Solar neutrino oscillation results and future prospect

18th, September 2025

II EU Workshop on Water Cherenkov Experiments for Precision Physics

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UNIVERSITY OF TOYAMA

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- Summary

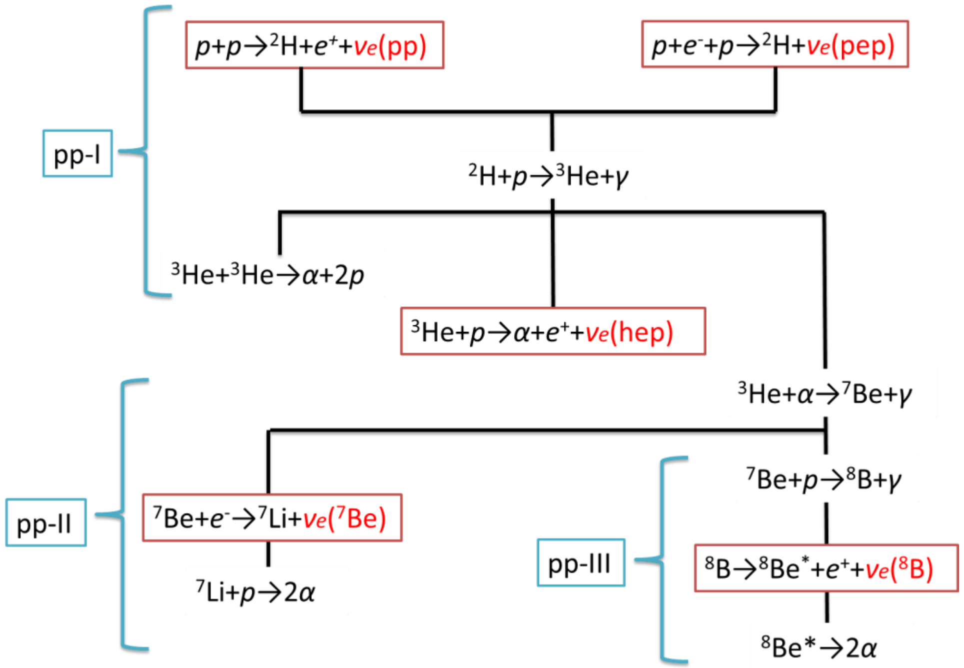
Solar neutrinos

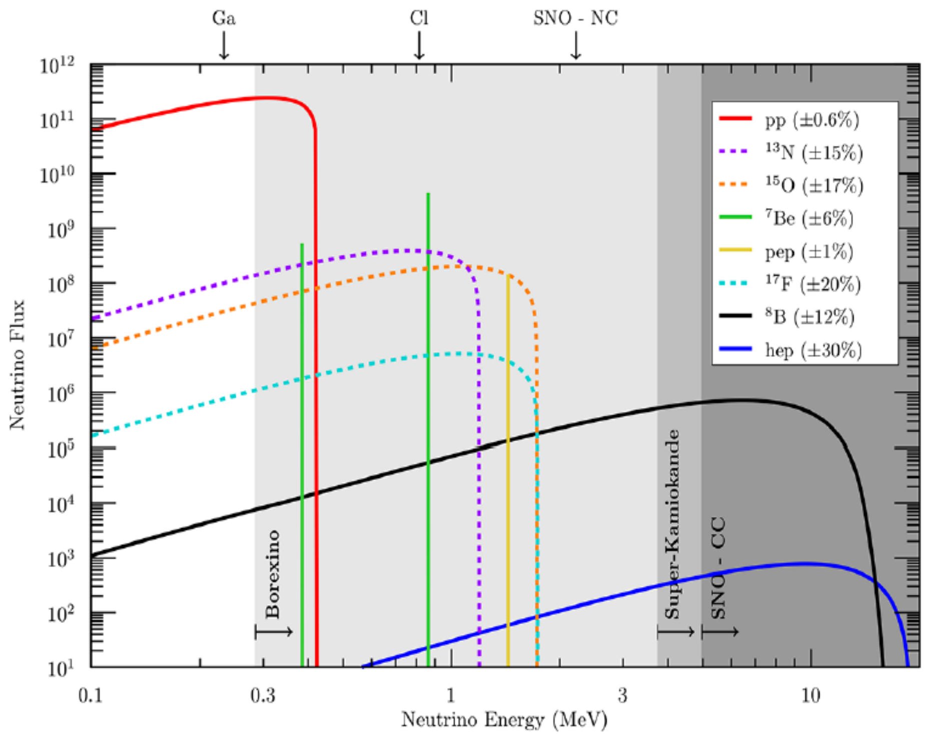
■ Production of solar neutrino

- Solar neutrinos are produced via nuclear fusions in the core.

$$4p \rightarrow \alpha + 2e^{+} + 2\nu_e + 26.7\mathrm{MeV} - E_\nu$$

- Several processes produce electron-neutrino (ν_e).
  → *pp*, *pep*, ^{7}Be, ^{8}B, *hep* and *CNO*
- Standard solar model (SSM) predicts their fluxes.

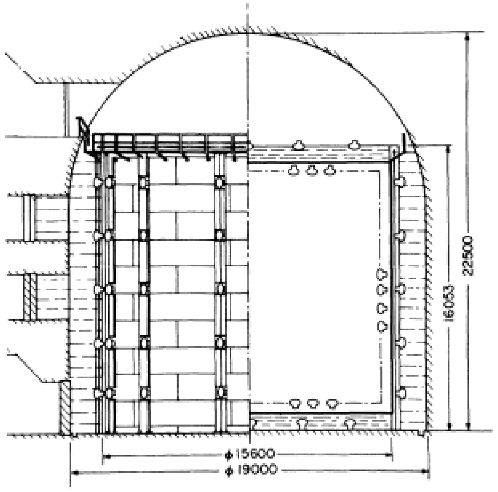




Water Cherenkov detectors

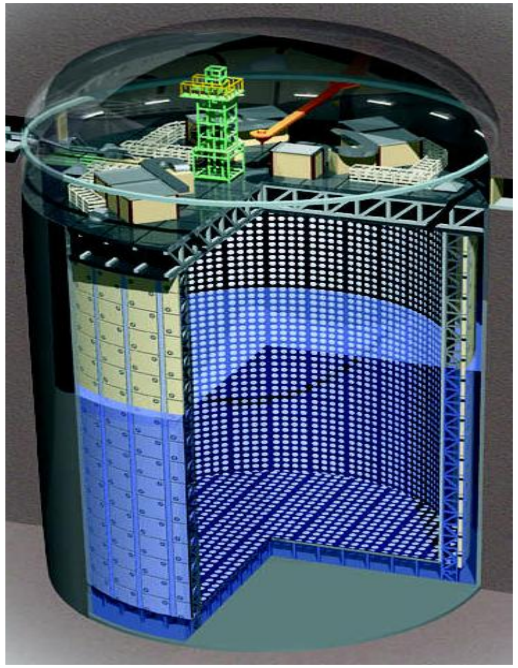
as solar neutrino detector

Kamiokande

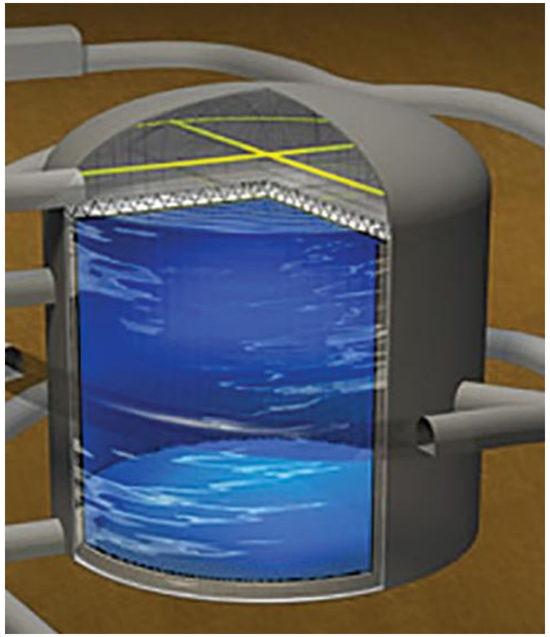


Phys. Rev. D 38, 448 (1998)

Super- Kamiokande

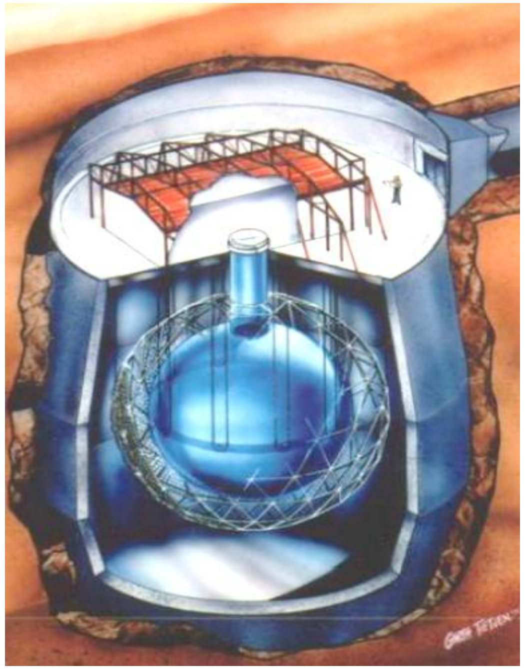


Hyper- Kamiokande



H_2O

SNO



Phys. Rev. C 75, 045502 (2007)

D_2O

Solar neutrino interactions in Water

Reaction channels

- Three reactions (CC/NC/ES) are used in the water Cherenkov detector.

Channel	Experiment	Reaction	Energy Threshold	Comment
Charged current (CC)	SNO	$\nu_e + d$ $\rightarrow e^- + p + p$	1.4 MeV	Sensitive only to ν_e → pure ν_e energy spectrum
Neutral current (NC)	SNO	$\nu_X + d$ $\rightarrow \nu_X + p + n$	2.2 MeV	Equally sensitive to all flavor but only to ^{8}B ν → Total ^{8}B neutrino flux
Elastic scattering (ES)	SK & SNO	$\nu_X + e^-$ $\rightarrow \nu_X + e^-$	------	Sensitive to all flavor Small contribution of $\nu_{\mu/\tau}$ Cross section: $\sigma_{\nu_e} = (6-7) \times \sigma_{\nu_{\mu/\tau}}$

Physics from reactions above

- The total ν_X flux and the ν_e flux would be separately determined.
- The CC/NC ratio gives the survival probability of solar neutrino.
- This provides independent test of the ν-oscillation hypothesis and the standard solar model (SSM).

