Supernova neutrinos and Supernova Relic Neutrinos using a Water Cherenkov Detector

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SN1987A

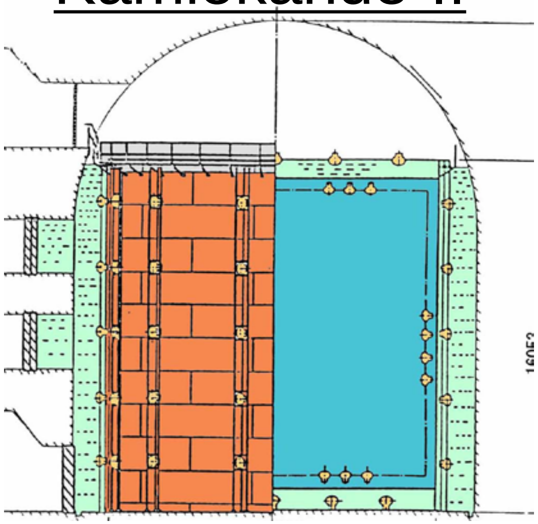
Contents

- What we have learned from SN1987A?
- What can we learn from current supernova detectors in the world
- Supernova relic neutrinos

  (Diffuse Supernova Neutrino Background)
  - Expected signals
  - SK-Gd project

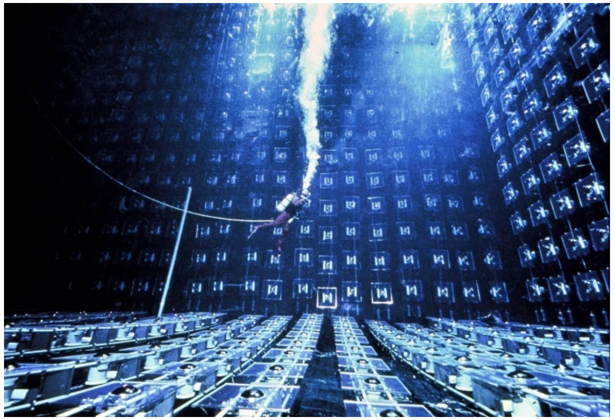
Detectors which observed SN1987A

Kamiokande-II



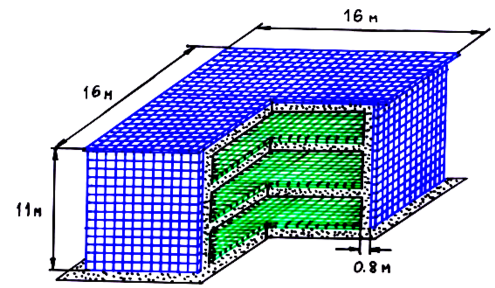
Japan Kamioka mine
2140ton fiducial
Water Cherenkov

IMB-3

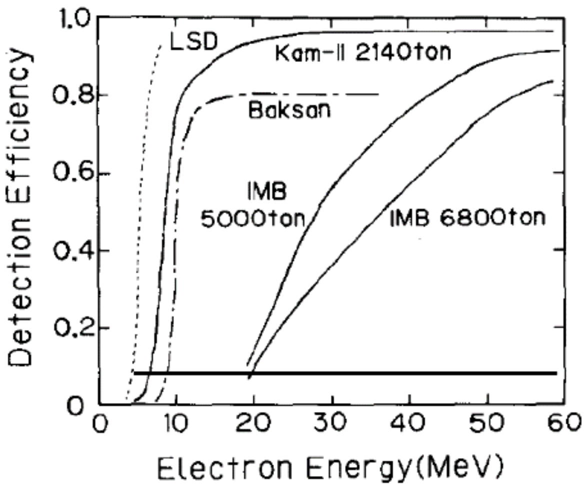


USA Ohio state Morton mine
～5000ton Fiducial
Water Charenkov

BAKSAN



Russia Baksan tunnel
330ton in 3150tanks
Liquid scintillator



Detection efficiencies (50% eff.)

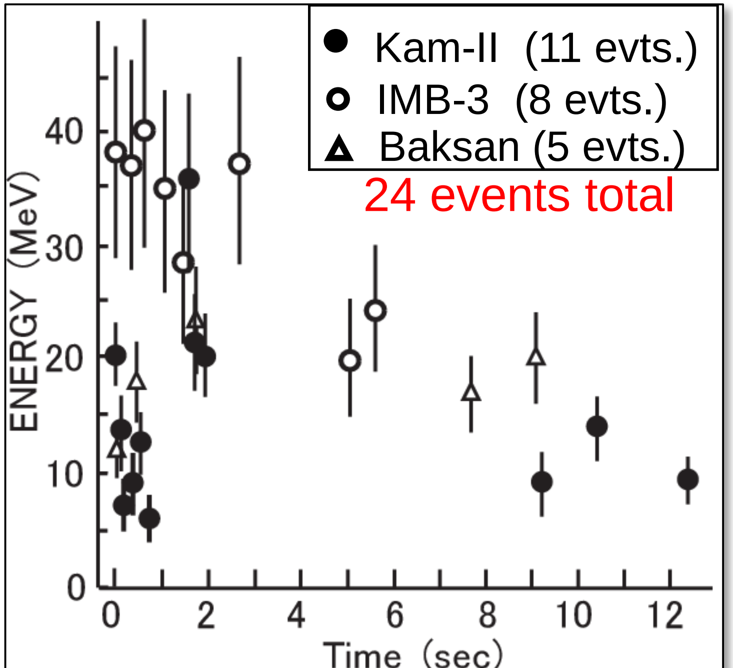
~8.5 MeV @ Kamiokande

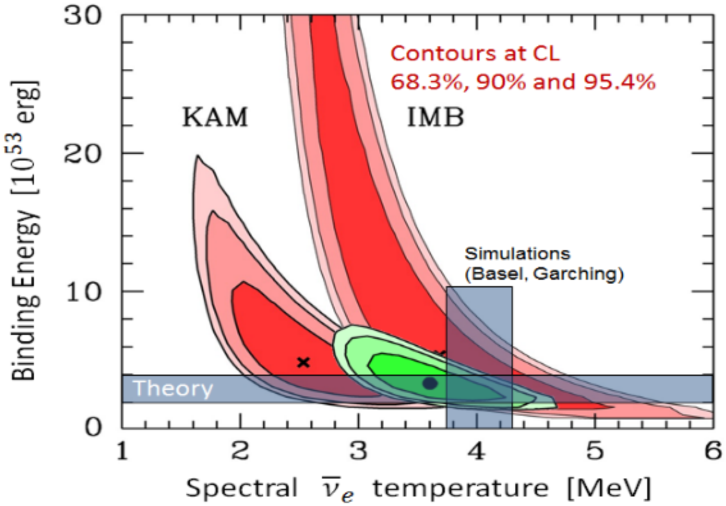
~28 MeV @ IMB

~10 MeV @ Baksan

Neutrino signals from SN1987A

Observed events



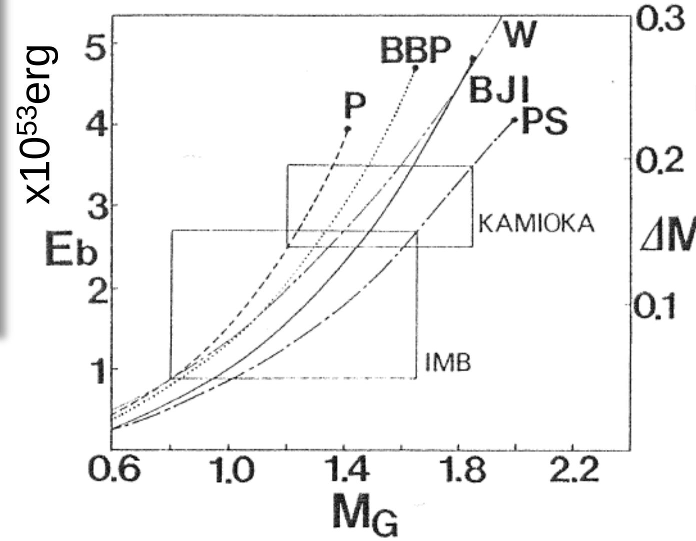


Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

What was learned?

Total energy released by $\overline{\nu}_e$: ~$5\text{x}10^{52}$ erg

→ Assuming equi-partition, total released energy is ~$3\text{x}10^{53}$ erg, which corresponds to a neutron star with 1.0-1.7$M_\odot$



