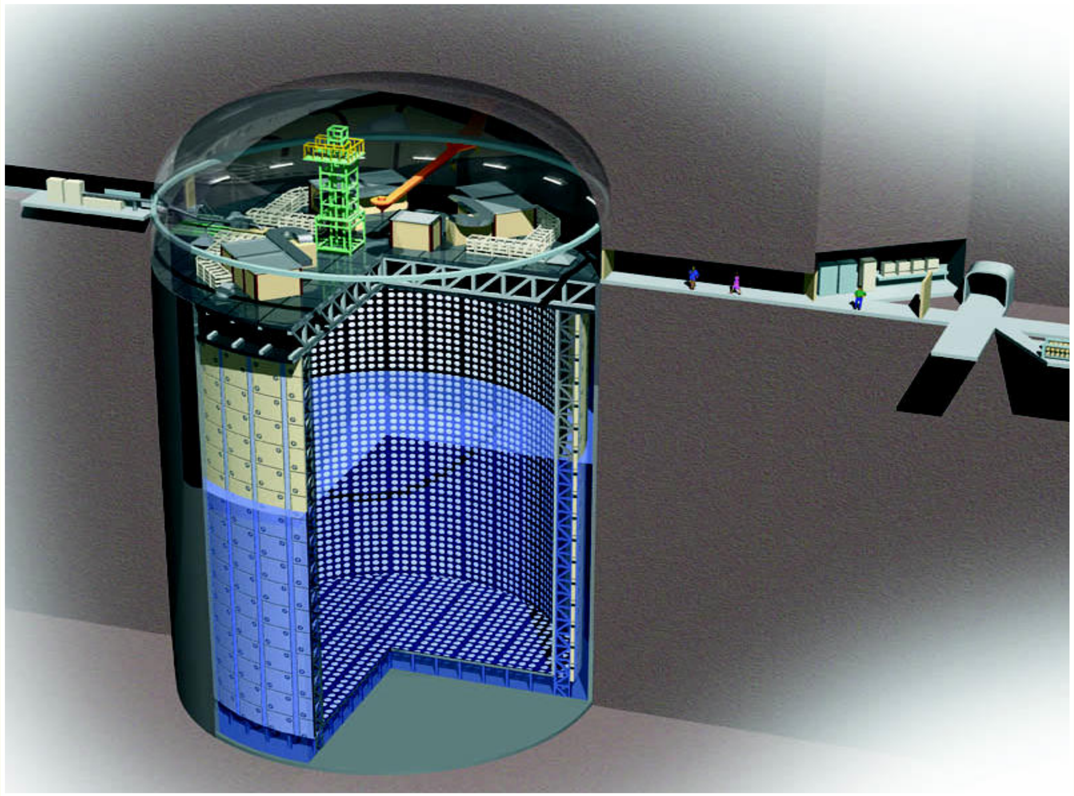
Super-Kamiokande



Yusuke Koshio

Okayama University

XVIII International Workshop on Neutrino Telescopes

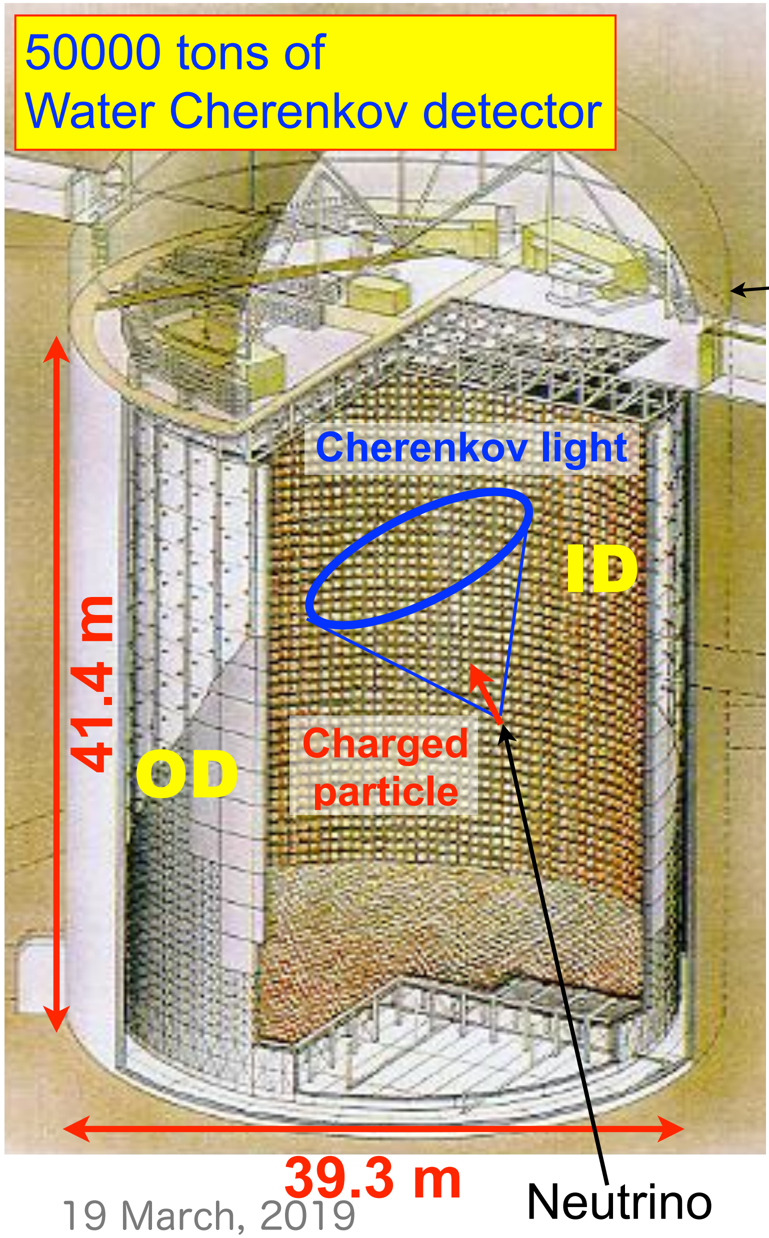
18-22 March, 2019, Venice, Italy

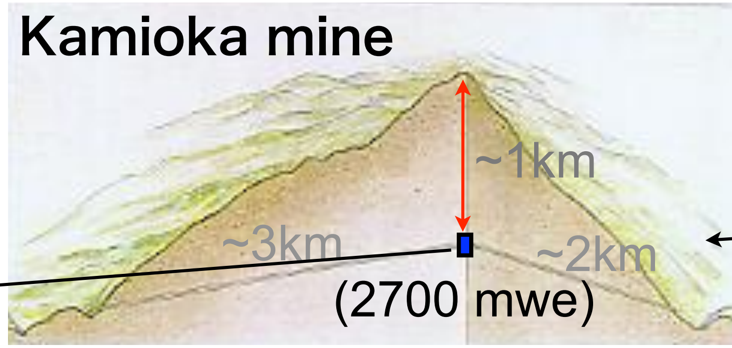
Super-Kamiokande collaboration

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
NFN 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

178 collaborators
from 45 institutes
10 countries

Super-Kamiokande

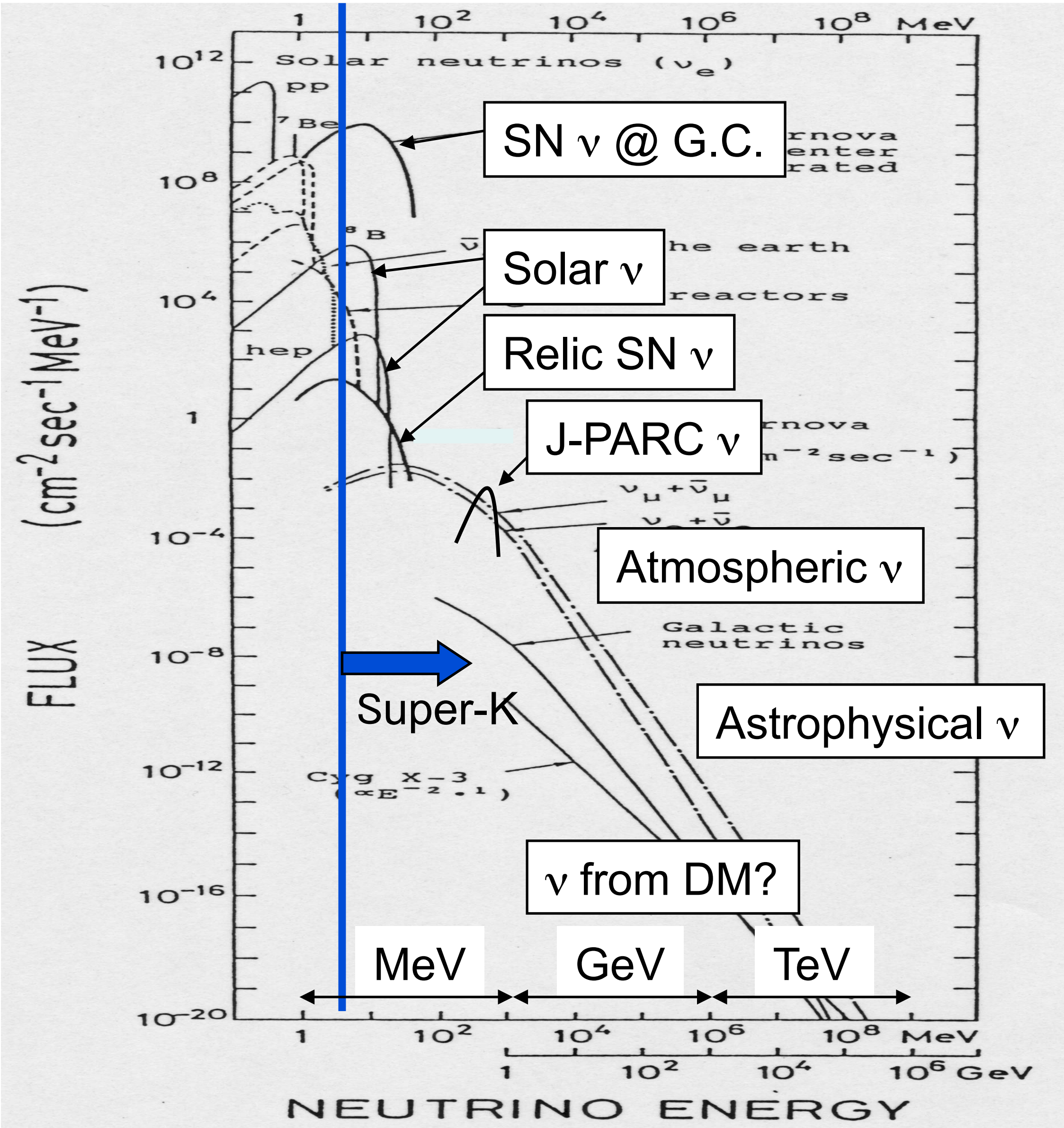




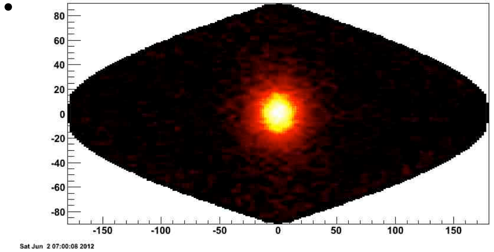
Phase	Period	Fiducial vol. (kton)	# of PMTs (coverage)	Energy thr.(MeV) (Kin. energy)
SK-I	1996.4 ~ 2001.7	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~ 2018.5	22.5 (>5.5MeV) 16.5 (4.5<E<5.5) 8.9 (<4.5MeV)		3.5
SK-V	2019.1 ~	just started!		

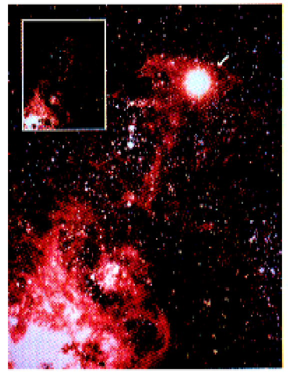
Running and improvements over 20 years

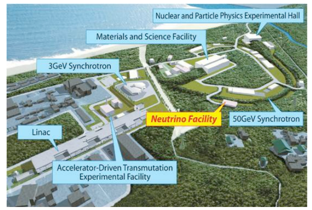
Multi-purpose detector

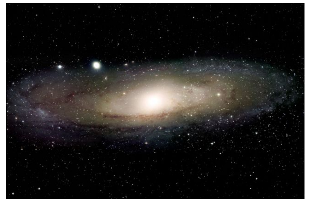


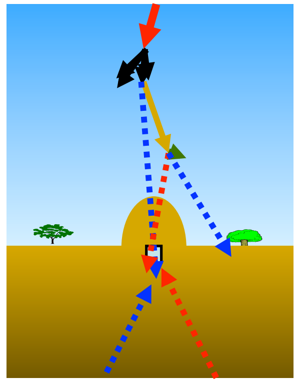
- Wide energy range of neutrinos
- Proton decay search
- Dark matter search
- etc..











