Precision solar neutrino measurements with Super-Kamiokande-IV

修士博士研究発表会

2013/02/22

中畑研究室　横澤　孝章

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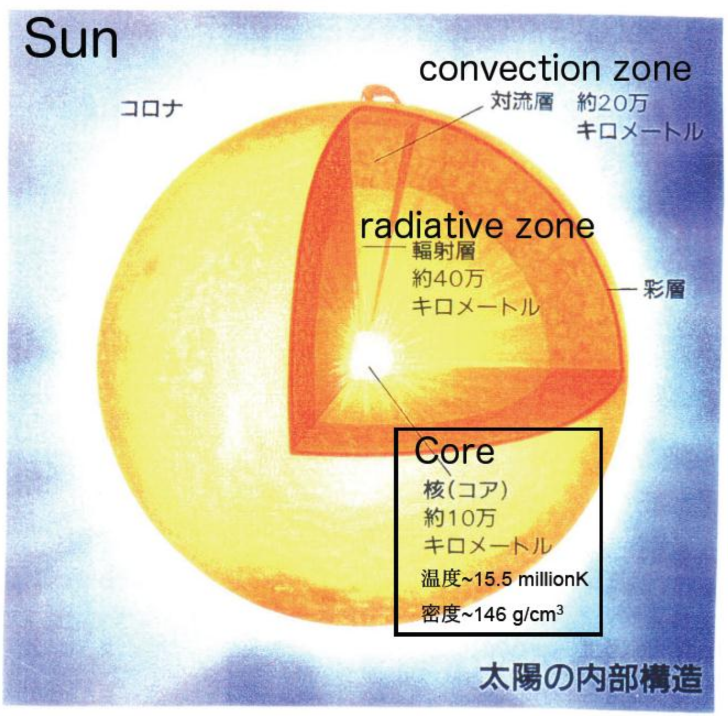
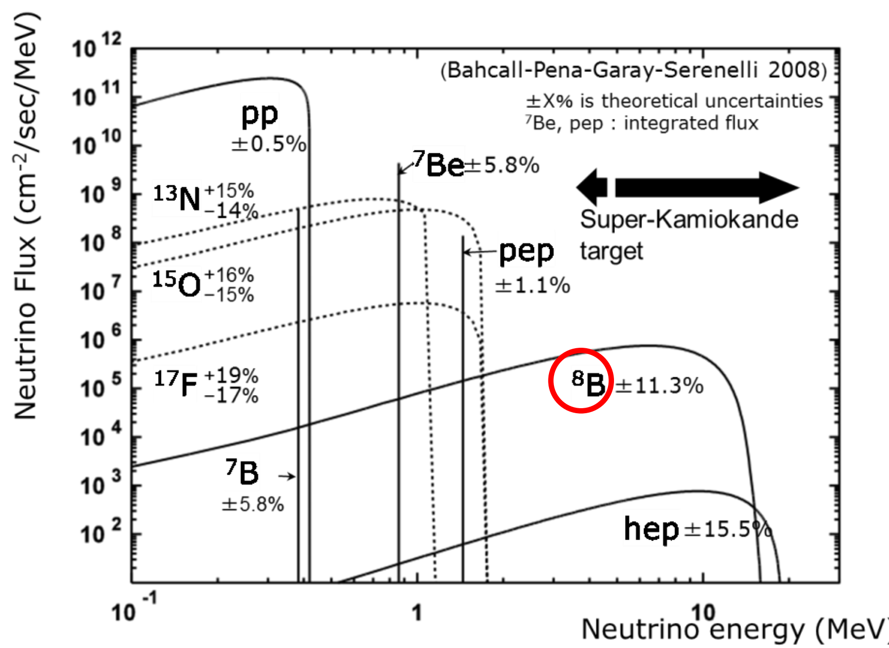
Solar neutrino

- The origin of solar energy : nuclear fusion reaction deep inside the Sun.

  $4p \rightarrow He + 2e^{+} + 2\nu_e$

- ~99% of the total solar luminosity : pp chain (~1% from CNO cycle).
- SK detector : sensitive to ^{8}B neutrinos





solar neutrinos energy spectrums

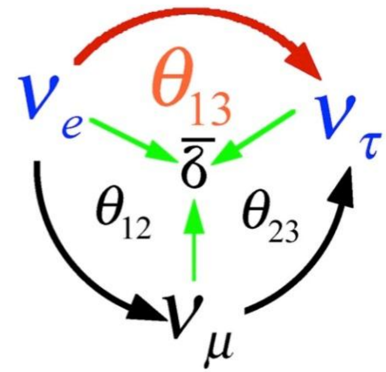
Neutrino oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{N} U^*_{\alpha i}|\nu_i\rangle$$

$|\nu_\alpha\rangle(\alpha = e, \mu, \tau)$:flavor eigenstate

$|\nu_i\rangle(i = 1, 2, 3)$:mass eigenstate

$$U_{MNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



Atmospheric
Long baseline

Solar
Reactor(KamLAND)

When traveling in vacuum;

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

delta mass square (m_2^2-m_1^2)

mixing angle

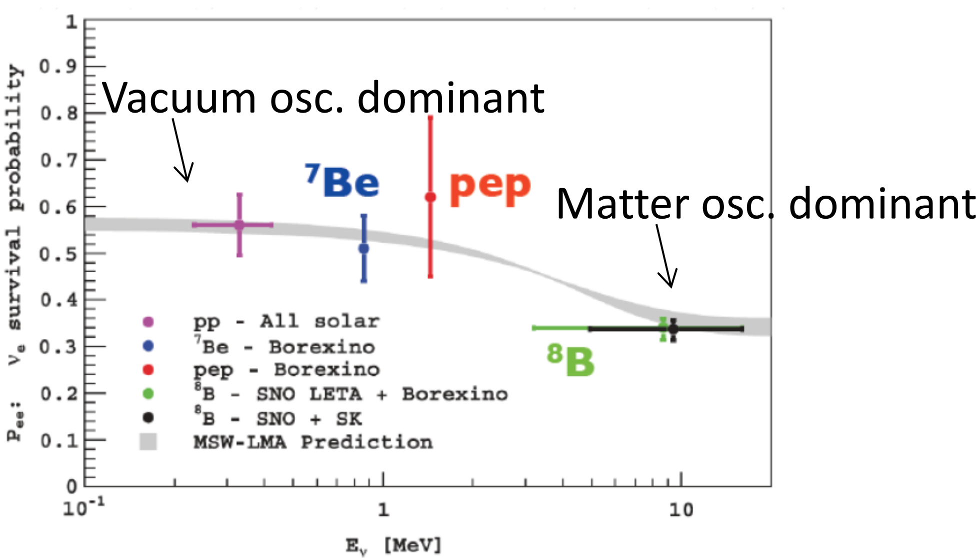
For solar neutrino case;

- need to take into account matter effect of Sun and Earth (MSW effect).

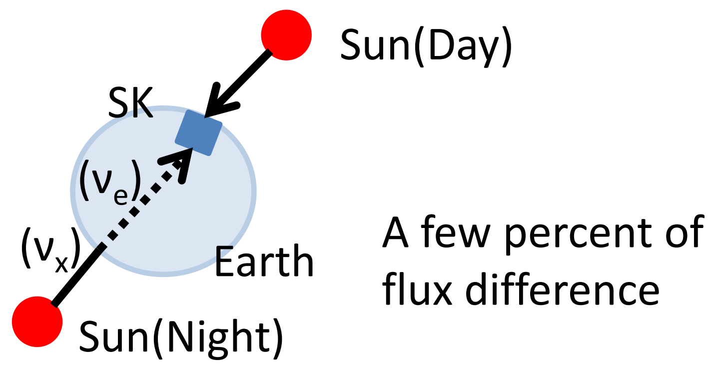
Hamiltonian -> $\mathcal{H} = \mathcal{H}_v + \mathcal{H}_M$ $\quad tan2\theta_M = \frac{tan2\theta}{1 - \frac{VE}{\Delta m^2 cos2\theta}}$ $\quad L_M = \frac{\pi}{1.27\sqrt{(2V + \frac{\Delta m^2}{E}\cos 2\theta)^2 + (\frac{\Delta m^2}{E}\sin 2\theta)^2}}$

Physics motivation

- Direct observation of the MSW effect
  - Energy spectrum distortion
    - Distorted by the the effect of sun matter(Upturn)
    - Lower energy data(<4.5MeV(kin)) with lower background
  - Day/Night flux asymmetry
    - A few percent of flux difference by the effect of earth matter
    - Large statistics and lower systematic uncertainty.