K. Sato and H. Suzuki
Phys.Lett.B196 (1987) 267

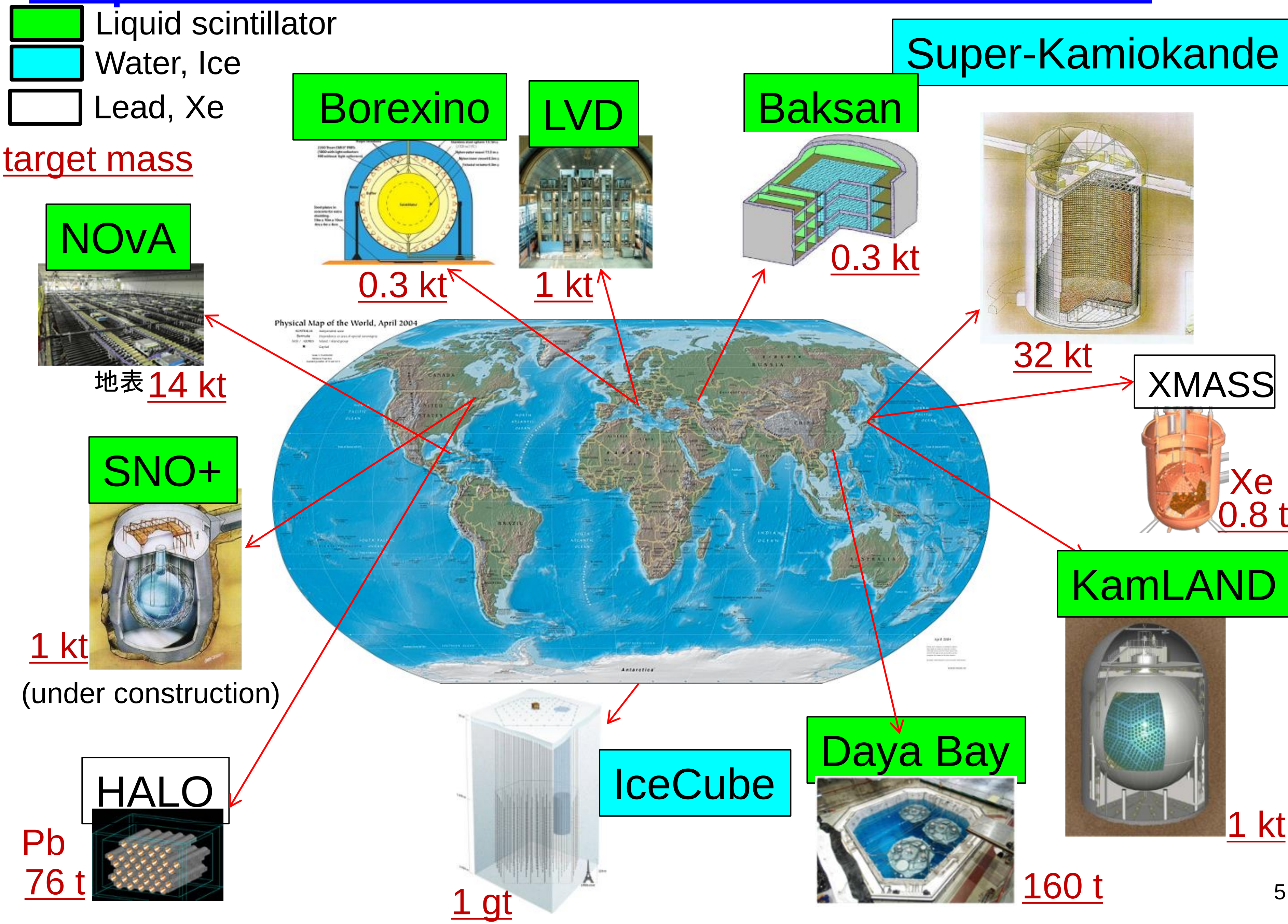
PRL 58, 2722 (1987)

The obtained binding energy is almost as expected.

Large error in neutrino mean energy.

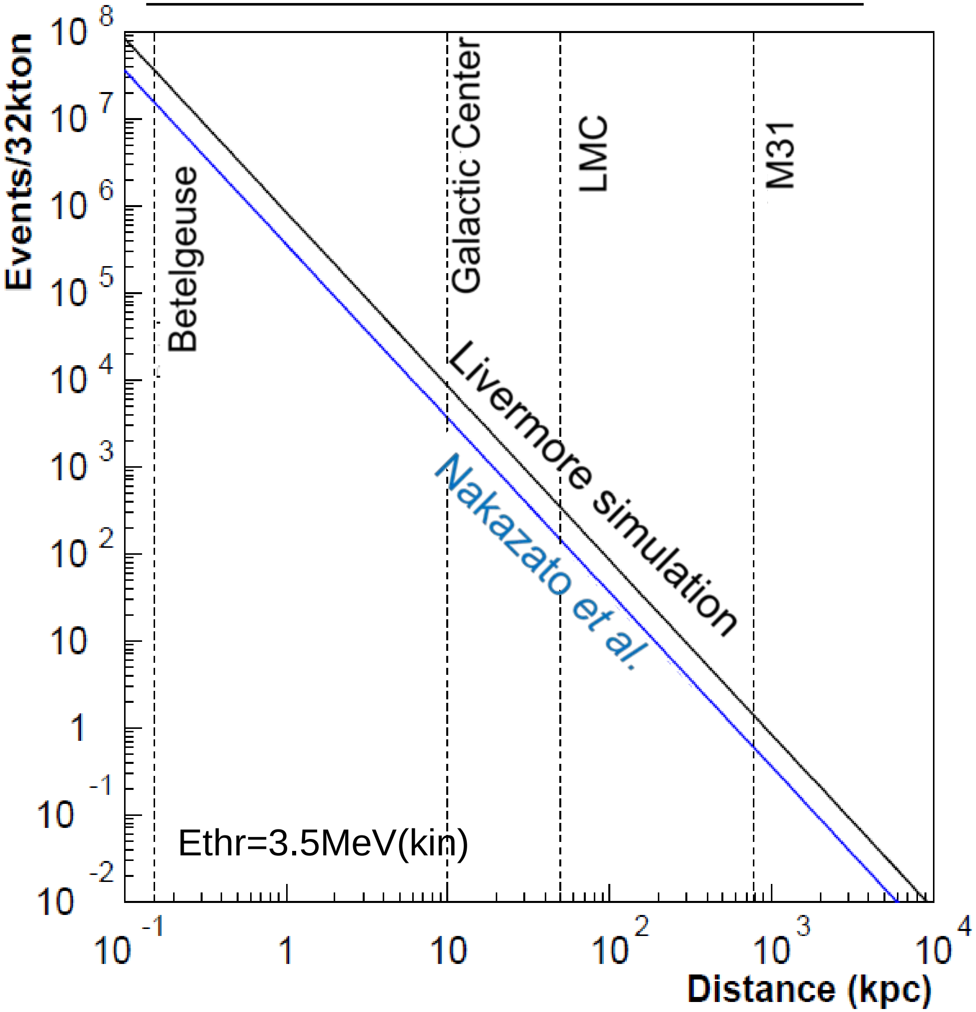
No detailed information of burst process.

Supernova burst detectors in the world

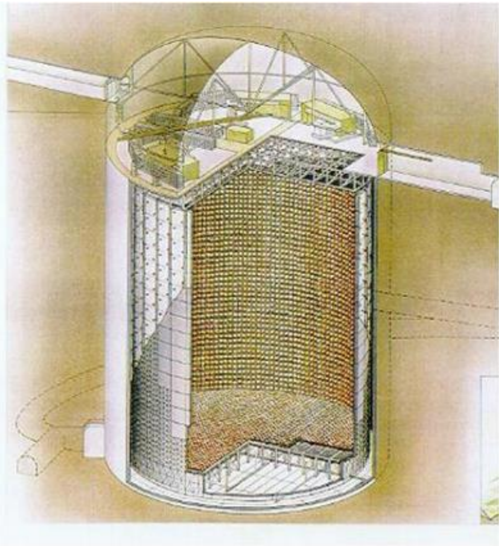


Super-K: Number of events

Number of events vs. distance



32kton water Cherenkov



For each interaction

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

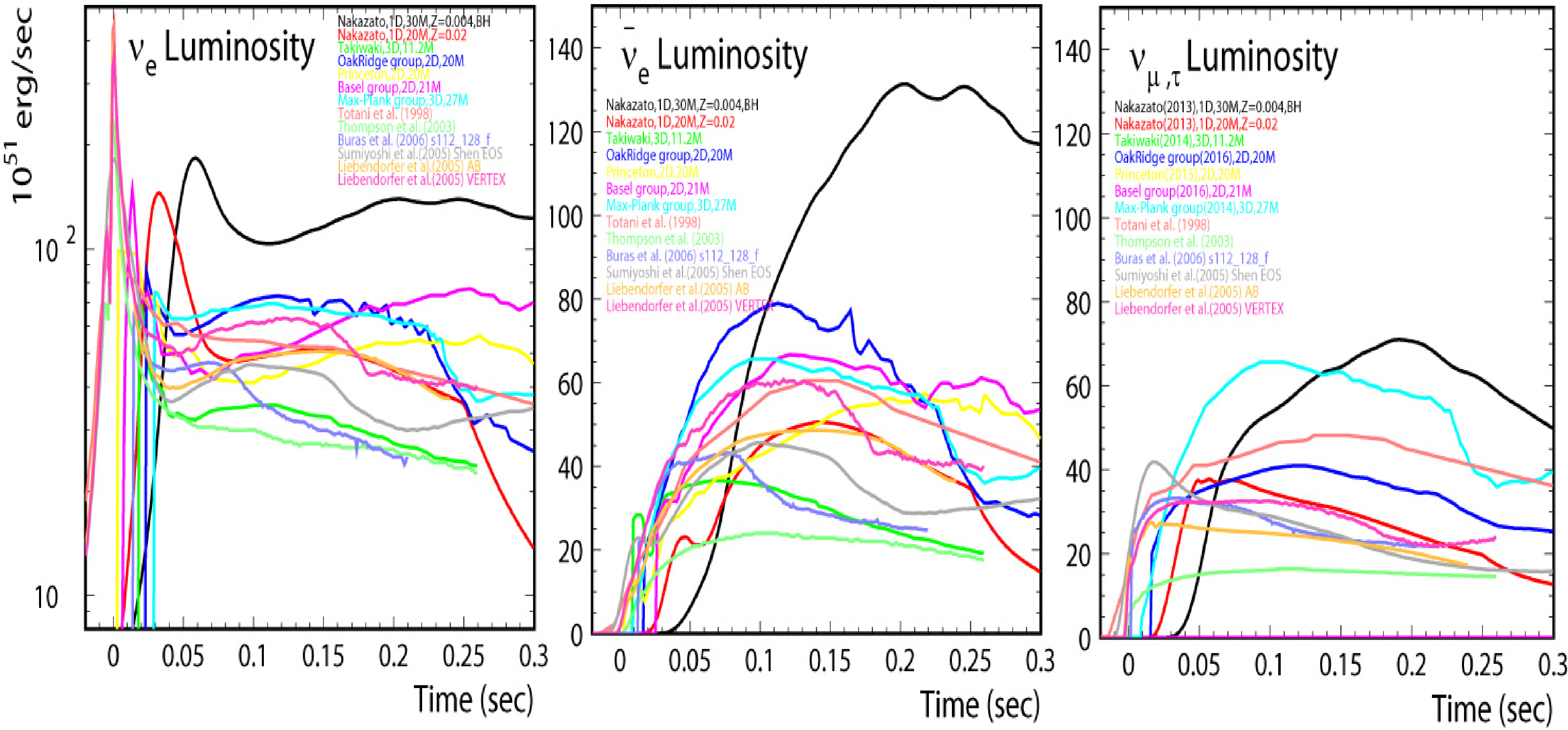
Directional info.

