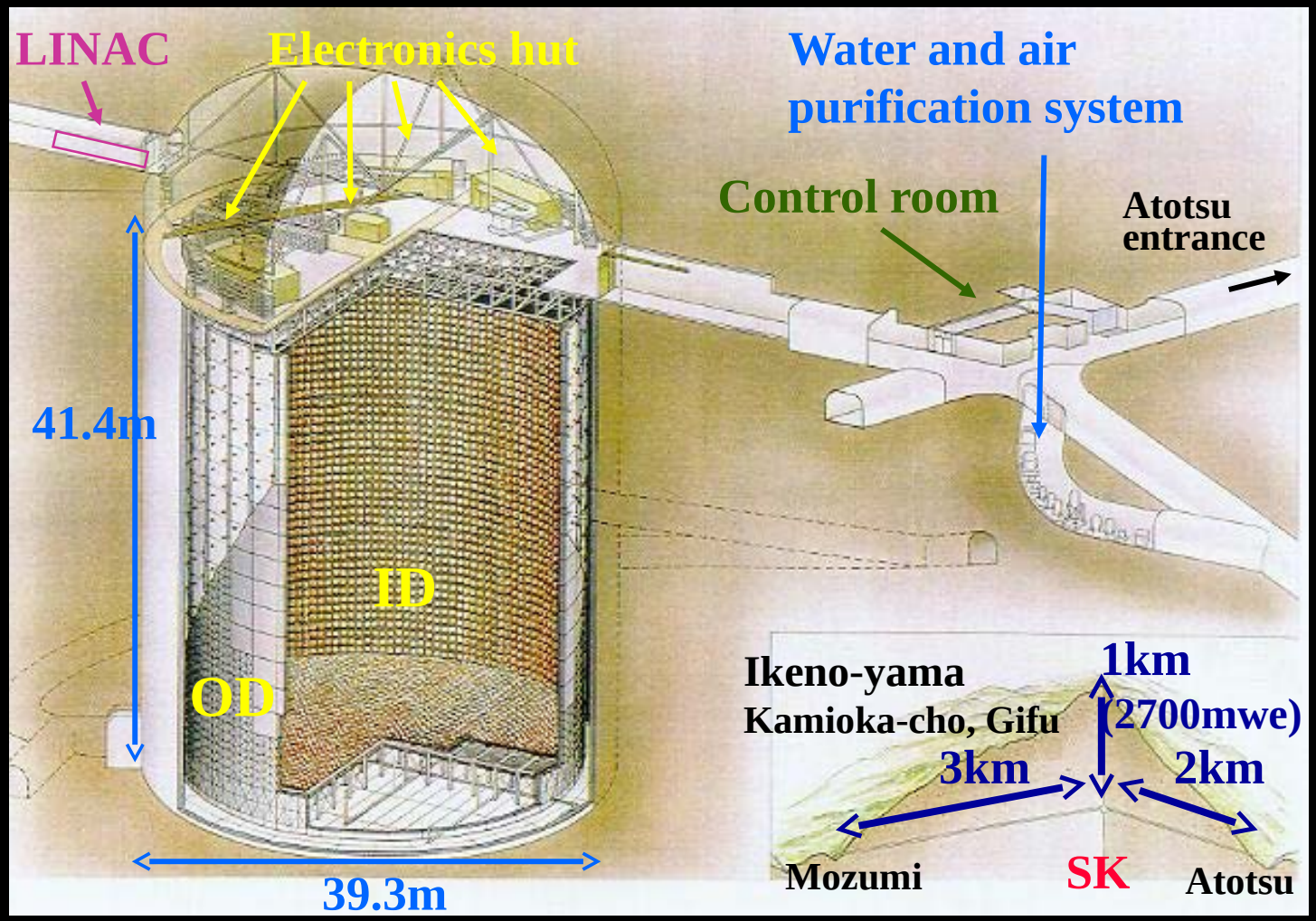
SuperK-Gd: the Gd future of Super-Kamiokande

Lluís Martí Magro, ICRR

36th ICRC July 31st, 2019. Madison, WI, USA

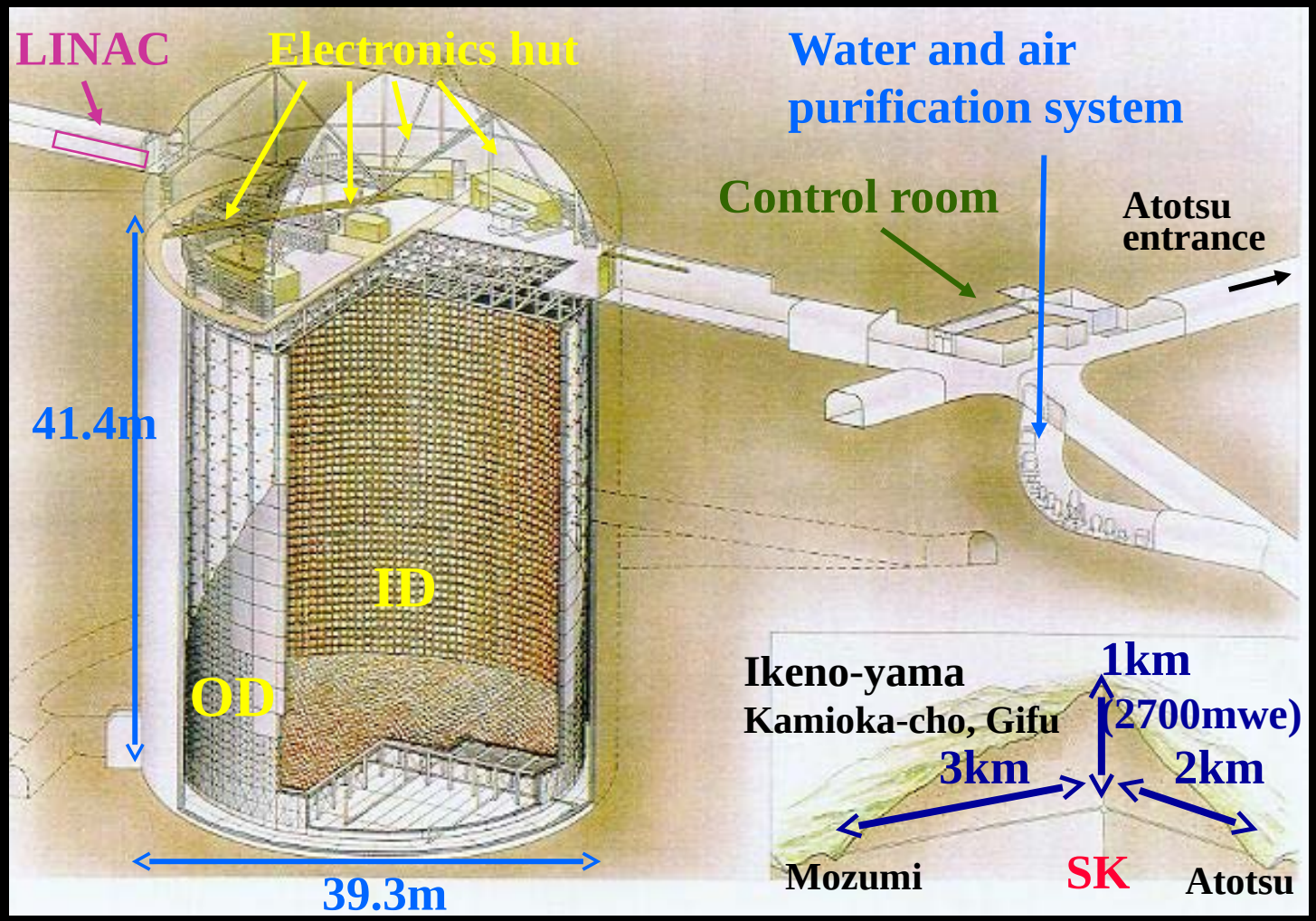
Super-Kamiokande Detector



- 50 kton water
- ~2 m OD viewed by 8-inch PMTs
- 32 kt ID viewed by 20-inch PMTs
- Trigger efficiency: >99%@3.5 MeV E_{kin}

	Phase	SK-I	SK-II	SK-III	SK-IV	SK-V
	Start - end	1996 Apr - 2001 Jul	2002 Oct - 2005 Oct	2006 Jul - 2008 Sep	2008 Sep - 2018 Mar	2019 Jan 29-
Number of PMTs	ID (coverage)	11146 **(40 %)**	5182 **(19 %)**	11129 **(40 %)**	11129 **(40 %)**	11129 **(40%)**
	OD	**1885**				**1885**

Super-Kamiokande Detector



Versatile detector:

Solar neutrinos
Atmospheric neutrinos
Proton decay
Supernovae
Supernova Relic Neutrinos
Indirect search for DM
and more

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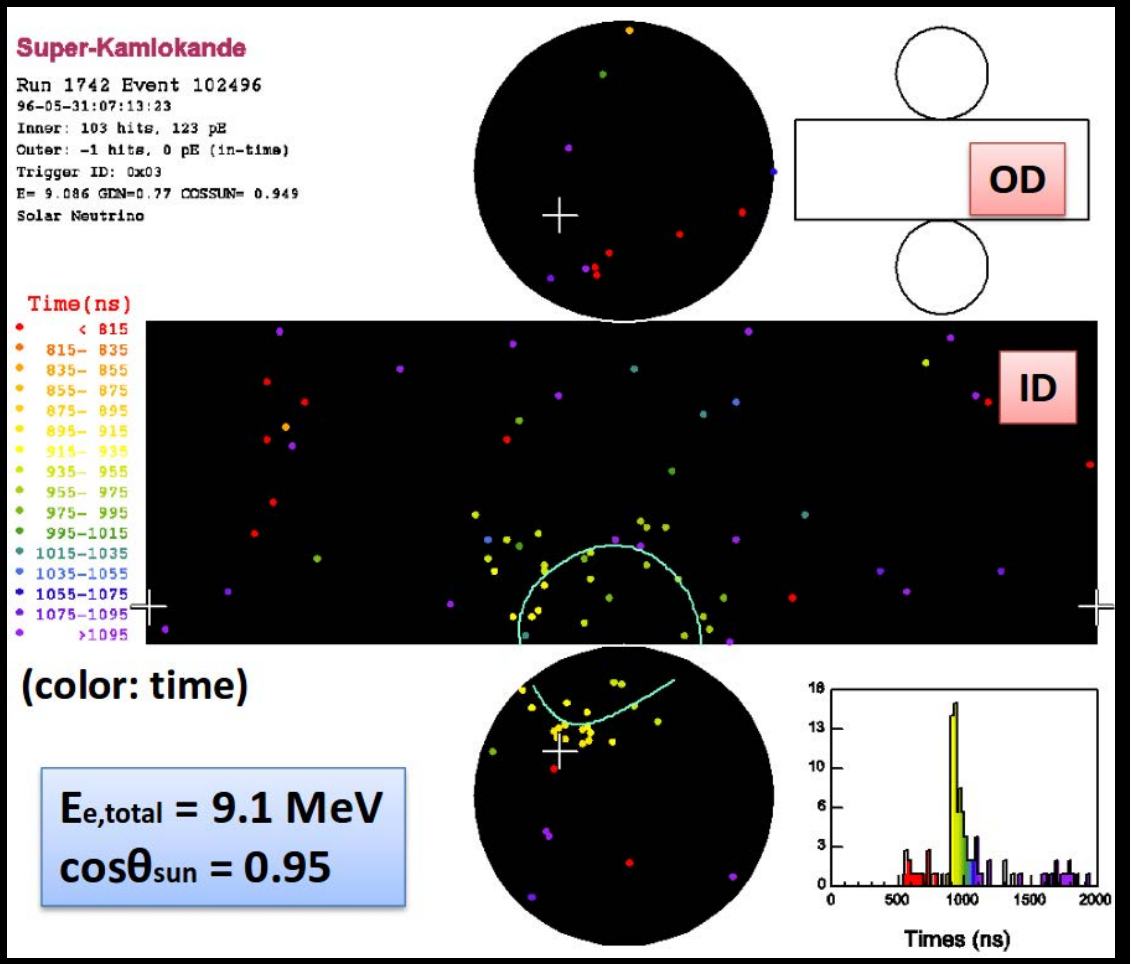
Low energy event reconstruction

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



Reconstruction:

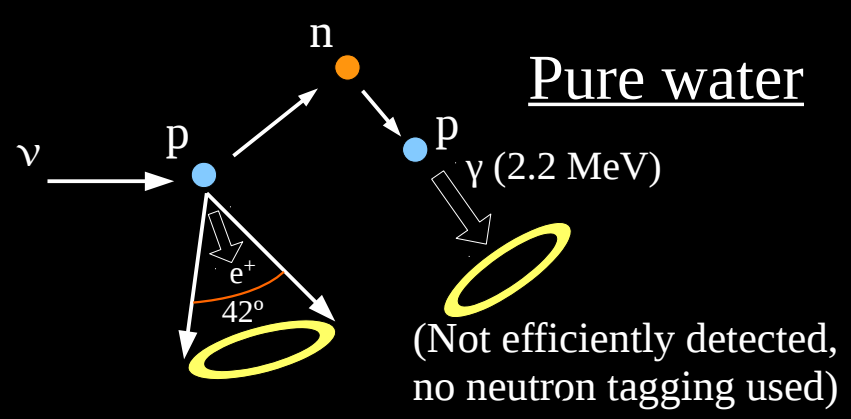
- **Interaction vertex:**
  - ➪ Timing information
- **Electron direction:**
  - ➪ Cherenkov Ring pattern
- **Electron energy:**
  - ➪ Number of hit PMTs, N_{eff} (~6 hit/MeV @ SK-I, III and IV)

