Neutrino physics : programs in Japan & Japan-France collaboration

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50th Anniversary of France-Japan Scientific Cooperation,
Miraikan, Tokyo, 2023/03/27

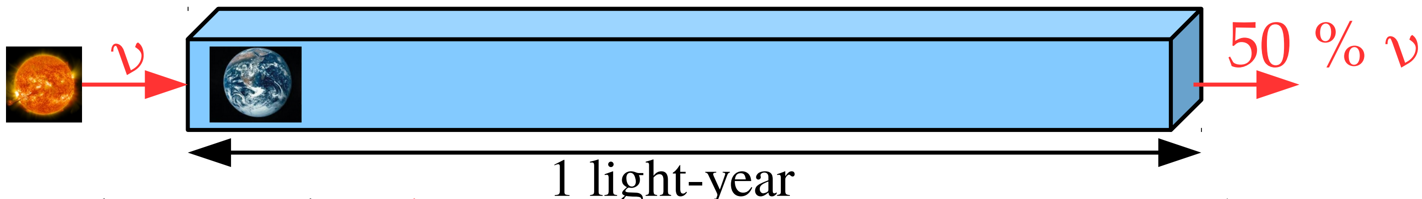
I. The past : 50th years ago until 2000

Neutrinos - 50 years ago

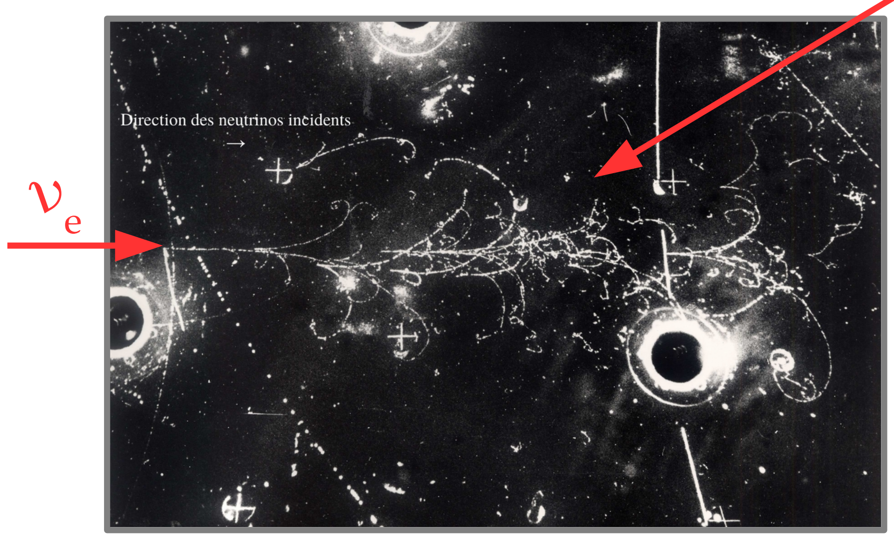
1. Neutrinos are the only known neutral leptons

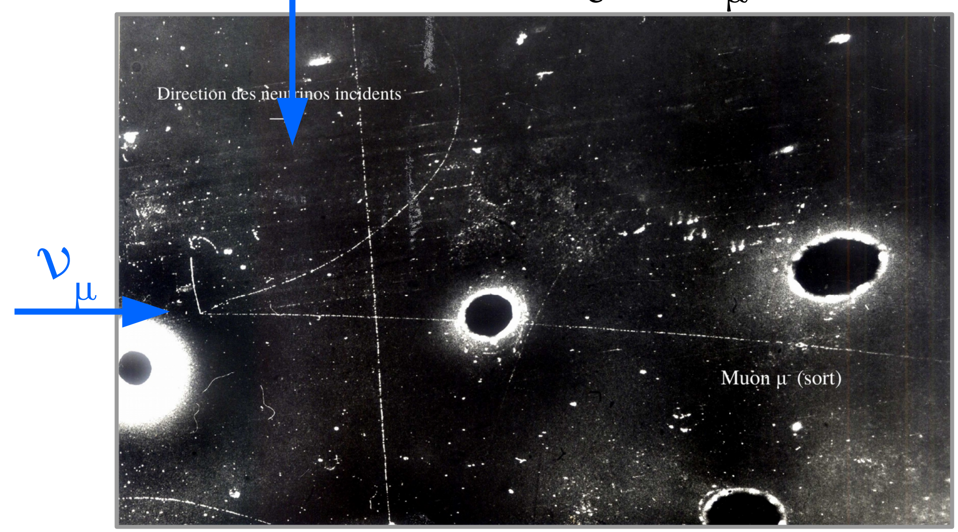
→ Interacts through weak (and grav.) interactions.

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



2. Two ν were observed : electron and muon neutrinos (ν_e & ν_μ)





3. ν are massless particles → Like photons .

→ Why : Usual (Dirac) mass term couples left and right handed components :

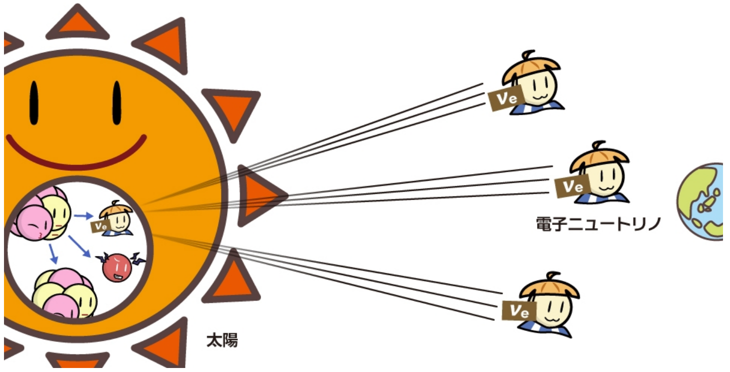
$$L_D^{mass} = -\frac{m}{2}\bar{\psi}\psi = \frac{m}{2}(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

→ But, no right-handed ν had been observed !

1967 : the solar neutrino anomaly

- Sun : Most intense ν source on Earth ! → 70 billion ν /s /cm²

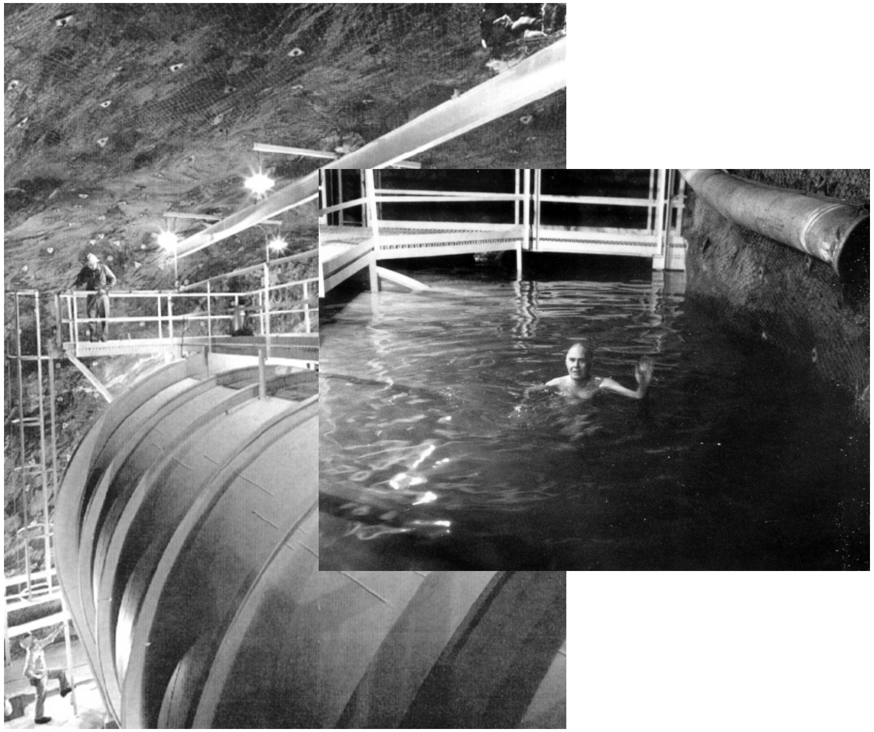
  → produced through nuclear fusion (νe)

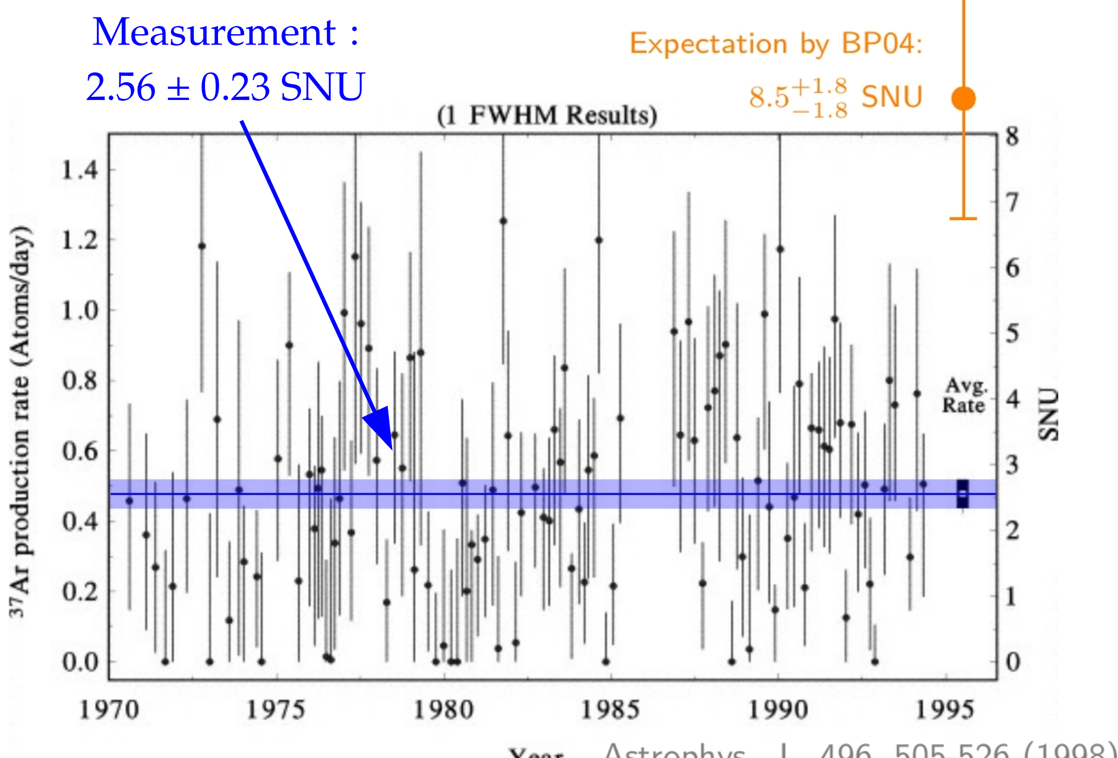


- 1967 : Davis installed Clore-filled detector in Homestake mine (US) to detect solar ν.

  → Rely on inverse β decay : $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + \mathrm{e}^-, \quad E_\nu^{th} = 0.814$ MeV

  → ^{37}Ar collected and counted.





Astrophys. J., 496, 505-526 (1998)

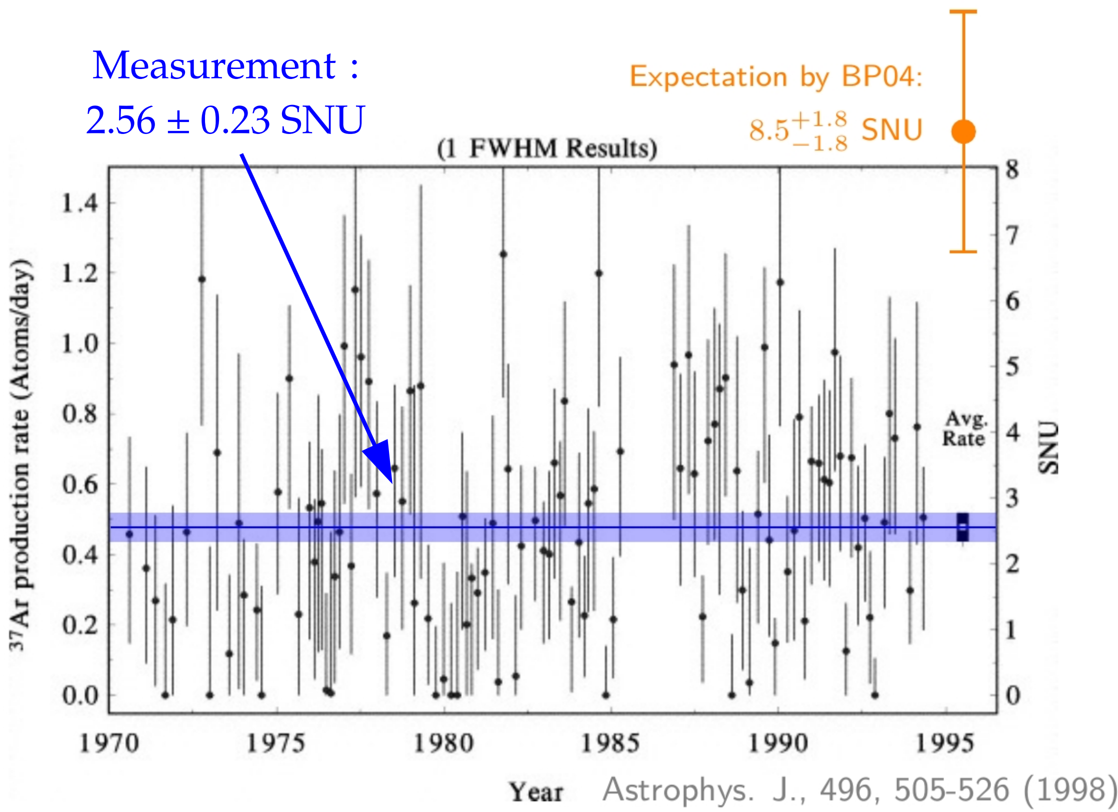
- Conclusions : number of observed neutrino = 1/3 expected flux !!

1967 : the solar neutrino anomaly

1. Solar neutrino model is wrong ? But works very well for visible γ…

2. Experimental issue ?

3. A monster eats neutrino along their way towards the Earth ?



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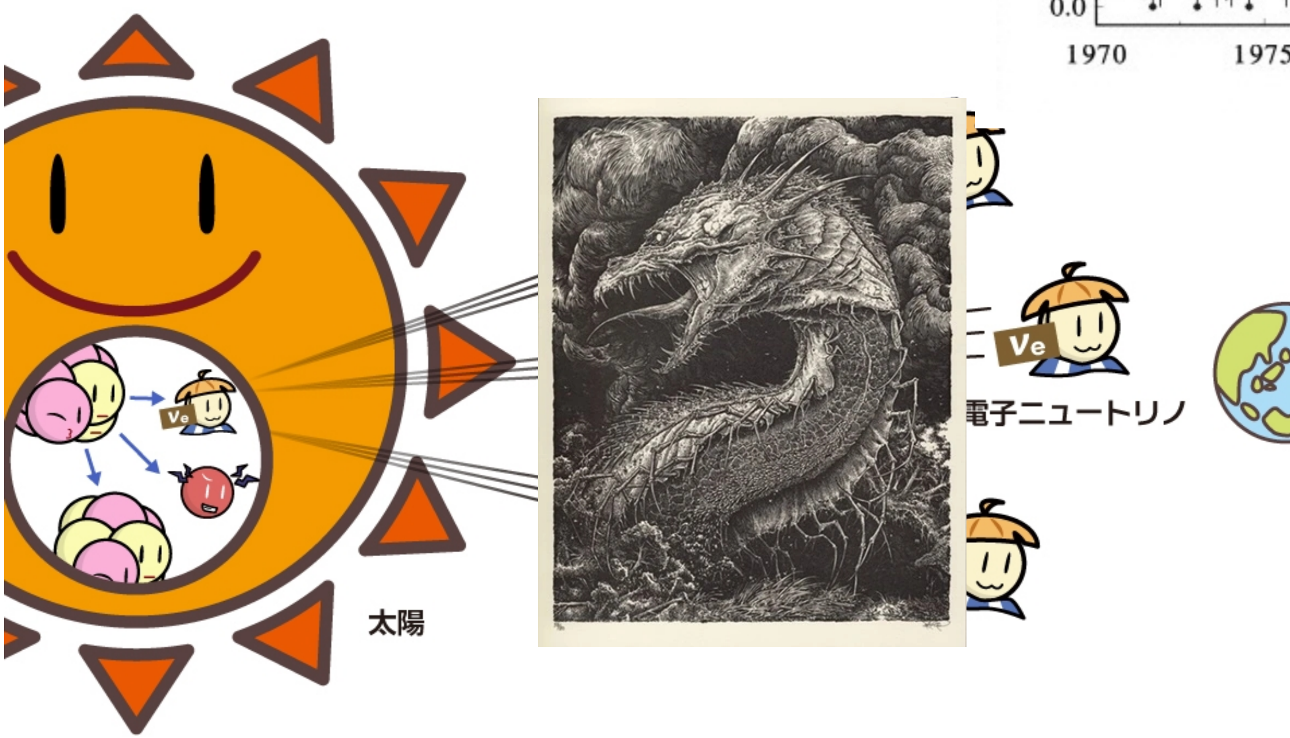
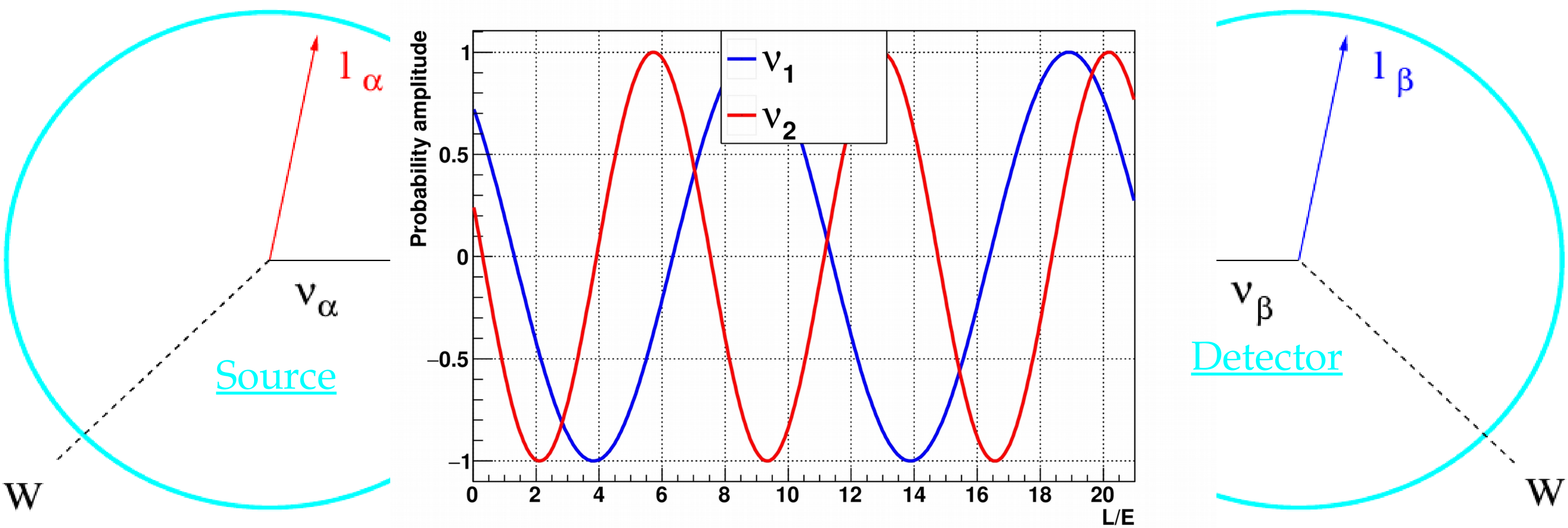


Neutrino oscillations

- Flavour states (interact) $(\nu_e,\nu_\mu) \neq$ mass states (propagates) (ν_1,ν_2)

→ Example :

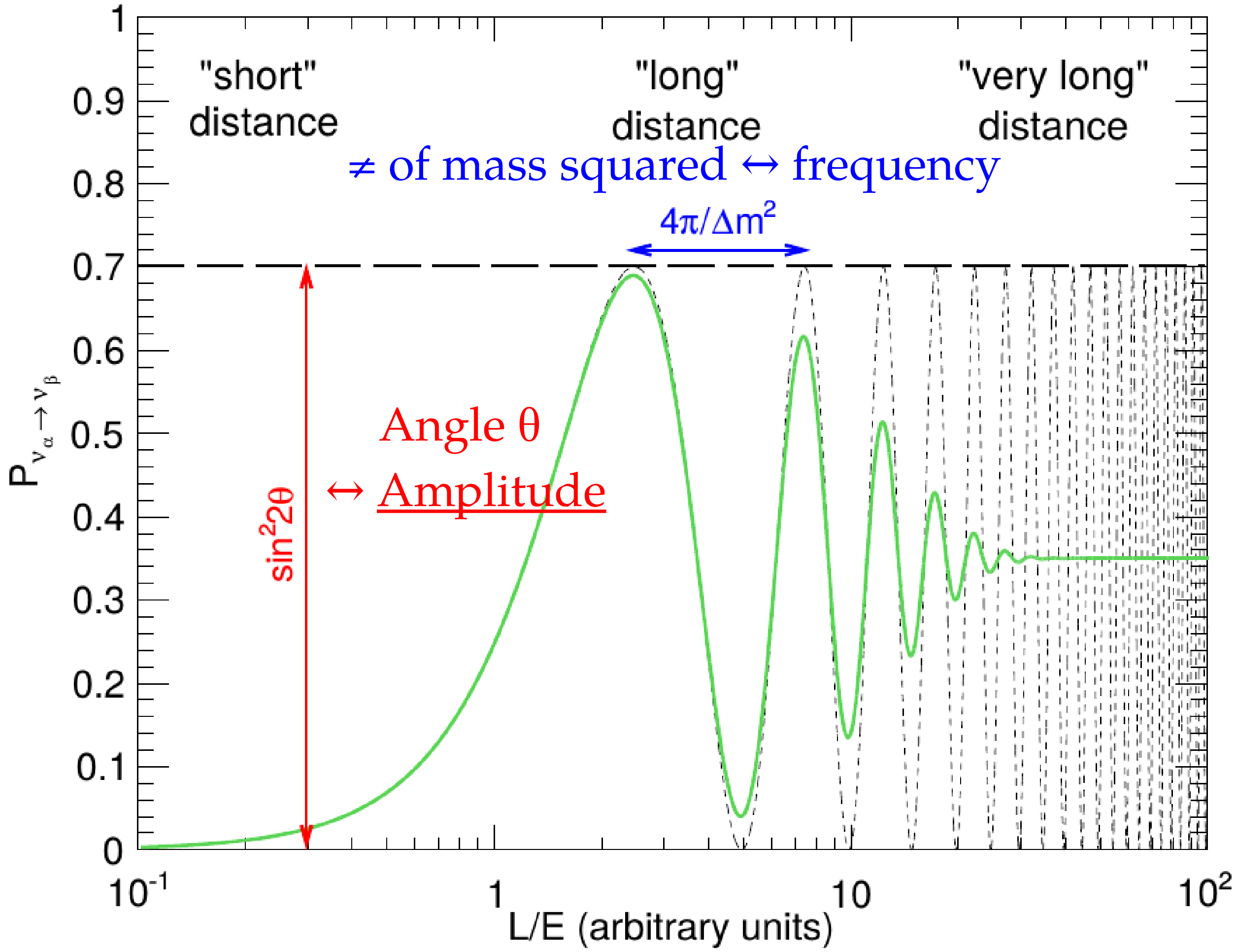
$\nu_e = 70\ \%\ \nu_1 + 30\ \%\ \nu_2$ $\qquad$ $\nu_\mu = 30\ \%\ \nu_1 + 70\ \%\ \nu_2$



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

- Oscillate if $m_1 \neq m_2 \rightarrow E_1 \neq E_2$.
- Davis only observed ν_e : → Can explain the disappearance ?

