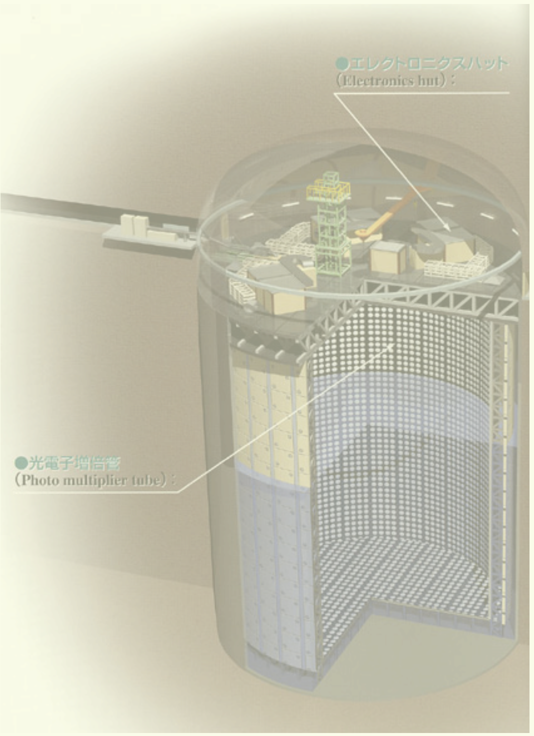
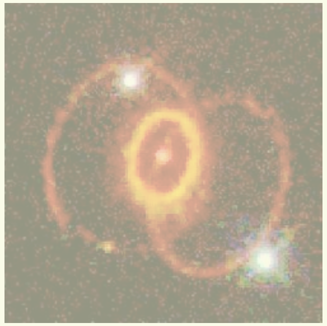
Super-Kamiokande low energy





Yusuke Koshio

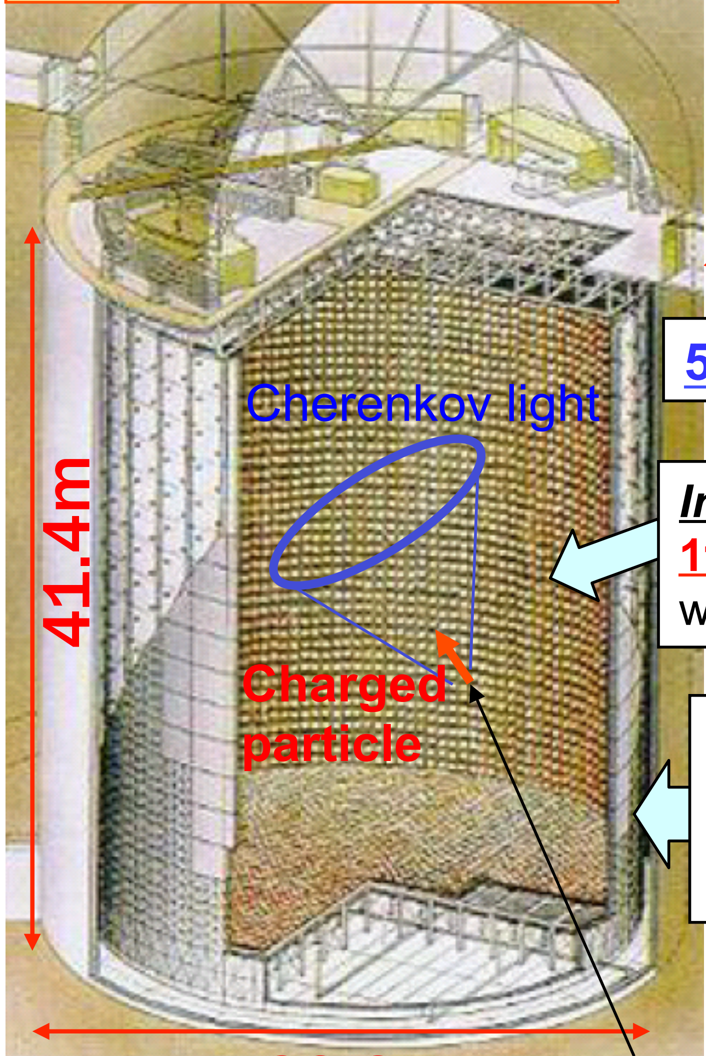
Okayama University

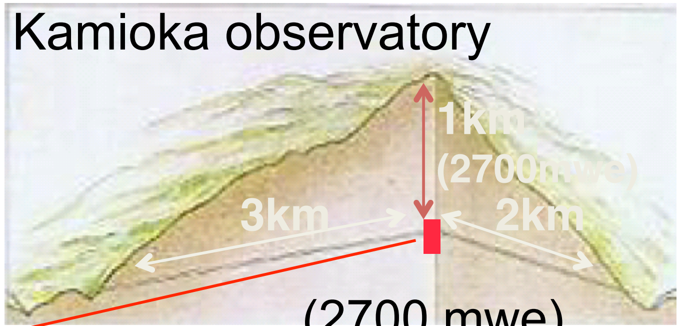
Kavli IPMU, Univ. of Tokyo

Multi-Messenger bi-monthly meeting, 15 April, 2014

Super-Kamiokande

Water Chernkov detector





(2700 mwe)

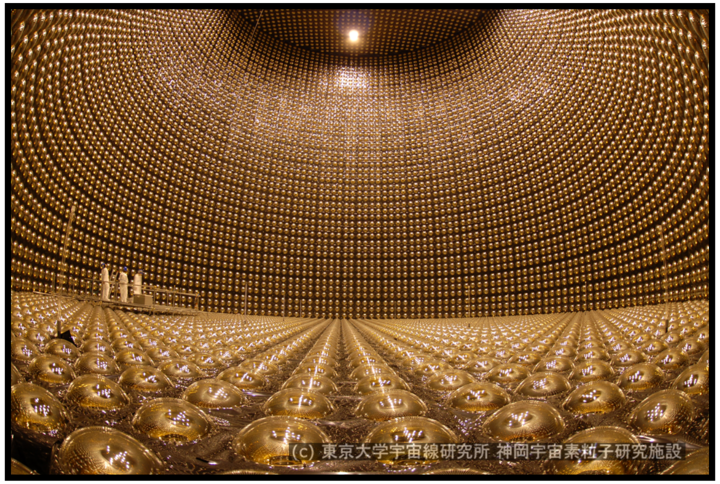
Since 1996

SK-1 (1996~2001)
SK-2 (2002~2005)
SK-3 (2006~2008)
SK-4 (2008~present)

50,000 tons of pure water

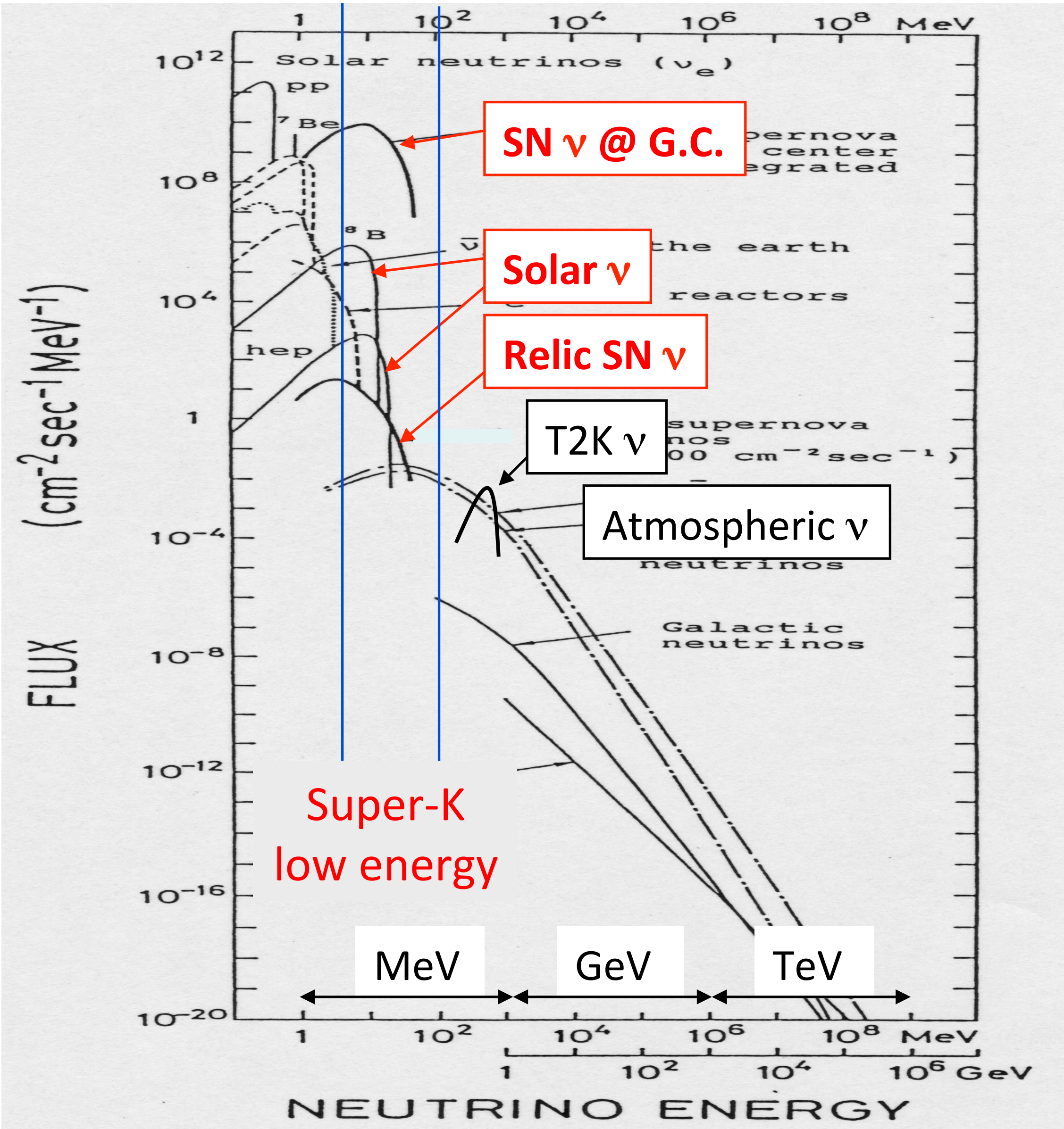
Inner detector:
11129 of 20” PMT
with acrylic cover

Outer detector:
1885 of 8” PMT
remove cosmic ray μ
γ and n shield from rock



3.5MeV(kin.) energy threshold

What's "low energy"



MeV~100MeV region

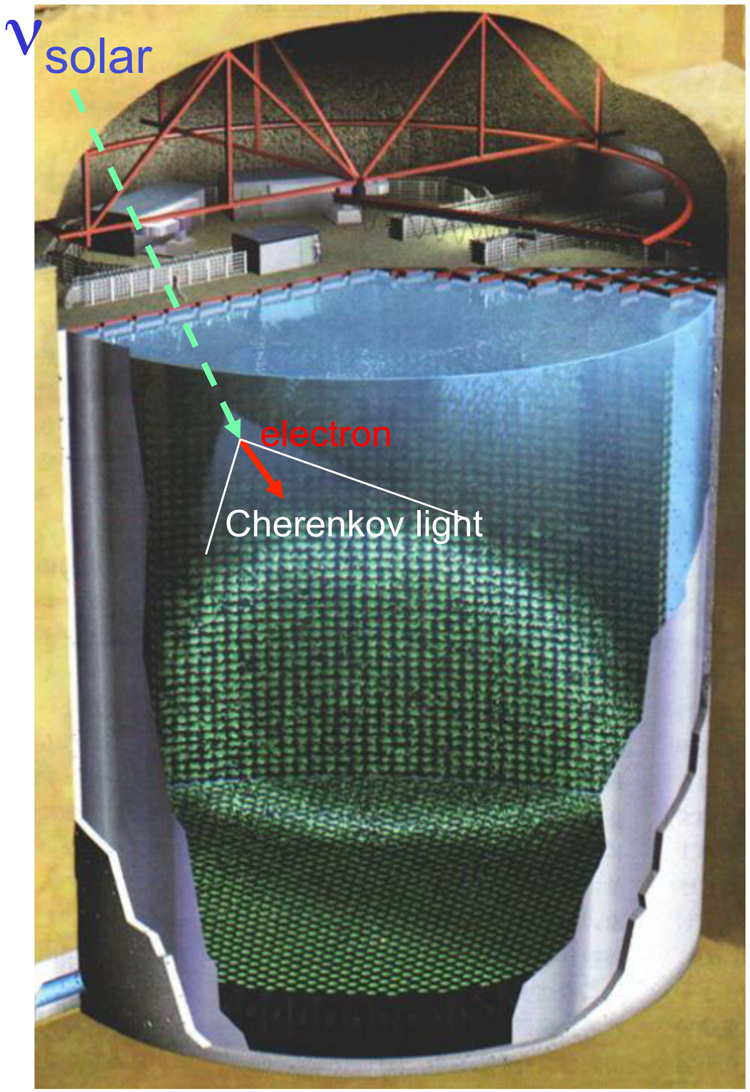
Main target:

