Recent Solar neutrino Results from Super-Kamiokande

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for the Super-Kamiokande collaboration

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科研費 KAKENHI

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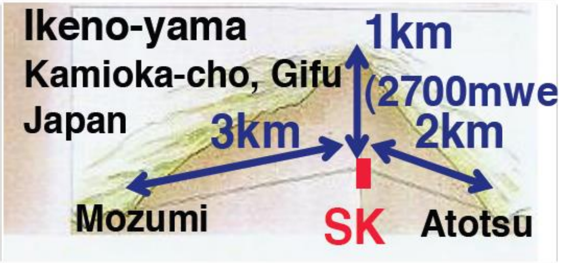
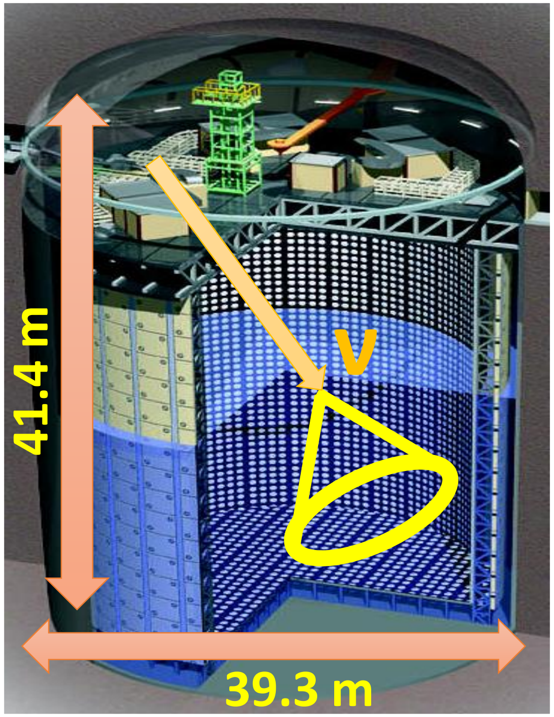
Contents

Super-Kamiokande

- **Super-Kamiokande detector**
  - **Located at Kamioka, Japan**
    - **1000 m under Ikenoyama mountain**
    - **2700 m water equivalent**
  - **50 kton ultra pure water tank**
    - **More than 11,000 20-inch PMTs for ID**
    - **22.5 kton for the fiducial volume**
  - **Water Cherenkov technique**
    - **Energy, direction, particle ID**
- **Many physics targets**
  - **Astrophysical neutrino (Solar, Supernova)**
  - **Atmospheric neutrino**
  - **Proton decay**
  - **Long base line neutrino (T2K)**
  - **Dark matter search etc…**

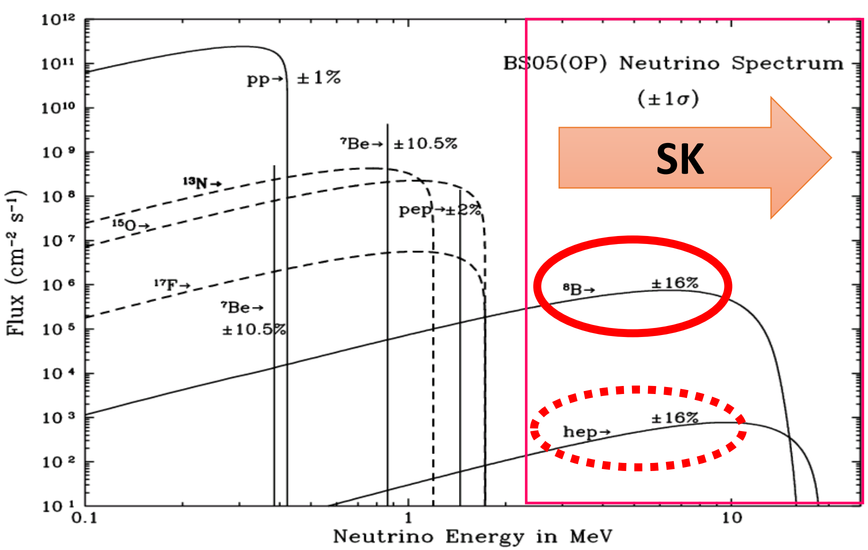


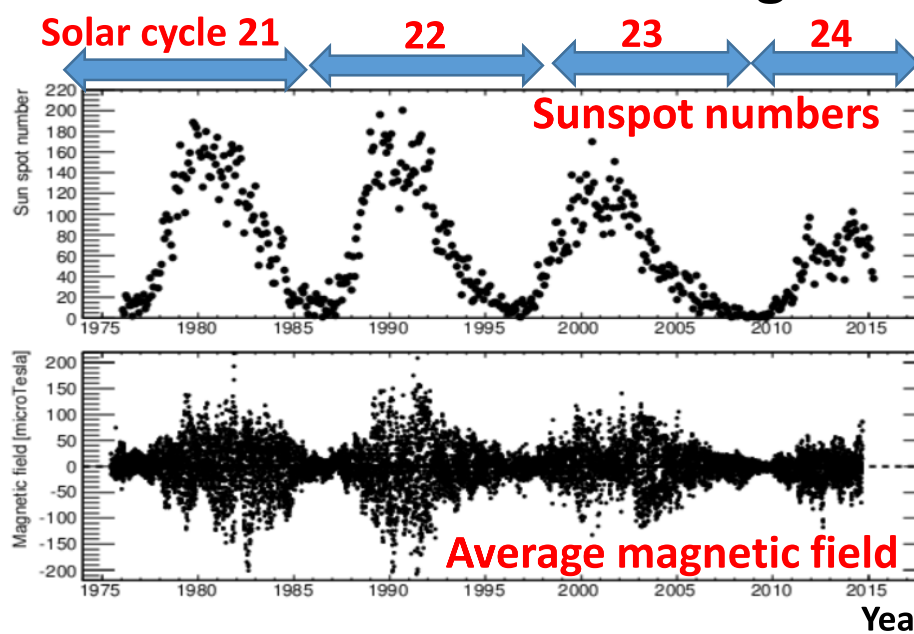


Solar ν 3.5-19.5 MeV	Supernova ν 20~100.0 MeV	Atmospheric ν and proton decay ~100 MeV GeV TeV PeV

Physics motivation (1)

- **Standard Solar Model (SSM) describes the profile of the Sun well.**
  - **SSM predicts the solar neutrino fluxes.**
  - **Super-K has observed ^{8}B neutrino because of its high energies (<~14 MeV).**
- **Several periodical solar activities are observed.**
  - **Variation of the sunspot number at the surface (~11 years).**
  - **The Sun itself oscillates due to the acoustic waves (~5 minutes).**
- **Searching for the periodic modulation of ν fluxes is interesting.**



