The Recent Results from Super-Kamiokande

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New Trends in High-Energy Physics 2016

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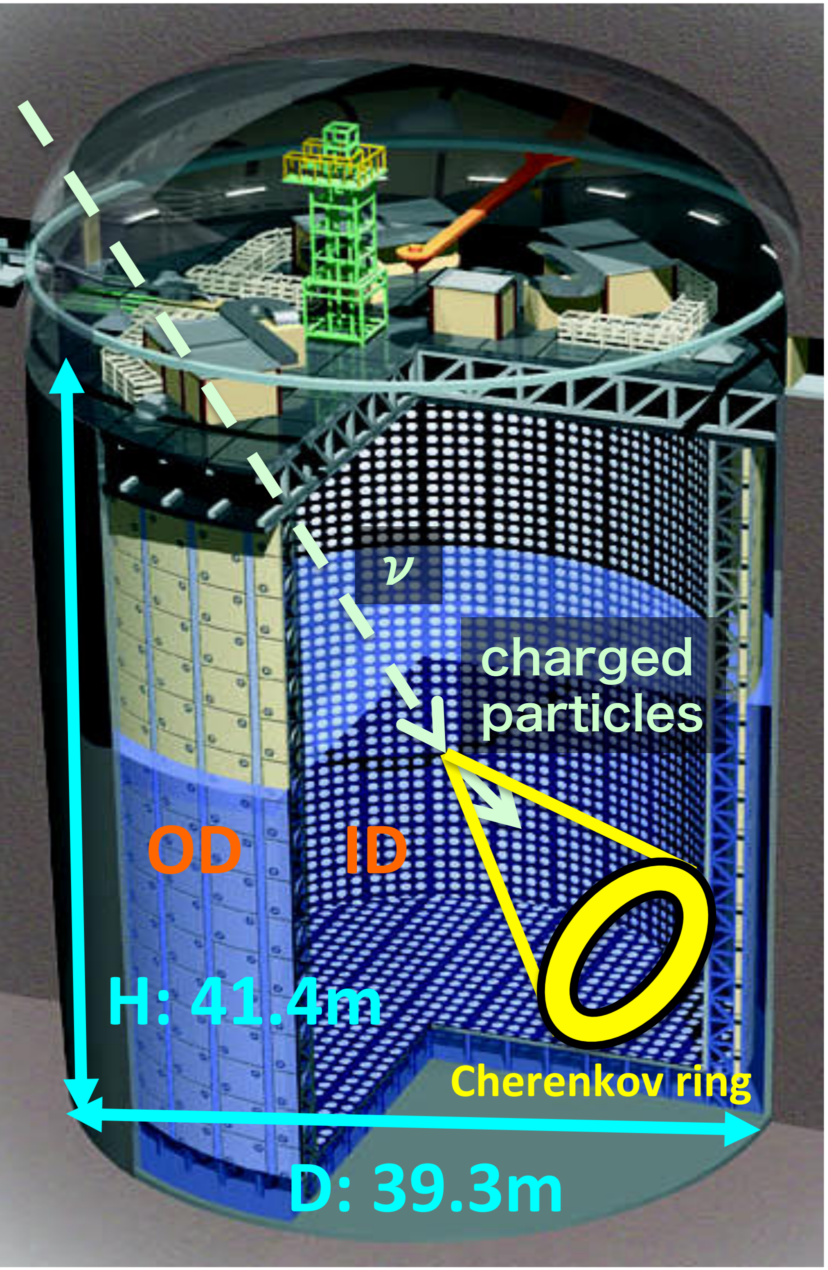
Becici, Budva, Montenegro

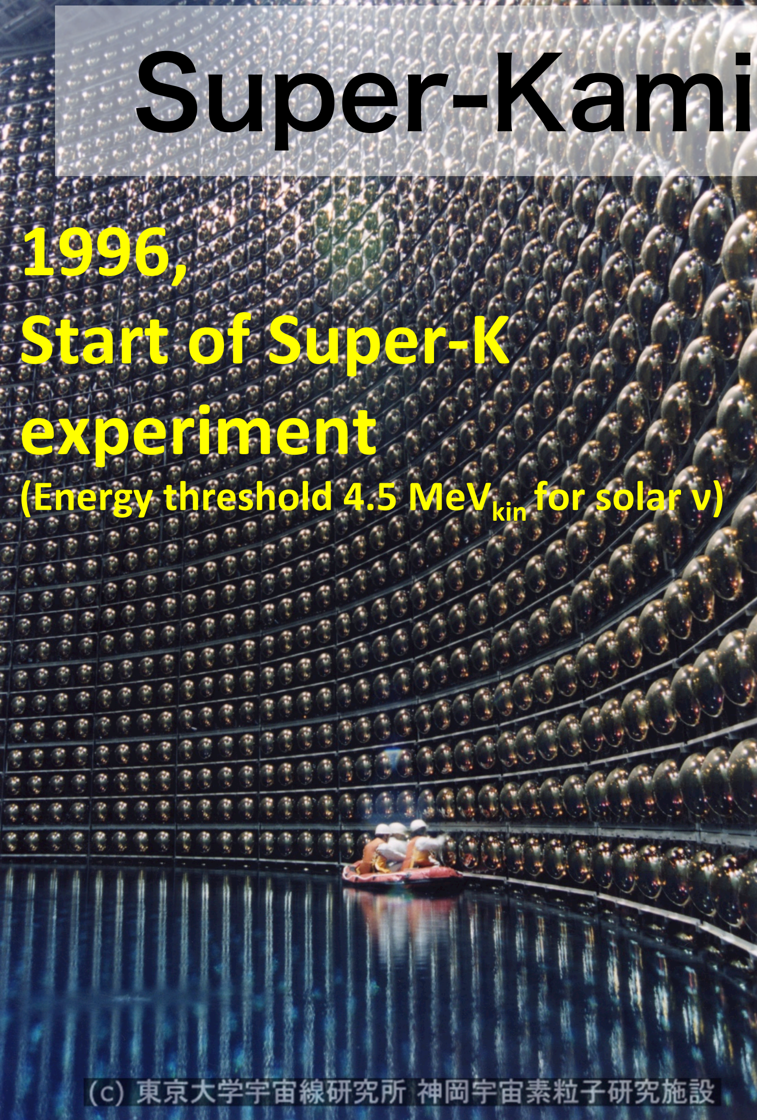
Super-Kamiokande Detector



Features of SK detector :

- Large water Cherenkov detector with 50kt ultra pure water.
- 22.5 kt fiducial volume.
- 1km under the Ikenoyama mountain in Japan. (2700 mwe)
- ~11,000 of 20" PMT for inner detector (ID)
  - 40% photo coverage
  - SK-II: Half PMT, photo coverage
- 1885 of 8" PMT for outer detector (OD)
- Reconstruction of energy, direction and PID is possible.

Super-Kamiokande Experiment



From April of 1996, the Super-K accumulated **atm./solar ν events**, searched for **nucleon decay**, cooperated with **ν beam exp.** and made improvement over 20 years!

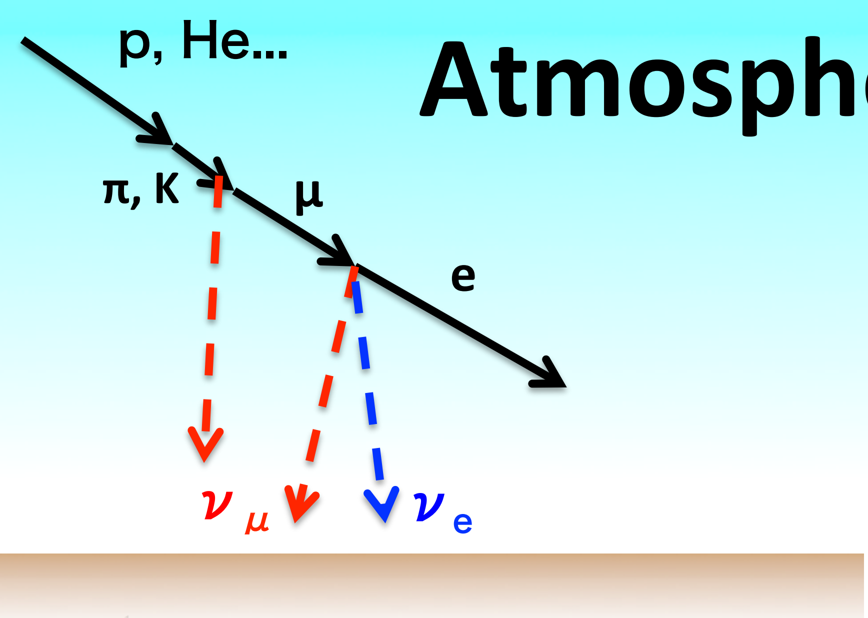
SK-I | SK-II | III | SK-IV

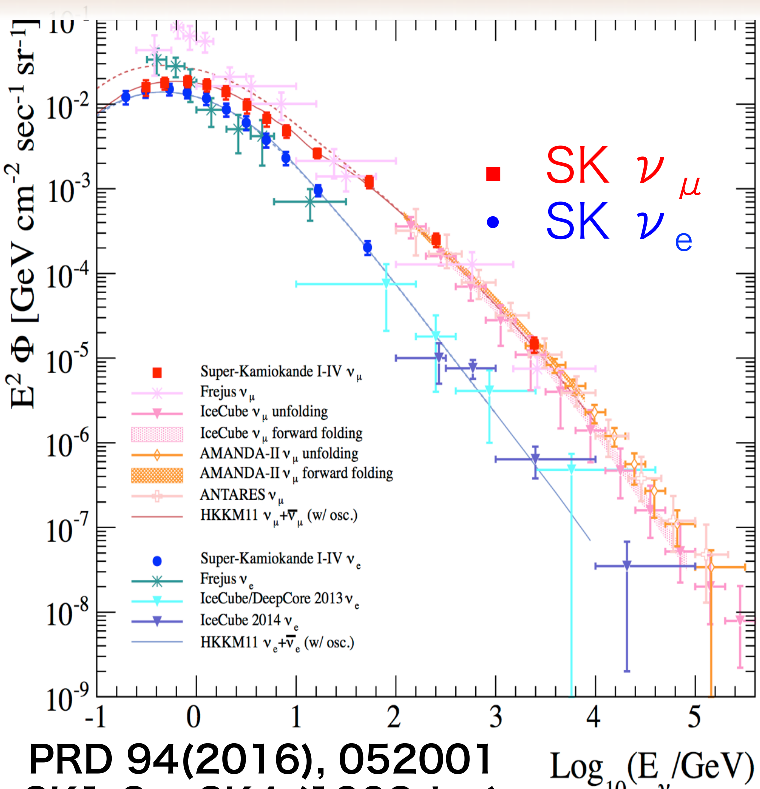
1996 2001 '02 '05 '06 '08 Today

K2K far detector ('99 – '04)

T2K far detector ('09 –)

Atmospheric Neutrino

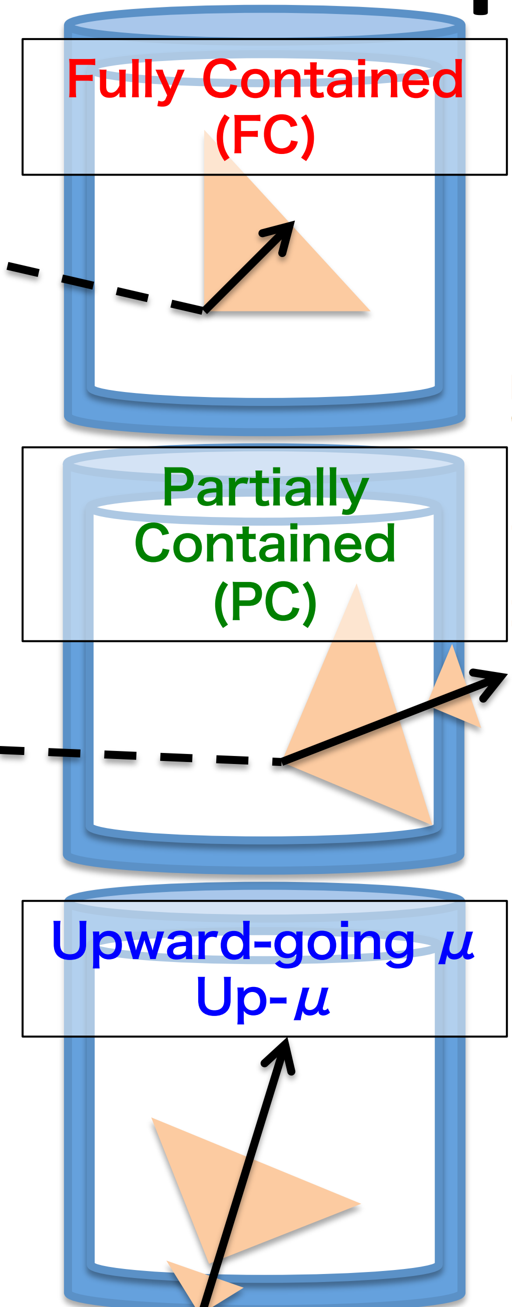


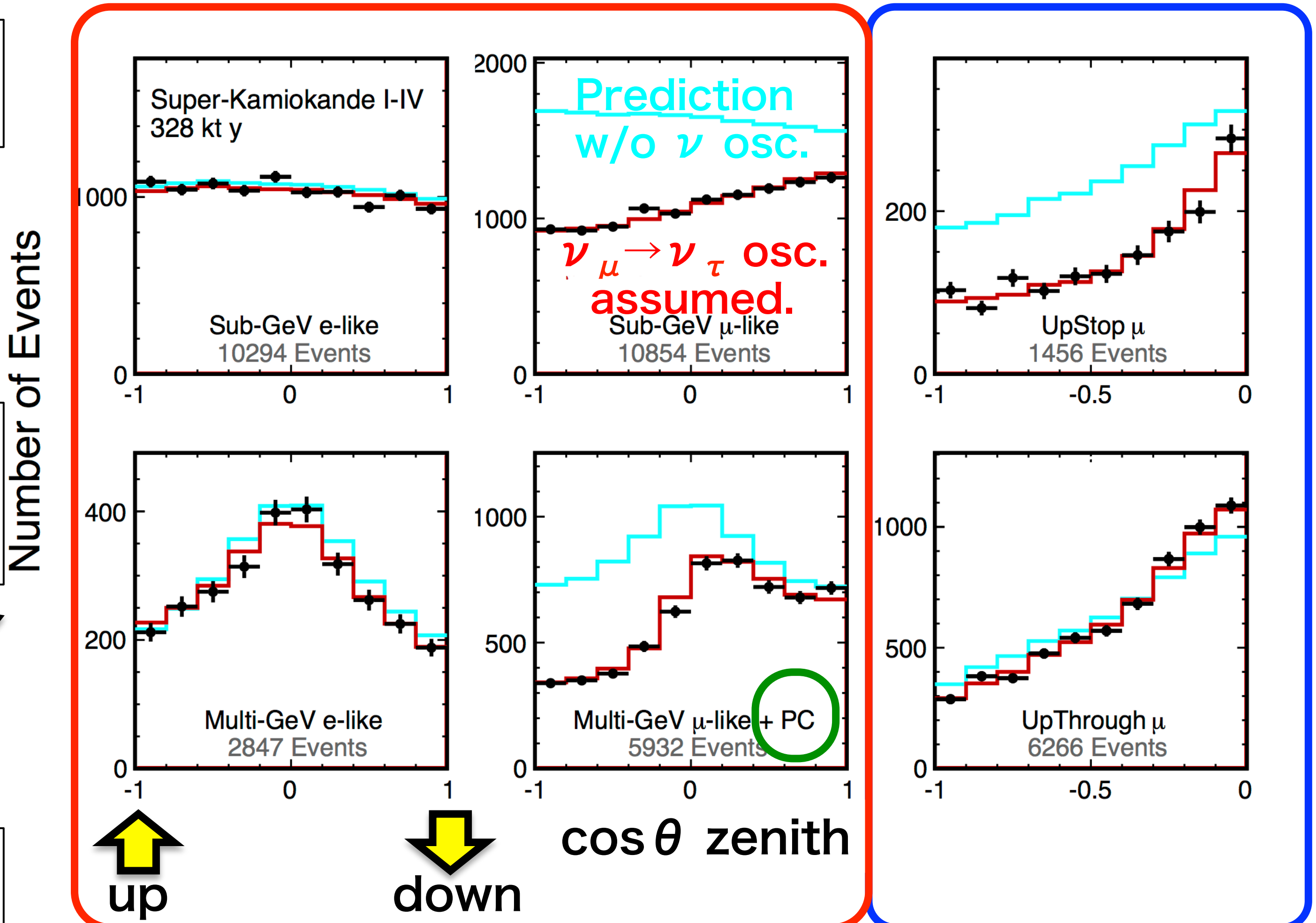


PRD 94(2016), 052001
SK1-3 + SK4 (1993day)

- Cosmic rays interact with air nuclei and the decay of π, K and μ produce **neutrinos**.
- **Neutrinos** travel 10 (down-going) - 13,000 (up-going) km before detection at SK.
- Both $\boldsymbol{\nu_\mu}$ and $\boldsymbol{\nu_e}$, both neutrinos and anti-neutrinos.
- Flux spans many decades in energy ~100 MeV – 100 TeV.
- Excellent tool for studies of neutrino oscillations.

