The latest results from the Super-Kamiokande experiment

2018 August 7th (Tue)

25th Anniversary of the Rencontres du Vietnam

WINDOWS ON THE UNIVERSE 2018@Quy Nhon, Vietnam

Yuuki Nakano for the Super-Kamiokande collaboration

(Kamioka Observatory, ICRR, The University of Tokyo)

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Contents

Super-Kamiokande collaboration

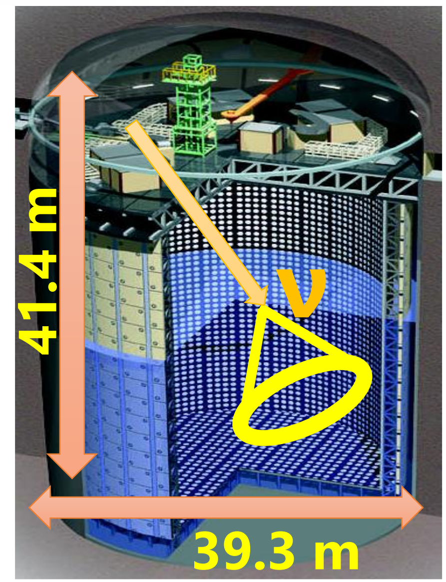
~165 people
45 institutes, 9 countries

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.
- Many physics targets: neutrino, proton decay…



■ History of SK

- Long term operation since 1996 (~22 years).
- 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].

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

- Flux & 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)*.
- $p \rightarrow e^+\pi^0$ and $p \rightarrow \mu^+\pi^0$: *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)*.

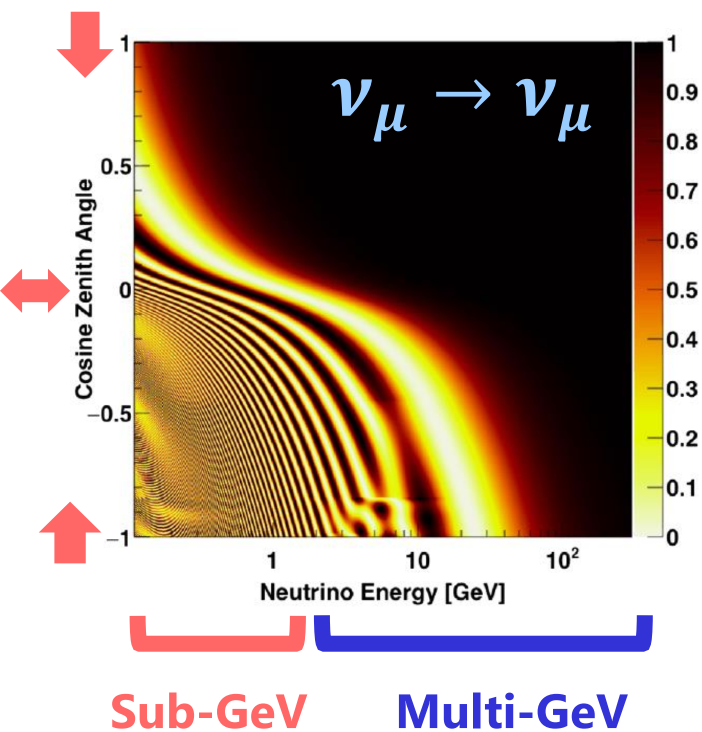
■ Others (Dark matter search, Sterile ν and Lorentz invariance…)

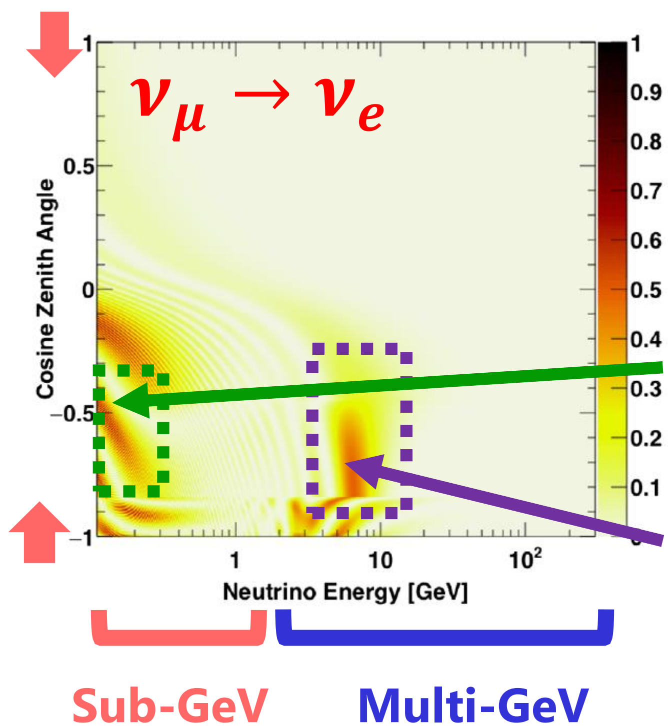
More detail: http://www-sk.icrr.u-tokyo.ac.jp/sk/publications/index.html

Atmospheric neutrino in SK

■ Oscillation probability and sub-leading effects

- SK has sensitivity to all PMNS parameters.
  → Atmospheric ν oscillation is **dominated by $\nu_\mu \rightarrow \nu_\tau$** $(\Delta m^2_{23}, \theta_{23})$.
- 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.





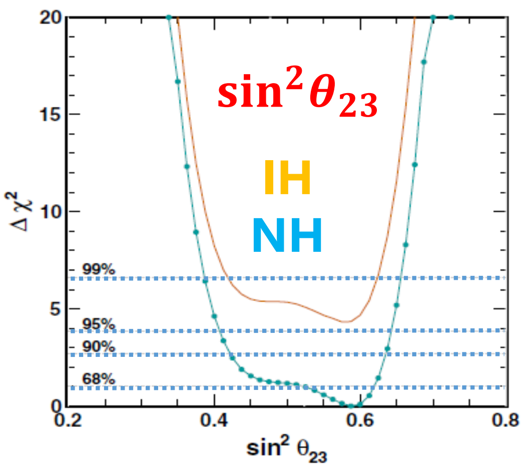
Due to solar term.
Flux normalization
changes by CP phase.

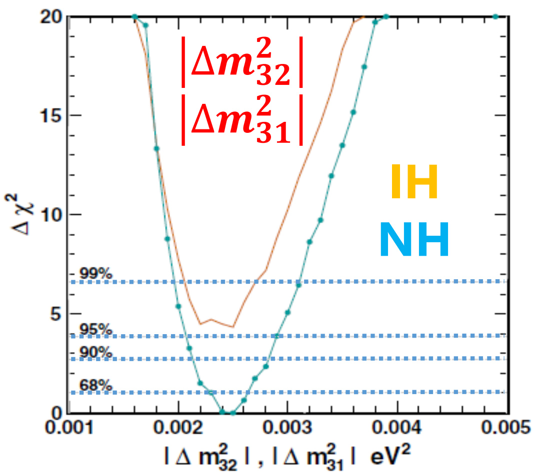
Resonant oscillation
due to finite θ_{13}.
Enhancement of ν_e
when normal hierarchy.
($\bar{\nu}_e$ when inverted)

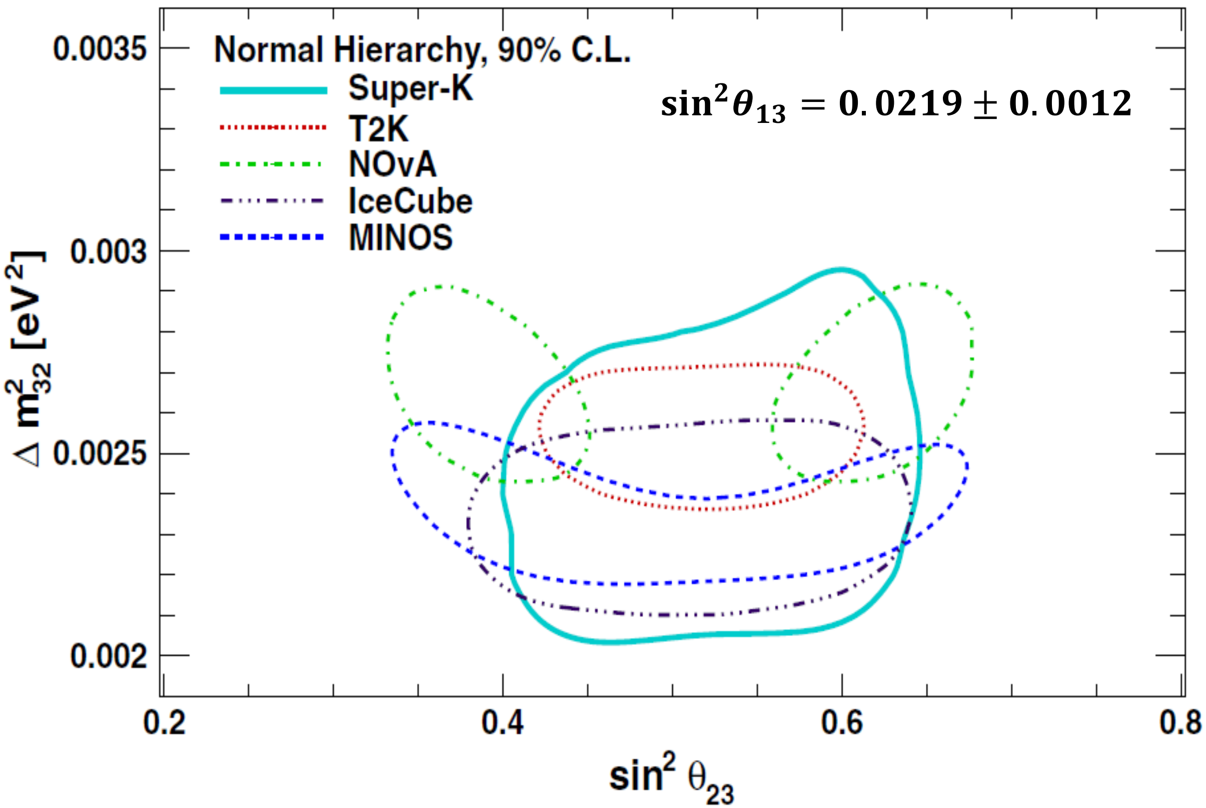
Neutrino oscillation analysis

■ Oscillation analysis (Only SK data)

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





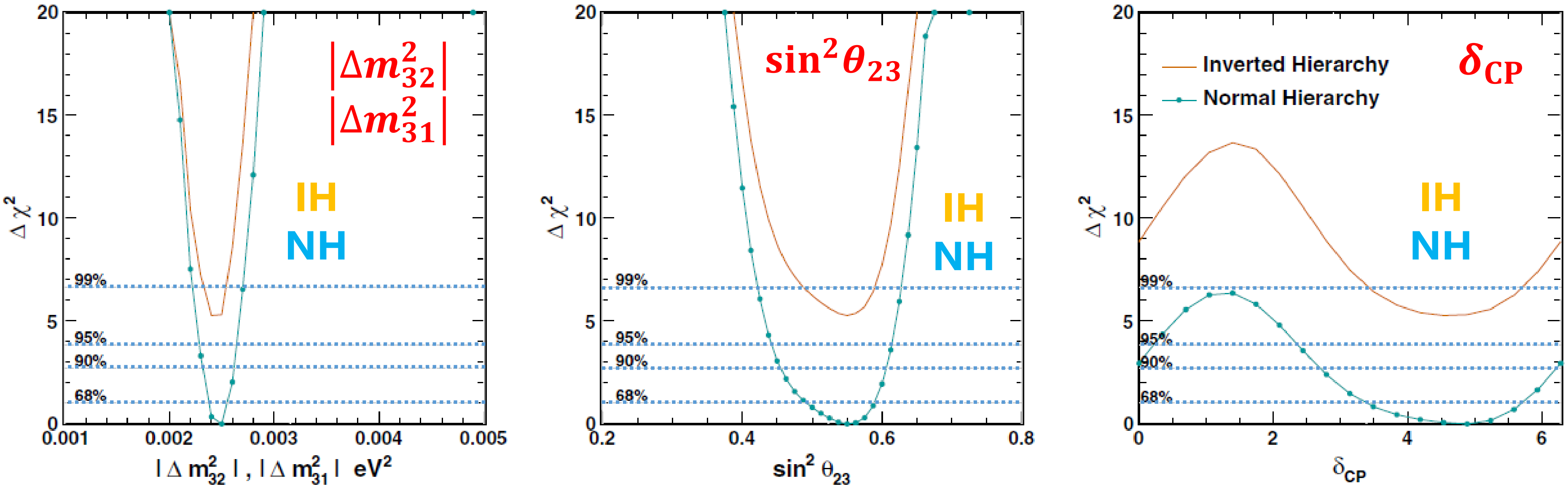


Other experiments results → before Neutrino2018

Neutrino oscillation analysis

■ Oscillation analysis with external constraint

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



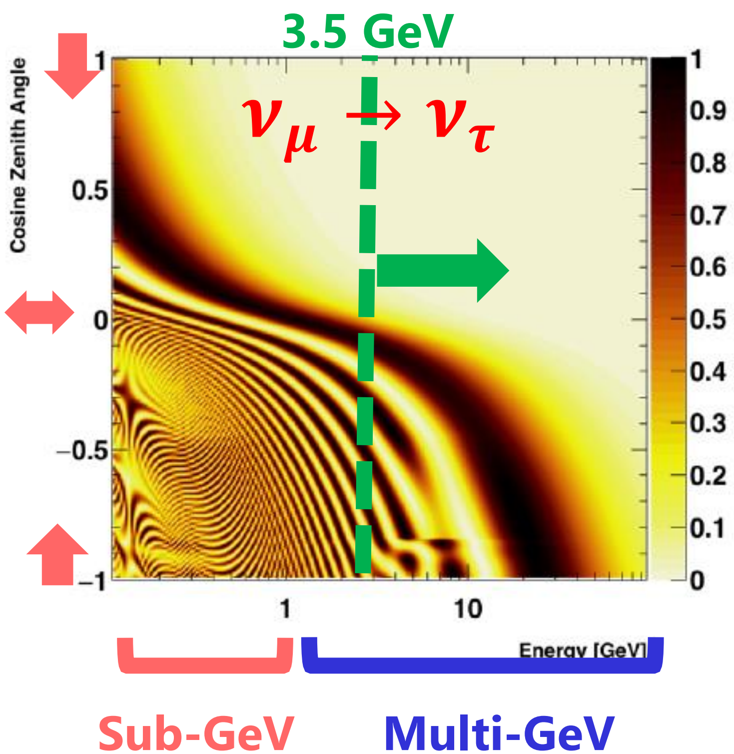
$\sin^2\theta_{13} = 0.0219 \pm 0.0012$ (fix)

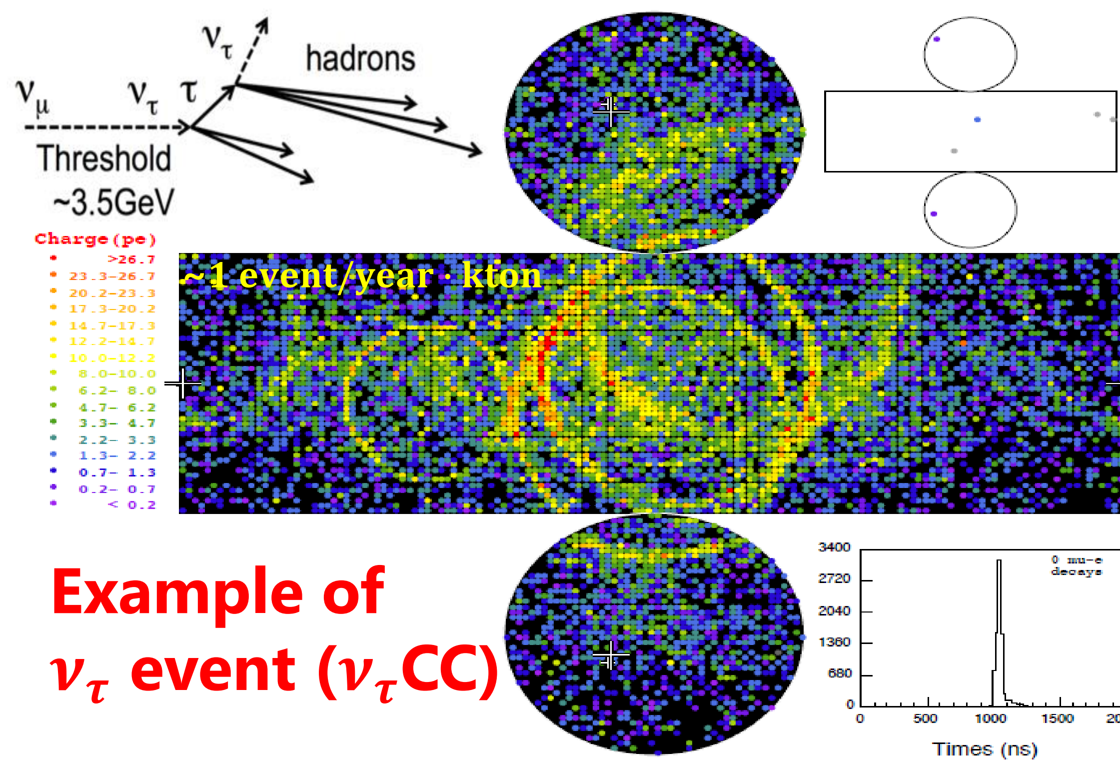
Mass hierarchy	χ^2	$\lvert\Delta m^2_{32,31}\rvert$ [$\times 10^{-3}$ eV^2]	$\sin^2\theta_{23}$	δ_{CP}
Normal	639.43	$2.50^{+0.05}_{-0.12}$	$0.550^{+0.039}_{-0.057}$	$4.88^{+0.81}_{-1.48}$
Inverted	644.70	$2.40^{+0.13}_{-0.06}$	$0.550^{+0.035}_{-0.051}$	$4.54^{+1.05}_{-0.97}$

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.





