Recent results from the joint oscillation analyses and diffuse supernova neutrino background searches at Super-Kamiokande

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Joint neutrino oscillation analyses: Atmospheric +Accelerator neutrinos

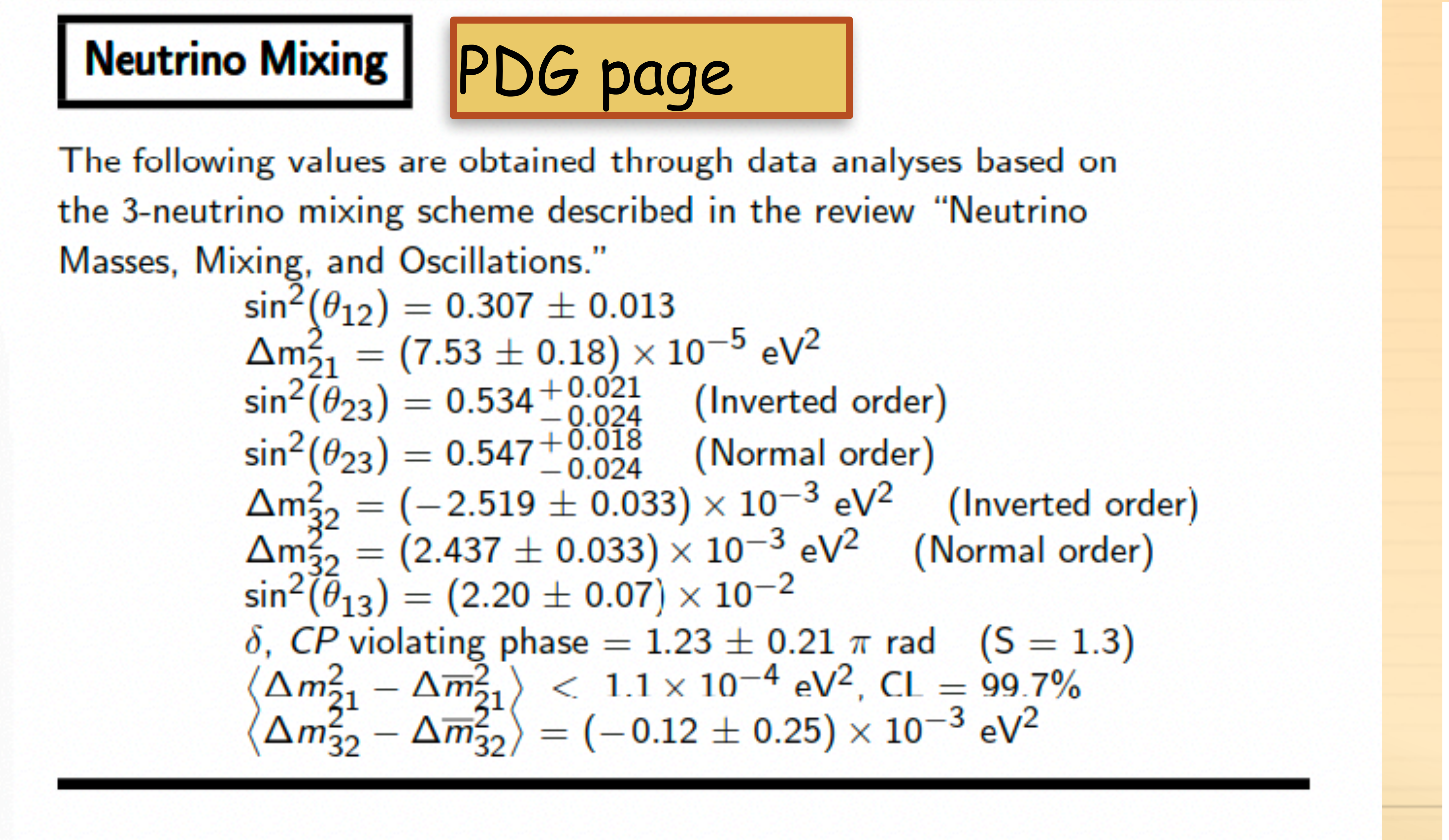
Neutrino oscillations- current picture

Pontecorvo - Maki - Nakagawa - Sakata (PMNS) matrix for 3 flavour neutrino oscillations

Flavor states | Atmospheric/Accelerator | Reactor/Accelerator | Solar | Mass states

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

where $c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$



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Neutrino Mixing

The following values are obtained through data analyses based on the 3-neutrino mixing scheme described in the review "Neutrino Masses, Mixing, and Oscillations."

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2

$\sin^2(\theta_{23}) = 0.534^{+0.021}_{-0.024}$ (Inverted order)

$\sin^2(\theta_{23}) = 0.547^{+0.018}_{-0.024}$ (Normal order)

$\Delta m^2_{32} = (-2.519 \pm 0.033) \times 10^{-3}$ eV^2 (Inverted order)

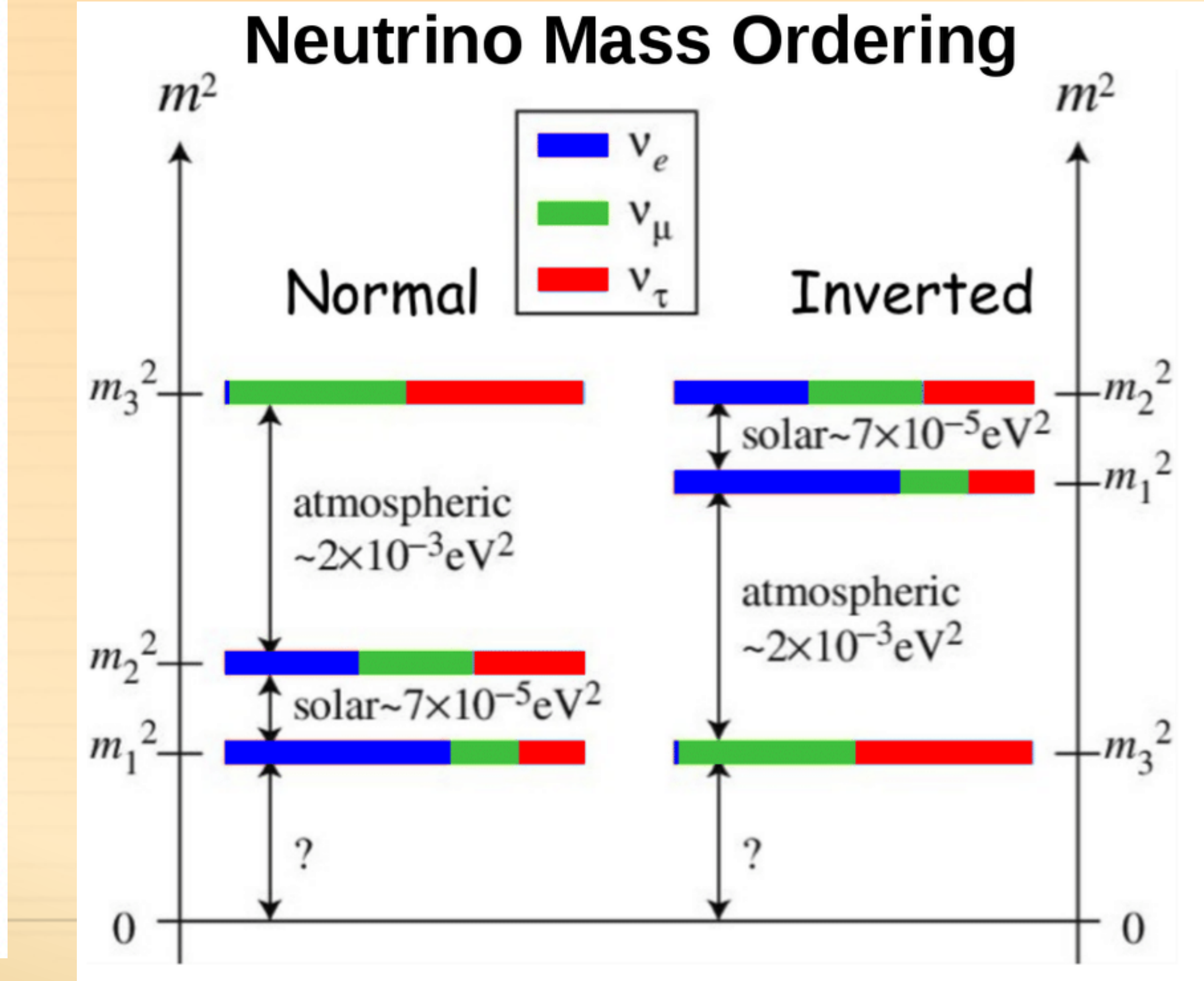
$\Delta m^2_{32} = (2.437 \pm 0.033) \times 10^{-3}$ eV^2 (Normal order)

$\sin^2(\theta_{13}) = (2.20 \pm 0.07) \times 10^{-2}$

δ, CP violating phase $= 1.23 \pm 0.21\ \pi$ rad (S = 1.3)

$\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle < 1.1 \times 10^{-4}$ eV^2, CL = 99.7%

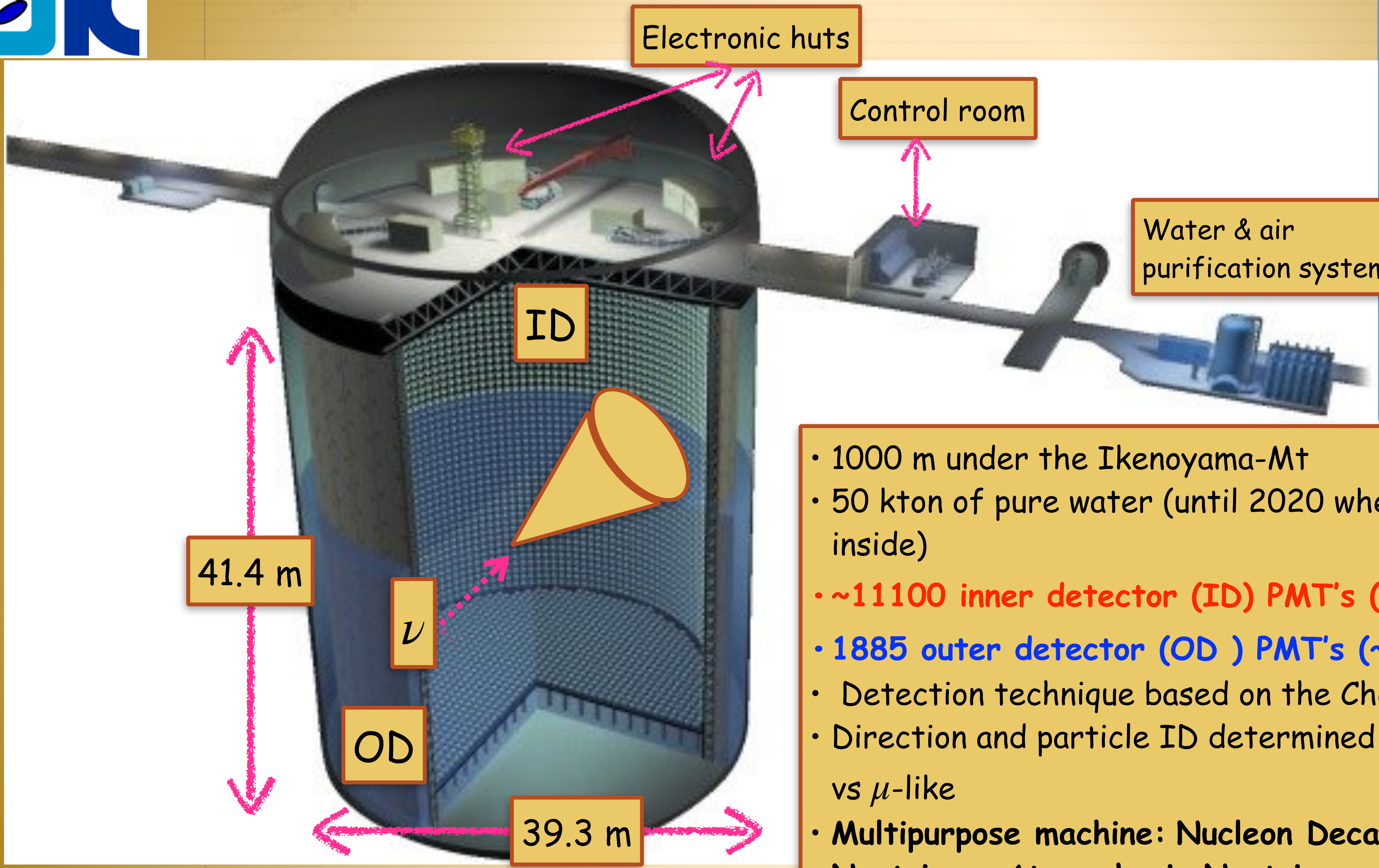
$\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle = (-0.12 \pm 0.25) \times 10^{-3}$ eV^2



Remaining questions:

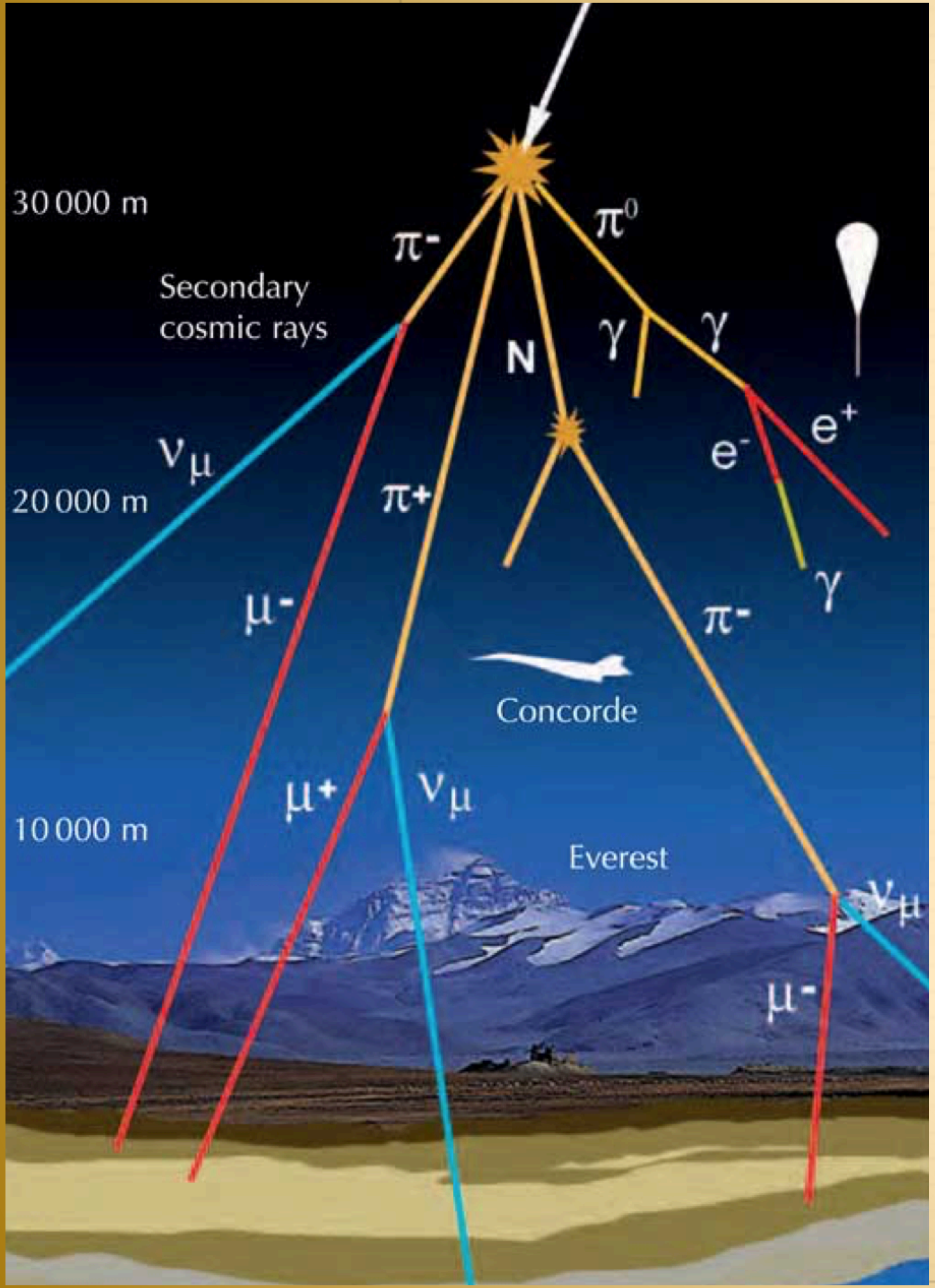
- Mass ordering ?
- Value of δ_{CP}, is it conserved or violated ?
- Octant of θ_{23}: smaller or larger ?

The Super-Kamiokande experiment

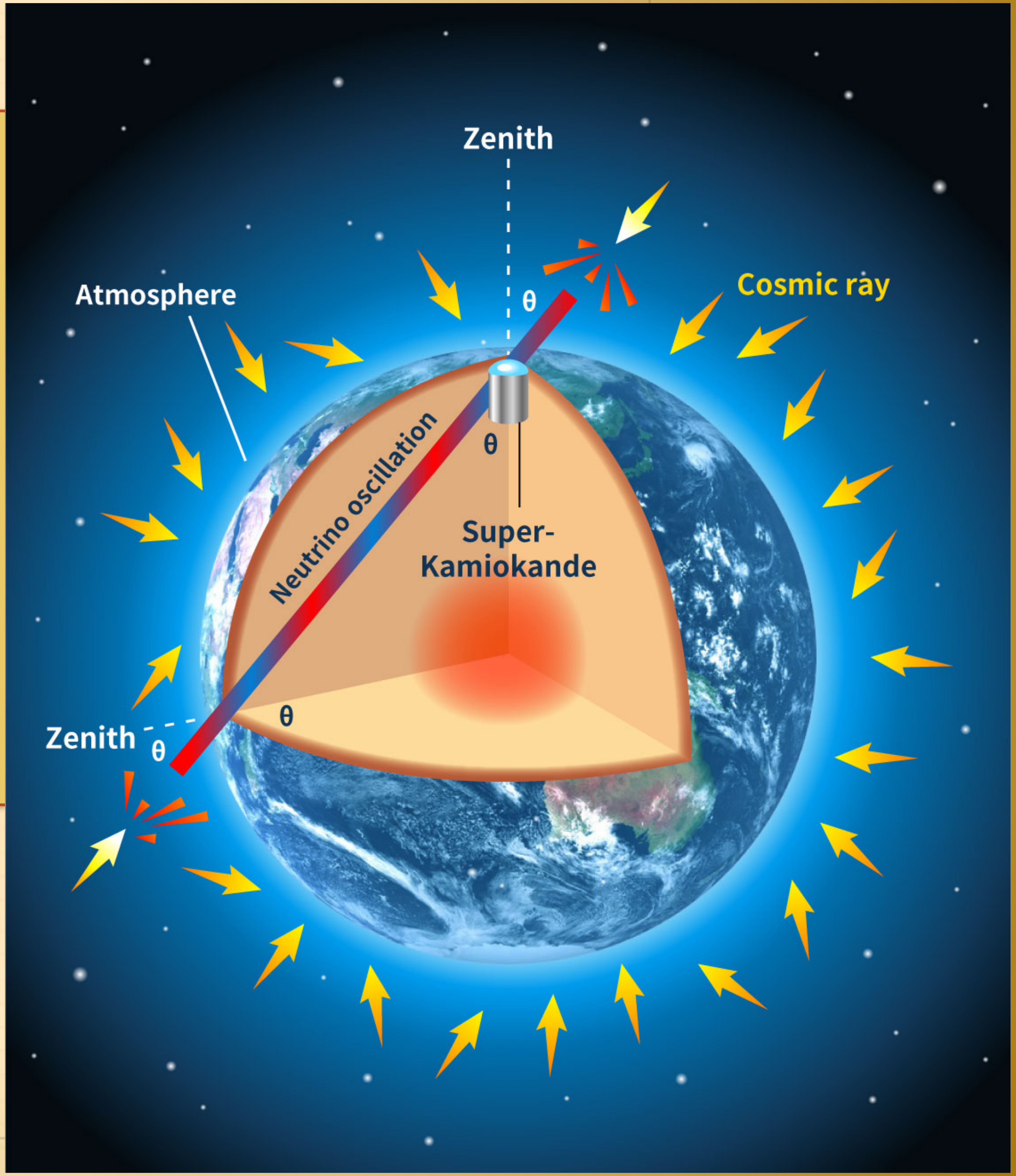


- 1000 m under the Ikenoyama-Mt
- 50 kton of pure water (until 2020 when Gd sulfate was added inside)
- **~11100 inner detector (ID) PMT's (~50cm ϕ)**
- **1885 outer detector (OD) PMT's (~20cm ϕ)**
- Detection technique based on the Cherenkov radiation
- Direction and particle ID determined from the ring pattern: e-like vs μ-like
- **Multipurpose machine: Nucleon Decay, Solar and Supernova Neutrinos, Atmospheric Neutrinos, Far detector for T2K**

Atmospheric neutrinos



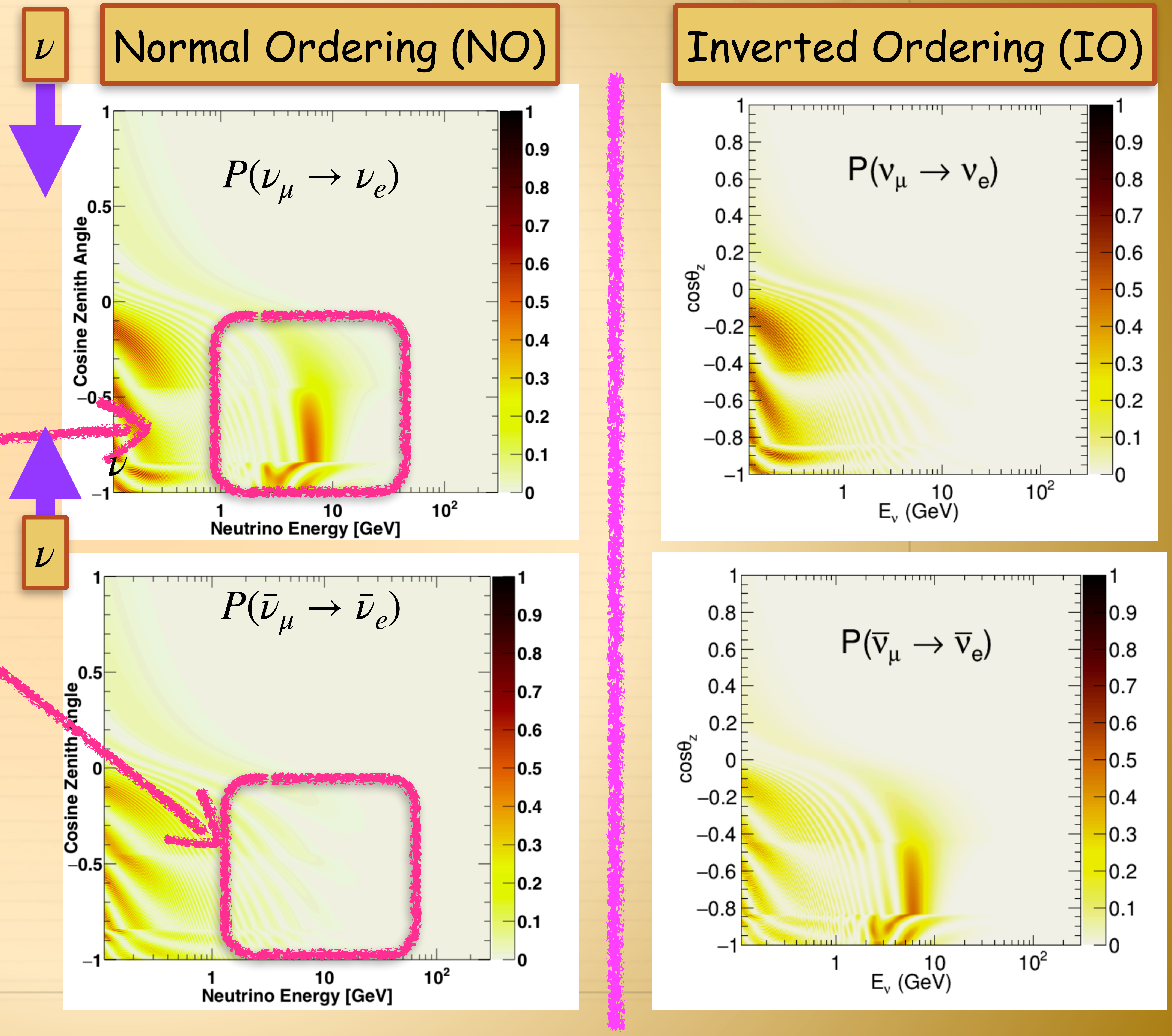
- Neutrinos are produced when cosmic particles, mainly protons, interact with the nuclei in the atmosphere:
  - with wide range of energy MeV- TeV produced isotropically about the Earth atmosphere
  - travel length varies 10km ~13000 km



Atmospheric neutrino oscillations

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

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

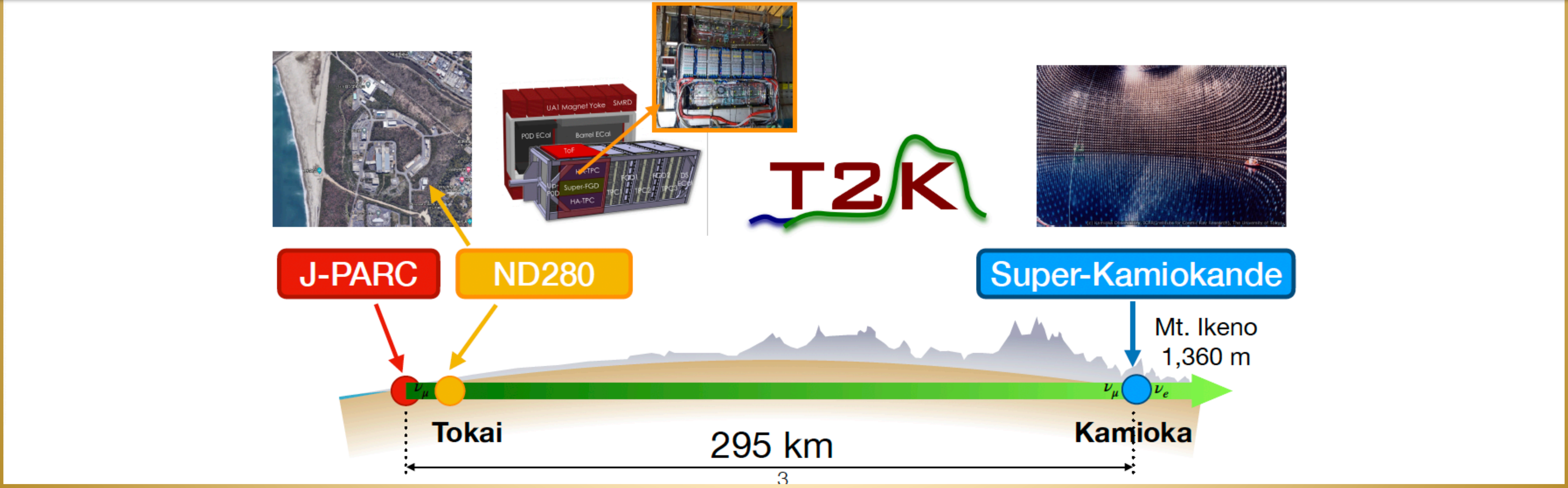


☆ Oscillograms plotted with: $\Delta m^2_{21} = 7.7 \times 10^{-5} \text{eV}^2$, $\sin^2\theta_{23} = 0.50$, $\sin^2\theta_{12} = 0.30$, $\sin^2\theta_{13} = 0.0219$ and $\delta_{CP} = 0$