Atmospheric ν Analysis Samples

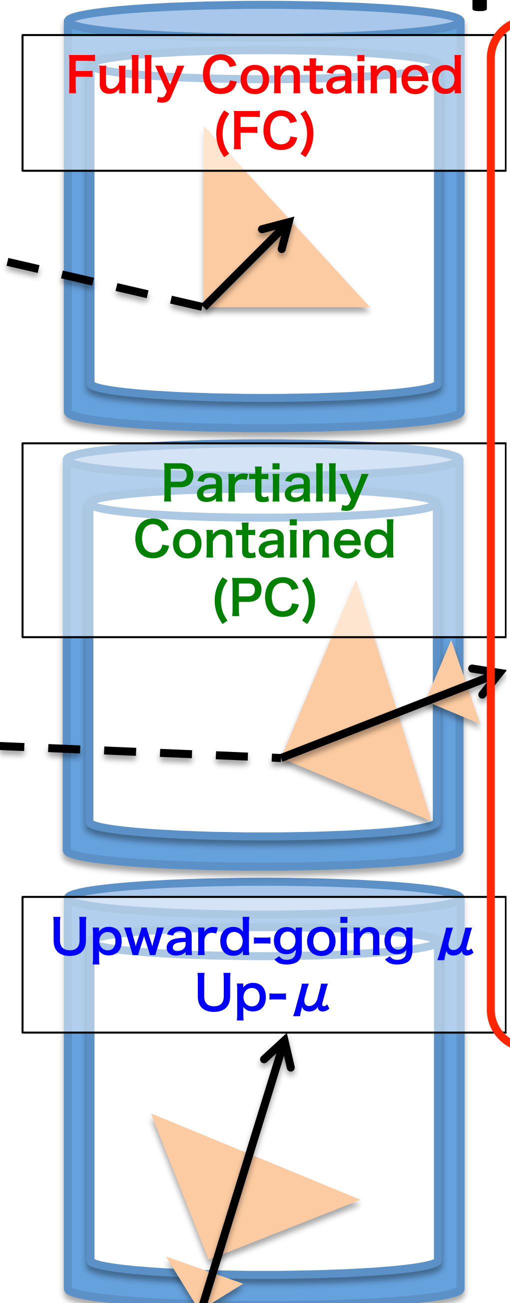


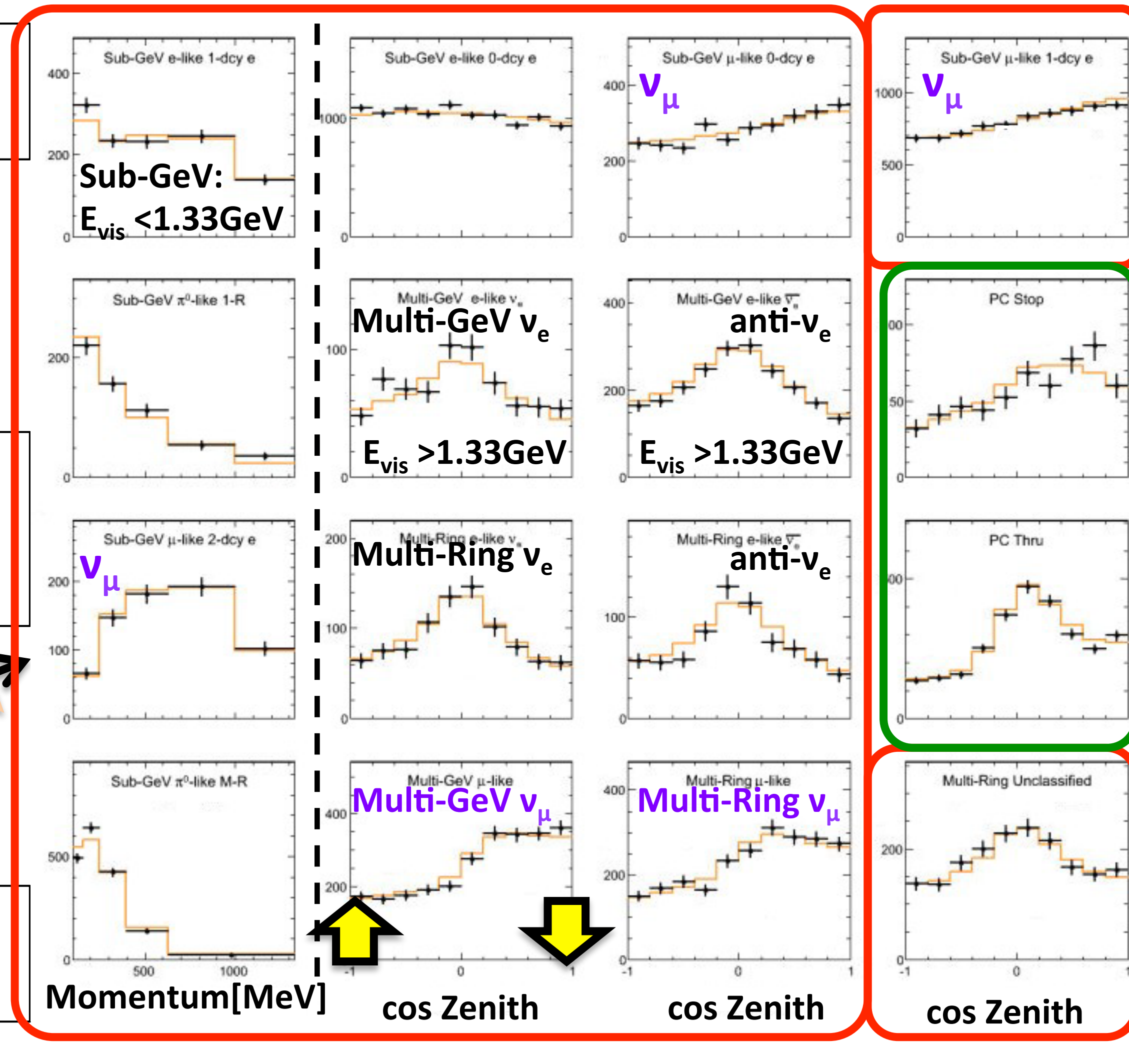


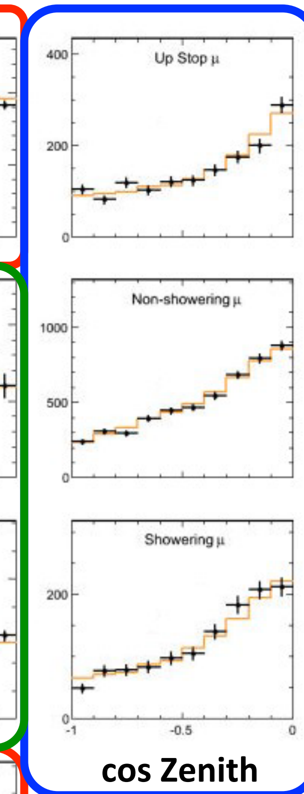
- Data: SK1-3 + SK4(2520d) = 0.33Mtyr
- Leading term: $\nu_\mu \rightarrow \nu_\tau$ oscillation (ν_μ disappearance)

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4c_{13}^2 s_{23}^2 (1 - c_{13}^2 s_{23}^2) \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E_\nu}\right)$$

Atmospheric ν Analysis Samples



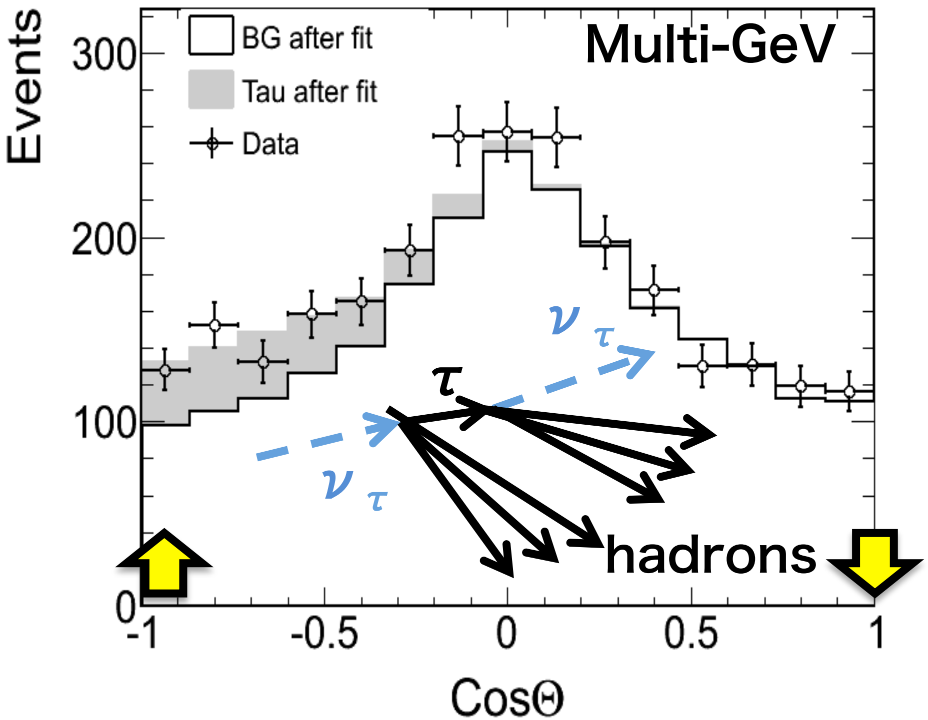




3 flavor osc. best fit is shown. (w, θ_{13})

- **19 analysis samples**: sub-divided by event topology (FC/PC, Up-μ), energy range, e/μ-like, and # of rings.
- Multi-GeV/Ring e-like samples are statistically separated to ν and anti-ν like samples.

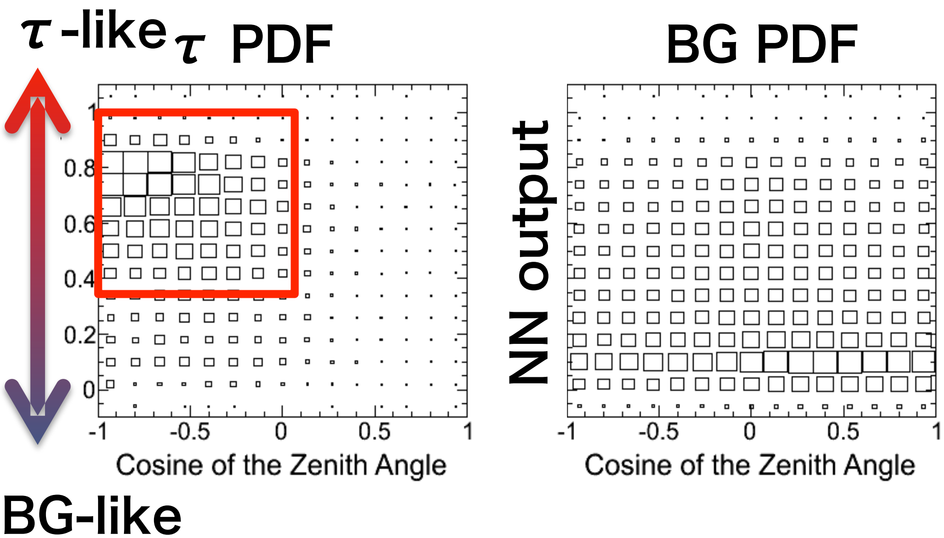
ν_τ Appearance Update



- $\nu_\mu \rightarrow \nu_\tau$ is the leading channel of atm. ν_μ oscillation.
- We reported the evidence of ν_τ appearance at SK in 2013.
  PRL110 (2013) 181802
- Search for the hadronic τ decay events with neural network.
- 2D un-binned fit to the binned τ-signal PDF and background PDF.

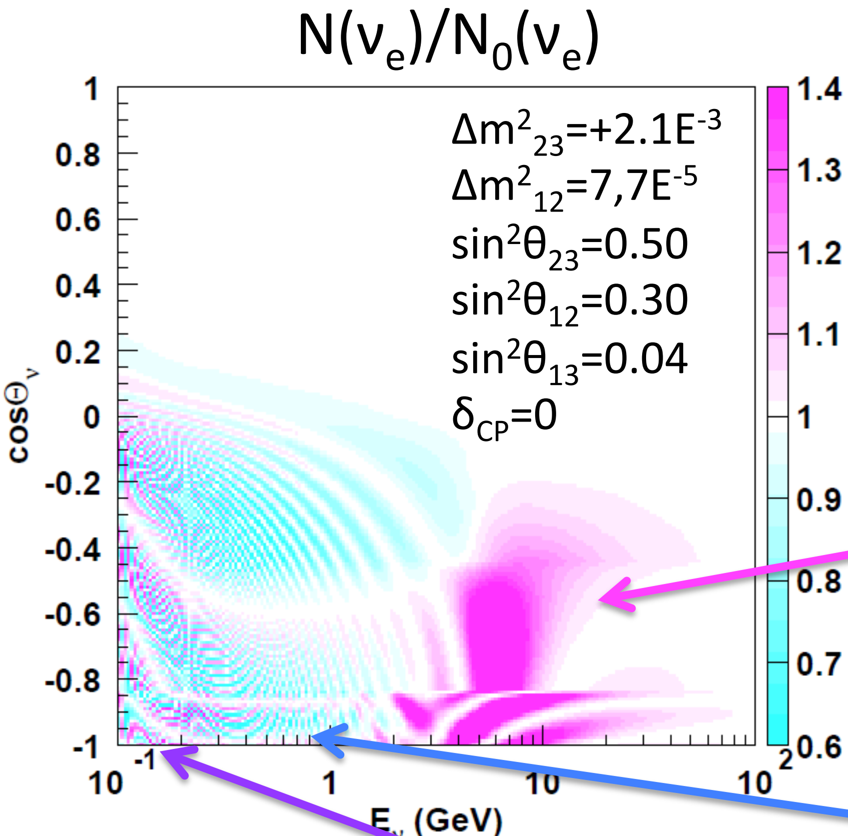
$$Data = BG\ PDF + \alpha\ \tau\ PDF + \Sigma\ \varepsilon_i\ PDF_i$$

- α is the magnitude of τ signal.
- PDF_i is the i-th syst. error to shift by 1σ. ε_i is its magnitude.