Supernova at 10 kpc
32kton SK volume
4.5MeV(kin) threshold
No oscillation case.

Livermore simulation T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

Nakazato et al. K.Nakazato, K.Sumiyoshi, H.Suzuki, T.Totani, H.Umeda, and S.Yamada, ApJ.Suppl. 205 (2013) 2, ($20M_{sun}$, trev=200msec, z=0.02 case)

Neutrino luminosity from various model predictions



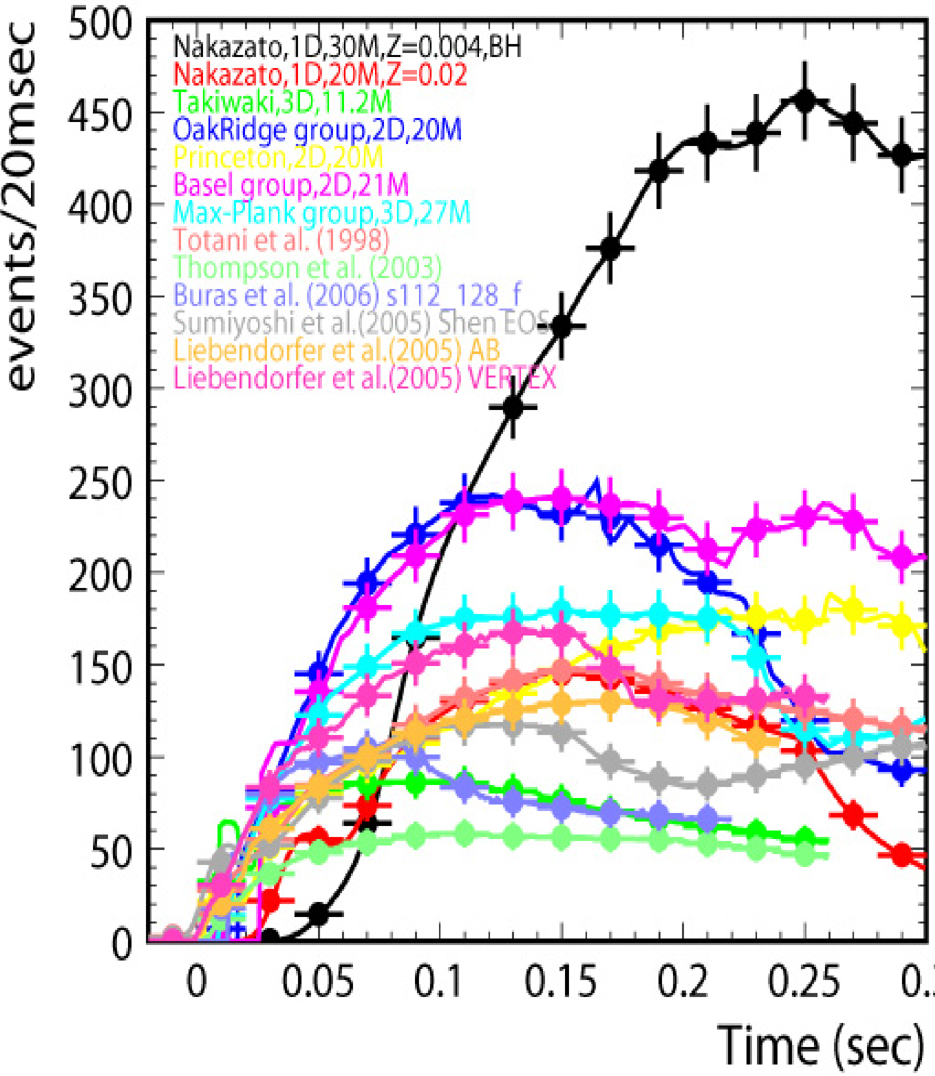
Nakazato(2013),1D,30M,Z=0.004,BH
Nakazato(2013),1D,20M,Z=0.02
Takiwaki(2014),3D,11.2M
OakRidge group(2016),2D,20M
Princeton(2015),2D,20M
Basel group(2016),2D,21M
Max-Plank group(2014),3D,27M
Totani et al. (1998)
Thompson et al. (2003)
Buras et al. (2006) s112_128_f
Sumiyoshi et al.(2005) Shen EOS
Liebendorfer et al.(2005) AB
Liebendorfer et al.(2005) VERTEX

Cooperation: H. Suzuki

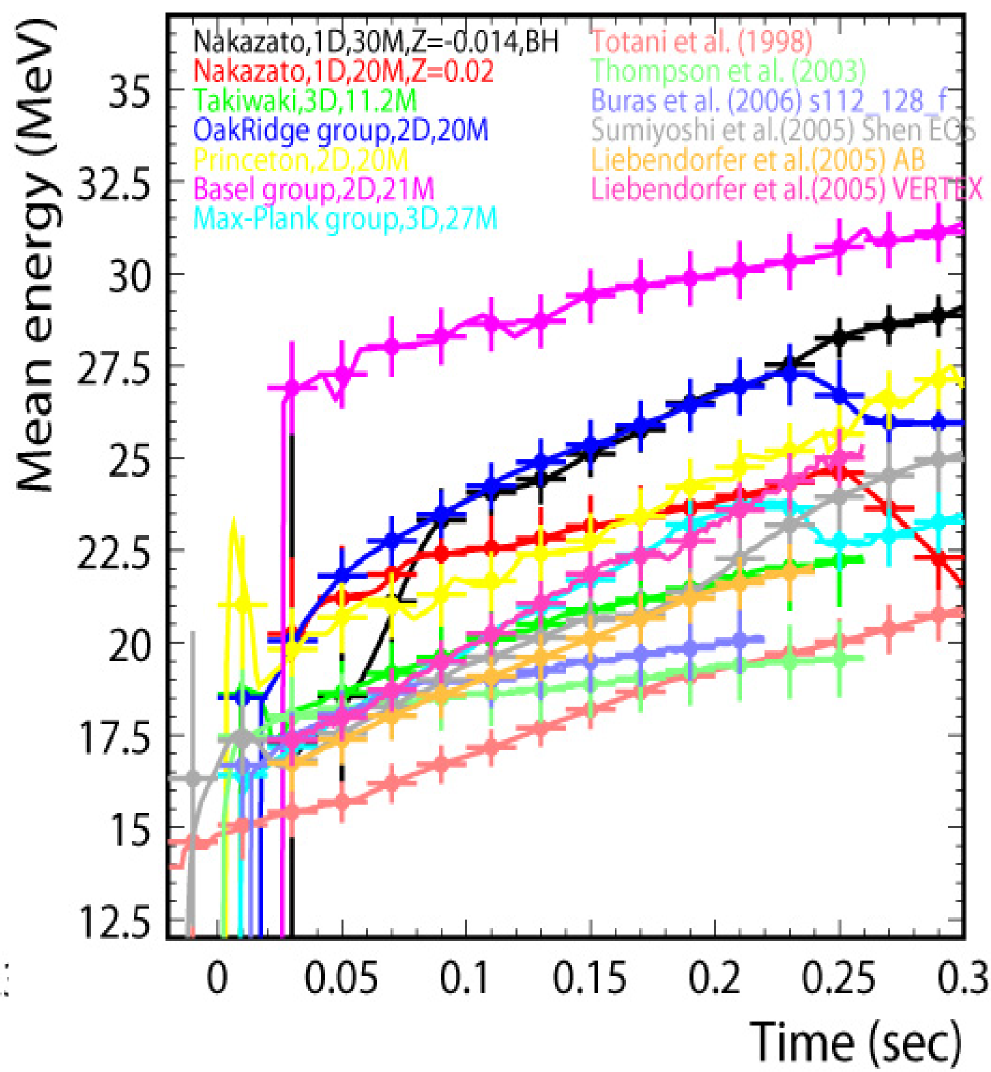
Sensitivity of Super-K for the model discrimination

10kpc supernova

Time variation of event rate



Time variation of mean energy

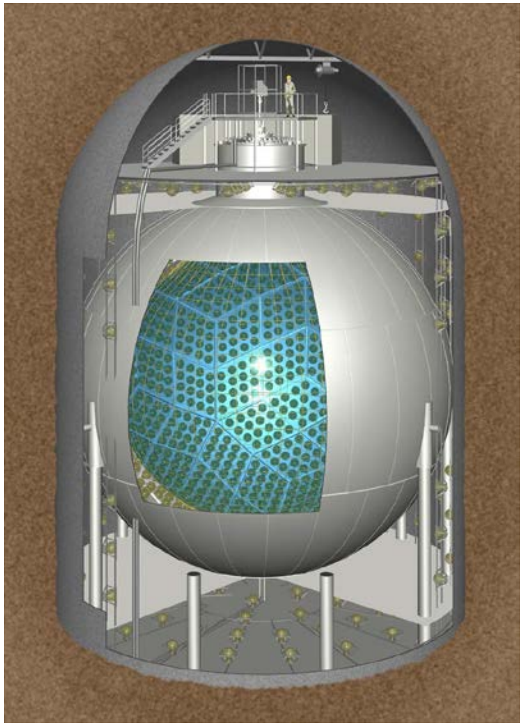


High statistics enough to discriminate models

Cooperation: H. Suzuki

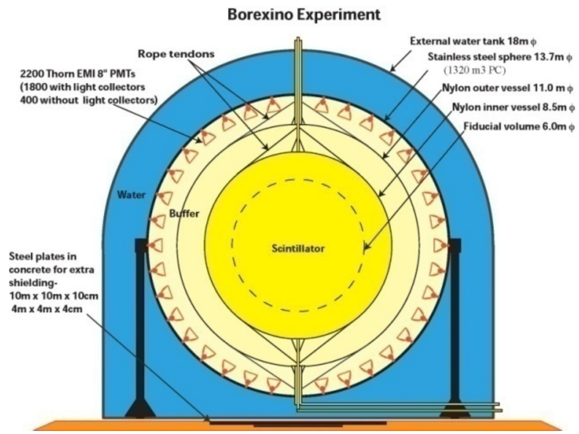
Single volume liquid scintillator detectors

KamLAND
(Kamioka, Japan)



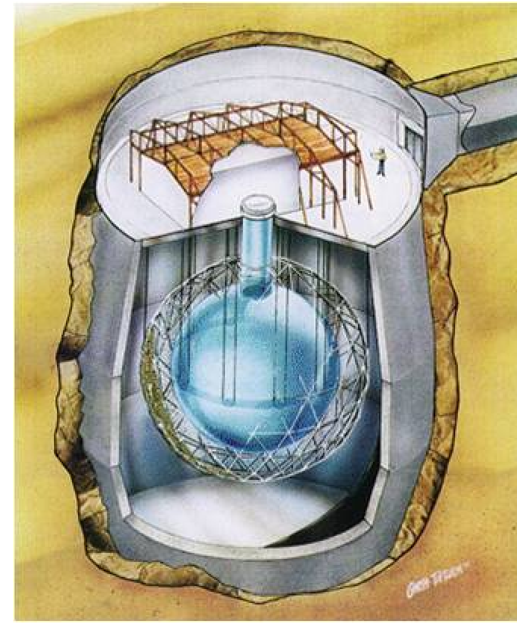
1000ton liq.sci.
Running since 2002.

