Neutrino Physics

Neutrino Oscillations in vacuum

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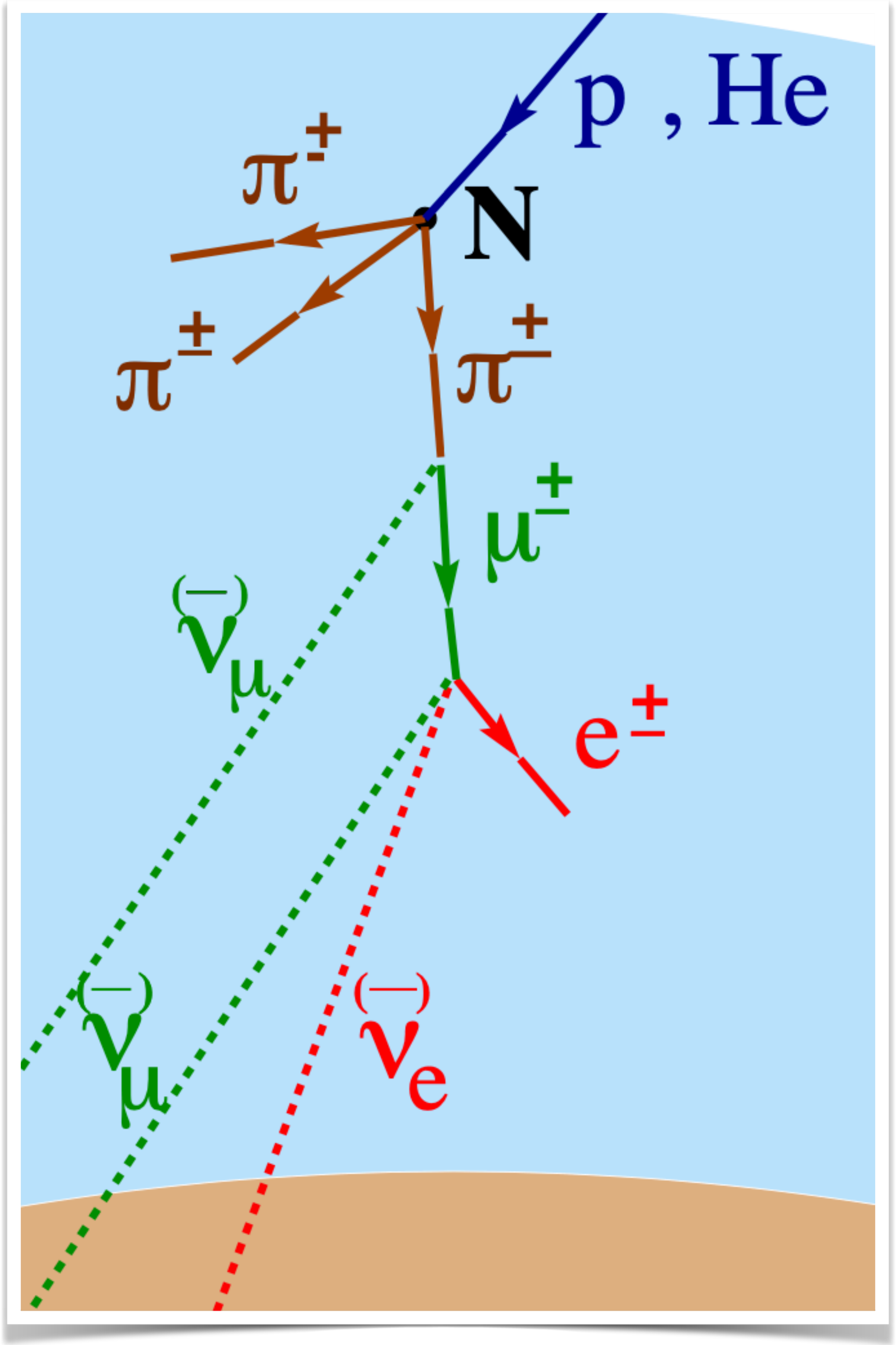
Atmospheric neutrinos

- Neutrinos produced via cosmic rays (accelerated protons, He) in the atmosphere



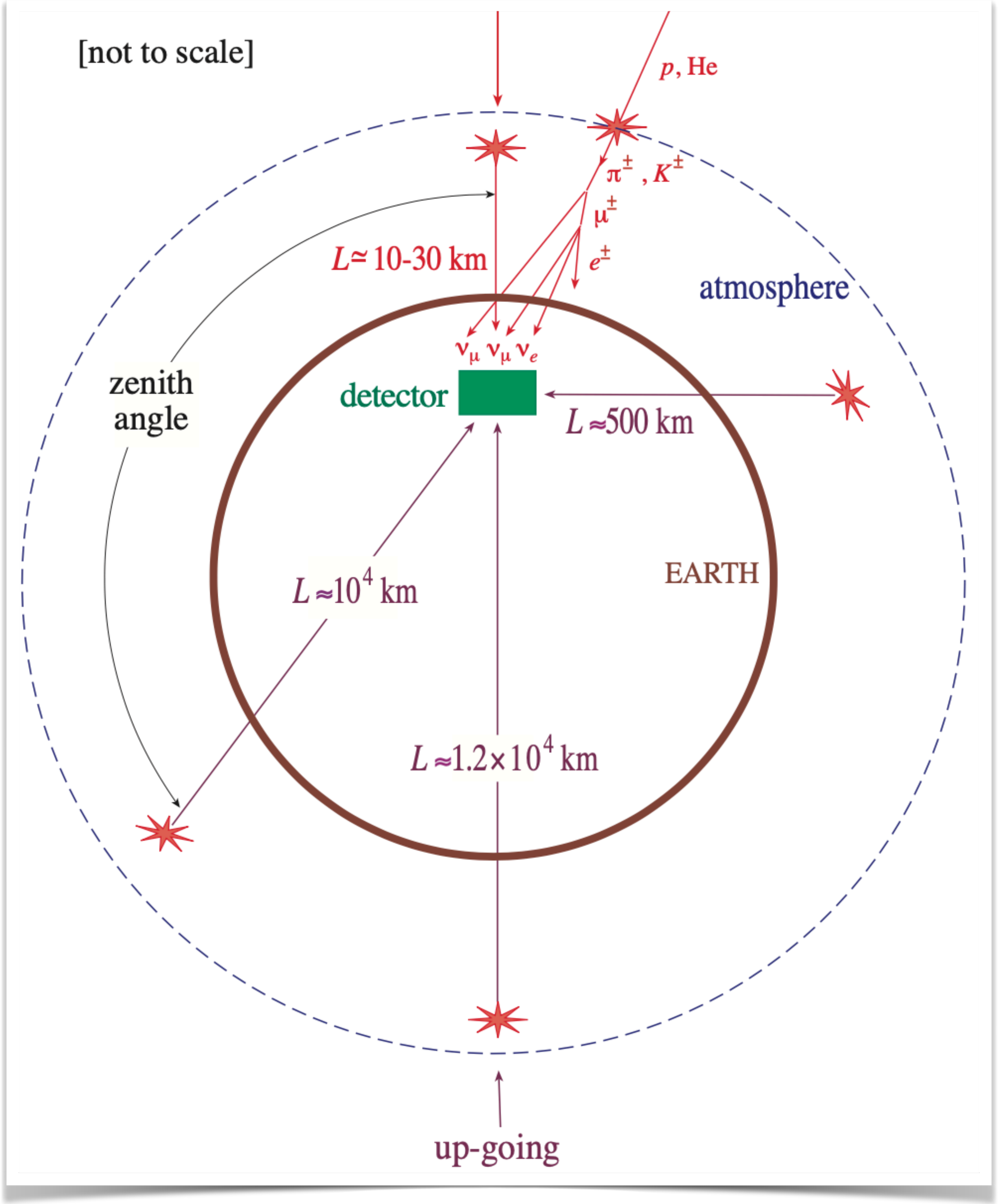
$$R_{\frac{\mu}{e}} \approx \frac{N_{\nu_\mu} + N_{\overline{\nu_\mu}}}{N_{\nu_e} + N_{\overline{\nu_e}}} \sim 2$$

