Solar neutrino results from Super-Kamiokande

Yuuki Nakano (Kobe University)
for Super-Kamiokande Collaboration

4th August 2016
ICHEP 2016
@Chicago, U.S.A.

ICHEP2016CHICAGO

38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS
AUGUST 3 - 10, 2016
CHICAGO

Solar neutrino

The nuclear fusion reaction in the core of the Sun.

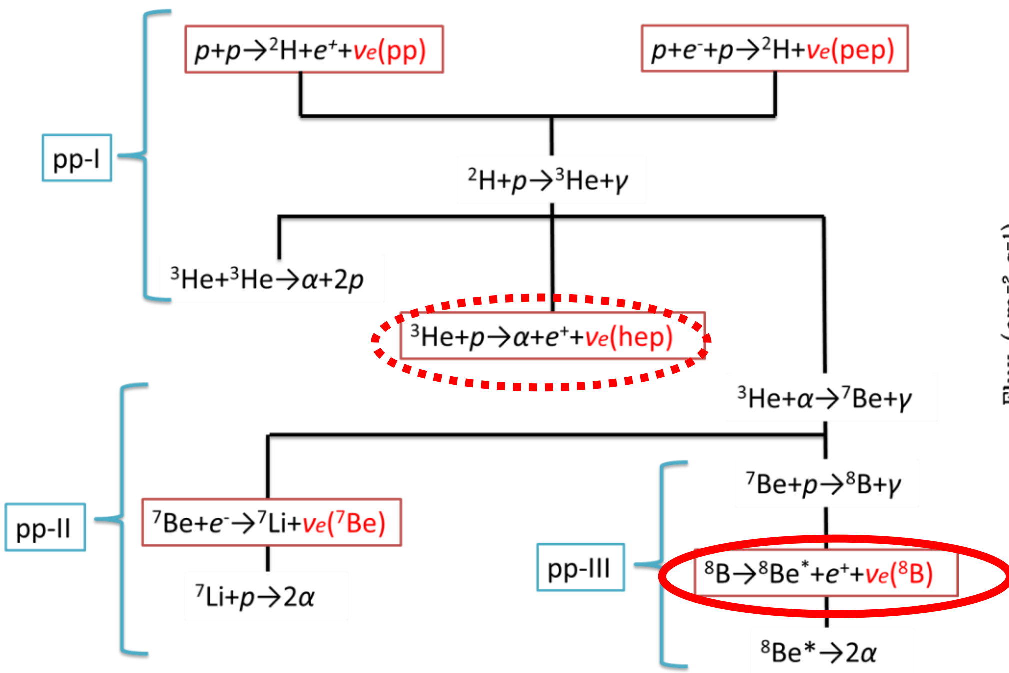
$$4p \to \alpha + 2e^+ + 2\nu_e + 26.7\text{MeV} - E_\nu$$

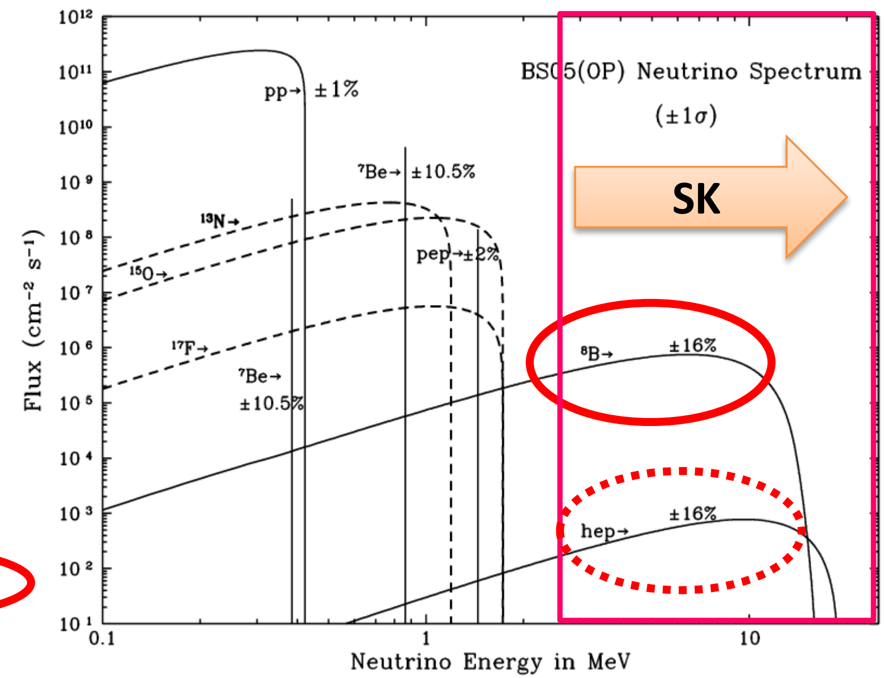
There are 5 reactions which emit electron neutrinos.

→ pp, pep, ^{7}Be, ^{8}B, hep

Their fluxes are predicted by the standard solar model (SSM).

Super-Kamiokande is sensitive to ^{8}B (hep) neutrinos.





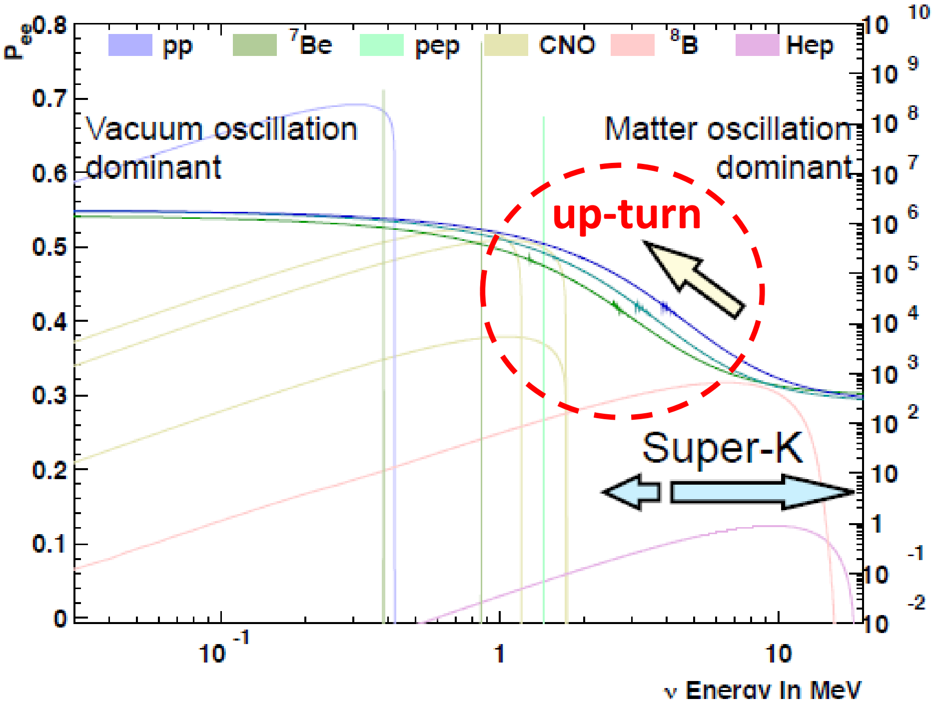
Astrophys. J. 621 (2005) 85.

Physics motivation for solar neutrino

◆Spectrum distortion

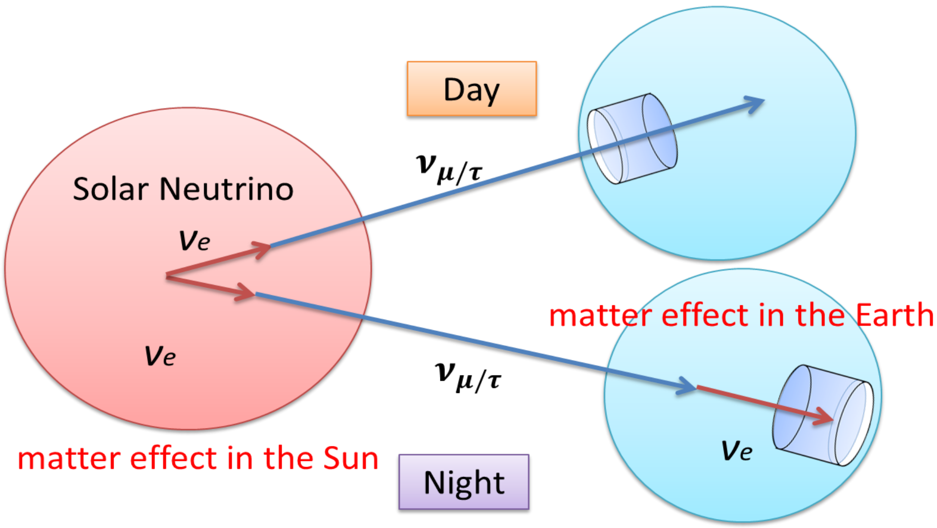
Super-K can search for the spectrum "up-turn" expected by neutrino oscillation MSW effect.

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}-\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$



◆Day/Night flux asymmetry

Due to the earth matter effect, electron neutrino is regenerated. The ^{8}B flux during night is higher than that during day.



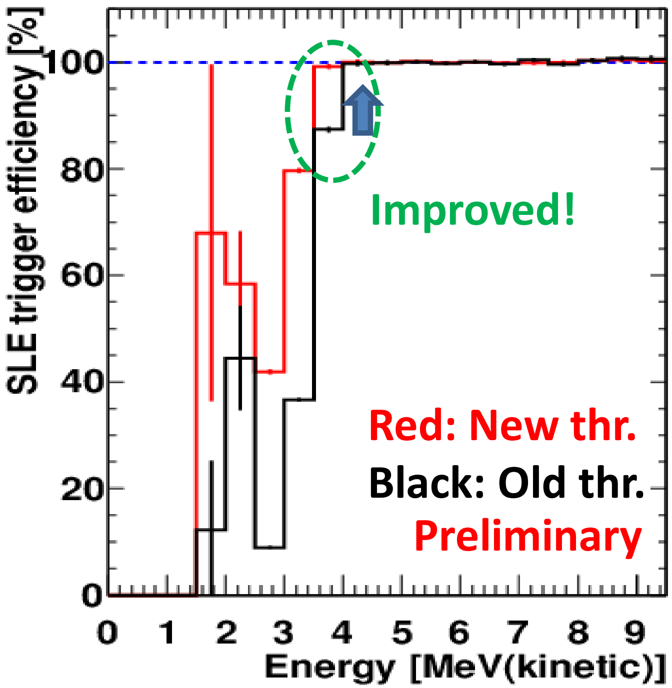
$$A_{\mathrm{DN}} = \frac{\Psi_{\mathrm{day}} - \Psi_{\mathrm{night}}}{(\Psi_{\mathrm{day}} + \Psi_{\mathrm{night}})/2}$$

Super-K Day/Night result
Phys. Rev. Lett. 112 (2014) 091805.

Solar neutrino analysis in Super-K

- Recently, we submitted a pre-print of the solar neutrino analysis result.
  - arXiv: 1606.07538 (SK-IV: 1664 days data sample).
- Updated results are presented (SK-IV: 2365 days sample).
  - ^{8}B solar neutrino flux.
  - Day/Night flux asymmetry (under preparation).
  - Energy spectrum.
  - Oscillation analysis result.
- Recent progress of solar analysis.
  - Yearly ^{8}B flux plot to see any correlation with solar activity.
  - Lower trigger threshold in May 2015.
    - Detection efficiency in 3.5-4.0 MeV_{kin}.
      ~84%→ ~99%.

Super-K Day/Night result : Phys. Rev. Lett. 112 (2014) 091805.