✓Solar neutrino

✓Super Nova neutrino

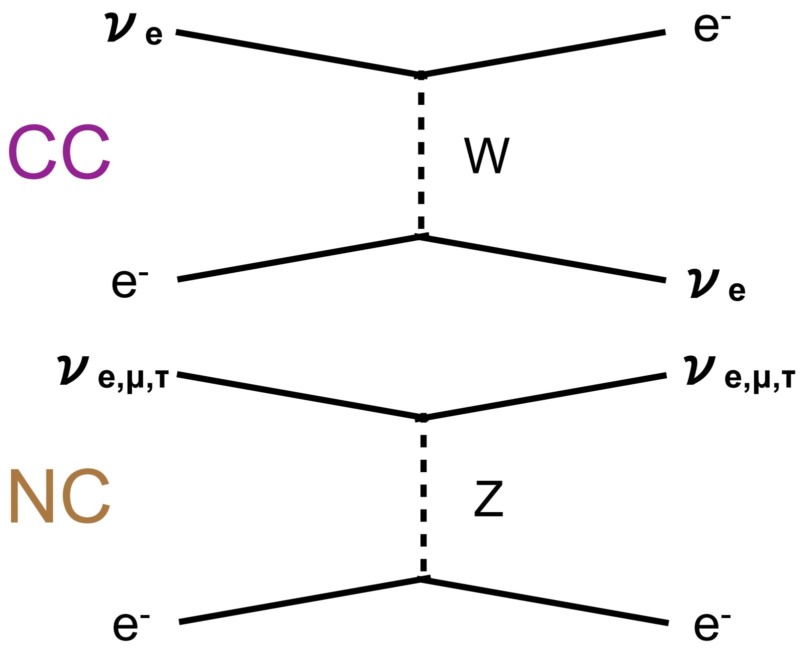
Solar neutrinos in Super-K

Observation in Super-K

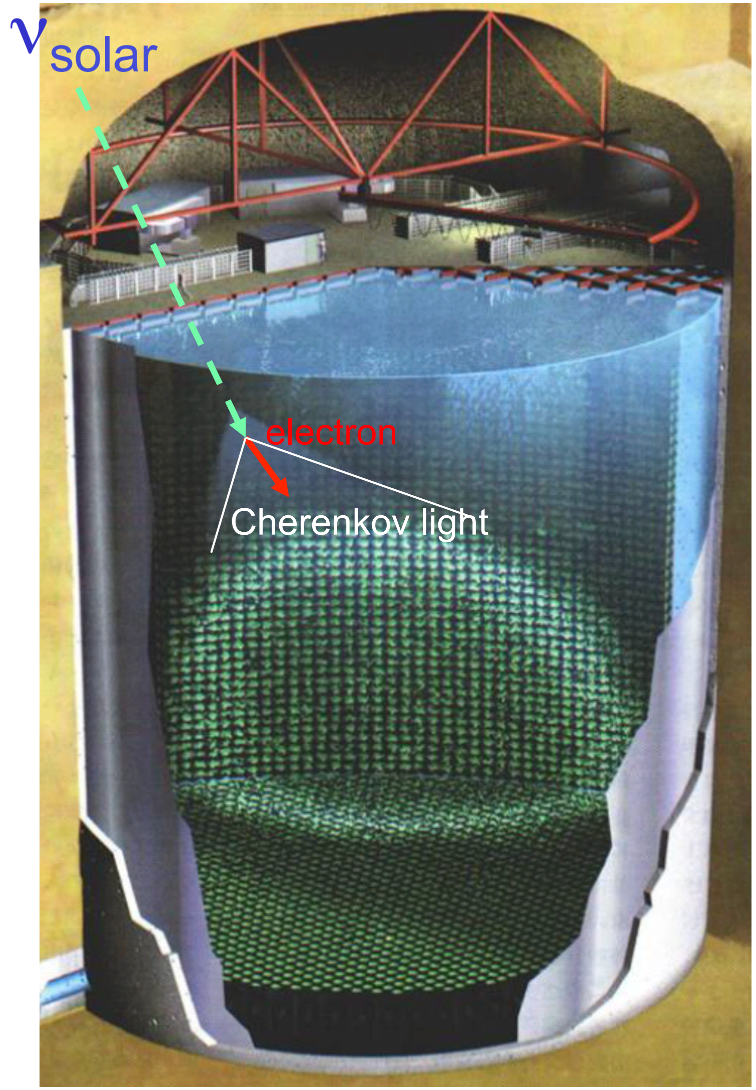


neutrino-electron elastic scattering

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



Observation in Super-K

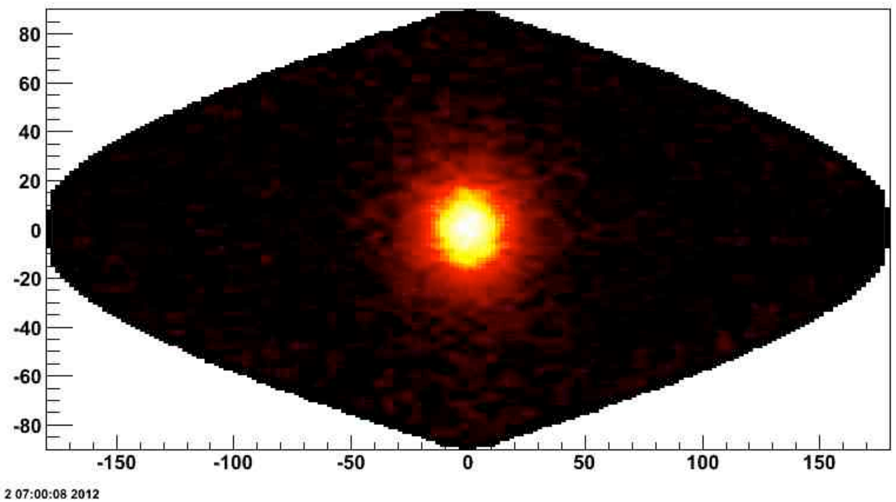


neutrino-electron elastic scattering

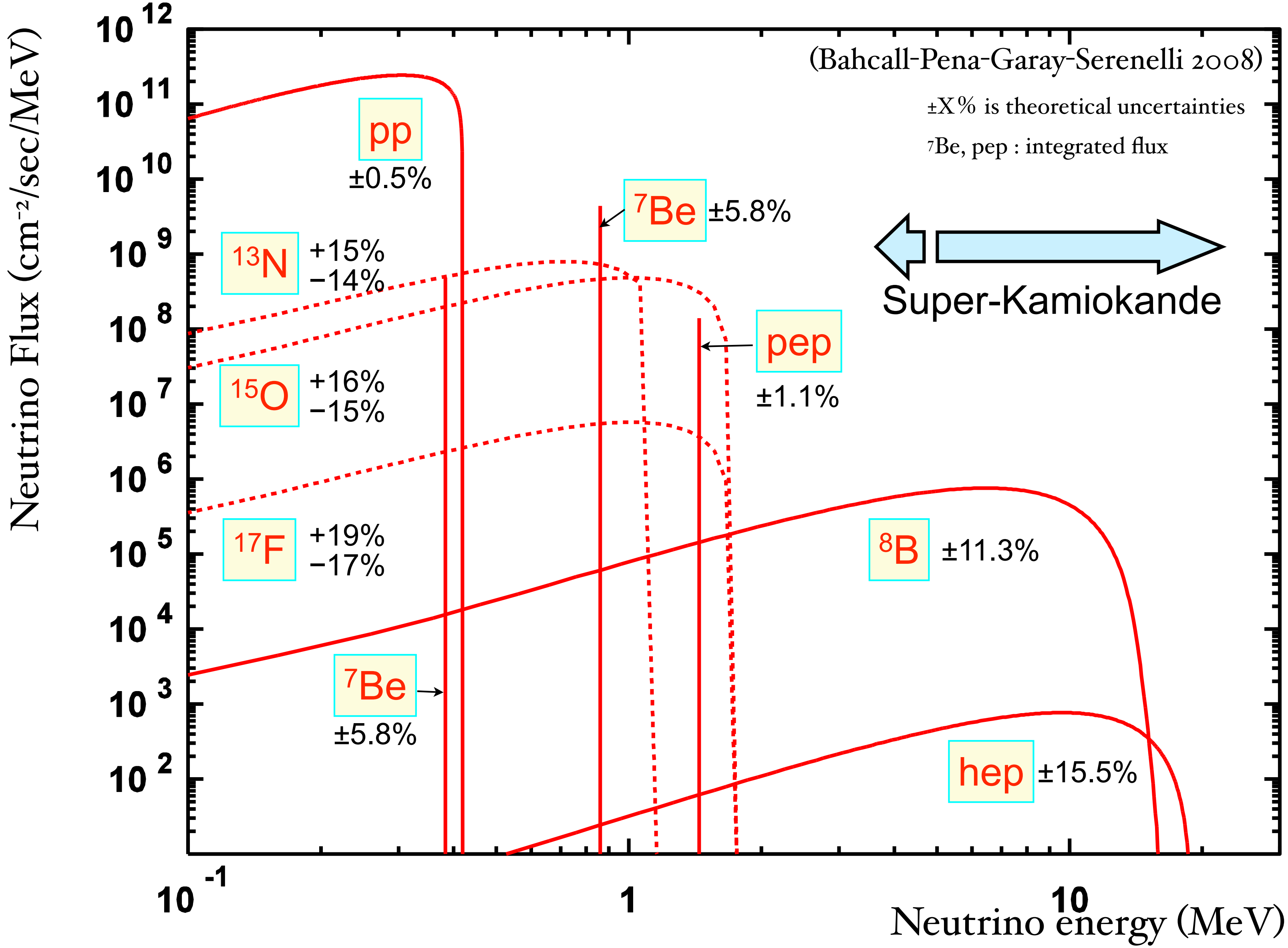
$$\nu + e^- \rightarrow \nu + e^-$$

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

✓Energy spectrum



Solar neutrino spectrum



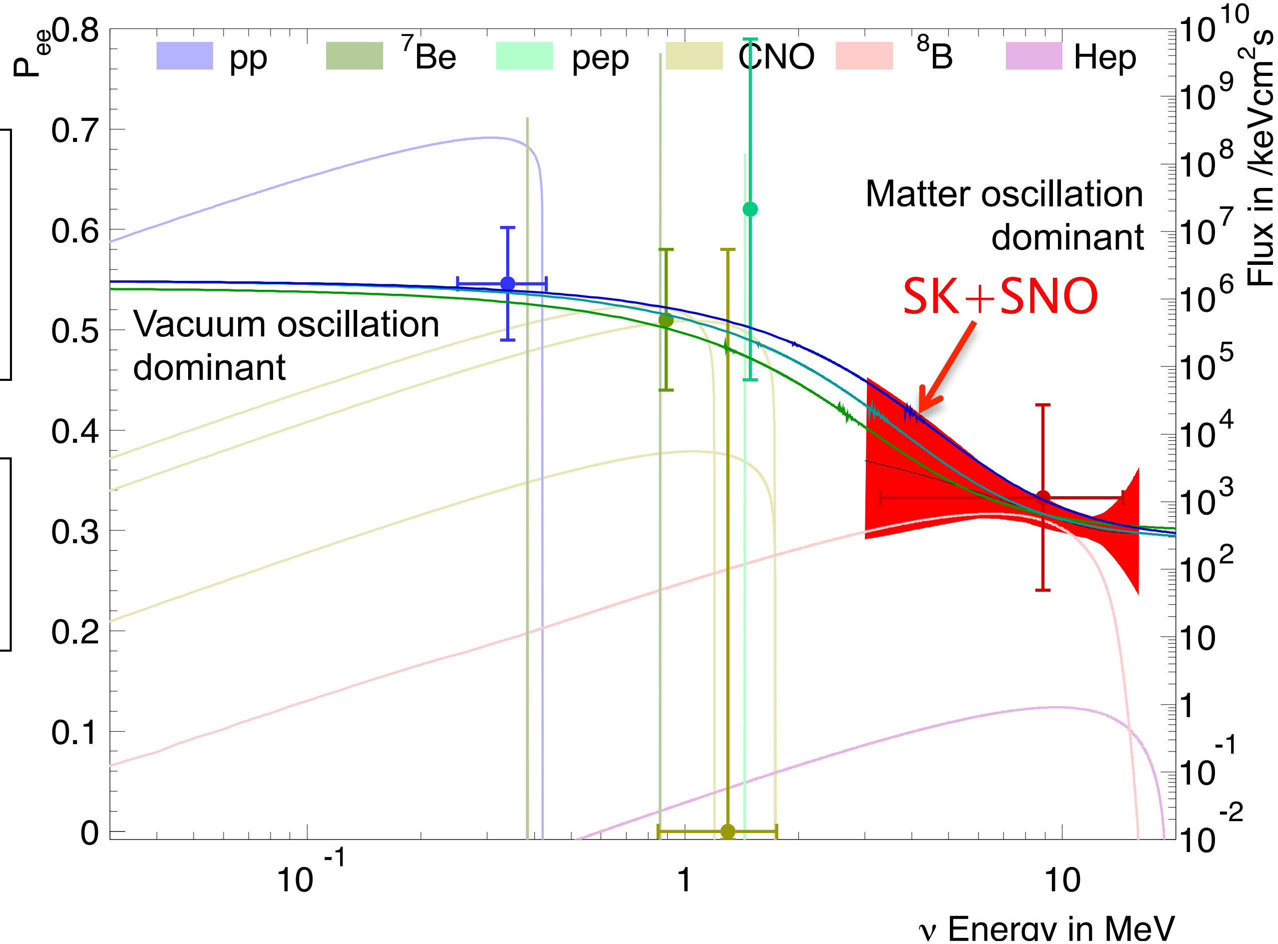
Motivation of the Super-K solar ν

See the neutrino oscillation MSW effect directly

Spectrum distortion

The MSW resonance will lead to the energy dependence of the neutrino survival probability with the signature "upturn".

