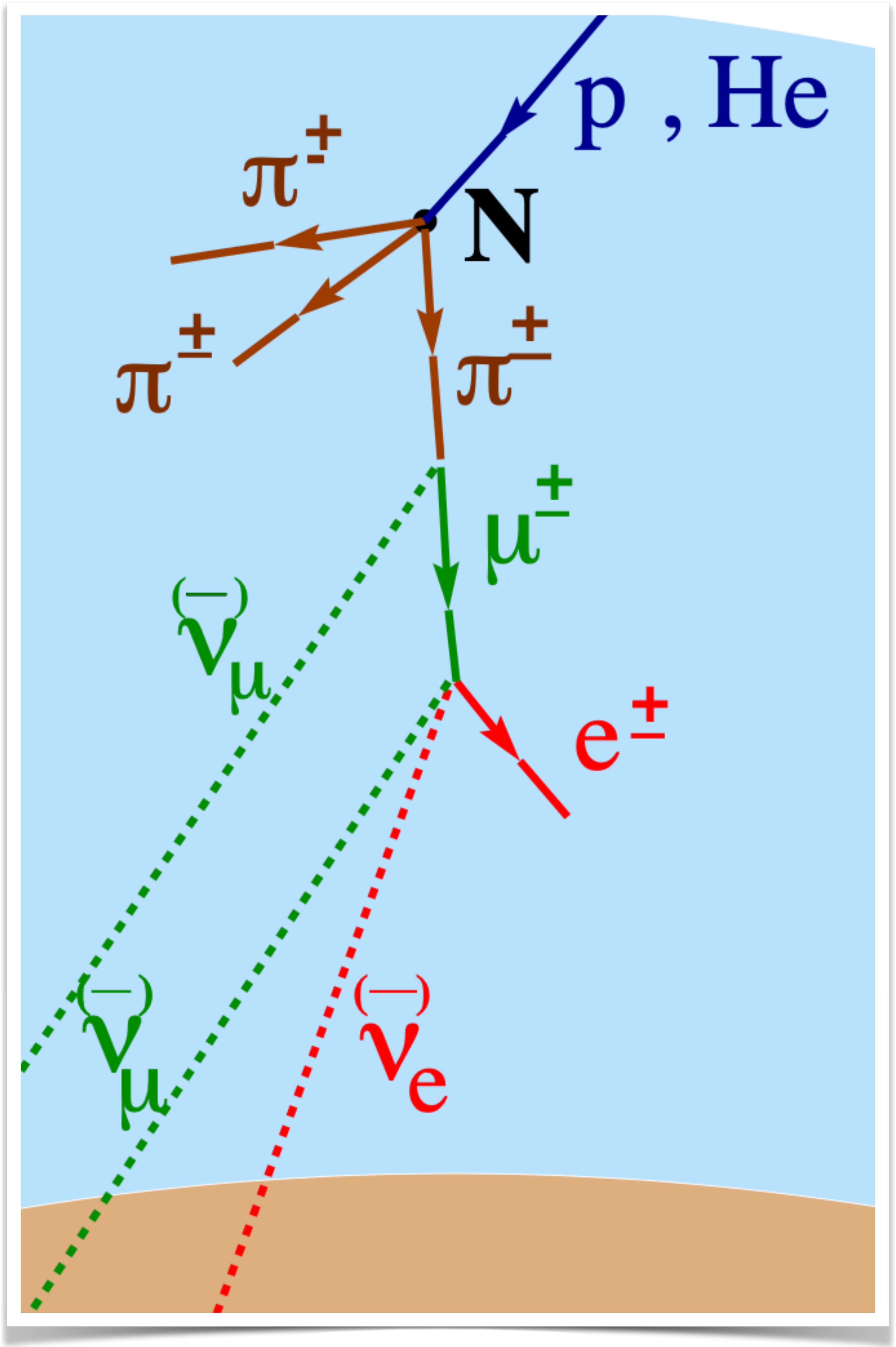
Neutrino Physics

Neutrino Oscillations in vacuum

Jessica Turner

Atmospheric neutrinos

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



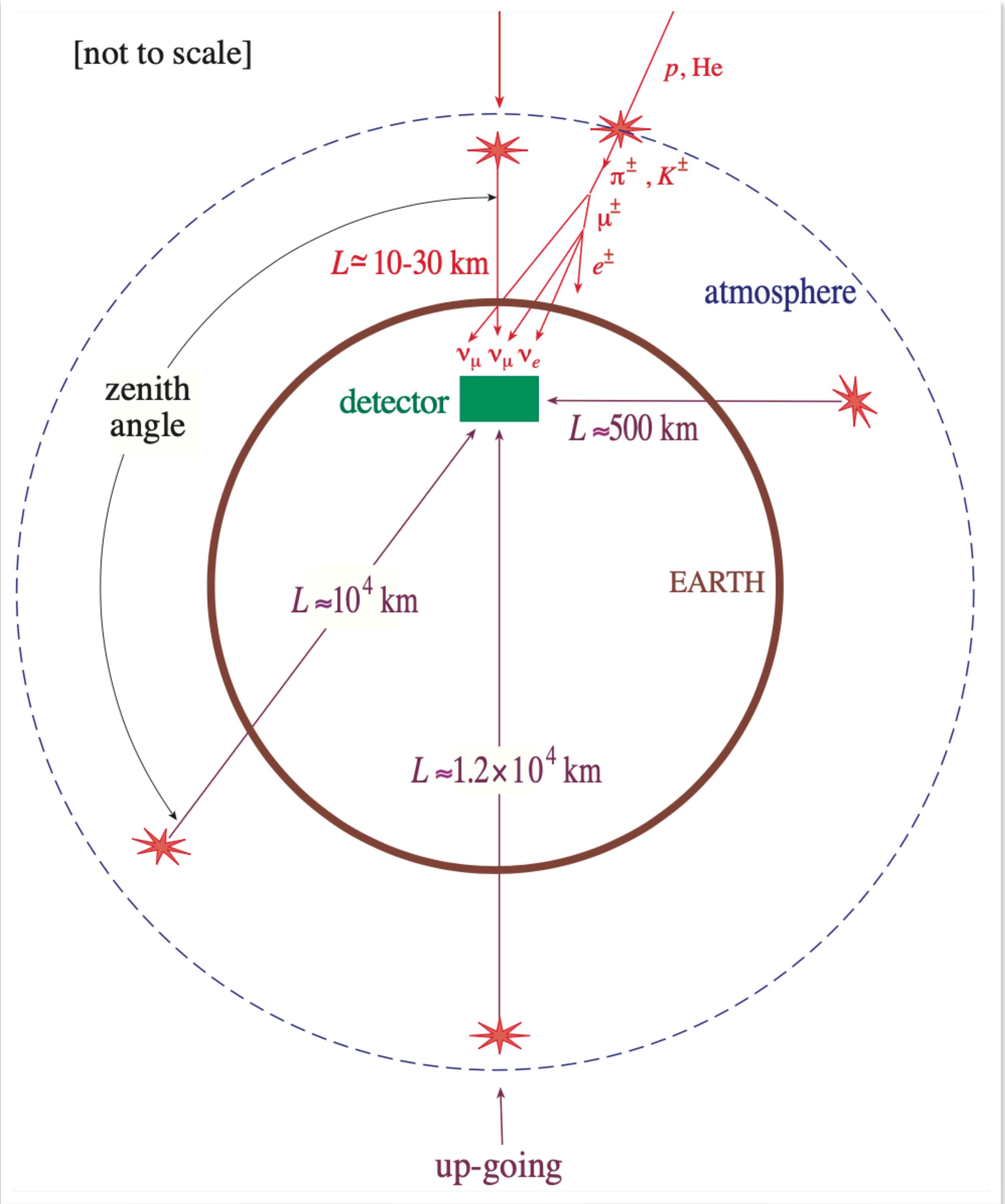
$$R_{\frac{\mu}{e}} \approx \frac{N_{\nu_\mu} + N_{\overline{\nu_\mu}}}{N_{\nu_e} + N_{\overline{\nu_e}}} \sim 2$$

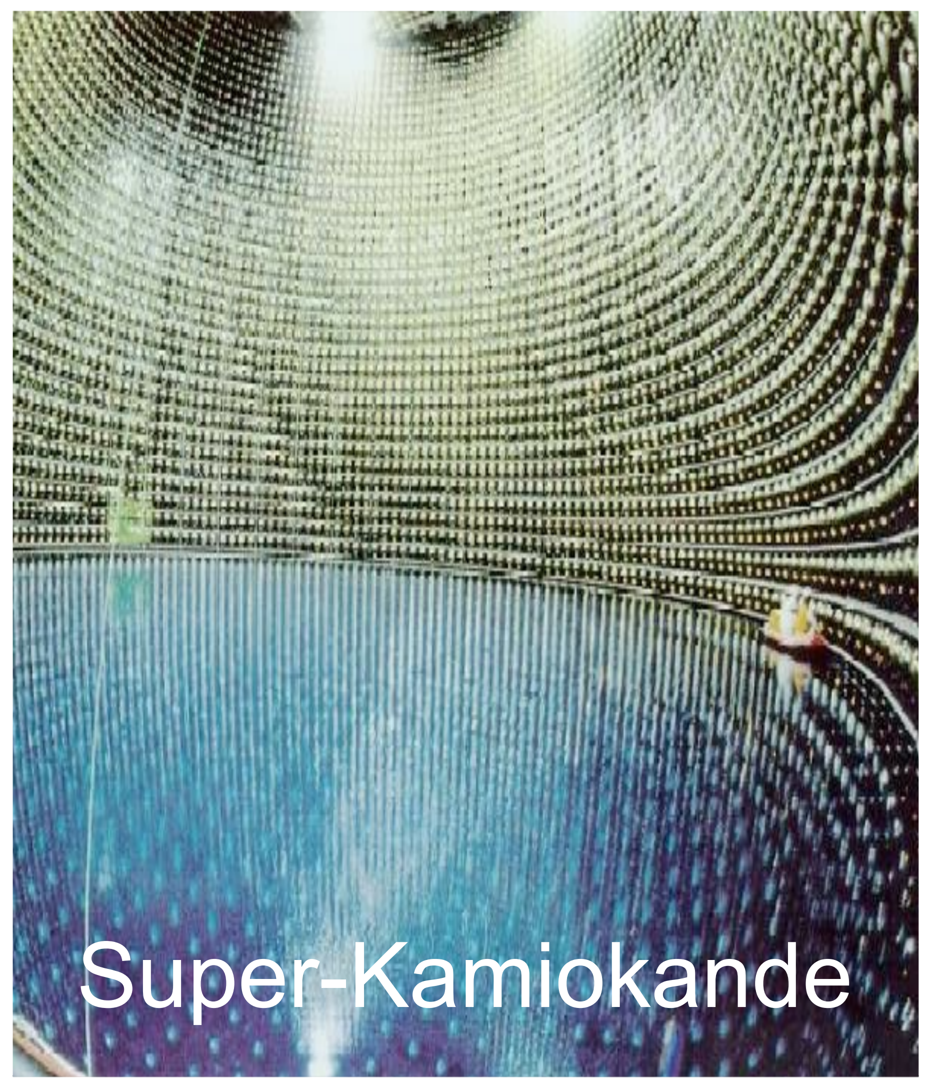
Exercise: show that

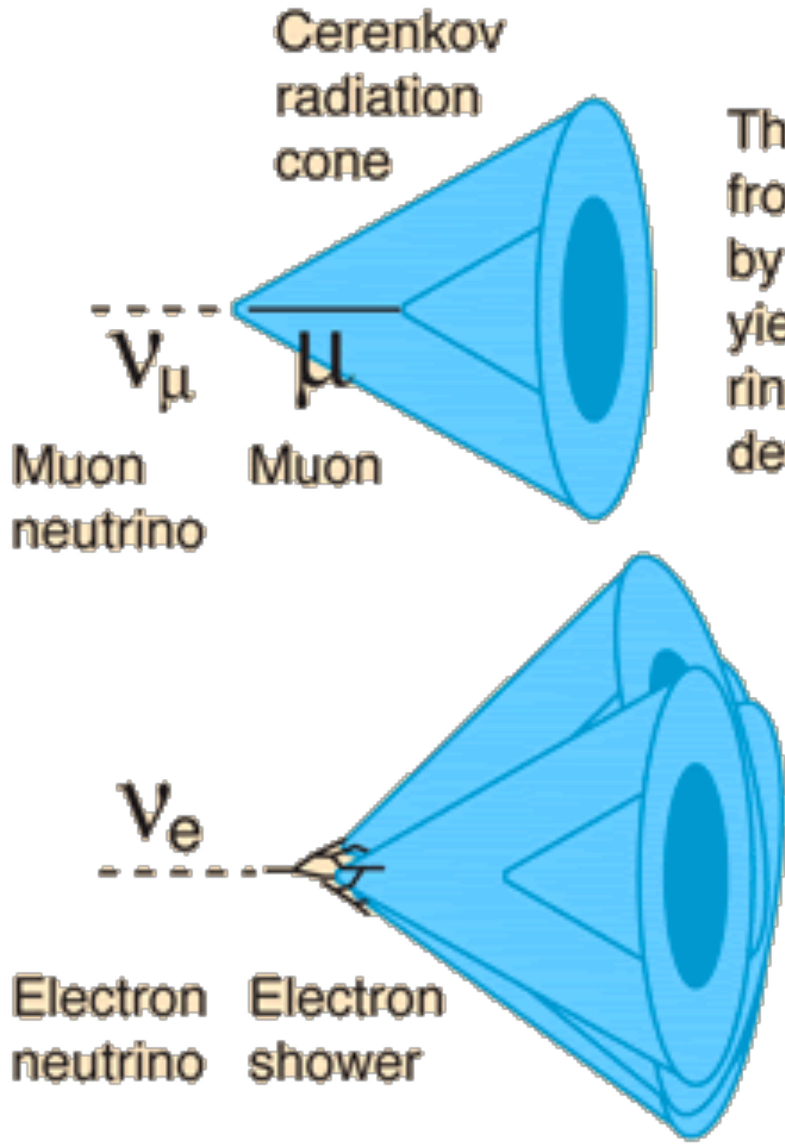
$$\frac{\Gamma\left(\pi^+ \to e^+\nu_e\right)}{\Gamma\left(\pi^+ \to \mu^+\nu_\mu\right)} \approx 2 \times 10^{-4}$$