☆ Phys. Rev. D. 97 072001

T2K experiment

- ν_μ **and** $\bar{\nu}_\mu$ **neutrino beam** produced at the Japan Proton Accelerator Research Complex in Tokai (J-PARC) with average mean energy $E_\nu \simeq 0.6$ **GeV**
- Neutrinos detected at the near detectors and far detector Super-Kamiokande
- **Searches of:**
  - $P(\nu_\mu \to \nu_e)$ **and** $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ **- appearance channel**
  - $P(\nu_\mu \to \nu_\mu)$ **and** $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ **- disappearance channel**



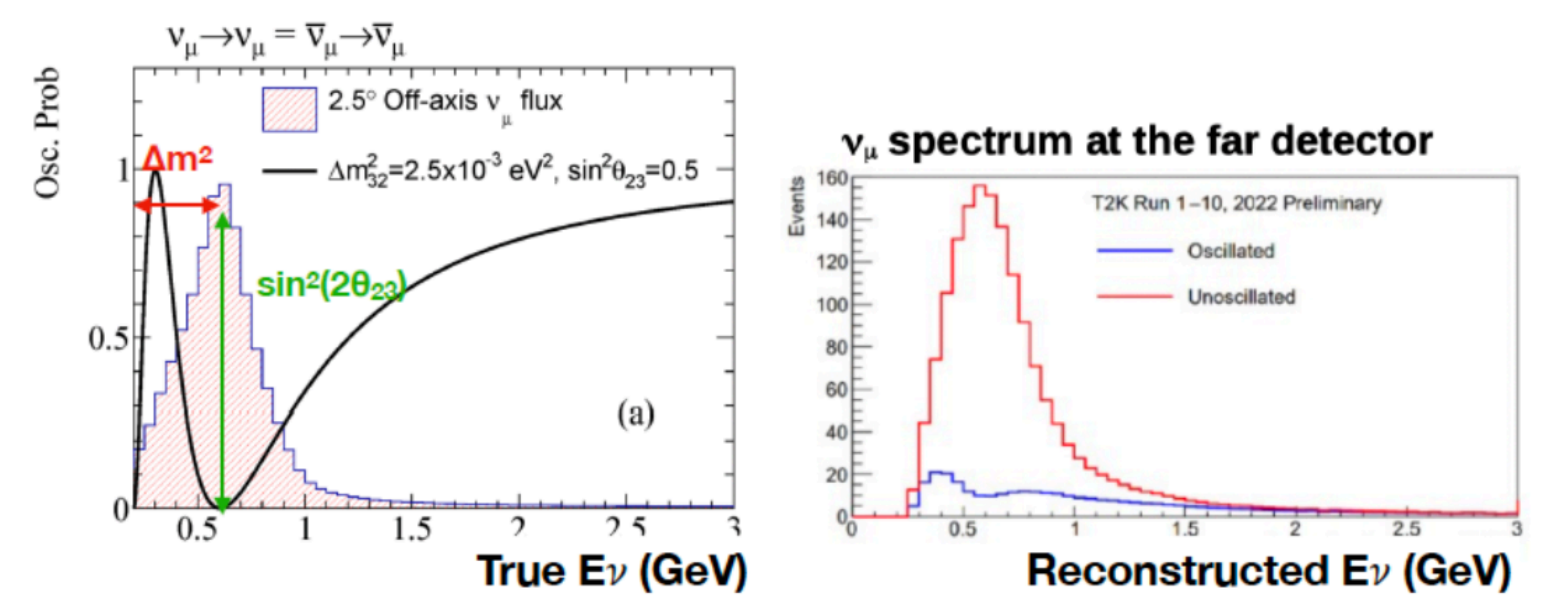
T2K experiment -physics case

$P(\nu_\mu \to \nu_\mu)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

- disappearance channel

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\frac{\Delta m^2_{32}L}{E_\nu})$$

- Same oscillation probability for ν and $\bar{\nu}$
- Sensitive to $|\Delta m^2_{32}|$ **and to** $\sin^2(2\theta_{23})$ - > **no sensitivity to mass ordering and** δ_{CP}



$P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

- appearance channel

$a = \Delta^2_{21}/\Delta^2_{31} \sim 1/30$

$J_0 = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13}$

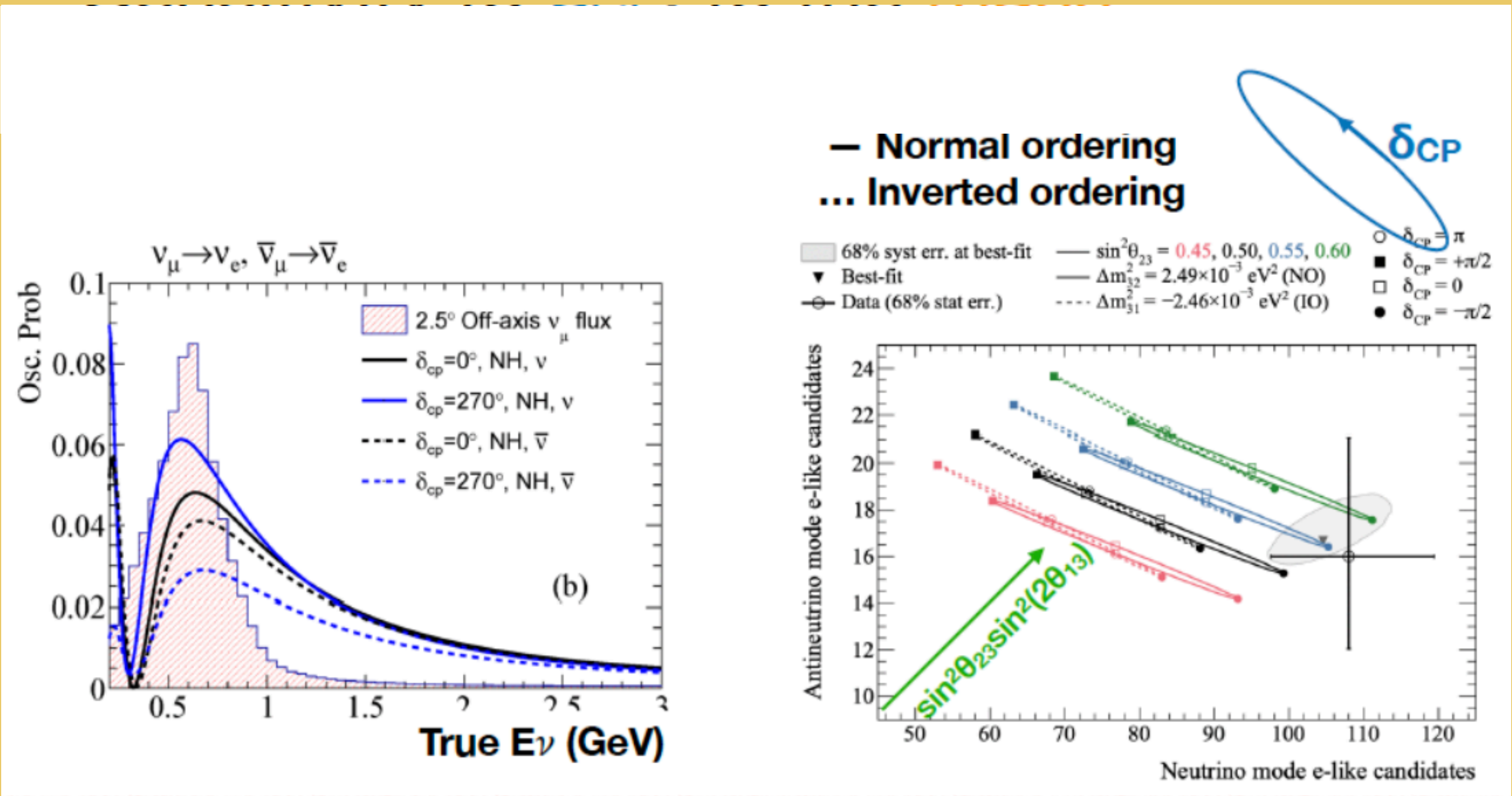
$A = (\mp)2\sqrt{2}G_F n_e E/\Delta m^2_{31}$

$$P(\overline{\nu_\mu} \to \overline{\nu_\mu}) = \simeq \sin^2(2\theta_{23})\frac{\sin^2(2\theta_{13})}{(A-1)^2}\sin^2[(A-1)\Delta_{31}$$

$$(\mp)a\frac{J_0 \sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}]$$

$$+a\frac{J_0 \cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] + O(a^2)$$

- Sensitive to δ_{CP} and **the mass ordering** and **octant of** θ_{23}



SK+T2K - motivation for join fit

Atmospheric Neutrinos @ Super-Kamiokande

- ☆Thanks to resonance effect in Earth mantle and core which appears for normal mass ordering (NO) and transition of $\nu_\mu \rightarrow \nu_e$ in energy range 2-10 GeV and it is not happening for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ for NO.
- ☆**Super-K atmospheric neutrinos are sensitive to mass ordering: normal (NO) vs inverted (IO).**

Beam Neutrinos @ T2K

- ☆T2K has **better sensitivity to δ_{CP}** from ν_e appearance channel and Δm^2_{32} and $\sin^2(2\theta_{23})$ from ν_μ disappearance channel
- ☆In T2K δ_{CP} and mass ordering **have similar effect on $\nu_e/\bar{\nu}_e$ event rates** (so called degeneracy of the oscillation parameters)

SK+T2K - motivation for join fit

Atmospheric Neutrinos @ Super-Kamiokande

☆Thanks to resonance effe
which appears for normal
transition of $\nu_\mu \rightarrow \nu_e$ in e
not happening for $\bar{\nu}_\mu \rightarrow$

☆**Super-K atmospheric r**
mass ordering: normal (

Beam Neutrinos @ T2K

☆T2K has **better sensitivity to** δ_{CP} from ν_e
d $\sin^2(2\theta_{23})$ from ν_μ

ave similar effect
degeneracy of the

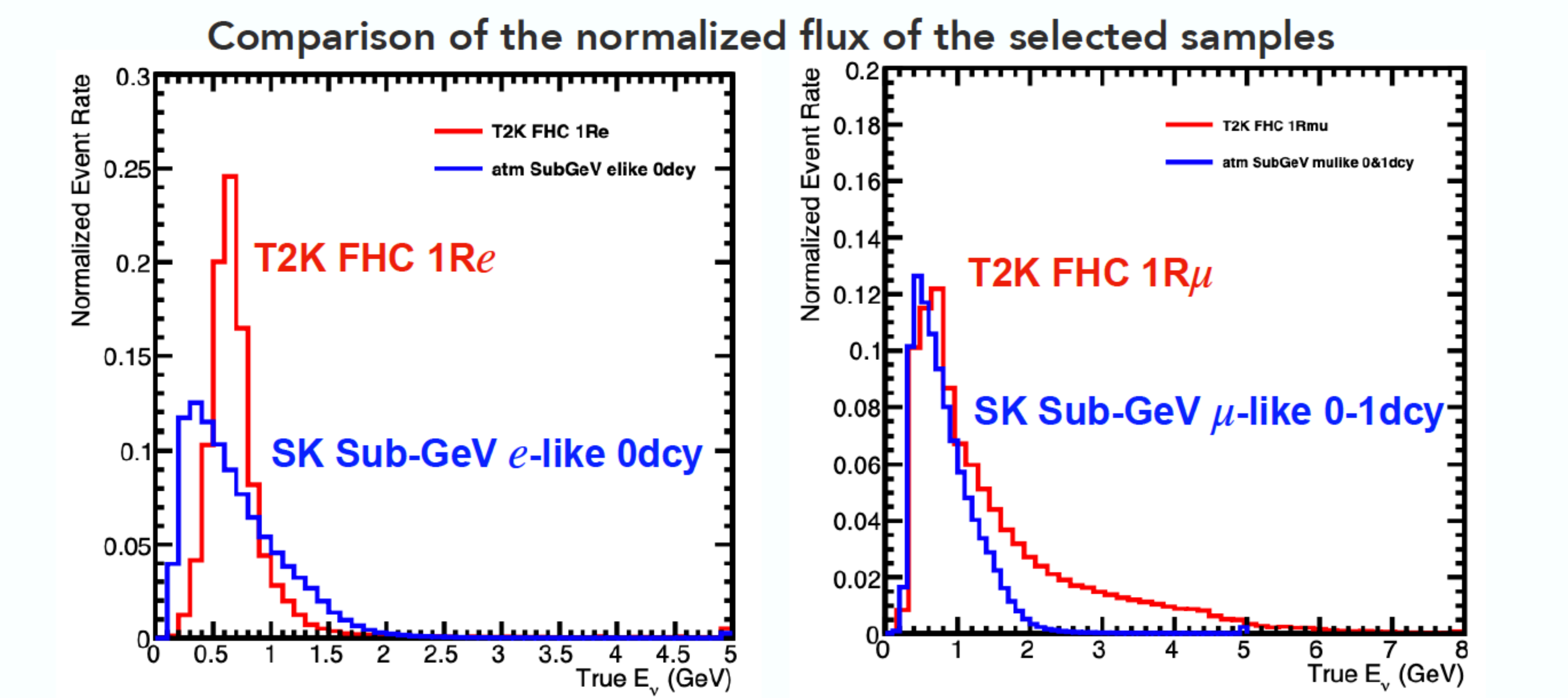
The both data sets use the SAME DETECTOR SUPER-KAMIOKANDE