Predicted distortion and current results
Phys. Rev. Lett. 107 141302(2011)



Schematic view of day/night asymmetry

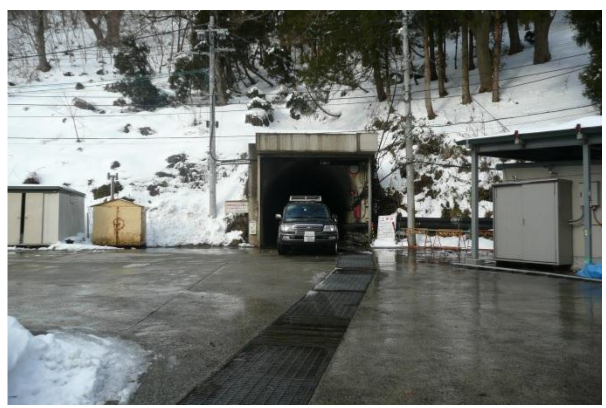
Super-Kamiokande detector

- Located 1000m underground at Ikenoyama (Kamioka)
  - reduce cosmic ray muon background (1/100,000)

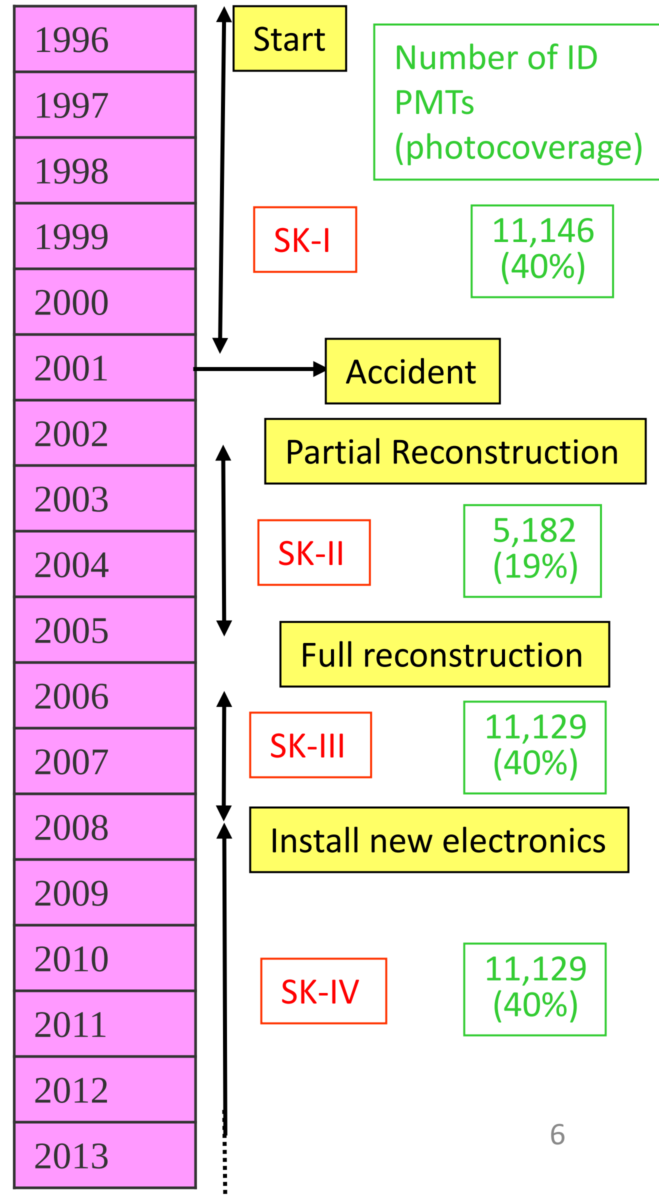
Ikenoyama (Summer)

Ikenoyama (Winter)

Kenkyu-tou

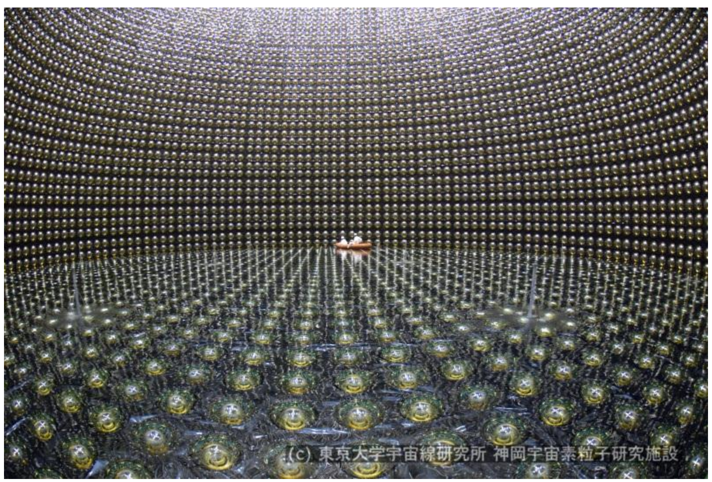


Mine-entrance

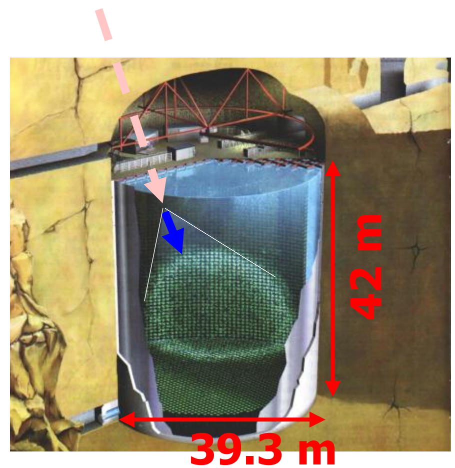


Super-Kamiokande detector

- Located 1000m underground at Ikenoyama (Kamioka)
  - reduce cosmic ray muon background (1/100,000)
- Large ring imaging water Cherenkov detector
  - 50,000 tons of pure water, ~11,000 PMT(ID)

