Solar results from Super-Kamiokande

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for Super-Kamiokande collaboration

Neutrino 2014, 3 June, 2014

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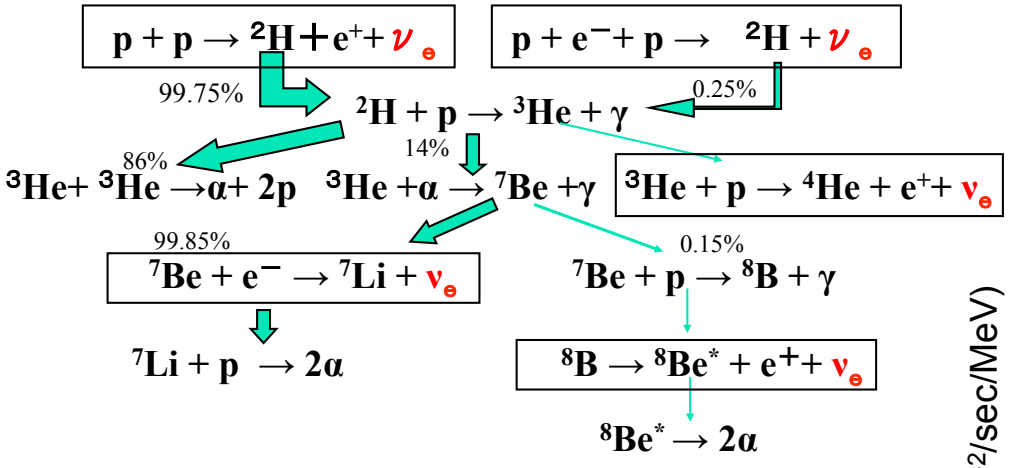
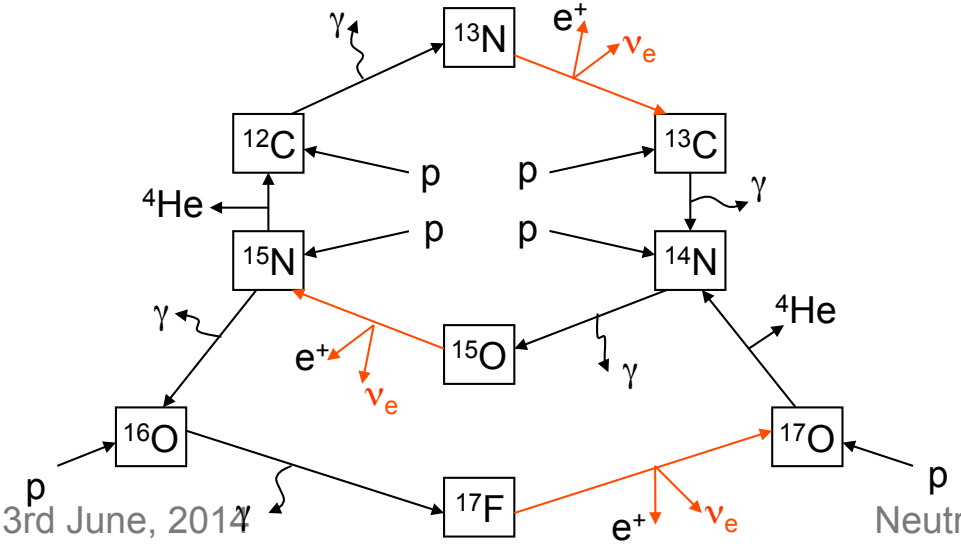
Introduction

Solar neutrino

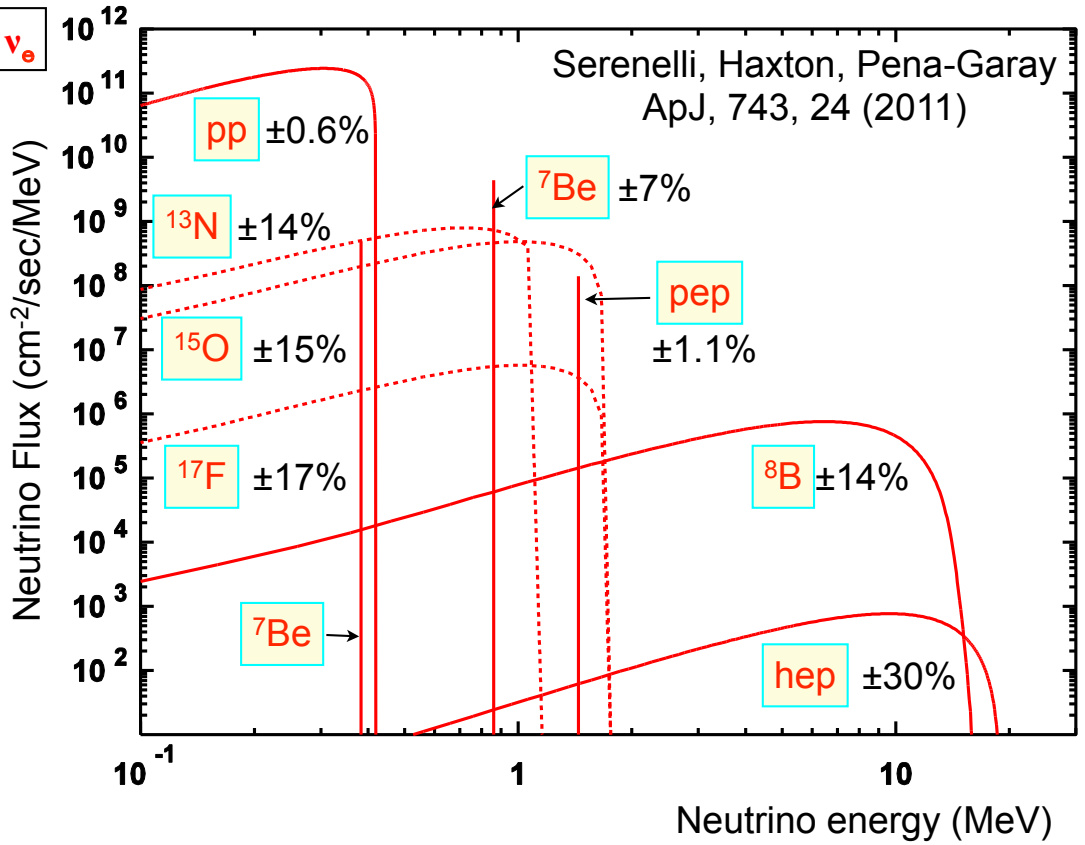
pp-chain



CNO cycle



Solar neutrino energy spectrum



Super-Kamiokande collaboration

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]

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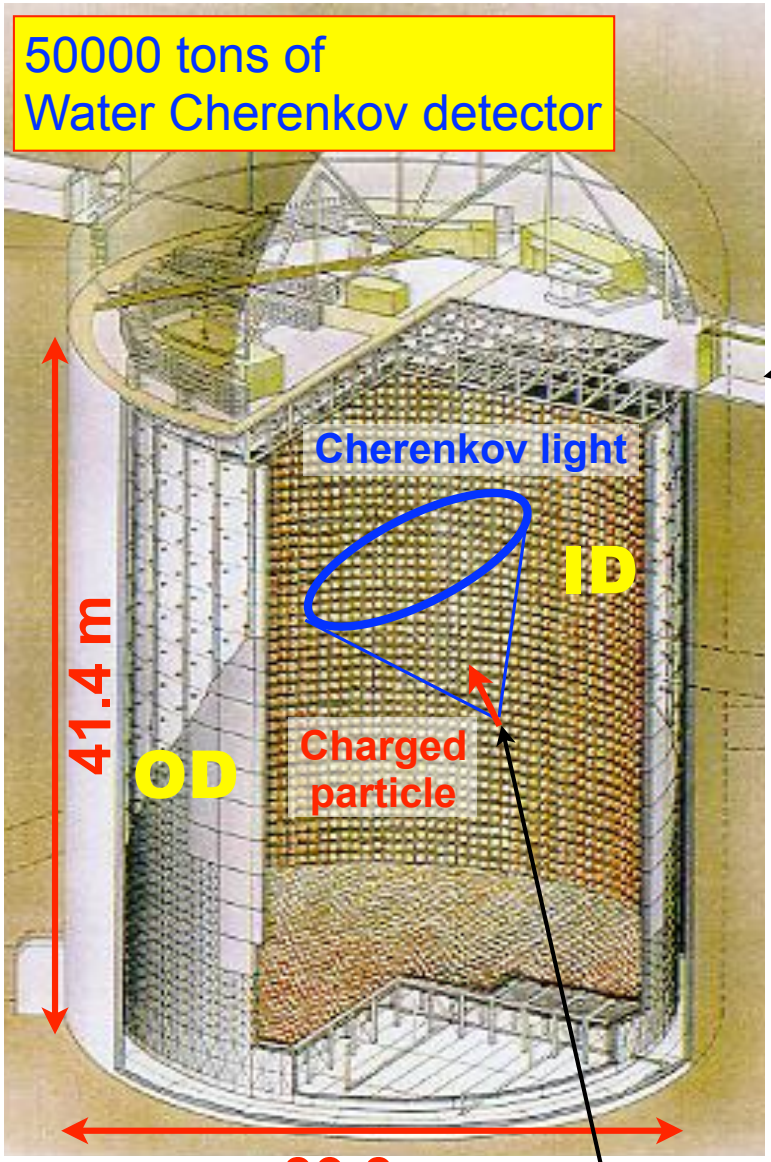
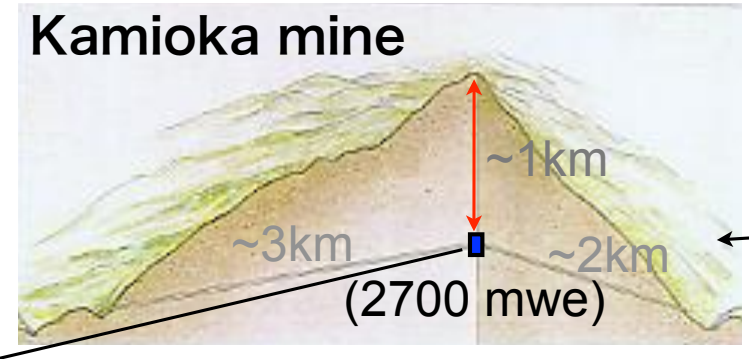
35 Warsaw University, Poland

~120 collaborators
35 institutions
7 countries

Super-Kamiokande (SK)





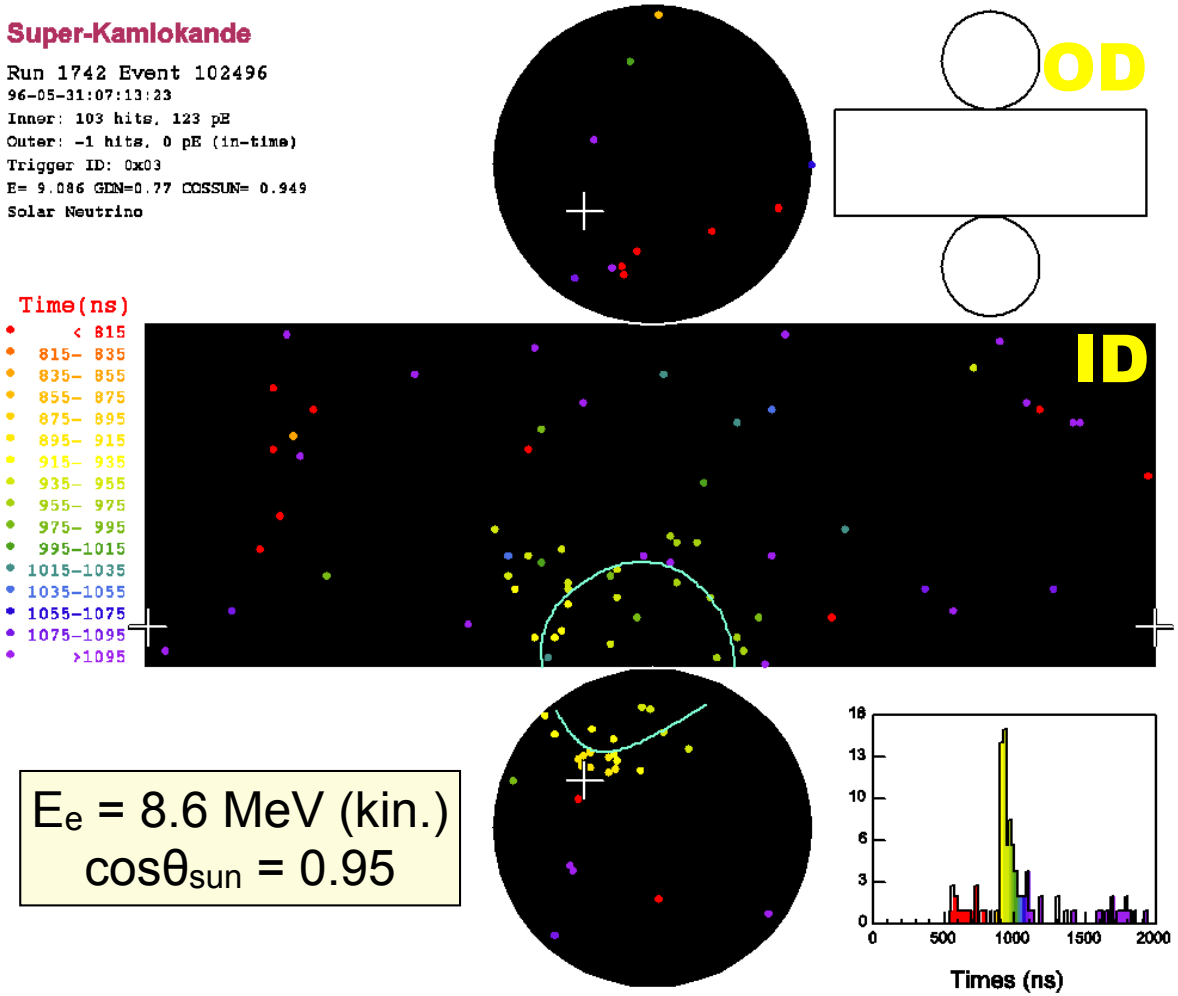
(For Solar neutrino analysis)

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	1669	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		**3.5**
				(coverage)	(Kinetic energy)

total **4504** days

Solar neutrino observation in SK

Typical event



E_e = 8.6 MeV (kin.)
$\cos\theta_{sun}$ = 0.95

neutrino-electron elastic scattering

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

- ✓Find solar direction
- ✓Realtime measurements
  - day-night flux differences
  - seasonal variation
- ✓Energy spectrum