Observed ^8B solar neutrino signal

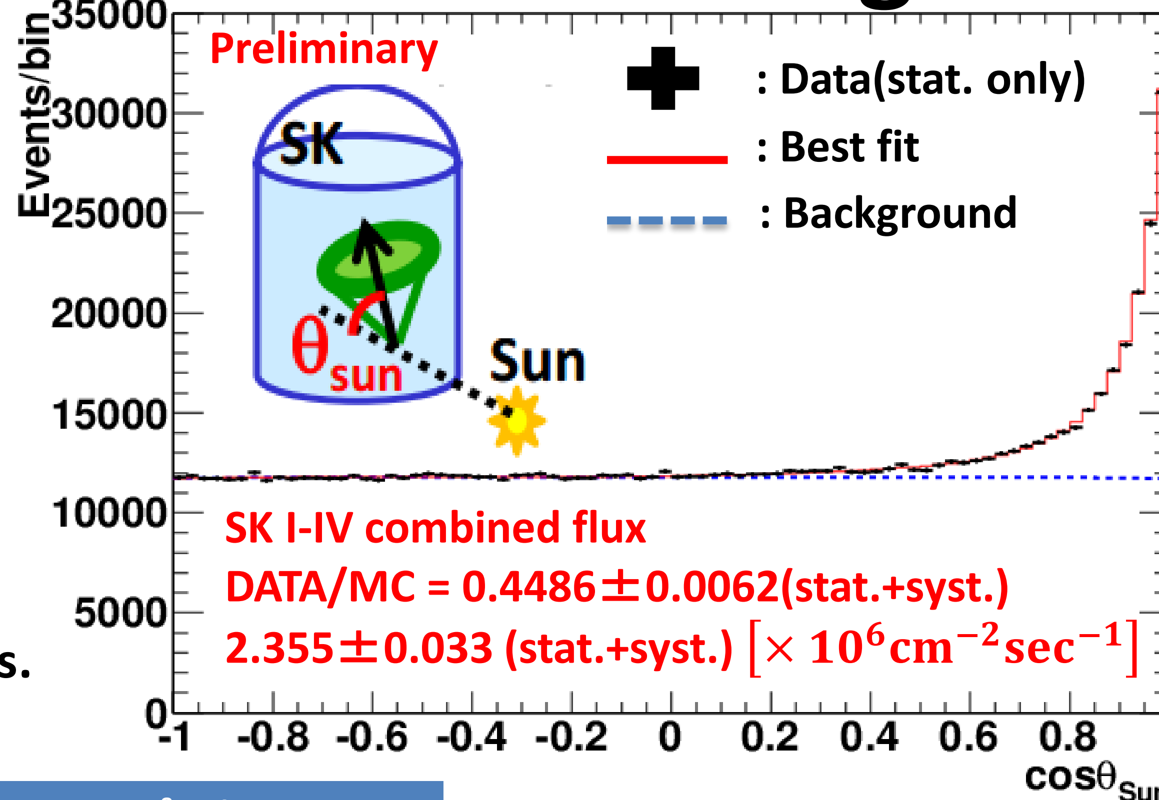
◆^8B neutrino measurement

Cherenkov light generated by electron scattered by neutrino.

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

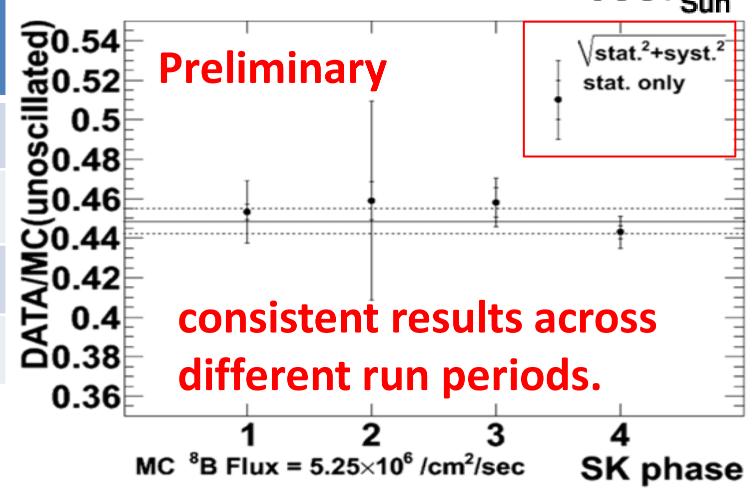
A total of about 84k solar neutrinos were observed.

Measured ^8B fluxes are consistent within uncertainties.



SK phase	Energy threshold [MeV(kin)]	Live time [day]	^8B Flux [$\times 10^6/cm^2/sec$]
SK I	4.5-19.5	1496	$2.38 \pm 0.02 \pm 0.08$
SK II	6.5-19.5	791	$2.41 \pm 0.05^{+0.16}_{-0.15}$
SK III	4.0-19.5	548	$2.40 \pm 0.04 \pm 0.05$
SK IV	3.5-19.5	2365	$2.32 \pm 0.02 \pm 0.04$

MC: $5.25 \times 10^6/cm^2/sec$
(SNO: NC current, Phys. Rev. C88 (2013) 022501.)



^{8}B solar neutrino yearly flux

◆Solar activity cycle

Sun spot numbers are strongly correlated with the solar activity cycle (~11 years).
SK has observed ^{8}B solar neutrino for ~19 years (More than 1.5 cycle).

◆^{8}B flux vs. sun spot

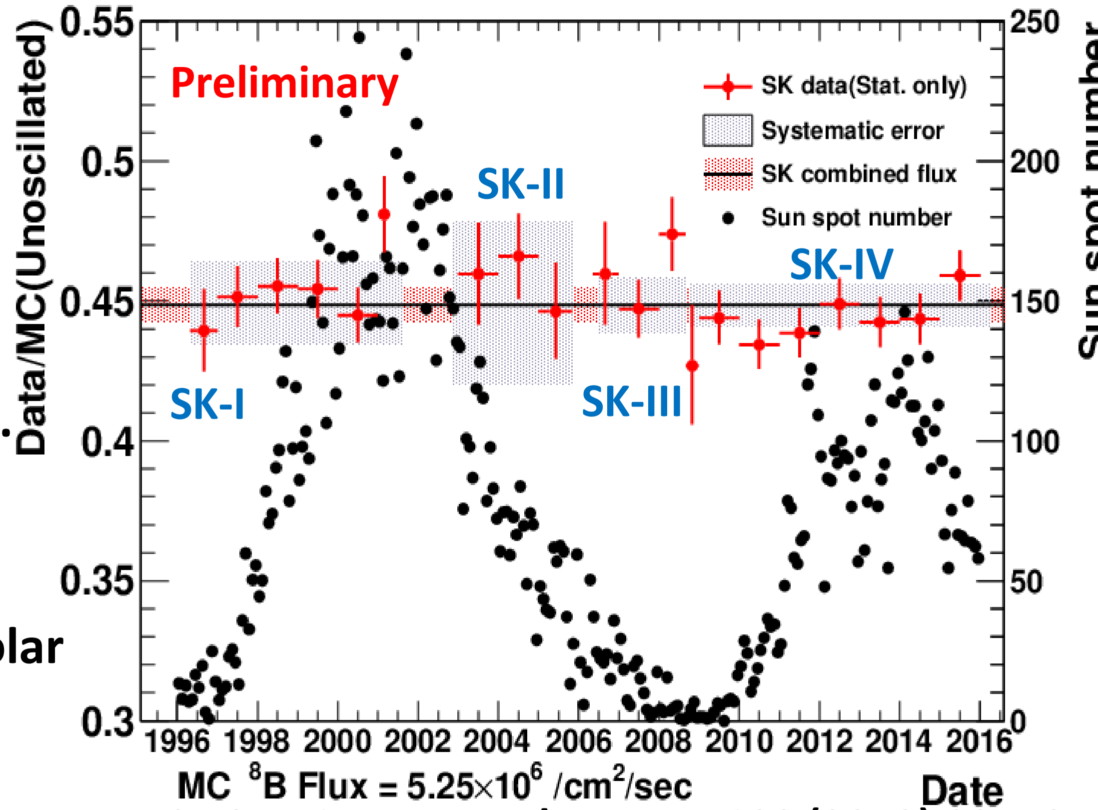
No correlation with the 11 years solar activity is observed.

$\chi^2 = 15.52/19(\mathrm{D.O.F})$

Preliminary

Prob. = 68.9 %

Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

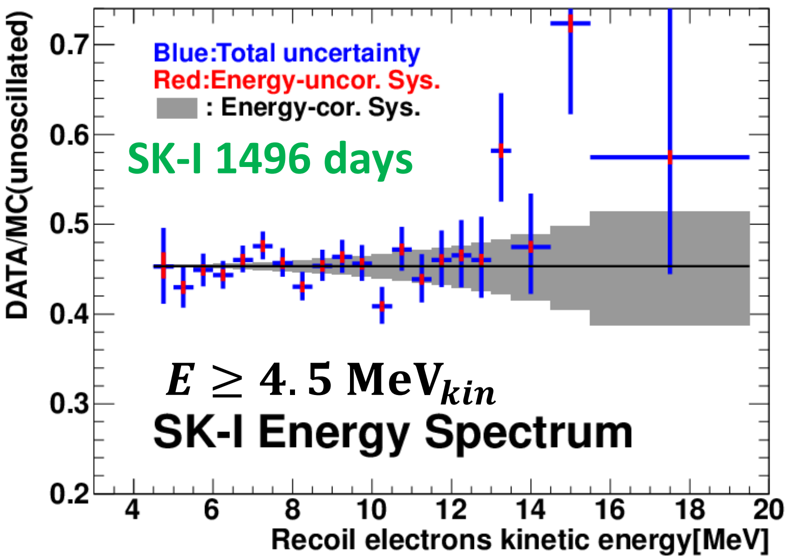


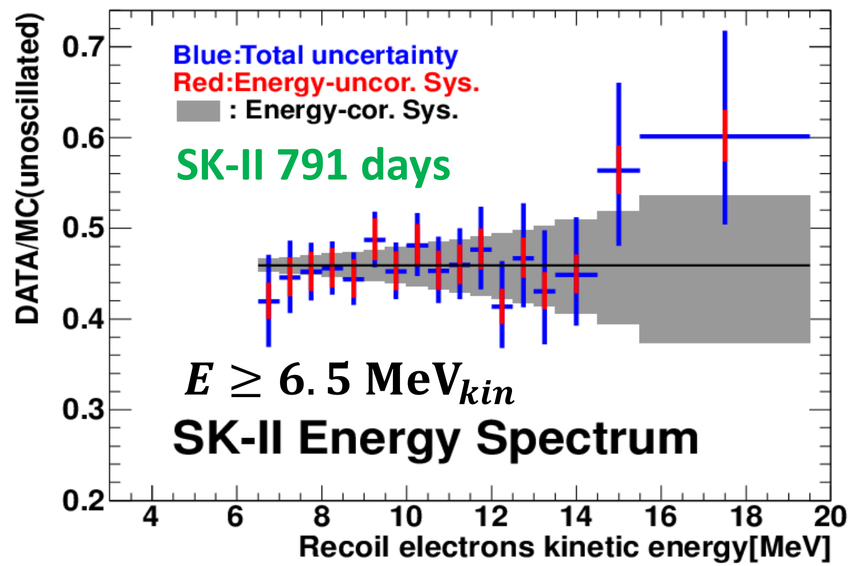
SNO: NC current, Phys. Rev. C88 (2013) 025501.

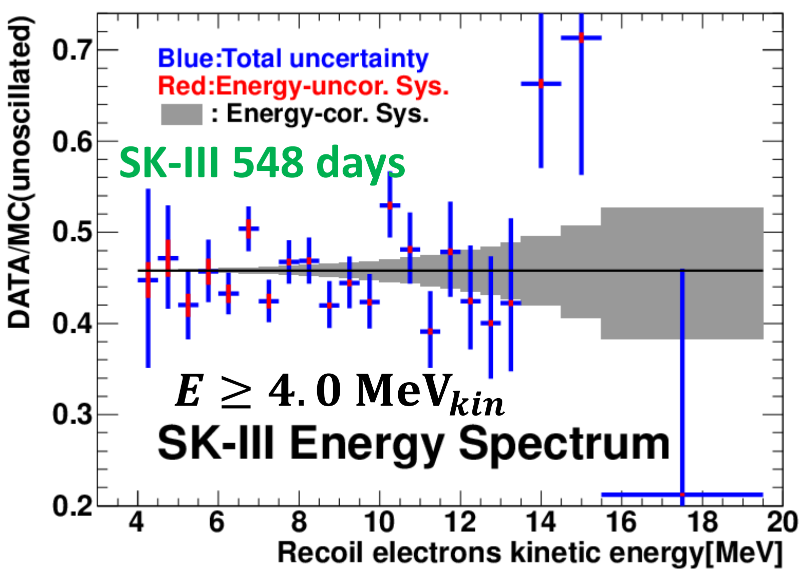
SK I-IV combined flux
DATA/MC = 0.4486±0.0062 (stat.+syst.)
2.355±0.033 (stat.+syst.) $[\times 10^6 \mathrm{cm}^{-2} \mathrm{sec}^{-1}]$

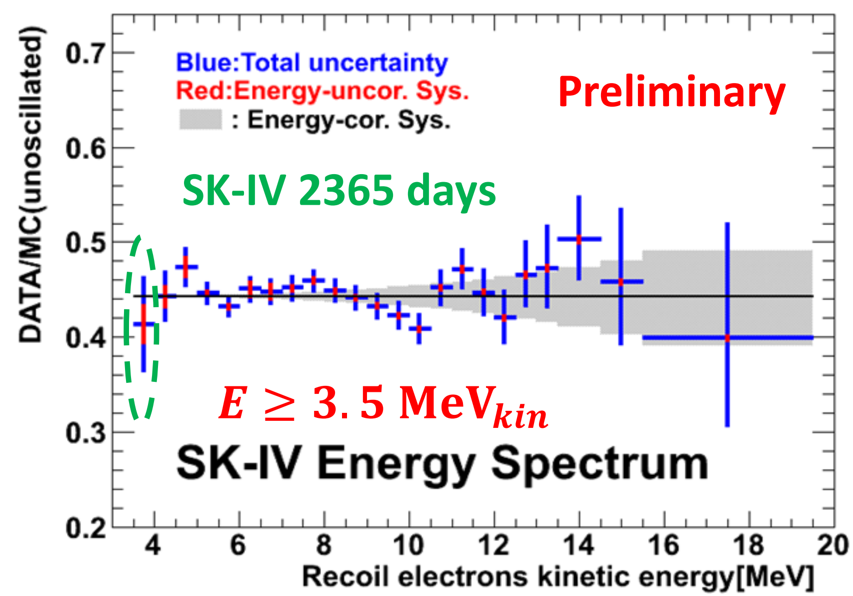
Sun spot number: http://www.sidc.be/silso/datafiles
Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

Recoil electron spectrum of each SK phase









MC: $5.25 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$ (SNO: NC current, Phys. Rev. C88 (2013) 025501.)

