Super-Kamiokande experiment

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on behalf of Super-Kamiokande collaboration

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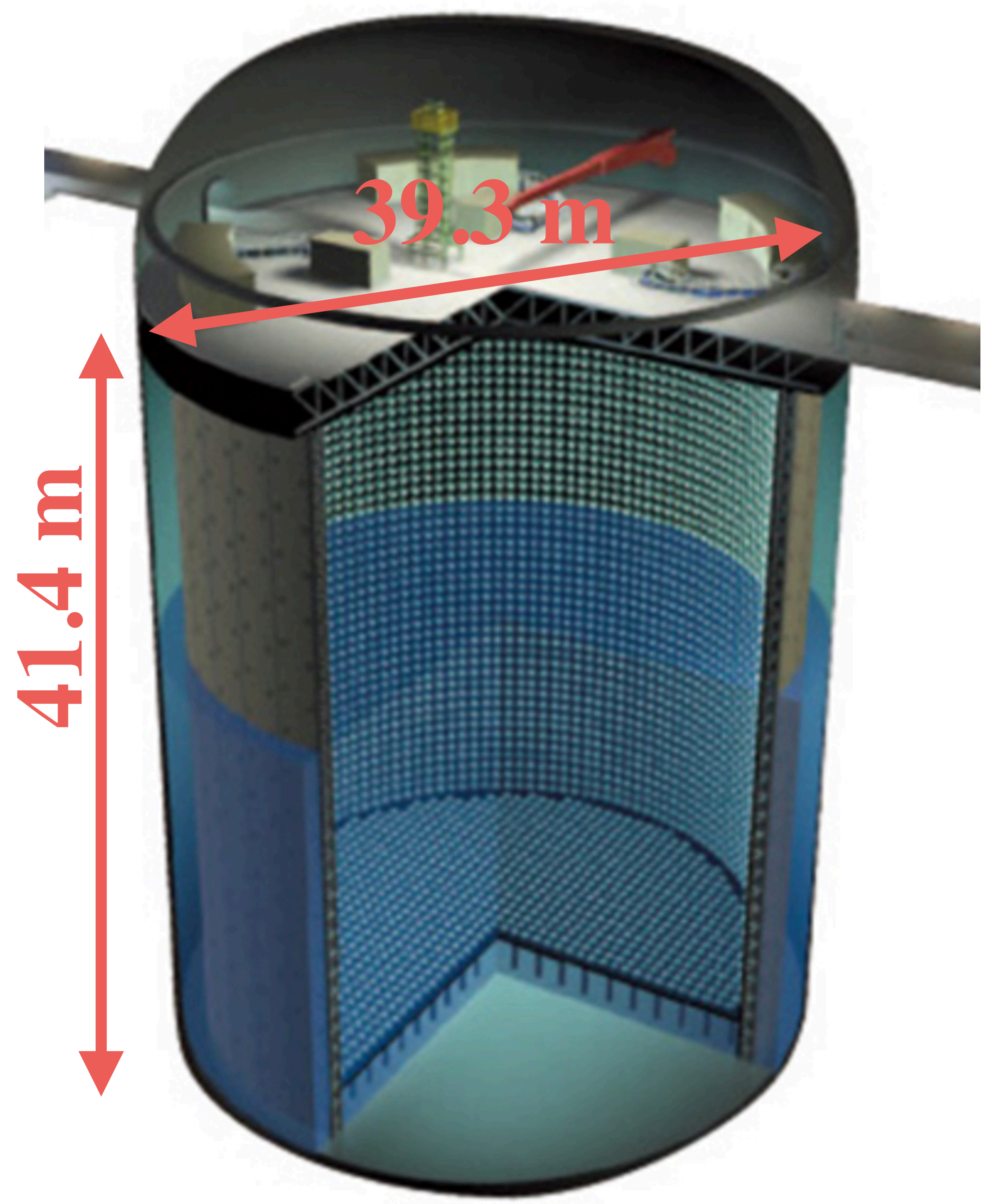
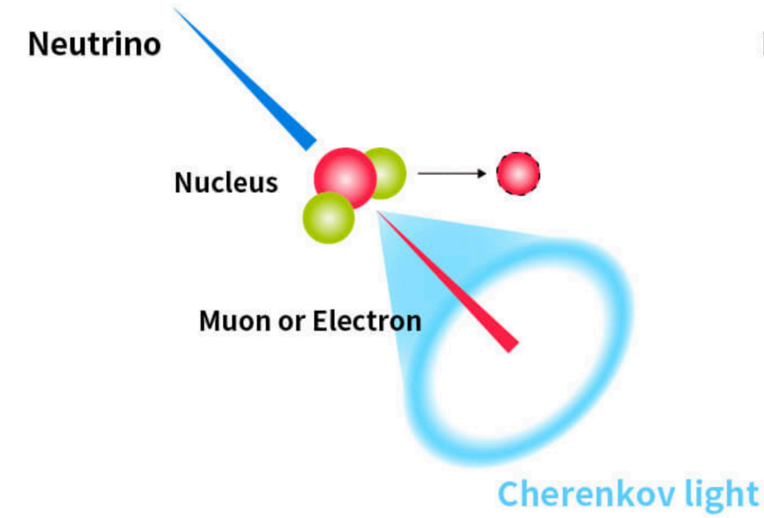
Super-Kamiokande(SK) experiment

- SK is the world's largest underground water Cherenkov detector with a cylindrical tank of 41.4 m height and 39.3m diameter.
- Since the start of operation in 1996, SK has been taking data to explore the neutrino properties, neutrino sources, and nucleon decay.
- Discovery of neutrino oscillation by SK lead to the nobel prize in 2015. **Now SK aims at more precise understanding of the neutrino oscillation.**

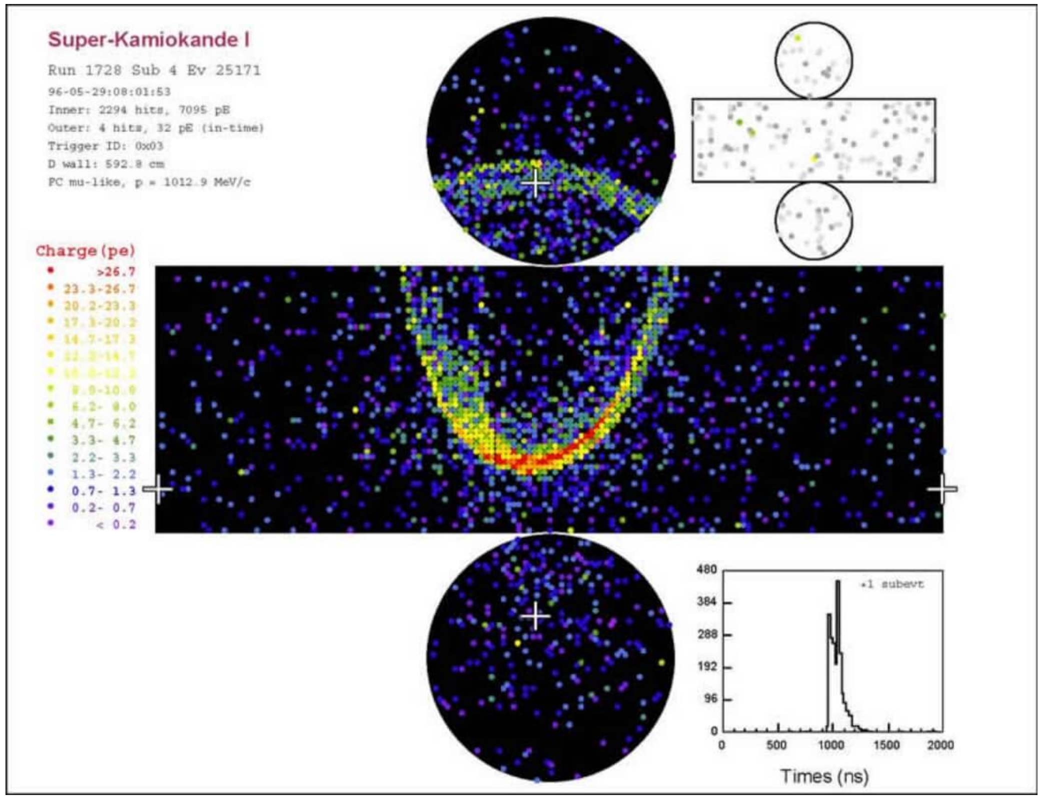


SK detector concept

- The SK tank is filled with 50 kton of ultra-pure water (1996~2020) or gadolinium-loaded water (2020~)



