Highlight talk from Super-Kamiokande

2018 July 12th (Thu)

7th International Conference on New Frontiers in Physics
ICNFP 2018 @Kolymbari, Crete, Greece

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(Kamioka Observatory, ICRR, The University of Tokyo)

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Super-Kamiokande collaboration

Photo in 2015

~165 people
45 institutes, 9 countries

Kamioka Observatory, ICRR, Univ. of Tokyo, Japan
RCCN, ICRR, Univ. of Tokyo, Japan
University Autonoma Madrid, Spain
University of British Columbia, Canada
Boston University, USA
University of California, Irvine, USA
California State University, USA
Chonnam National University, Korea
Duke University, USA
Fukuoka Institute of Technology, Japan
Gifu University, Japan
GIST, Korea
University of Hawaii, USA
Imperial College London, UK
INFN Bari, Italy
INFN Napoli, Italy

INFN Padova, Italy
INFN Roma, Italy
Kavli IPMU, The Univ. of Tokyo, Japan
KEK, Japan
Kobe University, Japan
Kyoto University, Japan
University of Liverpool, UK
LLR, Ecole polytechnique, France
Miyagi University of Education, Japan
ISEE, Nagoya University, Japan
NCBJ, Poland
Okayama University, Japan
Osaka University, Japan
University of Oxford, UK
Queen Mary University of London, UK
Seoul National University, Korea

University of Sheffield, UK
Shizuoka University of Welfare, Japan
Sungkyunkwan University, Korea
Stony Brook University, USA
Tokai University, Japan
The University of Tokyo, Japan
Tokyo Institute of Technology, Japan
Tokyo University of Science, japan
University of Toronto, Canada
TRIUMF, Canada
Tsinghua University, Korea
The University of Winnipeg, Canada
Yokohama National University, Japan

Super-Kamiokande (SK)

■ **Detector**

- **Located at Kamioka Japan.**
- **50 kton of ultra pure water tank.**
  - **20-inch PMTs, 11,129 for ID (since SK-III).**
  - **22.5 kton for analysis fiducial volume.**
- **Water Cherenkov light technique.**
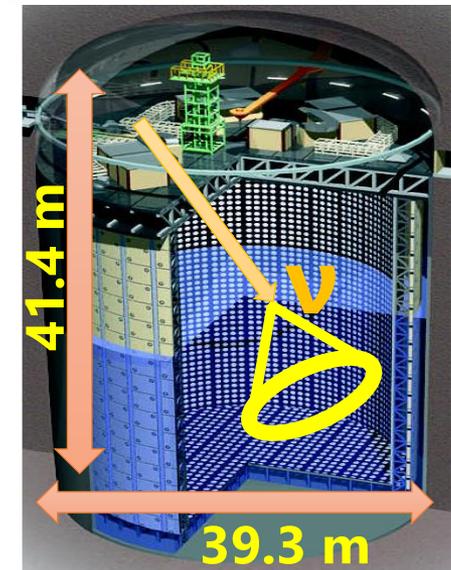
■ **History of SK**

- **Long term operation since 1996 (~22 years).**
- **Total live time is more than 5,500 days.**
- **Refurbishment works toward SK-Gd have started since May 31st, 2018.**

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
SK-I						SK-II				SK-III			SK-IV										SK-Gd	
PMT 11,146 (40%*)						5,182 (19%*)				11,129 (40%*)									Nobel prize					
4.5 MeV**						6.5 MeV**				4.0 MeV**			3.5 MeV**											

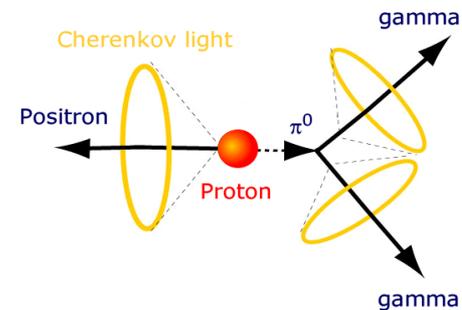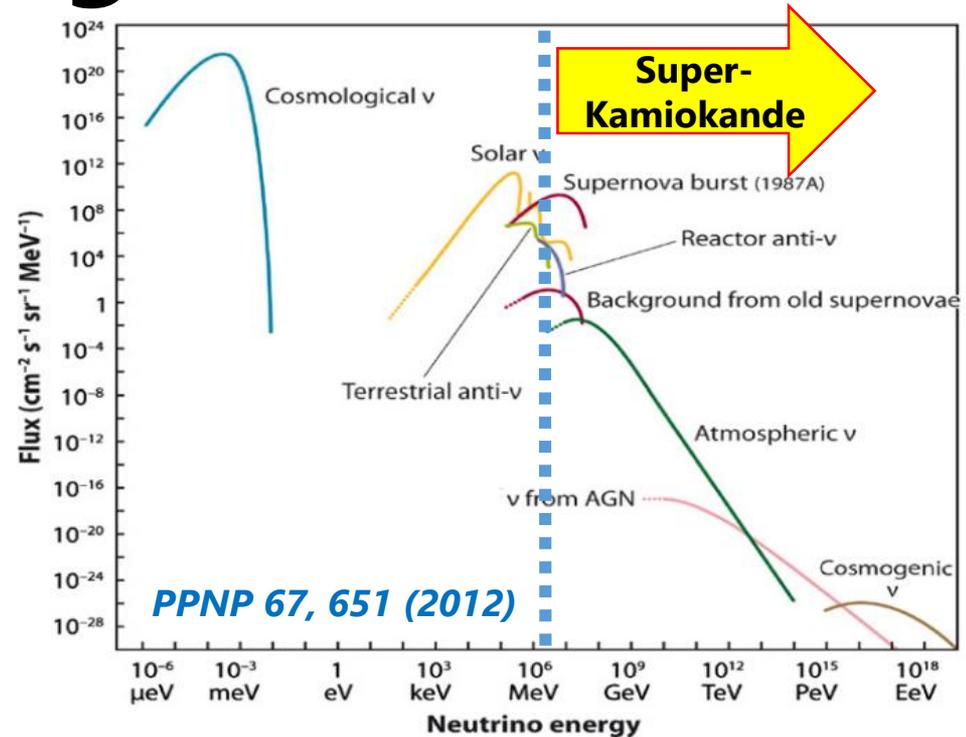*** Photo coverage [%], ** Recoil electron kinetic energy [MeV].**

Physics targets in SK

■ **Neutrinos**

  - **Astrophysical neutrinos**
    → **Solar neutrino**
    → **Supernova (relic) neutrino**

  - **Atmospheric neutrino**
  - **Accelerator (Long baseline)**

■ **Other physics**

  - **Proton decays**
  - **Dark matter search**
    → **From galactic center, Sun, Earth**
  - **Other exotic models**

PPNP 67, 651 (2012)

Solar ν	Supernova ν	Atmospheric ν and proton decay
< ~20 MeV	~20-~100 MeV	~100 MeV GeV TeV PeV

Recent publications from SK

■ **Atmospheric neutrino**
- **3-fravor oscillation analysis:** *Phys. Rev. D 97, 072001 (2018)*. ●
- **Tau neutrino cross section:** *arXiv:1711.0943 [hep-ex]*. ●
- **Atmospheric neutrino flux:** *Phys. Rev. D 94, 052001 (2016)*.

■ **Solar neutrino**
- **Energy spectrum measurement:** *Phys. Rev. D 94, 052010 (2016)*. ●
- **Day/night flux asymmetry:** *Phys. Rev. Lett. 112, 091805 (2014)*.

■ **Proton decay (nucleon decay)**
- **Anti-lepton plus meson:** *Phys. Rev. D 96, 012003 (2017)*.
- **$p \to e^+\pi^0$ and $p \to \mu^+\pi^0$:** *Phys. Rev. D 95, 012004 (2017)*.
- **Invisible particle & charged lepton:** *Phys. Rev. Lett. 115, 121803 (2015)*.
- **Dinucleon decay into π:** *Phys. Rev. D 91, 072009 (2015)*.

■ **Others (Dark matter search, Sterile ν and Lorentz invariance...)**
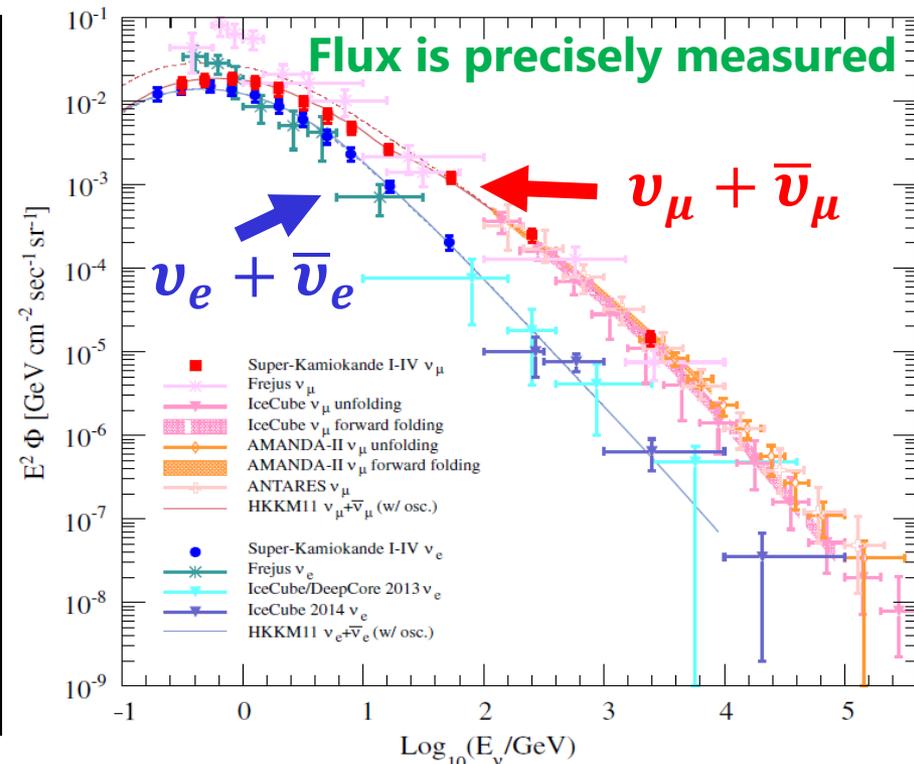
More detail: http://www-sk.icrr.u-tokyo.ac.jp/sk/publications/index.html

Atmospheric neutrino

■ **Feature of atmospheric neutrino**

- **Primary cosmic-ray interacts with nuclei in atmosphere.**
  → **π, K are produced and then μ, e are produced with neutrinos.**
- **Travel length: O(~10) km - 13,000 km (zenith angle dependence).**
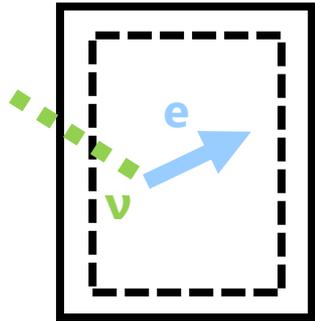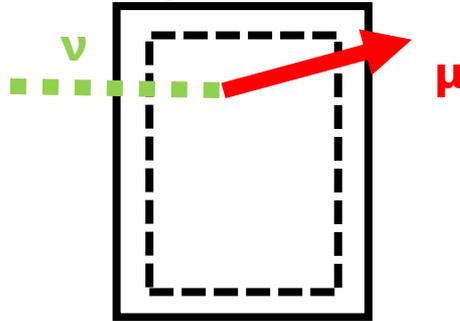- **Wide energy range : Sub-GeV to over TeV.**
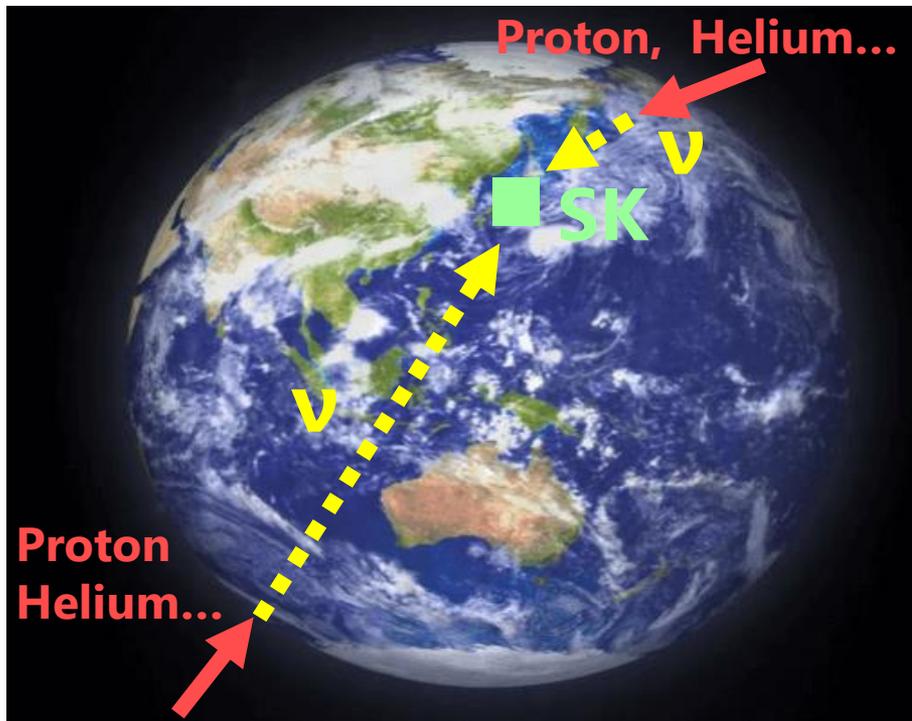
Isotropic flux of cosmic ray
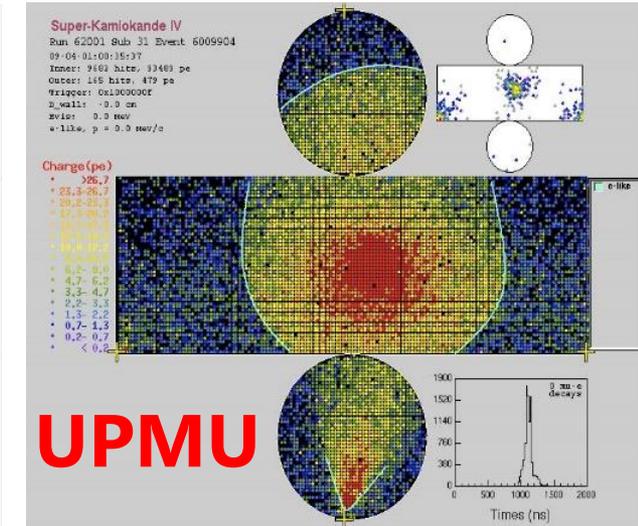
Category of neutrino events

Fully contained (FC)

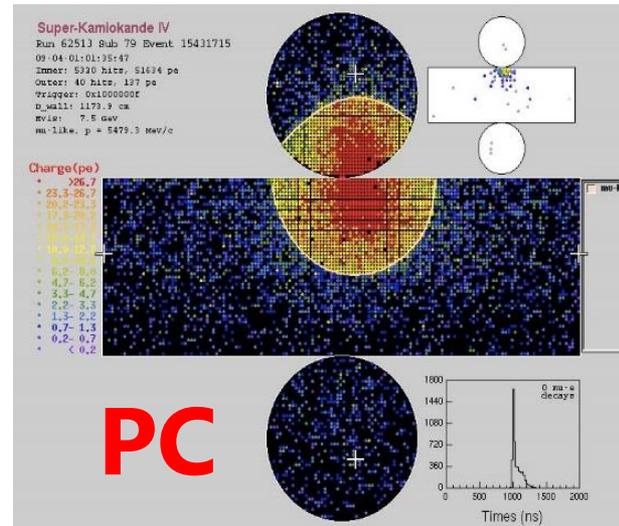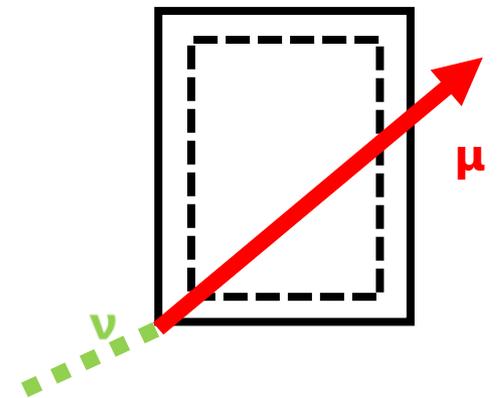**Also µ, multi-ring (decay electron)**

