Status of solar neutrino physics at SK

2018 September 21st (Fri)

European Workshop on Water Cherenkov Precision Detectors for Neutrino and Nucleon Decay Physics

TMEX 2018 WCP @Warsaw, Poland

Yuuki Nakano for the Super-Kamiokande collaboration

(Kamioka Observatory, ICRR, The University of Tokyo)

Supported by Grant-in-Aid for Young Scientists (B) 17K17880

Contents

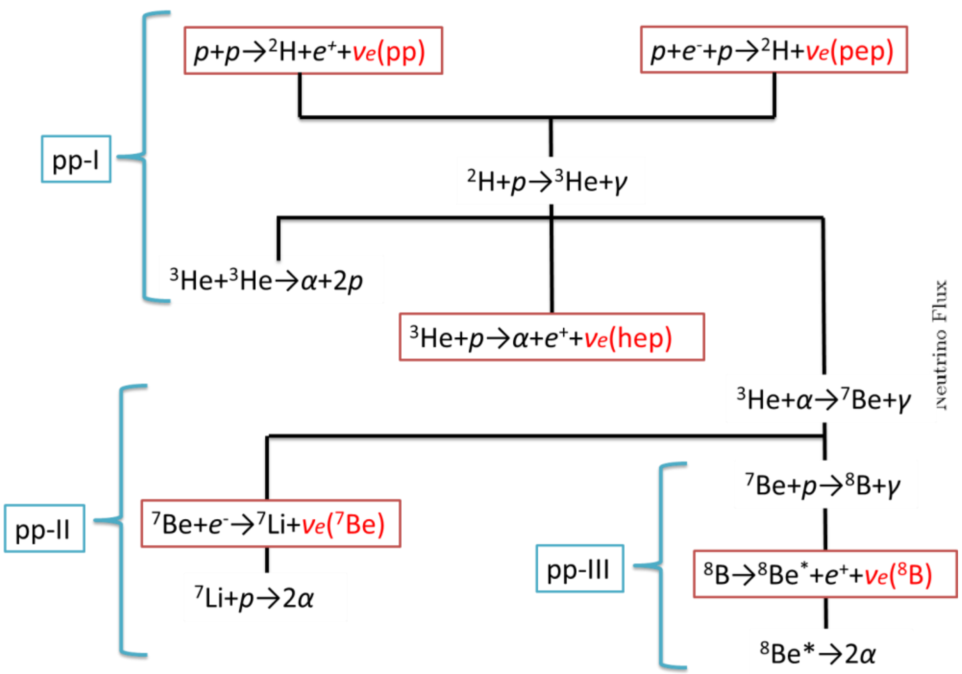
Solar neutrino

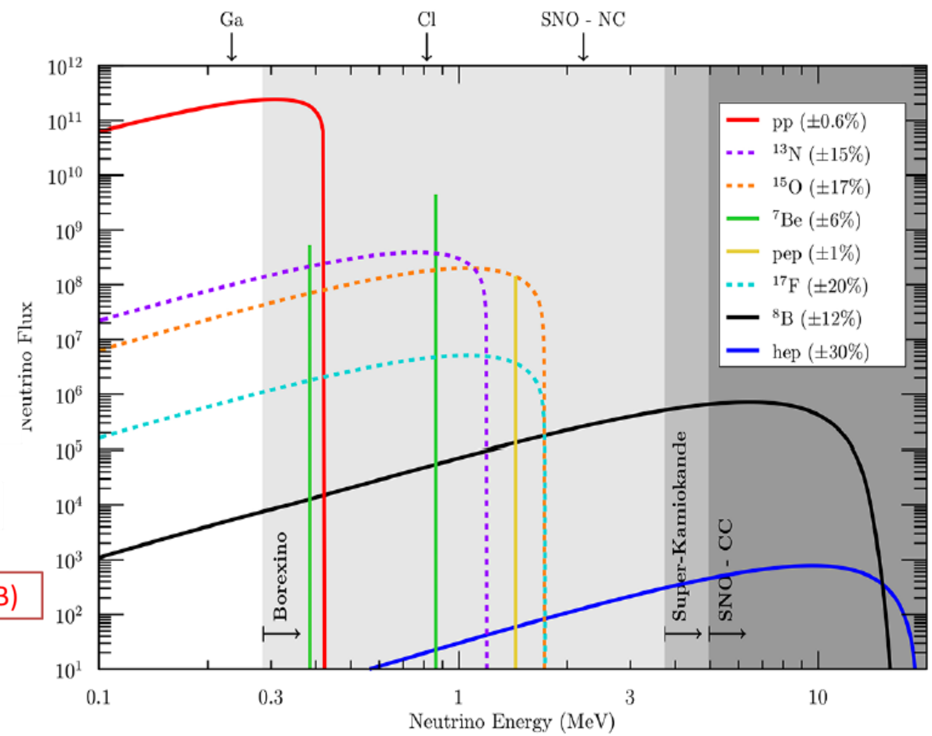
■ Production of solar neutrino

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

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

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

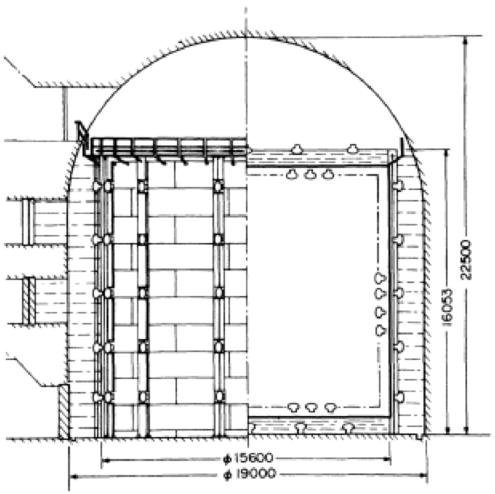




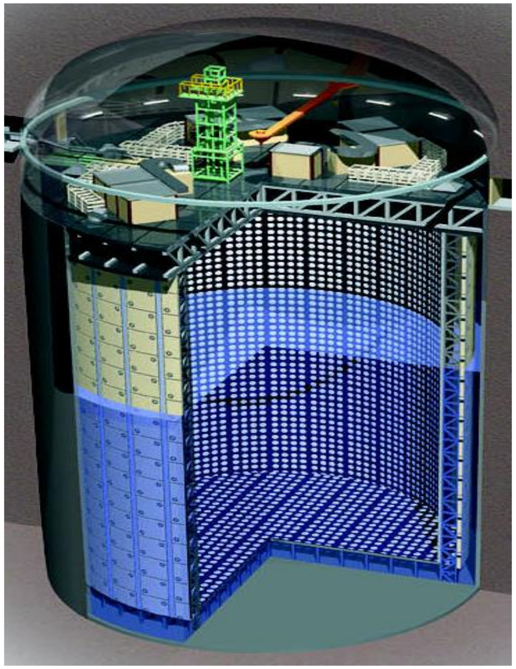
Water Cherenkov detectors

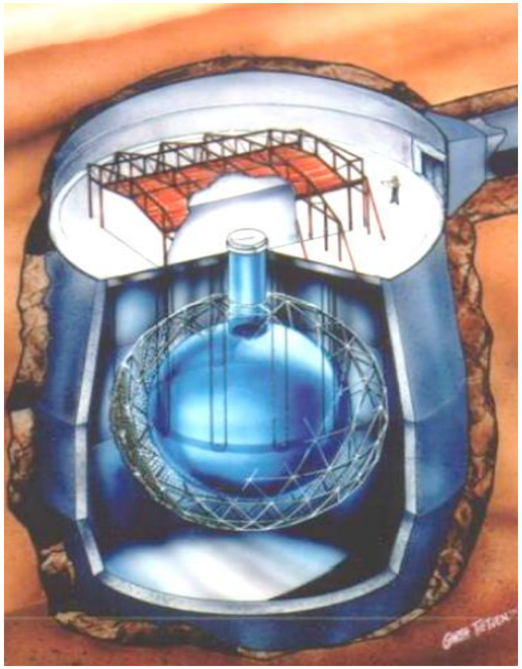
as solar neutrino detector

■ Kamiokande ■ Super- Kamiokande ■ SNO



Phys. Rev. D 38, 448 (1998).





Phys. Rev. C 75, 045502 (2007).

H_2O D_2O

Solar neutrino interactions in water

■ Reaction channels

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

Channel	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

- 4 possible oscillation solutions in 1990s.

