

# New results from the atmospheric neutrino oscillations at Super-Kamiokande

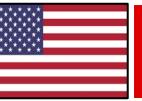
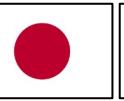
Magdalena Posiadała-Zezula  
University of Warsaw, Faculty of Physics

On behalf of the Super-Kamiokande  
Collaboration



# The Super-Kamiokande Collaboration

2019 Toyama meeting



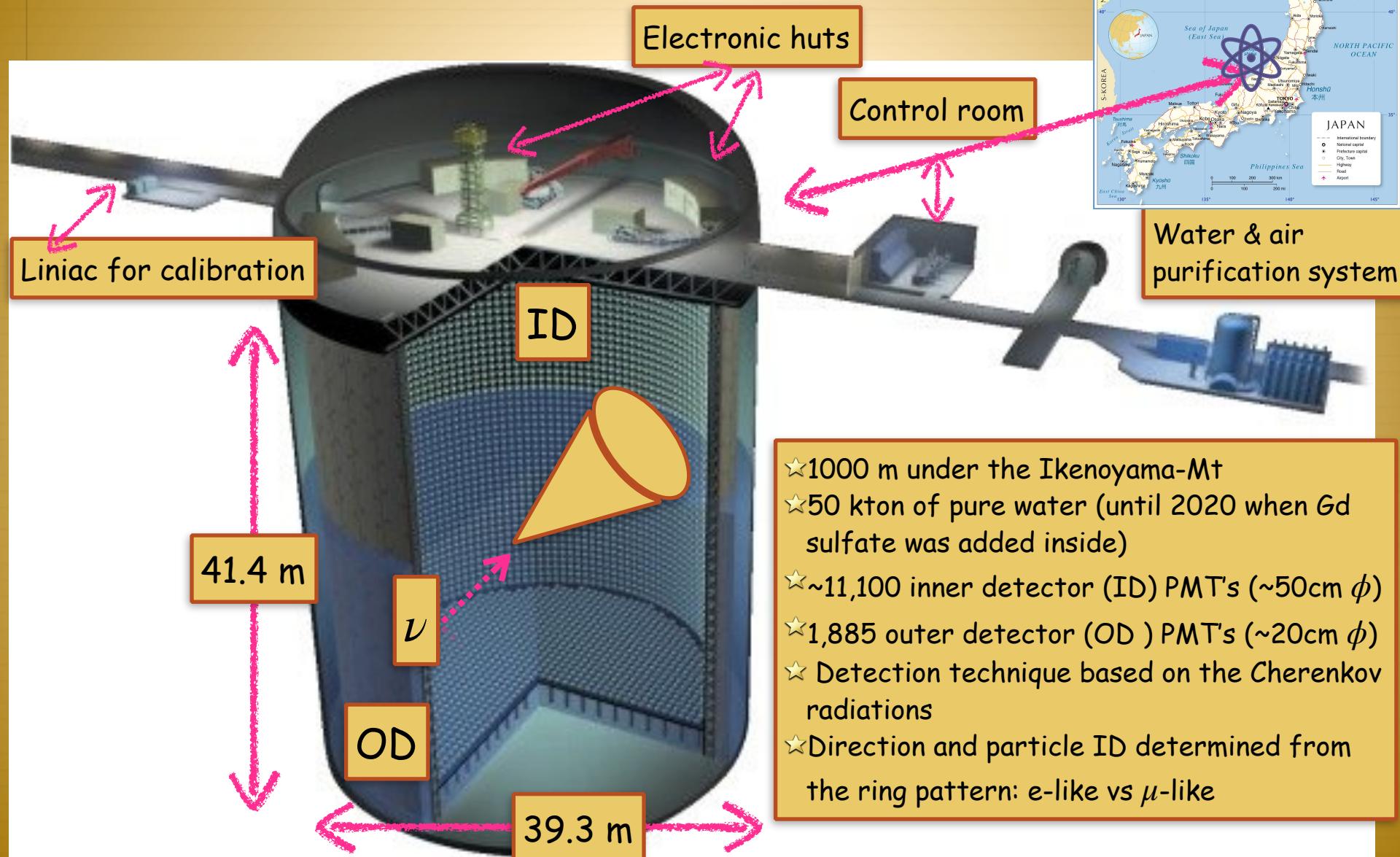
Kamioka Observatory, ICRR, Univ. of Tokyo, Japan  
RCCN, ICRR, Univ. of Tokyo, Japan  
University Autonoma Madrid, Spain  
BC Institute of Technology, Canada  
Boston University, USA  
University of California, Irvine, USA  
California State University, USA  
Chonnam National University, Korea  
Duke University, USA  
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Gifu University, Japan  
GIST, Korea  
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Kavli IPMU, The Univ. of Tokyo, Japan  
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King's College London, UK  
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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  
University of Oxford, UK

Rutherford Appleton Laboratory, UK  
Seoul National University, Korea  
University of Sheffield, UK  
Shizuoka University of Welfare, Japan  
Sungkyunkwan University, Korea  
Stony Brook University, USA  
Tohoku University, Japan  
Tokai University, Japan  
The University of Tokyo, Japan  
Tokyo Institute of Technology, Japan  
Tokyo University of Science, Japan  
TRIUMF, Canada  
Tsinghua University, China  
University of Warsaw, Poland  
Warwick University, UK  
The University of Winnipeg, Canada  
Yokohama National University, Japan

~230 collaborators from 51 institutes in 11 countries

# Super-Kamiokande detector



# Super-Kamiokande experiment



- ★ Super-Kamiokande (SK) has been taking data since 1996 and has come through seven run periods
- ★ Densely packed PMTs (40%/20% for SK-II) and good water quality provide excellent sensitivity for various physics targets.
- ★ In 2020 we have added Gd sulfate to the water in order to increase the sensitivity for neutron capture; this improved tagging of the reaction IBD



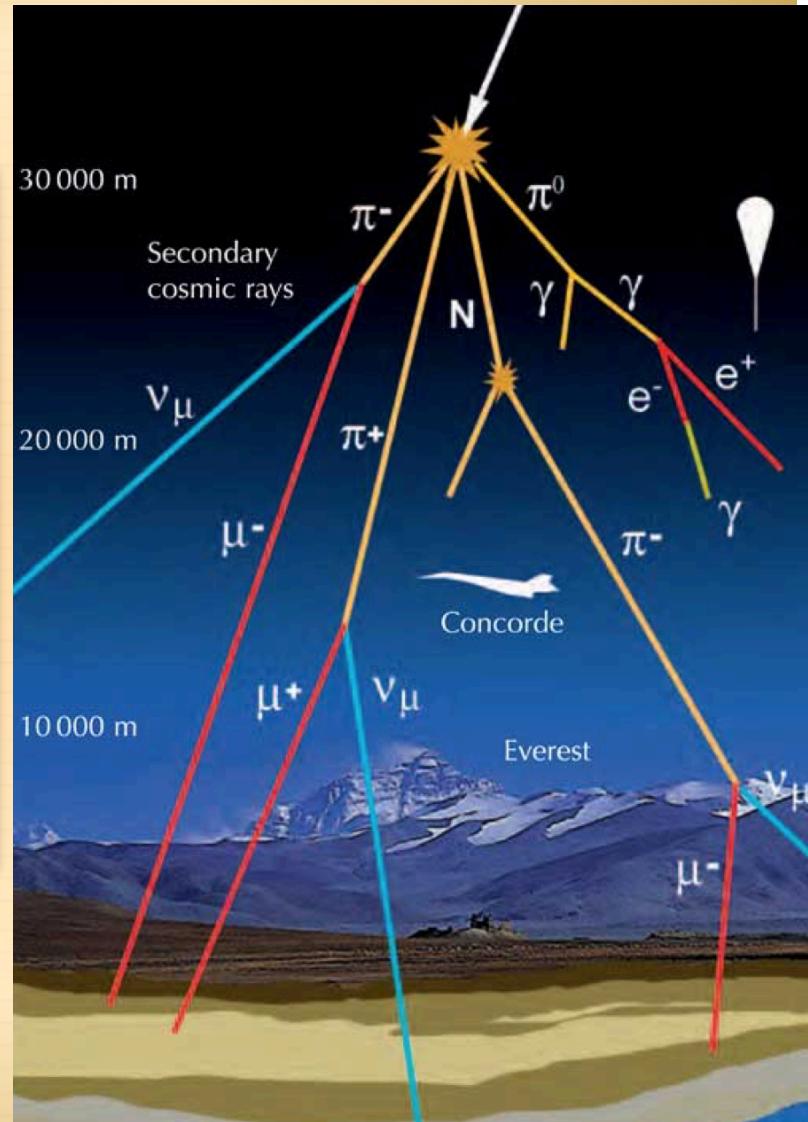
# Atmospheric neutrinos



★ Neutrinos are produced when cosmic protons interact with the nuclei in the atmosphere:

- ★  $p, A + \text{air} \rightarrow \pi^\pm, \pi^0, K^\pm, K^0$
- ★  $\pi^\pm, K^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)$
- ★  $\mu^\pm \rightarrow e^\pm + \nu_e (\bar{\nu}_e) + \nu_\mu (\bar{\nu}_\mu)$
- ★  $K^\pm, K_L^0 \rightarrow [\pi^\pm, \pi^0] + e^\pm + \nu_e (\bar{\nu}_e)$

