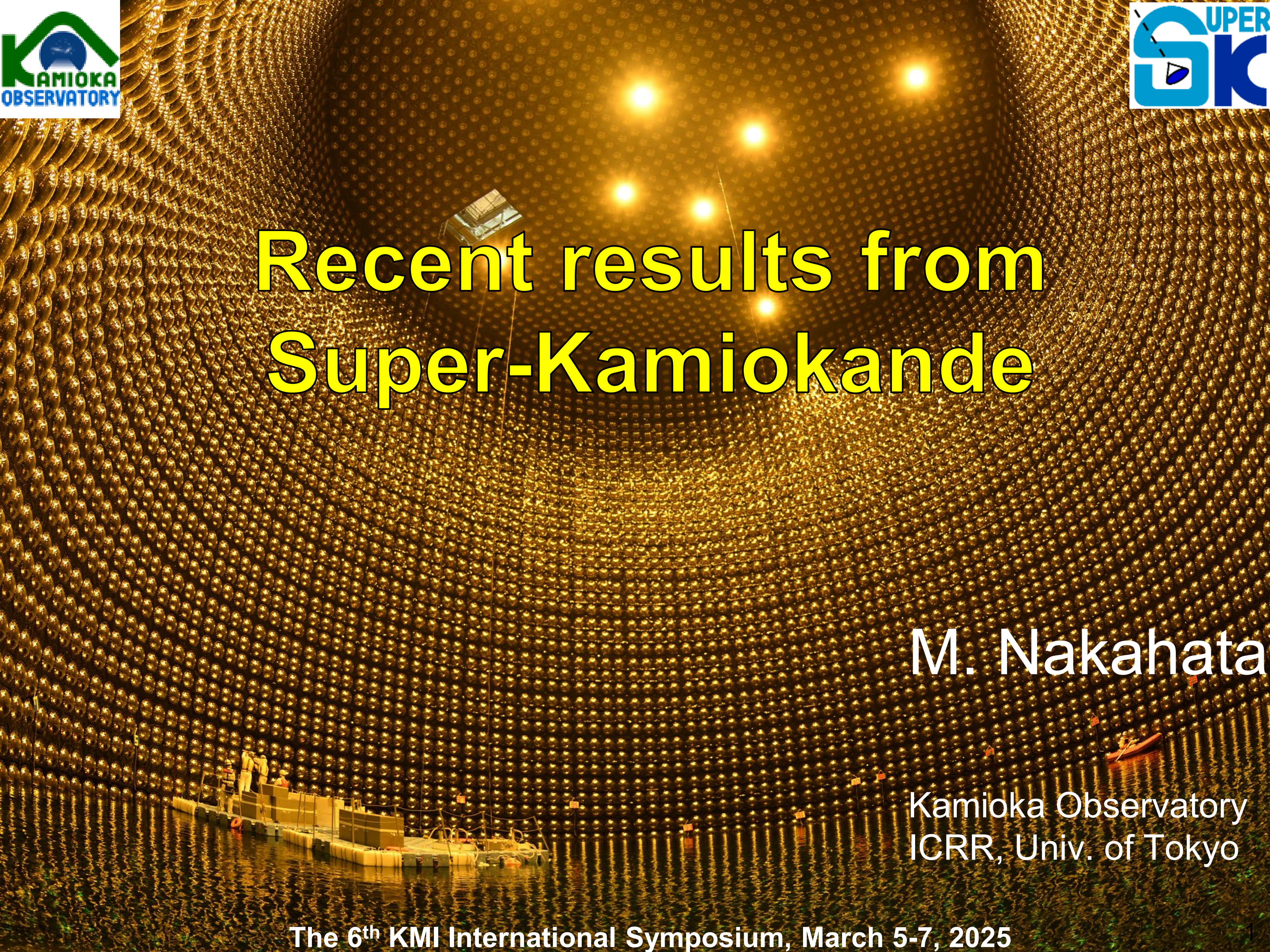


Recent results from Super-Kamiokande

M. Nakahata

Kamioka Observatory
ICRR, Univ. of Tokyo

The 6th KMI International Symposium, March 5-7, 2025

Contents

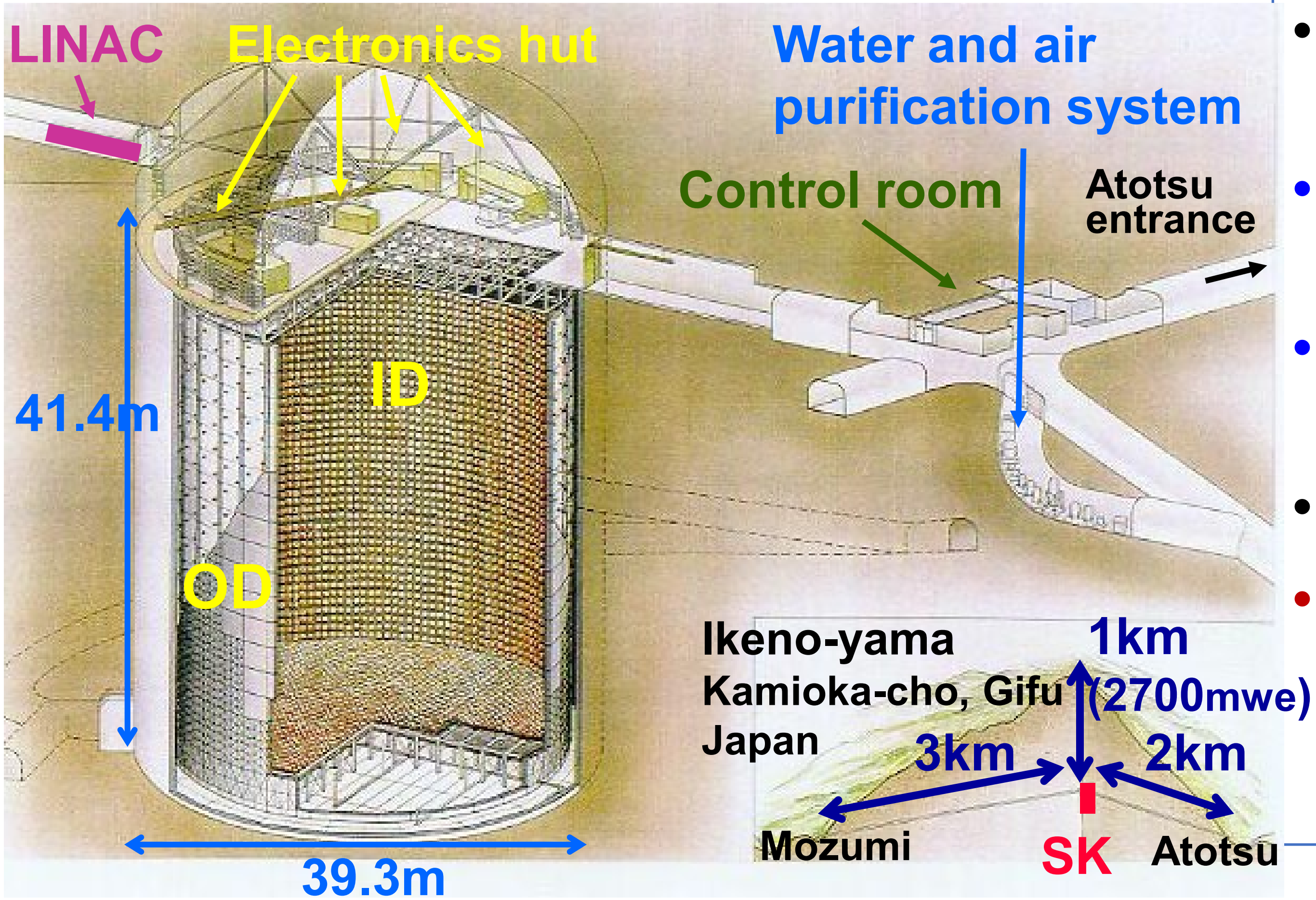
- Super-Kamiokande(SK,Super-K) detector
- Latest results from Super-K
  - Atmospheric neutrinos
  - Solar neutrinos
  - Proton decay searches
- SK-Gd phase
  - Physics with SK-Gd
  - Gd-loading in 2020 and 2022
  - Initial results with Gd-loaded data
- Summary

The Super-Kamiokande Collaboration

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
BC Institute of Technology, Canada
Boston University, USA
BMCC/CUNY, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France/Japan
INFN Bari, Italyl
NFN Napoli, Italy
INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
Keio University, Japan
KEK, Japan
King's College London, UK
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
University of Minnesota, USA
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
Osaka Electro-Communication Univ.,Japan
University of Oxford, UK
Rutherford Appleton Laboratory, UK
Seoul National University, Korea
University of Sheffield, UK
Shizuoka University of Welfare, Japan
University of Silesia in Katowice, Poland
Sungkyunkwan University, Korea
Tohoku University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, Japan
University of Toyama, Japan
TRIUMF, Canada
Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
Yokohama National University, Japan

~230 collaborators from 54 institutes in 11 countries

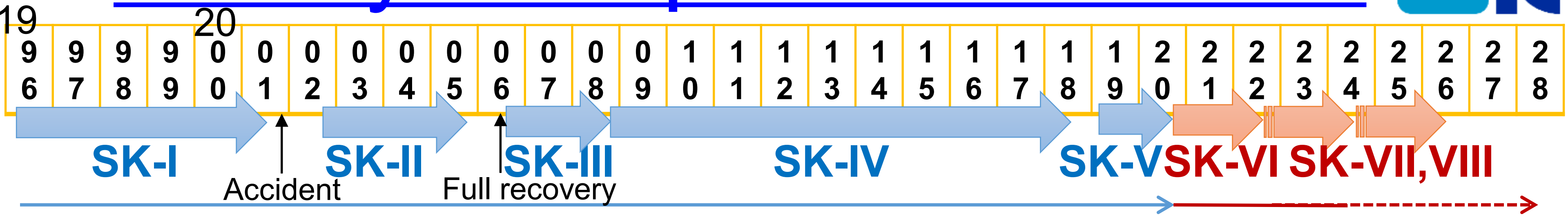
Super-Kamiokande detector



- 50 kton water Cherenkov
- 32kt photo-sensitive volume
- 22.5kt fid. vol. (2m from ID wall)
- SK-I: April 1996~
- SK-VIII is running

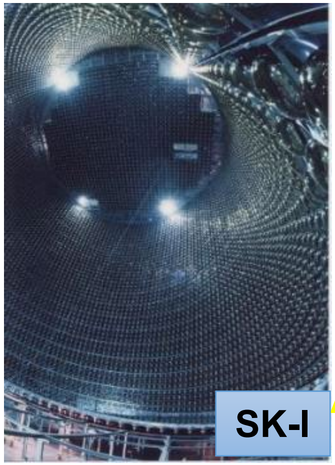
Inner Detector (ID) PMT: ~11,000 20-inch PMTs
Outer Detector (OD) PMT: 1885 8-inch PMTs

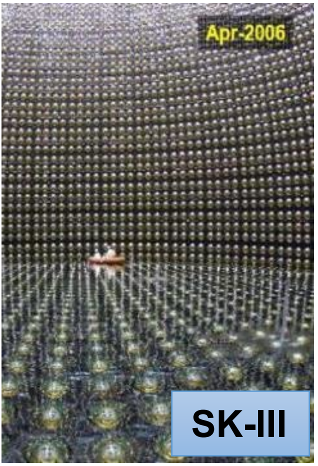
History of Super-Kamiokande



“SK” (pure water)

“SK-Gd” (Gd-loaded)





Water system
For SK-Gd
NIM A 1027
(2022) 166248

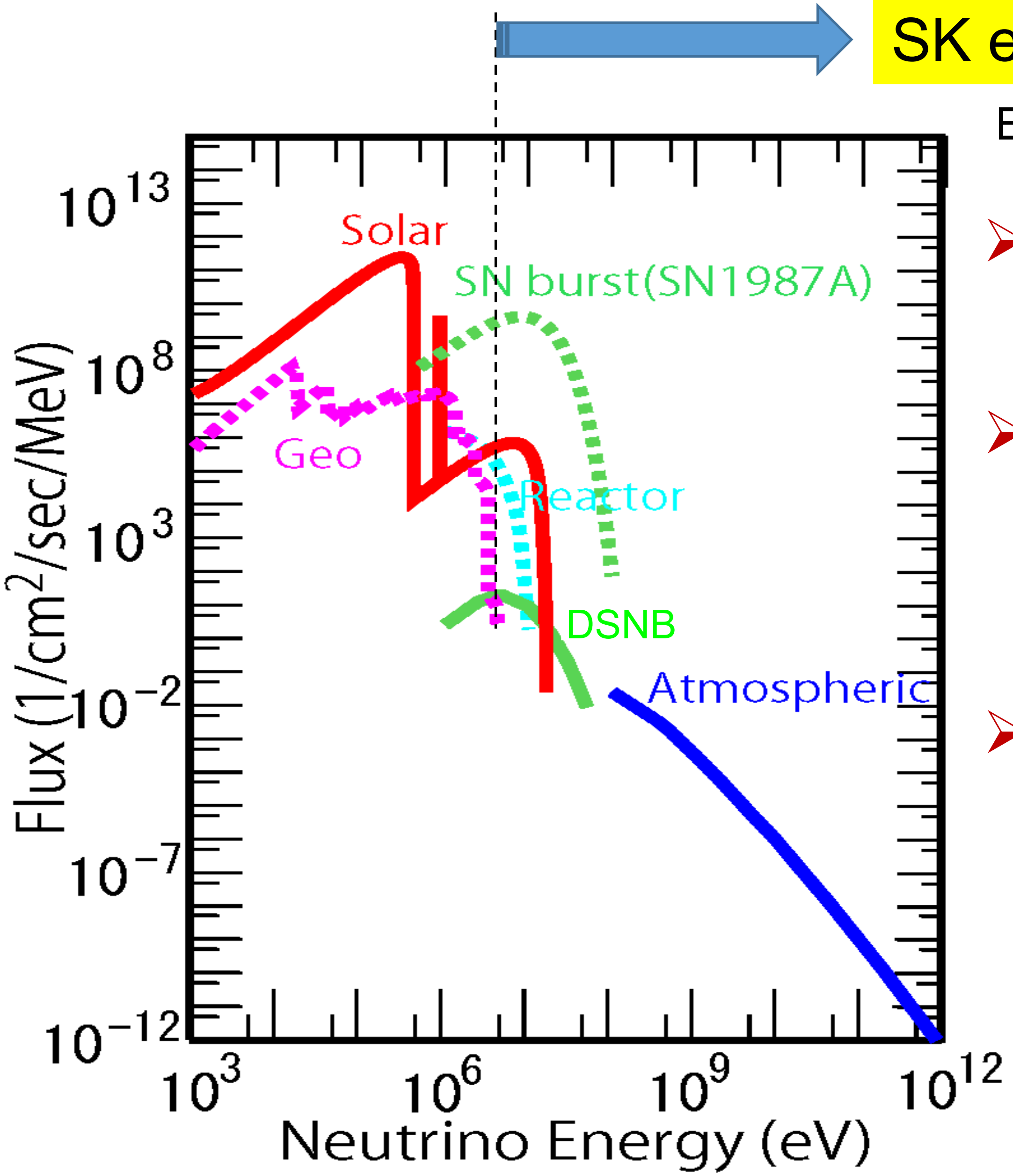
11146 ID PMTs (40% coverage)	**5182 ID PMTs (19% coverage)**	**11129 ID PMTs (40% coverage)**	**Electronics Upgrade**	**Refurbishment for SK-Gd**	**Neutron tagging with Gd**
4.49 MeV	**6.49 MeV**	**4.49 MeV**	**3.49 MeV**	**(~3.49 MeV)**	
1496 days	**791 days**	**548 days**	**2970 days**	**(~380 days)** ***(preliminary)***	

Gd concentration
SK-VI: 0.01%
(18 Aug. 2020-)
SK-VII~: 0.03%
(5 Jul. 2022 ~)

- 🟩 **Analysis energy threshold (recoil electron kinetic energy)**
- 🟪 **Live time for solar neutrino analysis**

Total live time for current oscillation analysis:
5805 days (SK-I~IV, for solar)
6511 days (SK-I~V, for atmospheric)

Neutrino energy range covered by SK



SK energy range

Energy threshold: 3.5 MeV
(in kinetic energy)

- Solar neutrinos
  - ~3.5(thr.) ~ 20 MeV
  - ~15 events/day
- Supernova neutrinos
  - A few ~ 20 MeV
  - Several thousand events
    (for 10kpc)
  - Expect a few DSNB per year
- Atmospheric neutrinos
  - ~100 MeV ~ a few 100 GeV
  - ~ 10 events/day

Study neutrino oscillations using those neutrinos.
Also, study astrophysics with those neutrinos.

