CP violation search in the lepton sector using long-baseline ν in Japan (Super-Kamiokande, T2K & Hyper-Kamiokande)

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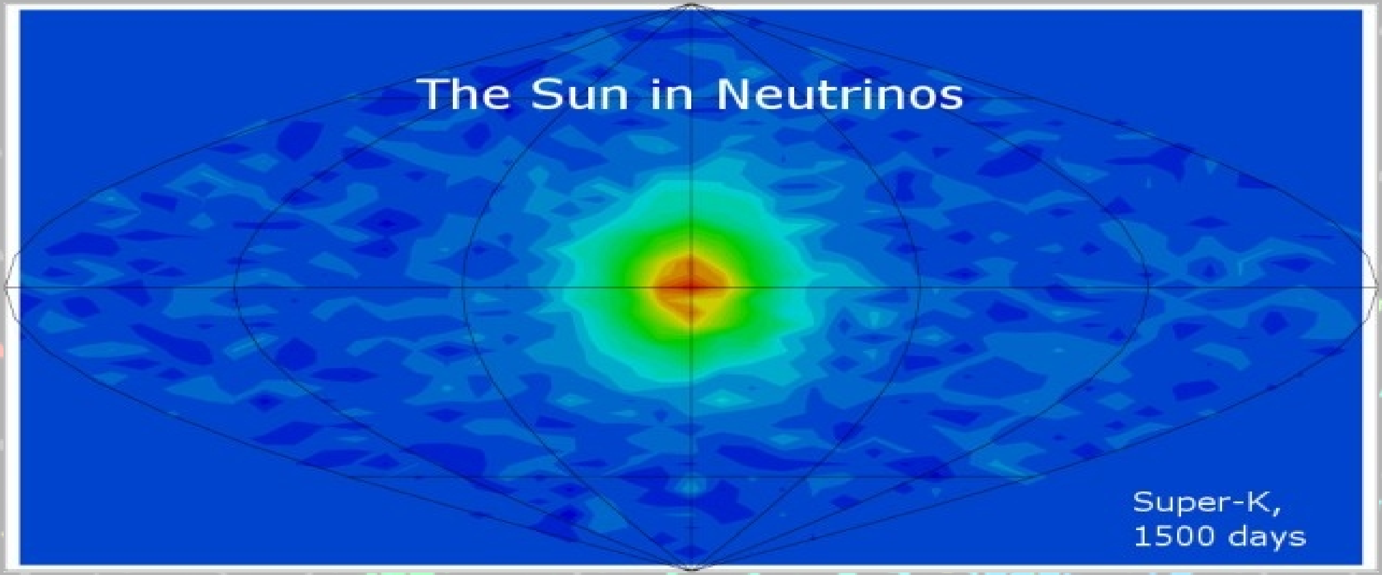
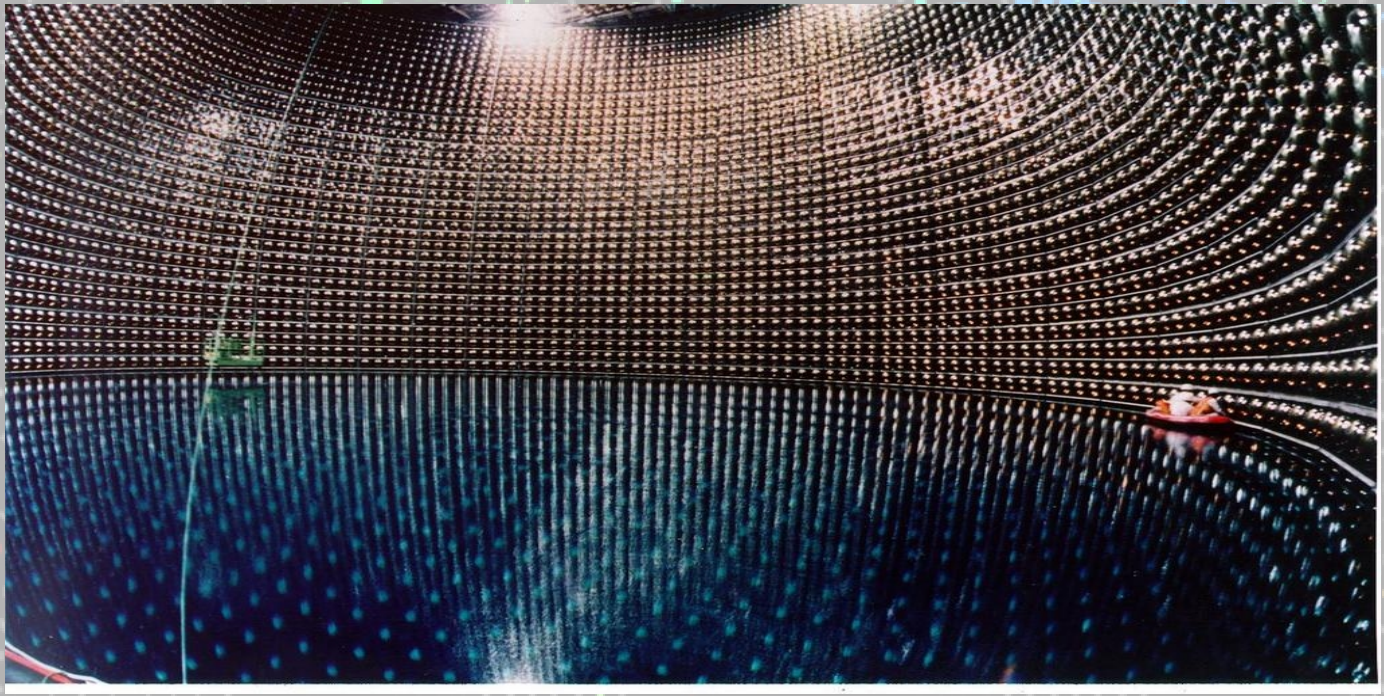
Congres SFP, Cite des sciences, Paris, 2023/07/04

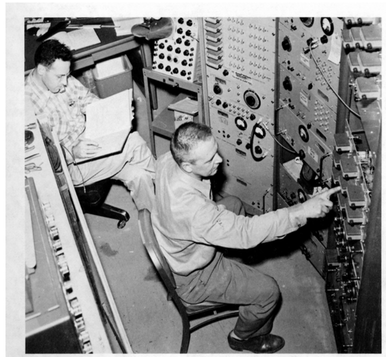


I. Neutrino before 2000's



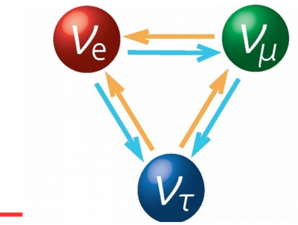
Selected discoveries in neutrino physics

Pauli :
Introduce neutrino to explain β spectrum (to save energy/spin conservation)

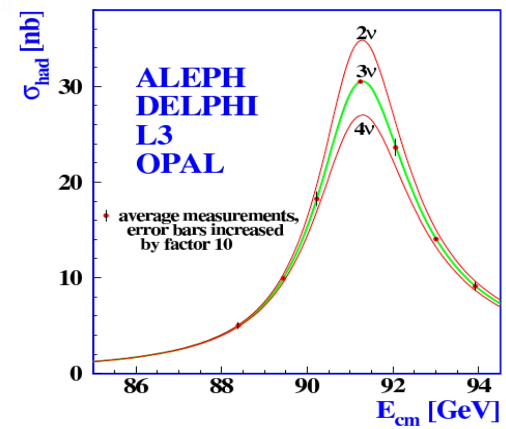


Reines & Cowan :
Experimental detection of neutrino (Savannah River reactor)

@BNL :
2 distinct neutrino families

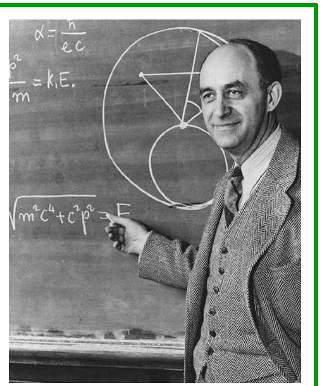


@LEP :
Only 3 active (Z int.) light (<45GeV) neutrino families

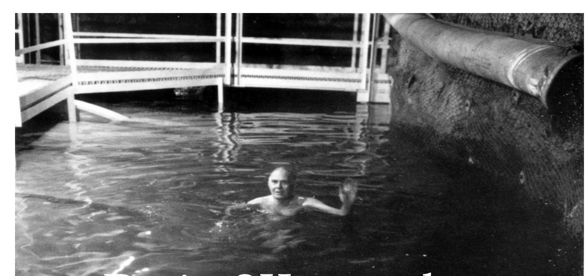


1930 | 1934 | 1956 | 1962 | 1967 | 1989

Fermi :
Neutrino incorporated in a theory of weak interactions



Maki-Nakagawa-Sakata:
Flavour states are superposition of mass states

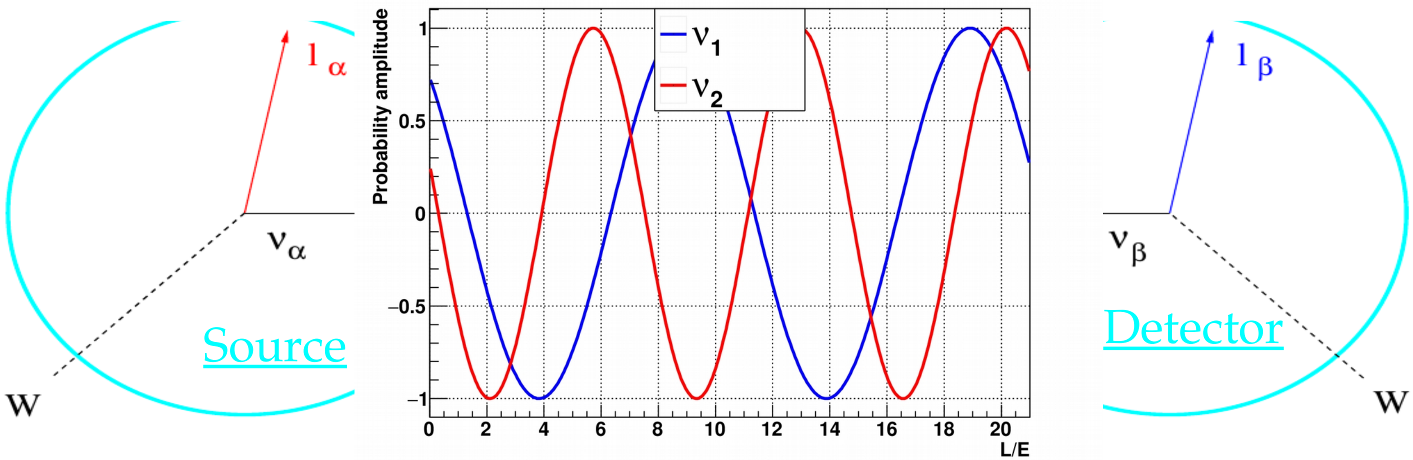


Davies@Homestake :
1st indication of solar ν deficit

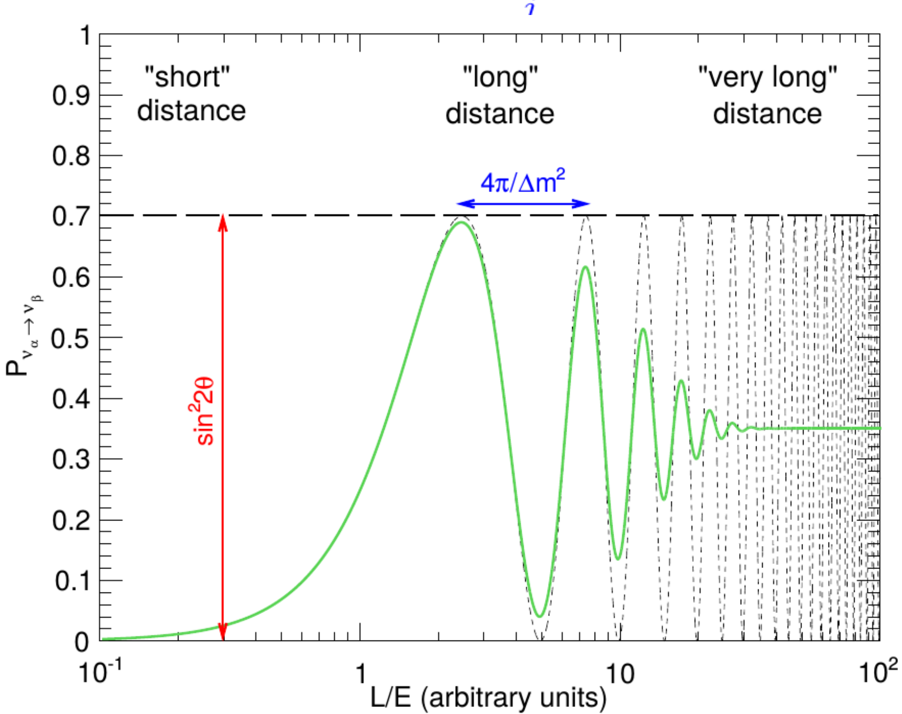
Neutrino oscillation in 2 flavour case

- Flavour states (interact) (ν_α,ν_β) ≠ mass states (propagates) (ν_1,ν_2).

$$\nu_\alpha = 70\ \%\ \nu_1 + 30\ \%\ \nu_2 \qquad \nu_\beta = 30\ \%\ \nu_1 + 70\ \%\ \nu_2$$



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha j}\,|\nu_j\rangle \qquad e^{-i(Et-p_j x)} \qquad |\nu_\beta\rangle = \sum_k U^*_{\beta k}\,|\nu_k\rangle$$



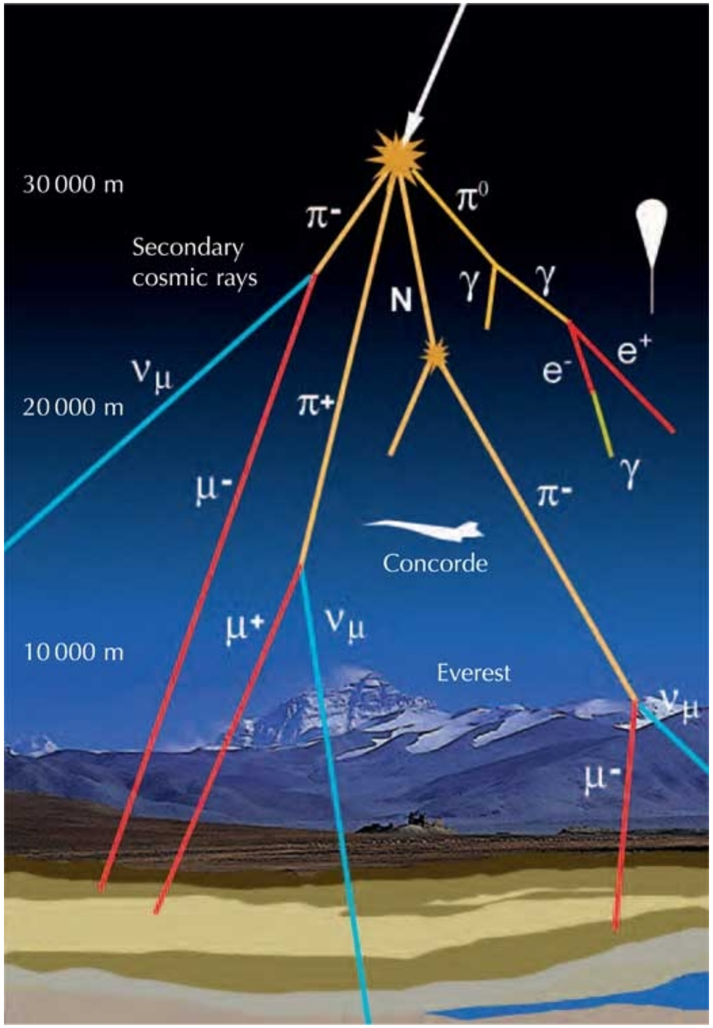
2 flavour approximation :