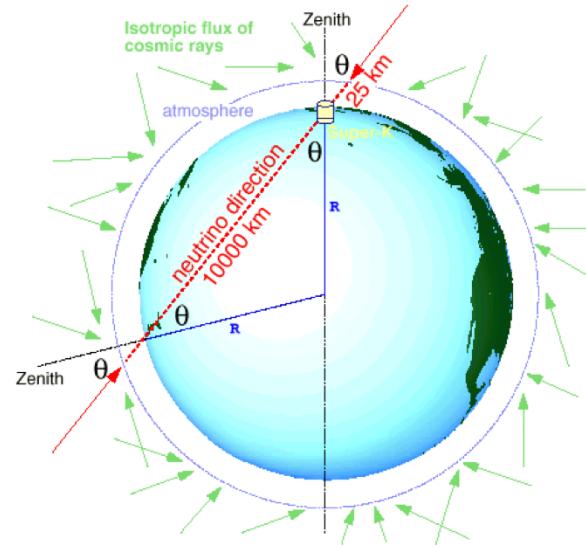
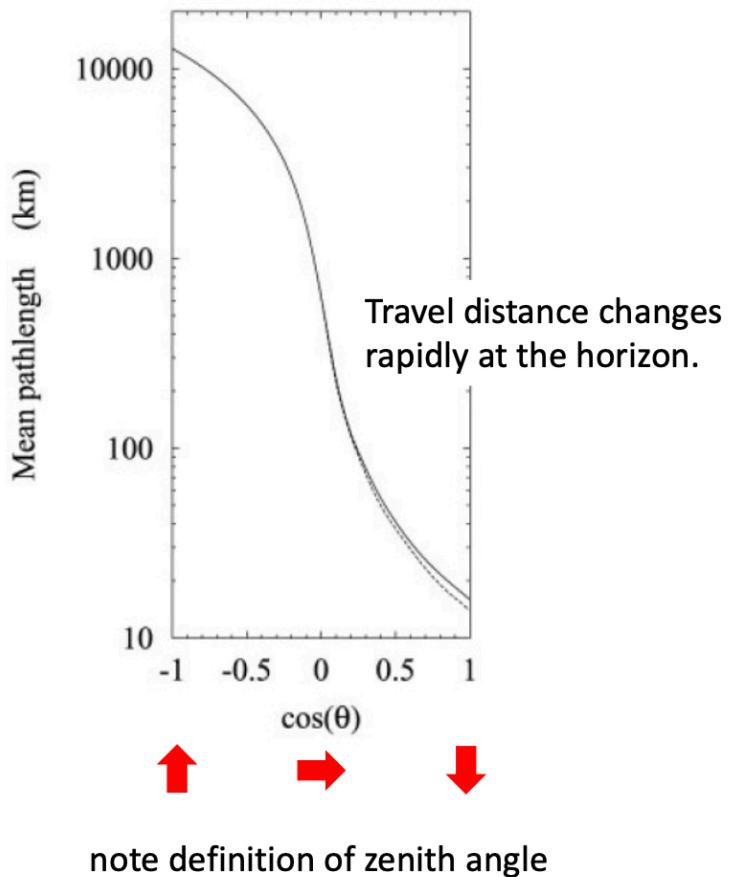
★ Neutrinos with wide range of energy MeV- PeV produced isotropically about the Earth atmosphere



# Travel distance



Atmospheric neutrinos travel  
15 km to 13000 km.

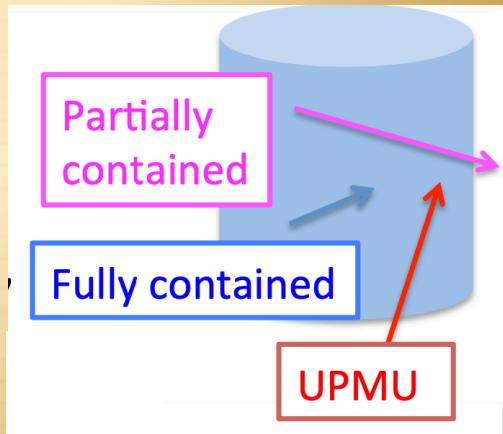


Sample  
selections at  
SK ->

Partially  
contained

Fully contained

UPMU



# Atmospheric neutrino oscillations



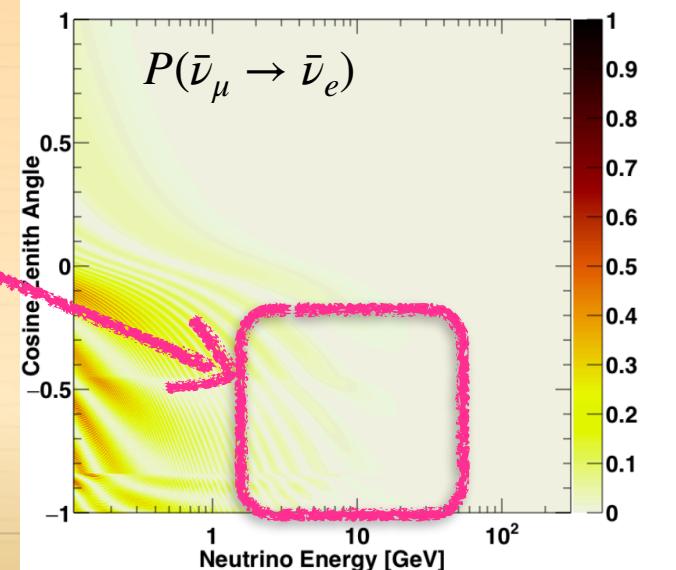
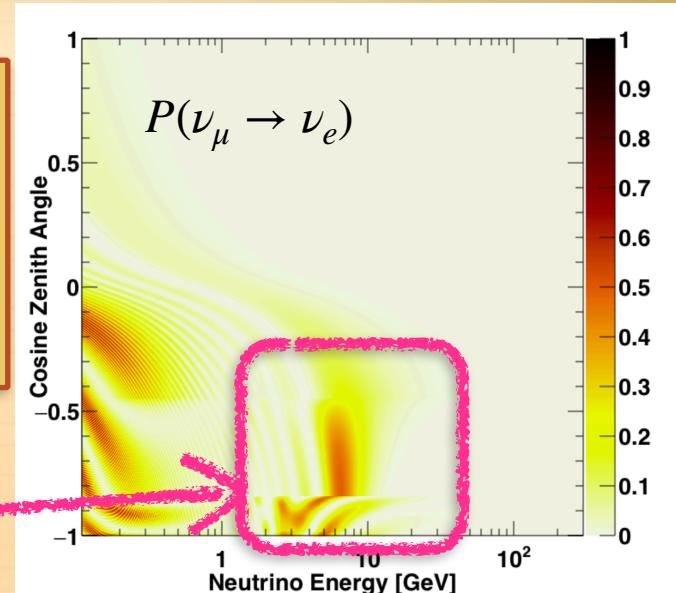
★ Oscillograms plotted for **normal ordering** (NO) with:  $\Delta m_{21}^2 = 7.7 \times 10^{-5}$ ,  $\sin^2 \theta_{23} = 0.50$ ,  $\sin^2 \theta_{12} = 0.30$ ,  $\sin^2 \theta_{13} = 0.0219$  and  $\delta_{CP} = 0$

Phys.Rev.D 97 (2018)

★ Impact of matter effects:

- ★ NO: enhancement of  $\nu_e$  appearance
- ★ NO: effect is not present for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- ★ IO: situation is reversed

★ Thanks to presence of matter effects we are sensitive to mass hierarchy



# Atmospheric neutrino oscillations



★ Three flavour analysis with:

★ Matter effects: - sensitive to mass hierarchy

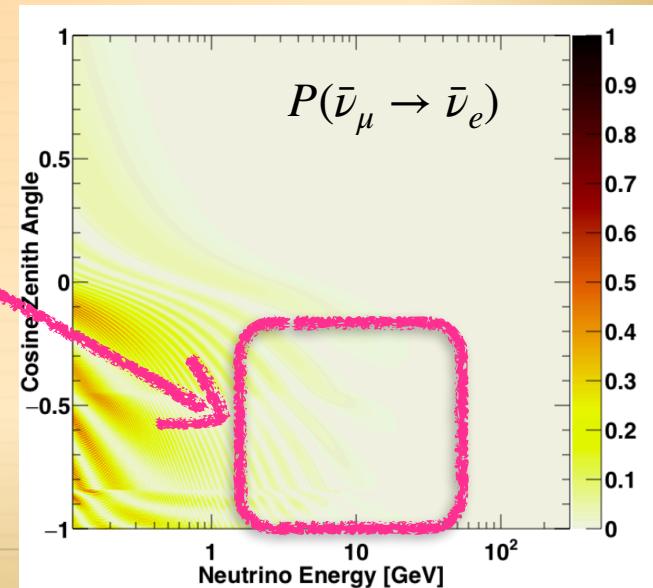
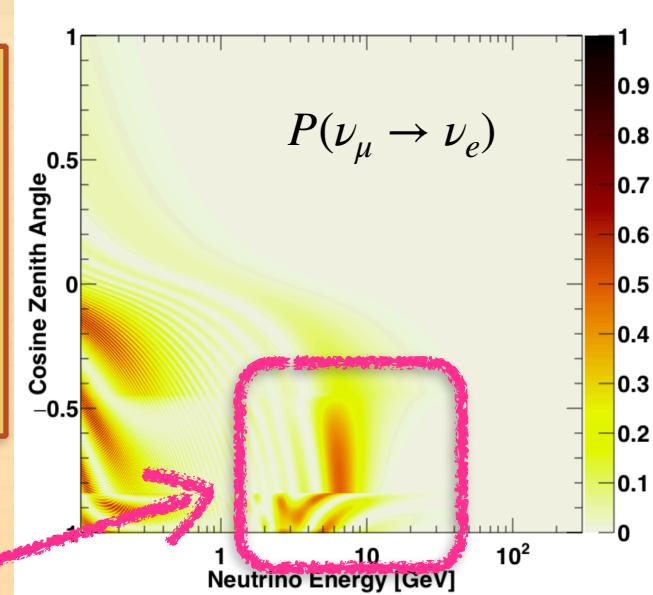
★ Oscillations of  $\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  are also sensitive to octant  $\theta_{23}$  and  $\delta_{CP}$

★  $\nu_e$  samples:

- ★ Multi-GeV e-like  $\nu_e$
- ★ Multi-Ring e-like  $\nu_e$

★  $\bar{\nu}_e$  samples:

- ★ Multi-GeV e-like  $\bar{\nu}_e$
- ★ Multi-Ring e-like  $\bar{\nu}_e$



# Oscillation analysis method at SK



★ Data are fit to the MC using  $\chi^2$  method assuming Poisson statistics and adding systematic errors as scaling factors on the MC in each bin (more in Phys.Rev.D 97 (2018))

