# Super-Kamiokande physics & astrophysics results

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Photo Credit: Piotr Mijakowski

# The Super-Kamiokande Collaboration


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Chonnam National University, Korea
Duke University, USA
Gifu University, Japan
GIST, Korea
University of Glasgow, UK
University of Hawaii, USA
IBS, Korea
IFIRSE, Vietnam
Imperial College London, UK
ILANCE, France/Japan

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INFN Padova, Italy
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Tsinghua University, China
University of Warsaw, Poland
Warwick University, UK
The University of Winnipeg, Canada
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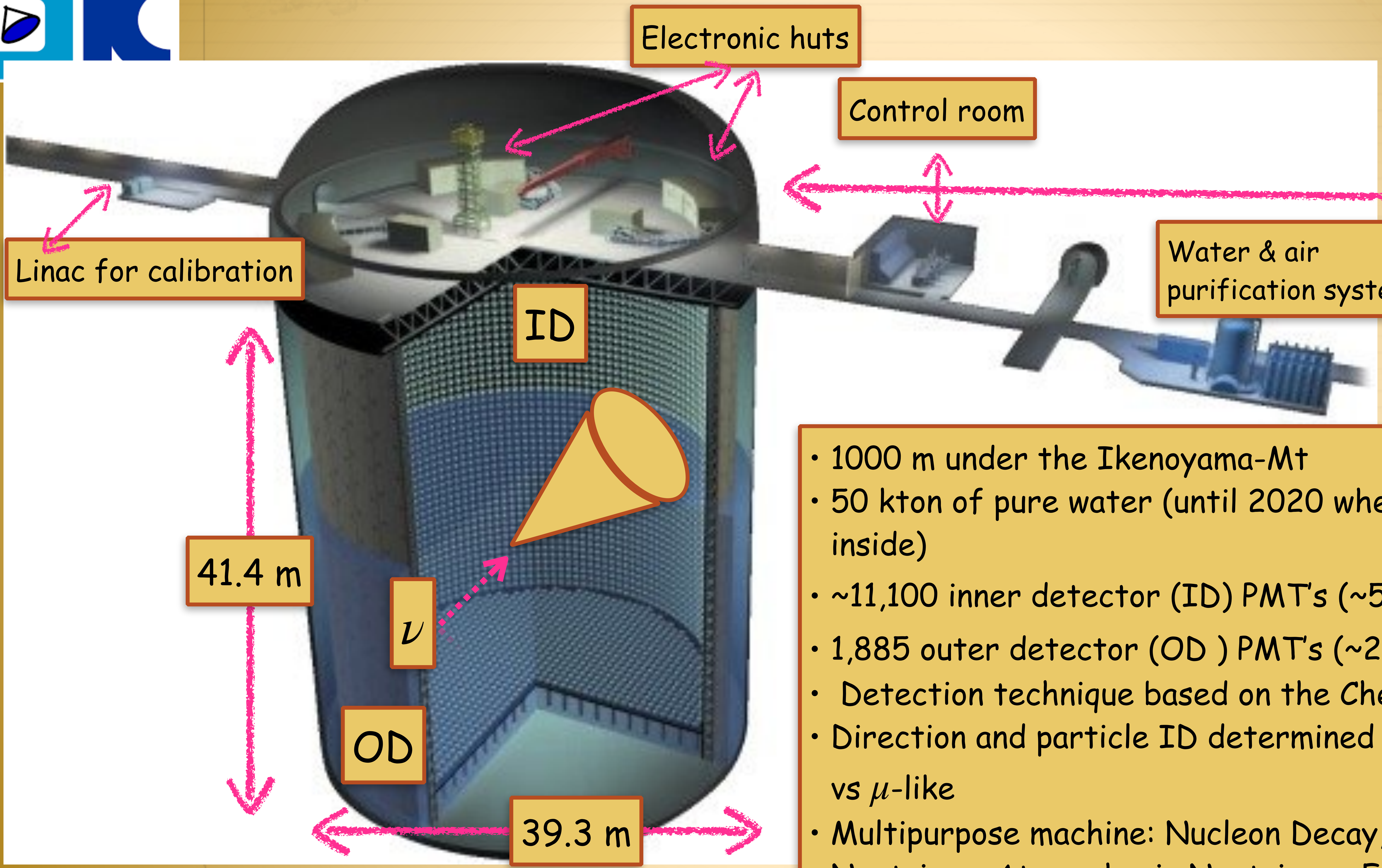
~230 collaborators from 53 institutes in 11 countries

# Super-Kamiokande detector

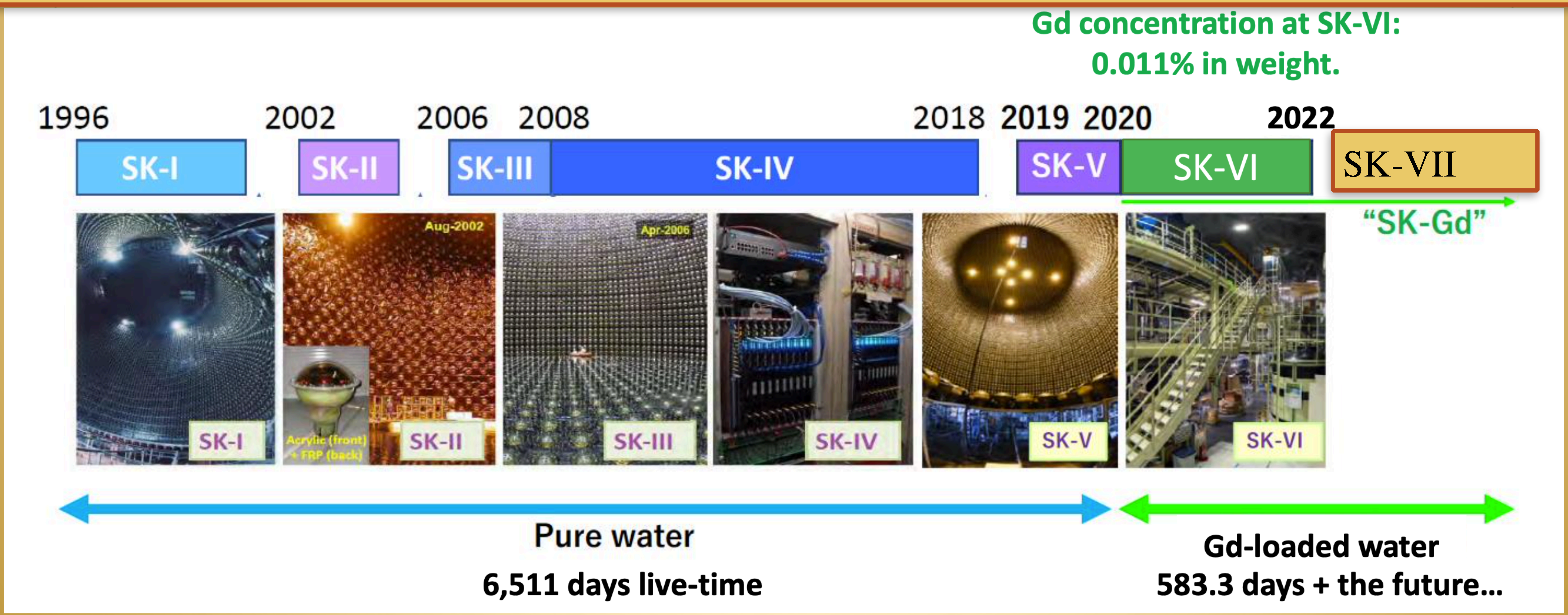




- 1000 m under the Ikenoyama-Mt
- 50 kton of pure water (until 2020 when Gd sulfate was added inside)
- ~11,100 inner detector (ID) PMT's (~50cm $\phi$)
- 1,885 outer detector (OD ) PMT's (~20cm $\phi$)
- Detection technique based on the Cherenkov radiation
- Direction and particle ID determined from the ring pattern: e-like vs $\mu$-like
- Multipurpose machine: Nucleon Decay, Solar and Supernova Neutrinos, Atmospheric Neutrinos, Far detector for T2K

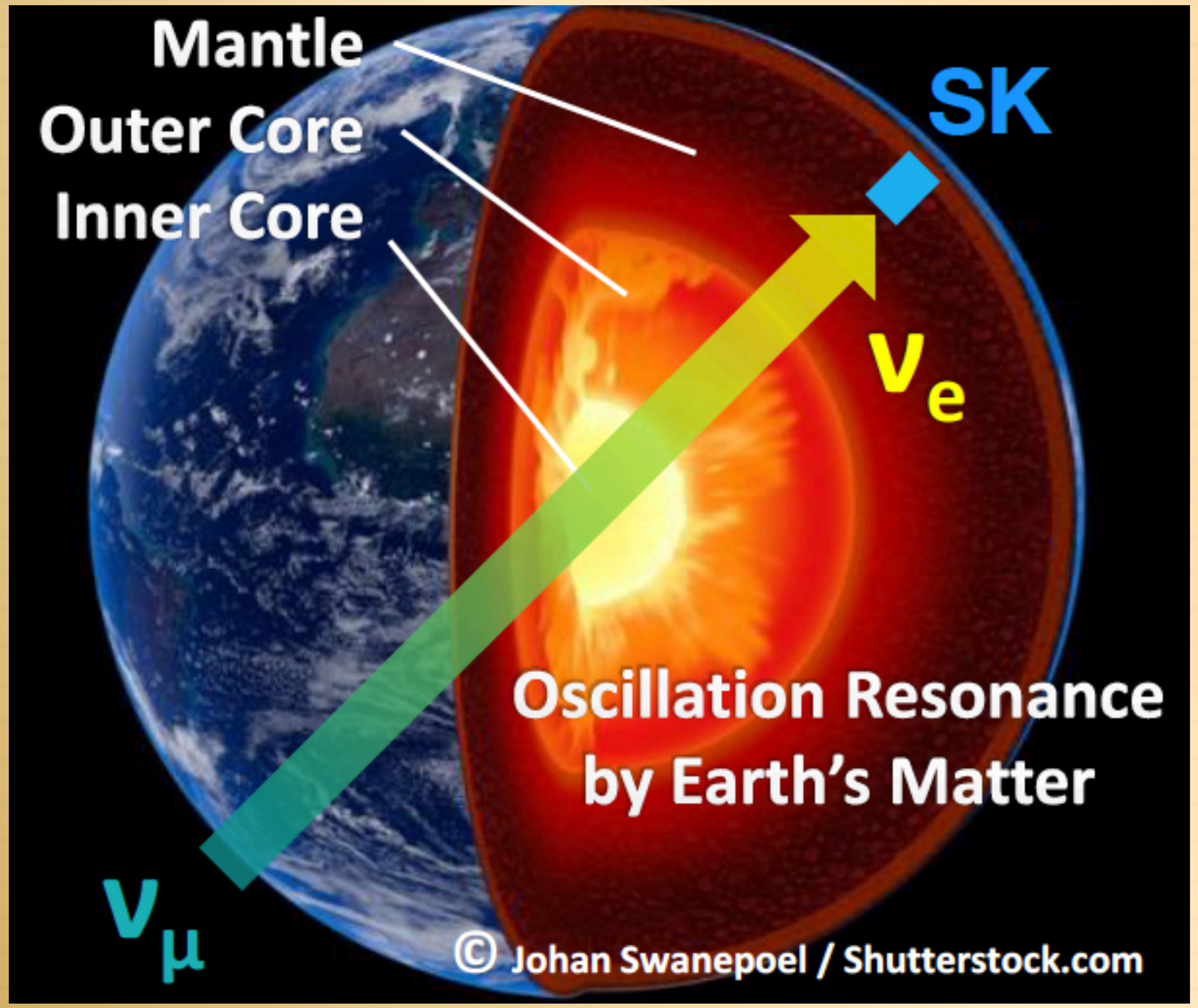
# The Super-Kamiokande experiment

- Super-Kamiokande 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.



# Atmospheric neutrinos

- Neutrinos are produced when cosmic protons interact with the nuclei in the atmosphere:
  - with wide range of energy MeV- PeV produced isotropically about the Earth atmosphere
  - travel length varies 10km~1300km



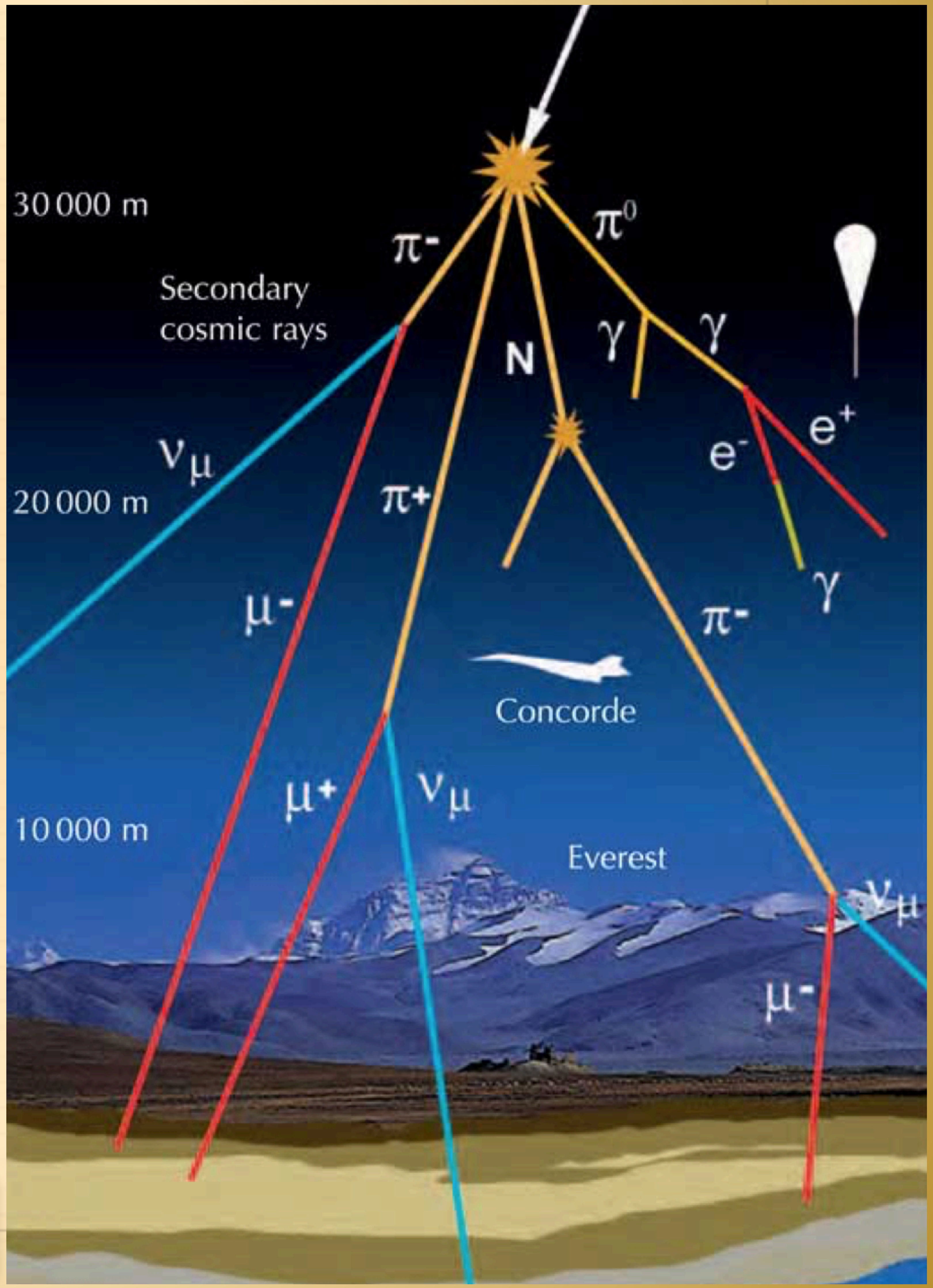



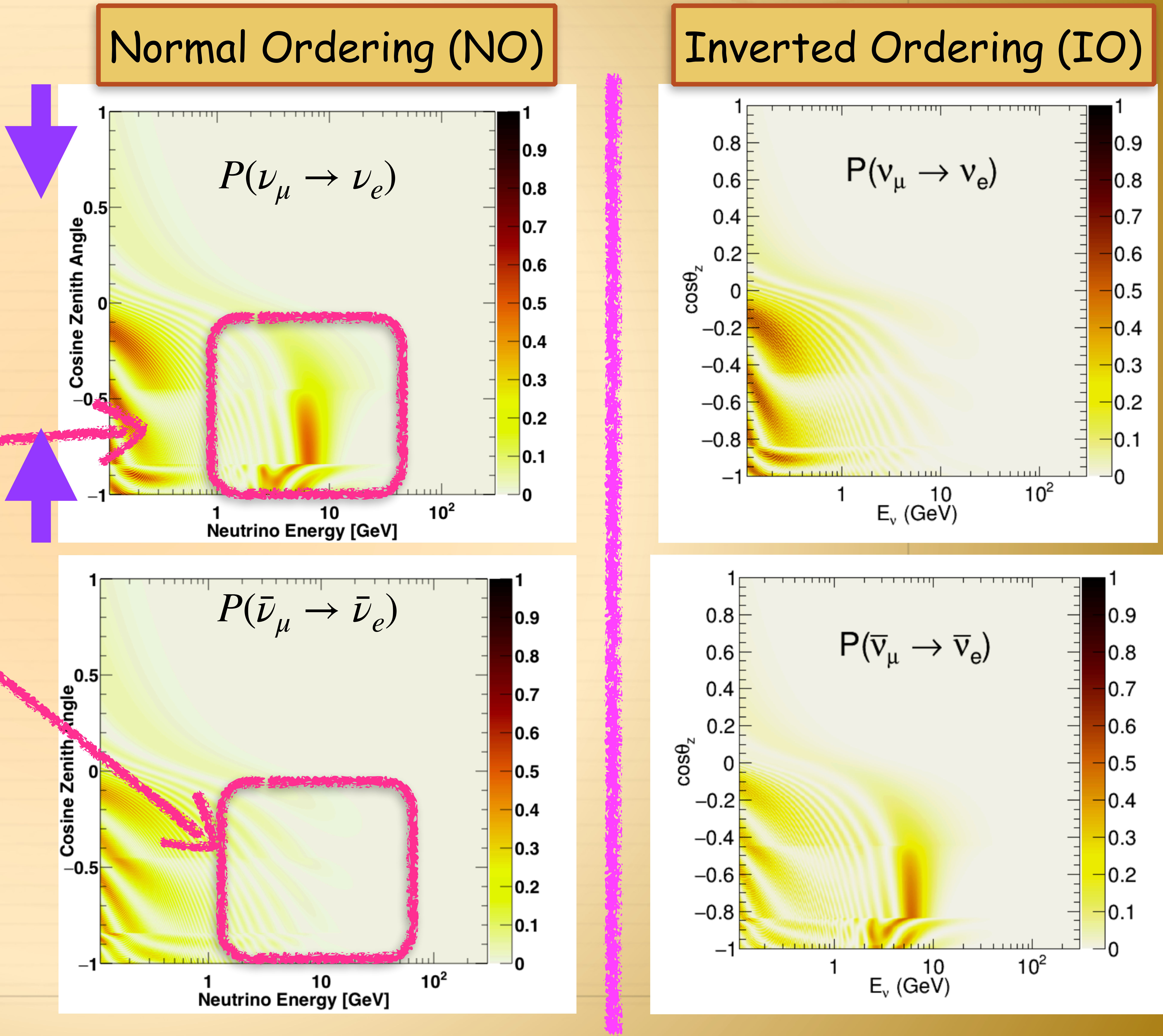

Photo: https://physicsopenlab.org/2016/01/10/cosmic-muons-decay/

# Atmospheric neutrino oscillations

- Oscillograms plotted with: $\Delta m^2_{21} = 7.7 \times 10^{-5}$, $\sin^2\theta_{23} = 0.50$, $\sin^2\theta_{12} = 0.30$, $\sin^2\theta_{13} = 0.0219$ and $\delta_{CP} = 0$
- Phys. Rev. D. 97 072001