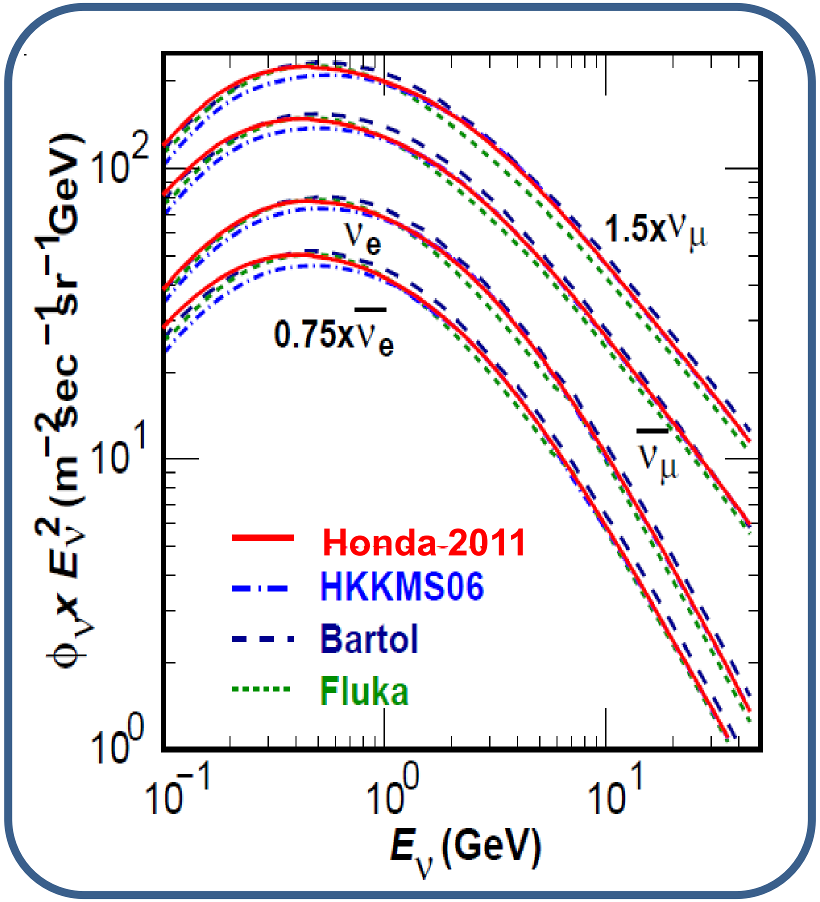
Atmospheric Neutrinos

- Cosmic rays interact with air nuclei and the decay of pions and kaons produce neutrinos

$$P + A \to N + \pi^{\pm} + X$$

$$\hookrightarrow \mu^{\pm} + \boxed{\overset{(-)}{\nu}_{\mu}}$$

$$\hookrightarrow e^{\pm} + \boxed{\overset{(-)}{\nu}_{e}} + \boxed{\overset{(-)}{\nu}_{\mu}}$$

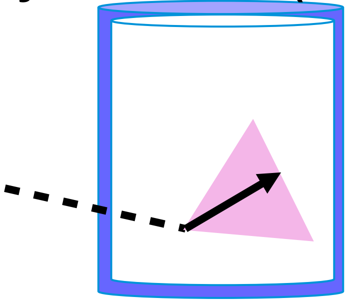


Honda et al., Phys. Rev. D83, 123001 (2011).

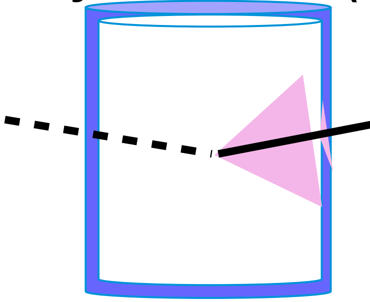
- νs travel 10 – 10,000 km before detection
- Both ν_μ and ν_e (ν_μ/ν_e = 2 at low energy)
- Both neutrinos and anti-neutrinos
  - ~ 30% of final analysis samples are antineutrinos
- Flux spans many decades in energy ~100 MeV – 100TeV
- Excellent tool for broad studies of neutrino oscillations

Atmospheric Neutrino Data

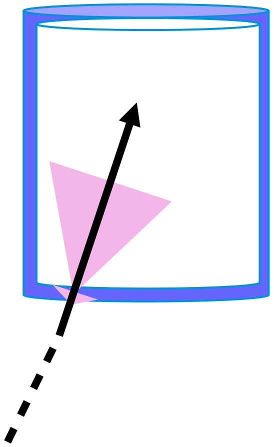
Fully Contained (FC)

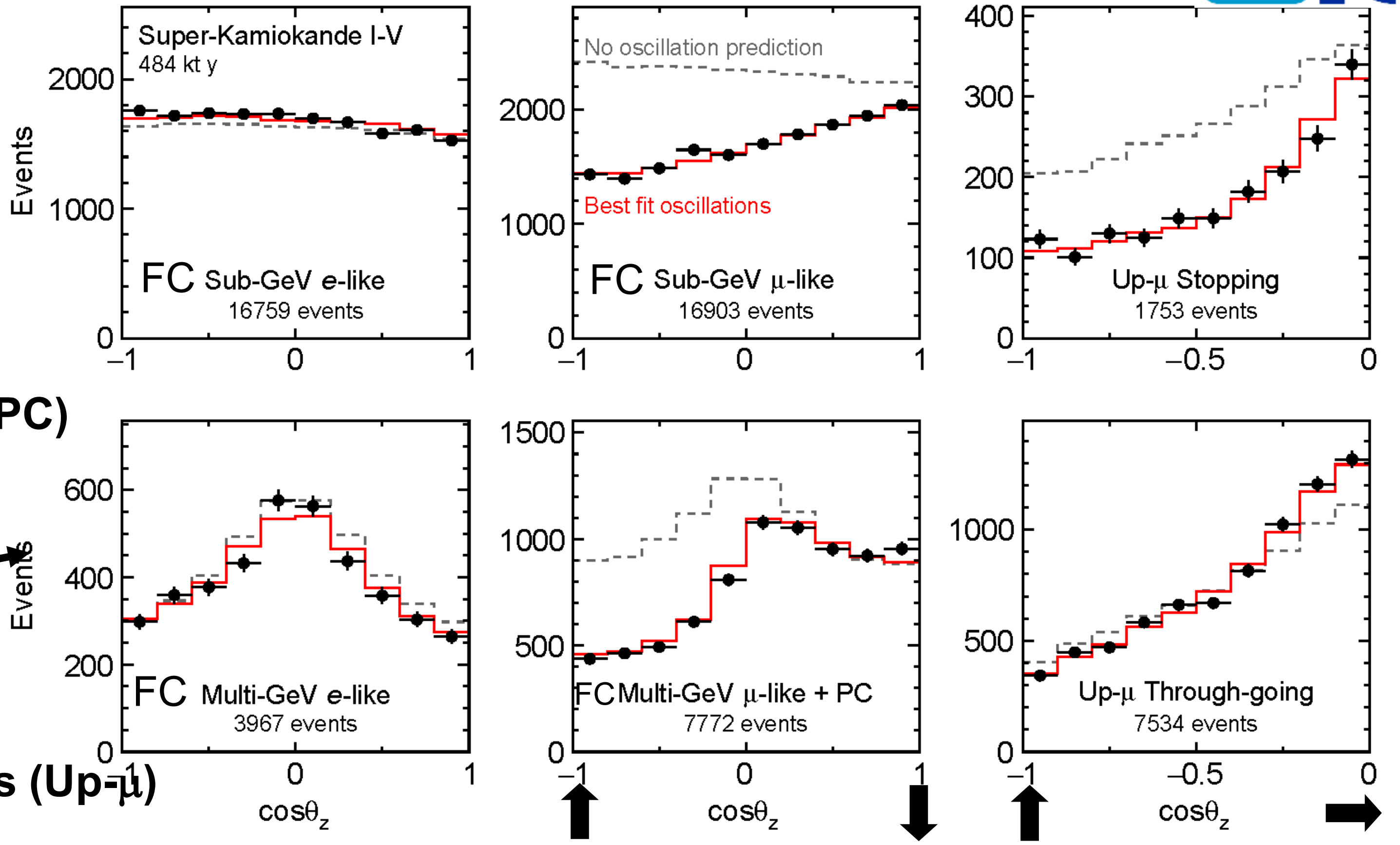


Partially Contained (PC)



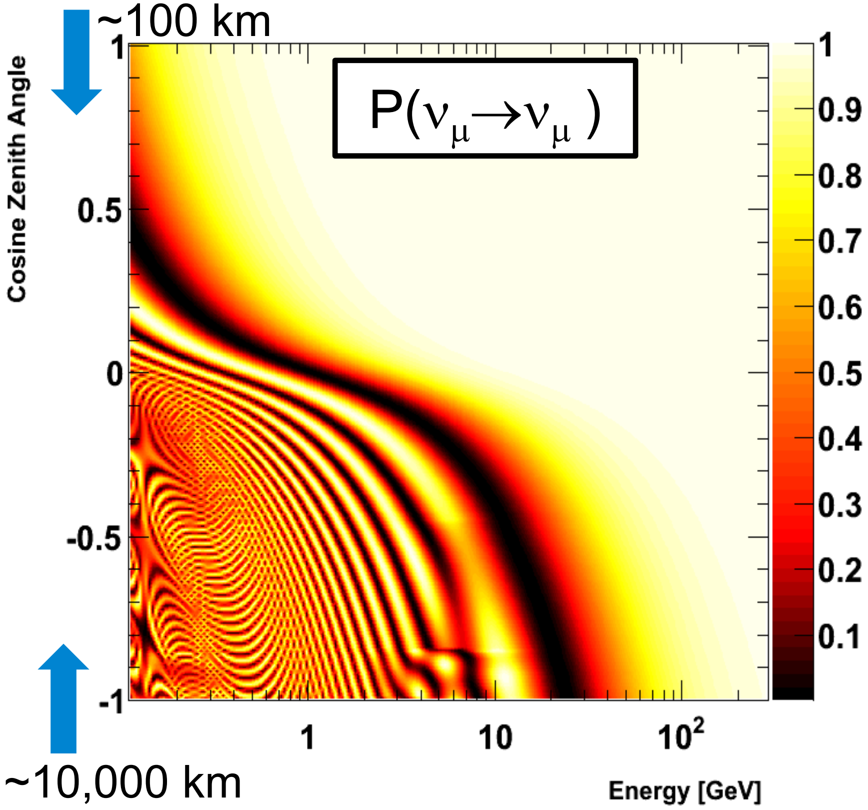
Upward-going Muons (Up-μ)

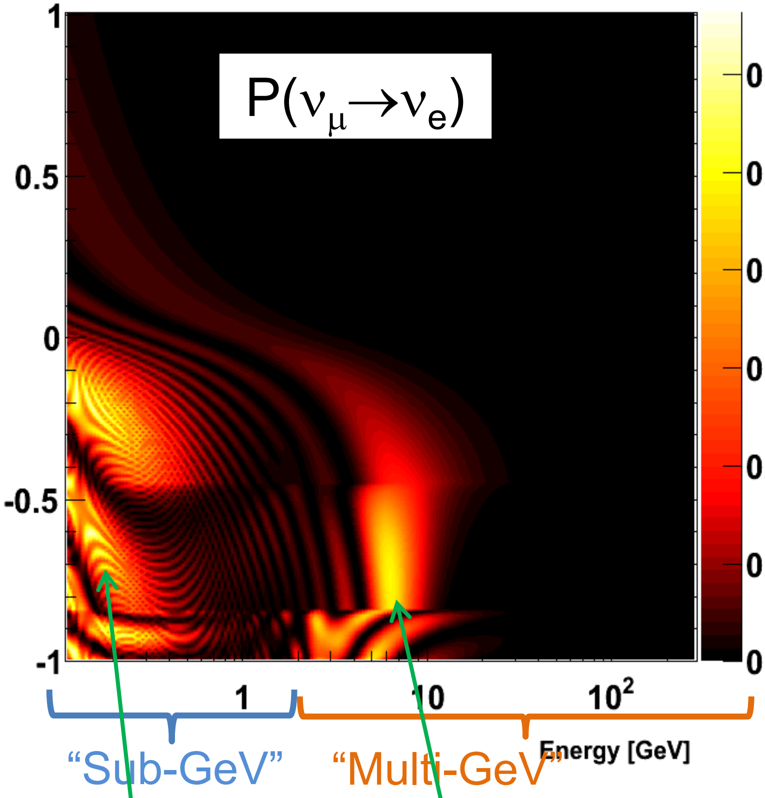




- **6,511 days** of atmospheric neutrino data (Through July 2020)
- **66,002 events** in total (52,628 FC, 4,086 PC, and 9,288 UP-μ)
- **29 analysis samples**: Sub-divided by event topology (FC/PC,UP-μ), energy range, e/μ–like, and # of rings, number of neutron candidates. Multi-GeV e-like samples are divided into ν-like and $\overline{\nu}$-like samples in order to improve sensitivity for mass hierarchy.

