Recent results from Super-Kamiokande

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for Super-K collaboration

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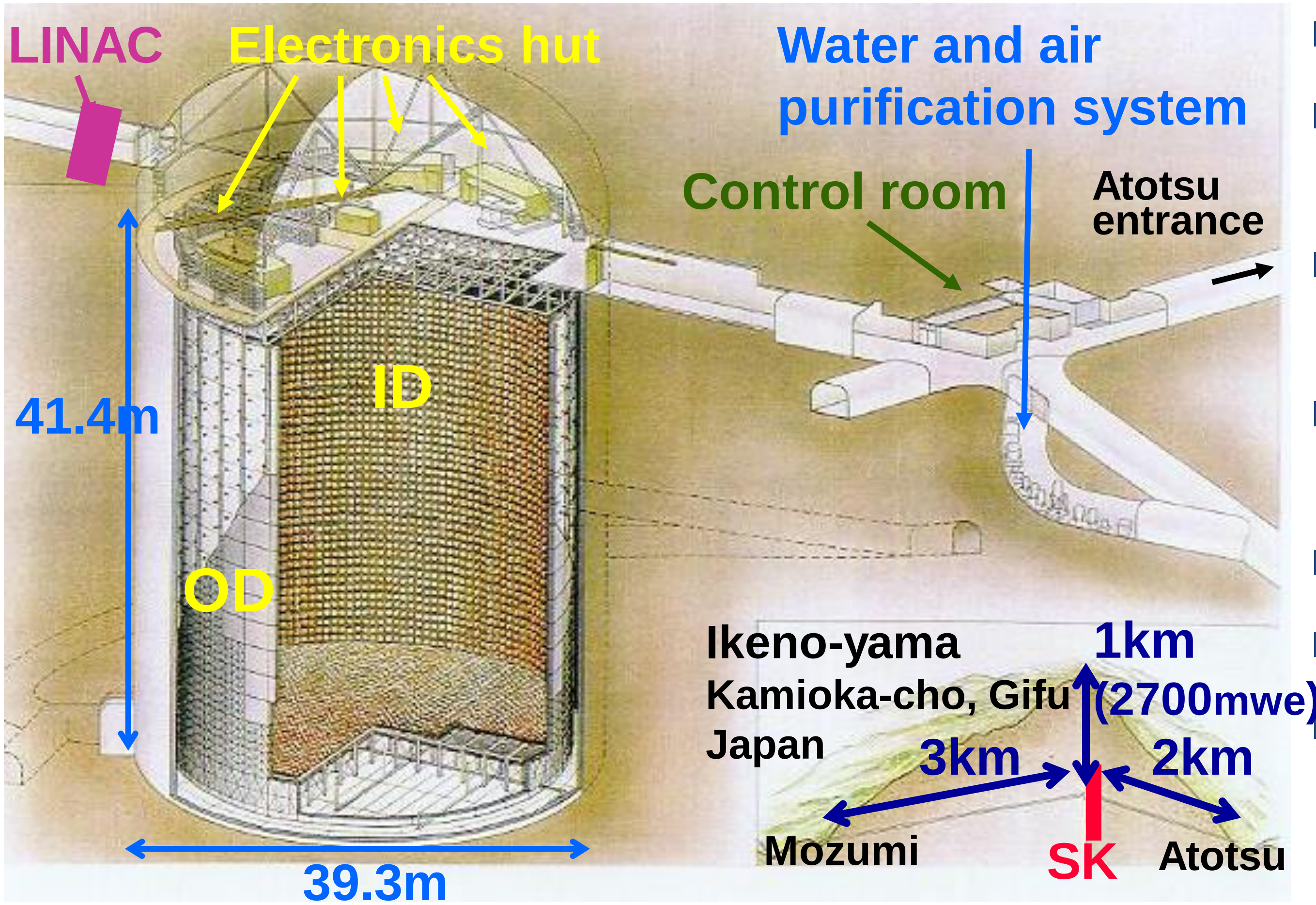
Super-Kamiokande Collaboration

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 TRIUMF, Canada
32 Tsinghua University, China
33 University of Washington, USA
34 National Centre For Nuclear Research, Poland

~120 collaborators
34 institutions
7 countries

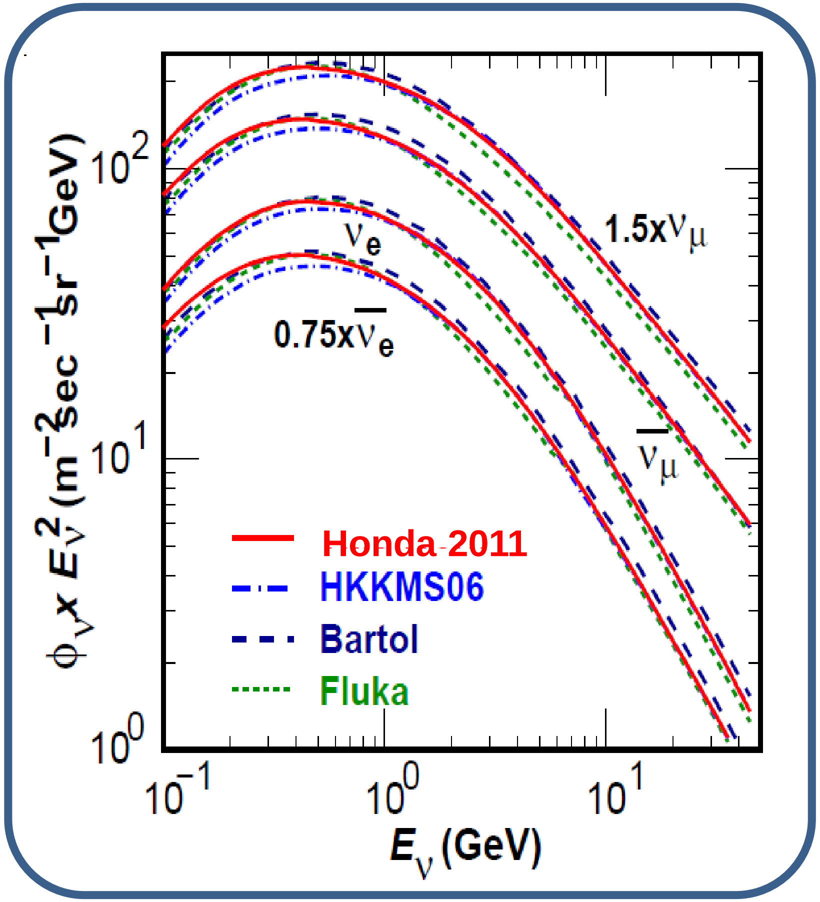
Super-Kamiokande detector



- 50kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- SK-IV is running
- Trigger efficiency
  - >99%@4.0MeV$_{kin}$
  - ~90%@3.5MeV$_{kin}$

Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

Atmospheric Neutrinos



Honda et al., Phys. Rev. D83, 123001 (2011).

- Cosmic rays interact with air nuclei and the decay of pions and kaons produce neutrinos

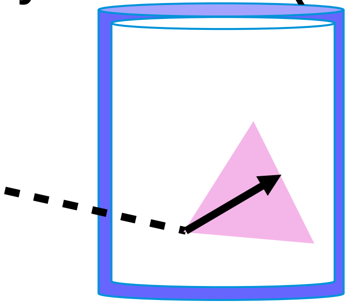
$$P + A \rightarrow N + \pi^{\pm} + X$$
$$\hookrightarrow \mu^{\pm} + \overset{(-)}{\nu}_\mu$$
$$\hookrightarrow e^{\pm} + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

- νs travel 10 – 10,000 km before detection
- Both ν_μ and ν_e (ν_μ/ν_e = 2 at low energy)
- Both neutrinos and anti-neutrinos
  - ~ 30% of final analysis samples are antineutrinos
- Flux spans many decades in energy ~100 MeV – 100TeV
- Excellent tool for broad studies of neutrino oscillations

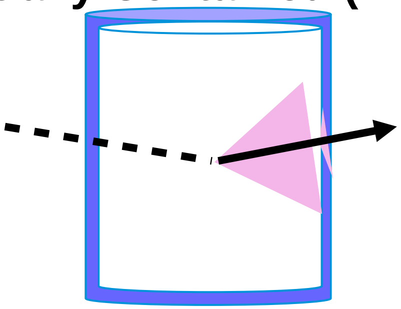
Atmospheric ν Analysis Samples

SK-I+II+III+IV, 4581 Days

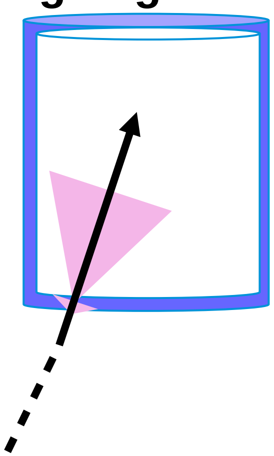
Fully Contained (FC)

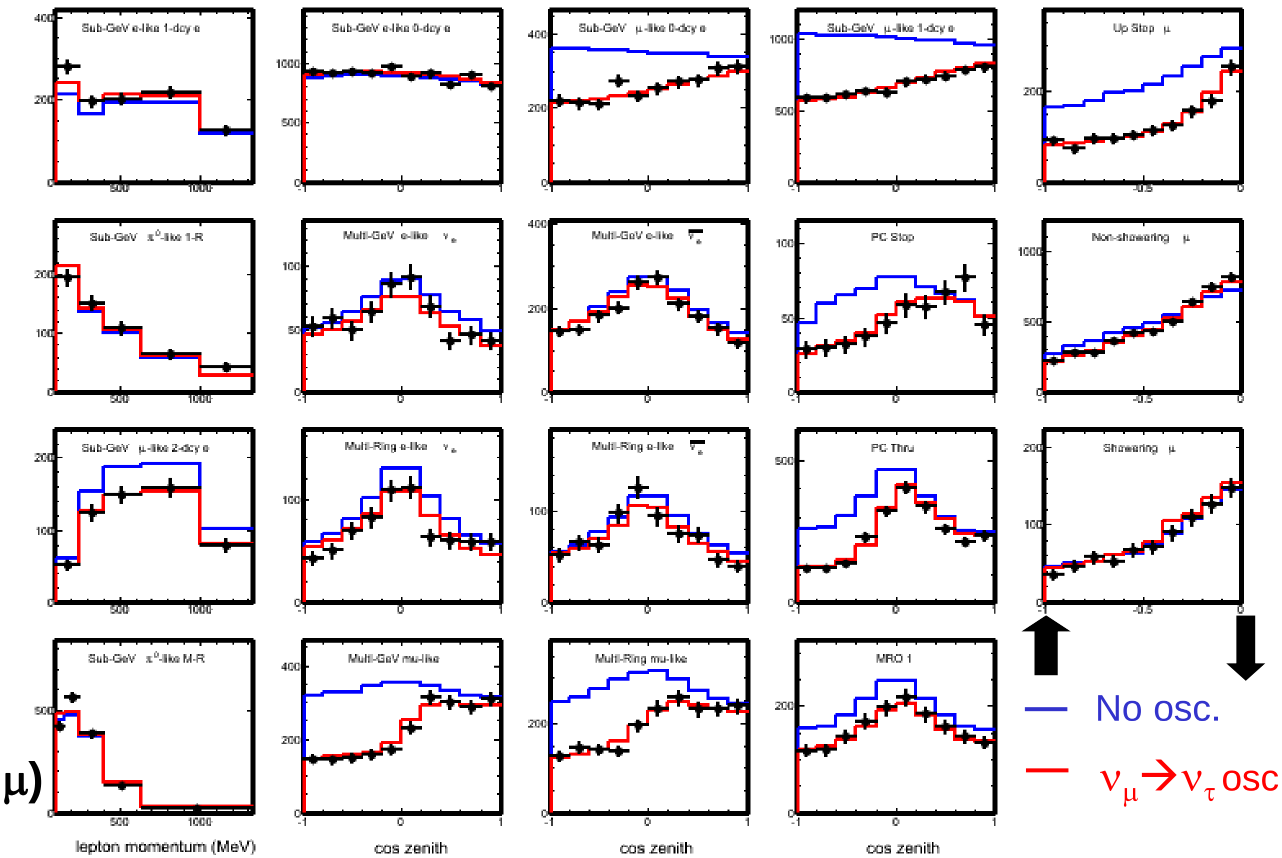


Partially Contained (PC)



Upward-going Muons (Up-μ)

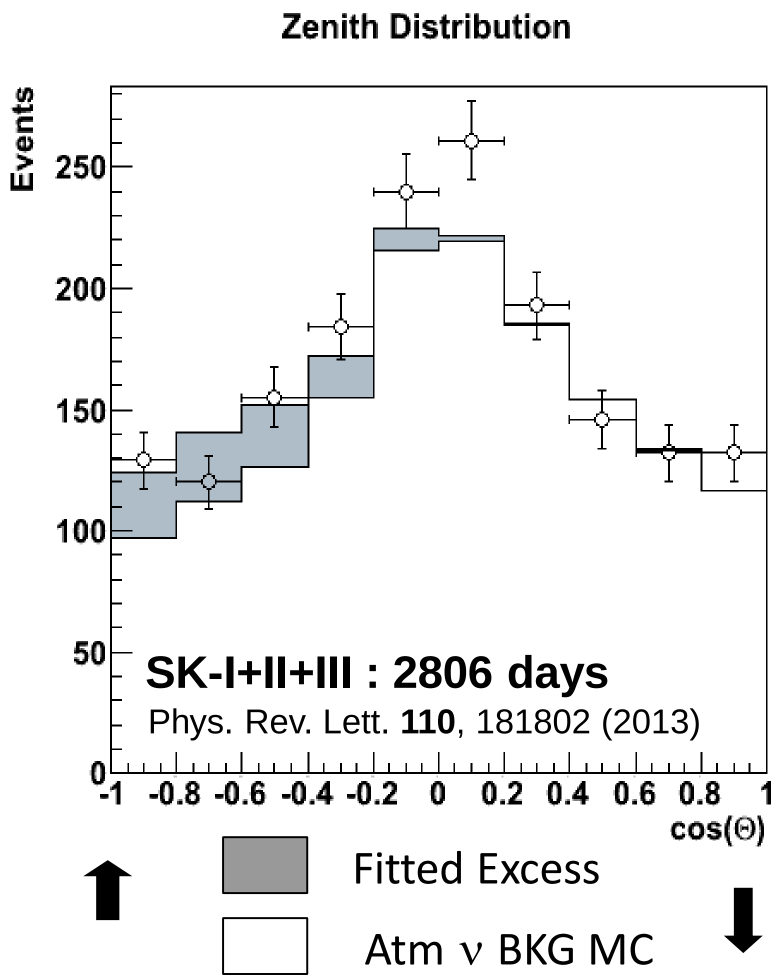




- **4581 days** of atmospheric neutrino data (till Feb.2014)
- **47,509 events** in total (37,708 FC, 2,885 PC, and 6,949 UP-μ)
- **19 analysis samples**: Sub-divided by event topology (FC/PC,UP-μ), energy range, e/μ–like, and # of rings. Multi-GeV e-like samples are divided into ν-like and $\overline{\nu}$–like samples.

