Detection of Supernova Neutrino at Super Kamiokande

NuInt 18 –12th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region

Gran Sasso Science Institute (GSSI)

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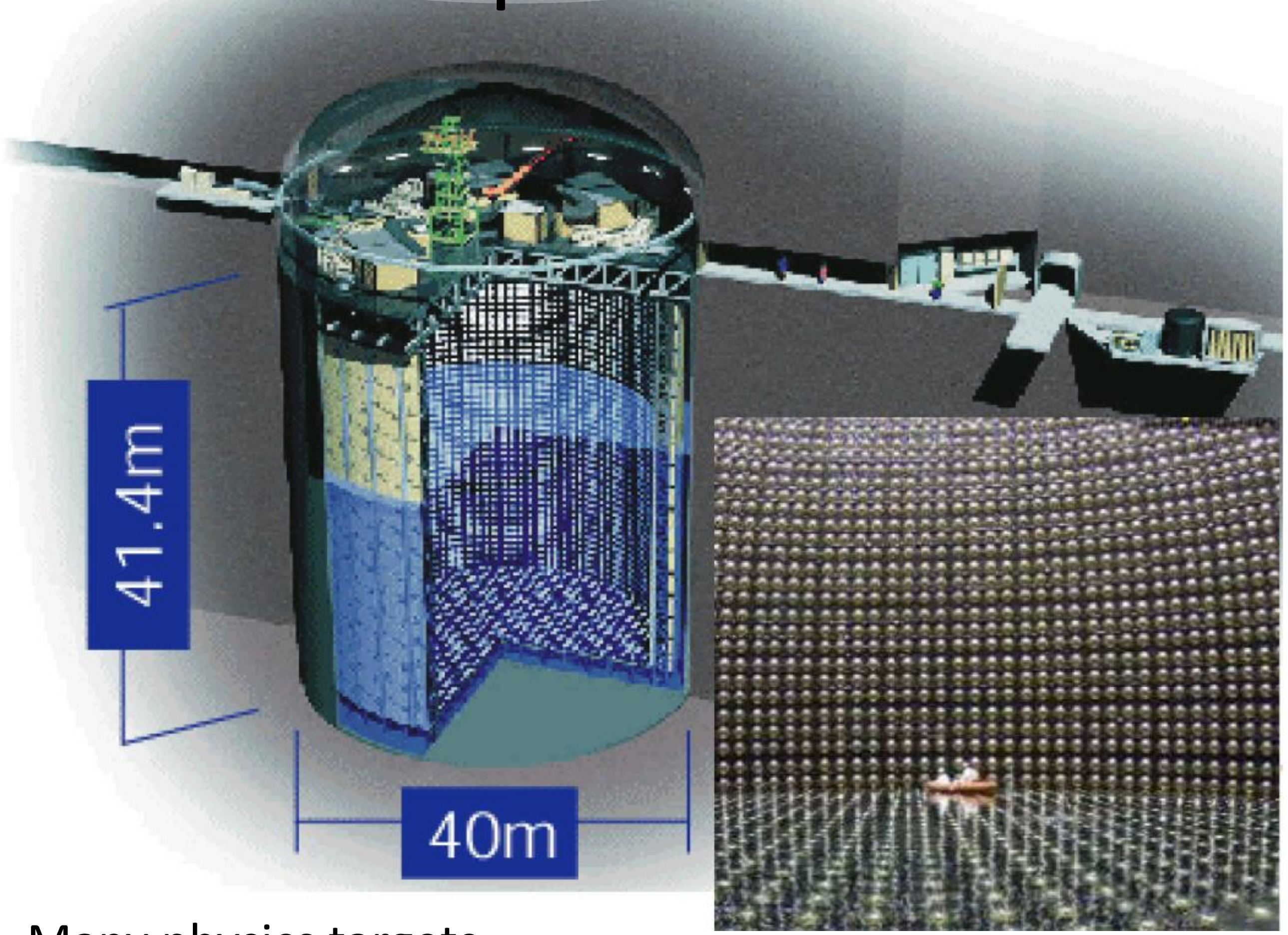
for the Super-Kamiokande collaboration

Super-Kamiokande (SK) detector



- The world largest pure water Cherenkov detector located in Kamioka mine (36° 25’ N, 137° 18’ E).
- 50 kton pure water (22.5 kton fiducial, 2m from the walls of the inner detector)
- 1,000 m (2,700 m w.e.) underground
- 11,129 20-inch PMTs in inner detector (ID)
- 1,885 8-inch PMTs in outer detector (OD)

- ~ 4.0 MeV energy (total) threshold
- SK-I: April 1996~
- SK-IV: ~ May 2018.
- Current: refurbishment for SK-Gd.

Many physics targets:

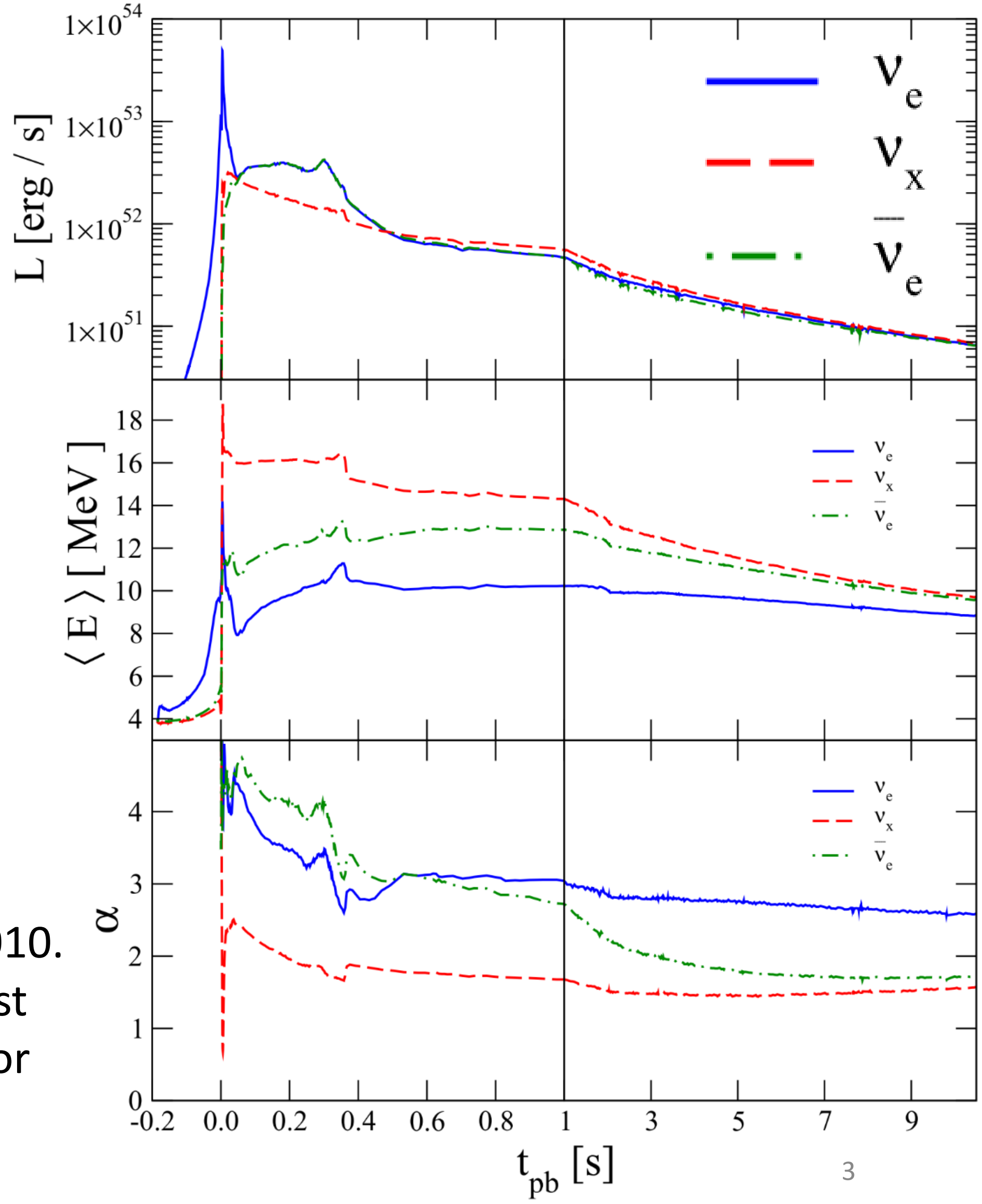
- Neutrino oscillation: atmospheric ν, solar ν, T2K beam
- Nucleon decay
- **Astrophysics**: **Supernova Relic Neutrino, Supernova burst**, WIMP search, monopole search, etc.

Neutrinos from core collapse supernovae

- Gravitational energy is released: ~3 × 10^{53} erg.
- Almost all (99%) of the energy is carried by neutrinos.
- Energy for explosion and optical emission is only ~1%.

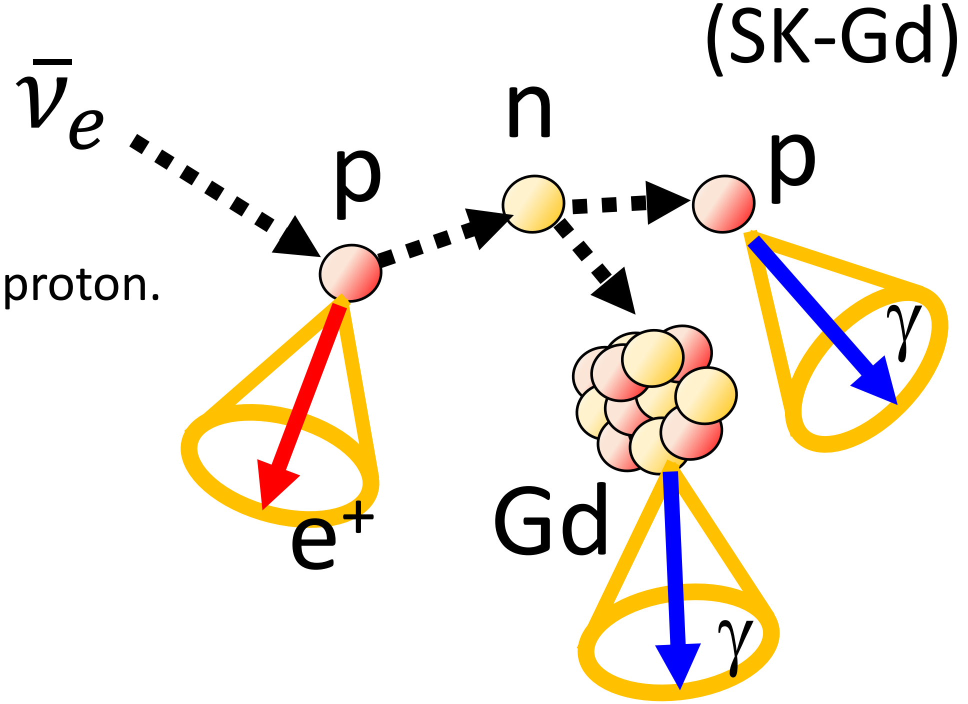
Time variation of luminosity, mean energy, and pinch parameter (α) →

- This figure is taken from S. Horiuchi and J. Kneller, arXiv: 1709.01515v2
- Fischer et al., Astron. and Astrophys., 517, p. A80, Jul. 2010.
- Sharp peak in ν_e around t_{pb} = 0 is the neutronization burst through e^-+p→ν_e+n from propagation of shock wave prior to the core explosion.
- Well-known hierarchy $\langle E_{\nu e}\rangle < \langle E_{\bar{\nu} e}\rangle < \langle E_{\nu x}\rangle$ is seen.

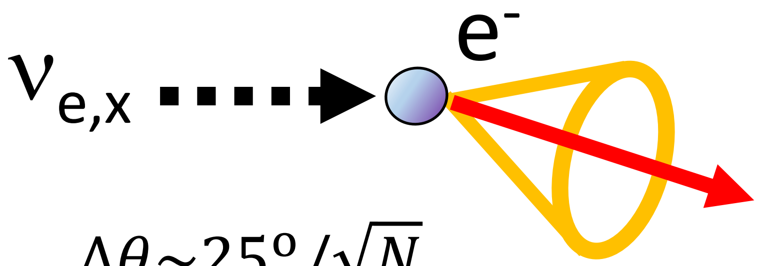


Main interactions for supernova ν in SK

- Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Dominant in water Cherenkov detector owing to lots of free proton.
  - ν energy is obtained from the e⁺ energy.
    $E_e \sim E_\nu - (m_n - m_p) \sim E_\nu - 1.3$ MeV, $E_\nu > 1.86$ MeV
  - Neutron tagging using delayed coincidence.
    $n + p \rightarrow d + \gamma$ (2.2 MeV),
    ($n + Gd \rightarrow Gd + \gamma$ (total ~8 MeV) if Gd is loaded)



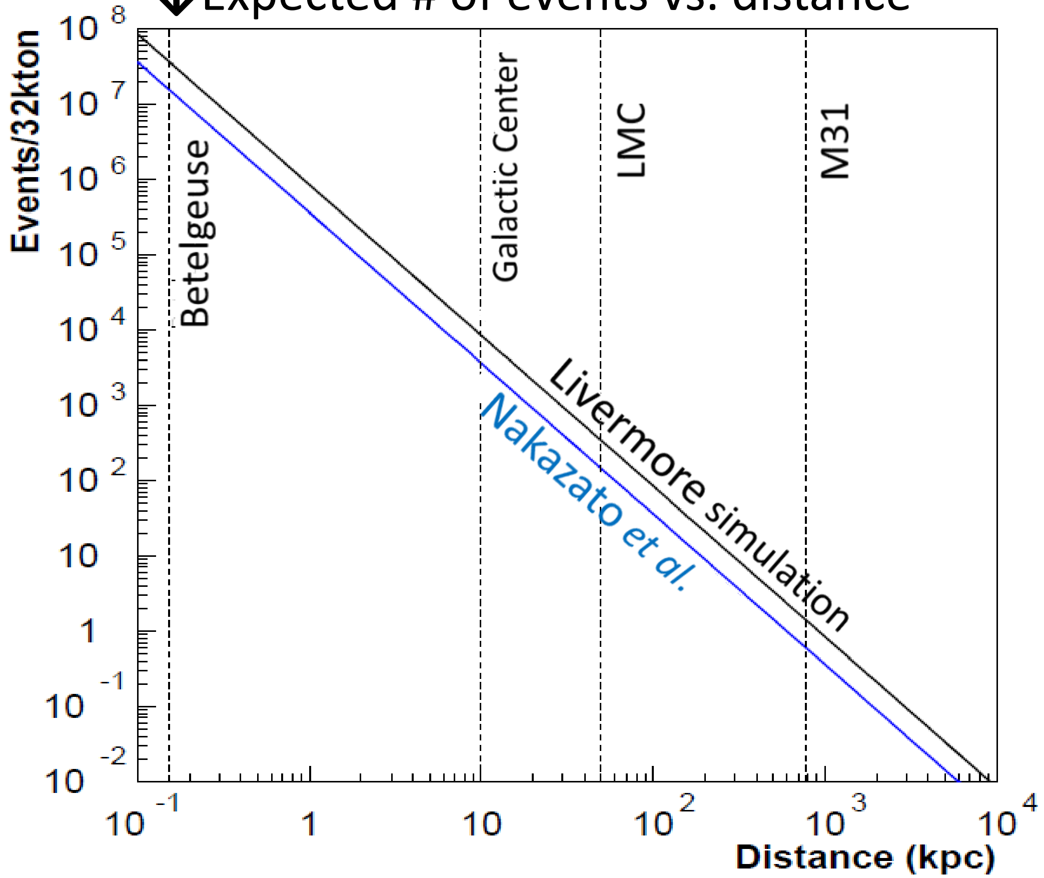
- Elastic scattering $\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$
  - All neutrinos are sensitive.
    The cross section for ν_e is larger than others because of CC effect.
  - Good directionality.
  - Only recoil electron energy is measurable (not ν energy).