Oscillation probability maps



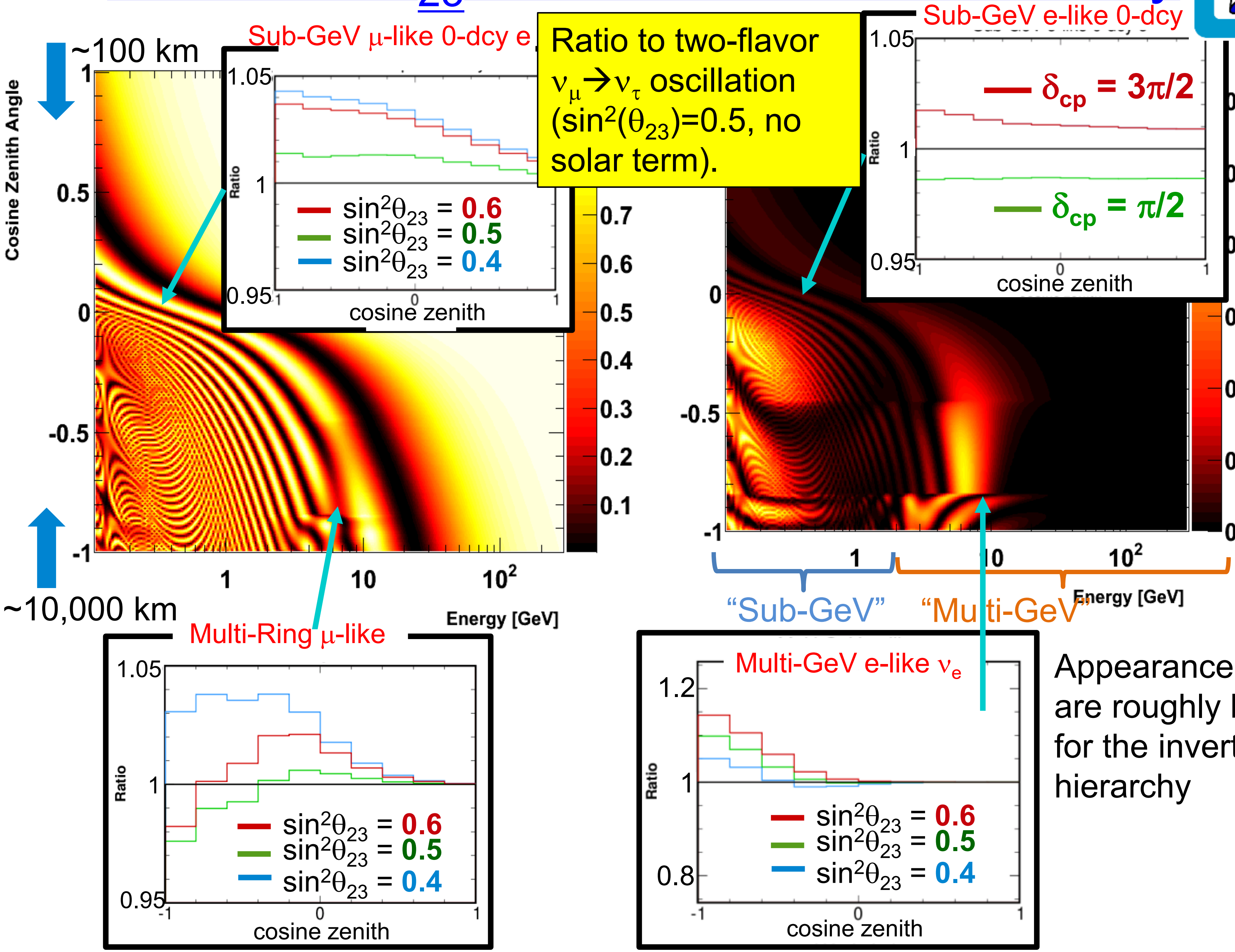


resonant oscillation due to finite θ_{13}

due to solar term

Oscillation parameters used here are
$\sin^2\theta_{12}=0.31$, $\sin^2\theta_{23}=0.5$, $\sin^2\theta_{13}=0.025$
$\Delta m^2_{12}=7.6\times10^{-5}$ eV^2, $\Delta m^2_{23}=2.5\times10^{-3}$ eV^2
Normal Hierarchy (NH)
δCP=0.0

Effects of θ_{23}, δCP and mass hierarchy

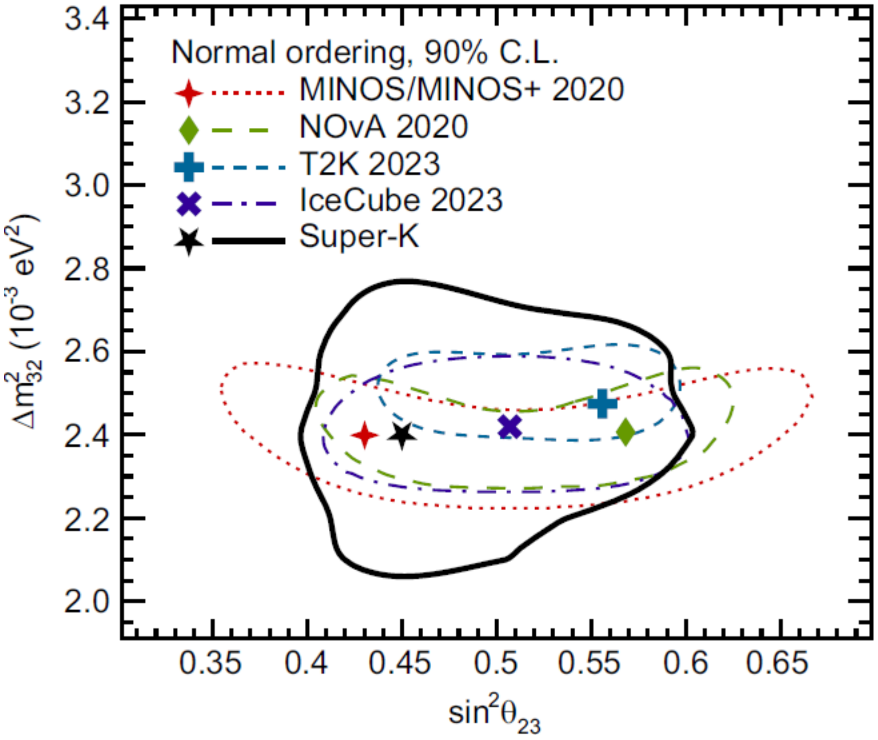


Ratio to two-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillation ($\sin^2(\theta_{23})$=0.5, no solar term).

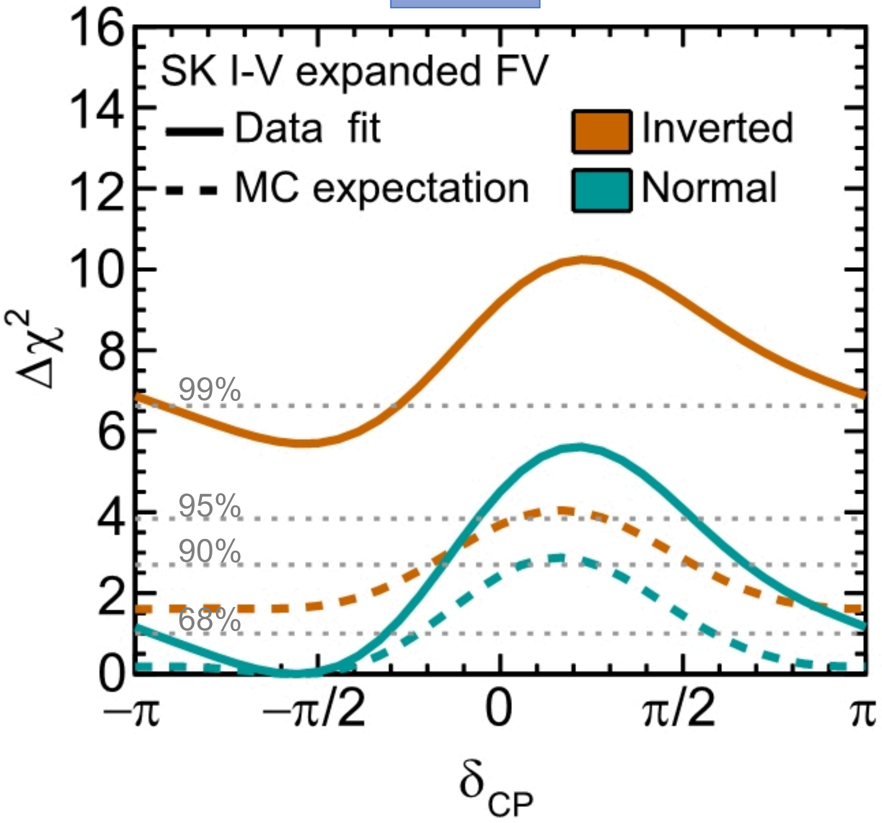
Appearance effects are roughly halved for the inverted hierarchy

Atm. ν oscillation analysis (SK only)

$sin^2\,\theta_{23}$ vs. Δm^2_{32}



δ_{CP}



Best-fit: (for both NH and IH)

- $sin^2\,\theta_{23} = 0.45$
- $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$

$\delta_{CP} \approx -\frac{\pi}{2}$ **is favored.**

Normal mass hierarchy is favored.

Inverted hierarchy is disfavored with 92.3 % C.L.

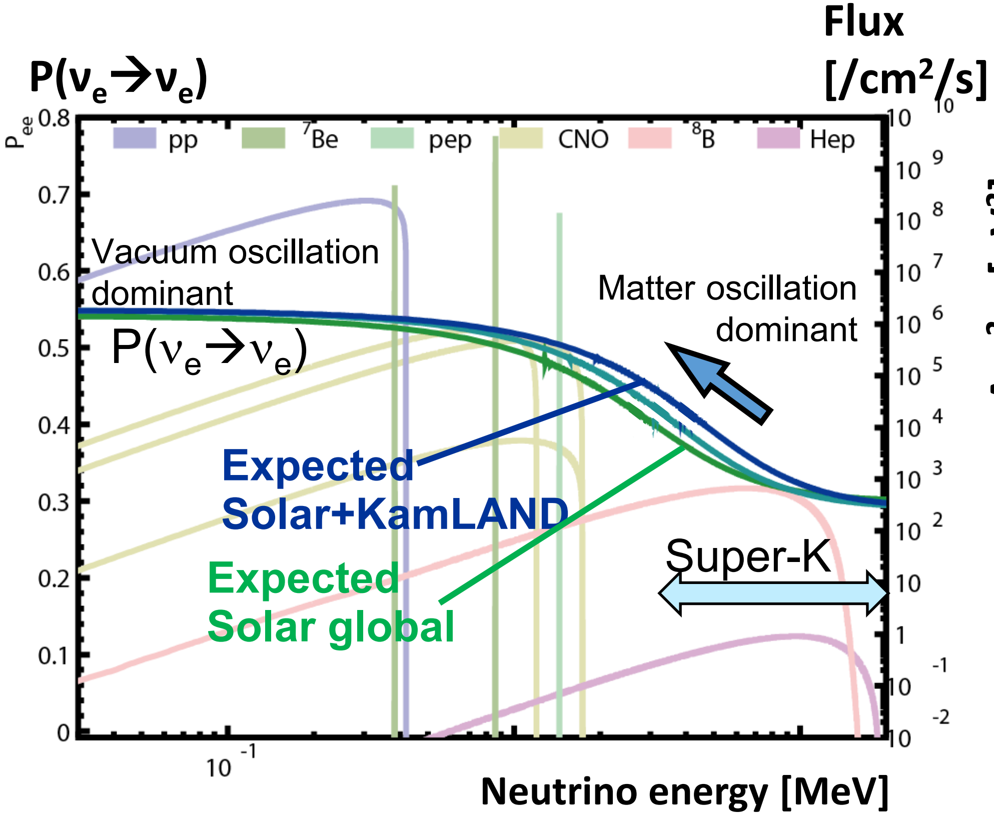
Solar neutrinos

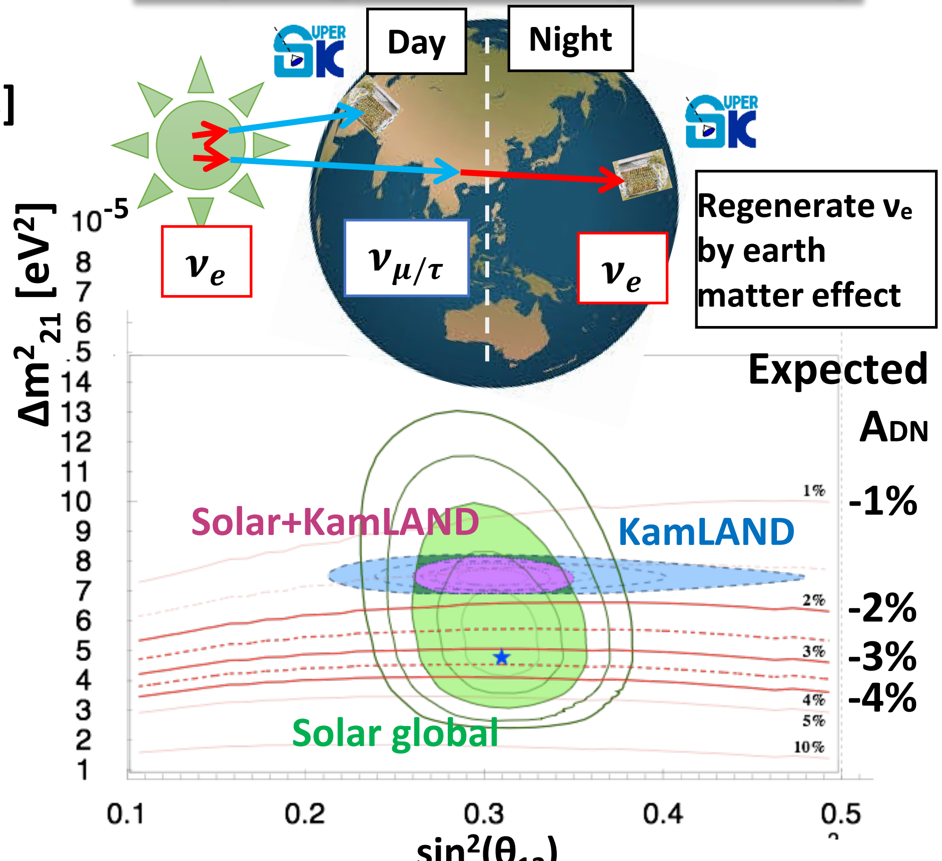
- High statistics measurement of ^{8}B solar neutrinos by $\nu + e^- \rightarrow \nu + e^-$ scattering
  - Possible time variation of the flux
  - Energy spectrum distortion due to solar matter effect
  - Day-night flux asymmetry due to earth matter effect