Example of
ν_τ event (ν_τCC)

Signal and cross section

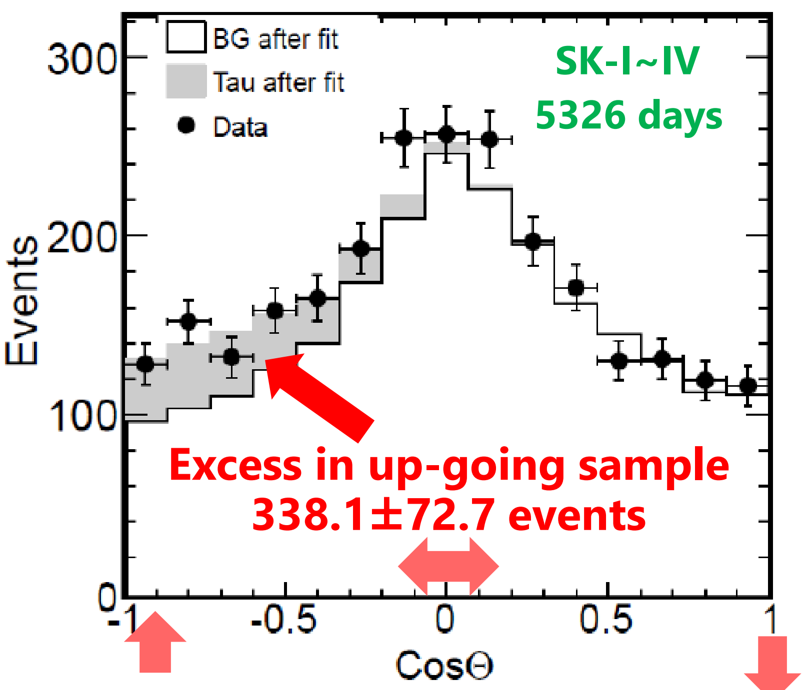
■ Analysis and its results

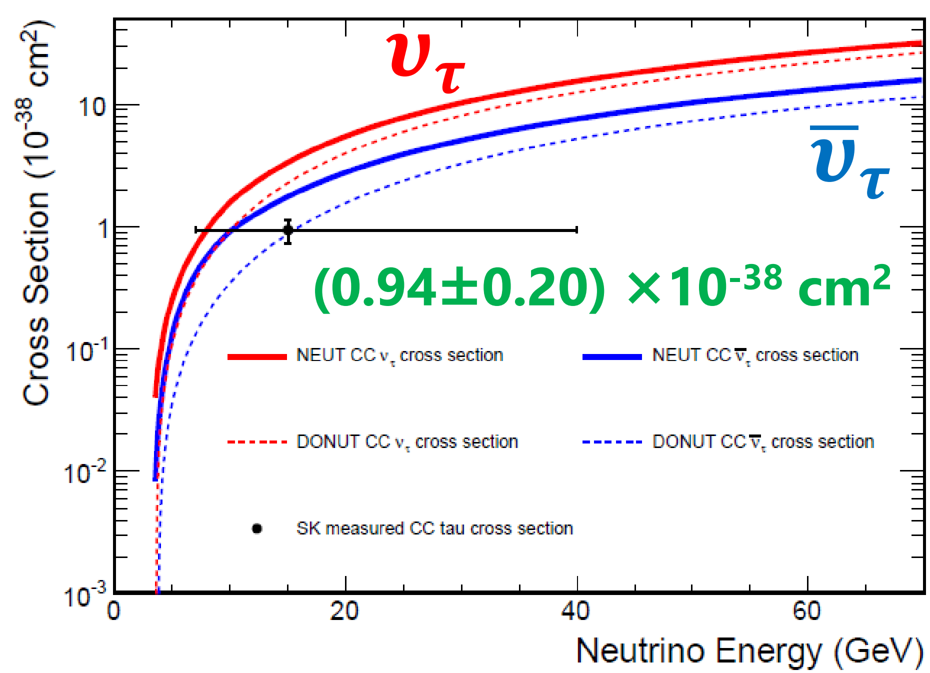
- Event selection is performed using Neural Network.
  → Discriminate tau signal from background: Efficiency 76%.
- 2D fit with signal scale parameter is evaluated.

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

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

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





Solar neutrino measurement in SK

■ Physics targets

(1) **Solar neutrino flux** measurement

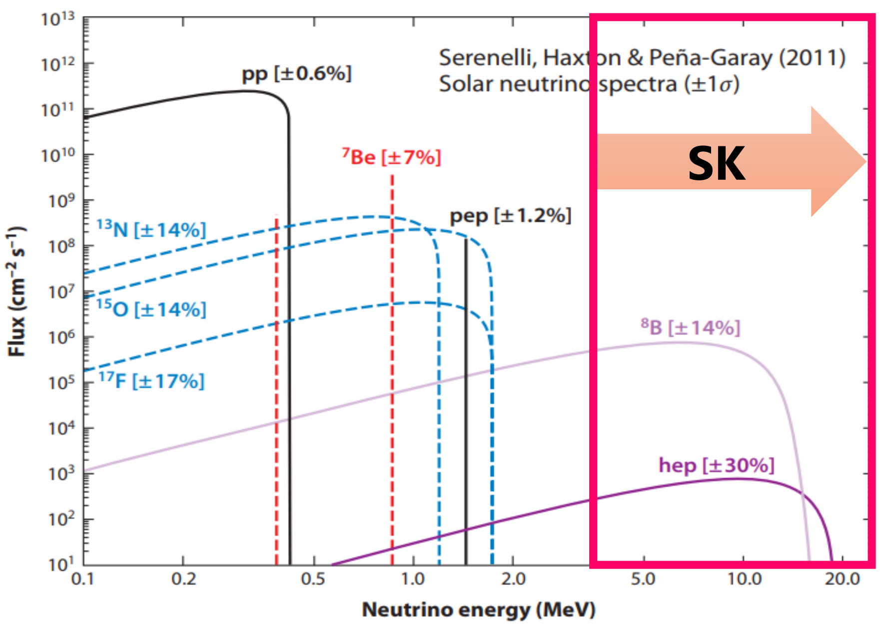
- Test any correlation with solar activity (sun spot number).

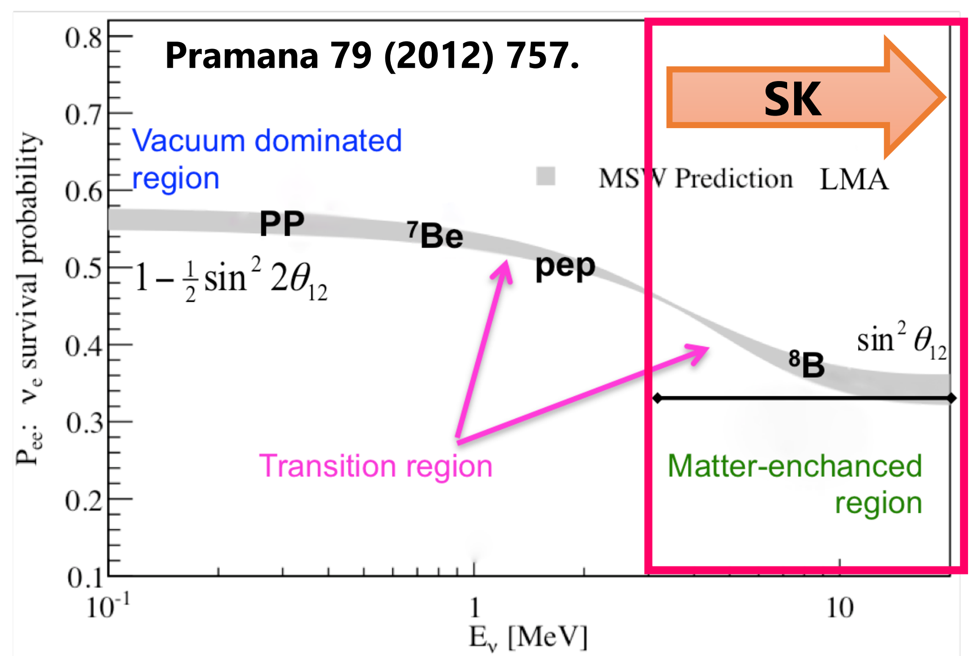
(2) Spectrum distortion (**Up-turn, MSW effect**)

- Test the transition of solar ν oscillation btw vacuum and matter.

(3) **Day-night flux asymmetry** (update is in progress)

- Observe the regeneration of ν_e due to the matter in the Earth.





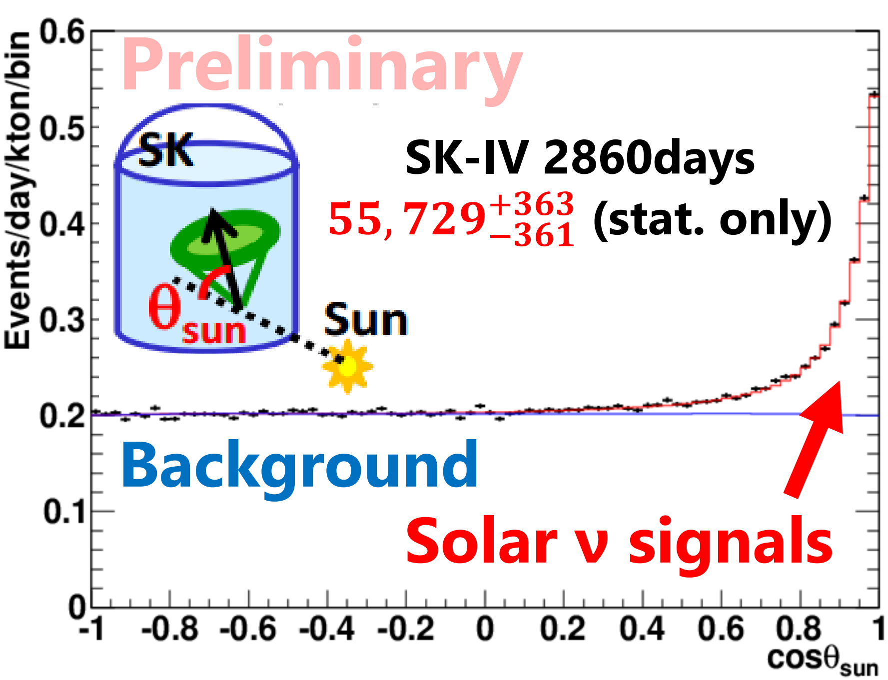
^{8}B solar neutrino flux

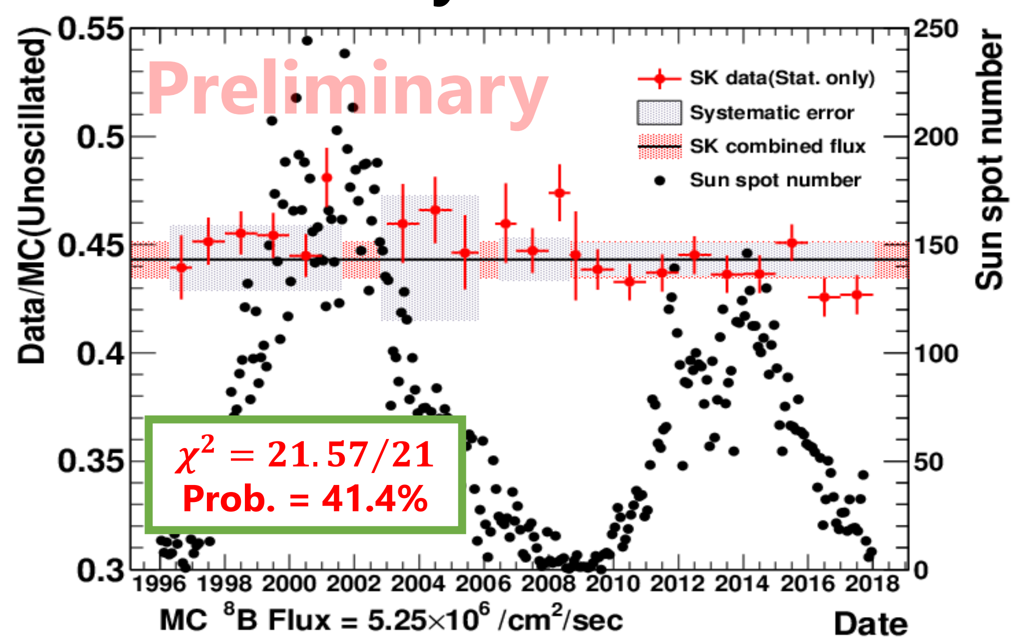
■ Flux measurements

- Elastic scattering: $\nu_X + e^- \rightarrow \nu_X + e^-$ (directional information).
  → Clear excess of ^{8}B solar ν event over the background level.
  SK flux/SNO NC flux = 0.4432±0.0084 (stat.+syst.).

■ Correlation of the flux with the solar activity

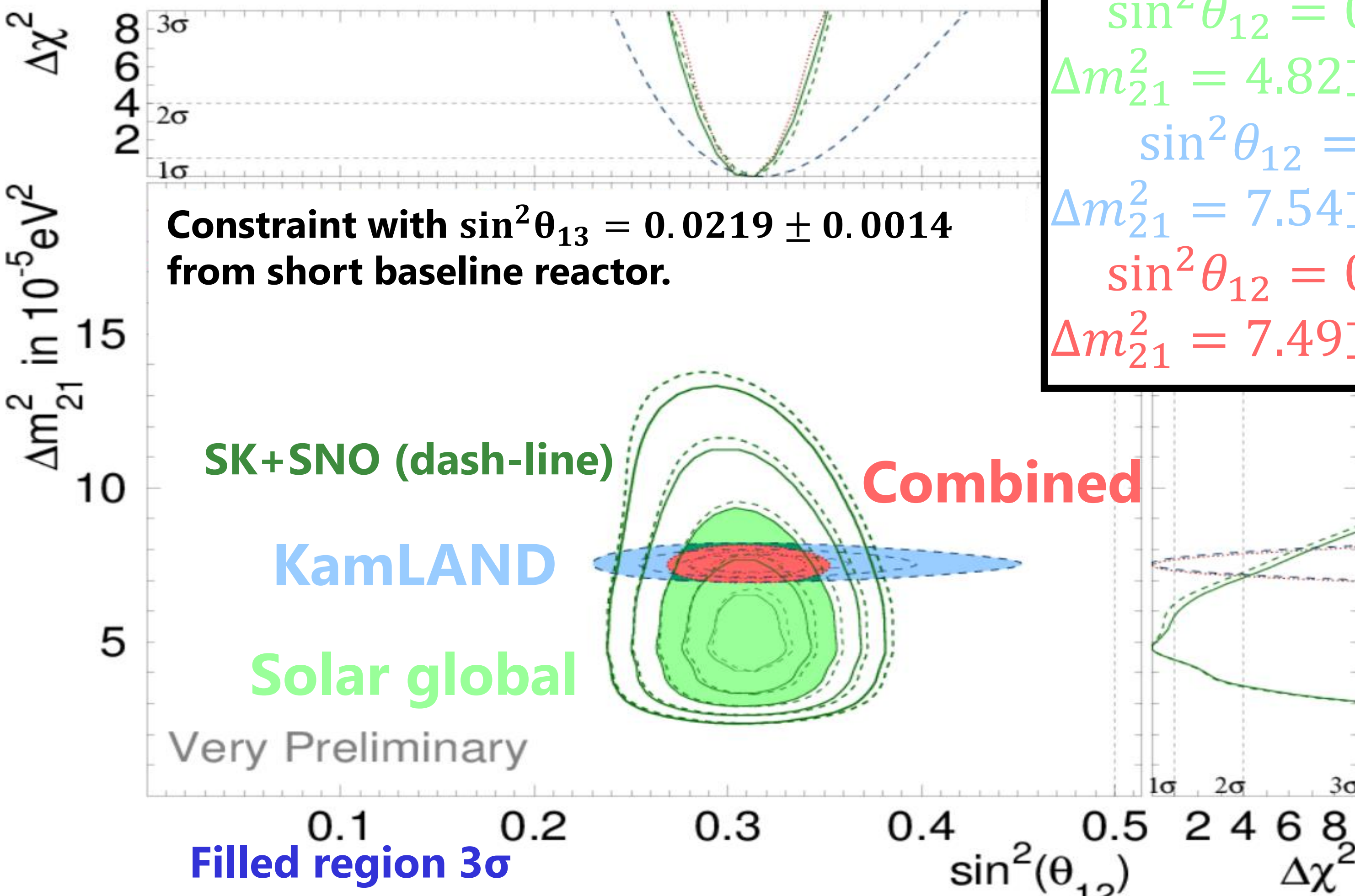
- Solar activity is strongly correlated with sunspot numbers.
- **No correlation** with the 11-years solar activity is observed.





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

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



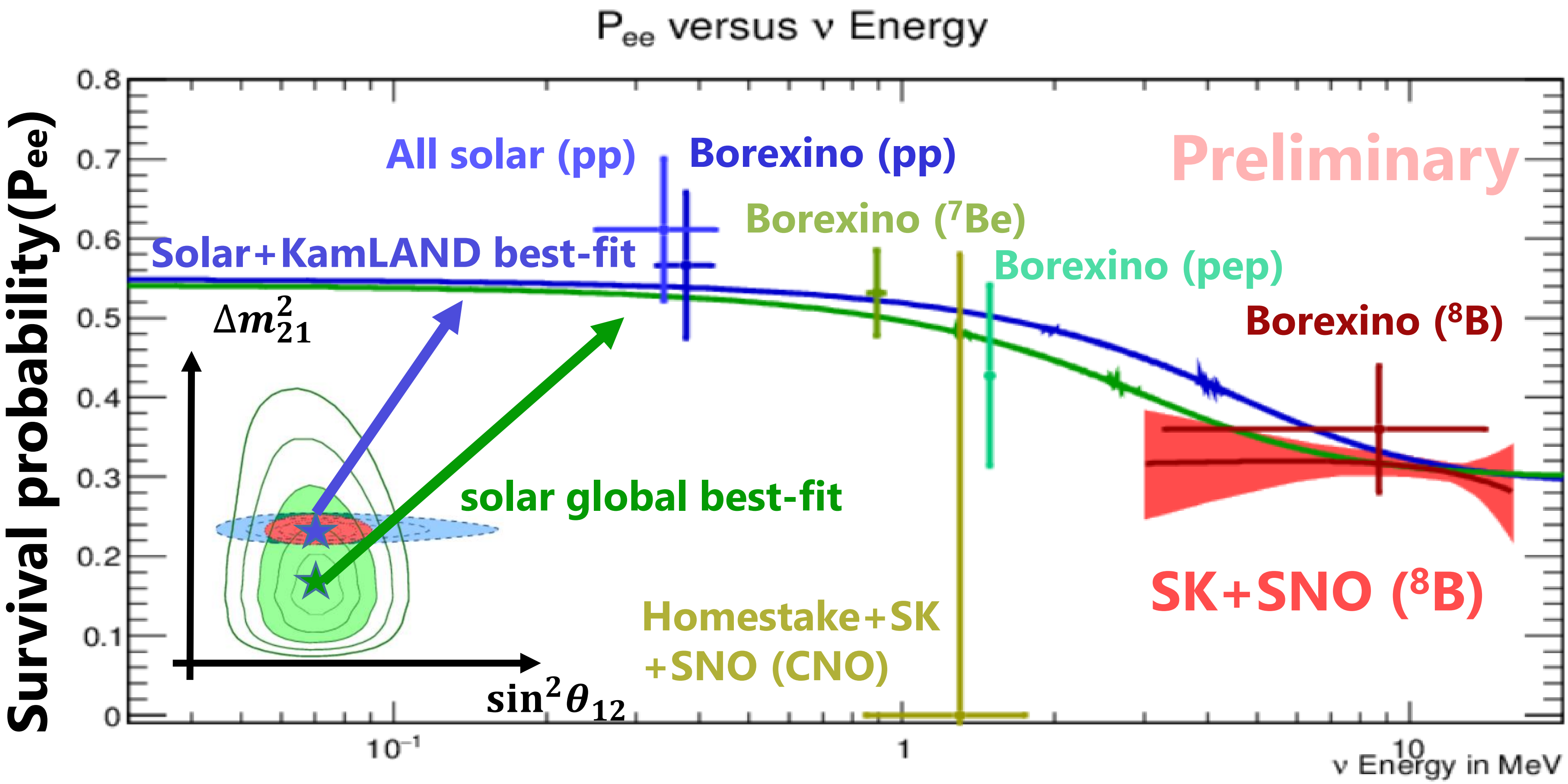
$\sin^2\theta_{12} = 0.310 \pm 0.014$
$\Delta m^2_{21} = 4.82^{+1.20}_{-0.60} \times 10^{-5}\ \mathrm{eV}^2$
$\sin^2\theta_{12} = 0.316^{+0.034}_{-0.026}$
$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\ \mathrm{eV}^2$
$\sin^2\theta_{12} = 0.310 \pm 0.012$
$\Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \times 10^{-5}\ \mathrm{eV}^2$

Oscillation parameters are determined using the latest solar ν data.
2σ tensition in Δm^2_{21} between the solar global and KamLAND.
Further precise measurement is required in future.