Evidence for ν_τ Appearance

Published at PRL 110,181802 (2013)



- Search for events consistent with hadronic decay of τ lepton
  - Multi-ring e-like events with visible energy above 1.3GeV.
- Negligible primary ν_τ flux so ν_τ must be oscillation-induced: **upward-going**
- Event selection performed by Neural Network
  - Total efficiency ~60%
- Fit 2D data on $\cos\theta$ and NN variable with "background" and signal

Data = $\alpha(\gamma)$ x bkg + $\beta(\gamma)$ x signal

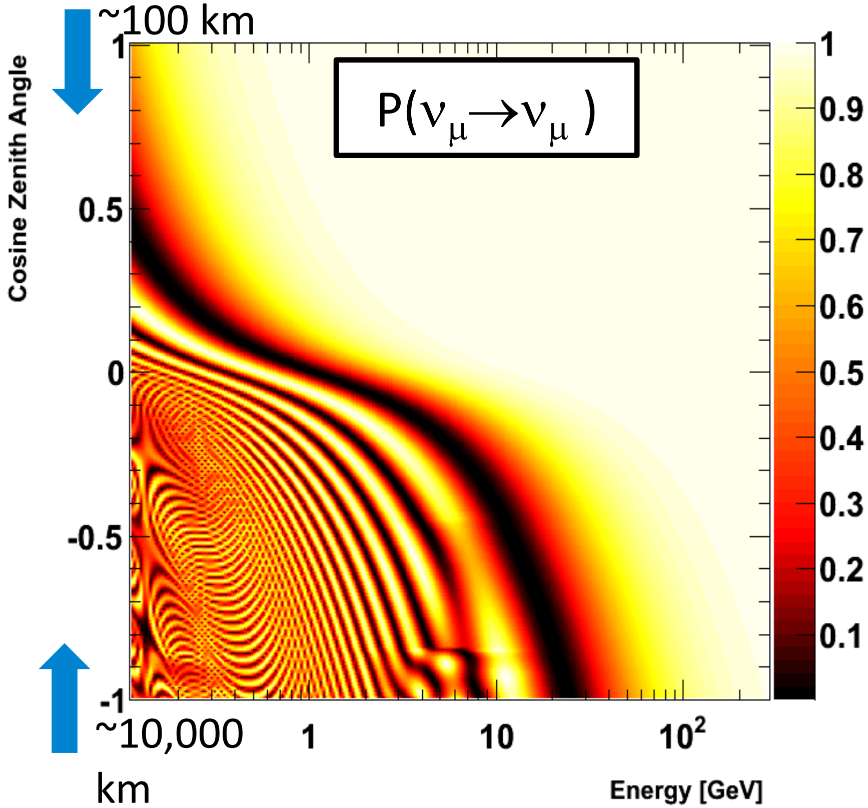
α, β: expectations of "background" and signal which depends on DIS normalization factor γ

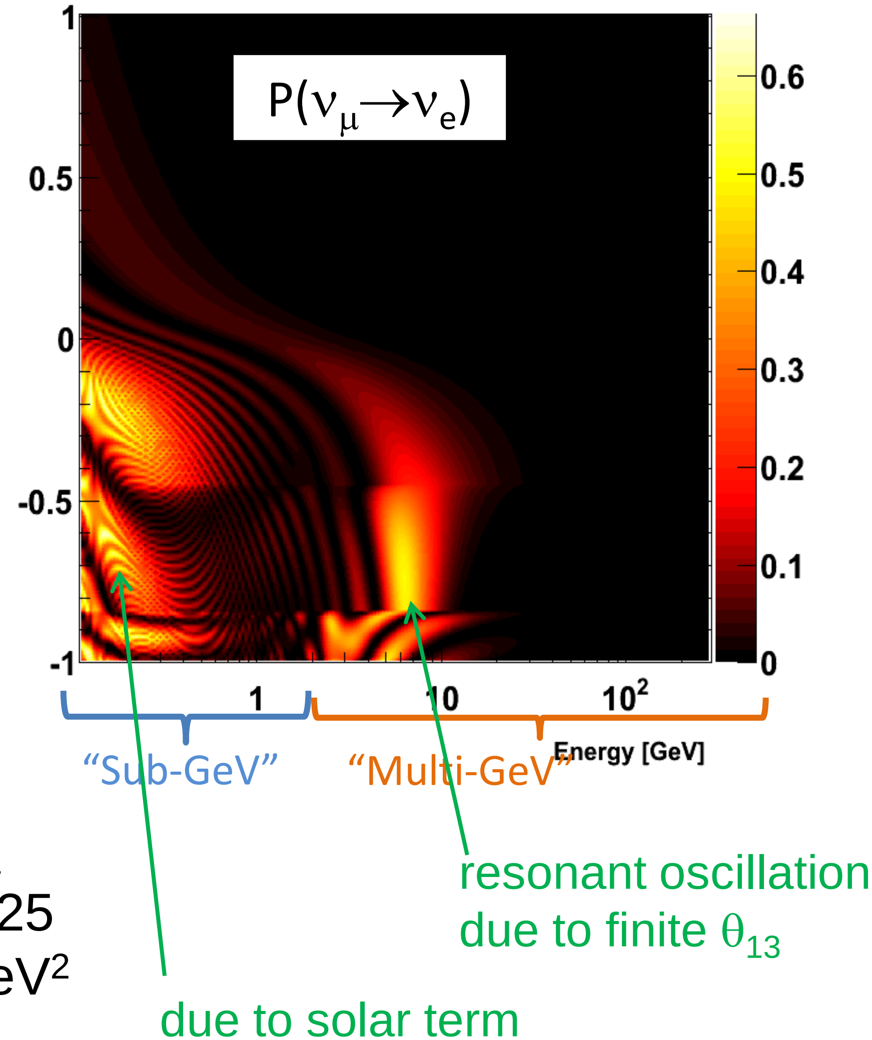
DIS: Deep Inelastic Scattering

Result	Background	DIS(γ)	Signal
SK-I+II+III	0.94 ± 0.02	1.10 ± 0.05	**1.42 ± 0.35**

This corresponds to the observed number of **180.1** ±44.3 (stat) +17.8-15.2 (sys) events, **3.8 σ** excess

Oscillation probability maps





Oscillation parameters used here are

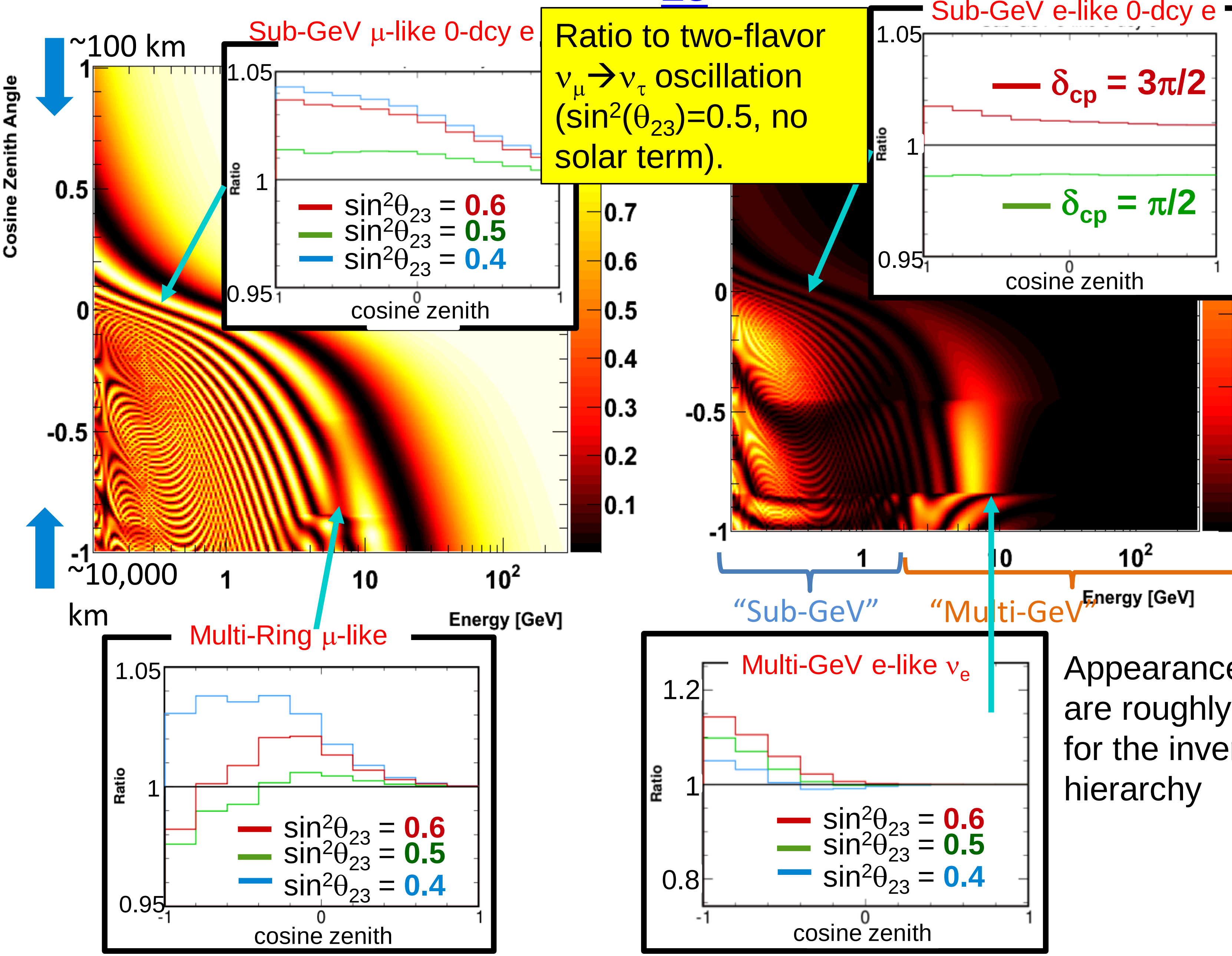
$\sin^2\theta_{12}$=0.31, $\sin^2\theta_{23}$=0.5, $\sin^2\theta_{13}$=0.025

Δm^2_{12}=7.6x10^{-5} eV^2, Δm^2_{23}=2.5x10^{-3} eV^2

Normal Hierarchy (NH)