$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$

Spectrum distortion

Day-Night flux asymmetry

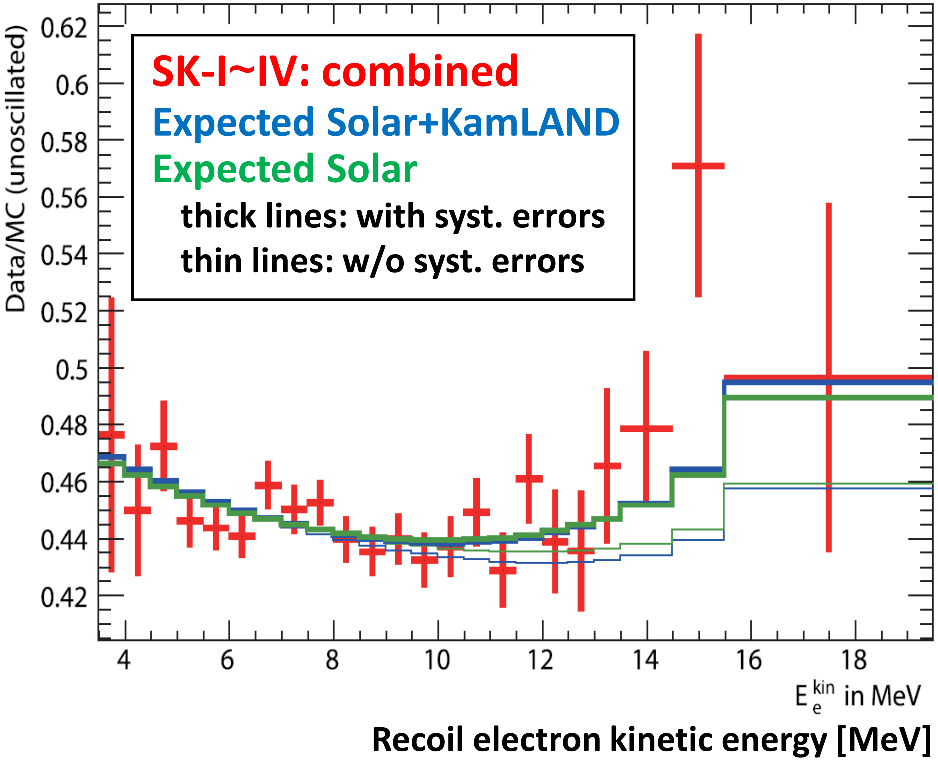




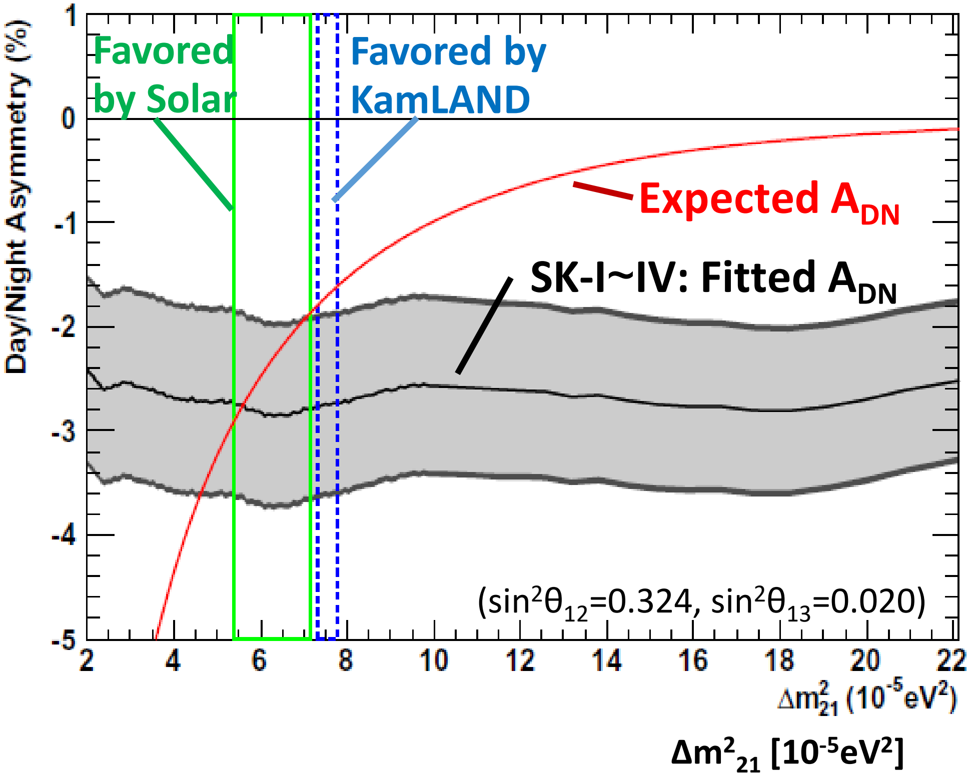
SK-I~IV solar neutrino data

Phys. Rev. D 109, 092001 (2024) SK 5805 days

Energy spectrum



Day/Night asymmetry (A_{DN})

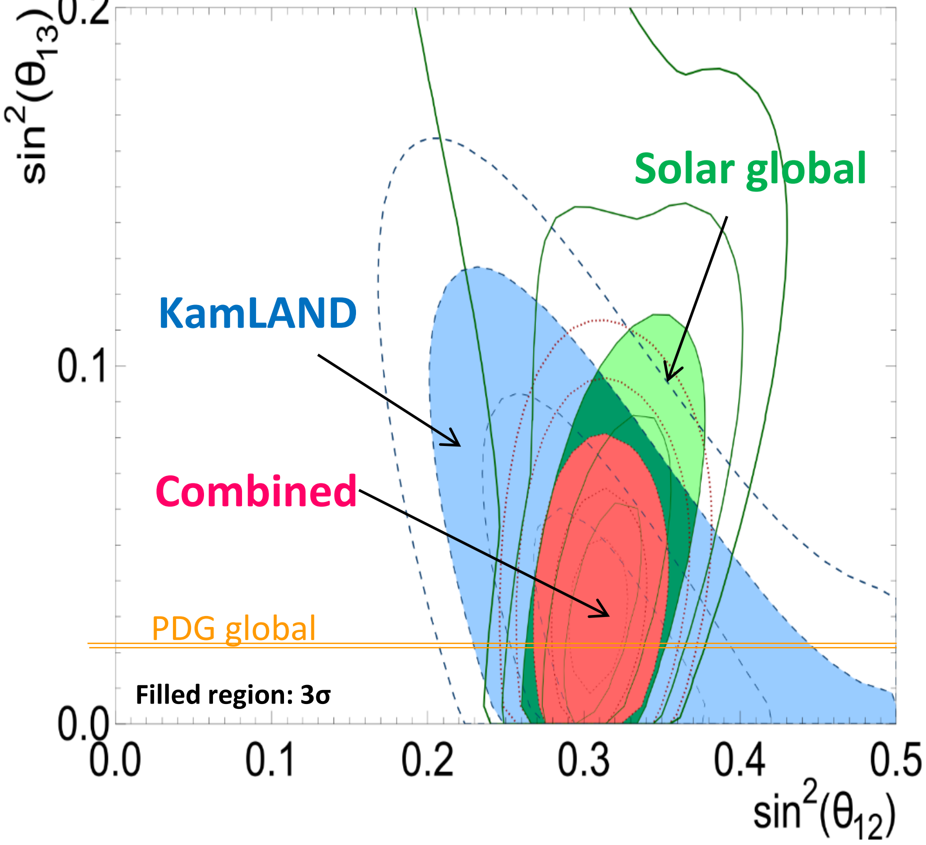


- Flat (i.e. energy independent) $P(\nu_e \rightarrow \nu_e)$ is disfavored with 1.5 sigma.
- Fitted A_{DN}(%)=-2.86 ±0.85(stat)±0.32(syst): 3.2σ different from 0 ($\sin^2\theta_{12}$=0.324, $\sin^2\theta_{13}$=0.020, and $\Delta m^2_{21}=6.1\cdot10^{-5}$eV^2)

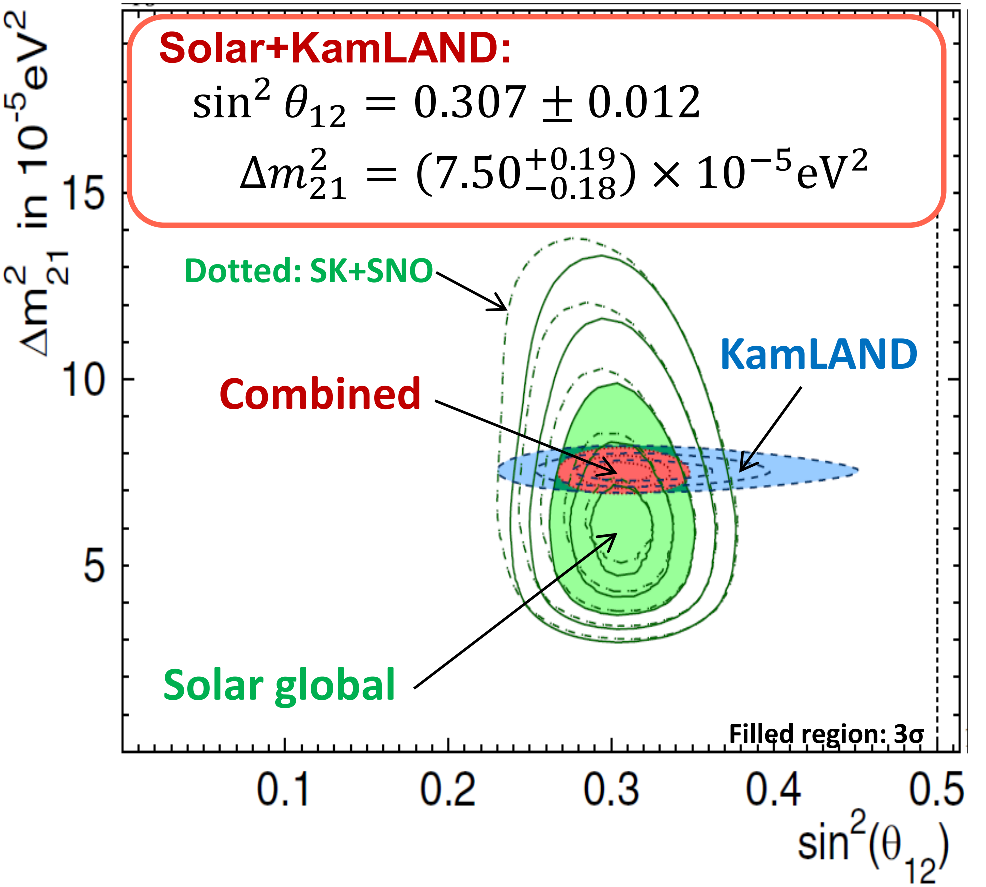
Solar ν oscillation results

Phys. Rev. D 109, 092001 (2024) **SK 5805 days**

Theta13 vs. Theta12



Solar ν oscillation parameters



Solar+KamLAND:

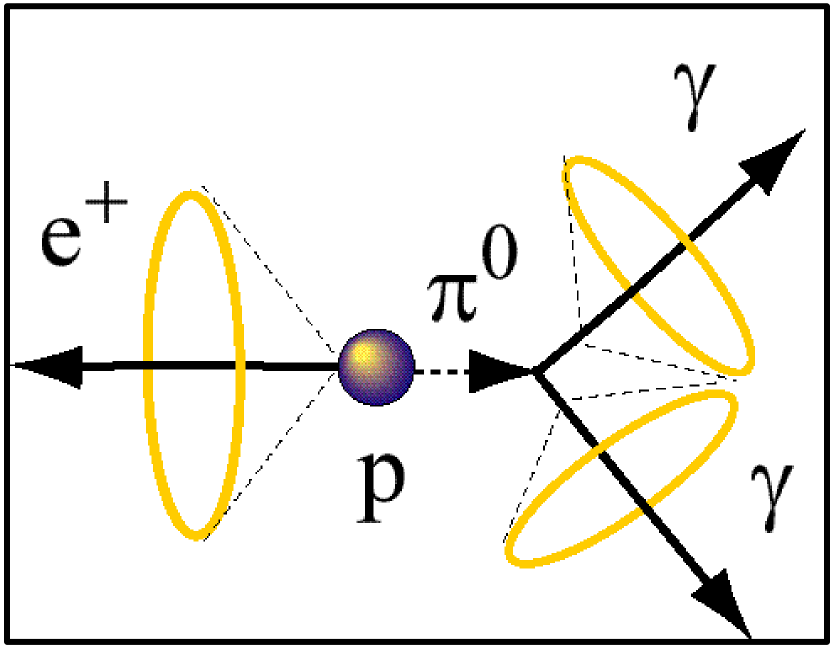
$$\sin^2\theta_{12} = 0.307 \pm 0.012$$

$$\Delta m^2_{21} = (7.50^{+0.19}_{-0.18}) \times 10^{-5}\mathrm{eV}^2$$

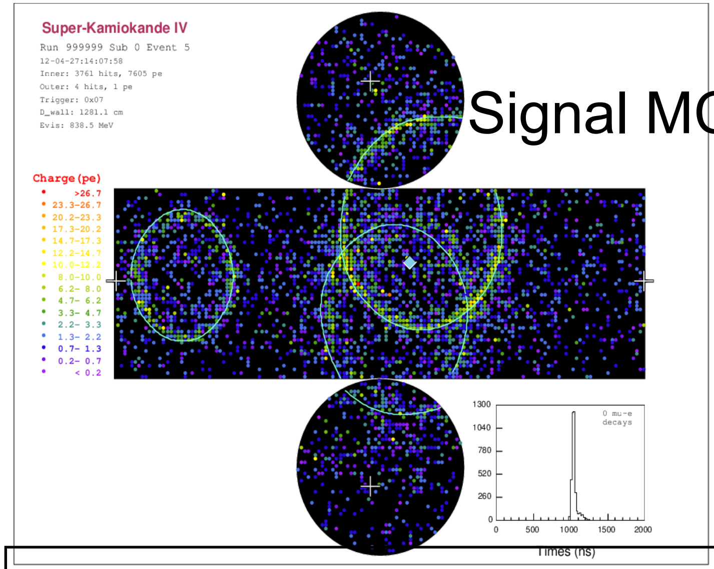
- Finite θ_{13} can be seen with ~2σ level.
- ~1.5 σ level tension in $\boldsymbol{\Delta m^2_{21}}$ between Solar global analysis and KamLAND.