Allowed survival probability

■ Comparison among solar neutrino experiments

- Super-K's spectrum is consistent with solar Δm^2_{21} within 1.2σ, while it disfavors KamLAND Δm^2_{21} by 2.0σ.
- Strongest constraint on Pee shape when combining SK+SNO.

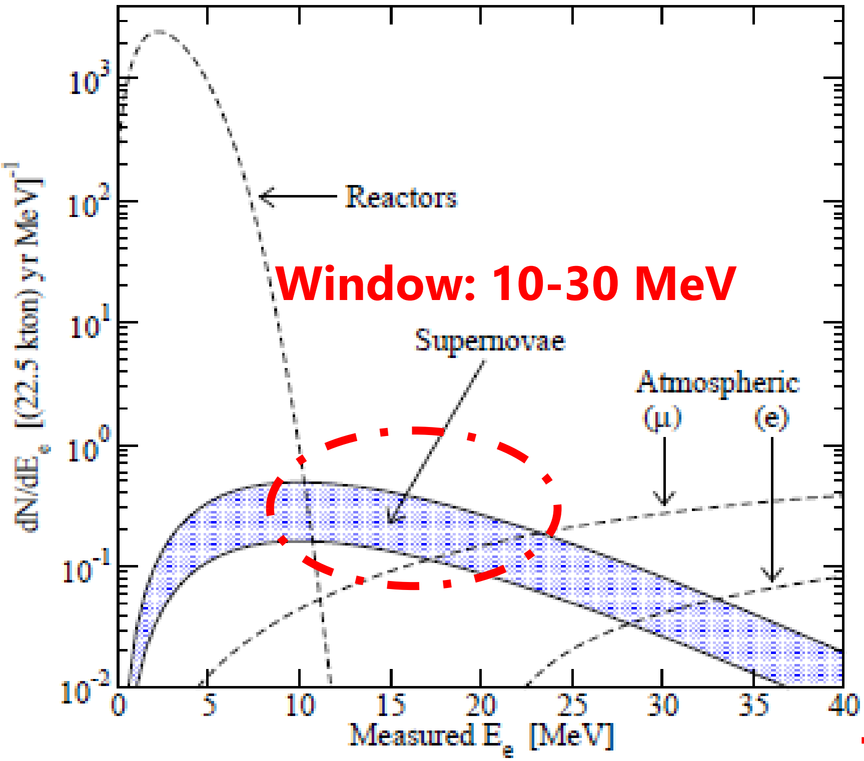


Future prospects (SK-Gd)

■ Supernova relic neutrino (SRN)

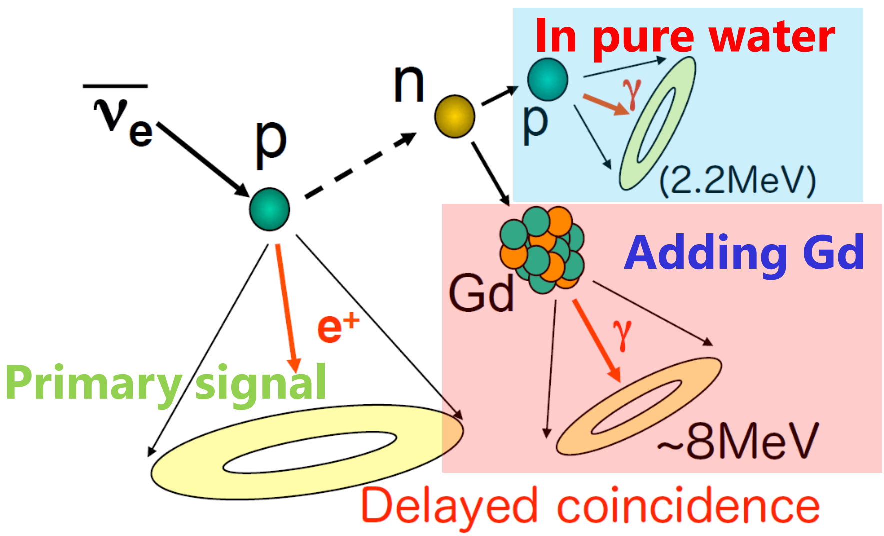
- SRN is generated from past supernova bursts.
- Further background reduction is required to search for SRN.
- Search for $\bar{\nu}_e + p \rightarrow e^+ + n$ using delayed coincidence technique.

→ **Tagging neutron** by adding **Gadolinium** into Super-Kamiokande.



Phys. Rev. Lett. 93 (2014) 171101.

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

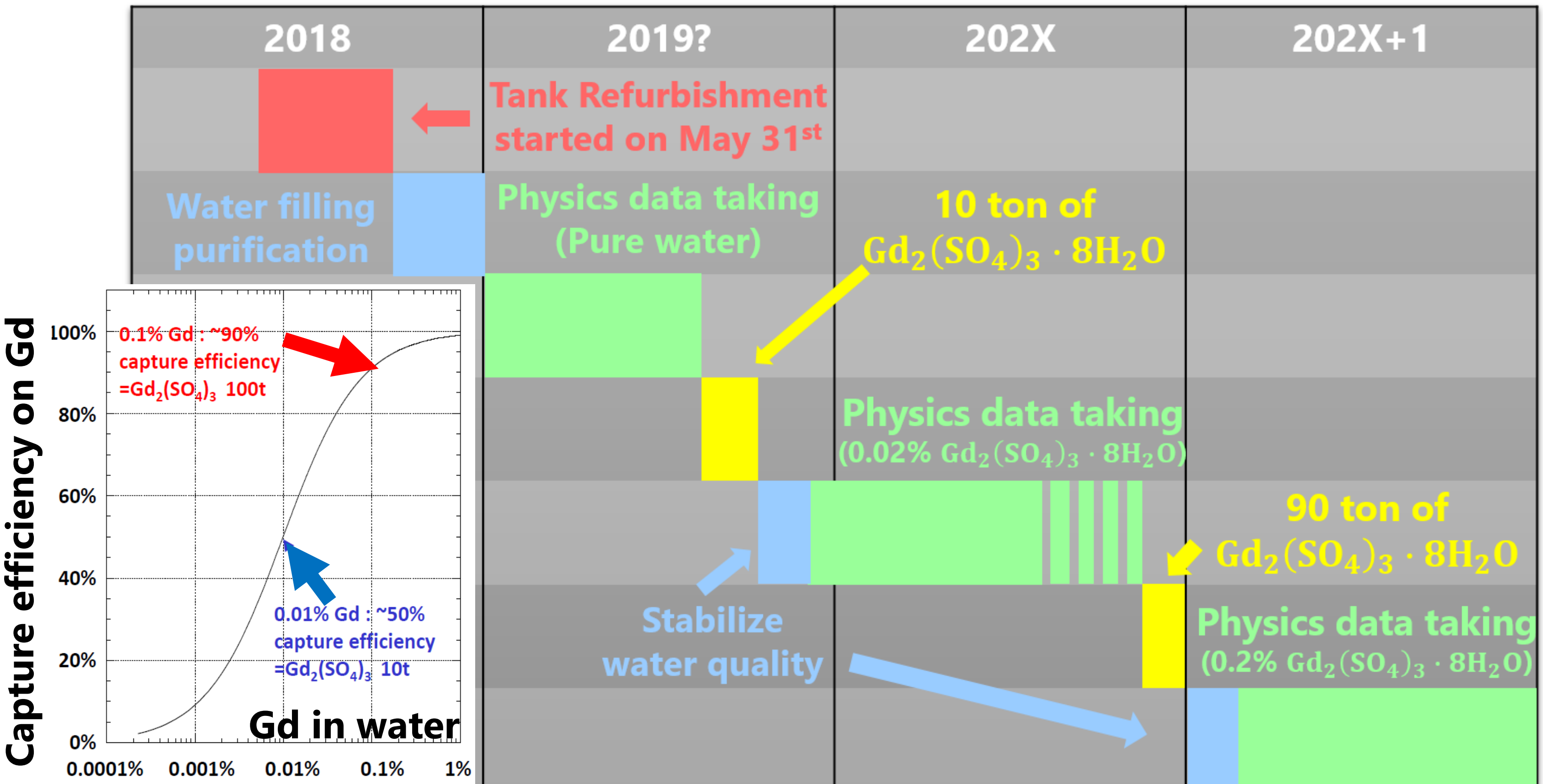


Time difference: ~30 μsec, Vertex : ~50 cm.

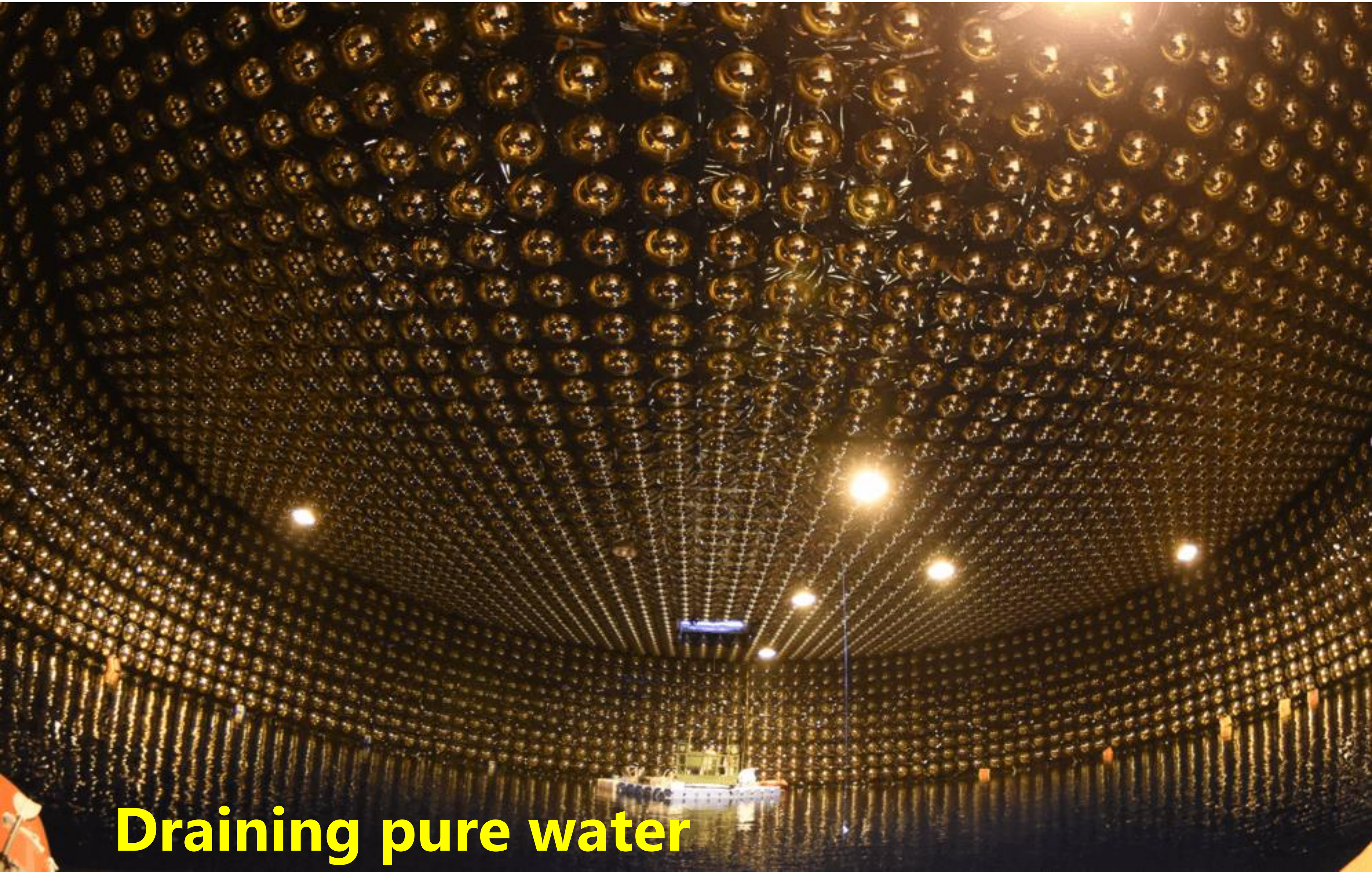
Time table for SK-Gd project

■ Tank refurbish work and future plan

- Refurbish work has started since May 31st, 2018.
  → For water leakage fixing & replacement of broken PMTs
- Dissolving Gd into SK is expected in late 2019 (earliest case).



Current status of refurbish work



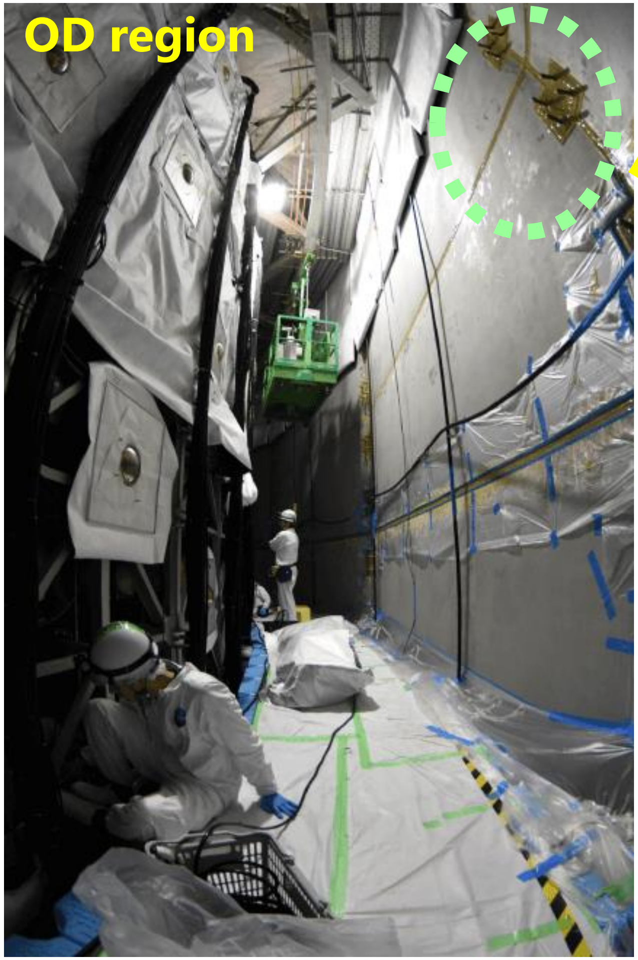
Draining pure water

Current status of refurbish work

■ PMT replacement

■ Water leakage fixing

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



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

- **Solar neutrino**
  → **No significant correlation with the solar activity.**
  → **2σ tensition 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

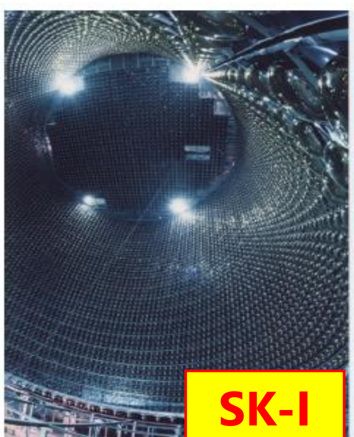
History of Super-Kamiokande

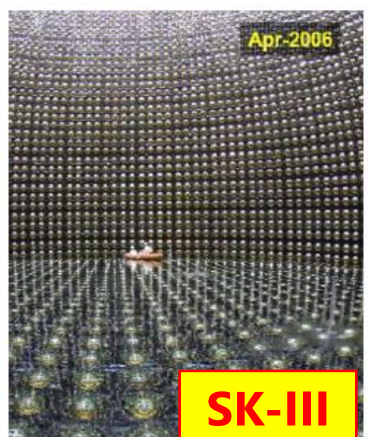
■ Brief history and current status

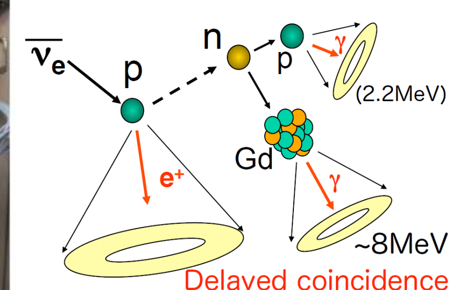
- SK-I started on 1996 April and SK-IV ended on 2018 May.
- Total live time is more than 5,500 days.
- Refurbishment works toward SK-Gd have started since May 31st.

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].