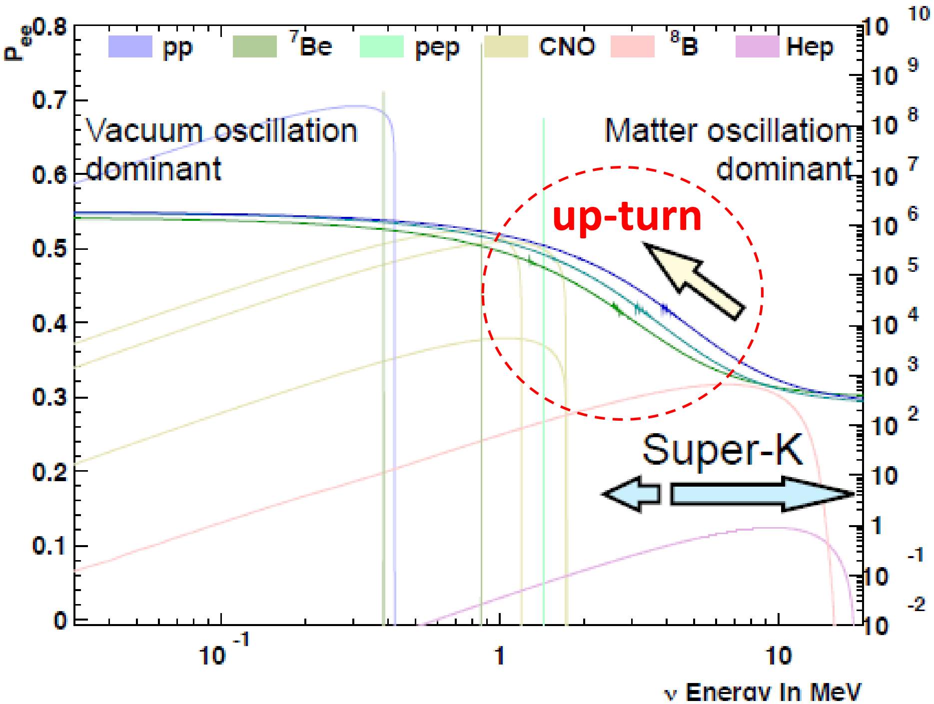


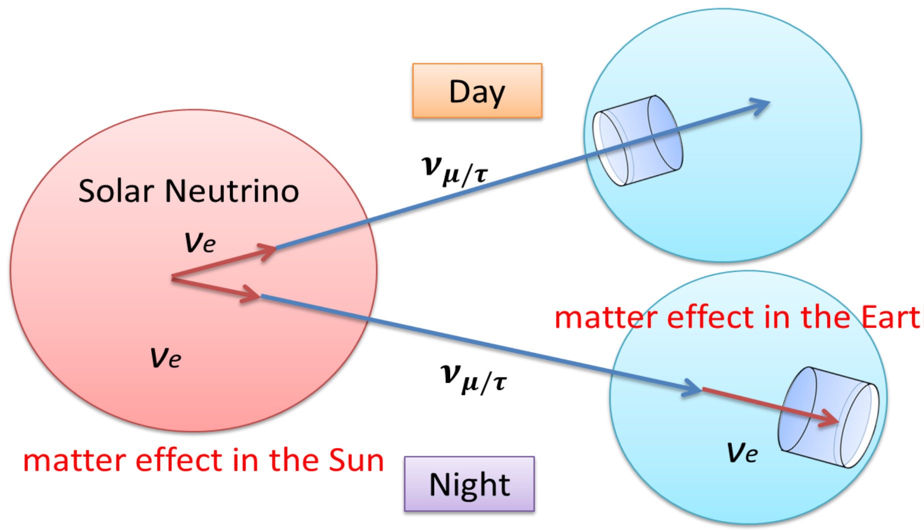
Left figure: Astrophys. J. 621 85 (2005).
Sunspot number is taken from http://solarscience.msfc.nasa.gov/greenwch/spot num.txt
Average magnetic field is taken from: http://wso.stanford.edu/meand/MF_timeseries.txt

Physics motivation (2)

- **Neutrino oscillation due to the matter effect (MSW effect)**
  - **Spectrum "up-turn" expected by MSW effect in the Sun.**
    → MSW effect leads to a resonant conversion of the higher energy ν.
  - **Day/Night flux asymmetry due to terrestrial matter effect.**
    → Regeneration of electron-ν is expected when ν pass through the Earth.

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



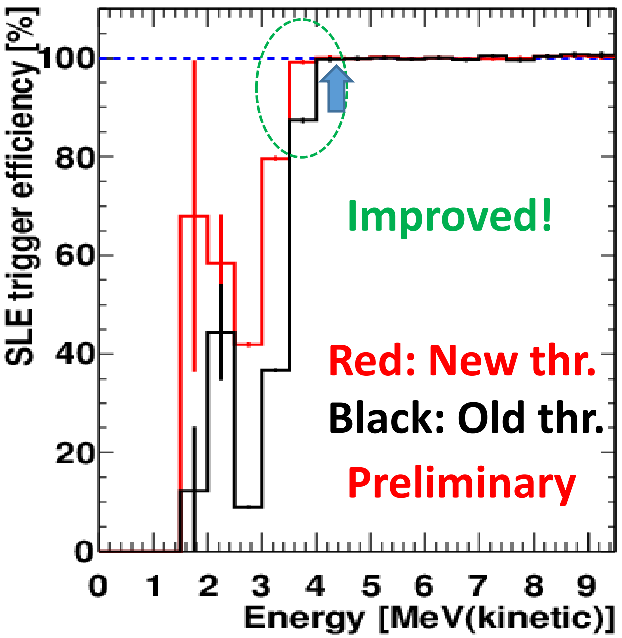


$$A_{DN} = \frac{\Psi_{day} - \Psi_{night}}{(\Psi_{day} + \Psi_{night})/2}$$

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

Solar neutrino analysis in Super-K

- **Last year, we submitted a paper about the solar neutrino analysis results (using SK-IV 1664 days data sample).**
  - **Phys. Rev. D 94, 052010 (2016), arXiv: 1606.07538**
- **Updated results are presented.**
  - **^{8}B solar neutrino flux with SK-IV 2365 days sample (5200 days).**
  - **Energy spectrum with SK-IV 2645 days sample (5480 days).**
- **Recent progress of solar analysis.**
  - **Yearly ^{8}B flux plot to see any correlation with solar activity.**
  - **Periodic modulation of solar ν flux.**
  - **Lower trigger threshold in May 2015.**
    - **Detection efficiency in 3.5-4.0 MeVkin. ~84%→ ~99%.**



Observed ^8B solar neutrino signal

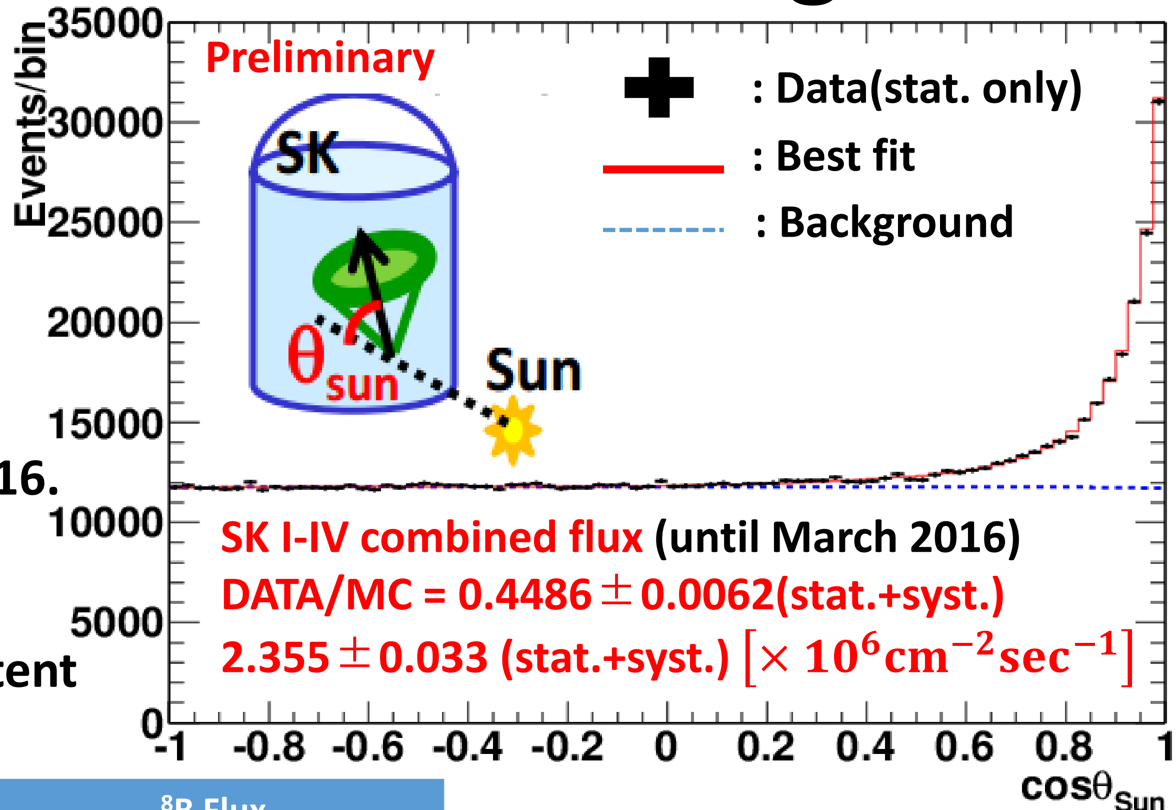
◆^8B neutrino measurement

Cherenkov light generated by recoil electron scattered with ν.