Search for Proton decays

Search for $p \rightarrow e^+\pi^0$



- **Positron and π^0 run back-to-back**
  - Momentum 459 MeV/c
- **All particles in the final stable are visible with Super-K**
  - **Able to reconstruct p mass and momentum**


Super-Kamiokande IV
Run 999999 Sub 0 Event 5
12-04-27:14:07:58
Inner: 3761 hits, 7605 pe
Outer: 4 hits, 1 pe
Trigger: 0x07
D_wall: 1281.1 cm
Evis: 838.5 MeV

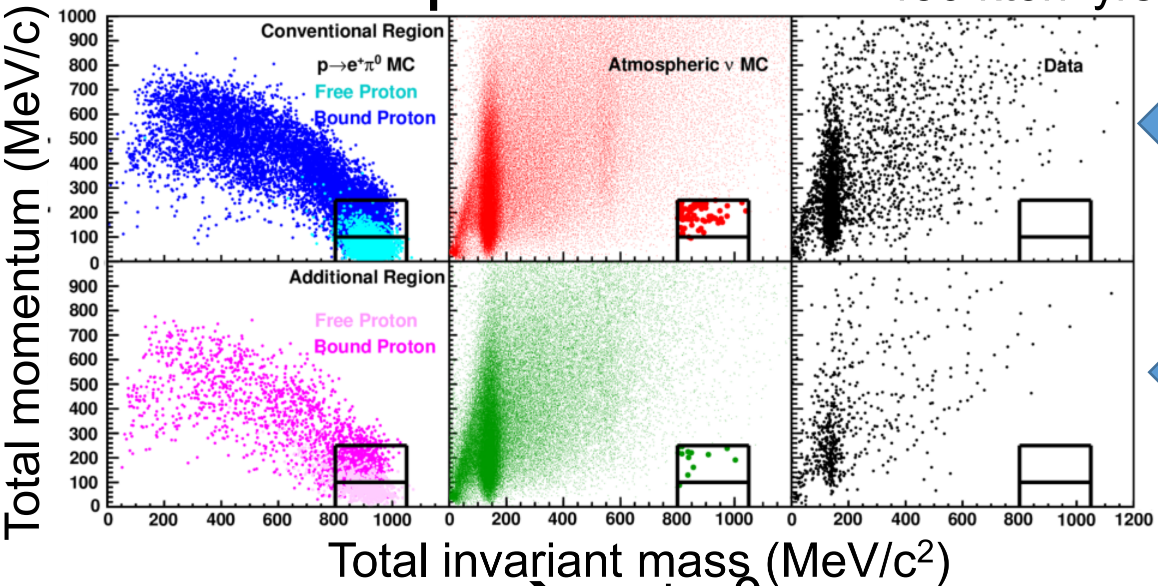
Signal MC

- Event selection:
  - All particles are fully contained in FV
    - (New!) Expand FV (dwall >200 cm → > 100 cm)
  - 2 or 3 rings (two of them from π0)
  - All particles are e-like, w/o Michel-e
  - $85 < M_{\pi 0} < 185$ MeV/c^2
  - $800 < M_p < 1050$ MeV/c^2
  - $100 < P_{tot} < 250$ or $P_{tot} < 100$MeV/c
  - Neutron-tagging (SK-IV)
    - Further reduce bkg by ~50%

Total mass vs Total momentum

p → $e^+\pi^0$

450 kton･yrs data



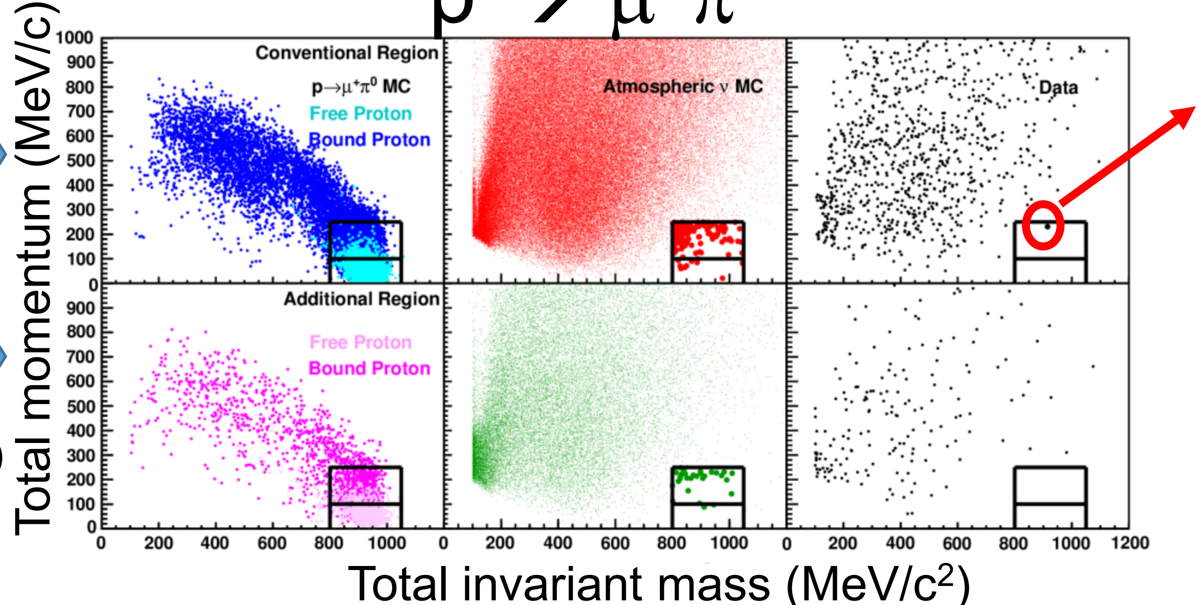
Conventional FV
(D_{wall} > 2m)

Additional FV
(D_{wall} =1~2m,
~ 20 % increase)

p → $\mu^+\pi^0$

Conventional FV
(D_{wall} > 2m)

Additional FV
(D_{wall} =1~2m,
~ 20 % increase)



One event
observed.
(expected BG:
0.94 evens)

Results on $p\rightarrow e^+\pi^0$ and $p\rightarrow \mu^+\pi^0$

	Eff(%)	Exp. BG (event)	Observed (event)
$p\rightarrow e^+\pi^0$			
Lower	18.1	0.02	0
Upper	19.5	058	0
$p\rightarrow \mu^+\pi^0$			
Lower	17.3	0.05	0
Upper	17.2	0.89	1

Lifetime limt (90% CL,450 kton・yrs data)

$p\rightarrow e^+\pi^0$: > $2.4\text{x}10^{34}$ years

$p\rightarrow \mu^+\pi^0$: > $1.6\text{x}10^{34}$ years

Nucleon decay limits for various decay modes

$p\to e^+\pi^0$ (450 kt·yrs)
$\tau/Br > 2.4 \times 10^{34}$ years

$p\to \mu^+\pi^0$ (450 kt·yrs)
$\tau/Br > 1.6 \times 10^{34}$ years

$p\to \bar{\nu} K^+$ (365kt·yrs)
$\tau/Br > 8.2 \times 10^{33}$ years

- Reached around 10^{34} years for favored decay modes.
- Searched systematically also for the other modes and reached 10^{32} - 10^{34} years.
- Strictest limits in the world.

Red: analyzed with > 365kt·yrs data
Green: analyzed with 350kt·yrs data
Blue: analyzed with SK I-III (173kt·yrs)

SK-Gd Phase

SK-Gd Phase:

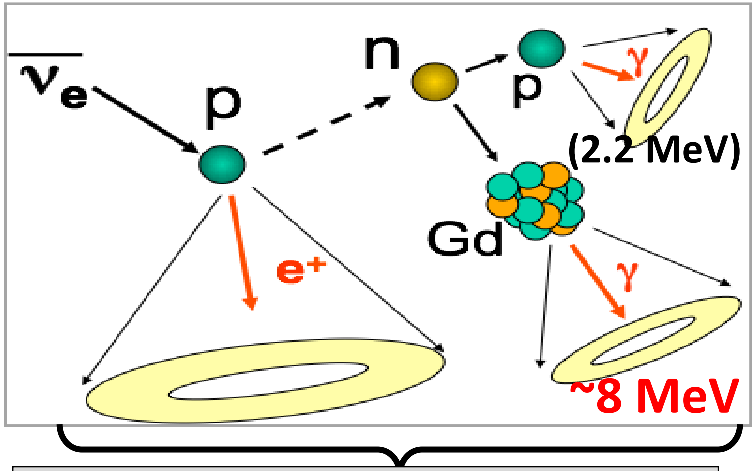
Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.

Physics targets:

- **Detect Diffuse Supernova Neutrino Background (DSNB)**
- **Improve pointing accuracy for supernova**
- **Early warning of nearby supernova from pre-burst signal (silicon burning)**
- **Enhance ν or $\bar{\nu}$ discrimination in atmospheric ν & T2K analysis**
- **Reduce backgrounds in proton decay search**

SK refurbishment was done in 2018

- **Fix water leakage, clean inside the detector**
- **Replace dead PMTs**
- **Improve water piping in the SK detector**



- **Reduce BG of $\bar{\nu}_e$ signal**
  - **Delayed coincidence**
  - **ΔT ~ 60 μs (@0.03% Gd)**
  - **Vertices within ~ 50 cm**

Gd concentration

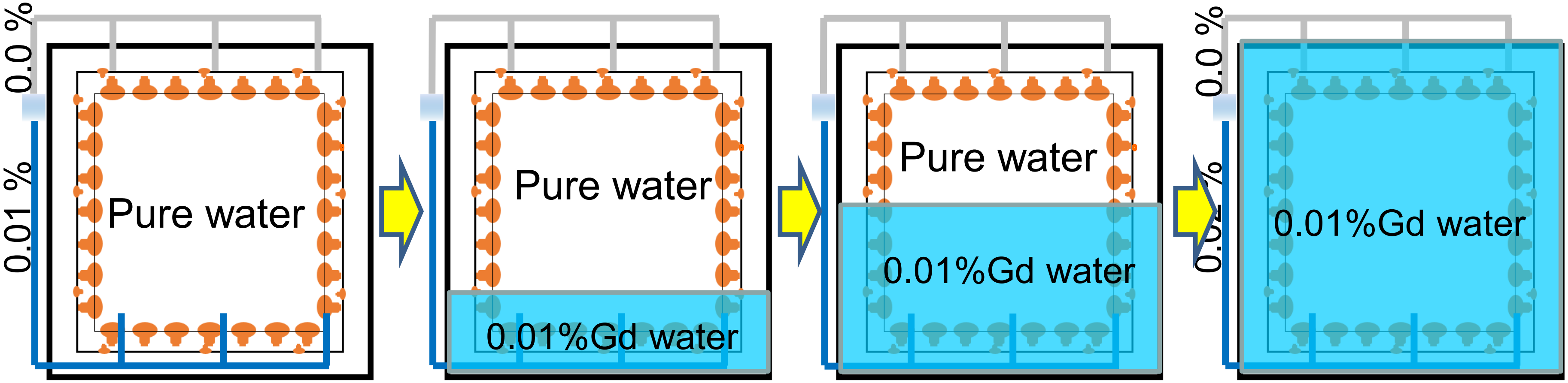
SK-VI: 0.01% (18 Aug. 2020-)
SK-VII: 0.03% (5 Jul. 2022-)

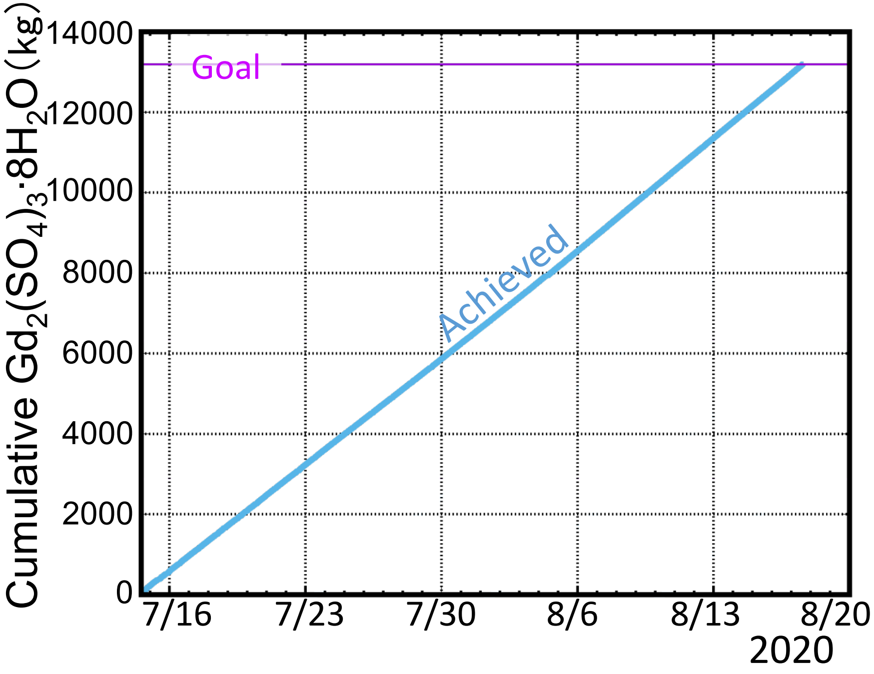
Neutron capture eff. in water

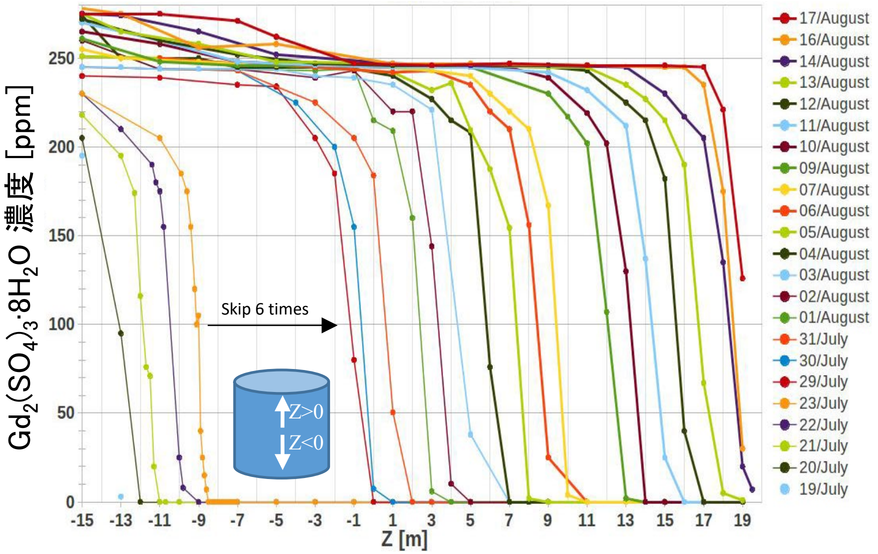
- **0.01% Gd : ~50% on Gd**
- **0.03% Gd : ~75% on Gd**

