Neutrino astrophysics prospects at Super-Kamiokande and Hyper-Kamiokande

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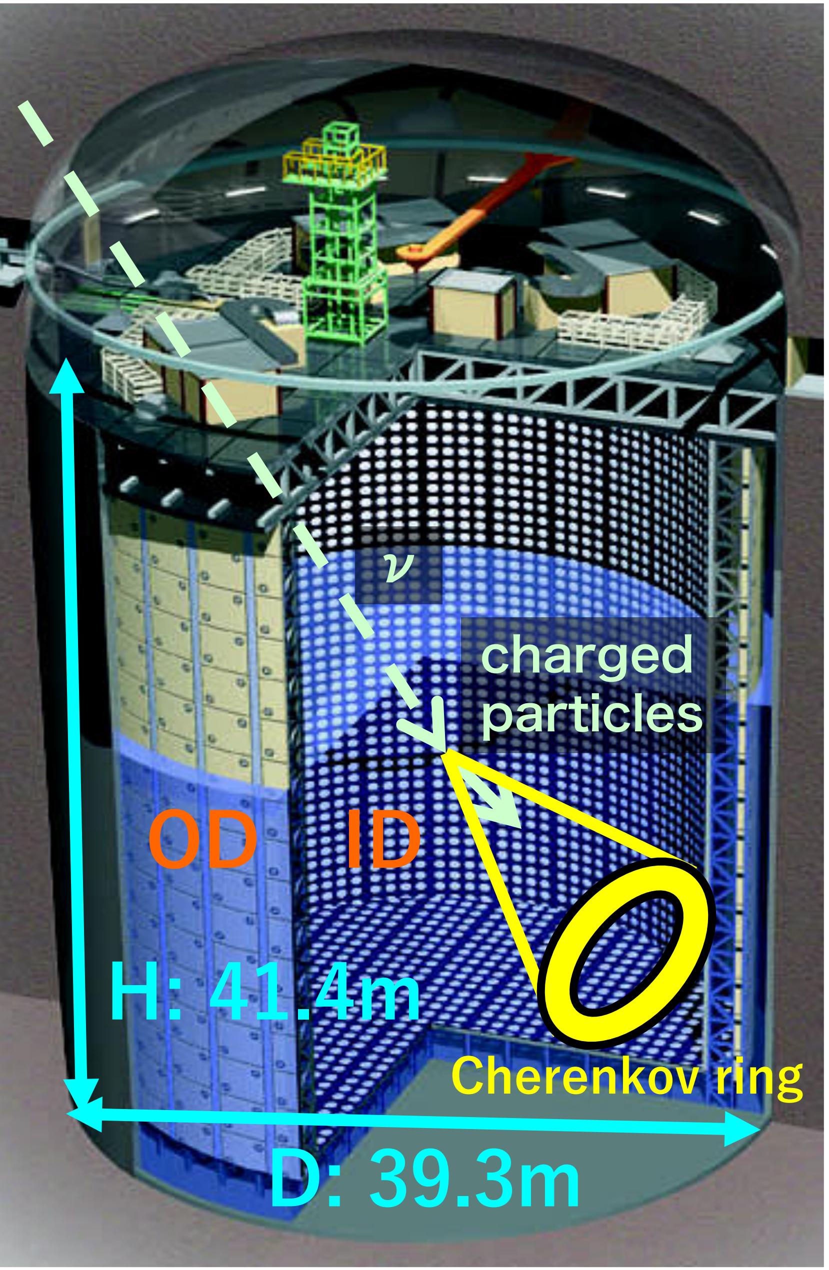
YITP workshop, 8th Dec. 2020

Kyoto, Japan and Online

Outline

- Overview of Super-Kamiokande
  - Current status toward Super-K Gd
- Supernova neutrino detection and prospects
  - Supernova burst neutrinos
  - Supernova relic neutrinos
- Overview of Hyper-Kamiokande
  - Prospects of Hyper-K
- Other astrophysical neutrinos
- Summary

Super-Kamiokande



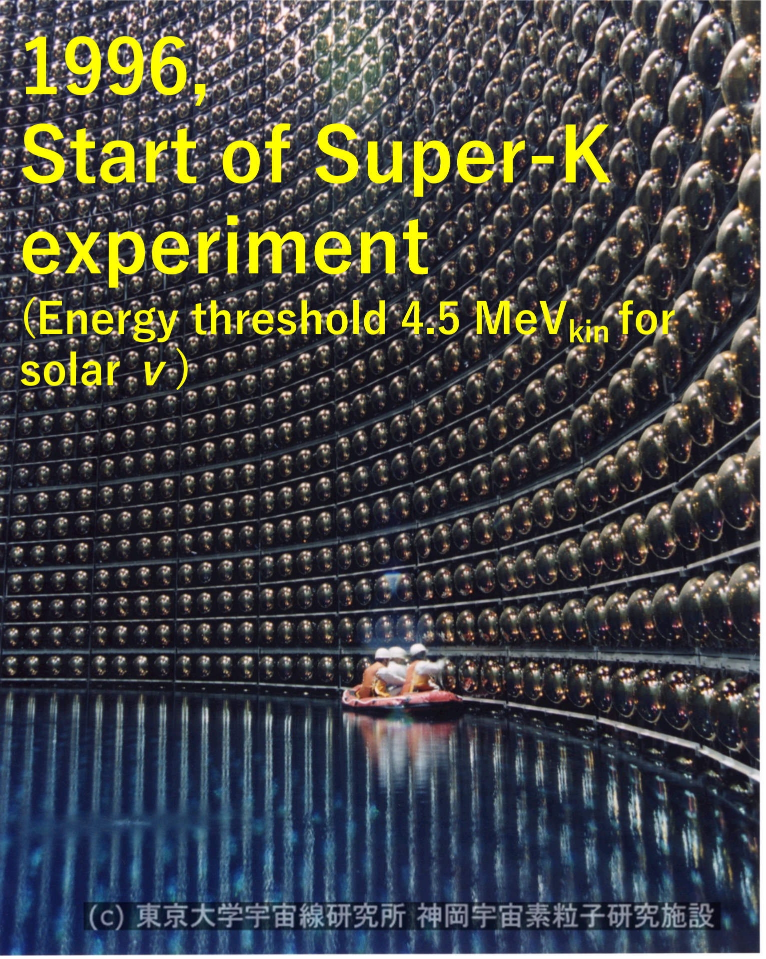
Features of SK detector

- 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).

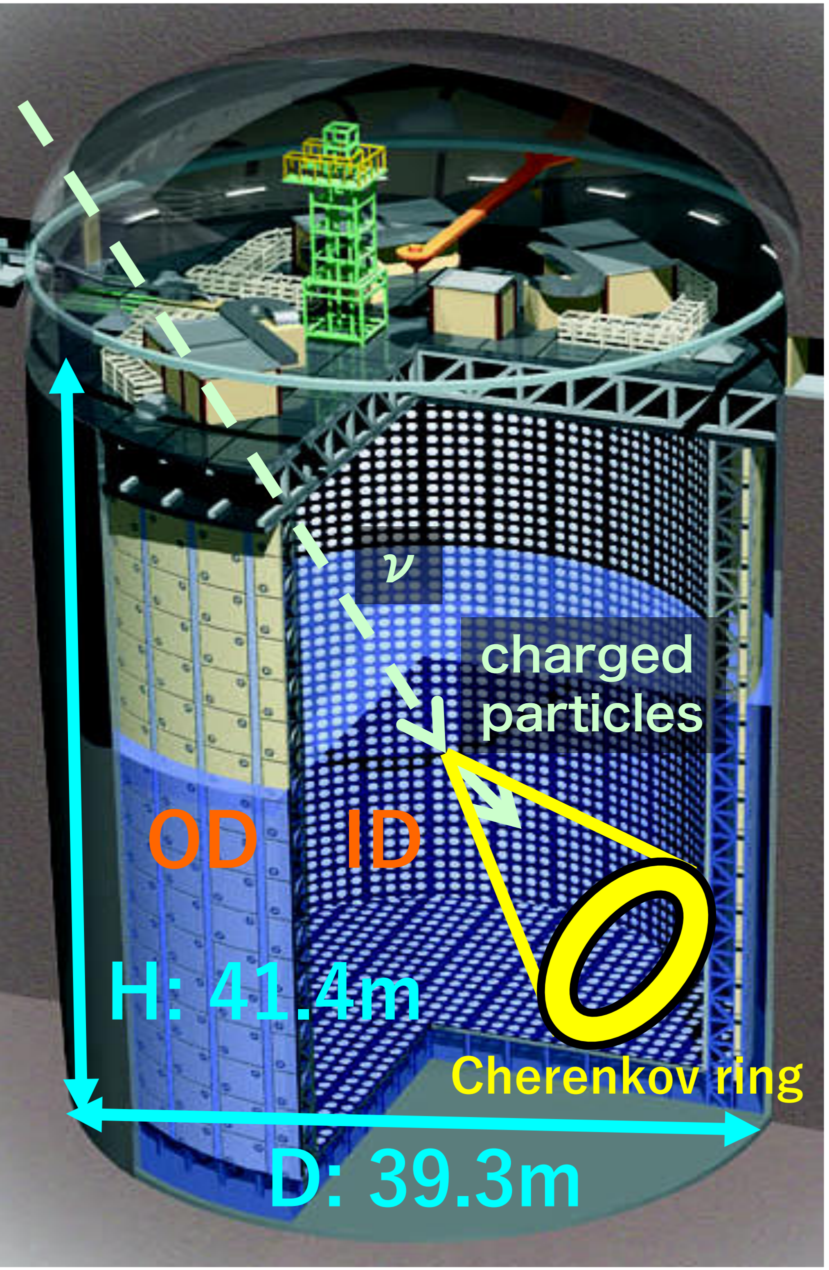
SK-I | SK-II | III | SK-IV | SK-V | SK-Gd

1996 2001 '02 '05 '06 '08 '18 '19 '20 July

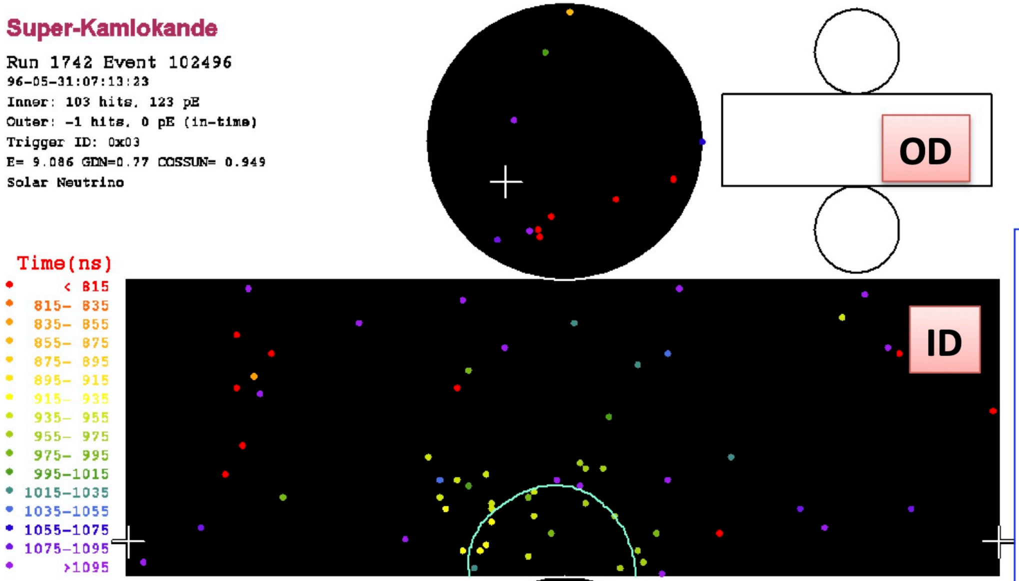
K2K far detector ('99 – '04)

T2K far detector ('09 –)

Event Reconstruction -1-

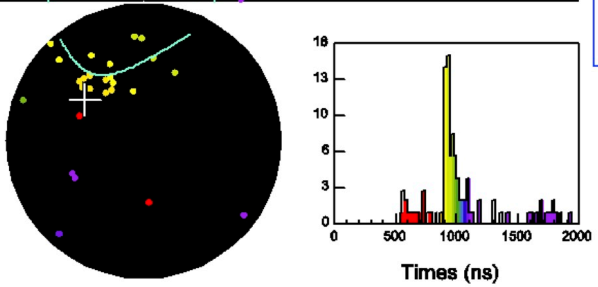


Typical low-energy event



(color: time)

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



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

(for solar neutrinos)