Detector performance

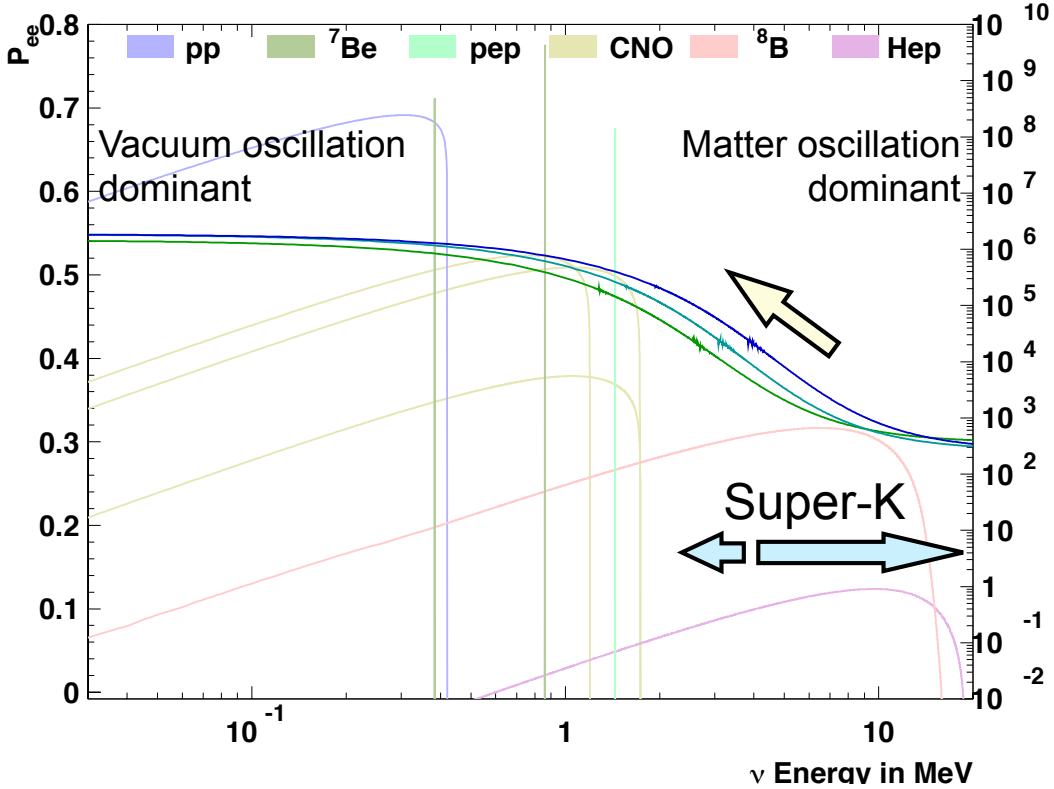
	resolution (10 MeV)	information
vertex	55cm	hit timing
direction	23deg.	hit pattern
energy	14%	# of hits.

~ 6 hits/MeV
well calibrated by LINAC and DT
within 0.5% precision

Motivation of the measurement

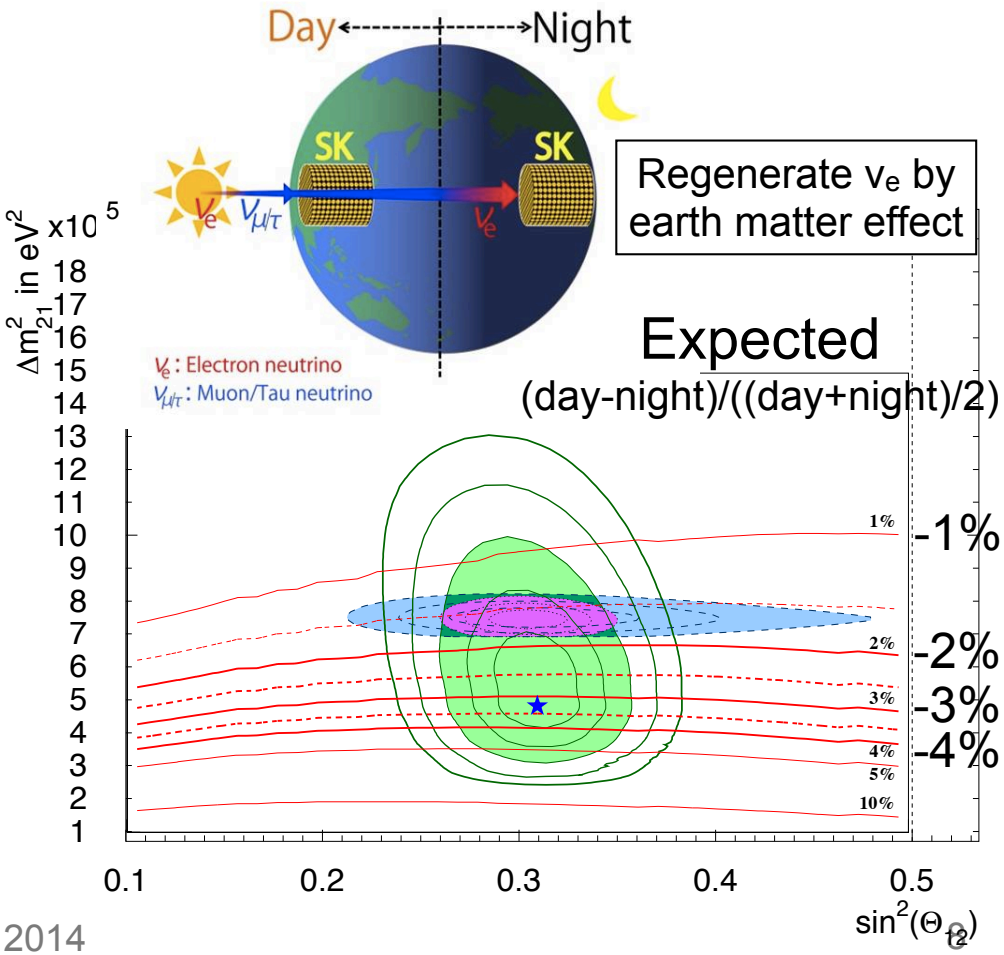
See the neutrino oscillation MSW effect directly

Spectrum distortion



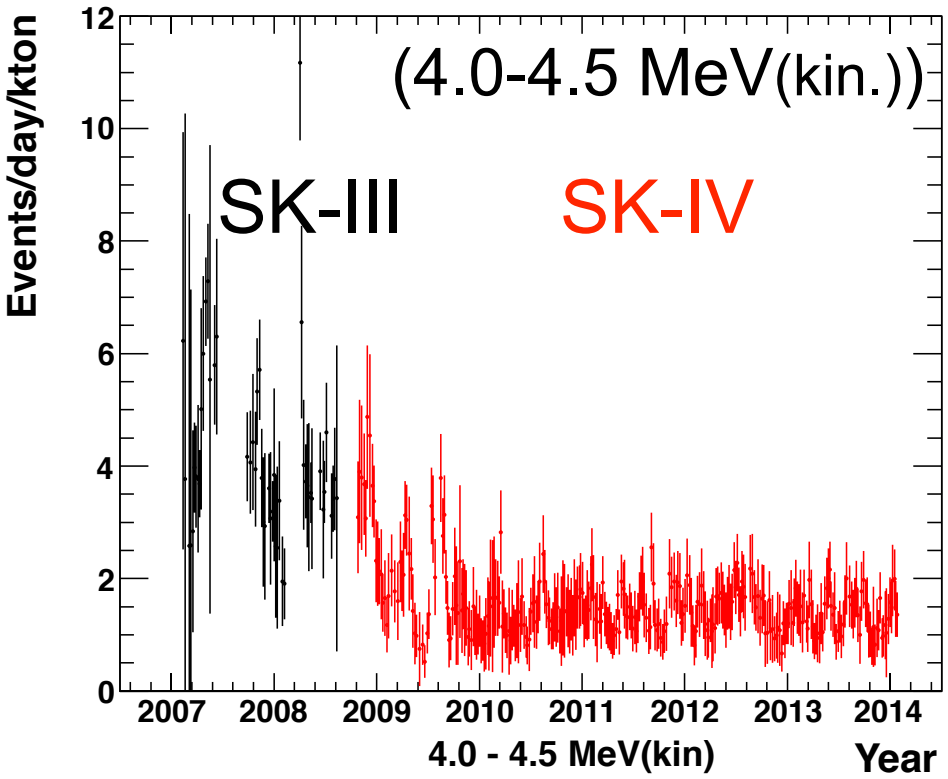
Super-K can search for the spectrum "upturn" expected by neutrino oscillation MSW effect

Day-Night flux asymmetry



Improvement in SK-IV

Lower background



Event rate becomes low and stable in SK-IV by improvement of the water system.

achieved 3.5 MeV(kin.) energy threshold

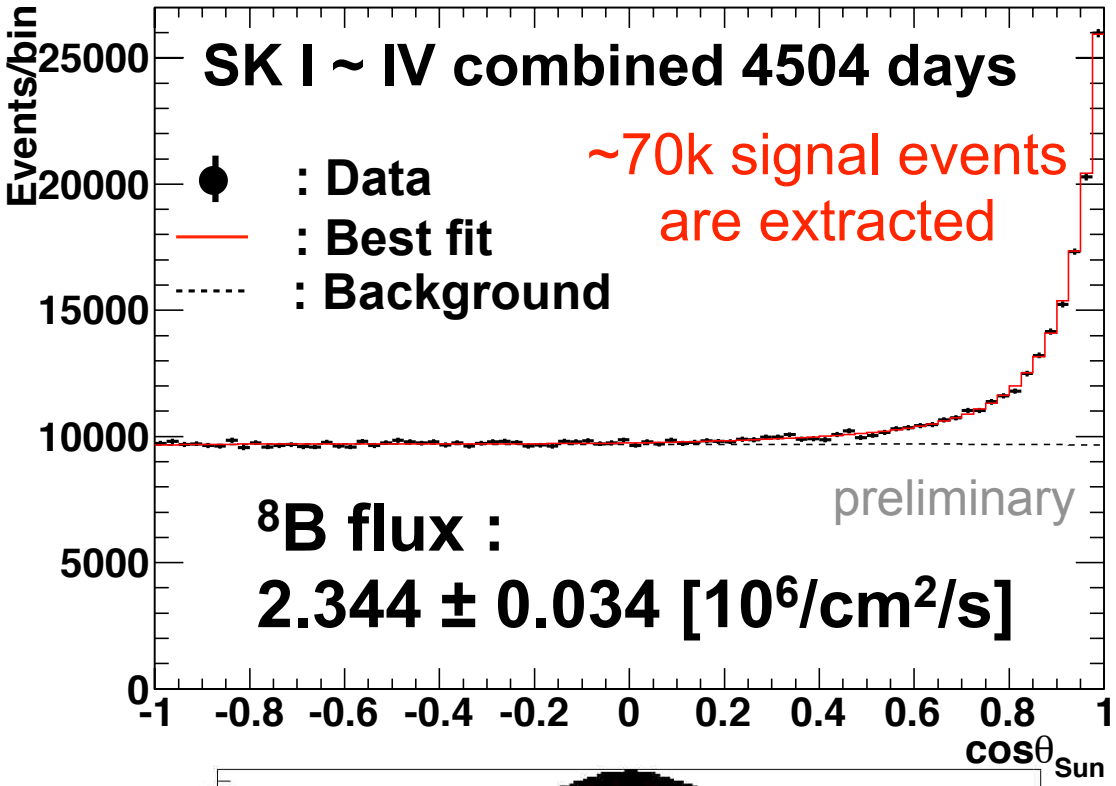
Reduce systematic error

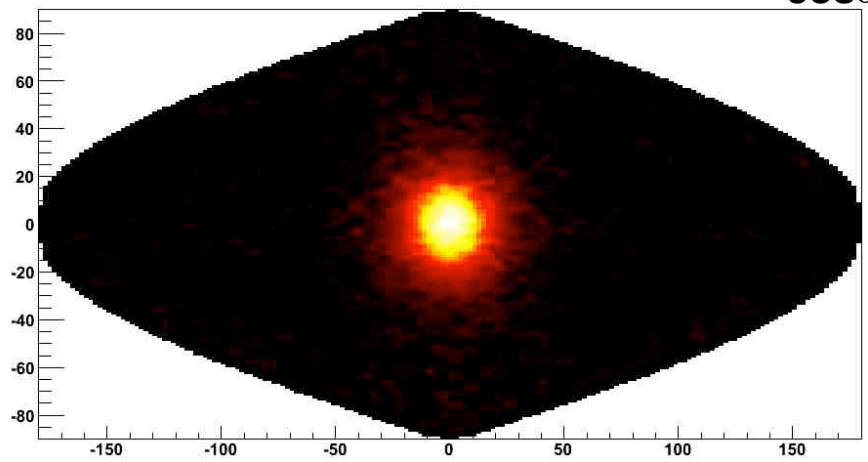
Source	SK-IV flux (3.5-19.5MeV)	SK-III flux (4.5-19.5MeV)
energy scale	+1.14, -1.16%	±1.4%
energy resolution	+0.14, -0.08%	±0.2%
B8 spectrum	+0.33, -0.37%	±0.2%
trigger efficiency	±0.1%	±0.5%
angular resolution	+0.32, -0.25%	±0.67%
vertex shift	±0.18%	±0.54%
BG event cut	±0.36%	±0.4%
hit pattern cut	±0.27%	±0.25%
another vertex cut	removed	±0.45%
spallation cut	±0.2%	±0.2%
gamma cut	±0.26%	±0.25%
cluster hit cut	+0.45, -0.44%	±0.5%
BG shape	±0.1%	±0.1%
signal extraction	±0.7%	±0.7%
cross section	±0.5%	±0.5%
Total	1.7 %	2.1 %