Borexino
(Gran Sasso, Italy)



300ton liq.sci.
Running since 2007.

SNO+
(SNO Lab.,Canada)



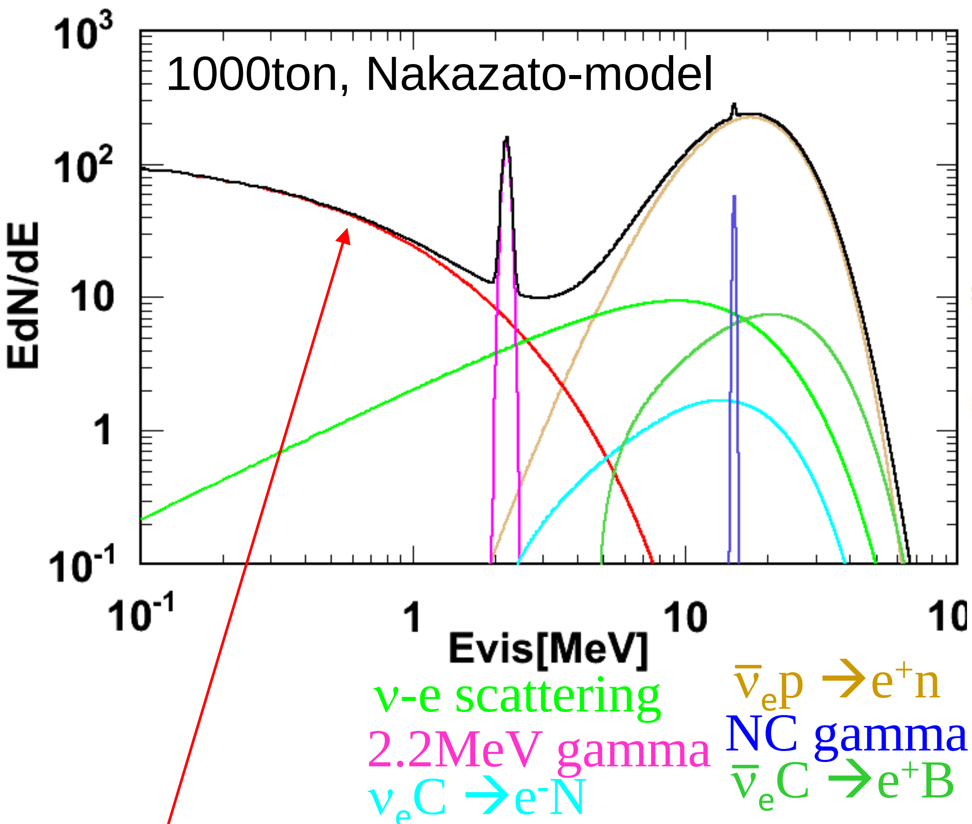
1000ton liq.sci.
Under construction.

From K.Inoue, G.Bellini, M.Chen

Energy spectrum expected at the liquid scintillation detectors

ν_x parameter measurement with νp elastic scattering events (3000t eqv.)

Expected energy spectrum (10kpc)

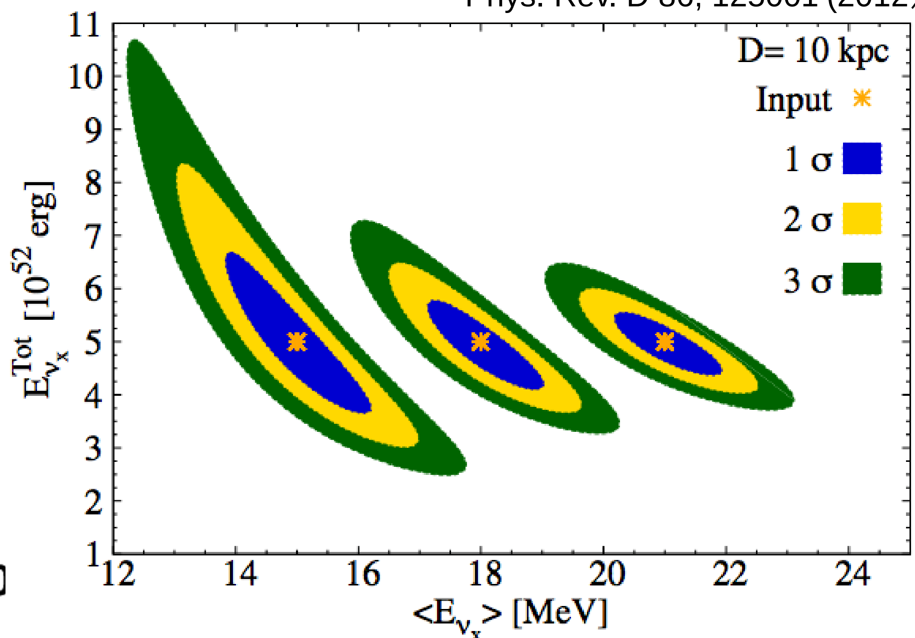


νp elastic scattering

~80 events about 200keV

~30 events about 500keV

Phys. Rev. D 86, 125001 (2012)



Determine luminosity and mean energy of ν_x

(ν_x : ν_μ , ν_τ at the source)