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

Neutron tagging in pure water

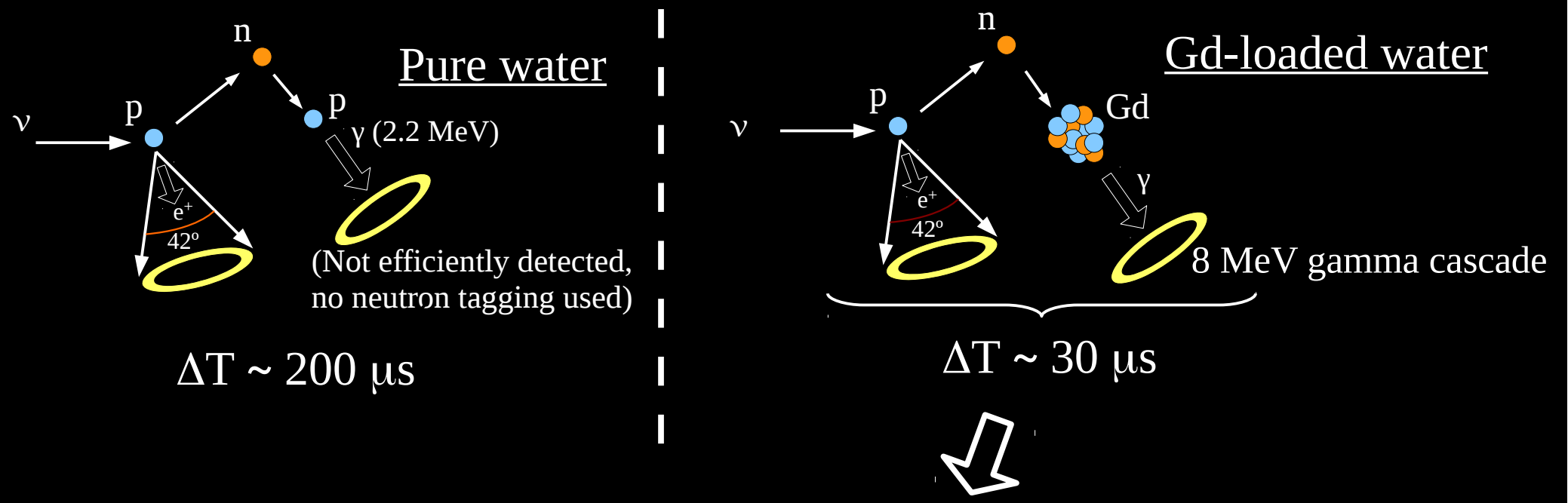


Pure water

(Not efficiently detected,
no neutron tagging used)

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

Neutron tagging in Gd loaded water

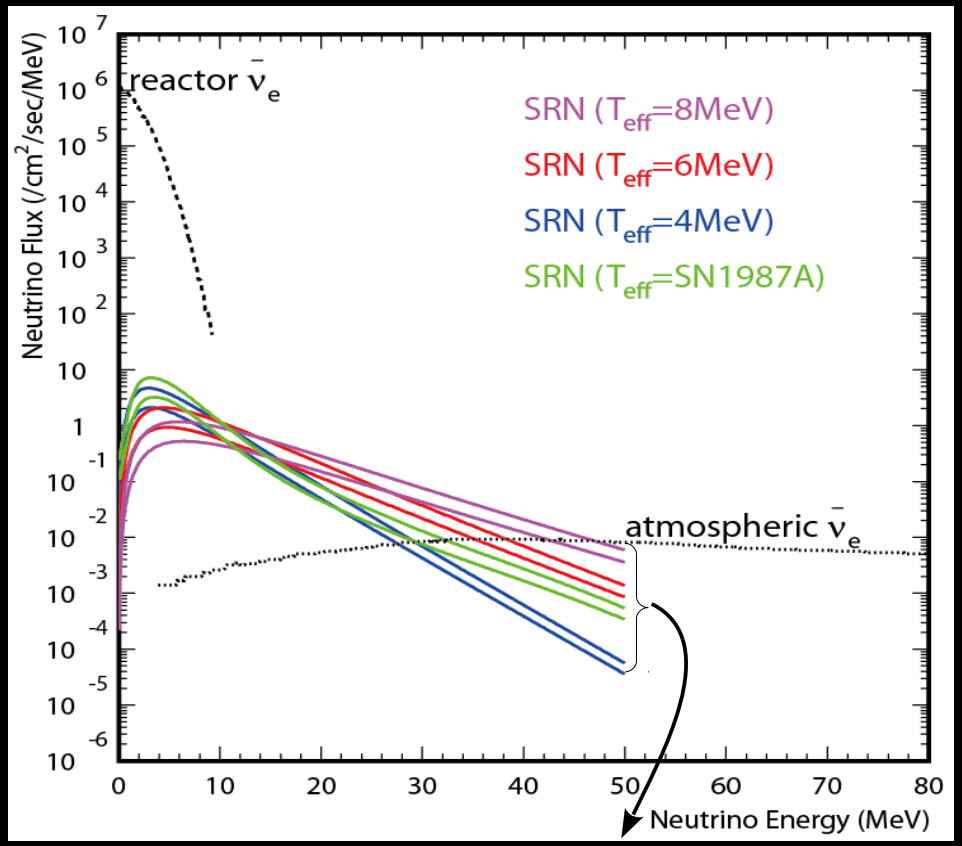


With tight time (delayed) and position coincidence between positron and neutron capture (90% neutron capture on Gd with 0.2% $Gd_2(SO_4)_3$ concentration) we will be able to tag neutrons with high efficiency

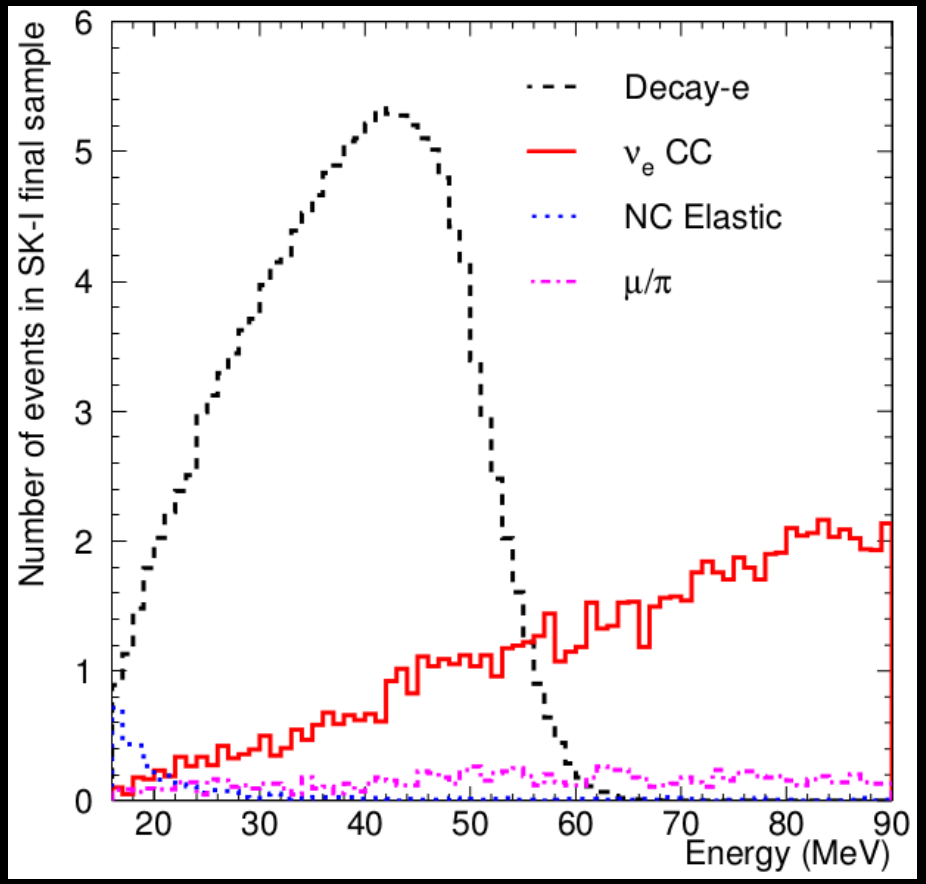
Idea proposed as GADZOOKS!
by Beacom & Vagins PRL.93, (2004) 171101

Supernova Relic Neutrinos

Supernova relic neutrinos (SRN) are those 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

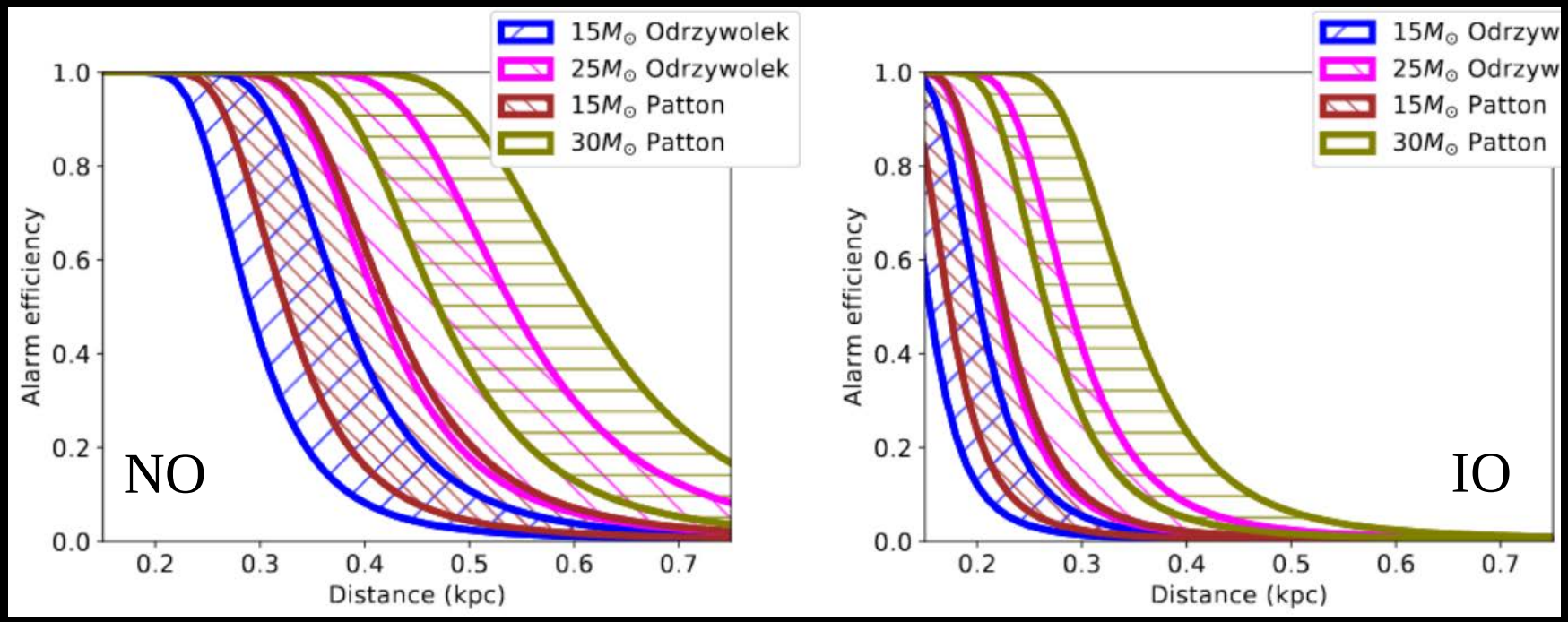
So far, irreducible backgrounds seriously limited the analysis

Other benefits from Gd

Core-collapse burst: gadolinium will allow us neutrino tagging, i.e. identify the dominant IBD 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
- Measure $\bar{\nu}_e$ and ν_e spectra

Pre-burst (nearby) signal: for M > 8 $M_\odot$ during Si burning

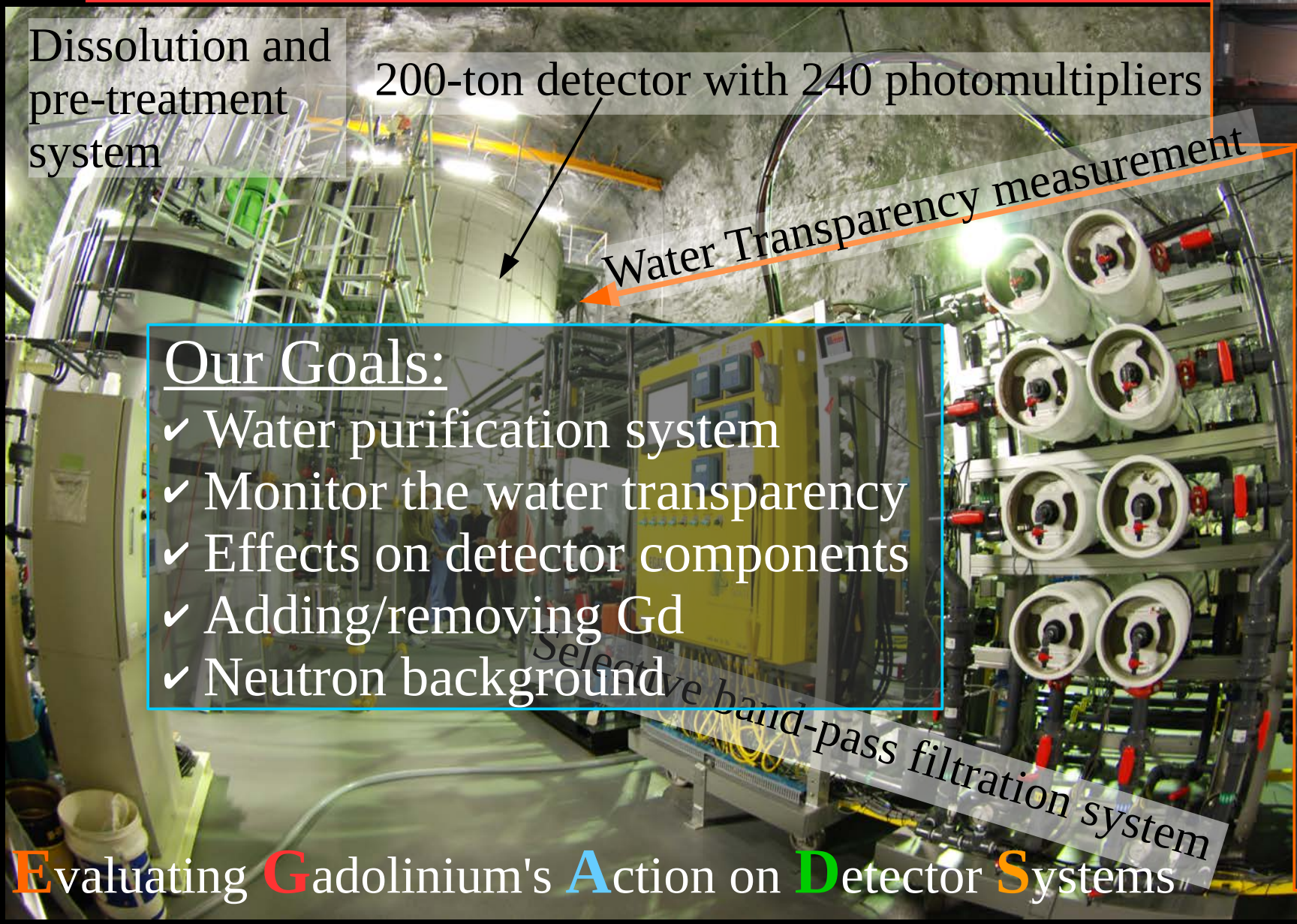


The road to SuperK-Gd: EGADS

Evaluating **G**adolinium's **A**ction on **D**etector **S**ystems

EGADS was build using the same materials as in SuperK
Because of all the exciting possibilities, in June 2009 the SK collaboration launched the EGADS project