SK +T2K joint fit analysis

- 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

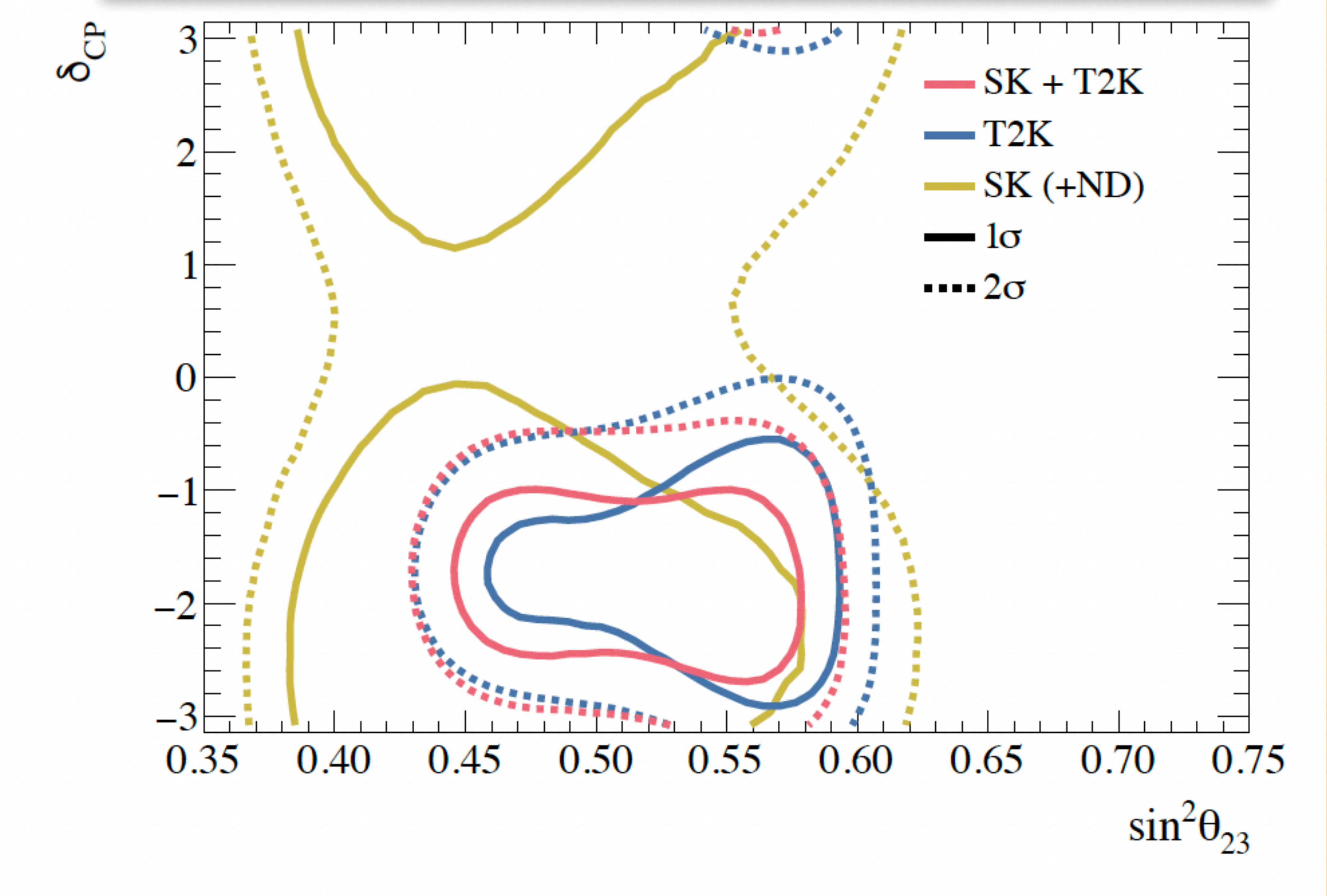
Phys.Rev.Lett. 134 (2025)

- SK4 data - 3244 days (2008-2018) - PTEP, 5, 053F01, (2019)
- T2K data published in Phys. Rev. D 108, 7, 072011, (2023)
- Future updates will include full SK atm statistics at least 50% more data and more data from T2K


Comparison of the normalized flux of the selected samples

SK +T2K joint fit results

Phys.Rev.Lett. 134 (2025)



- The $(\sin^2\theta_{23}, \delta_{CP})$ credible regions obtained with the SK, T2K, and combined **(SK+T2K)** dataset
- Reactor experiment measurements of θ_{13} using $\bar{\nu}_e$ disappearance, $\sin^2(2\theta_{13}) = 0.0853 \pm 0.0027$ are used as an external constraint.

These results show:

- an exclusion of the CP-conserving value of the Jarlskog invariant with a significance between. 1.9σ and 2.0σ,
- a limited preference for the normal ordering with 1.2σ exclusion of the inverted ordering,
- and no strong preference for the θ_{23} octant.

SK-Gd era

Diffuse supernova neutrino background (DSNB) searches at Super-Kamiokande

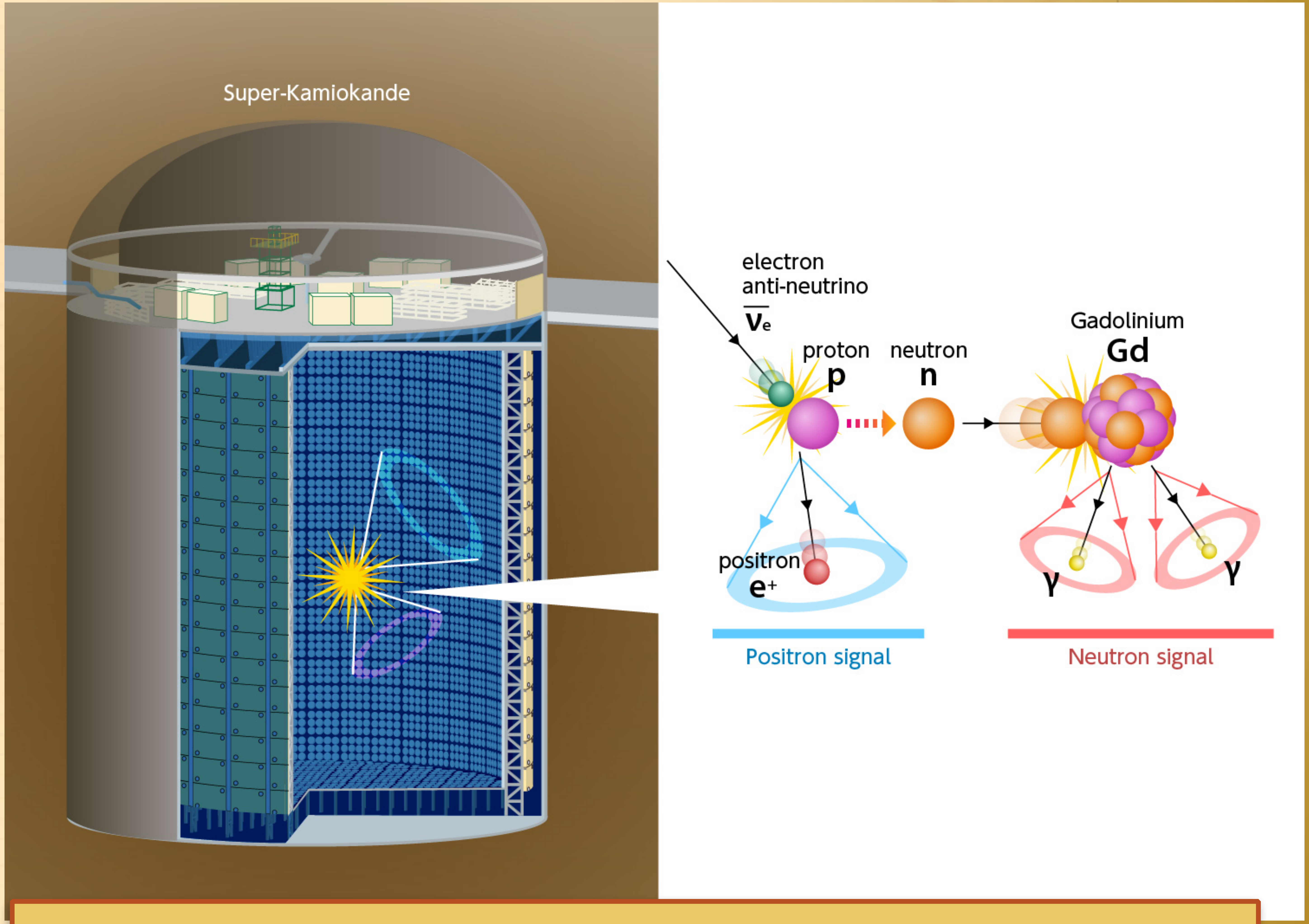
How can we detect DSNB @ SK ?

- Diffuse Supernova Neutrino Background (DSNB) - **"Relic" neutrinos** from past all distant Core-Collapse Supernova (CCSN)

- Detection channel :
  - **Inverse beta decay (IBD):**

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

  - Large cross-section in DSNB energy region
  - Simple topology with one e+ and n
  - Coincidence detection reduces enormous background
  - **Expected event rate: 0.13 event / kton/yr**



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

How can we detect DSNB @ SK ?

- Gd-loaded water @ SK with neutron tagging (2020-present): >956 days (SK-VI, VII)

- Detection channel :
  - **Inverse beta decay (IBD):**

    $\bar{\nu}_e + p \rightarrow n + e^+$
  - Large cross-section in DSNB energy region
  - Simple topology with one e+ and n
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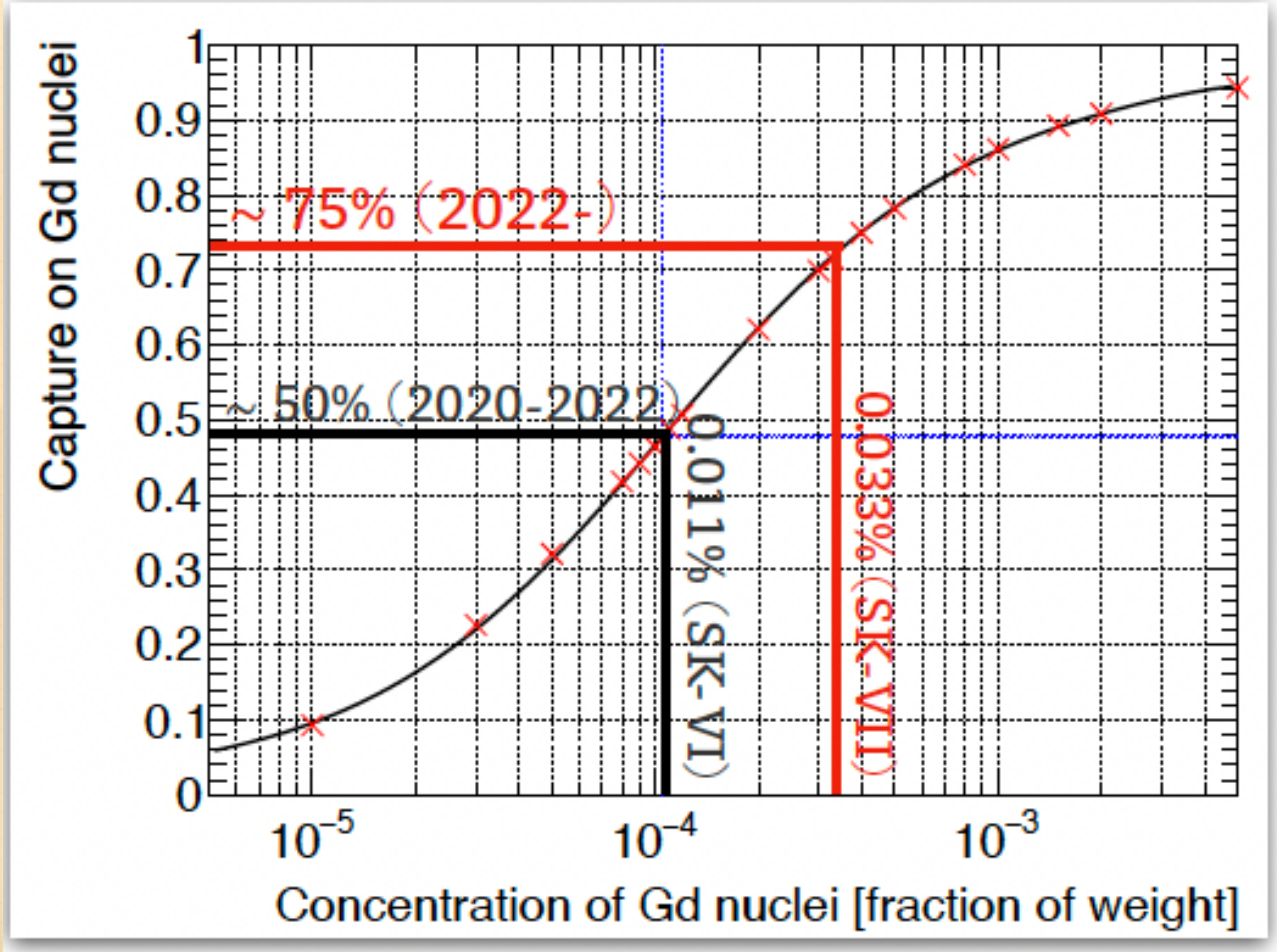
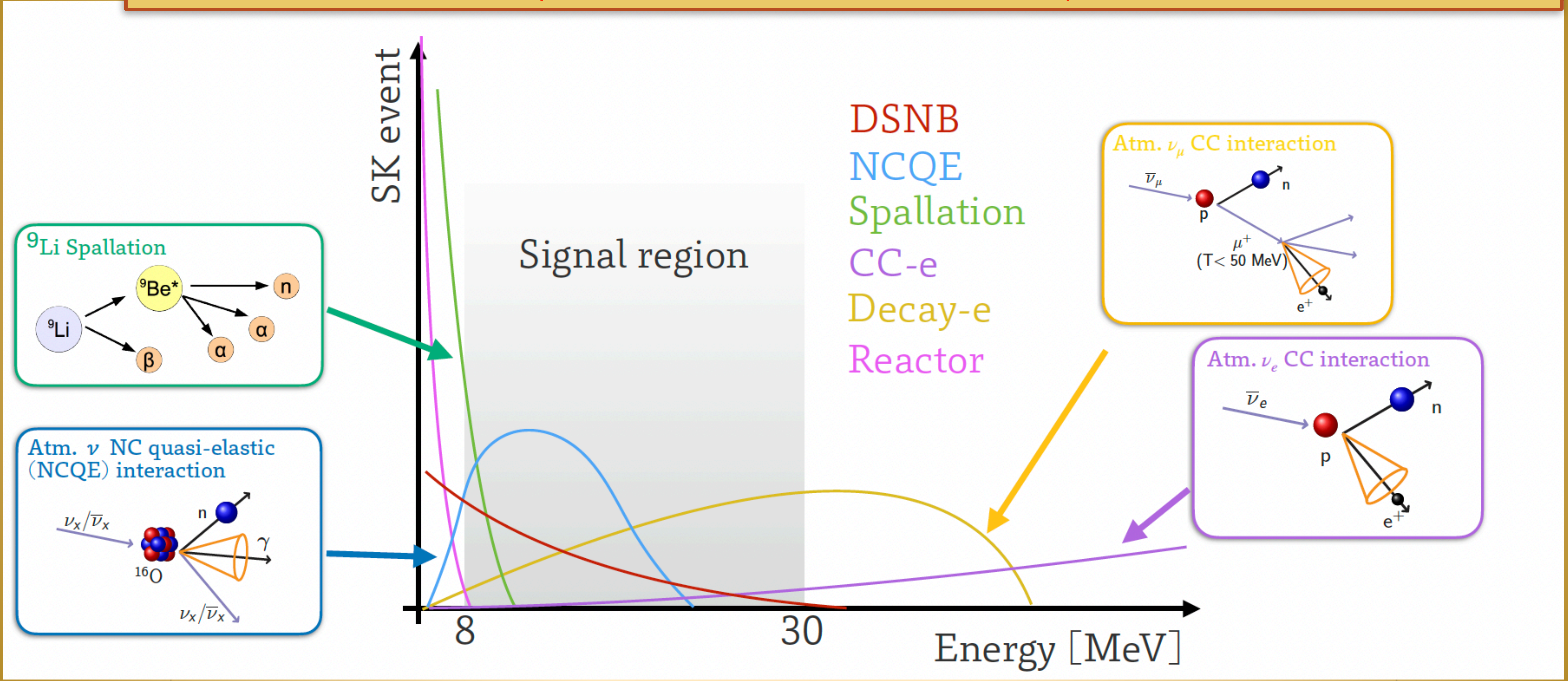