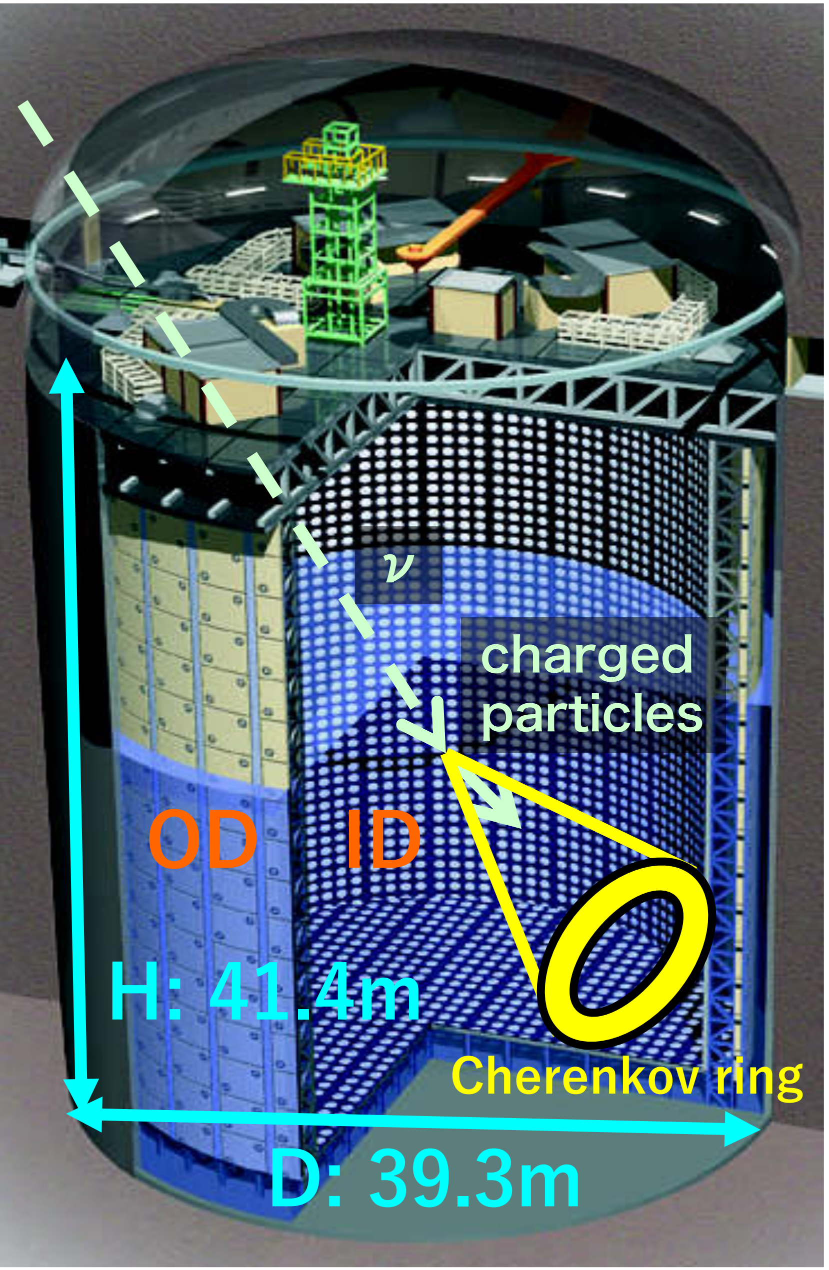
- Timing information ➡ vertex position
- Ring pattern ➡ direction
- Number of hit PMTs ➡ energy

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

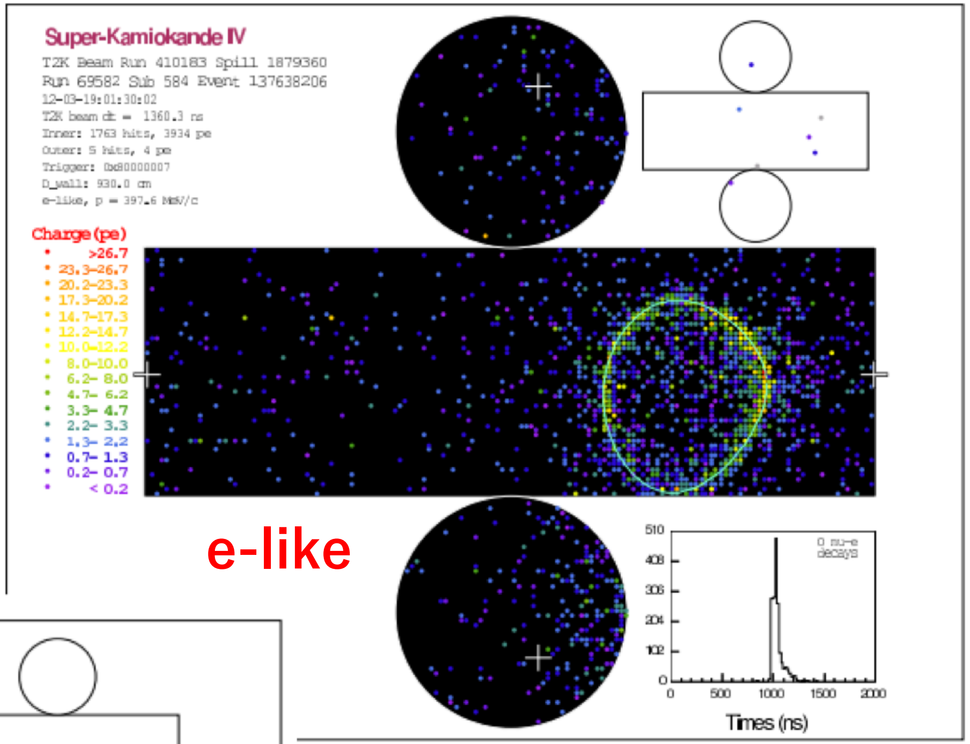
Resolutions (for 10MeV electrons) (software improvement)

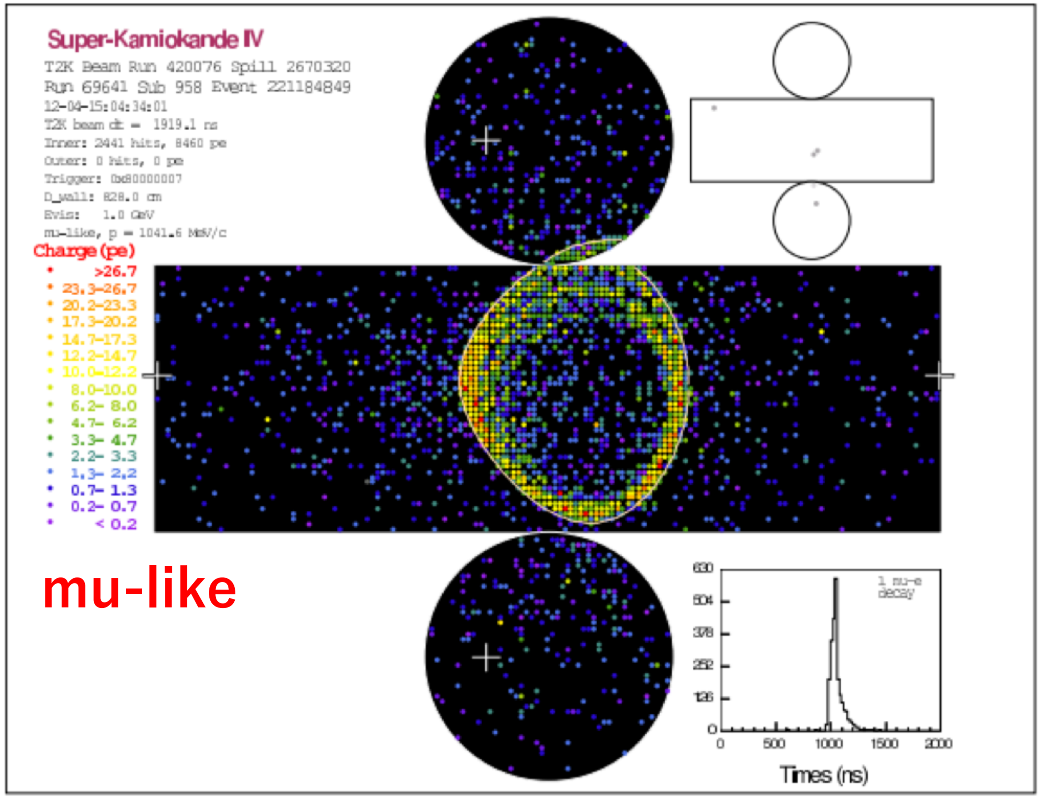
Energy: 14%	Vertex: 87cm	Direction: 26°	SK-I
Energy: 14%	Vertex: 55cm	Direction: 23°	SK-III

Event Reconstruction -2-



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



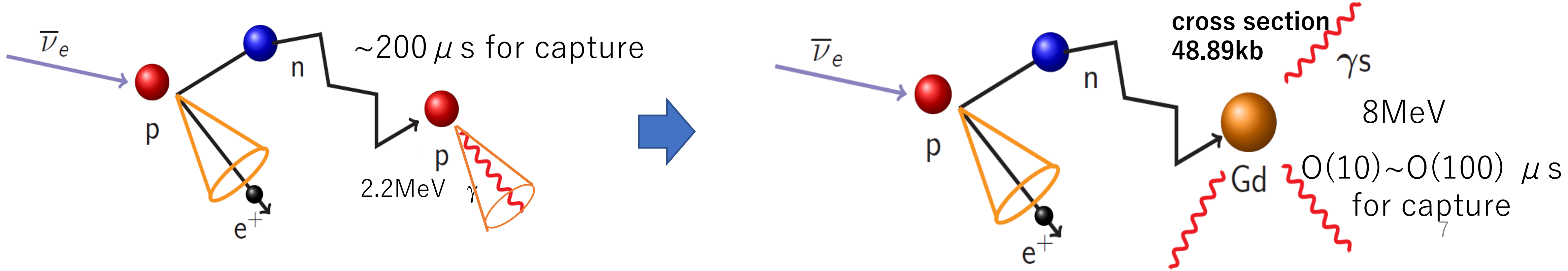


Figures are taken from:
Laura Munteanu, ICHEP2020

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

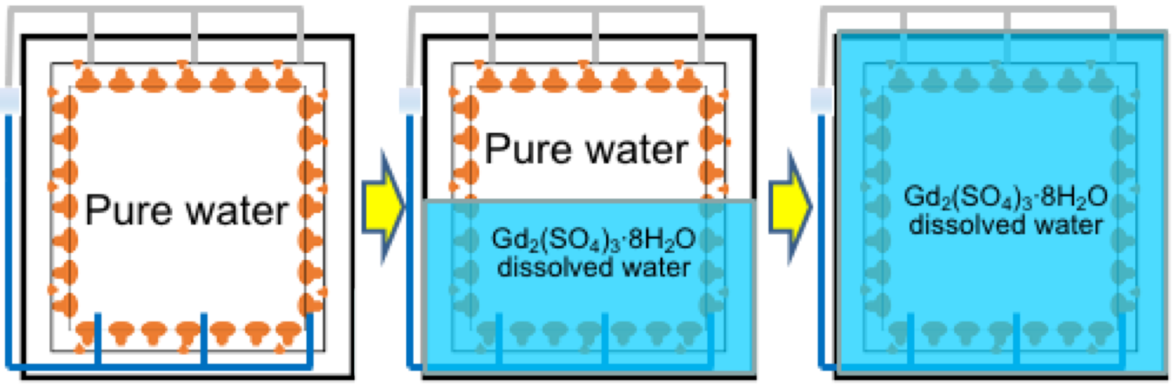
Physic targets

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

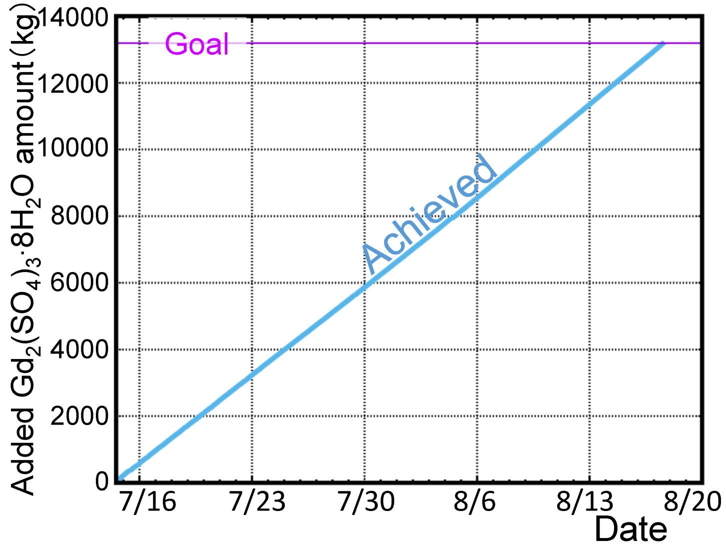
Current status

- 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.