The road to SuperK-Gd: EGADS



Our Goals:

- ✔ Water purification system
- ✔ Monitor the water transparency
- ✔ Effects on detector components
- ✔ Adding/removing Gd
- ✔ Neutron background

Evaluating **G**adolinium's **A**ction on **D**etector **S**ystems

EGADS was build using the same materials as in SuperK
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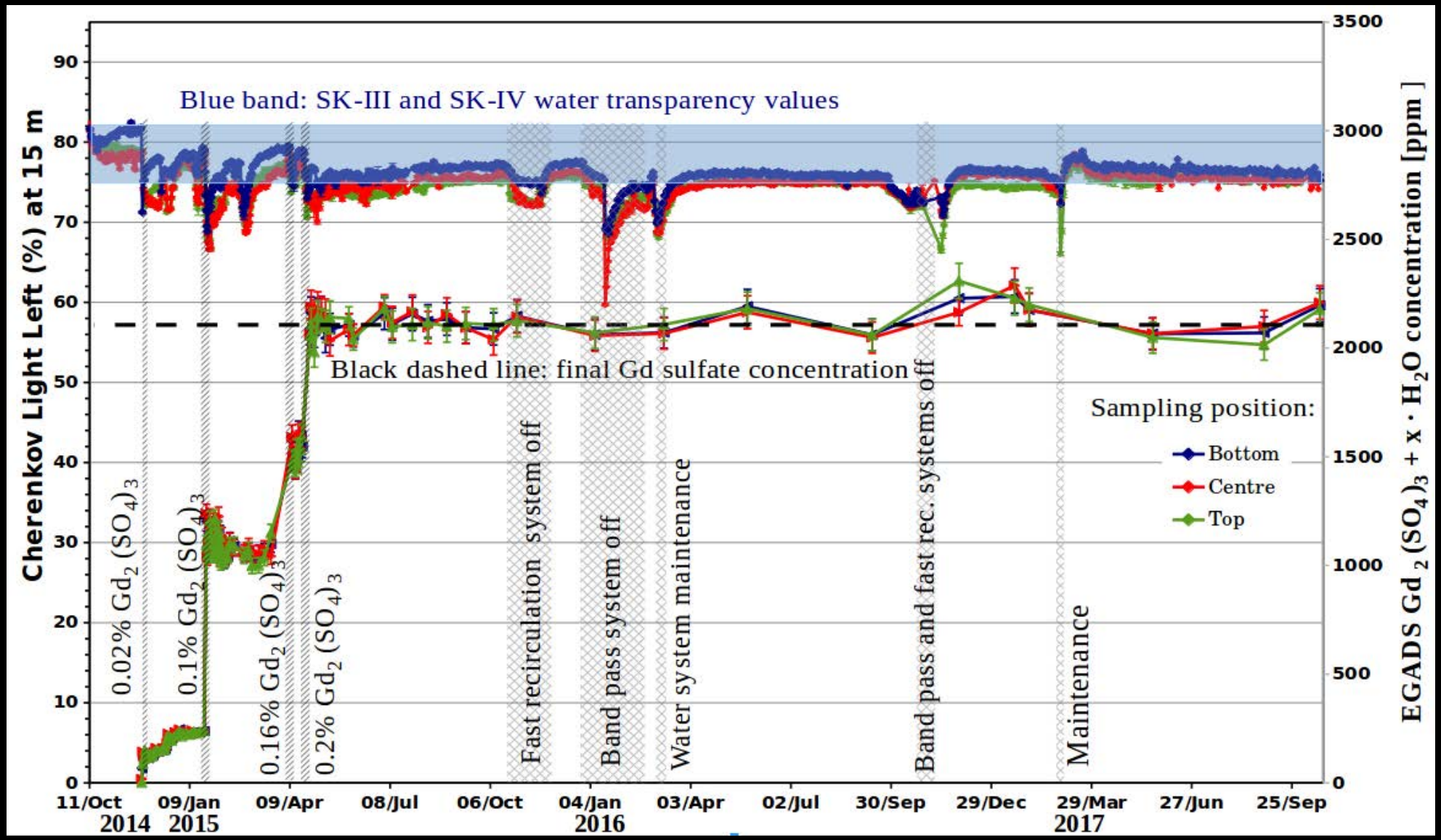
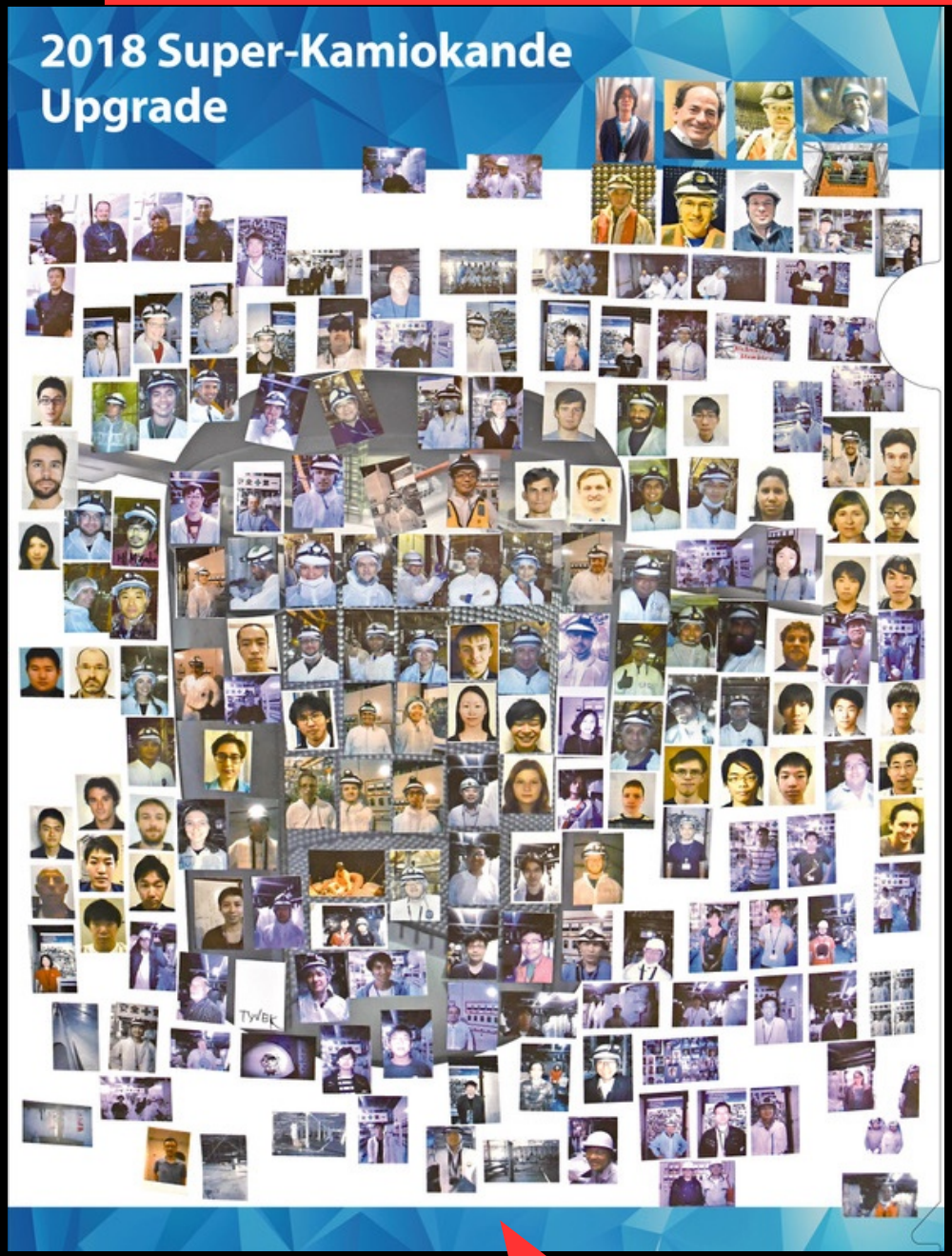
EGADS' main result



- 0.2 % Gd sulfate is as transparent to Cherenkov light as pure-water
- Our water system achieves this with no Gd losses
- Gd concentration is homogeneous in our detector

Super-Kamiokande upgrade



Refurbishment work:

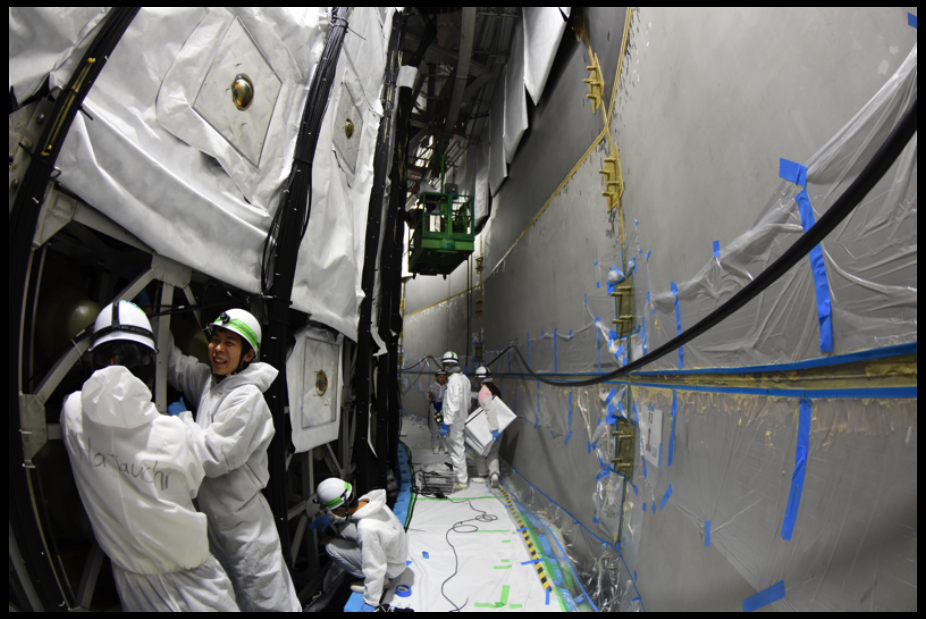
- Clean walls and detector structures and remove potential sources of rust
- Replace faulty ID and OD PMTs
- Replace the OD white Tyvek

Upgrade:

- New hall excavated for the new Gd water system
- Modify the in-tank piping

Thank you all for the hard work !!