while for protons is only 0.3 barn.

DSNB searches @ SK-Gd

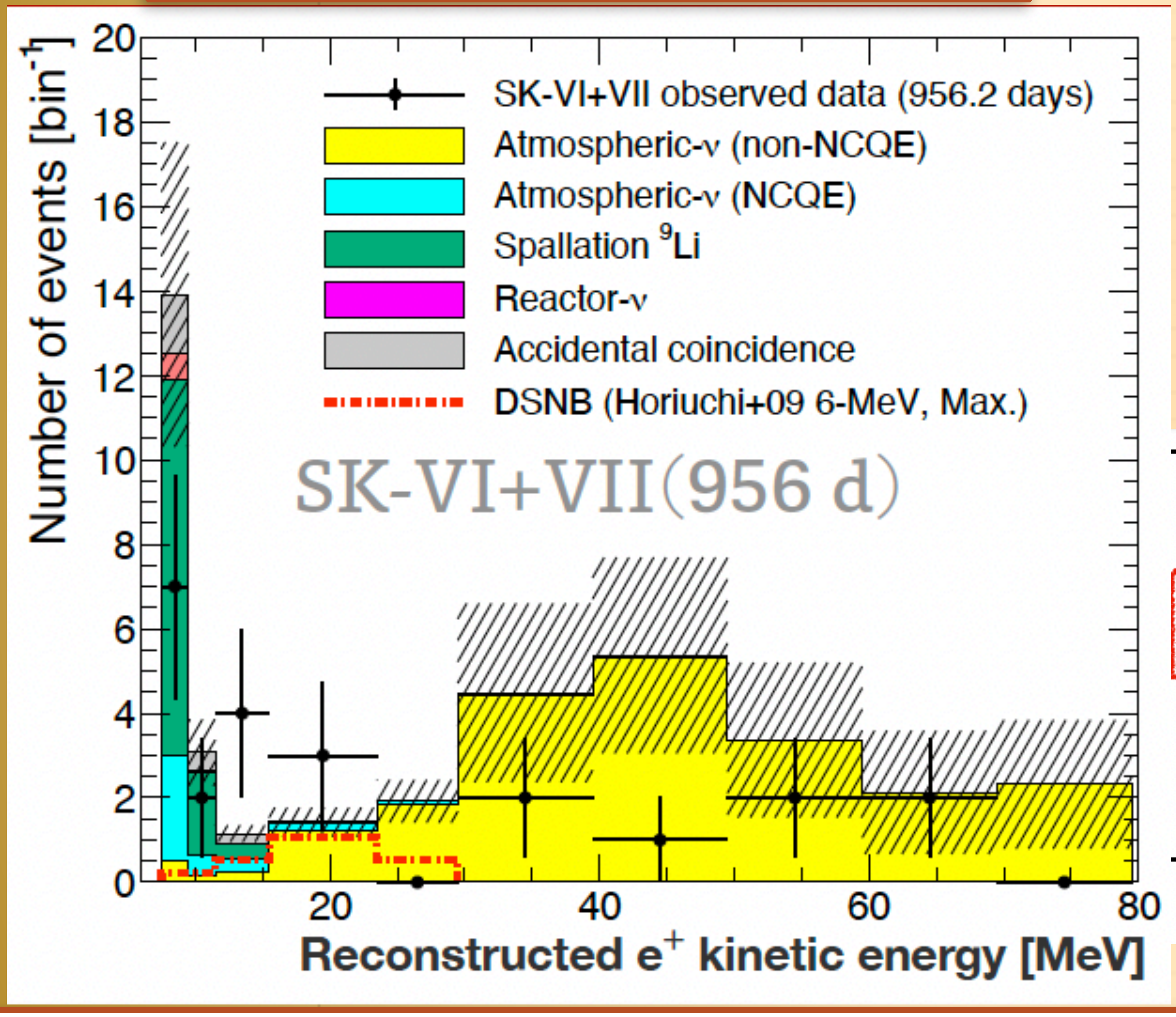
More details in first SK-Gd publication from DSNB searches AstroPhys. J. L 951 L27 (2023)



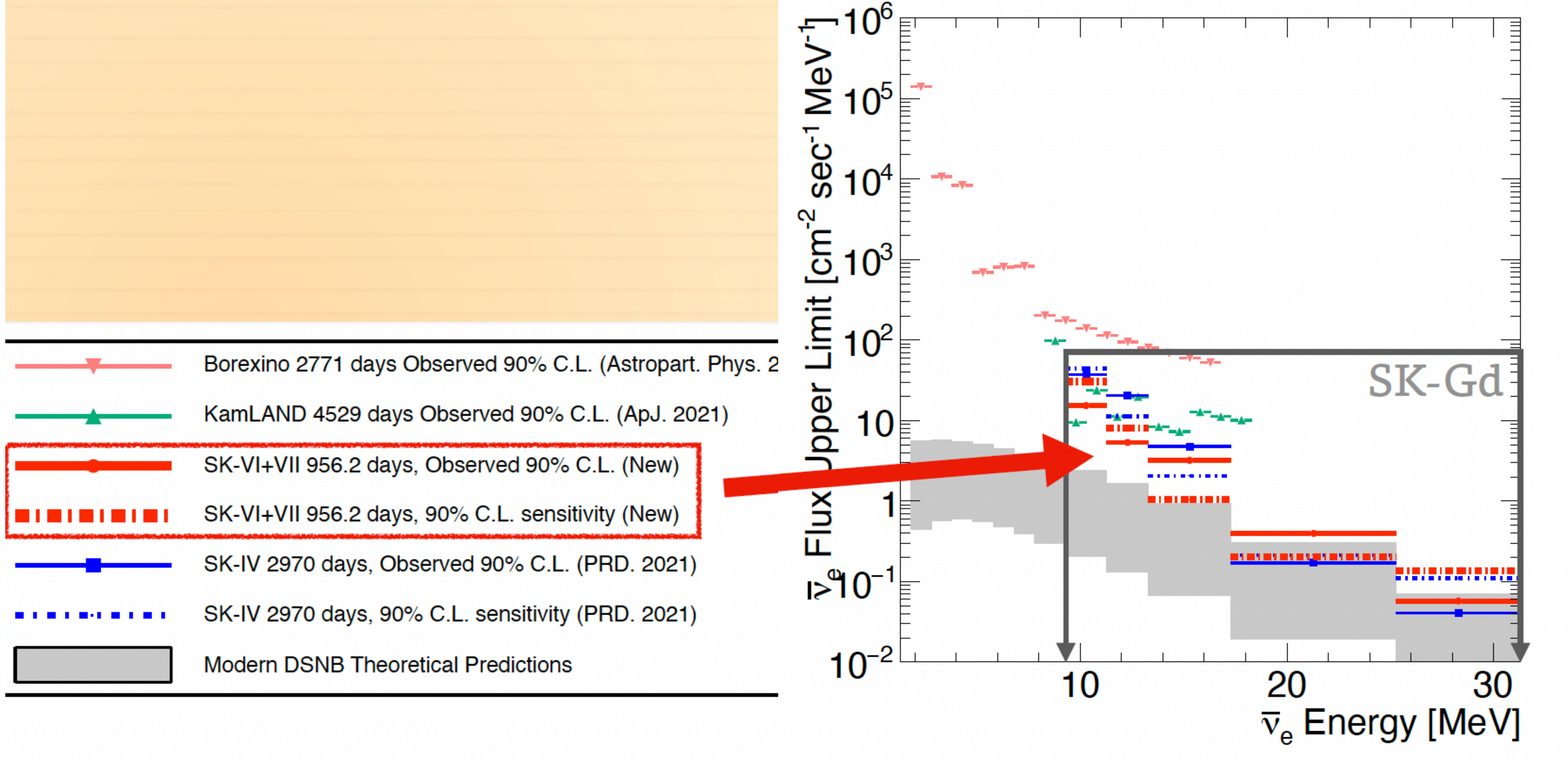
M. Harada "Review of Diffuse SN Neutrino Background " (Super-Kamiokande Collaboration), NEUTRINO 2024, Milan

DSNB results & spectral independent analysis

⭐SK-Gd energy spectrum



⭐Spectral-independent analysis



- ⭐Totally 956 days SK-Gd data
- ⭐No obvious excess of the signal (min. p-value=0.04)

- ⭐ 956 days of SK-Gd with Gd 0.01% (552 d) +0.03% (404 d) Spectrum independent analysis
- ⭐ Update the world stringent sensitivity for almost all bins

Summary

The joint oscillation analyses with Atmospheric neutrinos and T2K beam neutrinos :

- SK+T2K joint fit results - first combined analysis published in Phys.Rev.Lett. 134 (2025)
- Working now on **advanced joint fit oscillation analysis** with much more data of SK (50%) and T2K

DSNB searches @ SK- Gd:

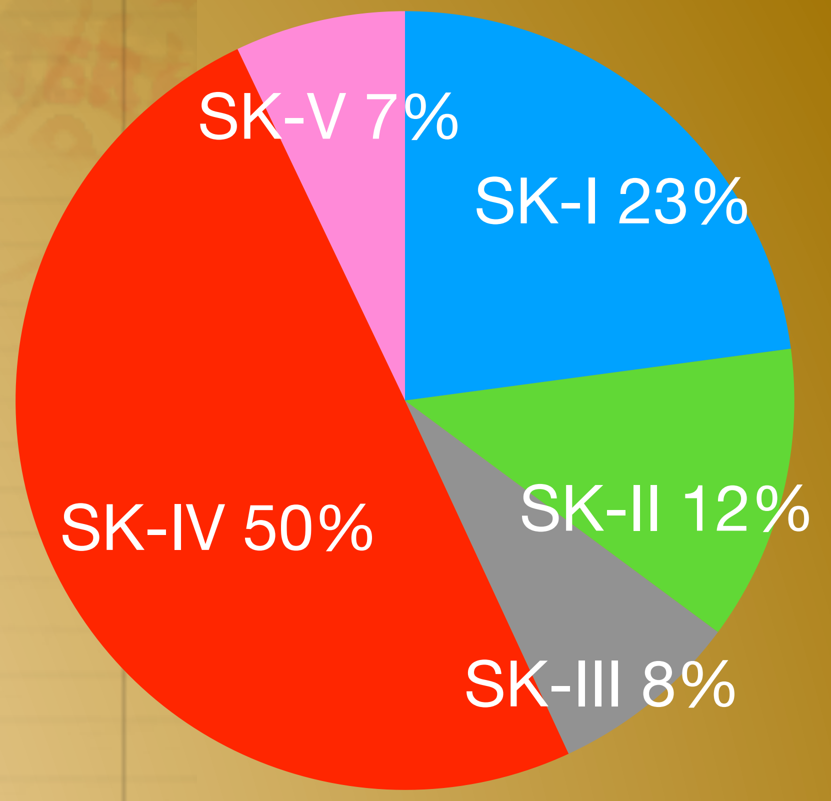
- SK experiment published first result in SK-Gd era with 552.2 days of Gd data: **AstroPhys. J. L 951 L27 (2023)**
- Recent update of DSNB search in SK-Gd using additional additional 404 days with 0.03% Gd (SK-VII) condensed Gd-water data was obtained.
  - **There is no significant DSNB signal yet but …**
  - **Looking forward to discovery of DSNB in the next decade !!**

Future: Hyper-Kamiokande experiment -> see Jan Kisiel talk

Thank you!