The 1st Gd-loading Jul.14 – Aug.17, 2020

The pure water in the SK tank was taken from the top and returned from the bottom in
0.02% $Gd_2(SO_4)_3$ solution (=**0.01% Gd** = **0.026% $Gd_2(SO_4)_3 \cdot 8H_2O$**)
It took 35 days to replace 50,000 tons of water at 60 m^3/h







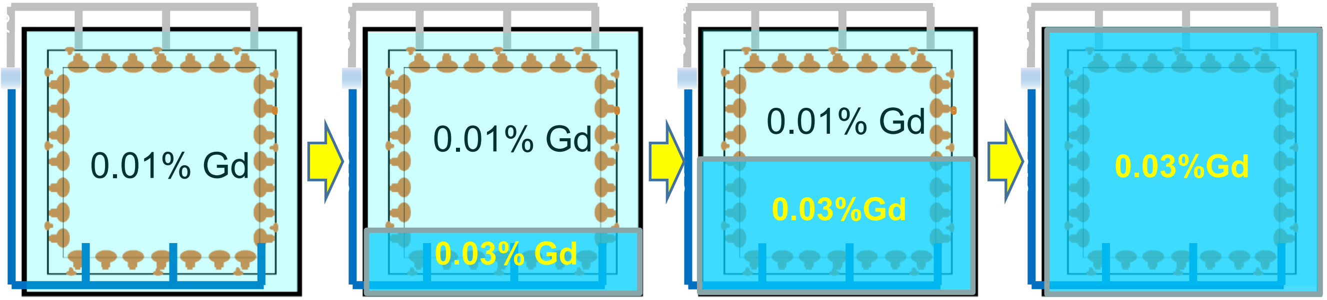
Gd was loaded quite smoothly

The 2nd Gd-loading Jun.1 – Jul.5, 2022

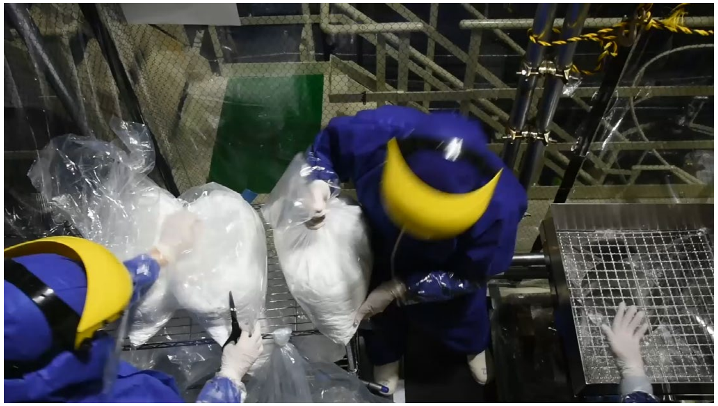
0.01% Gd water was taken from the top and returned from the bottom in **0.06% $Gd_2(SO_4)_3$** solution **(=0.03% Gd = 0.078% $Gd_2(SO_4)_3 \cdot 8H_2O$)**. It took 35 days to replace 50,000 tons of water at 60 m^3/h

One batch:
17 kg of $Gd_2(SO_4)_3 \cdot 8H_2O$
+ 1600 L of SK water

~900kg /day x 35 day.



26 tons of $Gd_2(SO_4)_3 \cdot 8H_2O$ was loaded.

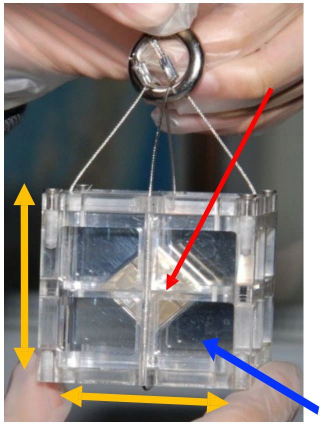


27tons
=1350 x 20kg cardboard boxes!

Gd concentration check after loading

- Neutron capture time is sensitive to Gd concentration. **NIM-A 1065 (2024) 169480**

Am/Be neutron source was deployed in SK



8 BGO Crystals

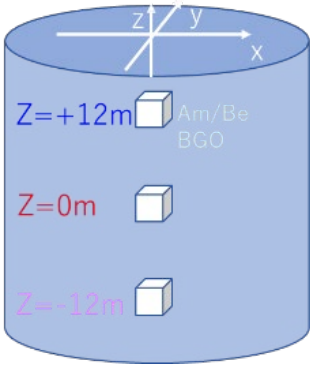
Am/Be neutron source

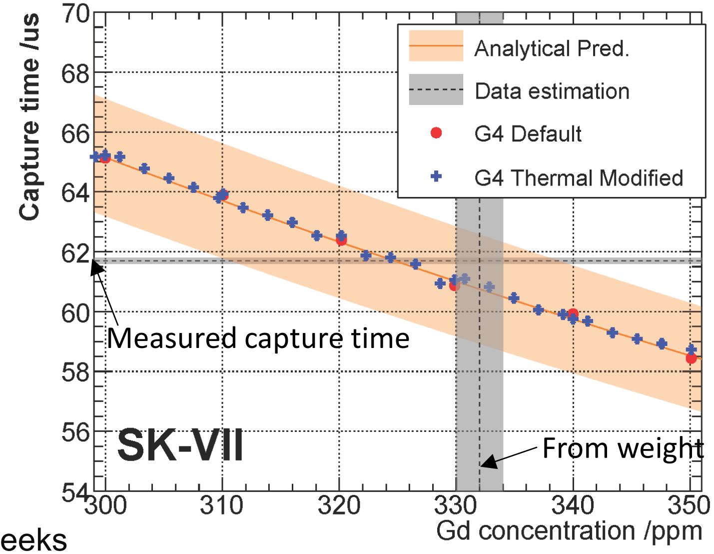
100~200 neutrons/s

$^{241}\mathrm{Am} \rightarrow {}^{237}\mathrm{Np} + \alpha$

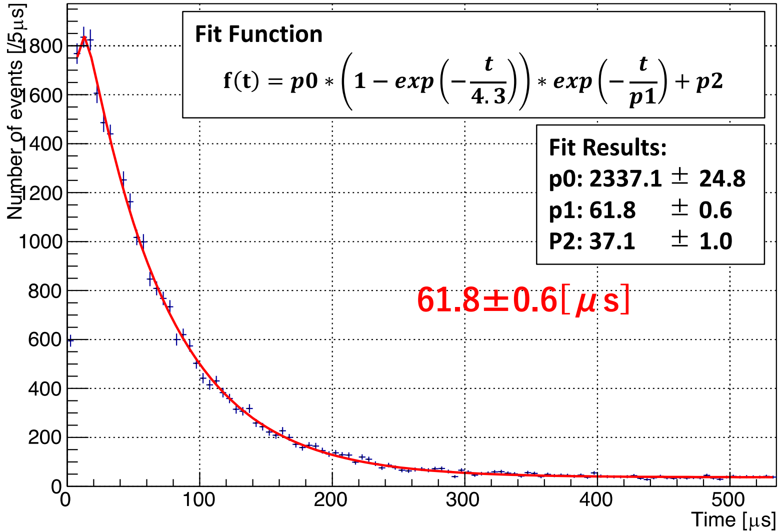
$^{9}\mathrm{Be} + \alpha \rightarrow {}^{13}\mathrm{C}^{*} + \mathrm{n}$ (2-6 MeV)

$^{13}\mathrm{C}^{*} \rightarrow {}^{12}\mathrm{C} + \gamma$ (4.43 MeV)





Time difference between scintillation and neutron capture γ-rays as of September 28, 2022

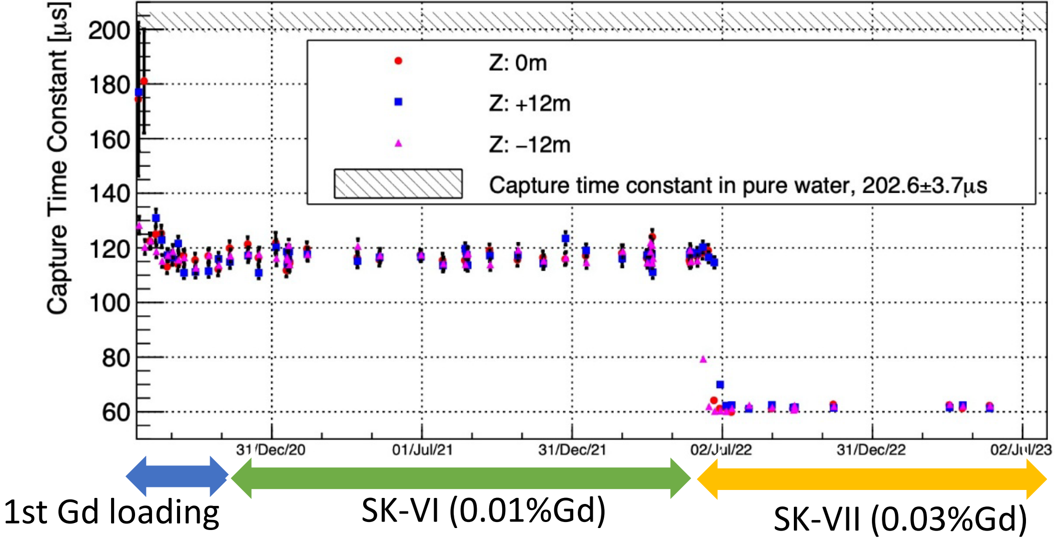


Fit Function

$$f(t) = p0 * \left(1 - exp\left(-\frac{t}{4.3}\right)\right) * exp\left(-\frac{t}{p1}\right) + p2$$

Fit Results:
p0: 2337.1 ± 24.8
p1: 61.8 ± 0.6
P2: 37.1 ± 1.0

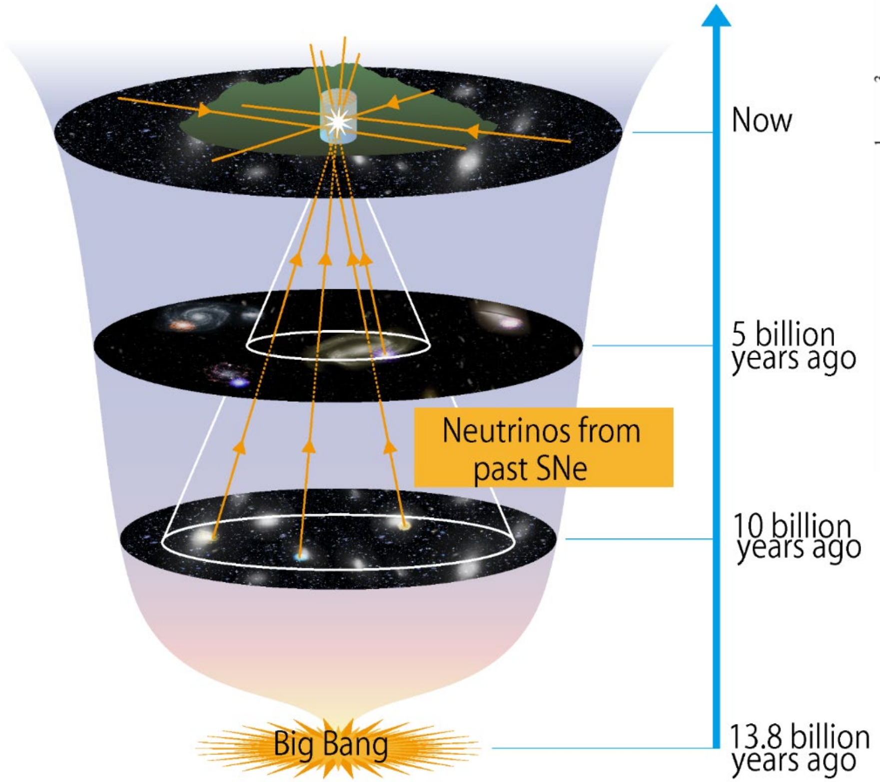
Every two weeks



Since September 2022 (SK-VII) :
The average capture time : 61.7±0.1 µs

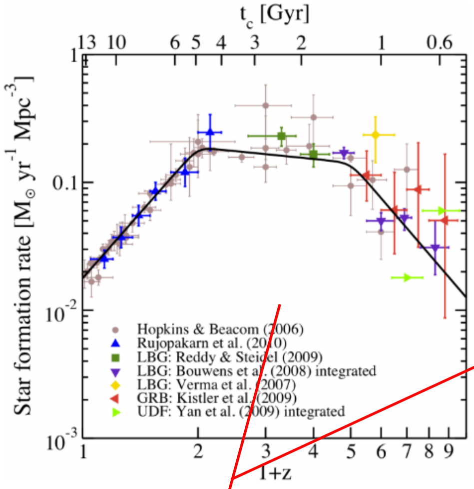
Diffuse Supernova Neutrino Background (DSNB)

$10^{22\text{-}23}$ stars in the universe（～10^{11} galaxies, ~$10^{11\text{-}12}$ stars/galaxy）
At present, we are getting neutrinos from 10^8 supernovae every year.