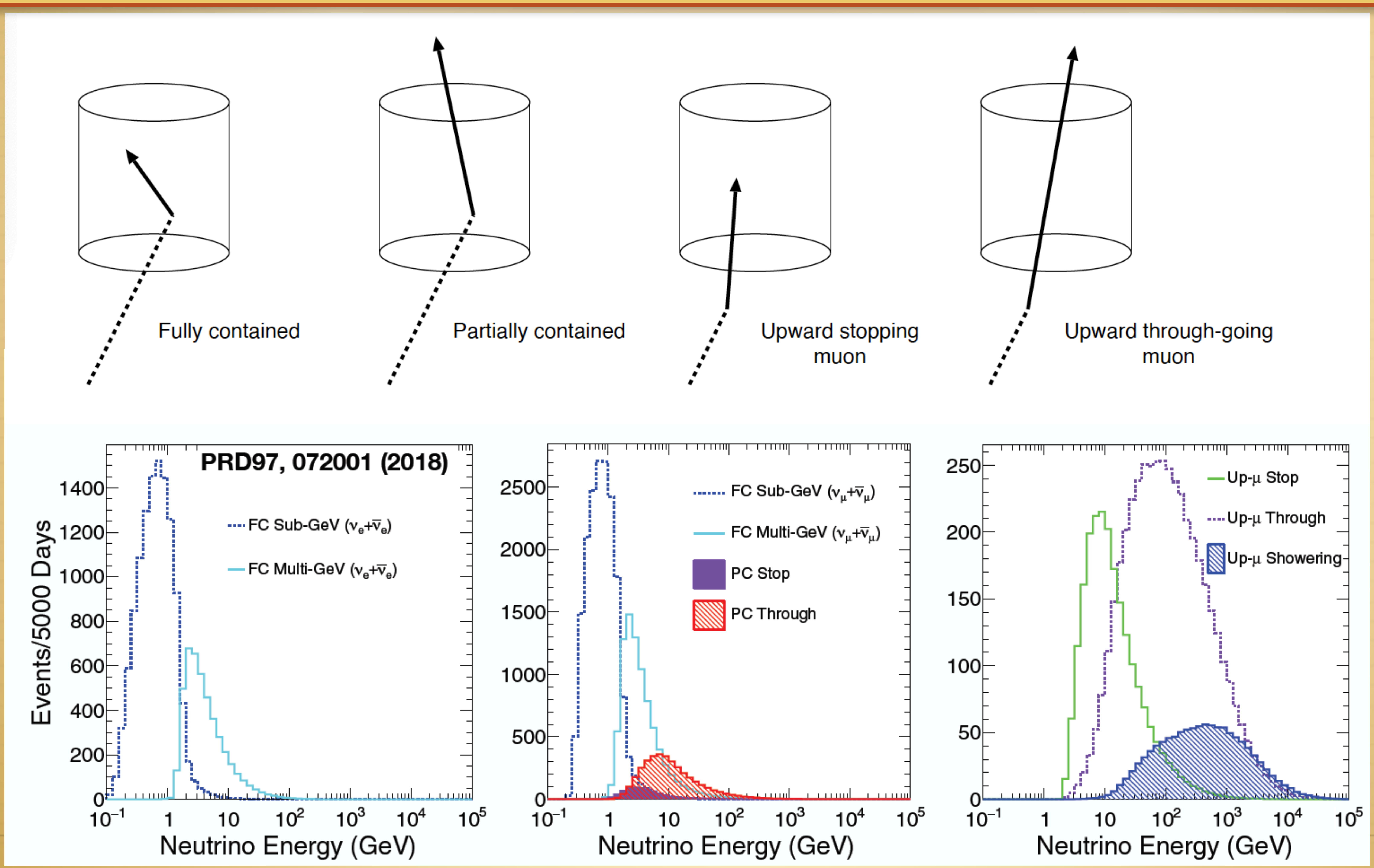
- Impact of matter effects:
  - NO: enhancement of $\nu_e$ appearance
  - NO: effect is not present for $\bar{\nu}_\mu \to \bar{\nu}_e$
  - IO; situation is reversed

- Thanks to presence of matter effects we are sensitive to neutrino mass ordering



# Super-K atmospheric neutrino event classification

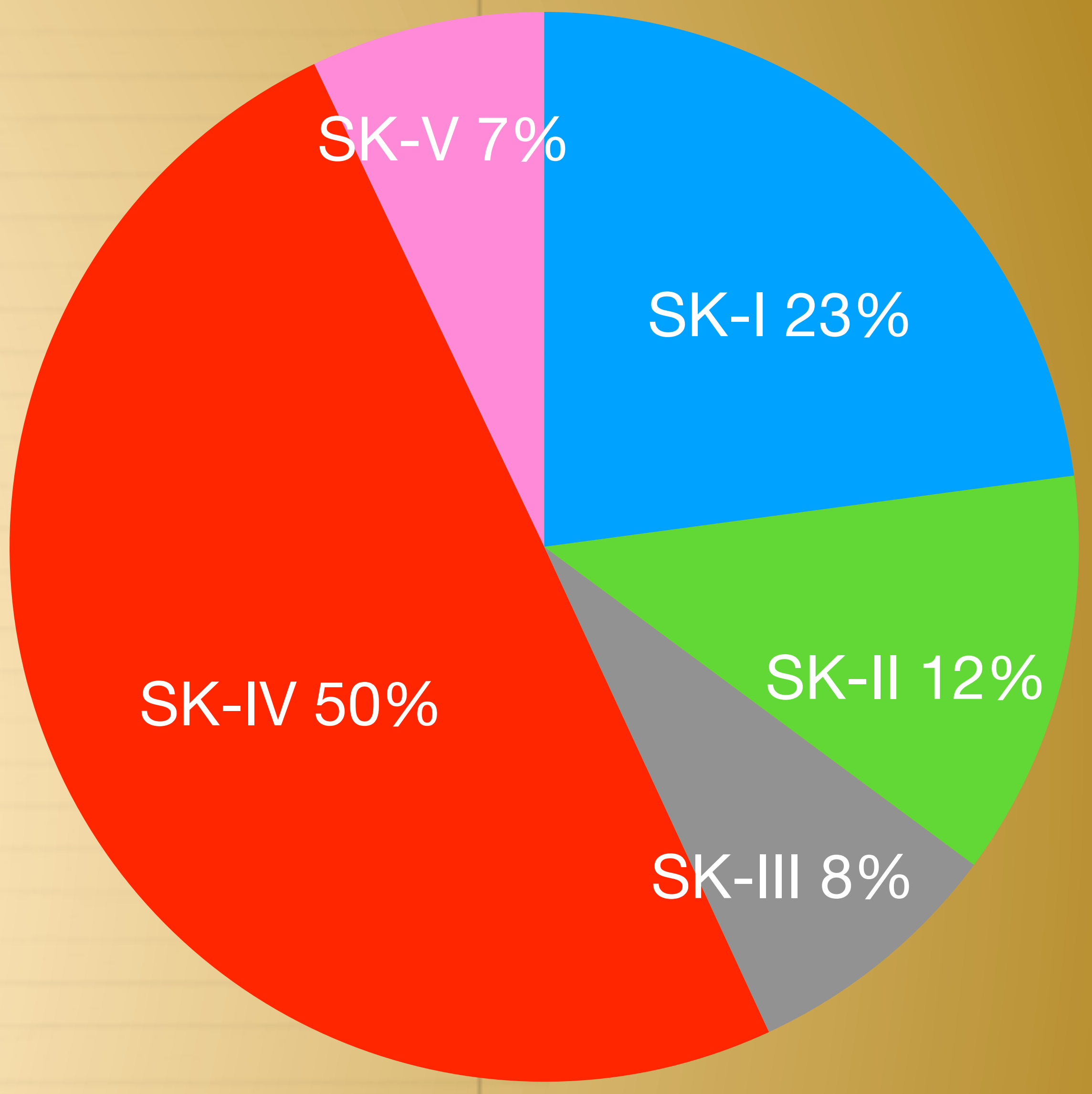
★Atmospheric neutrino events at Super-K are classified into several categories:



# SK atm-ν oscillation analysis improvements

- New results with full SK pure water phase (SK-I ~V) with several updates
  - New publication is being written
    - previously published results: PRD97, 072001 (2018): SK 5326 days, 328 kt·yr

- Updates since the previous analysis:
  - Expansion of fiducial volume and more lifetime: 6511 days, 484 kt·yr in total +50% of statistics
  - Event selection with neutron tagging on hydrogen (SK-IV~V)
    - Enhancement of statistical separation between $\nu$ and $\bar{\nu}$ events
  - New multi-ring event classification using a Boosted Decision Tree (BDT)
    - Improved charged current/neutral current separation
- Atmospheric $\nu$ oscillation fit with external constrains
  - $\theta_{13}$ from reactors