Posters

NT19P01 : C. Xu
NT19P03 : M. Harada
NT19P07 : F. Iacob

Neutrino oscillation

Mixing angle : Maki-Nakagawa-Sakata Matrix

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

Atm. and Acc.	Reactor and Acc.	Solar and KamLAND
$\theta_{23} \sim 45 \pm 5^\circ$	$\theta_{13} \sim 9^\circ$	$\theta_{12} \sim 34 \pm 3^\circ$
$\|\Delta m^2_{32}\| = 2.4 \times 10^{-3}\mathrm{eV}^2$		$\Delta m^2_{21} = +7.6 \times 10^{-5}\mathrm{eV}^2$

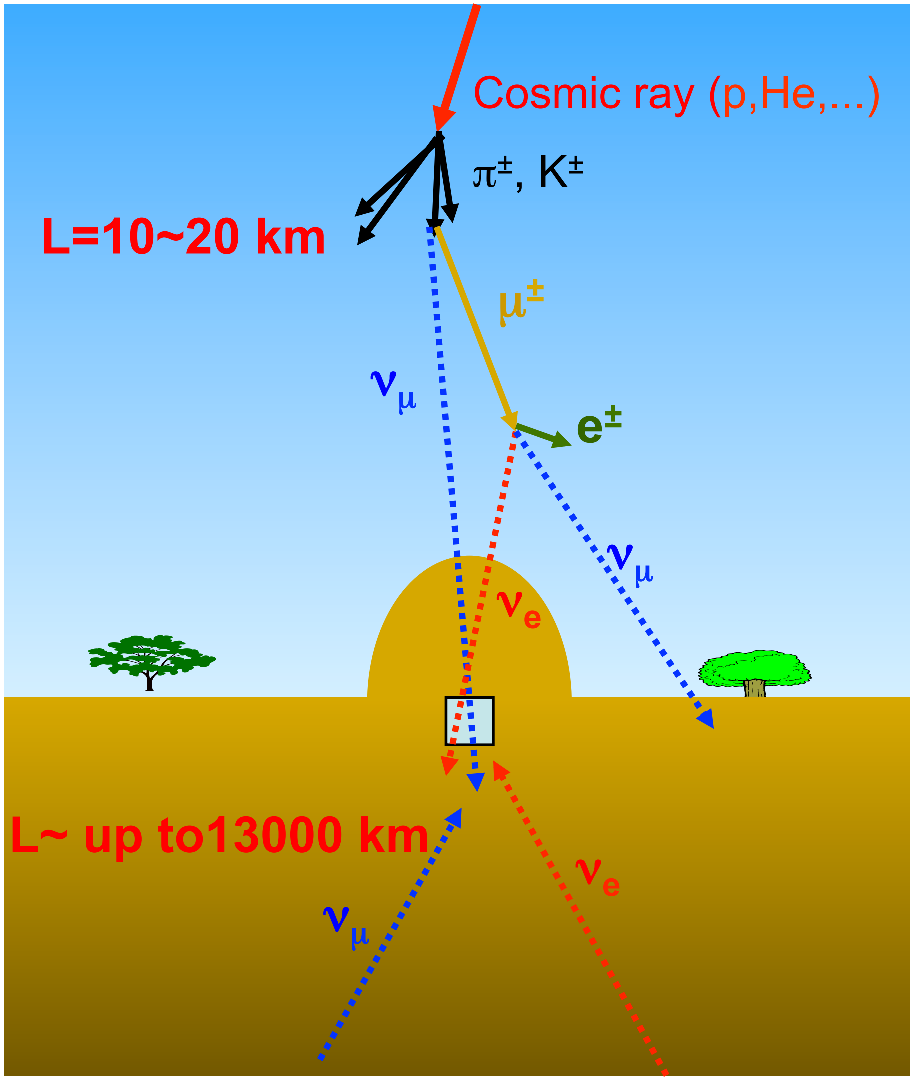
δ cp and Mass hierarchy of 2-3 are unknown

Atmospheric, Accelerator, Reactor

Atmospheric and solar neutrino measurement in Super-K play crucial role for determining the neutrino oscillation parameters

Atmospheric neutrino

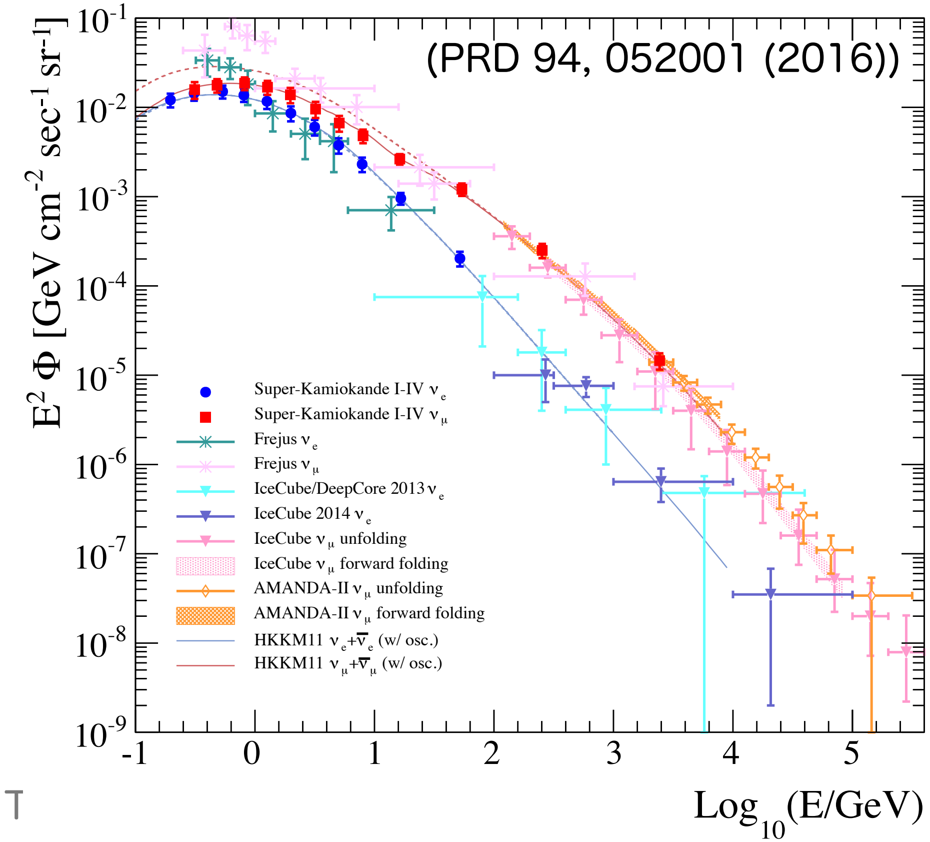
Atmospheric neutrinos



Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos.

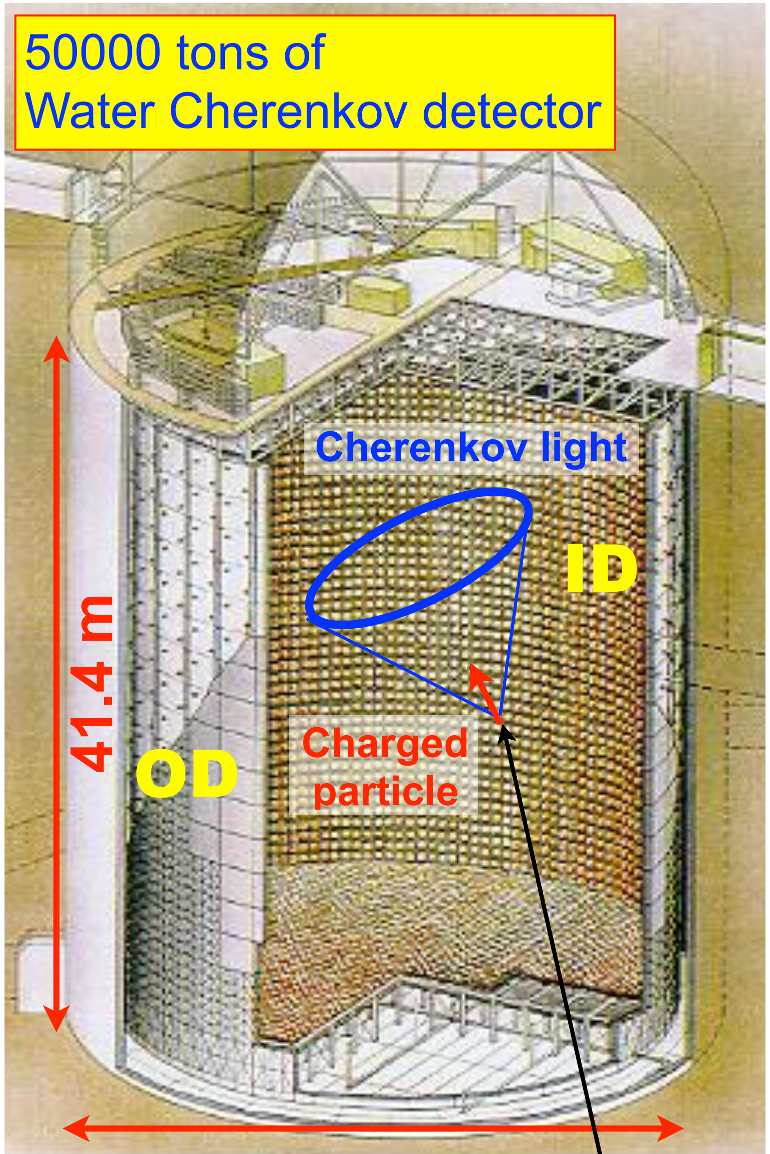
✓ Flux measurement by SK

✓ Model calculation is consistent with data.



Super-Kamiokande

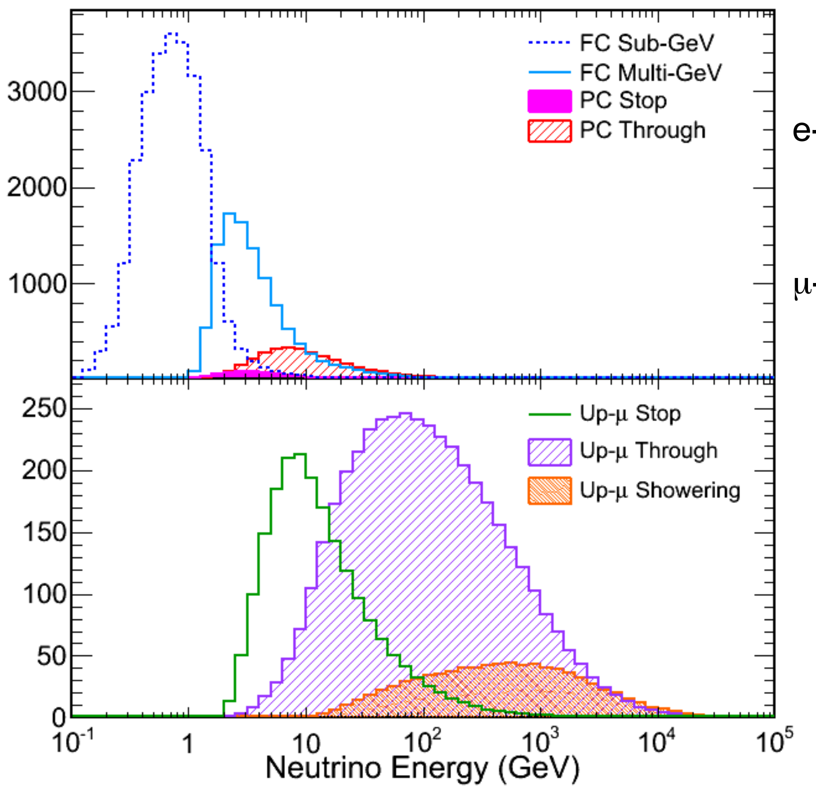
as an atmospheric neutrino detector



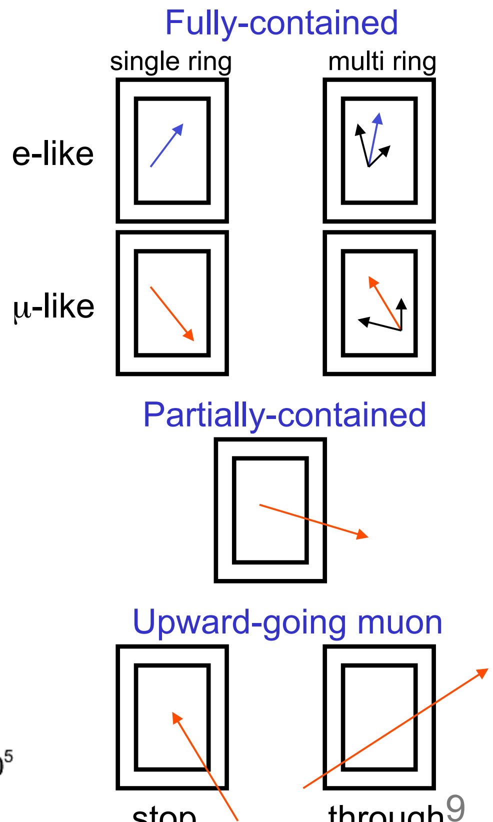
Neutrino interactions in SK

- (quasi-)elastic scattering : ν + N → l + N'
- single meson production : ν + N → l + N' + meson
- deep inelastic interaction : ν + N → l + N' + hadrons
- coherent pion production : ν + ^{16}O → l + ^{16}O + π