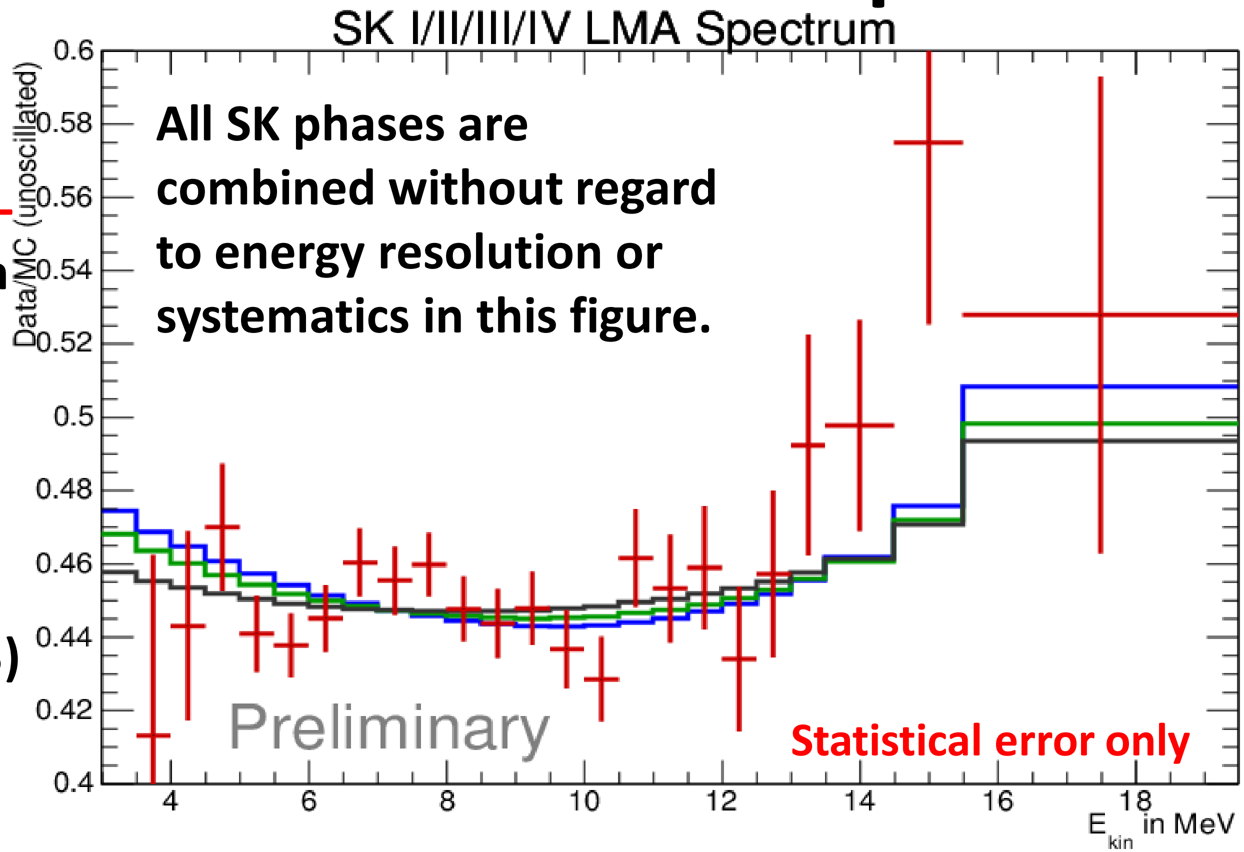
SK I-IV combined recoil electron spectrum

◆Spectrum shape

SK can search for the "up-turn" in its recoil electron energy spectrum.

SK-I: 1496 days ($E \geq 4.5$)
SK-II: 791 days ($E \geq 6.5$)
SK-III: 548 days ($E \geq 4.0$)
SK-IV: 2365 days ($E \geq 3.5$)
Total: 5200 days sample

The SK recoil electron spectrum disfavors the KamLAND best-fit parameters by about 2 σ.



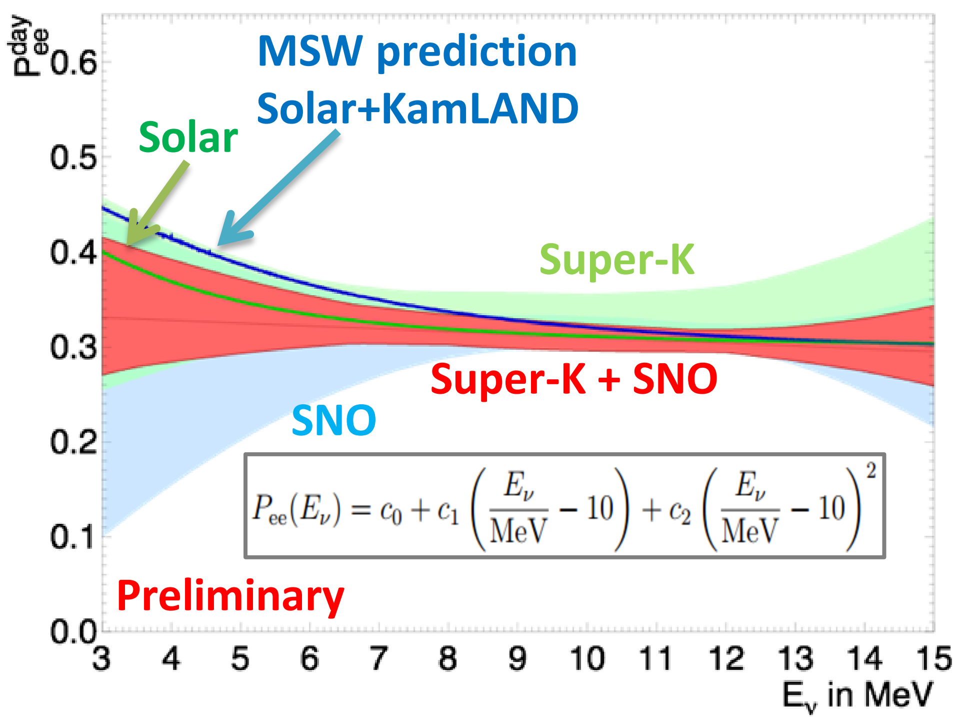
MC: 5.25×10^6/cm^2/sec (SNO: NC current, Phys. Rev. C88 (2013) 025501.)

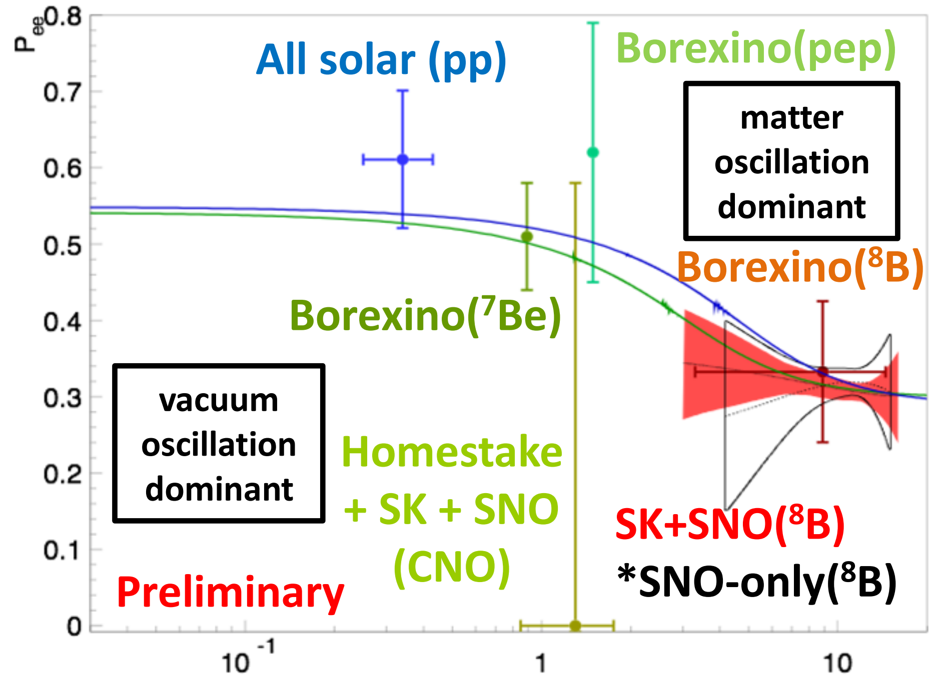
Total # of bins of SK I-IV is 83, 80 dof	χ^2
Solar + KamLAND	76.60
Solar global	73.86
Quadratic fit	72.33

Allowed survival probability

◆Neutrino energy spectrum shape

Neutrino energy spectrum was de-convoluted from the recoil energy spectrum.
Super-K more stringent < 7.5 MeV while SNO > 11.5 MeV.





*Phys. Rev. C88 (2013) 025501.

Super-K gives the world's strongest constraints on the shape of the survival probability in the transition region between vacuum oscillations and MSW resonance.

Global oscillation analysis input

◆SK

- SK-I 1496 days, Spectrum : 4.5-19.5MeV(kin.) + D/N : $E_{kin} \geqq 4.5$MeV
- SK-II 791 days, Spectrum : 6.5-19.5MeV(kin.) + D/N : $E_{kin} \geqq 7.0$MeV
- SK-III 548 days, Spectrum : 4.0-19.5MeV(kin.) + D/N : $E_{kin} \geqq 4.5$MeV
- SK-IV 2365 days, Spectrum : 3.5-19.5MeV(kin.) + D/N (1664 days) : $E_{kin} \geqq 4.5$MeV

arXiv: 1606.07538.
Updated from PRL 112 (2014) 091805.

◆SNO

- Parameterized analysis (c0,c1,c2,a0,a1) of all SNO phased published in Phys. Rev. C88 (2013) 025501.

The same method is applied to both SK and SNO with a_0 and a_1 to LMA expectation.

◆Radiochemical (Ga, Cl)

- Ga rate 66.1±3.1 SNU (All Ga global), Phys. Rev. C80 (2009) 015807.
- Cl rate 2.56±0.23 SNU, Astrophys. J. 496 (1988) 505.

◆Borexino

- ^{7}Be flux, Phys. Rev. Lett. 107 (2011) 141302.

Does NOT include Borexino pp 2014.
Nature 512 (2014) 383.