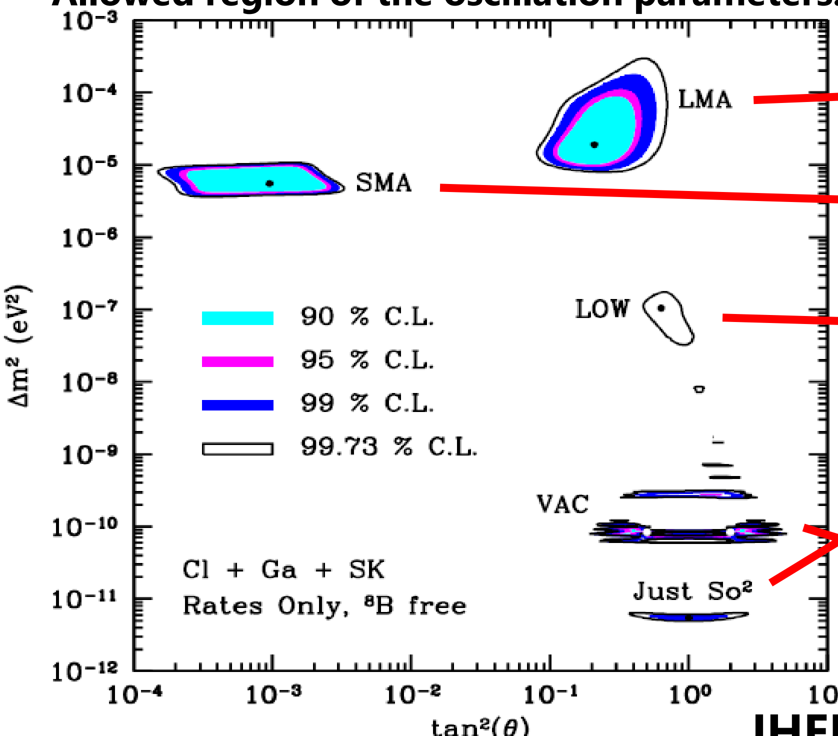
(1) LOW & LMA: No energy distortion, day/night flux difference.

(2) SMA: Large energy distortion.

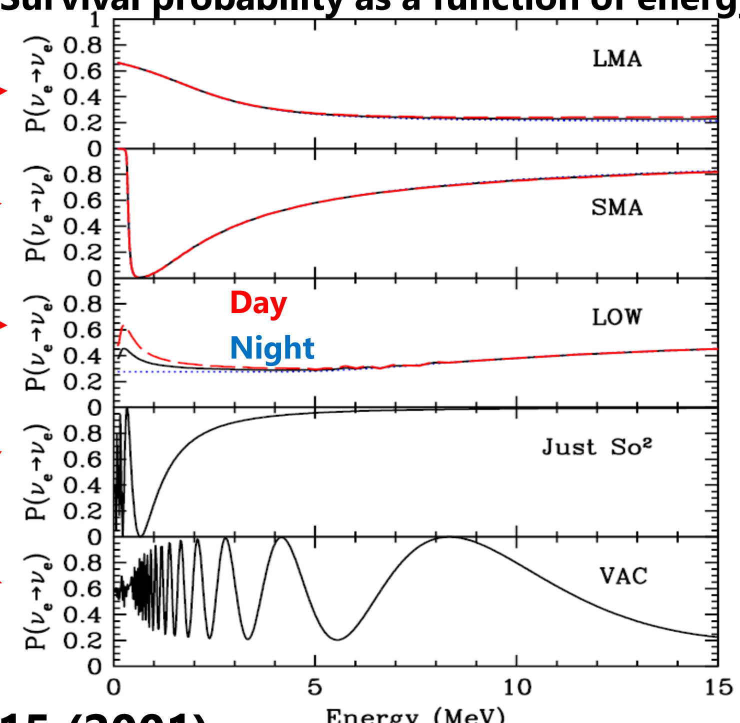
(3) VAC: Energy distortion, seasonal variation.

→ Energy spectrum, seasonal variation and day-night are key.

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.**
- **Observed rate over the SSM: 0.46±0.13(stat.)±0.08(syst.).**

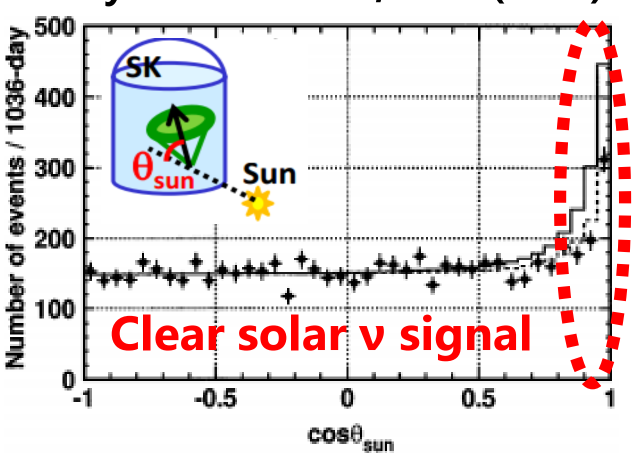
→ **Confirmation of the solar neutrino problem.** Phys. Rev. Lett. 63, 16 (1989).

■ Super-Kamiokande

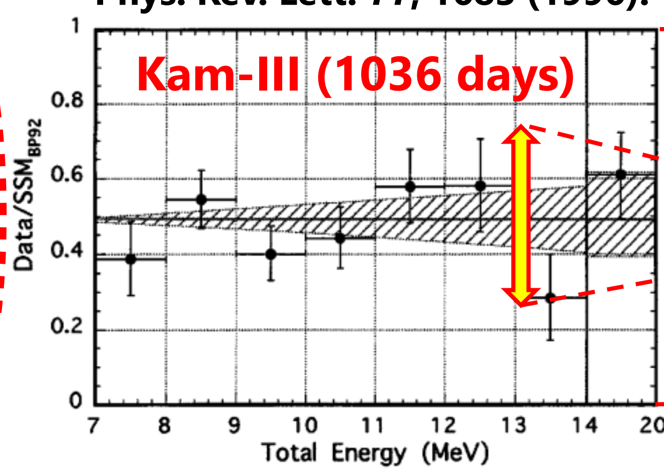
- **Precise flux/energy spectrum measurement.**

→ **No distortion in the energy spectrum.**

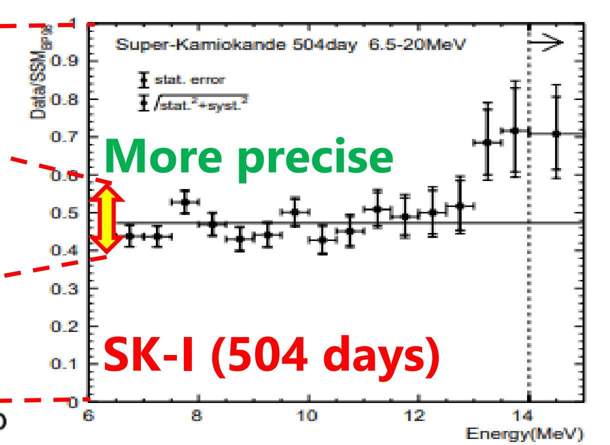
Phys. Rev. Lett. 77, 1683 (1996).



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



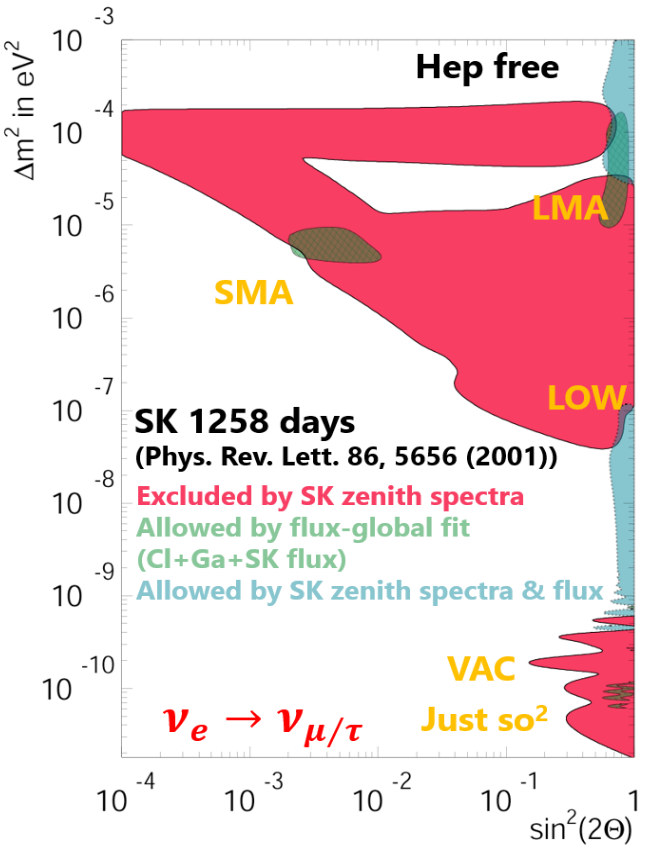
Phys. Rev. Lett. 82, 2430 (1999).