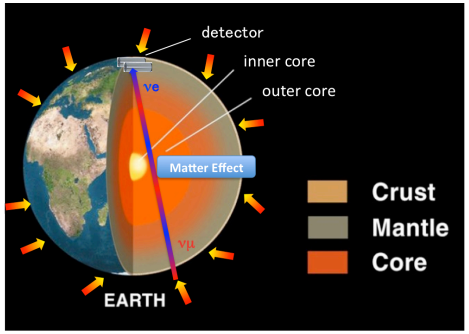
parent neutrino spectra



Event topology



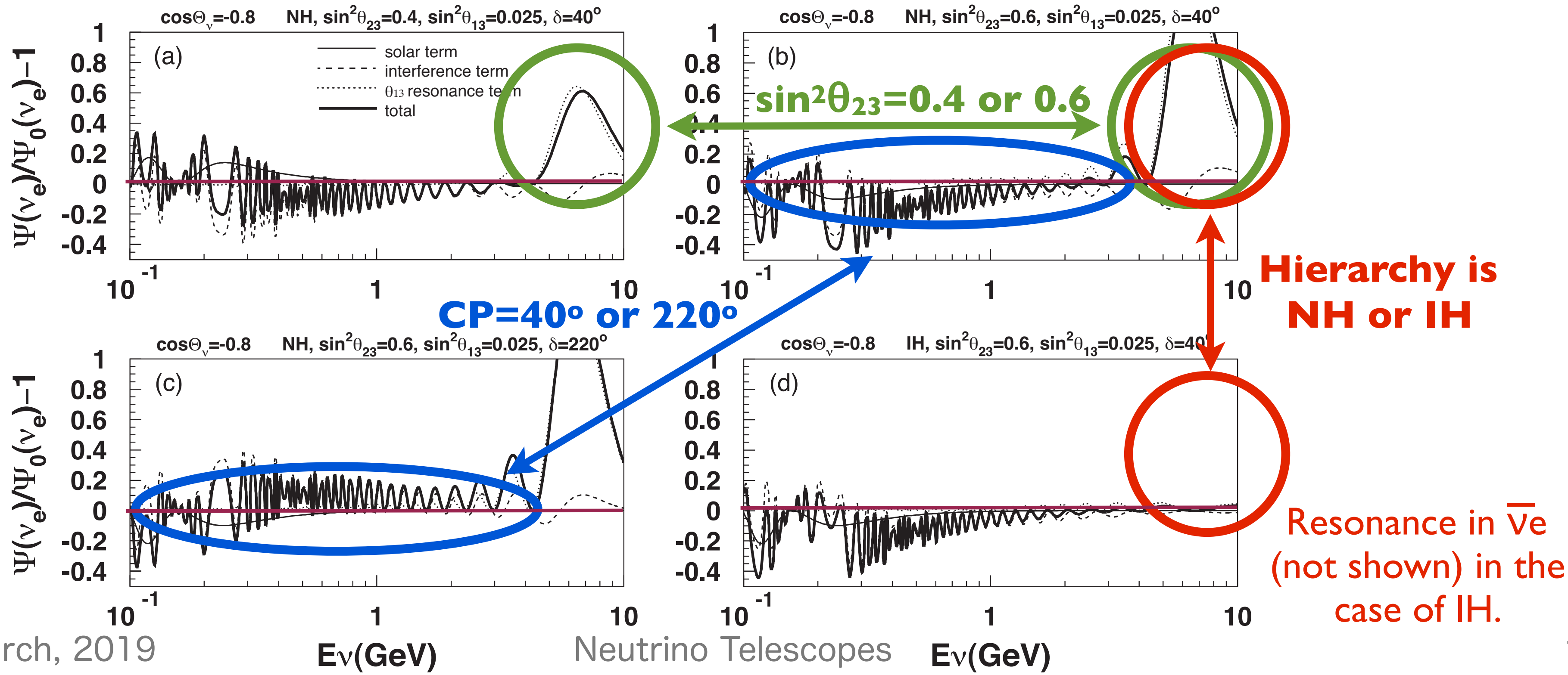
3 flavor neutrino oscillation analysis



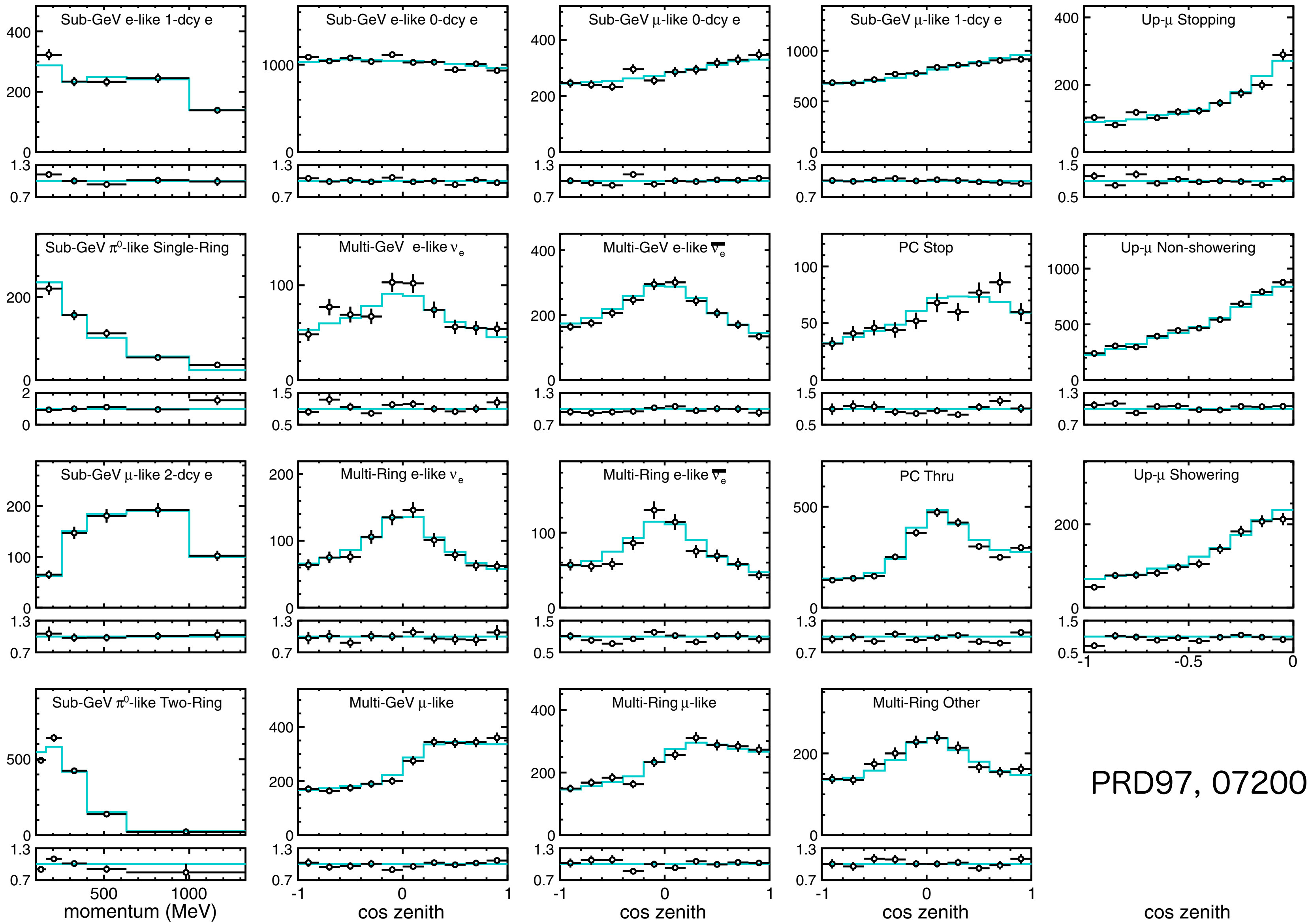
Consider all the sub-leading effects (Δm^2_{21}, matter)

- Mass hierarchy : resonance in multi-GeV ν_e or $\bar{\nu}_e$
- Octant θ_{23} : magnitude of the resonance
- δ_{CP} : interference btw two Δm^2 driven oscillation

Fractional change of upward ν_e flux ($\cos\theta_{zenith}$ = -0.8)



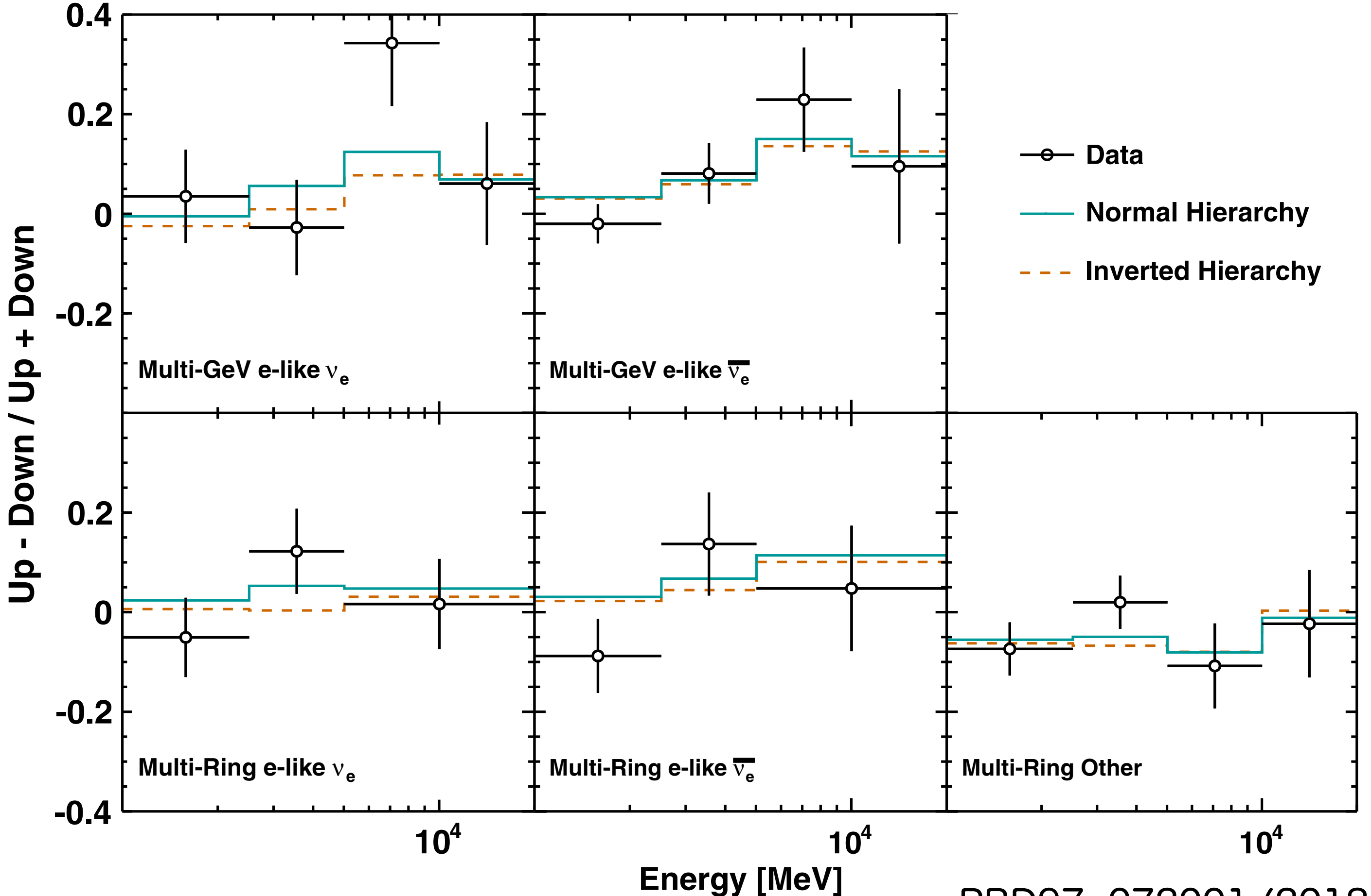
Results in Super-K



PRD97, 072001 (2018)

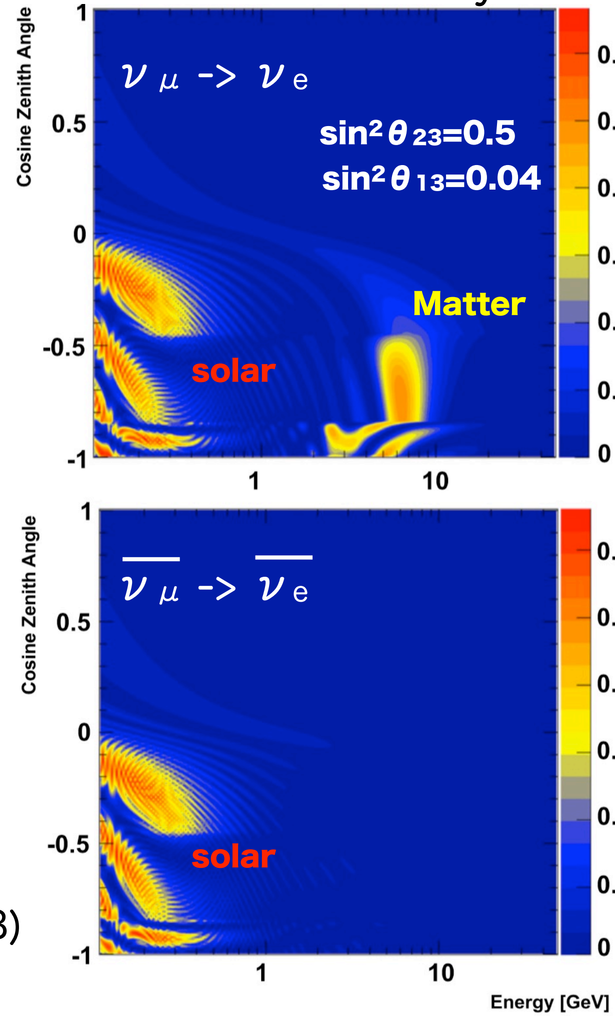
Results in Super-K

Upward ($\cos\theta$ <-0.4) to downward-going ($\cos\theta$ >0.4) event ratio as a function of energy, which emphasis the mass hierarchy



PRD97, 072001 (2018)

Normal hierarchy



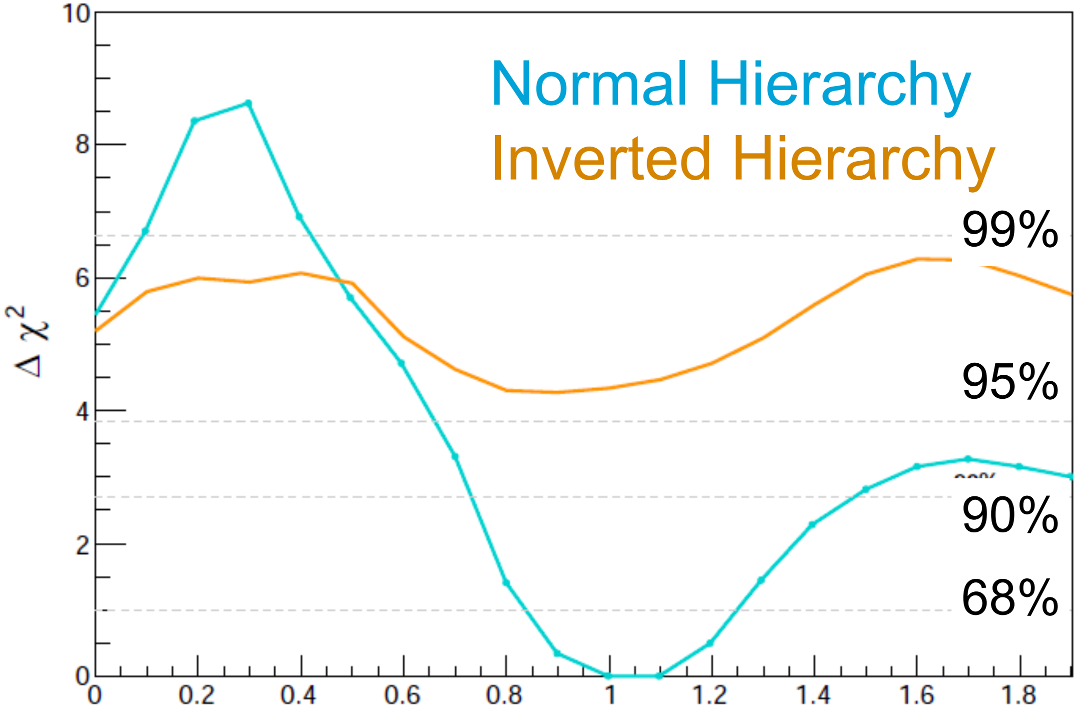
Matter effect fit

$$H_{\text{matter}} = \begin{pmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{pmatrix} + U^\dagger \begin{pmatrix} \alpha \mathrm{a} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} U$$