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

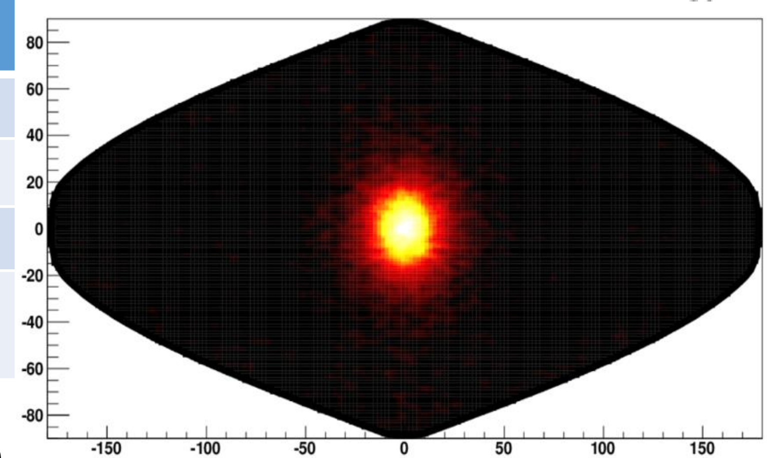
A total of **84k** solar neutrinos were observed until March 2016. (89k events until March 2017)

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 2645	$2.32 \pm 0.02 \pm 0.04$ Under preparation

MC: 5.25×10^6/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 ~20 years (More than 1.5 cycle).
Data taken until March 2016 is used.

◆^{8}B flux vs. sun spot

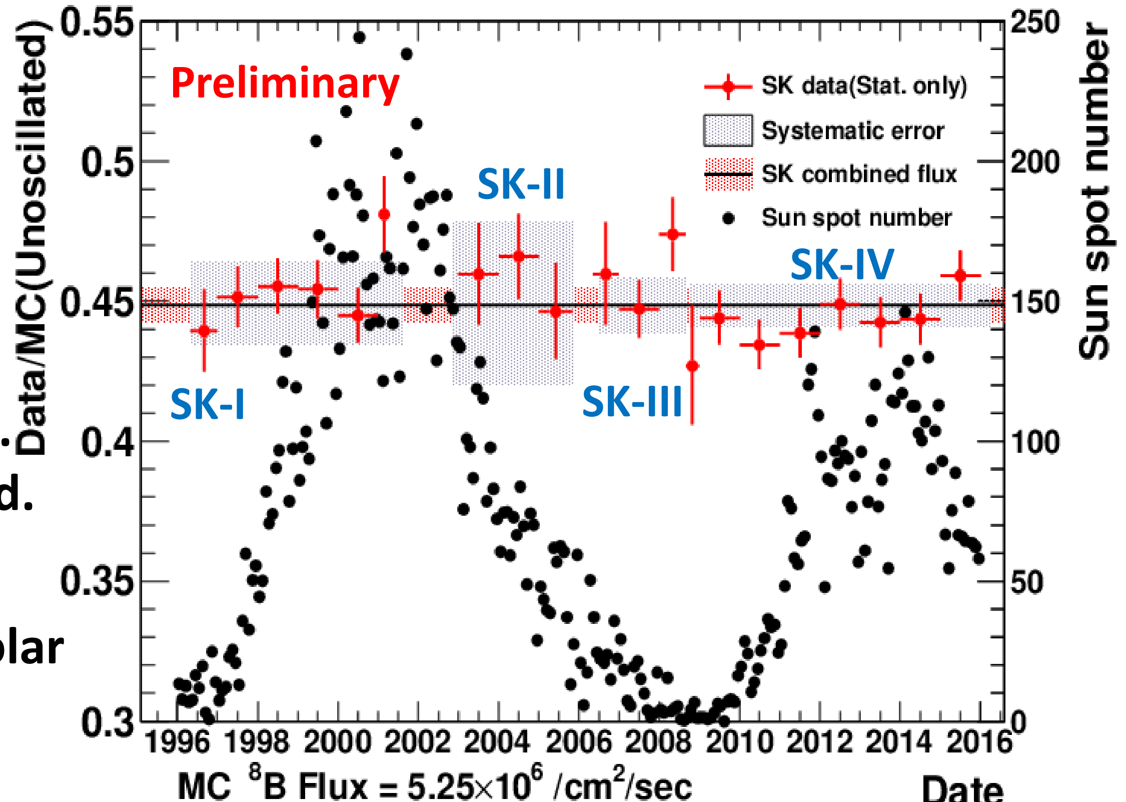
No correlation with the 11 years solar activity is observed.

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

Preliminary

Prob. = 68.9 %

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



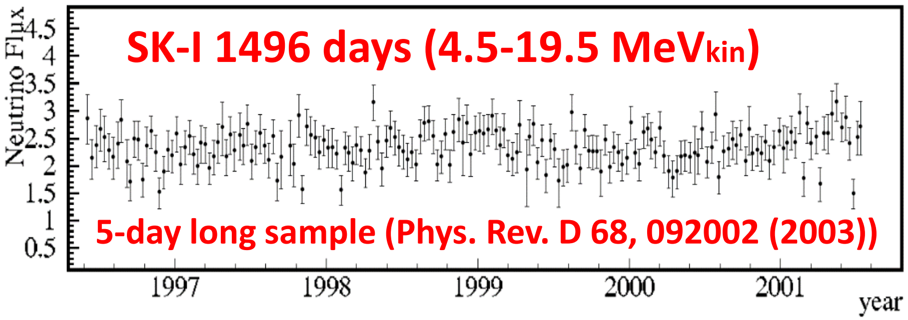
SNO: NC current, Phys. Rev. C88 (2013) 025501.

SK I-IV combined flux (until March 2016)
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.