Neutrino oscillations in vacuum

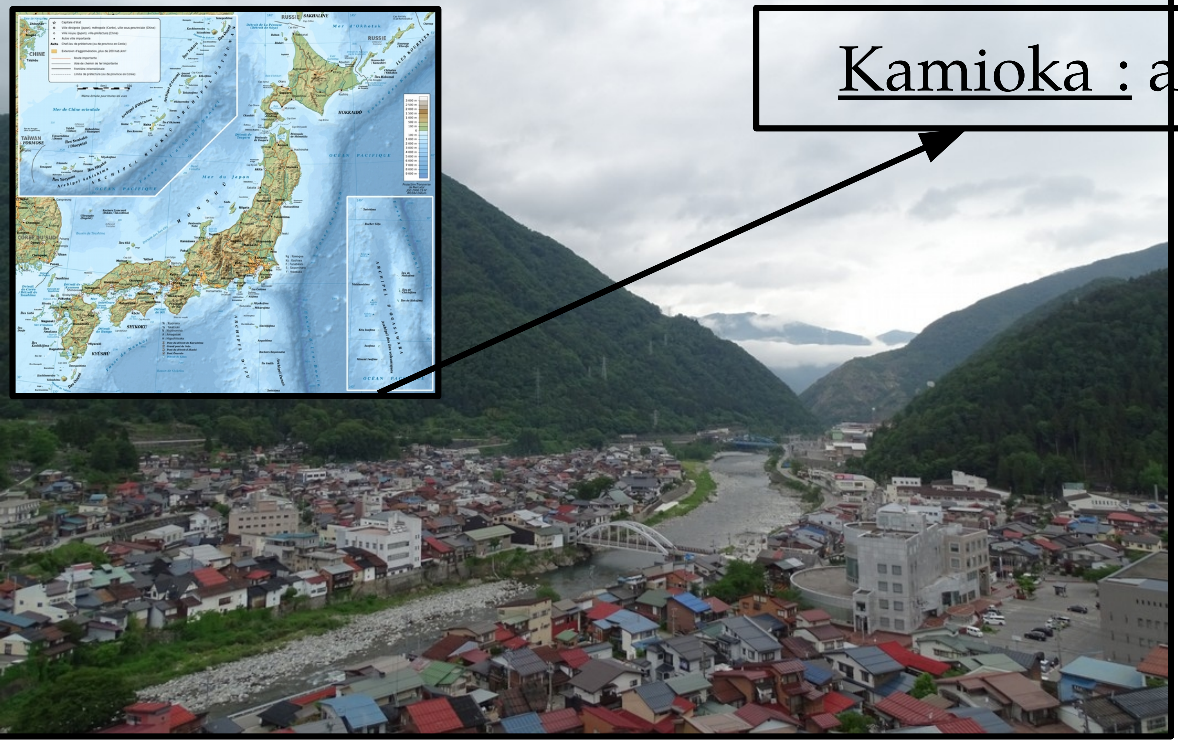


2 flavour approximation :

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

- 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.

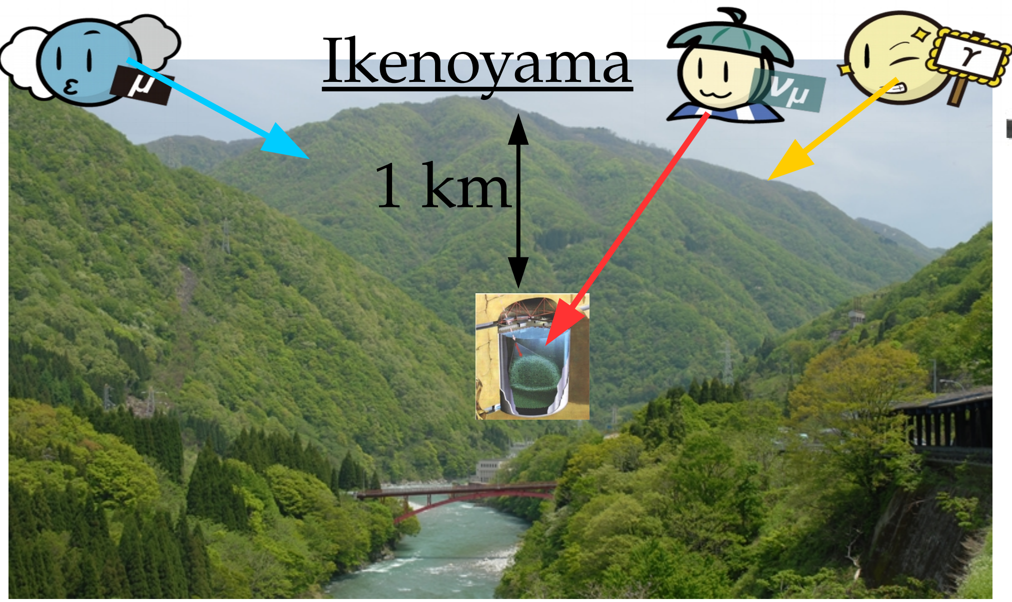
A trip to Kamioka



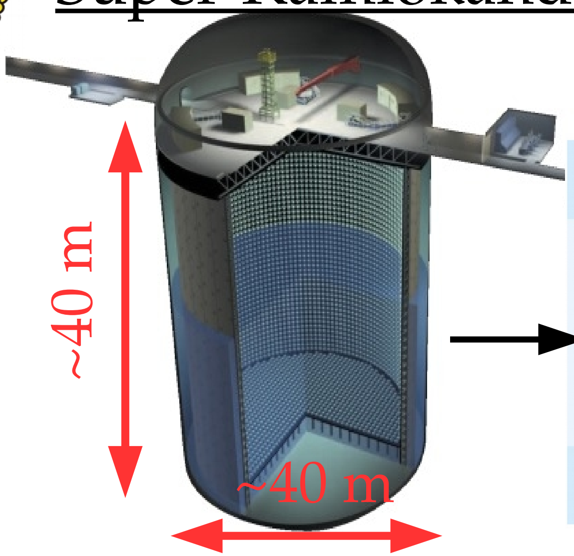
Kamioka : a little town in Gifu prefecture

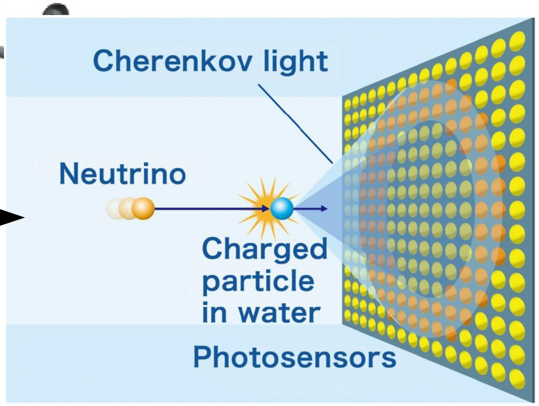
- A 50 kton water Cherenkov detector, located 1 km underground.

Ikenoyama



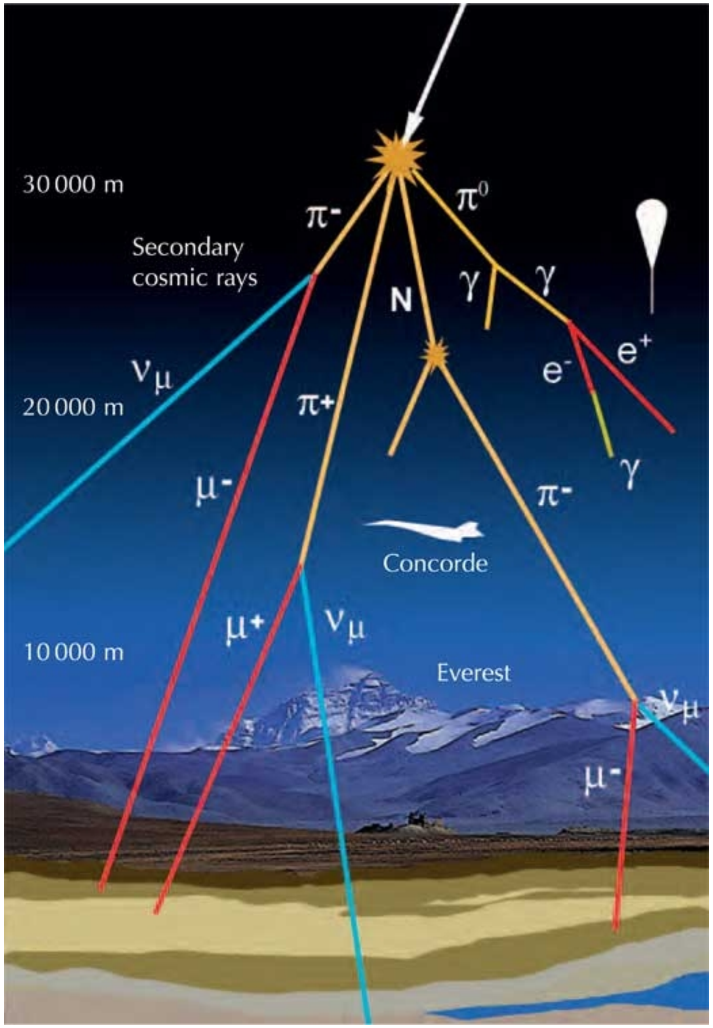
Super-Kamiokande

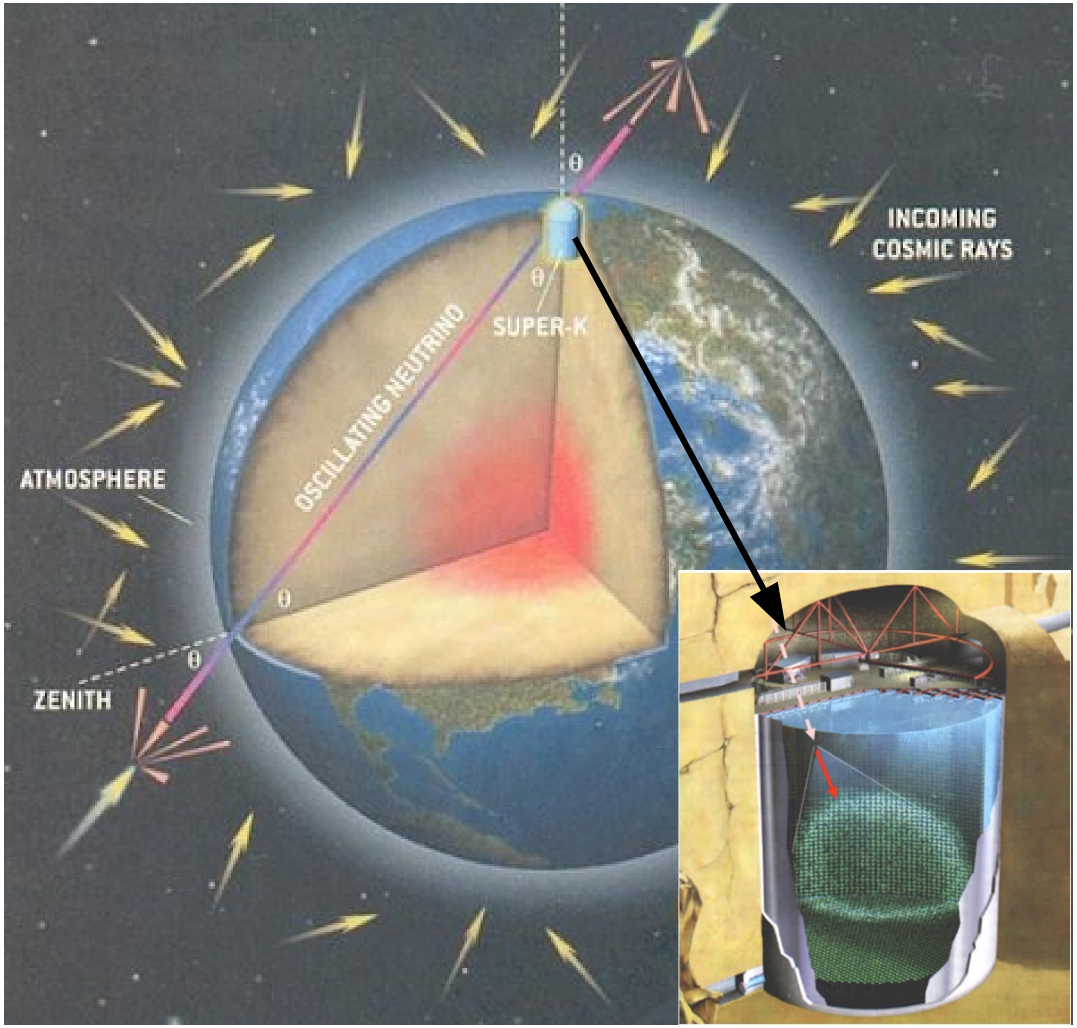




Atmospheric neutrinos in Super-K

- Neutrinos produced in cosmic ray decays.



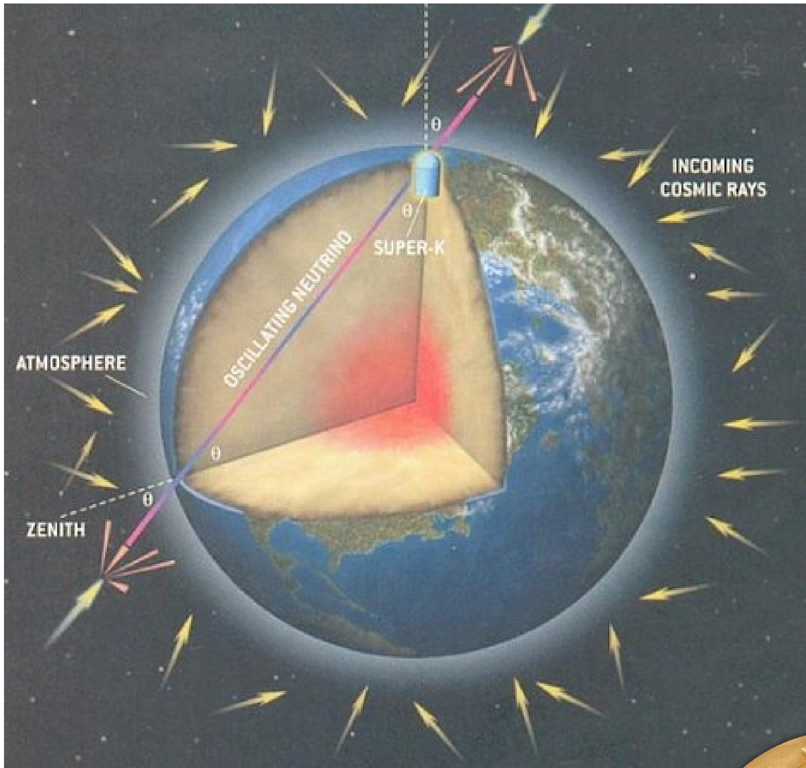


If no oscillations :

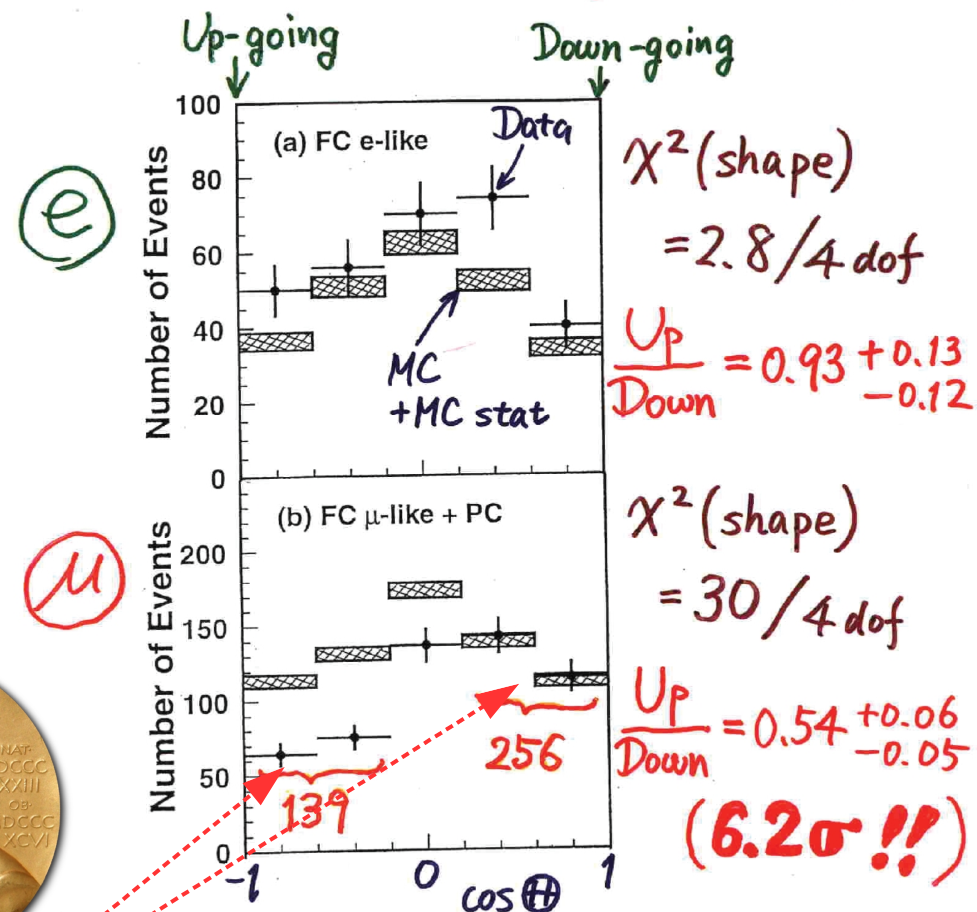
Atmospheric fluxes predicts ν_μ to ν_e ratio, $R = \dfrac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} \approx 2.$

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

1998 : Atmospheric neutrino oscillations



Zenith angle dependence (Multi-GeV)



※ Up/Down syst. error for μ-like

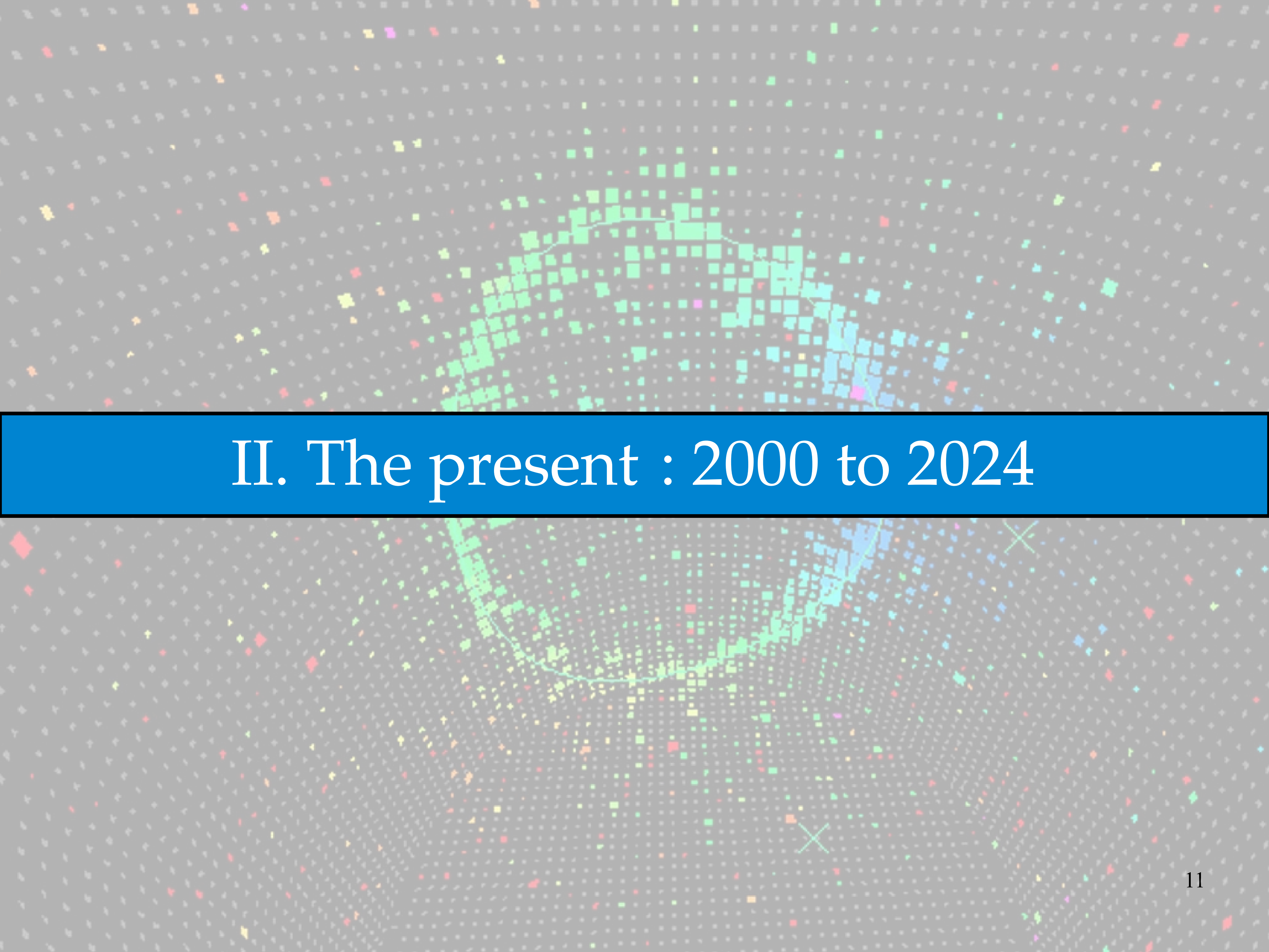
Prediction (flux calculation ······ ≲ 1% ; 1km rock above SK ···· 1.5%) 1.8%

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. The present : 2000 to 2024

Three flavour neutrino oscillations

- 3 flavour eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ 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}

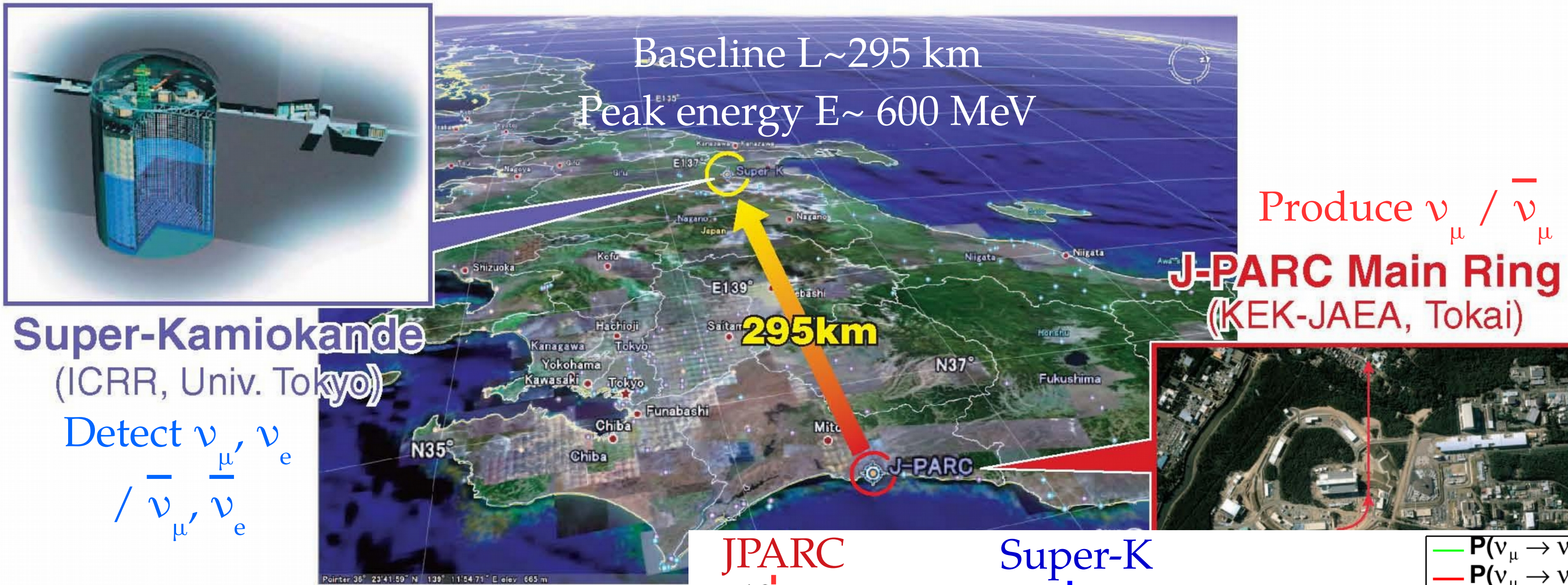
1 Dirac CP violation phase: δ_{CP}

- Recipe for precise measurement of neutrino oscillations :

1. Precise knowledge of neutrino flavour at production and detection.
2. Precise measurement of the neutrino energy.
3. Precise measurement of the neutrino baseline.