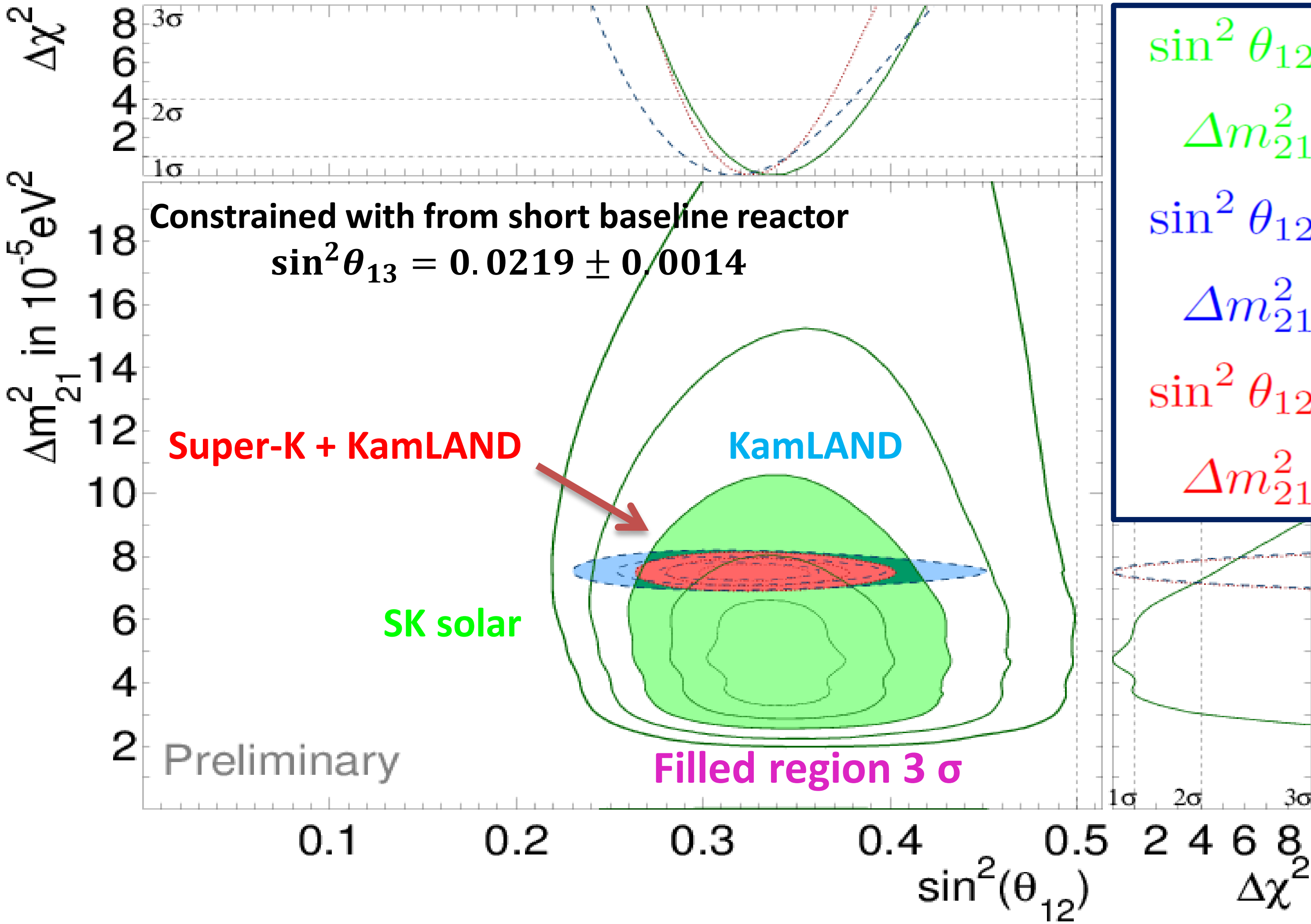
◆KamLAND reactor

- 3-flavor analysis , Phys. Rev. D88 (2013) 033001.

◆^{8}B spectrum

- Winter 2006, Phys. Rev. C73 (2006) 025503.

Super-K vs. KamLAND



$\sin^2\theta_{12} = 0.337^{+0.027}_{-0.023}$

$\Delta m^2_{21} = 4.74^{+1.40}_{-0.80}$

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

$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$

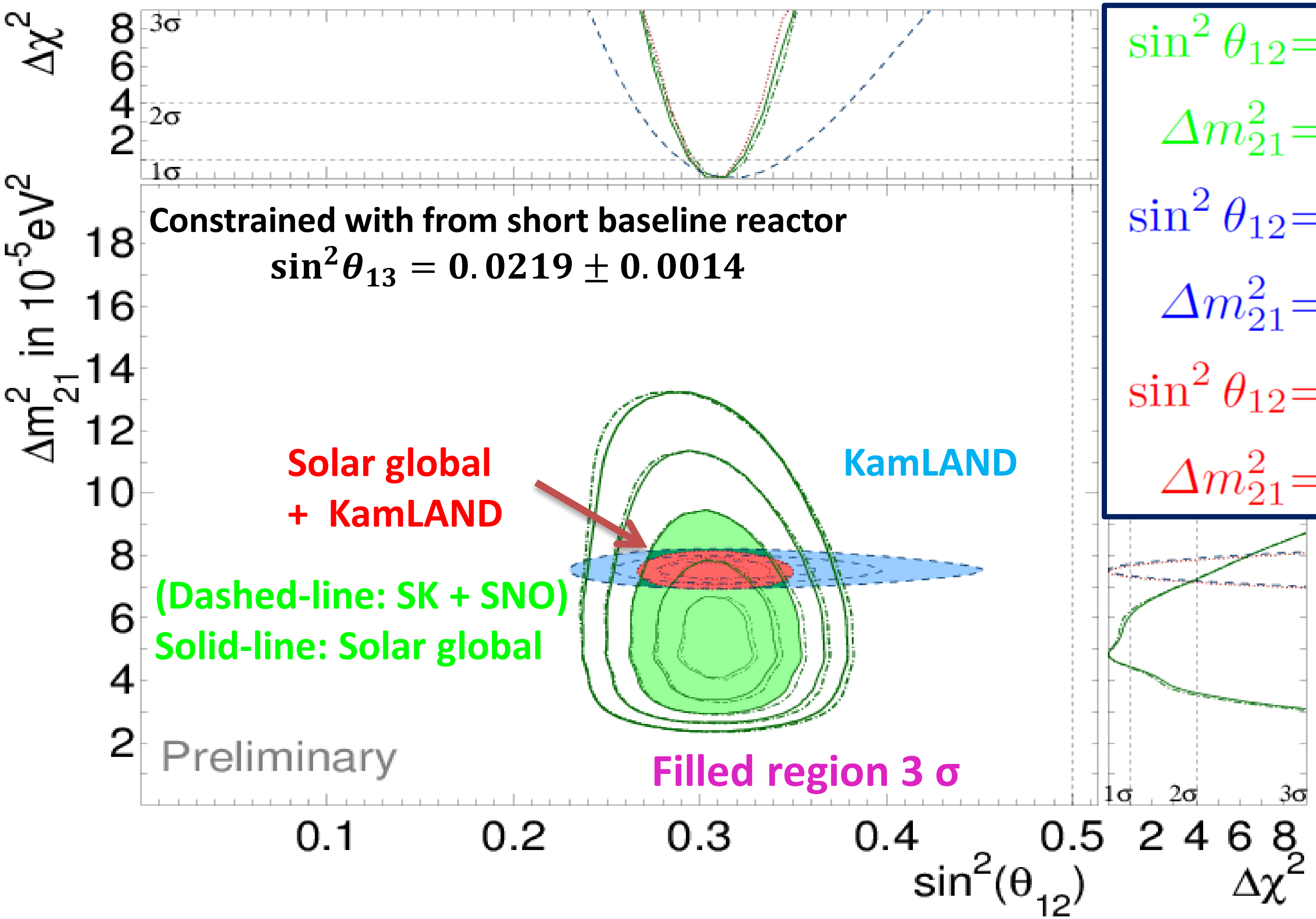
$\sin^2\theta_{12} = 0.326^{+0.022}_{-0.019}$

$\Delta m^2_{21} = 7.50^{+0.19}_{-0.17}$

The unit of $\Delta m_{21}{}^2$ is 10^{-5} eV^2

SK result uniquely selects the Large Mixing Angle MSW region by more than 3σ.
SK significantly contributes to the measurement of the solar angle.

Solar global vs. KamLAND



$\sin^2\theta_{12} = 0.311 \pm 0.014$

$\Delta m^2_{21} = 4.84^{+1.26}_{-0.60}$

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

$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$

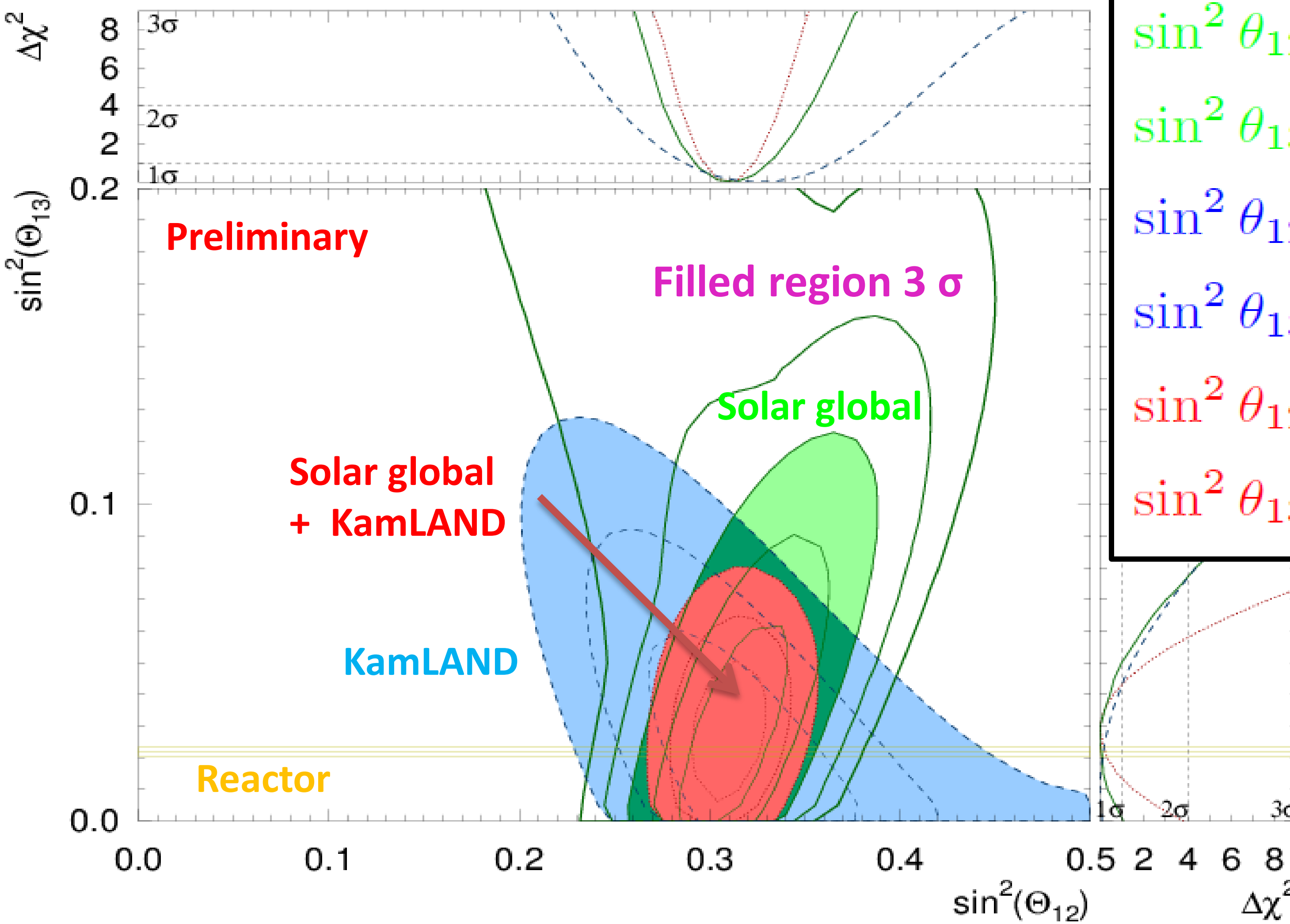
$\sin^2\theta_{12} = 0.308 \pm 0.012$

$\Delta m^2_{21} = 7.49^{+0.19}_{-0.18}$

The unit of $\Delta m_{21}{}^2$ is 10^{-5} eV^2

The SK spectrum and D/N data favor a lower m^2_{21} value than KamLAND's by more than 2σ and mostly determine this parameter in the solar neutrino oscillation fit.

3-flavor oscillation analysis



$\sin^2\theta_{12} = 0.311^{+0.022}_{-0.017}$

$\sin^2\theta_{13} = 0.027^{+0.025}_{-0.027}$

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

$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$

$\sin^2\theta_{12} = 0.310^{+0.014}_{-0.013}$

$\sin^2\theta_{13} = 0.029^{+0.014}_{-0.015}$

2σ level non-zero θ_{13} is obtained from Solar global + KamLAND.
Consistent with the reactor results.

