Solar neutrino results from Super Kamiokande

Yuuki Nakano
(ICRR, The Univ. of Tokyo)
for Super Kamiokande Collaboration

5th, August, 2015

ICRC 2015

@Hague, The Netherlands

ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands

Super Kamiokande

◆Feature of SK detector

Water Cherenkov ring Imaging(50 kton).

●Structure

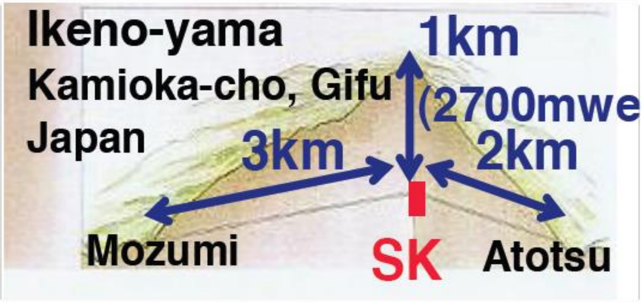
- Height 41.4 m
- Diameter 39.3 m

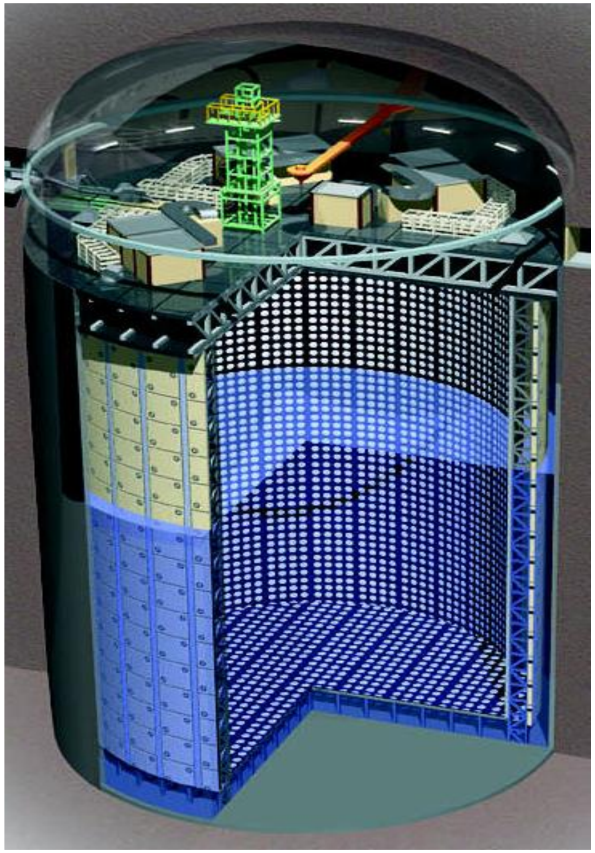
●Inner detector

- 32 kton viewed by 20-inch PMTs
  → fiducial volume 22.5 kton (2m from wall)
- 11129 PMTs (Photo coverage 40 %)

●Outer detector

- 2 m viewed by 1885 8-inch PMTs.





◆Physics target

-Long base line neutrino oscillation (T2K)

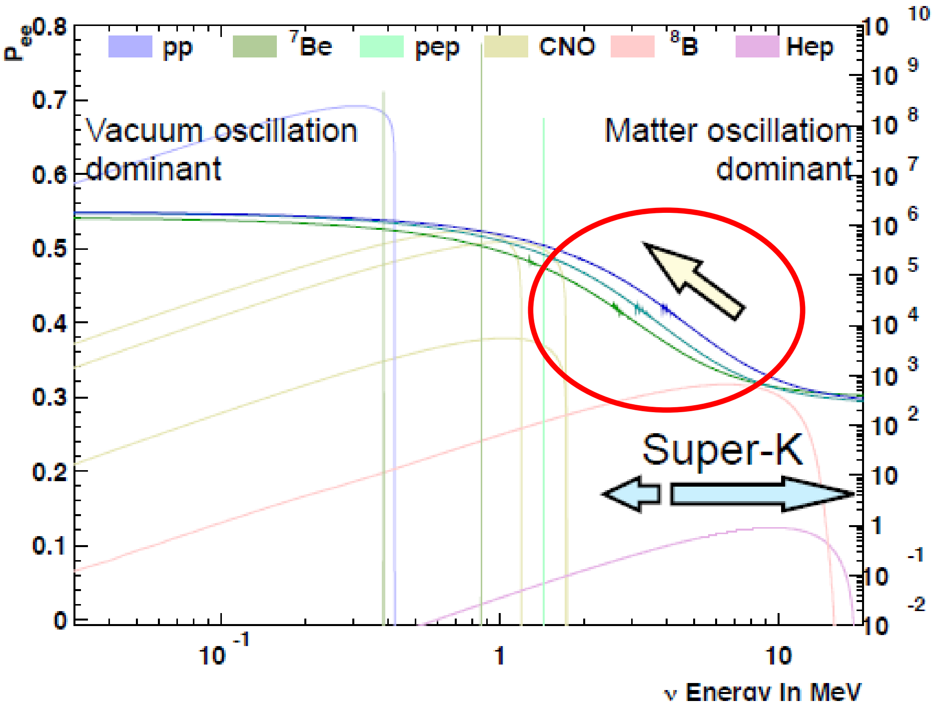
-Atmospheric, Solar, Supernova neutrinos

-Proton decay

Physics motivation for solar neutrino

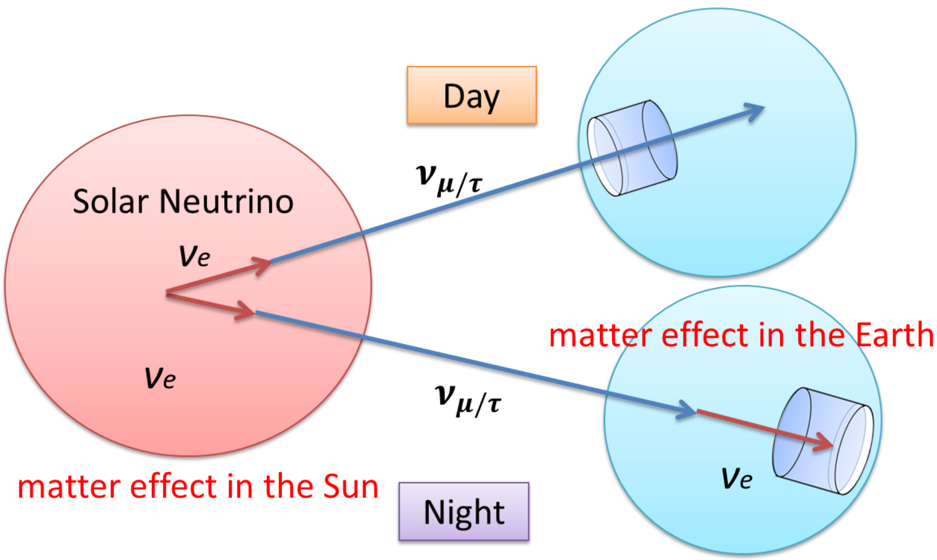
◆Spectrum distortion

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



◆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.



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

Observed ^8B solar neutrino signal

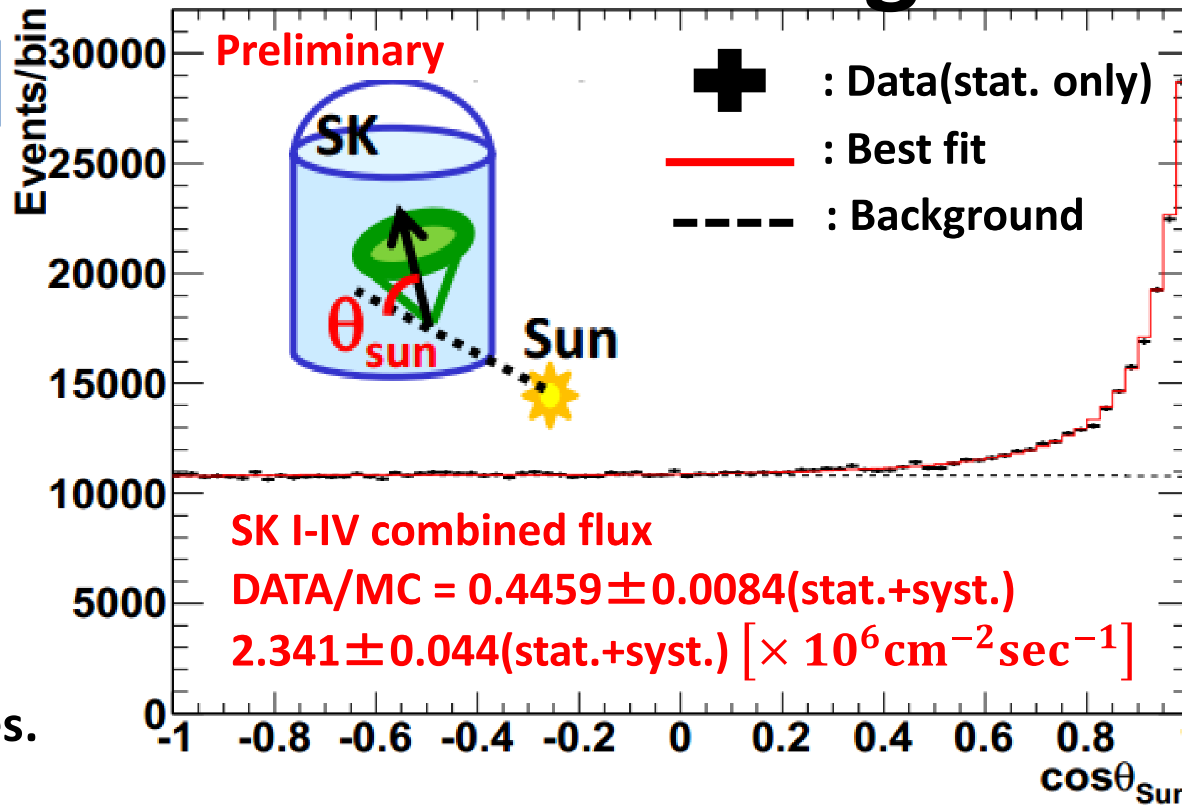
◆^8B neutrino measurement

Cherenkov light generated by electron scattered by neutrino.

