# Neutrino Physics

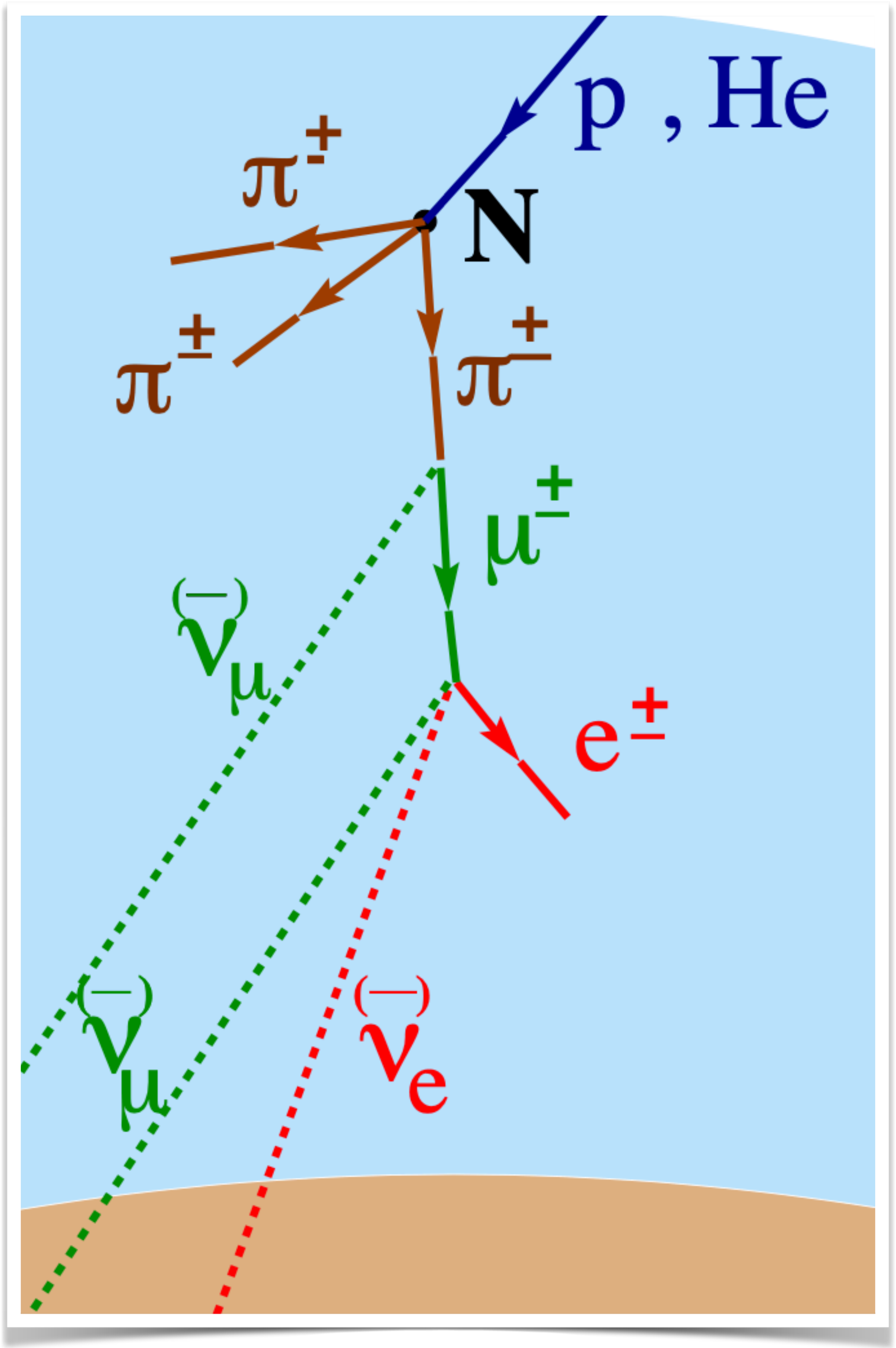
## Neutrino Oscillations in vacuum

## NExT PhD Workshop 2023

Jessica Turner

# Atmospheric neutrinos

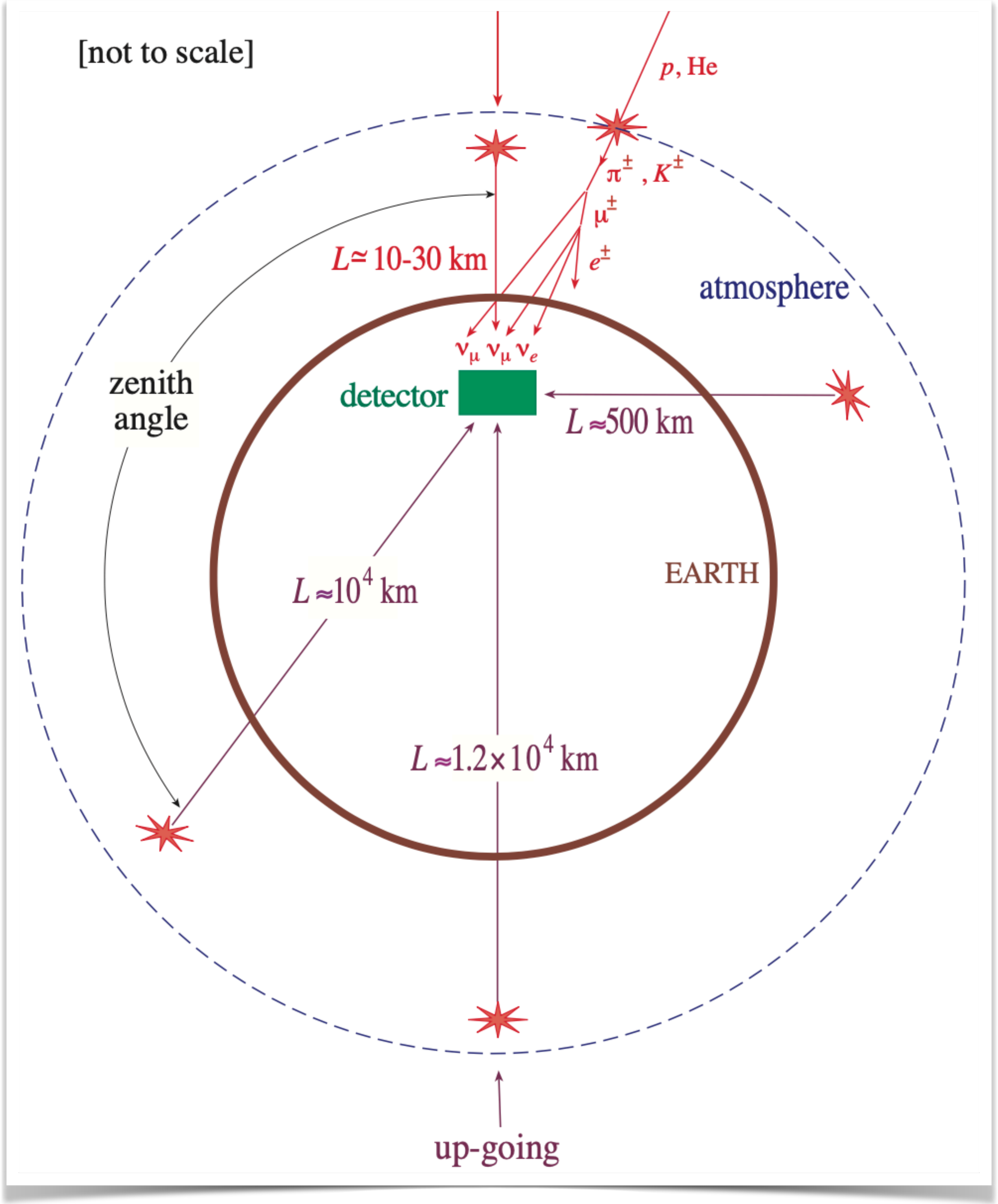
- Neutrinos produced via cosmic rays (accelerated protons, He) in the atmosphere