Super-Kamiokande refurbishment

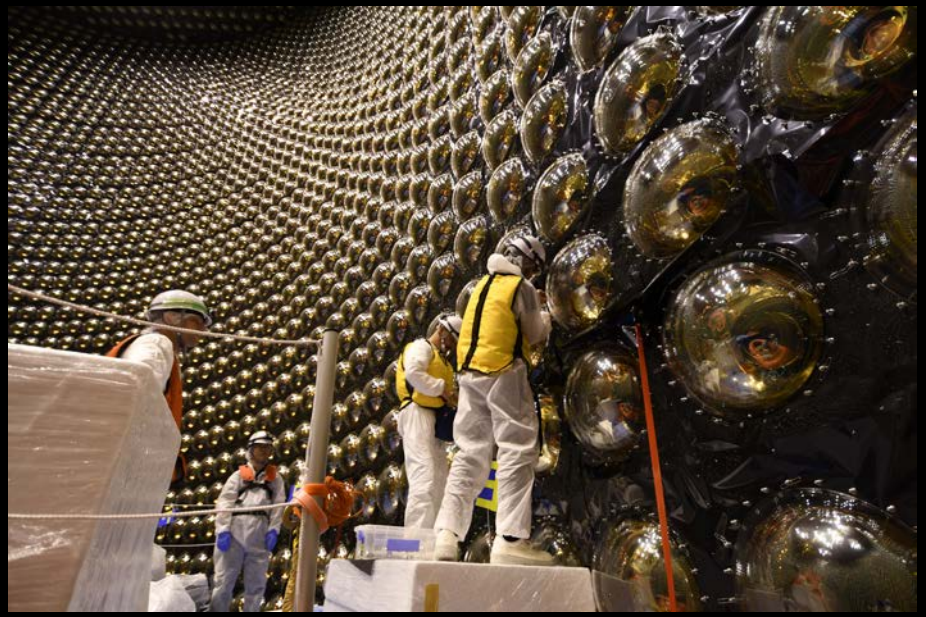


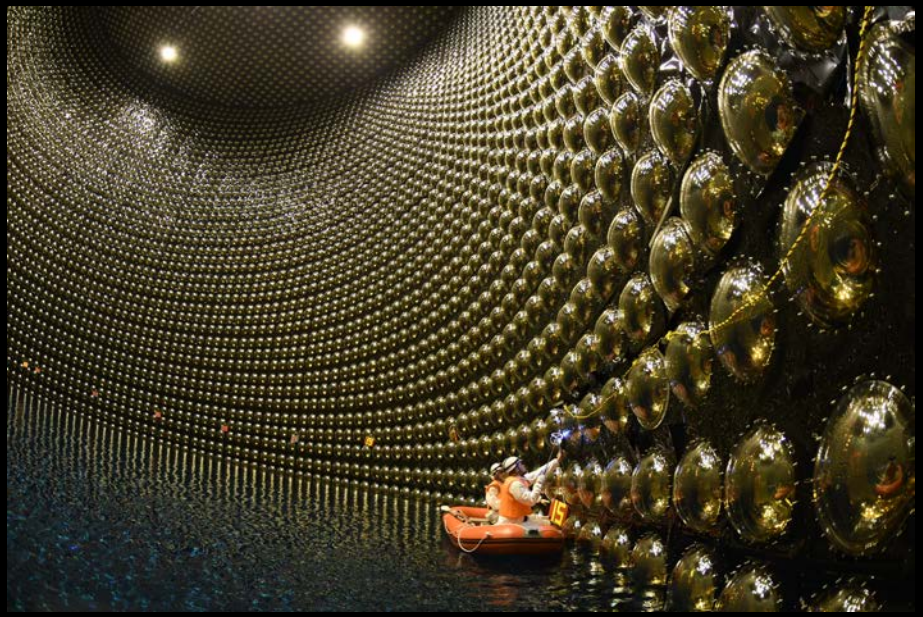
Walls, structure & floor cleaned

Damaged parts recovered

Special care of not leaving any pieces/tools behind

Super-Kamiokande ID PMT refurbishment

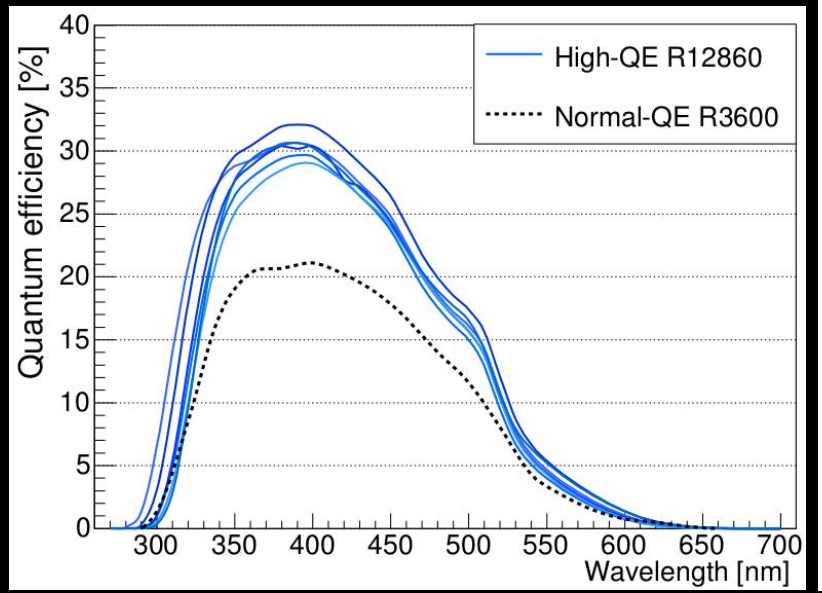


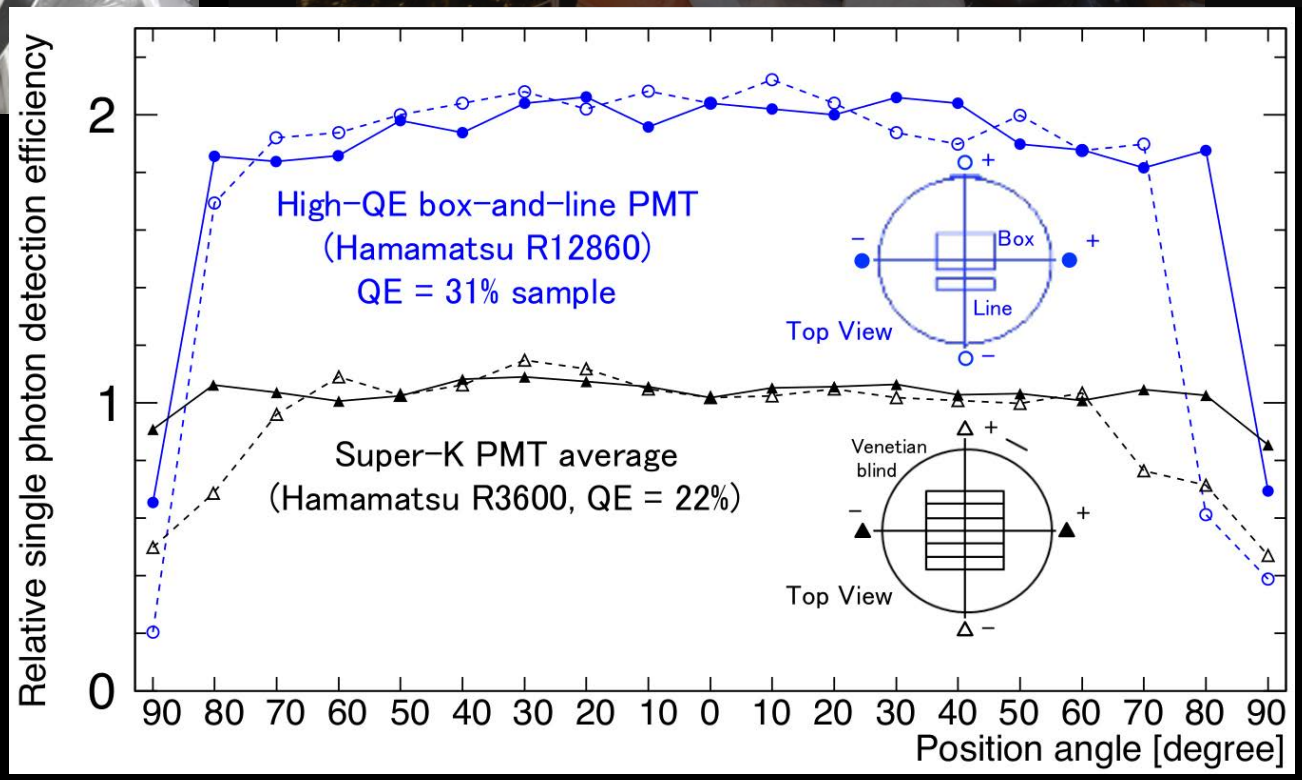


~ 140 ID PMTs replaced or connections checked/redone.

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)

Super-Kamiokande OD PMT refurbishment

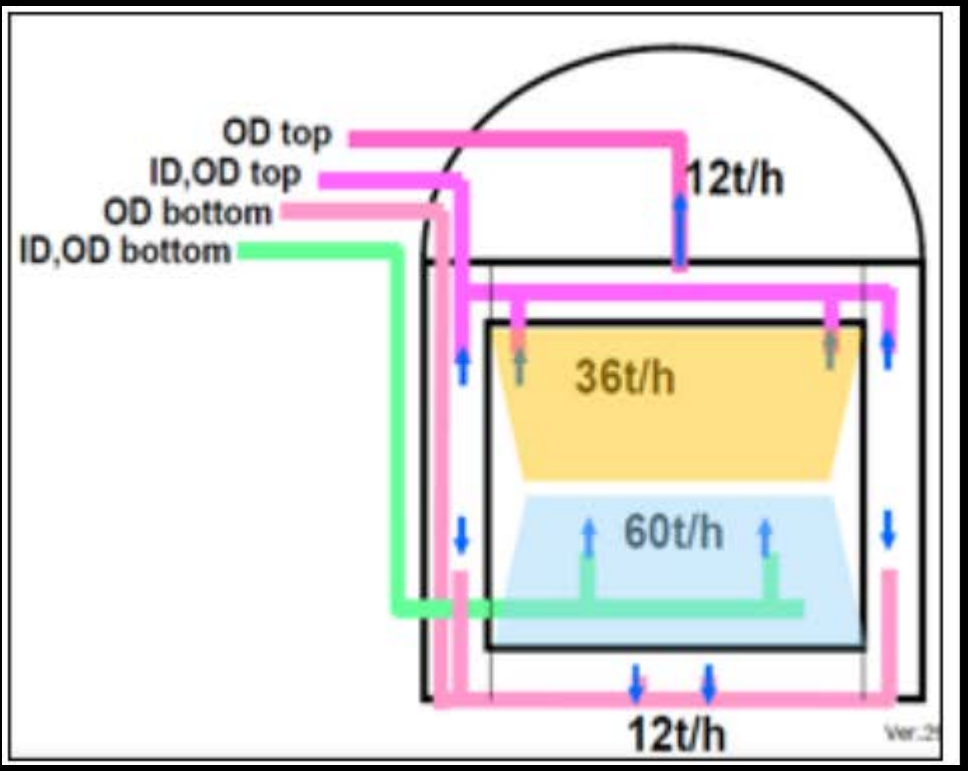
~200 OD PMTs are replaced (~100 on the top)

Super-Kamiokande Tyvek refurbishment

B-W and W-W Tyvek replacement

Super-Kamiokande upgrade

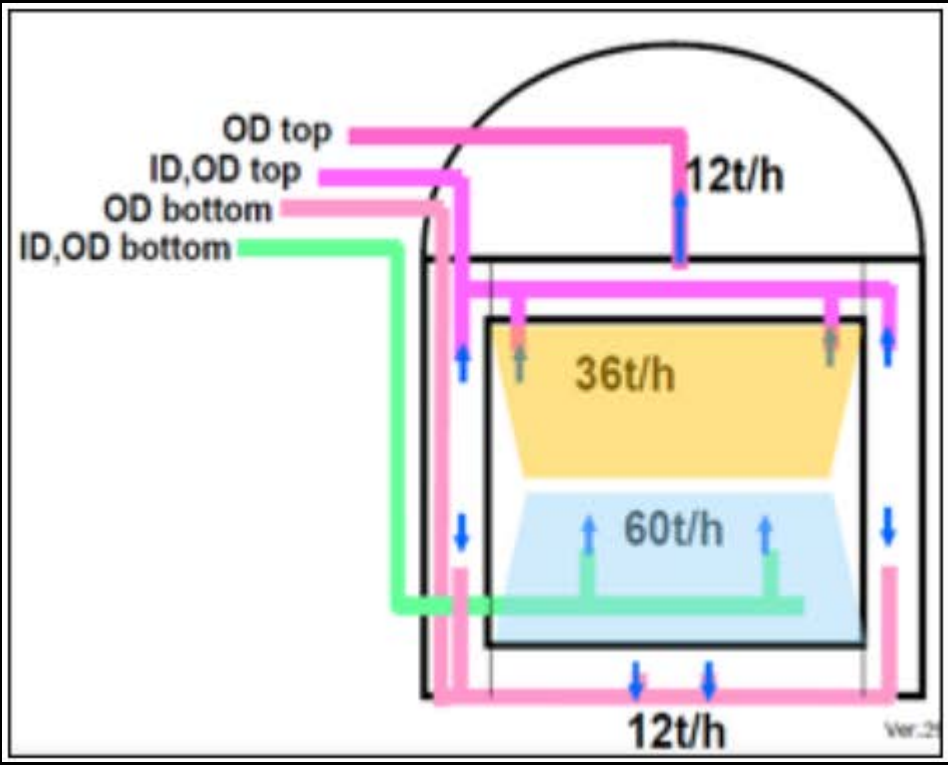
Old piping scheme (until SK-IV)



