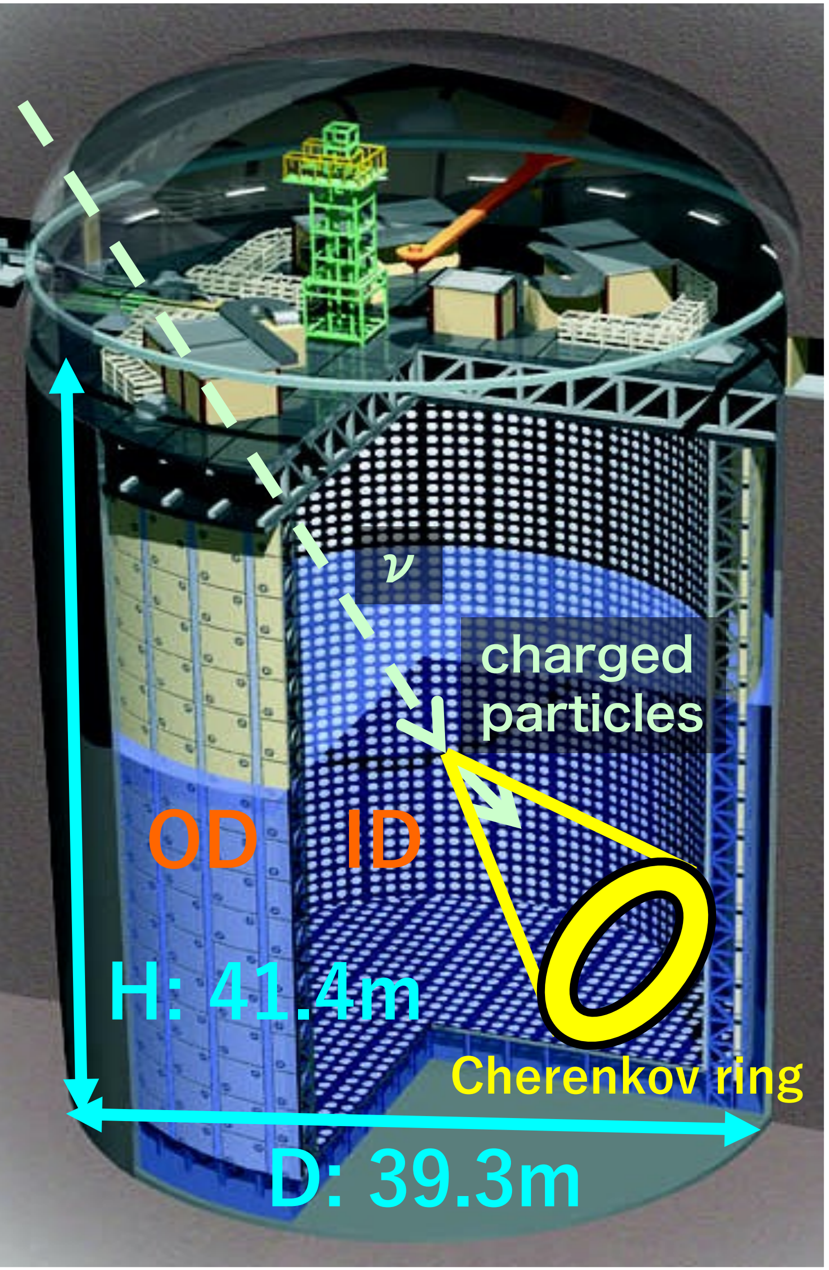
Overview: Super-Kamiokande and Super-K Gd

Takatomi Yano, ICRR, U-Tokyo.

ICRR young researcher's workshop, 5th Nov. 2021

Online

Super-Kamiokande



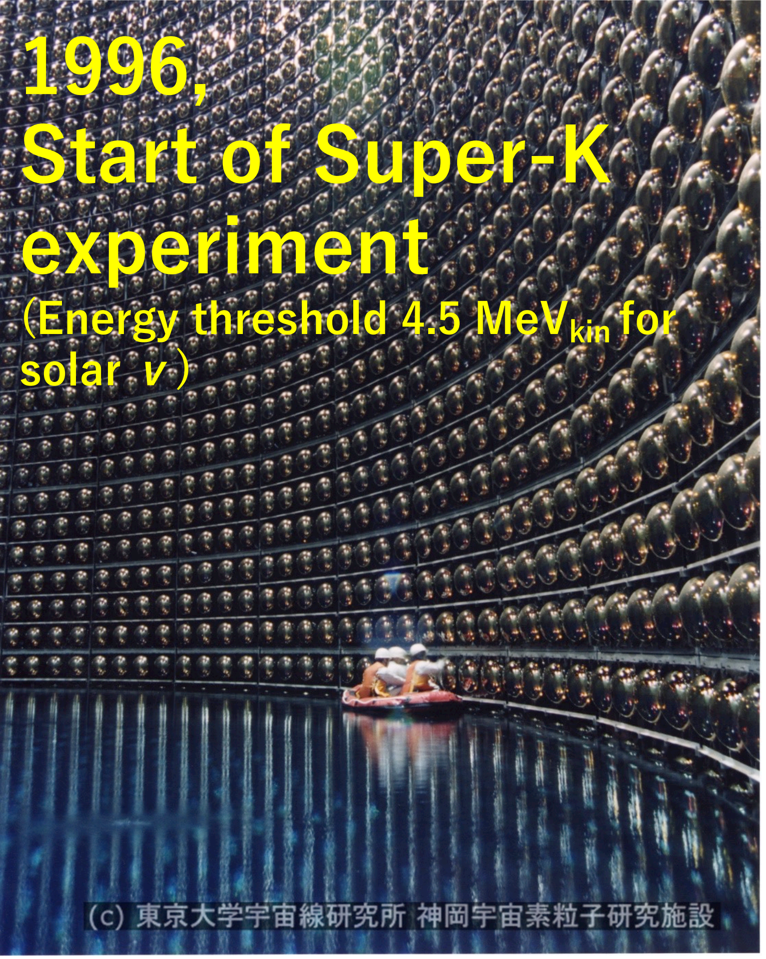
Features of SK detector

- Large water Cherenkov detector with **50kt ultra pure water**, providing **22.5 kt fiducial volume.**
- **1 km** under the Ikenoyama mountain in Japan (**2700 mwe**).
- **~11,000 of 20” PMT** for inner detector (ID).
  - **40%** photocathode coverage
  - SK-II: Half PMT and coverage
- **1885 of 8” PMT** for outer detector (OD).
- Studying neutrinos from wide variety of sources.
  - Solar neutrino
  - Supernova neutrinos
  - Atmospheric/Accelerator neutrinos

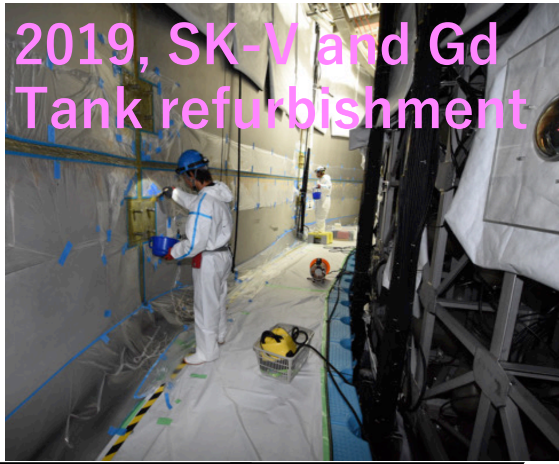
} O(1) to O(10) MeV (Solar neutrino, Supernova neutrinos)

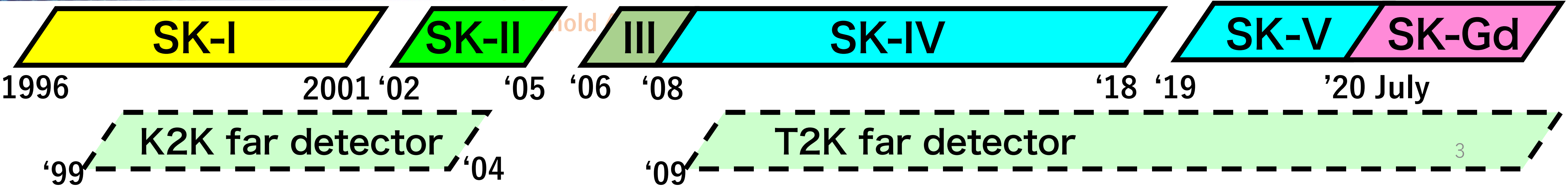
O(100) MeV to TeVs (Atmospheric/Accelerator neutrinos)

Super-Kamiokande history

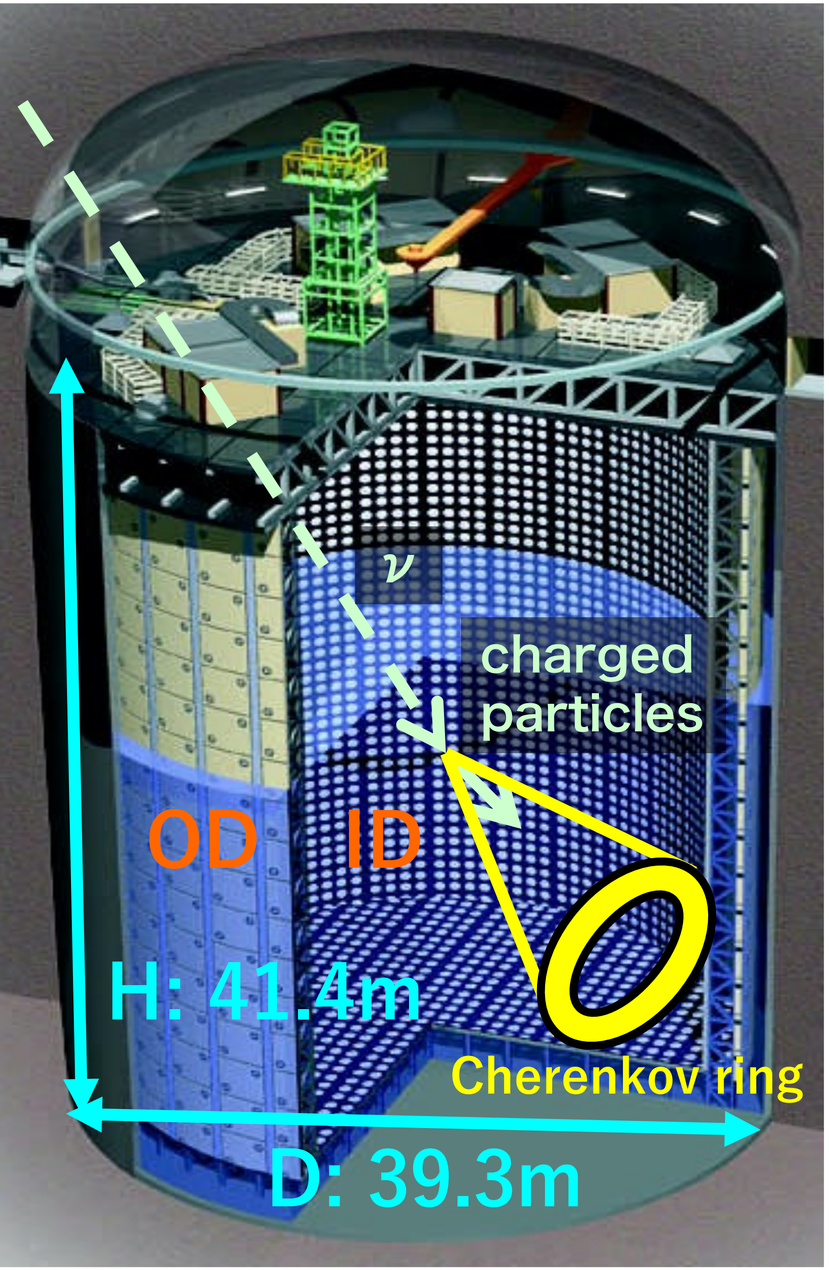


- From April of 1996, the Super-K accumulated **atm./solar ν events**, searched for **nucleon decay**, cooperated with **ν beam exp.** and made improvement over 20 years.
- After tank refurbishment work at 2019, Gadolinium sulfate is dissolved into SK tank water in the middle of 2020.
  - Aiming for first observation of diffused supernova neutrino background (supernova relic neutrino).

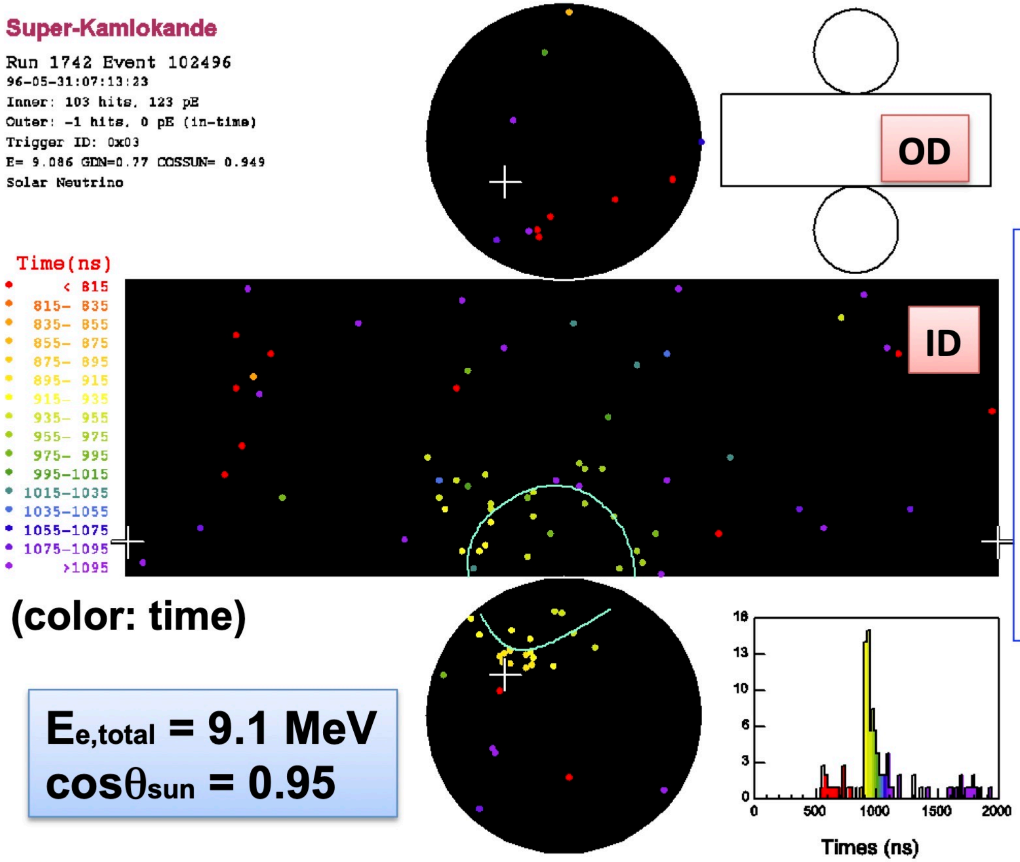




Event Reconstruction -1-



Typical low-energy event



(color: time)

$\nu + e^- \rightarrow \nu + e^-$

(for solar neutrinos)

- Timing information ➡ vertex position
- Ring pattern ➡ direction
- Number of hit PMTs ➡ energy