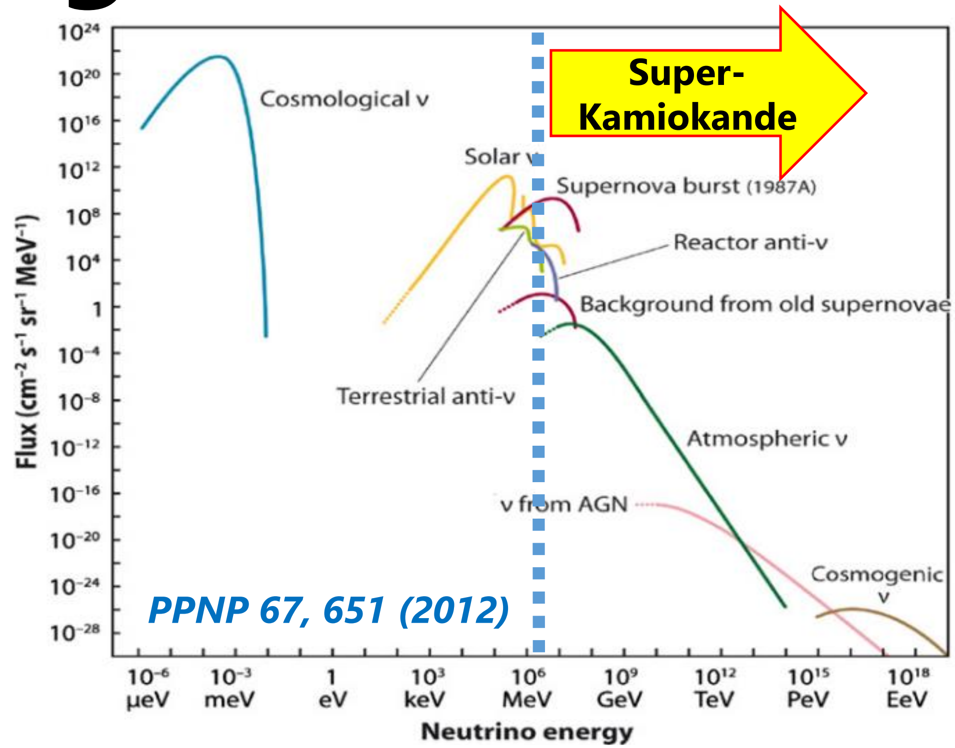




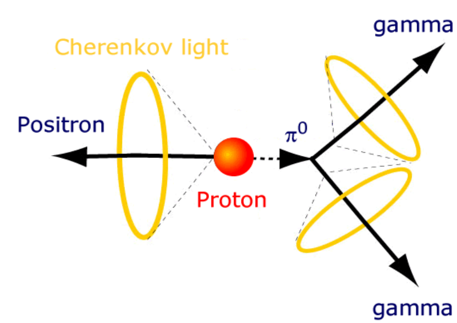
SK-Gd

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



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

3-flavor neutrino oscillation

■ Neutrino oscillation

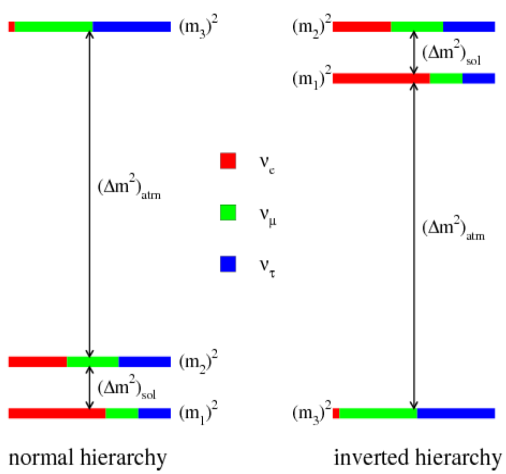
- Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.
- Mixing parameters (angles, mass splitting) has been measured by many neutrino experiments.

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

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

■ Unknown things

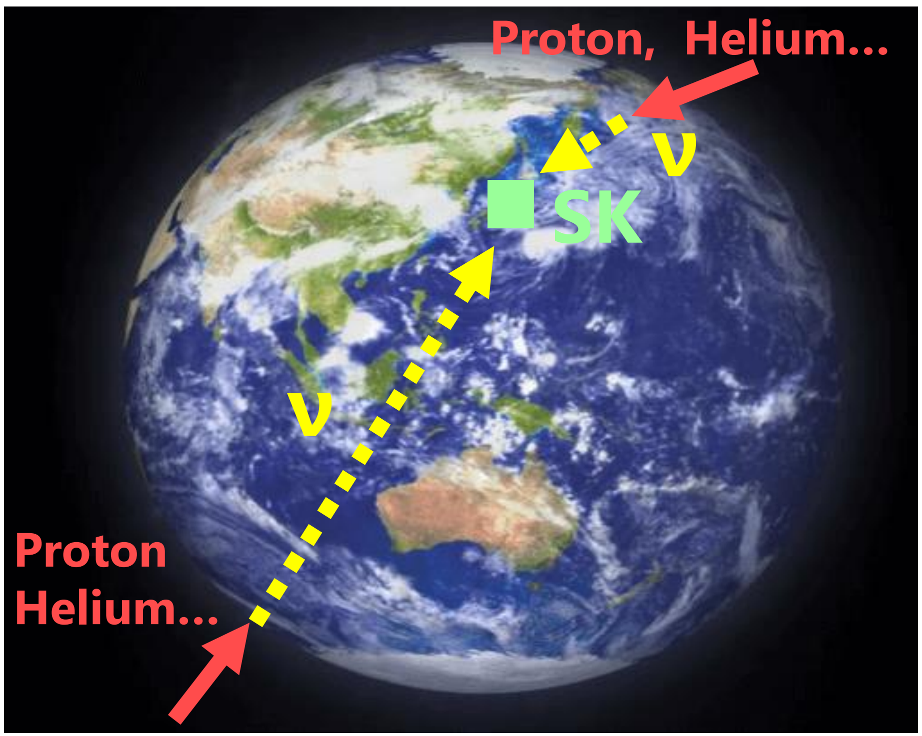
- CP violation phase (δ) in the lepton sector.
- Mass hierarchy (Normal/Inverted).
- θ_{23} octant ($\theta_{23} \lesseqgtr \pi/4$).



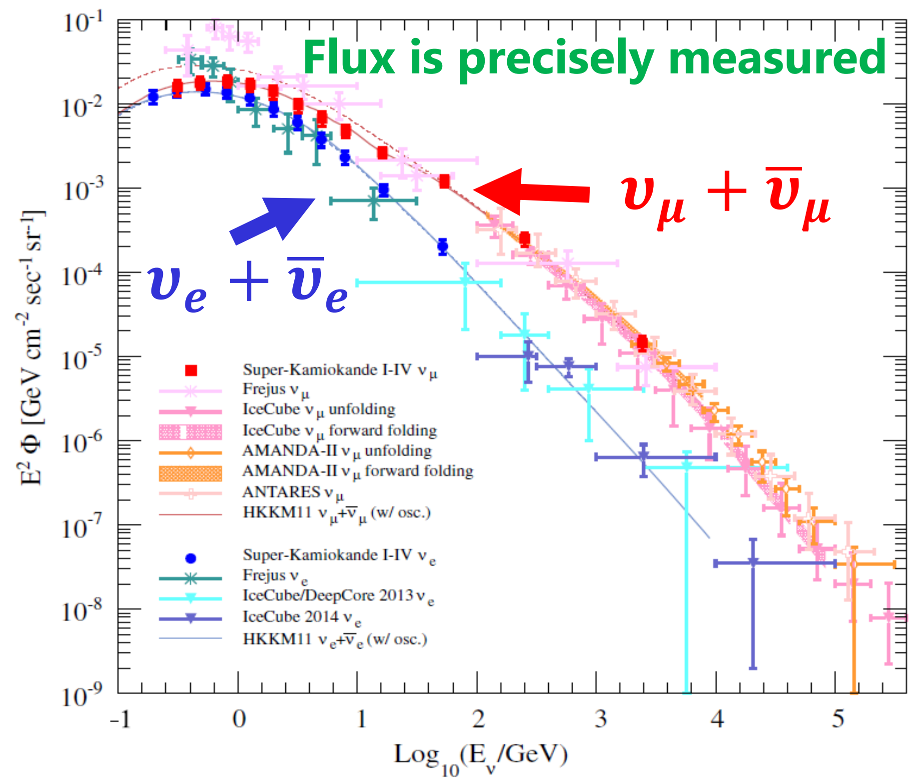
Atmospheric neutrino

■ Feature of atmospheric neutrino

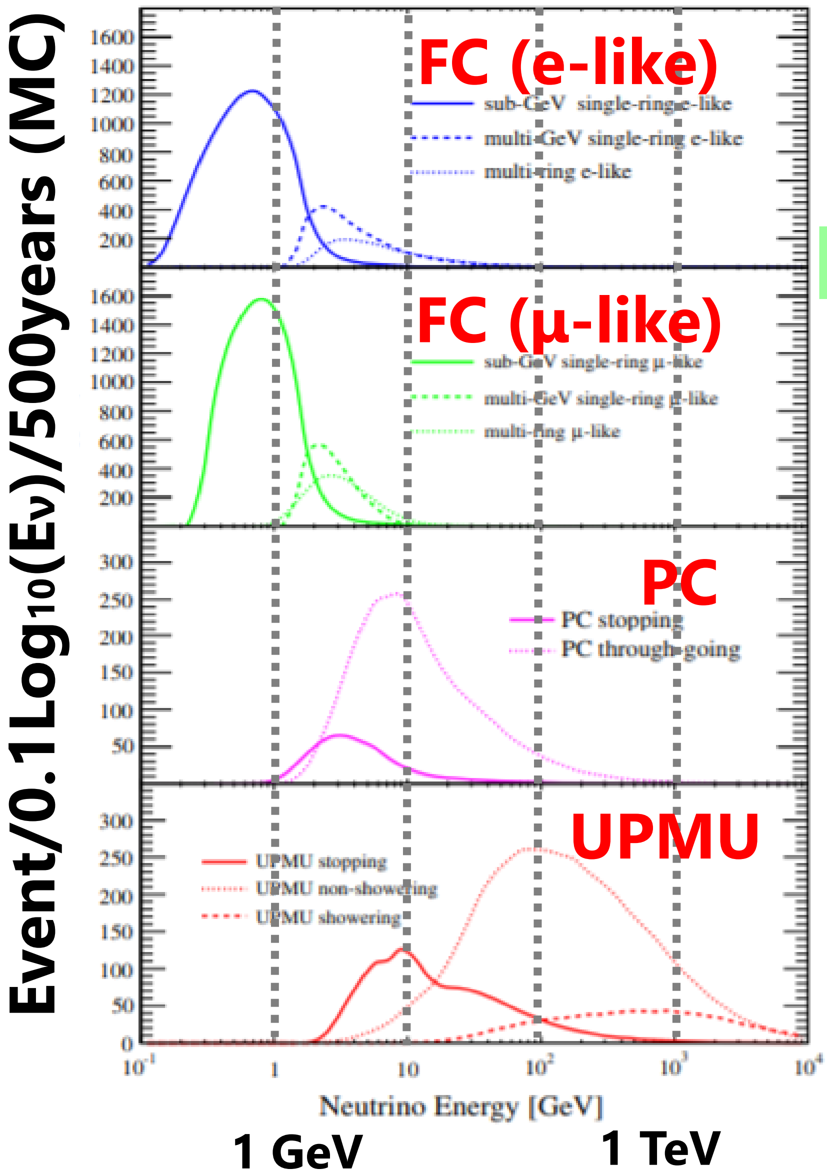
- Primary cosmic-ray interacts with nuclei in atmosphere.
  → ***π, K*** are produced and then ***μ, e*** are produced **with neutrinos**.
- Travel length: ***O*(~10) km - 13,000 km** (zenith angle dependence).
- Wide energy range : **Sub-GeV to over TeV**.

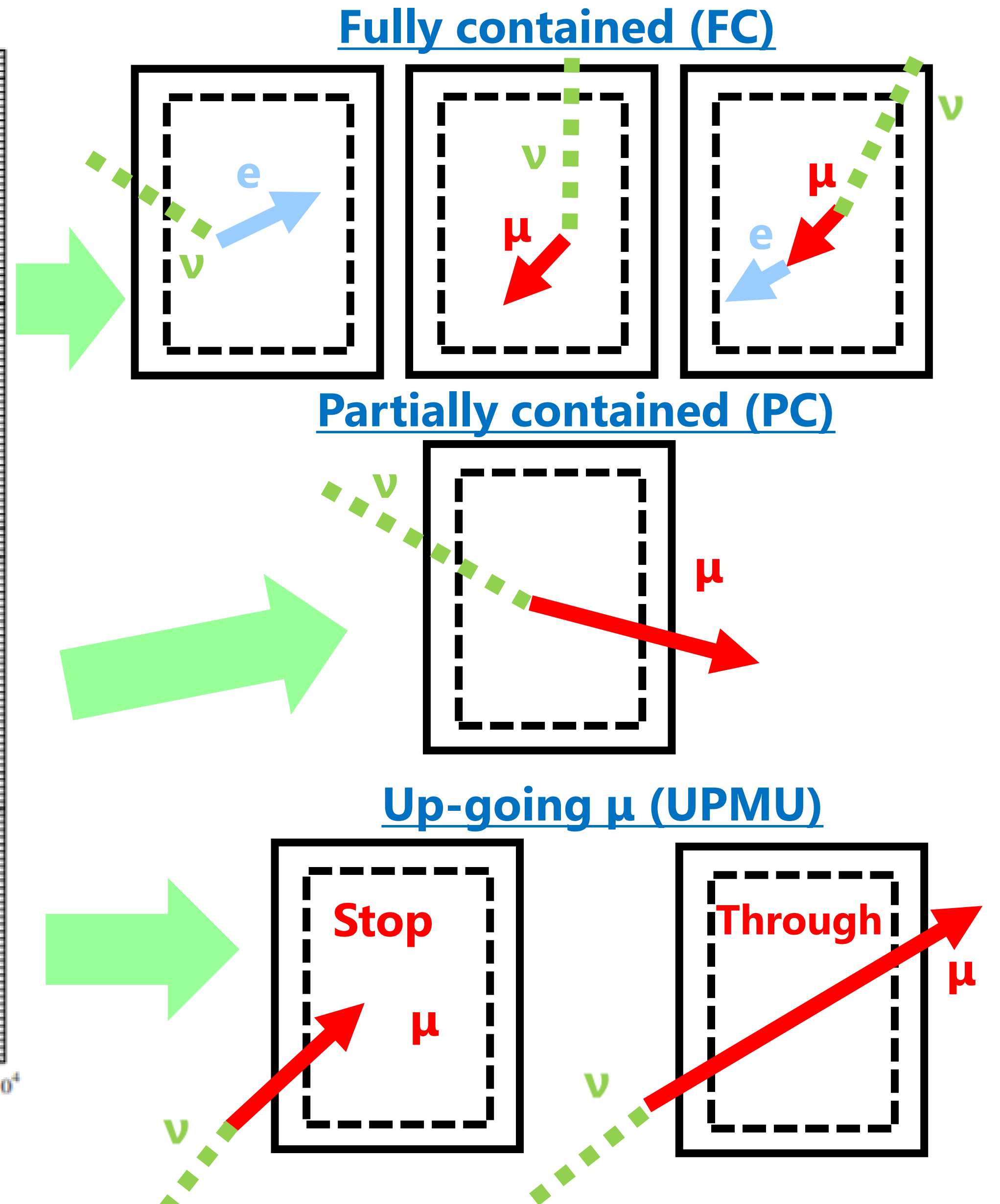


Isotropic flux of cosmic ray



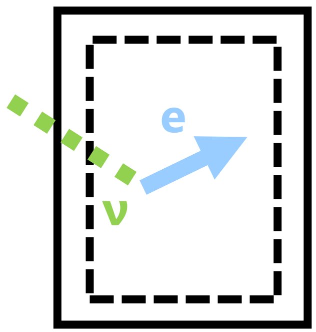
Topologies of atmospheric ν events





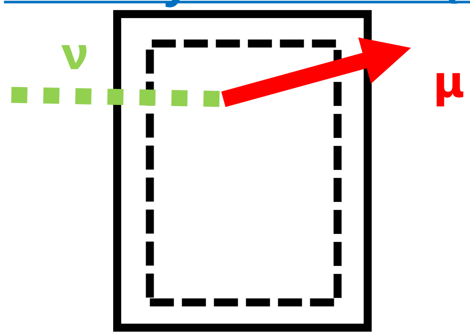
Category of neutrino events

Fully contained (FC)

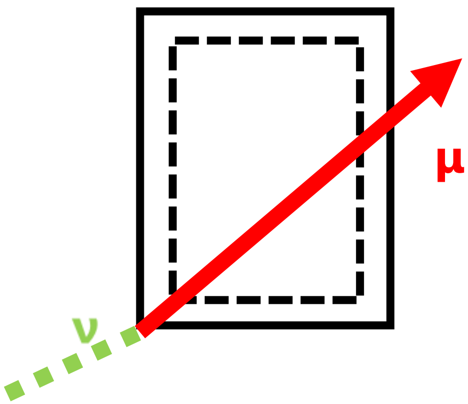


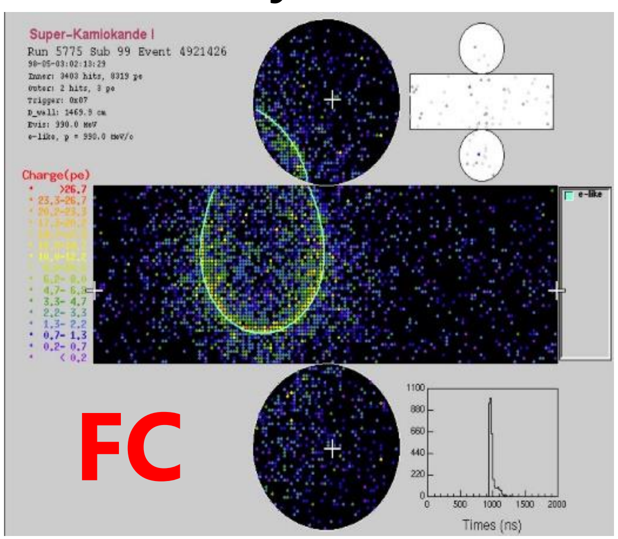
Also μ, multi-ring (decay electron)

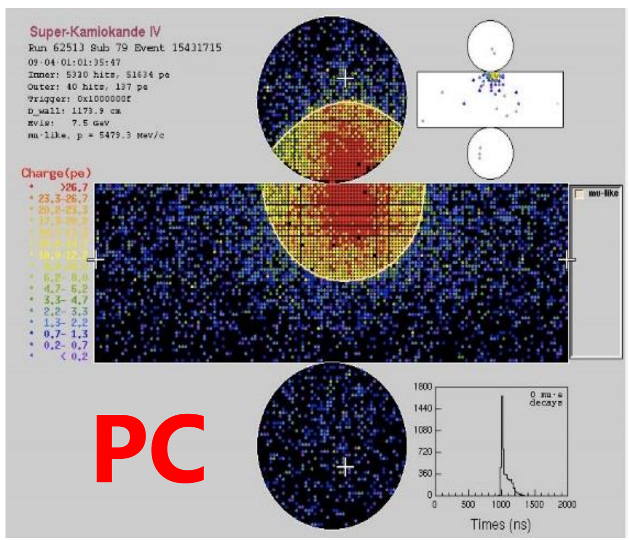
Partially contained (PC)

