Solar Neutrino Results from Super-Kamiokande

Workshop on Weak Interactions and Neutrinos (WIN2015)

Pierce Weatherly

UCI

For The Super-Kamiokande Collaboration

1 Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
2 RCCN, ICRResearch, Univ. of Tokyo, Japan
3 University Autonoma Madrid, Spain
4 University of British Columbia, Canada
5 Boston University, USA
6 Brookhaven National Laboratory, USA
7 University of California, Irvine, USA
8 California State University, USA
9 Chonnam National University, Korea
10 Duke University, USA
11 Fukuoka Institute of Technology, Japan
12 Gifu University, Japan
13 GIST College, Korea
14 University of Hawaii, USA
15 KEK, Japan
16 Kobe University, Japan
17 Kyoto University, Japan
18 Miyagi University of Education, Japan
19 STE, Nagoya University, Japan
20 SUNY, Stony Brook, USA
21 Okayama University, Japan
22 Osaka University, Japan
23 University of Regina, Canada
24 Seoul National University, Korea
25 Shizuoka University of Welfare, Japan
26 Sungkyunkwan University, Korea
27 Tokai University, Japan
28 University of Tokyo, Japan
29 Kavli IPMU (WPI), University of Tokyo, Japan
30 Dep. of Phys., University of Toronto, Canada
31 Inst. of Part. Phys., University of Toronto, Canada
32 TRIUMF, Canada
33 Tsinghua University, China
34 University of Washington, USA
35 Warsaw University, Poland

~120 collaborators
35 institutions
7 countries

Solar Neutrinos

pp chain
(branching %)

$p+p \rightarrow d+e^{+}+\nu_e$ (99.77%)

&

$p+e^{-}+p \rightarrow d+\nu_e$ (0.23%)

↓

$d+p \rightarrow {}^{3}He+\gamma$

↓

${}^{3}He+{}^{3}He \rightarrow \alpha+2p$ (84.92%)

&

${}^{3}He+p \rightarrow \alpha+e^{+}+\nu_e$ (10^{-5}%)

&

${}^{3}He+\alpha \rightarrow {}^{7}Be+\gamma$ (15.08%)

↓

${}^{7}Be+e^{-} \rightarrow {}^{7}Li+\nu_e$ (99.9%)

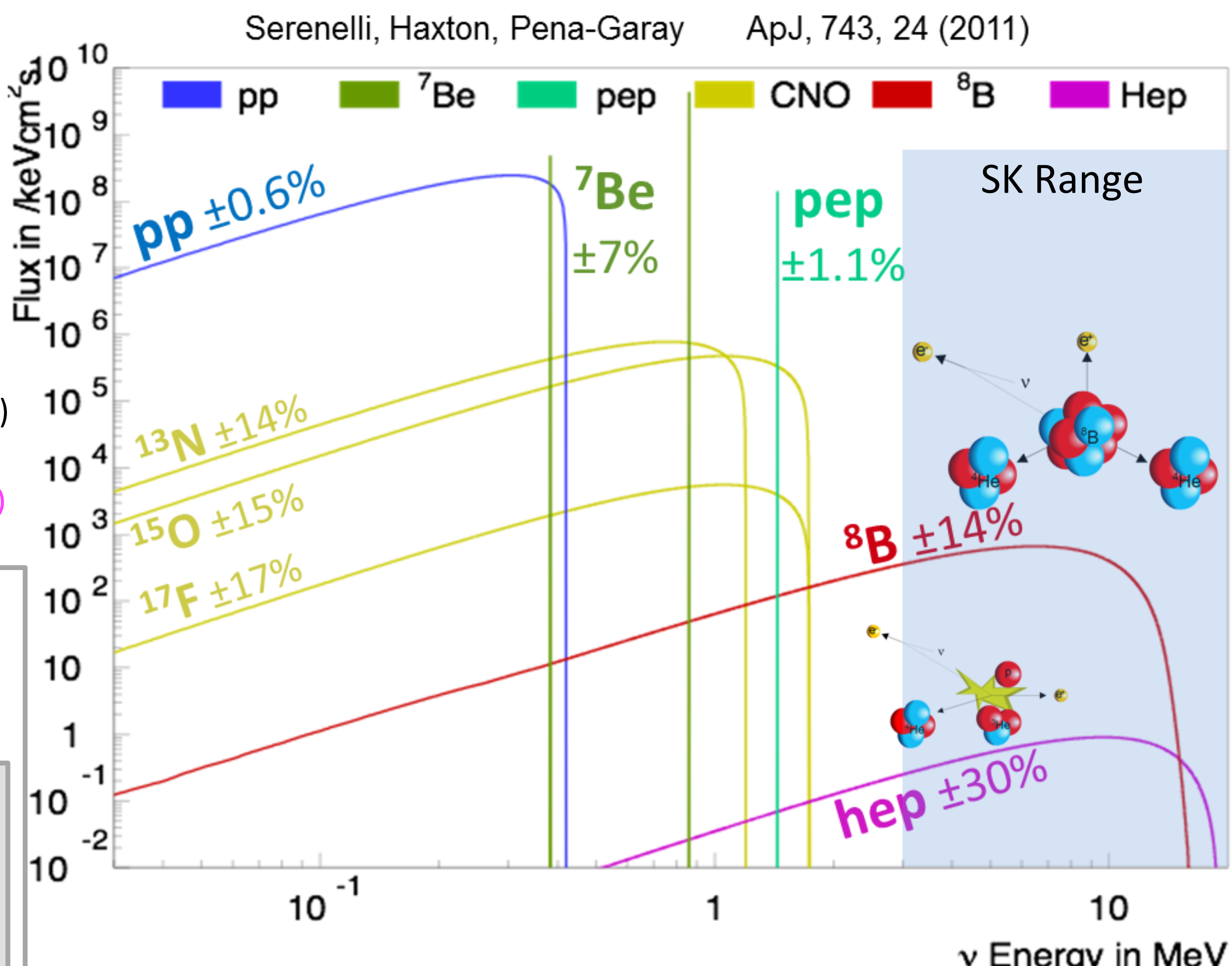
&

${}^{7}Be+p \rightarrow {}^{8}B+\gamma$ (0.1%)

↓

${}^{8}B+ \rightarrow {}^{8}Be^{*}+e^{+}+\nu_e$

${}^{7}Li+p \rightarrow \alpha+\alpha$; ${}^{8}Be^{*} \rightarrow \alpha+\alpha$

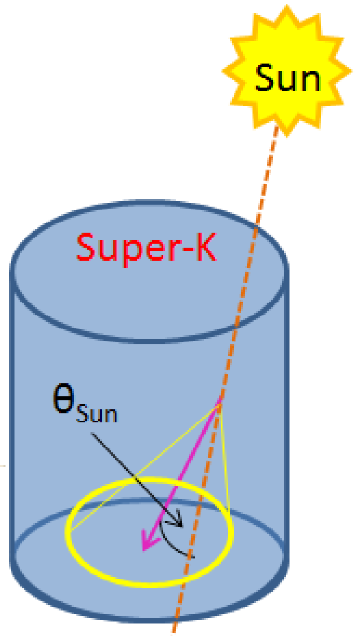


ν Detection Method

- Detection via elastic scattering:

  $\nu + e^- \rightarrow \nu + e^-$

  - Strongly Forward-Peaked
  - no threshold
- Measured recoil e^- spectrum gives integrated ν spectrum

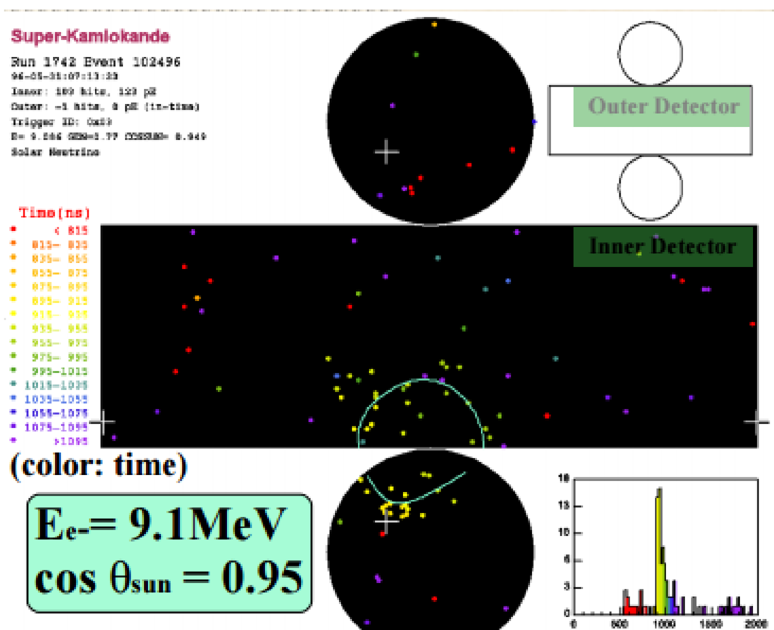


18 years of observations:

Continuous Measurements:

- Time variations
- Energy spectrum

Study U_{e1} & U_{e2} of U_{PMNS}

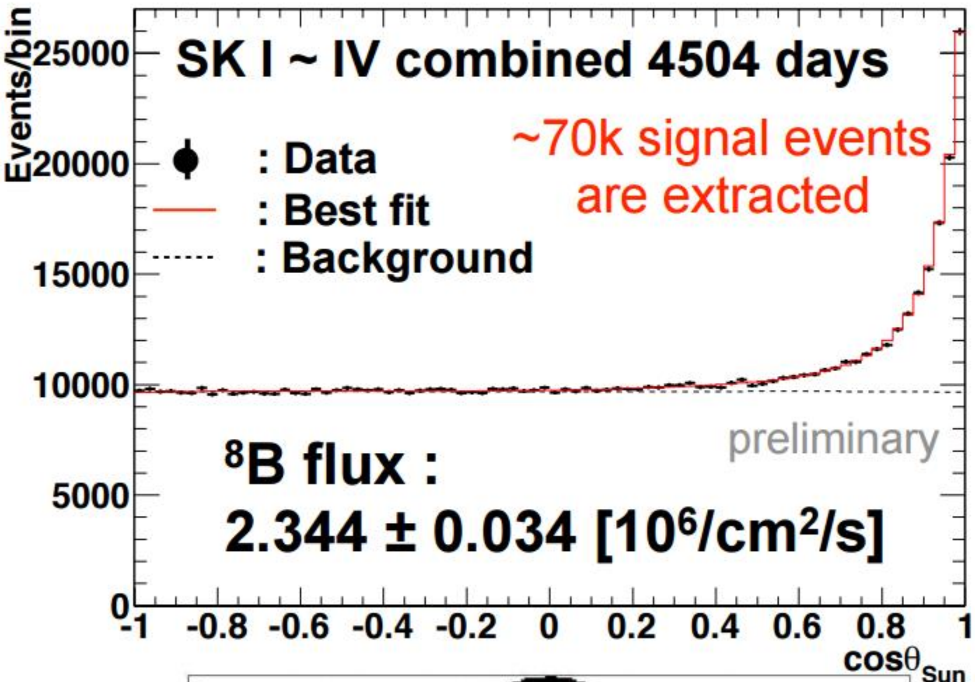


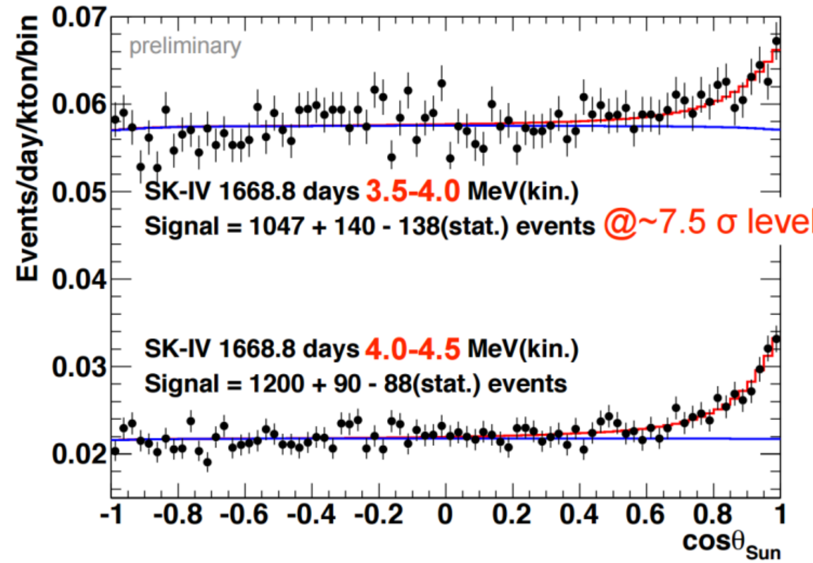
Courtesy Y. Takeuchi, Kobe University

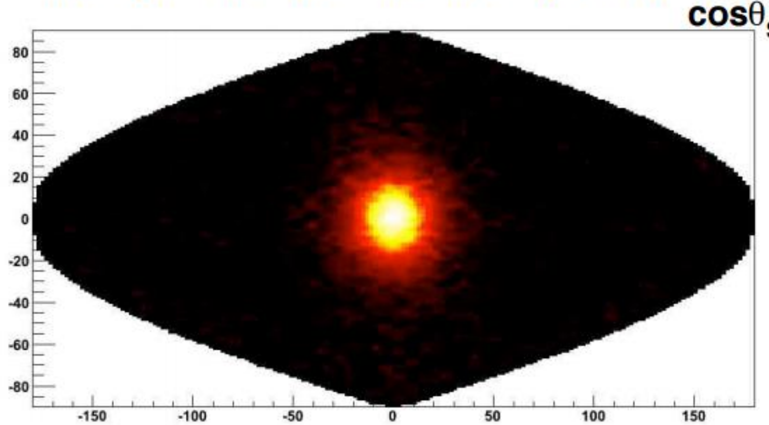
Detector Response at 10 MeV

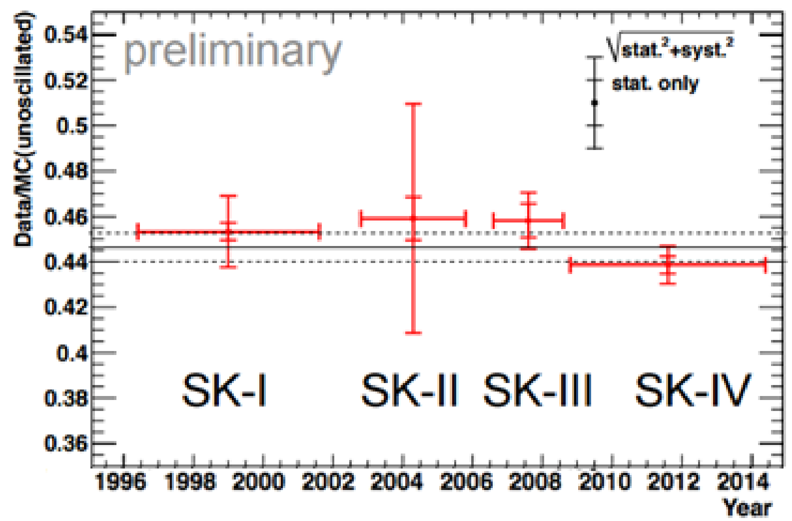
Detector Info	Reconstructed Info	Resolution
Hit timing	Vertex	52 cm
Hit Pattern	Direction	23^o
# hit PMTs	Energy (~6 hits/MeV)	14%