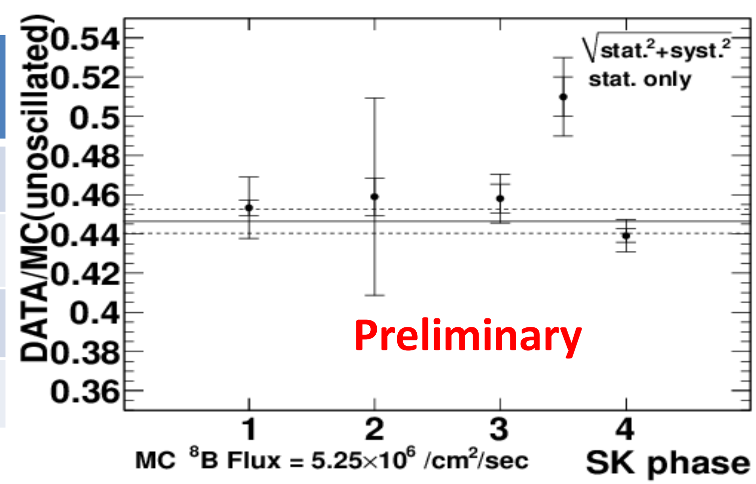
$$\upsilon_x + e^- \rightarrow \upsilon_x + e^-$$

A total of about 77k 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	2034	$2.31 \pm 0.02 \pm 0.04$



^{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 ~18 years (~1.5 cycle).

◆^{8}B flux vs sun spot

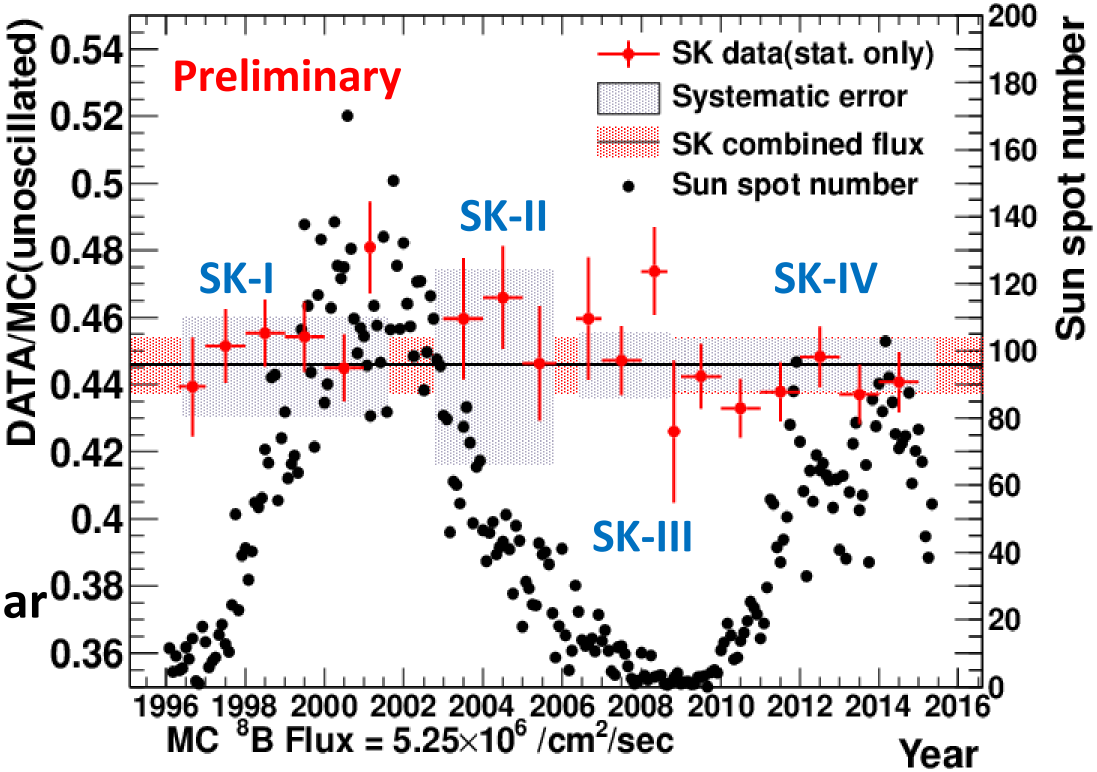
No correlation with the 11 years solar activity is observed.

$$\chi^2 = 13.10/18(\mathrm{D.O.F})$$

Preliminary

Prob. = 78.6 %

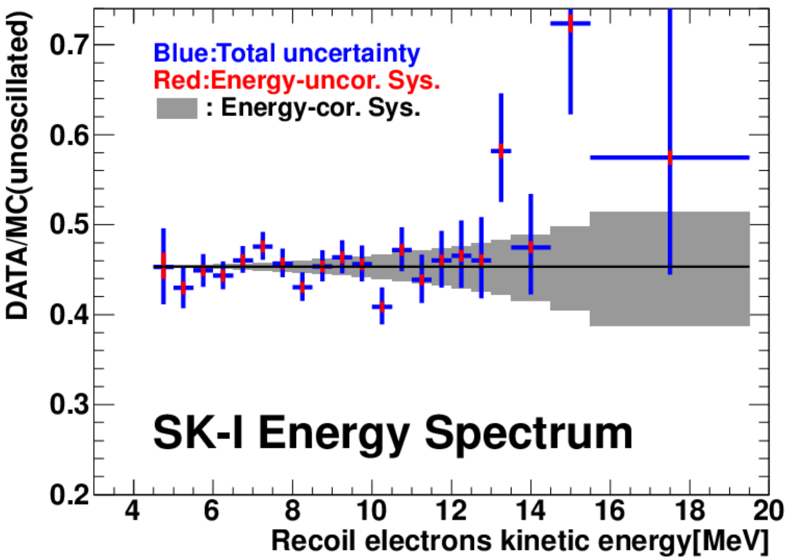
Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

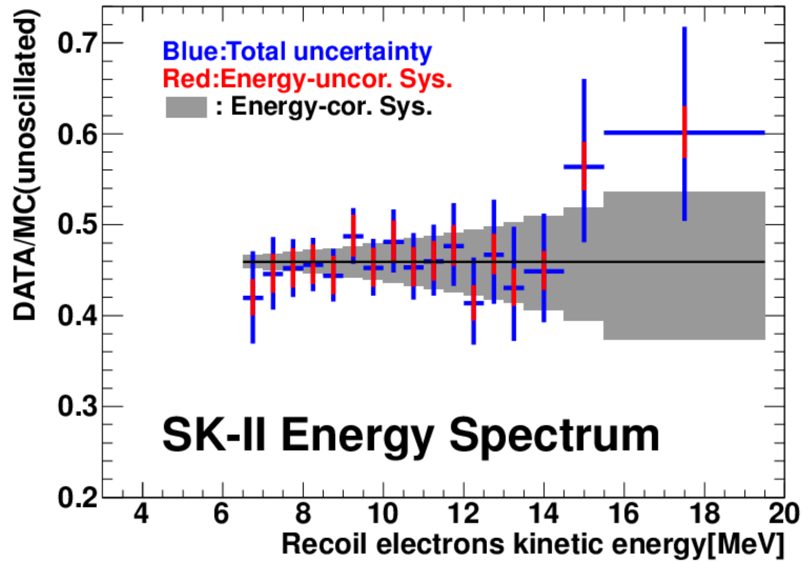


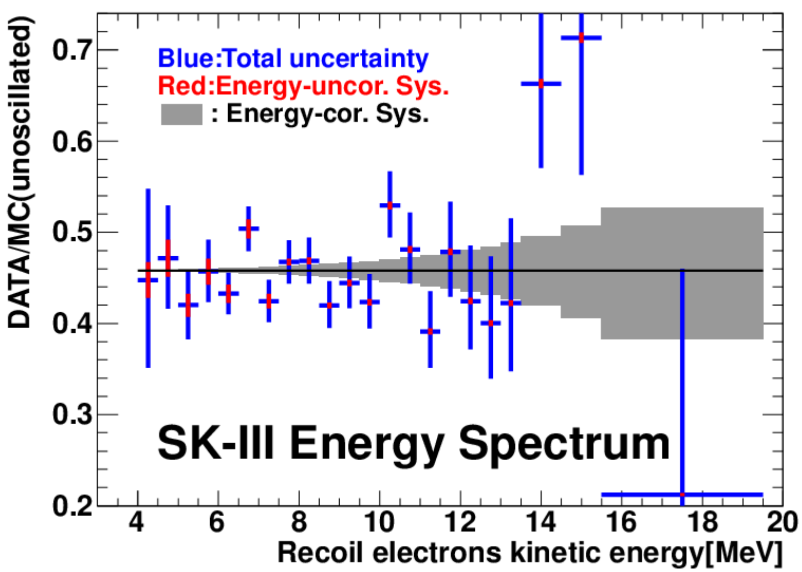
SK I-IV combined flux
DATA/MC = 0.4459±0.0084(stat.+syst.)
2.341±0.044(stat.+syst.) $[\times 10^6 \mathrm{cm}^{-2}\mathrm{sec}^{-1}]$

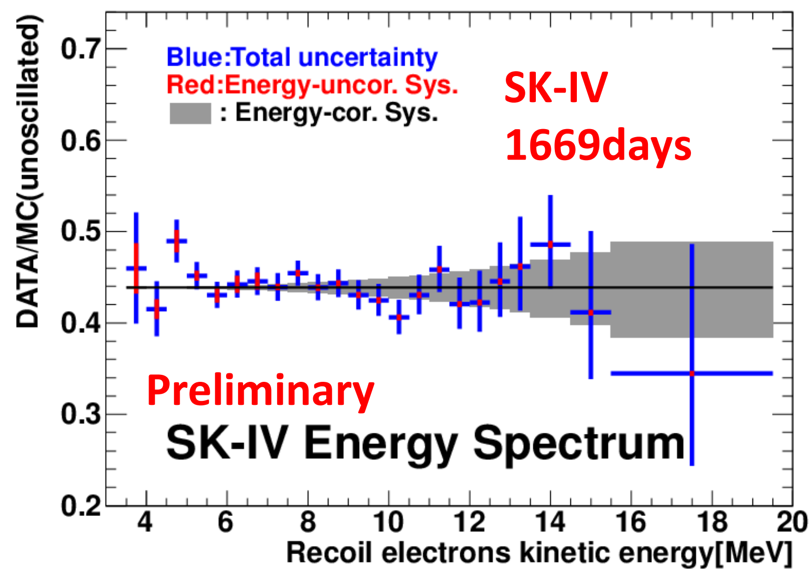
Sun spot number was obtained by the web page of NASA
http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt