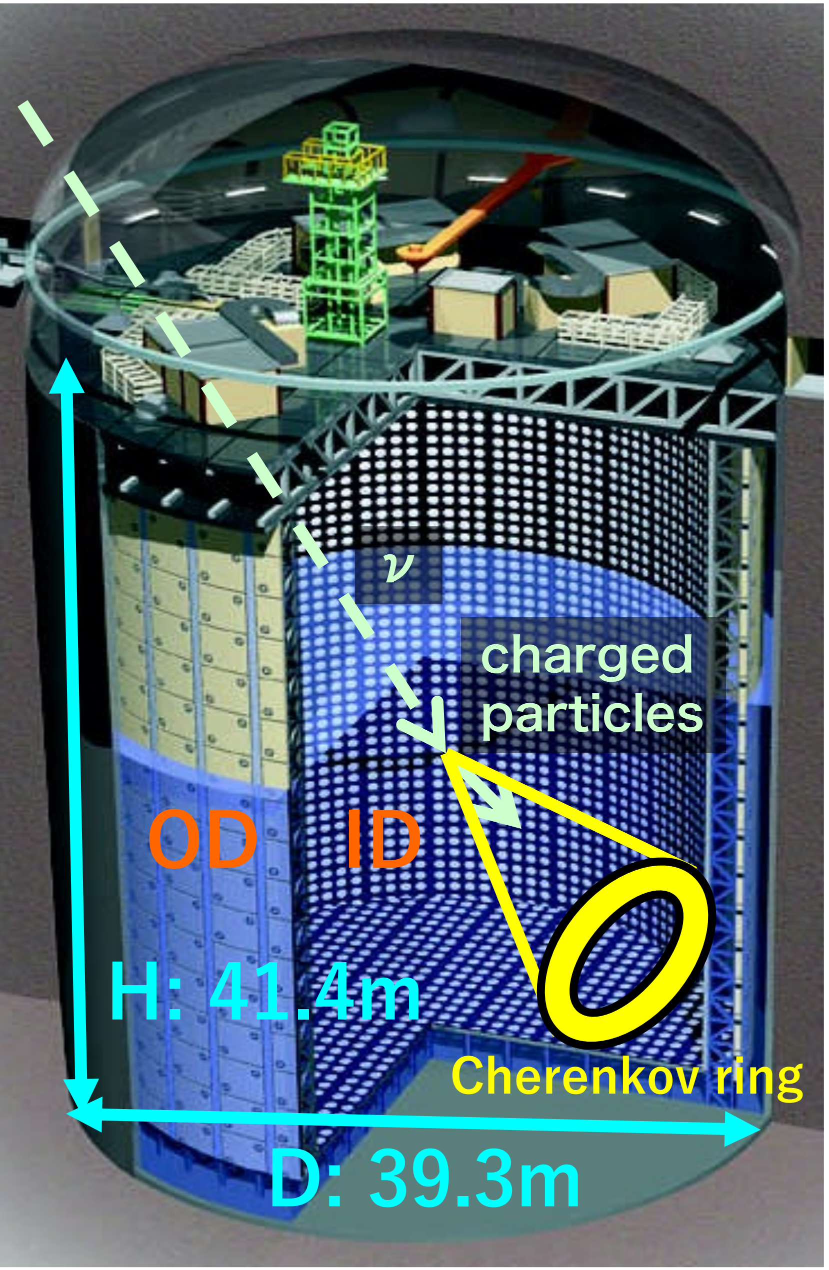
$E_{e,total}$ = 9.1 MeV
$\cos\theta_{sun}$ = 0.95

~6 hit / MeV (SK-I, III, IV)

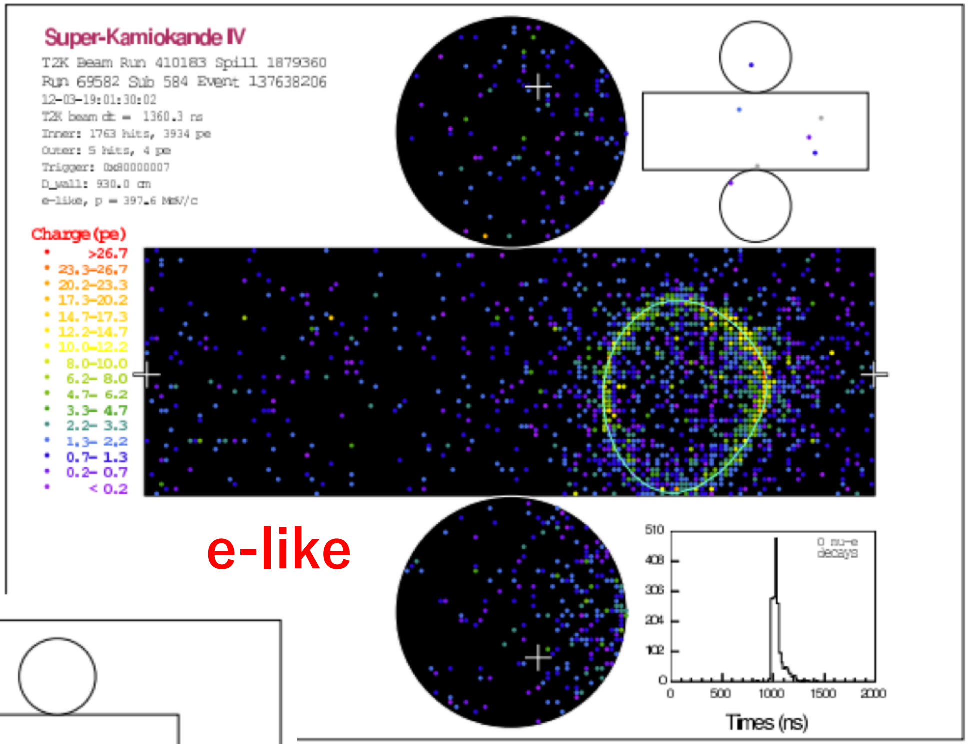
Resolutions (for 10MeV electrons) (software improvement)

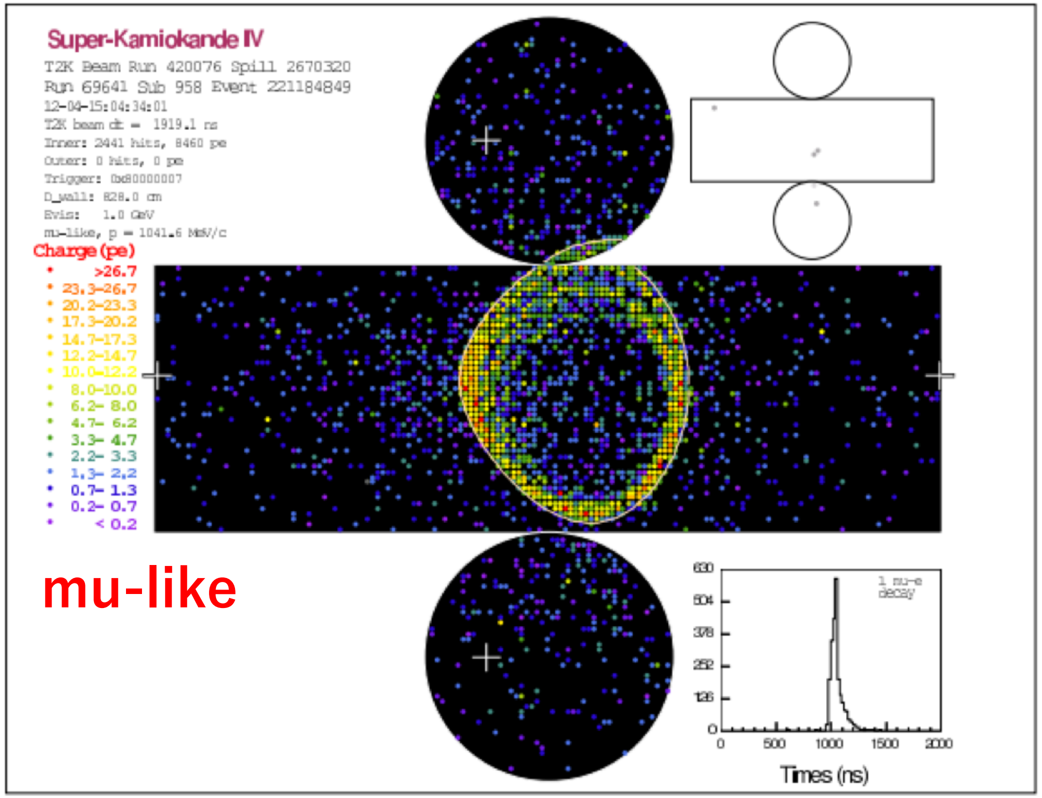
Energy: 14%	Vertex: 87cm	Direction: 26°	SK-I
Energy: 14%	Vertex: 55cm	Direction: 23°	SK-III

Event Reconstruction -2-



- e/ μ neutrino CC interactions can be separated at higher energy events (>O(100)MeV).
-
  - >99 % efficiency for e/ μ separation.



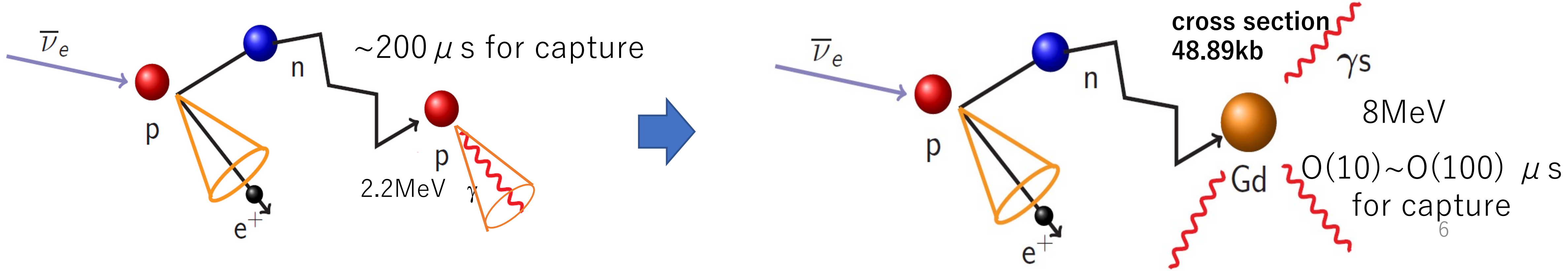


Figures are taken from:
Laura Munteanu, ICHEP2020

Super-Kamiokande Gadolinium Project (SK-Gd)

SK-Gd

- Dissolving Gd to Super-Kamiokande to significantly enhance detection capability of neutrons from ν interactions
  - J. F. Beacom and M. R. Vagins, Phys. Rev. Lett. 93 (2004) 17110
- **By coincidence method, low-energy anti-electron-neutrino interaction can be identified.**



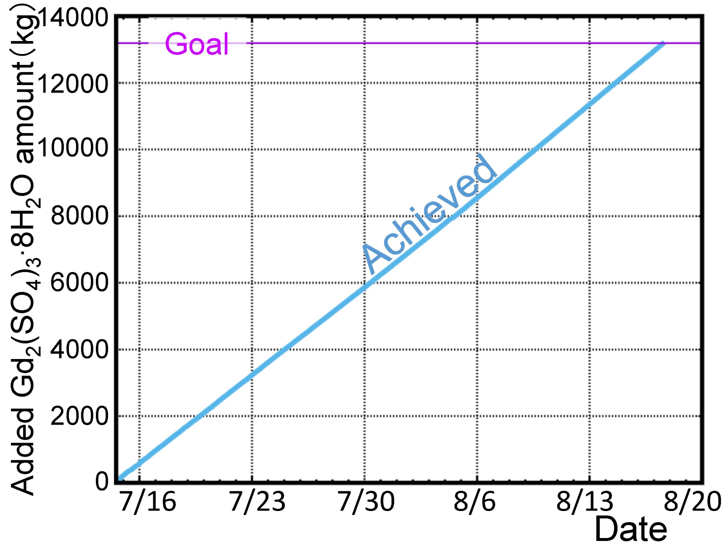
Physics target and status of SK-Gd

Physic targets

- Precursor of nearby supernova by Si-burning neutrinos
- Improve pointing accuracy for galactic supernova
- **Discovery of Supernova Relic Neutrinos**
- Others
  - Reducing proton-decay search background
  - Neutrino/anti-neutrino discrimination (for accelerator/atmospheric neutrinos)
  - Reactor neutrinos

Schematic view of Gd loading to Super-K

Amount of dissolved Gd



Current status

- Gd loading towards 0.02% $Gd_2(SO_4)_3$ concentration was performed from July to August 2020.
  - About 50% of neutron would be captured by Gd, enhancing neutron tagging efficiency by 2-3 times.
  - Final target: 90% of neutron tagging
- Now, SK-Gd is in commissioning phase.

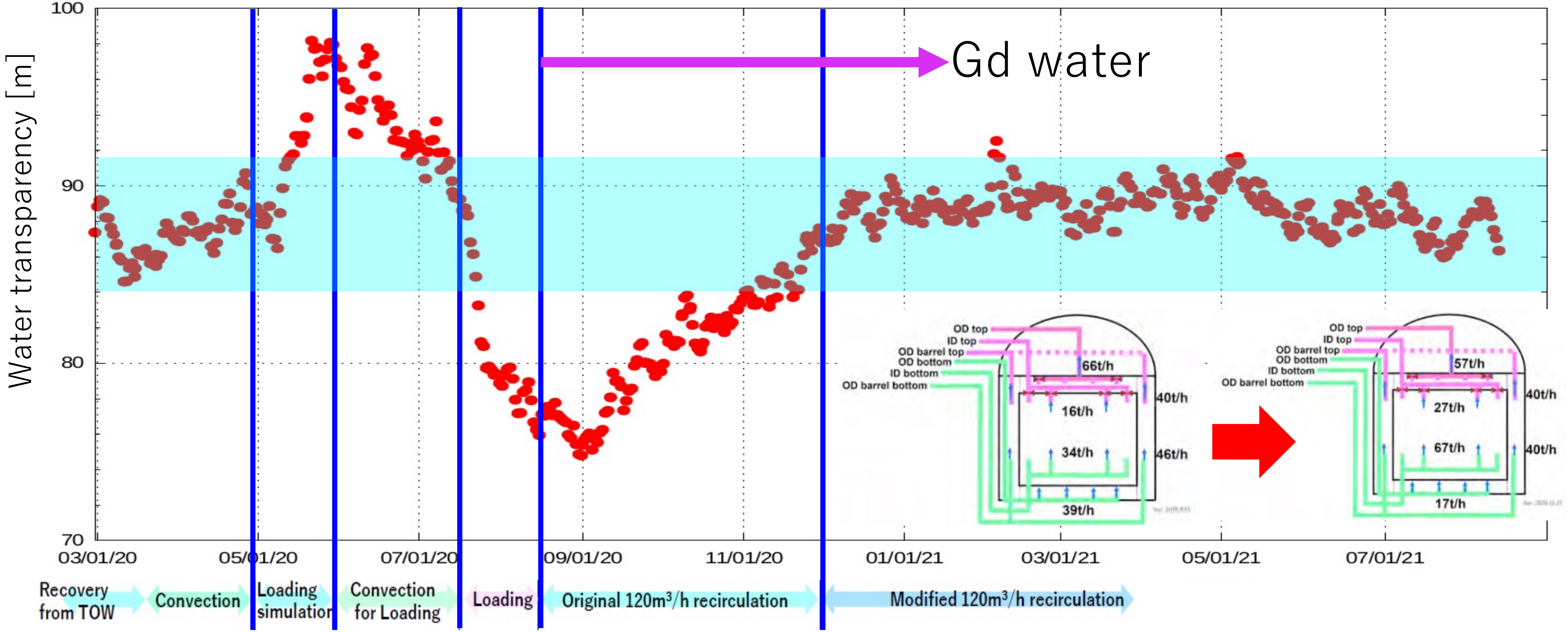
Figures are taken from: http://www-sk.icrr.u-tokyo.ac.jp/sk/news/2020/08/sk-gd-detail-e.html

Detector status

- Water transparency
- Gd concentration uniformity
- Neutron tagging check by AmBe source

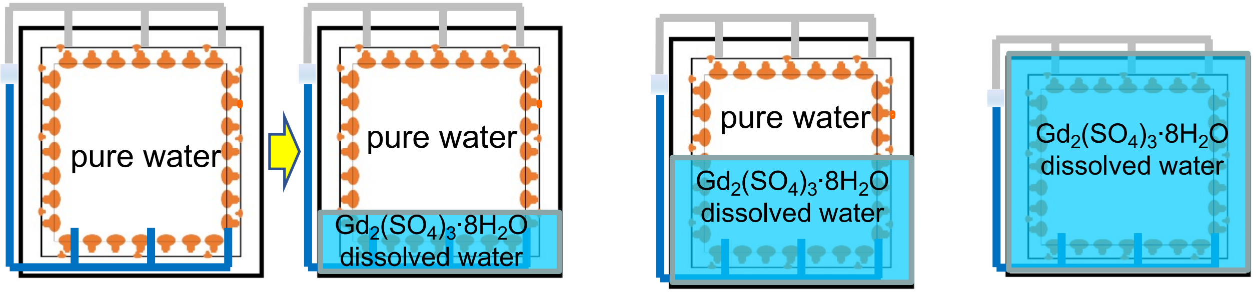
Water transparency

Light attenuation length measured with cosmic muons



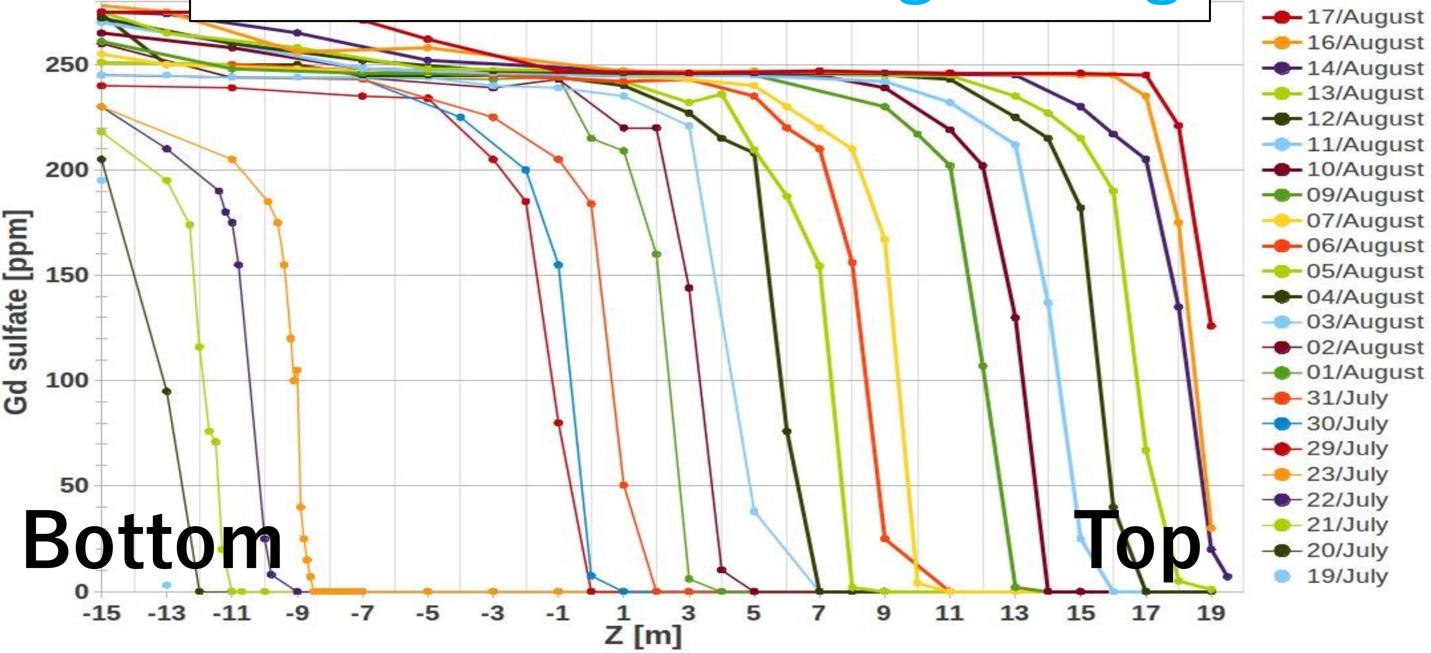
Stable water transparency has been recovered few month after the loading