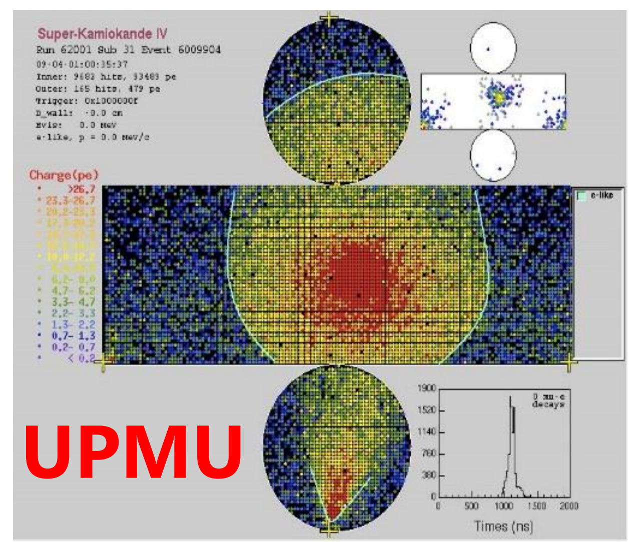


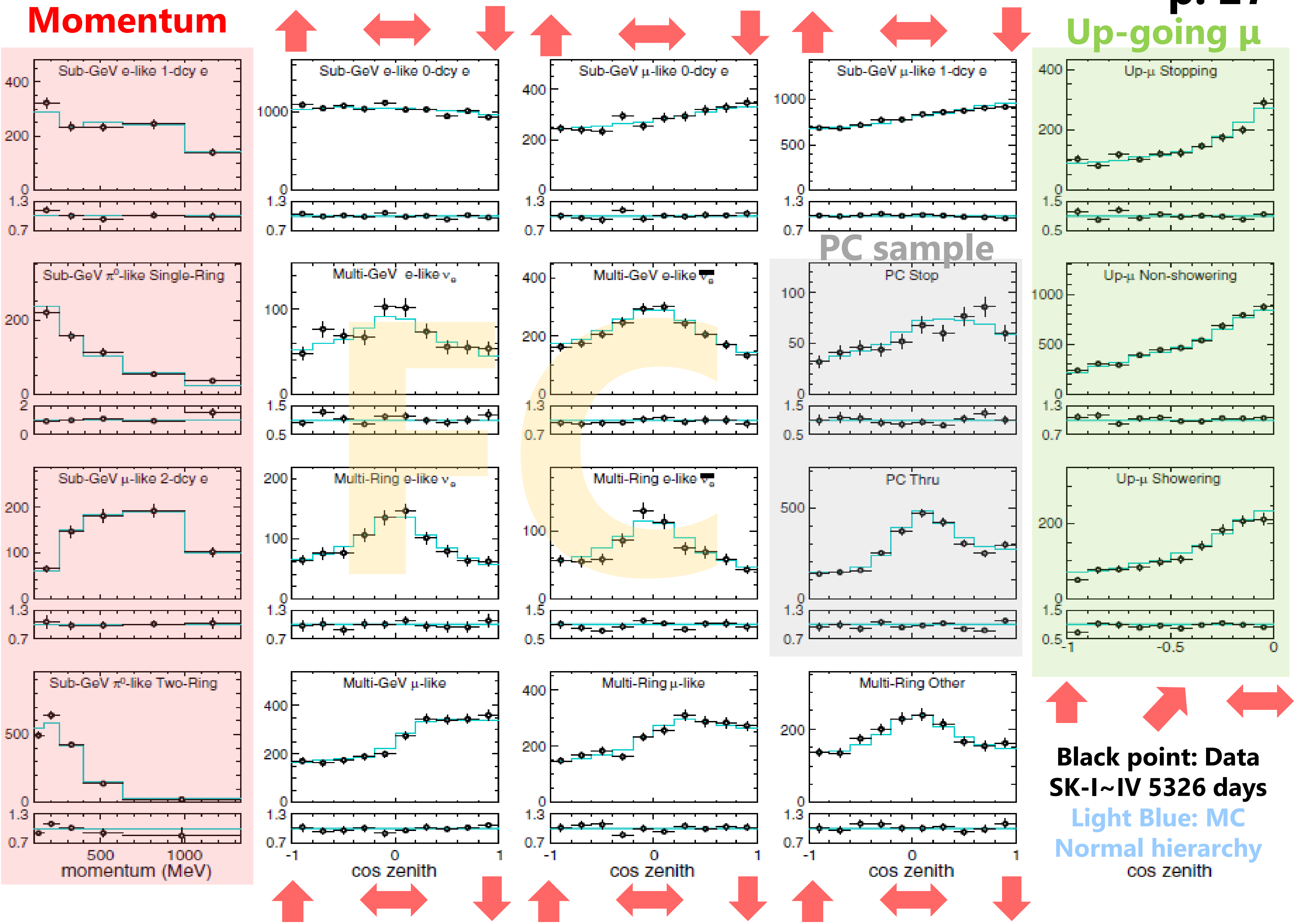
Up-going μ (UPMU)



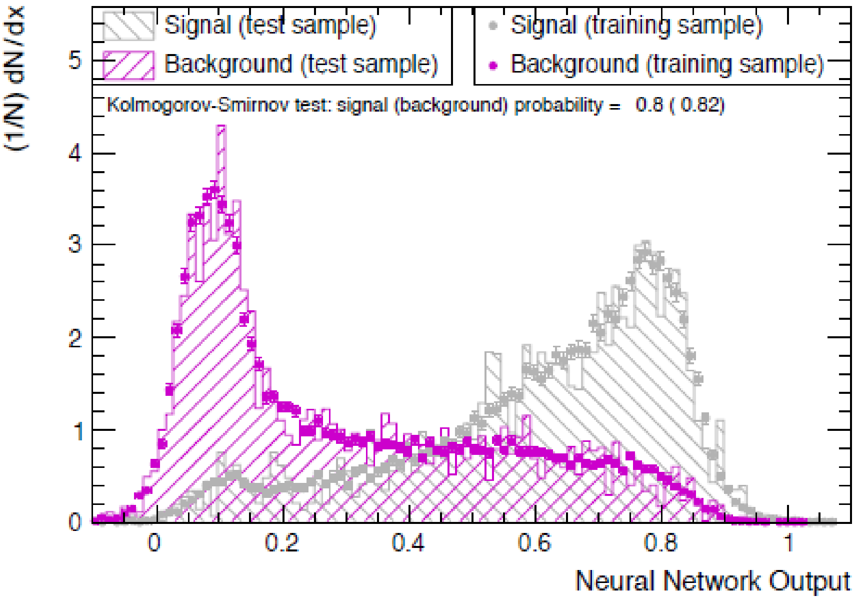


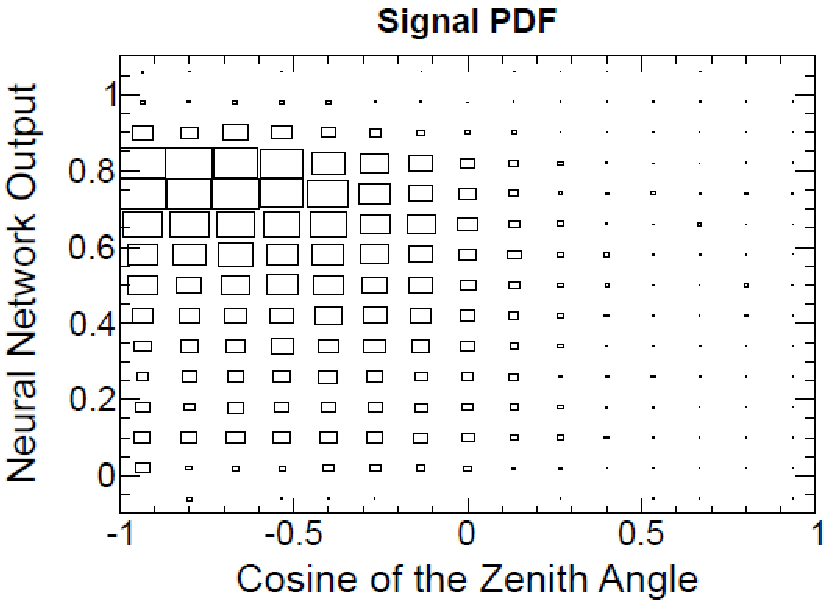


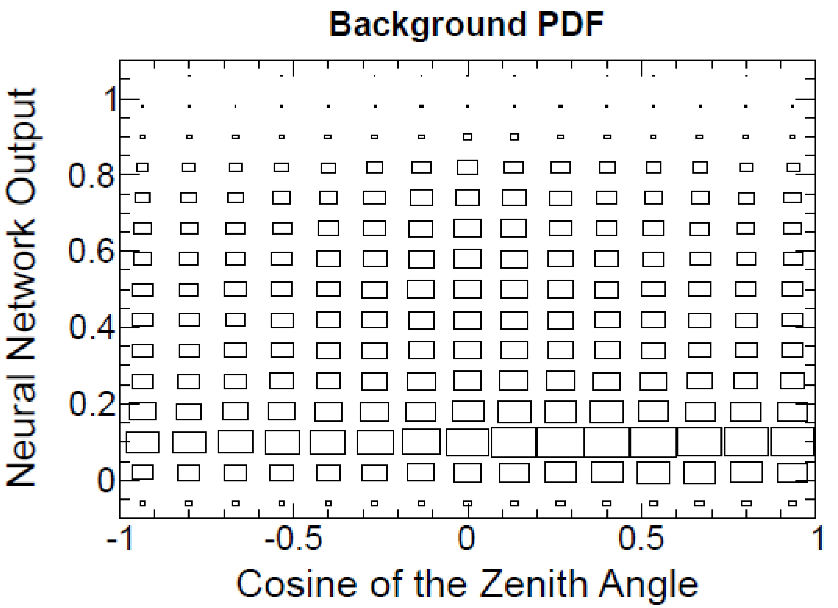



Momentum
Up-going μ
Sub-GeV e-like 1-dcy e
Sub-GeV e-like 0-dcy e
Sub-GeV μ-like 0-dcy e
Sub-GeV μ-like 1-dcy e
Up-μ Stopping
Sub-GeV π0-like Single-Ring
Multi-GeV e-like νe
Multi-GeV e-like ν̄e
PC sample
PC Stop
Up-μ Non-showering
Sub-GeV μ-like 2-dcy e
Multi-Ring e-like νe
Multi-Ring e-like ν̄e
PC Thru
Up-μ Showering
FC
Sub-GeV π0-like Two-Ring
Multi-GeV μ-like
Multi-Ring μ-like
Multi-Ring Other
momentum (MeV)
cos zenith
cos zenith
cos zenith
cos zenith
Black point: Data
SK-I~IV 5326 days
Light Blue: MC
Normal hierarchy

Tau signal discrimination







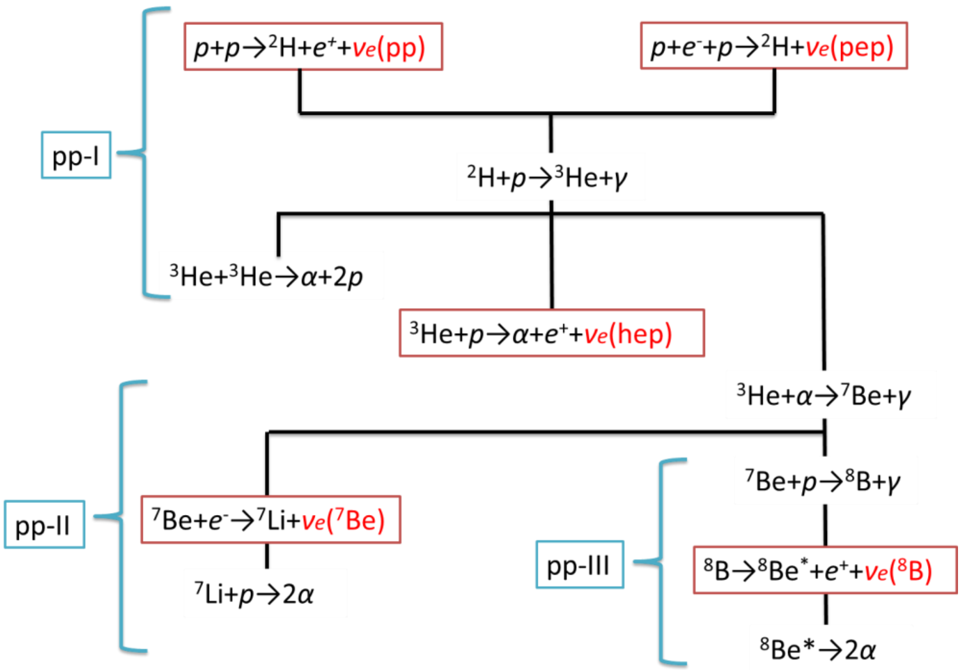
Solar neutrino

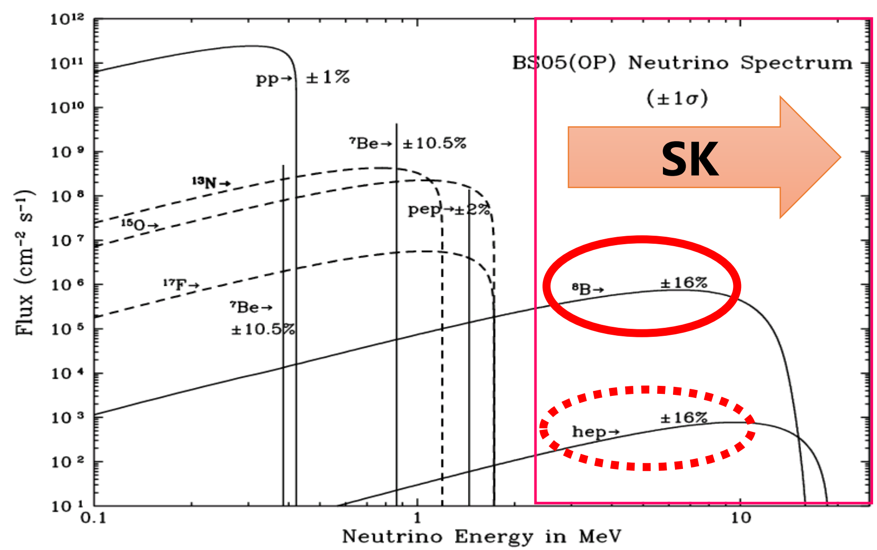
■ Production of solar neutrino

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

$$4p \rightarrow \alpha + 2e^{+} + 2\nu_e + 26.7\mathrm{MeV} - E_\nu$$

- 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).





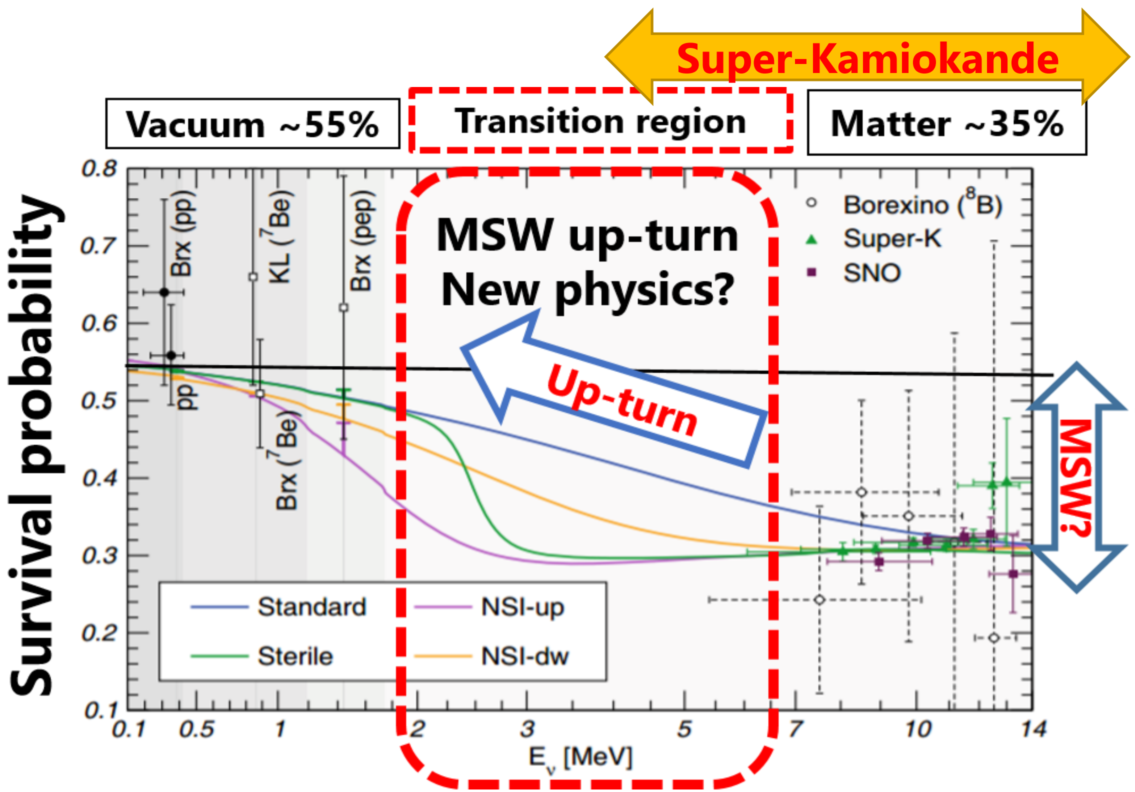
Astrophys. J. 621 85 (2005).

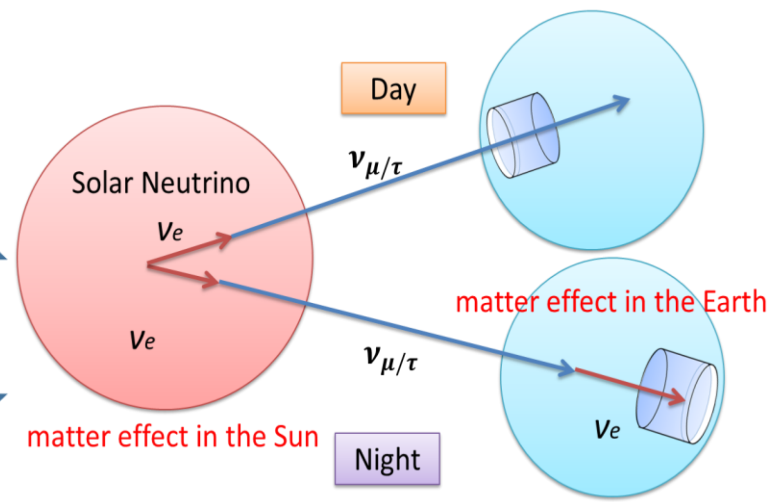
Motivations of solar neutrino

■ 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).