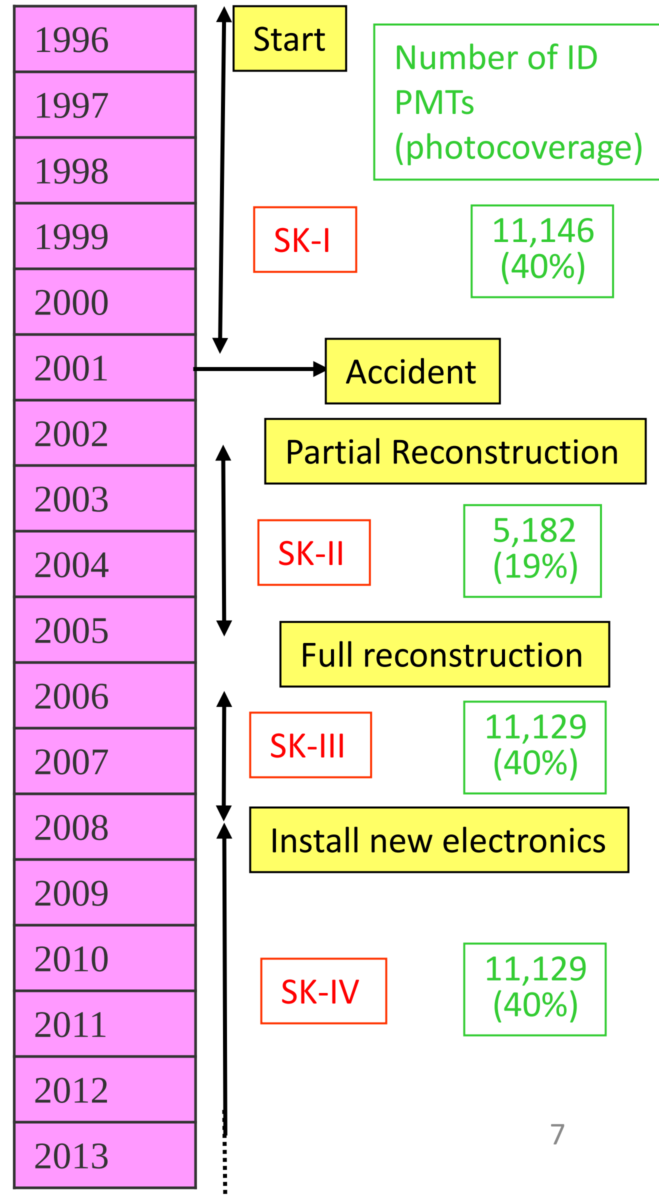


Inner part of SK detector



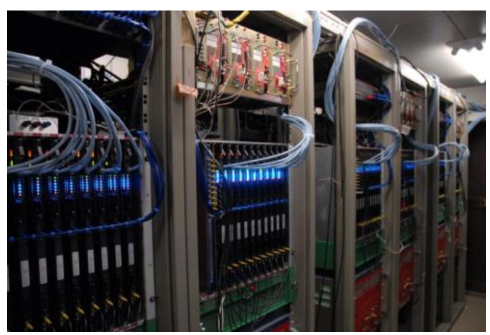
SK detector

20-inch PMT

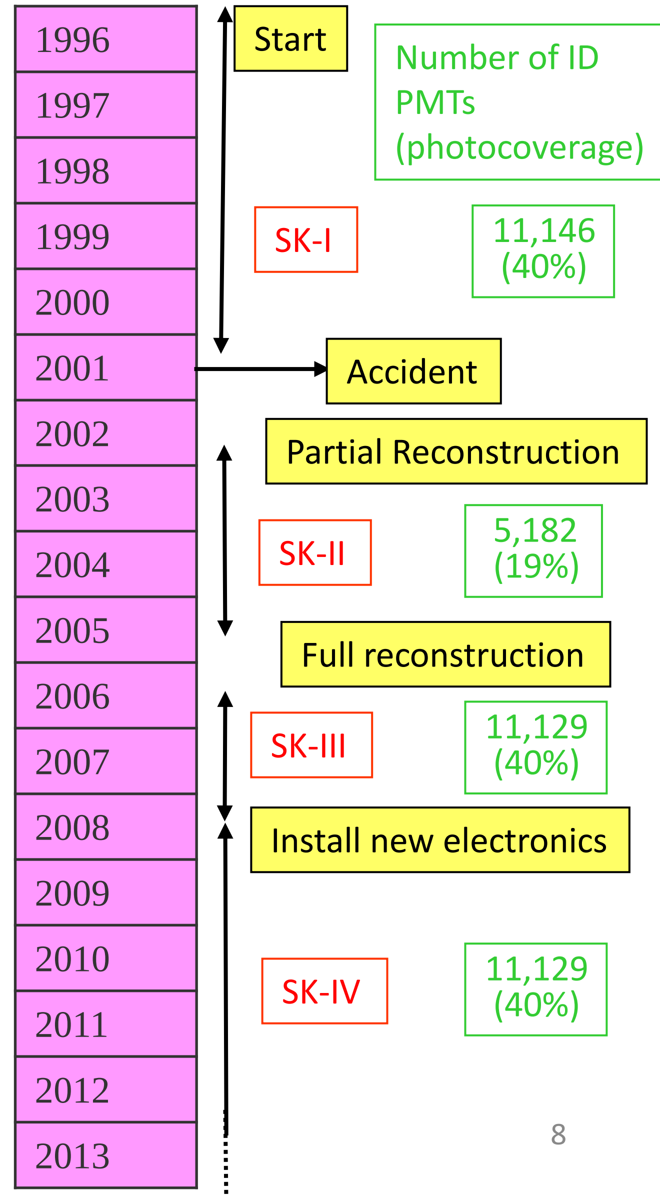


Super-Kamiokande detector

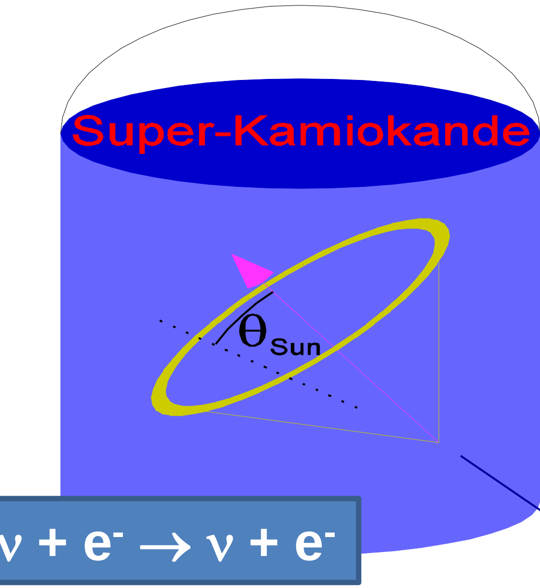
- Located 1000m underground at Ikenoyama (Kamioka)
  - reduce cosmic ray muon background (1/100,000)
- Large ring imaging water Cherenkov detector
  - 50,000 tons of pure water, ~13,000 PMT
- Start observation in 1996
  - In 2008, new electronics was installed (SK-IV)



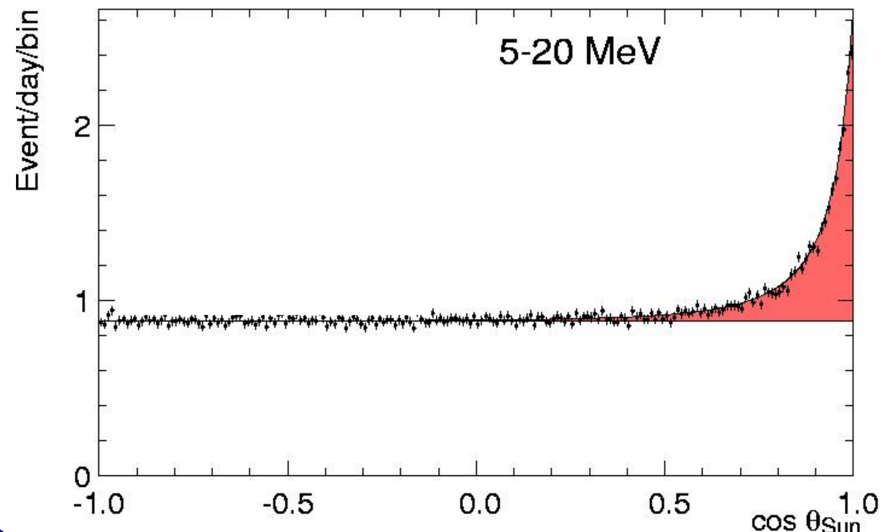
New electronics ; QBee

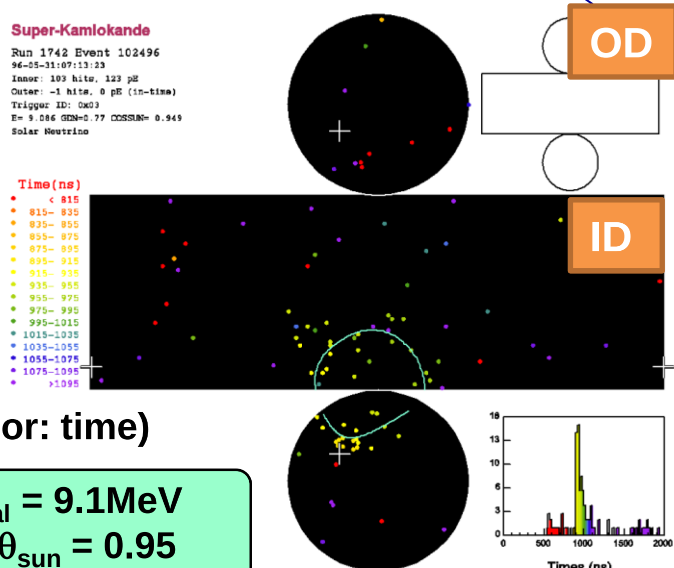


Solar neutrino measurements in SK



- reconstruct vertex and direction from PMT hit pattern
- Real time detection; day/night, seasonal observation
- Reconstruct energy from # of hit PMT (~6hit/MeV), energy spectrum observation

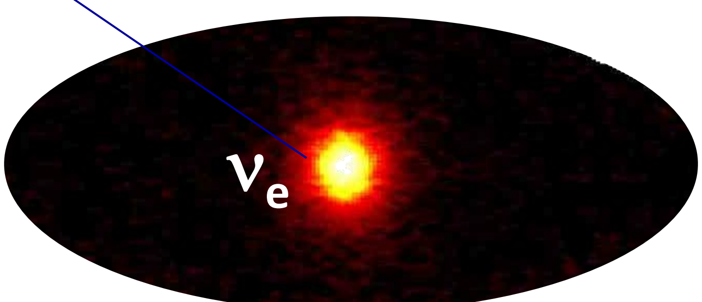




(color: time)

E_{total} = 9.1MeV
$\cos\theta_{sun}$ = 0.95

Event display



Picture of solar by neutrino

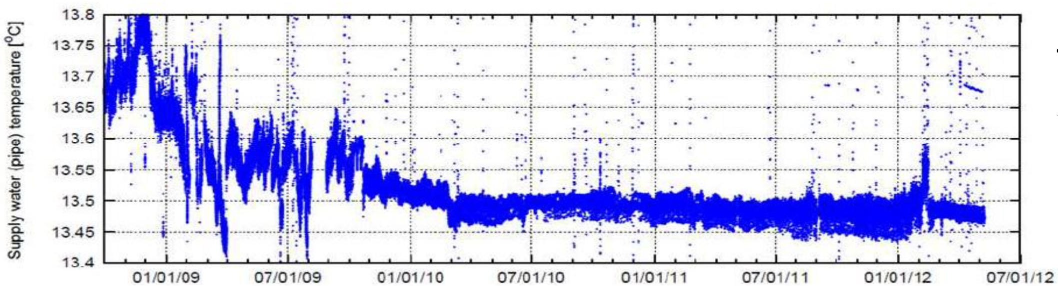
SK-IV solar neutrino analysis

- SK-IV data sets
  - livetime
    - 1069.3 days (Oct.2008 – Mar.2012)
  - Trigger efficiency
    - Used software trigger(34hits/200ns)
    - ~99%@4.0MeV(kin), ~86%@3.5MeV(kin)

- Improvement of water circulation system
- Improvement of solar neutrino MC
- data reduction
- Systematic uncertainties