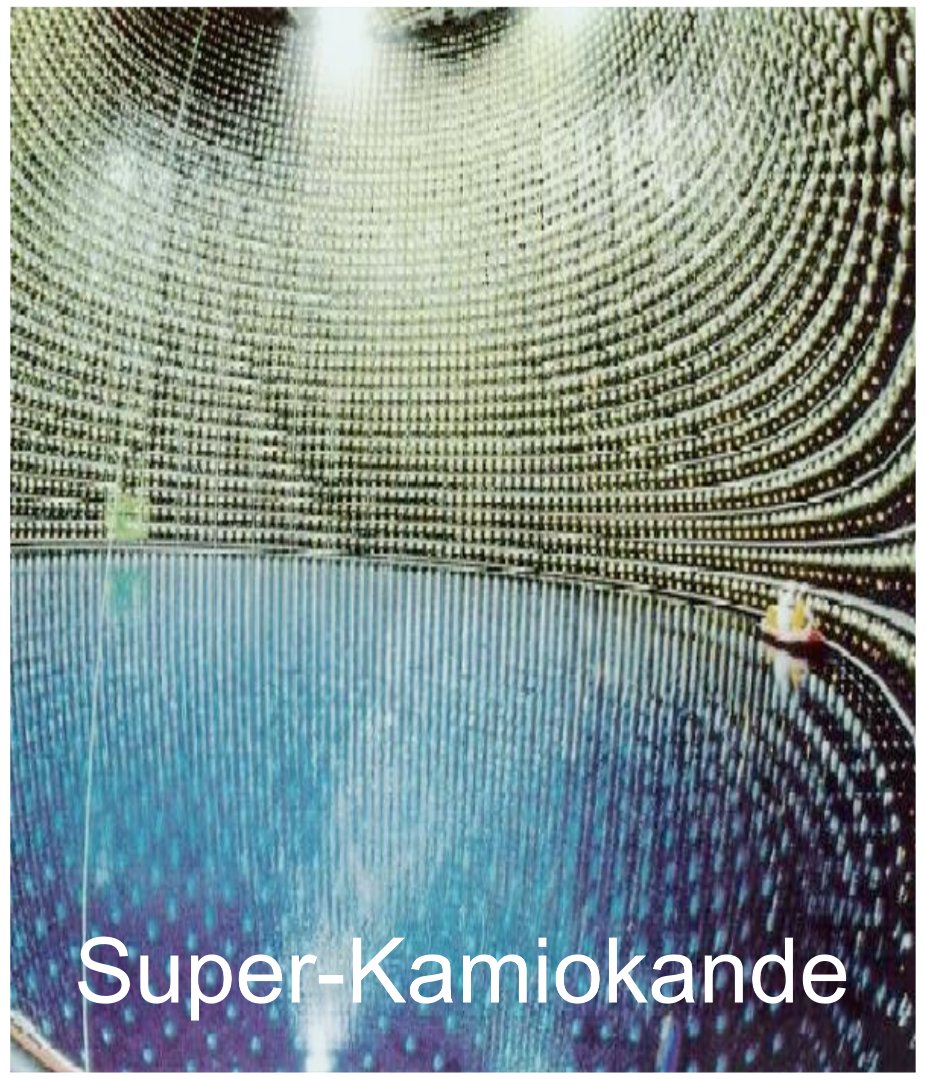
Exercise: show that

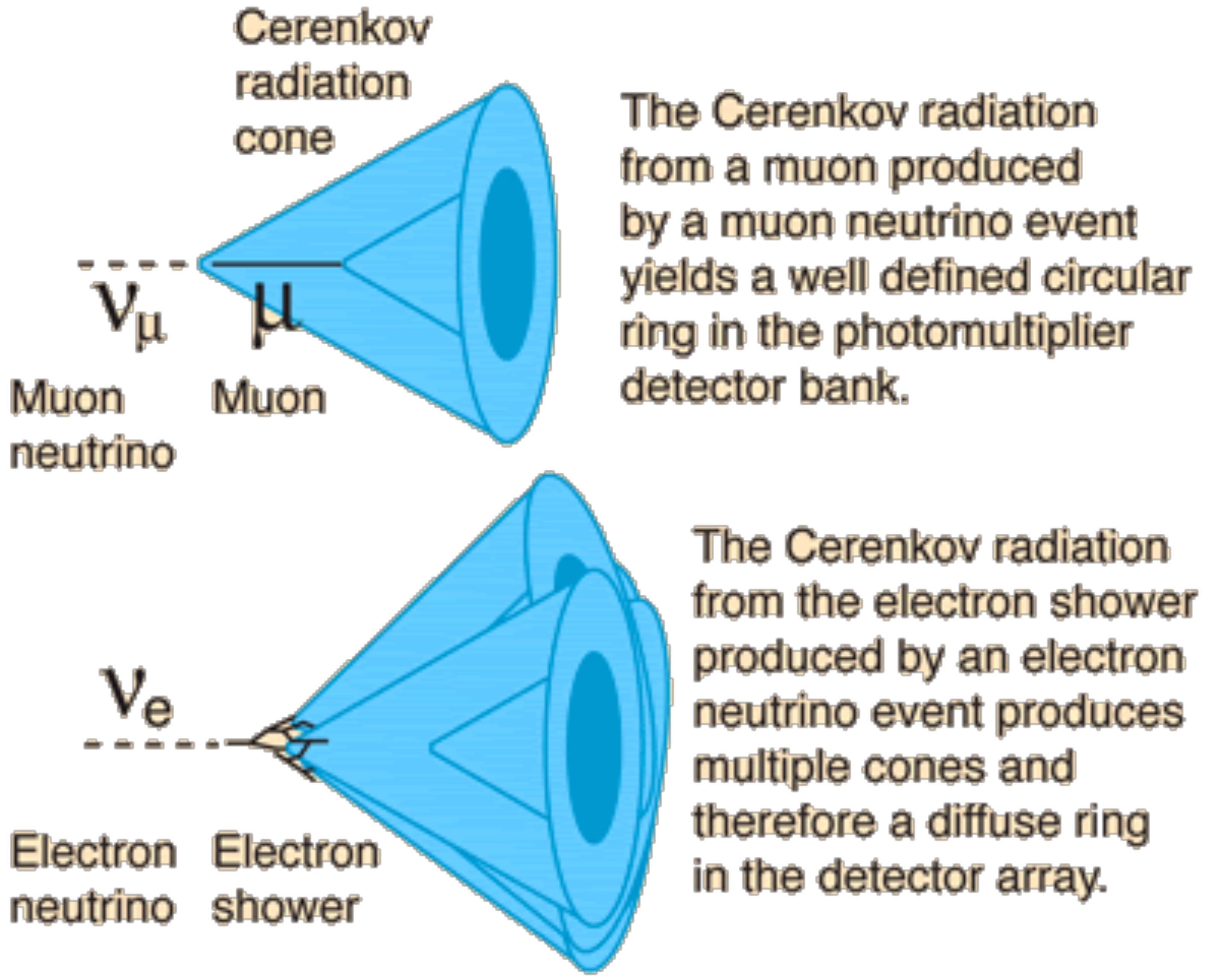
$$\frac{\Gamma\left(\pi^+ \to e^+ \nu_e\right)}{\Gamma\left(\pi^+ \to \mu^+ \nu_\mu\right)} \approx 2 \times 10^{-4}$$

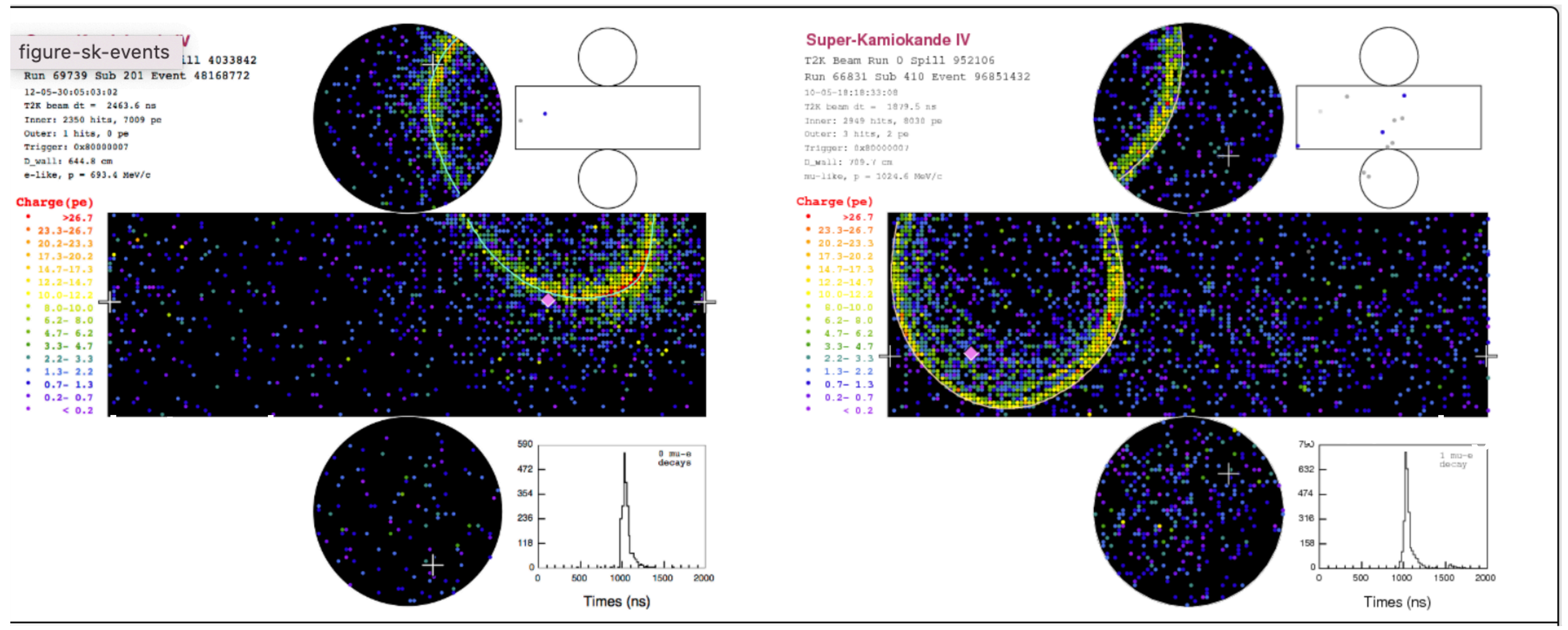
Atmospheric neutrinos

- 1998 Super-Kamiokande (50kton water cherenkov detector, 11146 PMTs) detected atmospheric neutrinos