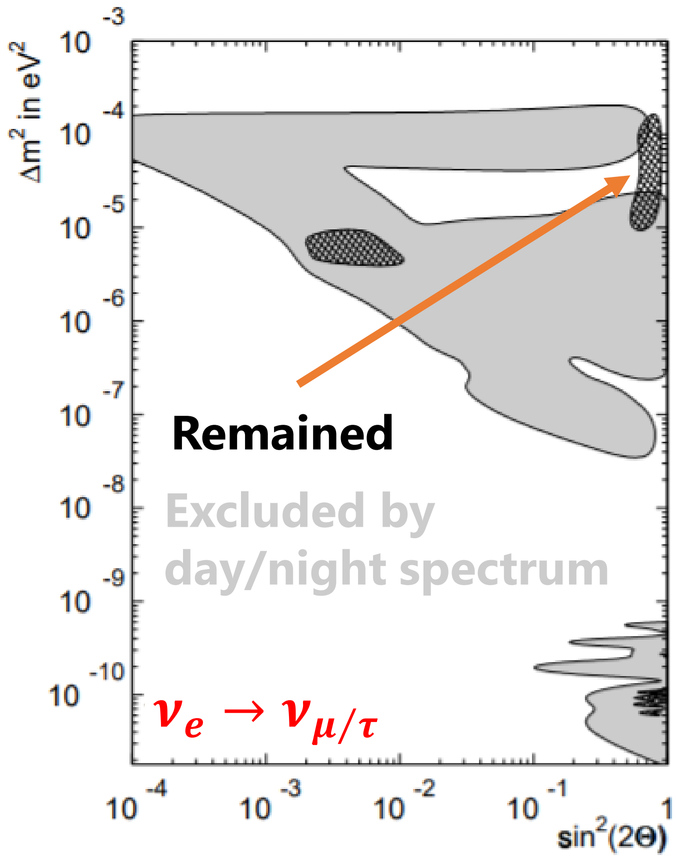


SK-I results

■ Era of precise measurement

- SK data: **No energy distortion, no significant zenith dependence** and **small day/night flux asymmetry**.
- SK data excluded SMA, VAC and demonstrated no Just so^2.
- SK data preferred LMA (higher Δm^2_{21} region of large mixing).





Flavor conversion

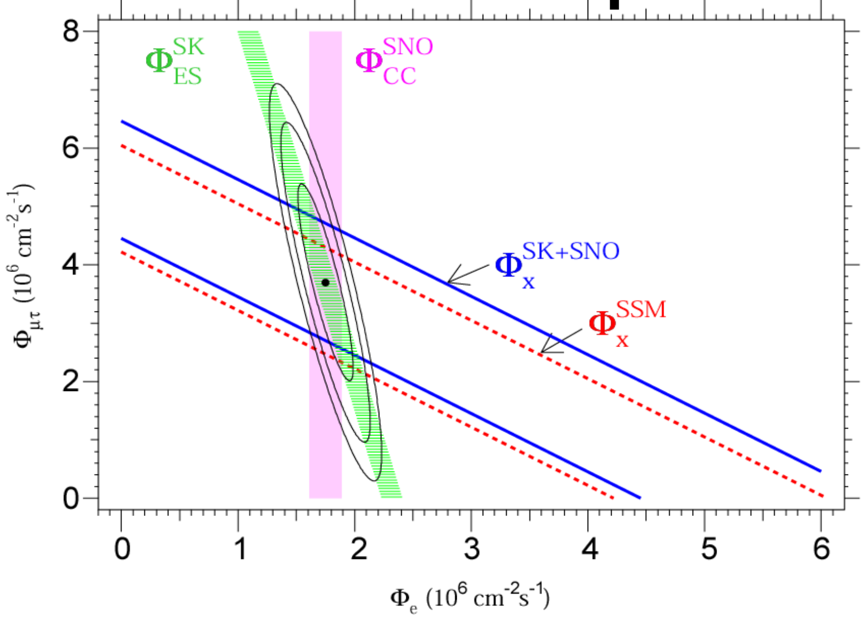
■ SNO's flux measurements with SK

- **The first evidence of the solar ν 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).

Neutrino oscillation

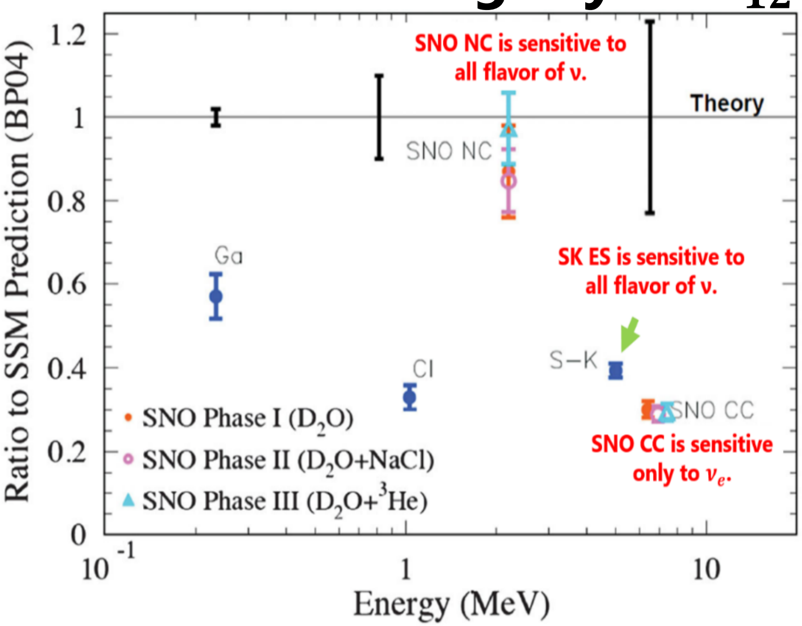
■ Survival probability

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

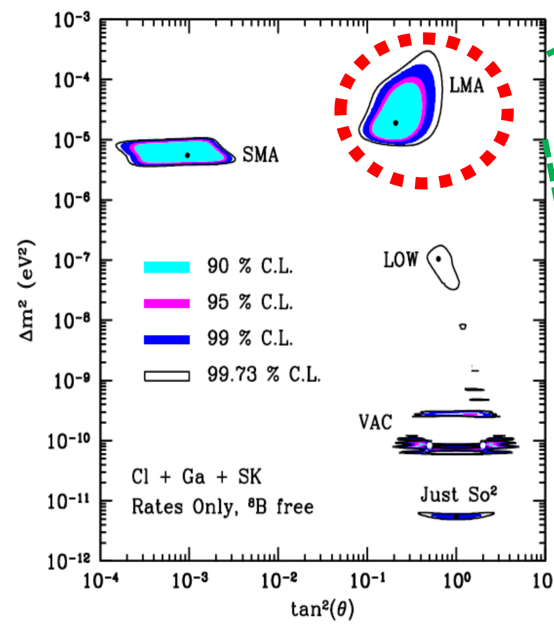
Measured total ^{8}B flux [$\times 10^6$ cm^{-2}sec^{-1}]	Prediction (BP04) [$\times 10^6$ cm^{-2}sec^{-1}]
$5.25 \pm 0.16^{+0.11}_{-0.13}$ Phys. Rev. C 88, 025501 (2013)	$5.79(1 \pm 0.23)$ Phys. Rev. Lett. 92, 121301 (2004)

- **The CC/NC ratio extracts survival probability: 0.317±0.016±0.009.**

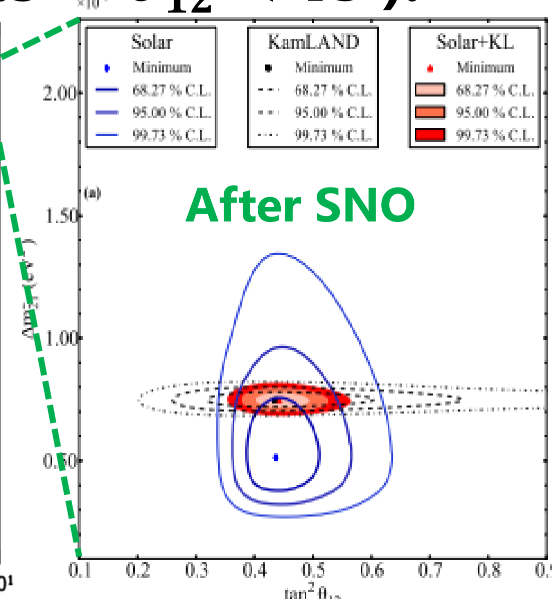
  → Octant ambiguity of θ_{12} is solved (CC/NC<0.5 → $\theta_{12} < 45^\circ$).