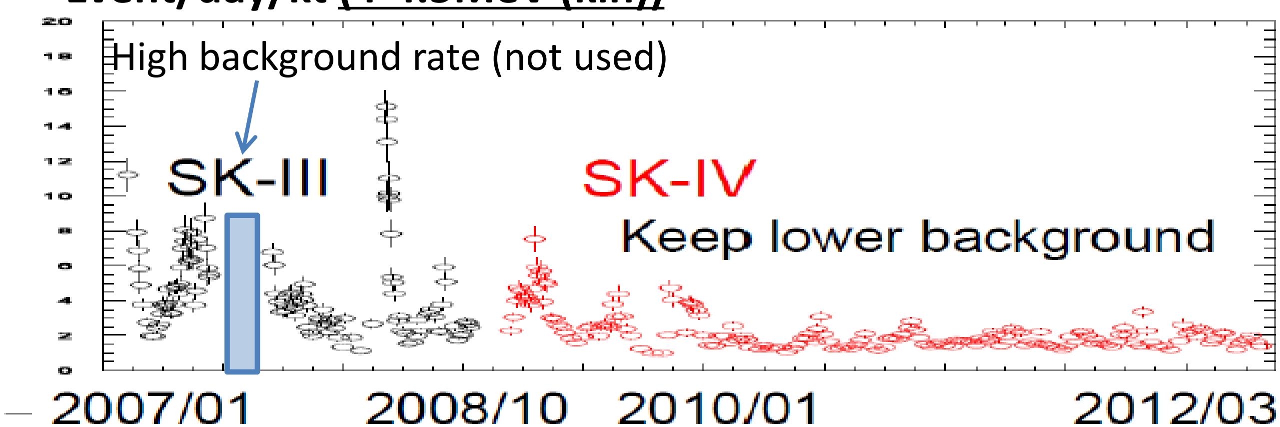
Improvement of water circulation system

- ➢lower background in the center of the detector (when SK-III)
    - ➢Keep backgrounds near the wall
- ➢Supply water temperature control system(Jan.2010)
    - ➢Control temperature within 0.01℃
    - ➢The convection rate was much smaller.

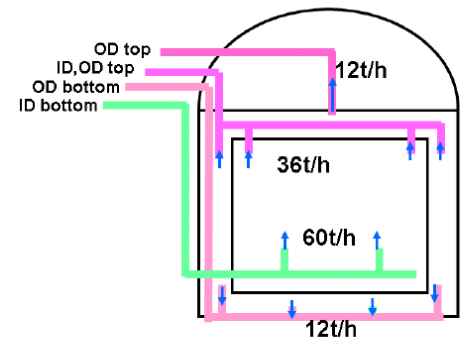


Time variation of supply water temperature

Event/day/kt __**(4-4.5MeV (kin))**__



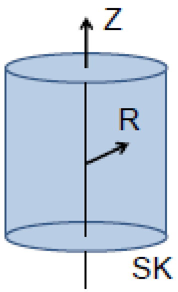
date



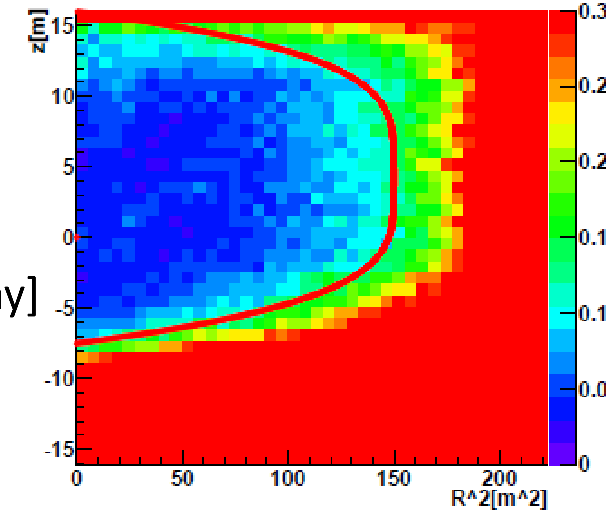
Water circulation system

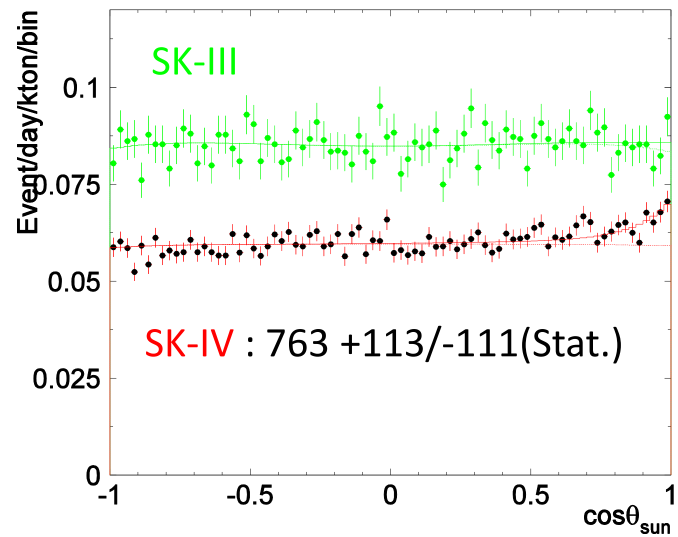
Solar angle distribution

3.5MeV-4.0MeV(kin)



[event/bin/day]
low -> high

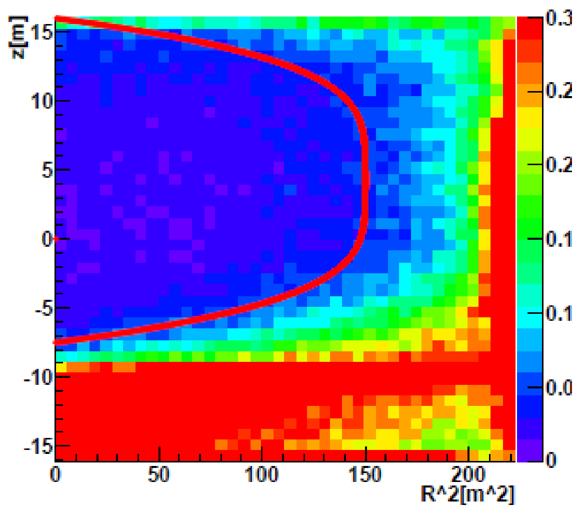


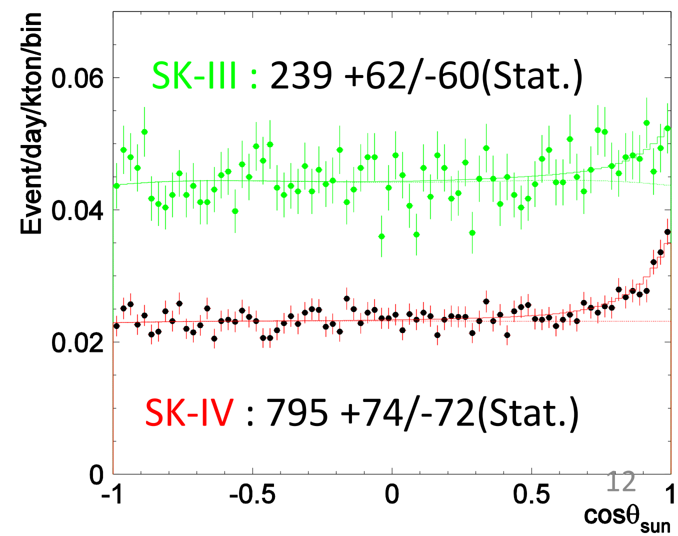


Tight fiducial shape

$$(x^2+y^2)+(\frac{150}{11.75^4}*|z-4.25|^4)\leq 150$$

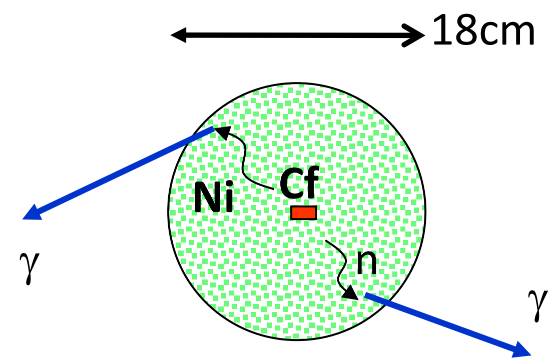
4.0MeV-4.5MeV(kin)