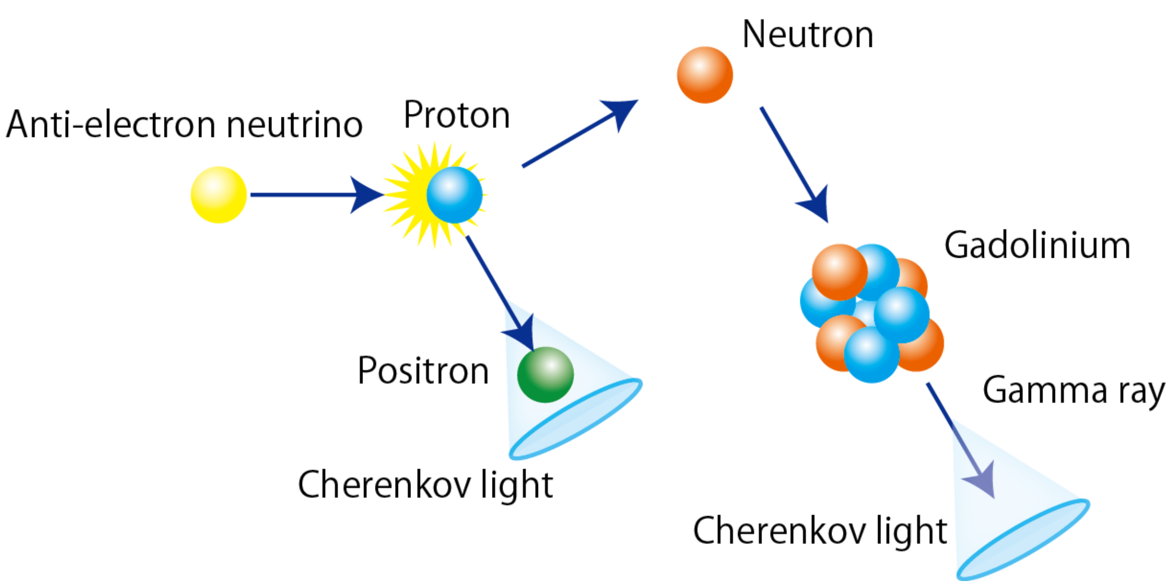
- In water, a ring of Cherenkov light is emitted when a charged particle travels faster than the speed of light in water.
- The Cherenkov light is detected by ~11,000 PMTs attached to the tank wall and reconstructed as a ring.

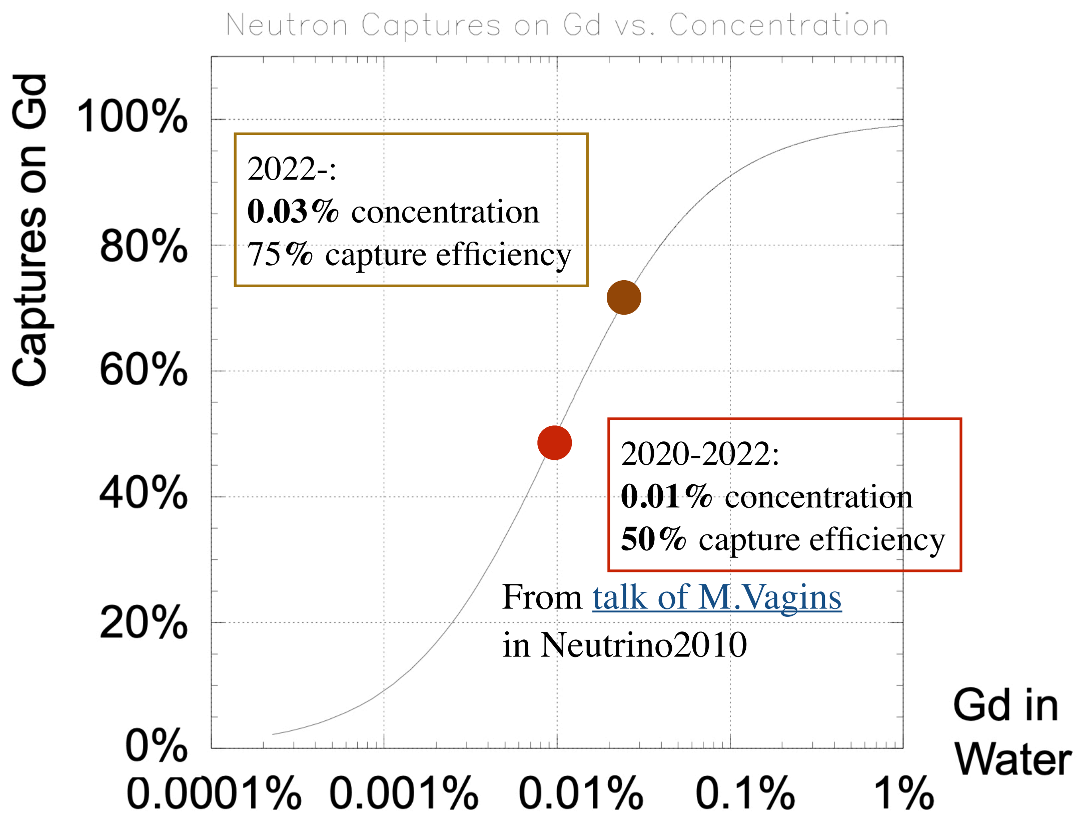


- The particle type, momentum, direction, vertex position e.t.c. can be extracted from the amount of light, shape and direction of the ring, and photon detection time of each PMT.
- Details can be found in https://doi.org/10.1142/9789819801107_0008

Recent news: Gd-loading

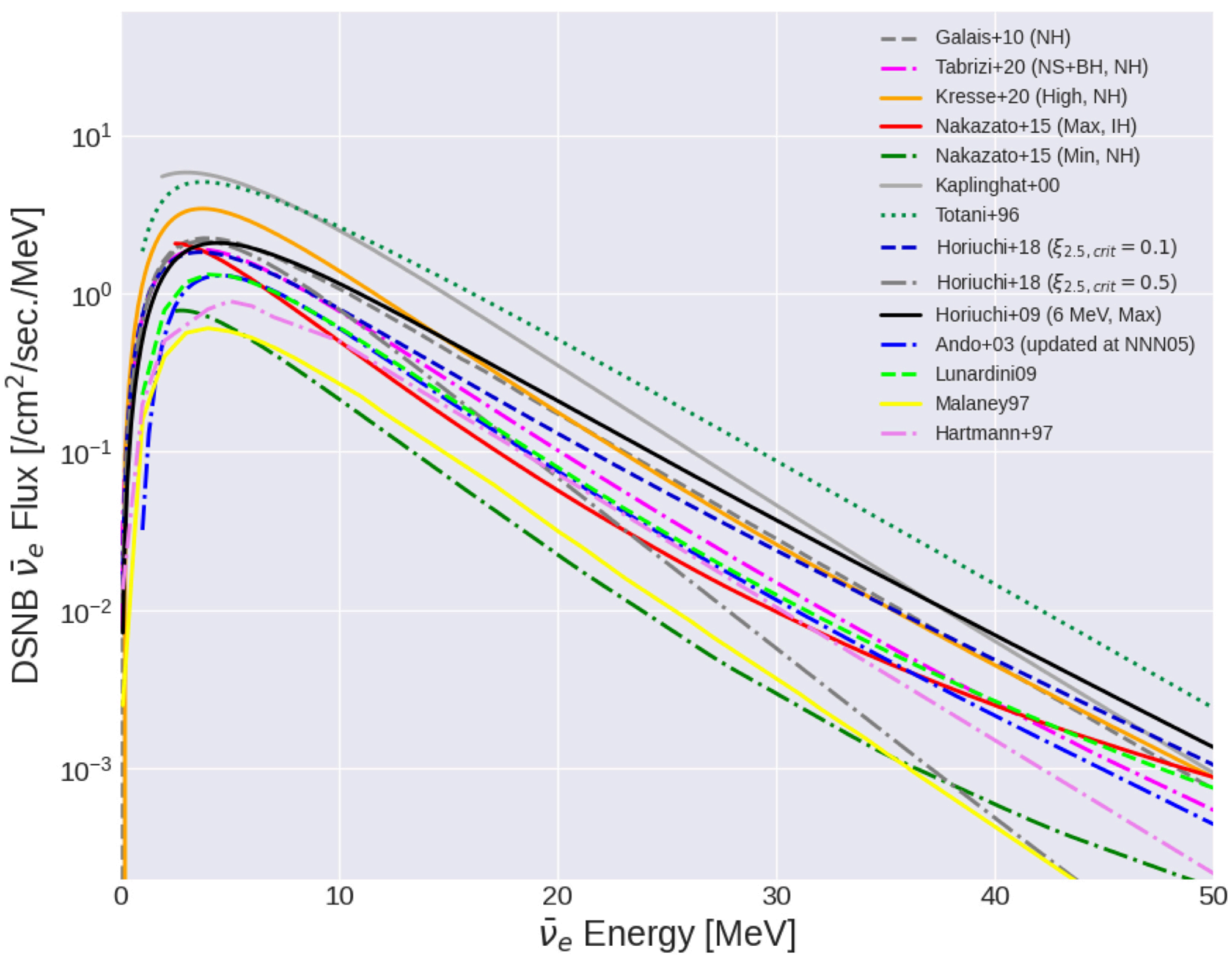
- Since 2020, SK is operated with Gd-loaded water for neutron-tagging.
  - Neutron is captured by Gd and emit gamma-rays with the total energy of ~8 MeV, which make EM showers emitting Cherenkov light.
- Gd loading campaigns were held in 2020 and 2022 to make the Gd concentration 0.01% and 0.03%, respectively.