Atmospheric neutrinos

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

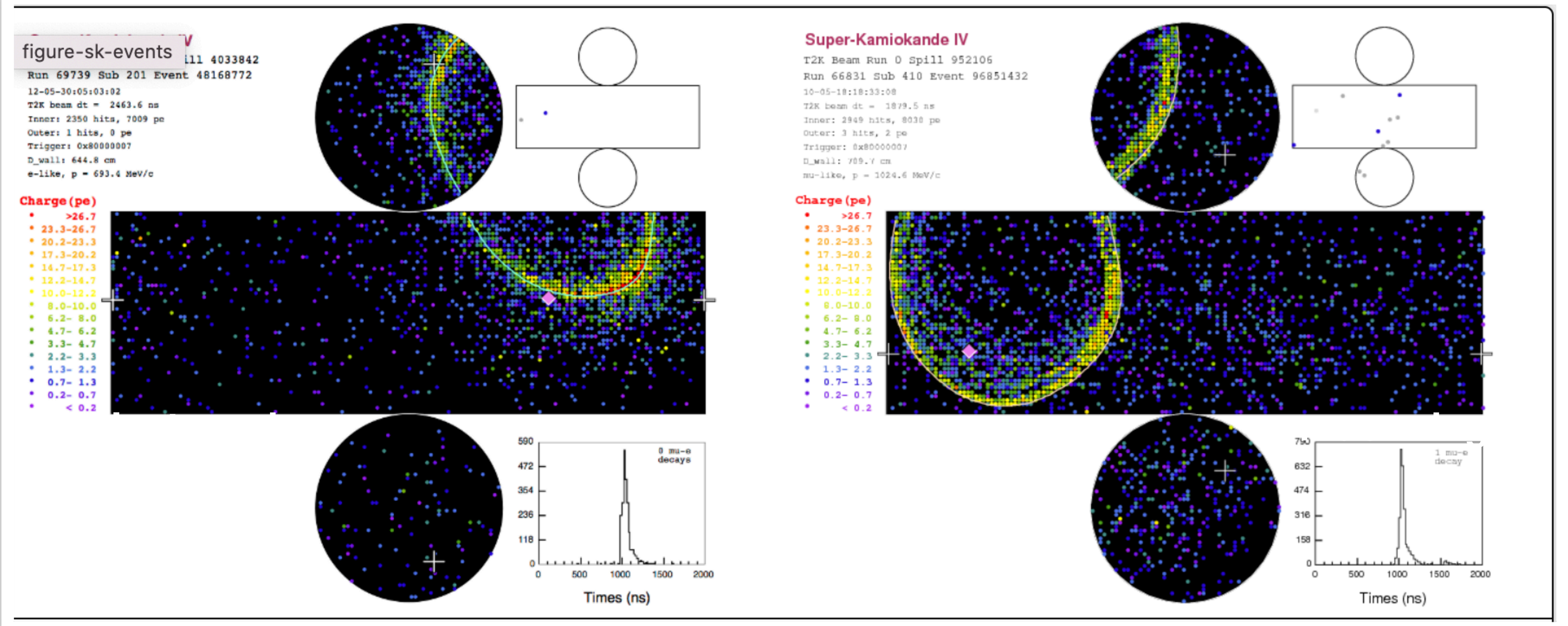






The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.



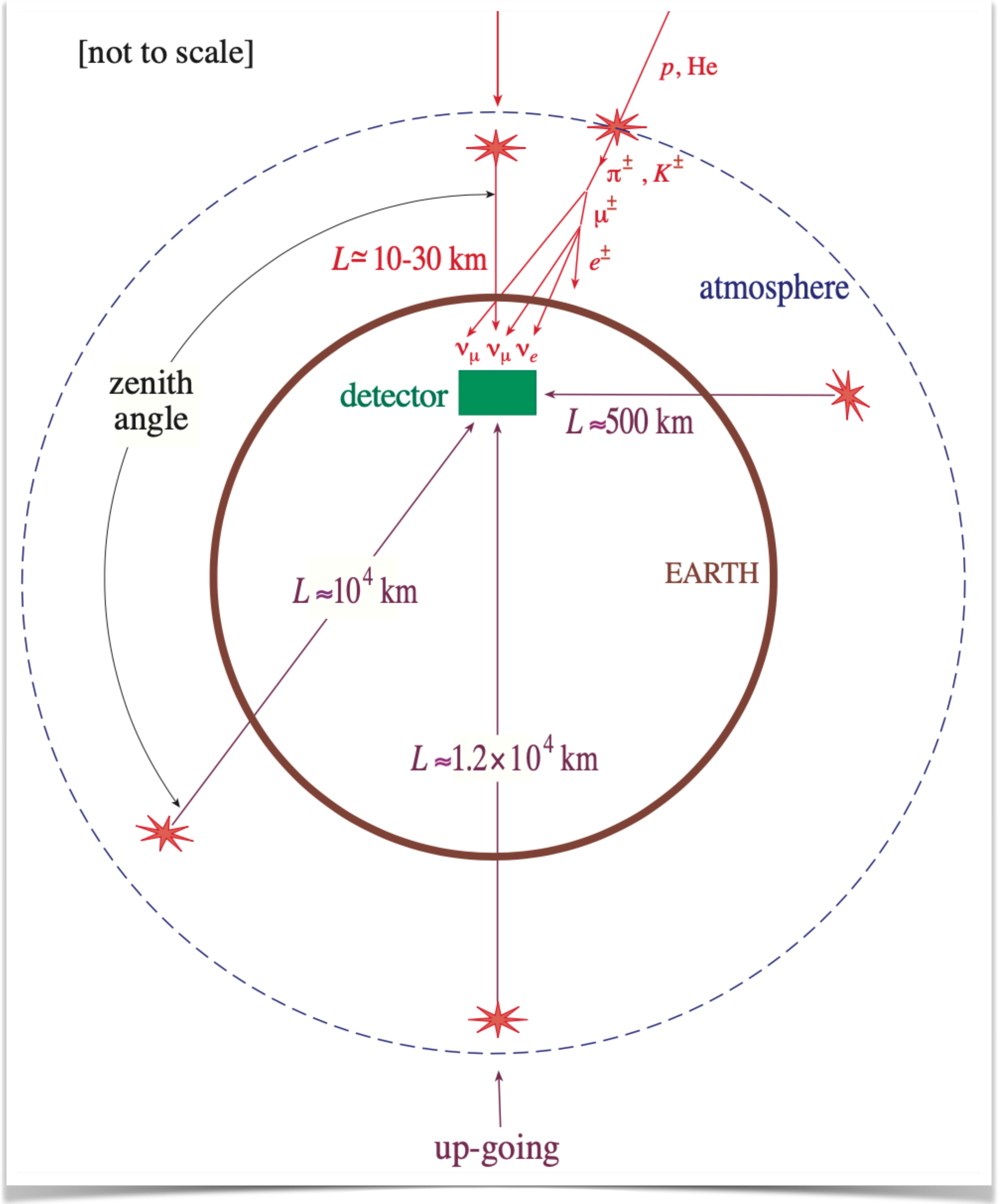
```
ill 4033842
Run 69739 Sub 201 Event 48168772
12-05-30:05:03:02
T2K beam dt =  2463.6 ns
Inner: 2350 hits, 7009 pe
Outer: 1 hits, 0 pe
Trigger: 0x80000007
D_wall: 644.8 cm
e-like, p = 693.4 MeV/c
```

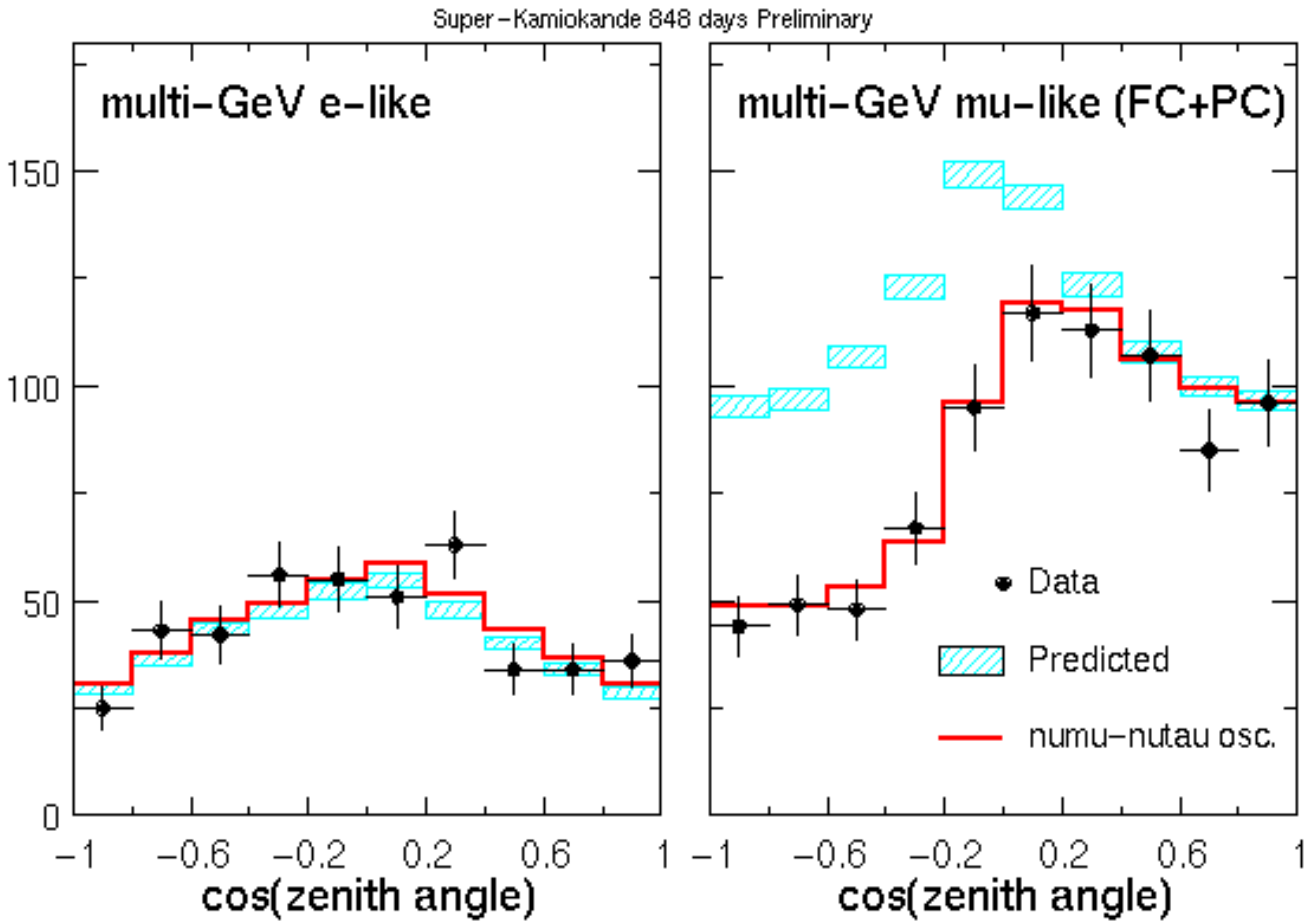
Super-Kamiokande IV

```
T2K Beam Run 0 Spill 952106
Run 66831 Sub 410 Event 96851432
10-05-18:18:33:08
T2K beam dt =  1879.5 ns
Inner: 2949 hits, 8030 pe
Outer: 3 hits, 2 pe
Trigger: 0x80000007
D_wall: 709.7 cm
mu-like, p = 1024.6 MeV/c
```