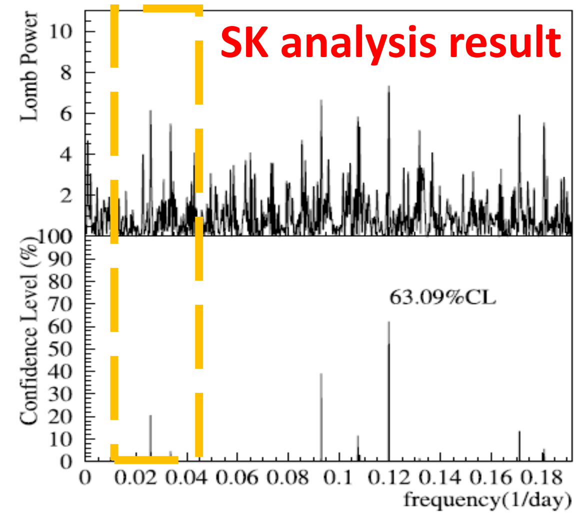
Periodic modulation analysis

- **SK collaboration reported the time variation of 5-day long sample of the observed ^{8}B ν flux (Phys. Rev. D 68, 092002 (2003)).**
- **SK performed a periodic analysis using Lomb-Scargle (LS) method.**



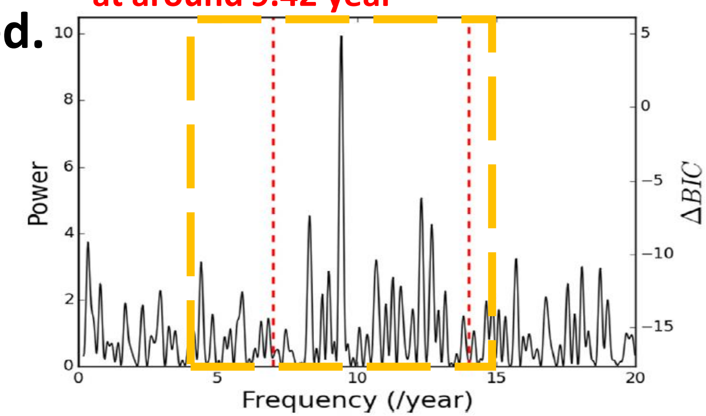
LS method

No clear periodic signal 5-15 $year^{-1}$.



- **Several papers reported that a maximum peak is observed at around 9.42 $year^{-1}$.**
  - **Cf.) Astropart. Phys. 82, 86-92 (2016).**
  - **Generalized Lomb-Scargle (GLS) method is used.**

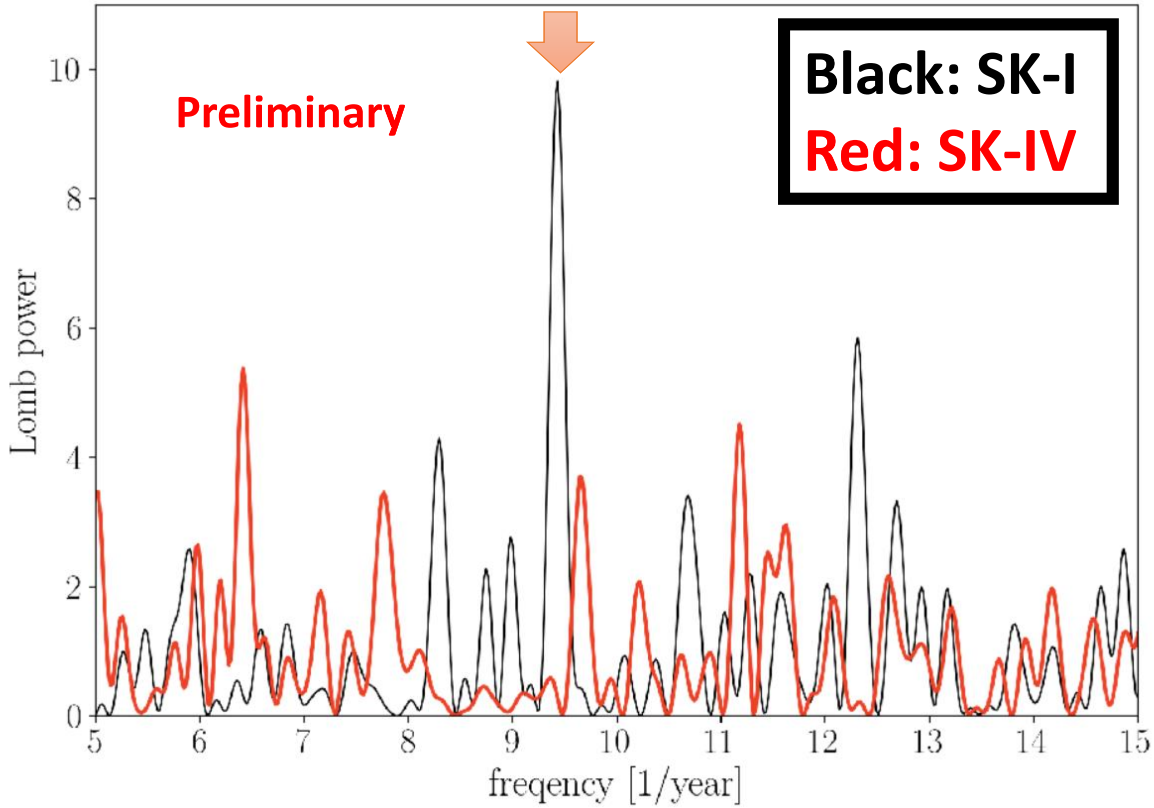
Several researchers found a peak at around 9.42 $year^{-1}$



- **SK has reanalyzed SK-I data with GLS method provided by astroML.**
- **SK-IV data is also analyzed with GLS.**

Periodic modulation results

- **Using the Generalized LS method, both SK-I and SK-IV are analyzed.**
- **5-day long sample is made from SK-I data and SK-IV data.**
  - **SK-I: 1496 days data (4.5-19.5 MeV_{kin}), Phys. Rev. D 68, 092002 (2003).**
  - **SK-IV: 1664 days data (4.5-19.5 MeV_{kin}), Phys. Rev. D 94, 052010 (2016).**
- **Search region 5-15 $year^{-1}$.**
- **Maximum peak at around 9.42 $year^{-1}$ is not found in SK-IV.**



Global oscillation analysis input

◆SK

- SK-I 1496 days, Spectrum : 4.5-19.5MeV(kin.) + D/N : Ekin≧4.5MeV
- SK-II 791 days, Spectrum : 6.5-19.5MeV(kin.) + D/N : Ekin≧7.0MeV
- SK-III 548 days, Spectrum : 4.0-19.5MeV(kin.) + D/N : Ekin≧4.5MeV
- SK-IV 2645 days, Spectrum : 3.5-19.5MeV(kin.) + D/N (1664 days) : Ekin≧4.5MeV

Spectrum (until March 2017): Updated from Phys. Rev. D 94, 052010 (2016).
Day/Night flux: 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