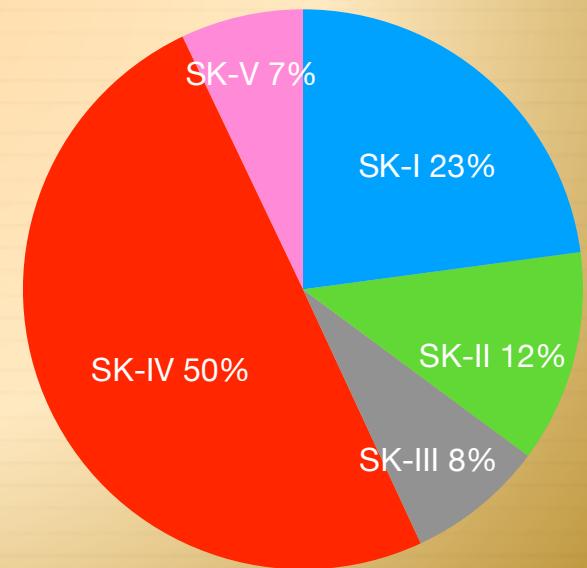
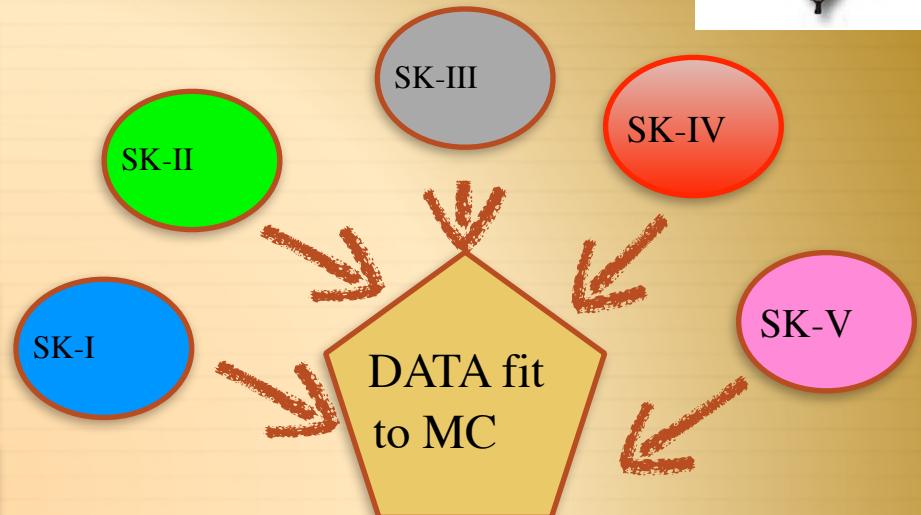
★ Reactor constraints on  $\sin^2 \theta_{13}$  :  $0.0220 \pm 0.0007$  (PDG2022)

★ Solar and Kamland:  $\sin^2 \theta_{12}, \Delta m_{21}^2$

★ Free to fit :  $\Delta m_{32}^2, \sin^2 \theta_{23}, MO(NO/IO), \delta_{CP}$

★ What is new in this analysis !!!

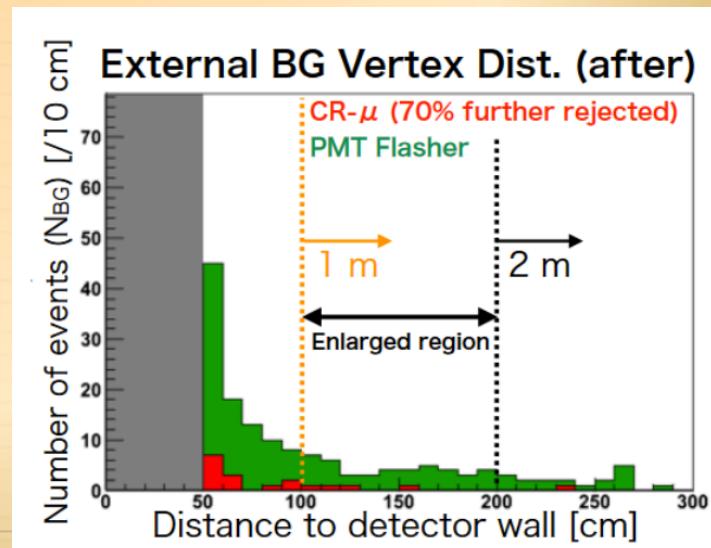
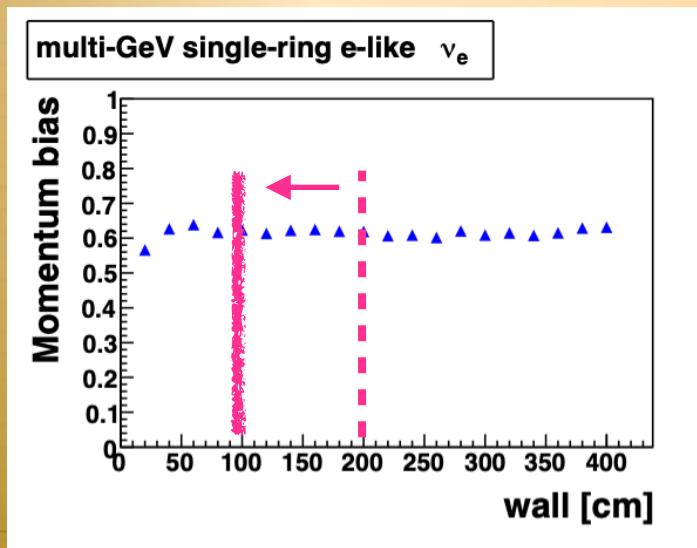
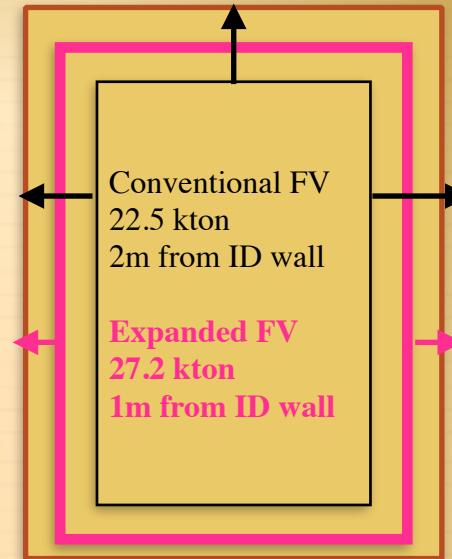
- ★ SK-V data added
- ★ Enlarged FV region;
- ★ New multi-ring selections
- ★ Systematics improvement



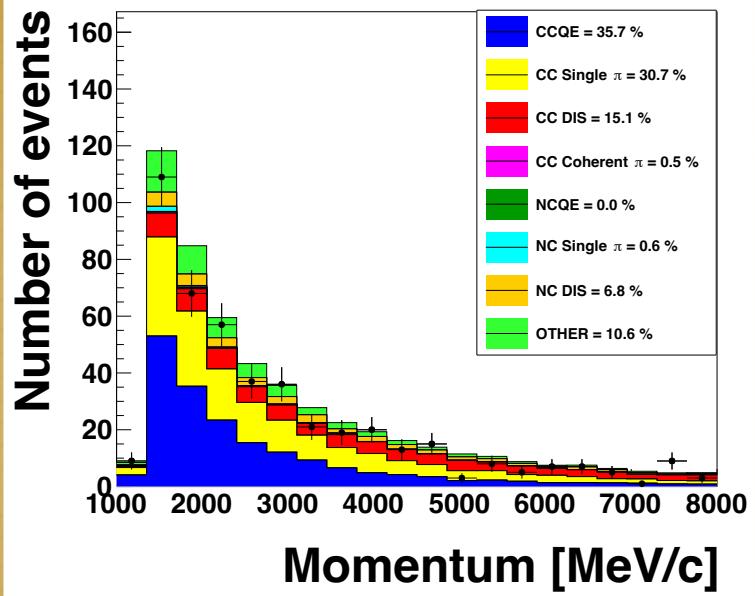
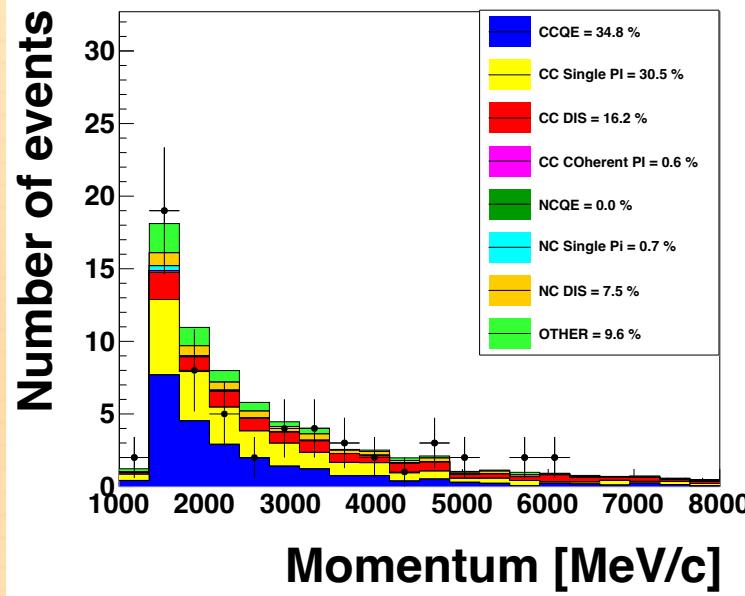
# Enlarging the Fiducial Volume (1)



- ★ So far only events with vertex reconstructed within 2m from the nearest wall have been used for the analysis (Conventional FV of 22.5kt)
- ★ Systematic uncertainties have been evaluated in expanded FV region.