Solar Peak (flux)



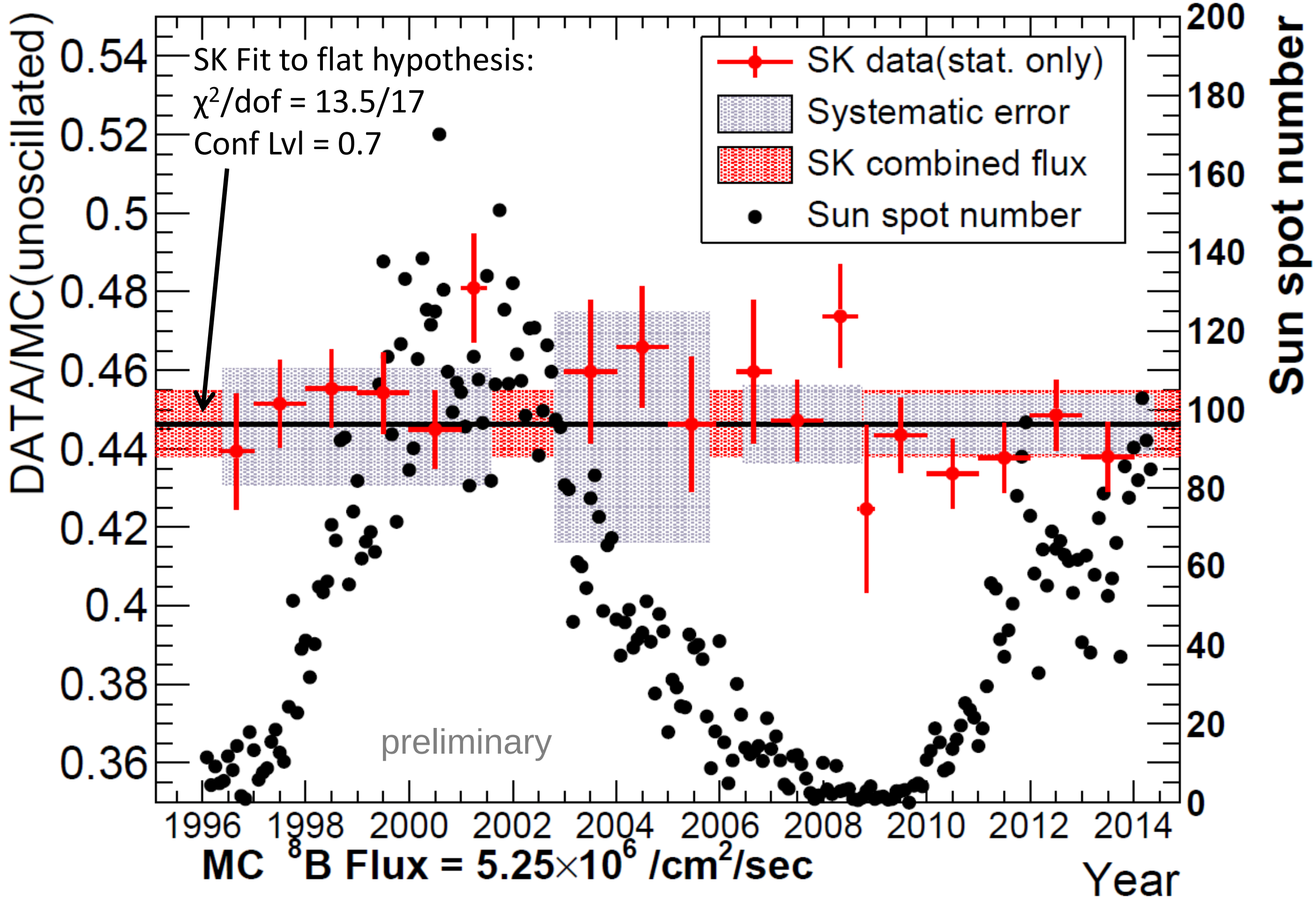






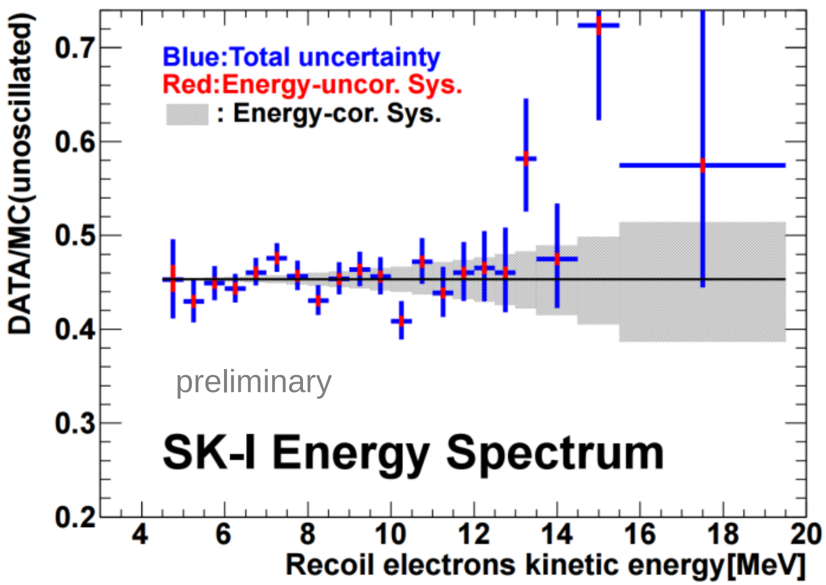
Other Time Variations: SK Yearly Plot + Sunspot Number

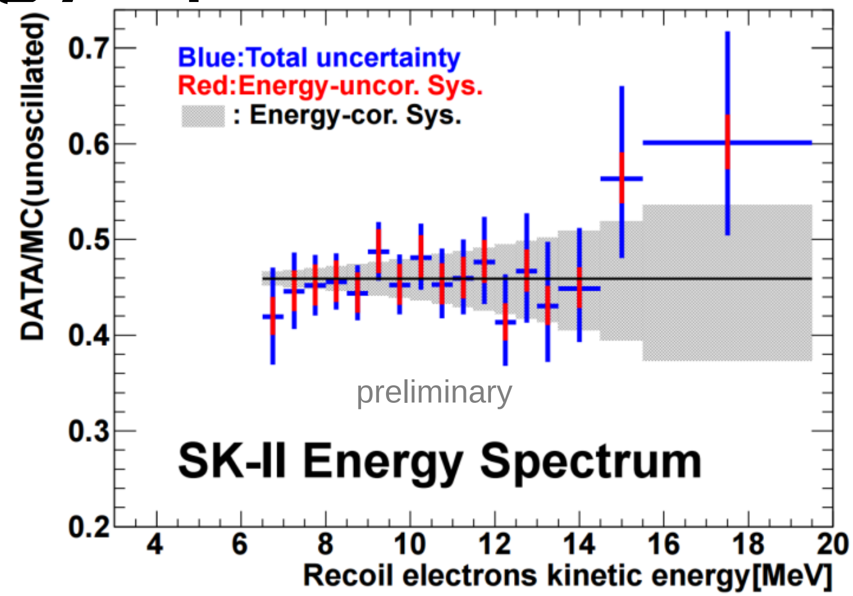
- No strong correlation between SK ν_{Solar} and Solar sunspot activity (number)
- Almost have ν_{Solar} SK data for 1.5 solar cycles

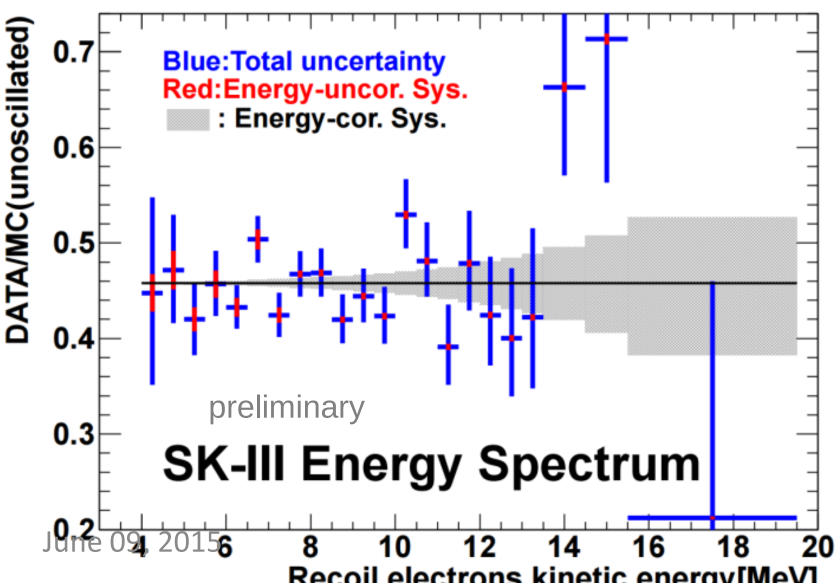


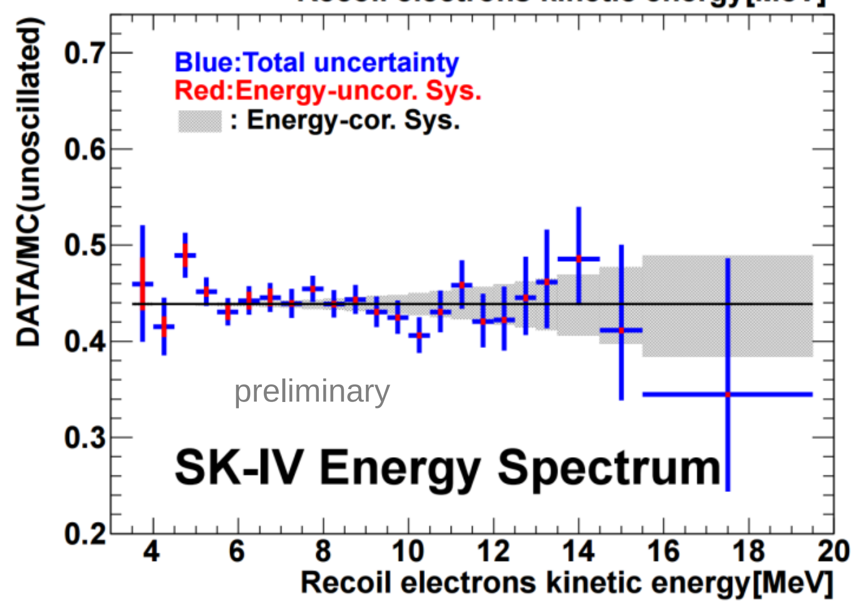
Sunspot Data: **http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt**

Recoil e$^-$ Energy Spectrum









Neutrino Oscillation

- Δm_{21}^2 and θ_{12} are important for solar neutrinos survival probability P_{ee}
  - Solar ν not sensitive to $\delta_{CP,}$ not very sensitive to θ_{13}

$$P_{ee} = |< \nu_e|\nu_e(t) > |2 = \left| \sum_i U_{ei}^* U_{ei}\ e^{-mi^2 L/2E} \right|^2$$

Pontecorvo–Maki–Nakagawa–Sakata mixing matrix (U_{PMNS})

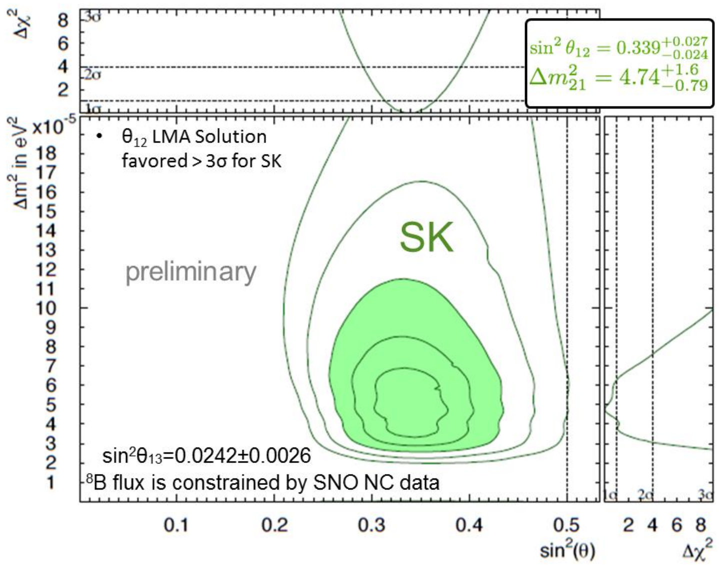
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$c_{ij} = \cos(\theta_{ij})$
$s_{ij} = \sin(\theta_{ij})$