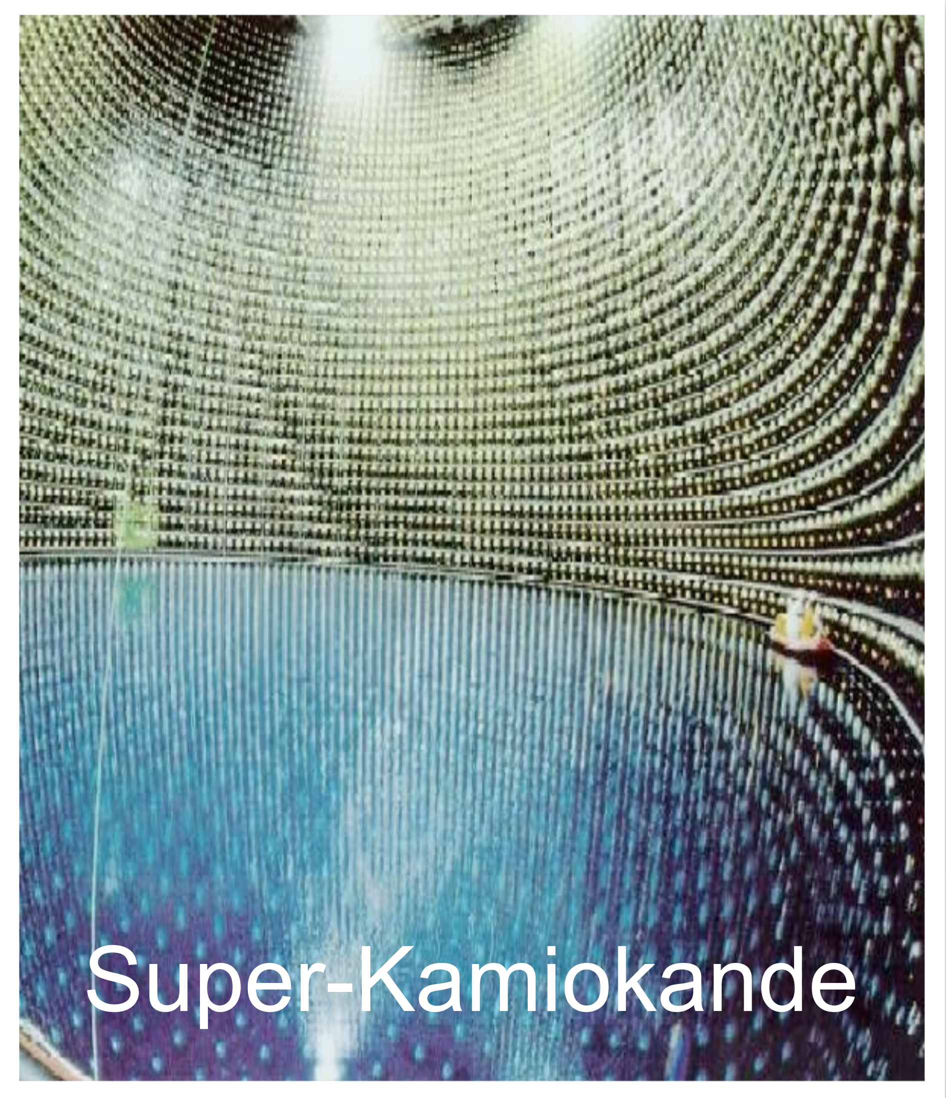


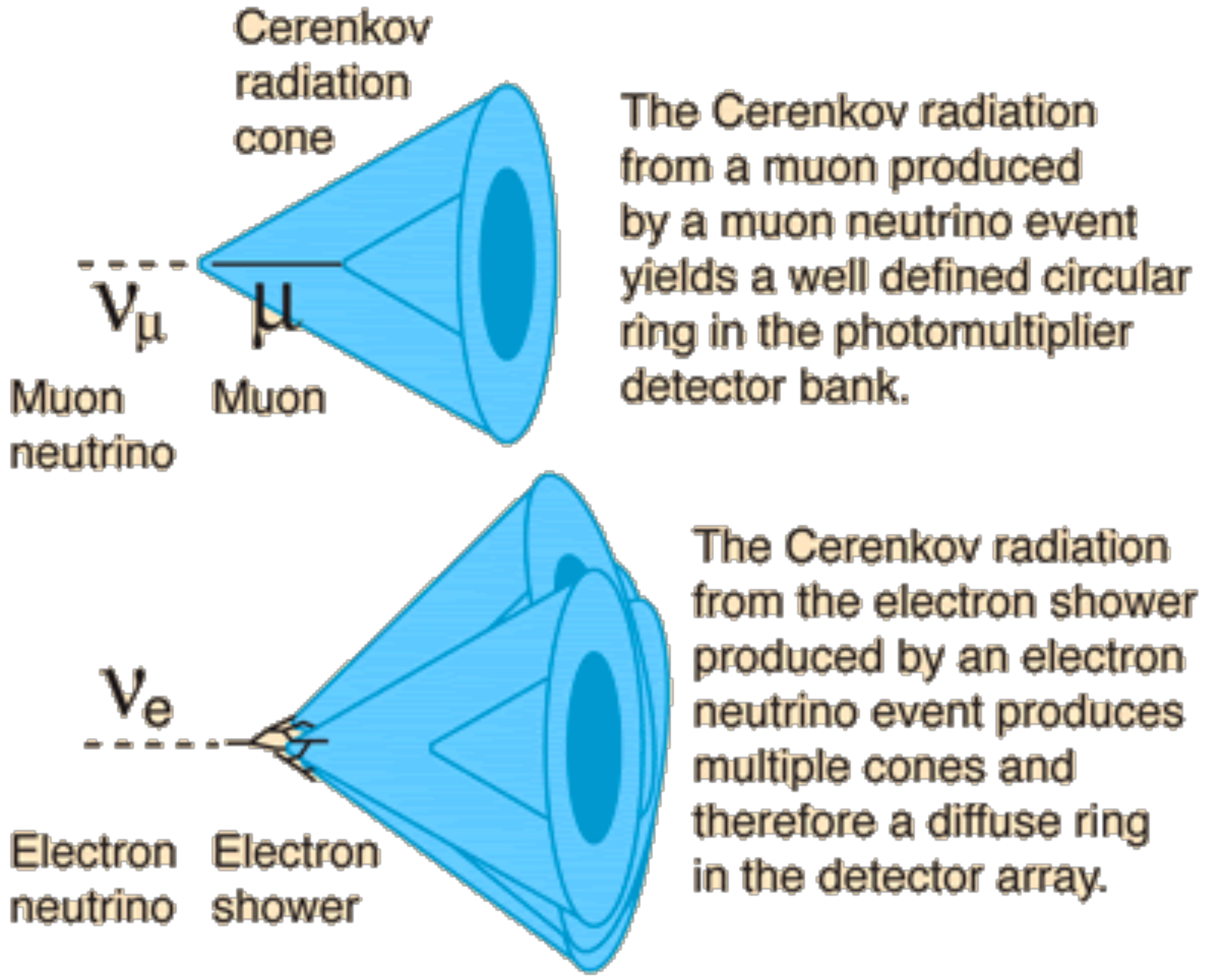

$$R_{\frac{\mu}{e}} \approx \frac{N_{\nu_\mu} + N_{\overline{\nu_\mu}}}{N_{\nu_e} + N_{\overline{\nu_e}}} \sim 2$$

