(Super→Hyper)-Kamiokande Gd

What factors at SK-Gd will determine whether or not we get HK-Gd

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Oct 29, 2020

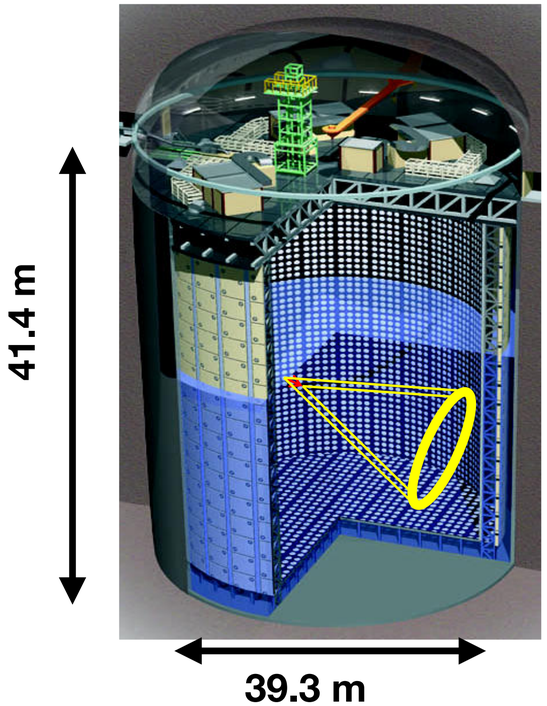
Snowmass2020 NF01 Topical Workshop No. 6

Contents

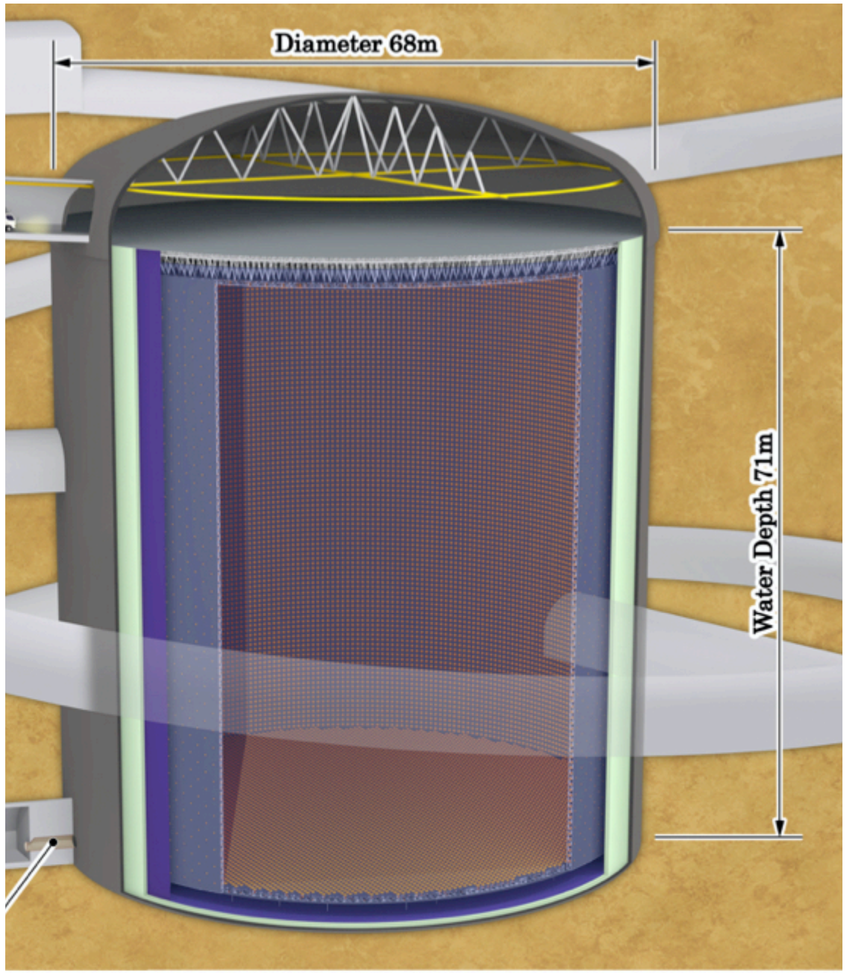
- Status of SK-Gd
- Motivation for HK-Gd
- Things need to be checked for HK-Gd
- Input from SK-Gd

Super-Kamiokande and Hyper-Kamiokande

Super-K



Hyper-K



	Super-K	Hyper-K
Fiducial mass	22.5 kton	188 kton
Overburden	~1000 m	~650 m
Number of inner-detector PMTs	11000	40000
Photo-coverage	40%	40% (2x sensitivity)
Operation	Pure water: 1996-2020 **Gd-loaded water: 2020-**	**Start in 2027**

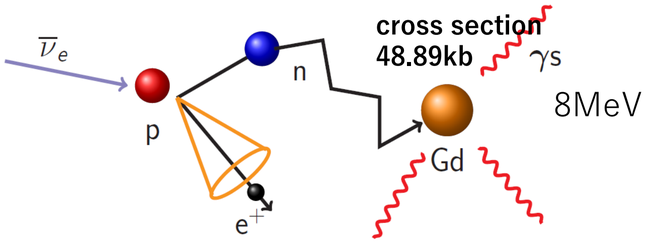
Super-Kamiokande Gadolinium Project (SK-Gd)

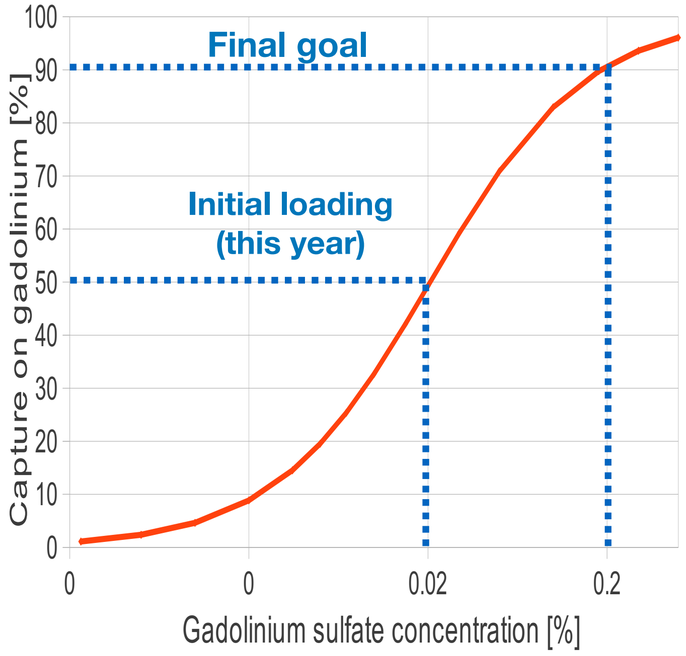
- Dissolving Gd to Super-Kamiokande to significantly enhance detection capability of neutrons from ν interactions

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

- Aiming for the **first observation of Diffuse Supernova Neutrino Backgrounds**
- Also aiming for:
  - Improving pointing accuracy for galactic supernova
  - Precursor of nearby supernova by Si-burning neutrinos
  - Reducing proton decay background
  - Neutrino/anti-neutrino discrimination (Long-baseline and atmospheric neutrinos)
  - Reactor neutrino measurements
- Final goal: 0.2% $Gd_2(SO_4)_3$ with 90% capture efficiency
- As the first step, loaded 0.02% of $Gd_2(SO_4)_3$ in 2020