Recoil electron spectrum of each SK phase







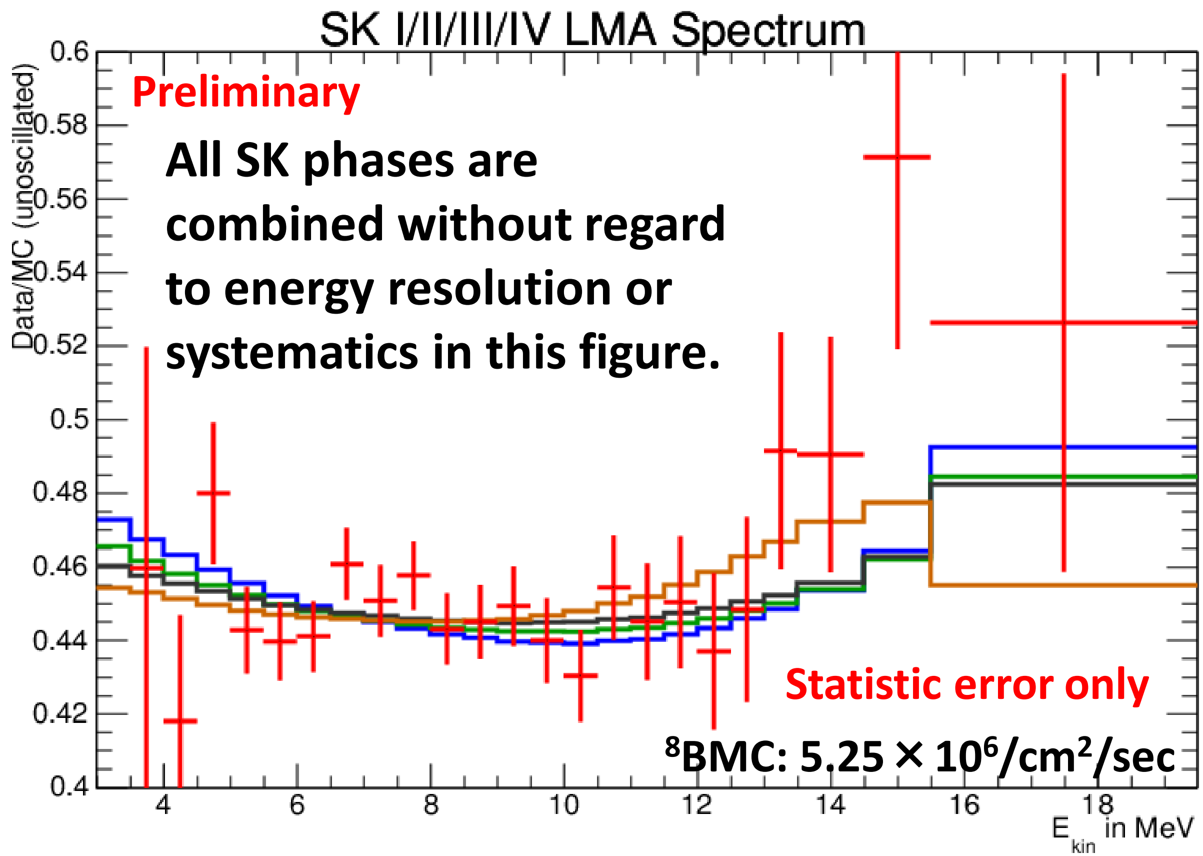


MC: $5.25 \times 10^6/cm^2/sec$

SK I-IV combined recoil electron spectrum

◆Spectrum shape

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



MSW is slightly disfavored by ~1.7 σ using the Solar + KamLAND best fit parameters, and ~1.0 σ using the Solar Global best fit parameters.

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

$$P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2}\left(\exp\left(e_2\left(\frac{E_\nu}{MeV} - 10\right)\right) - 1\right) \text{(exponential)}$$

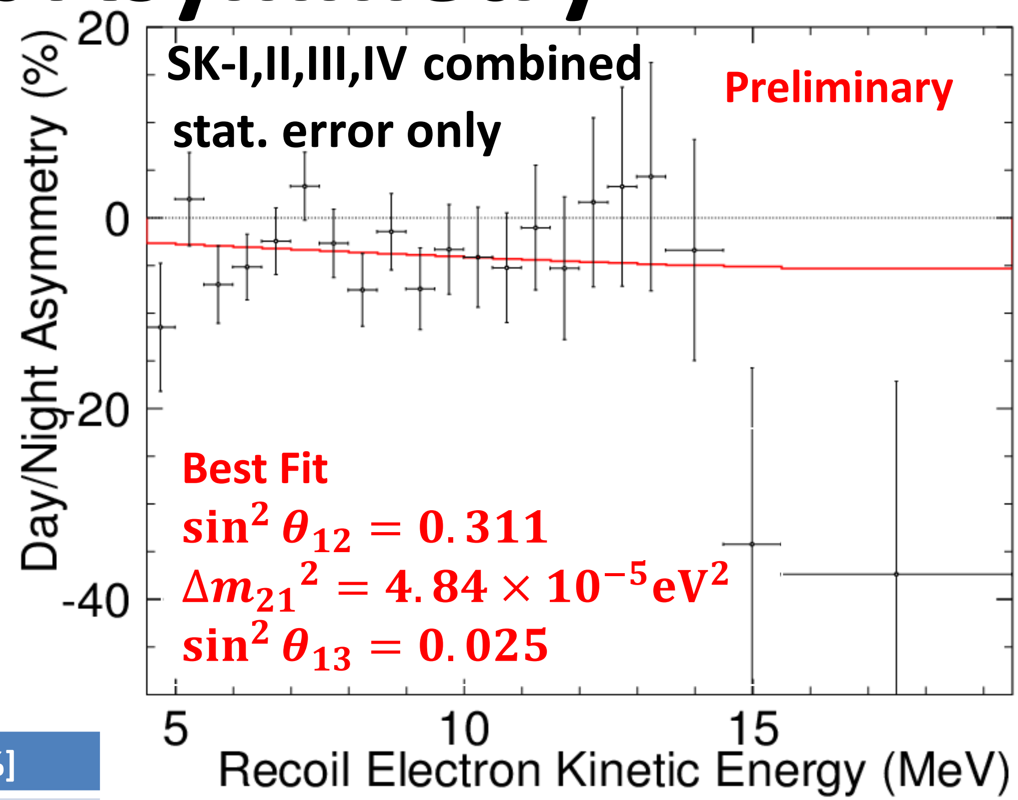
Total # of bins of SK I-IV is 83	χ^2
Solar + KamLAND	70.13
Solar global	68.14
Quadratic fit	67.67
Exponential	67.54

Day-Night Asymmetry

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

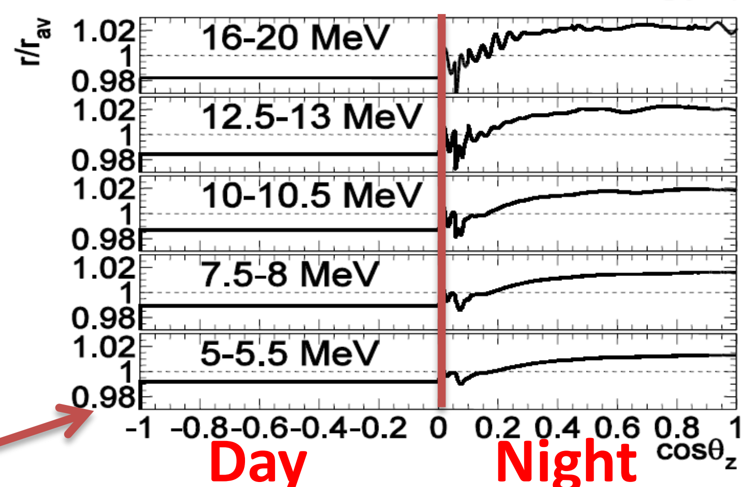
$$A_{\rm DN} = \frac{\Psi_{\rm day} - \Psi_{\rm night}}{(\Psi_{\rm day} + \Psi_{\rm night})/2}$$

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

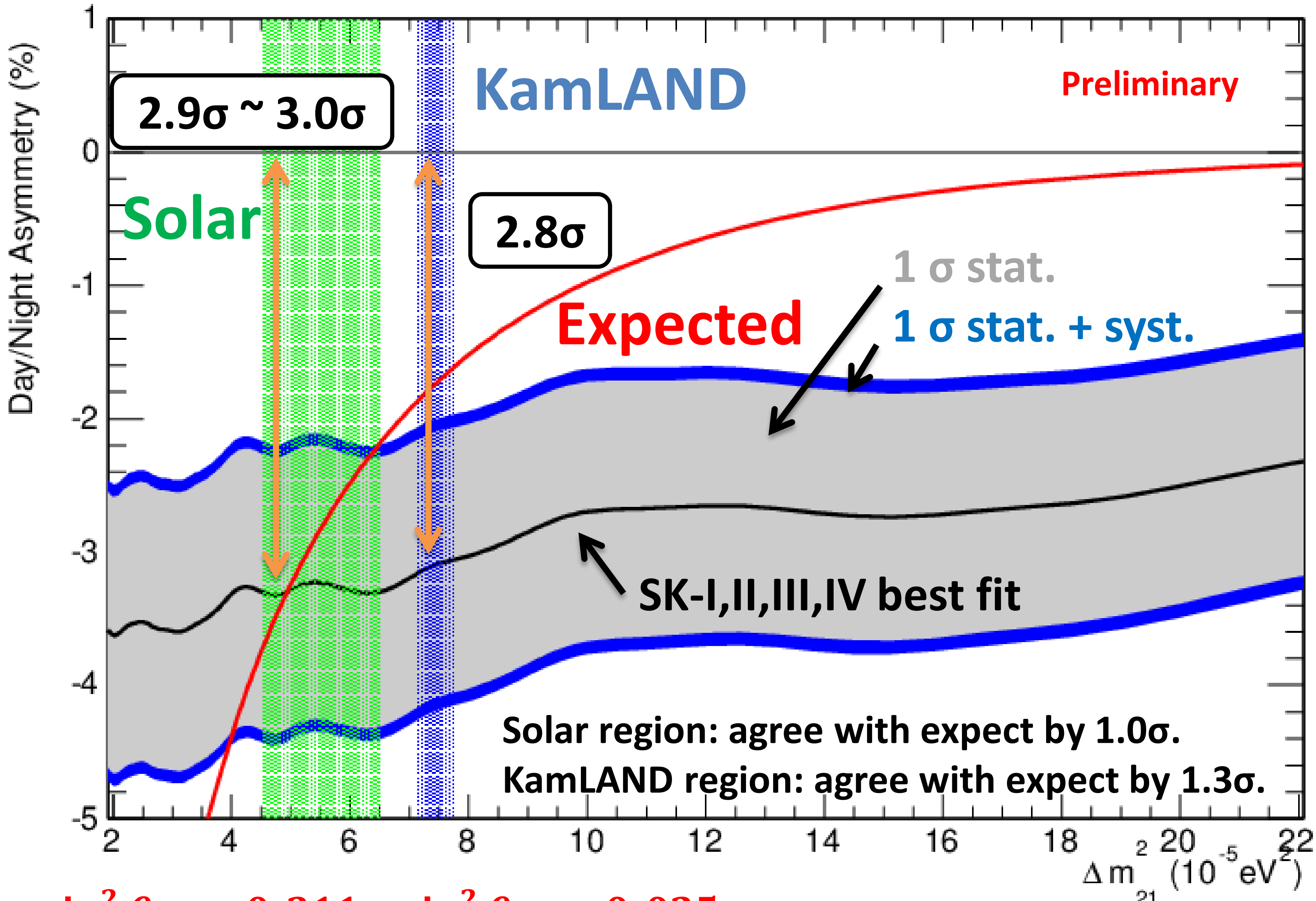


SK-phase	Amplitude fit [%]	Straight calc. [%]
SK-I	-2.0 ± 1.8 ± 1.0	-2.1± 2.0 ± 1.3
SK-II	-4.3 ± 3.8 ± 1.0	-5.5 ± 4.2 ± 3.7
SK-III	-4.2 ± 2.7 ± 0.7	-5.9 ± 3.2 ± 1.3
SK-IV	-3.6 ± 1.6 ± 0.6	-4.9 ± 1.8 ± 1.4
Combined	-3.3 ± 1.0 ± 0.5 (3.0 σ from zero)	-4.1 ± 1.2 ± 0.8 (2.8 σ from zero)