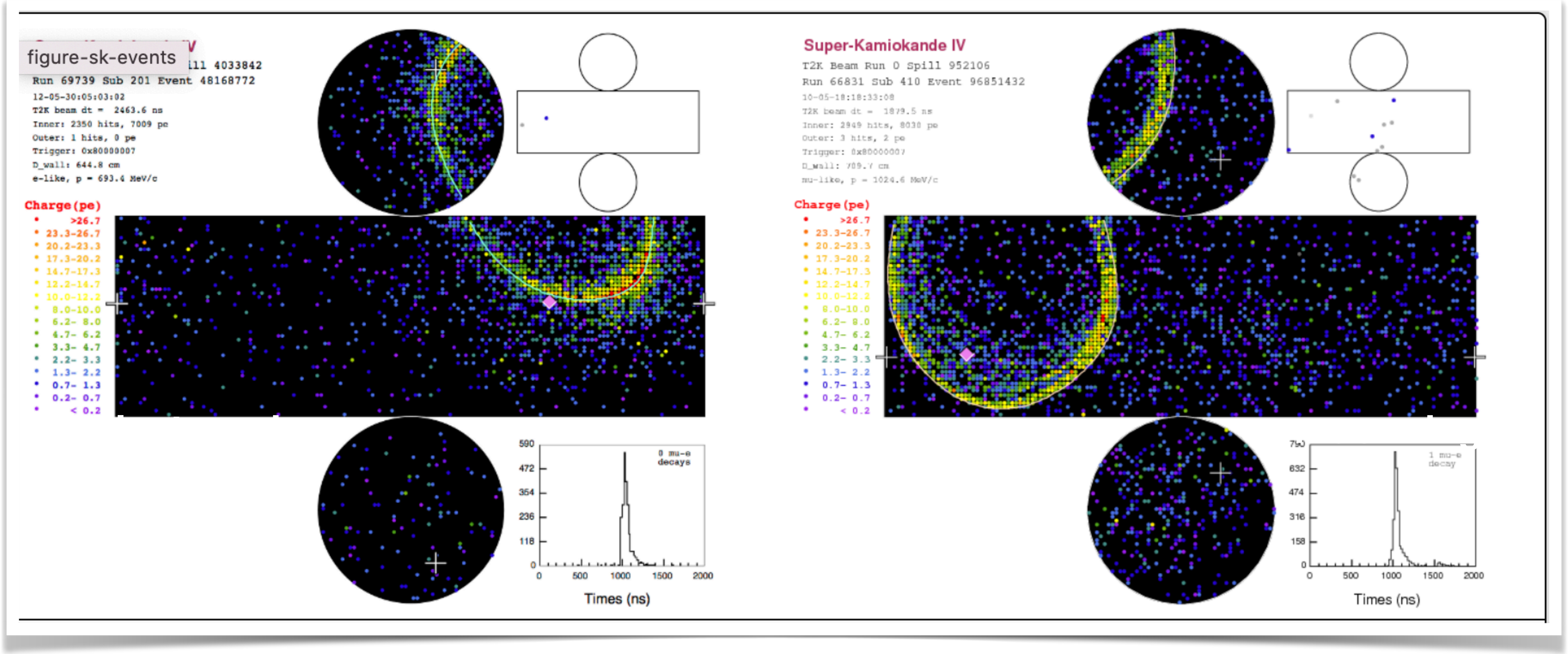
# Atmospheric neutrinos

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



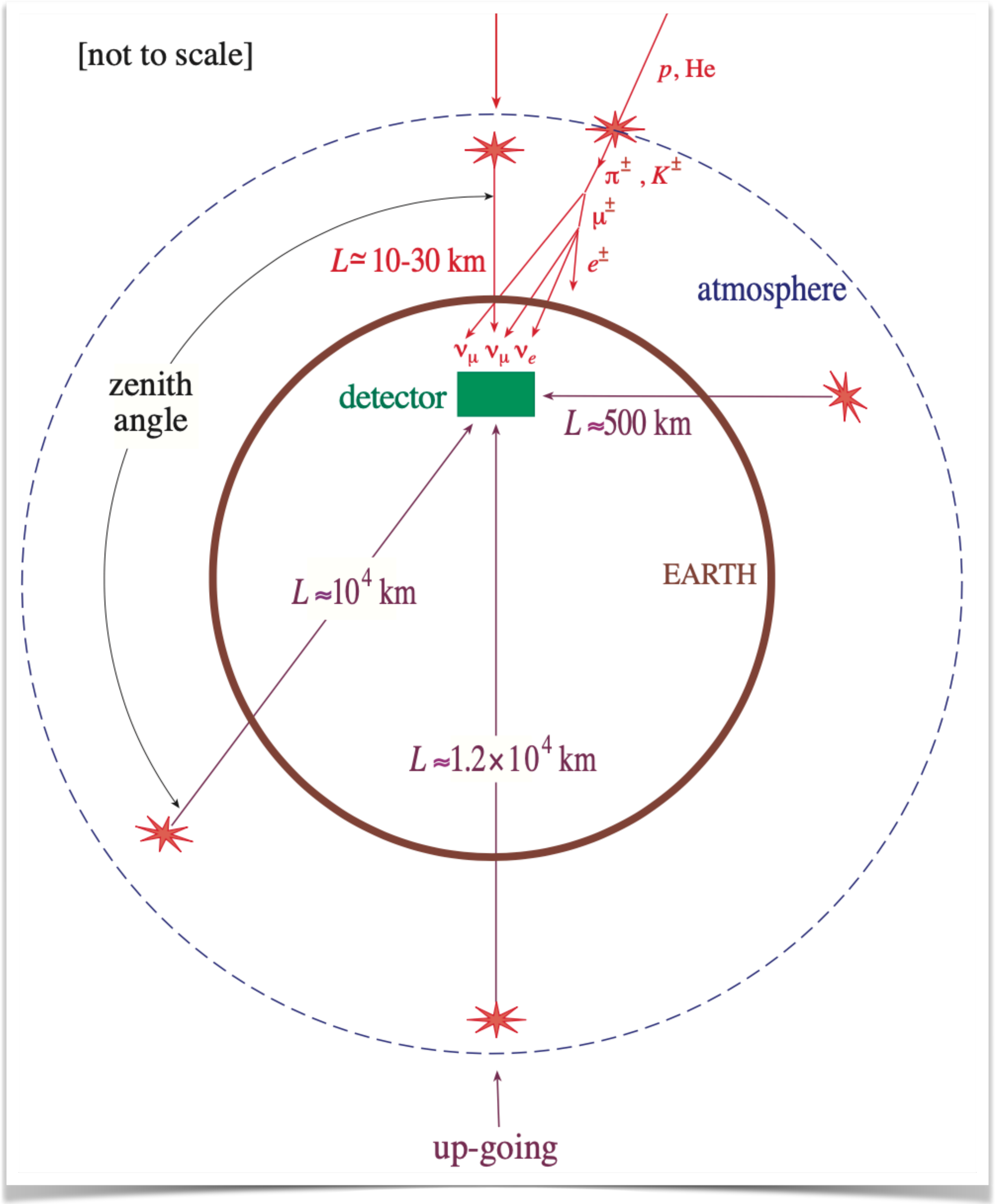



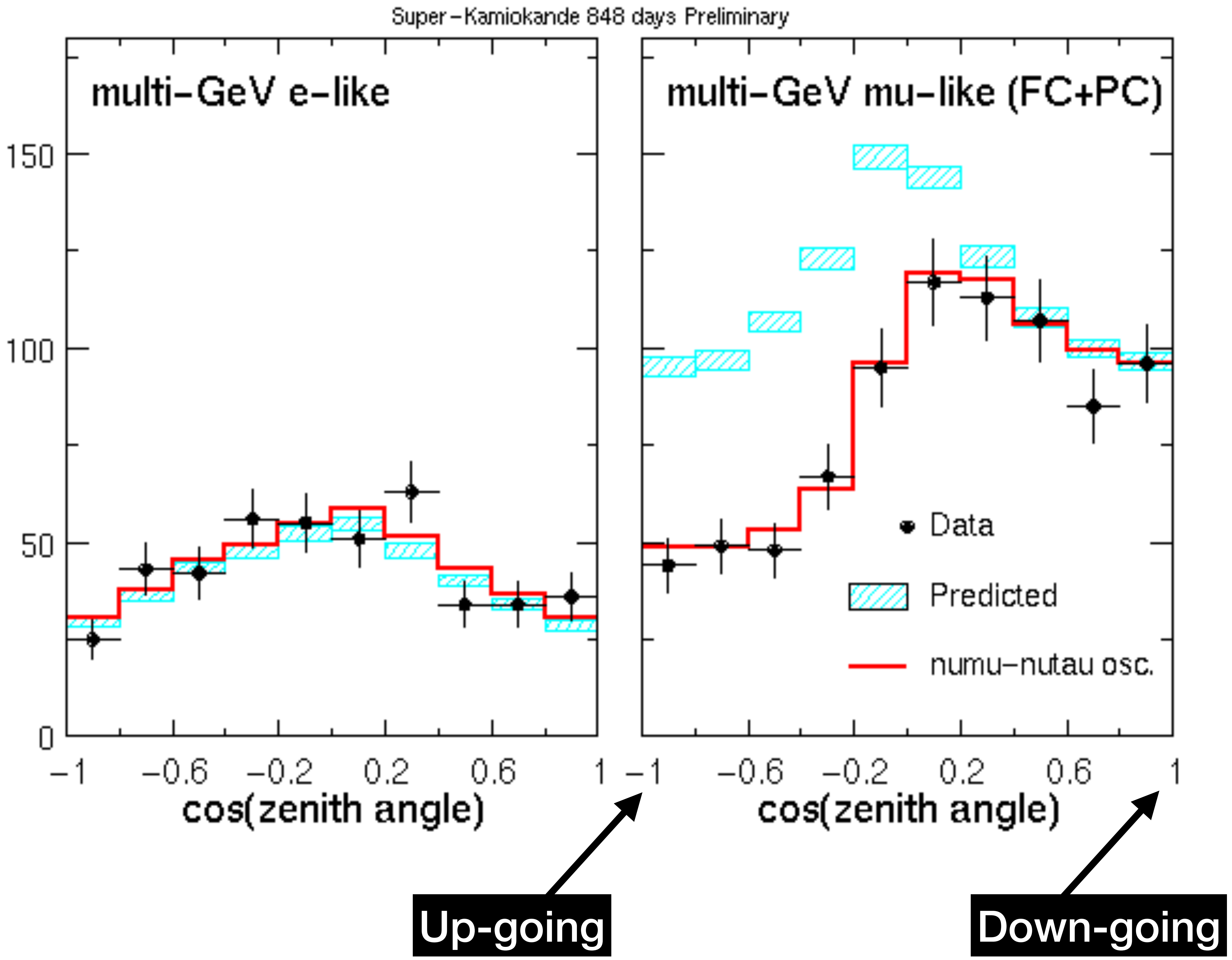



# Atmospheric neutrinos

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



# Board

$$
\begin{bmatrix} \nu_{\mathrm{e}} \\ \nu_{\mu} \\ \nu_{\tau} \end{bmatrix} = \begin{bmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}
$$

$$
U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

- If neutrinos are Dirac → 3 mixing angles + 1 phase

$$\begin{bmatrix} \nu_{\mathrm{e}} \\ \nu_{\mu} \\ \nu_{\tau} \end{bmatrix} = \begin{bmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