$\Delta\theta \sim 25^o/\sqrt{N}$
(10 MeV)

Detection of supernova ν at SK

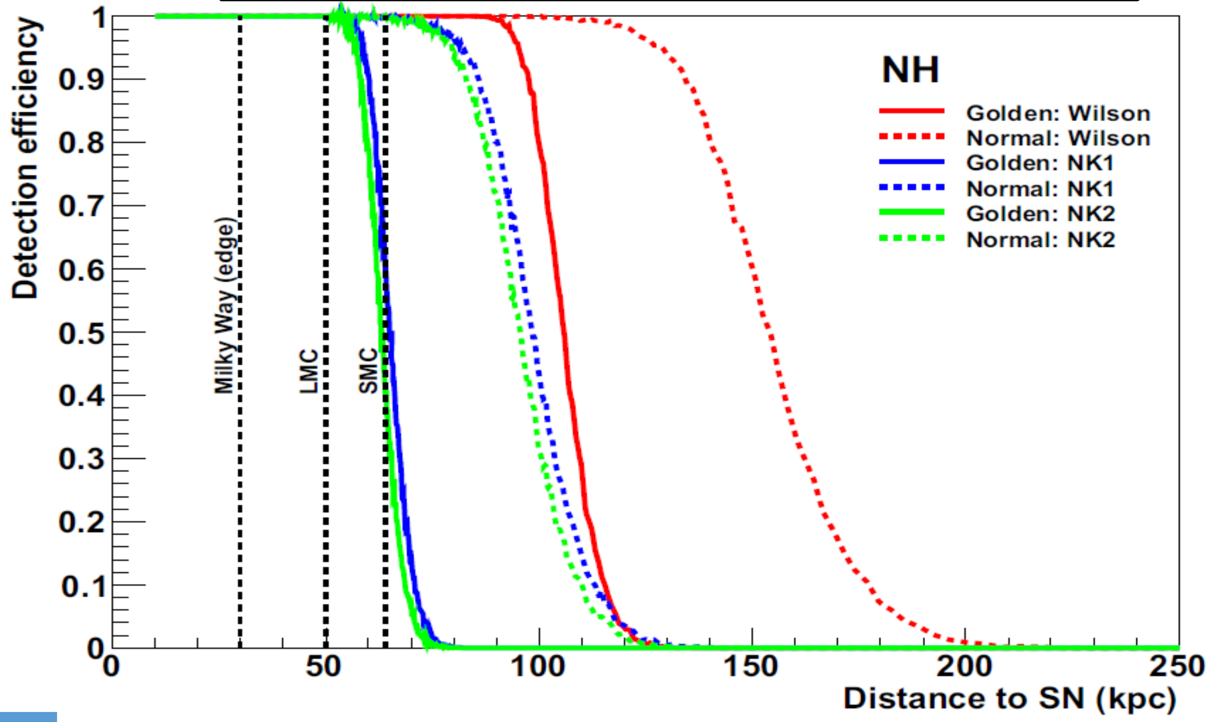
↓Expected # of events vs. distance



Livermore: T. Totani et al., ApJ. 496 (1998) 216

↓ Detection efficiency of the real time SN monitor. 100% efficiency for our galaxy and LMC for various models.

SK collaboration, Astropart. Phys. 81 (2016) 39–48



@10 kpc
32 kton SK volume
E_{th}: 4.5 MeV (kin)
No oscillation

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

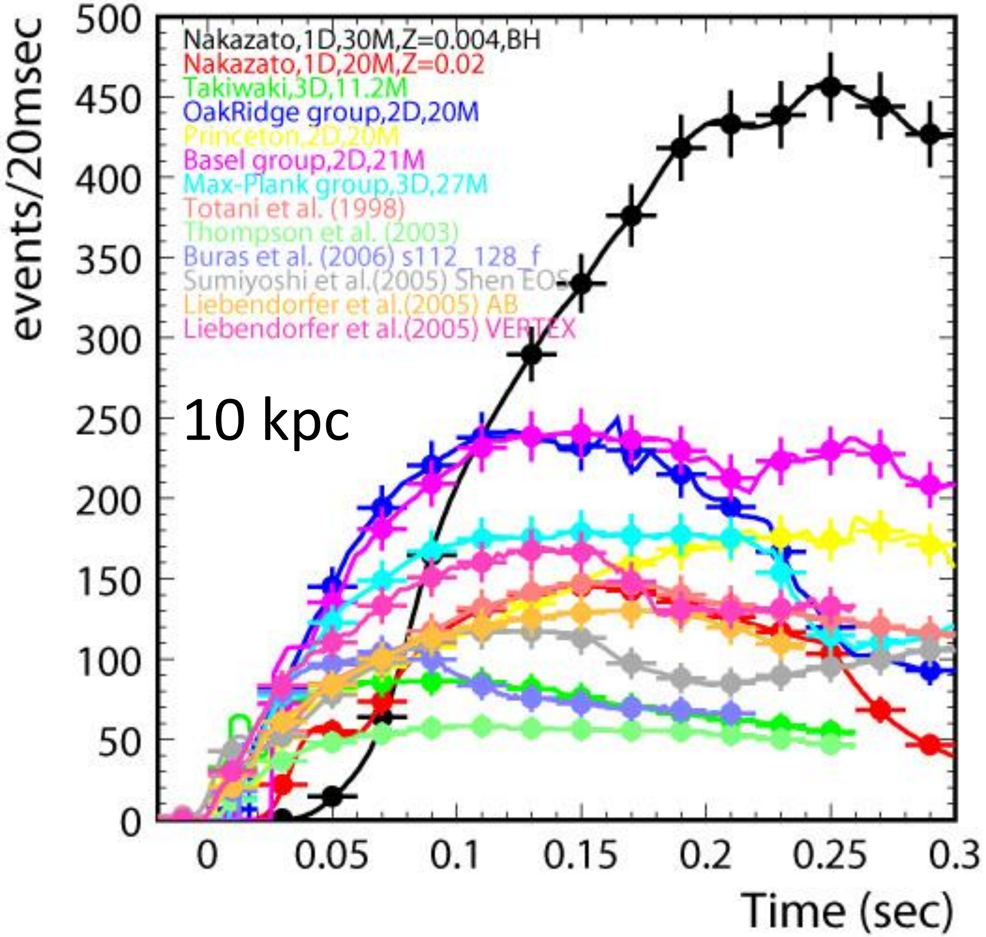
- **Wilson model** : *T. Totani, et al., Astrophys. J. 496 (1998) 216.*
- Nakazato (NK) model : *K. Nakazato, et al., Astrophys. J. Suppl. 205 (2013) 2.*
  - **NK1**: M = 20 solar mass, t_{revive} = 200 ms, Z = 0.02
  - **NK2**: M = 13 solar mass, t_{revive} = 100 ms, Z = 0.004

  (M: progenitor mass, t_{revive}: shock revival time, Z: metallicity)

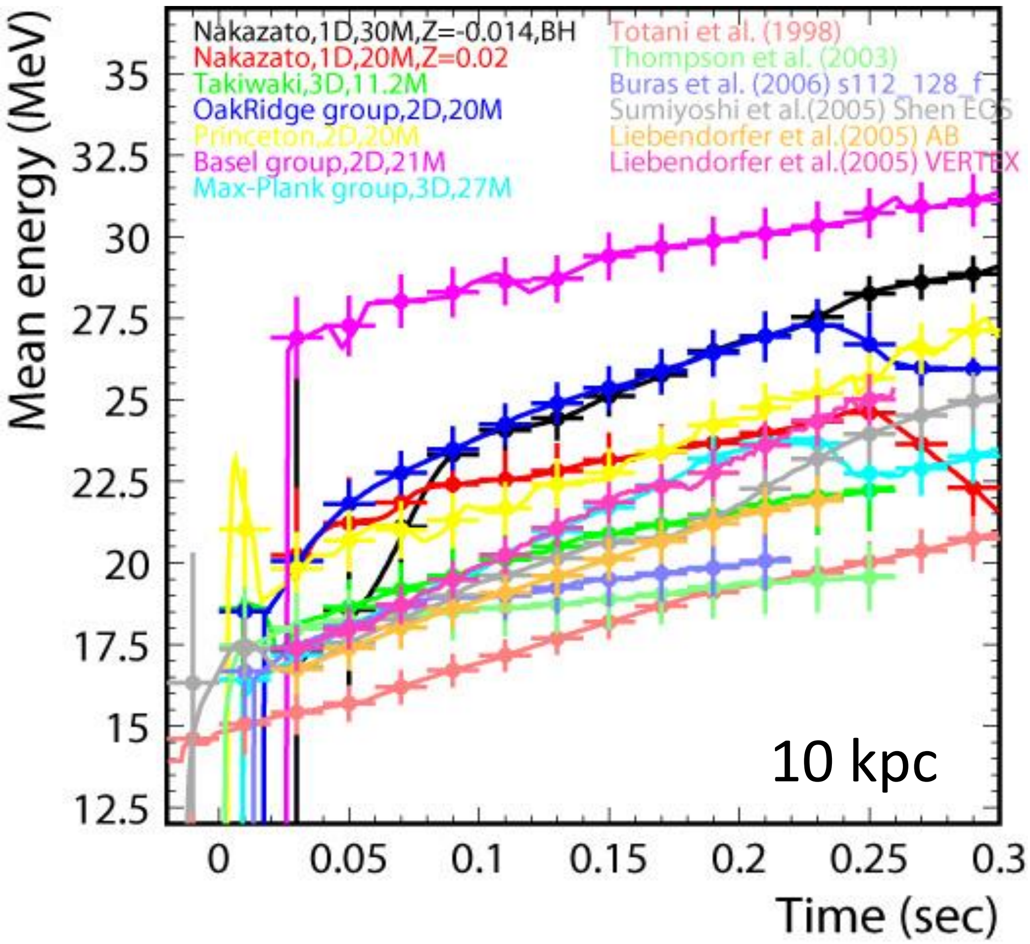
Time variation measurement by $\bar{\nu}_e$+p

- $\bar{\nu}_e p \rightarrow e^+ n$ events give direct energy information ($E_e = E_\nu - 1.3$ MeV)
- Enough statistics can be obtained to discriminate model predictions

Time variation of event rate

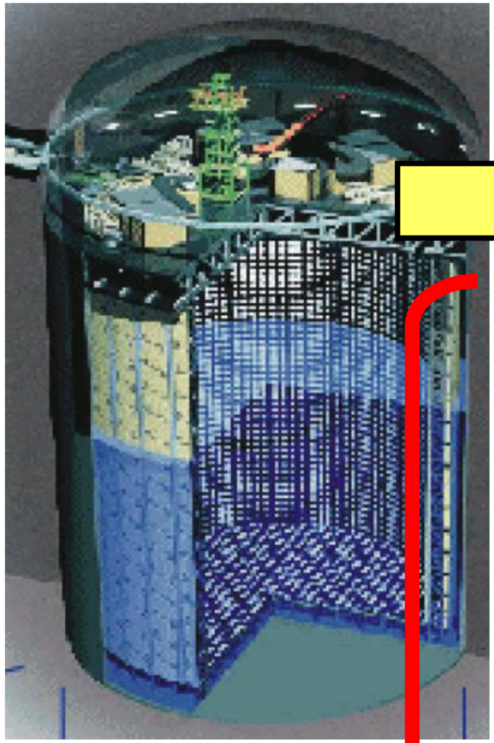


Time variation of mean energy



Real-time supernova burst monitor at SK

Astropart. Phys. 81 (2016) 39–48



DAQ → Off-line analysis

Independent system is running for the monitor

SN monitor process (> 7 MeV, 22.5 kton FV)
- Reformat process
- Event reconstruction
- Combine all data and fit SN direction

- $N_{cluster}$ >= 60 in sliding 20-second window
- Uniform vertex distribution

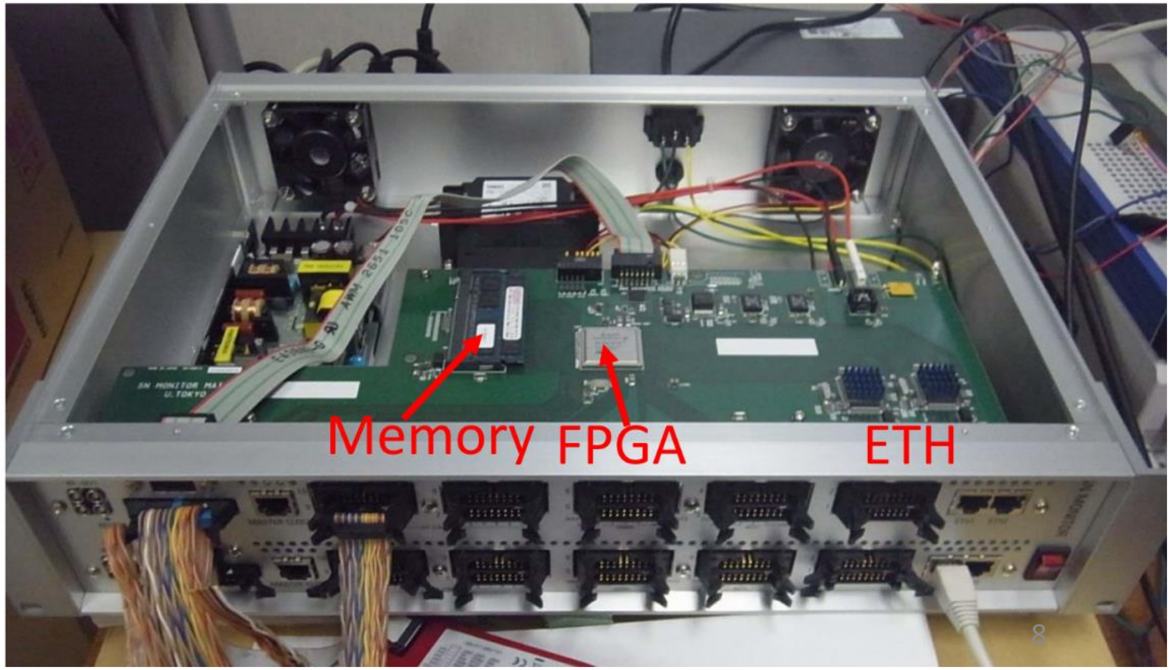
SN alarm (golden)
- Alert for SK shift
- Call and send alert email to experts. Have a meeting via TV conference system
  - Checking vertex distribution, energy, time profile, and direction, etc.

Within 15 min.

Electronics for very close SN

- Expected event rate is > 10^7 events / 10 sec in case of very close SN (ex. Betelgeus: 0.2 kpc)
- Dedicated electronics for very close SN was developed.
  - Save only number of hits every 16 ns.
    → energy x flux
  - No dead time.
  - Stable operation was confirmed.

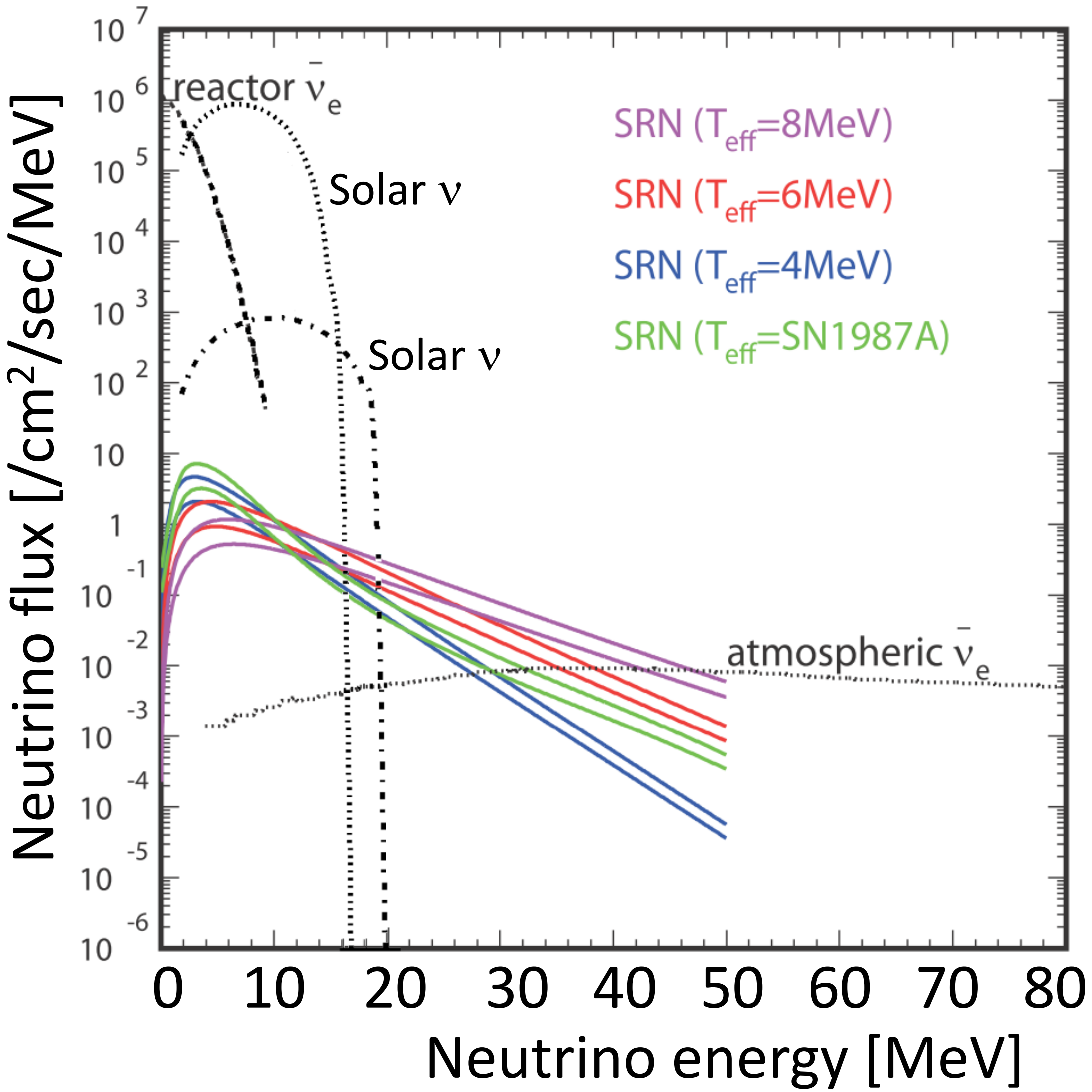
Super-Kamiokande is ready also for very close supernova.