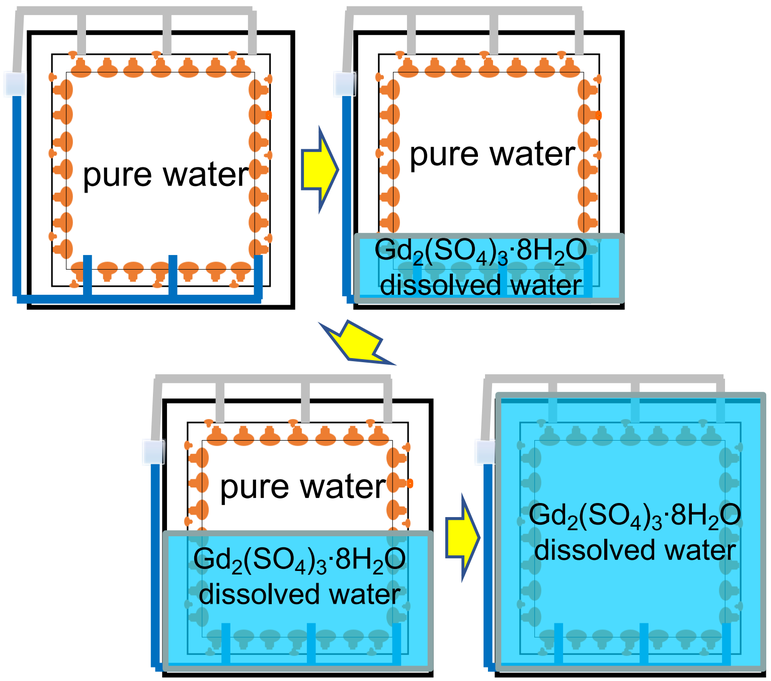
~50% n-capture on Gd

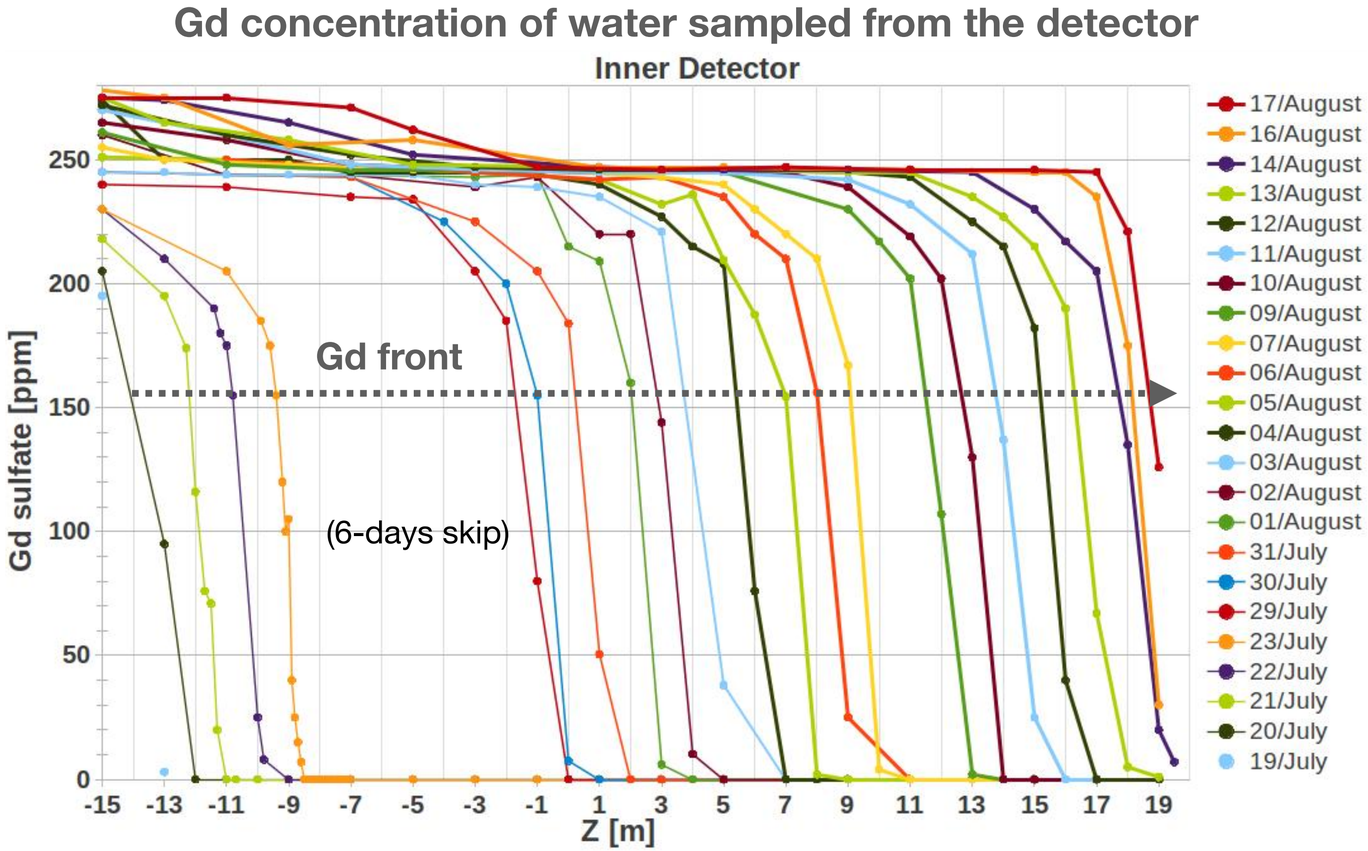




Gd loading

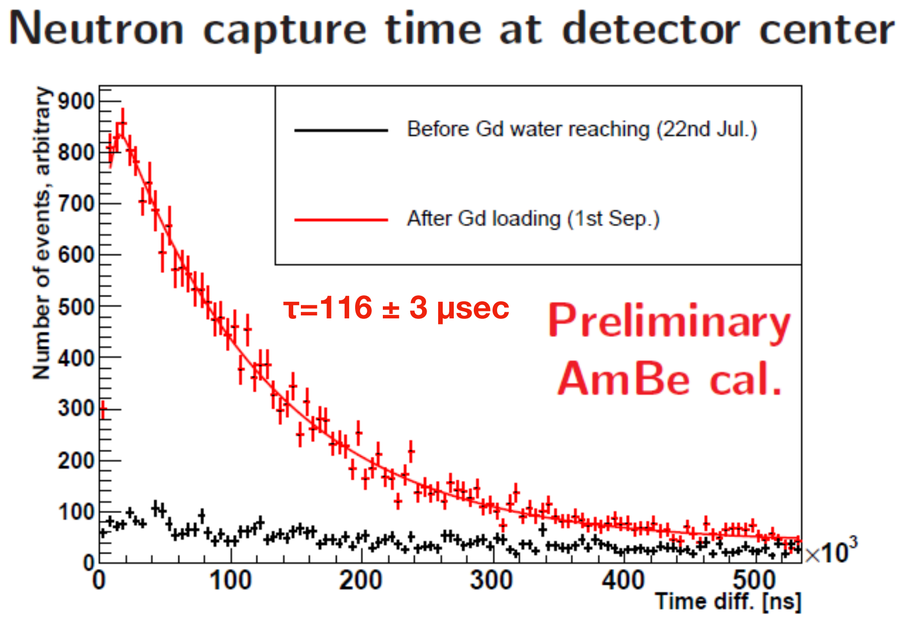
- Super-K successfully loaded 13 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ (5 tons of Gd)
- Loading done from July 14 through August 17, 2020
- Smooth injection from the bottom



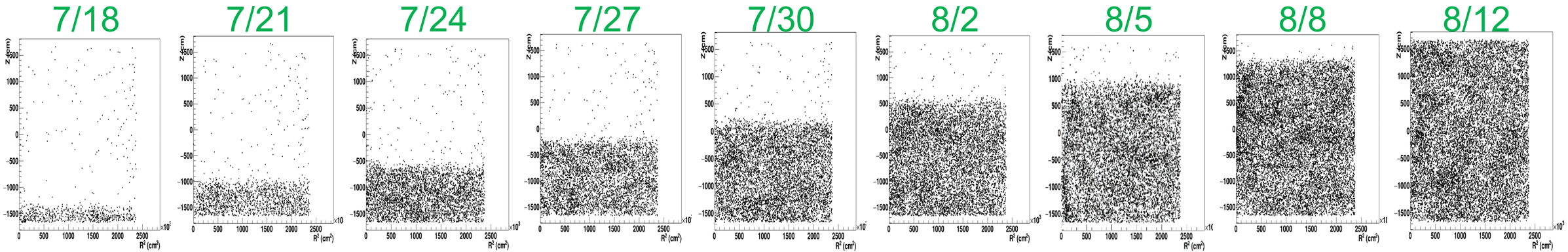


Gd in Super-Kamiokande!