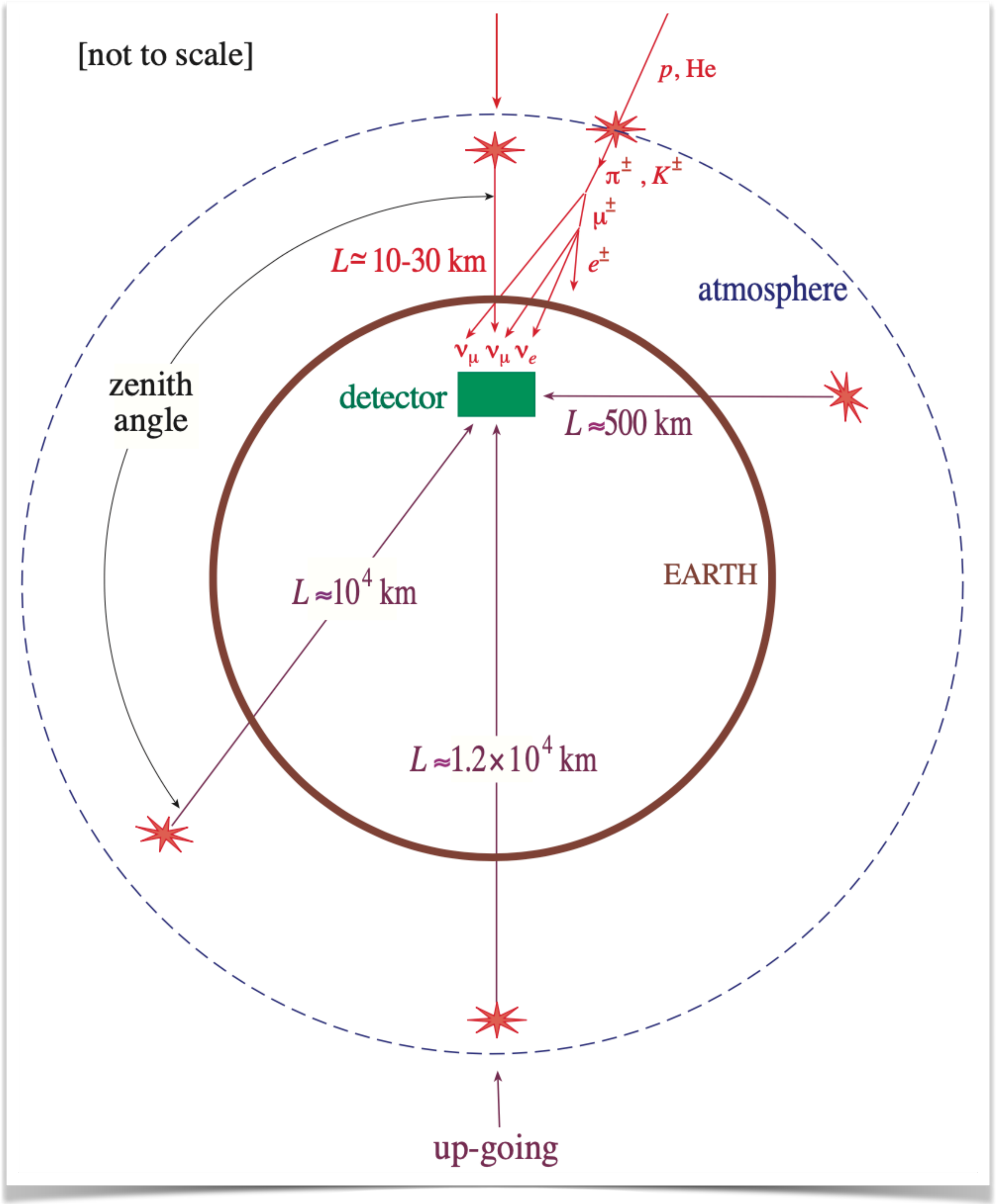


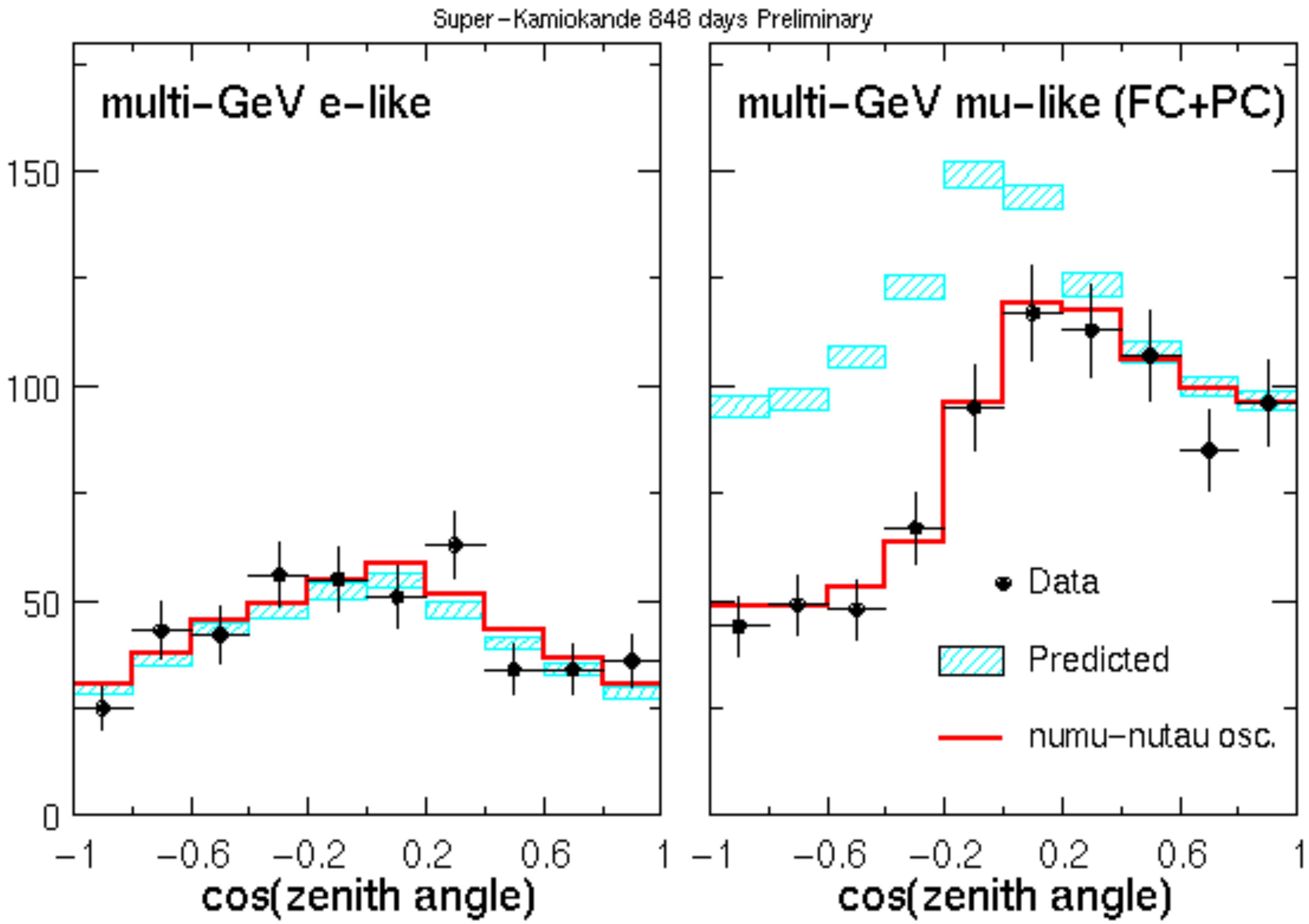




Atmospheric neutrinos

- 1998 Super-Kamiokande (50kton water cherenkov experiment) detected atmospheric neutrinos



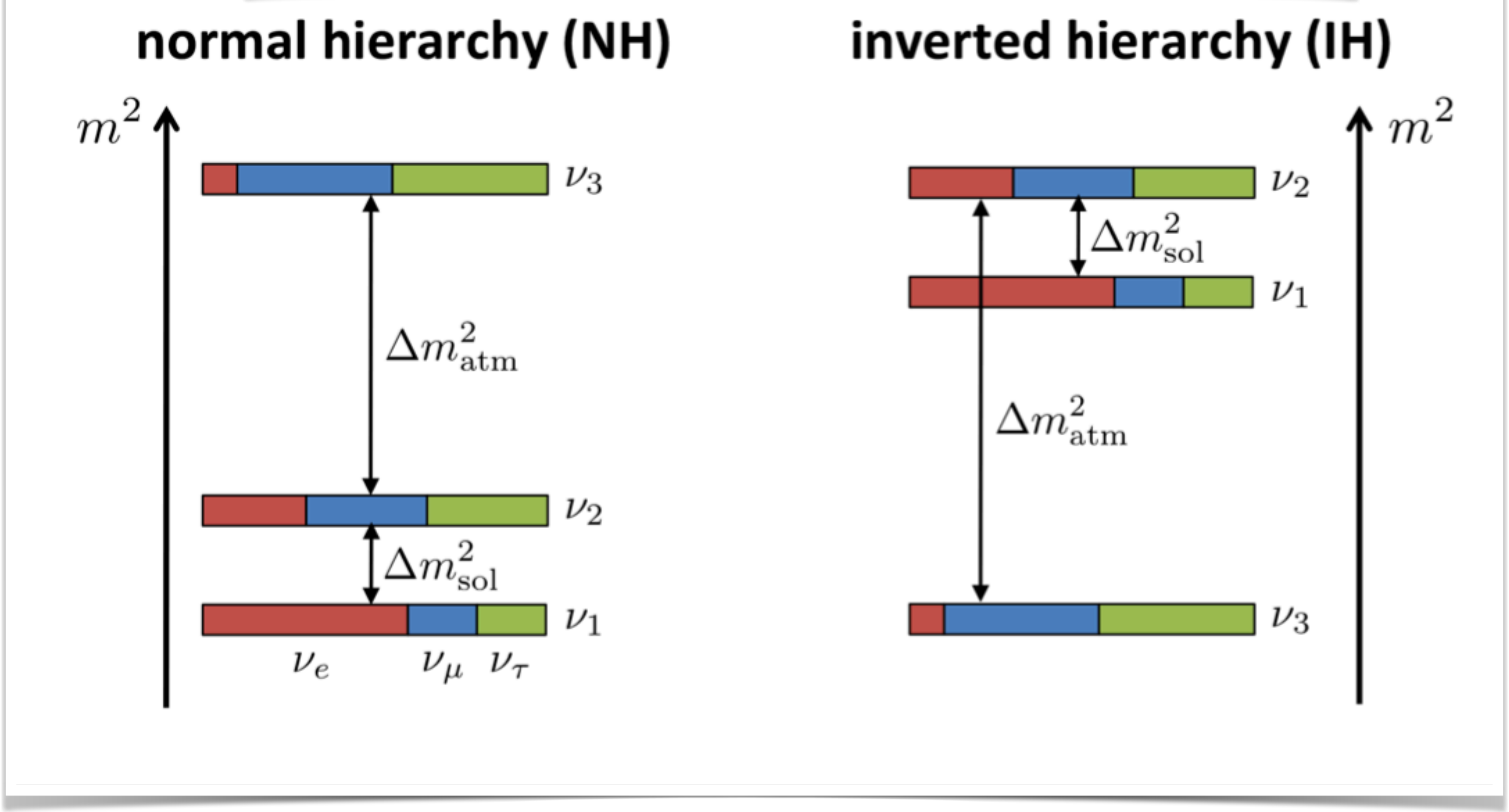


Board

Current knowledge

- Solar mass squared splitting: $\Delta m^2_{21} \sim 7.42 \times 10^{-5}\,\mathrm{eV}^2$
- Atmospheric mass squared splitting: $|\Delta m^2_{3\ell}| \sim 2.515 \times 10^{-3}\,\mathrm{eV}^2$

Normal hierarchy	$m_1 < m_2 < m_3 \implies \Delta m^2_{32} > 0,$
Inverted hierarchy	$m_3 < m_1 < m_2 \implies \Delta m^2_{32} < 0.$