Supernova Relic Neutrinos

- Since 1996, no burst was detected at Super-Kamiokande. It is estimated a supernova will occur a few times per century in a galaxy.
- However, all of the core collapse supernovae have released neutrinos throughout the history of the Universe.
  → **Supernova relic neutrinos (SRN)** or **diffuse supernova neutrino background (DSNB)**.

- There is signal window (~16–30 MeV) corresponding to the gap between the spectrum of solar and atmospheric neutrinos.
- Understanding and reduction of background events is very important.



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

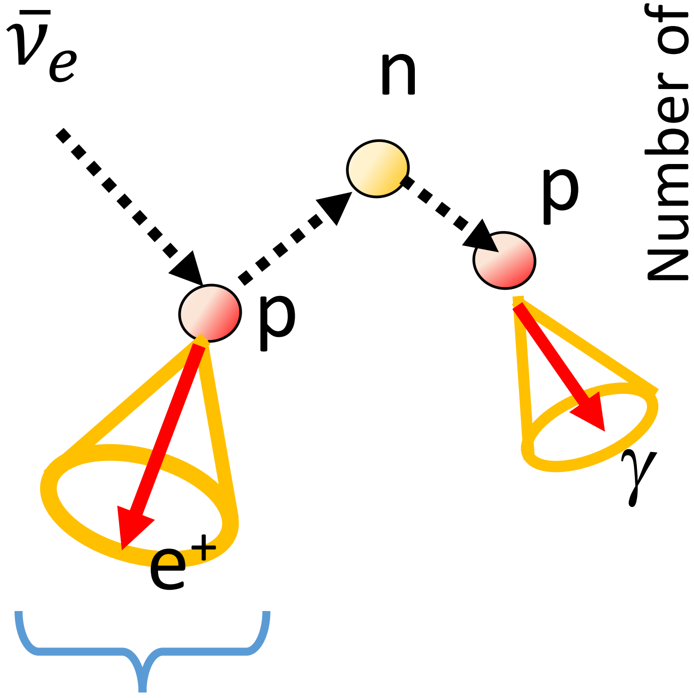
Supernova Relic Neutrino search at SK

Phys. Rev. D 85 (2012) 052007

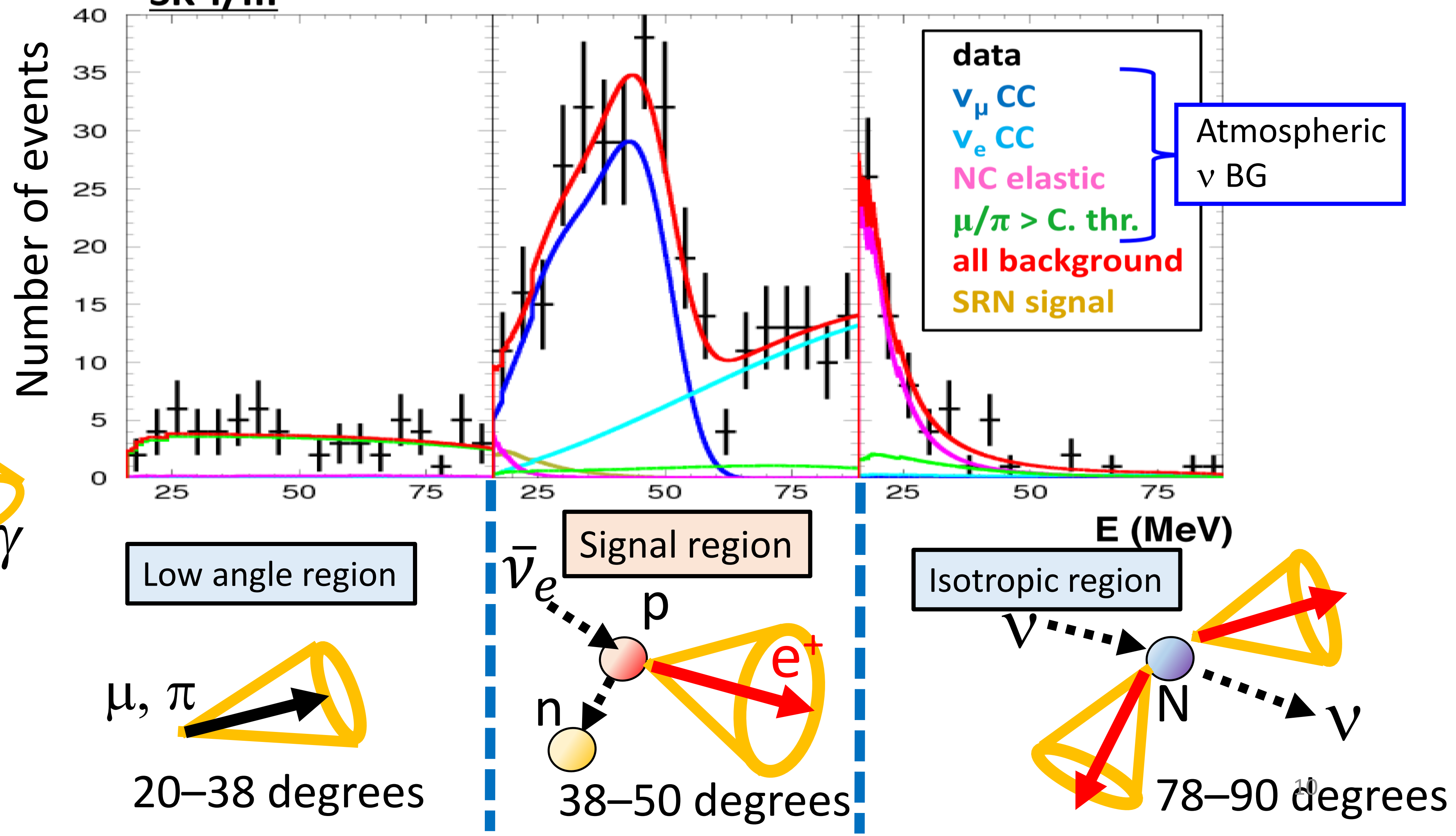
- SK combined 90% CL results: < 2.9 /cm²/s (> 16 MeV)

(assuming LMA model spectrum (Ando et al., 2005))

w/o neutron tagging



Only this signals were used

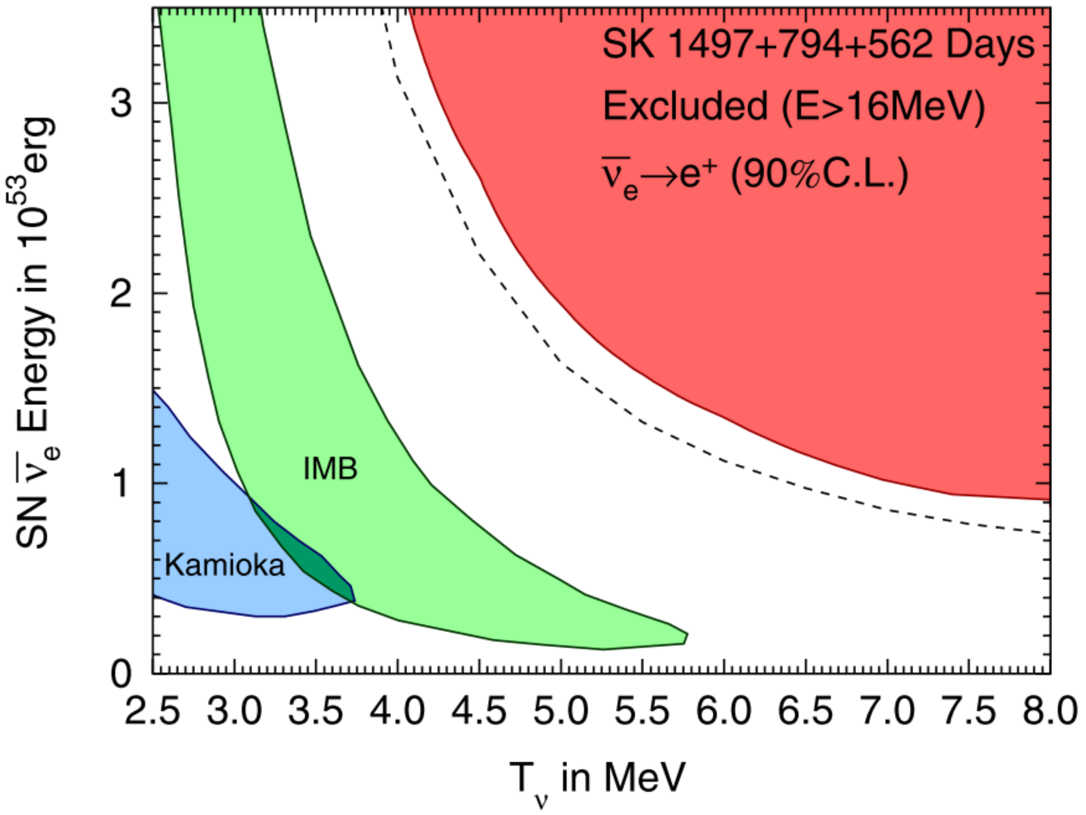


Upper limit from SK

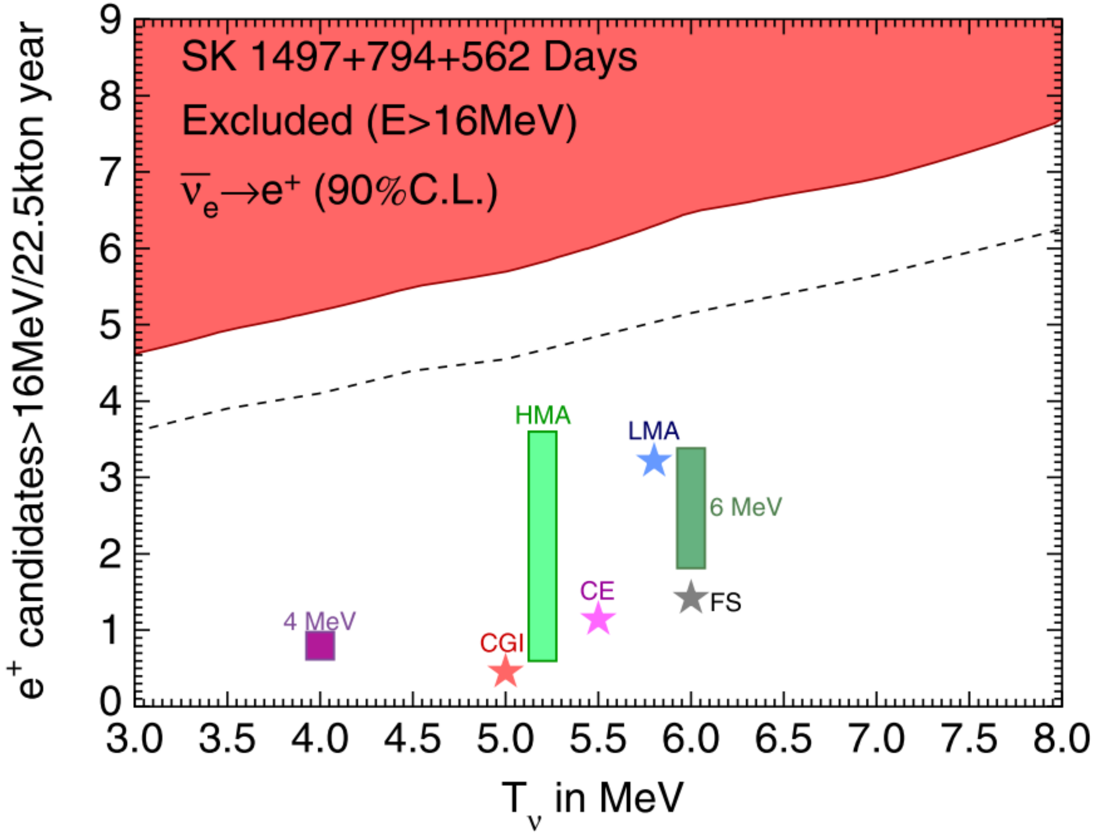
Phys. Rev. D 85 (2012) 052007

- Limit is very close to the best theoretical predictions.

Luminosity vs neutrino temperature



SRN event rate vs neutrino temperature

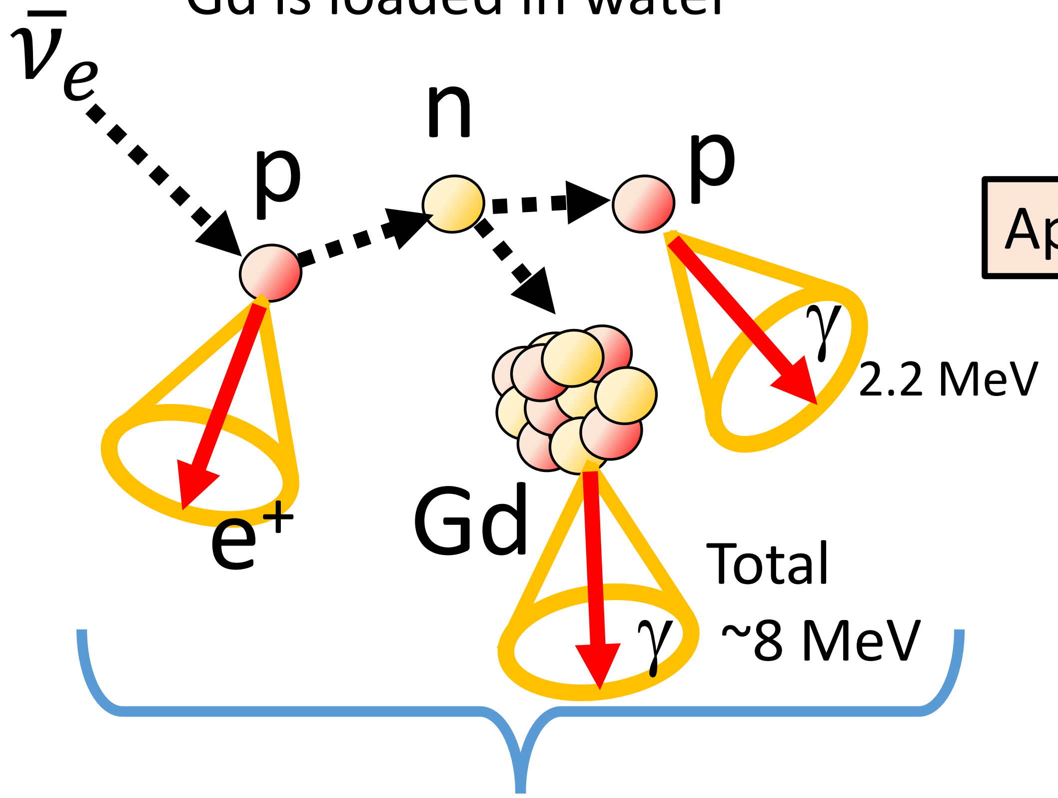


CGI: cosmic gas infall model, **HMA**: heavy metal abundance model
CE: chemical evolution model, **LMA**: large mixing angle model,
FS: failed supernova model

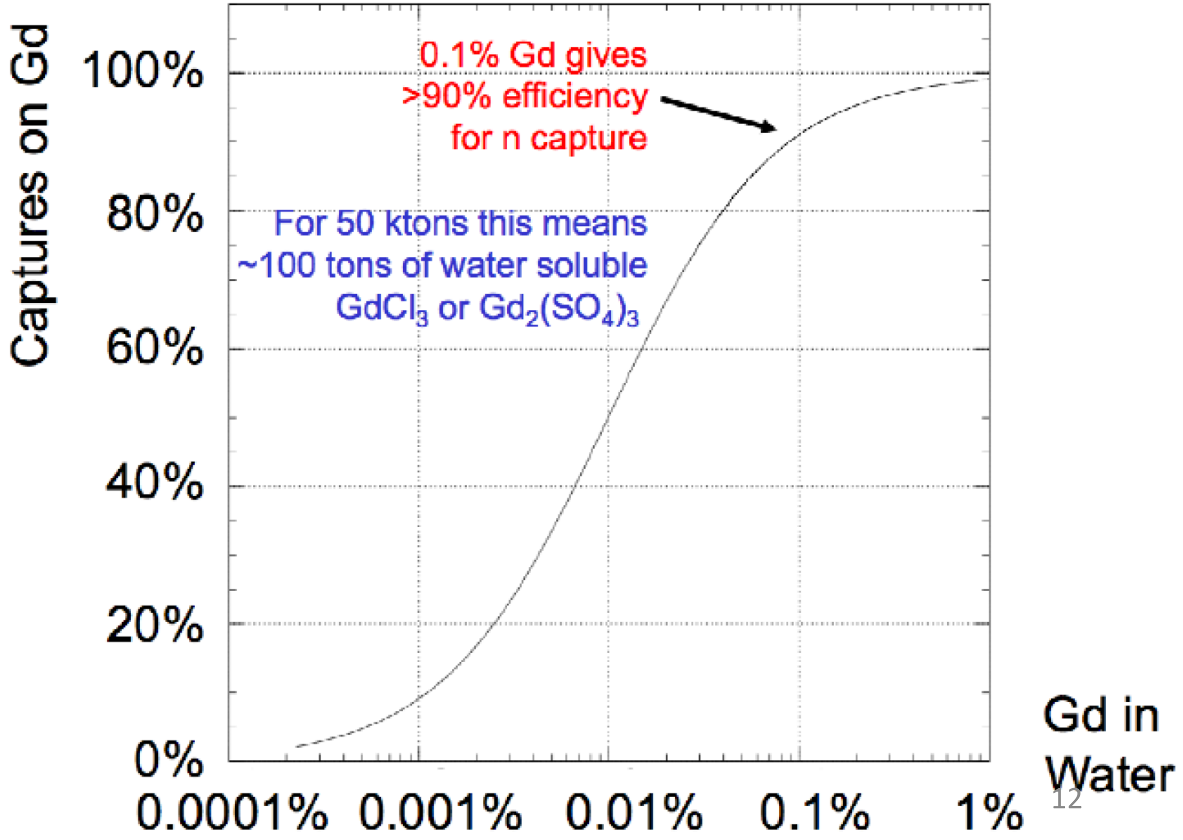
SK upgrade for supernova relic neutrino

GADZOOKS! was proposed: J. Beacom and M. Vagins, Phys. Rev. Lett. 93 (2004) 171101