- Successfully observed neutron capture on Gd!
  - AmBe neutron source
  - Neutrons induced by cosmic muons
- Observed capture time constant consistent with expectation from 0.02% $Gd_2(SO_4)_3$ concentration.
- Spallation neutrons shows movement of Gd-loaded water in the detector

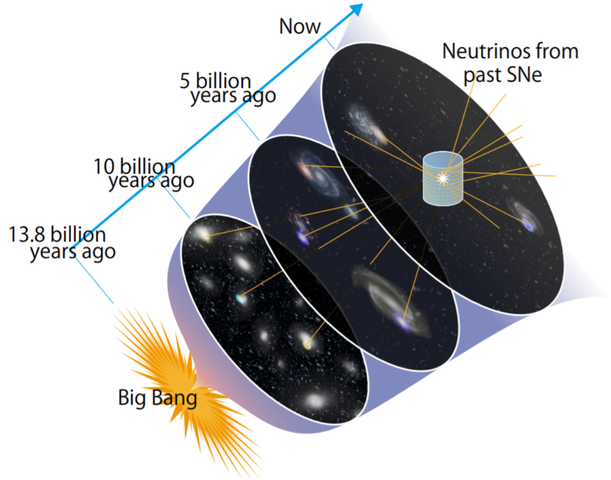


Vertex distribution of spallation neutron Gd(n,γ) candidates



Motivations for Gd in Hyper-K

Diffuse Supernova Neutrino Backgrounds (DSNB)



- Neutrinos produced from all the SN bursts and diffused in the current universe.
  ~ a few SN explosions every second

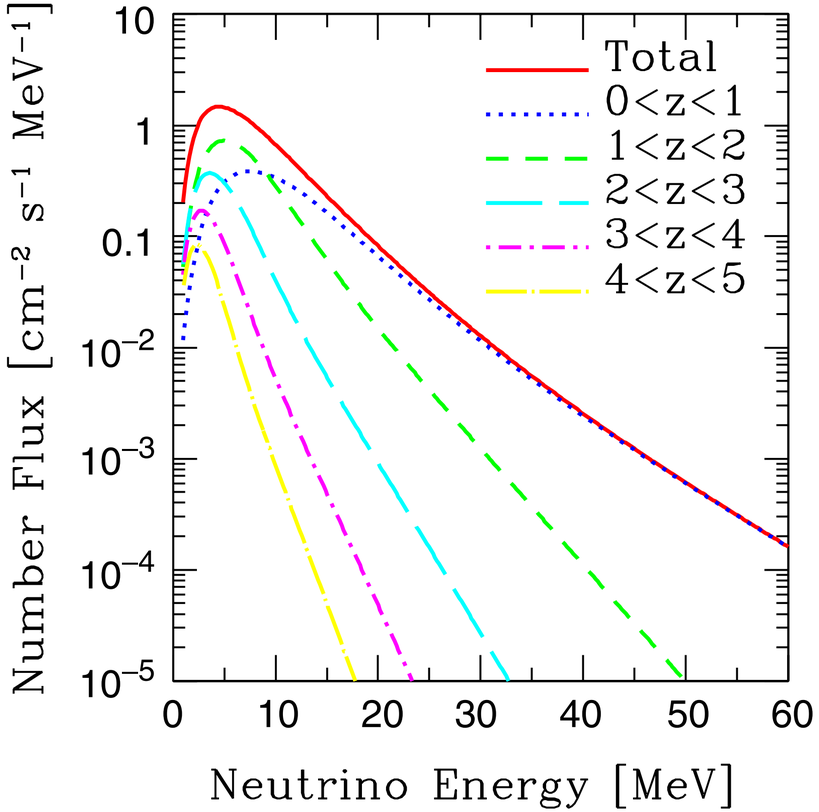
  O(10^{18}) SNe so far in this universe

- Can study history of SN bursts with neutrinos

$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

- Many astrophysics and particle physics implications:
  - Contribution of failed supernova
  - Neutrino oscillation effect in dense medium
  - Galaxy evolution
  - Supernova burst mechanism

S.Ando et al., Astrophys.J.607:20-31,2004



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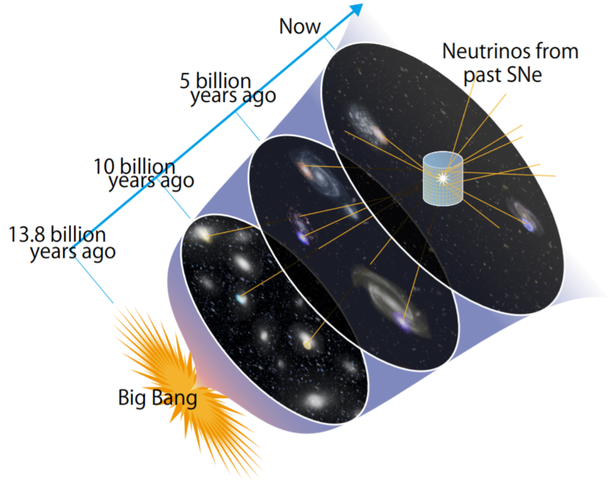

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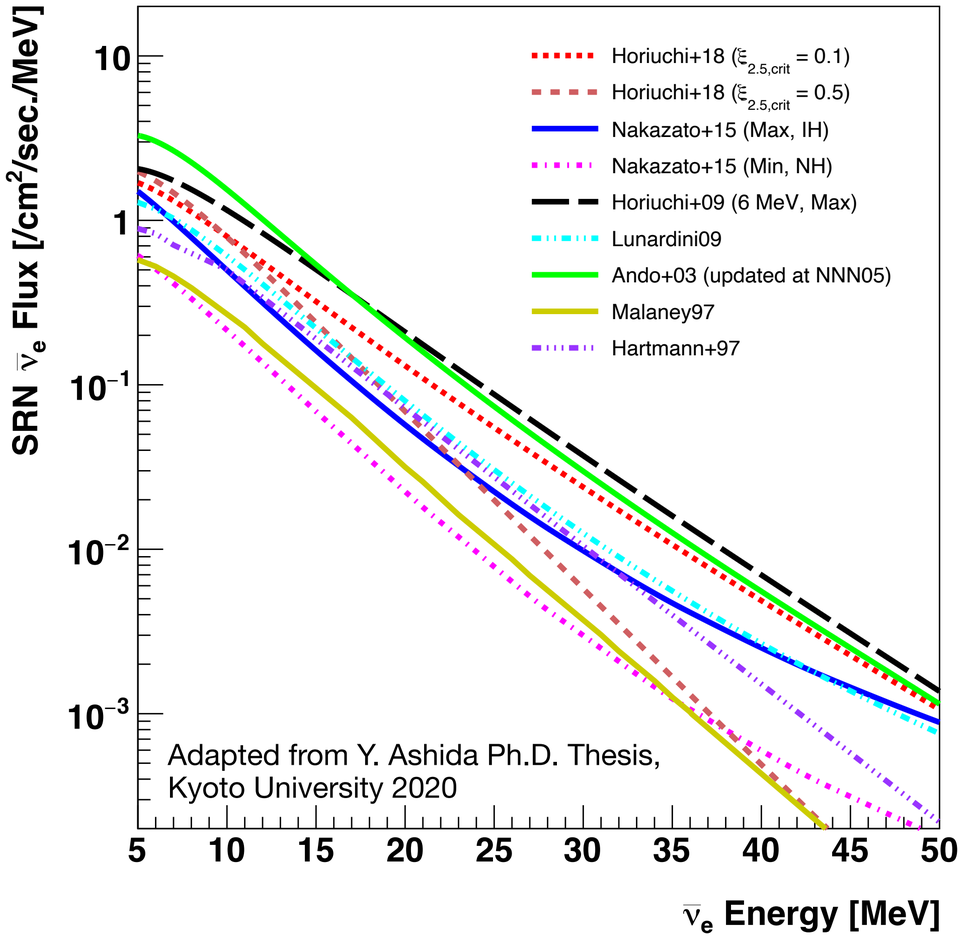
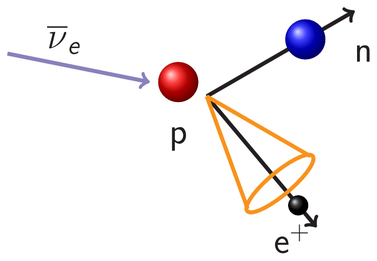


DSNB: Signal and Backgrounds

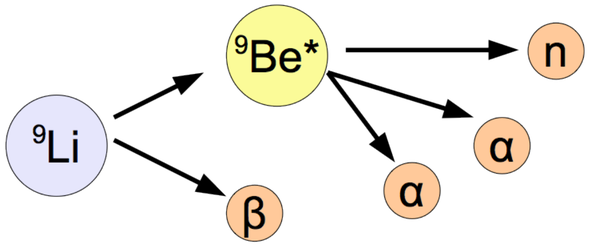
Rare event search: a few tens of interactions / year / HK

- Primary signal: Inverse Beta Decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)

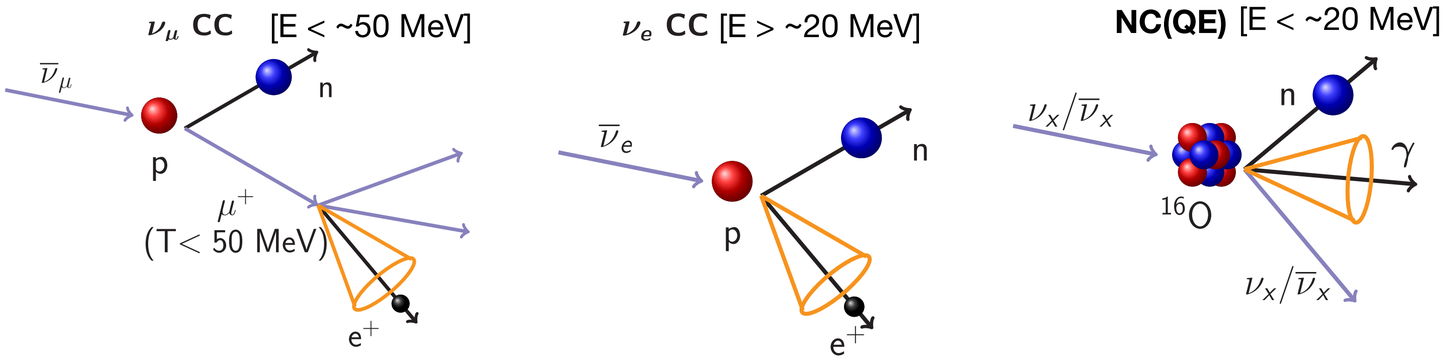


Detecting both position and neutron is the key to reduce backgrounds

- Backgrounds that mimic e^+ + n pair:
  - **^{9}Li (from cosmic μ spallation)** [E < ~15 MeV]