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

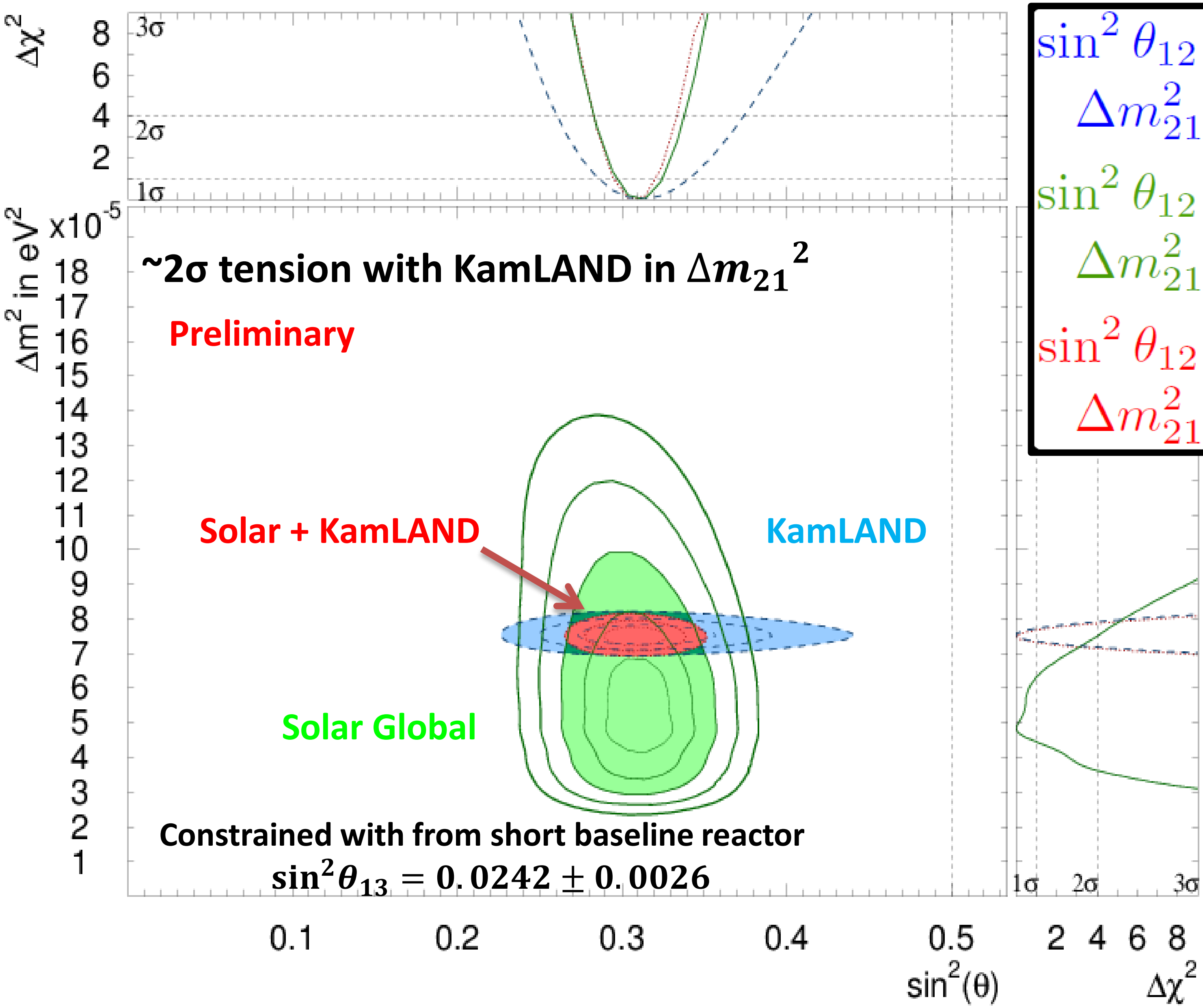


$\Delta m_{21}{}^2$ vs Day/Night Asymmetry



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

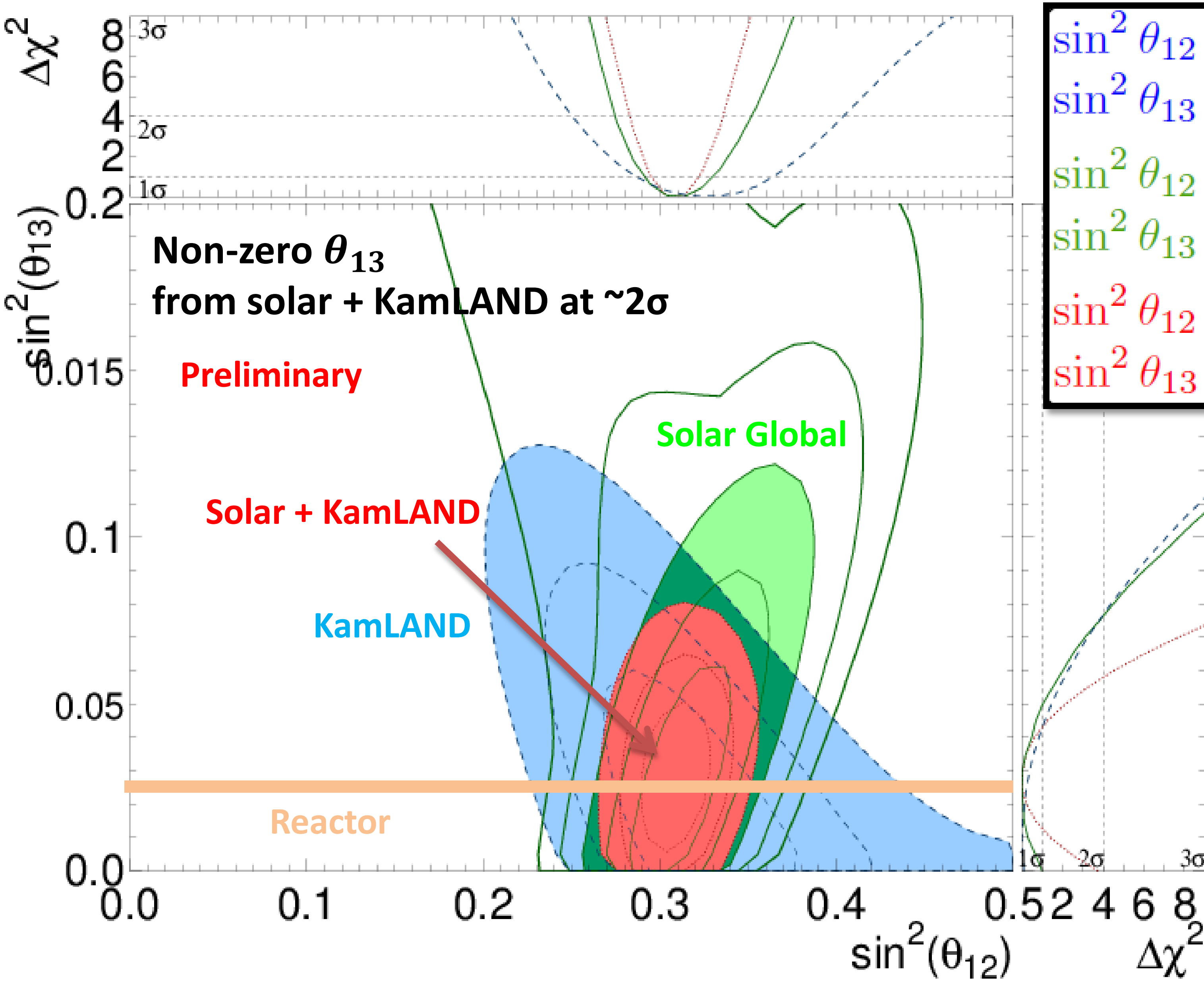
Oscillation analysis (1)



$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$$
$$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$$
$$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$$

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

Oscillation analysis (2)



$\sin^2\theta_{12} = 0.326^{+0.044}_{-0.037}$
$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$

$\sin^2\theta_{12} = 0.310^{+0.021}_{-0.017}$
$\sin^2\theta_{13} = 0.027^{+0.024}_{-0.028}$

$\sin^2\theta_{12} = 0.309^{+0.014}_{-0.013}$
$\sin^2\theta_{13} = 0.027^{+0.016}_{-0.014}$

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

Summary

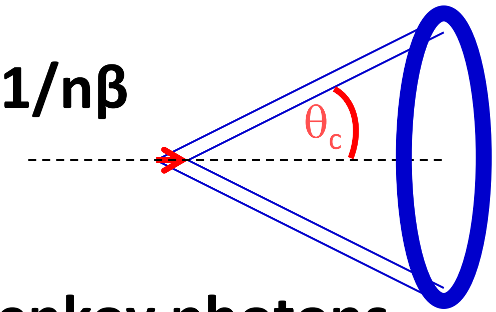
- **SK solar neutrino flux measurements agree across all phase.**
  - **No correlation with the solar activity cycle is seen.**
- **SK recoil electron energy spectrum slightly disfavors distortions.**
- **SK measures the solar neutrino day-night asymmetry.**
  - **First indication (2.8-3.0σ) of terrestrial matter effect on ^{8}B solar neutrino oscillation.**
- **Solar global + KamLAND analysis gives:**
  - $\Delta m_{21}{}^2 = 7.50^{+0.19}_{-0.18} \times 10^{-5}$ **eV^2 ,**
  - $\sin^2\theta_{12} = 0.308 \pm 0.013$ **,**
  - $\sin^2\theta_{13} = 0.027^{+0.016}_{-0.014}$ **.**