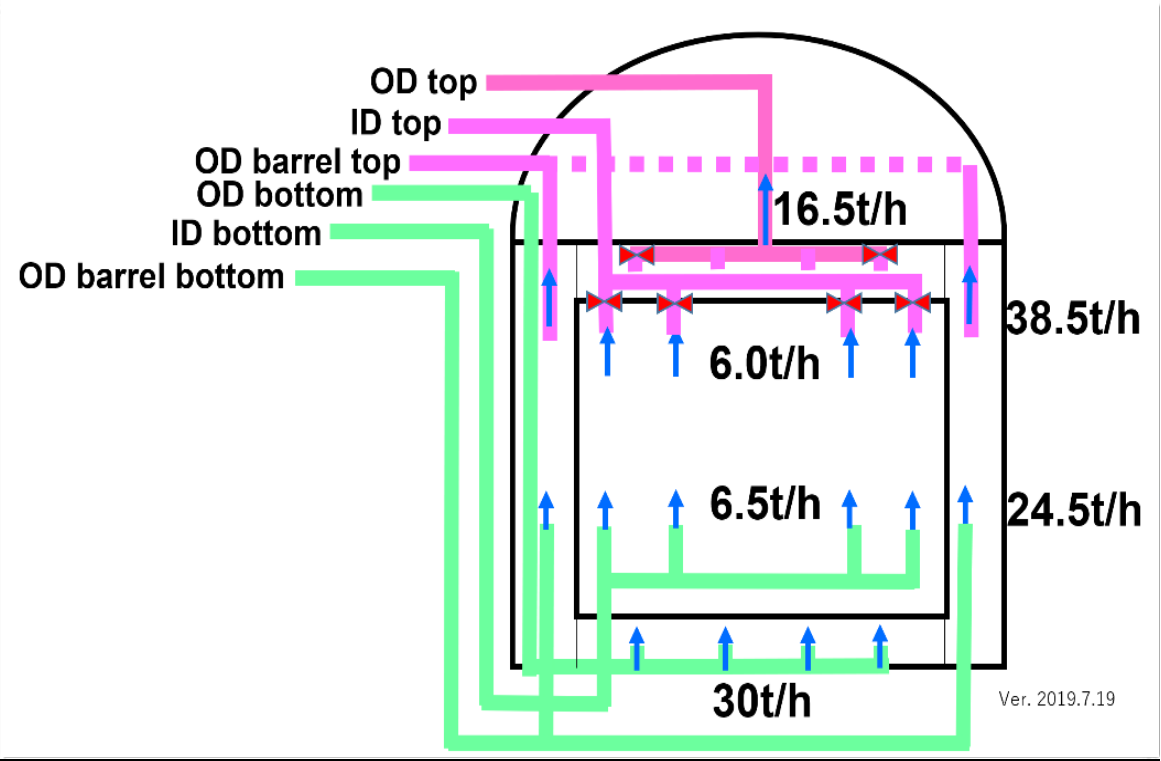
60 tons/h cleaning power
No control on OD flux
No control on individual valves

Super-Kamiokande upgrade

Old piping scheme (until SK-IV)



Current flow (SK-V)

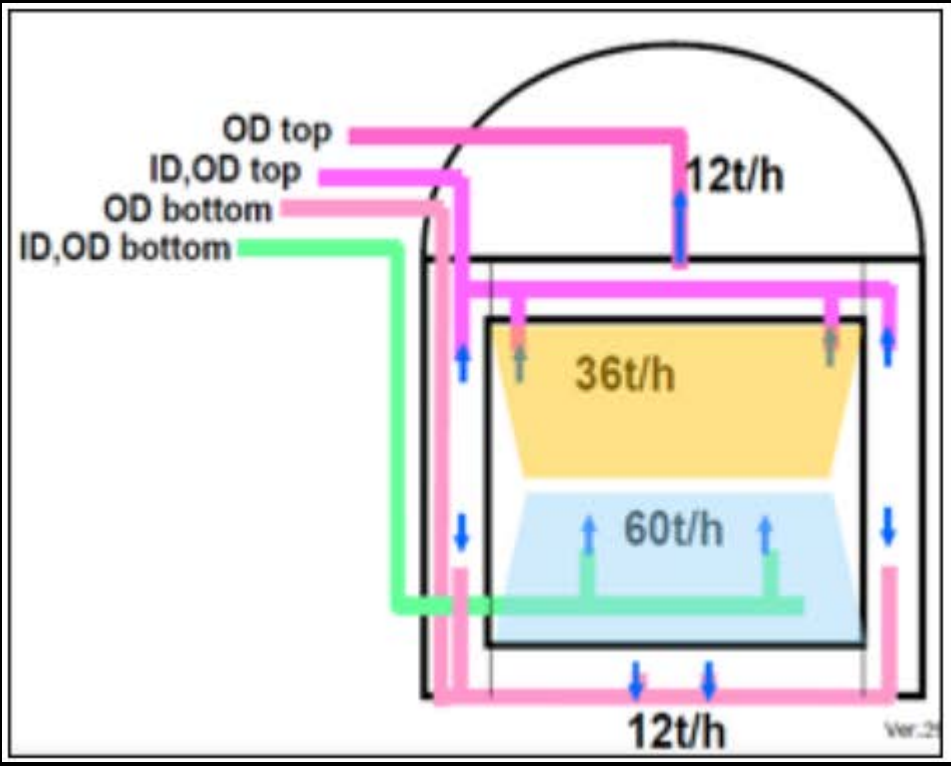


60 tons/h cleaning power
No control on OD flux
No control on individual valves

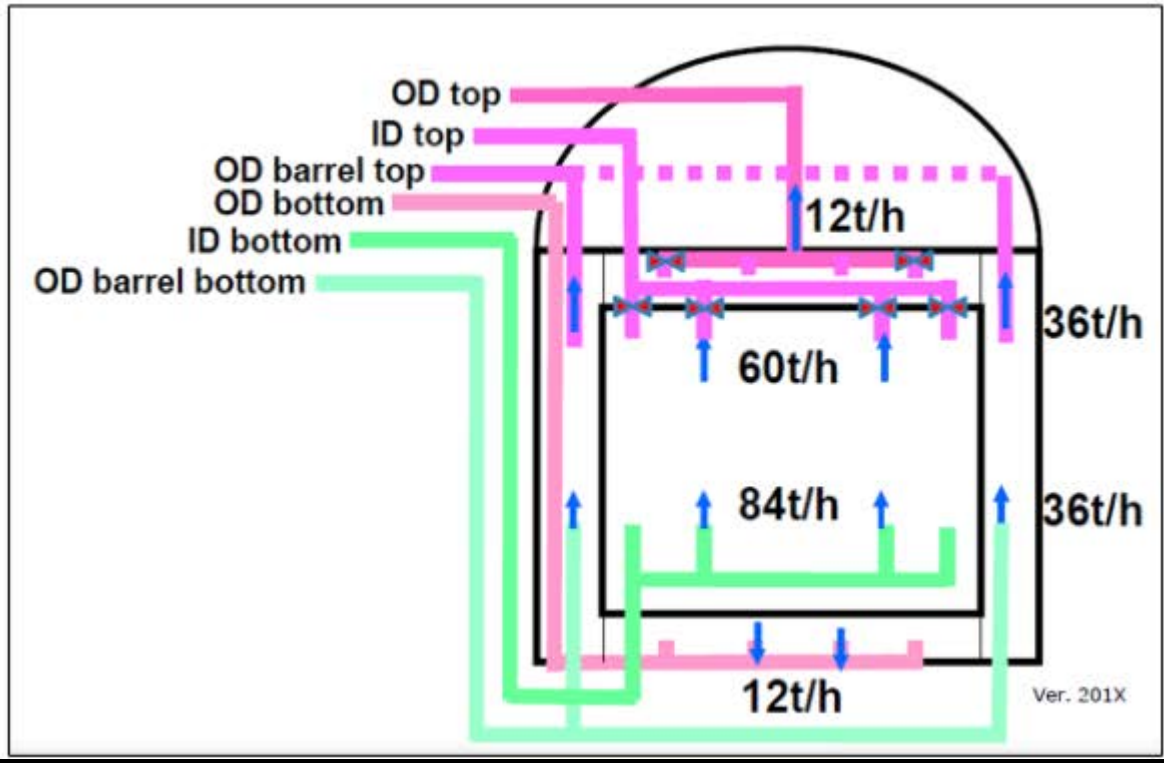
OD/ID independent flux + top&bottom independent flux in the outer

Super-Kamiokande upgrade

Old piping scheme (until SK-IV)



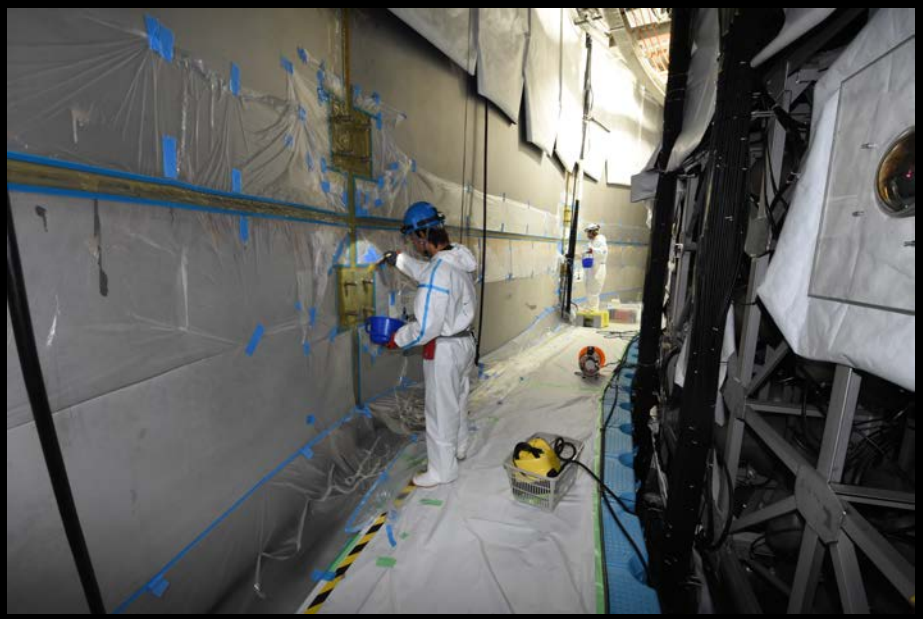
Approximate flow for SK-Gd



60 tons/h cleaning power
No control on OD flux
No control on individual valves

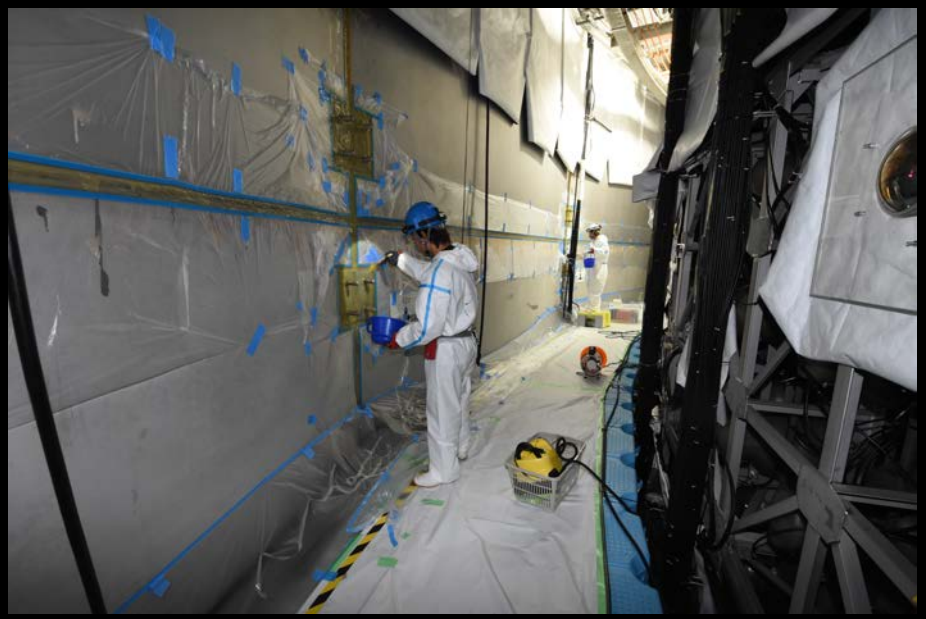
Increased cleaning power to 120 ton/h
OD/ID independent flux + top&bottom independent flux in the outer

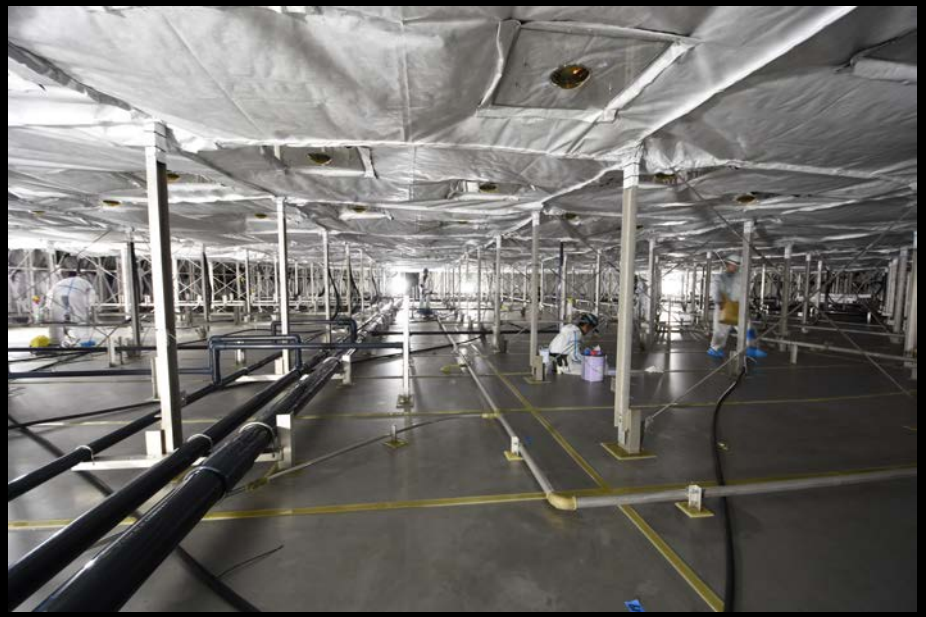
Super-Kamiokande refurbishment



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.





First steps in SK-Gd: timeline

Preparation of Gd sulfate and water system until end of 2019
Running with new water system from end 2019
Gd sulfate dissolution by March 2020
Commissioning (3 months and calibrations ~2-3 months)

Summary

Neutron tagging can be used in basically all analyses at SK and adding 0.2% of Gd sulfate will give us this capability

EGADS has shown it is feasible: we can remove impurities and maintain high transparency water, with basically no Gd losses, etc.