α = 1.47±0.32 (4.6σ from 0)
assuming NH. With nominal expectation (α=1): 3.3σ from 0.
(preliminary)

Atm. ν oscillation at SK



Pares and Smirnov hep-ph/039312

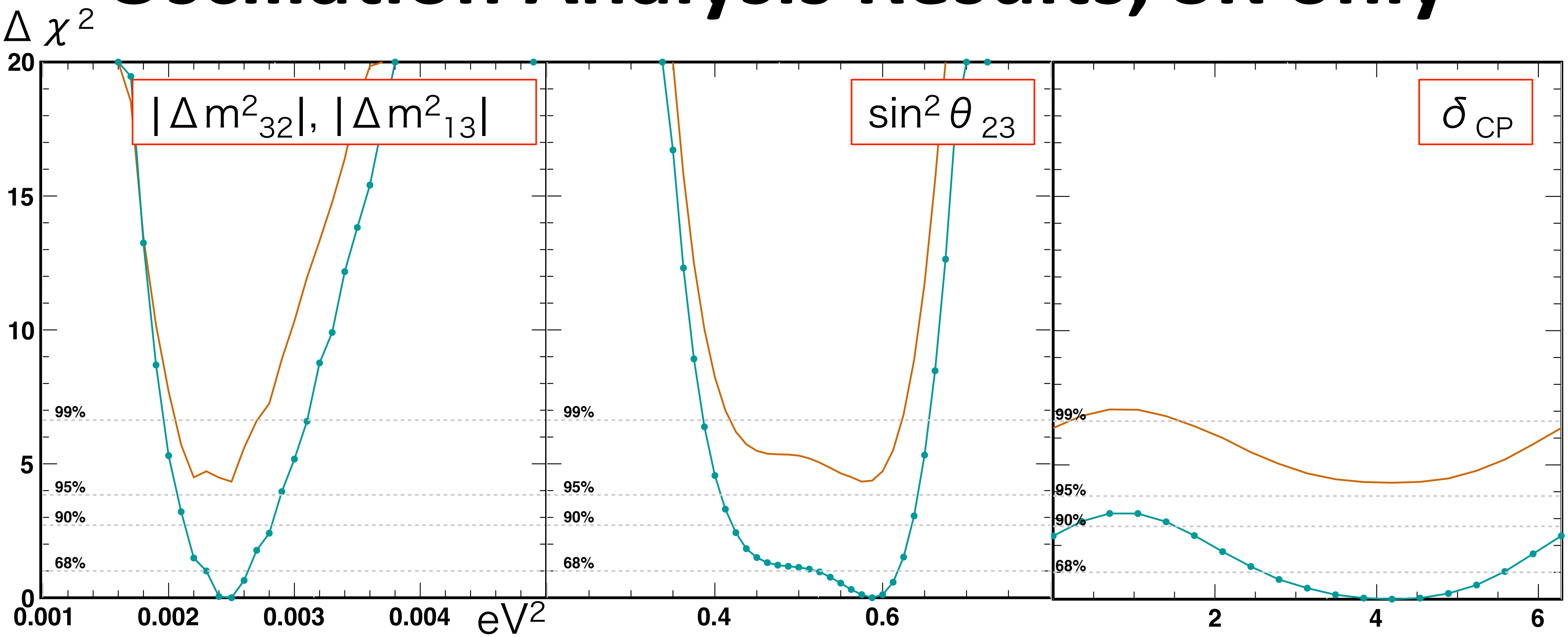
$$P(\nu_\mu \to \nu_e) = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E_\nu}\right)$$

$$\sin^2 2\theta_{13}^m = \frac{\sin^2 2\theta_{13}}{(A/\Delta m_{32}^2 - \cos 2\theta_{13})^2 + \sin^2 2\theta_{13}}$$

$$A = 2\sqrt{2} G_F N_e E_\nu$$

- The major parameter for the atm. ν osc. is Δm^2_{23} and $\sin^2 2\theta_{23}$.
- The effect of sub-leading parameters also could be extracted, e.g. MH, θ_{13}, δ_{CP} and θ_{23} octant.
- Sensitive to MH, θ_{23} octant, θ_{13}
  NH: more ν_e
  IH: more anti-ν_e
  (θ_{13} resonance conversion)
- Sensitive to δ_{CP}
  More ν_e for $\pi < \delta_{CP} < 2\pi$
  (interference)
- Sensitive to θ_{23} octant
  More ν_e for $\theta_{23} < \pi/2$
  (driven by Δm^2_{21} terms)

Oscillation Analysis Results, SK only



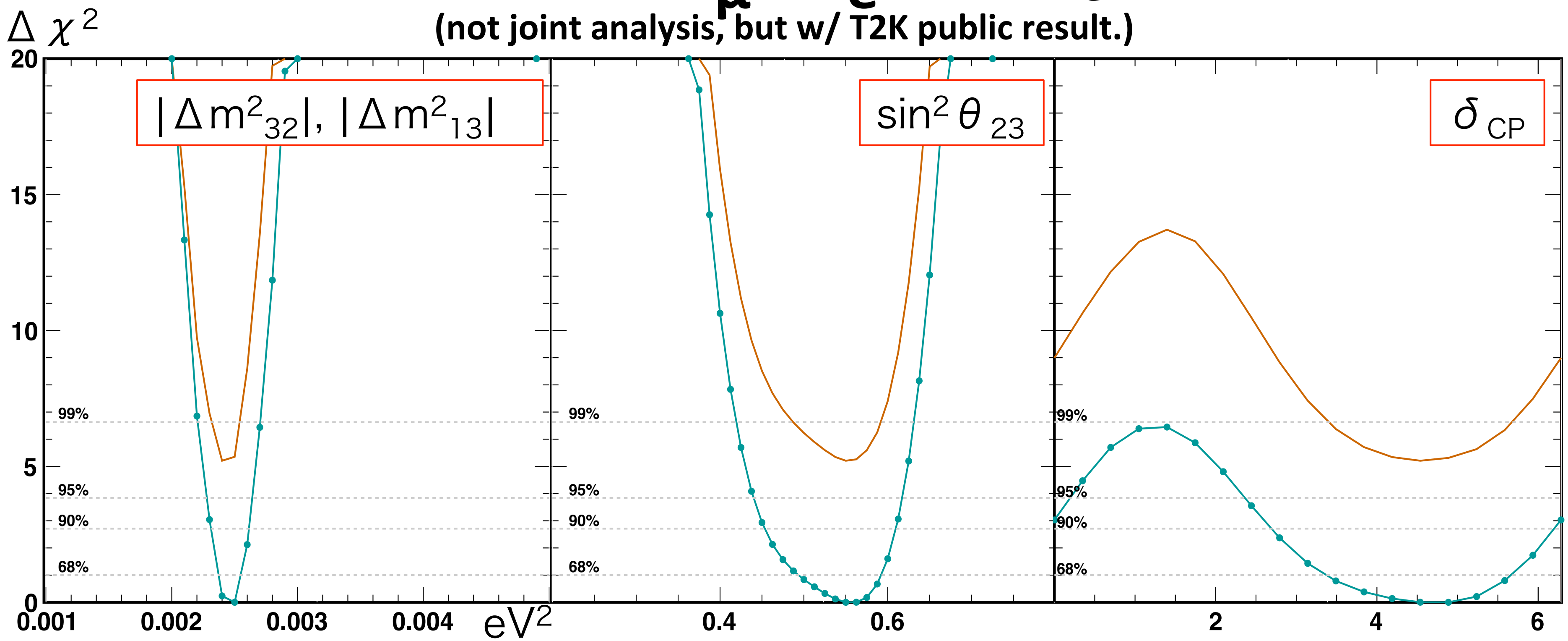
Fit (517dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23} [eV2]
SK (NH)	571.74	0.0219(fix)	4.189	0.587	2.5×10^{-3}
SK (IH)	576.08	0.0219(fix)	4.189	0.575	2.5×10^{-3}

- Constraints: $\sin^2\theta_{13}$ (PDG2015), $\sin^2\theta_{12}$ and Δm^2_{21} (Solar+KamLAND)
- Free to fit : $\sin^2\theta_{23}$, Δm^2_{32}, MH(IH/NH), δ_{CP}
- Normal hierarchy favored : $\chi^2_{NH}-\chi^2_{IH} = -4.3$ (-3.1of sensitivity expected for NH)

  Under IH hypothesis and toy MC, the probability to obtain $\Delta\chi^2$ of -4.3 or less is 0.031 ($\sin^2\theta_{23}$=0.6) and 0.007 ($\sin^2\theta_{23}$=0.4) Under NH, the probability is 0.446 ($\sin^2\theta_{23}$=0.6).

SK+T2K $\nu_\mu+\nu_e$ analysis

(not joint analysis, but w/ T2K public result.)



Fit (585dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	Δm^2_{23} [eV2]
SK (NH)	639.61	0.0219(fix)	4.887	0.55	2.4×10-3
SK (IH)	644.82	0.0219(fix)	4.538	0.55	2.5×10-3

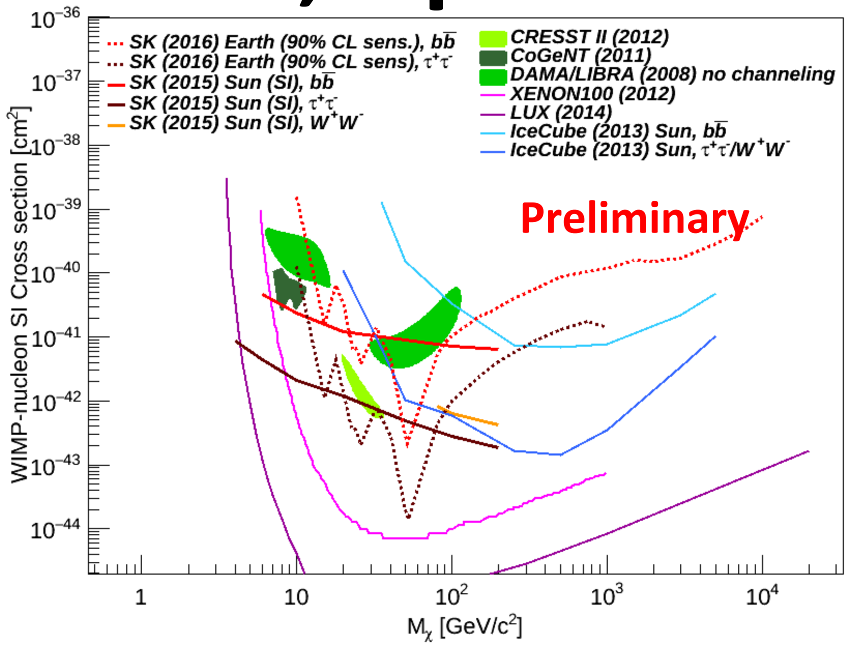
- Normal hierarchy favored at : $\chi^2_{NH}-\chi^2_{IH} = -5.2$
  (-3.8 was expected for SK best parameters, -3.1 for combined best)
  Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4). Under NH hypothesis, the probability is 0.43($\sin^2\theta_{23}$=0.6).

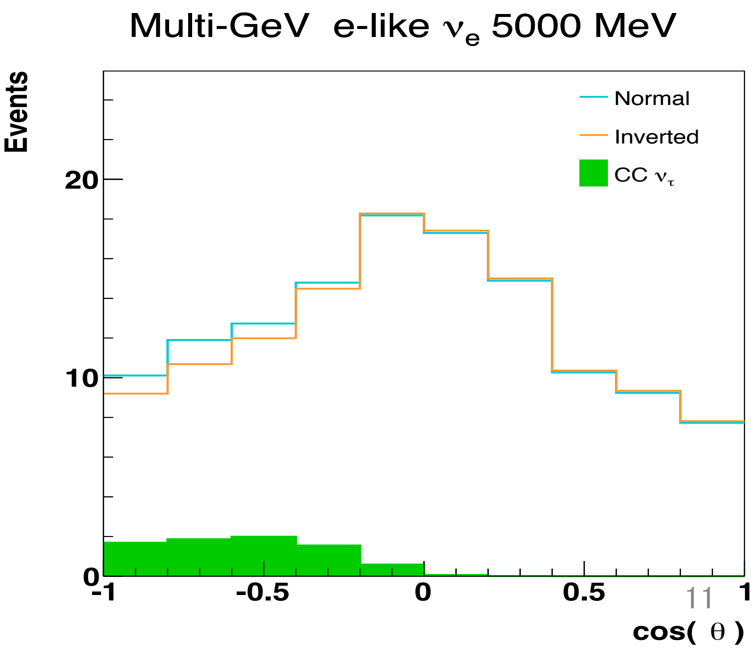
Other Atm. Related Results, Updates

- Recent publications
  - ν from ann. WIMPs in the Sun **(PRL 114 (2015) 141301)**
  - Sterile ν mixing **(PRD 91 (2015) 052109)**
  - Lorentz violation **(PRD 91 (2015) 052003)**

- Preliminary
  - Matter effect on atmospheric ν
  - ν from ann. WIMPs in the Earth
  - Galactic WIMPs
  - New reconstruction algorithm

- Future
  - τ neural net to improve MH results
  - Neutron tagging for ν/anti-ν
  - Energy correction with tagged n
  - Improvement of PID using timing info.

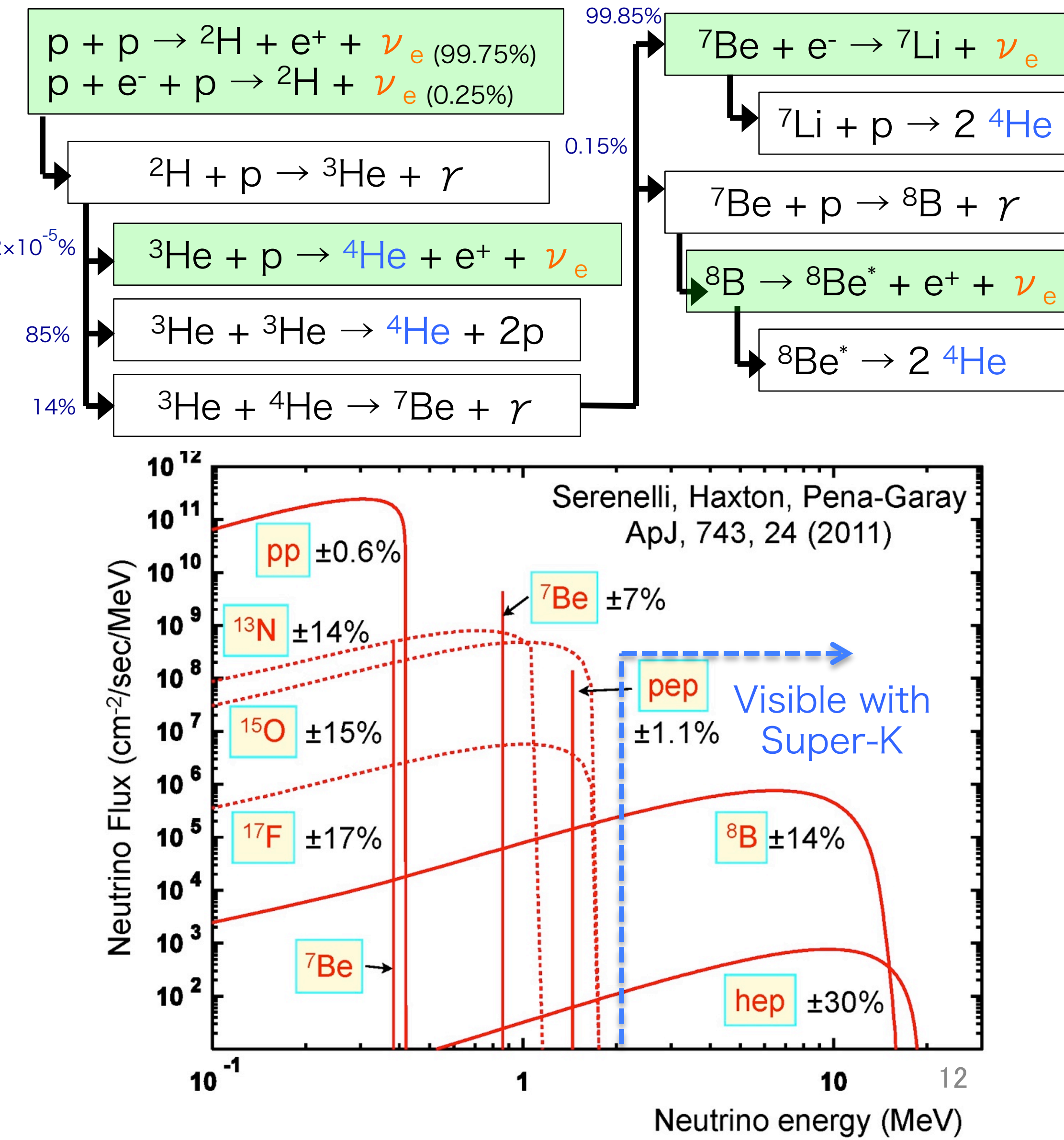




Solar Neutrino

- The **Sun** is burning with nuclear fusion reactions, called pp-chain and CNO-cycle, emitting neutrinos.
- Only neutrinos can bing out the information of “today’s” status of solar center.
- Their fluxes are predicted by the standard solar model (SSM).
- Super-K is sensitive to B8 (and hep) neutrinos.
  ~20 events/day

pp-chain & ν Energy specturm



Physics of Solar Neutrino

Spectrum distortion

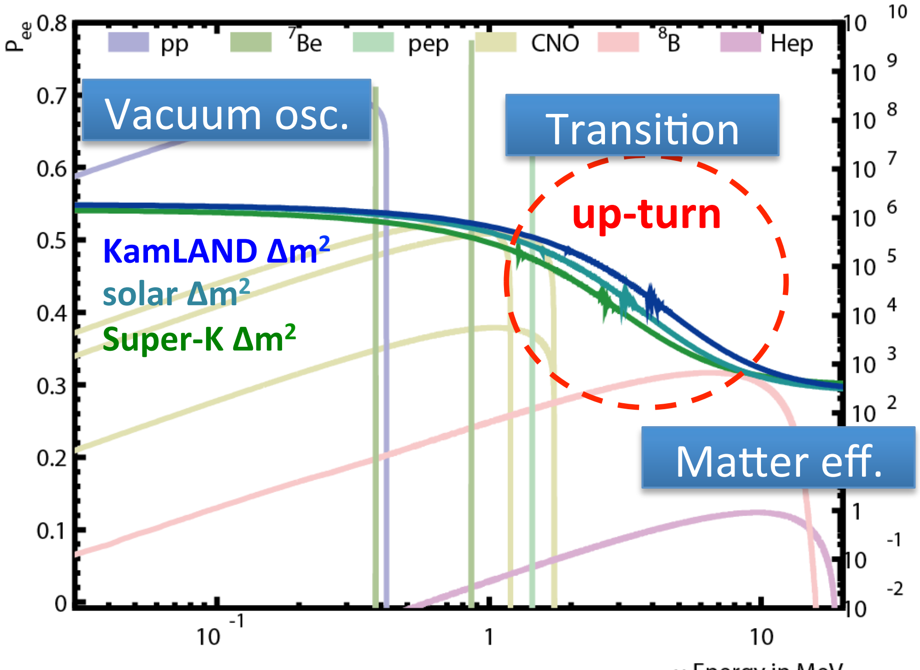
Super-K can search for the spectral upturn expected by neutrino oscillation MSW effect.
New physics beyond SM can exist. e.g. sterile ν, NSI