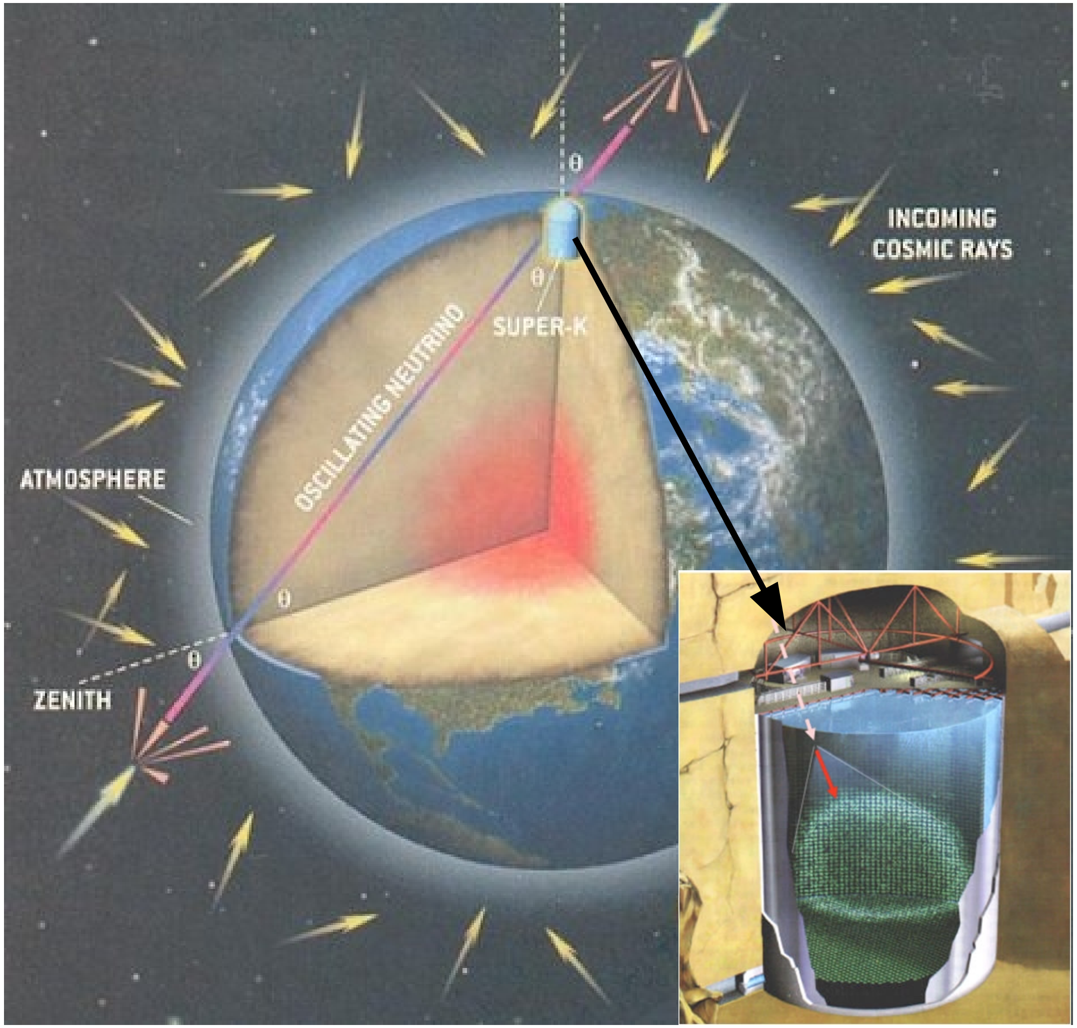
$$P_{\nu_\alpha\to\nu_\beta}(L,E) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Oscillation in L/E.
- Frequency : determined by the mass square difference : $\Delta m^2 = m^2_2 - m^2_1$
- Amplitude : determined by the mixing angle θ.

Atmospheric neutrinos in Super-K

- Neutrinos produced in cosmic ray decays.



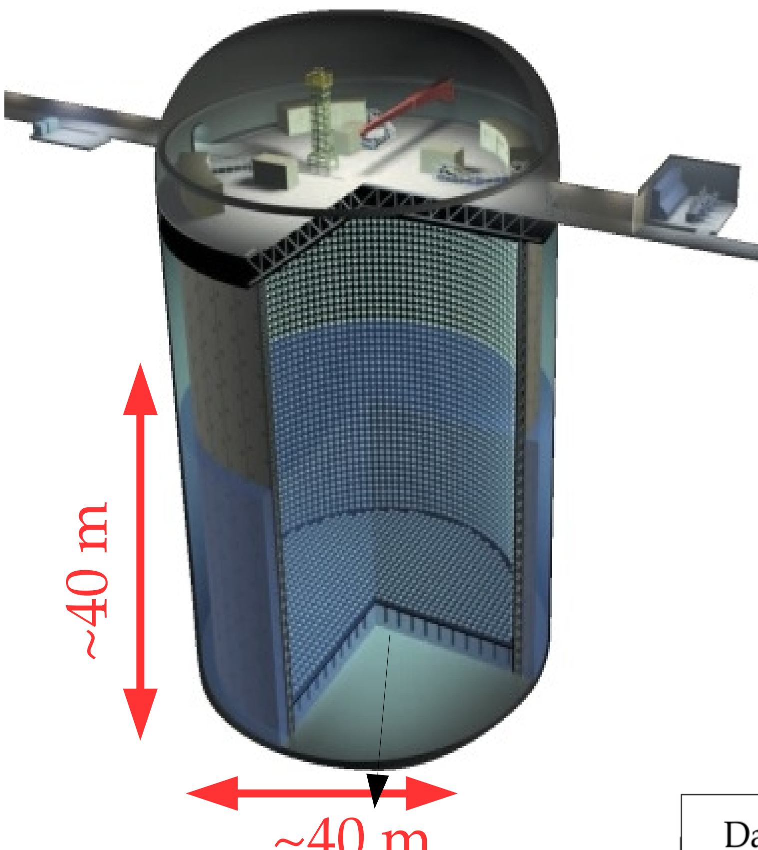


If no oscillations :

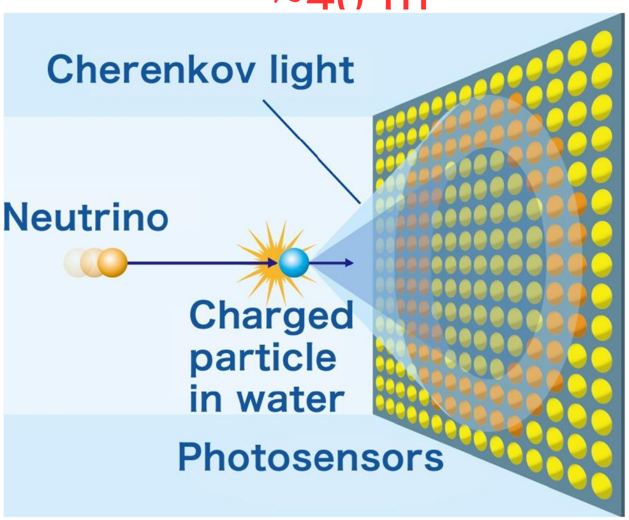
Atmospheric fluxes predicts ν_μ to ν_e ratio, $R = \dfrac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} \approx 2.$

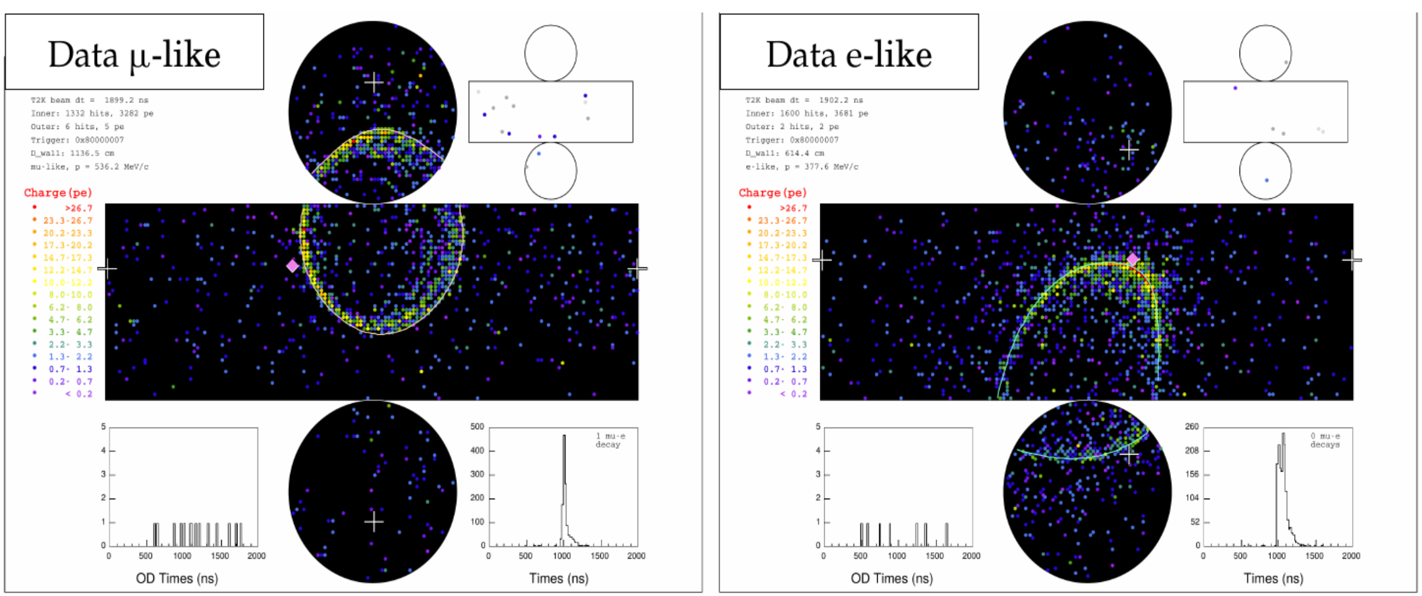
R should be independent from zenith angle as production is isotropic.

The Super-Kamiokande detector

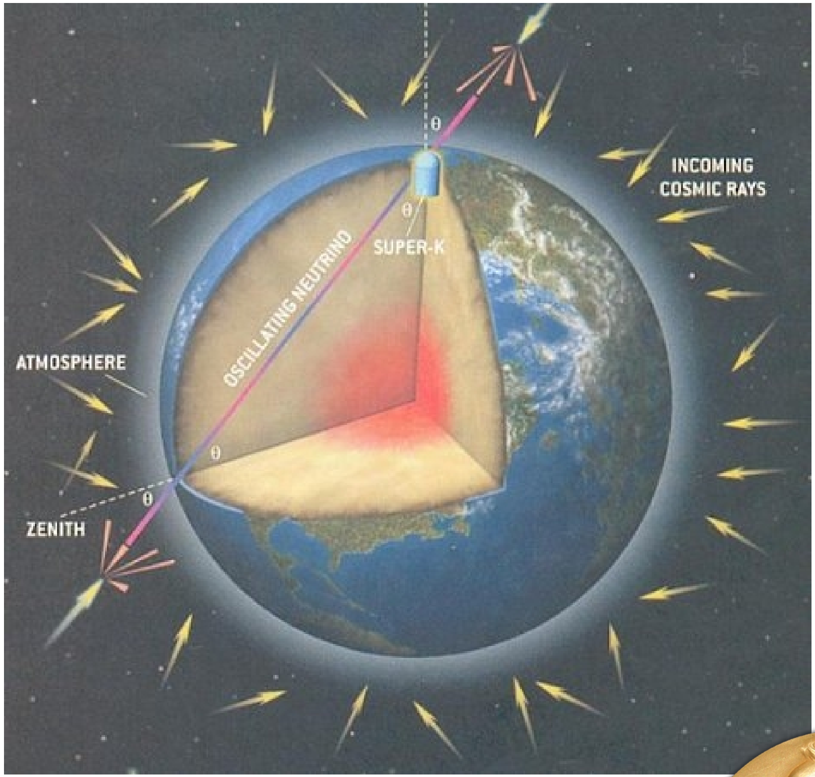


- A 50 kton water Cherenkov detector in Japan.
- Cherenkov light is detected by 11,000 PMTs.
- e / μ discriminated using ring shape.
- No charge sign discrimination
  → Unable to directly separate ν & ν.

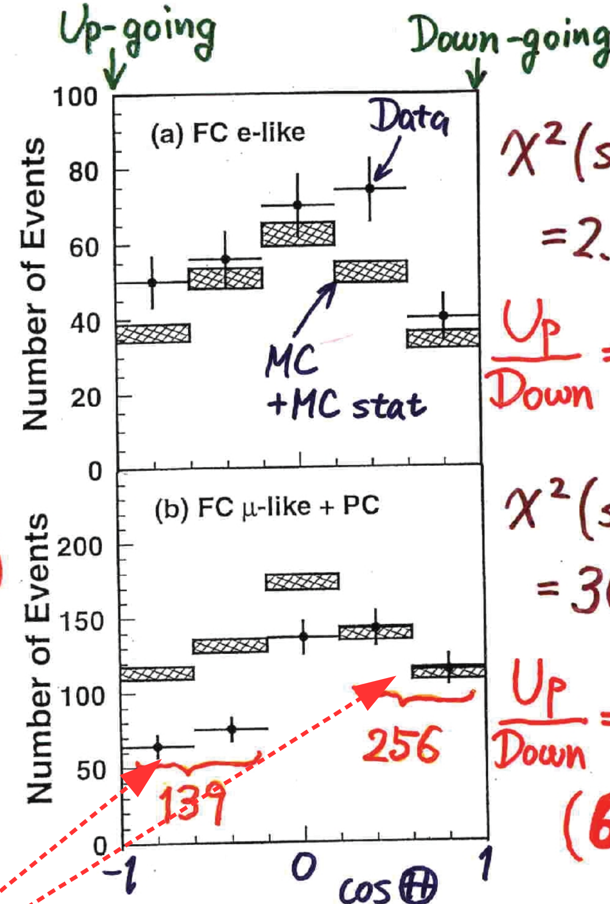




Atmospheric neutrinos



Zenith angle dependence (Multi-GeV)



(e): χ^2(shape) = 2.8/4 dof; $\frac{Up}{Down} = 0.93^{+0.13}_{-0.12}$

(μ): χ^2(shape) = 30/4 dof; $\frac{Up}{Down} = 0.54^{+0.06}_{-0.05}$

(6.2σ !!)