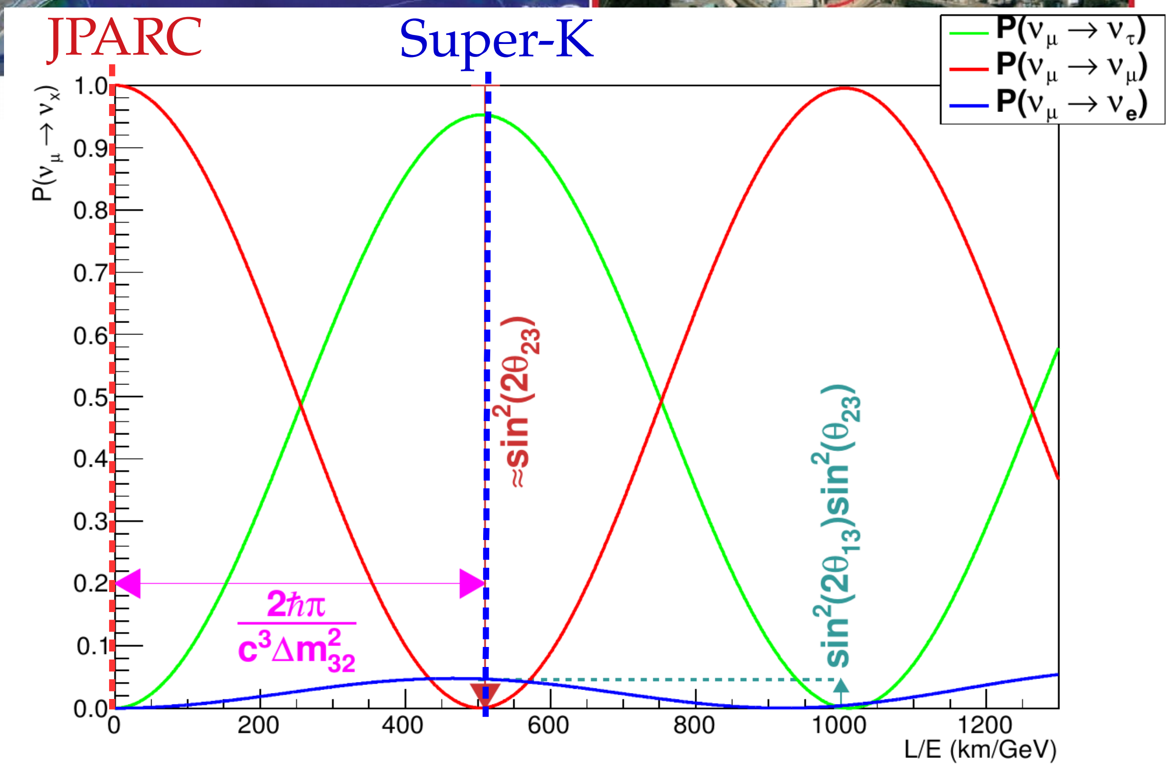
→ Constrain oscillations in L/E.

2010 - today : the Tokai-to-Kamioka experiment

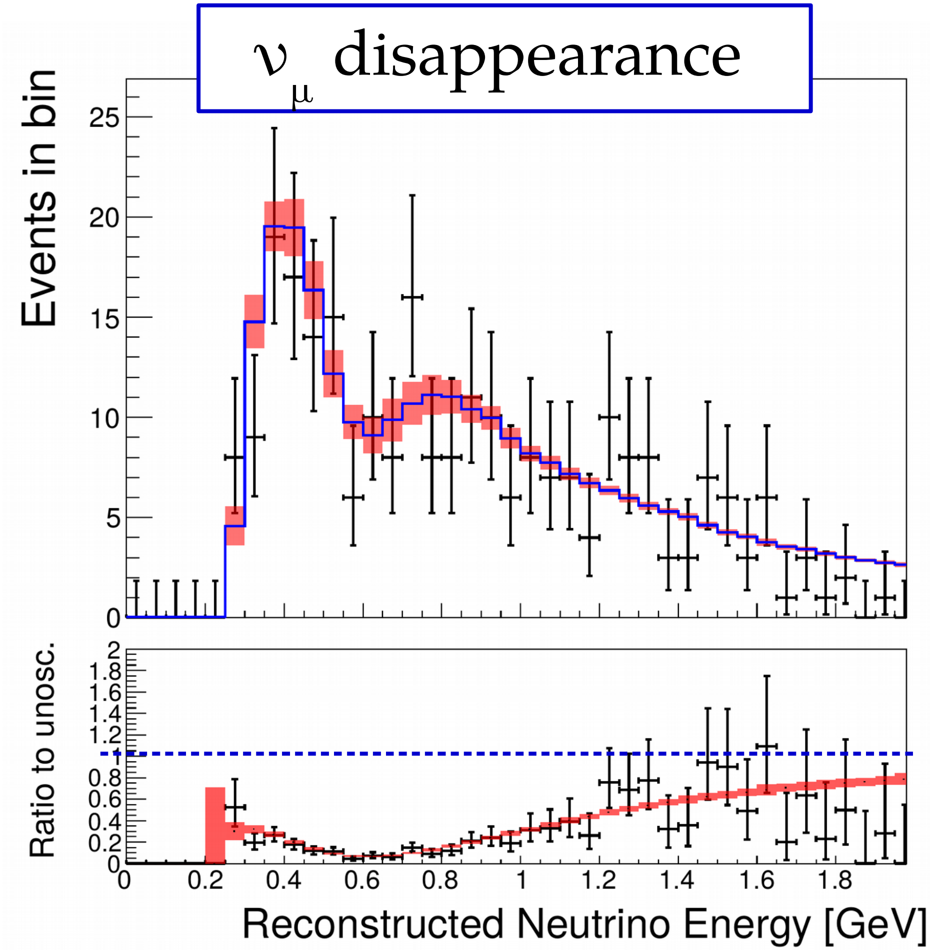


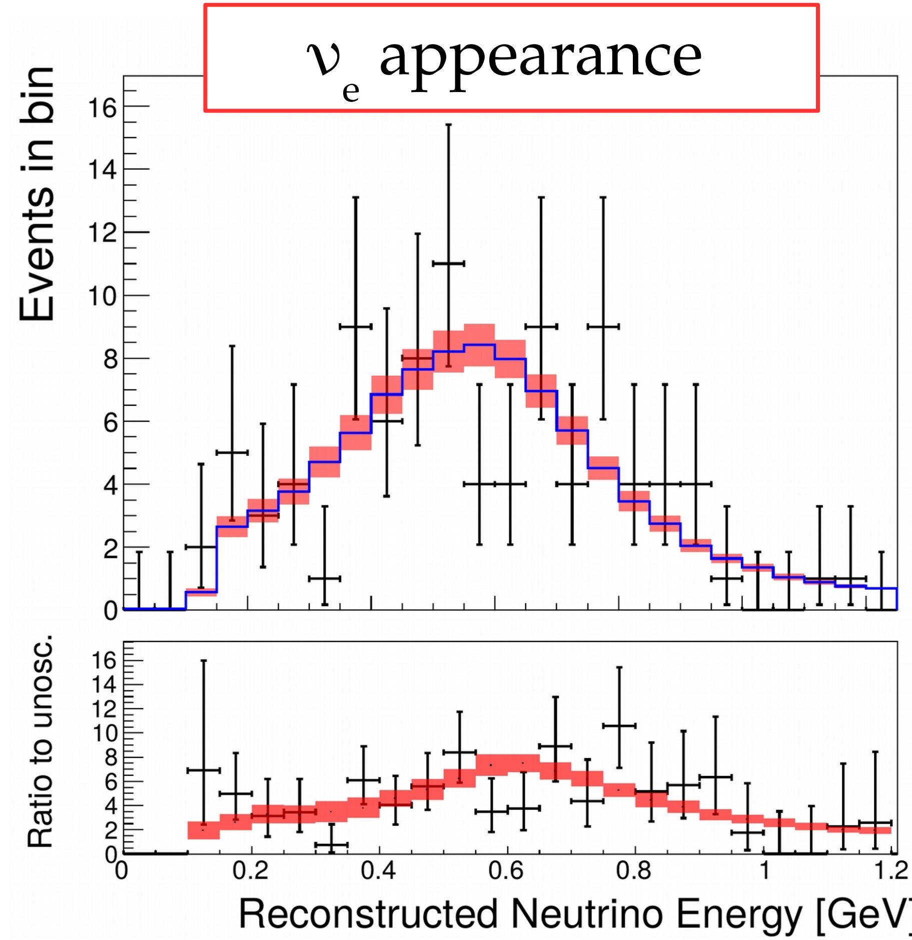
- Very pure ν_μ (> 95%) beam.
- Fine tuning of E_ν = 600 MeV.
- Fixed baseline = 295 km.

- Observe ν_μ disappearance and ν_e appearance.



T2K results





- <u>Observation of</u> ν_μ disappearance

→ World-leading constraints on θ_{23}, Δm^2_{32}.

- 1st direct observation of ν (ν_e) appearance

→ Breakthrough prize 2015

Three flavour neutrino oscillations

- 3 flavour eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$ and 3 mass states (ν_1, ν_2, ν_3).

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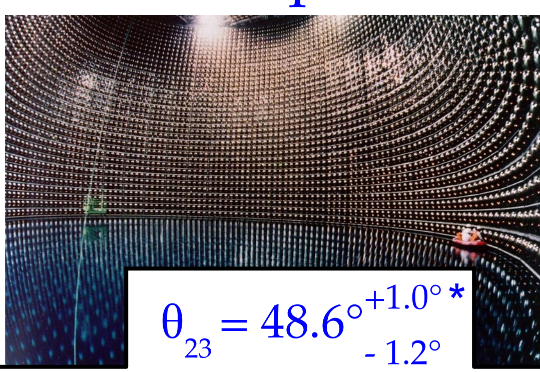
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & e^{-i\delta}s_{13}\\ & 1 & \\ -e^{i\delta}s_{13} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\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

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 »

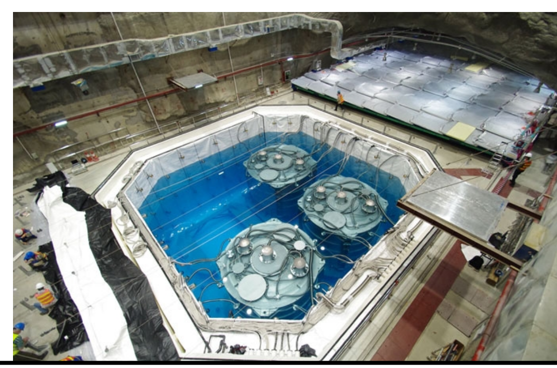


*3σ CL: [41.1° - 51.3°]

$\theta_{23} = 48.6°^{+1.0°}_{-1.2°}$ *

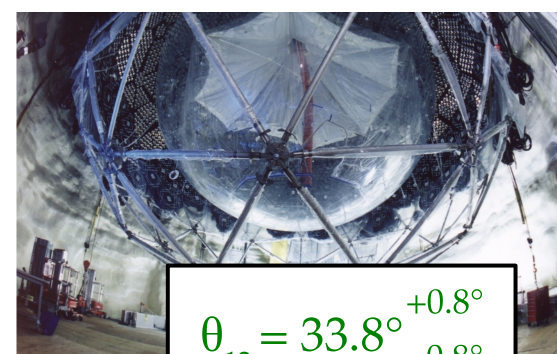
$|\Delta m^2_{32}| = (245.4^{+2.9}_{-3.1}) \times 10^{-5}$ eV²

« Reactor »



$\theta_{13} = 8.60° \pm 0.13°$

« Solar »

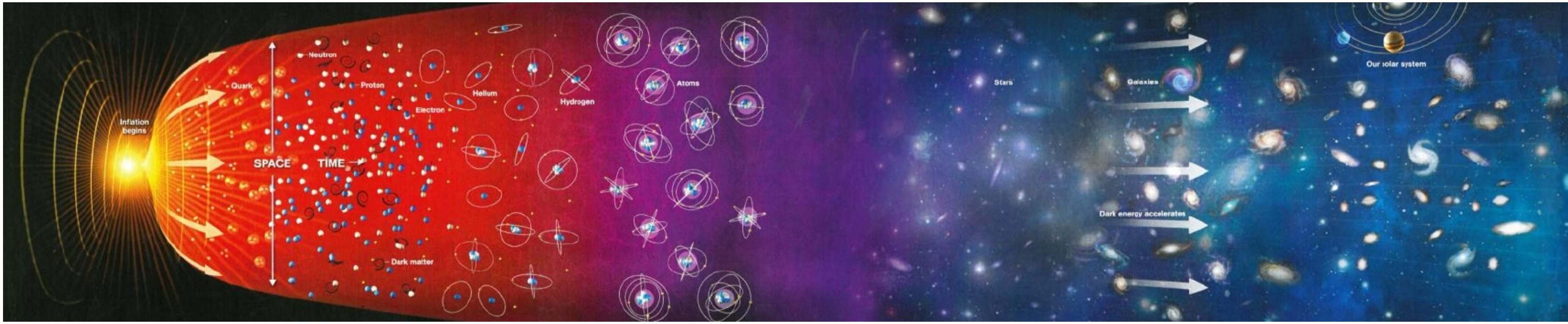


$\theta_{12} = 33.8°^{+0.8°}_{-0.8°}$

$\Delta m^2_{12} = (7.39^{+2.1}_{-2.0}) \times 10^{-5}$ eV²

Why measuring CP violation is important ?

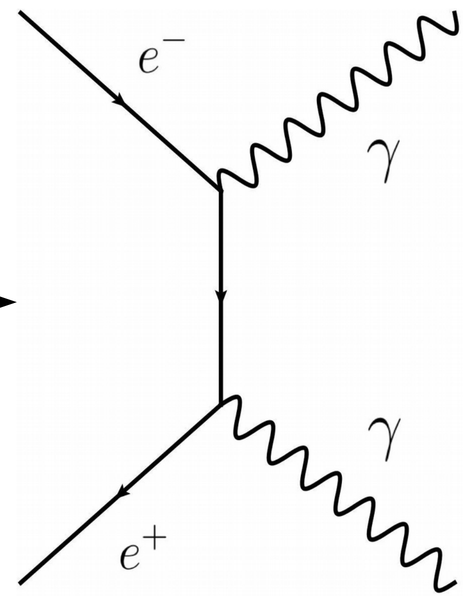
<u>Why our universe is only made of matter ?</u>



<u>Initial Universe :</u>

50 % matter

50 % antimatter



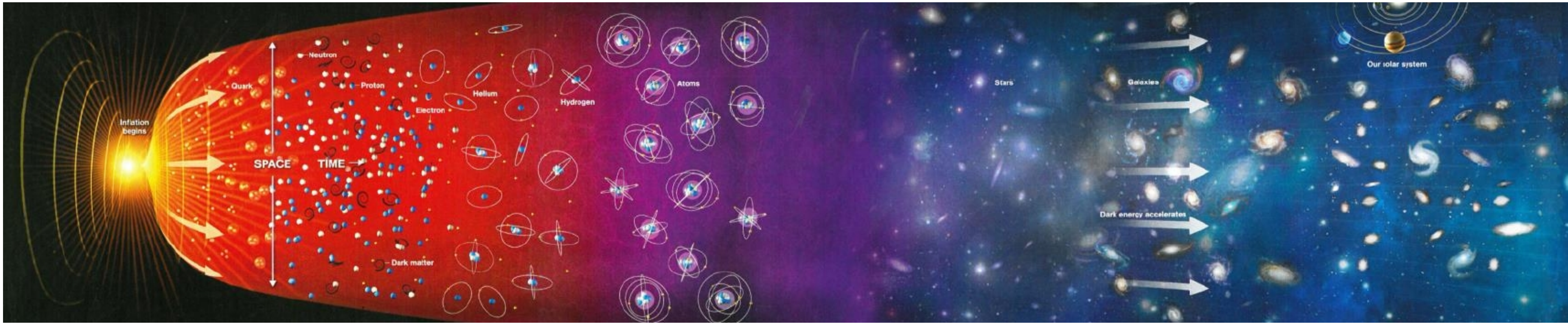
Time

Matter-antimatter annihilation

→ Only light remains !

Why measuring CP violation is important ?

Why our universe is only made of matter ?



- How do we evolve from a symmetric universe to a matter-dominated one ?

Initial Universe :

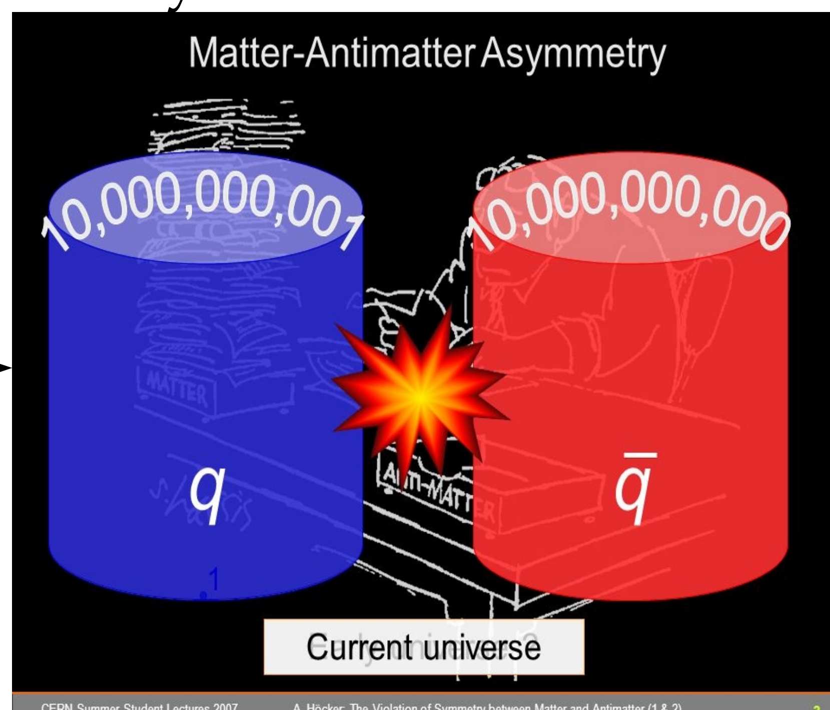
50 % matter

50 % antimatter

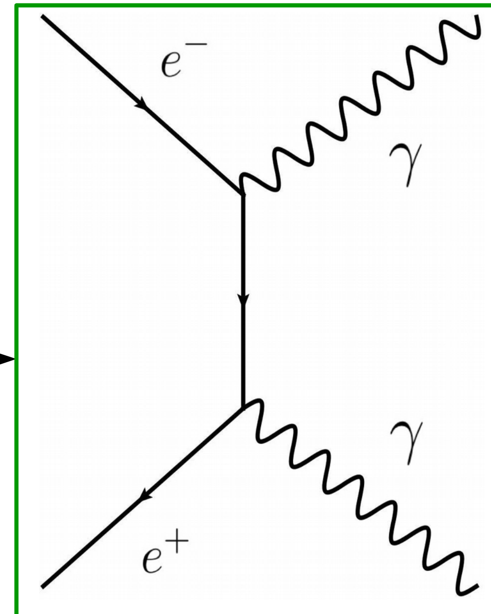
↓

CP violating process ??