Gd is loaded in water



Approved by the SK collaboration in 2015 as “SK-Gd”

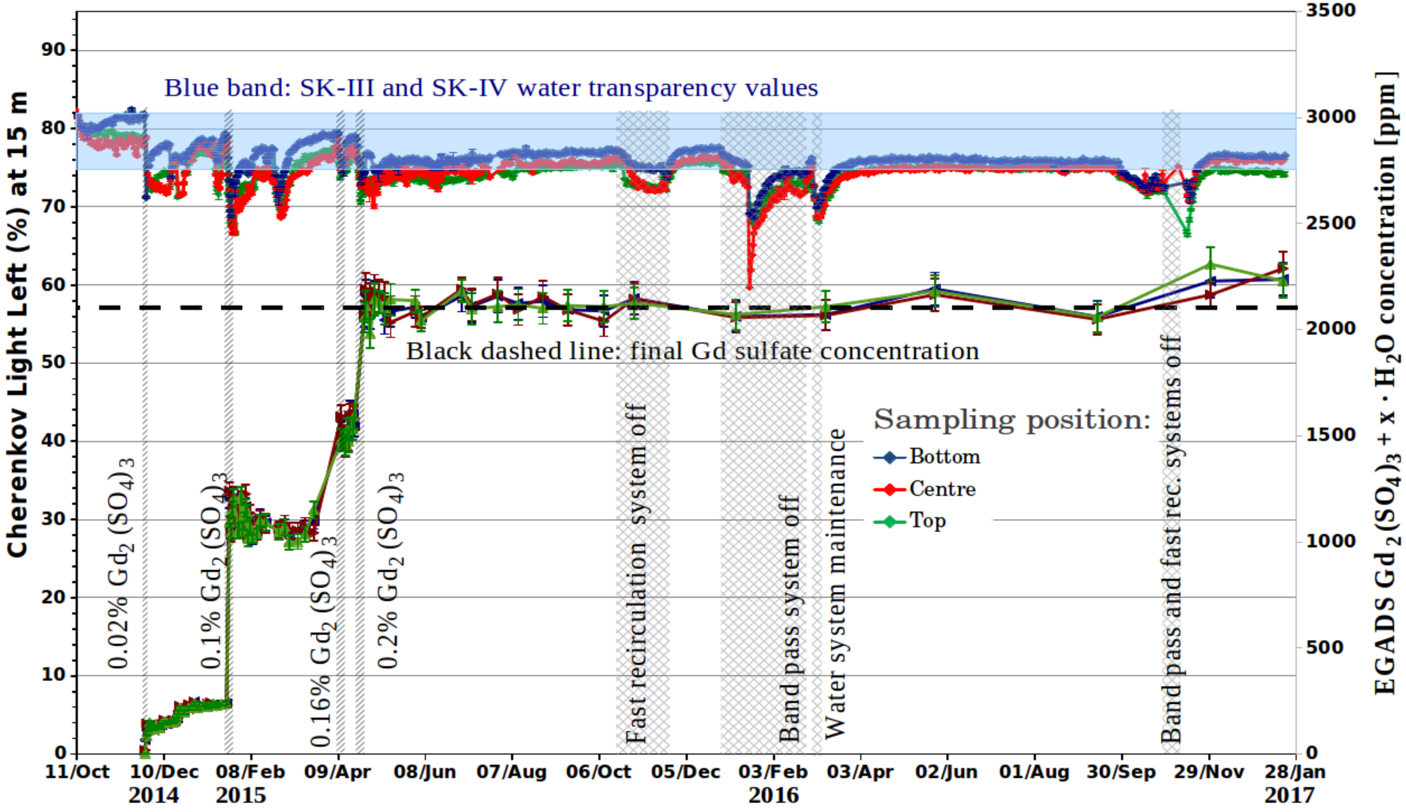


By using delayed coincidence signal,
background is drastically suppressed for $\bar{\nu}_e$ signal

- ΔT ~ 30 μsec
- Vertices within ~50 cm

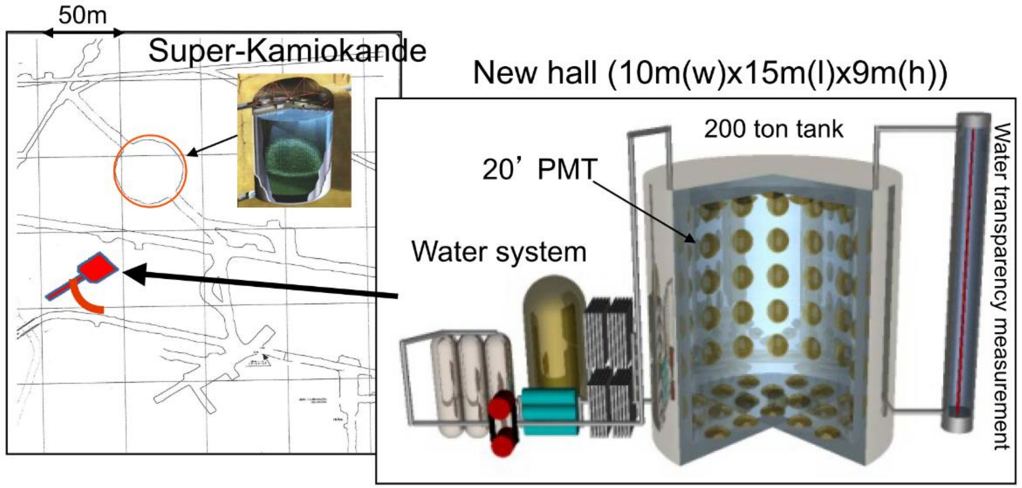
R&D for water + Gd technology

- R&D was conducted by using 200 ton water tank, which is Evaluating Gadolinium's Action on Detector System (EGADS)



→ The light left at 15 m has been stable at ~75% for 0.2% $Gd_2(SO_4)_3$
Corresponding to ~92% of SK-IV average.
→ >99.99% of Gd remains after water circulation for more than 350 times.

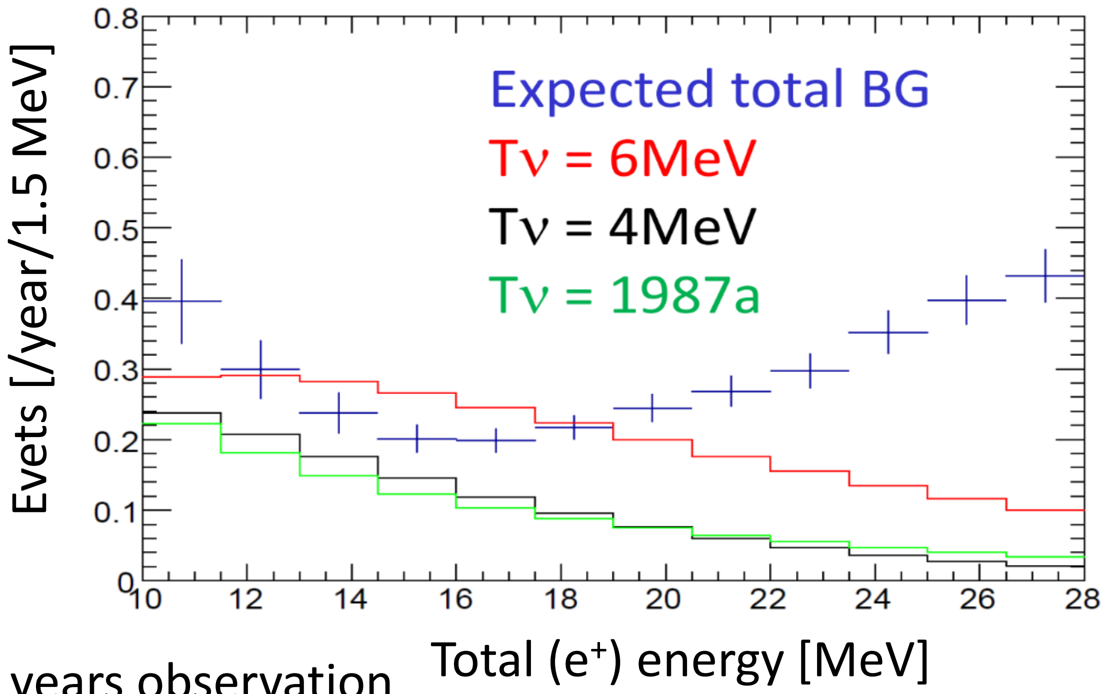
- The technology was well established.
  - Selective water purification system
  - Good and stable water transparency
  - Introducing and removing of Gd
  - Effect to detector
  - Effect from environment neutrons
  - Neutron tagging efficiency
  - etc.



EGADS

Physics expectation in SK-Gd

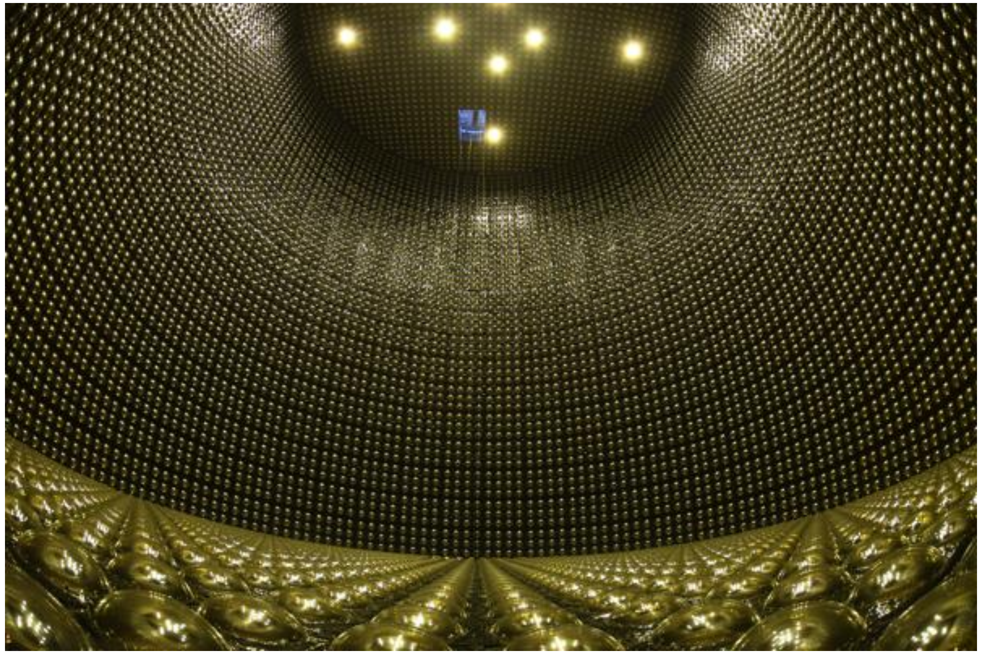
- Supernova relic neutrino flux:
  S. Horiuchi, J. F. Beacom, and E. Dwek, PRD, 79 (2009) 083013
- It depends on typical/actual SN emission spectrum.



↓Expected # of signals and backgrounds through SK-Gd 10 years observation

HBD model	10–16 MeV	16–28 MeV	Total	significance
T_{eff} = 8 MeV	11.3	19.9	31.2	5.3 σ
T_{eff} = 6 MeV	11.3	13.5	24.8	4.3 σ
T_{eff} = 4 MeV	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	–

For realization of SK-Gd



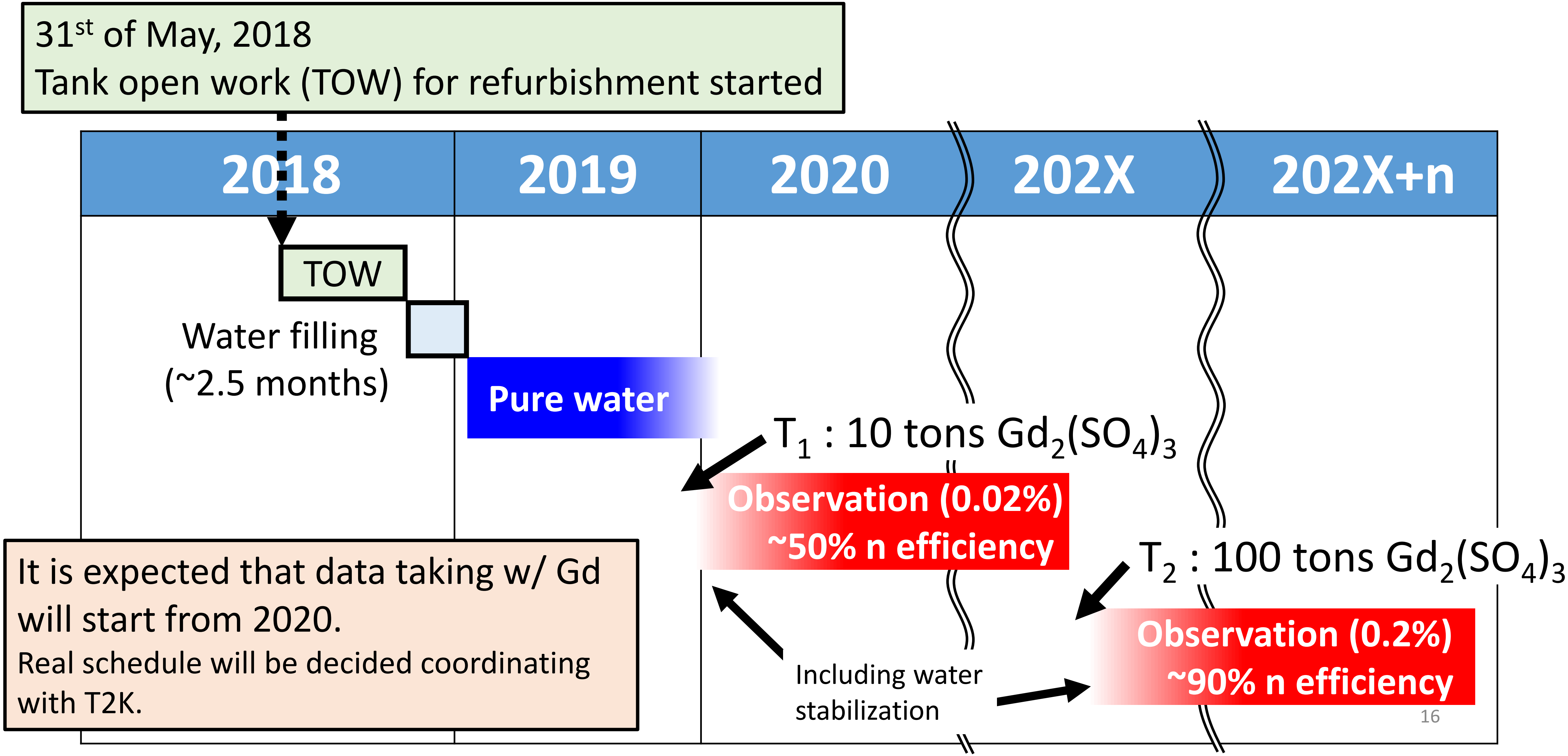
The tank refurbishment work started on 31st of May 2018 for realization of SK-Gd.

- **Stopping the leakage**
  - The SK water tank has a small leak which is estimated to be ~1 ton/day.
  - Before loading of Gd, the leakage has to be fixed from the view point of environmental safety.

- **Upgrade of the water piping in the tank**
  - The water piping is also improved for achievement a uniform Gd concentration inside the tank and keeping a good water transparency.
  - Flow rate will be increased from 60 to 120 ton/h.