※ Up/Down syst. error for μ-like

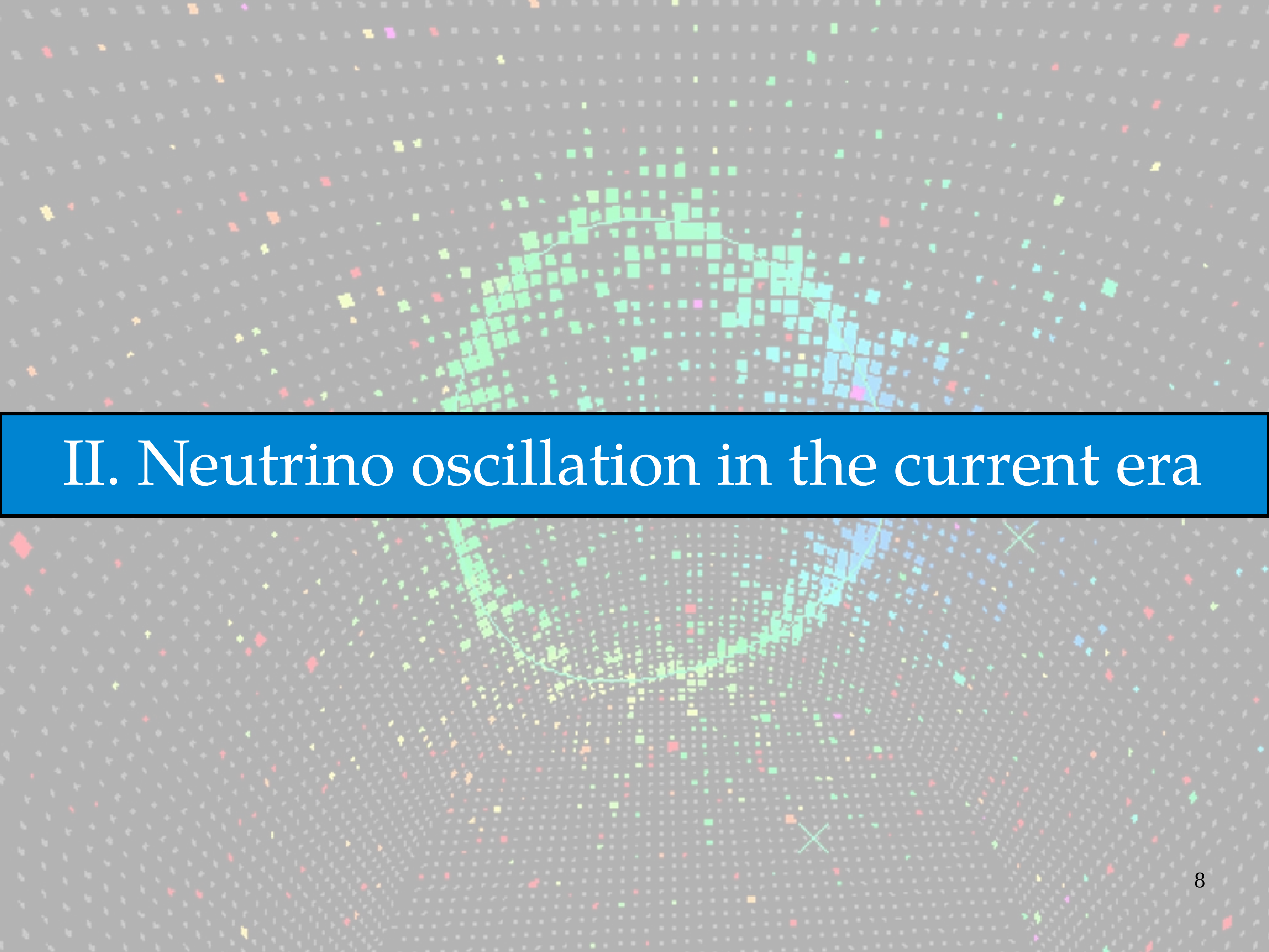
Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background …. < 2%) 2.1%

Observations :

- R < 2.
- R varies with zenith angle ↔ L dependency

→ Definite proof of ν oscillation.



II. Neutrino oscillation in the current era

Three flavour neutrino oscillations

- 3 flavour eigenstates (ν_e, ν_μ, ν_τ) and 3 mass states (ν_1, ν_2, ν_3).

→ PMNS symetries allows to rewrite 3D matrix into three 2D rotations.

$$c_{ij} = \cos\theta_{ij} \text{ and } s_{ij} = \sin\theta_{ij}$$

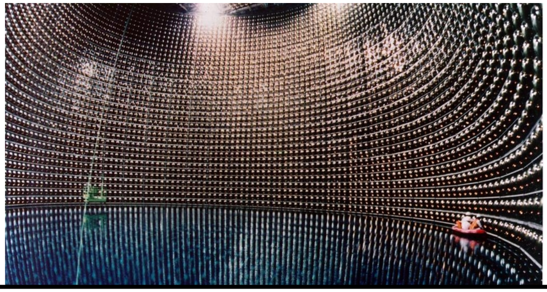
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\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

3 mixing angles: Θ_{23}, Θ_{13}, Θ_{12}

2 mass square differences : Δm^2_{32}, Δm^2_{21}

1 Dirac CP violation phase: δ_{CP}

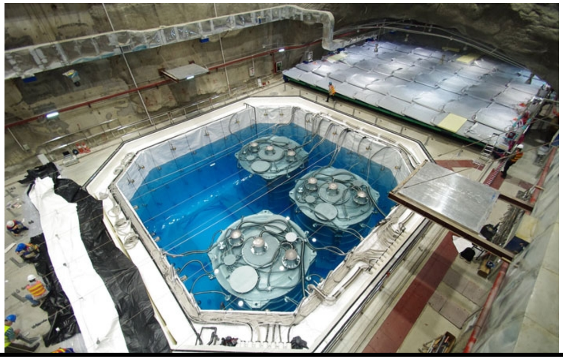
« Atmospheric »



$\Theta_{23} = 45° \pm 7°$

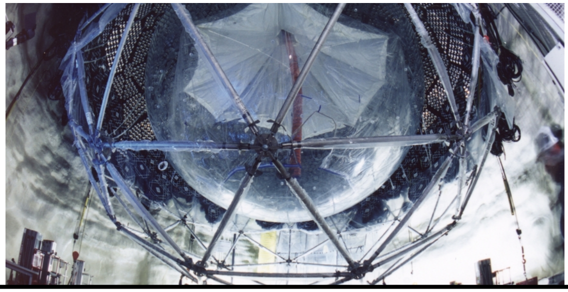
$|\Delta m^2_{32}| = (232^{+12}_{-8}) \times 10^{-5}\ eV^2$

« Reactor »



$\Theta_{13} = 9.0° \pm 2.9°$

« Solar »



$\Theta_{12} = 33.9° \pm 4.5°$

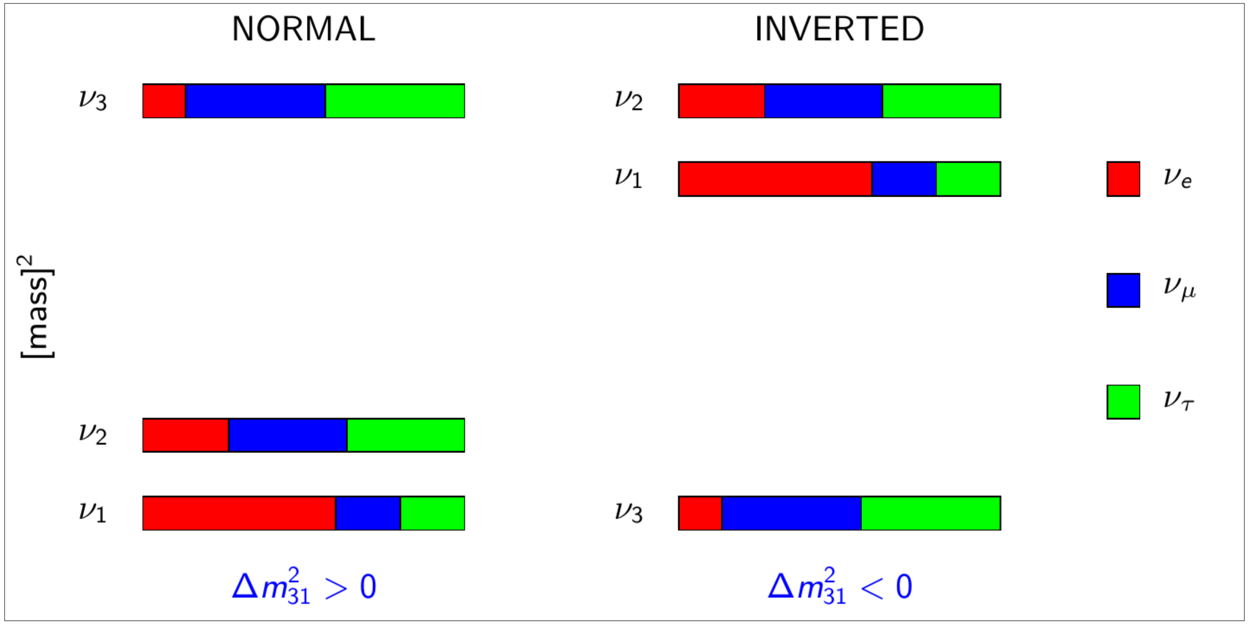
$\Delta m^2_{12} = (7.50 \pm 0.20) \times 10^{-5}\ eV^2$

Open issues in neutrino oscillations

- Is CP violated in the neutrino sector ?$\rightarrow$ Is $P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$?

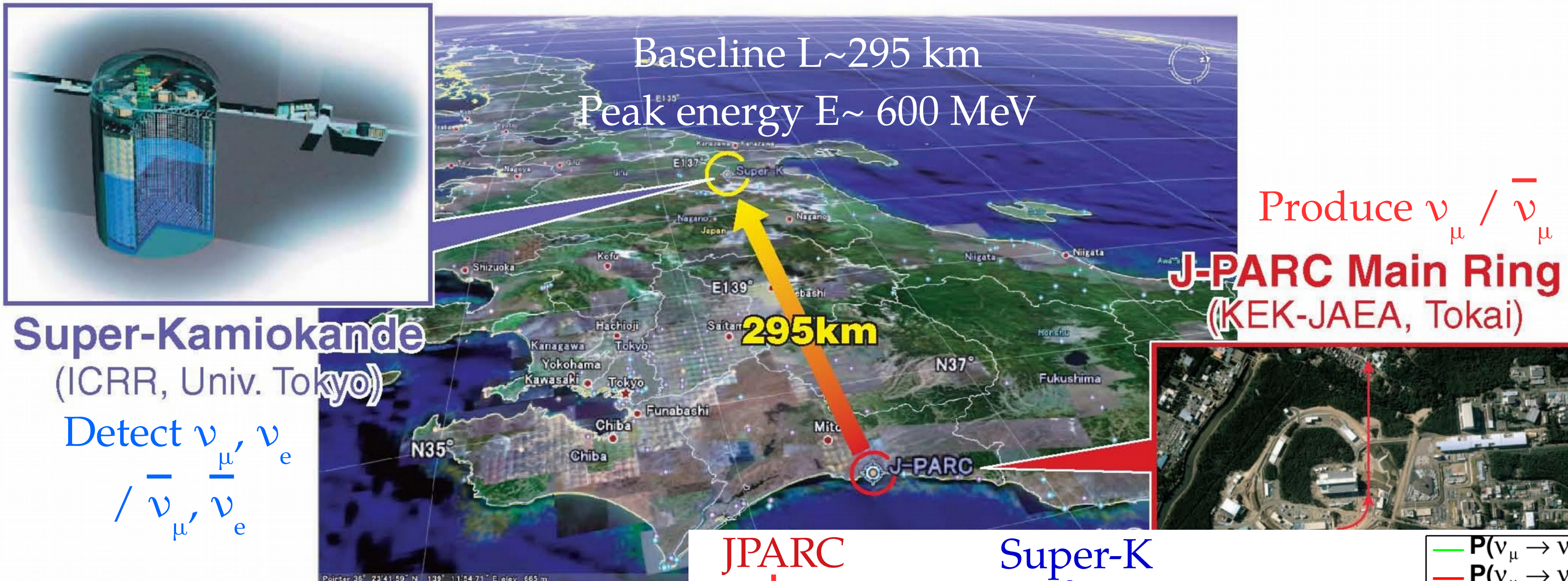
- What is the neutrino mass ordering : affect nucleosynthesis in SN…
  $\rightarrow$ Oscillations in vacuum provides only $|\Delta m^2|$.
  $\rightarrow$ Matter effect in the Sun provides : $m_2 > m_1$.
  $\rightarrow$ Detected through matter effect in the Earth.

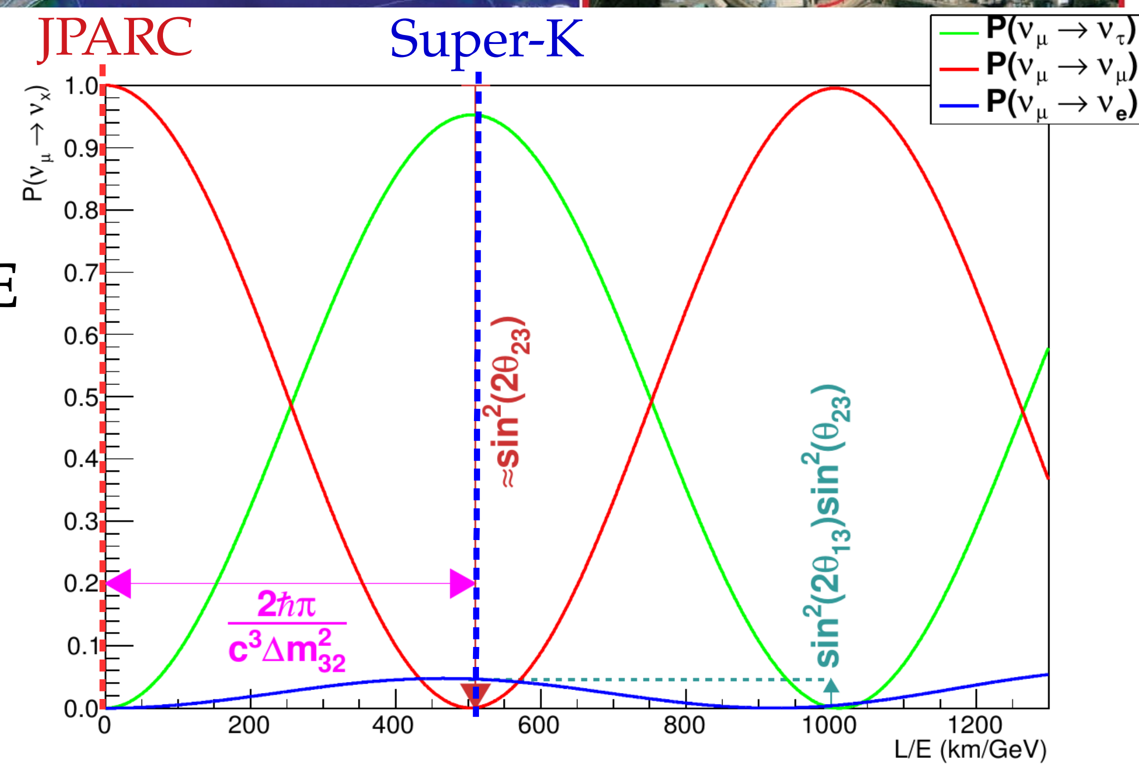
$\rightarrow$ 2 orderings :



- Is there maximal mixing in the atmospheric sector
  $\rightarrow \theta_{23} = 45^o$?
  $\rightarrow$ Hidden symmetry ?