Schematic view of Gd loading to Super-K



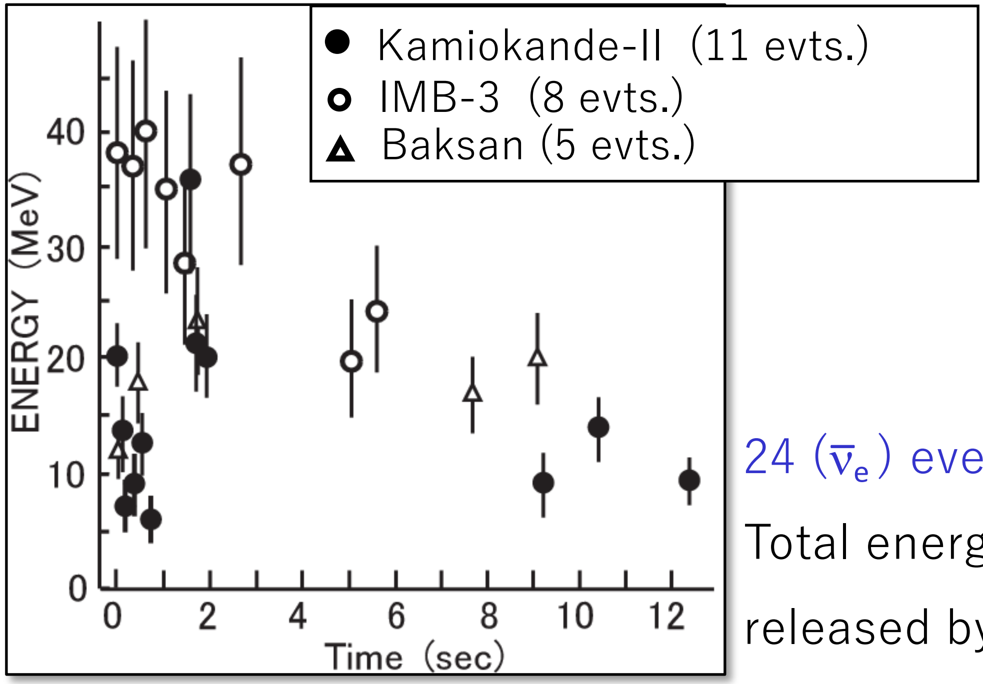
Amount of dissolved Gd



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

Supernova neutrinos from 1987A

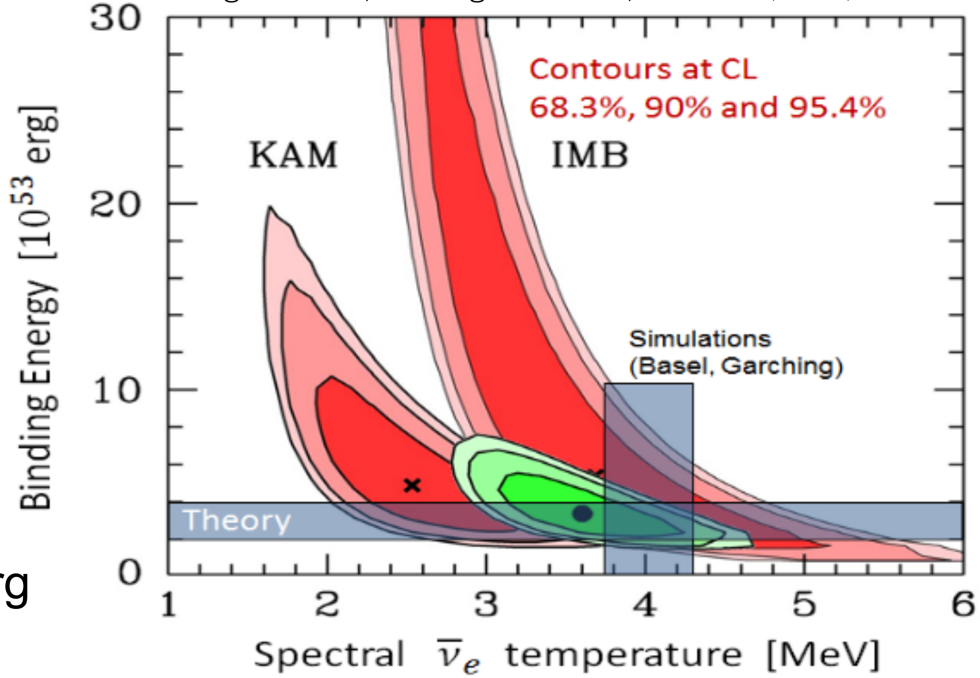
- The only detected SN neutrinos are from LMC(50kpc)



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

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

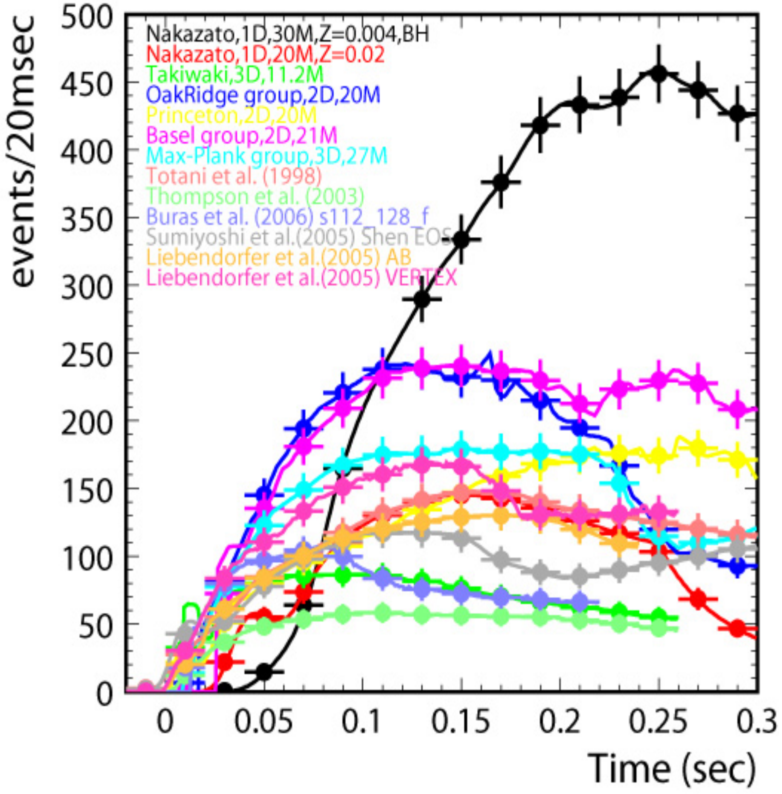
Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194



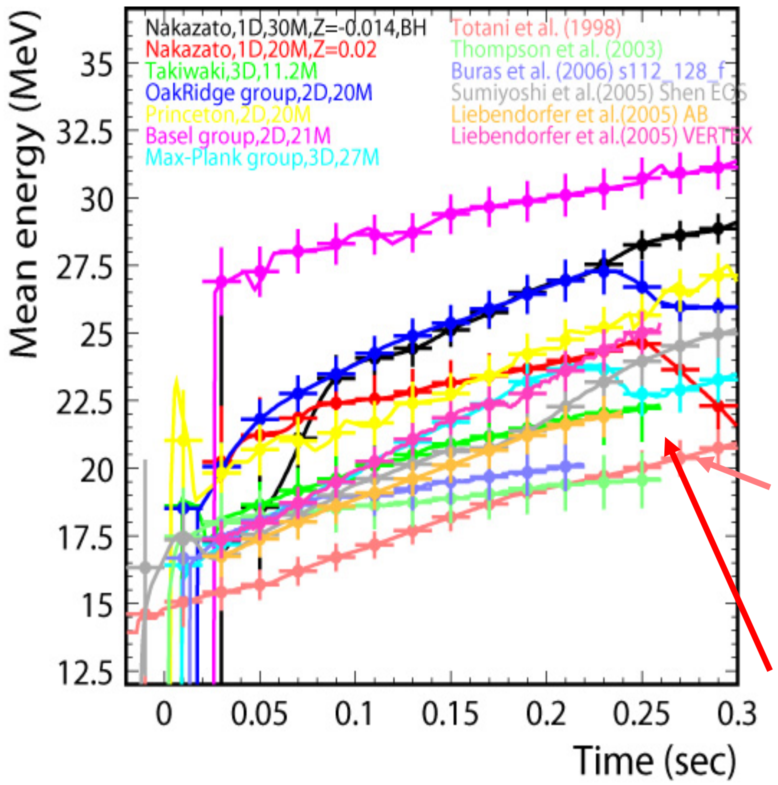
- The obtained binding energy is almost as expected, but large error in neutrino mean energy. No detailed information of burst process.
- We need energy, flavor and time structure.
- Supernova will be most interested target for Multi-messenger measurement with SK.

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

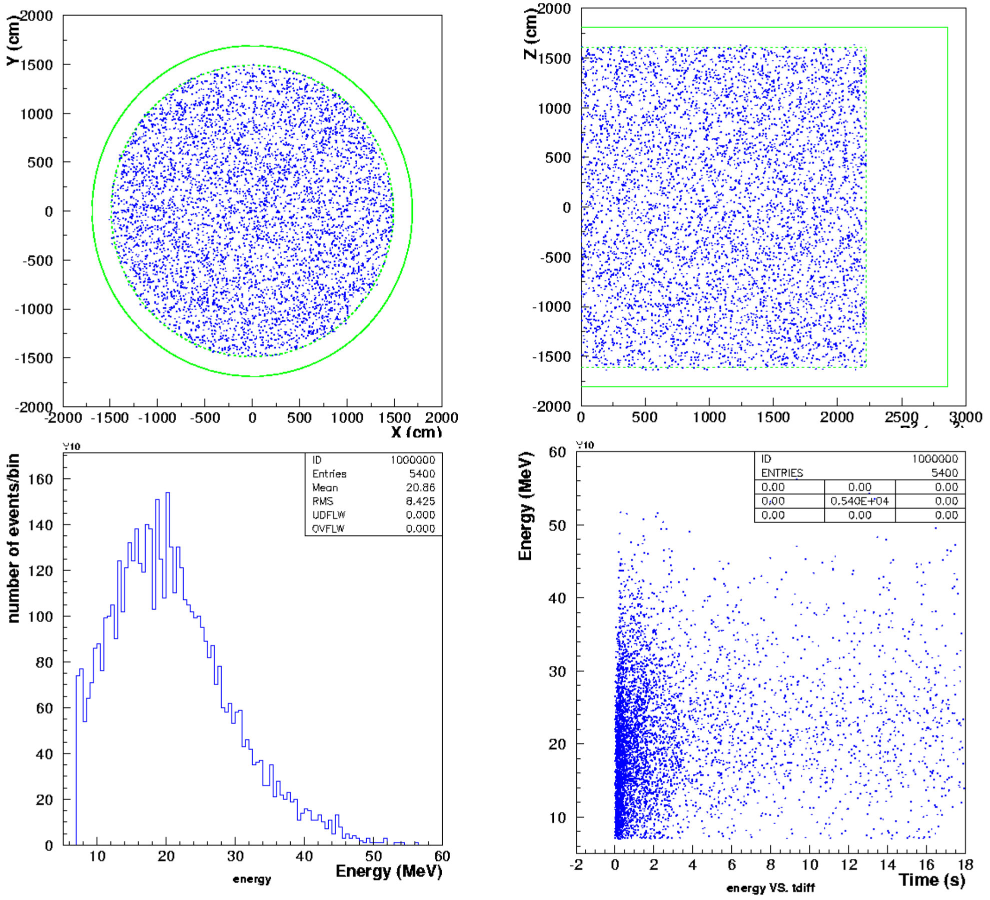
"Totani1998" as a reference

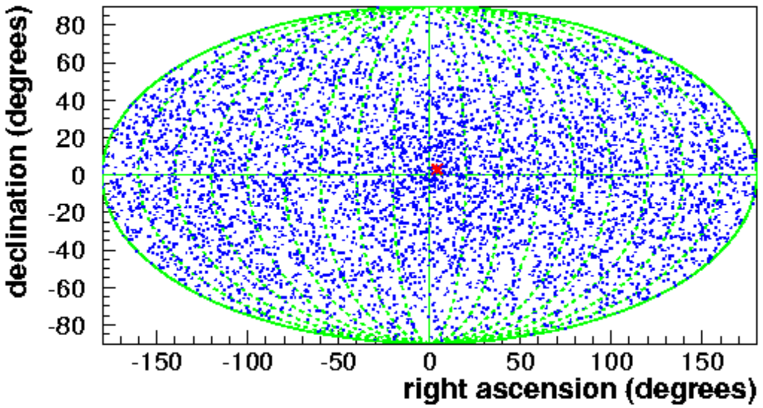
"Nakazato" as a reference

- 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





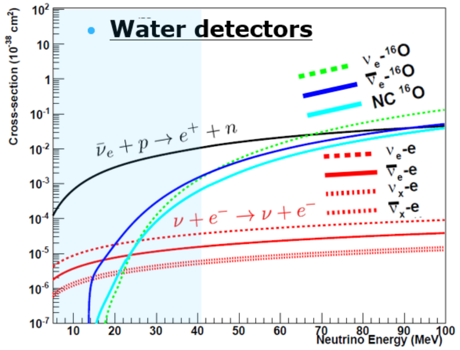
SN simulation @10kpc, Wilson (Totani1998) model

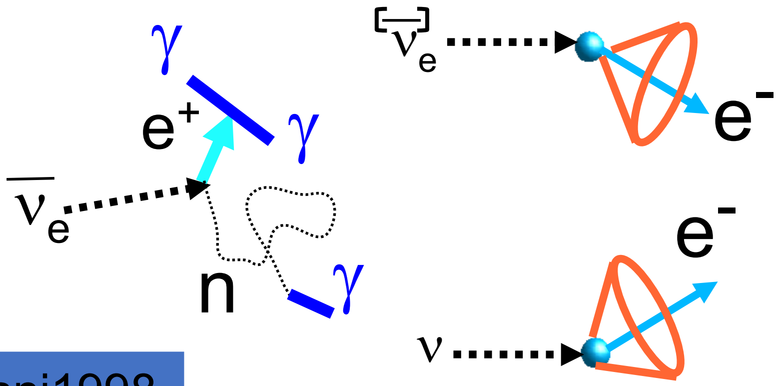
- Golden Alarm (Definition):
  - 60 events in 20sec
- The process time depends on the events
  - It takes about 10 minutes for the process of 10k events
  - Alarm will sent to SNEWS, IAU CBAT, ATEL, GCN. (< 1hour)
  - Quicker alert system is needed for covering type Ib/Ic stars.