From K. Ishidoshiro

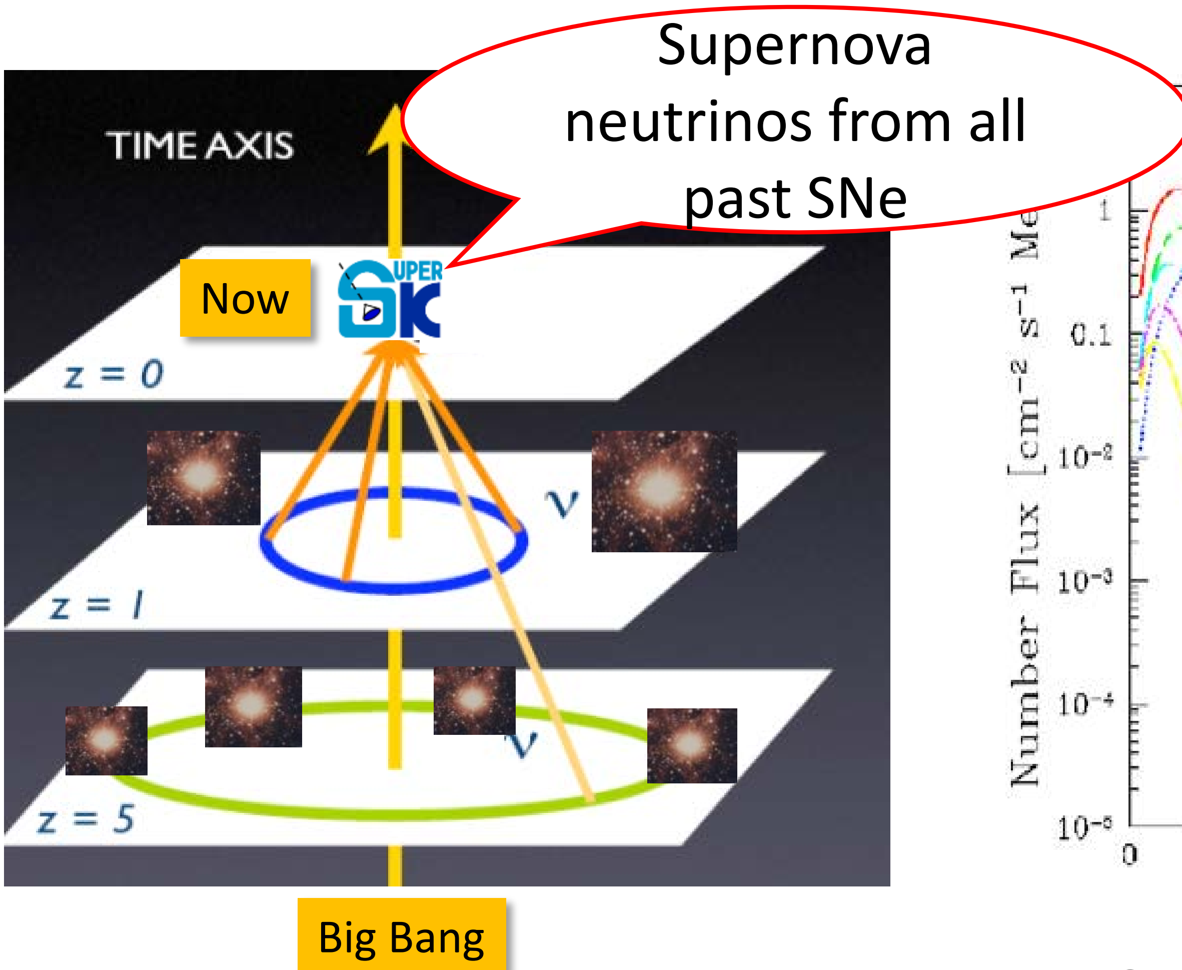
Estimates of the Galactic SN rate

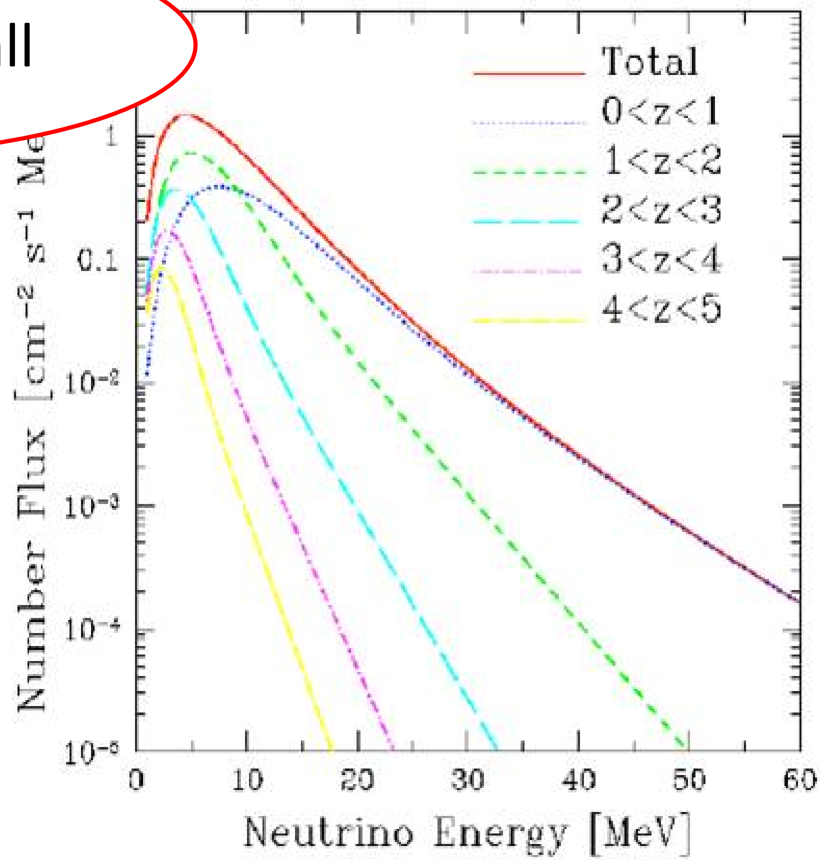
- From historical record
  - $3.4^{+7.8}_{-2.8}$ SNe / 100yrs (Adams et al., ApJ,778,164(2013))
  - $2.5^{+0.8}_{-0.5}$ SNe / 100yrs (Tammann et al., ApJS,92,487(1994))
  - 5.7 ± 1.7 SNe / 100yrs (Strom, A&A,288,L1(1994))
- Massive star birthrate
  - 1－2 SNe / 100yrs (Reed, AJ,130,1652(2005))
- ^{26}Al from massive stars
  - 1.9 ± 1.1 SNe/ 100yrs (Diehl et al.,Natur,439,452006(2006))
- Pulsar rate
  - 2.8 ± 0.1 SNe/ 100yrs (Keane&Kramer,MNRAS,391,2009(2008))
  - 10.8^{+7}_{-5} SNe/ 100yrs (Faucher-Giguère&Kaspi.,ApJ,643,332(2006))
- From Extragalactic SN rate
  - 2.8 ± 0.6 SNe/ 100yrs (Li et al.,MNRAS,412,1473(2011))

Contents from Adams et al., ApJ,778,164(2013))

Supernova Relic Neutrinos

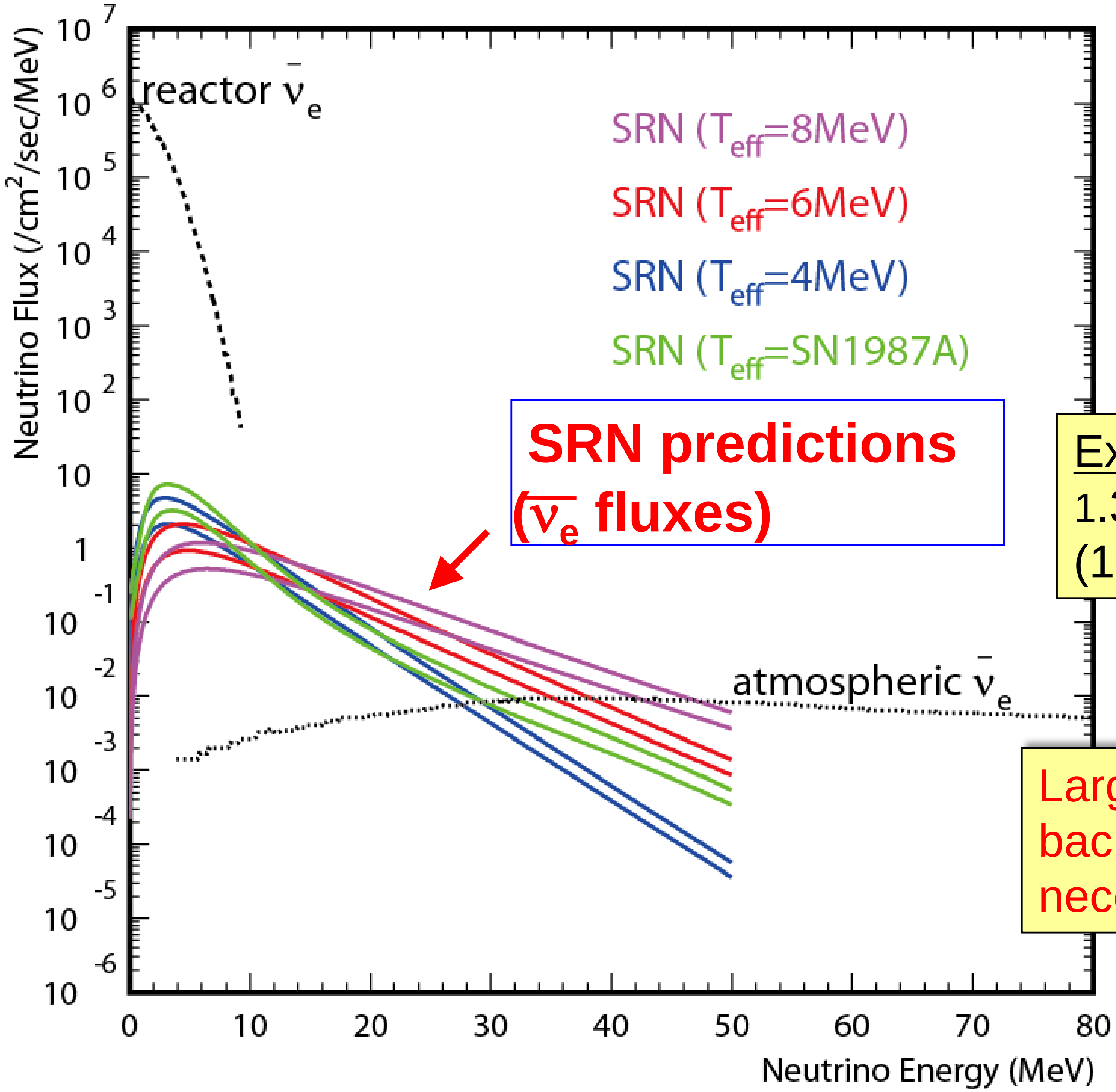
10^{10} stars/galaxy $\times\, 10^{10}$ galaxy $\times$ 0.3%(massive star->SN) ~$O(10^{17})$SNe





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

Supernova Relic Neutrinos



SRN predictions ($\bar{\nu}_e$ fluxes)

SRN flux from Horiuchi et al. PRD, 79, 083013 (2009)

Expected SRN events
1.3 -6.7 events/year/22.5kt (10-30MeV)

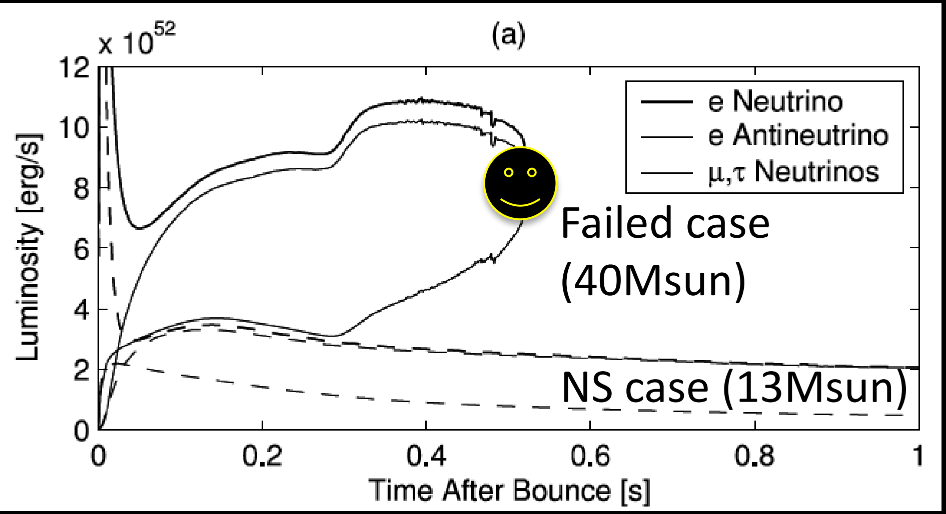
SK fiducial volume

Large target mass and high background reduction are necessary.