Back up

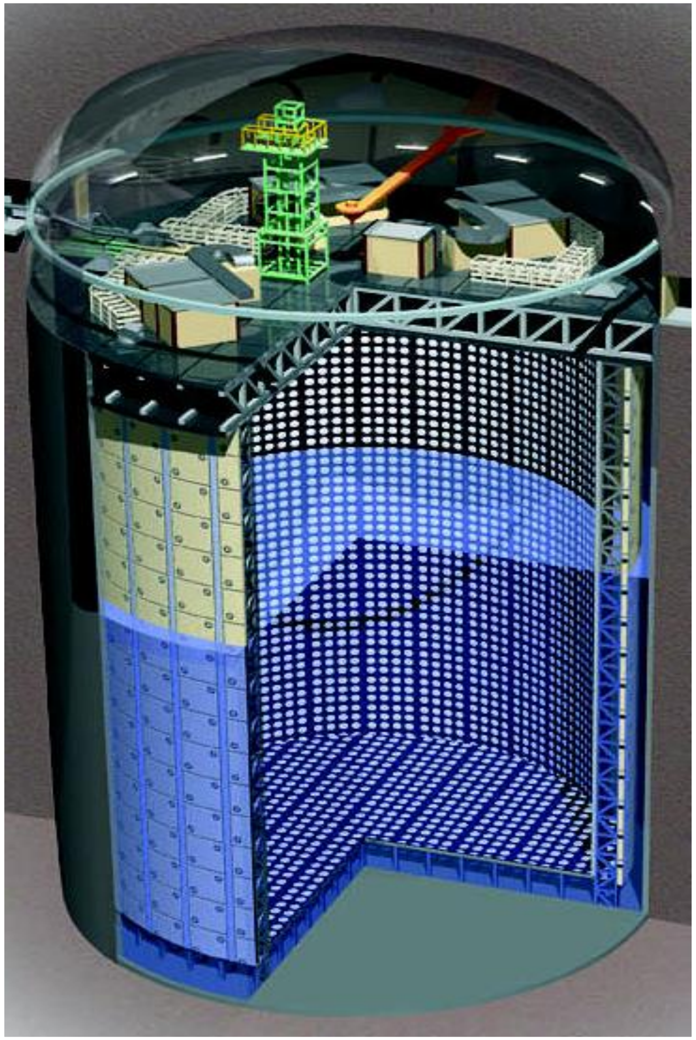
Detection method

◆Cherenkov light

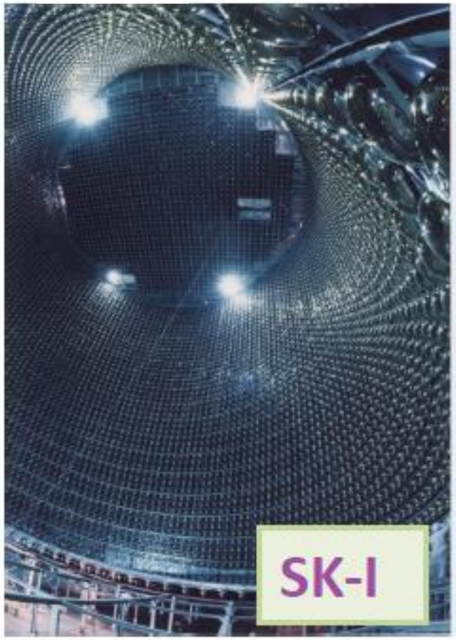
- Emission if $n \times \beta > 1$
  n : refractive index (water ~ 1.33)
  β : p/E
- Direction : $\cos\Theta = 1/n\beta$
  $\Theta \sim 42^\circ$

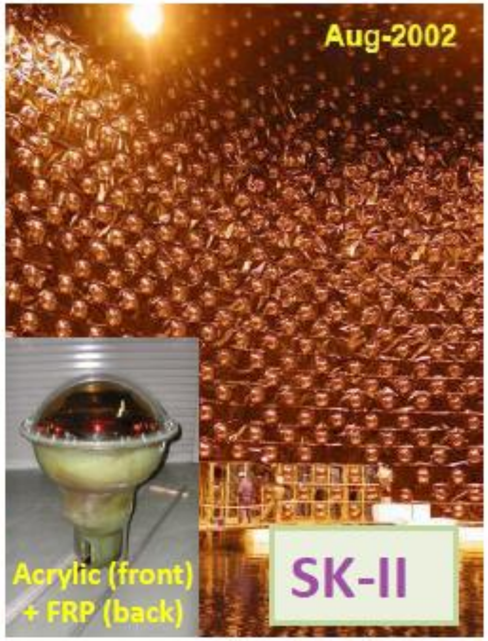


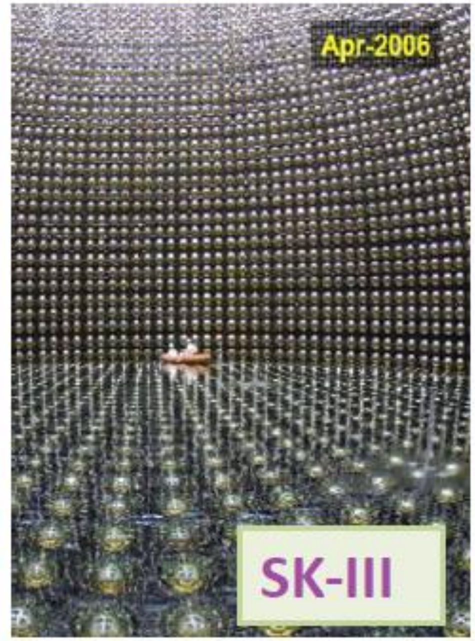
- \# of emitted Cherenkov photons
  ~ 340 photons/1cm



History of Super Kamiokande







1996/4 ~2001/7	2002/10 ~2005/10	2006/7 ~2008/8	2008/9 ~ Running
	(※)With Acrylic + FRP	(※)Recovered	(※)New electronics

◆PMT(ID)

11146 PMTs	5182 PMTs	11129 PMTs	11129 PMTs
40% photo coverage	19% photo coverage	40% photo coverage	40% photo coverage

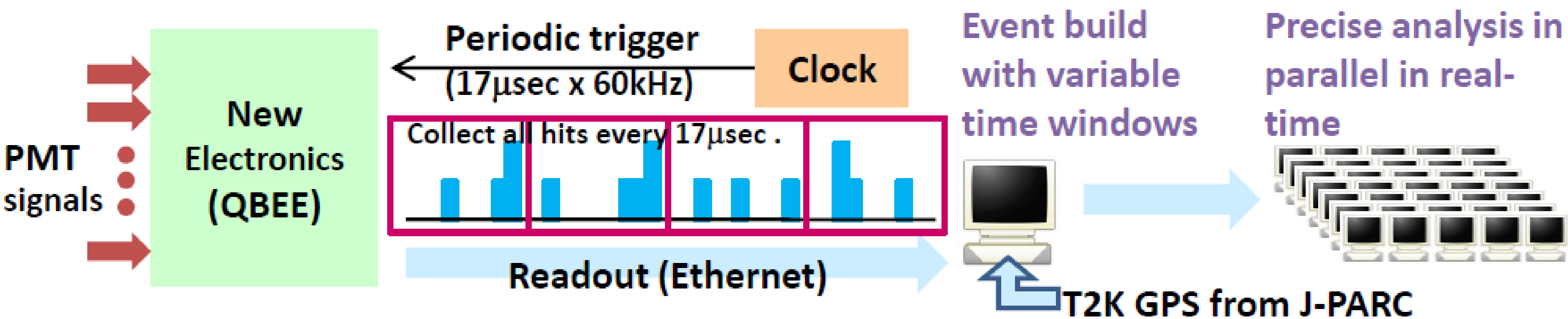
◆Kinetic Energy threshold

			Current	Target
4.5 MeV	6.5 MeV	4.0 MeV	3.5 MeV	More lower

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

Typical low energy event in SK

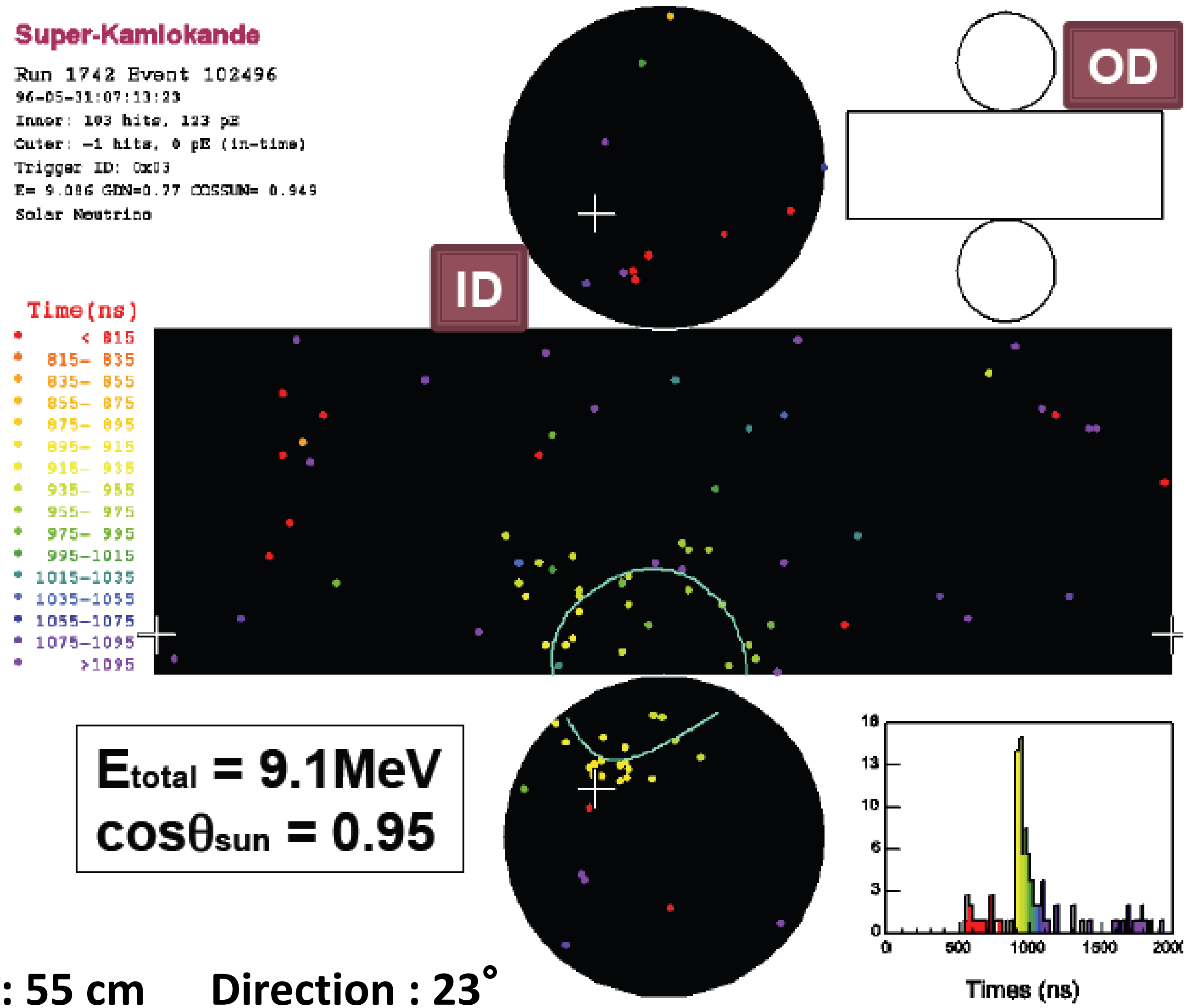
◆How to detect

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)

The Sun

◆The Sun

The Sun is a main-sequence star at the stage of stable hydrogen burning. It produces an intense flux of electron neutrinos as a consequence of the nuclear fusion reactions.

