Status of Super Kamiokande-Gd

and Hyper Kamiokande

@Saclay

November 13 2017

Hiroyuki Sekiya

ICRR:Institute for Cosmic Ray Research, University of Tokyo

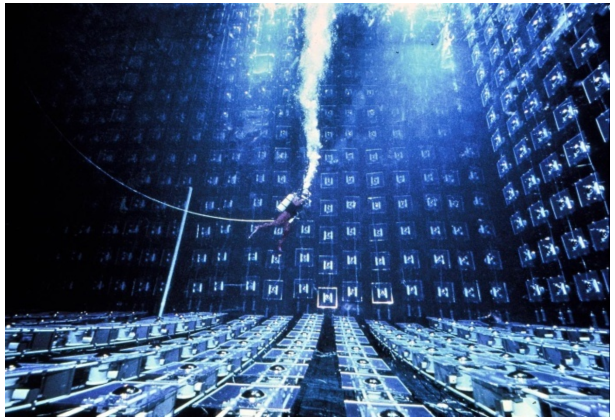
IPMU:Kavli Institute for the Physics and Mathematics of the Universe

NNSO:Next Generation Neutrino Science Organization, University of Tokyo

Total 75 pages

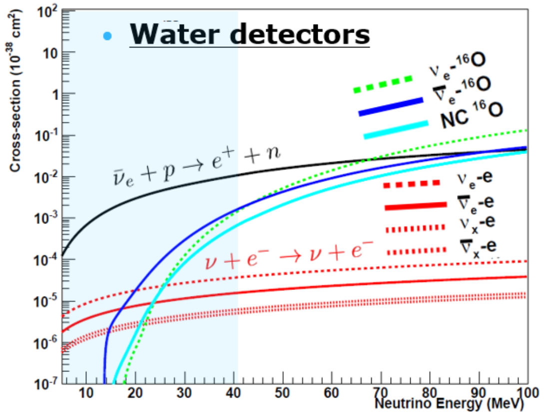
Detectors that observed 1987A

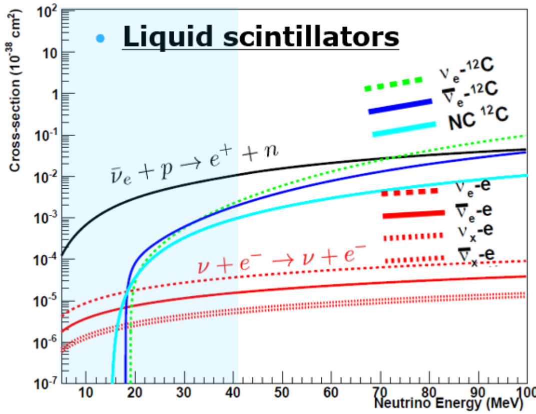
- **Kamiokande-II**
  - 2140 ton FV
  - Water Cherenkov
  - > 8.5MeV



- **IMB-3**
  - ~5000 ton FV
  - Water Cherenkov
  - > 28 MeV

- **BAKSAN**
  - Total 330ton
  - Liquid Scintillator
  - > 10 MeV





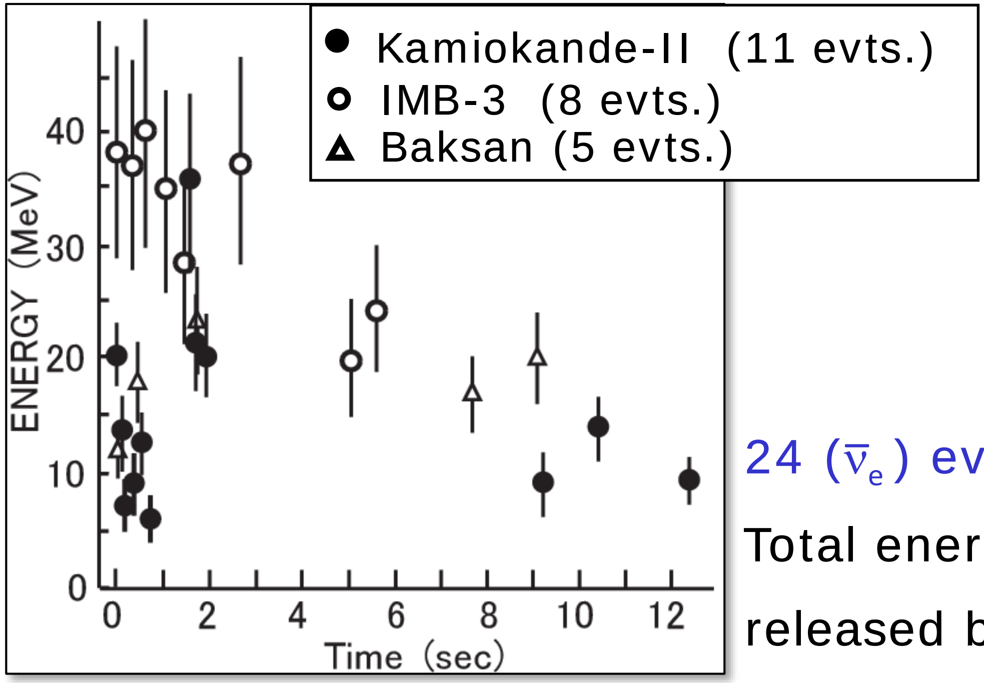
- Essentially, inverse beta decay events.

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

SNOwGLoBES
http://www.phy.duke.edu/~schol/snowglobes/

Supernova neutrinos from 1987A

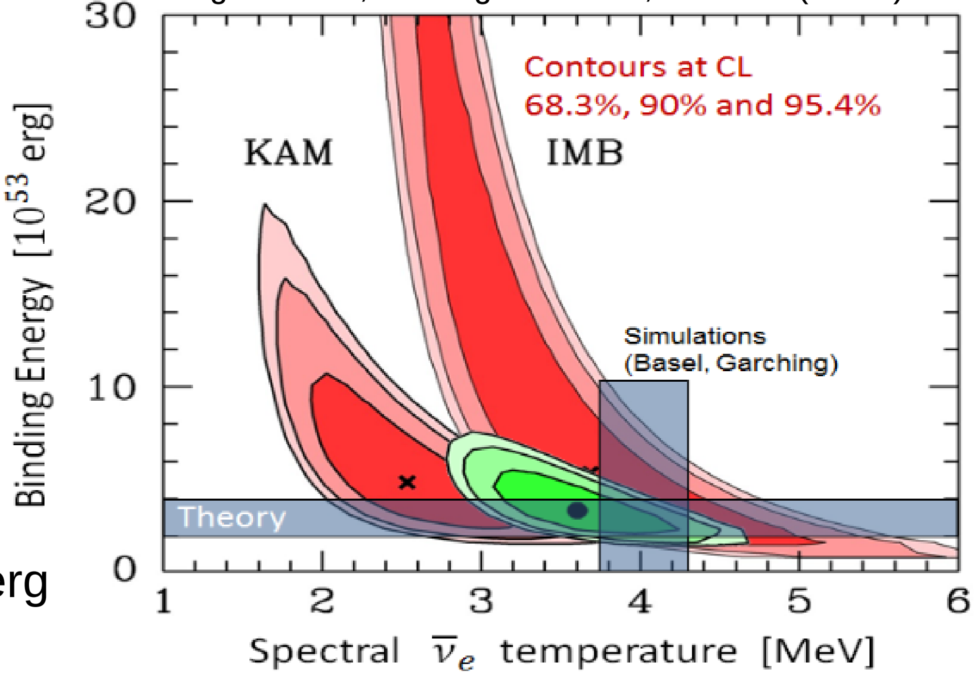
- The only detected SN neutrinos are from LMC(50kpc)



24 ($\bar{\nu}_e$) events in total.

Total energy released by $\bar{\nu}_e$: ~5x10^{52} erg

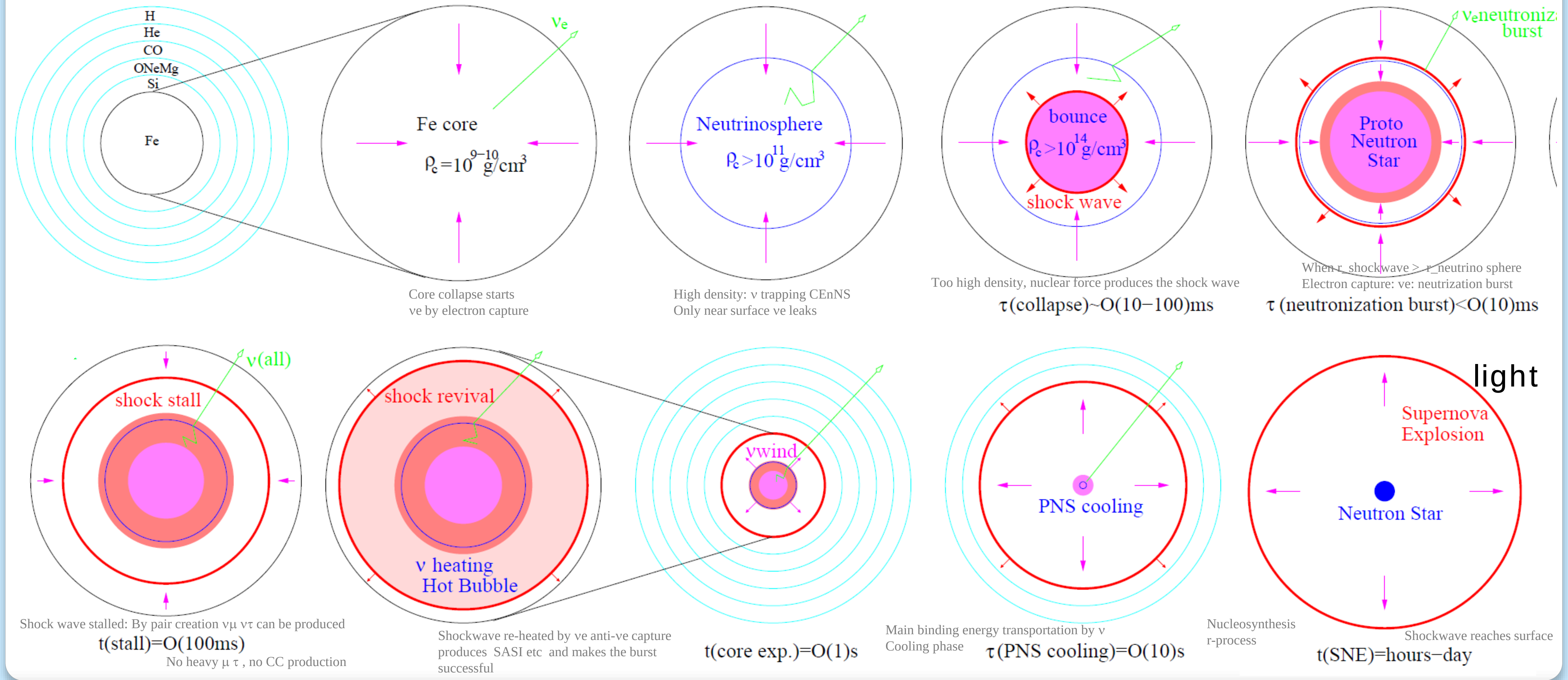
Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194



- The obtained binding energy is almost as expected, but large error in neutrino mean energy. No detailed information of burst process.
- We need energy, flavor and time structure.

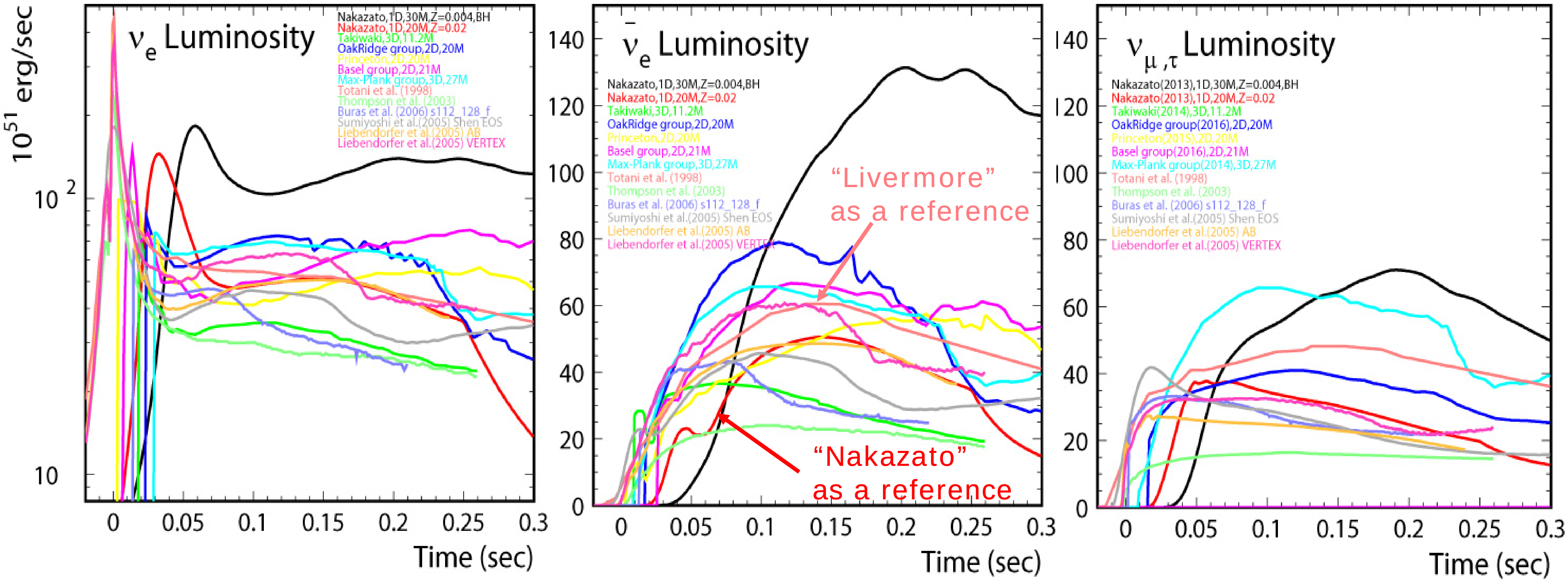
Neutrinos should play the leading role in core collapse supernovae

"standard" CCSN by Hideyuki Suzuki



Many models… Need data!

Figures: H.Suzuki, M. Nakahata

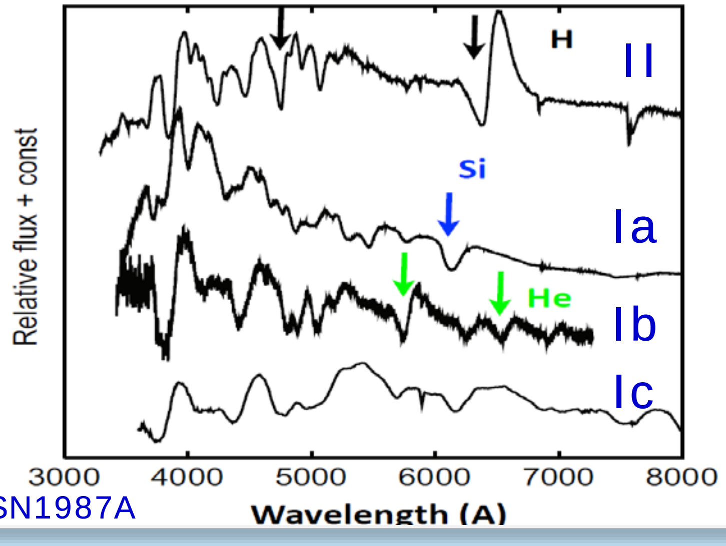


Classification of SNe

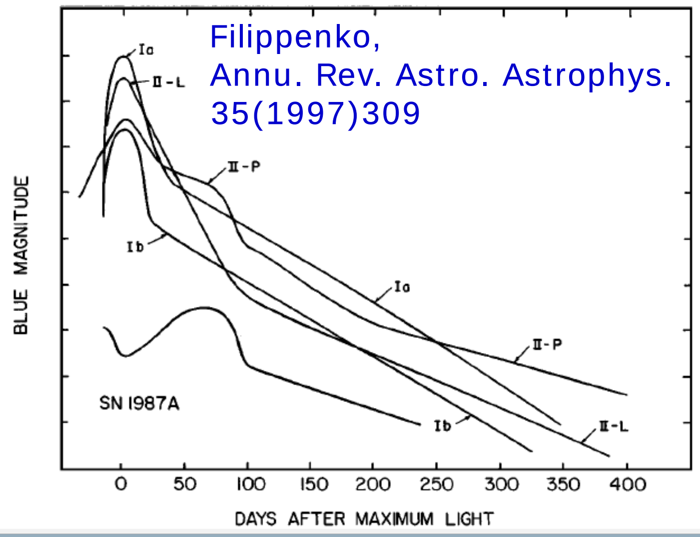
Type		Spectral feature			Light curve	mechanism	
		H	Si	He		thermonuclear	Core collapse
I	Ia	×	○			○	
	Ib	×	×	○			○
	Ic	×	×	×			○
II	IIP	○			Plateau		○
	IIL	○			Linear		○
	IIn	○(nallow)					○

- Hydrogen absorption line: I or II
- Feature in spectra: small letter
- Feature in light curve: capital letter

Outer layer remains in PLbc order



M. Tanaka
@30 years from SN1987A

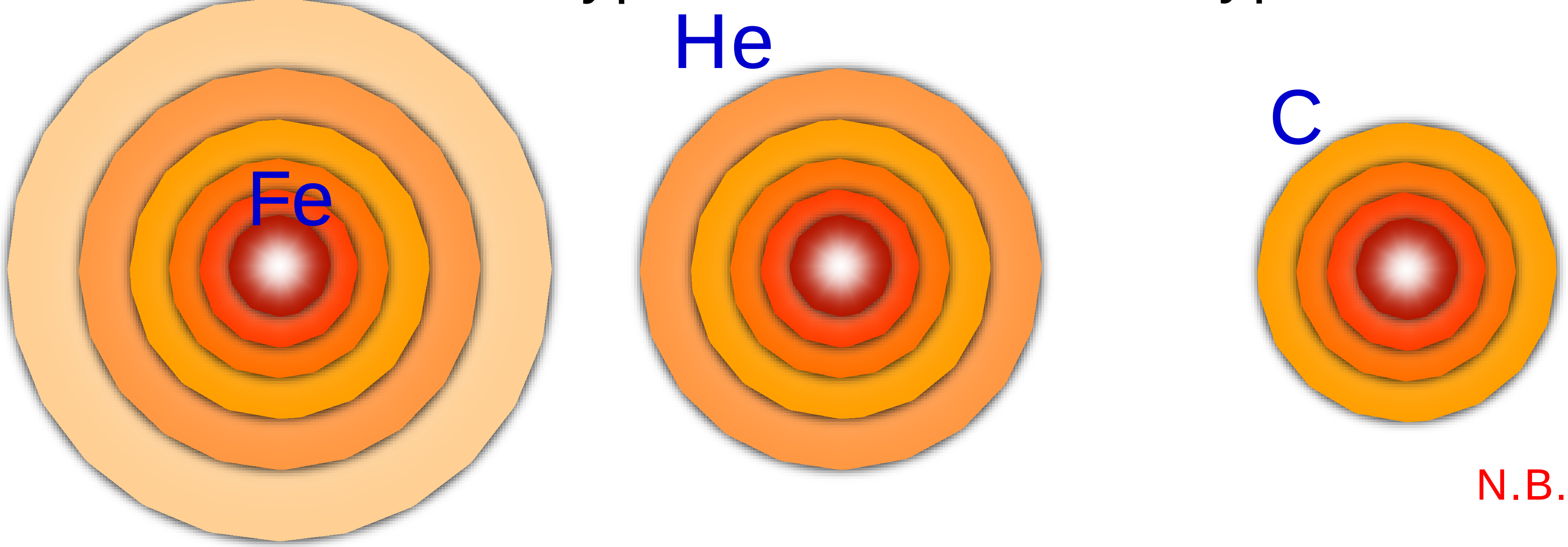


Filippenko,
Annu. Rev. Astro. Astrophys.
35(1997)309

Progenitors of CCSN

M. Tanaka
@30 years from SN1987A

- Type II H
- Type Ib
- Type Ic



N.B. figures in arbitrary size

Red supergiants
$R \sim 1000 R_\odot$

Wolf-Rayet stars
$R \sim 1\text{-}10 R_\odot$

Average shock speed inside of the star
$v \sim 10{,}000\ \mathrm{km\ s^{-1}} = 10^9\ \mathrm{cm\ s^{-1}}$

$\Delta T = T_{optical} - T_{neutrino}$

$R_\odot \sim 7 \times 10^{10}\mathrm{cm}$

$\Delta T \sim R/v \sim 1\mathrm{day}$

$\Delta T \sim R/v \sim 1\text{-}10\mathrm{min}$

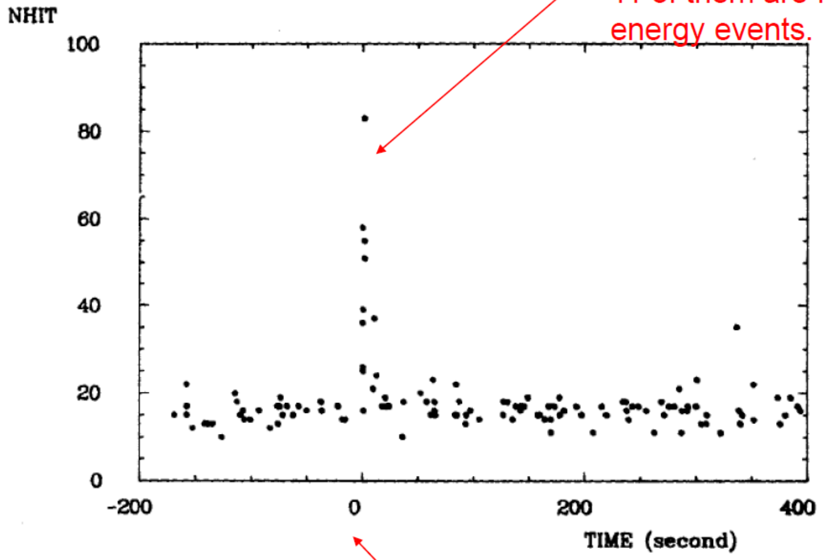
30 years ago

- SN1987A

M. Nakahata@30 years from SN1987A

Vertical axis:
Number of hit PMTs for each event,
which is almost proportional to energy

12 events within 13sec.
11 of them are higher
energy events.



$T_{neutrono}$ = 23.31 UTC

at 16:35:35 on Feb.23, 1987

ΔT~ 3 hours

http://www.cbat.eps.harvard.edu/iauc/04300/04316.html

Circular No. 4316

Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION
Postal Address: Central Bureau for Astronomical Telegrams
Smithsonian Astrophysical Observatory, Cambridge, MA 02138, U.S.A.
TWX 710-320-6842 ASTROGRAM CAM Telephone 617-495-7244/7440/7444

SUPERNOVA 1987A IN THE LARGE MAGELLANIC CLOUD

W. Kunkel and B. Madore, Las Campanas Observatory, report the discovery by Ian Shelton, University of Toronto Las Campanas Station, of a mag 5 object, ostensibly a supernova, in the Large Magellanic Cloud at R.A. = 5h35m.4, Decl. = -69 16' (equinox 1987.2), 18' west and 10' south of 30 Dor and possibly involved with the association NGC 2044. The discovery was made around Feb. 24.23 UT on a 3-hr exposure with a 0.25-m astrograph beginning on Feb. 24.06, and the object had evidently brightened by at least about 8 mag since the previous night. An independent suspected sighting was made visually by Oscar Duhalde, also at Las Campanas, around Feb. 24.2. The object had brightened to about mag 4.5 by Feb. 24.33.

F. M. Bateson, Royal Astronomical Society of New Zealand, informs us that the object was discovered independently by Albert Jones, Nelson, on Feb. 24.37 UT (position R.A. = 5h35m.8, Decl. = -69 18', equinox 1950.0) at mag 6.5-7.0 (in clouds); he estimated mv = 5.1 on Feb. 24.46. B. Moreno and S. Walker, Auckland Observatory, obtained V = 4.81, B-V = +0.085, U-B = -0.836 on Feb. 24.454 UT.

R. H. McNaught, Siding Spring Observatory, communicates the following visual magnitude estimates by G. Garradd (G) and himself (M): Feb. 24.455, 4.8 (M); 24.472, 4.8 (M); 24.635, 4.4 (G); 24.679, 4.5 (M); 24.717, 4.4 (M). McNaught obtained the following precise position with the University of Aston Hewitt Satellite Schmidt camera: R.A. = 5h35m50s.22, Decl. = -69 17'59".2 (equinox 1950.0, uncertainty 2"). The object appears on films from the previous night: Feb. 23.443, 6.0; 23.445, 6.2. He also notes the position of a blue star, of mv about 12 and not obviously variable during the past century (through Feb. 22.4): R.A. = 5h35m50s.12, Decl. = -69 17'58".0 (equinox 1950.0; x = 15447, y = 9261 in the Harvard LMC system). Films by Garradd confirm that the field was identical down to mag 14.5 on Jan. 24 and Feb. 22.

B. Warner, University of Texas, reports that a spectroscopic observation by J. Menzies on Feb. 24.9 UT with the 1.9-m reflector at the South African Astronomical Observatory shows the 615-nm dip, indicating that the object may be a supernova of type I.

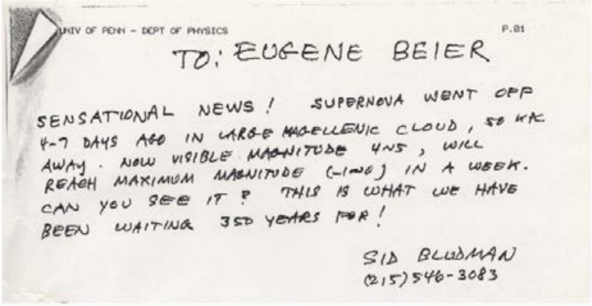
$T_{optical}$ = 23.44 UTC

SN1987A@Kamiokande

M. Nakahata@30 years from SN1987A and the future

Day 3

Feb. 25th, 1987: A fax was sent to Univ. of Tokyo



UNIV OF PENN - DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4~5, WILL REACH MAXIMUM MAGNITUDE (~1~2) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215)546-3083

Totsuka asked Kamioka shift to send recent data tapes.

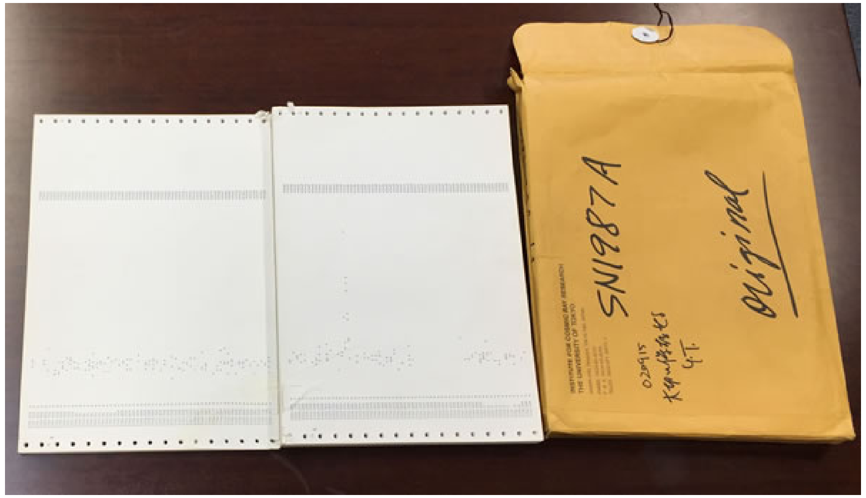
Day 4

Feb. 27th(Fri): The data tapes arrived at Univ. of Tokyo and Nakahata analyzed the data.

NHK

Day 5

Feb. 28th(Sat): Hirata and Nakahata found the neutrino signals and made plots with Totsuka and Oyama.



Day 6

Mar. 1st(Sun): Totsuka tried to report this discovery to Koshiba but it was not possible because Koshiba was at the Hakone hot spring….
Totsuka went to Kamioka for a work.

Day 7

Mar. 2nd(Mon): Nakahata reported the discovery to Koshiba. Koshiba said "You must analyze all Kamiokande data and demonstrate that this is the only signal."

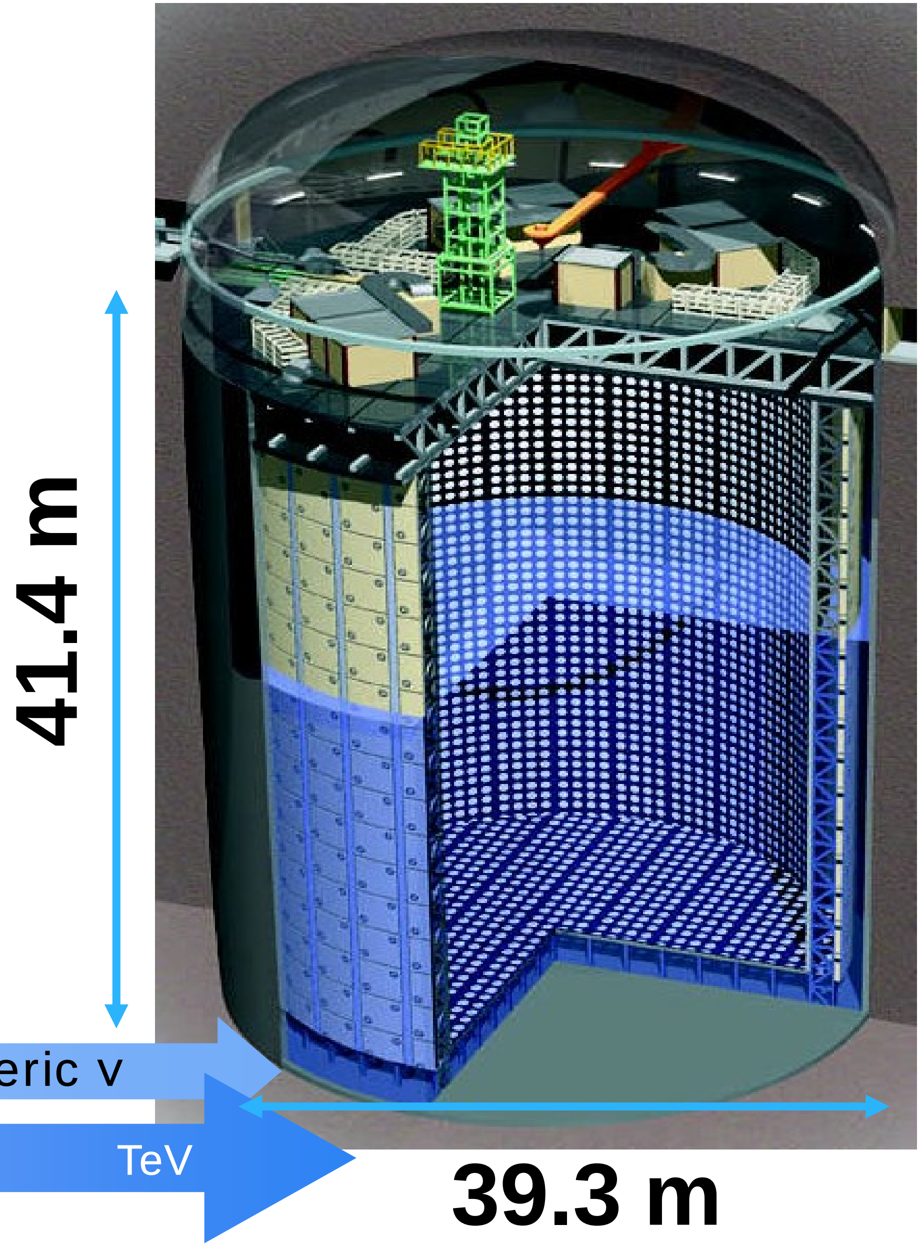
Mar. 2nd – 6th : Data analysis day after day without (enough) sleep

Day 12

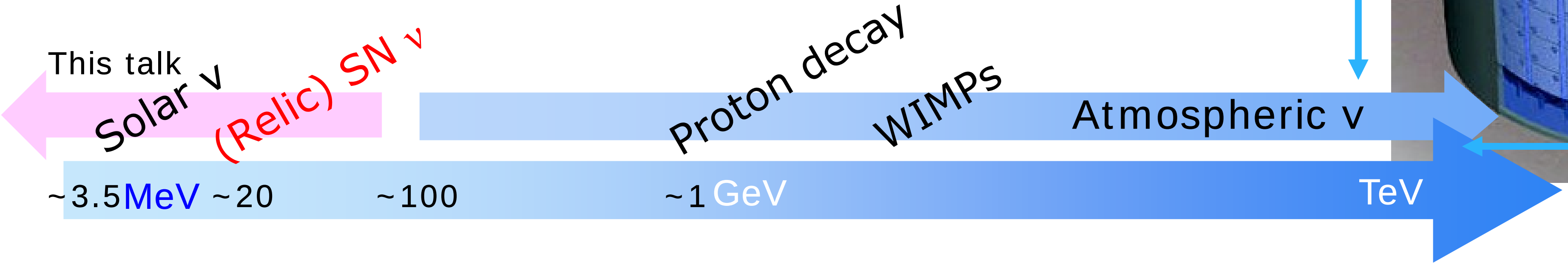
Mar. 7th(Sat): The paper was sent to Physical Review Letters by a postal mail.