WIT (Wide-band Intelligent Trigger)

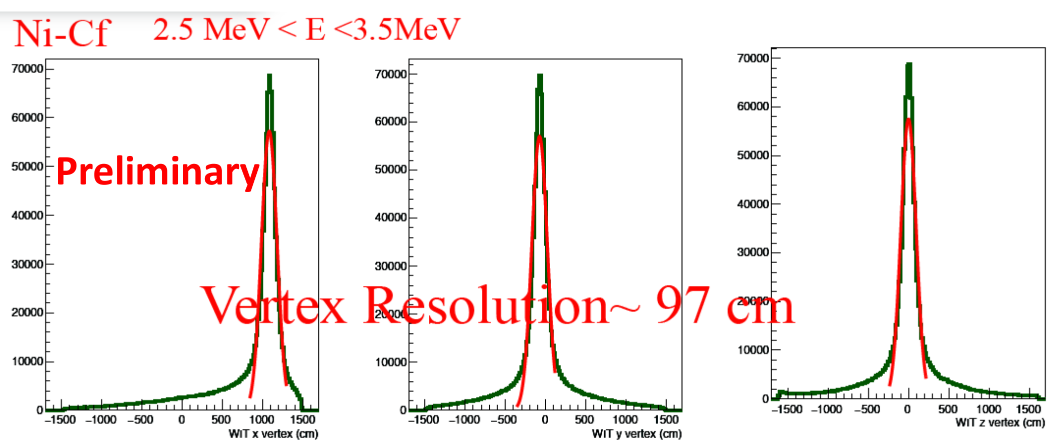
◆Physics motivation

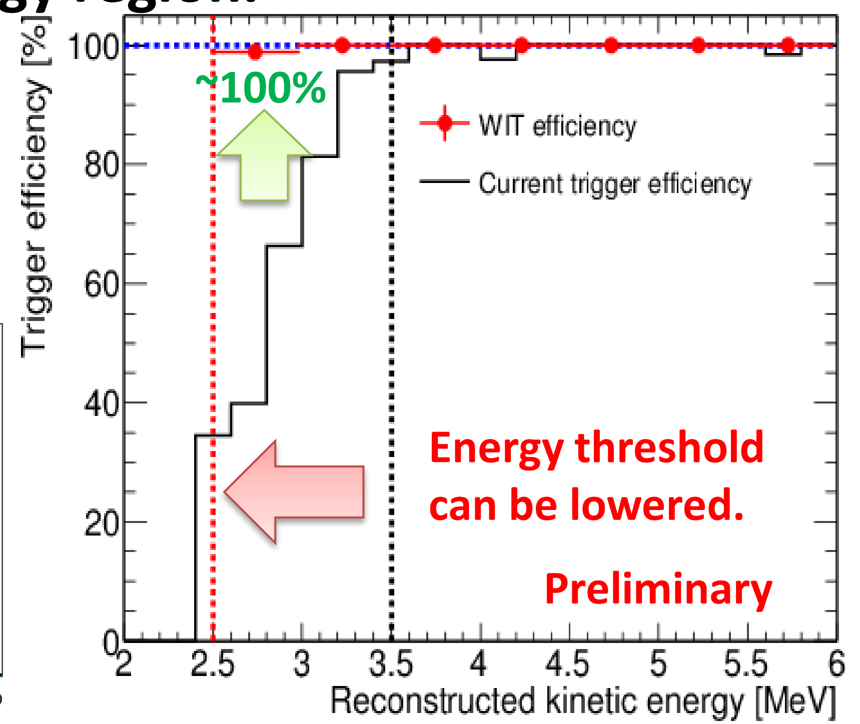
To improve the sensitivity to the MSW resonance in the low energy solar neutrino, the energy threshold should be lowered.

WIT system can accumulate low energy recoil electrons above 2.5 MeV_{kin} to explore the lower energy region.

◆Performance

Using Ni-Cf calibration source, detection efficiency is evaluated.





Summary

- SK solar neutrino flux measurements agree across all phase.
  - No correlation with the solar activity cycle is seen.
- SK recoil electron energy spectrum slightly disfavors distortions.
- Solar global + KamLAND analysis gives:
  - $\Delta m_{21}{}^2 = 7.49^{+0.19}_{-0.18} \times 10^{-5}$ eV^2 ,
  - $\sin^2\theta_{12} = 0.308 \pm 0.012$,
  - $\sin^2\theta_{13} = 0.029^{+0.014}_{-0.015}$.
- SK has started data taking at energy threshold of about 2.5 MeV$_{kin}$ and will continue to push into the transition region.
- SK collaboration approved the SK-Gd project.
  - See H. Sekiya Poster August 8th.

Back

up

Detection method

◆Cherenkov light

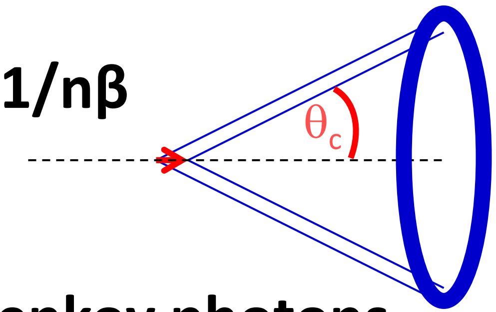
● Emission if $n \times \beta > 1$

n : refractive index (water ~ 1.33)

β : p/E

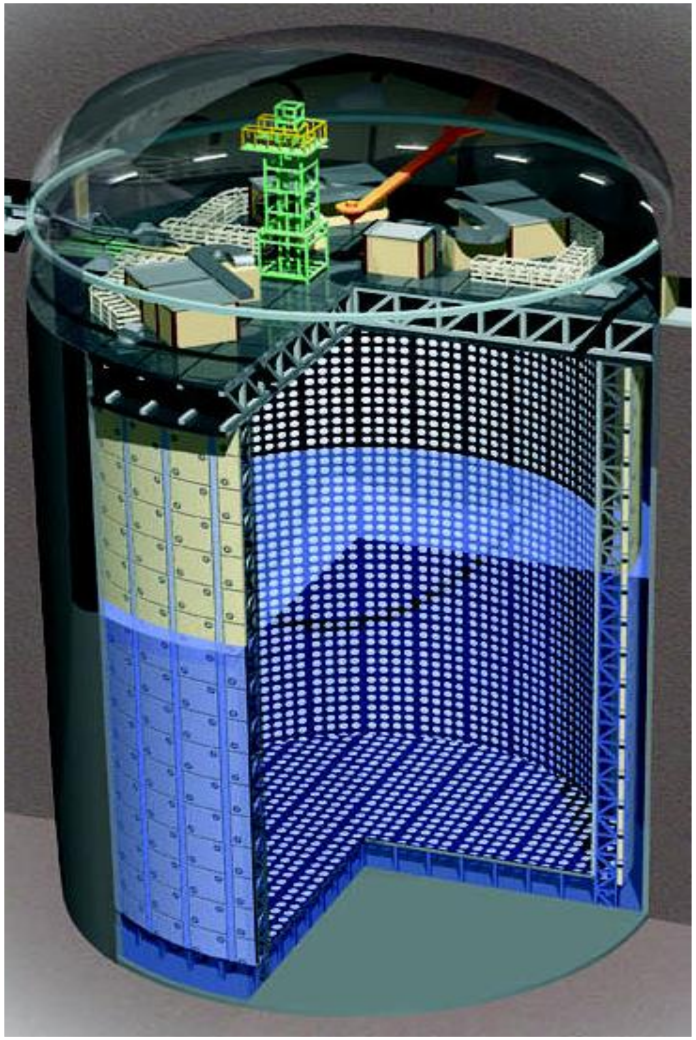
● Direction : $\cos\Theta = 1/n\beta$

$\Theta \sim 42^\circ$

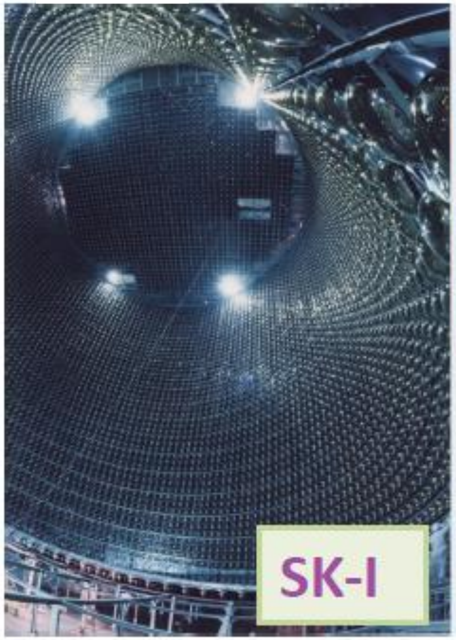


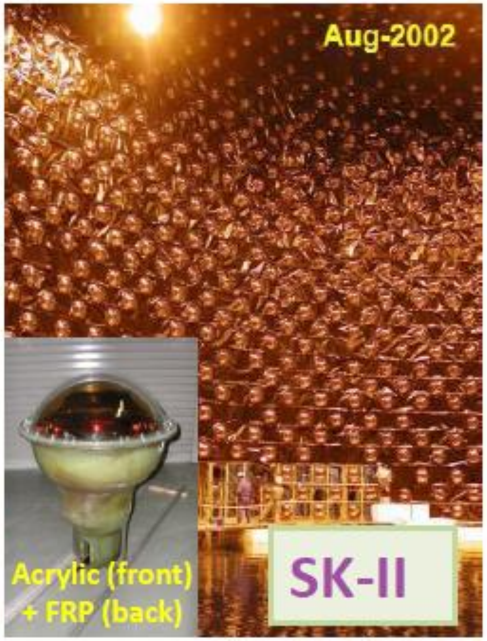
● # of emitted Cherenkov photons

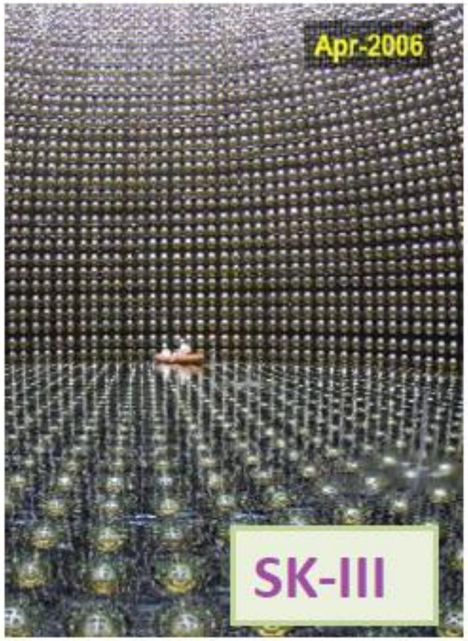
~ 340 photons/1cm



History of Super Kamiokande







1996/4 ~2001/7	2002/10 ~2005/10	2006/7 ~2008/8	2008/9 ~ Running
◆PMT(ID)	(※)With Acrylic + FRP	(※)Recovered	(※)New electronics
11146 PMTs 40% photo coverage	5182 PMTs 19% photo coverage	11129 PMTs 40% photo coverage	11129 PMTs 40% photo coverage

◆Kinetic Energy threshold

SK-I	SK-II	SK-III	SK-IV Current	SK-IV Target
4.5 MeV	6.5 MeV	4.0 MeV	3.5 MeV	More lower