  - **Atmospheric neutrinos**

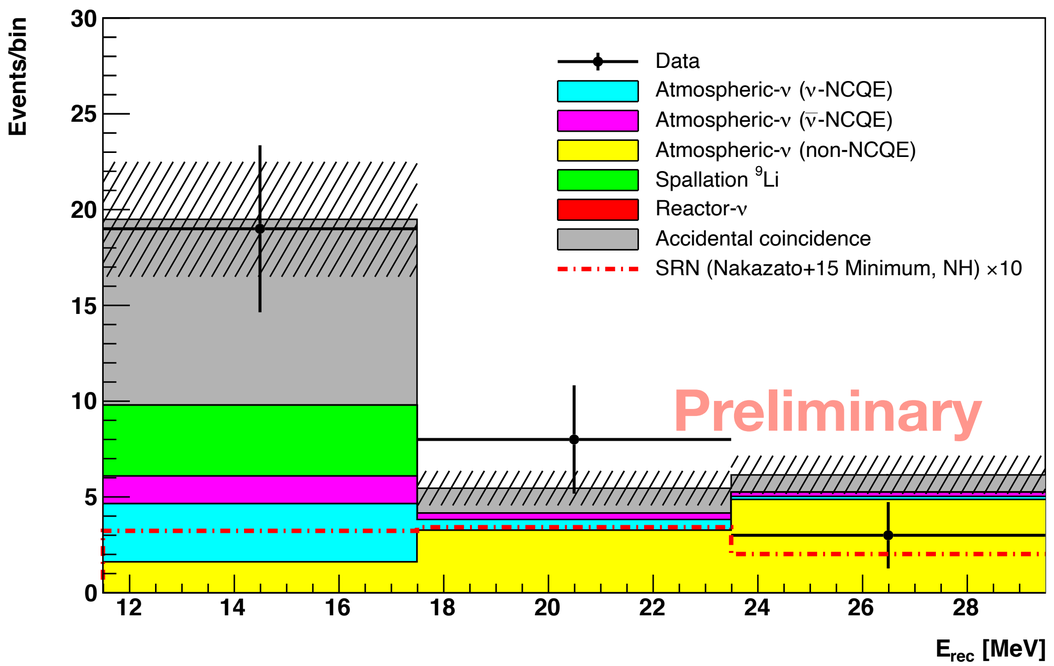


  - **Accidental coincidence (mostly spallation products + fake-neutrons)** [E < ~15 MeV]
  - **Reactor neutrinos** [E < ~10 MeV]

DSNB Search prospects

- Current best limit set by SK (pure water)
  - Limit within factor 2-3 from the most optimistic models.
- SK-Gd:
  - Sensitivity will reach optimistic models in several years
  - Aiming for the first observation of DSNB
- **HK (pure water)**
  - **Search region likely limited to E > 16 MeV due to spallation backgrounds**
  - **Larger atmospheric neutrino backgrounds**
- **HK-Gd:**
  - **Significant reduction of spallation backgrounds at E < 20 MeV**
  - **Measurement of DSNB *spectrum* at E > 10 MeV with 100s of events!**
  - **Study supernova rate down to Z~1**

Super-Kamiokande IV, 2970 days with n-tag (pure water)



Search Results & Integrated SRN Electron Antineutrino Flux [/cm²/sec.]

E_ν region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	**9.48**	**1.35**	**0.82**
SK-IV 2970 days (Observed)	**9.08**	**2.22**	**0.35**
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Ando+03 (updated at NNN05)	2.652	0.796	0.261

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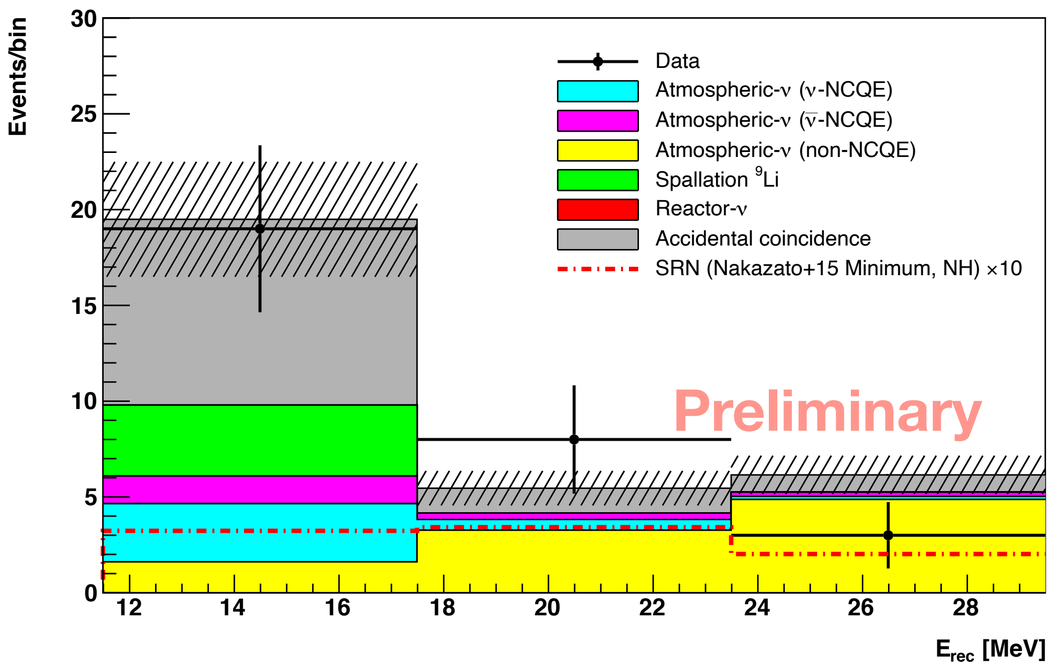
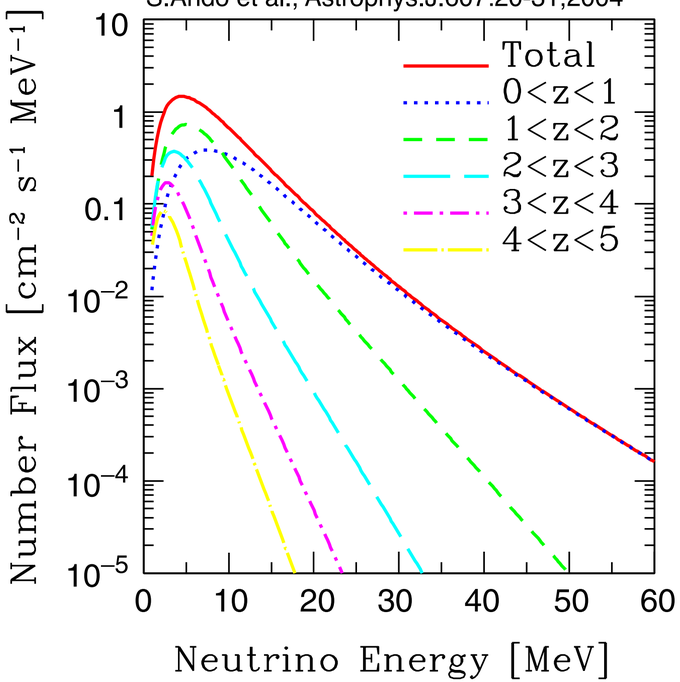