Atmospheric neutrinos

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





Board

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

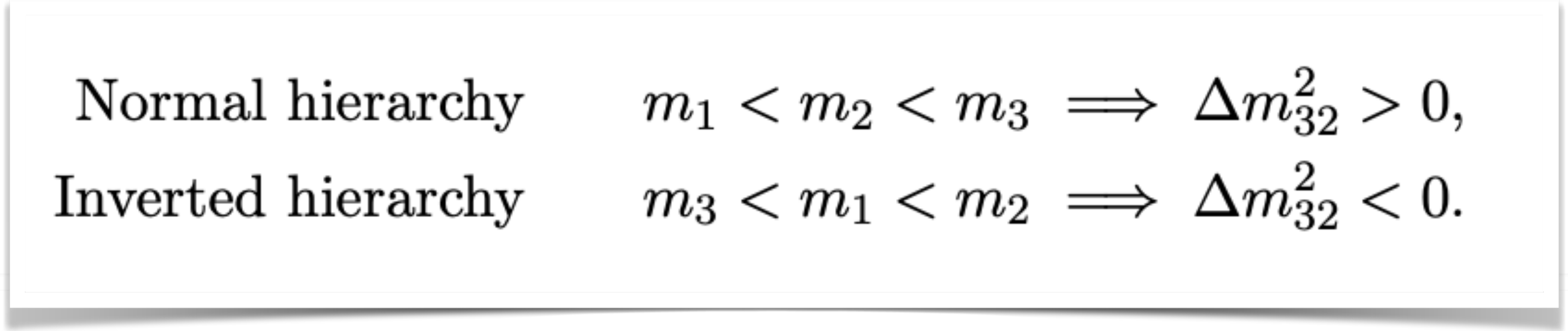
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 &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

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

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

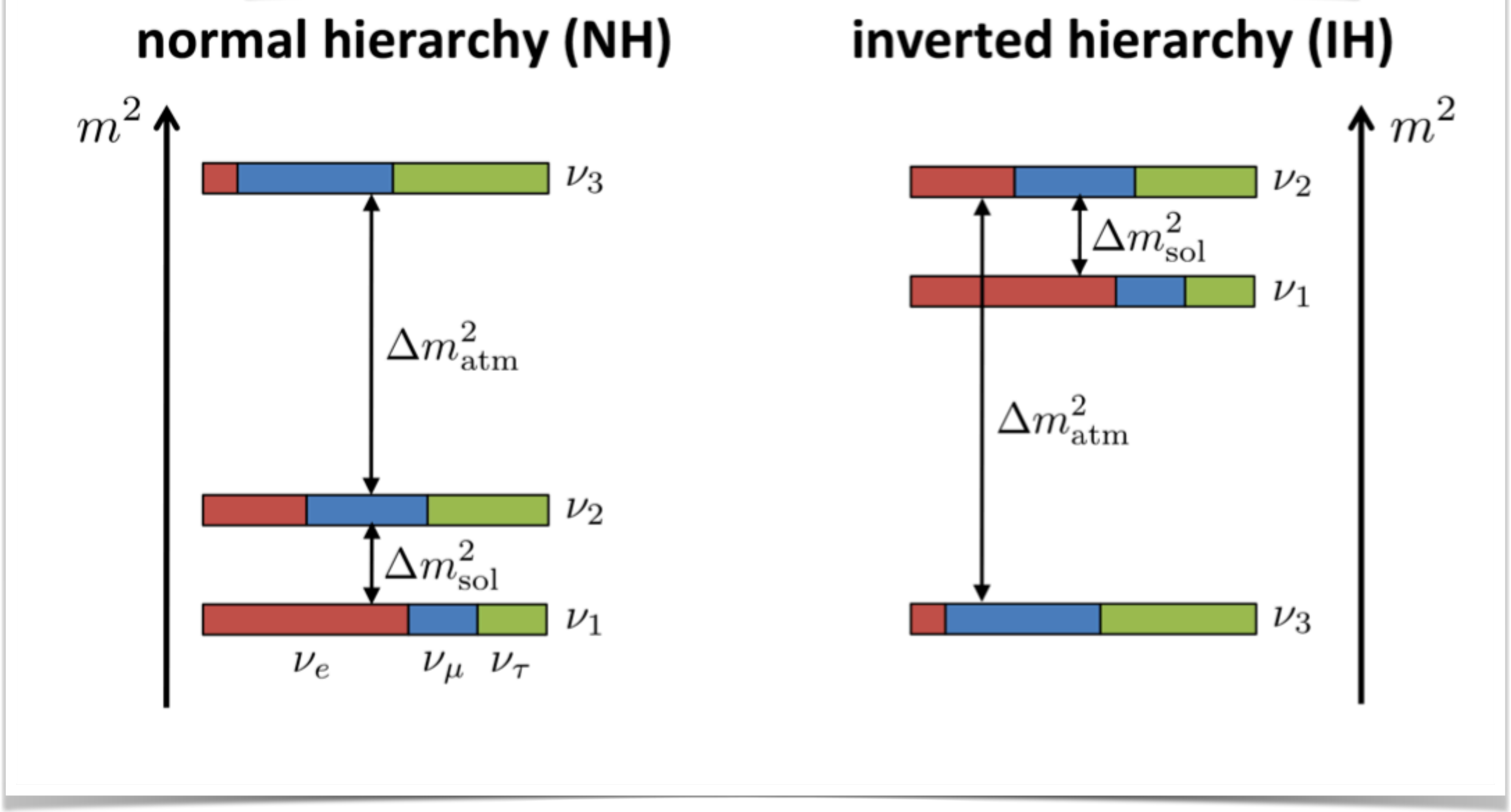
Current knowledge

- 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 $m_1 < m_2 < m_3 \implies \Delta m^2_{32} > 0,$

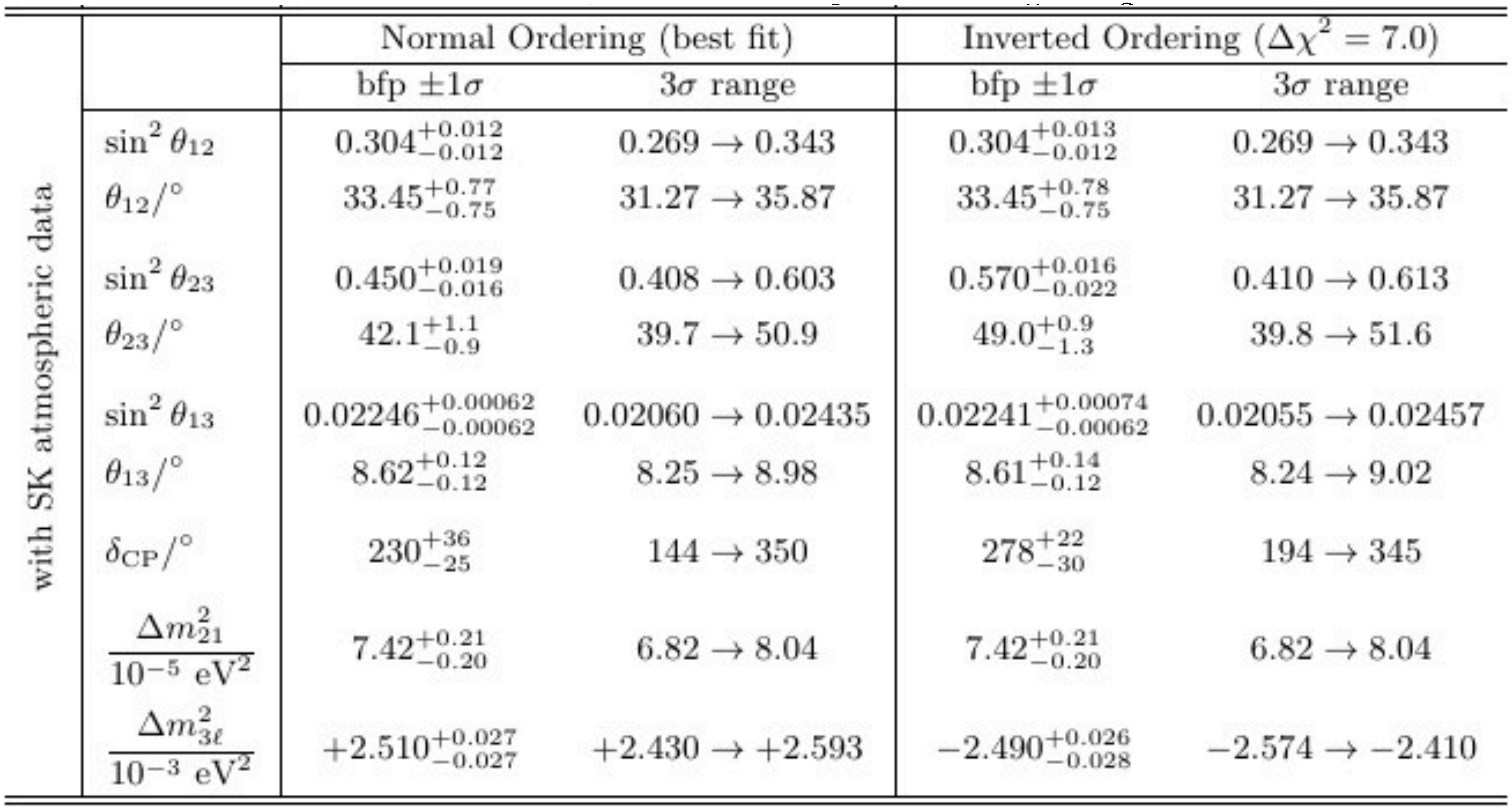
Inverted hierarchy $m_3 < m_1 < m_2 \implies \Delta m^2_{32} < 0.$



Current knowledge

www.nu-fit.org

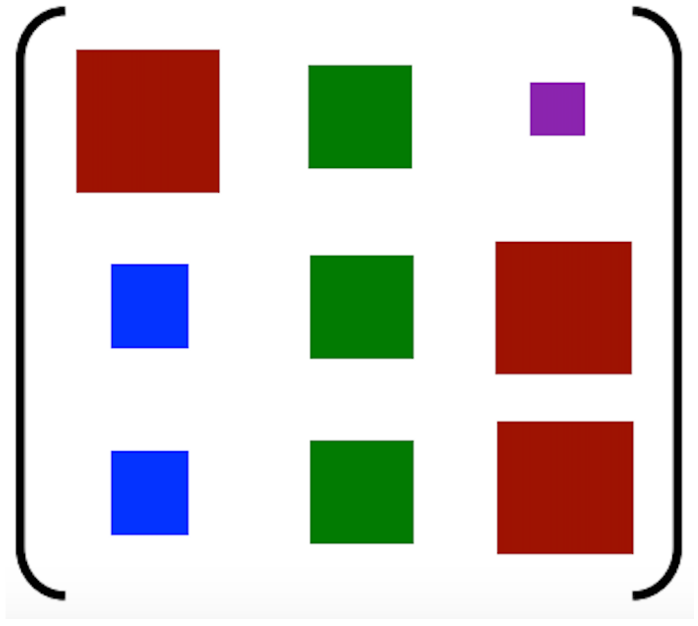
Nu-fit global fit 5.1



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{\mathrm{CP}}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

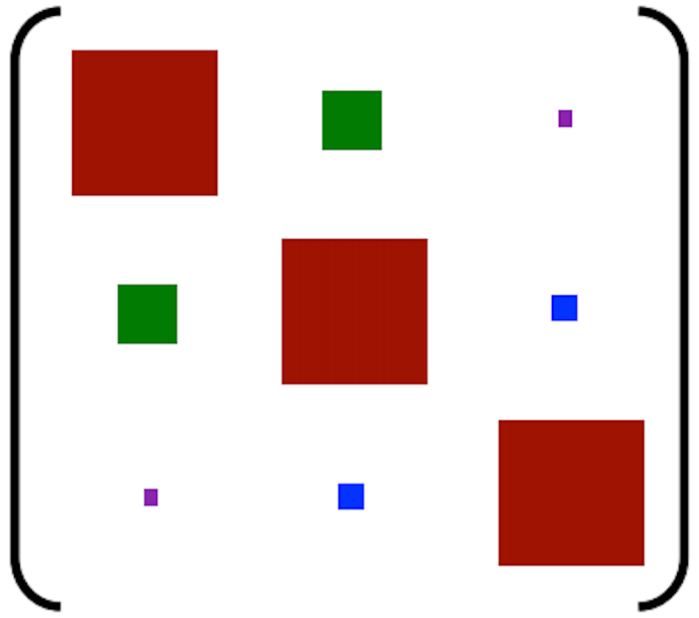
Current knowledge

Lepton Sector

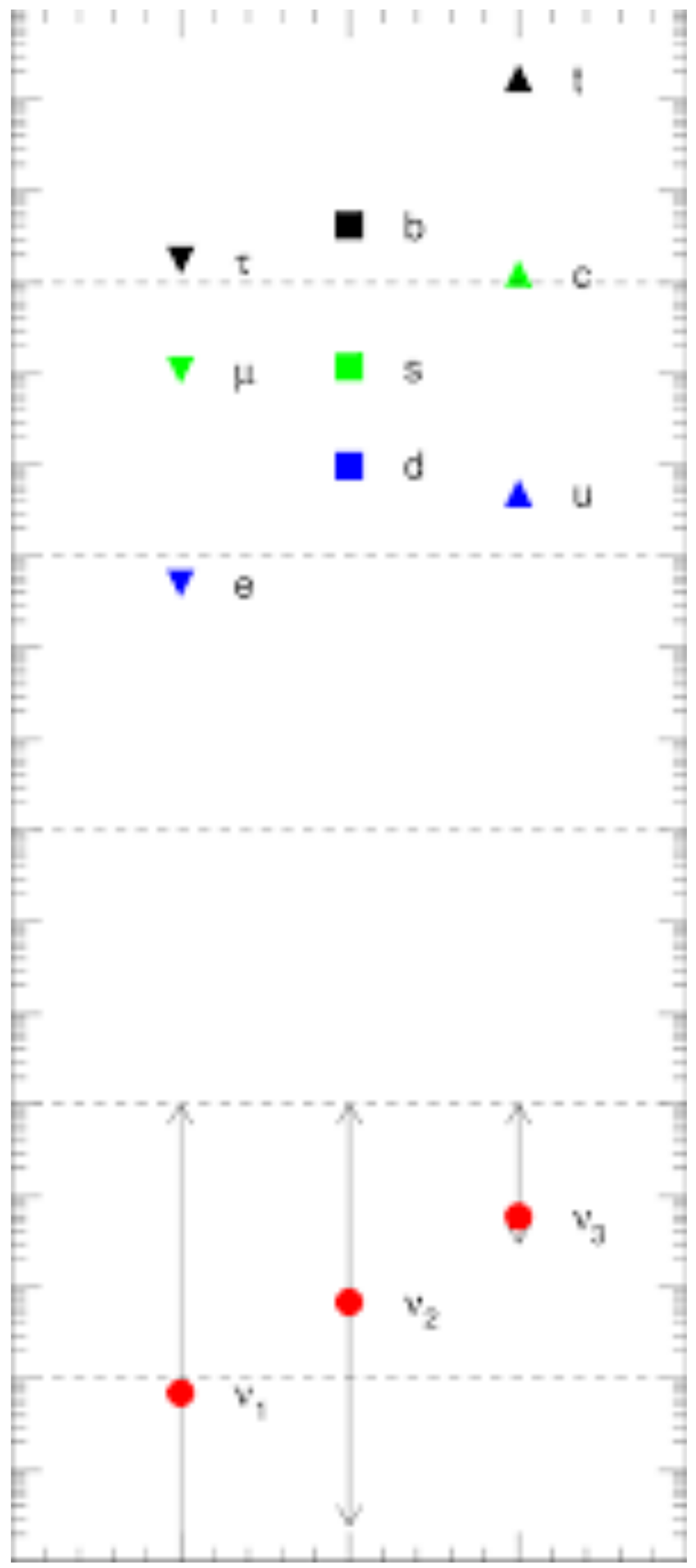


$$\sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.4 & 0.5 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quark Sector