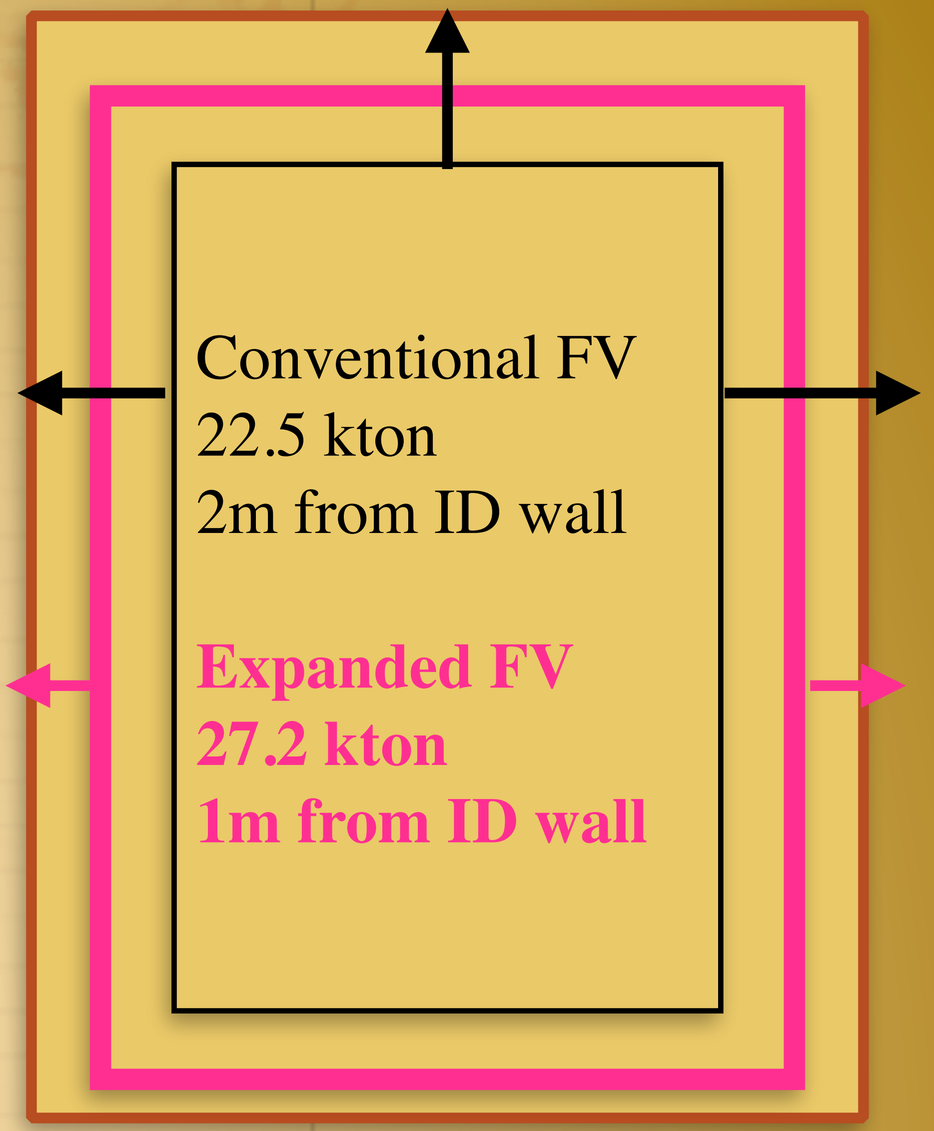


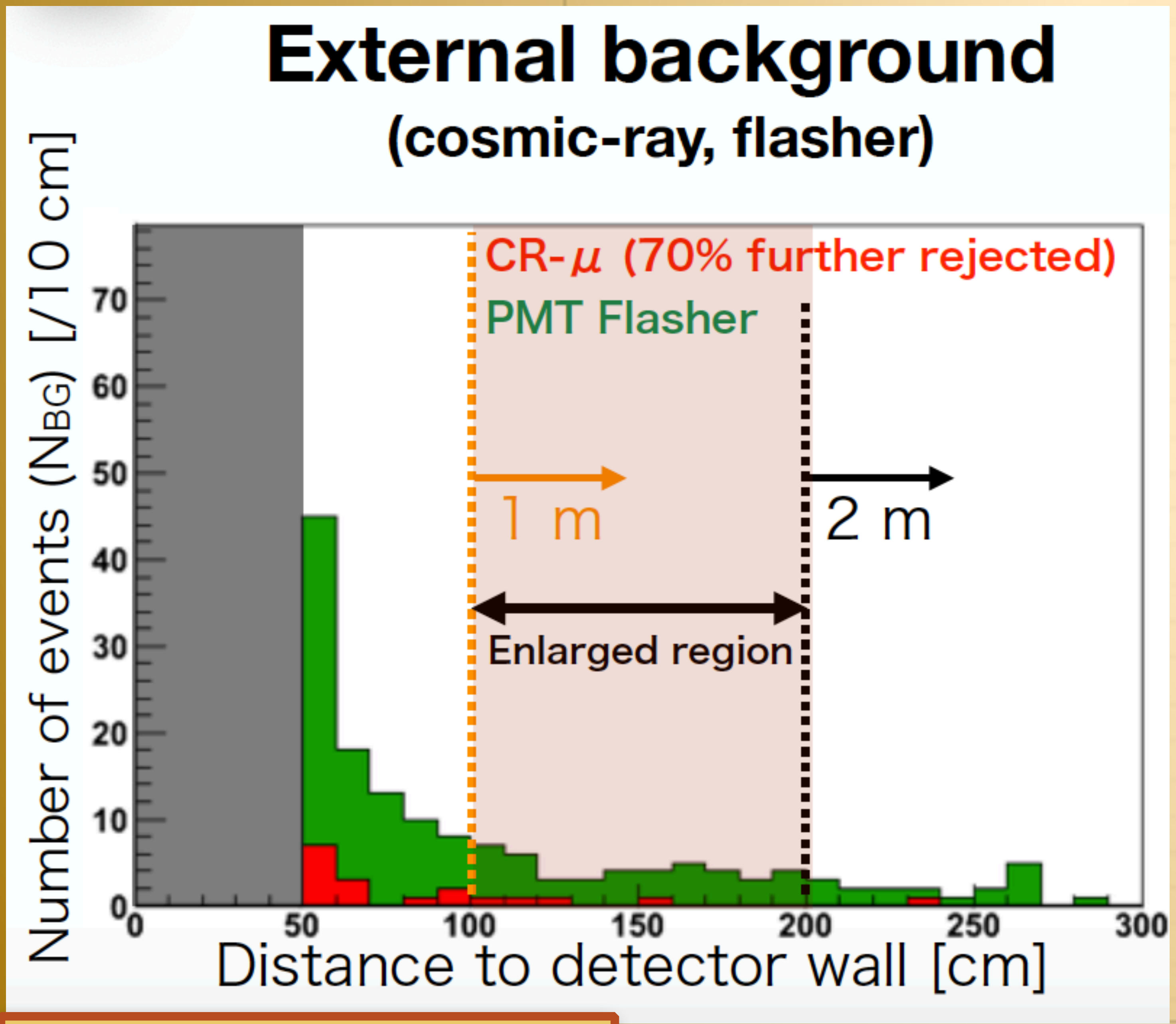
# Enlarging the Fiducial Volume

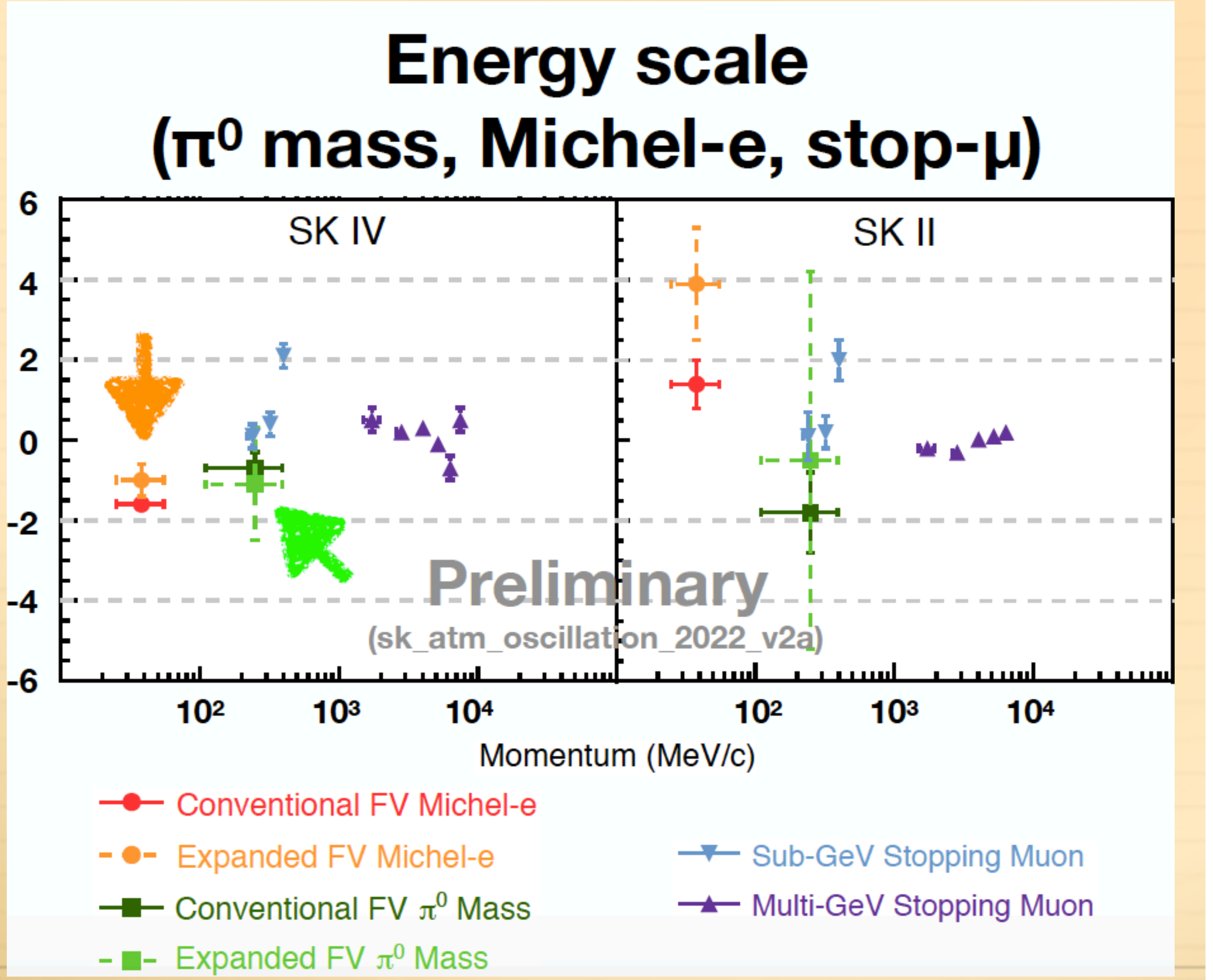
Distance btw vertex and nearest ID wall surface = "wall"

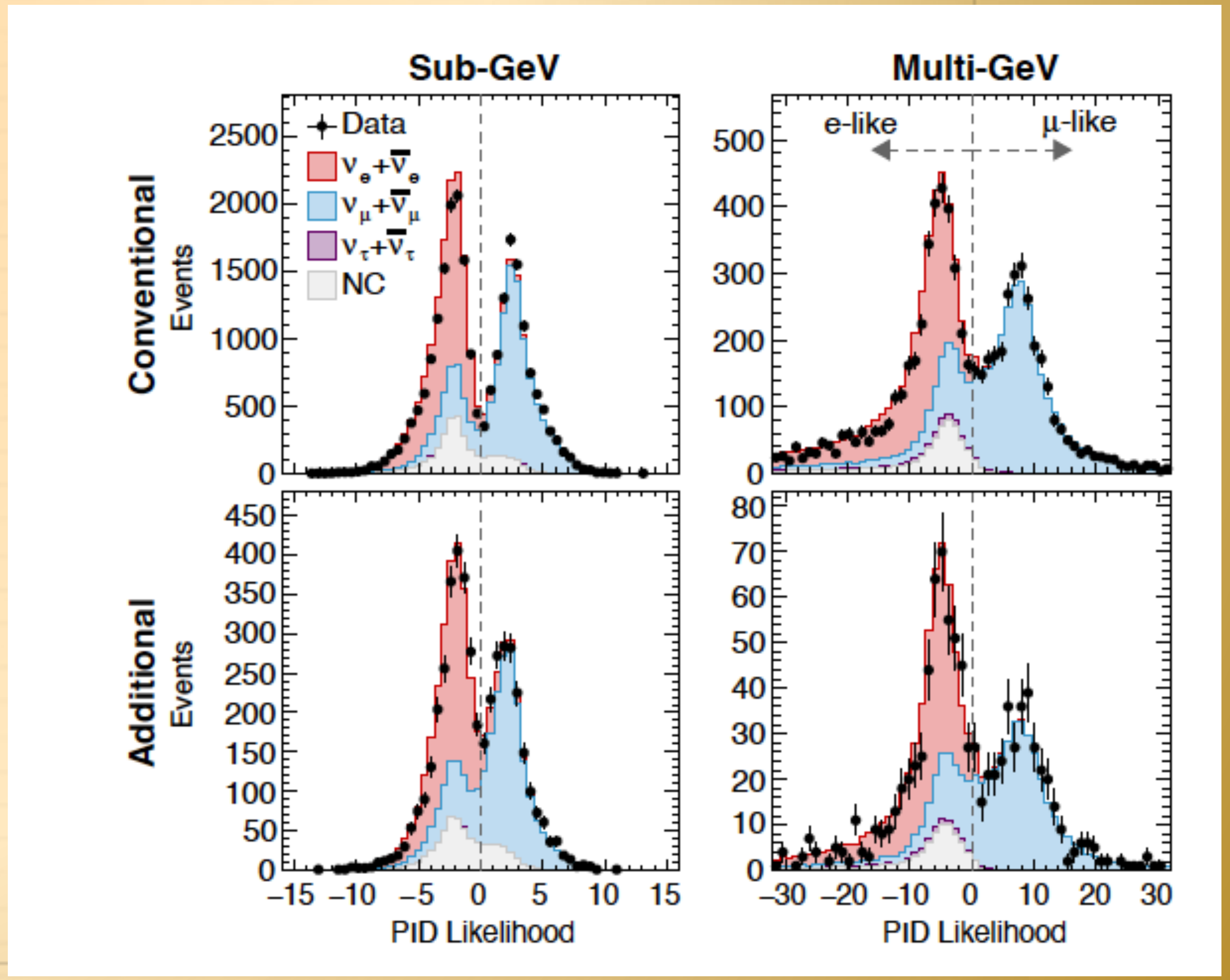
- Conventional fiducial volume defined as wall > 2m
- Expanded fiducial volume to wall > 1m (for all SK periods)
  - ★Increased fiducial volume by 20% (22.5kt → 27.2kt)

- Confirmed no significant increase of non-ν background and no significant bias in reconstruction (ex. energy scale)
- Systematics in the expanded region recalculated and under control



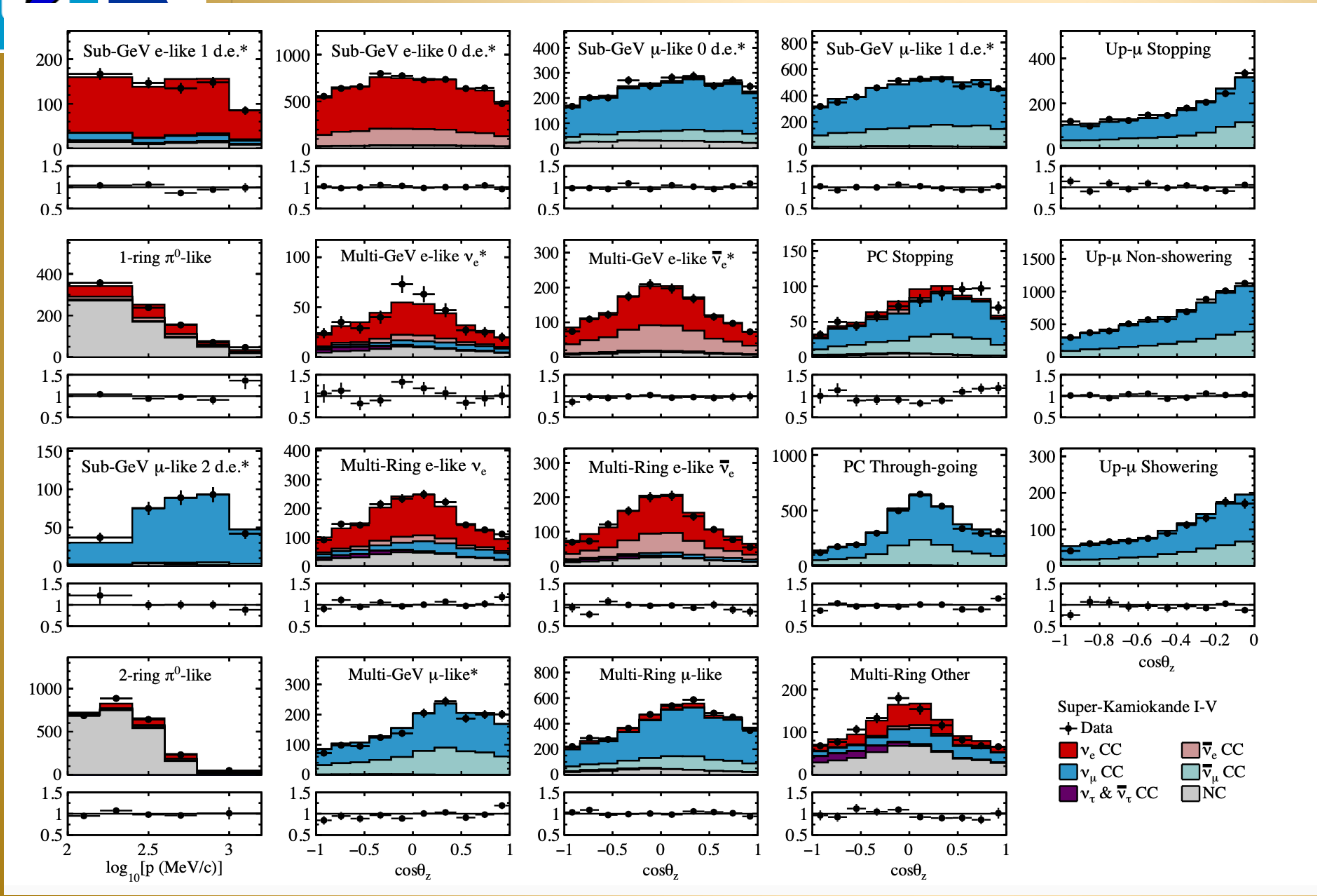




PRD 201, 112011 (2020)

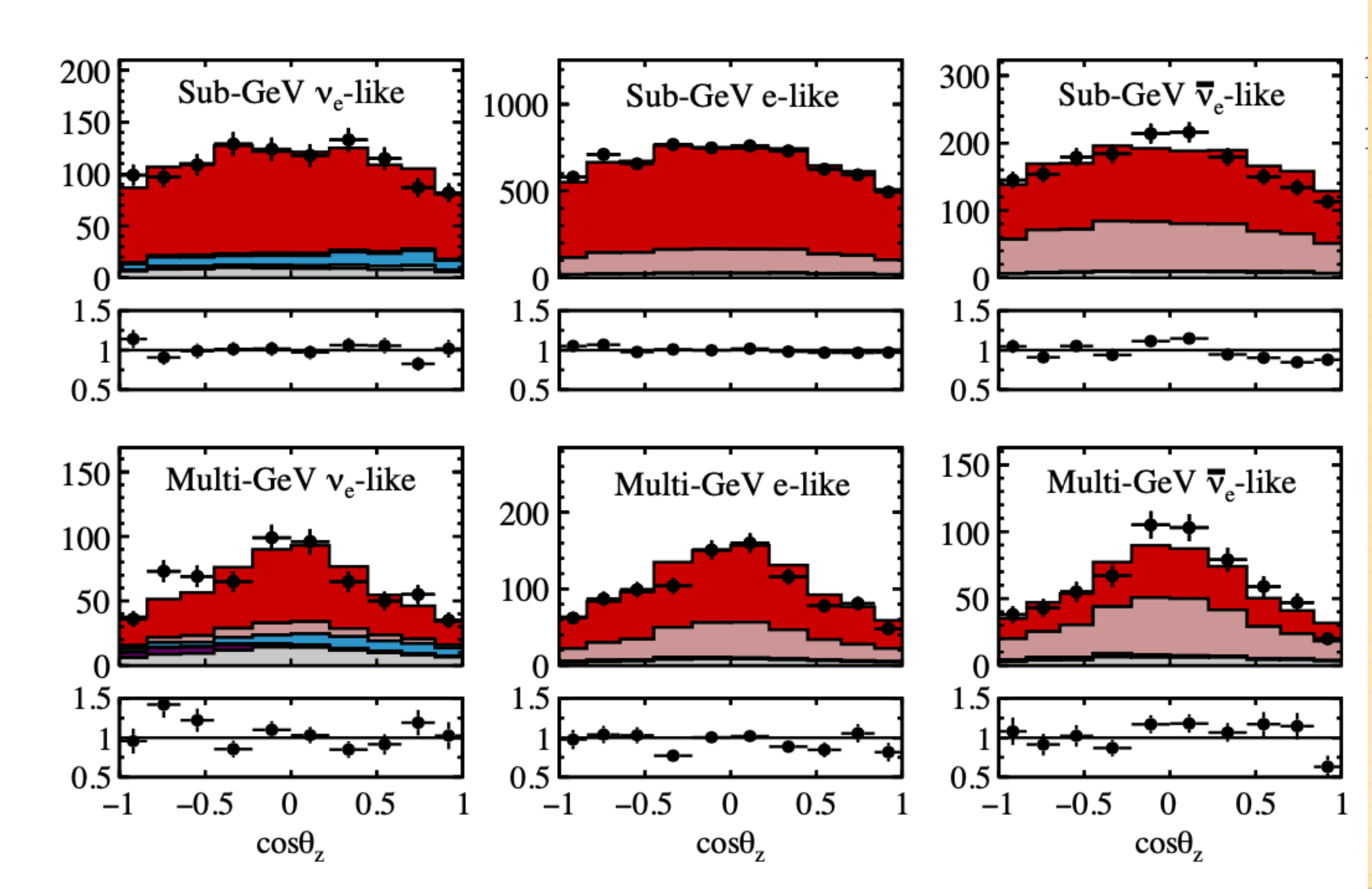
# Super-K samples

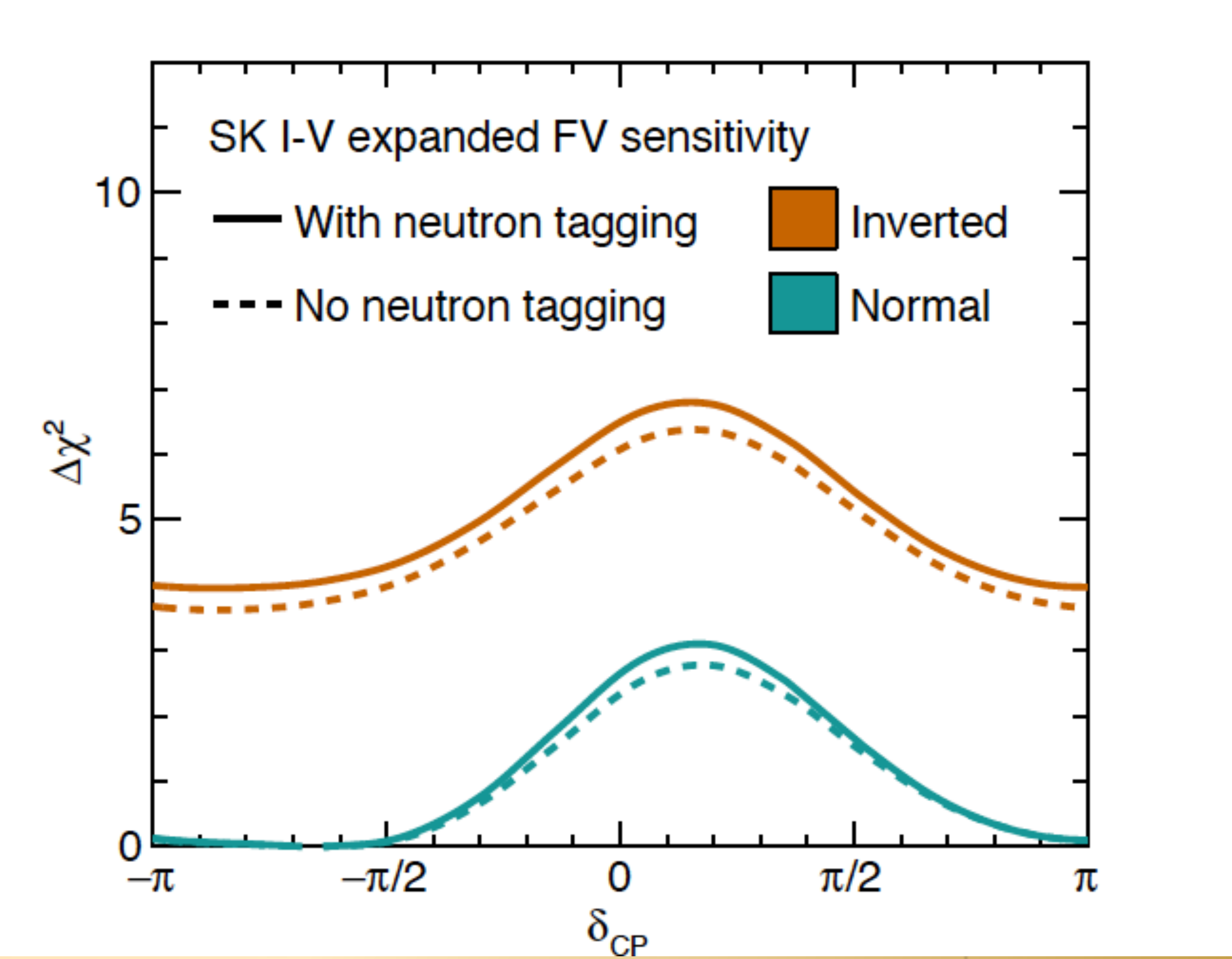



- FC: Sub-GeV and Multi-GeV samples with SK-I~III data, no neutron tagging included*
- PC, UPMU, FC $\pi^0$, FC Multi-Ring samples uses SK-I~V data,