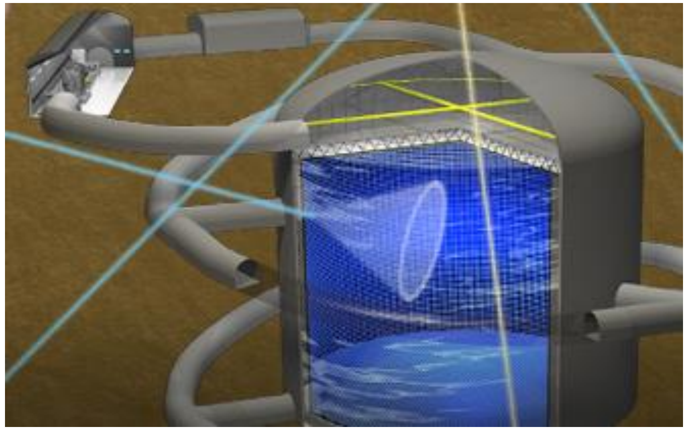
http://www-sk.icrr.u-tokyo.ac.jp/sk/tankopen2018/photo.html

A planned time line toward SK-Gd

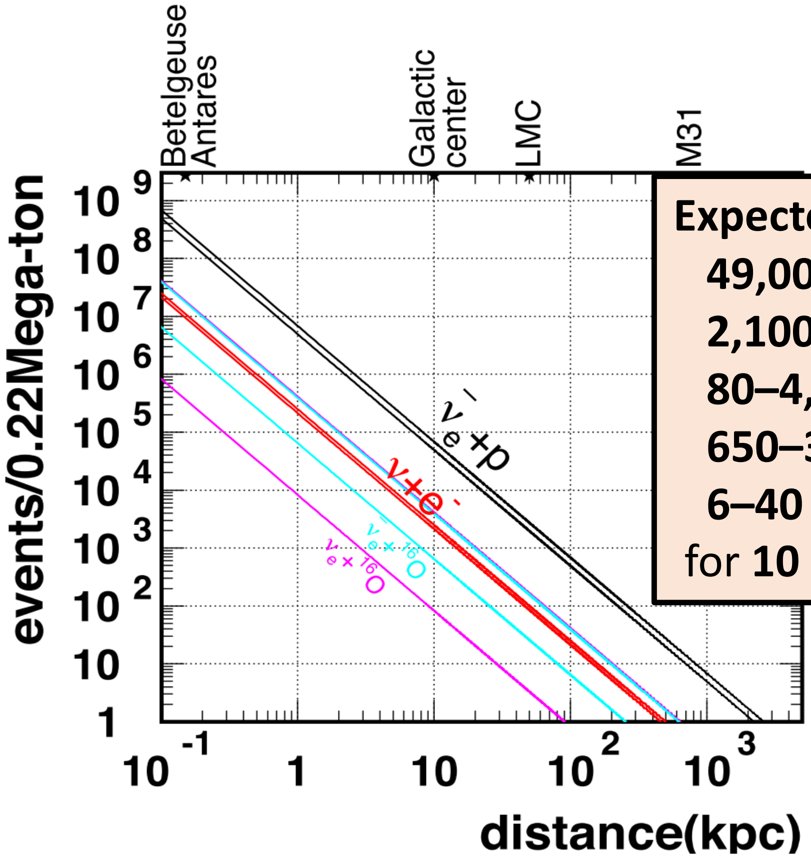


Supernova search at Hyper-Kamiokande

- The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in Apr. 2020.
- Construction will be completed in 2026.
- There is sensitivity for supernova nearby galaxies.



- 'Hyper-Kamiokande' design report arXiv:1805.04163



Expected # of events

49,000–6,8000 $\bar{\nu}_e + p$

2,100–2,500 $\nu + e^-$

80–4,100 $\nu_e + {}^{16}O$ CC

650–3,900 $\nu_e + {}^{16}O$ CC

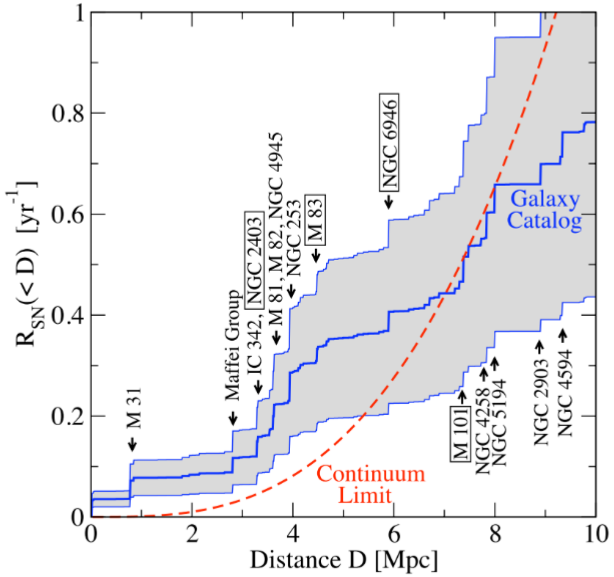
6–40 $\nu + e^-$ (neutronization)

for **10 kpc** supernovae

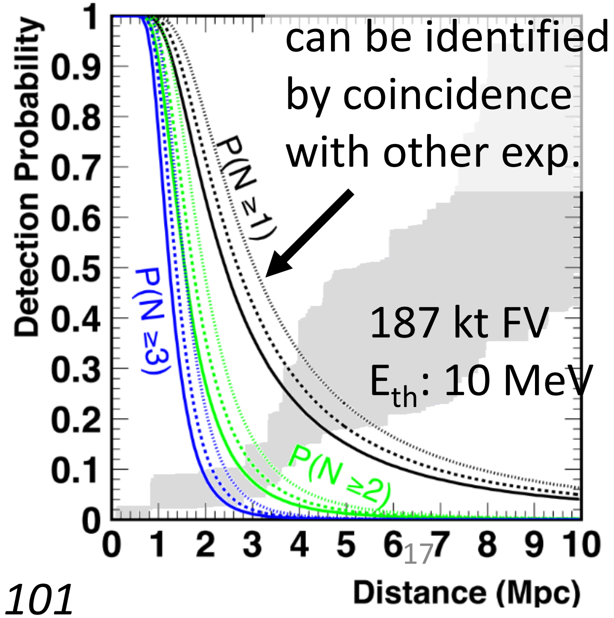
1 tank, 220 kton

Livermore model: T. Totani et. al., ApJ. 496 (1998) 216

Cumulative calculated SN rate



S. Ando et al., PRL 95 (2005) 171101



Even 1 event can be identified by coincidence with other exp.

187 kt FV

E_{th}: 10 MeV

Summary

- Super-Kamiokande has been ready for supernova for ~20 years.
  - If supernova happens in near G.C., ~8000 events will be detected and important information to understand the supernova mechanism will be obtained.
  - Limits for supernova relic neutrino are very close to theoretical prediction.

- Super-Kamiokande upgrade for supernova relic neutrino (SK-Gd)
  - The tank refurbishment work for SK-Gd is being conducted.
  - Data taking with Gd (0.02% of $Gd_2(SO_4)_3$) is expected to start from 2020.

- Hyper-Kamiokande has potential to detect supernova nearby galaxy.

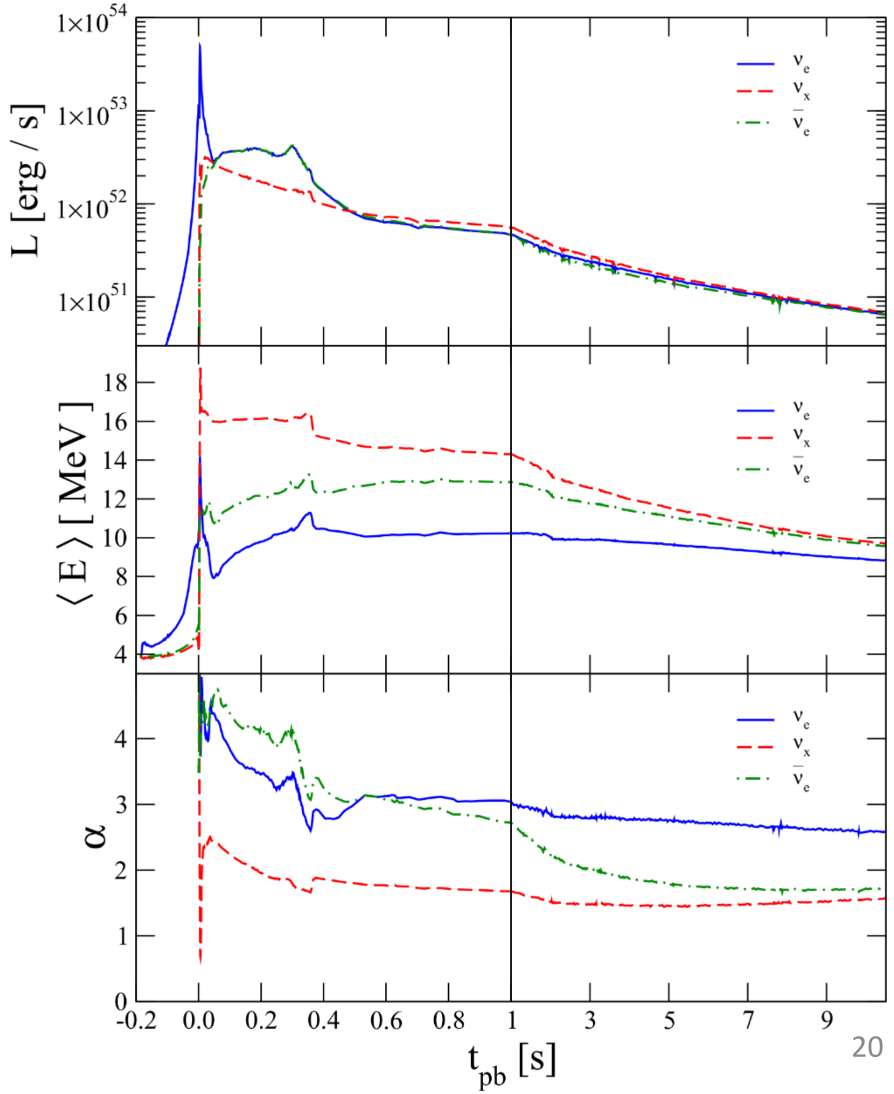
Backup

Luminosity, mean energy and pinch parameter

Figure is taken from S. Horiuchi and J. Kneller, arXiv:1709.01515v2

- This figure is taken from S. Horiuchi and J. Kneller, arXiv: 1709.01515v2
- Results are from T. Fischer et al., Astron. And Astrophys., vol. 517, p. A80, Jul, 2010
- Progenitor: 10.8 solar mass.
- t_{pb}: postbounce time.
- Pinch parameter (a): spectral deviation from Fermi-Dirac distribution.

- The accretion phase lasts until $t_{pb} \approx 0.3$ sec, and the shock is revived.
- Because multi-dimensional simulations are computationally expensive, there are few works extend beyond $t_{pb} > 1$ sec. Most of our theoretical understanding of the neutrino emission during the cooling phase comes from 1-dimensional simulations.



of expected events at SK

SK collaboration, Astropart. Phys. 81 (2016) 39–48

Table 1: Numbers of expected events at SK in the 22.5-kton fiducial volume with the 7 MeV total energy threshold for a SN burst with a distance of 10 kpc. We estimated these numbers using SK MC: we generate 3,000 ensembles of the MC samples, reconstructed the events with the SK standard reconstruction tool, applied the selection criteria, and then calculated the average numbers.

	Wilson			NK1			NK2		
	no osc.	NH	IH	no osc.	NH	IH	no osc.	NH	IH
$\bar{\nu}_e + p \to e^+ + n$	4923	5667	7587	2076	2399	2745	1878	2252	2652
$\nu_e + e^- \to \nu_e + e^-$	74	130	114	43	56	56	39	54	54
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	25	29	37	10	12	14	9	11	13
$\nu_x + e^- \to \nu_x + e^-$	41	33	34	17	19	18	17	17	17
$\bar{\nu}_x + e^- \to \bar{\nu}_x + e^-$	34	33	29	14	14	14	13	13	14
$\nu_e + ^{16}\mathrm{O} \to e^- + X$	8	662	479	22	78	74	16	72	68
$\bar{\nu}_e + ^{16}\mathrm{O} \to e^+ + X$	64	196	531	27	48	70	20	41	64
total	5169	6750	8811	2209	2626	2991	1992	2460	2882

- Wilson model : *T. Totani, et al., Astrophys. J. 496 (1998) 216.*
- Nakazato (NK) model : *K. Nakazato, et al., Astrophys. J. Suppl. 205 (2013) 2.*
  - NK1: M = 20 solar mass, t_{revive} = 200 ms, Z = 0.02
  - NK2: M = 13 solar mass, t_{revive} = 100 ms, Z = 0.004

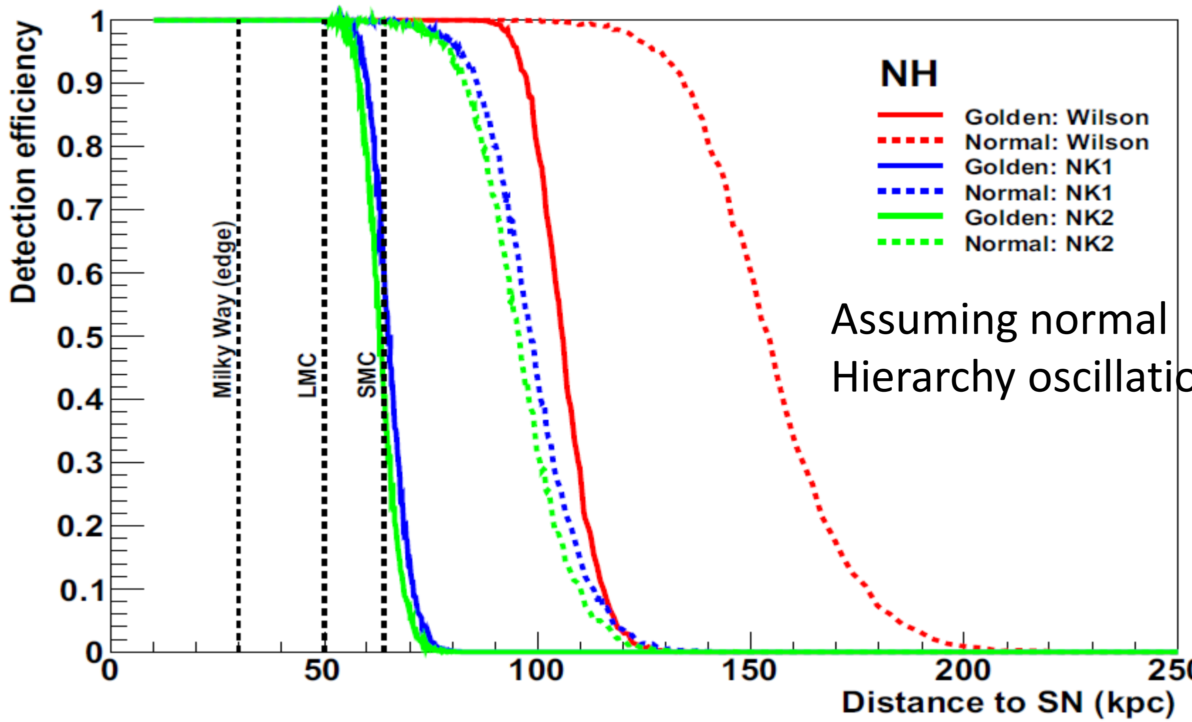
  (M: progenitor mass, t_{revive}: shock revival time, Z: metallicity)

The difference between w/ and w/o osc. is mainly coming from difference of ne energy spectra. The average energy of ν_e is smaller than that of ν_x when those neutrinos are emitted from the neutrino-sphere. Through neutrino osc. ν_x are converted to ν_e and therefore the average energy of ν_e at SK increases.

Detection efficiency of the real time SN monitor

SK collaboration, Astropart. Phys. 81 (2016) 39–48

↓ Detection efficiency of the real time SN monitor. 100% efficiency for our galaxy and LMC for various models.



- Condition
  - **Golden**: # of events >= 60 in 20 sec. and volume like (D=3)

    → SNEWS, ATEL, GCN, IAU-CBAT
  - **Normal**: 60 > # of events >= 25 in 20 sec and volume like (D=3)

    → sent alert to expert.
    Expert check the events.