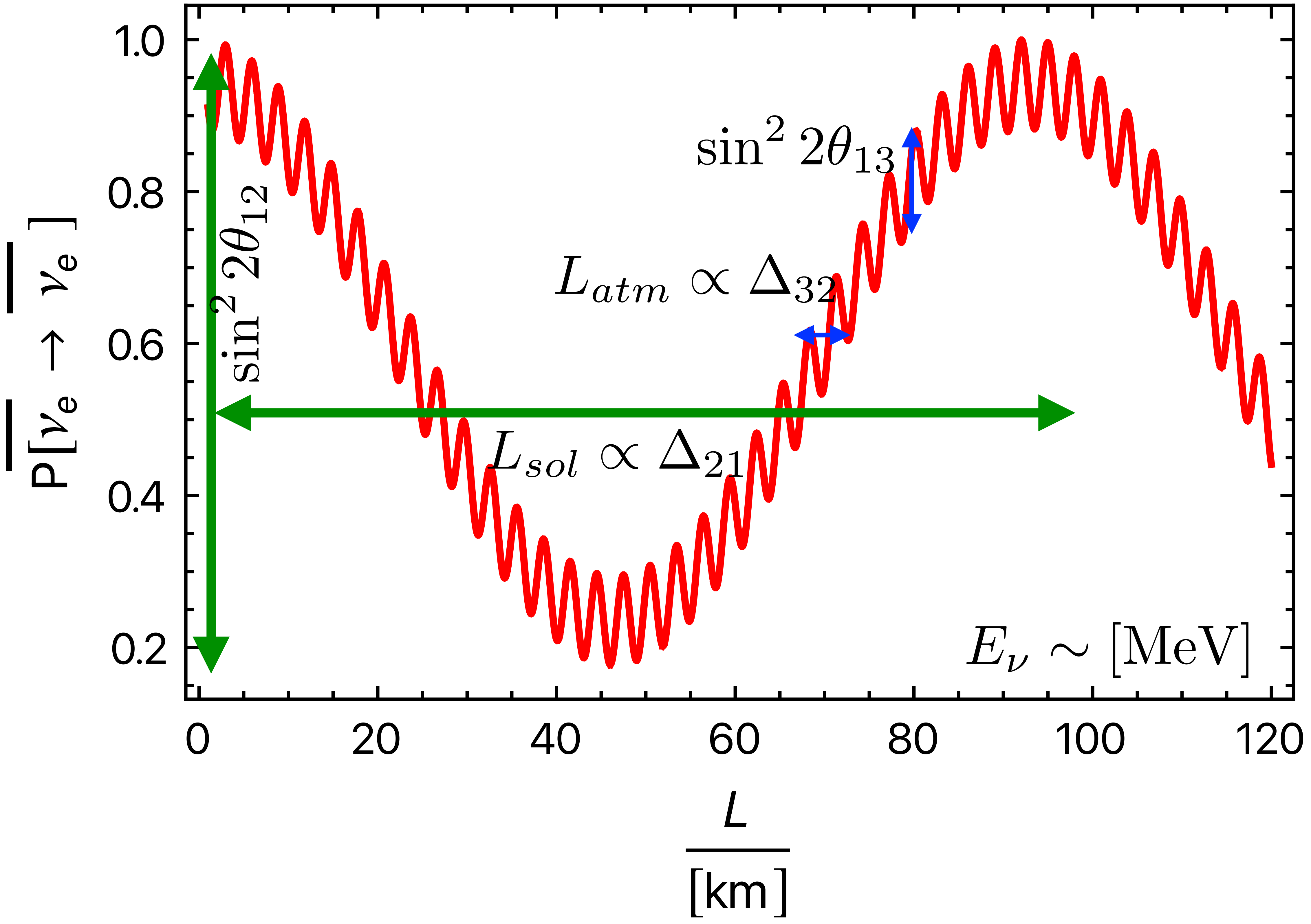
$$\sim \begin{pmatrix} 0.98 & 0.2 & 0.0 \\ 0.2 & 0.99 & 0.0 \\ 0.0 & 0.04 & 1.0 \end{pmatrix}$$



- 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

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



Consider the wavelength of each contribution

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

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

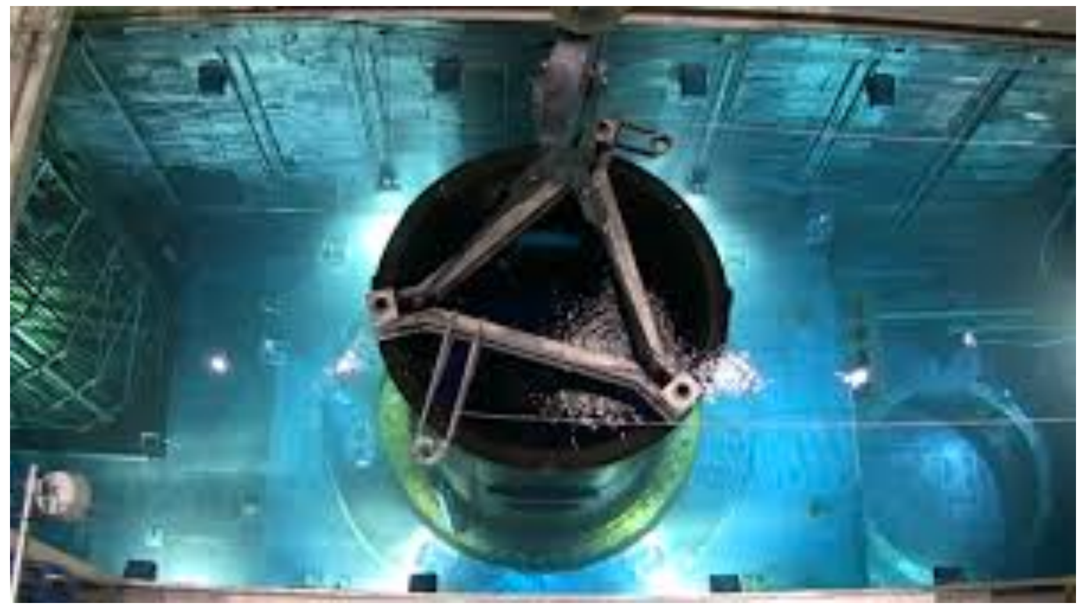
$\Delta m^2_{21} \sim 10^{-5}\,\mathrm{eV}^2$ $\quad E_\nu \sim \mathrm{MeV}$ $\quad L_{sol} \sim 30\,\mathrm{km}$

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

Neutrino oscillation physics - reactor experiments

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

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

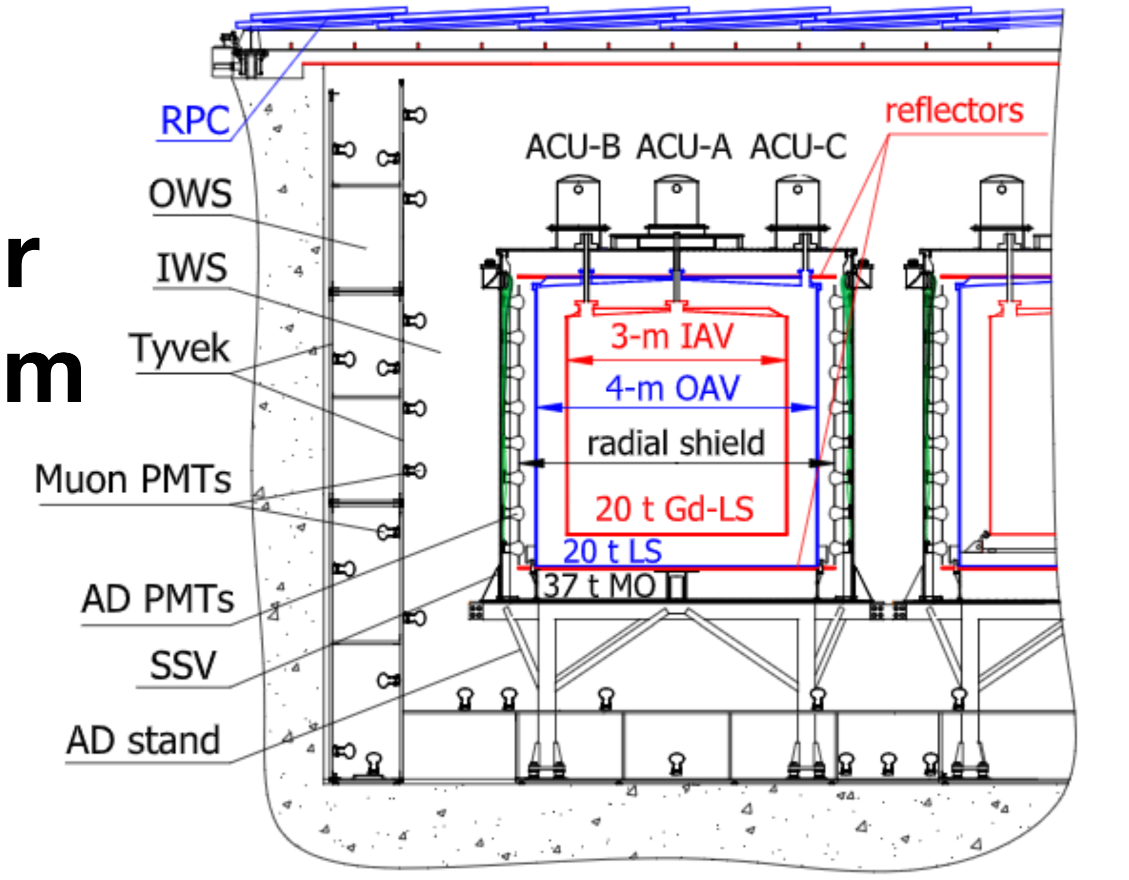


$\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$ $\overline{\nu}_e$

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

$$\xrightarrow[4\,\mathrm{km}]{\langle E_\nu \rangle \sim \mathrm{MeV}}$$

Liquid scintillator doped Gadolinium



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

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

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

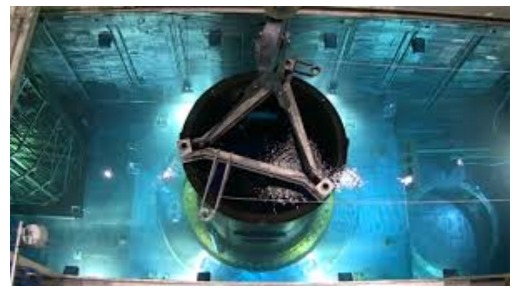
- At such short baselines, the short wavelength term dominates

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

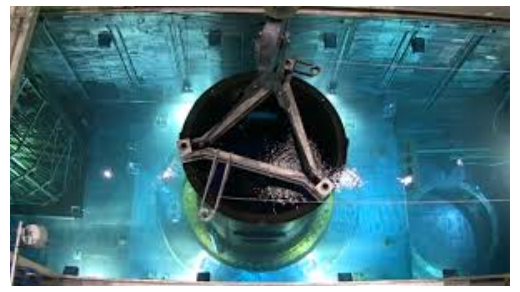
$$P\left(\overline{\nu_e} \rightarrow \overline{\nu_e}\right) \approx 1 - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

Neutrino oscillation physics - reactor experiments

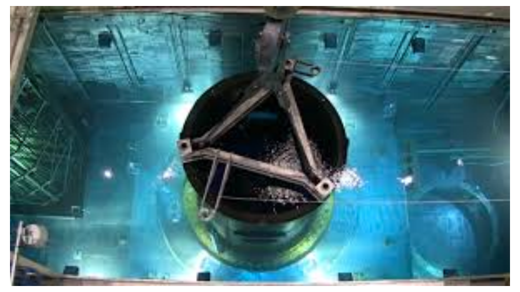
- KamLand is a medium baseline reactor experiment in same cavern as SK