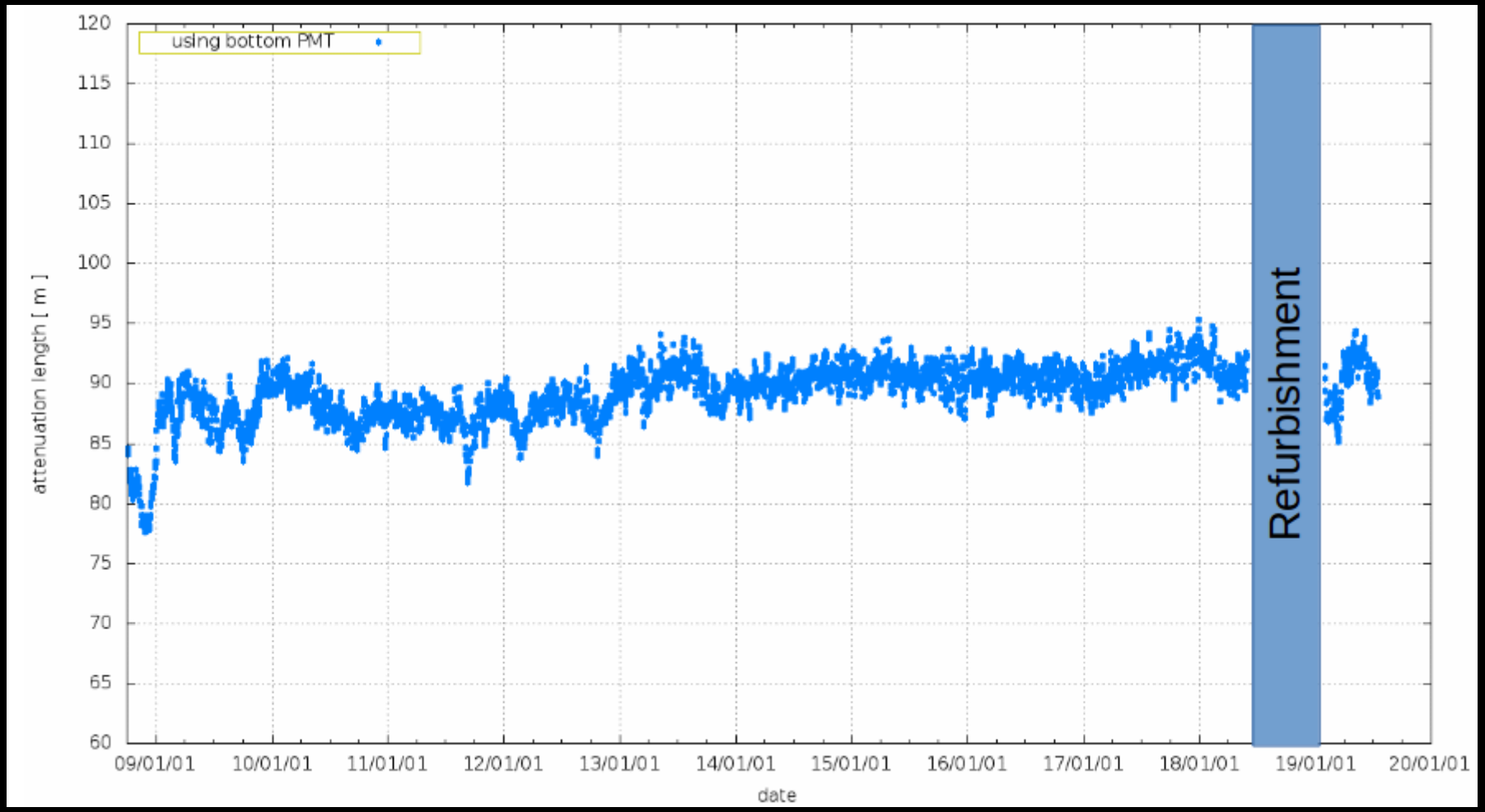
Refurbishment work at SK done:

- Detector structure and walls were refurbished
- Faulty OD and ID PMTs replaced.
- Water leak currently undetectable
- Piping upgraded

Preparing for the first Gd loading until end of this year and dissolving in early 2020.

<u>Exciting physics days ahead with neutron tagging at SuperK-Gd</u> !!

Super-Kamiokande water transparency

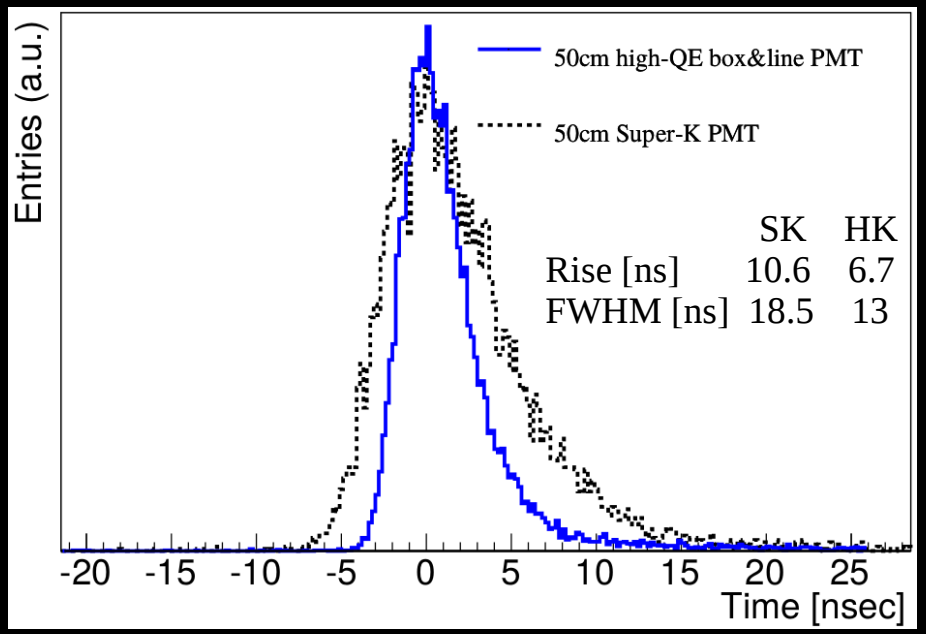


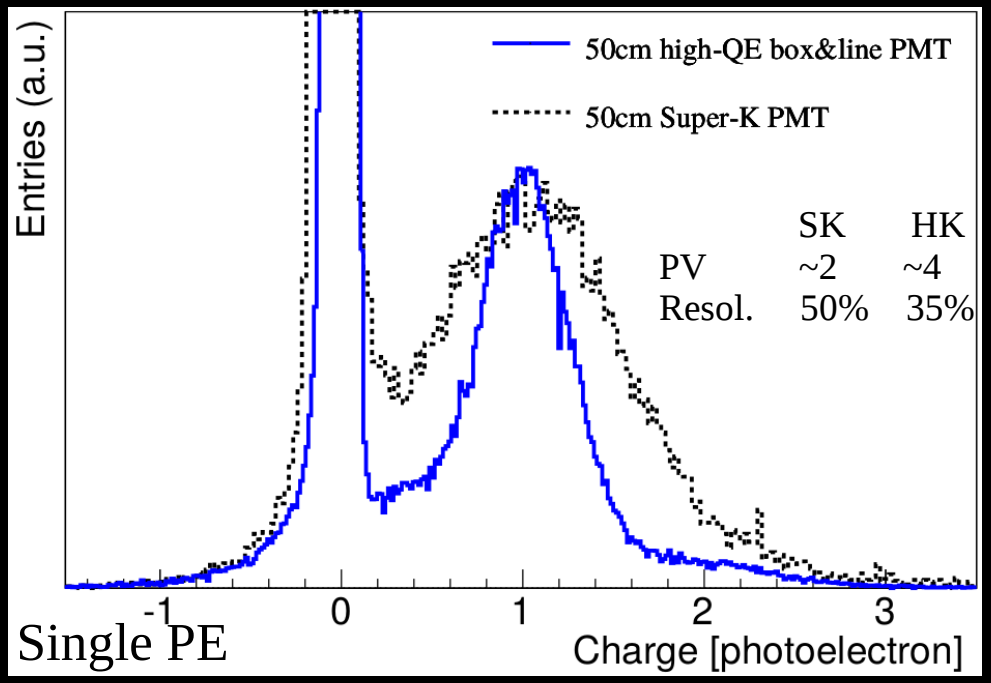
Careful work and early water cleaning allowed for a fast water transparency recovery after refurbishment.

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

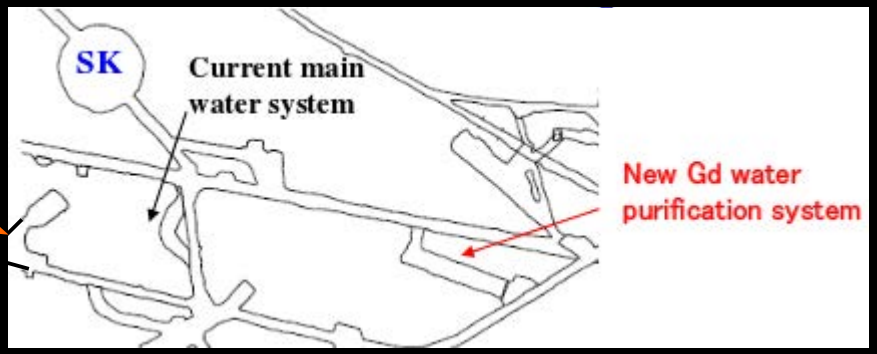
50-cm HQE B&L R12860





New Water System for SuperK-Gd

EGADS



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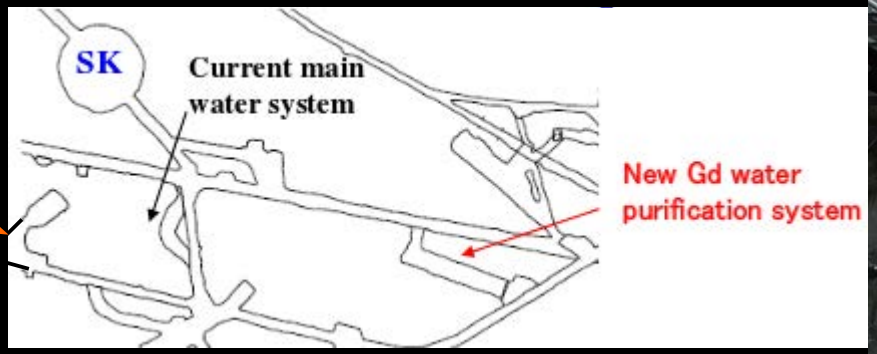
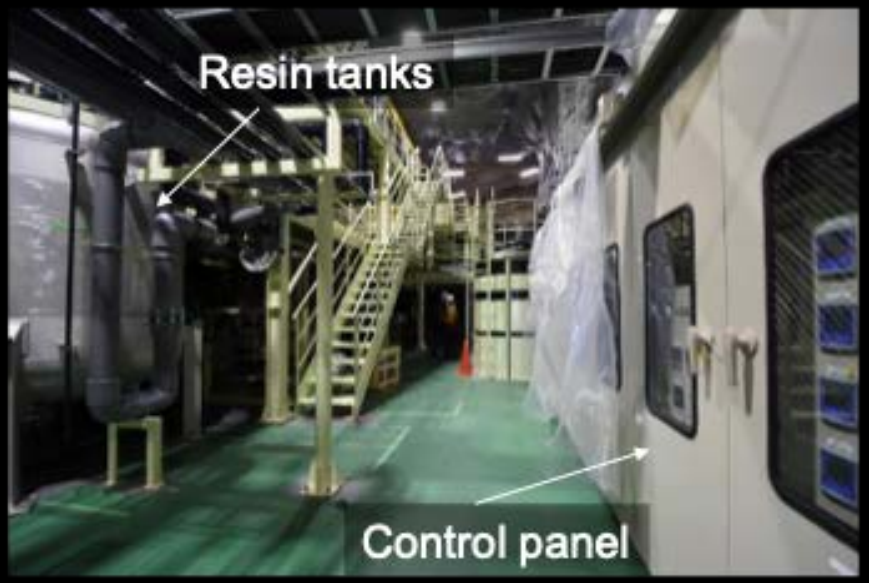


Cavern for the new water system has been excavated

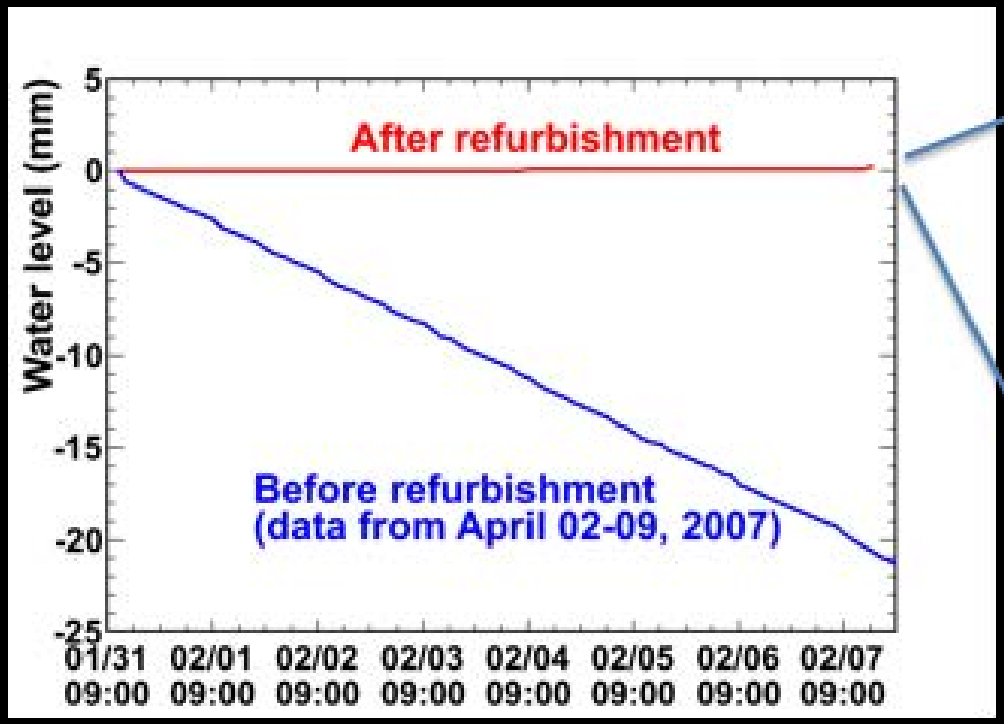
Equipment has been already installed (Gd solution, etc)