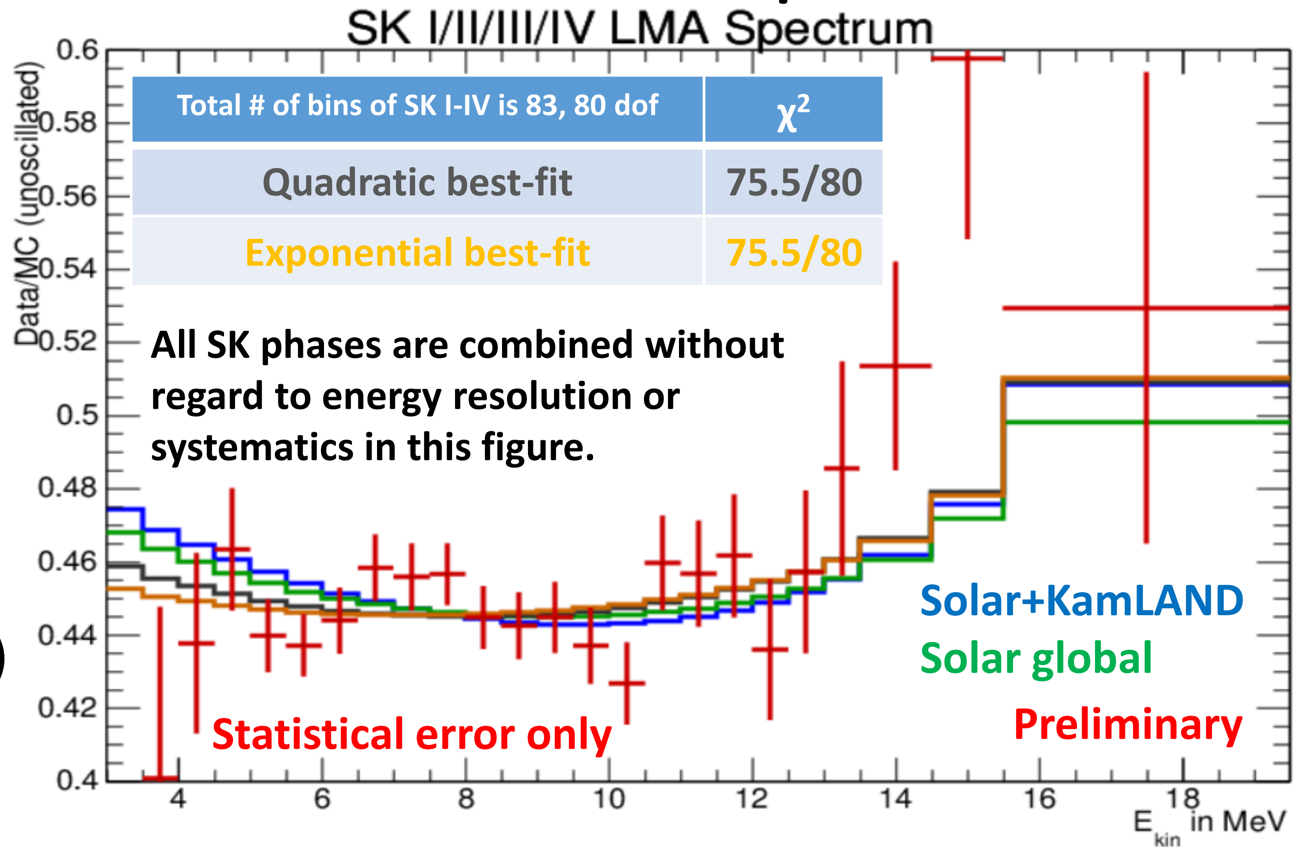
- Winter 2006, Phys. Rev. C73 (2006) 025503.

SK I-IV combined recoil electron spectrum

◆Spectrum shape

SK searches 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: 2645 days ($E \geq 3.5$)
Total: 5480 days sample



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

The SK recoil electron spectrum is consistent within ~1σ with the MSW up-turn for the solar global best fit parameters, and marginally consistent within ~2σ with the MSW up-turn for the solar+KamLAND best fit parameters.

Summary

- **Super-Kamiokande has taken solar neutrinos for more 20 years.**
- **Precise solar neutrino flux measurement is performed.**
  - **SK-IV result: 2.32 ± 0.02(stat.) ± 0.04(syst.) [$\times 10^6/cm^2/sec$].**
- **SK solar neutrino flux measurements agree across all phase.**
  - **Combined result: 2.355 ± 0.033 (stat.+syst.) [$\times 10^6/cm^2/sec$].**
  - **Fully consistent with a constant solar neutrino flux emitted by the Sun.**
  - **No correlation with the solar activity cycle is seen.**
- **Preliminary periodic modulation analysis is performed.**
  - **Maximum peak at around 9.43 $year^{-1}$ is not found in SK-IV.**
- **Recoil electron energy spectrum is consistent with the MSW up-turn.**
  - **~1σ for the solar global best-fit parameters**
  - **~2σ for the solar+KamLAND best-fit parameters.**