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

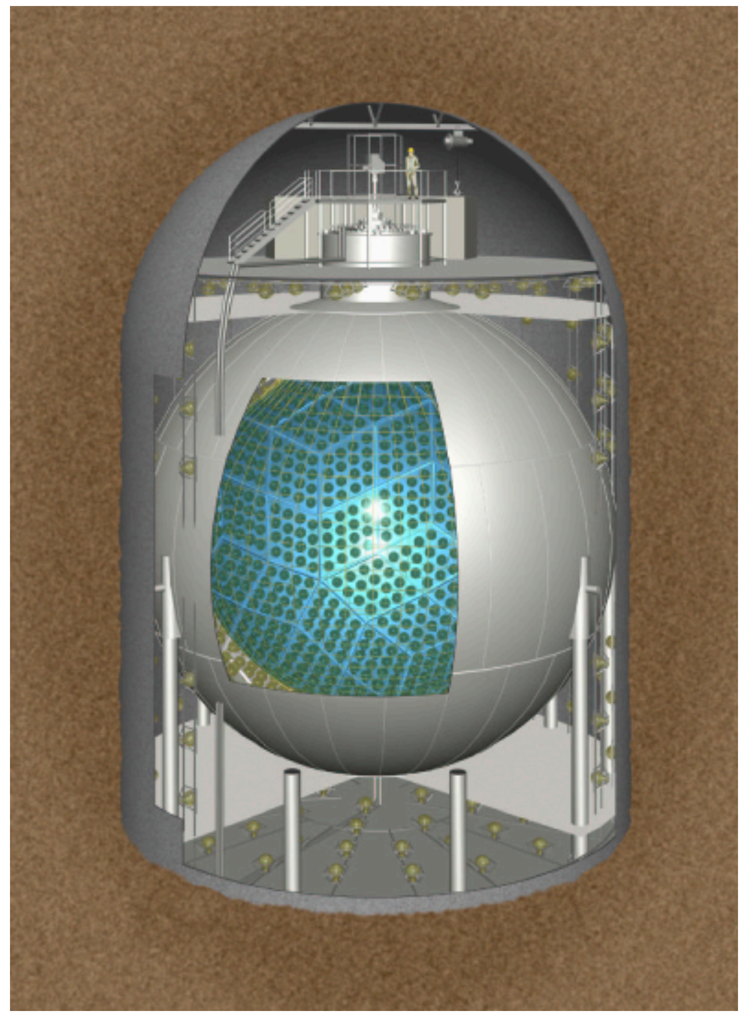


$\overline{\nu}_e$ $\overline{\nu}_e$

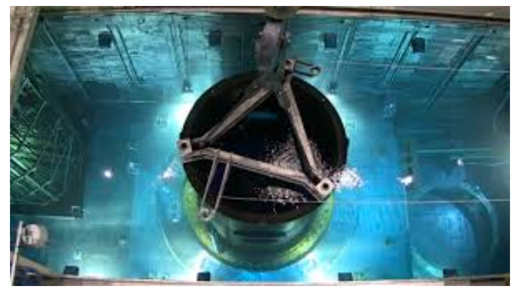


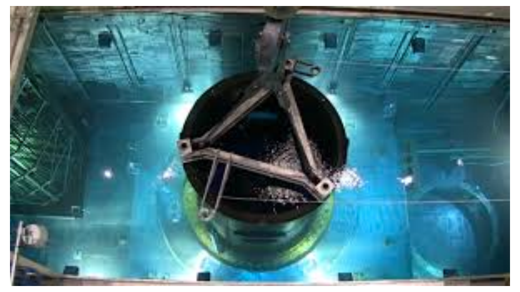
$\overline{\nu}_e$ $\overline{\nu}_e$

Liquid scintillator 9600 PMTs



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

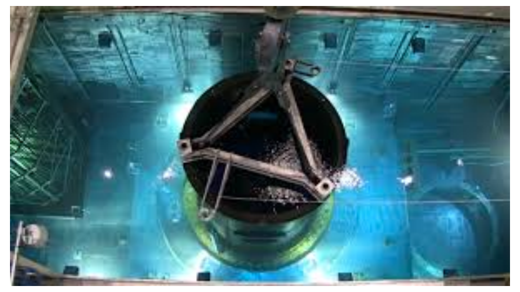




$\overline{\nu}_e$

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

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



- Baseline between **130 - 240 km**

Neutrino oscillation physics - reactor experiments

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

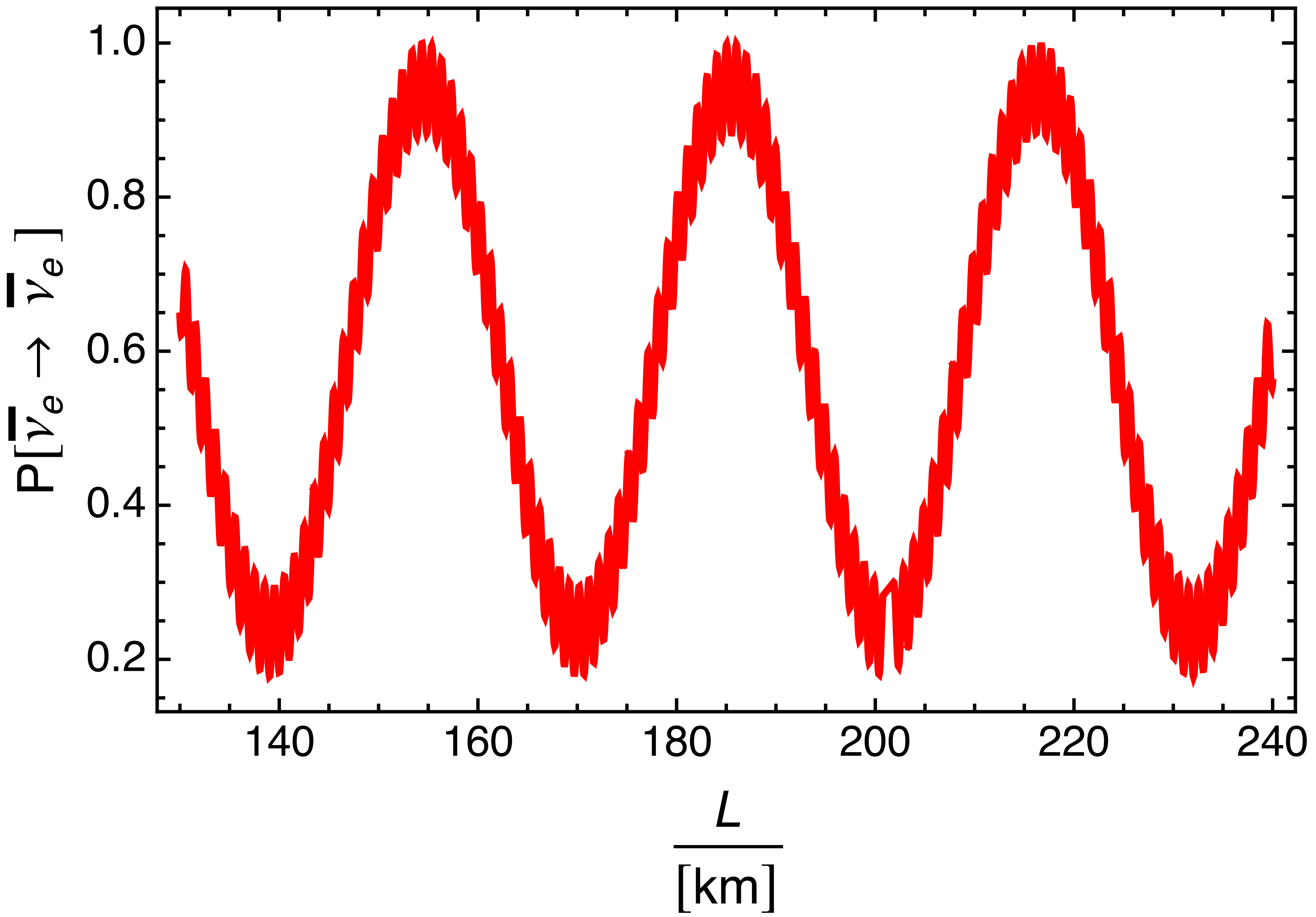
$$P\left(\overline{\nu_e} \to \overline{\nu_e}\right) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\sin^2\Delta_{32}$$