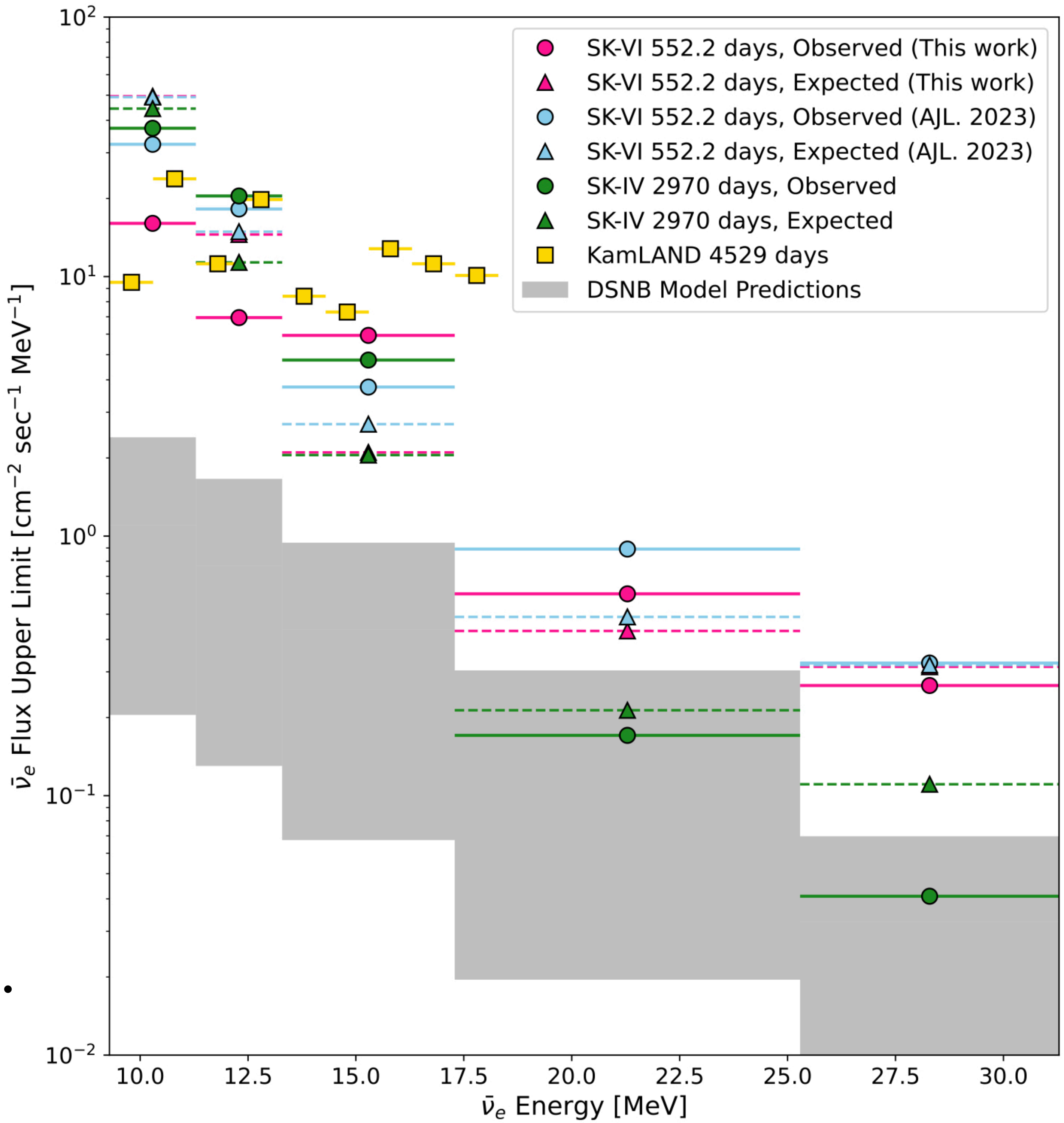
DSNB

- By the analysis of SN1987a, Kamiokande revealed that neutrinos are emitted by supernovae. (Nobel prize in 2002)
- This indicates that the Universe is filled by the neutrinos emitted from past supernovae, known as diffuse supernova neutrino background(DSNB).
- The evidence of DSNB is not observed yet. Discovery one of the goals in SK.
- In the DSNB energy range (O(1)~O(10) MeV), the $p + \bar{\nu}_e \rightarrow n + e^+$ process has the largest cross section Neutron tagging has important role and the sensitivity can be enhanced by Gd.



DSNB

- Now the search is performed on both pure water phase of 2970 days and Gd phase of 552 days (only the 0.01% concentration period).
- The evidence of the DSNB is not observed yet, but t**he sensitivity is reaching to the region predicted by theories.**
- **Further sensitivity is expected by combining more data with more Gd concentration period**. Look forward to the future results.



Neutrino oscillation

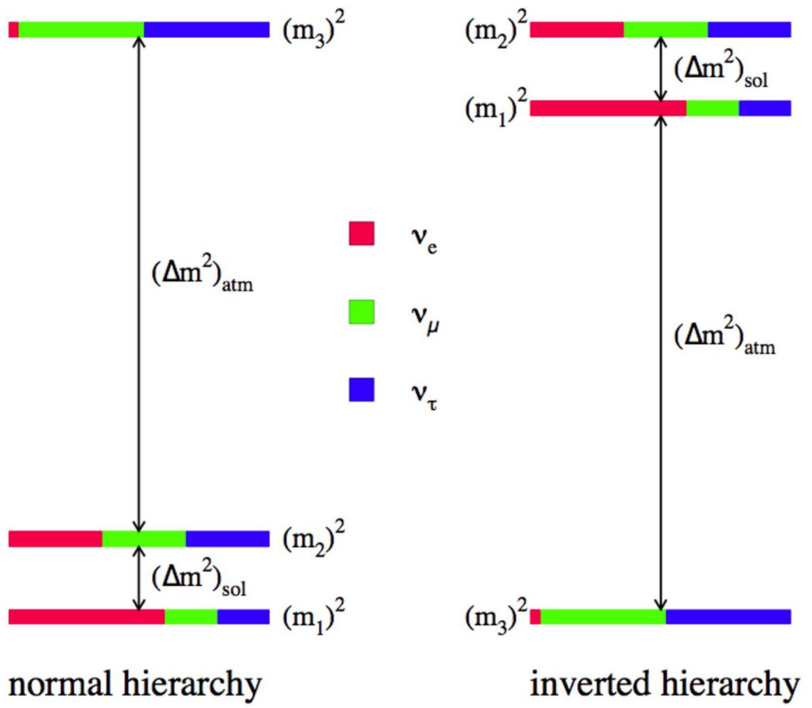
- Neutrino oscillation probability can be determined by the MNS parameters and mass squared differences.

MNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

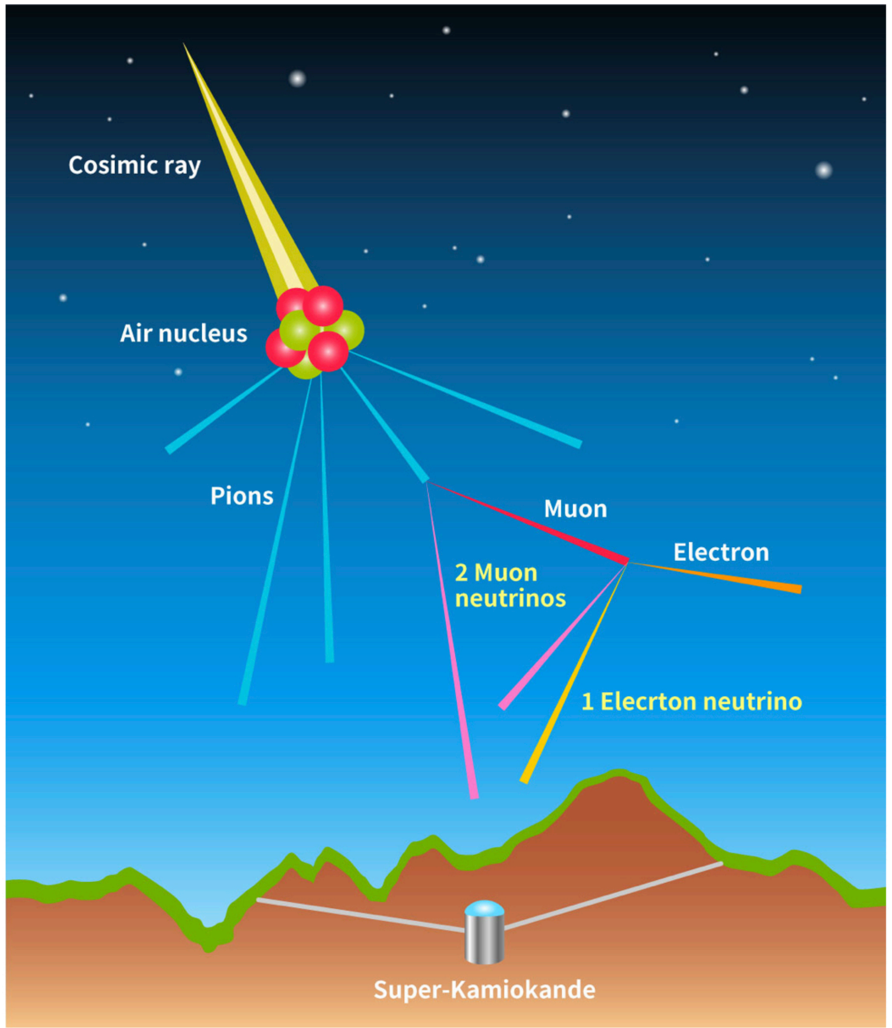
  - $\theta_{12}, \theta_{23}, \theta_{13}$ are already experimentally determined.
    - $\theta_{12} = 33.62^{\circ}{}^{+0.78^\circ}_{-0.76^\circ}$ $\theta_{23} = 47.2^{\circ}{}^{+1.9^\circ}_{-3.9^\circ}$ $\theta_{13} = 8.54^{\circ}{}^{+0.15^\circ}_{-0.15^\circ}$
  - **δ_{CP}=0 is not experimentally rejected by 5σ.** (T2K rejected by 3σ).