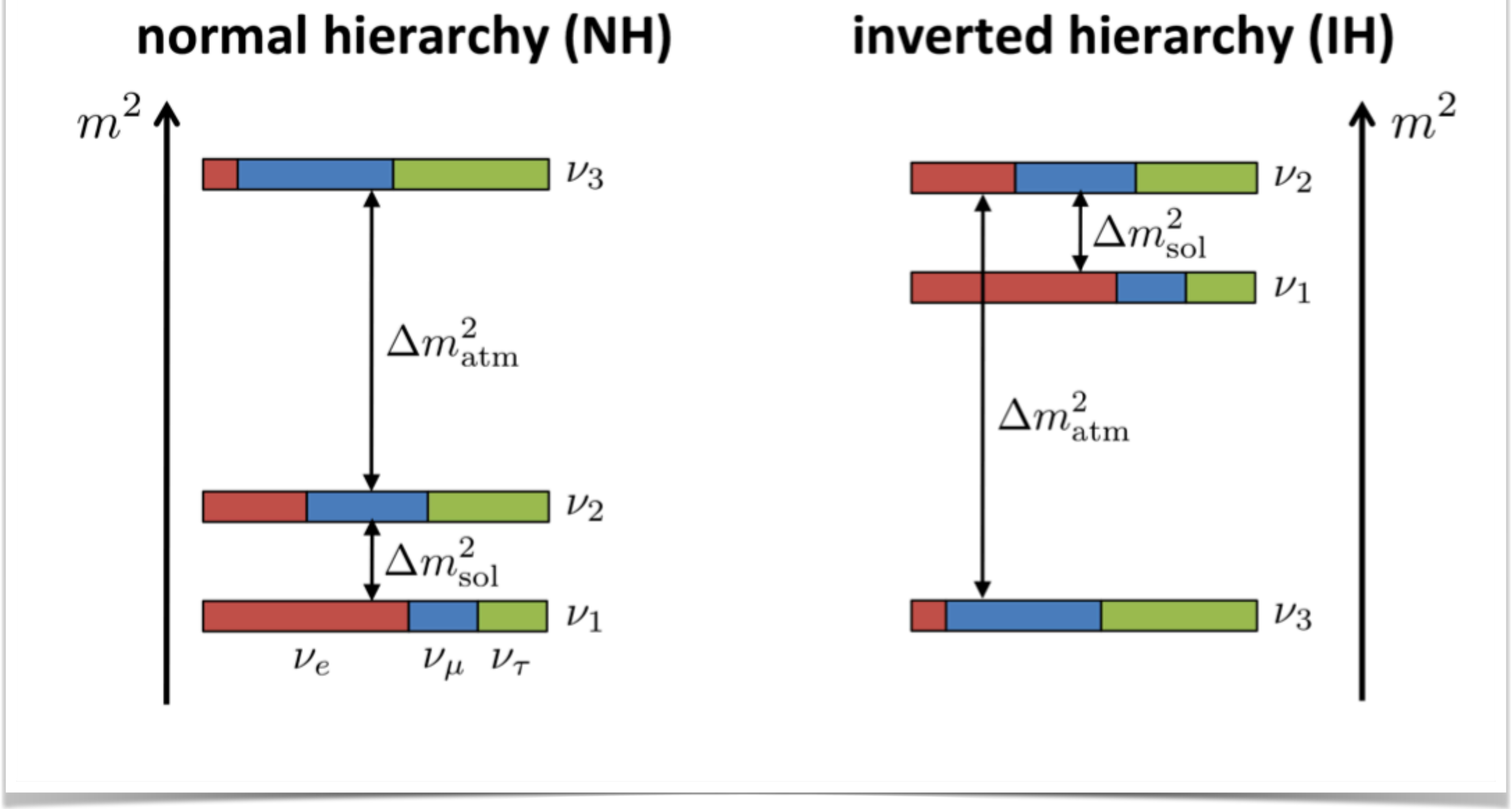
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{bmatrix}$$

- If neutrinos are Majorana → 3 mixing angles + 3 phase

# Current knowledge

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

$$\begin{array}{ll} \text{Normal hierarchy} & m_1 < m_2 < m_3 \implies \Delta m^2_{32} > 0, \\ \text{Inverted hierarchy} & m_3 < m_1 < m_2 \implies \Delta m^2_{32} < 0. \end{array}$$



# Current knowledge

www.nu-fit.org

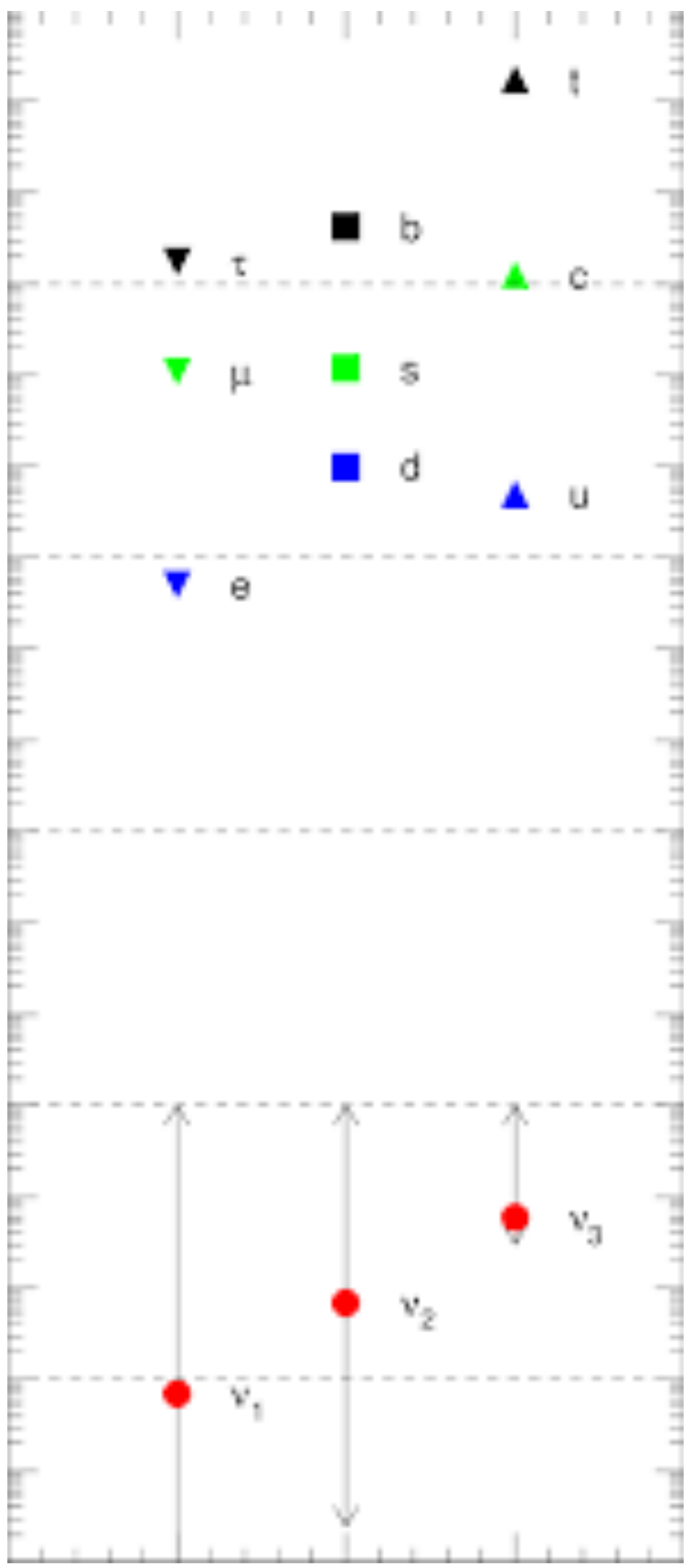
**Nu-fit global fit 5.1**

with SK atmospheric data

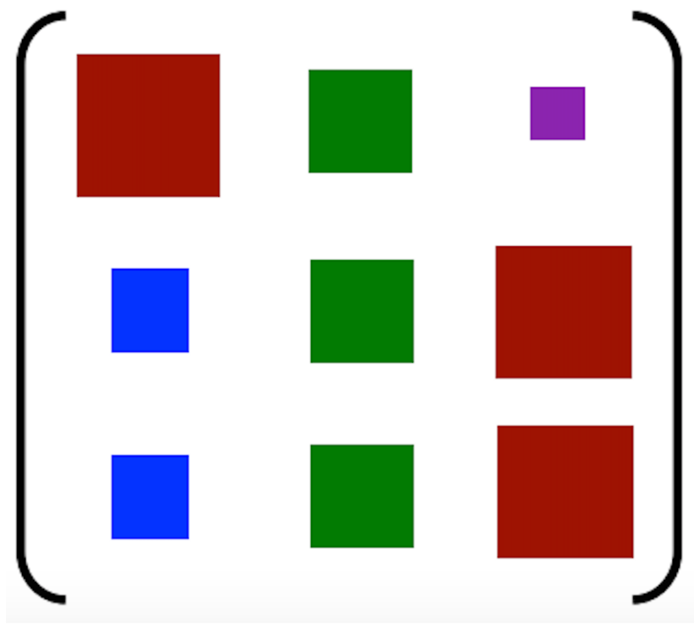
| | Normal Ordering (best fit) | | Inverted Ordering ($\Delta\chi^2 = 7.0$) | |
|---|---|---|---|---|
| | bfp $\pm 1\sigma$ | $3\sigma$ range | bfp $\pm 1\sigma$ | $3\sigma$ range |
| $\sin^2\theta_{12}$ | $0.304^{+0.012}_{-0.012}$ | $0.269 \to 0.343$ | $0.304^{+0.013}_{-0.012}$ | $0.269 \to 0.343$ |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

| mixing parameter | relative uncertainty ($3\sigma$) | Quark sector equivalent |
|---|---|---|
| $\theta_{13}$ | 4.7% | 4.0% |
| $\theta_{23}$ | 22% | 5.2% |
| $\theta_{12}$ | 7.3% | 0.3% |
| $\delta$ | 100% | |
| $\Delta m^2_{21}$ | 8% | |
| $\lvert\Delta m^2_{31}\rvert$ | 3.5% | |