Super-Kamiokande

- 50kton pure water Cherenkov detector
- 1km (2.7km w.e) underground in Kamioka
- 11129 50cm PMTs
  in Inner Detector
- 1885 20cm PMTs
  in Outer Detector



Physics targets of Super-Kamiokande



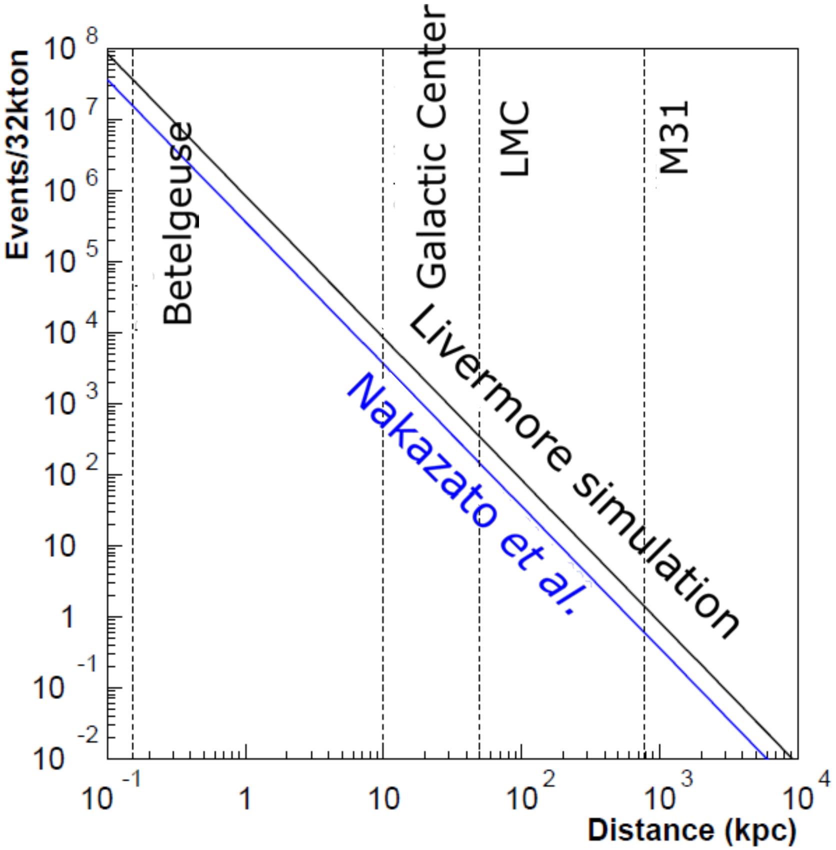
The SN detector

Supernova at 10 kpc
events in 32kton

Livermore: ApJ.496,216(1998)
Nakazato: ApJ.Suppl. 205 (2013) 2
$20M_{sun}$, trev=200msec, z=0.02

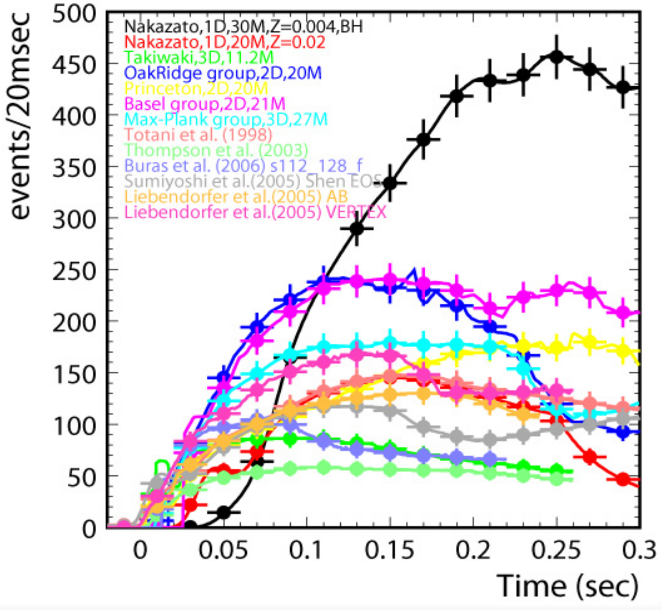
- **Super Kamiokande IV**
  - 32k ton FV > 4.5 $\mathrm{MeV}_{(kin)}$
  - 8.8k ton FV > 3.5$\mathrm{MeV}_{(kin)}$

	Livermore	Nakazato
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

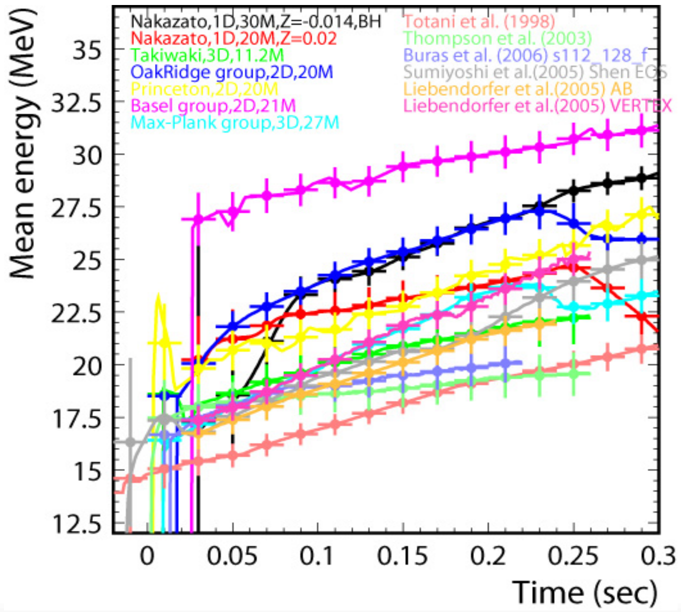


Enough statistics to discriminate models!

Time variation of event rate

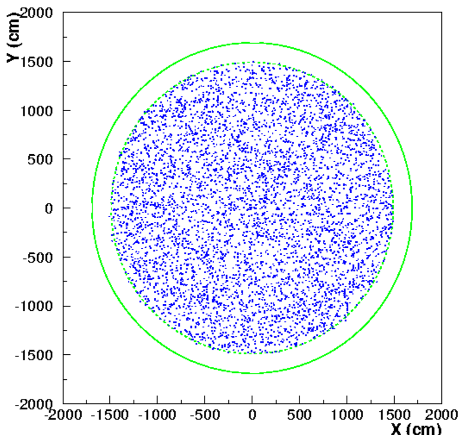


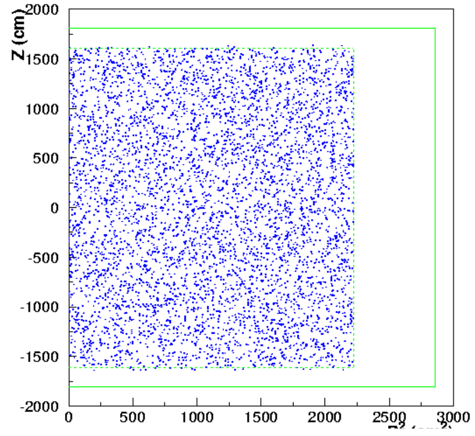
Time variation of mean energy

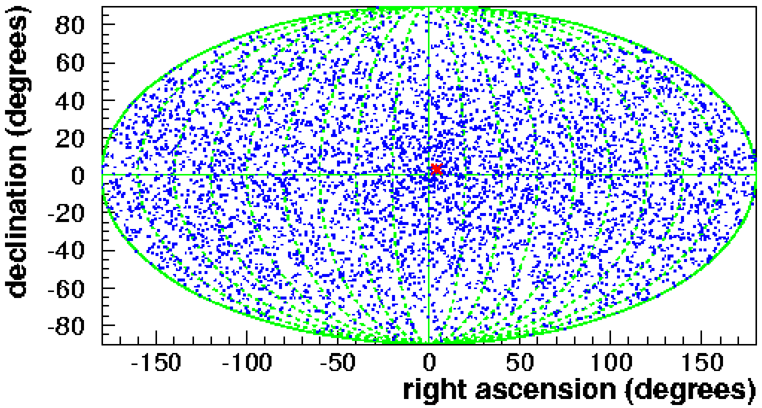


If it happens now@Super-K

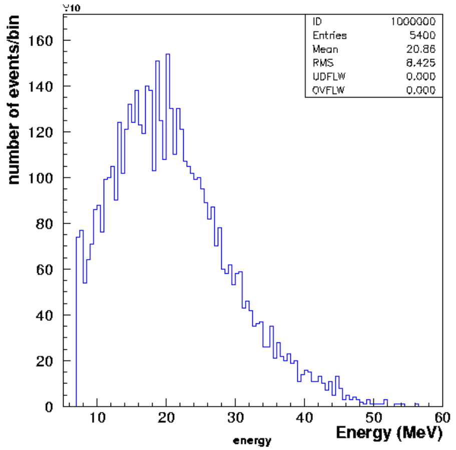
- SN simulation @10kpc (RA=0, decl=0), generated by Wilson model
- SNwatch: Real-time supernova neutrino burst monitor   Astropart. Phys. 81(2016)39
  - **In several minutes, alarm to shifts, automatic e-mail and phone call to the experts**

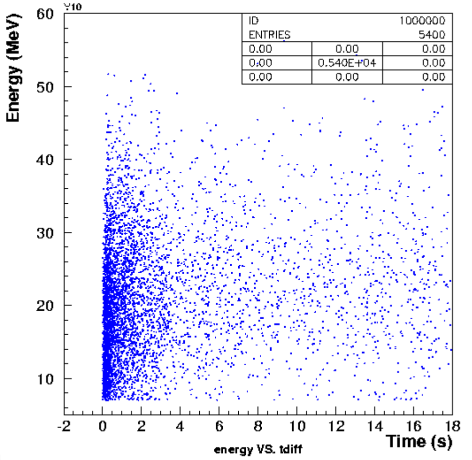







```
Subject: DRILL!: SNwatch GOLDEN alarm of all info.: run=074132 srun=000434
Date: Sat, 24 Oct 2015 23:25:08 +0900

*********** event cluster information ***********

The followings are information of the SN candidate.

Time Information:
--------------------------------------------------
Fst evt info.: evtno=1028040 time= 2015/Oct/24 23:20:42 (JST)
Lst evt info.: evtno=1036600 time= 2015/Oct/24 23:20:59 (JST)
--------------------------------------------------
Fst evt GPS time = 2015/Oct/24 14:20:42 2838[us] (UT)
Lst evt GPS time = 2015/Oct/24 14:20:59 889838[us] (UT)
--------------------------------------------------
Time range (sec.)      | 17.8870
--------------------------------------------------

Basic Information:
--------------------------------------------------
Run number             | 74132
--------------------------------------------------
Subrun number          | 434
--------------------------------------------------
Number of events       | 5227
 in the cluster        |
--------------------------------------------------
Estimated distance     | 7.55 to 10.36 (kpc)
for +-1 sigma range    |
```

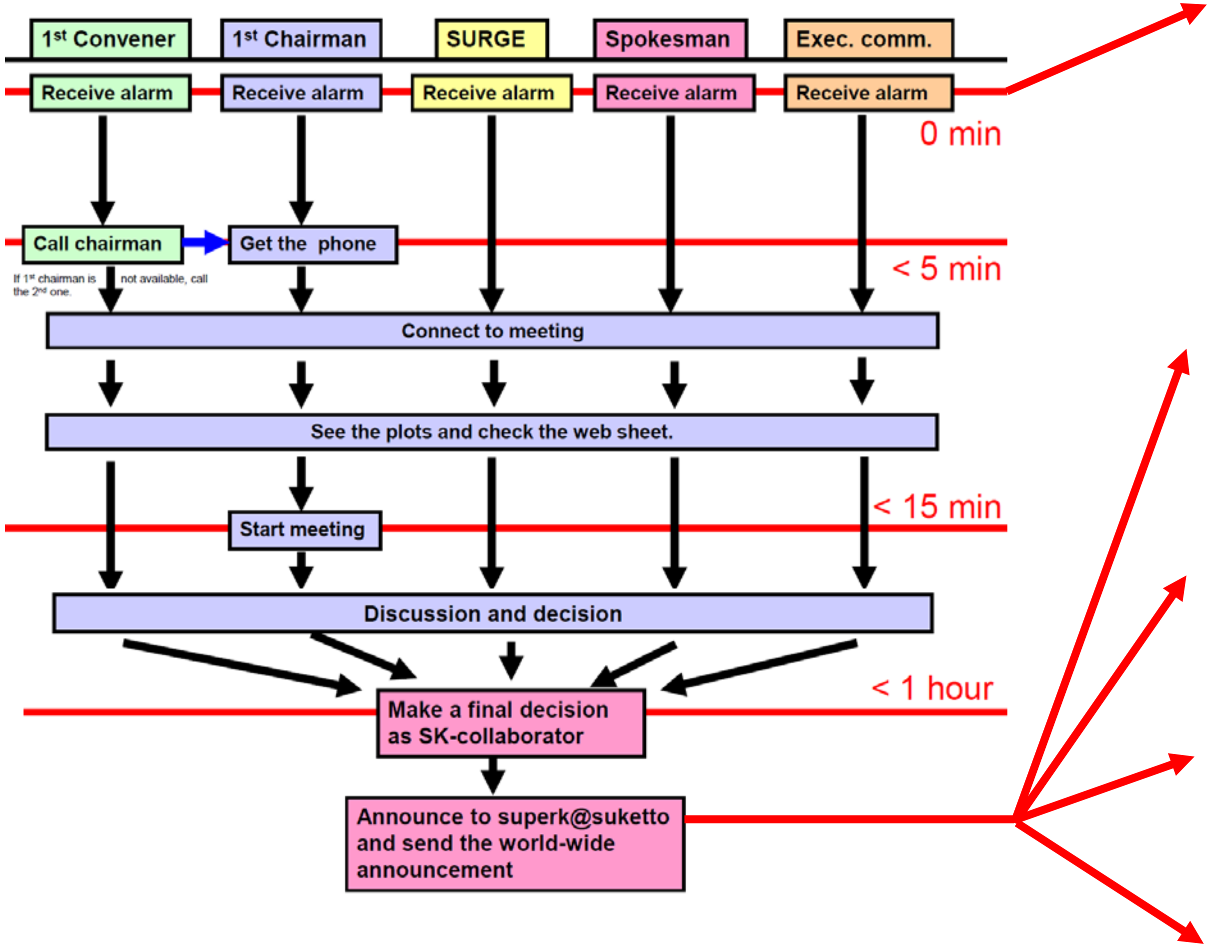




- Golden Alarm:
  - 60 events in 20sec
- The process time depends on the total number of event
  - 1st alarm is issued after processing initial 1000 events
    - 1-2min
  - After finishing all the events, 2nd alarm

Announcements

SURGE:
Supernova Urgent Response Group of Experts



SNEWS level "0"

SNEWS:
SuperNova Early Warning System

http://snews.bnl.gov/

Super-K (Japan), LVD (Italy), Ice Cube (South Pole), KamLAND (Japan), Borexino (Italy) Daya Bay (China), and HALO (Canada).

- IAU CBAT: International Astronomical Union Central Bureau for Astronomical Telegrams

  http://www.cbat.eps.harvard.edu/

- ATEL: The Astronomer's telegram

  http://www.astronomerstelegram.org/

- GCN: The Gamma-ray Coordinates Network

  https://gcn.gsfc.nasa.gov/

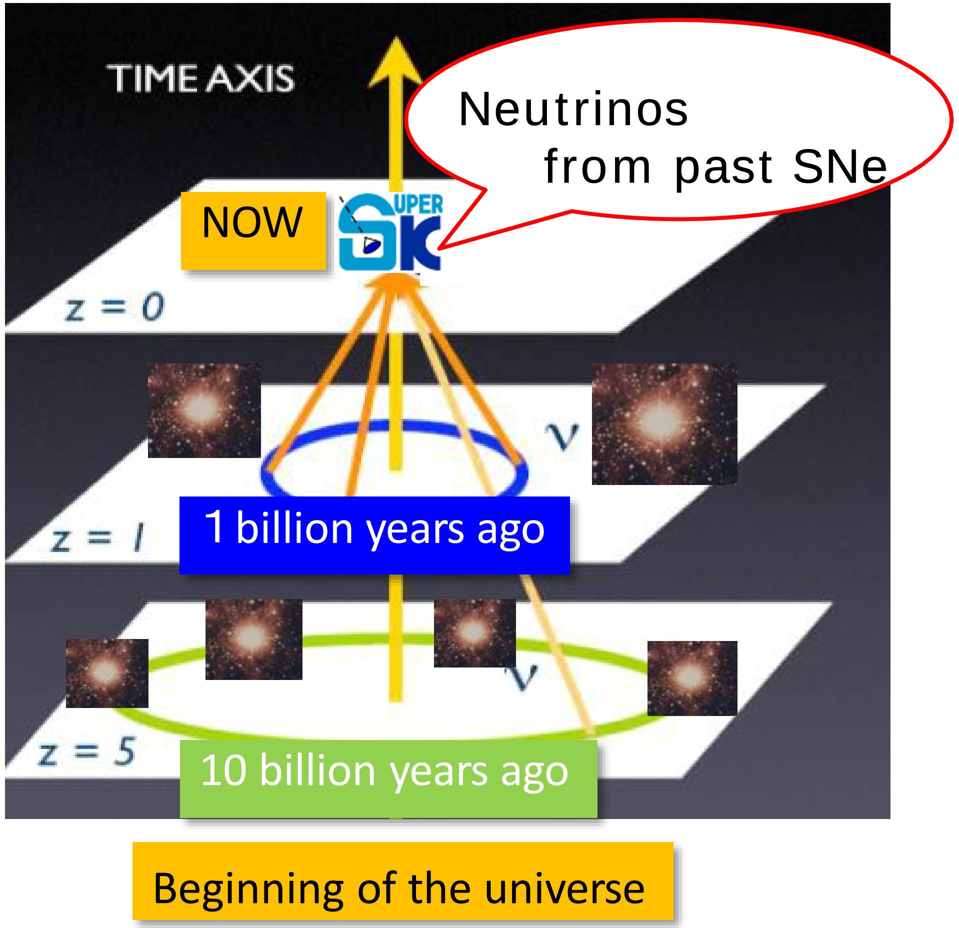
- SNEWs level ”3” confirmed alarm

Anyway… 30 years has been passed

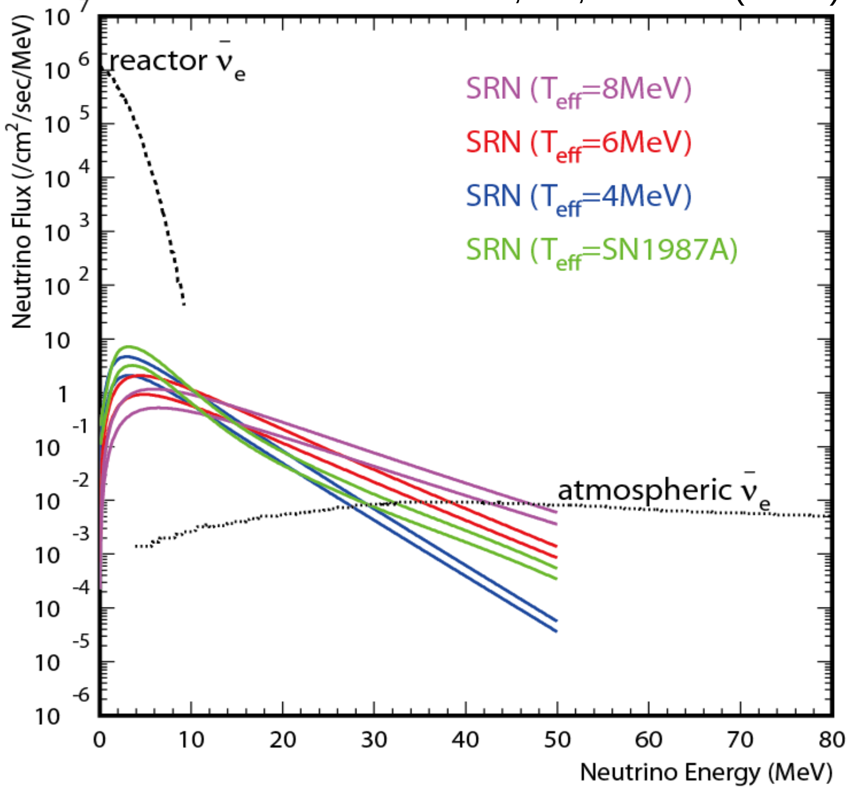
Supernova neutrino from z=5

Diffuse Supernova Neutrino Background(DSNB)

- 10^{10} stellar/galaxy ×10^{10} galaxies ×0.3%(become SNe) ~*O*(10^{17})SNe



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

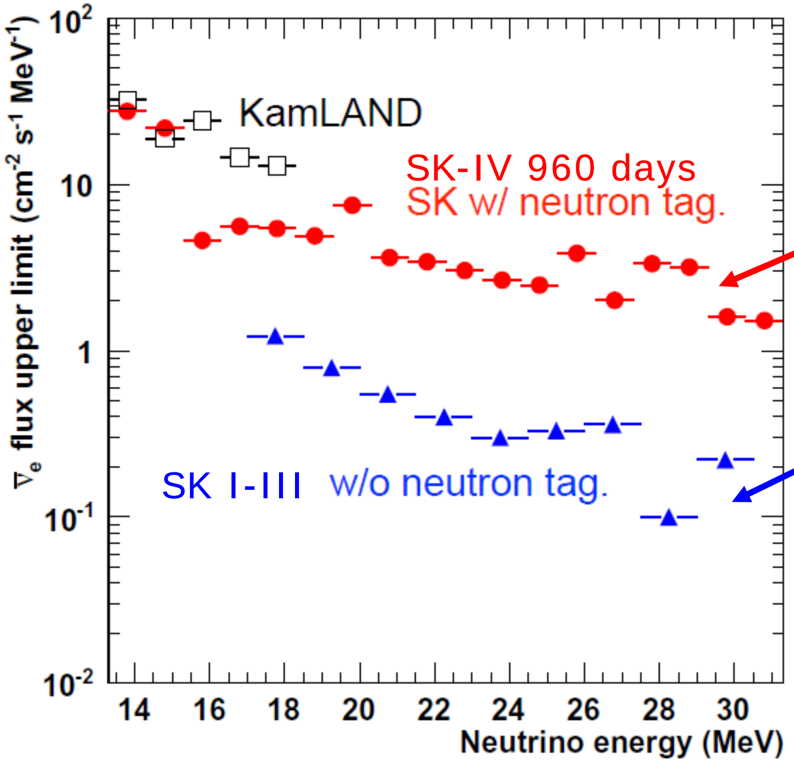


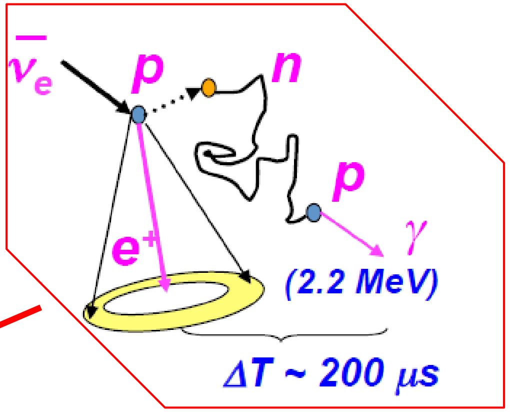
Search window for SK : From ~10MeV to ~30MeV

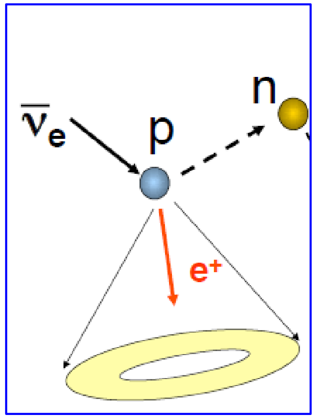
Status of DSNB search

Comparison with expected $\bar{\nu}_e$ signal

SK collaboration, Astropart. Phys. 60, 41-46 (2015)



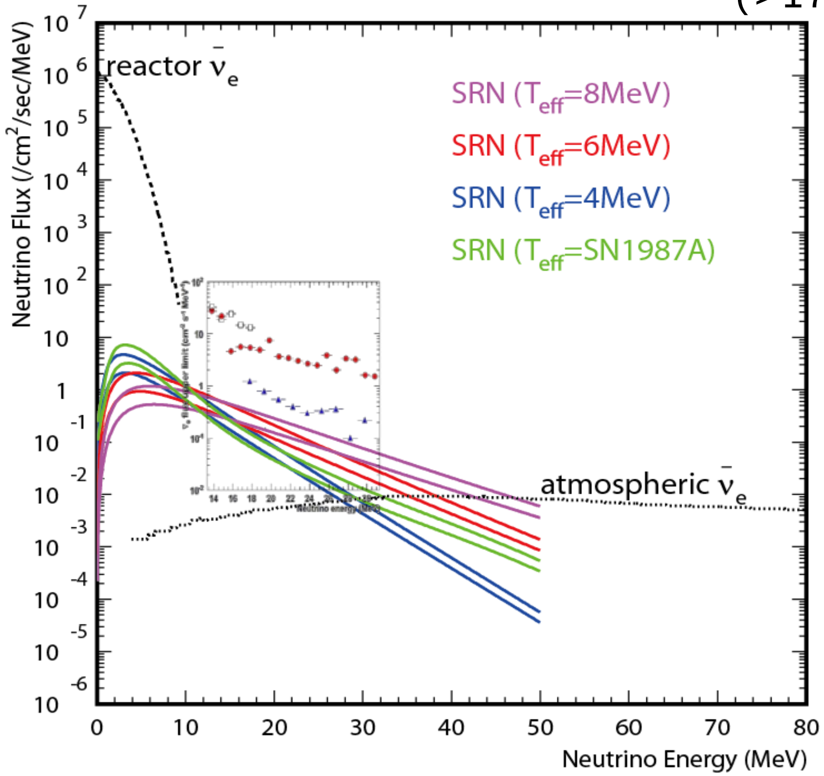




Theoretical flux prediction : 0.3~1.5 /cm^2/s

Current best limit by SK: 2.8~3.1 /cm^2/s

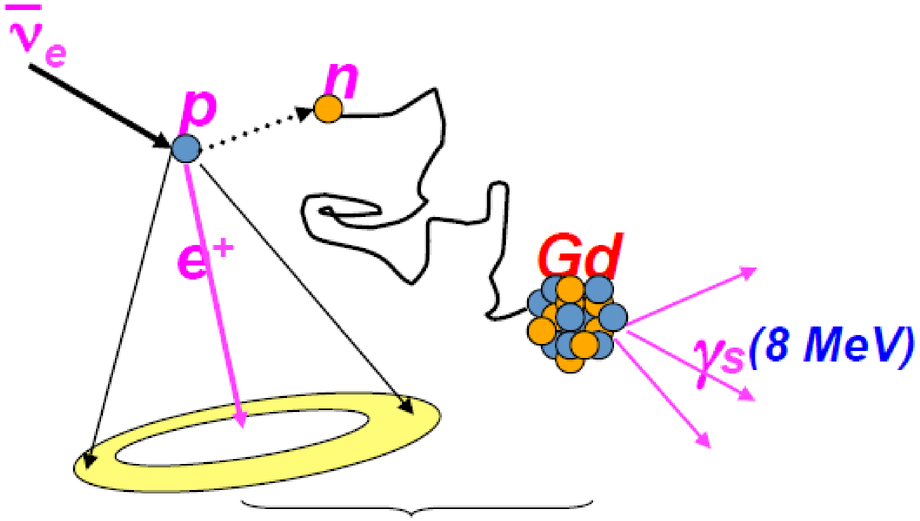
(>17.3MeV)



- Limited by backgrounds
  - More than 1 order BG reduction is needed!
  - Neutron tagging efficiency (by proton) is low... RI BG and low trigger efficiency