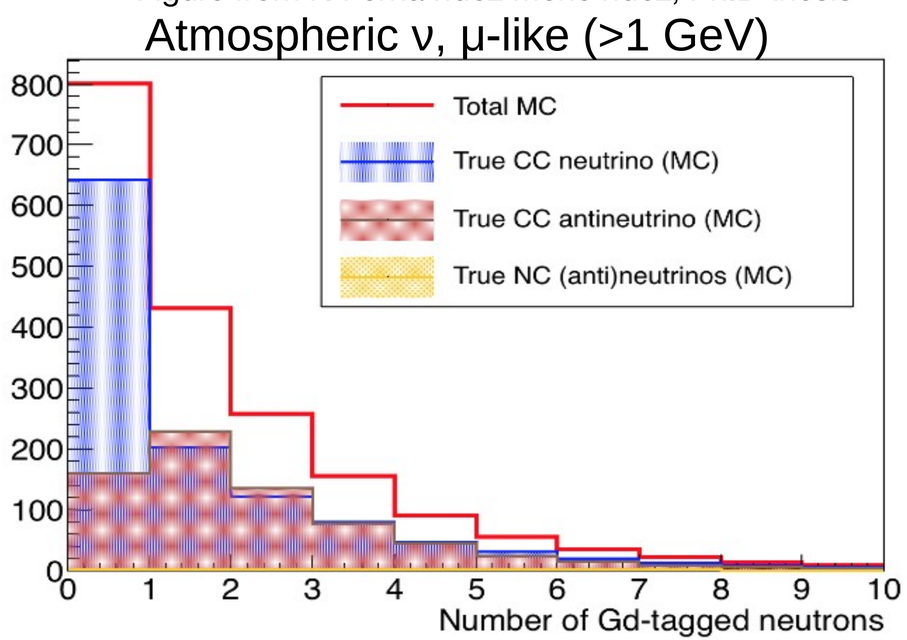
S.Ando et al., Astrophys.J.607:20-31,2004



Improving reconstruction for GeV neutrinos

- Neutron information can also be used to:
  - Separate neutrino and antineutrinos
  - Improve energy reconstruction w/ neutron counting

Figure from P. Ferna´ndez Mene´ndez, Ph.D thesis



Neutron tagging (w/ H) already used for the current atmospheric neutrino oscillation analysis at SK

https://indico.fnal.gov/event/45296/contributions/195925/attachments/134181/165935/wendell_skatm_prospects_202009_upload.pdf

25% tagging eff.

Sample	nue	nuebar	numu (tot)	Tau (tot)	NC
2018 nu-like	0.604	0.088	0.100	0.033	0.156
2018 nubar-like	0.546	0.372	0.009	0.010	0.063
2020 nu-like	0.592	0.086	0.110	0.033	0.159
2020 e-like	0.628	0.281	0.007	0.007	0.057
2020 nubar-like	0.423	0.460	0.010	0.014	0.077

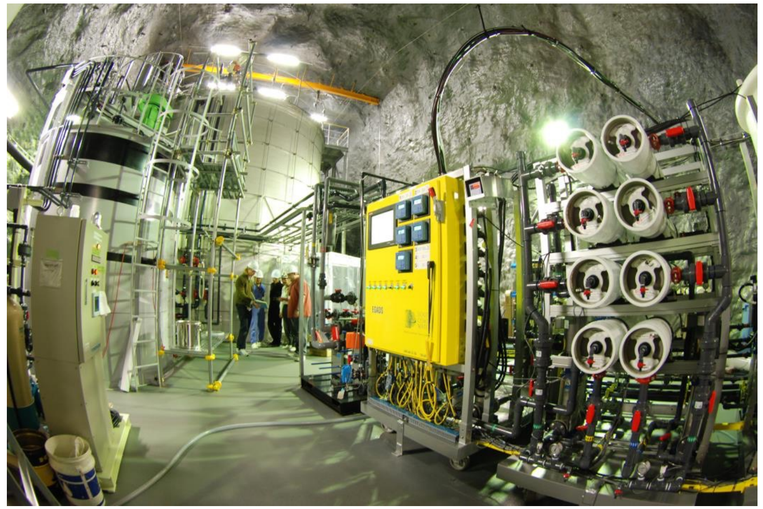
Improved n-tag with Gd further improves CPV, MO, θ_{23} and Δm^2_{32} measurements with long-baseline and atmospheric neutrinos

Checklist for HyperK-Gd

	Check items		Status
Mandatory	**No water leak from the tank**		Design/construction ongoing
To keep physics performance	**Optical property of water**	**Soak test of detector components**	✔ (for SK, ongoing for HK)
		Transparency in the SK tank	*Being studied at SK-Gd*
	RI in water	**Purification of $Gd_2(SO_4)_3$ powder**	✔ (for SK)
		Event rate in the SK tank	*Being studied at SK-Gd*
To make physics case stronger	**Enhancement with neutrons**	**Study/Reduction of backgrounds for DSNB**	*Being studied at SK-Gd*
		Event reconstruction improvements for GeV neutrinos (atm/lbl)	*Being studied at SK-Gd*

Many things depends on studies at SK-Gd!

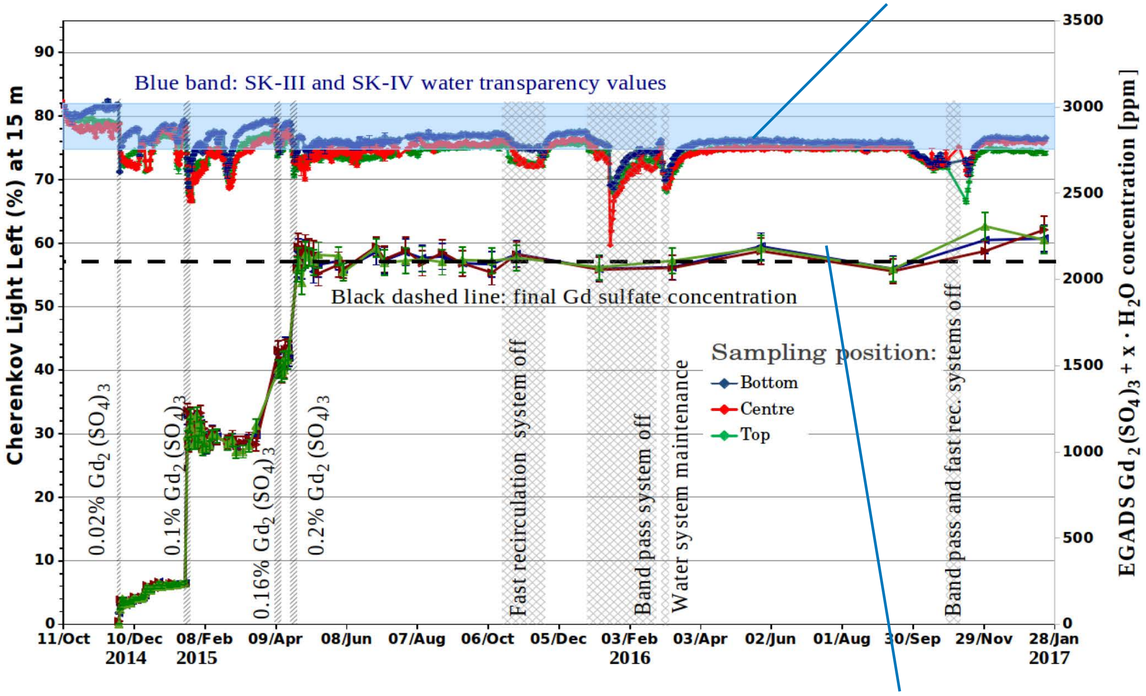
Optical properties of water



- Prior to dissolving Gd to Super-K, we did:
  - Soak testing of all the detector components
  - Test with 200 m^3 tank (EGADS) that mimics Super-K environment
- Successfully kept water transparency in the 200 m^3 tank at the current SK level without losing Gd

200 m^3 tank (EGADS)