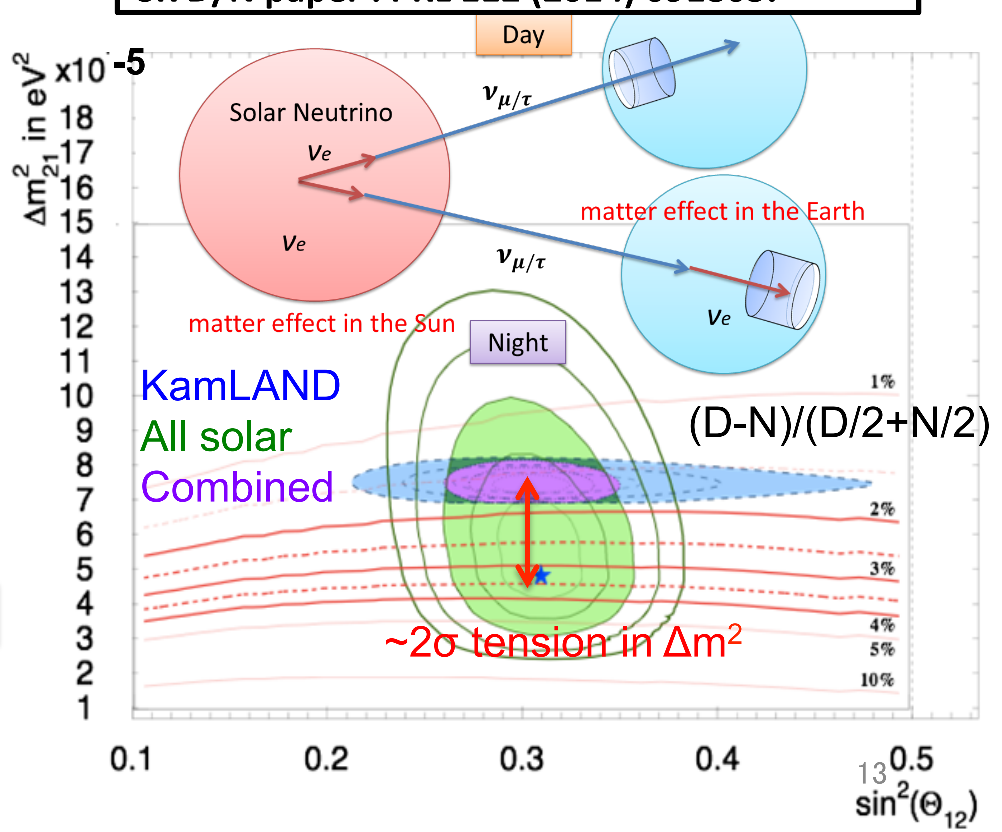
Day/Night flux asymmetry

Due to the earth matter effect, electron neutrino is regenerated.
The ^{8}B flux during night is higher than that during day.

SK D/N paper : PRL 112 (2014) 091805.

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$





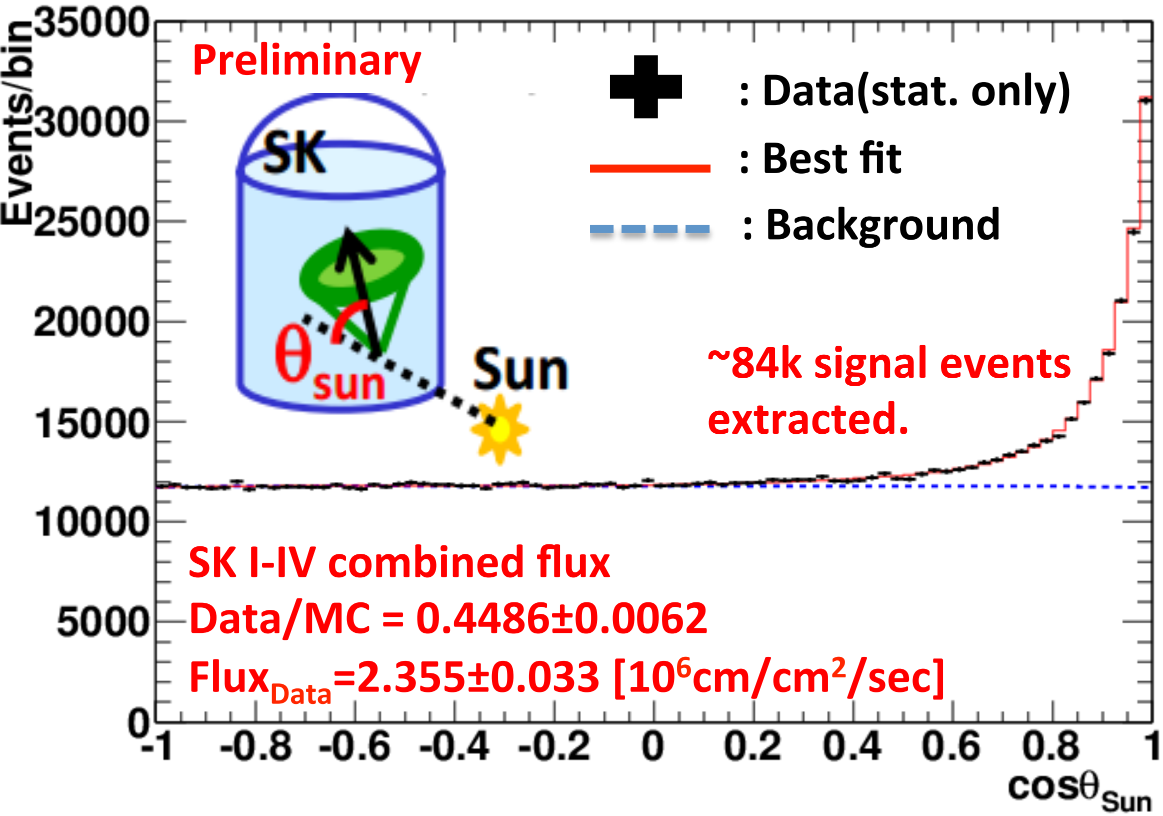
Recent Updates of Solar ν

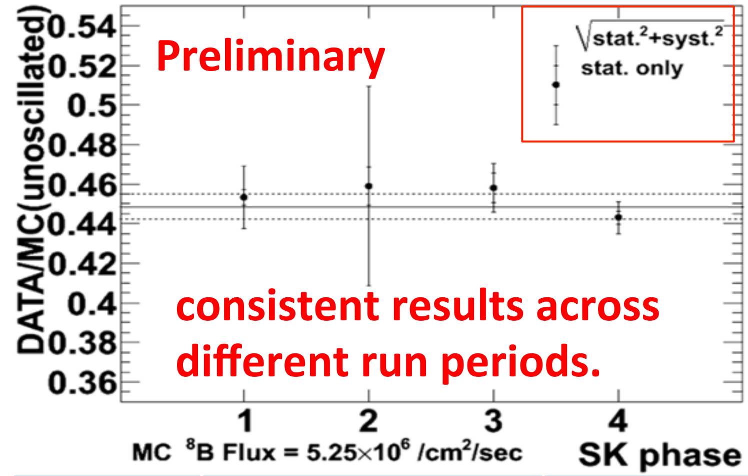
- SK-IV solar neutrino analysis result is published:
  PRD 94 (2016) 052010 (arXiv: 1606.07538, SK-IV 1664 days)

- In following updates, SK-IV 2365 days sample is used.
- Trigger threshold is lowered in May 2015.
  - Detection efficiency at 3.5-4.0 MeV_{kin} : ~84% → 99%.

- Energy spectrum and flux
- Oscillation analysis with updated spectrum and flux
- Systematic uncertainty on D/N analysis is under updating.

Observed solar ν signal

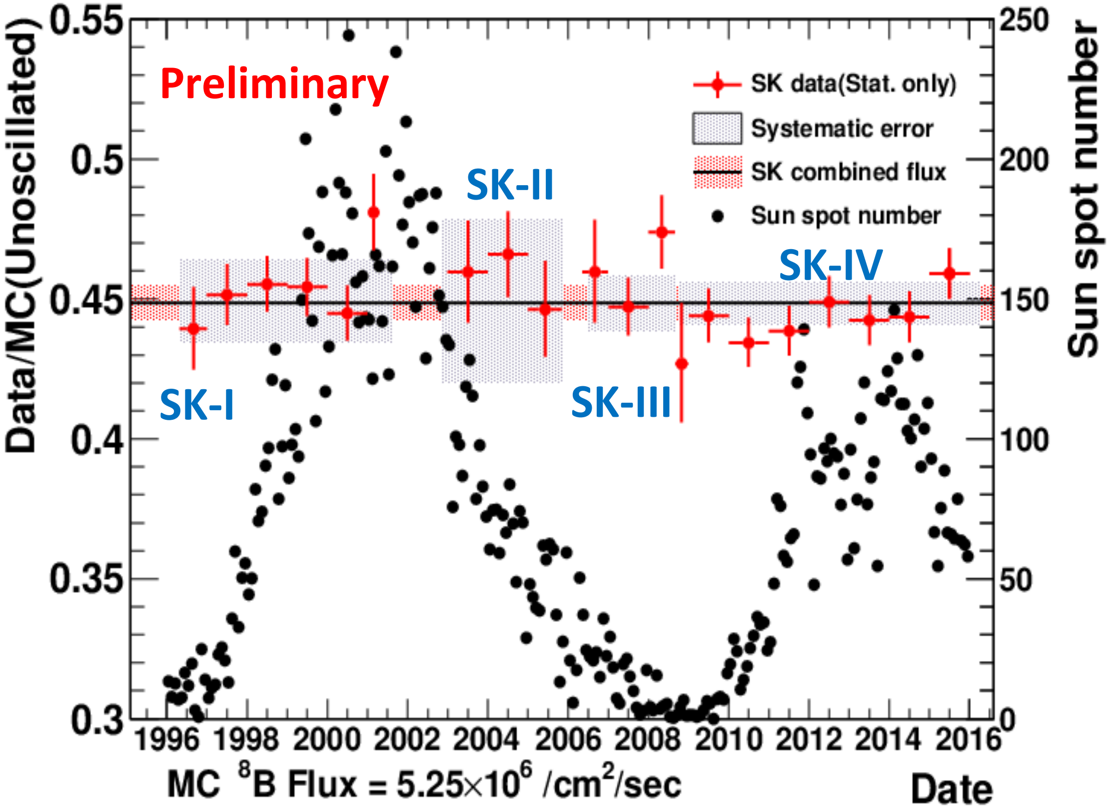




SK phase	Energy threshold [MeV(kin)]	Live time [day]
SK I	4.5-19.5	1496
SK II	6.5-19.5	791
SK III	4.0-19.5	548
SK IV	3.5-19.5	2365

- Data/MC(unoscillated) = 0.4486±0.0062.
- Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun in all SK phases.

^8B solar ν flux yearly plot



Sunspot #: http://www.sidc.be/silso/datafiles

Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

Solar activity cycle

The solar activity cycle of ~11 years is observed with sun spot numbers.

SK has observed the solar neutrino for ~19 years, i.e. > 1.5 cycles.

For the constant flux assumption, $\chi^2 = 15.52/19$ D.O.F.

The probability is 68.9%. (preliminary)

No significant correlation with the solar activity is seen.

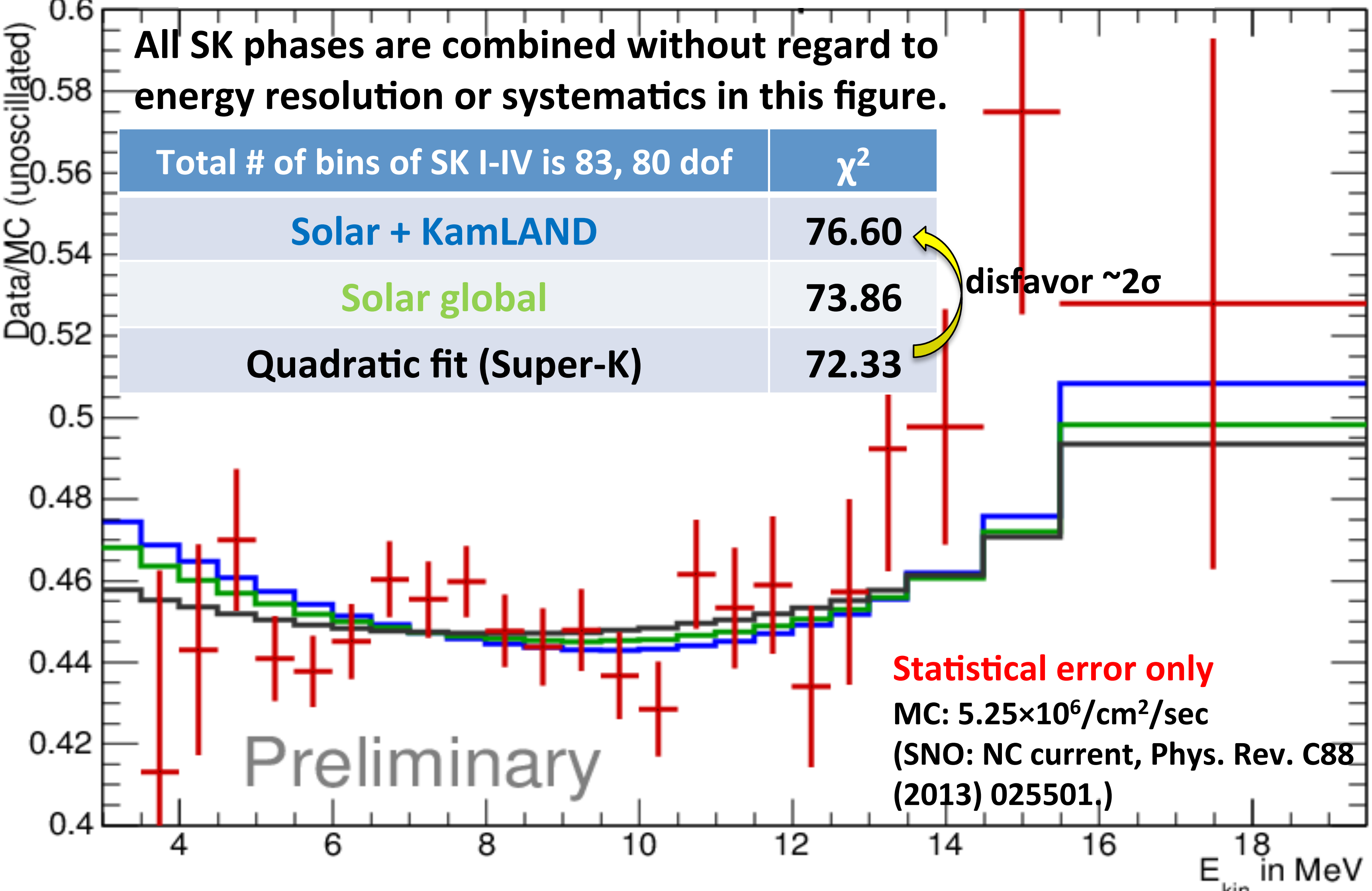
Recoil electron spectrum for all SK phases

SKI/II/III + SK-IV 2365 days (5200 days in total.)