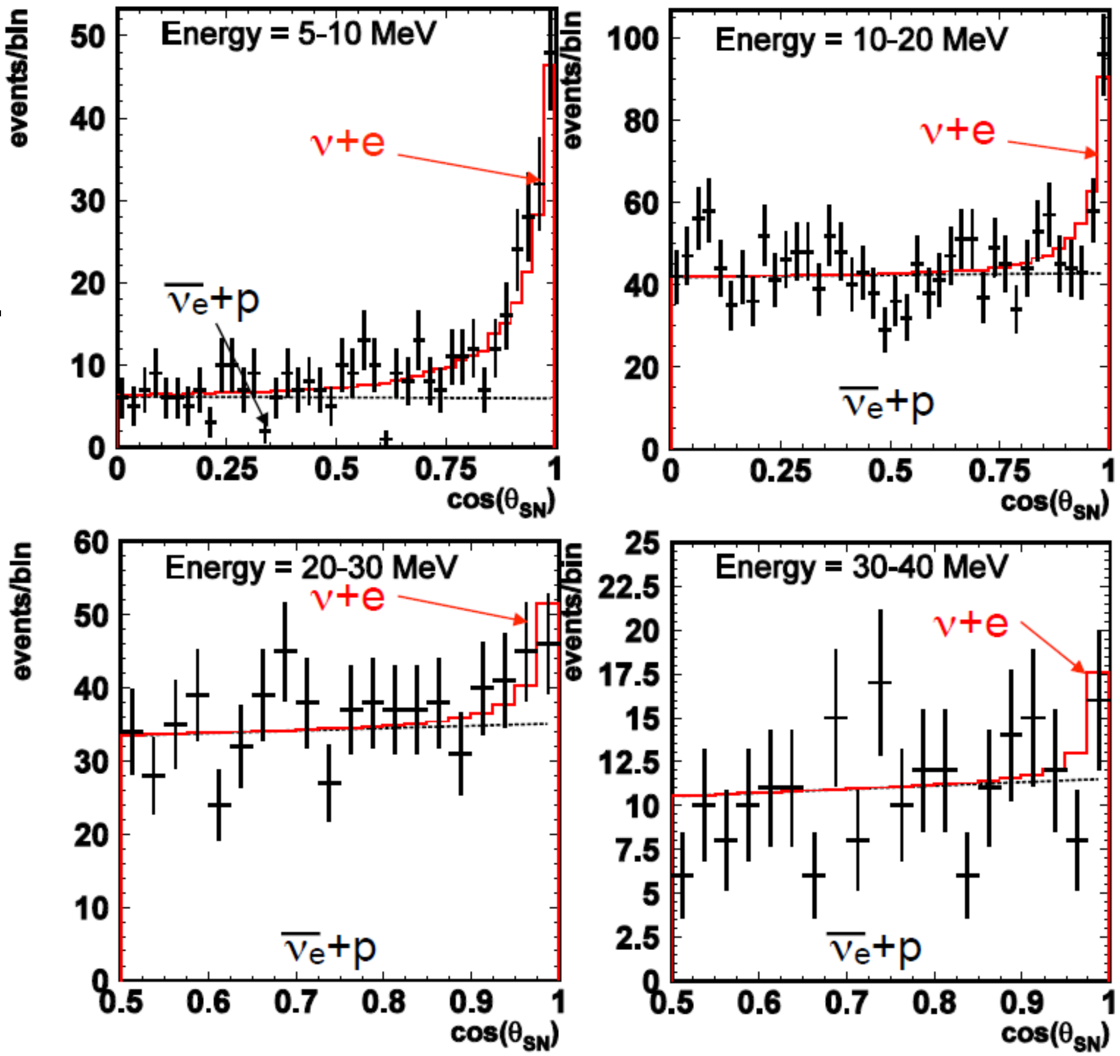
Pointing accuracy

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

Pointing accuracy ~5° @10kpc SN





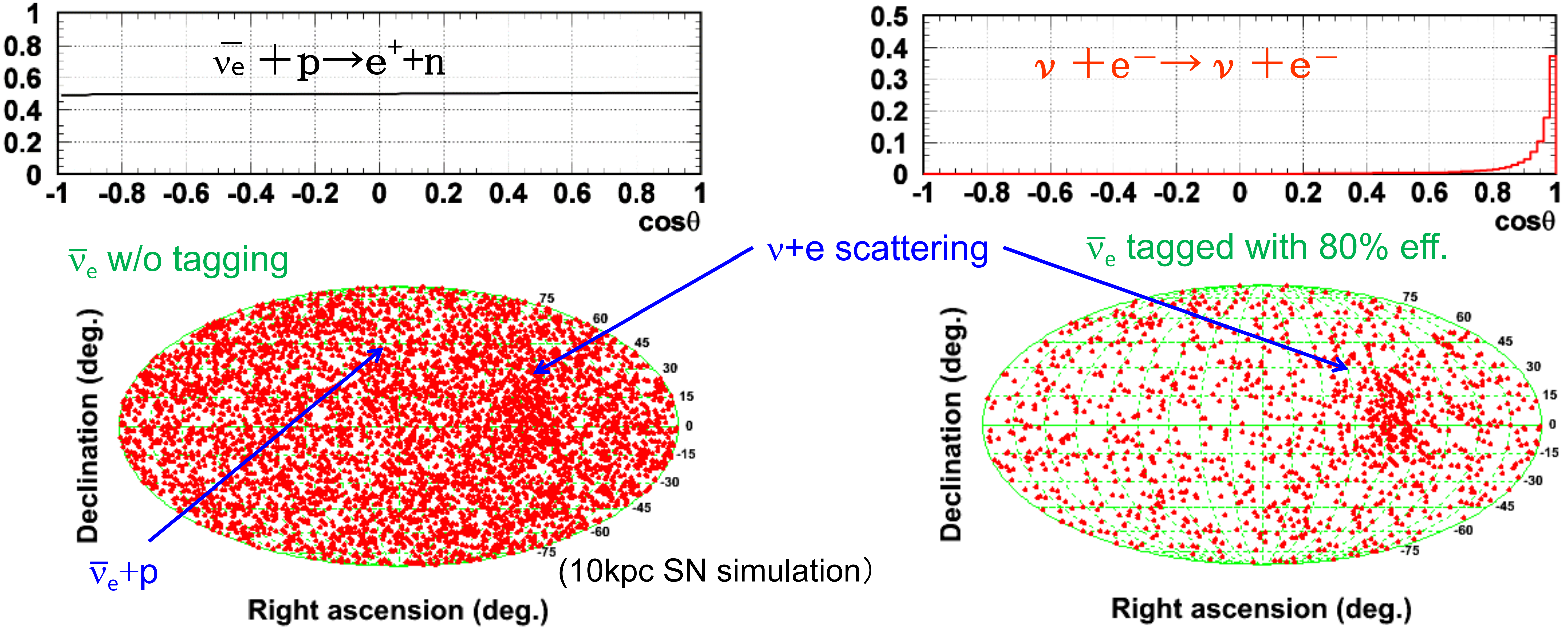


	Totani1998
$\bar{\nu}_e p \rightarrow e^+ n$	7300
$\nu + e^- \rightarrow \nu + e^-$	320
^{16}O CC	110

- BG reduction by neutron tagging
  - → SK-Gd

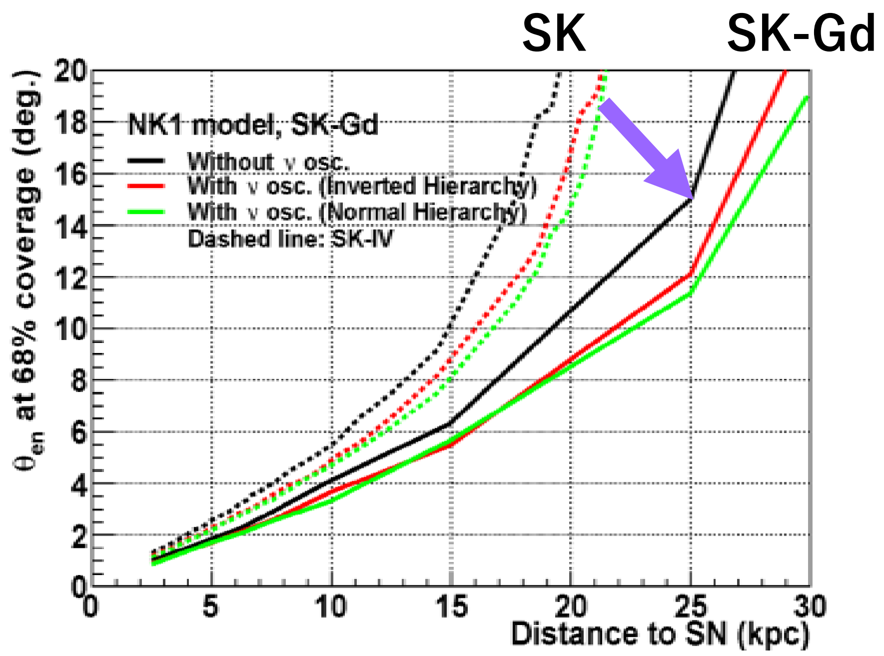
SK-Gd pointing accuracy

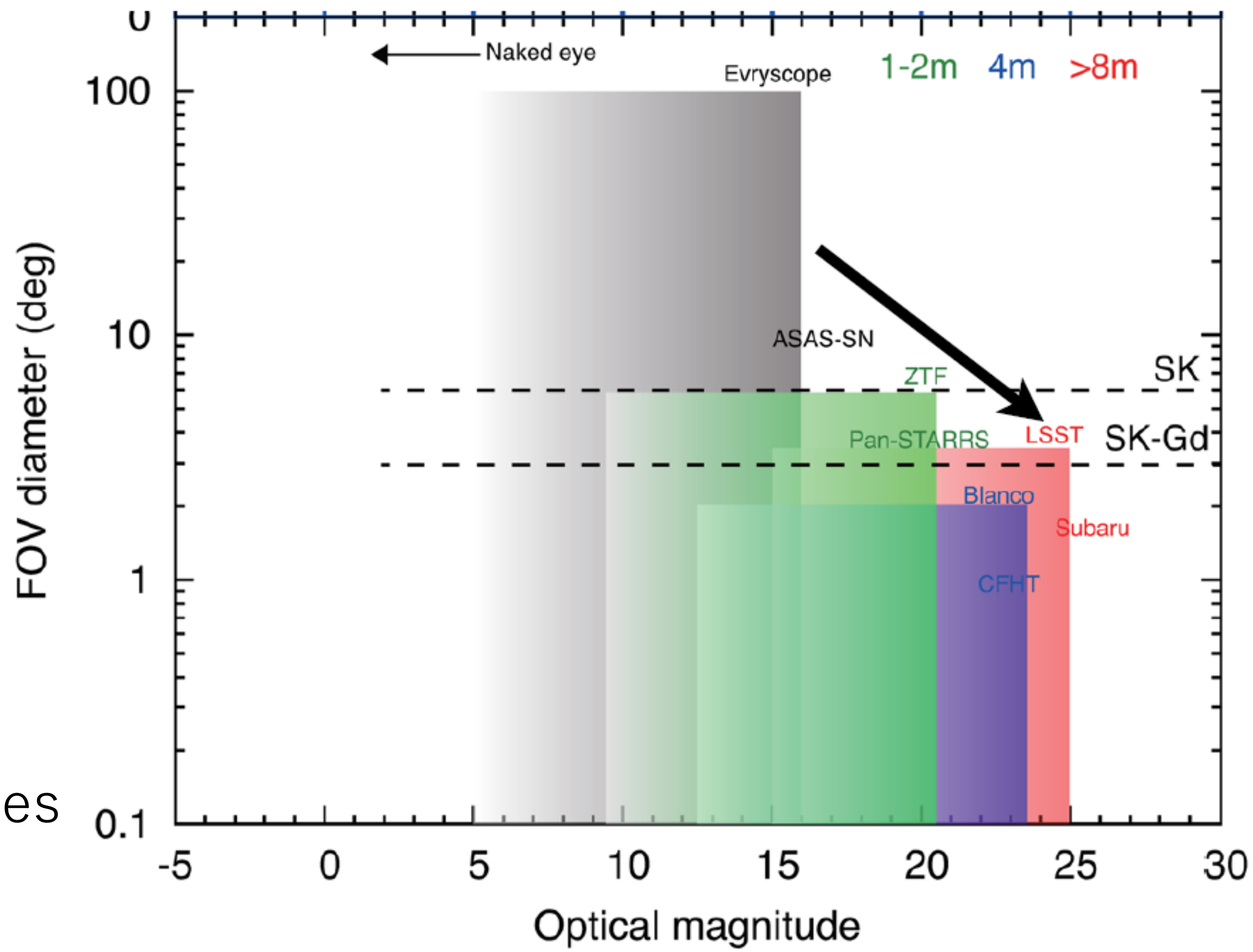
- $\bar{\nu}_e$ events can be tagged and rejected, and directional events (ν_e+e scattering events) are enhanced.