Gd concentration in SK tank

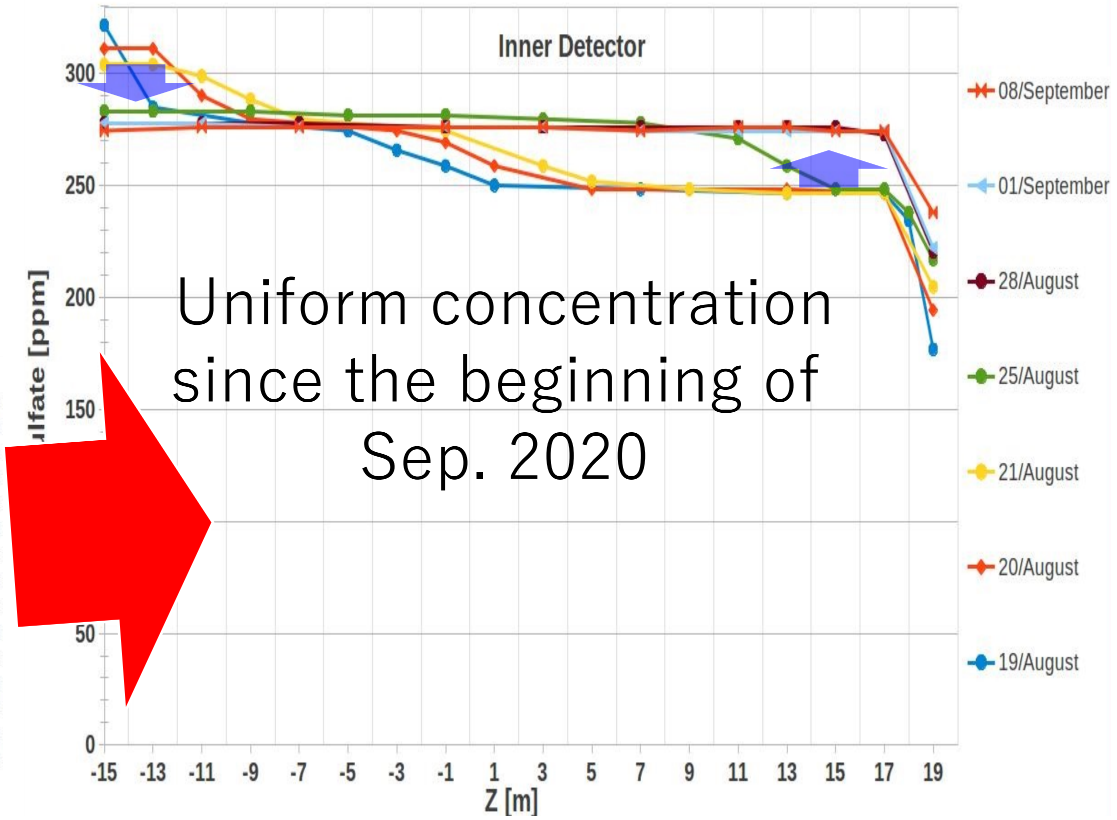


Suck pure water from top, dissolve Gd, and supply cold Gd water from the bottom of SK.

Gd concentration **during loading**



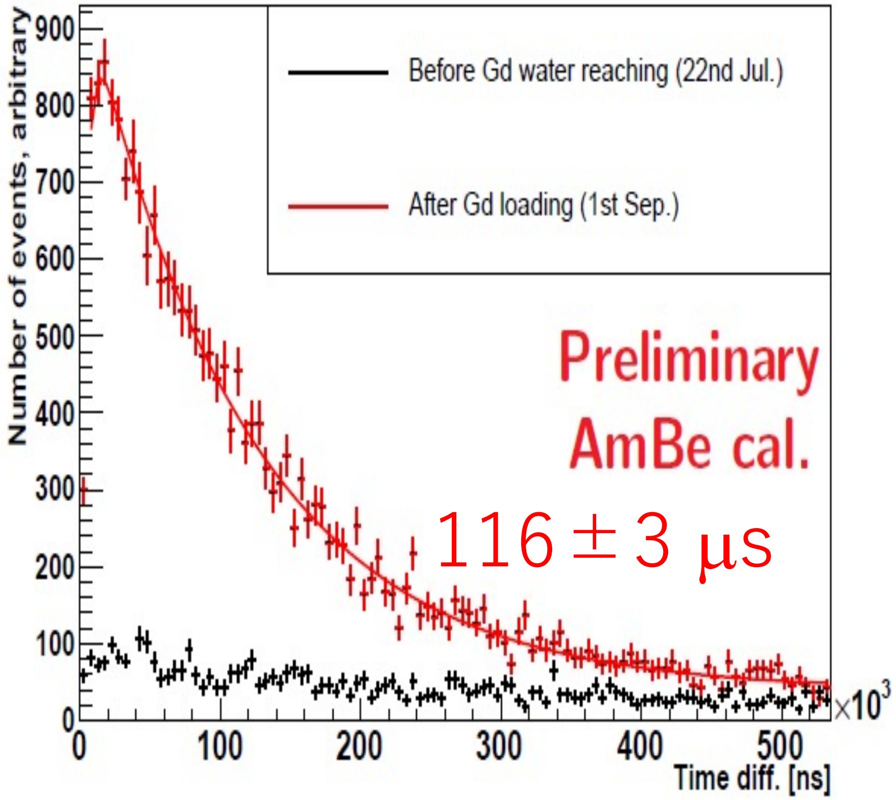
Gd concentration **after loading**



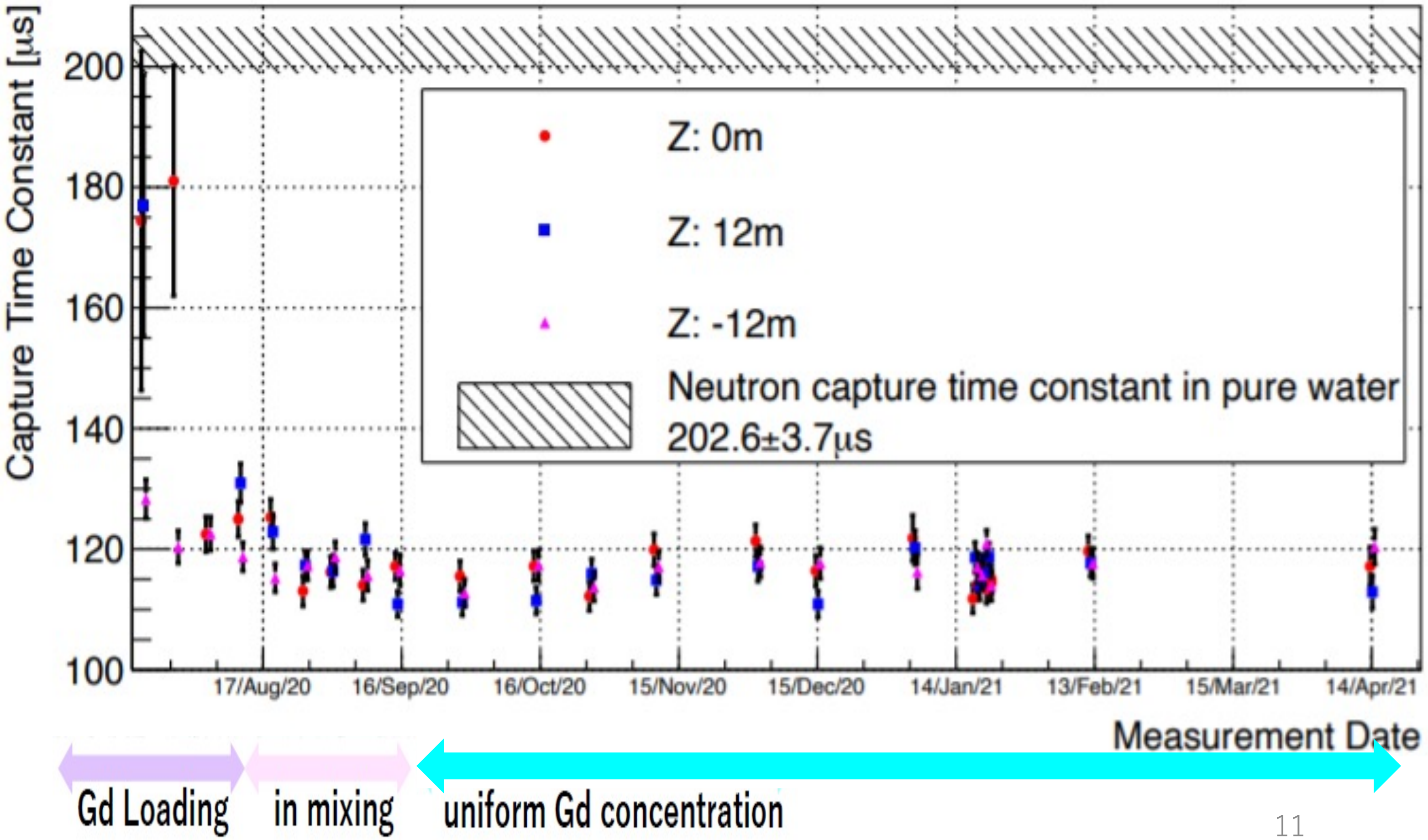
Uniform concentration since the beginning of Sep. 2020

Gd uniformity check by AmBe

- Calibration with Am/Be : neutron + 4.4 MeV gamma-ray source
- Neutron capture signal after gamma-ray is obtained
- Expected time constant at 0.01% Gd concentration : **116 μ sec**

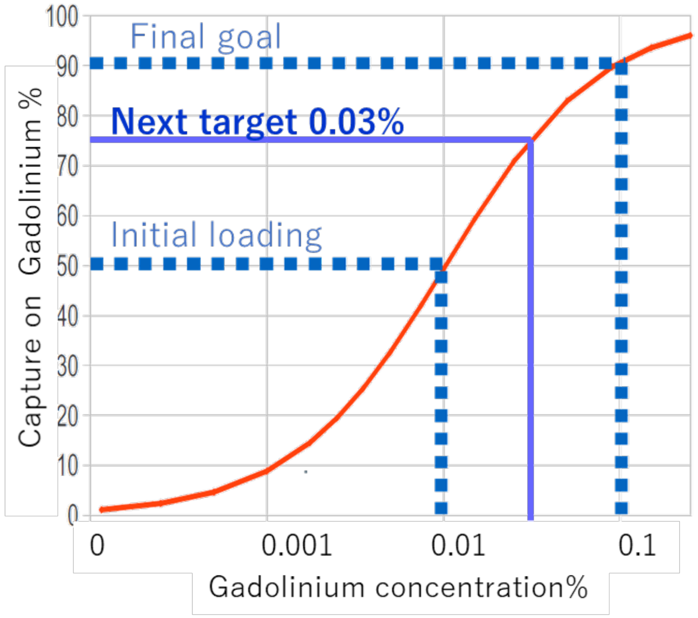


Preliminary

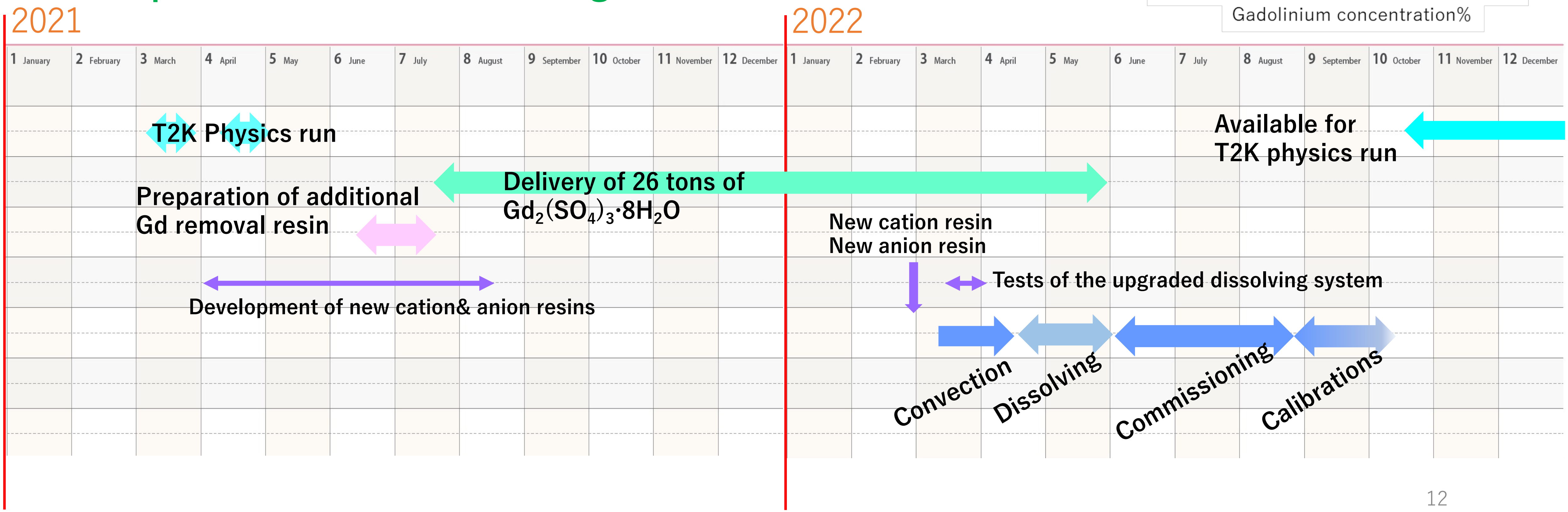


Plans

- Aiming to dissolve up to ~26 tons of additional $Gd_2(SO_4)_3{\cdot}8H_2O$ in 2022
  - Target Gd concentration: 0.03% (Currently 0.01%)
  - Gd capture efficiency: 75% (Currently 50%)