→



→

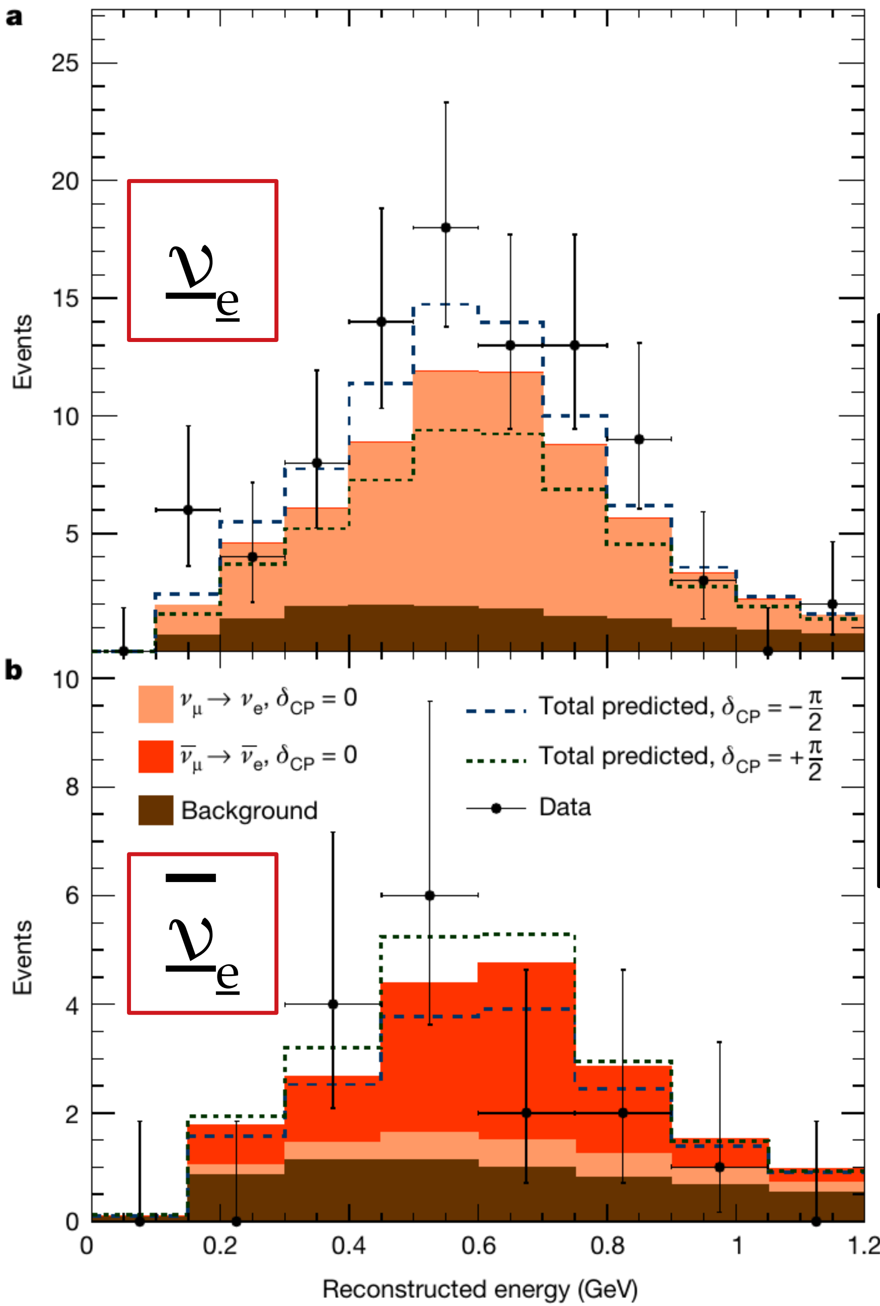


A tiny portion of matter survives

- Searched for decades in quark sector → too small.

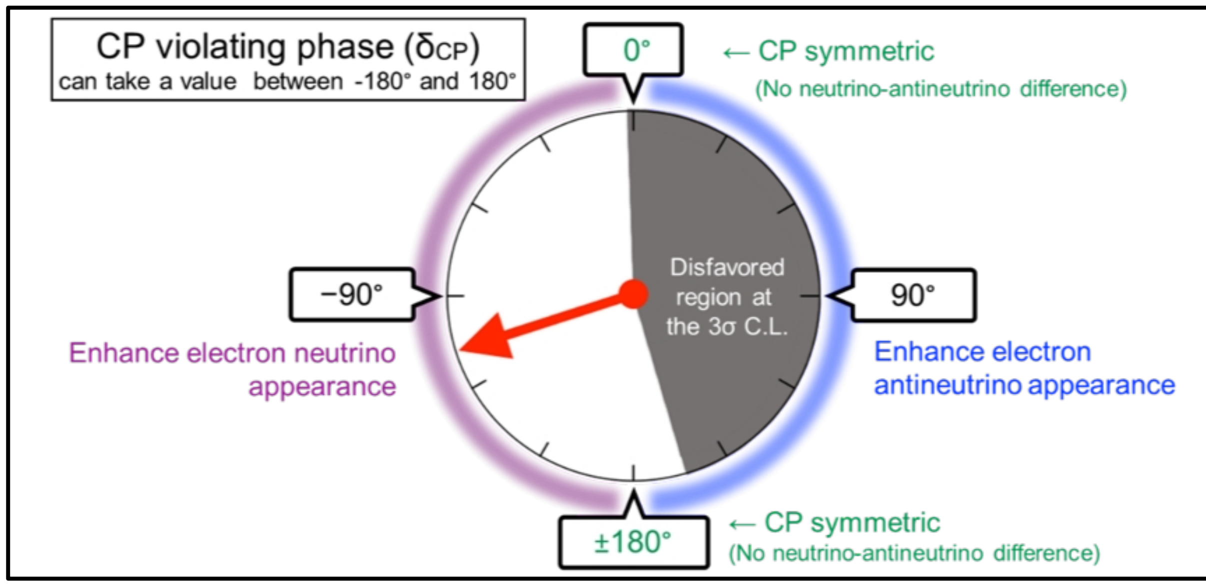
CP violation first indication by T2K

- T2K accelerator can creates a pure beam of ν_μ or $\bar{\nu}_\mu$.



- ν / $\bar{\nu}$ asymmetry : ν_e appearance > $\bar{\nu}_e$.

  → 1st experiment to exclude CP symmetry (> 90 % C.L)



- T2K favours maximal asymmetry :

  δ = -90° → sin δ = - 1.

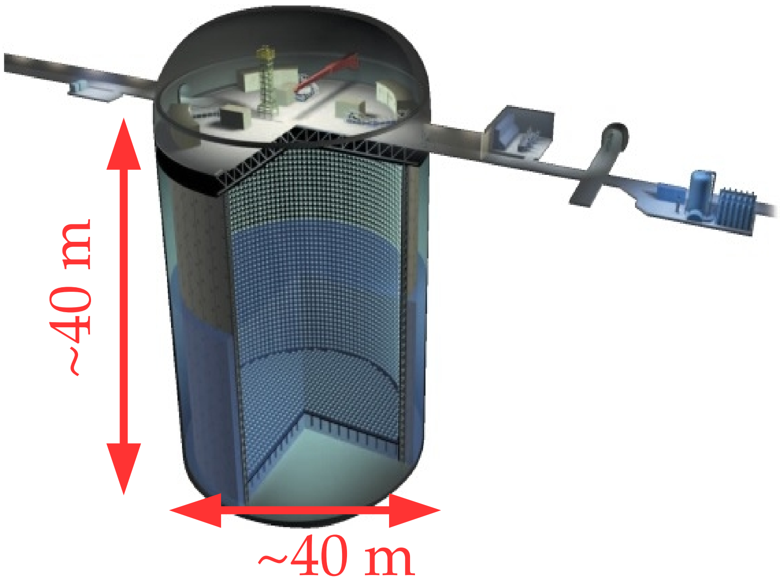
→ Nature's cover in 2020.

III. The future : Hyper-Kamiokande

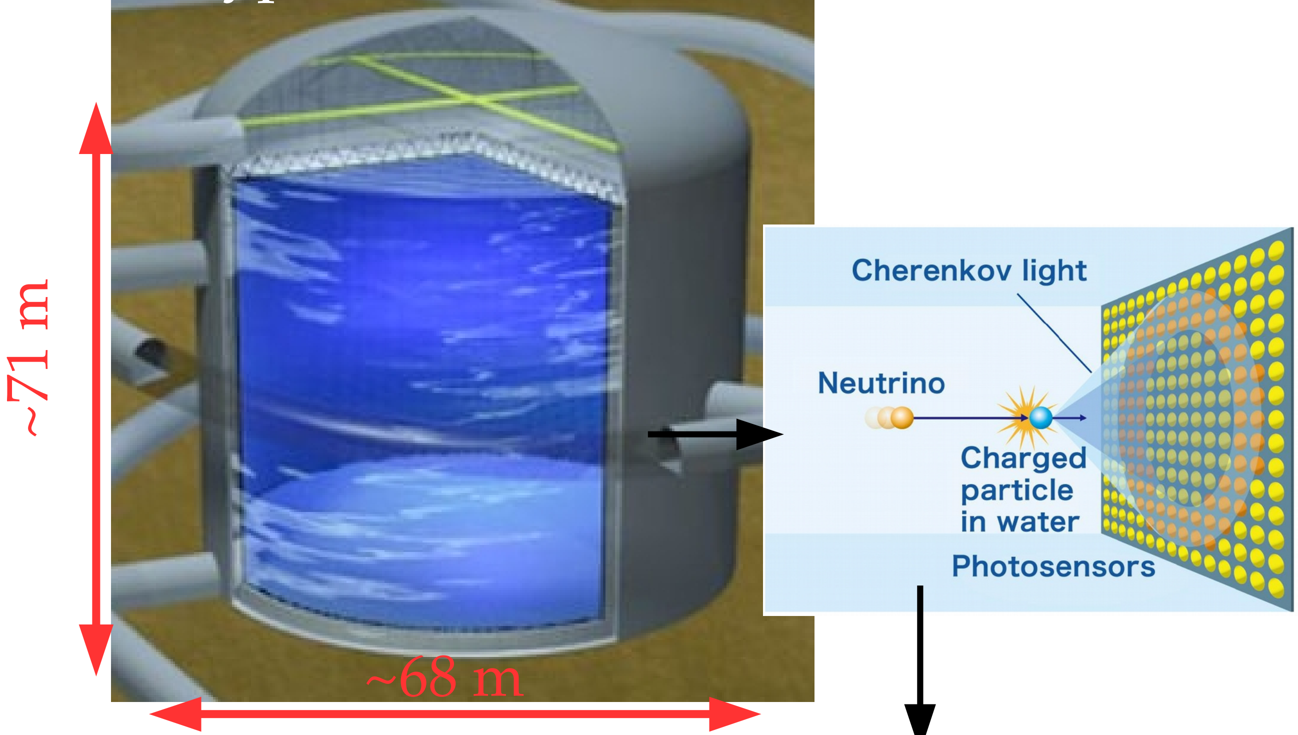
The next generation observatory : Hyper-K

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

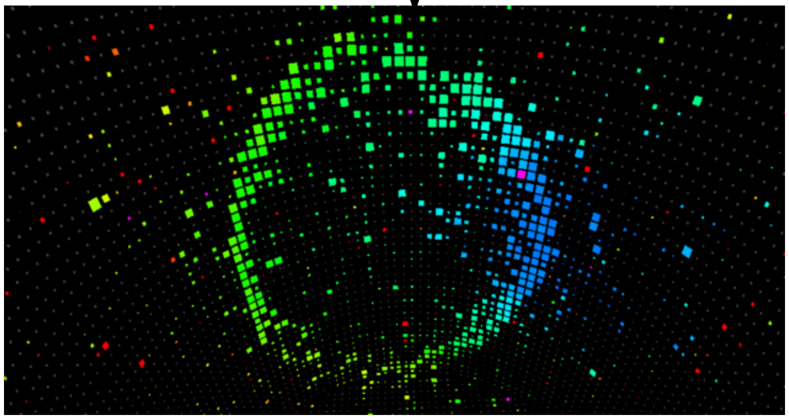
Super-Kamiokande



Hyper-Kamiokande

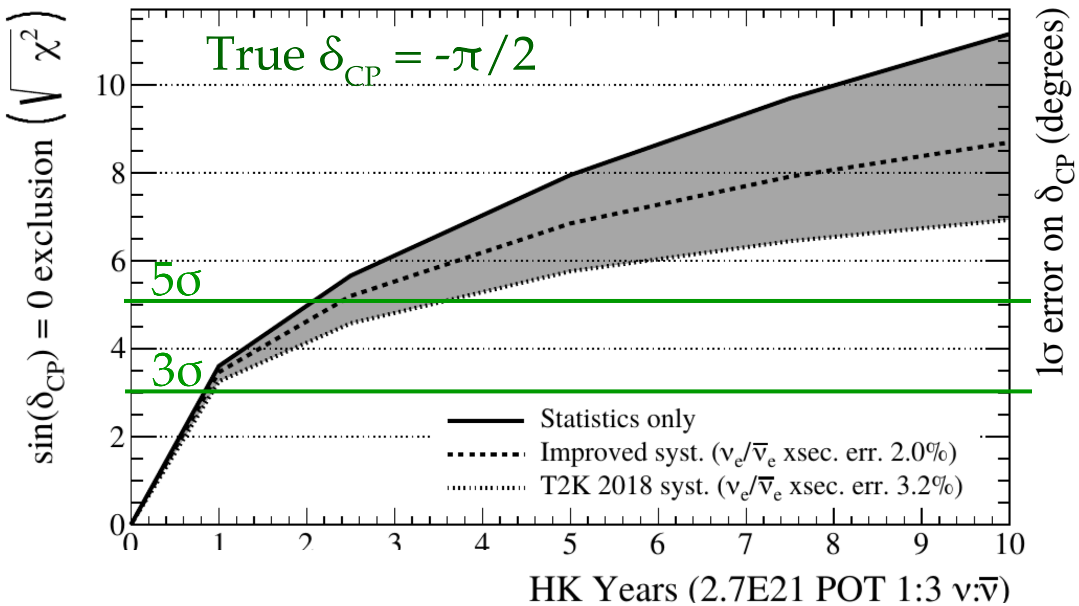


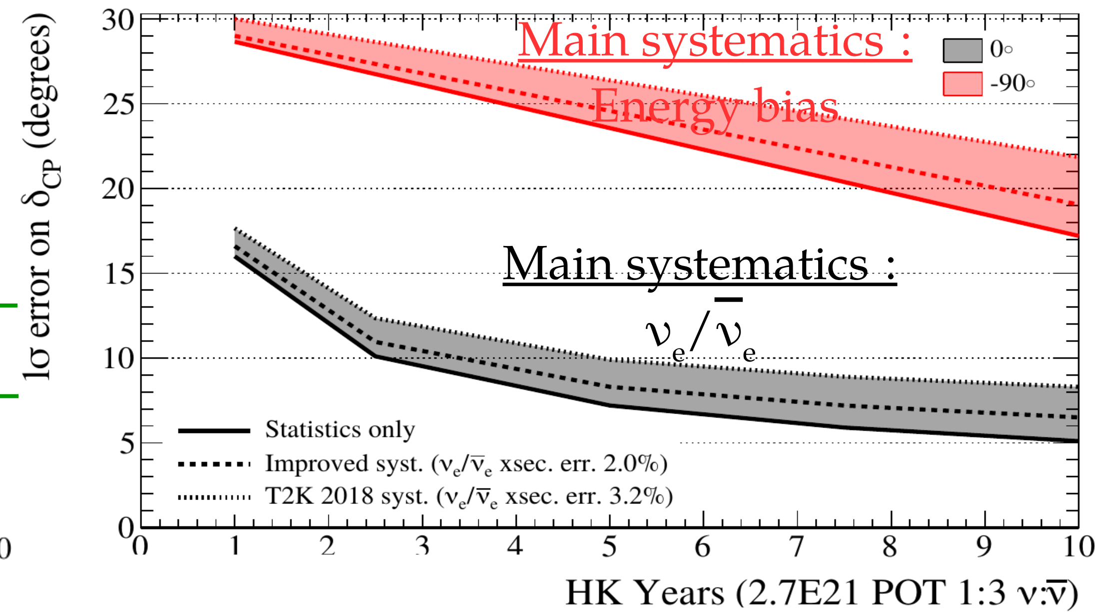
	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% (×2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton



Sensitivity to CP violation

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





- $\delta_{CP} = -\pi/2$: 5σ after 2-3 years of data taking : known in 2029-2030 !

→ Independent from ↓ systematic uncertainties.

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

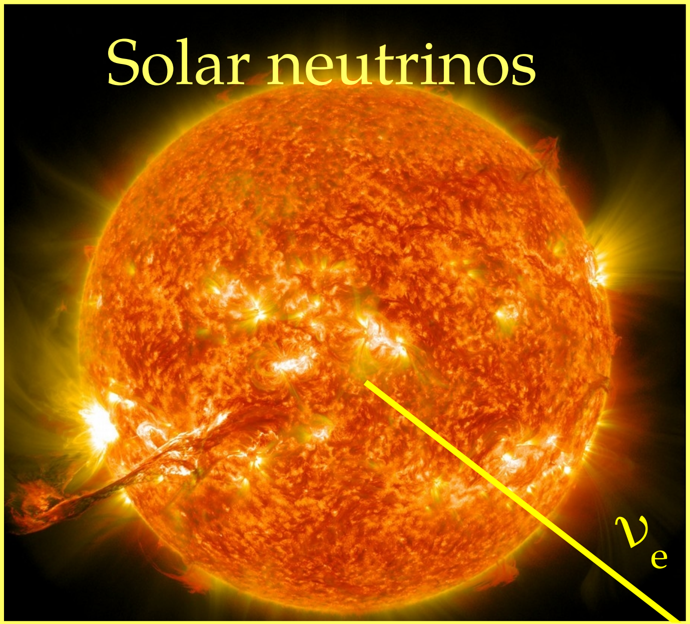
- After CPV is determined, accurate measurement of δ_{CP} will be crucial

→ Maximal CPV, leptogenesis, symetries of lepton's generations …

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

Physics case

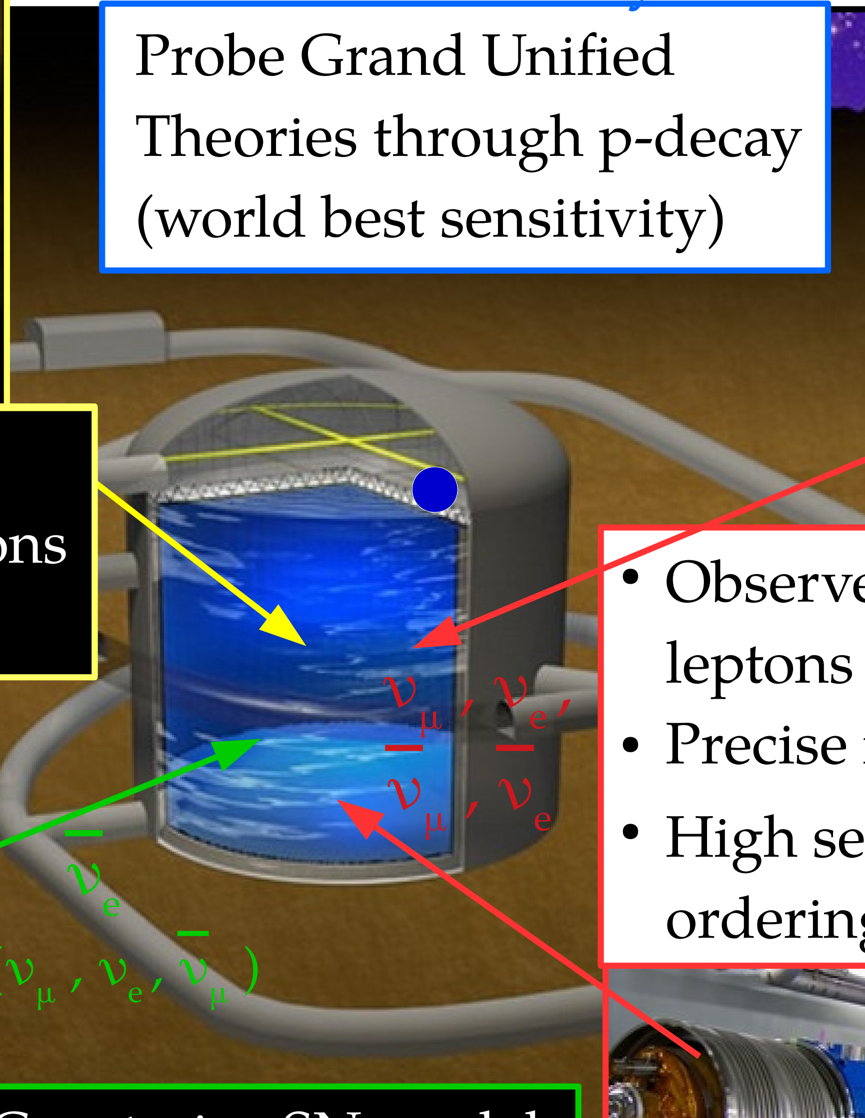
Solar neutrinos



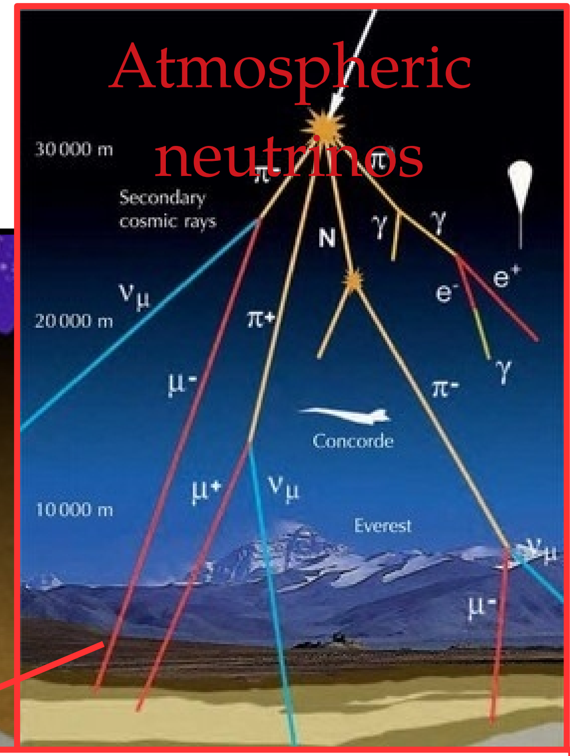
- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

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

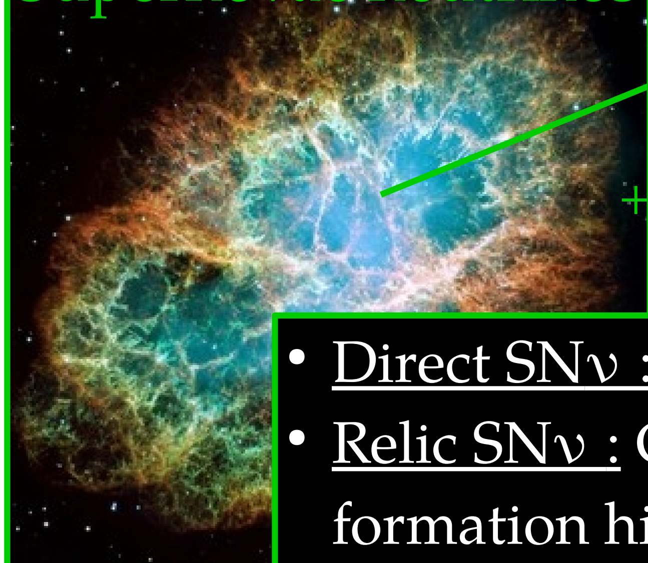


Atmospheric neutrinos

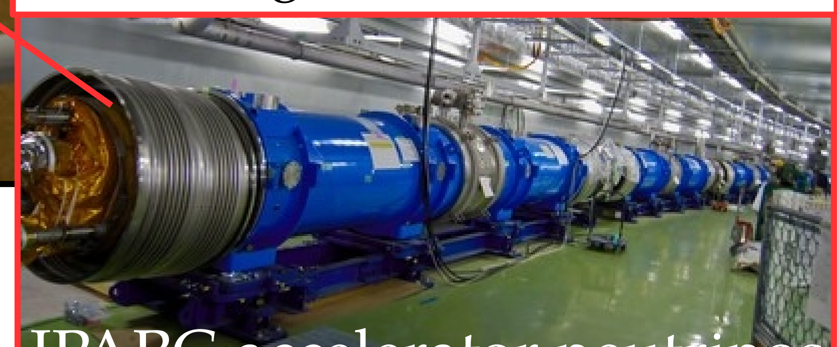


- Observe CP violation for leptons at 5σ
- Precise measurement of δ_{CP} .
- High sensitivity to ν mass ordering.