Typical low energy event in SK

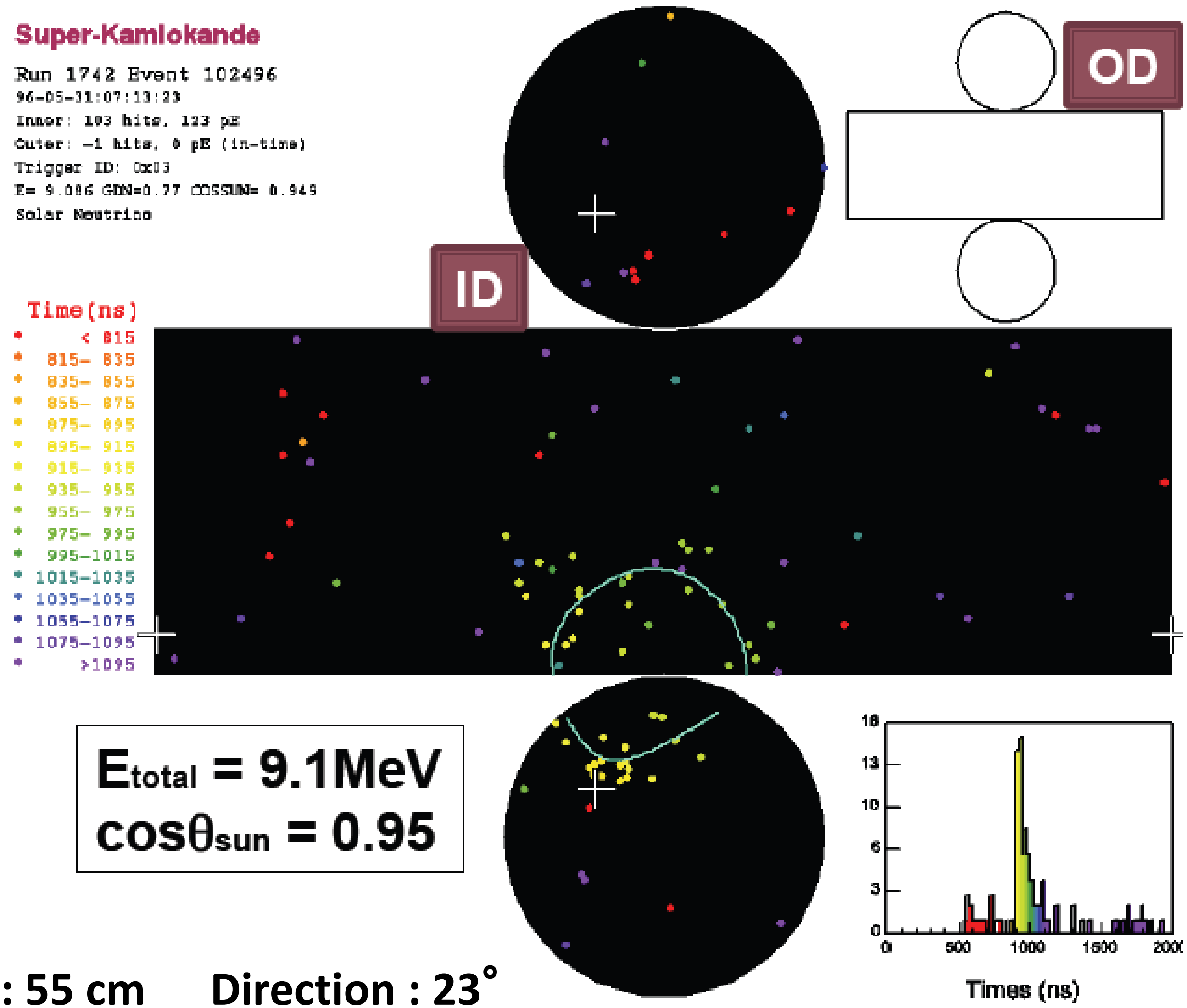
◆How to detect

Elastic scattering(ES) reaction is used for solar neutrinos

$$\upsilon_x + e^- \rightarrow \upsilon_x + e^-$$

◆Reconstruction

- ●Timing information
  →Vertex position
- ●Ring pattern
  →Direction
- ●Number of hit PMTs
  →Energy(~6hits/MeV)



◆Resolutions

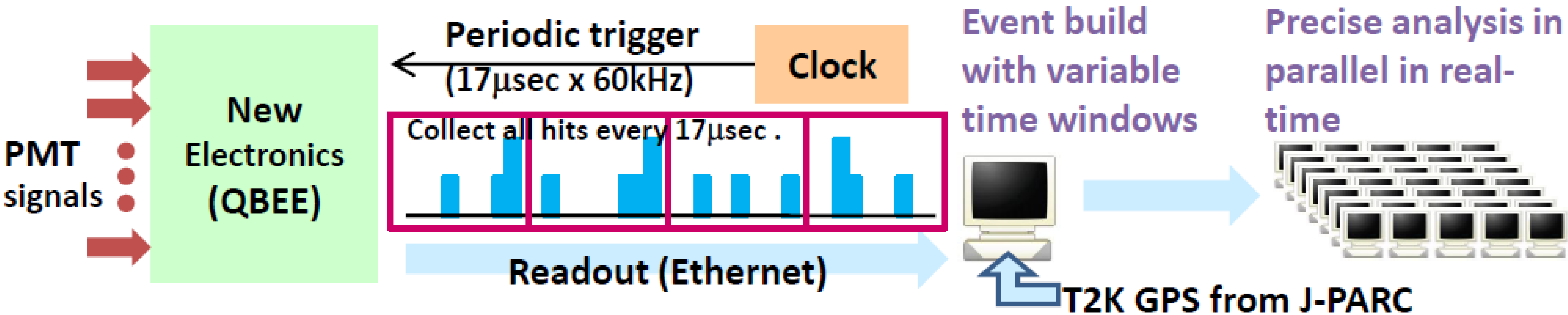
Energy : 14 %   Vertex : 55 cm   Direction : 23°

(for E = 9.5 MeV(kin.) electron)

SK-IV new DAQ system

◆New front-end electronics

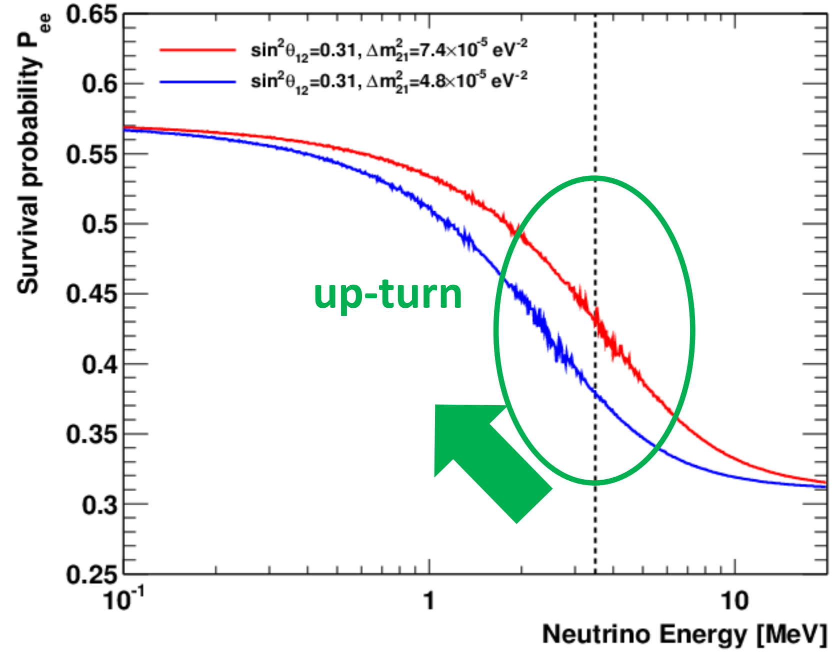
SK-I, II, III : partial data above threshold were read(1.3 micro sec window ×3kHz).
→ SK-IV : All hits are read, then apply complex triggers with software.



◆Typical event time window

Type	Time [μsec]
Super low energy (SLE) events(< ~6.5 MeV, 3kHz)	-0.5/+1.0
Normal Events(> ~6.5 MeV, 35Hz)	-5/+35
Supernova relic neutrino candidates(SRN) (> ~8 MeV)	-5/+35 + 500(AFT)
T2K events (beam spill timing)	-512/+512

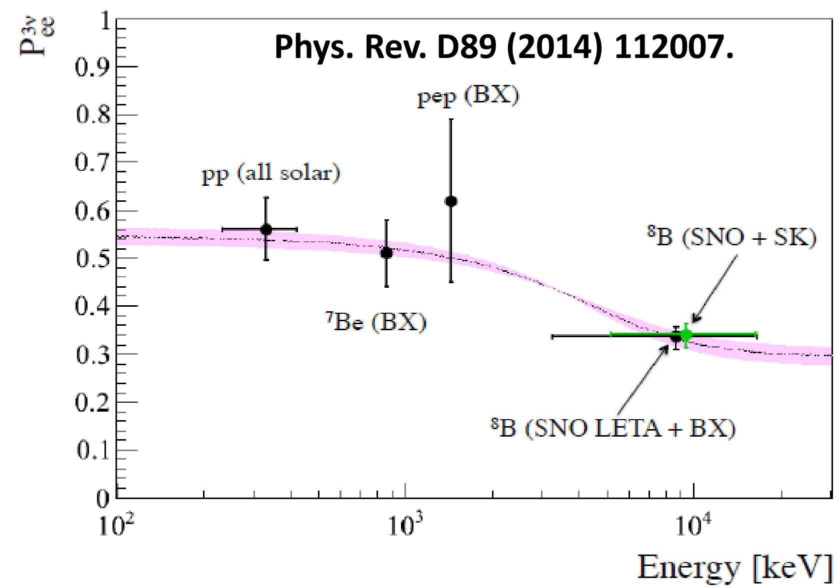
How to approach (up-turn)



"Up-turn" due to the matter effect in the Sun is expected <~6 MeV.
→ The effect can be seen in the low energy region in the SK detector.

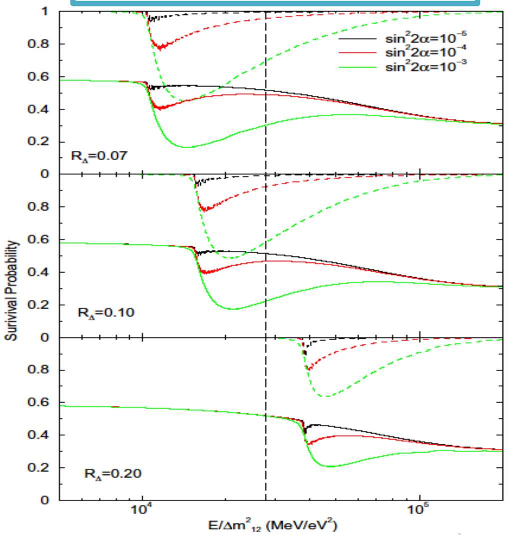
It is required to
(1)Lower the energy threshold, identify the origin of BG event.
→ Rn measurement/Rn analysis

(2)Precisely understand the "detection efficiency" of low energy solar neutrino event
→ various calibration sources
ex) LINAC, Ni, deuterium



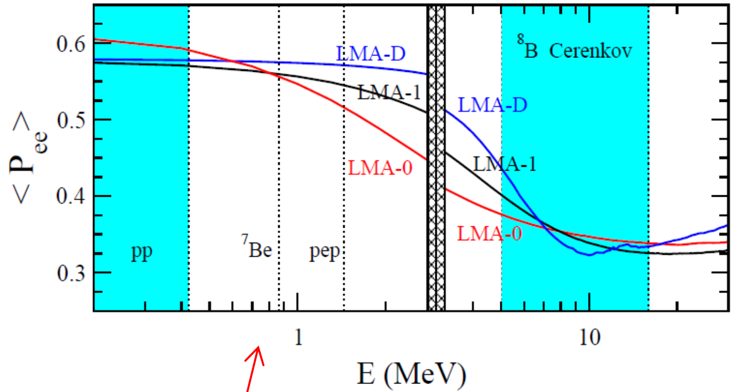
Non-standard models to predict flat spectrum

Sterile neutrino



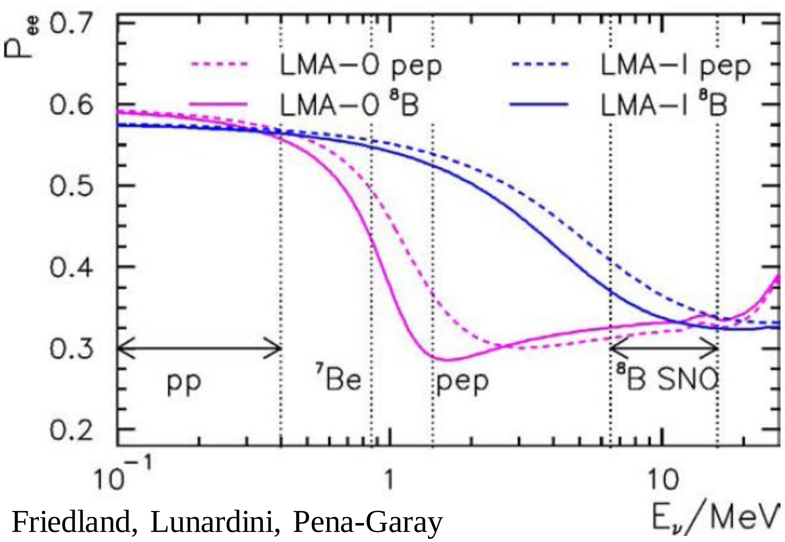
$$R_{\Delta} \equiv \frac{\Delta m^2_{01}}{\Delta m^2_{21}}$$

Holanda and Smirnov, Phys.Rev.D69(2004)113002. (hep-ph/0307266)