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



JHEP 05, 015 (2001).



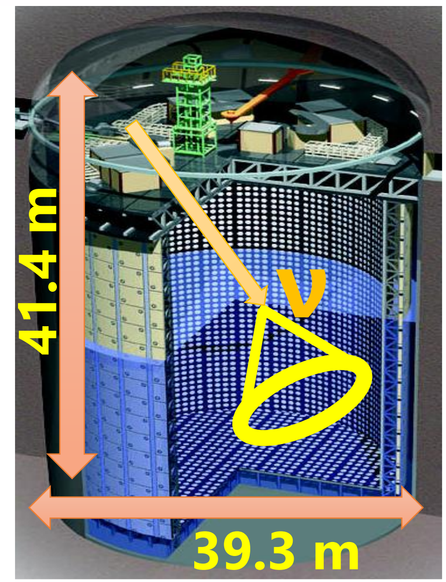
Nucl. Phys. B (Proc. Suppl.) 237-238 (2013) 107-110.

The latest results from SK

Super-Kamiokande (SK)

■ Detector

- Located at Kamioka Japan.
- 50 kton of ultra pure water tank.
  - 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 (~22 years).
- Total live time is more than 5,500 days.
- Refurbishment works toward SK-Gd have started since May 31st, 2018.

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
SK-I						SK-II				SK-III			SK-IV										SK-Gd	
PMT 11,146 (40%*)						5,182 (19%*)				11,129 (40%*)									Nobel prize					
4.5 MeV**						6.5 MeV**				4.0 MeV**			3.5 MeV**											

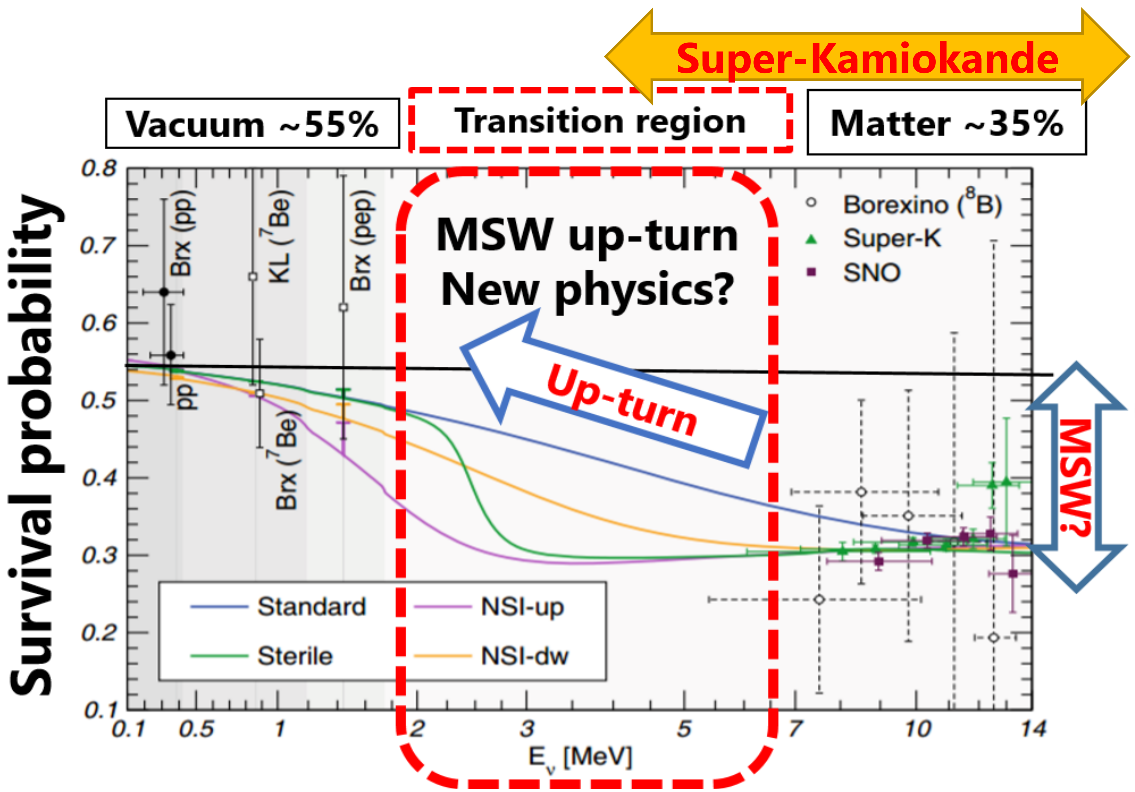
* Photo coverage [%], ** Recoil electron kinetic energy [MeV].

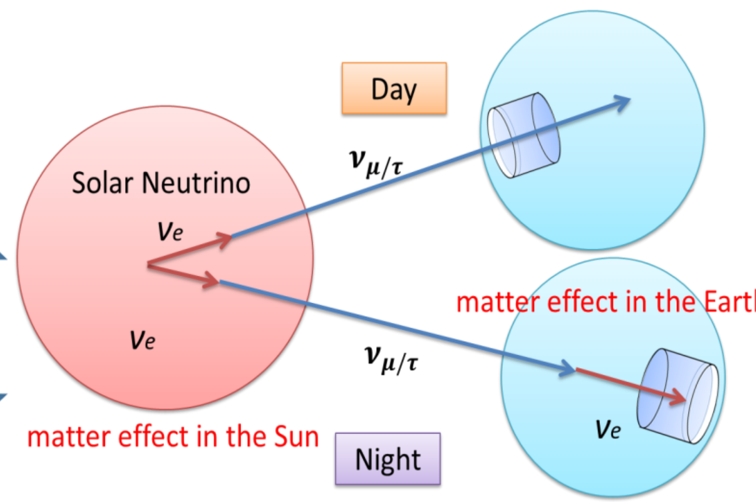
Motivations of solar neutrino

■ Goal of solar neutrino measurement in SK

(1) Test the transition of solar ν oscillation btw vacuum and matter.
→ Lowering threshold & reducing BG to test **MSW up-turn**.

(2) Day-night flux asymmetry
→ **Regeneration** of ν_e due to the Earth's matter effect is expected.
(~2.5σ indication, update of this analysis is in progress).