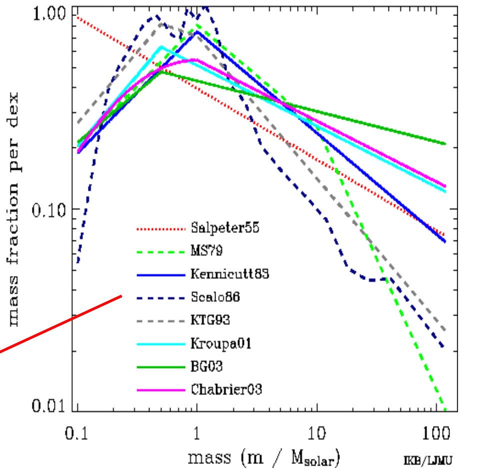


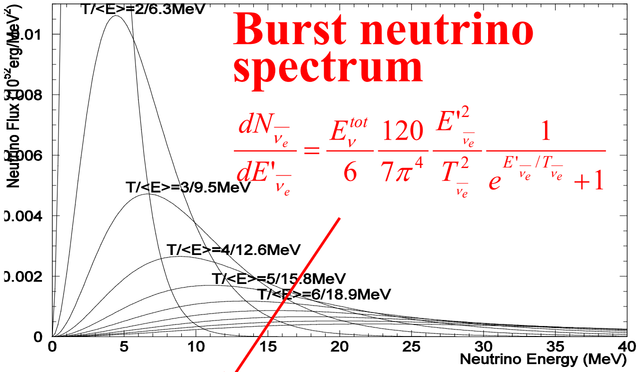
Horiuchi,Beacom(2010)

Star Formation Rate



Initial Mass Function





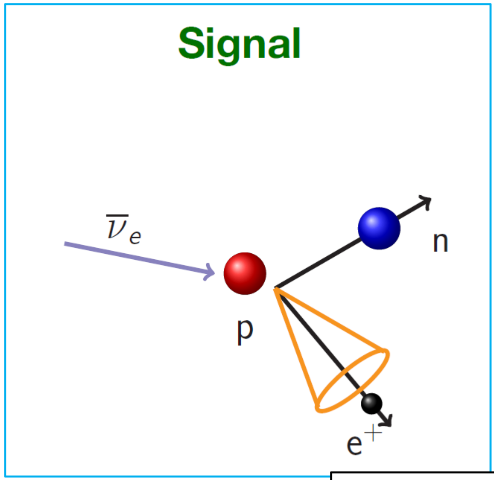
Burst neutrino spectrum

$$\frac{dN_{\bar{\nu}_e}}{dE'_{\bar{\nu}_e}} = \frac{E_\nu^{tot}}{6}\,\frac{120}{7\pi^4}\,\frac{E'^2_{\bar{\nu}_e}}{T^2_{\bar{\nu}_e}}\,\frac{1}{e^{E'_{\bar{\nu}_e}/T_{\bar{\nu}_e}}+1}$$

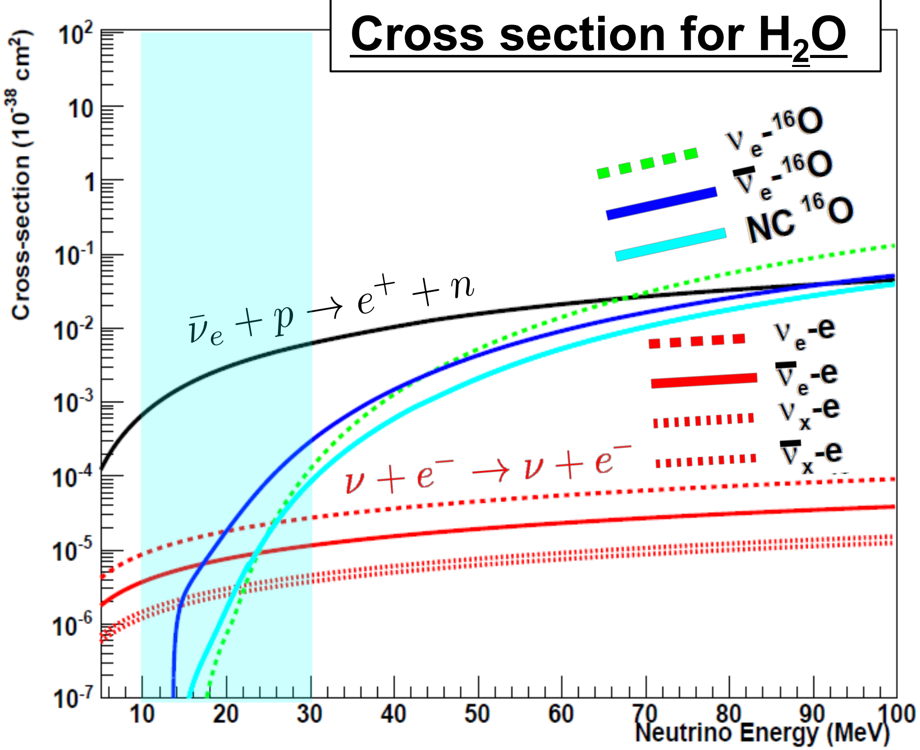
We can study
star formation history and
averaged neutrino spectrum.

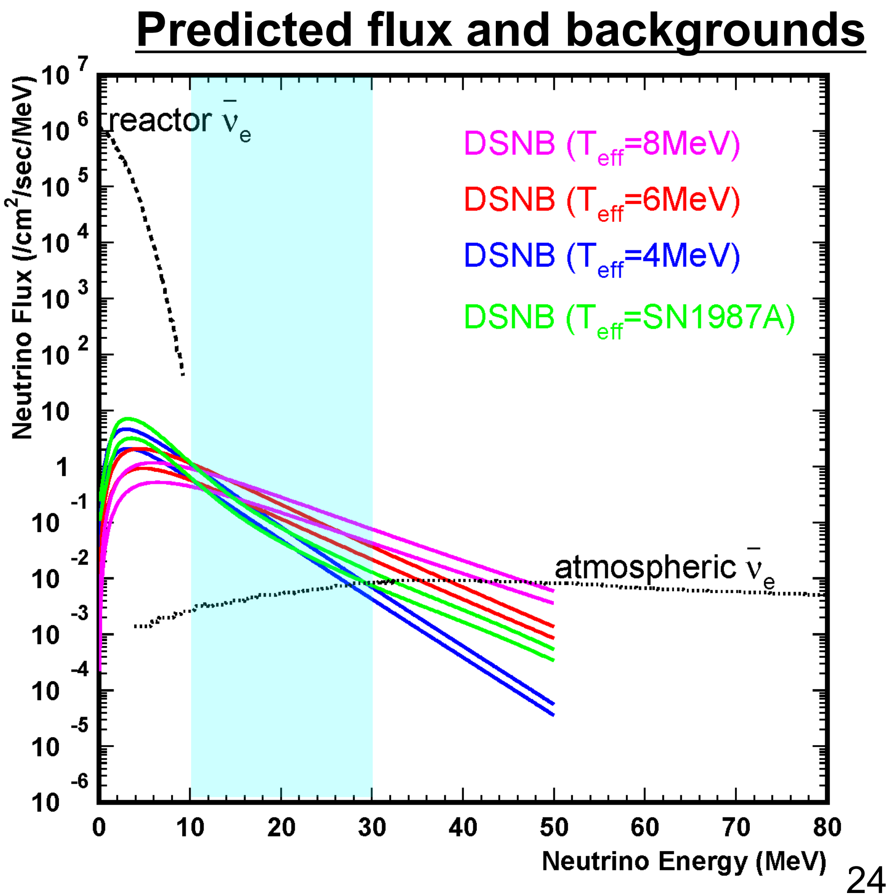
$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\mathrm{SN}}(z)\,\frac{dN_\nu(E'_\nu)}{dE'_\nu}\,(1+z)\,\frac{dt}{dz}\,dz$$

DSNB signal in Super-Kamiokande


Signal

- **Main channel:** Inverse beta decay ($\overline{\nu}_e + p \rightarrow e^+ + n$).
- **Signal window:** Between reactor neutrinos and atmospheric neutrinos.
- **Event rate:** A few interactions/year/SK


Cross section for H_2O

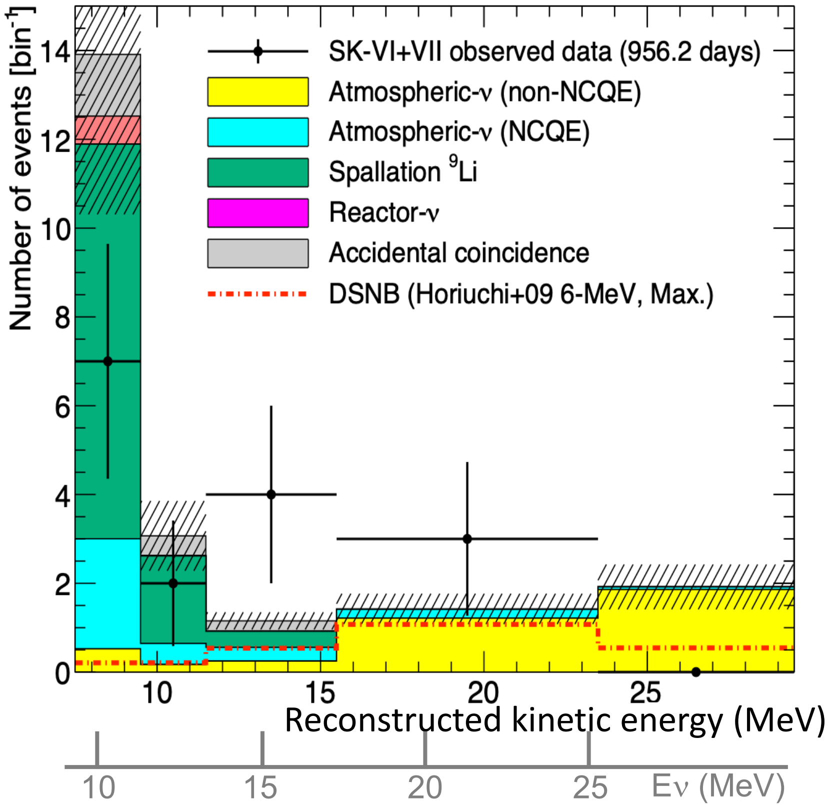

Predicted flux and backgrounds

Preliminary DSNB search results (with SK-Gd)

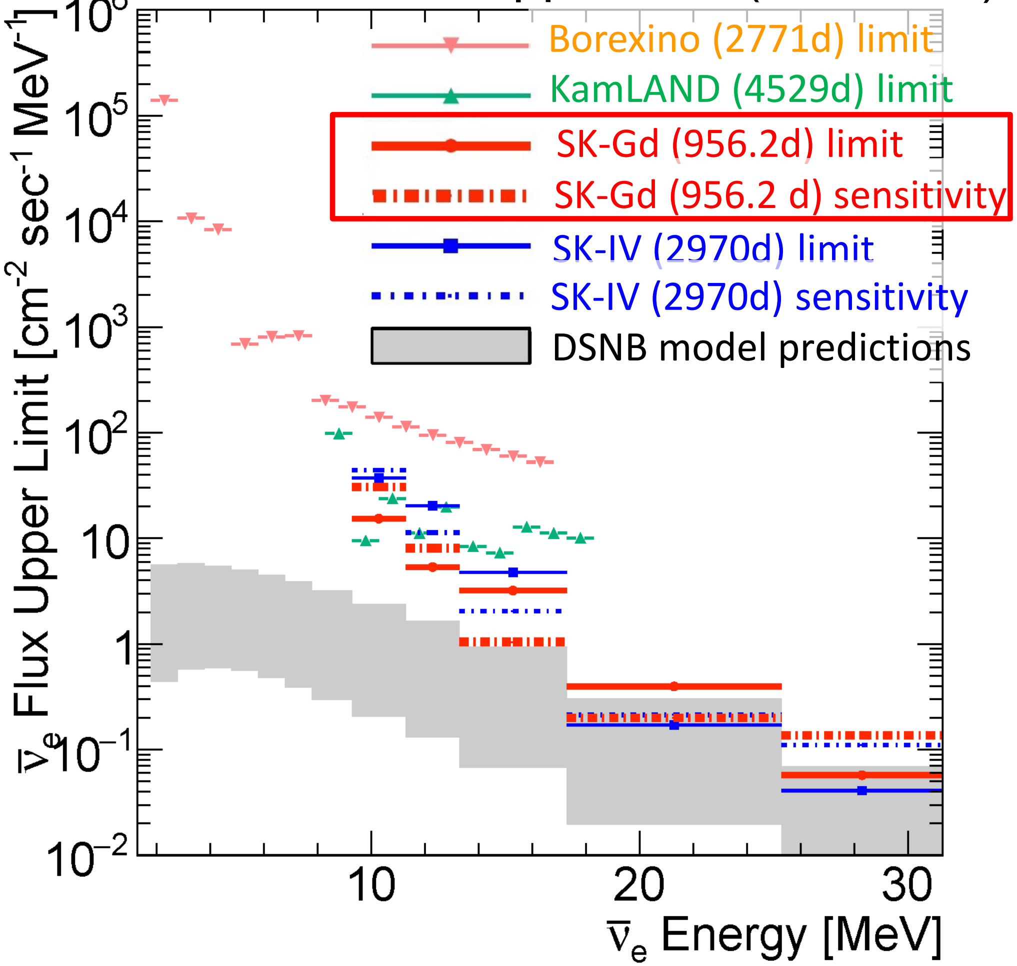
SK-Gd data 956.2 days

(SK-VI (0.01%Gd): 552.2 days, SK-VII(0.03%Gd): 404.0days)

Energy spectrum



Neutrino flux upper limit (90% C.L.)

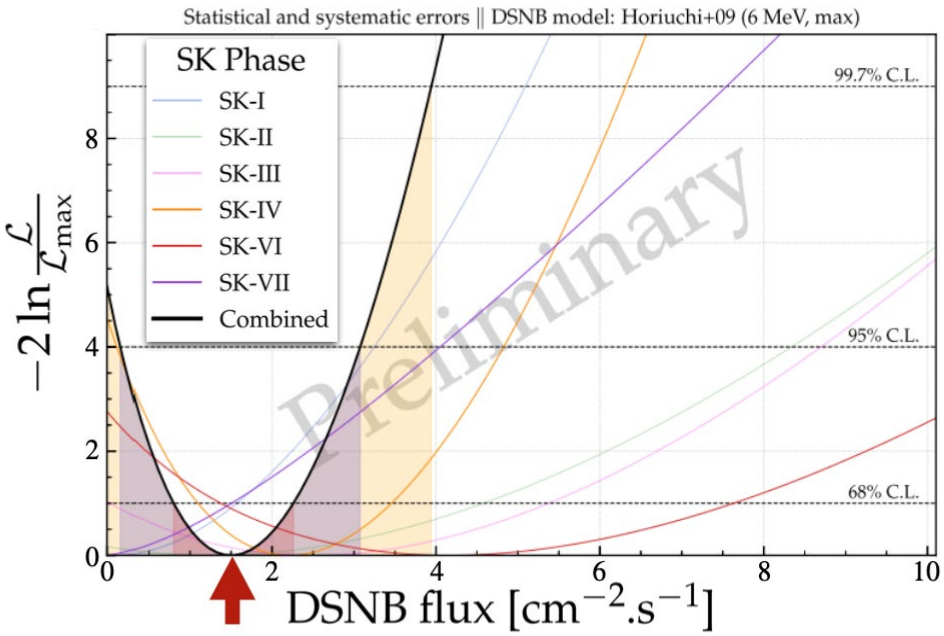


SK sensitivity get into the model prediction region for Eν > 14 MeV.
SK-Gd gives world best flux limit for Eν > 12 MeV.
Interesting to see future progress in 14 – 25 MeV energy range.