Observing failed collapse

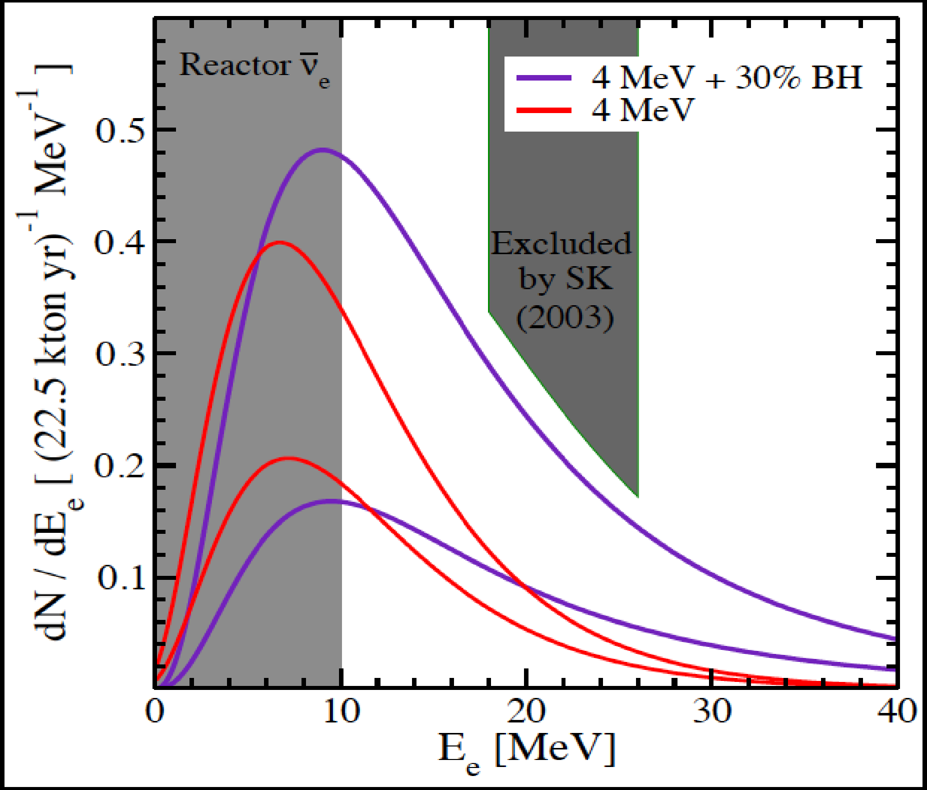
Galactic core collapse: neutrino emission drops; can be detected

Beacom et al (2001)



Liebendoerfer et al (2004)

Diffuse supernova neutrino background: *guaranteed* signal, failed collapse can significantly increase the expected flux.

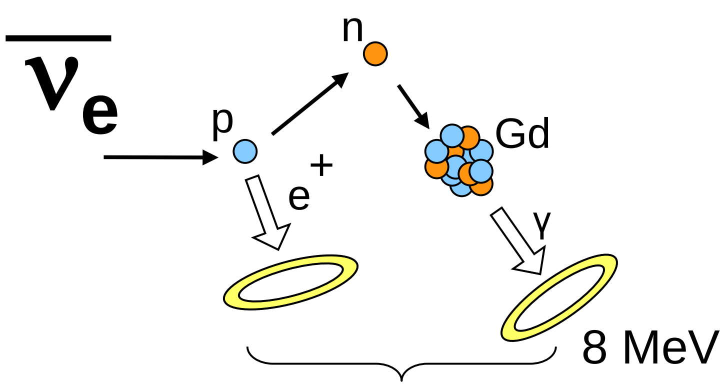


Lunardini (2009), Lien et al (2010), Keehn & Lunardini (2010), Nakazato (2013),Yuksel & Kistler (2014)

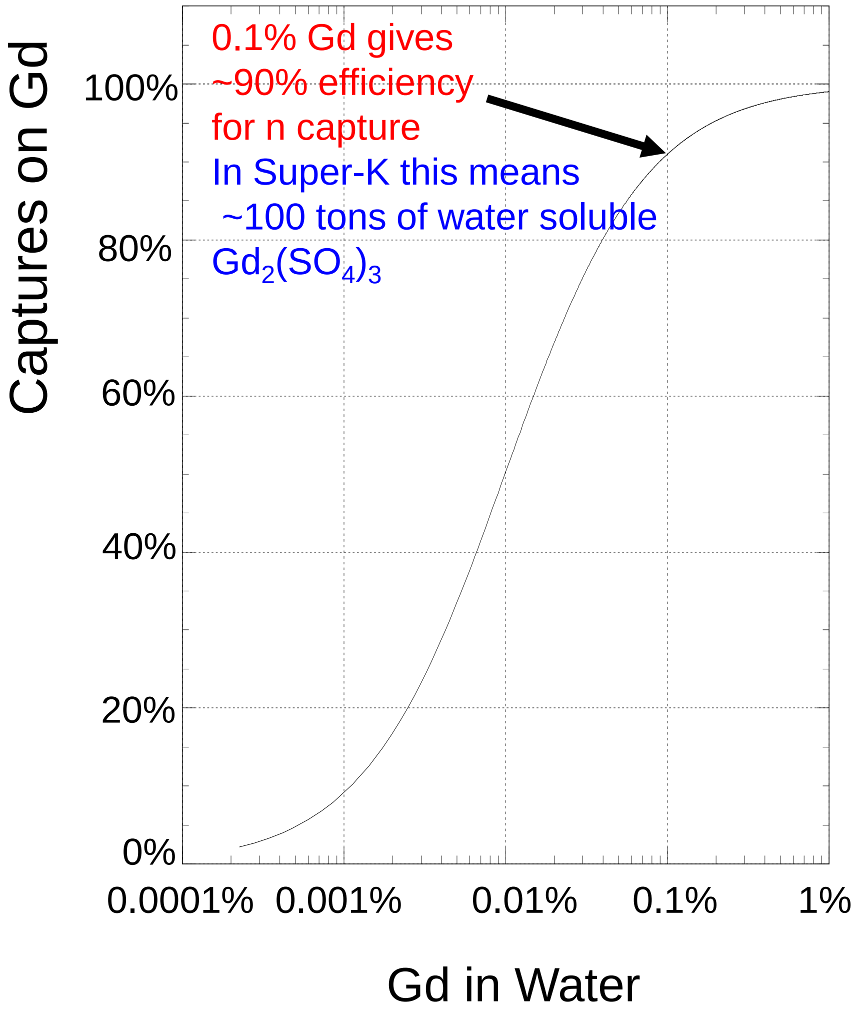
Gadolinium project at Super-K: SK-Gd

Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.

Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.