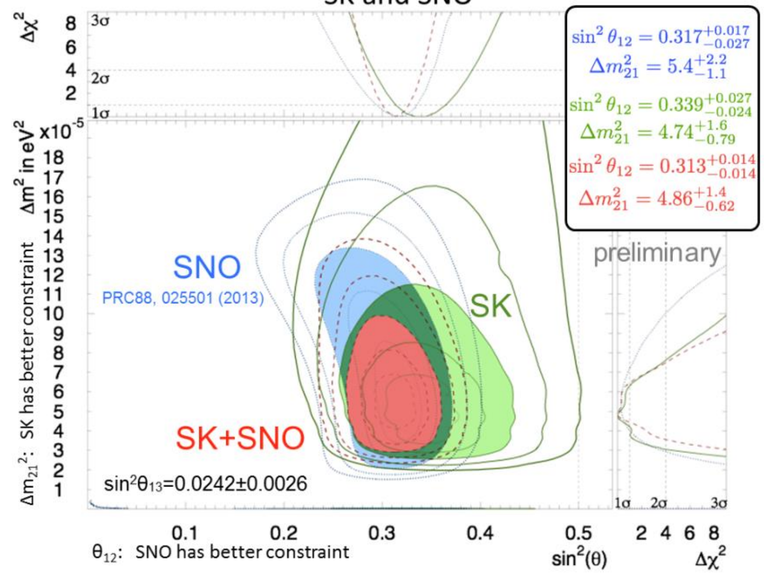
$$U_{PMNS} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

Solar Oscillation Parameters: Δm_{21}^2 and $\sin^2(\theta_{12})$

SK I-IV Combined



SK and SNO

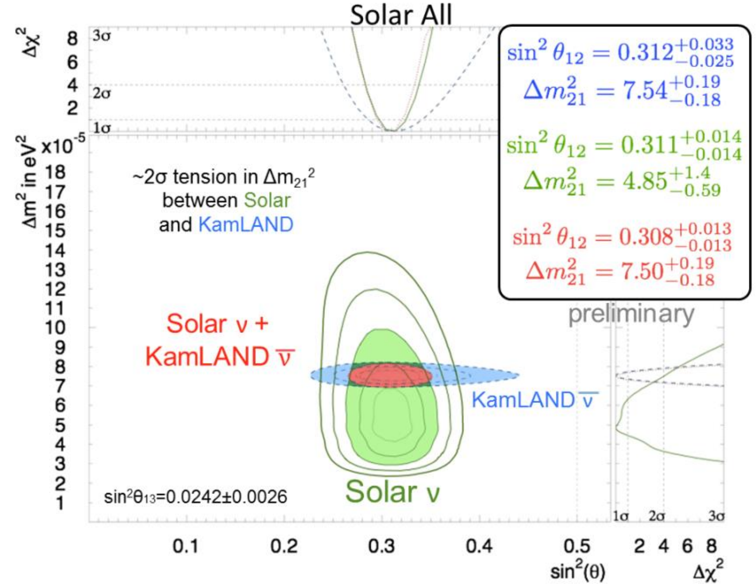


Data set for global solar analysis

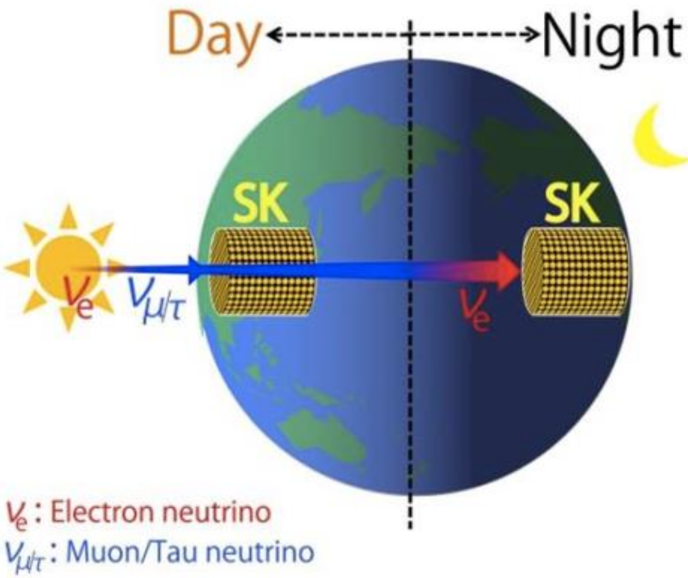
Does Not Include Borixino pp 2014

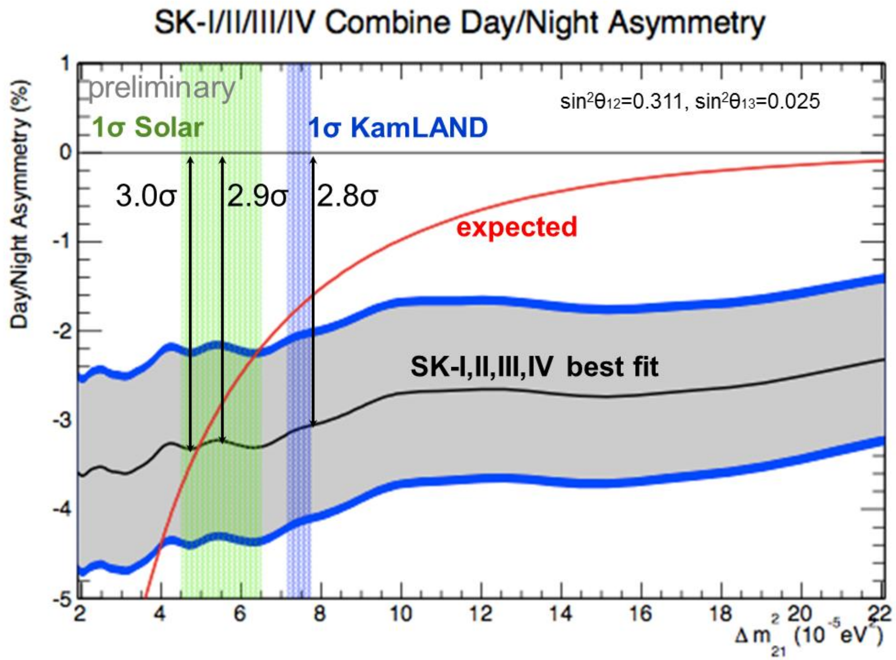
- ✓ **SK:**
  - **SK-I 1496 days, spectrum 4.5-19.5 MeV(kin.)+D/N:E_{kin}>4.5 MeV**
  - **SK-II 791 days, spectrum 6.5-19.5 MeV(kin.)+D/N: E_{kin}>7.0 MeV**
  - **SK-III 548 days, spectrum 4.0-19.5 MeV(kin.)+D/N: E_{kin}>4.5 MeV**
  - **SK-IV 1669 days, spectrum 3.5-19.5 MeV(kin.)+D/N: E_{kin}>4.5 MeV**
- ✓ **SNO:**
  - **Parameterized analysis (c_0, c_1, c_2, a_0, a_1) of all SNO phased. (PRC88, 025501 (2013))**
  - **(Note: the same method is applied to both SK and SNO with a_0 and a_1 to LMA expectation.)**
- ✓ **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, 505 (1998))**
- ✓ **Borexino: Latest ^{7}Be flux (PRL 107, 141302 (2011))**
- ✓ **KamLAND reactor : Latest (3-flavor) analysis (PRD88, 3, 033001 (2013))**
- ✓ **^{8}B spectrum: Winter 2006 (PRC73, 73, 025503 (2006))**
- ✓ **^{8}B and hep flux free, if not mentioned.**

Solar All



Δm_{21}^2 and Day/Night Asymmetry

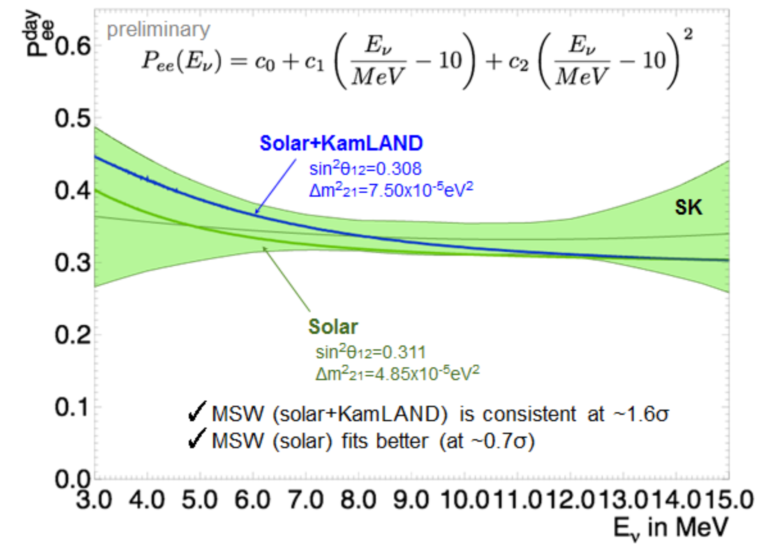


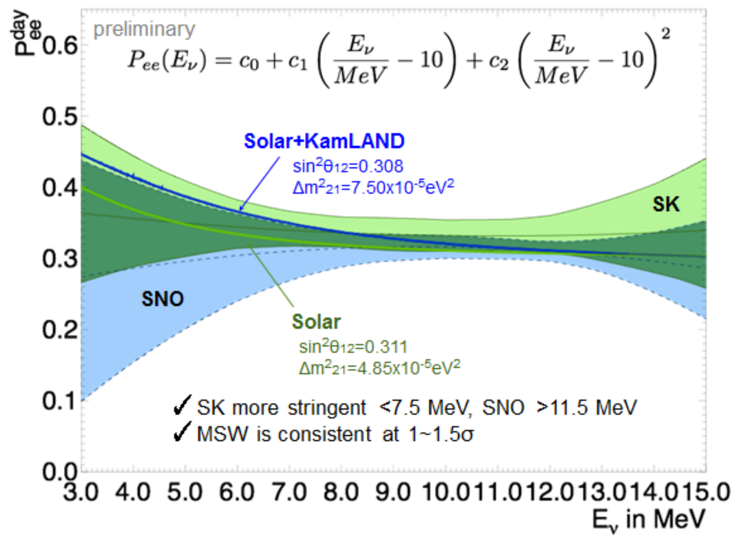


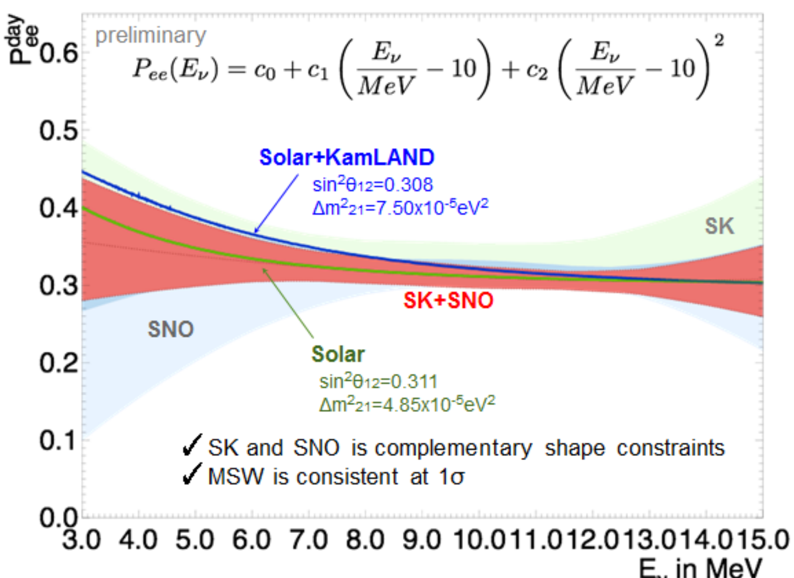
preliminary	Amplitude fit		Straight calc. (D-N)/((D+N)/2)
	$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2	$\Delta m^2_{21}=7.50\times10^{-5}$ eV^2	
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
combined	-3.3±1.0±0.5%	-3.1±1.0±0.5%	-4.1±1.2±0.8%
non-zero significance	3.0σ	2.8σ	2.8σ

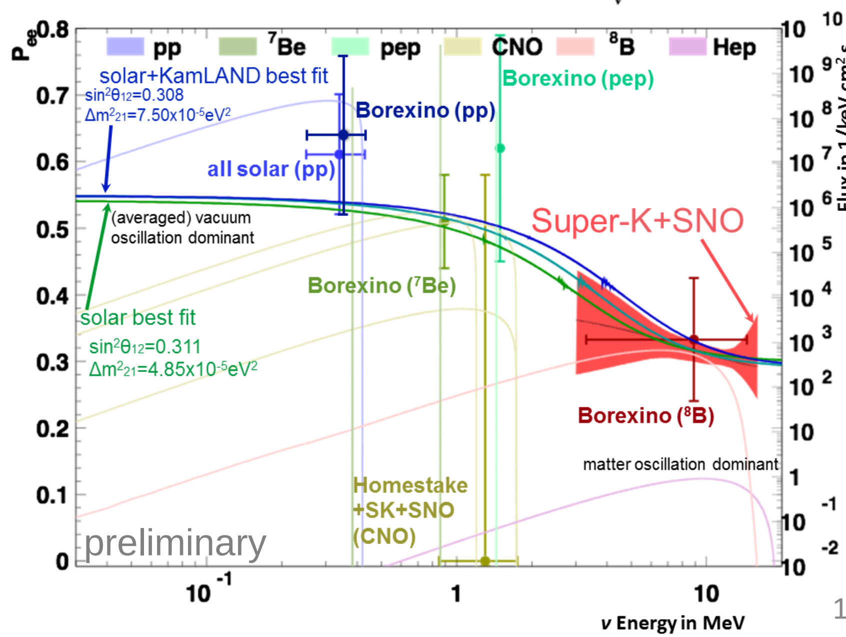
($\sin^2\theta_{12}=0.311$, $\sin^2\theta_{13}=0.025$)