Impact of SK-Gd

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





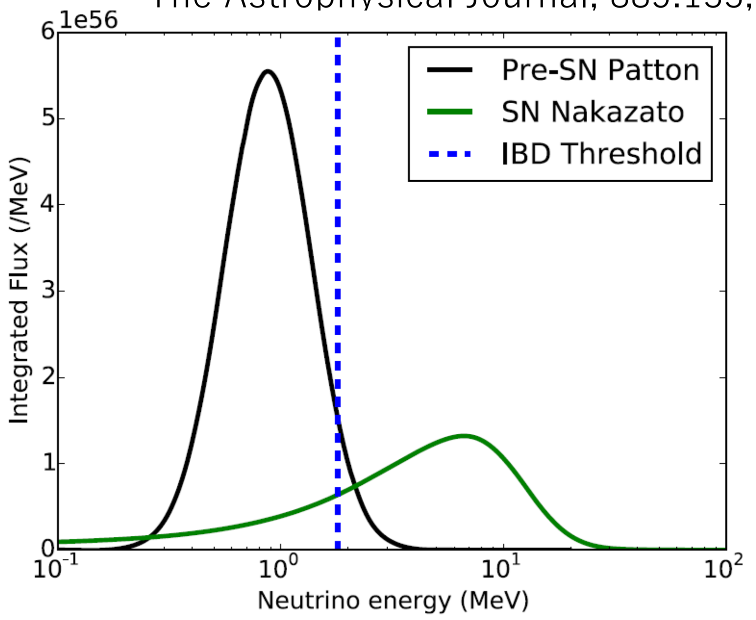
For 10kpc SN ~5° → ~3°

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

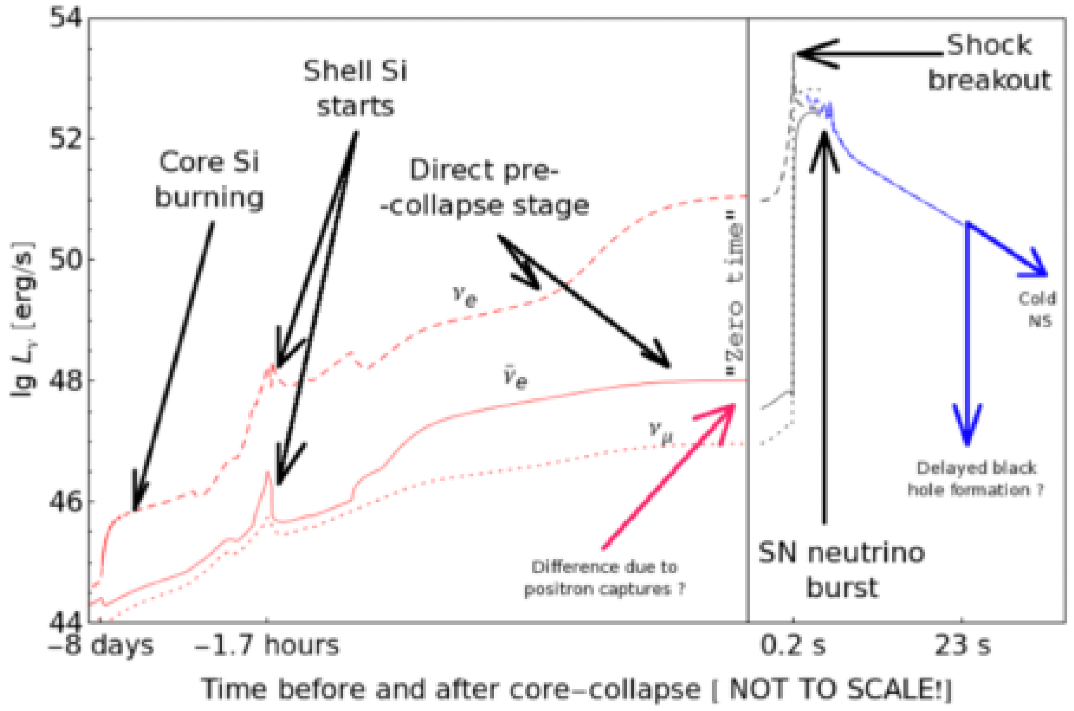
Pre-supernova signals

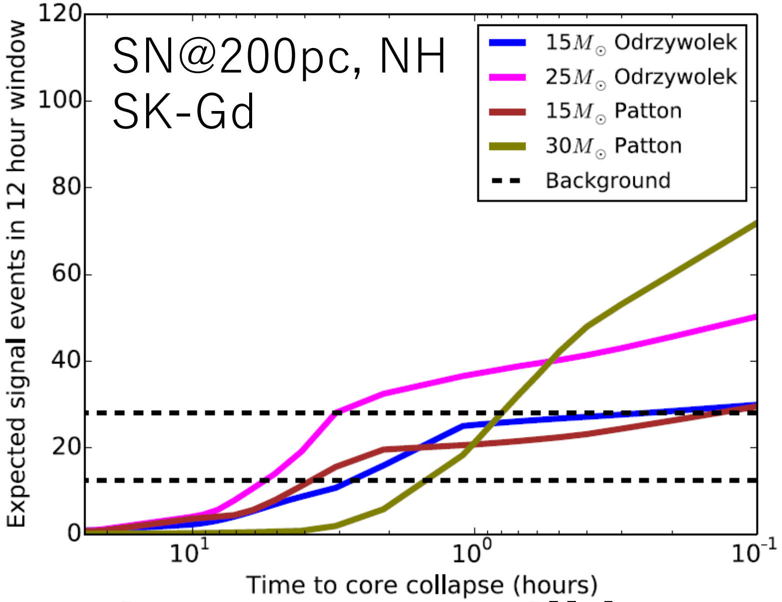
- Precursor signal from Si-burning is detectable with SK-Gd
  - Pre-SN's ν energy is lower than SN's
  - Gd loading is essential.

The Astrophysical Journal, 885:133, 2019



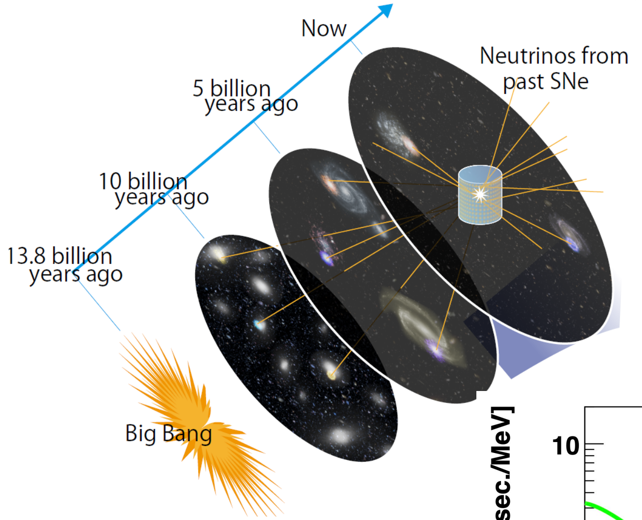
Odrzywolek & Heger, 2010



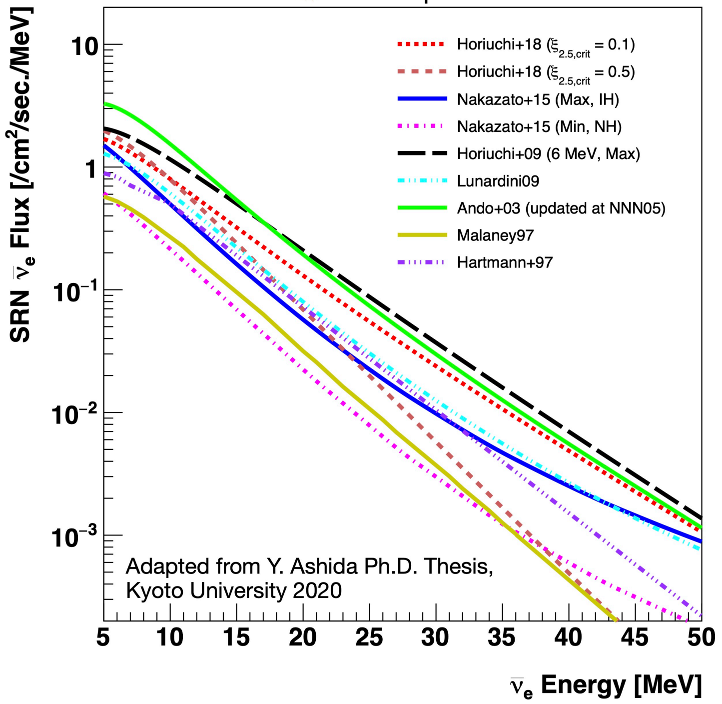


Early warning system will be prepared.

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

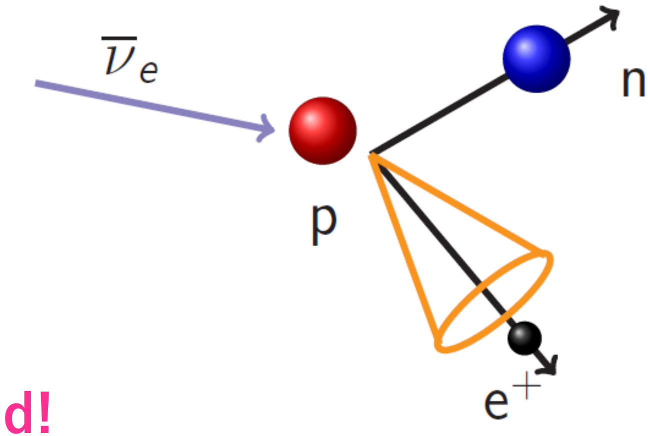
$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z\mathrm{max}} R_{\mathrm{SN}}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

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

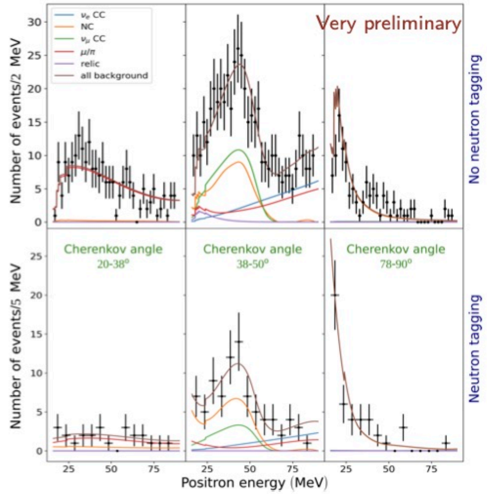


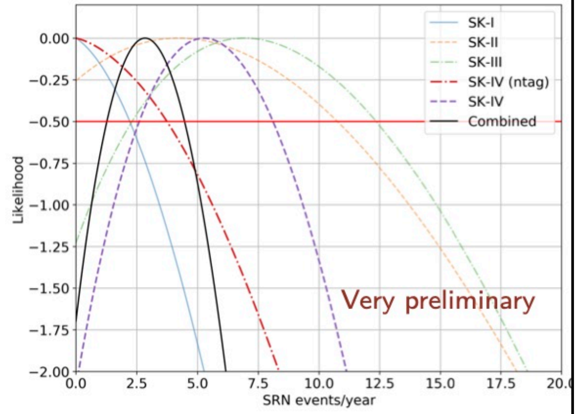
- Inverse beta decay channel is the probe for DSNB.
- Super-K holds the current best limits for the DSNB flux.
- Sensitivity limited by backgrounds
  - However, only one order magnitude above theoretical predictions.

  → (**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 ($1.7\ \mathrm{cm}^{-2}/\mathrm{s}$):

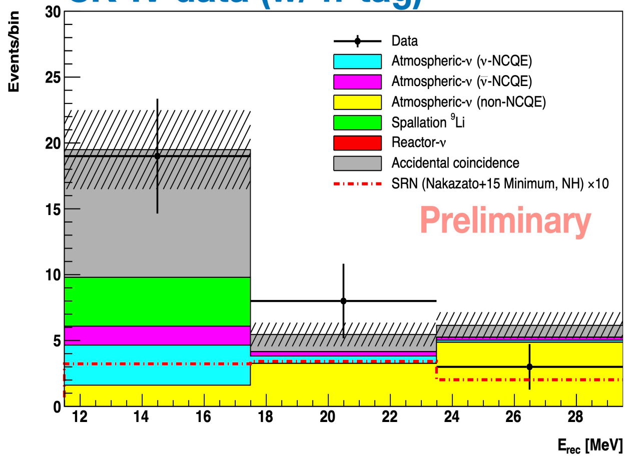
SK-IV (no neutron tagging) : $\Phi_{90} = 4.9\ \mathrm{cm}^{-2}/\mathrm{s}$

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

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

13 / 15

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

[red box]: Models within a factor of 3

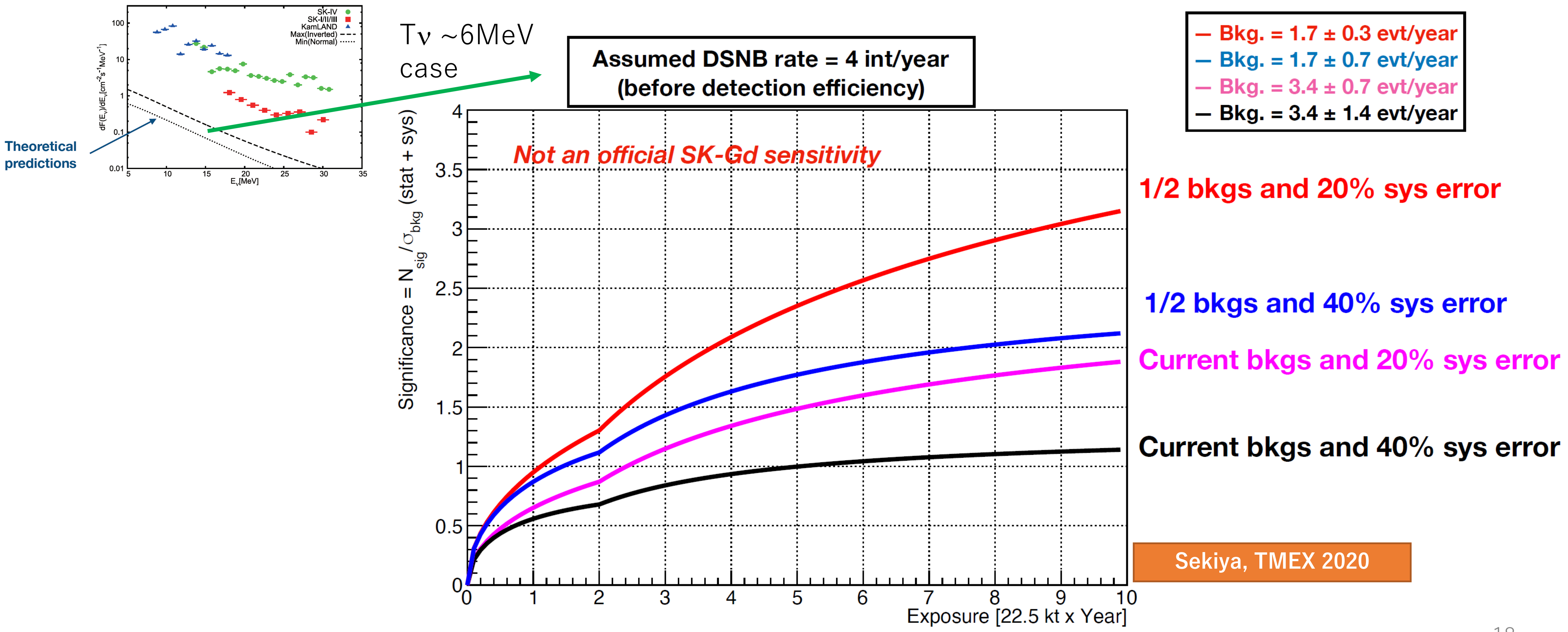
- No significant excess found
- Set one of the most stringent limits above 13.3 MeV
- Many model predictions are within several factors from the current limit
- Sensitivity limited by small statistics and backgrounds