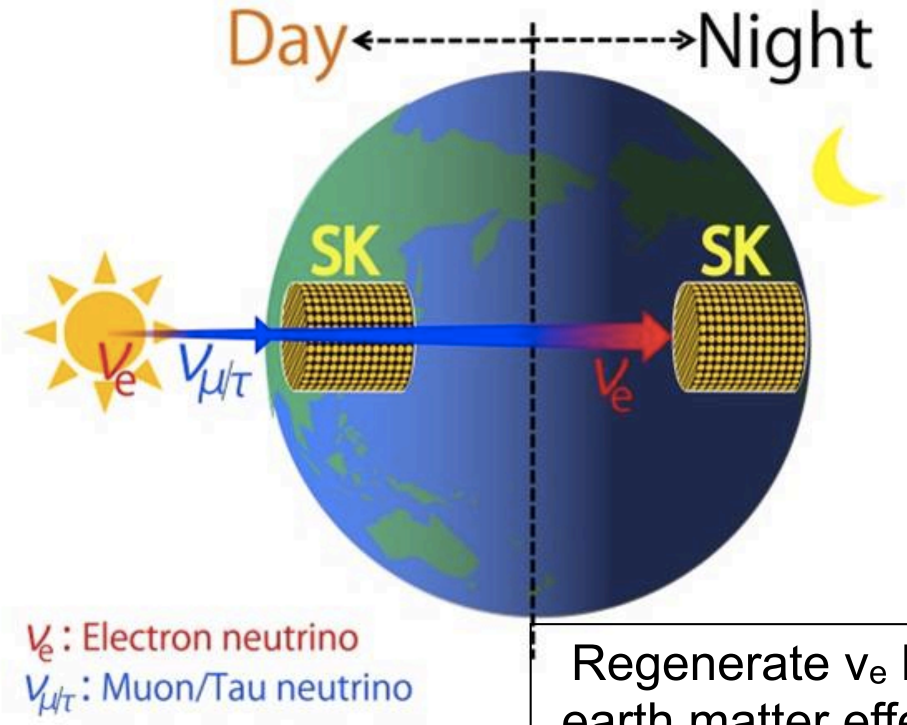
Super-K can search for the "upturn" in its recoil electron energy spectrum



Motivation of the Super-K solar ν

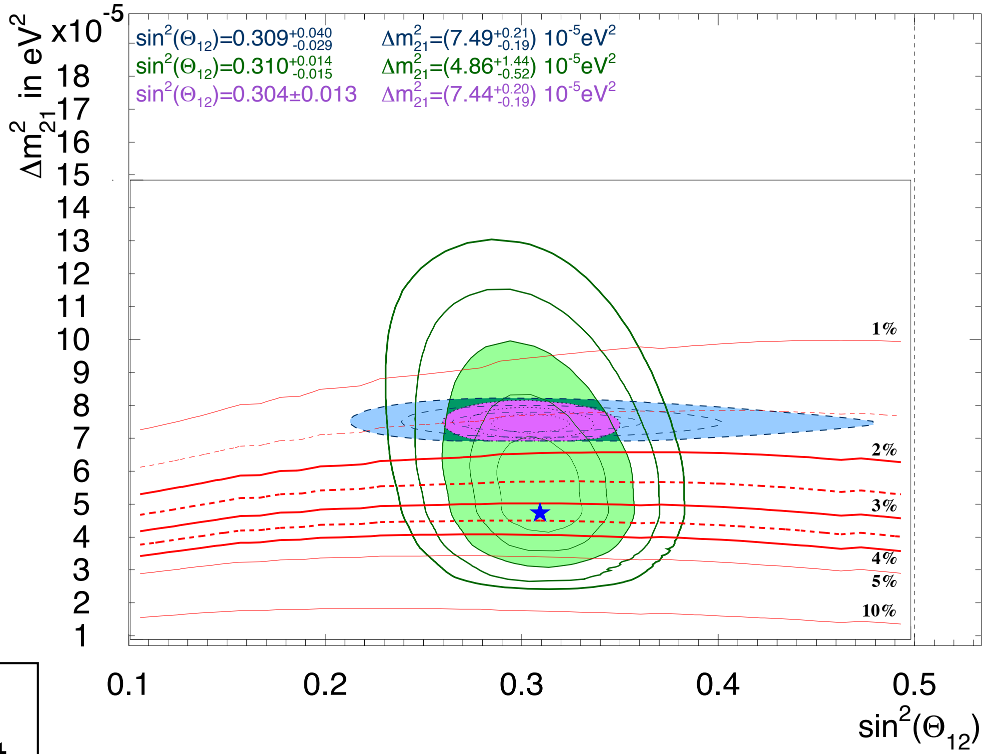
See the neutrino oscillation MSW effect directly

Day-Night flux asymmetry



Regenerate ν_e by earth matter effect

Adn=(day-night)/((day+night)/2)
(expected)



Results in Super-K

Recent publish

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]

(The Super-Kamiokande Collaboration)

PRL: Editor's Suggestion!

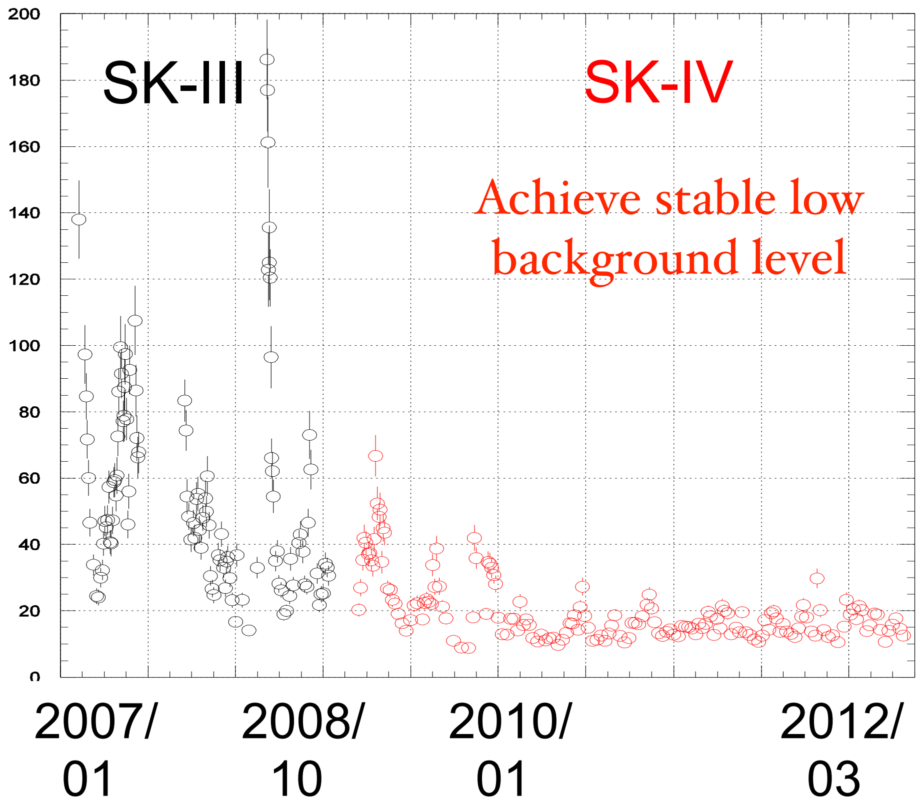
Data set

- 16 years (1996~2012) of data
  - 1496 days (SK-I), 791 days (SK-II), 548 days (SK-III), 1306 days (SK-IV)
- Improvement for SK-IV
  - Lower background
  - Reduce systematic error
  - Lower threshold (3.5MeV(kin.))

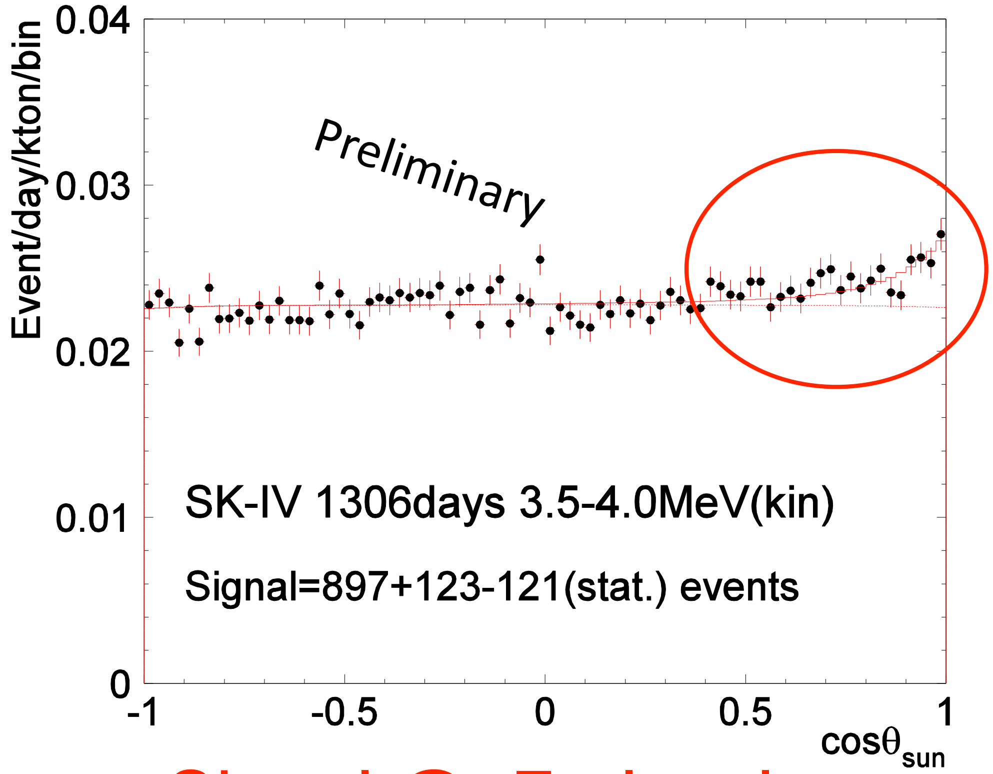
1.7% for flux
(2.1% for SK-III)
(3.2% for SK-I)

Lower background

[event/day/kton @ 4.0-4.5MeV(kin.)]



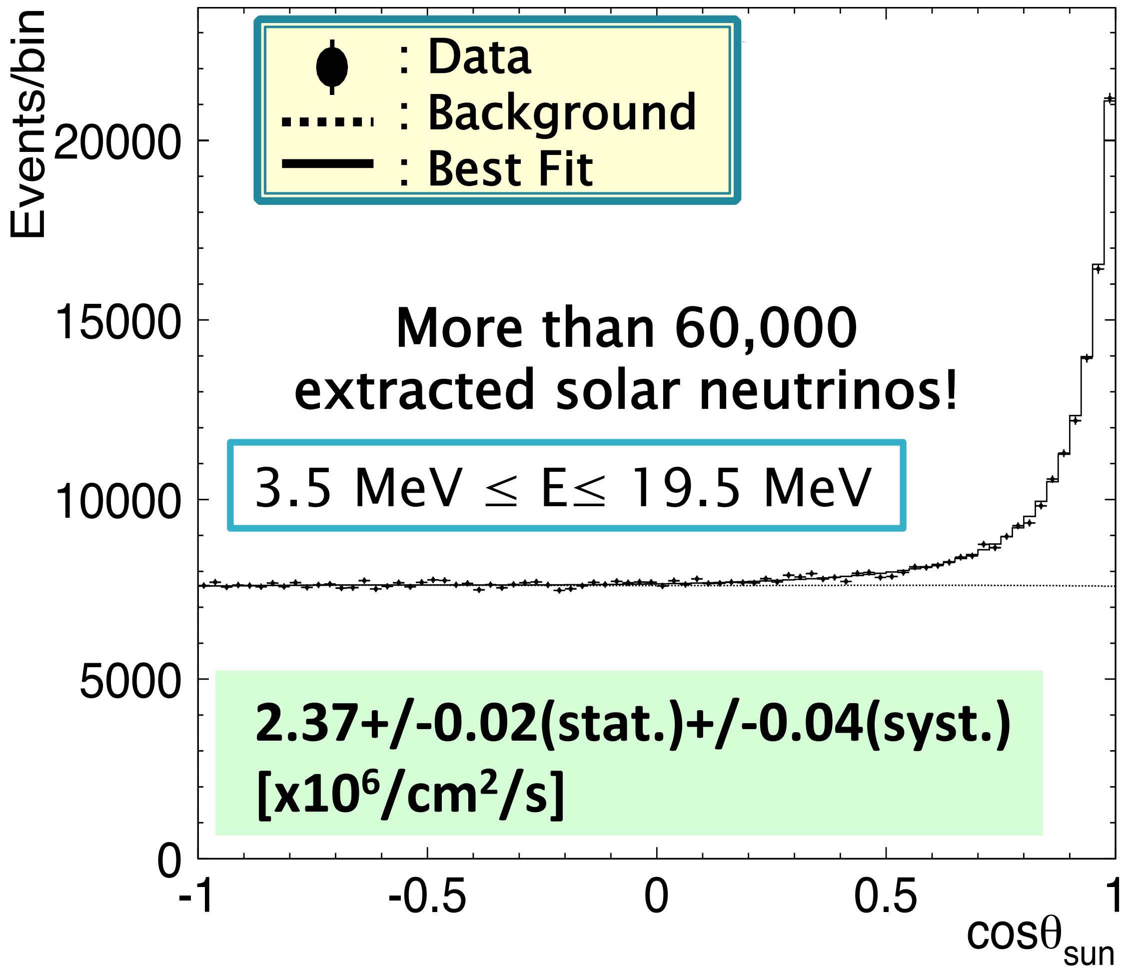
Solar angular distribution (3.5~4.0MeV(kin.))