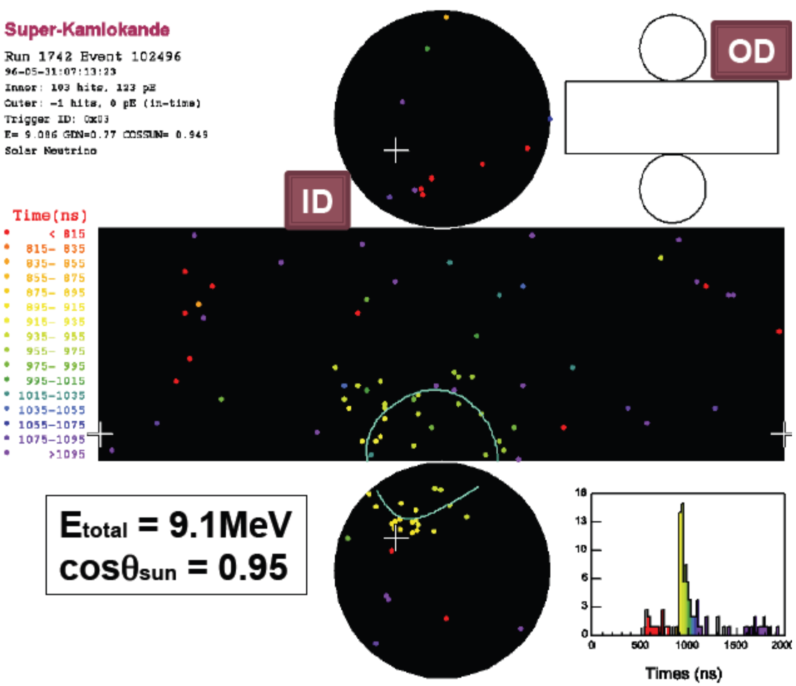


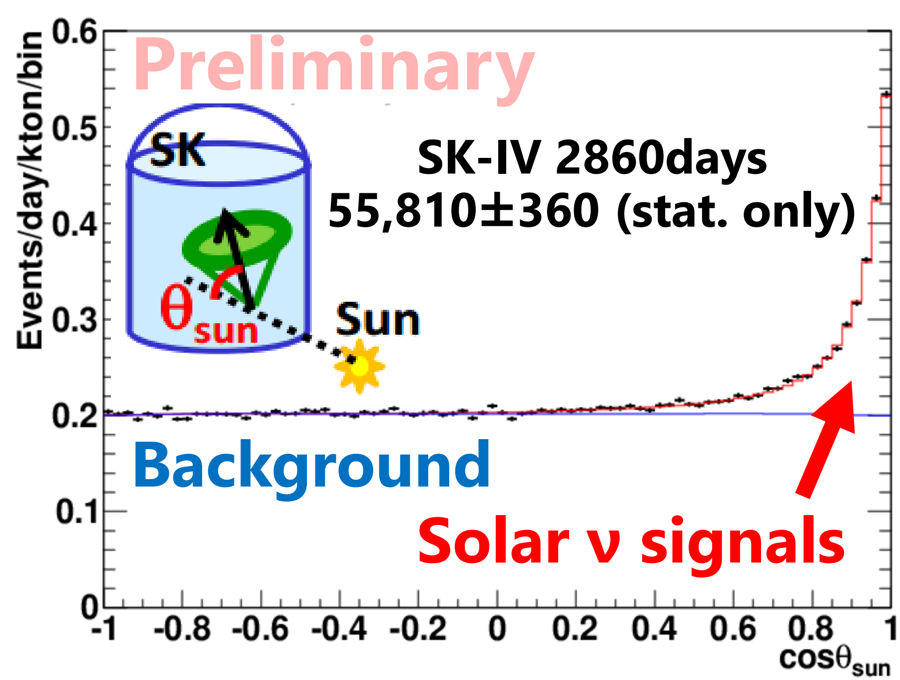
^{8}B solar neutrino measurement

■ ^{8}B solar neutrino signals

- Elastic scattering ($\upsilon_X + e^- \rightarrow \upsilon_X + e^-$).
  (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 5695 days: ~93k events).





^{8}B solar neutrino flux

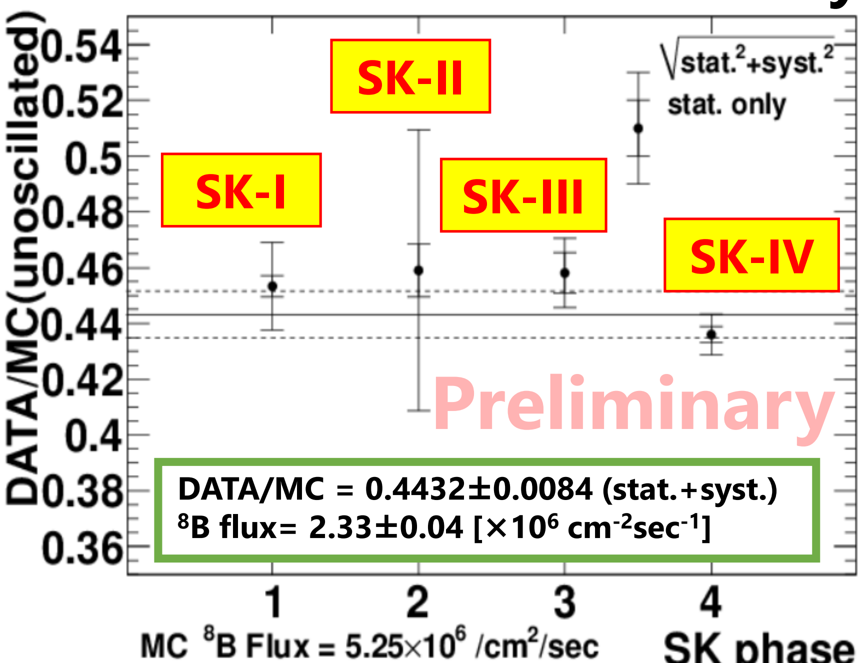
■ Flux measurements

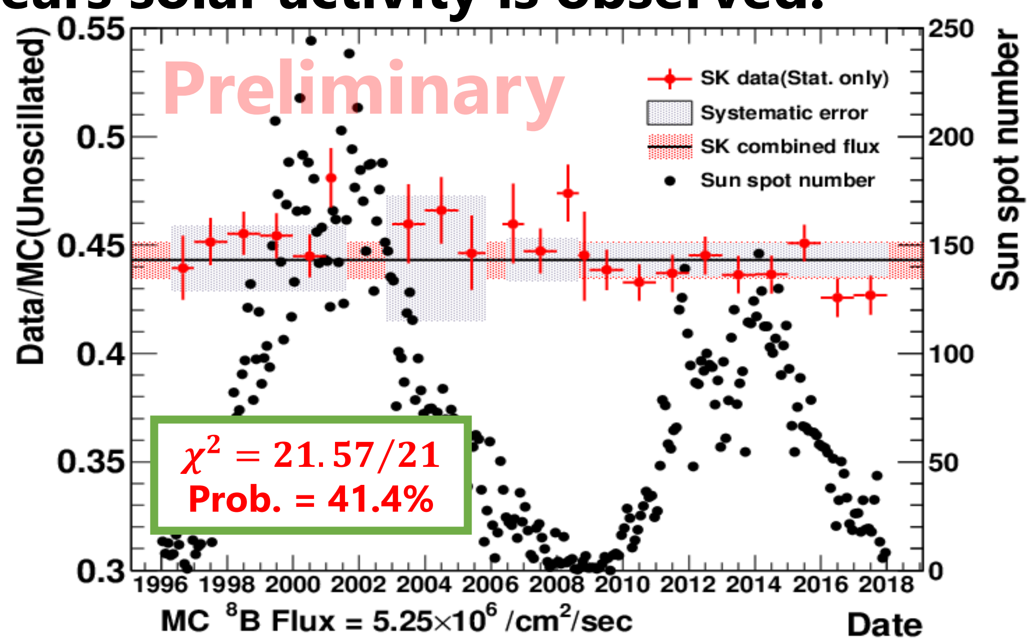
- SK has measured the ^{8}B solar neutrino flux for 22 years.
  → Fluxes are consistent within uncertainties among all SK phases.

SK ES flux/SNO NC flux	^{8}B solar ν flux assuming no oscillation [$\times 10^6$ cm^{-2}sec^{-1}]
0.4432 ± 0.0084 (stat.+syst.)	2.33 ± 0.04 (stat.+syst.)

■ Correlation of the flux with the solar activity

- Solar activity is strongly correlated with sunspot numbers.
- No correlation with the 11-years solar activity is observed.





Sun spot number: http://www.sidc.be/silso/datafiles
Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

Day-night flux asymmetry

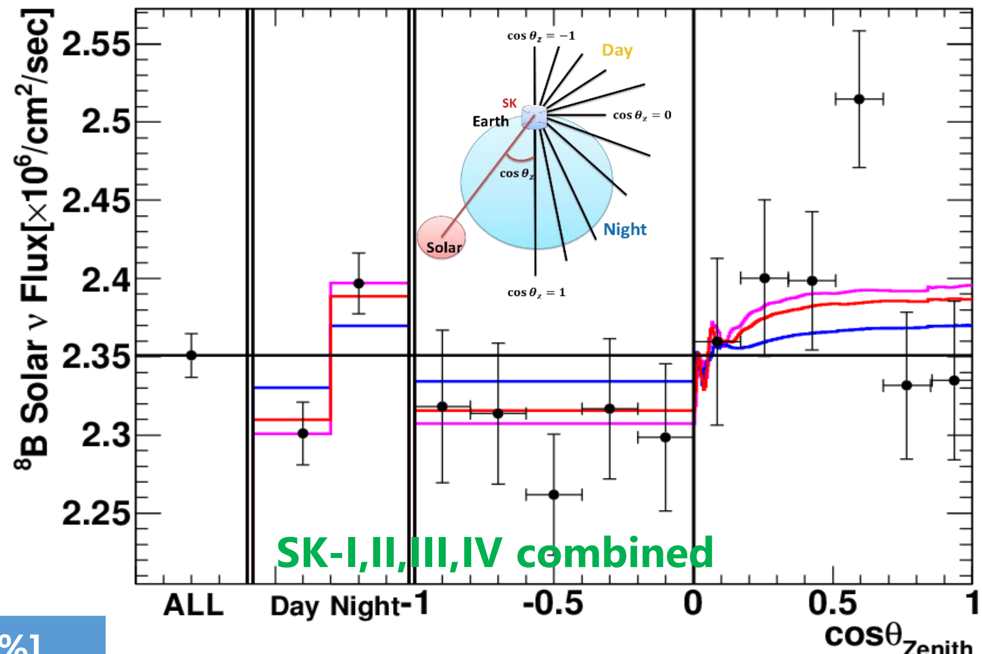
Updated from Phys. Rev. Lett. 112 (2014) 091805.