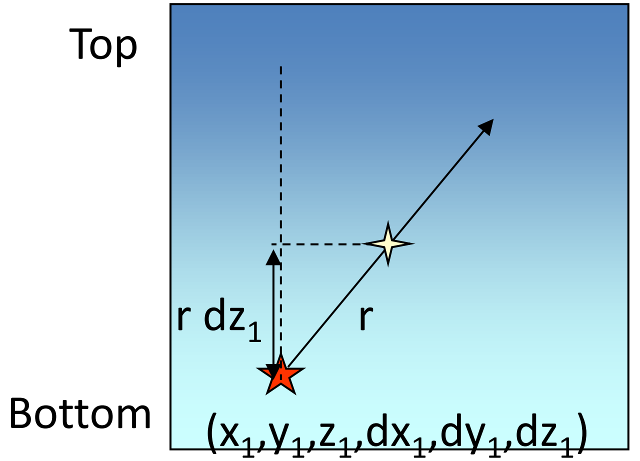
Improvement of solar neutrino MC

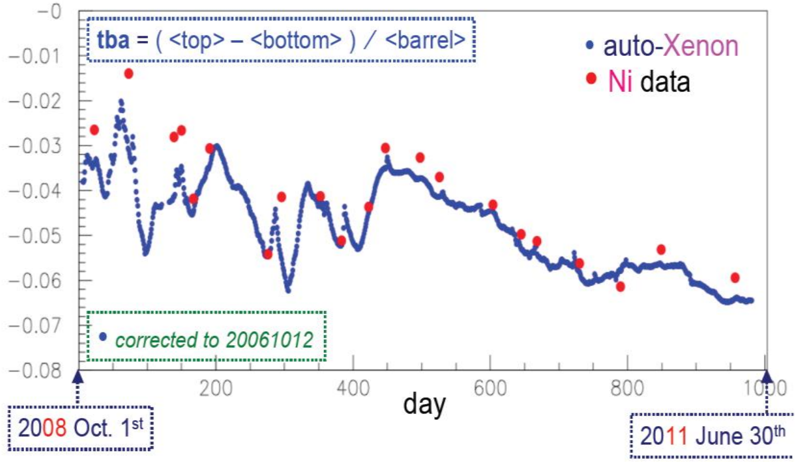
- Position dependence of water transparency
  - Supply purified water from bottom and drain from top
  - Introduce Top Bottom Asymmetry parameter (TBA)



- Time variation of TBA
  - Xe light source (1event/min)
  - Nickel source (emit ~9MeV gamma ray uniformly)

- $WT(\lambda)=1/(\alpha_{abs}(1+\beta*z)+\alpha_{sca}+\alpha_{asca})$
  - β : degree of TBA (Tuned by hit pattern of Ni calibration)
  - Introduce to SK-III,IV solar neutrino MC

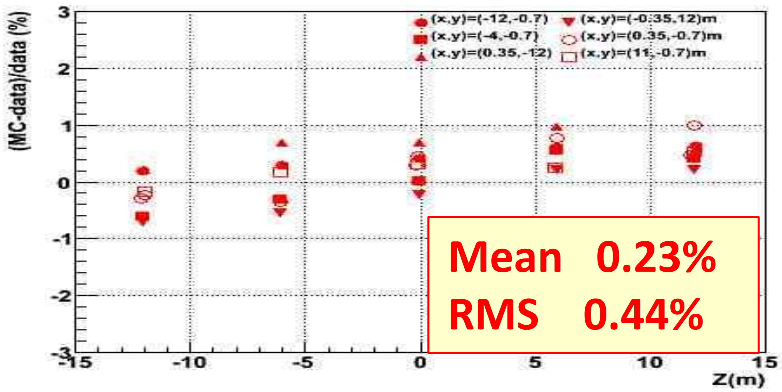


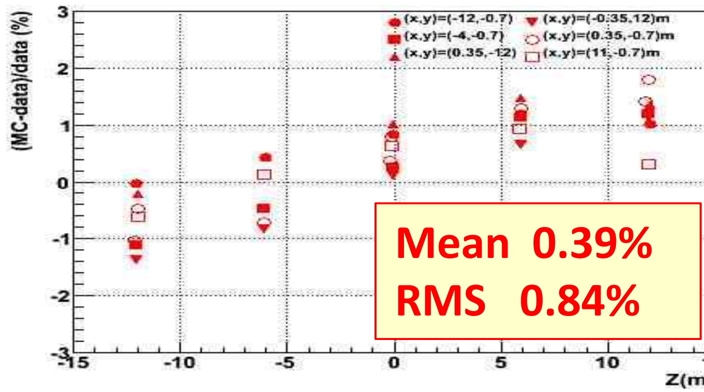


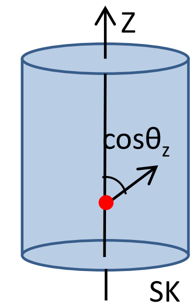
Improvement of solar neutrino MC

With TBA in MC | **Without TBA in MC**

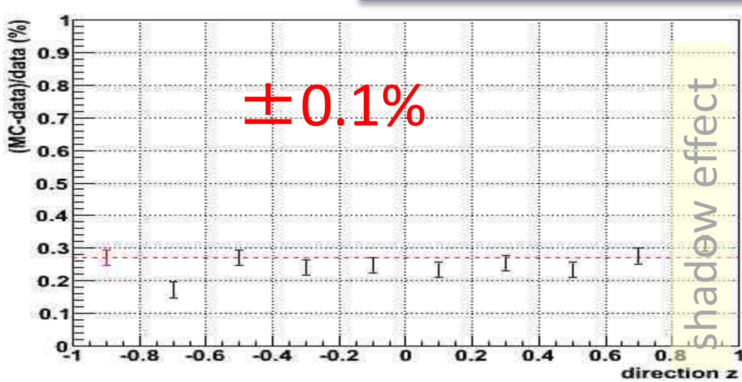
Position dependence of energy scale(SK-IV)

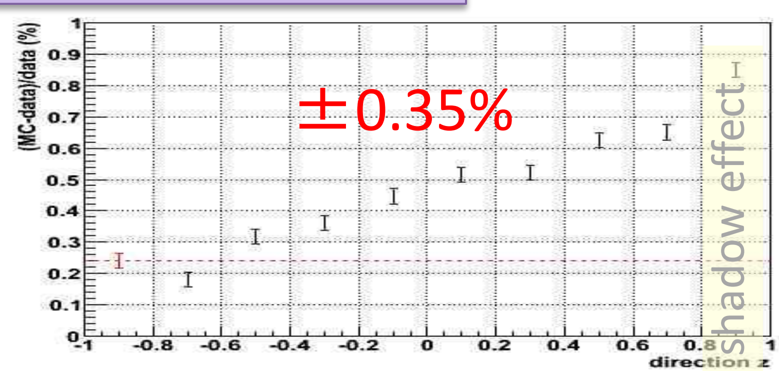






Direction dependence of energy scale(SK-IV)





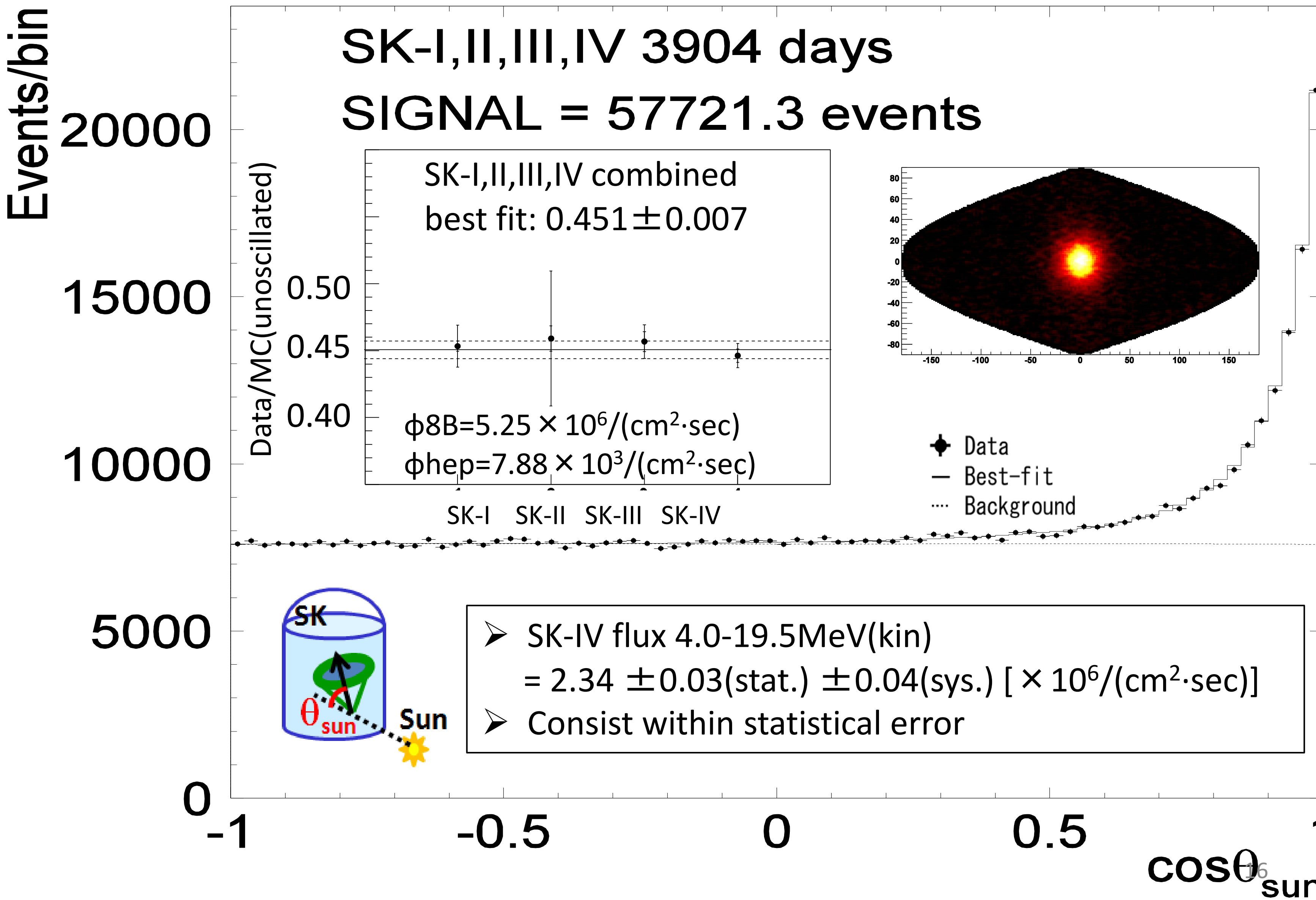
- Success to reduce energy scale systematics (Especially direction dependence)
- SK-I ; 0.5% SK-III ; 0.25% (SK-III solar MC is also improved)