# Super-K samples with neutron tagging

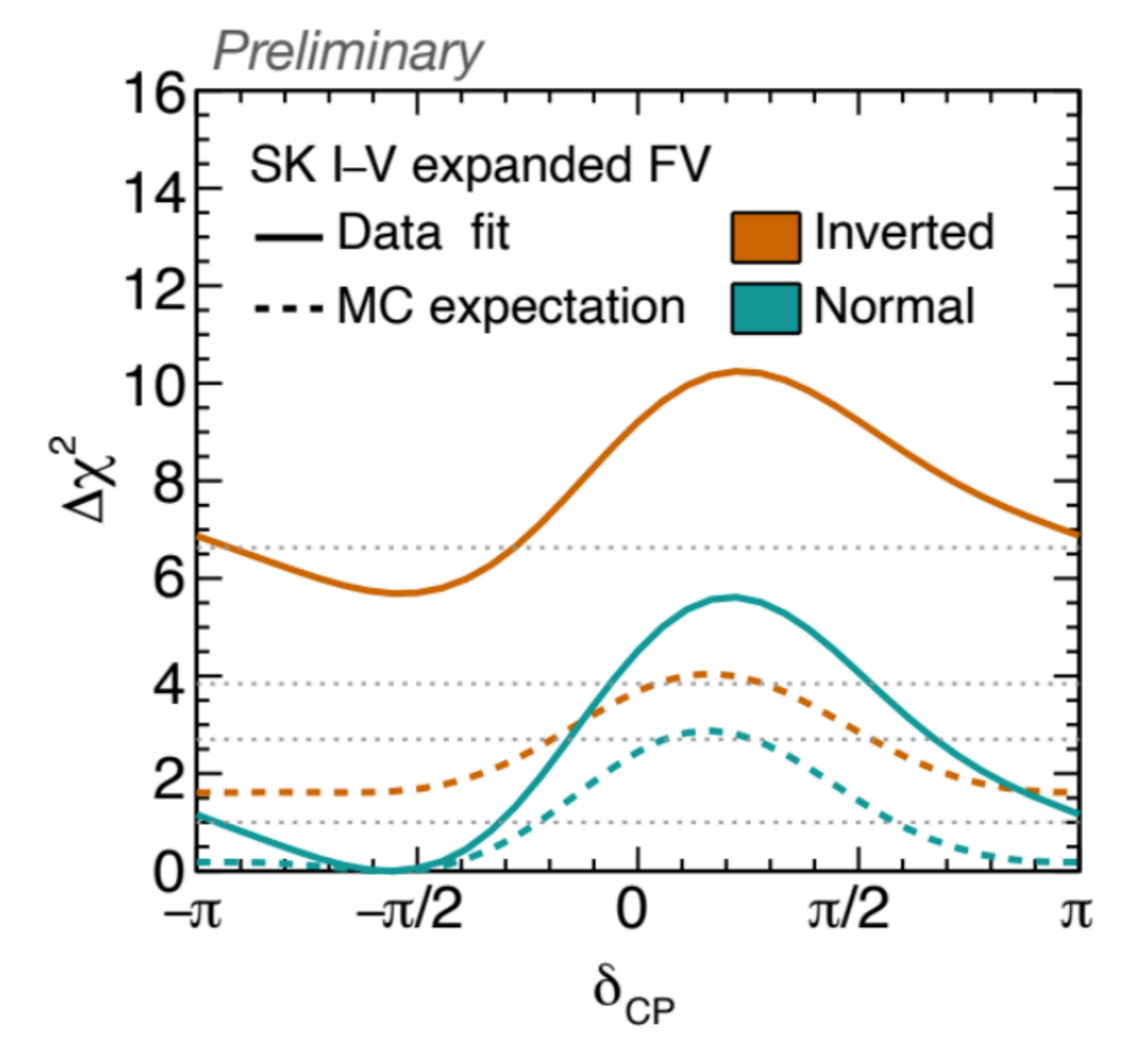
- Additional selections done for SK -IV and SK-V data period, with neutron tagging on Hydrogen.
- Improves separation between $\nu$ and $\bar{\nu}$ events

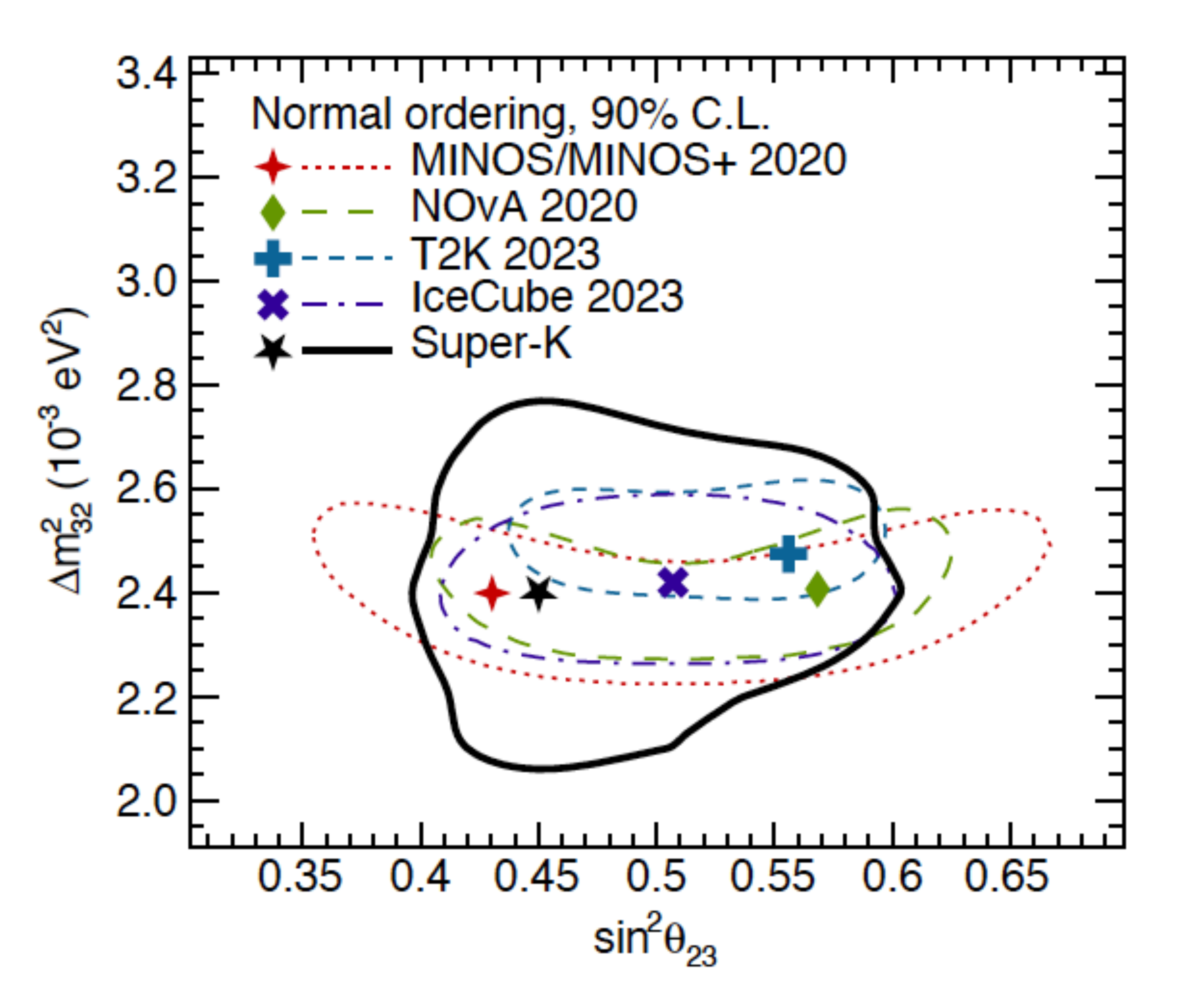


# SK atmospheric $\nu$ results

With $\sin^2\theta_{13}$ constrained
$sin^2\theta_{13} = 0.0220 \pm 0.0007$
[PTEP 2022, 083C01 (2022)]




**SK 2023 best fit results:** Normal ordering, $\delta_{CP} \simeq -\pi/2$, $\Delta m^2_{32} \simeq 2.4 \cdot 10^{-3}$eV$^2$, $\sin^2\theta_{23} \simeq 0.45$

Mass ordering: $\Delta\chi^2_{I.O-N.O} \simeq 5.7$

This analysis prefers NO over the IO at the 92.3% confidence level.

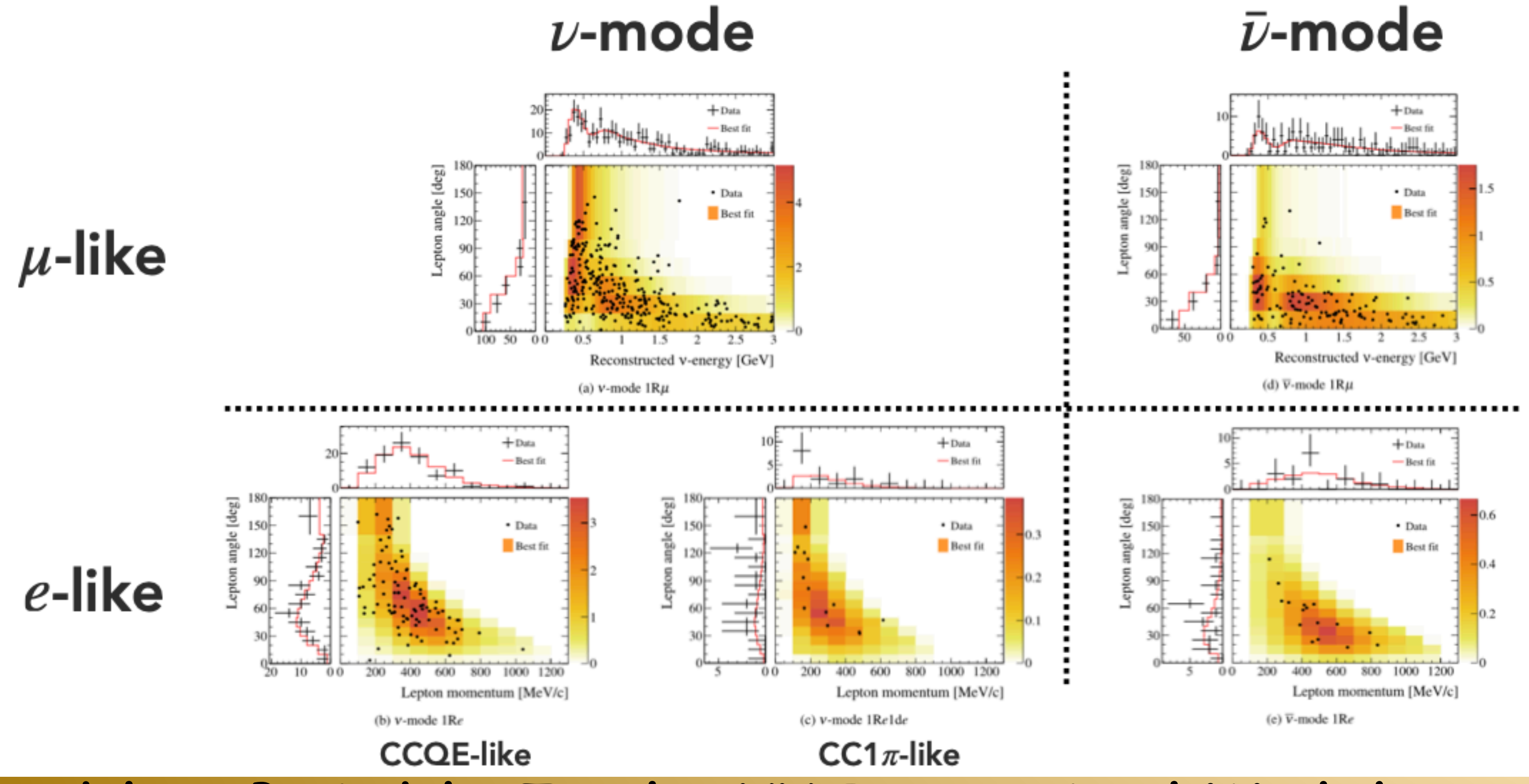
# SK +T2K joint fit analysis

NEW !

- Motivation of the Joint Analysis:
  - T2K and SK use the same detector and have samples with similar energy ranges and similar selections.
  - We can take into account **the correlations of the systematic uncertainties**
  - T2K near detector can be used to constrain the cross-section uncertainties for the low -energy atmospheric samples as well
  - T2K has better sensitivity to $\delta_{CP}$ from $\nu_\mu \rightarrow \nu_e$ oscillation and to $\theta_{23}, \Delta m^2_{32}$ from $\nu_\mu -> \nu_\mu$ channel (this is true for antineutrinos as well)
  - SK has **stronger discrimination of the mass ordering** thanks to the **matter effect** at the few GeV

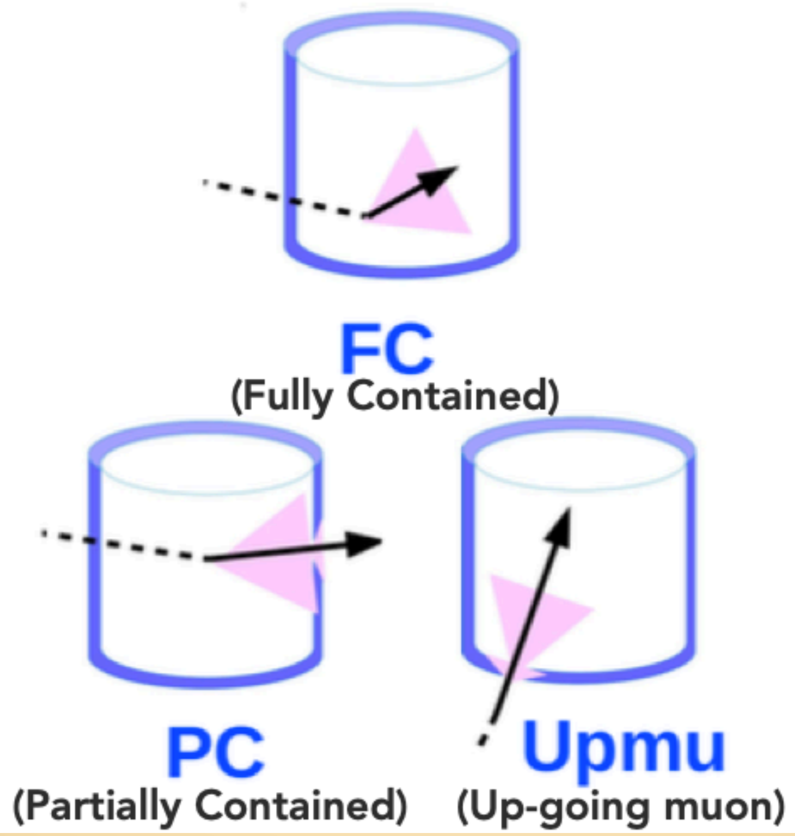
**T2K Run 1-10** (not the latest analysis)
[Eur.Phys.J.C 83 (2023) 9, 782]

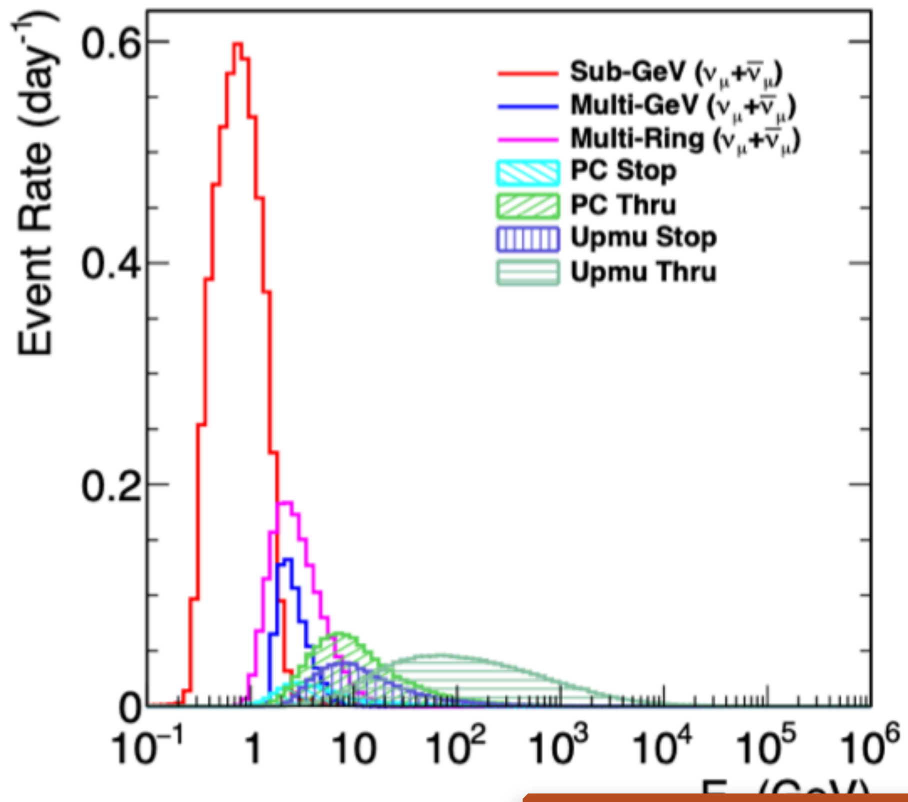
- Neutrino mode: $19.7 \times 10^{20}$ POT
- Antineutrino mode: $16.3 \times 10^{20}$ POT
- Mean neutrino energy ~ 0.6 GeV




**SK IV atmospheric neutrinos**
[PTEP 2019 (2019) 5, 053F01]

- 3244.4 days of data taking
- 18 samples depending on the event topologies and neutrino energies
- **Wider energy ranges** than T2K