Supernovae neutrinos

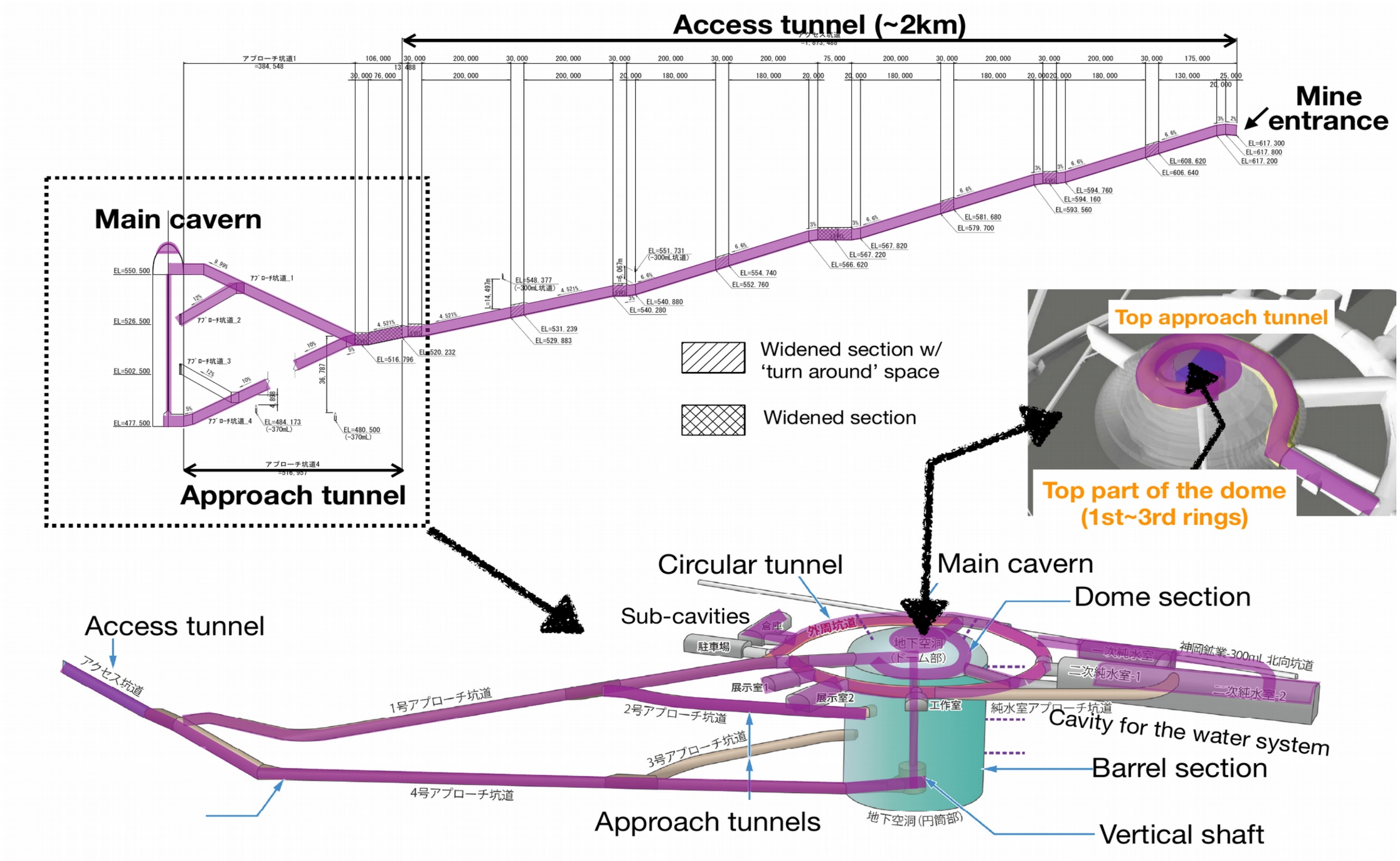


- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

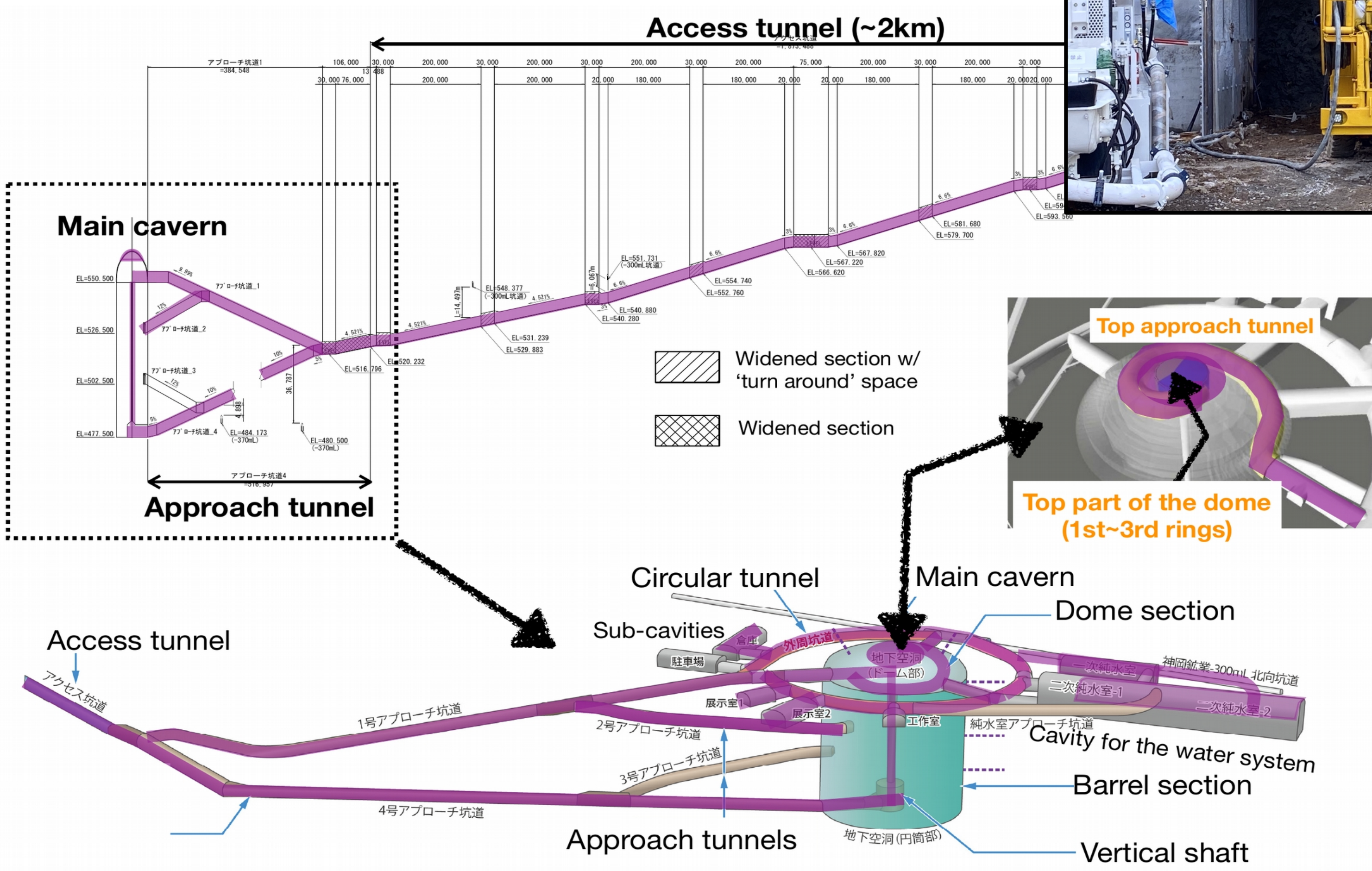


JPARC accelerator neutrinos

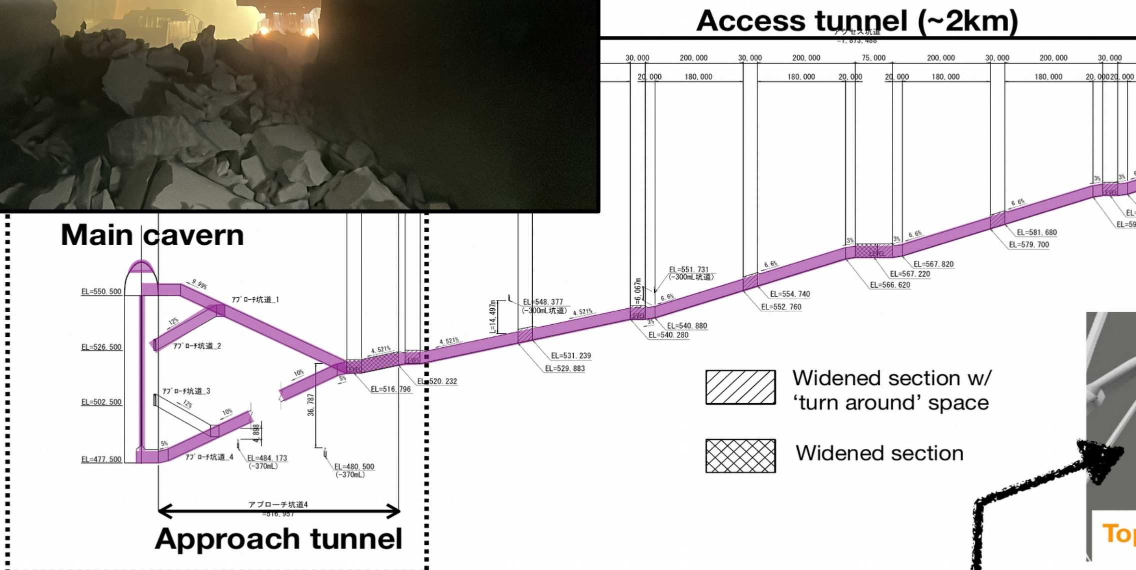
Hyper-K excavation

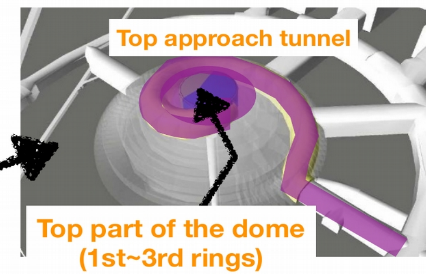


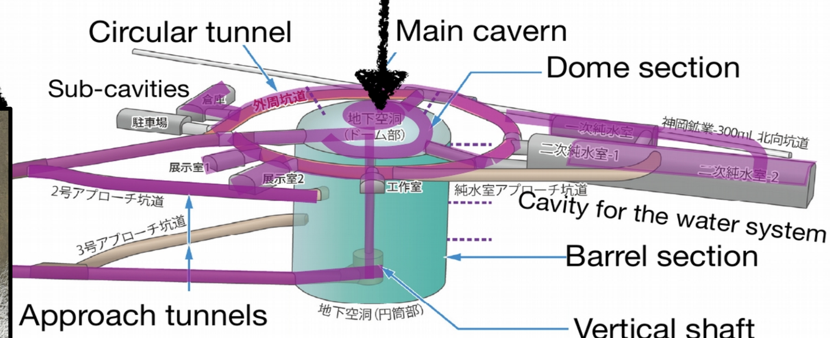
Hyper-K excavatio



-K excavatio







- Access tunnel excavation (25/02/22) ✓
- Approach tunnel excavation → Done ✓

Hyper-K caverns excavation

Dome section

Filtering system cavern

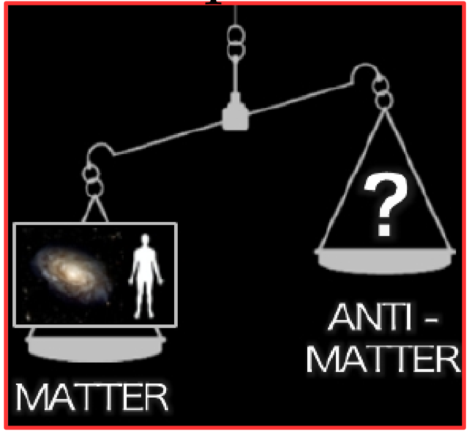
Finalizing the excavation (this year) !

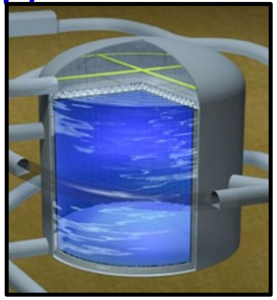
Conclusions

- Neutrino physics has completely changed in the last 50 years.
  → Highly driven by the discoveries in Japan : neutrino oscillation, precise measurement of PMNS matrix, first hint of CP violation…
  → Collaboration between Japan & France started in 2006.

- Future is even brighter : entered an era where ν can be used to probe most fundamental questions about our Universe :

1. Are they the source of matter-antimatter asymmetry ?
→ C. Quach: use improved reconstruction w/ AI to probe CP violation.
2. Probe supernovae exploding in black-hole or neutron stars through history of universe → L. Perisse talk.
3. Can fundamental interactions be unified at high-E ?

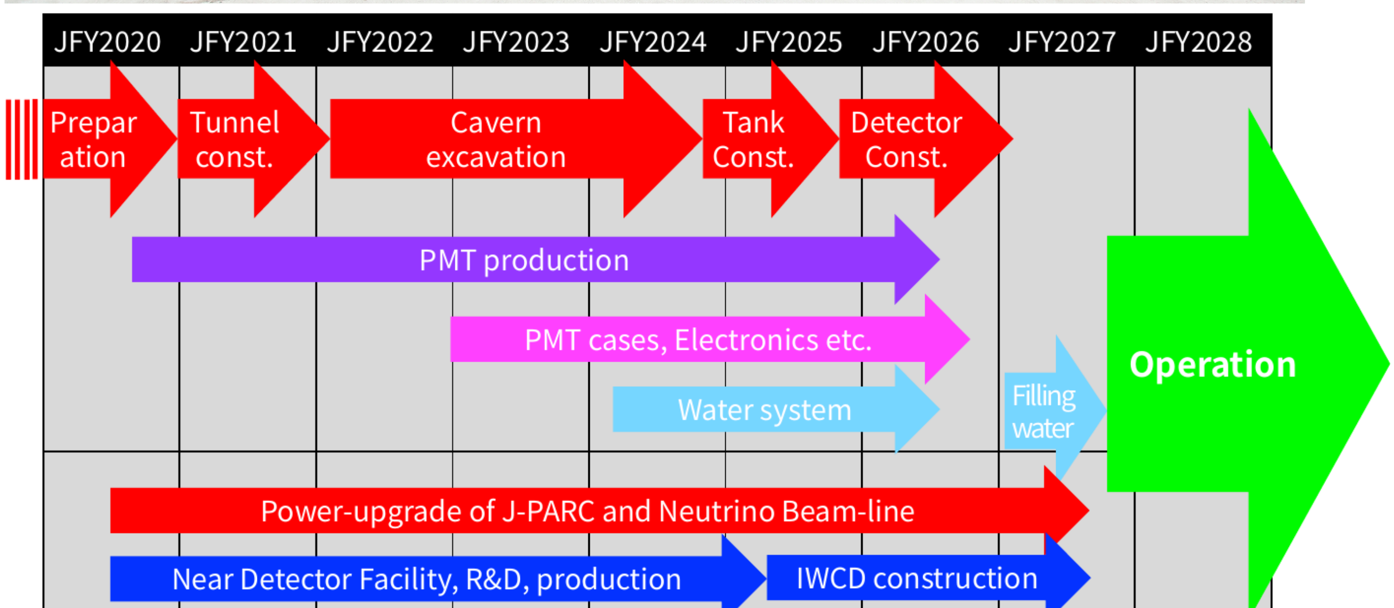




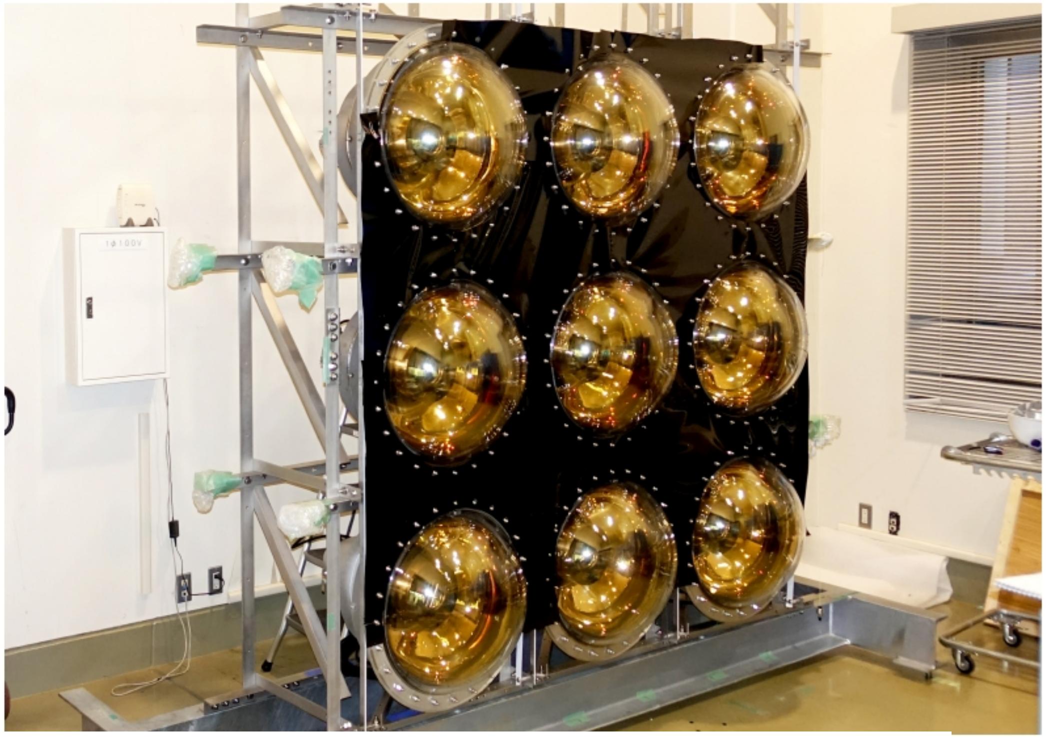
- Hyper-K will be the leading experiment in ν physics in the next 20 years !

Additional slides

Hyper-K schedule



PMT production & delivery

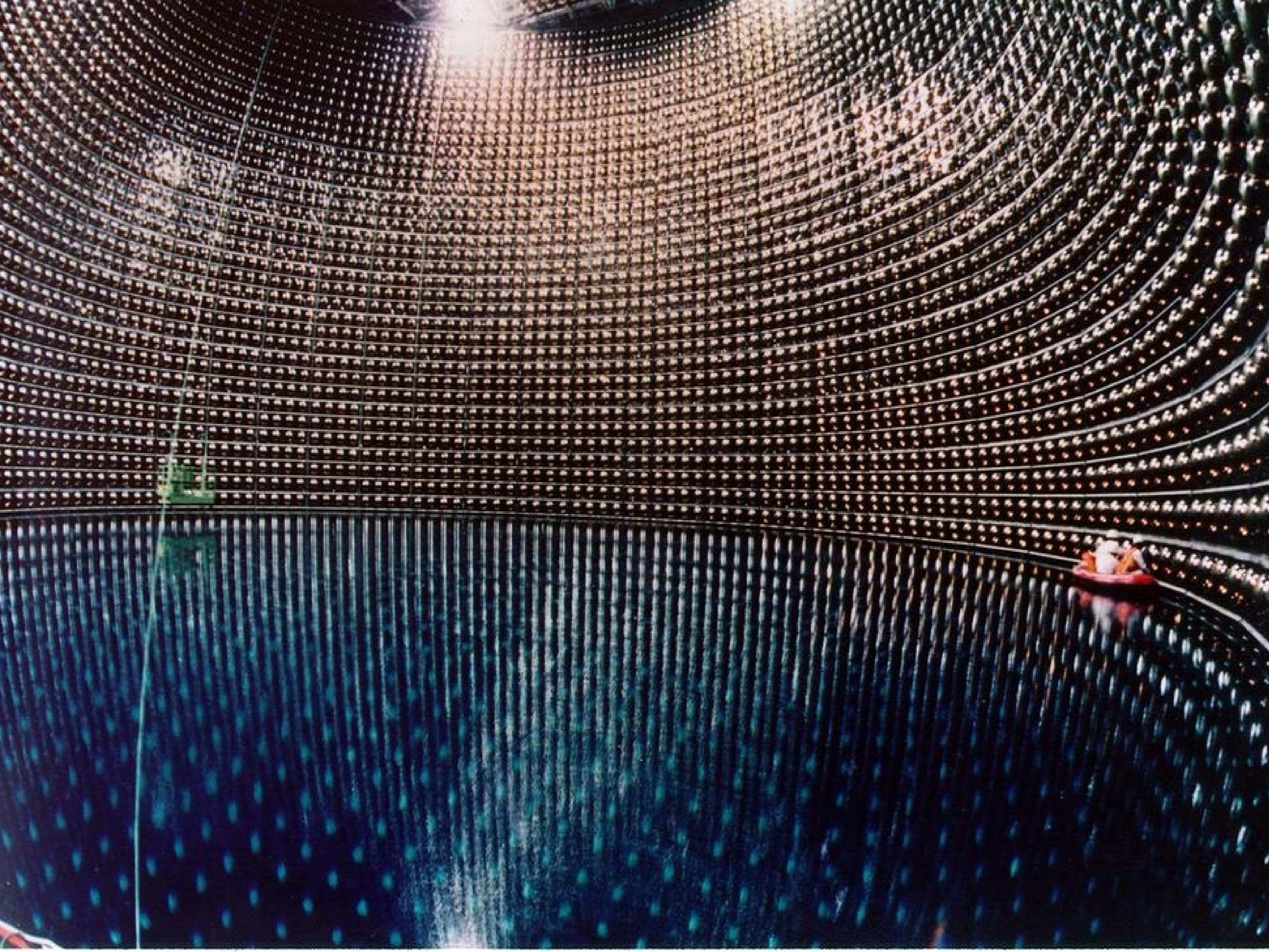



The Hyper-K collaboration

<u>The Hyper-K collaboration :</u>

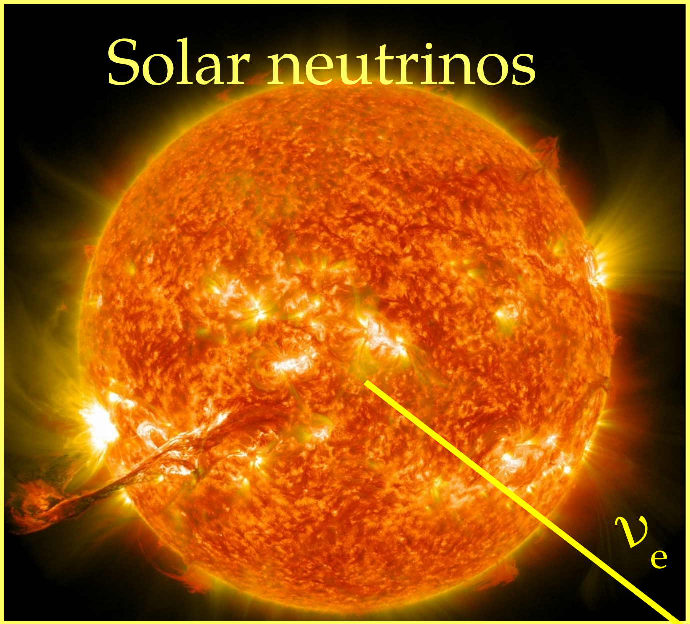
~550 members located in 102 institutes from 21 countries

<u>March 2023 :</u> our very 1st collaboration meeting in person after Covid !