^{8}B Survival Probability: Quadratic Fit, Upturn







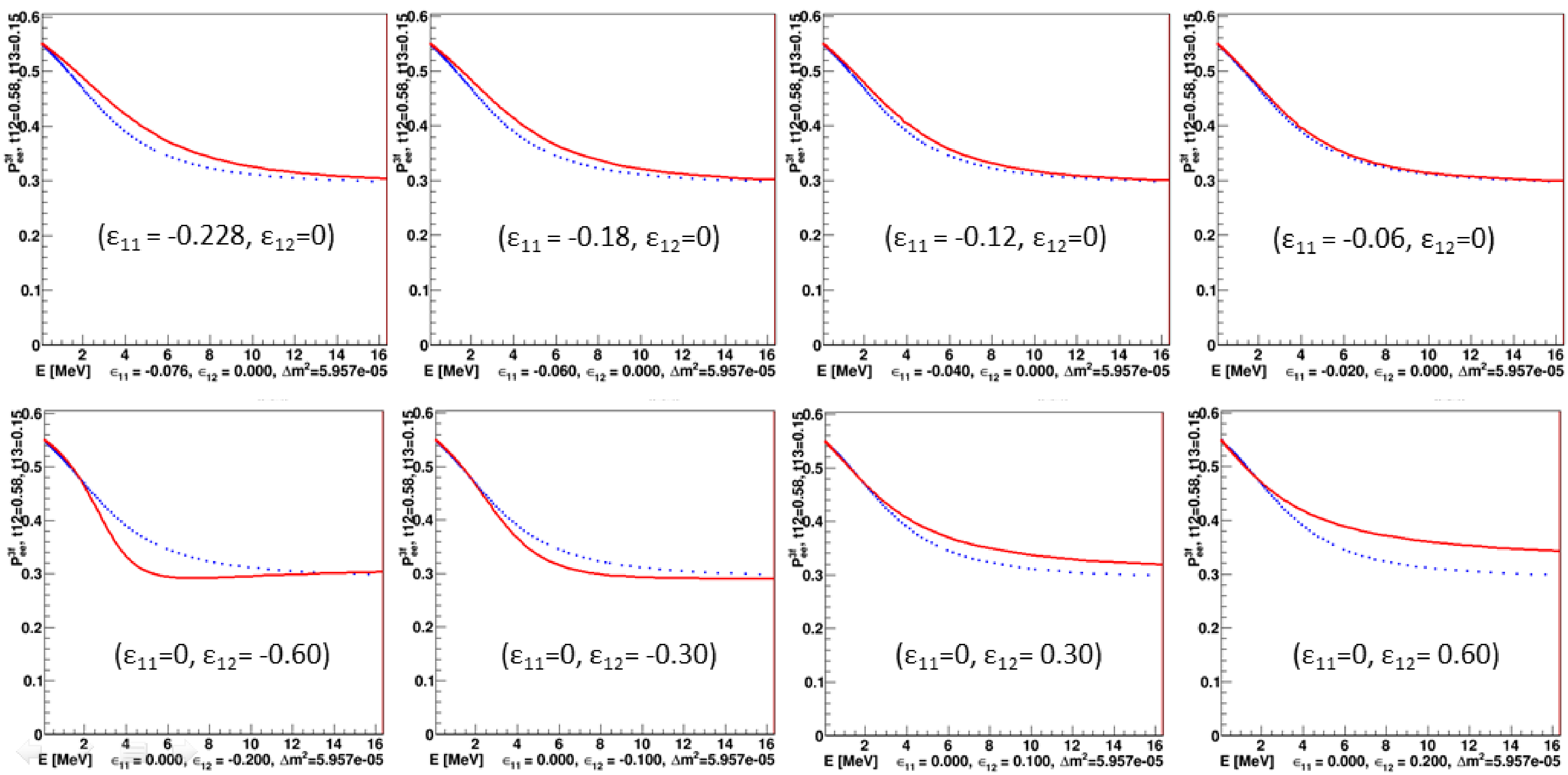


Non-Standard Interactions (NSI)

- Extension of the MSW Effect (Set muon-related terms to zero 🚫)
- Solar P^{2f}_{ee} analytical calculation*, converted to P^{3f}_{ee} calculation
  - Why does SK & SNO prefer no upturn?
  - Can NSI allow for better fit to flat SK recoil e⁻ spectrum?
  - Can it describe the lack of MSW upturn in SK data?
  - Set limits on NSI parameters.
- $\varepsilon_{11} = \varepsilon_{ee} - \varepsilon_{\tau\tau} \sin^2\theta_{23}$ & $\varepsilon_{12} = -2\varepsilon_{e\tau} \sin\theta_{23}$

$$H_{\rm mat} = \sqrt{2} G_F n_e \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu}^* & \varepsilon_{e\tau}^* \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}^* \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

^{8}B: NSI and non-NSI $(\varepsilon_{11}, \varepsilon_{12}) = (0,0)$



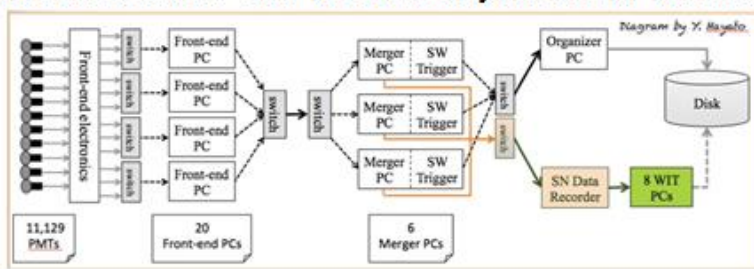
*Friedland, Lunardini and Pena-Garay Phys.Lett.B594:347,2004

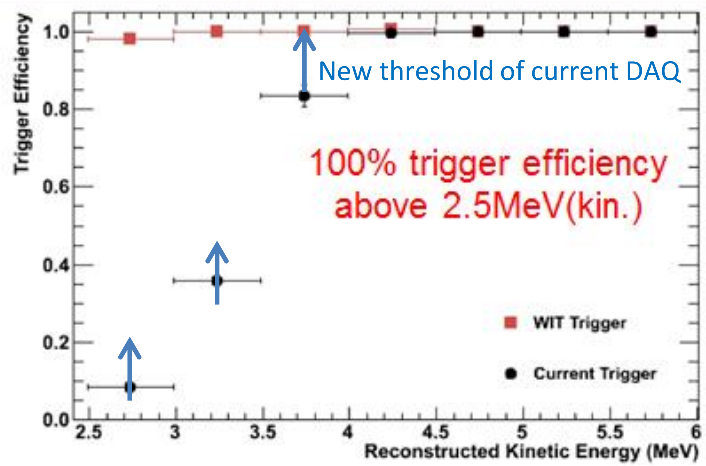
WIT/Future

- SK is pushing low energy threshold to attack the MSW upturn:
  - SK standard DAQ threshold being lowered
  - 100 % efficiency@ 3.5 MeV kinetic energy threshold
  - A couple of weeks of WIT data collected
    - Commissioning of the system, background cuts
    - 2.5 MeV kinetic energy threshold (100% efficiency)
    - Continuous running soon.

WIT (Wide-band Intelligent Trigger)

Reconstruction and Reduction just after Front-end





Summary

- Super-K has been detecting ^8B solar neutrinos for about 18 years via elastic scattering off e^- in H_2O, and has measured the solar flux with large statistics
- Super-K has made competitive measurements of the solar oscillation parameters Δm_{21}^2 and θ_{12}, along with a measurement of the Day/Night Asymmetry
- Super-K is further exploring the MSW upturn by lowering its energy threshold via WIT and the standard DAQ; also performing search for Non-Standard Neutrino Interactions

Backup

PRL 112, 091805 (2014) PHYSICAL REVIEW LETTERS week ending 7 MARCH 2014

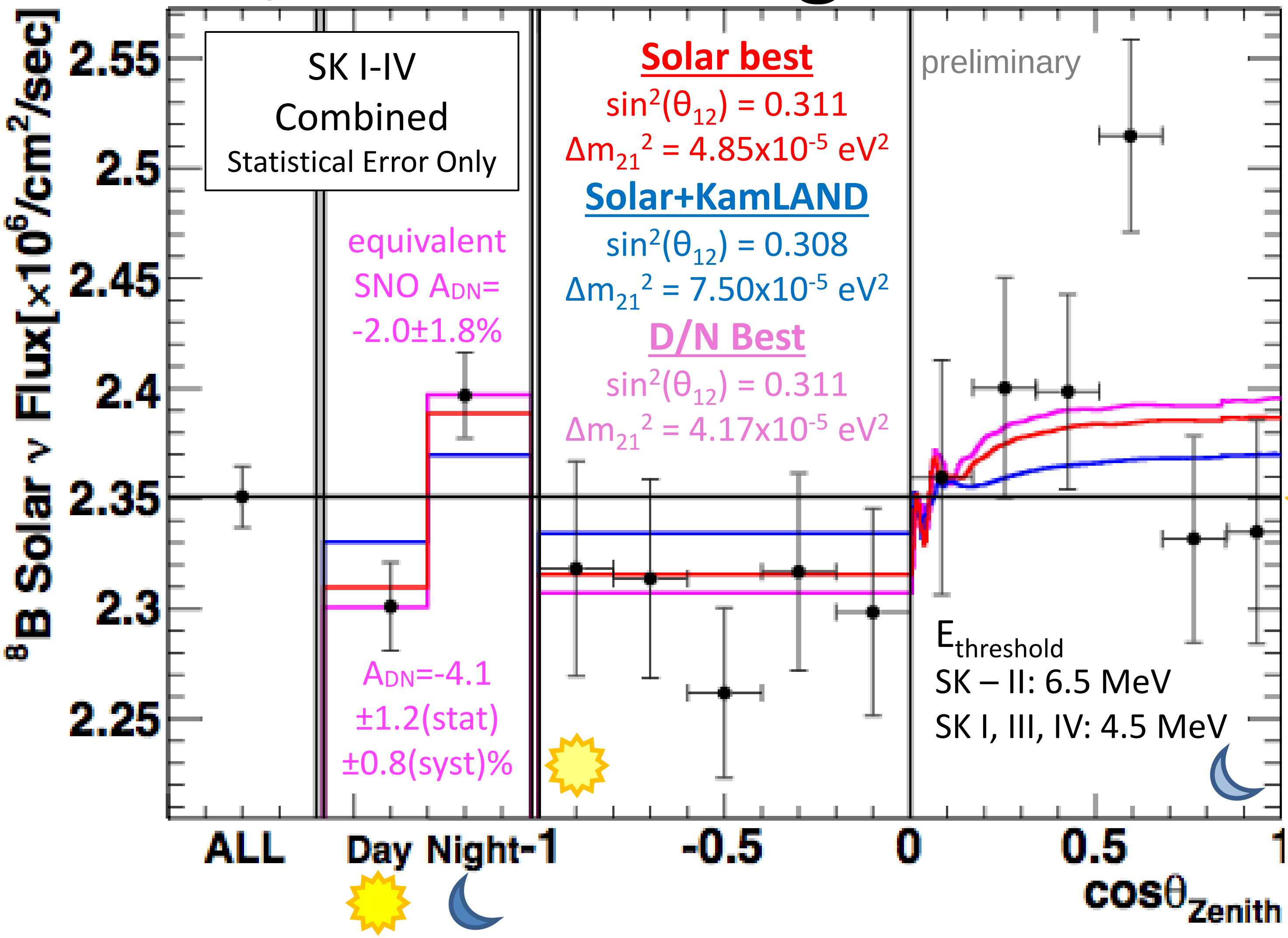
First Indication of Terrestrial Matter Effects on Solar Neutrino Oscillation