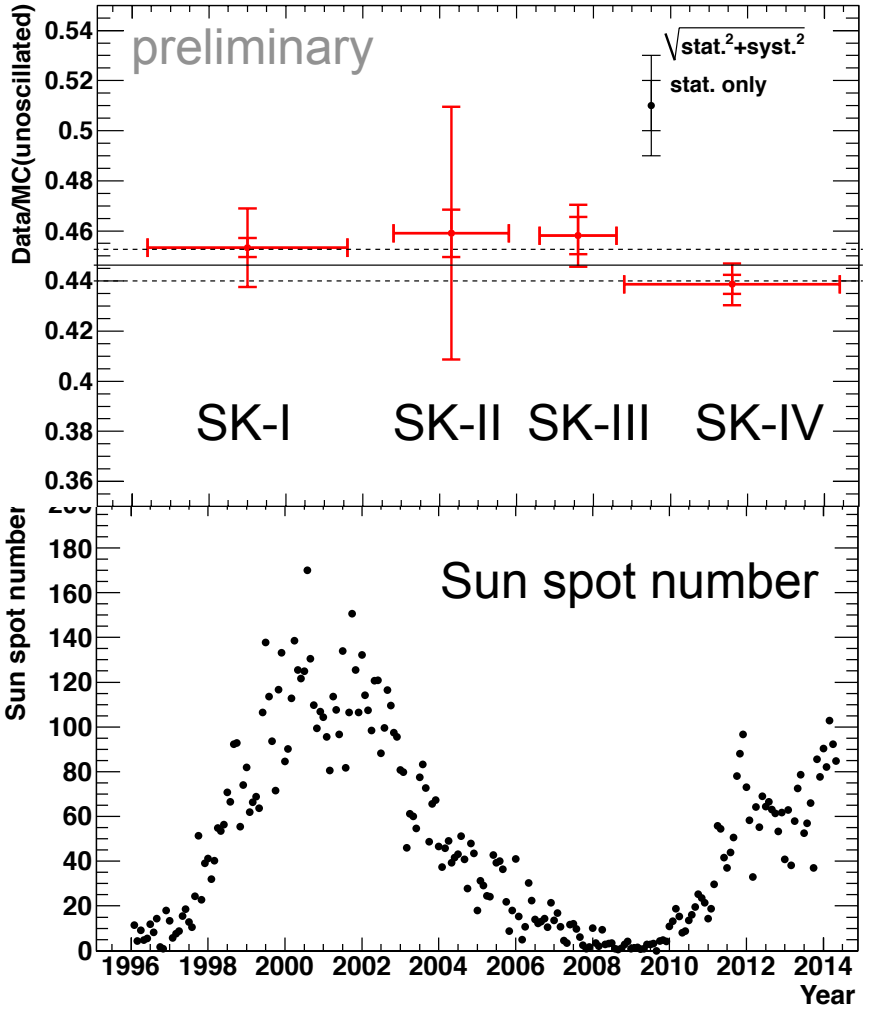
(+3.5, -3.2 % for SK-I)

SK all phase combined results (updated with latest SK-IV result) - Flux -

Observed solar neutrino signal

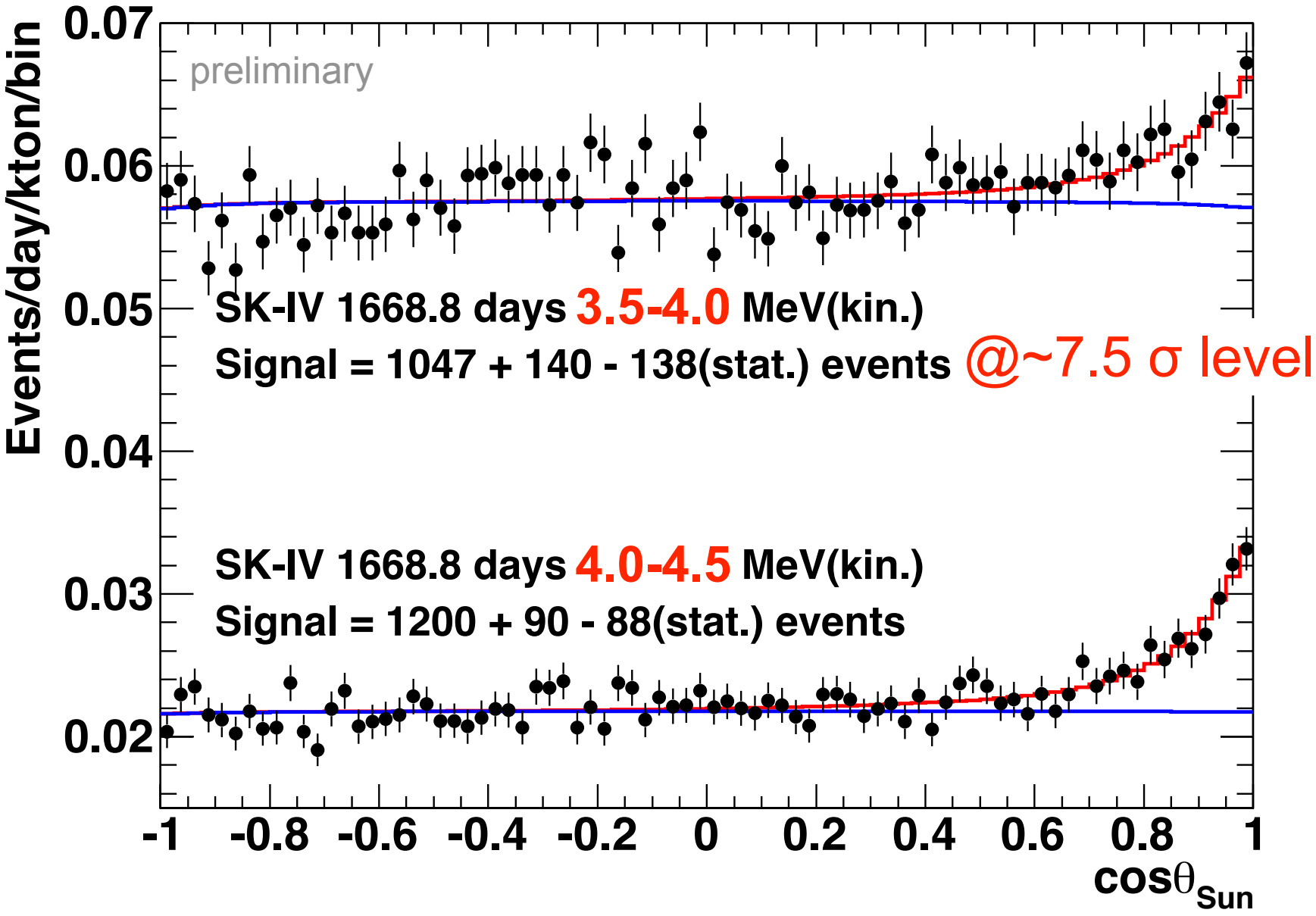






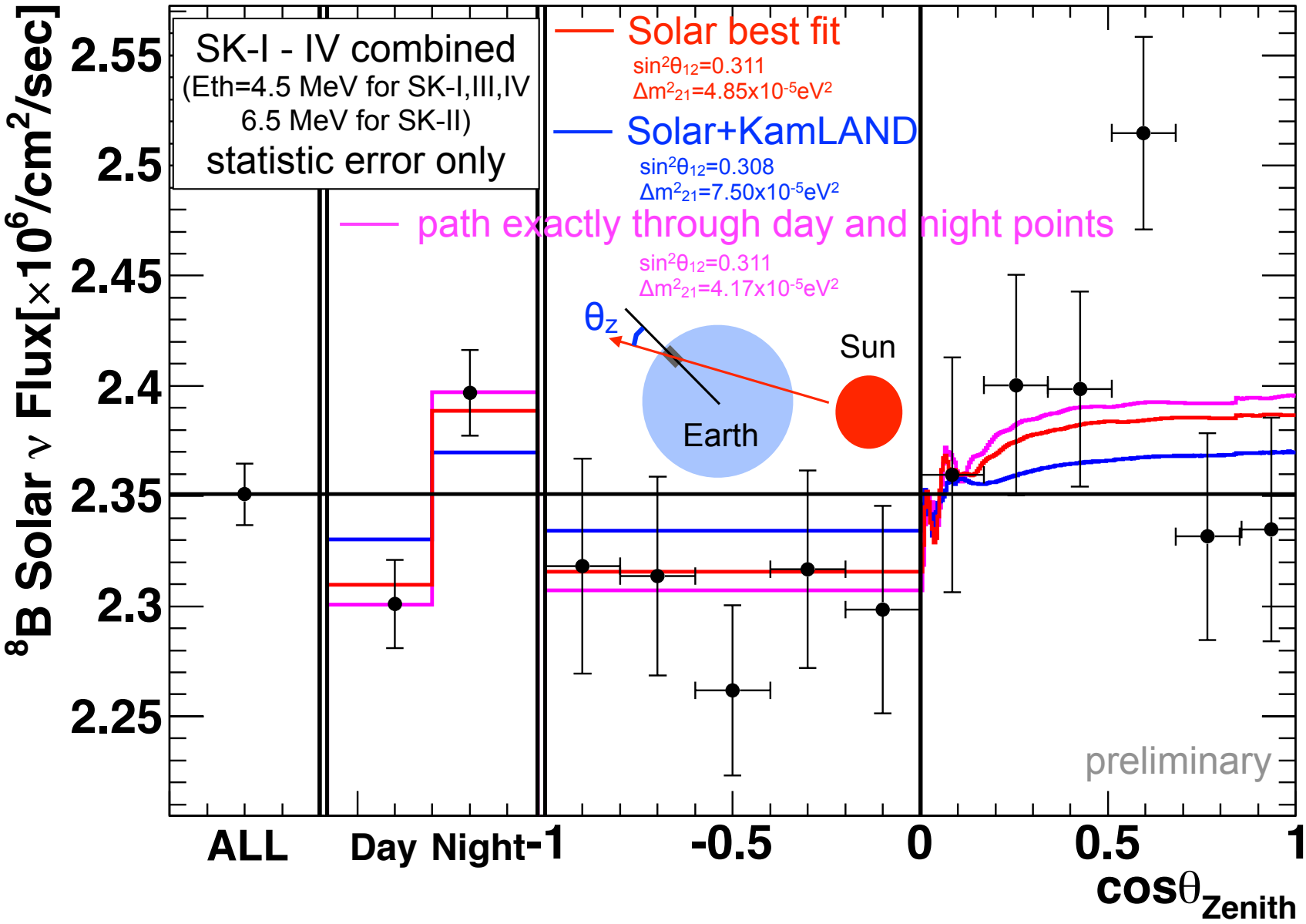
No correlation with solar activity is seen.
More sophisticated analyses such as yearly flux plot are being prepared.

Signal in the lowest energy bins



SK all phase combined results (updated with latest SK-IV result) - Day/Night -

Zenith angle distribution

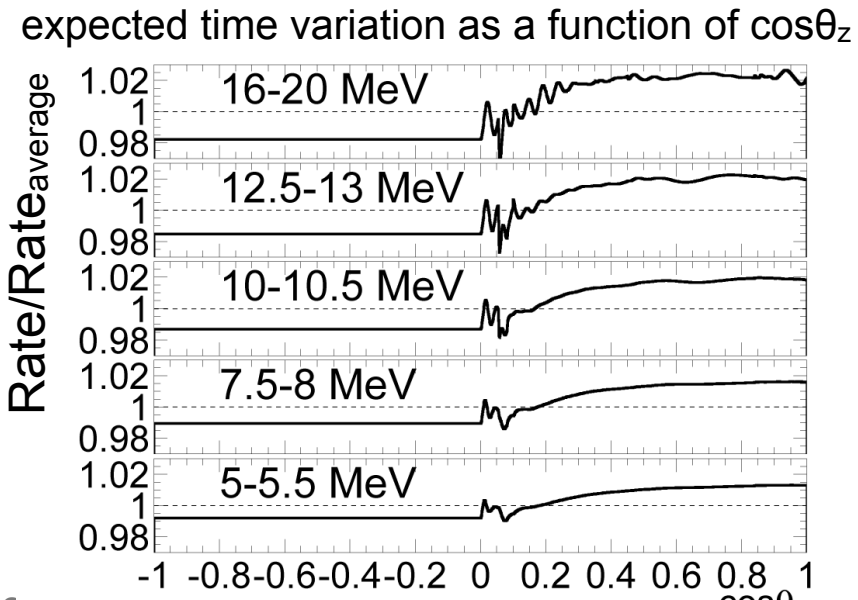


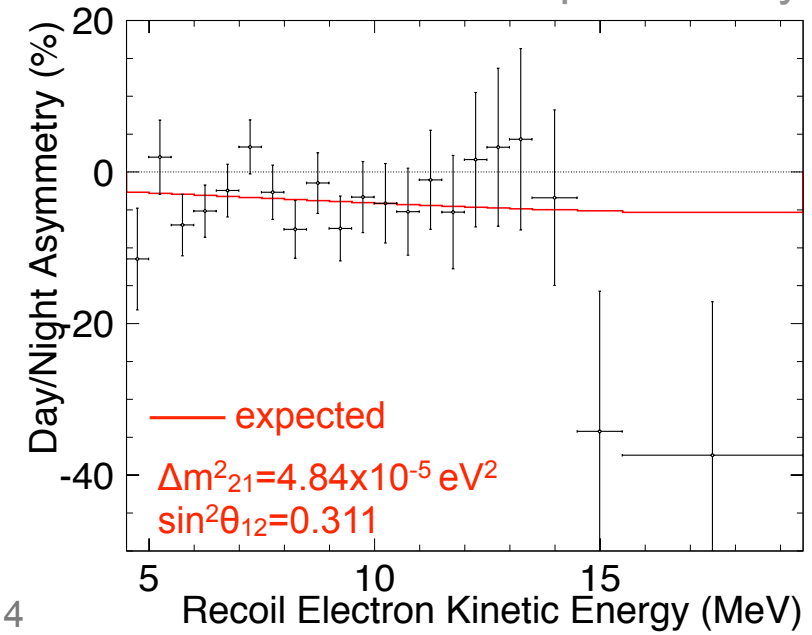
Day/Night differences

	Amplitude fit		Straight calc.
	$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2	$\Delta m^2_{21}=7.50\times10^{-5}$ eV^2	(D-N)/((D+N)/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	3.0 σ	2.8 σ	2.8 σ