Flux systematic uncertainty

Source	SK-IV Flux (4.0-19.5MeV(kin))	SK-III Flux (4.5-19.5MeV(kin))	SK-I Flux (4.5-19.5MeV(kin))
Energy Scale	±1.2%	±1.4%	±1.6%
Energy resolution	±0.15%	±0.2%	
8B spectrum	±0.33%	±0.4%	+1.1/-1.0%
Trigger efficiency	±0.1%	±0.5%	+0.4/-0.3%
Vertex shift	±0.17%	±0.54%	±1.3%
Reduction	±0.6%	±0.9%	+2.1/-1.6%
Spallation dead time	±0.2%	±0.2%	±0.2%
Background shape	±0.1%	±0.1%	±0.1%
Angular resolution	±0.36%	±0.67%	±1.2%
Signal extract method	±0.7%	±0.7%	
Cross section	±0.5%	±0.5%	±0.5%
Total	**±1.7%**	**±2.1%**	**+3.5/-3.2%**

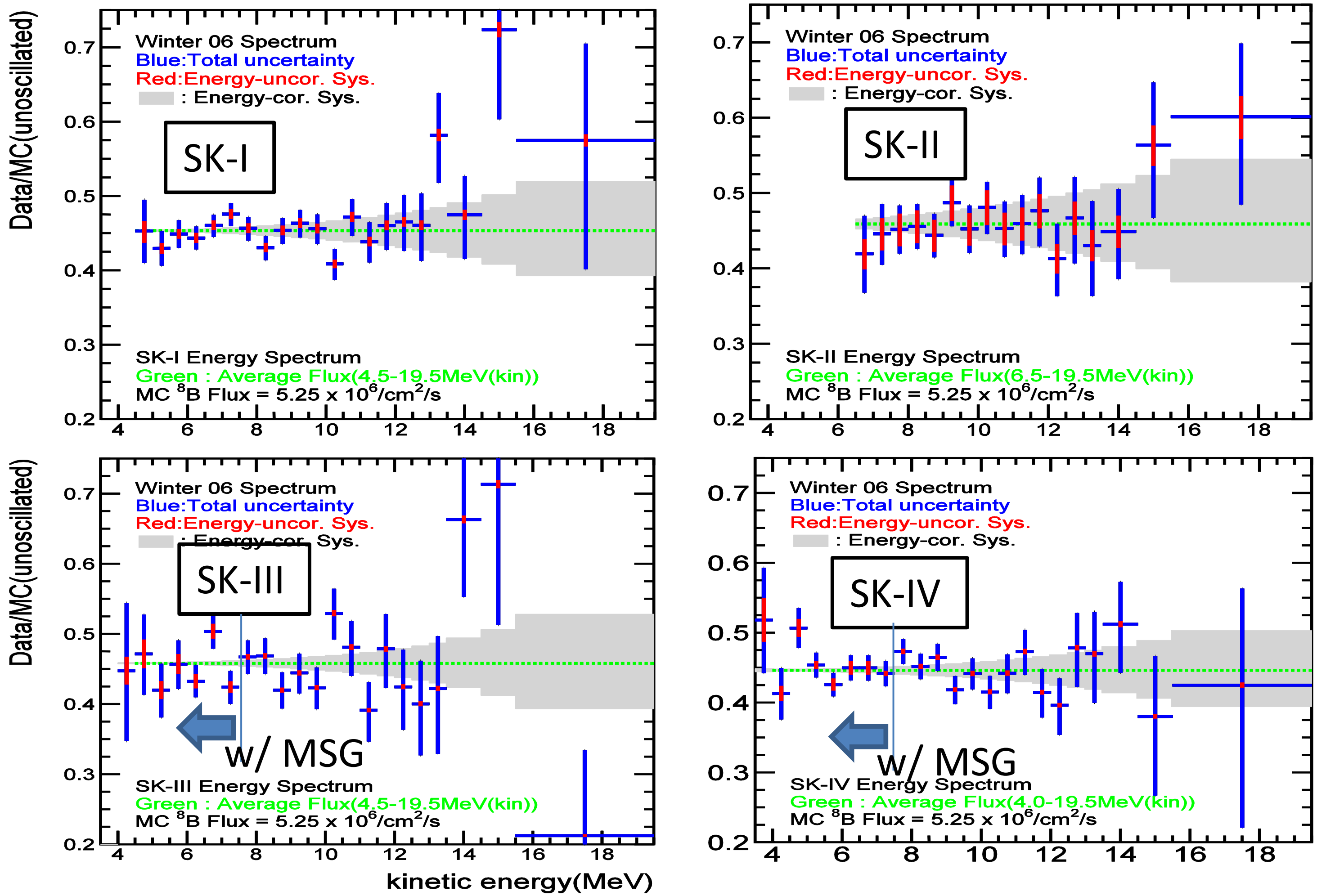
- Best value compared with SK-I,III

Solar neutrino flux



- SK-IV flux 4.0-19.5MeV(kin) = 2.34 ±0.03(stat.) ±0.04(sys.) [$\times 10^6$/(cm^2·sec)]
- Consist within statistical error

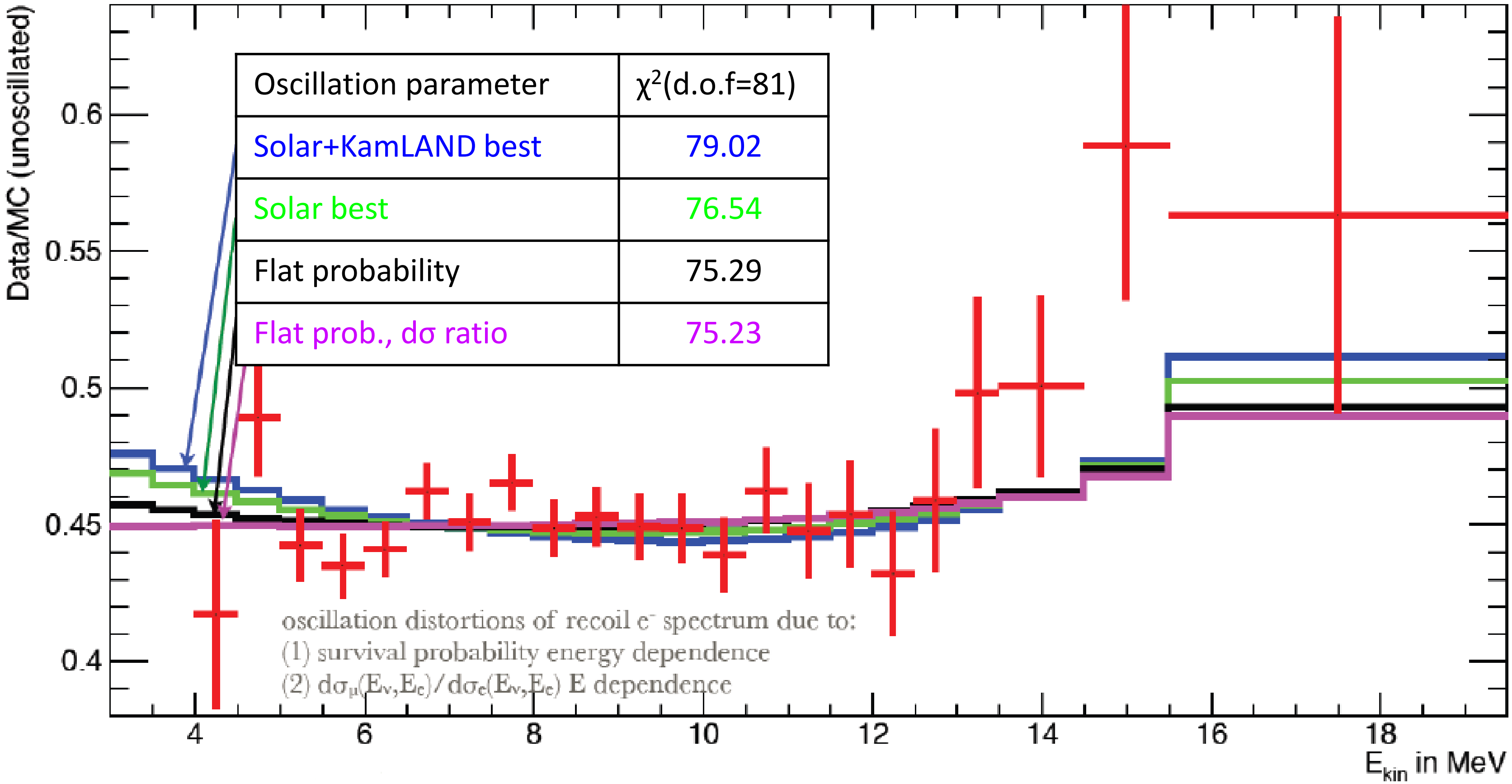
Energy spectrum (SKI-IV)