Photo Credit: Piotr Mijakowski

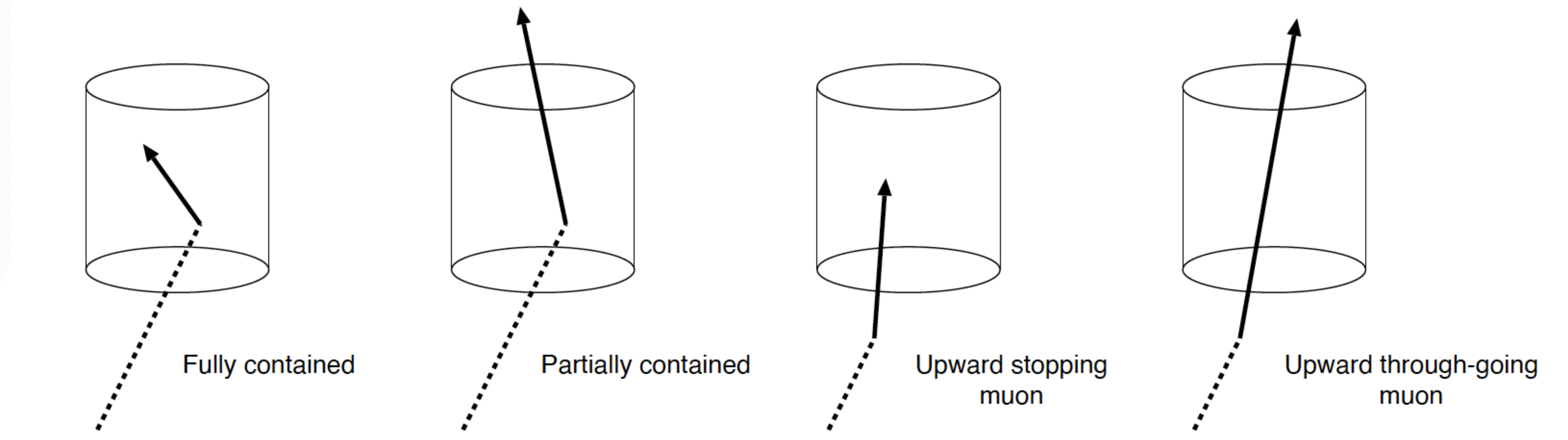
Zenith angle atmospheric neutrino oscillation analysis



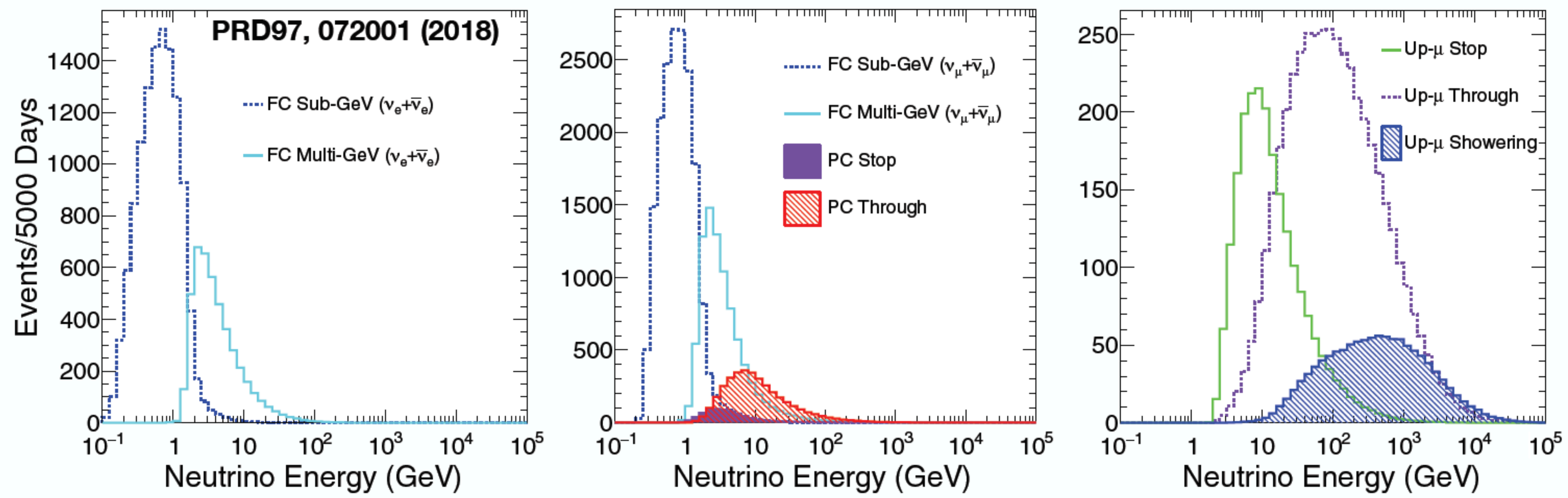
- Latest results with **full SK pure water phase (SK1-5)**:
  - Latest publication - **Phys. Rev. D 109, 072014 – Published on 24 April 2024**
  - Previously published results: Phys. Rev. D97, 072001 (2018)

- 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 (SK4-5)**
  - New multi-ring event classification using a Boosted Decision Tree (BDT)
    - Improved charged current/neutral current separation
- Atmospheric ν oscillation fit with external constrains
  - θ_{13} from reactors

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

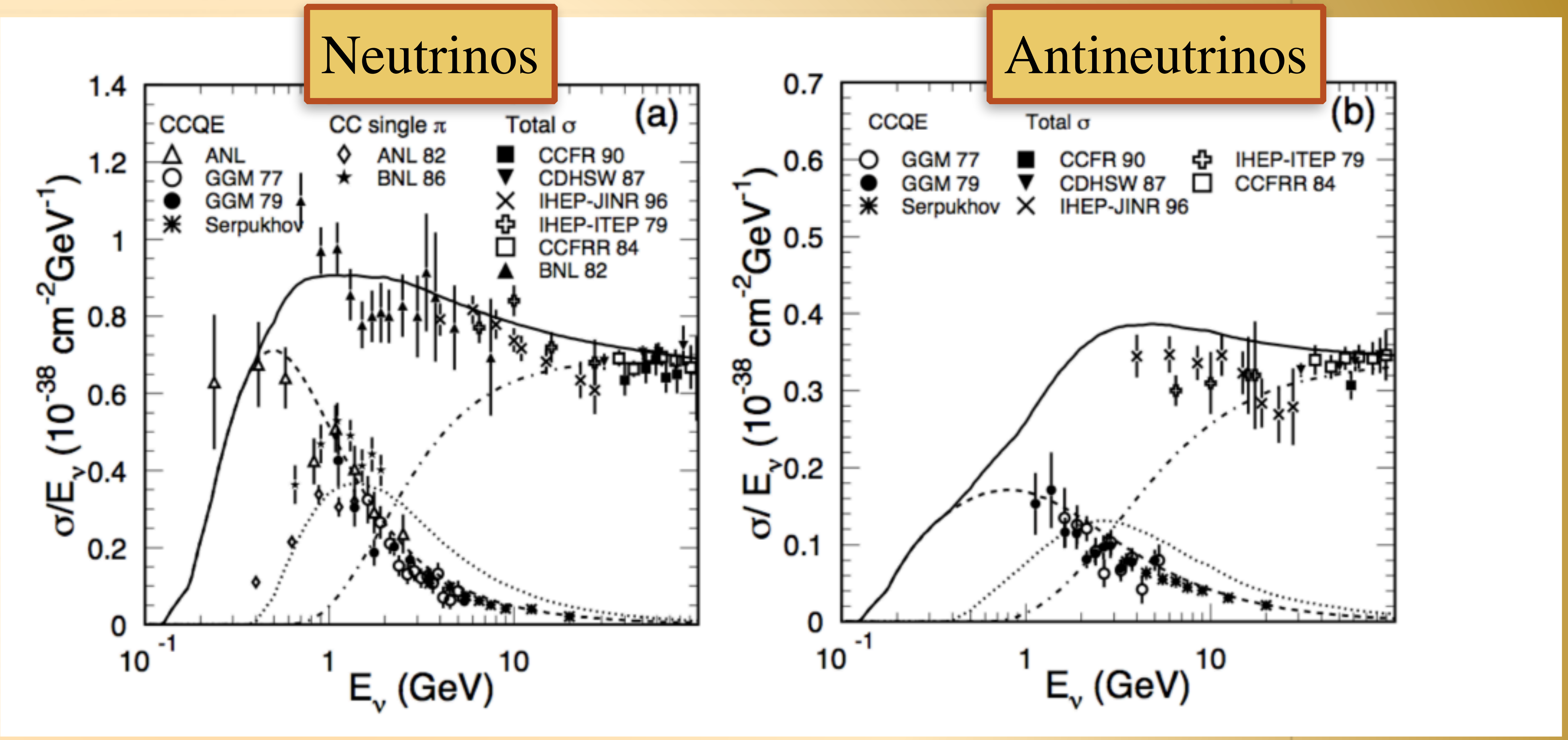


Expected energy spectra of atm-ν samples

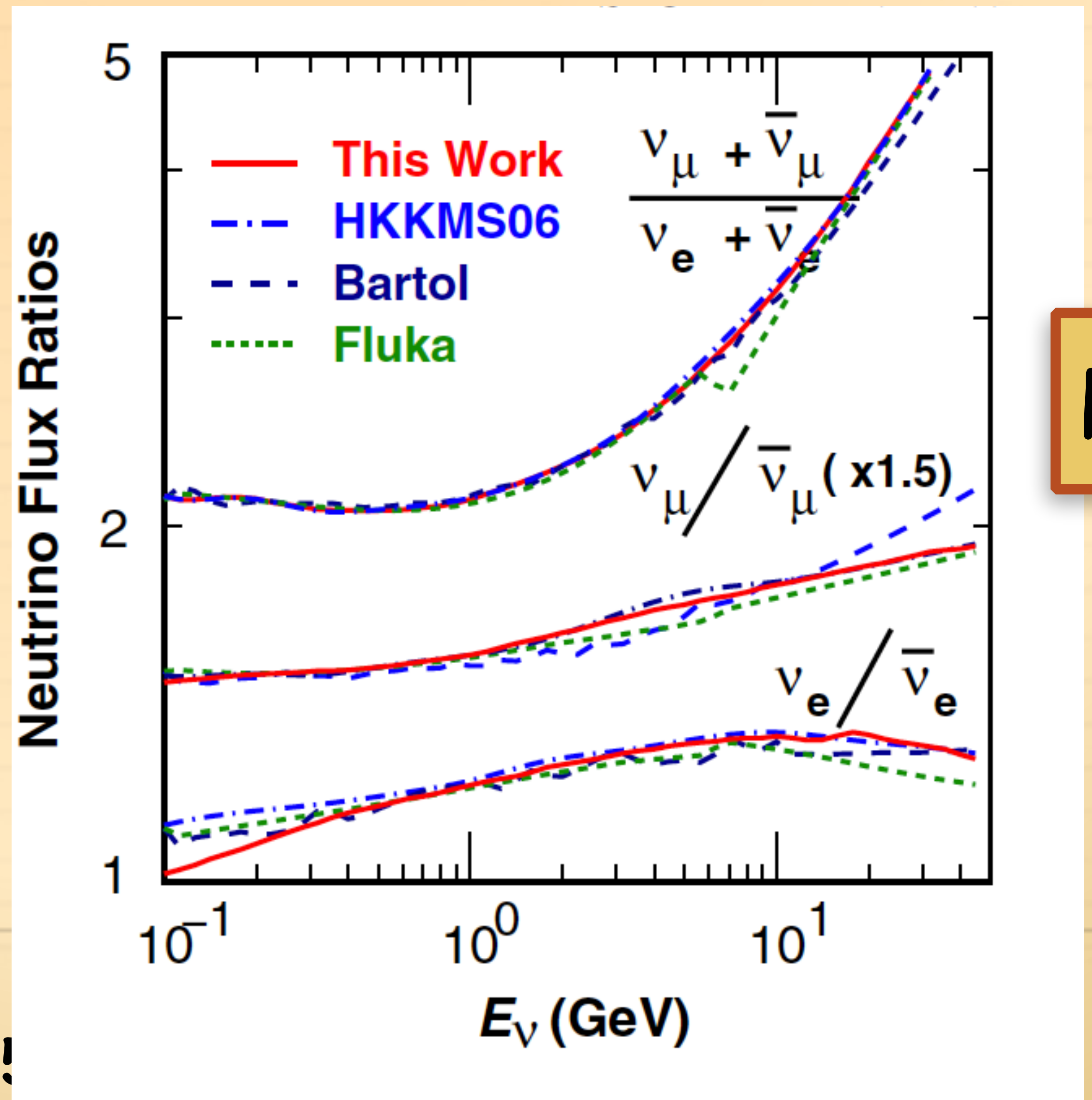


Separation of ν_e and $\bar{\nu}_e$

- **Separation of ν_e and $\bar{\nu}_e$ is important for mass ordering searches**
- No magnetic filed in the Super-K detector to do that
- However we have larger cross-section and flux for ν_e than $\bar{\nu}_e$ which results in **twice more ν_e interactions than $\bar{\nu}_e$ in the Super-K detector**