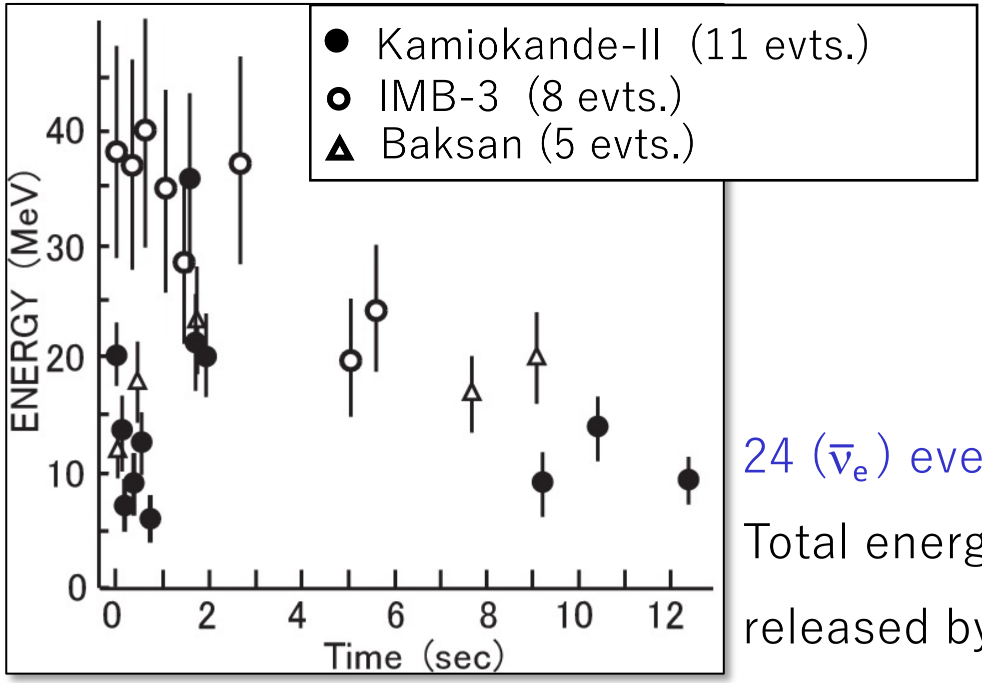


Current plan for the next Gd-loading



Supernova neutrinos from 1987A

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

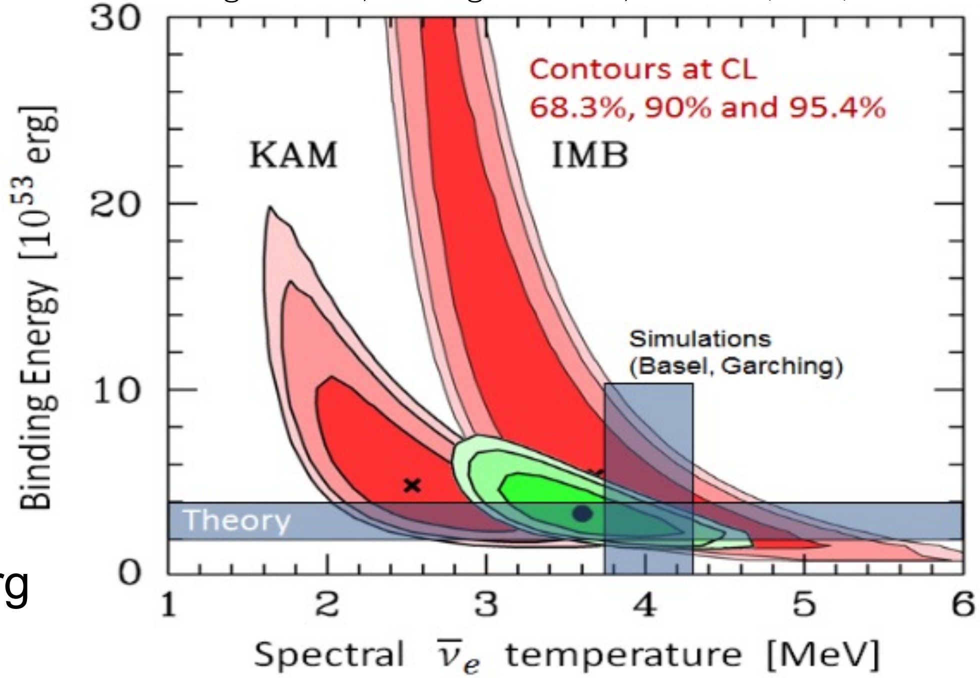


24 ($\overline{\nu}_e$) events in total.

Total energy

released by $\overline{\nu}_e$: ~5x10^{52} erg

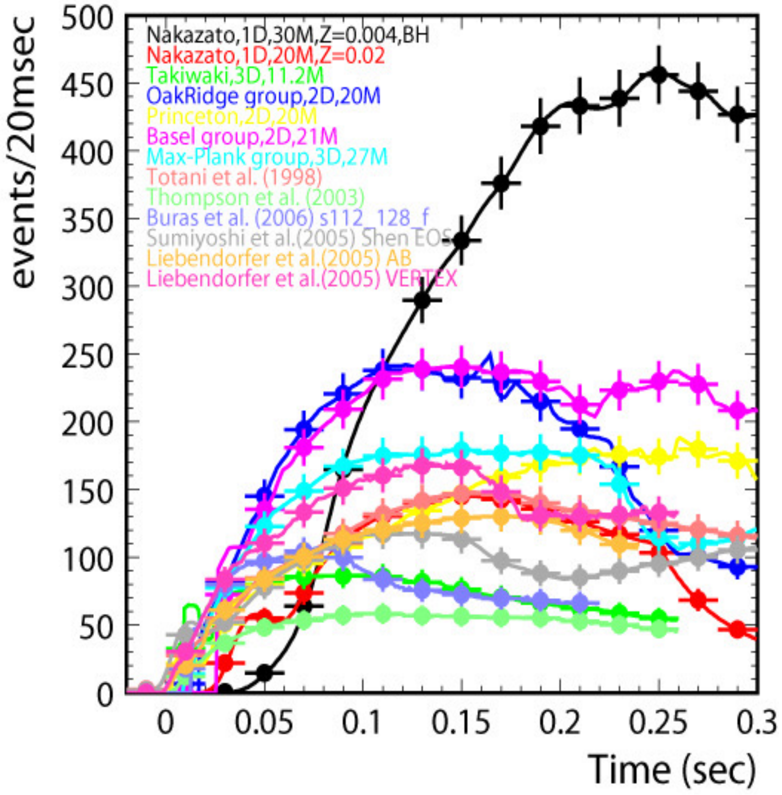
Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194



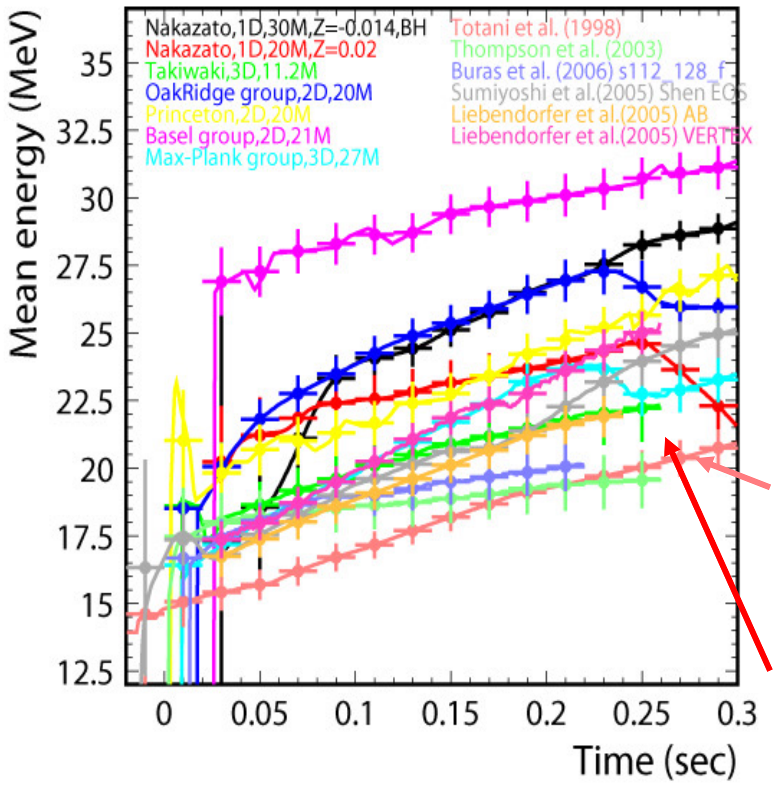
- The obtained binding energy is almost as expected, but large error in neutrino mean energy. No detailed information of burst process.
- We need energy, flavor and time structure.
- Supernova will be most interested target for Multi-messenger measurement with SK.

Many models today. Need data!

Time variation of event rate



Time variation of mean energy



SN at 10 kpc, Super-K

	Totani1998	Nakazato
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

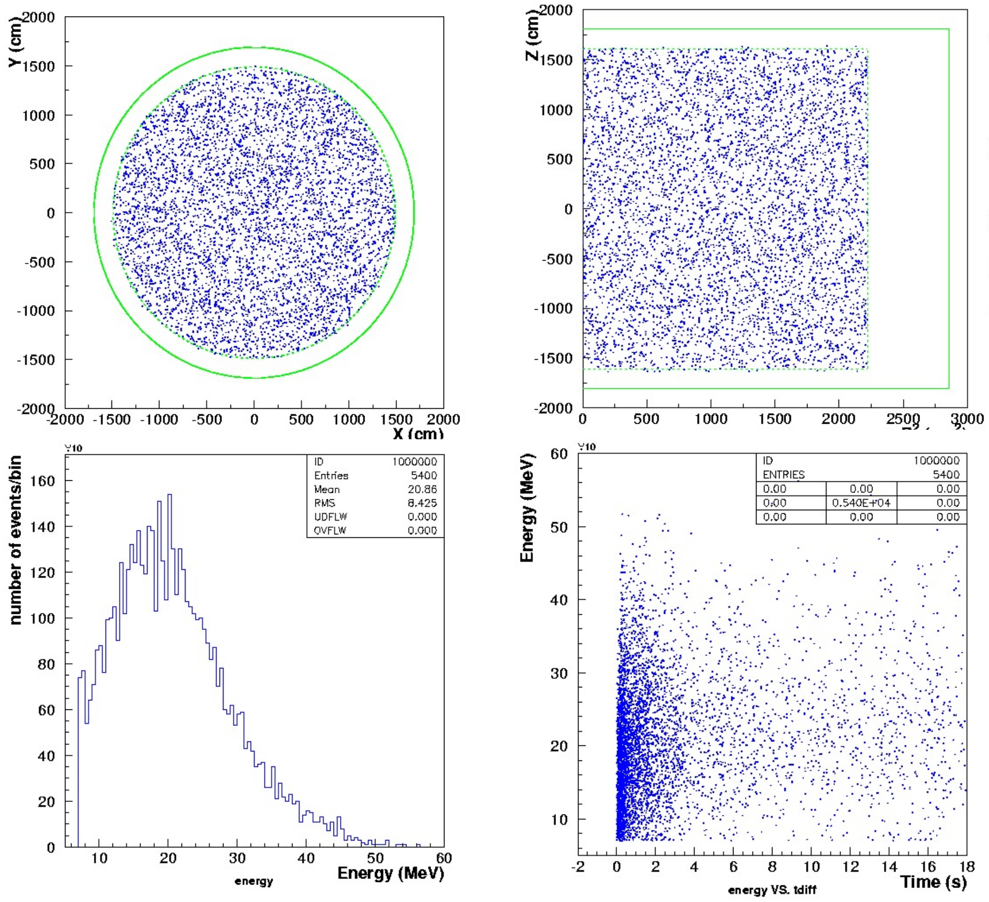
"Totani1998" as a reference

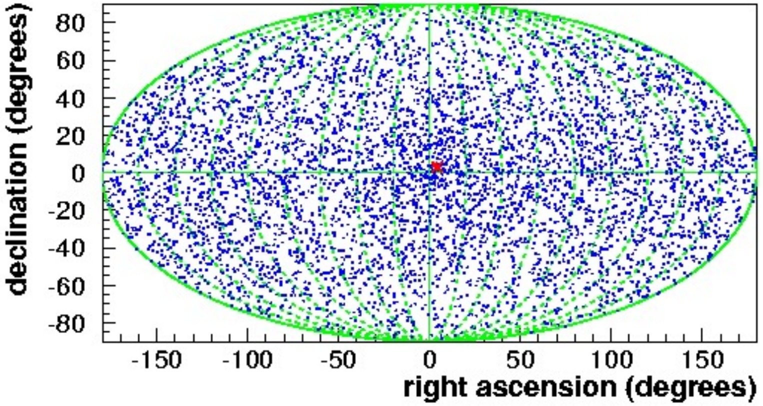
"Nakazato" as a reference

- Recent multi-dimensional supernova simulations successfully reproduce SN explosion.
  - Several explosion mechanism (SASI, Rotation, Convection), EOS (soft/hard SN core)
- Difficulty: Neutrino oscillation in high density
  - MSW effect in much much higher density than that in SUN!, Collective effect (oscillation)

What if SN happens now? @Super-K

- **SK's directional information is important for optical telescopes in the multi-messenger astronomy era.**
- SNwatch: Real-time supernova neutrino burst monitor   Astropart. Phys. 81(2016)39
  - In several minutes plots are generated automatically and auto-emails+ auto-phone calls follow





- Golden Alarm (Definition):
  - 60 events in 20sec
- The process time depends on the events
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  - Quicker alert system is needed for covering type Ib/Ic stars.

SN simulation @10kpc, Wilson (Totani1998) model

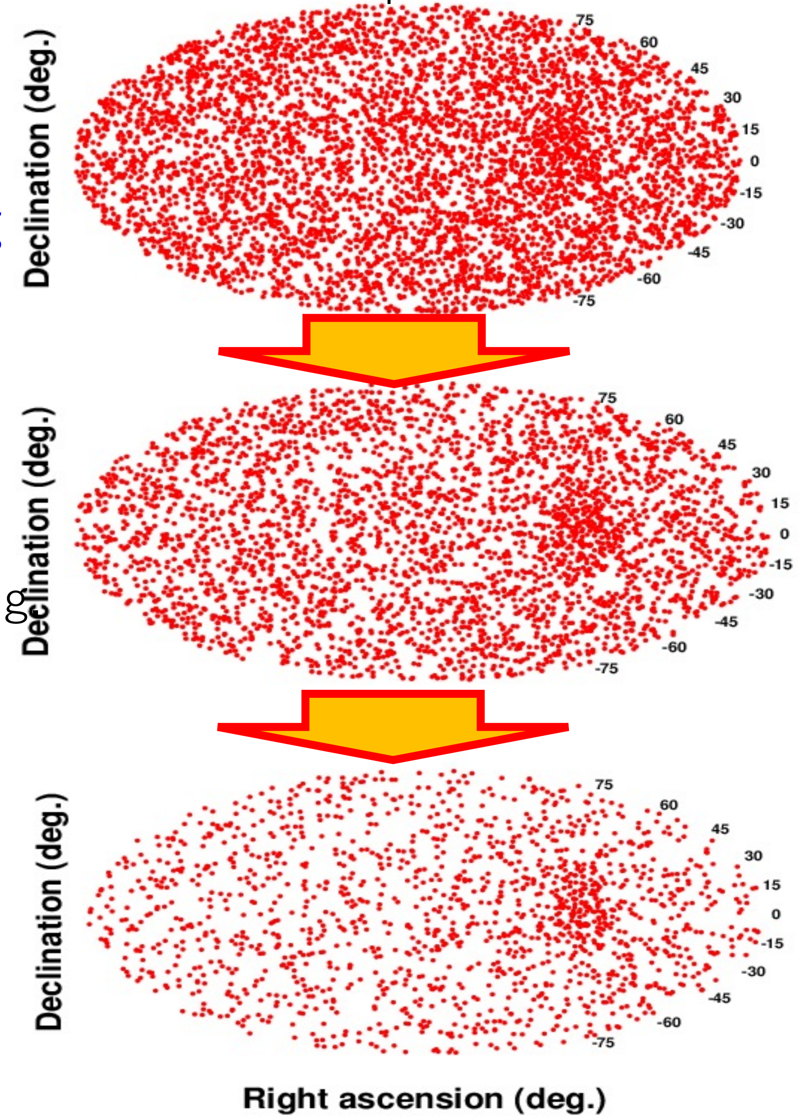
Expected improvement of SN pointing accuracy

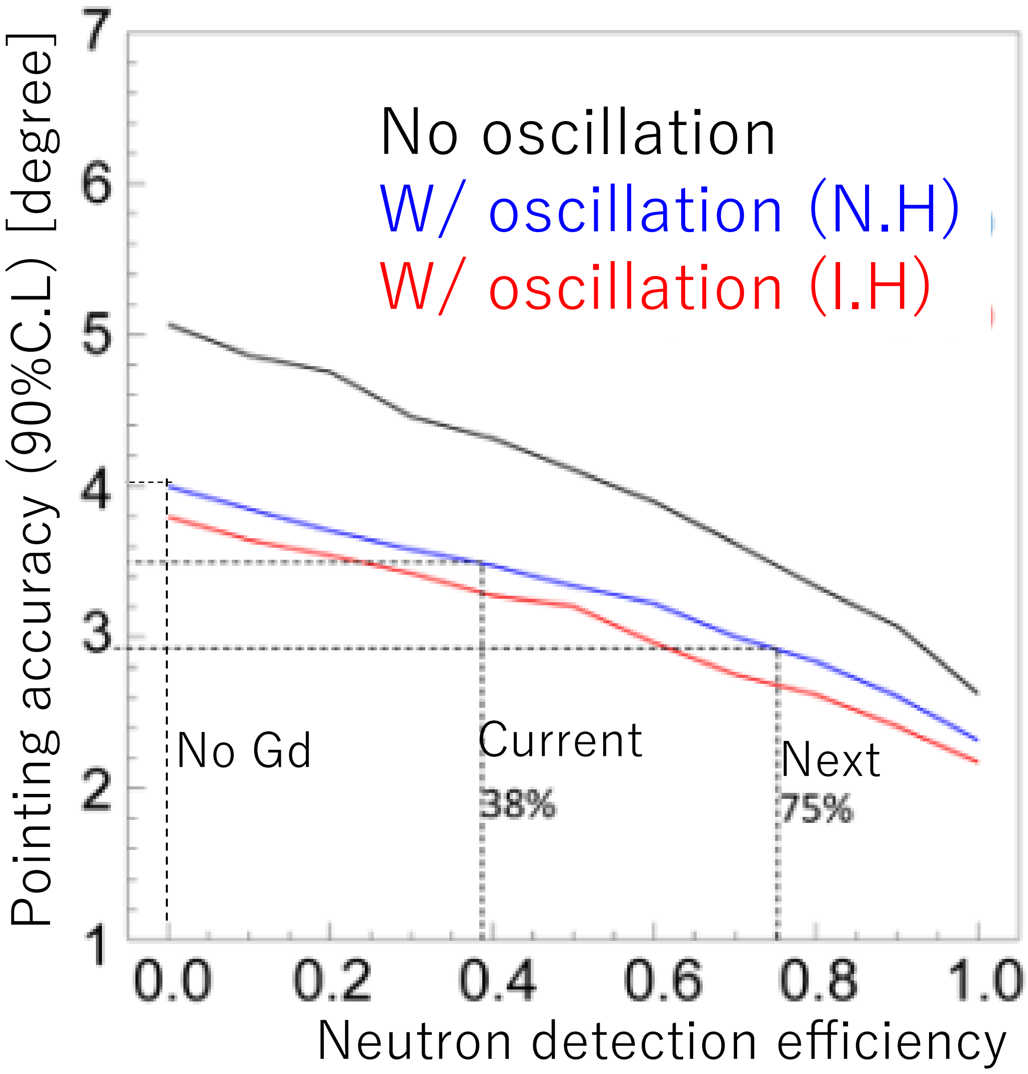
10kpc SN

No Gd
Pointing accuracy at 10kpc SN :4deg (N.H case)