The Gadolinium project

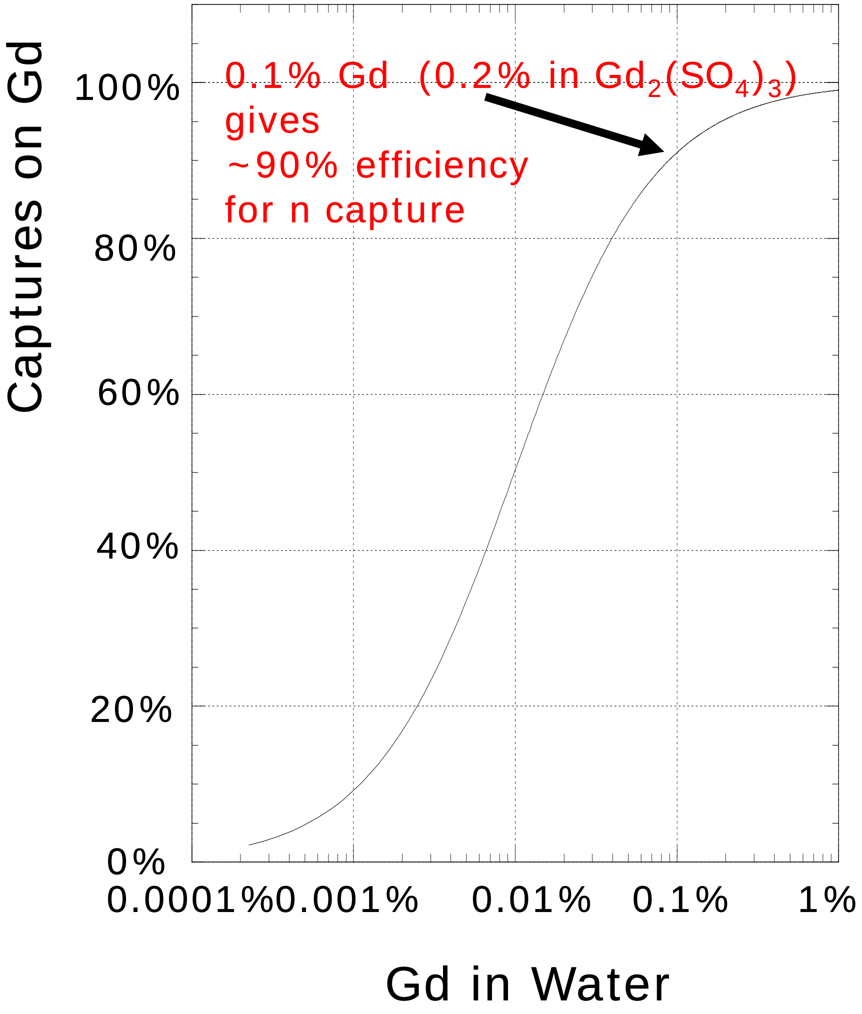
- To identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.
- Large cross section for thermal neutron (48.89kb)
- Neutron captured Gd emits 3-4 γs in total 8 MeV
  - Well above most of BG from RIs and the SK trigger threshold
- 90% of Gd capture efficiency at 0.1% loading
- $Gd_2(SO_4)_3$ was selected to dissolve→0.2% loading
  - In Super-K, it corresponds to 100 tons of loading



for 0.1% Gd

$Gd_2(SO_4)_3$

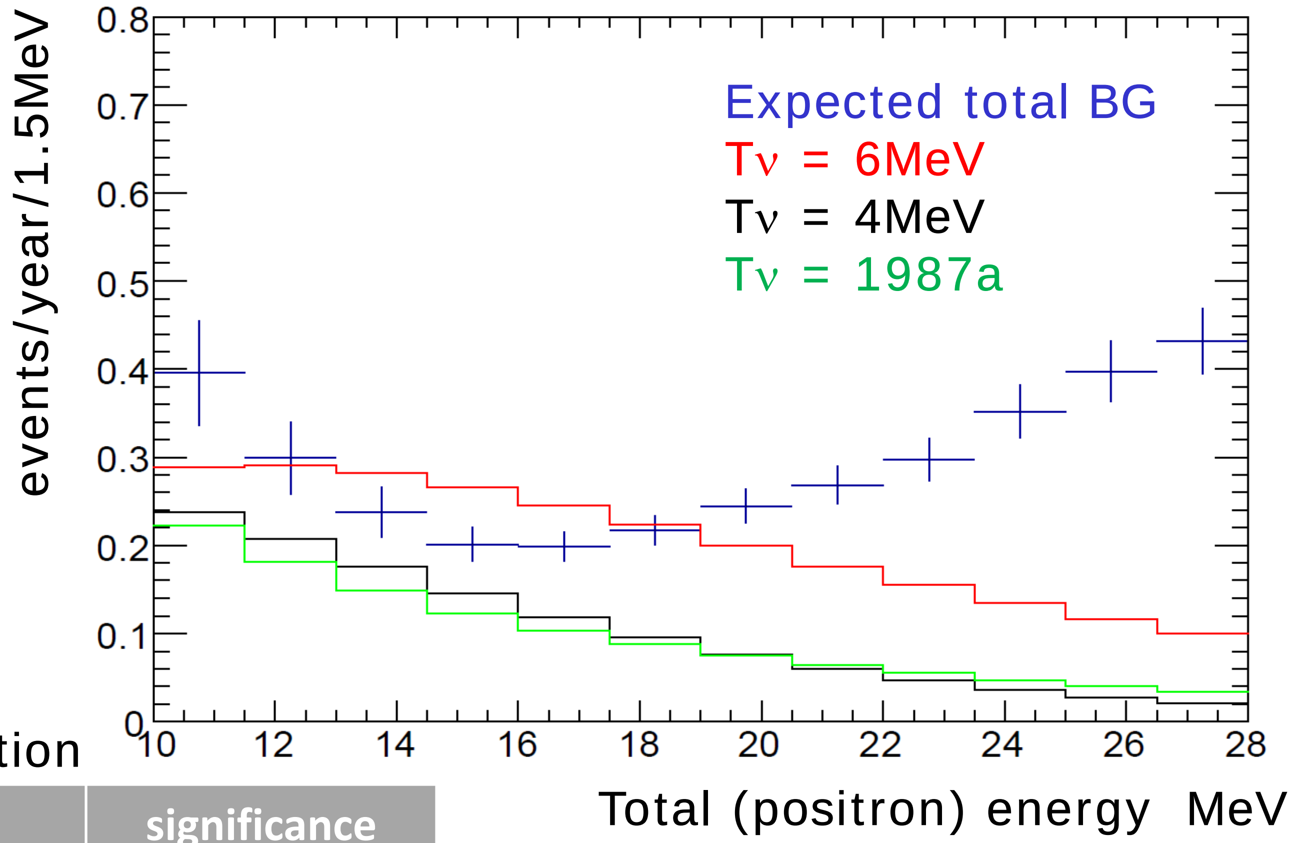
Beacom and Vagins PRL93,171101 (2004)



Expected signal

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

- It depends on typical/actual SN emission spectrum



DSNB events number with 10 years observation

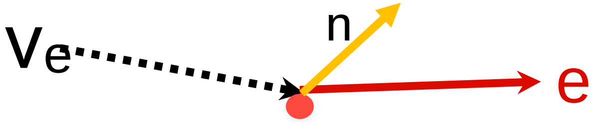
HBD models	10-16MeV (evts/10yrs)	16-28MeV (evts/10yrs)	Total (10-28MeV)	significance (2 energy bin)
T_{eff} 8MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987a	5.1	6.8	11.9	2.1 σ
BG	10	24	34	----

- First observation is within SK-Gd's reach!
- Further BG reduction with topological cuts (NN,..) are expected.

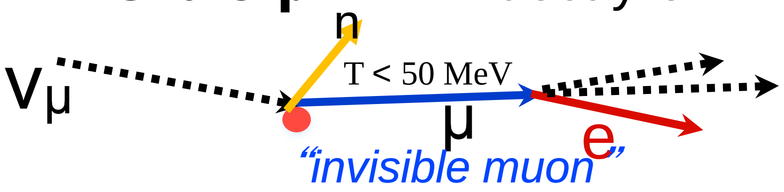
Remaining BG: atmospheric neutrino

- CC

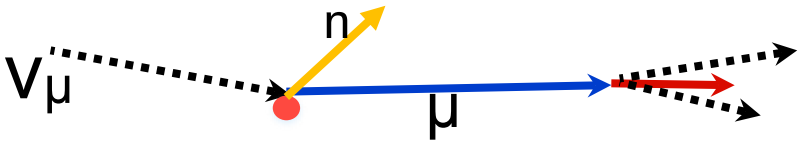
(anti-) ν_e CC



Invisible μ n + decay-e

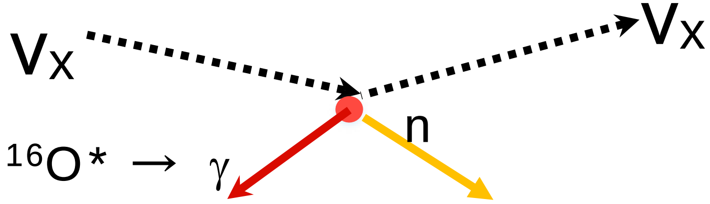


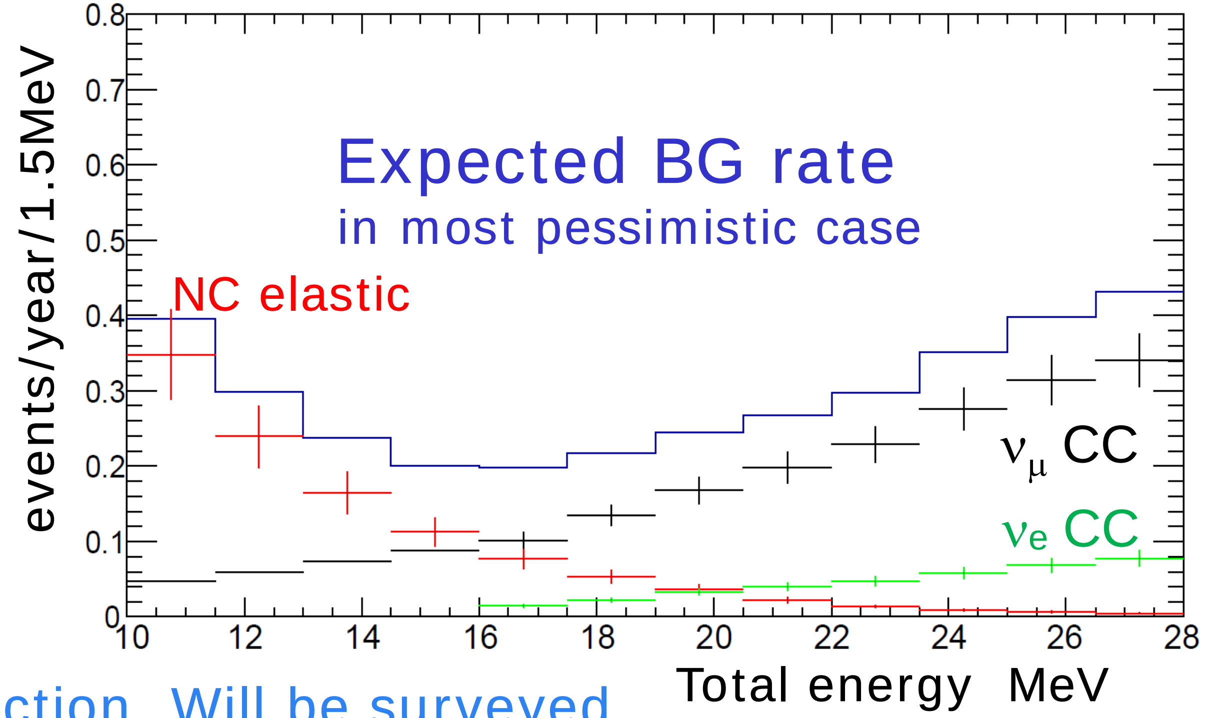
μ generation



- NC

NC elastic de-excitation γ

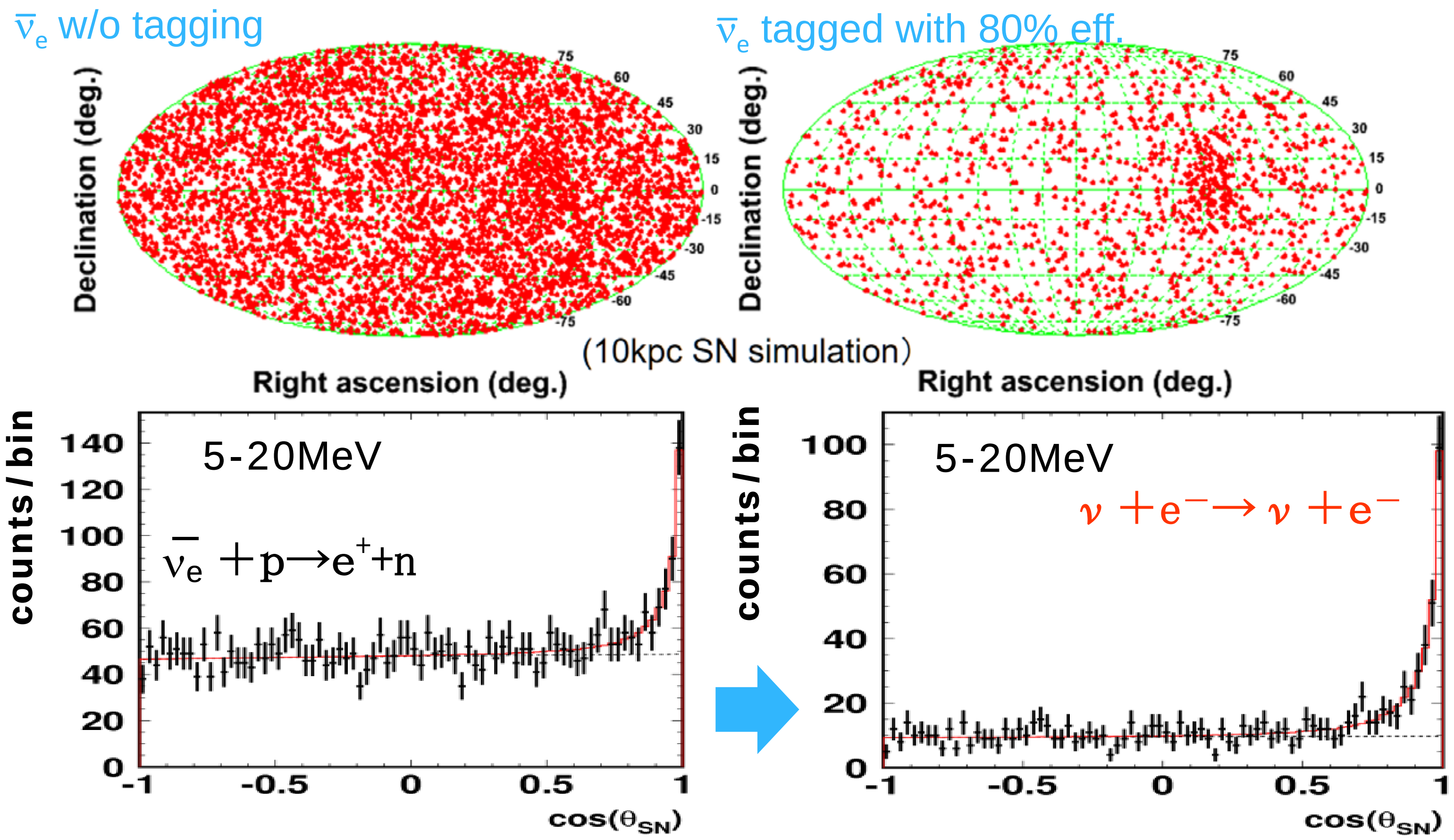




Vertex information gives further BG reduction. Will be surveyed.

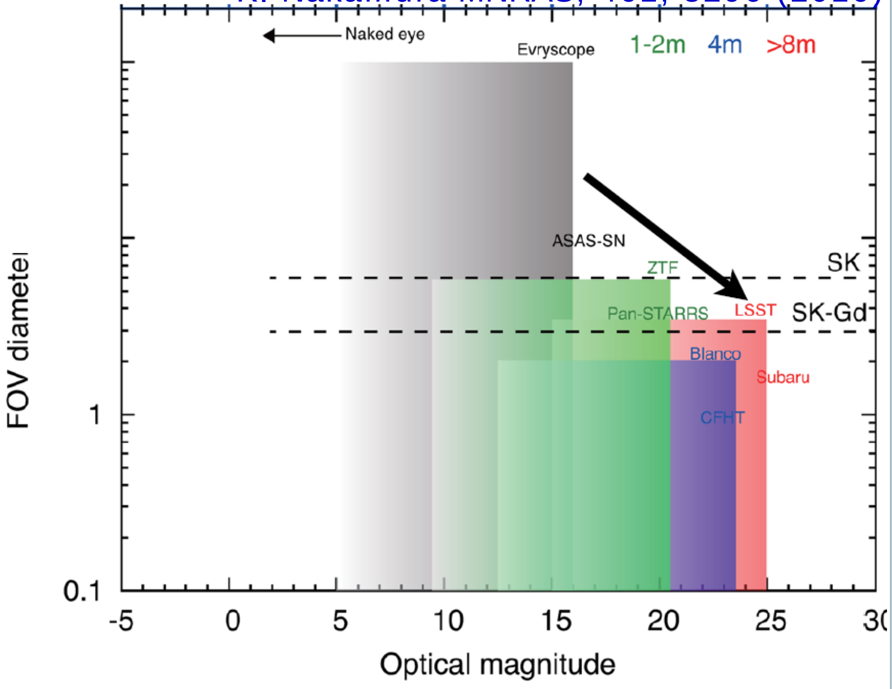
SK-Gd for SN burst

- If $\bar{\nu}_e$ can be tagged, directional events (ν+e scattering events) are enhanced. Pointing accuracy will be improved. For 10kpc SN ~5° → ~3° (@90%C.L.)



It helps the large optical telescope!

K. Nakamura MNRAS, 461, 3296 (2016)



R&D items and recent progresses

1st level
Environmental Safety

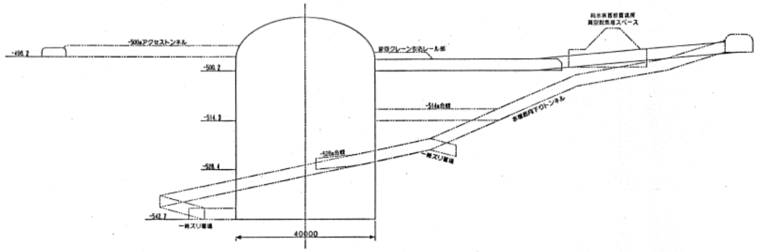
2nd level
Minimize negative impacts to current physics programs at SK

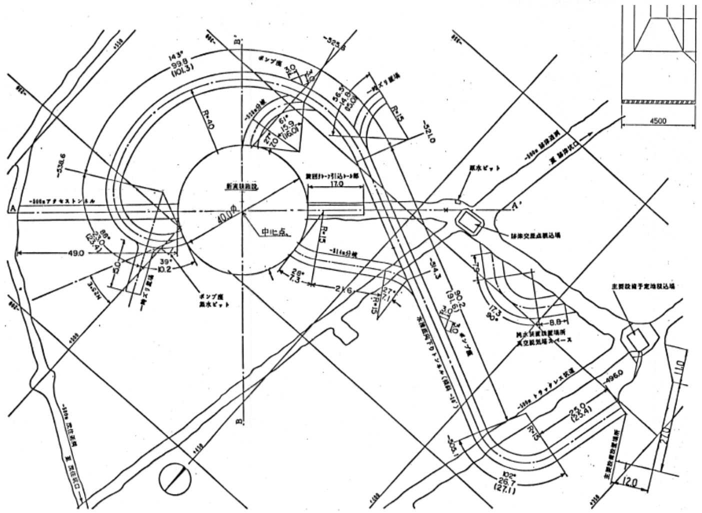
3rd level
Further investigate physics capability with n-tagging

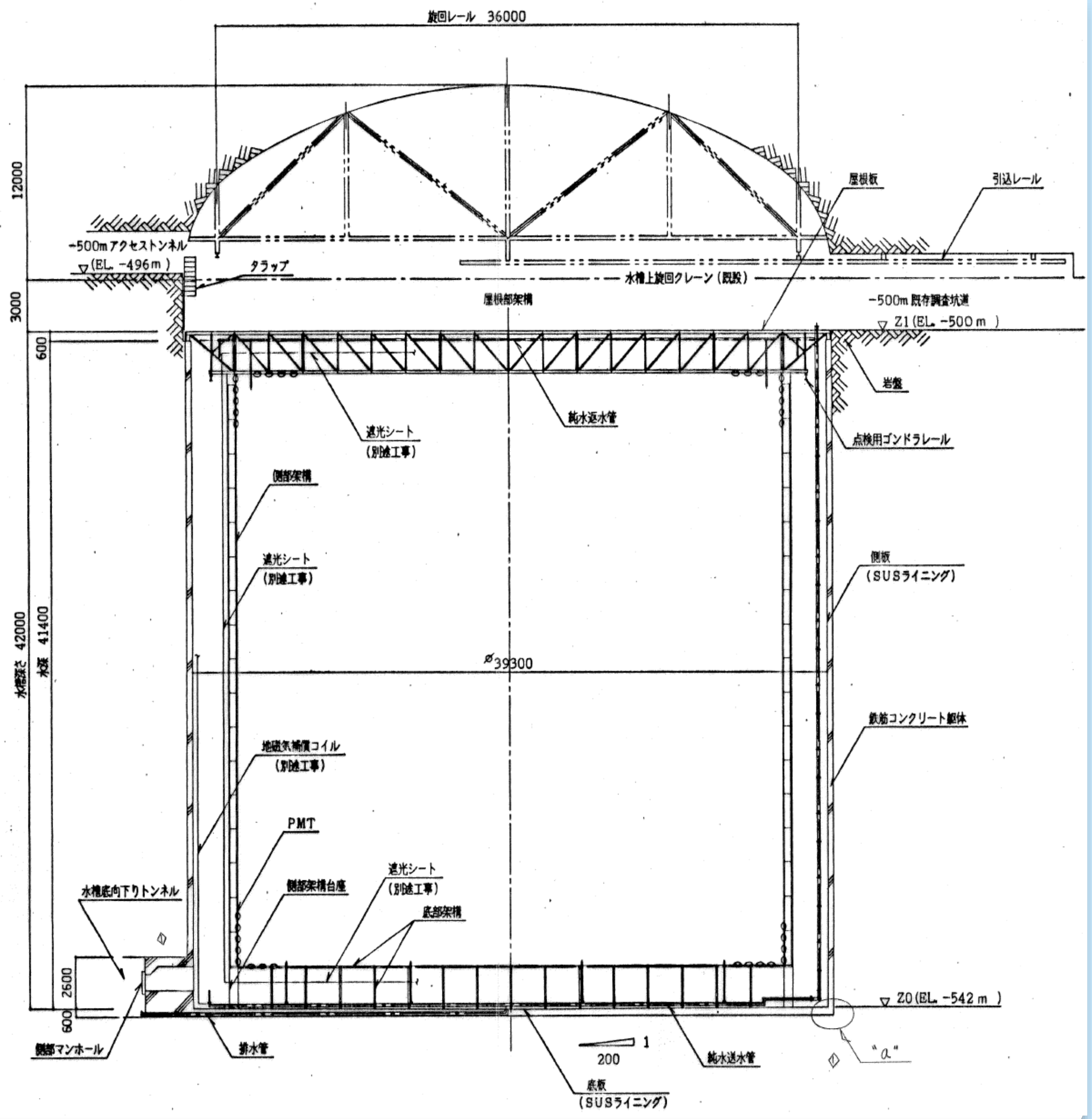
- Stopping the SK leakage
  - Estimation of the leak location
  - Development of leak-fixing method
- Reduction of RIs from $Gd_2(SO_4)_3$ powder
  - Test of Ra removal resins
  - Material screening with HP-Ge detectors
  - High sensitivity measurement with ICP-MS
- Test with the EGADS demonstrator
  - Continuous monitoring of the water quality
  - Continuous monitoring of Gd concentration
  - Demonstration of Gd-captured neutron signal/QBEE upgrade
- Construction of the new water system
- Gd gamma measurements and improved simulation of Gd capture

Super-K structure

- Made of SUS304





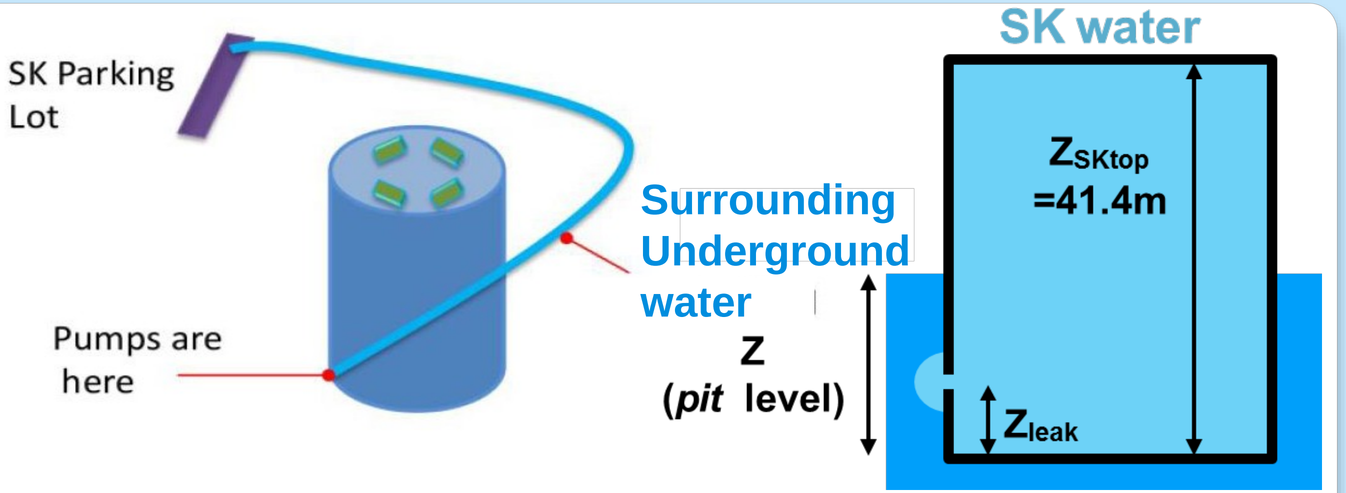


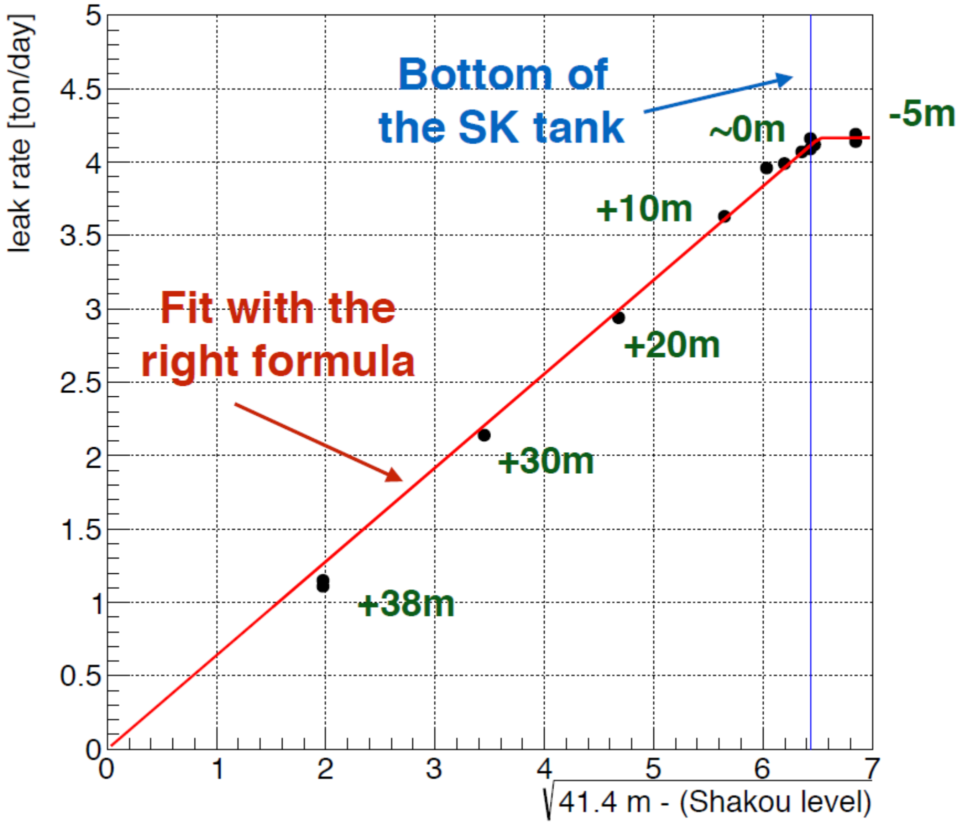
SK water leakage

- SK water is leaking at ~1 ton/day.
- In order to survey the location of the leakage, by changing the water level of the inclined pit (access tunnel to the bottom of SK), water leak rate was precisely measured from Nov. 2016 to Mar. 2017
  - Changes water pressure to the tank
- Assuming just one leakage point,

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

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





Leak-fixing method

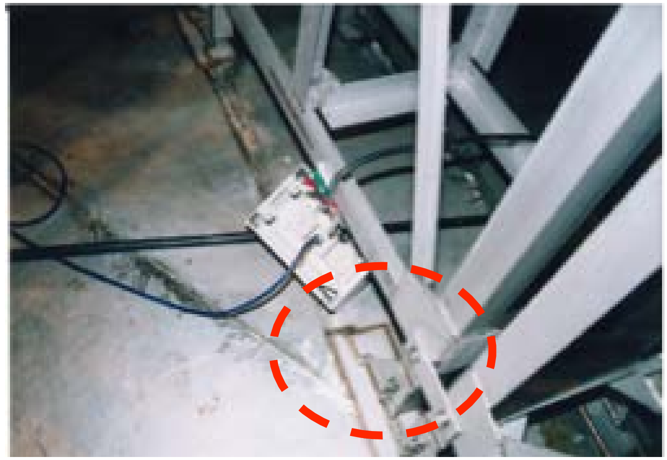
- Paint all the welding lines with 2 sealing materials
  - **Bio-seal 197**:
    Fill pinholes and cracks in steel plates
  - **Poly-urea based sealant**:
    Newly-developed, flexible and low-background
- Tests for the new sealant:

  Mechanical strength
  - No problem after applying 5 atm pressure in Gd-loaded water for 6 months so far.
  - Passed the JIS standard for attachment

  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

Most suspicious;
Anchors of the PMT frame



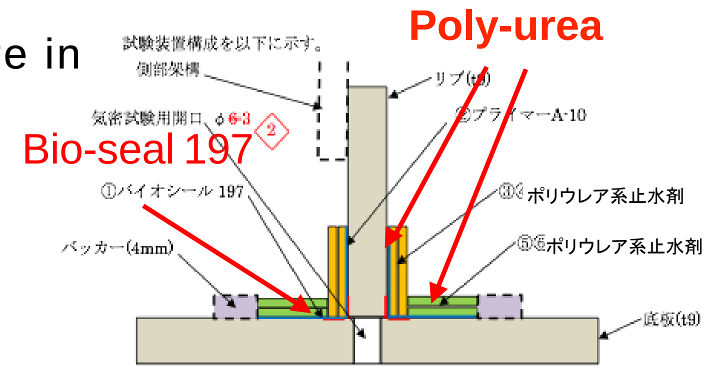
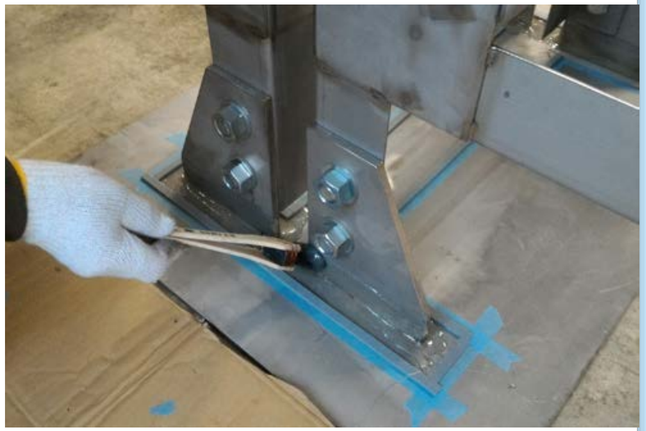


図-1 底面側部架構用リブ止水試験装置 概要図

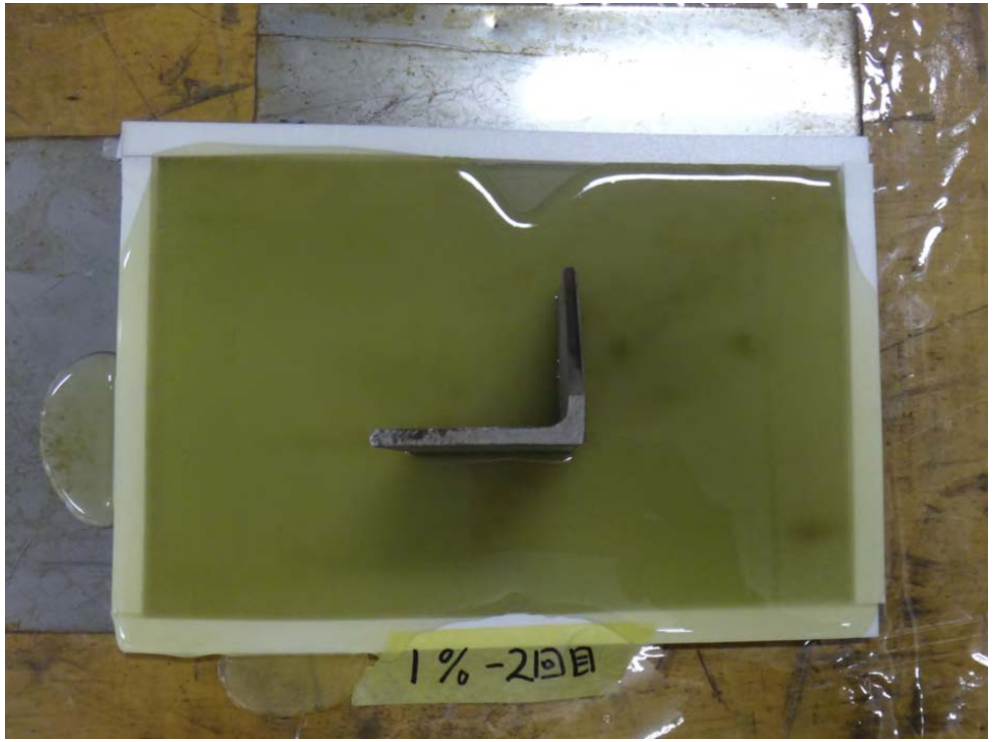
Mock-up simulation



The new sealant

High viscosity version for wall

Low viscosity version for floor



Development of the sealant

- MineGuard™ is widely used in Kamioka and SNOLab.