Back up

Typical low energy event in SK

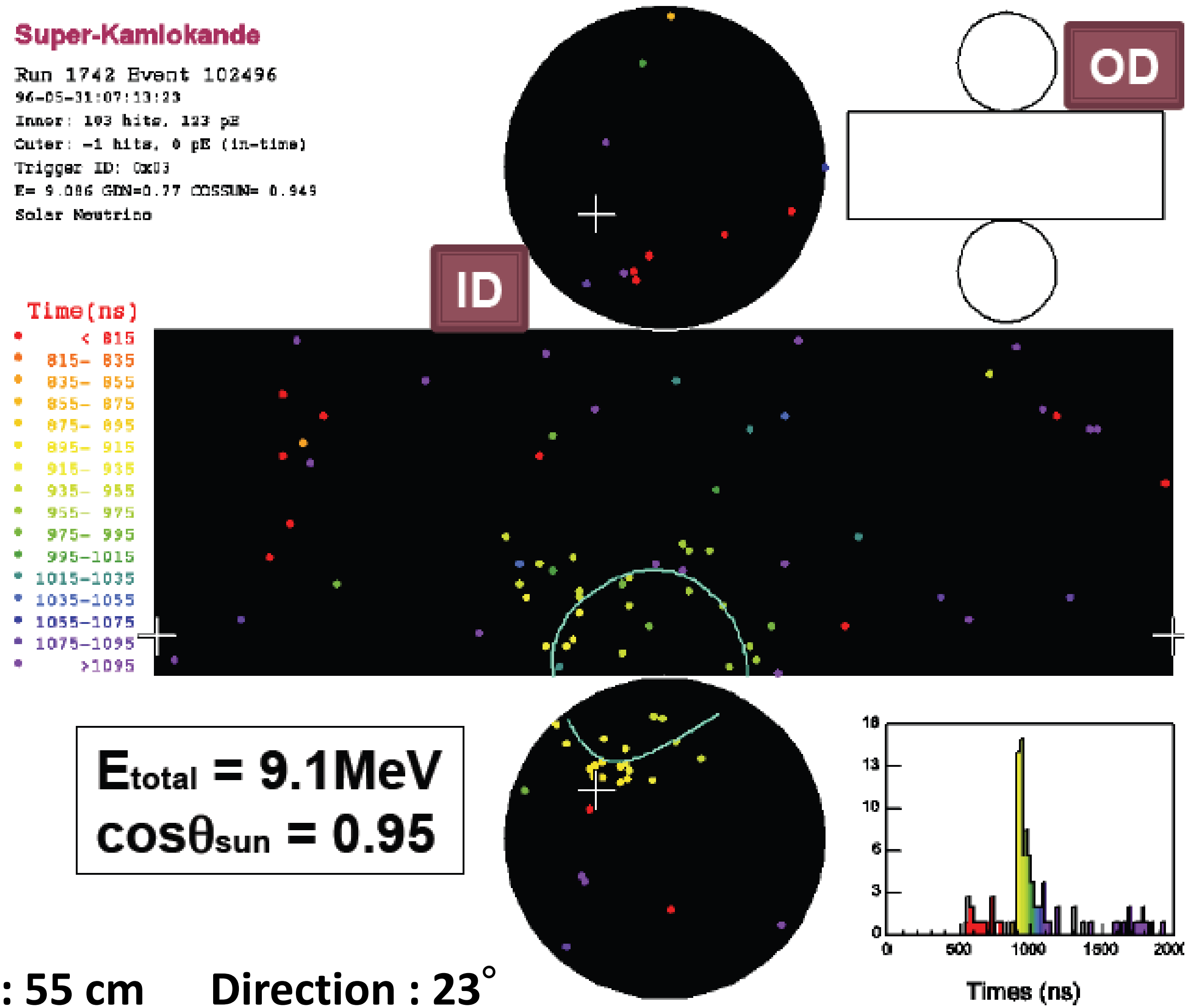
◆How to detect

Elastic scattering(ES) reaction is used for solar neutrinos

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

◆Reconstruction

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



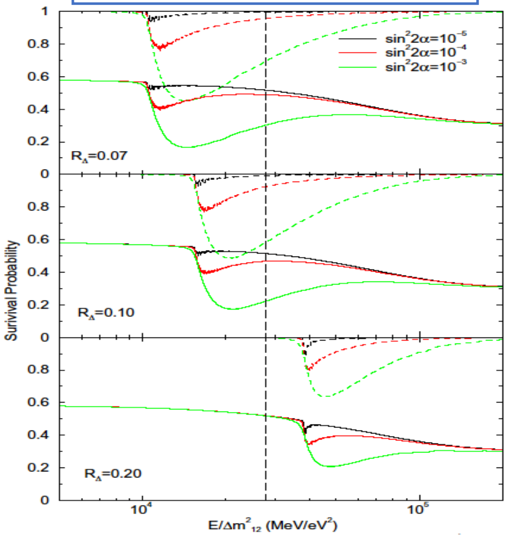
◆Resolutions

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

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

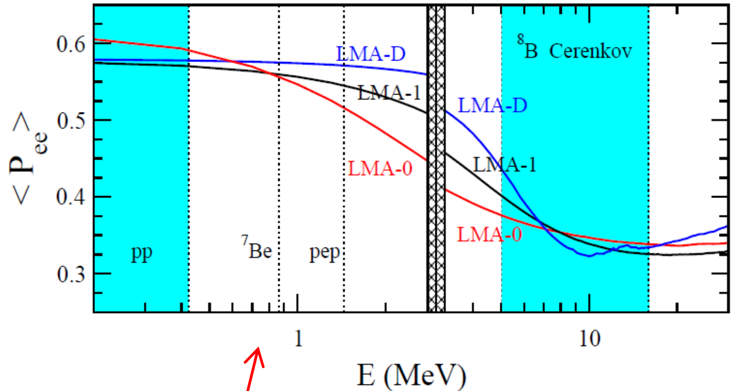
Non-standard models to predict flat spectrum

Sterile neutrino



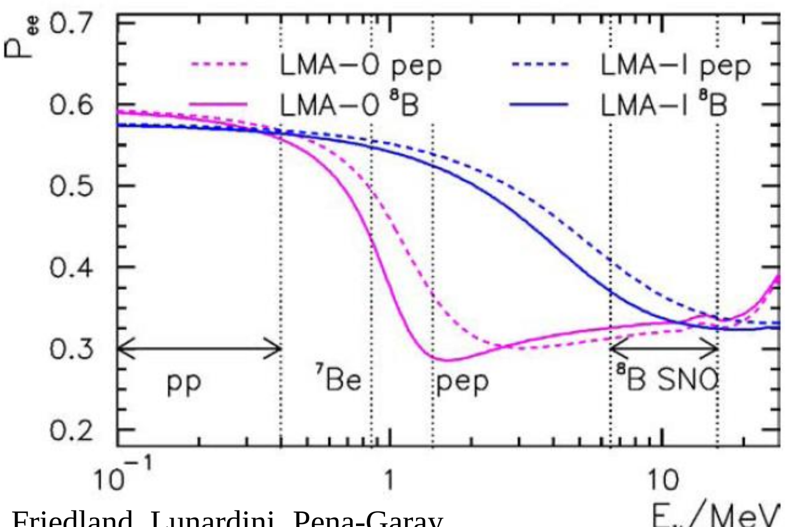
$$R_\Delta \equiv \frac{\Delta m^2_{01}}{\Delta m^2_{21}}$$

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



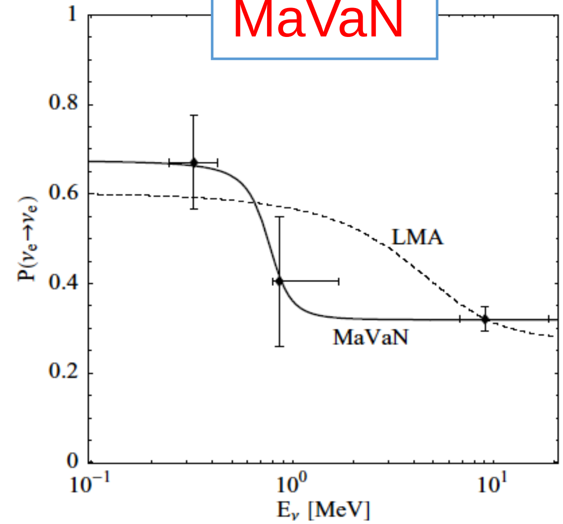
Miranda, Tortola and Valle, JHEP 0610:008,2006. (hep-ph/0406280)

Non standard Interaction

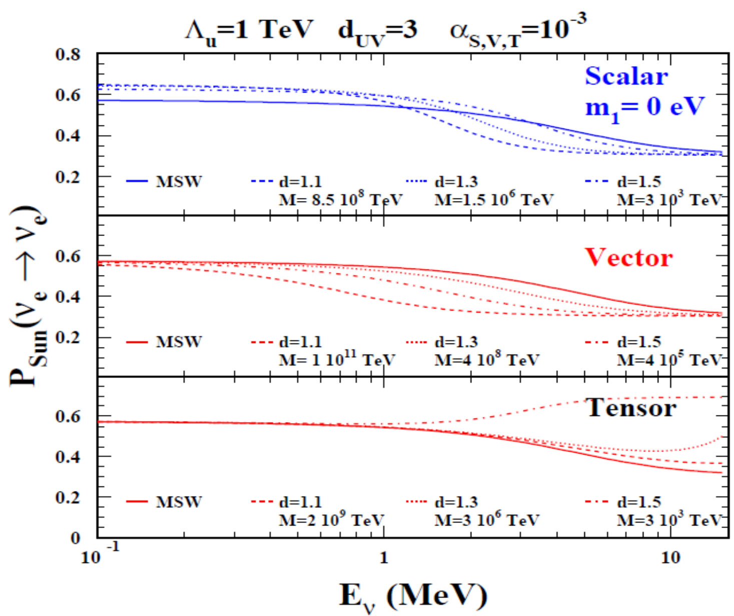


Friedland, Lunardini, Pena-Garay PLB594(2004)347(hep-ph/0402266)

MaVaN



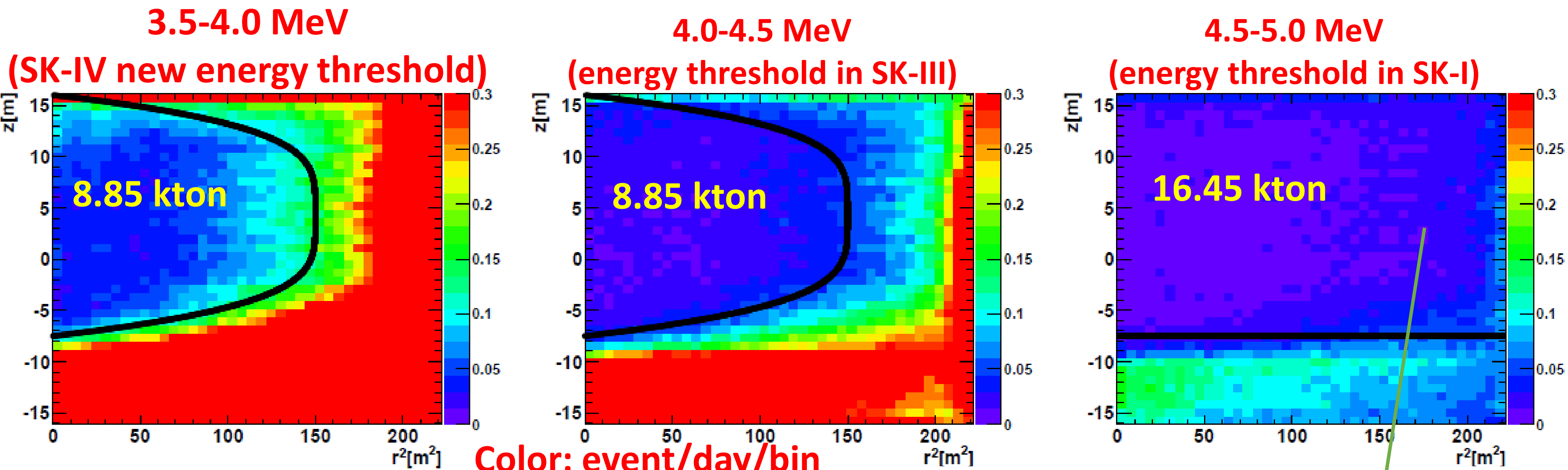
Barger, Huber and Marfatia, Phys.Rev.Lett.95:211802,2005 (hep-ph/0502196)