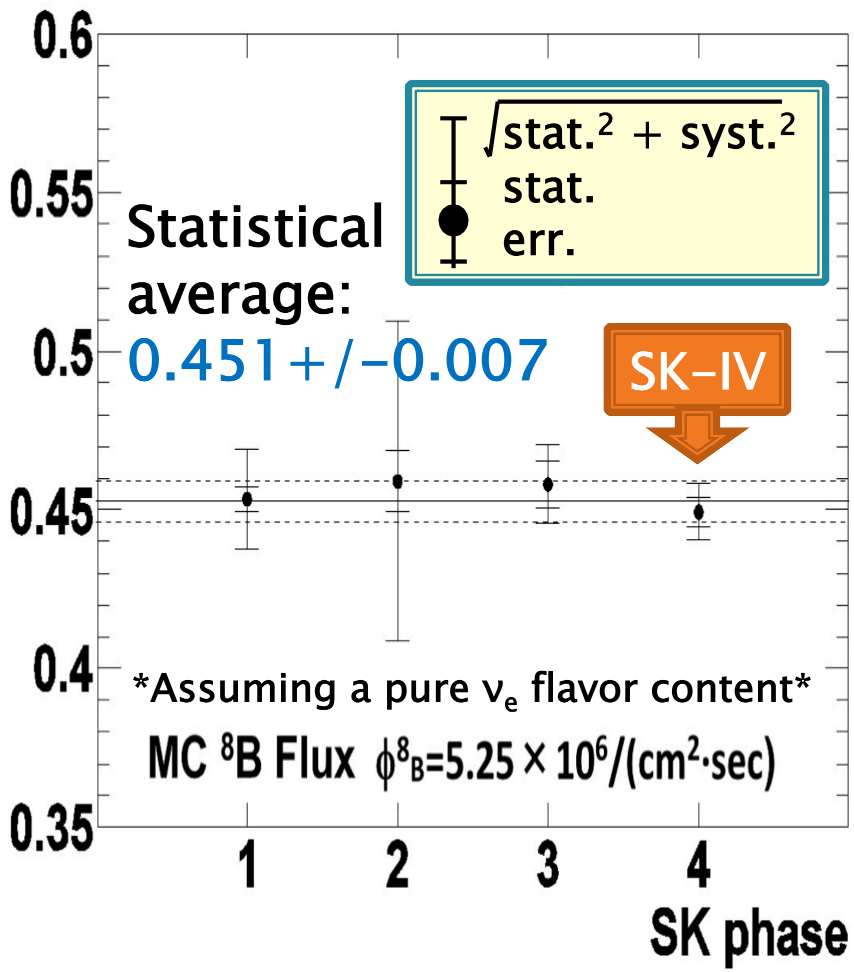
Signal @~7σ level

Observed solar neutrino events

SK I ~ IV

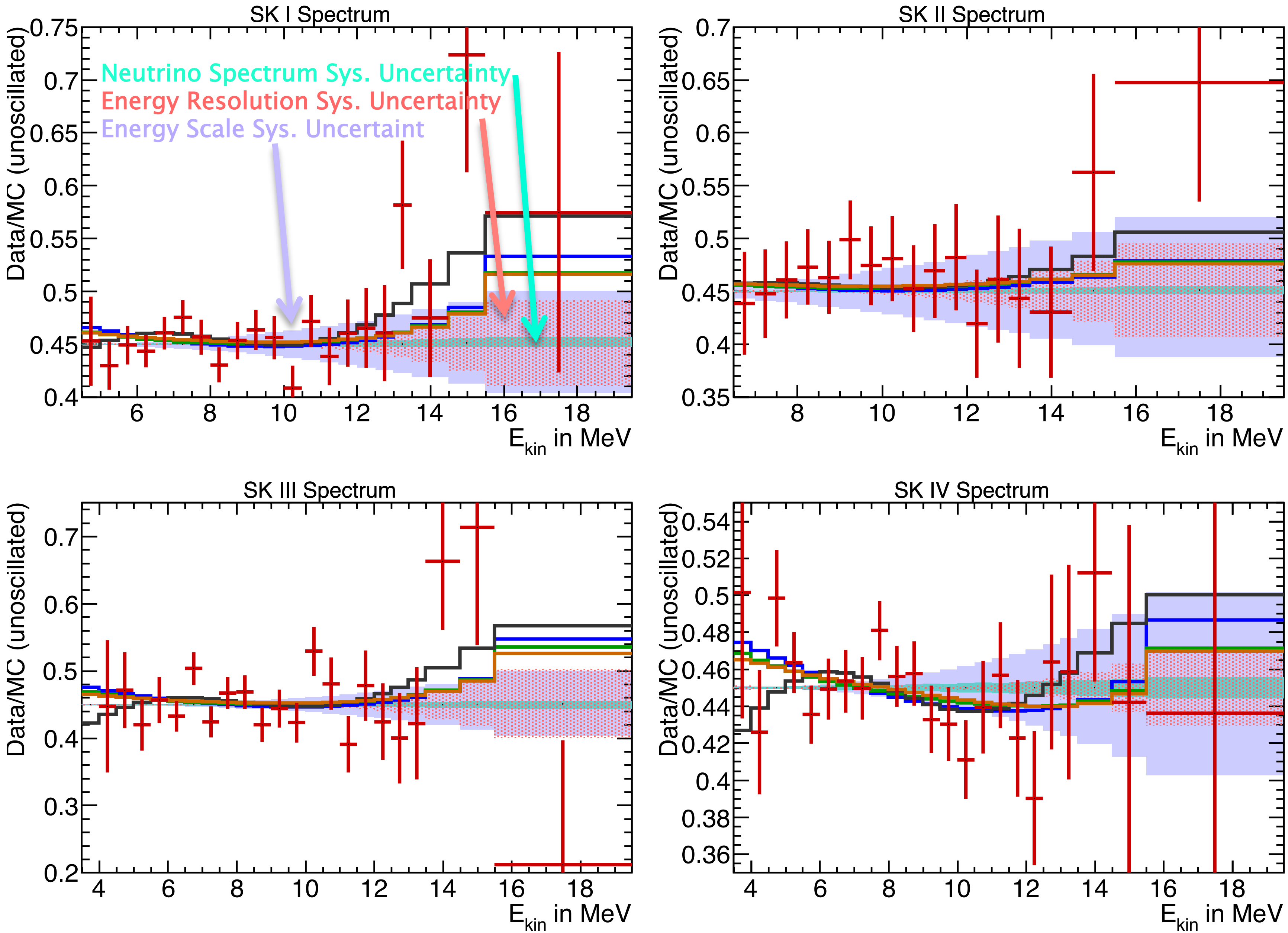


Flux in each SK phase

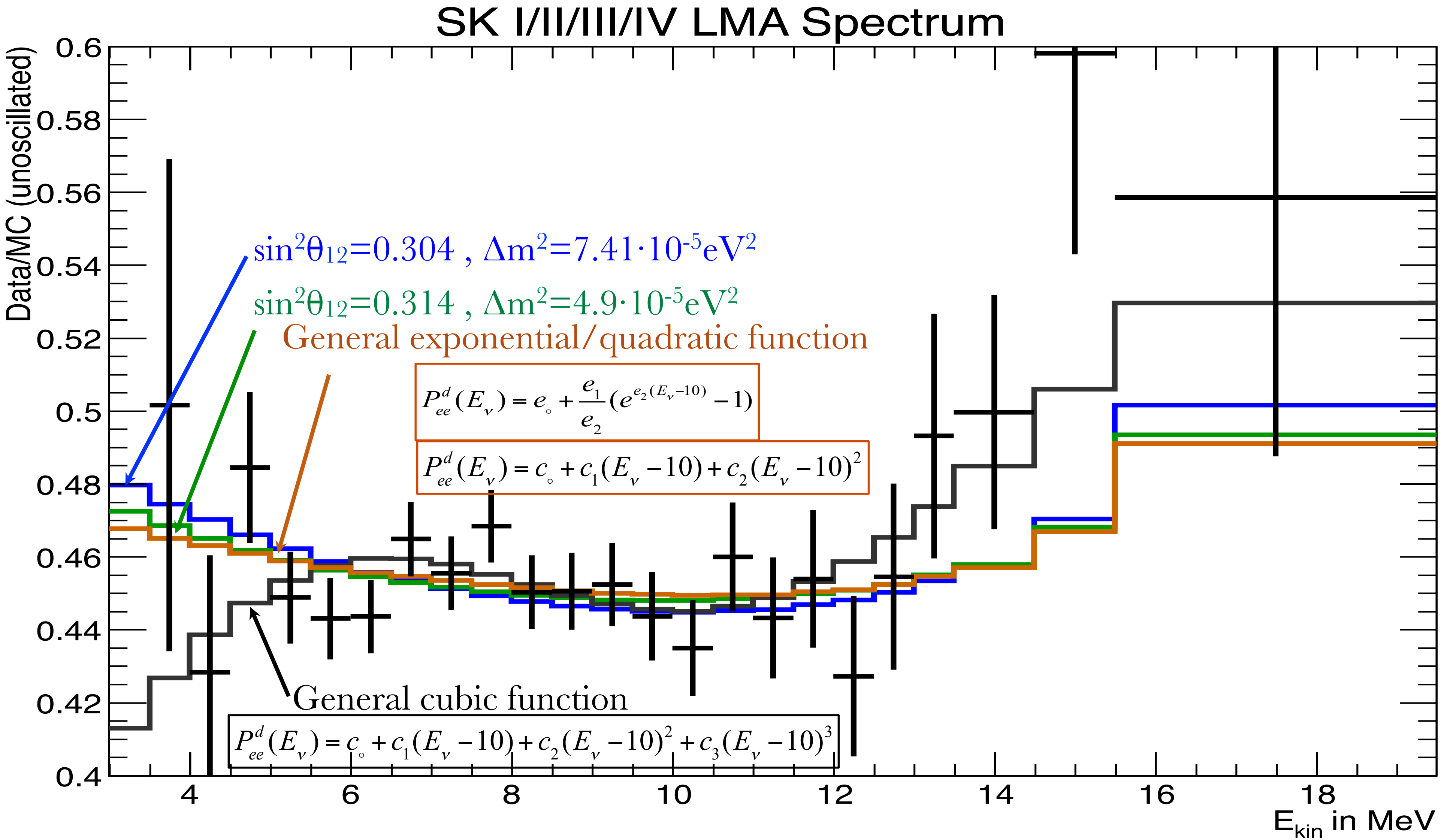


Spectrum

Recoil electron spectrum

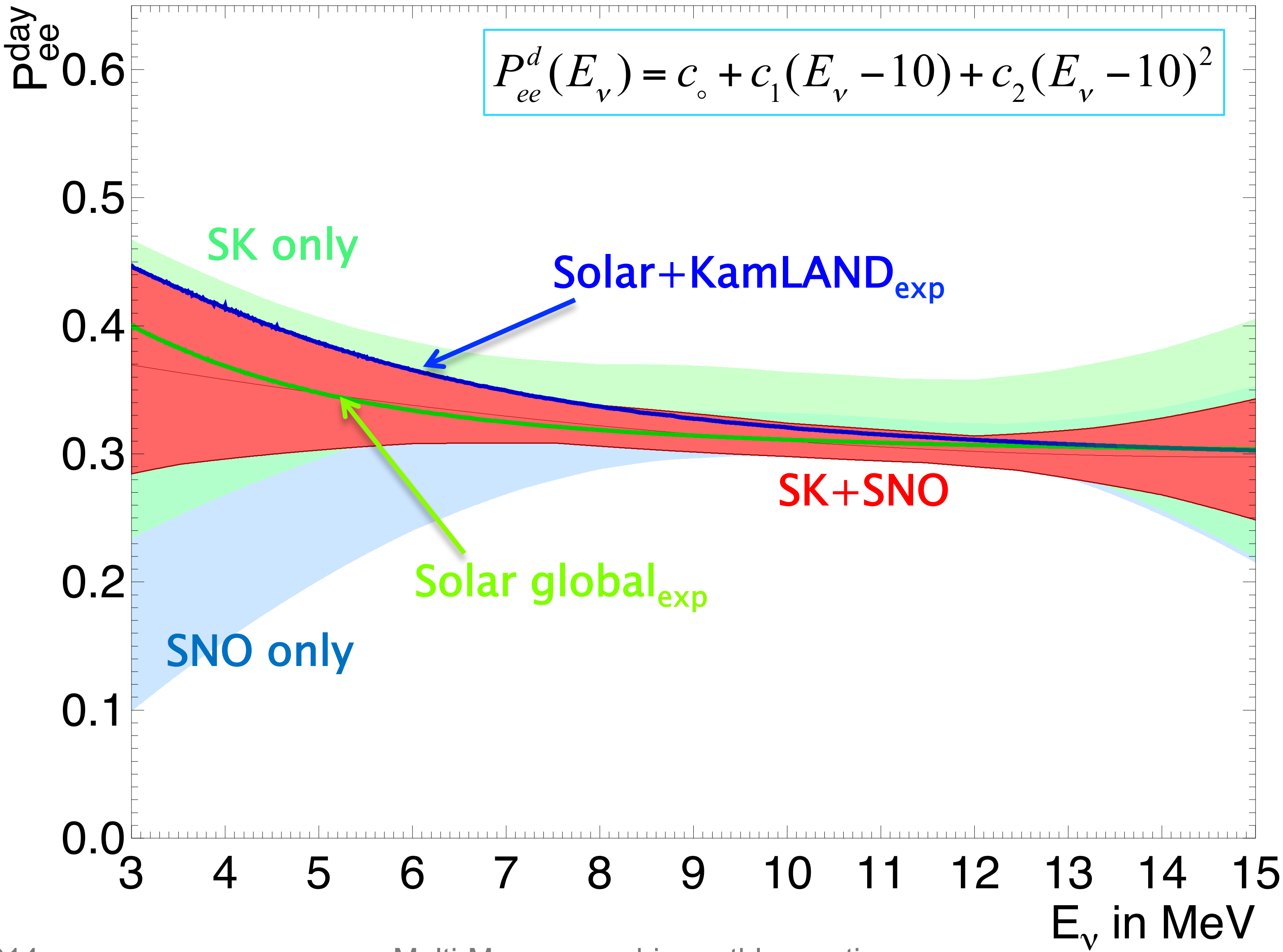


Upturn?



SK I/II/III/IV LMA Spectrum
Data/MC (unoscillated)
0.6
0.58
0.56
0.54
0.52
0.5
0.48
0.46
0.44
0.42
0.4
4
6
8
10
12
14
16
18
E_kin in MeV
sin²θ12=0.304 , Δm²=7.41·10⁻⁵eV²
sin²θ12=0.314 , Δm²=4.9·10⁻⁵eV²
General exponential/quadratic function
$P^d_{ee}(E_\nu) = e_\circ + \frac{e_1}{e_2}(e^{e_2(E_\nu - 10)} - 1)$
$P^d_{ee}(E_\nu) = c_\circ + c_1(E_\nu - 10) + c_2(E_\nu - 10)^2$