Current knowledge

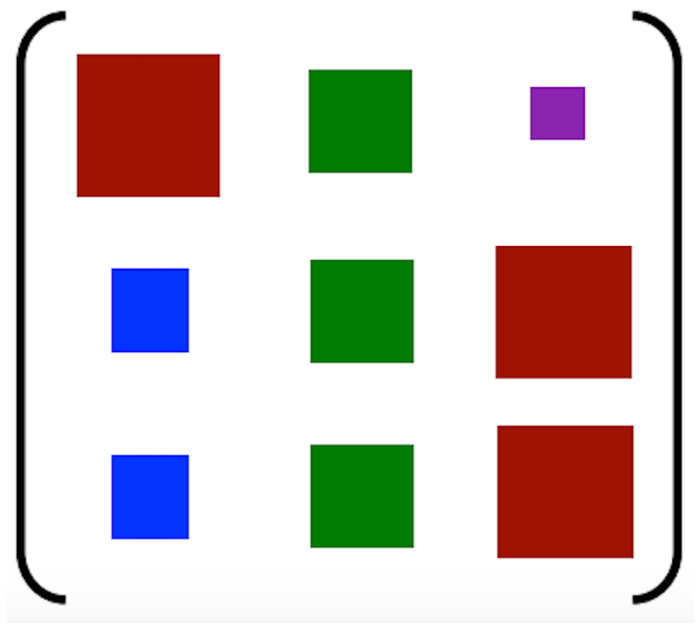
Nu-fit global fit 5.1

www.nu-fit.org

with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

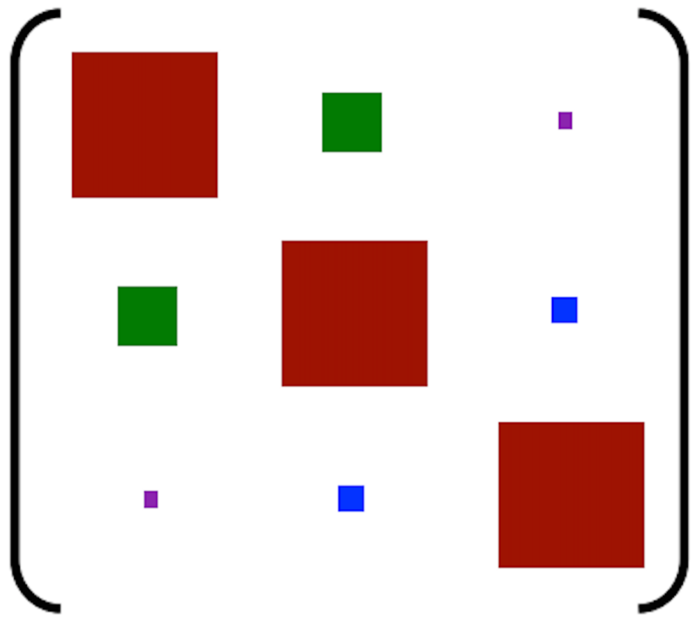
Current knowledge

Lepton Sector

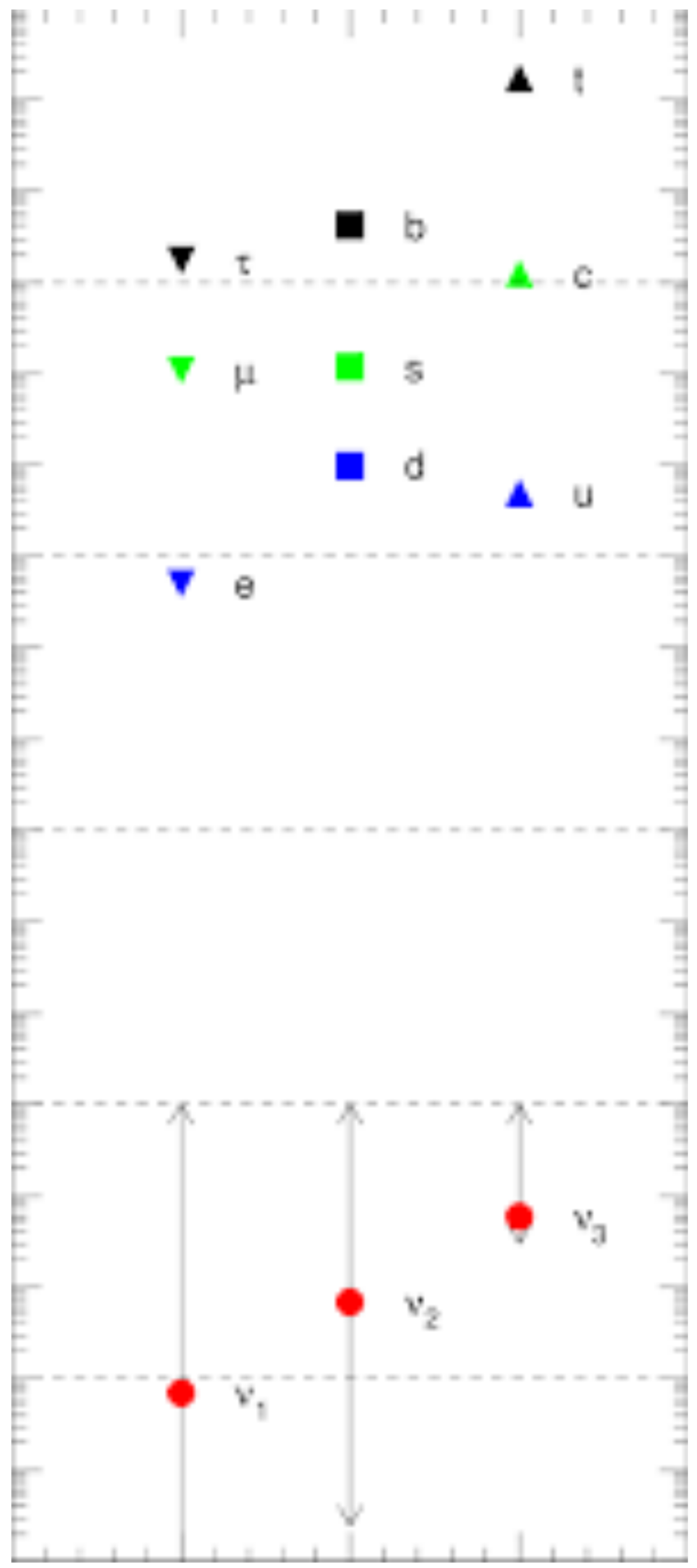


$$\sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.4 & 0.5 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quark Sector



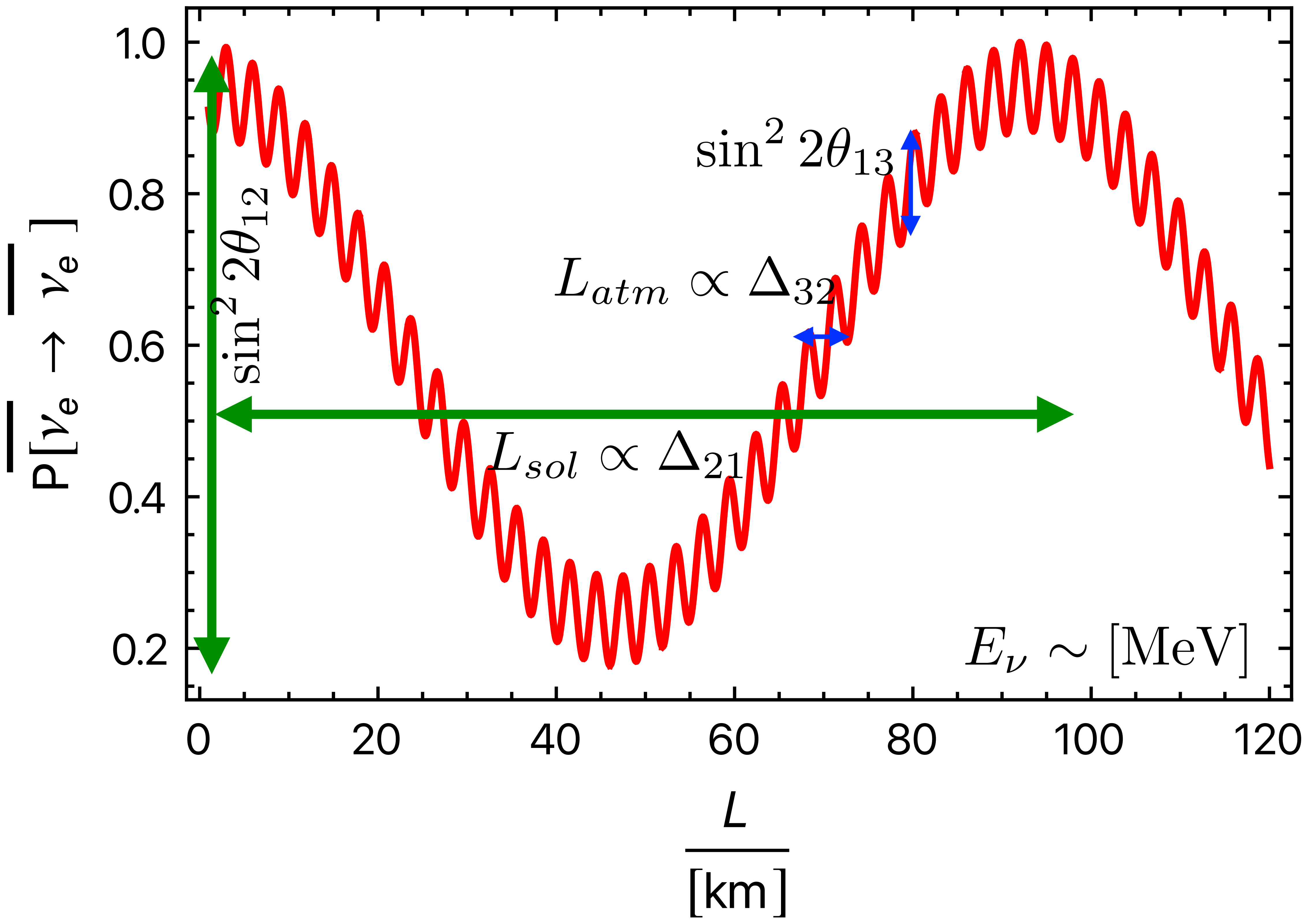
$$\sim \begin{pmatrix} 0.98 & 0.2 & 0.0 \\ 0.2 & 0.99 & 0.0 \\ 0.0 & 0.04 & 1.0 \end{pmatrix}$$



- The mixing and masses of each sector of the SM are so different, better measurements can help us understand why

Neutrino oscillation physics - reactor experiments

$$P(\overline{\nu_e} \to \overline{\nu_e}) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$



Consider the wavelength of each contribution

$$\Delta_{ij} = \left(\frac{1.27\Delta m^2_{ij}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

$$\left(\frac{1.27\Delta m^2_{ij}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right) = \pi \implies L[\mathrm{km}] = \frac{\pi E_\nu[\mathrm{GeV}]}{\Delta m^2_{ij}[\mathrm{eV}^2] \times 1.27}$$

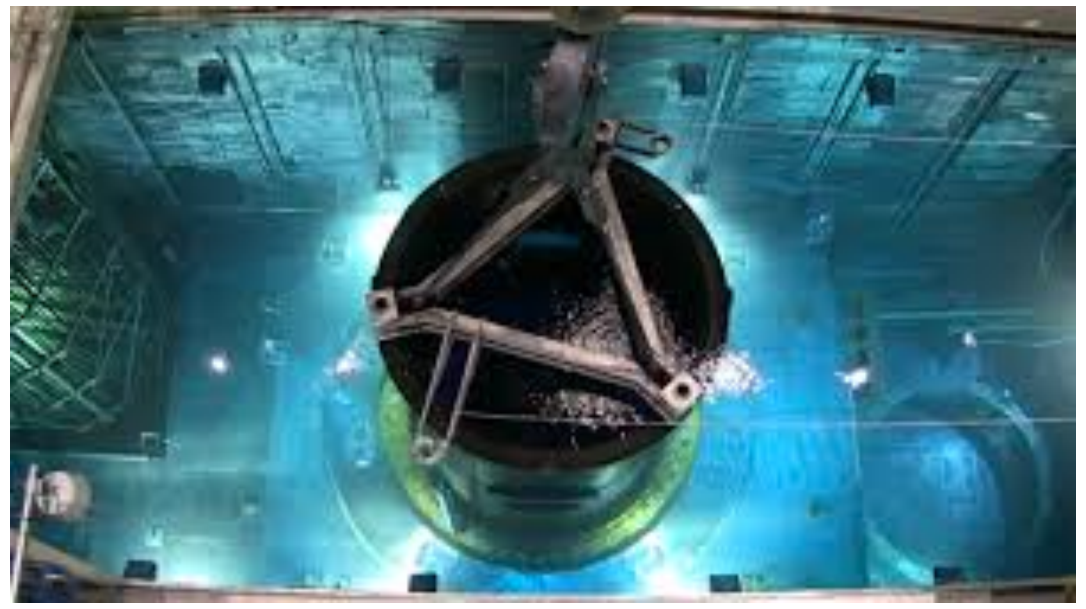
$\Delta m^2_{21} \sim 10^{-5}\,\mathrm{eV}^2$ $\quad E_\nu \sim \mathrm{MeV}$ $\quad L_{sol} \sim 30\,\mathrm{km}$

$\Delta m_{32} \sim 10^{-3}\,\mathrm{eV}^2$ $\quad L_{atm} \sim 0.8\,\mathrm{km}$

Neutrino oscillation physics - reactor experiments

- Daya Bay, RENO and Double Chooz measured reactor mixing angle in 2012

$\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$



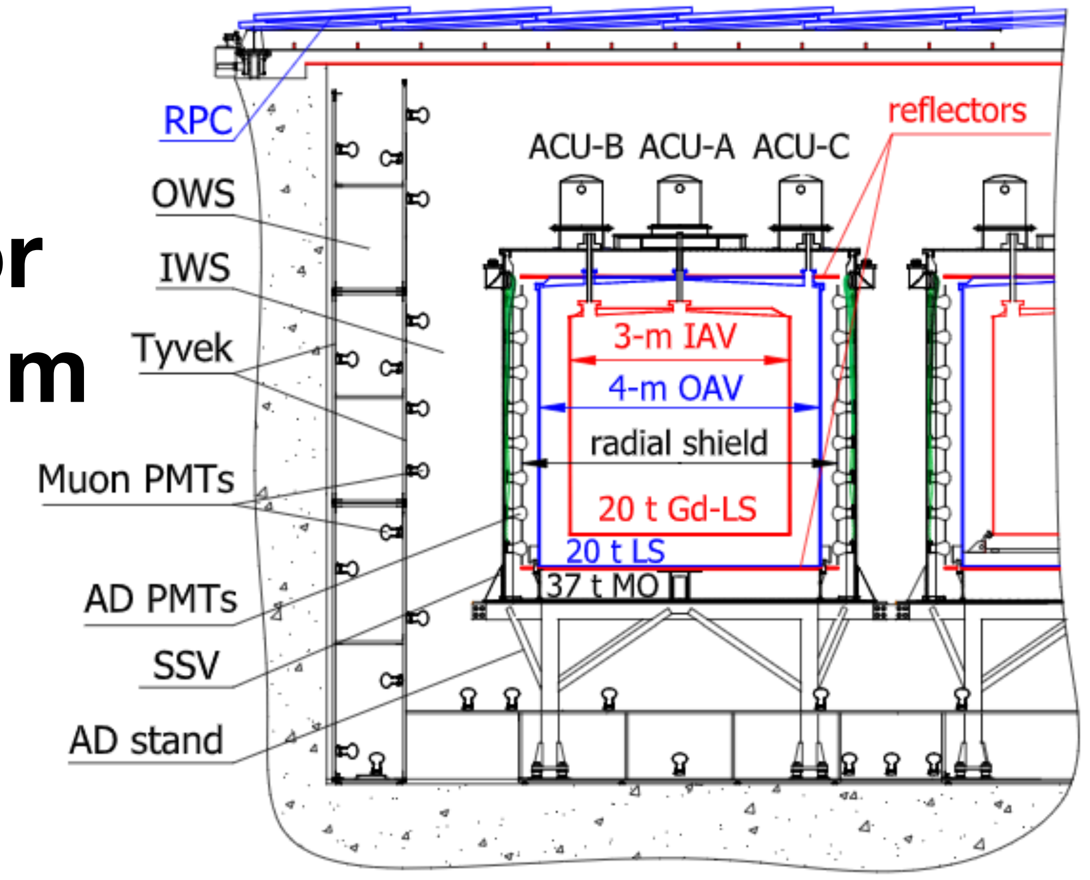
$\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$