- **Wilson model** : *T. Totani, et al., Astrophys. J. 496 (1998) 216.*
- Nakazato (NK) model : *K. Nakazato, et al., Astrophys. J. Suppl. 205 (2013) 2.*
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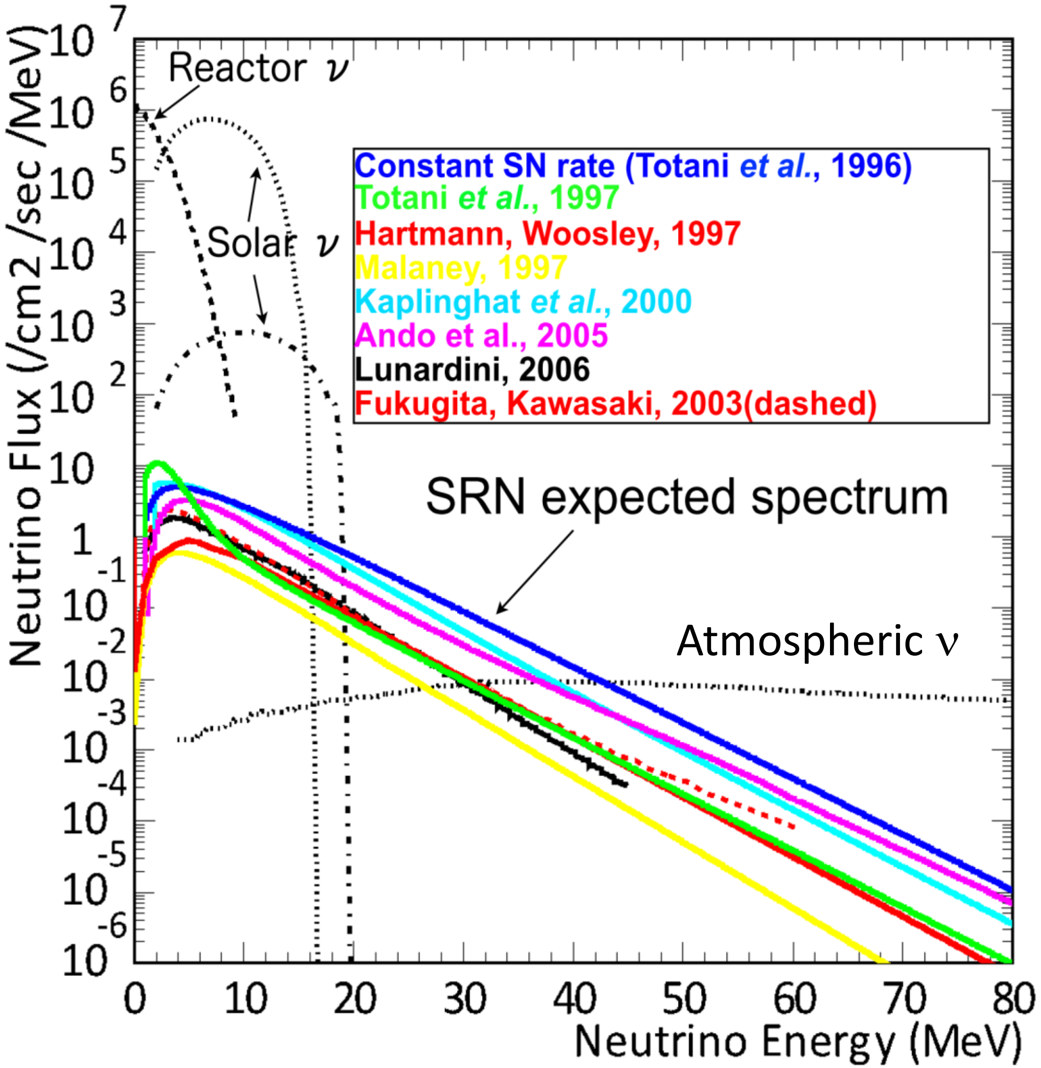
  (M: progenitor mass, t_{revive}: shock revival time, Z: metallicity)

Supernova Relic Neutrinos

- **Constant SN rate model**: Totani, Sato, and Yoshii, Astrophys. J. 460 (1996) 303.
- **Cosmic gas infall model**: Malaney, Astropart. Phys. 7 (1997) 125.
- **Chemical evolution model**: D. H. Hartmann and S. E. Woosley, Astropart. Phys. 7 (1997) 137.
- **Heavy metal abundance model**: M. Kaplinghat, G. Steigman, and T. P. Walker, Phys. Rev. D 62 (2000) 043001
- **Large mixing angle (LMA)** : Ando, Sato, and Totani, Astropart. Phys. 18 (2003) 307.
  The flux of the LMA model is increased by a factor of 2.56 at NNN05.
- **Failed supernova model**: Lunardini, Phys. Rev. Let. 102 (2009) 231101



Supernova relic neutrino search at super-Kamiokande

K. Bays et al., Physical Rev. D 85 (2012) 052007

- 2853 live days
- 2.8–3.1 ν_e cm^{-2} s^{-1} > 16 MeV total positron energy (17.3 MeV E_ν)
- Improved from 2013 result
  - Increasing of efficiency : up to ~75%
  - Lower energy threshold : down to 16 MeV
  - Considering additional BG: NC elastic, μ/π production
  - Larger statistic
- Data reduction
  - Noise cut
  - Fiducial volume cut (22.5 ktons)
  - Spallation cut
  - Solar angle cut
  - Incoming event cut
  - Decay electron cut
  - Pion cut
  - Cherenkov angle (38 < signal < 50 degrees)
  - Others:
- BG sources
  - (1) Atmospheric ν_μ CC events
  - (2) ν_e CC events
  - (3) Atmospheric ν neutral current (NC) elastic events
  - (4) μ/π production from atmospheric ν

BG modeling using the SK MC based on GEANT3 and NEUT

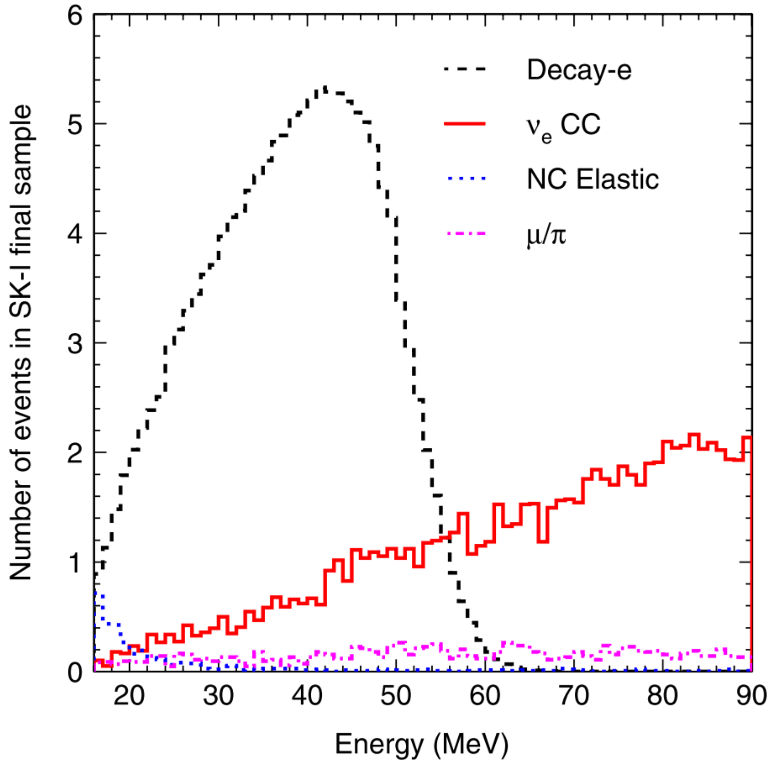


FIG. 11 (color online). Spectra of the four remaining backgrounds in the signal Cherenkov angle region with all reduction cuts applied. The ν_μ CC channel is from decay electron data; the other three are from MC. All are scaled to the SK-I LMA best fit result.

Supernova relic neutrino search at super-Kamiokande

K. Bays et al., Physical Rev. D 85 (2012) 052007

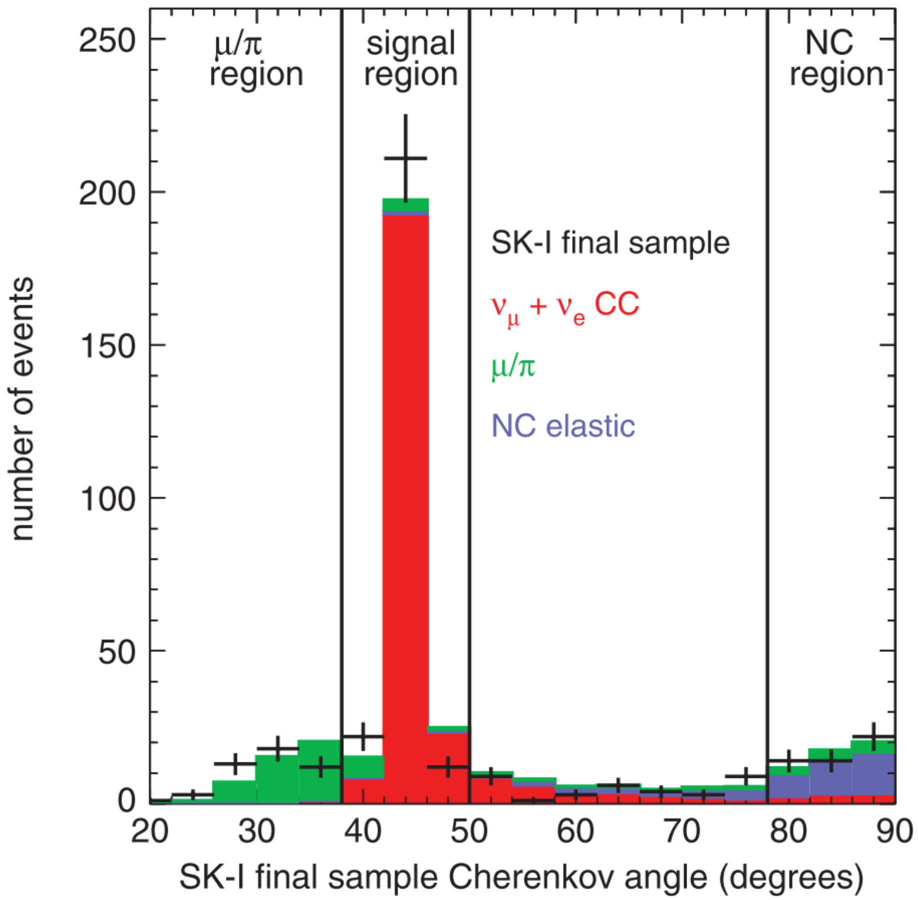


FIG. 12 (color). Cherenkov angle of SK-I combined final data (all cuts except Cherenkov angle cut applied) overlaid with distributions of the four remaining backgrounds from SK-I MC (same cuts applied). The division of Cherenkov angle regions is also pictured.

← Cherenkov angle distribution of 4 remaining backgrounds.

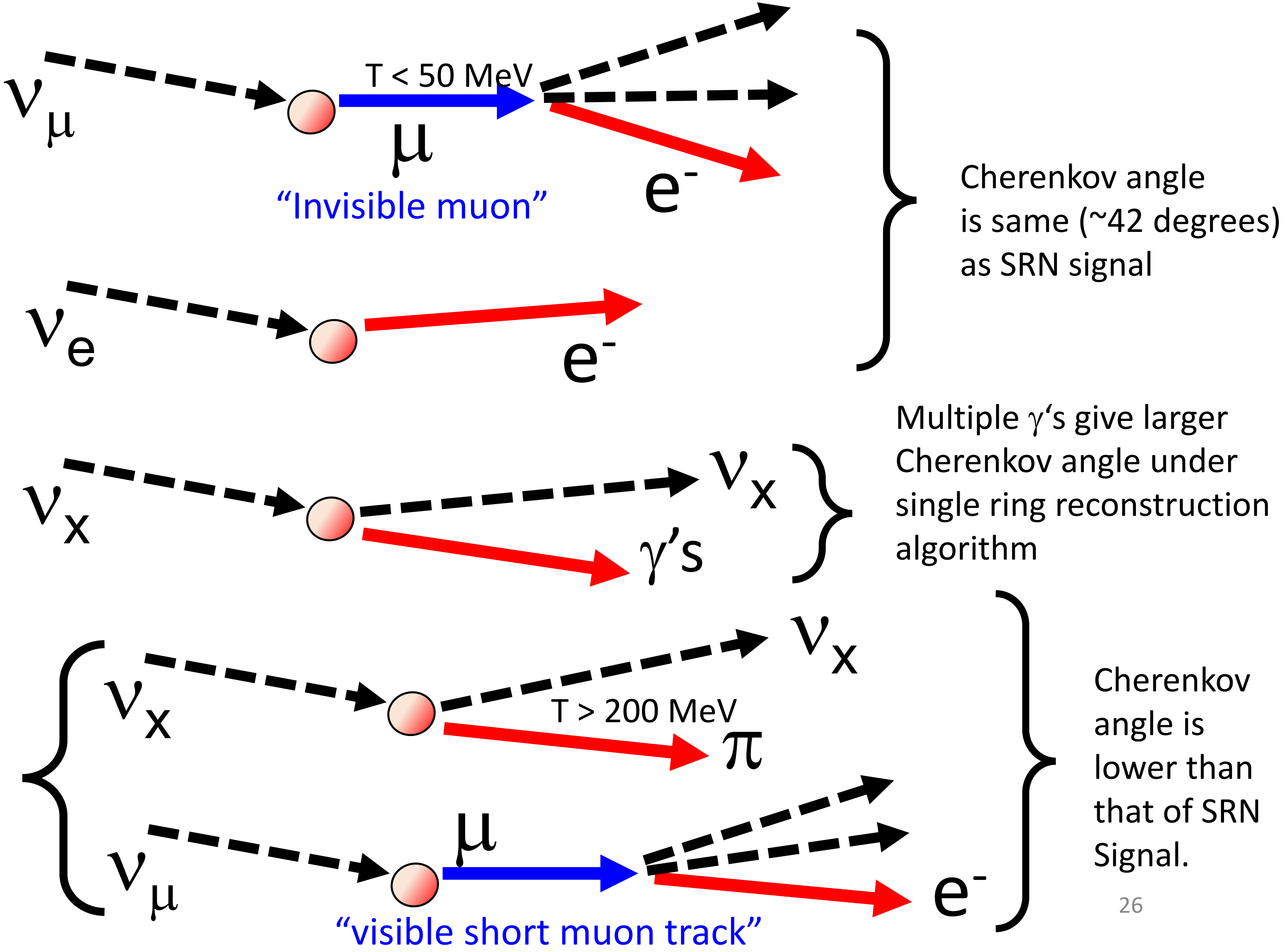
Remaining background consist of 4 categories:
(all are originated from atmospheric ν)
(1) ν_μ CC : invisible μ + decay electron
(2) ν_e CC :
(3) NC elastic
(4) μ/p

(1) and (2) have similar Cherenkov angle (around 42 degrees) as SRN signal.
(4) has smaller Cherenkov angle because of lower speed.
(3) generates multiple γ's which is reconstructed isotropic (higher angle) from single ring algorithm.

Background events of SRN

K. Bays et al., Physical Rev. D 85 (2012) 052007

- Decay electron from atmospheric ν_μ
- ν_e CC from atmospheric ν_e
- NC elastic from atmospheric ν
- μ/π from atmospheric ν



Supernova relic neutrino search at super-Kamiokande

K. Bays et al., Physical Rev. D 85 (2012) 052007

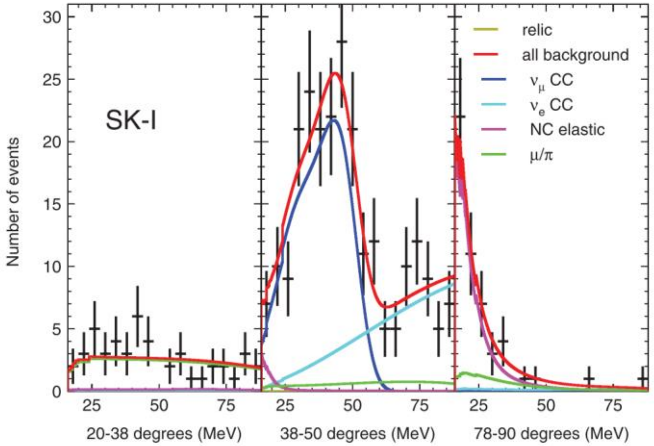


FIG. 14 (color). SK-I LMA best fit result. The relic best fit is negative, so a relic fit of 0 is shown.

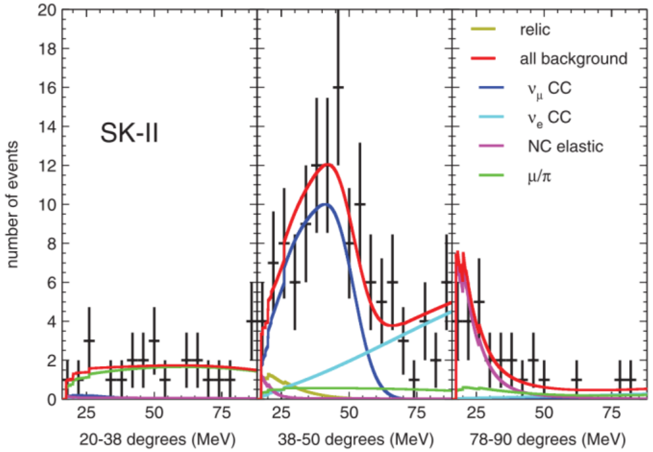


FIG. 15 (color). SK-II LMA best fit result. The relic best fit is 3.05 events per year interacting in the detector (before reduction efficiencies).