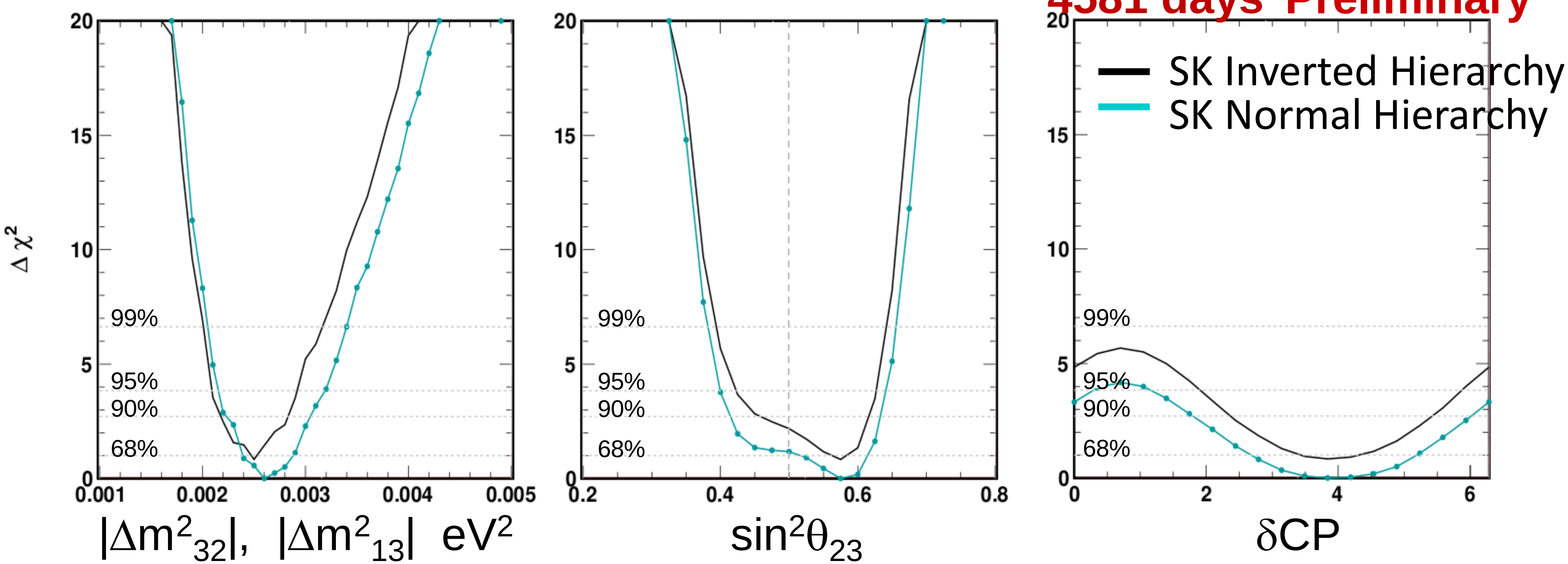
δCP=0.0

Effects of θ_{23} and δCP



Appearance effects are roughly halved for the inverted hierarchy

θ13 Fixed Analysis (NH+IH) SK Only

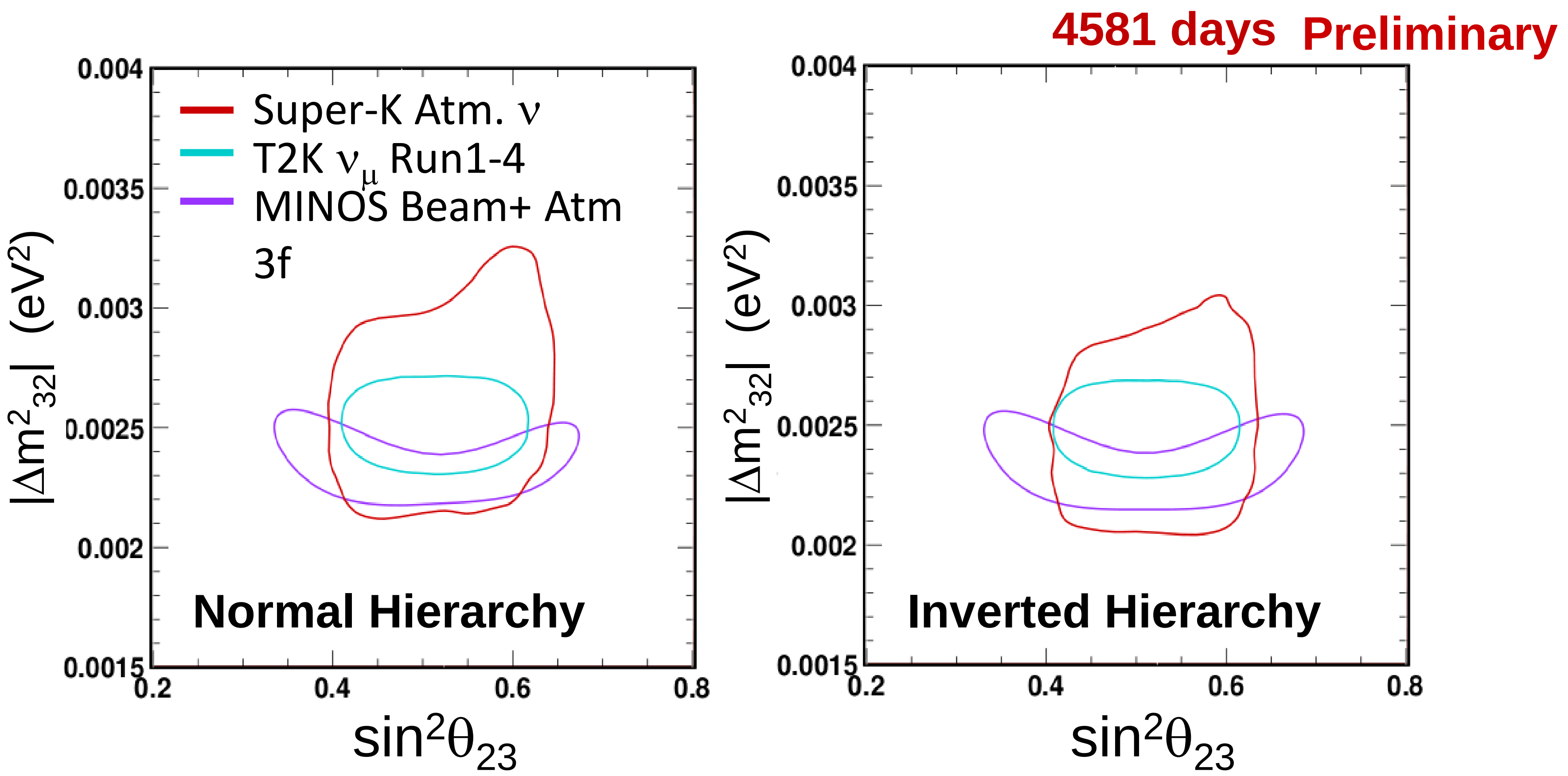


Fit (517 dof)	$\chi 2$	$\sin^2\theta_{13}$	δ_{cp}	$\sin^2\theta_{23}$	Δm^2_{23} (eV^2)
SK (NH)	559.8	0.025	3.84	0.57	2.6×10^{-3}
SK (IH)	560.7	0.025	3.84	0.57	2.5×10^{-3}

- θ_{13} fixed to PDG average, but its uncertainty is included as a systematic error
- Offset in these curves shows the difference in the hierarchies

- **Normal** hierarchy favored at: $\chi^2_{IH} - \chi^2_{NH}$ = **0.9**

Comparison with T2K and MINOS

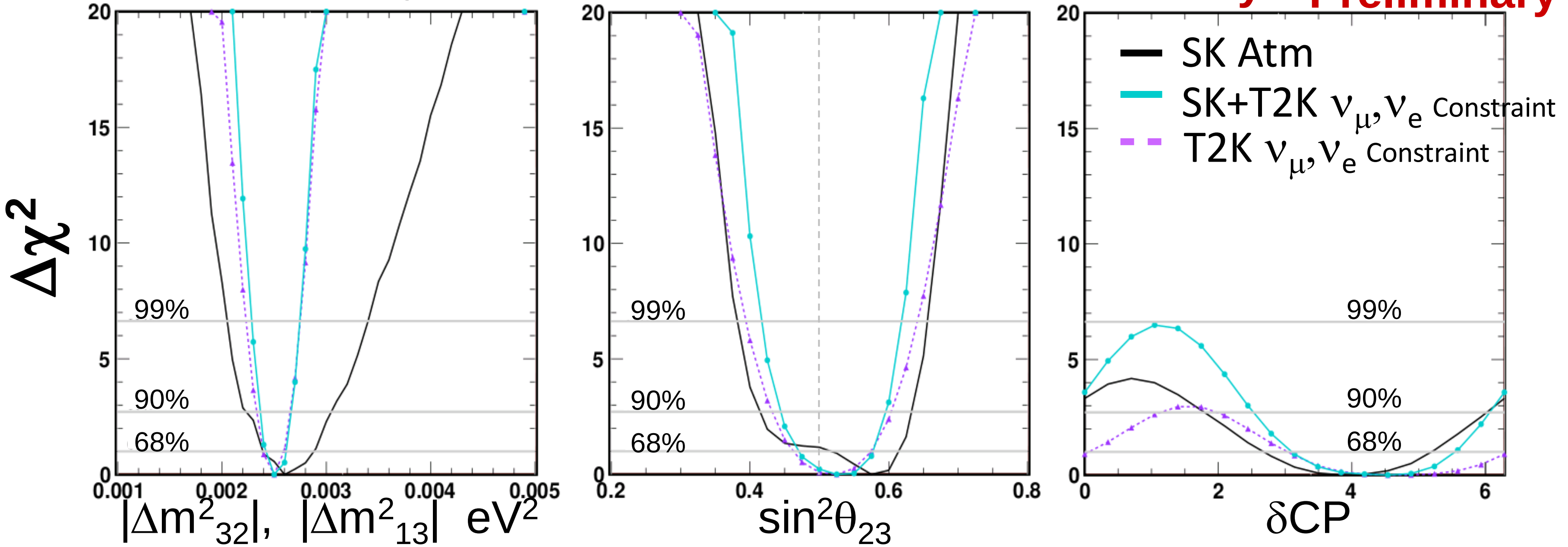


- They are consistent to each other.
- SK's sensitivity in Mass Hierarchy and δCP can be improved by incorporating constraints from these measurements.

θ13 Fixed SK + T2K (external constraint)

Normal Hierarchy

4581 days **Preliminary**

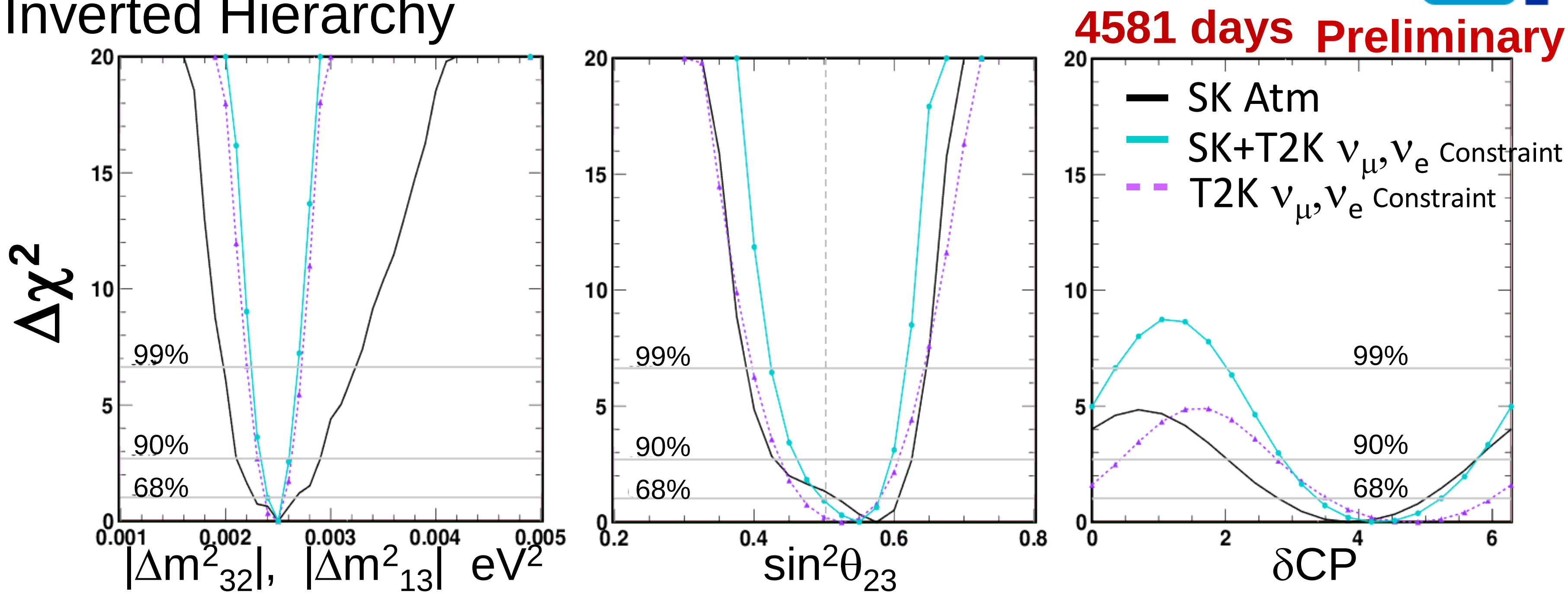


Fit (543 dof)	χ2	$\sin^2\theta_{13}$	δ_{cp}	$\sin^2\theta_{23}$	Δm^2_{23} (eV^2)
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5x10^{-3}
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5x10^{-3}

- **Normal** hierarchy favored at: $\chi^2_{IH} - \chi^2_{NH}$ = **1.2** (0.9 SK only)
- Some fraction of CP phase is excluded at 90% C.L.
- **CP** Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

θ13 Fixed SK + T2K (external constraint)

Inverted Hierarchy



Fit (543 dof)	$\chi 2$	$\sin^2\theta_{13}$	δ_{cp}	$\sin^2\theta_{23}$	Δm^2_{23} (eV^2)
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5×10^{-3}
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5×10^{-3}

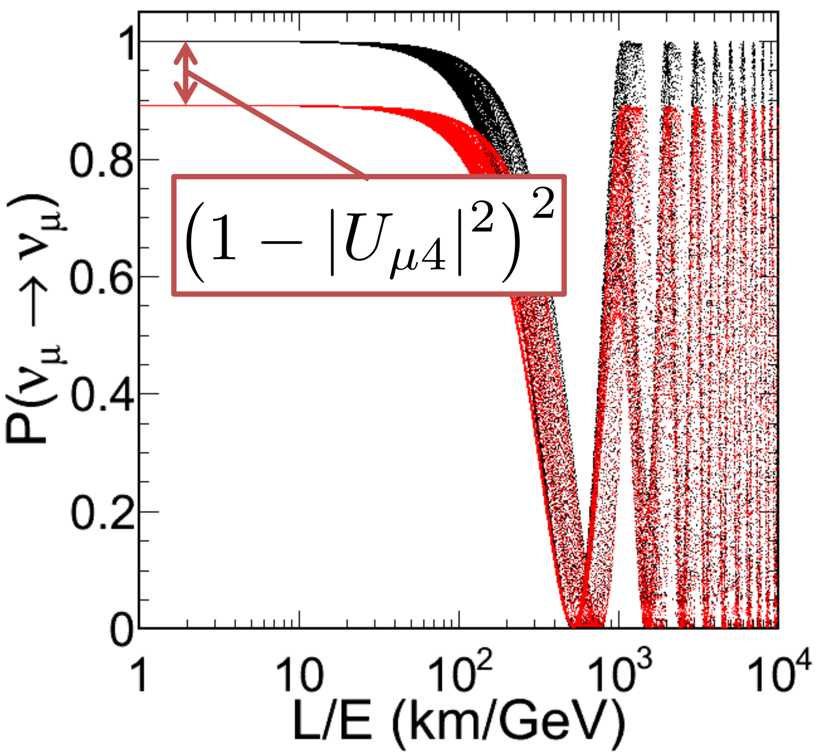
- **Normal** hierarchy favored at: $\chi^2_{IH} - \chi^2_{NH}$ = **1.2** (0.9 SK only)
- Some fraction of CP phase is excluded at 90% C.L.
- **CP** Conservation ($\sin\delta_{cp} = 0$) allowed at (at least) 90% C.L. for both hierarchies

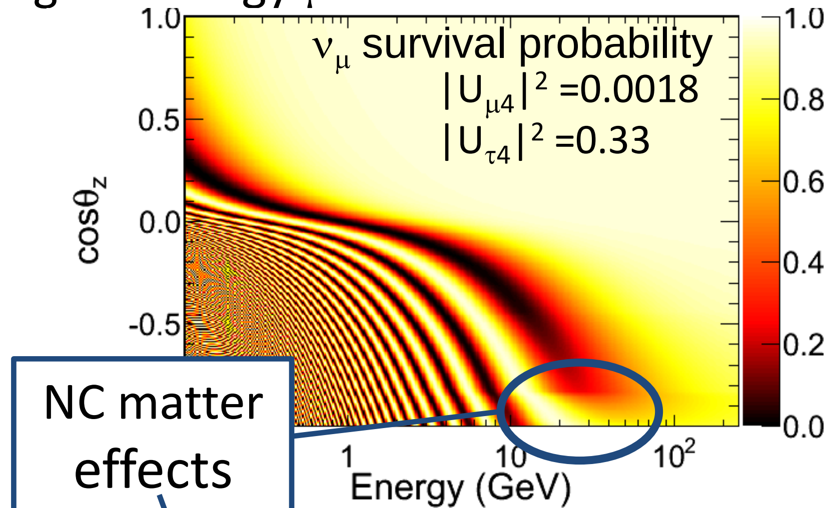
Sterile Neutrino Oscillations in Atmospheric Neutrinos