General cubic function
$P^d_{ee}(E_\nu) = c_\circ + c_1(E_\nu - 10) + c_2(E_\nu - 10)^2 + c_3(E_\nu - 10)^3$

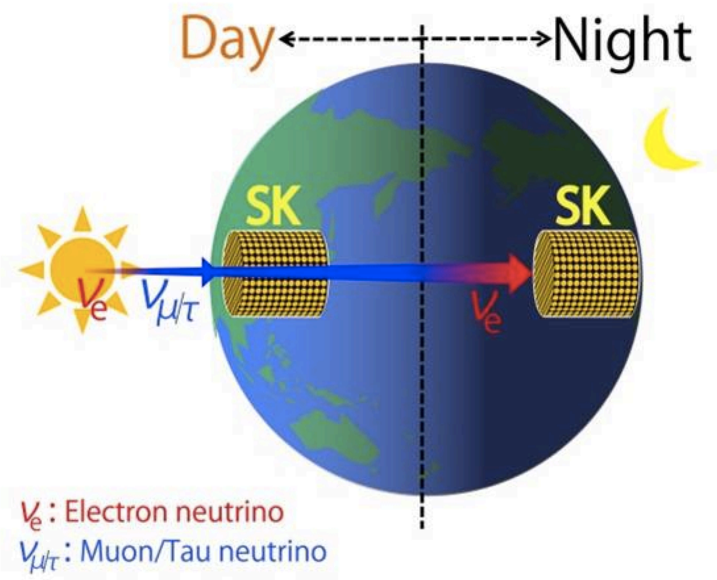
Allowed survival probability

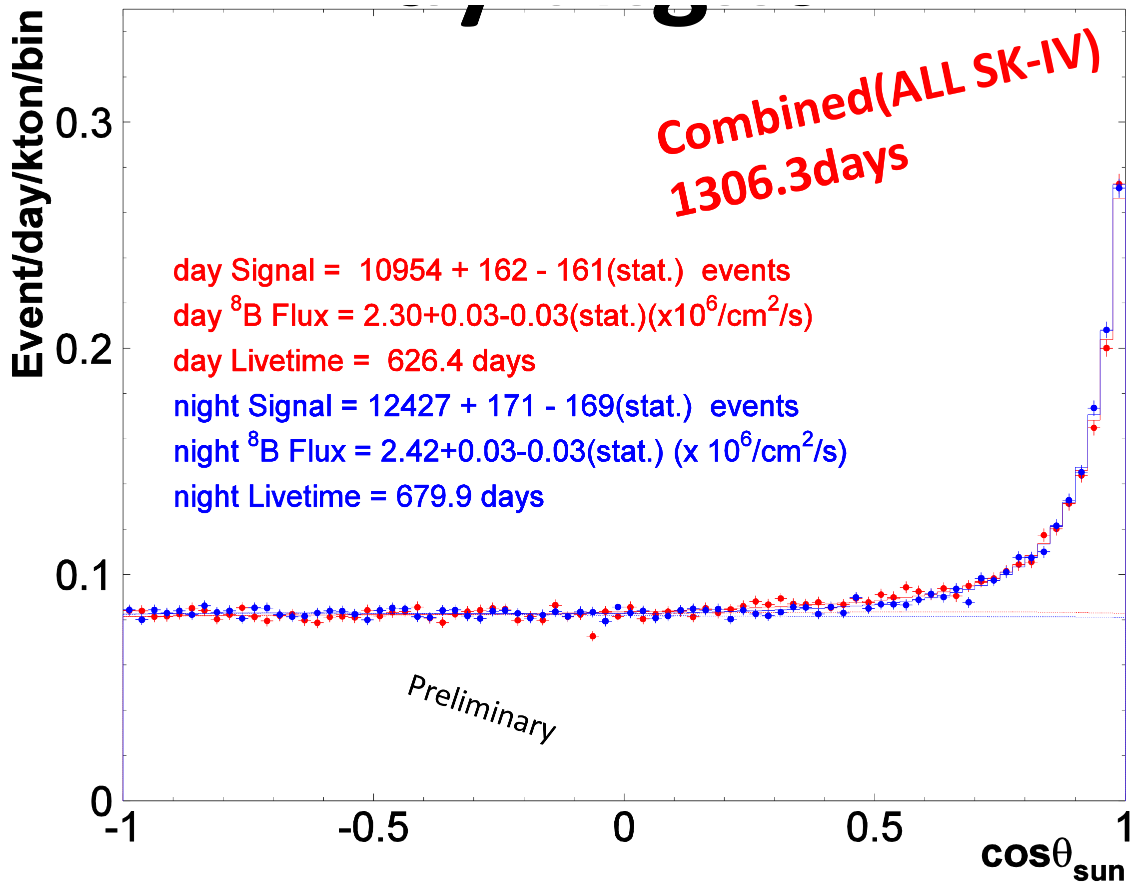


Day-Night flux differences

Analysis -1-

Day/Night asymmetry

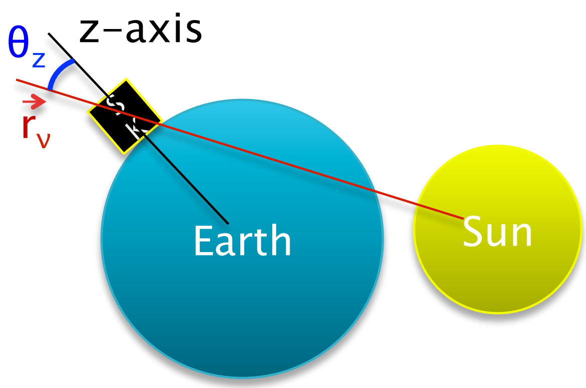


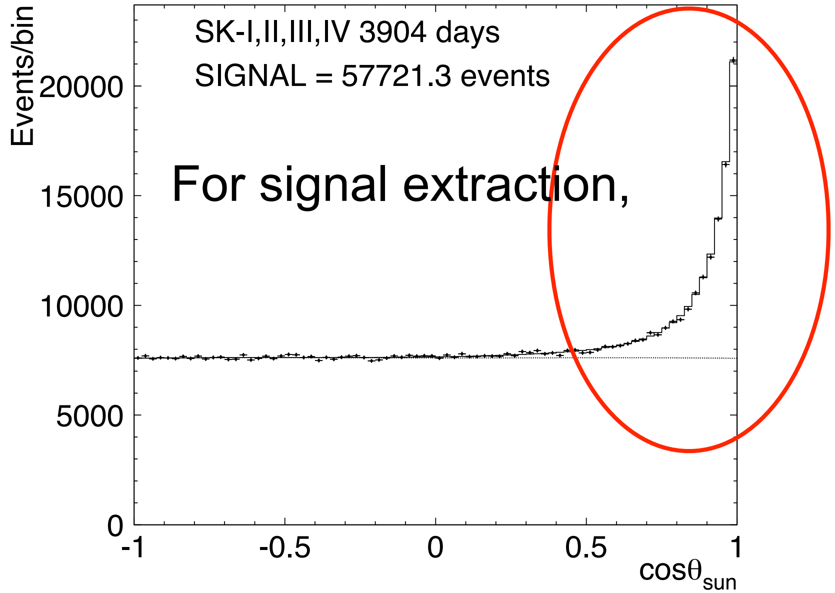


$$A_{DN} = \frac{\Phi_D - \Phi_N}{1/2(\Phi_D + \Phi_N)}$$

Analysis -2-

Day/Night amplitude

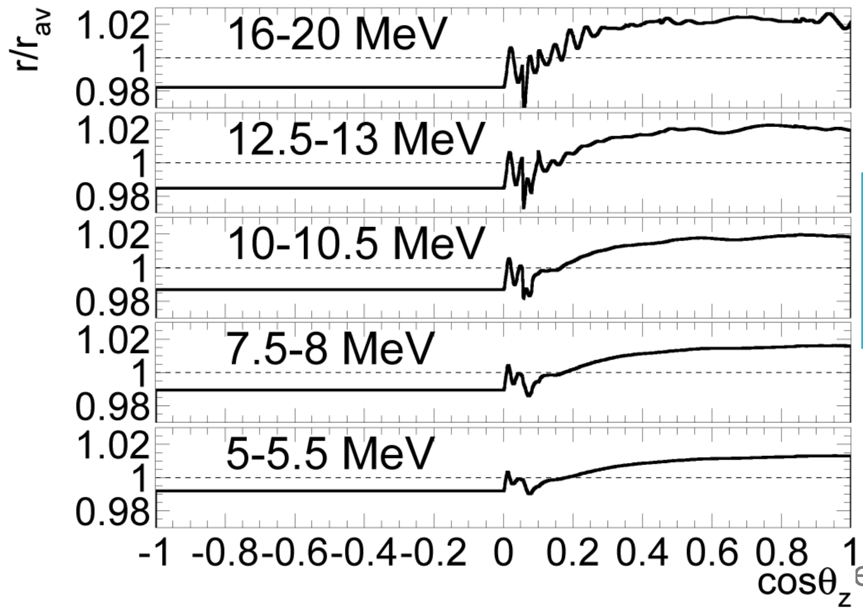




$$\mathcal{L} = e^{-\left(\sum_i B_i + S\right)} \prod_{i=1}^{N_{bin}} \prod_{\nu=1}^{n_i} \left(\beta_i(c_\nu)B_i + \sigma_i(c_\nu) \times z_i(t_\nu) m_i S\right)$$