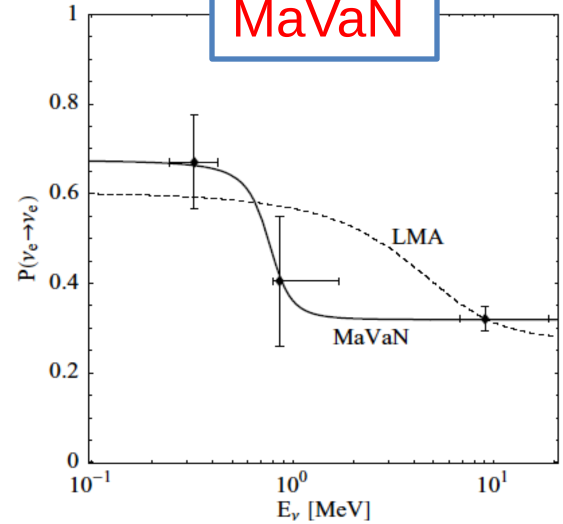
Miranda, Tortola and Valle, JHEP 0610:008,2006. (hep-ph/0406280)

Non standard Interaction

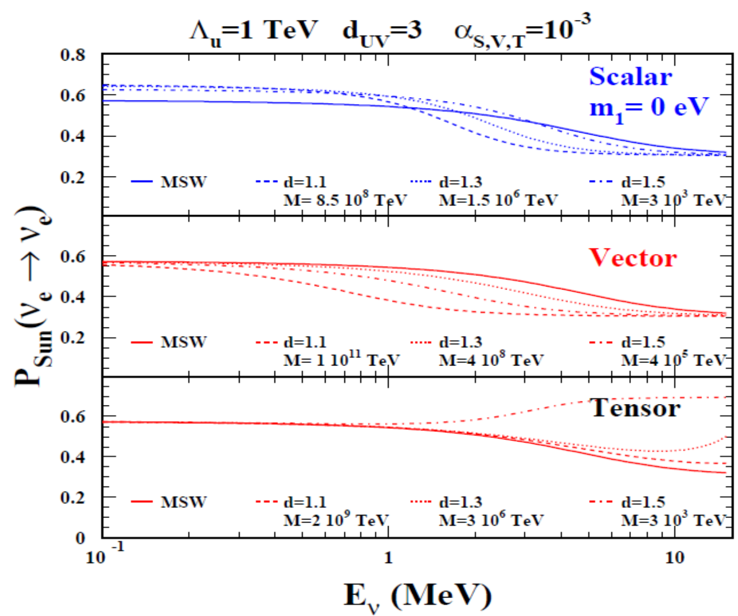


Friedland, Lunardini, Pena-Garay PLB594(2004)347(hep-ph/0402266)

MaVaN



Barger, Huber and Marfatia, Phys.Rev.Lett.95:211802,2005 (hep-ph/0502196)



Gonzalez-Garcia,Holanda,Zukanovich ,Funchal, JCAP 0806:019,2008. (hep-ph/0803.1180)

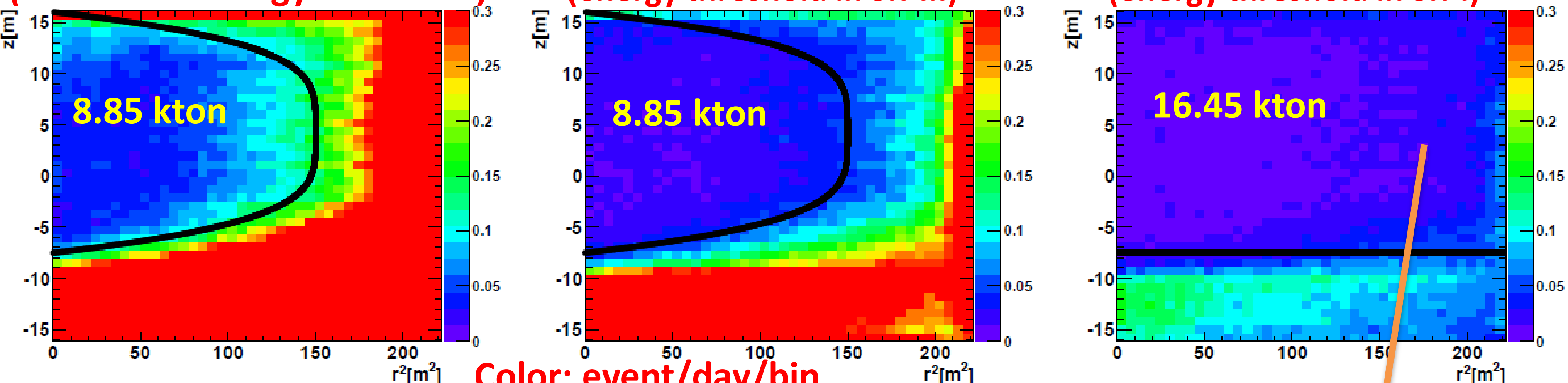
Unparticle

Tight Fiducial volume

3.5-4.0 MeV
(SK-IV new energy threshold)

4.0-4.5 MeV
(energy threshold in SK-III)

4.5-5.0 MeV
(energy threshold in SK-I)



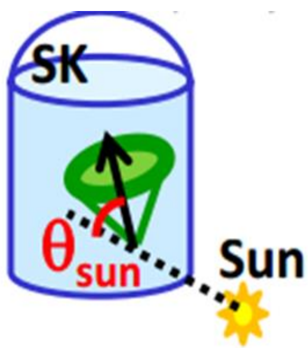
Color: event/day/bin

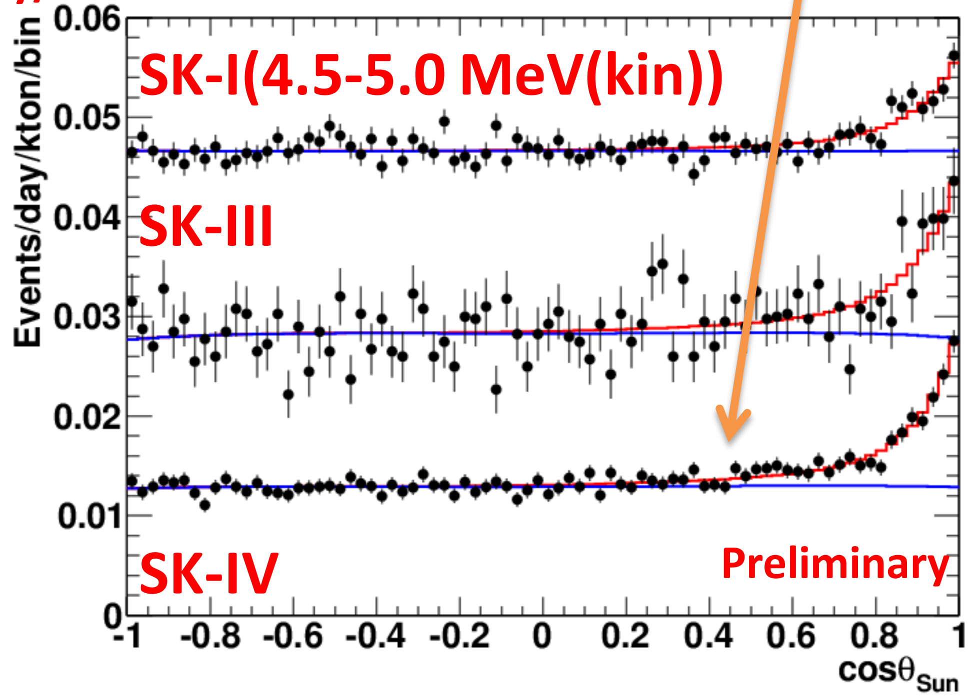
◆solar ν observation

Elastic scattering

$$\nu_x + e^- \to \nu_x + e^-$$

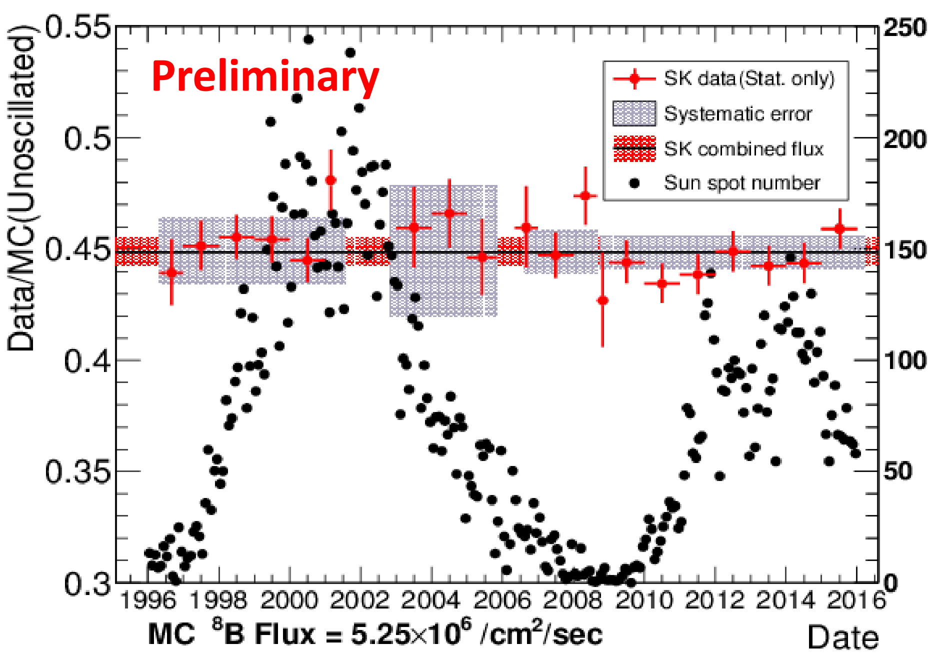
Solar neutrino signals are seen around cosΘsun =1.
Background event
→ Other direction (cosΘsun<0)

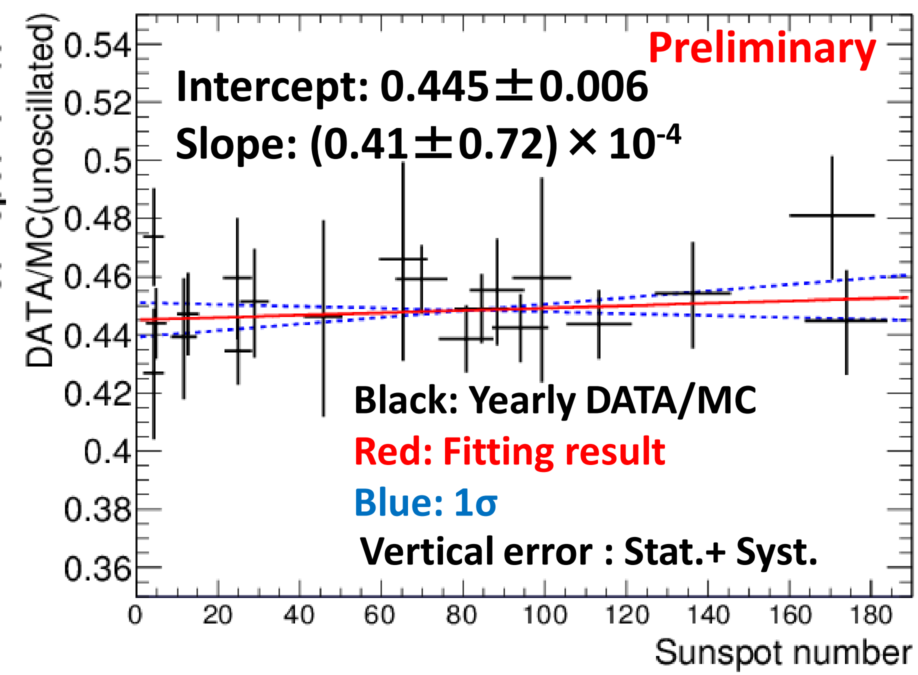




Does sunspot number affect the solar ^{8}B flux?