$\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$

$\langle E_\nu \rangle \sim \mathrm{MeV}$

$4\,\mathrm{km}$

Liquid scintillator doped Gadolinium



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

$$e^+ + e^- \rightarrow 2\,\mathrm{prompt}\,\gamma$$

$$\mathrm{Gd} + n \rightarrow \mathrm{Gd}^* \rightarrow \mathrm{Gd} + \gamma$$

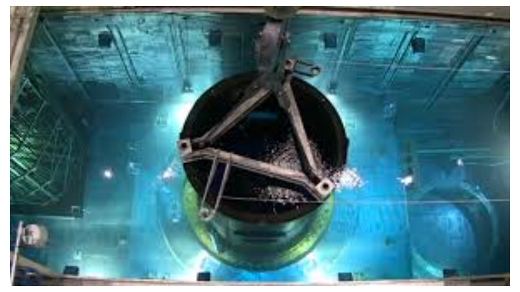
- At such short baselines, the short wavelength term dominates

$$P(\overline{\nu_e} \rightarrow \overline{\nu_e}) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \underline{\sin^2 2\theta_{13}\sin^2\Delta_{32}}$$

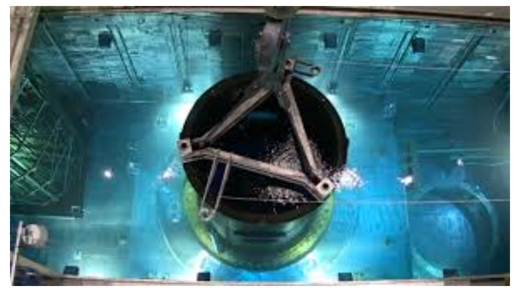
$$P\left(\overline{\nu_e} \rightarrow \overline{\nu_e}\right) \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

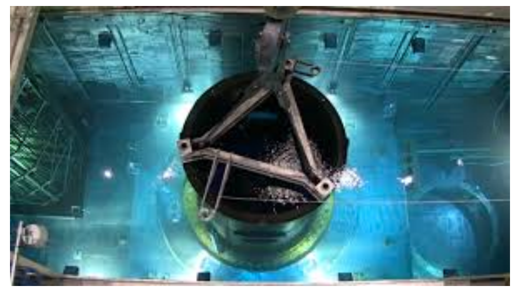
Neutrino oscillation physics - reactor experiments

- KamLand is a medium baseline reactor experiment in same cavern as SK



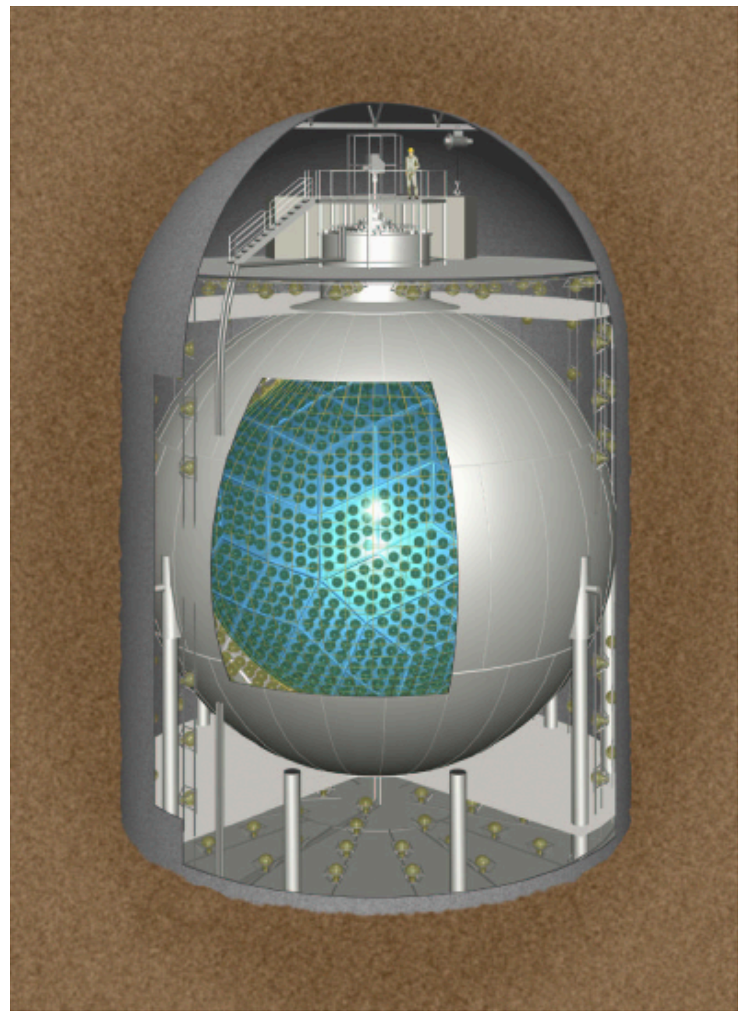
$\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$





$\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$

Liquid scintillator
9600 PMTs



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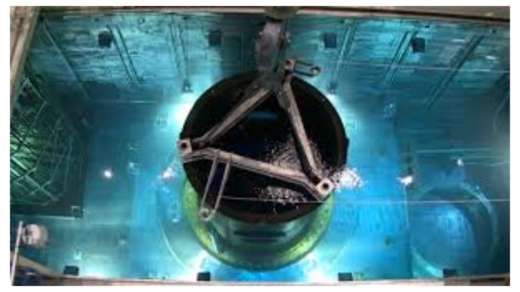
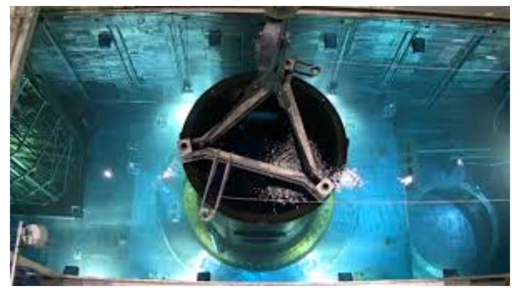
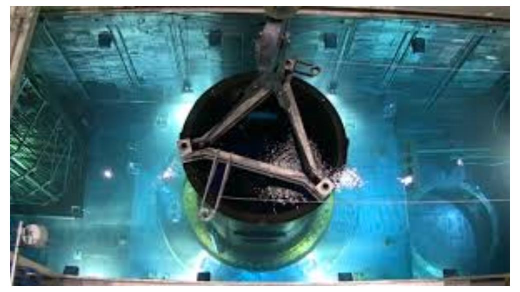




$\overline{\nu}_e$

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

$\overline{\nu}_e$ $\overline{\nu}_e$



- Baseline between **130 - 240 km**

Neutrino oscillation physics - reactor experiments

- Medium baseline $\Longrightarrow$ KamLand cannot resolve short wavelength oscillations:

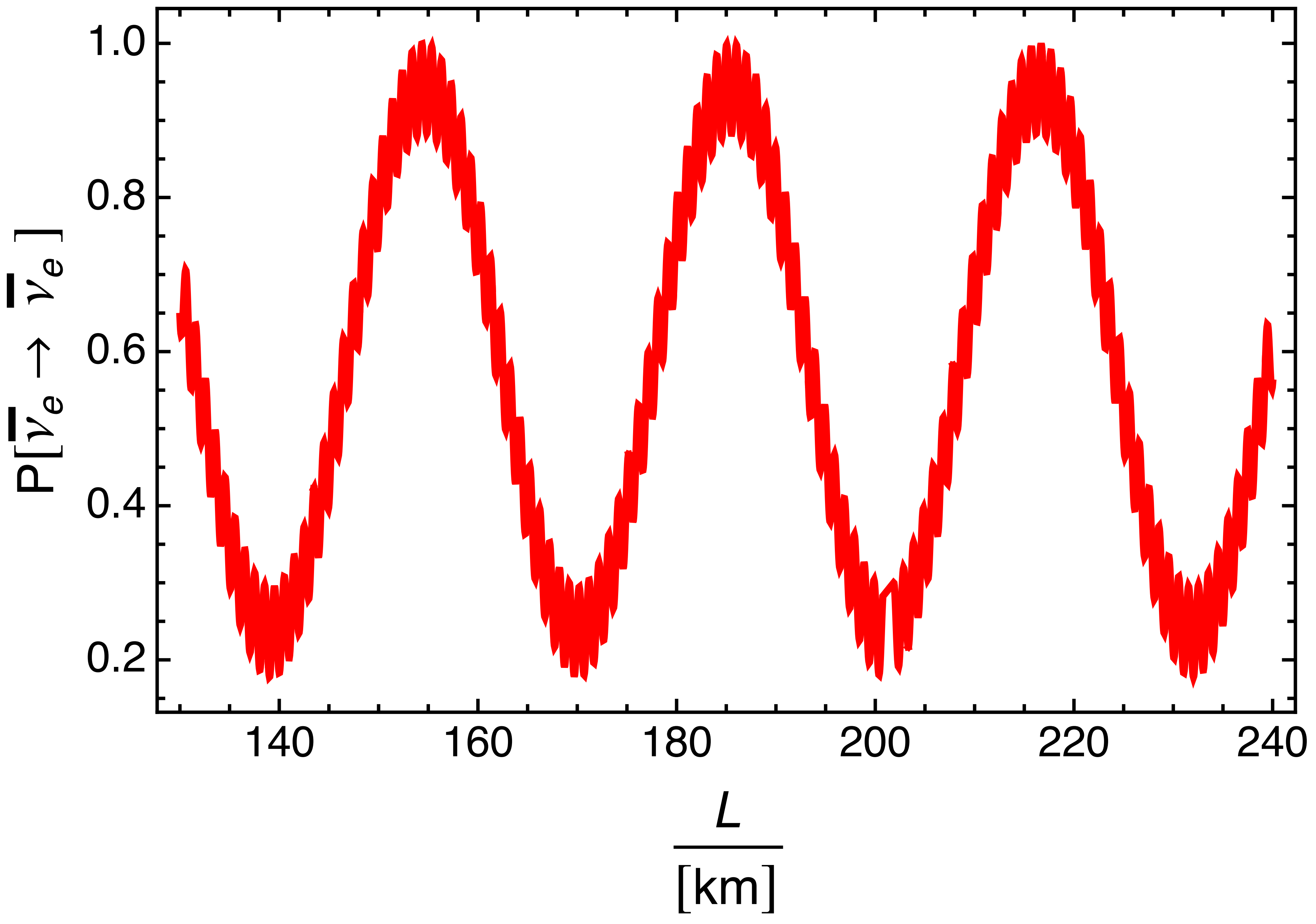
$$P\left(\overline{\nu_e} \to \overline{\nu_e}\right) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

$$\approx \underbrace{\cos^4\theta_{13}}_{\sim 1}\left(1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}\right)$$