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

Property	Values
Luminosity	3.86×10^{33} erg/s
Radius	6.96×10^{10} cm
Thickness of the convective zone	~ 1.8×10^{10} cm
Age	~ 4.5×10^{9} years
Surface temperature	~ 5.58×10^{3} K
Core temperature	~ 1.56×10^{7} K
Core density	~ 148 g/cm^3

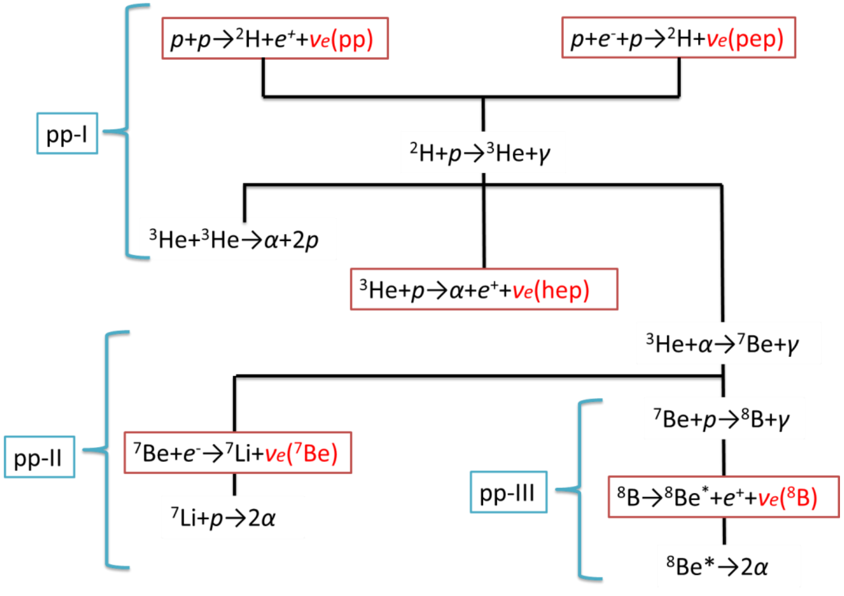
Solar neutrino

◆Solar neutrino

- Electron type neutrino emitted from the core of the Sun.

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

- These neutrinos carry away about 2-3% of the total energy emitted by the Sun.
- From the observed solar luminosity, the solar flux of neutrinos is about **6.0×10^{10} cm^{-2}s^{-1}** on the Earth.

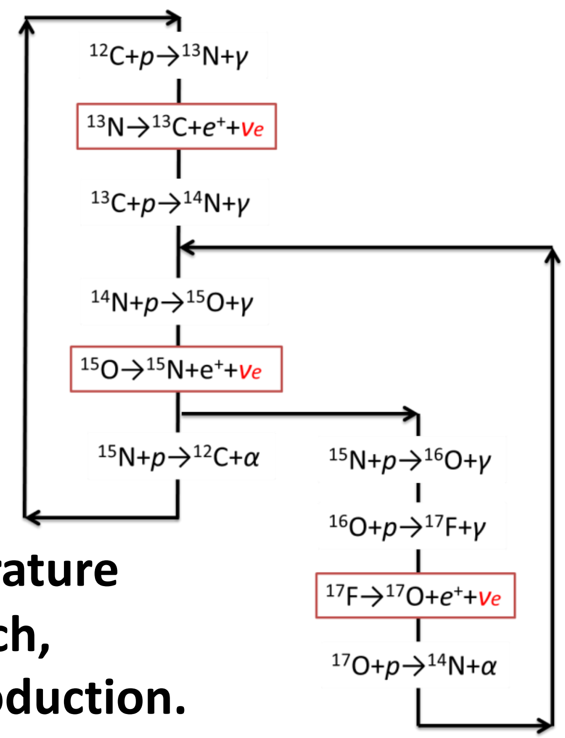


◆pp chain

The main process responsible for the helium production.
→detail is next page.

◆CNO cycle

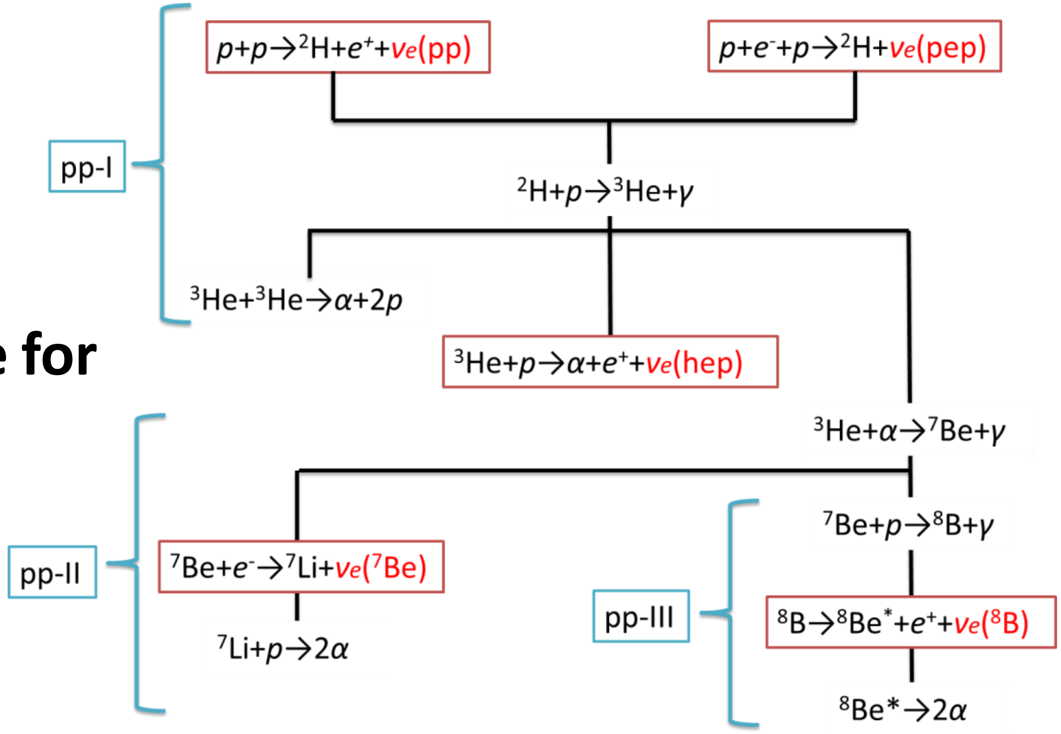
This cycle dominates over the pp chain only if the temperature exceeds 1.8×10^{7} K. For the Sun, this condition is not much, therefore this cycle contributes only **1.5%** to neutrino production.



pp chain

◆pp chain

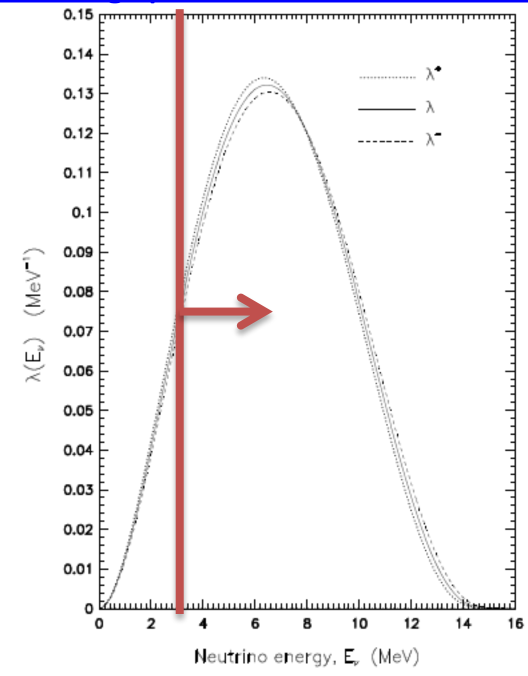
The main process responsible for the helium production.
5 kind of solar neutrinos are produced via this chain.



Type	Contribution	Reaction	Energy[MeV]
pp	86%(pp+pep)	$p+p\rightarrow {}^2\mathrm{H}+e^++\nu_e$	≤ 0.42
pep		$p+e^-+p\rightarrow {}^2\mathrm{H}+\nu_e$	1.44
hep	10^{-7}	${}^3\mathrm{He}+p\rightarrow {}^4\mathrm{He}+e^++\nu_e$	≤ 18.77
^{7}Be	14%	${}^7\mathrm{Be}+e^-\rightarrow {}^7\mathrm{Li}+\nu_e$	0.861
^{8}B	10^{-4}	${}^8\mathrm{B}\rightarrow {}^8\mathrm{Be}^*+e^++\nu_e$	≤ 14.06

^{8}B solar neutrino

http://arxiv.org/pdf/nucl-th/9601044.pdf



◆^{8}B neutrino

This neutrino is emitted through ^{8}B decay.

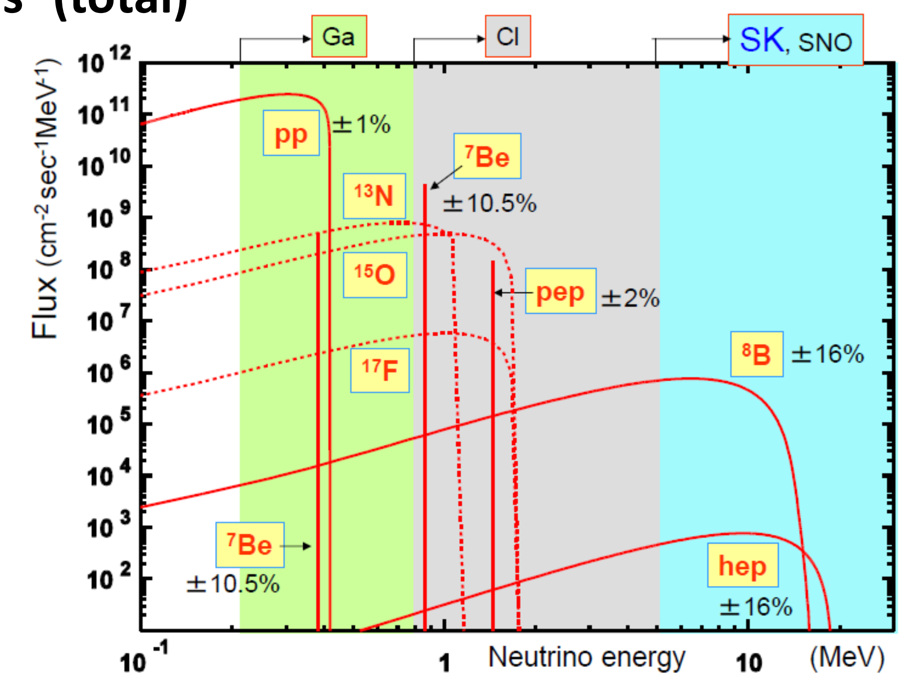
$$^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e (\leq 14.06\mathrm{MeV})$$