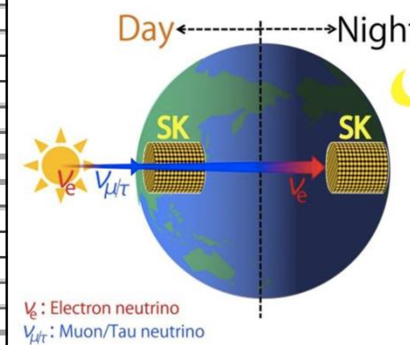
A. Renshaw,[7,†] K. Abe,[1,29] Y. Hayato,[1,29] K. Iyogi,[1] J. Kameda,[1,29] Y. Kishimoto,[1,29] M. Miura,[1,29] S. Moriyama,[1,29] M. Nakahata,[1,29] Y. Nakano,[1] S. Nakayama,[1,29] H. Sekiya,[1,29] M. Shiozawa,[1,29] Y. Suzuki,[1,29] A. Takeda,[1,29] Y. Takenaga,[1] T. Tomura,[1,29] K. Ueno,[1] T. Yokozawa,[1] R. A. Wendell,[1,29] T. Irvine,[2] T. Kajita,[2,29] K. Kaneyuki,[2,29,*] K. P. Lee,[2] Y. Nishimura,[2] K. Okumura,[2,29] T. McLachlan,[2] L. Labarga,[3] S. Berkman,[4] H. A. Tanaka,[4,31] S. Tobayama,[4] E. Kearns,[5,29] J. L. Raaf,[5] J. L. Stone,[5,29] L. R. Sulak,[5] M. Goldhabar,[6,*] K. Bays,[7] G. Carminati,[7] W. R. Kropp,[7] S. Mine,[7] M. B. Smy,[7,29] H. W. Sobel,[7,29] K. S. Ganezer,[8] J. Hill,[8] W. E. Keig,[8] N. Hong,[9] J. Y. Kim,[9] I. T. Lim,[9] T. Akiri,[10] A. Himmel,[10] K. Scholberg,[10,29] C. W. Walter,[10,29] T. Wongjirad,[10] T. Ishizuka,[11] S. Tasaka,[12] J. S. Jang,[13] J. G. Learned,[14] S. Matsuno,[14] S. N. Smith,[14] T. Hasegawa,[15] T. Ishida,[15] T. Ishii,[15] T. Kobayashi,[15] T. Nakadaira,[15] K. Nakamura,[15,29] Y. Oyama,[15] K. Sakashita,[15] T. Sekiguchi,[15] T. Tsukamoto,[15] A. T. Suzuki,[16] Y. Takeuchi,[16] C. Bronner,[17] S. Hirota,[17] K. Huang,[17] K. Ieki,[17] M. Ikeda,[17] T. Kikawa,[17] A. Minamino,[17] T. Nakaya,[17,29] K. Suzuki,[17] S. Takahashi,[17] Y. Fukuda,[18] K. Choi,[19] Y. Itow,[19] G. Mitsuka,[19] P. Mijakowski,[35] J. Hignight,[20] J. Imber,[20] C. K. Jung,[20] C. Yanagisawa,[20] H. Ishino,[21] A. Kibayashi,[21] Y. Koshio,[21] T. Mori,[21] M. Sakuda,[21] T. Yano,[21] Y. Kuno,[22] R. Tacik,[23,32] S. B. Kim,[24] H. Okazawa,[25] Y. Choi,[26] K. Nishijima,[27] M. Koshiba,[28] Y. Totsuka,[28,*] M. Yokoyama,[28,29] K. Martens,[29] Ll. Marti,[29] M. R. Vagins,[29,7] J. F. Martin,[30] P. de Perio,[30] A. Konaka,[32] M. J. Wilking,[32] S. Chen,[33] Y. Zhang,[33] and R. J. Wilkes[34]

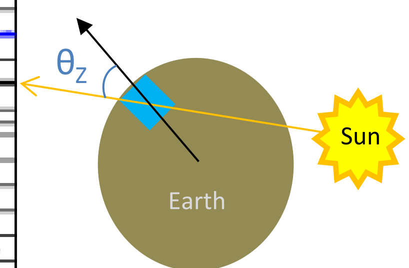
1 Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
2 RCCN, ICRResearch, Univ. of Tokyo, Japan
3 University Autonoma Madrid, Spain
4 University of British Columbia, Canada
5 Boston University, USA
6 Brookhaven National Laboratory, USA
7 University of California, Irvine, USA
8 California State University, USA
9 Chonnam National University, Korea
10 Duke University, USA
11 Fukuoka Institute of Technology, Japan
12 Gifu University, Japan
13 GIST College, Korea
14 University of Hawaii, USA
15 KEK, Japan
16 Kobe University, Japan
17 Kyoto University, Japan
18 Miyagi University of Education, Japan
19 STE, Nagoya University, Japan
20 SUNY, Stony Brook, USA
21 Okayama University, Japan
22 Osaka University, Japan
23 University of Regina, Canada
24 Seoul National University, Korea
25 Shizuoka University of Welfare, Japan
26 Sungkyunkwan University, Korea
27 Tokai University, Japan
28 University of Tokyo, Japan
29 Kavli IPMU (WPI), University of Tokyo, Japan
30 Dep. of Phys., University of Toronto, Canada
31 Inst. of Part. Phys., University of Toronto, Canada
32 TRIUMF, Canada
33 Tsinghua University, China
34 University of Washington, USA
35 Warsaw University, Poland

~120 collaborators
35 institutions
7 countries

D/N Zenith Angle Distribution

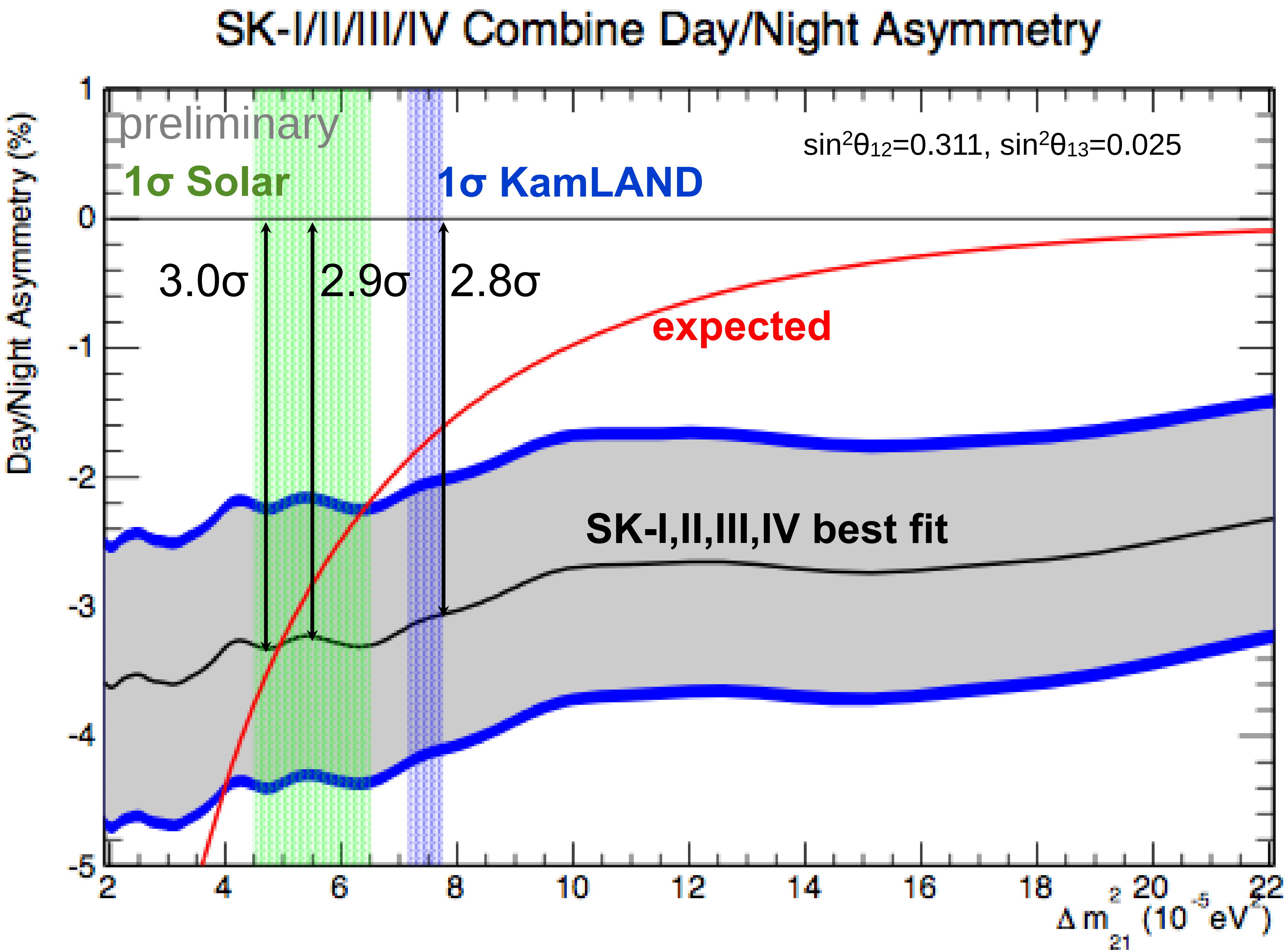






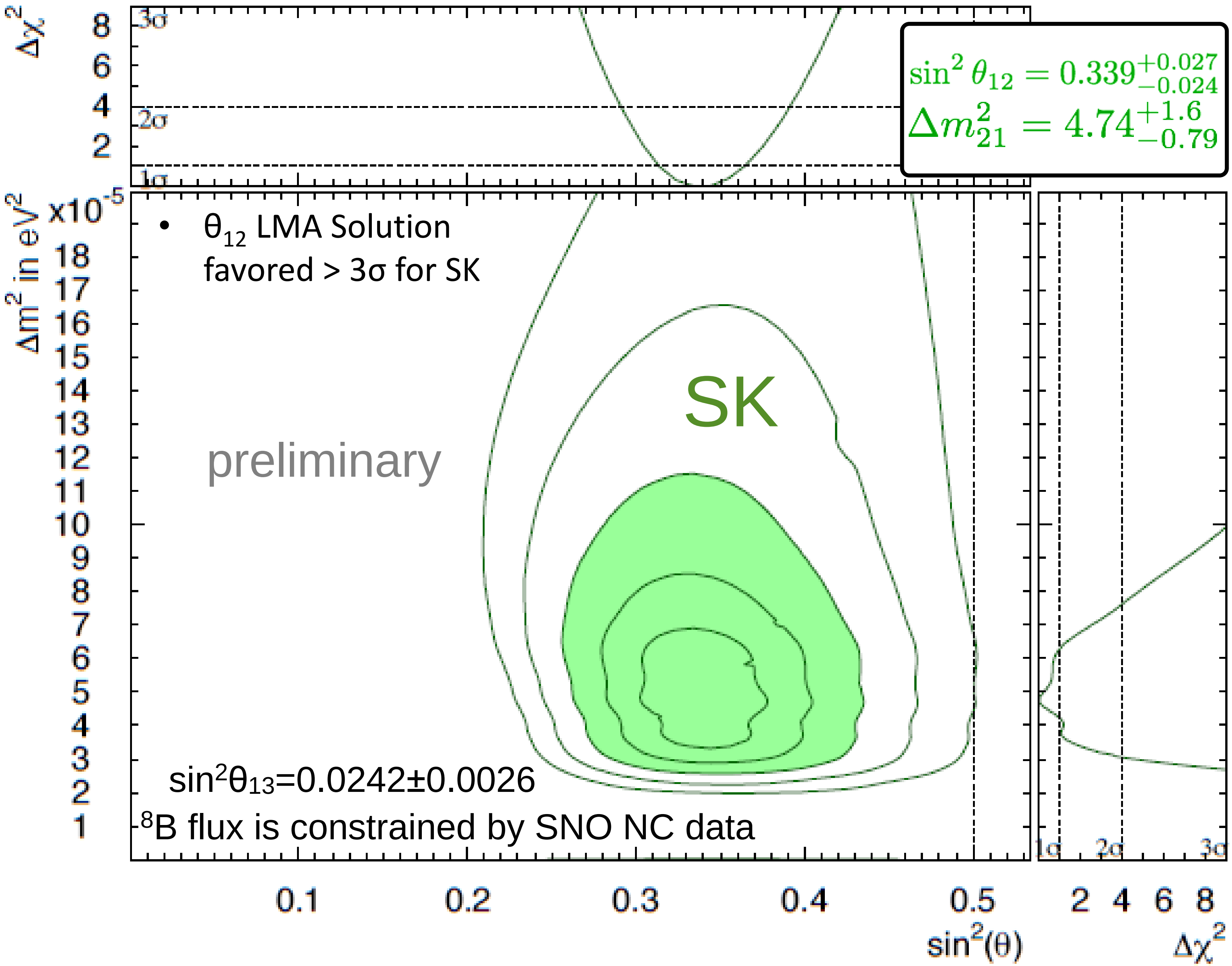
Day/Night Asymmetry
Straight Calc:

$$A_{DN} = \frac{R_D - RN}{(RD + RN)/2}$$

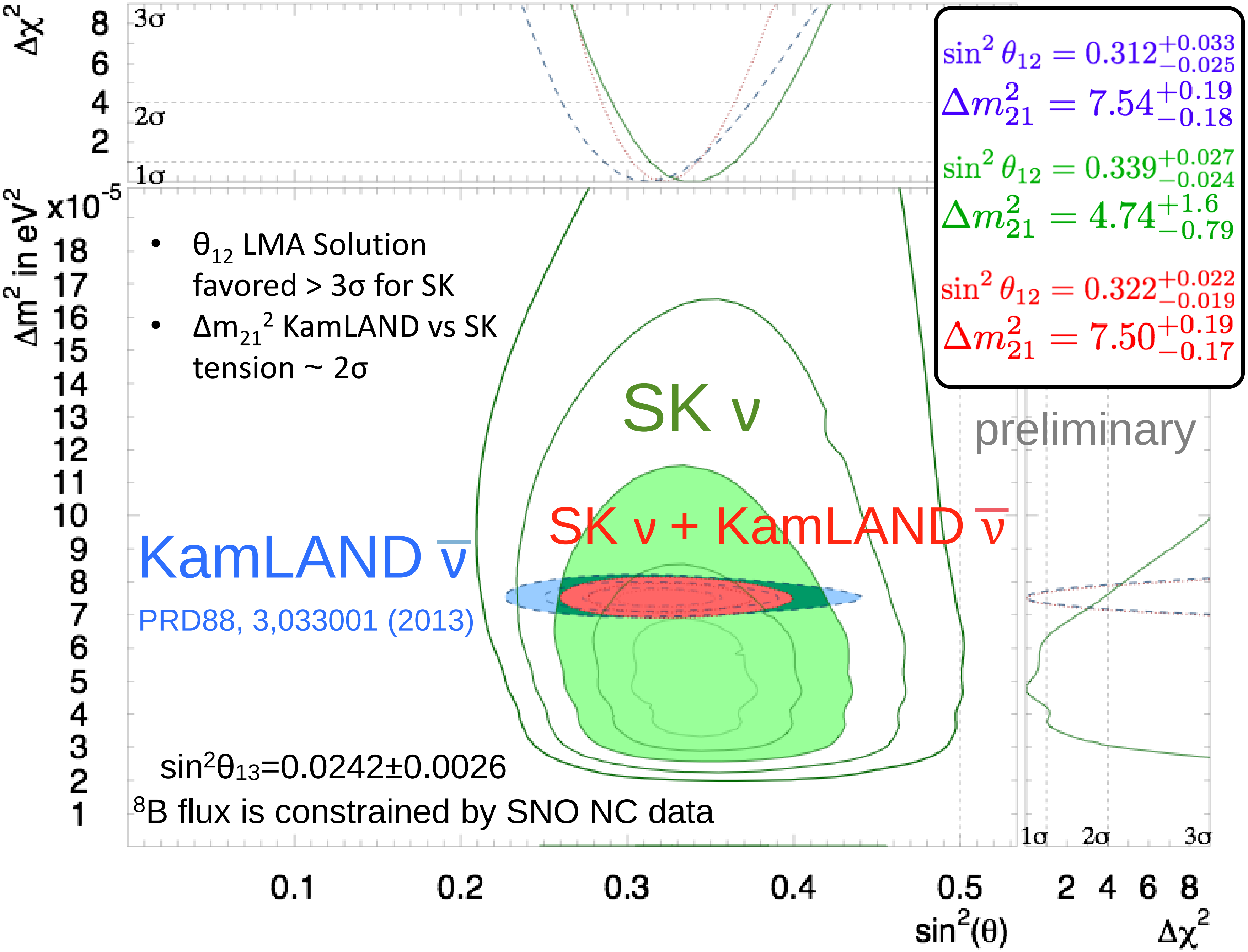


SK-I/II/III/IV Combine Day/Night Asymmetry
preliminary
1σ Solar
1σ KamLAND
sin²θ12=0.311, sin²θ13=0.025
3.0σ
2.9σ
2.8σ
expected
SK-I,II,III,IV best fit
Day/Night Asymmetry (%)
Δ m²21 (10⁻⁵ eV²)