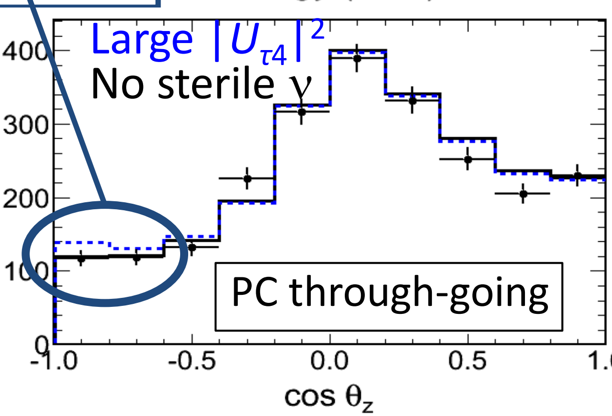
PMNS / Sterile

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- $|U_{\mu 4}|^2$
  Induces a decrease in event rate of μ-like data of all energies and zenith angles
- $|U_{\tau 4}|^2$
  Shape distortion of angular distribution of higher energy μ-like data

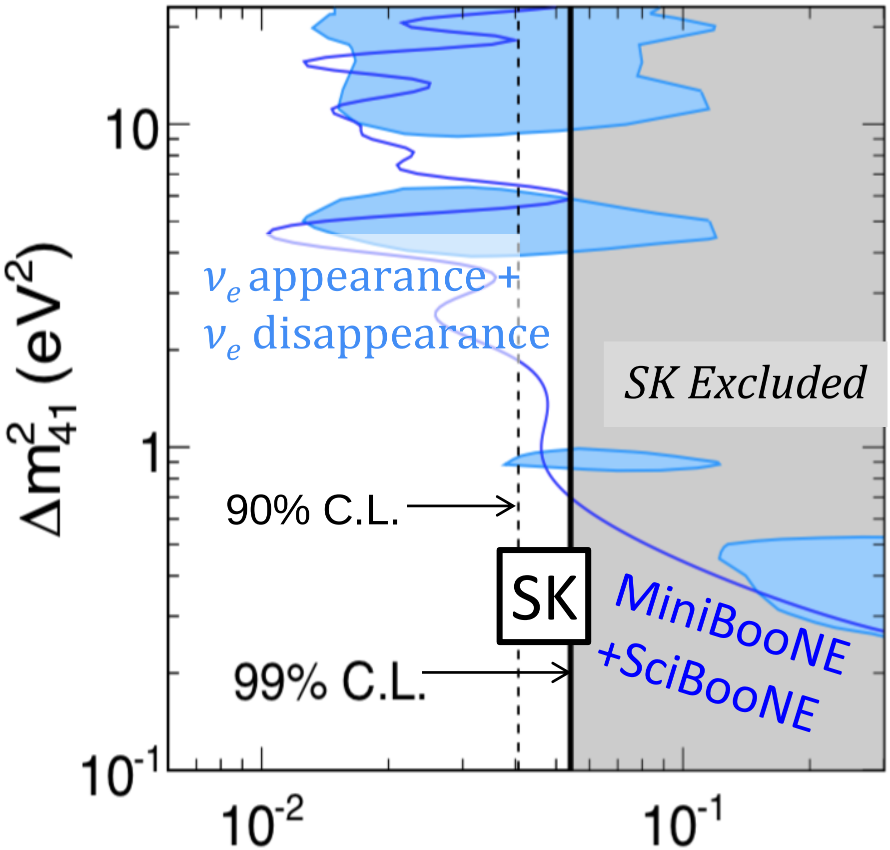




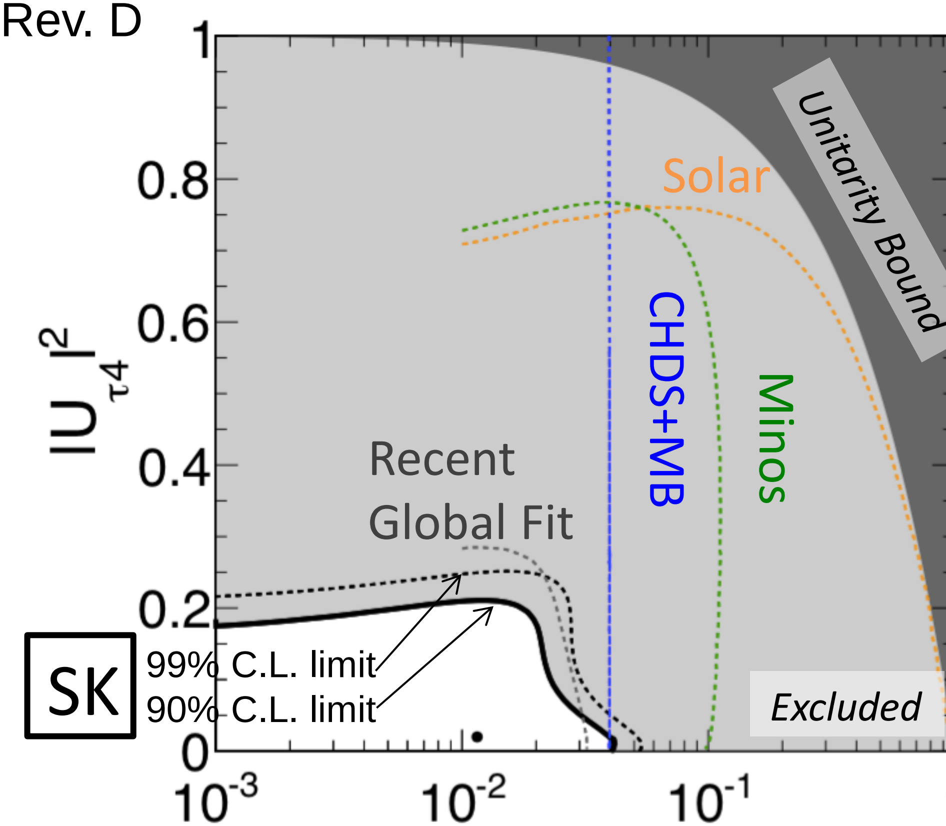


Limits on Sterile Neutrino Oscillations

arXiv:1410.2008, accepted by Phys. Rev. D



PRD86, 052009 (2012)
JHEP 1305 (2013) 050



All comparisons from:
JHEP 1305 (2013) 050

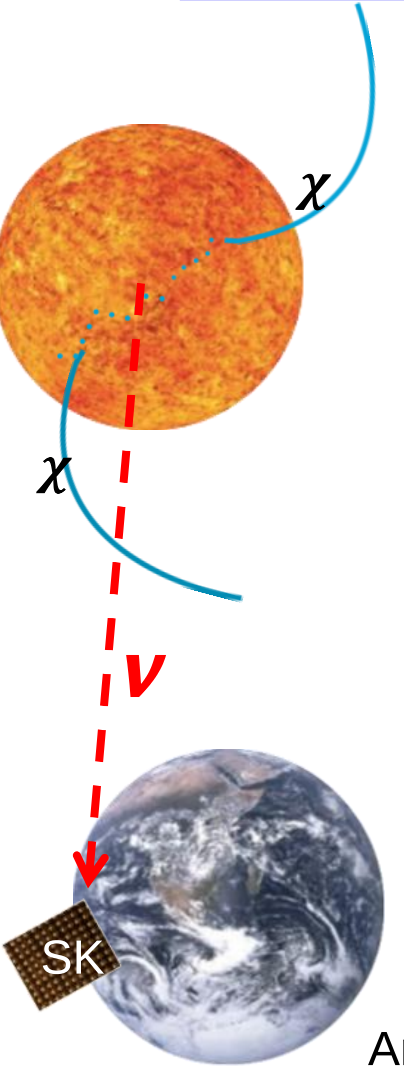
$|U_{\mu4}|^2 < 0.041$ at 90% C.L.
$|U_{\mu4}|^2 < 0.054$ at 99% C.L.

$|U_{\tau4}|^2 < 0.23$ at 99% C.L.

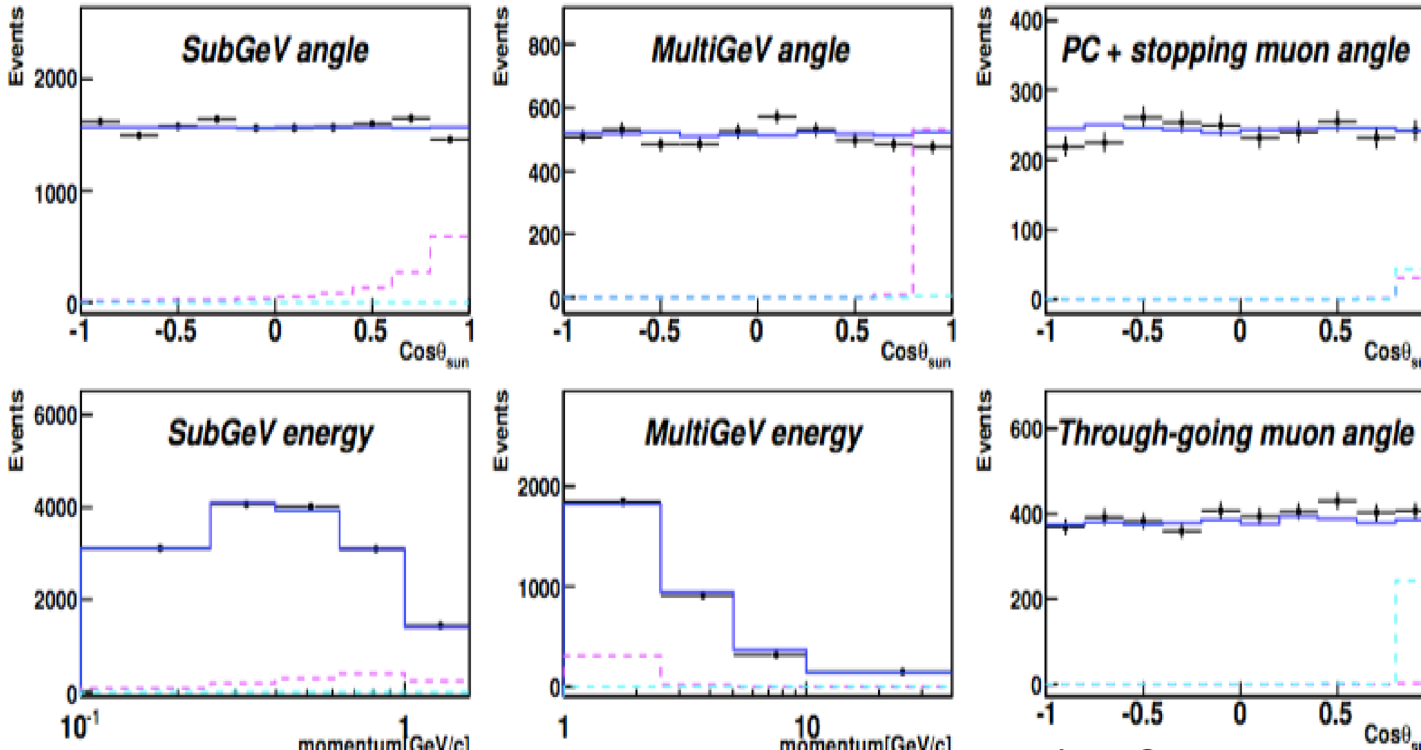
Lack of sterile matter effects places a strong constraint.

$(\nu_\mu \rightarrow \nu_\tau)+(\nu_\mu \rightarrow \nu_s)$ oscillation is not favored.

Indirect WIMP search using the Sun



Fit SK data with atmospheric neutrino MC + WIMP neutrino MC, to search for neutrinos from WIMP annihilation in the sun.
All SK I-IV data (all category, energy, flavors) are used.

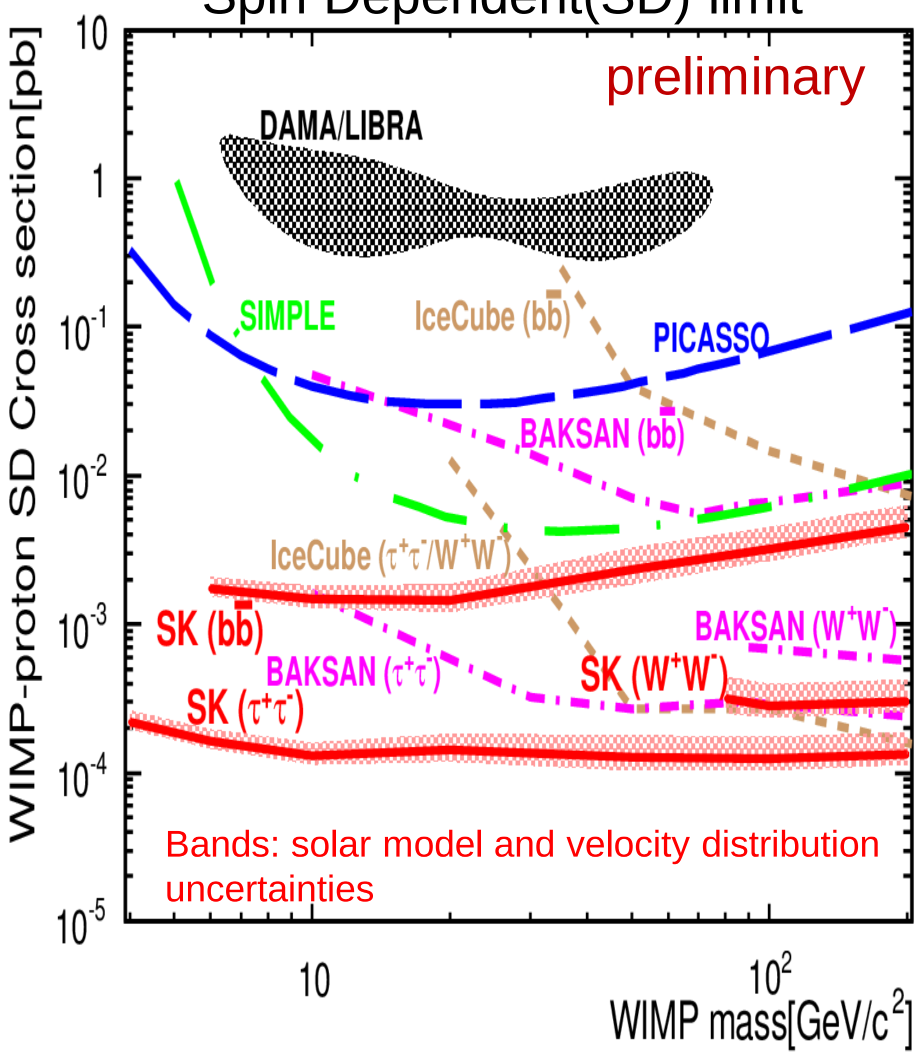


(cosΘ_{sun}=1: direction from the Sun)