Partially contained (PC)

Up-going µ (UPMU)

FC

PC

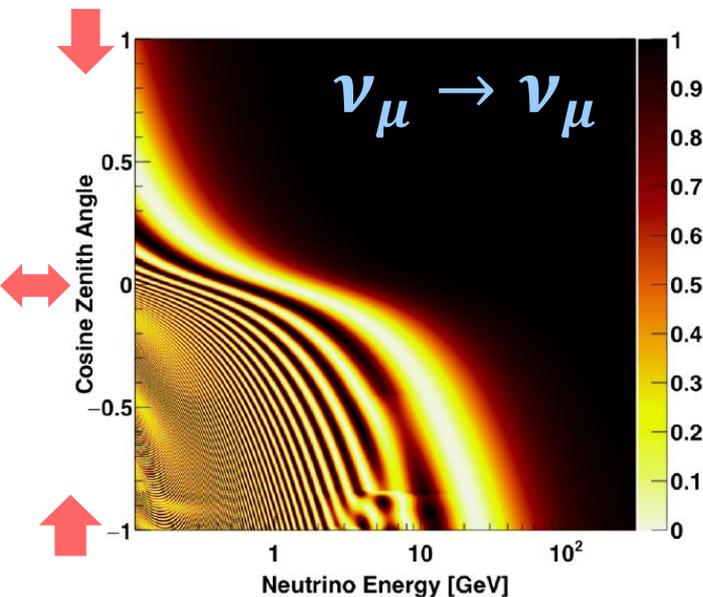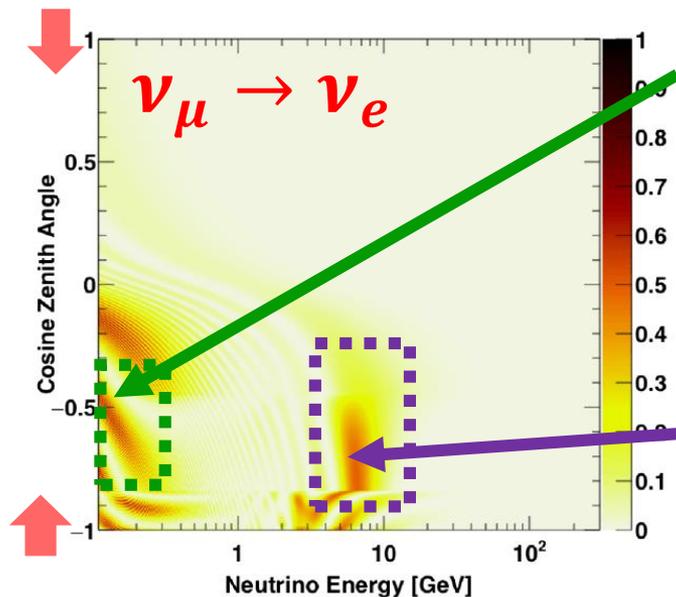**UPMU**
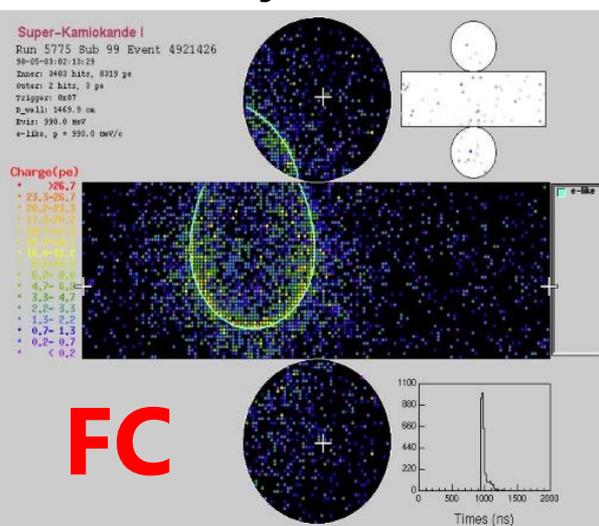
Atmospheric neutrino in SK

■ **Oscillation probability and sub-leading effects**
- **SK has sensitivity to all PMNS parameters.**
  → **Atmospheric ν oscillation is dominated by $\nu_\mu \rightarrow \nu_\tau$ $\left(\Delta m_{23}^2, \theta_{23}\right)$.**
- **Sub-leading effects are expected in ν_e sample.**
  → **Resonant oscillation due to matter effect in the Earth.**
  → **Sensitive to mass hierarchy, θ_{23} octant and CP phase.**

$\nu_\mu \rightarrow \nu_\mu$
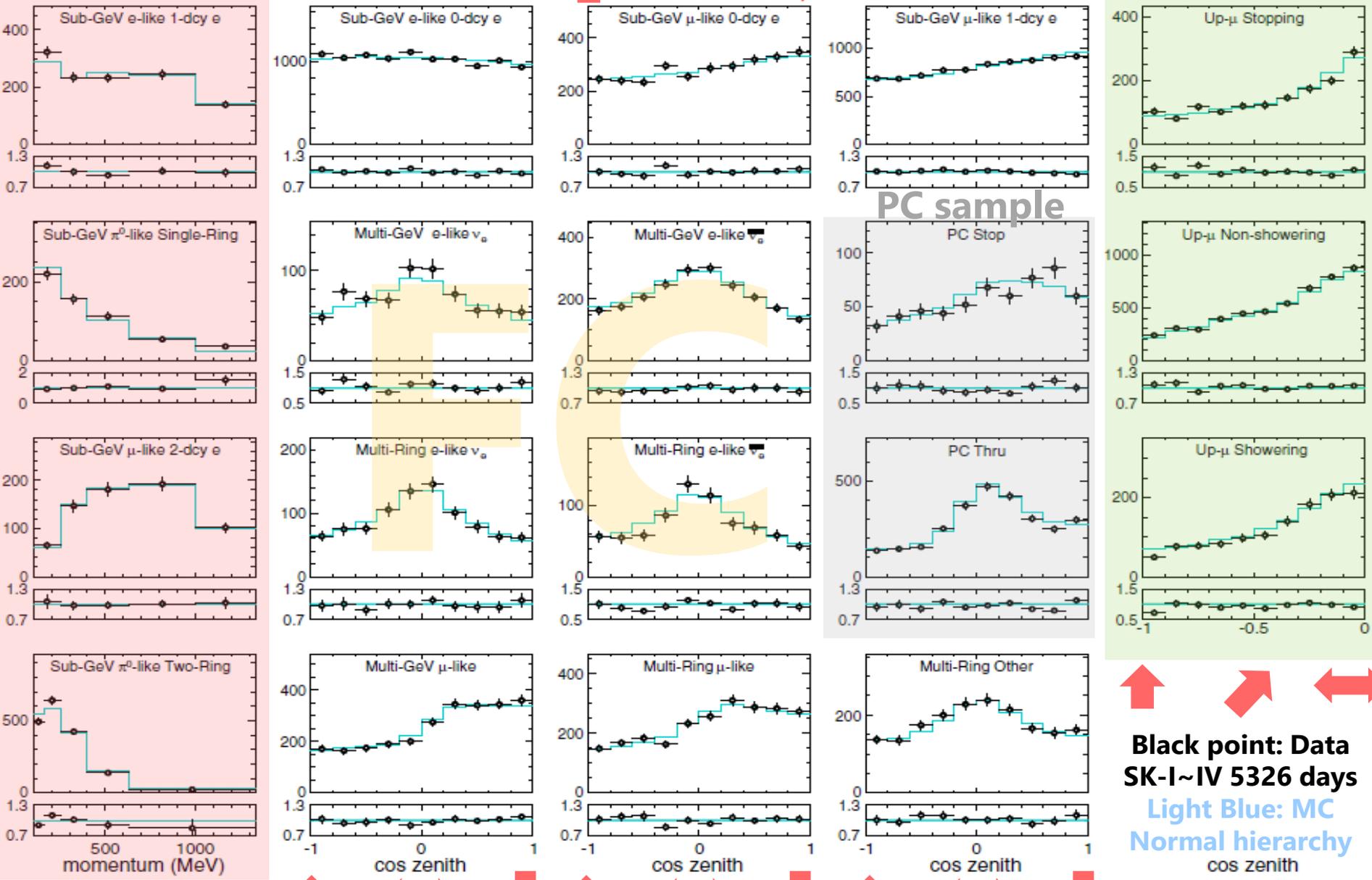
$\nu_\mu \rightarrow \nu_e$

Due to solar term. Flux normalization changes by CP phase.

Resonant oscillation due to finite θ_{13}.

Enhancement of ν_e when normal hierarchy. ($\overline{\nu}_e$ when inverted)

Sub-GeV   **Multi-GeV**   **Sub-GeV**   **Multi-GeV**

Momentum

Up-going μ

PC sample

Black point: Data
SK-I~IV 5326 days
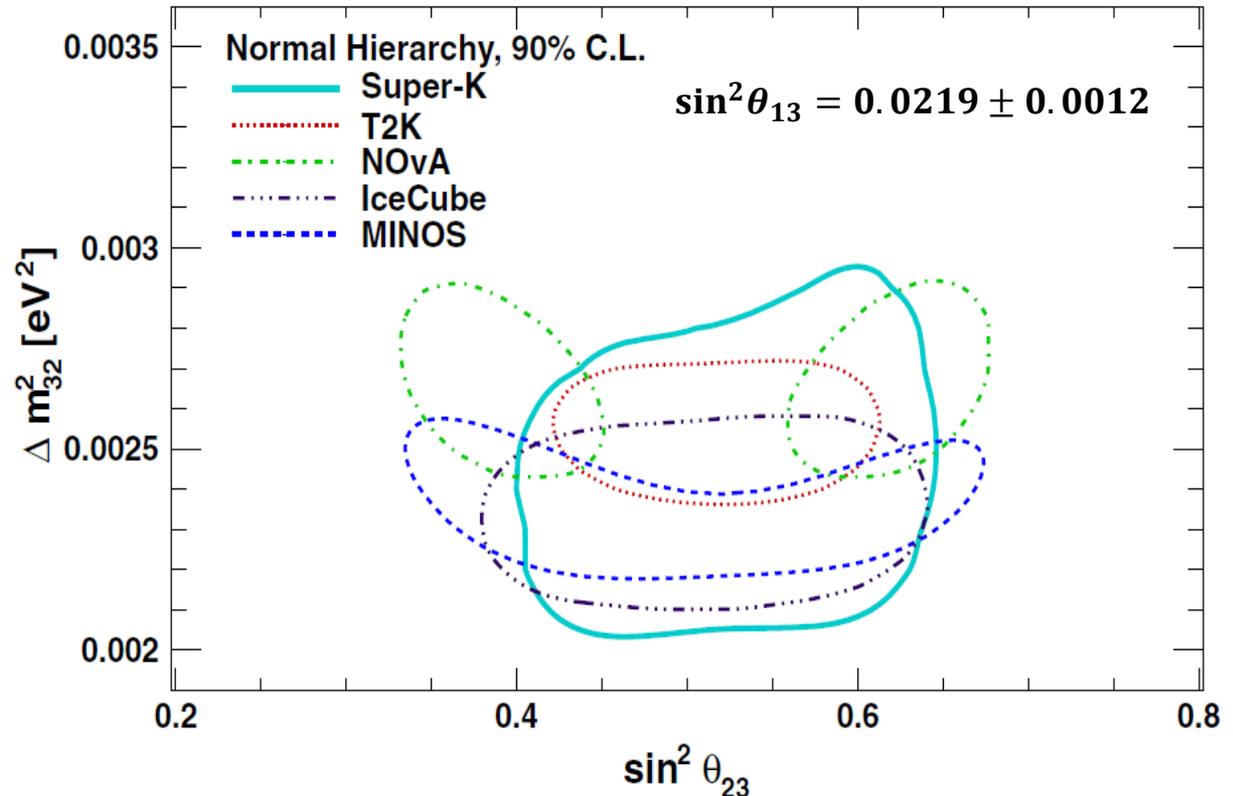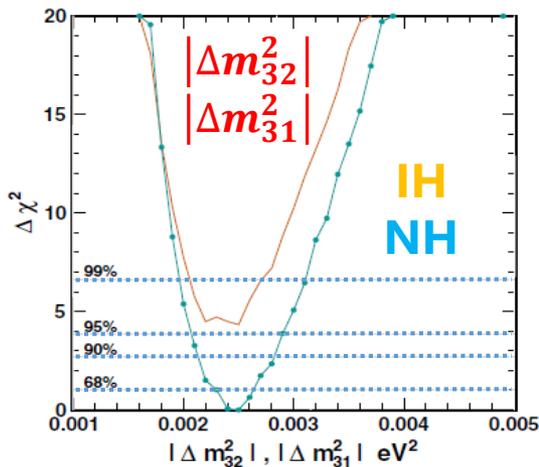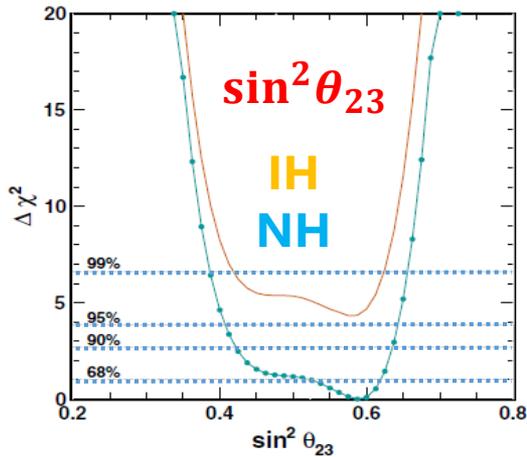Light Blue: MC
Normal hierarchy
cos zenith

Neutrino oscillation analysis

■ **Oscillation analysis (Only SK data)**

- **Data set: SK-IV 2519 days → SK-I~IV: 5326 days (328 kton · year).**
- **Scan χ^2 for , $\sin^2\theta_{23}$, Δm^2 → $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.33$ (SK only).**

Normal Hierarchy, 90% C.L.
- Super-K
- T2K
- NOvA
- IceCube
- MINOS
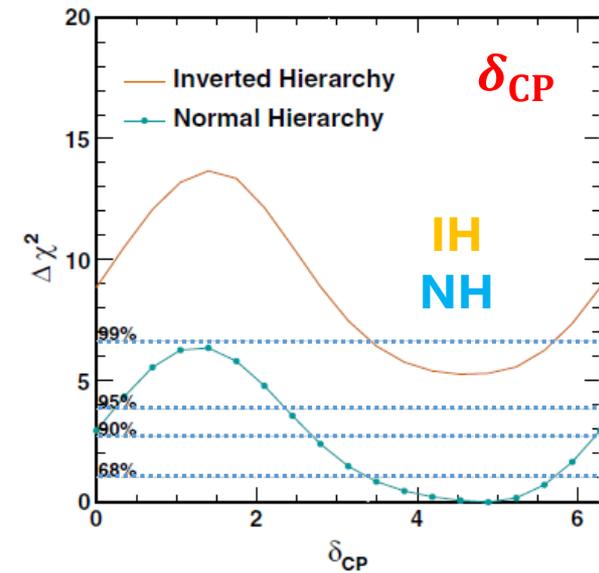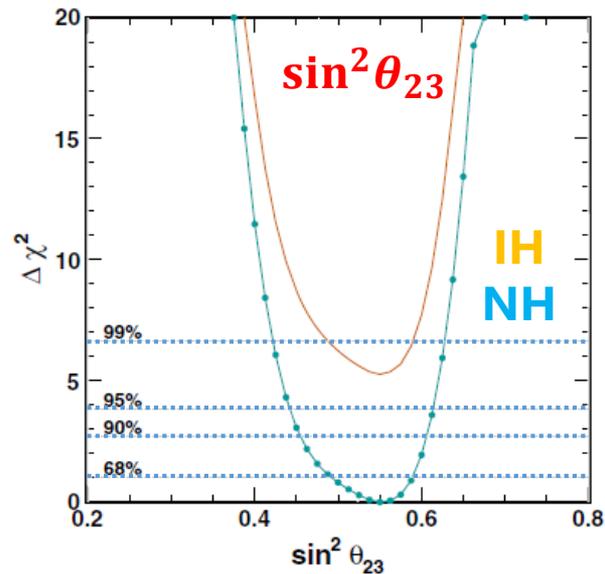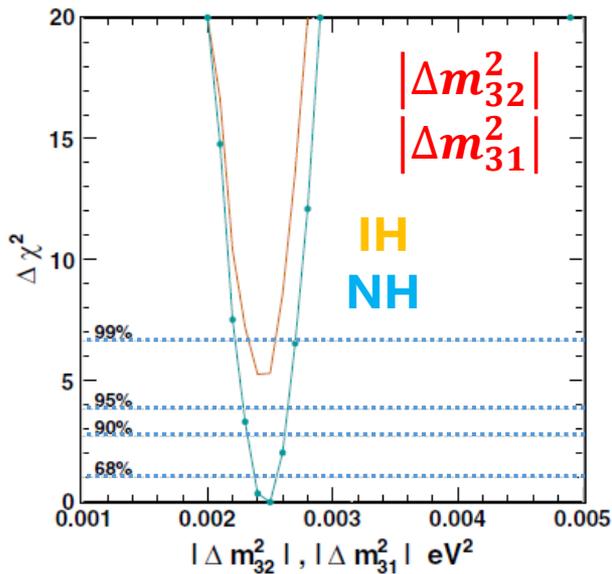
$\sin^2\theta_{13} = 0.0219 \pm 0.0012$

Other experiments results → before Neutrino2018

Neutrino oscillation analysis

■ **Oscillation analysis with external constraint**

- **Introduce constraint from T2K public data and reactor results.**
- **Normal hierarchy is slightly preferred**, $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$.