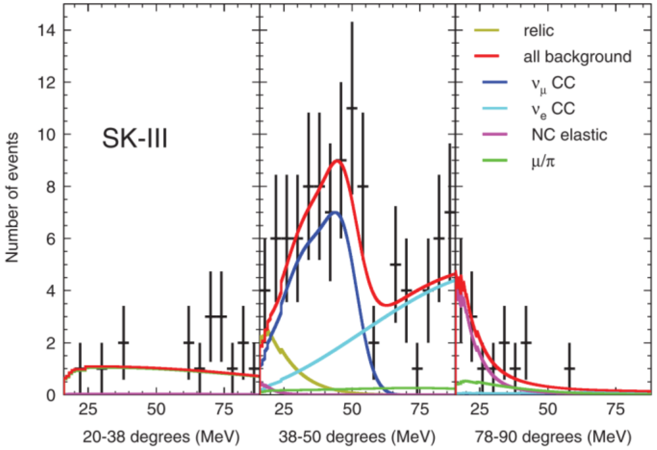
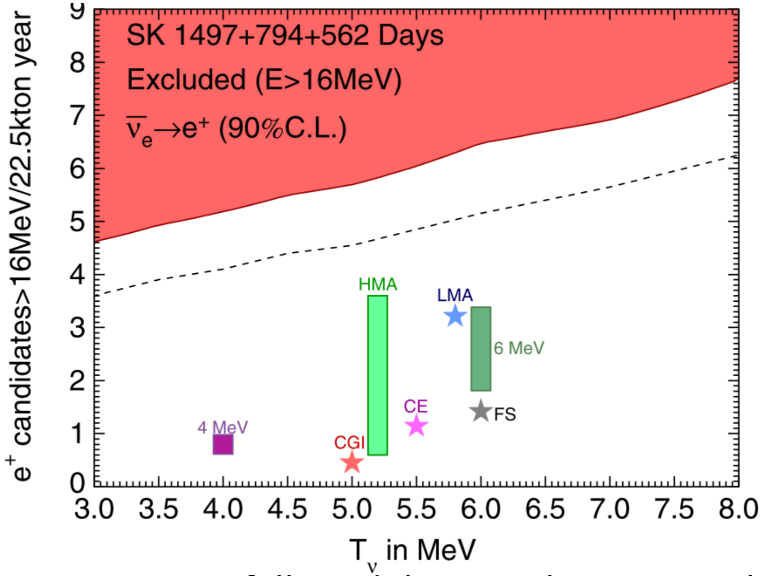


FIG. 16 (color). SK-III LMA best fit result. The relic best fit is 6.9 events per year interacting in the detector (before reduction efficiencies).



CGI: cosmic gas infall model, **HMA**: heavy metal abundance model
CE: chemical evolution model, **LMA**: large mixing angle model, **FS**: failed supernova model

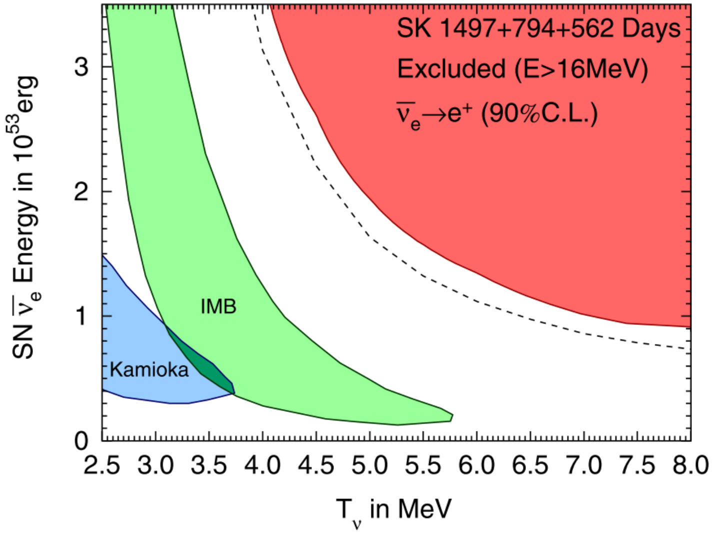


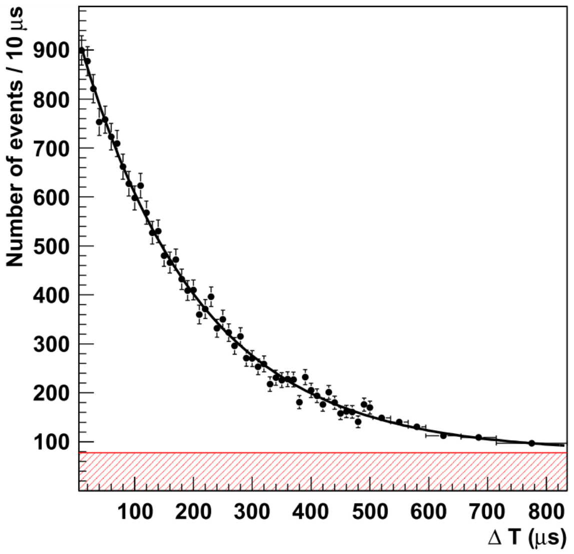
FIG. 18 (color online). Results plotted as an exclusion contour in SN neutrino luminosity vs neutrino temperature parameter space. The Irvine-Michigan-Brookhaven (IMB) and Kamiokande allowed areas for 1987A data are shown (originally from [35]) along with our new 90% C.L. result. The dashed line shows the individual 90% C.L. results of each temperature considered separately, which is not a true two-dimensional exclusion contour. Results are in the form of Fig. 6 from [32].

SRN search at SK with neutron tagging

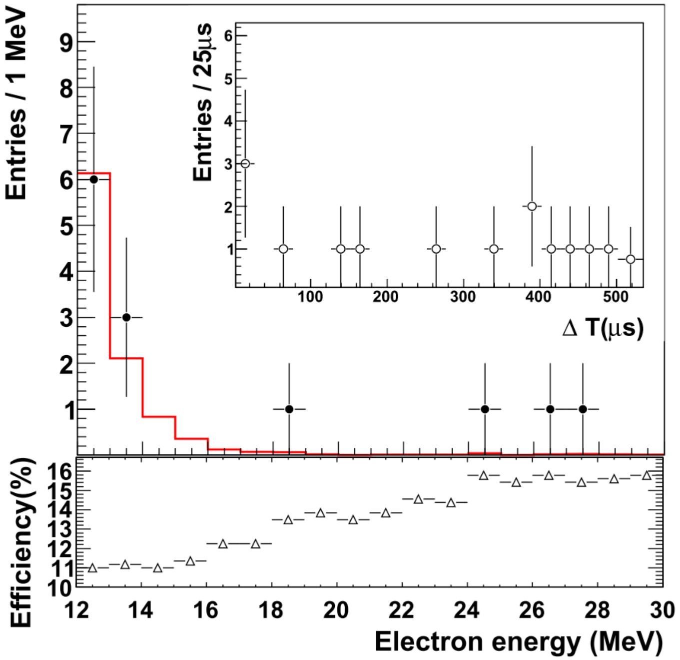
H. Zhang et al., Astropart. Phys. 60 (2015) 41–46

- 960 days of data in SK-IV.
- Neutron tagging efficiency: $(17.74 \pm 0.04_{stat.} \pm 1.05_{sys.})\%$

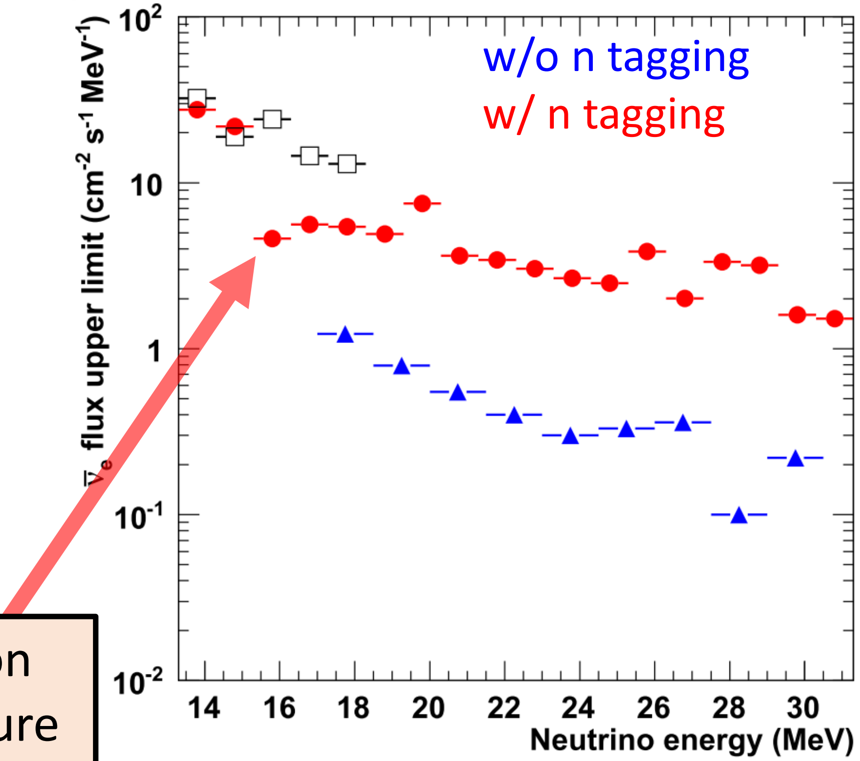
ΔT distribution for the Am/Be data.



Positron energy spectrum of the IBD candidate (13 events).



Model-independent 90% CL differential upper limit on SRN $\bar{\nu}_e$ for SK-IV



The world best limit below 16 MeV was derived. Although neutron detection efficiency is very low because of low energy of the γ from the neutron capture on H. It shows a high potential of neutron tagging techniques.

SEARCH FOR SUPERNOVA NEUTRINO BURSTS AT SUPER-KAMIOKANDE

M. Ikeda et al., Astrophys. J. 669 (2007) 519–524

- SK-I and II: 2589.2 live days
- Full detection efficiency (100%) around 100 kpc.
- No bursts was found: 90% CL upper limit is 0.32 SN/year < 100 kpc.
- Three kinds of searches were conducted:
  - (1) Distant supernova search
  - (2) Supernova burst search with low energy threshold
  - (3) Neutronization burst search
- (1) Distant supernova search
  - Time window: >= 2 events/20 sec
  - (ex.) expected # of events in the Andromeda galaxy (~700 kpc) is ~2.
  - Best energy threshold was set from maximum (detection probability)/√# of chance coincidence → 17 MeV
- (2) Supernova burst search with low energy threshold
  - Time windows:
    - >= 3 events/0.5 sec
    - >= 4 events/2 sec
    - >= 8 events/10 sec
  - Energy threshold: 6.5 MeV (SK-I) and 7.0 MeV (SK-II)
- (3) Neutronization burst search
  - Time window:
    - >= 2 events/1 msec
    - >= 2 events/10 msec
    - >= 2 events/100 msec

R_{mean}: averaged spatial distance between each event.

Sumdir was also used for (3)

(3) Results of neutronization burst search

TABLE 2
NUMBER OF CANDIDATES AND BACKGROUNDS IN NEUTRONIZATION BURST SEARCH

	SK-I		SK-II	
Criterion	Candidate	BG[a]	Candidate	BG[a]
$\geq$ 2events/1msec	1	2.10	0	0.125
$\geq$ 2events/10msec	19	19.1	0	1.25
$\geq$ 2events/100msec	194	191	10	12.5
$\geq$ 3events/1msec	0	9.90×10^{-6}	0	1.65×10^{-7}
$\geq$ 3events/10msec	0	9.78×10^{-4}	0	1.65×10^{-5}
$\geq$ 3events/100msec	0	9.78×10^{-2}	0	1.65×10^{-3}

[a] The number of backgrounds was calculated from the chance coincidence rate of non-supernova signals such as solar neutrino events, flasher events, and spallation events in the data samples.

SEARCH FOR SUPERNOVA NEUTRINO BURSTS AT SUPER-KAMIOKANDE

M. Ikeda et al., Astrophys. J. 669 (2007) 519–524

(1) Distant supernova search

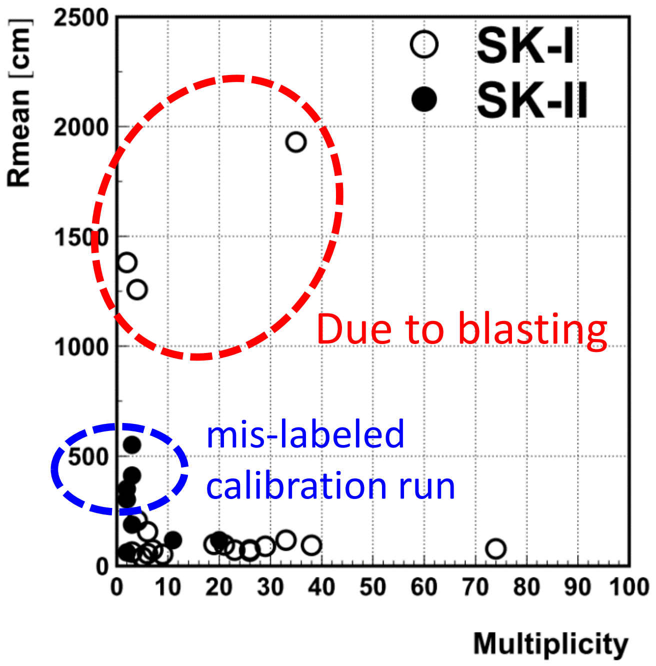


FIG. 3.— Correlation between the multiplicity and R_{mean} for obtained clusters from data (open circle: SK-I, closed circle: SK-II). There were 19 clusters observed in SK-I and 8 clusters in SK-II.

(2) Supernova burst search with low energy threshold

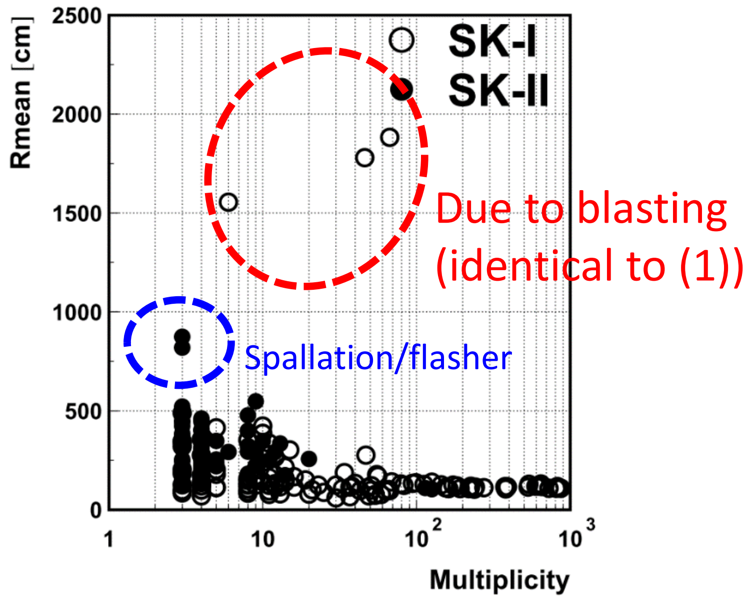


FIG. 4.— Correlation between the multiplicity and R_{mean} for obtained clusters from data (open circle: SK-I, closed circle: SK-II). There are 121 and 53 clusters observed in SK-I and SK-II respectively. If a cluster satisfies more than one criterion, the circle for the cluster represents the largest multiplicity, and R_{mean} for the cluster is calculated from the multiplicity of events.

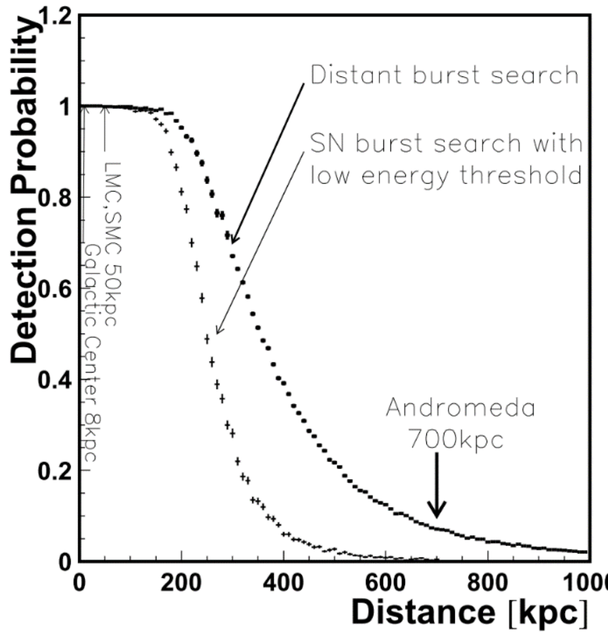
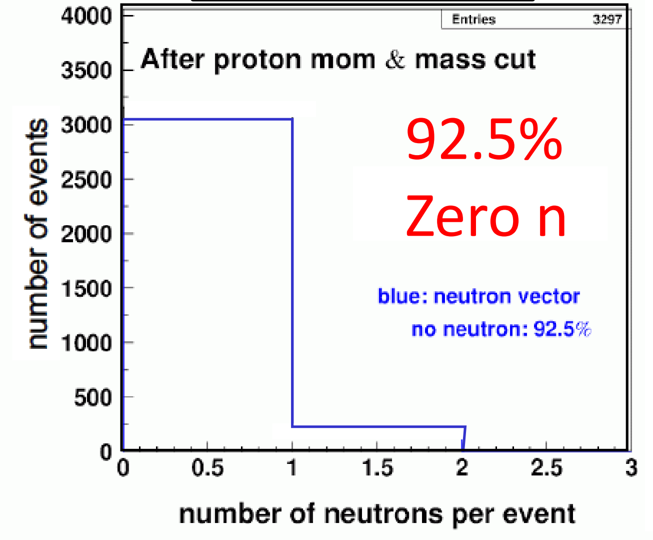


FIG. 6.— The probability of detecting supernovae assuming a specific supernova model at SK. Full (100%) detection probability is retained out to around 100 kpc.