Water transparency



Gd concentration

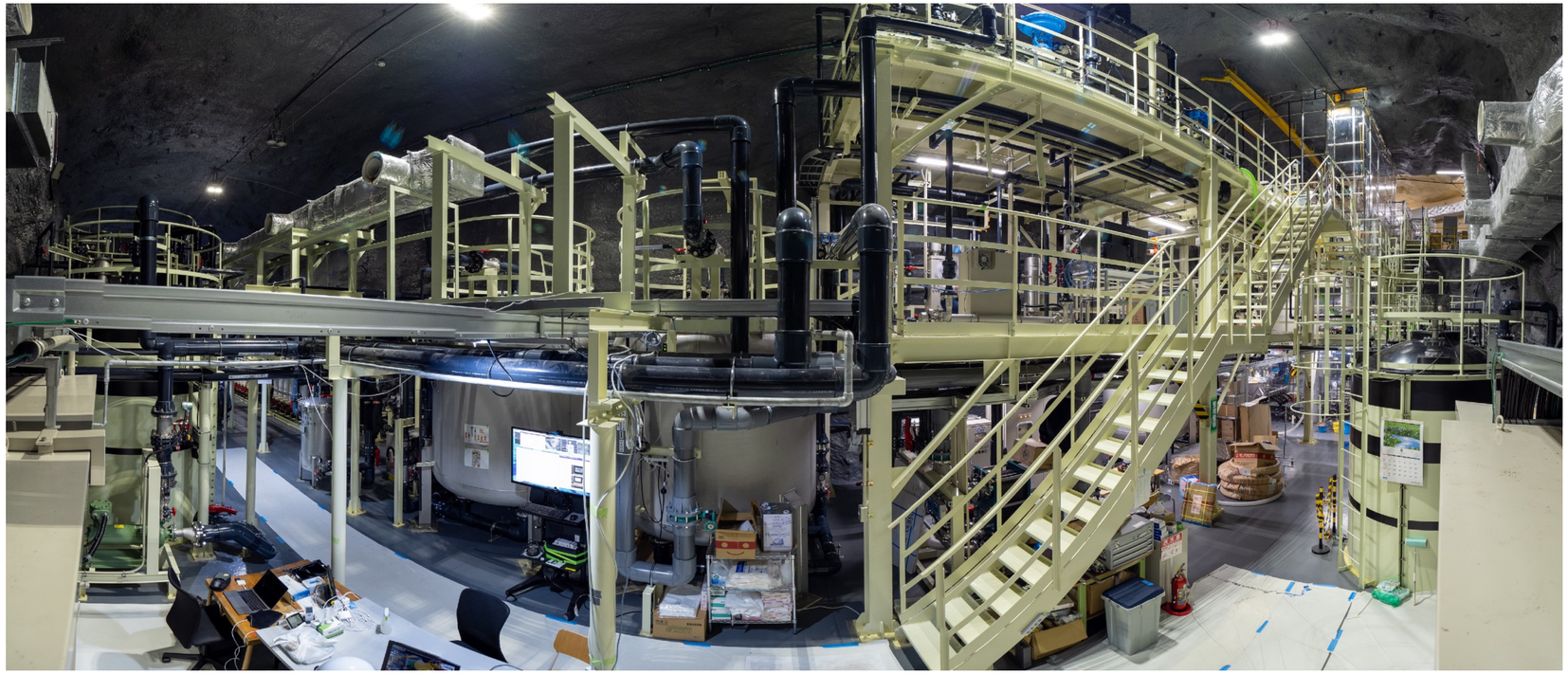
Nucl.Instrum.Meth.A 959 (2020) 163549

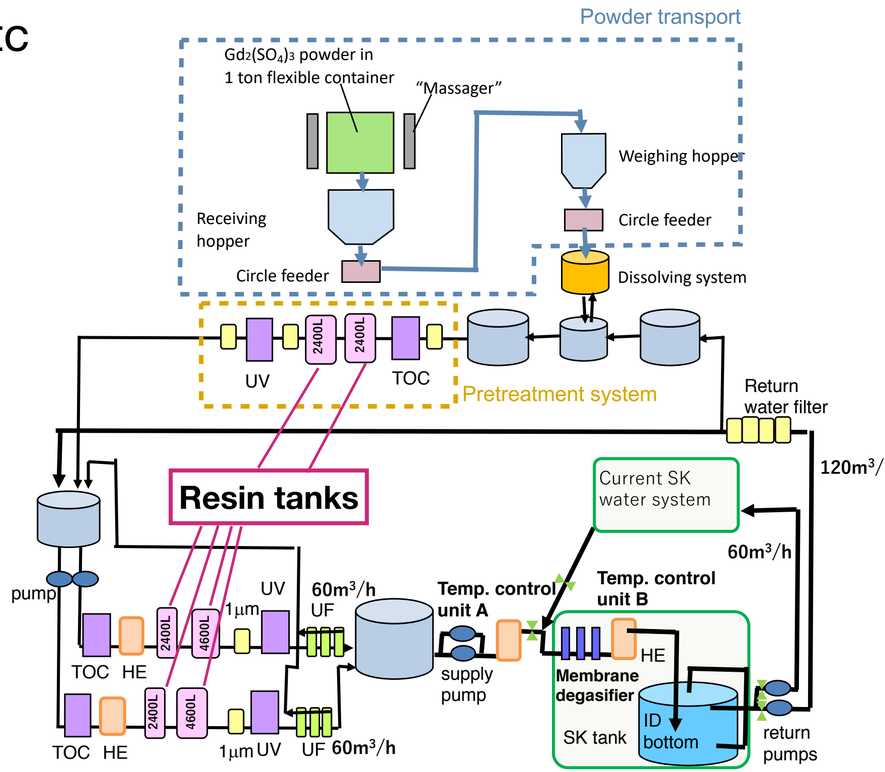
To keep physics performance

Water purification for SK-Gd

- Dedicated Gd-dissolving and Gd-water purification system for Super-Kamiokande
- Recirculating SK water through the new system at 120 m³/h
- Carefully monitoring water quality w/ calibration sources, cosmic muons etc

Real test with the Super-K detector has just started!





To keep physics performance

RI in Gd powder

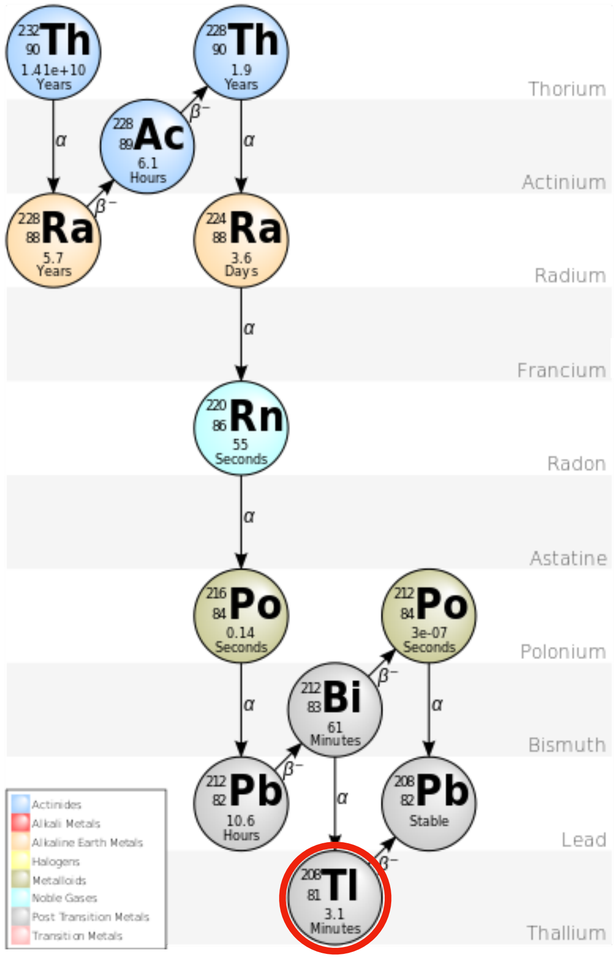
- Radio impurities in Gd powder:
  - Backgrounds to solar and supernova neutrinos
  - Most problematic: ^{208}Tl in ^{232}Th chain
  - Stringent requirement for RI imposed

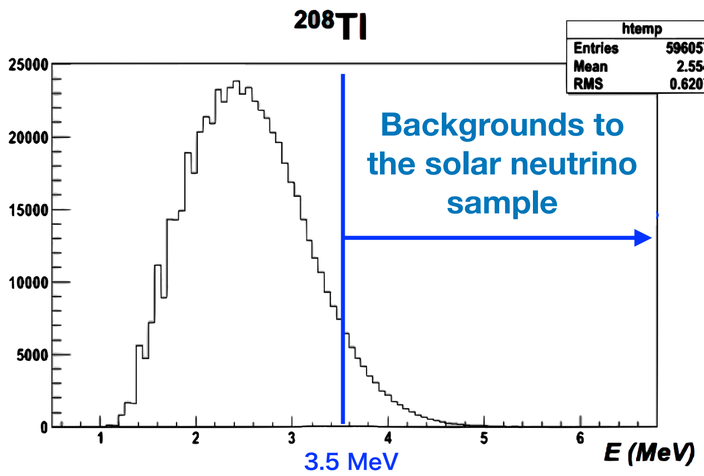
    ^{232}Th: < 0.05 mBq /kg, ^{238}U: < 0.5 mBq/kg etc

- Developed methods to evaluate low concentration RI

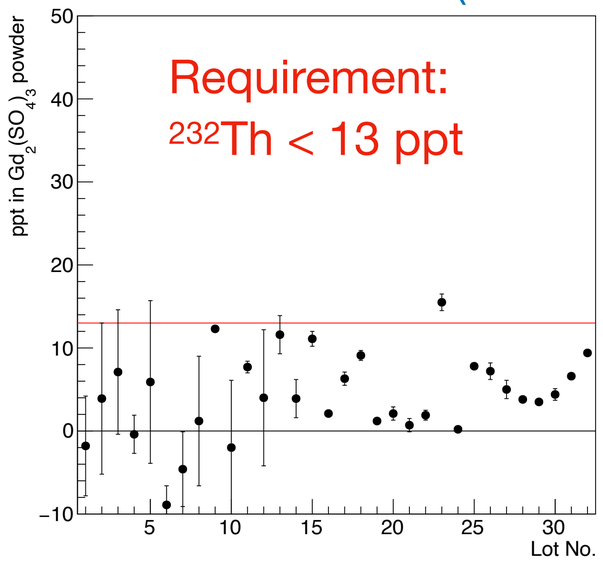
  PTEP 2017 (2017) 11, 113H01
  PTEP 2018 (2018) 9, 091H01
  arXiv: 2006.09664

- Screened at multiple sites
  - ICP-MS: Kamioka
  - HPGe: Canfranc, Boulby and Kamioka
- Worked with production companies and achieved the required purity
- Now 13 tons of those Gd powder is in SK!