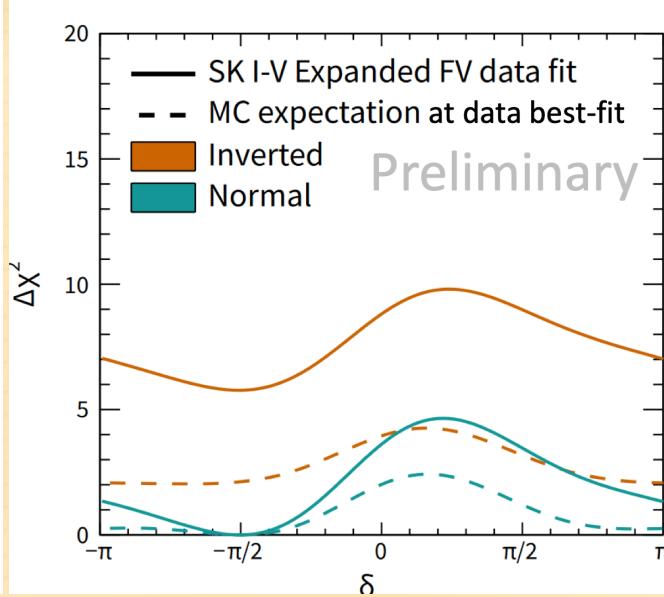
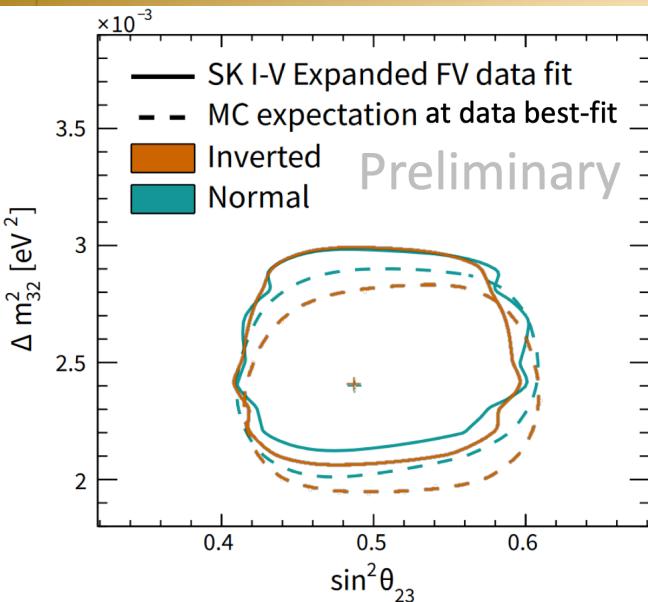


## Enlarging the Fiducial Volume (2)

multi-GeV single-ring  $\bar{\nu}_e$ -like conv. FVmulti-GeV single-ring  $\bar{\nu}_e$ -like exp. FV

★ Expansion of FV region allow us to increase the statistics by 20% keeping systematic uncertainties still satisfactory

# SK only: parameters determination



**SK atmospheric neutrino data favours:**

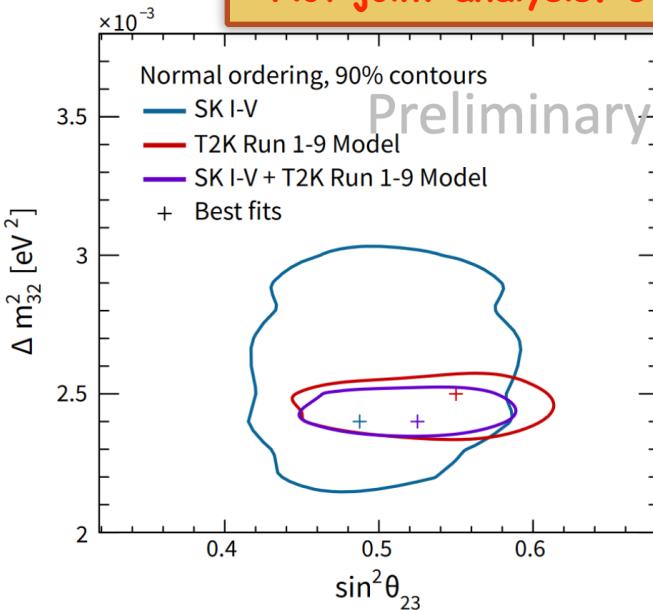
- ★ Maximal mixing
- ★ NO ( $\Delta\chi^2 = 5.8$ )
- ★  $\delta_{CP} \simeq -\frac{\pi}{2}$

930 bins	$\chi^2$	$\delta_{CP} \in [0, 2\pi]$	$\sin^2 \theta_{23}$	$\Delta m^2_{23}$
SK NO	<b>1000.42</b>	<b>4.71</b>	<b>0.49</b>	$2.4 \times 10^{-3} \text{ eV}^2$
SK IO	<b>1006.19</b>	<b>4.71</b>	<b>0.49</b>	$2.4 \times 10^{-3} \text{ eV}^2$

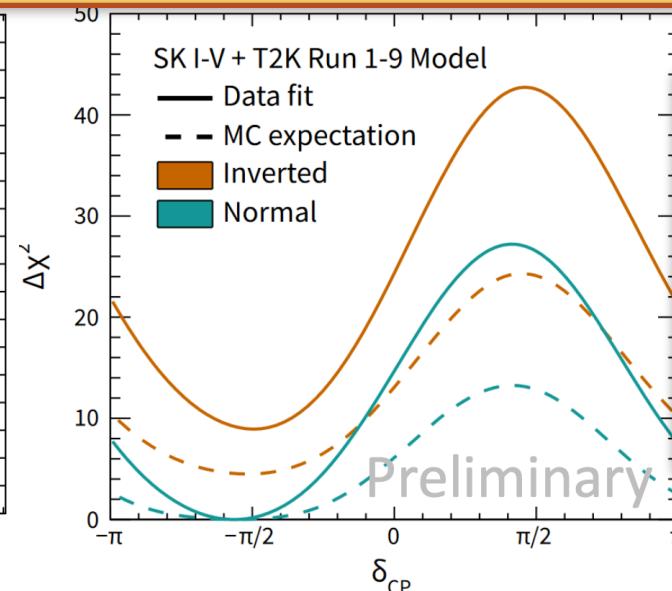
## parameters determination



★ Not joint analysis. Using published T2K Run 1-9 data



Preliminary



Preliminary

SK + external T2K constrains favour:

- ★ Maximal mixing
- ★ NO ( $\Delta\chi^2 = 8.9$ )
- ★  $\delta_{CP} \simeq -\frac{\pi}{2}$

930 bins	$\chi^2$	$\delta_{CP} \in [0, 2\pi]$	$\sin^2 \theta_{23}$	$\Delta m^2_{23}$
SK+T2K NO	<b>1086.33</b>	<b>4.54</b>	<b>0.53</b>	$2.4 \times 10^{-3} \text{ eV}^2$
SK +T2K IO	<b>1095.25</b>	<b>4.71</b>	<b>0.53</b>	$2.4 \times 10^{-3} \text{ eV}^2$

★ SK is sensitive to mass ordering; T2K sensitive to  $\delta_{CP}$



# SK-Gd era

## Gadolinium project at Super-K: SK-Gd

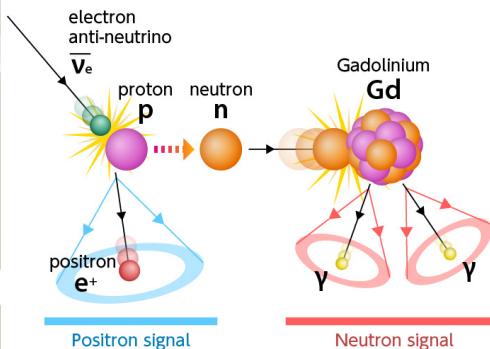
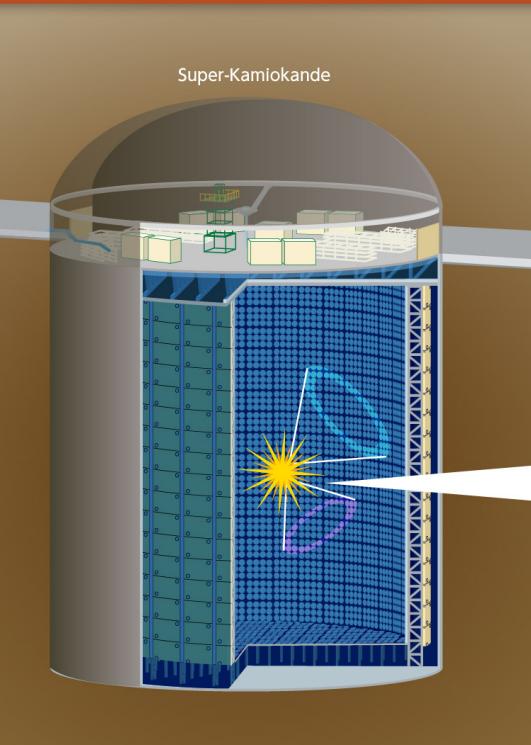


# Why Gd salt was added ?

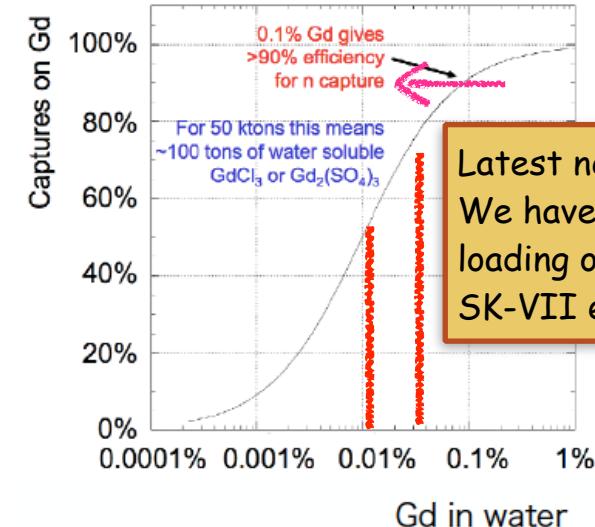


MAIN AIM: improves SK's ability to observe the sea of neutrinos, known as "supernova relic neutrinos"

For atmospheric neutrino oscillations: we may be able to improve neutrino-antineutrino separation



Dissolve Gadolinium into Super-K  
J.Beacon and M.Vagins,  
Phys.Rev.Lett.93(2004)171101