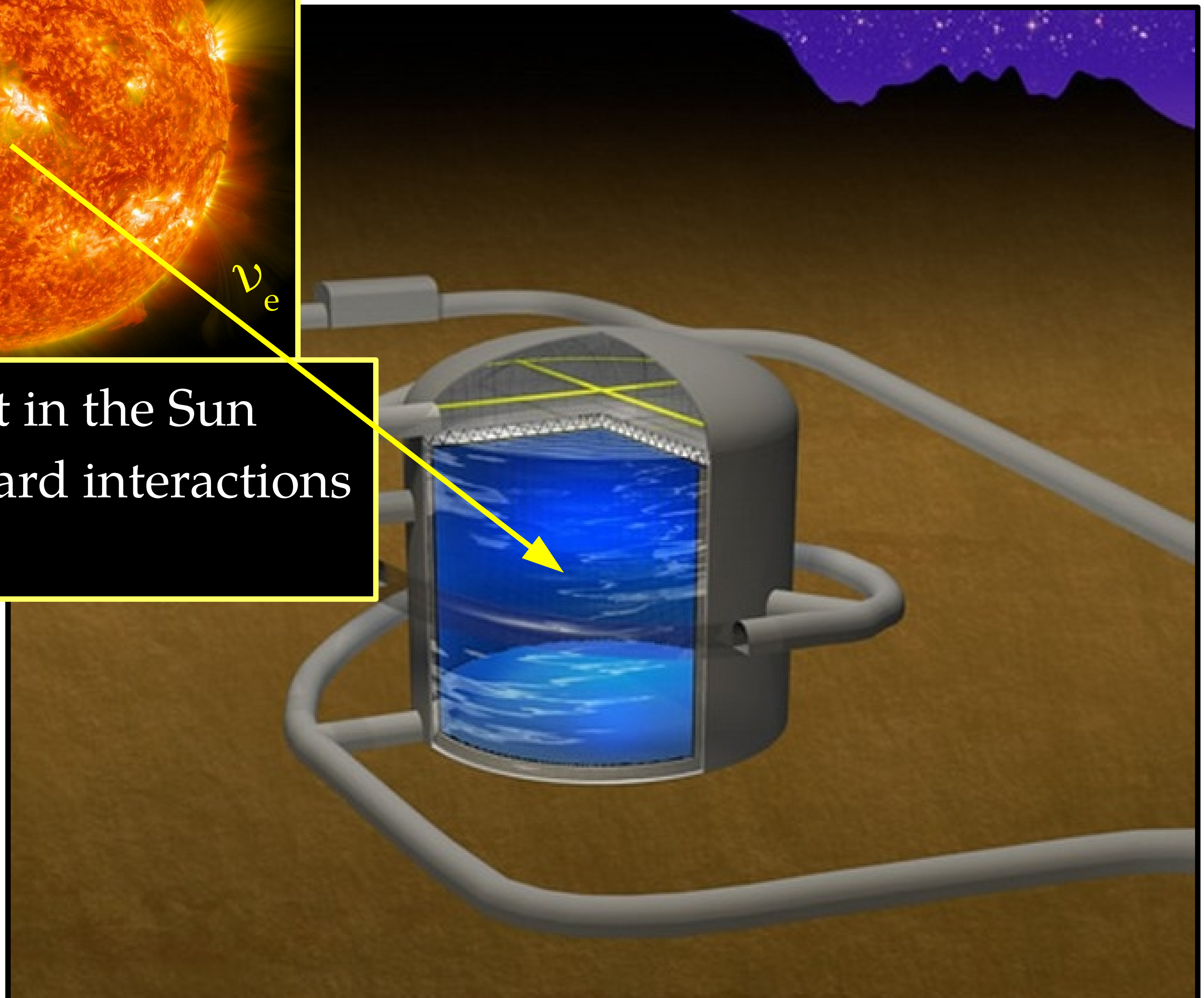



Achilles

Physics case



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

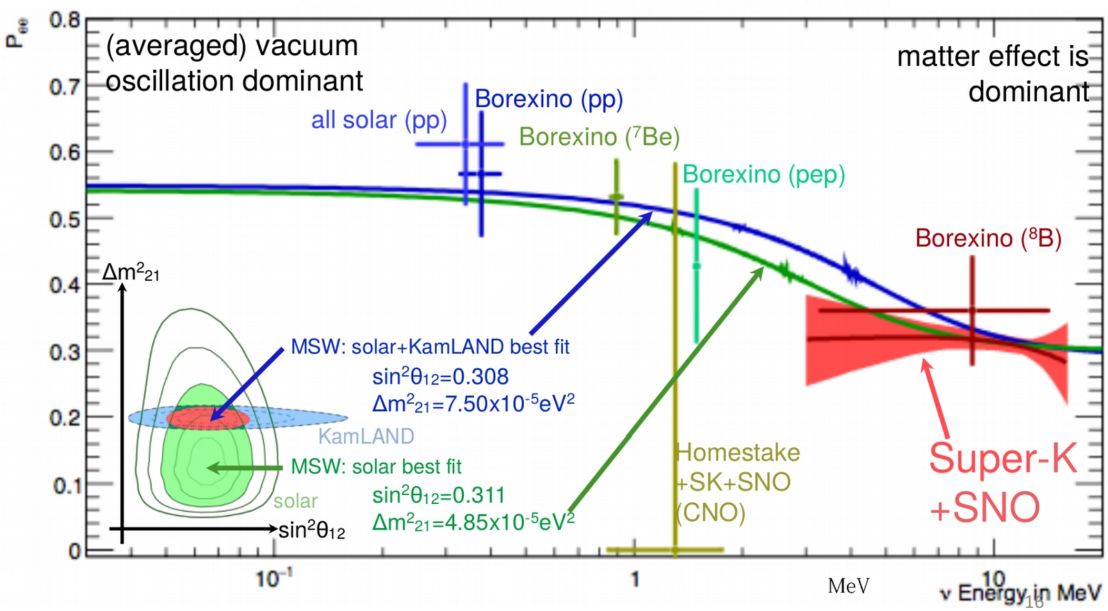


Solar neutrinos : upturn

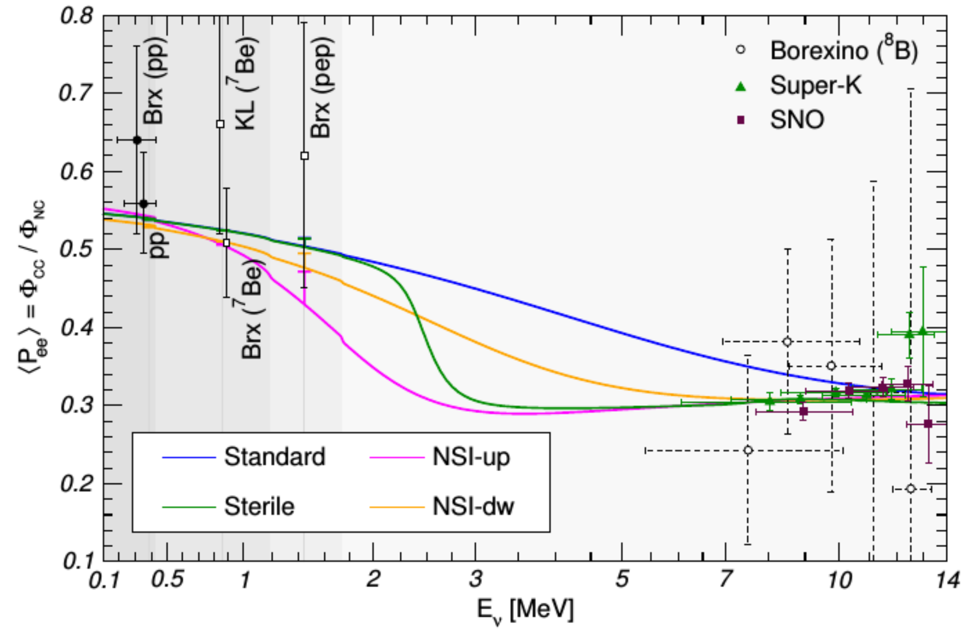
- <u>Probe solar ν :</u> SK/SNO found a high matter effect in the Sun

  ↔ Solar upturn shifted to lower energies

[Ikeda M., SK, Neutrino 2018]



[arXiv:1507.0587]

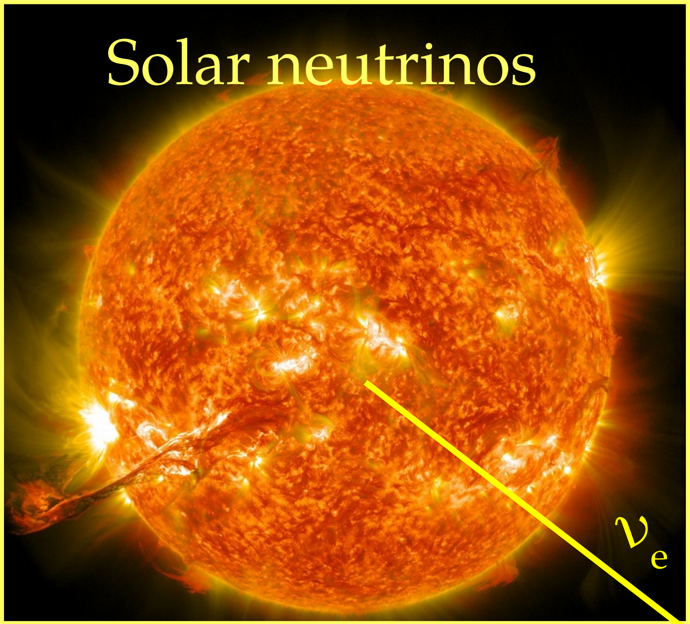


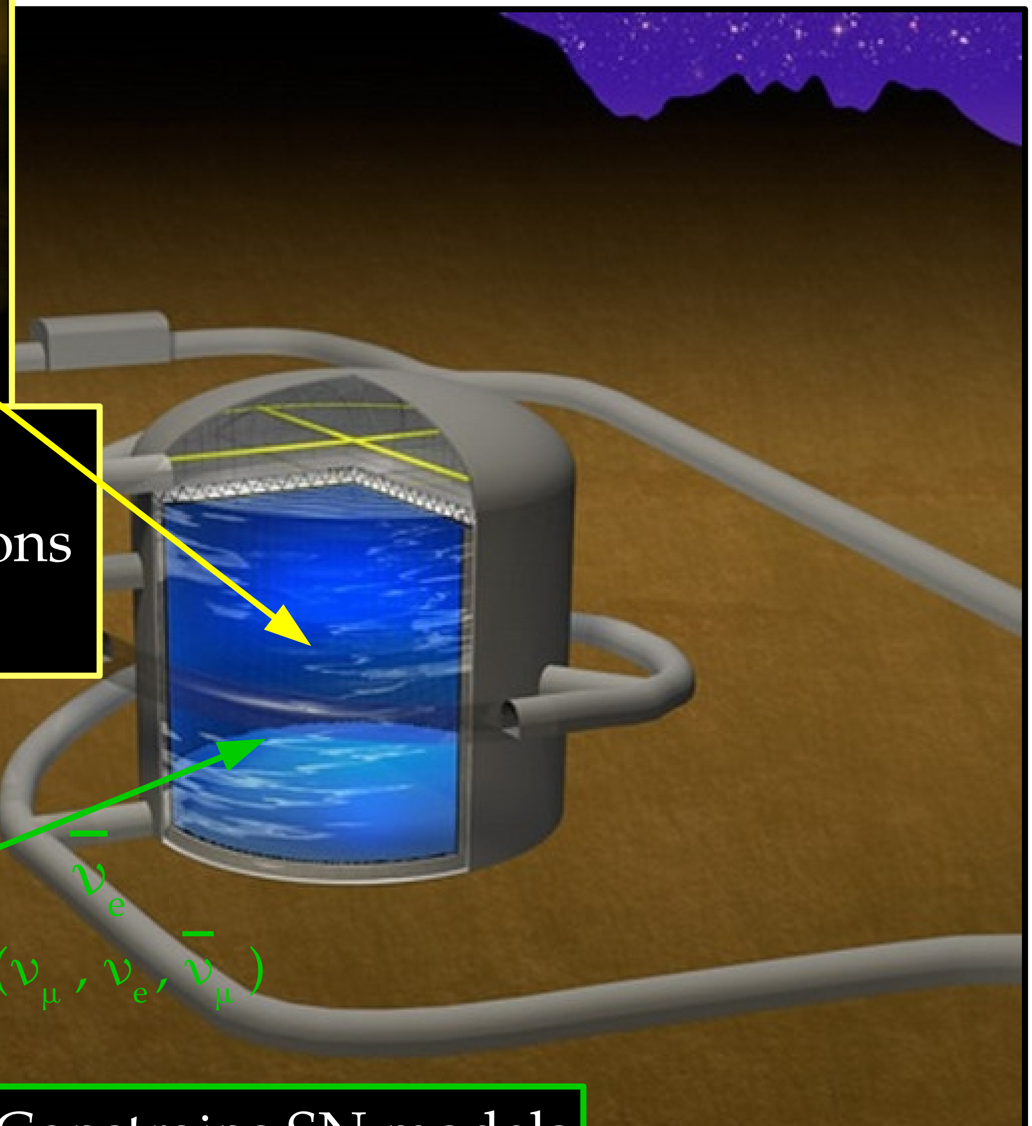
- SK deviates from standard upturn scenario > 2σ . [Moriyama S., SK, Neutrino 2016]

- <u>Displacement of the upturn can be explained by :</u>
  - Statistical fluctuation ?
  - Light sterile neutrino ?
  - Non Standard Interaction in the dense Sun ?

Physics case

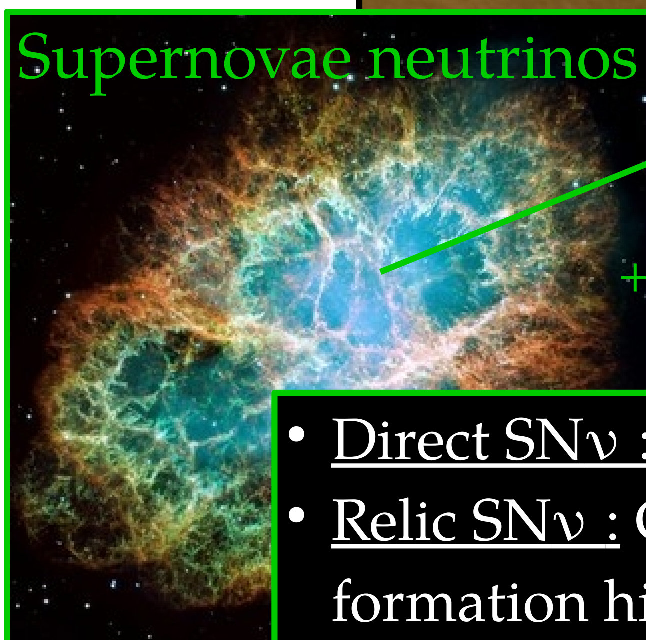
Solar neutrinos





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

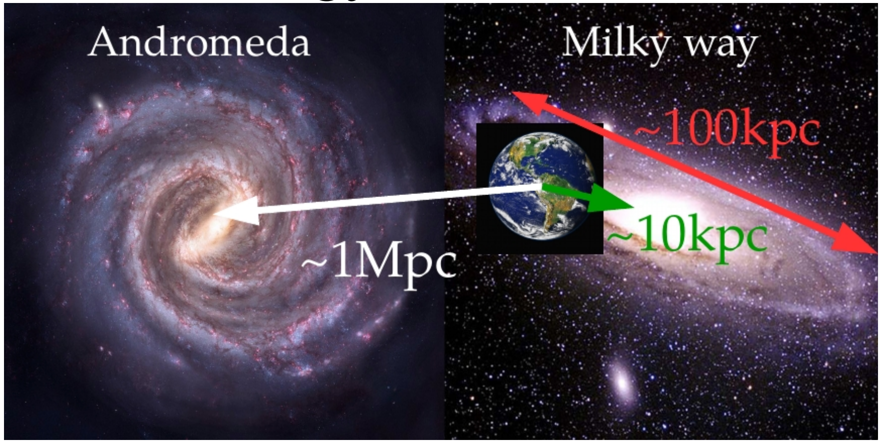
Supernovae neutrinos



- <u>Direct SNν :</u> Constrains SN models.
- <u>Relic SNν :</u> Constrains cosmic star formation history

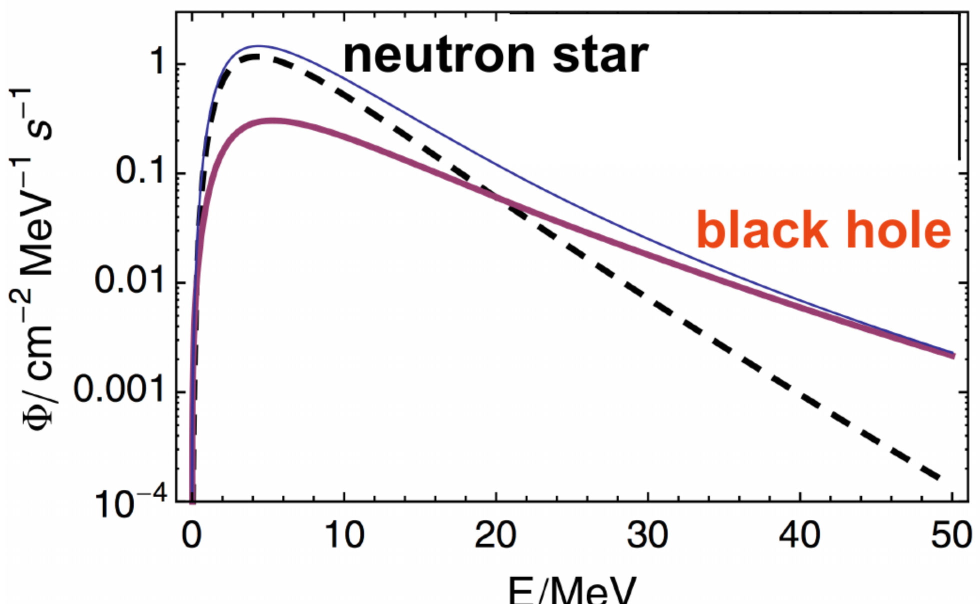
Supernovae neutrinos

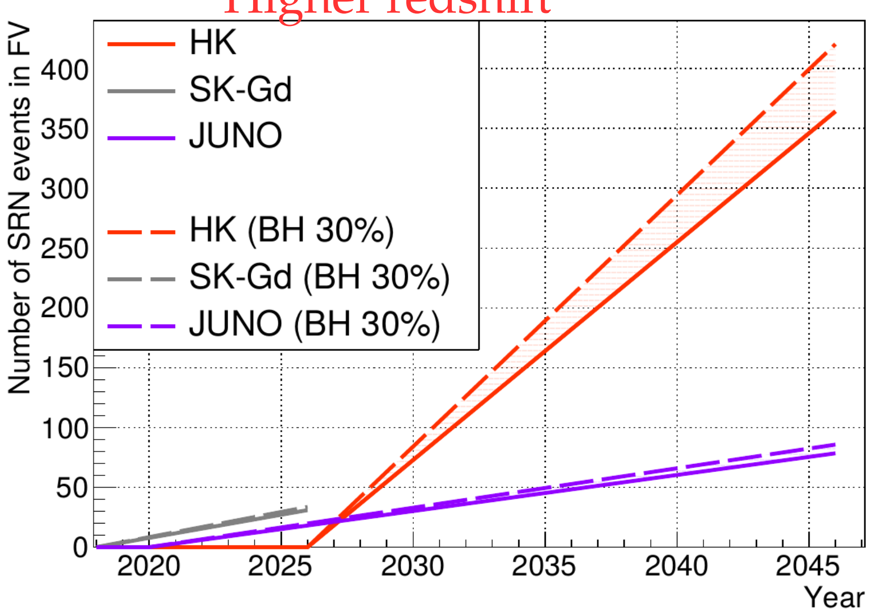
- Unique probe for supernovae ν : 99 % of SN energy → ν.
  - But direct ν detection very rare.
  - HK also sensitive to extra-galactic SNν from Andromeda !