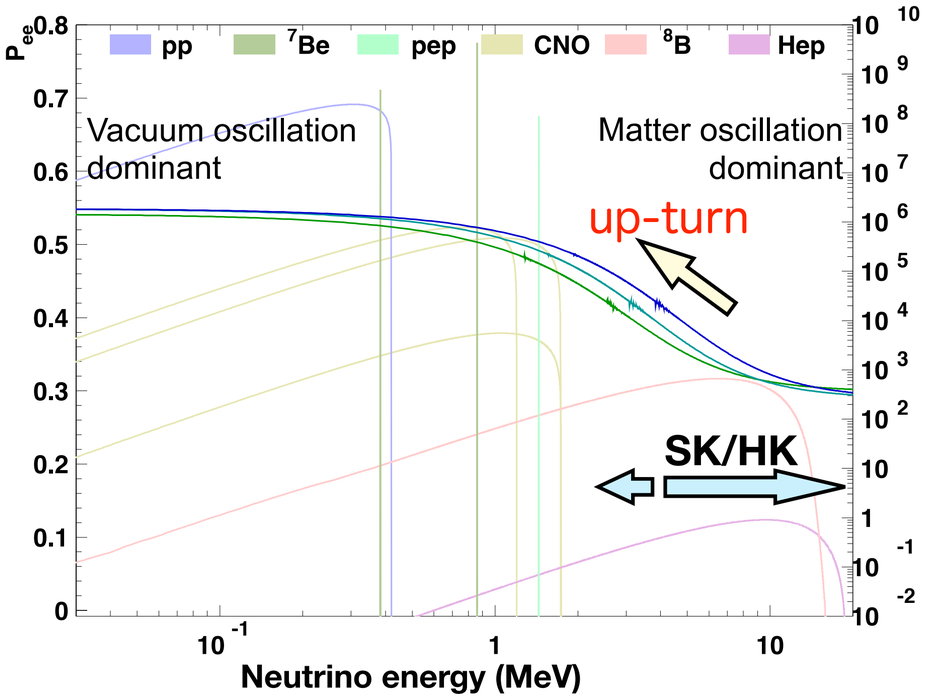
Th contamination (ICP-MS)

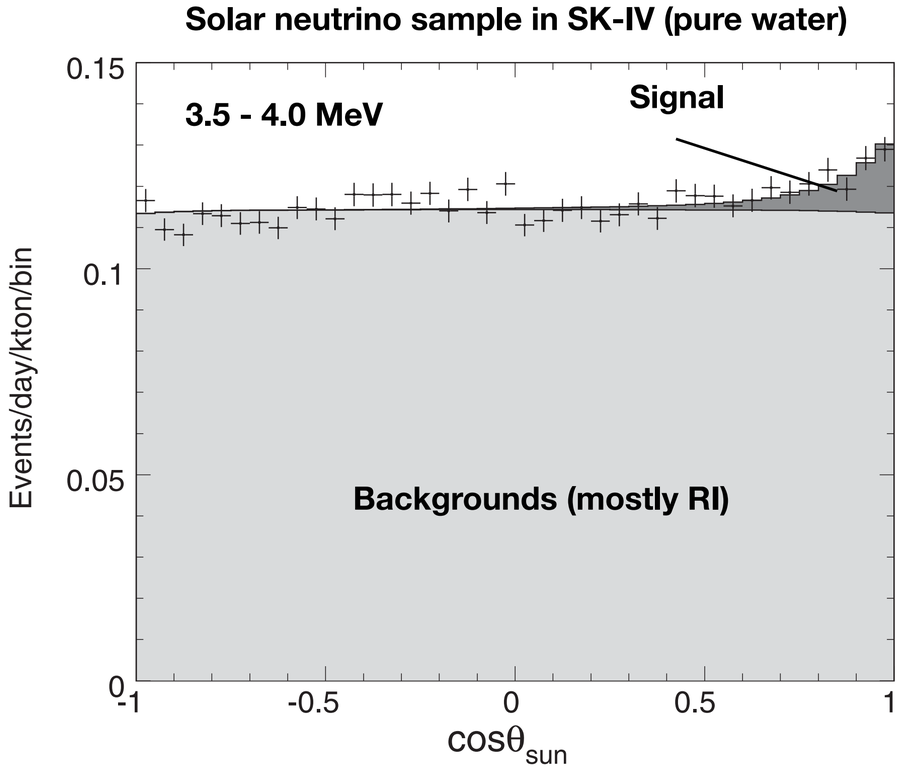


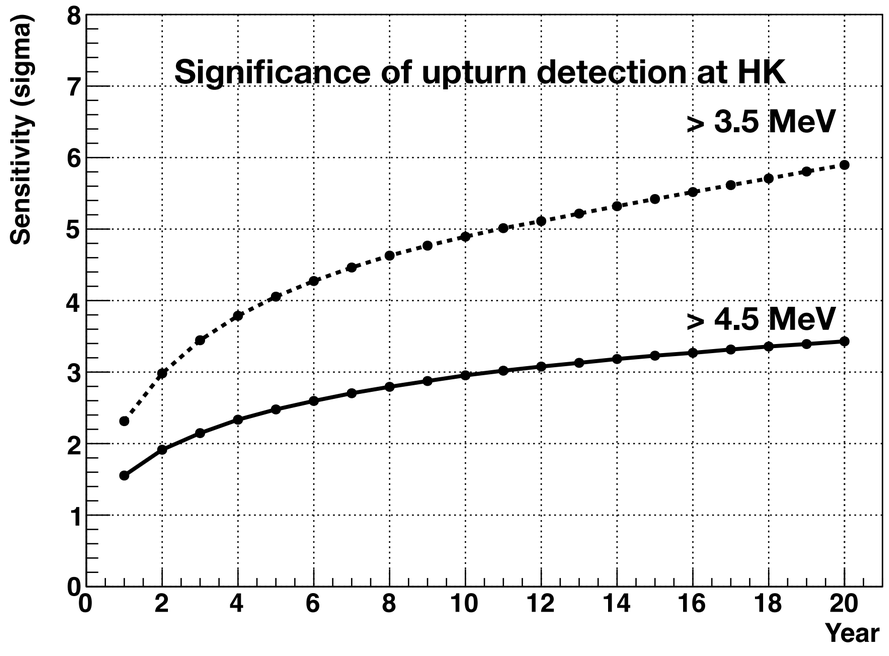
To keep physics performance

RI impacts to solar neutrinos

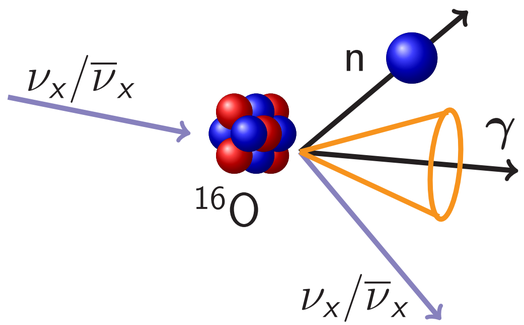
- Major goal of solar neutrino measurements at HK:
  - Detection of spectrum “up-turn” at the vacuum to matter dominant oscillation transition region
  - Key: lowering the energy threshold
- Sensitivity at the lowest energy region limited by RI in the detector
- **Critical to demonstrate background rate in SK-Gd**







NCQE measurement w/ acc. neutrino beam

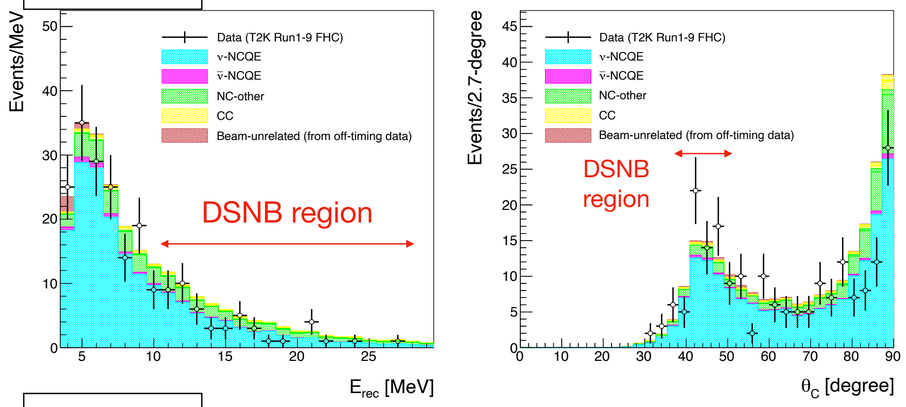


- Atmospheric neutrino NCQE interactions:
  - Most problematic backgrounds for DSNB searches
- Unique feature for SK and HK: control sample of NCQE interactions w/ accelerator neutrino beam from J-PARC
- Large part of beam energy spectrum overlaps with atmospheric neutrinos
- Recent measurement at SK with the T2K beam: Phys.Rev.D 100 (2019) 11, 112009
- Still statistics is poor in the region of interest. Precision will be improved with more data