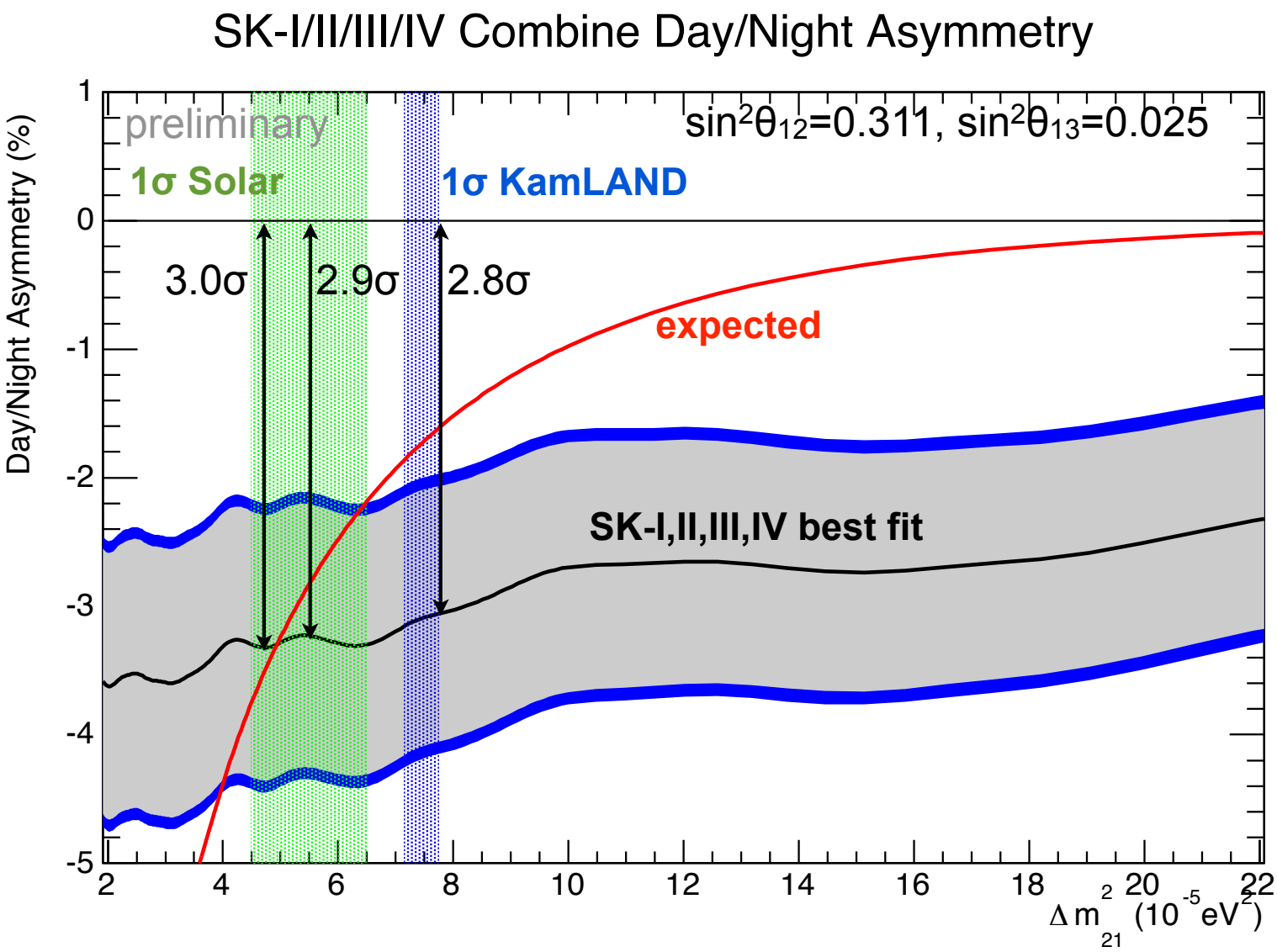
($\sin^2\theta_{12}=0.311$, $\sin^2\theta_{13}=0.025$)

preliminary





Δm^2_{21} dependence



Solar region

✓ differ from zero by 2.9~3.0σ

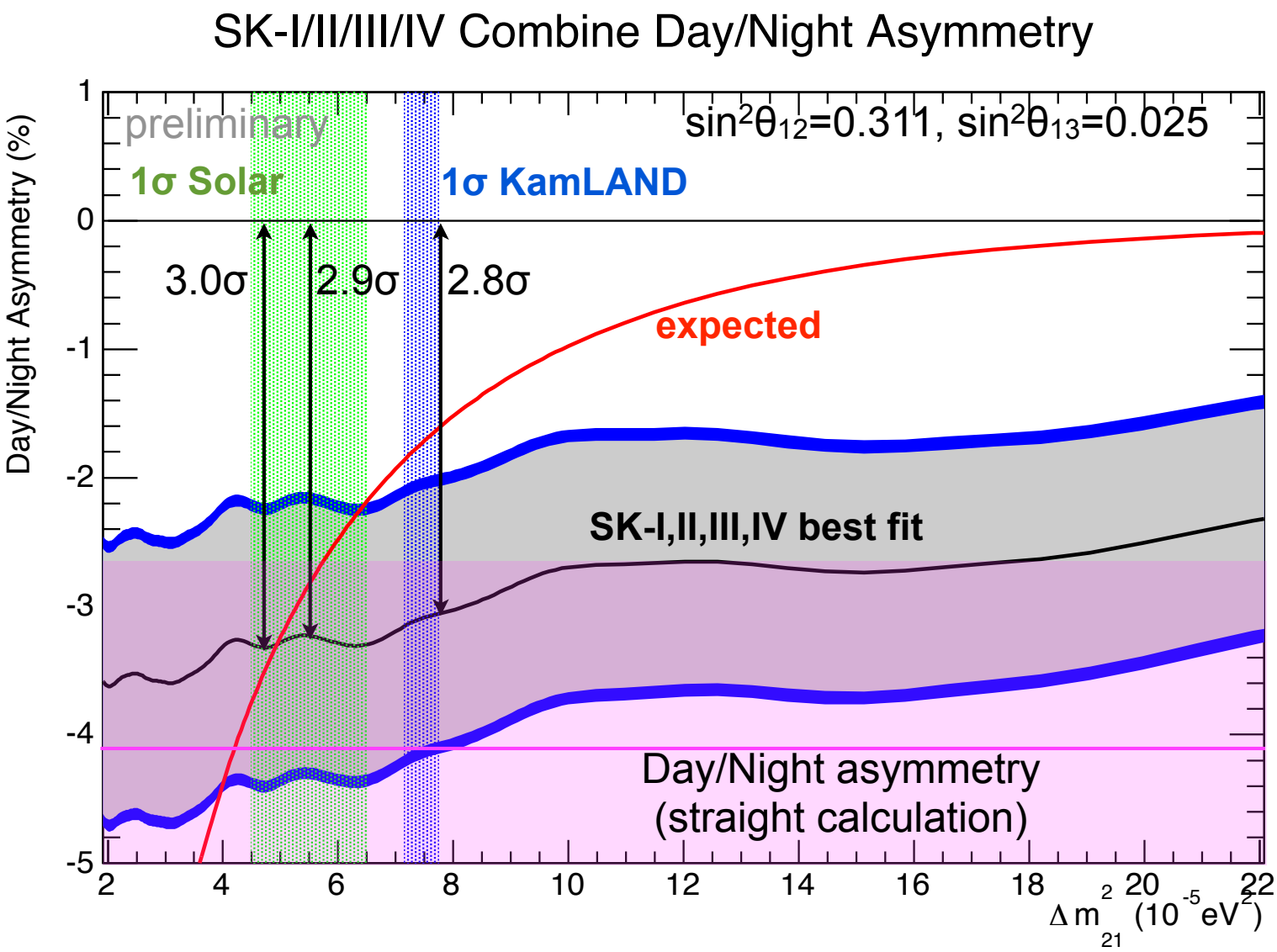
✓ agree with expect by 1.0σ

KamLAND region

✓ differ from zero by more than 2.8σ

✓ agree with expect by 1.3σ

Δm^2_{21} dependence



Solar region

✓ differ from zero by 2.9~3.0σ

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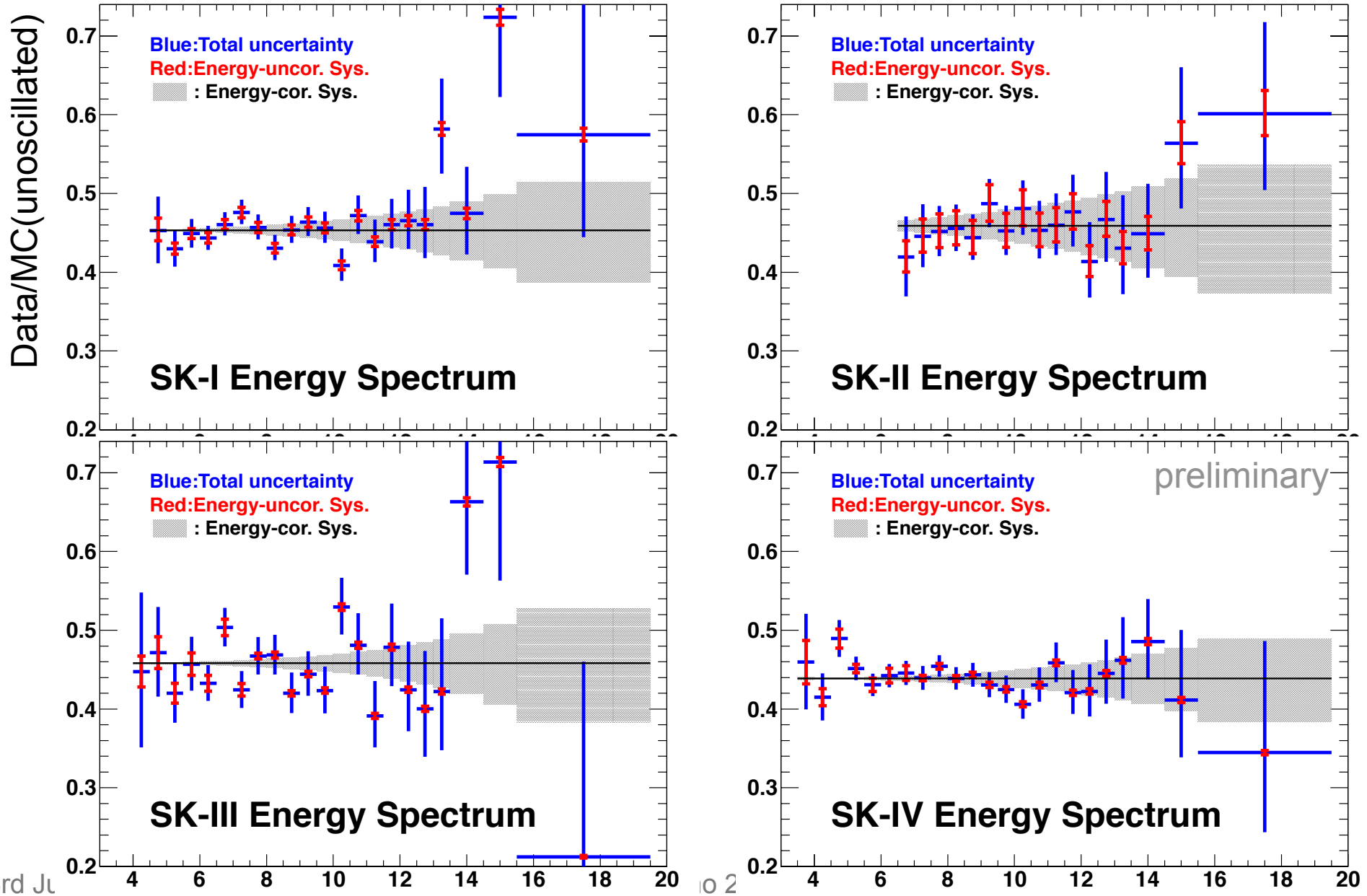
KamLAND region

✓ differ from zero by more than 2.8σ

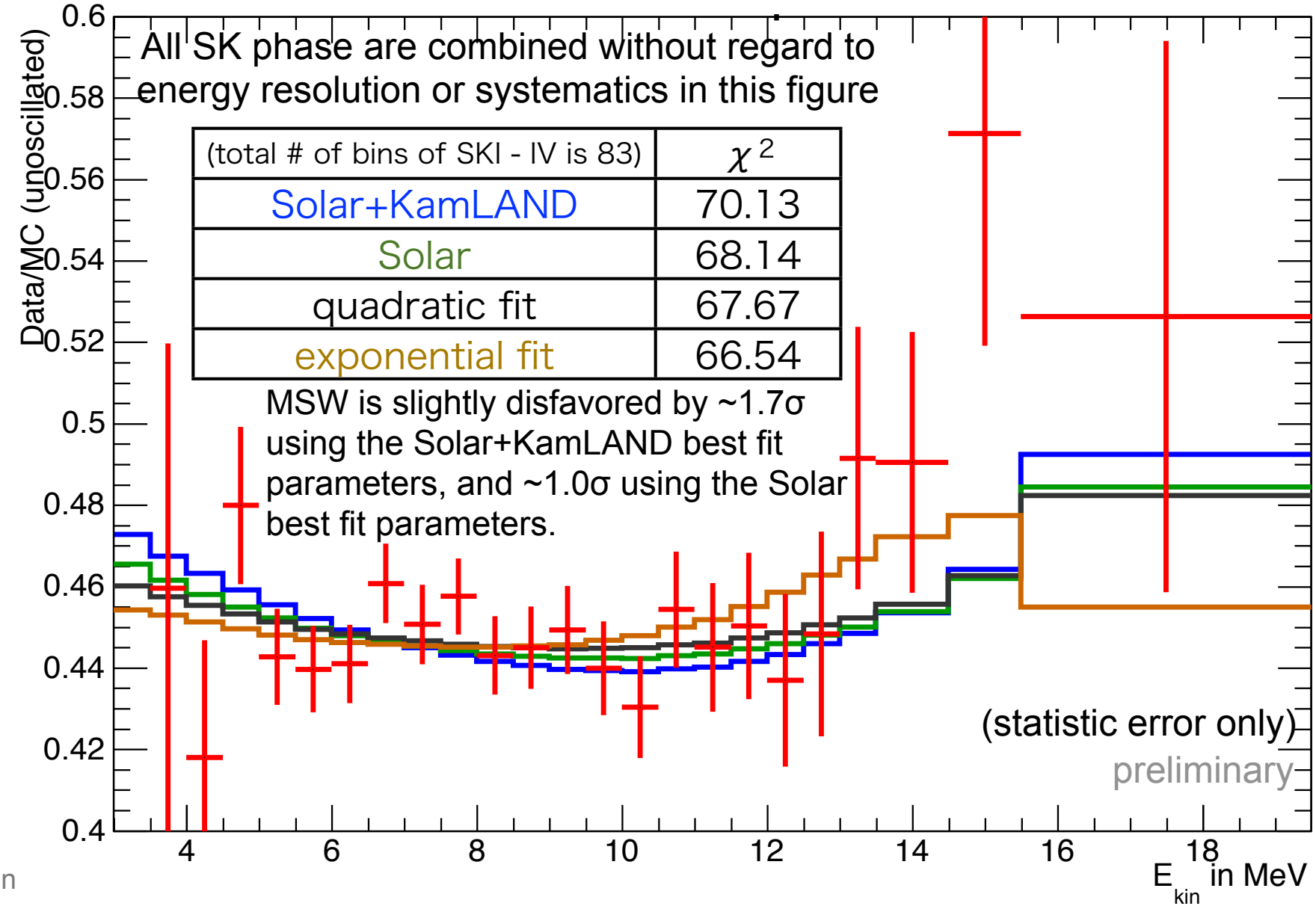
✓ agree with expect by 1.3σ

SK all phase combined results (updated with latest SK-IV result) - Spectrum -

Recoil electron spectrum



Recoil electron spectrum



Neutrino energy spectrum shape

- ✓ Neutrino energy spectrum was de-convoluted from the electron recoil spectrum.
- ✓ The following generic functions are used as a survival probability;
  - quadratic