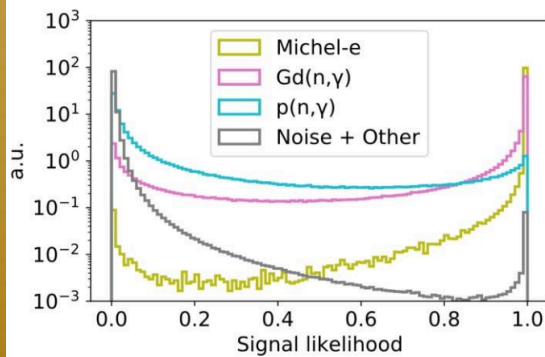
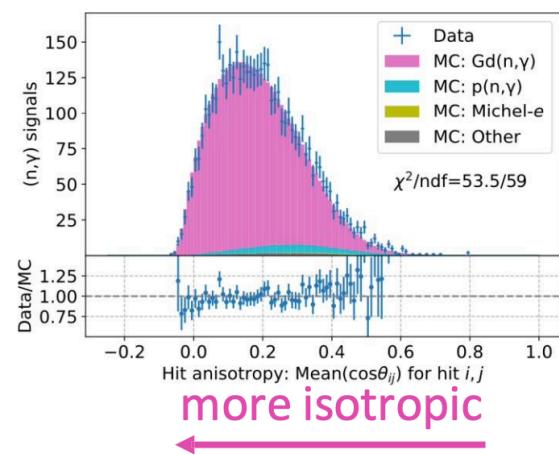
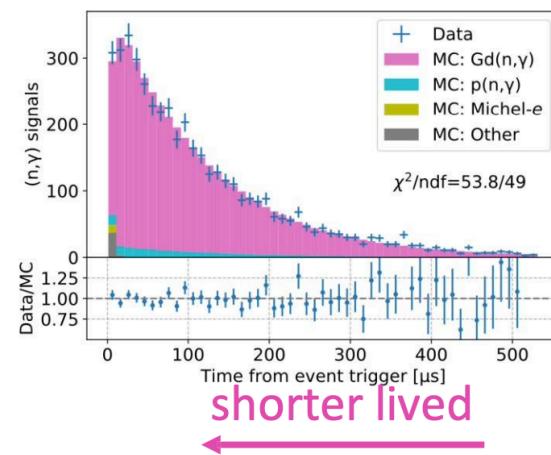
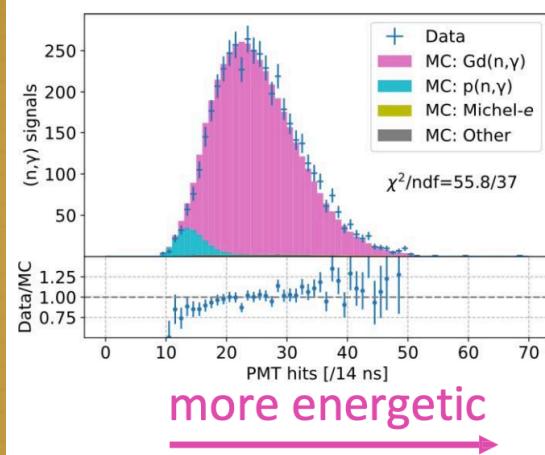
Latest news:  
We have finished Gd loading on July 5th!!  
SK-VII era

Cross section for neutron capture for Gd is 49000 barns, while for protons is only 0.3 barn.

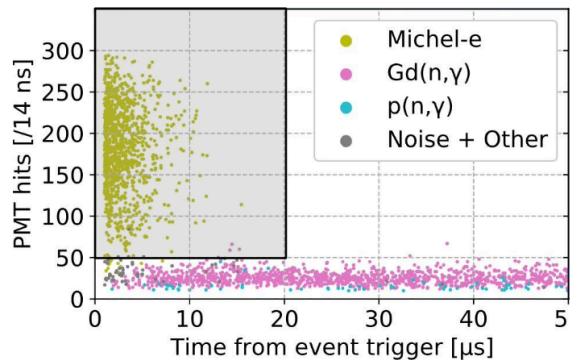
# SK-VI: Neutron Capture Signal



Comparing neutron captures on **Hydrogen** and neutron captures on **Gadolinium**:



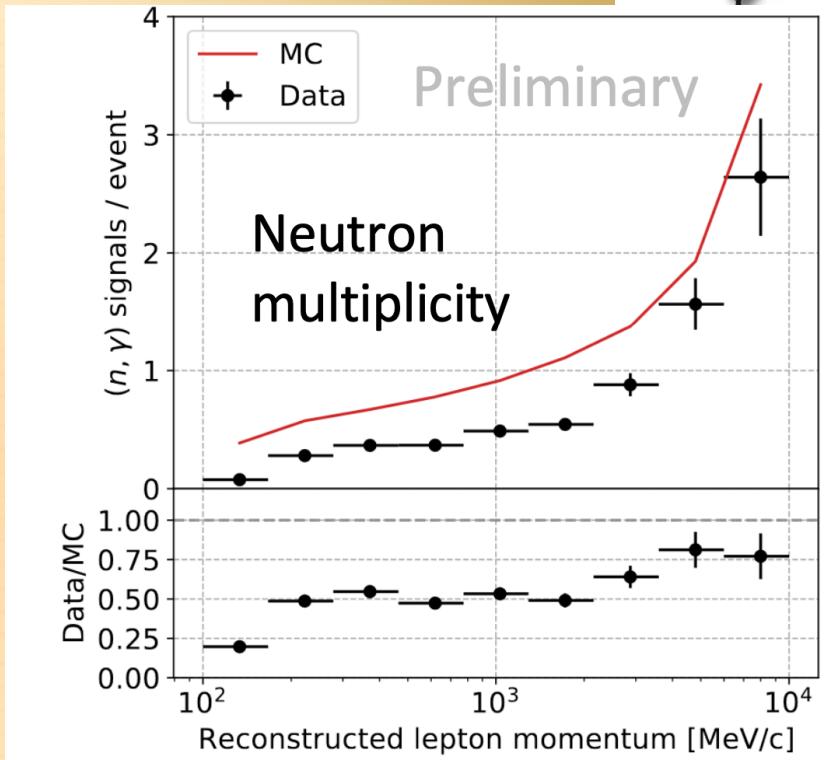
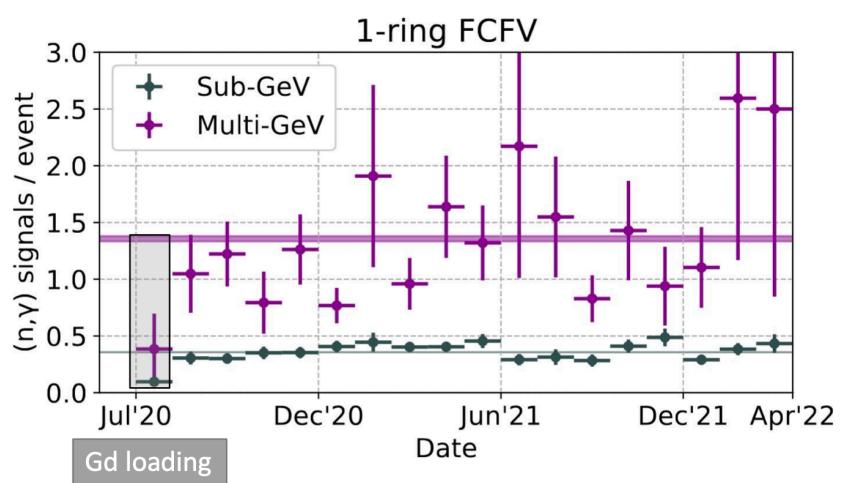
- Neural network to select neutron candidates
- Cuts to remove remaining Michel electrons



## SK-VI: Neutron Measurement



- ★ Stable neutron multiplicity since Gd loading
- ★ Higher neutron multiplicity at higher energy events



- ★ Measured neutron multiplicity is lower than present **MC predictions**.
- ★ Neutron production needs model improvement and development.

# Summary

★ Atmospheric neutrino oscillation analysis  
is:

- ★ favouring NO,  $\delta_{CP} \simeq -\frac{\pi}{2}$  and maximal  $\sin^2 \theta_{23}$
- ★ with all pure water data sets (SK-I ~V),
- ★ with expanded fiducial volume.
- ★ SK-Gd
- ★ SK-VI (Gd~0.01%) analysis is ongoing
- ★ SK-VII (Gd~0.03%) just started!



Extra slides

# Earth's density

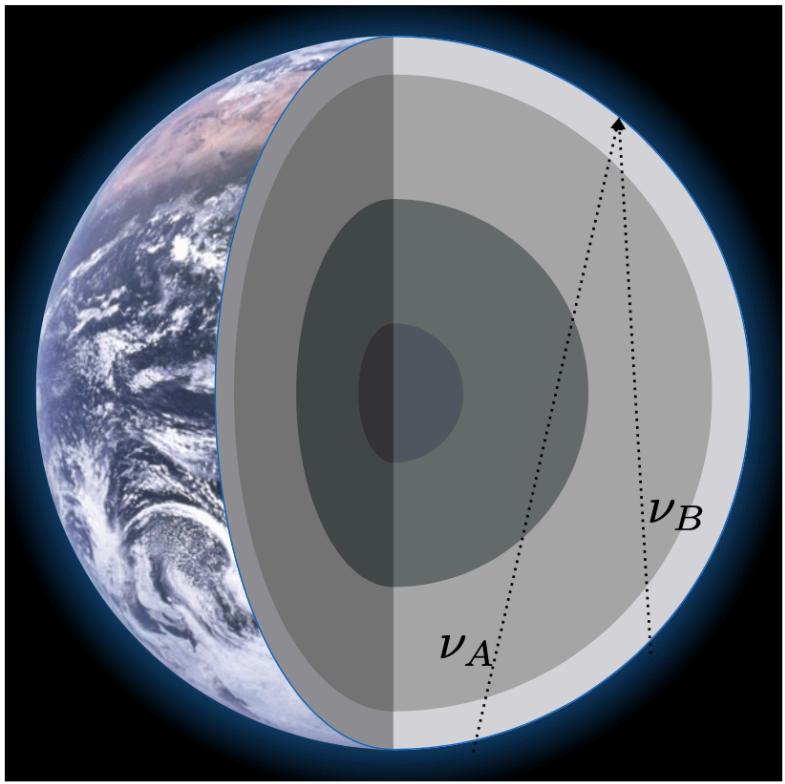


FIG. 1. The propagation of two neutrinos through the simplified model of the Earth used in the analysis below. Both  $\nu_A$  and  $\nu_B$  are produced in the atmosphere.  $\nu_A$  then experiences 6 oscillation steps (air  $\rightarrow$  crust  $\rightarrow$  mantle  $\rightarrow$  outer core  $\rightarrow$  mantle  $\rightarrow$  crust), while  $\nu_B$  experiences 4 oscillation steps (air  $\rightarrow$  crust  $\rightarrow$  mantle  $\rightarrow$  crust).