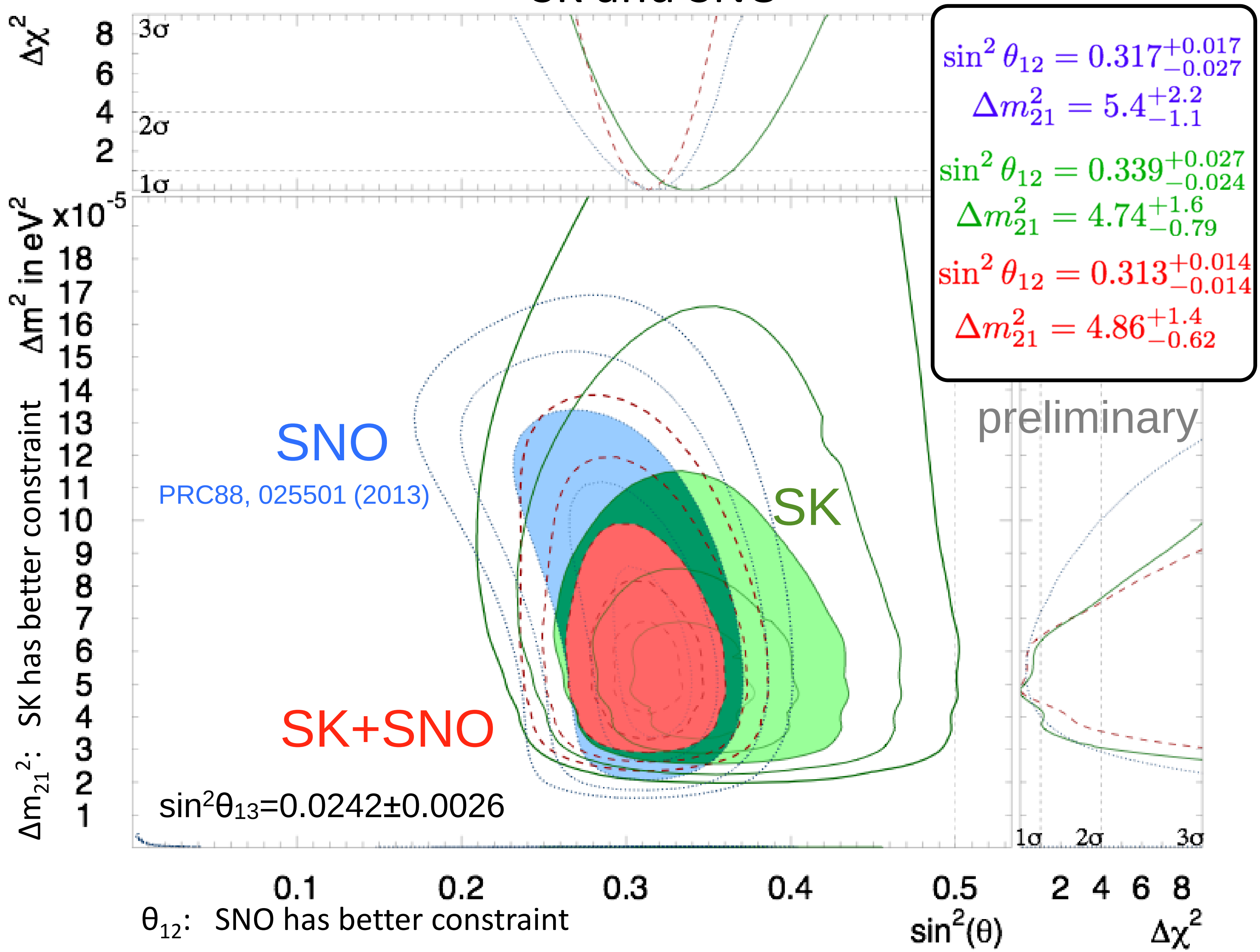
SK I-IV Combined



SK I-IV Combined

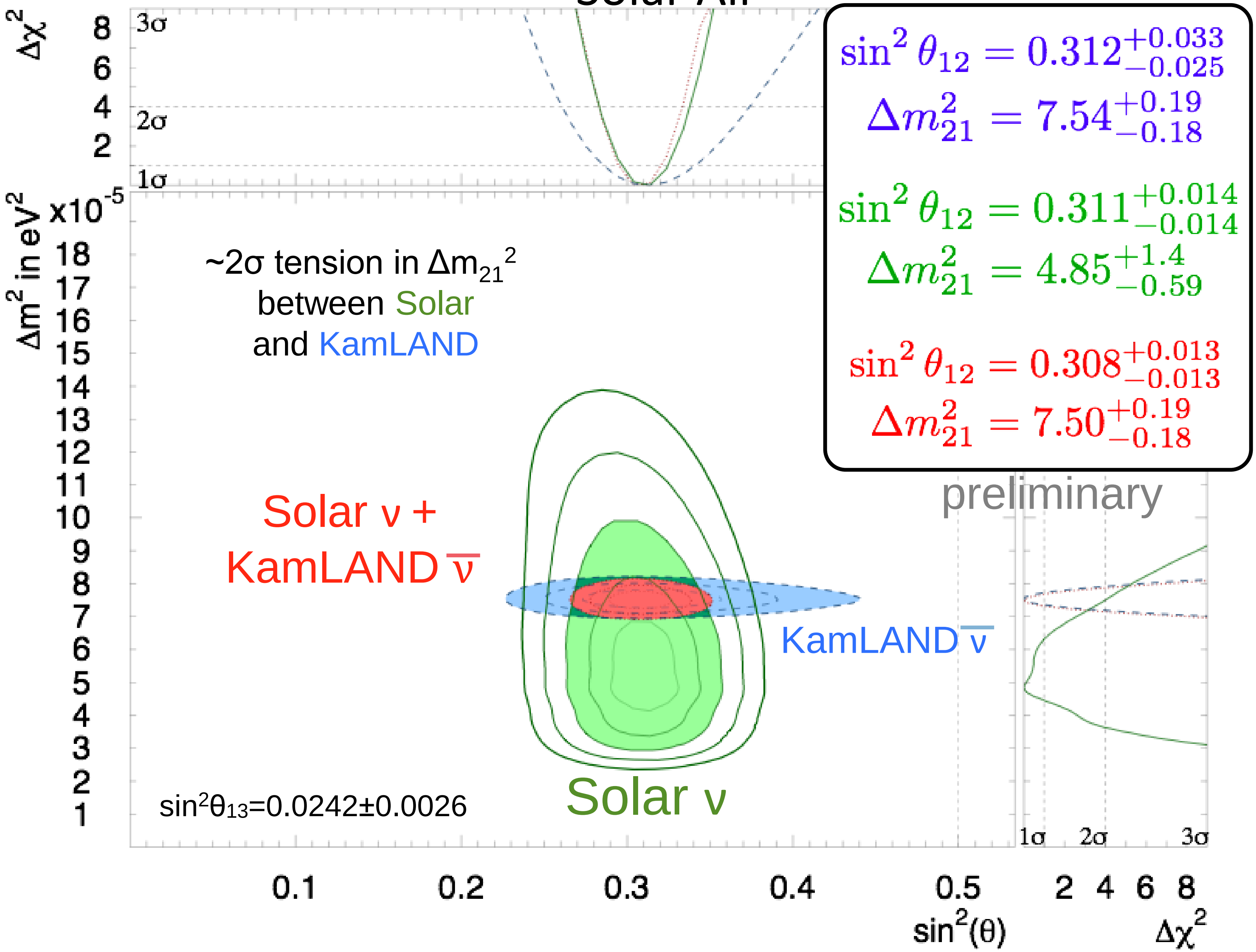


SK and SNO

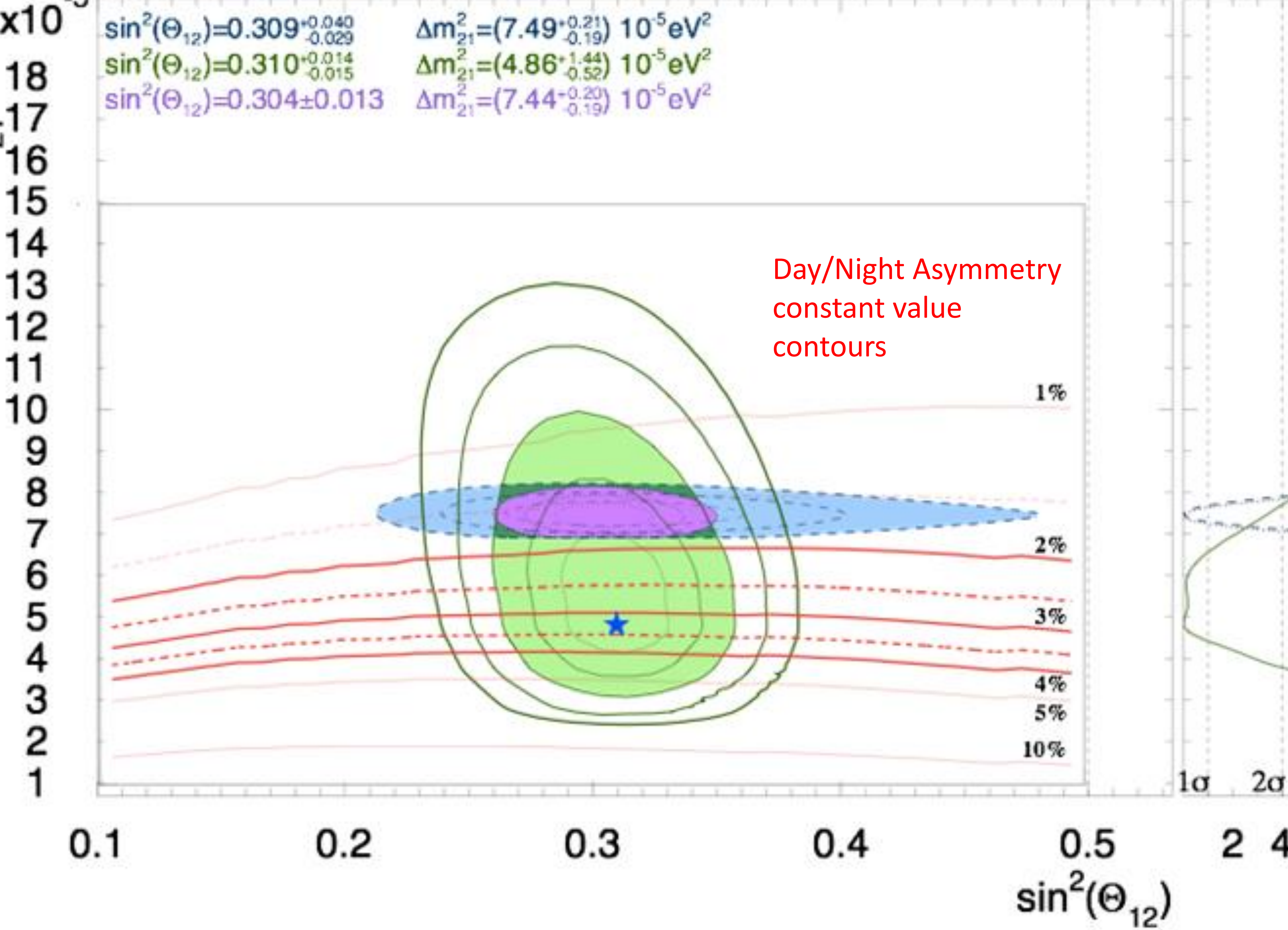


$\sin^2\theta_{12} = 0.317^{+0.017}_{-0.027}$
$\Delta m^2_{21} = 5.4^{+2.2}_{-1.1}$
$\sin^2\theta_{12} = 0.339^{+0.027}_{-0.024}$
$\Delta m^2_{21} = 4.74^{+1.6}_{-0.79}$
$\sin^2\theta_{12} = 0.313^{+0.014}_{-0.014}$
$\Delta m^2_{21} = 4.86^{+1.4}_{-0.62}$
preliminary
SNO
PRC88, 025501 (2013)
SK
SK+SNO
$\sin^2\theta_{13}$=0.0242±0.0026
$\Delta\chi^2$
Δm^2 in eV^2 x10^{-5}
$\sin^2(\theta)$
1σ
2σ
3σ
Δm^2_{21}: SK has better constraint
θ_{12}: SNO has better constraint