DSNB analysis using whole SK data

Spectrum fitting analysis using the whole SK data

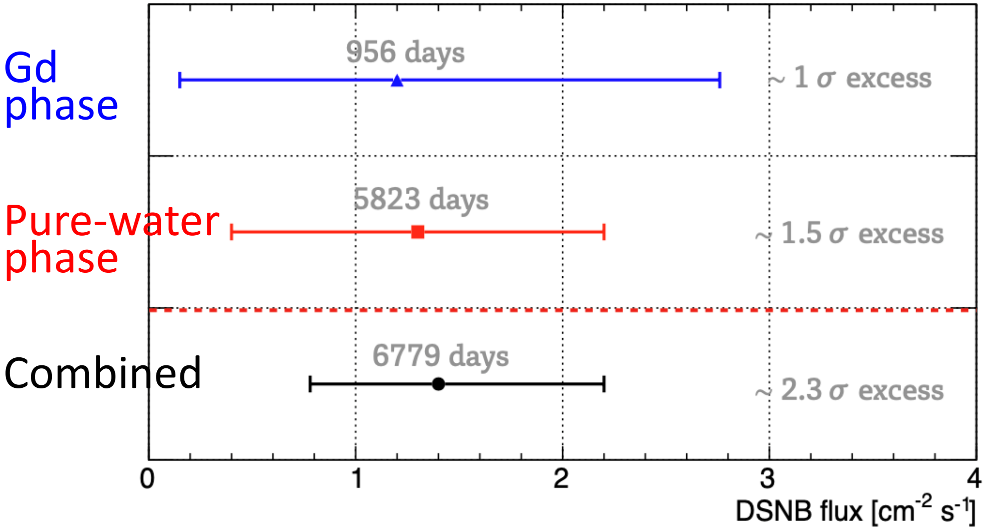
- Total 6779 days of SK (5823 d pure-water and 956 d Gd-water) combined.
- Only Eν > 17.3 MeV data is used to neglect enormous spallation background.
- Suppress uncertainty of background prediction by fitting both N_n=1, N_n≠1.



Results

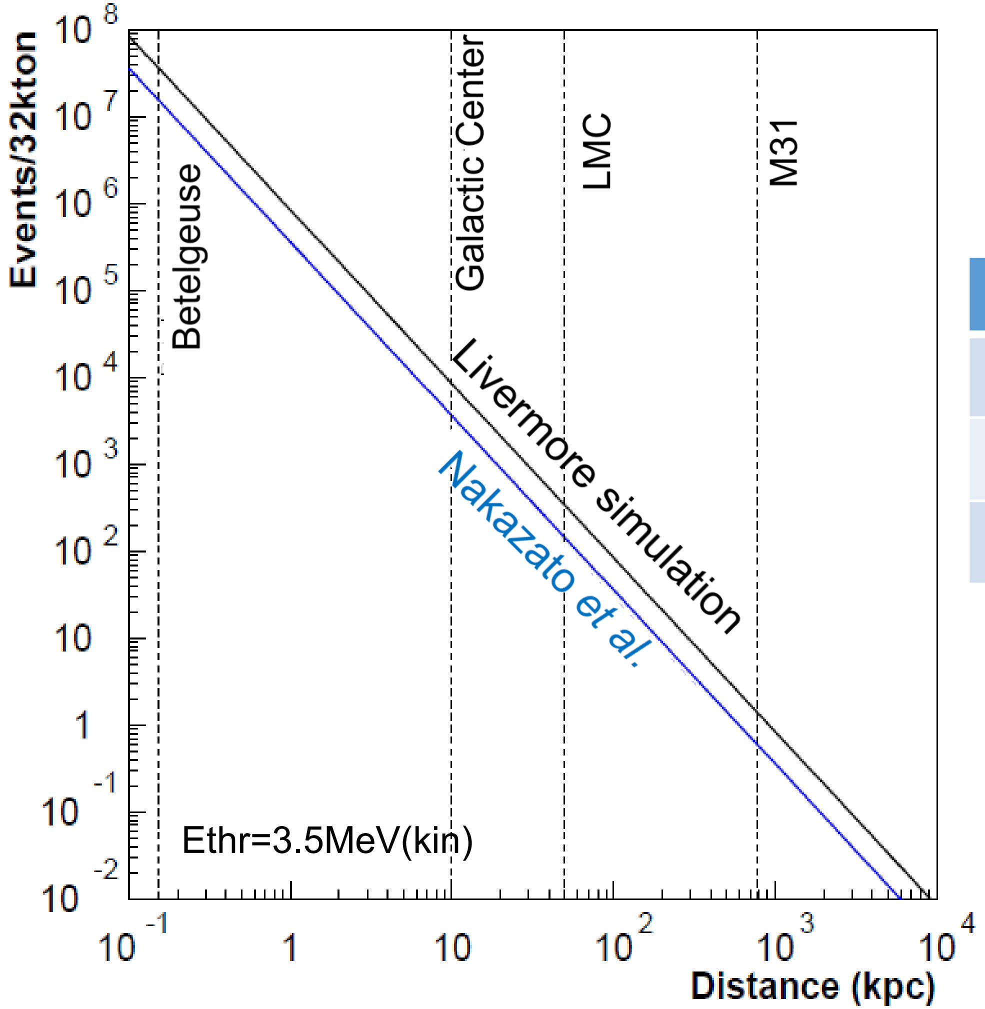
- Sensitivity of SK-Gd ~1000 days exposure is already comparable level with ~6000 days of pure-water SK.
- Best fit of whole SK data is $1.4^{+0.8}_{-0.6}$ /cm² /s for Eν > 17.3 MeV.

➡ exhibit ~2.3σ excess!!



Galactic Supernova Search at Super-K

Number of events vs. distance



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)

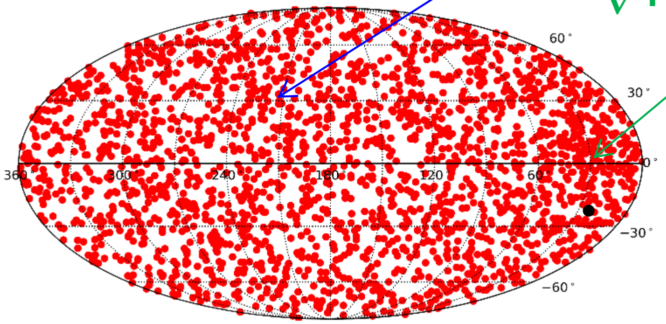
In case of Galactic supernova pointing accuracy has been improved with Gd

Simulation of skymap of observed events (10 kpc SN)

All events

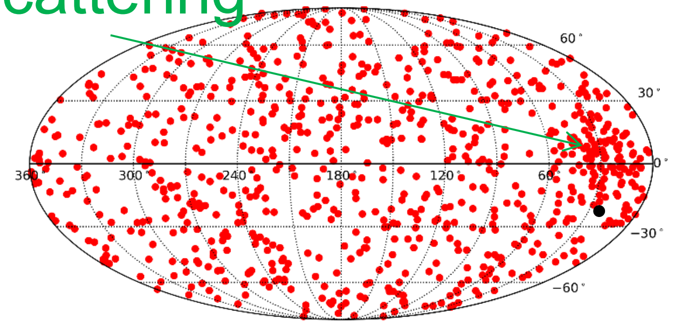
$\bar{\nu}_e p \rightarrow e^+ n$

ν+e scattering



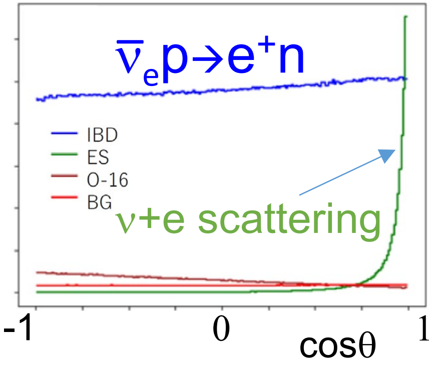
SN burst events w/o IBD tagging
(10kpc simulation)

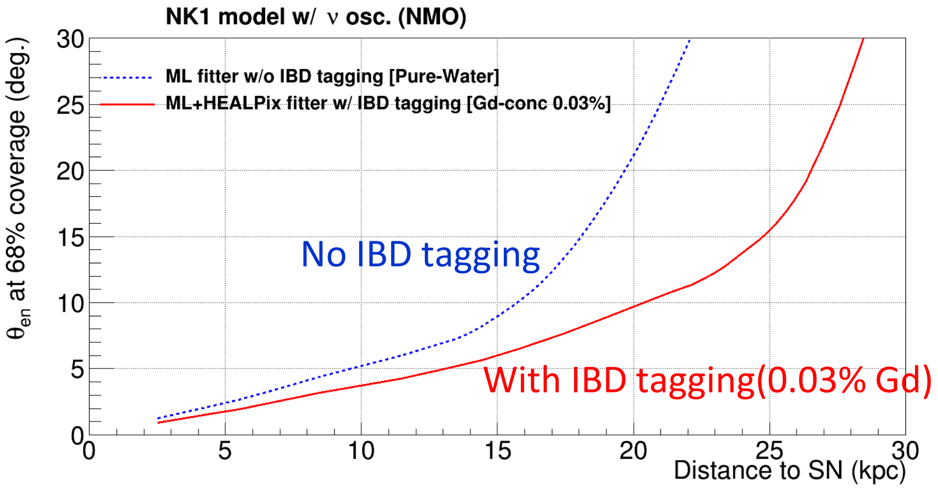
Tagged $\bar{\nu}_e$ are removed



SN burst events w/ 72% IBD events tagged/removed
(10kpc simulation)
(Expected with 0.1% Gd)

Angular distribution of each interaction

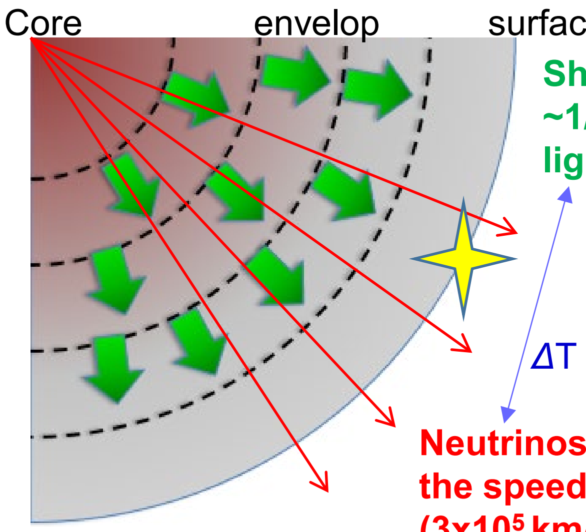




Current status

With 0.03% Gd (46% IBD tagging efficiency), the supernova direction pointing accuracy is ~3.7 degrees at 10 kpc.

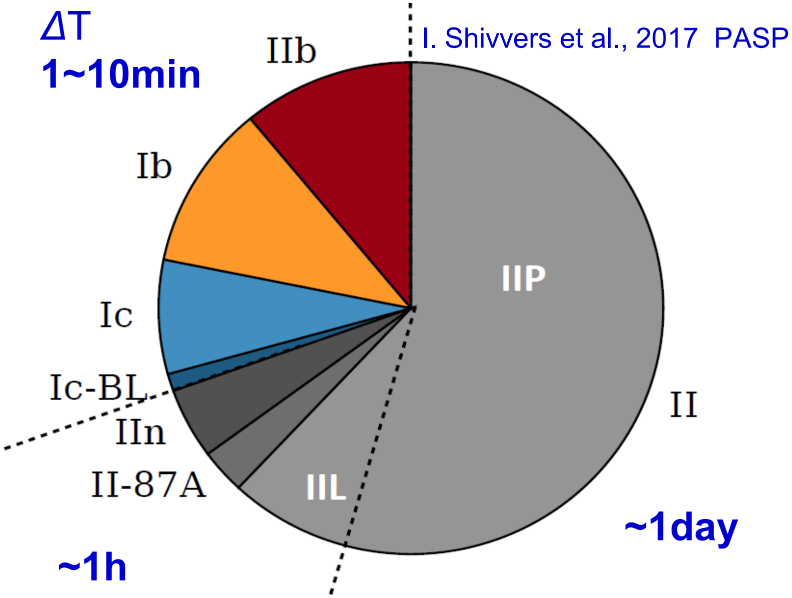
Role of SK in Multi-messenger astronomy



Shock wave travels with ~1/30 of the speed of light (~10^4 km/sec).

Shock breakout happens when the shock wave arrives at the surface.

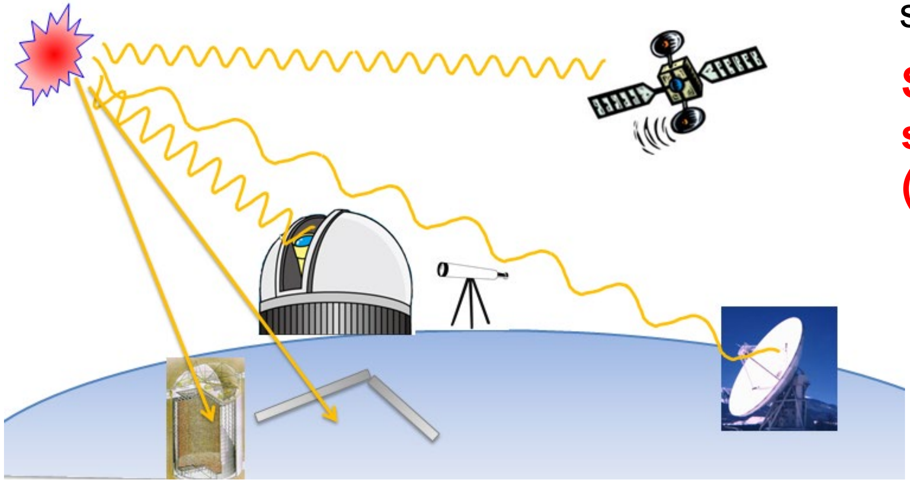
Neutrinos travel with the speed of light ($3\text{x}10^5$ km/sec)



I. Shivvers et al., 2017 PASP

For ~70% of SNe, the time difference is several hours to tens of hours. For remaining ~30%, that is several minutes.

SK will send a GCN Notice alert when a supernova burst is detected within ~1.5 minutes (at present).



Using elastic scattering, the Super-K detector is the world’s best detector for determining direction of the supernova.

Summary

- Super-Kamiokande discovered neutrino oscillations by atmospheric and solar neutrinos.
- Precise measurements of neutrino oscillations are still ongoing at SK.
- Gd was loaded to Super-K tank in 2020 and 2022 and the detector is running now with 0.03% Gd which gives 75% capture efficiency for neutrons.
- SK-Gd will improve various physics, especially, DSNB and supernova burst neutrinos.