α: scaling factor

$$\mathrm{a} = \sqrt{2}\mathrm{G_f N_e}$$

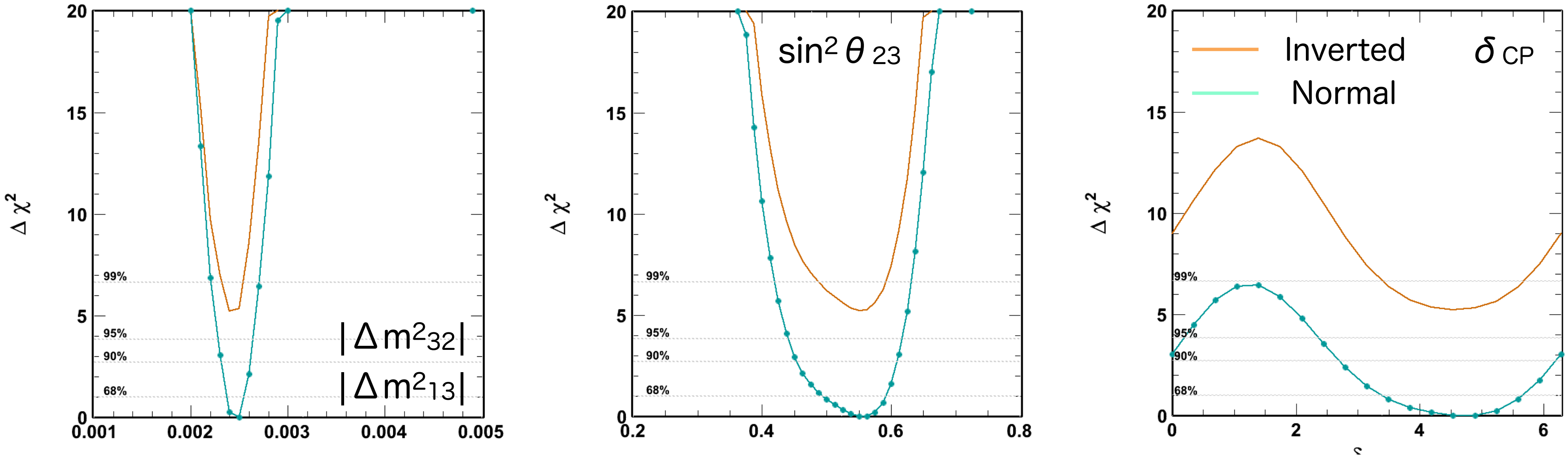
PRD97, 072001 (2018)



✓ Best fit α=1 for NH, consistent with standard matter effect.

✓ $\Delta \chi^2$=5.2 for α=0. Data disfavors zero matter-effect > 2σ level.

Parameter determination

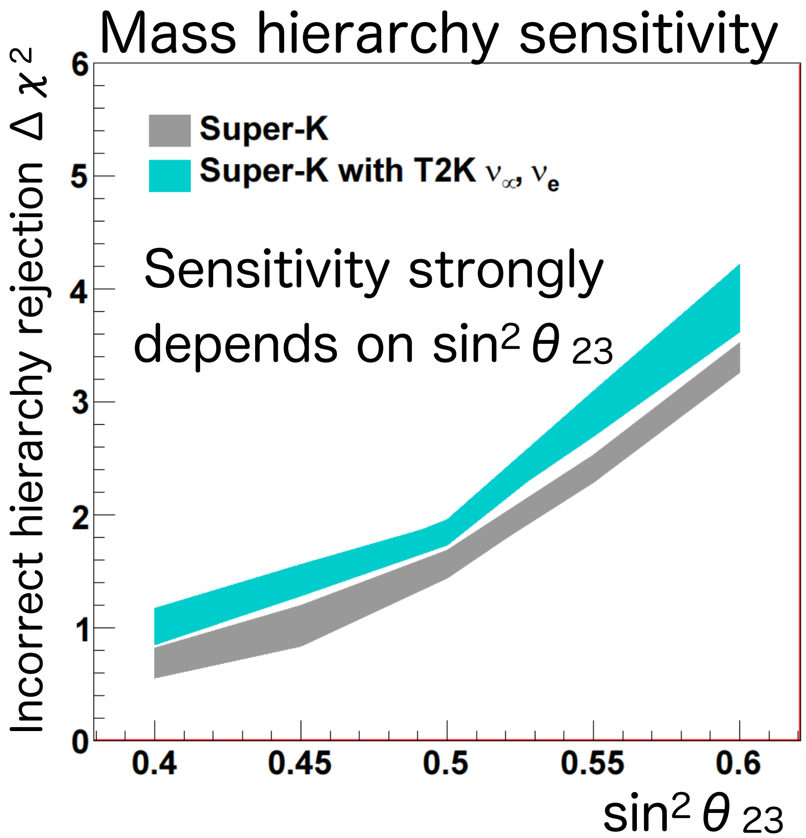


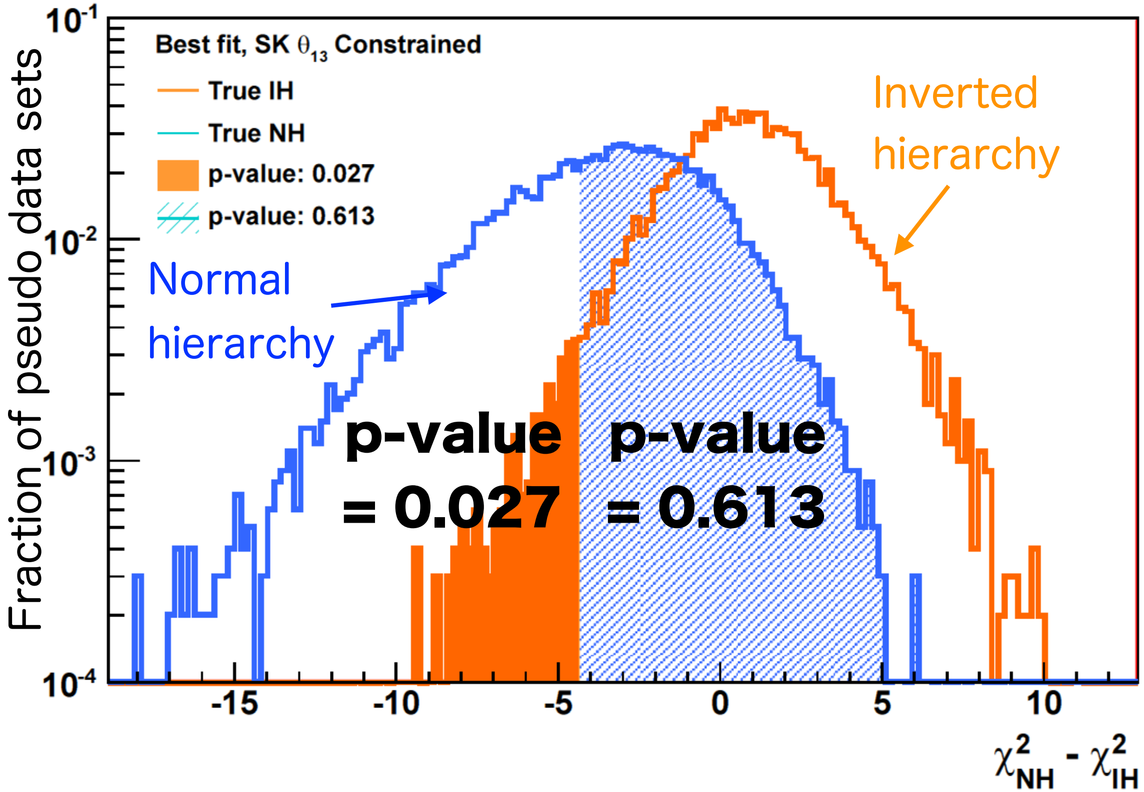
Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	$\lvert\Delta m^2_{32}\rvert \mathrm{eV}^2$	$\sin^2\theta_{23}$	δ_{CP}
SK+T2K (IH)	644.70	0.0219 (fix)	$2.40^{+0.13}_{-0.05} \times 10^{-3}$	$0.550^{+0.035}_{-0.051}$	$4.54^{+1.05}_{-0.97}$
SK+T2K (NH)	639.43		$2.50^{+0.05}_{-0.12} \times 10^{-3}$	$0.550^{+0.039}_{-0.057}$	$4.88^{+0.81}_{-1.48}$

✓ $\Delta\chi^2=\chi^2_{NH}-\chi^2_{IH}$=-4.33 (SK only), -5.27 (SK + T2K) PRD97, 072001 (2018)

✓ Normal hierarchy is favored by 81.9~96.7% (SK only) and 91.9~94.5% (SK+T2K) @ parameters allowed at 90% C.L.

Parameter determination



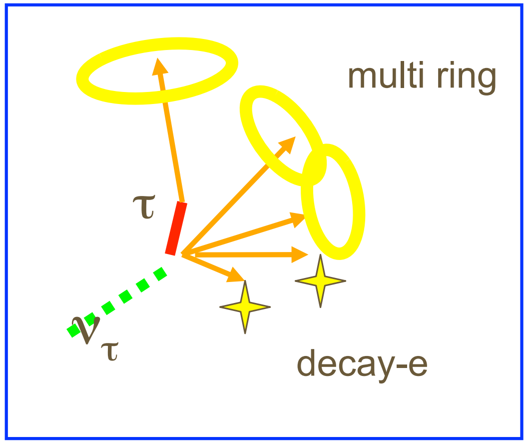


✓ $\Delta\chi^2=\chi^2_{NH}-\chi^2_{IH}$=-5.27 (SK+T2K), -4.33 (SK only) PRD97, 072001 (2018)

✓ Normal hierarchy is favored by 81.9~96.7% (SK only) and 91.9~94.5% (SK+T2K) @ parameters allowed at 90% C.L.

τ neutrino appearance

Hard to identify event by event
but can be statistically seen

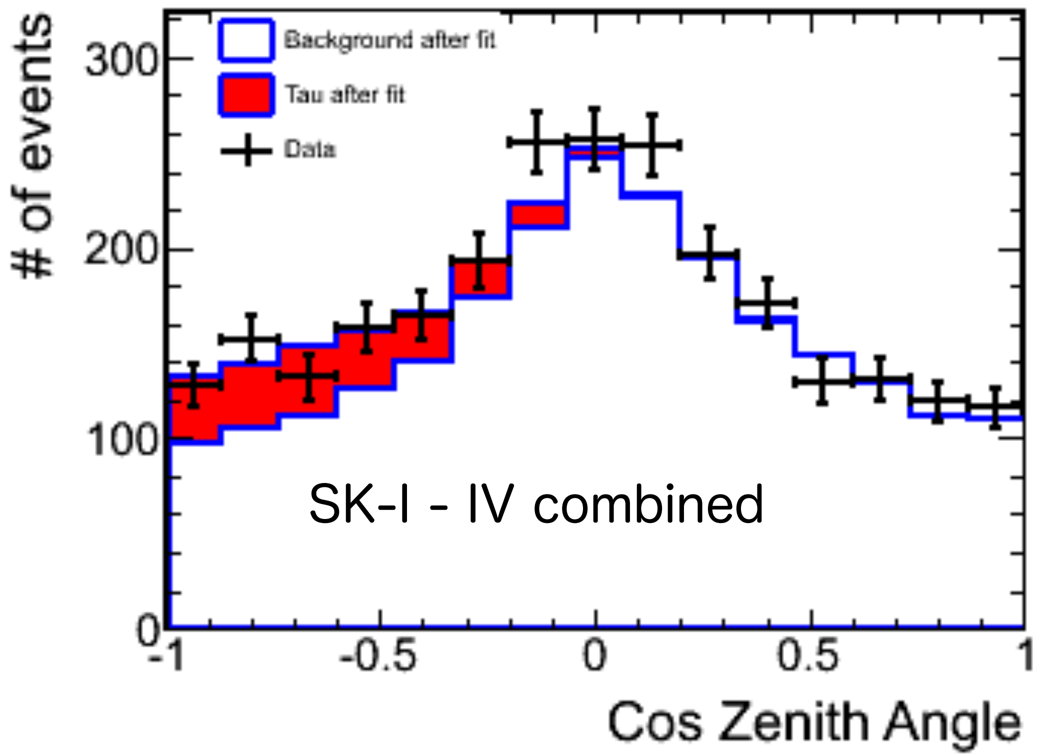


Search for events consistent with hadronic decays of tau lepton using neural network method

data=PDF(BG)+α x PDF(τ)+Σ ε_i x PDF$_i$

PDF of i-th sys. error shifting by 1σ

Multi-ring e-like sample



τ fraction is found to be 1.47±0.32, which is 4.6σ from 0.

PRD98, 052006 (2018)

Summary of atmospheric ν

- Full 3 flavor oscillation analysis is performed to extract neutrino oscillation parameters using SK-I to SK-IV, 5326 days, 328 kt・yr.
- Data consistent with Earth's matter effect more than 2σ level.
- Normal hierarchy is favored as 91.9~94.5% in combined with T2K.
- Tau appearance is found at 4.6σ.