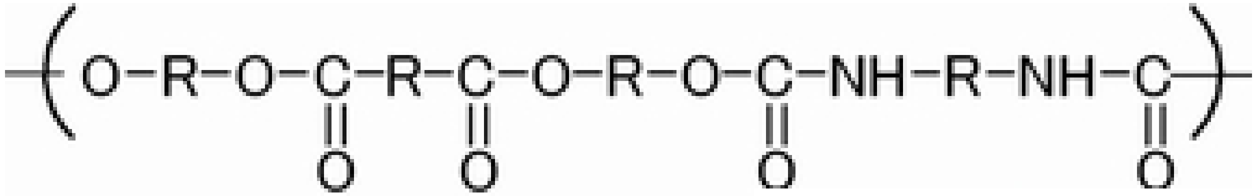
Wall of SK area

Lining of SNO detector

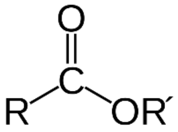
- Base material
  - Poly-urethane
- Two types of product
  - Paint type
  - Spray type
- For paint type, $CaCO_3$ is necessary for increasing viscosity

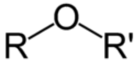
Fatal problem of MineGuard

- A chain of organic units joined by urethane links（-NHCOO-）



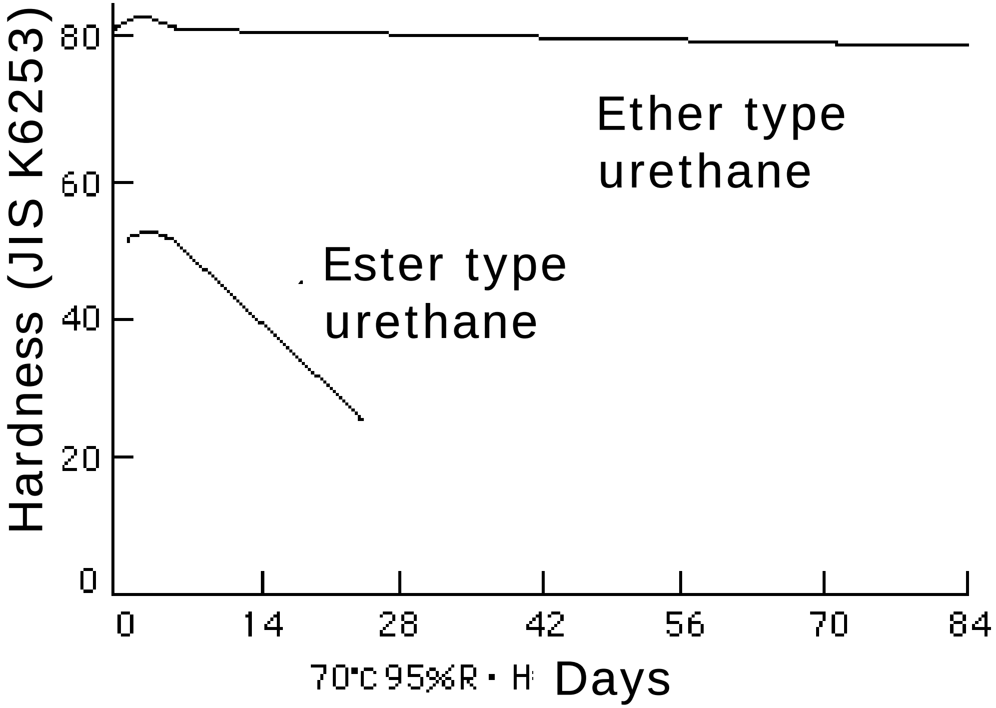
- R is Ester or Ether





- Both links are broken by H_2O ;

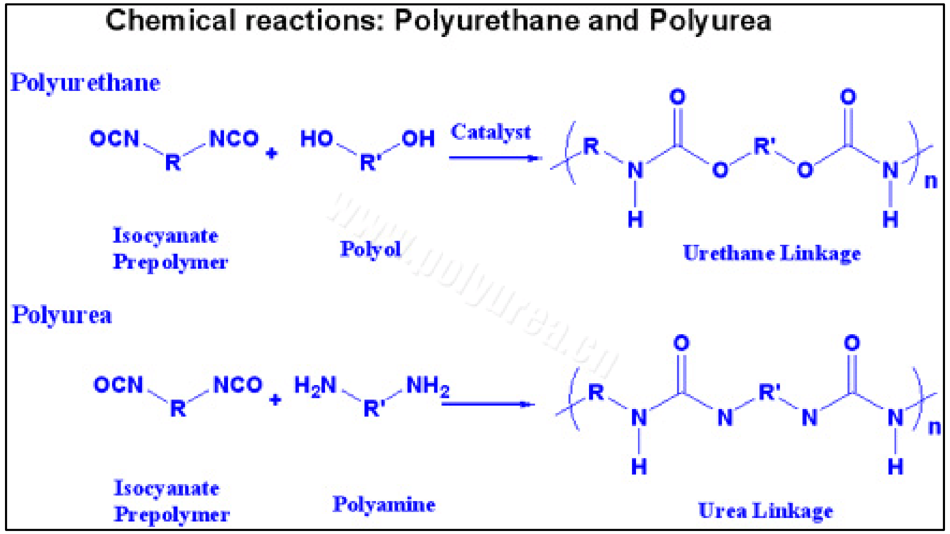
Hydrolysis



畑村洋太郎　失敗知識データベース

Poly-urea based type

- Stronger for H_2O
- The cocktails were screened by Ge.
- $CaCO_3$ is RI source, SiO_2 is used.



New product
“MineGuard C6”

RIs in typical 5N $Gd_2(SO_4)_3 \cdot 8H_2O$ powder

- With considerations of 100tons-availability

Chain	Main sub-chain isotope	Radioactive concentration (*mBq/kg*)
^{238}U	^{238}U	50
	^{226}Ra	5
^{232}Th	^{228}Ra	10
	^{228}Th	100
^{235}U	^{235}U	32
	^{227}Ac/ ^{227}Th	300

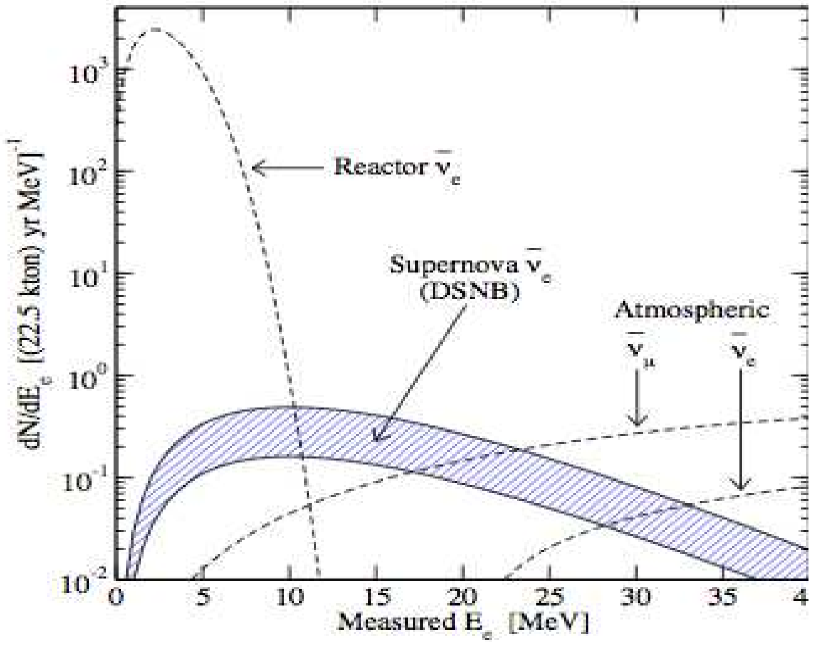
RI BG estimations for DSNB itself

- Expected signal: ~5 events/year/FV
  - prompt signal (e+): 10 - 20 MeV
  - delayed signal from neutron capture
- BG

  ^{238}U Spontaneous Fission:

  - Assuming 50 mBq/kg of ^{238}U
  - $5\cdot10^{-7}$ SF/decay
  - $N[E_\gamma \geq 10.5MeV] = \int_{10.5}^{\infty} \frac{1}{1.4} e^{-\frac{E}{1.4}} dE = 5.4\cdot 10^{-4}$ SFs with Eγ>10 MeV
  - 28% of SFs with only 1 neutron

~ 5.5 [γ(Eγ>10.5 MeV) + 1n] / year / FV

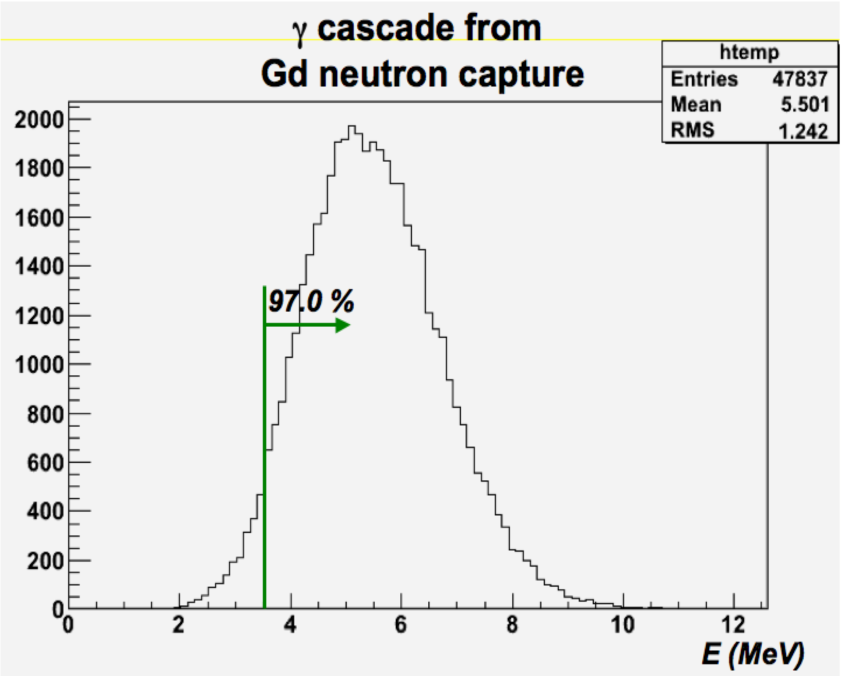


More than 1 order of U reduction

RI BG estimations for Solar neutrinos

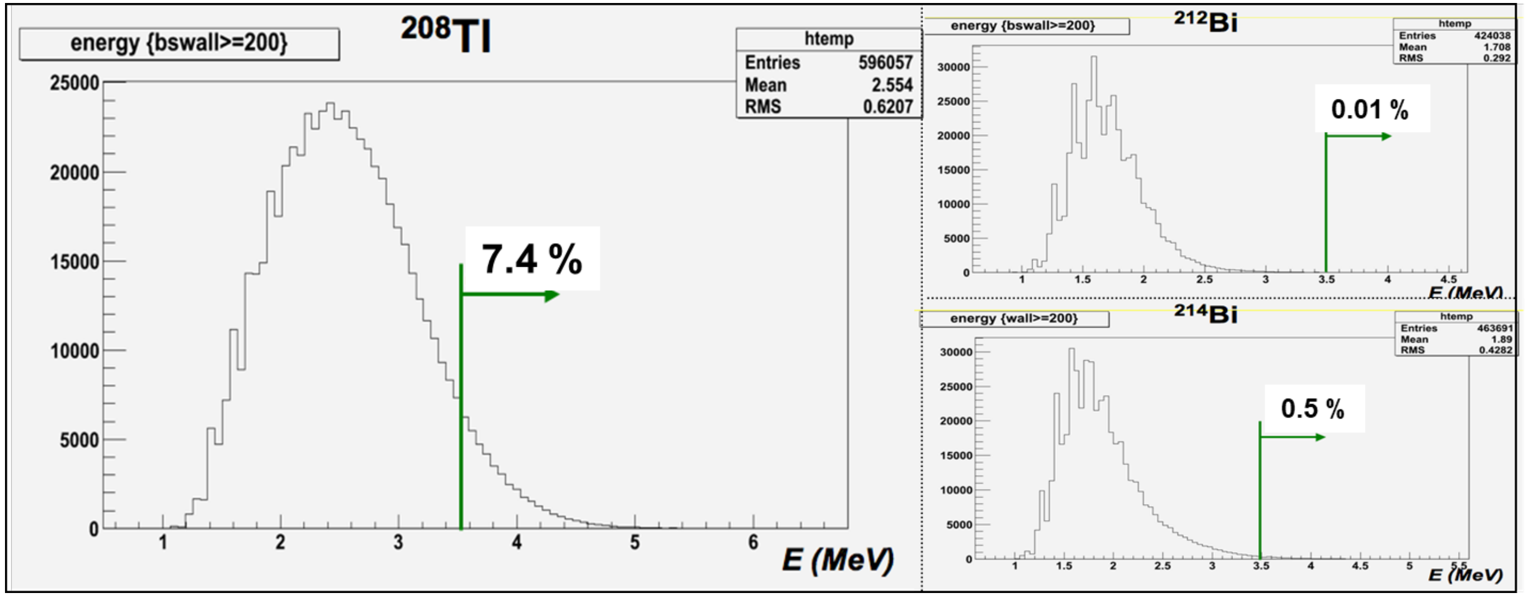
- Current SK 3.5MeV threshold final data sample (~BG from Rn in FV)
  ~200events/day/FV
- Neutron BG from ^{238}U
  - 90% can be captured and emit γ cascade
  - 36% of neutron-captured γs escape from standard solar cuts in the current analysis
    - ~320events/day/ FV

More than 1 order of U reduction



RI BG estimations for Solar neutrinos

- β,γ BG from ^{232}Th ^{226}Ra



- Solar cuts efficiencies

  ^{208}Tl: 0.21% ^{212}Bi: < 2x10^{-4} % ^{214}Bi: 0.01 %

- Decay intensities:

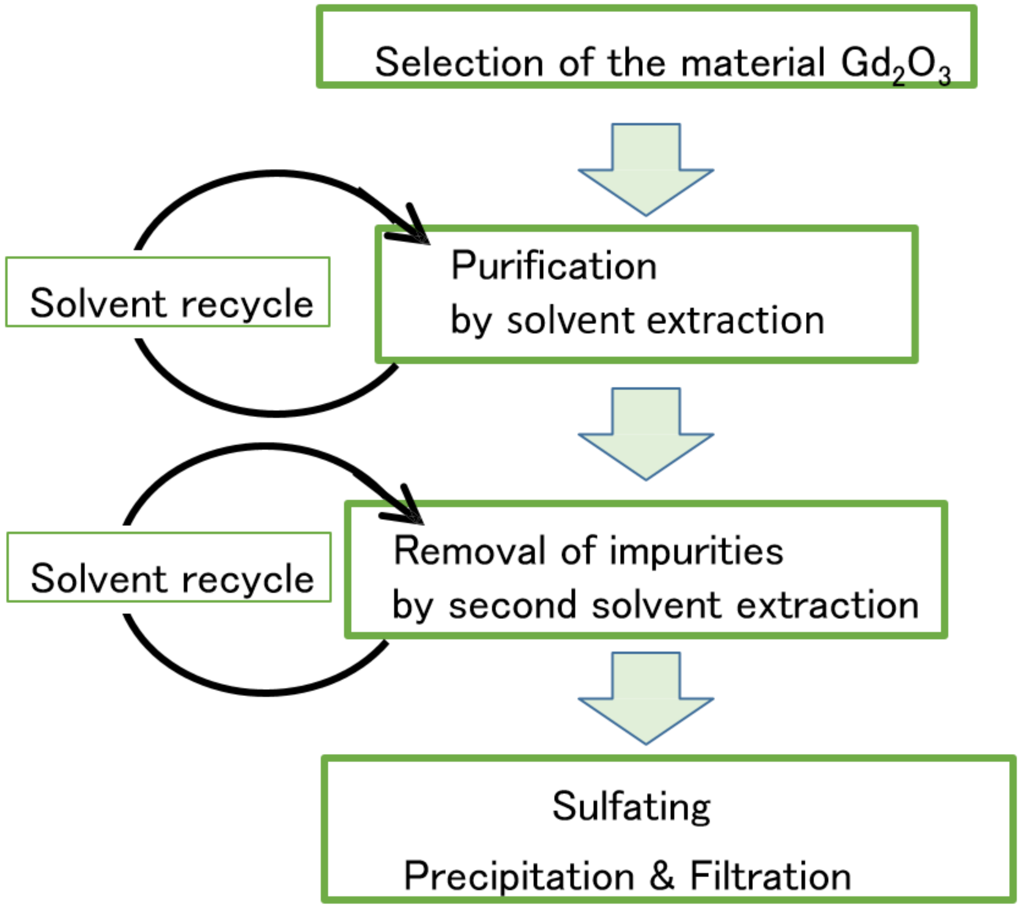
  ^{208}Tl: (100x36%) mBq/kg ^{212}Bi: (100x64%) mBq/kg ^{214}Bi: 5 mBq/kg

~3 x 10 ^{5} events/day/ FV ... Fatal BG!!

4 order of Th/Ra reduction

Low RI $Gd_2(SO_4)_3$ development

- Intensively developing pure powder with several companies.



Low RI $Gd_2(SO_4)_3$ evaluation

- Collaboration with underground Labs.

  ~1 mBq/kg : Ge detectors in Canfranc, Boulby, LNGS and Kamioka

  ~0.1mBq/kg : ICP-MS in Kamioka

- 3 companies had reached U goal, B#2 has reached Th goal for the first time!

Chain	238U			232Th			235U	
Isotope	^{238}U		^{226}Ra	^{232}Th	^{228}Ra	^{228}Th	^{235}U	$^{227}Ac/^{227}Th$
Goal*	< 5		< 0.5	< 0.05	< 0.05	< 0.05	< 3	< 3
Detector	Ge	ICPMS	Ge	ICPMS	Ge	Ge	Ge	Ge
CompanyA #1	< 13	0.6	0.7±0.4	1.8	< 0.39	1.7±0.4	< 1.3	< 3.1
CompanyA #2	-	<0.04	-	0.09	-	-	-	-
CompanyB #1	< 25	0.2	< 0.6	0.2	< 0.7	0.9±0.3	< 3.1	< 6.1
CompanyB #2**		<0.04		0.02				
CompanyC	< 10	<0.04	< 0.3	0.06	< 0.2	< 0.3	< 0.3	< 1.2

unit [mBq/kg $(Gd_2SO_4)_3$)]

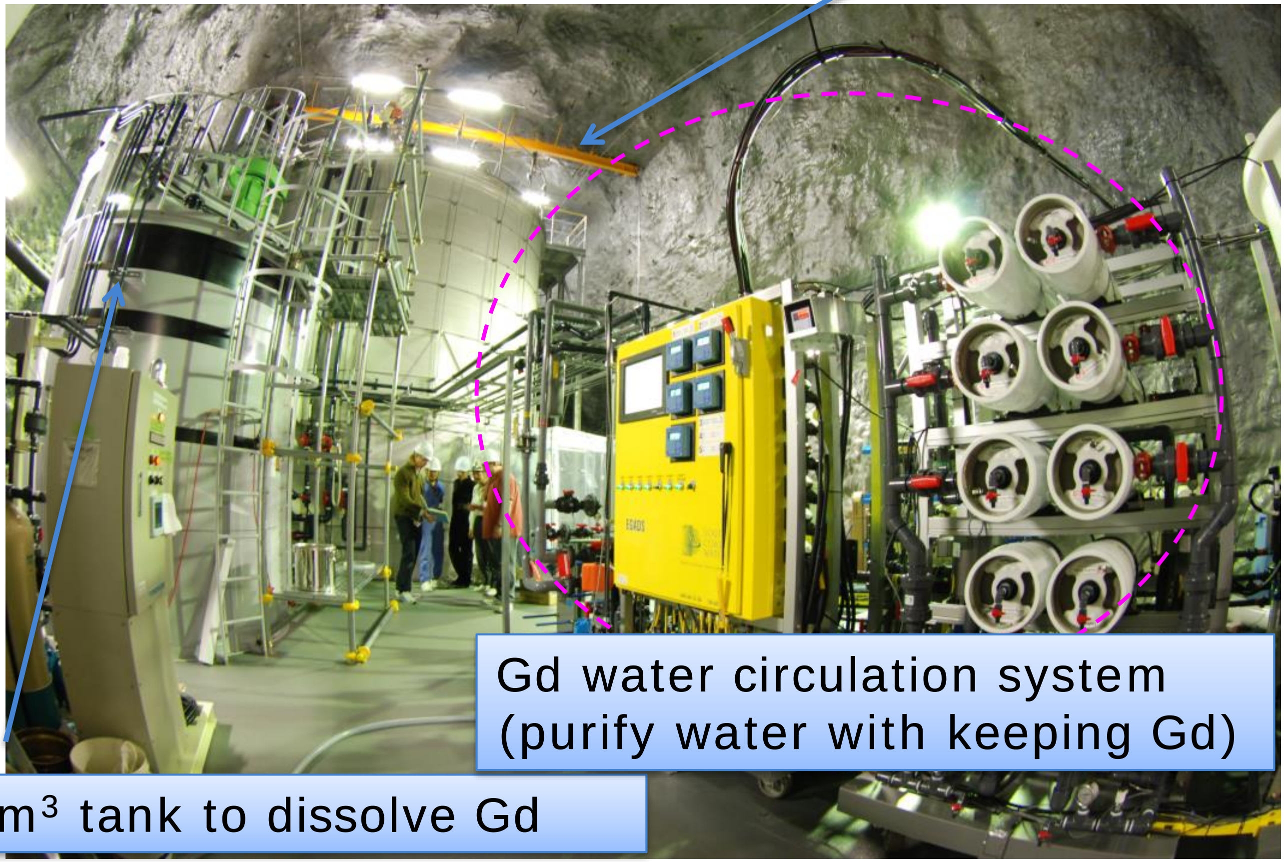
*Goal is for 0.2% solution

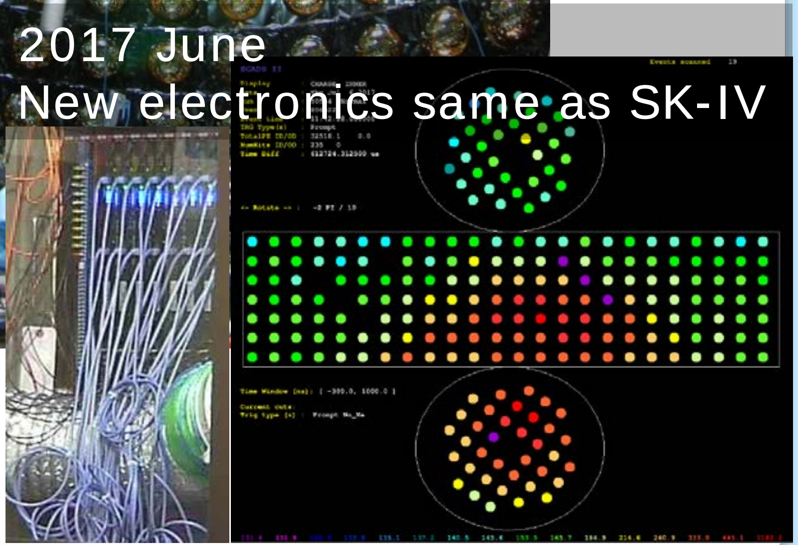
**Under measurement by Ge in Canfranc

EGADS

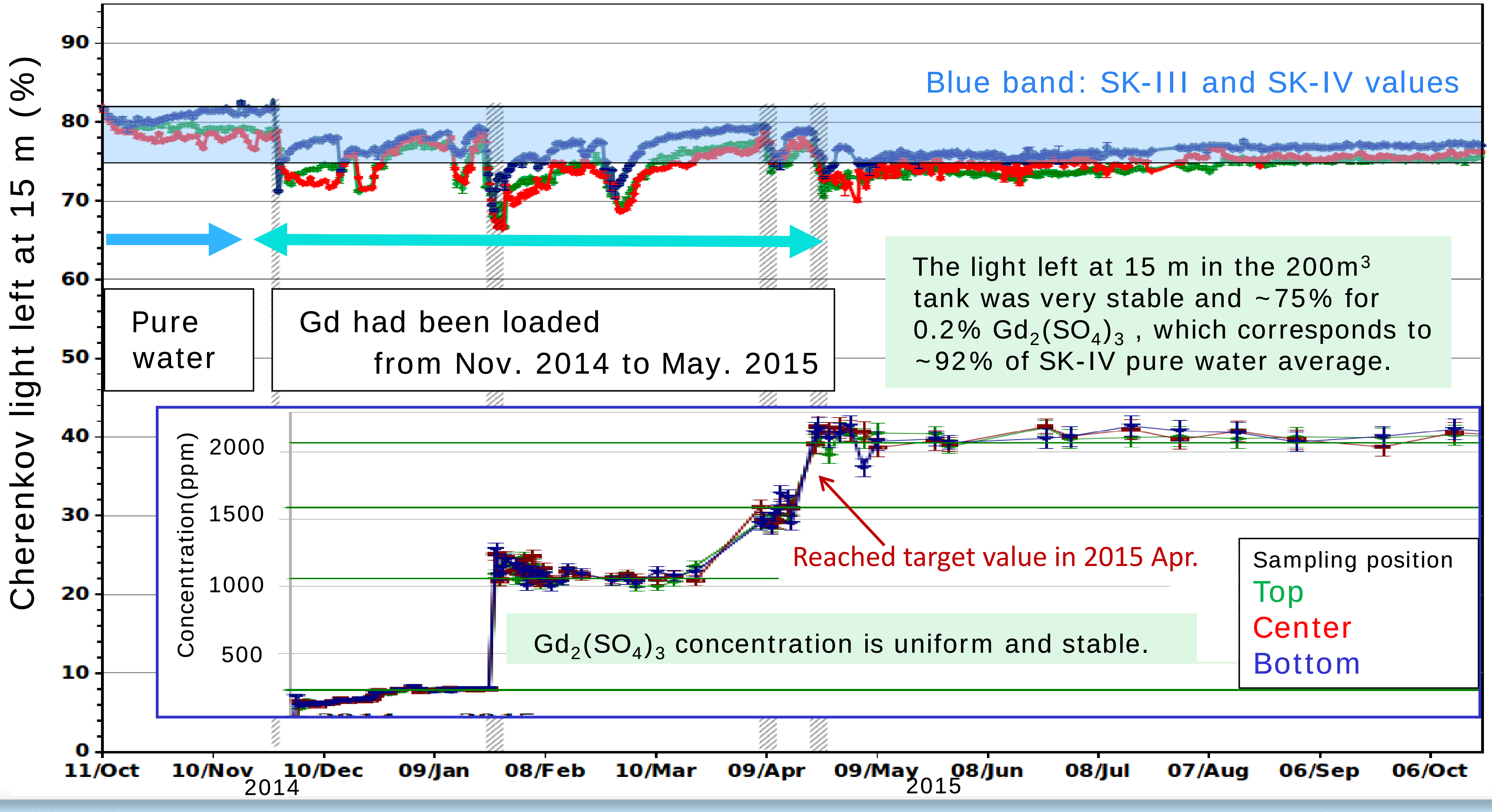
Evaluating Gadolinium's Action on Detector Systems

- To study the Gd water quality with actual detector materials.
- The detector fully mimic Super-K detector;
  SUS frame, PMT and PMT case, black sheets, etc.
- Tests for Hyper-K; 13 HPDs

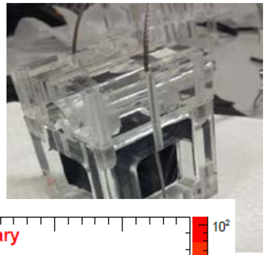




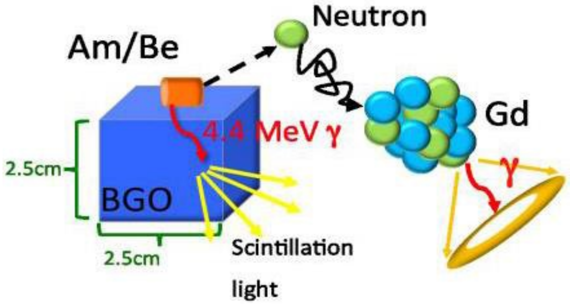
Water quality and $Gd_2(SO_4)_3$ concentration in EGADS