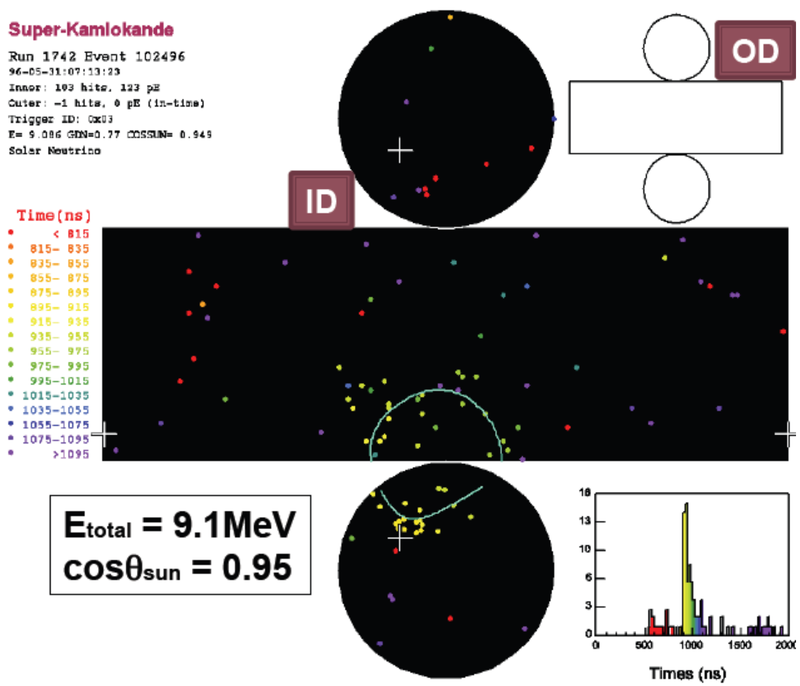


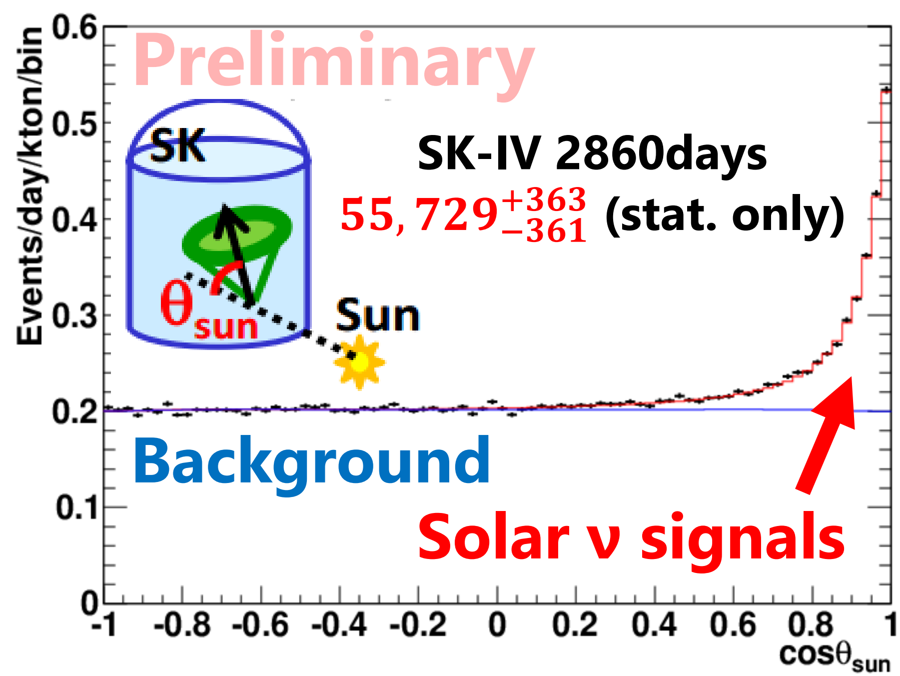
^{8}B solar neutrino measurement

■ ^{8}B solar neutrino signals

- **Elastic scattering** ($\nu_X + e^- \rightarrow \nu_X + e^-$).
  (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**).





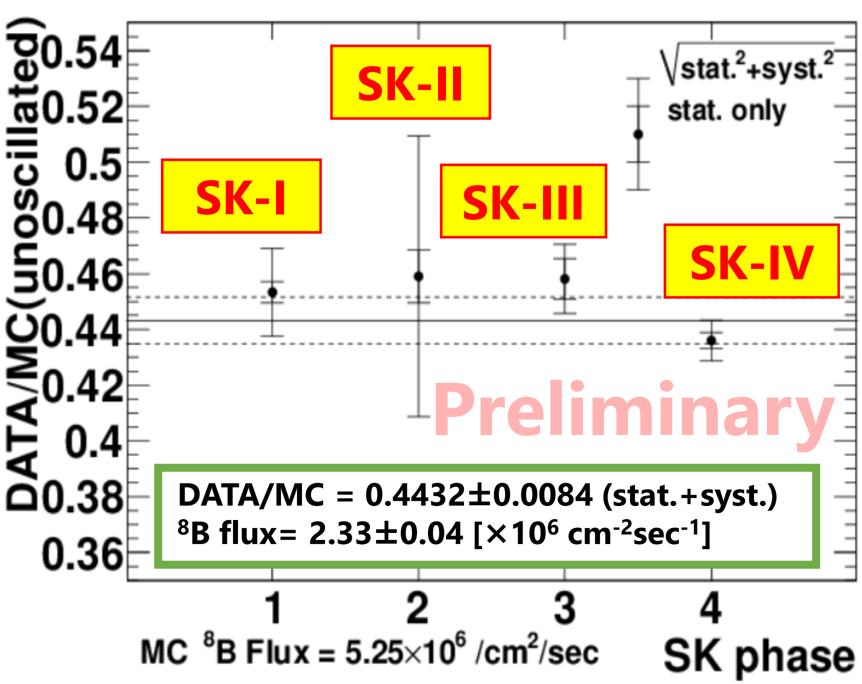
^{8}B solar neutrino flux

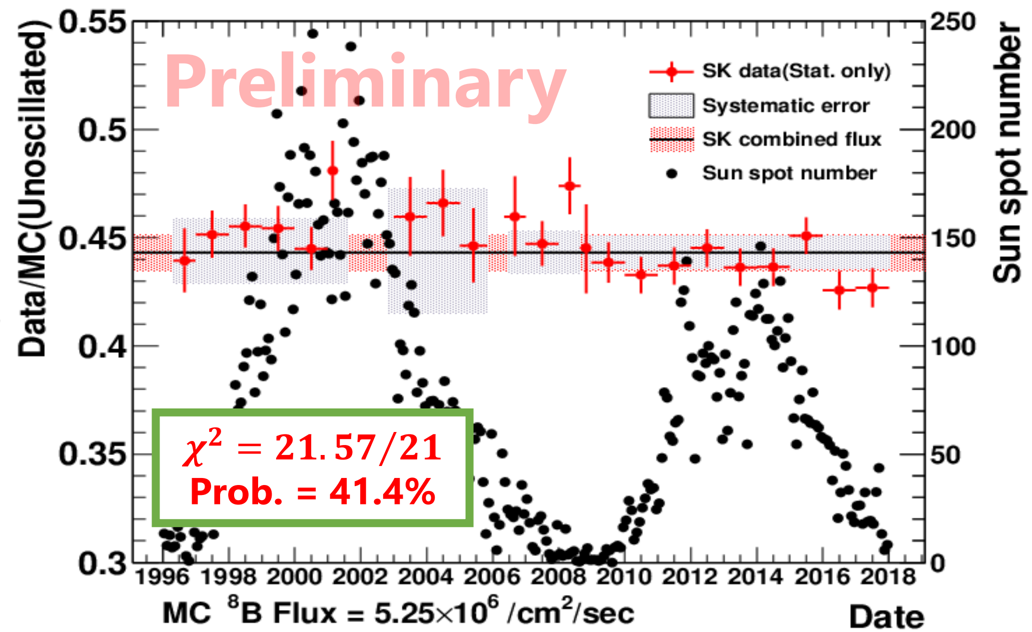
■ Flux measurements

- 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

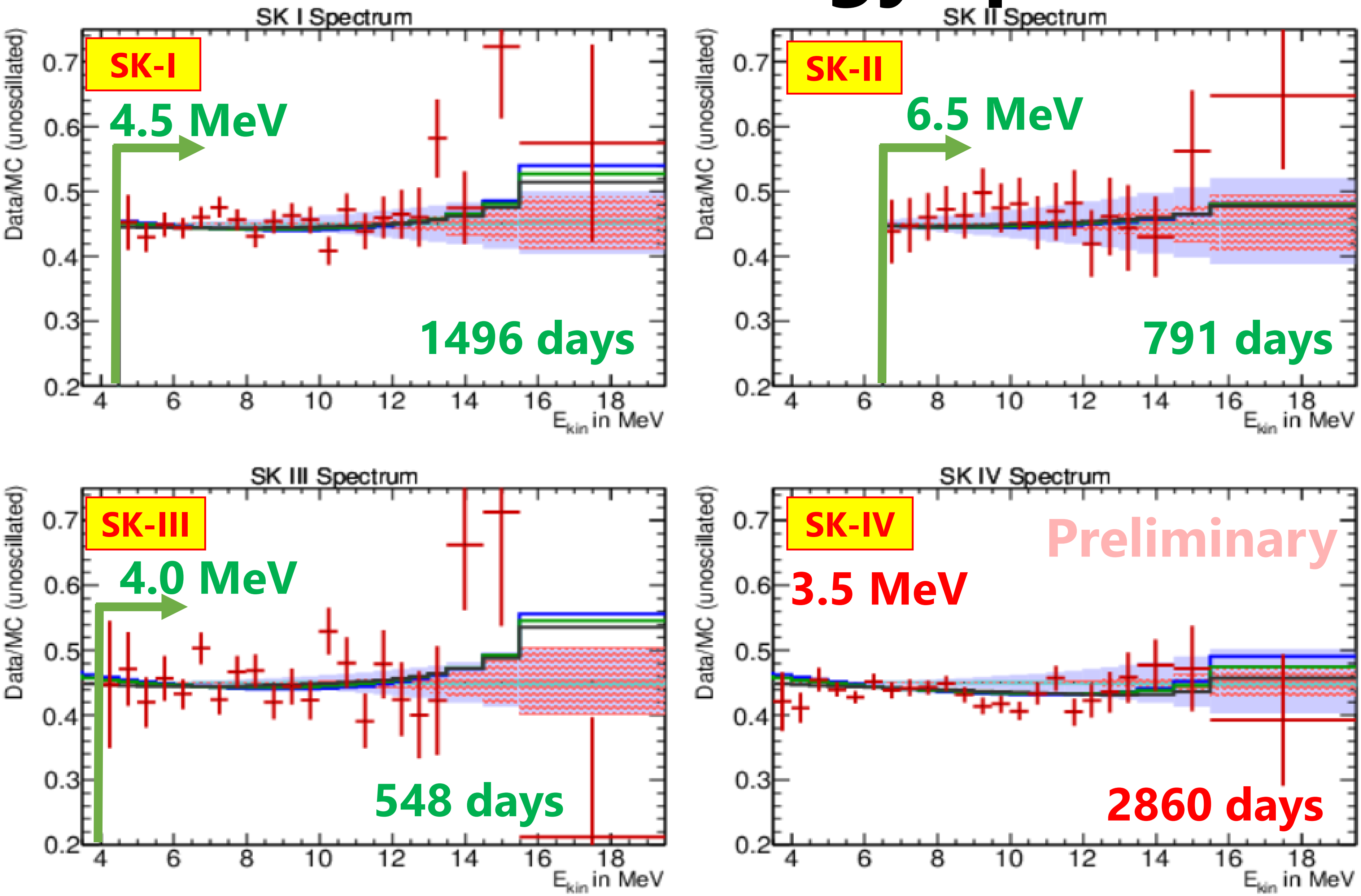
- Solar activity is strongly correlated with sunspot numbers.
- **No correlation** with the 11-years solar activity is observed.





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

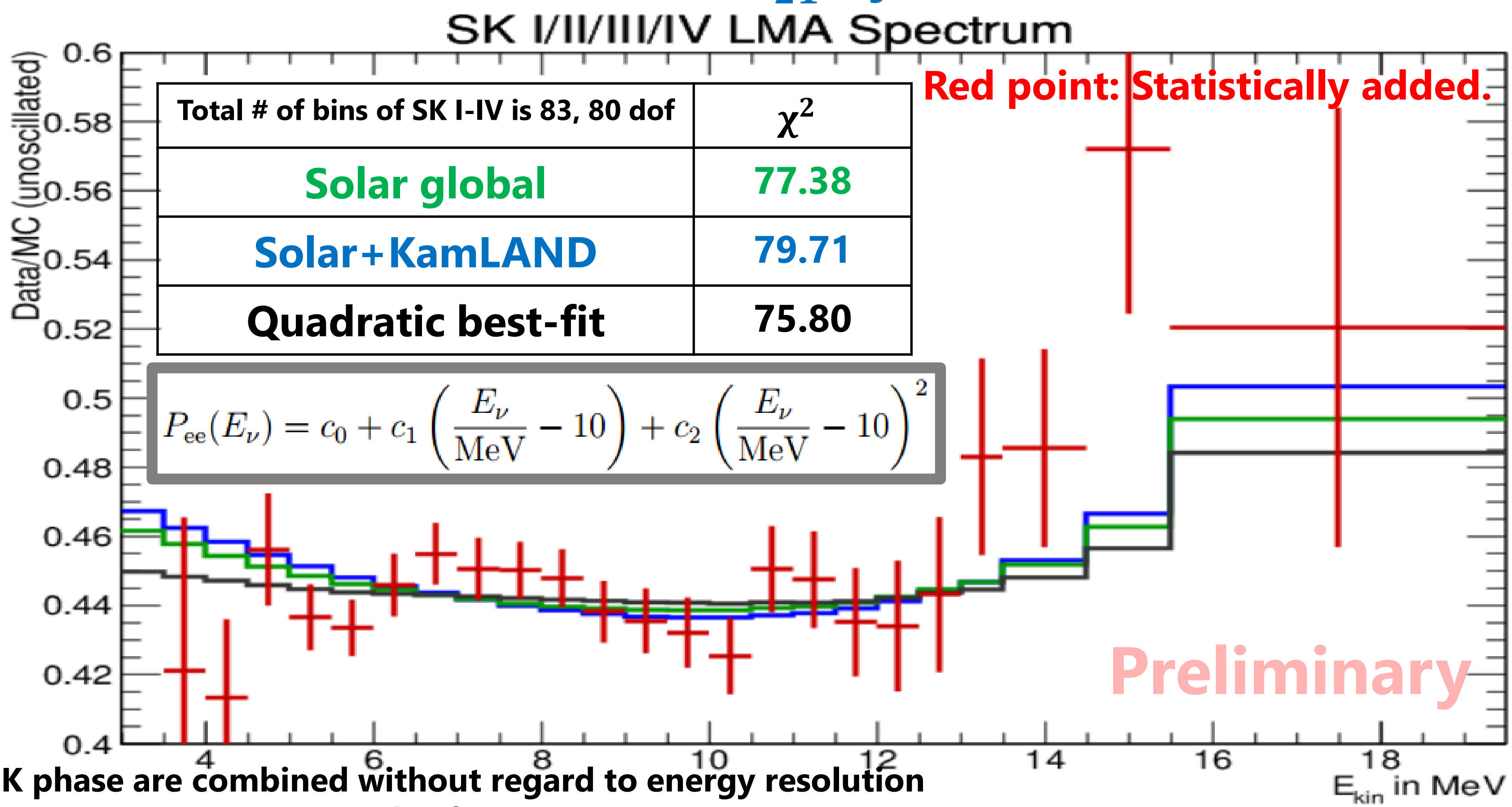
Recoil electron energy spectrum



Combined spectrum

■ Energy spectrum vs. MSW predictions

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



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

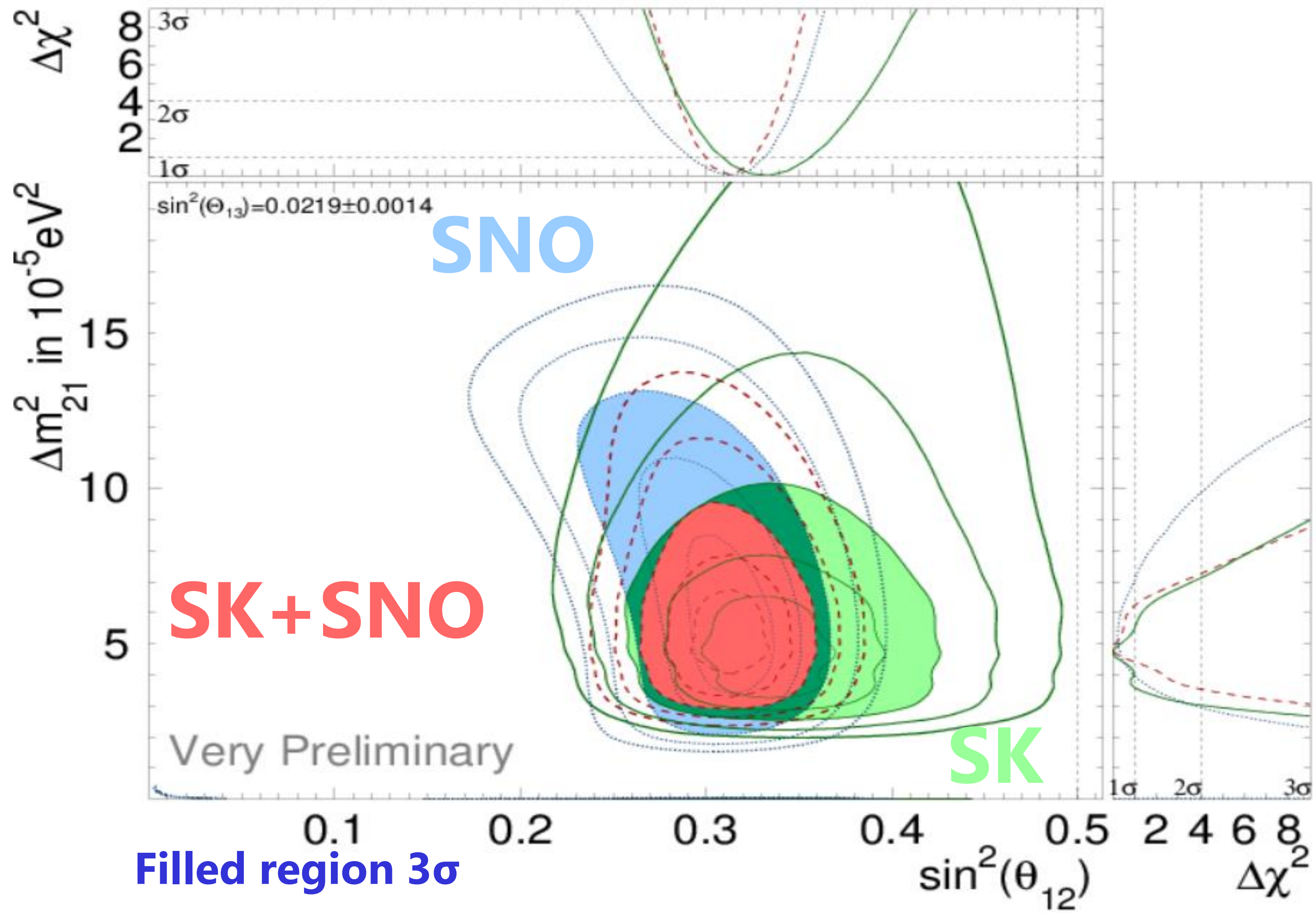
$$P_{ee}(E_\nu) = c_0 + c_1\left(\frac{E_\nu}{\mathrm{MeV}} - 10\right) + c_2\left(\frac{E_\nu}{\mathrm{MeV}} - 10\right)^2$$

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

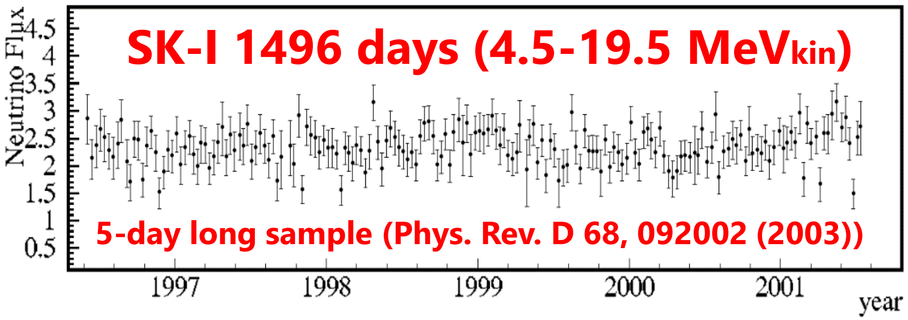
- SK result **uniquely selects the LMA-MSW** region by more than **3σ**.
- SK (SNO) gives the best constrain on Δm^2_{21} ($\sin^2\theta$).



