Super-K Gd

その1、期待される成果とこれまでの技術開発

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第32回ニュートリノ研究会「超新星背景ニュートリノ」

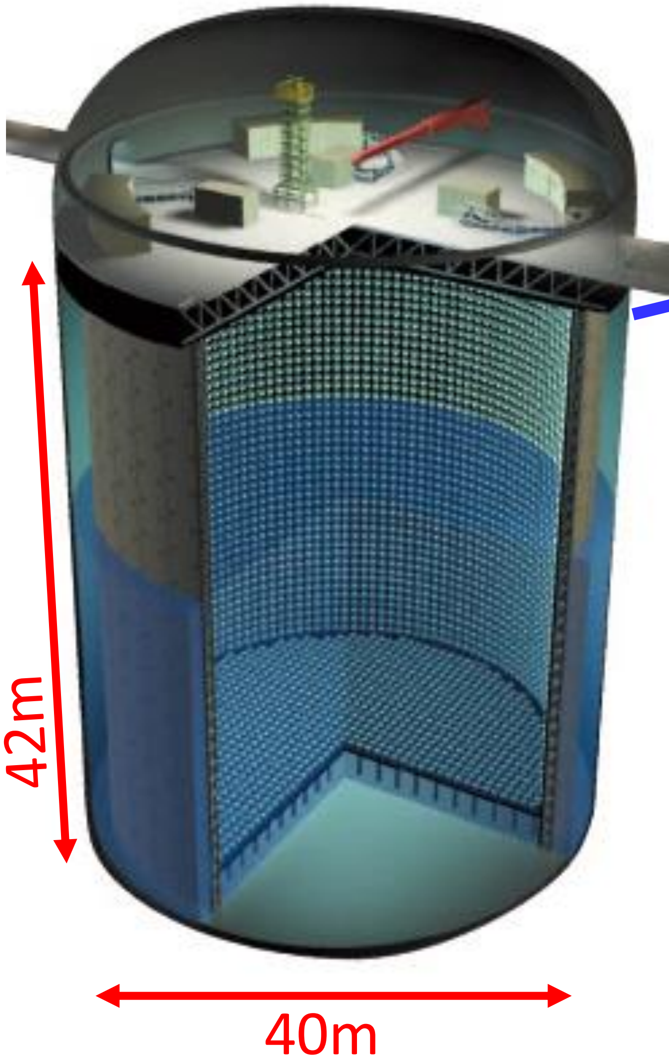
Contents

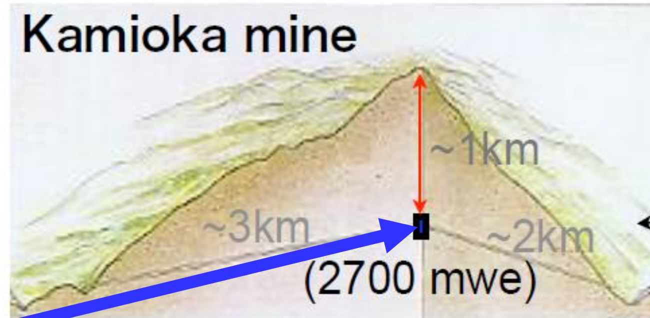
- Introduction to SK-Gd
- Physics motivations
- R&D to realize SK-Gd
- Summary

Comming soon

Super-Kamiokande

50000 tons of
Water Cherenkov detector



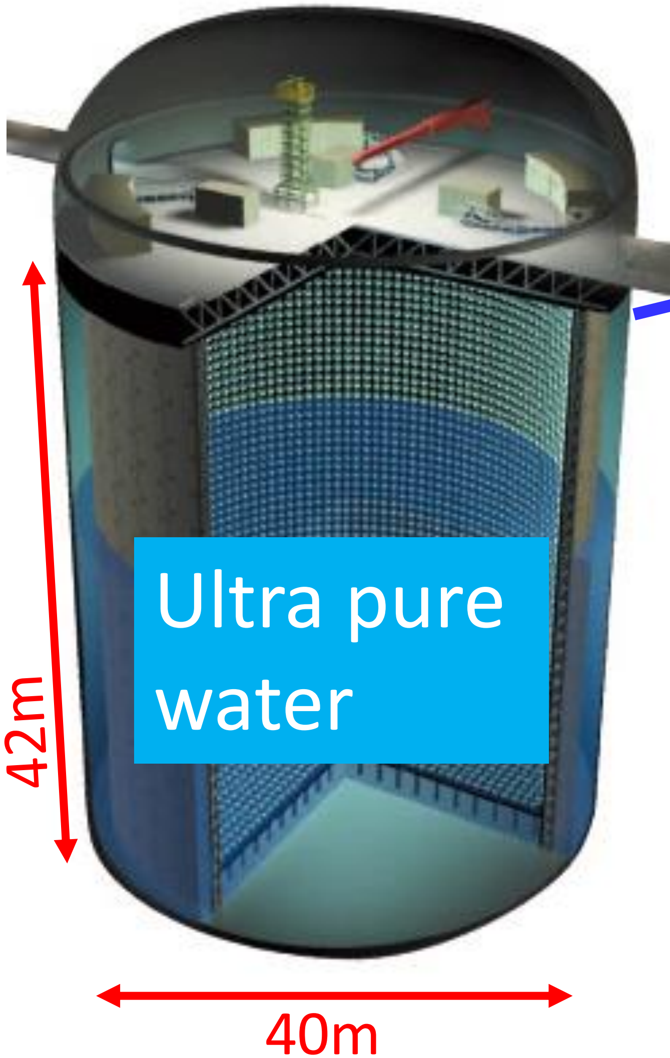


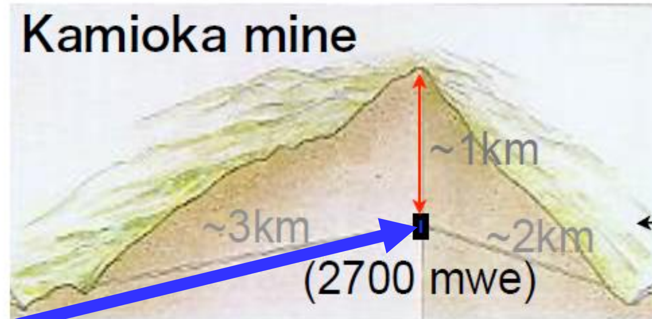
(For Solar neutrino analysis)

Phase	Period	Livetime	Fid. vol.	ID PMTs	KinE thr.
I	1996.4~ 2001.7	1496 (days)	22.5 (kton)	11146 (40%)	4.5 (MeV)
II	2002.10~ 2005.10	791		5182 (20%)	6.5
III	2006.7~ 2008.8	548	22.5 (>5.5 MeV) 13.3 (<5.5 MeV)	11129 (40%)	4.5
IV	2008.9~ 2019.1	2860	22.5 (>5.5MeV) 16.5 (4.5<E<5.5) 8.85(<4.5MeV)		3.5
V	2019.2~				

Super-Kamiokande

50000 tons of
Water Cherenkov detector





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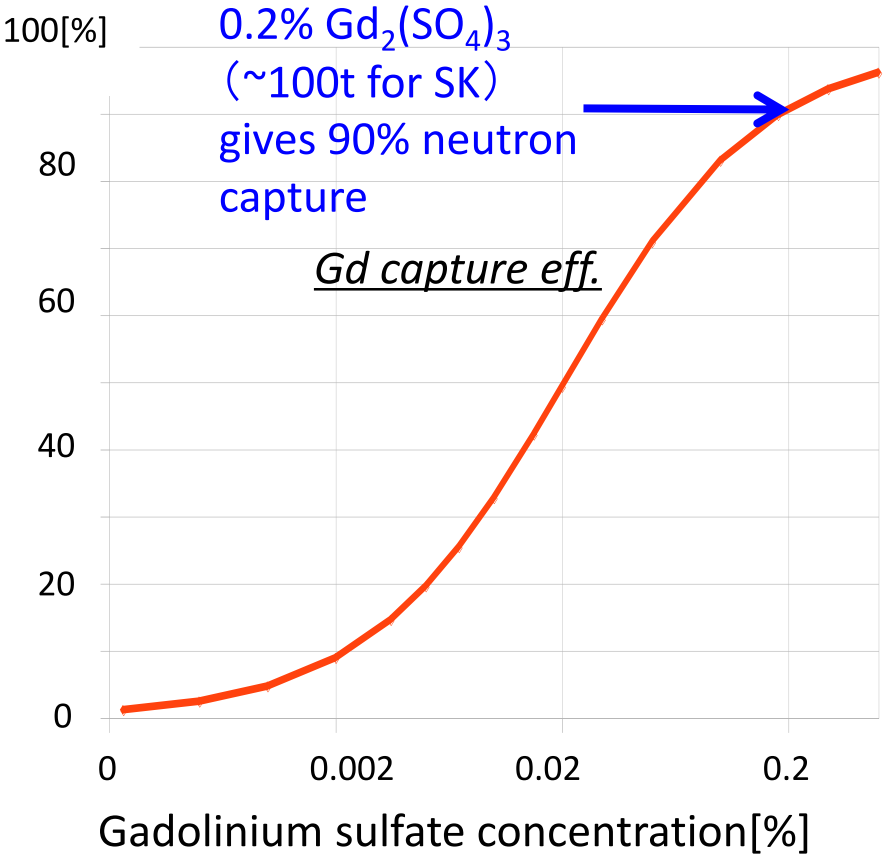
Super K-Gd

Beacom and Vagins PRL93,171101 (2004)

- Large cross section for thermal neutron (48.89kb)
- Neutron captured Gd emits 3-4 γ ray in total 8 MeV
- **We can tag $\bar{\nu}_e$ by using the delayed coincidence technique.**



Physics targets:

(1) Supernova relic neutrino (SRN)