- Estimate systematic uncertainties for each phase.
- Obtained flat consistent

Energy spectrum (SK-I,II,III,IV combined)

- Statistic error only
- Estimate χ^2 in each SK phase

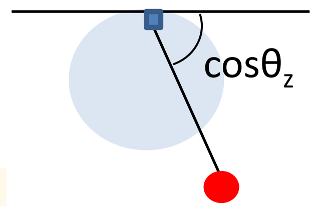


Oscillation parameter	χ^2(d.o.f=81)
Solar+KamLAND best	79.02
Solar best	76.54
Flat probability	75.29
Flat prob., dσ ratio	75.23

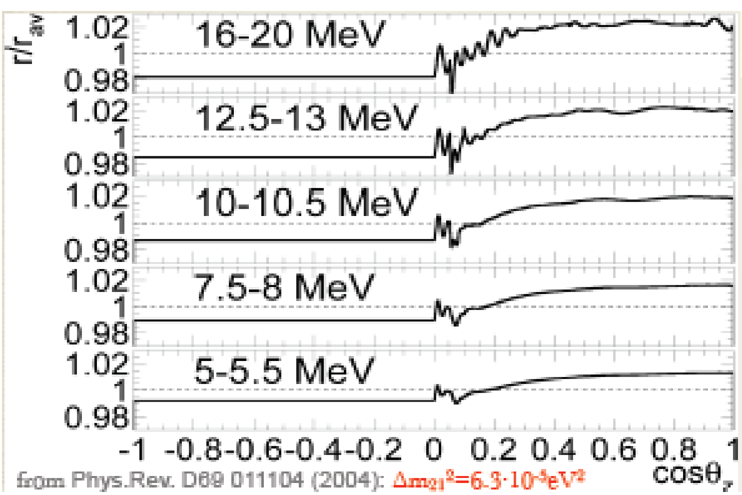
‘Flat probability’ is favored 1.1-1.9σ level

Day/night asymmetry analysis

- Unbinned Day/night analysis (PRD69,011104, D/N amplitude) is applied in each SK phase, then obtained Day/Night asymmetry values.
  - consider energy and zenith angle dependence of event rate variation
- Day/Night asymmetry consistent with zero @2.3σ



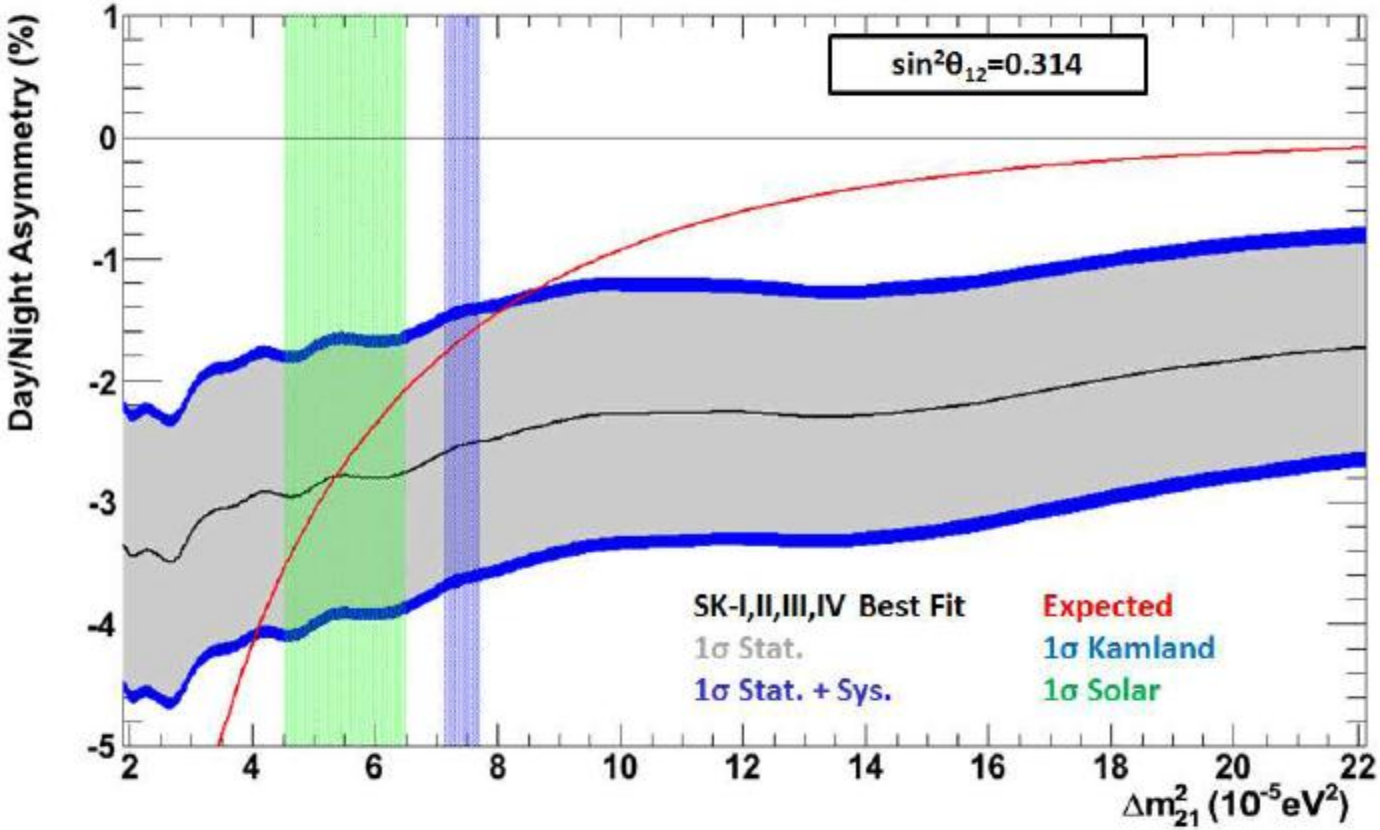
$$A_{DN} = \frac{\text{Day flux} - \text{Night flux}}{0.5\,(\text{Day flux} + \text{Night flux})}$$



Predicted energy and zenith angle dependence

Phase	D/N amplitude
SK-I	-2.0±1.7±1.0%
SK-II	-4.3±3.8±1.0%
SK-III	-4.3±2.7±0.7%
SK-IV	-2.8±1.9±0.7%
SKcomb.	-2.8±1.1±0.5%