Filled region 3σ

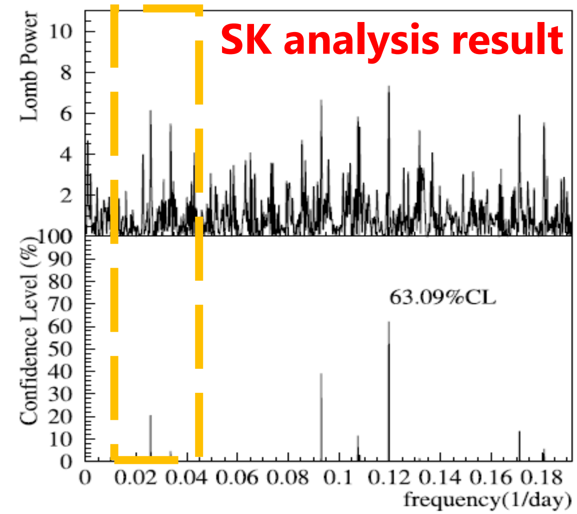
Periodic modulation analysis

- 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.



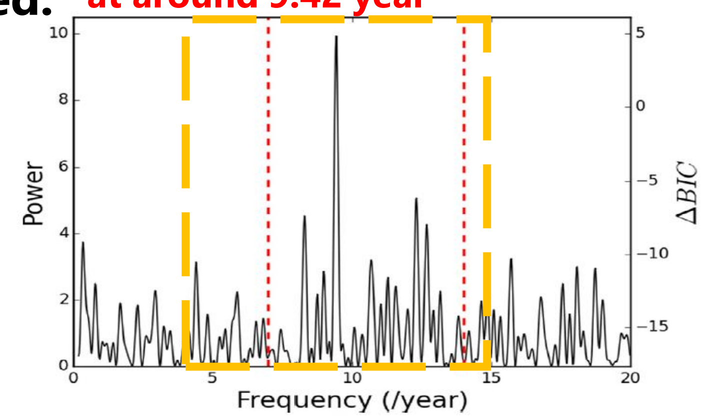
LS method

No clear periodic signal 5-15 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.

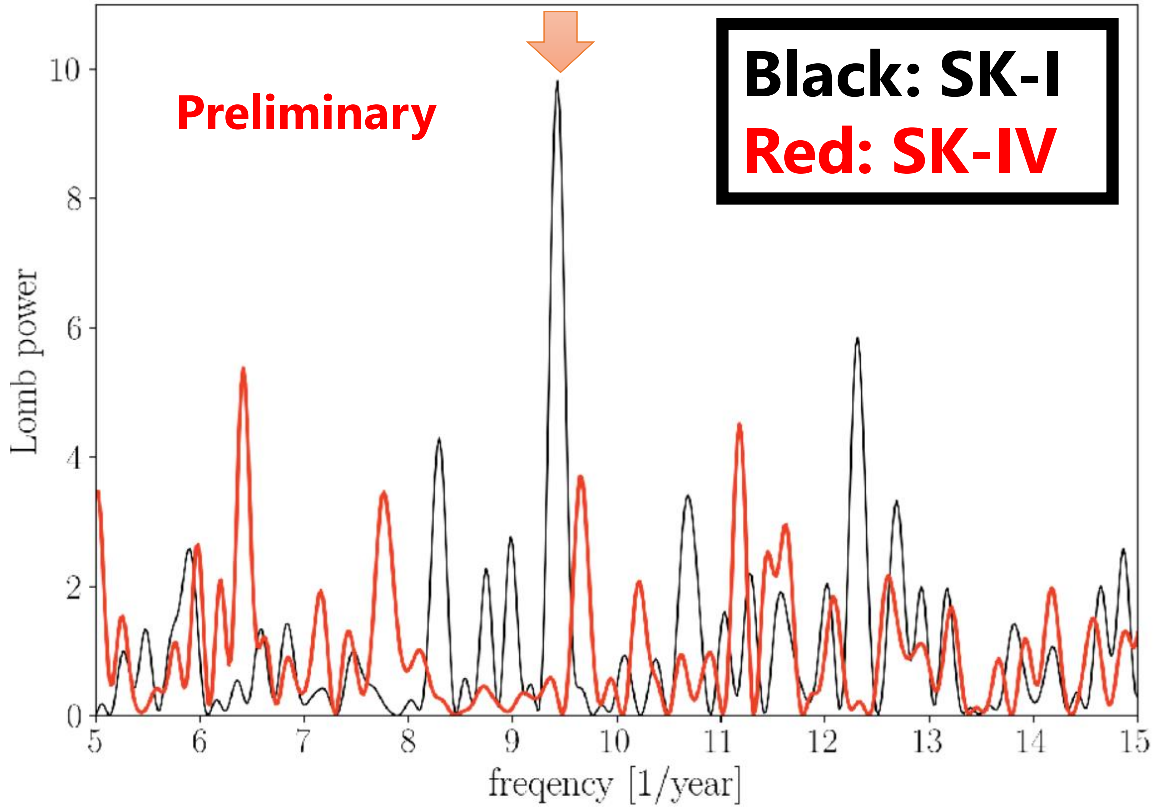
Several researchers found a peak at around 9.42 year^{-1}



- SK has reanalyzed SK-I data with GLS method provided by astroML.
- SK-IV data is also analyzed with GLS.

Periodic modulation results

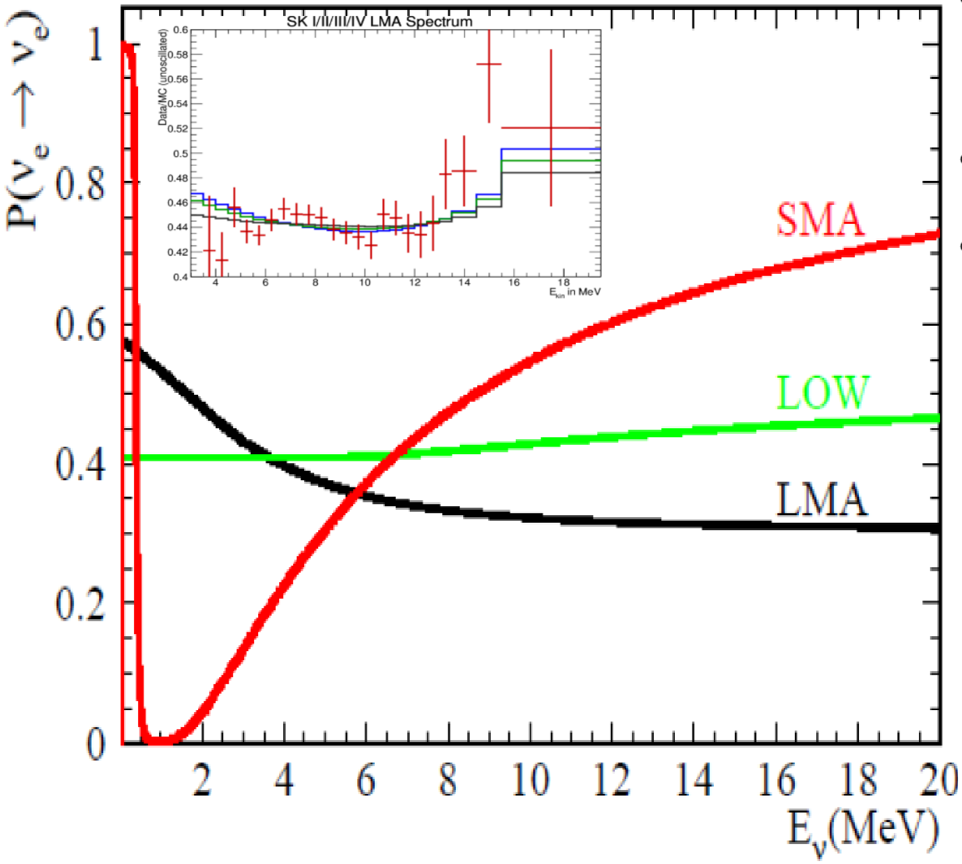
- Using the Generalized LS method, both SK-I and SK-IV are analyzed.
- 5-day long sample is made from SK-I data and SK-IV data.
  - SK-I: 1496 days data (4.5-19.5 MeV_{kin}), Phys. Rev. D 68, 092002 (2003).
  - SK-IV: 1664 days data (4.5-19.5 MeV_{kin}), Phys. Rev. D 94, 052010 (2016).
- Search region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

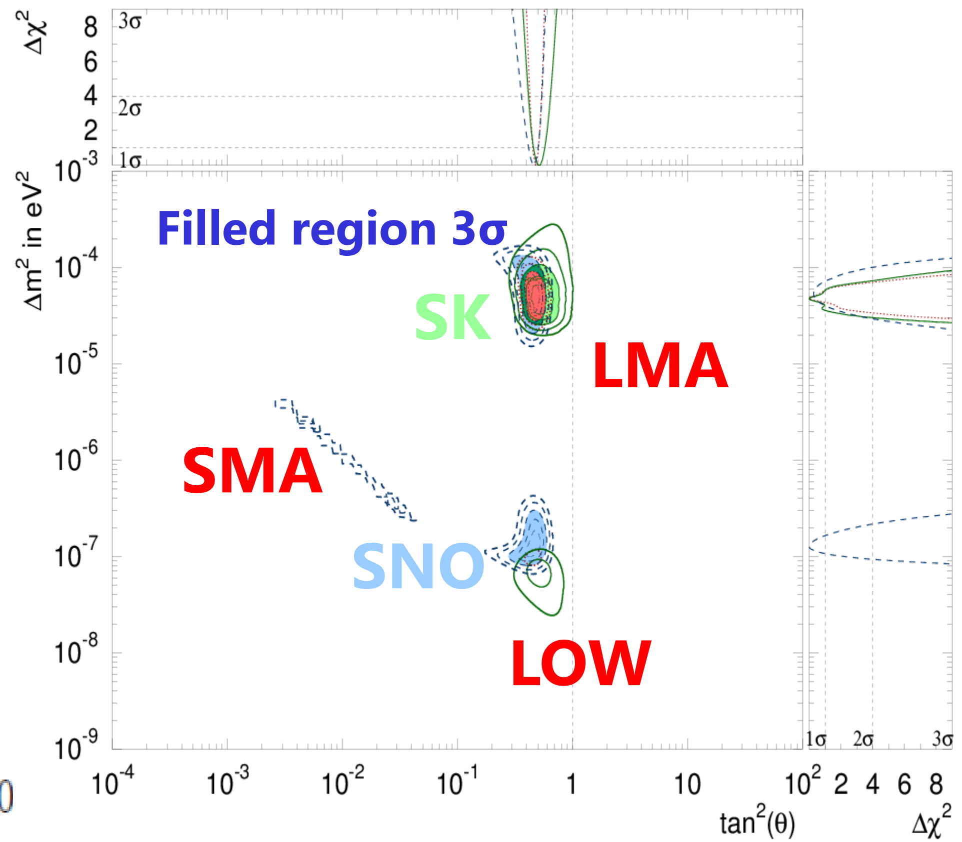


Survival probability & oscillation parameters

■ 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)

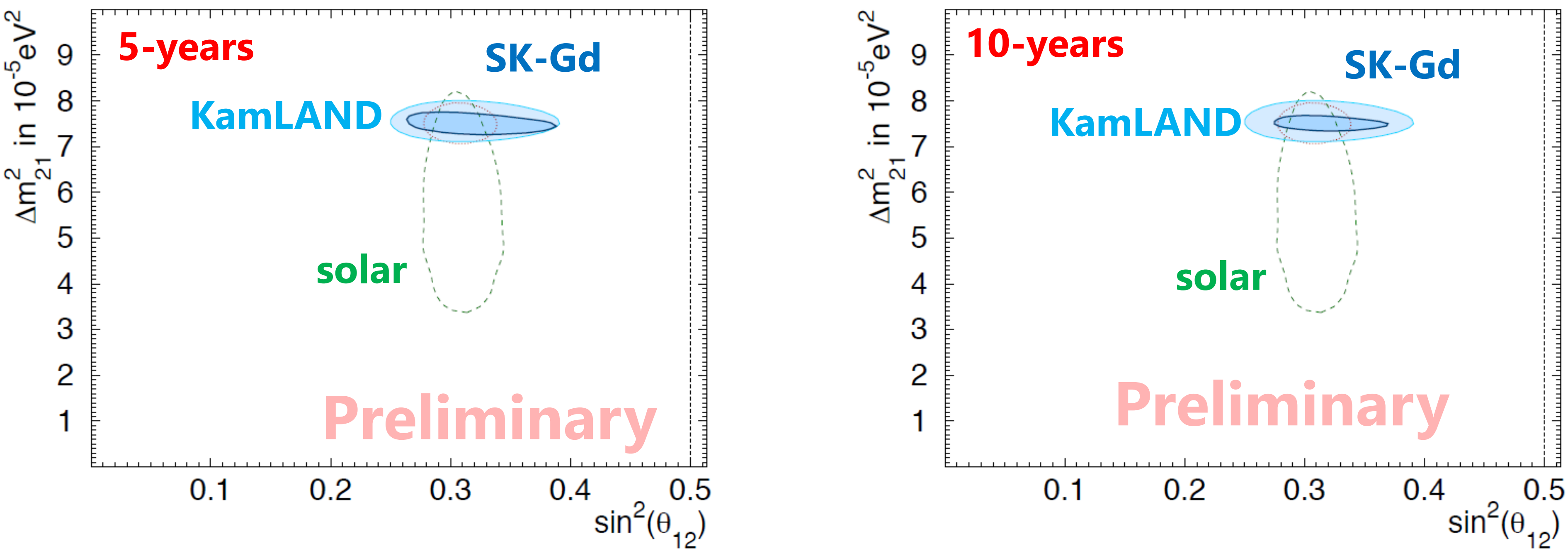




Reactor neutrino in SK-Gd

■ Anti-neutrino measurement

- Reactor neutrino can be measured in SK-Gd using neutron tag.
  → SK has a chance to determine ($\sin^2\theta_{12}, \Delta m^2_{21}$) of neutrino and anti-neutrino by one detector.
- Comparison with KamLAND's result is much important to check CPT violation between neutrino and anti-neutrino.



Day-night flux asymmetry

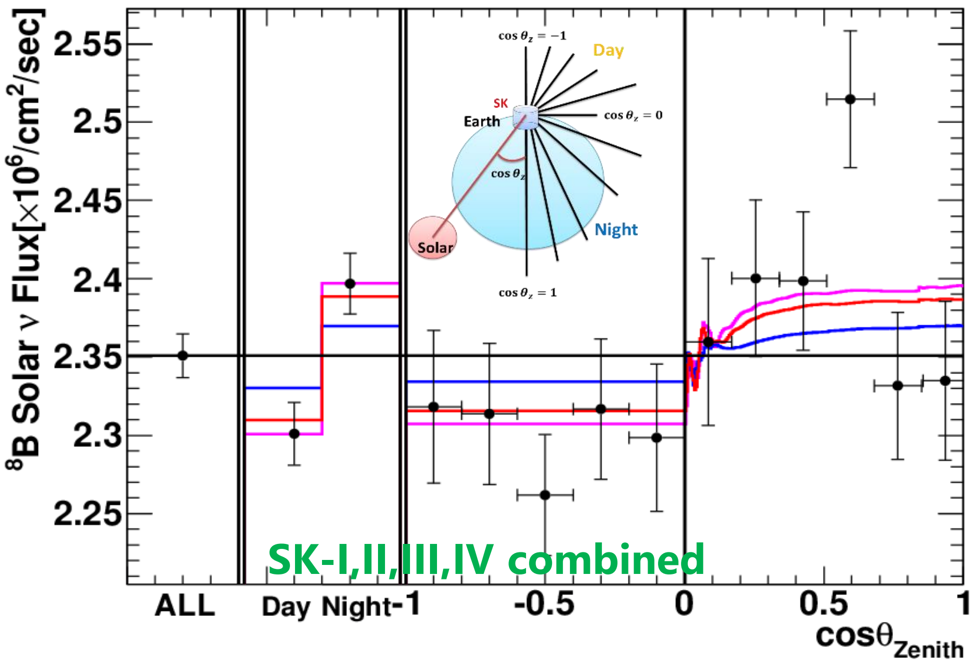
Updated from Phys. Rev. Lett. 112 (2014) 091805.

■ Flux measurement

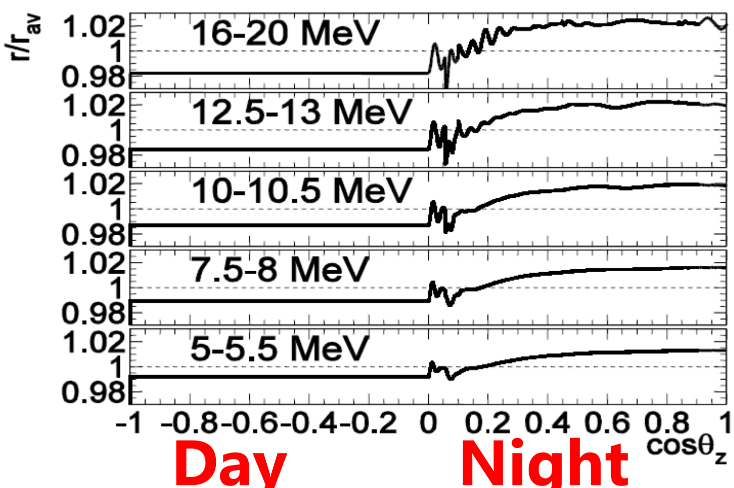
- Regeneration of ν_e in night.
  → Higher flux in night.

$$A_{DN} = \frac{\Psi_{day} - \Psi_{night}}{(\Psi_{day} + \Psi_{night})/2}$$

- Regeneration depends on oscillation parameters.
- Update is in progress.