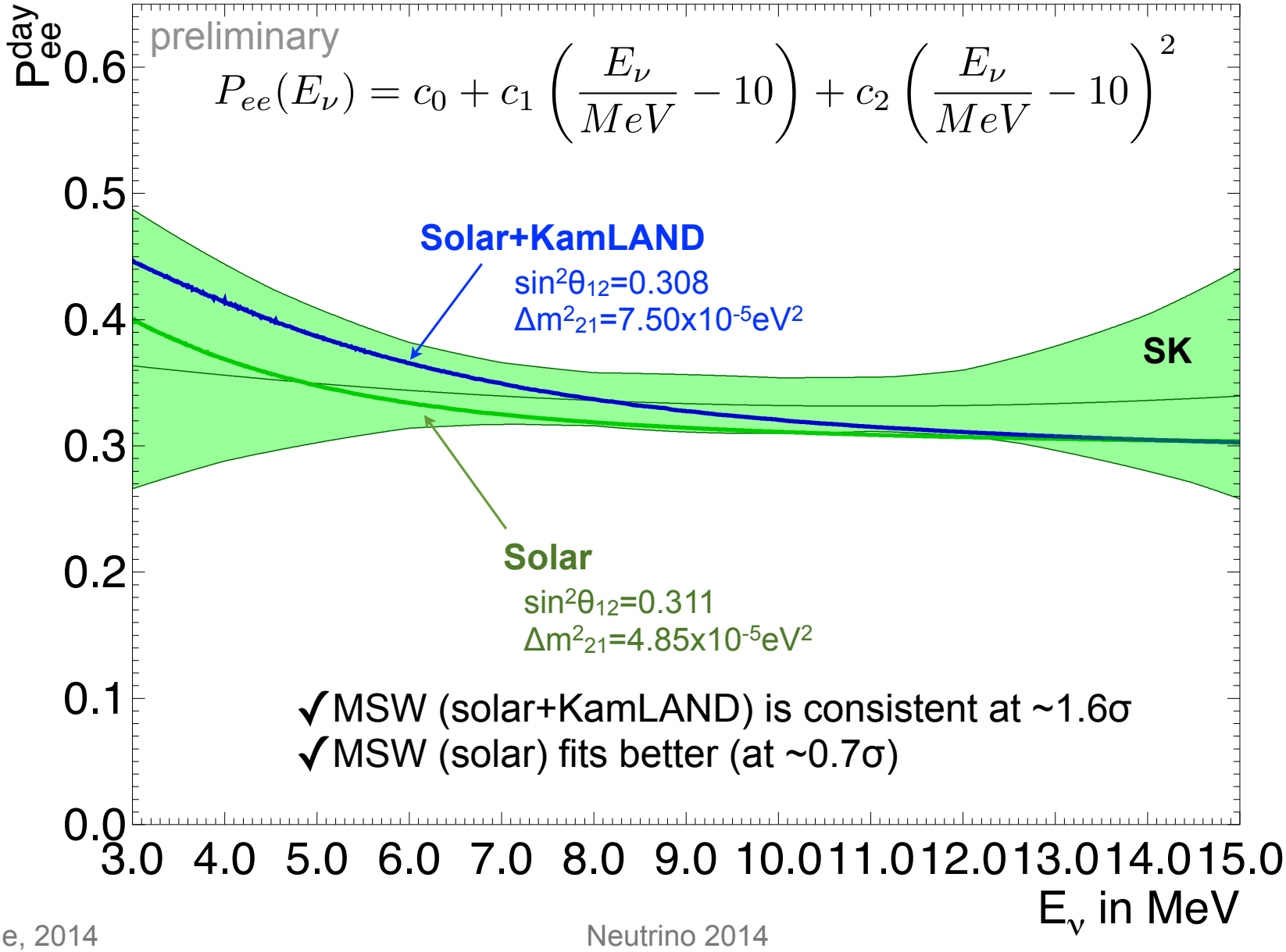
$$P_{ee}(E_\nu) = c_0 + c_1\left(\frac{E_\nu}{MeV} - 10\right) + c_2\left(\frac{E_\nu}{MeV} - 10\right)^2$$

  - exponential

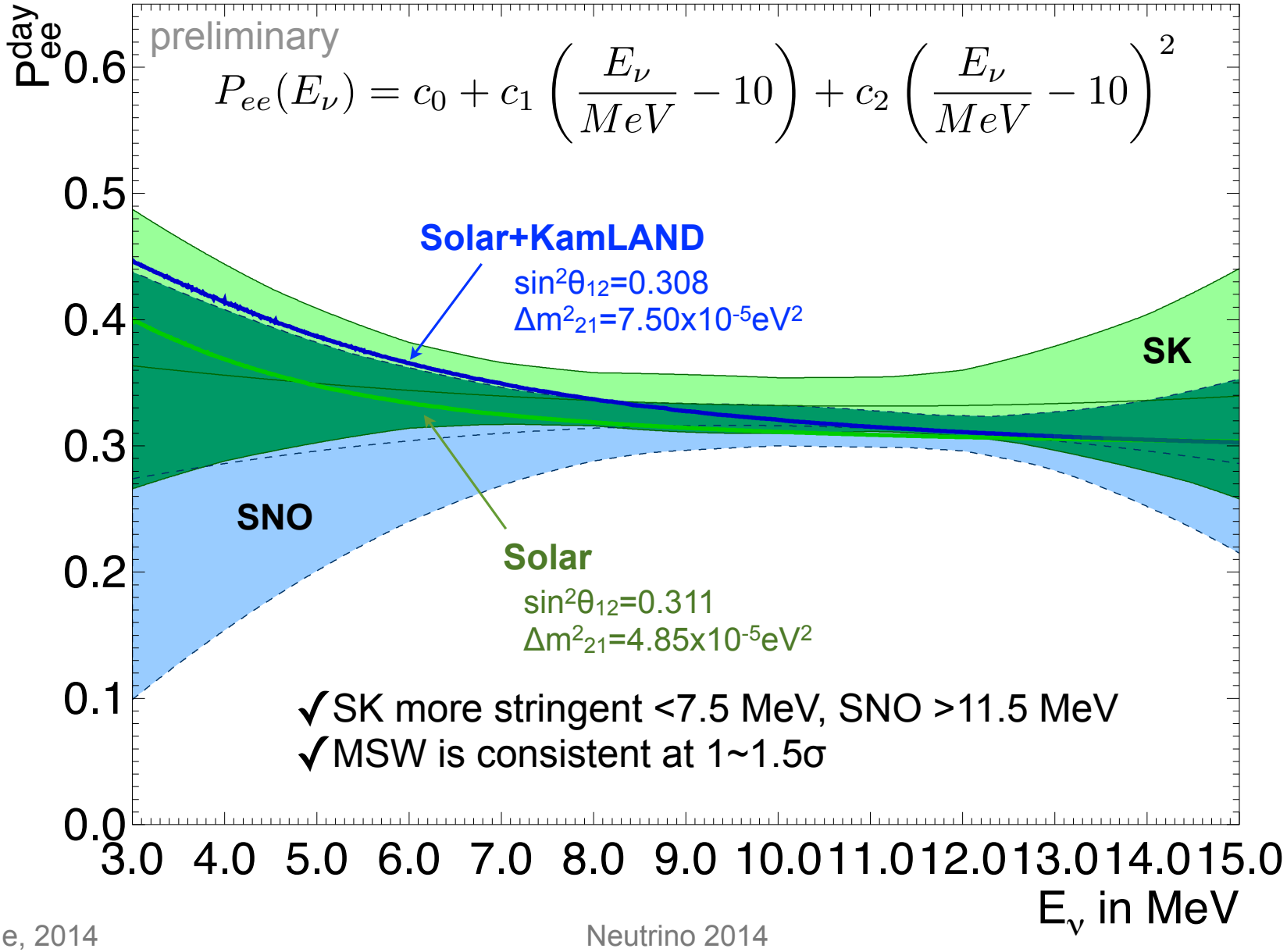
$$P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2}\left(\exp\left(e_2(\frac{E_\nu}{MeV} - 10)\right) - 1\right)$$

- ✓ All the SK-I to IV recoil electron spectrum constrain the fit parameters (e_i, c_i) of these functions, including the correlation between SK phases and energy bins.
- ✓ Get the allowed $P_{ee}(E_\nu)$ using allowed (e_i, c_i).