$\sin^2\theta_{13} = 0.0219 \pm 0.0012$ **(fix)**

Mass hierarchy	χ^2	$|\Delta m^2_{32,31}|$ [$\times 10^{-3}$ eV^2]	$\sin^2\theta_{23}$	δ_{CP}
Normal	**639.43**	$2.50^{+0.05}_{-0.12}$	$0.550^{+0.039}_{-0.057}$	$4.88^{+0.81}_{-1.48}$
Inverted	**644.70**	$2.40^{+0.13}_{-0.06}$	$0.550^{+0.035}_{-0.051}$	$4.54^{+1.05}_{-0.97}$

Tau neutrino appearance

■ **Tau neutrino in atmospheric sample**

- **Detection of ν_τ is critical for verifying 3-flavor mixing scheme.**
  - **→ Search for hadronic decay of τ lepton.**
- **More than 3.5 GeV, Up-going sample has a chance.**
- **Hard to identify event by event but can be statistically seen.**

3.5 GeV

$\nu_\mu \rightarrow \nu_\tau$

Sub-GeV   Multi-GeV

ν_μ ν_τ τ hadrons
Threshold ~3.5GeV

Charge(pe)
- >26.7
- 23.3–26.7
- 20.2–23.3
- 17.3–20.2
- 14.7–17.3
- 12.2–14.7
- 10.0–12.2
- 8.0–10.0
- 6.2– 8.0
- 4.7– 6.2
- 3.3– 4.7
- 2.2– 3.3
- 1.3– 2.2
- 0.7– 1.3
- 0.2– 0.7
- < 0.2

~1 event/year · kton

Example of ν_τ event (ν_τCC)
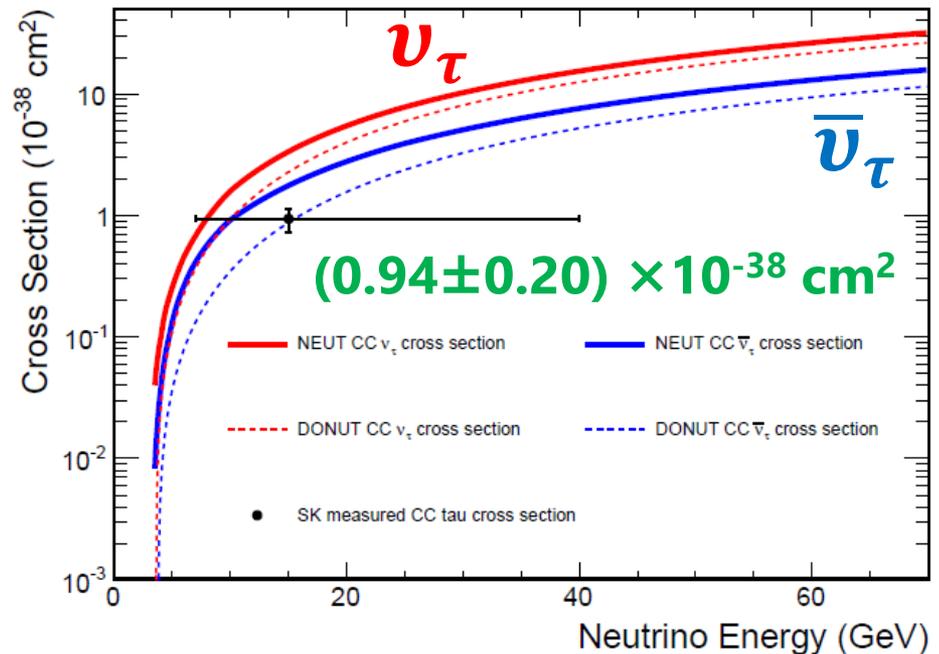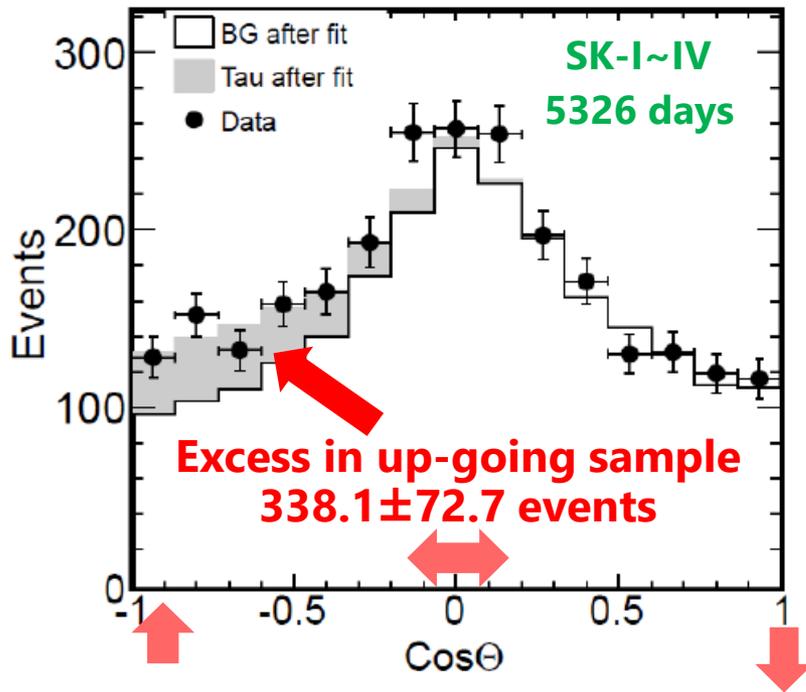
Times (ns)
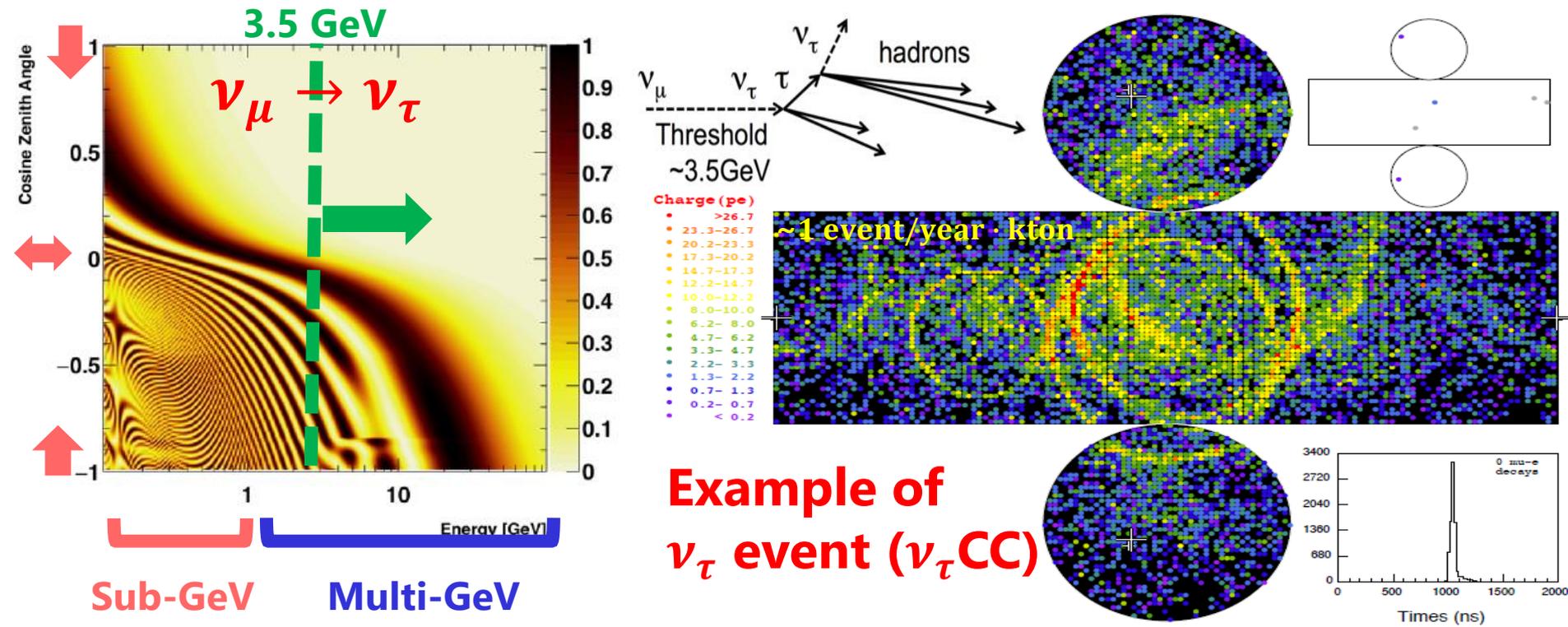
Signal and cross section

■ **Analysis and its results**

- **Event selection is performed using Neural Network.**
  → **Discriminate tau signal from background: Efficiency 76%.**
- **2D fit with signal scale parameter is evaluated.**

$$Data = PDF_{\mathrm{BG}} + \alpha \times PDF_{\tau-\mathrm{like}} + \sum \varepsilon_i PDF_i$$

α = 0: no τ contribution
α = 1: MC expected

- **α = 1.47±0.32 (stat.+syst.) → 4.6σ from 0 (NH assumed).**

SK-I~IV
5326 days

Excess in up-going sample
338.1±72.7 events

ν_τ

$\overline{\nu}_\tau$

(0.94±0.20) ×10⁻³⁸ cm²

(0.94±0.20) $\times 10^{-38}$ cm²

Solar neutrino

■ **Production of solar neutrino**

- **Solar neutrinos are produced via nuclear fusions in the core.**

$$4p \rightarrow \alpha + 2e^+ + 2\nu_e + 26.7\text{MeV} - E_\nu$$
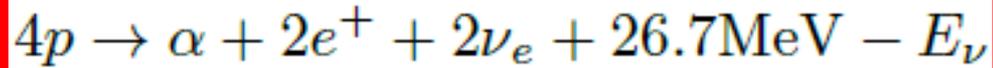
- **Several processes makes electron-neutrino.**
  → *pp, pep,* ^{7}Be, ^{8}B, *hep* and *CNO*
- **Standard solar model predicts their fluxes (SK can detect ^{8}B/hep).**
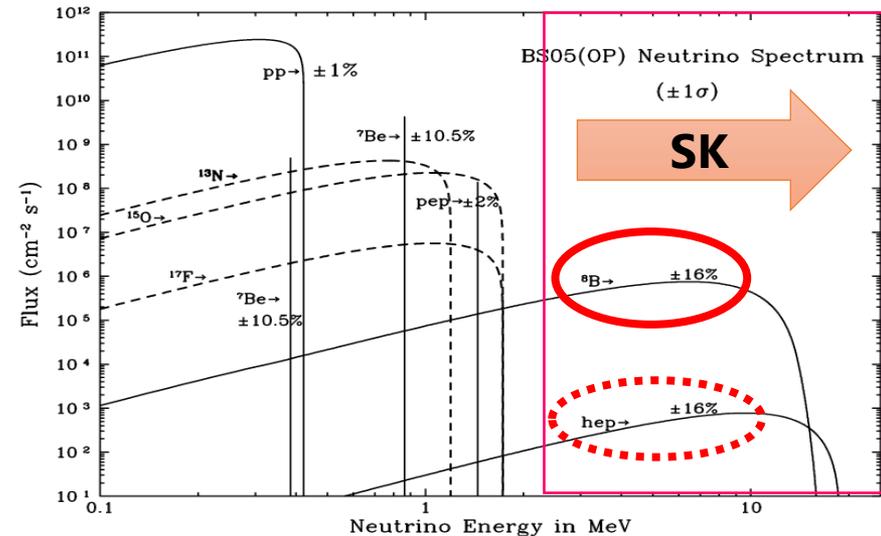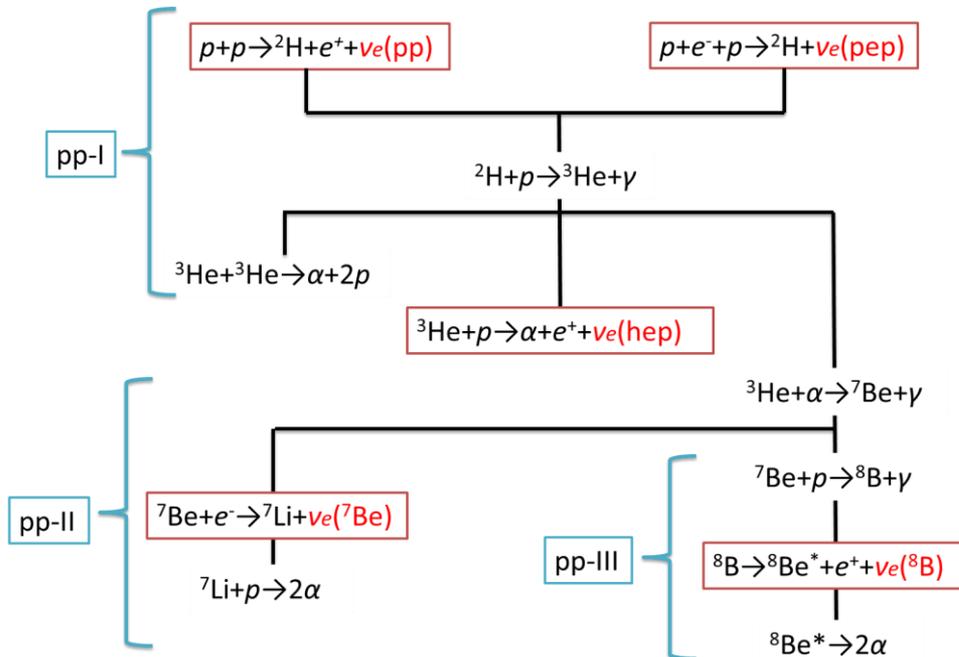
Astrophys. J. 621 85 (2005).