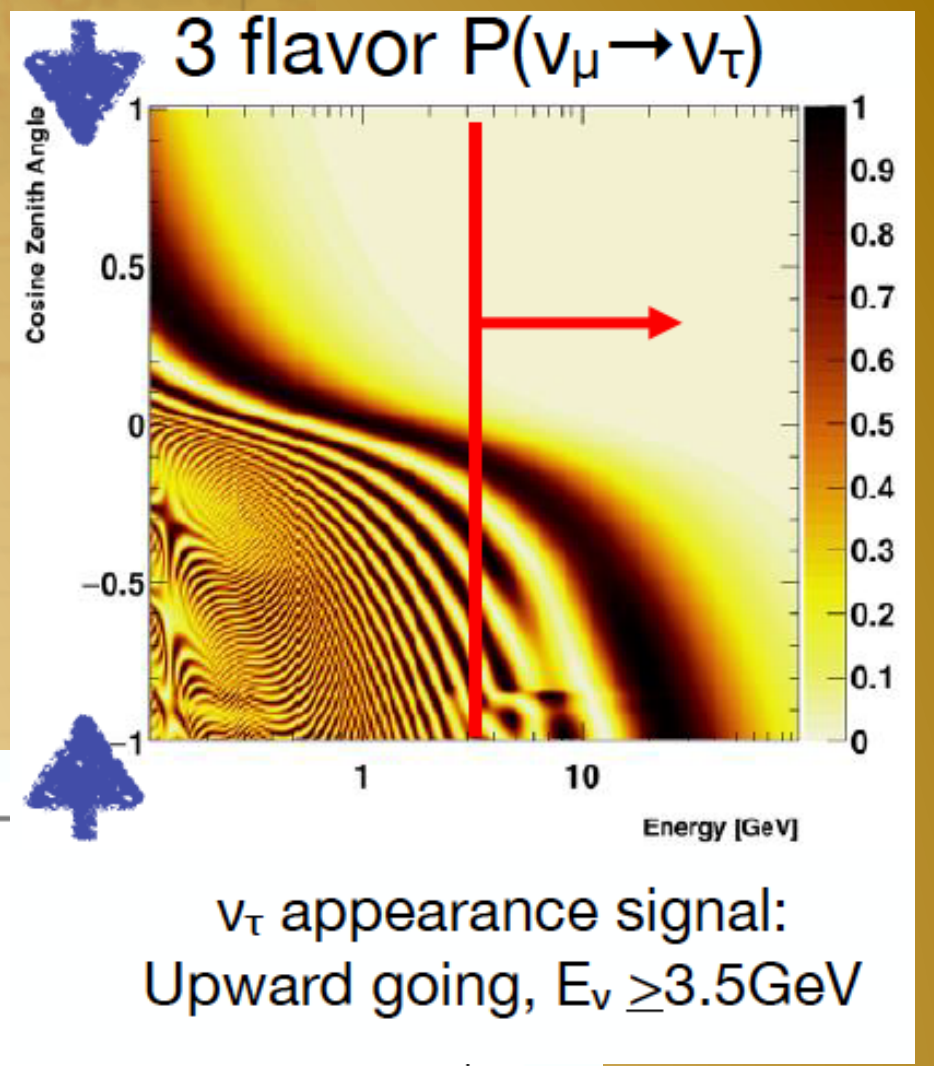

See the talks on this conference from Adrien Blanchet and Thomas Holvey



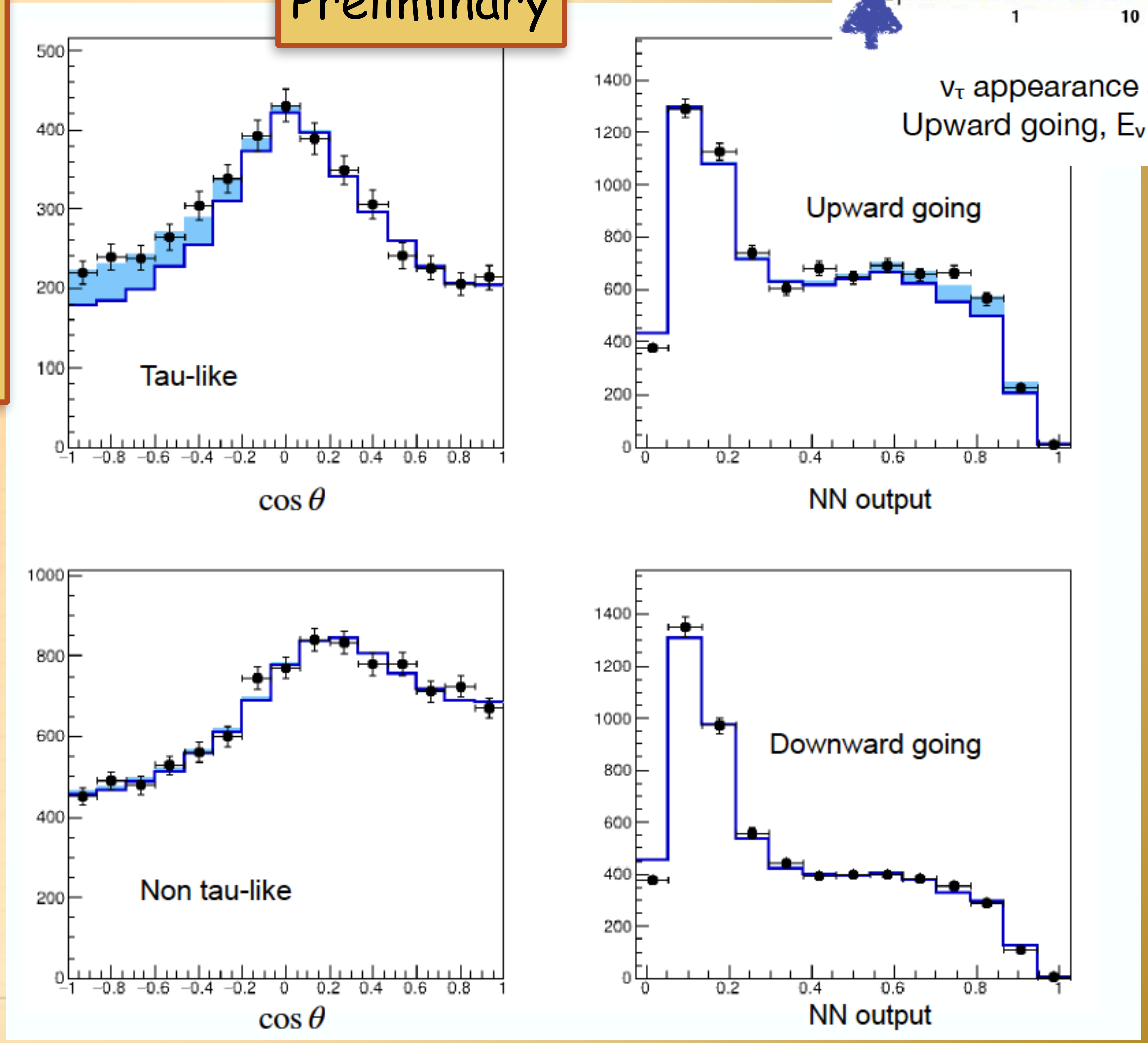
Taken from A.Eguchi NNN23

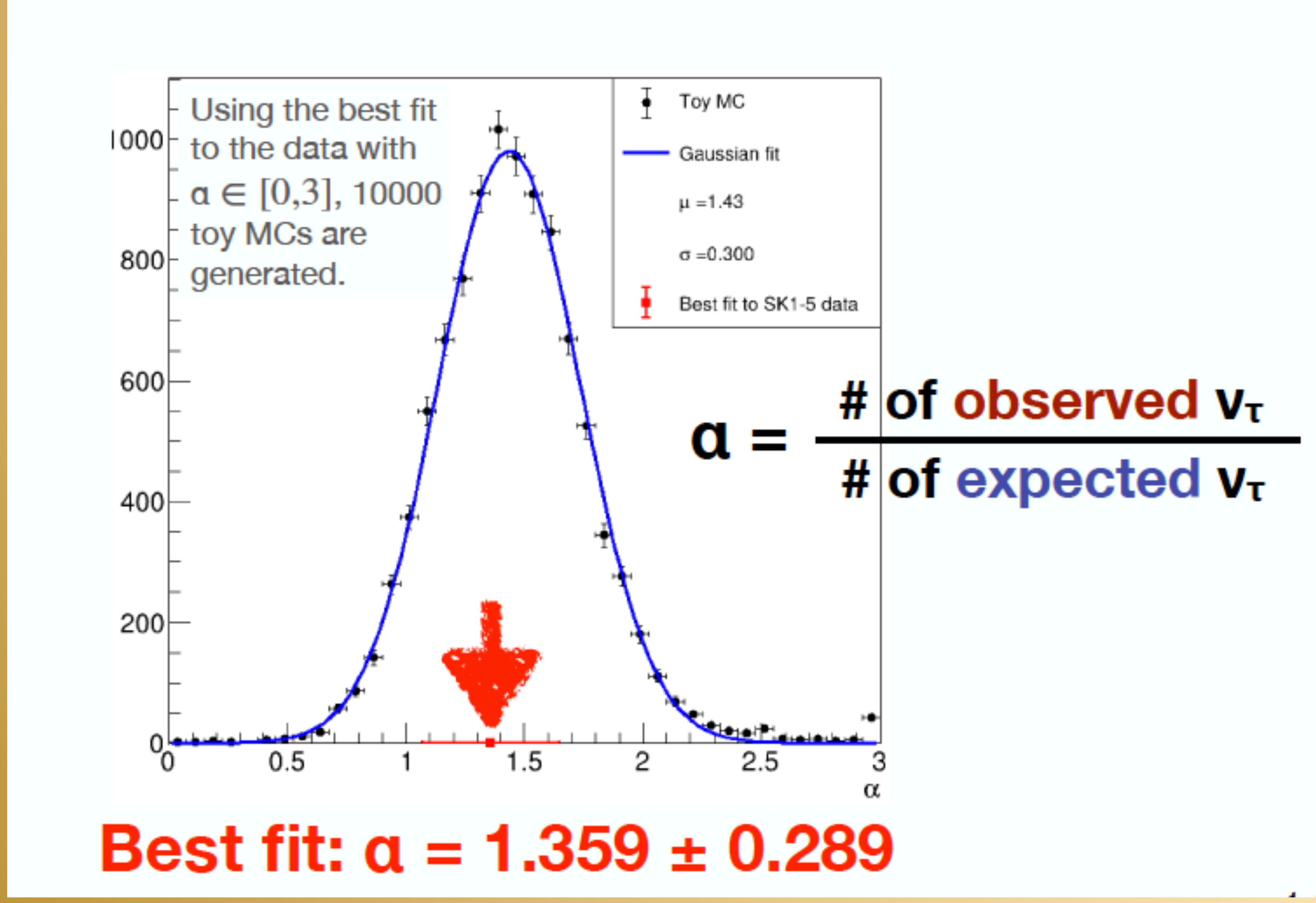
# $\nu_\tau$ appearance searches

- Updates since the last publication in 2018 PRD98 052006 (2018)
  - Full SK pure water phases (SK-I~V data)
    - Additional 2 years of SK-IV and SK-V data added
  - Expanded fiducial volume - overall 50% more data added
- Best fit of $\nu_\tau$ normalisation parameter: $\alpha = 1.359 \pm 0.289$
- Excluding no $\nu_\tau$ appearance ($\alpha = 0$) at 4.8$\sigma$ significance, p-value: $7{,}5 \cdot 10^{-7}$
- Observed # of $\nu_\tau$ CC events: $428 \pm 92$ (normal MO)