Current 3.5deg
(0.01%Gd,
Search for delayed signal with current trigger threshold)

Next 2.9 deg
(0.03%Gd,
lowering threshold)





Aiming to improve the accuracy to < 3 degree after the next loading

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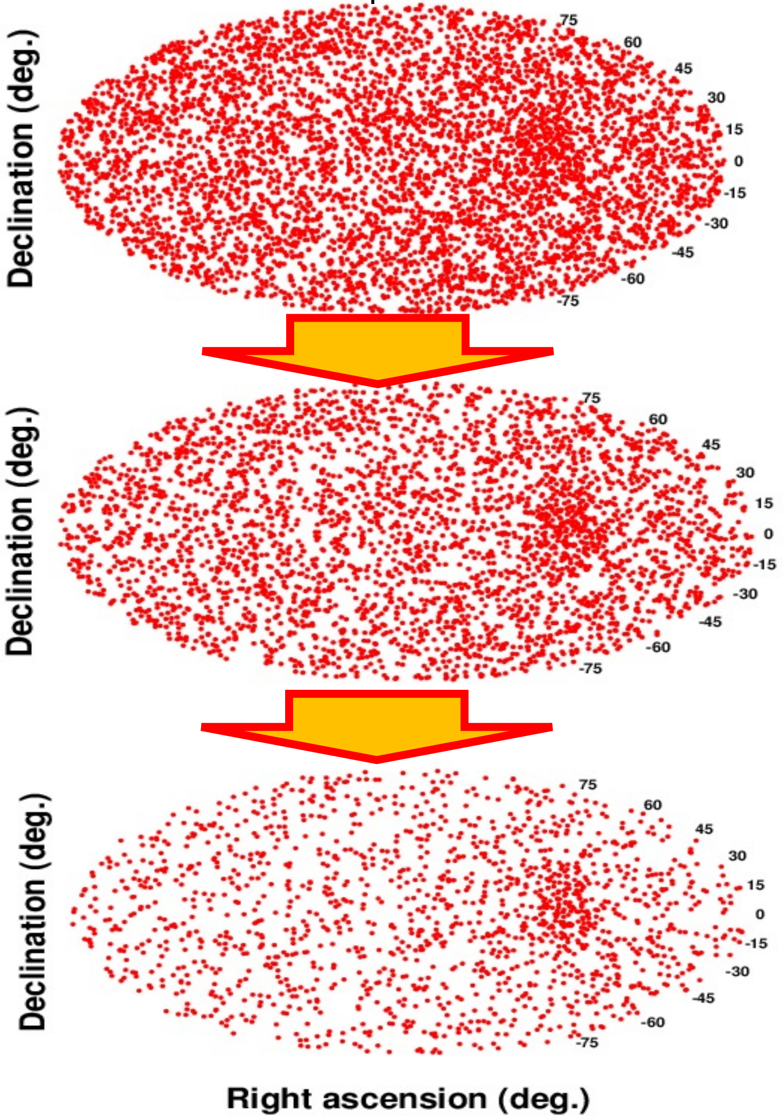

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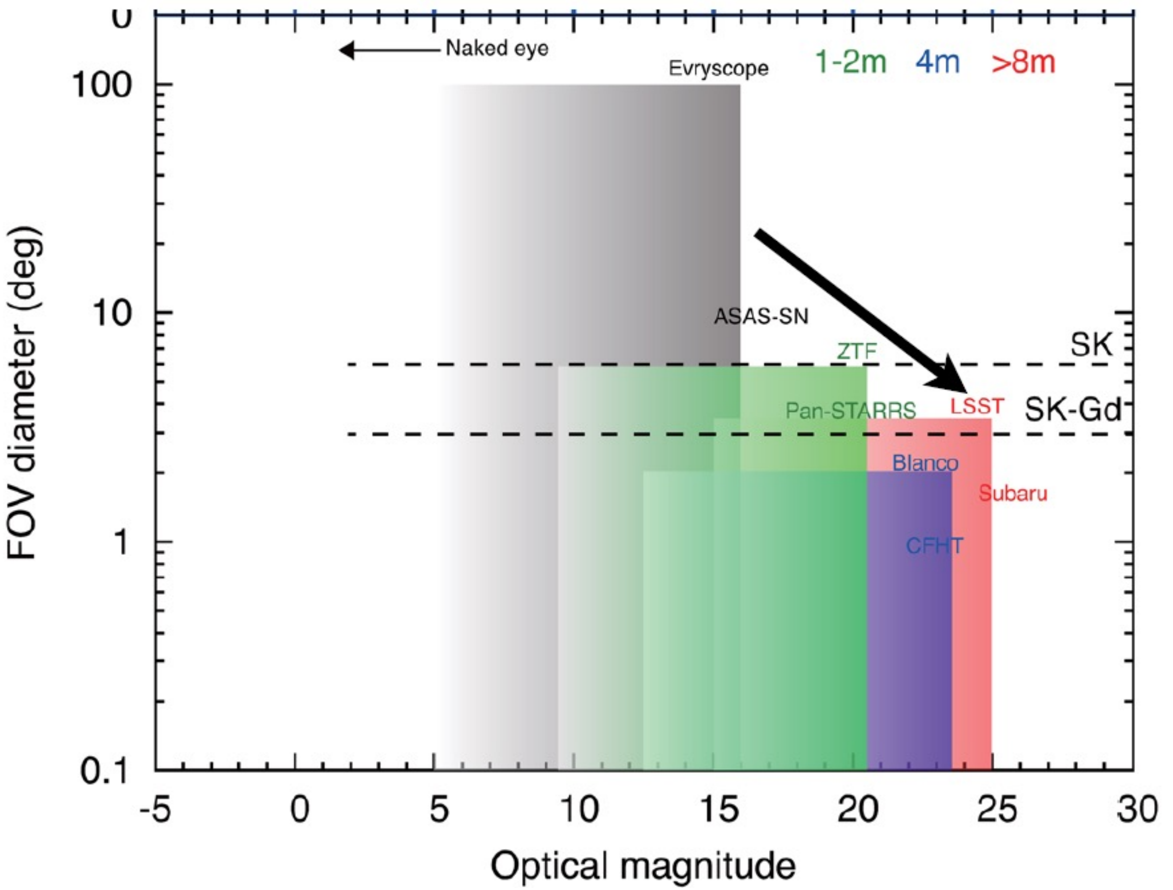
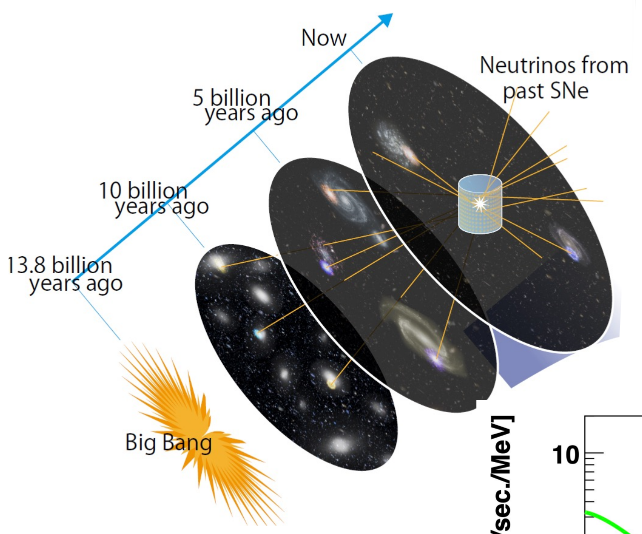
Nakamura, Horiuchi et al., MNRAS, 461, 3296 (2016)

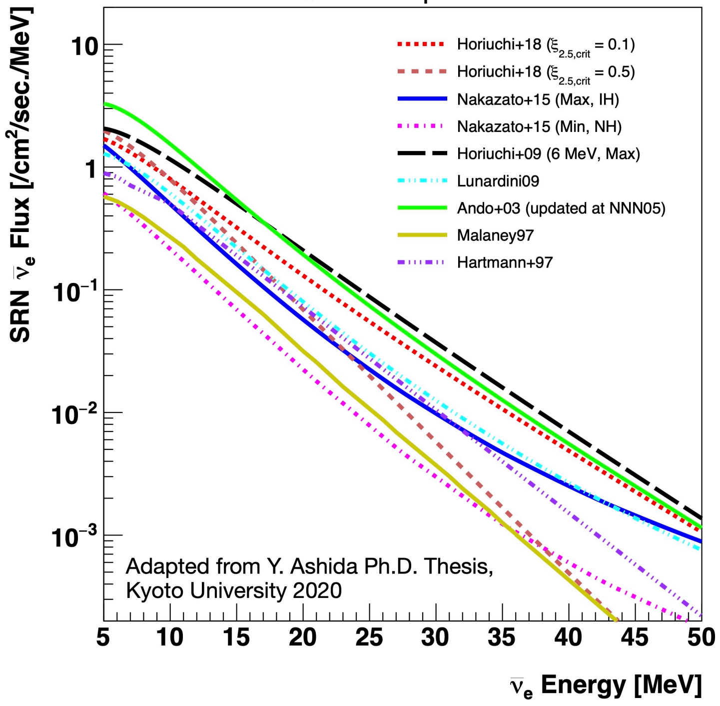


Aiming to improve the accuracy to < 3 degree after the next loading

Diffused Supernova Neutrino Backgrounds
Supernova Relic Neutrino



DSNB flux predictions



- **Neutrinos produced from the past SN bursts and diffused in the current universe.**
  - ~ a few SN explosions every second → O(10^{18}) SNe so far in this universe
  - Can study history of SN bursts with neutrinos

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

Physics of DSNB (SRN)

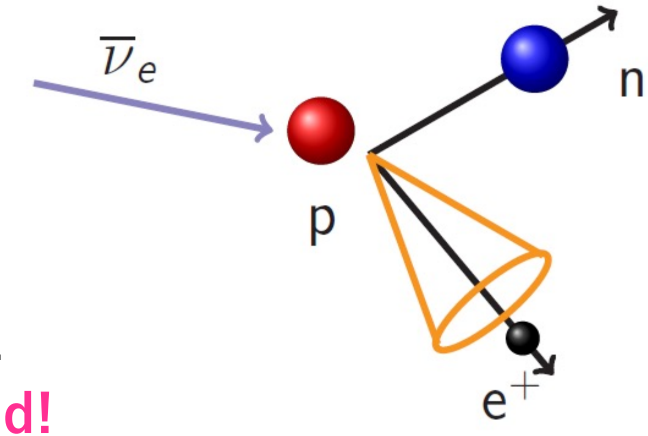
- Test of star formation rate
  - Factor ~2 discrepancy between rates of formations and SNe.
- Energy spectrum of SN burst neutrinos
  - Temperature inside the SN
- Extraordinary SN
  - BH formation, dim supernova

DSNB signal in SK

- Inverse beta decay channel is the probe for DSNB.
- Super-K holds the current best limits for the DSNB flux.
- Sensitivity limited by backgrounds
  - However, only one order magnitude above theoretical predictions.

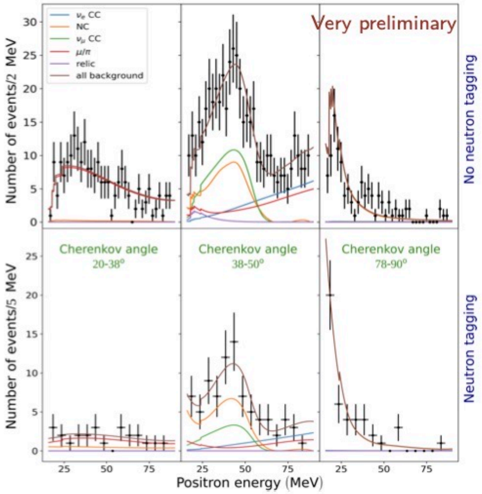
  → (High efficiency and low background) Neutron tagging with Gd!

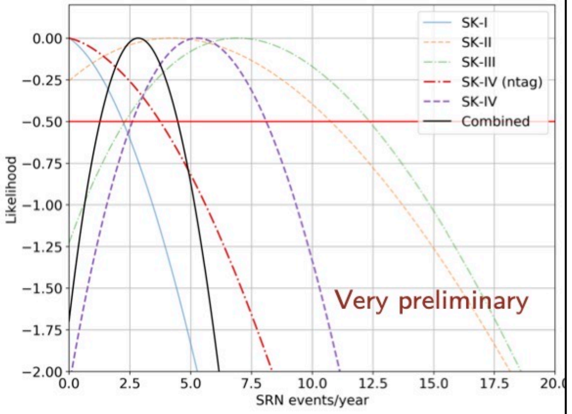
Inverse beta decay channel



Combination of SK-I to IV for the Ando (optimistic) model

S. Hedri, ICHEP 2020





- Slight excess at low energy without neutron tagging
- Current 90% C.L. limits on the Ando model flux (1.7 cm^{-2}/s):

SK-IV (no neutron tagging) : $\Phi_{90} = 4.9\ cm^{-2}/s$

SK-IV (neutron tagging): $\Phi_{90} = 3.8\ cm^{-2}/s$

Combined (22.5 × 2853 kton.day) : $\Phi_{90} = 2.7\ cm^{-2}/s$

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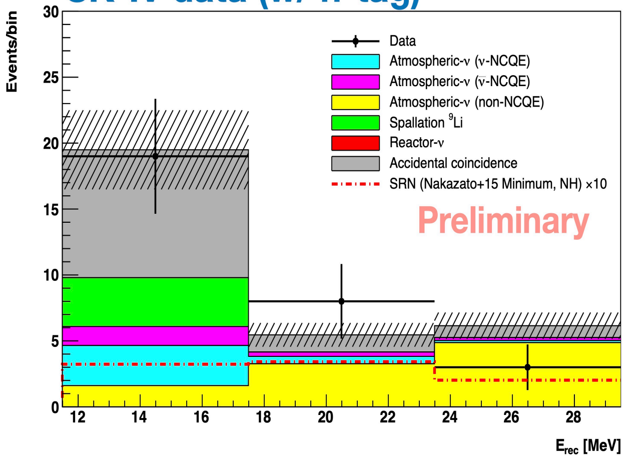
SK-IV data (w/ n-tag)



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

E_ν region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	9.48	1.35	0.82
SK-IV 2970 days (Observed)	9.08	2.22	0.35
Horiuchi+18 ($\xi_{2.5,crit}$ = 0.1)	1.583	0.553	0.173
Horiuchi+18 ($\xi_{2.5,crit}$ = 0.5)	1.108	0.252	0.050
Nakazato+15 (Maximum, IH)	0.798	0.236	0.081
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Lunardini09	1.032	0.321	0.098
Ando+03 (updated at NNN05)	2.652	0.796	0.261
Malaney97	0.469	0.125	0.034
Hartmann+97	0.947	0.297	0.093

□: Models within a factor of 3

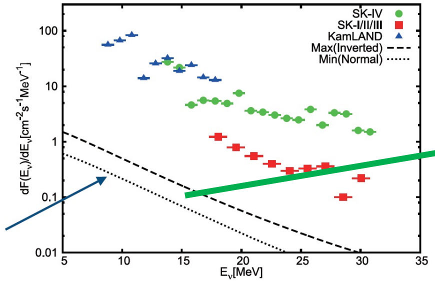
- No significant excess found
- Set one of the most stringent limits above 13.3 MeV
- Many model predictions are within several factors from the current limit
- Sensitivity limited by small statistics and backgrounds