(2) Improve pointing accuracy for galactic supernova

(3) Precursor of nearby supernova by Si-burning neutrinos

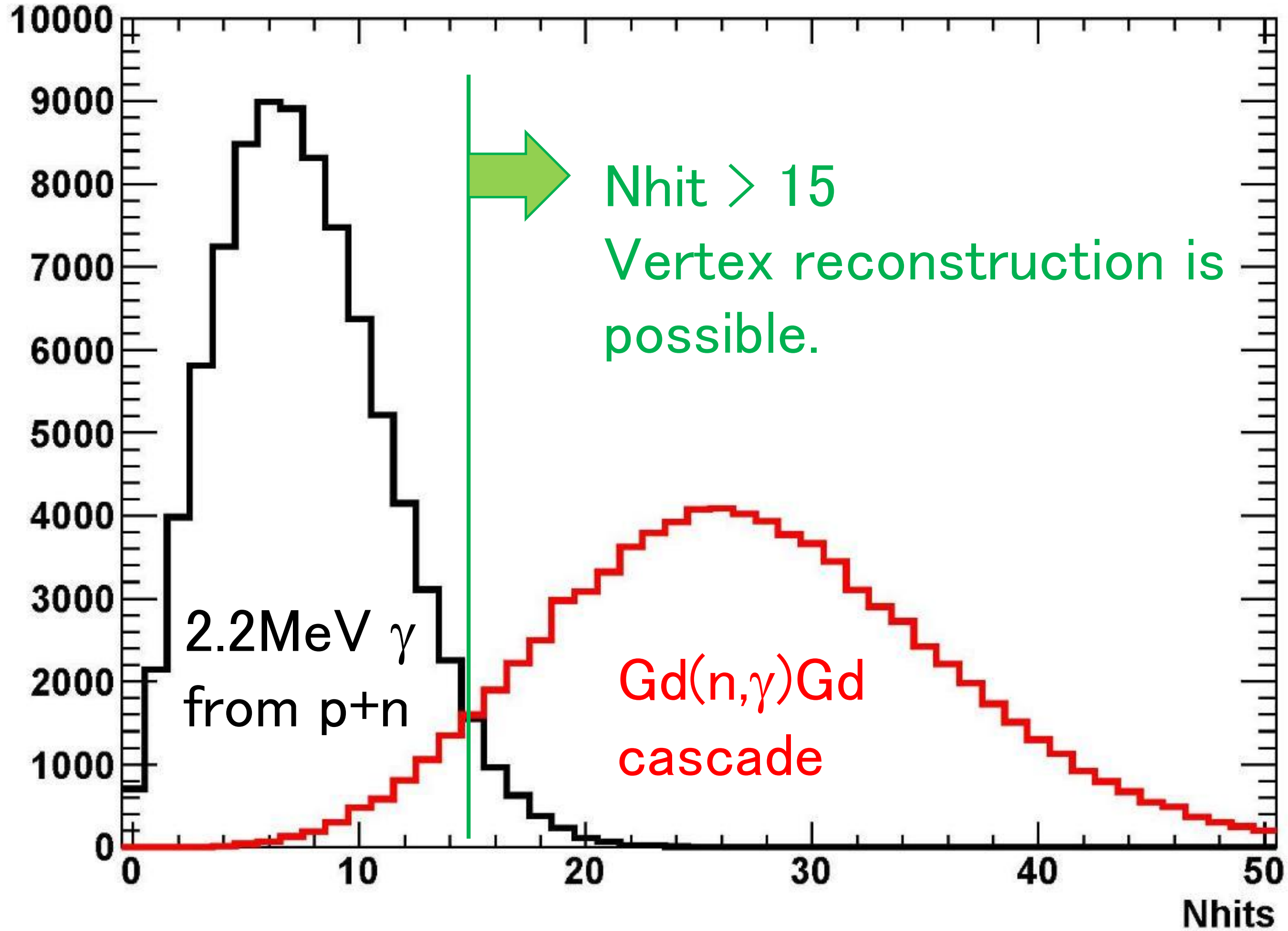
(4) Reduce proton decay background

(5) Neutrino/anti-neutrino discrimination (Long-baseline and atm nu's)

(6) Reactor neutrinos

Why Gd (not 2.2MeV γ) for neutron tagging

Number of hit PMT (Nhit) distributions



Efficiency and fake probability

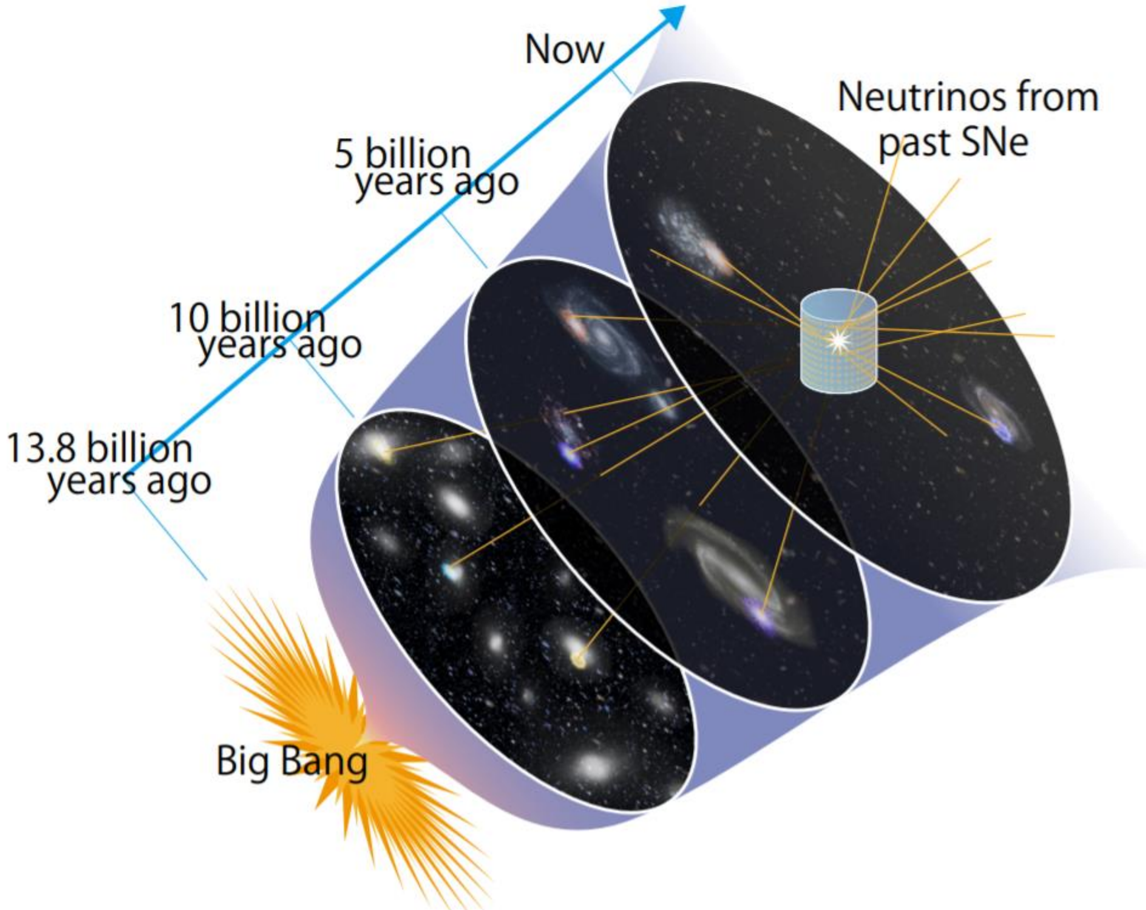
2.2MeV γ: Efficiency: 10～20%, fake probability: $\sim 10^{-2}$

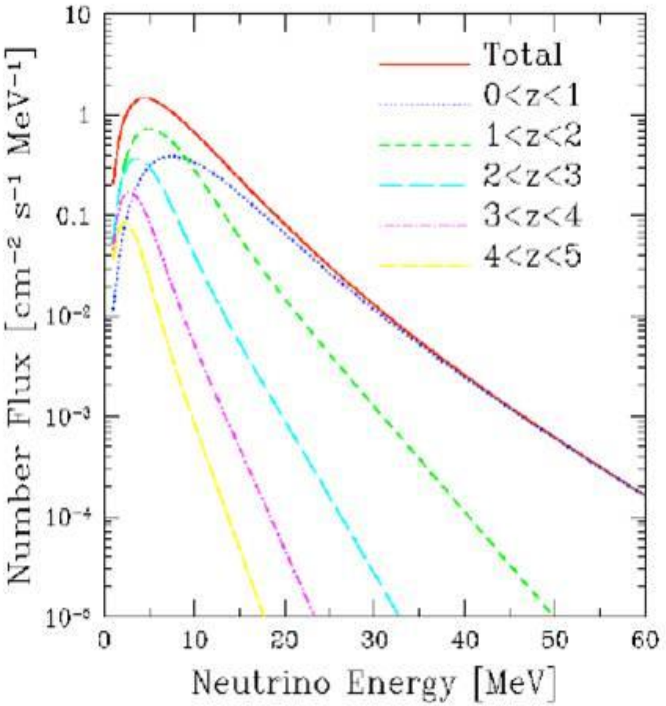
Gd(n,γ)Gd: Efficiency: >80%, fake probability: $< 10^{-4}$

Physics motivation

Supernova Relic Neutrino (SRN)

Discovery of neutrinos from past supernovae!