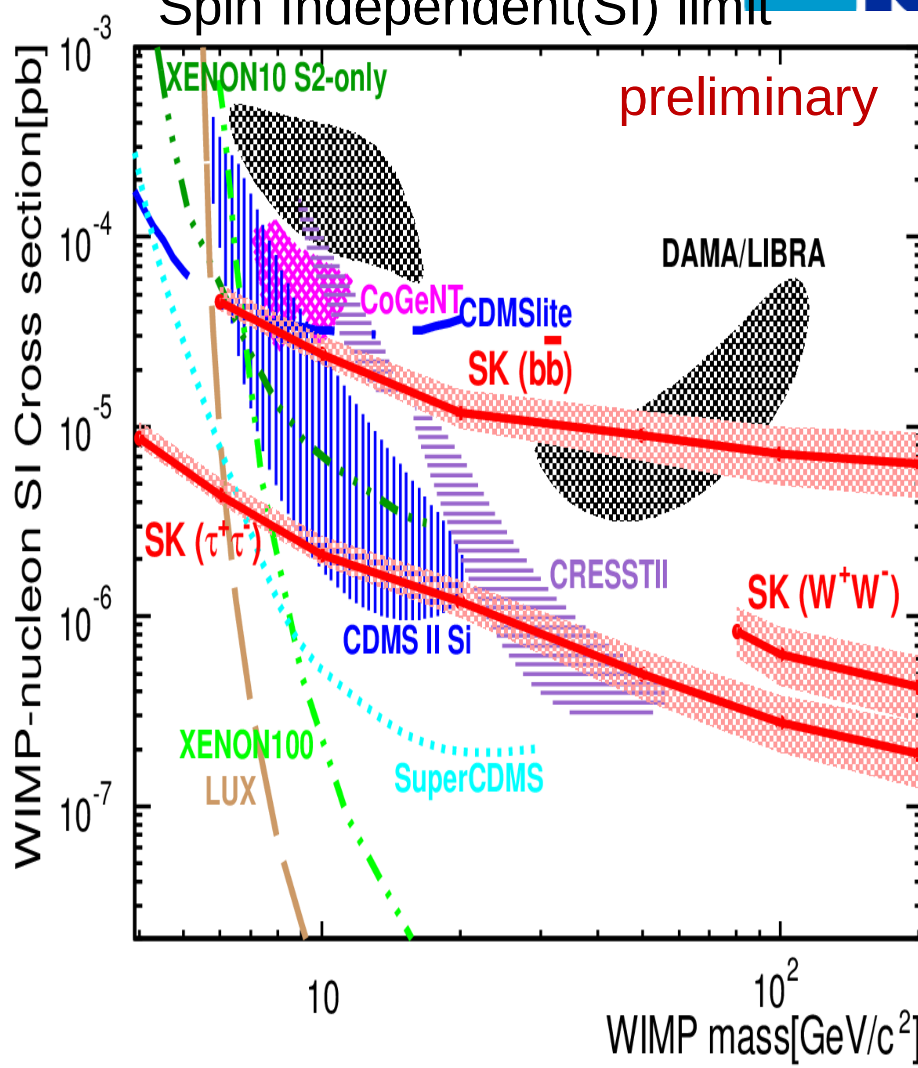
Angular and reconstructed momentum distributions
black dots: SK I-IV Data
Blue lines: Atmospheric neutrino MC
Dashed lines: WIMP neutrino signal for the 6-GeV $b\bar{b}$ channel(magenta)
200-GeV $\tau^+\tau^-$ channel (cyan) with arbitrary magnitude

Indirect WIMP search limits

Spin Dependent(SD) limit



Spin Independent(SI) limit



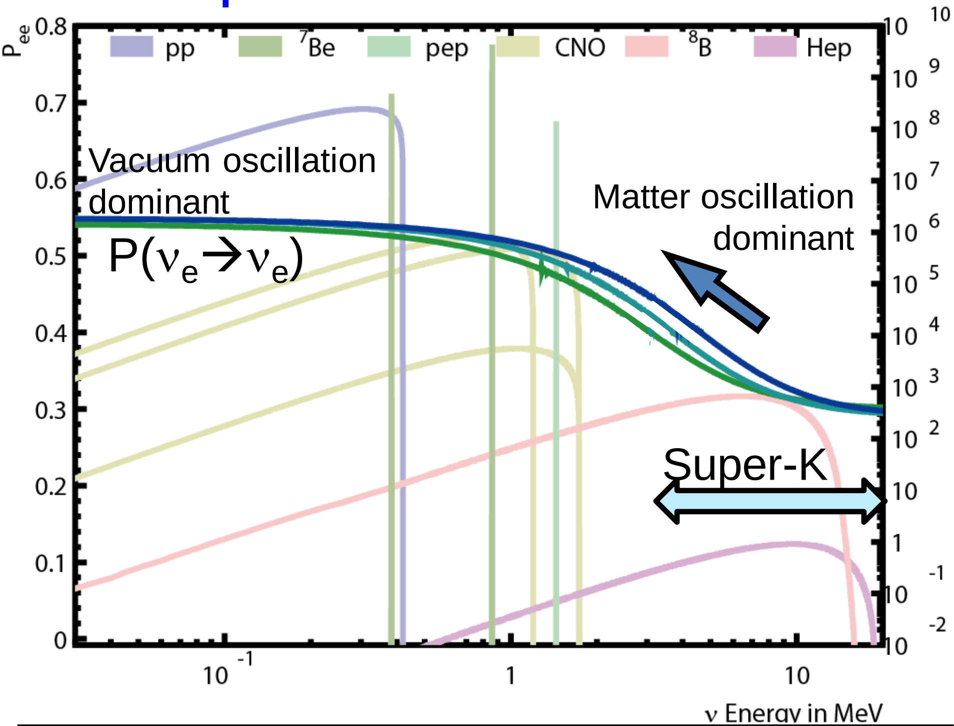
SD: SK places the most stringent constraint to date for WIMP masses below 200 GeV.

SI: Set new limit for very light WIMP (< 6 GeV). With $\tau^+\tau^-$ channel, SK excludes DAMA signal and most of the CDMS region.

^{8}B solar neutrino measurement

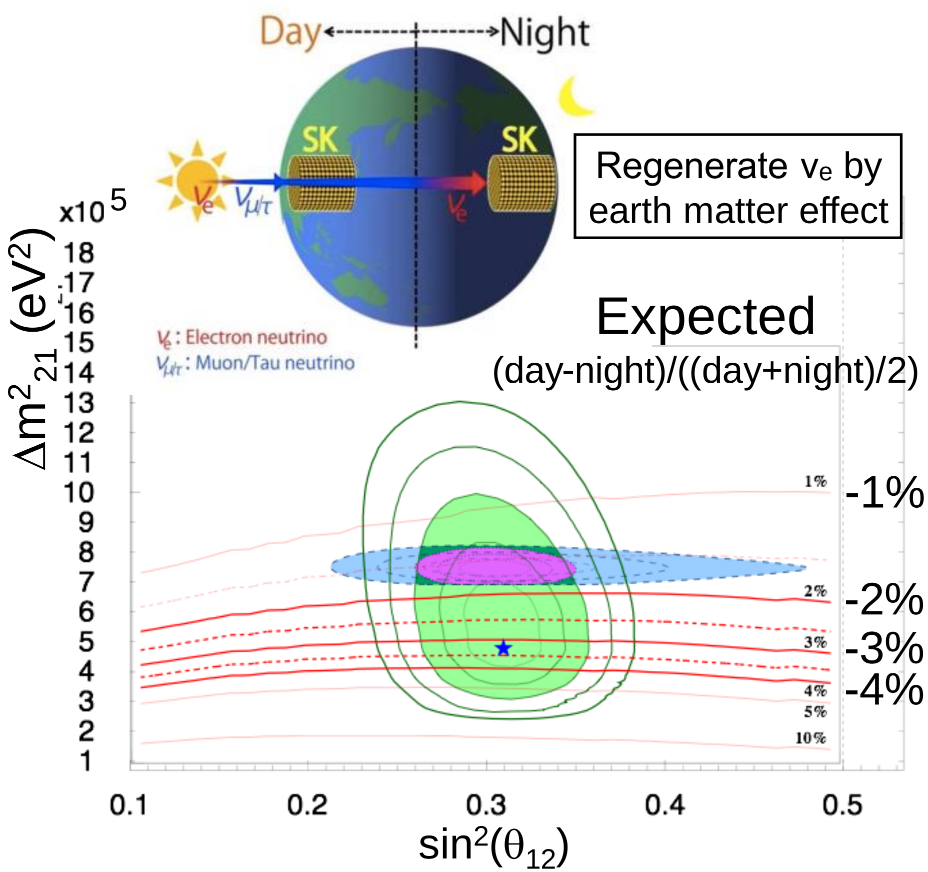
- High statistics (~20events/day) measurement of ^{8}B solar neutrinos
  - Possible time variation of the flux
  - Energy spectrum distortion due to solar matter effect
  - Day-night flux asymmetry due to earth mattect

Spectrum distortion

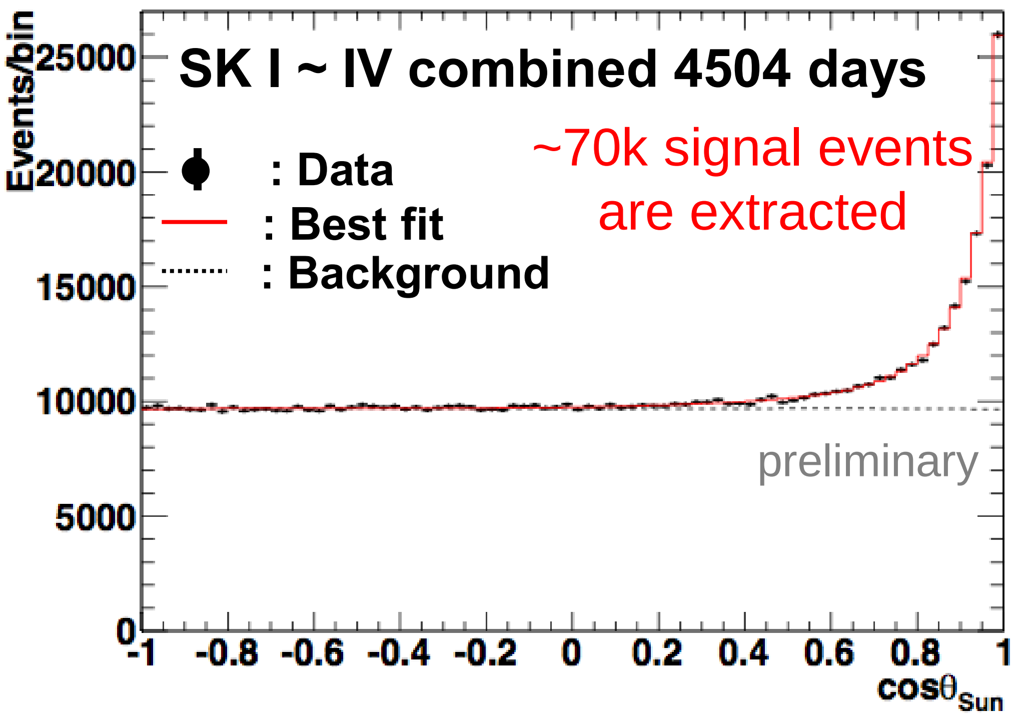


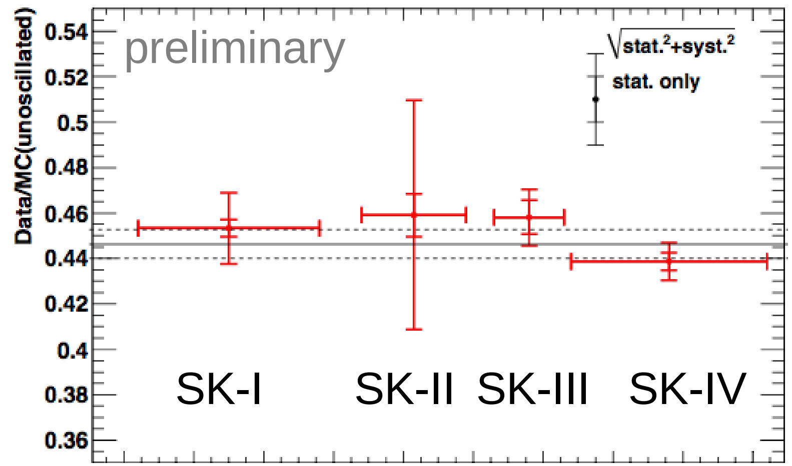
Super-K can search for the spectrum "upturn" expected by neutrino oscillation MSW effect

Day-Night flux asymmetry

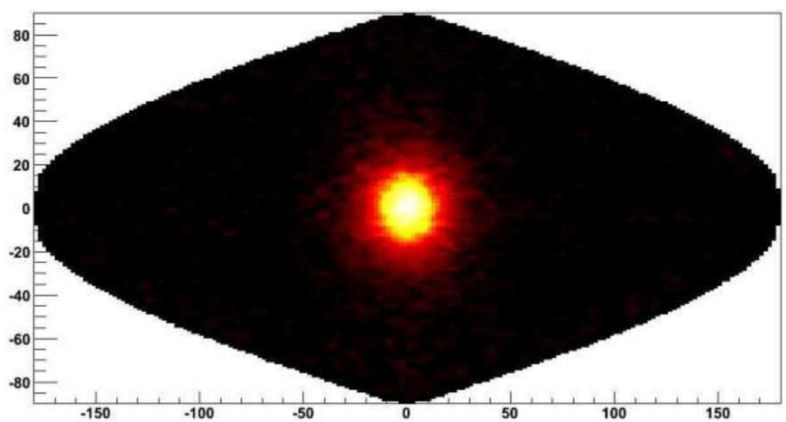


^{8}B solar neutrino flux





Fluxes from all SK phases are consistent to each other within their errors.