# Current knowledge

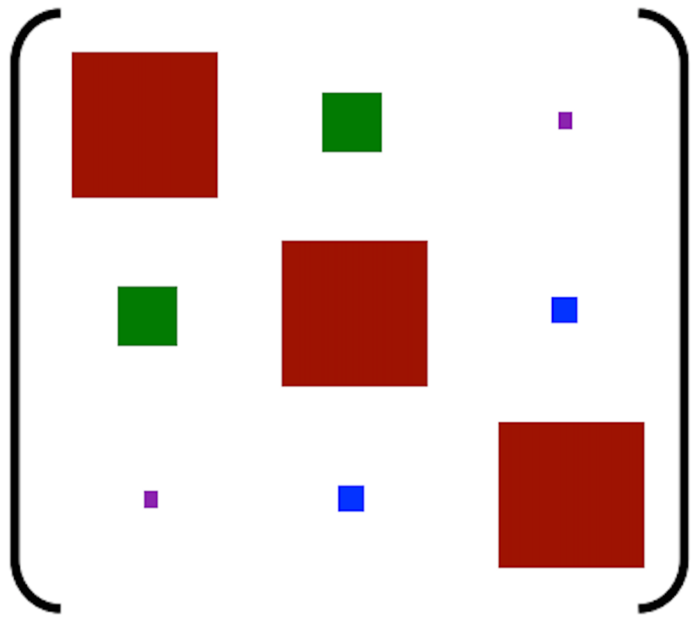



**Lepton Sector**



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

**Quark Sector**

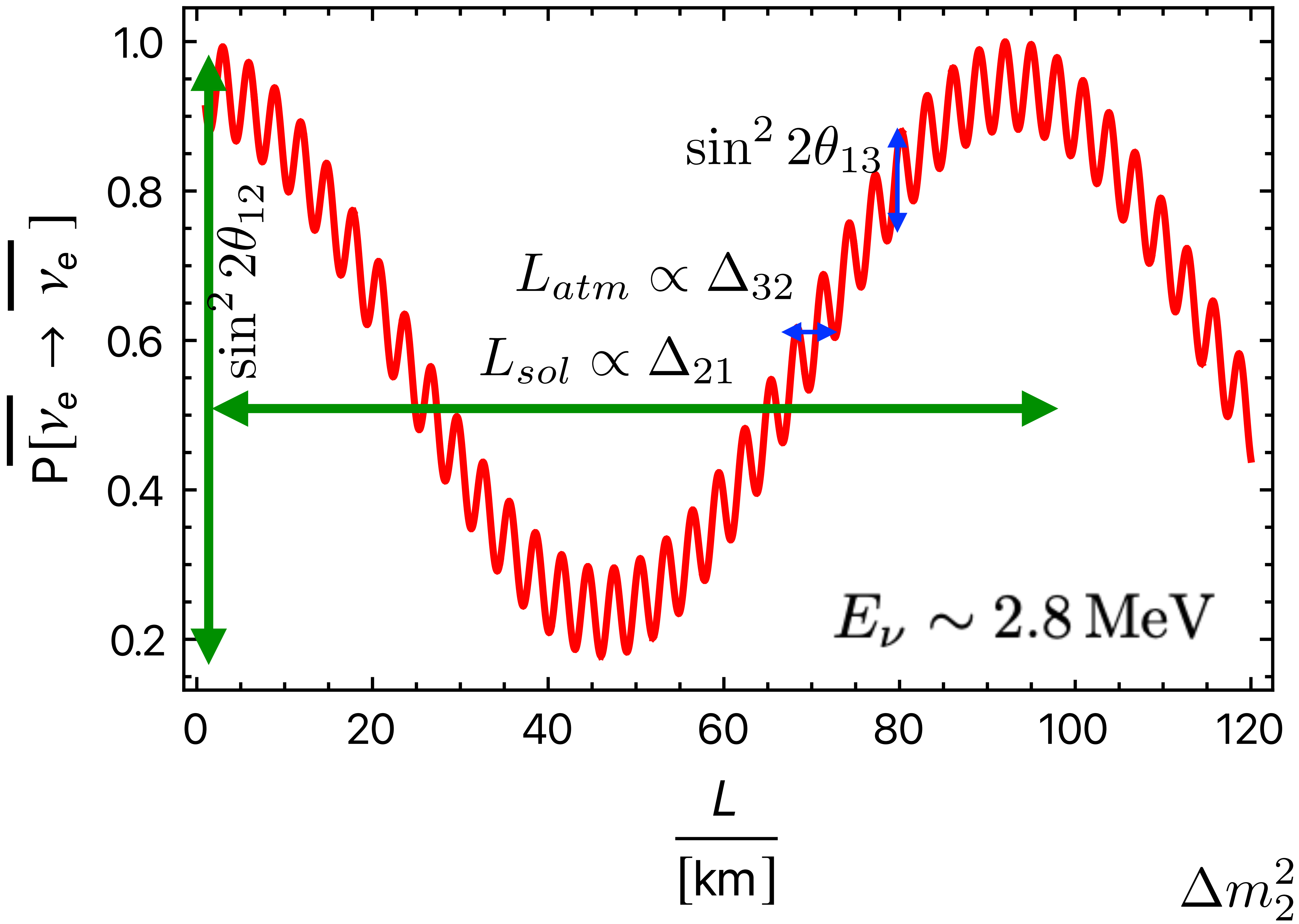


$$\sim \begin{pmatrix} 0.98 & 0.2 & 0.0 \\ 0.2 & 0.99 & 0.0 \\ 0.0 & 0.04 & 1.0 \end{pmatrix}$$

- 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

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




Consider the wavelength of each contribution

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

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

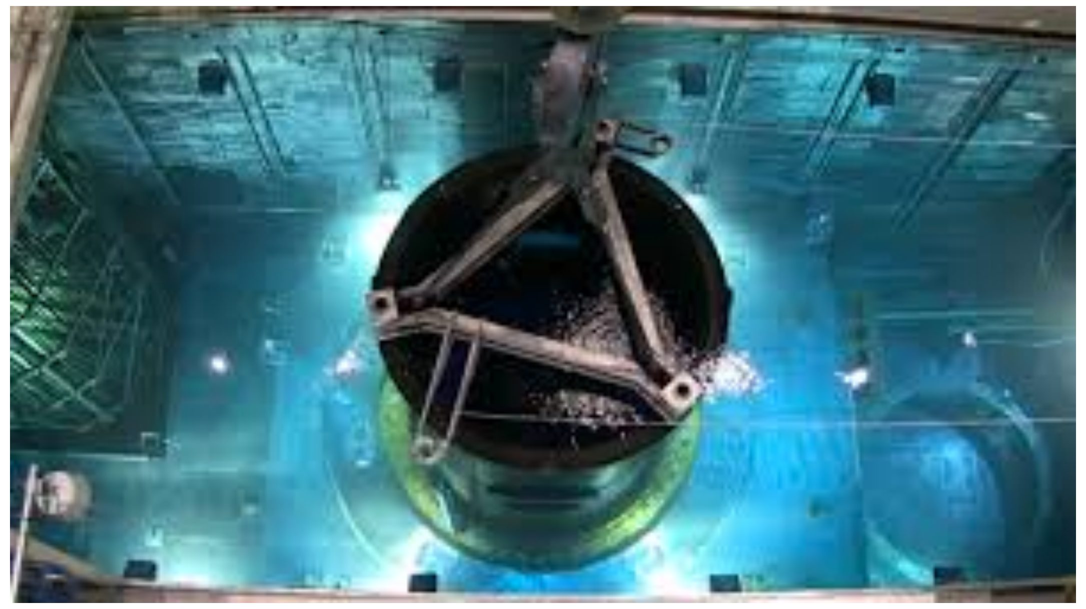
$\Delta m^2_{21} \sim 7.4 \times 10^{-5}\mathrm{eV}^2$ $\quad E_\nu \sim 2.8\,\mathrm{MeV}$ $\quad L_{\mathrm{sol}} \sim 90$ km

$\Delta m_{32} \sim 2.5 \times 10^{-3}\mathrm{eV}^2$ $\quad L_{\mathrm{atm}} \sim 2.8$ km