$$1 - \frac{1}{2}\sin^2 2x = \cos(x)^4 + \sin(x)^4$$

neglect $\mathcal{O}(\sin^4(\theta_{13}))$

$$\langle \sin^2\Delta_{32}\rangle = \frac{1}{2}$$



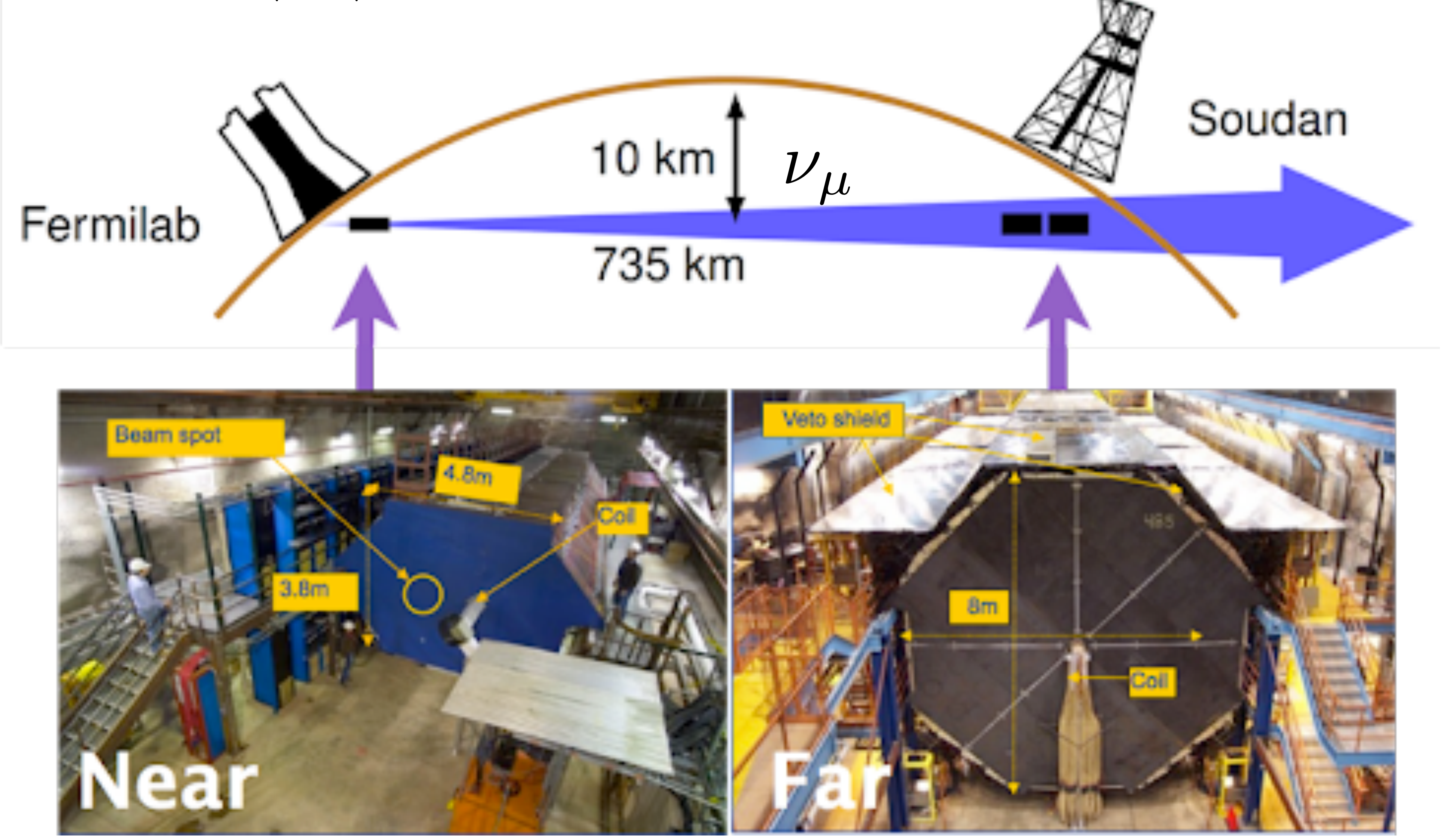
- Survival probability KamLand measures $\theta_{12},\ \Delta m^2_{21}$

Neutrino oscillation physics - accelerator experiments

- Long baseline accelerator experiment such as MINOS, NOvA and T2K can determine the atmospheric angle and mass squared splitting.

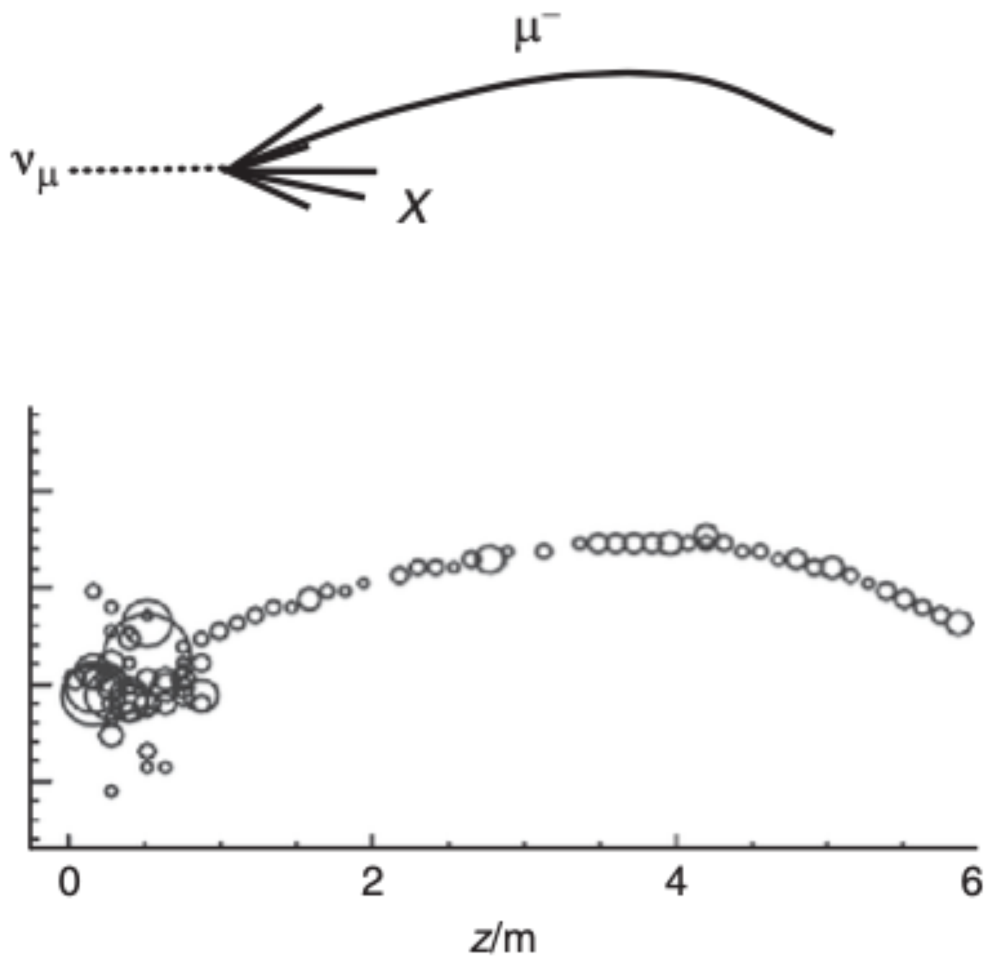
- Long baseline experiments have **near detector** $\Longrightarrow$ **unoscillated neutrino energy spectrum** and far detector & **far detector** $\Longrightarrow$ **oscillated spectrum**

$\langle E_\nu \rangle \sim \mathrm{GeV}$



FD planes of iron 4cm wide plastic scintillator strips

Magnetised momentum muon from CC interactions



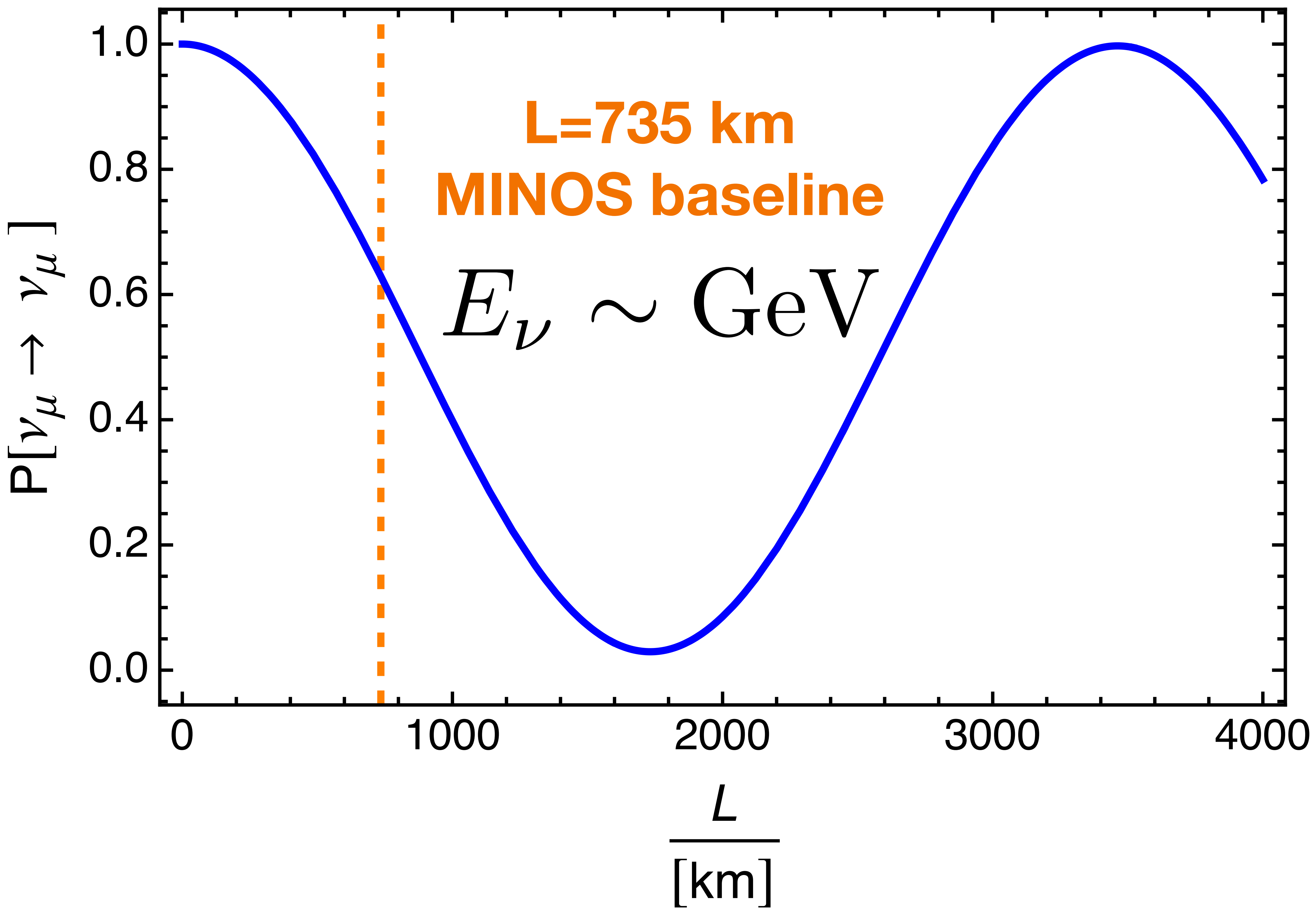
Size of circle indicates amount light recorded In scintillators