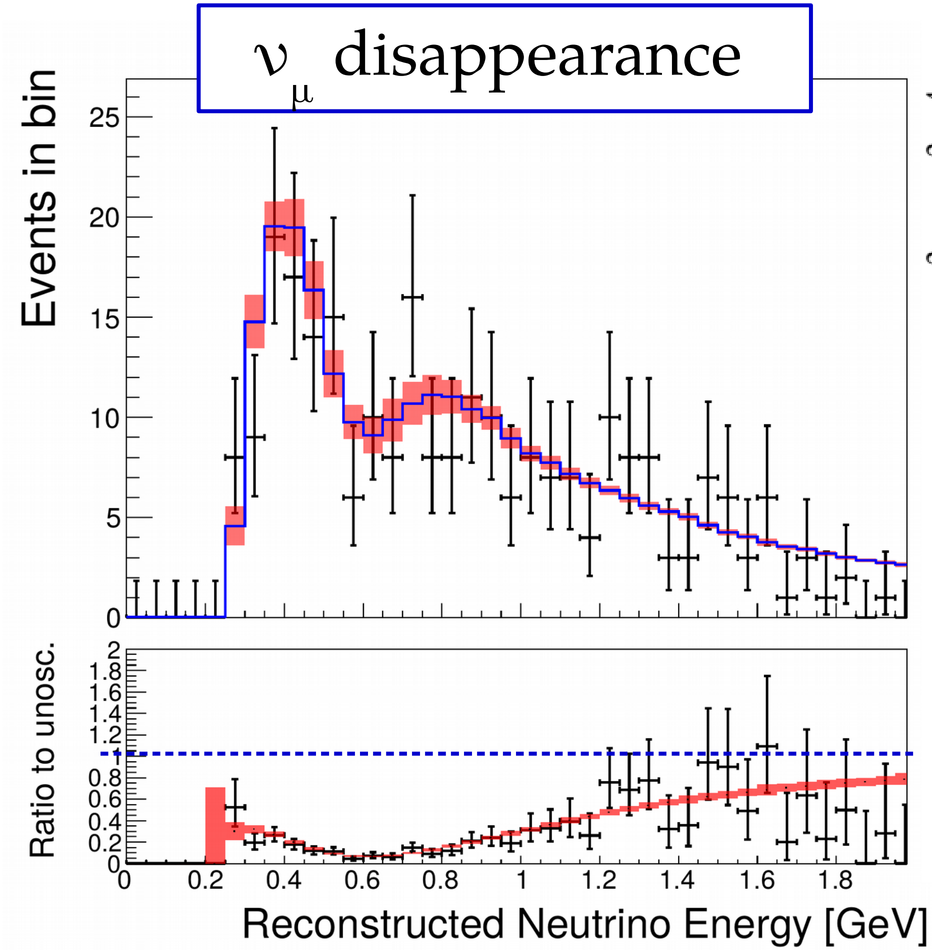
The Tokai-to-Kamioka experiment

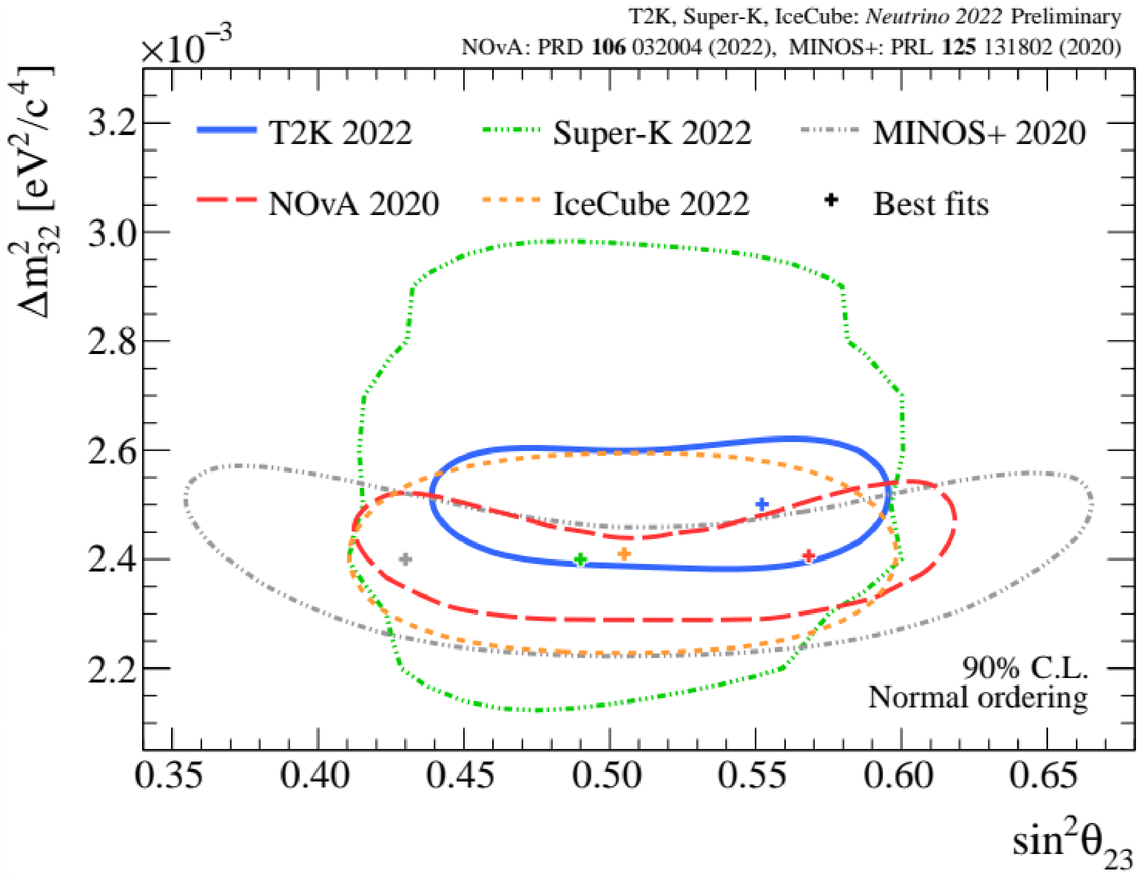




- Pure & intense ν_μ beam.
- Fixed L & tuned E_ν → **Tune L/E to maximize oscillation.**
- Observe ν_μ disappearance and ν_e appearance.
- Can select ν or $\bar{\nu}$ → **Test CPV**.

T2K results





- <u>Measure ν_μ disappearance</u> → World-leading constraints on Θ_{23}, Δm^2_{32}.

- <u>68 % C.I :</u> $0.49 \leq \sin^2\theta_{23} \leq 0.58$ → Compatible with maximal mixing.

Use of ν_e appearance channel

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$
$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} + \ldots$$

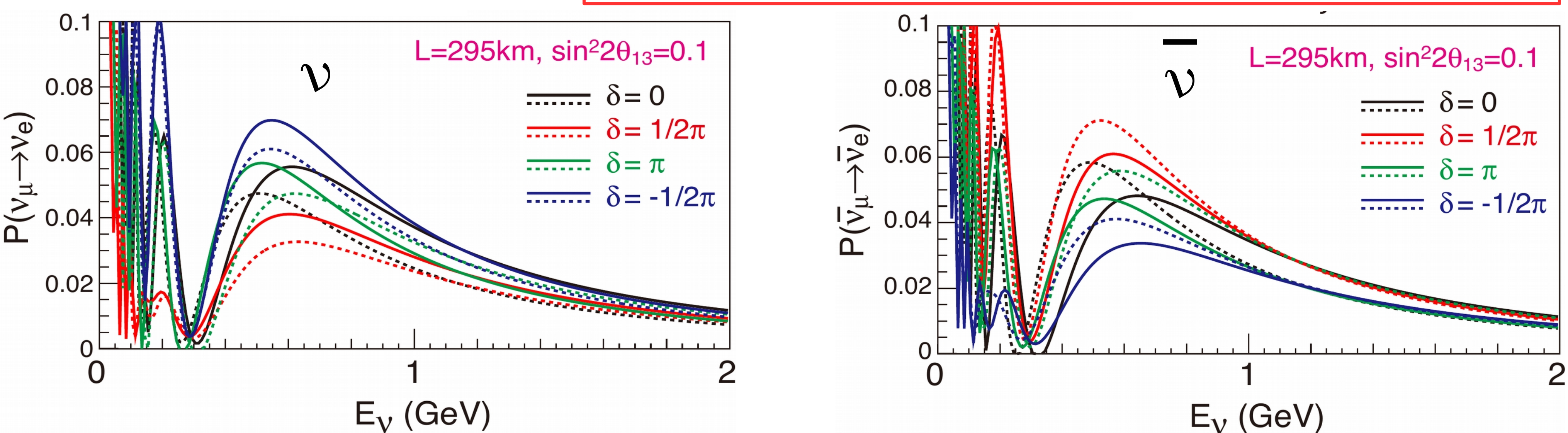
1. $\sin^2(2\theta_{13})$: Leading term

2. CP violation effect:

→ sinδ is CP odd : opposite effect for ν / $\bar{\nu}$

→ If $\delta_{CP} = -\pi/2$: ↑ $\nu_\mu \to \nu_e$ & ↓ $\bar{\nu}_\mu \to \bar{\nu}_e$.

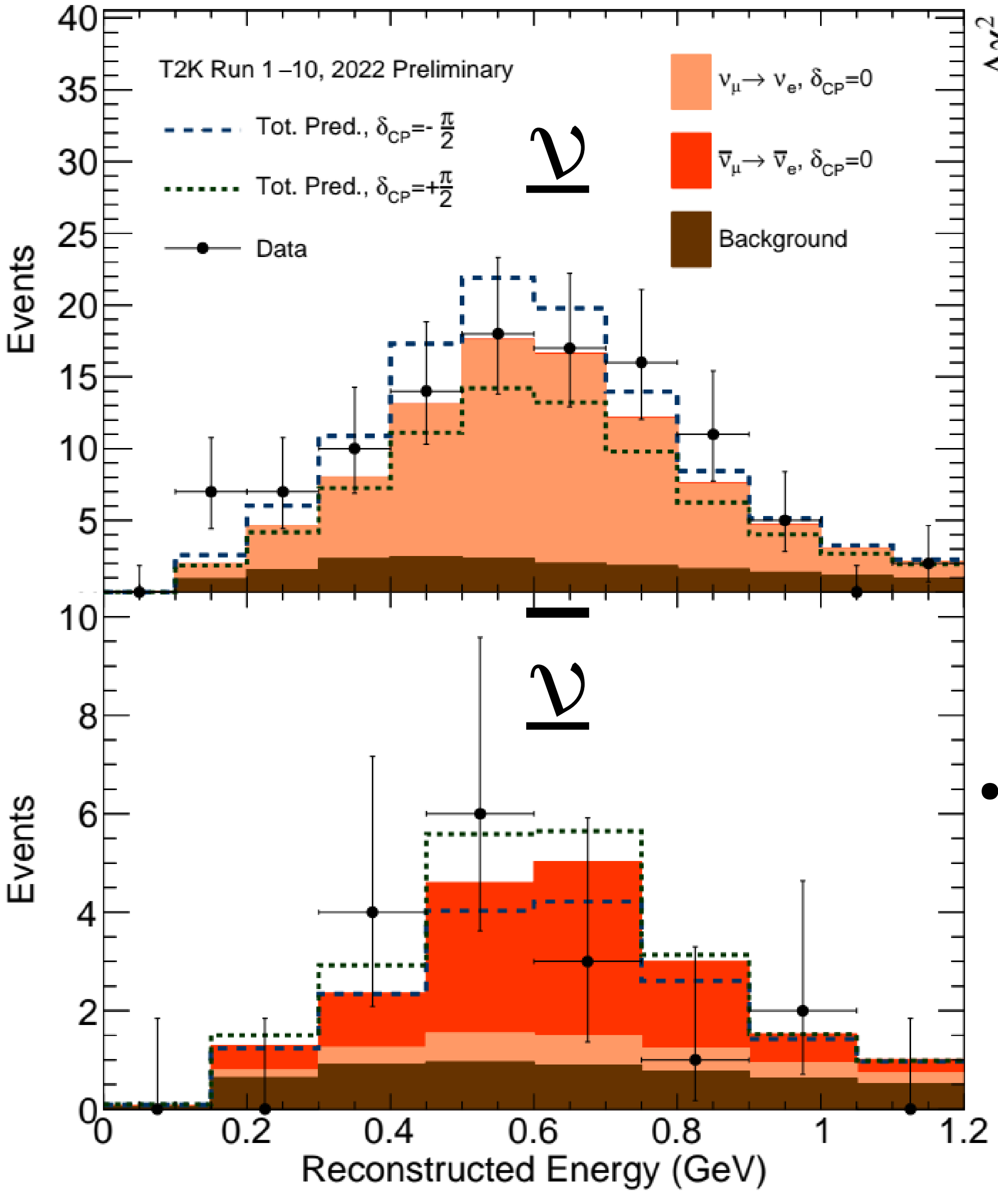
→ ~27% @T2K ($\sin^2(2\theta_{23})=1$)