Motivations of solar neutrino

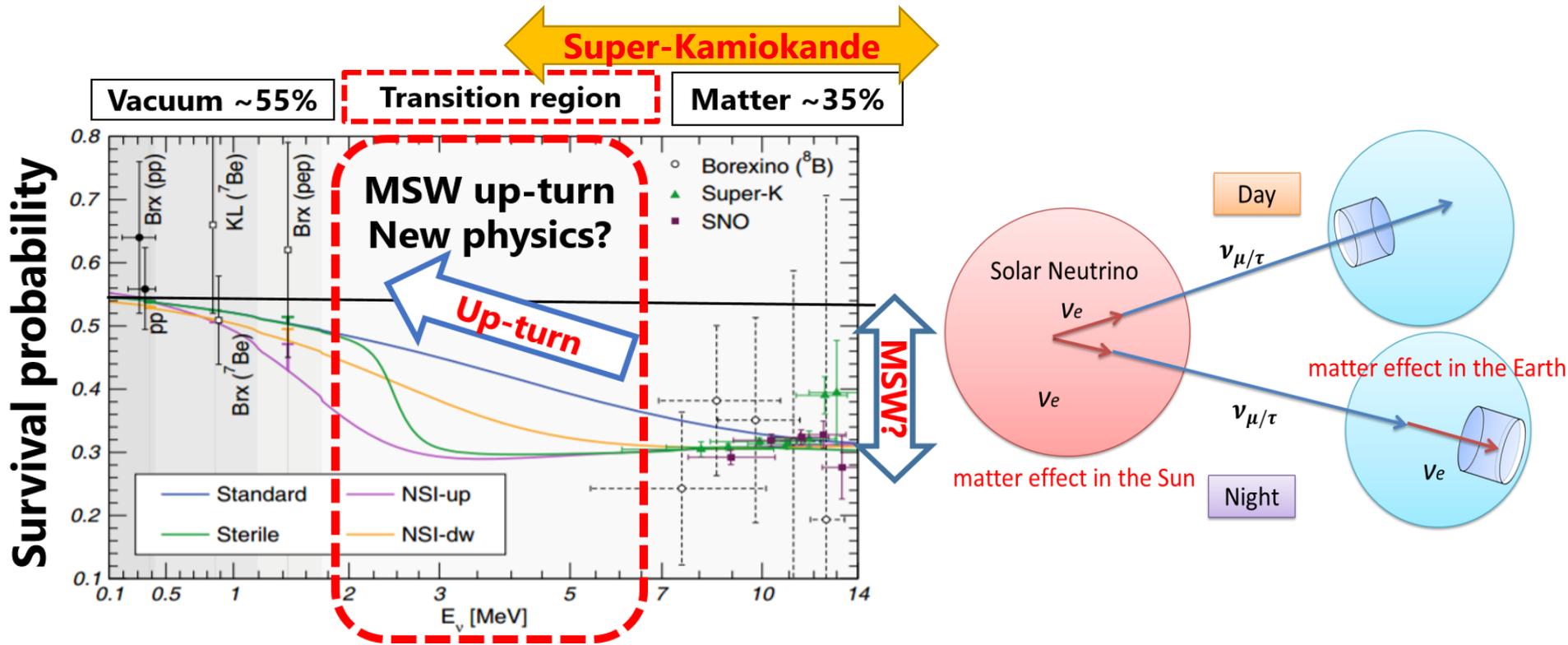■ **Goal of solar neutrino measurement in SK**

(1) Test the transition of solar ν oscillation btw vacuum and matter.
   → Lowering threshold & reducing BG to test MSW up-turn.
(2) Day-night flux asymmetry
   → Regeneration of ν_e due to the Earth's matter effect is expected.
   (~2.5σ indication, update of this analysis is in progress).
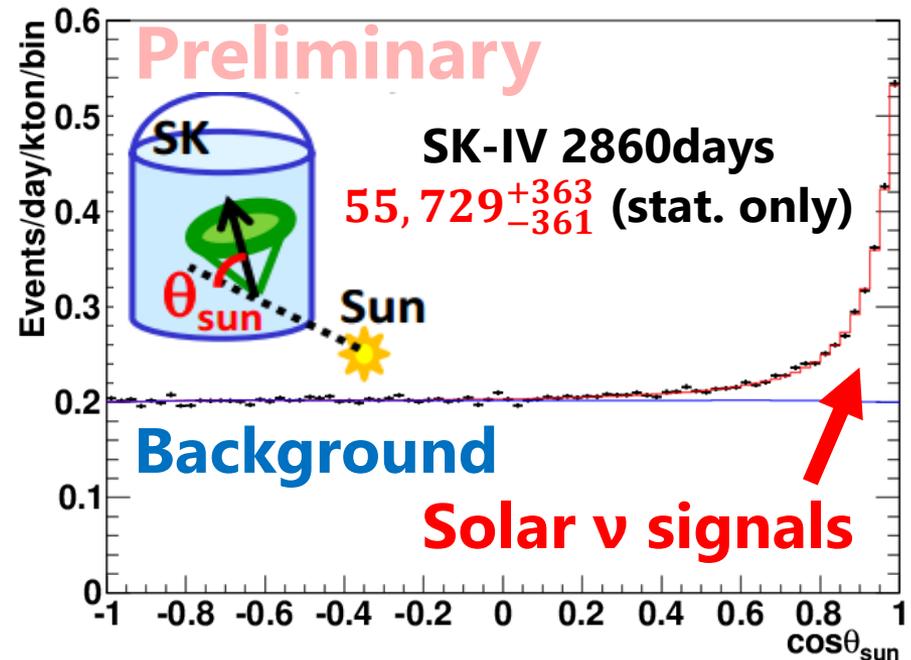
⁸B solar neutrino measurement

■ **⁸B solar neutrino signals**

- **Elastic scattering** $(v_X + e^- \rightarrow v_X + e^-)$.
  (1) Timing → **Vertex position** & **real-time** measurement
  (2) Ring pattern → **Direction** of the incoming neutrino
  (3) # of hit PMTs → **Energy** (~6 p.e./MeV)

- ~20 events/day in SK-IV (SK-I~IV 5695 days: **~93k events**).

E_{total} = 9.1MeV
$\cos\theta_{sun}$ = 0.95

Preliminary

SK-IV 2860days
$55,729^{+363}_{-361}$ (stat. only)

θ_{sun} Sun

Background

Solar ν signals
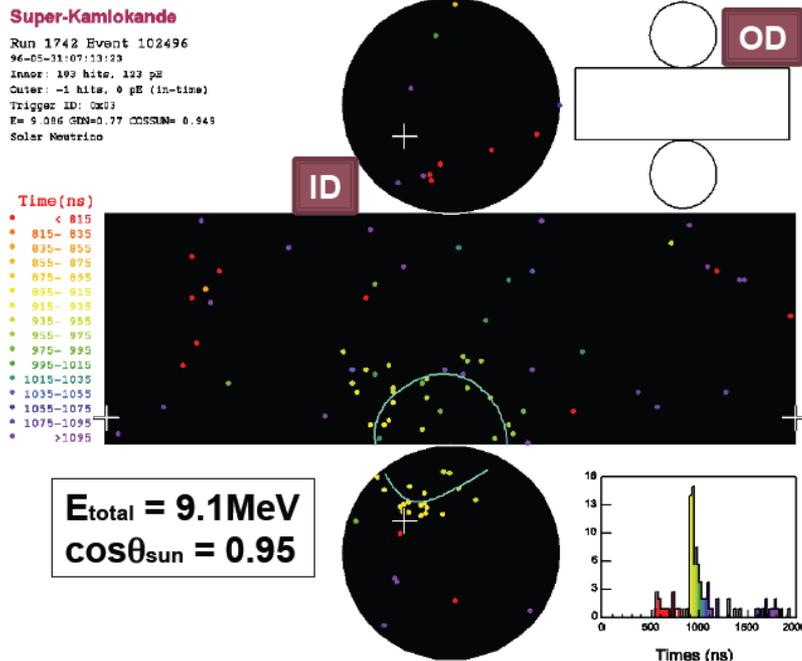
^{8}B solar neutrino flux

■ **Flux measurements**

- **SK has measured the ^{8}B solar neutrino flux for 22 years.**
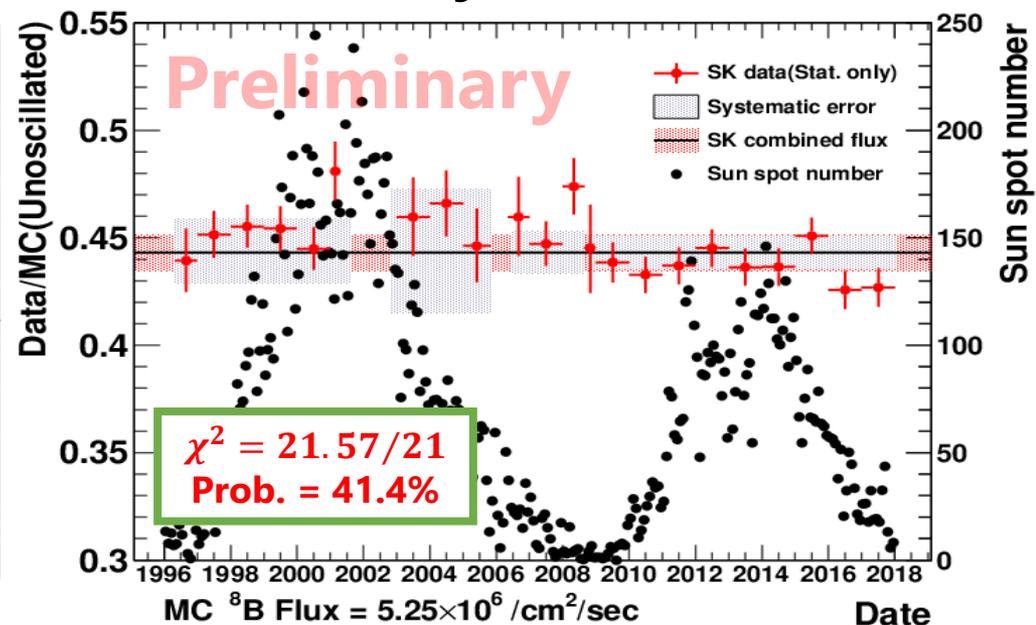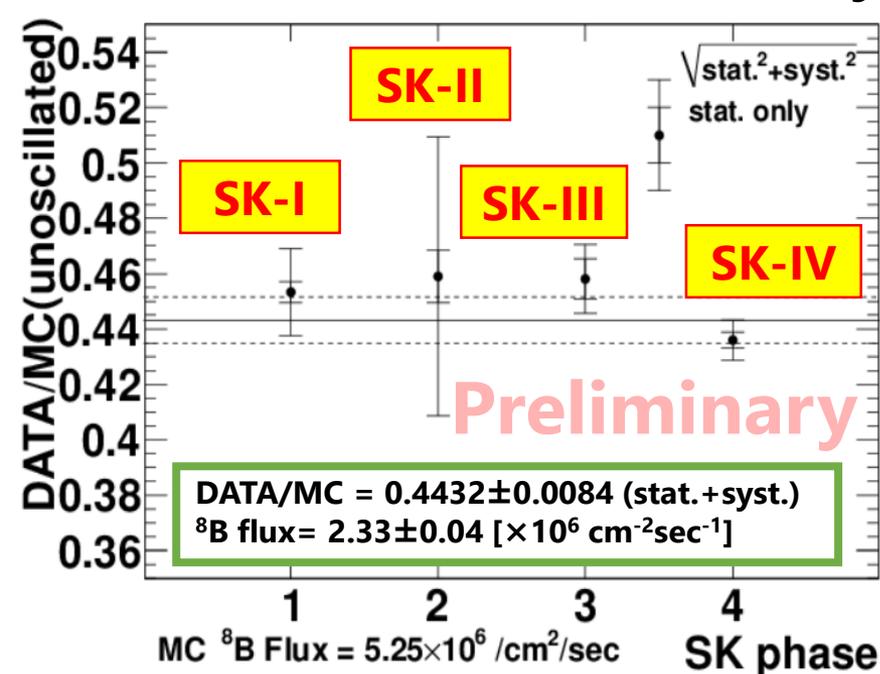 - → **Fluxes are consistent within uncertainties among all SK phases.**
  SK flux/SNO NC flux = 0.4432±0.0084 (stat.+syst.).

■ **Correlation of the flux with the solar activity**

- **Solar activity is strongly correlated with sunspot numbers.**
- **No correlation with the 11-years solar activity is observed.**

DATA/MC = 0.4432±0.0084 (stat.+syst.)
^{8}B flux= 2.33±0.04 [×10^6 cm^{-2}sec^{-1}]

MC ^{8}B Flux = 5.25×10^6 /cm^2/sec   SK phase

$\chi^2 = 21.57/21$
Prob. = 41.4%

MC ^{8}B Flux = 5.25×10^6 /cm^2/sec   Date

Sun spot number: http://www.sidc.be/silso/datafiles
Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