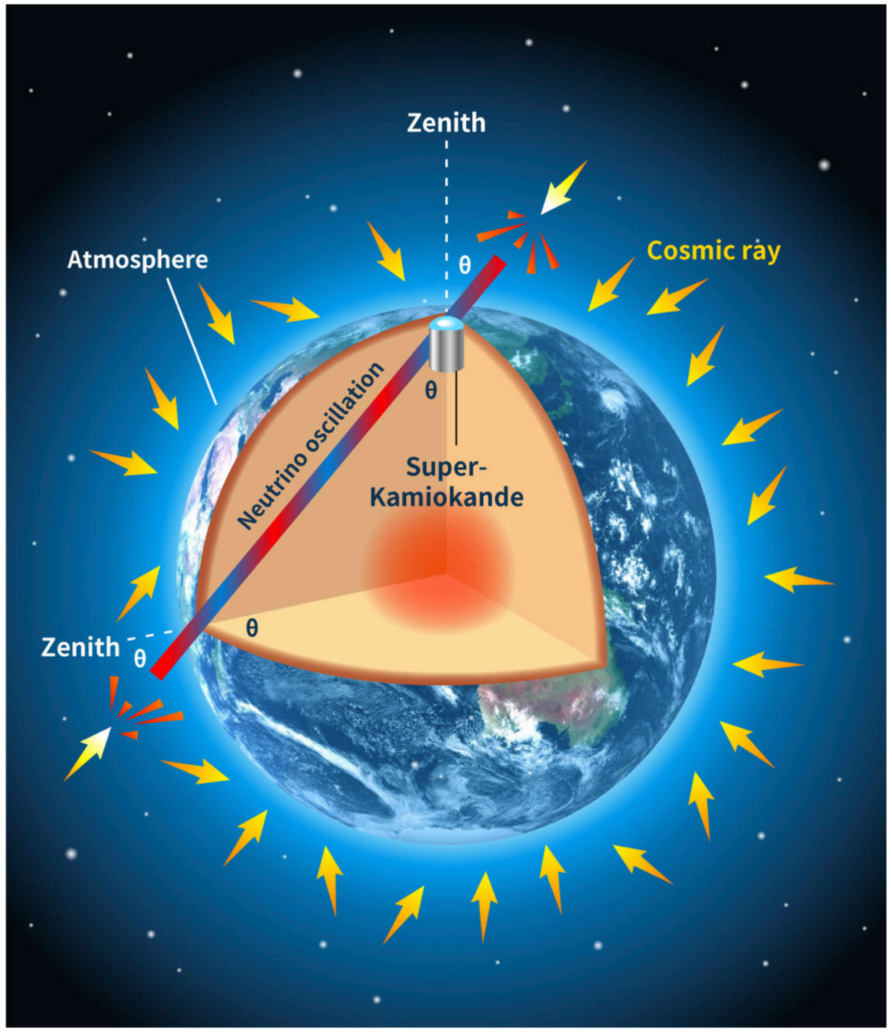
- Mass squared differences are also determined.
  - $\Delta m^2_{12} = 0.759 \times 10^{-4} eV^2$
  - $\Delta m^2_{13} \sim = \Delta m^2_{32} = 23.2 \times 10^{-4} eV^2$
- **Mass ordering is not kwon yet.**
  - $m_3 \gg m_1, m_2$ (Normal ordering)
  - $m_1, m_2 \gg m_3$ (Inverted ordering)



Atmospheric neutrino

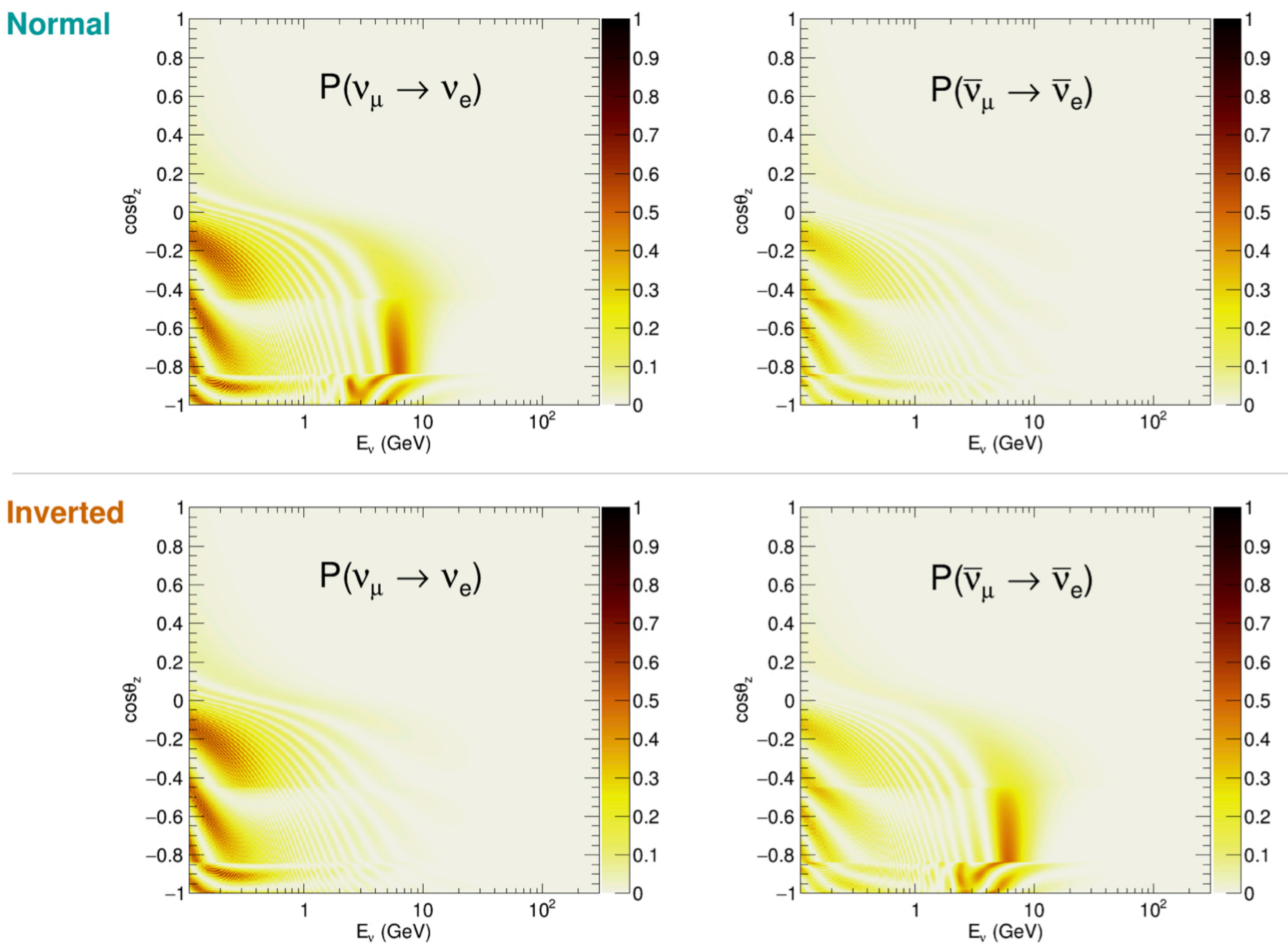
- **Atmospheric neutrino is a powerful tool to explore the neutrino oscillation.**
- By the interaction between primary cosmic ray and the atmosphere, $\nu_\mu(\bar{\nu}_\mu)$ and $\nu_e(\bar{\nu}_e)$ are produced with the amount ratio of 2:1.