All SK phases are combined without regard to energy resolution or systematics in this figure.

Total # of bins of SK I-IV is 83, 80 dof	χ^2
Solar + KamLAND	76.60
Solar global	73.86
Quadratic fit (Super-K)	72.33

disfavor ~2σ



Statistical error only

MC: 5.25×10^6/cm^2/sec

(SNO: NC current, Phys. Rev. C88 (2013) 025501.)

MSW prediction with Solar+KamLAND is disfavored by about 2σ.

Global oscillation analysis input

- **SK**
  - SK-I 1496 days, Spectrum : 4.5-19.5MeV(kin.) + D/N : $E_{kin} \geqq 4.5$MeV
  - SK-II 791 days, Spectrum : 6.5-19.5MeV(kin.) + D/N : $E_{kin} \geqq 7.0$MeV
  - SK-III 548 days, Spectrum : 4.0-19.5MeV(kin.) + D/N : $E_{kin} \geqq 4.5$MeV
  - SK-IV 2365 days, Spectrum : 3.5-19.5MeV(kin.) + D/N (1664 days) : $E_{kin} \geqq 4.5$MeV

arXiv: 1606.07538.
Updated from PRL 112 (2014) 091805.

- **SNO**
  - Parameterized analysis (c0,c1,c2,a0,a1) of all SNO phased published in Phys. Rev. C88 (2013) 025501.

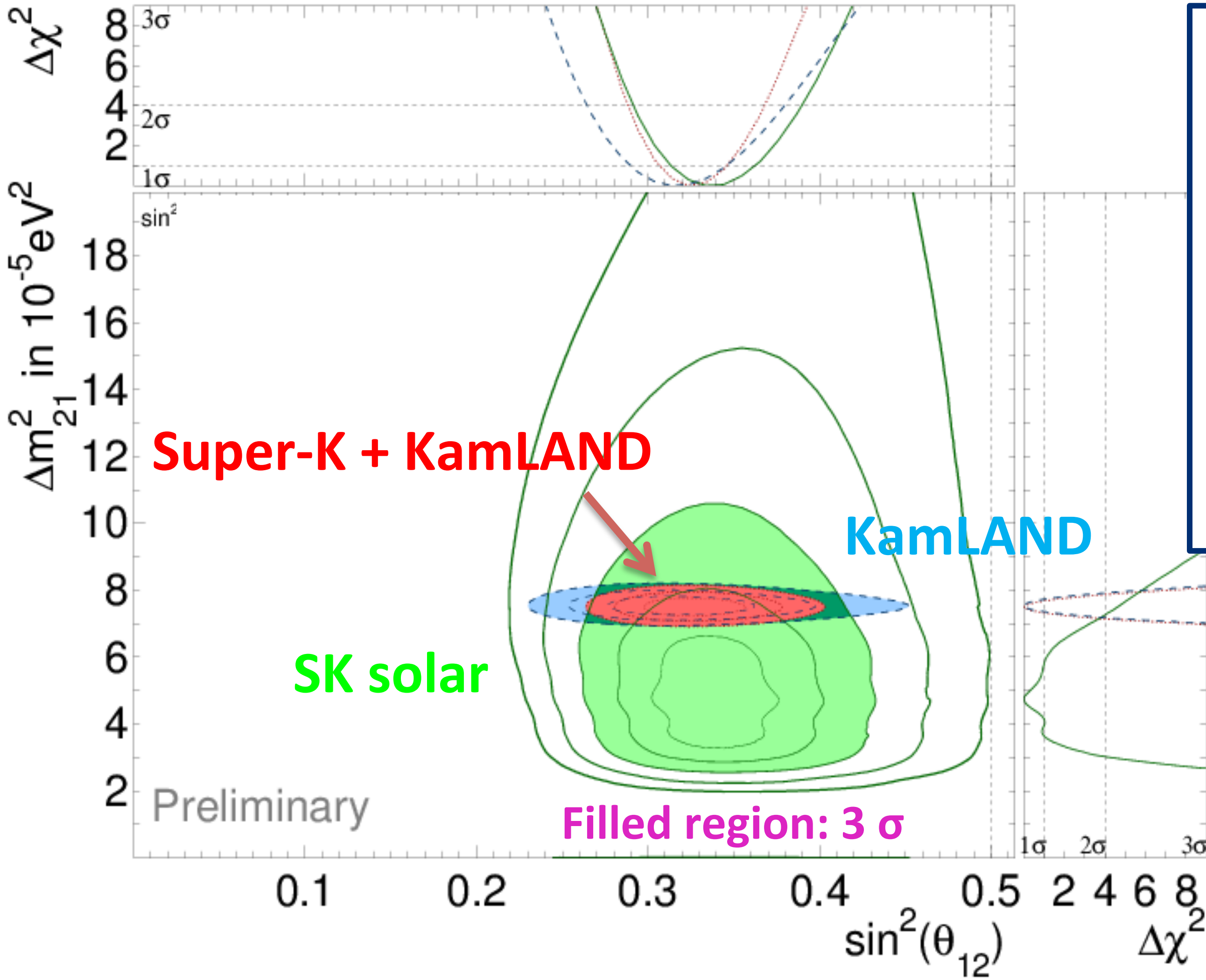
The same method is applied to both SK and SNO with a_0 and a_1 to LMA expectation.

- **Radiochemical (Ga, Cl)**
  - Ga rate 66.1±3.1 SNU (All Ga global), Phys. Rev. C80 (2009) 015807.
  - Cl rate 2.56±0.23 SNU, Astrophys. J. 496 (1988) 505.
- **Borexino**
  - ^{7}Be flux, Phys. Rev. Lett. 107 (2011) 141302.

Does NOT include Borexino pp 2014. Nature 512 (2014) 383.

- **KamLAND reactor**
  - 3-flavor analysis , Phys. Rev. D88 (2013) 033001.
- **^{8}B spectrum**
  - Winter 2006, Phys. Rev. C73 (2006) 025503.

Super-K vs. KamLAND



$$\sin^2\theta_{12} = 0.337^{+0.027}_{-0.023}$$

$$\Delta m^2_{21} = 4.74^{+1.40}_{-0.80}$$

$$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$$

$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$

$$\sin^2\theta_{12} = 0.326^{+0.022}_{-0.019}$$

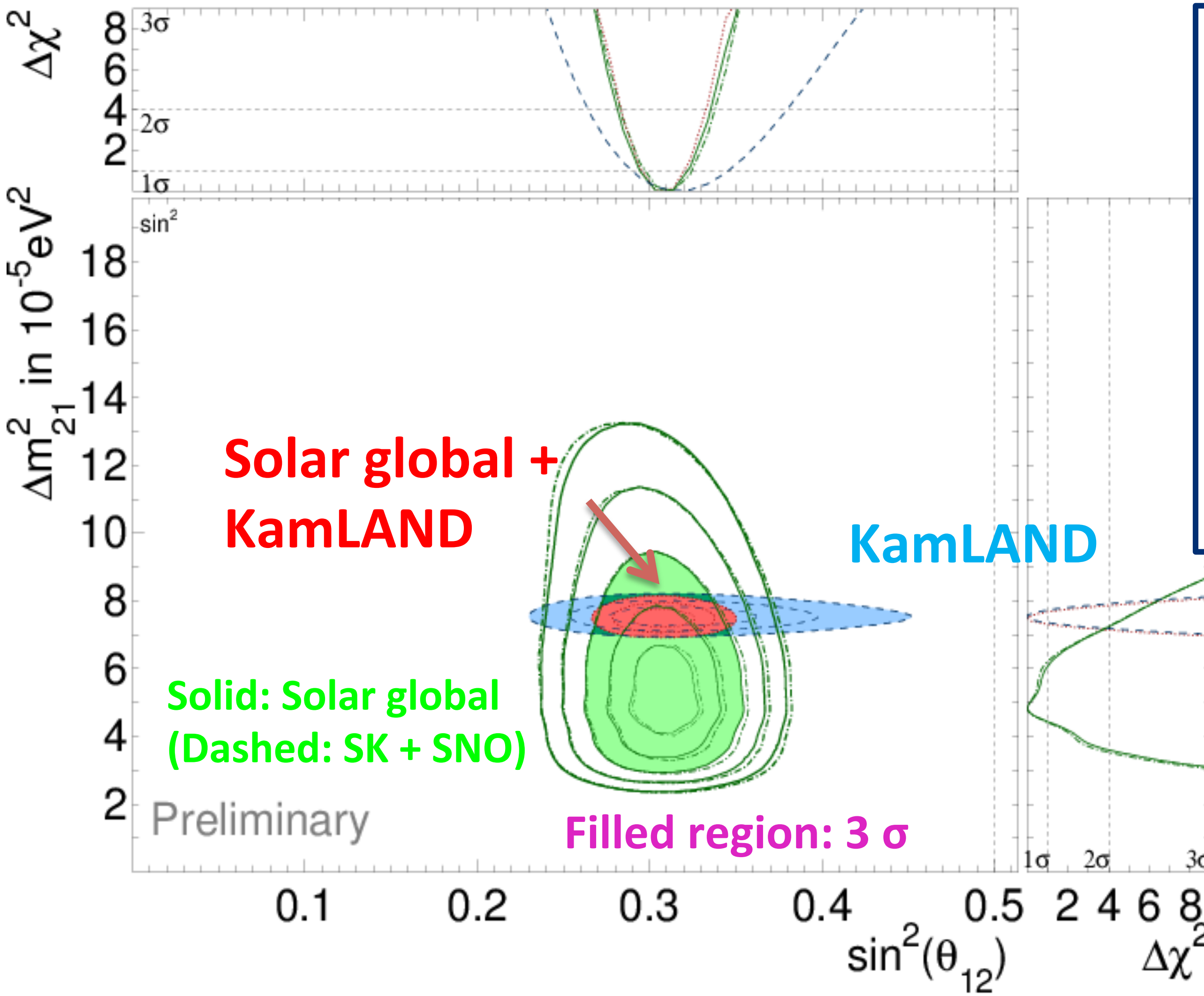
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.17}$$

The unit of Δm^2 is $10^{-5}eV^2$.

Constrained with $\sin^2\theta_{13} = 0.0219 \pm 0.0014$ from SBL reactor exp.

SK result uniquely selects the LMA solution by more than 3σ.
SK significantly contributes to the measurement of $\sin^2\theta_{12}$.

Solar Global vs. KamLAND



$\sin^2\theta_{12} = 0.311 \pm 0.014$

$\Delta m^2_{21} = 4.84^{+1.26}_{-0.60}$

$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$

$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$

$\sin^2\theta_{12} = 0.308 \pm 0.012$

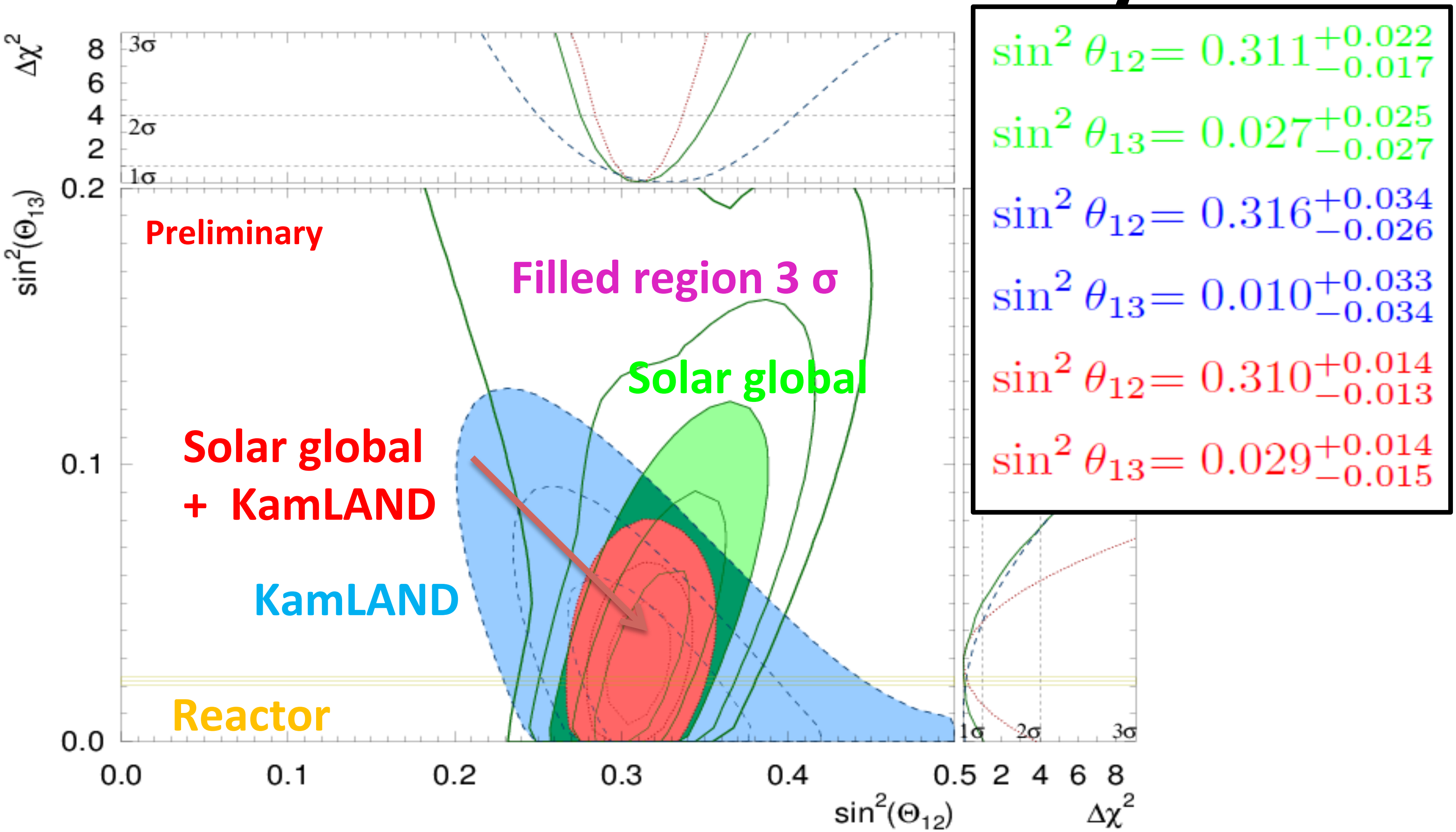
$\Delta m^2_{21} = 7.49^{+0.19}_{-0.18}$

The unit of Δm^2 is 10^{-5}eV^2.

Constrained with $\sin^2\theta_{13} = 0.0219 \pm 0.0014$ from SBL reactor exp.

The solar global result favor a lower Δm^2_{21} value than KamLAND's by more than 2σ.

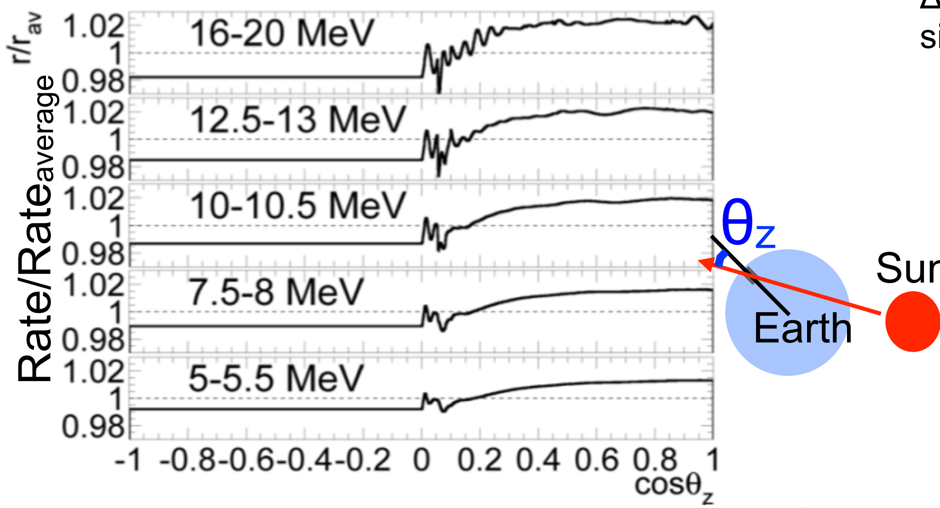
3-flavor oscillation analysis



Non-zero θ_{13} is obtained by 2σ level, from Solar global + KamLAND result.
The result is consistent with that of reactor.

