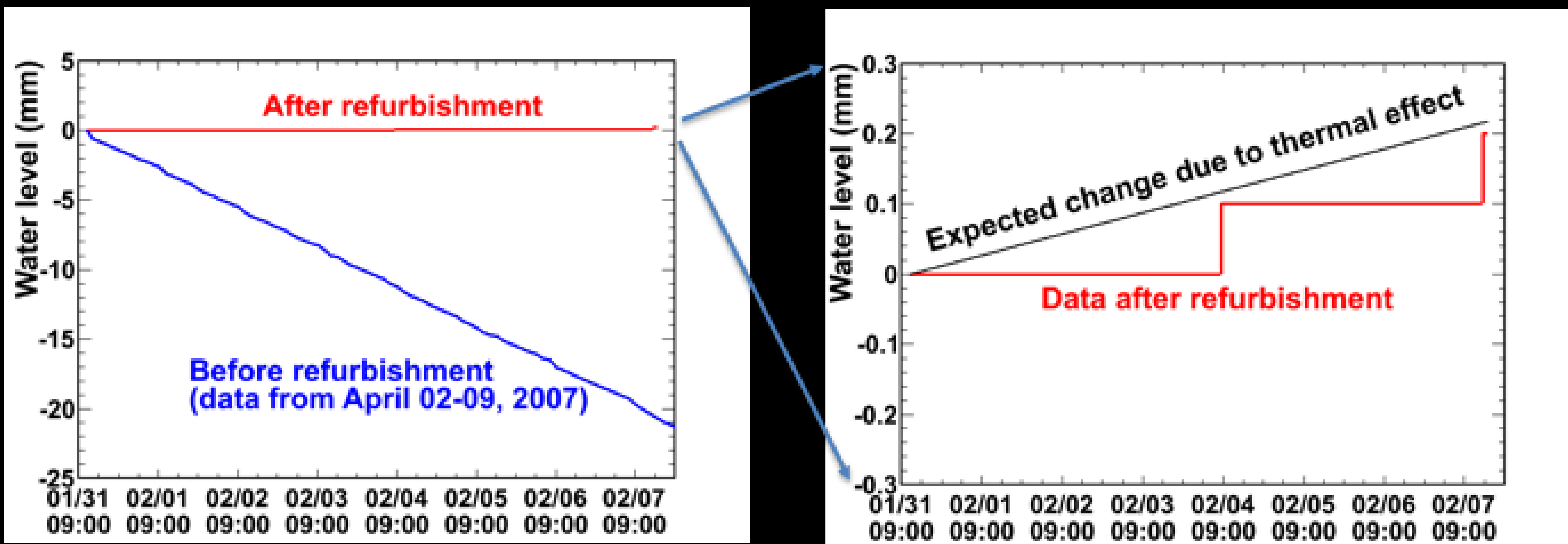
Equipment has been already installed (Gd solution, etc)

New Water System for SuperK-Gd



Super-Kamiokande leak status

There was no drop in the water level (no leak). The rise of ~0.1 mm observed at 8:27 on February 4 and 14:30 on February 7, respectively, is consistent with the prediction due to the volumetric expansion of water from heat inflow.

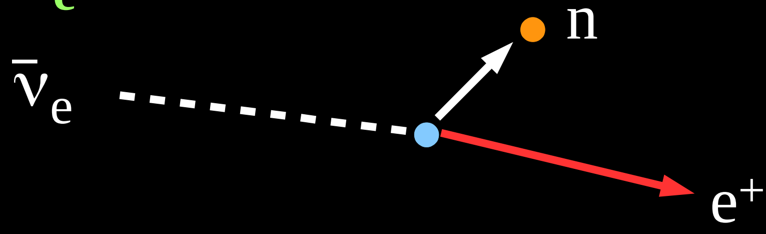


Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day. This is less than 1/200th of the leak rate observed before the 2018/2019 tank refurbishment.