Solar neutrino oscillation

■ Allowed oscillation parameters

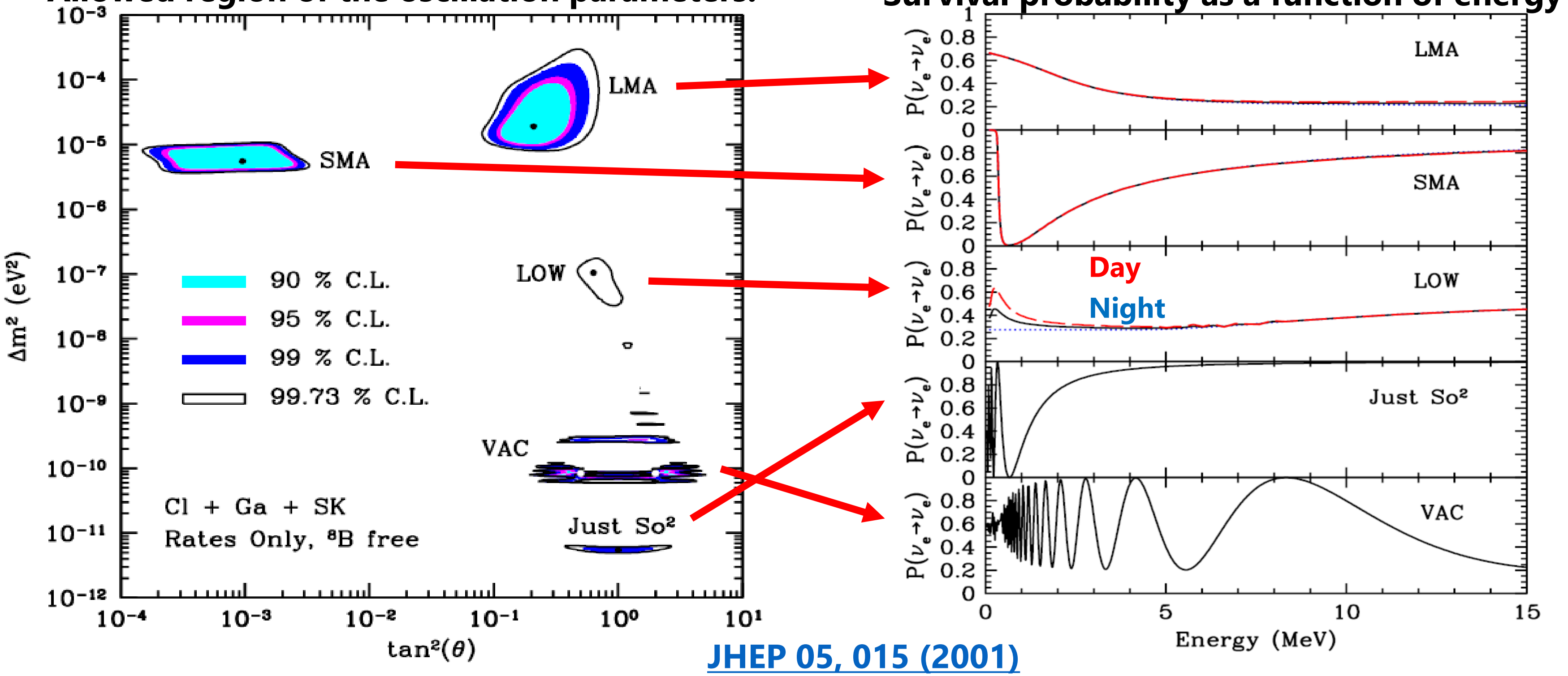
- Four possible oscillation solutions in 1990s.

(1) LOW & LMA: No energy distortion, and small day/night flux difference.
(2) SMA: Large energy distortion at low energy.
(3) VAC: Energy distortion, and seasonal variation.

→ Energy spectrum, seasonal variation, and day-night flux asymmetry are key to determine the solution.

Allowed region of the oscillation parameters.

Survival probability as a function of energy



JHEP 05, 015 (2001)

Kamiokande & SK-I

■ Kamiokande

- First real-time measurement of solar neutrino.
  → Signals really come from the Sun by reconstructing the direction of scattered electrons.

- Observed rate over the SSM: 0.46±0.13(stat.)±0.08(syst.). Phys. Rev. Lett. 63, 16 (1989)

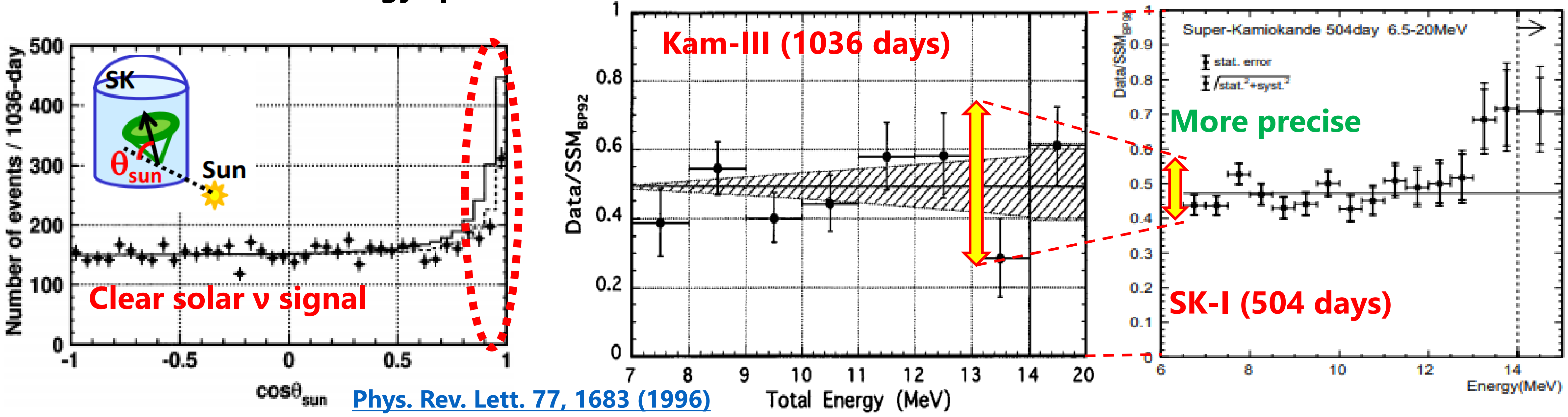
→ Confirmation of the solar neutrino problem.

■ Super-Kamiokande

- Precise flux/energy spectrum measurement.

→ No distortion in the energy spectrum.

Phys. Rev. Lett. 82, 2430 (1999)

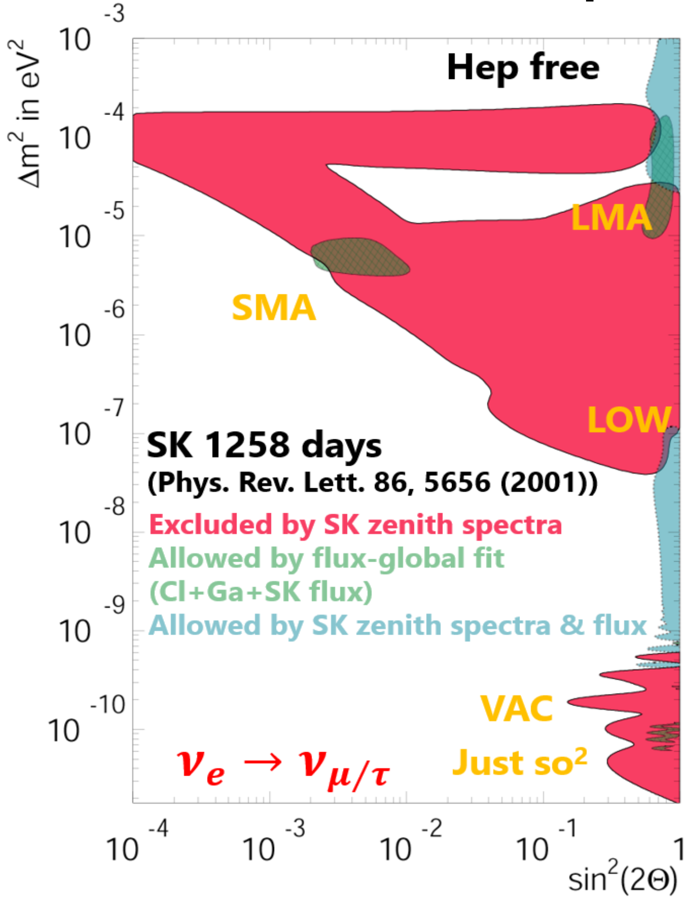


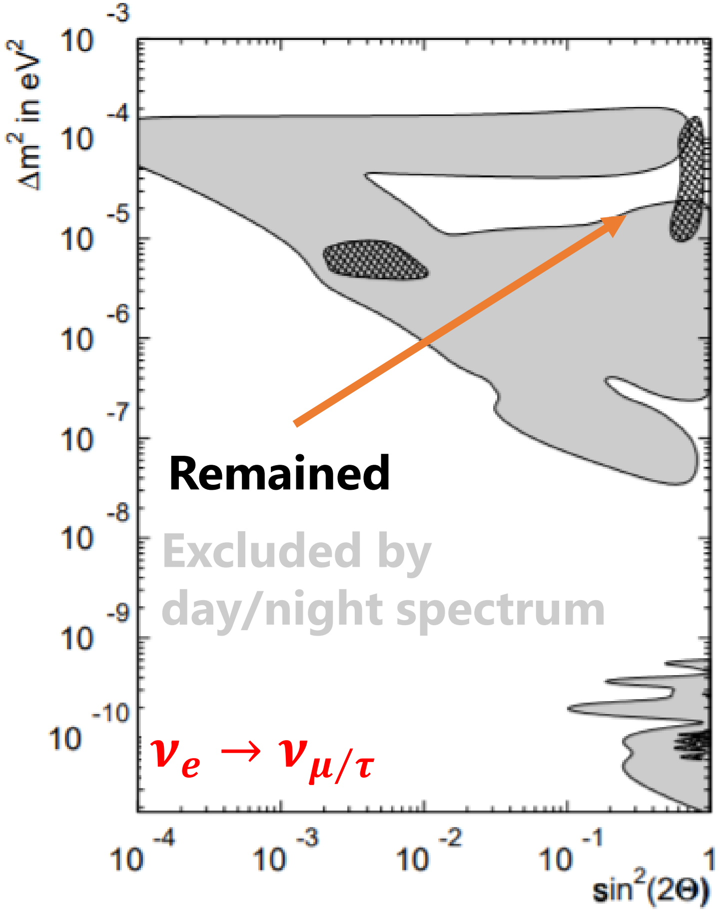
Phys. Rev. Lett. 77, 1683 (1996)

SK-I results

■ Era of precise measurement

- SK data confirmed:
  1) No energy distortion, no significant zenith dependence and small day/night flux asymmetry.
  2) SK's zenith angle spectra excluded SMA, VAC and demonstrated no Just so².
  3) SK's zenith spectra and flux measurement preferred LMA (higher Δm_{21}^2 region of large mixing).