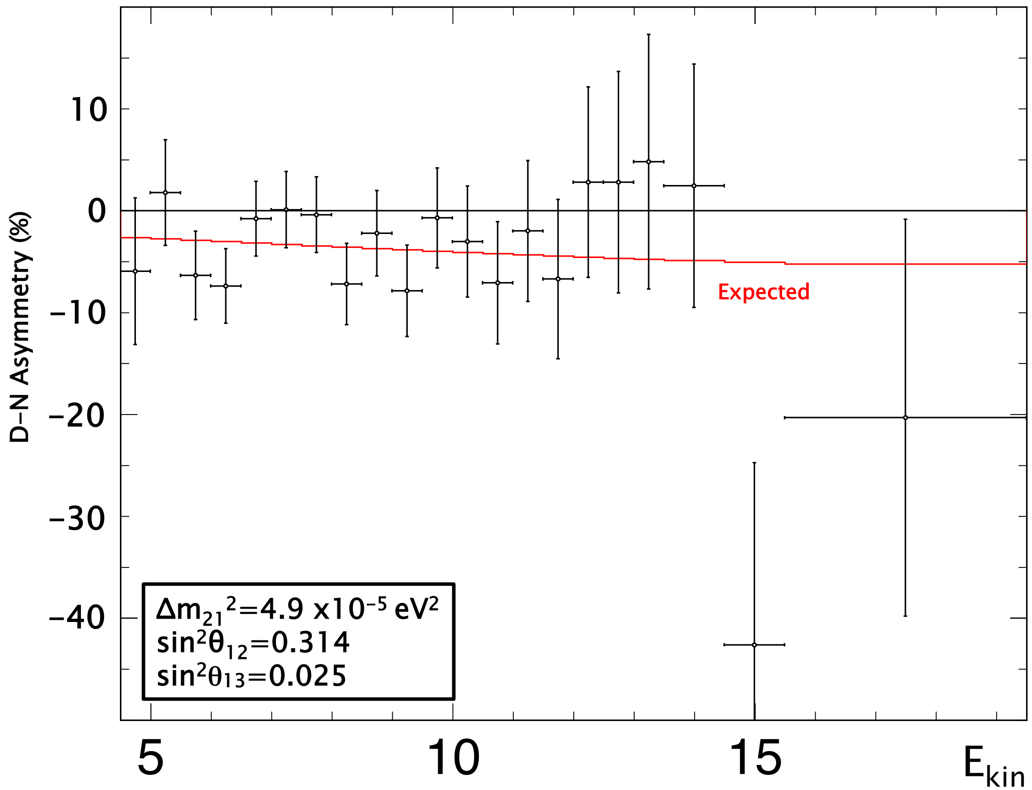
$$z_i(t_\nu) \Rightarrow z_i(\alpha, t) = \frac{1 + \alpha((1 + a_i) r_i(t) / r_i^{av} - 1)}{1 + \alpha a_i} \times z_{\exp}(t)$$

α : day-night asym. scaling factor



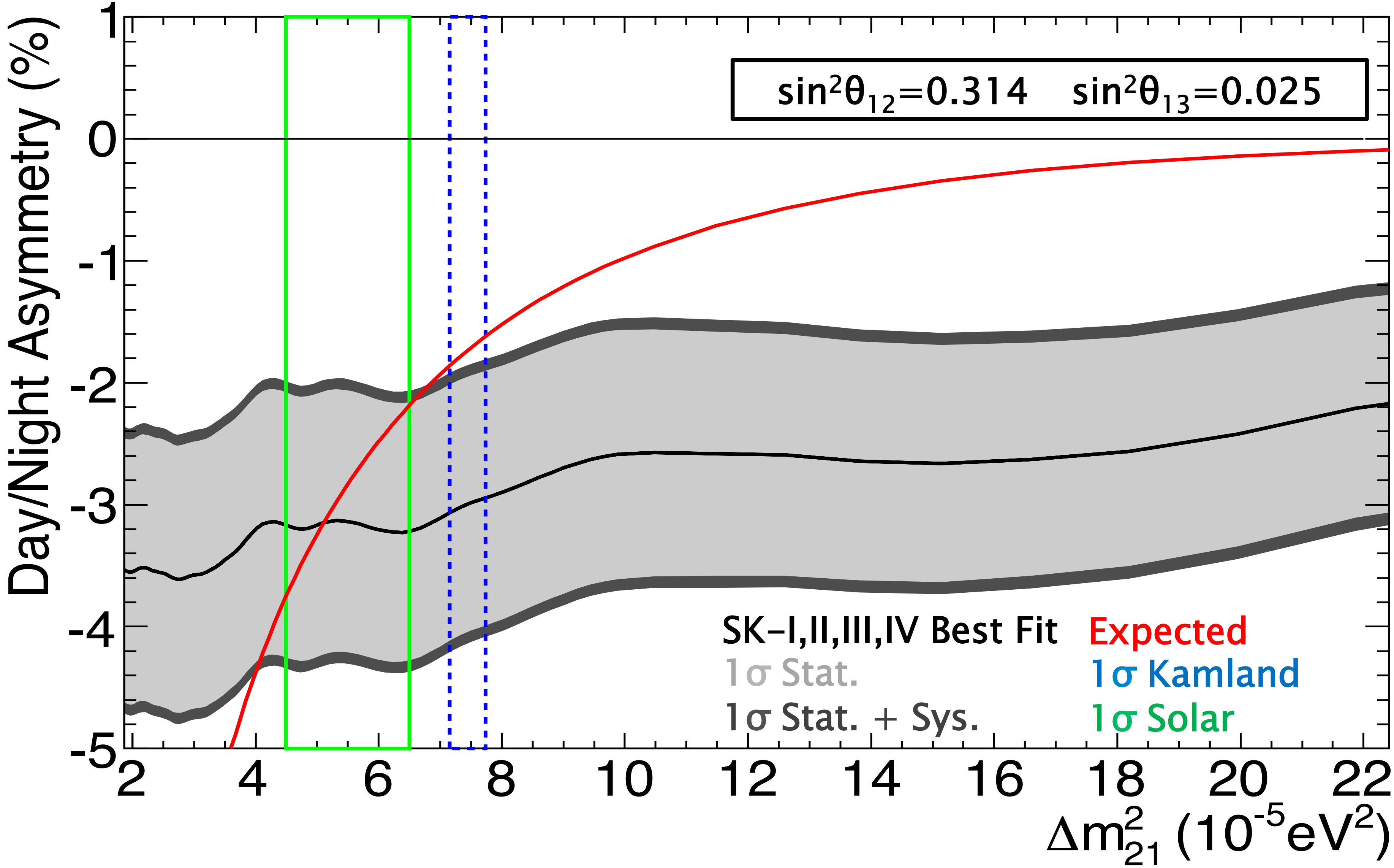
Results

experiment	D/N amplitude	A_{DN}
SK-I	-2.0±1.7±1.0%	-2.1±2.0±1.3%
SK-II	-4.3±3.8±1.0%	-5.5±4.2±3.7%
SK-III	-4.3±2.7±0.7%	-5.9±3.2±1.3%
SK-IV	-3.4±1.8±0.6%	-5.3±2.0±1.4%
SK comb.	**-3.2±1.1±0.5%**	-4.2±1.2±0.8%



Day/Night asymmetry derivates from zero by 2.7 σ

Δm^2 dependence



Neutrino oscillation analysis

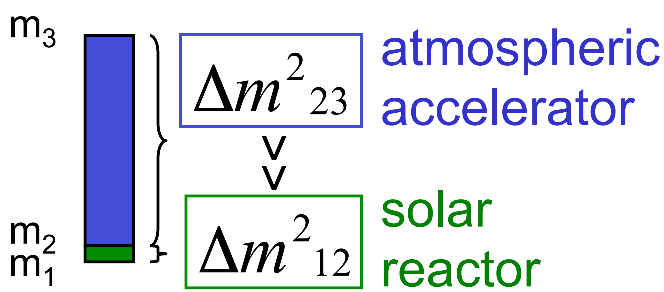
Neutrino oscillation

- Mixing angle

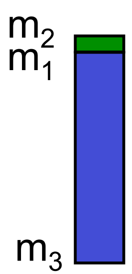
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric accelerator}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{all neutrino sources}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar reactor}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigenstate | atmospheric accelerator | all neutrino sources | solar reactor | Mass eigenstate