Latest result of atmospheric neutrino

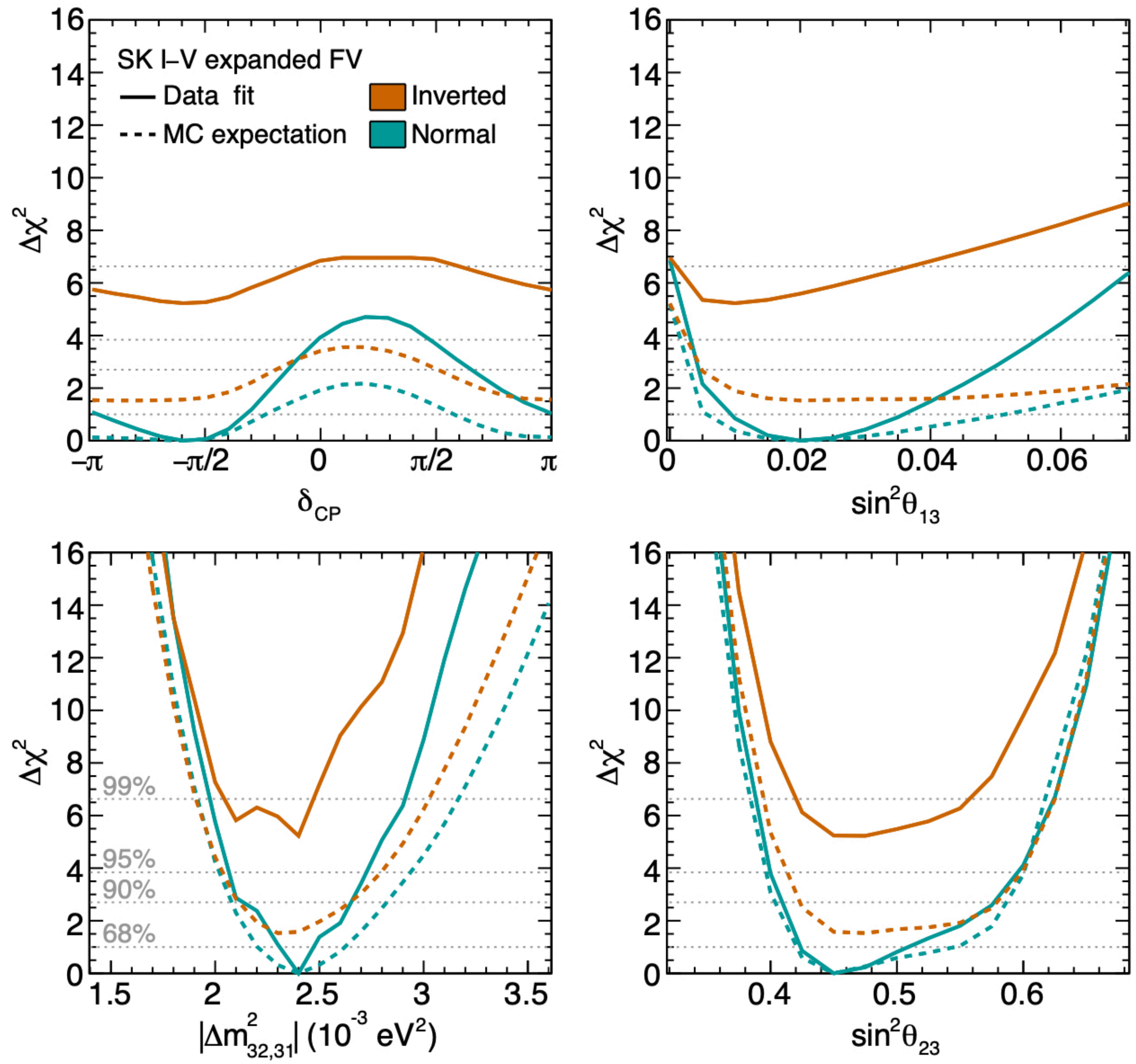
- As a result of neutrino oscillation, the flavor ratio of the atmospheric neutrino depends on the zenith angle and energy.
- The oscillation pattern also depends on the mass ordering.



Latest result of atmospheric neutrino

- The latest analysis was performed with the data of complete pure water phase, between 1996 and 2020, corresponding to the exposure of 484.2 kton-year (more than 10 times larger than the exposure of the neutrino oscillation discovery analysis!).

- Detailed analysis of the $\nu_e, \bar{\nu}_e, \nu_\mu(\bar{\nu}_\mu)$ components depending on the zenith angle and energy set strong constraints on the oscillation parameters.



From Phys. Rev. D 109, 072014

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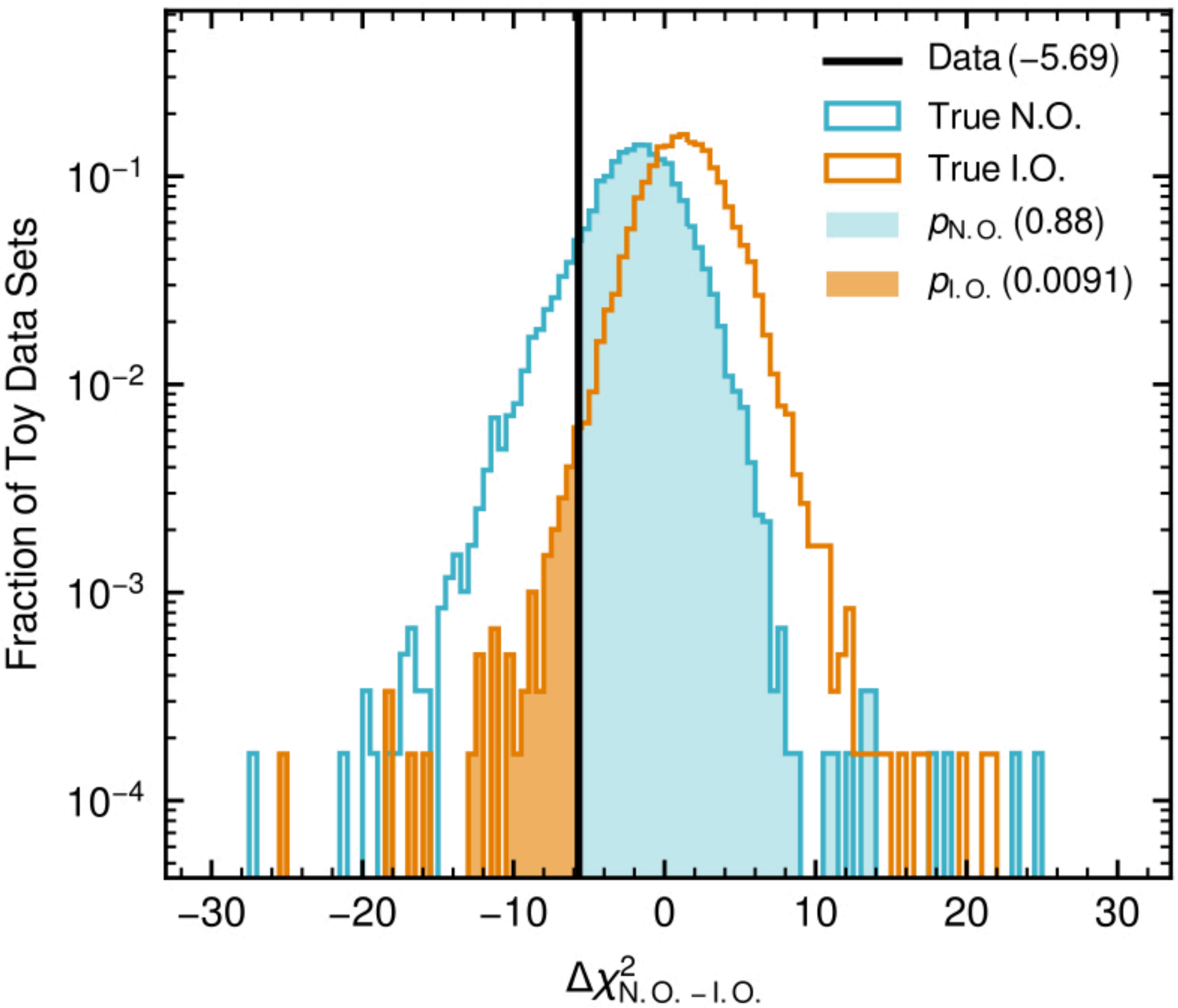
- **It prefers the normal ordering at 92.3 % confidence level**

From Phys. Rev. D 109, 072014



Solar neutrino

- As well as the atmospheric neutrinos, neutrinos coming from the Sun (solar neutrino) is an important physics target in SK.
- It is more challenging to detect the solar neutrinos in SK than the atmospheric neutrinos because the energy range is much lower.
    - Solar neutrino is O(1) MeV while the atmospheric neutrino is typically O(10) MeV ~ GeV.
    - With the improved electronics, SK can record the events with the threshold of ~3.5 MeV in electron kinetic energy since 2008.