Flavor conversion

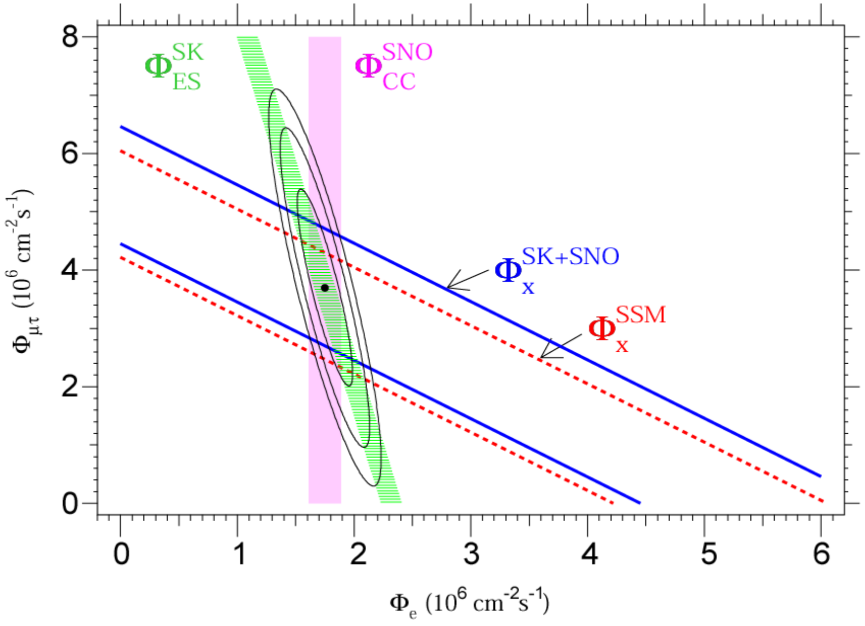
■ SNO's flux measurements with SK

- The first evidence of the solar neutrino oscillation was obtained by comparing SK ES with SNO CC (non-electron ν component in ES).

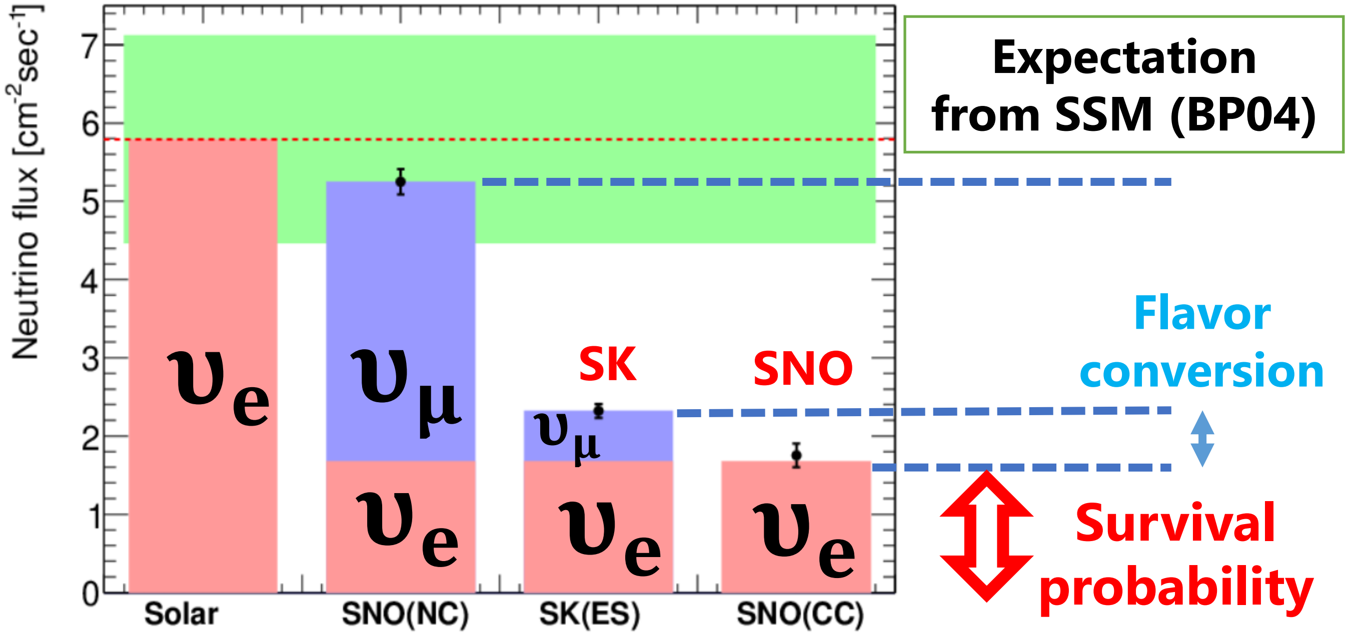
SNO CC	ν_e	$1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{syst.}) \pm 0.05(\text{thor.}) \times 10^6$ cm^{-2} sec^{-1}
SK ES	$\nu_e + 0.15\,(\nu_\mu + \nu_\tau)$	$2.39 \pm 0.34(\text{stat.})^{+0.15}_{-0.14}(\text{syst.}) \times 10^6$ cm^{-2} sec^{-1}
Difference		$(0.57 \pm 0.17) \times 10^6$ cm^{-2} sec^{-1}

→ Clear evidence for non-zero ν_μ/ν_τ flux (flavor change, 3.3σ).

→ Either of the results alone could not provided the evidence.



Phys. Rev. Lett. 87, 071301 (2001)



Next page

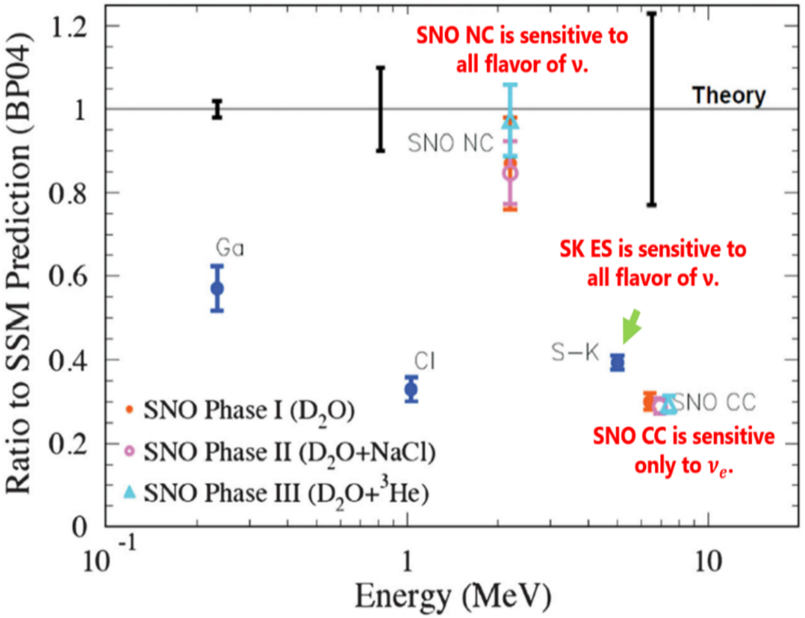
Solar neutrino oscillation with SNO

■ Survival probability

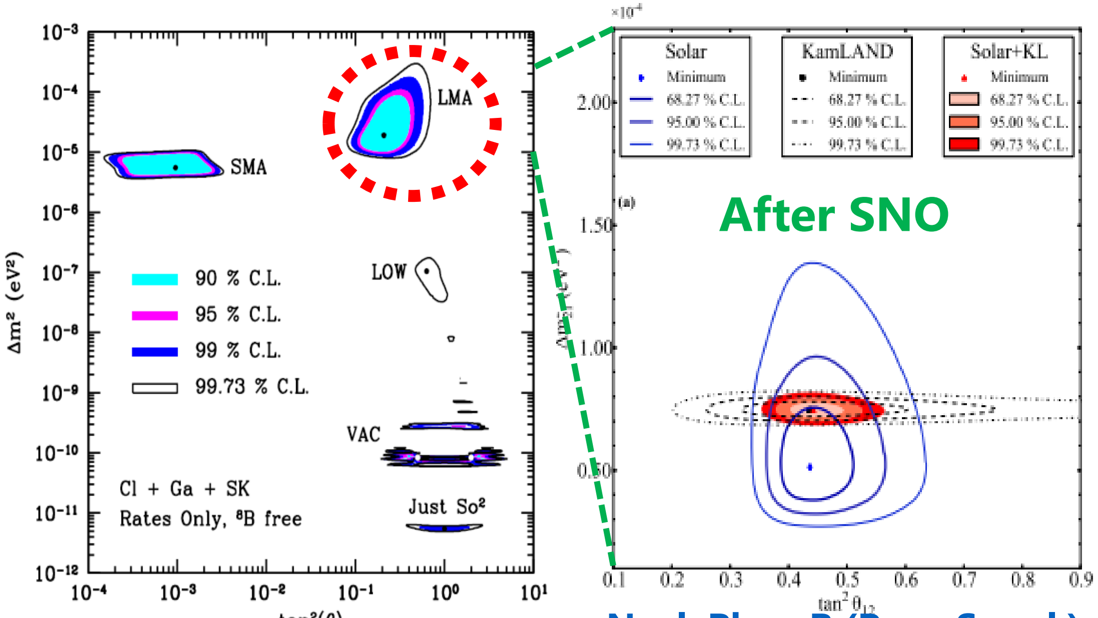
- **NC flux measurement is in good agreement with the prediction of the total ^8B solar neutrino in SSM.**

Measured total ^8B flux [$\times 10^6$ cm^{-2}sec^{-1}]	Prediction (BP04) [$\times 10^6$ cm^{-2}sec^{-1}]
$5.25 \pm 0.16^{+0.11}_{-0.13}$ Phys. Rev. C 88, 025501 (2013)	$5.79\,(1 \pm 0.23)$ Phys. Rev. Lett. 92, 121301 (2004)

- **The CC/NC ratio extracts the survival probability of solar electron neutrino: 0.317±0.016±0.009.**
  → Octant ambiguity of θ_{12} is solved (CC/NC<0.5 → $\theta_{12} < 45^\circ$).