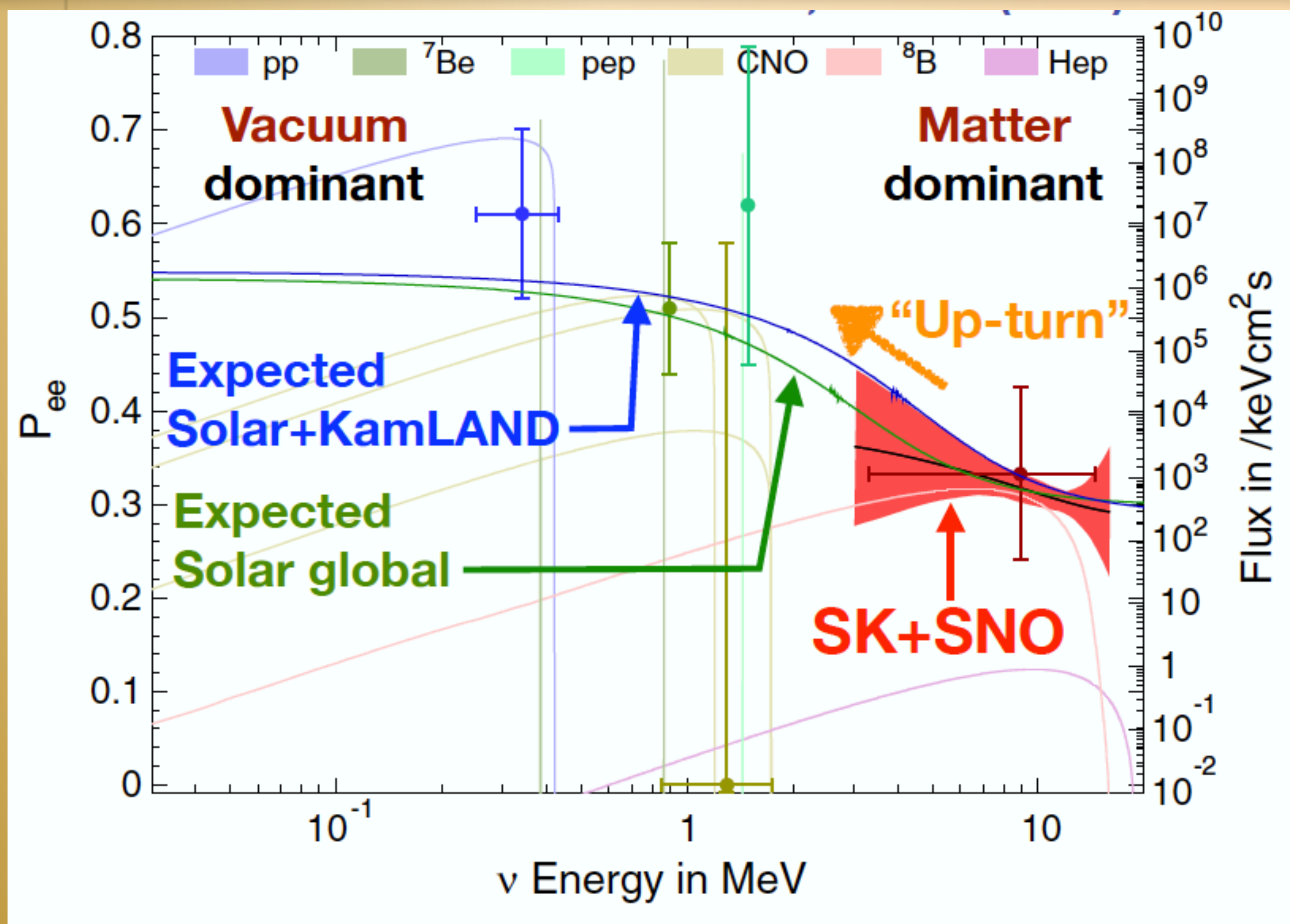

Preliminary

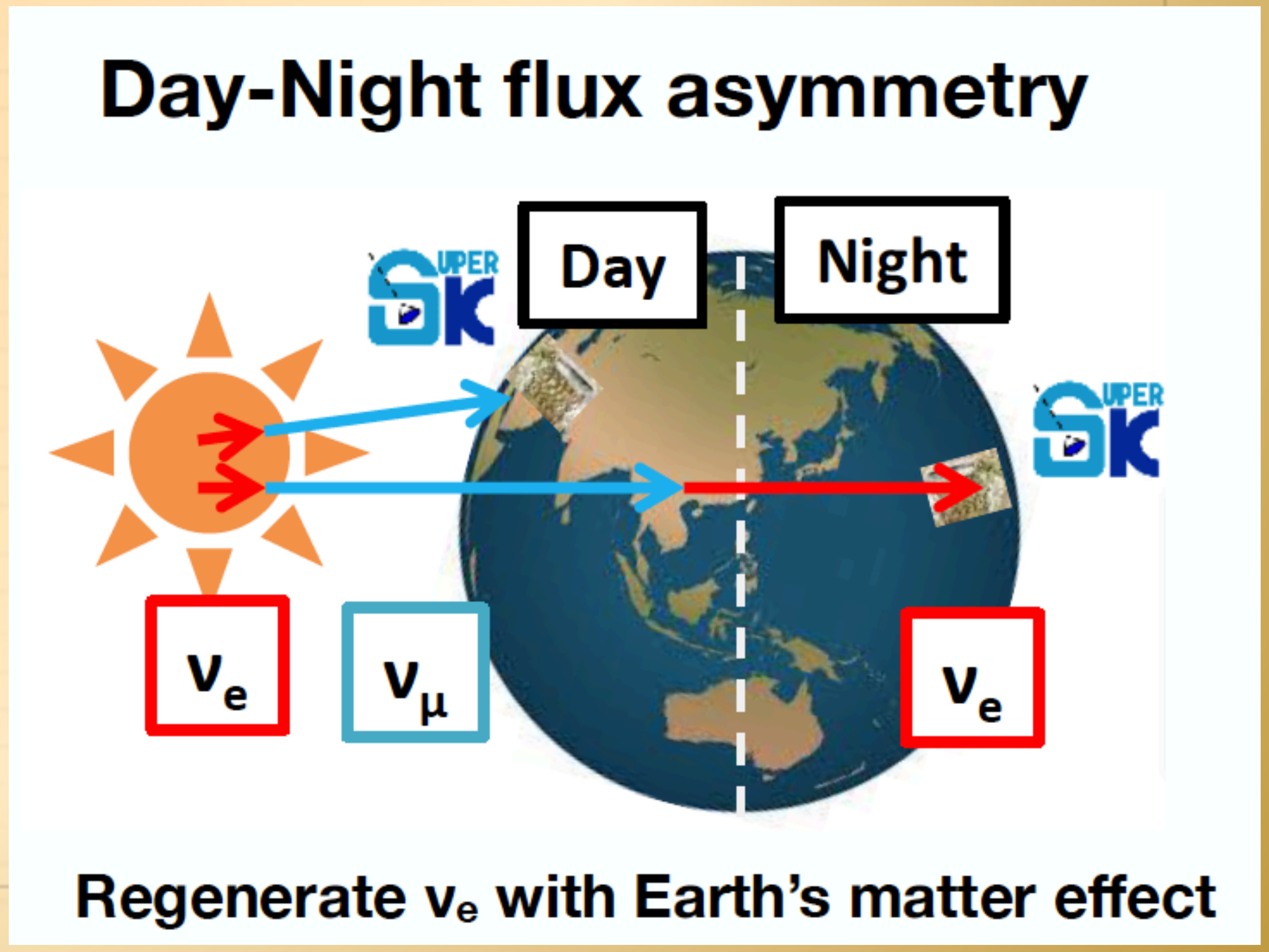


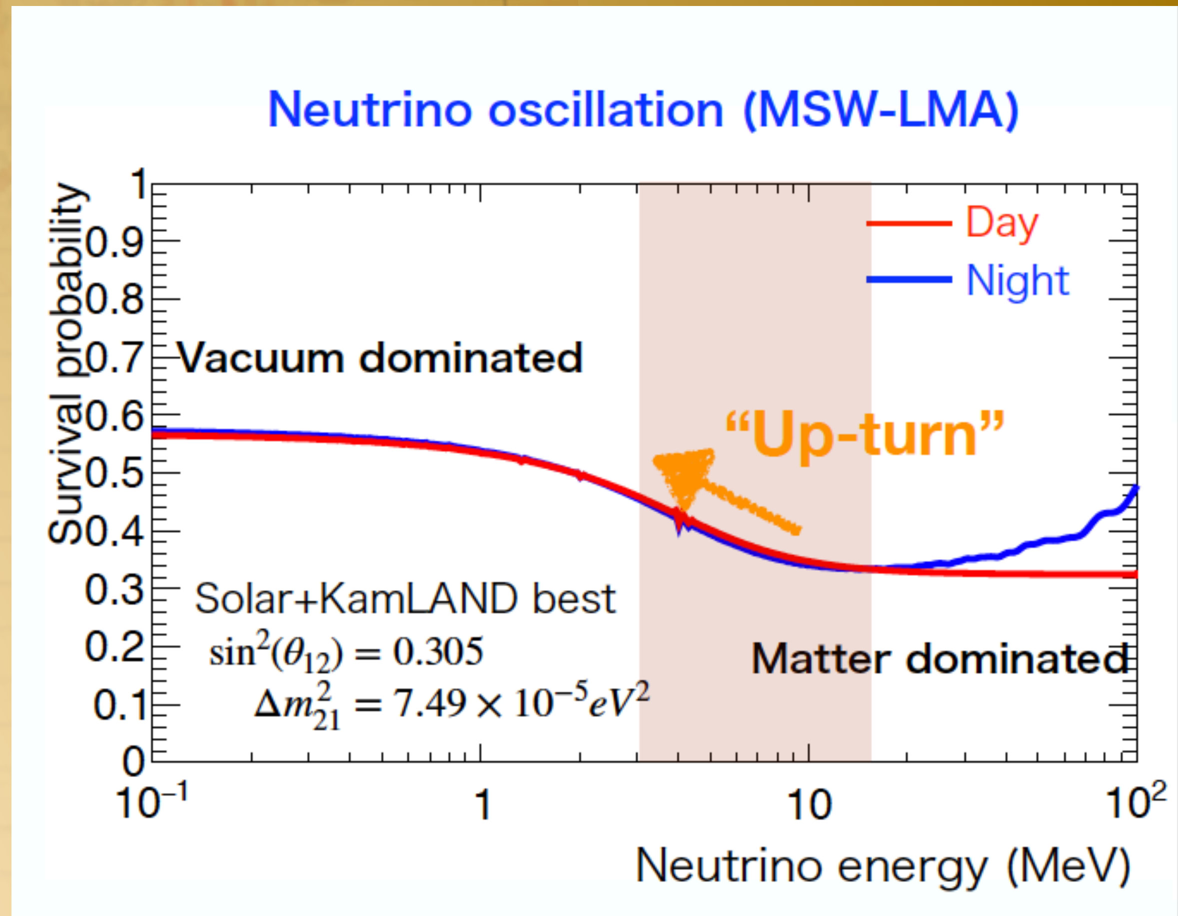
# Solar $\nu$ searches at SK

- Intense neutrinos coming from nuclear fusion in the Sun:
  - $^{8}B$ **neutrinos** recorded by SK with direction and energy information
  - Sensitive to $\theta_{12}$ and $\Delta m^2_{21}$
- Precision test of the MSW oscillation model
  - Precise measurement of spectrum at the vacuum-to-matter transition "up-turn"
    - Sensitive to matter effects in the Sun
  - Measurement of Day/Night flux asymmetry
    - Sensitive to matter effects in the Earth

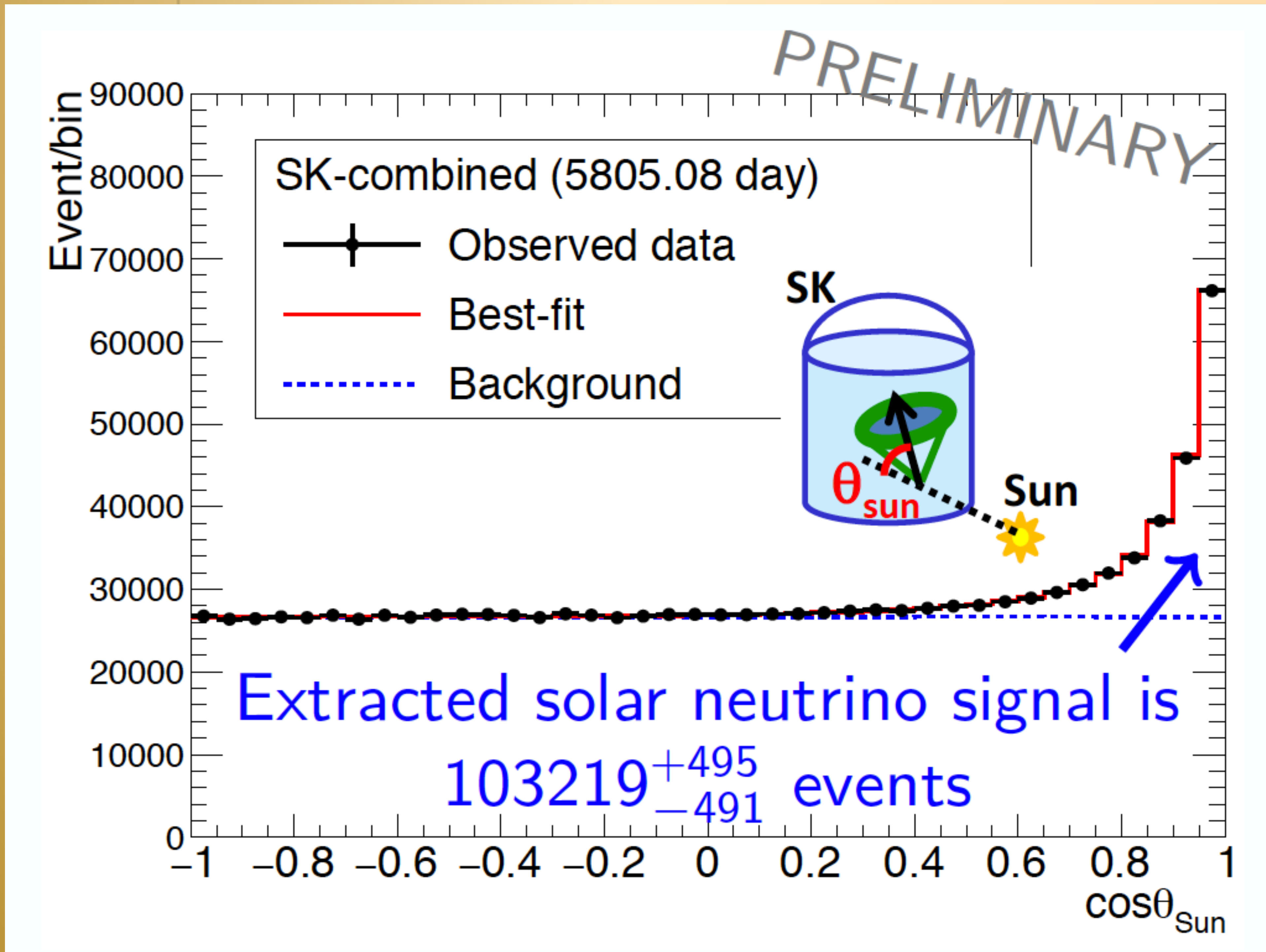


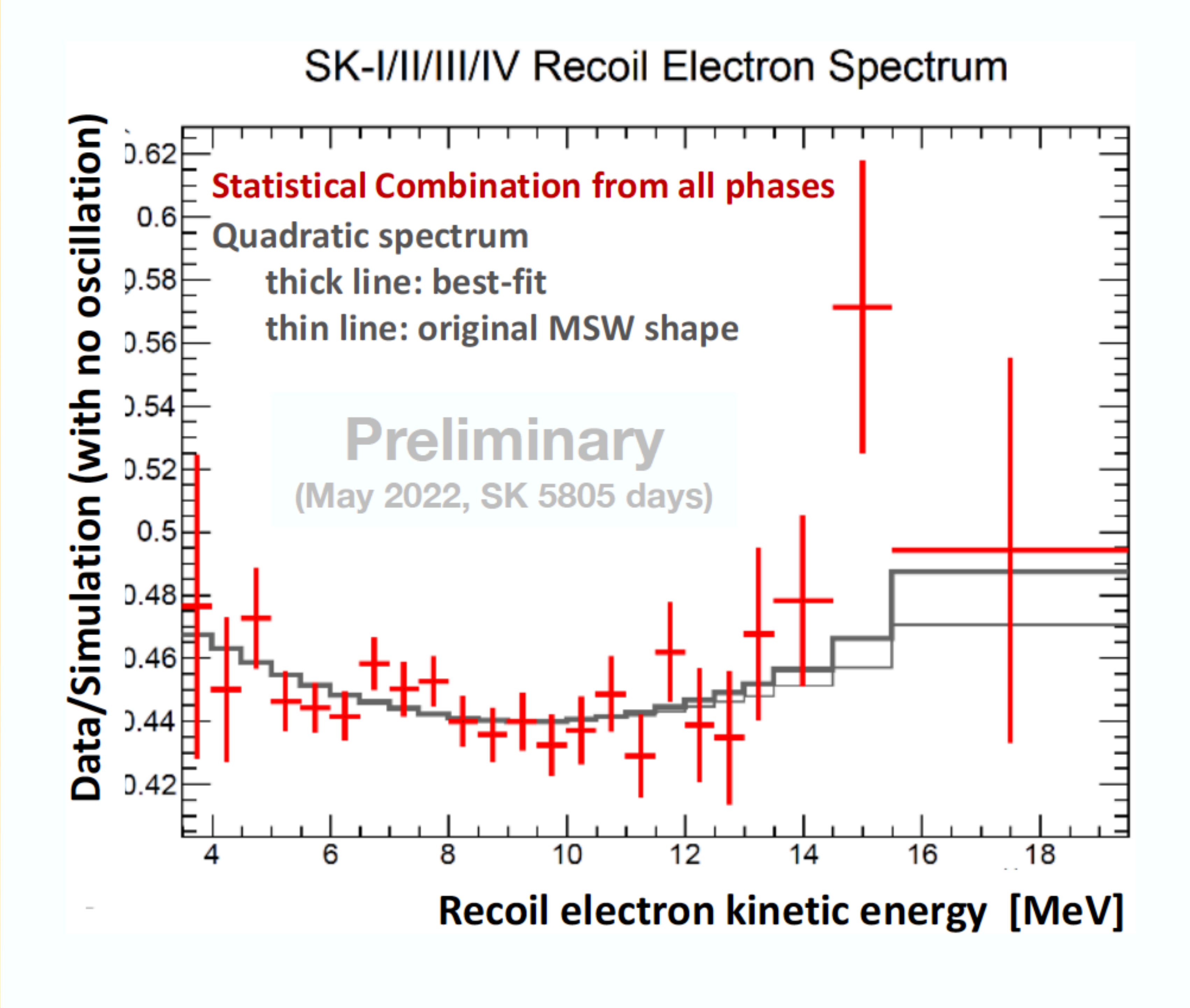



# Solar $\nu$ searches at SK



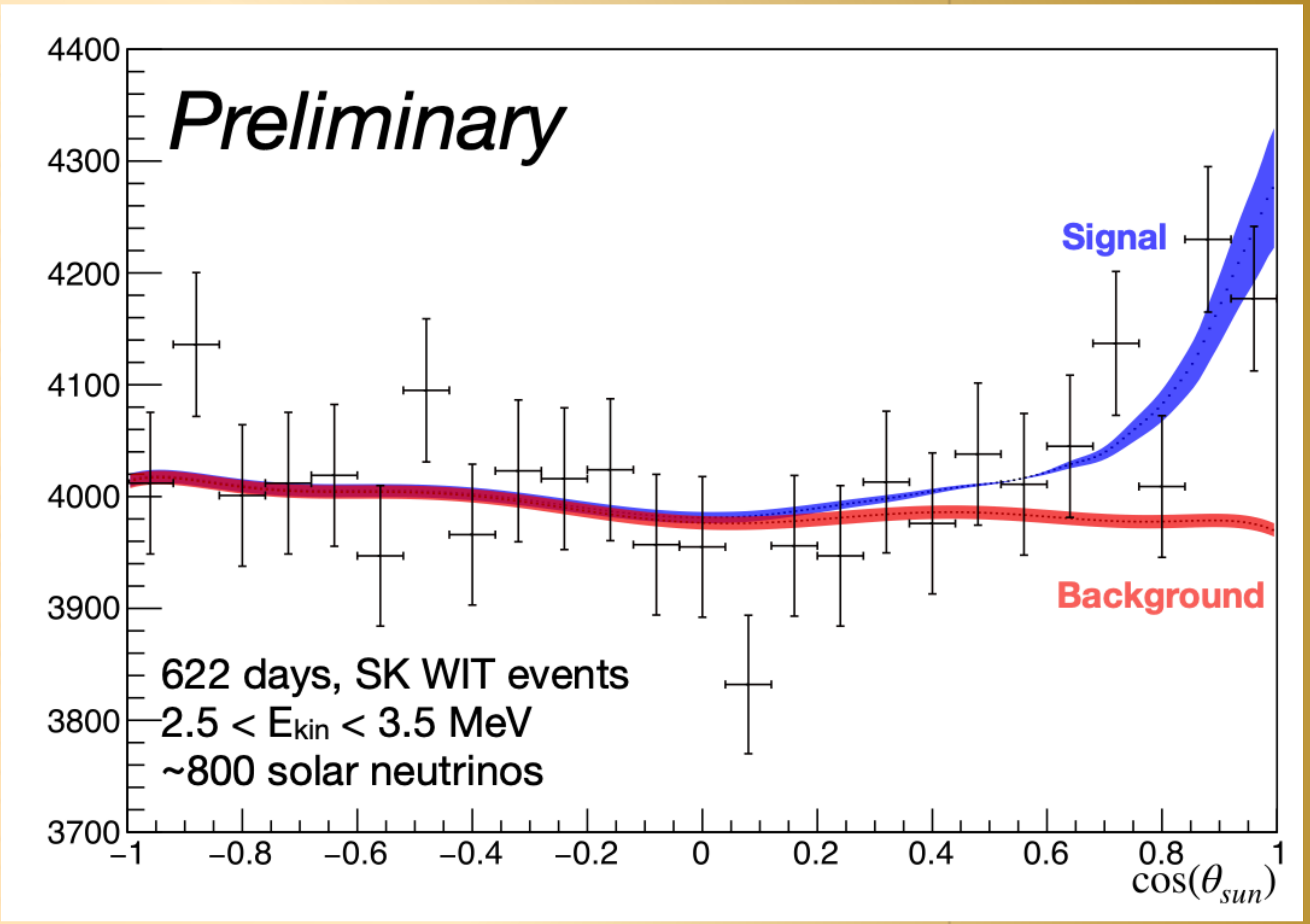

- SK measurement of solar neutrinos
  - Detecting recoil electron from elastic scattering
  - Robust signal extraction using angular correlation with the Sun
- Total # of observed solar $\nu$ events >$10^5$ in phases SK-I~IV (5805 days)
  - Energy spectrum slightly favours "up-turn", more data needed



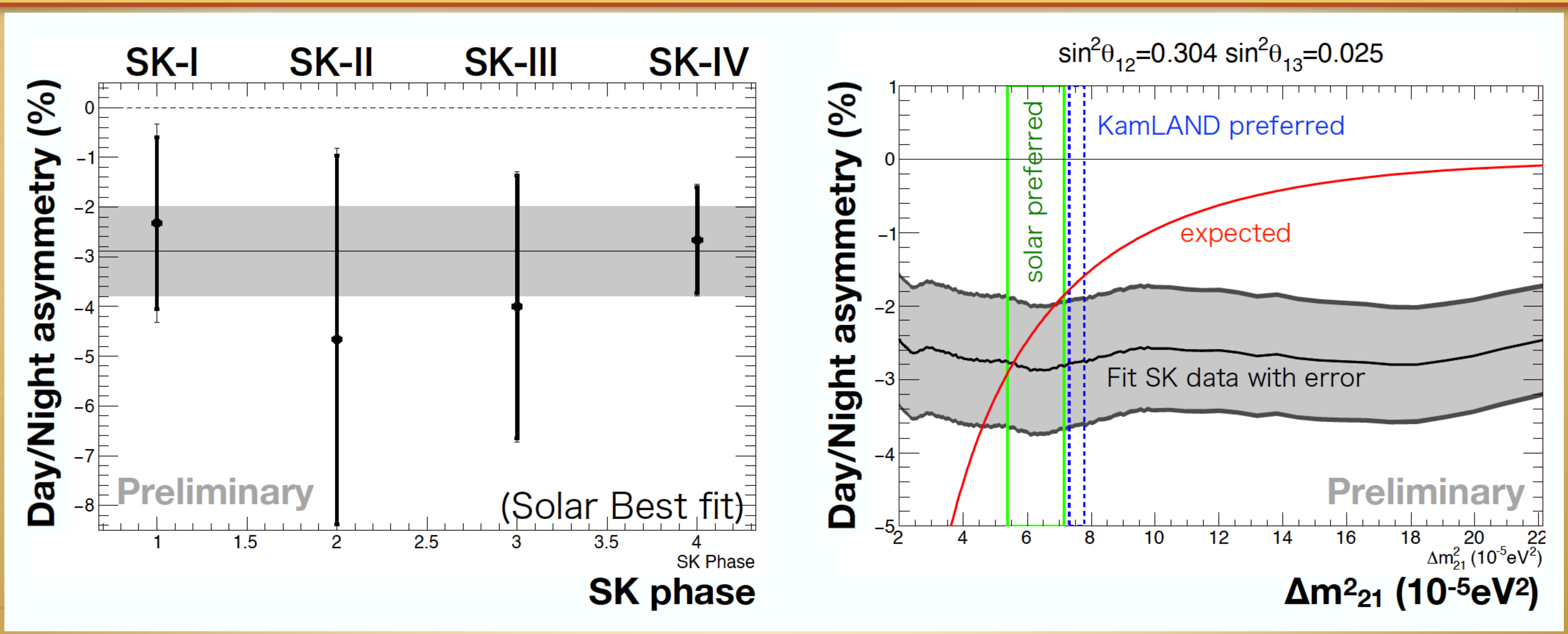
# Solar $\nu$ searches at SK - lowering neutrino energy thresholds