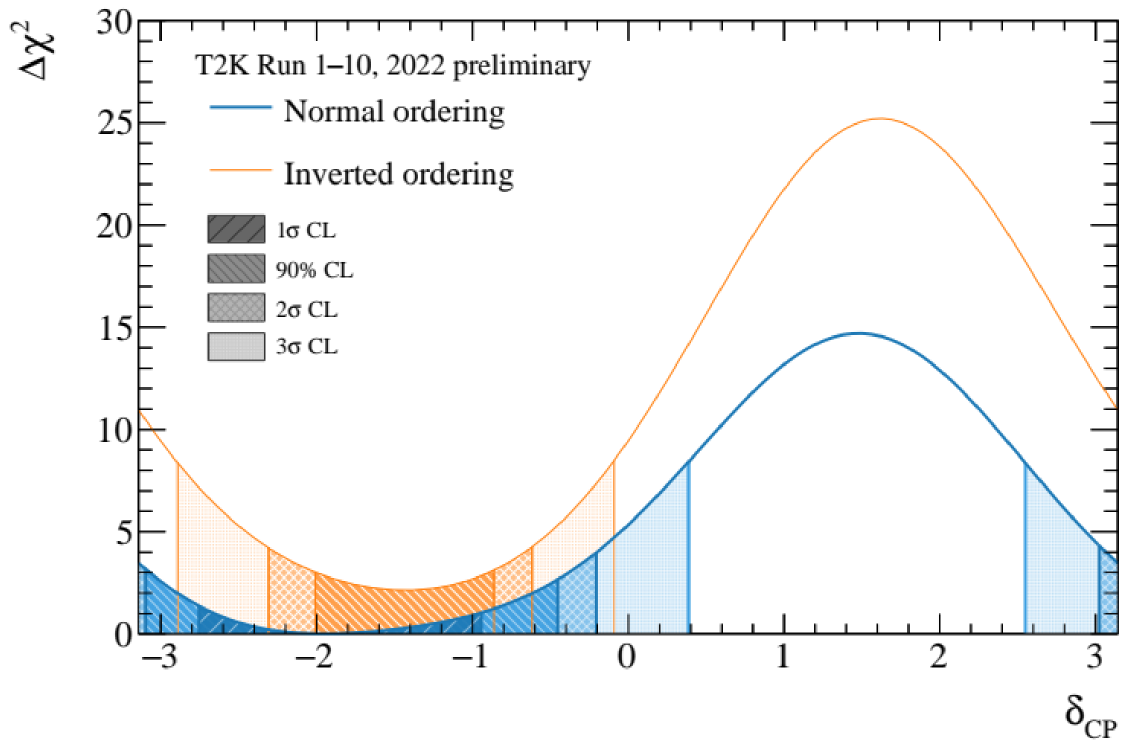


3. Mass ordering effect:

→ Same as δ_{CP} effect opposite effect for ν / $\bar{\nu}$ (~10% effect)

T2K results in the appearance channel





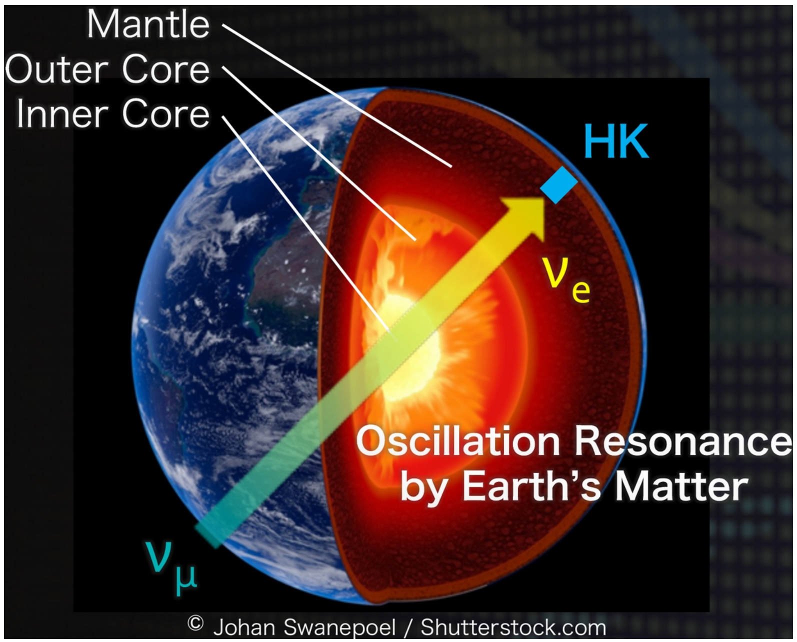
- CP conservation excluded > 90 % C.L.

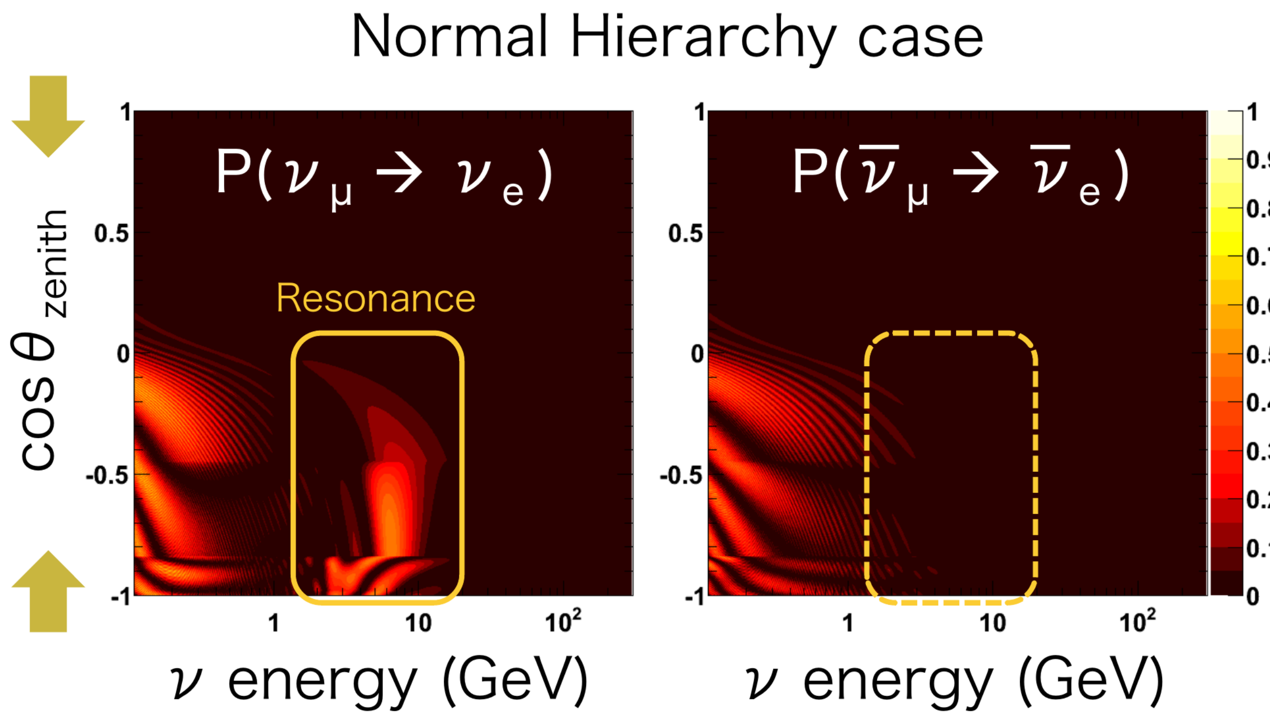
- Normal ordering is (very) midly preferred ($\Delta\chi^2 = 2.5$)

→ Limited sensitivity due to short-baseline (295 km).

Atmospheric neutrinos

- <u>Mass-ordering can be measured through matter effects</u>
  → The longer the baseline, the higher the effects



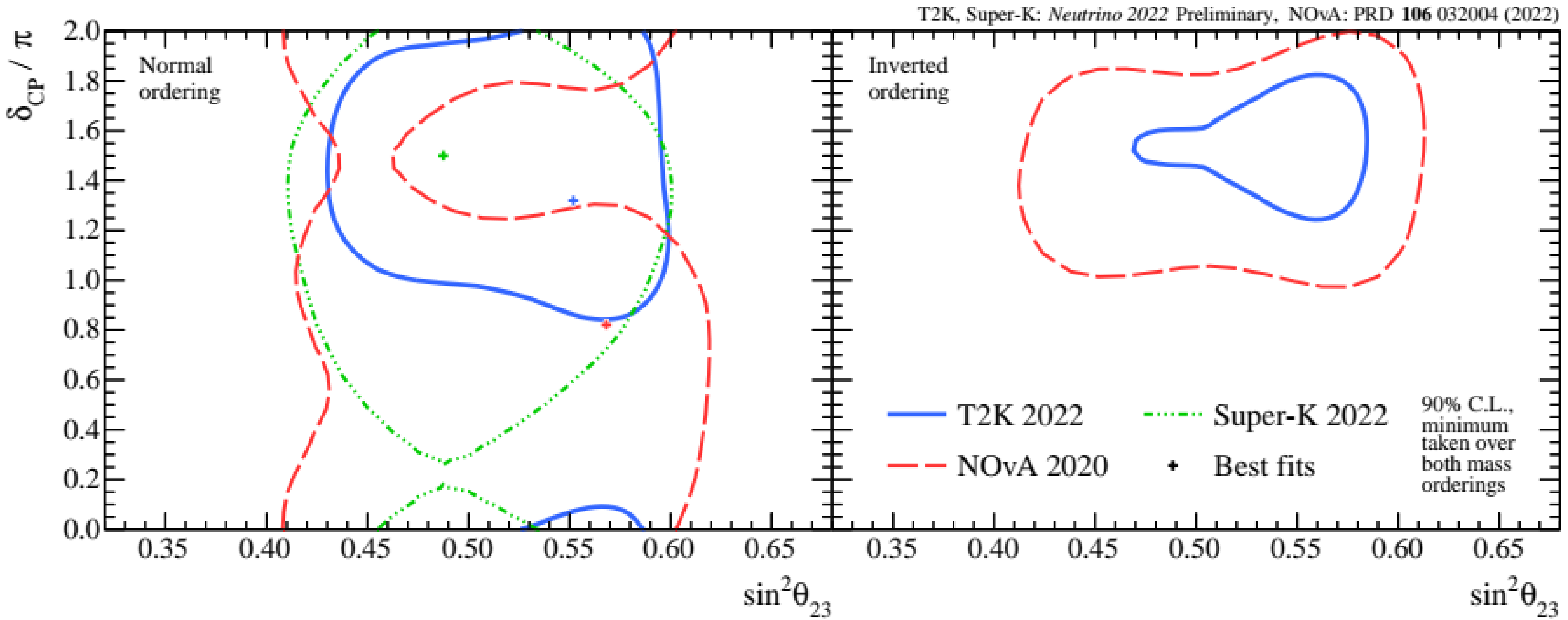


- Mass ordering determined with upward-going multi-GeV ν_e sample :

atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline

  - <u>Normal ordering :</u> enhancement of $\nu_\mu \rightarrow \nu_e$.
  - <u>Inverted ordering :</u> enhancement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

δ_{CP} and mass-hierarchy



- Inverted ordering also disfavoured by SK > 2σ ($\Delta\chi^2 = 5.8$)
  → Enhanced sensitivity to mass-ordering.

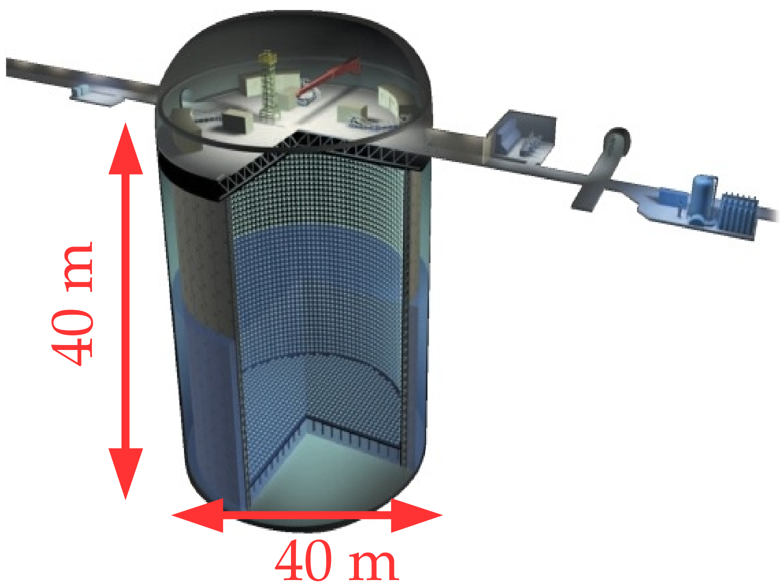
- CP conservation (sin δ_{CP} =0) excluded by T2K (90 % C.L) and SK (> 1σ).
  → Maximal CPV ($\delta_{CP} = 3\pi/2$) favoured by T2K & SK, whatever MO.
  → Sentivity is more shallow for atmospherics.

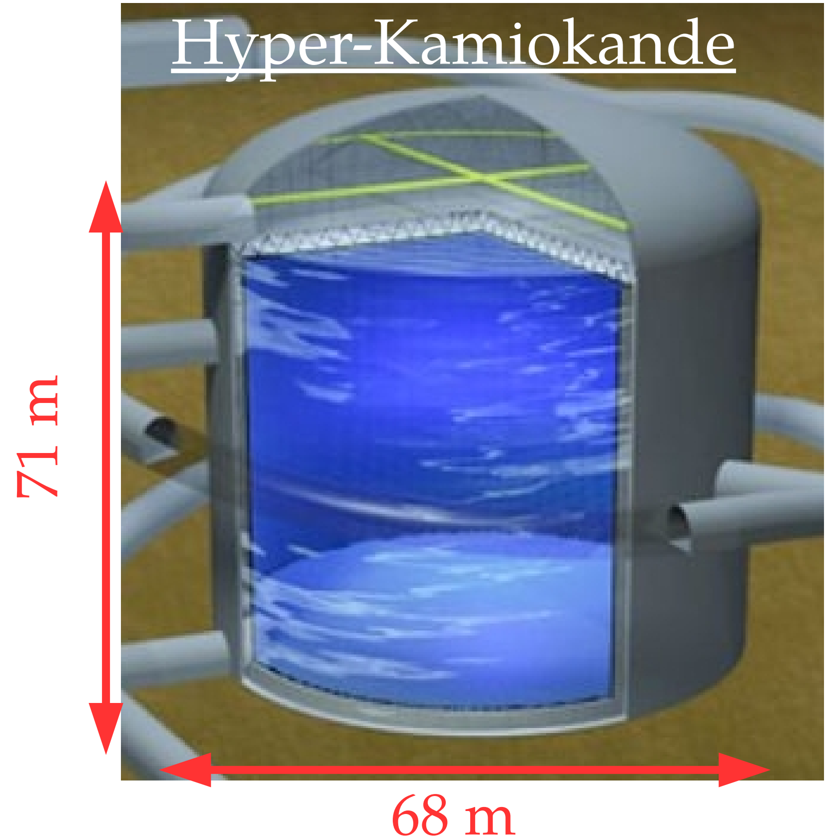
III. Neutrino oscillation in the coming years

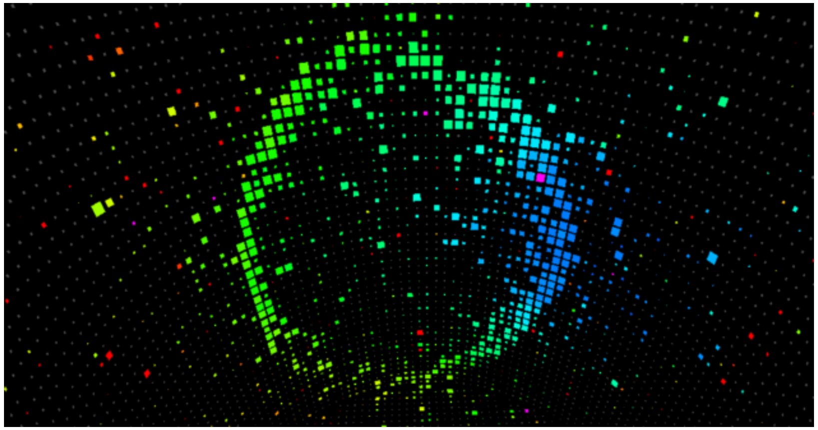
Next generation of experiments : Hyper-K