# Neutrino oscillation physics - reactor experiments

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

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

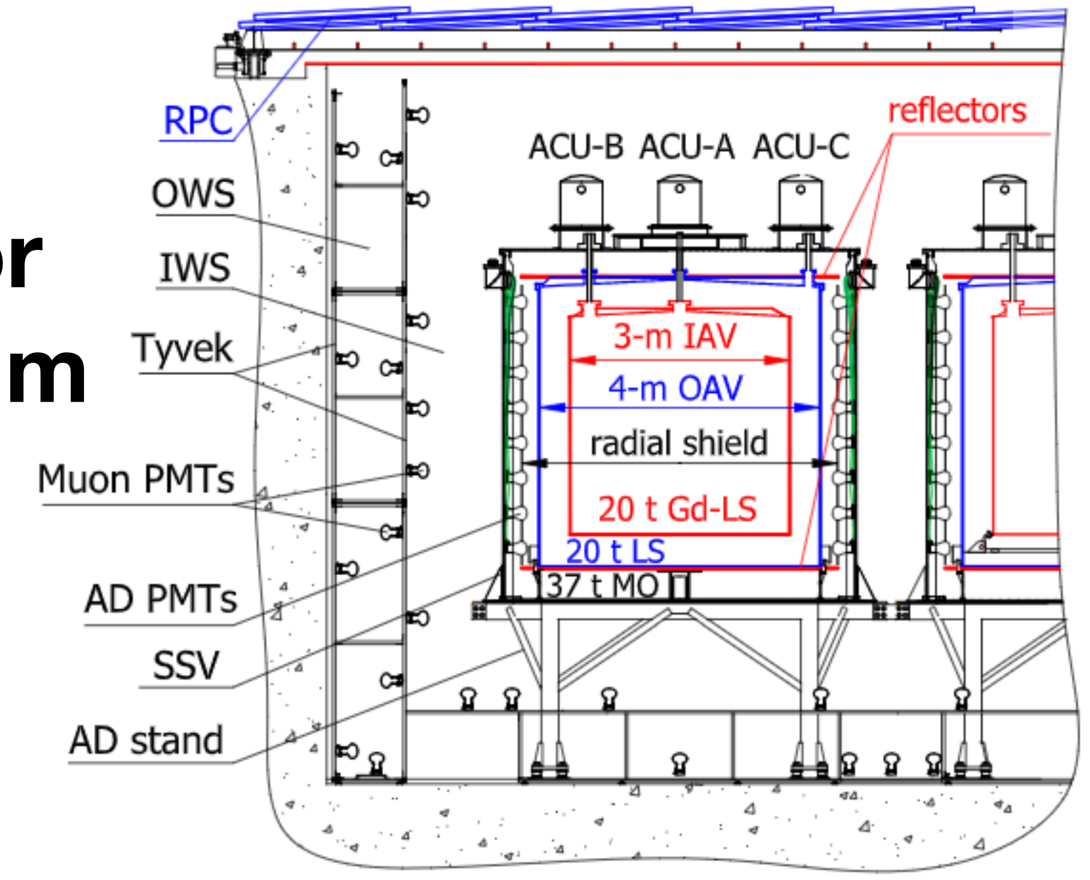


$\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$

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

$4\,\mathrm{km}$

**Liquid scintillator doped Gadolinium**




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

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

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

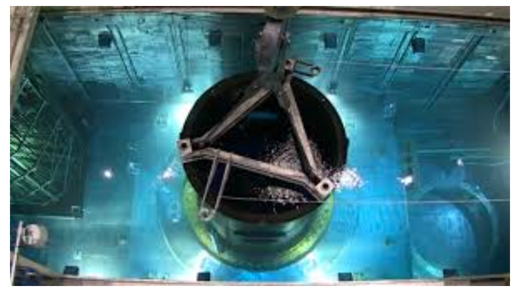
- At such short baselines, the short wavelength term dominates

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

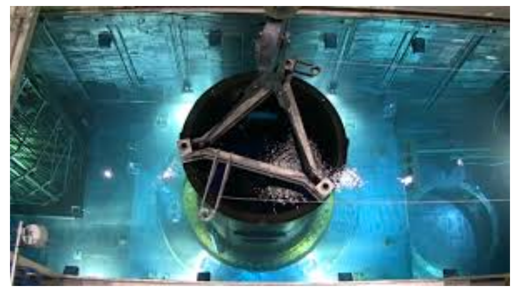
$$P\left(\overline{\nu_e} \to \overline{\nu_e}\right) \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

# Neutrino oscillation physics - reactor experiments

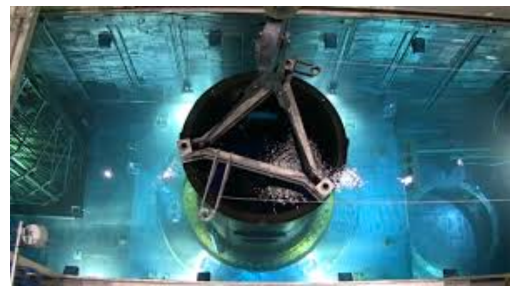
- KamLand is a medium baseline reactor experiment in same cavern as SK