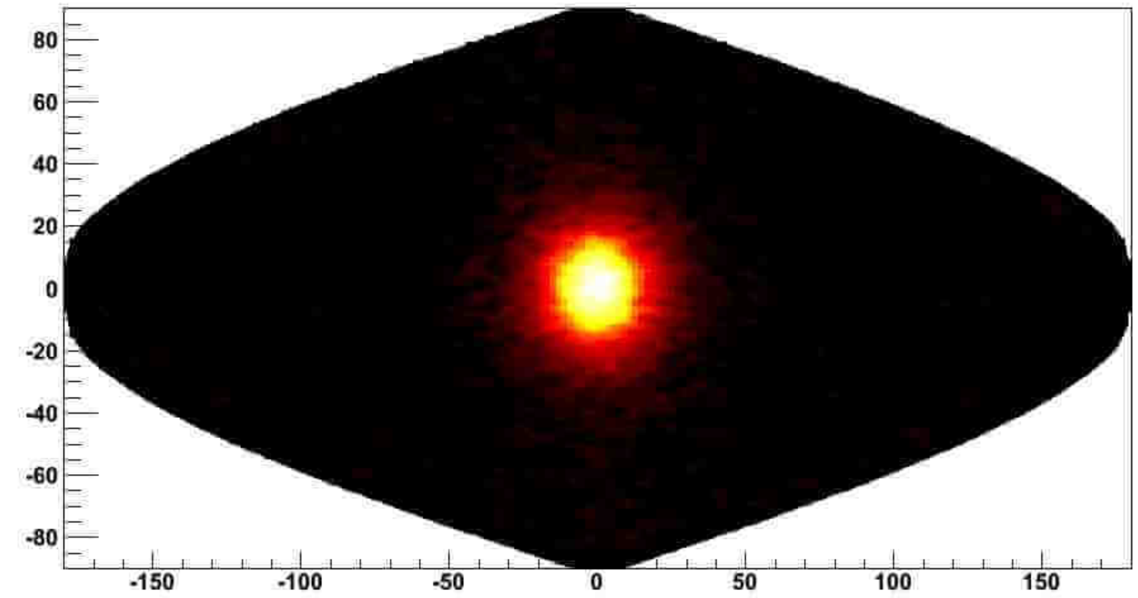
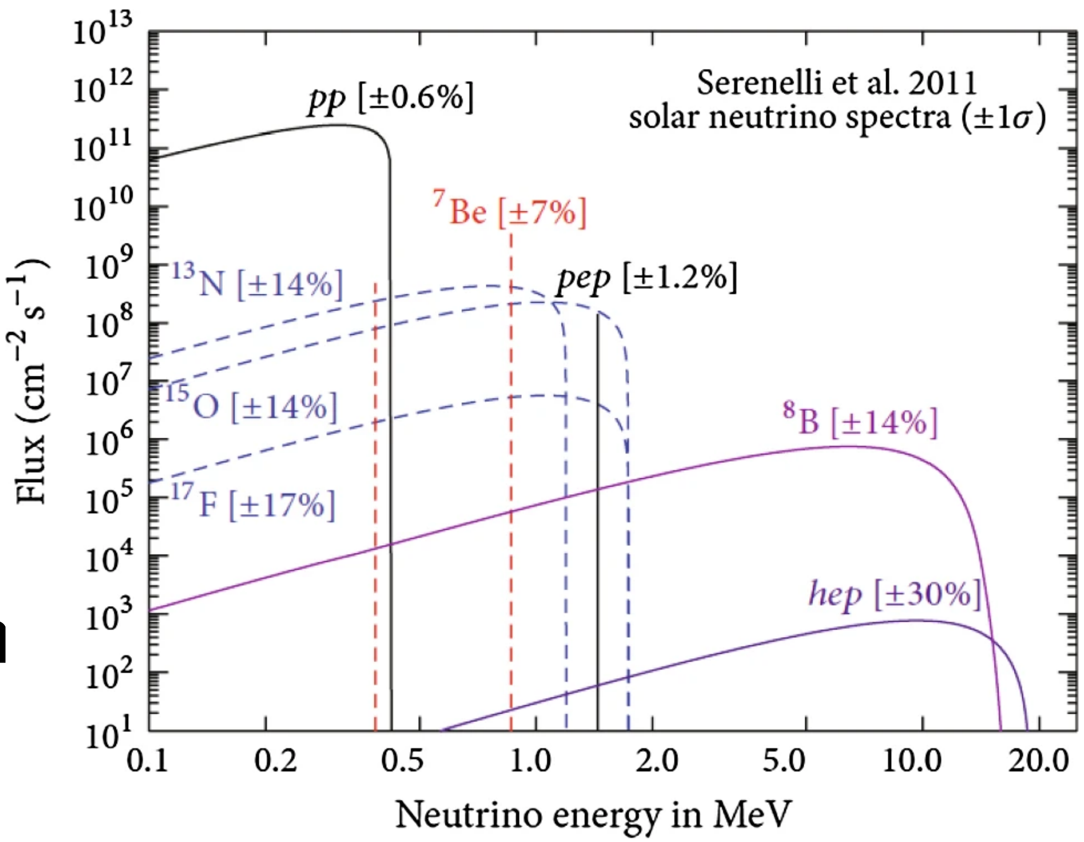


Image of the sun seen by neutrinos. From the website of ICRR



From Eur. Phys. J. C 79, 298 (2019)

Solar neutrino oscillation

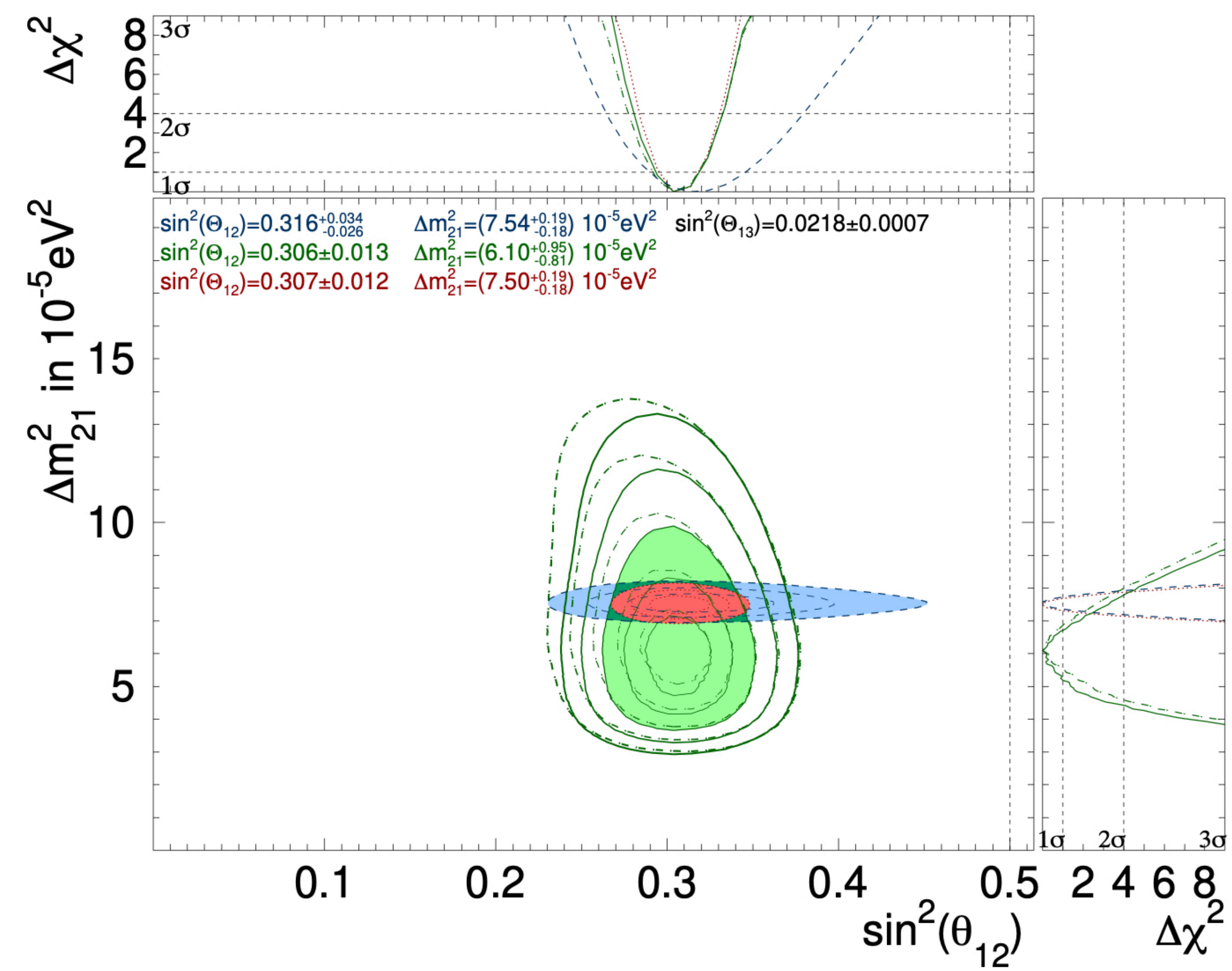
- In the solar neutrino energy range, only the ν_e can interact with the charged current. So **the survival probability of ν_e can be extracted from the recorded events**.
- As the θ_{13} and θ_{13} have small impact in the ν_e survival probability, θ_{12} and Δm^2_{21} can be constrained by the solar neutrino analysis.
- By the analysis of 5805 days data, SK set the constraint of

$$\sin^2\theta_{12} = 0.306 \pm 0.013$$
$$\Delta m^2_{21} = (6.10^{+0.95}_{-0.81}) \times 10^{-5}\ \mathrm{eV}^2$$

- Further constraint is achieved by combination with KAMLAND,

$$\sin^2\theta_{12} = 0.307 \pm 0.012$$
$$\Delta m^2_{21} = (7.50^{+0.19}_{-0.18}) \times 10^{-5}$$

- 1.5σ tension was observed in Δm^2_{21} between SK and KAMLAND.