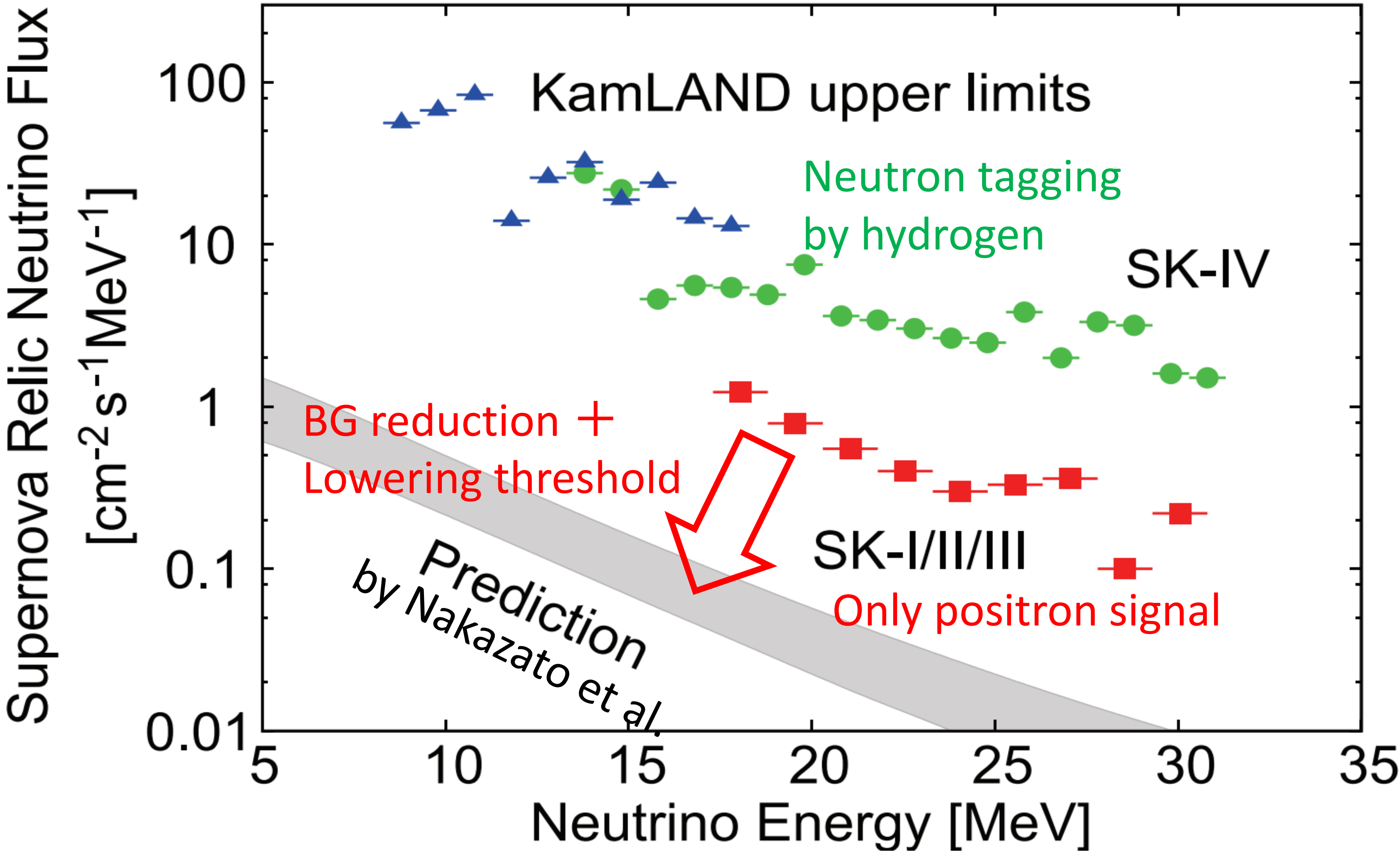




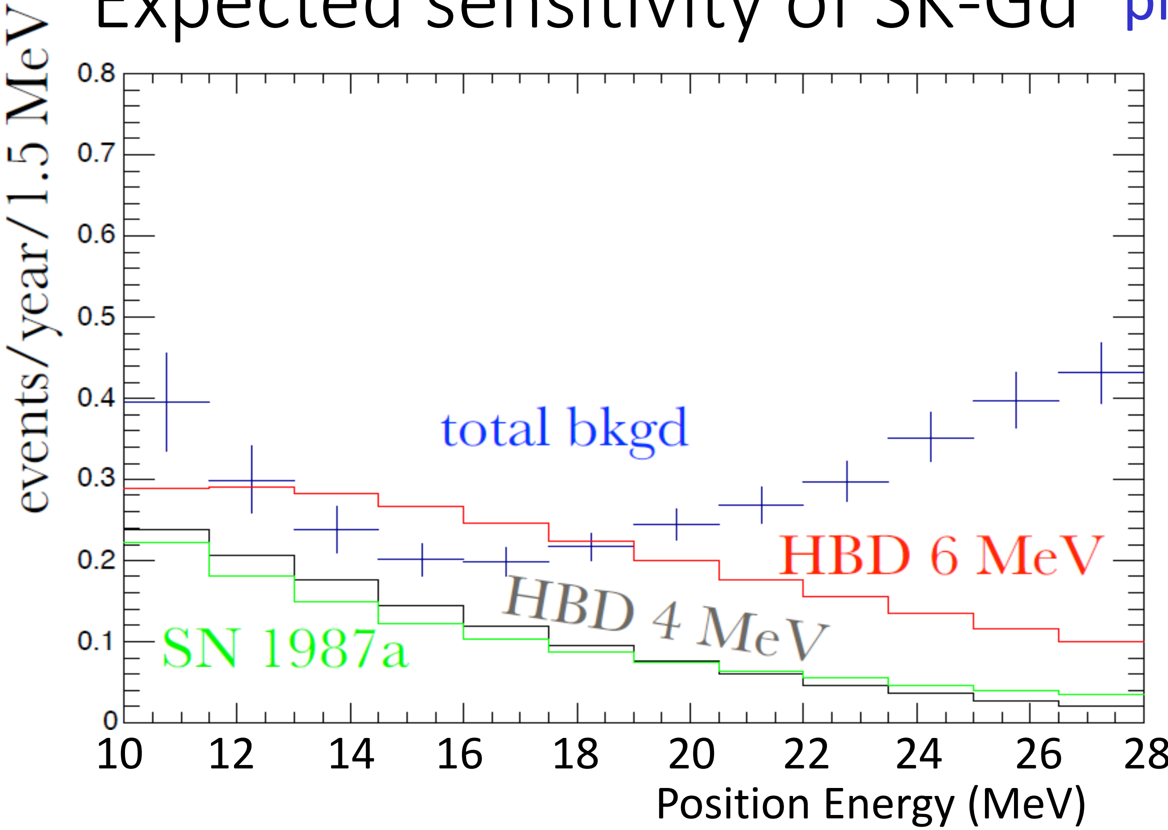
S.Ando, Astrophys.J. 607, 20(2004)

Theoretical flux prediction : 0.3~1.5 /cm2/s (17.3MeV threshold)

Current SRN searches



Expected sensitivity of SK-Gd preliminary



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

BG assumption in SK-Gd

- ν_μ CC BG become 1/4
- ν_e CC BG become 2/3
- NC elastic BG 1/3

(requiring only one neutron)

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

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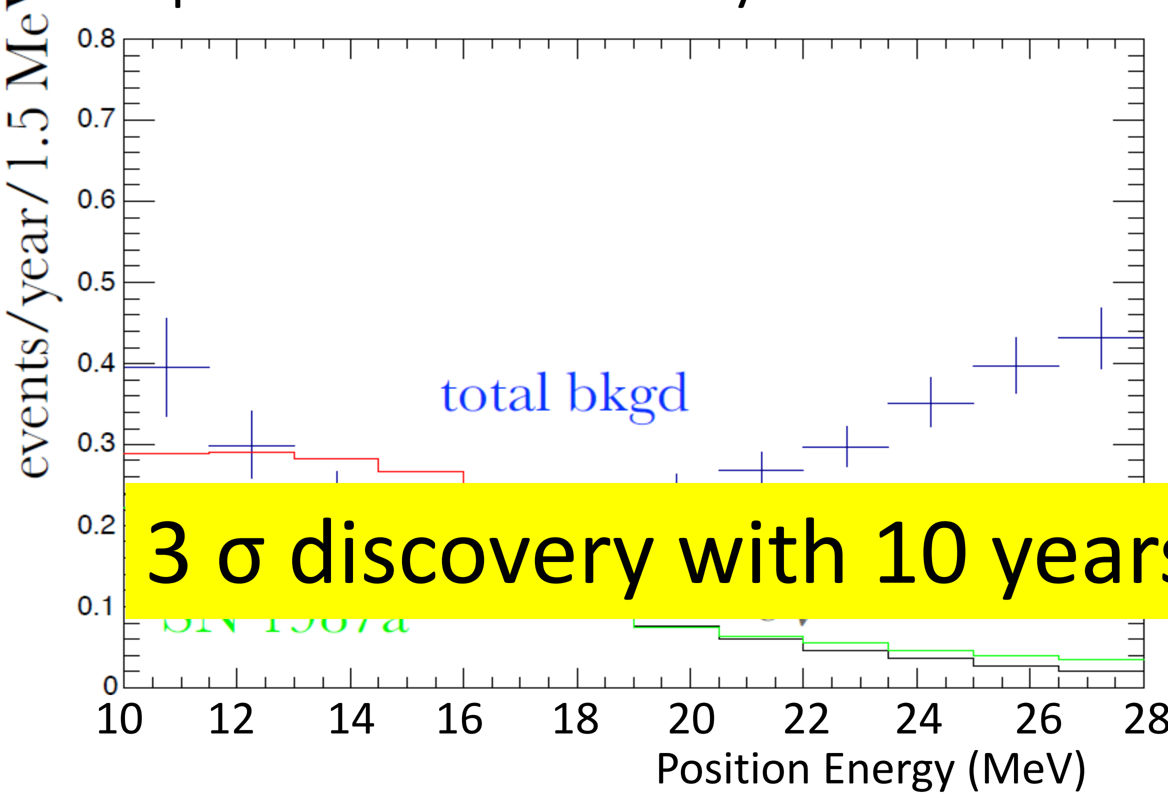

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3 σ discovery with 10 years observation