→Will be significantly improved with better neutron tagging in SK-Gd

Nakajima, Neutrino 2020

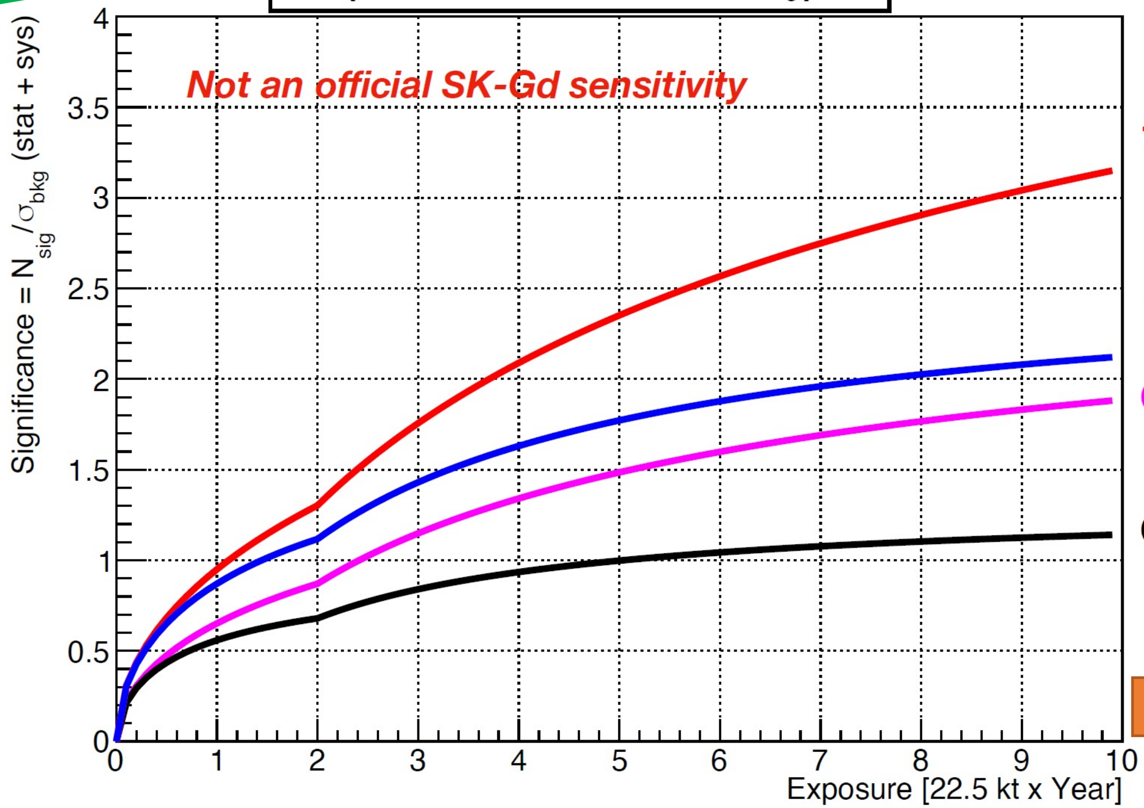
DSNB sensitivity

- Assuming neutron tagging efficiency increased to >70% in 2022



Theoretical predictions

Tν ~6MeV case



Sekiya, TMEX 2020

Summary

- The first loading of Gd sulfate was done in summer 2020
- SK detector status after the first Gd loading:
  - Water transparency is good and stable
  - Gd concentration is uniform and stable
  - Aiming for the first observation of Diffuse Supernova Neutrino Background in 10 years.

- More Gd will be added in the next year
  - Target is 0.03% Gd concentration
    - Capture efficiency by Gd will be 75%
  - Low RI Gd sulfate production for the next loading has been started
  - Supernova detection
    - Better pointing accuracy (< 3degree) with 0.03% Gd concentration

Supernova neutrinos from 1987A

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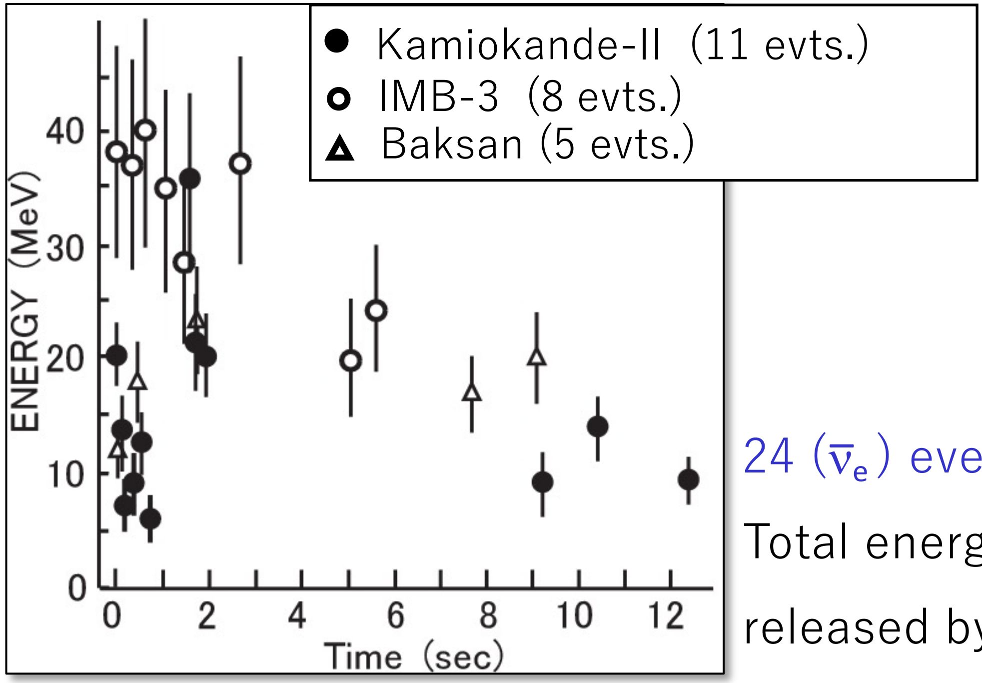

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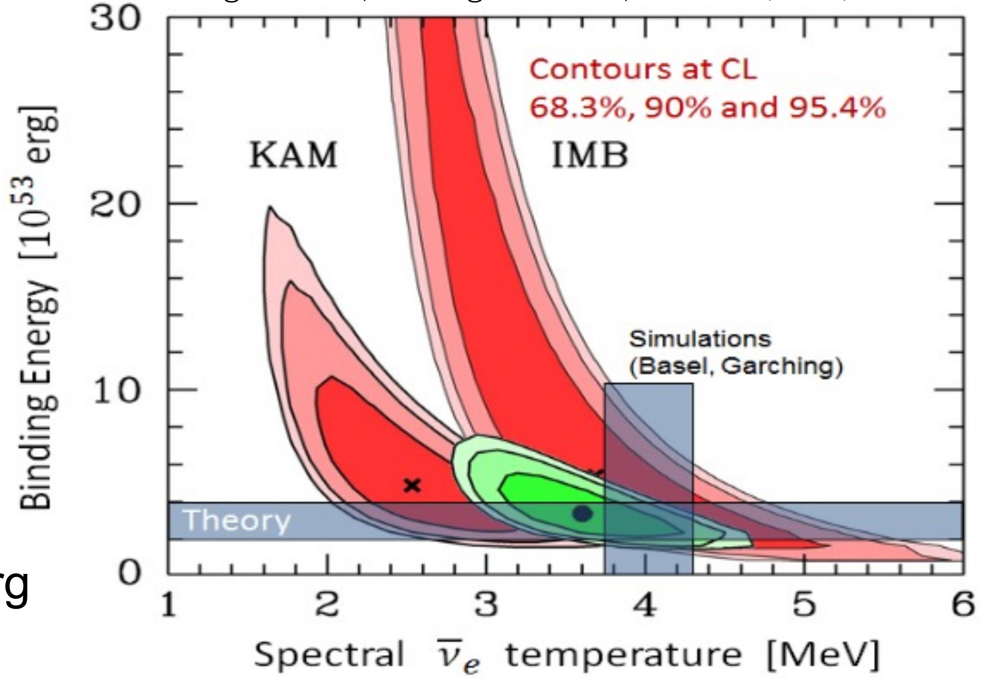

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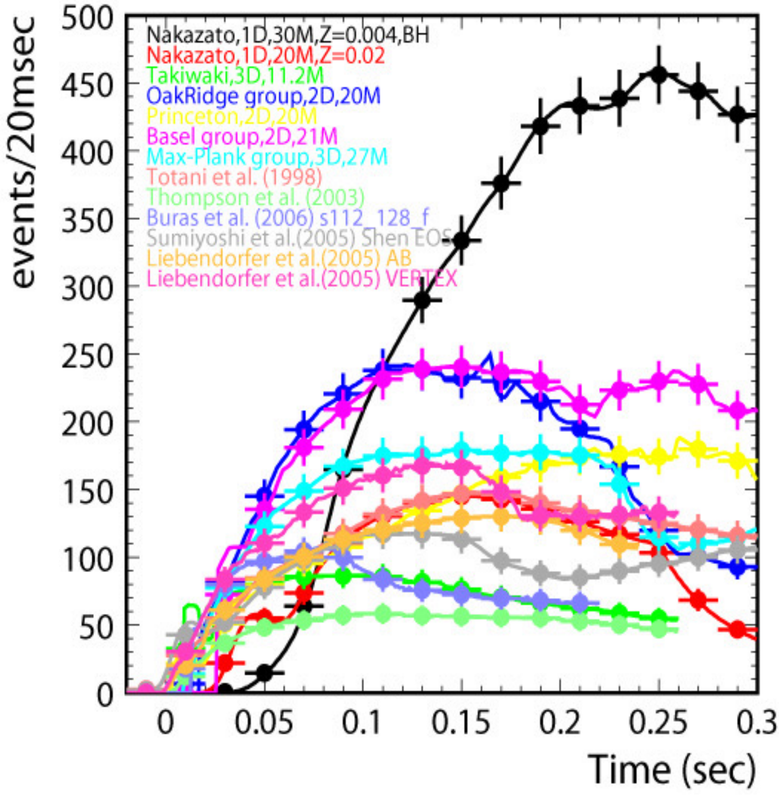

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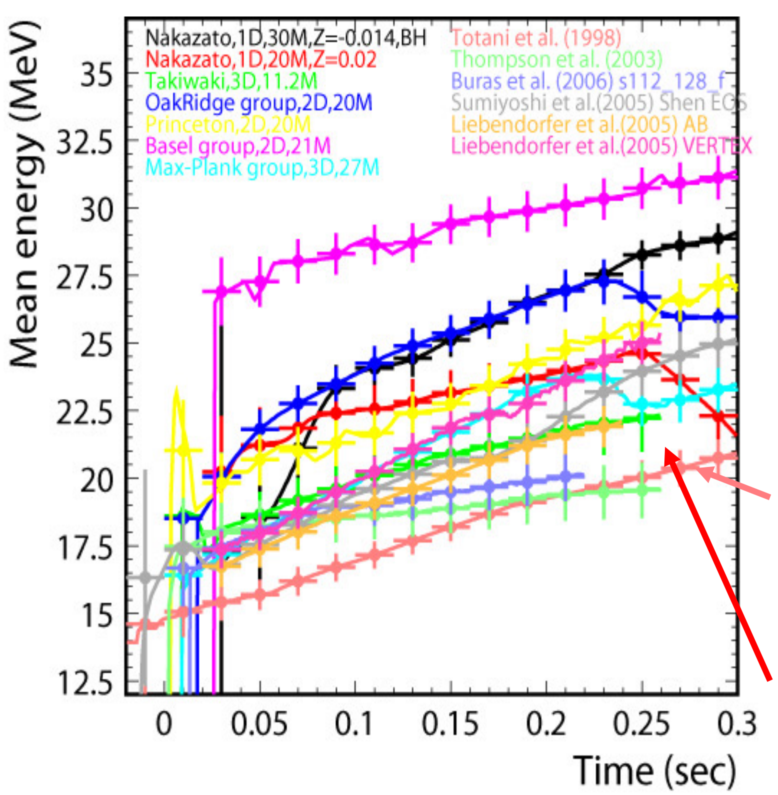

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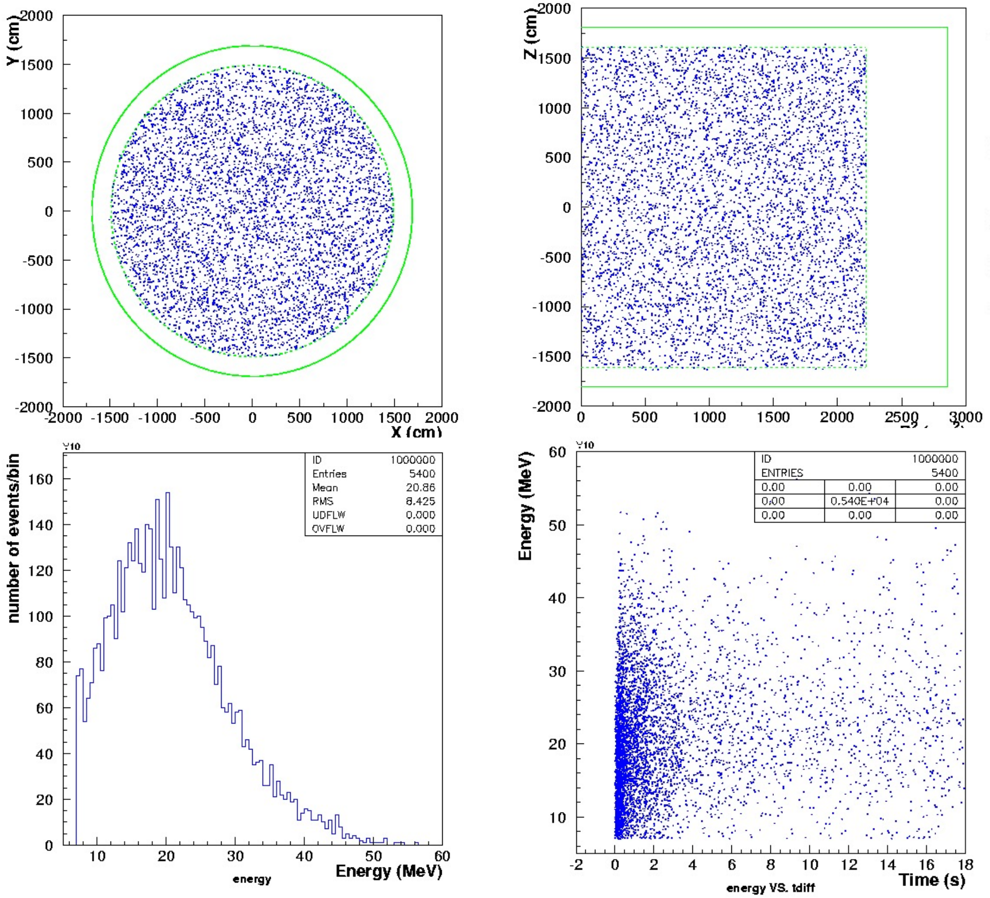

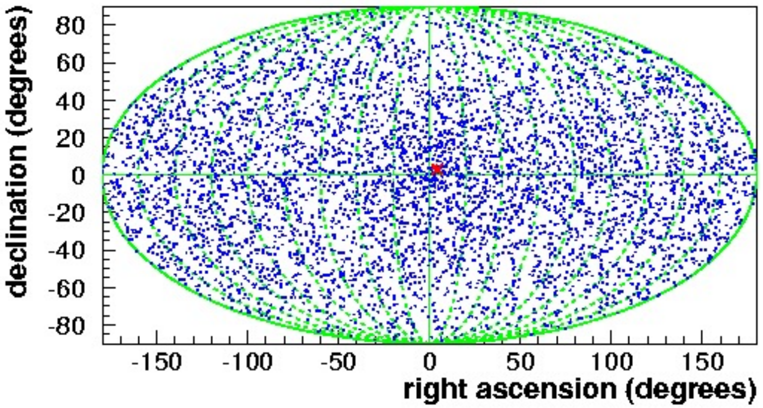

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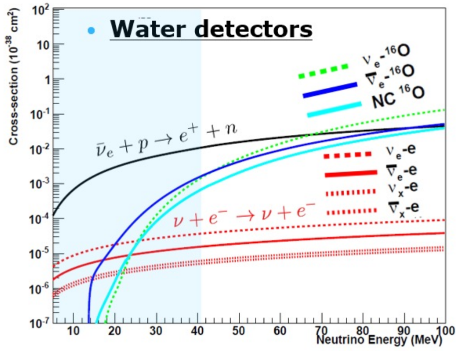
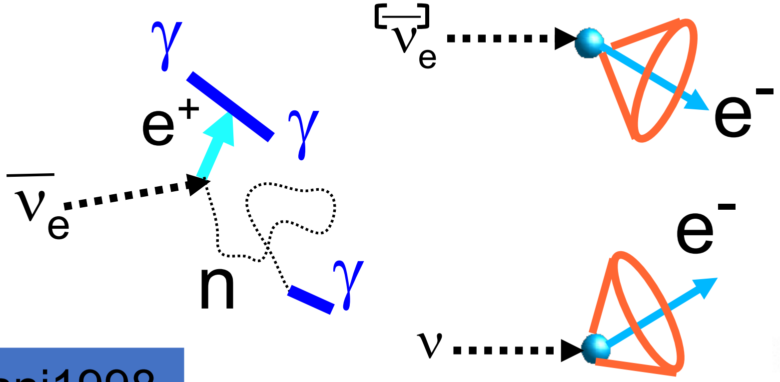
Pointing accuracy