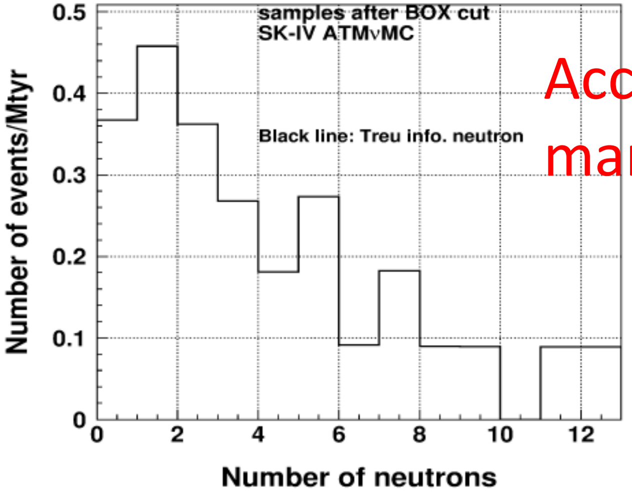
Improvement for proton decay by neutron tagging

- Neutron multiplicity for $P \to e^+p^0$ MC (left) and atmospheric ν BG (right)

$P \to e^+p^0$ MC



Atmospheric ν BG

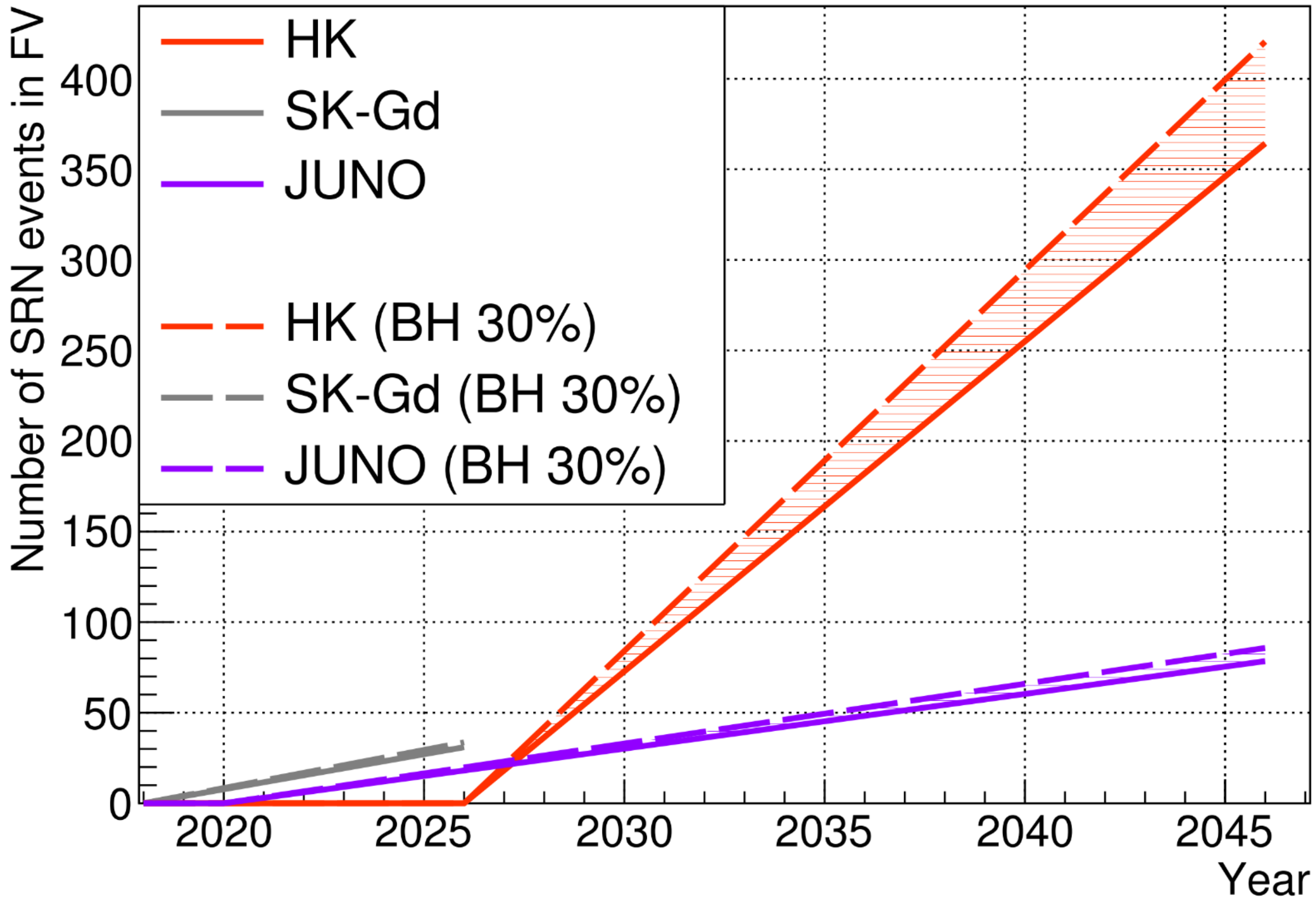


Accompany many n

- Current BG level: 0.58 events/10 years
- BG with neutron anti-tag: 0.098 events/10 years

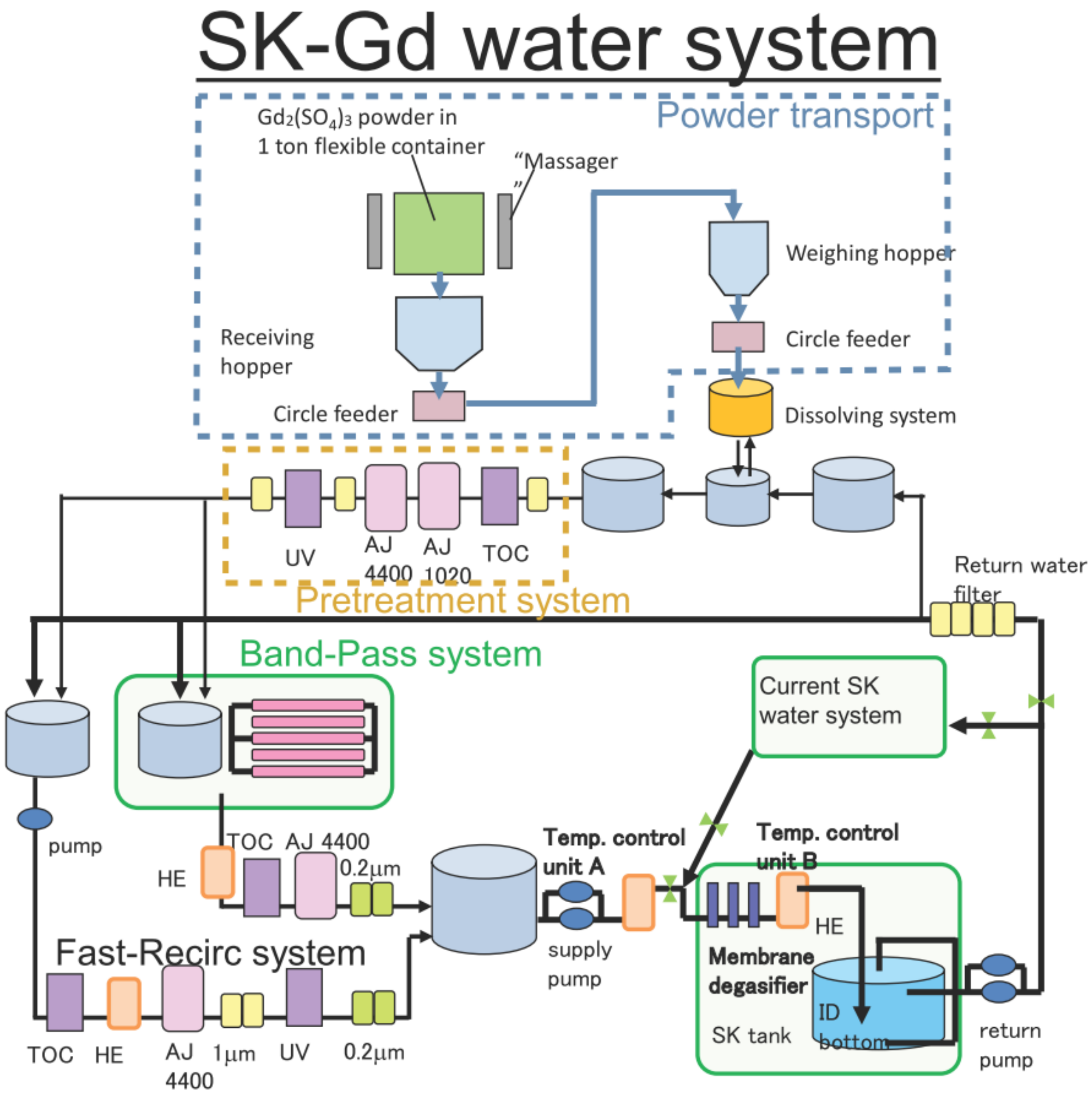
→ BG probability (for observation of 1 event) will be decreased from 44% (w/o anti-tag) to 9% (w/ anti-tag)

Expected # of SRN events at Hyper-K

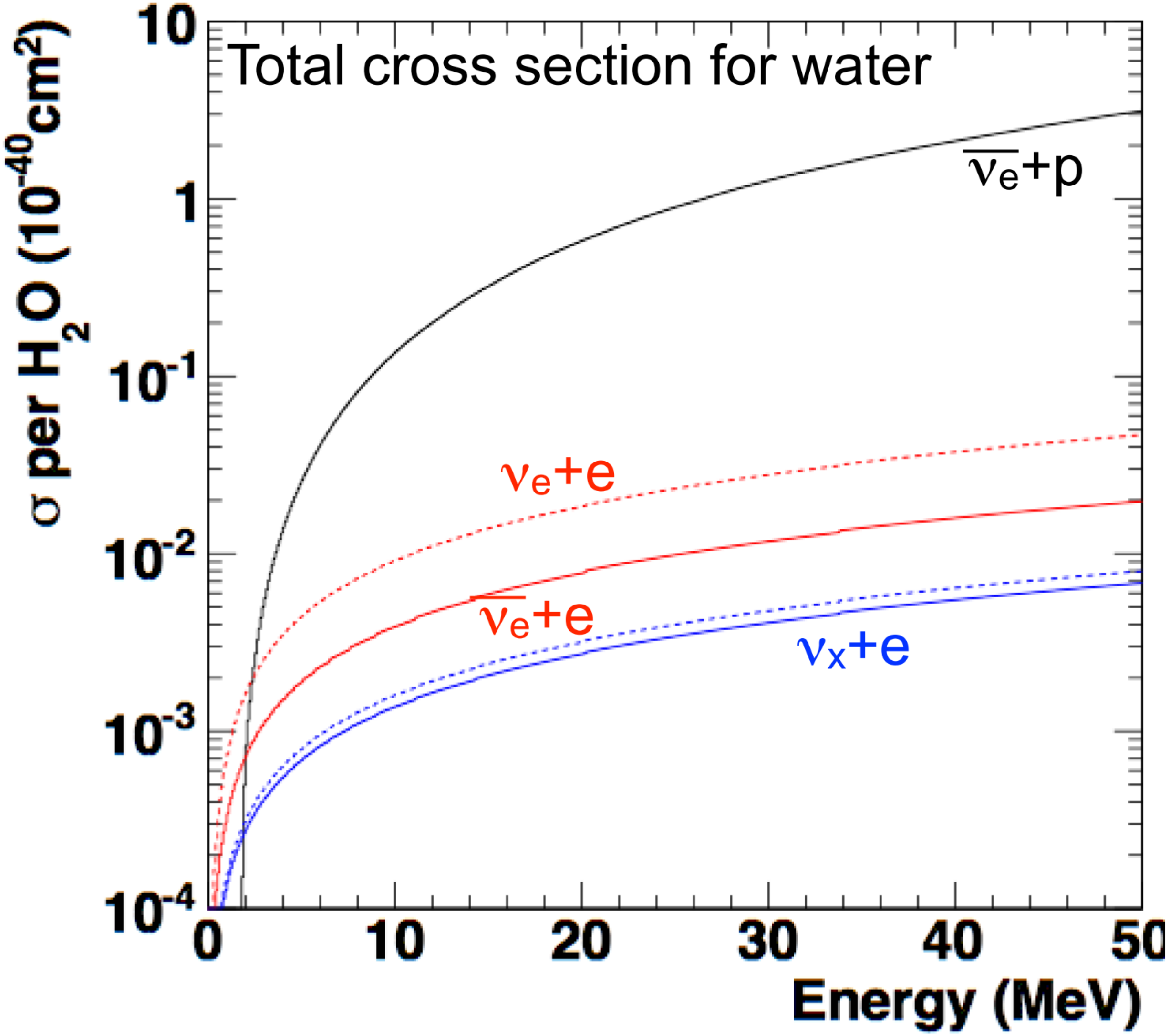


Gd dissolution and purification system

- The system consists of
  - Gadolinium sulfate transportation unit
  - Dissolving unit
  - Pre-treatment unit
  - Main purification unit
- The system is installed in Lab-G located ~160 m away from the SK tank.
- Gadolinium dissolution into the SK tank in 17 days (120 m^3/h flow).

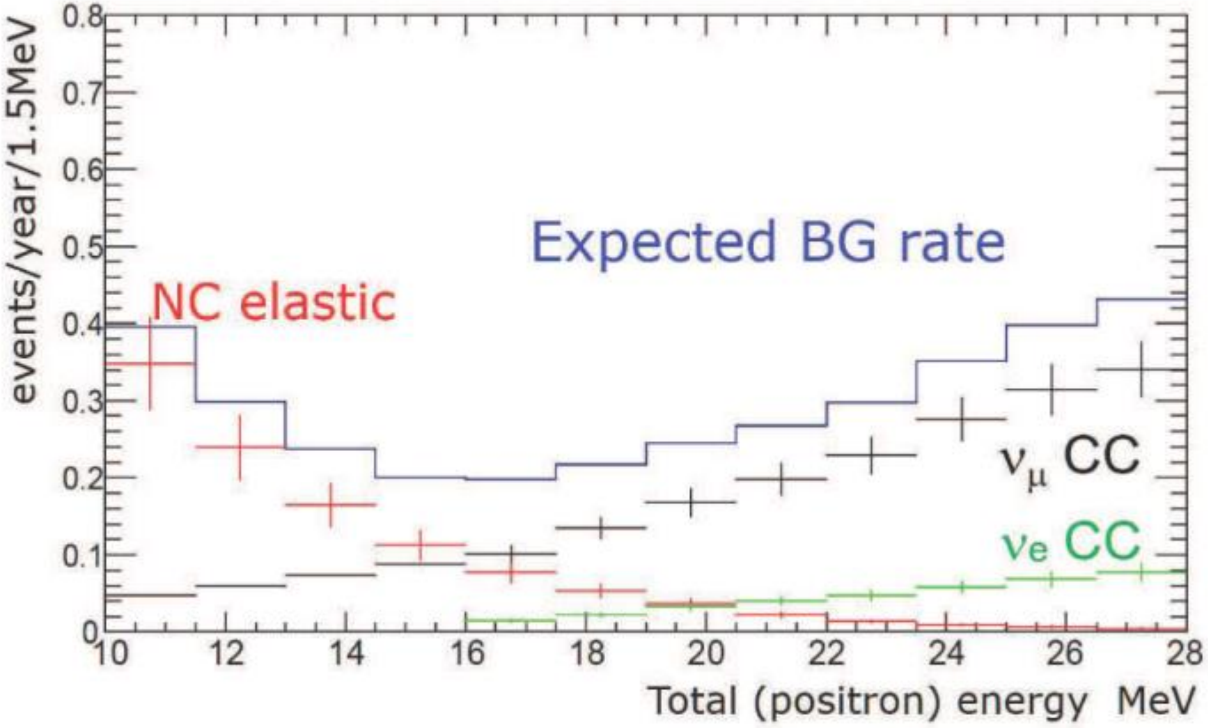


Total cross section for water



Expected SRN spectra in SK-Gd

- Expected BG components of SK-Gd



- Expected SRN spectra of some models

S. Horiuchi et al., Phys. Rev. D79 (2009) 083013