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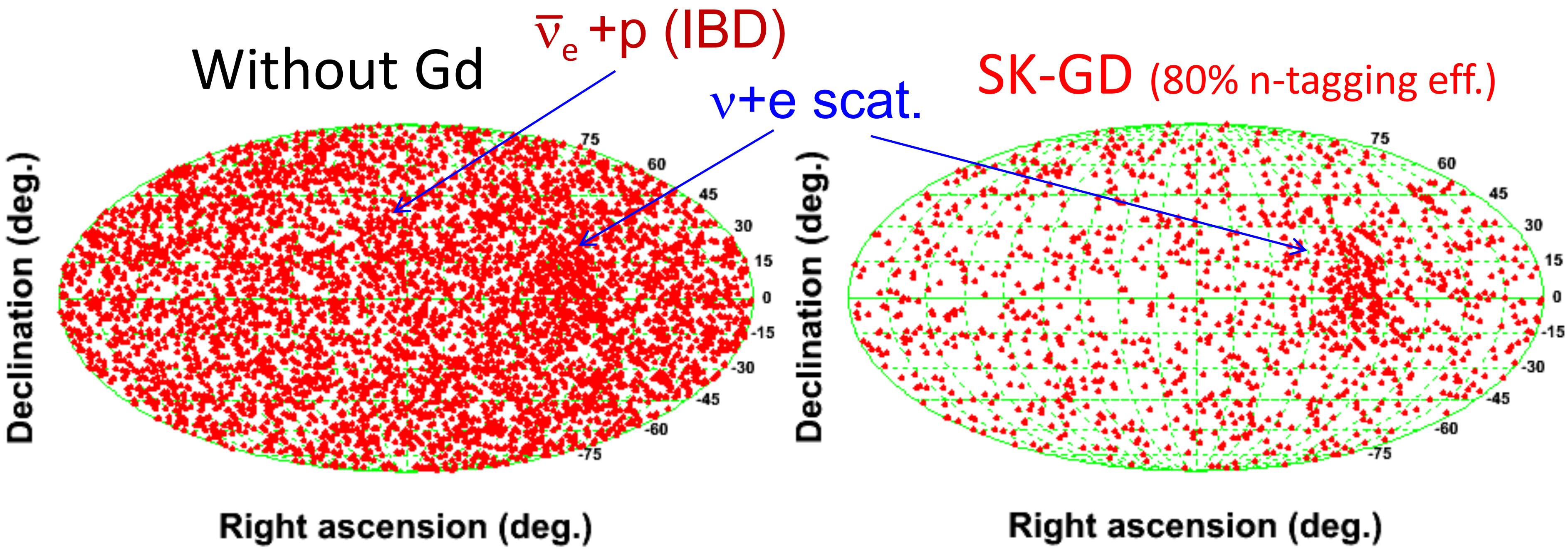
Improvement of SN pointing accuracy

Simulation of SN at 10kp



By tagging IBD with Gd signal, ν-e scattering signal can be extracted.

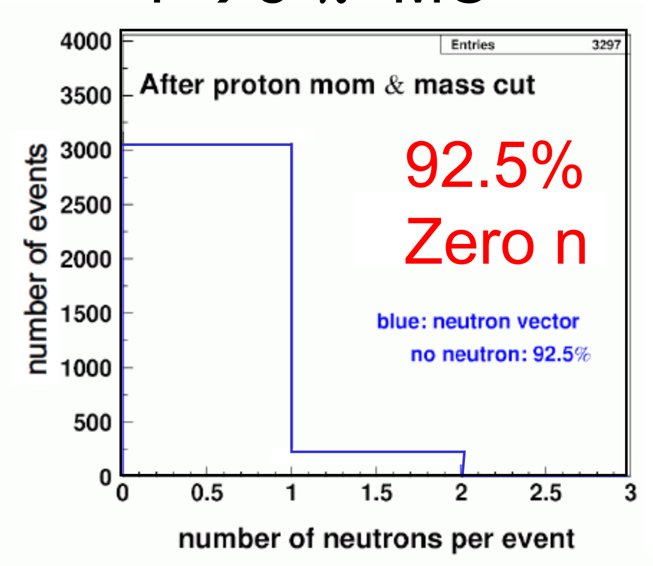
Pointing accuracy for SN at 10 kpc.

Improvement; 4~5° → ~3° (90%C.L.)

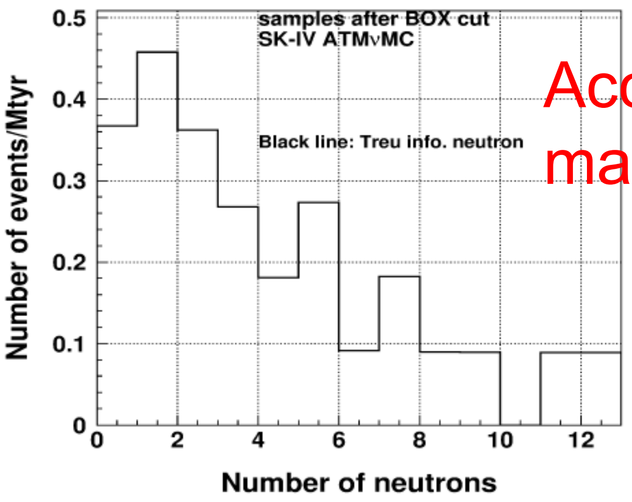
Improvement for Proton decay

Neutron multiplicity for

$P \rightarrow e^+\pi^0$ MC



Atmospheric ν BG



Accompany many n

<u>If one proton decay event is observed at Super-K after 10 years</u>

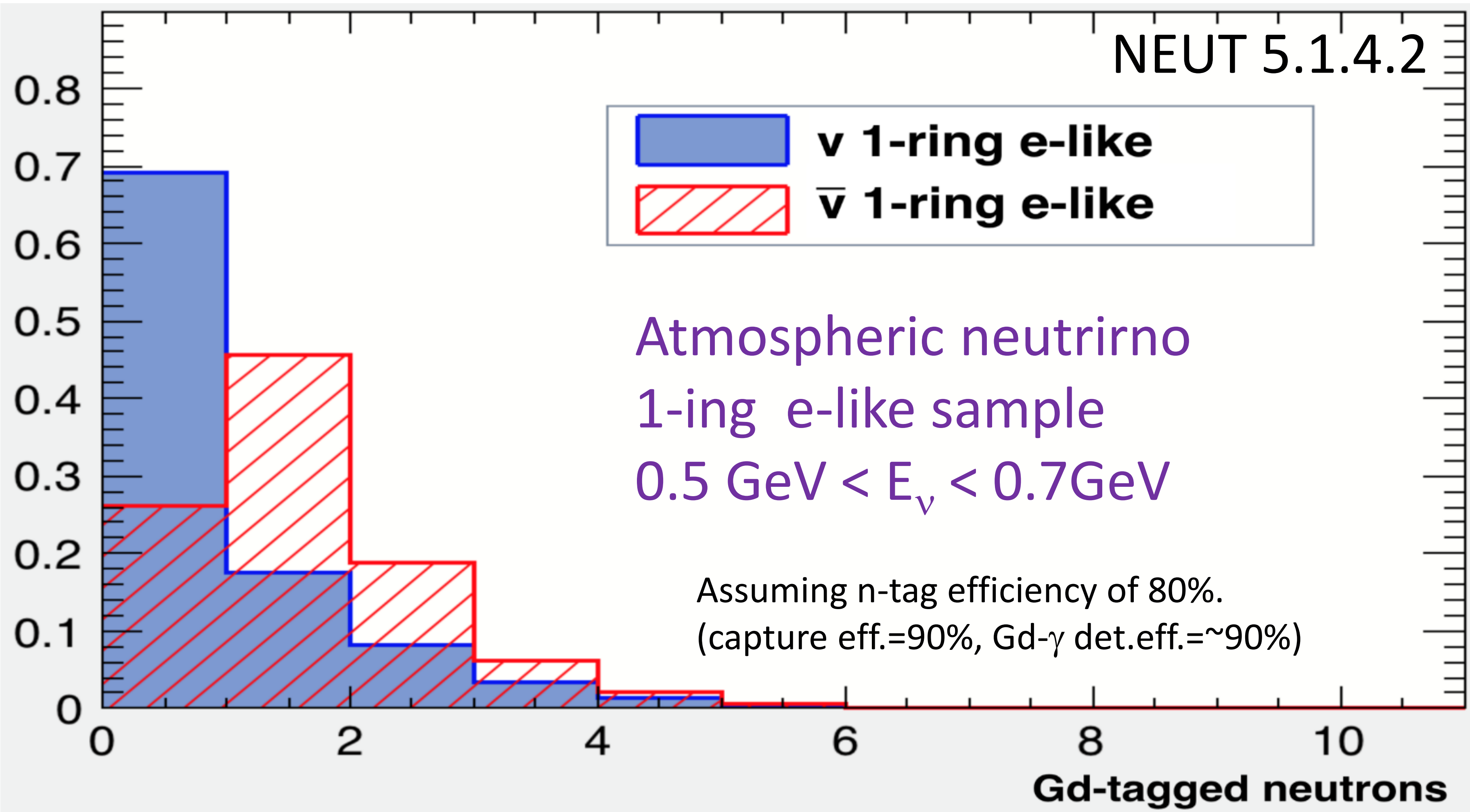
Current background level: 0.58 events/10 years

Background with neutron anti-tag: 0.098 events/10 years

Background probability will be decreased from 44%(w/o n) to 9%(w/ n).