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

Unparticle

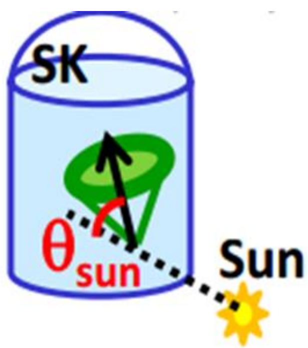
Tight Fiducial volume

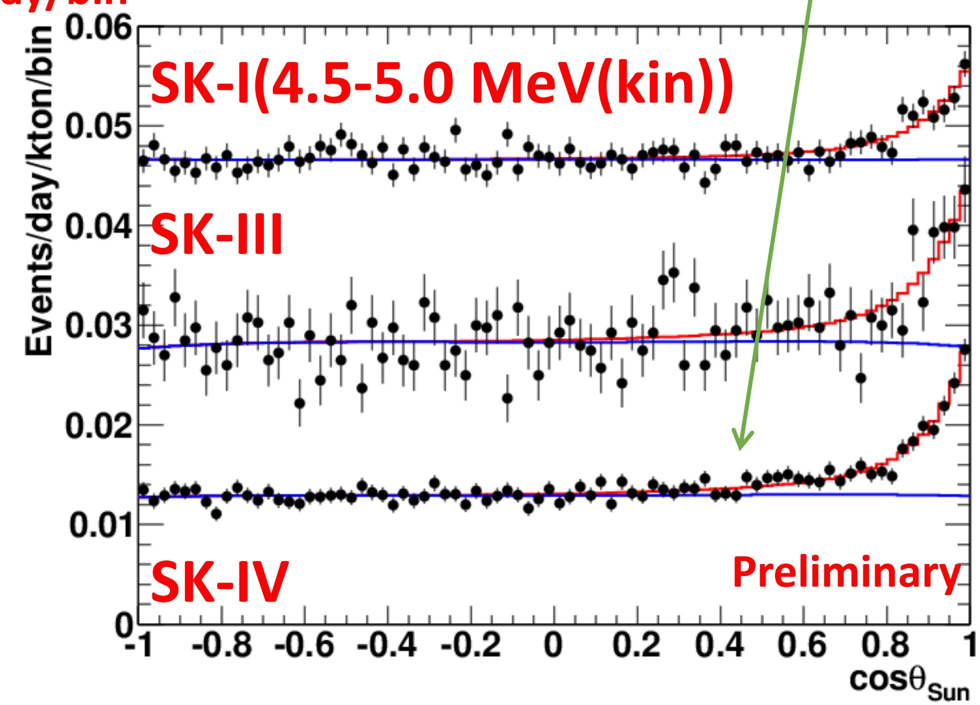


◆solar ν observation

Elastic scattering

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

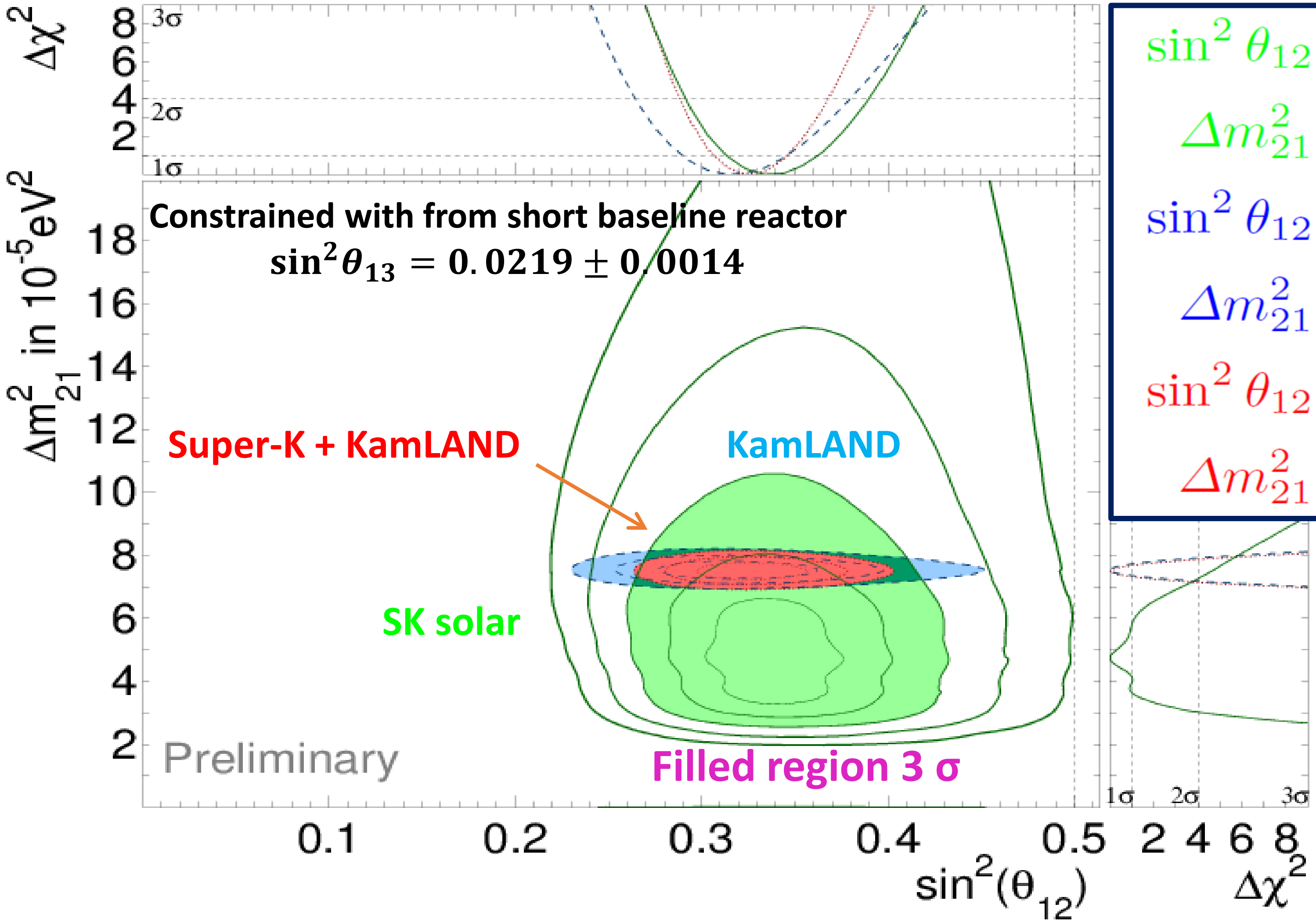




Solar neutrino signals are seen around $\cos\Theta_{sun} = 1$.