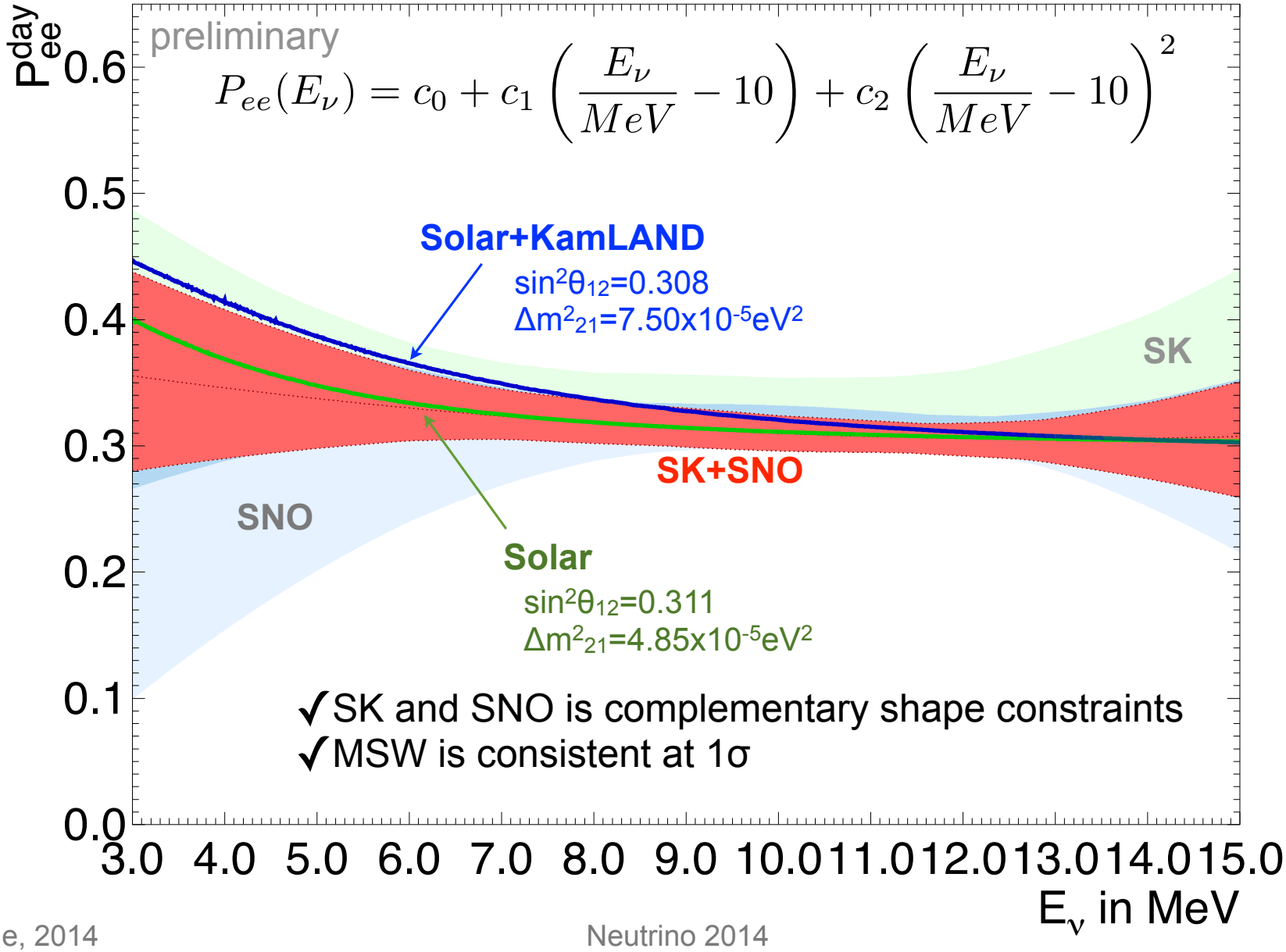
Allowed survival probability



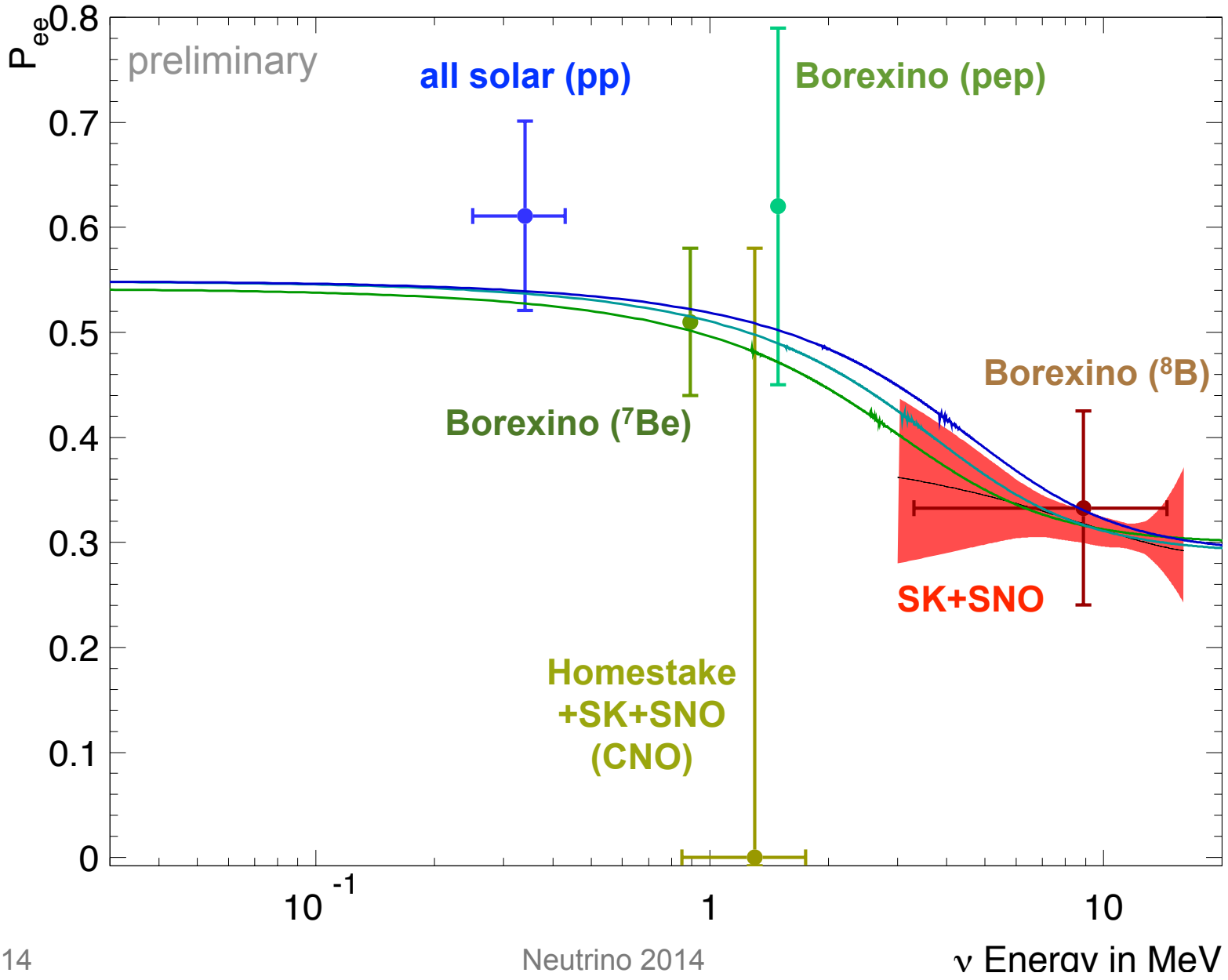
Allowed survival probability



Allowed survival probability

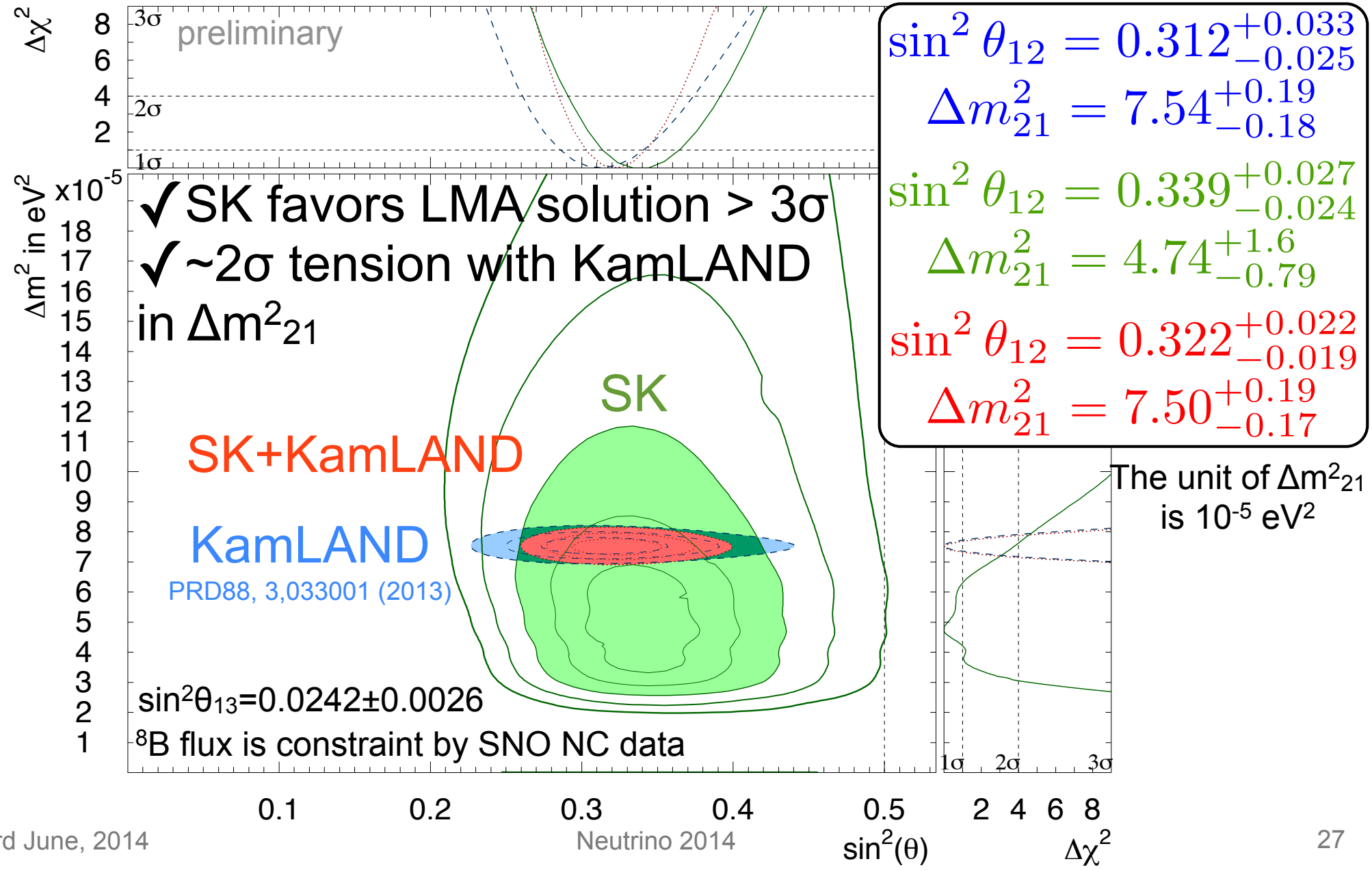


Allowed survival probability

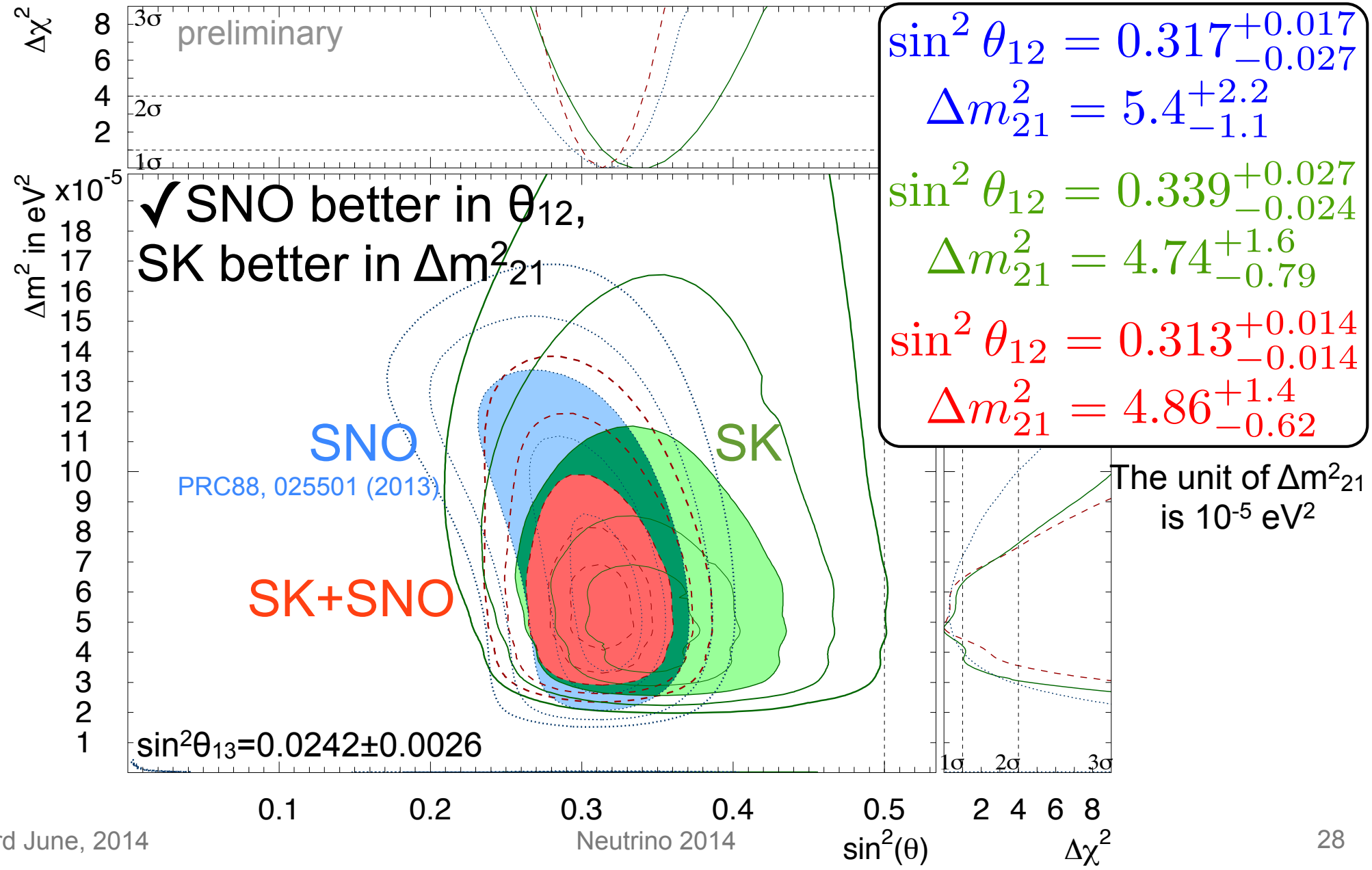


Neutrino oscillation analysis

SK I - IV combined



SK and SNO


preliminary
✓SNO better in θ12,
SK better in Δm2 21
SNO
PRC88, 025501 (2013)
SK
SK+SNO
sin²θ13=0.0242±0.0026
$\sin^2\theta_{12} = 0.317^{+0.017}_{-0.027}$
$\Delta m^2_{21} = 5.4^{+2.2}_{-1.1}$
$\sin^2\theta_{12} = 0.339^{+0.027}_{-0.024}$
$\Delta m^2_{21} = 4.74^{+1.6}_{-0.79}$
$\sin^2\theta_{12} = 0.313^{+0.014}_{-0.014}$
$\Delta m^2_{21} = 4.86^{+1.4}_{-0.62}$
The unit of Δm²21 is 10⁻⁵ eV²
Δχ²
Δm² in eV² x10⁻⁵
sin²(θ)
Δχ²
1σ
2σ
3σ