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

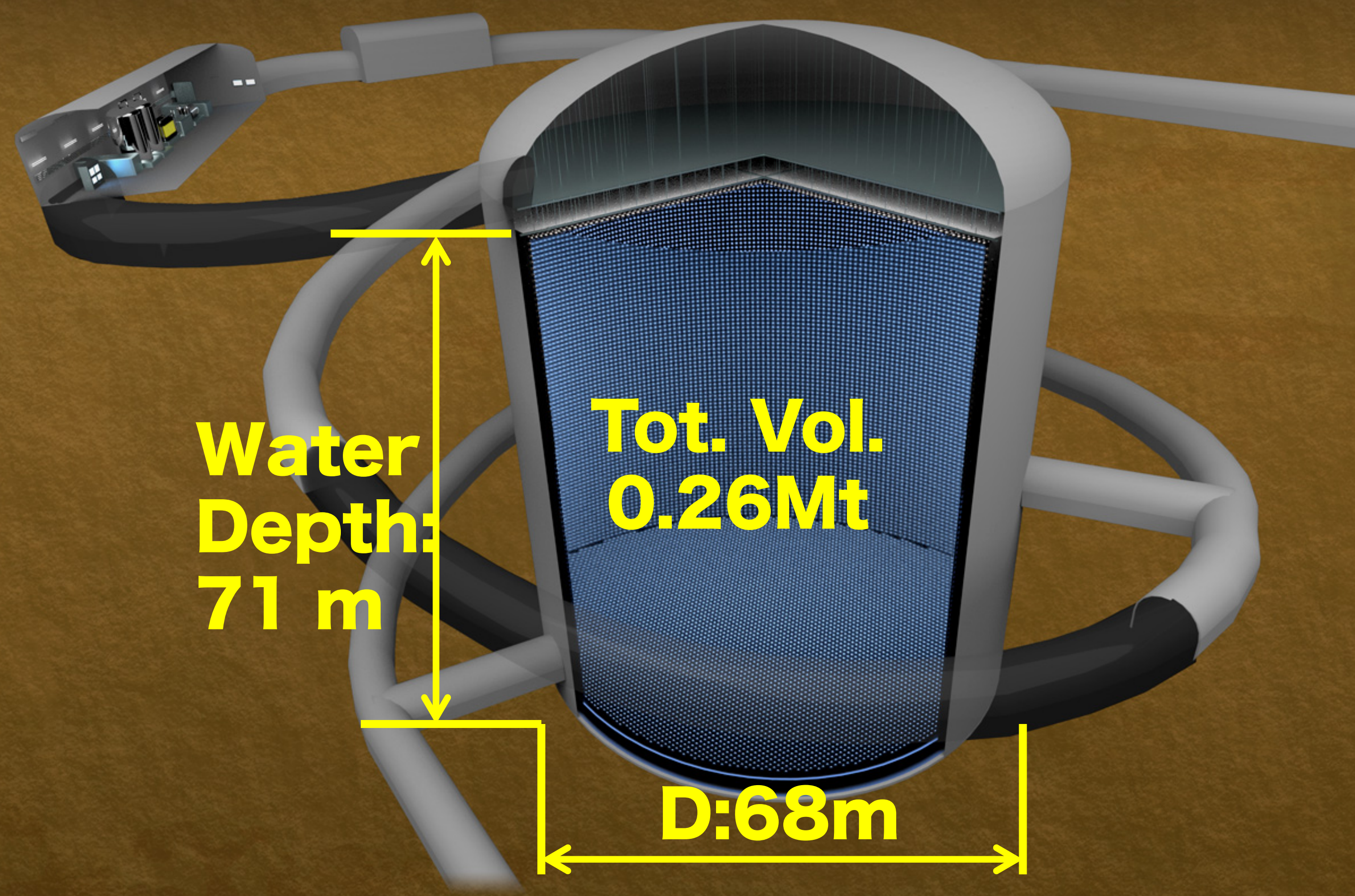
Nakajima, Neutrino 2020

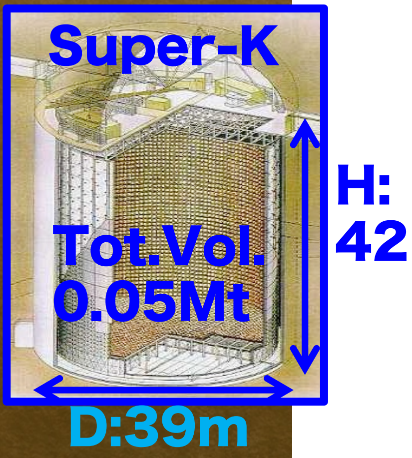
DSNB sensitivity

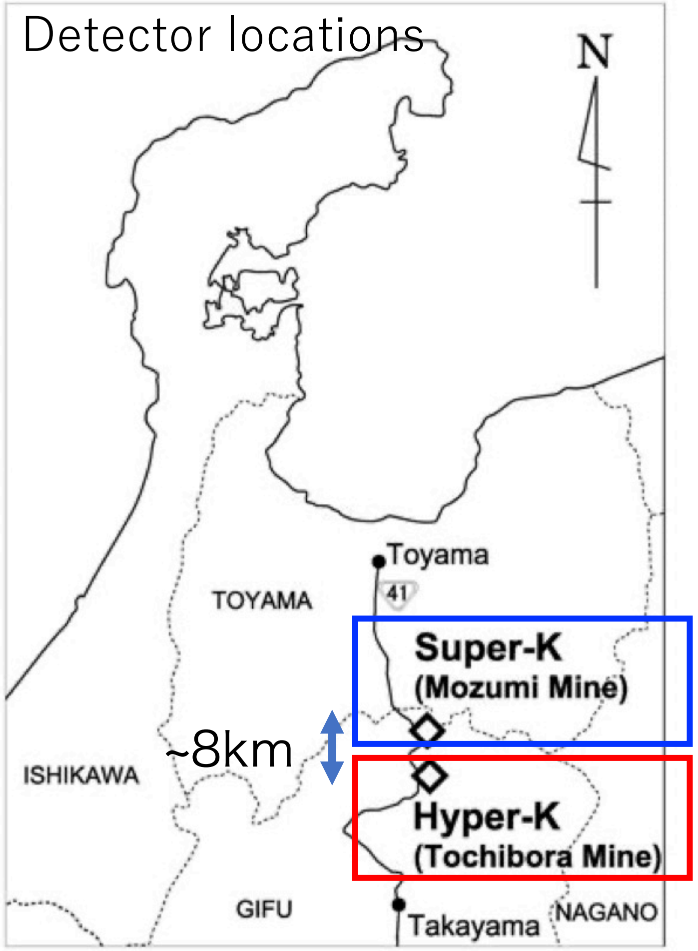
- Assuming neutron tagging efficiency increased to >70% in 2022



Hyper-Kamiokande





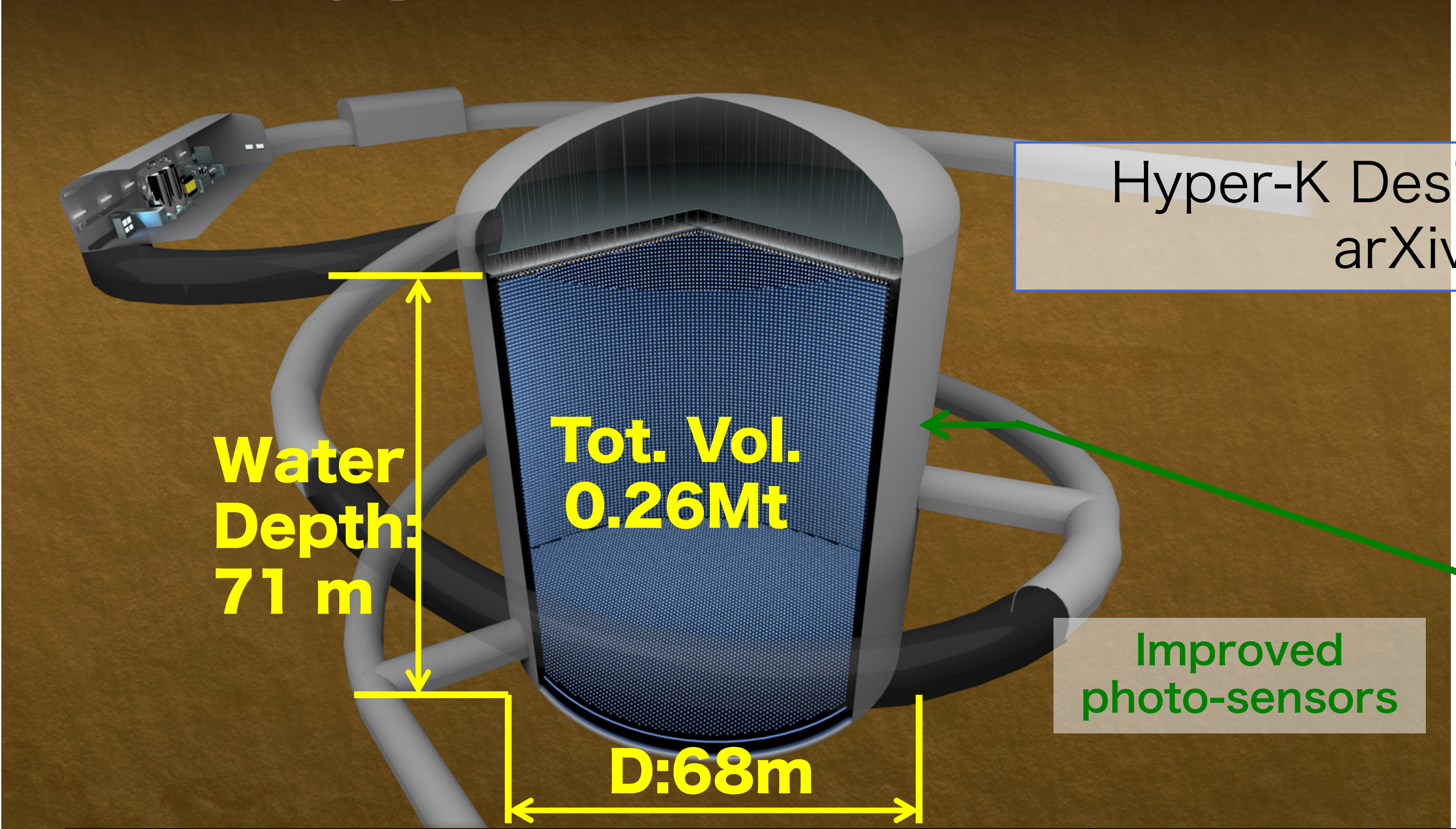


Next generation large water Cherenkov detector

- 2020 Feb: Hyper-Kamiokande is officially approved by Japanese Diet.
- 2027: Observation with Hyper-Kamiokande will be started.

Hyper-Kamiokande

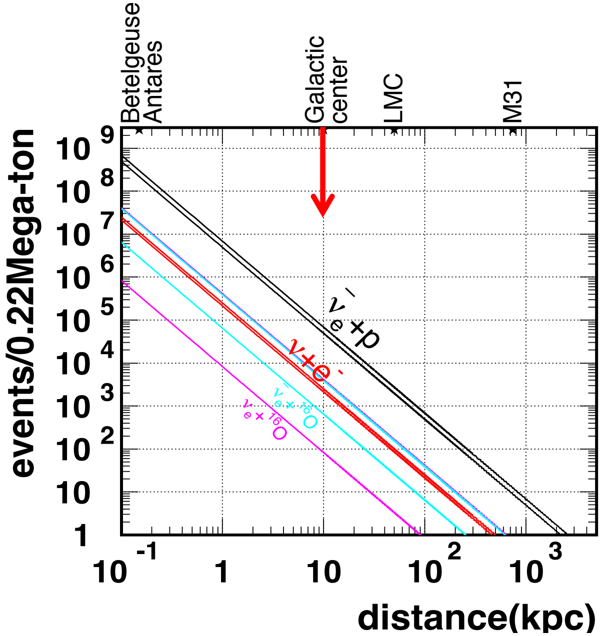
Hyper-K Design Report is available:
arXiv: 1805.04163



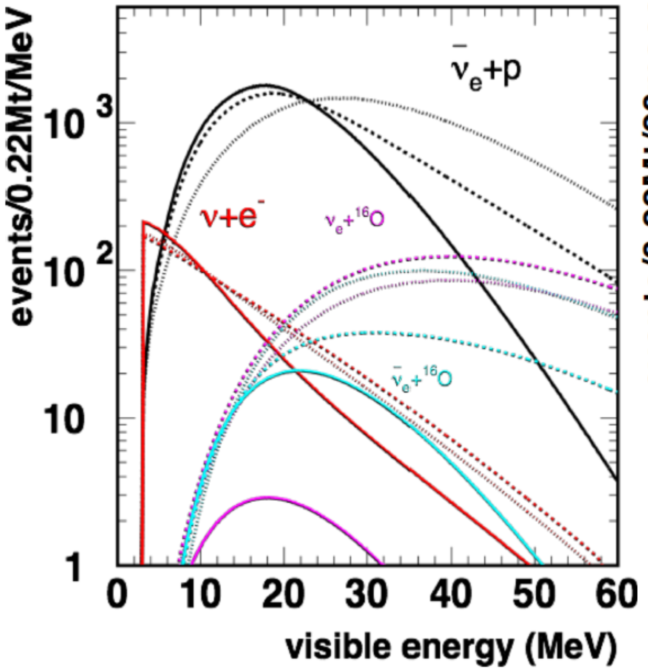
Design	Hyper-Kamiokande	Super-Kamiokande
No. of PMTs (ID/OD)	40,000 / 6,700 (Design Report)	11,129 / 1,885
Photocathode coverage	40% (×2 efficient p.e. detection)	40%
Total / Fiducial V.	0.26 Mt / 0.19Mt (Design Report)	50 kt / 22.5 kt

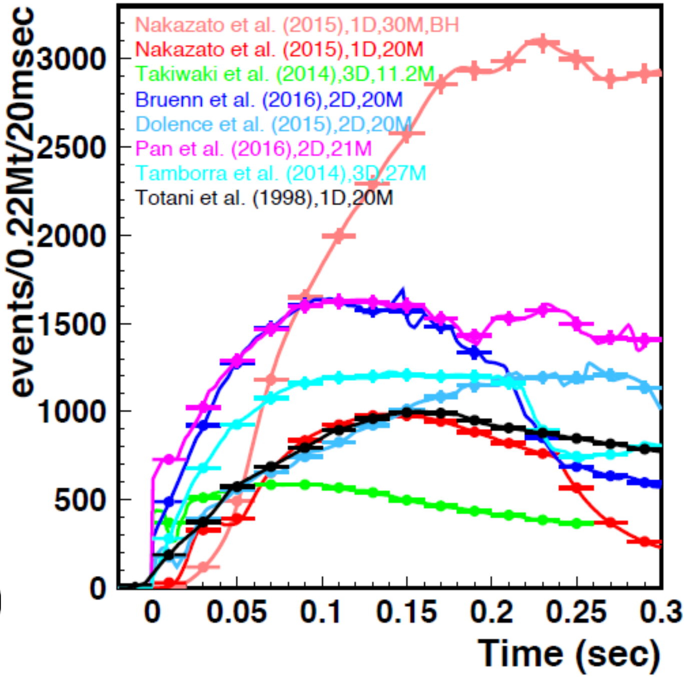
Expected events in HK

- SK 32kt → HK 220kt
  - 54000-90000 events are expected for SN at galactic center (10 kpc).