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

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

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

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

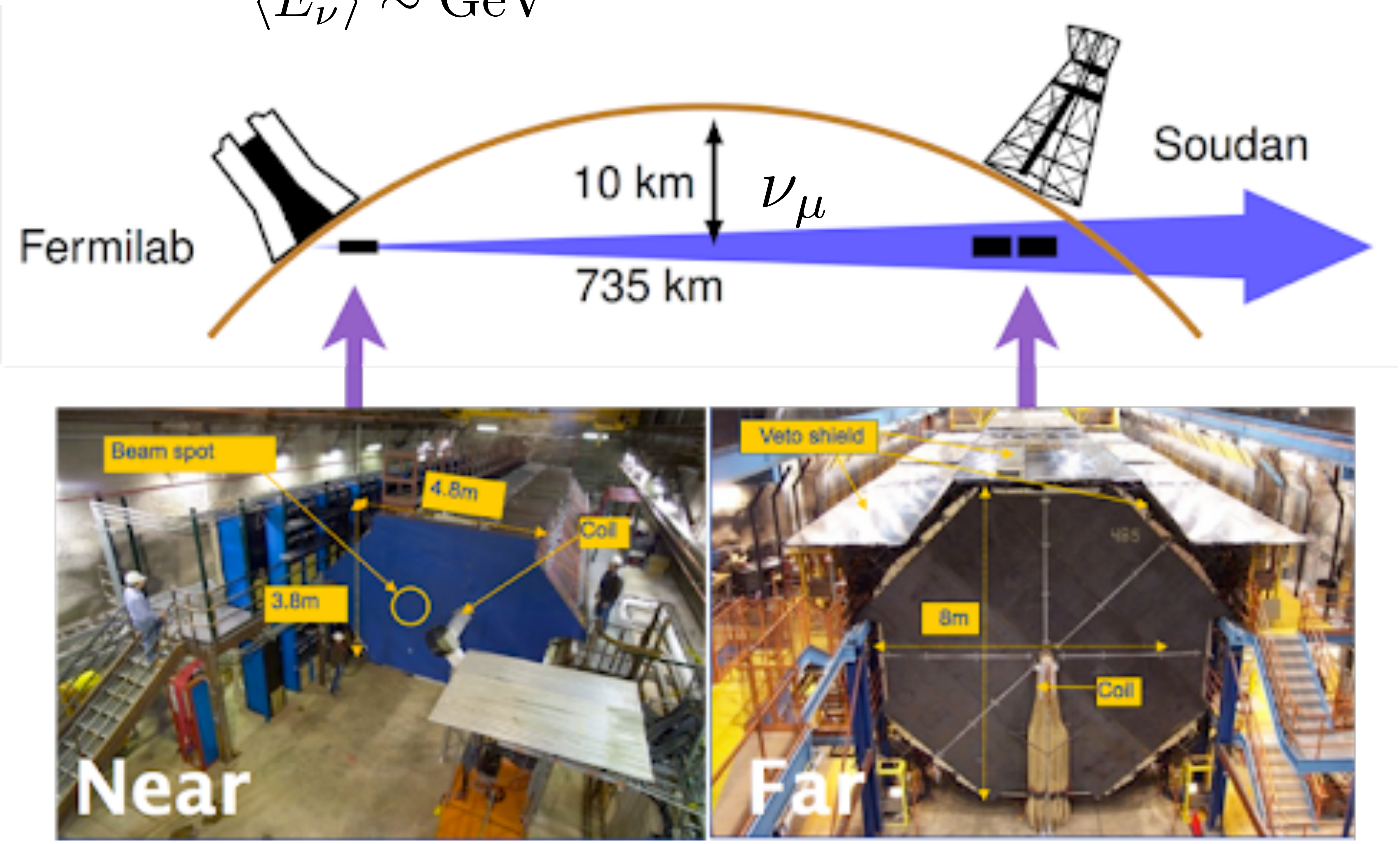


- Survival probability KamLand measures $\theta_{12},\ \Delta m^2_{21}$

Neutrino oscillation physics - accelerator experiments

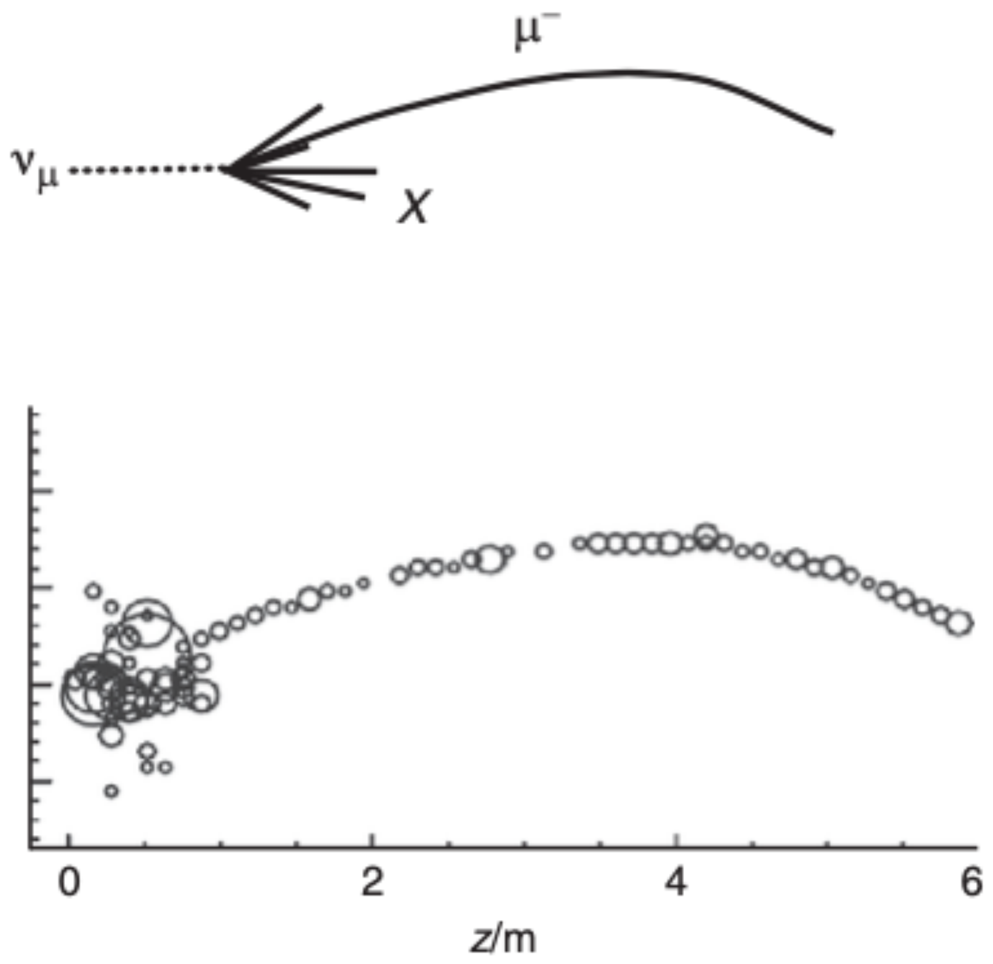
- Long baseline accelerator experiment such as **MINOS**, NOvA and T2K can determine the atmospheric angle and mass squared splitting.

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



FD planes of iron 4cm wide plastic scintillator strips

Magnetised momentum muon from CC interactions



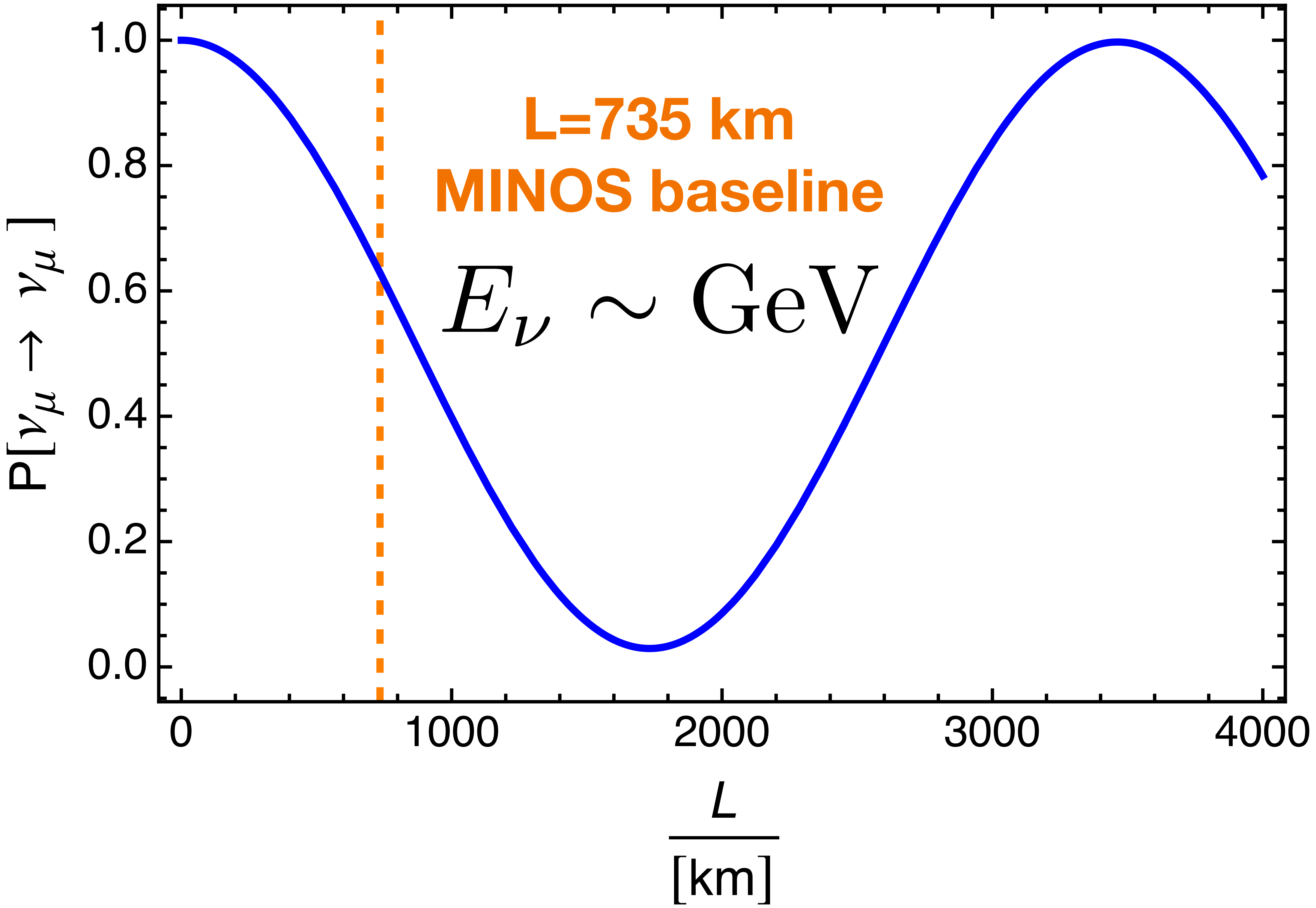
Size of circle indicates amount light recorded In scintillators in MINOS

Neutrino oscillation physics - accelerator experiments

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

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

dominant term since reactor mixing angle small



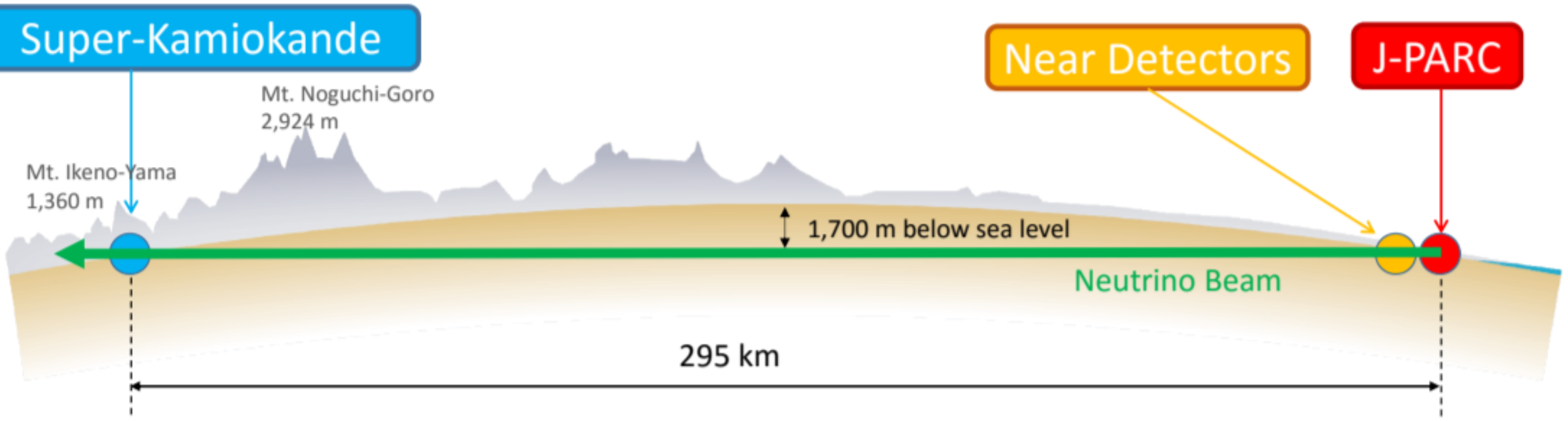
Neutrino oscillation physics - CP-violation

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

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

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

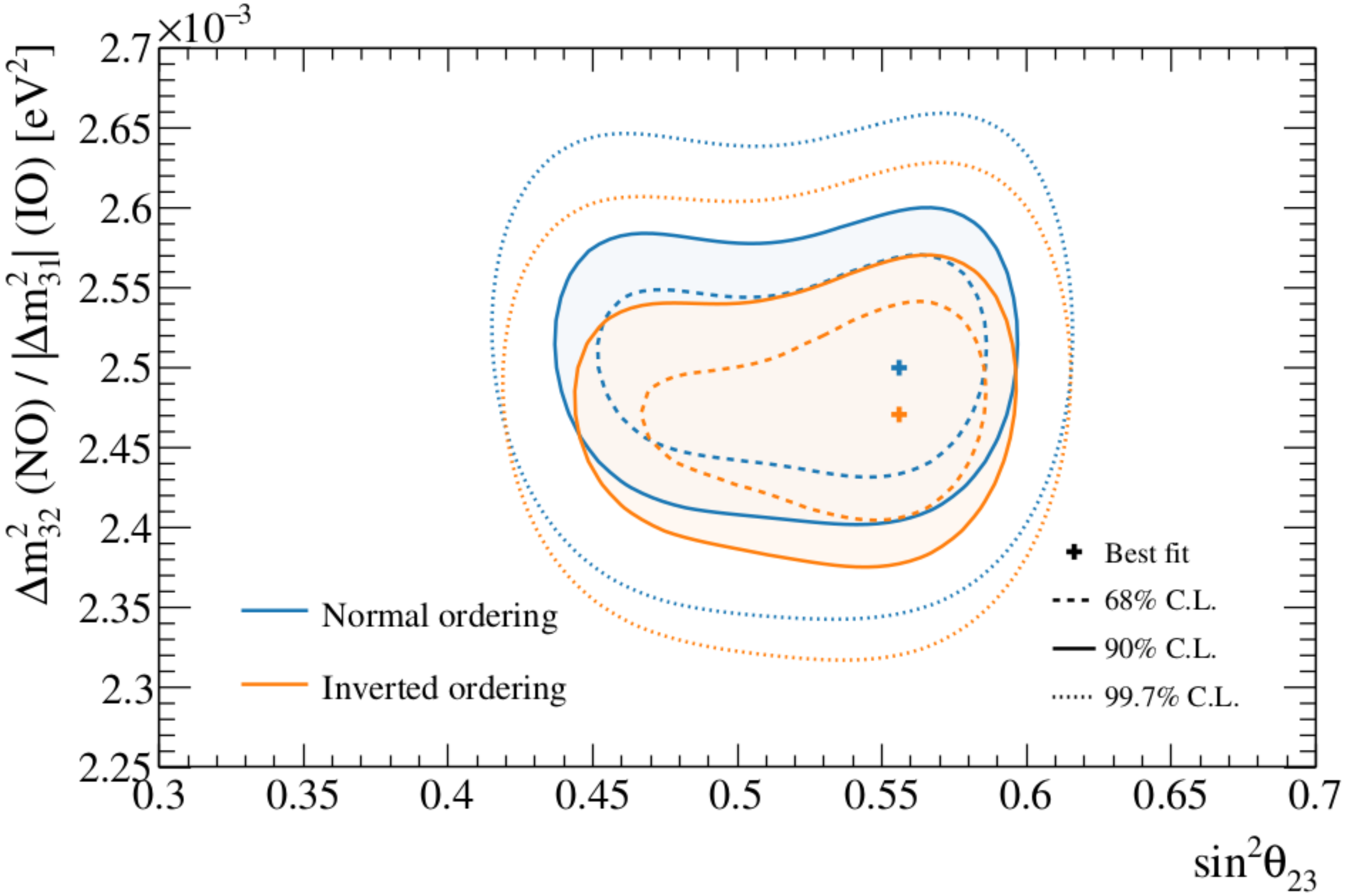
- What is the current status of CP-violation in the neutrino sector?