Region	$R_{\min}$ (km)	$R_{\max}$ (km)	density (g/cm <sup>3</sup> )
inner core	0	1220	13.0
outer core	1220	3480	11.3
mantle	3480	5701	5.0
crust	5701	6371	3.3

TABLE I. Model of the Earth used in the analysis, a simplified version of the PREM.

- ★ We use spherical density profile of Earth model (PREM) with inputs shown in Table I
- ★ NOTE: We have tried using full PREM model with 82 layers but it provides no perceptible change in the sensitivity of the Super-K analysis
- ★ So simplified matter profile is adopted to reduce computation times

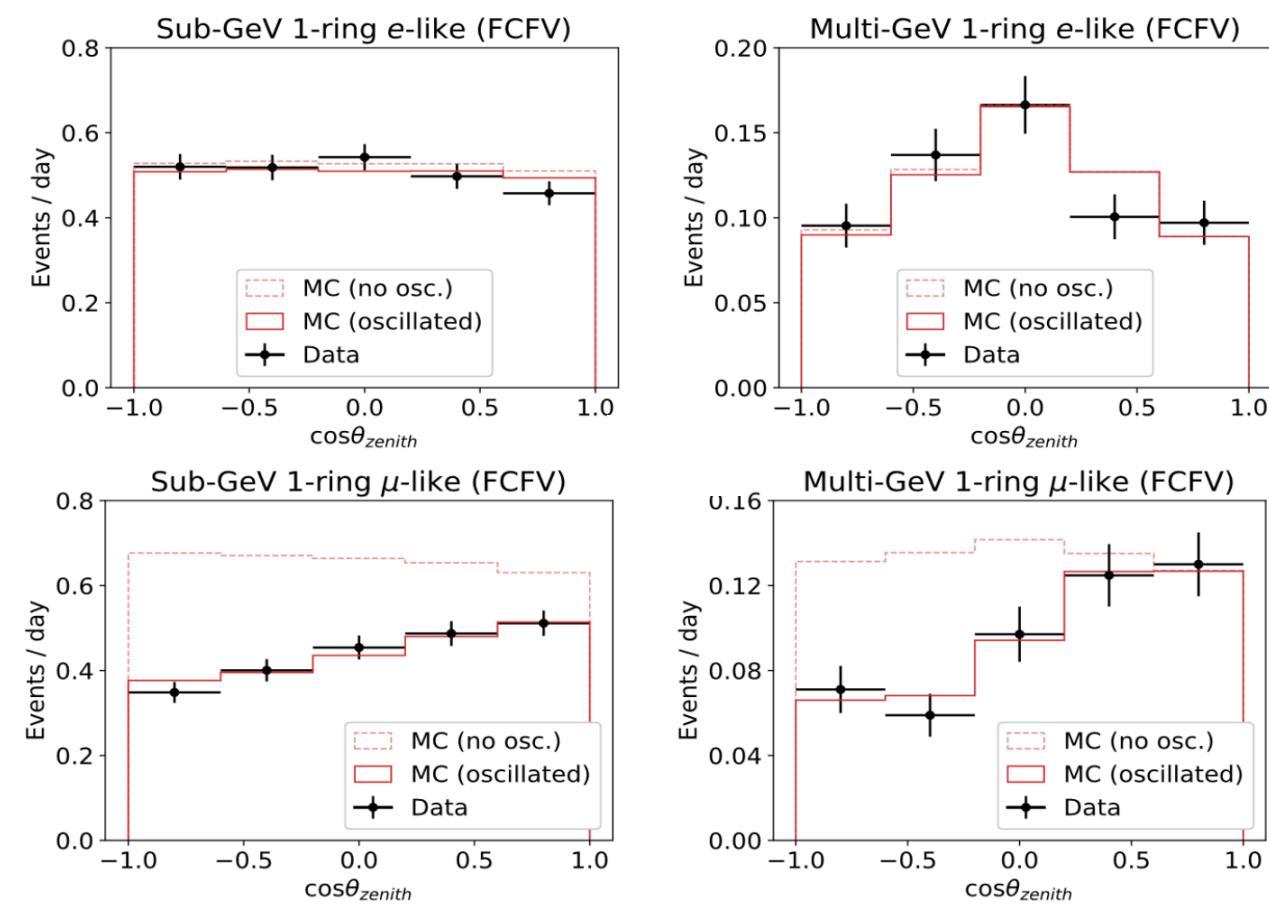
# SK - VI performance



★ At SK- VI Gd loading has exceeded the 0.011% which corresponds to 50% of neutron tagging efficiency

★ On June 1st 2022 we have started SK-VII period with more Gd being added to SK tank!

★ Stay tuned !



HE- $\nu$  samples

## Fully contained (FC):

- Reconstructed vertex in ID
- OD hits < 16

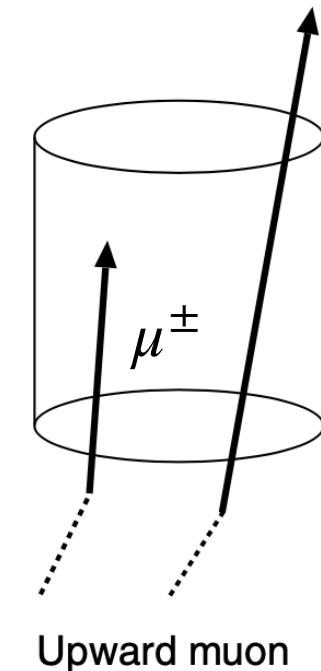
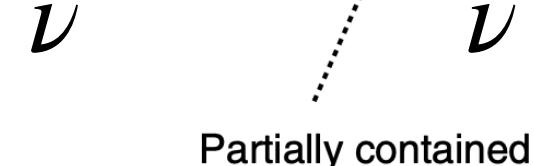
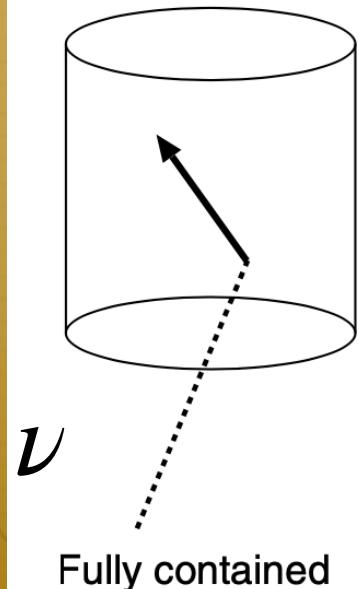
## Partially contained (PC):

- Reconstructed vertex in ID
- OD hits  $\geq 16$

## Upward-going muons (UPMU):

- Through-going with requirement of track length  $> 7$  m
- Stopping in the detector

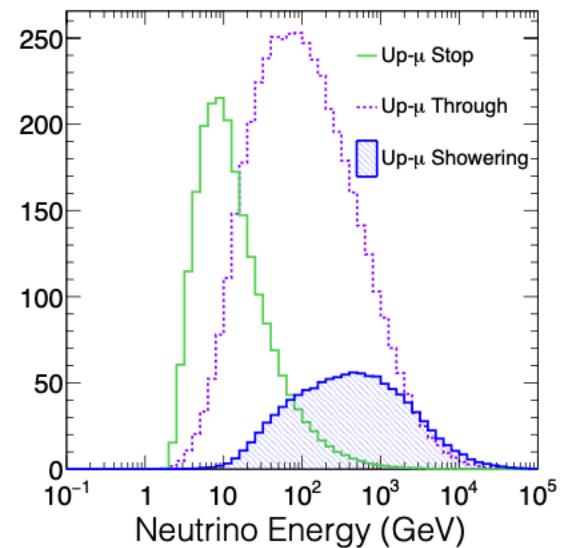
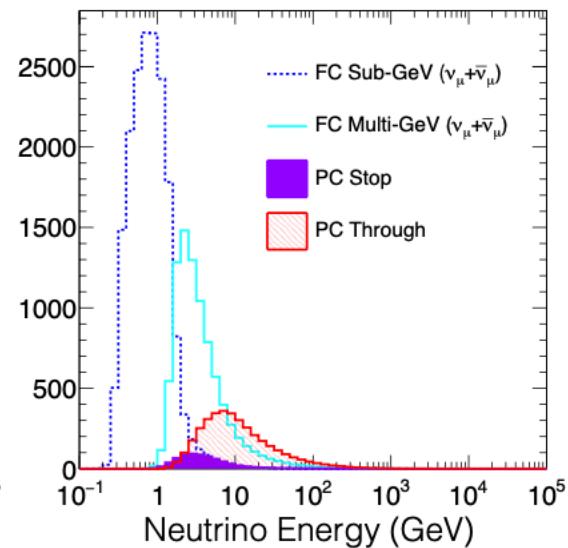
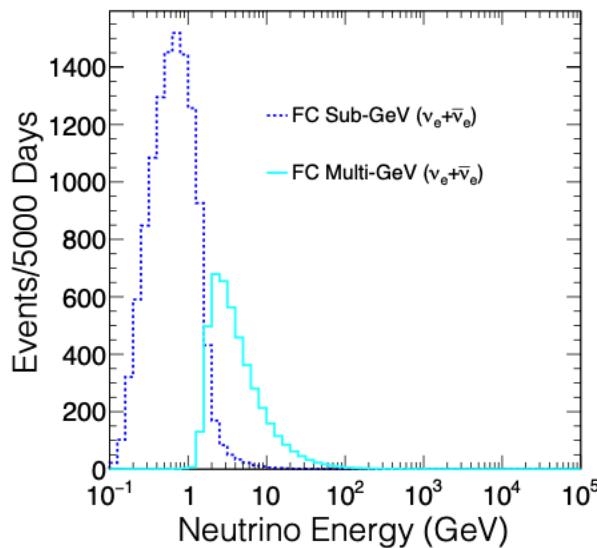
For events classified as FC and PC, the neutrino interacts within the fiducial volume, defined as the region located more than 100 cm from the ID wall