SN at 10 kpc





Supernova model discrimination

Model discrimination between five supernova models are recently studied.

J. Migenda, Neutrino 2020.

With 300 events, corresponds supernovae at 60-100 kpc, >97% identification was realized.

J.Migenda Neutrino 2020, Poster

True model \ Identified as (NMO/IMO)	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	982/999	2/1	16/0	0/0	0/0
Nakazato	1/0	999/1000	0/0	0/0	0/0
Tamborra	16/0	0/0	980/974	2/1	2/25
Totani	0/0	0/0	0/0	1000/1000	0/0
Vartanyan	0/0	0/0	0/8	0/0	1000/992

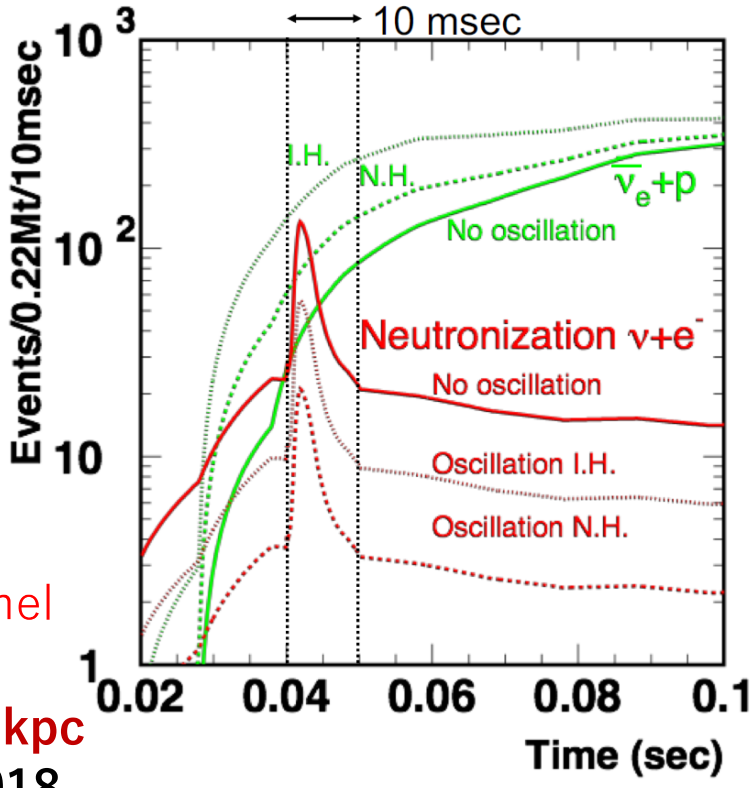
Table shows how many data sets for a given model were identified as which model for normal/inverted mass ordering.

Power of the statistics

- Direct observation of key features of SN mechanism

Neutronization burst

When shockwave pass through the neutrino sphere



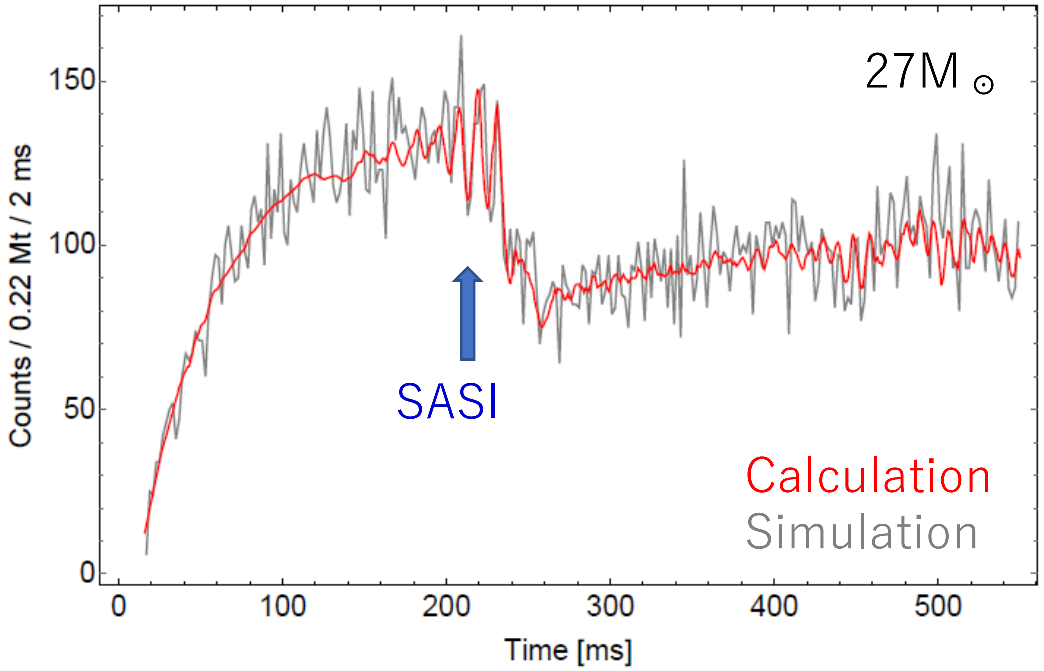
ES channel

SN at 10 kpc

Totani2018

SASI? Convection?

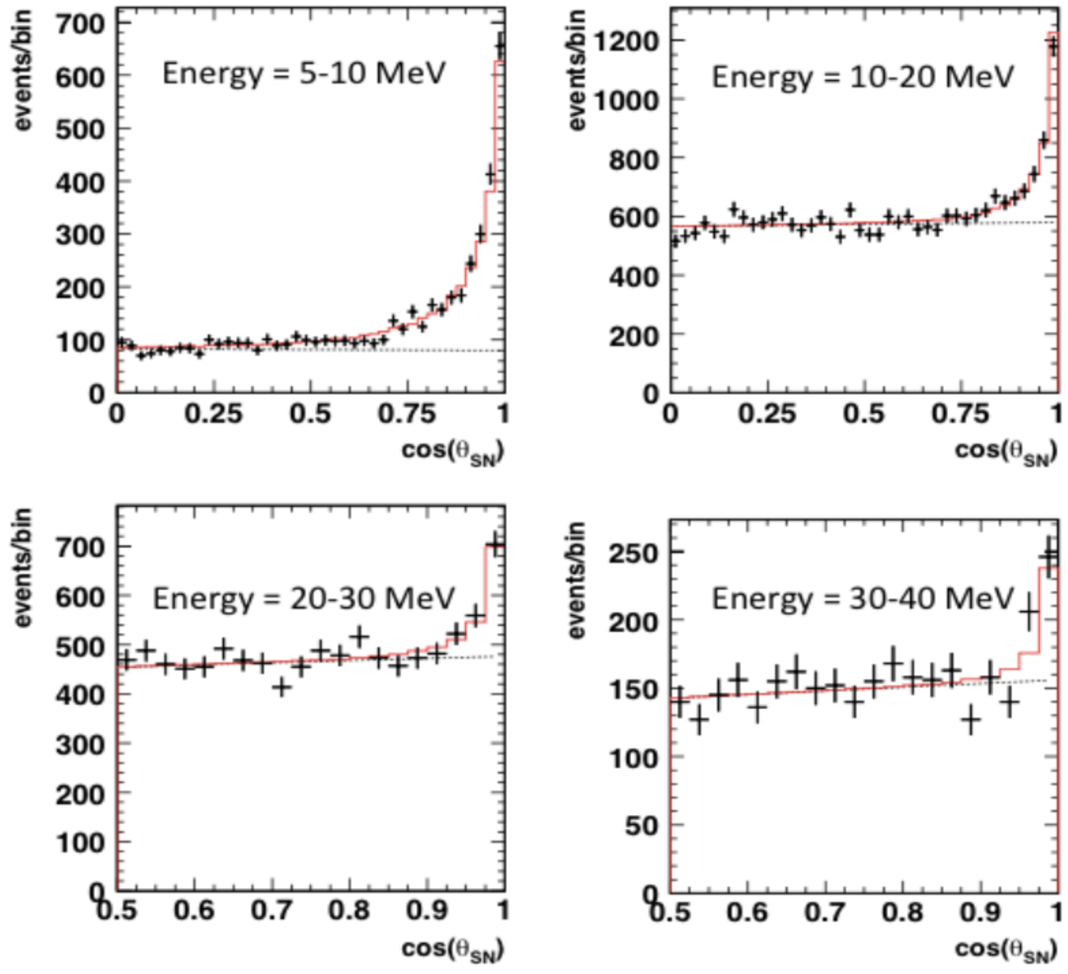
Shock revival by neutrino heating?
Key phenomenon of the burst!