■ Flux measurement

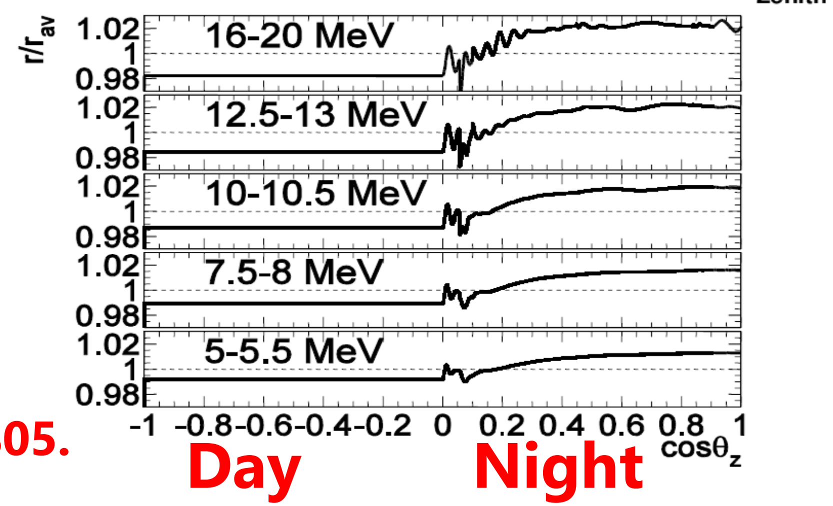
- Regeneration of ν_e in night.
  → **Higher flux in night.**

$$A_{\mathrm{DN}} = \frac{\Psi_{\mathrm{day}} - \Psi_{\mathrm{night}}}{(\Psi_{\mathrm{day}} + \Psi_{\mathrm{night}})/2}$$

- Regeneration depends on oscillation parameters.
- Update analysis is in progress.

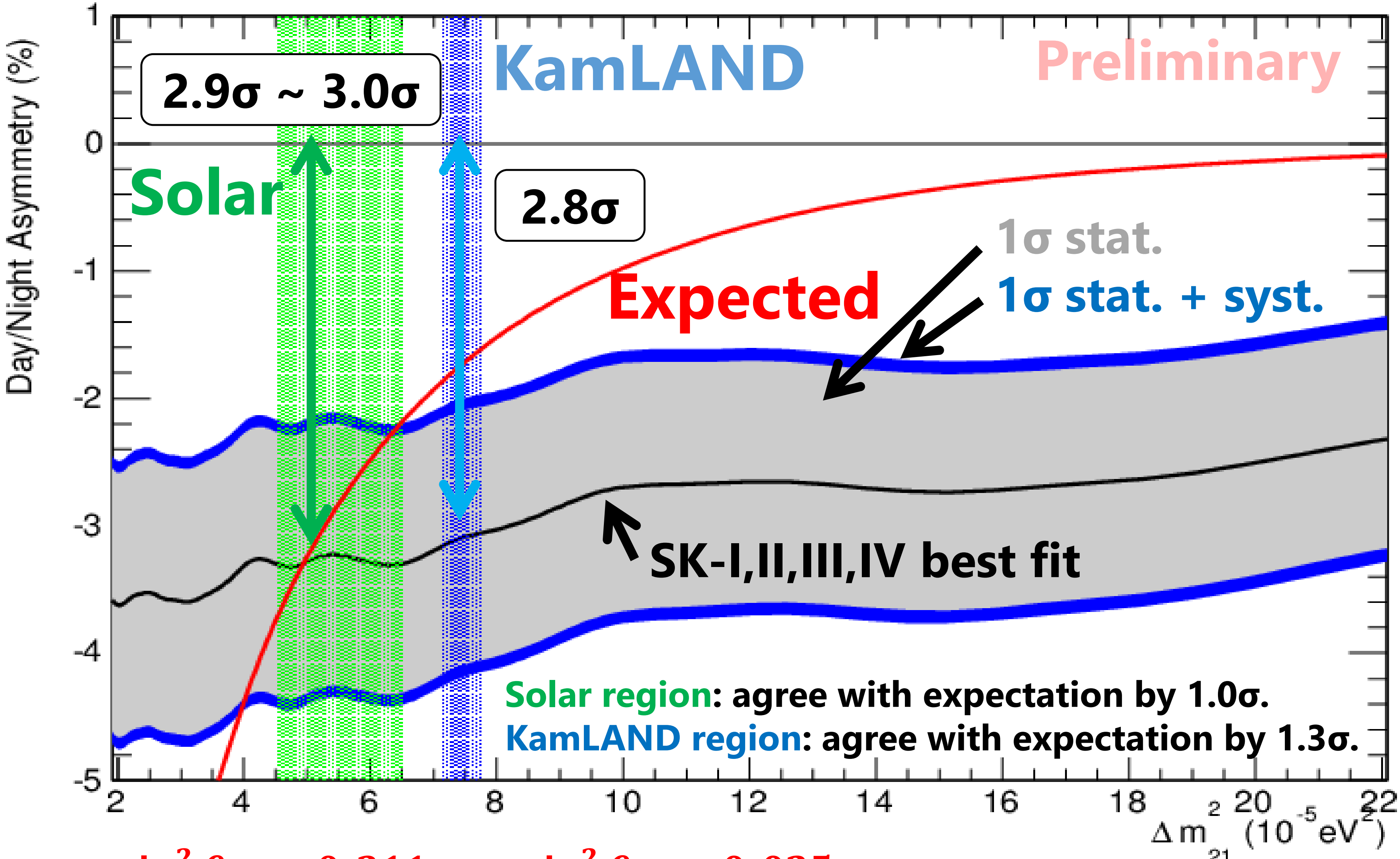


SK-phase	Amplitude fit [%]	Straight calc. [%]
SK-I	-2.0 ± 1.8 ± 1.0	-2.1± 2.0 ± 1.3
SK-II	-4.3 ± 3.8 ± 1.0	-5.5 ± 4.2 ± 3.7
SK-III	-4.2 ± 2.7 ± 0.7	-5.9 ± 3.2 ± 1.3
SK-IV	-3.6 ± 1.6 ± 0.6	-4.9 ± 1.8 ± 1.4
Combined	-3.3 ± 1.0 ± 0.5 (3.0 σ from zero)	-4.1 ± 1.2 ± 0.8 (2.8 σ from zero)



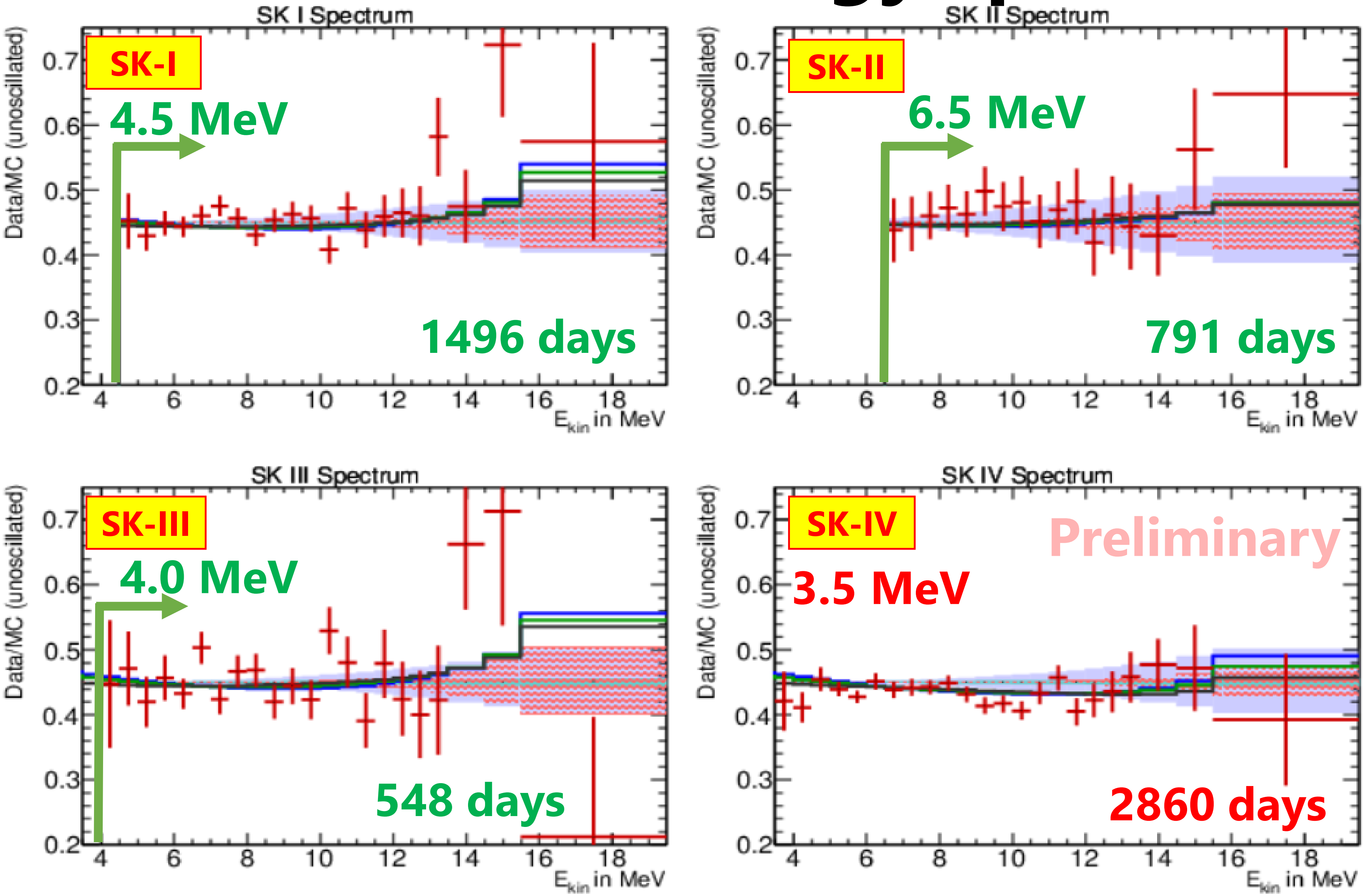
Updated from Phys. Rev. Lett. 112 (2014) 091805.