T2K/Atomospheric neutrinos

Number of neutrons from a neutrino interaction in T2K energy range



ν_e and $\bar{\nu}_e$ separation using number of neutrons : ~70%

R&D to realize SK-Gd

R&D items

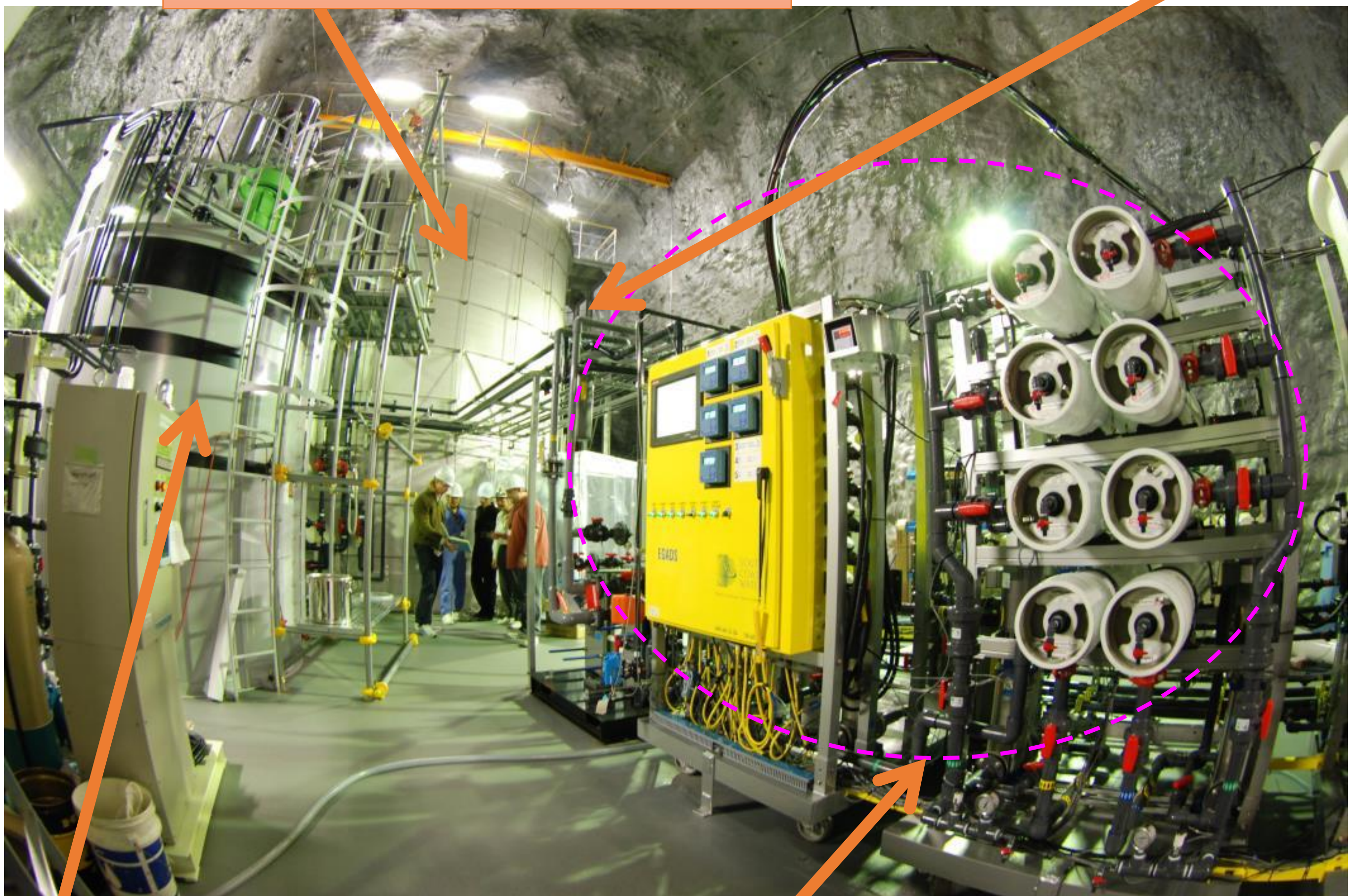
- ☑ Gd water transparency must be similar to SK water
- ☑ Effect of Gd to detector materials
- ☑ Effect of Gd water quality to physics analysis
- ☑ Reduction of radioactive backgrounds in Gd powder
- ☑ How to stop leak of SK detector (Next talk)

EGADS

Evaluating Gadolinium's Action on Detector Systems

200 m³ tank with 240 PMTs

Transparency measurement (UDEAL)



15m³ tank to dissolve Gd

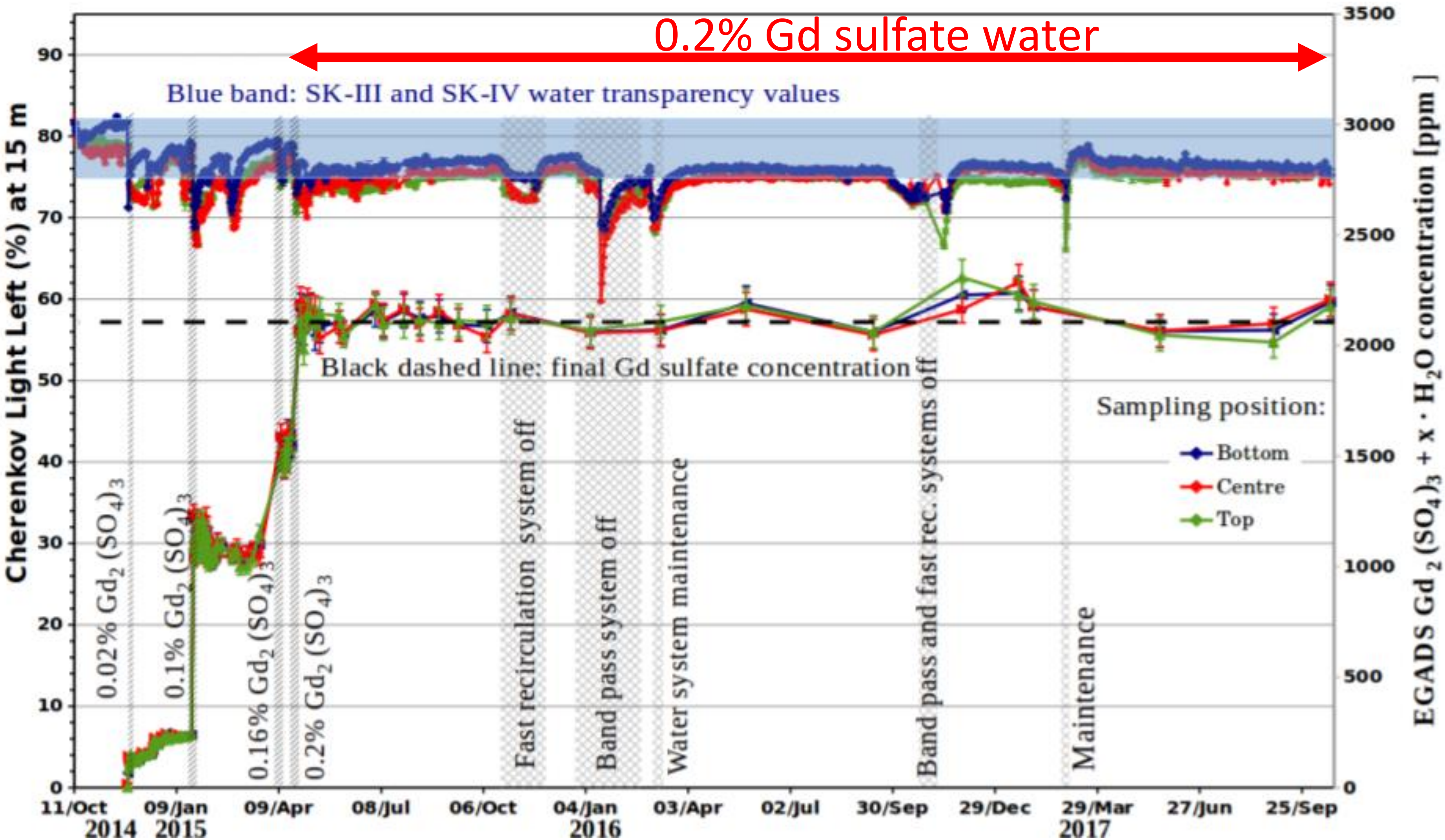
Gd water circulation system (purify water with Gd)

EGADS detector: Baby-Kamiokande

One of main goals for EGADS is to study the Gd water quality with actual detector materials.
Thus, the detector fully mimic Super-K detector.
: SUS frame, PMT and PMT case, black sheets, etc.

Gd dissolving test has been performed since Oct.2014. and finished Apr. 2015

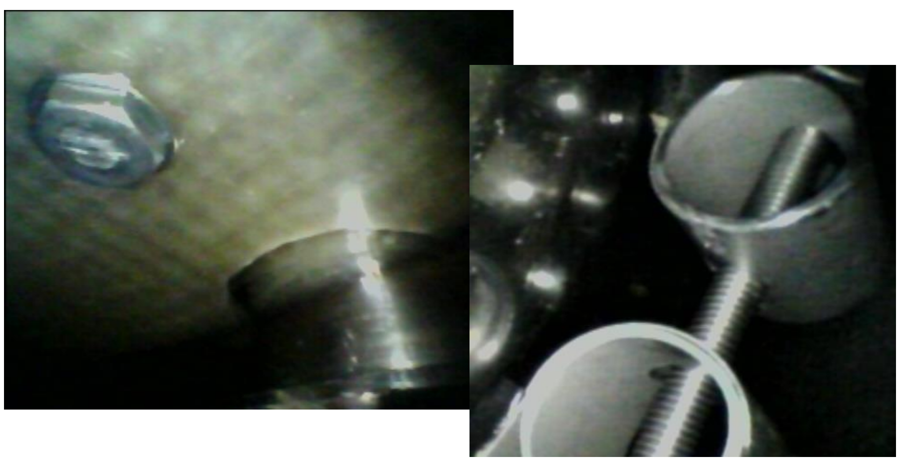
Transparency of Gd water with PMTs



The light left at 15 m in the 200m^3 tank was ~75% for 0.2% $Gd_2(SO_4)_3$, which corresponds to ~92% of SK-IV pure water average.

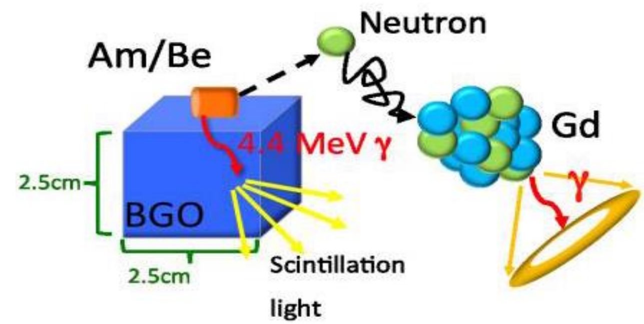
EGADS inspection after ~3years of GD water operation

EGADS tank looks fine.
We did not find large source of rust.
The stainless steel supports look shining.