Neutron calibration in EGADS

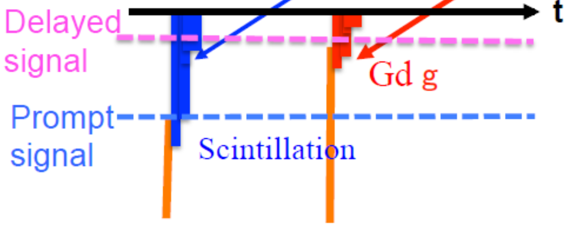


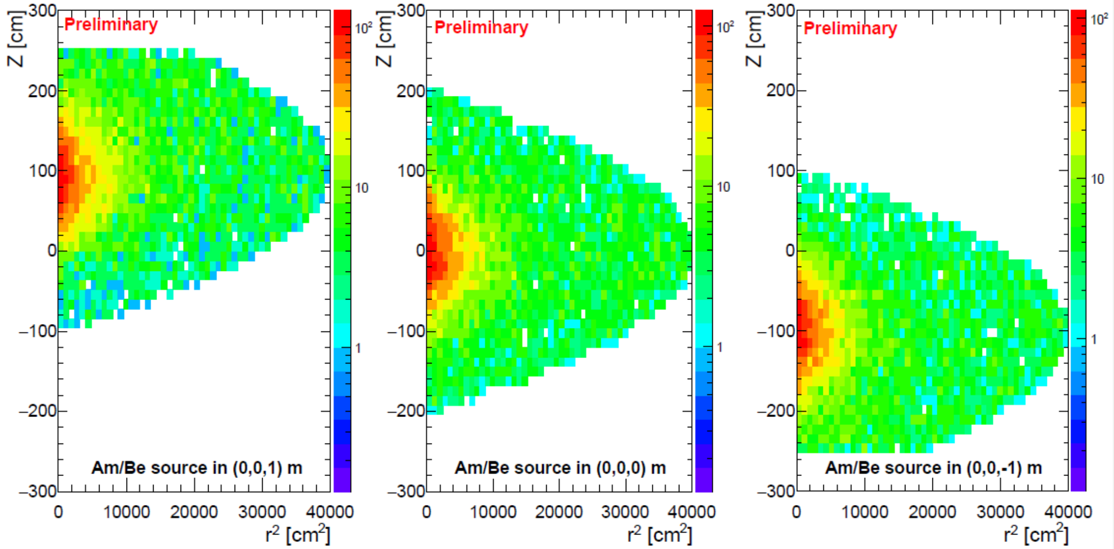
- Am/Be + BGO deployed in EGADS



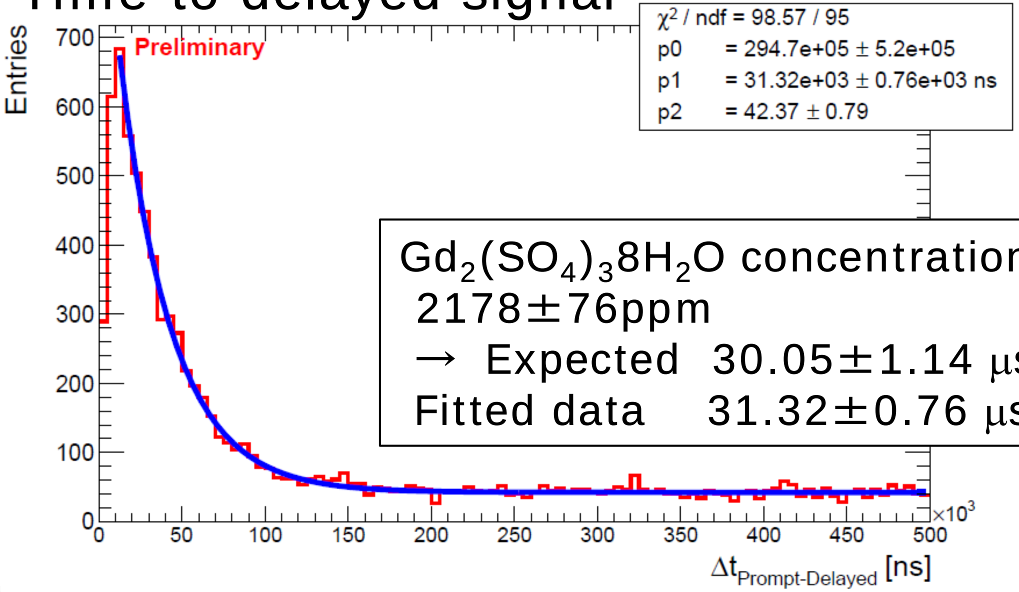
$^{241}Am \rightarrow {}^{237}Np + a$

$^{9}Be + a \rightarrow {}^{12}C + g(4.4MeV) + n$



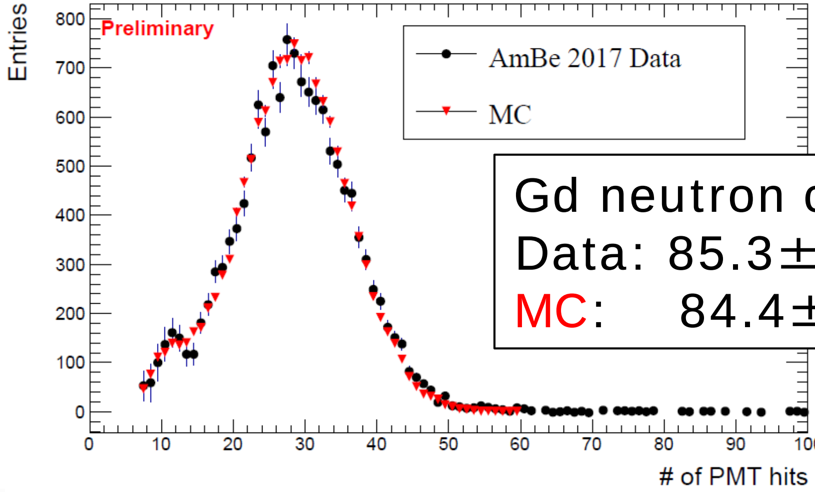


Time to delayed signal



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

Delayed signal spectrum



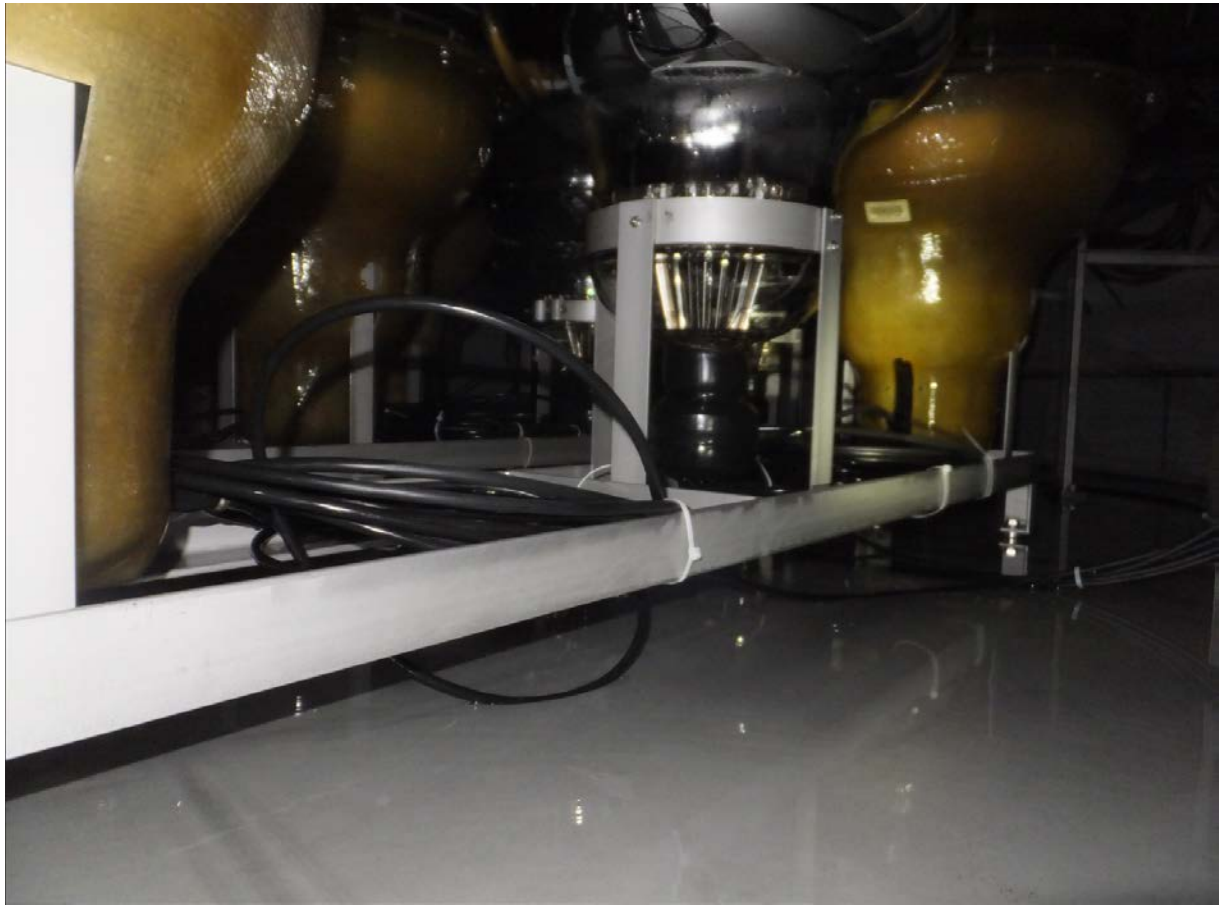
Gd neutron capture efficiency
Data: 85.3±0.9% (stat)
MC: 84.4± 0.3% (stat)

Inspection after 3 years operation

- Everything looked beautiful and shiny with 0.2% $Gd_2(SO_4)_3$ water

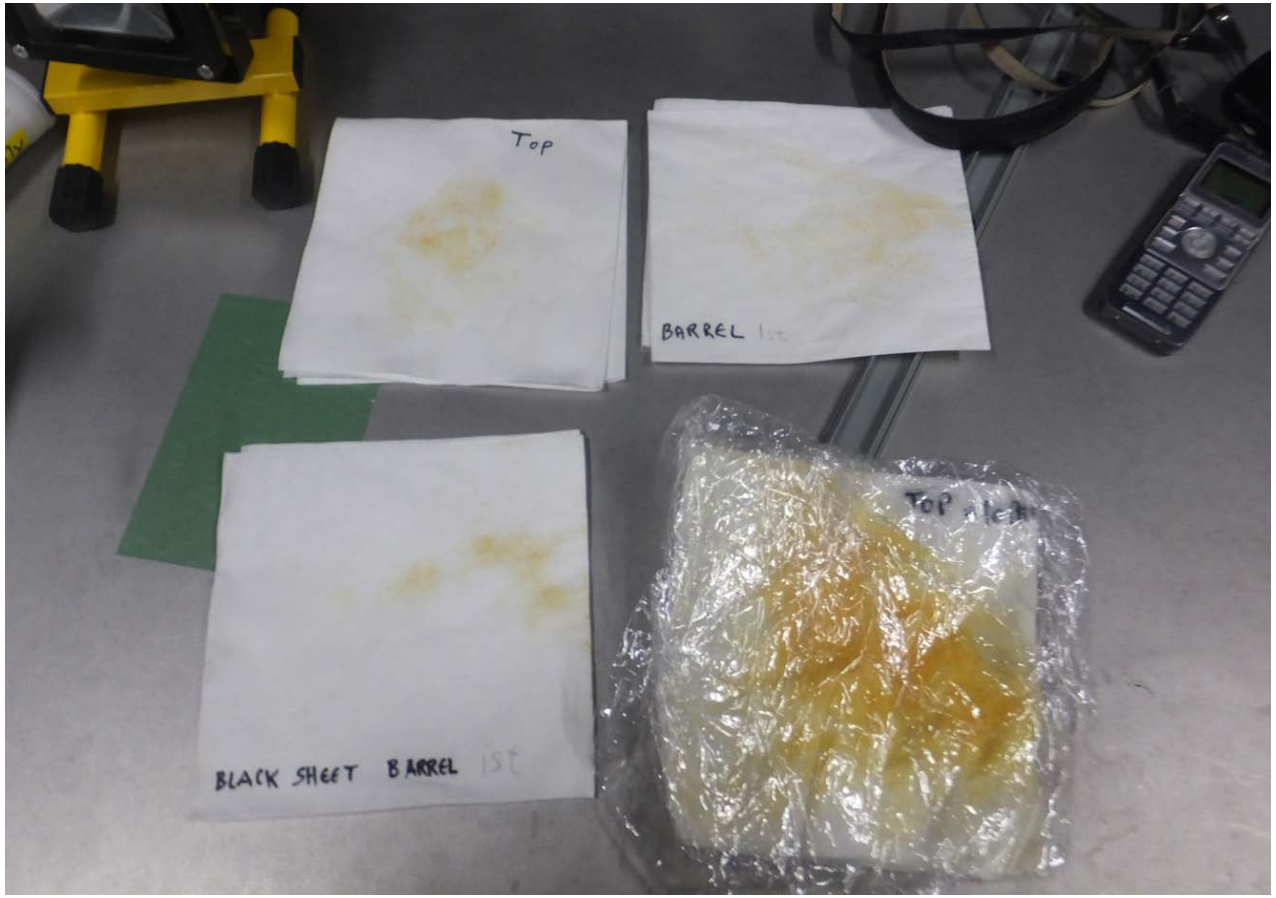
Bottom region as of Nov 3 2017

- Everything looked beautiful and shiny with 0.2% $Gd_2(SO_4)_3$ water



Bacteria in EGADS degrade the WT

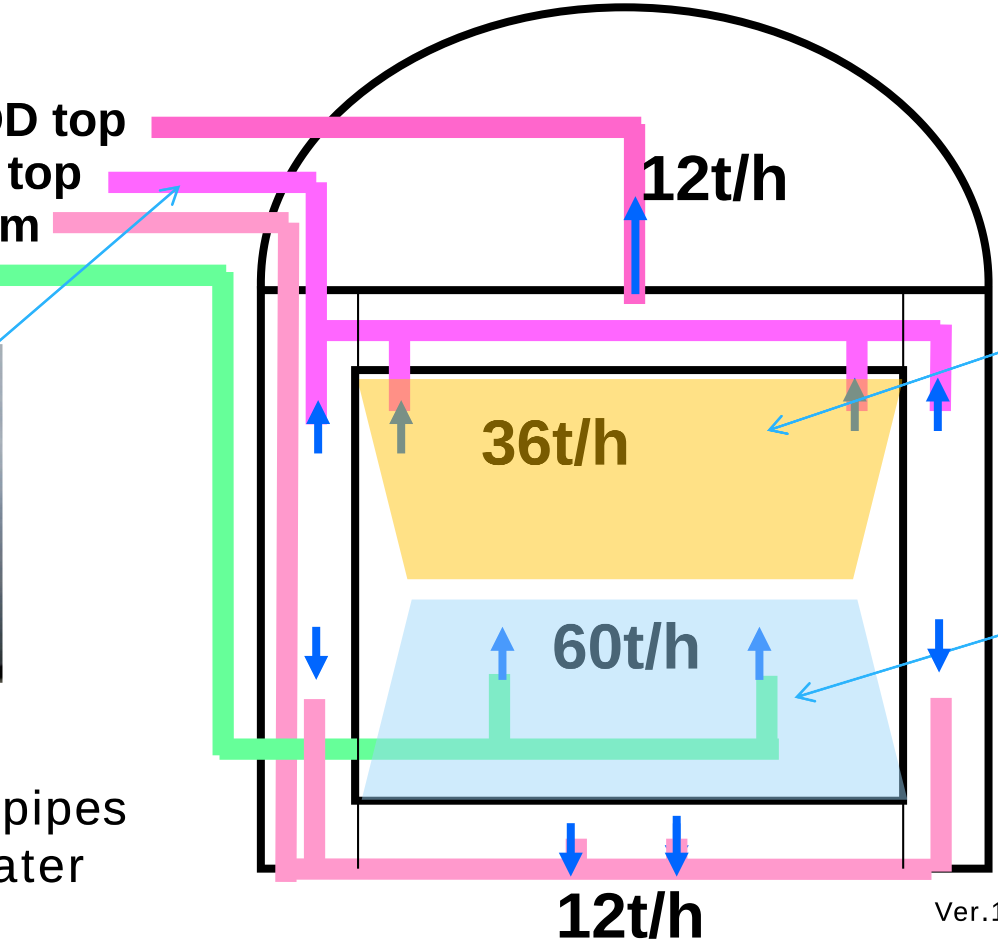
- Surface of PMT/blacksheets



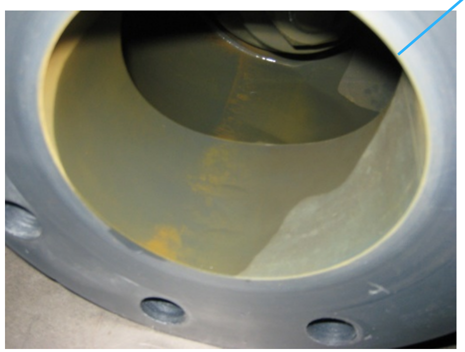
Bacteria in SK-IV

- Intentional water stagnation in FV

Bacteria-rich,
(bad water transperency)
but Rn-less region



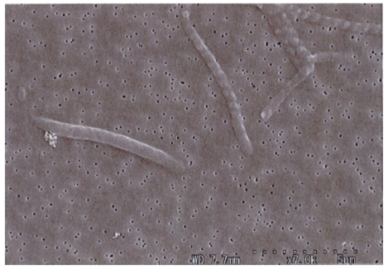
Rn-rich
(supply water, PMT)
but good water transparency
region

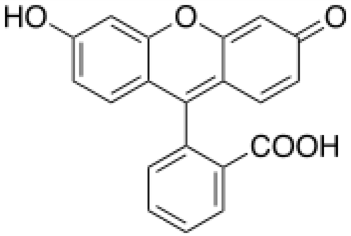


Yellow powder
in the return water pipes
which makes the water
transparency worse

Ver.14May 2012

According to literatures



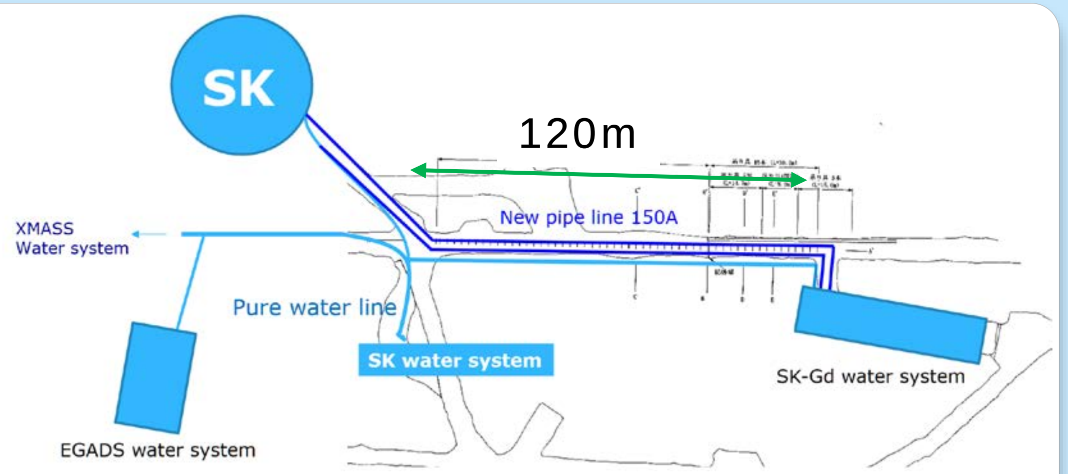


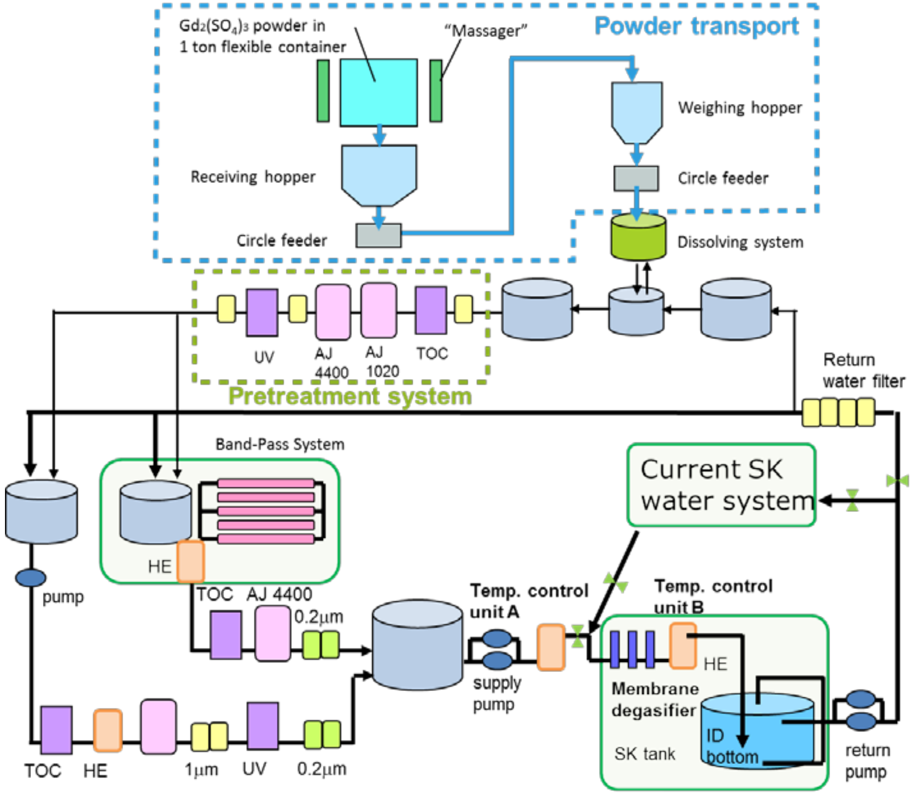
- *Pseudomonas genus*
  - Aerobic
  - Need P,K,Na,Mg,Ca,Fe,Al…
  - Many of them make fluorescent dyes (fluorescein) which absorb blue lights (peak 494nm) and emit green lights (peak 521nm).
  - On the wall(surface; tyvek, blacksheet, FRP, acrylic), there should be their nests!
- Top half region water: Air-rich , but what else is different from the water in bottom half? what is the nutrition for the bacteria?

SK-Gd water system

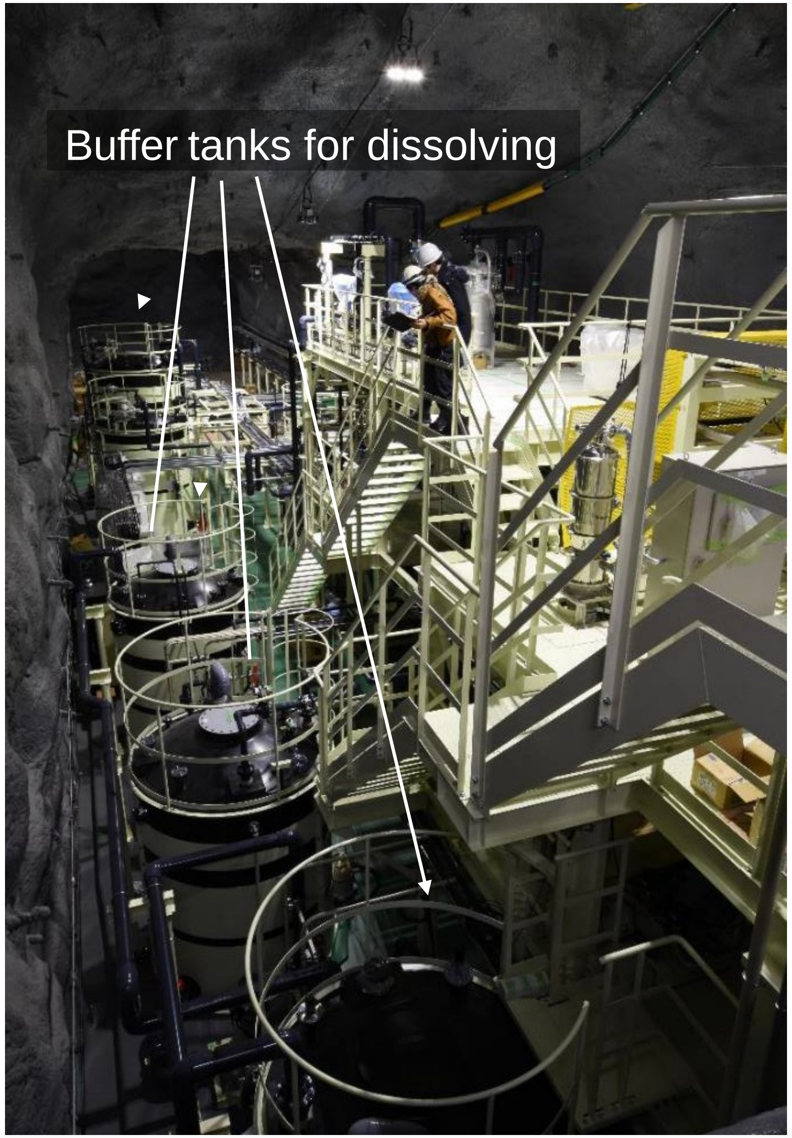
- Dissolving system
- Pretreatment system
- Re-circulation system

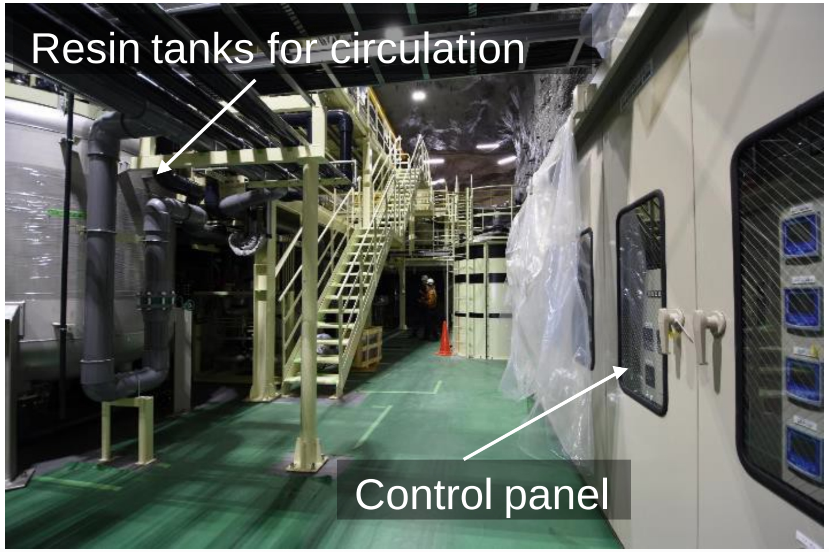
120t/h recirculation!
(currently 60t/h)





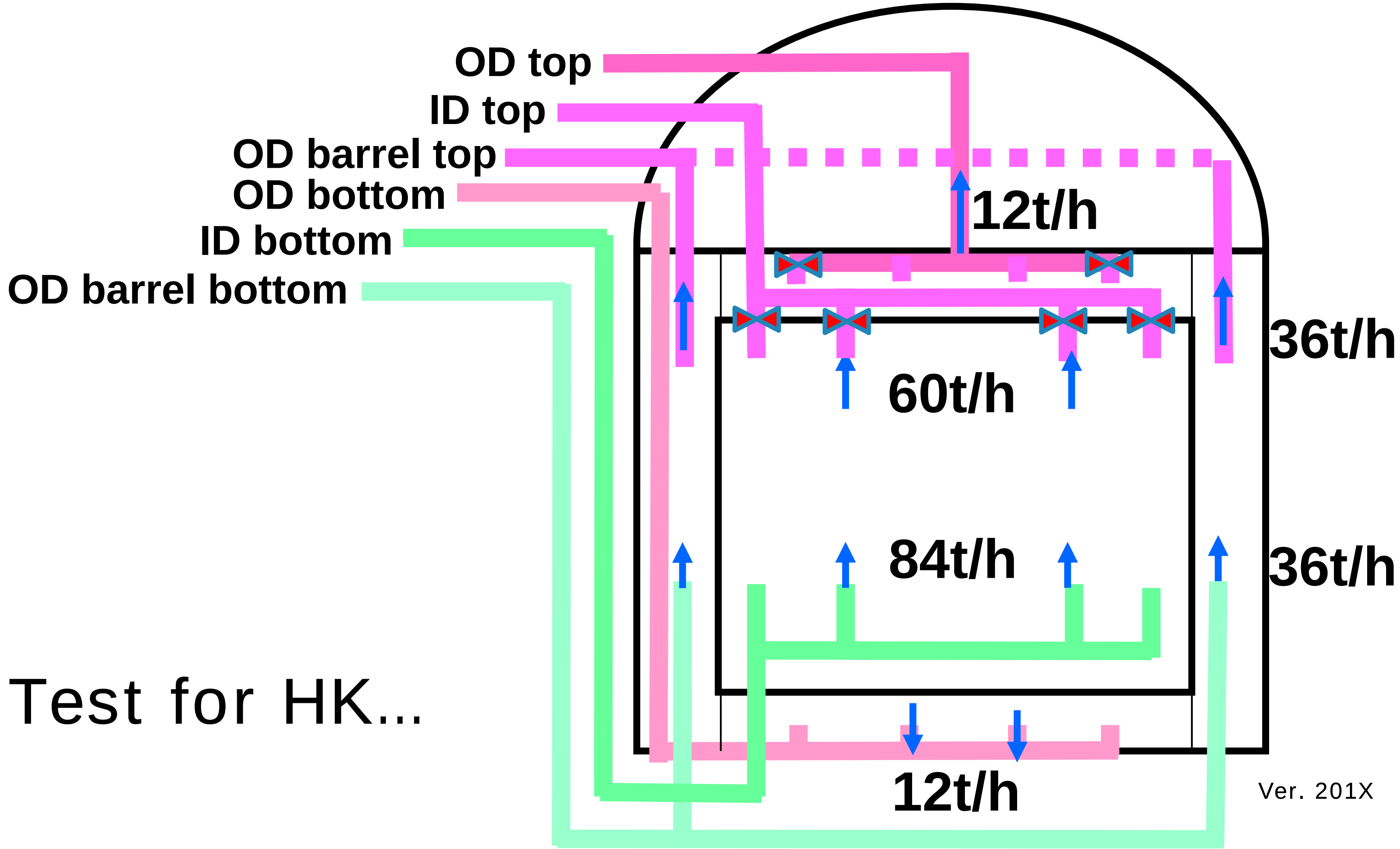
SK-Gd water system





Upgraded plumbing in SK

- For doubled recirculation flow rate and more symmetric inlets/outlets



- Test for HK...

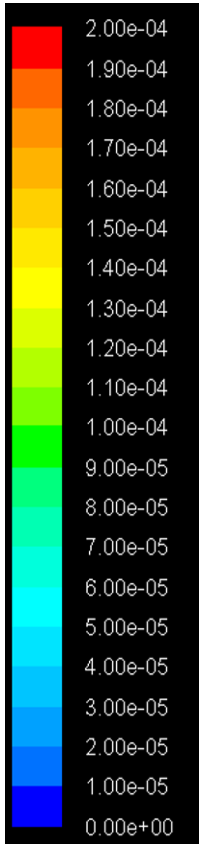
Flow simulation

- In dissolving phase, water temperature affects Gd concentration
  - Lower temperature water must be supplied.