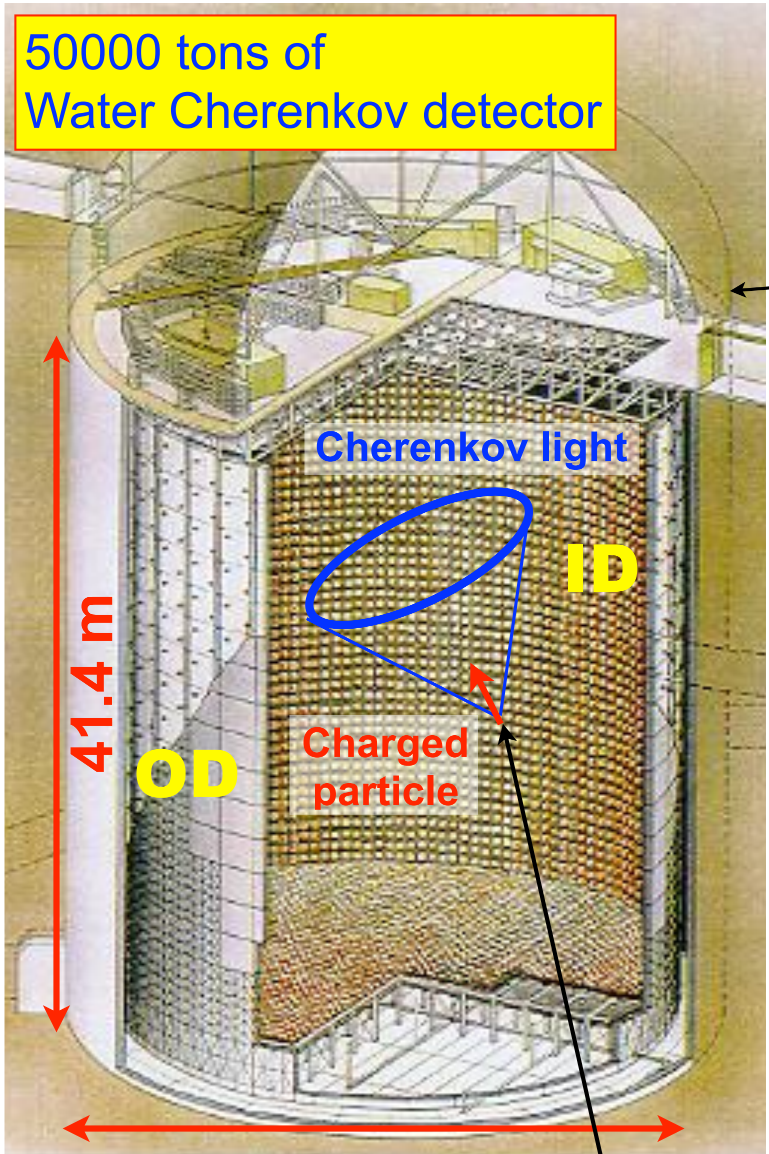
Summary of atmospheric ν

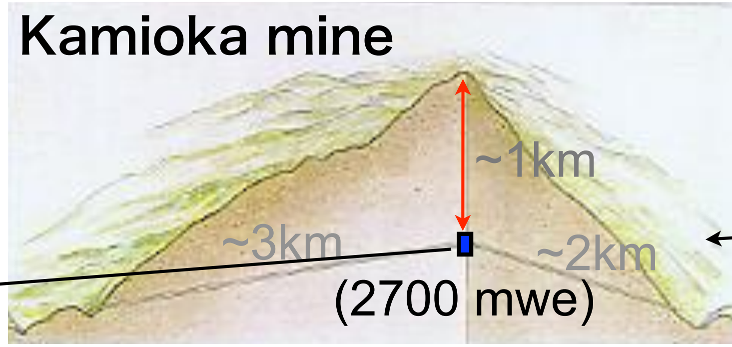
- Increased statistics with new event reconstruction tools will be appeared soon. At first, fiducial volume of SK-IV is expand to 27 kton (from 22.5 kton), arXiv: 1901.03230, also just approved in PTEP. As the next step, expand for entire period.
- Neutron information (~20% tagging efficiency) is used to identify neutrino flavor and to determine neutrino energy.
- SK-Gd in preparation. (see later) $\nu_e/\bar{\nu}_e$ separation and energy determination will be improved.

Solar neutrino

Super-Kamiokande

as a solar neutrino detector





Phase	Period	Live time (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~ 2018.5	2860	22.5 (>5.5MeV) 16.5 (4.5<E<5.5) 8.9 (<4.5MeV)		3.5

total 5695 days

(coverage)(Kin. energy)

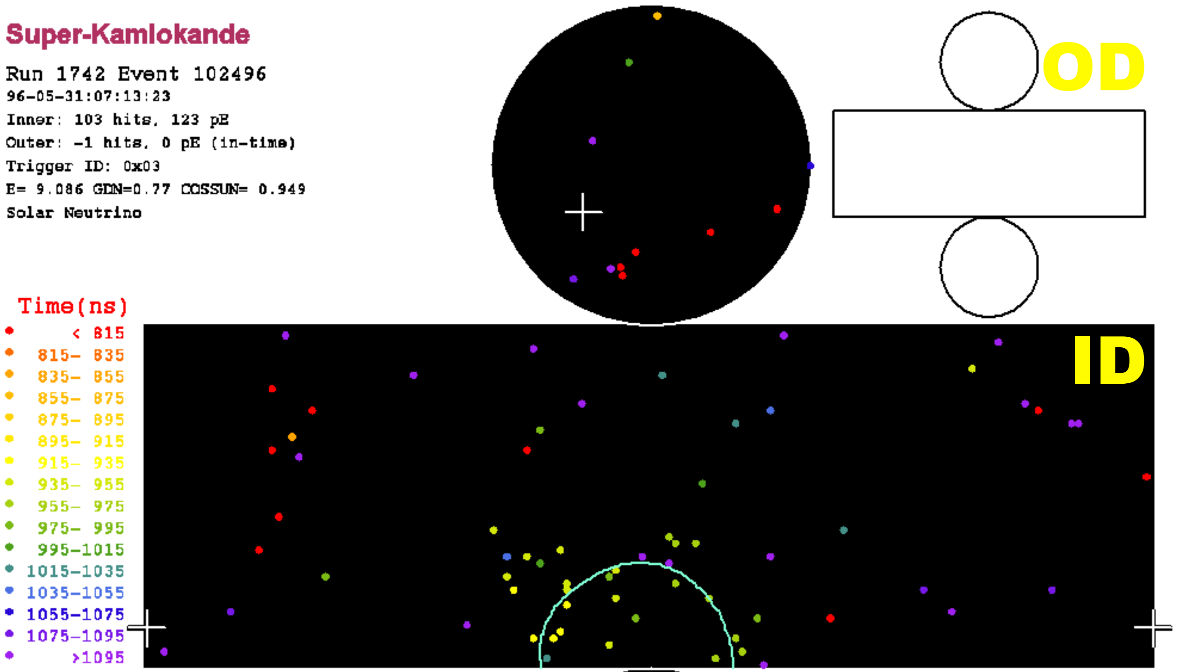
Super-Kamiokande

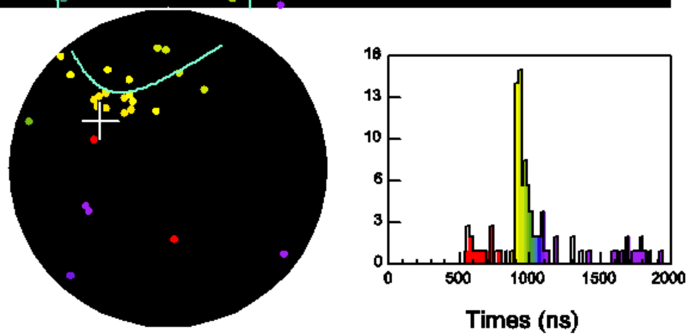
as a solar neutrino detector

neutrino-electron elastic scattering

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

Typical event





E_e = 8.6 MeV (kin.)
$\cos\theta_{sun}$ = 0.95

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

Detector performance

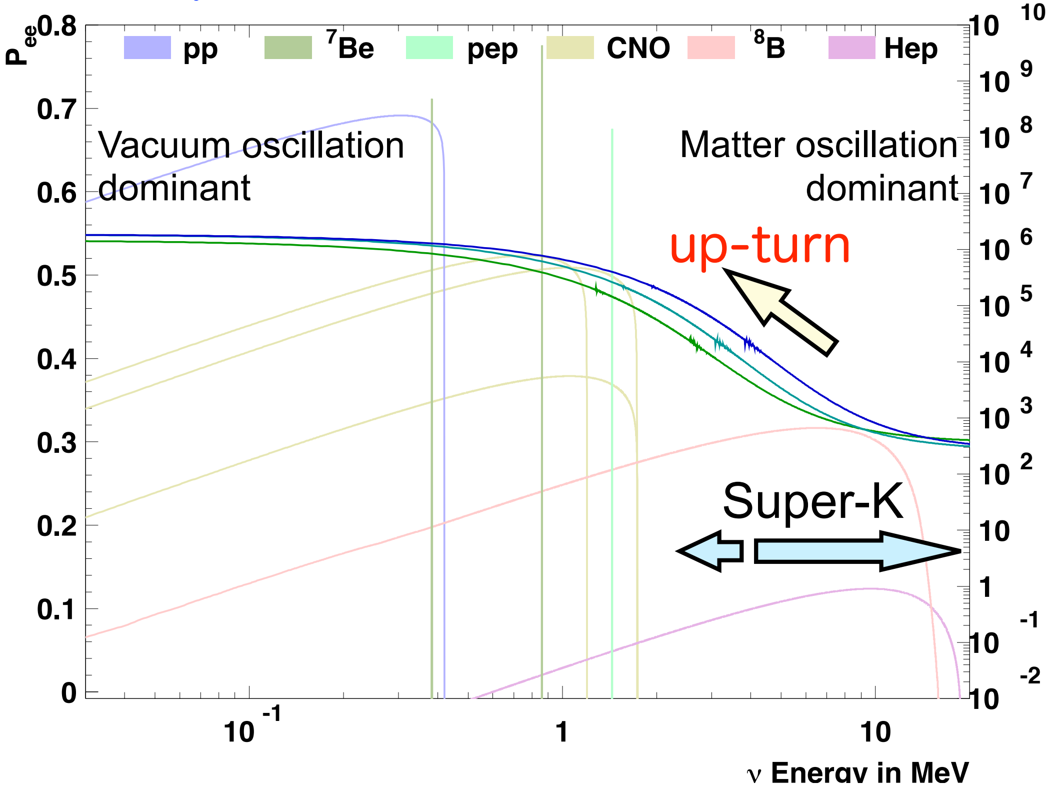
	resolution (10 MeV)	information
vertex	55cm	hit timing
direction	23deg.	hit pattern
energy	14%	# of hits.

~ 6 hits/MeV
well calibrated by LINAC and DT within 0.5% precision

Motivation of the measurement

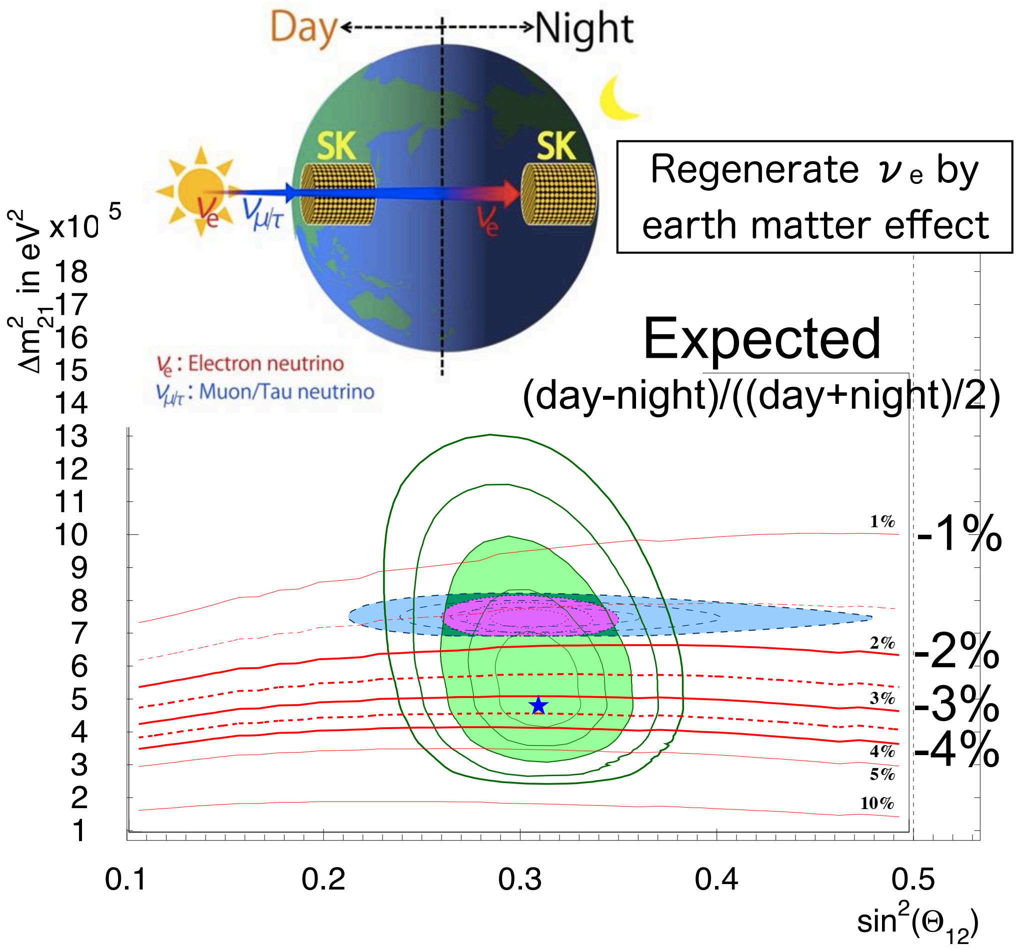
See the neutrino oscillation MSW effect directly