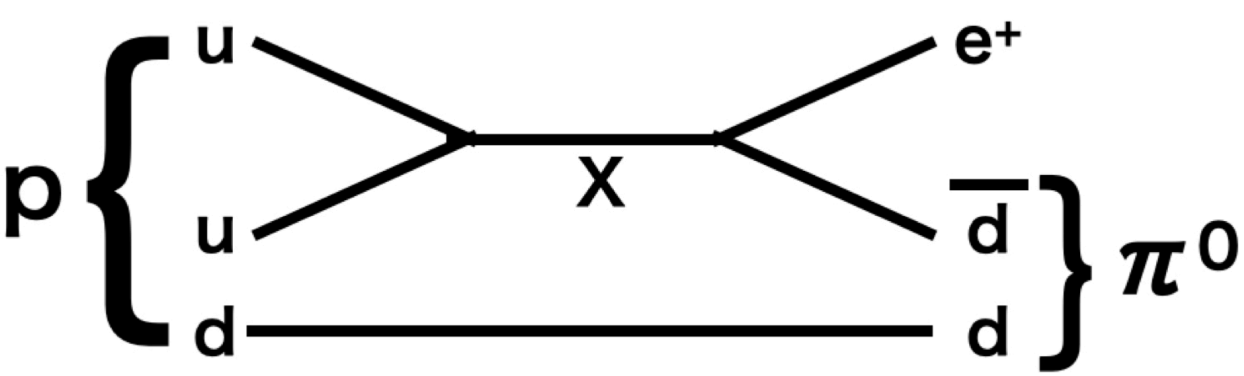


From Phys. Rev. D 109, 092001 (2024)

Proton decay

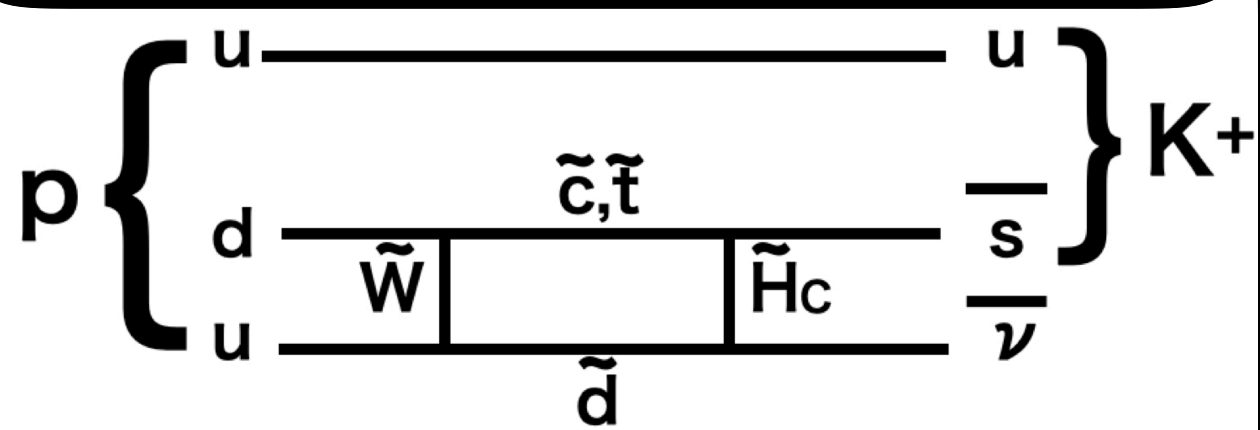
- Proton decay (or neutron decay) is also one of the important physics target in SK.
- Proton decay is prohibited in SM, but it is predicted by GUT models. **Observation of proton decay can be a strong evidence of GUT.**
- Two decay modes are intensively searched because they are predicted in leading models, and other possible modes are also widely searched.

$p \to e^+\pi^0$



- Dominant in non-SUSY models
- Current limit: $\tau/\Gamma > 2.4 \times 10^{34}$ **years**.

$p \to \bar{\nu} K^+$



- Dominant in SUSY models
- Current limit: $\tau/\Gamma > 8.2 \times 10^{33}$ **years**.

Proton decay

- Other possible decay modes including neutron decay and dinucleon decay are also searched in SK.
- In most of the modes, SK sets the best limit in the world.

Decay mode	SK detector	Exposure [kt-years]	Lifetime limit [years]	Reference	Comments
$p \to e^+\pi^0$	I–IV	450	2.4×10^{34}	[20]	Expanded FV
$p \to \mu^+\pi^0$	I–IV	450	1.6×10^{34}	[20]	Expanded FV
$p \to \bar{\nu}\pi^+$	I–III	173	3.9×10^{32}	[21]	
$n \to \bar{\nu}\pi^0$	I–III	173	1.1×10^{33}	[21]	
$p \to e^+\eta$	I–IV	373	1.4×10^{34}	In prep.	
$p \to \mu^+\eta$	I–IV	373	7.3×10^{33}	In prep.	
$p \to e^+\rho^0$	I–IV	316	7.2×10^{32}	[22]	A part of SK IV data
$p \to \mu^+\rho^0$	I–IV	316	5.7×10^{32}	[22]	A part of SK IV data
$p \to e^+\omega$	I–IV	316	1.6×10^{33}	[22]	A part of SK IV data
$p \to \mu^+\omega$	I–IV	316	2.8×10^{33}	[22]	A part of SK IV data
$n \to e^+\pi^-$	I–IV	316	5.3×10^{33}	[22]	A part of SK IV data
$n \to \mu^+\pi^-$	I–IV	316	3.5×10^{33}	[22]	A part of SK IV data
$n \to e^+\rho^-$	I–IV	316	3.0×10^{31}	[22]	A part of SK IV data
$n \to \mu^+\rho^-$	I–IV	316	6.0×10^{31}	[22]	A part of SK IV data
$p \to e^+\pi^0\pi^0$	I–V	401	7.2×10^{33}	In prep.	
$p \to \mu^+\pi^0\pi^0$	I–V	401	4.5×10^{33}	In prep.	
$p \to e^+e^+e^-$	I–IV	373	3.4×10^{34}	[23]	
$p \to \mu^+e^+e^-$	I–IV	373	2.3×10^{34}	[23]	
$p \to \mu^-e^+e^+$	I–IV	373	1.9×10^{34}	[23]	
$p \to e^+\mu^+\mu^-$	I–IV	373	9.2×10^{33}	[23]	
$p \to e^-\mu^+\mu^+$	I–IV	373	1.1×10^{34}	[23]	
$p \to \mu^+\mu^+\mu^-$	I–IV	373	1.0×10^{34}	[23]	
$p \to e^+\nu\nu$	I–IV	273	1.7×10^{32}	[24]	A part of SK IV data
$p \to \mu^+\nu\nu$	I–IV	273	2.2×10^{32}	[24]	A part of SK IV data
$p \to e^+X$	I–IV	273	7.9×10^{32}	[25]	A part of SK IV data
$p \to \mu^+X$	I–IV	273	4.1×10^{32}	[25]	A part of SK IV data
$n \to \nu\gamma$	I–IV	273	5.5×10^{32}	[25]	A part of SK IV data
$p \to \nu K^+$	I–IV	365	8.2×10^{33}	[26]	A part of SK IV data
$p \to \mu^+K^0$	I–IV	373	3.6×10^{33}	[27]	
$p \to e^+K^0$	I	92	1.3×10^{33}	[28]	
$p \to \mu^+K^0$	I	92	1.0×10^{33}	[28]	