HE- $\nu$  samples

Fully contained (FC)

Partially contained (PC)

Upward-going muons  
(UPMU):

Expected neutrino energy spectra of different event categories

# Multi-GeV samples @ SK-IV

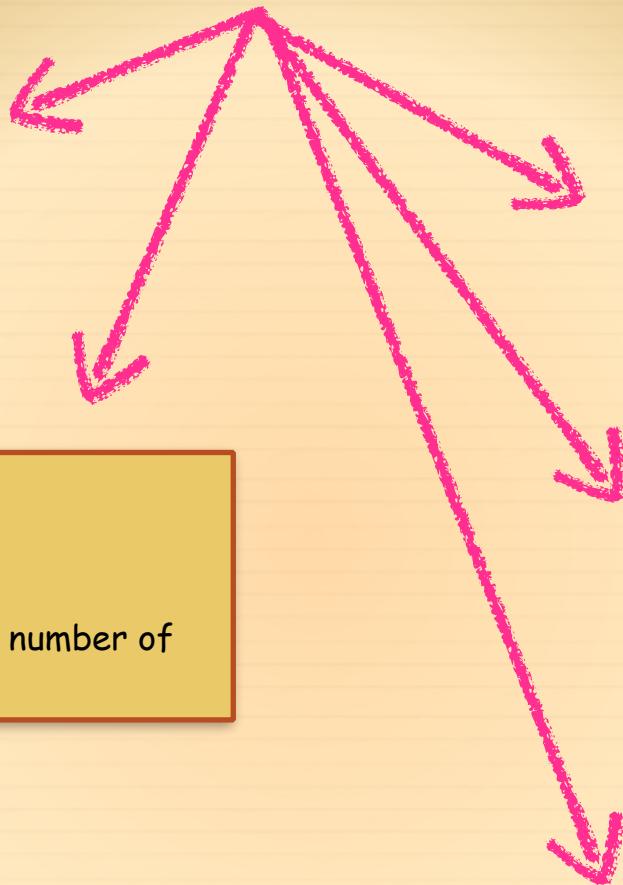


$\bar{\nu}_\mu$  like

- Number of decay electrons=1
- Number of tagged neutrons>0

$\nu_\mu$  like:

- Number of decay electrons  $\neq$ 1
- Number of decay electrons =1 and number of tagged neutrons=0



$\bar{\nu}_e$  like

- Number of decay electrons=0
- Number of tagged neutrons>0

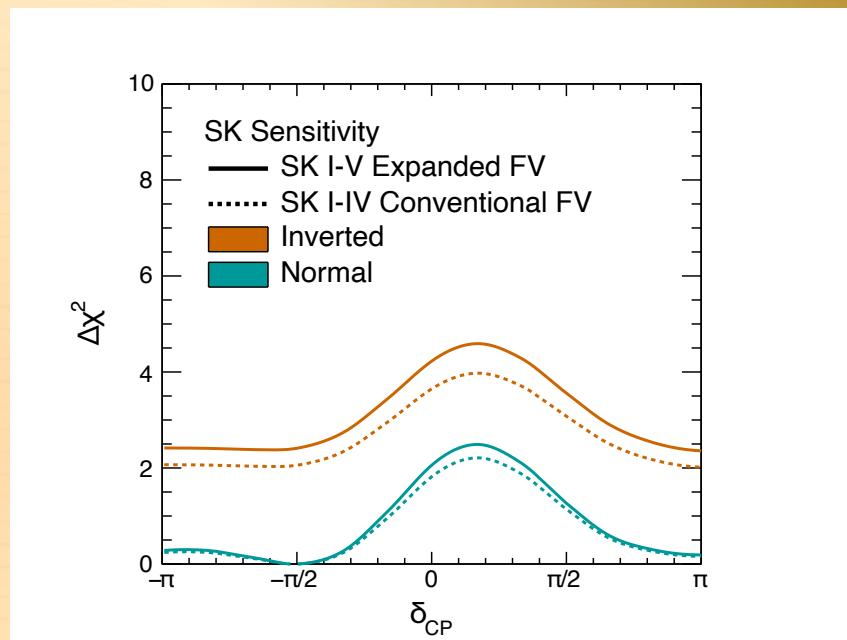
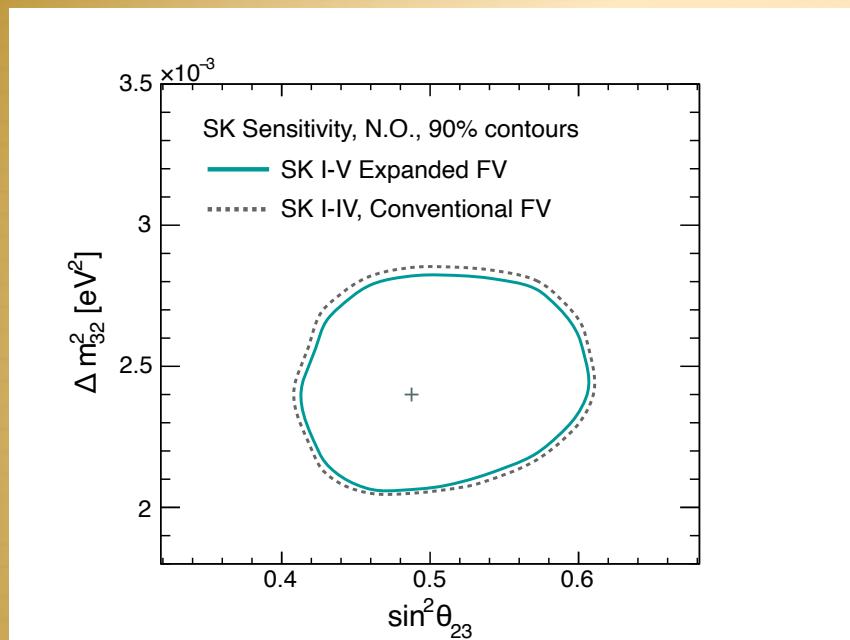
$\nu_e + \bar{\nu}_e$  like

- Number of decay electrons=0
- Number of tagged neutrons=0

$\nu_e$  like:

- Number of decay electrons >0

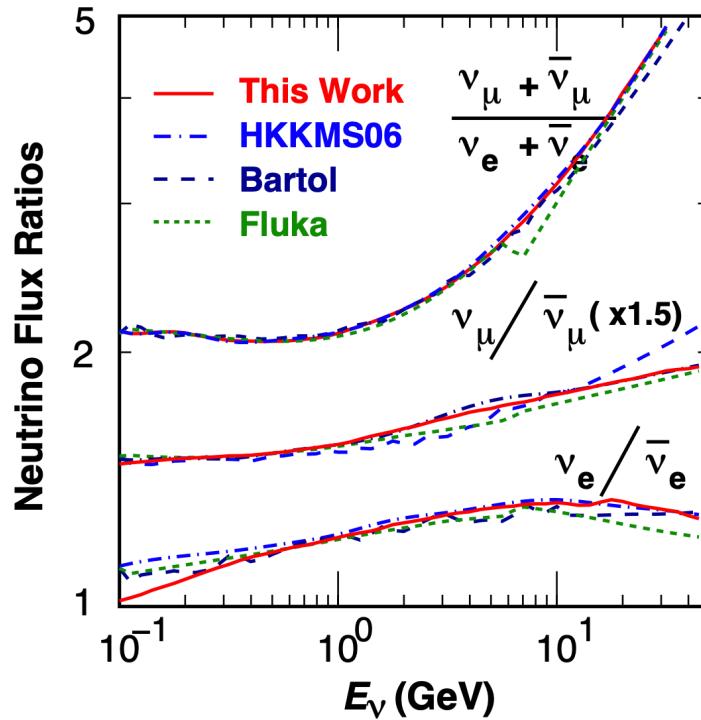
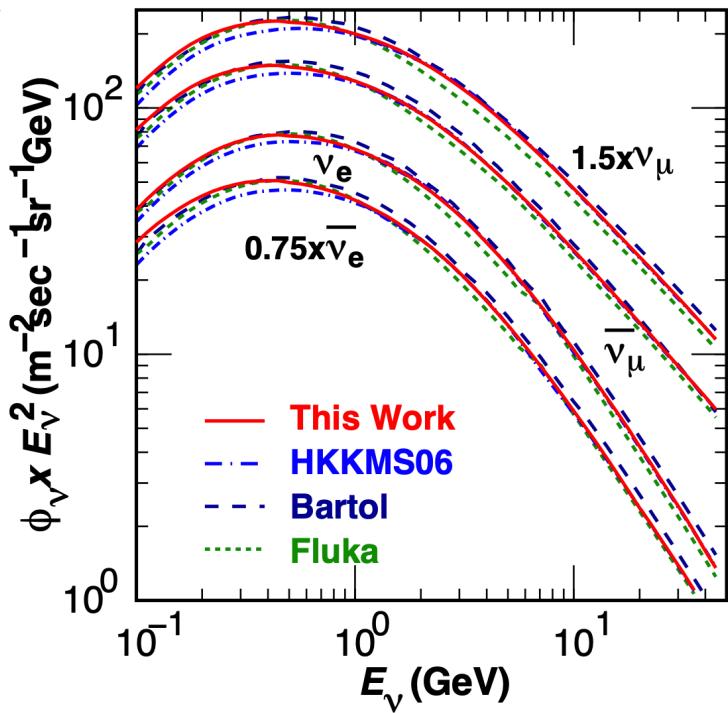
# SK only - parameters determination



# Atmospheric neutrino flux



- ★ The simulation of atmospheric neutrinos is performed following the flux calculation of Honda et. al M. Honda, T. Kajita, K. Kasahara, and S. Midorikawa, Phys.Rev. D83, 123001 (2011), arXiv:1102.2688 [astro-ph.HE] and using the NEUT simulation software.