Recoil electron energy spectrum

SK-I — 4.5 MeV — 1496 days
SK-II — 6.5 MeV — 791 days
SK-III — 4.0 MeV — 548 days
SK-IV — 3.5 MeV — Preliminary — 2860 days
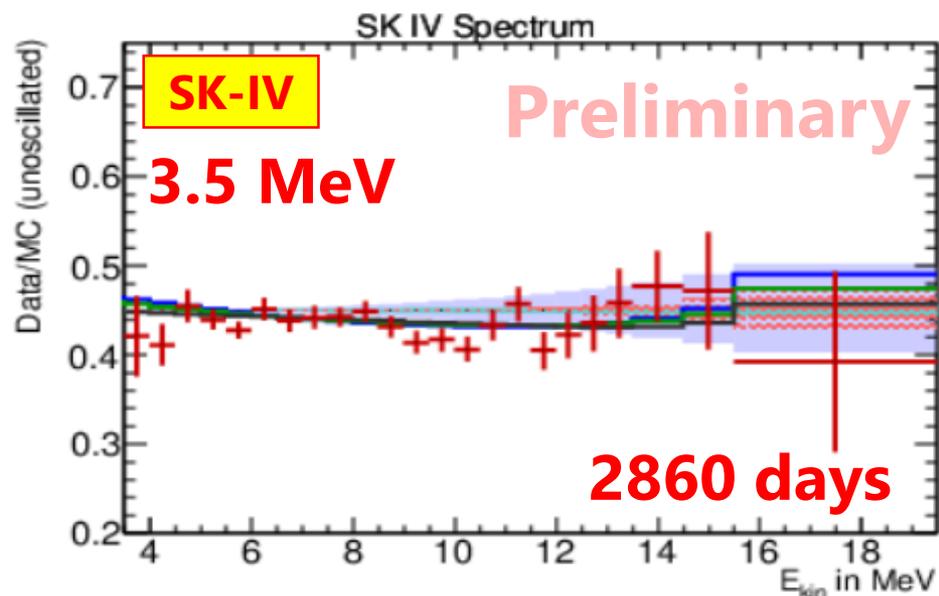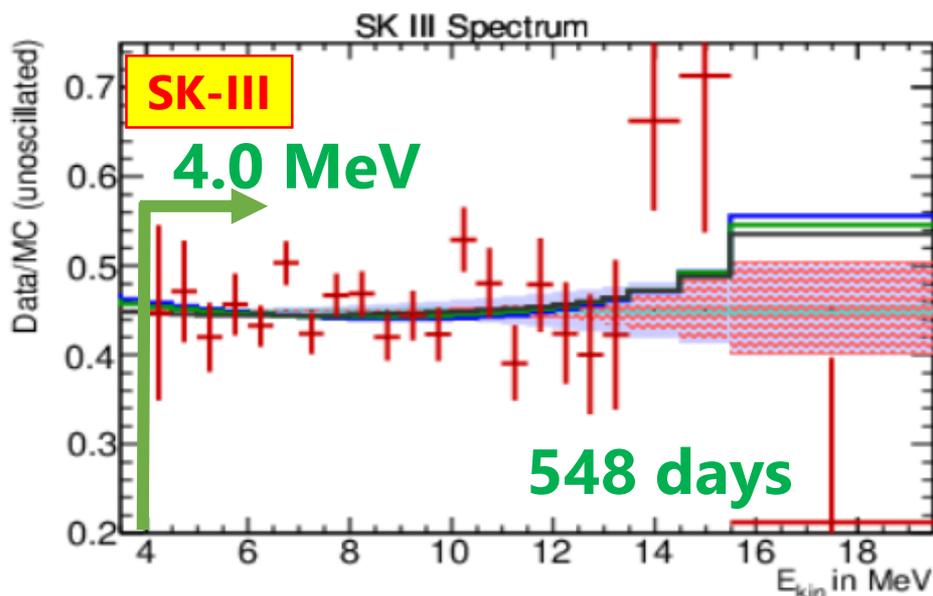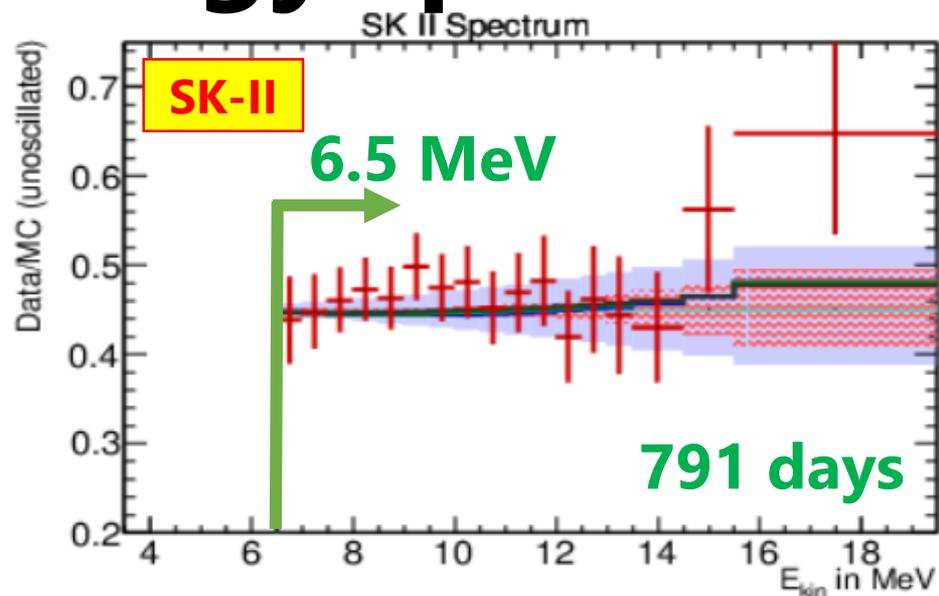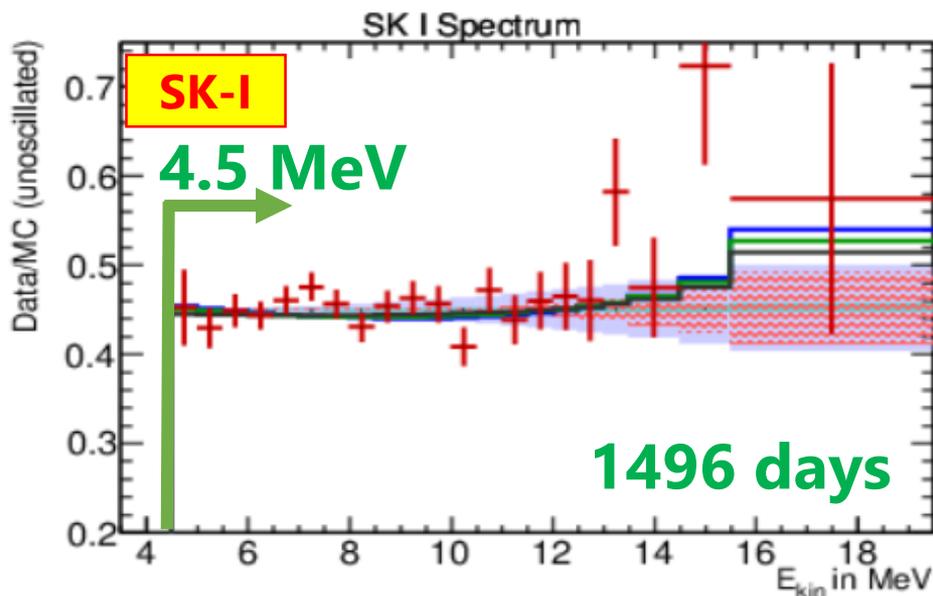
Combined spectrum

■ **Energy spectrum vs. MSW predictions**

- **Introduce quadratic function to test the MSW prediction.**
- **Quadratic fit is consistent with solar Δm_{21}^2 within 1.2σ, while it disfavors KamLAND Δm_{21}^2 by 2.0σ.**

SK I/II/III/IV LMA Spectrum
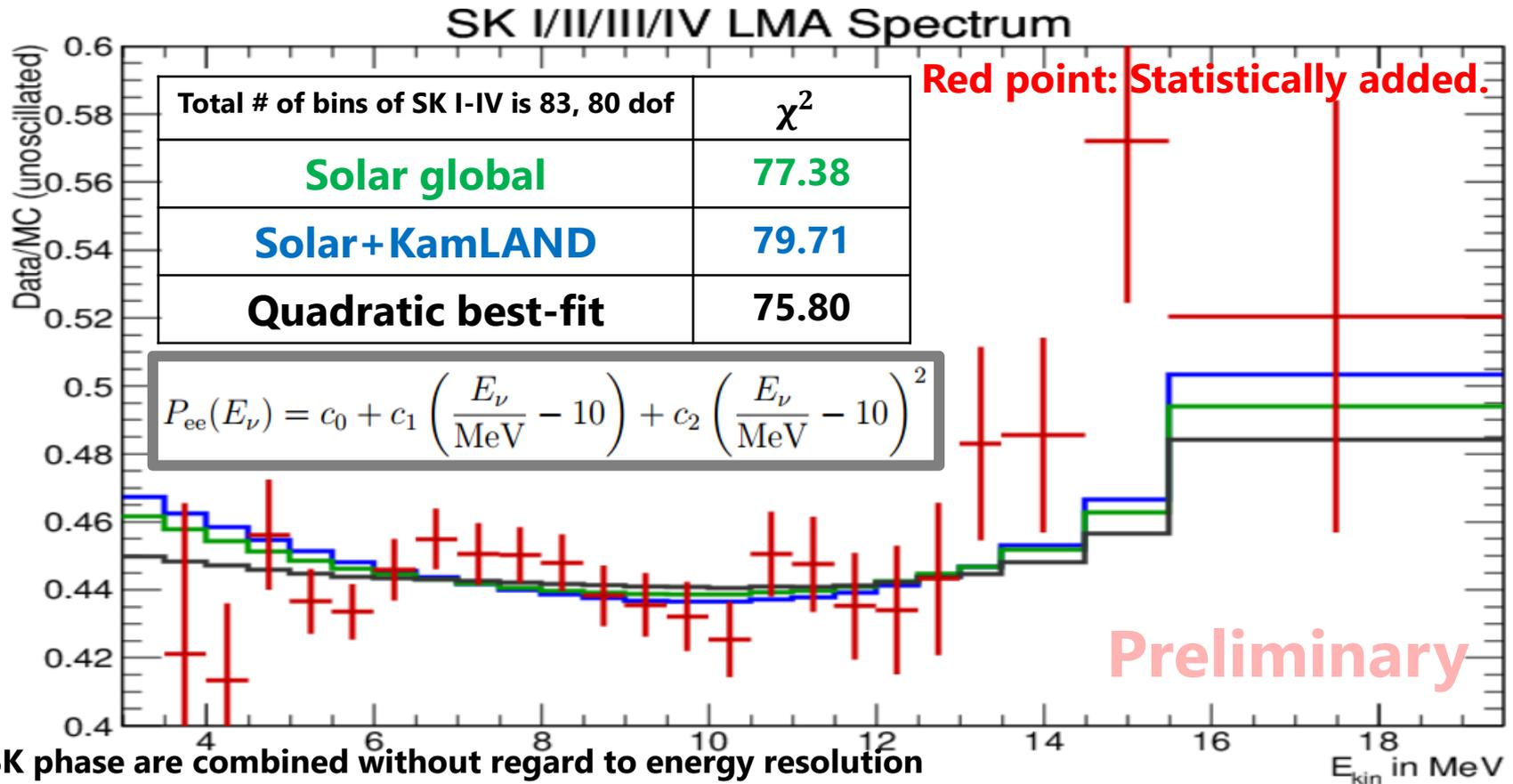
Red point: Statistically added.

Total # of bins of SK I-IV is 83, 80 dof	χ^2
Solar global	**77.38**
Solar+KamLAND	**79.71**
Quadratic best-fit	**75.80**

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

Preliminary

Data/MC (unoscillated) vs E_{kin} in MeV

All SK phase are combined without regard to energy resolution or systematic uncertainty in this figure.

Constraint on $\sin^2\theta_{12}, \Delta m^2_{21}$ (SK vs. SNO)

■ **Oscillation parameters from SK and SNO**

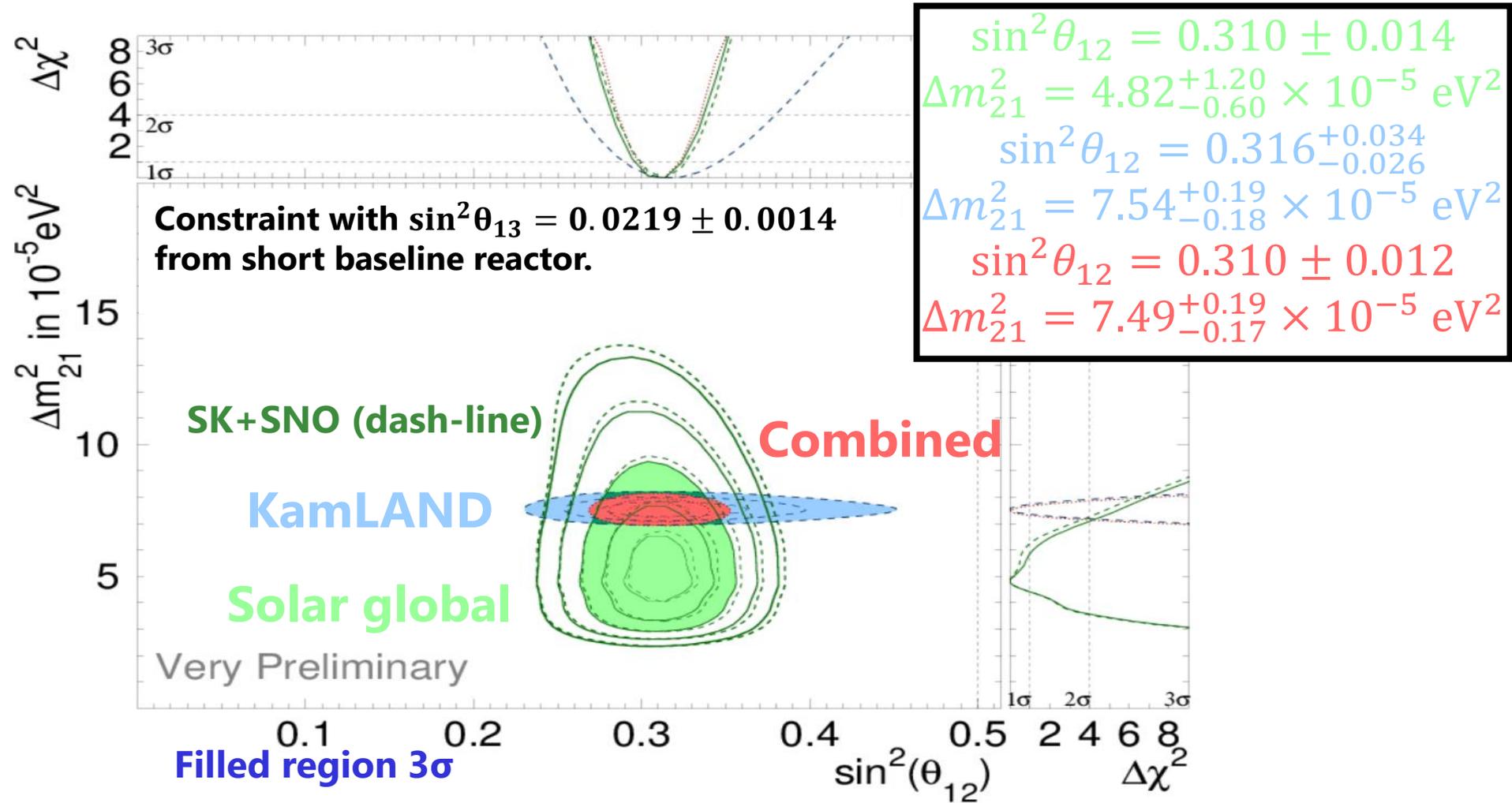- **SK result uniquely selects the LMA-MSW region by more than 3σ.**

- **SK (SNO) gives the best constrain on Δm^2_{21} ($\sin^2\theta$).**
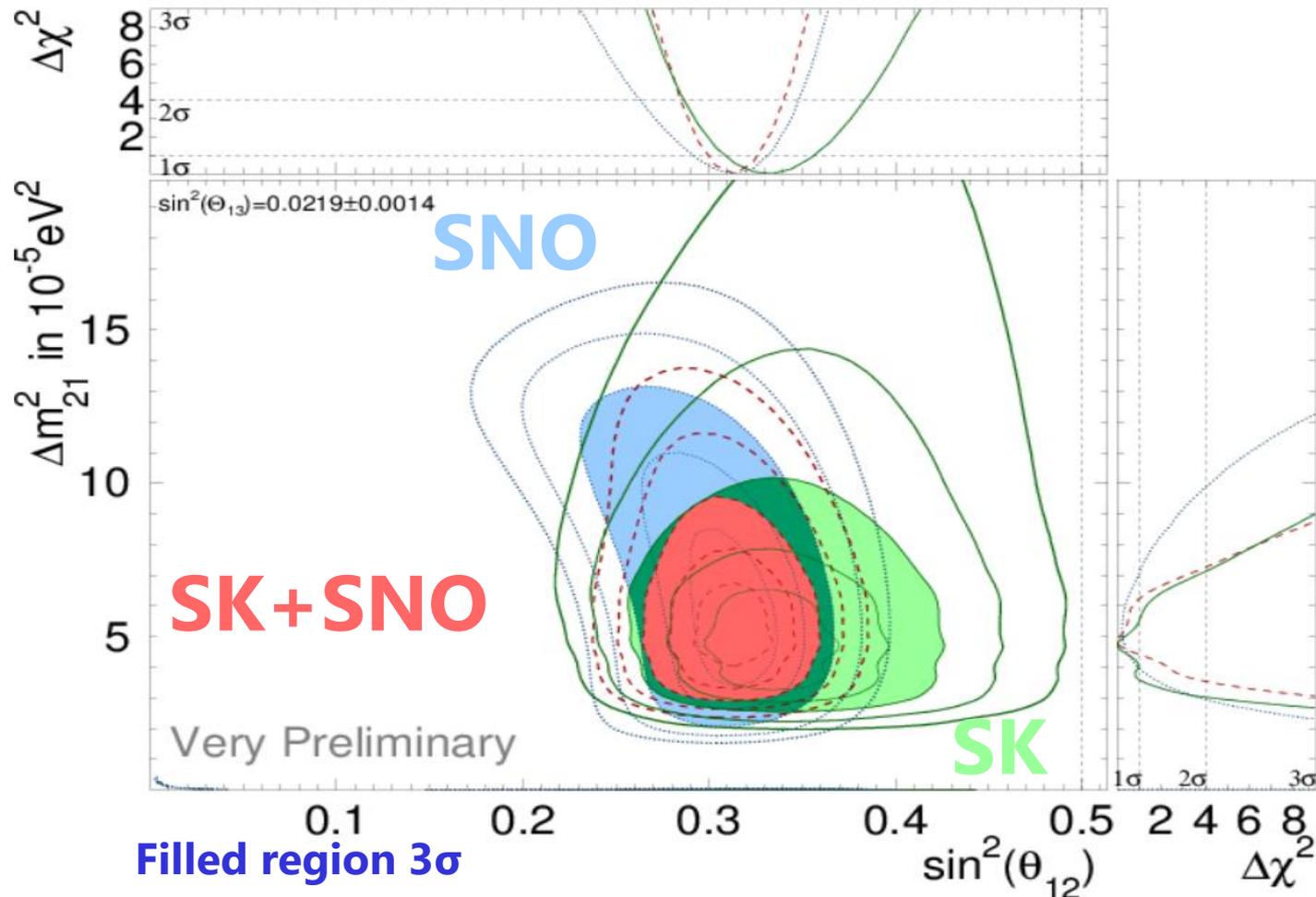
# Constraint on $\sin^2\theta_{12}, \Delta m_{21}^2$ (solar vs. KamLAND)

$\sin^2\theta_{12} = 0.310 \pm 0.014$

$\Delta m_{21}^2 = 4.82^{+1.20}_{-0.60} \times 10^{-5} \ \mathrm{eV}^2$

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

$\Delta m_{21}^2 = 7.54^{+0.19}_{-0.18} \times 10^{-5} \ \mathrm{eV}^2$

$\sin^2\theta_{12} = 0.310 \pm 0.012$

$\Delta m_{21}^2 = 7.49^{+0.19}_{-0.17} \times 10^{-5} \ \mathrm{eV}^2$

Constraint with $\sin^2\theta_{13} = 0.0219 \pm 0.0014$ from short baseline reactor.