SK I-IV combined flux:

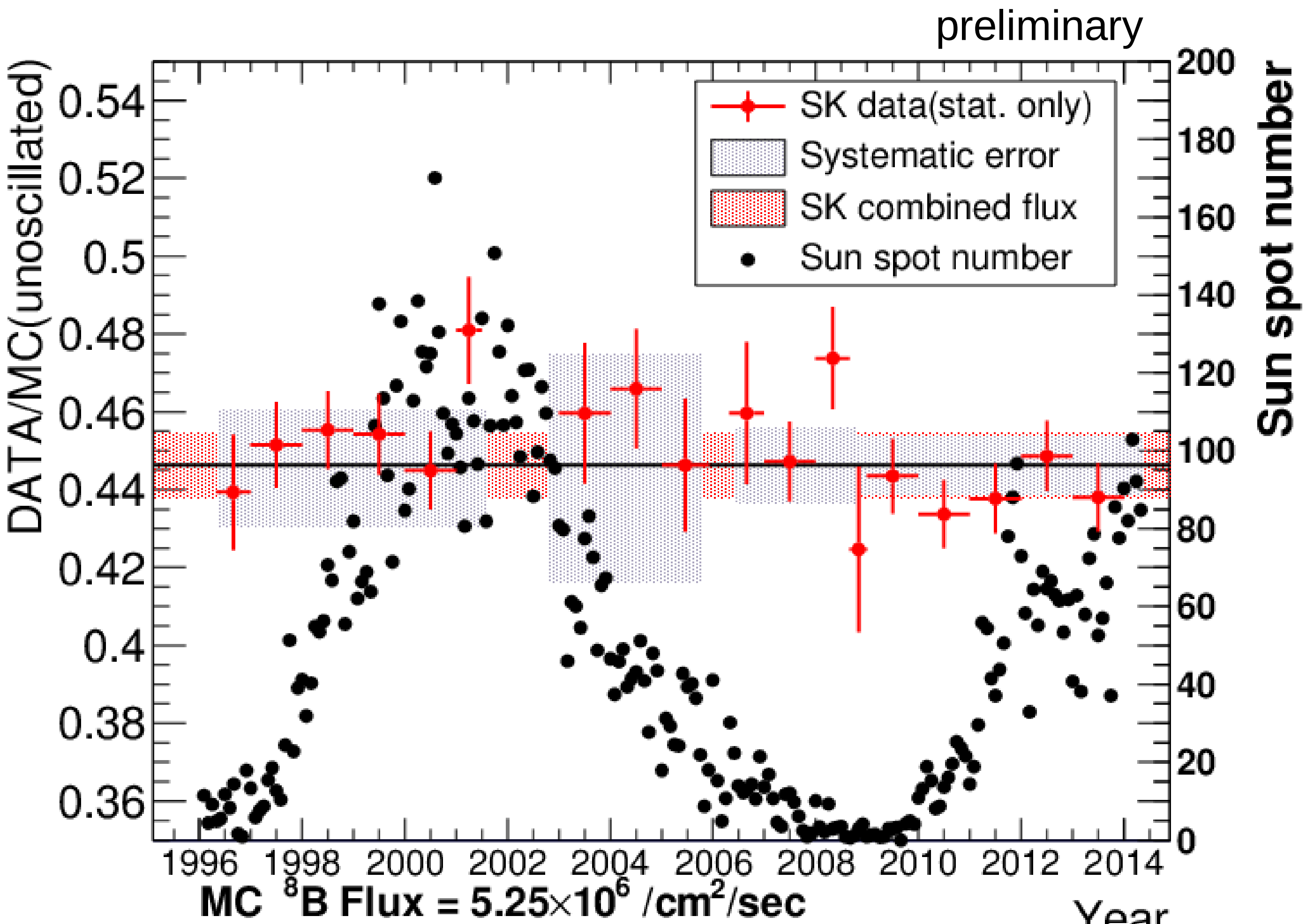
DATA/MC = 0.4463±0.0085 (stat.+sys.)

(MC ^{8}B flux: 5.25×10^6/cm^2/s)

Observed effective ^{8}B flux :

2.343 ± 0.044 (stat.+sys.) [10^6/cm^2/s]

^{8}B solar neutrino flux yearly plot



Sun spot number from http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt

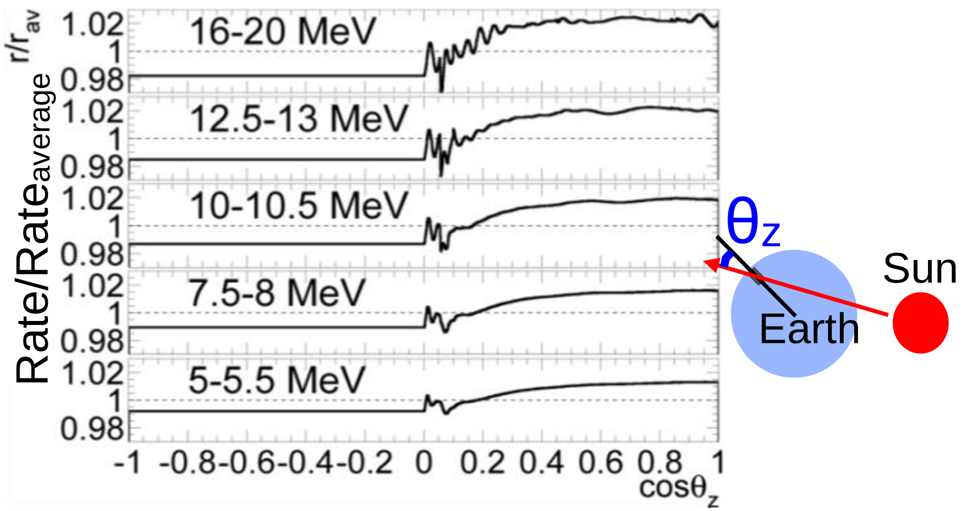
χ^2=13.53 / 17 D.O.F. → prob. = 70%

No significant correlation with the solar activity is seen.

Day/Night asymmetry(A_{DN})

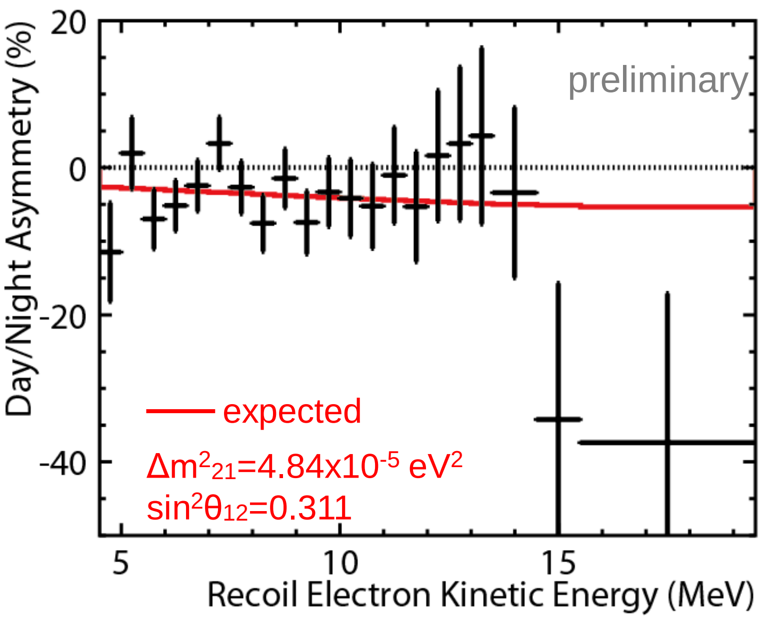
Assuming the expected time variation as a function of $\cos\theta_z$ like below, amplitude of A_{DN} was fitted.

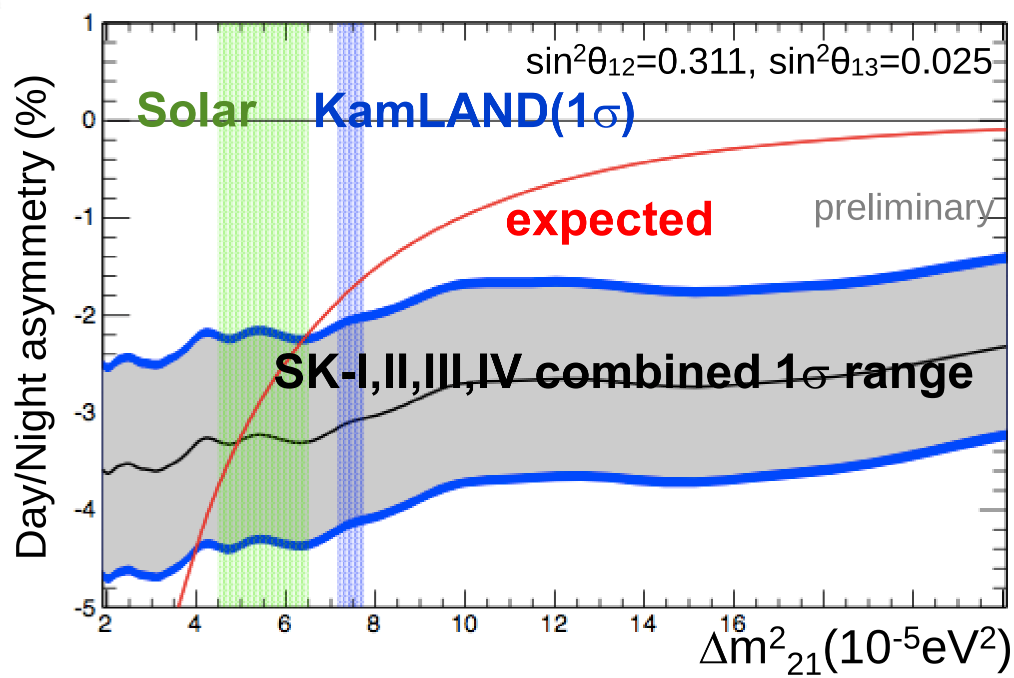
$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$



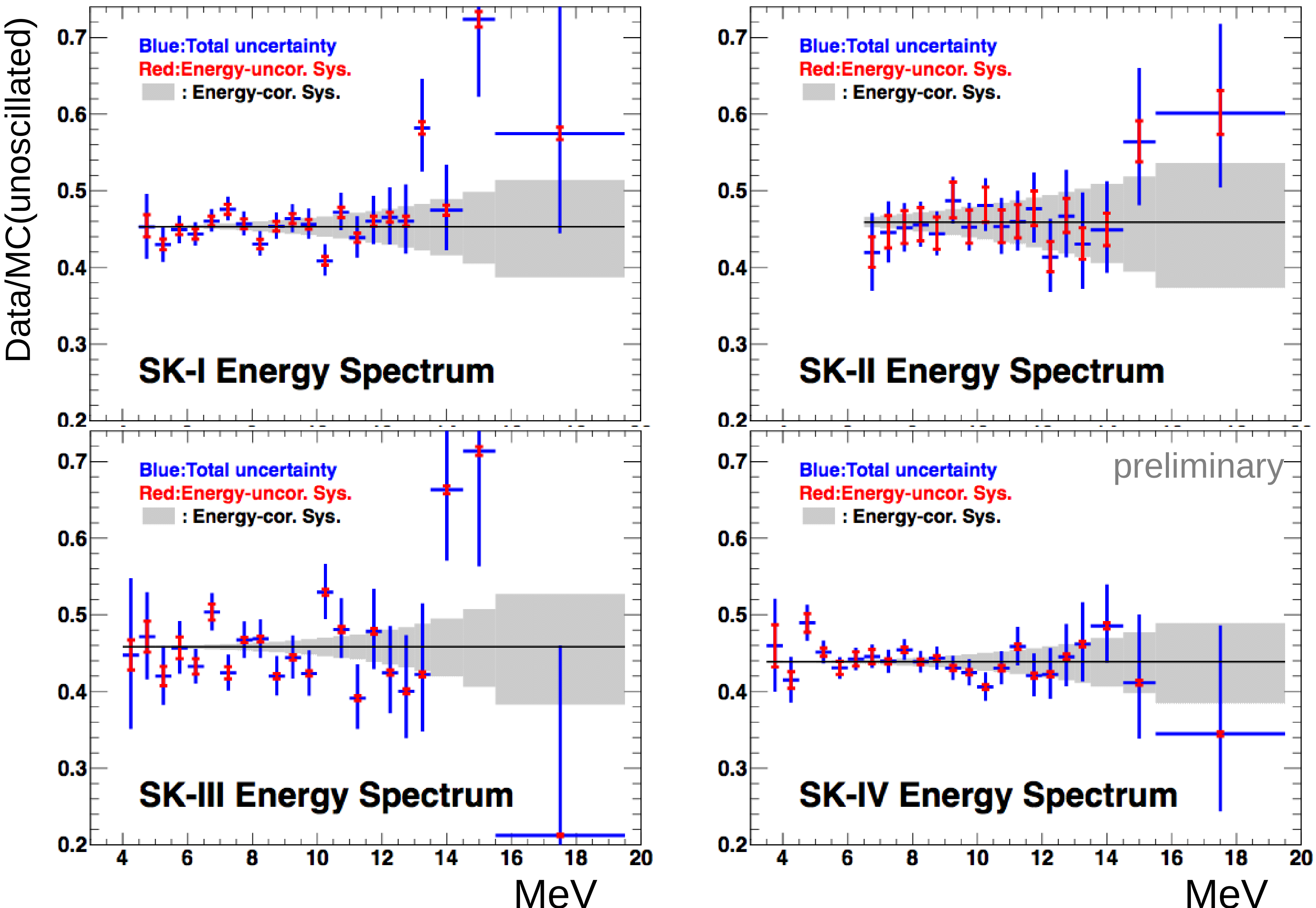
preliminary

	A_{DN}
SK-I	-2.0±1.8±1.0%
SK-II	-4.4±3.8±1.0%
SK-III	-4.2±2.7±0.7%
SK-IV	-3.6±1.6±0.6%
combined	-3.3±1.0±0.5%
non-zero significance	3.0σ