Neutrinos

Antineutrinos



Phys. Rev. D 83 123001 (2011)

$\nu/\bar{\nu}$ separation @ SK before neutron tagging

$$\nu_e + N \rightarrow N + e^- + \pi^+$$

$$\pi^+ \rightarrow \mu^+ \rightarrow e^+$$

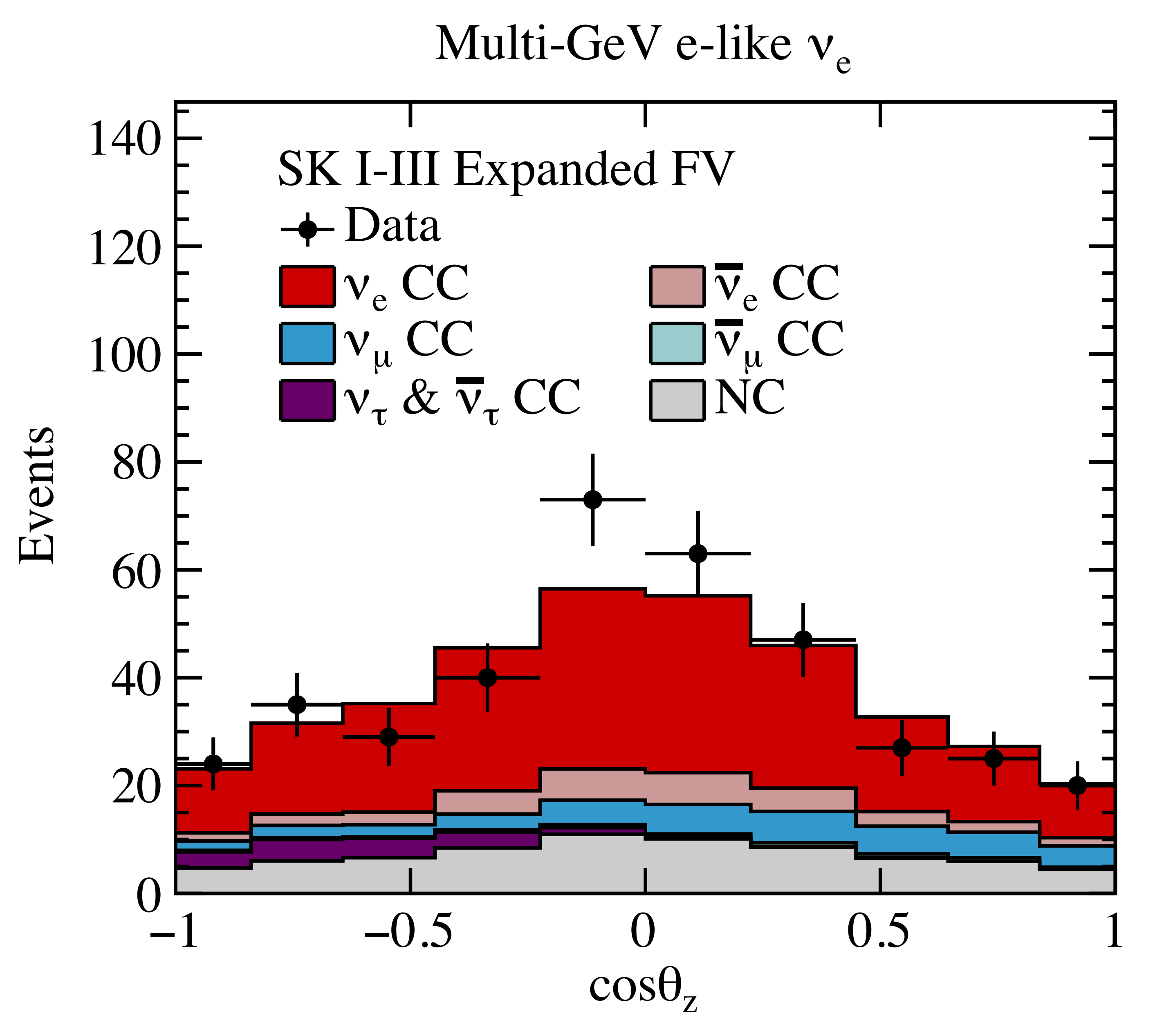
Delayed “decay electron”

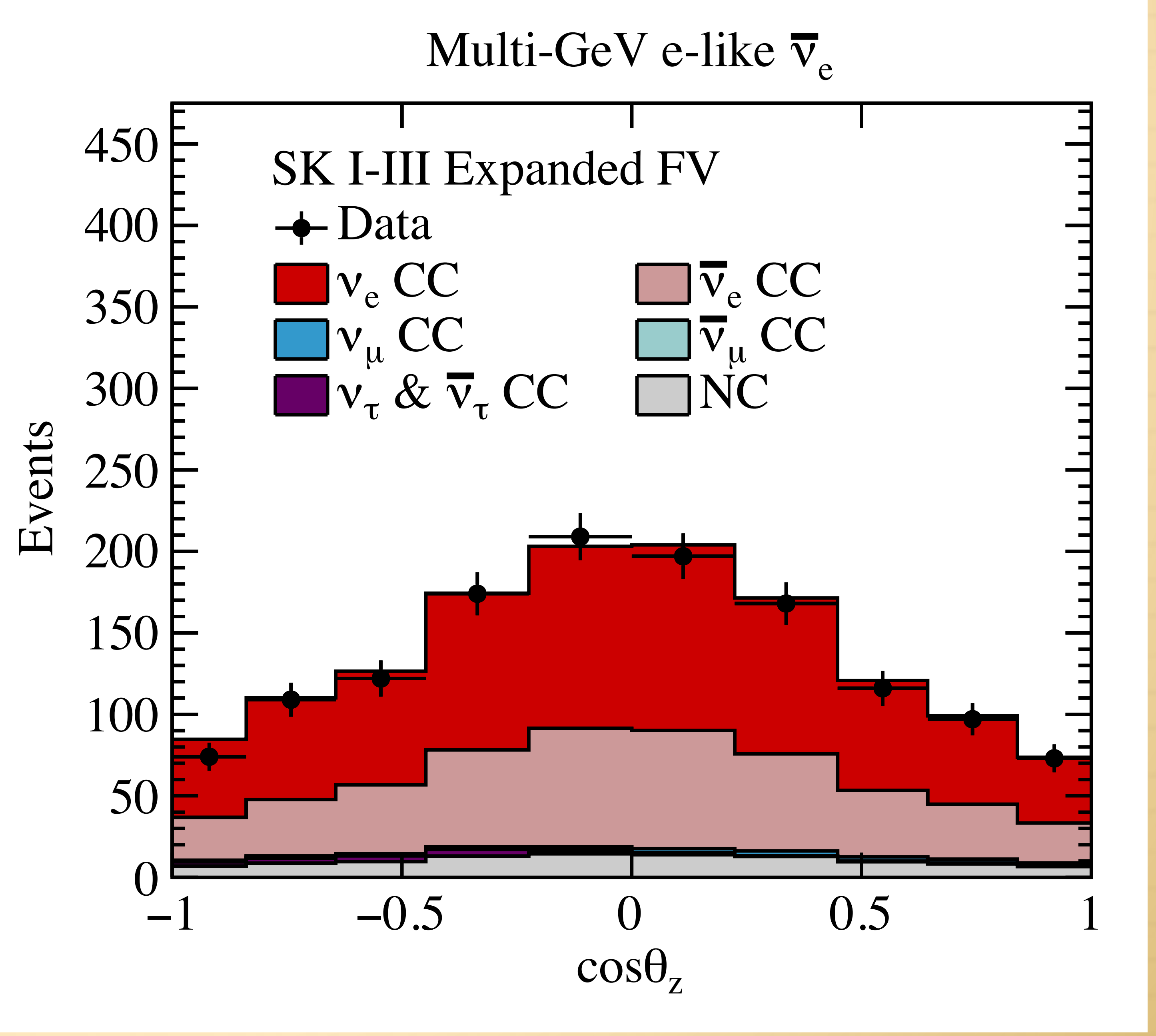
$$\bar{\nu}_e + N \rightarrow N + e^+ + \pi^-$$

π^- mostly absorbed by Oxygen

🟥 ν_e (56%)

▨ $\bar{\nu}_e$ (9%)





🟥 ν_e (56%)

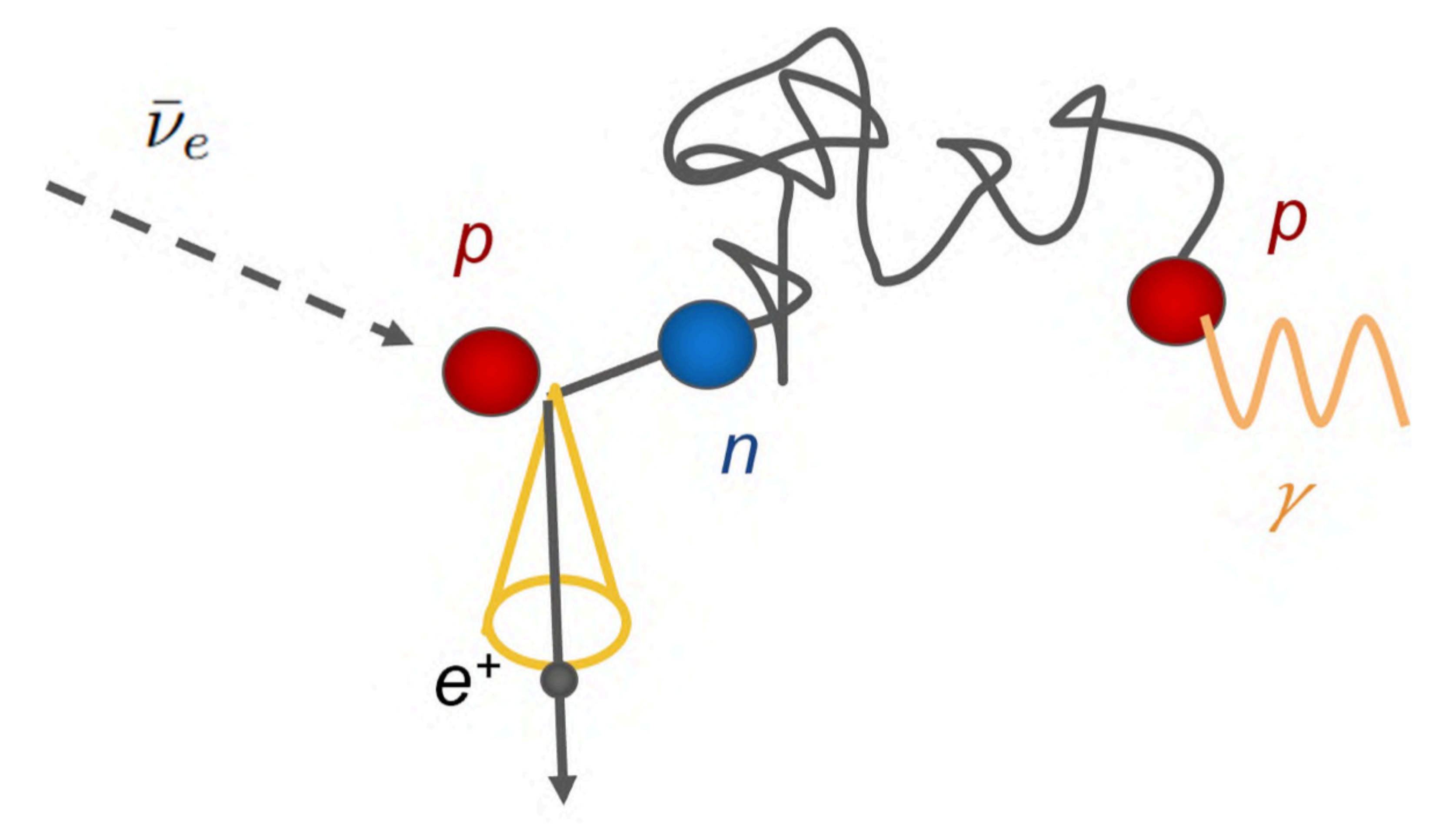
▨ $\bar{\nu}_e$ (34%)

Neutron tagging on hydrogen at Super-K

Possible from SK-IV period

Reminder:
$\nu_e + n \rightarrow e^- + p$
$\bar{\nu}_e + p \rightarrow e^+ + n$

- IBD reaction: $\bar{\nu}_e + p \rightarrow n + e^+$
- Neutron tagging may happen on hydrogen.
  - $n + p \rightarrow d + \gamma(2.2MeV)$
  - The gamma ray may then scatter electrons (Compton scattering) in the water, accelerating some of them above the Cherenkov threshold.
  - Identifying the light from those electrons can be used to infer the presence of the gamma ray and hence its parent neutron.