Solar All

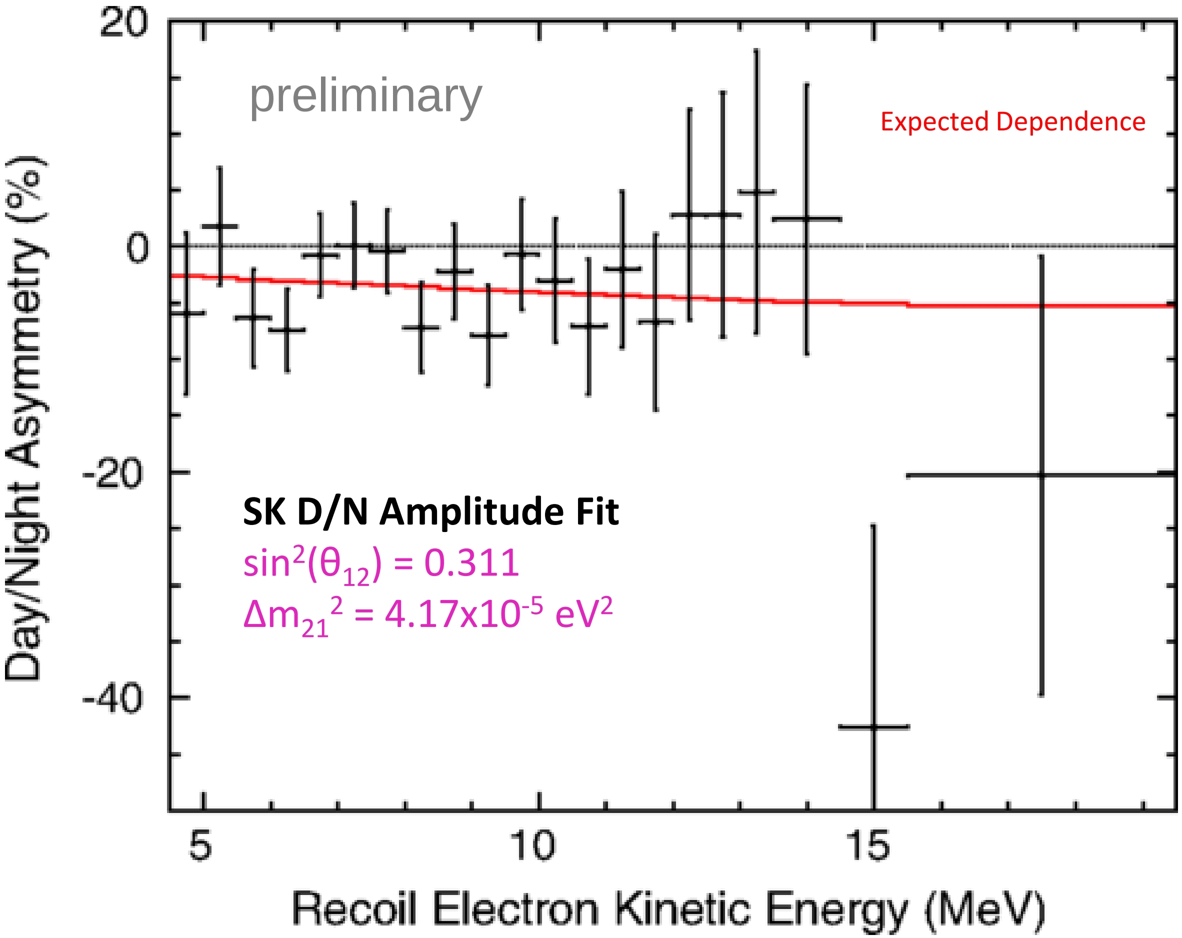


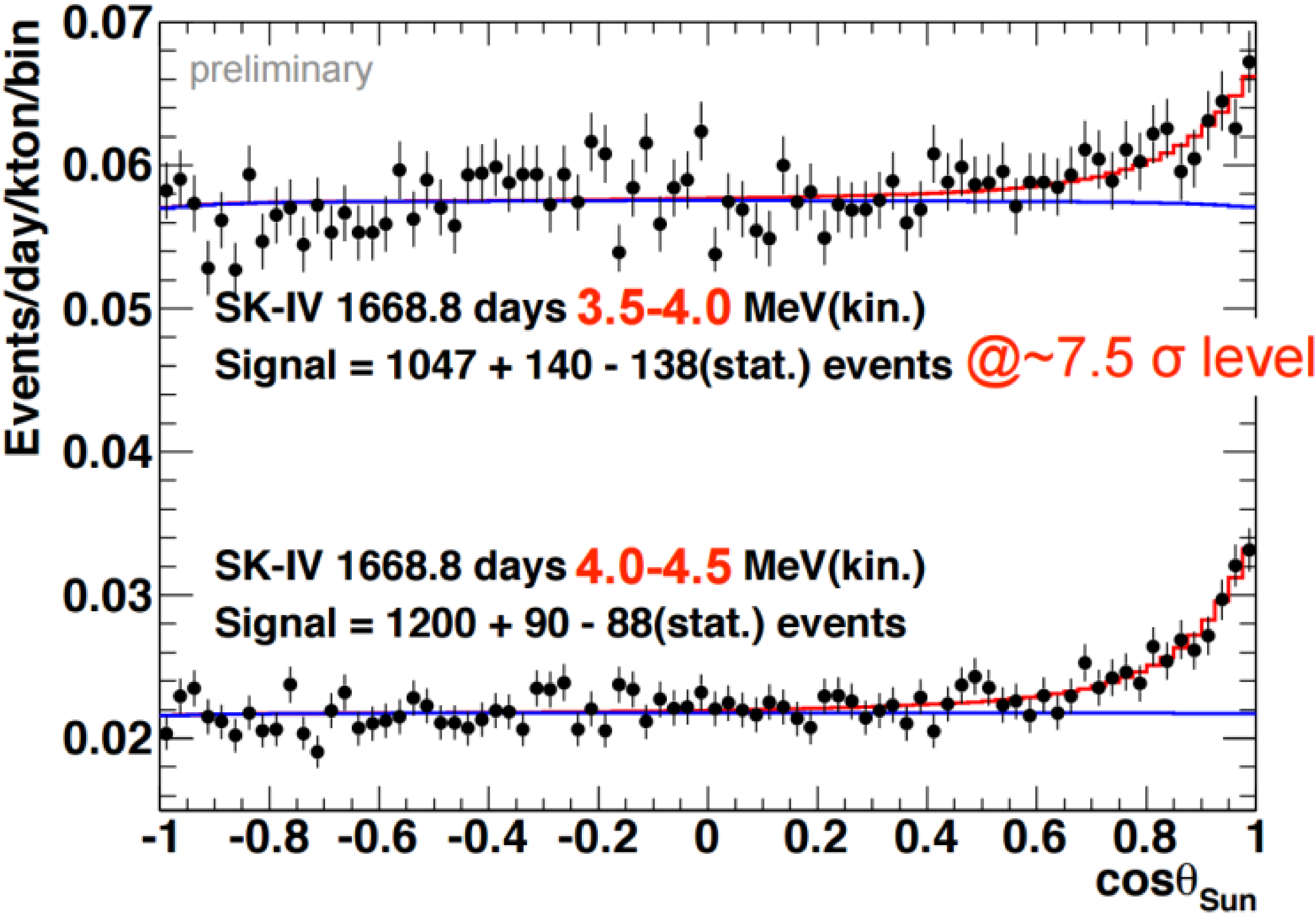
$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$
$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$
$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$
$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$
$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$
~2σ tension in Δm_{21}^2 between Solar and KamLAND
Solar ν + KamLAND $\overline{\nu}$
KamLAND $\overline{\nu}$
Solar ν
preliminary
$\sin^2\theta_{13}$=0.0242±0.0026
$\Delta\chi^2$
Δm^2 in eV^2 $\times 10^{-5}$
$\sin^2(\theta)$
1σ
2σ
3σ



x10
$\sin^2(\Theta_{12})=0.309^{+0.040}_{-0.029}$
$\Delta m^2_{21}=(7.49^{+0.21}_{-0.19})\ 10^{-5}eV^2$
$\sin^2(\Theta_{12})=0.310^{+0.014}_{-0.015}$
$\Delta m^2_{21}=(4.86^{+1.44}_{-0.52})\ 10^{-5}eV^2$
$\sin^2(\Theta_{12})=0.304\pm0.013$
$\Delta m^2_{21}=(7.44^{+0.20}_{-0.19})\ 10^{-5}eV^2$
Day/Night Asymmetry
constant value
contours
1%
2%
3%
4%
5%
10%
1σ
2σ
0.1
0.2
0.3
0.4
0.5
$\sin^2(\Theta_{12})$

D/N Asymmetry vs Recoil e^- Kinetic Energy





Events/day/kton/bin
0.07
0.06
0.05
0.04
0.03
0.02
preliminary
SK-IV 1668.8 days 3.5-4.0 MeV(kin.)
Signal = 1047 + 140 - 138(stat.) events
@~7.5 σ level
SK-IV 1668.8 days 4.0-4.5 MeV(kin.)
Signal = 1200 + 90 - 88(stat.) events
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cosθ_Sun

Data set for global solar analysis

Does Not Include Borixino pp 2014

✓ **SK:**

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

✓ **SNO:**

- **Parameterized analysis (c_0, c_1, c_2, a_0, a_1) of all SNO phased. (PRC88, 025501 (2013))**

(Note: the same method is applied to both SK and SNO with a_0 and a_1 to LMA expectation.)

✓ **Radiochemical: Cl, Ga**

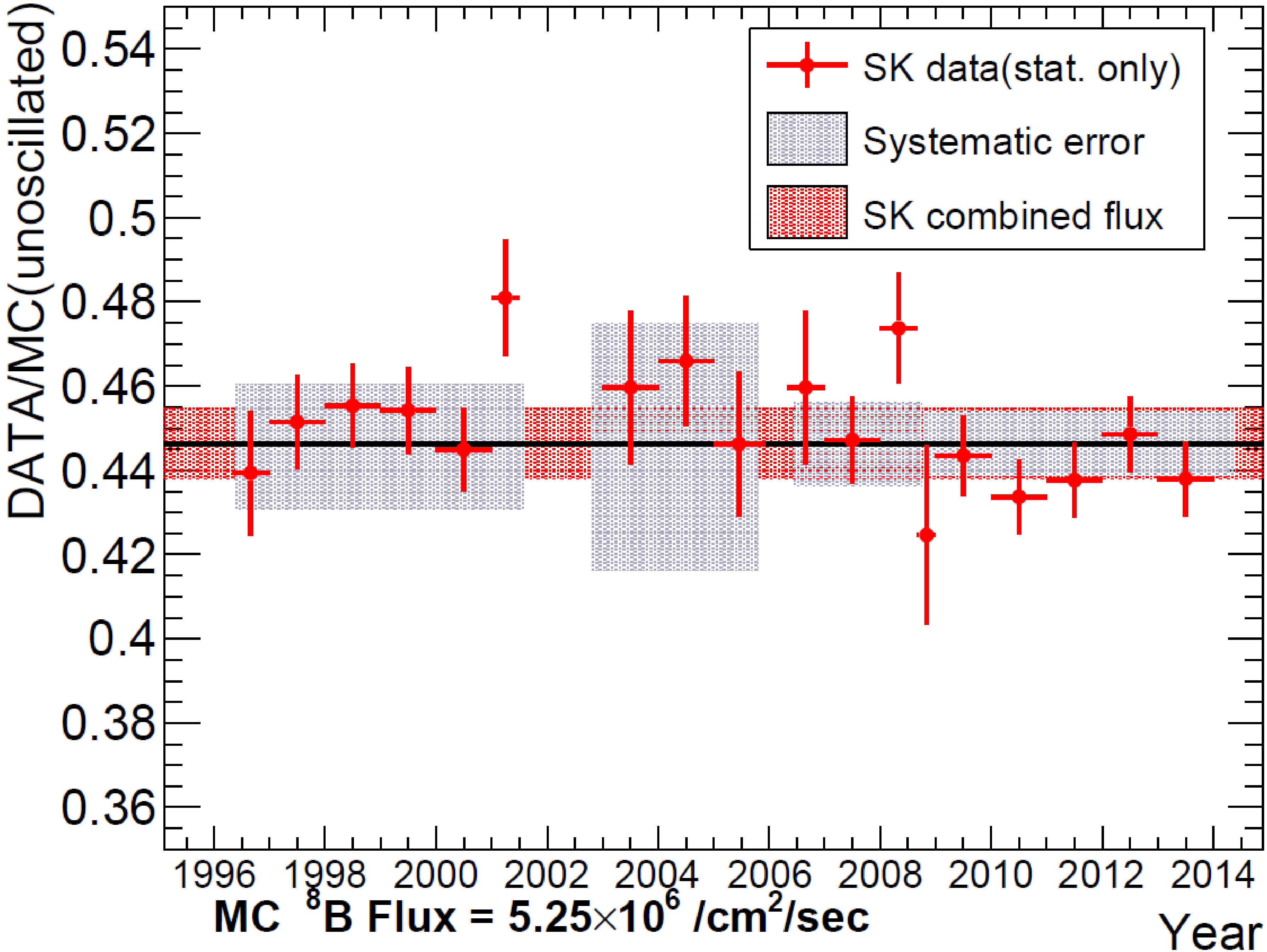
- **Ga rate: 66.1±3.1 SNU (All Ga global) (PRC80, 015807 (2009))**
- **Cl rate: 2.56±0.23 SNU(Astrophys. J.496, 505 (1998))**