$\Delta m_{21}{}^2$ vs Day/Night Asymmetry



$\sin^2\theta_{12} = 0.311$, $\sin^2\theta_{13} = 0.025$

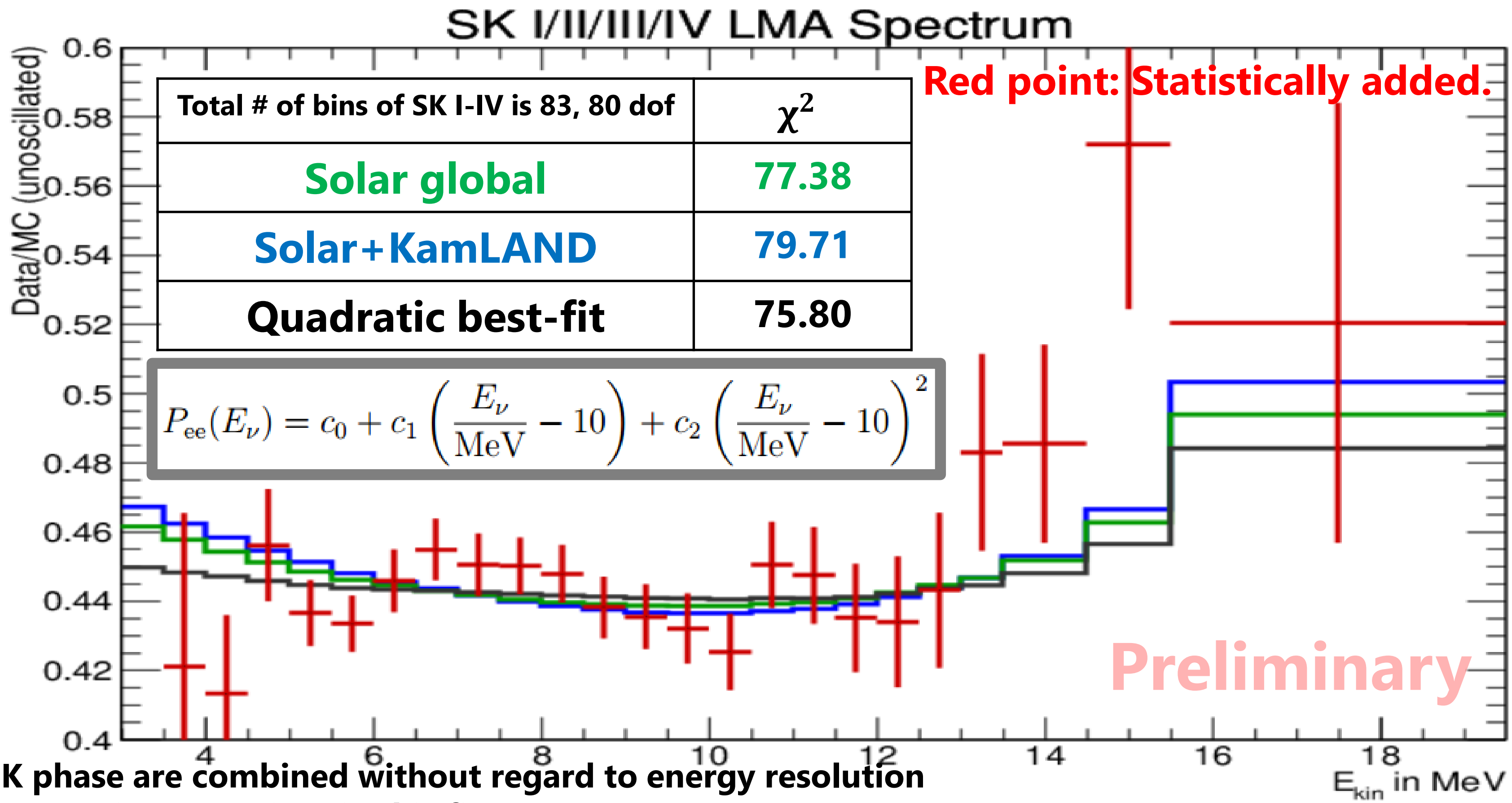
Recoil electron energy spectrum



Combined spectrum

■ Energy spectrum vs. MSW predictions

- Introduce quadratic function to test the MSW prediction.
- Quadratic fit is consistent with solar Δm^2_{21} within 1.2σ, while it disfavors KamLAND Δm^2_{21} by 2.0σ.



Total # of bins of SK I-IV is 83, 80 dof	χ^2
Solar global	77.38
Solar+KamLAND	79.71
Quadratic best-fit	75.80

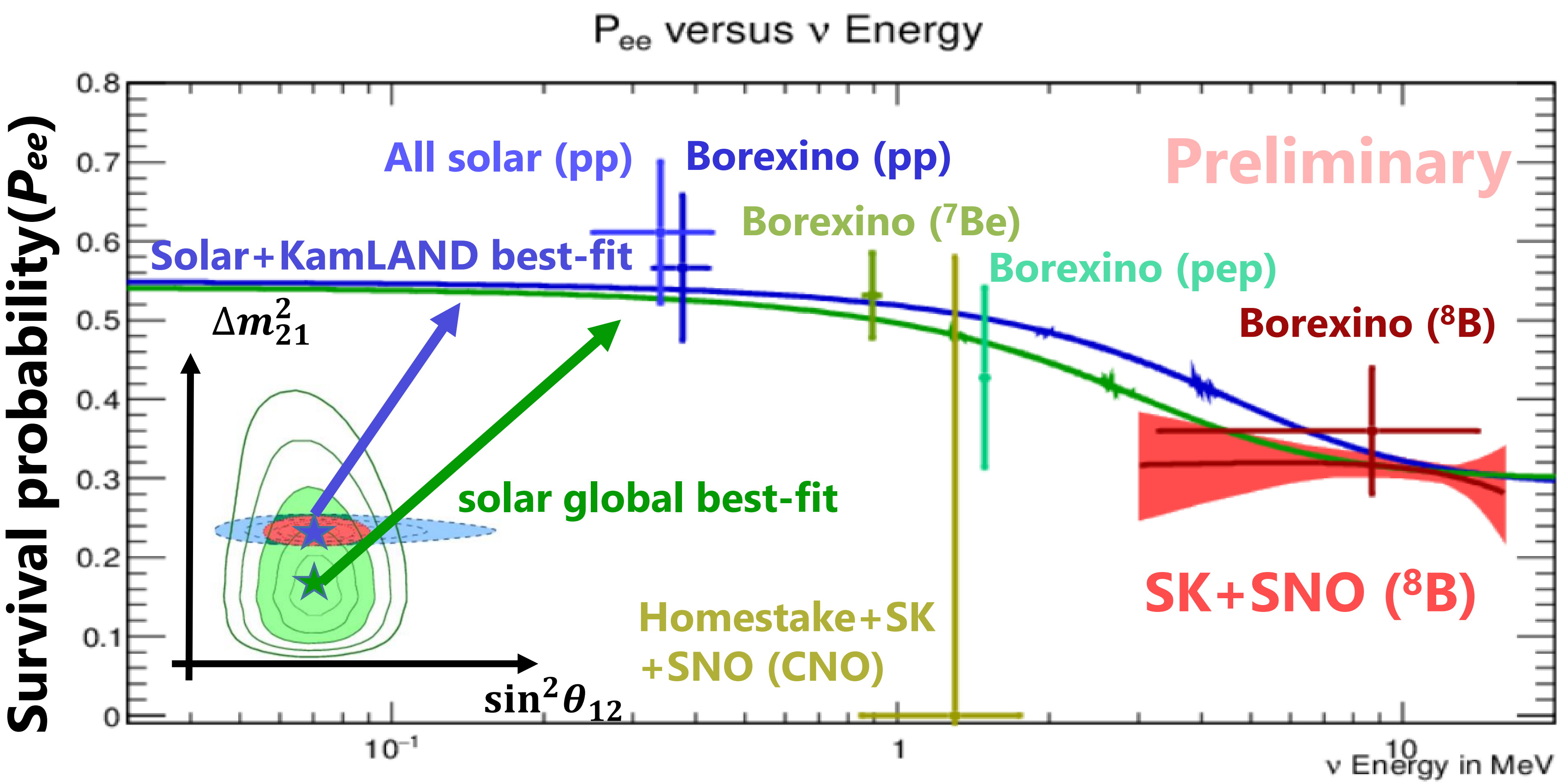
$$P_{\mathrm{ee}}(E_\nu) = c_0 + c_1\left(\frac{E_\nu}{\mathrm{MeV}} - 10\right) + c_2\left(\frac{E_\nu}{\mathrm{MeV}} - 10\right)^2$$