**To check the stability of the observed ^{8}B solar neutrino flux,
The flux vs the sun spot number is evaluated.
Since the value of slope is consistent with 0,
no significant correlation is observed using 20-years SK data.**





New : http://www.sidc.be/silso/datafiles

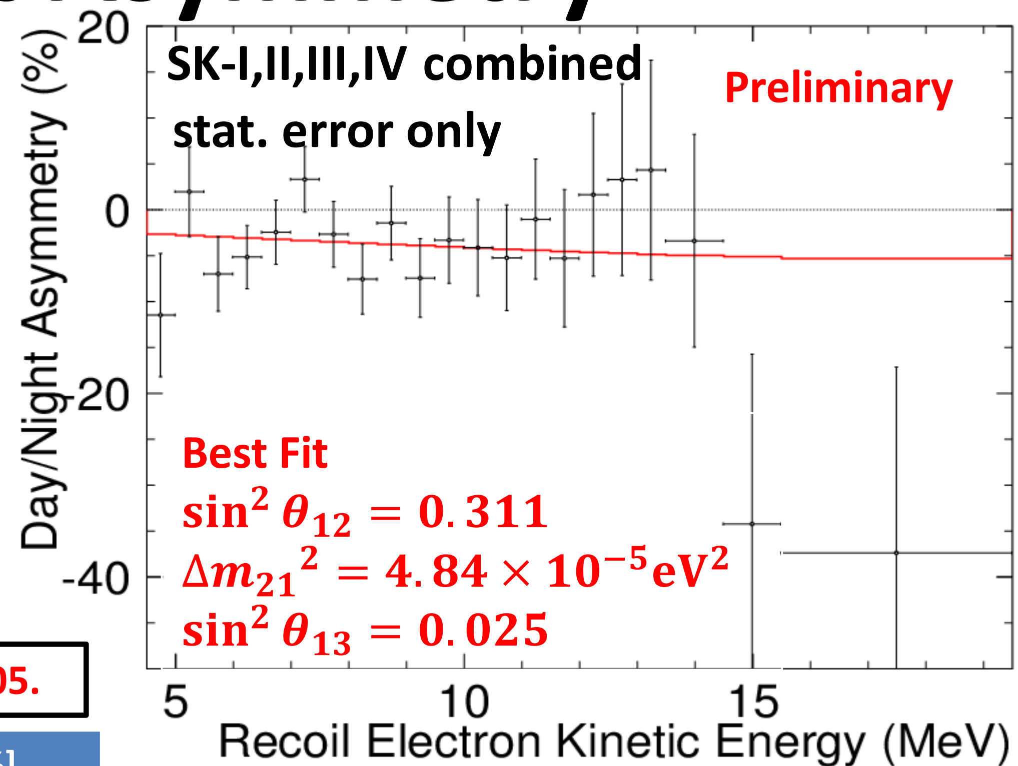
Sun spot number, Source: WDC-SILSO, Royal Observatory of Belgium, Brussels

Day-Night Asymmetry

Day-Night asymmetry is expected to be ~3 % in the SK energy region.

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

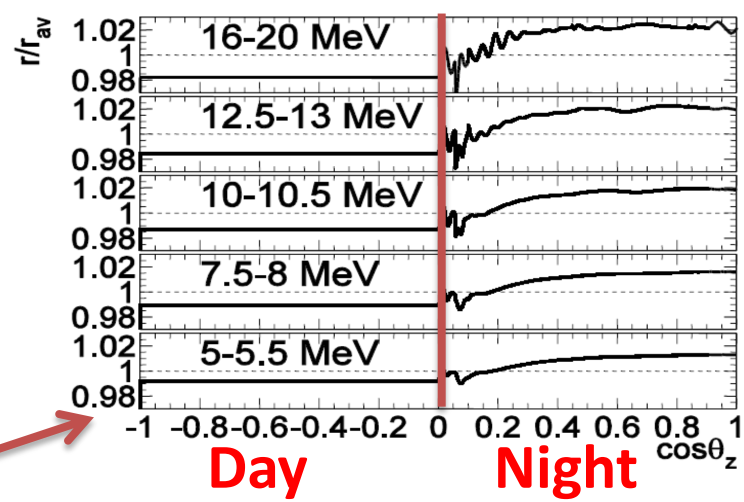
SK confirms a higher solar neutrino flux at night than during the day. This is a **"direct" indication** for matter enhanced neutrino oscillation.



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

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)

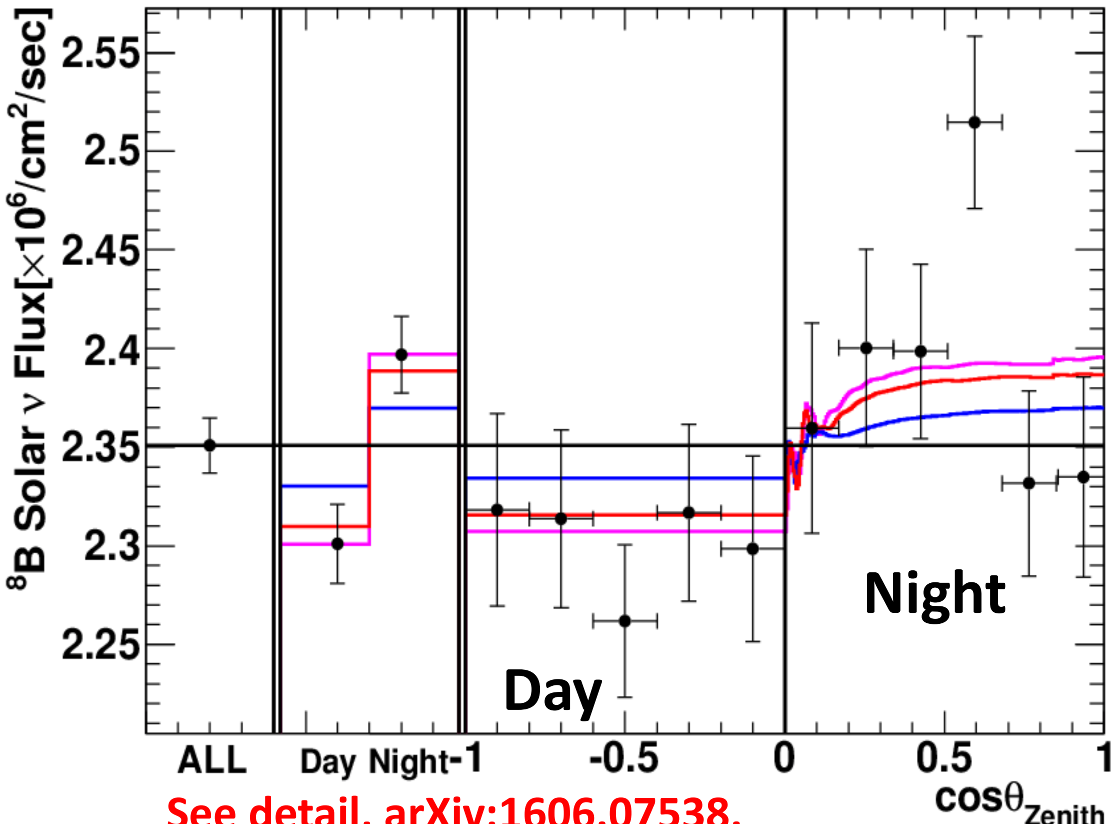
Expected time variation as a function of $\cos\theta_z$

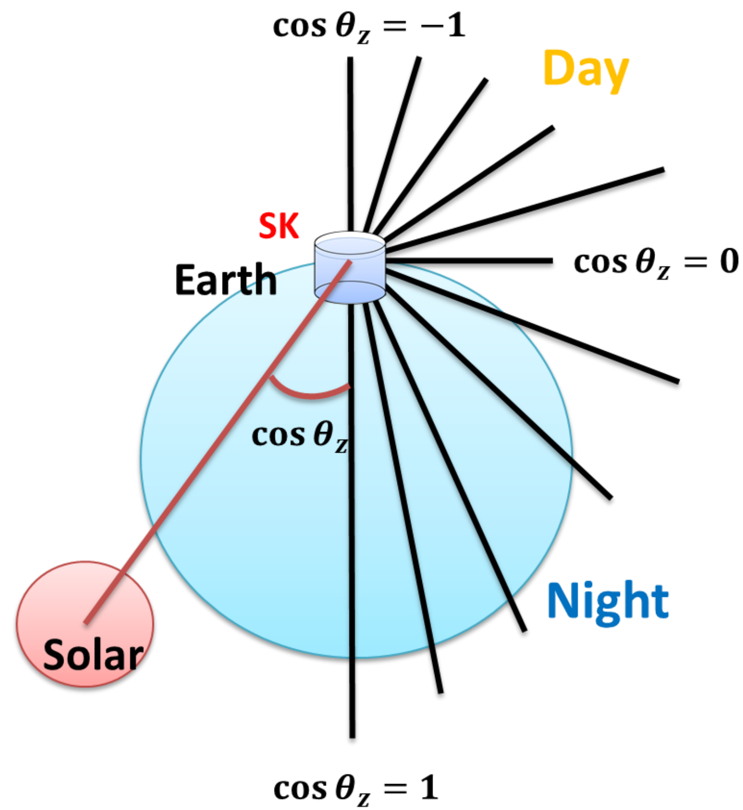


Day/Night asymmetry

◆zenith angle distribution

Clear flux difference between day-time and night-time.
Solar neutrino flux during night-time is higher than day-time.



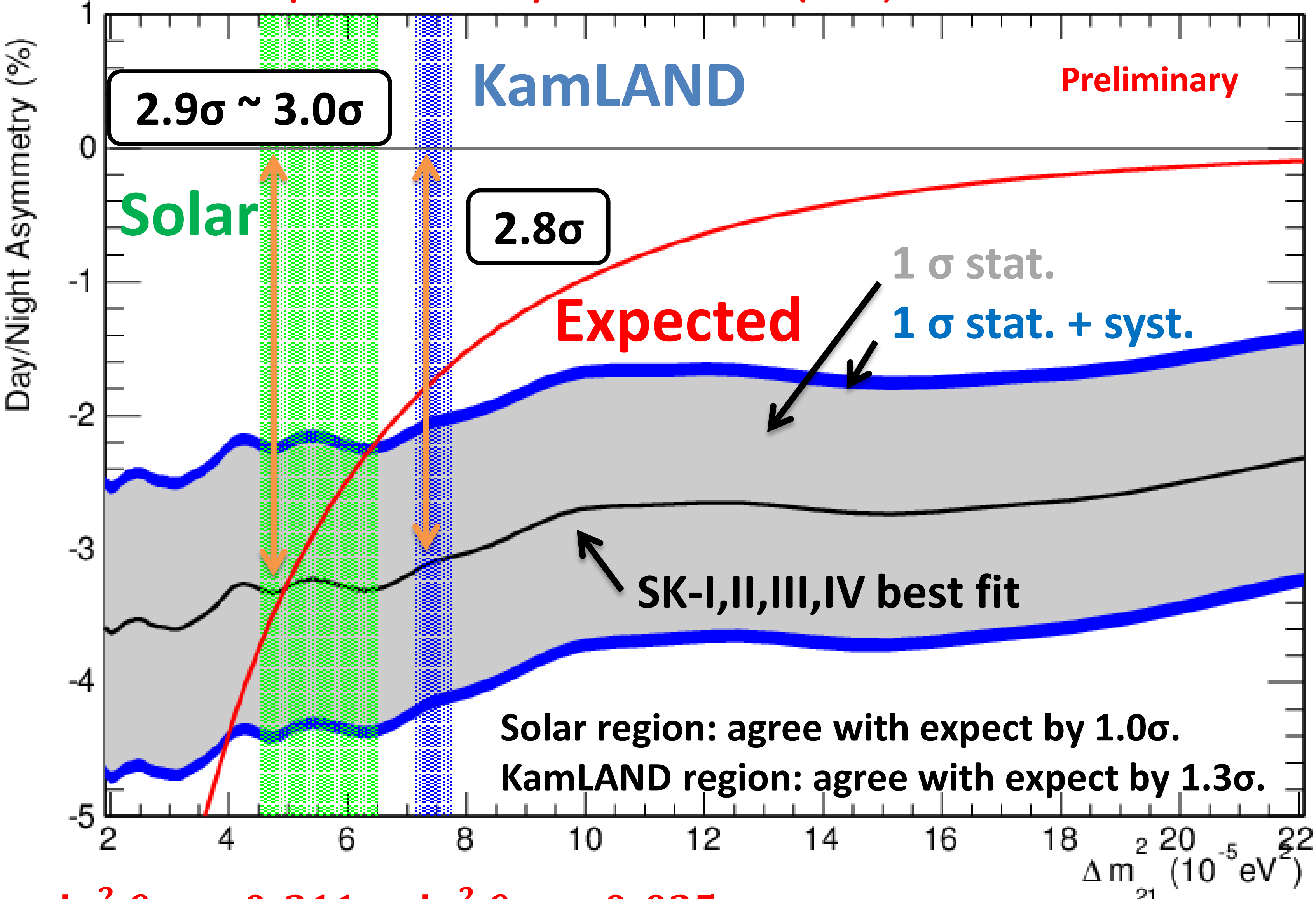


See detail, arXiv:1606.07538.
Updated from Phys. Rev. Lett. 112 (2014) 091805.

SK - I,II,III,IV combined

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

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



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