Neutrino oscillation physics - accelerator experiments

- Long baseline accelerator experiment: MINOS, NOvA and T2K determine the **atmospheric angle** and **mass squared splitting**.

$$P\left(v_\mu \to v_\mu\right) = 1 - 4\sin^2\left(\theta_{23}\right)\cos^2\left(\theta_{13}\right)\left[1 - \sin^2\left(\theta_{23}\right)\cos^2\left(\theta_{13}\right)\right]\sin^2\Delta_{32}$$
$$= 1 - \left[\underline{\sin^2\left(2\theta_{23}\right)\cos^2\left(\theta_{13}\right)} + \sin^2\left(2\theta_{13}\right)\sin^2\left(\theta_{23}\right)\right]\sin^2\Delta_{32}$$

dominant term since reactor mixing angle small



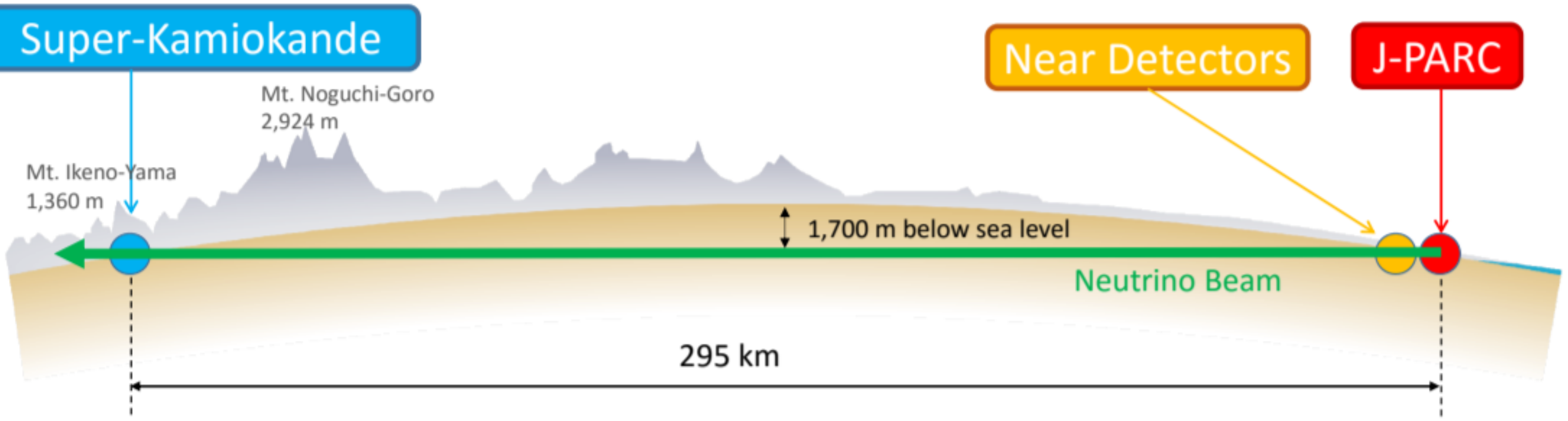
Neutrino oscillation physics - CP-violation

- To observe CP-violation $\Longrightarrow$ difference between an oscillation process and its CP-conjugate process:

$$(\nu_\mu \to \nu_e) \xrightarrow{\text{CP}} (\overline{\nu_\mu} \to \overline{\nu_e})$$

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e}) \propto \mathrm{Im}\left[U_{e1}^* U_{\mu 1} U_{e2} U_{\mu 2}^*\right] \sin\Delta_{12} \sin\Delta_{13} \sin\Delta_{23}$$

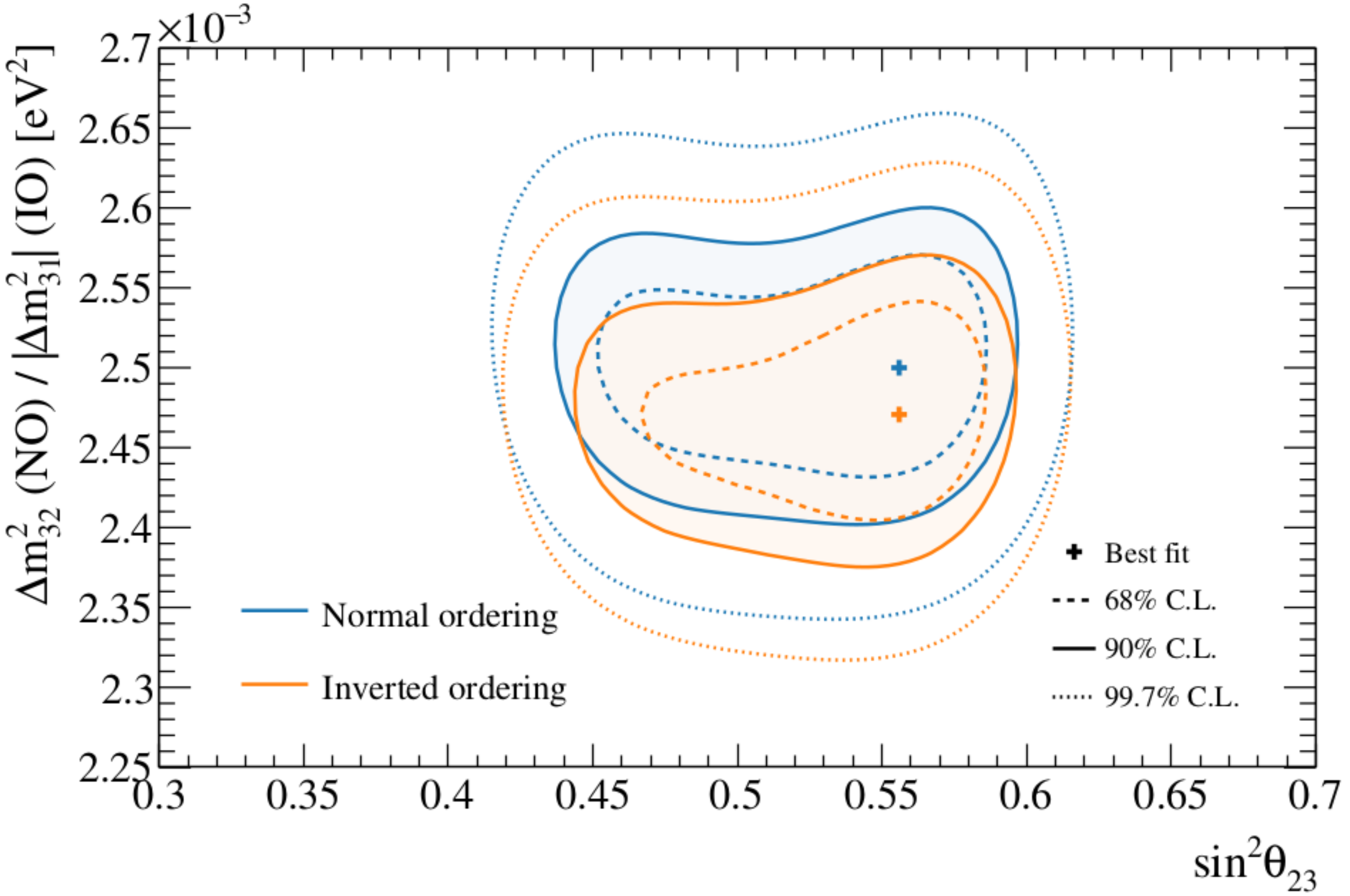
- What is the current status of CP-violation in the neutrino sector?