¼ model

(Initial T,Supply T) 13.75℃,13.75℃ 13.75℃, 14.25℃ 13.75℃, 15.15℃ 13.75℃, 13.06℃

0.02%

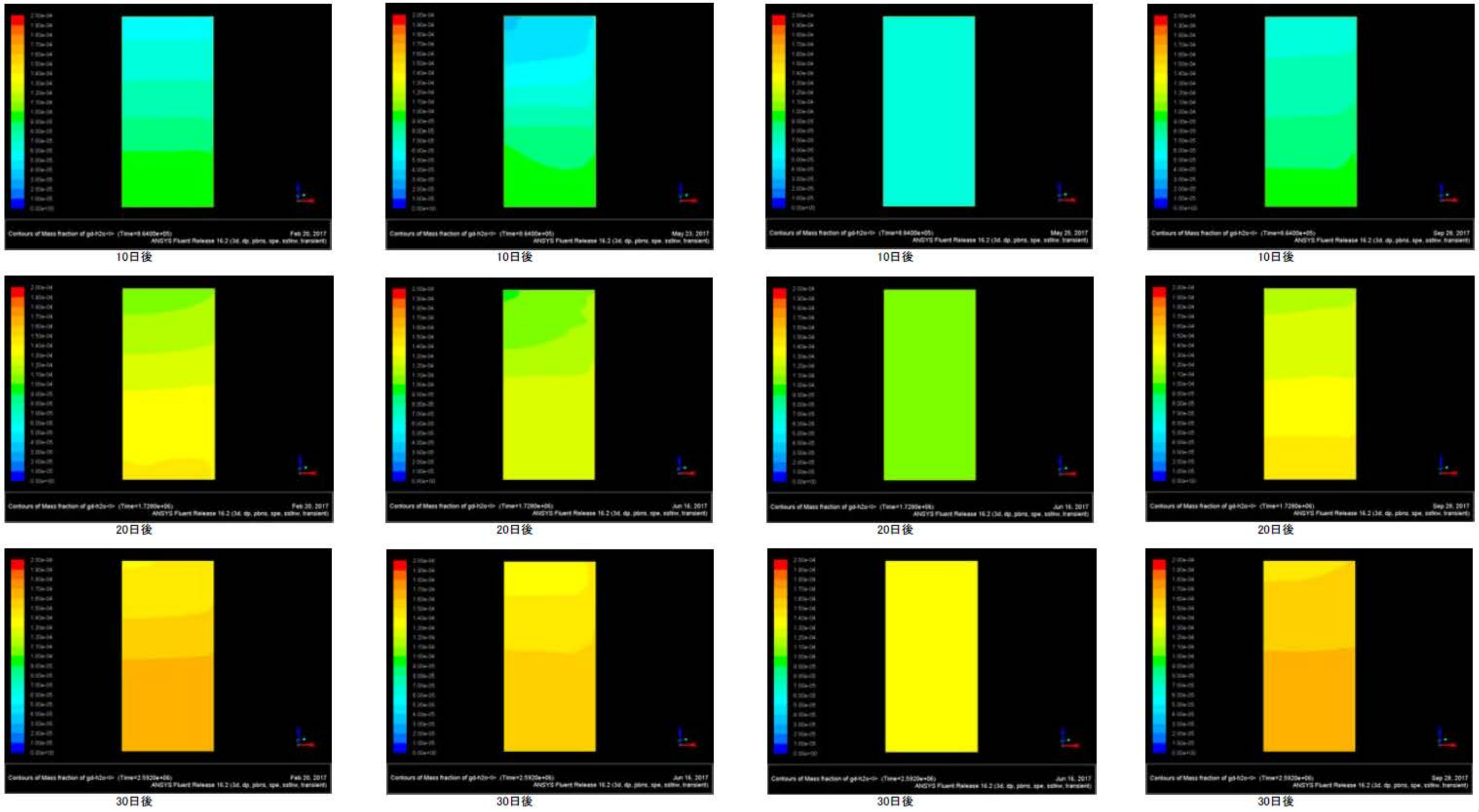


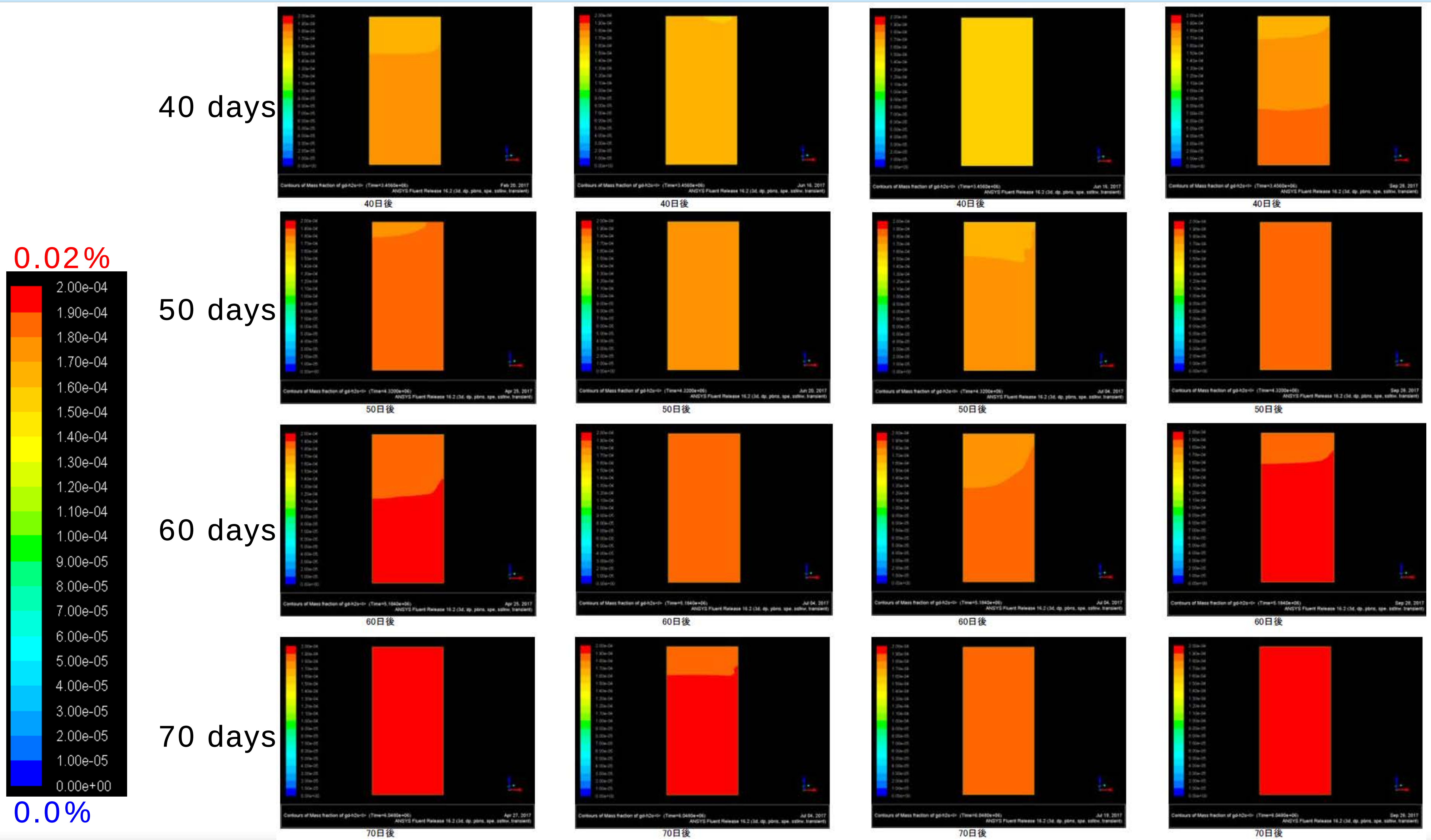
0.0%

10 days

20 days

30 days




0.02%
2.00e-04
1.90e-04
1.80e-04
1.70e-04
1.60e-04
1.50e-04
1.40e-04
1.30e-04
1.20e-04
1.10e-04
1.00e-04
9.00e-05
8.00e-05
7.00e-05
6.00e-05
5.00e-05
4.00e-05
3.00e-05
2.00e-05
1.00e-05
0.00e+00
0.0%
40 days
50 days
60 days
70 days
40日後
50日後
60日後
70日後

T2K

- CP δ is the issue

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric/accelerator
$\theta_{23} = (45\pm3)°$
$|\Delta m^2_{32}| = (2.52\pm0.04)\text{x}10^{-3}\ \text{eV}^2$

Reactor/accelerator
$\theta_{13} = (8.5\pm0.15)°$
$|\Delta m^2_{31}| = (2.52\pm0.04)\text{x}10^{-3}\ \text{eV}^2$
$\delta_{CP} \approx -90°$ (best fit)

Solar/reactor
$\theta_{13} = (33.6\pm0.8)°$
$\Delta m^2_{21} = (7.50\pm0.18)\text{x}10^{-5}\ \text{eV}^2$

Electron neutrino appearance channel

$$\begin{aligned}P(\nu_\mu \to \nu_e) \simeq{}& \sin^2 2\theta_{13}\sin^2\theta_{23}\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}\\ &-\alpha\sin\delta\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}\\ &+\alpha\cos\delta\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}\\ &+\mathcal{O}(\alpha^2)\end{aligned}$$

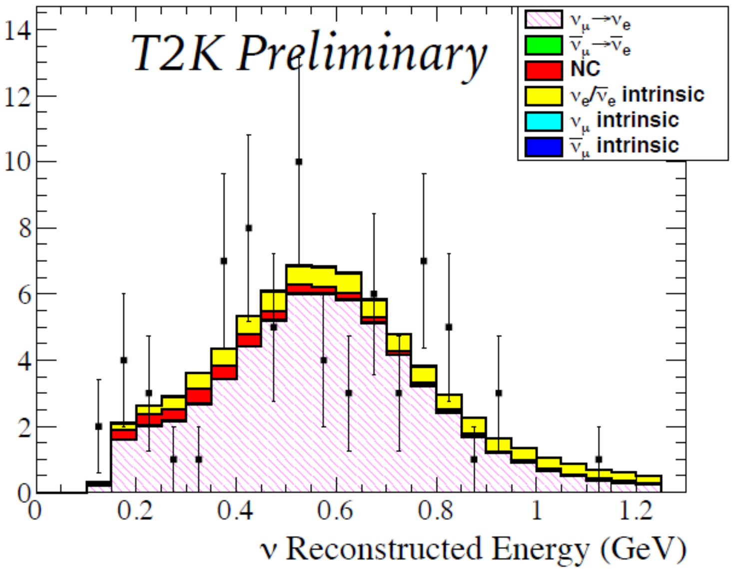
$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \qquad \Delta = \frac{\Delta m^2_{31}L}{4E} \qquad x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

$$P(\bar{\nu_\mu} \to \bar{\nu_e})$$
$$\delta \to -\delta$$

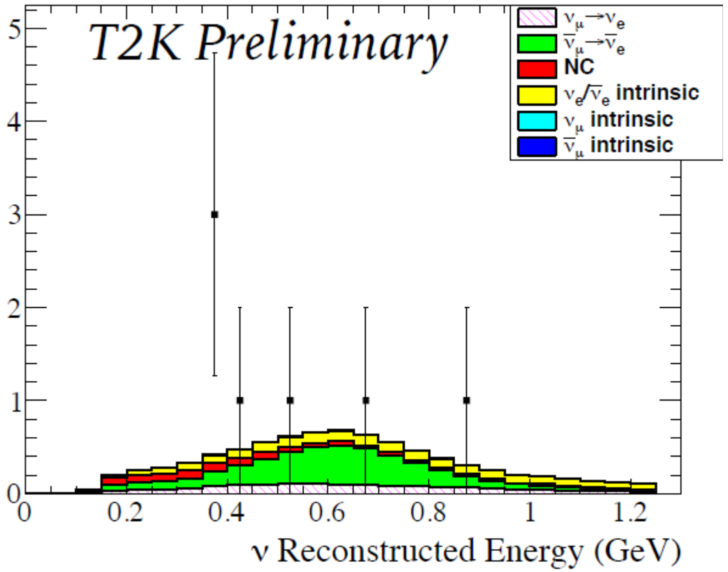
If sinδ≠0: Asymmetry of appearance probabilities for ν (↑) and anti-ν(↓)

T2K status

ν beam

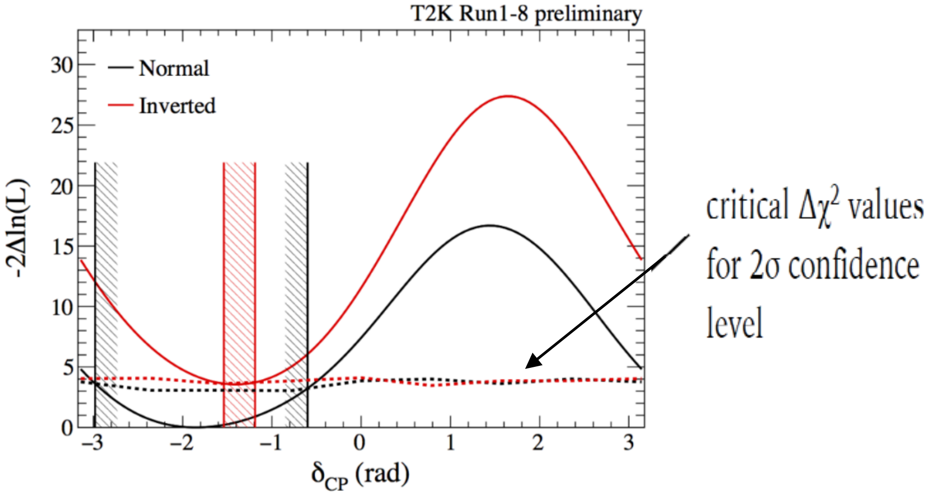


anti-ν beam



Preliminary	Predicted rates				Observed
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Events
ν beam	73.5	61.5	49.9	62.0	74
anti-ν beam	7.93	9.04	10.04	8.93	7

- Results on δ



Best fit point: -1.83 radians in Normal Hierarchy

The 1σ CL confidence interval: Normal hierarchy: [-2.49, -1.23] radians

The 2σ CL confidence interval: Normal hierarchy: [-2.98, -0.60] radians
Inverted hierarchy: [-1.54, -1.19] radians

CP conserving values (0,π) fall outside of the 2σ CL intervals

- More statistics!

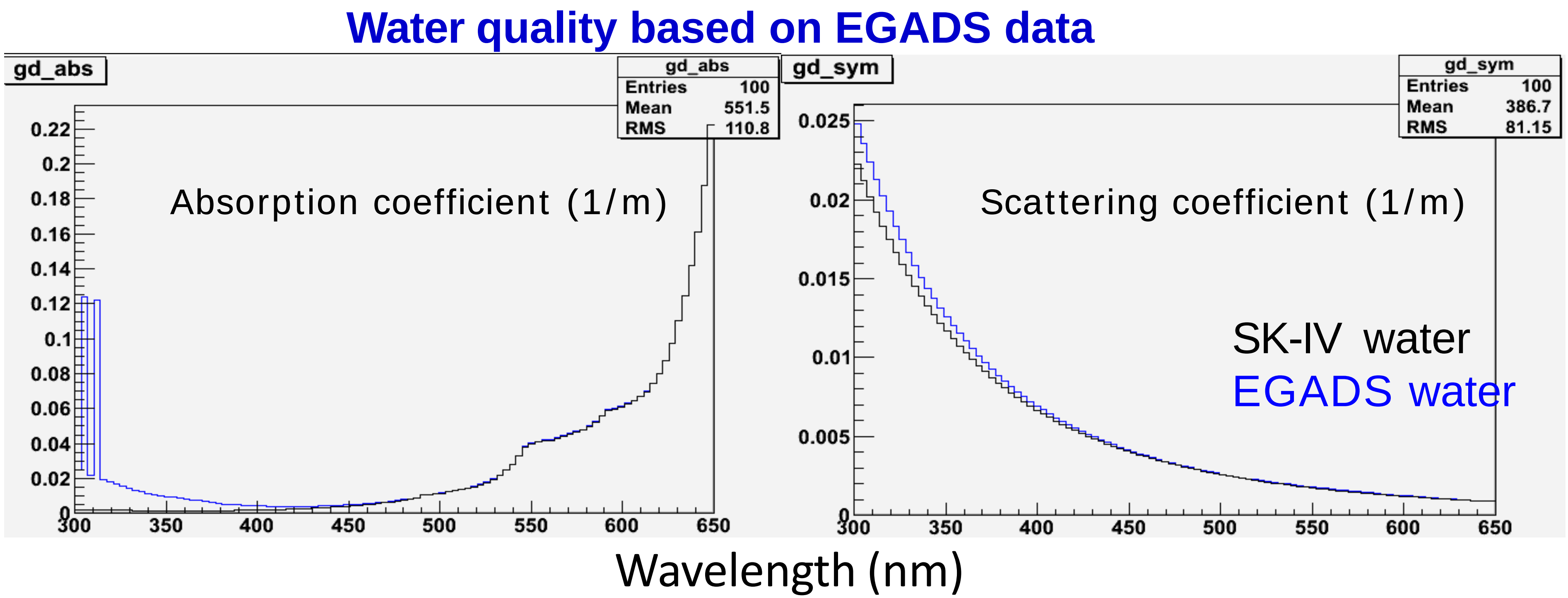
Gd effects on T2K (Preliminary MC study)

- Negative impacts
  - Change of reconstruction performance w/ degraded water
  - Contamination of n-Gd events into decay-electron sample

- Positive impacts
  - anti-ν/ν separation w/ neutron-tagging
  - Improving for energy reconstruction w/ neutron counting?
  - Improving neutrino interaction measurements

Degraded water transparency

- EGADS WT may be nothing to do with $Gd_2(SO_4)_3$, but ~8% loss of light yield assumed

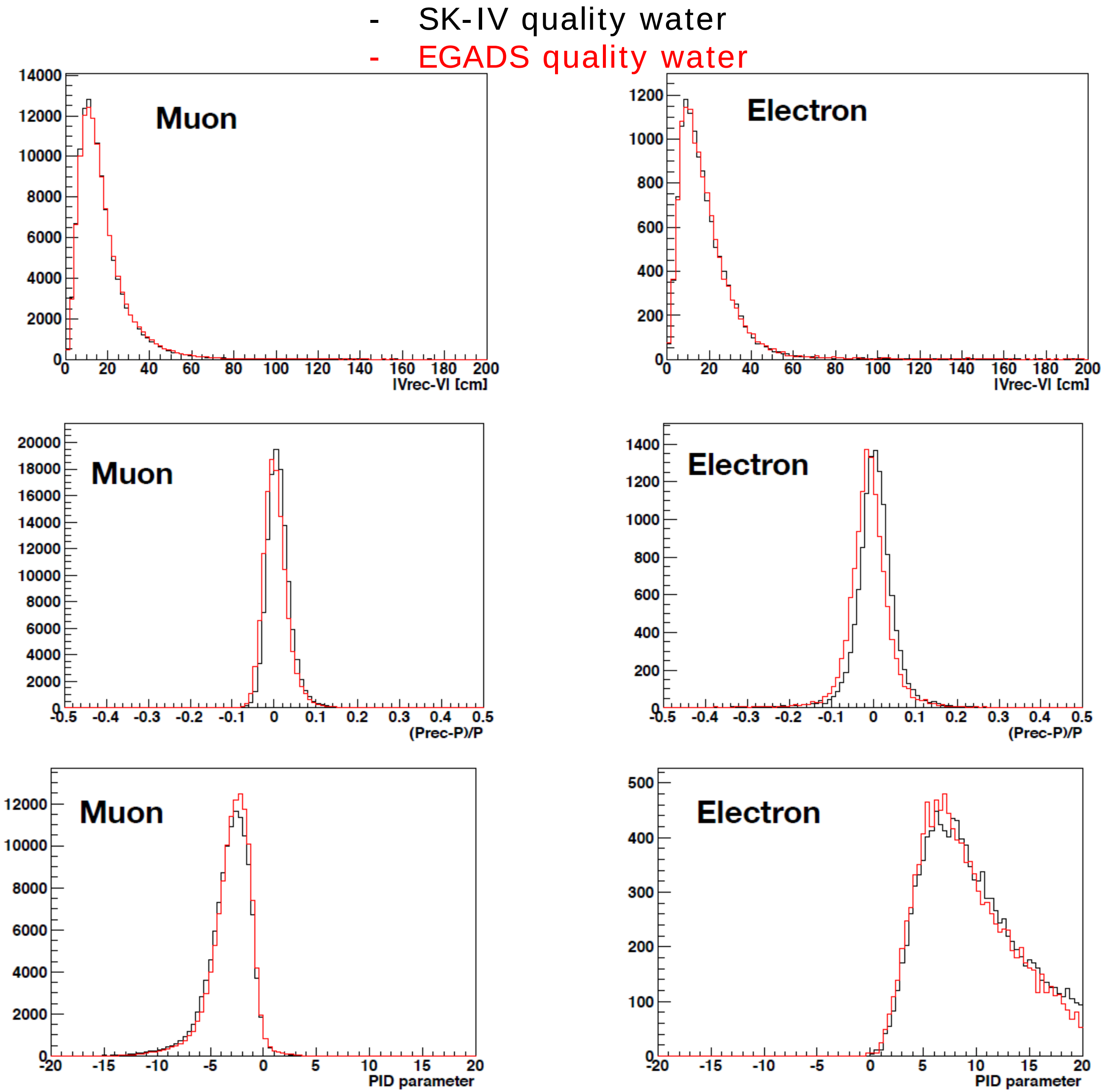


8% degrade :90% due to absorption and 10% due to scattering

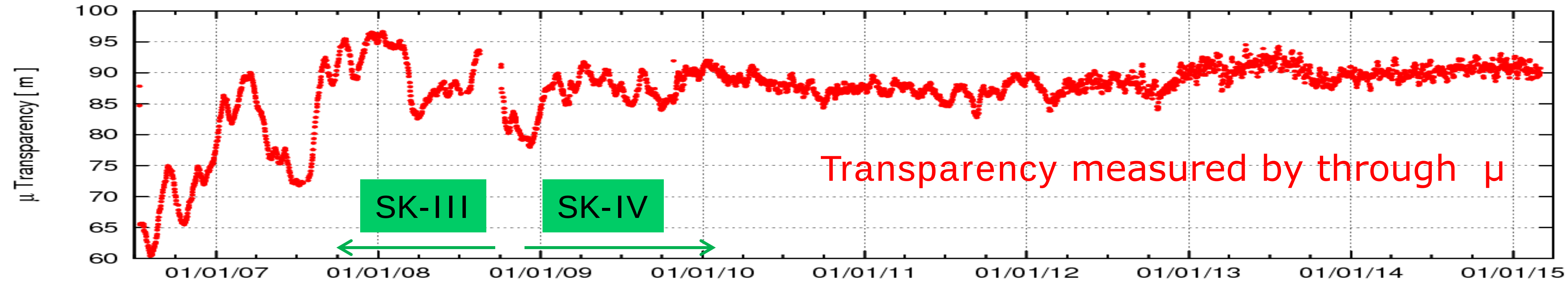
Reconstruction performance was checked by single particle events of muon and electron (CCQE events with 1-Ring reconstructed by fitter)

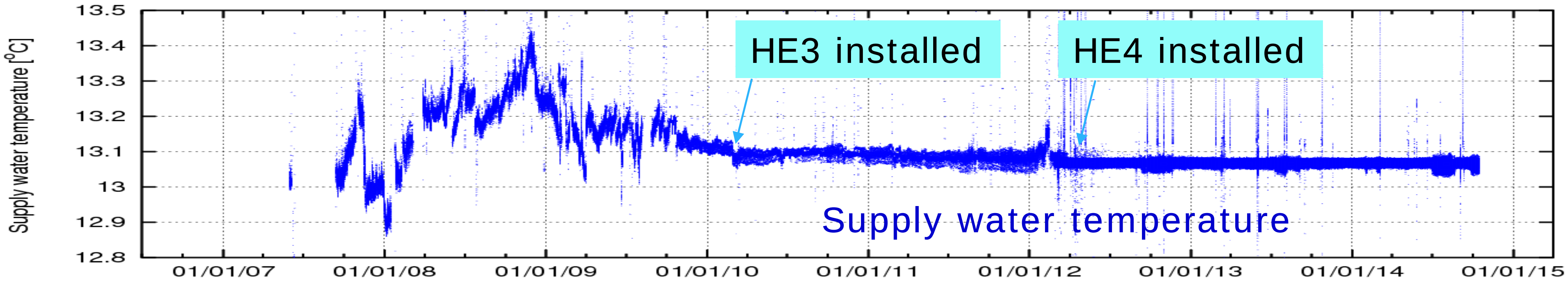
Distributions

- Vertex resolution
- Momentum resolution
    - Slightly biased but it can be retuned.
- PID

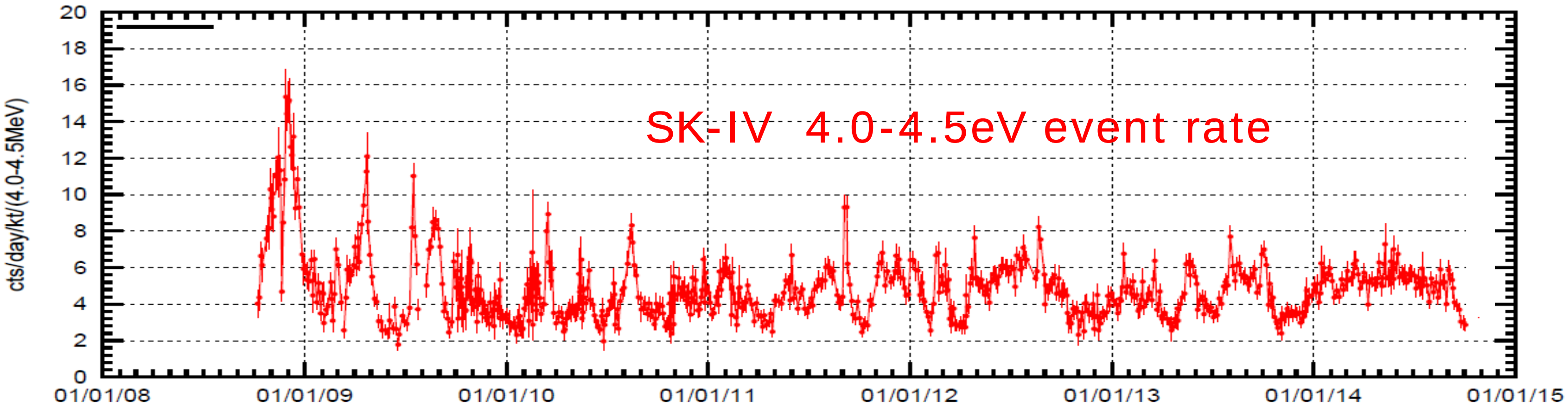


It should be OK, we have been used 8%-degraded data in SK.



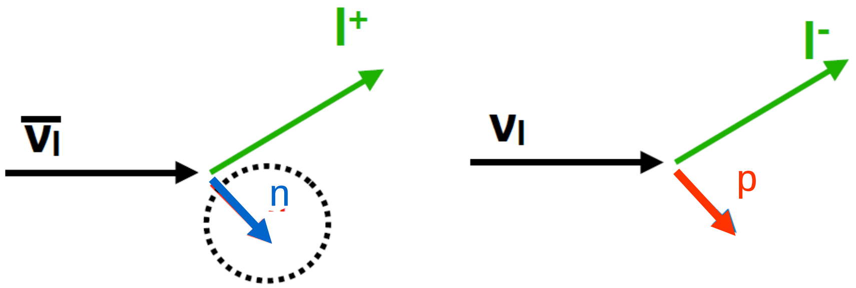


As long as it is stable, it should be OK.



T2K event selection

- Final sample can be further divided into neutrino-like and antineutrino-like sample using n-tag information.



ν_e CC0π Selection	ν_μ CC0π Selection
1-Ring, FCFV , Evis > 30 MeV	
PID: e-like	PID: μ-like
E_{vis} > 100 MeV, E_{rec} < 1.25 GeV	p_μ > 200 MeV
#(decay-e) = 0	***#(decay-e) <= 1***
π^0 rejection by kinematics	$\pi^{+/-}$ rejection by kinematics

Conventional cuts

Further separation w/ n-tag

Yes → $\overline{\nu}_e$-like Sample

No → ν_e-like Sample

Yes → $\overline{\nu}_\mu$-like Sample

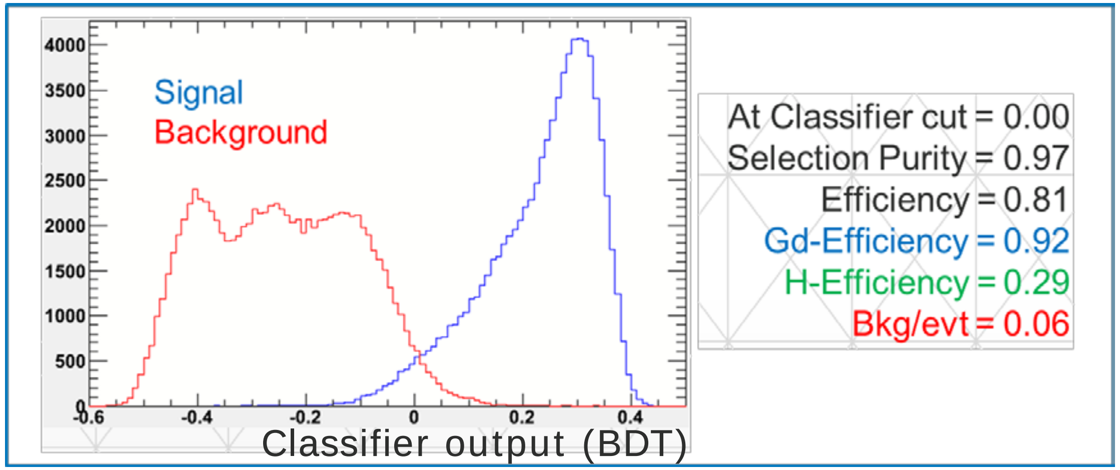
No → ν_μ-like Sample

Neutron tagging:
under development w/ machine learning

- Initial selection
  - 1 < dt < 200 (μsec)
  - 7 < N10 < 50, N200 < 140

NXX=number of PMT hits in XXns

- Multivariate analysis w/ Boosted Decision Tree (BDT)
  - TMVA/ROOT
  - Inputs
    - Basic hit variables:
      - time dt
      - NXX
    - Neutron fitter variables:
      - vertex position, energy, fit goodness
    - Isotropy variables
      - isotropy of PMT hits in space
  - output

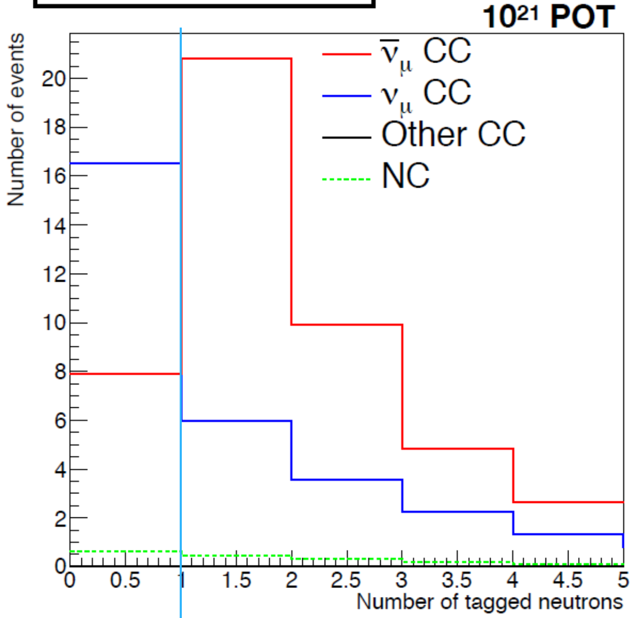


$$\beta_l = \frac{2}{N(N-1)} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P_l(\cos\theta_{ij})$$

Zero neutron cut (Preliminary)

- ν, anti-ν separation

$\overline{\nu}_{\mu}$ disappearance sample

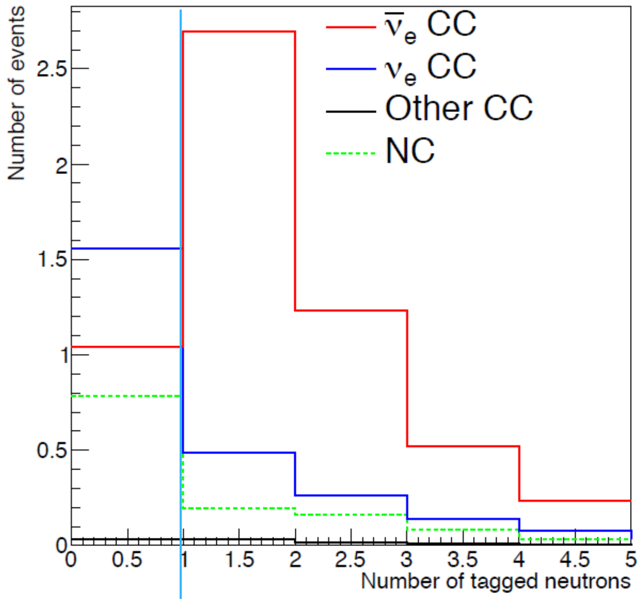


$\overline{\nu}_{\mu}$-like

Efficiency for #n >= 1

$\overline{\nu}_{\mu}$ CC: 0.84
ν_{μ} CC: 0.48
Other CC: 0.54
NC: 0.67

$\overline{\nu}_{e}$ appearance sample



$\overline{\nu}_{e}$-like

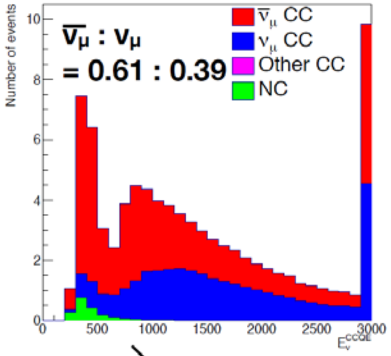
Efficiency for #n >= 1

$\overline{\nu}_{e}$ CC: 0.83
ν_{e} CC: 0.40
Other CC: 0.70
NC: 0.42

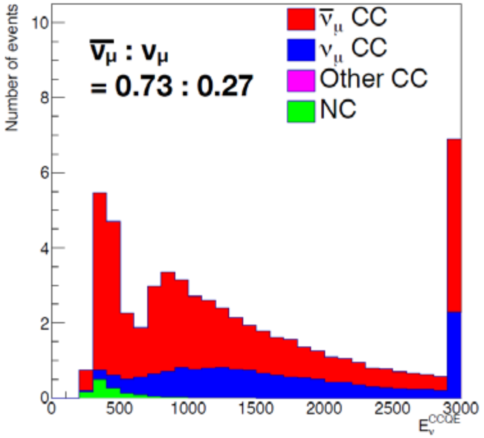
In anti-ν mode (preliminary)