- Need to **lower current SK solar neutrino energy threshold** to observe transition between matter and vacuum oscillations in solar neutrinos. Background-limited
  - **Recoil electron kinetic energy 2.49MeV**
  - Dedicated hardware (WIT) searches un-triggered data for low-energy events & fits for fiducial vertex in real-time
  - Solar neutrino identification down to 2.5 MeV recoil energy using BDT & WIT data



# Day/Night asymmetry at SK

- Day/Night flux asymmetry: $A_{D/N} = \frac{\Phi_{day} - \Phi_{night}}{0.5(\Phi_{day} + \Phi_{night})}$
  - Expected D/N asymmetry ~3% in the SK energy range for solar neutrinos
- Sk confirmed a higher solar $\nu$ flux at the night that that at daytime with significance 3.2$\sigma$ for the Solar best fit case, 3.1$\sigma$ for the Global best fit case

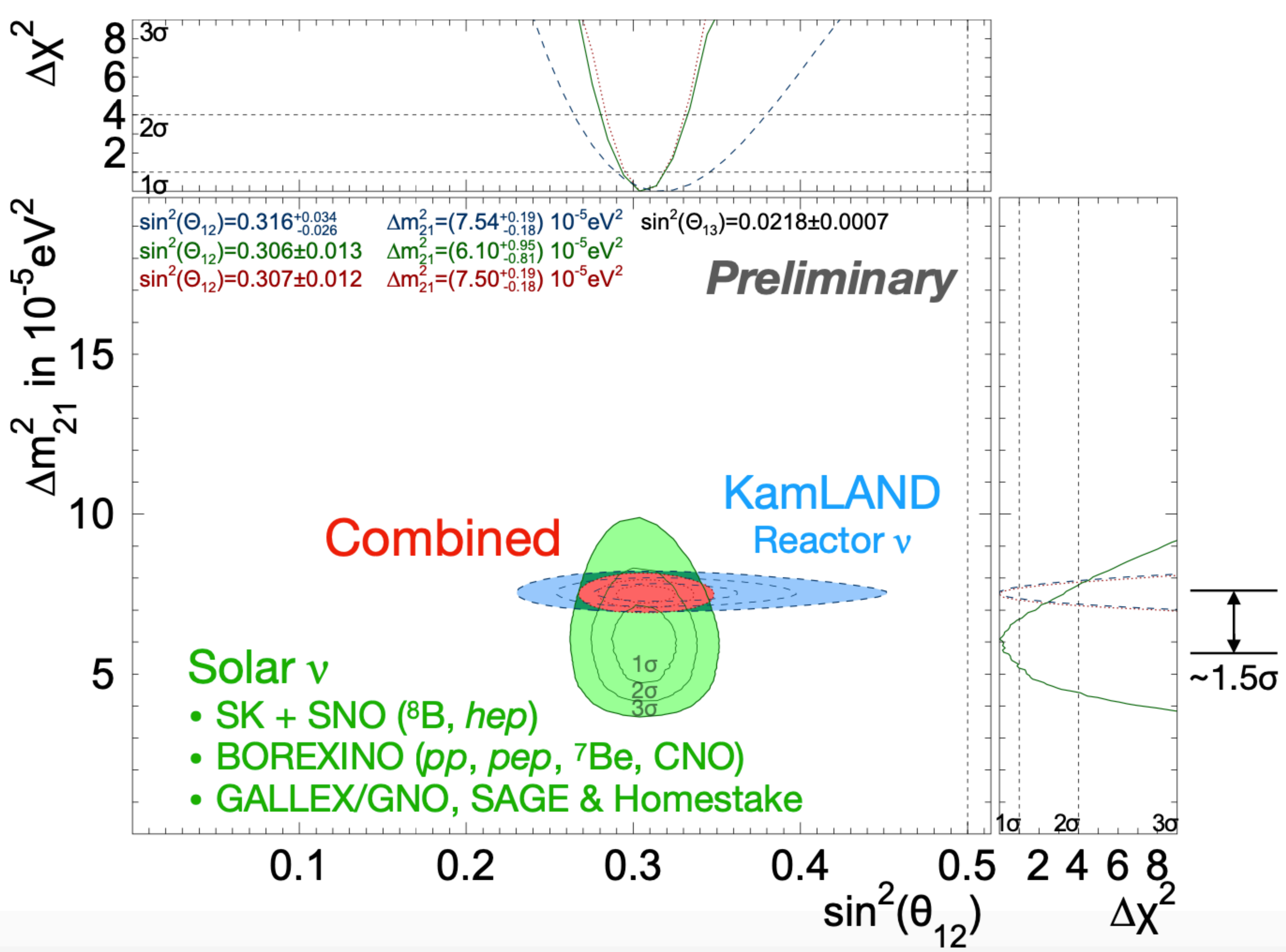


# Solar $\nu$ oscillation parameters

- There is 1.5$\sigma$ tension between SK+SNO and KamLAND in $\Delta m^2_{21}$

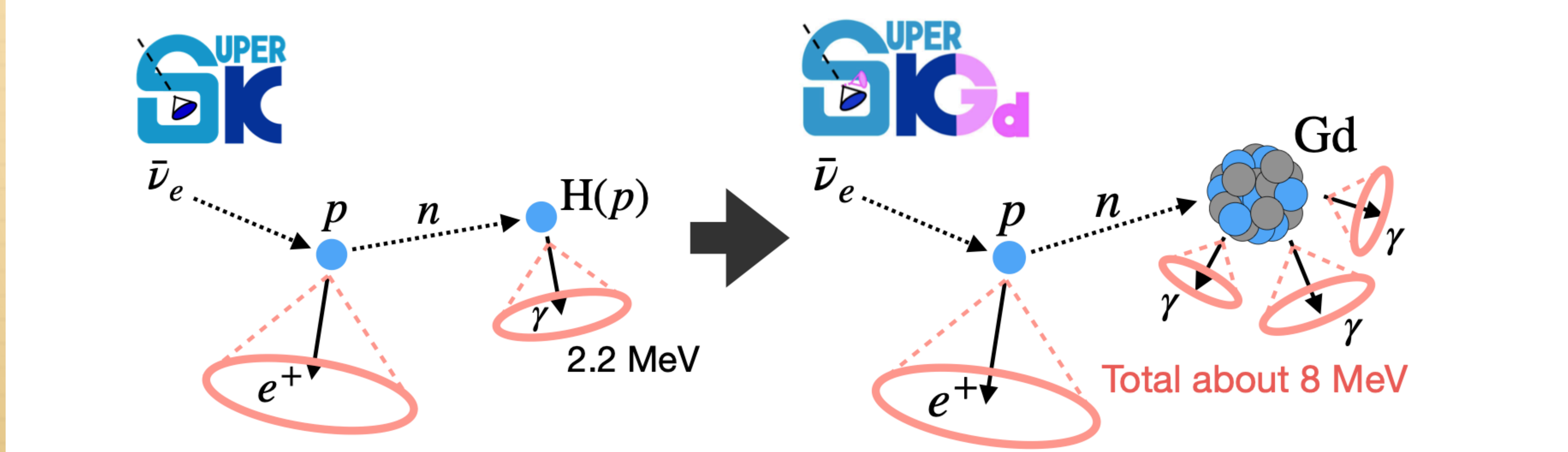
**Best fit oscillation parameters**

| Experiment | $\sin^2\theta_{12}$ | $\Delta m^2_{21}$ |
|---|---|---|
| KamLAND | $0.316^{+0.034}_{-0.026}$ | $7.54^{+0.19}_{-0.18}\times10^{-5}$ eV$^2$ |
| SK + SNO | $0.305\pm0.014$ | $6.10^{+1.04}_{-0.75}\times10^{-5}$ eV$^2$ |
| Combined | $0.305^{+0.013}_{-0.012}$ | $7.49^{+0.19}_{-0.17}\times10^{-5}$ eV$^2$ |



# SK-Gd era

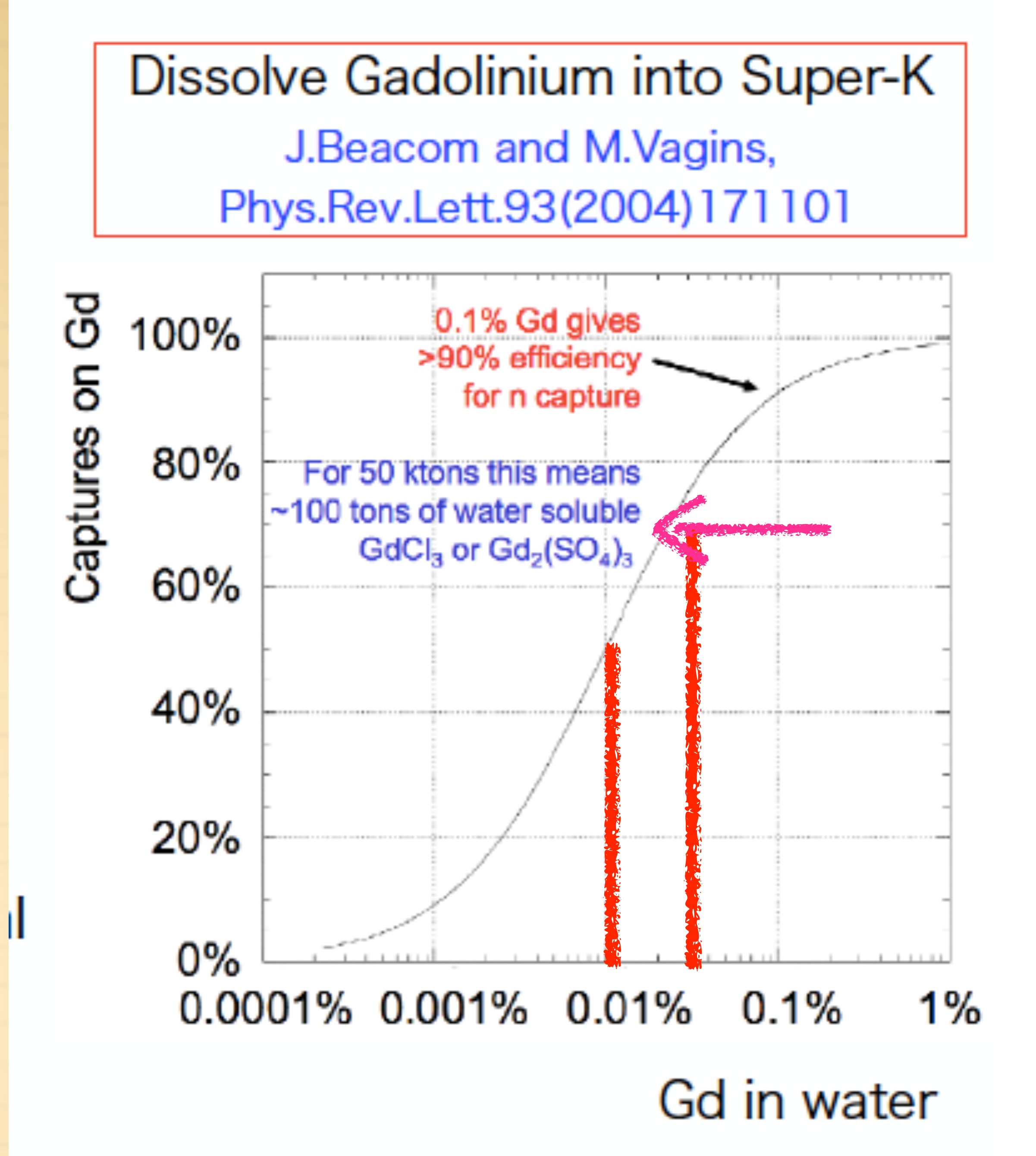
## Gadolinium project at Super-K: SK-Gd

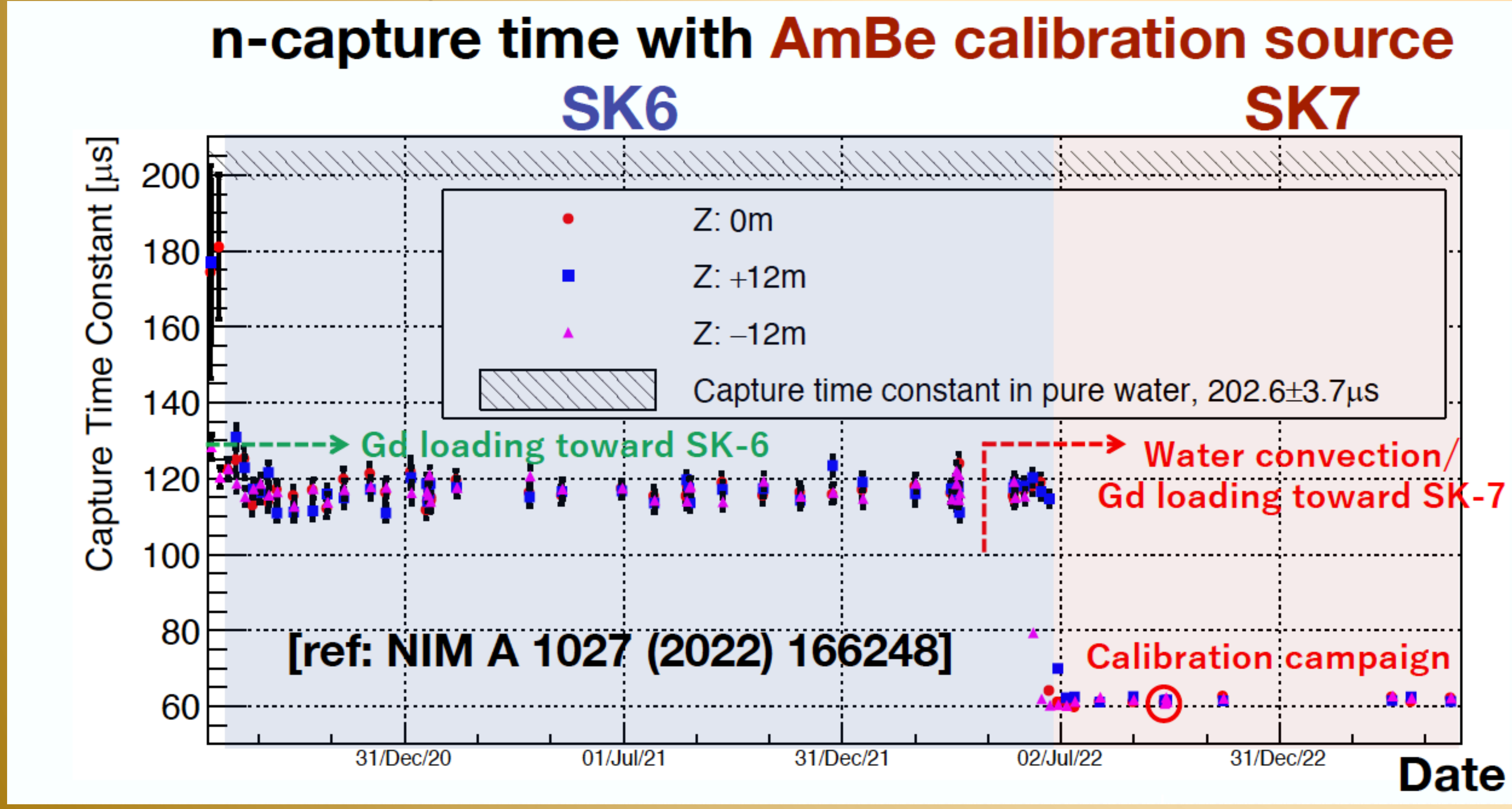


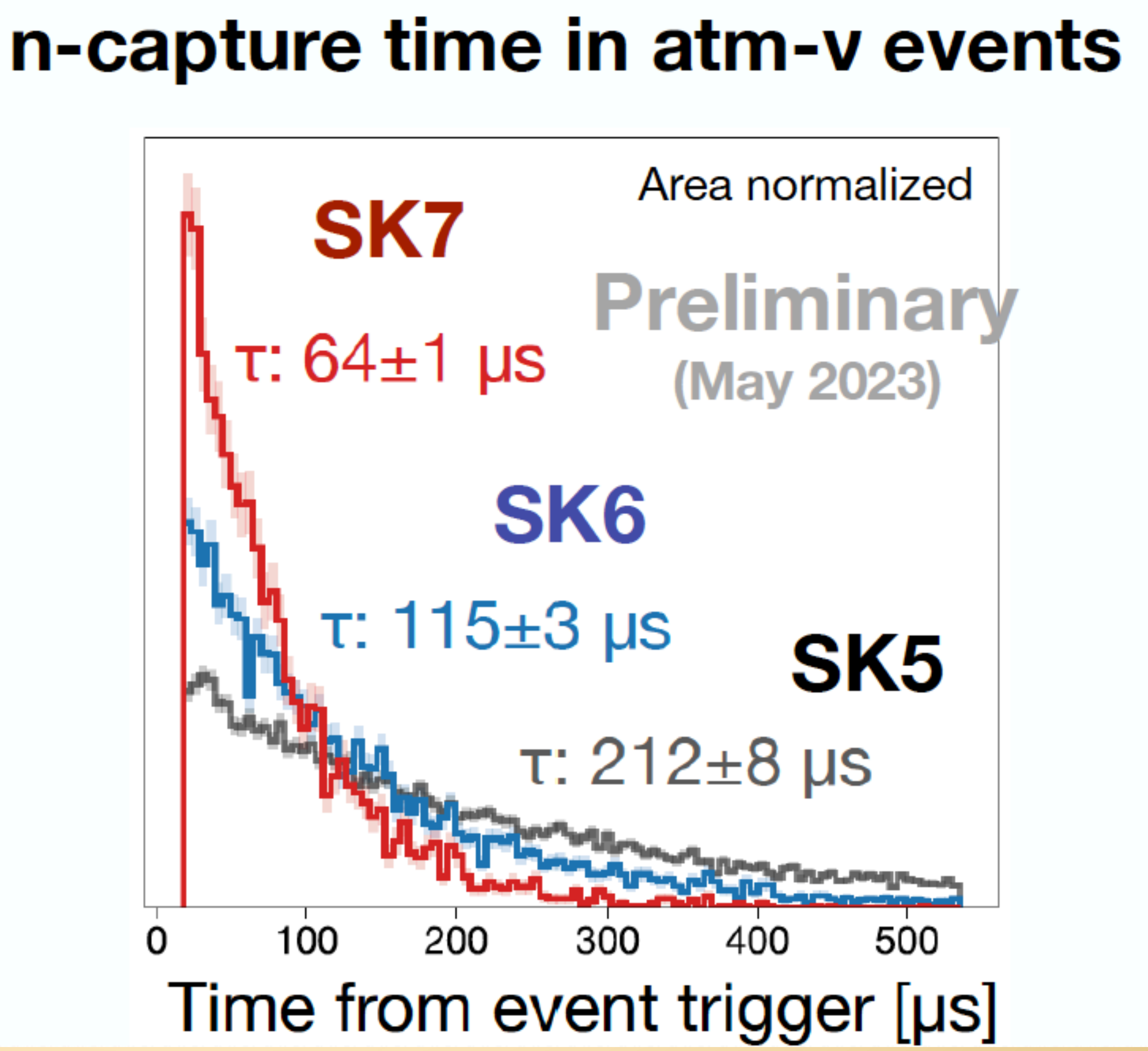

e.g. Inverse-beta decay: IBD

# Why Gd salt was added ?

- SK-Gd: add Gd sulphate to ultra pure water to enhance neutron tagging efficiency
- Physics targets:
  - Detect the world's first Diffuse Supernova Neutrino Background (DSNB)
  - Improvement of supernova direction pointing accuracy and allowing pre-supernova neutrino detection (early warning for SN).
  - Enhance ν and $\bar{\nu}$ identification in atmospheric ν and T2K analyses
  - Reduce background in nucleon decay search
- Observed clear increase of neutron candidates and shorter capture time
- Confirmed uniformity of Gd concentration over SK detector and its stability over time