✓ **Borexino: Latest ^{7}Be flux (PRL 107, 141302 (2011))**

✓ **KamLAND reactor : Latest (3-flavor) analysis (PRD88, 3, 033001 (2013))**

✓ **^{8}B spectrum: Winter 2006 (PRC73, 73, 025503 (2006))**

✓ **^{8}B and hep flux free, if not mentioned.**

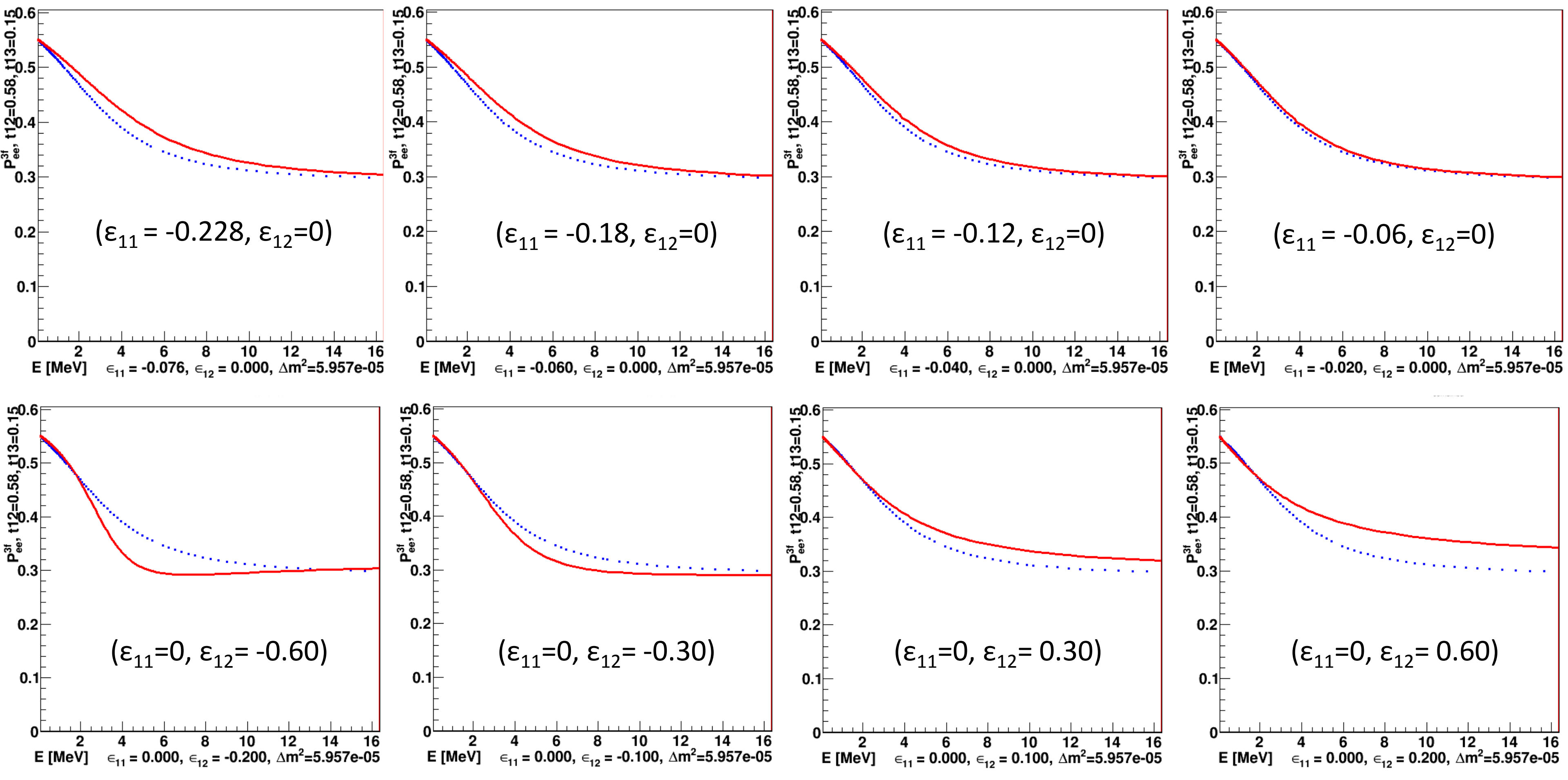


DATA/MC(unoscillated)
0.54
0.52
0.5
0.48
0.46
0.44
0.42
0.4
0.38
0.36
SK data(stat. only)
Systematic error
SK combined flux
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
MC ^{8}B Flux = 5.25×10^6 /cm^2/sec
Year

How do the ε_{ij} parameters affect P_{ee}^{3f} ?

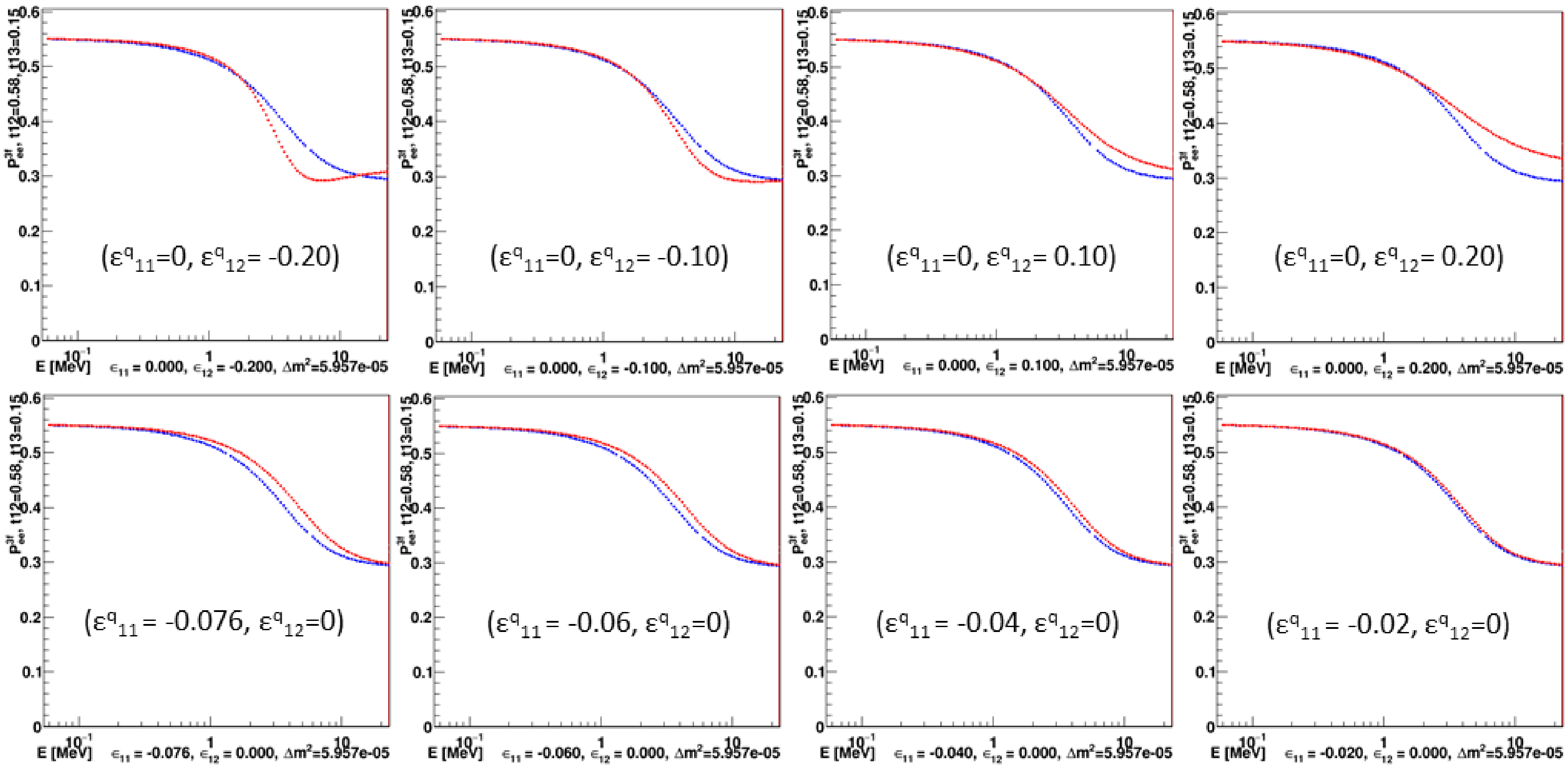
Solar analysis best fit values of θ_{12}, θ_{13}, and Δm_{12}^2

^{8}B: NSI and non-NSI $(\varepsilon_{11}, \varepsilon_{12})$ =(0,0)



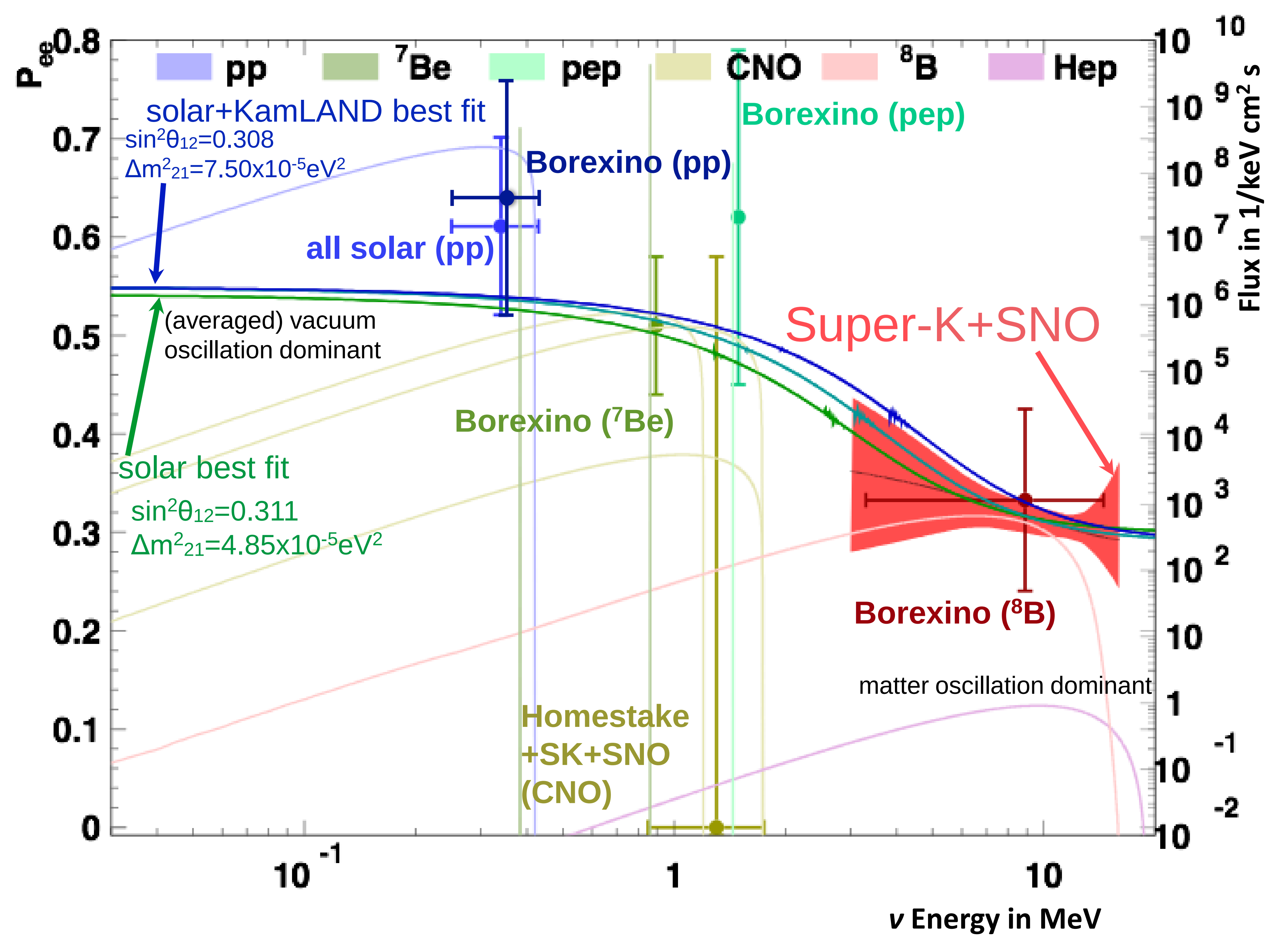
Pee NSI Log(E_ν)

^{8}B: NSI and non-NSI $(\varepsilon^q_{11}, \varepsilon^q_{12}) = (0,0)$



	Amplitude fit		Straight calc. (D-N)/((D+N)/2)
	$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2	$\Delta m^2_{21}=7.50\times10^{-5}$ eV^2	
SK-I	-2.0±1.8±1.0%	-1.9±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.4±3.8±1.0%	-4.4±3.6±1.0%	-5.5±4.2±3.7%
SK-III	-4.2±2.7±0.7%	-3.8±2.6±0.7%	-5.9±3.2±1.3%
SK-IV	-3.6±1.6±0.6%	-3.3±1.5±0.6%	-4.9±1.8±1.4%
combined	-3.3±1.0±0.5%	-3.1±1.0±0.5%	-4.1±1.2±0.8%
non-zero significance	3.0σ	2.8σ	2.8σ

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



P_{ee}
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
pp
^{7}Be
pep
CNO
^{8}B
Hep
solar+KamLAND best fit
$\sin^2\theta_{12}$=0.308
Δm^2_{21}=7.50x10^{-5}eV^2
Borexino (pp)
all solar (pp)
Borexino (pep)
(averaged) vacuum
oscillation dominant
Super-K+SNO
Borexino (^{7}Be)
solar best fit
$\sin^2\theta_{12}$=0.311
Δm^2_{21}=4.85x10^{-5}eV^2
Borexino (^{8}B)
matter oscillation dominant
Homestake
+SK+SNO
(CNO)
10^{-1}
1
10
ν Energy in MeV
Flux in 1/keV cm^2 s
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}