Rev. Mod. Phys. 88, 030502 (2016)



JHEP 05, 015 (2001)

Nucl. Phys. B (Proc. Suppl.) 237-238 (2013) 107-110

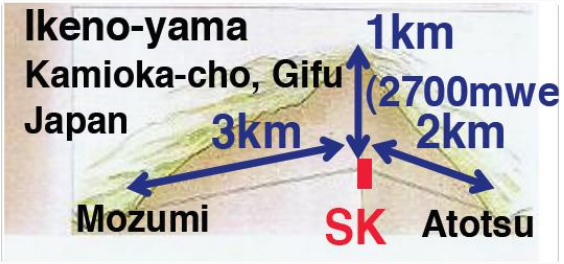
The latest results from SK

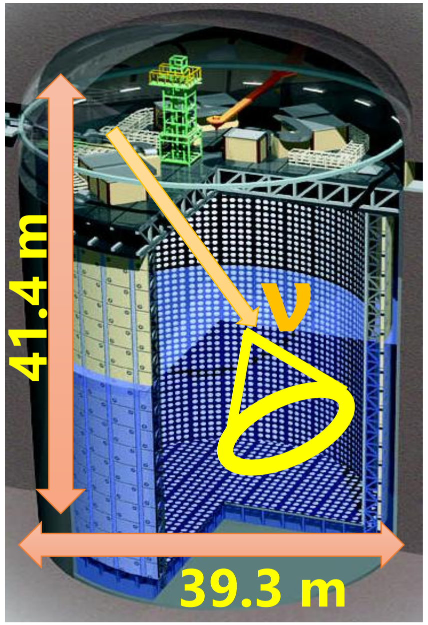
(pure water phase only)

Super-Kamiokande

■ Detector

- Located at Kamioka Japan.
- 50 kton of ultra pure water tank until 2018 and Gd-loaded water after 2020.
  - 20-inch PMTs, 11,129 for ID (since SK-III).
  - 22.5 kton for analysis fiducial volume.
- Water Cherenkov light technique.





■ History of SK

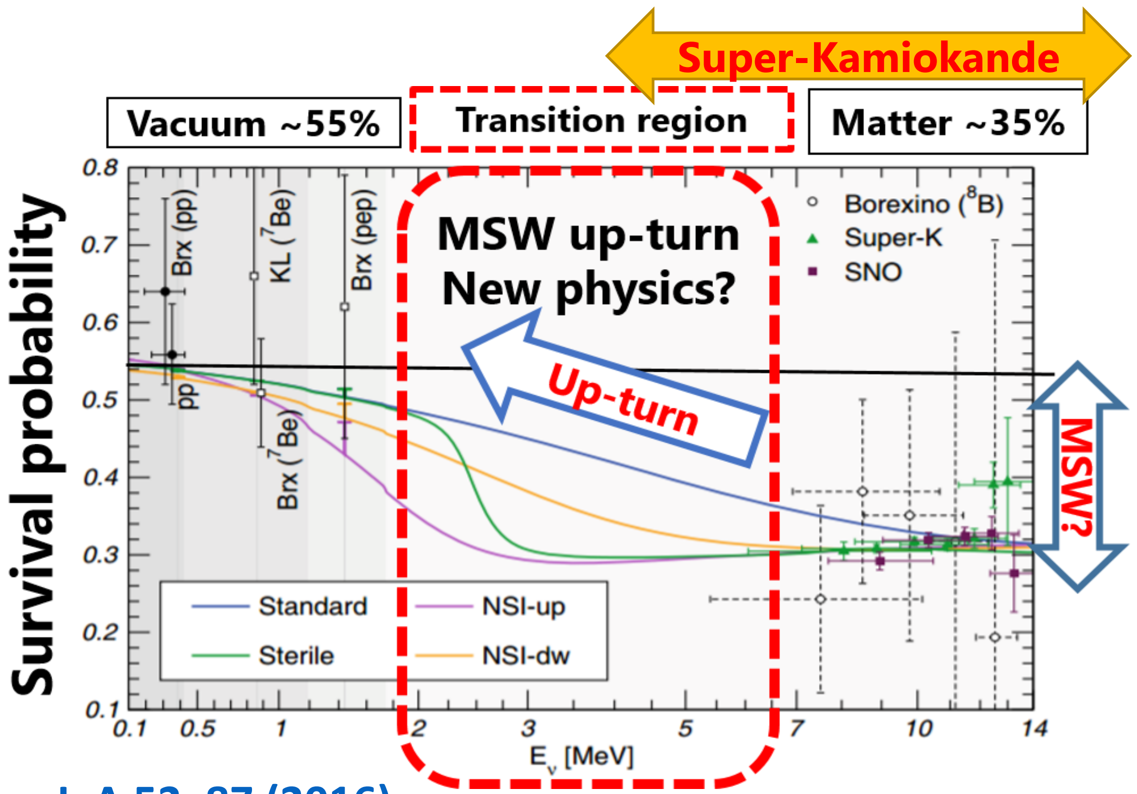
- Long term operation since 1996 (~30 years).
- Gd-loading after 2020 to start SK-Gd project [See Sekiya-san's and Mark's slides].
- 8-th phase started in 2024 summer after fixing the broken magnetic coils.

Motivation

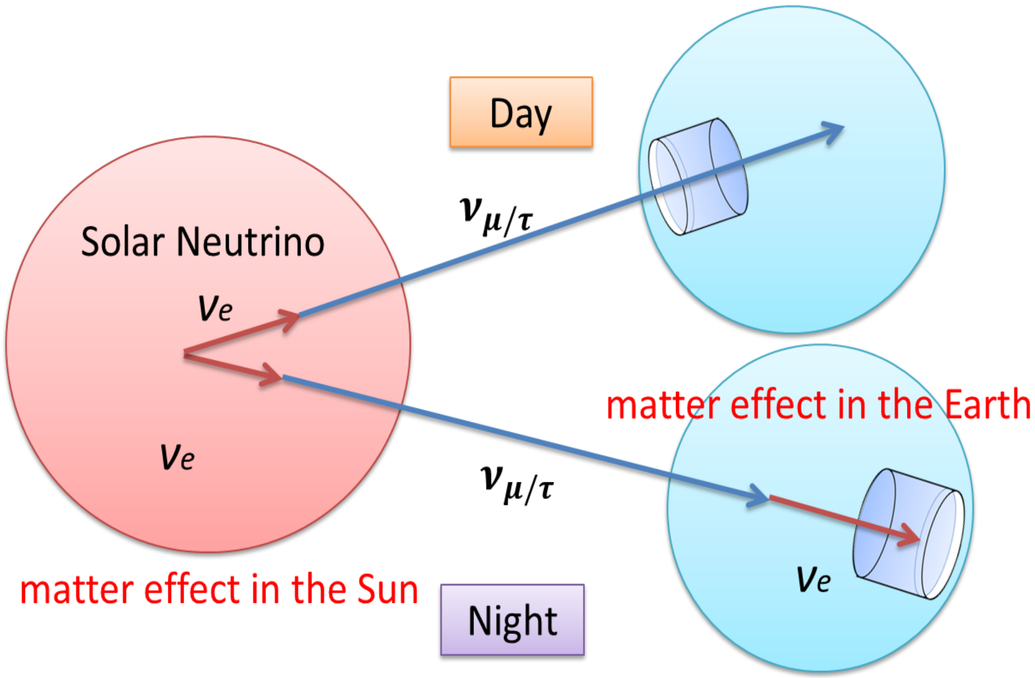
■ Goal of solar neutrino measurement in SK

(1) Test the transition of solar neutrino oscillation between vacuum and matter dominant regions.
→ Lowering threshold & reducing radioactive background events to test MSW up-turn.

(2) Day-night flux asymmetry
→ Regeneration of ν_e due to the Earth's matter effect is expected.