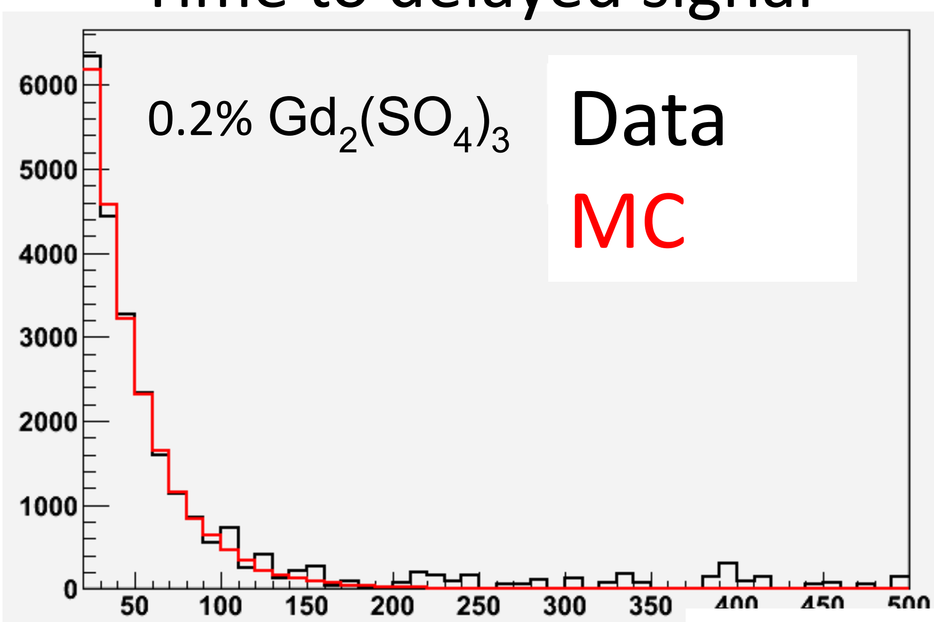
Inside of FRP covers

Neutron capture signal@EGADS



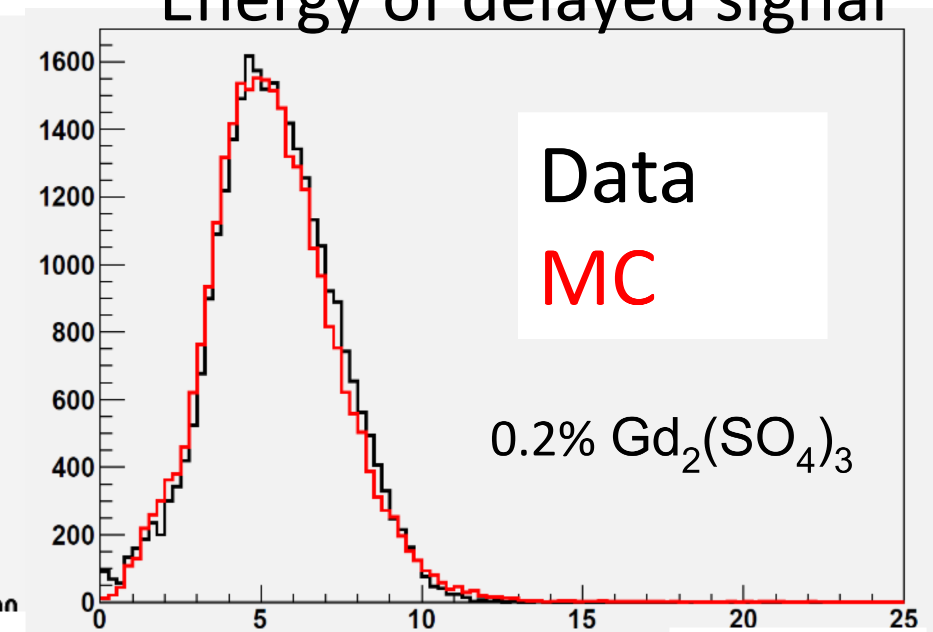
by Xu et al.

Time to delayed signal



[μsec]

Energy of delayed signal



[MeV]

Average capture time;

Data 29.9±0.3 [μsec], MC 30.0 ±0.8 [μsec]

Super-K performance checks

- SK detector simulation with water transparency in 0.2% Gd sulfate period
- High energy reconstructions
  - Atmospheric / T2K
- Low energy reconstructions
  - Solar / SRN

Effect on High energy (atm.v, T2K)

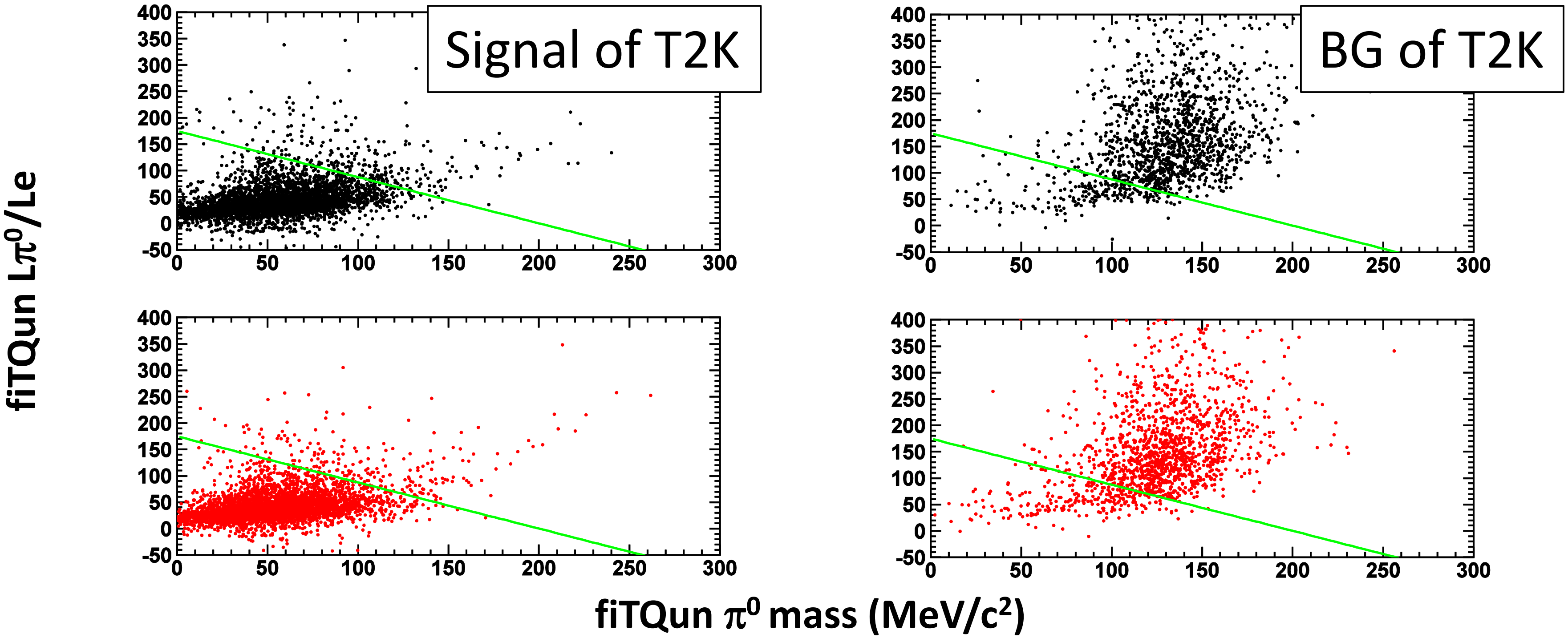
	Pure water	Gd water
Momentum resolution		
electron (500MeV)	4.9%	4.9%
muon(500MeV)	2.5%	2.5%
Miss-PID(%)		
muon(500MeV)→e-like	0.59±0.12	1.00±0.15
π^0(500MeV)→ T2K1Re	4.7±0.3	6.1±0.4
Number of T2K events (nu-mode 3.9*10^{21} POT)		
Appearance signal	98.5	97.7
Appearance BG	24.6	25.2
Disappearance signal	622.2	623.8
Disappearance BG	45.6	48.6

e/π^0 separation (ex. 500MeV/c)

By Mine

pure
Gd water

e MC $\qquad$ π^0 MC



e MC, det. ε(%)

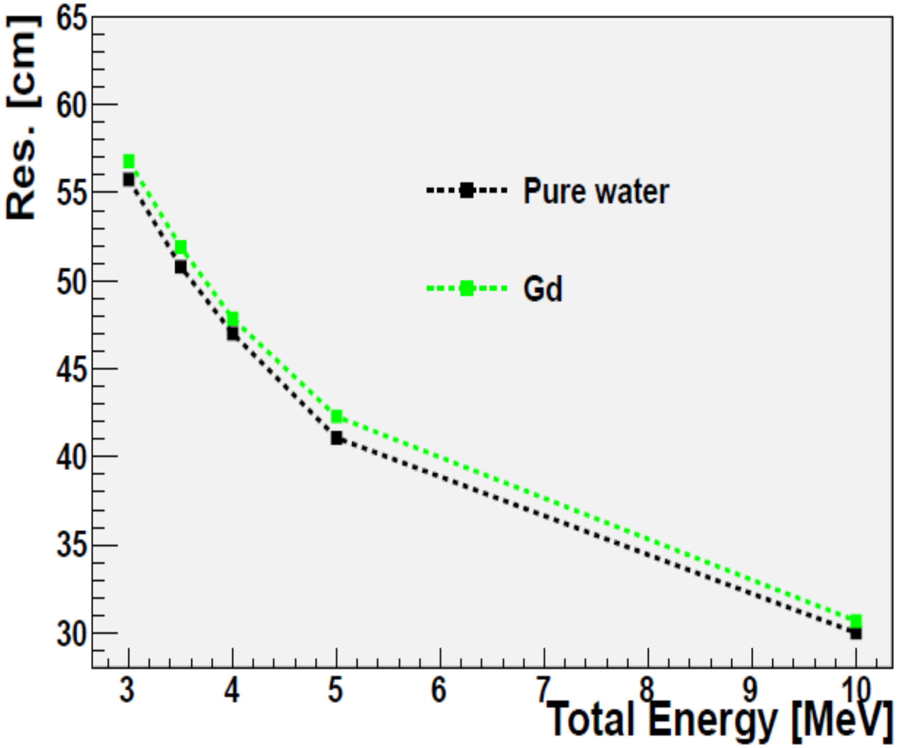
true (MeV/c)	pure	Gd water
250	92.9±2.1	91.9±2.1
500	89.3±2.0	88.4±2.0
1000	75.7±1.8	77.7±1.8

π^0 MC, remain ε(%)