This neutrino carries away higher energy.
→ can detect with SK

But, the contribution for the flux is low(10^{-4}).
→ 5.79×10^6 cm^{-2}s^{-1} (SSM) / 6.0×10^{10} cm^{-2}s^{-1}(total)
→ need to prepare big scale detectors

◆Neutrino Energy Spectrum

Energy spectrum of each solar neutrino branches are shown →
(values mean theoretical uncertainty)



Global oscillation analysis input

◆SK

- SK-I 1496days, Spectrum : 4.5-19.5MeV(kin.) + D/N : $E_{kin} \geqq 4.5$MeV
- SK-II 791days, Spectrum : 6.5-19.5MeV(kin.) + D/N : $E_{kin} \geqq 7.0$MeV
- SK-III 548days, Spectrum : 4.0-19.5MeV(kin.) + D/N : $E_{kin} \geqq 4.5$MeV
- SK-IV 1669days, Spectrum : 3.5-19.5MeV(kin.) + D/N : $E_{kin} \geqq 4.5$MeV

◆SNO

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

◆Radiochemical (Cl, Ga)

- Ga rate 66.1±3.1 SNU (All Ga global) (PRC80, 015807(2009))
- Cl rate 2.56±0.23 (Astrophys.J. 496(1988) 505)

◆Borexino

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

Does NOT include Borexino pp 2014

◆KamLAND reactor

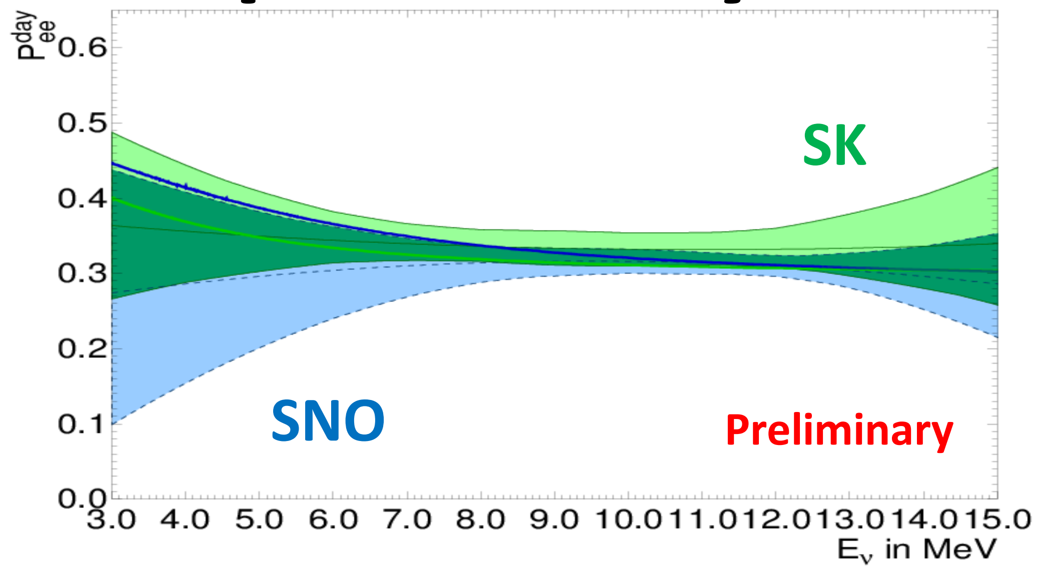
- Latest(3-flavor) analysis -> PRD88, 3, 033001 (2013)

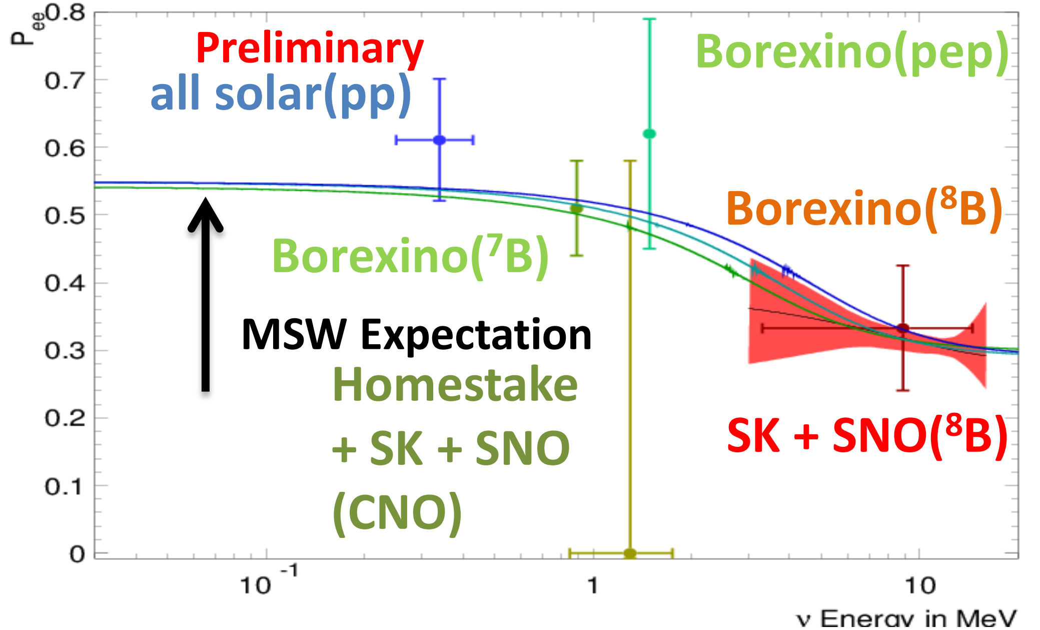
◆^{8}B spectrum

- Winter 2006 → PRC73, 73, 025503 (2006)

Allowed survival probability

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





Searching for the Day/Night effect

$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{\rm bins}} \prod_{\nu=1}^{n_i} \left(\beta_i(c_\nu) B_i + \sigma_i(c_\nu) m_i S\right)$$

$N_{\rm bin} = 23$ **: 20 bins (0.5MeV from 3.5MeV), 2 bins (1MeV) and 1bin (4MeV)**

B_i **: # of background events, energy bins i**

S **: # of signal events**

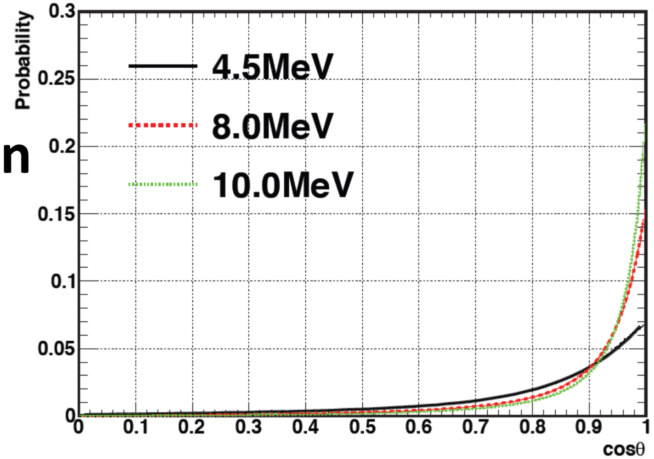
$c_\nu = \cos\theta_{\nu,{\rm Sun}}$ **: angle from solar direction**

$\beta_i(c_\nu)$ **: background shapes**

$\sigma_i(c_\nu)$ **: signal shapes (solar peak)**

$m_i = \frac{{\rm MC}_i}{\sum_k {\rm MC}_k}$ **: MC ratio of energy bin i**

$\sigma_i(c_\nu)$



$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{\rm bins}} \prod_{\nu=1}^{n_i} \left(\beta_i(c_\nu) B_i + \sigma_i(c_\nu) z_i(t_\nu) m_i S\right)$$

$z_i(t_\nu)$ **: New signal factor can include any time variable, such as zenith angle (day/night effect),distance(eccentricity, seasonal), etc.**

Searching for the Day/Night effect(2)

$$\mathcal{L} = e^{-(\sum_i B_i + S)} \prod_{i=1}^{N_{\text{bins}}} \prod_{\nu=1}^{n_i} (\beta_i(c_\nu) B_i + \sigma_i(c_\nu) z_i(t_\nu) m_i S)$$

$$z_i(t_\nu) \to z_i(\alpha, t) = \frac{1 + \alpha((1 + a_i) r_i(t)/r_i^{\text{ave}} - 1)}{1 + \alpha a_i} \times z_{\text{exp}}(t)$$

α : Day/Night scaling parameter

a_i : Effective Day/Night asymmetry

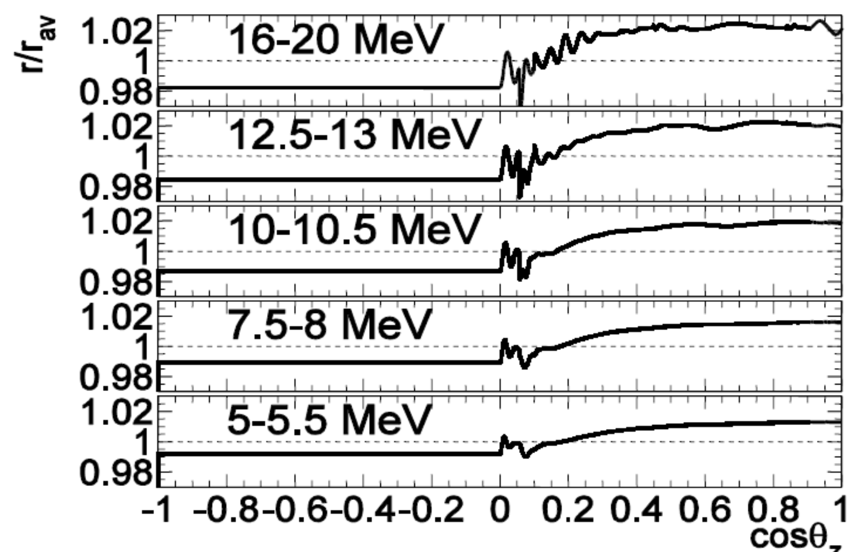
$r_i(t)$: rate in zenith bin of event(MC)

r_i^{ave} : livetime averaged rate

$$A_{\text{DN}} = \frac{r_i^{\text{day}} - r_i^{\text{night}}}{(r_i^{\text{day}} - r_i^{\text{night}})/2} = \alpha \times A_{\text{DN},i}$$

$z_{\text{exp}}(t)$

: take into account eccentricity corrections and the Day/Night MC efficiency difference, does not depends on α