Data set for global solar analysis

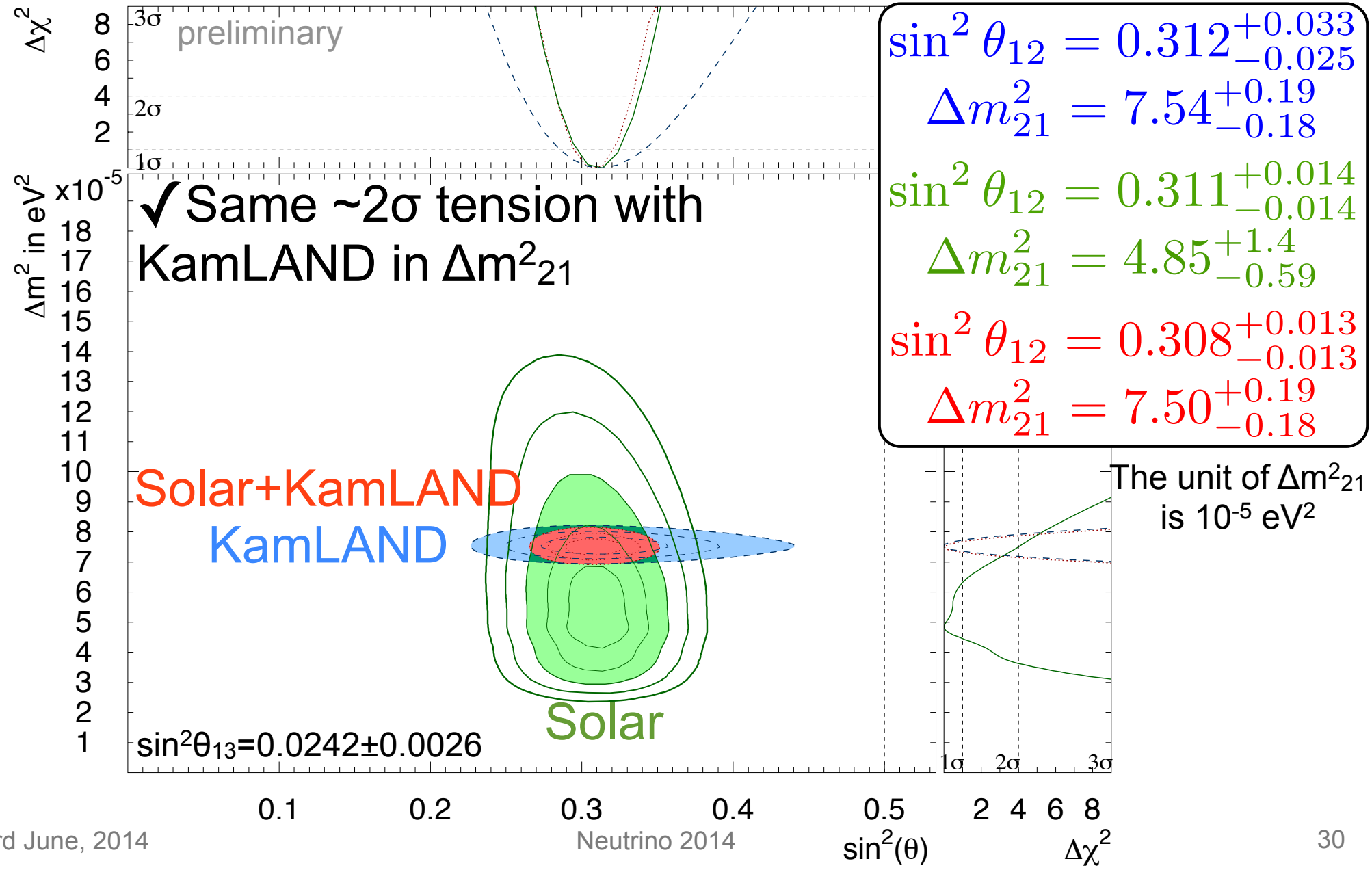
The most up-to-date data are used

- ✓ **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))**

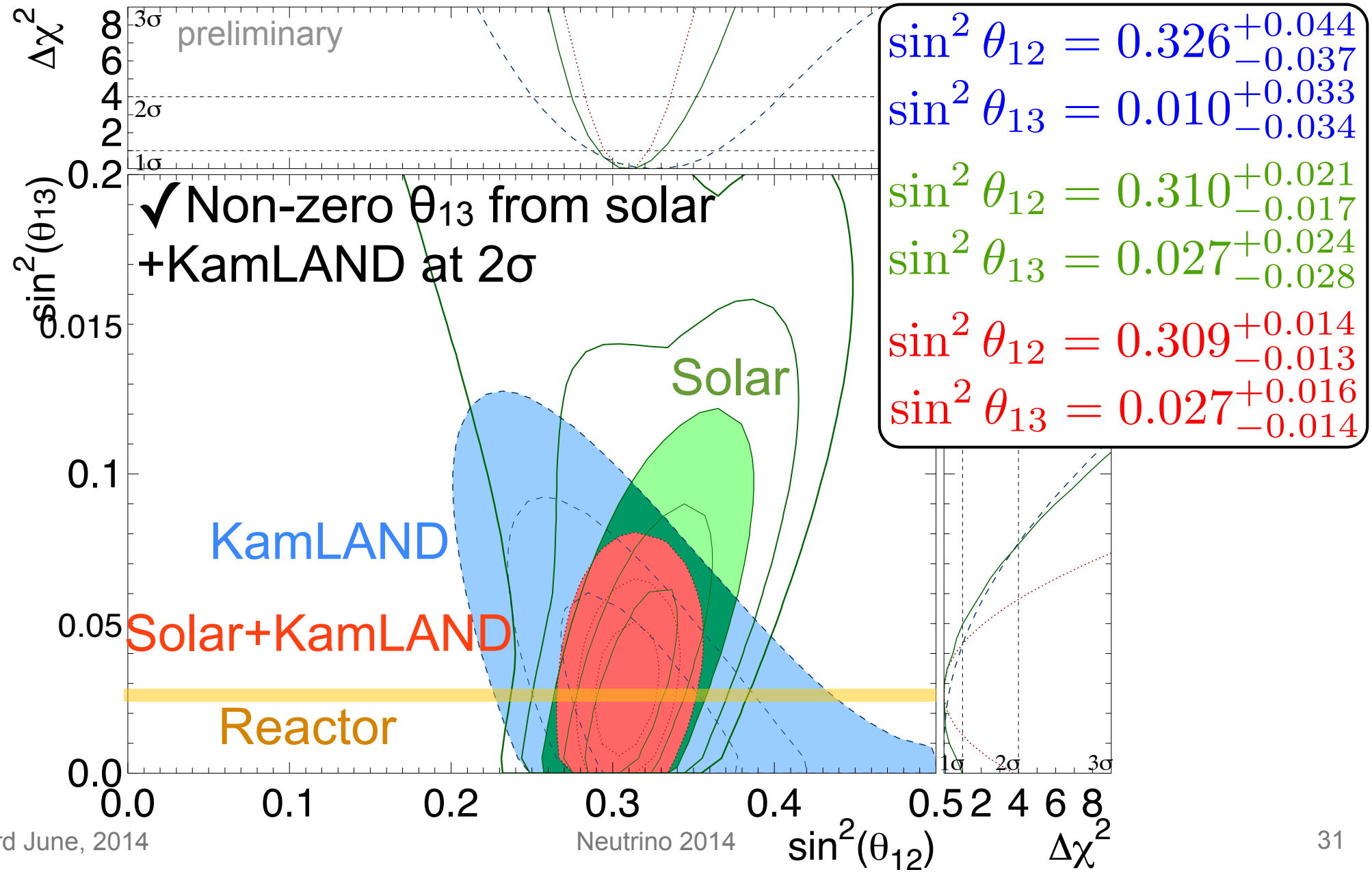
(Note: the same method is applied to both SK and SNO with a_0 and a_1 to LMA expectation.)

- ✓ **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


preliminary
Δχ²
3σ
2σ
1σ
Δm² in eV² x10⁻⁵
✓Same ~2σ tension with KamLAND in Δm²21
Solar+KamLAND
KamLAND
Solar
sin²θ13=0.0242±0.0026
sin²(θ)
Δχ²
1σ 2σ 3σ
$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$
$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$
$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$
$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$
$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$
The unit of Δm²21 is 10⁻⁵ eV²

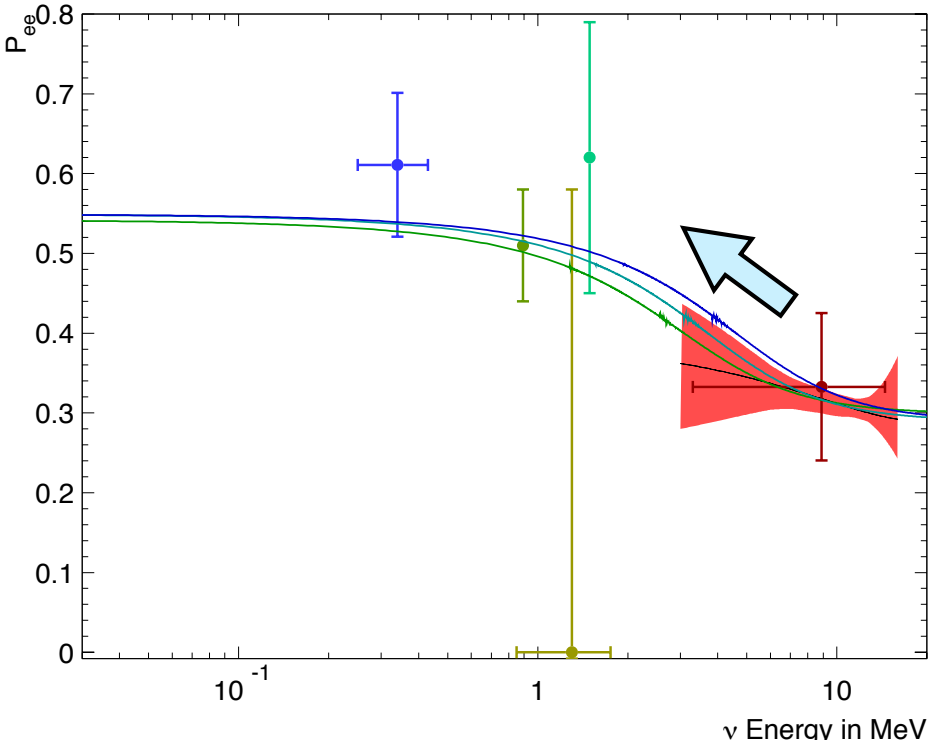
Without reactor θ_{13} constraint



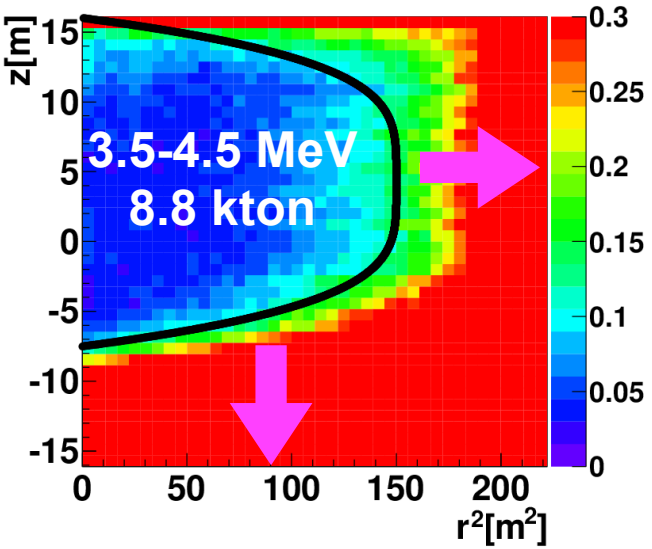
Future prospects

Target in future

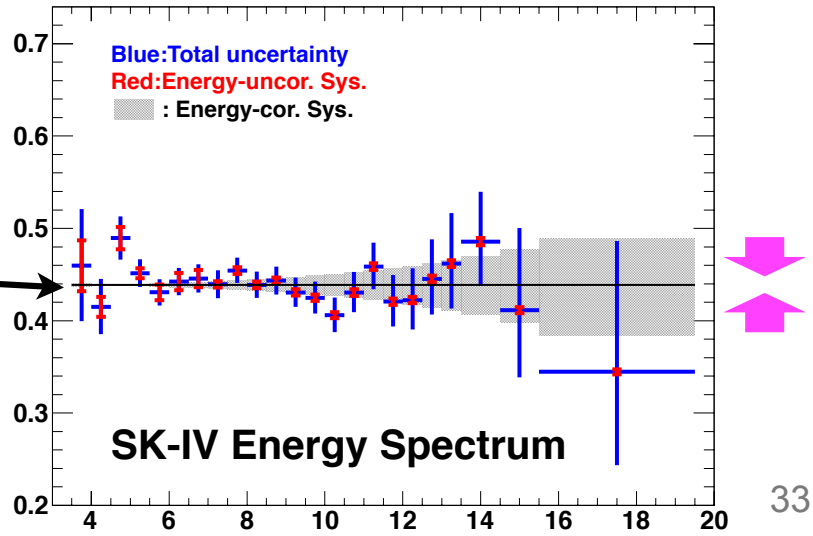
To see the spectrum “upturn”



✓Reduce B.G. and enlarge F.V.



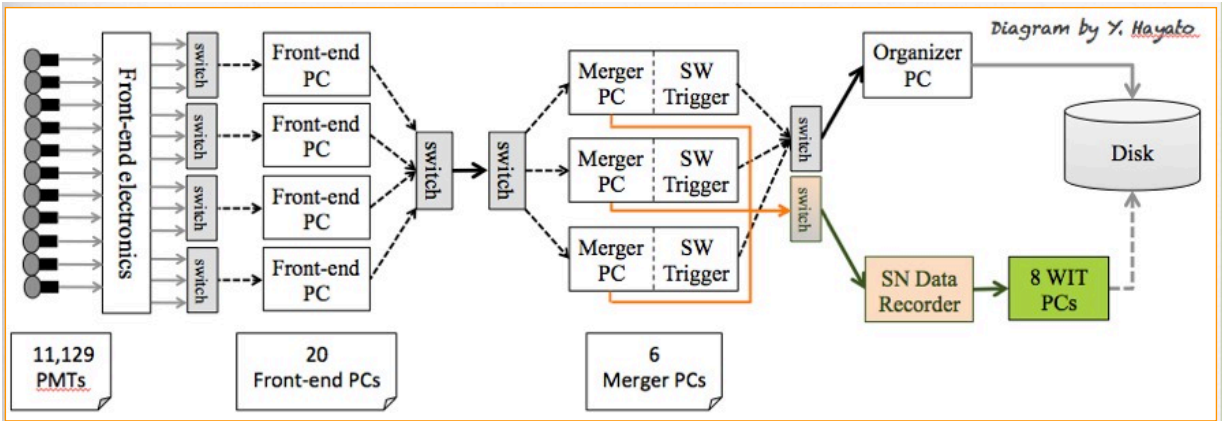
✓Reduce energy correlated systematic error

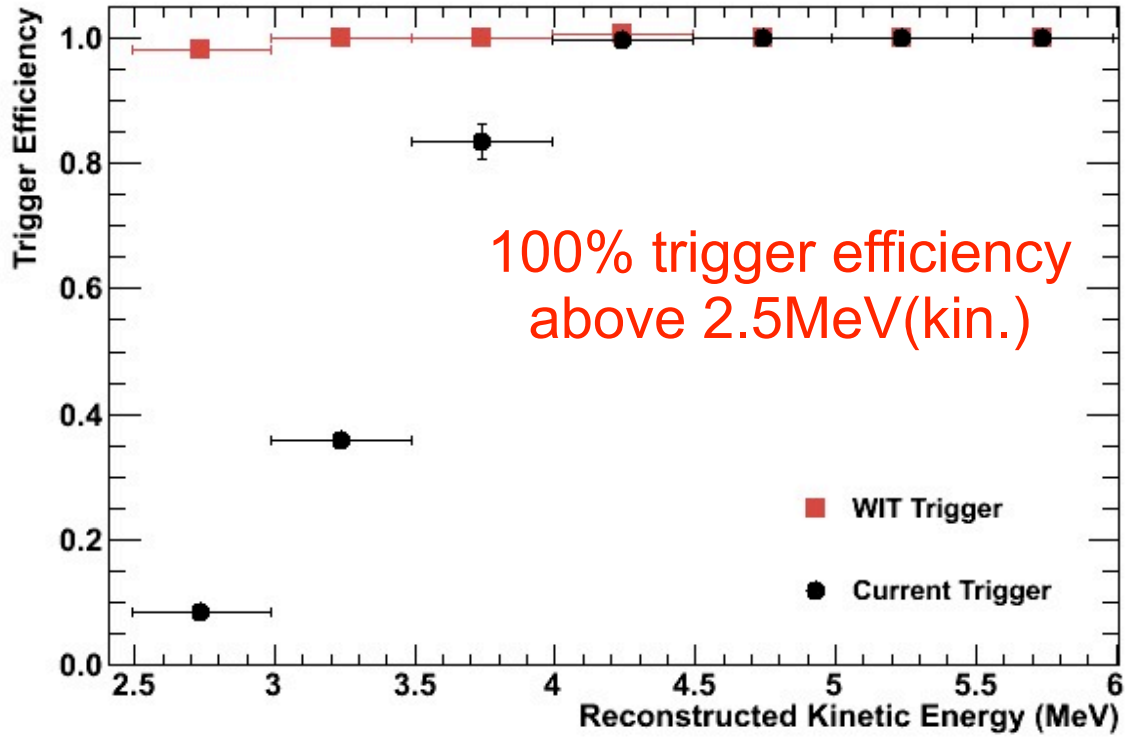


✓More solar neutrino signal in low energy region
-> new trigger system

WIT (Wide-band Intelligent Trigger)

Reconstruction and Reduction just after Front-end





Just started

Summary

- ✓ SK has observed ~70000 solar neutrino interactions in ~4500days (1.5 solar cycles), by far the largest sample of solar neutrino events in the world.
- ✓ SK data provide the first indication (at 2.8~3.0 sigma) of terrestrial matter effects on ^{8}B solar neutrino oscillation. This is the first observation using a single detector and identical neutrino beams that matter affects neutrino oscillations.
- ✓ SK has successfully lowered the analysis threshold to ~3.5 MeV kinetic recoil electron energy.
- ✓ SK gives the world's strongest constraints on the shape of the survival probability $P_{ee}(E_\nu)$ in the transition region between vacuum oscillations and MSW resonance.
- ✓ SK spectrum results slightly disfavor the MSW resonance curves, but are consistent with MSW prediction within 1-1.7 sigma.