- Next generation of neutrino observatory in Japan→ construction 2020-27
  → A 260 kton water Cherenkov detector → <u>Fiducial Mass ~ 8 x SK.</u>

<u>Super-Kamiokande</u>



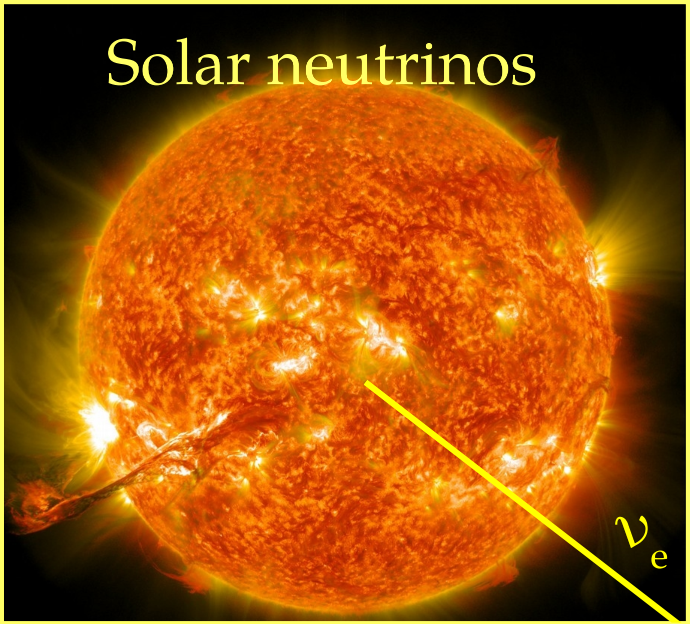




	Super-K	Hyper-K (1st tank)
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**40,000**
Photo-coverage	40%	40% (**x2 sensitivity**)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

Physics case

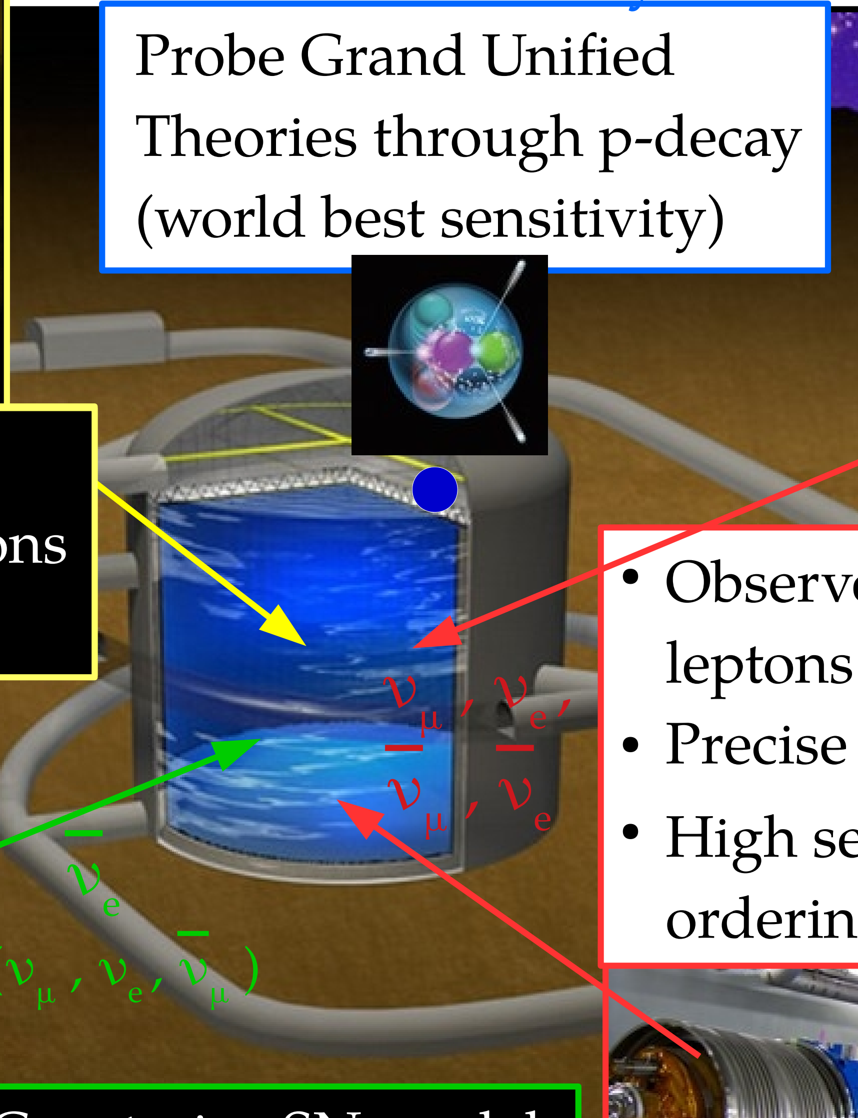
Solar neutrinos



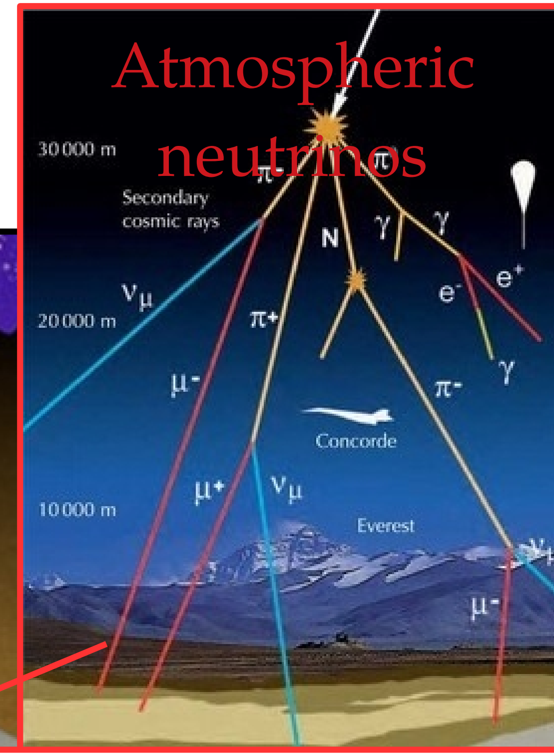
- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

Probe Grand Unified Theories through p-decay (world best sensitivity)

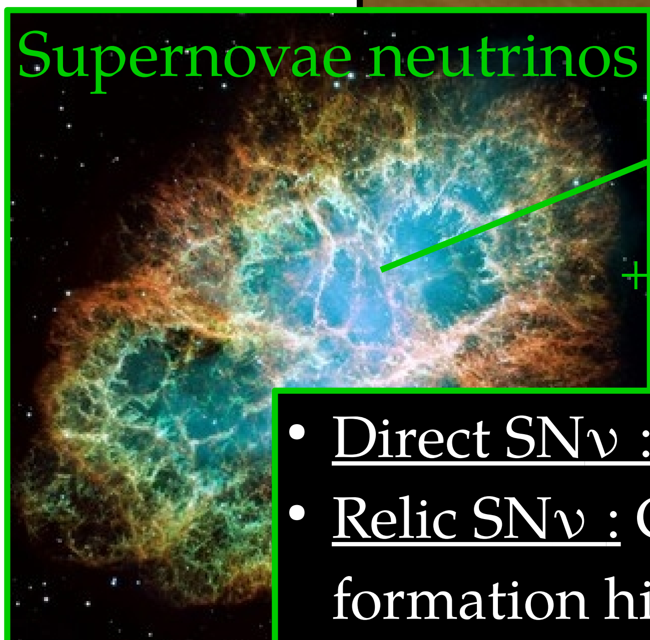


Atmospheric neutrinos



- Observe CP violation for leptons at 5σ
- Precise measurement of δ_{CP} .
- High sensitivity to ν mass ordering.

Supernovae neutrinos

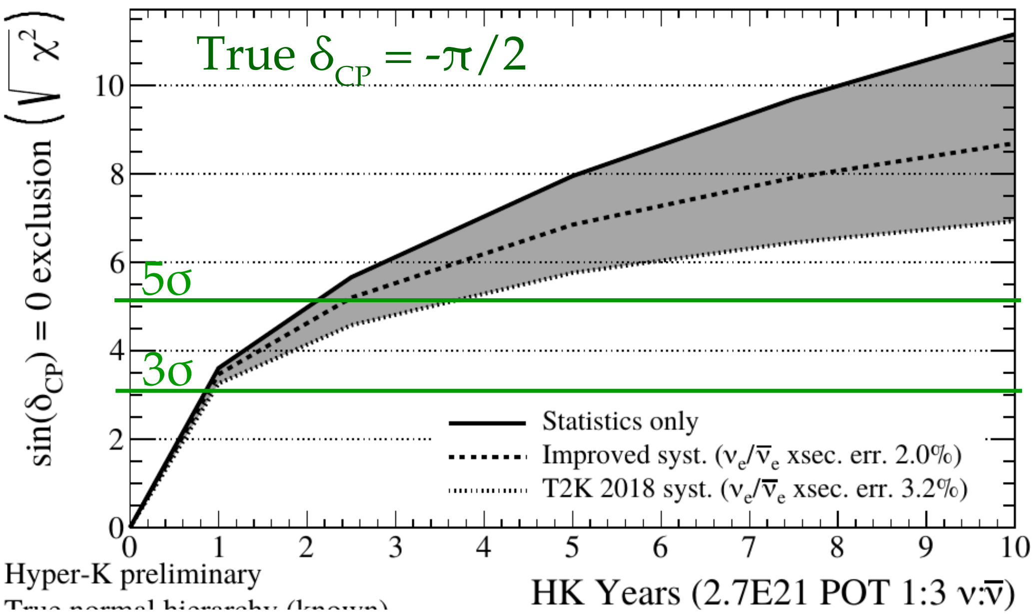


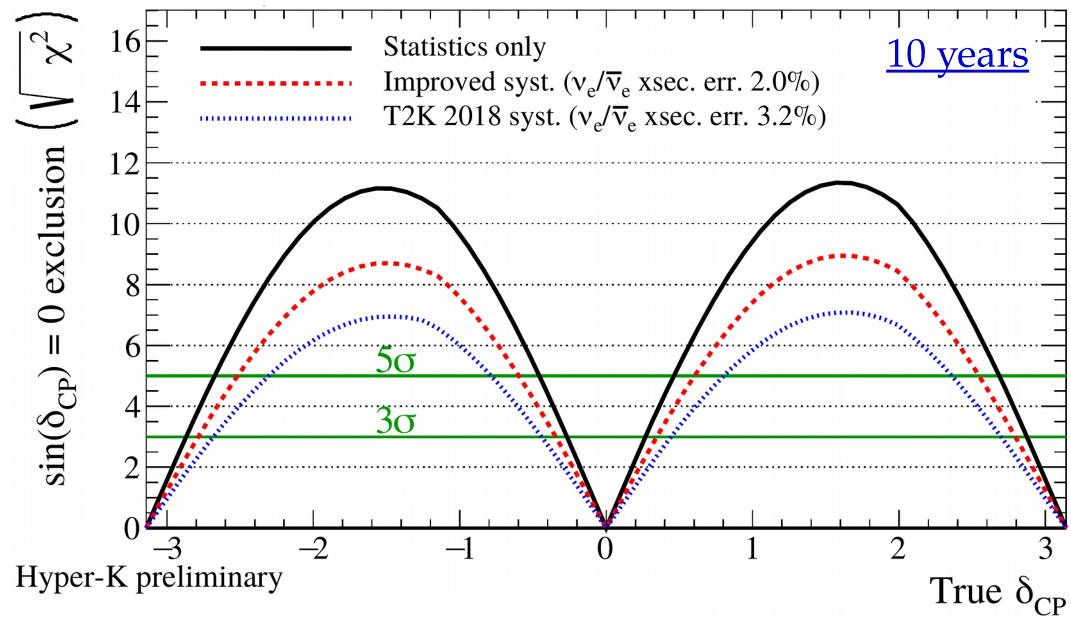
- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

JPARC accelerator neutrinos

Sensitivity to CP violation

- Assuming a run $\nu:\bar{\nu}$ = 1:3 @1.3MW (can be adjusted).





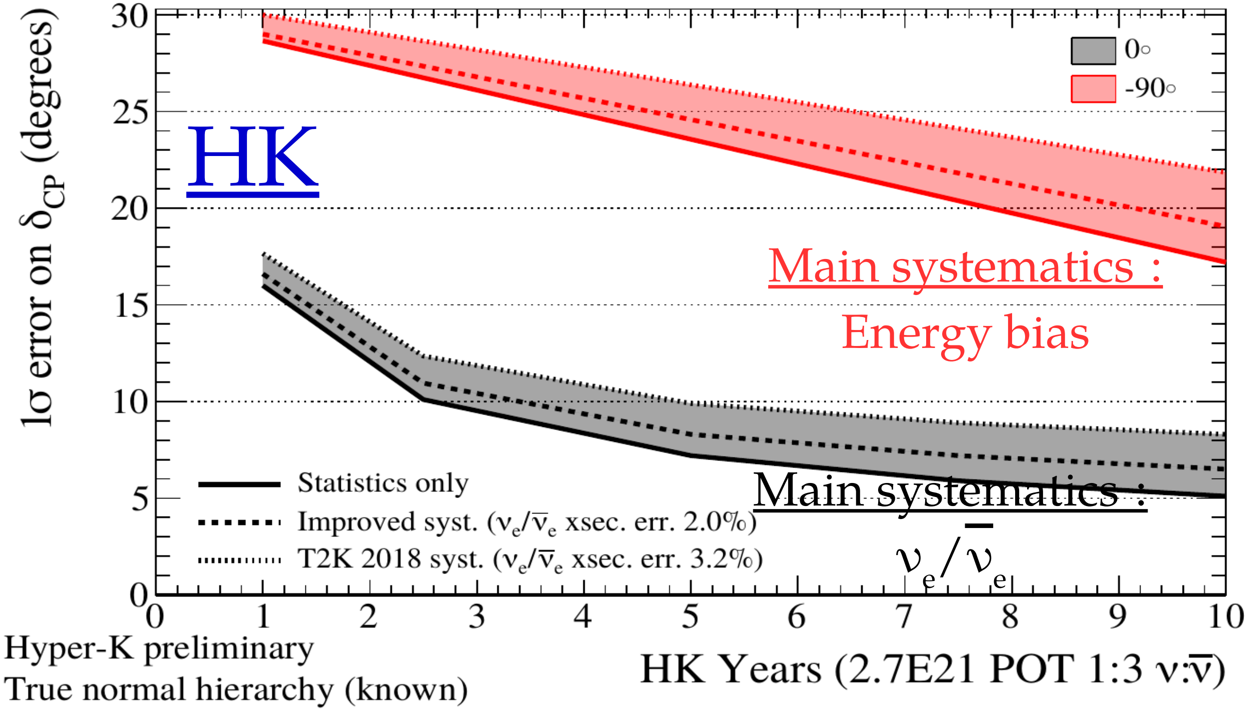
- δ_{CP} = -π/2: 5σ after 2-3 years of data taking : known in 2029-2030 !
  → Independent from ↓ systematic uncertainties.