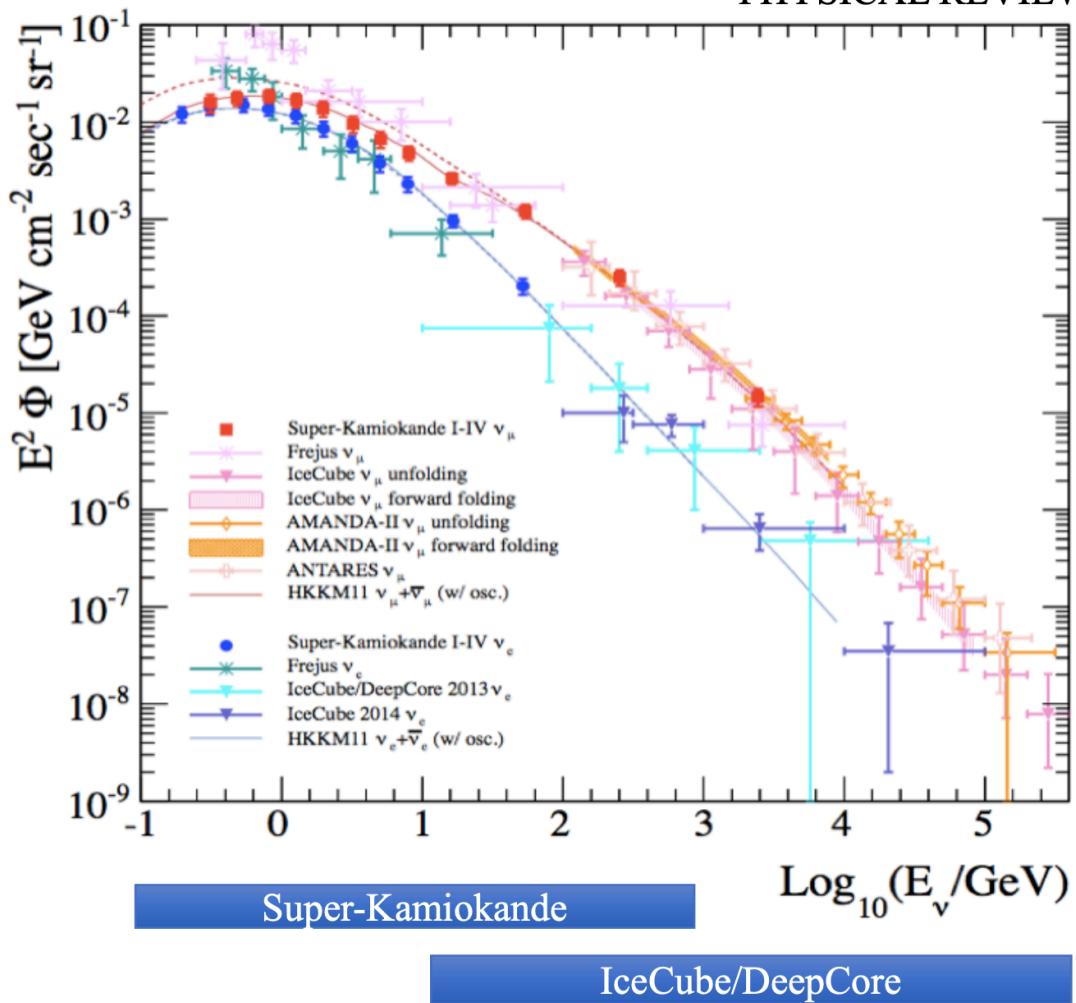


# Atmospheric neutrino flux



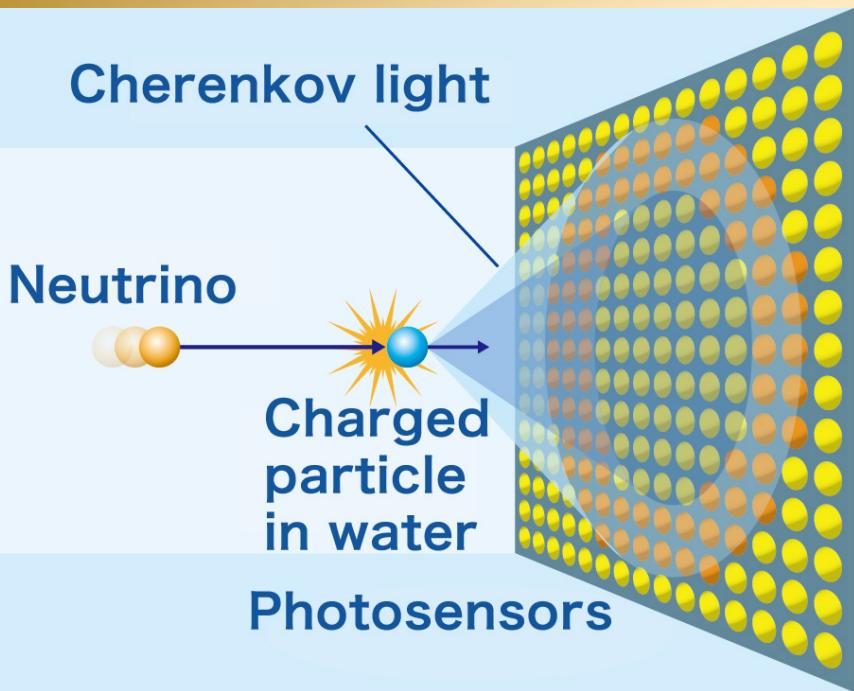
## Atmospheric Neutrino Flux:

PHYSICAL REVIEW D 94, 052001 (2016)



R. Wendell talk at:  
29<sup>th</sup> International Symposium  
on Lepton Photon Interactions  
at High Energies 2019

# Detection technique



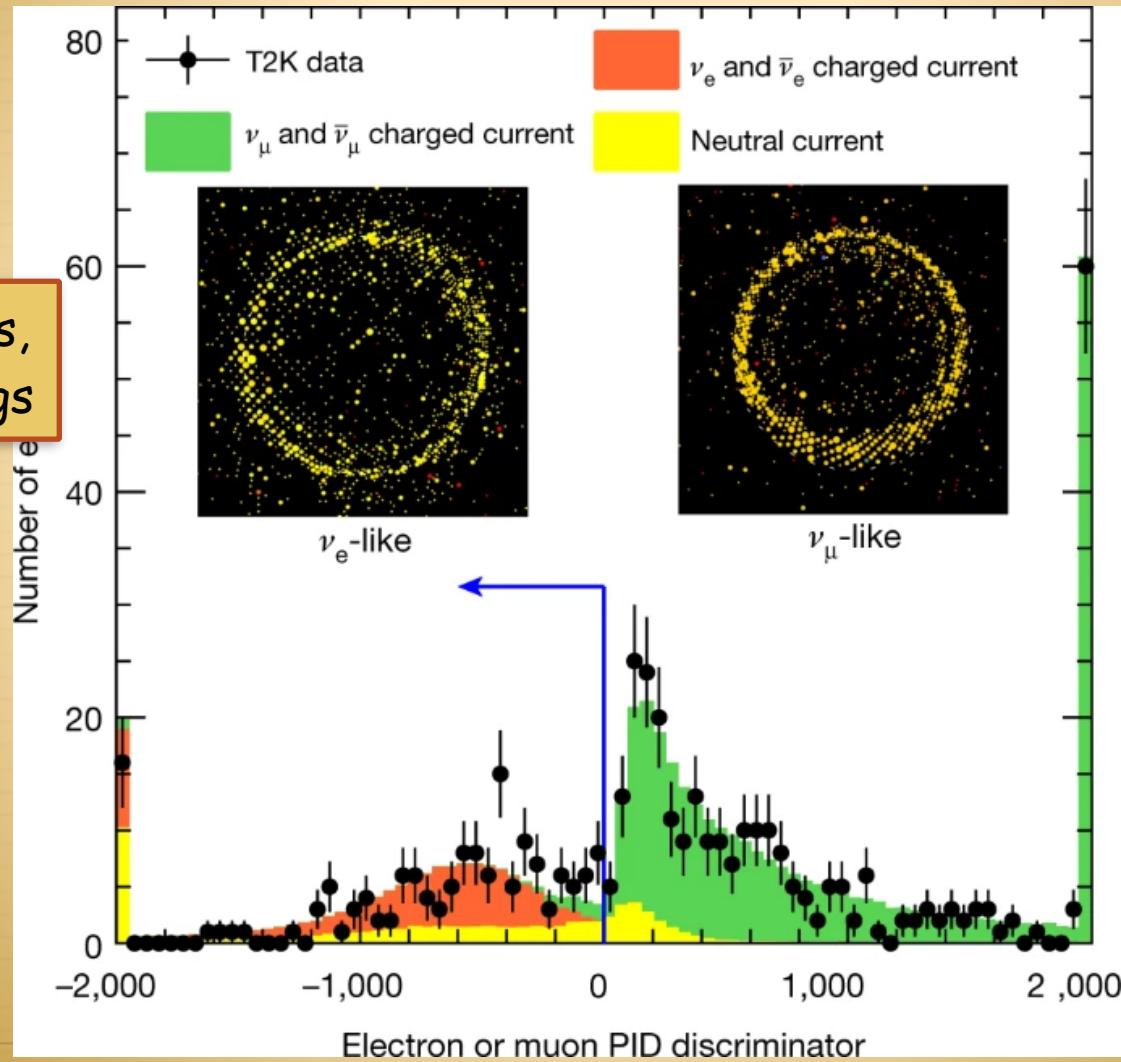
- In water, light travels about 25% slower than it does in a vacuum and it is possible for an energetic particle to travel faster than light.
- A blue light called **Cherenkov light** is emitted by charged particle.
- This light is detected by an array of light sensitive PMT's
- By measuring the brightness, shape, and direction of the ring we can figure out how much energy the particle had, whether it is a muon or electron, and which way it was going.



# Separation between $\mu$ and e in Cherenkov detectors



Fuzzy edges,  
blurred rings



Sharp edges of  
the ring