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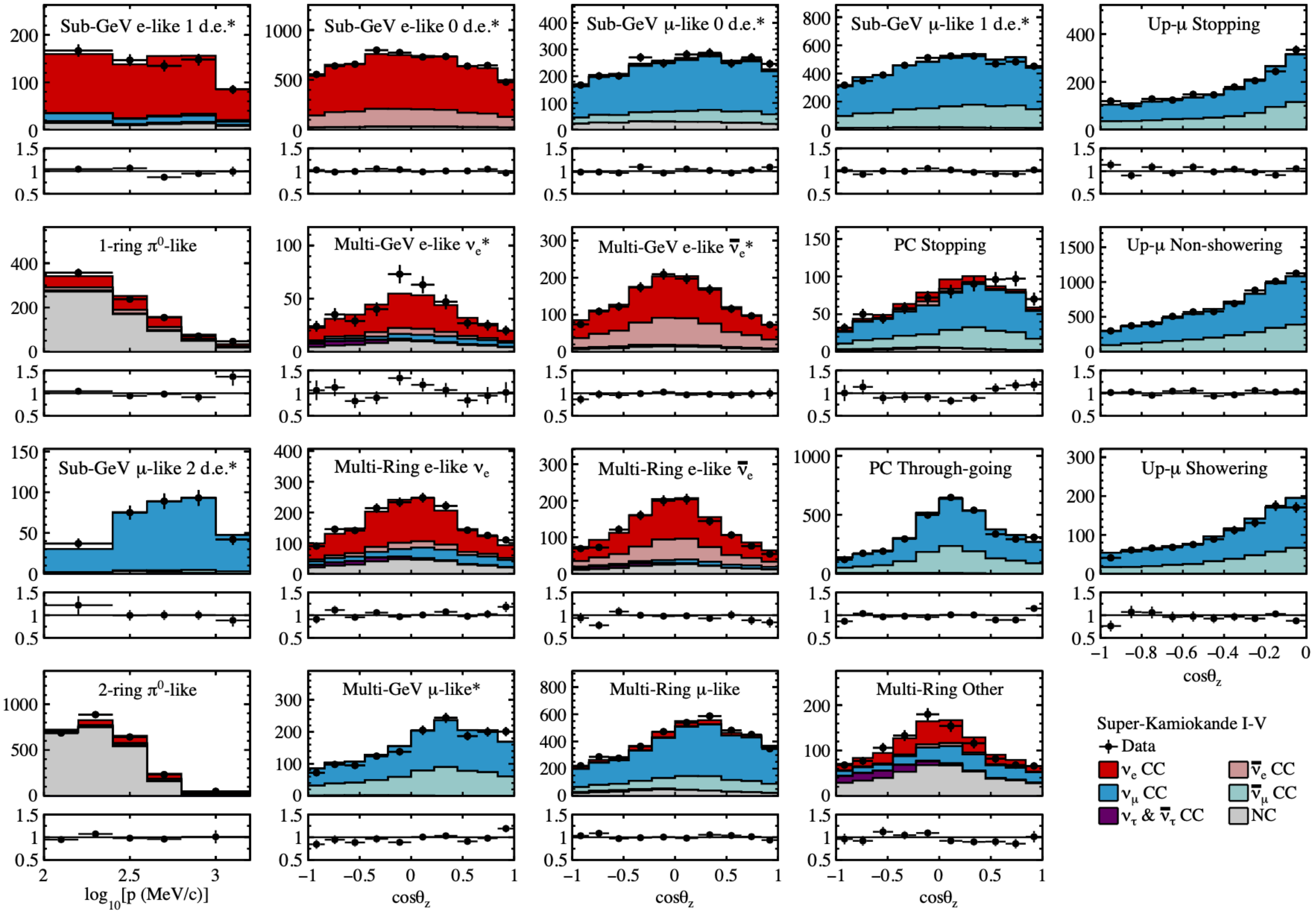
Zenith angle or momentum distributions



- Zenith angle or momentum distributions for the 19 analysis samples **without neutron tagging.**
- FC: Sub-GeV and Multi-GeV samples with SK-I~III data, no neutron tagging included*
- PC, UPMU, FC π^0, FC Multi-Ring samples use SK-I~V data,

SK samples - impact of neutron tagging

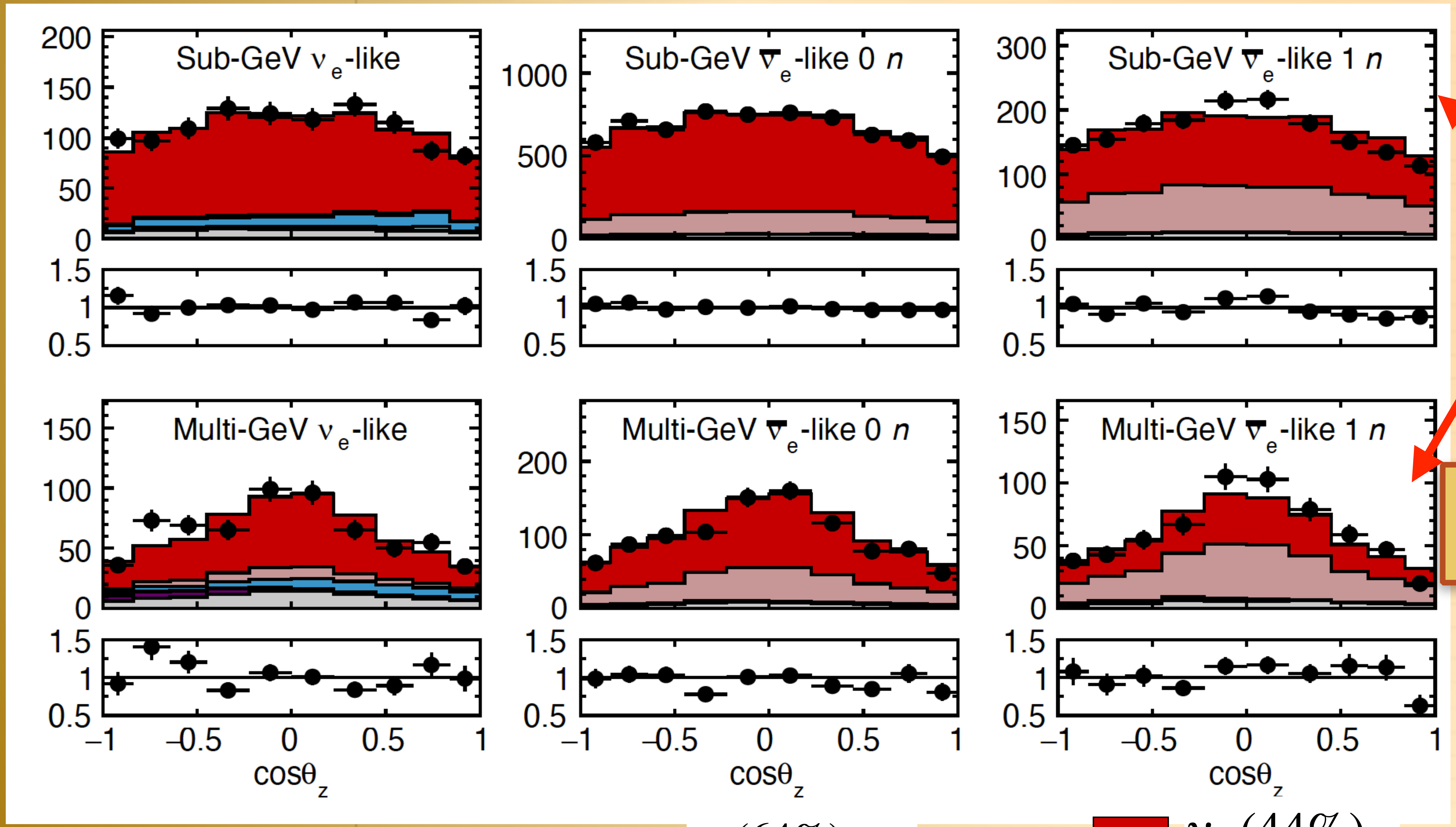
- Additional selections done for SK4 and SK5 data period, **with neutron tagging on Hydrogen.**
- Improves separation between ν and $\bar{\nu}$ events

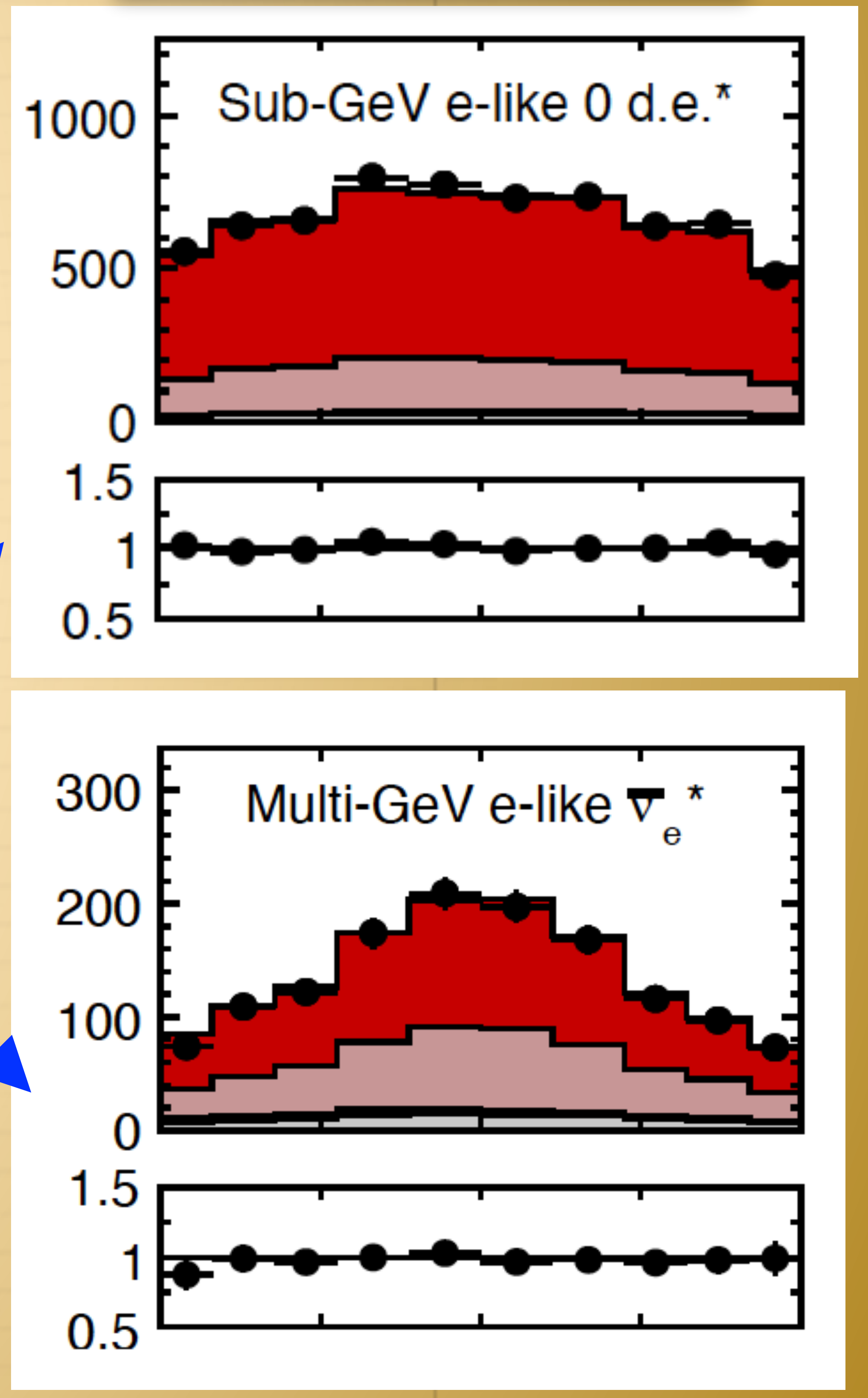
d.e. ≥ 1 + any # of neut.

d.e.=0 + # of neut. $= 0$

d.e.=0 + # of neut. ≥ 1

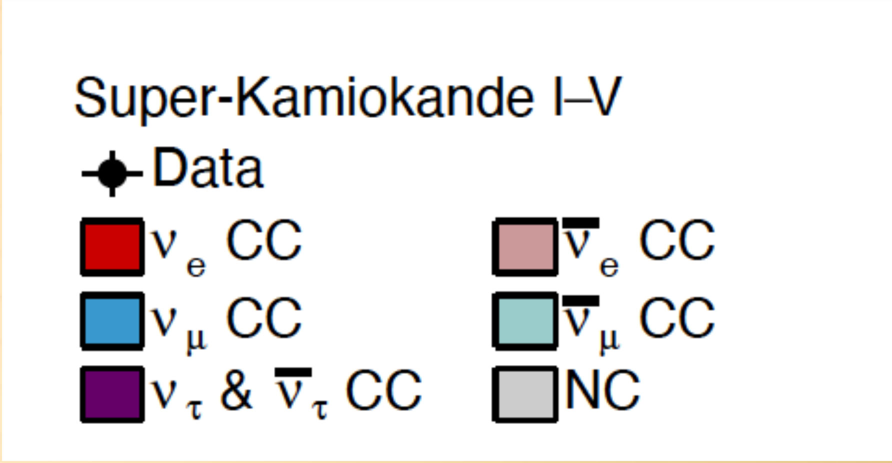
d.e.=0





New selections with neutron tagging

Old selections
Phys. Rev. D97, 072001 (2018)



🟥 ν_e (64%)
🟥 $\bar{\nu}_e$ (29%)

🟥 ν_e (44%)
🟥 $\bar{\nu}_e$ (46%)

🟥 ν_e (56%)
🟥 $\bar{\nu}_e$ (34%)

SK samples - impact of neutron tagging

- Additional selections done for SK4 and SK5 data period, **with neutron tagging on Hydrogen**.
- Improves separation between ν and $\bar{\nu}$ events