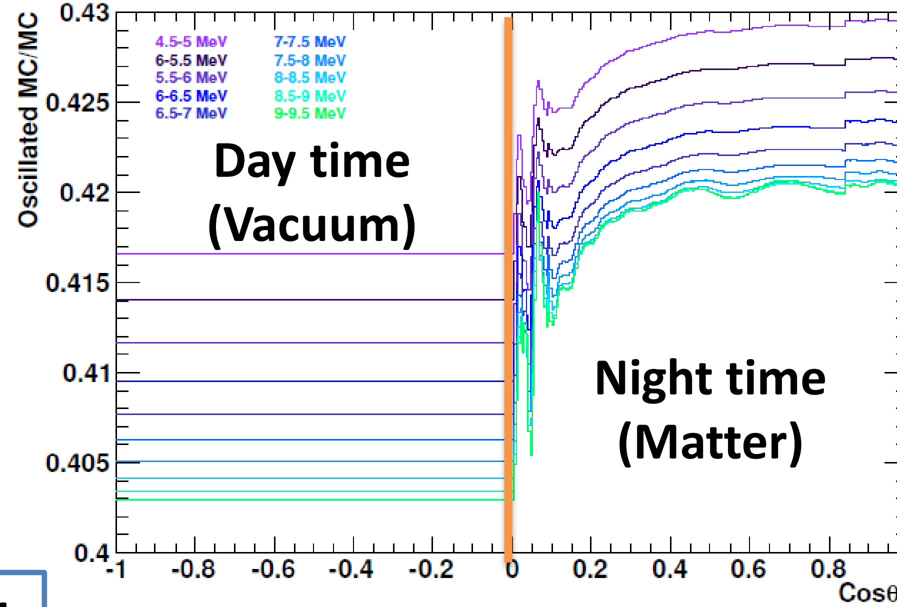


Day/Night Asymmetry

◆Day/Night Asymmetry

Compare ^{8}B solar neutrino flux(Ψ) during day/night time.

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



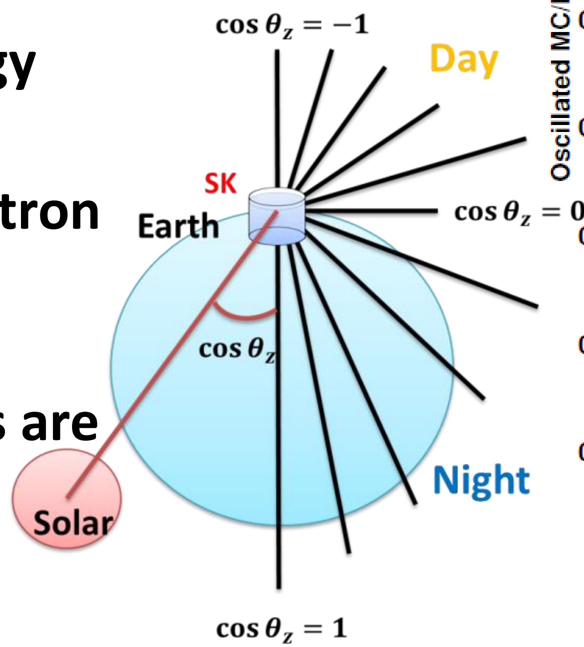
◆Neutrino oscillation due to matter effect

A_{DN} depends on

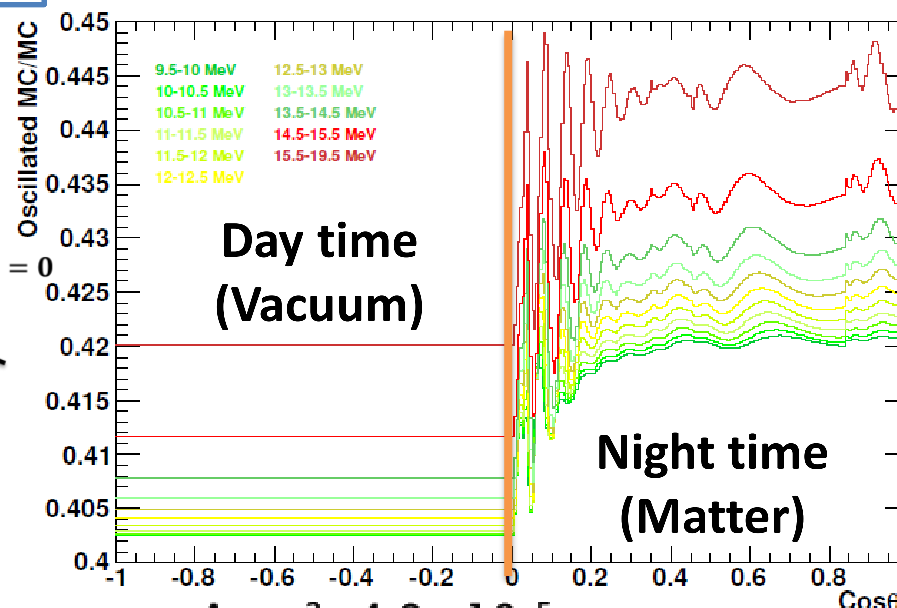
(1)Neutrino energy

(2)Mass $\Delta m_{21}{}^{2}$

(3)Density of electron in the Earth



These parameters are considered in our analysis.

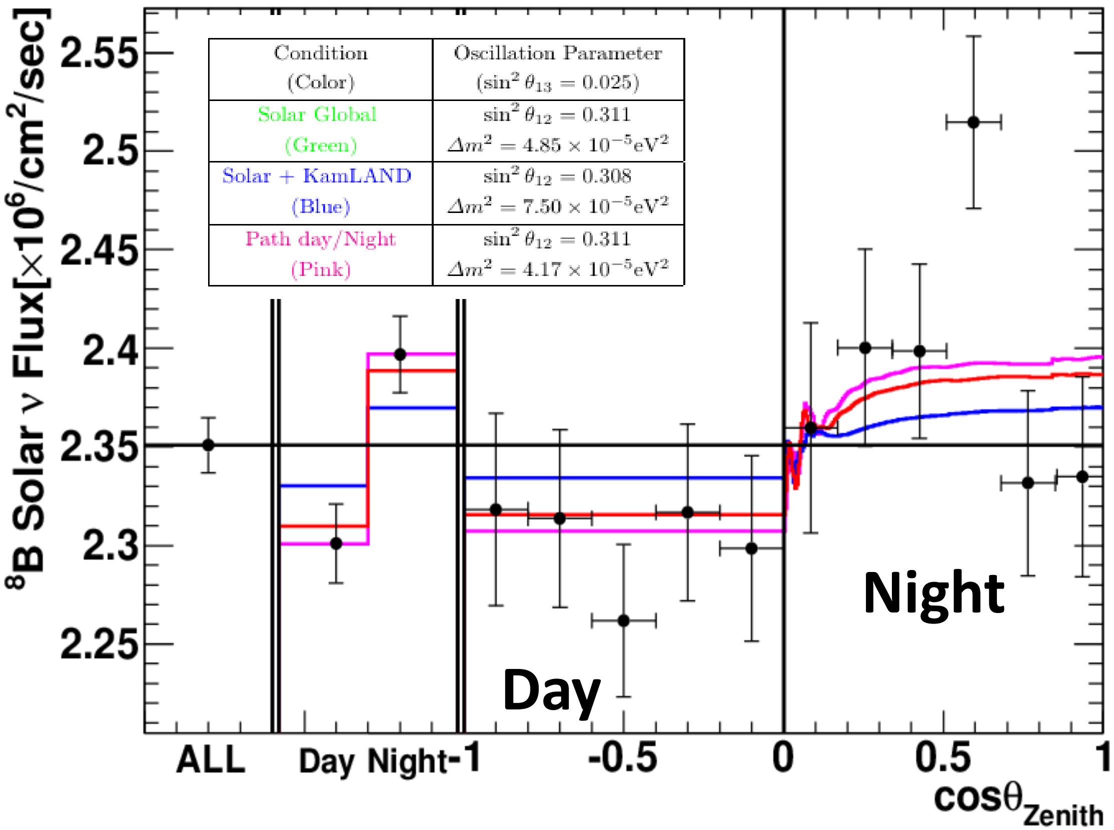


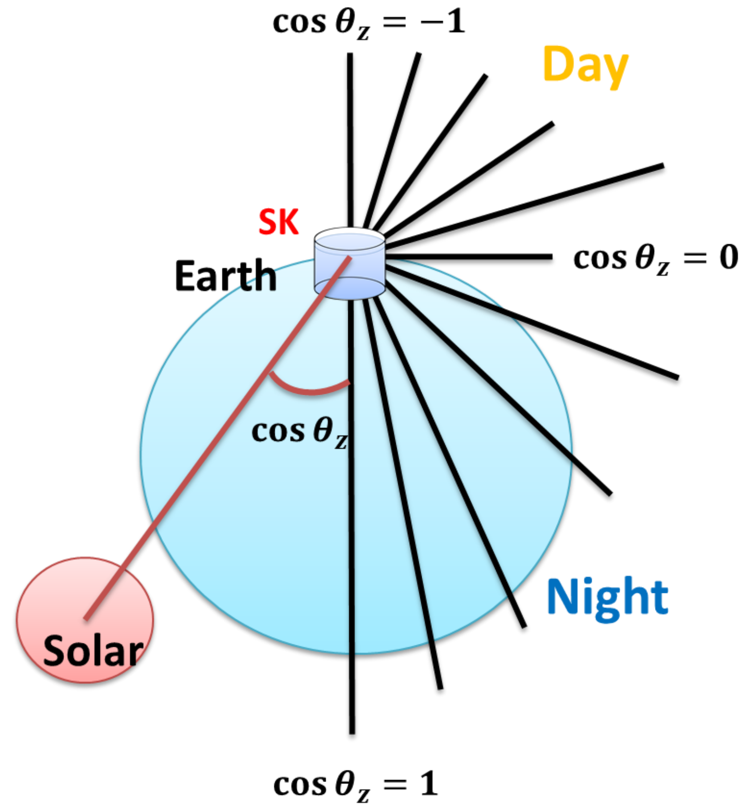
$\Delta m_{21}{}^{2}=4.9 \times 10^{-5}$
$\sin^{2}\theta_{12}=0.314$

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.





SK - I,II,III,IV combined

ADN systematics

- Large reduction in energy scale error from SK-I to SK-III comes from introduction of z-dependence water transparency parameter into MC.
- External event cut had a negligible affect in SK-I and SK-II because no tight fiducial volume cut was applied.
- Total errors among SK phases are considered uncorrelated

	SK-I	SK-II	SK-III	SK-IV
Energy scale	0.8%	0.8%	0.2%	0.05%
Energy resolution	0.05%	0.05%	0.05%	0.05%
Background shape	0.6%	0.6%	0.6%	0.6%
External event cut	-	-	0.2%	0.1%
Earth model	0.01%	0.01%	0.01%	0.01%
Total	1.0%	1.0%	0.7%	0.6%