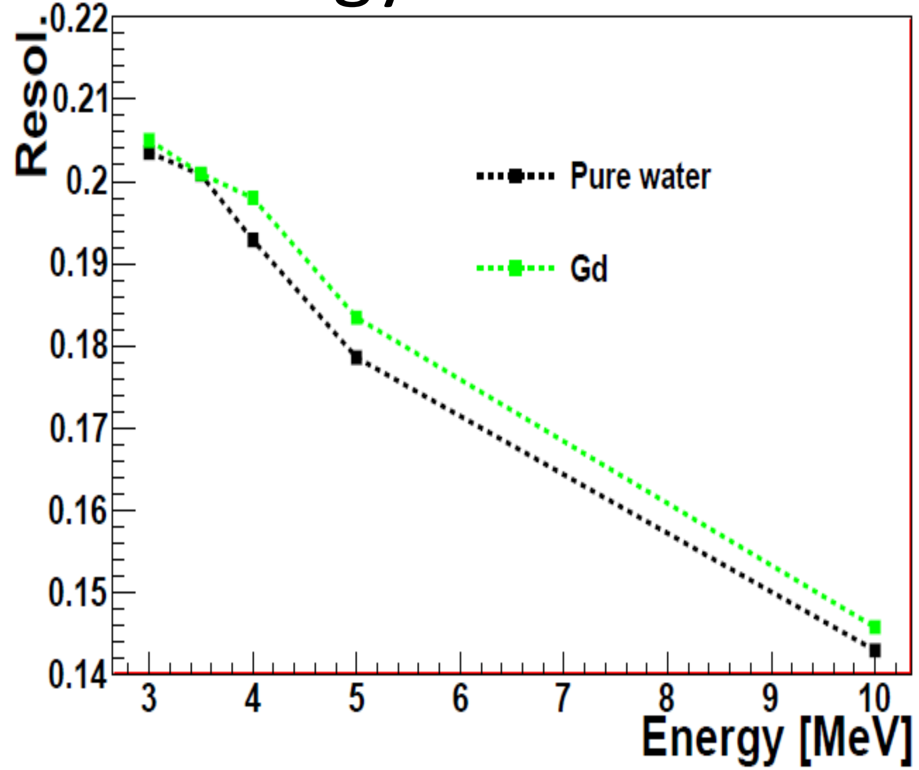
true (MeV/c)	pure	Gd water
250	1.7±0.2	1.9±0.2
500	4.7±0.3	6.1±0.4
1000	15.8±0.7	16.7±0.7

Effect on Low energy (solar ν, SRN)

Vertex resolution



Energy resolution

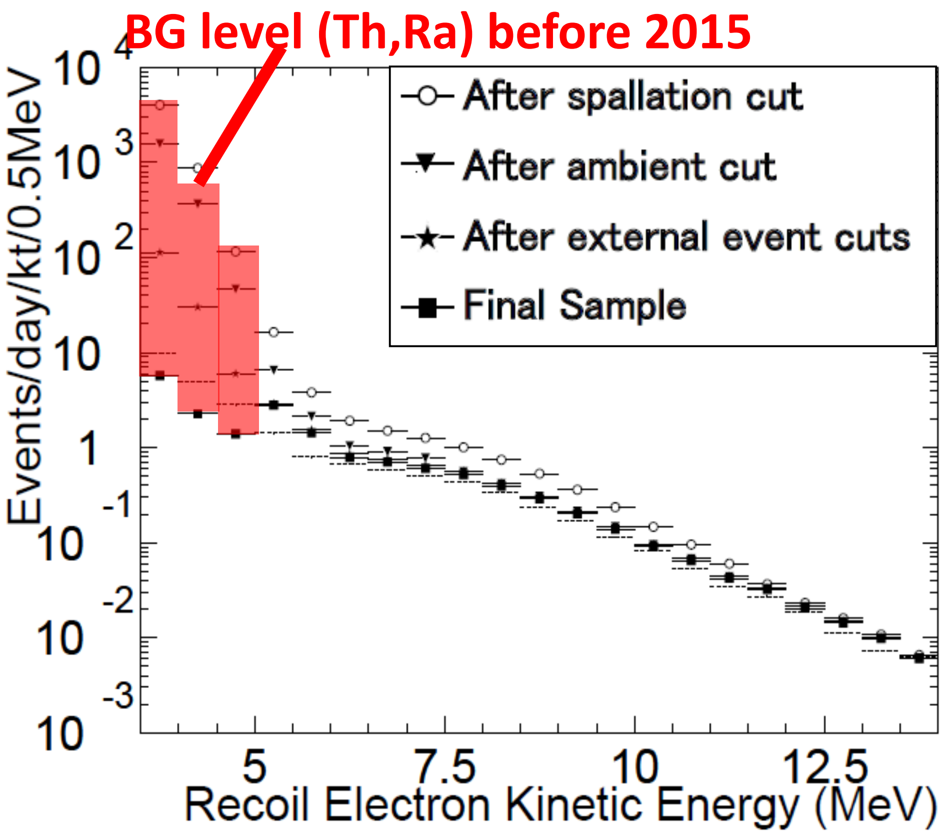


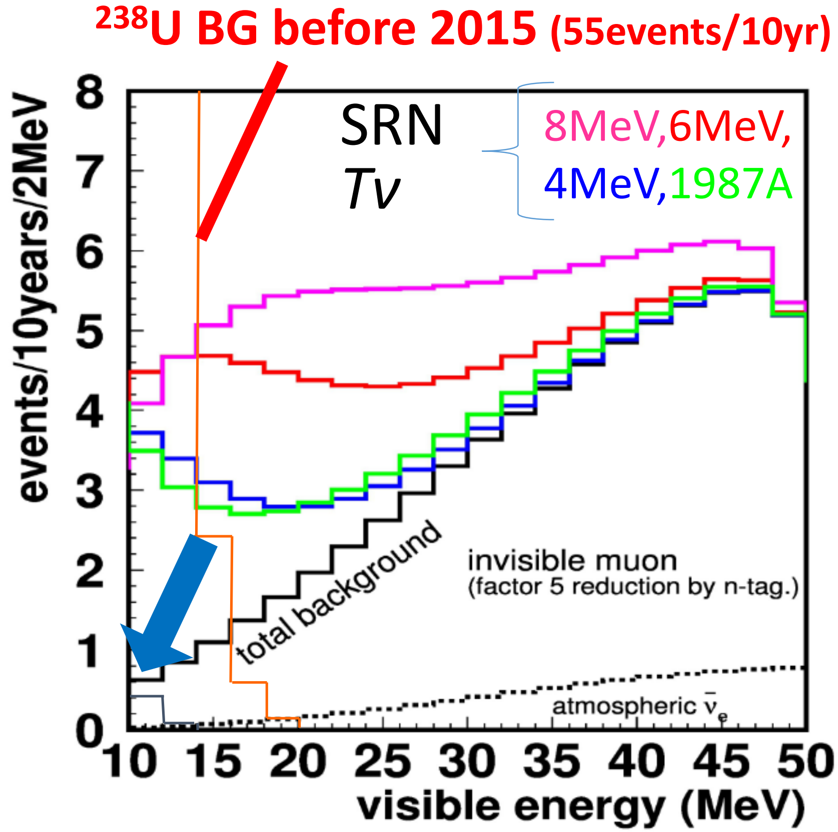
Note that plots are 0 suppressed

Acceptable for existing Lowe analyses.

Ultra high purity Gd production

Impact to the physic analysis





Spectrum of solar neutrino sample
Below 5MeV, it is dominated by radioactive BG.

Spontaneous fission of ^{238}U with γ and n will be BG in SRN search.

Requirement of RI in Gd powder

Requirement for each isotope

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

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

1/10 ~ 1/1000 reductions were needed!

R&D of clean Gd

Researchers :
 Evaluation of “ultra low” RI.
Company side :
make sample based on our input

- Ge detectors
  - Easy to make samples
  - Many detecors（Kamioka, Canfranc, Boulby)
  - Good sensitivity: < 0.5 mBq/kg ($Gd_2(SO_4)_3 \cdot 8H_2O$) for Ra/Th
  - Can check whole decay chain
- ICP-MS
  - Super high sensitivity Th~0.1 mBq/kg($Gd_2(SO_4)_3 \cdot 8H_2O$)
- Rn emanation
  - Racan be measured at ~0.1mBq/kg

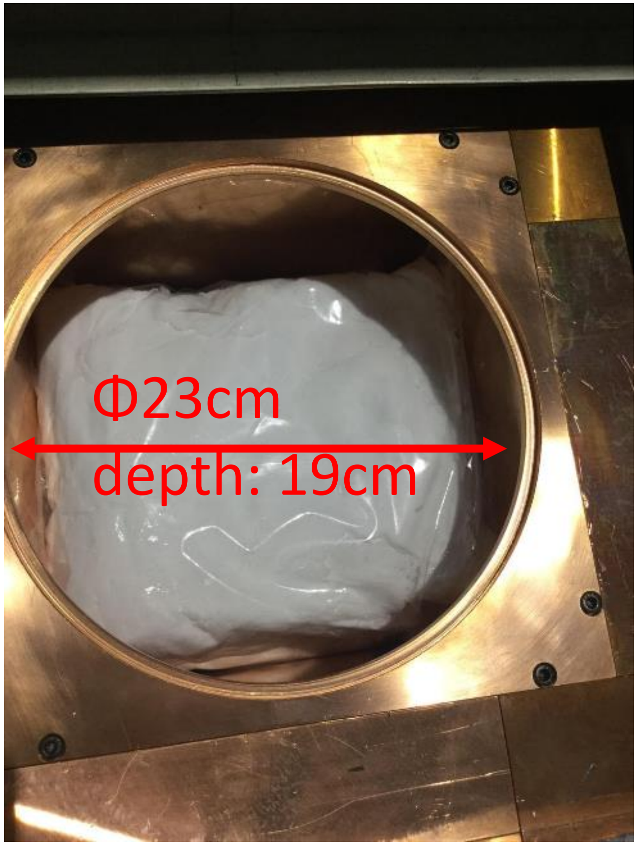
Ge detectors

- We can do parallel measurements at Kamioka, Canfranc, Boulby.
  - Please see following talks.
  - In Kamioka, one of Ge detectors is always running for SK-Gd sample.
- High sensitivity for Ra226.
- High sensitivity measurement in Kamioka is under development.