All SK phase are combined without regard to energy resolution or systematic uncertainty in this figure.

Allowed survival probability

■ Comparison among solar neutrino experiments

- Neutrino energy spectrum is de-convoluted from the recoil electron energy spectrum → Extract survival probability (P_{ee}).
- This analysis gives **the strongest constraint** on P_{ee} shape.



Global oscillation analysis input

■ Super-Kamiokande

Phase	Livetime [days]	Recoil electron spectrum	Day/Night
SK-I	1496	4.5-19.5 MeV	Above 4.5 MeV
SK-II	791	6.5-19.5 MeV	Above 7.0 MeV
SK-III	548	4.0-19.5 MeV	Above 4.5 MeV
SK-IV	2860	3.5-19.5 MeV (Updated: Phys. Rev. D 94, 052010 (2016))	Above 4.5 MeV (1664 days) (Phys. Rev. Lett. 112, 091805 (2014))

■ SNO

- Three phases combined: Phys. Rev. C 88, 025501 (2013).

■ Radiochemical (Ga, Cl)

- Ga rate: 66.1±3.1 SNU, Phys. Rev. C 80, 015807 (2009).
- Cl rate: 2.56±0.23 SNU, Astrophys. J. 496, 505 (1998).

■ Borexino

- ^{7}Be flux: arXiv:1707.09279. (Phase-II result)

■ KamLAND

- 3 flavor analysis: Phys. Rev. D 88, 033001 (2013).

■ ^{8}B spectrum

- Winter spectrum: Phys. Rev. C 73, 025503 (2006).

Constraint on $\sin^2\theta_{12}, \Delta m^2_{21}$(solar vs. KamLAND)

$\sin^2\theta_{12} = 0.310 \pm 0.014$

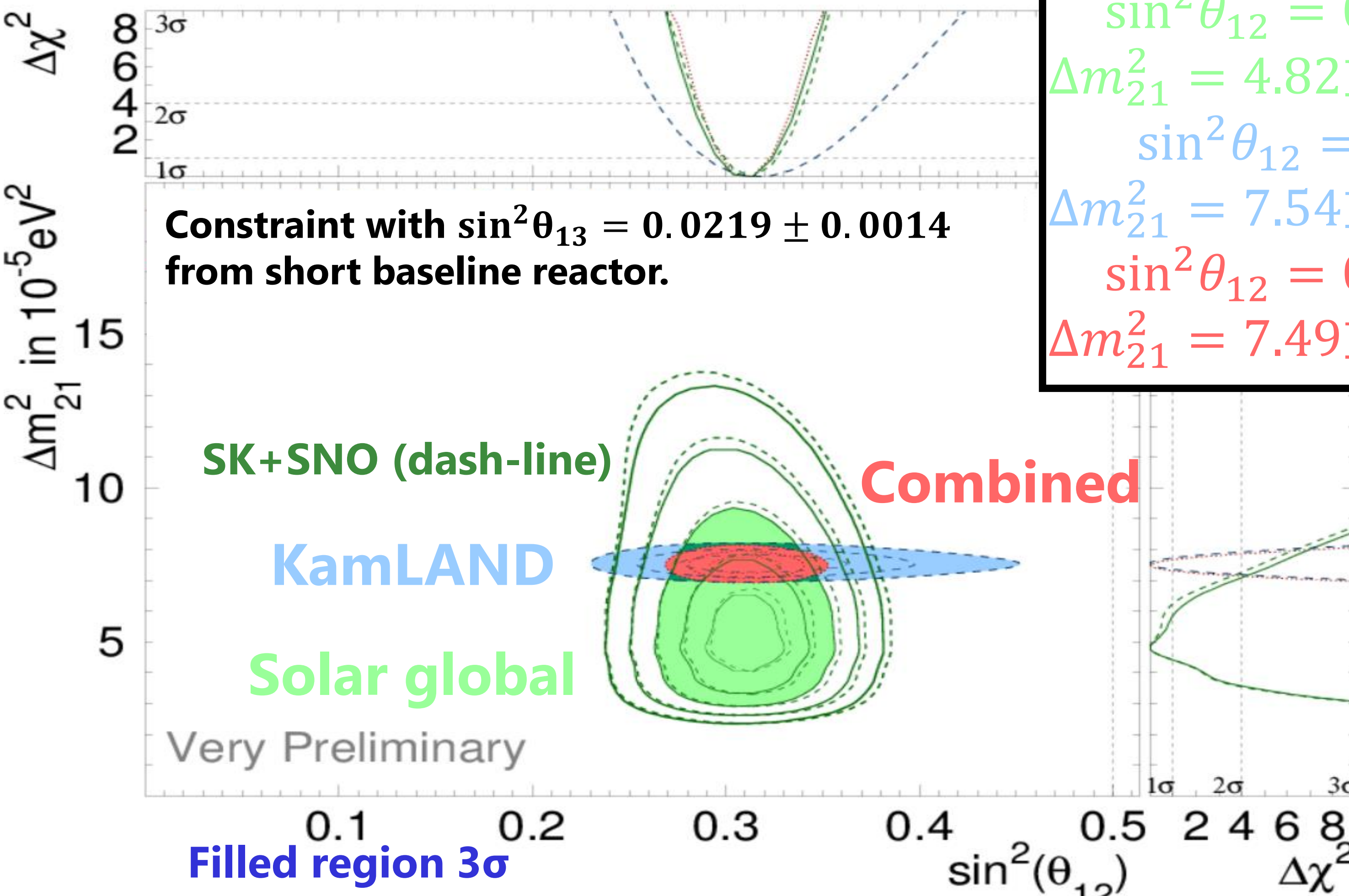
$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60} \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$

$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\ \mathrm{eV}^2$

$\sin^2\theta_{12} = 0.310 \pm 0.012$

$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5}\ \mathrm{eV}^2$



Oscillation parameters are determined using the latest solar ν data.

2σ tensition in Δm^2_{21} between the solar global and KamLAND.

Further precise measurement is required in future.

Summary

- Last 20 years, water Cherenkov detectors (Kamiokande/SK/SNO) contribute to the solar neutrino measurement.
  → Determined the total ^{8}B solar neutrino flux.
  → Found flavor conversion of solar neutrino.

- Solar neutrino results from SK
  ■ Solar neutrino flux measurements:
  → Elastic scattering rate: 2.33±0.04 (stat.+syst.) $\times 10^6$ cm^{-2}sec^{-1}.
  → ^{8}B ν flux has no significant correlation with the solar activity.

  ■ Recoil electron energy spectrum:
  → Achieved at the lowest energy threshold: 3.5 MeV.
  → SK+SNO spectrum shape gives strong constraint on P_{ee} shape.

  ■ Oscillation parameters:
  → $\sin^2\theta_{12} = 0.310 \pm 0.012$, $\Delta m_{21}{}^2 = 7.49^{+0.19}_{-0.17} \times 10^{-5}$ eV^2.
  → 2σ tensition in Δm^2_{21} between the solar global and KamLAND.