SK+SNO (dash-line)

Combined

KamLAND

Solar global

Very Preliminary

Filled region 3σ

2σ tension in Δm_{21}^2 between the solar global and KamLAND. Further precise measurement is required in future.

Allowed survival probability

■ **Comparison among solar neutrino experiments**
 - **Neutrino energy spectrum is de-convoluted from the recoil electron energy spectrum → Extract survival probability (P$_{ee}$).**
 - **This analysis gives the strongest constraint on P$_{ee}$ shape.**

P$_{ee}$ versus ν Energy
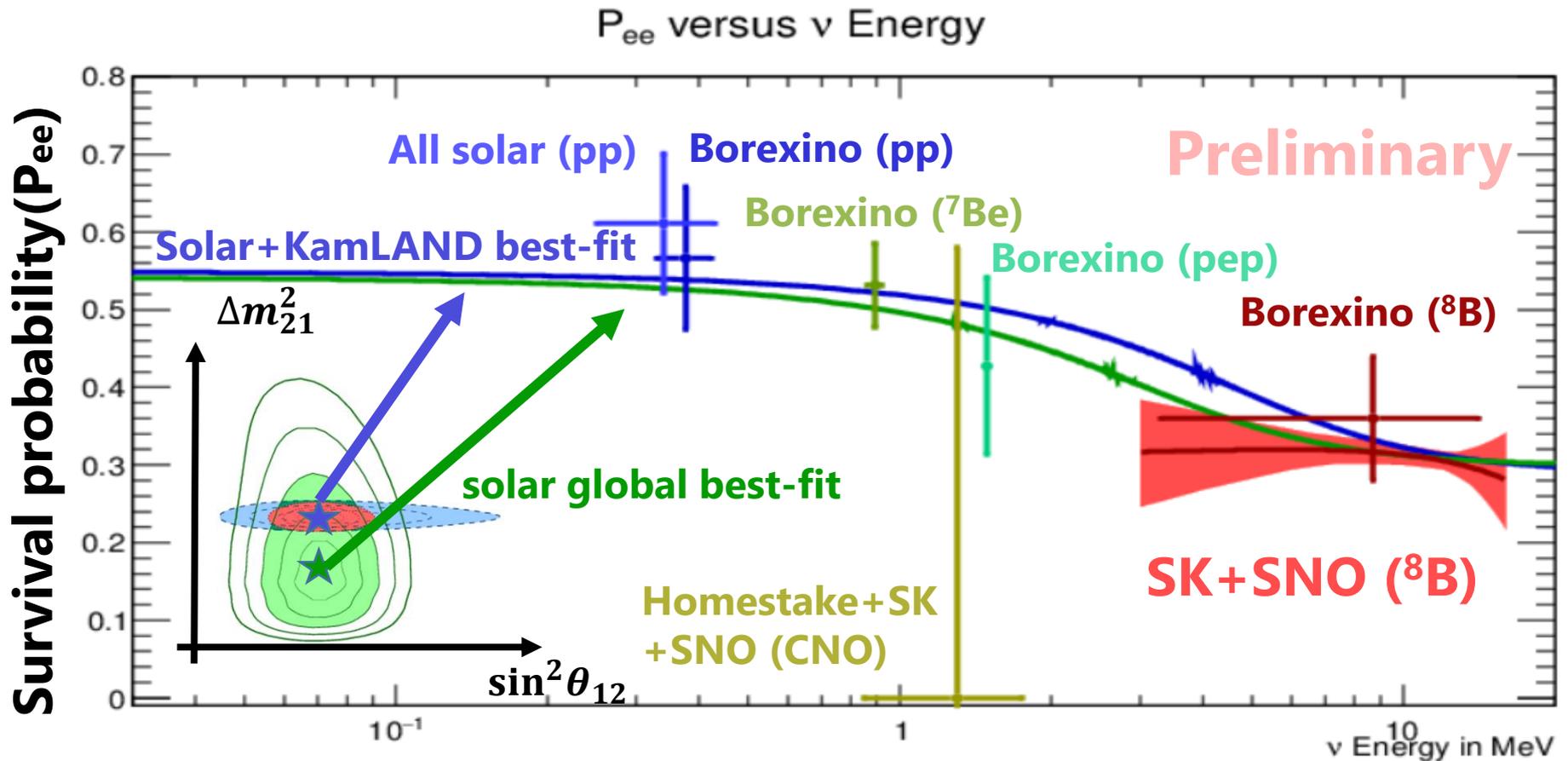
Future prospects (SK-Gd)

■ **Supernova relic neutrino (SRN)**

- **SRN is generated from past supernova bursts.**
- **Further background reduction is required to search for SRN.**
- **Search for $\overline{\nu}_e + p \rightarrow e^+ + n$ using delayed coincidence technique.**
→ **Tagging neutron by adding Gadolinium into Super-Kamiokande.**

Window: 10-30 MeV

Upper limits
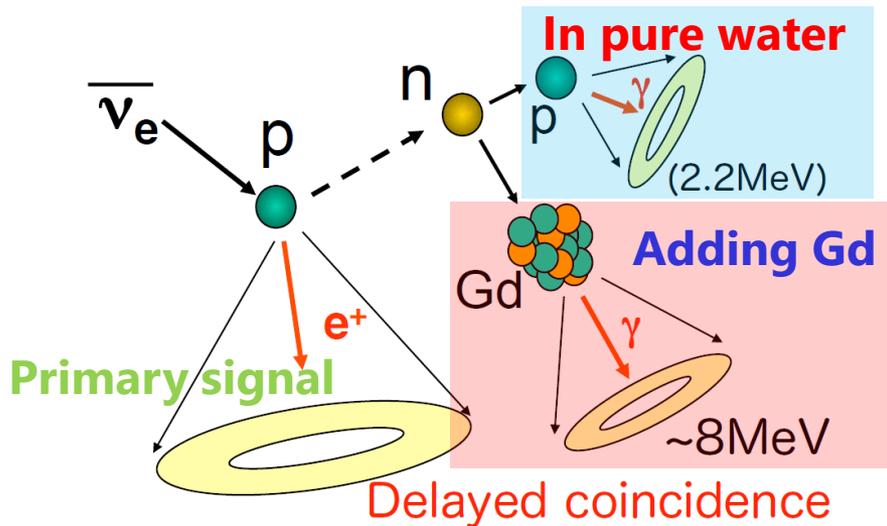
Theoretical model
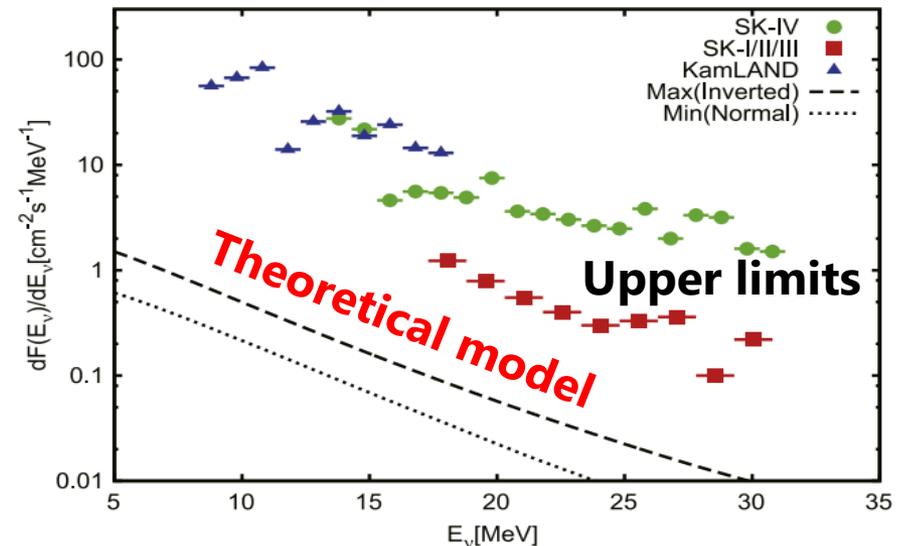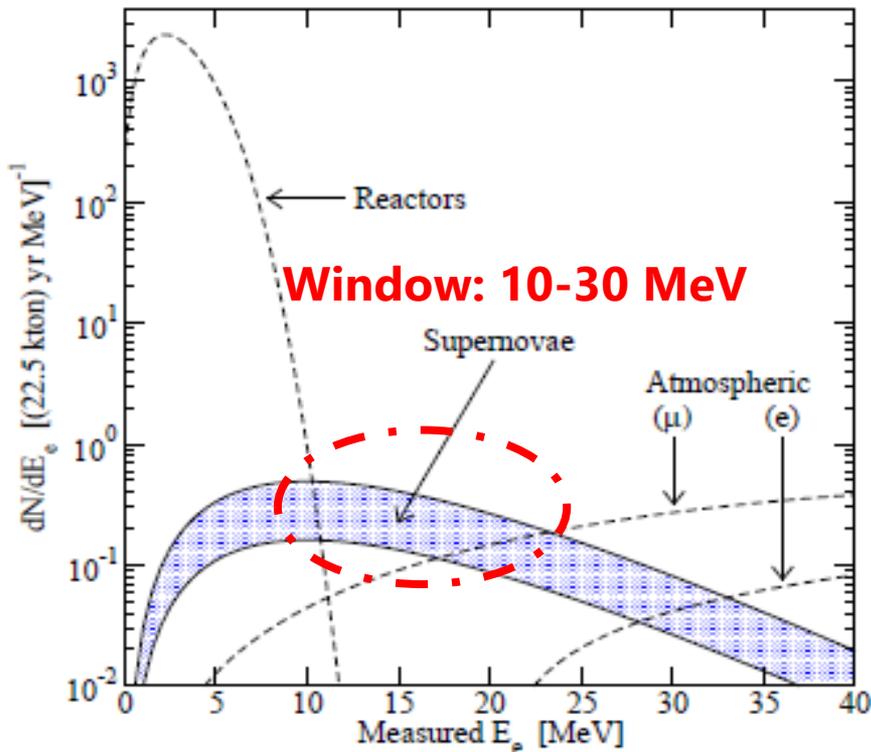
Figure 1. 90% C.L. differential upper limits on $\overline{\nu}_e$ flux of SRNs. The squares, circles and triangles are results for Super-Kamiokande (SK-I/II/III, Bays et al. 2012), Super-Kamiokande with a neutron-tagging (SK-IV, Zhang et al. 2015) and KamLAND (Gando et al. 2012). Dashed and dotted lines correspond to our theoretical models with maximum and minimum values of SRN event rate, respectively (see also Table 3).
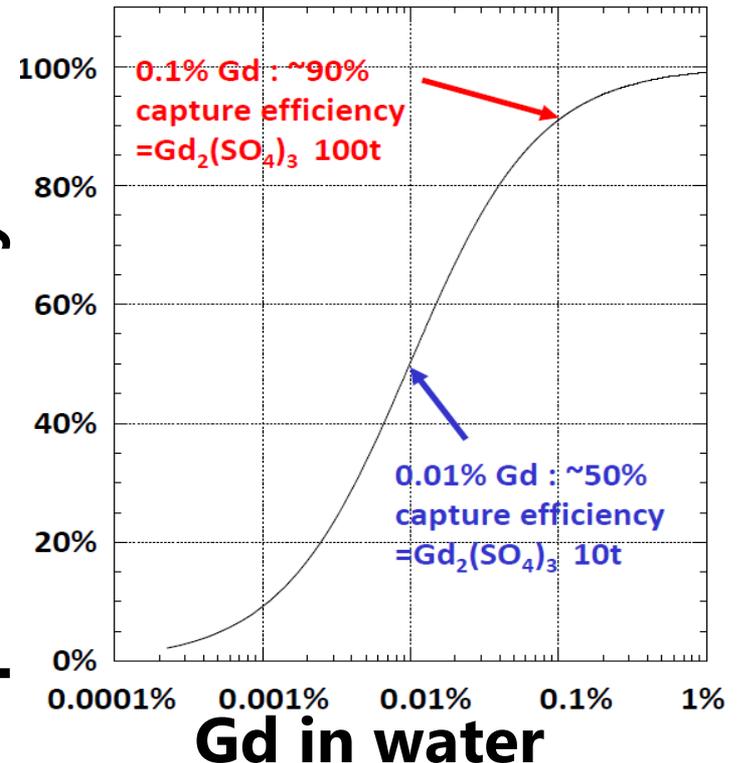
Phys. Rev. Lett. 93 (2014) 171101.   **Astrophys. J. 804 (2015) 75.**

Why Gadolinium (Gd)

■ **Neutron tagging**

- Neutron tagging with hydrogen (free proton) is **only ~18% in SK**.
  → Because of small energy of γ-ray (2.2 MeV).
- Gd has a large thermal-neutron cross section.
  → Possible to **identify $\overline{\nu}_e$ interaction** with delayed coincidence.
  → Large background reduction is expected for $\overline{\nu}_e + p \to e^+ + n$.

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

In pure water

(2.2MeV)

Adding Gd

Gd

~8MeV

Primary signal

Delayed coincidence

Time difference: ~30 μsec, Vertex : ~50 cm.