Spectrum distortion

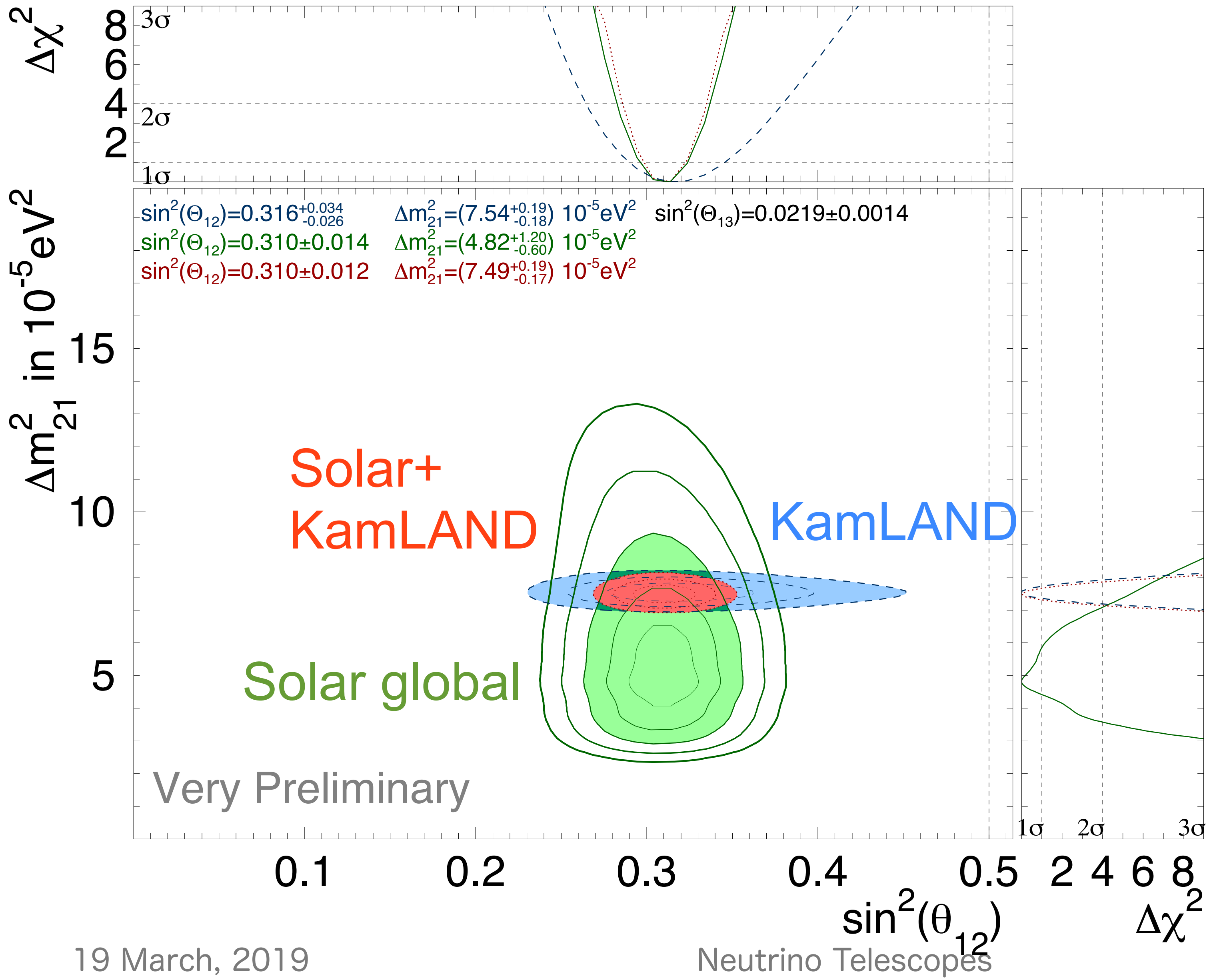


Super-K can search for the spectrum "upturn" expected by neutrino oscillation MSW effect

Day-Night flux asymmetry



Neutrino oscillation

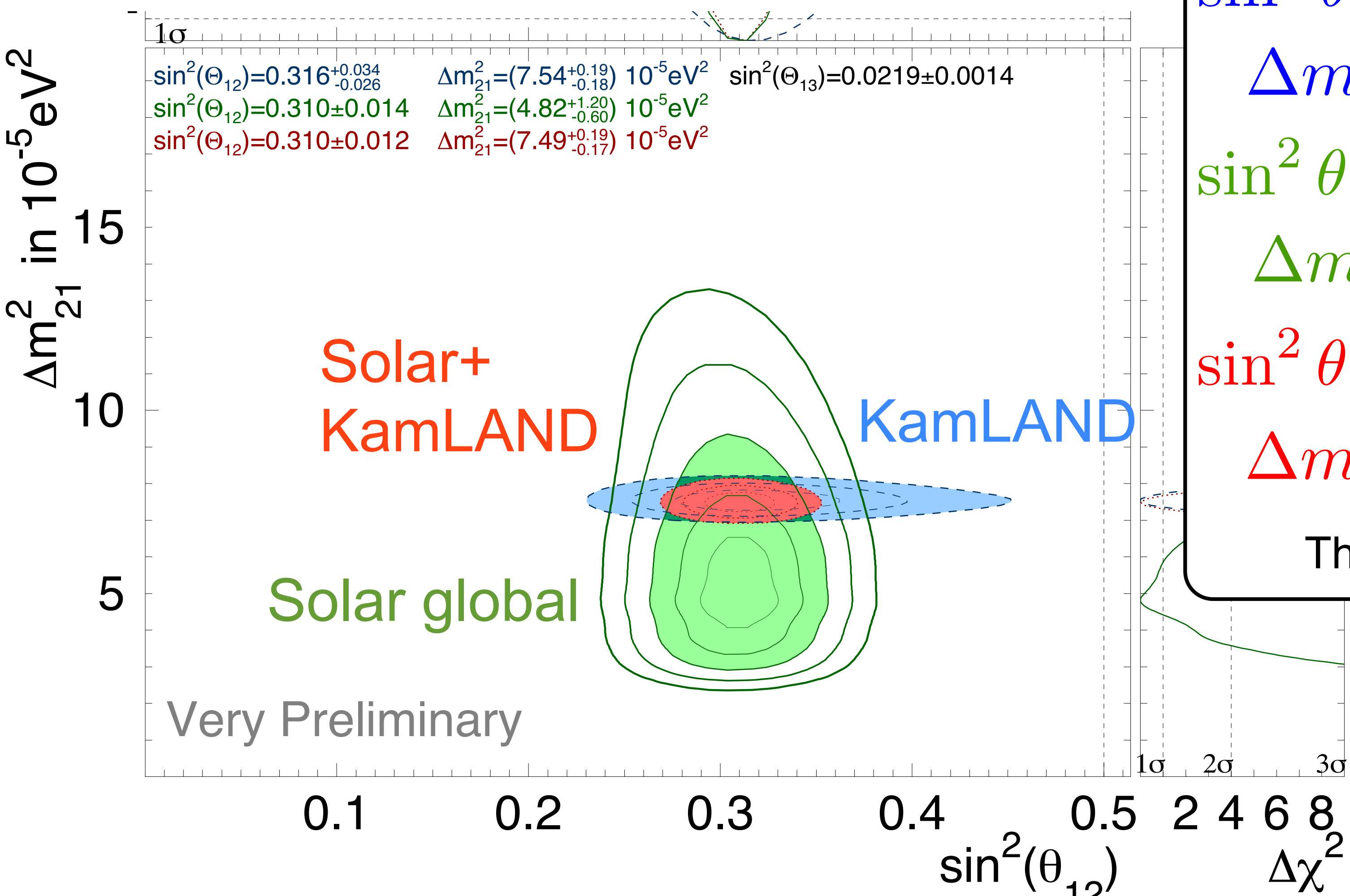


M. Ikeda, Neutrino 2018

DOI: 10.5281/zenodo.1286857

Neutrino oscillation

~2σ tension between solar global and KamLAND in Δm^2_{21}



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

The unit of Δm^2_{21} is 10^{-5} eV^2

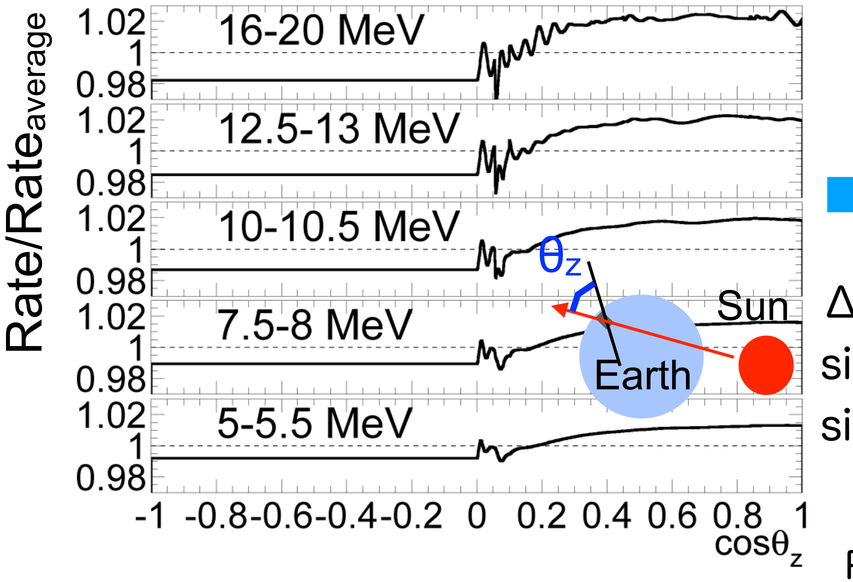
$\sin^2\theta_{13}=0.0219\pm0.0014$

M. Ikeda, Neutrino 2018

DOI: 10.5281/zenodo.1286857

Day/Night asymmetry

expected time variation as a function of $\cos\theta_z$



PRD94, 052010 (2016)

Day/Night Amplitude is fitted to

-3.3±1.0±0.5%

$\Delta m^2_{21}=4.84\times10^{-5}\ eV^2$

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

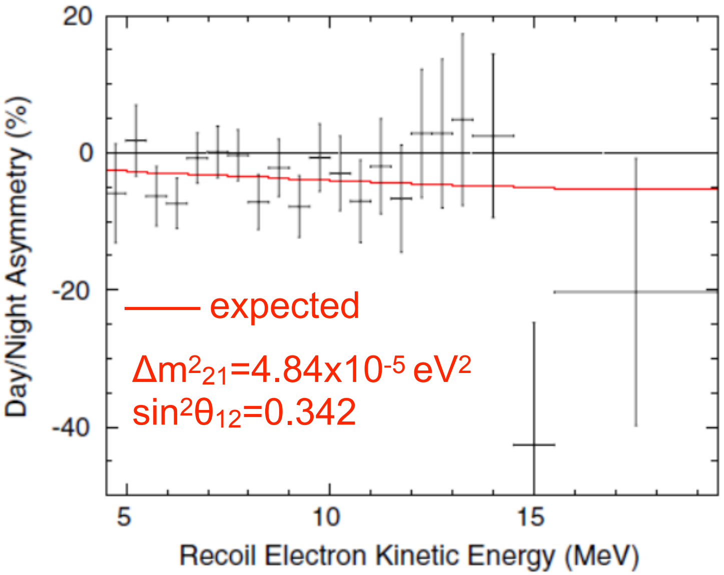
$\sin^2\theta_{13}=0.025$

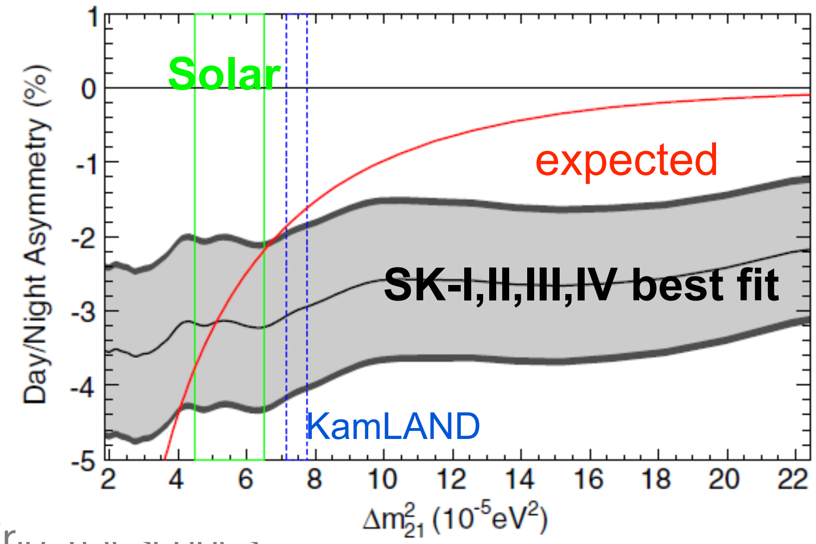
Non-zero significance is

2.9 σ

in SK-I to IV (4499 days)

PRL112, 091805 (2014)