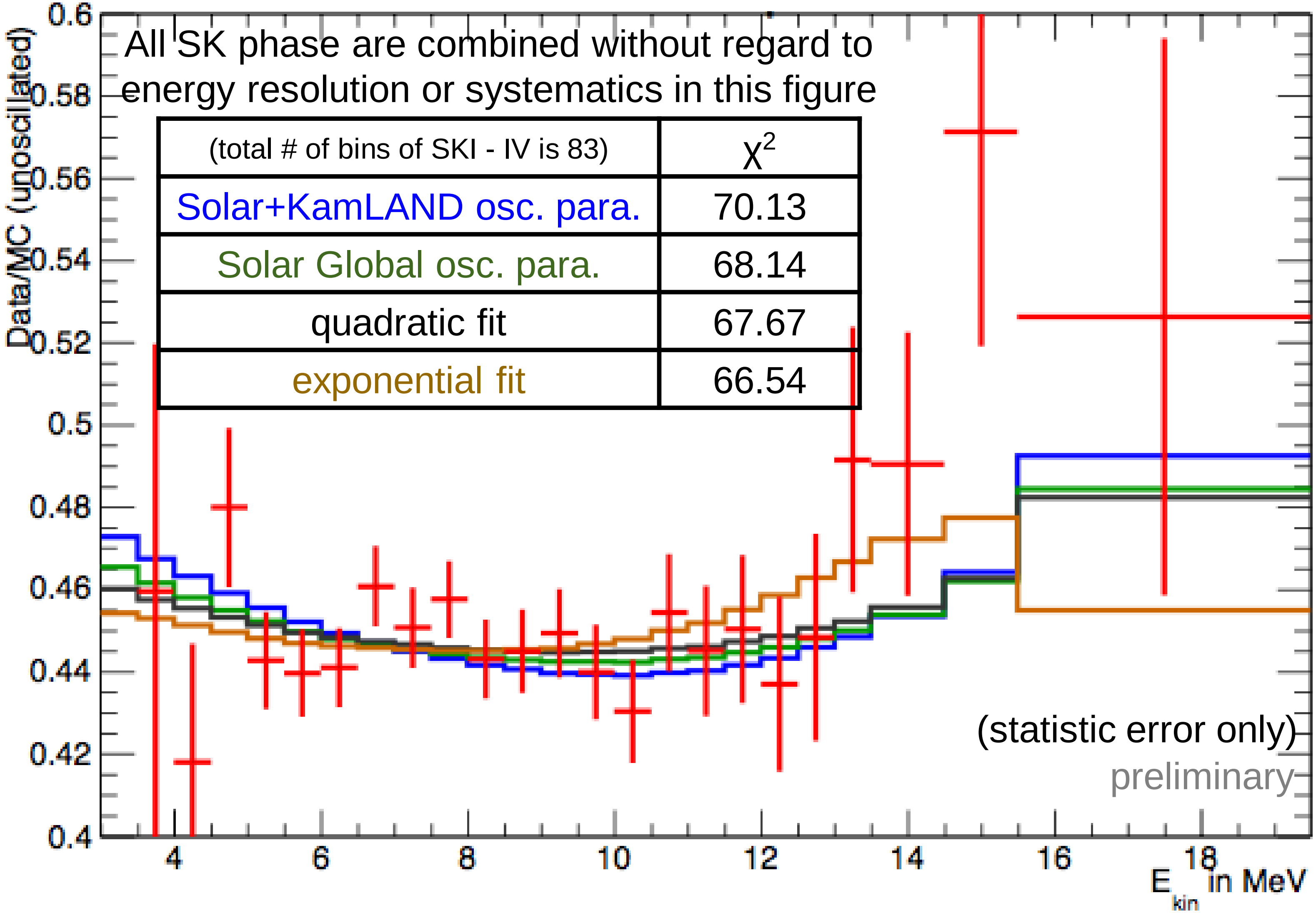


Recoil electron spectrum of each phase



(MC: 5.25×10^6/cm^2/s)

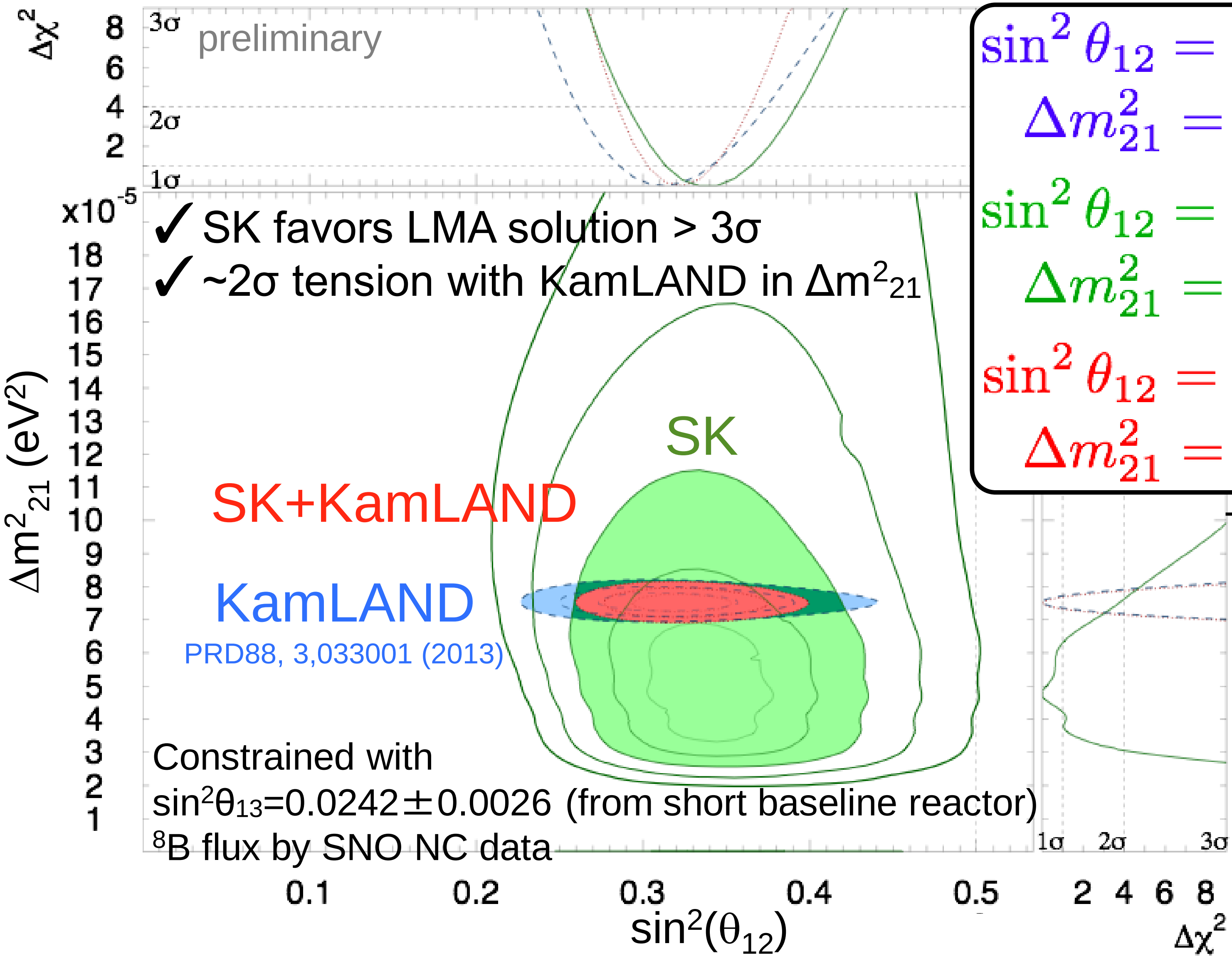
SK I-IV combined Recoil electron spectrum



(total # of bins of SKI - IV is 83)	χ^2
Solar+KamLAND osc. para.	70.13
Solar Global osc. para.	68.14
quadratic fit	67.67
exponential fit	66.54

MSW is slightly disfavored by ~1.7σ using the Solar+KamLAND best fit parameters, and ~1.0σ using the Solar Global best fit parameters.

θ_{12} and Δm^2_{21} from SK vs. KamLAND



✓ SK favors LMA solution > 3σ

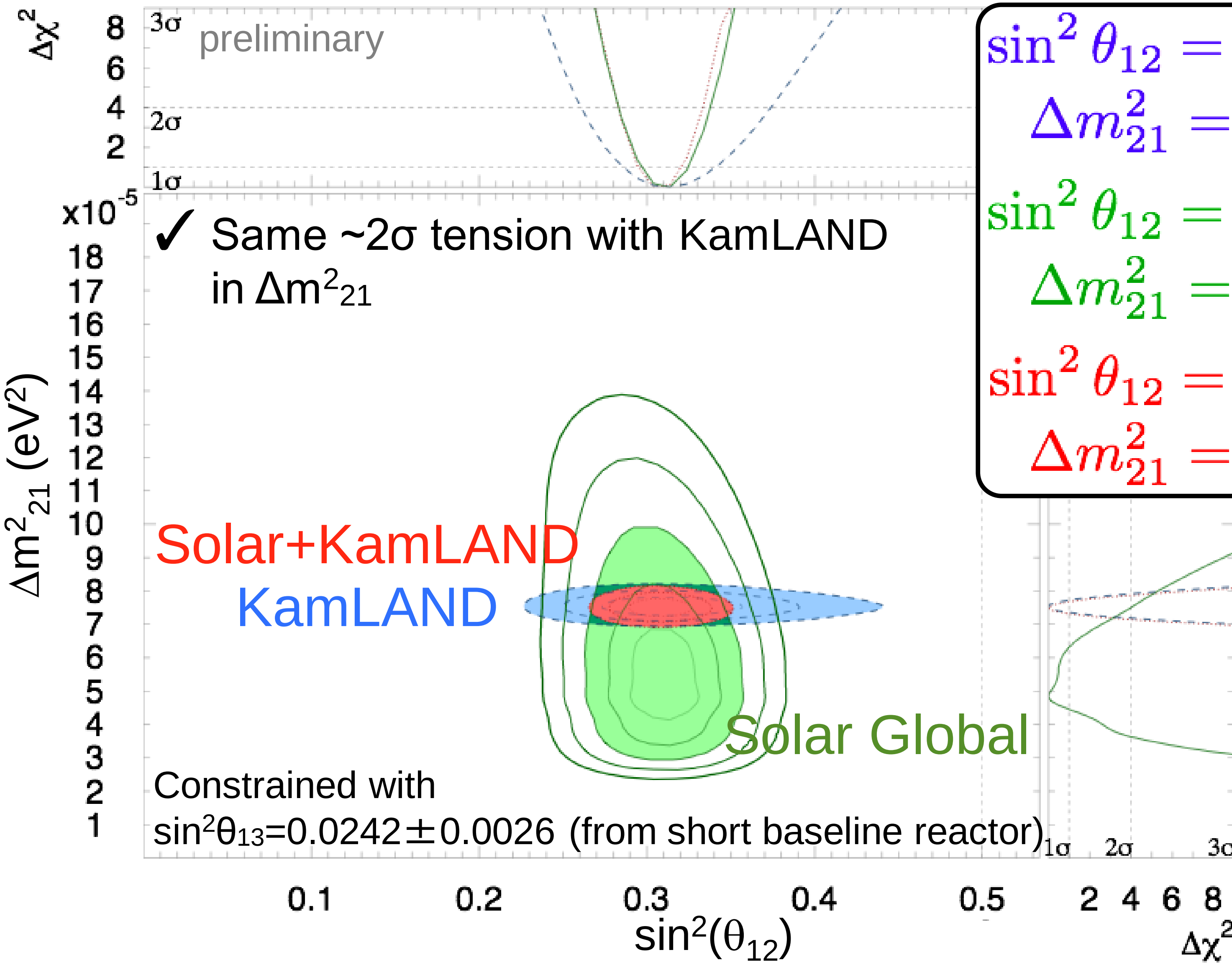
✓ ~2σ tension with KamLAND in Δm^2_{21}

$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.339^{+0.027}_{-0.024}$$
$$\Delta m^2_{21} = 4.74^{+1.6}_{-0.79}$$
$$\sin^2\theta_{12} = 0.322^{+0.022}_{-0.019}$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.17}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

Constrained with
$\sin^2\theta_{13}=0.0242\pm0.0026$ (from short baseline reactor)
^{8}B flux by SNO NC data

θ_{12} and Δm^2_{21} from Solar Global vs. KamLAND



✓ Same ~2σ tension with KamLAND in Δm^2_{21}

Constrained with $\sin^2\theta_{13}=0.0242\pm0.0026$ (from short baseline reactor)

$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$$
$$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$$
$$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

Data set for the solar global analysis

The most up-to-dated data are used

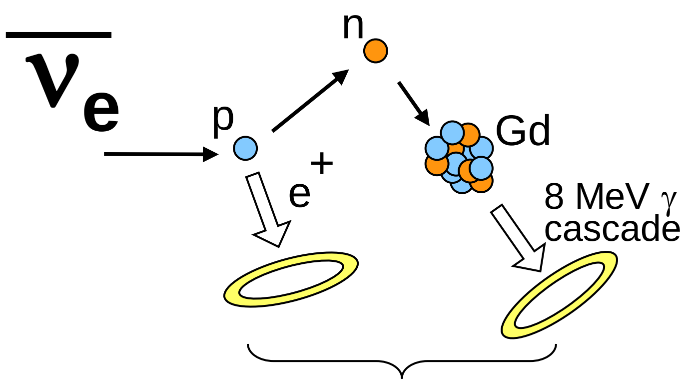
- **SK:**
  - SK-I 1496 days, spectrum 4.5-19.5 MeV(kin.)+D/N:E_{kin}>4.5 MeV
  - SK-II 791 days, spectrum 6.5-19.5 MeV(kin.)+D/N: E_{kin}>7.0 MeV
  - SK-III 548 days, spectrum 4.0-19.5 MeV(kin.)+D/N: E_{kin}>4.5 MeV
  - SK-IV 1669 days, spectrum 3.5-19.5 MeV(kin.)+D/N: E_{kin}>4.5 MeV
- **SNO:**
  -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

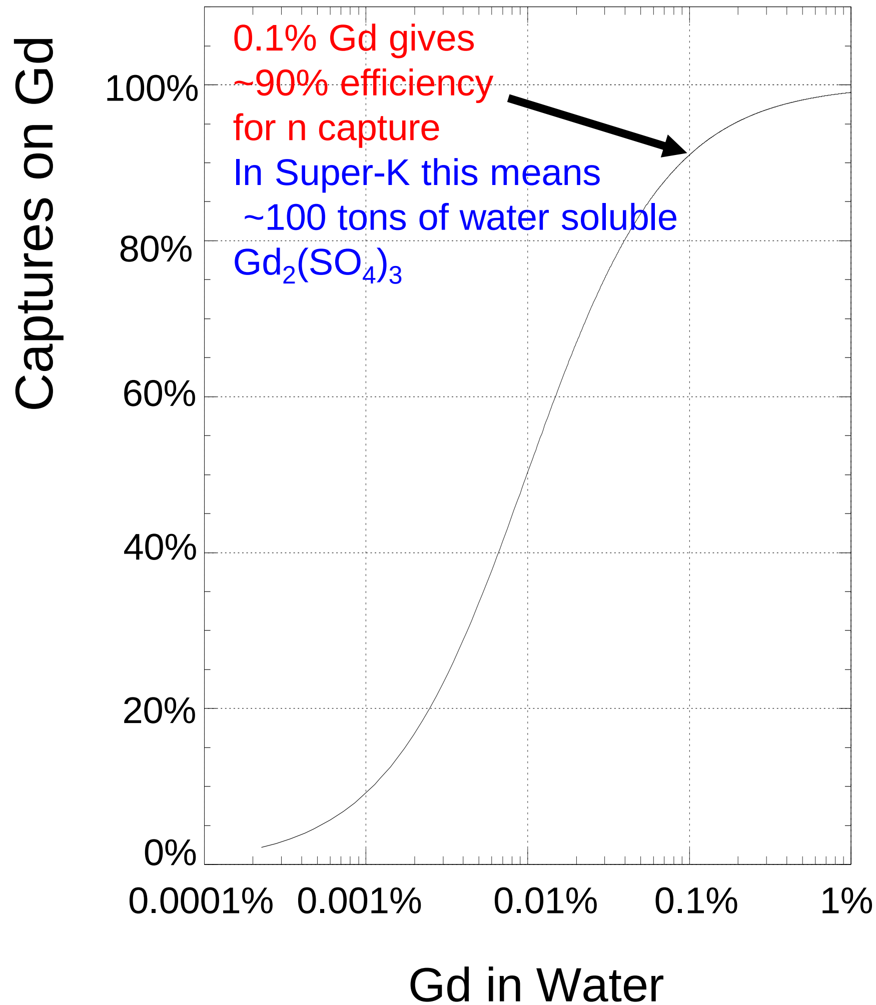
GADZOOKS! project

Identify $\bar{\nu}_e p$ events by neutron tagging with Gadolinium.