Atmospheric ν backgrounds

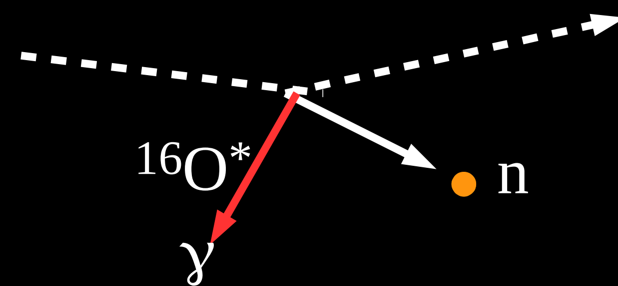
- **Charge Current:**

$\bar{\nu}_e$ CC

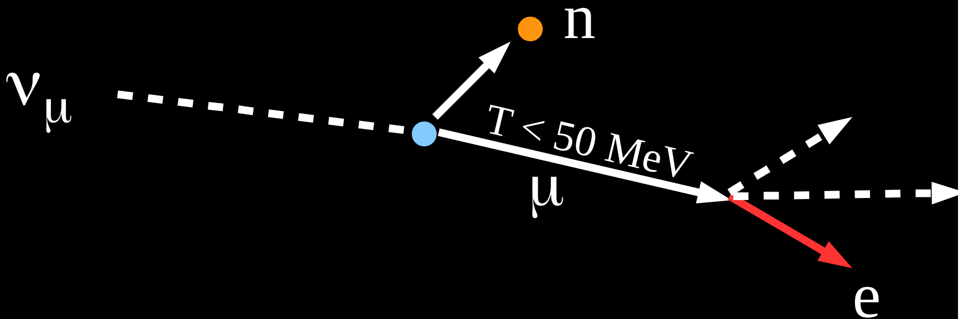


- **Neutral Current:**

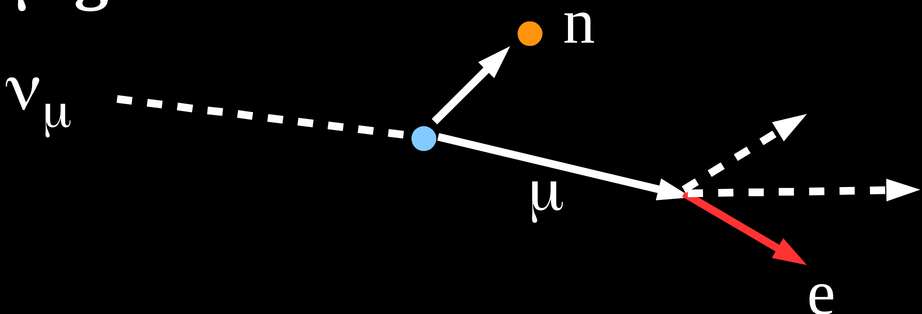
NC elastic

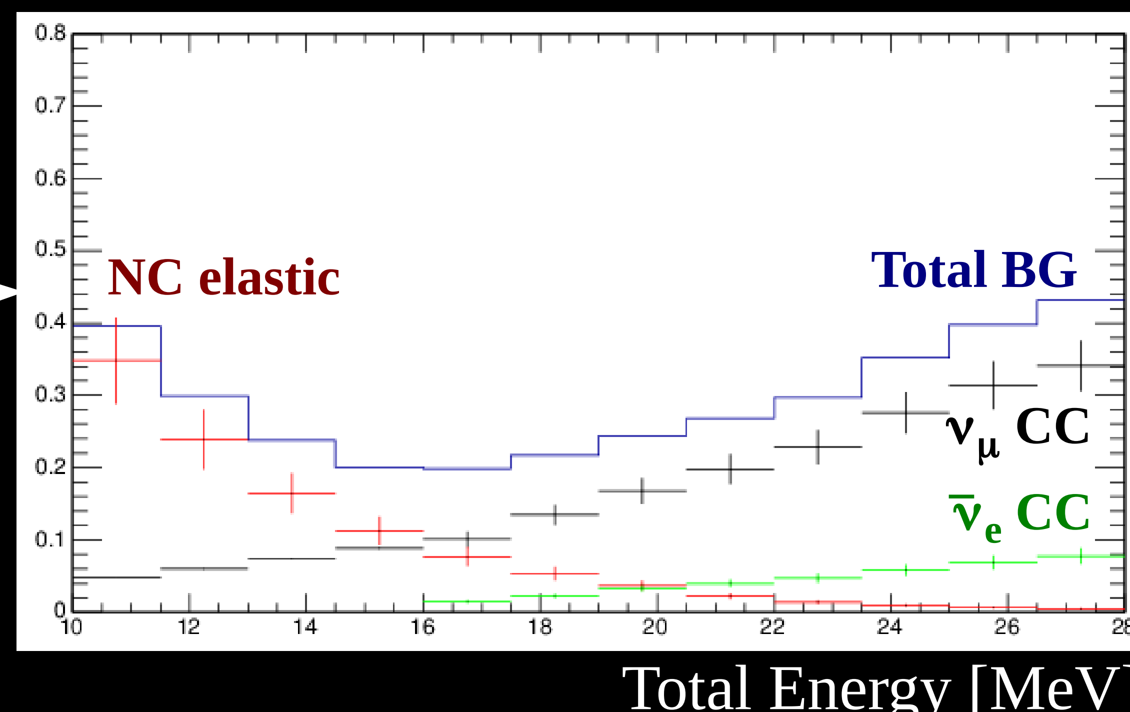


Invisible μ:



μ generation:



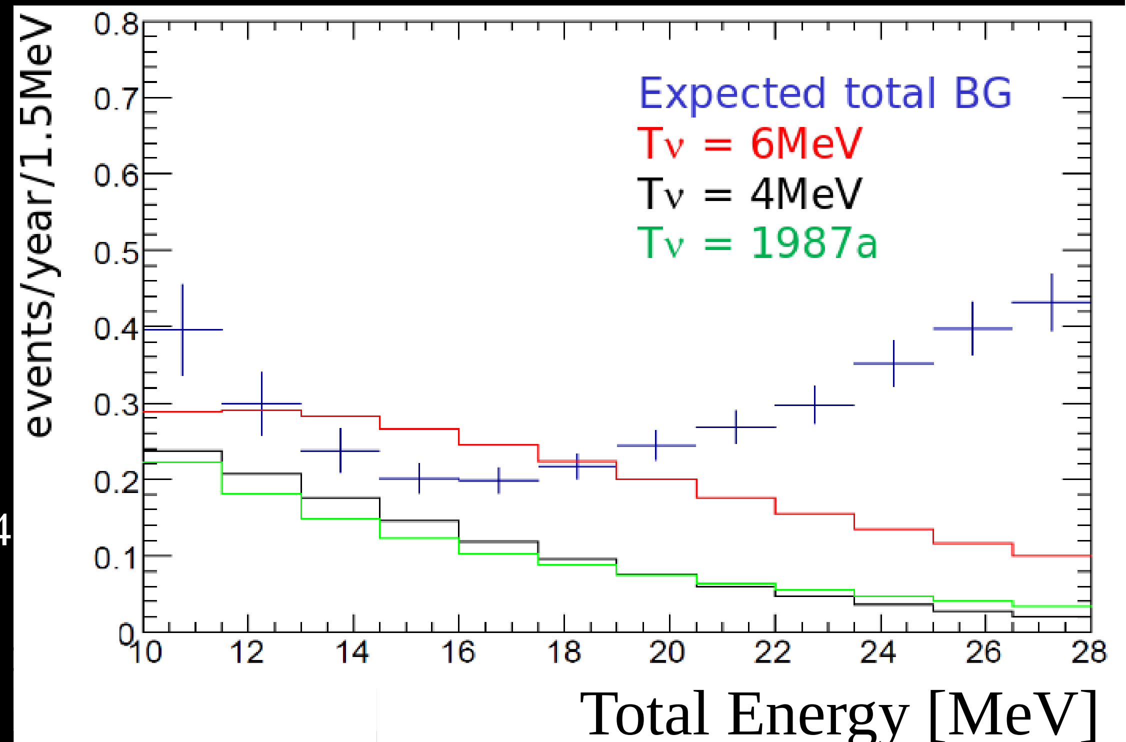


Background vs expected signal

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

The detection of SRN depends on the typical SN emission spectrum

$T_\nu \sim 5\ (M_{NS}/1.4M_\odot)^{1/3}\ (R_{NS}/10\mathrm{km})^{-3/4}$



SRN number of expected events after 10 years of observation

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

With SuperK-Gd the first SRN observation is within our reach!!