- Neutrino mass differences

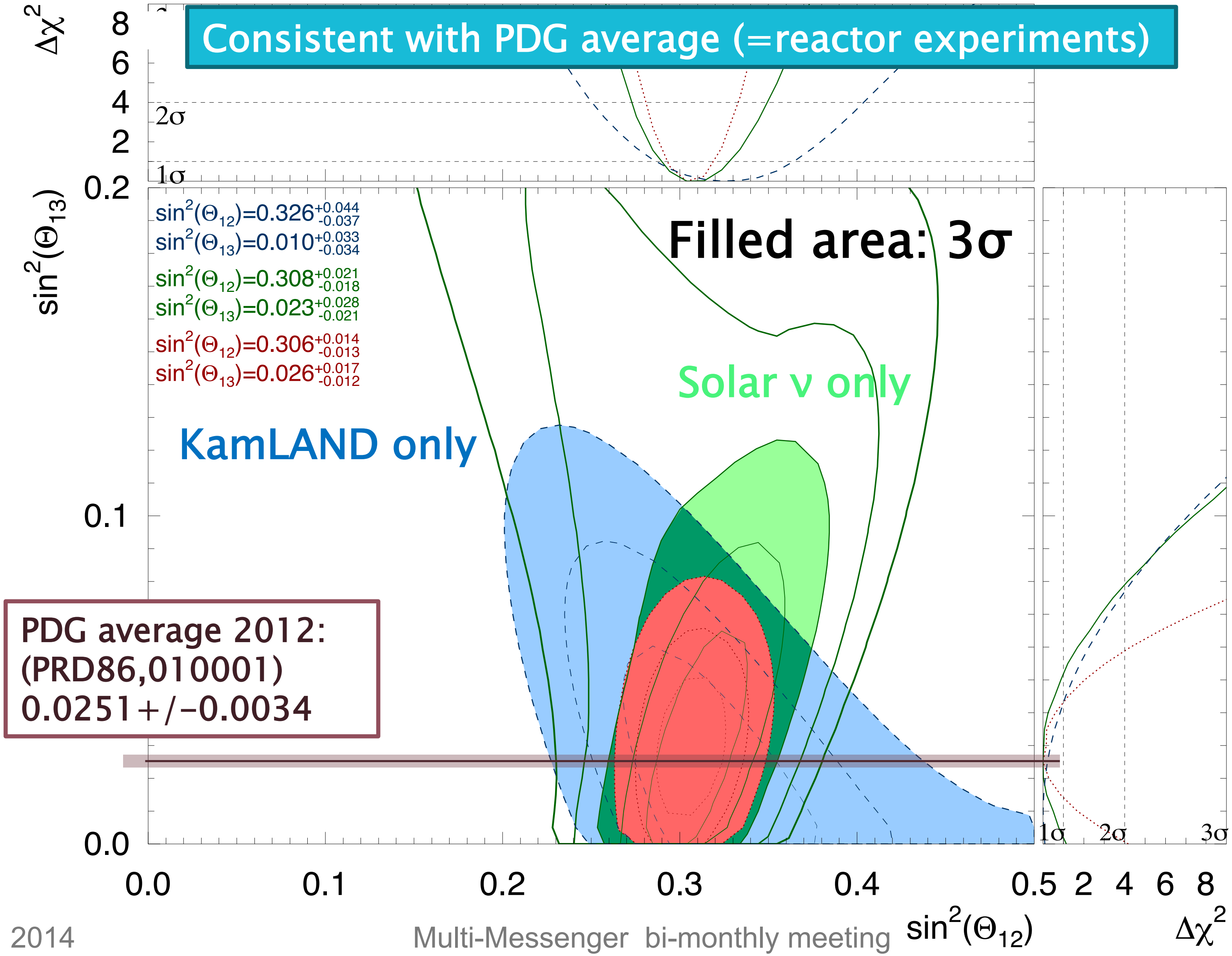


Normal hierarchy



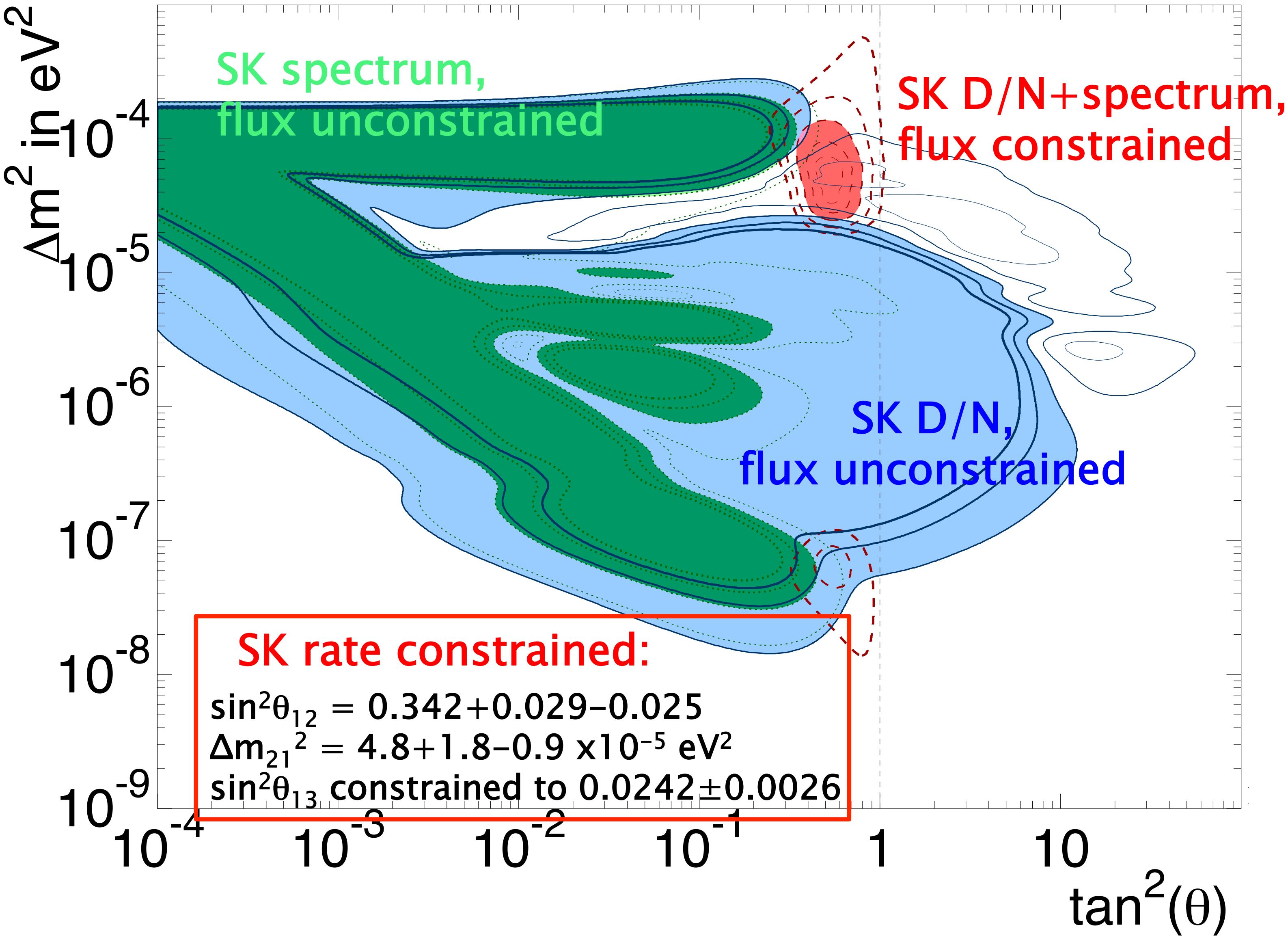
Inverted hierarchy

Theta-13



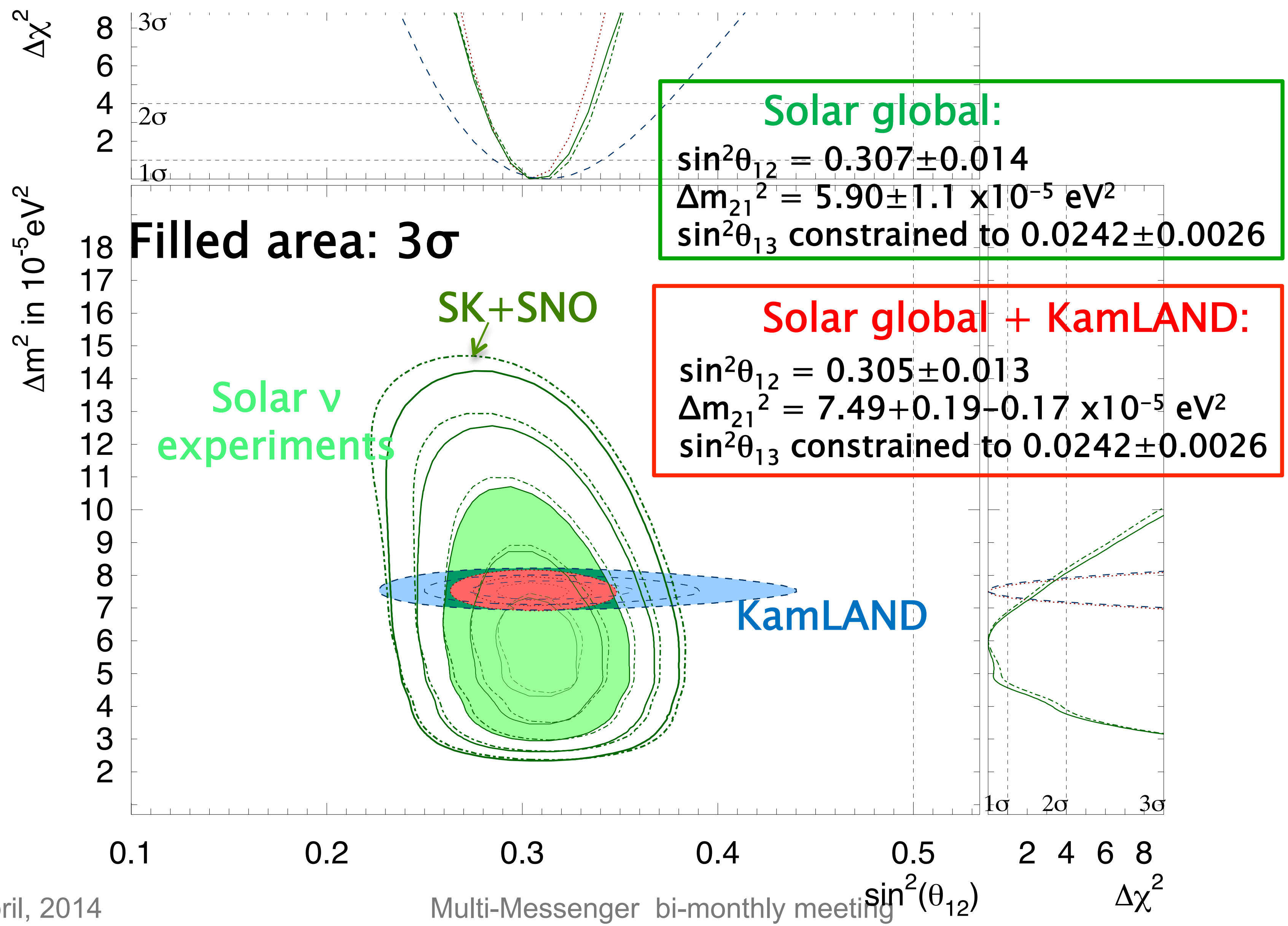
Consistent with PDG average (=reactor experiments)
Filled area: 3σ
Solar ν only
KamLAND only
PDG average 2012:
(PRD86,010001)
0.0251+/-0.0034
$\sin^2(\Theta_{12})=0.326^{+0.044}_{-0.037}$
$\sin^2(\Theta_{13})=0.010^{+0.033}_{-0.034}$
$\sin^2(\Theta_{12})=0.308^{+0.021}_{-0.018}$
$\sin^2(\Theta_{13})=0.023^{+0.028}_{-0.021}$
$\sin^2(\Theta_{12})=0.306^{+0.014}_{-0.013}$
$\sin^2(\Theta_{13})=0.026^{+0.017}_{-0.012}$
$\Delta\chi^2$
$\sin^2(\Theta_{13})$
$\sin^2(\Theta_{12})$
1σ
2σ
3σ