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

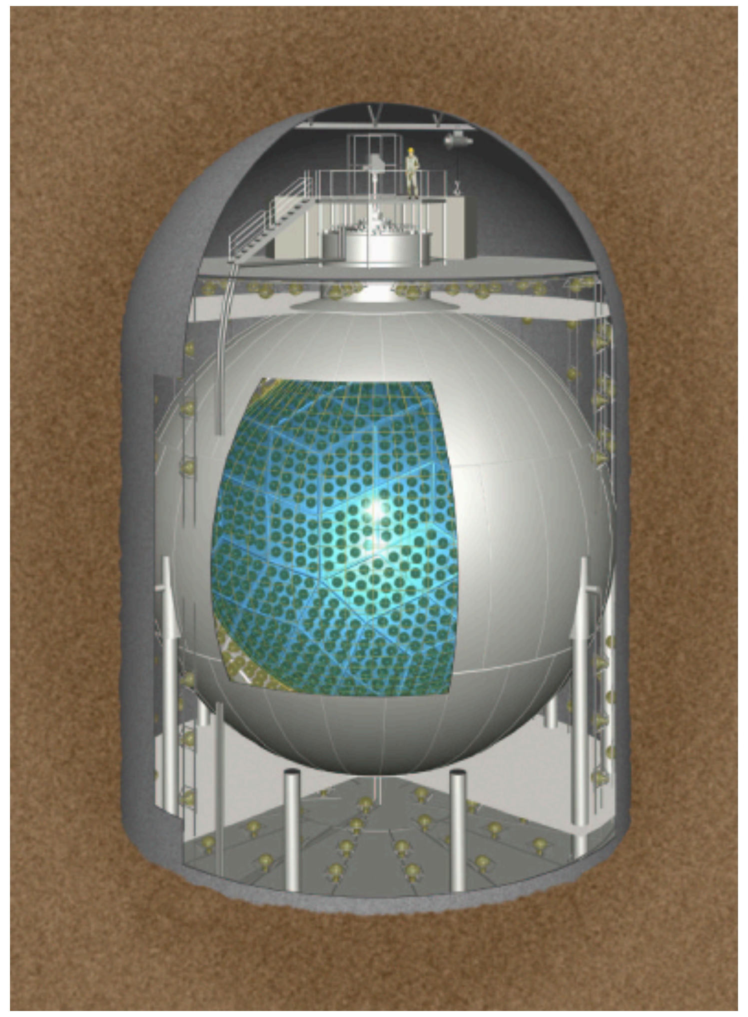


$\overline{\nu}_e$ $\overline{\nu}_e$

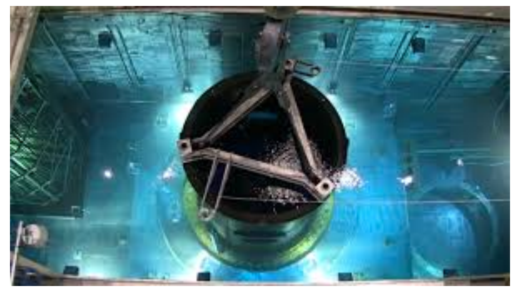


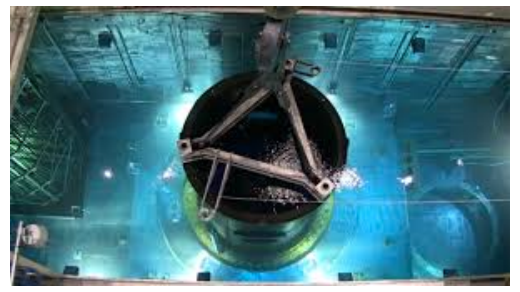
$\overline{\nu}_e$

**Liquid scintillator 9600 PMTs**



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

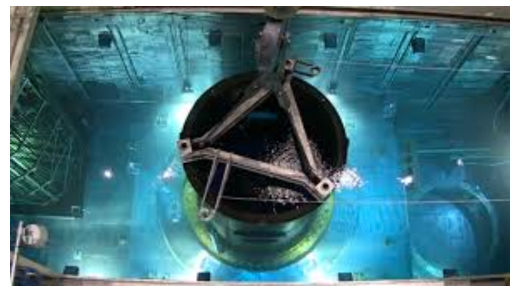




$\overline{\nu}_e$

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

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



- Baseline between **130 - 240 km**

# Neutrino oscillation physics - reactor experiments

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

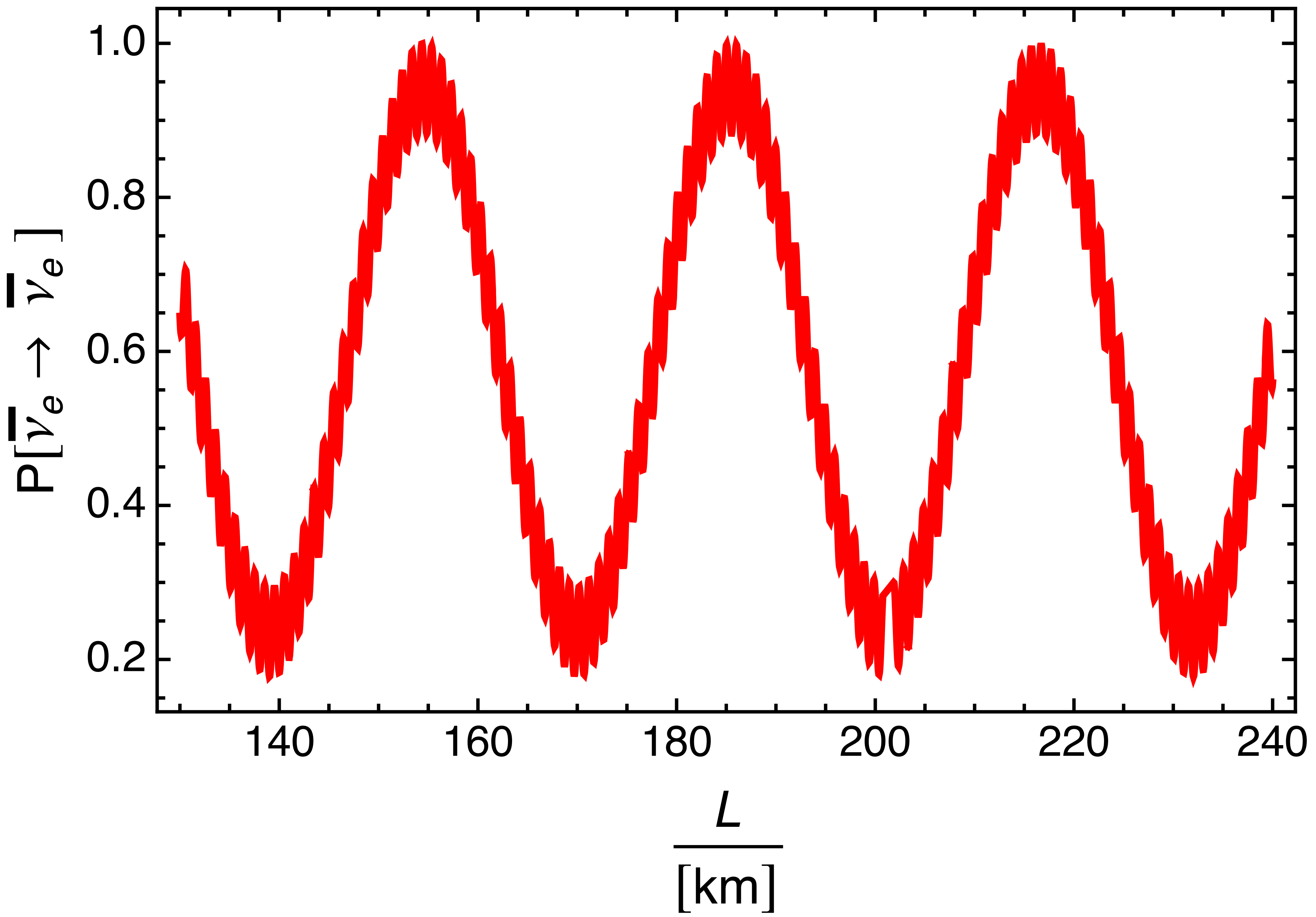
$$P(\overline{\nu_e} \to \overline{\nu_e}) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