- $\bar{\nu}_\mu$ disappearance sample

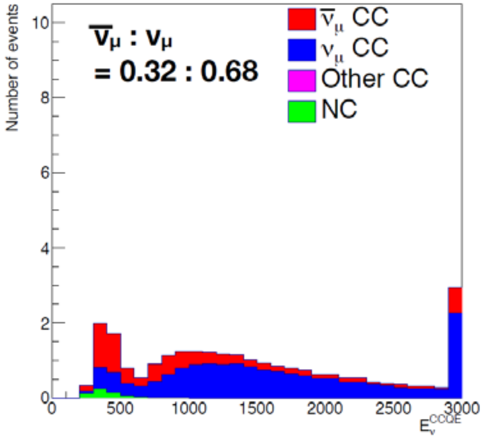
No n-tag info used 10[21] POT



w/ tagged neutron



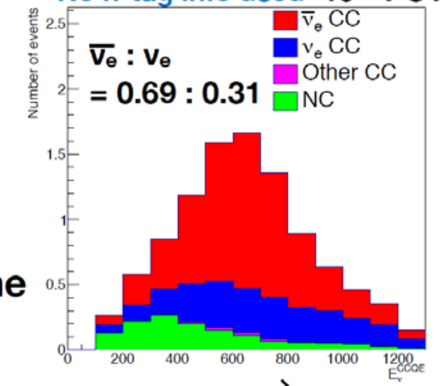
w/o tagged neutron



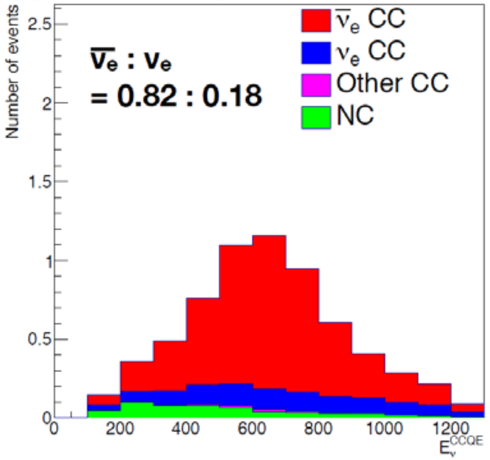
- **Powerful discrimination of "wrong-sign" backgrounds**
- **Also show energy dependence of the separation efficiency**

- $\bar{\nu}_e$ appearance sample

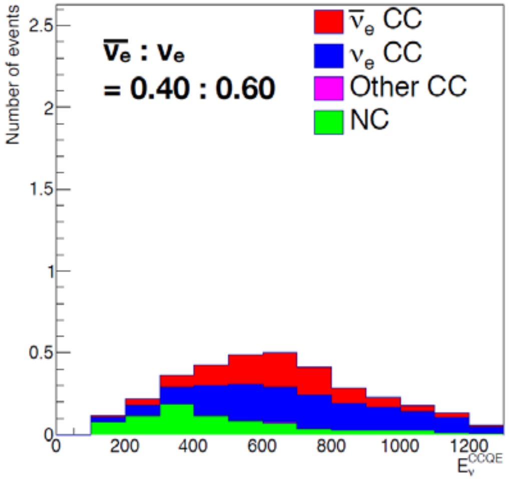
No n-tag info used 10[21] POT



w/ tagged neutron



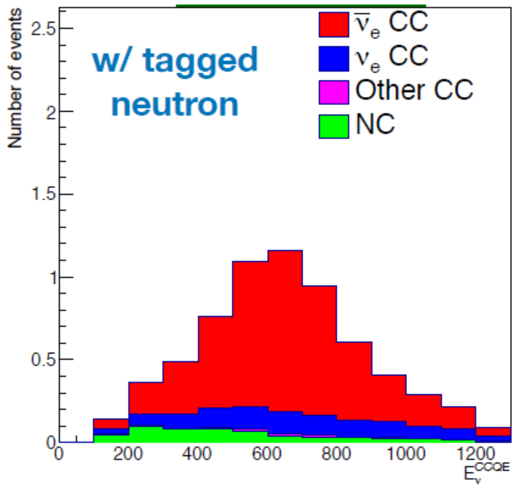
w/o tagged neutron

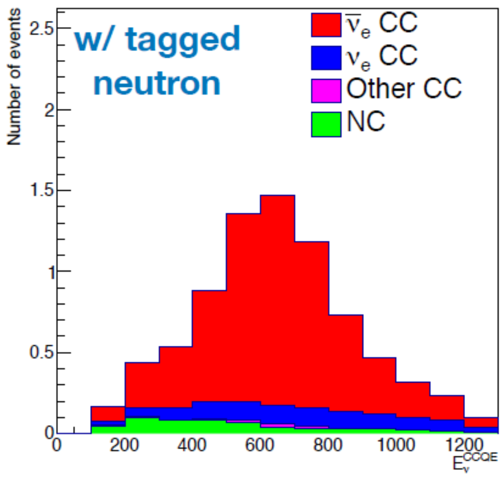


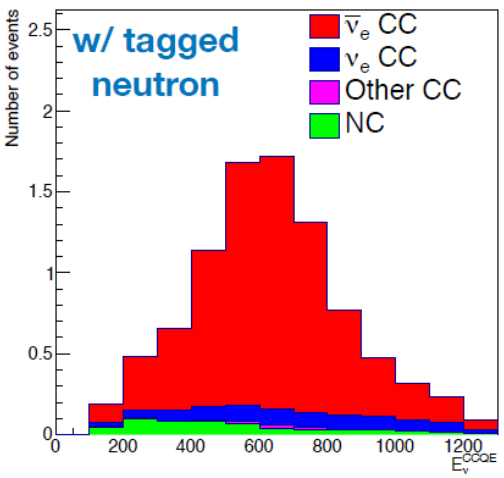
- **Similarly, expect powerful discrimination of wrong-sign backgrounds**

δ_{cp} dependence in ν_e appearance (preliminary)

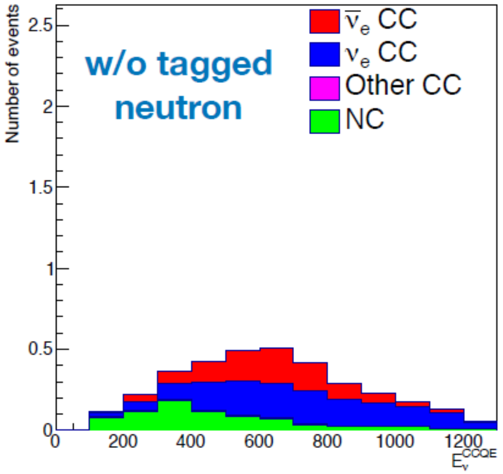
- Fraction of n-tagged event provides another handle to constrain δ_{CP}

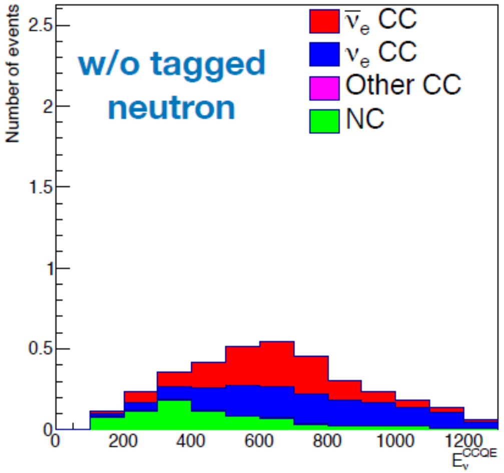


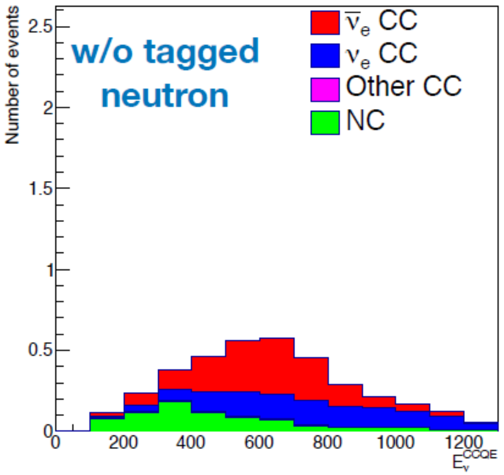




$\delta_{CP} = -\pi/2$ $\delta_{CP} = 0$ $\delta_{CP} = \pi/2$

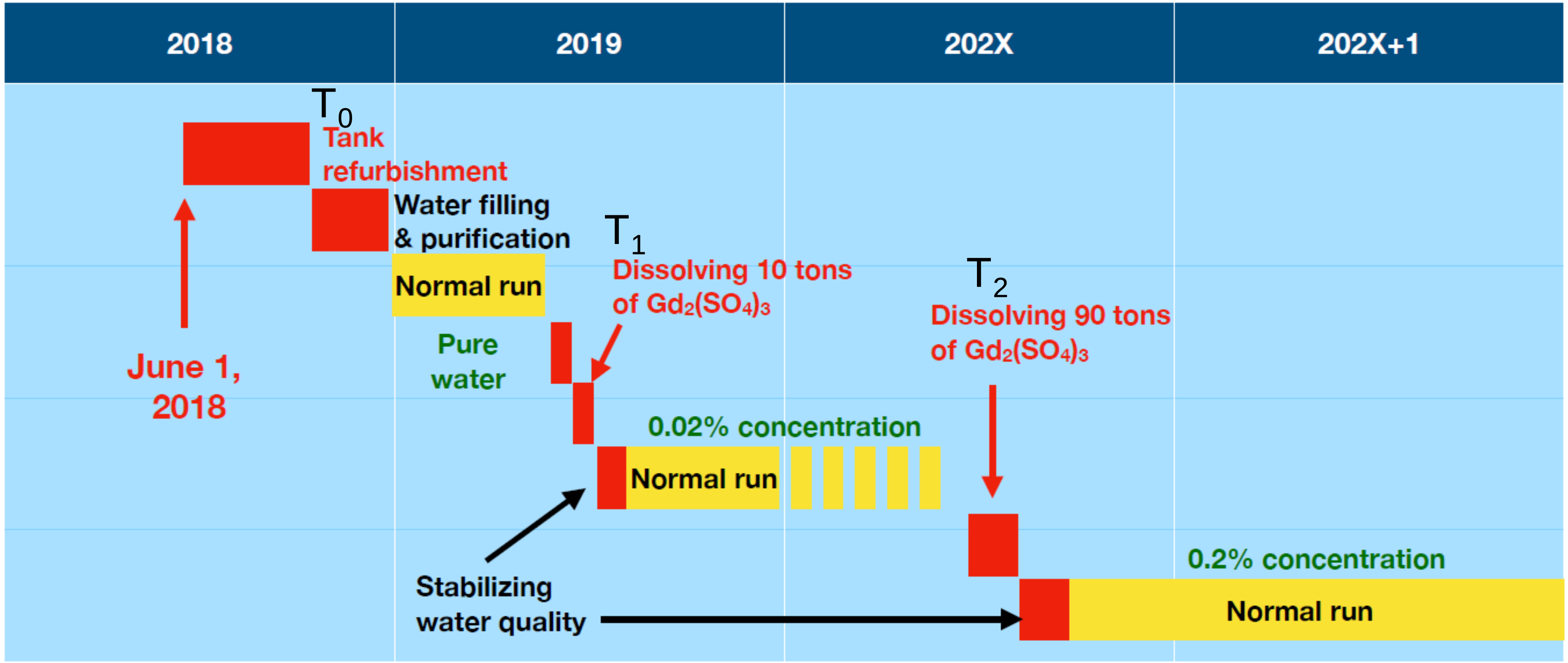






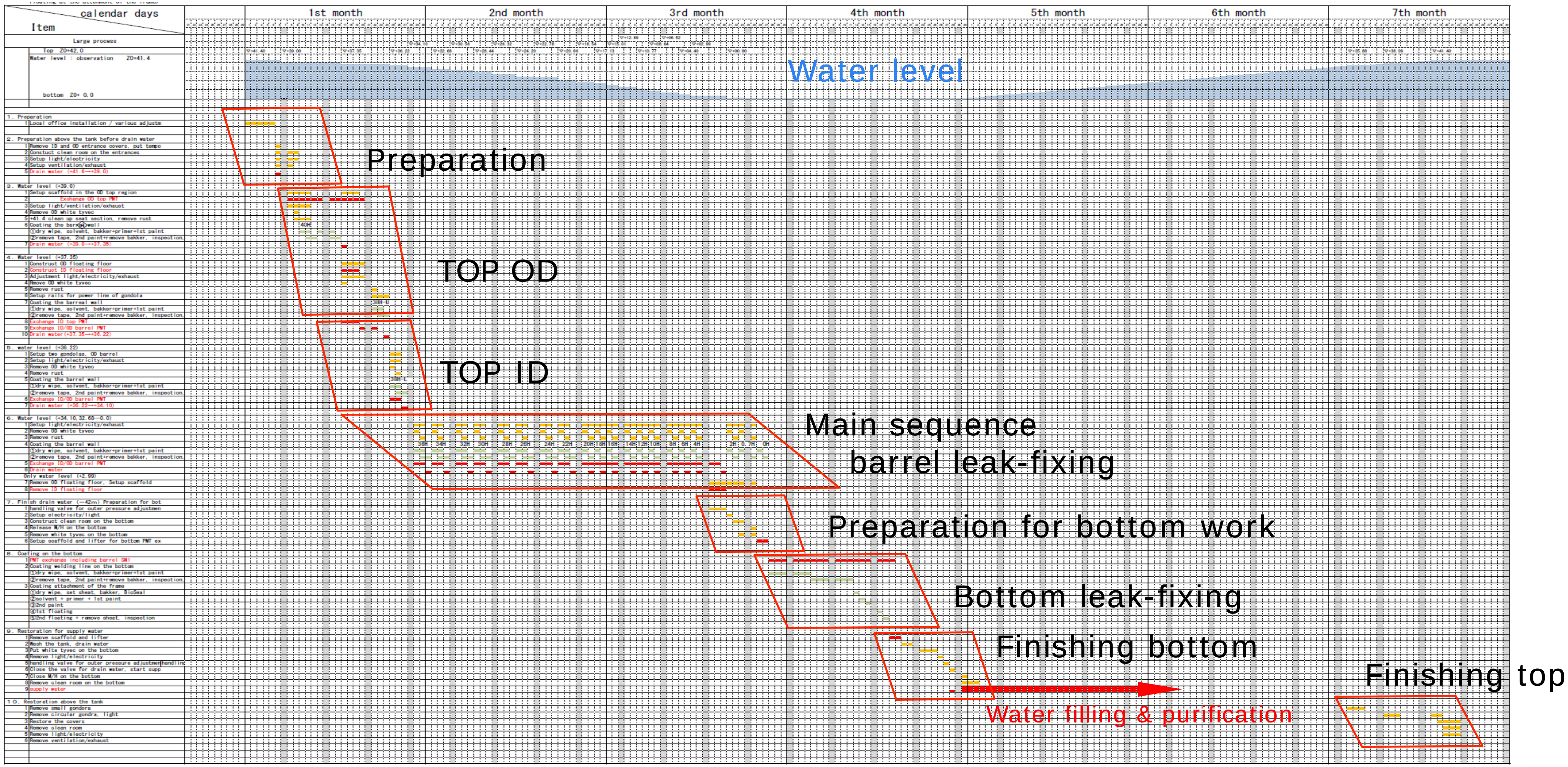
Timeline (SK Plan)

- 3 steps (T_0,T_1,T_2) to get 0.2% concentration
- T2K and SK agreed to set T_0 in 2018
  - In JPARC PAC meeting, T_0 was decided on June. 1st 2018.



Detailed 2018 schedule of SK refurbishment

- Day-by-day schedule … In total, 6.5 months are required to resume SK physics run.



SK-Gd

- SK-Gd project tries to catch neutrinos from past SNe before Hyper-K running.
- A lot of progresses made recently on leak fixing, background reduction and water system construction, and further preparation is ongoing for the SK refurbishment in 2018.

More Global Timeline
Hyper Kamiokande

- Japan-based seamless program to get timely results

Present

Super-K, 22kton Fid. mass

J-PARC 470kW beam (T2K)

SK-Gd(2019~)

J-PARC >750kW (T2K-II)

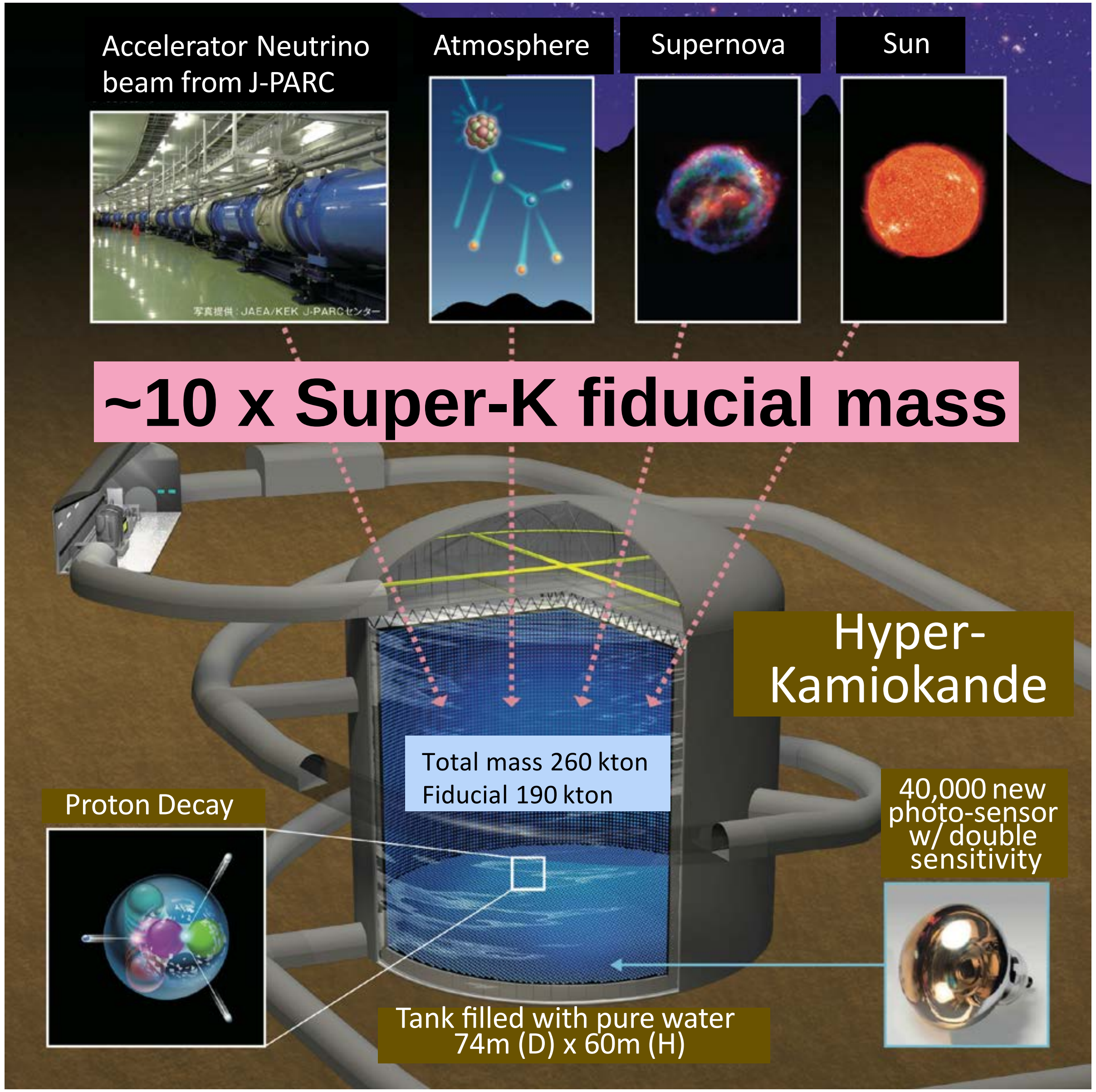
2026-

Hyper-Kamiokande

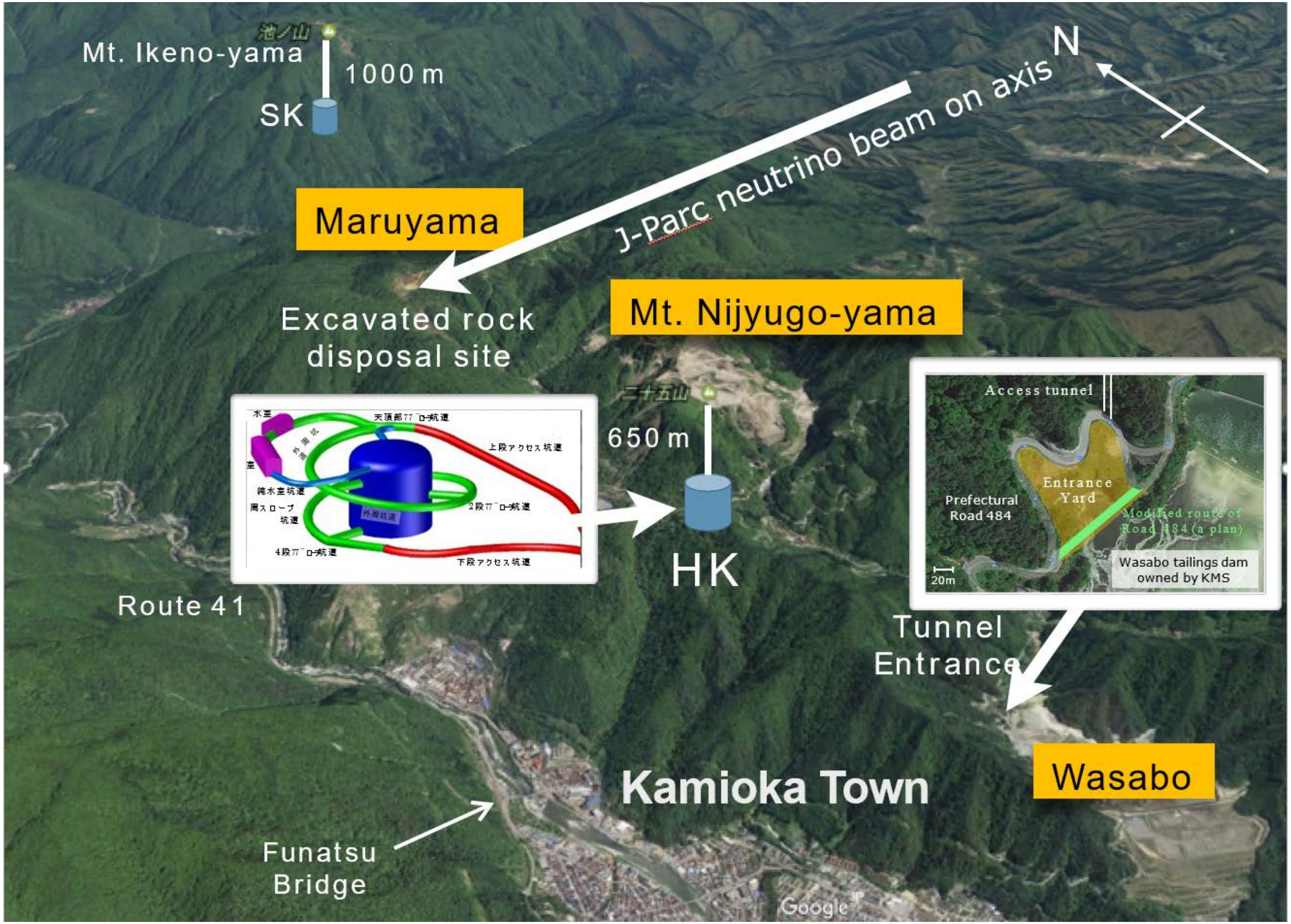
2026~, 190kton mass, >1.3MW beam

Hyper Kamiokande

- 650m underground in Kamioka
- 10 x Super-K FV
- 1.3MW neutrino beam from J-PARC, and natural neutrino sources
- Photo-sensors with double single-photon-sensitivity



HK site



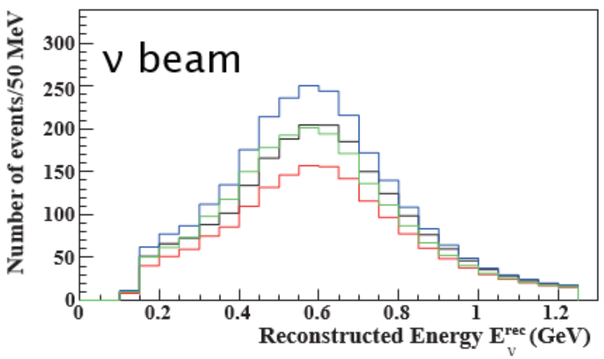
池ノ山
Mt. Ikeno-yama
1000 m
SK
J-Parc neutrino beam on axis
N
Maruyama
Excavated rock disposal site
Mt. Nijyugo-yama
二十五山
650 m
HK
天頂部アプローチ坑道
上段アクセス坑道
純水室坑道
2段アプローチ坑道
4段アプローチ坑道
下段アクセス坑道
Access tunnel
Entrance Yard
Prefectural Road 484
Modified route of Road 484 (a plan)
Wasabo tailings dam owned by KMS
20m
Route 41
Tunnel Entrance
Wasabo
Kamioka Town
Funatsu Bridge
Google

CP Violation

10 years
(13MW×10^7s)

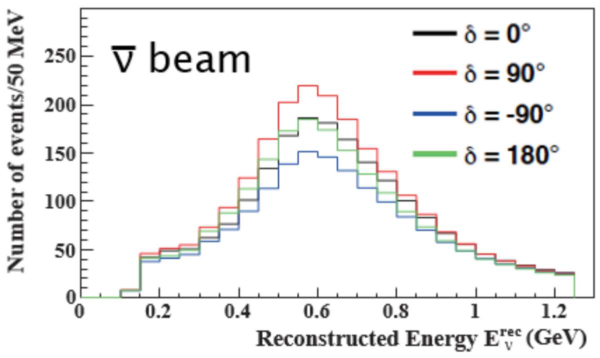
ν_e appearance

Neutrino mode: appearance



$\overline{\nu}_e$ appearance

Antineutrino mode: appearance



After T2K:

- With >5σ significance, Hyper-K will measure CP δ w/ precision of < 20 degree.
- Confirm/exclude the PMNS framework and CPV origin.

expected number of event in ν_e / $\overline{\nu}_e$ appearance (10 years)

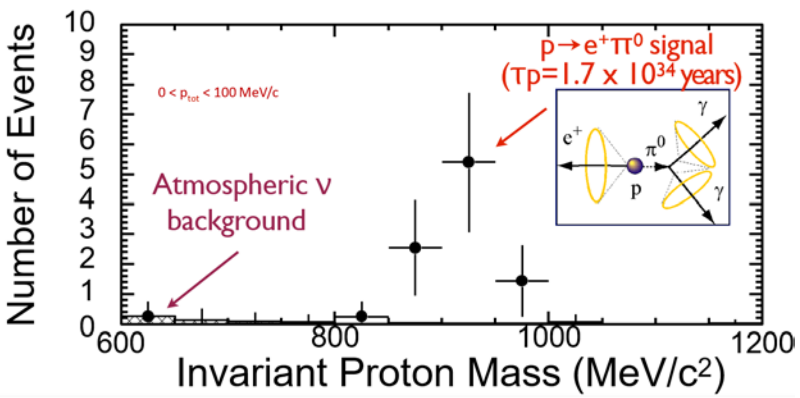
		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG Total	
ν mode	Events	1643	15	7	0	248	11	134	400	2058
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\overline{\nu}$ mode	Events	206	1183	2	2	101	216	196	517	1906
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