- SN-relic neutrino → new constraints on cosmic star history → May be first detected in SK-Gd.
  → But spectrum determined by HK : Low energy ↔ Probe older stars

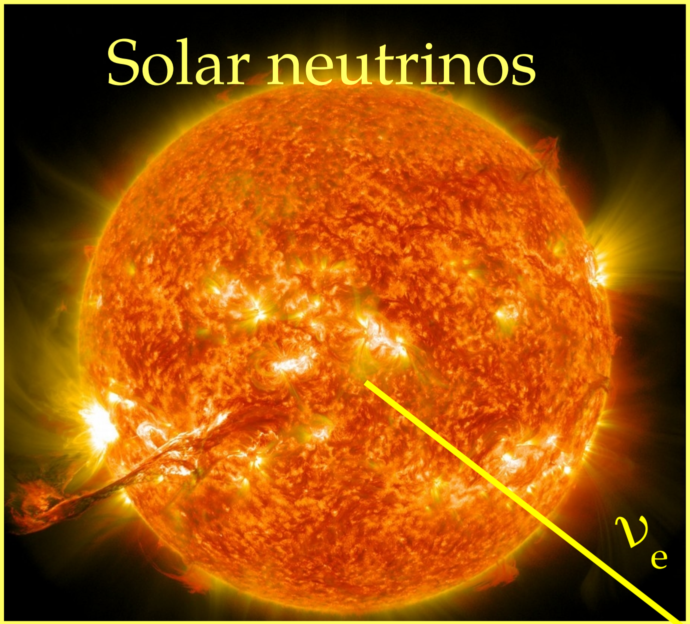
Higher redshift





- SK-Gd & then, HK are the pioneer experiments of this domain !

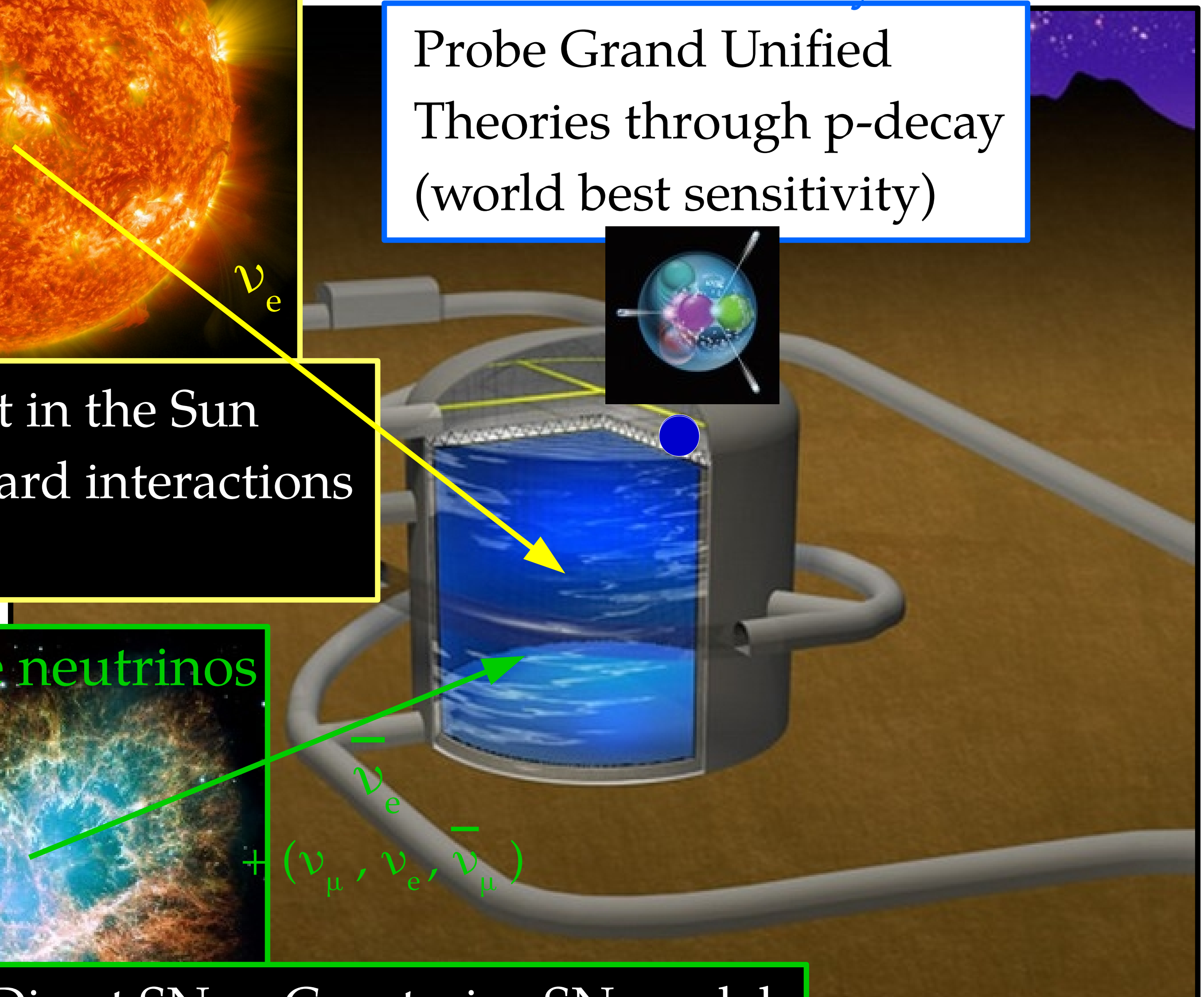
Physics case

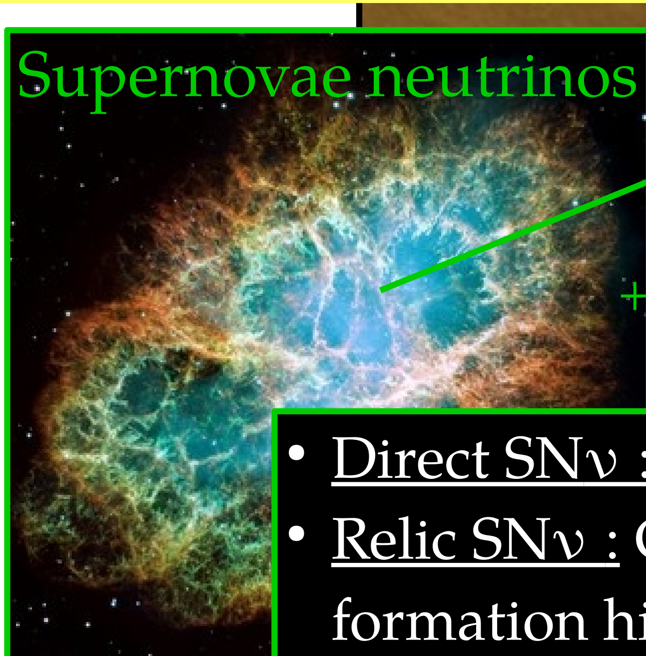


- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

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



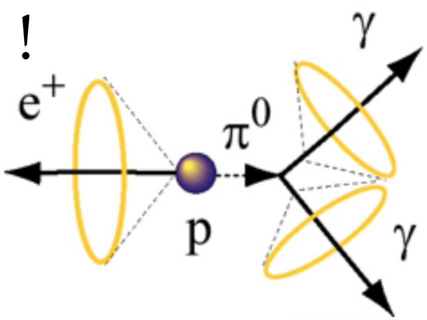


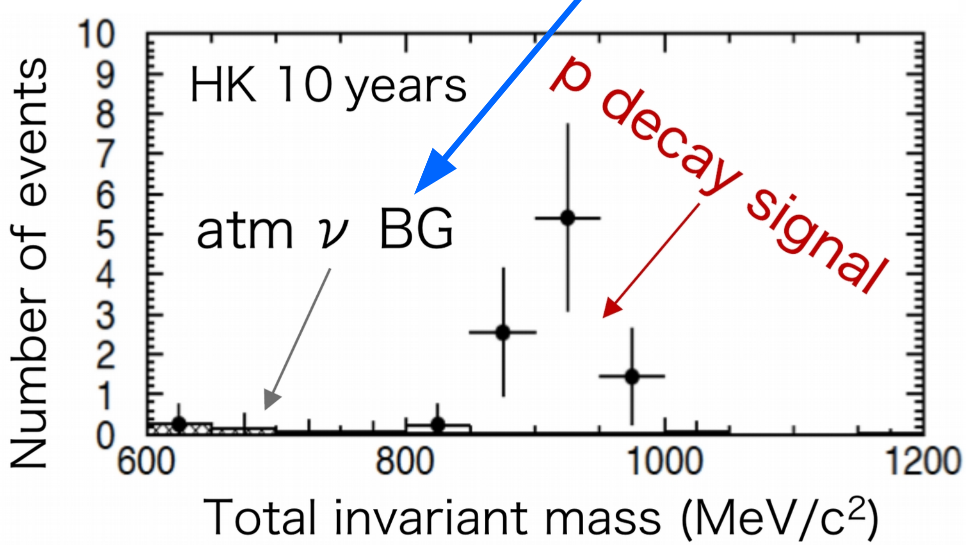
- <u>Direct SNν :</u> Constrains SN models.
- <u>Relic SNν :</u> Constrains cosmic star formation history

GUT and proton decay

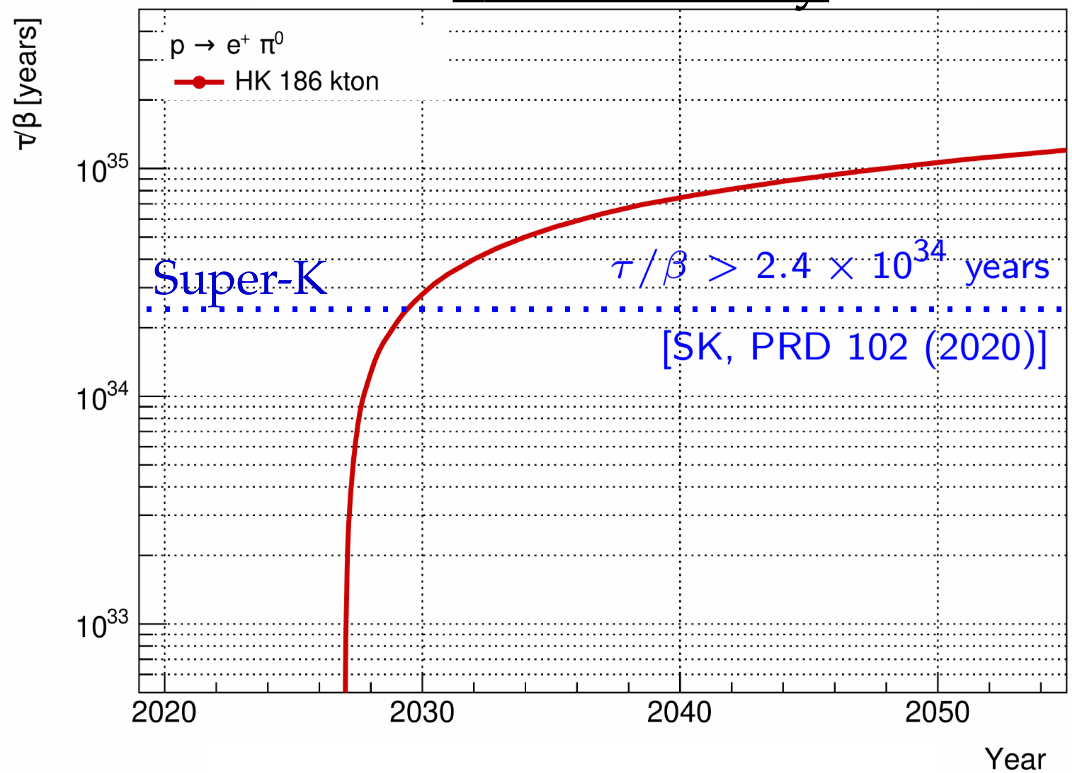
- Probe Grand Unified Theories at a new scale through proton decay.

- <u>Golden channel :</u> $p \to e^+ + \pi^0 \to$ Almost background free !
  $\to$ Requires 2γ & reconstructed energy = Invariant M_P
  $\to$ <u>Bkg :</u> Atmospheric ν producing e.g. a π^0.





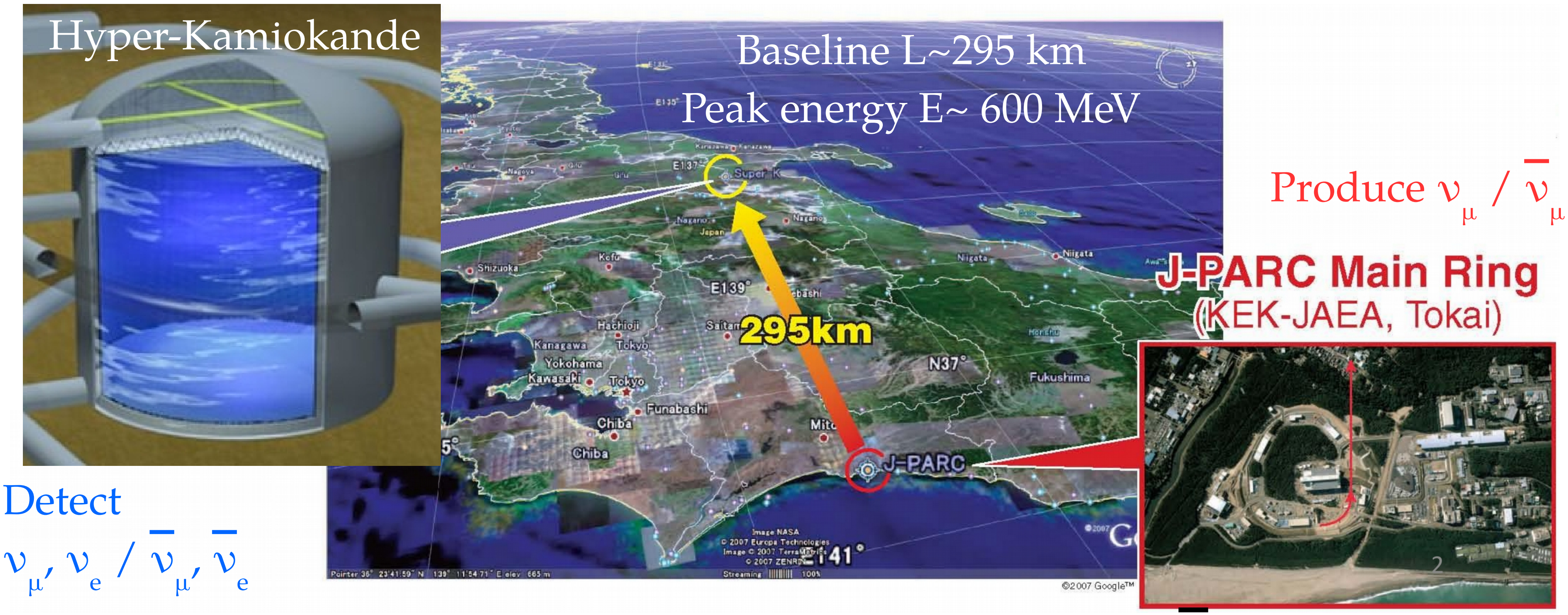
3σ sensitivity



- 3σ sensitivity reach τ_P /Br = 10^{35} years → 1 order of magnitude beyond current best limits (Super-K)

Focus on CP violation

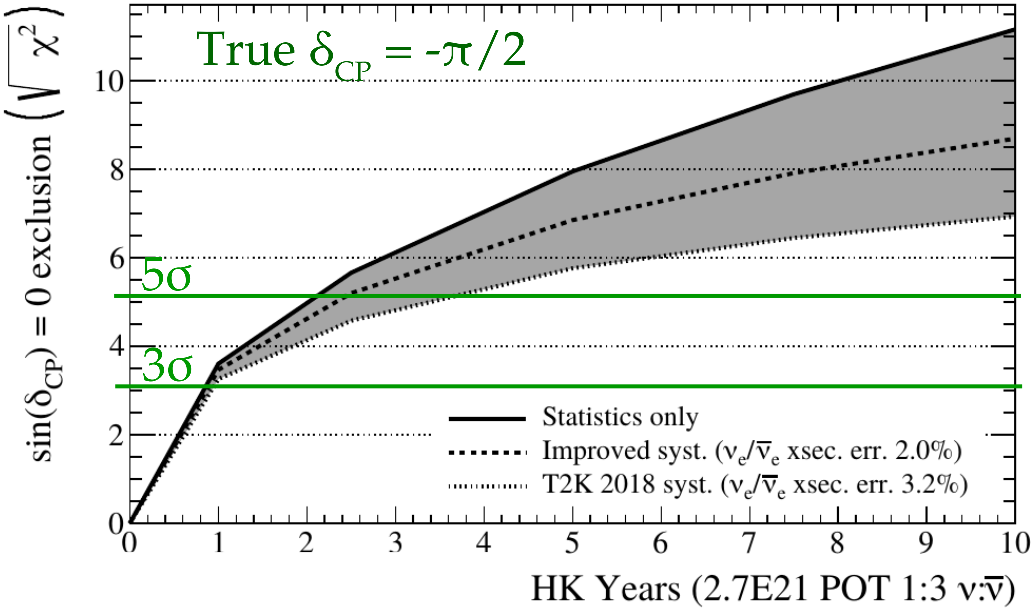
- CP violation search essentially based on accelerator ν : T2HK

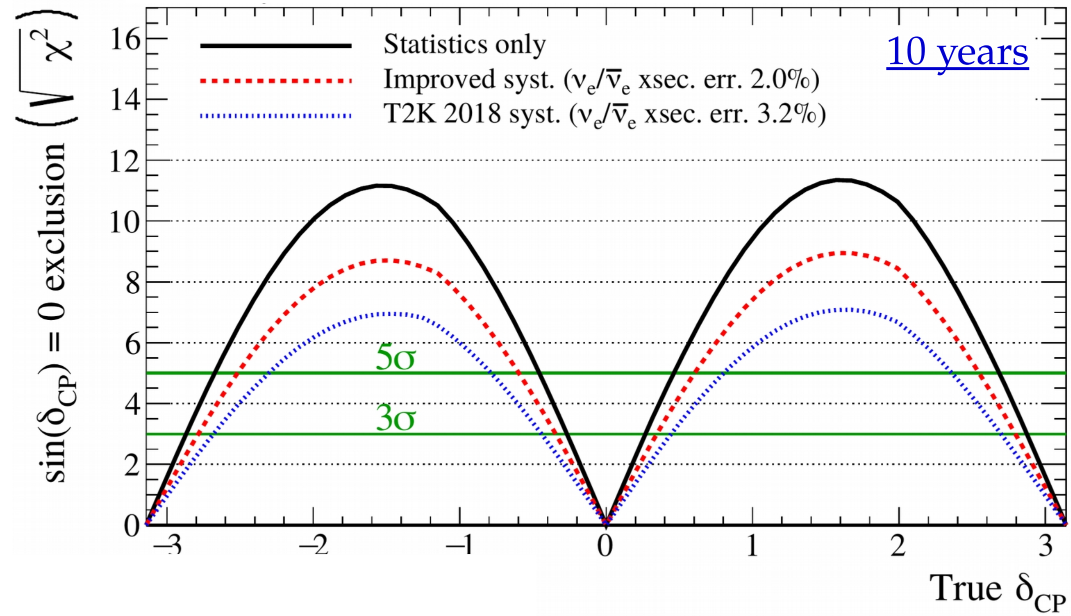


- ν_e appearance in a ν_μ beam and ν_μ disappearance & $\bar{\nu}$ equivalents.
- Compare $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$: ideal probe to CP-violation !
- Use T2K beamline : $\Longrightarrow$ Quick start ! Which relies on 2 milestones.
  1. ↓ time to accumulate statistics → Beam upgrade to 1.3 MW.
  2. ↓ systematic uncertainties → Constrains ν_μ & ν_e flux before oscillation with two near-detectors.

Sensitivity to CP violation

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





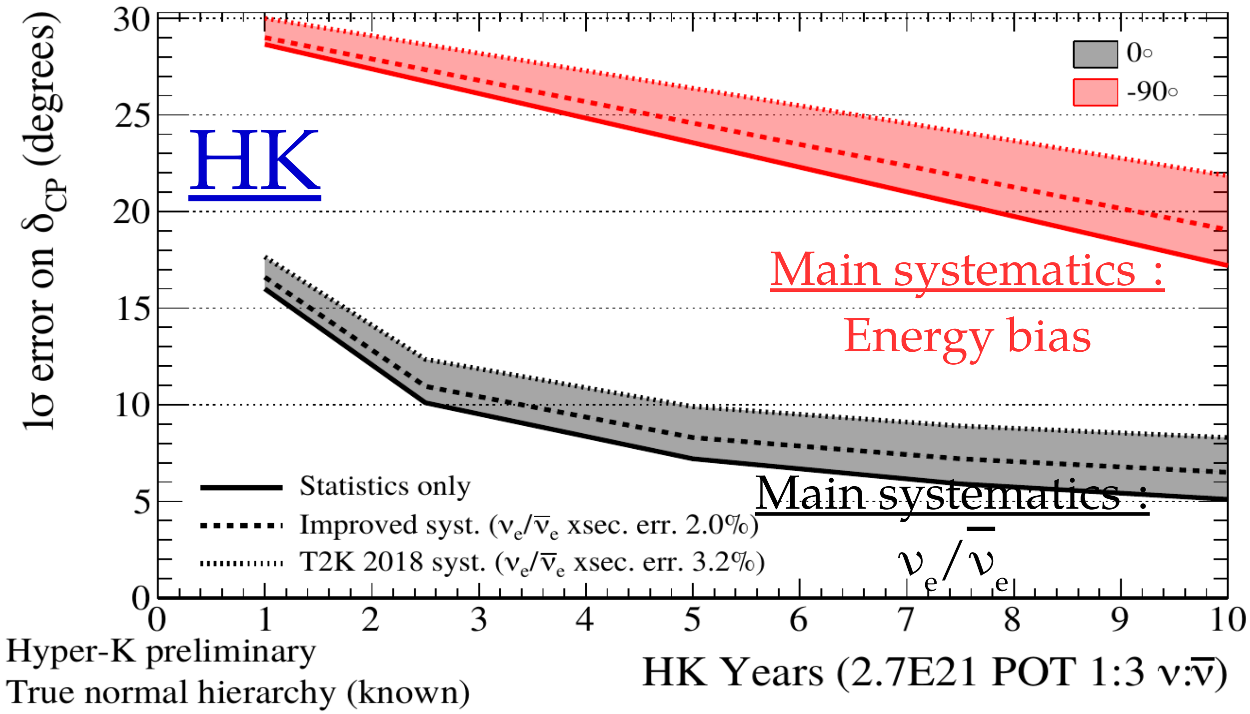
- δ_{CP} = -π/2: 5σ after 2-3 years of data taking : known in 2029-2030 !
  → Independent from ↓ systematic uncertainties.

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

- HK has world-best sensitivity to CP violation for the coming generation… if mass-ordering is known !

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 ...