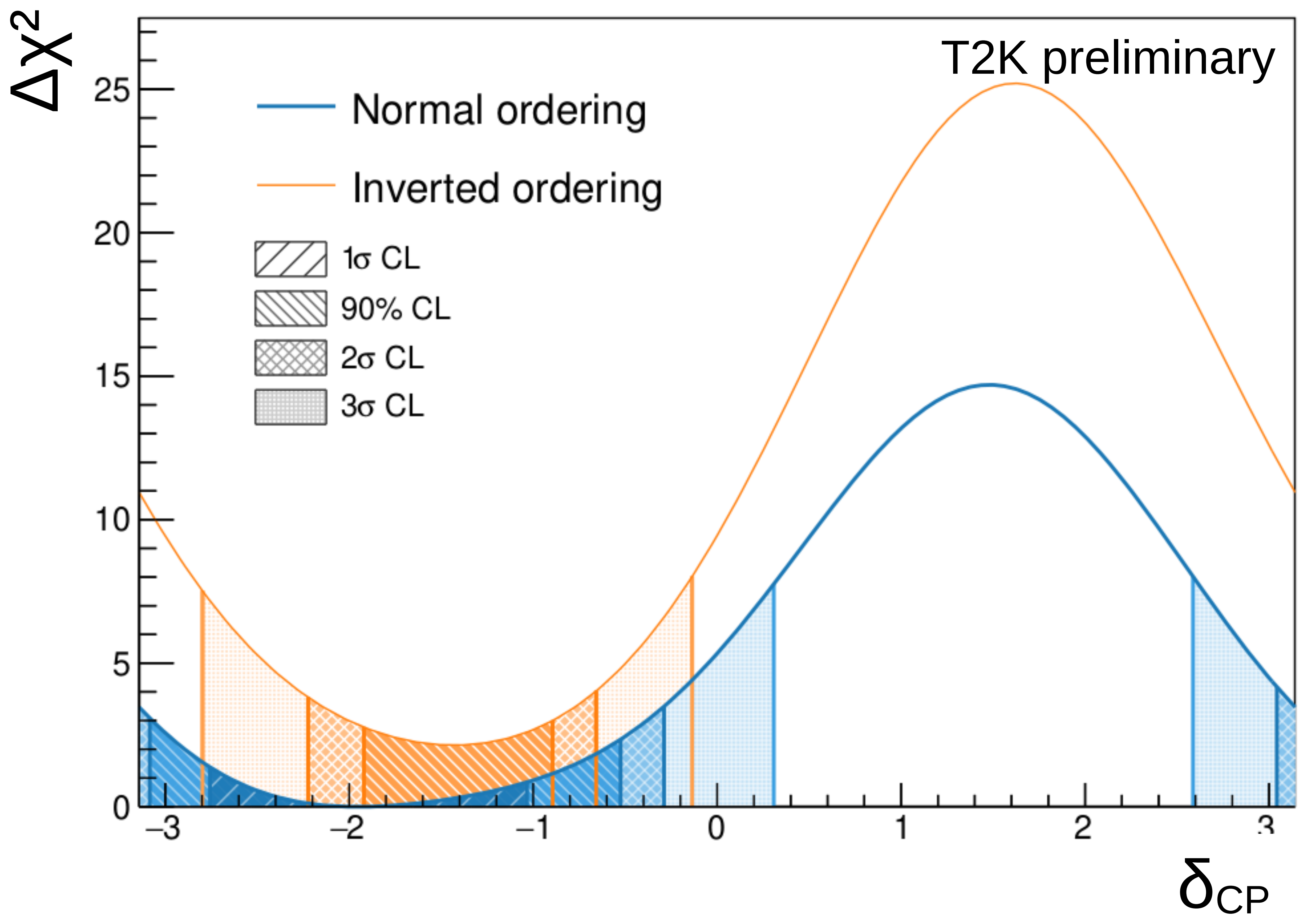


T2K

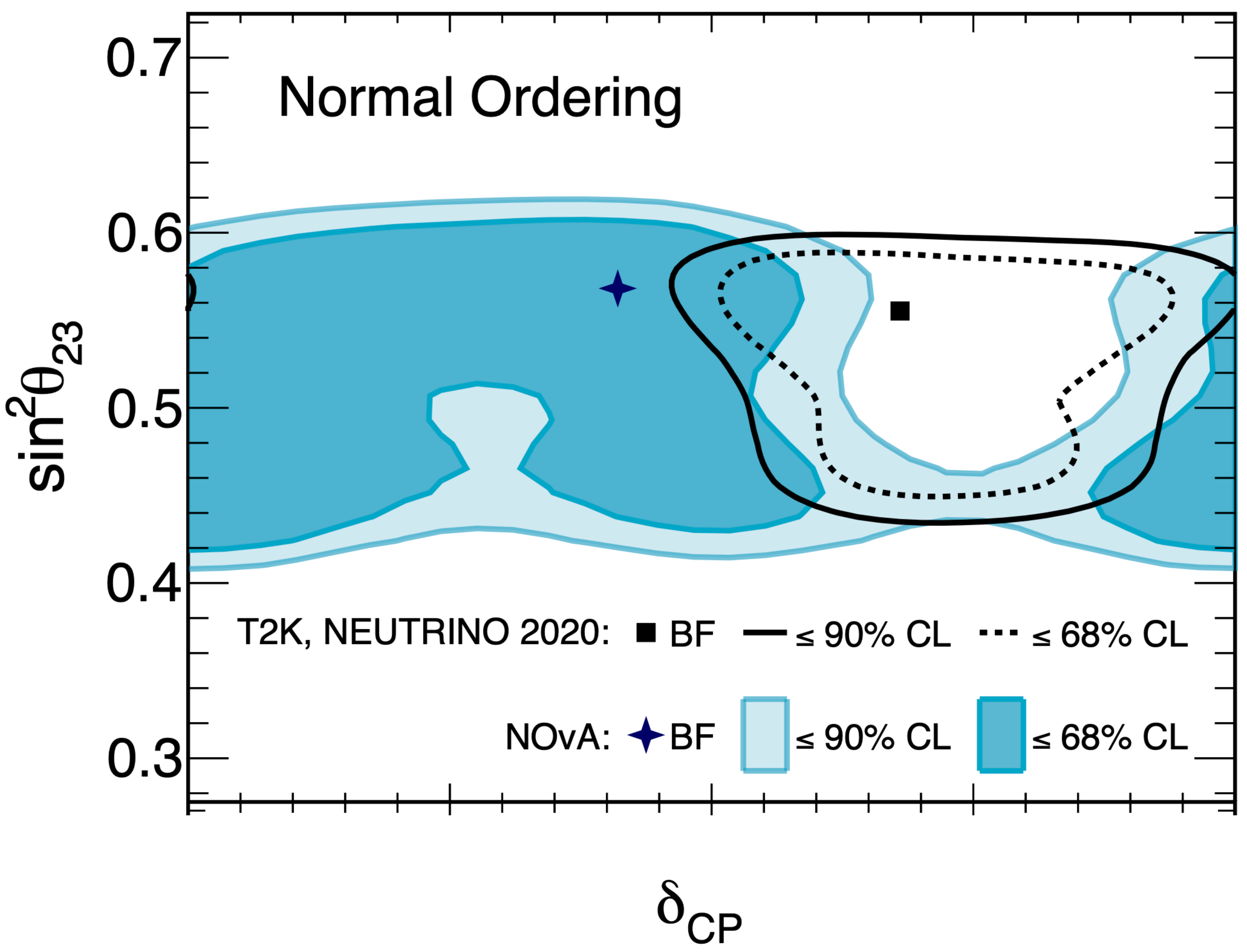
NoVA

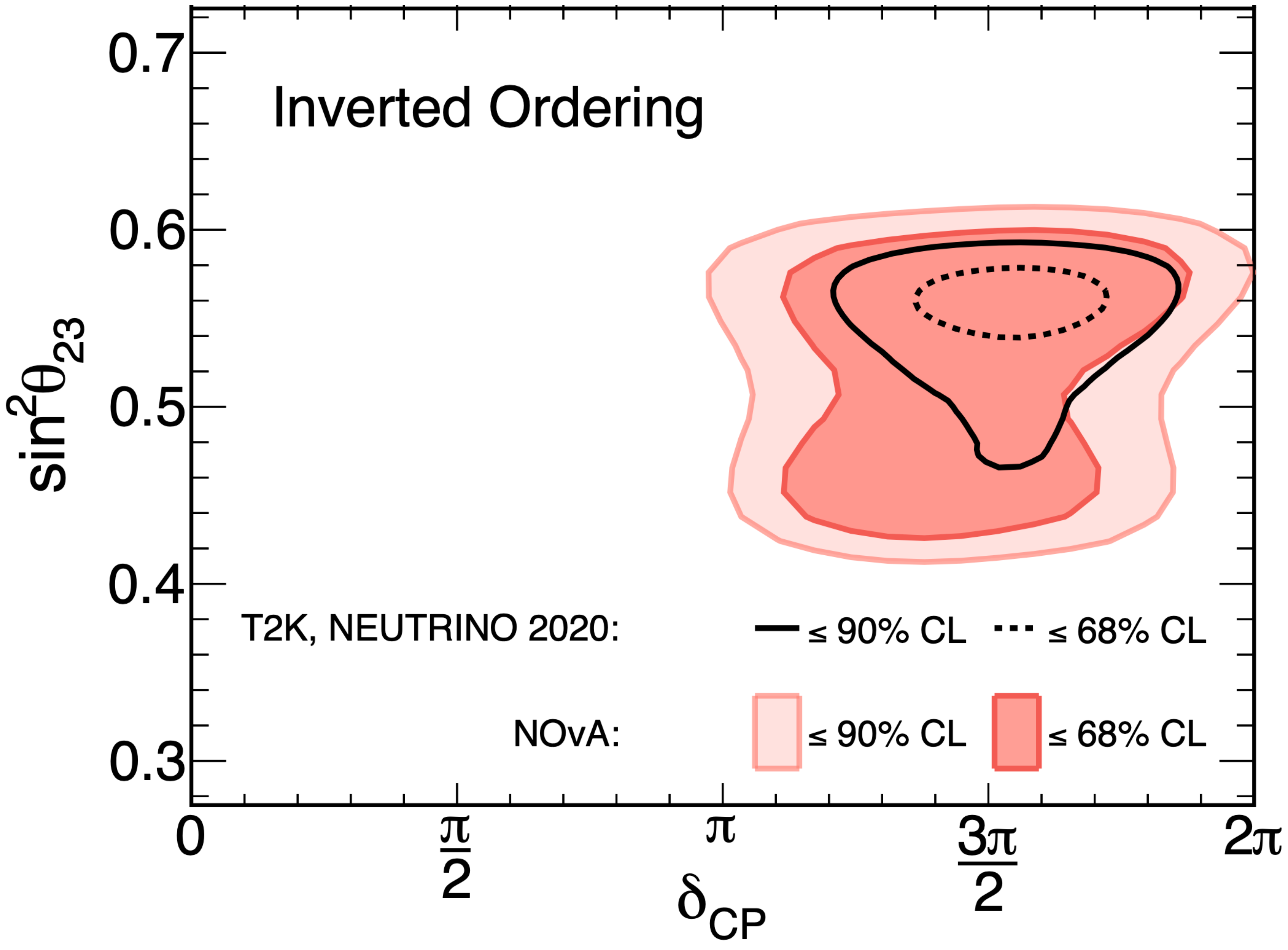
- T2K mild preference $\theta_{23} > 45^\circ$ and normal ordering
- T2K disfavours CP-conservation at 90% CL

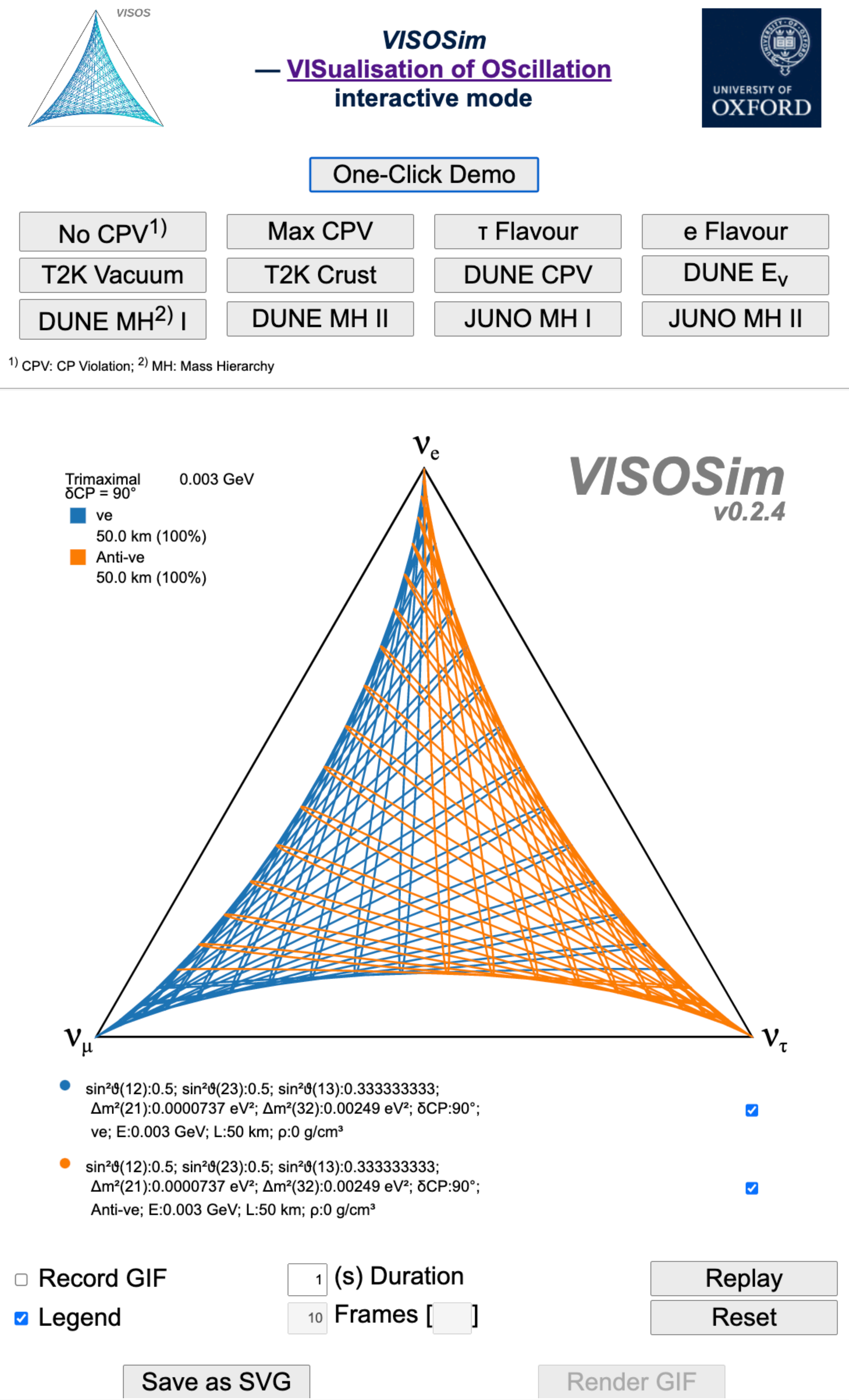




- NOVA has preference for normal ordering, $\delta \sim 145^\circ$
- Exclude IO and $\delta = \pi/2 \ > 3\sigma$