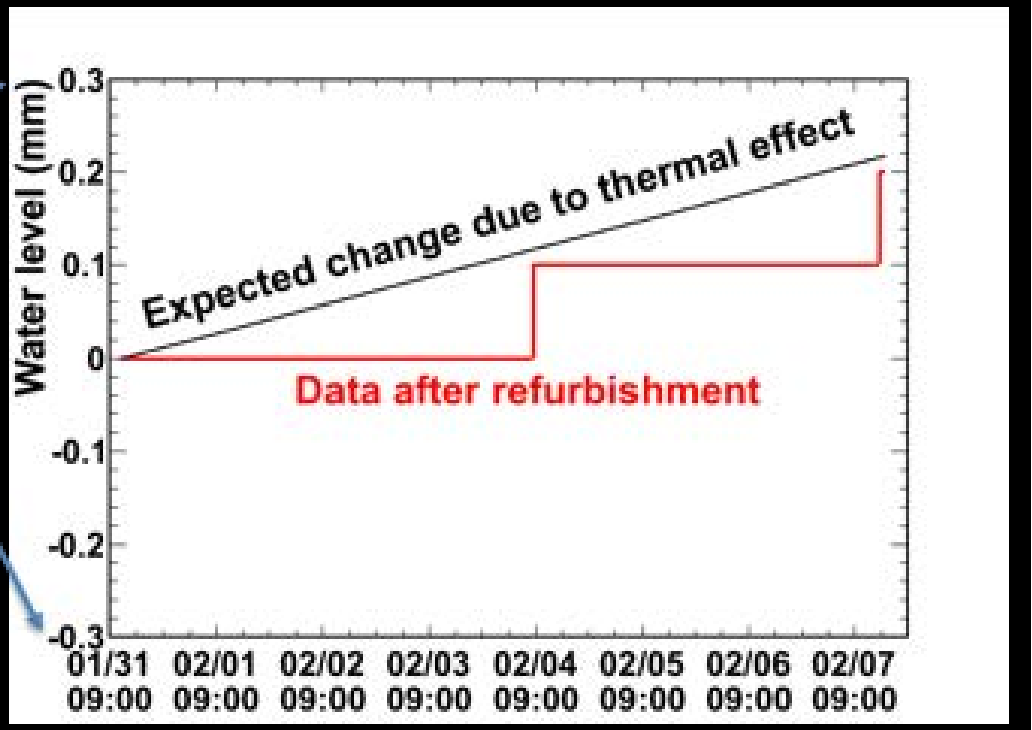
New Water System for SuperK-Gd



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.

Backgrounds

Relevant radioactive contamination, typical impurities in untreated Gd sulfate and our requirements from our physics goals:

Chain	Part of the chain	Typical (mBq/Kg)	SRN (mBq/Kg)	Solar (mBq/Kg)
^{238}U	^{238}U	50	< 5	-
	^{226}Ra	5	-	< 0.5
^{232}Th	^{232}Th	10	-	< 0.05
	^{228}Th	100	-	< 0.05
^{235}U	^{235}U	32	-	< 3
	$^{227}Ac/^{227}Th$	300	-	< 3

Backgrounds

Relevant radioactive contamination, typical impurities in untreated Gd sulfate and our requirements from our physics goals:

Chain	Part of the chain	Typical (mBq/Kg)	SRN (mBq/Kg)	Solar (mBq/Kg)	Company A	Company B	Company C
^{238}U	^{238}U	50	< 5	-	< 0.04	< 0.04	< 0.04
	^{226}Ra	5	-	< 0.5	< 0.2	< 0.2	~ 1
^{232}Th	^{232}Th	10	-	< 0.05	0.02	0.06	0.09
	^{228}Th	100	-	< 0.05	< 0.3	< 0.26	~ 2
^{235}U	^{235}U	32	-	< 3	< 0.4	< 0.3	< 1.3
	$^{227}Ac/^{227}Th$	300	-	< 3	< 1.5	< 1.2	< 3.1

We plan to use resins AJ4400 and AJ1020 to further remove U and Ra after dissolving Gd sulfate

Measurements done at Canfranc, Boulby and Kamioka
Company names hidden

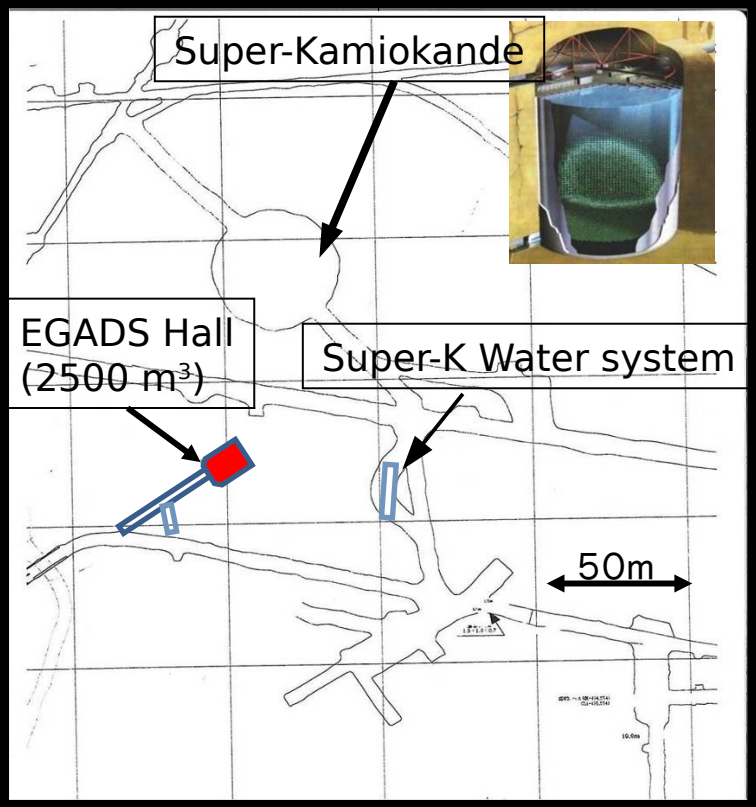
The road to SuperK-Gd: EGADS

Because of all the exciting possibilities, in June 2009 the SuperK collaboration launched the EGADS project

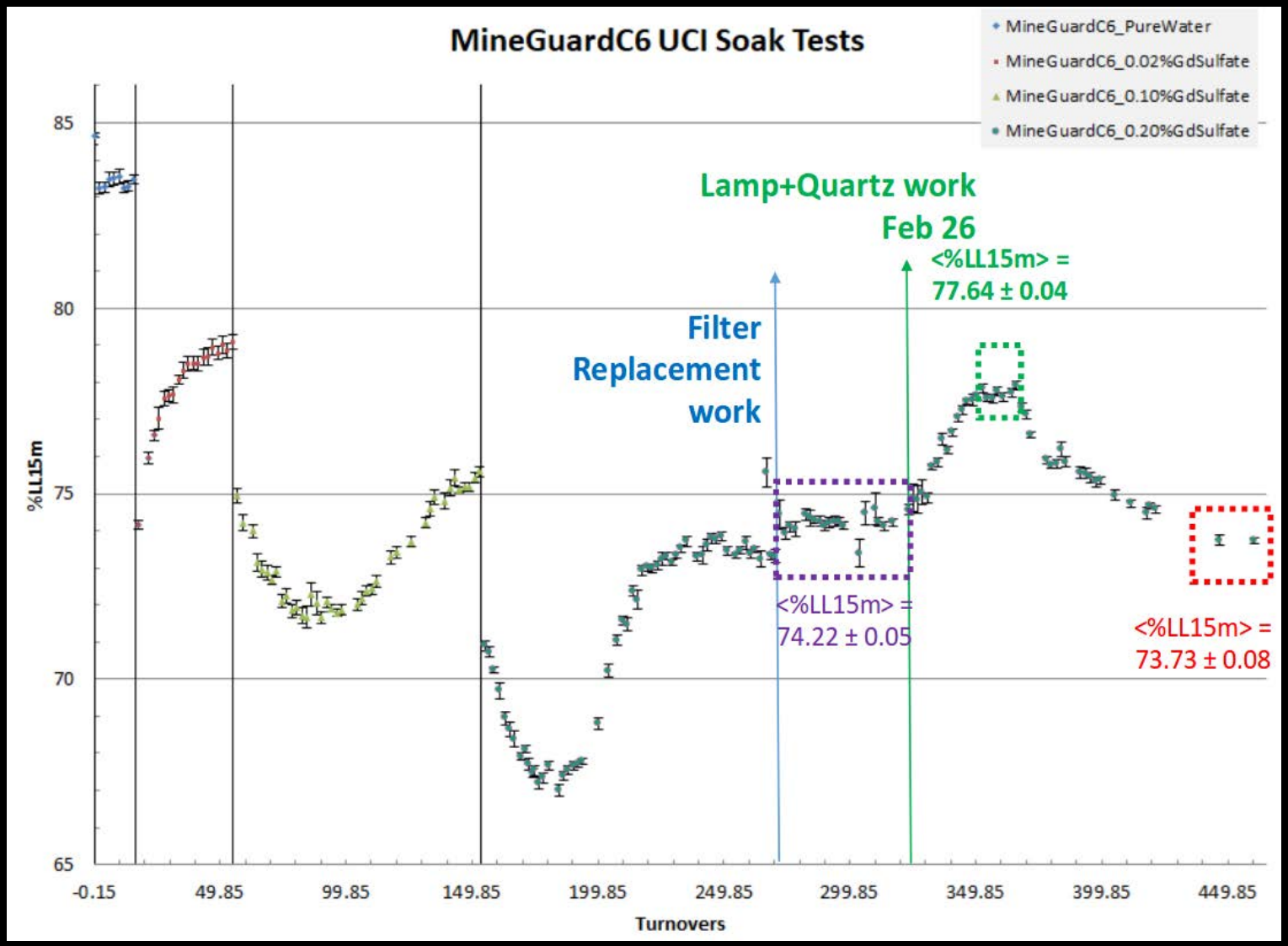
Evaluating **G**adolinium's **A**ction on **D**etector **S**ystems

Our Goals:

- ✔ Water purification system
- ✔ Monitor the water transparency
- ✔ Effects on detector components
- ✔ Adding/removing Gd
- ✔ Neutron background



Mine-guard-C soak tests



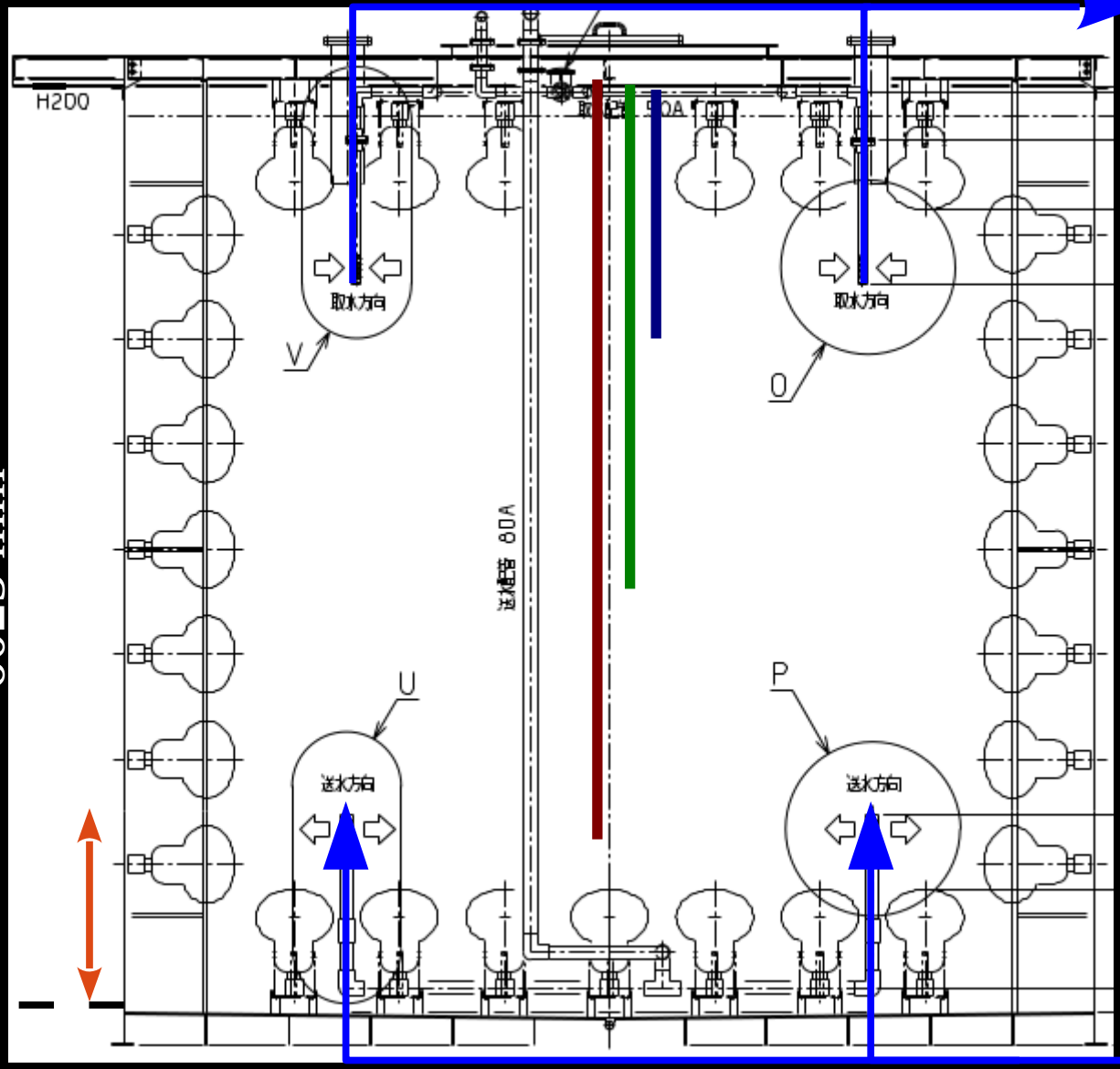
Soaked Mine-guard-C in Gd loaded water with good results: Cherenkov ilght loss in 15 m is 77.64 % (well within the typical SK-III SK-IV values)