Day/Night asymmetry(A_{DN})

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

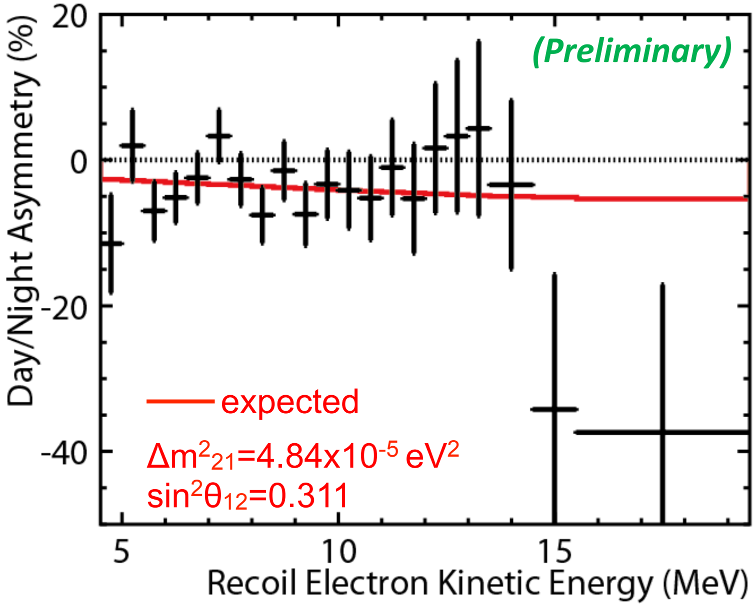


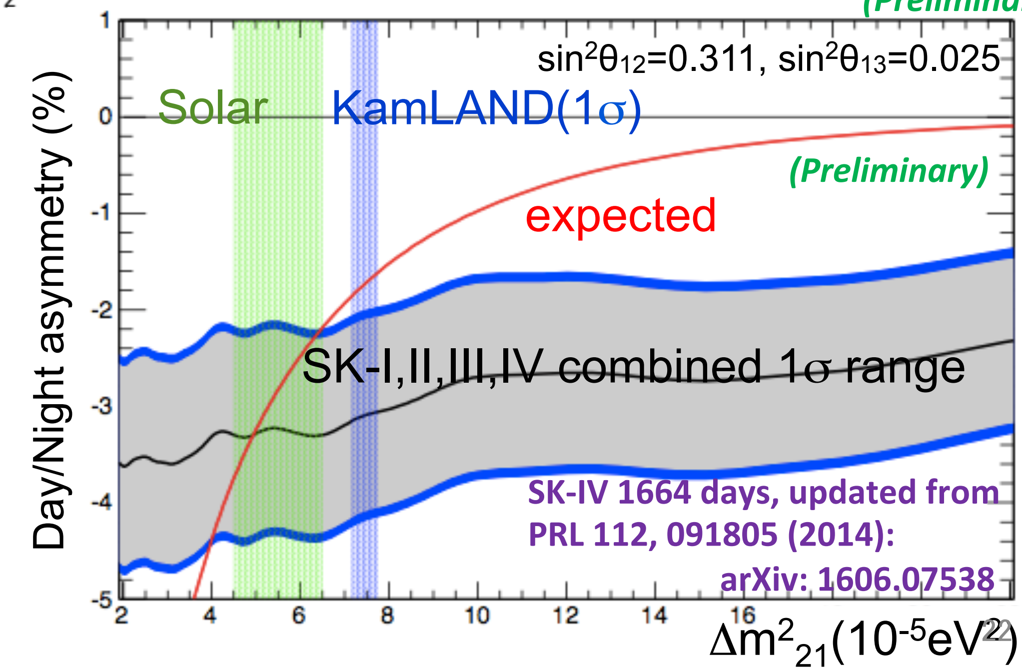
For solar global parameter:
Δm^2_{21}=4.84x10^{-5} eV^2
$\sin^2\theta_{12}$=0.311

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

	A^{fit}_{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

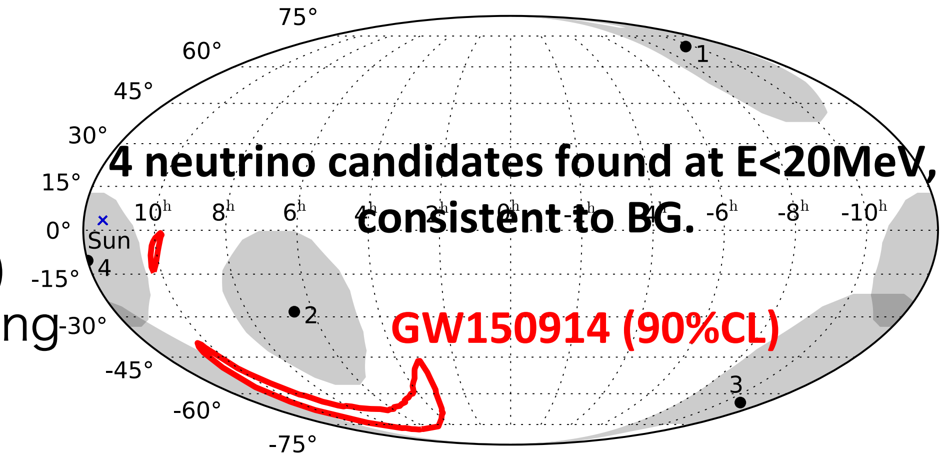
(Preliminary)





Other Related Results, Updates

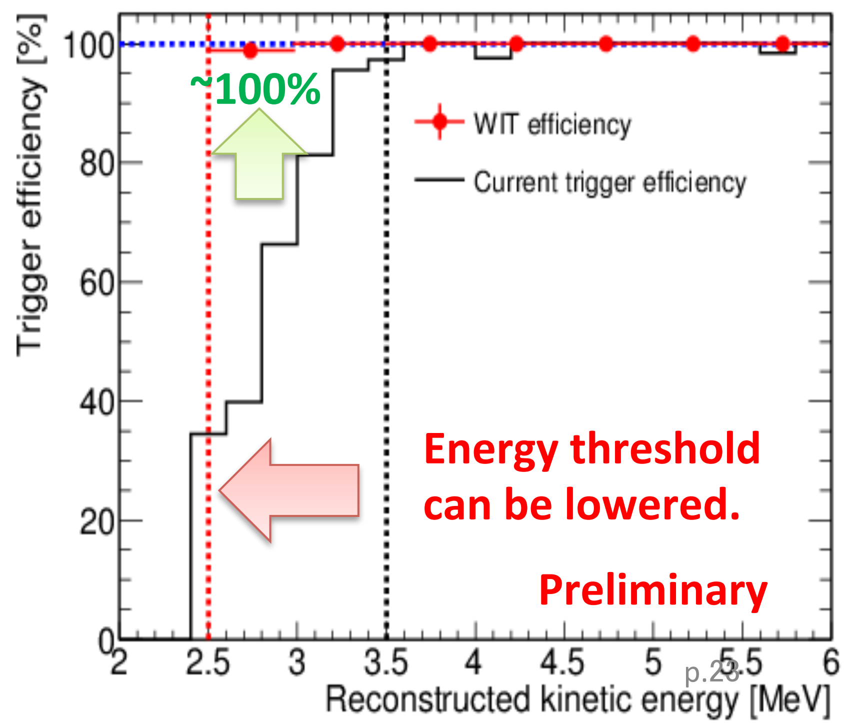
- Recent publications
  Search for νs from GW events
  (arXiv:1608.08745, submitted to ApJ)
  Spallation measurement w/ n tagging
  (PRD 93 (2016) 012004)



0 neutrino candidates for GW151226.

- Preliminary study and Future
  Intelligent trigger for lower energy.
  → Spectral upturn study with $2.5\mathrm{MeV}_{kin}$ threshold.

  Detector upgrade by 0.1% **Gd** loading.
  → **SK-Gd** (aiming upgrade at 2018)
  → Neutron tagging with Gd(n,g) reaction
  → Significant BG reduction for supernova relic neutrino search, etc.



Nucleon Decay at Super-K

- Testing baryon number violation is an essential and high priority objective of particle physics.
  - Predicted by beyond-SM, like GUT.
- SK has the world's best sensitivity on nucleon lifetime.
  - No evidence so far.
  - We keep discovery potential and increase statistics.

Decay mode	$\lvert\Delta(B-L)\rvert$	Lifetime lower limit at 90% CL (years)	Paper (previous result)
$p \to e^+\pi^0$	0	(*) 1.67×10^{34}	(PRD 85, 112001 (2012))
$p \to \nu K^+$	$0(\bar{\nu})$, $2(\nu)$	6.61×10^{33}	(PRD 90, 072005 (2014))
$p \to \mu^+\pi^0$	0	(*) 7.78×10^{33}	(PRD 85, 112001 (2012))
$p \to e^+/\mu^+(\eta,\rho,\omega)$	0	$(0.04\text{-}4.2) \times 10^{33}$	PRD 85, 112001 (2012)
$p \to \mu^+K^0$	0	1.6×10^{33}	PRD 86, 012006 (2012)
$n \to \bar{\nu}\pi^0$, $p \to \bar{\nu}\pi^+$	0	1.1×10^{33}, 3.9×10^{32}	PRL 113, 121802 (2014)
$p \to e^+/\mu^+\nu\nu$	$0(\bar{\nu}\nu)$, $2(\nu\nu,\bar{\nu}\bar{\nu})$	$1.7/2.2 \times 10^{32}$	PRL 113, 101801 (2014)
$p \to e^+/\mu^+X$	?	$7.9/4.1 \times 10^{32}$	arXiv:1508.05530, accepted by PRL
$n \to \nu\gamma$	$0(\bar{\nu})$, $2(\nu)$	5.5×10^{32}	arXiv:1508.05530, accepted by PRL
$pp \to K^+K^+$	2	1.7×10^{32}	PRL 112, 131803 (2014)
$pp \to \pi^+\pi^+$, $pn \to \pi^+\pi^0$, $nn \to \pi^0\pi^0$	2	7.22×10^{31}, $1{,}70 \times 10^{32}$, 4.04×10^{32}	PRD 91, 072009 (2015)
$np \to (e^+,\mu^+,\tau^+)\nu$	$0(\bar{\nu})$, $2(\nu)$	$(0.22\text{-}5.5) \times 10^{32}$	arXiv:1508.05530, accepted by PRL
$n\text{-}\bar{n}$ oscillation	2	1.9×10^{32}	PRD 91, 072006 (2015)

S.Mine, TAUP 2015.

Summary

- **Atmospheric neutrino**
  - Tau neutrino appearance update: significance of signal 4.6σ.
  - Mass hierarchy: stronger preference to NH.

  $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH}$ = -4.3 (SK only, θ_{13} fix), -5.2 (SK+T2K, θ_{13} fix)
  - δ_{CP} and θ_{23} octant: slightly weaker constraints than before

- **Solar neutrino**
  - SK spectrum and D/N data favor a lower Δm^2_{21} value than KamLAND's by more than 2σ and mostly determine this parameter in the solar ν oscillation fit.
  - SK has started data taking at energy threshold of about 2.5 MeV_{kin} and will continue to push into the transition region.

- **Nucleon decay**
  - No evidence of nucleon decay so far.
  - We'll increase statistics and improve sensitivity by sophisticated reconstruction algorithm, reducing sys. errors.

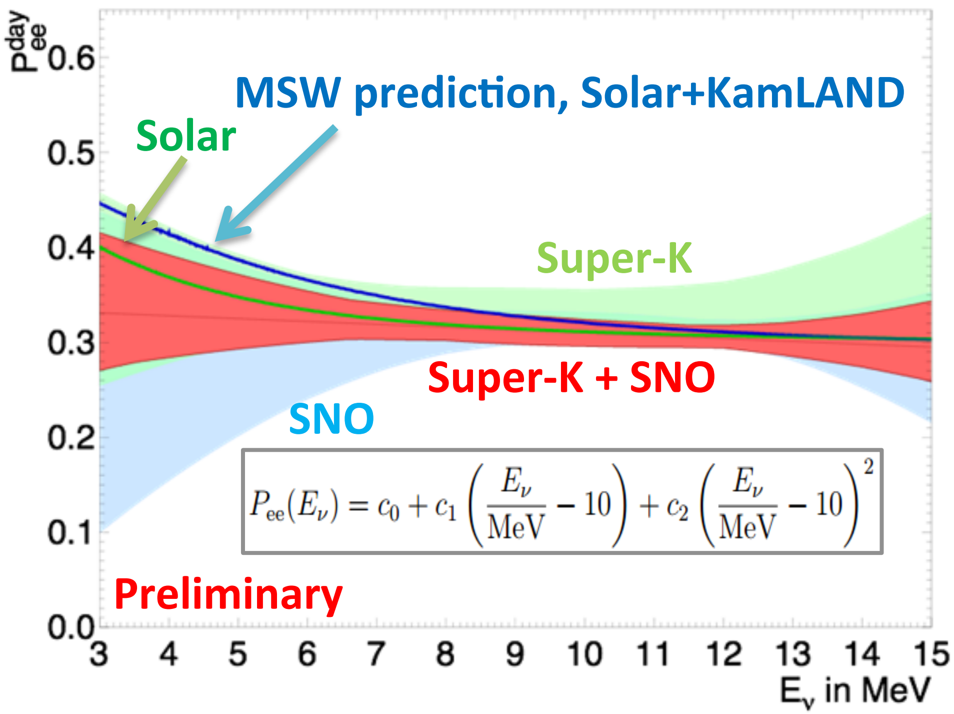
Super-Kamiokande Collaboration

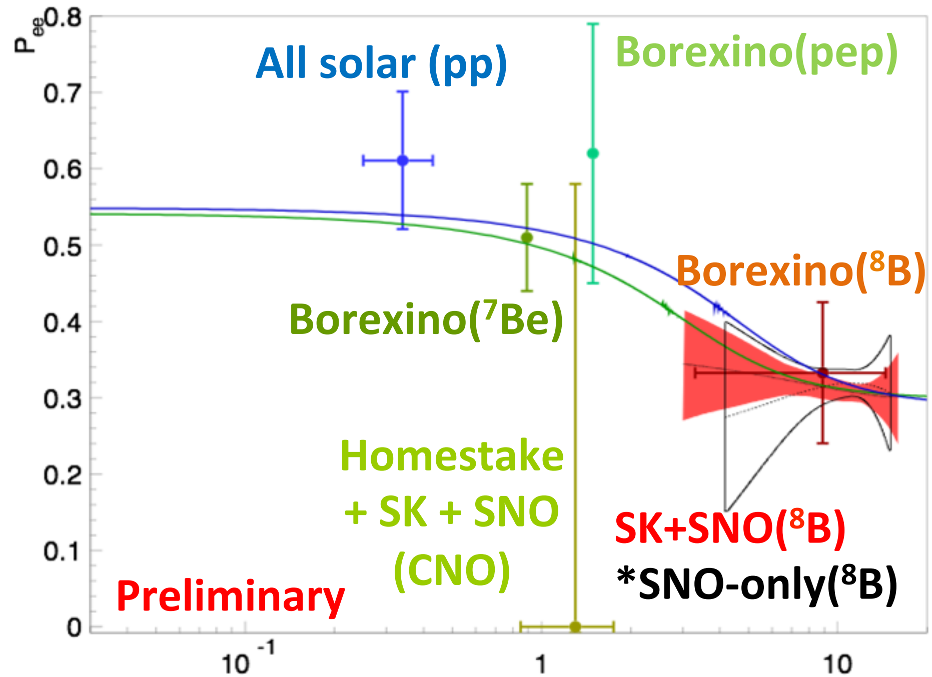
1 Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
2 RCCN, ICRResearch, Univ. of Tokyo, Japan
3 University Autonoma Madrid, Spain
4 University of British Columbia, Canada
5 Boston University, USA
6 Brookhaven National Laboratory, USA
7 University of California, Irvine, USA
8 California State University, 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 Imperial College London, UK
16 KEK, Japan
17 Kobe University, Japan
18 Kyoto University, Japan
19 University of Liverpool, UK
20 Miyagi University of Education, Japan
21 National Centre For Nuclear Research, Poland
22 Okayama University, Japan
23 Osaka University, Japan
24 University of Oxford, UK
25 Queen Mary University of London, UK
26 University of Regina, Canada
27 Seoul National University, Korea
28 University of Sheffield, UK
29 Shizuoka University of Welfare, Japan
30 STE, Nagoya University, Japan
31 Sungkyunkwan University, Korea
32 SUNY, Stony Brook, USA
33 Tokai University, Japan
34 University of Tokyo, Japan
35 Kavli IPMU (WPI), University of Tokyo, Japan
36 Dep. of Phys., University of Toronto, Canada
37 TRIUMF, Canada
38 Tsinghua University, China
39 University of Washington, USA

~150 collaborators, 39 institutes, 8 countries.