- HK 10 years : 5σ sensitivity on 60% of δ_{CP} values.

- HK has world-best sensitivity to CP violation for the coming generation.

Precise measurement of δ_{CP}

- After CPV is determined, accurate measurement of δ_{CP} will be crucial
  → Maximal CPV, leptogenesis, symetries of lepton's generations ...



	5 years	10 years
CP conserved ($\delta_{CP} = 0$)	8°	6°
Max XPV (δ_{CP} = $-\pi/2$)	25°	19°

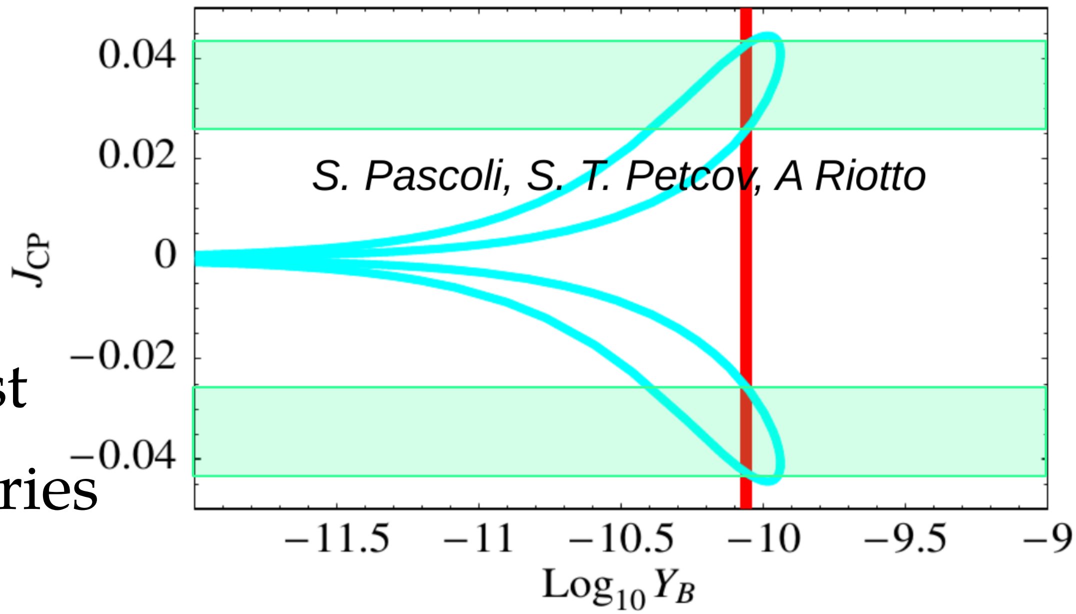
- HK will be the world-leading experiment to measure δ_{CP} and constrains CP-violation in the next 20 years !

Conclusions

- Super-K discovered the neutrino oscillation 25 years ago.
  → Since this, ν physics has known an incredible boost in last 20 years
  → Oscillation discovered & PMNS matrix has been almost completed.

- Opened the possibility to measure CPV in neutrino oscillation
  → May be a crucial milestone to explain the matter/antimatter asymetry.
  → We found the 1st indication of CP violation in lepton sector w/ T2K
  → Hope to find the 1st 3σ evidence using T2K + SK-atmospheric.

- Next generation already under-construction : Hyper-K.
  → 1st observation of CP violation.
  → Precise determination δ_{CP} to test Maximal CPV, leptogenesis, symetries of lepton's generations …
  → Unique test of PMNS unitarity : see Joao's talk.



Additional slides

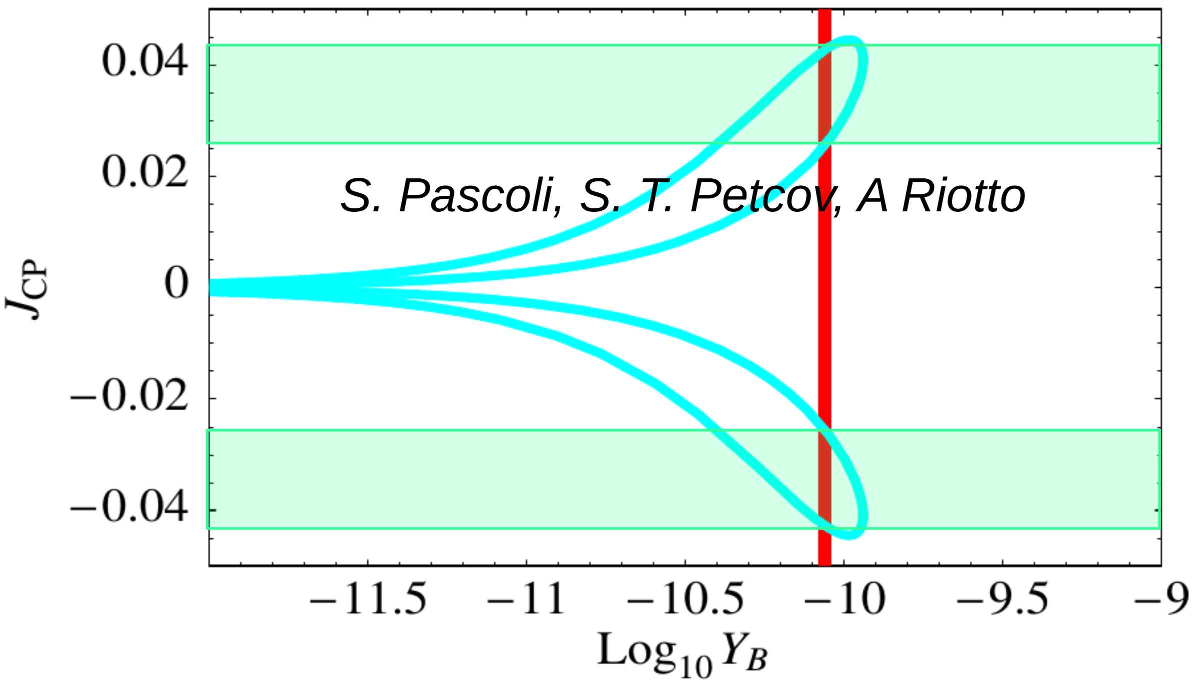
Matter/antimatter asymmetry

- <u>ν CP violation at low E maybe the key to matter/antimatter asymetry</u>
  → Class of theories directly link low E δ_{CP} to matter/antimat. asymetry.

$$\Delta P = P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) \propto J_{CP}$$

$$|Y_B| \cong 2.8 \times 10^{-13} |\sin\delta| \left(\frac{s_{13}}{0.2}\right)\left(\frac{M_1}{10^9\ \text{GeV}}\right)$$

- First step is to actually measure if CP is violated…



Precision on $\sin\delta_{CP}$
↔ Precision on leptogenesis models

<u>Lower limit for leptogenesis :</u>
$|\sin\theta_{13} \sin\delta_{CP}| \geq 0.11$
→ $|\sin\delta| \geq 0.78$

Flavour symmetries

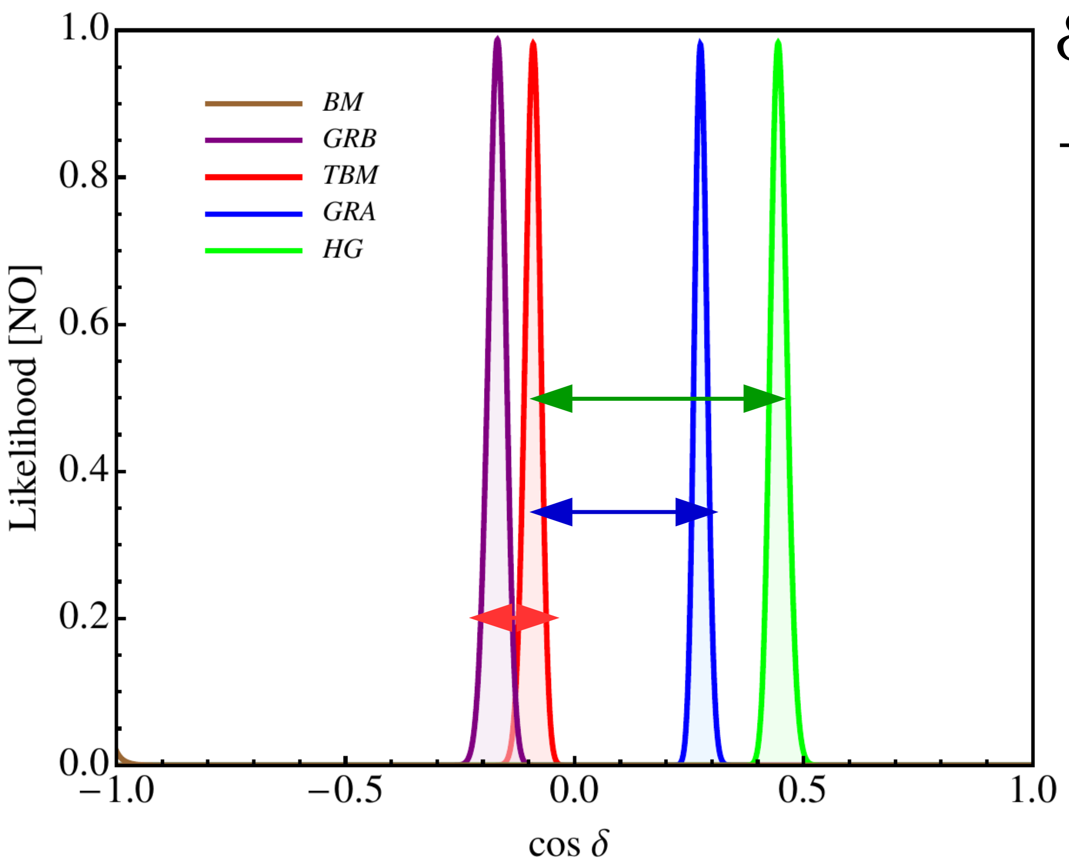
- <u>Models of lepton flavour symetries could be also tested</u>

$e \leftrightarrow \mu \leftrightarrow \tau$

$\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$

Lepton generation symetric models → Links PMNS parameters

$$\cos\delta = \frac{\cos 2\theta_{23}\ \cos 2\theta_{13}}{\sin 2\theta_{23}\ \sin\theta_{13}\,(2 - 3\sin^2\theta_{13})^{\frac{1}{2}}}$$



δ_{CP} = less well-known parameter

→ Limits the model constraints.

<u>Model separation requires :</u>

First separation : $\delta\,[\delta_{CP}] < 30°$

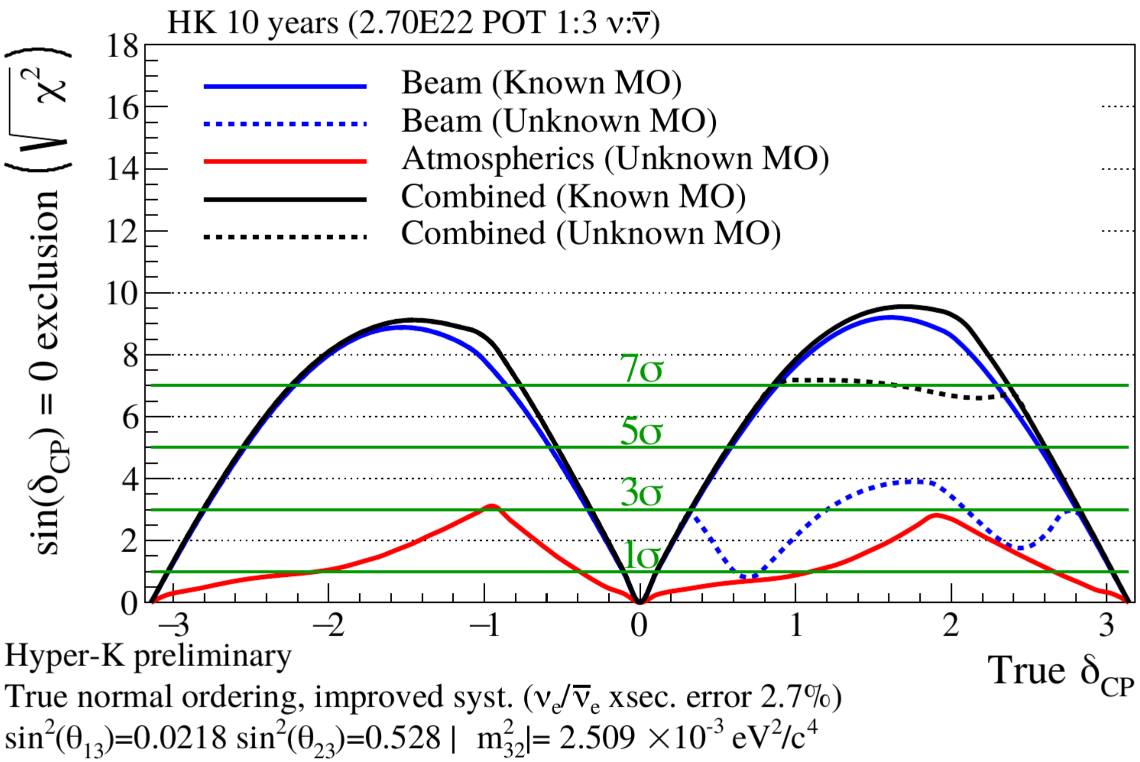
Good separation : $\delta\,[\delta_{CP}] < 23°$

Great separation : $\delta\,[\delta_{CP}] < 5°$

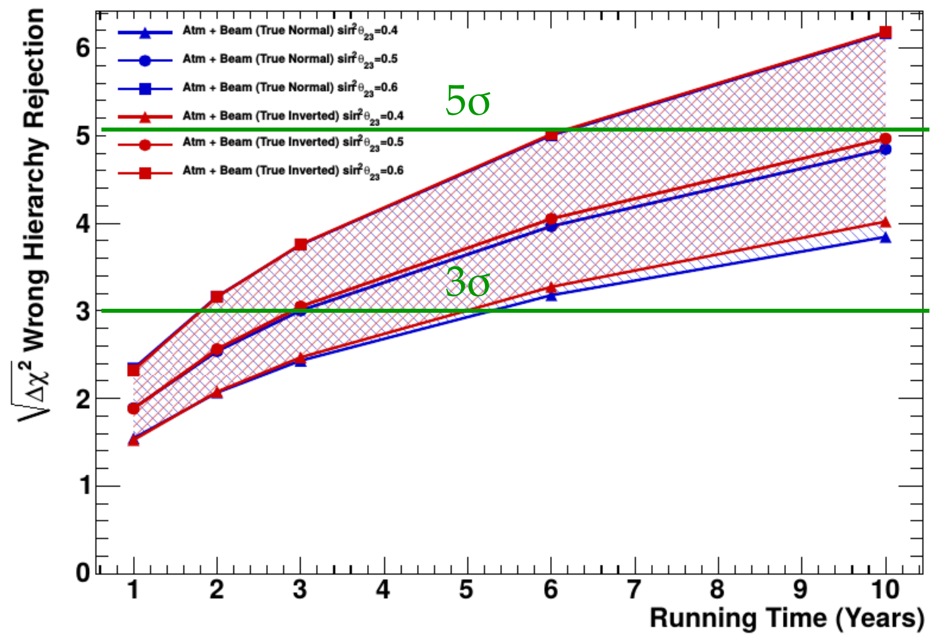
→ Precision of our experiments ?