Result in Super-K



■ $\sin^2\theta_{13}$ is fixed at 0.025

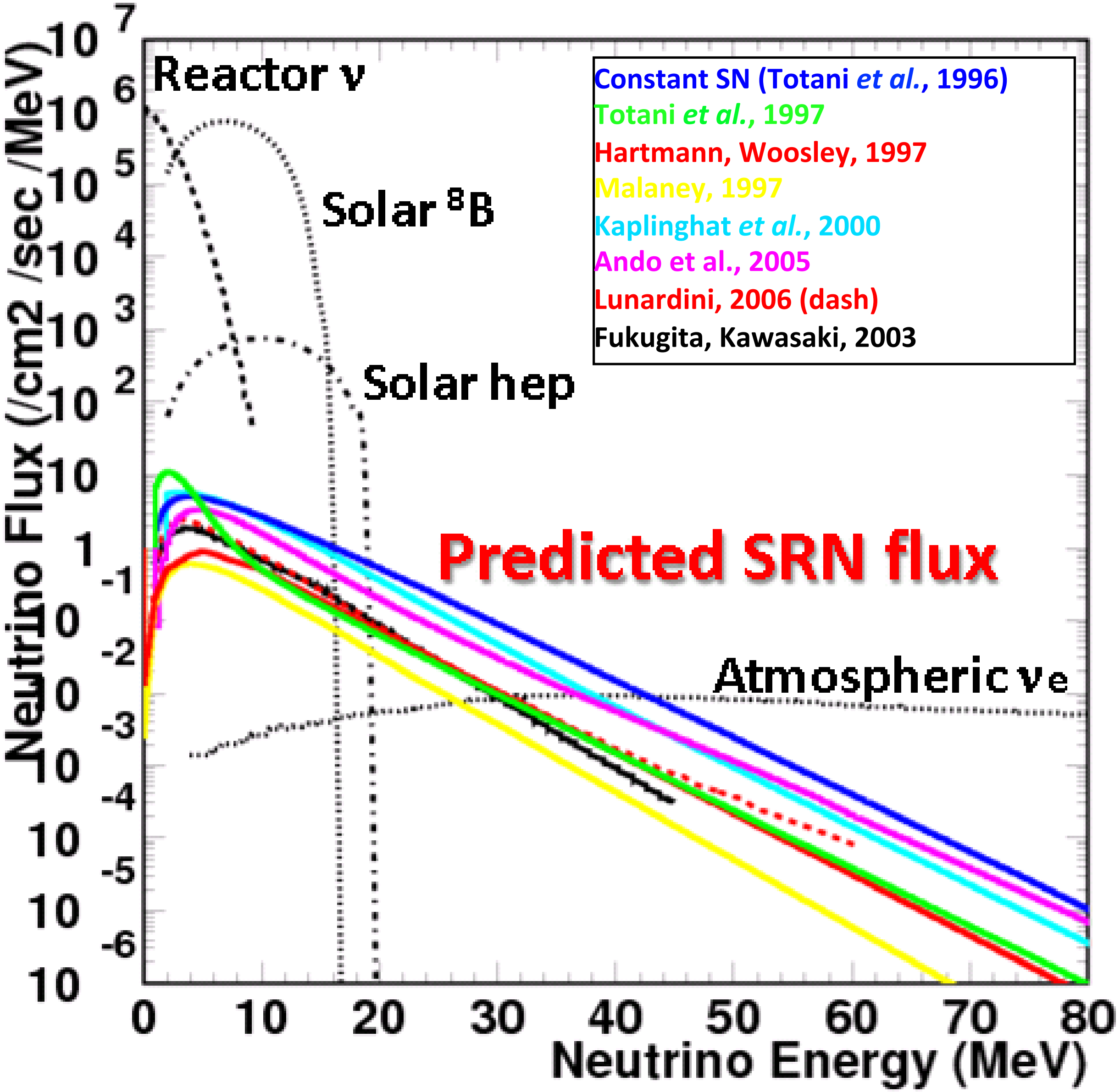
All solar neutrino data with KamLand



Supernova Relic Neutrinos

the diffuse neutrino background originates all the past supernovae

Predicted SRN flux



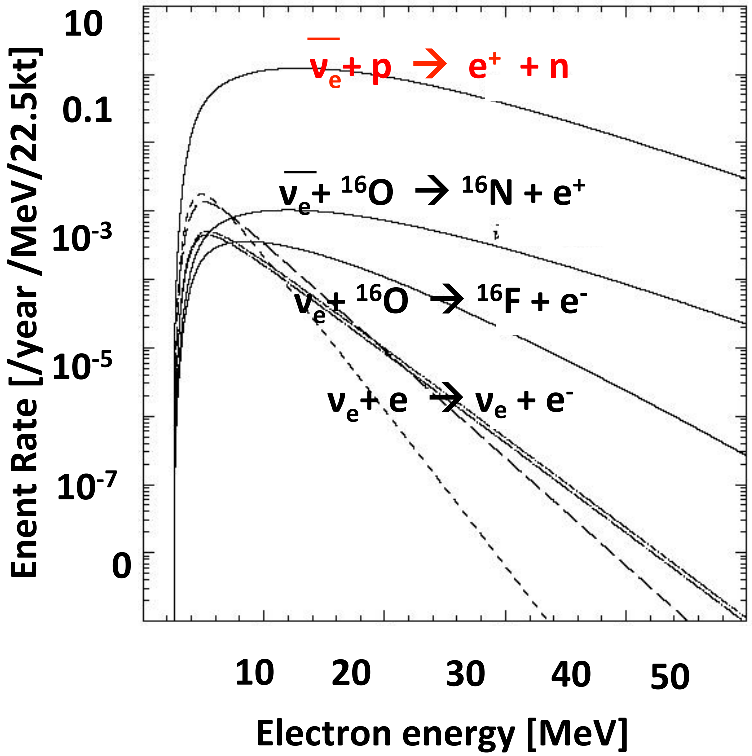
Observation in Super-K

Dominant process is inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

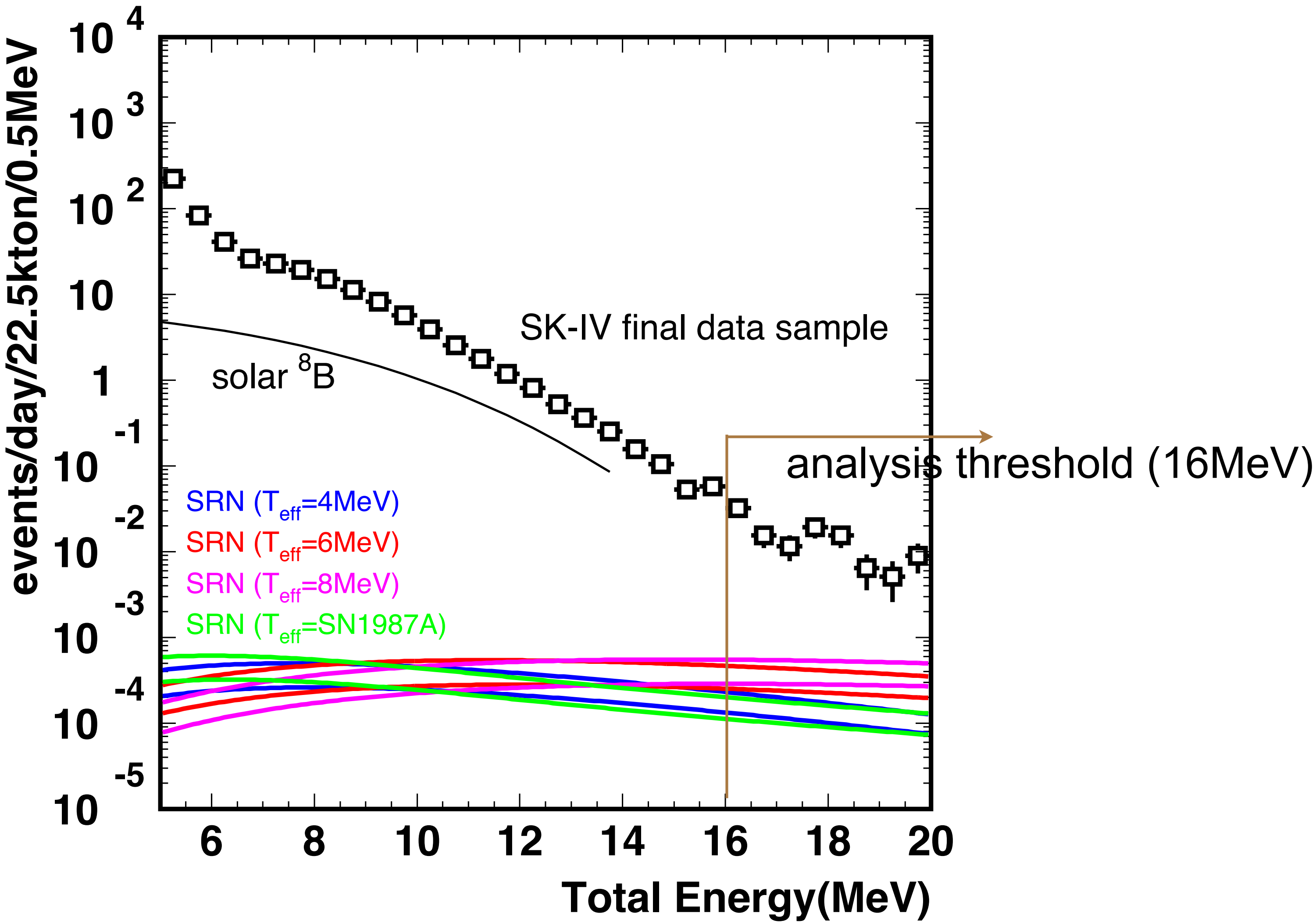
✓Only positron is used for the current analysis.
(Ee=Ev−1.3[MeV])

✓2.2MeV gamma tagging is also going on.



Expected number of SRN events
1.3 - 6.7 ev/yr/22.5kton for Ee : 10-30MeV
0.3 - 1.9 ev/yr/22.5kton for Ee : 16-30MeV

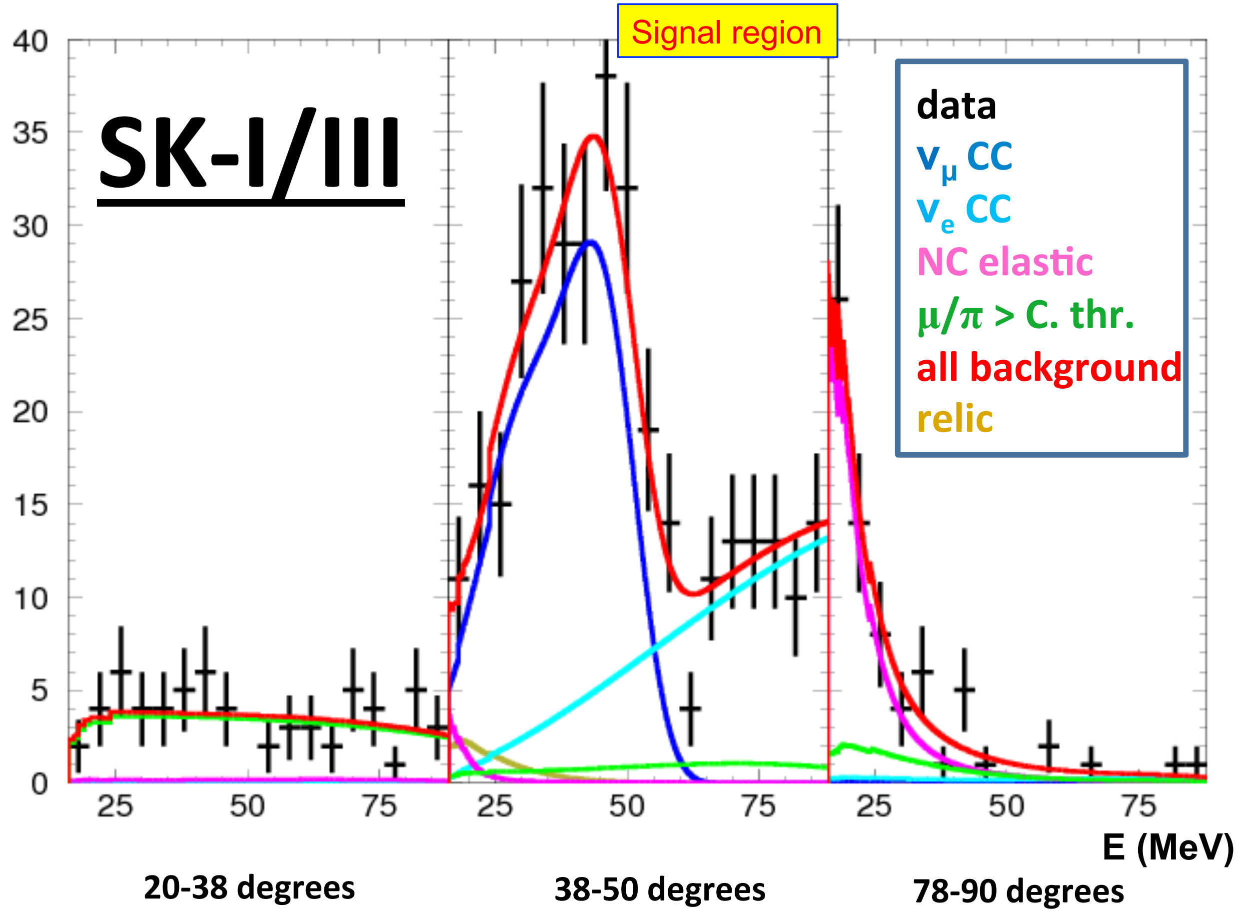
Background

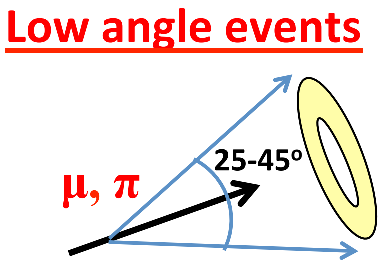


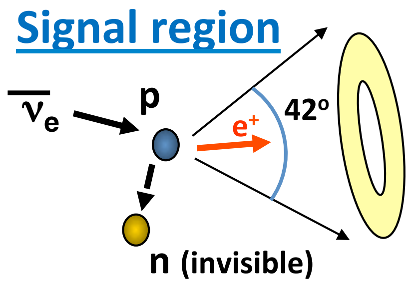
events/day/22.5kton/0.5MeV
10 4
10 3
10 2
10
1
10 -1
10 -2
10 -3
10 -4
10 -5
6
8
10
12
14
16
18
20
Total Energy(MeV)
SK-IV final data sample
solar 8B
SRN (Teff=4MeV)
SRN (Teff=6MeV)
SRN (Teff=8MeV)
SRN (Teff=SN1987A)
analysis threshold (16MeV)

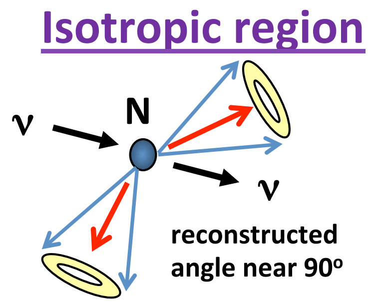
Phys. Rev. D 85, 052007 (2012)

Spectrum fit



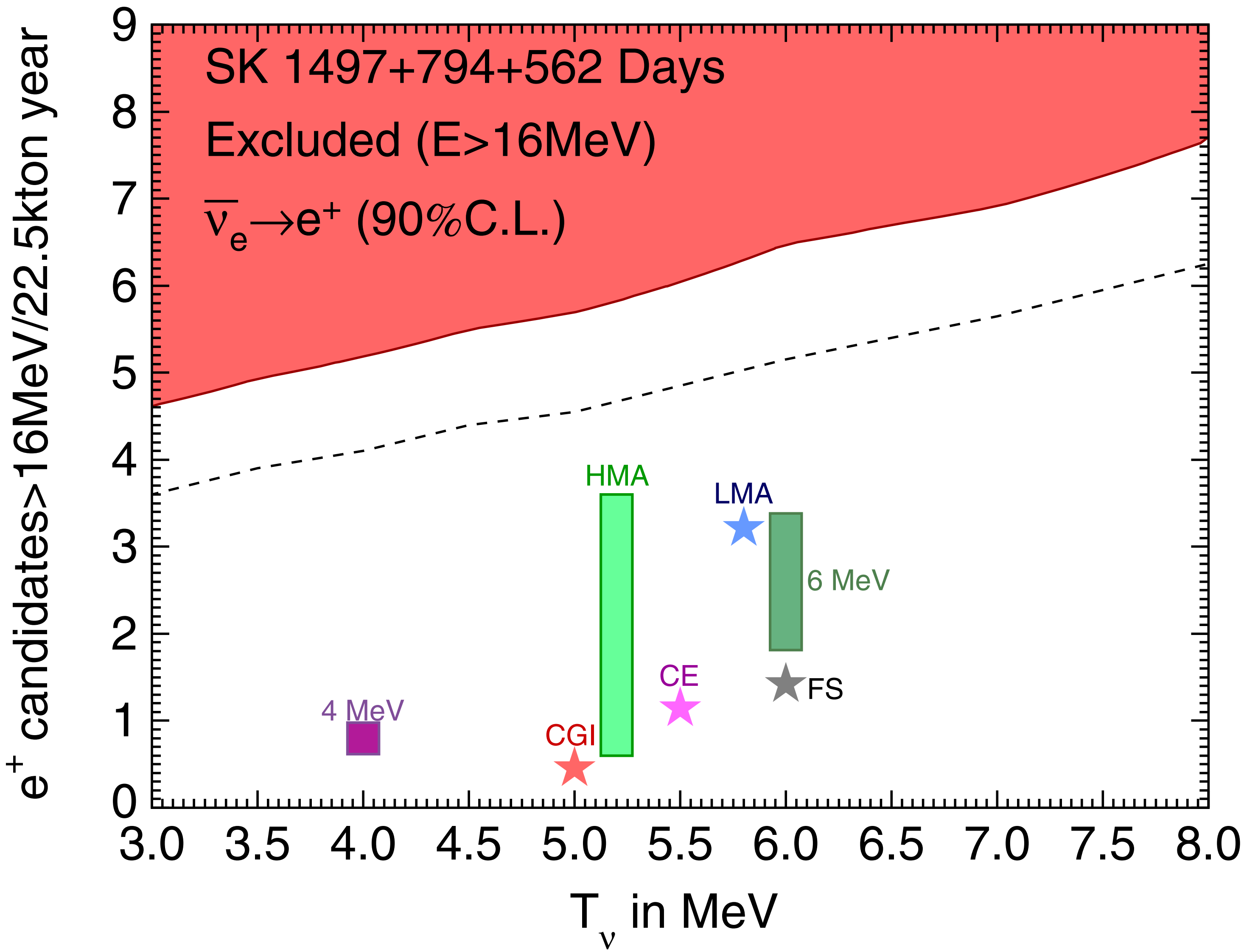






Phys. Rev. D 85, 052007 (2012)

Constraint region



Summary

- Super-Kamiokande is successfully keep going and has several improvement.
- Solar Neutrinos:
  - No significant spectrum distortion can be seen.
  - First indication for the solar neutrino day/night flux asymmetry (@2.7σ), gives direct indication for matter enhanced neutrino oscillation.
- Supernova Relic Neutrinos:
  - Combined analysis from SK-1 to 3 have done.
  - No significant signal can be seen, but SK derives the most severe constraint results.