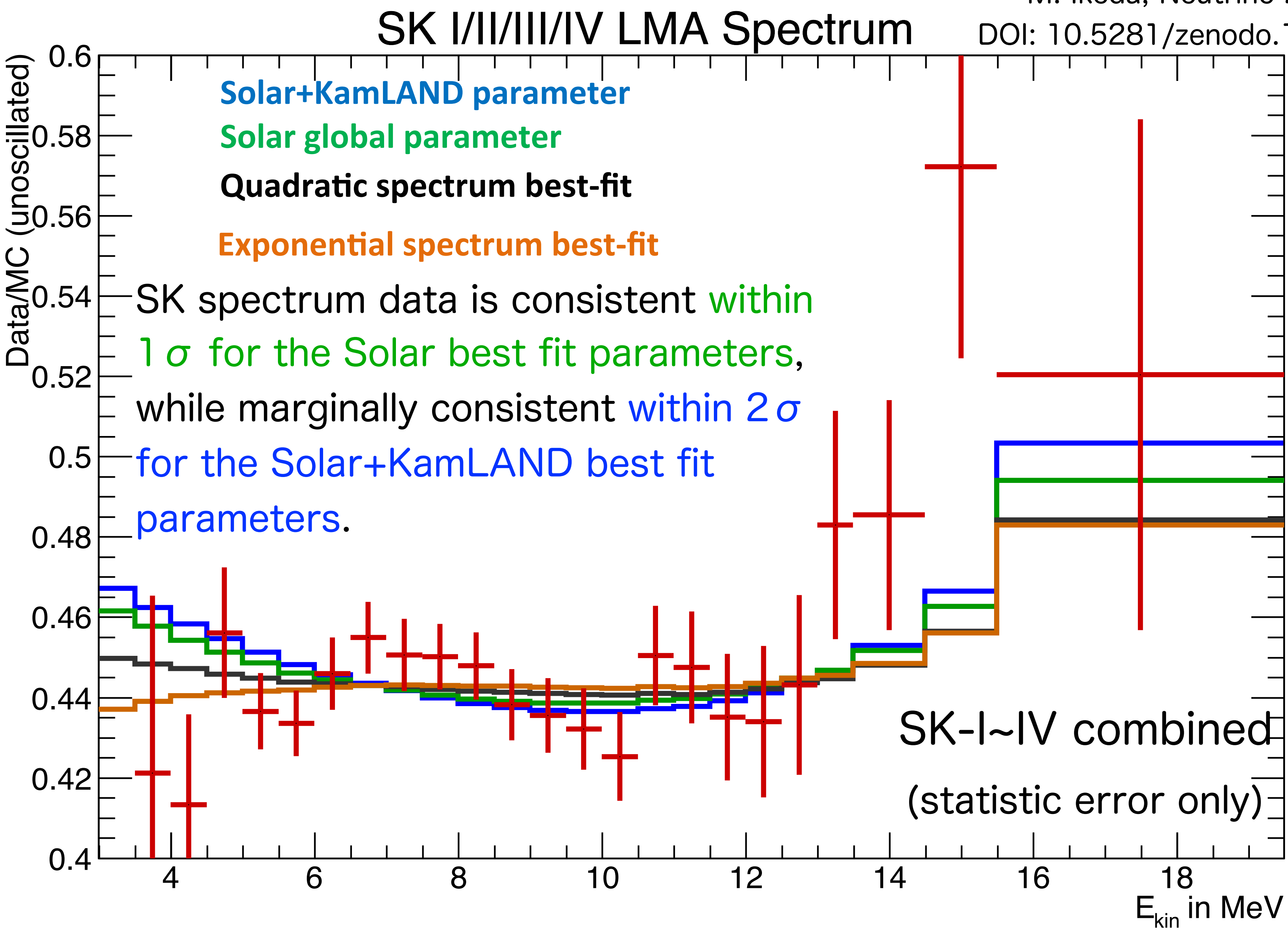




Preliminary

Recoil electron spectrum

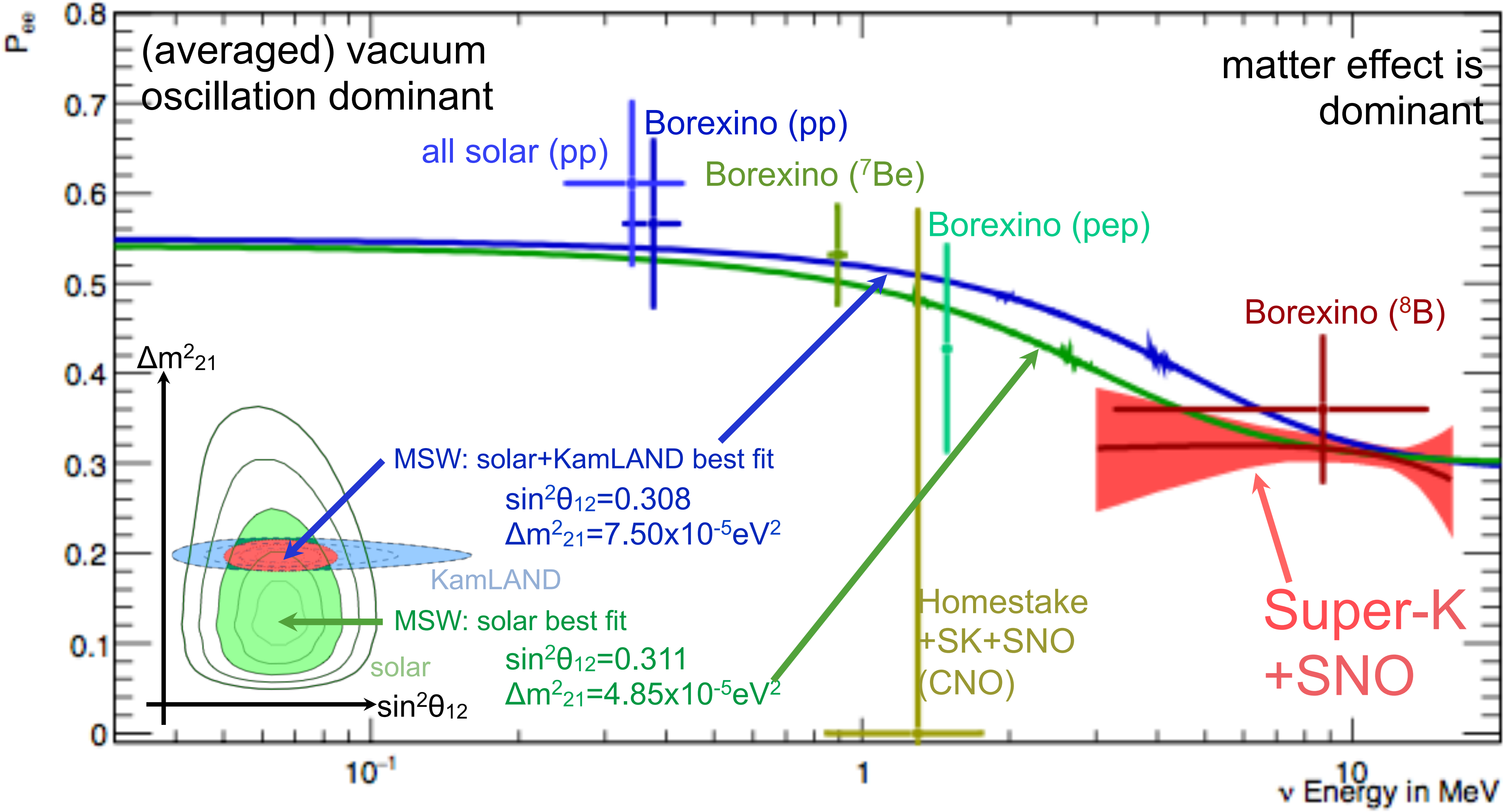
M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857



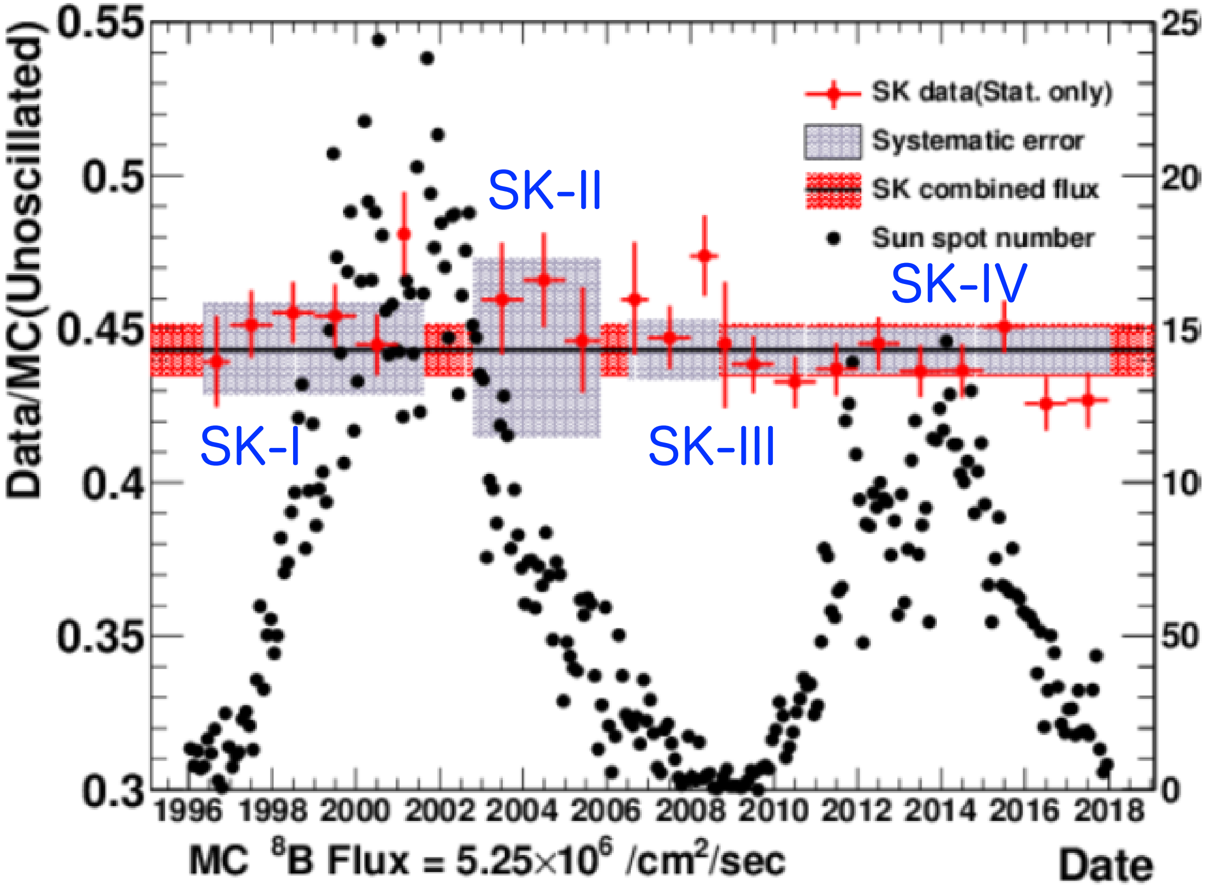
Preliminary

Survival probabilities

M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857



Yearly solar neutrino flux



M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857

^{8}B flux vs sun spot

No correlation with 11 years solar activity is observed

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

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

Solar neutrino rate measurement in SK is fully consistent with a constant solar neutrino flux emitted by the Sun

Summary of solar ν

- Data taking in SK-IV is finished. The preliminary results are consistent with the previous results.
  - Indication of Day-Night asymmetry has been found in Super-K at ~3σ level.
  - 2σ tension between solar and KamLAND Δm_{21}^2 is seen. Day-night measurement in Hyper-K can determine the parameter.
  - Any distortion of periodical flux variation cannot be seen.

Summary of solar ν

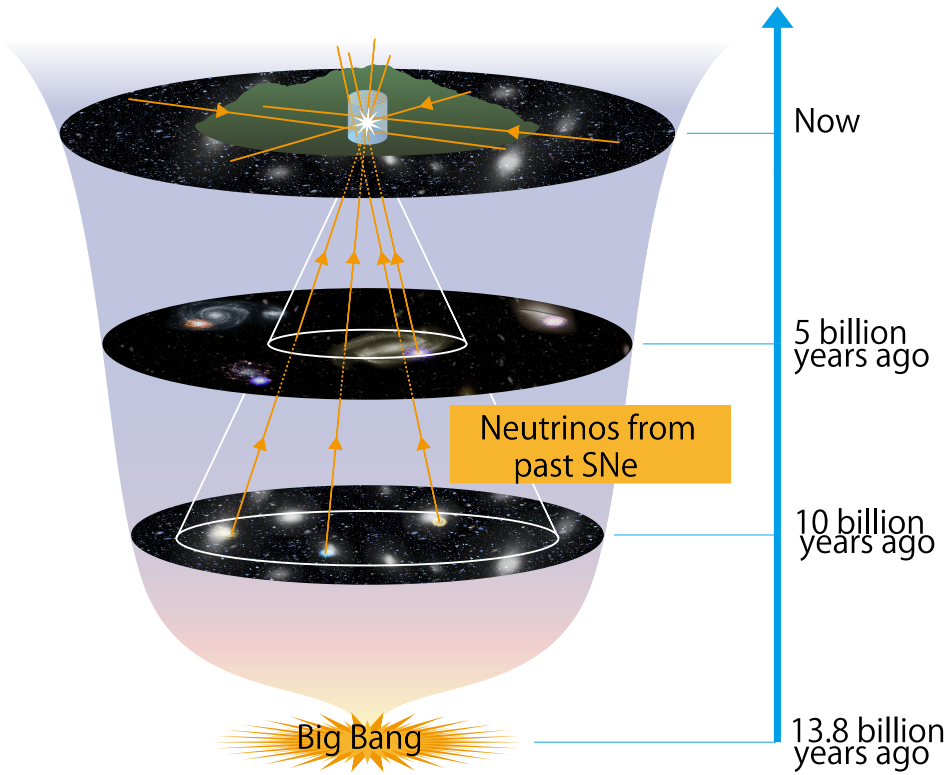
- Non standard interaction analysis is on going.
- Lowering threshold : WIT system, which applies reconstruction and reduction just after front-end.
- Reduction of spallation event will be improved.
- Keep continuing solar neutrino analysis in Super-K Gd era.

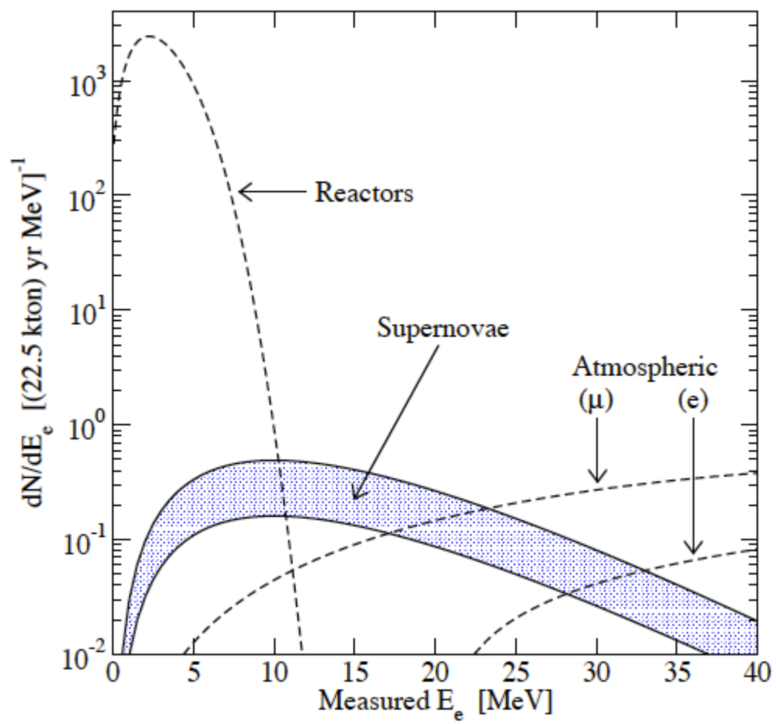
Toward the next decade

Super-K Gd

For the first observation of DSNB

(Diffuse Supernova Neutrino Background)

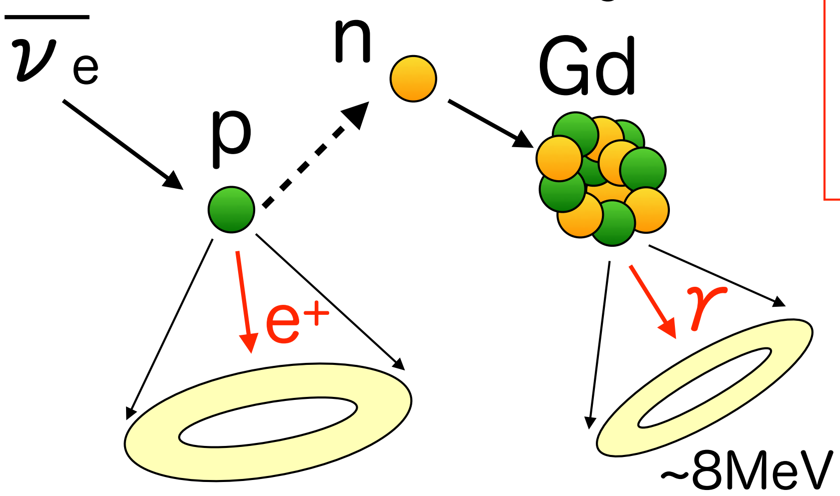




How to reduce atmospheric neutrino BG?