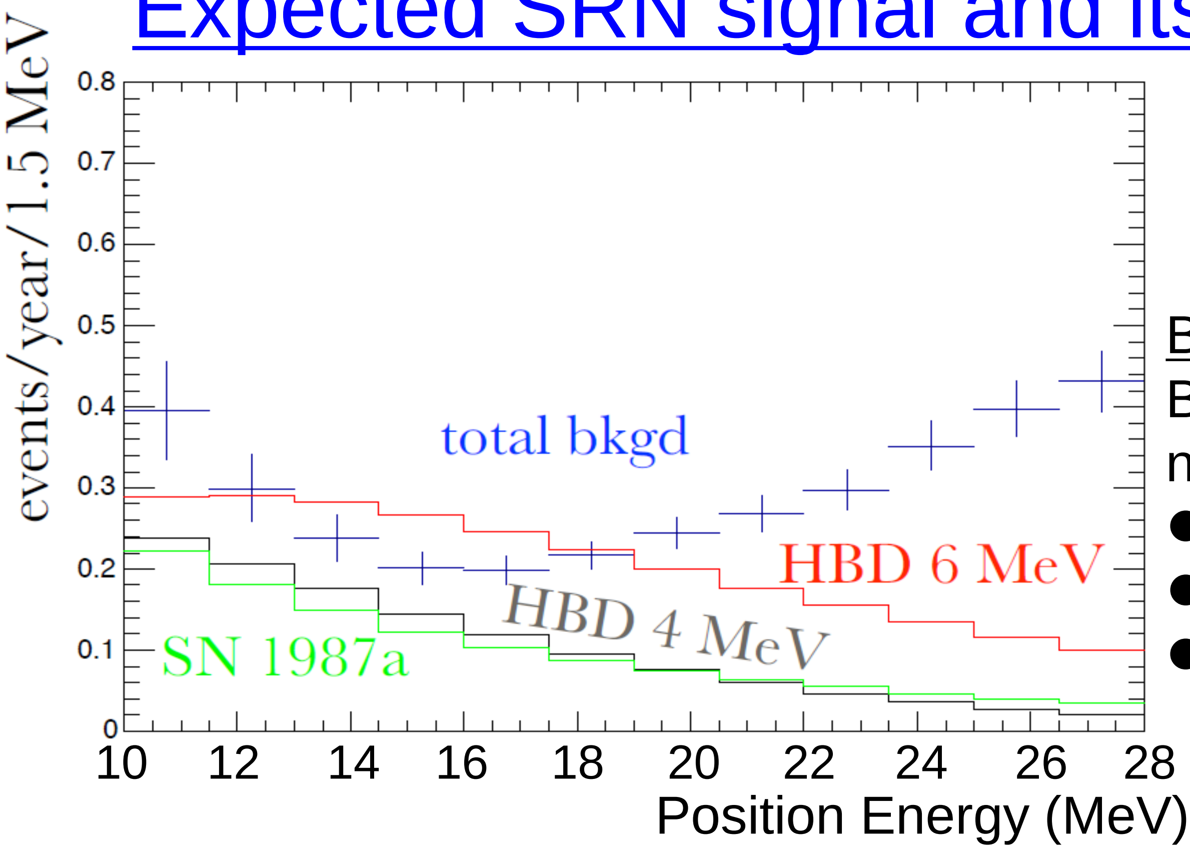


ΔT~20μs
Vertices within 50cm



Expected SRN signal and its significance

preliminary



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

<u>BG assumption</u>

BG can be reduced by neutron tagging as follows

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

In case of Galactic supernova

Improve pointing accuracy

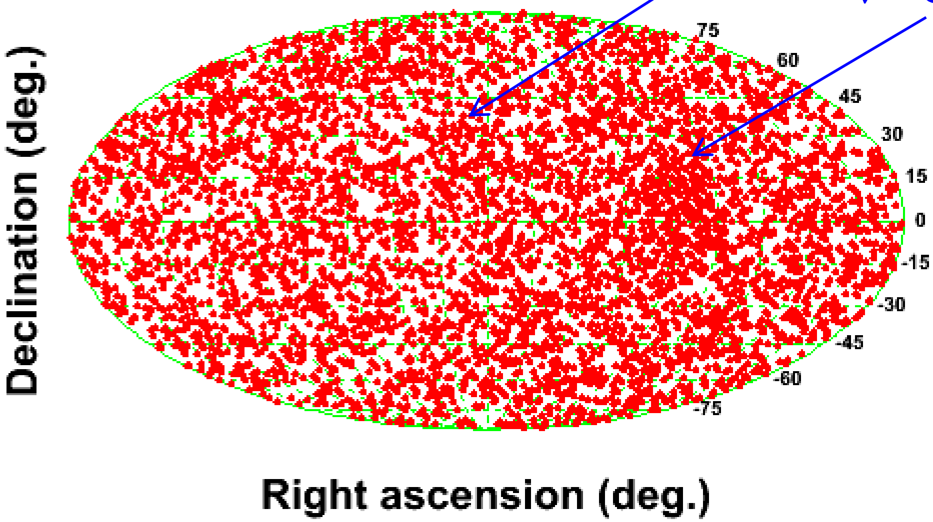
(10kpc SN simulation)

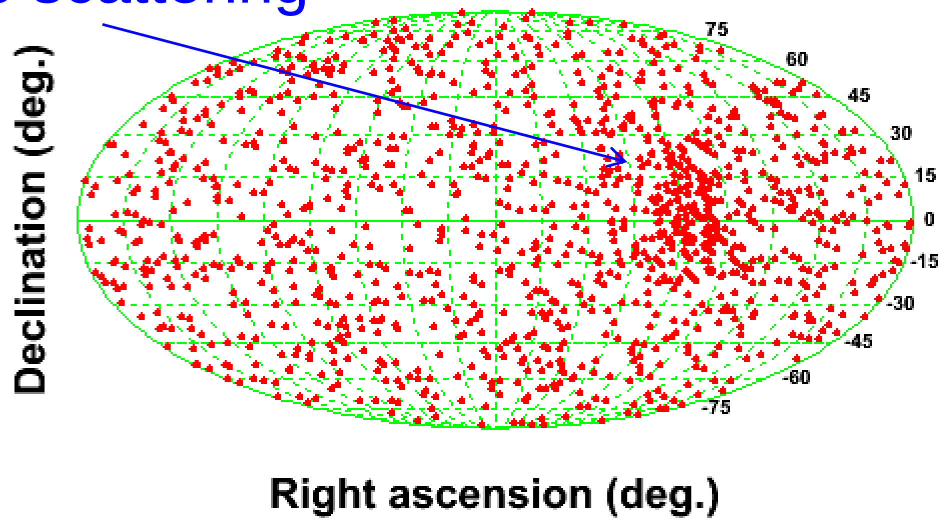
$\bar{\nu}_e$ w/o tagging

$\bar{\nu}_e$+p

$\bar{\nu}_e$ tagged with 80% eff.

ν+e scattering





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

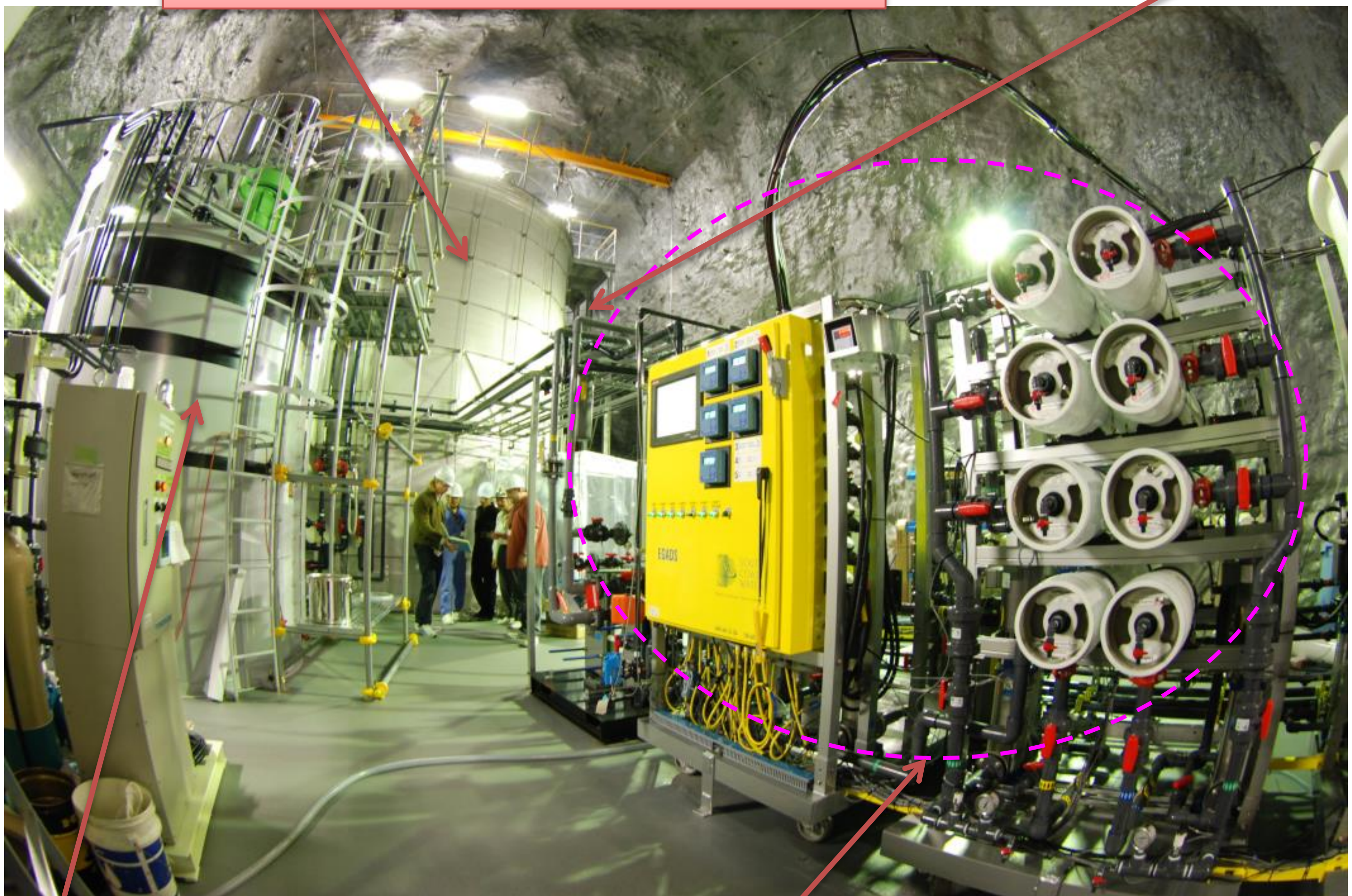
(Note: It is better than Field of View size of LSST.)

EGADS

Evaluating Gadolinium's Action on Detector Systems

Transparency measurement (UDEAL)

200 m^3 test tank with 240 PMTs



15m^3 tank to dissolve Gd

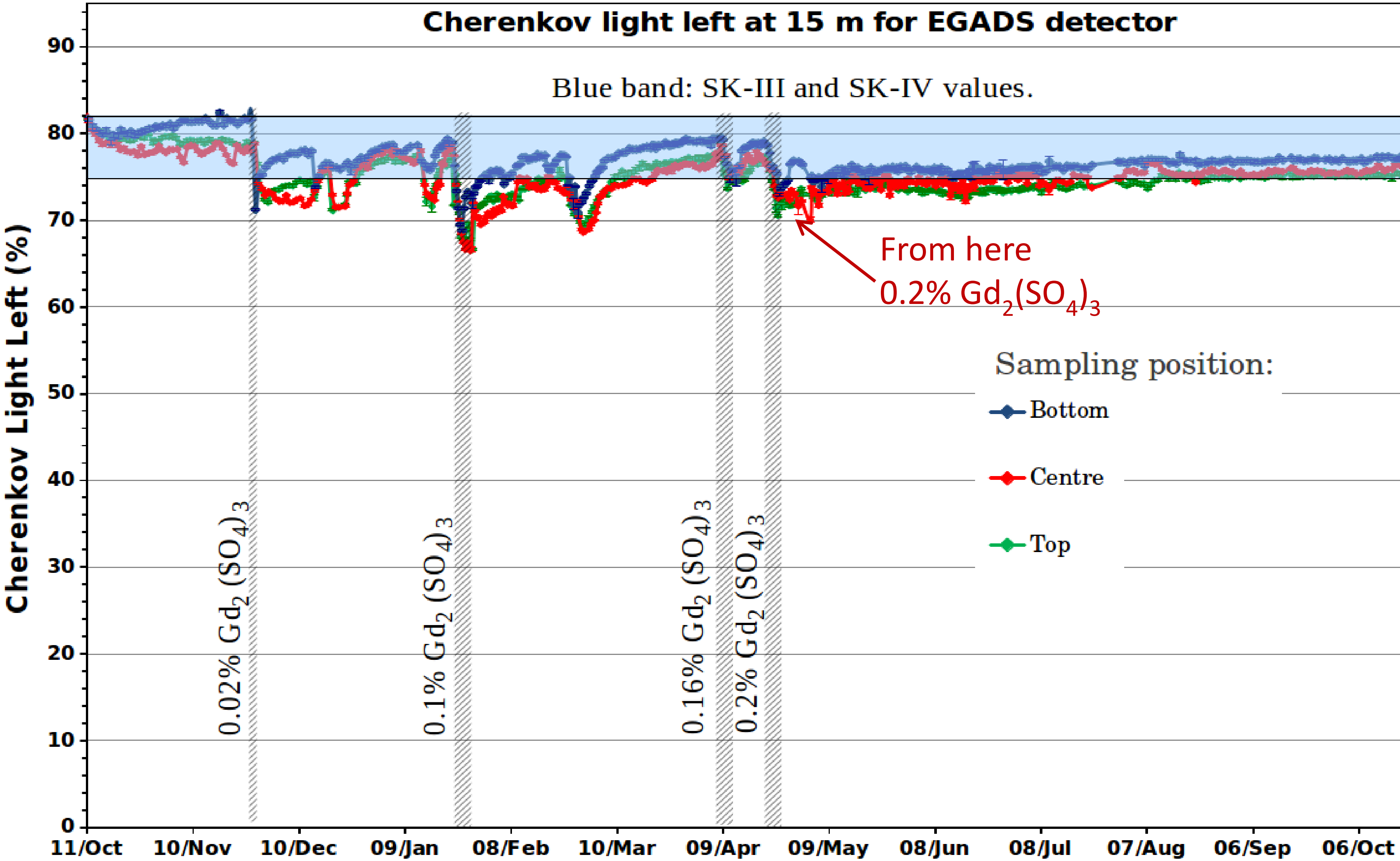
Gd water circulation system (purify water with Gd)