Capture efficiency on Gd

0.1% Gd : ~90% capture efficiency =Gd$_2$(SO$_4$)$_3$ 100t

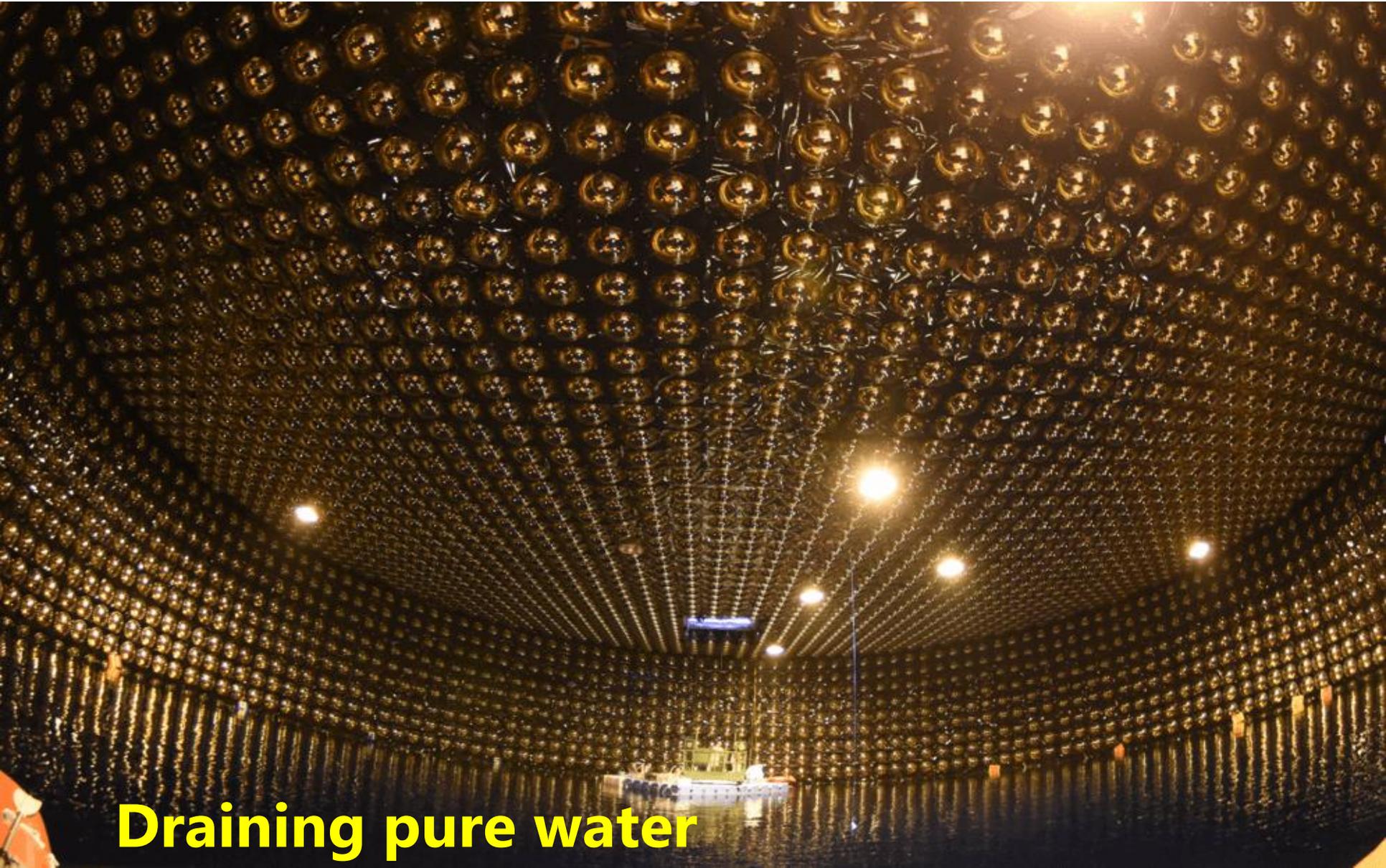0.01% Gd : ~50% capture efficiency =Gd$_2$(SO$_4$)$_3$ 10t

Gd in water

Time table for SK-Gd project

■ **Tank refurbish work and future plan**
 - **Refurbish work has started since May 31st.**
  → **For water leakage fixing & replacement of broken PMTs**
 - **Dissolving Gd into SK is expected in late 2019 (earliest case).**

2018	2019?	202X	202X+1

Tank Refurbishment started on May 31st

Water filling purification

Physics data taking (Pure water)

10 ton of $Gd_2(SO_4)_3 \cdot 8H_2O$

Physics data taking (0.02% $Gd_2(SO_4)_3 \cdot 8H_2O$)

90 ton of $Gd_2(SO_4)_3 \cdot 8H_2O$

Stabilize water quality

Physics data taking (0.2% $Gd_2(SO_4)_3 \cdot 8H_2O$)
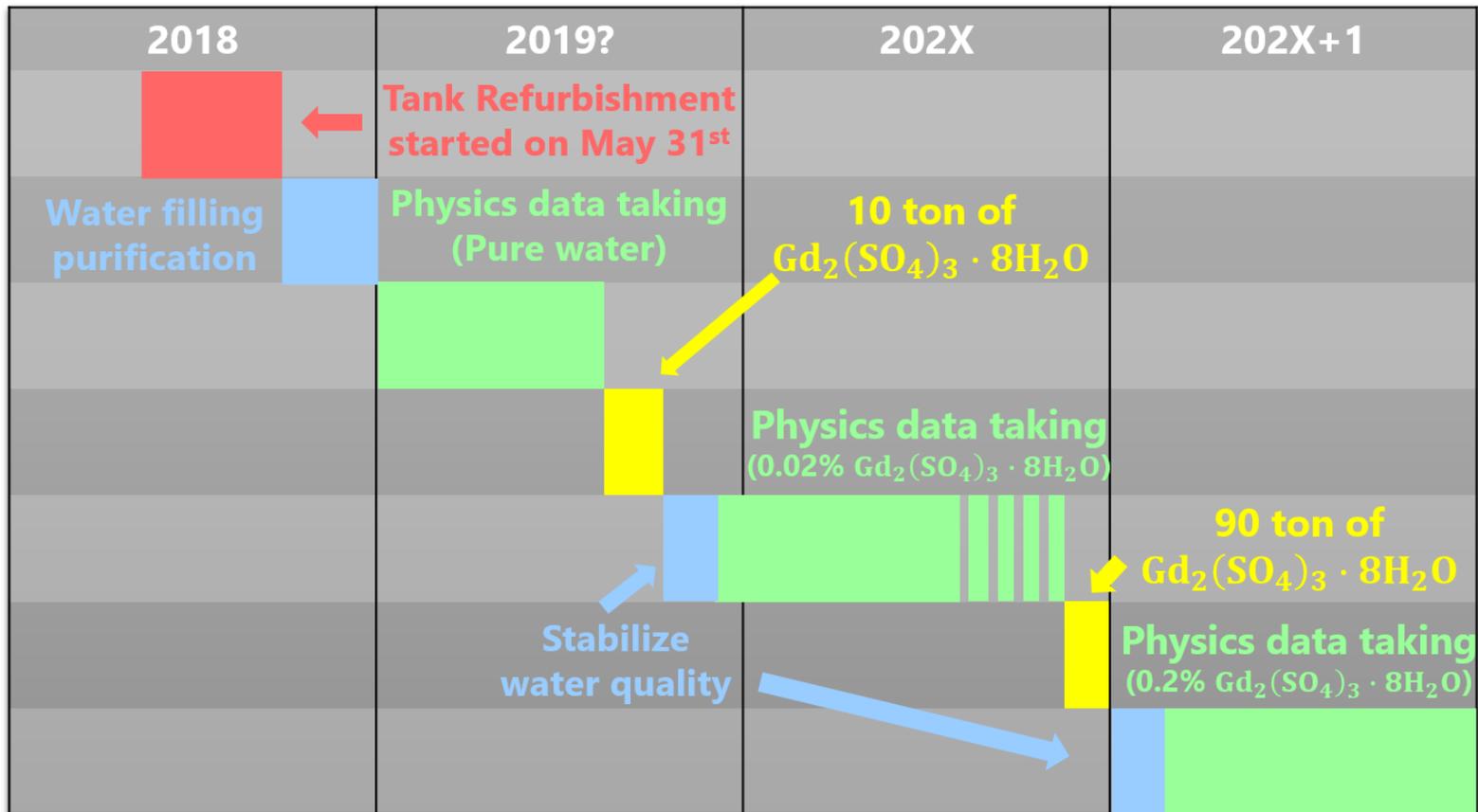
Current status of refurbish work

Draining pure water

Current status of refurbish work

■ PMT replacement

20-inch ID PMT

8-inch OD PMT

■ Water leakage fixing

Sealant materials are used to fix water leakage from welding point.

OD region
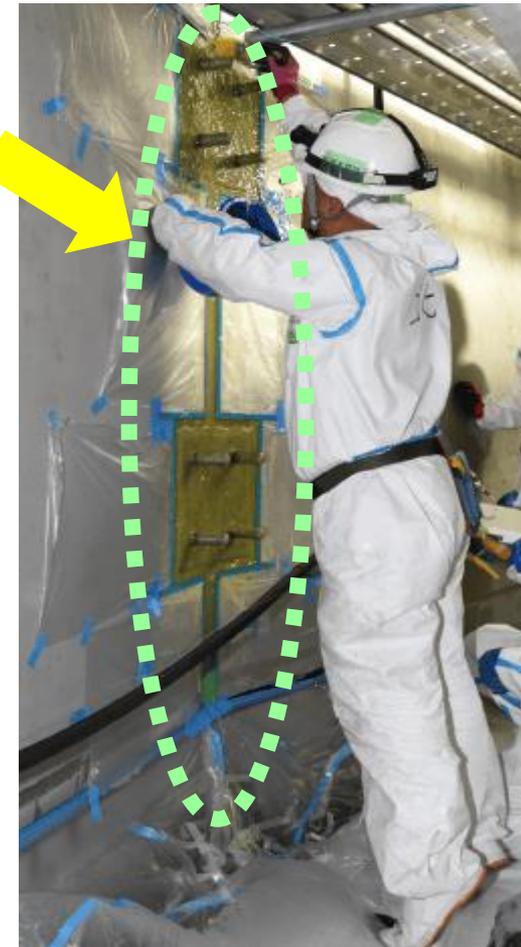
Summary

- **Super-Kamiokande is the multi-purpose detector.**
  - → **Many physics targets, such as neutrino, proton decay and so on.**

- **Atmospheric neutrino**
  - → **Mass hierarchy: Preference to Normal hierarchy**
    $$\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2 \text{ (SK+T2K).}$$
  - → **Tau neutrino appearance: Significance of signal 4.6σ.**

- **Solar neutrino**
  - → **No significant correlation with the solar activity.**
  - → **2σ tension in** Δm^2_{21} **between the solar global and KamLAND.**

- **Future prospect**
  - **Refurbish work toward SK-Gd is on-going.**
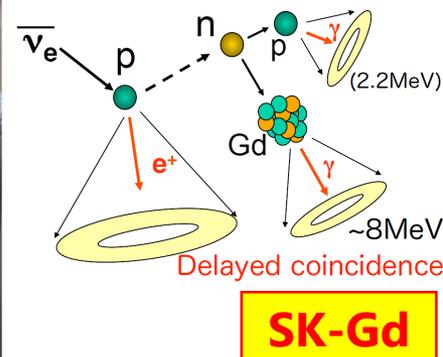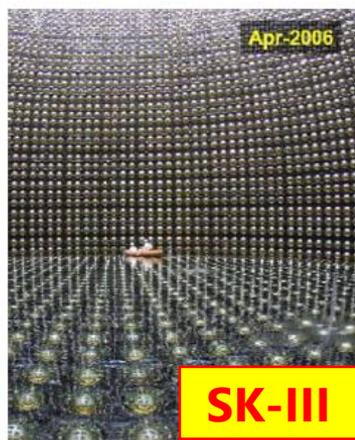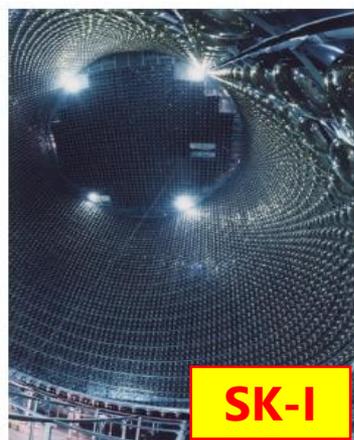 - **Resume data taking in early 2019.**

Back up slides

History of Super-Kamiokande

■ **Brief history and current status**

- **SK-I started on 1996 April and SK-IV ended on 2018 May.**
- **Total live time is more than 5,500 days.**
- **Refurbishment works toward SK-Gd have started since May 31st.**

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
SK-I						SK-II				SK-III			SK-IV										SK-Gd	
PMT 11,146 (40%*)						5,182 (19%*)				11,129 (40%*)														
4.5 MeV**						6.5 MeV**				4.0 MeV**			3.5 MeV**											

* Photo coverage [%], ** Recoil electron kinetic energy [MeV].

SK-I

Aug-2002
Acrylic (front) + FRP (back)
SK-II

Apr-2006
SK-III

SK-IV

$\overline{\nu}_e$ n p γ (2.2MeV)
p e+
Gd γ ~8MeV
Delayed coincidence
SK-Gd

# 3-flavor neutrino oscillation

■ Neutrino oscillation

- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.
- Mixing parameters (angles, mass splitting) has been measured by many neutrino experiments.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

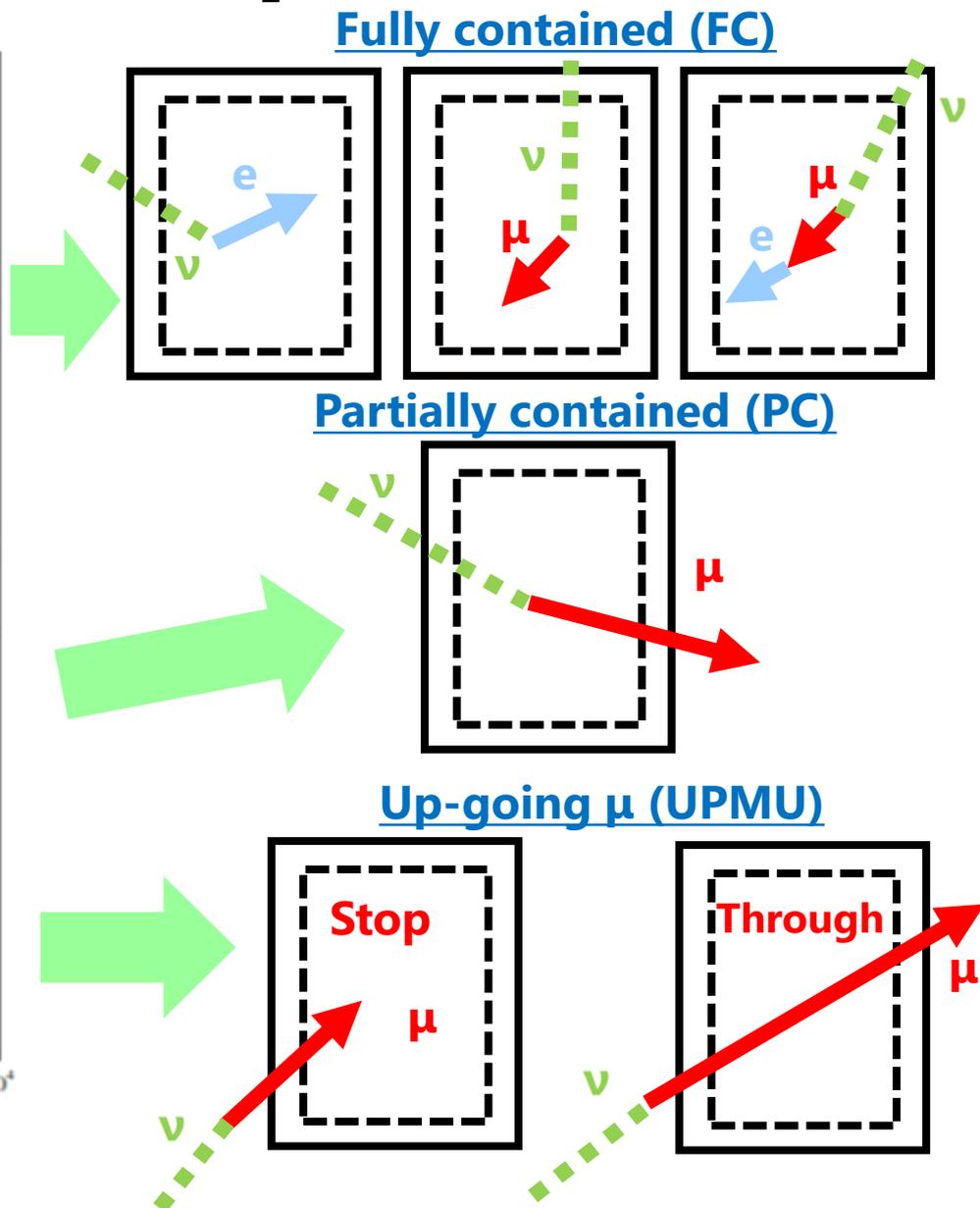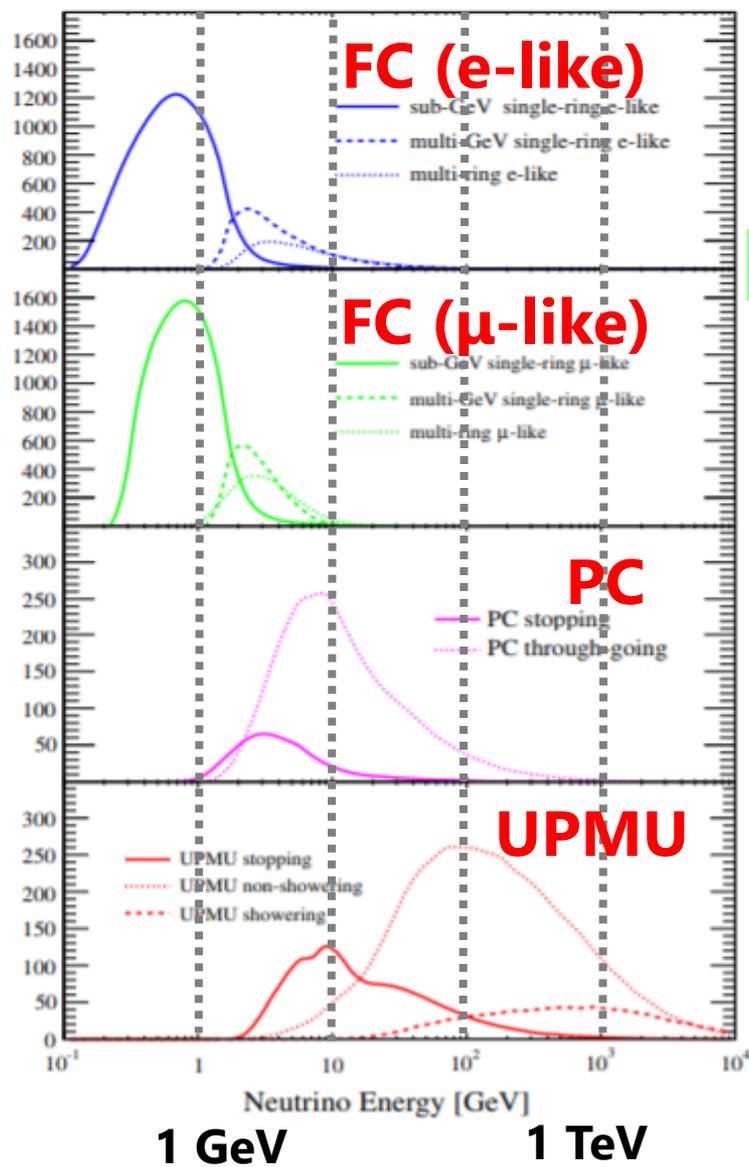Atmospheric, Accelerator　　Reactor, Accelerator　　Solar, Reactor (KamLAND)