One of Ge detector
In Kamioka (LabA)

High sensitivity measurement in Kamioka

- In Kamioka, **Ichimura** san is developing high sensitivity measurement.
  - Sample amount : 8kg (before <1kg)
  - Sensitivity for Ra226 :
    < 0.4mBq/kg with 12 days
- Ge detector in Canfranc:
  - Sample amount ~5kg
  - Long term (> 1month) measurement
  - Sensitivity for Ra 226:
    <0.2 mBq/kg



*More improvements for the shield structure will be done so that we can put larger amount of samples

* Ra concentration by resin is under development by Ito san (Okayama) and Ichimura san

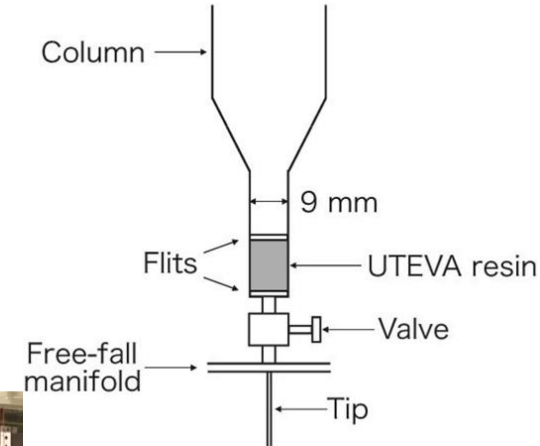
Evaluation of super-low level U/Th

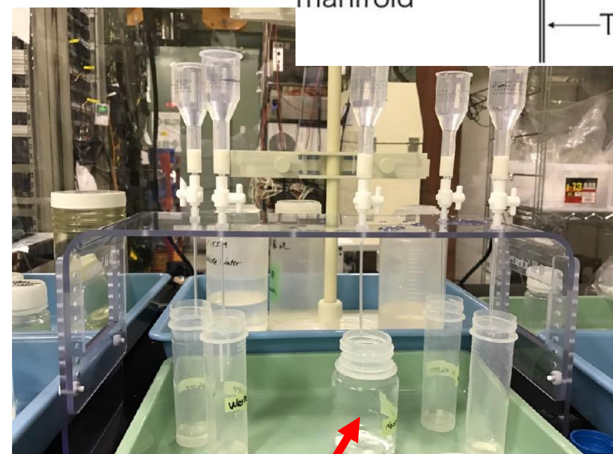
- S. Ito san has developped a method to measure super-low level U/Th in Gd powder
- Requiements:

  238U < 400ppb (5mBq/kg),

  232Th< 12ppt (0.05mBq/kg)

  - Separation and extraction of U/Th from Gd solution using resin
    - To remove matrix effect of Gd
    - S.Ito et al. PTEP 2017 113H01





Auto-sampler is covered by clean booth.→**Class 100**

R&D of super pure Gd sulfate powder

- Radio impurity measured w/ two methods:

Ge detector: Sensitive to almost 0.1 mBq/kg (Canfranc, Boulby and Kamioka)

ICPMS: For isotopes w/ long life (Kamioka)

* 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	-	~ 0.04	< 11	< 0.04	< 10	< 0.04
	^{226}Ra	5	< 0.5	-	—	<0.2	—	< 0.2	—
^{232}Th	^{232}Th	100	< 0.05	-	~ 0.09		0.02	—	0.06
	^{228}Ra	10	< 0.05	-	—	< 0.3	—	< 0.2	—
	^{228}Th	100	< 0.05	-	—	< 0.3	—	< 0.3	—
^{235}U	^{235}U	30	< 3	-	—	< 0.4	—	< 0.3	—
	$^{227}Ac/Th$	300	< 3	-	—	< 1.7	—	< 1.2	—

Unit: [mBq/kg $(Gd_2SO_4)_3$ $8H_2O$]

Company B achieved goals for U, 226Ra and 232Th

First mass production of ultra high purity Gd sulfate

Kamioka mine @2018/12/21

Quality check by company

- Production of 1.5 t has been finished
  - 0.5 ton × 3 batches
  - For each batch, the production company checked its quality.
  - They confirmed that all 3 batches meet our specifications

Elements	Specification	Measured value (ICPMS) batch1	batch2	batch3
U	< 0.4 ppb*	< 0.4 ppb	< 0.4 ppb	< 0.4 ppb
Th	< 0.013 ppb*	< 0.013 ppb [0.011ppb]	< 0.013 ppb [0.004ppb]	< 0.013 ppb [0.004ppb]
Ce	< 0.05 ppm	< 0.01 ppm	< 0.01 ppm	< 0.01 ppm

*Correspond to 238U < 5mBq/kg, 233Th < 0.05 mBq/kg

No specification for Ra because they cannot measure it

Quality check at Kamioka

Goal (mBq/kg)		Bach 1	Bach 2	Batch 3
238U < 5	ICPMS	< 0.02	0.02	0.04
	Ge	<9.45	<9.89	<28.4
232Th< 0.05	ICPMS	0.04	0.02	0.04
	Ge	<0.20	<0.21	0.16
226Ra< 0.5	Ge	0.46±0.24	<0.33	<0.20

ICPMS by Ito san(Okayama U) , Ge by Ichimura san (ICRR)

We confirmed 226Ra is also less than our requirement.

Further reduction of RI with ion exchange resin

For Ra and U

- In $Gd_2(SO_4)_3$ solution, Ra^{2+}
- In case of pH ≧～6, U forms $UO_2(SO_4)_3^{4-}$

They should be removed by ion-exchange resin.

For SK-Gd, resin must not remove Gd^{3+} and SO_4^{2-}

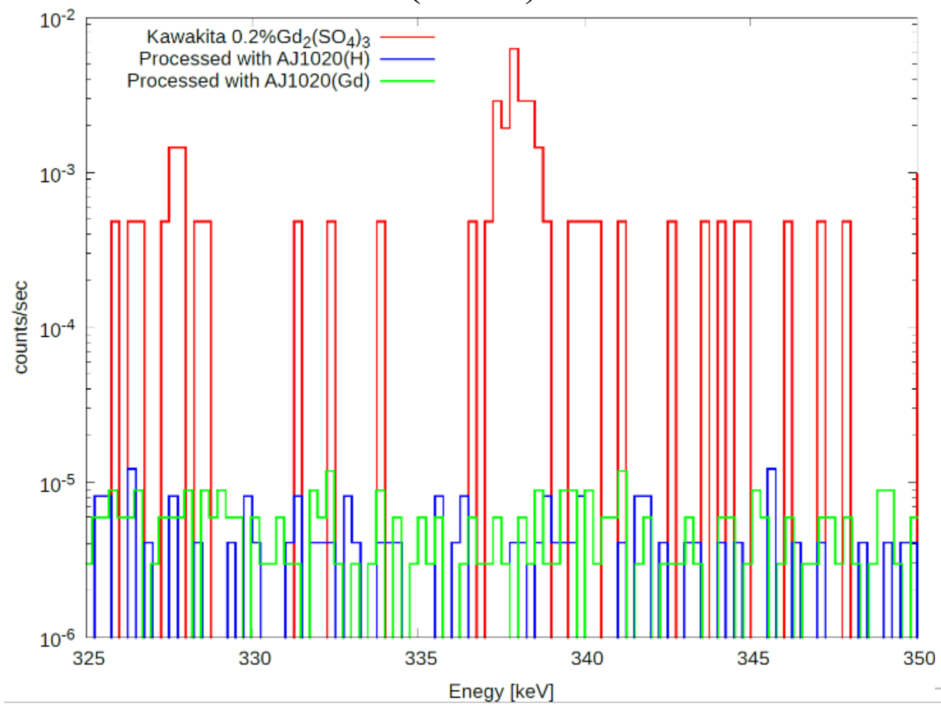
- U：Anion-exchange resin
  - We confirmed U can be removed by this resin.

- Ra：Cation exchange resin
  - Test of Ra removal using Ra rich water.
  - Test for ~mBq/m3 level, we need low BG resin.

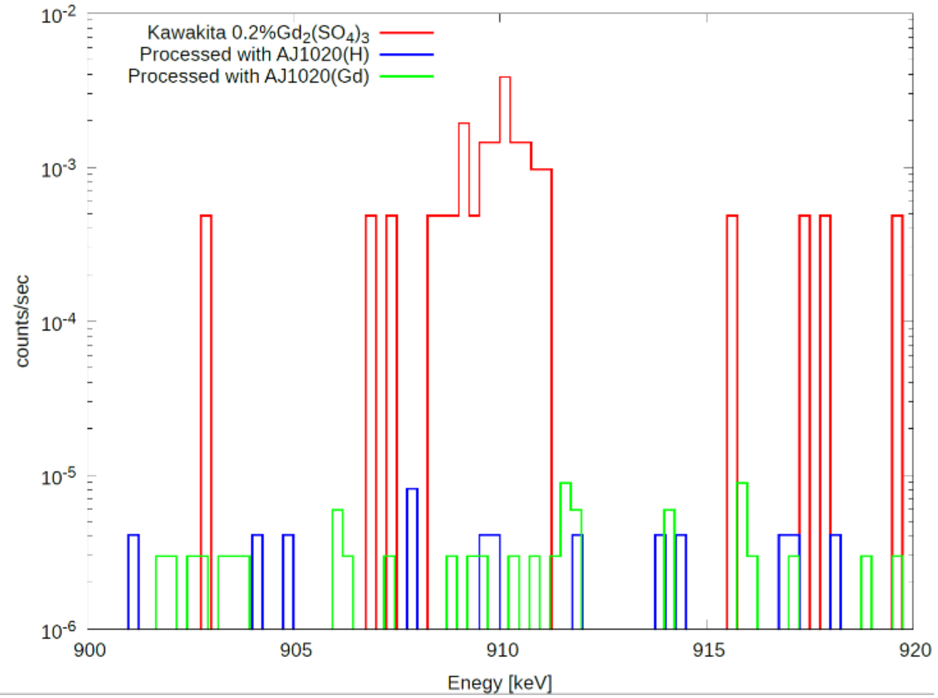
Ra removal by resin using Ra rich Gd water (~500Bq/m^3)

- Red: w/o resin. Blue/Green: resin 1 pass
- Reduction of 3 order of magnitude in 0.2% $Gd_2(SO_4)_3$

^{228}Ra in Th-chain (^{228}Ac)



^{226}Ra in U-chain



Blue: usual cation exchange resin,

Green: special resin which doesn't remove Gd

New Cation exchange resin using low RI Gd-sulfate

Test in EGADS is on going (water transparency), Ra removal test will be done soon.

Summary

- Main R&D of SK-Gd project has been finished.
  - EGADS started in 2009 to evaluate Gd effect to SK.
  - In 2015, we achieved resolving 0.2% (target value) of Gd sulfate after PMT installation without a large loss of water quality.
  - Almost 3 years of Gd water period,
- Current status and plan of SK-Gd will be presented by Nakajima san.
- Let’s enjoy neutron tagging physics with SK-Gd!