Day/night asymmetry analysis

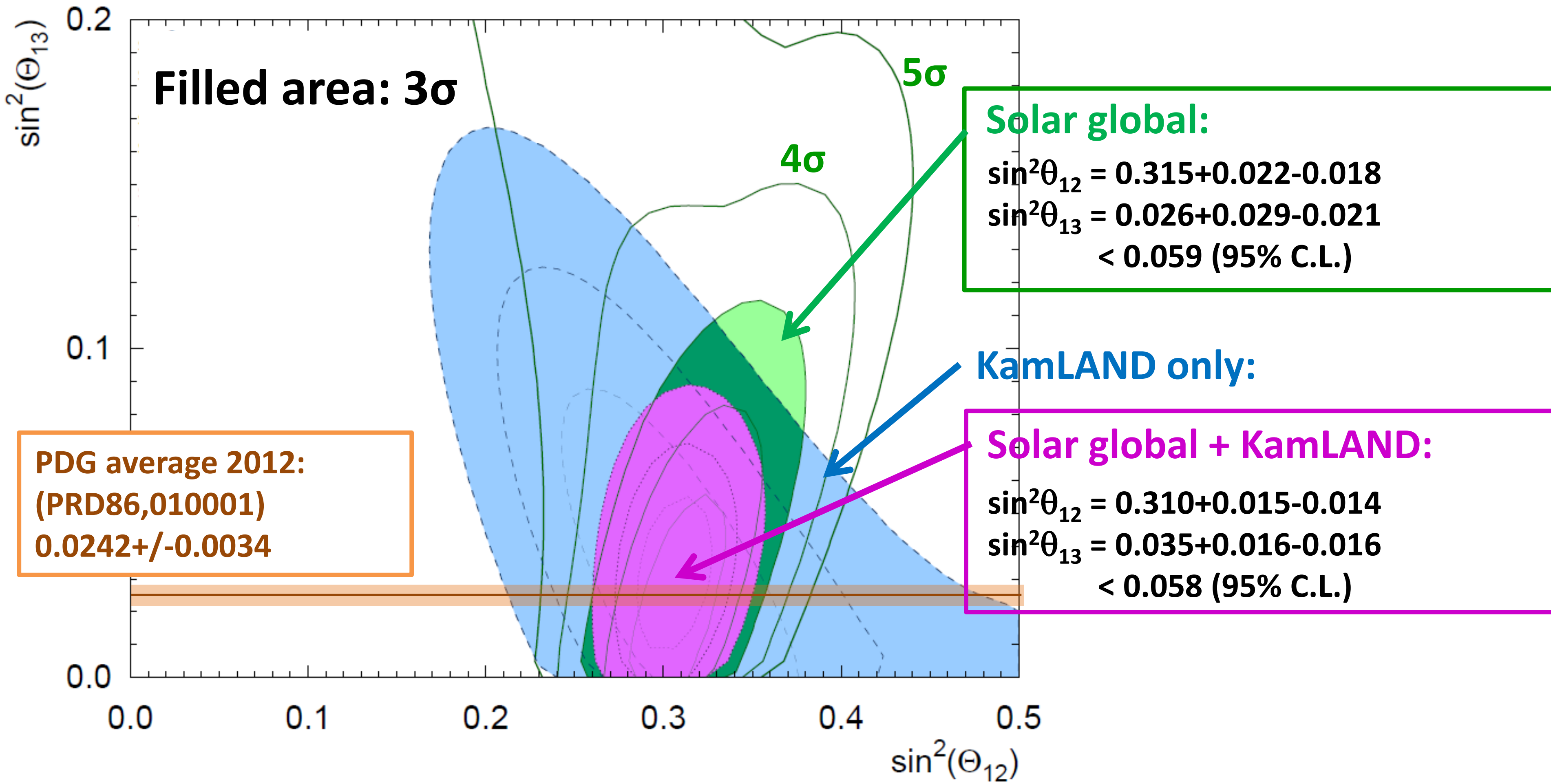


- D/N Asymmetry has sensitivity to Δm_{21}^2
- D/N Asymmetry has small sensitivity to $\sin^2\theta_{12}$

Global solar analysis

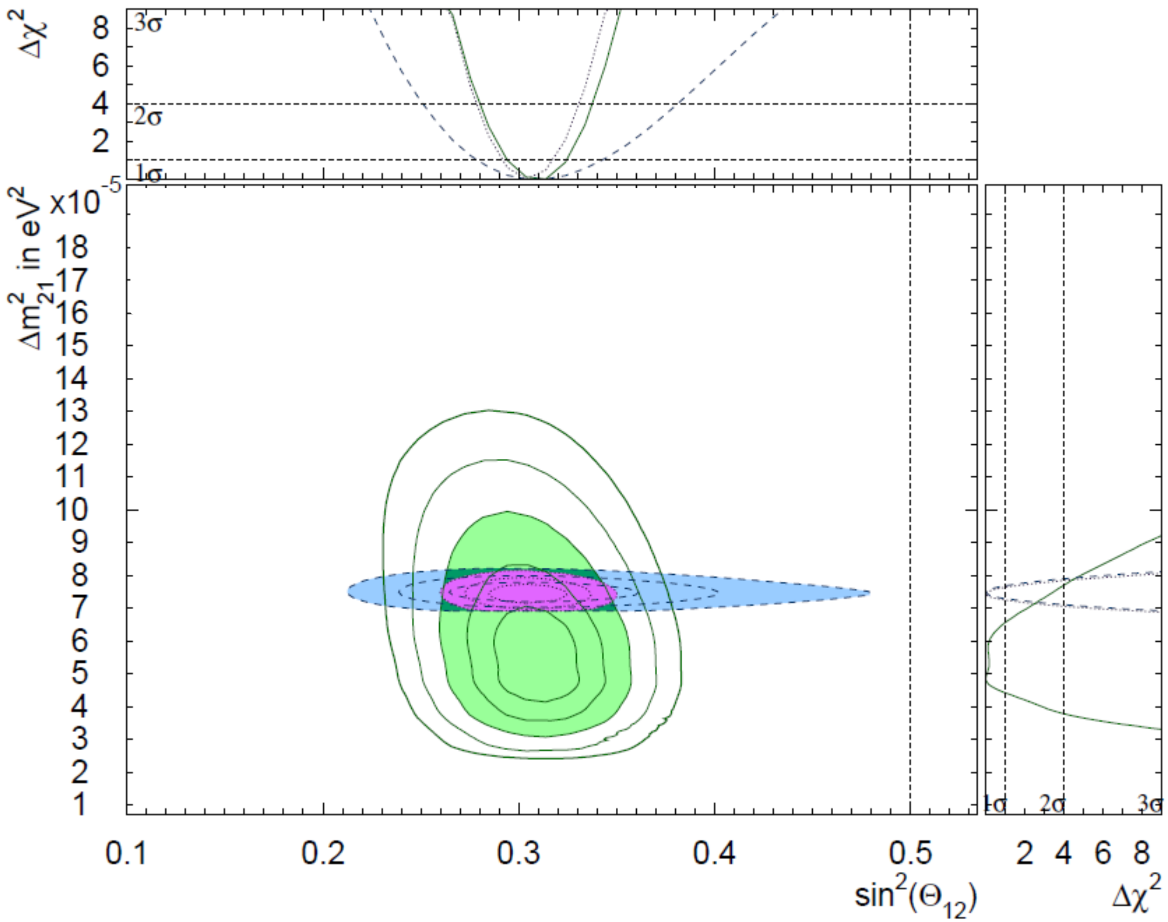
- **Solar neutrino experiments (red : newly add in this analysis)**
  - SK
    - SK-I 1496 days, spectrum 4.5-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
    - SK-II 791 days, spectrum 6.5-19.5MeV(kin) + D/N : E ≥ 7.0MeV(kin)
    - SK-III 548 days, spectrum 4.0-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
    - SK-IV 1069 days, spectrum 4.0-19.5MeV(kin) + D/N : E ≥ 4.5MeV(kin)
  - SNO : SNO combined (arXiv:1109.0763) (NC flux = (5.25+/-0.20) $10^6 cm^{-2} s^{-1}$)
  - Radiochemical : Cl, Ga
    - Ga rate: 66.1+/-3.1 SNU (All Ga global) (PRC80, 015807(2009))
    - Cl rate: 2.56+/-0.23 SNU (Astrophys. J. 496 (1998) 505)
  - Borexino : PRL107, 141302 (2011)
- **Reactor neutrino experiment**
  - KamLAND : PRL 100, 221803 (2008)

Global oscillation analysis (free Sinθ_{13})



- Non-zero θ13 value @2.2σ
- consistent with Short Baseline experiments

Global oscillation analysis (fixed $\sin\theta_{13}$)



Solar global:

$\Delta m^2 = (4.86^{+1.44}_{-0.52})$ [$\times 10^{-5}$eV^2]

$\sin^2\theta_{12} = 0.314^{+0.014}_{-0.015}$

KamLAND:

$\Delta m^2 = (7.49+/-0.2)$ [$\times 10^{-5}$eV^2]

$\sin^2\theta_{12} = 0.309^{+0.034}_{-0.030}$

Solar global + KamLAND:

$\Delta m^2 = (7.45^{+0.20}_{-0.19})$ [$\times 10^{-5}$eV^2]

$\sin^2\theta_{12} = 0.307+/-0.014$

- There is some tension for $\Delta m_{21}{}^2$ between solar global and KamLAND (~1.9σ)

Summary

- SK-IV solar neutrino analysis ; livetime=1060.3days
  - With new temp. control system, continuously low background
  - ~99%trg. eff.@4.0MeV(kin), 86%trg. eff.@3.5MeV(kin)
  - Introducing position dependence of water transparency, reducing position dependence of water transparency(0.35->0.1[%])
  - Flux systematic error(4.0-19.5MeV(kin)) is estimated by 1.7[%]
- SK combined energy spectrum shows 'Flat probability' is favored 1.1-1.9σ level
- SK combined day/night asymmetry is obtained non-zero value@2.3σ
- From Global oscillation analysis, the oscillation parameters is obtained by;
  - $\mathrm{Sin}^2(\theta_{12})=0.314^{+0.014}_{-0.015}$ $\Delta m_{21}^2=(4.86^{+1.44}_{-0.52})\ [10^{-5}\mathrm{eV}^2]$
- There is some tension for Δm_{21}^2 between solar global and KamLAND (~1.9σ)