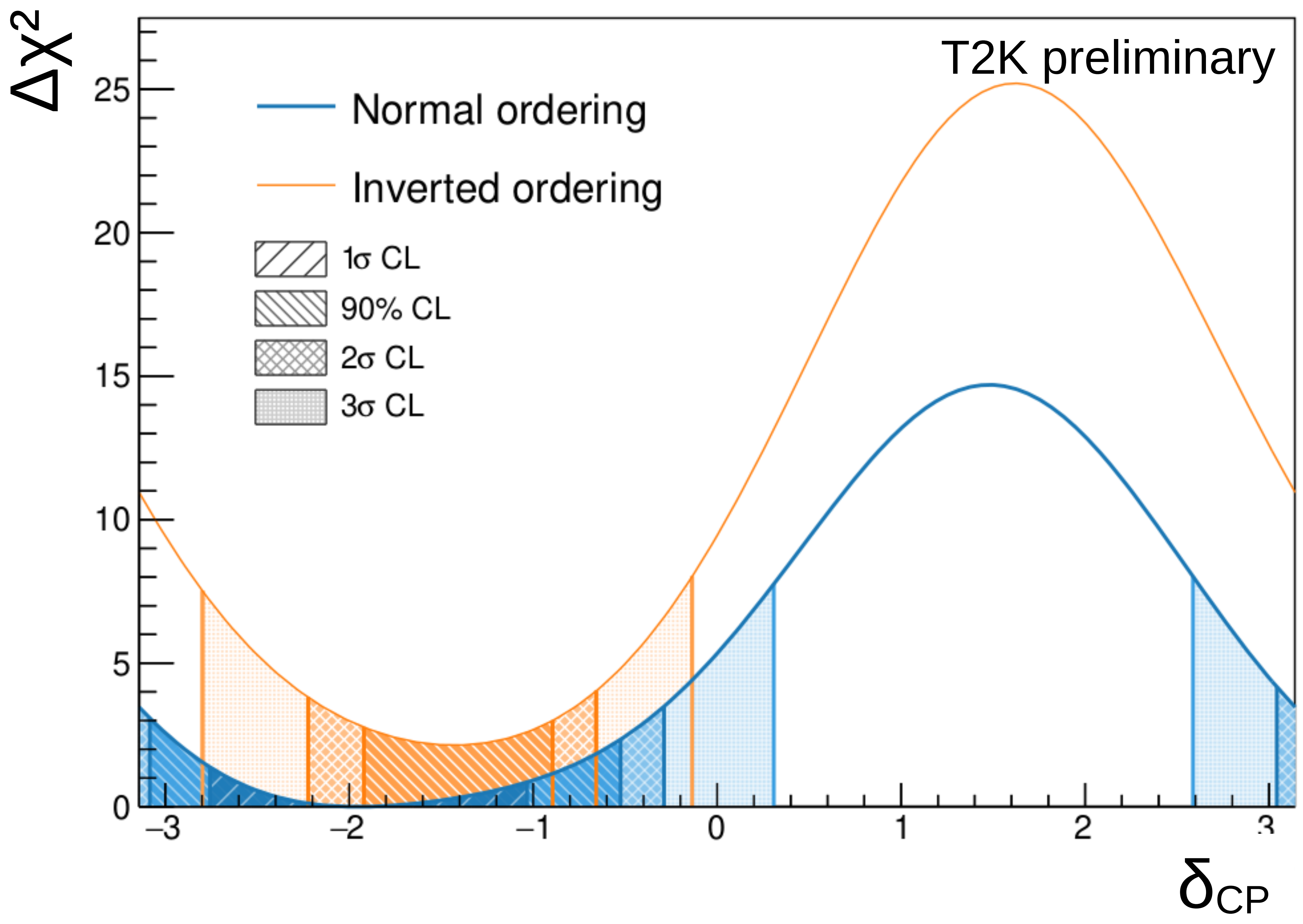


T2K

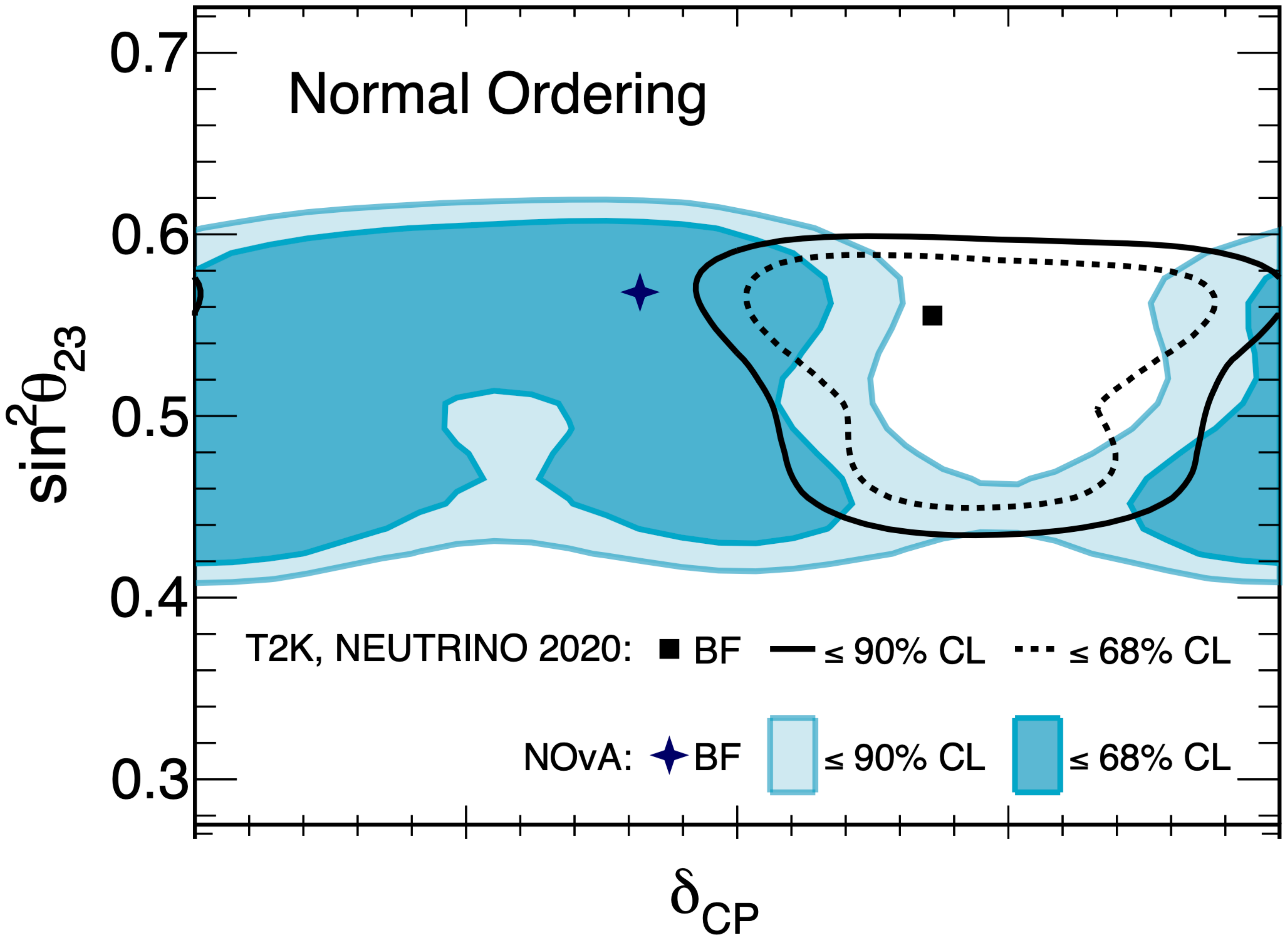
NoVA

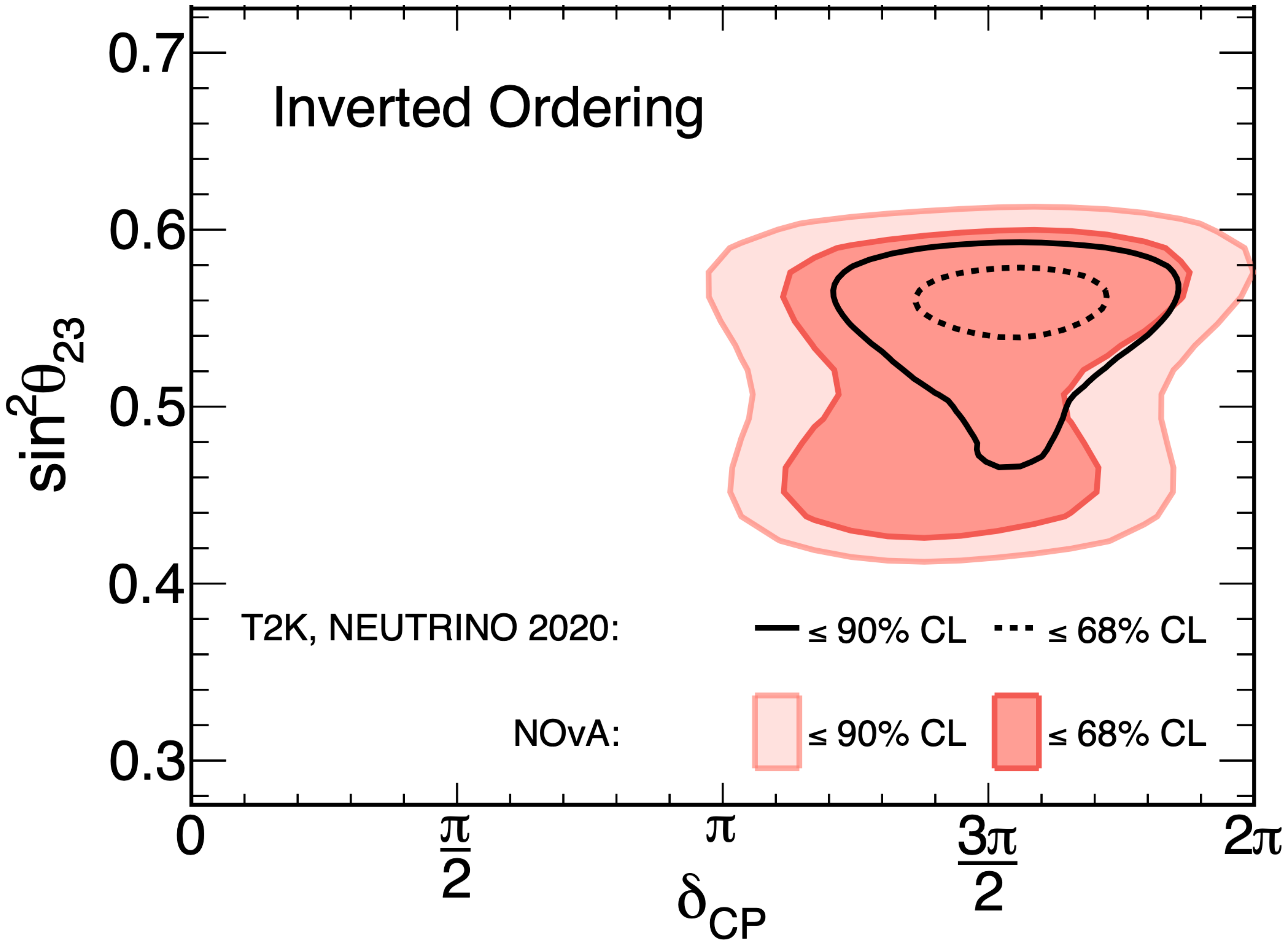
- T2K mild preference $\theta_{23} > 45^\circ$ and normal ordering
- T2K disfavours CP-conservation at 90% CL

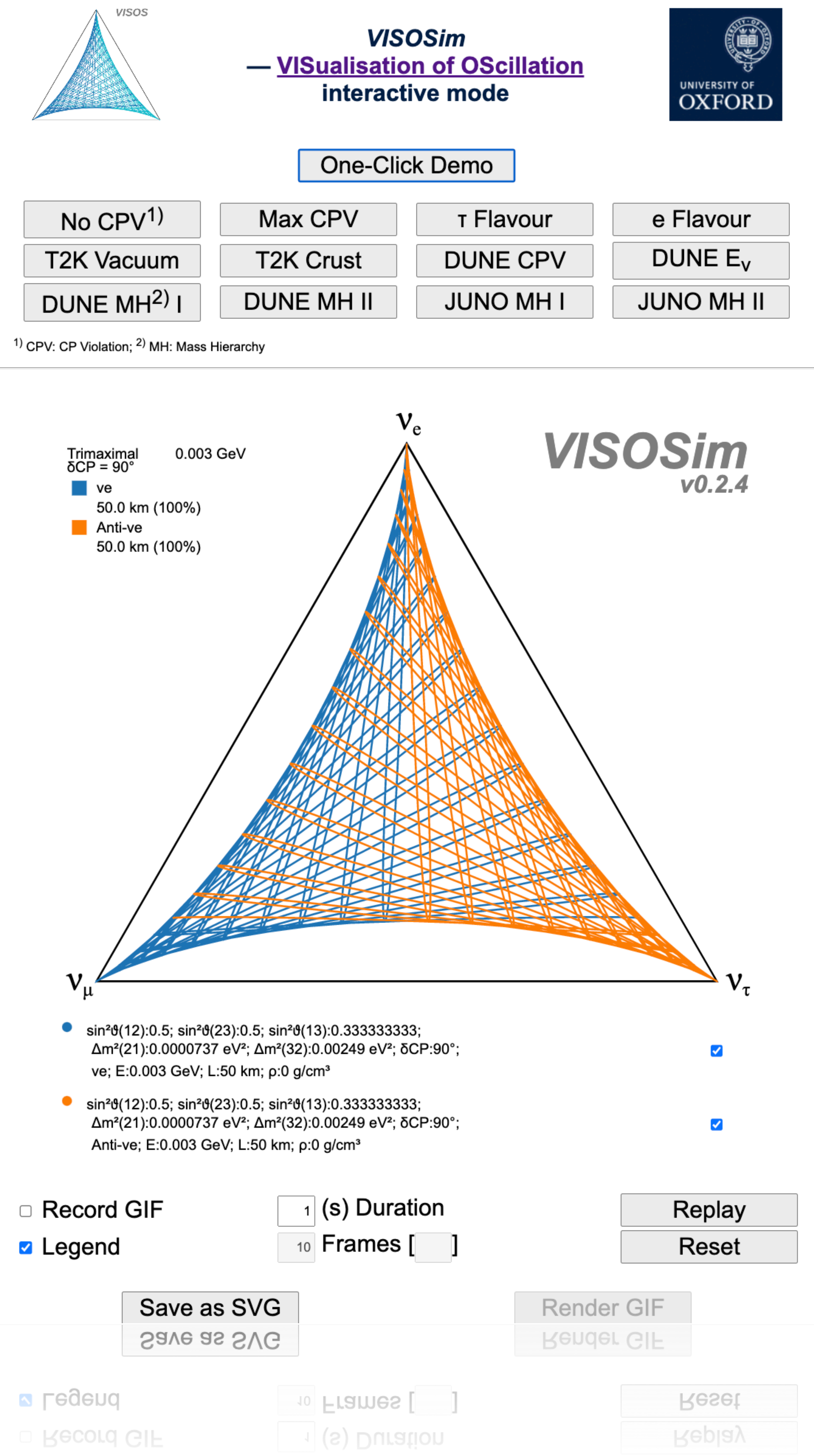




- NOVA has preference for normal ordering, $\delta \sim 145^\circ$
- Exclude IO and $\delta = \pi/2 \; > 3\sigma$







There are amazing neutrino Oscillation visualisation tools, check these out!

http://www-pnp.physics.ox.ac.uk/~luxi/visos/

http://www-pnp.physics.ox.ac.uk/~luxi/visos/im/

Thanks to Xianguo Lu