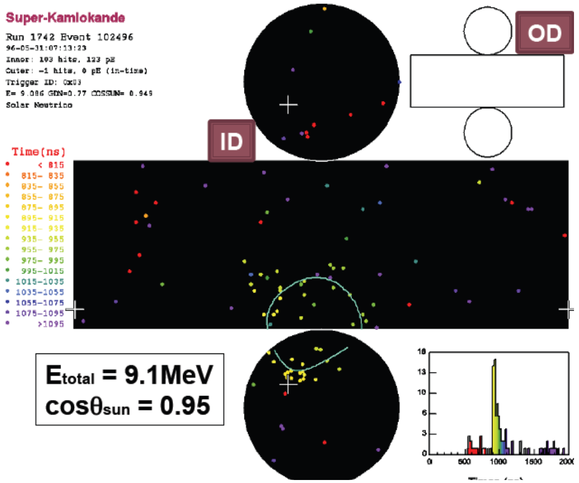
Eur. Phys. J. A 52, 87 (2016)



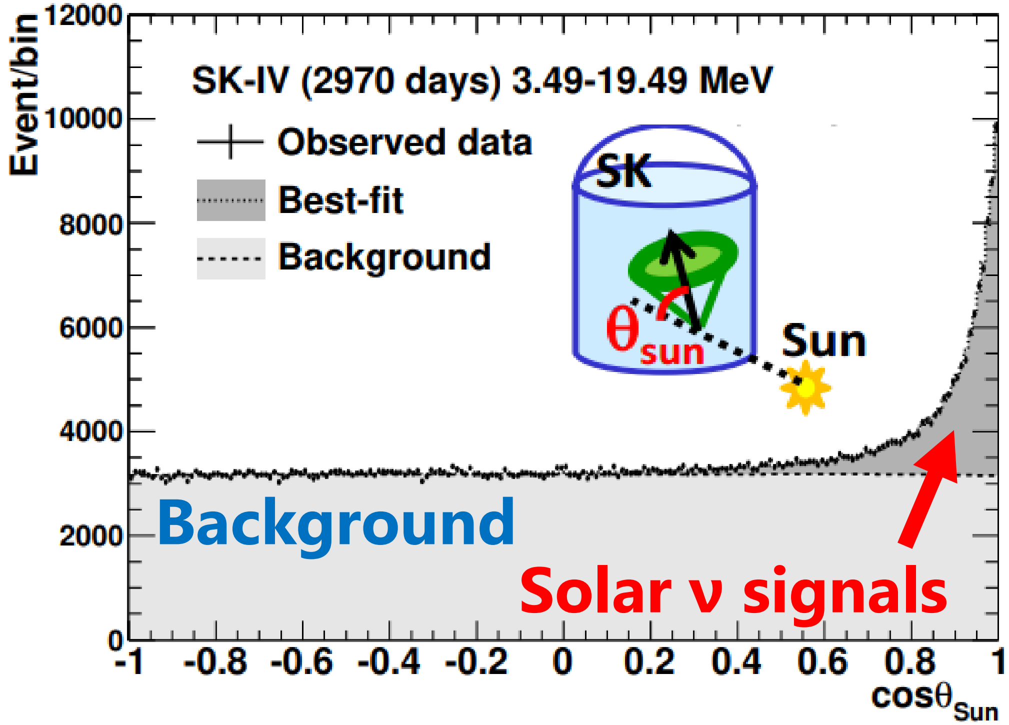
^{8}B solar neutrino detection

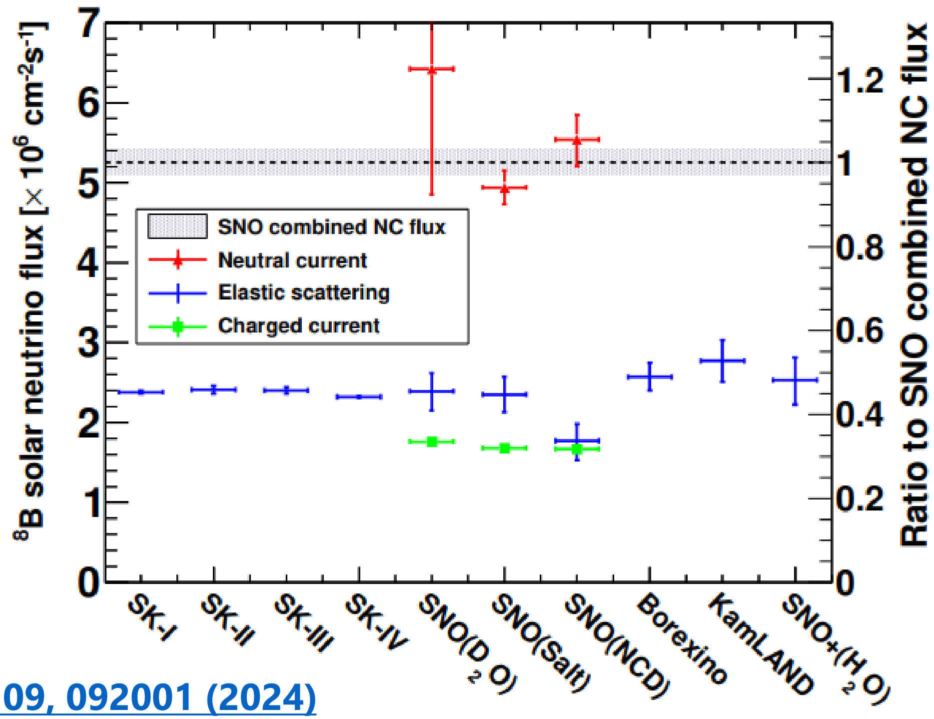
■ ^{8}B solar neutrino signals

- Elastic scattering ($\nu_X + e^- \rightarrow \nu_X + e^-$).
  (1) Timing → Vertex position & real-time measurement
  (2) Ring pattern → Direction of the incoming neutrino
  (3) # of hit PMTs → Energy (~6 p.e./MeV)



- ~20 events/day in SK-IV (SK-I~IV 5805 days: More than 100k events).





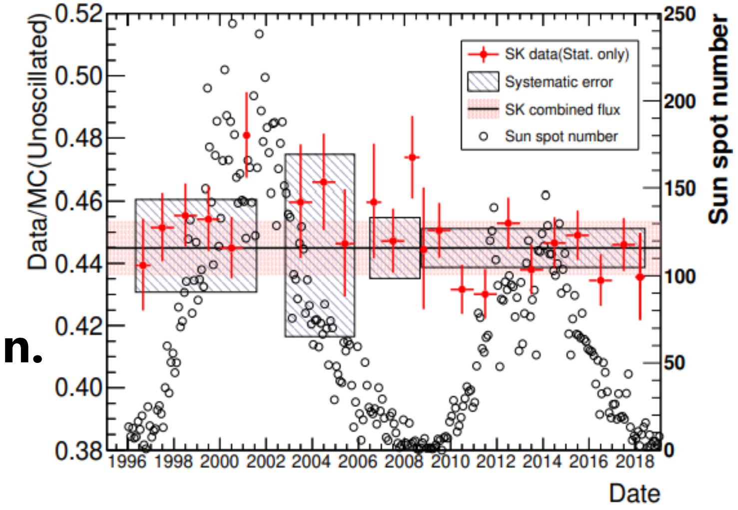
Phys. Rev. D 109, 092001 (2024)

Solar neutrino flux (interaction rate)

■ Modulation search

- Yearly measured flux is **stable with no correlation with solar activity**.

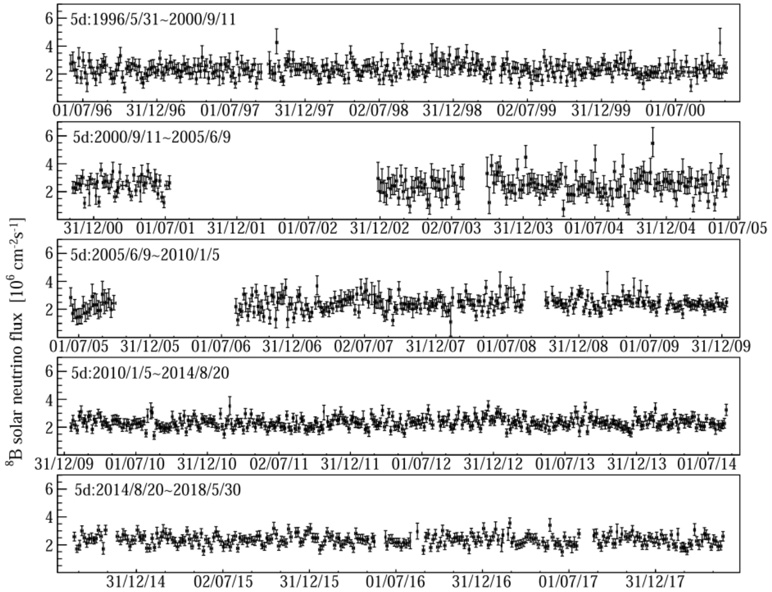
Phys. Rev. D 109, 092001 (2024)

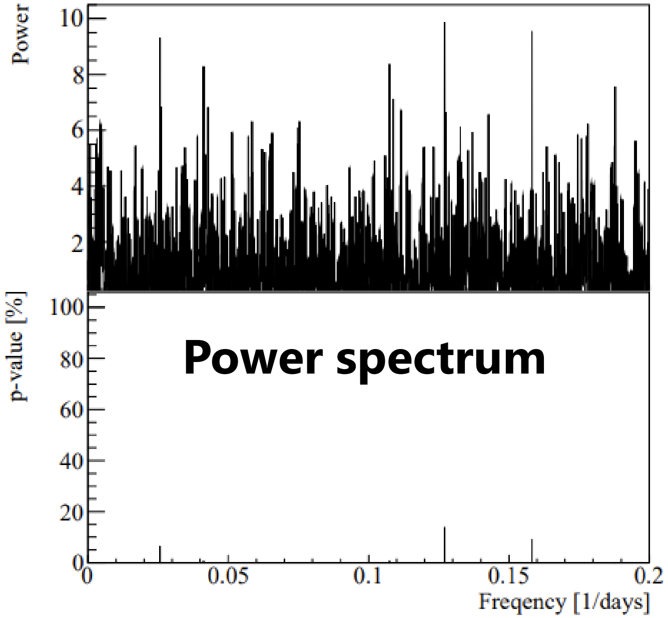


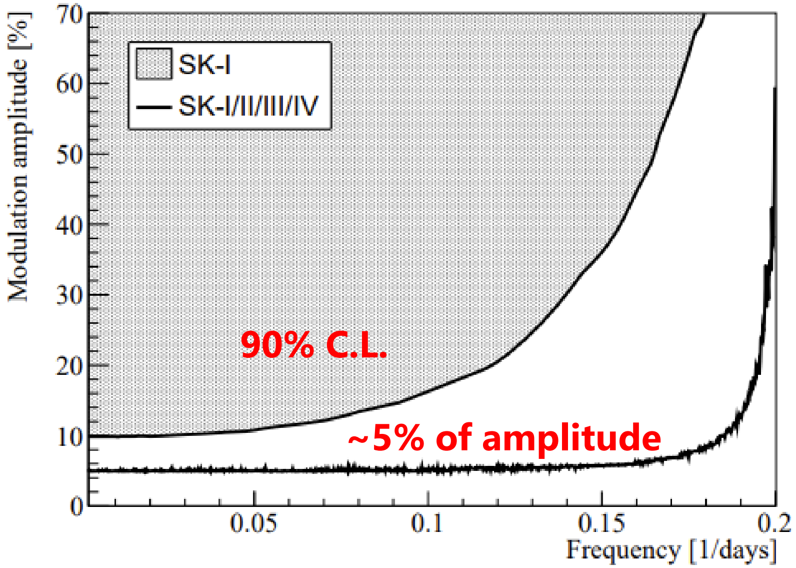
- Searched for periodic signal of ^{8}B solar neutrinos in 5-days binned data.
  → Lomb-Scargle method. Phys. Rev. Lett. 132, 241803 (2024)

- Found **no significant periodic change** of ^{8}B solar neutrino flux except for the modulation due to the elliptic orbit of the Earth around the Sun.