Background event
→ Other direction ($\cos\Theta_{sun} < 0$)

Super-K vs. KamLAND



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

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

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

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

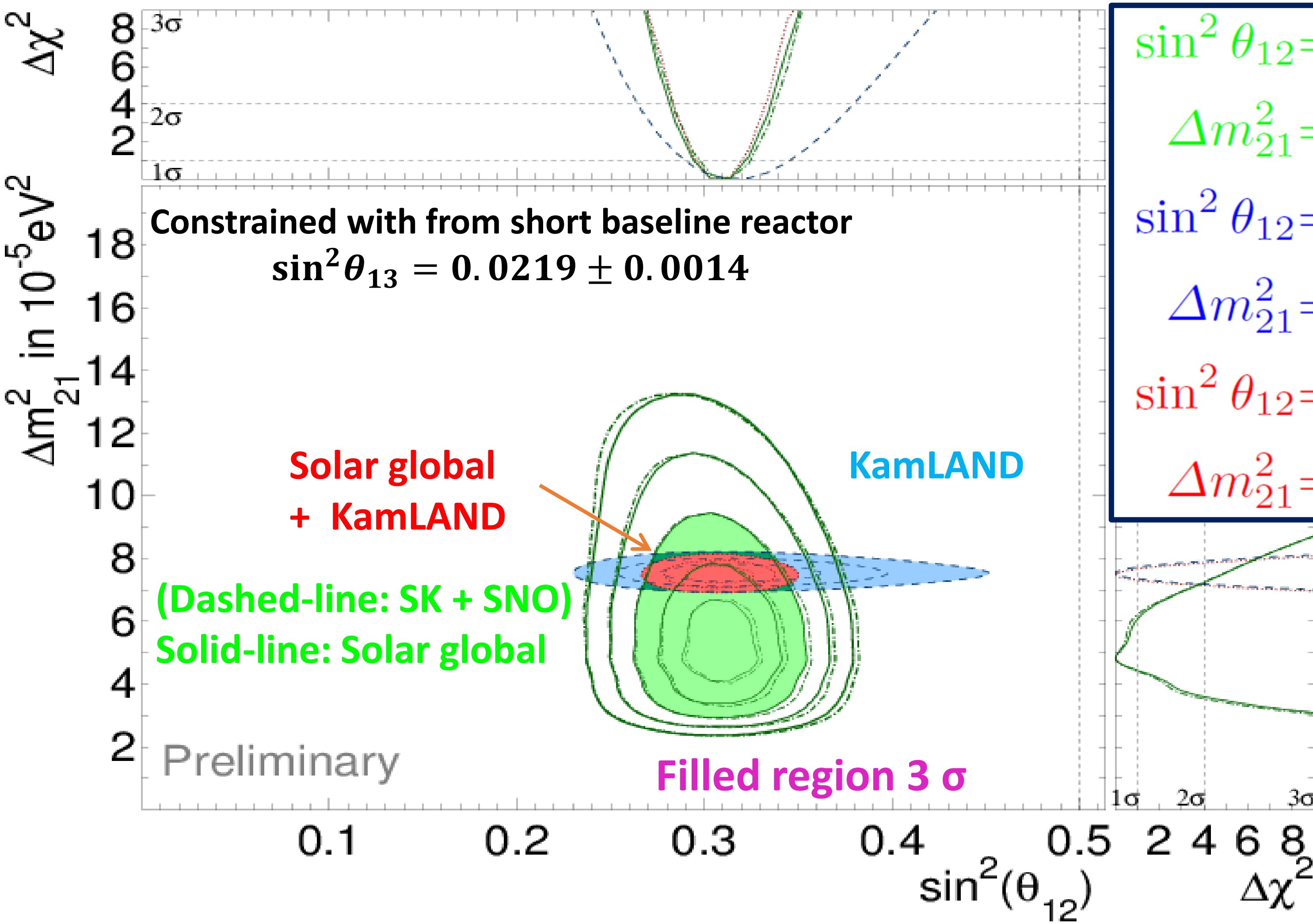
$\sin^2\theta_{12} = 0.326^{+0.022}_{-0.019}$

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

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



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

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

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

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

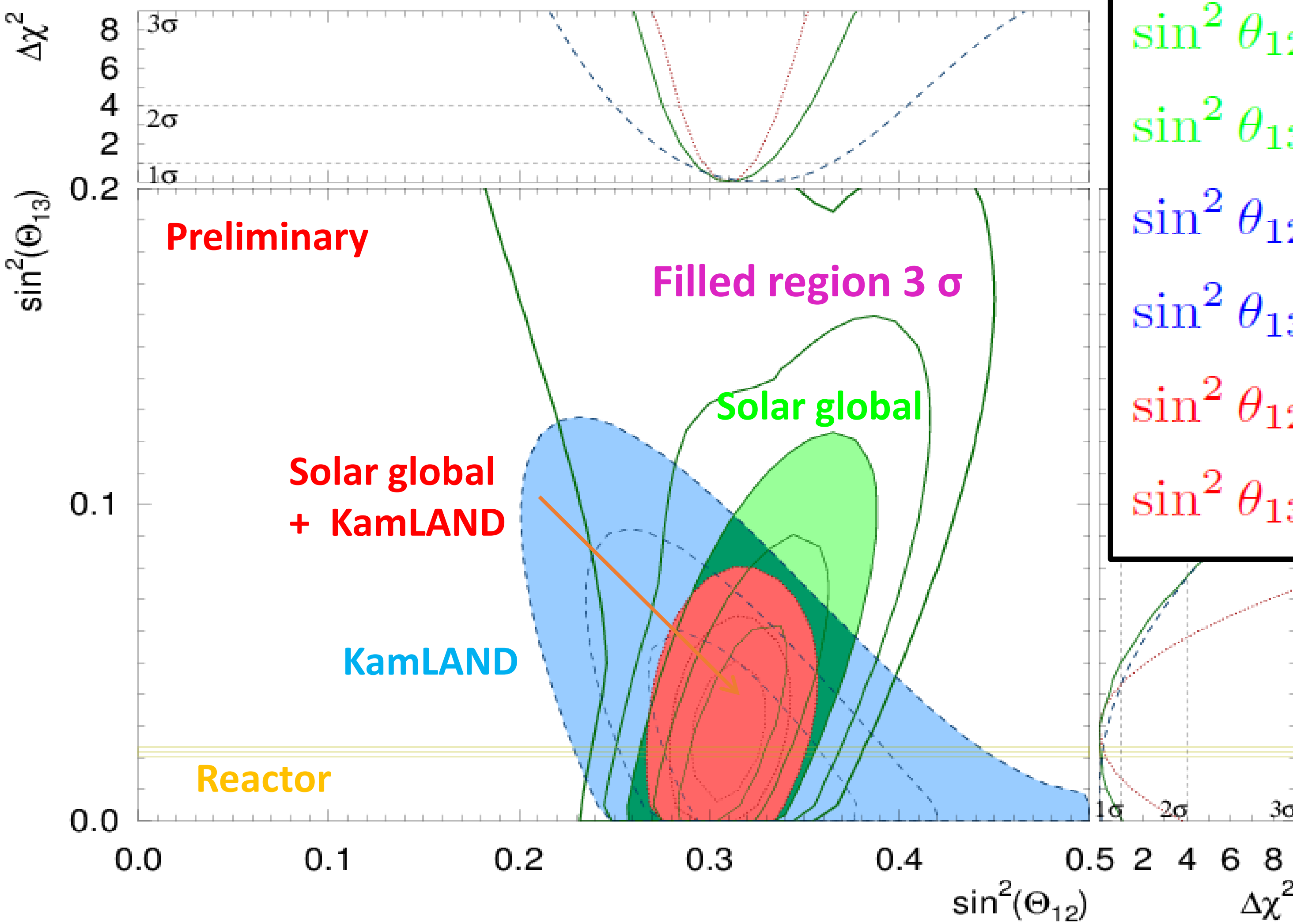
$\sin^2\theta_{12} = 0.308 \pm 0.012$

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

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.