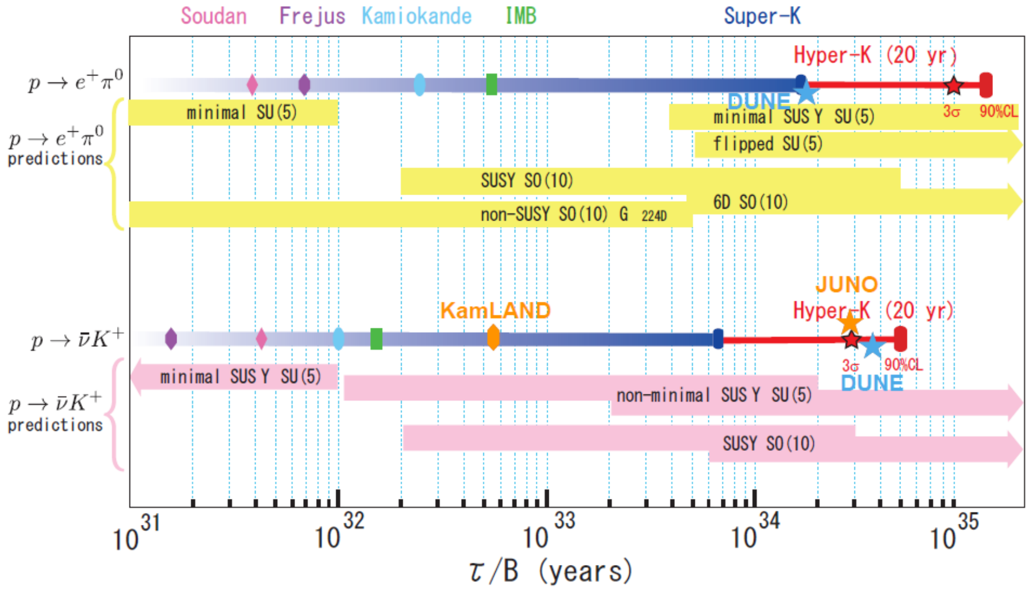
Proton decay

- Background elimination is still possible.
- Hyper-K is only realistic approach to proton lifetime

beyond 10^{35} years

Hyper-K 10 years





Current detectors

Super-K	50 kton H_2O
KamLAND	1 kton LS

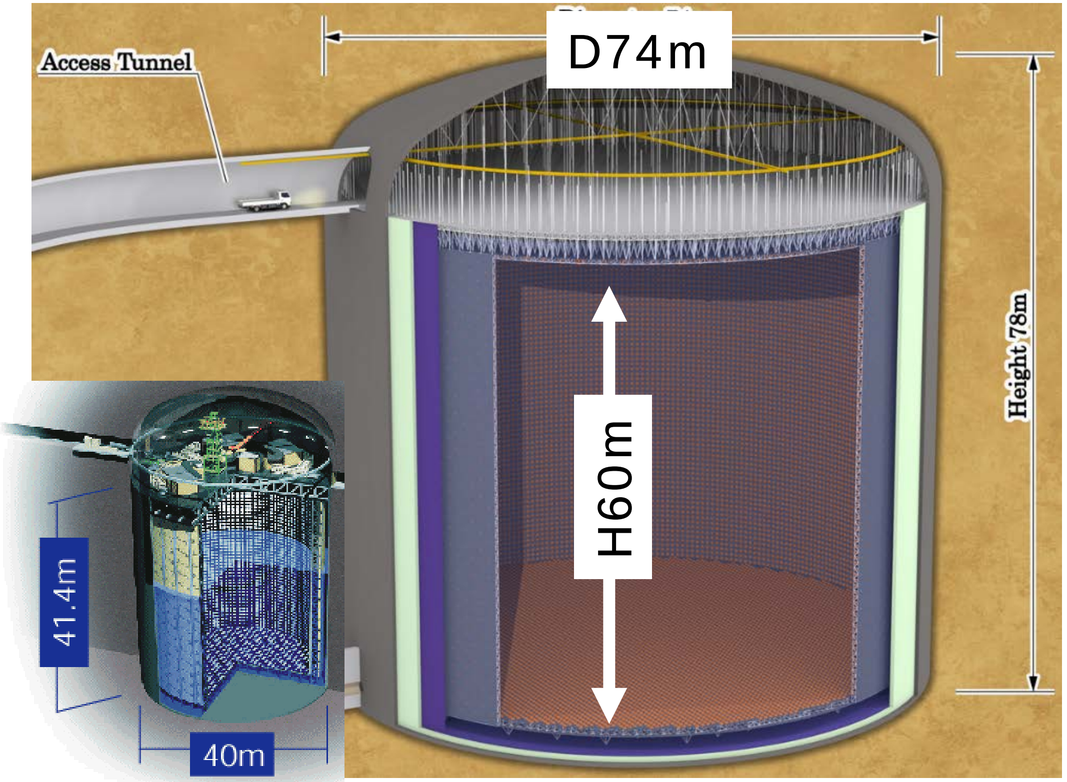
Future detectors

JUNO	17 kton LS
DUNE	40 kton Ar
Hyper-K	187 kton H_2O

search sensitivity ~10^{35} years

Supernovae

- **The SN detector**
  - 260k ton total
  - 220k ton ID for SN observation



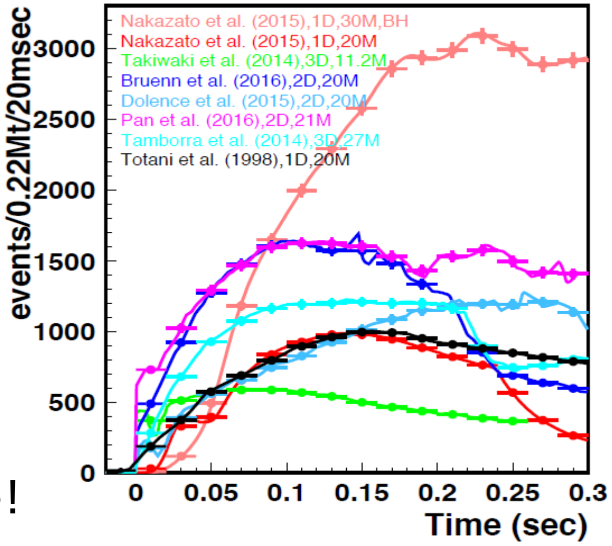
Supernova at 10 kpc
events in 220kton

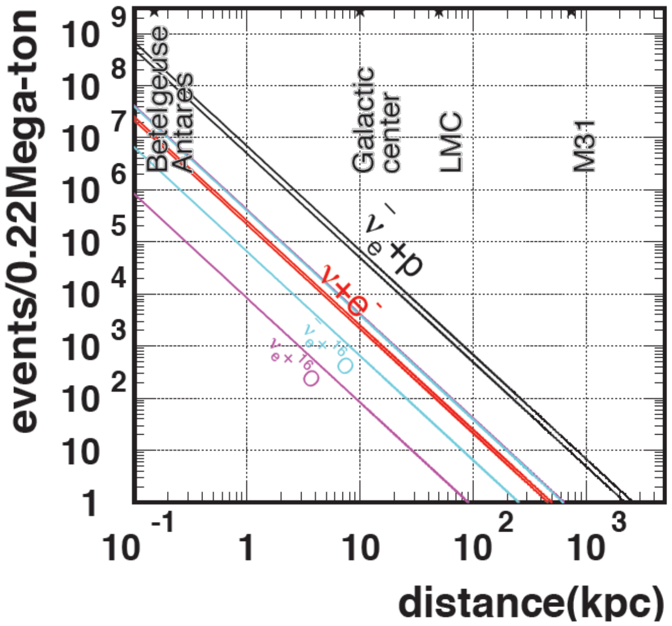
Nakazato:
ApJ.Suppl. 205 (2013) 2

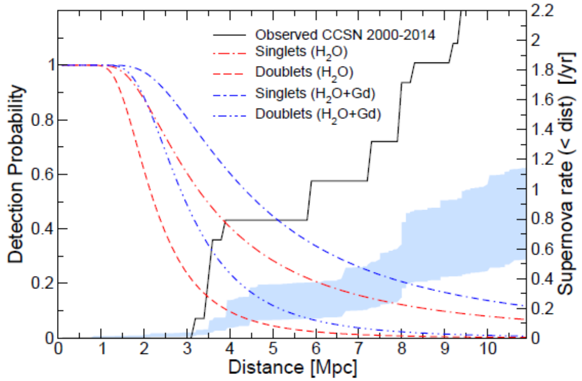
	Nakazato
$\bar{\nu}_e p \rightarrow e^+ n$	21300
$\nu + e^- \rightarrow \nu + e^-$	1200
^{16}O CC	410

statistical error invisible!

Time variation of event rate







K. Nakamura MNRAS, 461, 3296 (2016)

20 year of operation
At least
~ 1 events < 10Mpc

Hyper-Kamiokande Timeline with DUNE

Year	DUNE	Hyper-Kamiokande
2017	Far detector cavern excavation	
2018	Prototype detector test @CERN	Licensing procedure, Preparatory construction, Geological survey
2019		Access tunnel construction &
2020		Detector cavern excavation
2021	Start 1st detector (10kt) construction	
2022		
2023	Start 2nd detector (10kt) construction	Tank liner construction,
2024	Commissioning of two detectors (3rd and 4th detectors in stage)	Photo-sensor installation
2025		Water filling
2026	**Start neutrino beam delivery (1.2MW)**	**Start detector operation & neutrino beam (1.3MW)**

The very important milestone in Aug. 2017

http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu4/toushin/1388523.htm

- Hyper-K has been listed in the MEXT Roadmap2017
  - Ministry of Education, Culture, Sports, Science and Technology
  - The funding agency
- 7 projects are listed:
  - Genome, HL-LHC, HK, SPICA, LiteBIRD, atto-second pulse laser, and photon factory
- HK got highest evaluation result (a,a)
  - 5 projects got (a,a)

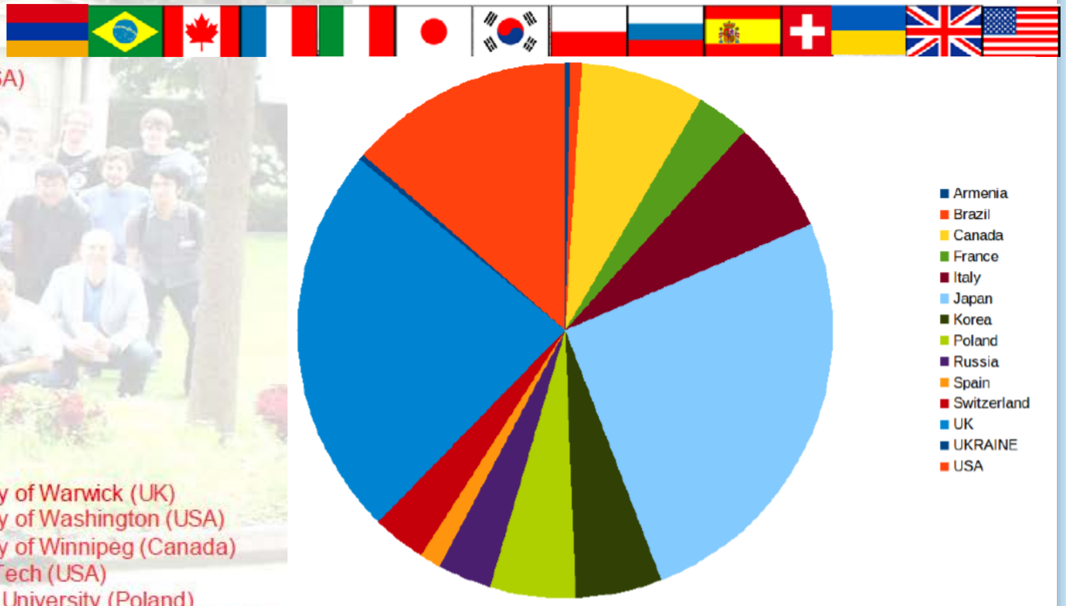
What's next in Japan

- FY2018 general account budget was request by MEXT in Aug. Draft budget will be announced by MoF in Dec.
  - Currently we are asked to wait until Dec.
  - Big projects in Japan sometimes get startup budget before construction start like the case for Super-K

Organization

Proto-collaboration

Gifu University (Japan)
High Energy Accelerator Research Organization (KEK) (Japan)
Kobe University (Japan)
Kyoto University (Japan)
Miyagi University of Education (Japan)
Nagoya University (Japan)
Okayama University (Japan)
Osaka City University (Japan)
Tohoku University (Japan)
Tokai University (Japan)
University of Tokyo, Earthquake Research Institute (Japan)
University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory (Japan)
University of Tokyo, Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos (Japan)
University of Tokyo (Japan)
University of Tokyo, Institute for the Physics and Mathematics of the Universe (Japan)
Tokyo Institute of Technology (Japan)
Boston University (USA)
Chonnam National University (Korea)
Dongshin University (Korea)
Duke University (USA)
Imperial College London (UK)
INFN and Dipartimento Interateneo di Fisica di Bari (Italy)
INFN-LNF (Italy)
INFN and Università di Napoli (Italy)
INFN and Università di Padova (Italy)
INFN Roma (Italy)
Institute for Nuclear Research (Russia)
Iowa State University (USA)
IRFU, CEA Saclay (France)
Laboratoire Leprince-Ringuet, Ecole Polytechnique (France)
Lancaster University (UK)
Los Alamos National Laboratory (USA)
Louisiana State University (USA)
National Centre for Nuclear Research (Poland)
Pontificia Universidade Catolica do Rio de Janeiro (Brazil)
Queen Mary, University of London (UK)
Royal Holloway University of London (UK)
Seoul National University (Korea)
Seoyeong University (Korea)
State University of New York at Stony Brook (USA)
STFC Rutherford Appleton Laboratory (UK)
Sungkyunkwan University (Korea)
The California State University Dominguez Hills (USA)
TRIUMF (Canada)
University Autonoma Madrid (Spain)
University of British Columbia (Canada)
University of California, Davis (USA)
University of California, Irvine (USA)
University of Edinburgh (UK)
University of Geneva (Switzerland)
University of Kiyv (Ukraine)
University of Hawaii (USA)
University of Liverpool (UK)
University of Oxford (UK)
University of Pittsburgh (USA)
University of Regina (Canada)
University of Rochester (USA)
Universidade de Sao Paulo (Brazil)
University of Sheffield (UK)
University of Toronto (Canada)
University of Warsaw (Poland)
University of Warwick (UK)
University of Washington (USA)
University of Winnipeg (Canada)
Virginia Tech (USA)
Wroclaw University (Poland)
Yerevan Physics Institute (Armenia)
York University (Canada)

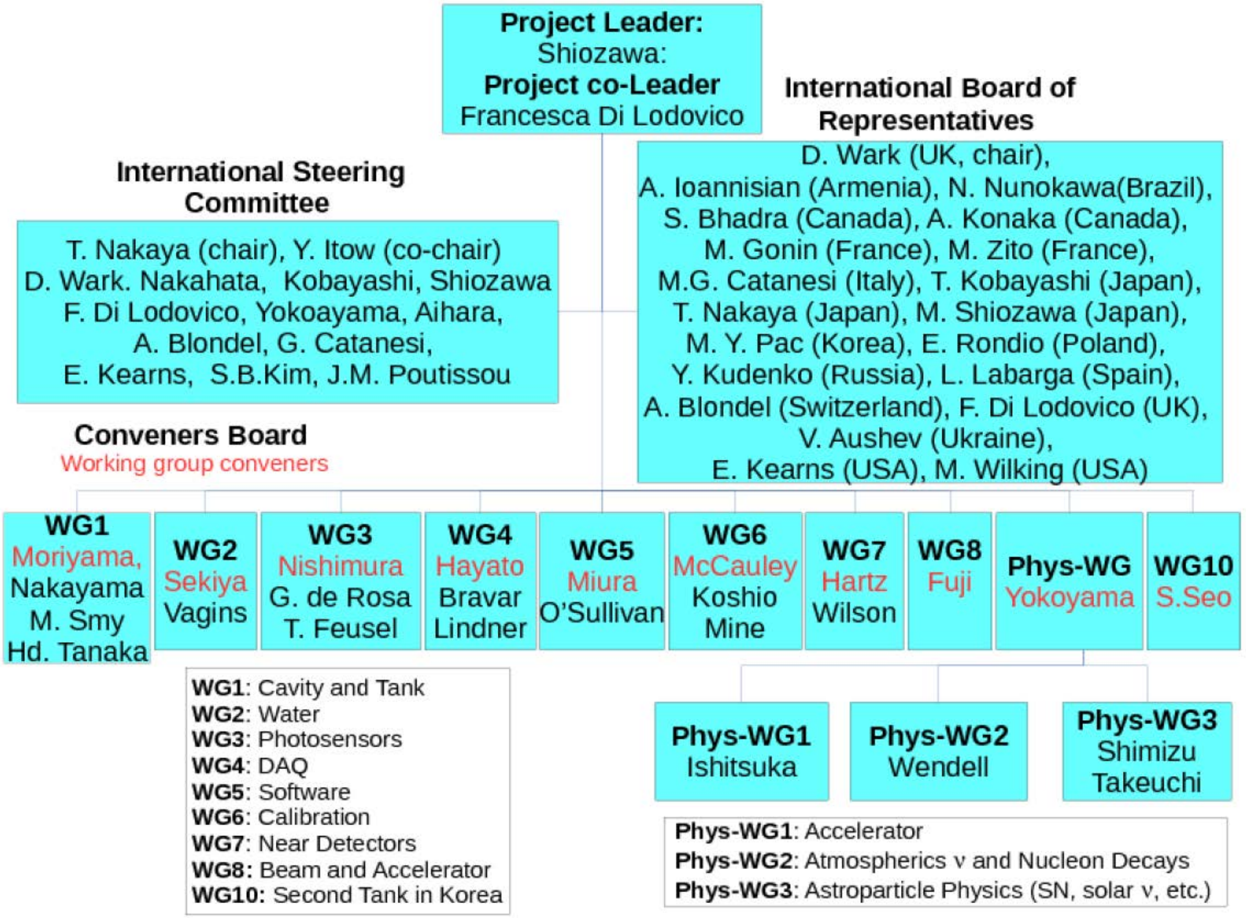


14 Countries, 71 Institutes, ~300 members and growing
~75% international collaborators

Organization

- Japan takes responsibility of the detector cavern & tank, the half of inner detector PMTs, J-PARC upgrade, and facility for the near detector system.
- UTokyo leads the Hyper-K, KEK leads J-PARC

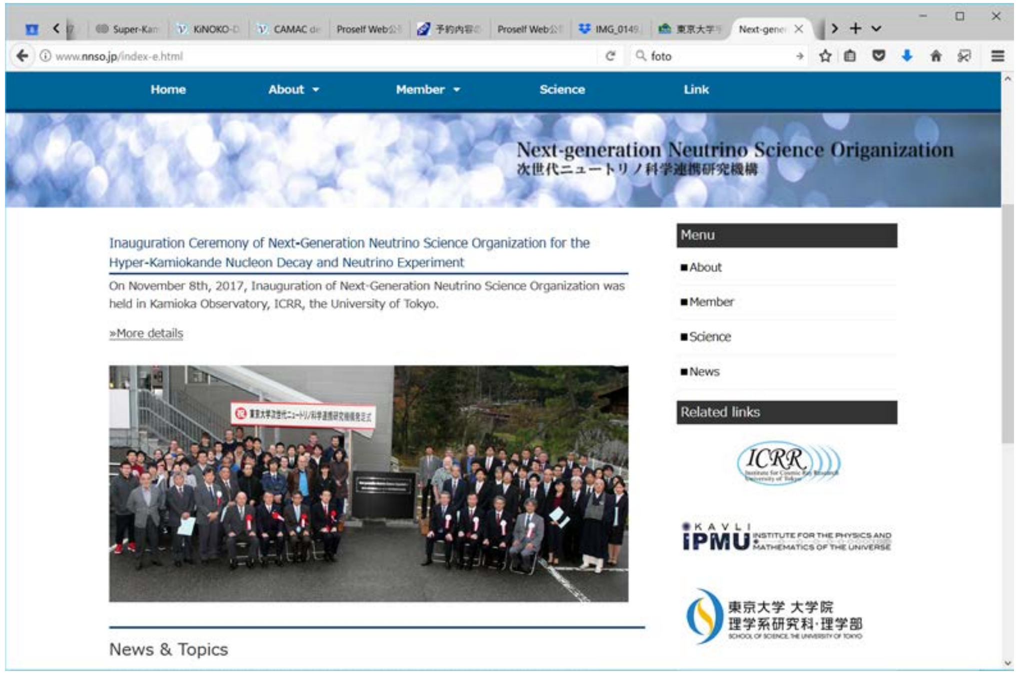
International organization



NNSO -The host organization in UTokyo

- Launched on October 1st
  - “In particular, it aims to advance what will become its flagship facility, the Hyper-Kamiokande project.”

www.nnso.jp

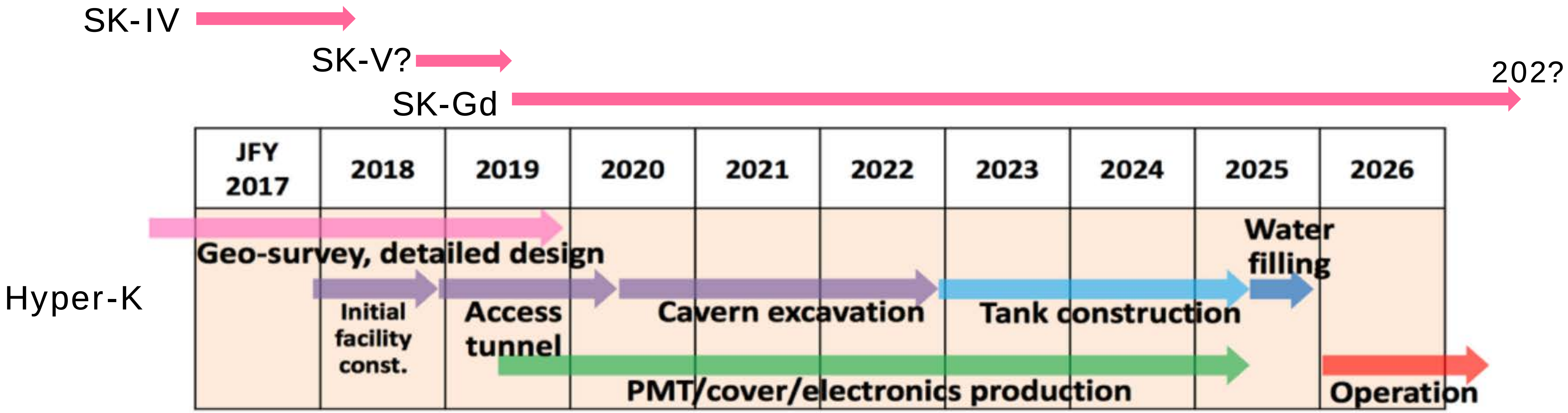


5 days ago

- Inauguration Ceremony on November 8th

Final remark

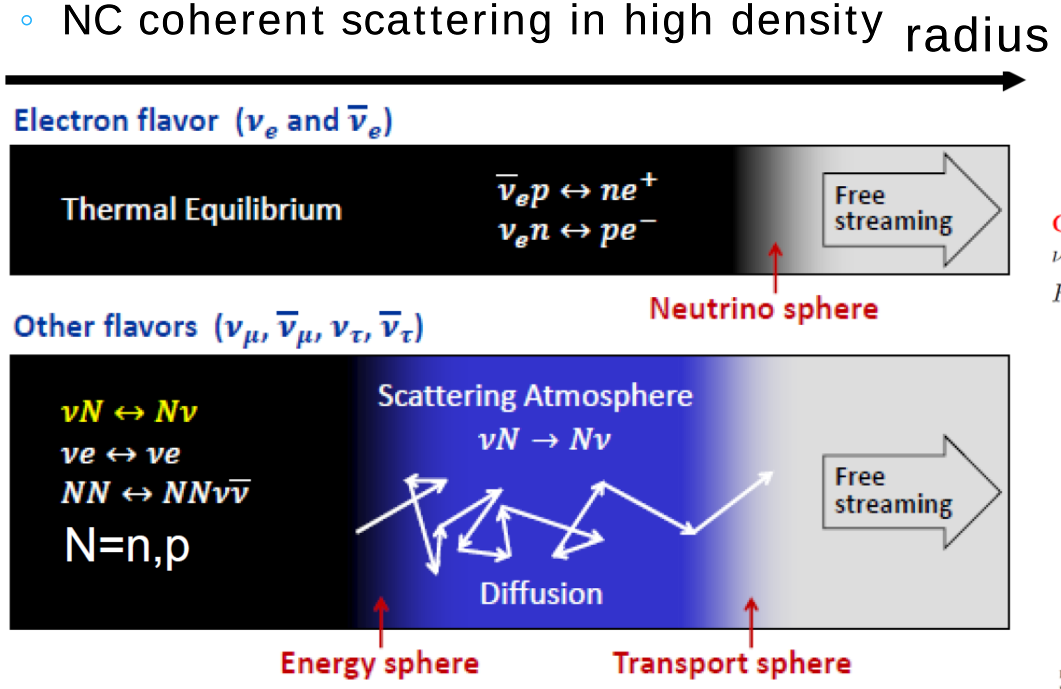
- Both SK-Gd and Hyper-K have ready-to-go design.
- The seamless program will have rich physics with world-leading science outputs.
- Open for international participants



Extra slides

Difficult part

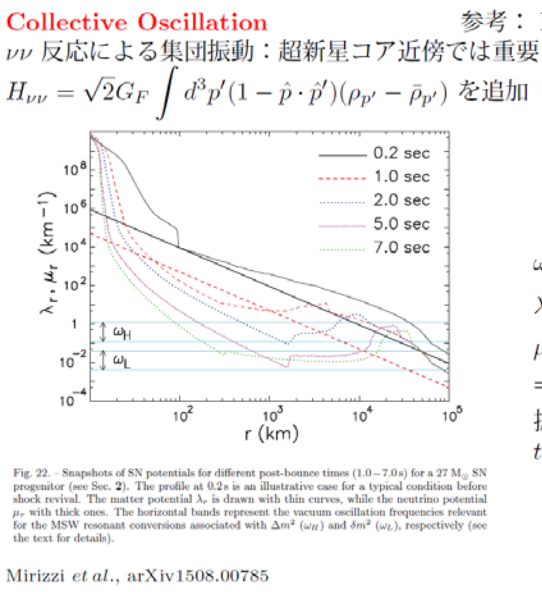
- Neutrino interactions in transportation/trapping
  - SN cannot burst without neutrino.
  - NC coherent scattering in high density

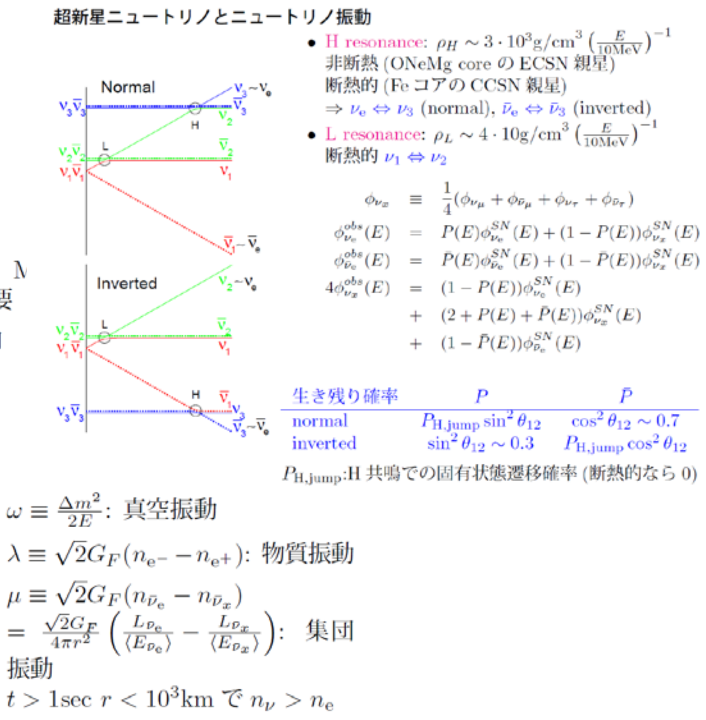


Janka 20

- Neutrino oscillation
  - Makes the calculation complicated
  - In ultra high density matter
  - Even Solar MSW has not yet been directly observed..

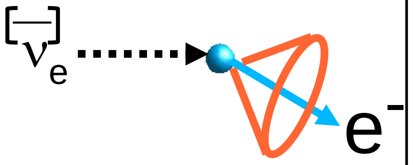
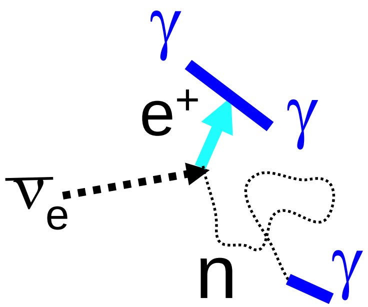
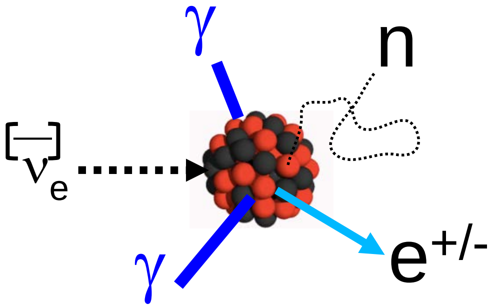
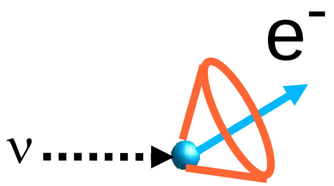
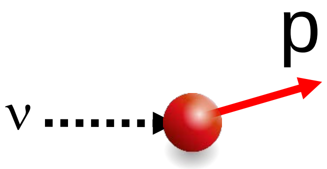
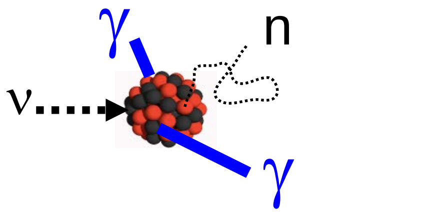
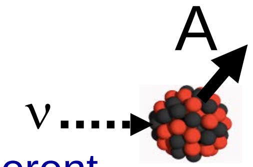
H. Suzuki





Supernova-relevant neutrino interactions

Kate Scholberg Neutrino2014

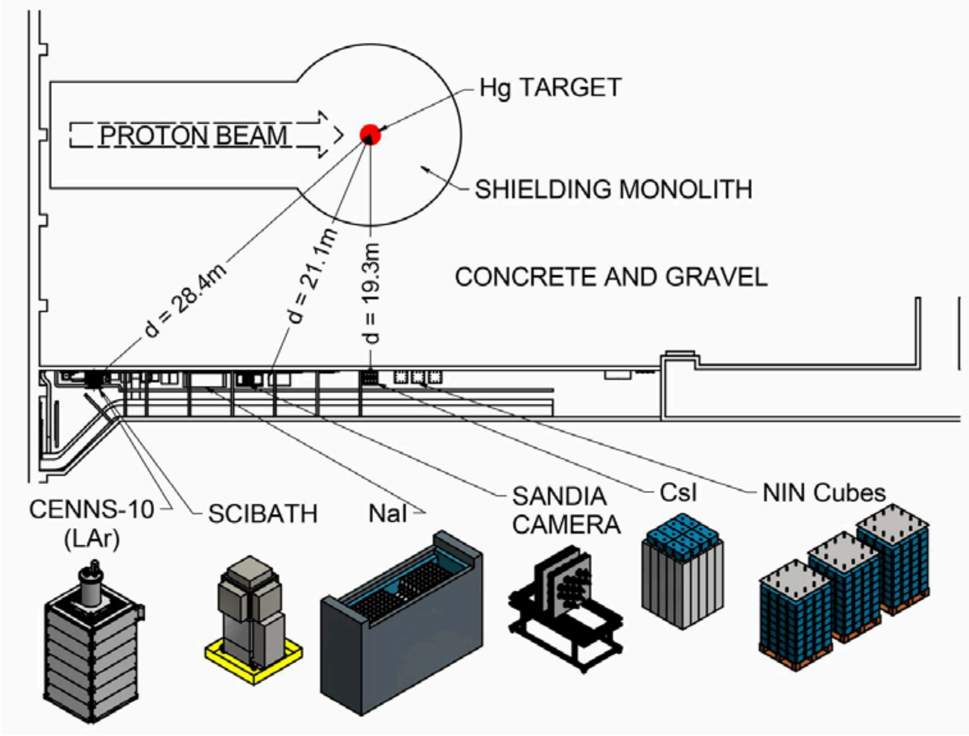
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N,Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEνNS)

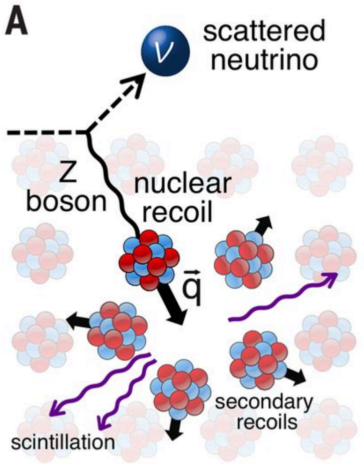
CEνNS was observed in 2017

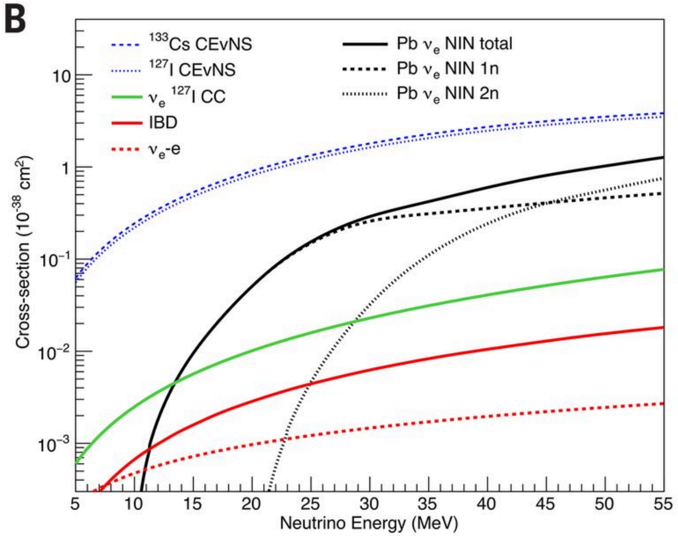
Science 03 Aug 2017:eaao0990

- By COHERENT

Spallation Neutron Source
Oak Ridge National Laboratory







CsI 14.6kg