18

240 PMTs in the 200 m^3 tank

The detector fully mimic Super-K detector.
Gd dissolving test has been performed since Oct.2014. (see next page)

Transparency of Gd-loaded water

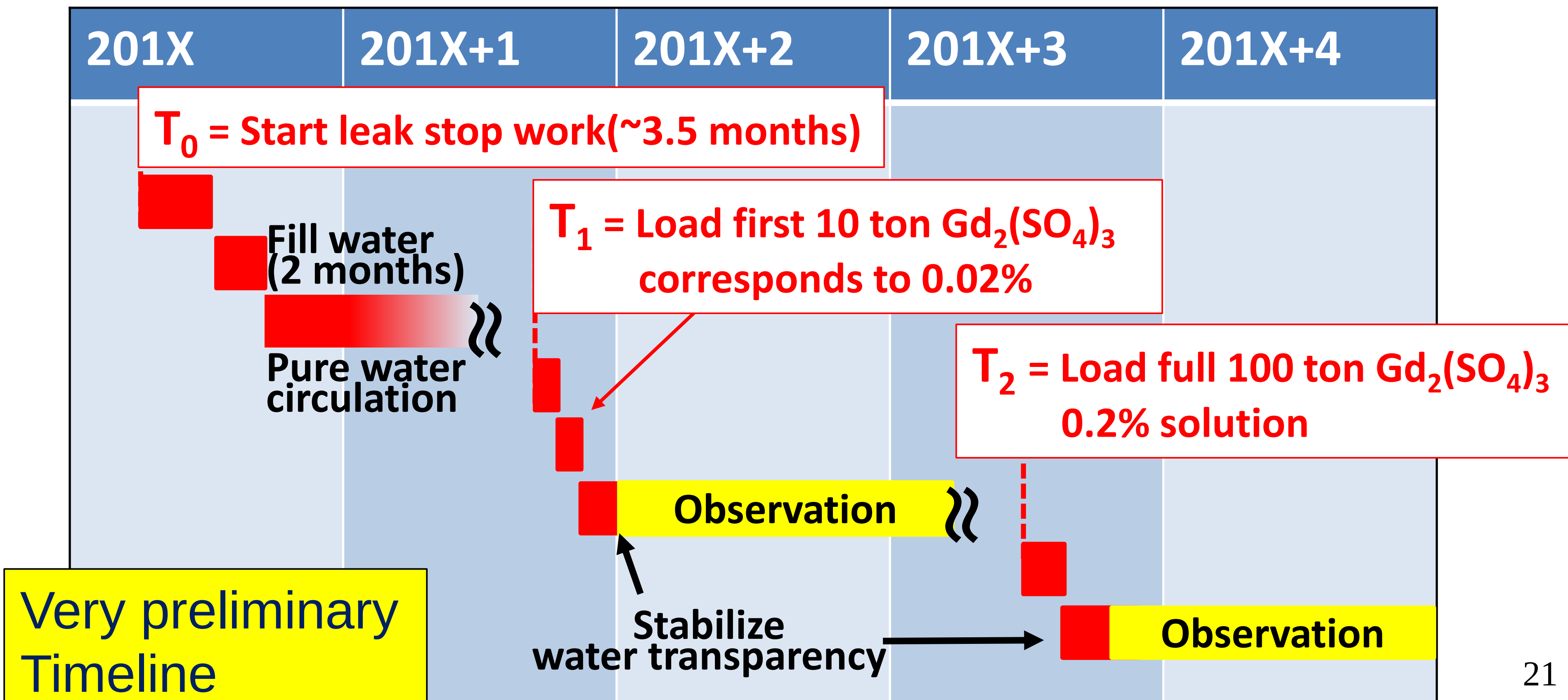


The light left at 15 m in the 200m^3 tank was ~75% for 0.2% $Gd_2(SO_4)_3$, which corresponds to ~92% of SK-IV pure water average.

Approval of the SK-Gd project, agreement with T2K and timeline

On June 27, 2015, the Super-Kamiokande collaboration approved the SK-Gd project which will enhance neutrino detectability by dissolving gadolinium in the Super-K water.

T2K and SK will jointly develop a protocol to make the decision about when to trigger the SK-Gd project, taking into account the needs of both experiments, including preparation for the refurbishment of the SK tank and readiness of the SK-Gd project, and the T2K schedule including the J-PARC MR power upgrade. Given the currently anticipated schedules, the expected time of the refurbishment is 2018.

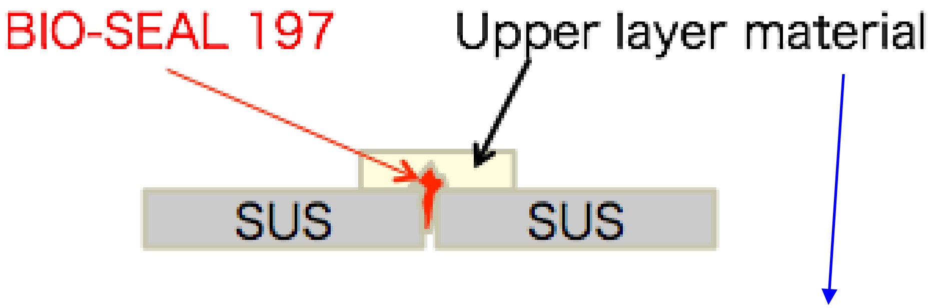


How to stop the leak

At present, water leak rate is about 1-2 tons/days. We plan to reduce it more than one orders of magnitude.

Cover welded places with sealing materials

Cover with two layers.
Lower layer is BIO-SEAL 197 (epoxy resin) which sneaks into small gaps, and upper layer is a viscous material which allows more displacement.



This material must be leak tight, water tight and low Rn emanation. We have developed such material.

Intrinsic RIs in $Gd_2(SO_4)_3$ could add BG in ^{8}B solar n region of spectrum

- BG reduction ➔ Purification of 100 tons of $Gd_2(SO_4)_3$

Typical $Gd_2(SO_4)_3$ on the market

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

For SRN

Expected signal ~5 events/year/FV

- ^{238}U Spontaneous Fission:

  ~ 5.5 [γ($E\gamma$>10.5 MeV) + 1n] / year / FV

1 order reduction

For solar neutrino

Current BG ~200 events/day/FV

- U (n) ~320events/day/ FV

1 order reduction

- Th/Ra (β,γ)~3 x 10^{5} events/day/ FV

3 orders reduction

Approach #1: Remove radio-isotopes from normal $Gd_2(SO_4)_3$ ourselves

- Removal of U and Ra
  - Ra exists in $Gd_2(SO_4)_3$ water in the form of Ra^{2+}
  - At pH above 6, U exists as uranyl sulfate complex $UO_2(SO_4)_3^{4-}$

Ion-exchange resins can be used, while Gd^{3+} and SO_4^{2-} must be kept.
Special resins have been developed.

- U removal anion resin (AJ4400) is established (1-2 orders reduction).
- Ra removal cation resin (AJ1020) is under tests. Reduction of 3 orders of magnitude was confirmed using high Ra contentration water.

- Removal of Th and Rn
  - These exist in neutral form.
  - Under tests.
    - Colloidal Th: w/ filter
    - Rn: degasification

Cation resin (AJ1020) test bench @ EGADS

Approach #2: Cooperative development of pure $Gd_2(SO_4)_3$ with chemical companies

- We are cooperating with several companies to produce clean $Gd_2(SO_4)_3$ / Gd_2O_3.

Ex.) ^{232}Th: Existing samples of high purity Gd powders are ~50X cleaner.

RI of existing samples (mBq/kg)

Chain		Gd2(SO4)3 Sample A*	Gd2(SO4)3 Sample B	Gd2O3 Sample C	Gd2O3 Sample D
^{238}U	^{238}U	< 37	<139	<280	<317
	^{226}Ra	< 0.8	<2.1	<4	<8.9
^{232}Th	^{228}Ra	< 1.1	2.8±1.9	<10	<4.39
	^{228}Th	2.0 ± 0.5	1.8±0.9	<9	
^{235}U	^{235}U	< 0.6	<2.4	<7	<52.2
	^{227}Ac/^{227}Th	11 ± 4	<10	<11	
Others	^{40}K	< 3	<14	<11	<44.6
	^{137}Cs	2.6 ± 0.3	<0.9	<0.8	<1.85

* Company of sample A cannot provide 100 tons of $Gd_2(SO_4)_3$

Conclusions

- Only SN1987A so far for supernova neutrinos. We learned that basic principle of supernova explosion is OK but more data are necessary to understand detailed mechanism.
- Many detectors in the world are waiting for next supernova.
- SK-Gd project:
  - SK collaboration approved the project.
  - Actual timeline will be determined taking into account the T2K schedule.
  - Study for radioactive background reduction for SK-Gd is in progress.