Appendix

Allowed survival probability

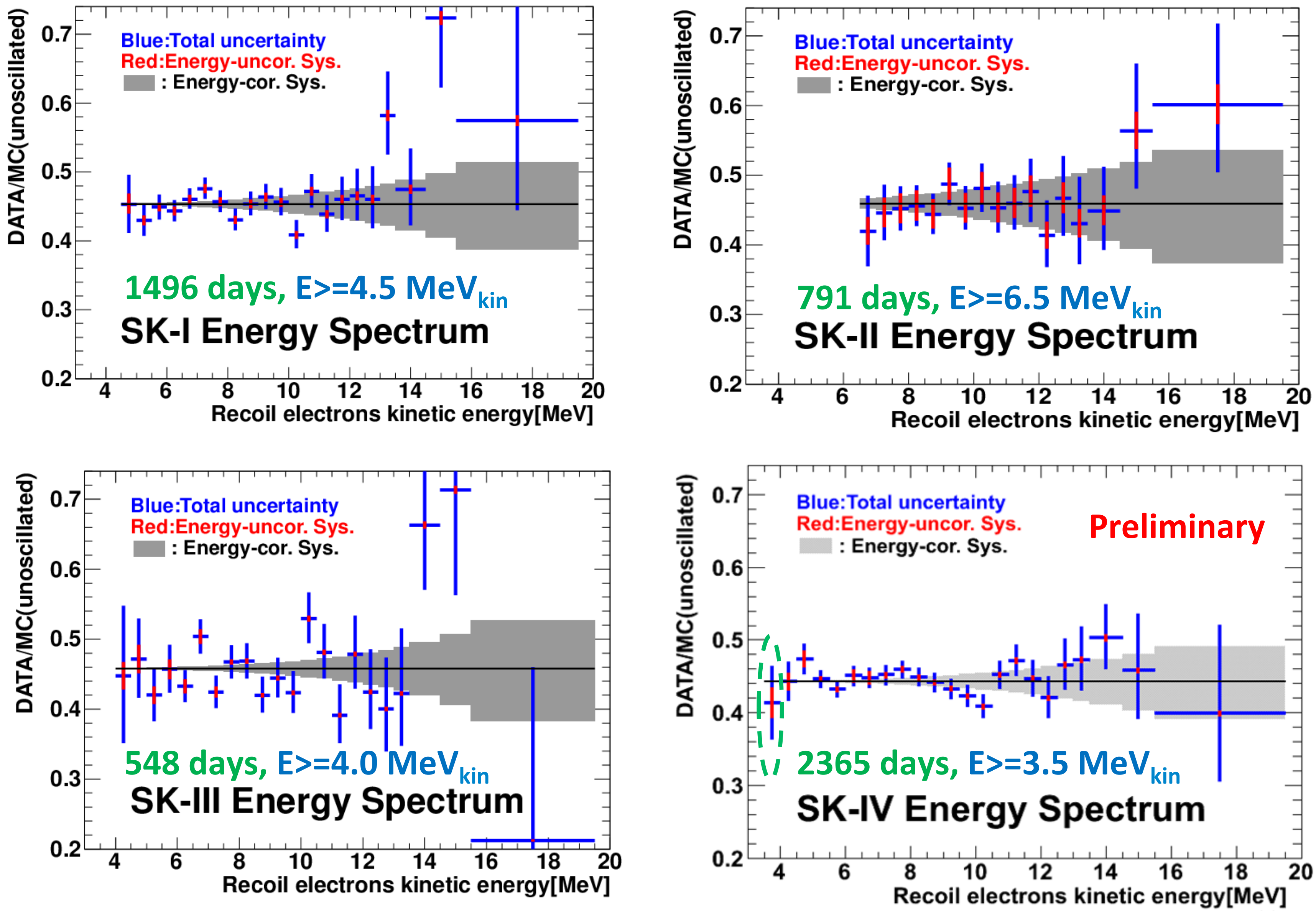




*Phys. Rev. C88 (2013) 025501.

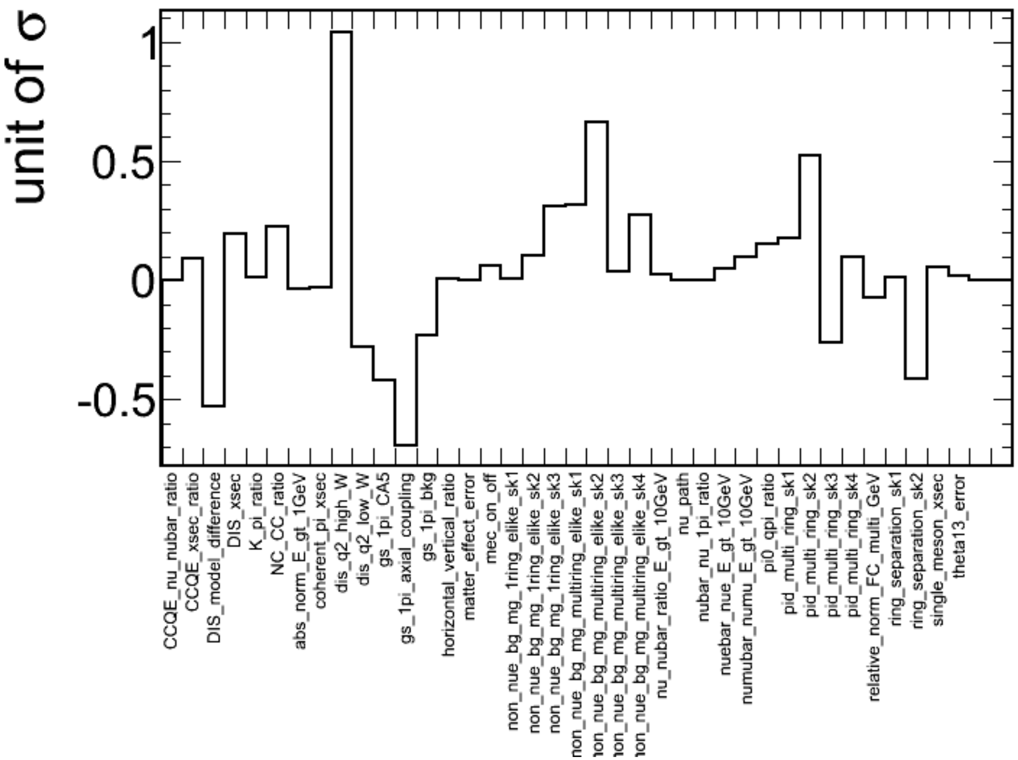
- Neutrino energy spectrum was de-convoluted from the recoil energy spectrum.
- Super-K result is more stringent below 7,5 MeV, while SN is above 11.5 MeV.
- Super-K gives the world's strongest constraints on the shape of the survival probability in the transition region between vacuum oscillations and MSW resonance.

Recoil electron spectrum of each SK phase

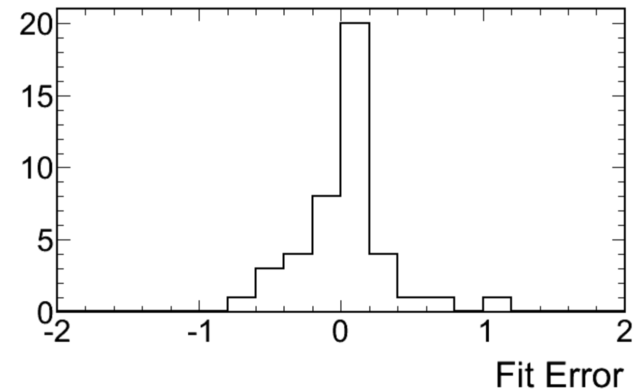


MC: 5.25×10^{6}/cm^{2}/sec (SNO: NC current, Phys. Rev. C88 (2013) 025501.)

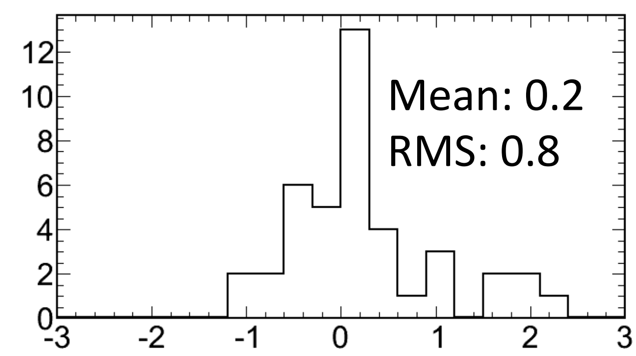
Fitted systematic errors in tau analysis



Fitted value of systematic terms, distributed around 0.



Fitted deviation in unit of σ of systematic errors



$$\frac{error_{fit} - mean}{sigma_{input} - sigma_{fit}}$$

$\nu_\mu \rightarrow \nu_e$ oscillation in atm. ν

Okumura, TAUP 2013.

ν_e oscillation due to non-zero θ_{13} provides atm. nu. observation to investigate mass hierarch effect

$\nu_\mu \rightarrow \nu_e$ osc. probability in matter:

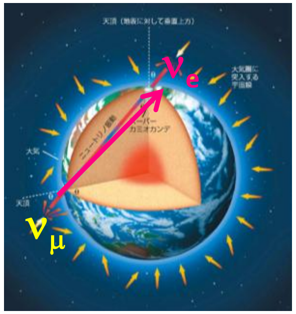
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}^M \sin^2\left(\frac{1.27\Delta m^2_{31,M}L}{E}\right)$$

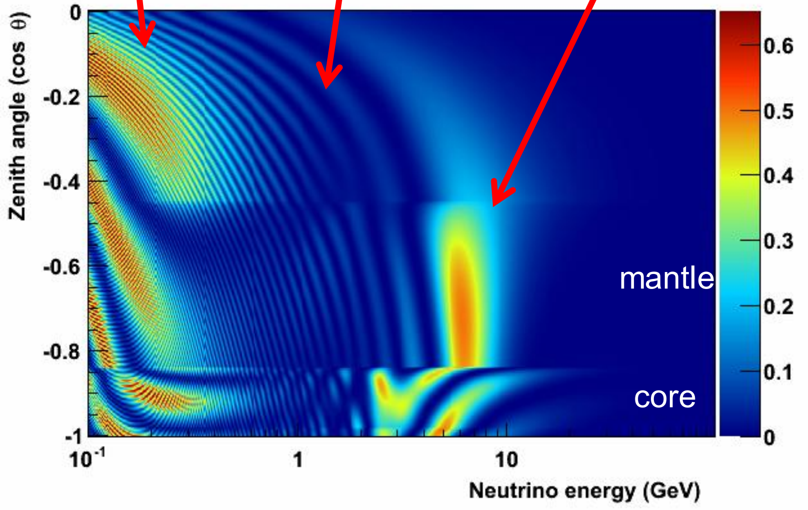
$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A_{CC}/\Delta m^2_{31}\right)^2 + \sin^2 2\theta_{13}}$$

$\sin^2\theta_{13,M}$ has resonance feature when $A_{CC} \sim \Delta m^2_{31}\cos 2\theta_{13}$ $\quad (A_{CC} = 2\sqrt{2}G_F N_e E)$

$\nu_\mu \rightarrow \nu_e$ resonance in multi-GeV region

$P(\nu_\mu \rightarrow \nu_e)$ of earth-throughgoing ν :





Occurrence of resonance feature depends on neutrino type and mass hierarchy:

Okumura, TAUP 2013.

$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A_{CC}/\Delta m_{31}^2\right)^2 + \sin^2 2\theta_{13}}$$

In case of Inverted hierarchy:

$$\Delta m^2 \rightarrow -\Delta m^2$$

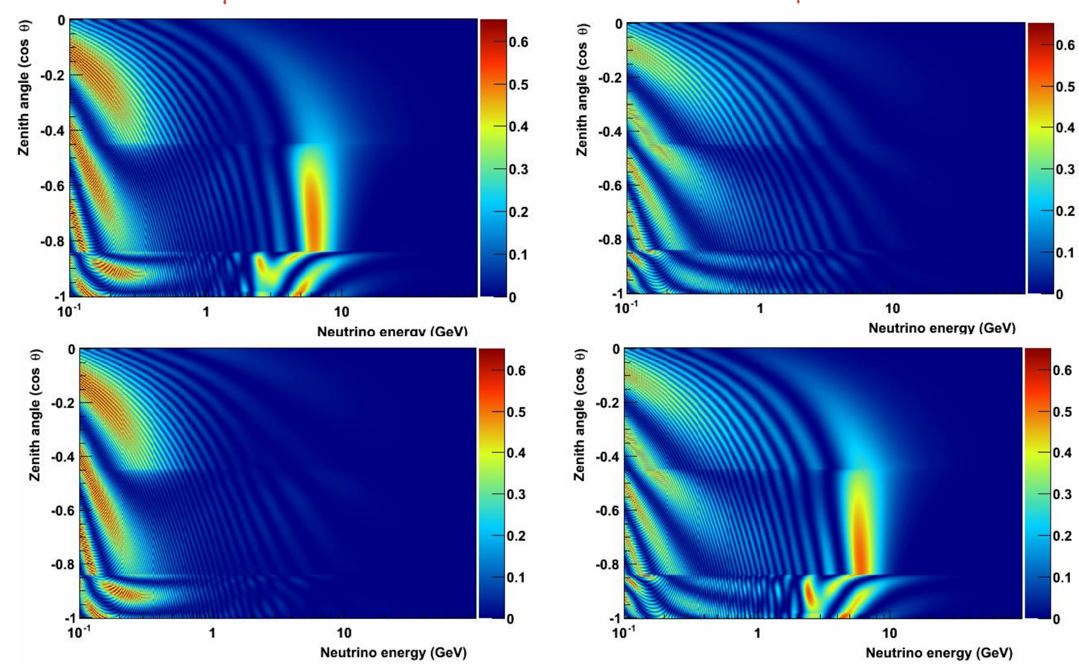
In case of anti neutrino :

$$A_{CC} \rightarrow -A_{CC}$$

$\nu_\mu \rightarrow \nu_e$ anti-$\nu_\mu \rightarrow$ anti-ν_e

Normal hierarchy

Inverted hierarchy



Possible to determine mass hierarchy if we identify in which neutrino (ν_e or anti- ν_e) enhancement is occurring

$\nu_\mu \rightarrow \nu_e$ oscillation in atm. ν Okumura, TAUP 2013.

ν_e oscillation due to non-zero θ_{13} provides atm. nu. observation to investigate mass hierarch effect

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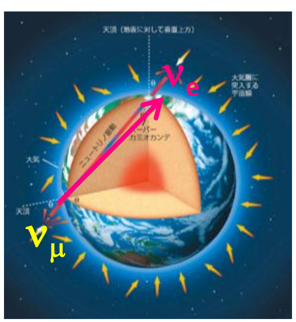

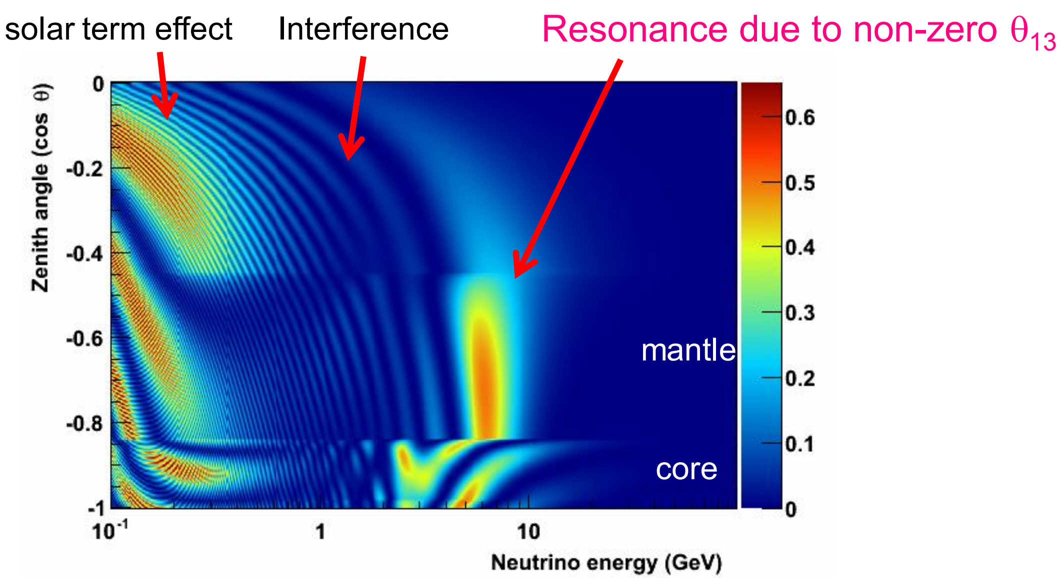

Occurrence of resonance feature depends on neutrino type and mass hierarchy:

Okumura, TAUP 2013.