EGADS detector

Sampling positions at 1660 mm, 3320 mm and 4990 mm from top of the tank (for water transparency, UDEAL, and Gd concentration measurements)

240 PMTs were installed in summer 2013

6025 mm



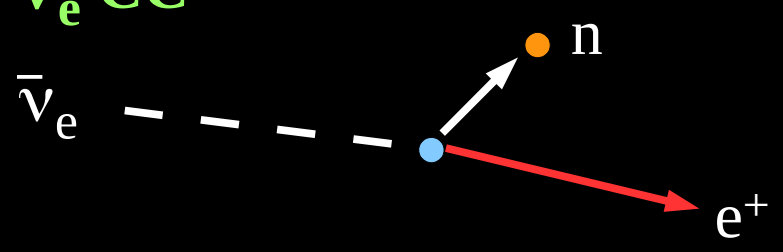
to water system

from water system

Atmospheric ν backgrounds

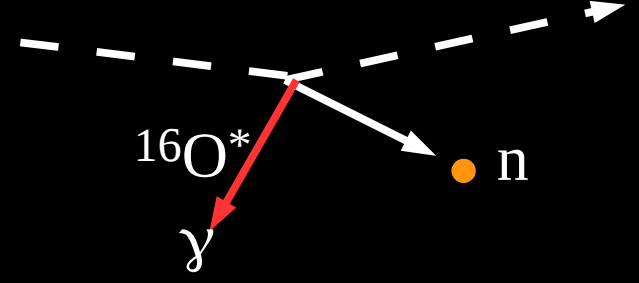
- **Charge Current:**

$\bar{\nu}_e$ CC

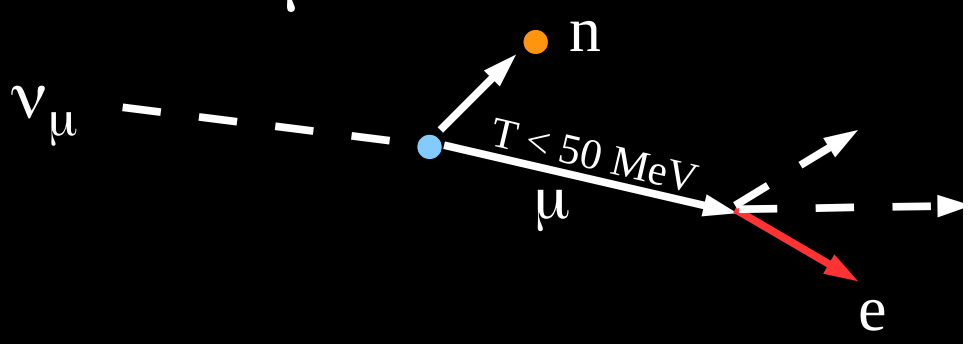


- **Neutral Current:**

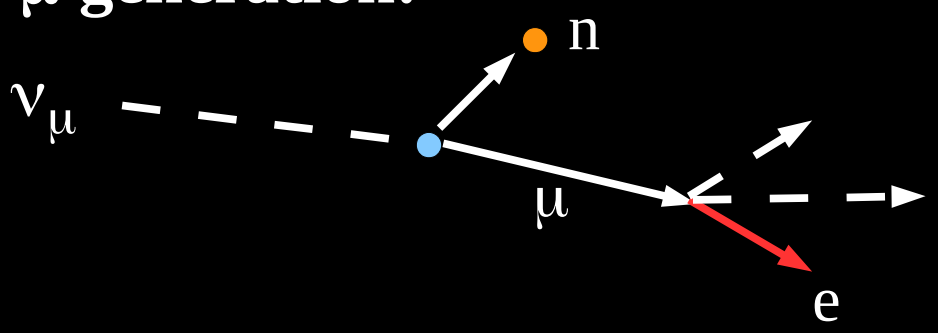
NC elastic

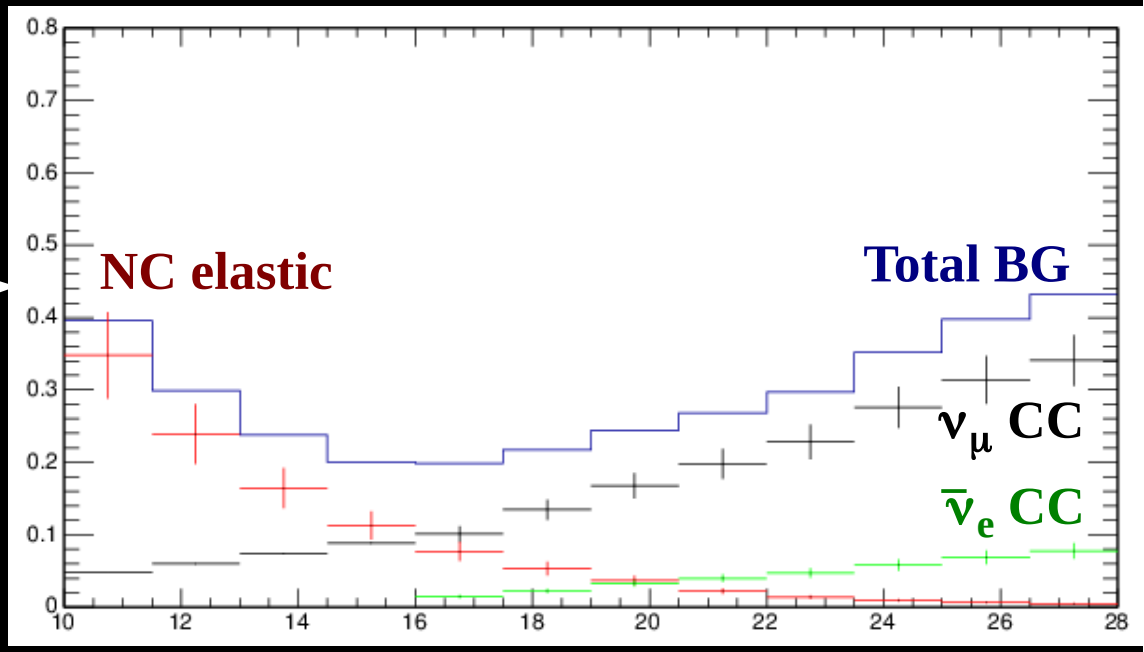


Invisible μ:



μ generation:





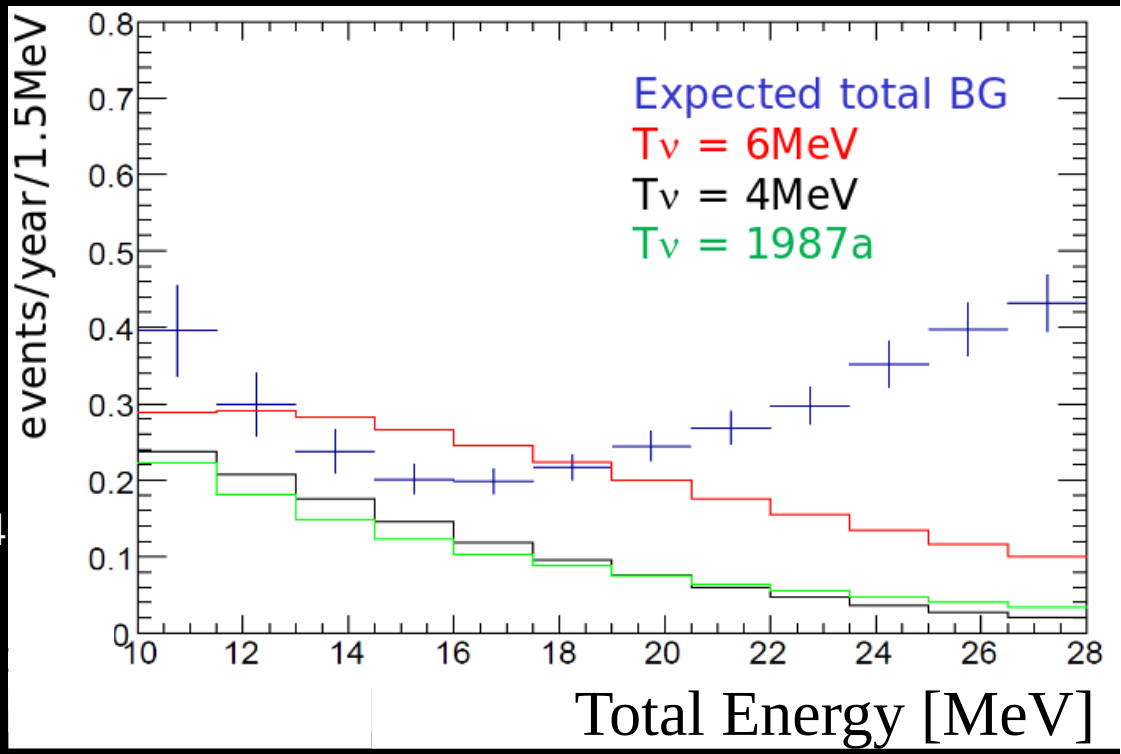
Total Energy [MeV]

Background vs expected signal

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

The detection of SRN depends on the typical SN emission spectrum

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

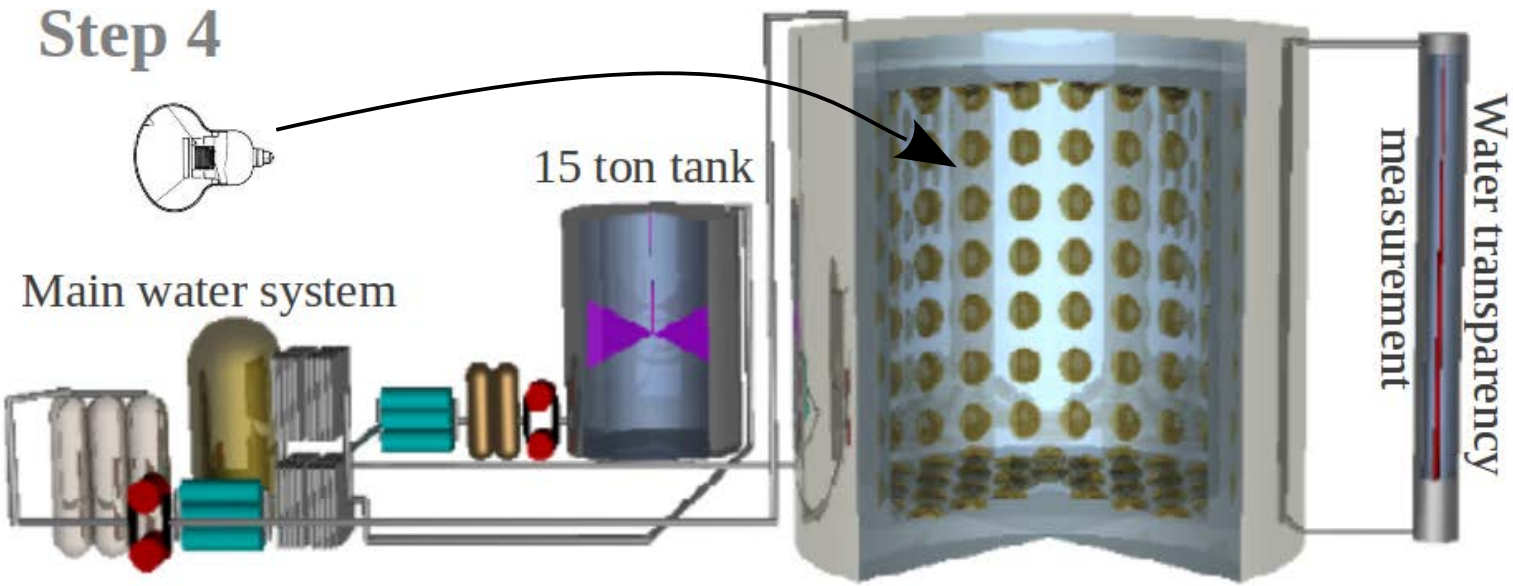


SRN number of expected events after 10 years of observation

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!!

Step 4: EGADS Detector



- **Step 1:** Circulation through the 200 ton tank with pure water (first half 2011 pure water circulation) **Done!**
- **Step 2:** Circulation through the 15 ton tank with $Gd_2(SO_4)_3$ (from middle 2011 to end 2012) **Done!**
- **Step 3:** Circulation though the 200 ton tank with $Gd_2(SO_4)_3$ **Done!**
- **Step 4:** PMT mounting (240 in total). **Done!**
- **Step 5:** Full realization of the EGADS project **Done!**