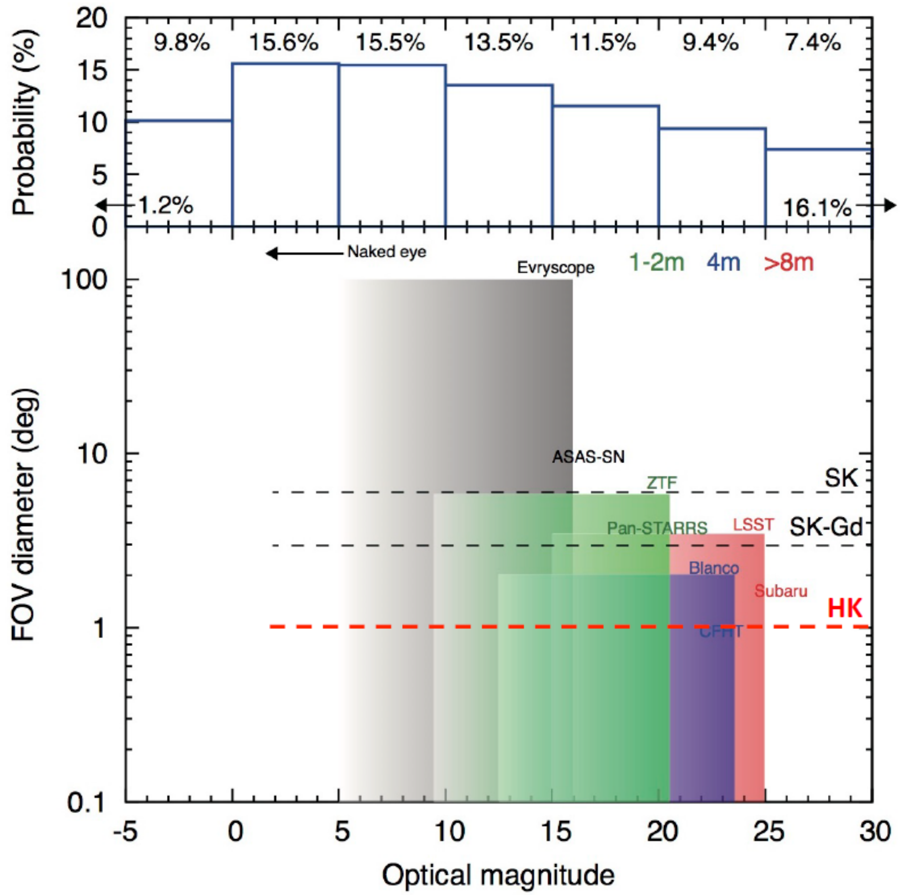


Pointing accuracy of HK

- Further help for Multi-messenger observation

Totani1998 10kpc



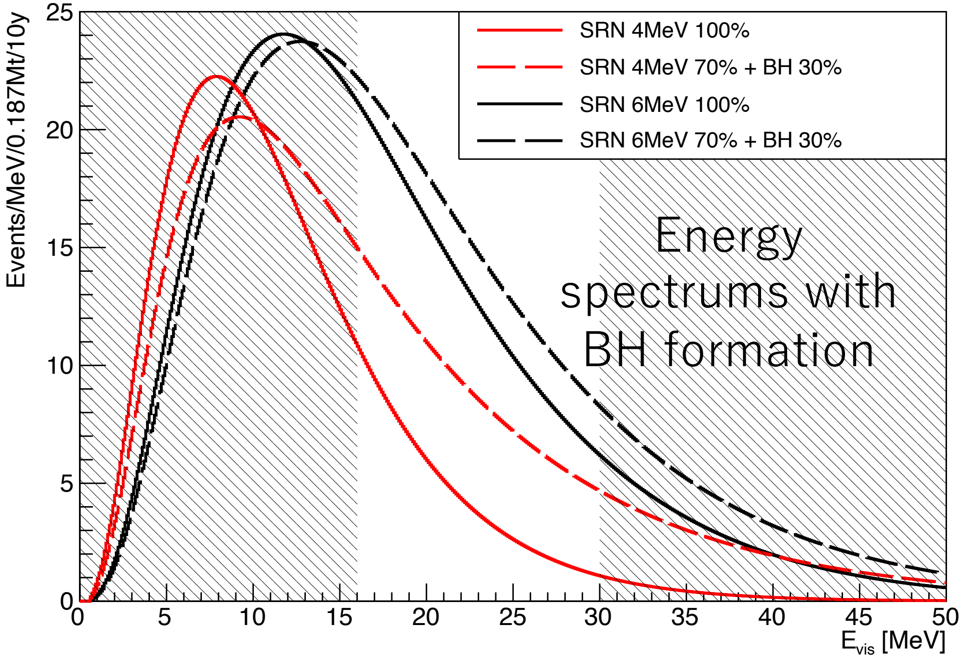


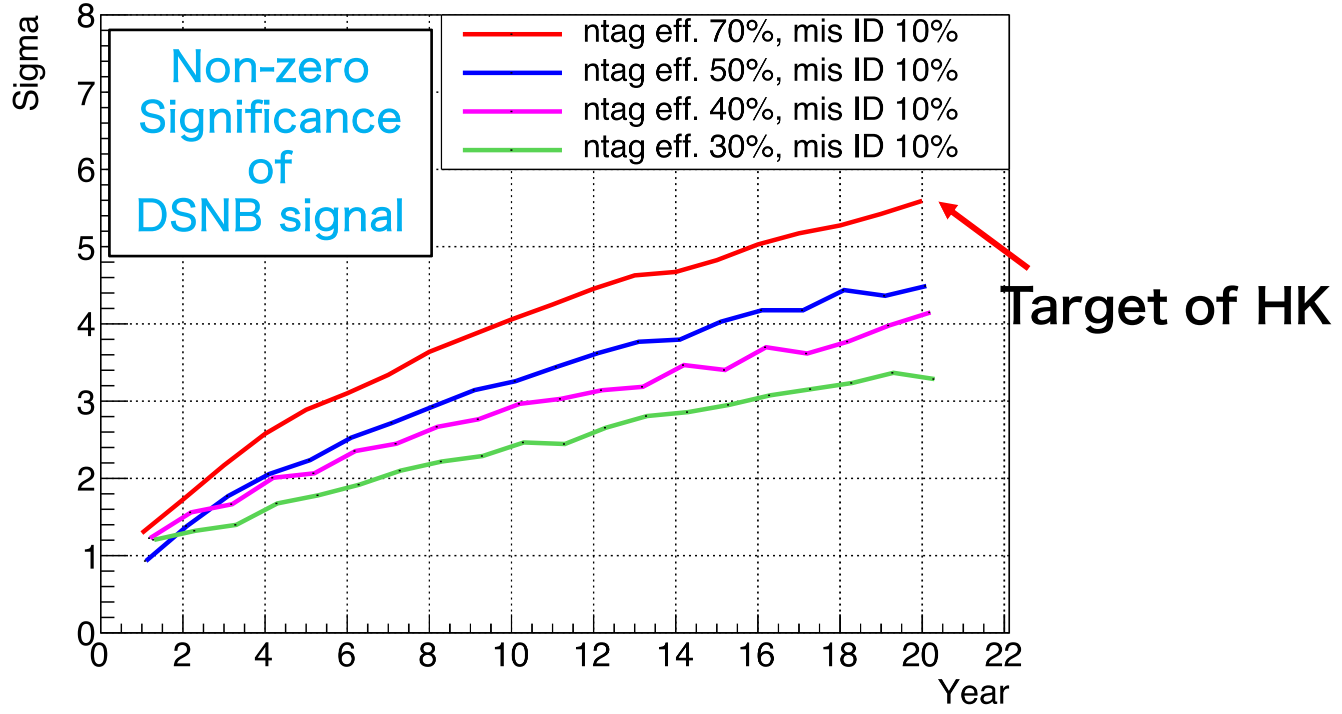
1～2° @10kpc SN

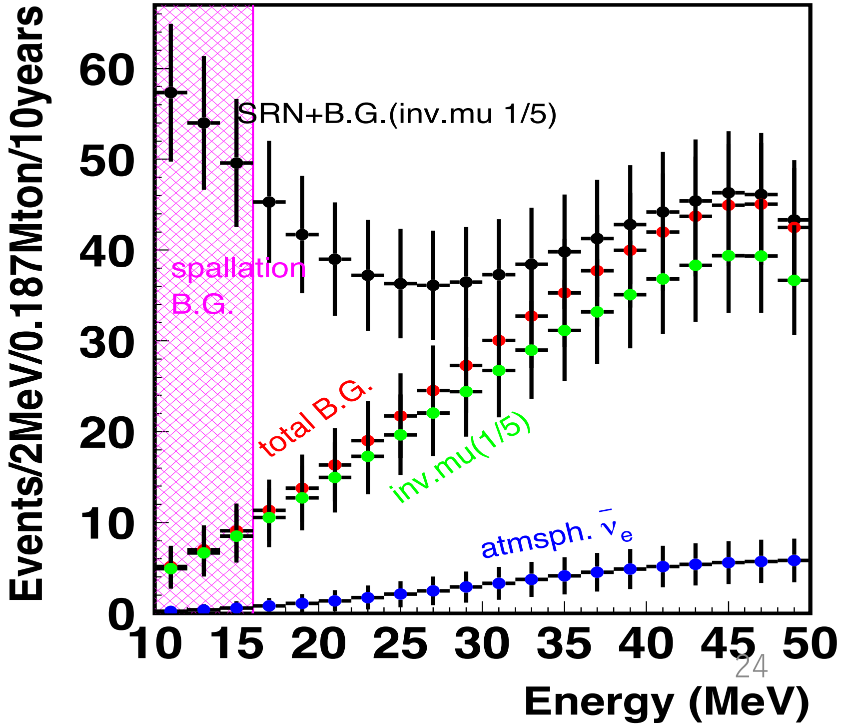
DSNB (SRN) with HK

DSNB(SRN) with Hyper-K

- DSNB(SRN) can be observed by HK in 10y with **~70±17** events.
- It is $> 4\sigma$ for SRN signal.
- We will go beyond the discovery and aim to measurement of SRN.







What is not covered here…

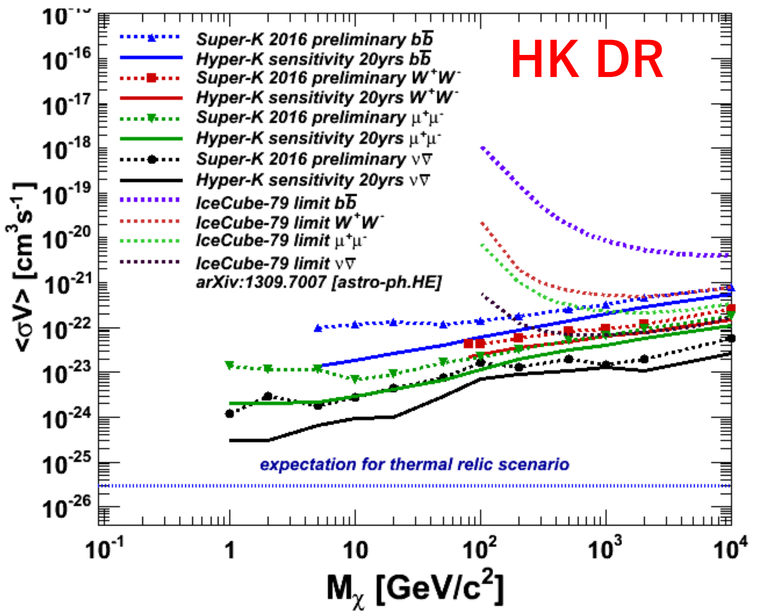
Indirect DM search

- Search for WIMPs annihilation in galactic center or halo.
- Recently SK 2016 preliminary is published as :
    - Phys. Rev. D 102, 072002 (2020)
- DM annihilation in the Sun or the Earth is also target.

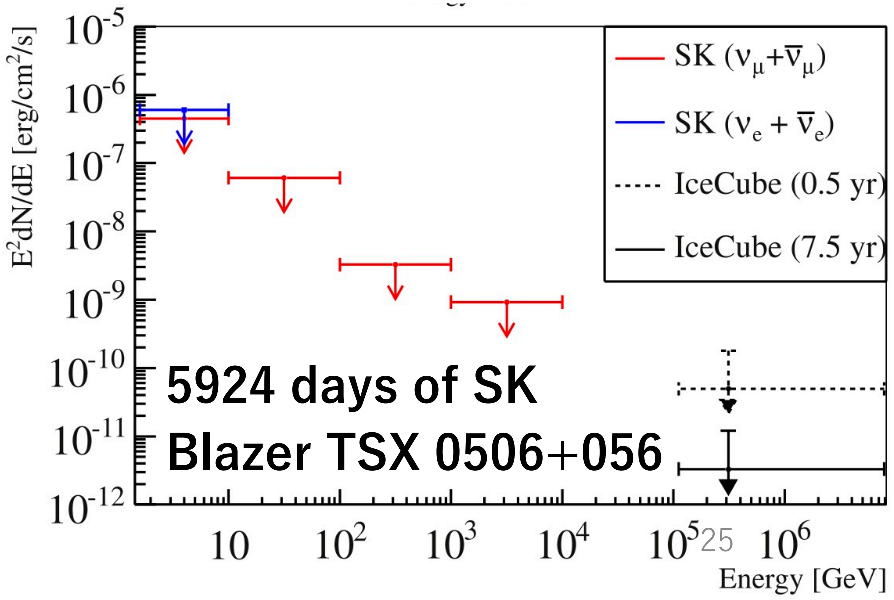
Neutrino follow-up with GW, Blazer

- Very (or Ultra) high energy neutrinos are detected by IceCube detector, corresponding to GW and Blazer.
- Super-K is also preforming follow-up analysis, but have not found important event excess.
    - GW: Astrophys. J. Lett. 857, L4 (2018), Astrophys. J. L., 830, 1 (2016), M. Laumoureux at Neutrino 2020 (poster)
    - Blazer: Astrophys. J. Lett. 887, L6 (2019)
- Hyper-K will improve sensitivity with the detector area and volume.

90% upper limit, DM annihilation in galactic center



90% upper limit, neutrino flux from blazer



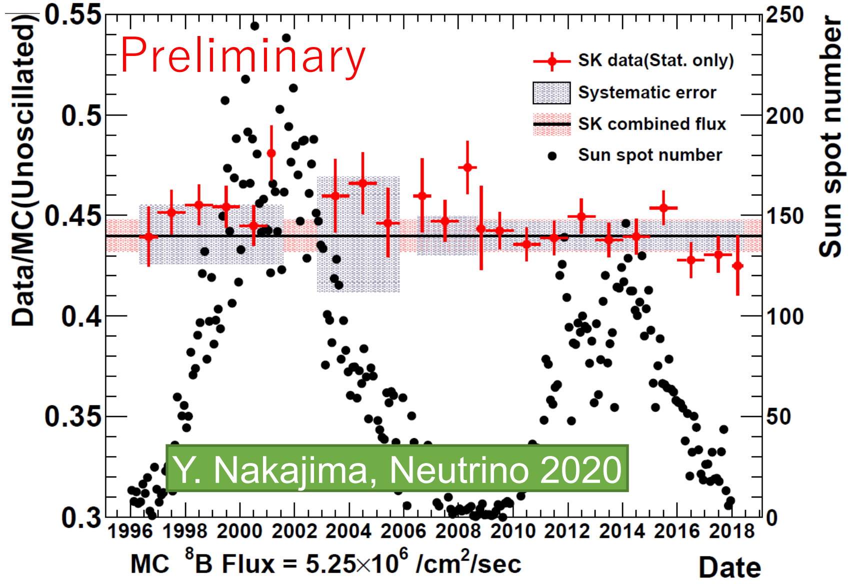
What is not covered here…

Solar neutrinos

- Importance of solar nu meas. in particle physics and astrophysics
  - Precision measurement, Δm^2_{21}
    - Day/Night asymmetry
  - Solar nu spectrum up-turn

  - Discovery of Hep neutrino
  - Variation of solar ν flux

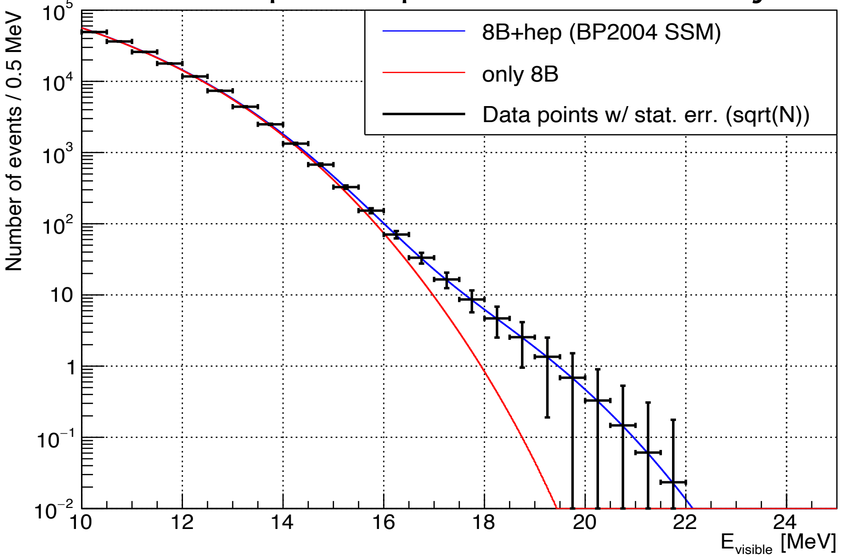
Yearly ν variation & Sun spots (SK)



Hep process neutrino

- Undiscovered solar neutrino in pp-chain, with small branching ratio.
- With Hyper-K 10 years, there is chance to discover.
- → **To test the solar models.**
  - 1.8 ~ 3 σ, 10y

^{8}B and Hep nu spectrum, HK 10 years



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.