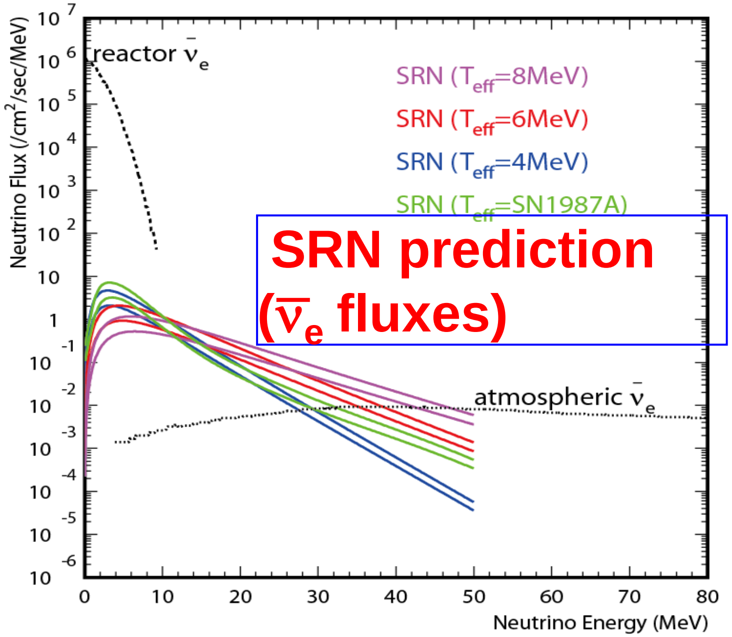
Gadolinium has large neutron capture cross section and emit 8MeV gamma cascade.



ΔT~20μs
Vertices within 50cm



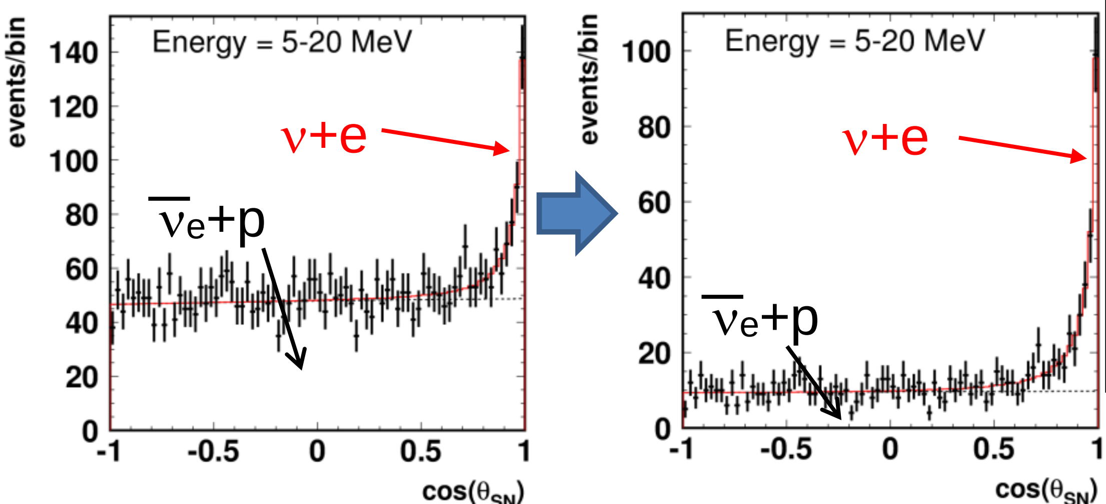
Physics with GADZOOKS!



Supernova Relic Neutrinos (SRN)

- Open widow for SRN at 10-30MeV
- Expected event rate 1.3 -6.7 events/year/22.5kt(10-30MeV)
- Study supernova rate from the beginning of universe.
- Averaged energy spectrum.

Improve pointing accuracy for supernova bursts, e.g. 4~5°→ 3°(90%C.L.) for 10kpc



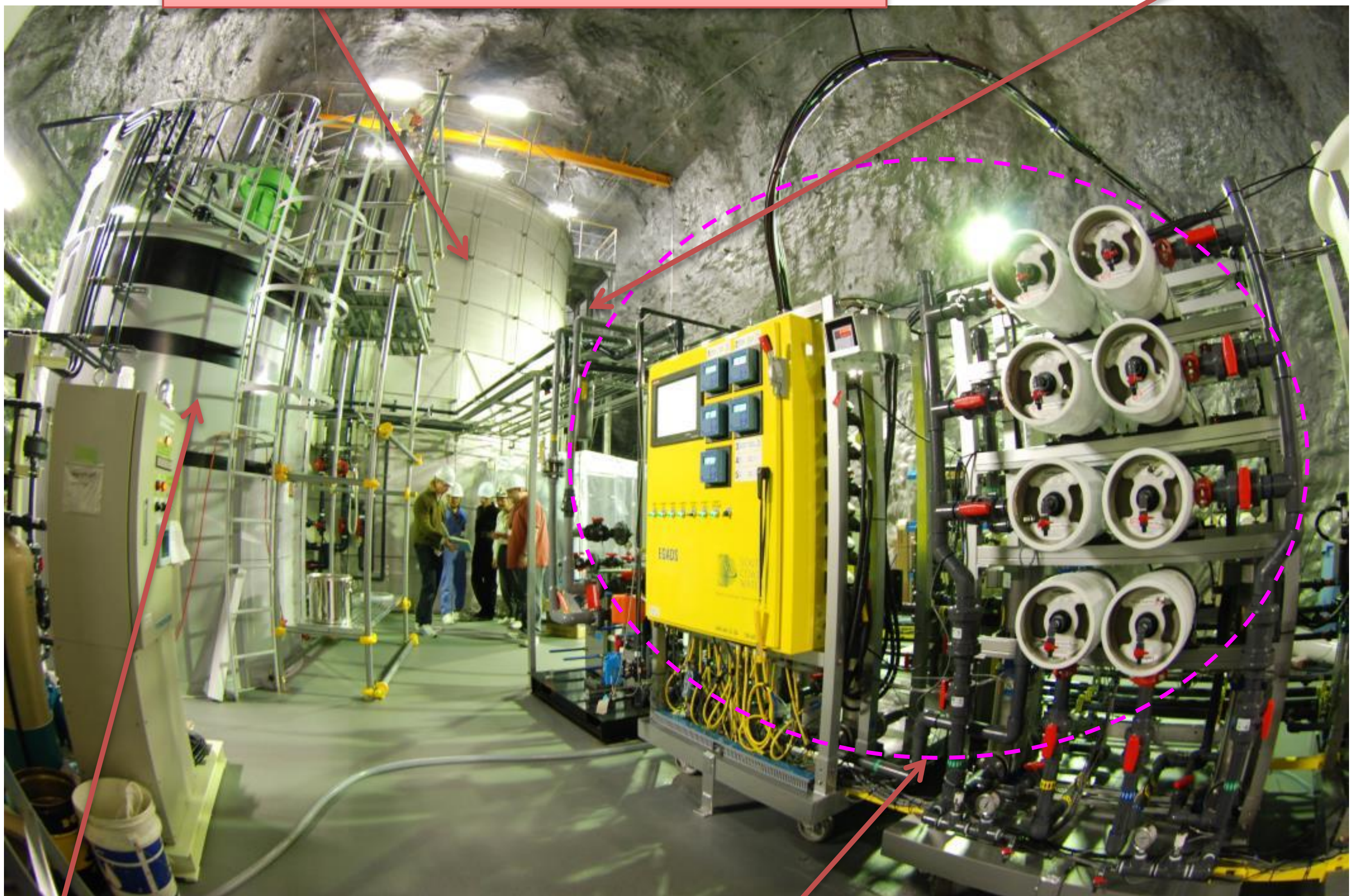
- Precise measurement of θ_{12} and Δm^2_{21} by reactor neutrinos.
- Discriminate proton decay (essentially no neutron) and atmospheric neutrino background(with neutrons).
- Neutrino/anti-neutrino identification.

EGADS

Evaluating Gadolinium's Action on Detector Systems

Transparency measurement (UDEAL)

200 m^3 test tank with 240 PMTs



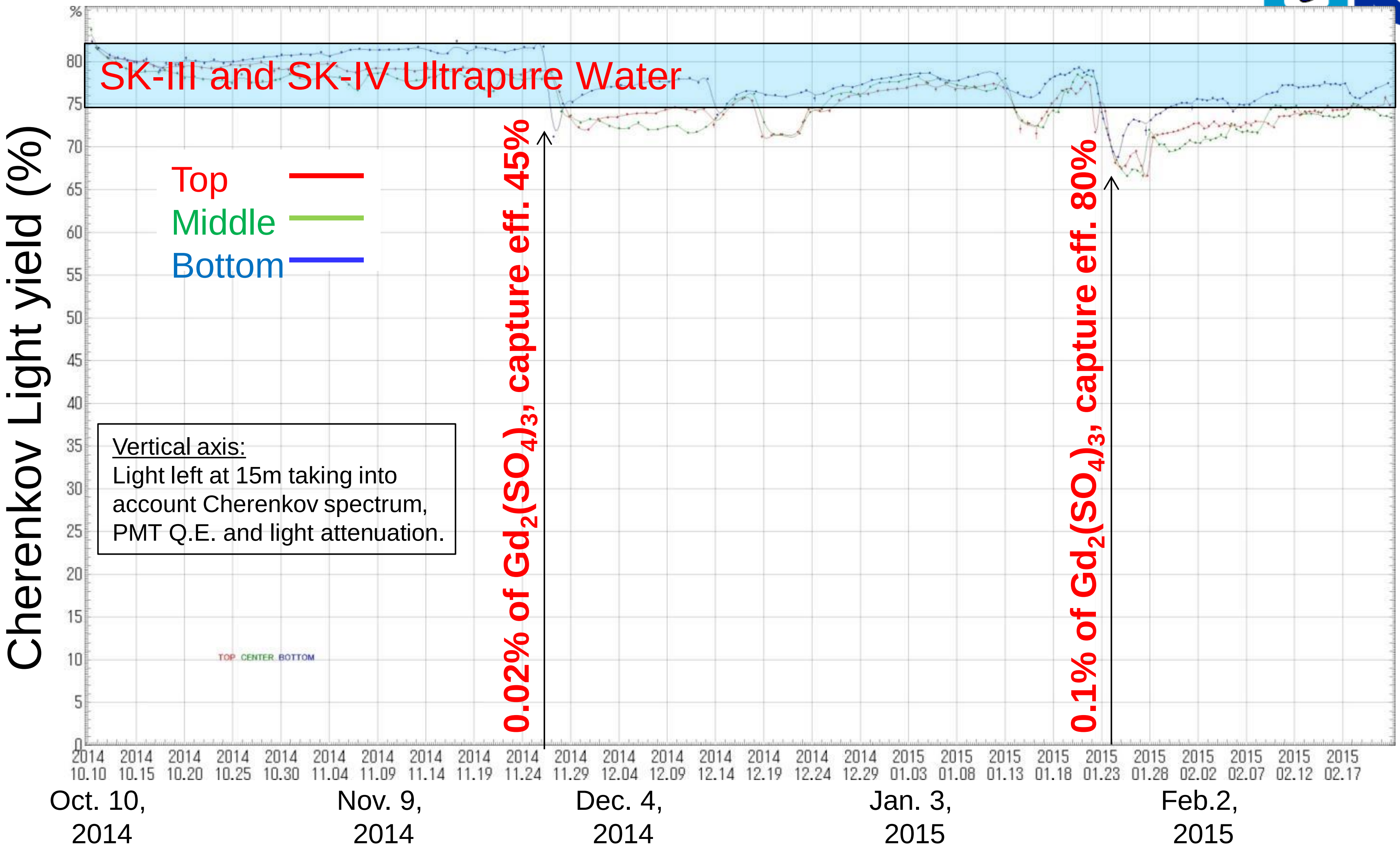
15m^3 tank to dissolve Gd

Gd water circulation system (purify water with Gd)

240 PMTs were mounted in the 200 m^3 tank in 2013.

The detector fully mimic Super-K detector.
Gd dissolving test has been performed since Oct.2014. (see next page)
After good water transparency is demonstrated with 0.2% $Gd_2(SO_4)_3$ (0.1% Gd), the GADZOOOKS! proposal will be discussed in the SK collaboration.

Transparency of Gd-loaded water (after mounting PMTs)



Dissolving test is going well. The water transparency is SK pure water level even with 0.1% $Gd_2(SO_4)_3$. It will soon reach 0.2% $Gd_2(SO_4)_3$ (target value).

Summary

- **Atmospheric neutrinos**
  - Tau neutrino appearance with 3.8σ level.
  - Normal hierarchy favored at: $\chi^2_{IH} - \chi^2_{NH} = 0.9$ by SK only, and 1.2 by SK+T2K.
- **Indirect dark matter search**
  - SK places the most stringent constraint for SD below 200GeV.
  - Set new limit for light WIMPs (<6GeV) for SI.
- **Solar neutrinos**
  - No significant correlation with solar activity.
  - Day/night asymmetry observed with 3σ level.
  - In energy spectrum, MSW is slightly disfavored by 1~1.7σ.
  - About 2σ tension in Δm^2_{21} between SK(Solar Global) and KamLAND.
- **R&D for GADZOOKS! project (EGADS) is going well.**