Summary

- ✓ SK measurements strongly constrain neutrino oscillation parameters:
  - SK uniquely selects the Large Mixing Angle MSW region by >3sigma,
  - gives world's best constraint on solar Δm^2 using neutrinos,
  - and significantly contributes to the measurement of the solar angle.
- ✓ There is a 2 sigma tension between SK's neutrino and KamLAND's anti-neutrino measurement of the solar Δm^2.
- ✓ Last month SK started taking data at ~2.5 MeV at ~100% trigger efficiency. Stay tuned for very low energy SK solar neutrino data.

See also the Y.Nakano's poster (#145 session 1)

Thank You!

Backup

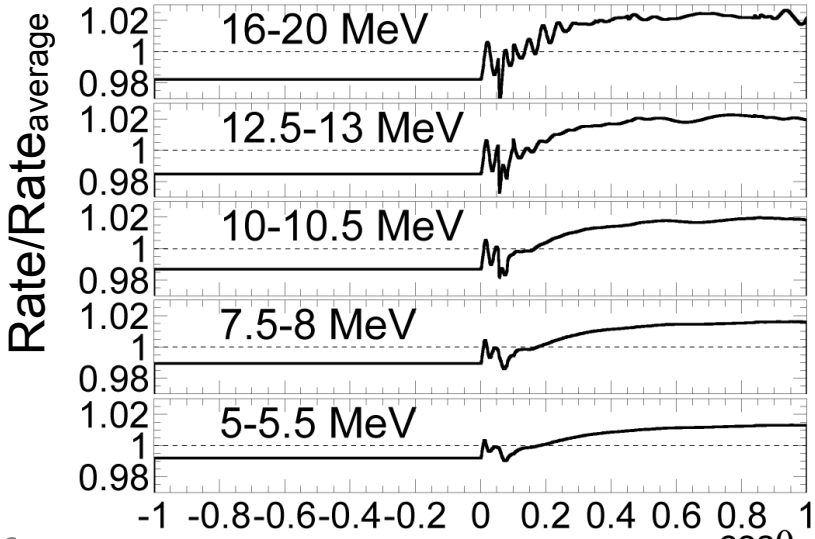
Day/Night differences

	Amplitude fit		Straight calc.
	$\Delta m^2_{21}=4.84\times10^{-5}$ eV^2	$\Delta m^2_{21}=7.50\times10^{-5}$ eV^2	(D-N)/((D+N)/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	3.0 σ	2.8 σ	2.8 σ

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

preliminary

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

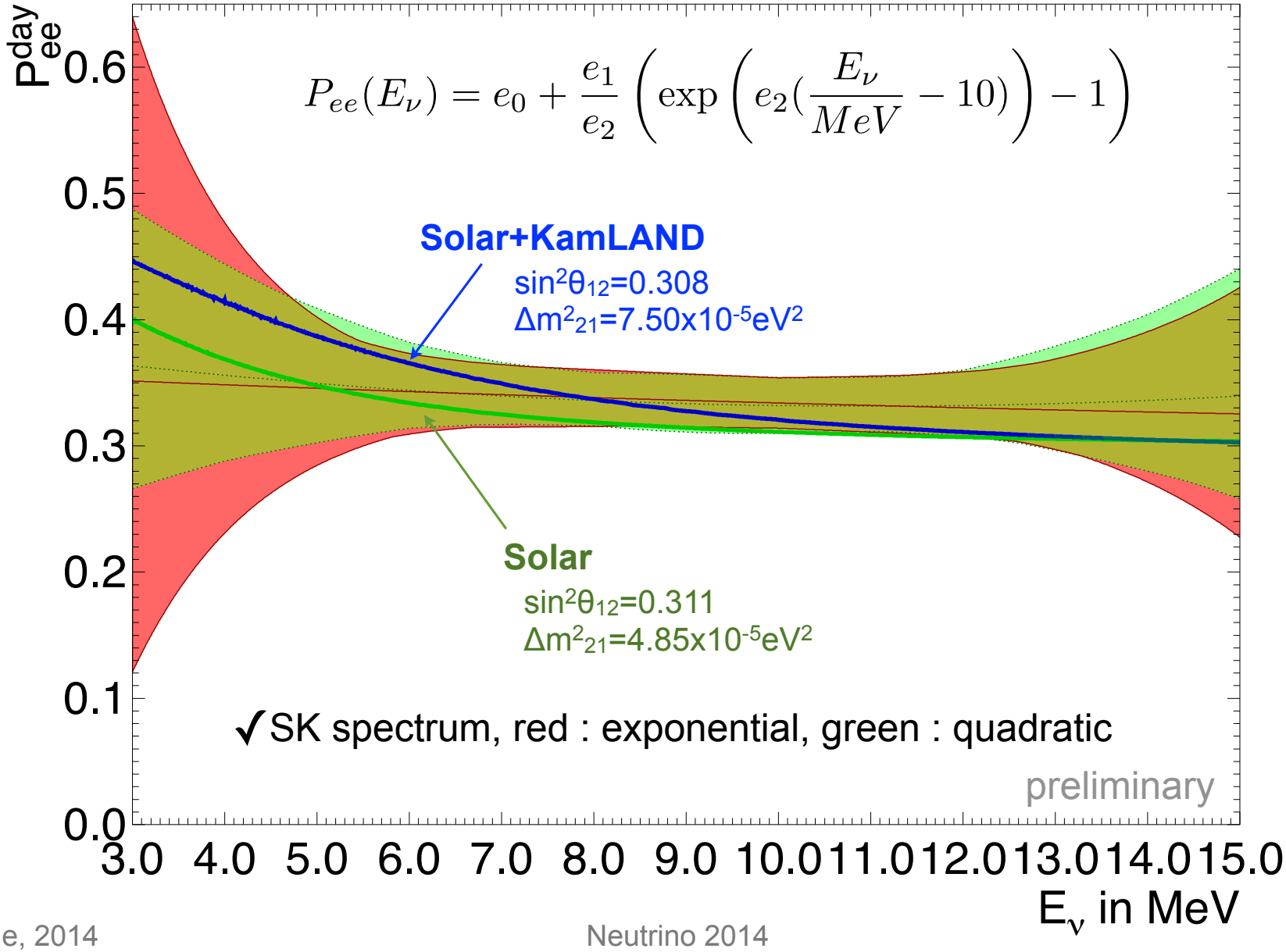


$$\mathcal{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} \left(\beta_i(c_\nu) B_i + \sigma_i(c_\nu) \times z_i(t_\nu) m_i S\right)$$

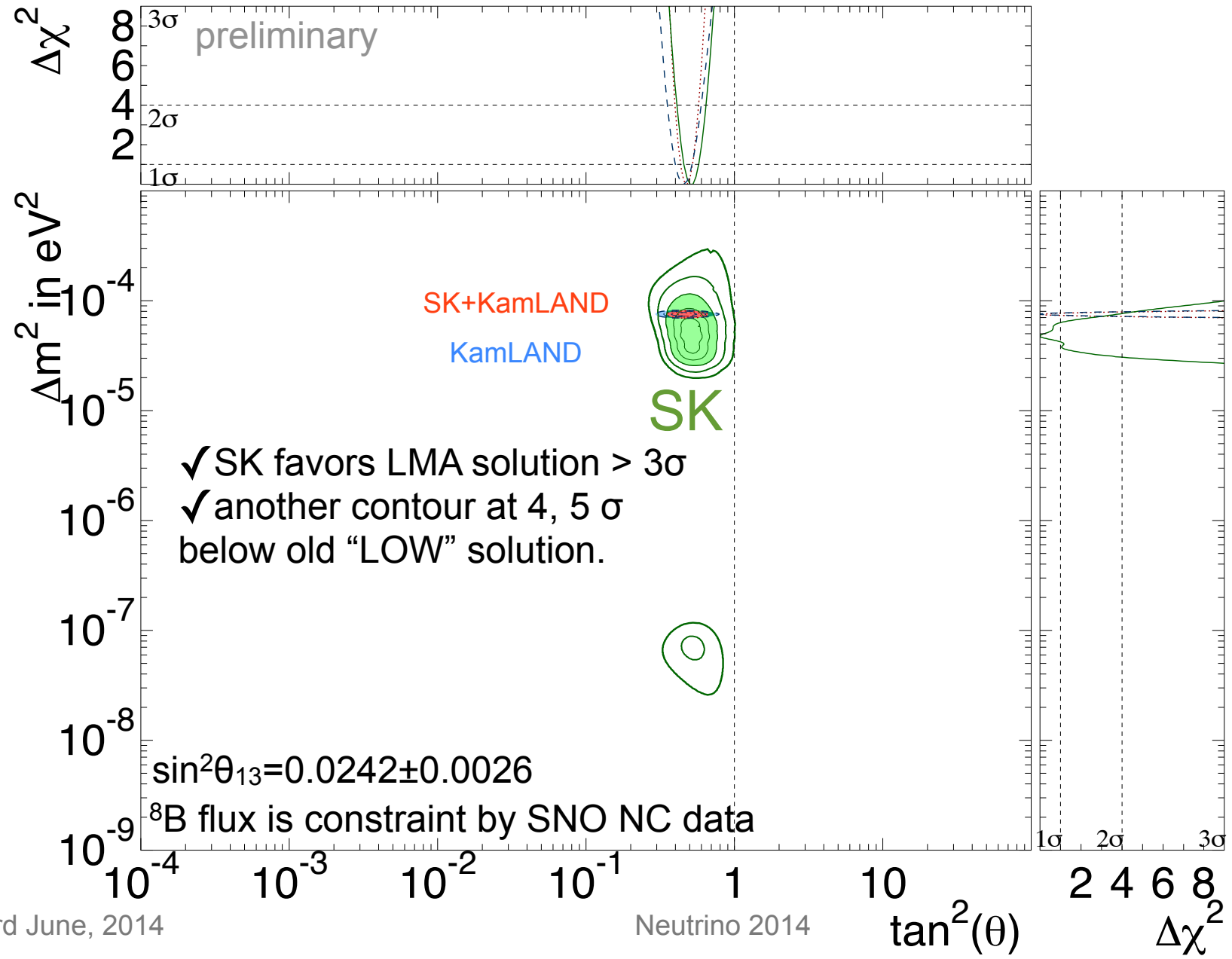
$$z_i(t_\nu) \Rightarrow z_i(\alpha, t) = \frac{1+\alpha((1+a_i) r_i(t) / r_i^{av} - 1)}{1+\alpha a_i} \times z_{\exp}(t)$$

α : day-night asym. scaling factor

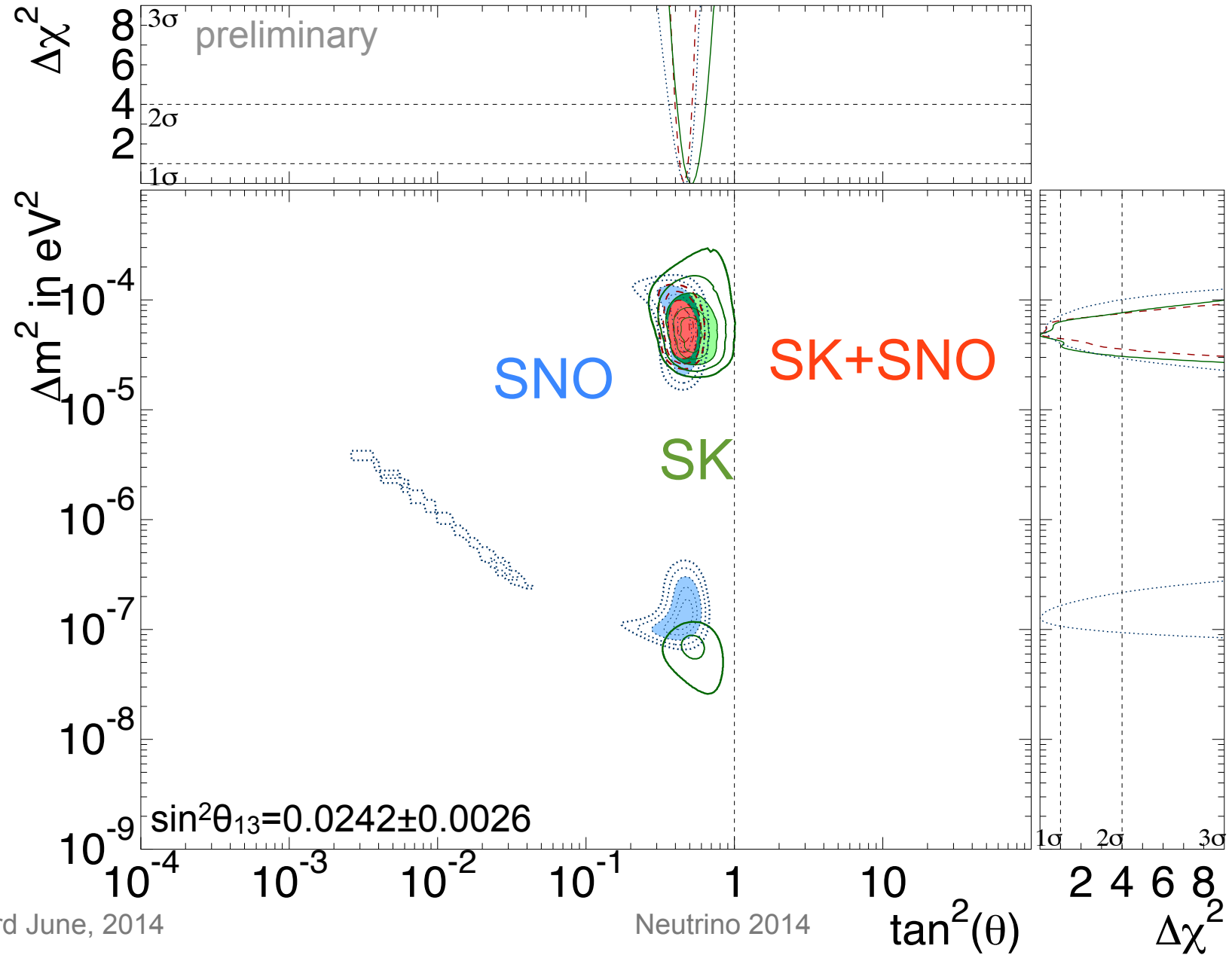
exponential parameterization



SK I - IV combined



SK and SNO


preliminary
3σ
2σ
1σ
$\Delta\chi^2$
Δm^2 in eV^2
SNO
SK
SK+SNO
$\sin^2\theta_{13}=0.0242\pm0.0026$
$\tan^2(\theta)$
$\Delta\chi^2$