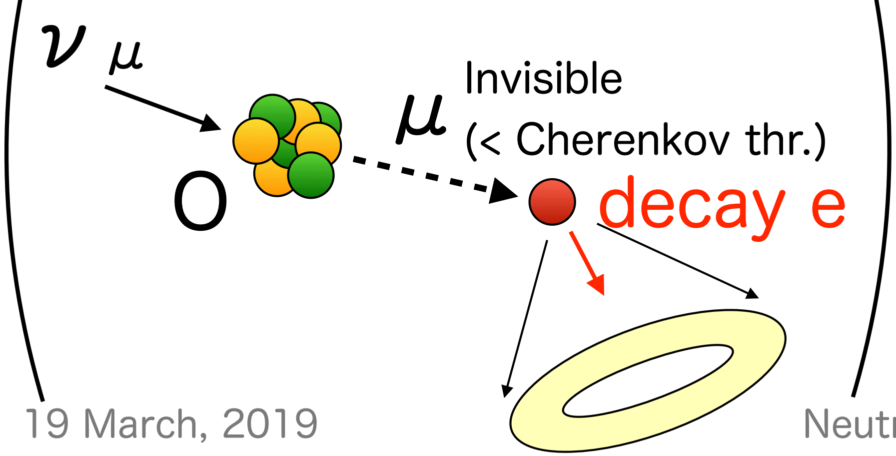
Super-K Gd

Inverse beta decay



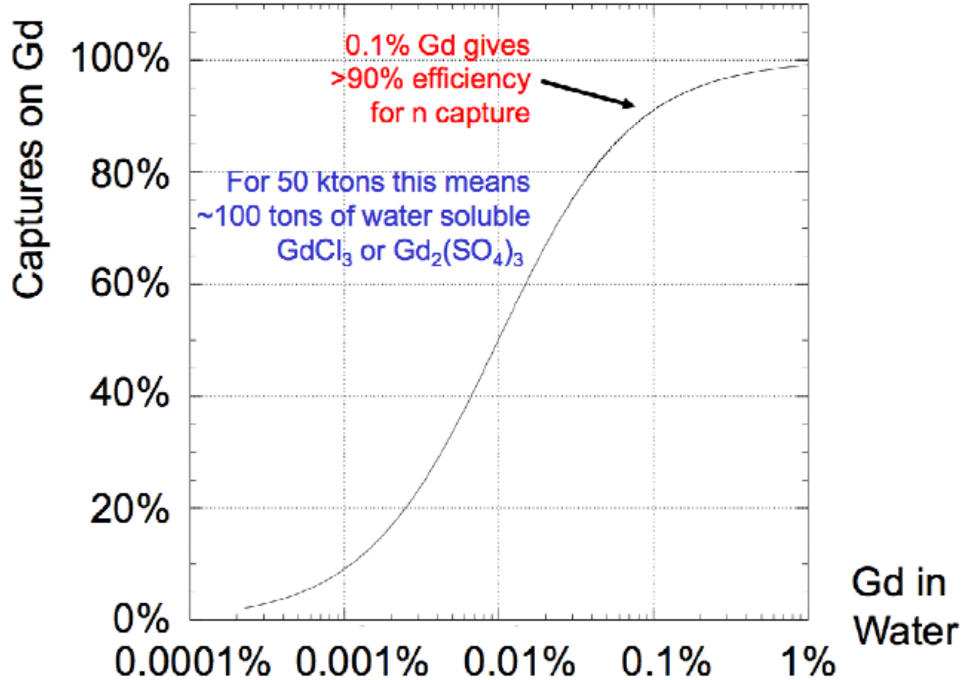
Delayed coincidence

Atmospheric ν BG



Dissolve Gadolinium into Super-K

J.Beacom and M.Vagins, Phys.Rev.Lett.93(2004)171101

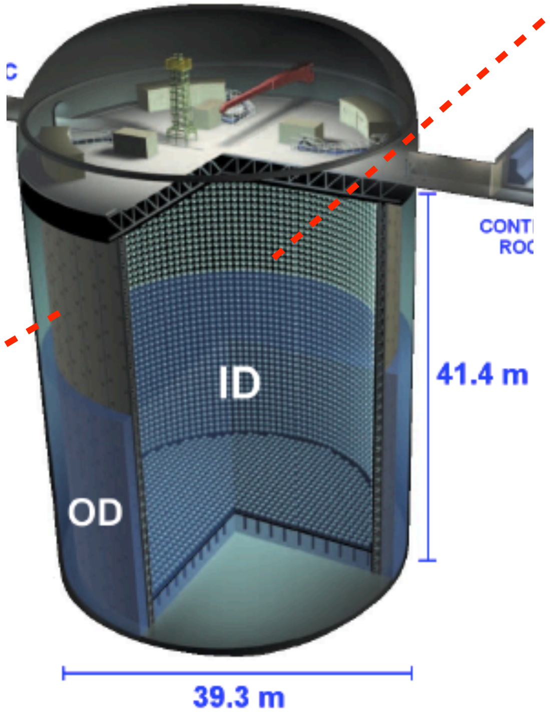


~90% of neutrons are tagged in 0.2% $Gd_2(SO_4)_3$ (0.1% Gd)

Super-K tank refurbishment

- Stop water leak (~3ton/day)
- Change bad PMTs
- Install new water pipe for better water control
- Cleaning


Change bad PMTs

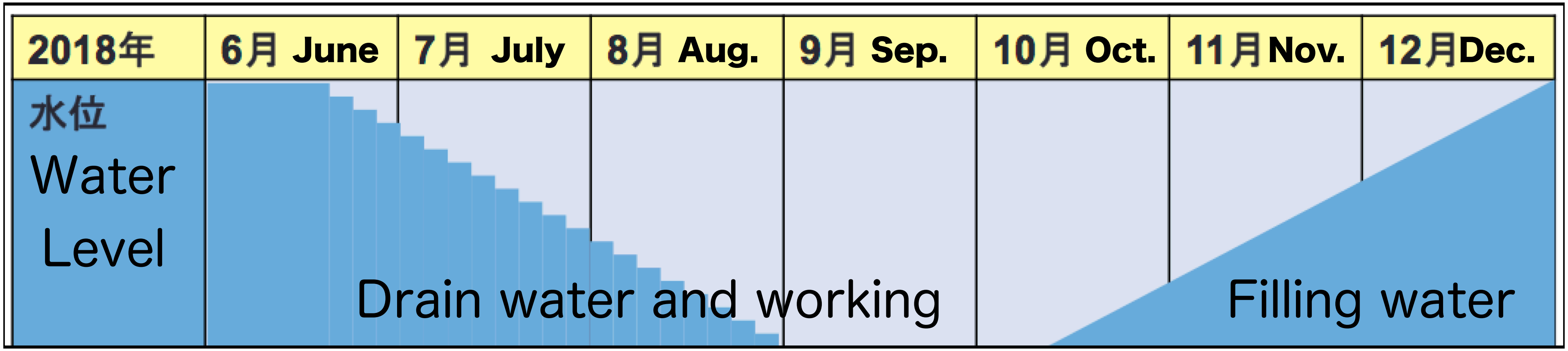



Seal whole welding lines


Install new water pipe

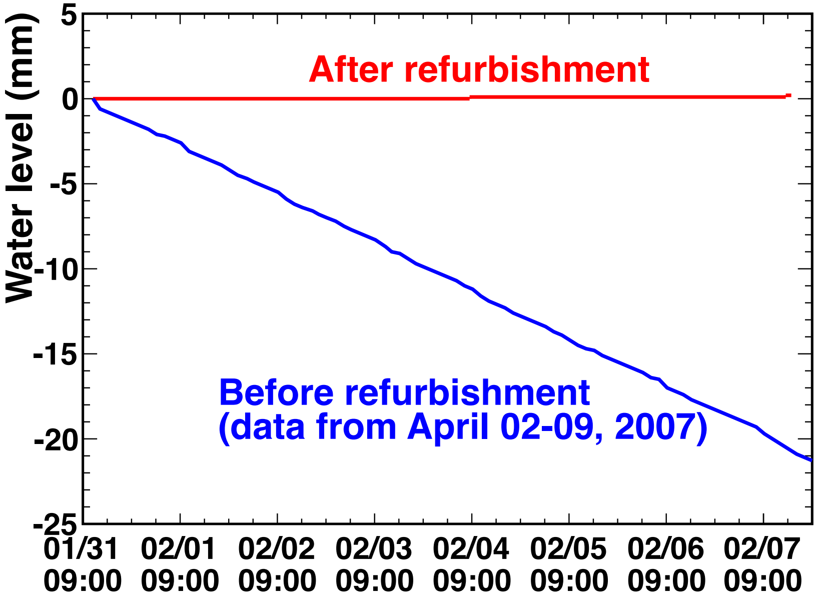
Super-K tank refurbishment

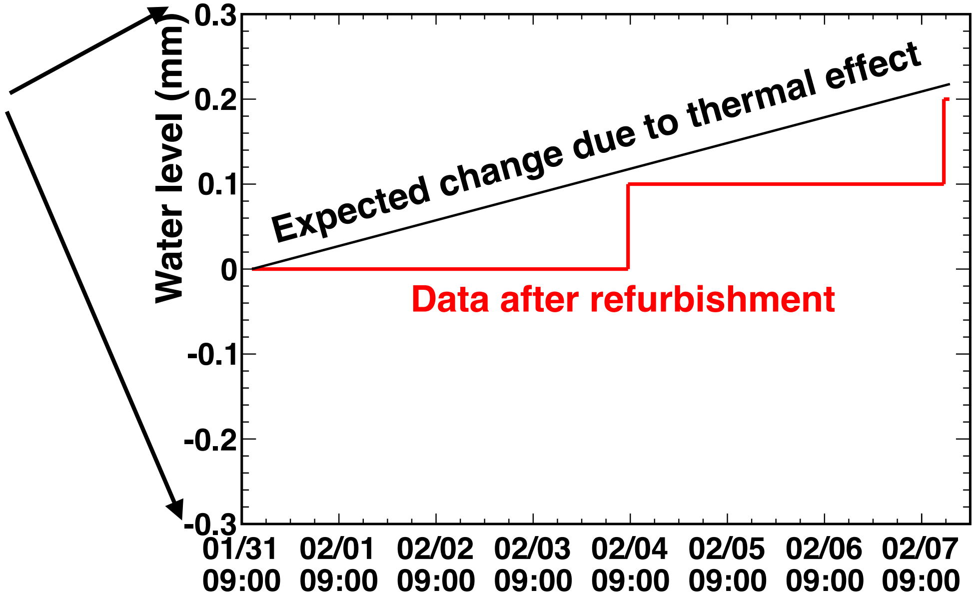
- Start on 31st May, work on barrel part draining water. After complete draining in the end of August, working on bottom part.
- Start filling water in the middle of October.
- After complete filling water on 29th January, 2019, resume the data taking as SK-V.



Water leakage from SK tank

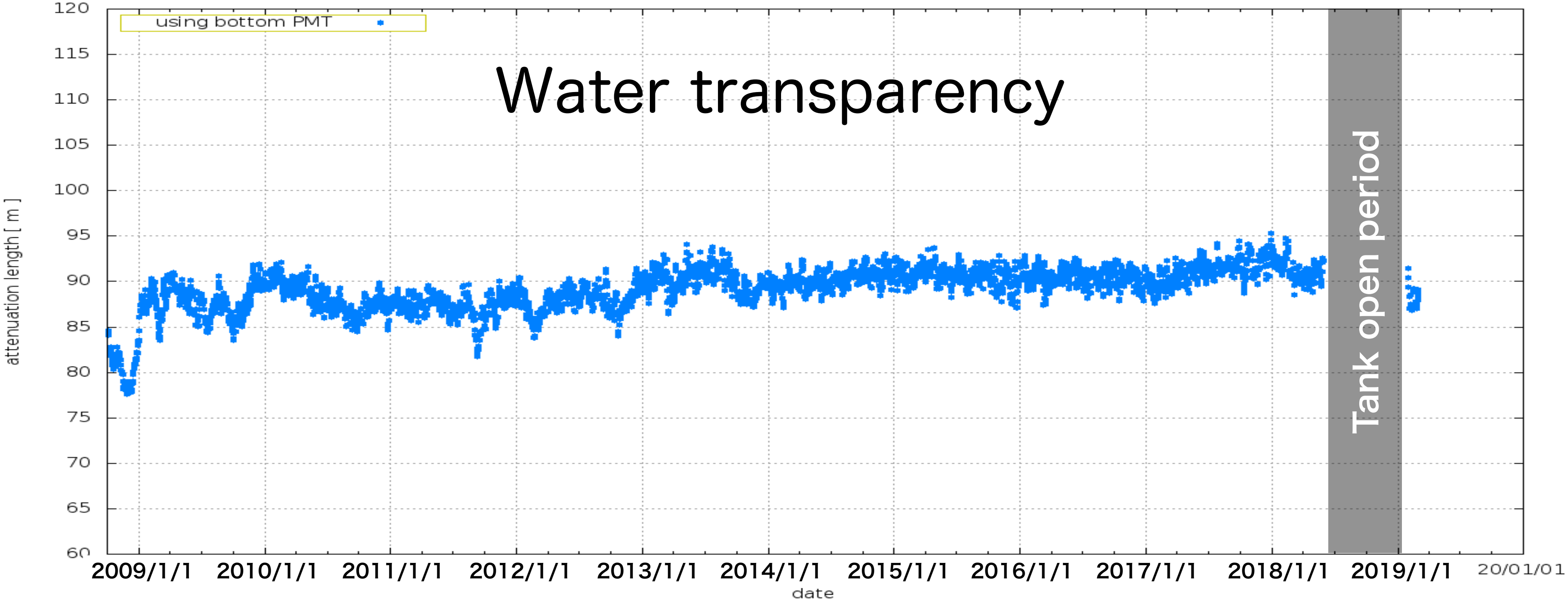
After filling the tank completely with water, we started the water leakage measurement from 11:30 on 31st January to 15:52 on 7th February, 2019. (7 days 4 hours 22 minutes in total)





- Currently we do not observe any water leakage from the SK tank within the accuracy of our measurement, which is less than 0.017 tons per day.
- This is less than 1/200th of the leak rate observed before the tank refurbishment.

Just started new phase of SK



- Thanks to water circulation during water filling phase, similar water transparency was achieved as in the period before the tank open.
- In February, HV adjustment, detector calibration has been performed.
- Normal data taking also works well.