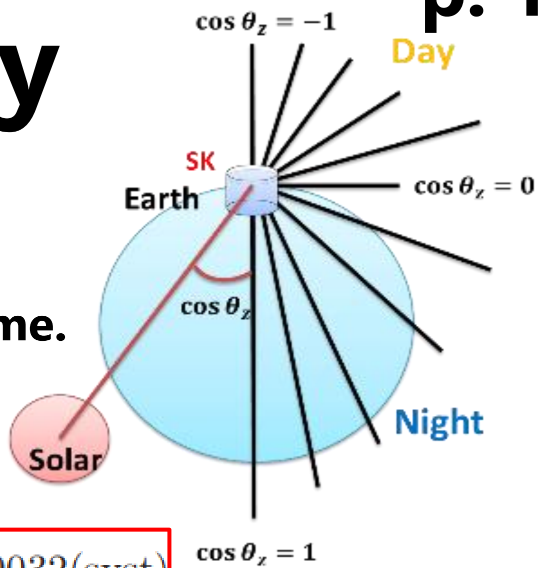
- Set the upper limits of **modulation amplitude** of solar neutrino.







Day/night flux asymmetry

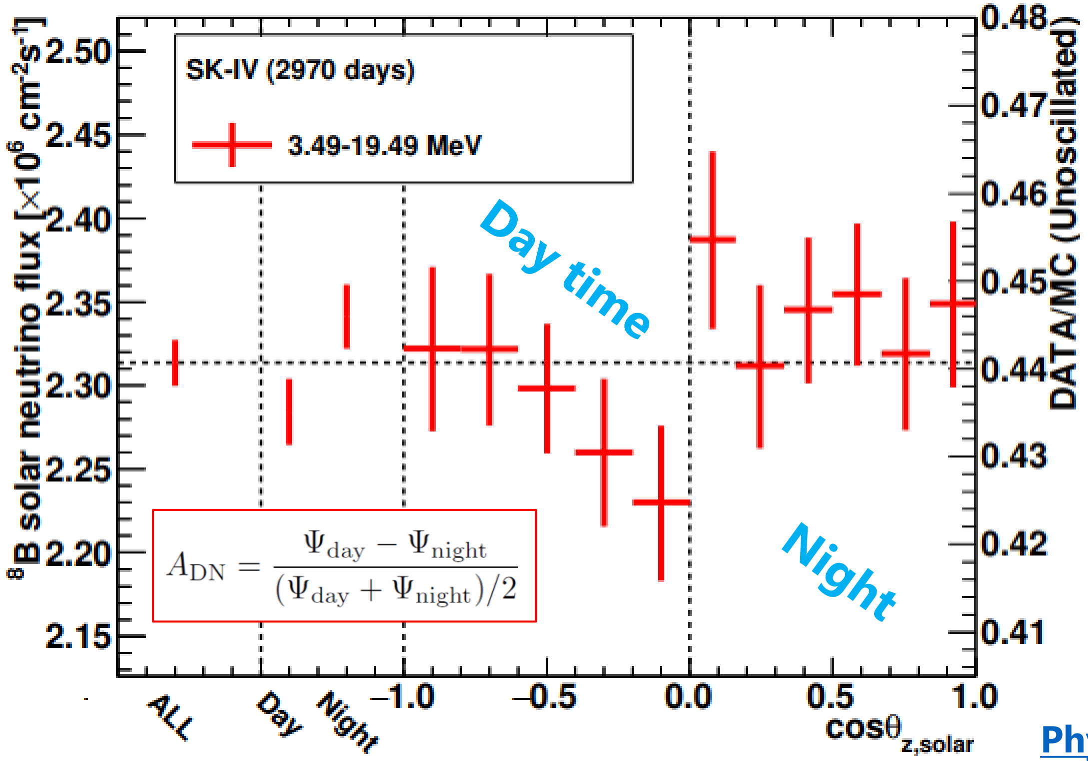


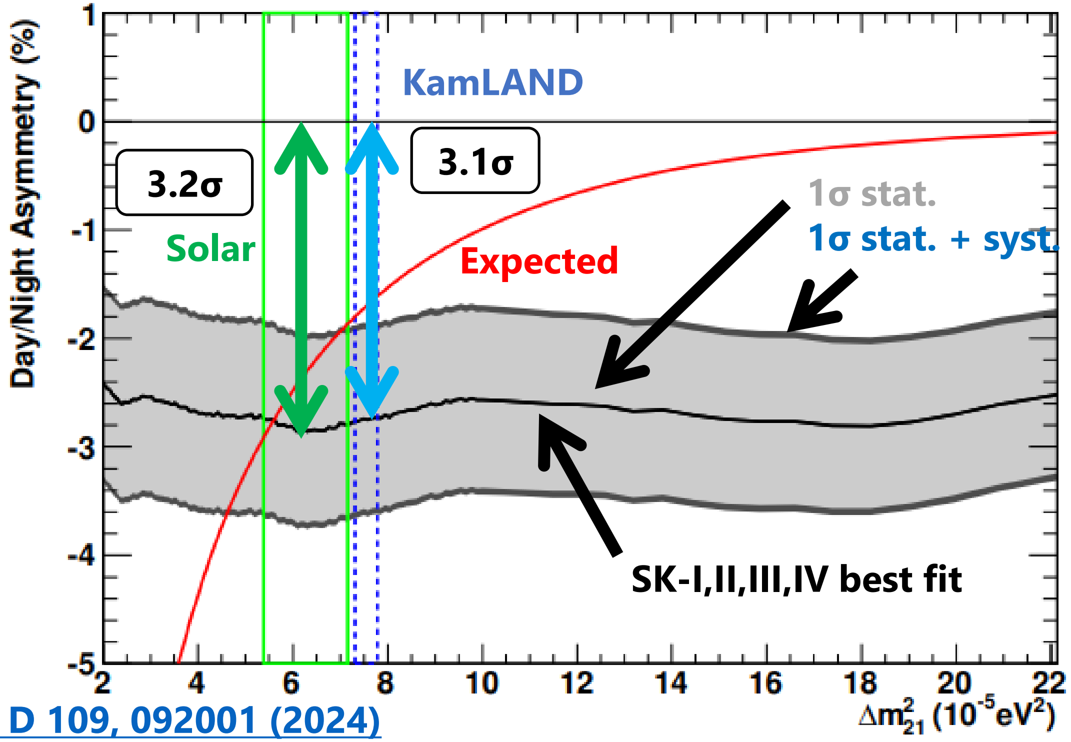
■ Amplitude fit

- Because of re-generation of electron neutrino **by matter effect in the Earth**, the interaction rate of elastic scattering in night-time is higher than that in day-time.

- Considering the operation time, electron density in neutrino path, the **amplitude of the day/night flux asymmetry** is determined.

$$A_{\rm D/N}^{\rm SK,fit} = -0.0286 \pm 0.0085({\rm stat.}) \pm 0.0032({\rm syst})$$





Phys. Rev. D 109, 092001 (2024)