■ Unknown things

- **CP violation phase (δ)** in the lepton sector.
- **Mass hierarchy** (Normal/Inverted).
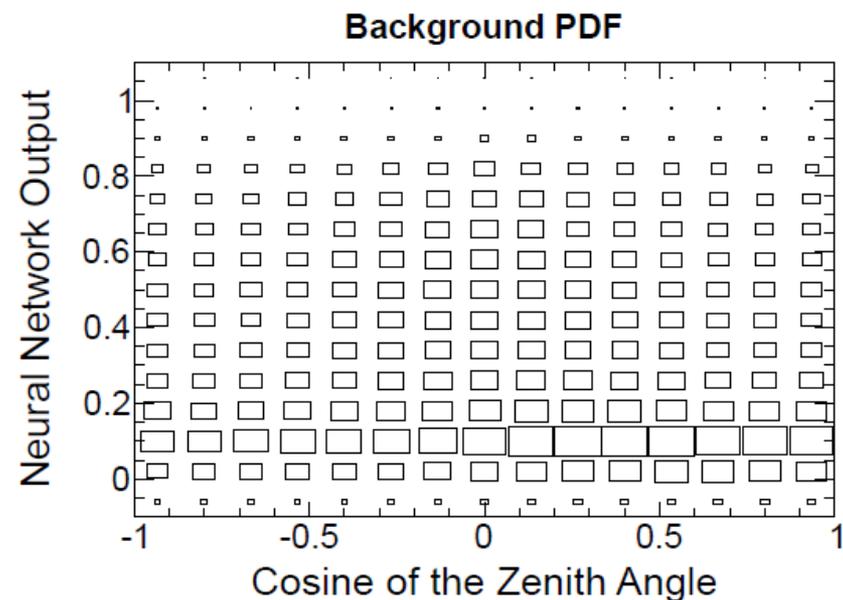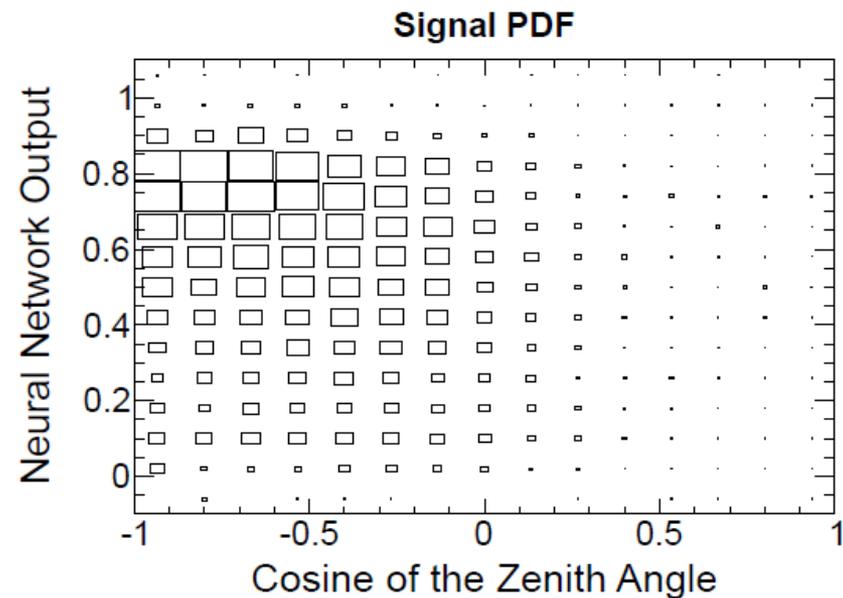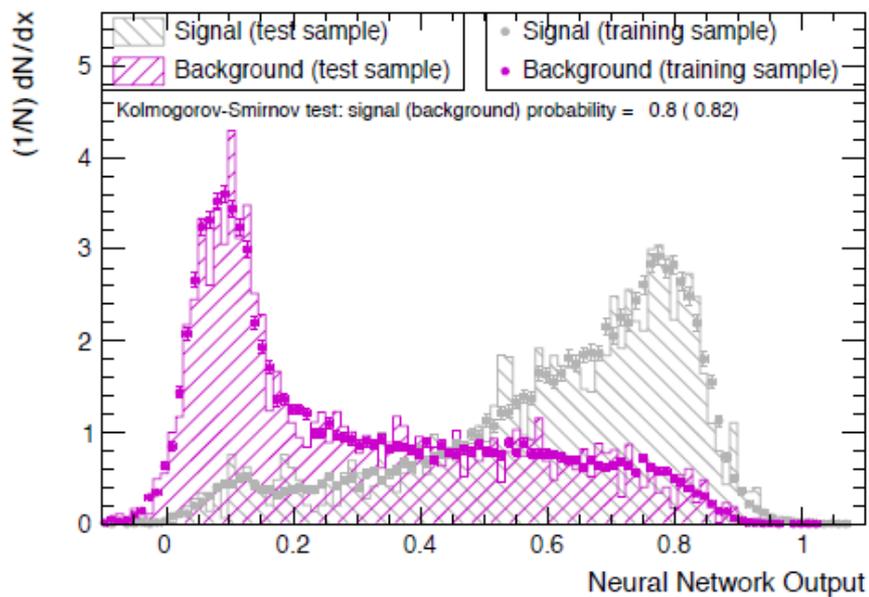- θ_{23} octant ($\theta_{23} \lessgtr \pi/4$).
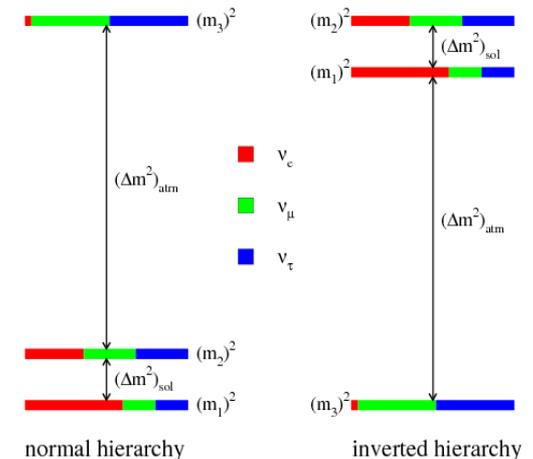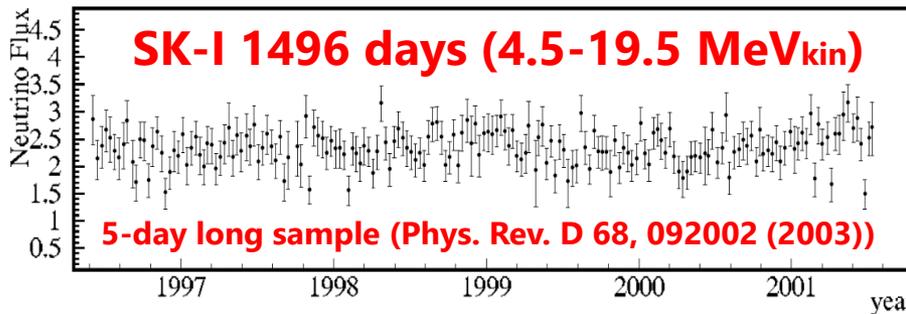
Topologies of atmospheric ν events

Tau signal discrimination

Periodic modulation analysis

- SK collaboration reported the time variation of 5-day long sample of the observed ^8B ν flux (Phys. Rev. D 68, 092002 (2003)).

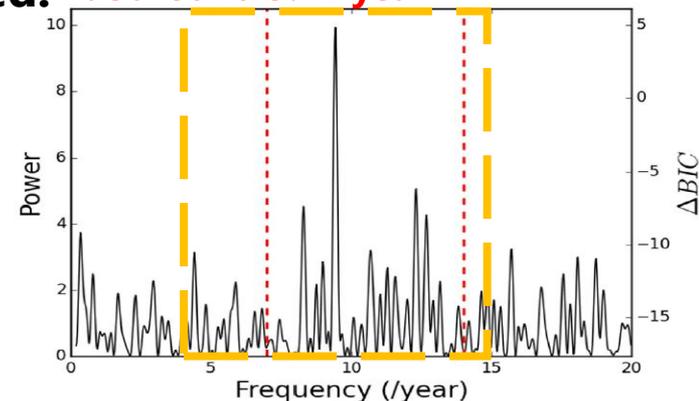- SK performed a periodic analysis using Lomb-Scargle (LS) method.

SK-I 1496 days (4.5-19.5 MeV$_{kin}$)

5-day long sample (Phys. Rev. D 68, 092002 (2003))

LS method

No clear periodic signal 5-15 year^{-1}.

SK analysis result
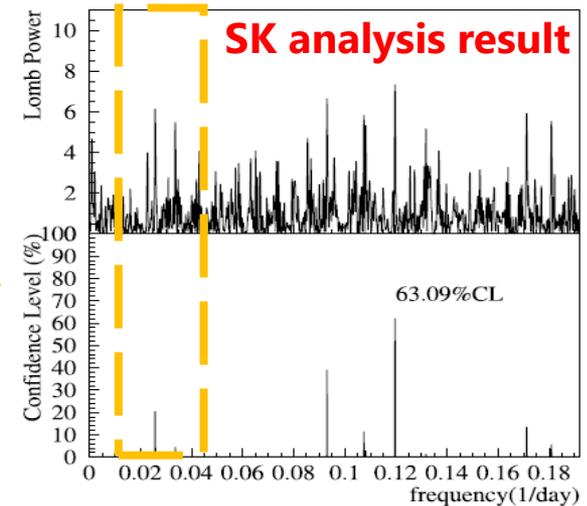
Several researchers found a peak at around 9.42 year^{-1}

- Several papers reported that a maximum peak is observed at around 9.42 year^{-1} .
  - Cf.) Astropart. Phys. 82, 86-92 (2016).
  - Generalized Lomb-Scargle (GLS) method is used.

- SK has reanalyzed SK-I data with GLS method provided by astroML.

- SK-IV data is also analyzed with GLS.

Periodic modulation results

- **Using the Generalized LS method, both SK-I and SK-IV are analyzed.**
- **5-day long sample is made from SK-I data and SK-IV data.**
  - **SK-I: 1496 days data (4.5-19.5 MeV$_{kin}$), Phys. Rev. D 68, 092002 (2003).**
  - **SK-IV: 1664 days data (4.5-19.5 MeV$_{kin}$), Phys. Rev. D 94, 052010 (2016).**
- **Search region 5-15 year^{-1}.**
- **Maximum peak at around 9.42 year^{-1} is not found in SK-IV.**

Preliminary

Black: SK-I
Red: SK-IV
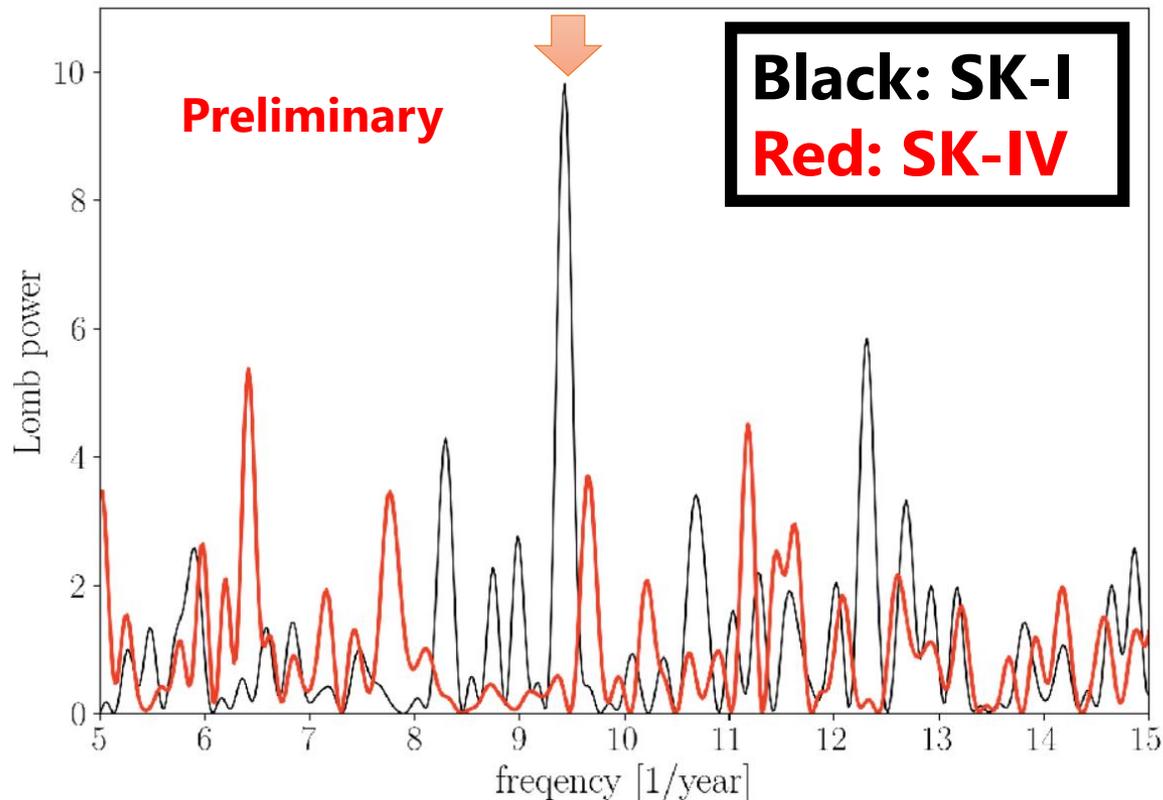
Survival probability & oscillation parameters

■ **Shape of energy spectrum**

- **Energy spectrum shape is sensitive to the oscillation parameters.**
- **SK uniquely selects MSW-LMA region by more than 3σ.**
  (While SNO can selects LOW solution within 3σ)