$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} - A_{CC}/\Delta m_{31}^2\right)^2 + \sin^2 2\theta_{13}}$$

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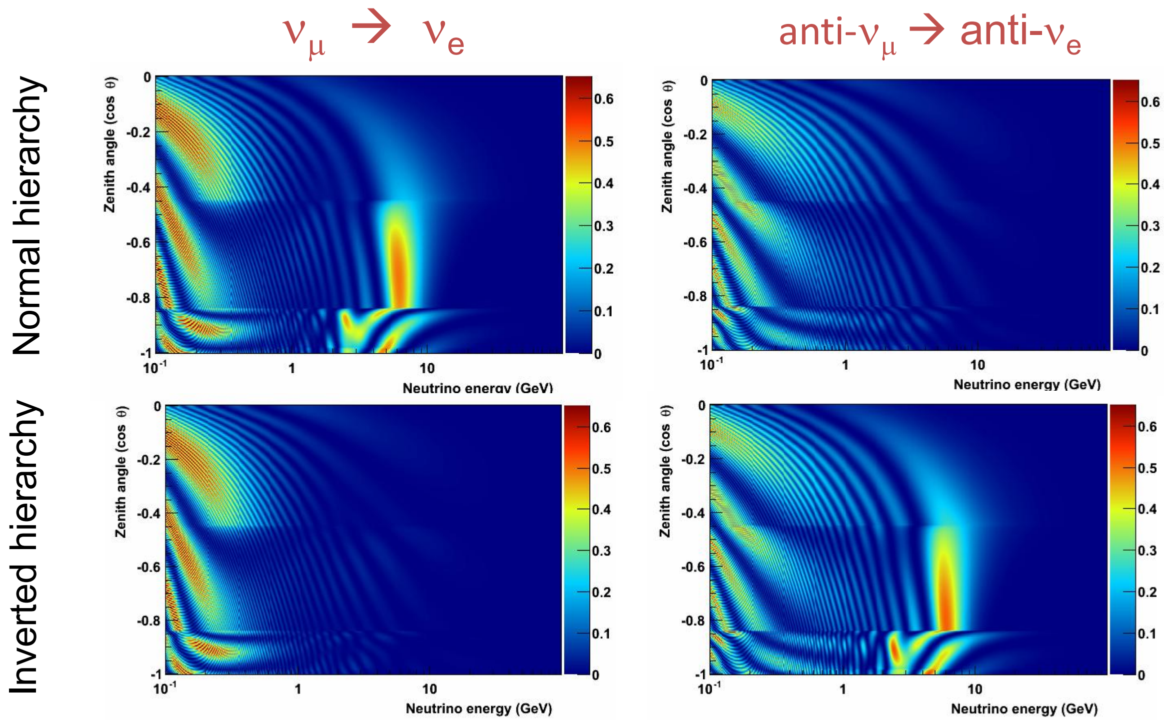
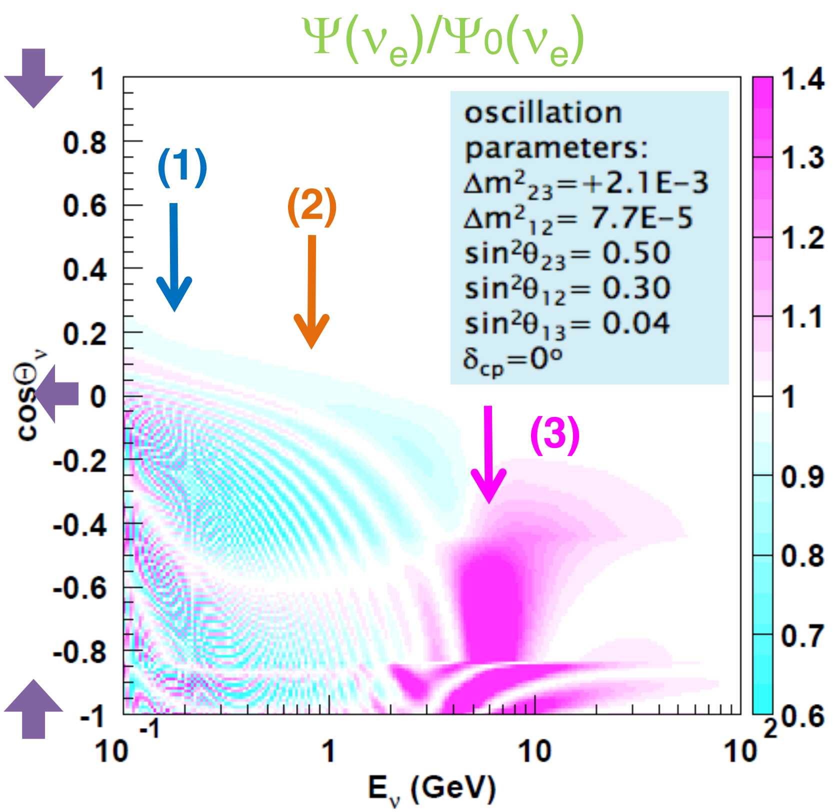


Possible to determine mass hierarchy if we identify in which neutrino (ν_e or anti- ν_e) enhancement is occurring

θ_{23} and δ_{CP} effects

Okumura, TAUP 2013.

ν_e flux ratio of
$\sin^2\theta_{13}$ =0.04 and θ_{13} =0



Pares and Smirnov
hep-ph/039312

$$\Psi(\nu_e)/\Psi_0(\nu_e) - 1 \cong$$

$$P_2(r \cdot c_{23}^2 - 1) \quad \text{(1)}$$

$$-r \cdot \tilde{s}_{13} \cdot \tilde{c}_{13} \cdot \sin 2\theta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2) \quad \text{(2)}$$

$$+2 \cdot \tilde{s}_{13}^2(r \cdot s_{23}^2 - 1) \quad \text{(3)}$$

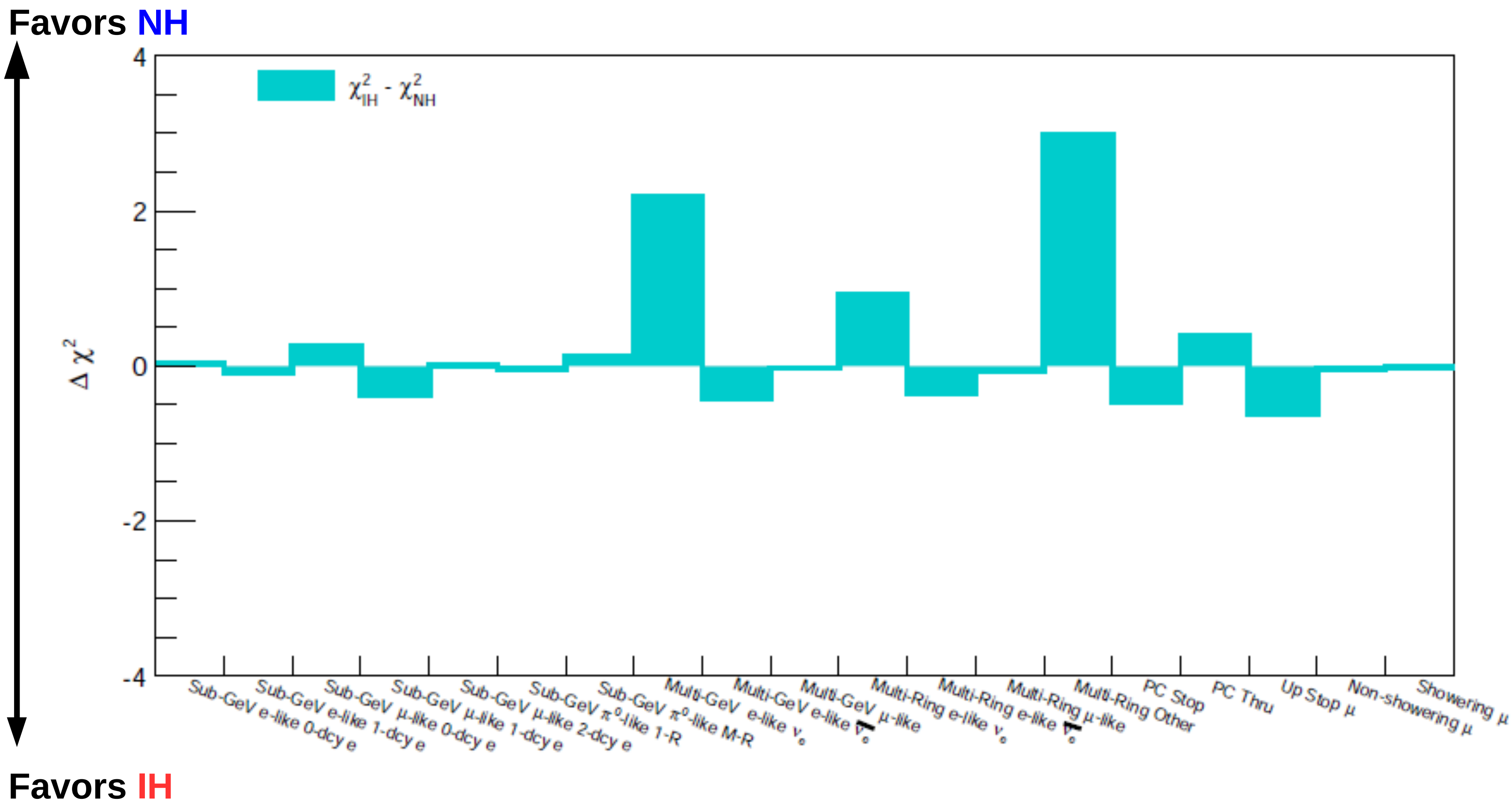
r : νμ/νe flux ratio (~2 at low energy)

(1) driven by Δm^2_{sol} →
sensitive to θ_{23} octant

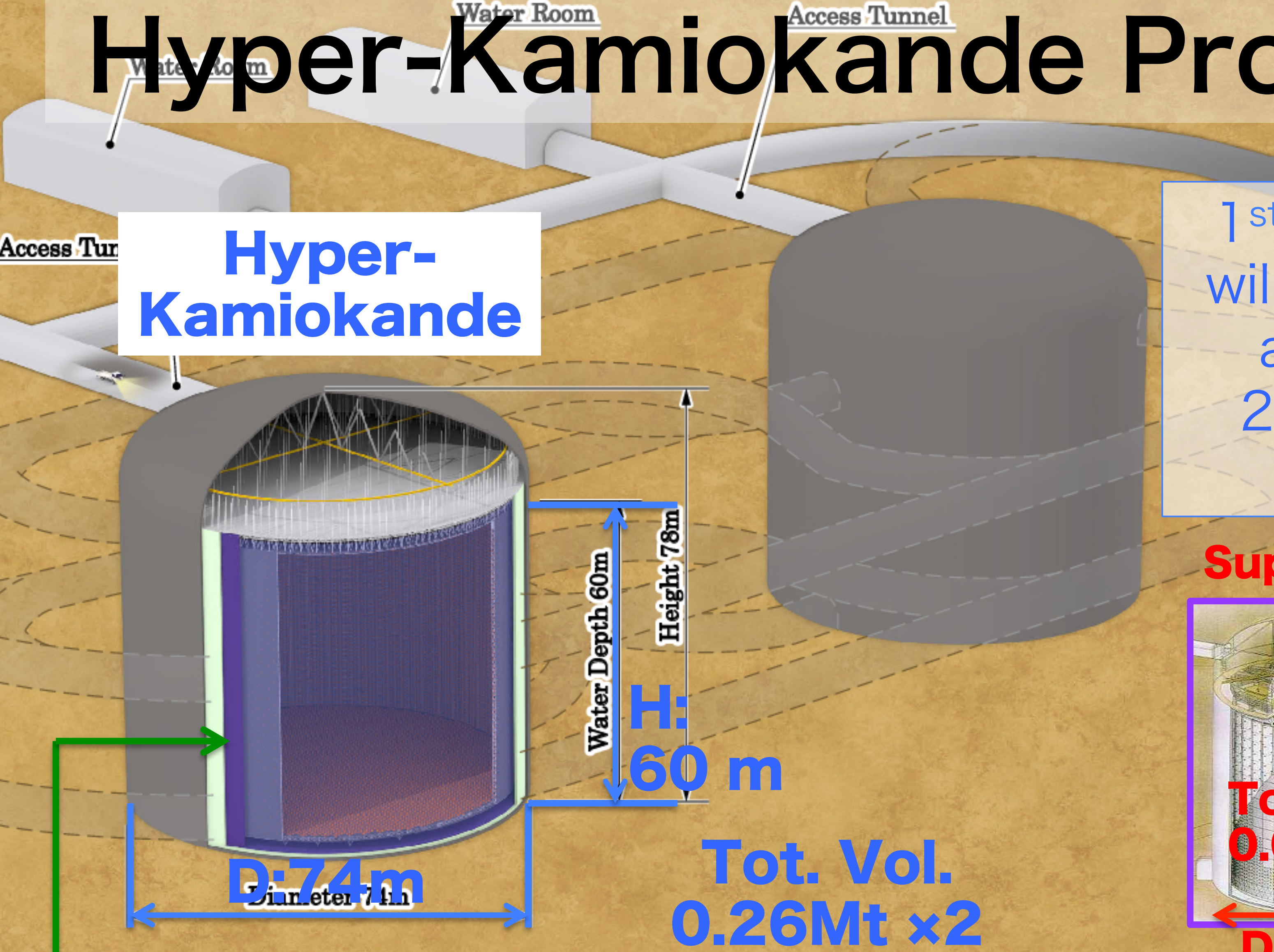
(2) Interference →
sensitive to δ_{CP}

(3) θ_{13} resonance →
sensitive to θ_{23}, θ_{13}, MH

Hierarchy Preference SK Only

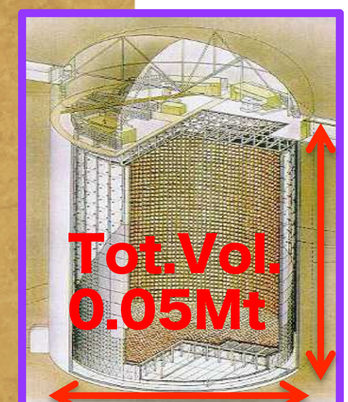


Hyper-Kamiokande Project



1st detector will be ready at 2026. 2nd will be 2032.

Super-K



More total and fiducial (x16 times) volume.
New photo-sensors (QE×CE = ~×2).
Higher sensitivity on each **physics topics.**

Hyper-Kamiokande Proto-Collaboration

16 institutes from Japan

- Kamioka Observatory, ICRR, University of Tokyo, Japan
- Kavli IPMU, University of Tokyo, Japan
- KEK, Japan
- Kobe University, Japan
- Kyoto University, Japan
- Miyagi University of Education, Japan
- Nagoya University, Japan
- Okayama University, Japan
- Osaka City University, Japan
- Tohoku University, Japan
- Tokyo Institute of Technology, Japan
- University of Tokyo, Japan etc.

- 16 Institutes from **USA**
- 11 Institutes from **UK**
- 6 Institutes from **Canada**
- 6 Institutes from **Korea**
- 5 Institutes from **Italy**
- 4 Institutes from **Poland**
- 2 Institutes from **France**
- 2 Institutes from **Brazil**
- 1 Institute from **Russia**
- 1 Institute from **Switzerland**
- 1 Institute from **Ecuador**
- 1 Institute from **Armenia**
- 1 Institute from **Spain**

- 298 members
- 73 institutes