Recoil electron energy spectrum measurement

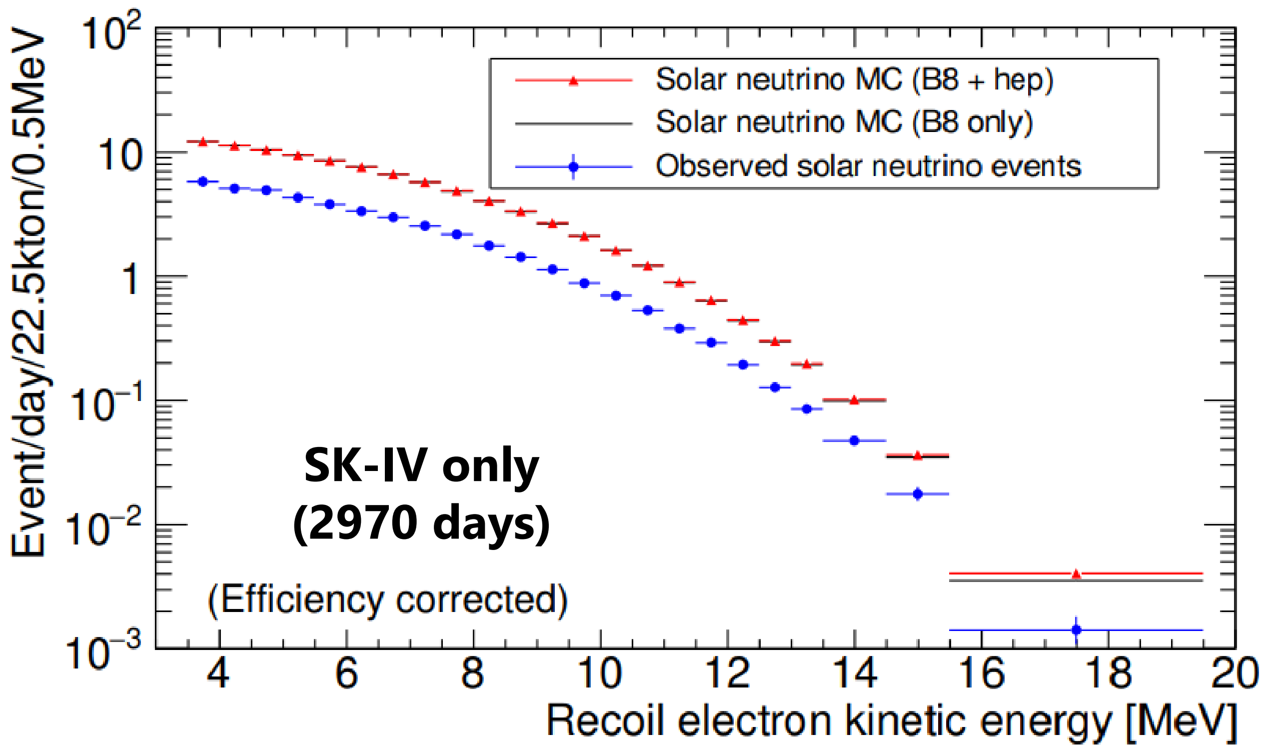
~1.5×10^{15} km

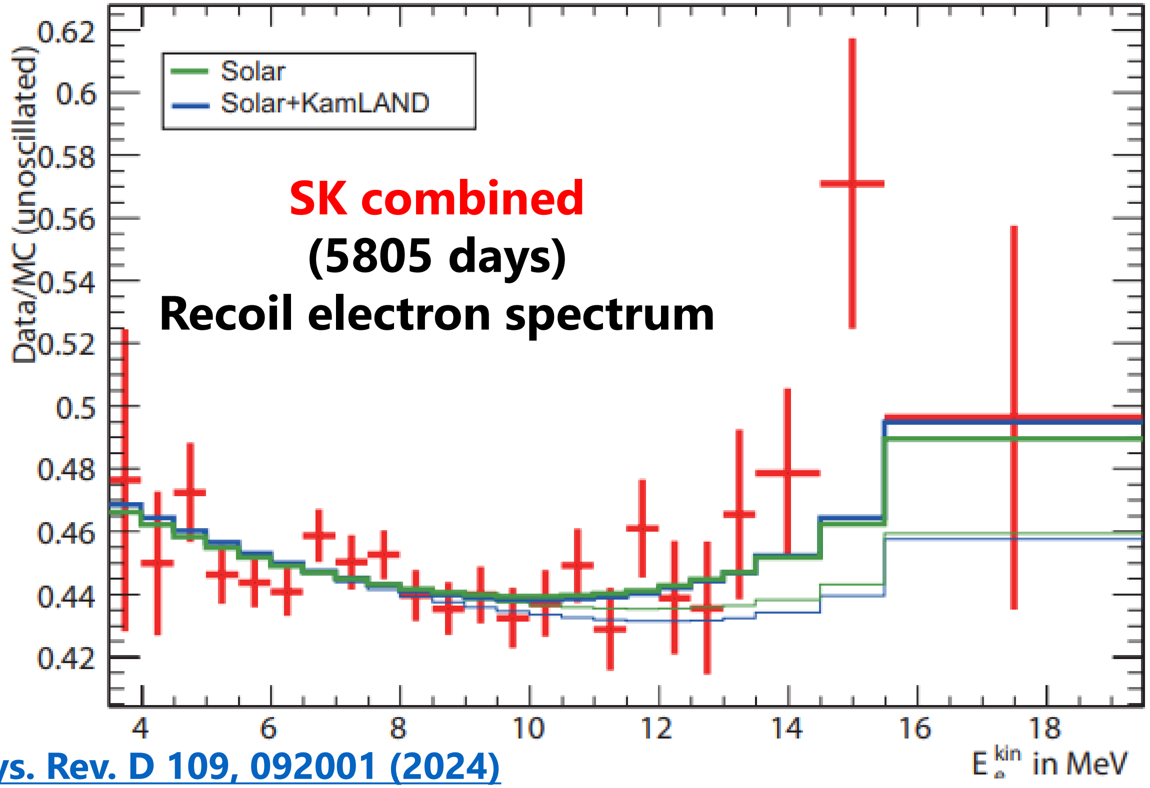
$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2 L}{E}\right)$$

■ Energy spectrum vs. MSW predictions

- To determine the oscillation parameters, spectrum measurement is important.

- Comparing the observed ^{8}B solar neutrino interaction rate with the MC prediction (w/o oscillation).
- SK combined spectrum data slightly favors the MSW-upturn by 1.3σ for Solar
  0.9σ for Solar+KamLAND.





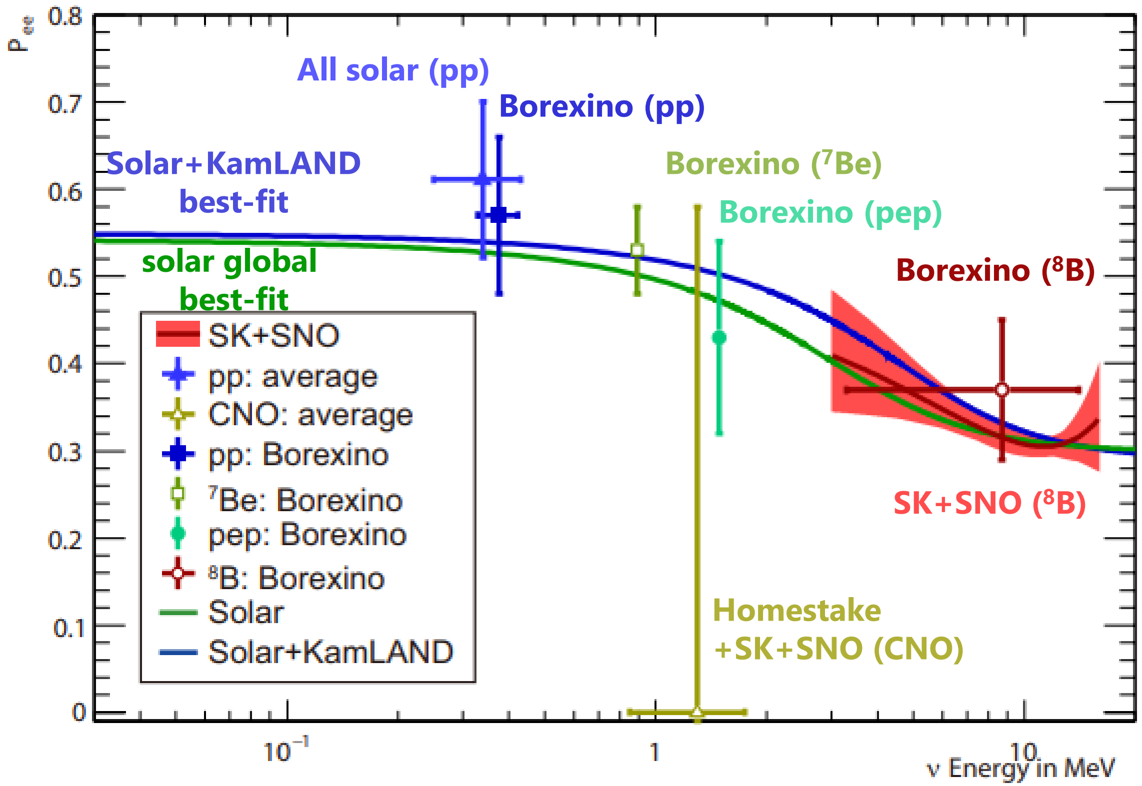
Phys. Rev. D 109, 092001 (2024)

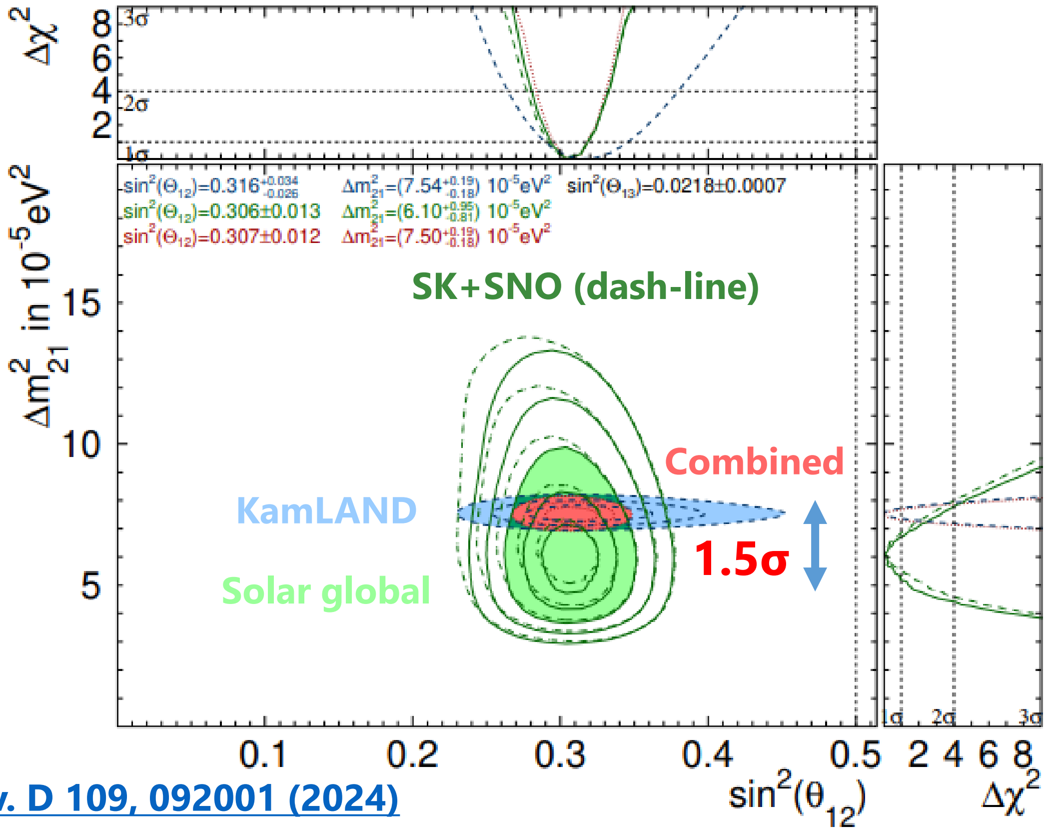
Survival probability and oscillation parameters

■ Comparison among solar neutrino experiments

- Neutrino energy spectrum is de-convoluted from the recoil electron energy spectrum.
  → Extracting survival probability (P_{ee}) and giving **the strongest constraint** on P_{ee} shape.