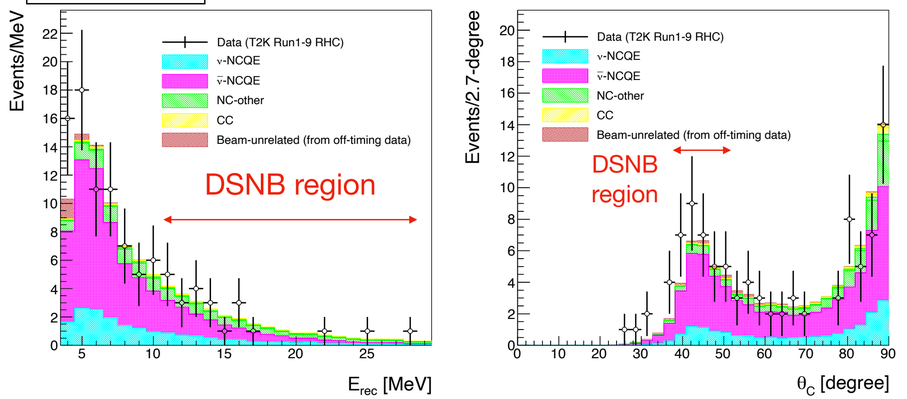
Analysis w/ neutron tagging ongoing

ν-mode

Figures from Phys.Rev.D 100 (2019) 11, 112009



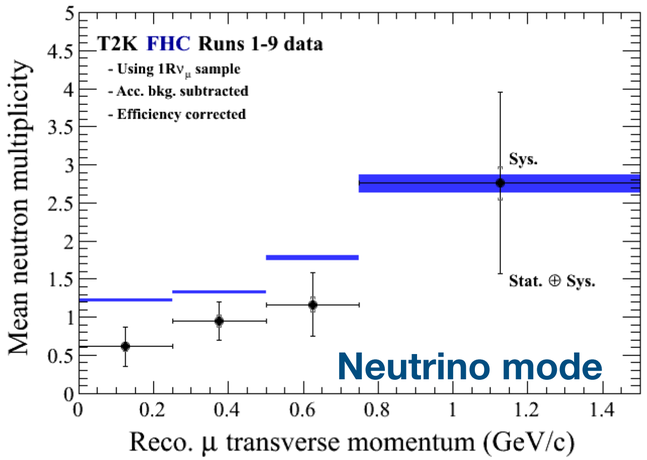
ν̄-mode

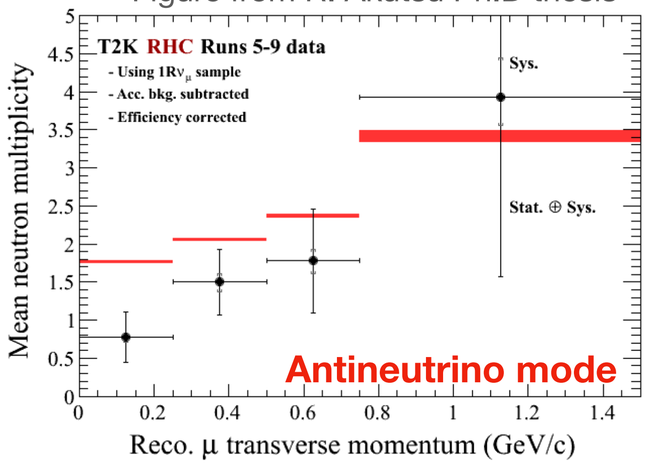


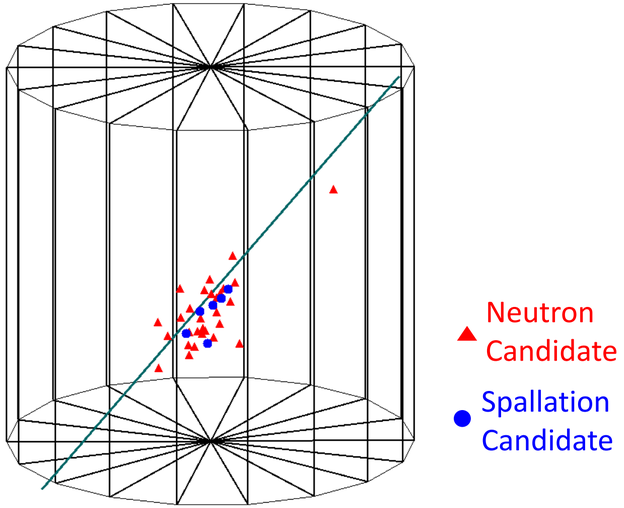
More studies at SK-Gd

- Neutron yield measurement with T2K accelerator neutrino beam
  - Recently made the first measurement of neutron yield from neutrino and antineutrino CC interactions
  - **Important input for utilizing neutrons for neutrino/antineutrino separation etc (GeV neutrinos)**
  - **Constrains atmospheric neutrino backgrounds for DSNB**
- Measurement of spallation products with neutrons
  - Spallation products often associated with "neutron cloud"
  - **Can improved spallation rejection with n-Gd for solar ν and DSNB observation**

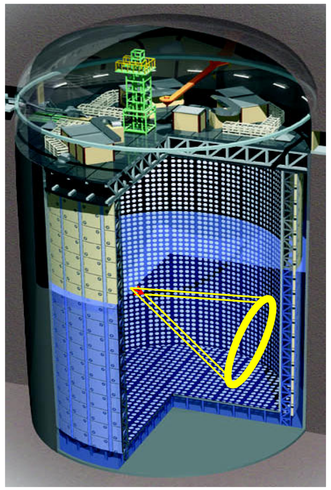
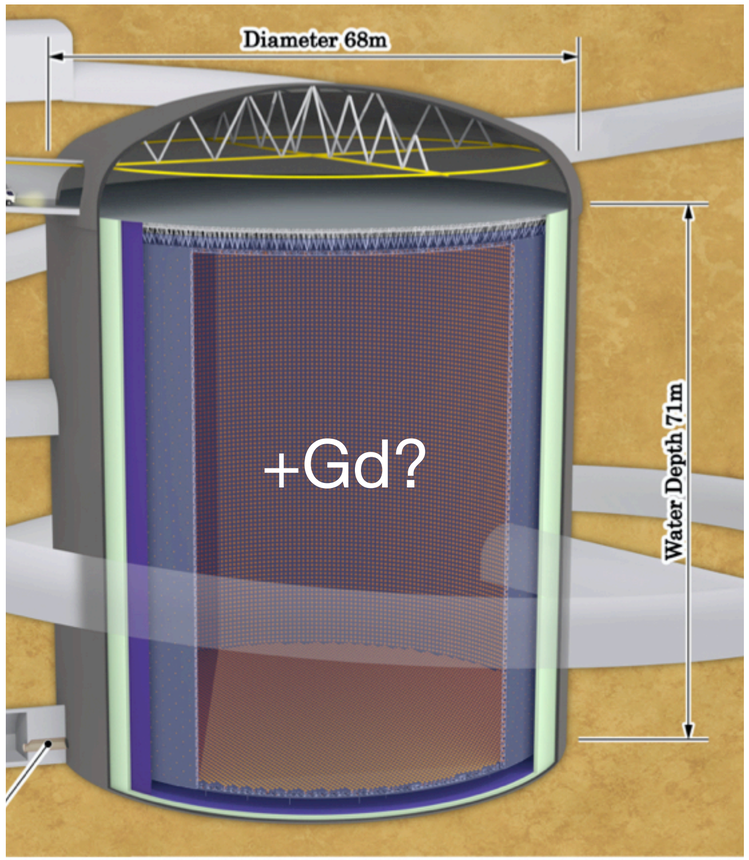
Figure from R. Akutsu Ph.D thesis







Results and technique used for SK-Gd directly applicable to HK(-Gd)

Summary

- New era of SK, SK-Gd, have just started!
- HK-Gd would provide great opportunity for:
  - Precise measurement of DSNB
  - Enhanced measurements of GeV neutrino oscillation with
    - Neutrino/antineutrino separation
    - Improved energy reconstruction
  - And many more!
- Data from SK-Gd will provide crucial imputes for realization for HK-Gd
  - Optical quality and RI of Gd-loaded water
  - Enhancement of physics potential with neutrons
- **Stay tuned for near future results from SK-Gd!**