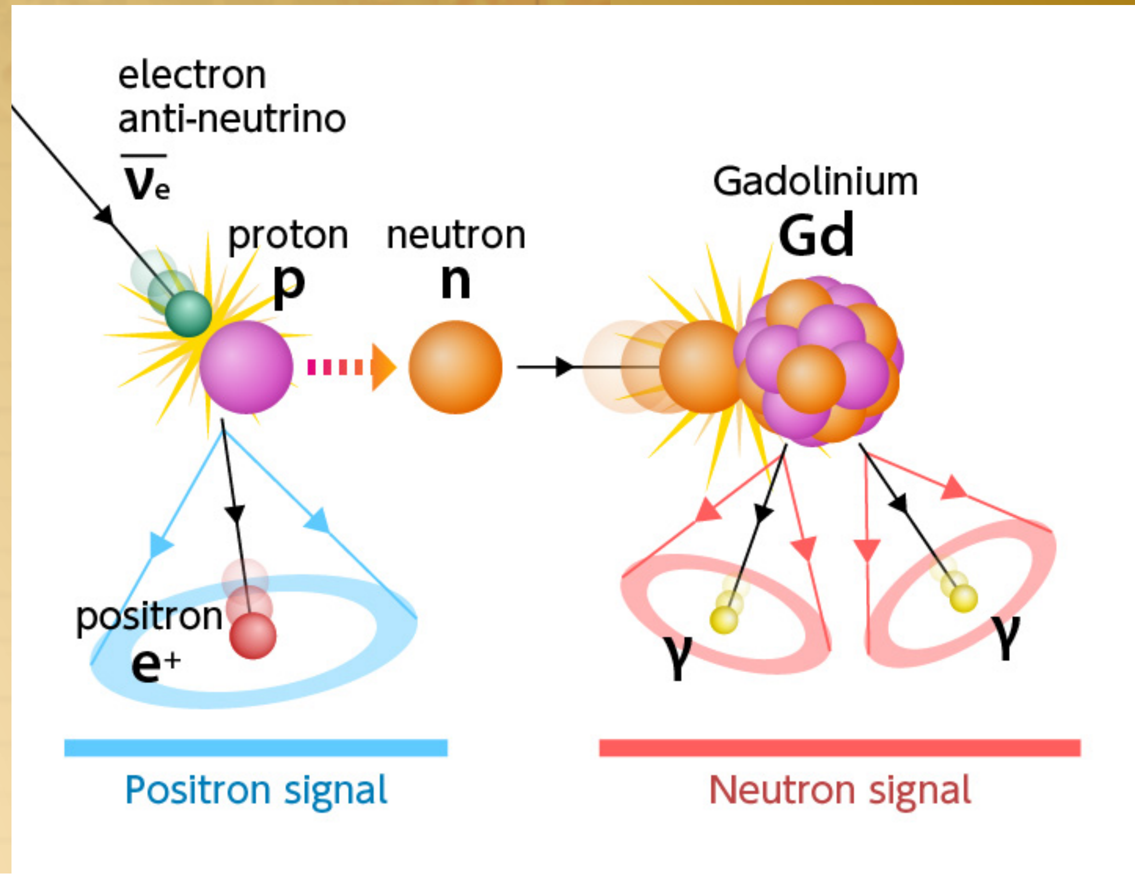



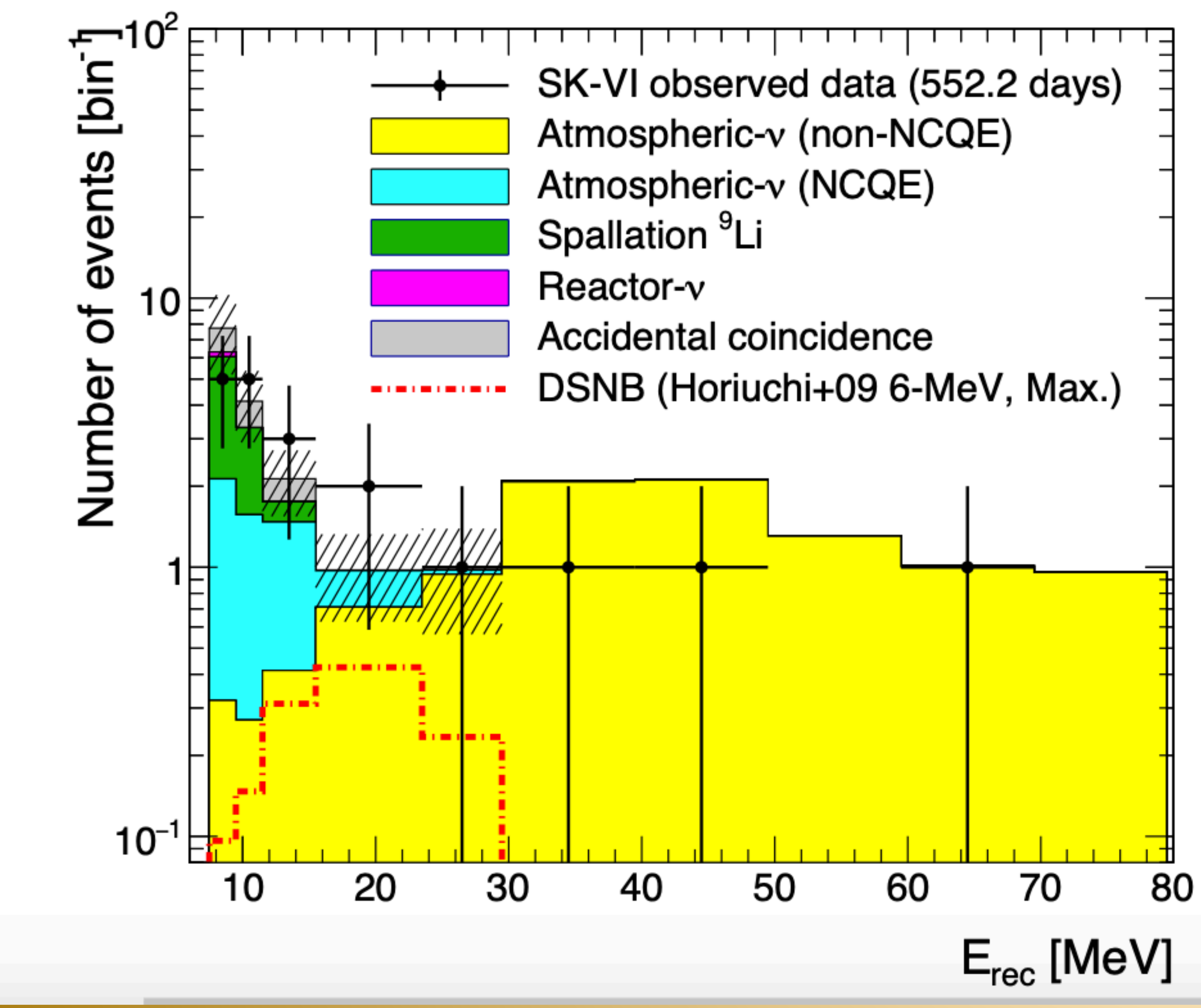

We have finished Gd loading on July 25th!! 2022
SK-VII era is now on

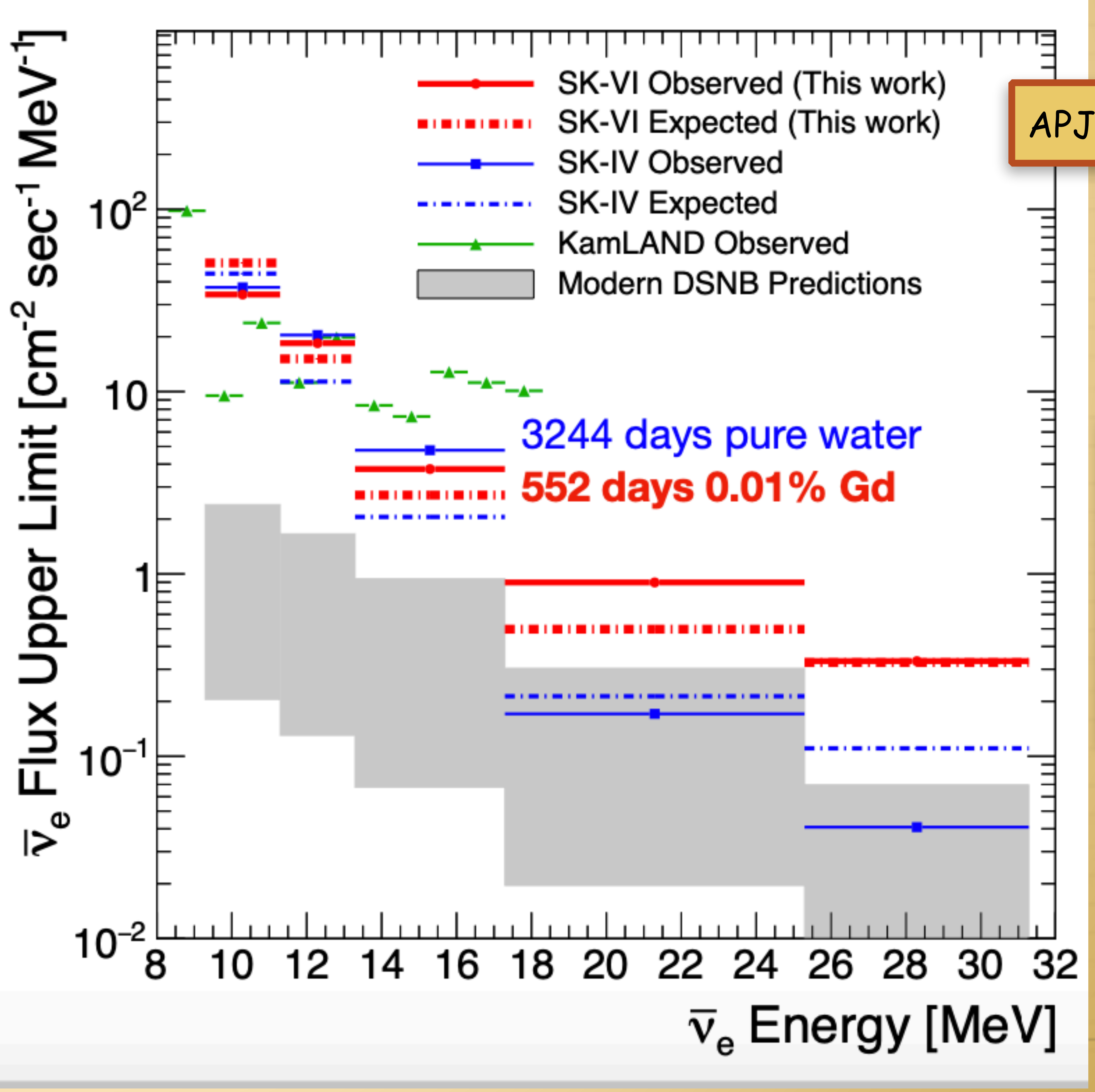
# SK-GD DSNB analysis

**Diffuse Supernova Neutrino Background (DSNB)** Integrated flux of the neutrinos emitted from past all Supernovae:

- Not-yet observed neutrino source expected from all past supernova
- ~7.5–30 MeV IBD signal window avoids reactor neutrinos & atmospheric background
- 0.01% SK-Gd data analysed: Sensitivity is close to theoretical predictions, competitive with pure water phases




APJ LETT 951:L27

See the dedicated talk on this conference from Masayuki Harada

# Summary

**Atmospheric neutrinos:**

- Analysed all pure water data sets (SK-I ~V) and with expanded fiducial volume (total 27.2kton) and using information on neutron tagging on hydrogen - new paper in preparation
- New results of the SK+T2K joint fit
- New results on $\nu_\tau$ appearance searches

**Solar neutrinos:**

- Global analysis including SK I-IV is compatible with KamLAND
- Lowering the energy threshold to 2.49MeV (kinetic energy) aiming to see the "up-turn"

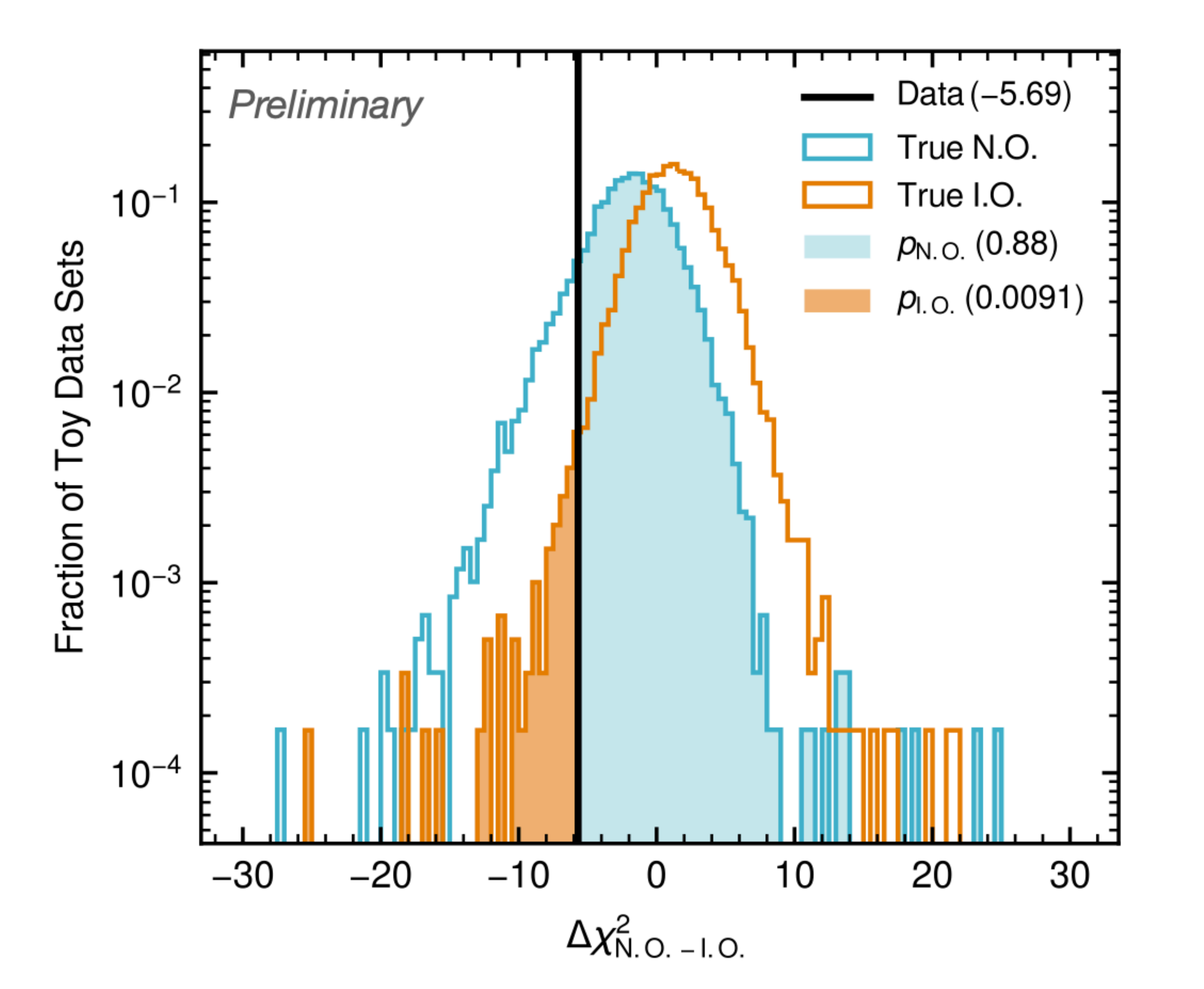
**SK- Gd:**

- Neutron tagging is working, observing many more captures
- First DSNB search in SK-Gd was performed using the data from Aug. 2020 to Jun. 2022. No significant excess over expected background was seen


Thank you!

Photo Credit: Piotr Mijakowski

# Mass ordering significance




- Generate toy data sets to obtain distribution of $\Delta\chi^2_{NO-IO}$
- SK data fit result has lower probability of occurring for a true inverted ordering than normal, but is also more extreme than normal ordering median (exceeds sensitivity)
- Compute CLS statistic to correct probability of rejecting the inverted ordering given simultaneous agreement with normal ordering:

$$\mathrm{CL}_S = \frac{p_{\mathrm{IO}}}{1 - p_{\mathrm{NO}}} \approx 0.077$$

*Reject inverted ordering at the ~92% confidence level.*