VISOSim
— VISualisation of OScillation
interactive mode

1) CPV: CP Violation; 2) MH: Mass Hierarchy

Trimaximal δCP = 90° 0.003 GeV
🟦 ve
50.0 km (100%)
🟧 Anti-ve
50.0 km (100%)

● sin²ϑ(12):0.5; sin²ϑ(23):0.5; sin²ϑ(13):0.333333333; Δm²(21):0.0000737 eV²; Δm²(32):0.00249 eV²; δCP:90°; ve; E:0.003 GeV; L:50 km; ρ:0 g/cm³ ☑

● sin²ϑ(12):0.5; sin²ϑ(23):0.5; sin²ϑ(13):0.333333333; Δm²(21):0.0000737 eV²; Δm²(32):0.00249 eV²; δCP:90°; Anti-ve; E:0.003 GeV; L:50 km; ρ:0 g/cm³ ☑

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

Neutrino Physics

Neutrino Oscillations in matter

Jessica Turner

Solar neutrinos - PP chain

- The Sun shines by making hydrogen → helium. There are two main ways of doing this: pp chain or CNO cycle

pp-chain I

Step 1 $p + p \longrightarrow d + e^+ + \nu_e$

Step 2 $p + d \longrightarrow {}^3He + \gamma$

Step 3 repeat steps 1 & 2

Step 4 ${}^3He + {}^3He \longrightarrow {}^4He + d + d$

Sun most loses its energy (98.5 %) through pp-chain. This is **pp-I chain** and occurs around **85% of the time**

Binding energy of deuterium ~ 2.2 MeV $\implies E_\nu < 0.5$ MeV

pp-neutrinos are hard to detect

Solar neutrinos - PP chain

- The Sun shines by making hydrogen into helium. There are two main ways of doing this: pp chain or CNO cycle

pp-chain II

Step1 $^{4}He + {}^{3}He \longrightarrow {}^{7}Be + \gamma$

pp-II chain occurs around **15%** of the time

Step2 $^{7}Be + e^{-} \longrightarrow {}^{7}Li + \nu_e$

Step3 $^{7}Li + p \longrightarrow 2\,{}^{4}He$

Solar neutrinos - PP chain

- The Sun shines by making hydrogen into helium. There are two main ways of doing this: pp chain or CNO cycle

pp-chain III

Step 1 $\quad {}^4He + {}^3He \rightarrow {}^7Be + \gamma$

Step 2 $\quad {}^7Be + p \rightarrow {}^8B + \gamma$

Step 3

$$\begin{tikzcd} {}^8B \arrow[r] & {}^8Be^* \arrow[dr] & + e^+ + \nu_e \\ & & 2\,{}^4He \end{tikzcd}$$

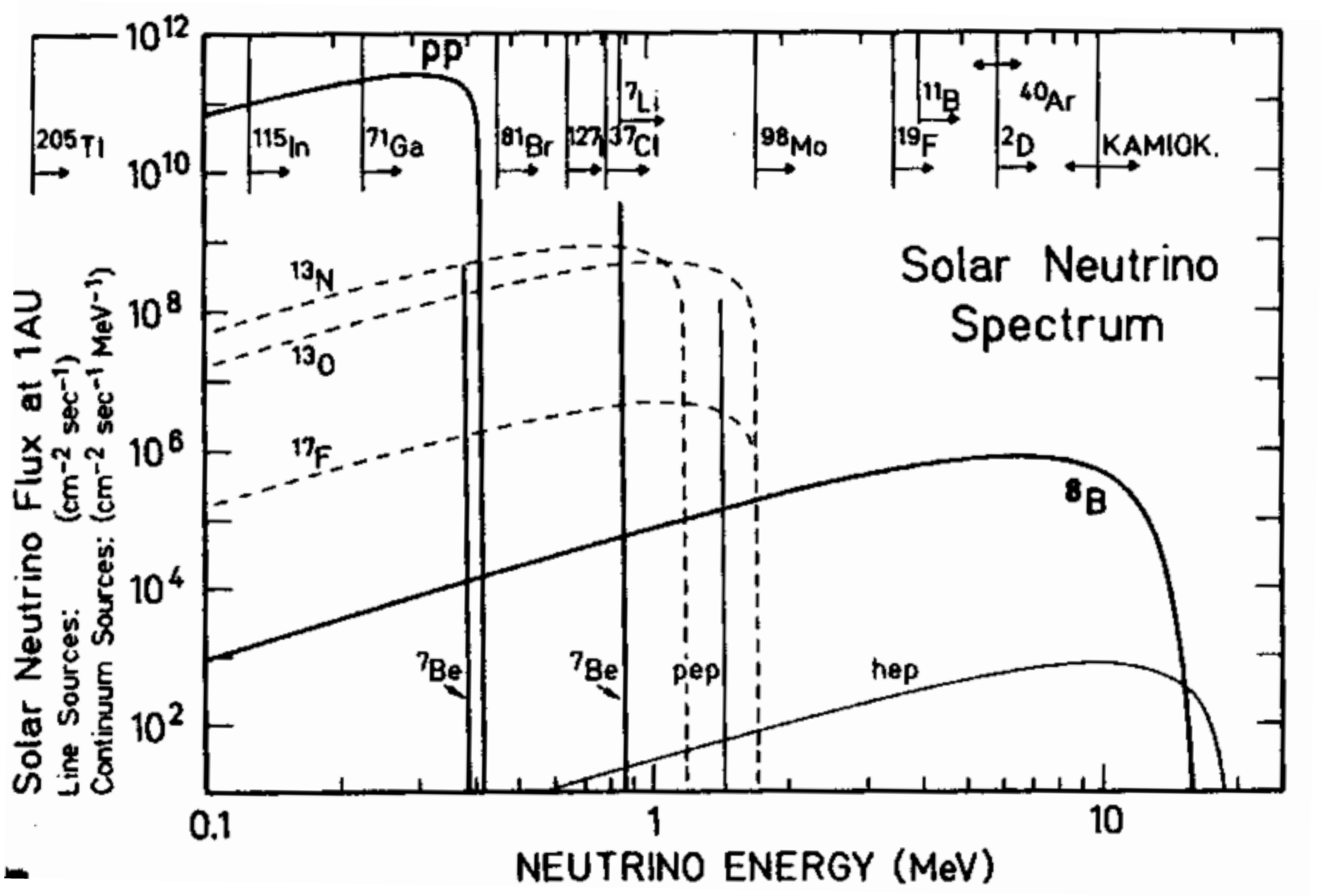
pp-III chain occurs around **0.3%** of the time

Neutrinos produced in this reaction have energies up to 15 MeV

Solar neutrinos - CNO cycle

$$
\begin{aligned}
{}^{12}C + {}^{1}H &\rightarrow {}^{13}N + \gamma \\
{}^{13}N &\rightarrow {}^{13}C + e^{+} + \boxed{\nu_e} \\
{}^{13}C + {}^{1}H &\rightarrow {}^{14}N + \gamma \\
{}^{14}N + {}^{1}H &\rightarrow {}^{15}O + \gamma \\
{}^{15}O &\rightarrow {}^{15}N + e^{+} + \boxed{\nu_e} \\
{}^{15}N + {}^{1}H &\rightarrow {}^{12}C + {}^{4}He
\end{aligned}
$$

- Many nuclear processes (pp chain and CNO cycle) produces electron neutrinos
- Energies of the neutrinos will differ, depending on the reaction.



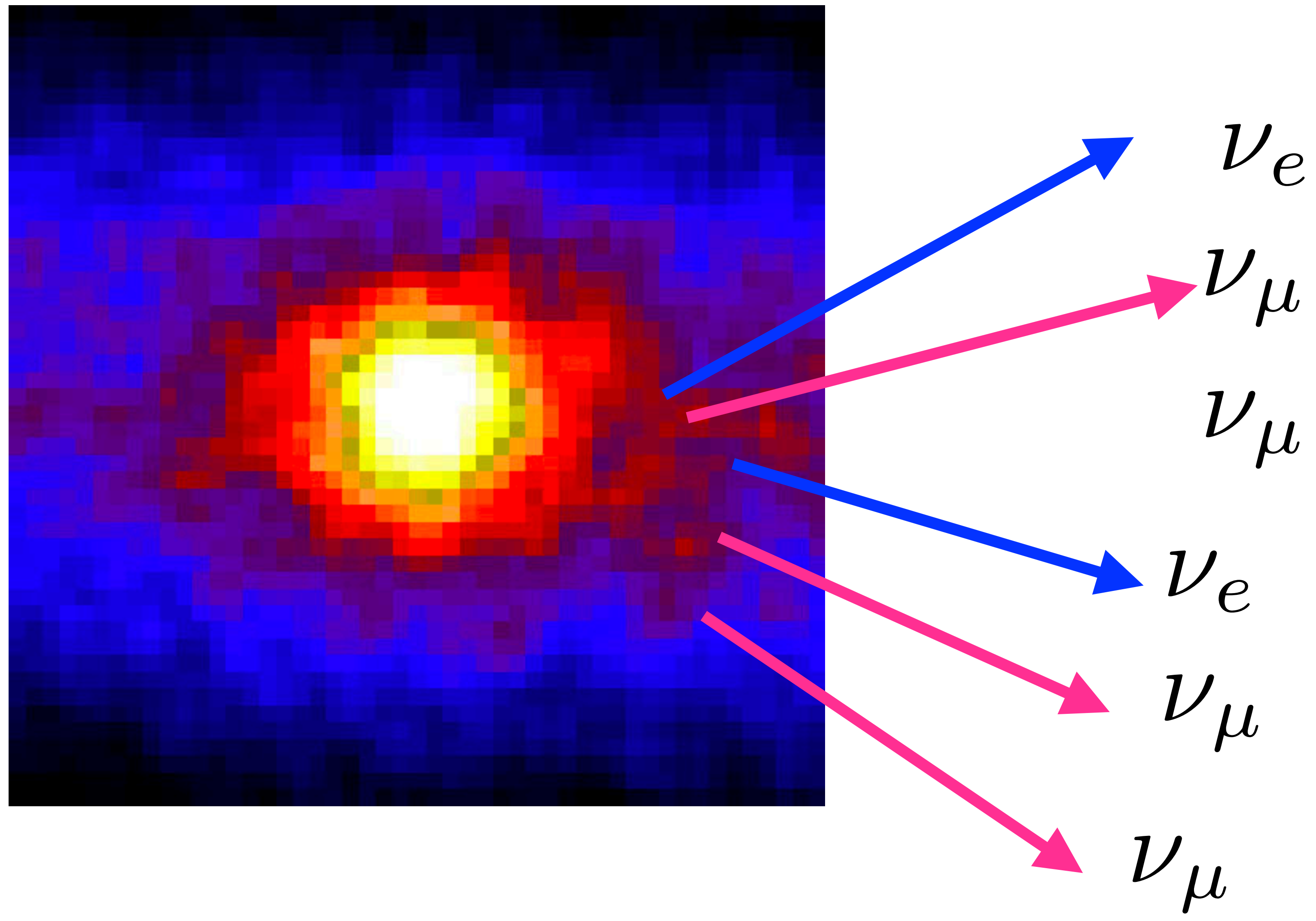
Board

Solar neutrinos

- 1964 Homestake experiment (headed by Davis & Bahcall) detected solar neutrinos but there were approximately 2/3 less than expected from Bahcall's Standard Solar Model prediction.
- It was initially proposed that the solar models were wrong.
- Or that two experiment Homestake and GALLEX were wrong!
- As you can guess, the resolution to this problem is neither!

Solar neutrinos

- Confirmation of neutrino oscillations came in 2001 by the Sudbury Neutrino. They measured not only electron neutrino flux but all flavour neutrinos via NC interactions



SNO 1 ton heavy water (D_2O) tank surrounded by 9600 PMTs. Deuterium has binding energy 2.2 MeV $\Longrightarrow$SNO can detect Boron 8 solar neutrinos.

$\nu_e + d \to p + p + e^-$	Charged current (CC)
$\nu_x + d \to p + n + \nu_x$	Neutral current (NC)
$\nu_x + e^- \to \nu_x + e^-$	Elastic scattering (ES)