- Advantage of WC detectors
  - Inverse beta events are useless
  - Excess of elastic scattering events

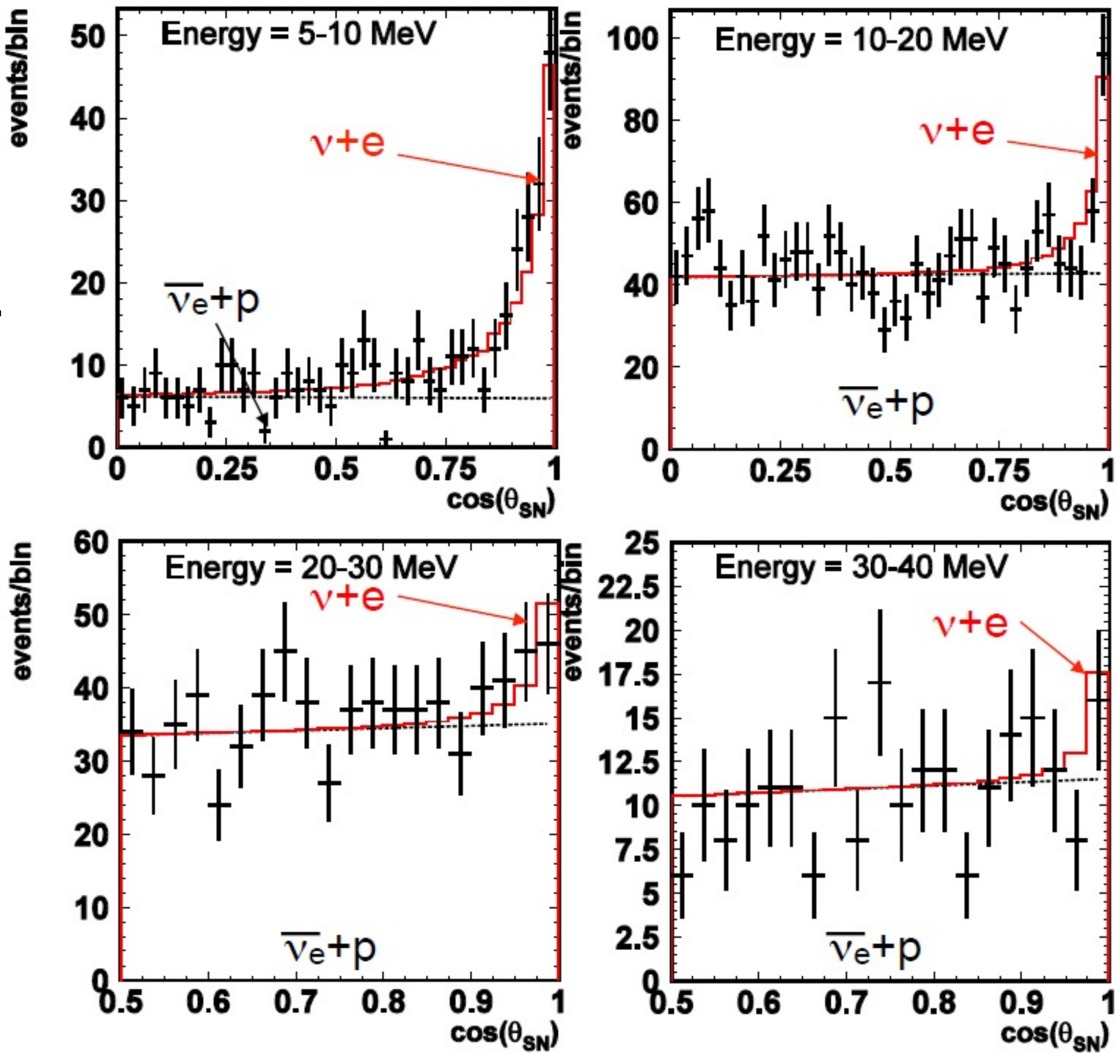




	Totani1998
$\bar{\nu}_e p \rightarrow e^+ n$	7300
$\nu + e^- \rightarrow \nu + e^-$	320
^{16}O CC	110

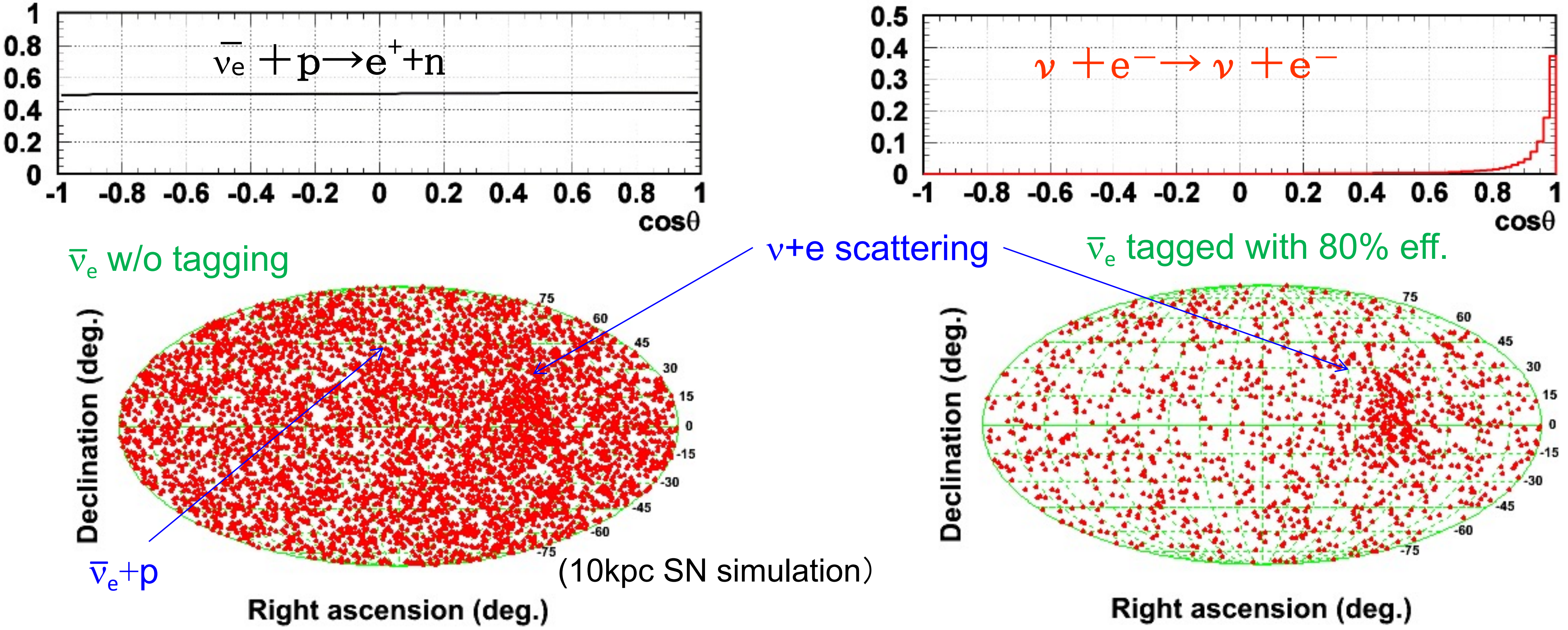
- BG reduction by neutron tagging
  - → SK-Gd

Pointing accuracy ~5° @10kpc SN



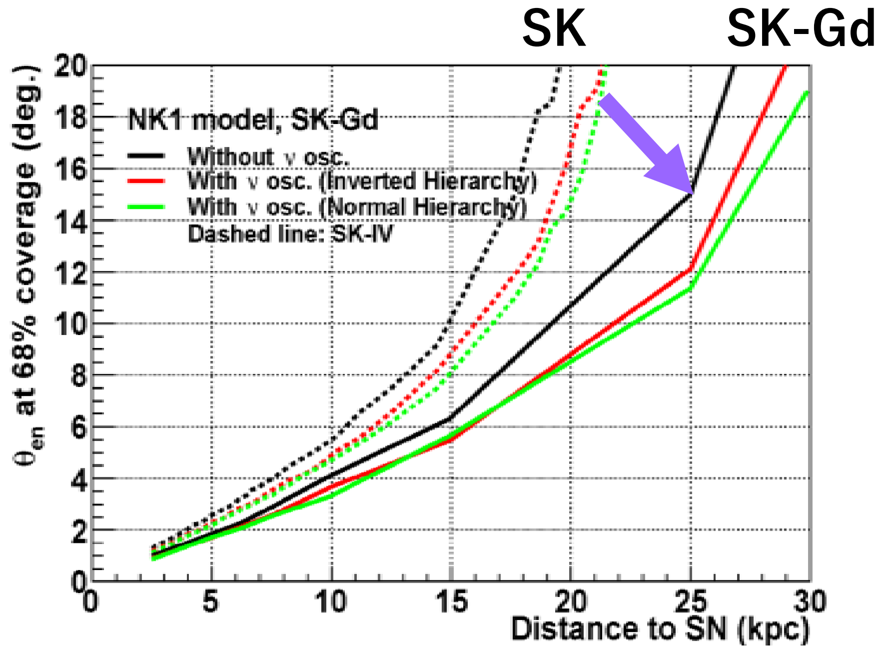
SK-Gd pointing accuracy

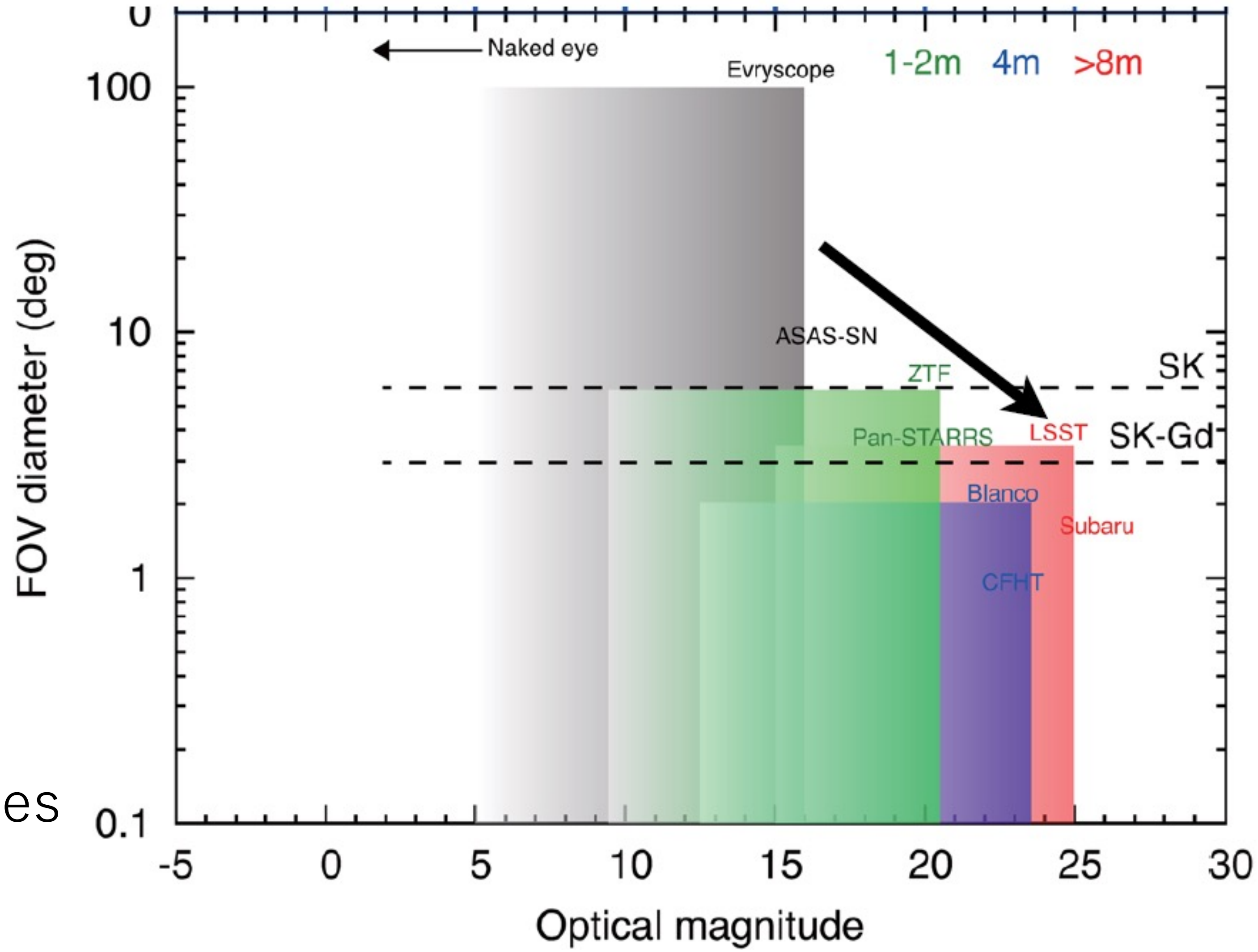
- $\bar{\nu}_e$ events can be tagged and rejected, and directional events (ν_e+e scattering events) are enhanced.



Impact of SK-Gd

Nakamura, Horiuchi et al., MNRAS, 461, 3296 (2016)





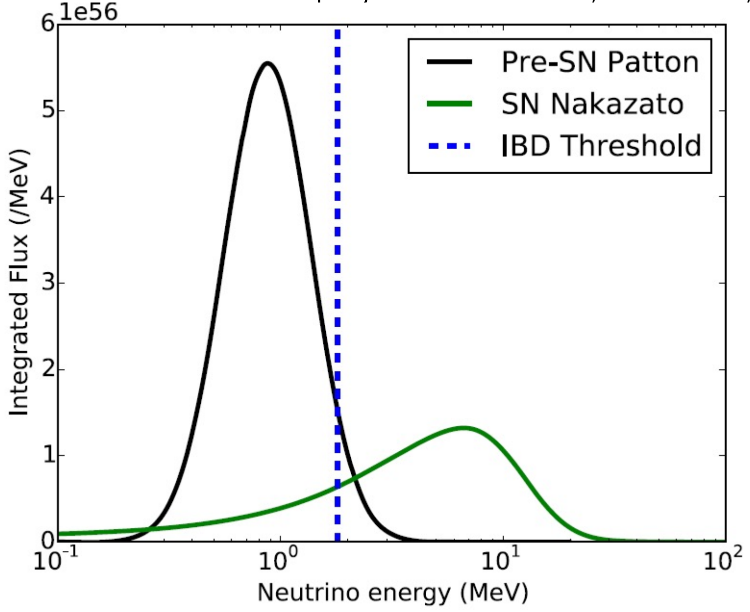
For 10kpc SN ~5° → ~3°

- Pointing in 3° accuracy will allow the follow-up with large telescopes
- Please note that our definition is one-side angle. (half of FOV)

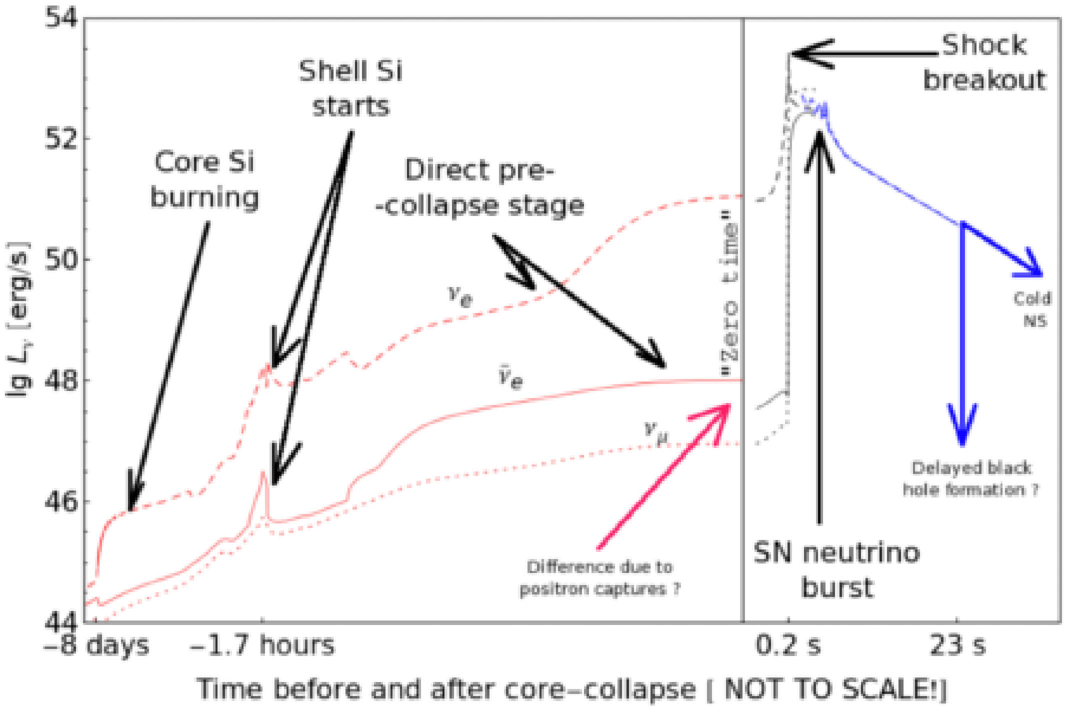
Pre-supernova signals

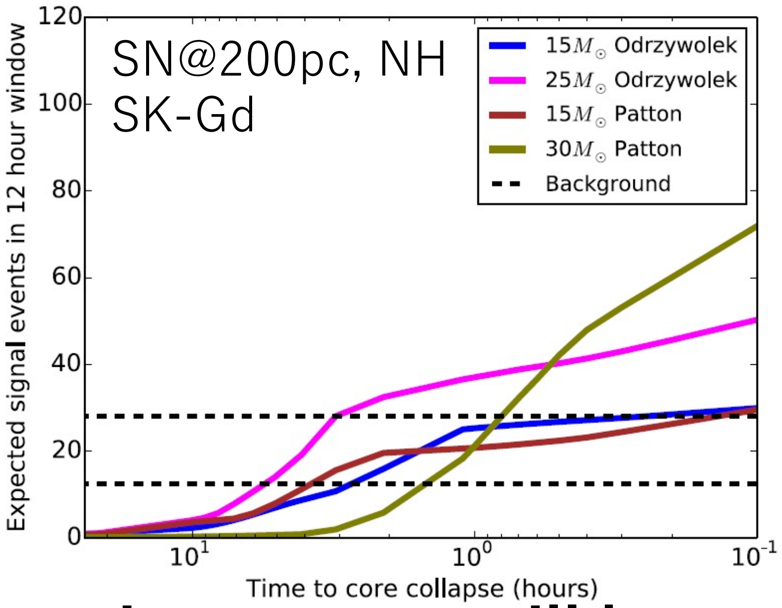
- Precursor signal from Si-burning is detectable with SK-Gd
  - Pre-SN’s ν energy is lower than SN’s
  - Gd loading is essential.