Combination of atmospheric + beam ν

Impact on CPV sensitivity



Sensitivity to mass ordering



- <u>Even if MO is not known when HK starts</u>

→ Sensitivity to CPV is little affected if we add atmospheric ν.

- <u>MO would be determined by :</u>

  → HK after ≥ 6-10 years via atmospheric.

One remaining main issue in oscillations

→ Measure δ_{CP} parameter aka the CP violation parameter.

→ Use ν_e / $\bar{\nu}_e$ appearance in T2K

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$
$$+8c_{13}^2 s_{12} s_{13} s_{23} (c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} + \dots$$

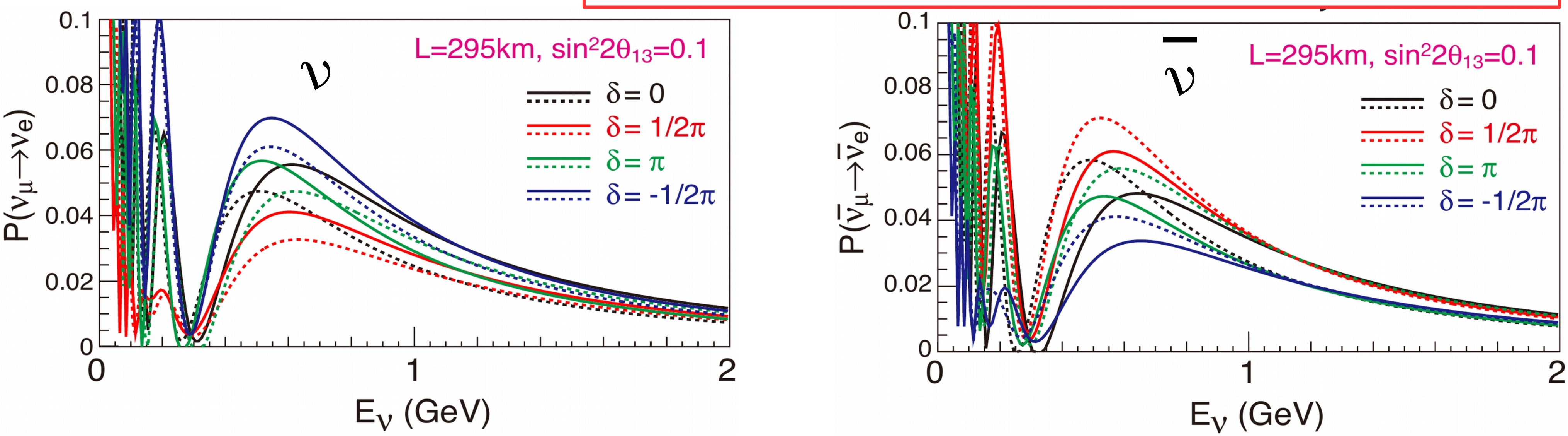
1. $\sin^2(2\theta_{13})$: Leading term

2. CP violation effect:

→ $\sin\delta$ is CP odd : opposite effect for ν / $\bar{\nu}$

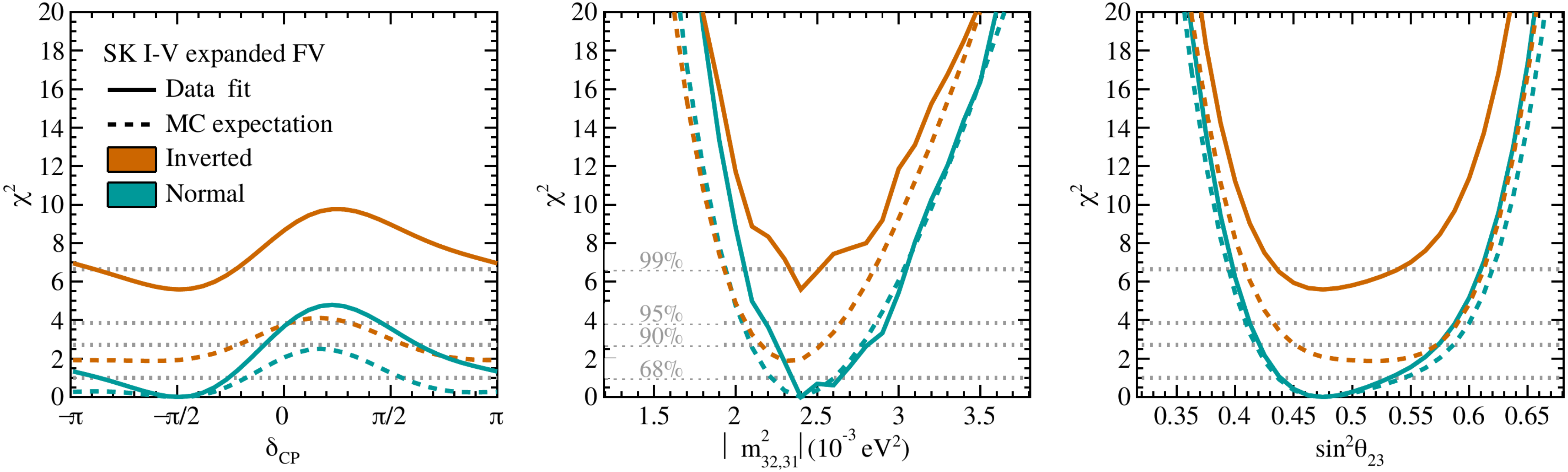
→ If $\delta_{CP} = -\pi/2$: ↑ $\nu_\mu \to \nu_e$ & ↓ $\bar{\nu}_\mu \to \bar{\nu}_e$.

→ ~27% @T2K ($\sin^2(2\theta_{23})=1$)



Atmsheric neutrin since 1998

- Neutrinos produced in cosmic ray decays.

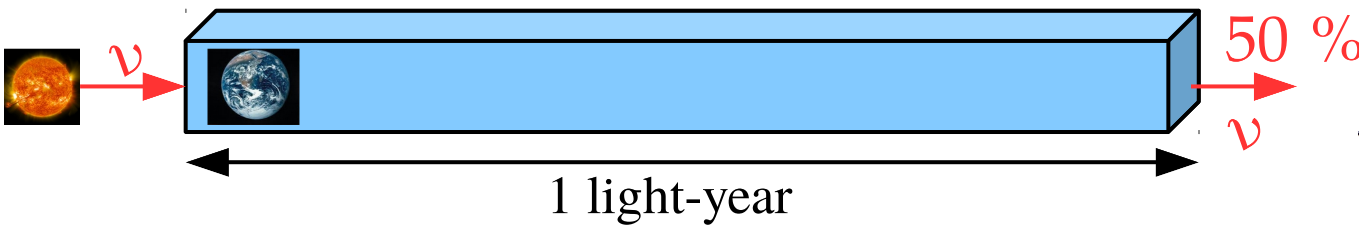


Neutrinos ?

1. ν are the only known neutral leptons

→ interacts through weak (and grav.) interactions.

→ 1 light year of lead to stop 50% ν !



2. ν are extremely (suspiciously?) light.

→ Absolute mass unknown, only upper limits.

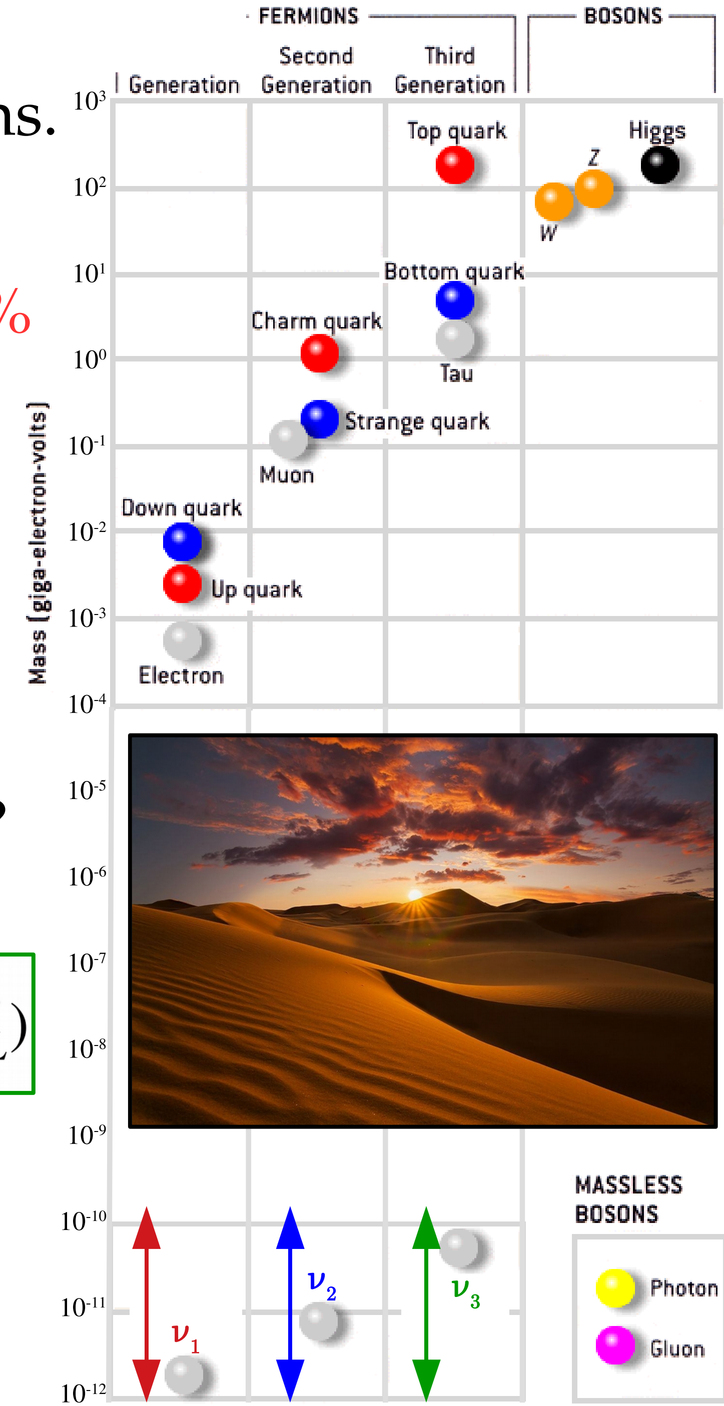
→ > 6 order of magnitude < other SM masses.

→ Is the origin of ν mass ≠ from other particles?

Dirac ? or/and Majorana ?

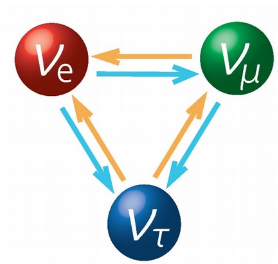
$$L^{D}_{mass} = [\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L]$$

$$L^L_M = -\frac{1}{2} M_L(\overline{\nu^c_L}\nu_L + \overline{\nu_L}\nu^c_L)$$



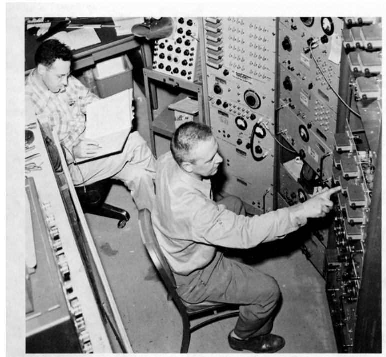
3. Neutrino « oscillates » !

→ The 3 neutrino flavours can change to other ones.



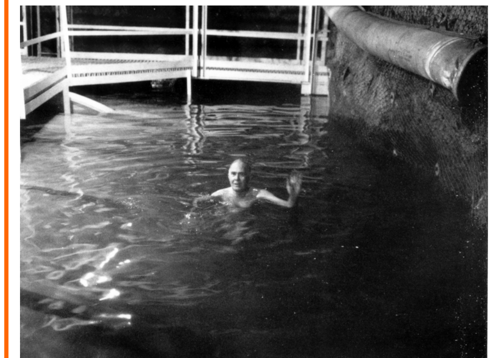
Selected discoveries in neutrino physics

Pauli :
Introduce neutrino to explain β spectrum (to save energy/spin conservation)

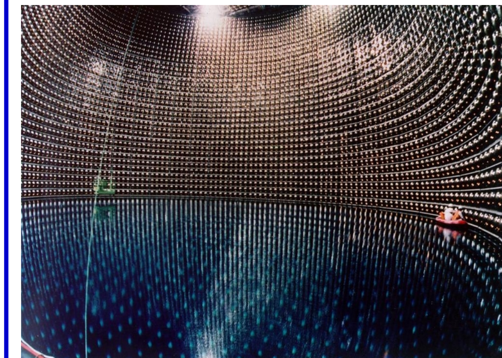


Reines & Cowan :
Experimental detection of neutrino (Savannah River reactor)

@BNL :
2 distinct neutrino families



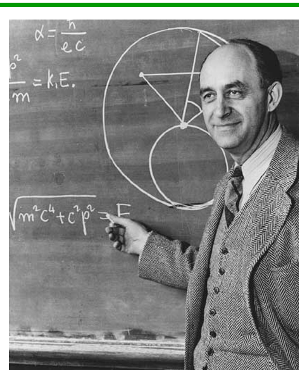
Davies@Homestake :
First indication of solar neutrino deficit



@SK :
Direct observation of neutrino oscillation (atmos.)

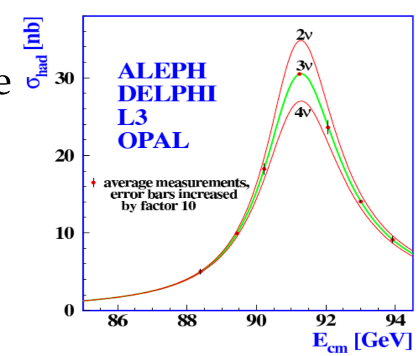
1930 | 1934 | 1956 | 1962 | 1967 | 1989 | 1998 | 2001

Fermi :
Neutrino incorporated in a theory of weak interactions



Maki-Nakagawa-Sakata:
Flavour states are superposition of mass states

@LEP :
Only 3 active (Z int.) light (<45GeV) neutrino families



@SNO :
Solar neutrino explained by oscillation