SK-phase	Amplitude fit [%]	Straight calc. [%]
SK-I	-2.0 ± 1.8 ± 1.0	-2.1± 2.0 ± 1.3
SK-II	-4.3 ± 3.8 ± 1.0	-5.5 ± 4.2 ± 3.7
SK-III	-4.2 ± 2.7 ± 0.7	-5.9 ± 3.2 ± 1.3
SK-IV	-3.6 ± 1.6 ± 0.6	-4.9 ± 1.8 ± 1.4
Combined	-3.3 ± 1.0 ± 0.5 (3.0 σ from zero)	-4.1 ± 1.2 ± 0.8 (2.8 σ from zero)

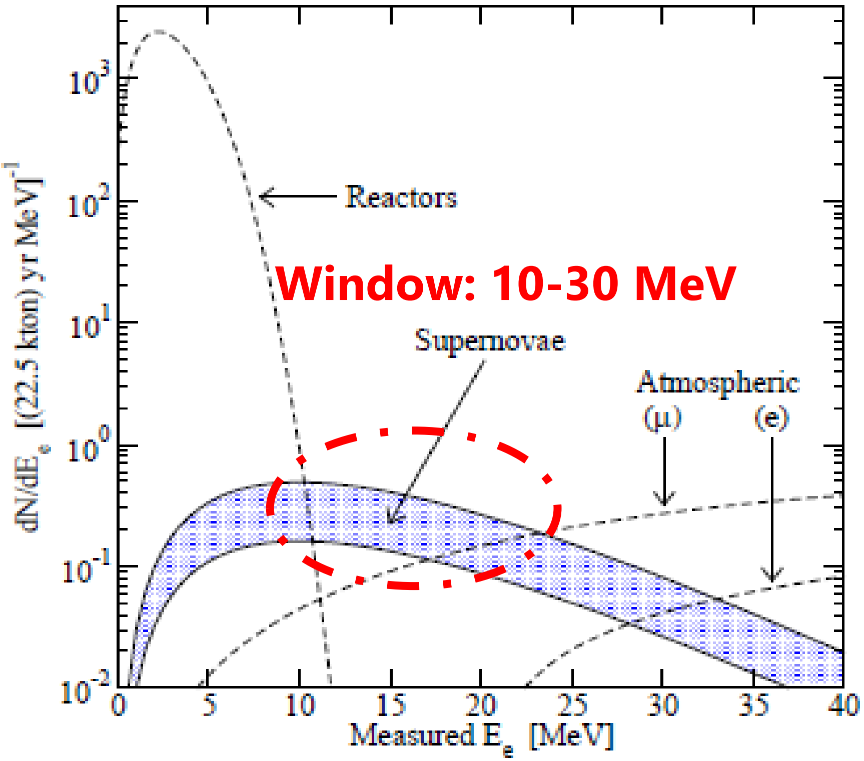


Future prospects (SK-Gd)

■ Supernova relic neutrino (SRN)

- SRN is generated from past supernova bursts.
- Further background reduction is required to search for SRN.
- Search for $\bar{\nu}_e + p \rightarrow e^+ + n$ using delayed coincidence technique.

→ **Tagging neutron** by adding **Gadolinium** into Super-Kamiokande.



Phys. Rev. Lett. 93 (2014) 171101.

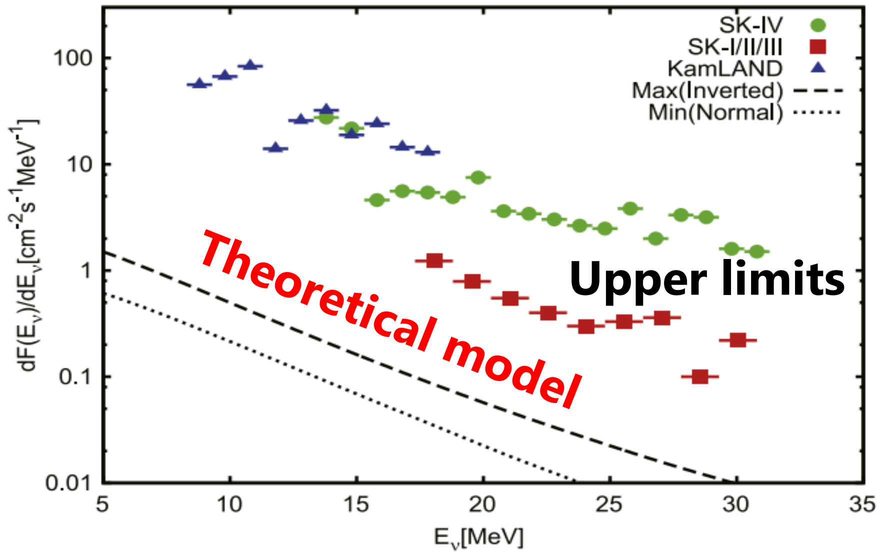


Figure 1. 90% C.L. differential upper limits on $\bar{\nu}_e$ flux of SRNs. The squares, circles and triangles are results for Super-Kamiokande (SK-I/II/III, Bays et al. 2012), Super-Kamiokande with a neutron-tagging (SK-IV, Zhang et al. 2015) and KamLAND (Gando et al. 2012). Dashed and dotted lines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

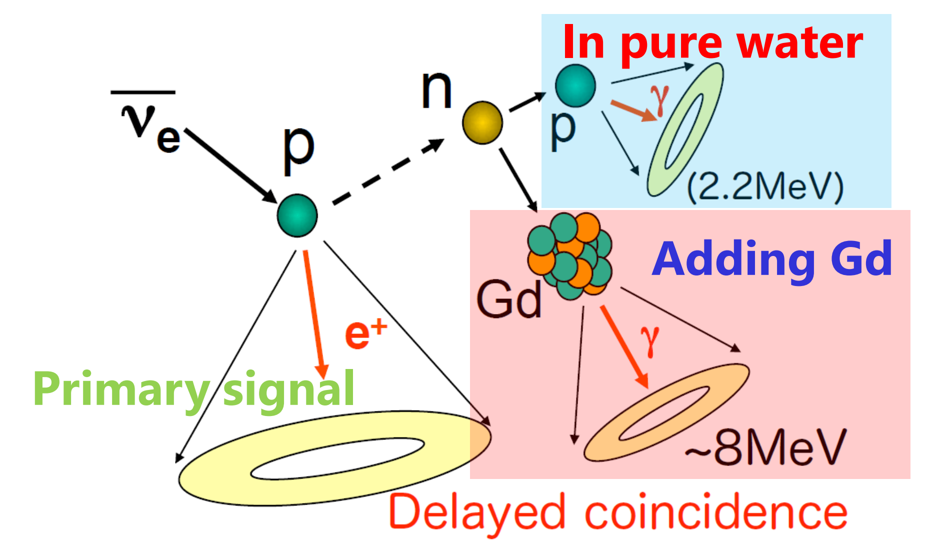
Astrophys. J. 804 (2015) 75.

Why Gadolinium (Gd)

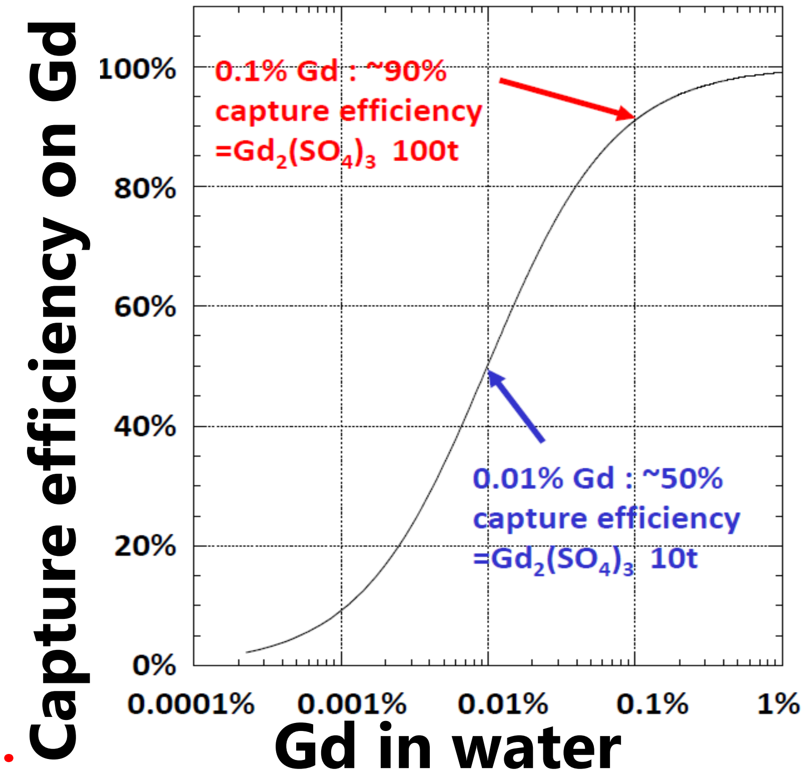
■ Neutron tagging

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

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



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



Water system for SK-Gd

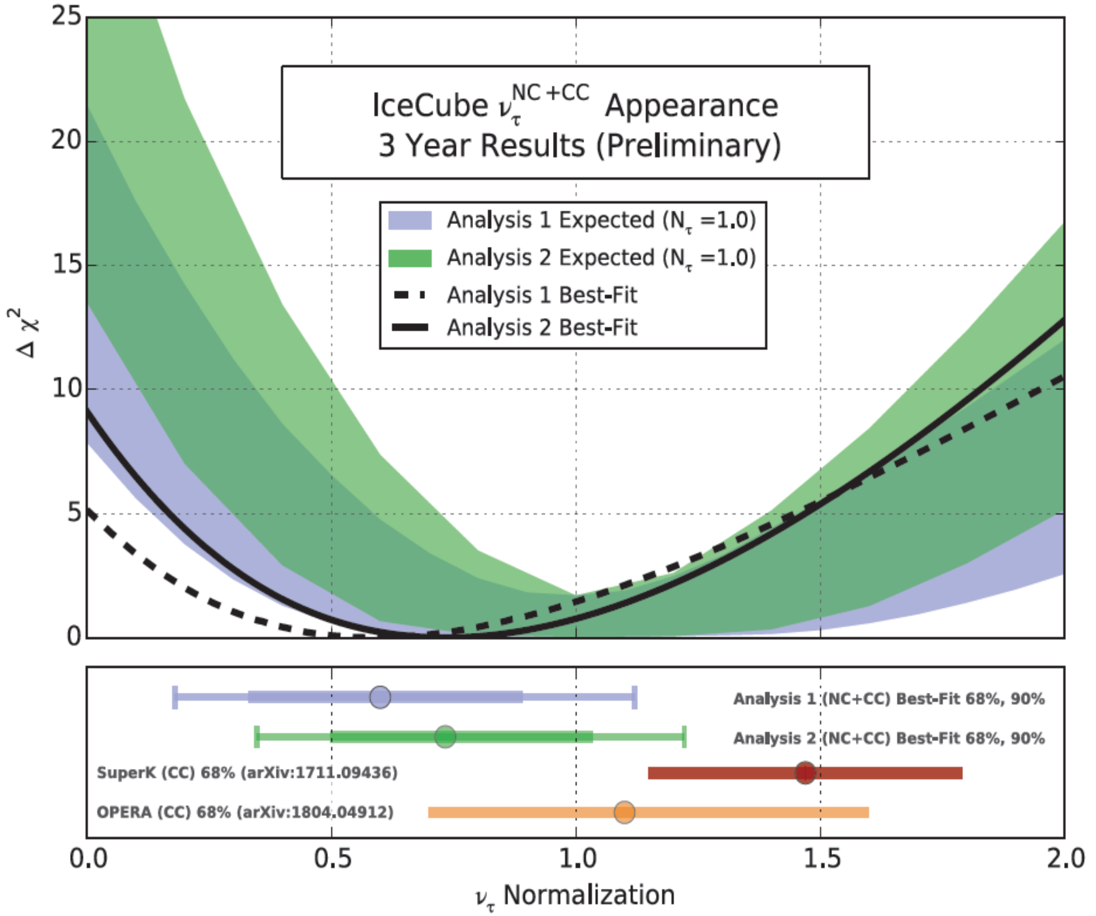
Water system for SK-Gd

Tau neutrino appearance

■ Strength

- Data is compared with the latest MC simulations.
- Uncertainties are dominated with statics.

Experiment (Channel)	ντ normalization
IceCube analysis 1 (NC+CC)	0.59±0.31±0.25
IceCube analysis 2 (NC+CC)	0.73±0.31±0.24
Super-K (CC)	1.47±0.32
OPERA (CC)	$1.1^{+0.5}_{-0.4}$



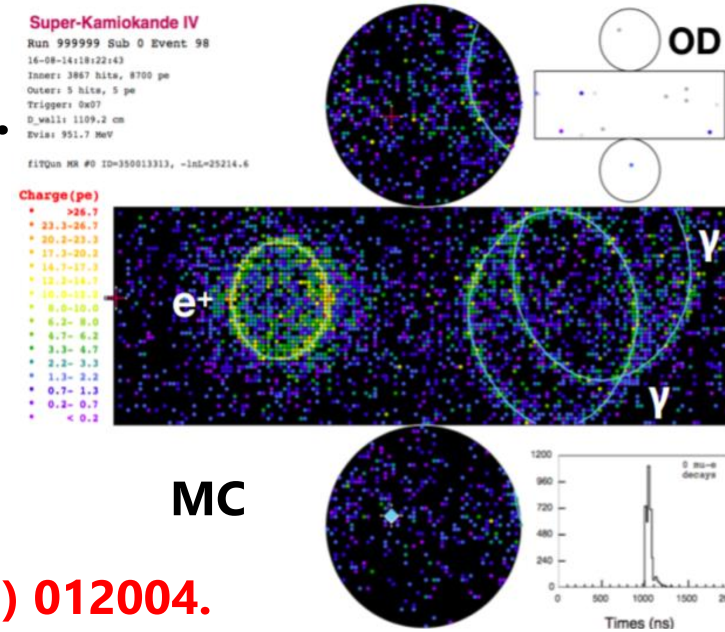
1.0 = MC expected

Neutrino 2018 Poster presented by Philipp Eller, Feifei Huang and Michael Larson
https://doi.org/10.5281/zenodo.1304920

Proton decay($p \to e^+\pi^0$, $p \to \mu^+\pi^0$)

■ $p \to e^+\pi^0$

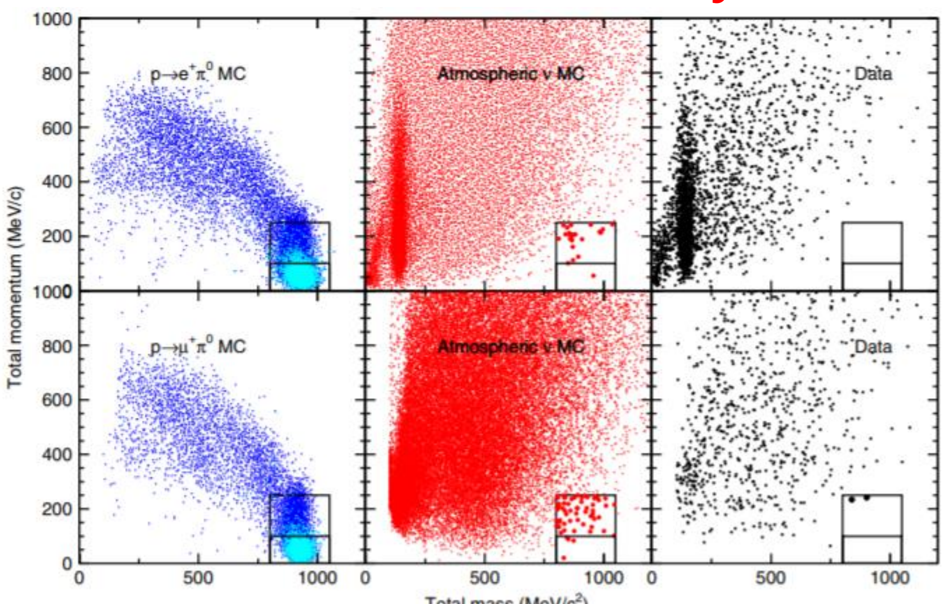
- e^+ and π^0 is back-to-back (459 MeV/c). $\pi0 \to \gamma\gamma$ (all particles are visible).
- No event, lifetime > 1.6×10^{34} years.

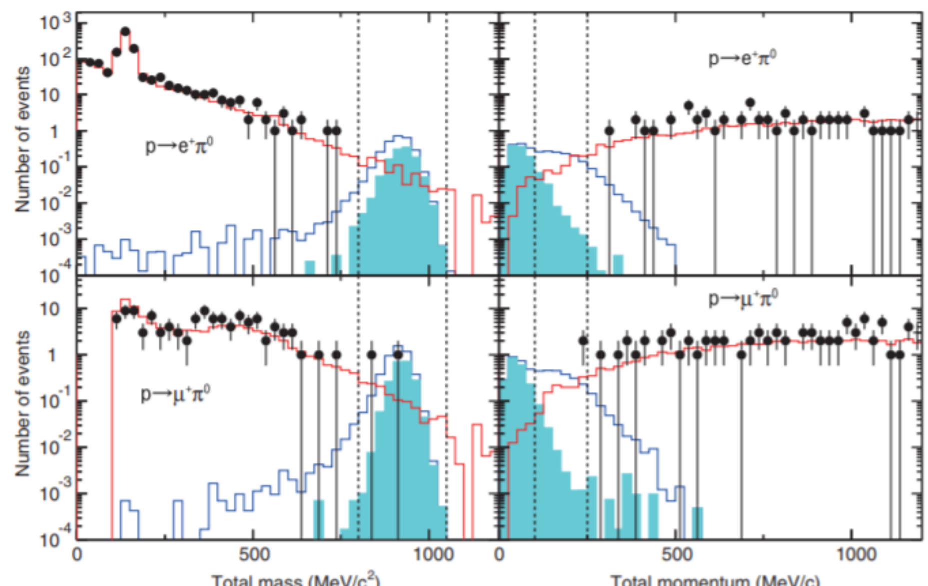


■ $p \to \mu^+\pi^0$

- Michel-e from μ and γγ are searched.
- 2 events, lifetime > 7.7×10^{33} years.

Detail: Phys. Rev. D 95, (2017) 012004.





Proton decay (exotic modes)

■ Anti-lepton and meson

- Phys. Rev. D 96 (2017) 012003.

■ Dinucleon/two proton decay

- Phys. Rev. Lett. 115 (2015) 121803.
- Under preparation.