- Oscillation parameters are determined precisely and compared with KamLAND (reactor).
  → Observes **a tension in Δm^2_{21}** between solar global and KamLAND results **by 1.5σ (*CPT* violation? or BSM?)**.





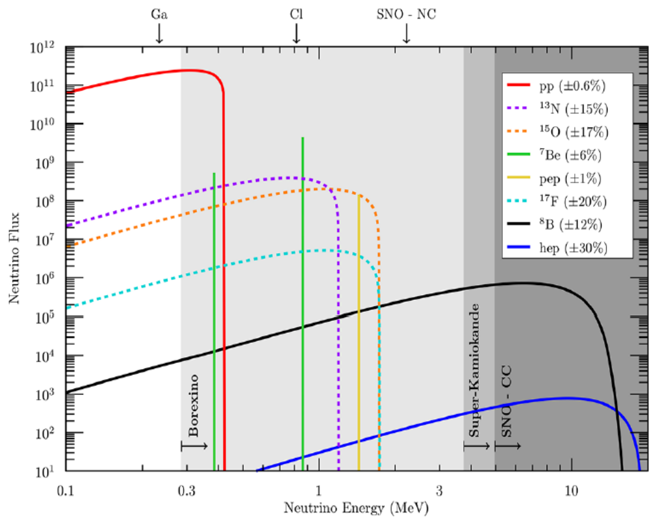
[Phys. Rev. D 109, 092001 (2024)]

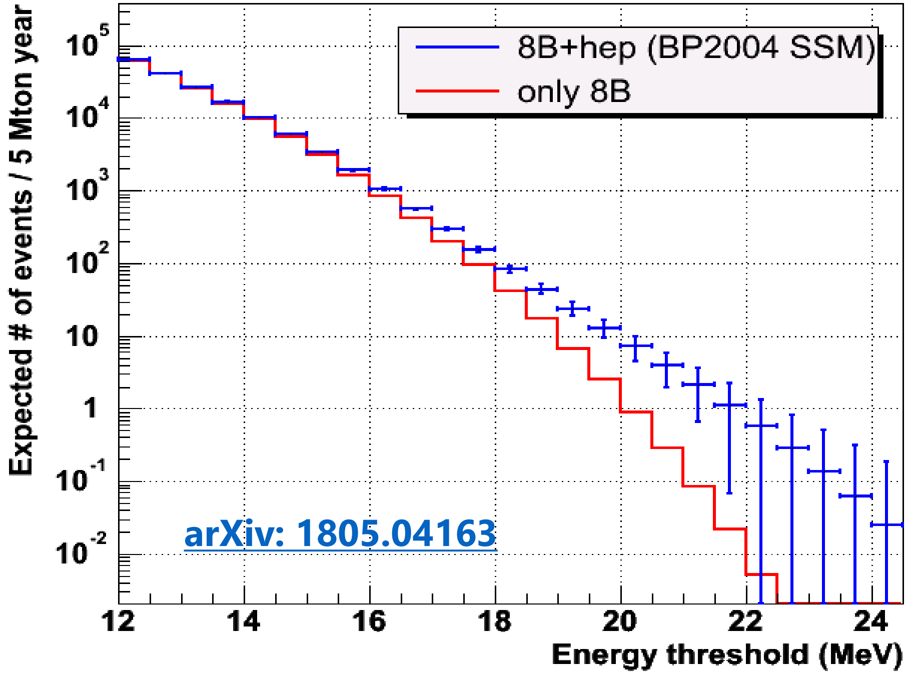
Future prospect

What is next?

■ Remaining items for solar neutrinos

1) ***Hep*** **neutrinos**
   - Not yet detected.
   → Expect to detect by the Hyper-Kamiokande
   by improving the systematic uncertainty of energy resolution.





2) ***pp*, *pep*, and ^{7}Be neutrinos**
   - Future scintillator detectors, such as SNO+, JUNO, and dark matter detectors.
   - Full understanding of the MSW effect in the Sun.

3) **Structure and motion of the Sun**
   - See next pages.

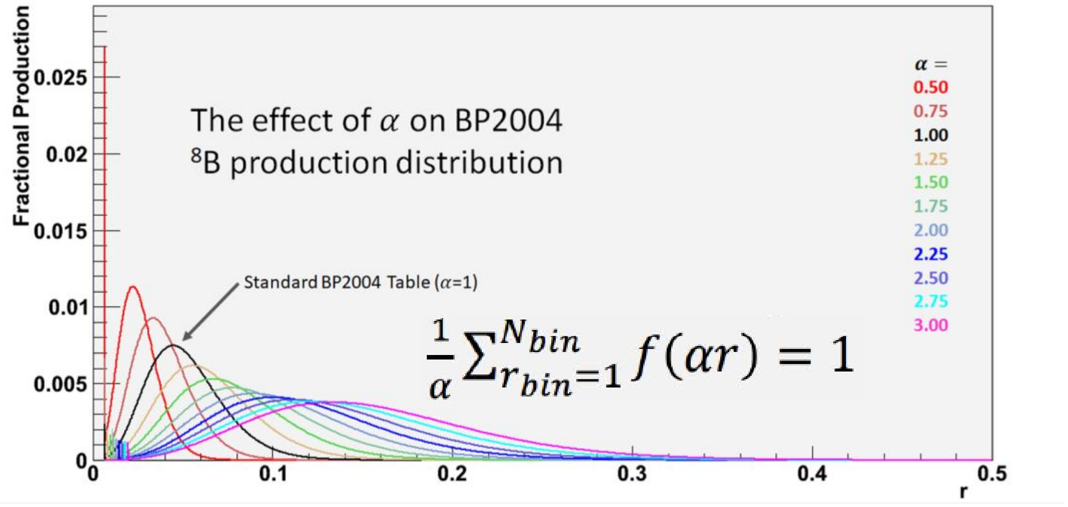
4) ***CPT*** **violation test**
   - After loading Gd in the SK detector, reactor neutrinos from Japanese reactors are expected.
   → SK also measures ϑ_{12} and Δm^2_{21} of both neutrino and anti-neutrino using the single detector.

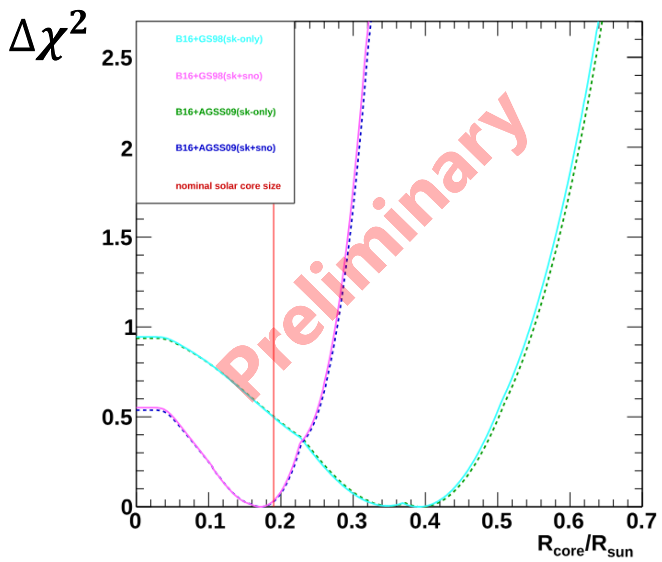
Neutrinos to set through the Sun structure

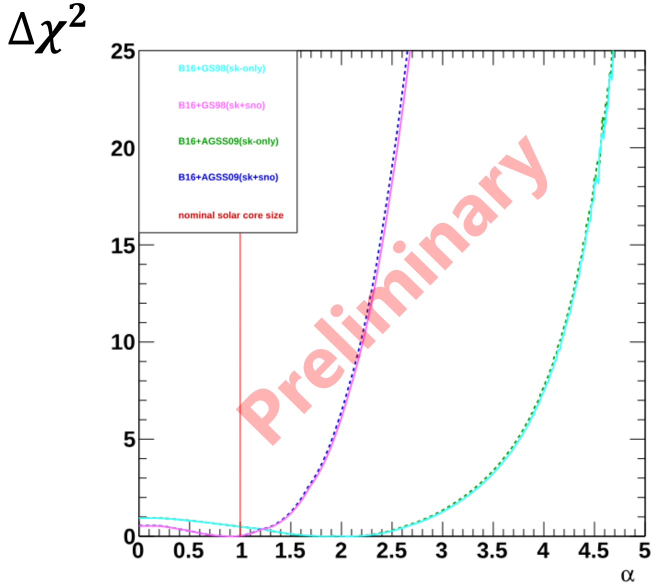
■ Size of solar core

Phys. Rev. Lett. 117, 211101 (2016)
arXiv: 2504.10583

- Survival probability changes depending on the path from the production site to the Earth.
- Keep the standard ^{8}B solar neutrino flux by changing the location of production (introducing scale factor α).
  → **First constraint on the size of solar core.**







■ Solar *g*-mode oscillation

- **Not yet detected by optical light** at the surface of the Sun (while 5-minutes *p*-mode was detected).
- Propagating in the central region of the Sun (1-2 hours) and results in the change of electron density.
- May **affect neutrino fluxes** depending on its amplitude [theoretical study in preparation].

- SNO experiment searched for such periodic change, but no significant signal was observed.
  So, Super-K and Hyper-K can search for such periodic change in ^{8}B solar neutrinos.

Astrophys. J. 710, 540 (2010)

Summary

- **History with Water Cherenkov detectors**
  - **Significantly contributed to understand “flavor conversion” of solar neutrinos.**

- **Solar neutrino results by Super-Kamiokande**
  - **Precise measurement of flux, spectrum, oscillation parameters.**
    - **About 3% of day/night flux asymmetry.**
    - **Favors the MSW upturn.**
  - **Mixing angle is consistent with anti-electron neutrino measurement by KamLAND but has a tension by 1.5σ on the mass difference.**

- **Future prospect**
  - **Further studies are required to understand:**
    - **Hep neutrinos, the MSW effect with scintillation detectors.**
    - ***CPT* violation test by the single neutrino detector.**
    - **Determination of the size of solar core.**
    - **Searches for possible periodic fluctuation due to g-mode oscillations.**

Back up slides