The Astrophysical Journal, 885:133, 2019



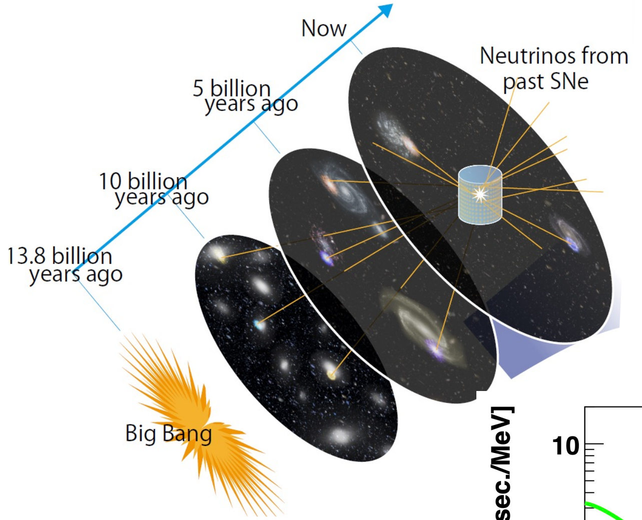
Odrzywolek & Heger, 2010



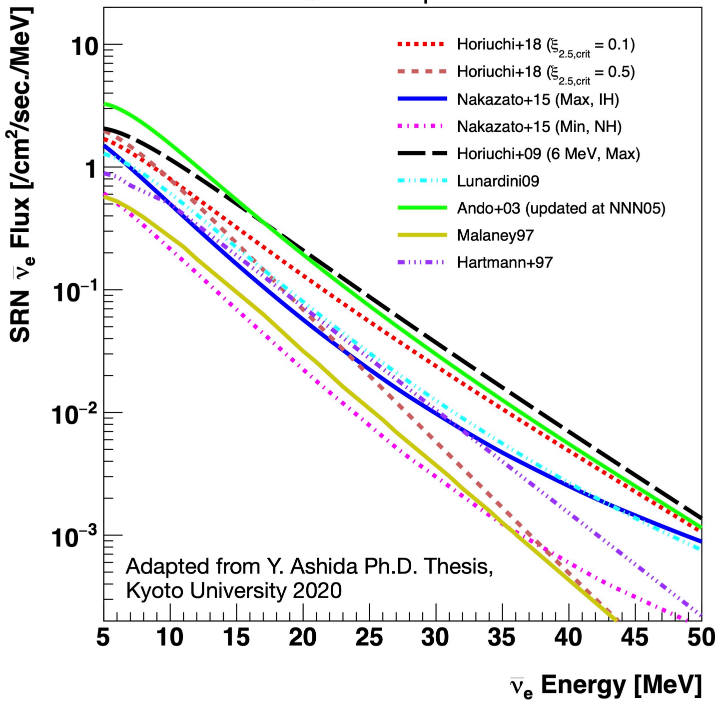


Early warning system will be prepared.

Diffused Supernova Neutrino Backgrounds
Supernova Relic Neutrino



DSNB flux predictions



- **Neutrinos produced from the past SN bursts and diffused in the current universe.**
  - ~ a few SN explosions every second → O(10^{18}) SNe so far in this universe
  - Can study history of SN bursts with neutrinos

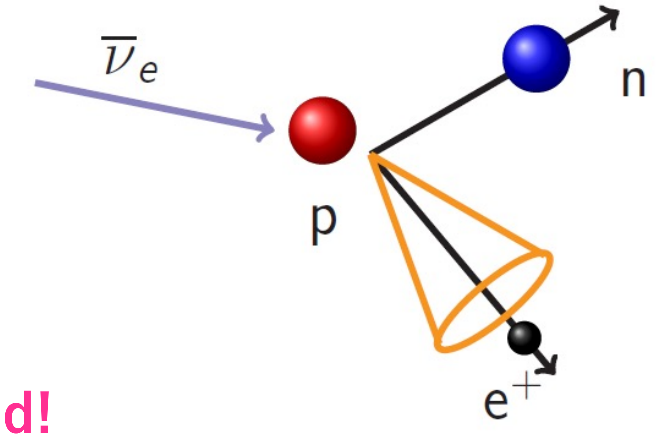
$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z\mathrm{max}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

Physics of DSNB (SRN)

- Test of star formation rate
  - Factor ~2 discrepancy between rates of formations and SNe.
- Energy spectrum of SN burst neutrinos
  - Temperature inside the SN
- Extraordinary SN
  - BH formation, dim supernova

DSNB signal in SK

Inverse beta decay channel

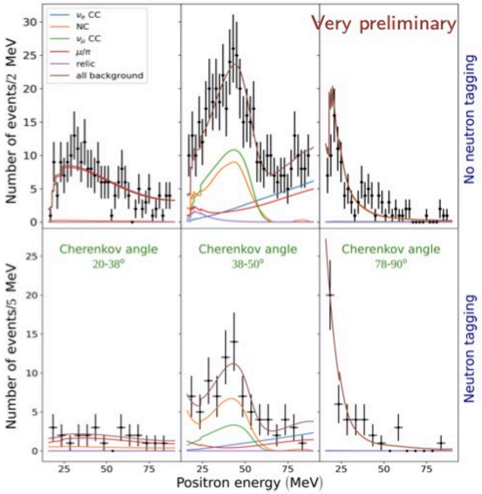


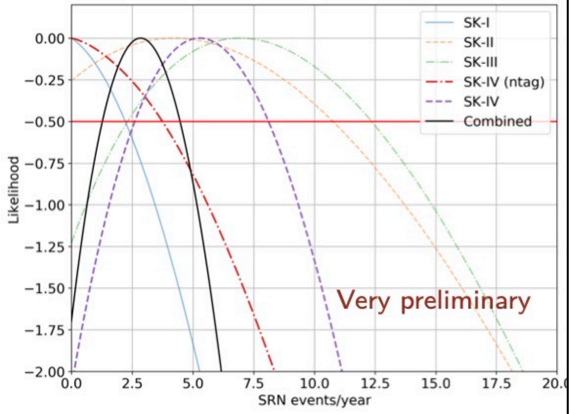
- Inverse beta decay channel is the probe for DSNB.
- Super-K holds the current best limits for the DSNB flux.
- Sensitivity limited by backgrounds
  - However, only one order magnitude above theoretical predictions.

  → (High efficiency and low background) Neutron tagging with Gd!

Combination of SK-I to IV for the Ando (optimistic) model

S. Hedri, ICHEP 2020





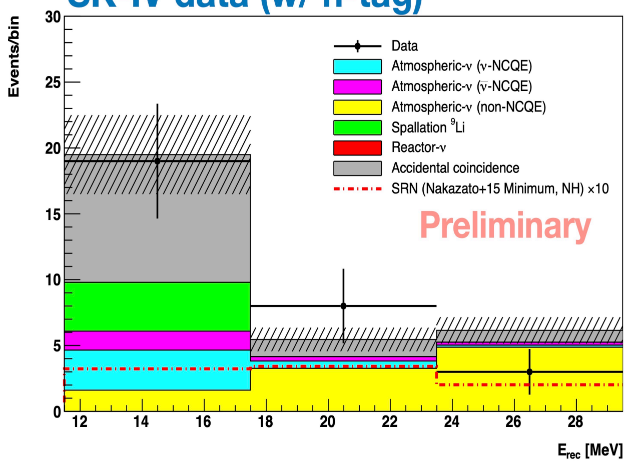
- Slight excess at low energy without neutron tagging
- Current 90% C.L. limits on the Ando model flux ($1.7\ \mathrm{cm}^{-2}/\mathrm{s}$):

SK-IV (no neutron tagging) : $\Phi_{90} = 4.9\ \mathrm{cm}^{-2}/\mathrm{s}$

SK-IV (neutron tagging): $\Phi_{90} = 3.8\ \mathrm{cm}^{-2}/\mathrm{s}$

Combined (22.5×2853 kton.day) : $\Phi_{90} = 2.7\ \mathrm{cm}^{-2}/\mathrm{s}$

SK-IV data (w/ n-tag)



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

E_ν region [MeV]	13.3–19.3	19.3–25.3	25.3–31.3
SK-IV 2970 days (Expected)	**9.48**	**1.35**	**0.82**
SK-IV 2970 days (Observed)	**9.08**	**2.22**	**0.35**
Horiuchi+18 ($\xi_{2.5,crit} = 0.1$)	1.583	0.553	0.173
Horiuchi+18 ($\xi_{2.5,crit} = 0.5$)	1.108	0.252	0.050
Nakazato+15 (Maximum, IH)	0.798	0.236	0.081
Nakazato+15 (Minimum, NH)	0.337	0.089	0.026
Horiuchi+09 (6 MeV, Maximum)	2.534	0.887	0.314
Lunardini09	1.032	0.321	0.098
Ando+03 (updated at NNN05)	2.652	0.796	0.261
Malaney97	0.469	0.125	0.034
Hartmann+97	0.947	0.297	0.093

☐: Models within a factor of 3

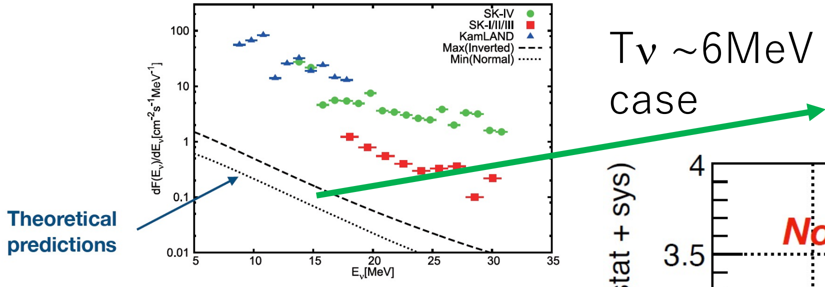
- No significant excess found
- Set one of the most stringent limits above 13.3 MeV
- Many model predictions are within several factors from the current limit
- Sensitivity limited by small statistics and backgrounds

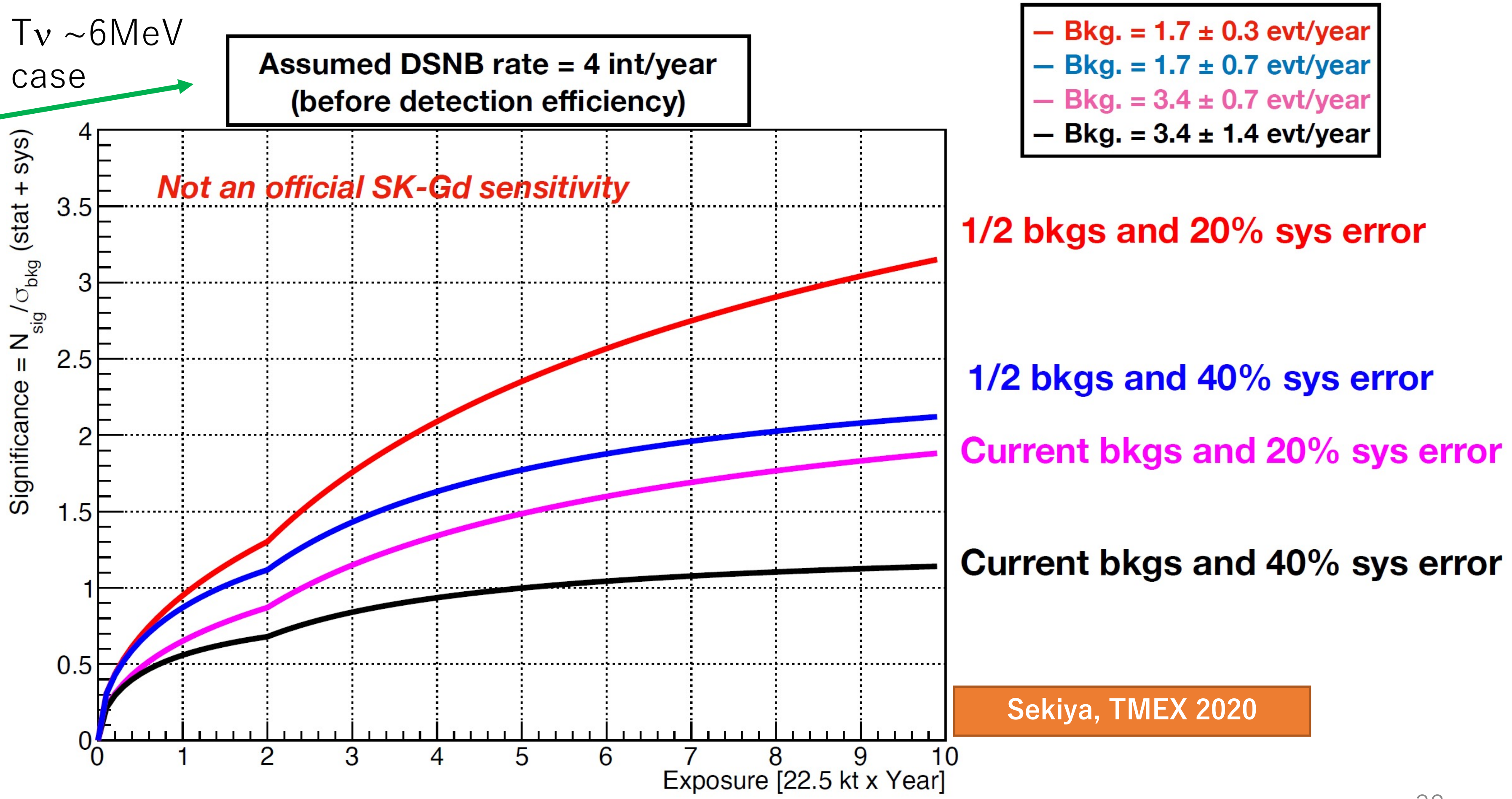
  →**Will be significantly improved with better neutron tagging in SK-Gd**

Nakajima, Neutrino 2020

DSNB sensitivity

- Assuming neutron tagging efficiency increased to >70% in 2022





Sekiya, TMEX 2020

Summary

- Super-K is starting new experimental phase, Super-K Gd.
  - Neutrino/Anti-neutrino separation of high efficiency neutron tagging.
  - Gd loading is started at July 2020.
- Super-K Gd will provides more pointing accuracy and a new early warning system for supernova burst neutrinos.
  - Aiming for the first observation of Diffuse Supernova Neutrino Background in 10 years.
- Hyper-K has been funded and started to construct.
  - The observation will be started in 2027.
  - Supernova neutrino detections are important target for SK/HK.
- Other astrophysical source, solar neutrino, indirect DM, GW and Blazer follow-up will be also continued with SK/HK.