From the presentation by S.Mine in NNN23

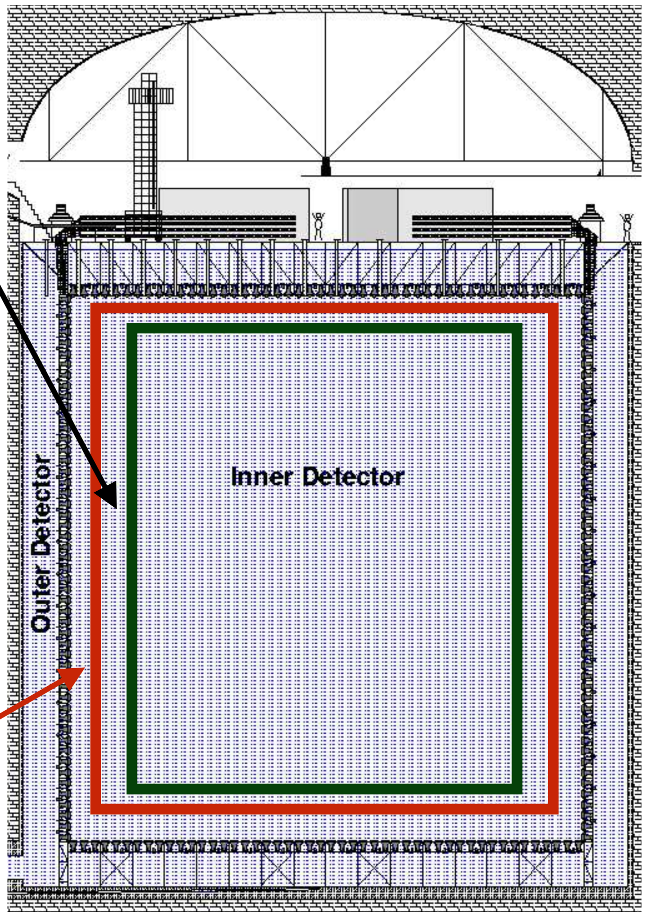
$pp \to e^+e^+$	I–IV	373	4.2×10^{33}	[29]	
$nn \to e^+e^-$	I–IV	373	4.2×10^{33}	[29]	
$nn \to \gamma\gamma$	I–IV	373	4.1×10^{33}	[29]	
$pp \to e^+\mu^+$	I–IV	373	4.4×10^{33}	[29]	
$nn \to e^+\mu^-$	I–IV	373	4.4×10^{33}	[29]	
$nn \to e^-\mu^+$	I–IV	373	4.4×10^{33}	[29]	
$pp \to \mu^+\mu^+$	I–IV	373	4.4×10^{33}	[29]	
$nn \to \mu^+\mu^-$	I–IV	373	4.4×10^{33}	[29]	
$pp \to \pi^+\pi^+$	I–IV	282	7.2×10^{31}	[30]	A part of SK IV data
$pn \to \pi^+\pi^0$	I–IV	282	1.7×10^{32}	[30]	A part of SK IV data
$nn \to \pi^0\pi^0$	I–IV	282	4.0×10^{32}	[30]	A part of SK IV data
$np \to e^+\nu$	I–IV	273	2.6×10^{32}	[25]	A part of SK IV data
$np \to \mu^+\nu$	I–IV	273	2.2×10^{32}	[25]	A part of SK IV data
$np \to \tau^+\nu$	I–IV	273	2.9×10^{31}	[25]	A part of SK IV data
$pp \to K^+K^+$	I	92	1.7×10^{32}	[31]	
$n \to \bar{n}$	I–IV	373	3.6×10^{32}	[32]	

Recent attempts

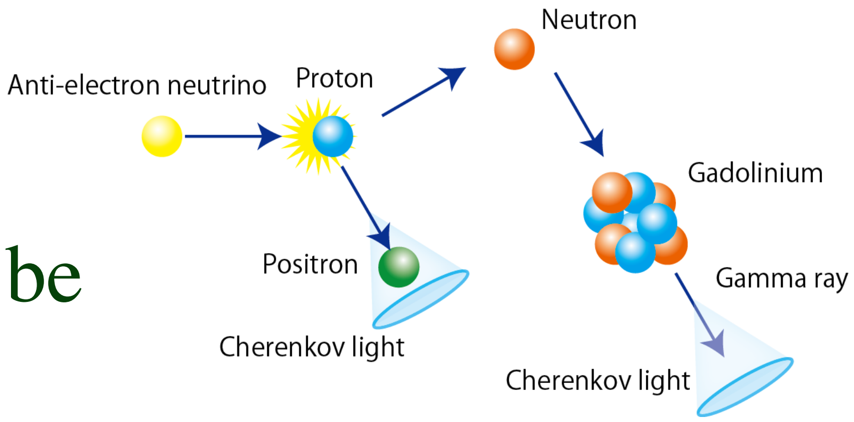
- SK tries to realize more sensitive analysis by many attempts.
  - **Enlarged fiducial volume**
    - In the convention analyses, the fiducial volume is defined as the volume >2m from the wall.
    - Enlarged fiducial volume is defined as >1m, Corresponding to **~20% increase of the exposure**.
    - The latest $p \to e^+\pi^0$ and $p \to \mu^+\pi^0$ analysis was performed using the enlarged volume.
      - PhysRevD.102.112011

Conventional fiducial volume

Enlarged fiducial volume

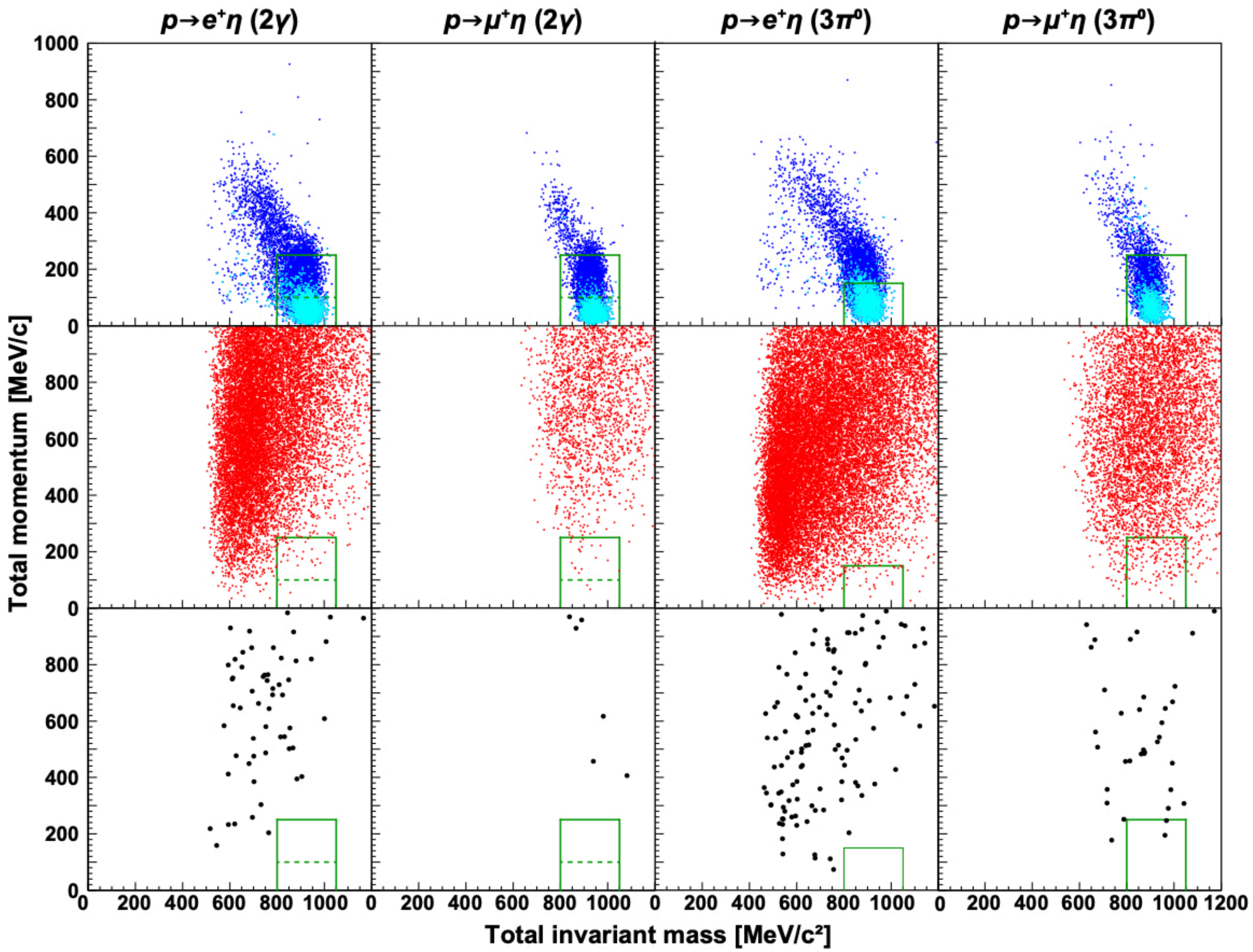


  - **Neutron tagging**
    - Neutron tagging is applied to minimize the background from the atmospheric neutrinos.
    - Neutron tagging with pure water is adopted in the data of 2008~.
    - Analyses with more sensitive tagging by Gd will be published in near future.



Latest published analysis

- The search for $p \to e^+\eta, p \to \mu^+\eta$ using the data of 1996-2018 was published in Phys. Rev. D 110, 112011 (2024).



- No significant excess was observed and the lower lifetime limit was set: $\tau/\Gamma > 1.4 \times 10^{34}$ years $(p \to e^+\eta)$, 7.3×10^{33} years $(p \to \mu^+\eta)$

Summary

- Since the start of the operation in 1996, SK has been exploring important cosmological and elementary particle physics, including neutrino and proton decay.

- In 2020, SK was upgraded by adopting the Gd-loaded water to enhance the neutron tagging performance. Now the neutron capture efficiency of 75% is achieved by the Gd concentration of 0.03%.

- In both neutrino and proton decay fields, SK has been updating many analysis channels.

- In near future, new physics results with new neutron-tagging techniques by Gd will be presented.
  Keep Watching SK.

Back up