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

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

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

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

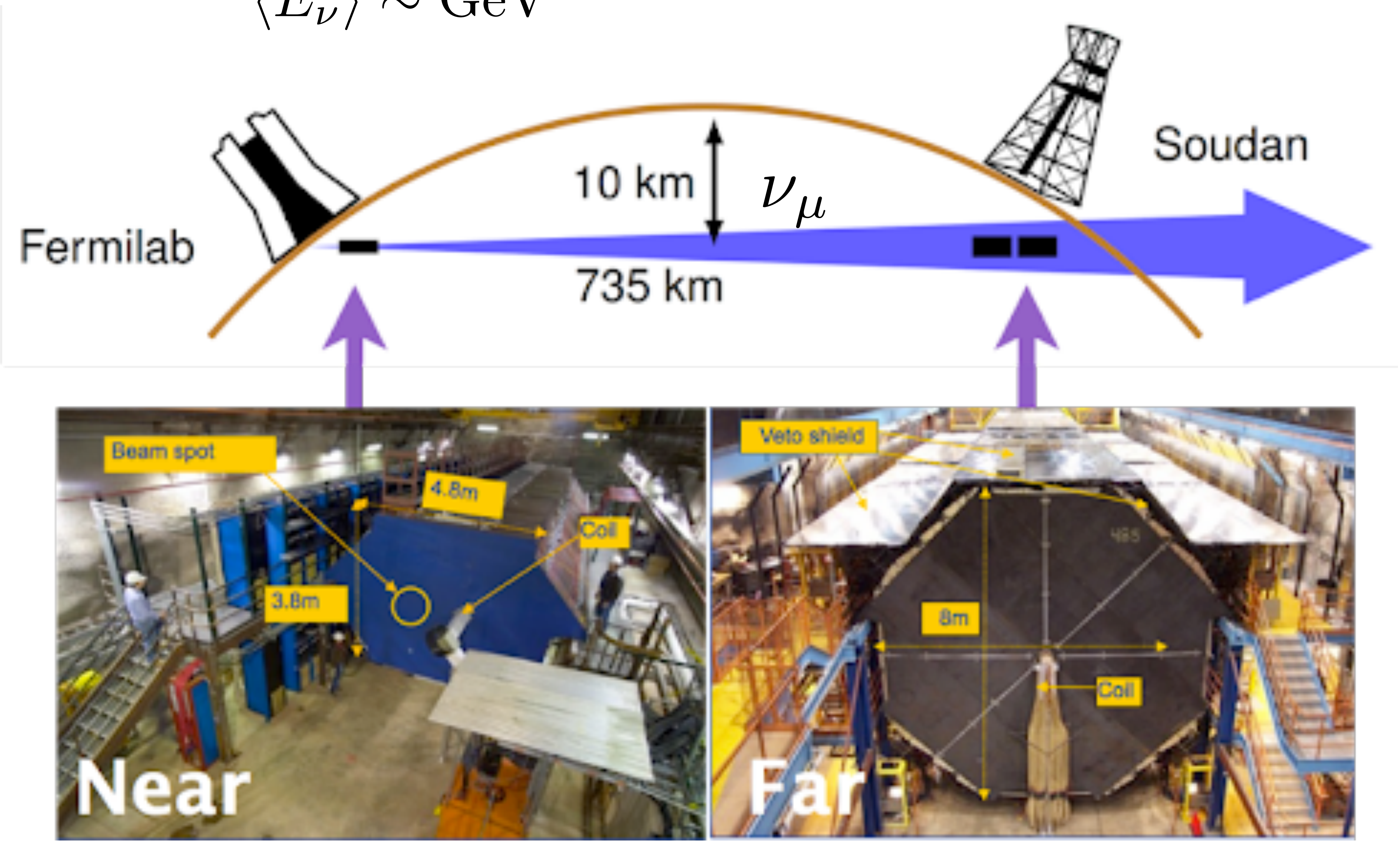



- Survival probability KamLand measures $\theta_{12},\ \Delta m^2_{21}$

# Neutrino oscillation physics - accelerator experiments

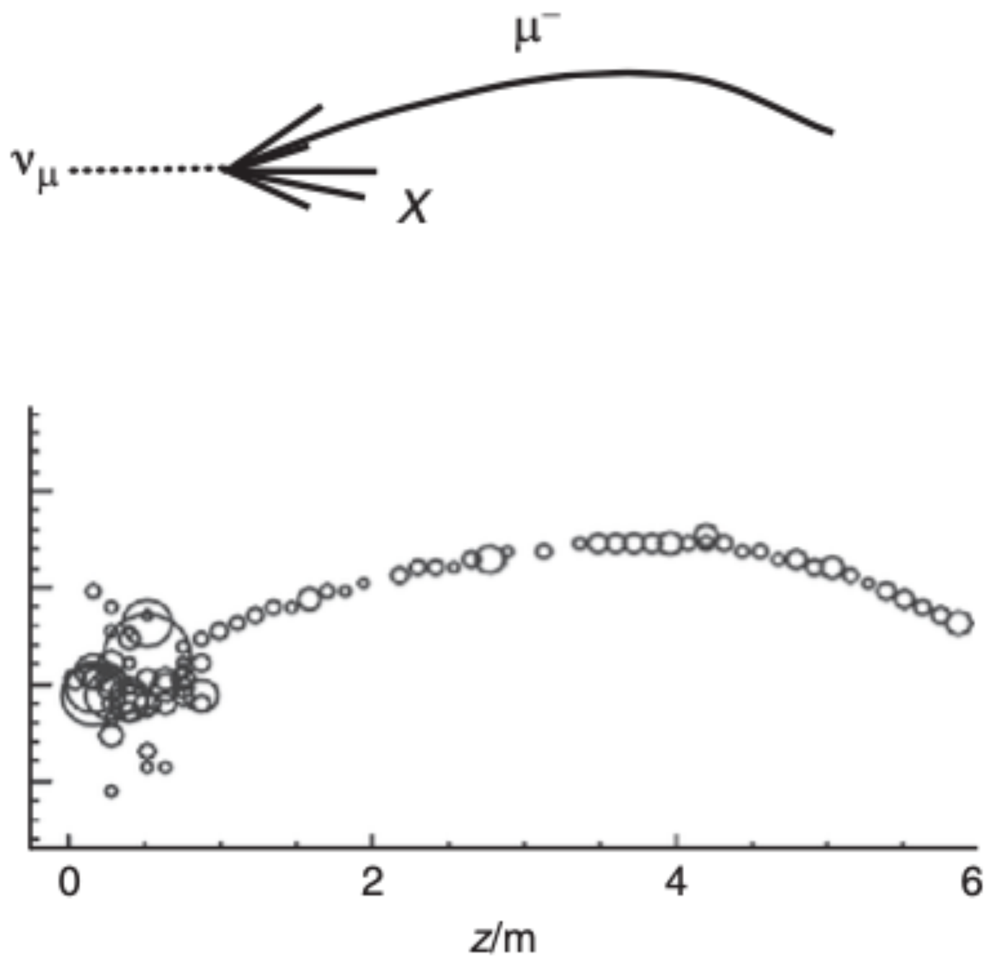
- Long baseline accelerator experiment such as **MINOS**, NOvA and T2K can determine the atmospheric angle and mass squared splitting.

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




**FD planes of iron 4cm wide plastic scintillator strips**

**Magnetised momentum muon from CC interactions**



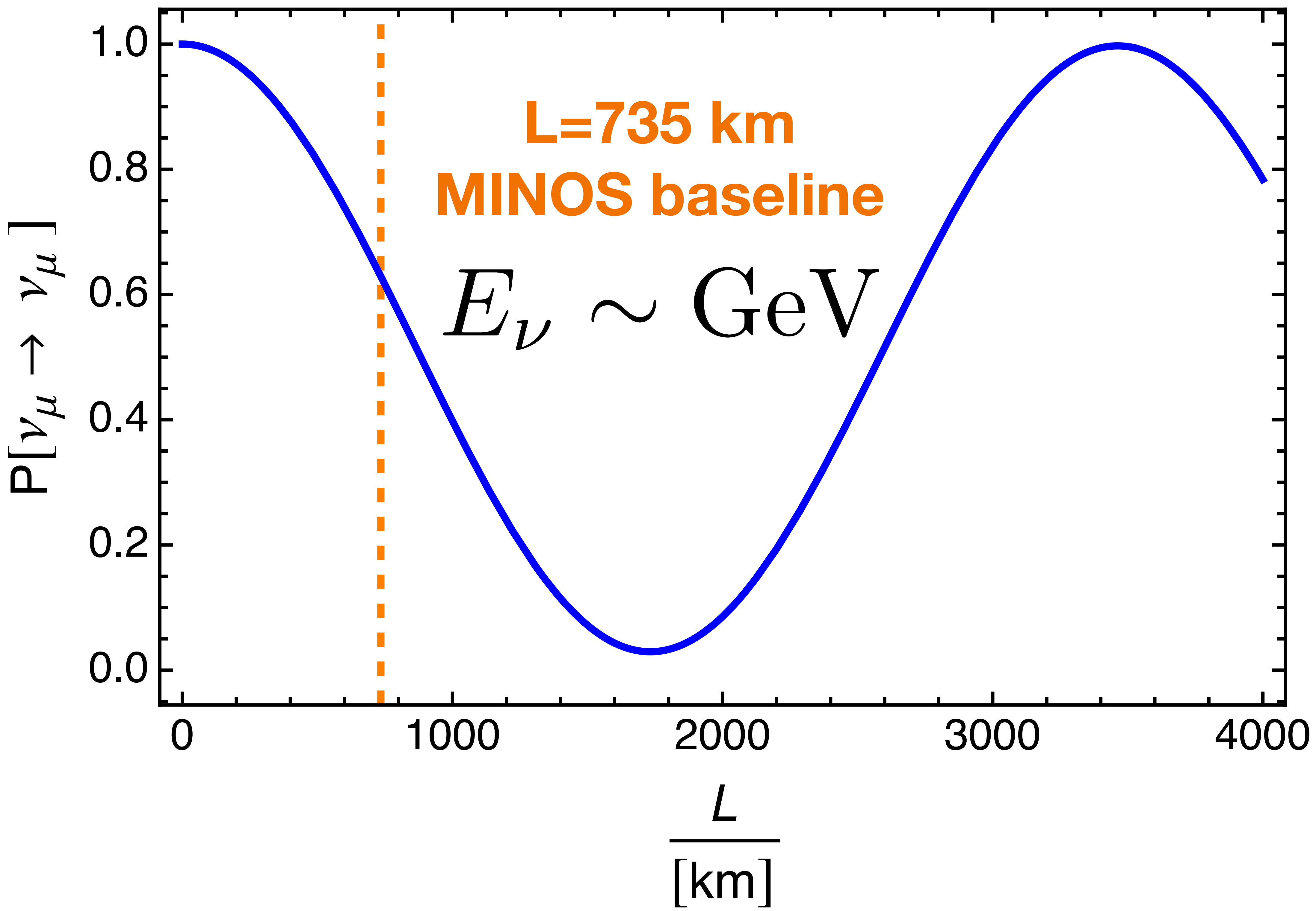

**Size of circle indicates amount light recorded In scintillators in MINOS**

# Neutrino oscillation physics - accelerator experiments

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

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

**dominant term since reactor mixing angle small**



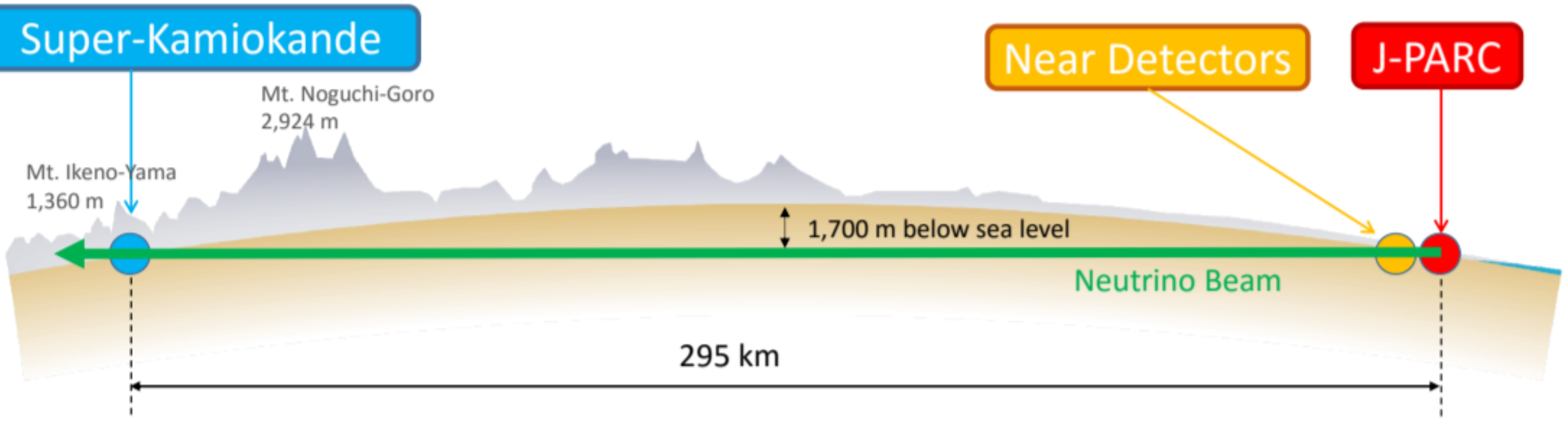
# Neutrino oscillation physics - CP-violation

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

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

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

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




**T2K**


**NoVA**

- Both NOvA and T2K show a mild preference for normal ordering & $\theta_{23} > 45°$
- NOVA preference for $\delta \sim 145°$, T2K for $\delta \sim 255°$