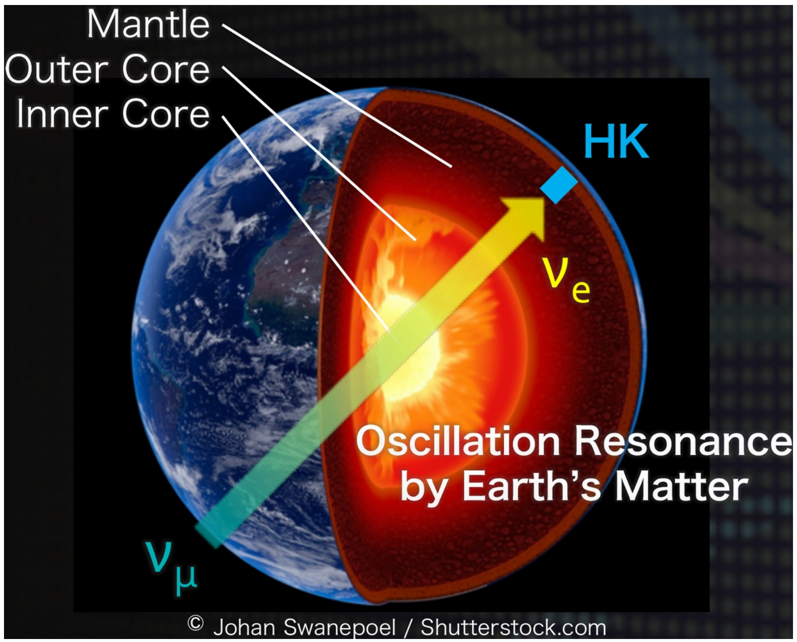
	5 years	10 years
CP conserved ($\delta_{CP} = 0$)	8°	6°
Max XPV ($\delta_{CP} = -\pi/2$)	25°	19°

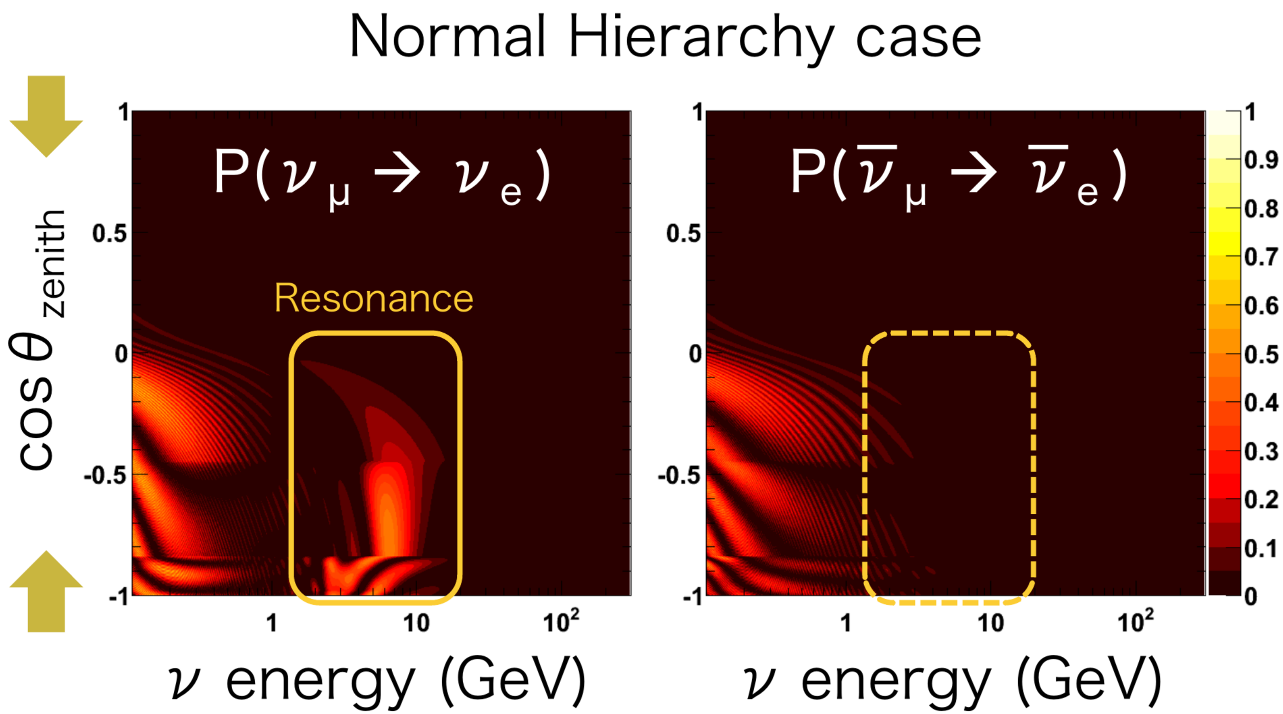
- HK will be the world-leading experiment to measure δ_{CP} and constrains CP-violation in the next 20 years !

Atmospheric neutrinos

- <u>Mass-ordering can be measured through matter effects</u>

  → The longer the baseline, the higher the effects





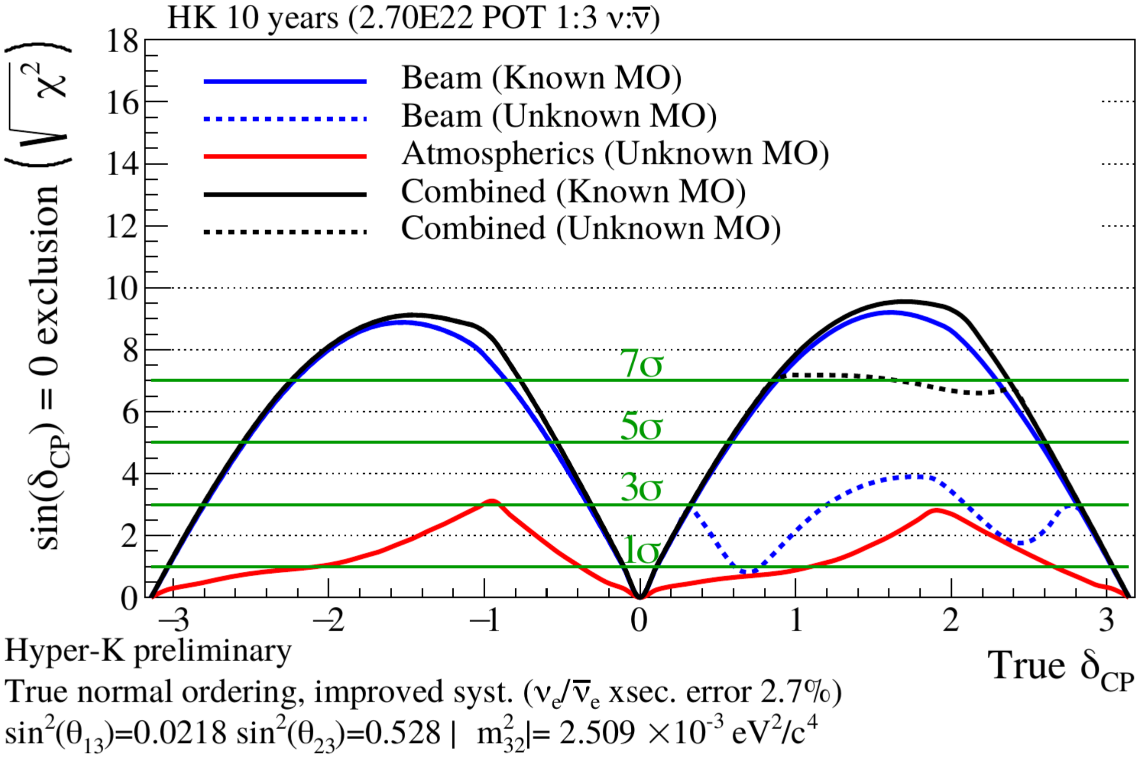
- Mass ordering determined with upward-going multi-GeV ν_e sample :

atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline

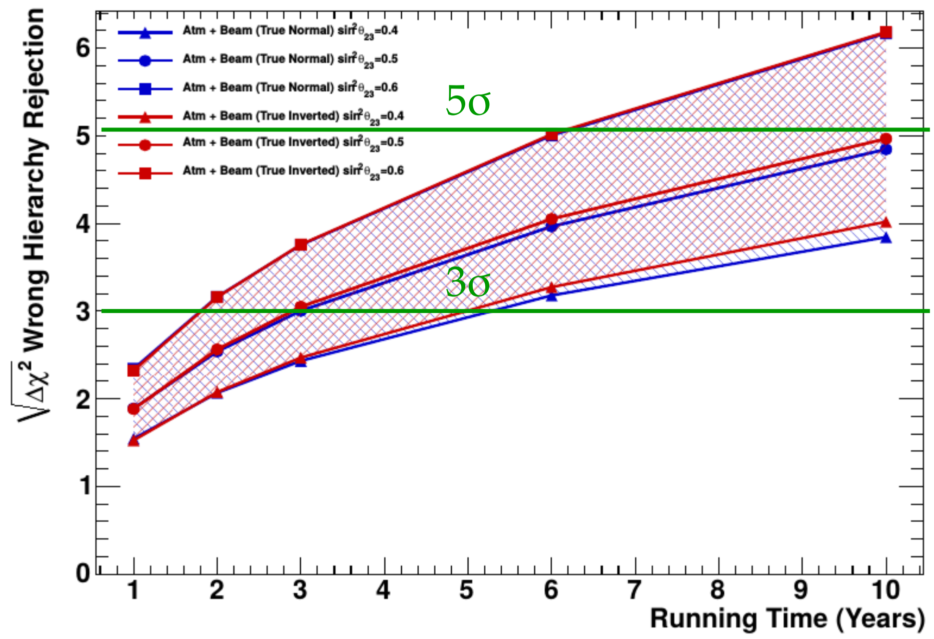
  - <u>Normal hierarchy :</u> enhancement of $\nu_\mu \to \nu_e$.
  - <u>Inverted hierarchy :</u> enhancement of $\bar{\nu}_\mu \to \bar{\nu}_e$.

Combination of atmospheric + beam ν

Impact on CPV sensitivity



Sensitivity to mass ordering



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

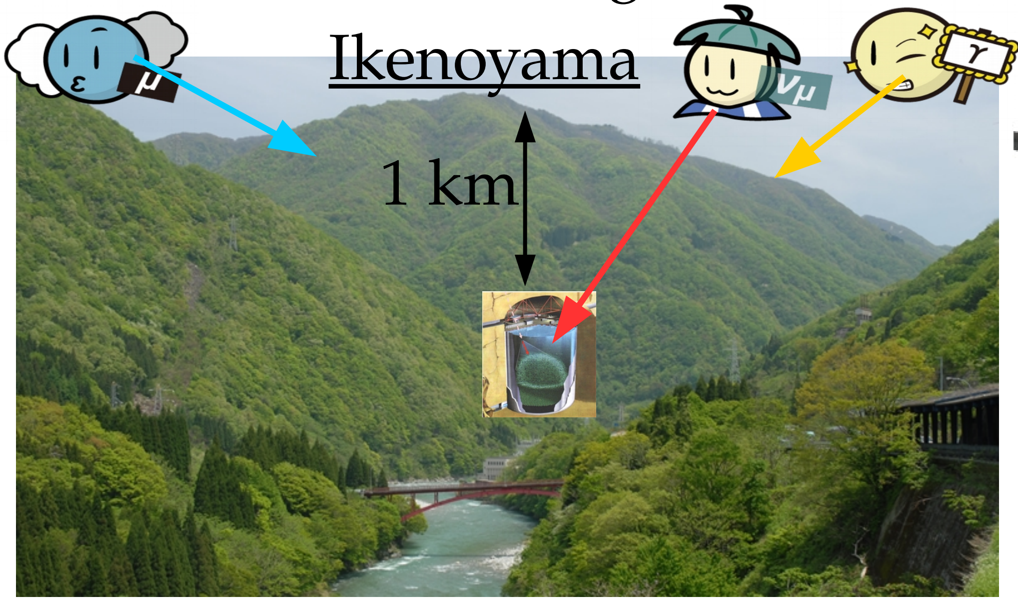
→ Sensitivity to CPV is little affected if we add atmospheric ν.

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

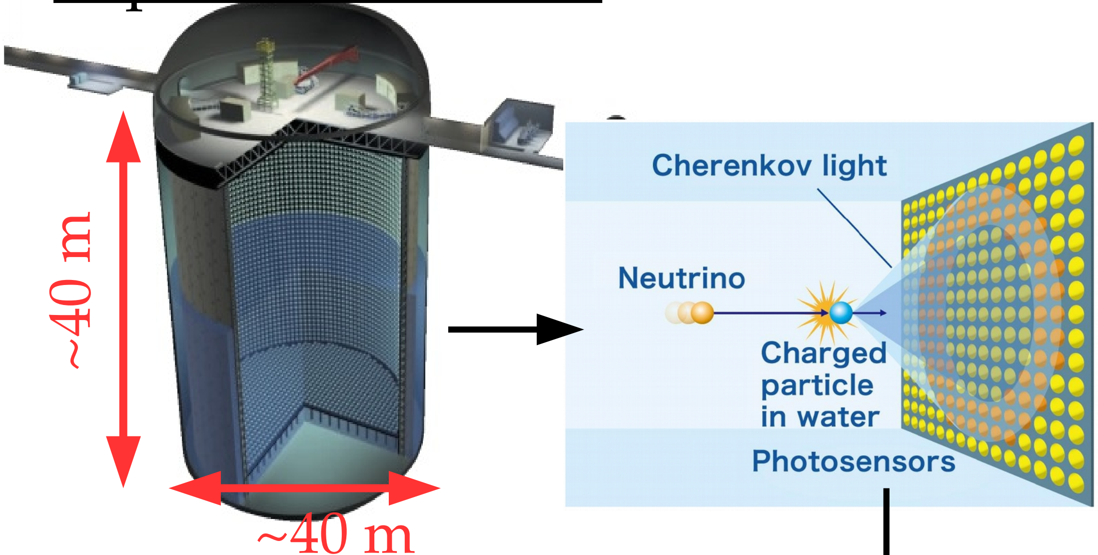
  → HK after ≥ 6-10 years via atmospheric.

The Super-Kamiokande detector

- A 50 kton water Cherenkov detector, located 1 km undeground to stop cosmic muons background.

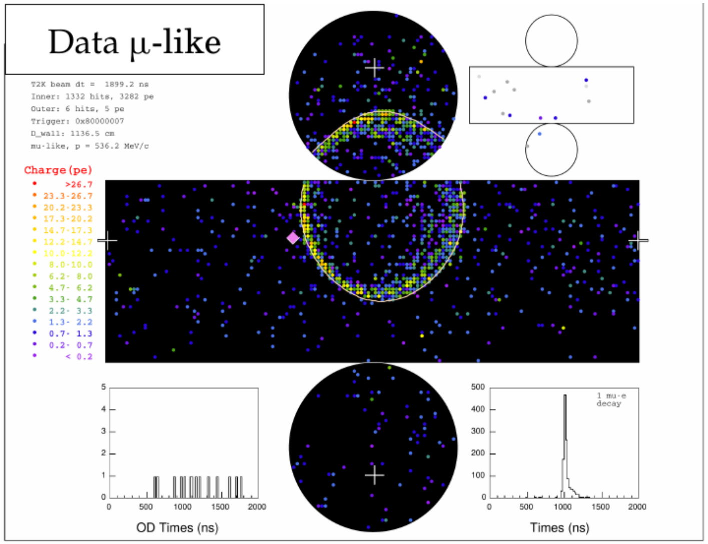


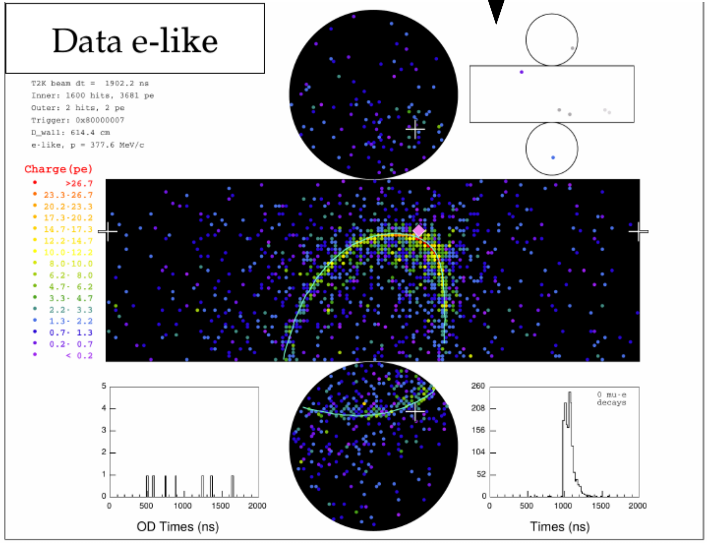
Super-Kamiokande



- Cherenkov ring detected using > 11,000 photo-multiplier tubes.

- ν_e / ν_μ separation using ring shape.





Open issues in neutrino oscillations

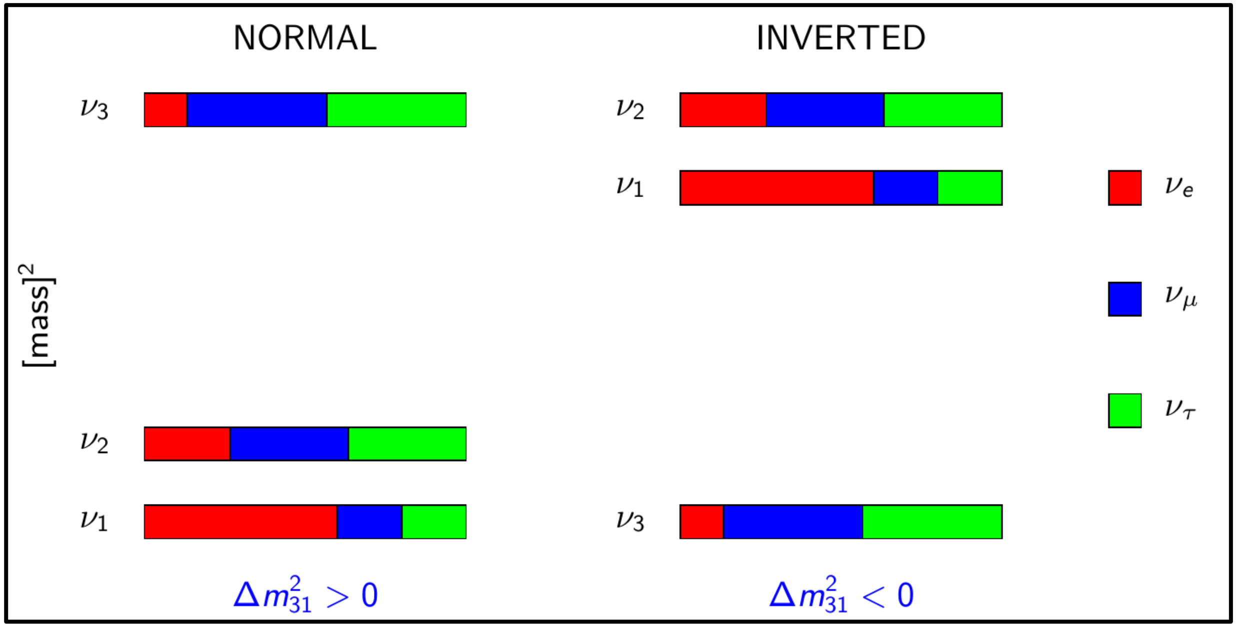
- <u>What is ν mass ordering (MO):</u> affect nucleosynthesis in Supernovae…

  → Oscillations in vacuum provides only $|\Delta m^2|$.

  → Matter effect in the Sun provides : $m_2 > m_1$.

  → Need matter effect in Earth to measure MO.

  → The longer the baseline, the higher the effect.

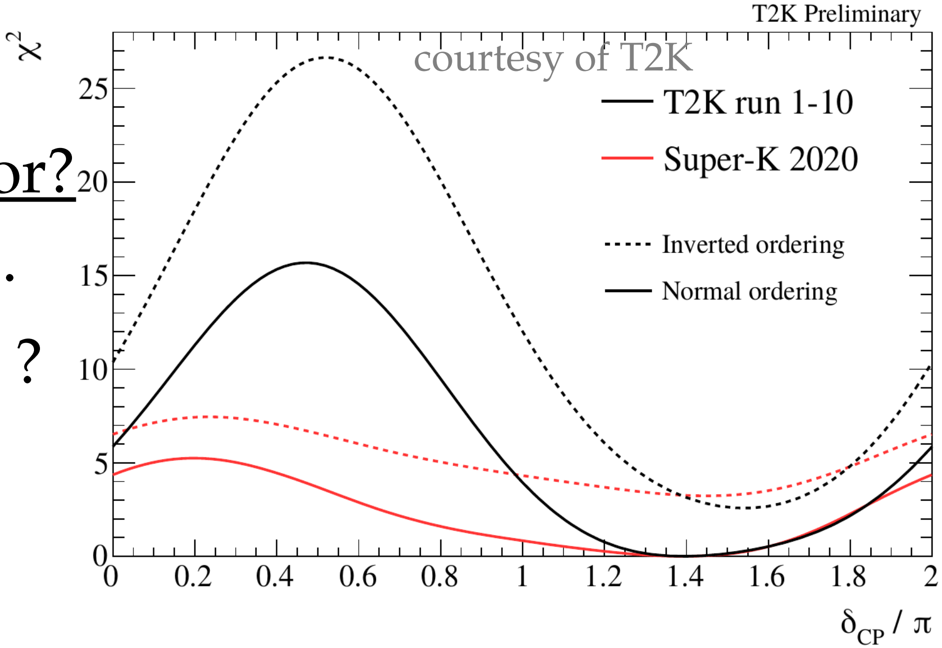


- <u>Is CP-symmetry violated in lepton sector?</u>

  → $P(\nu_\alpha \to \nu_\beta) \neq P(\overline{\nu}_\alpha \to \overline{\nu}_\beta) \leftrightarrow \sin\delta_{CP} \neq 0.$

  → Is CP maximally violated $\delta_{CP} = -\pi/2$?

  → Could be very 1st hints towards matter-antimatter asymmetry !

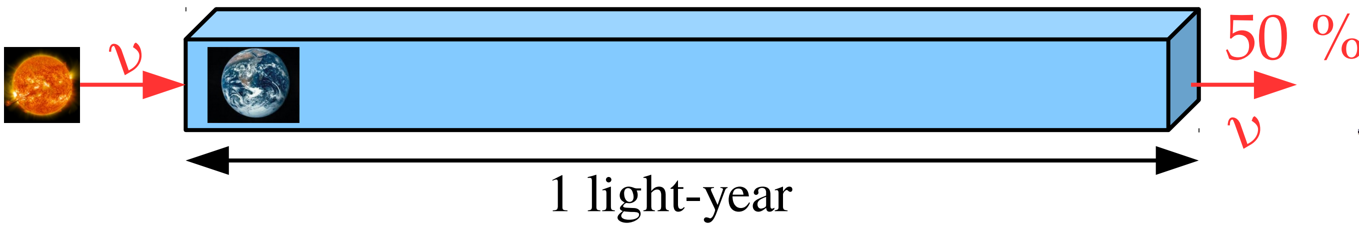


Neutrinos ?

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?

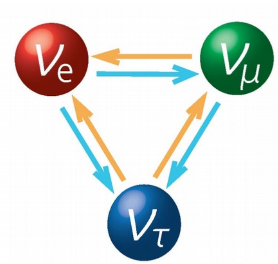
Dirac ? or/and Majorana ?

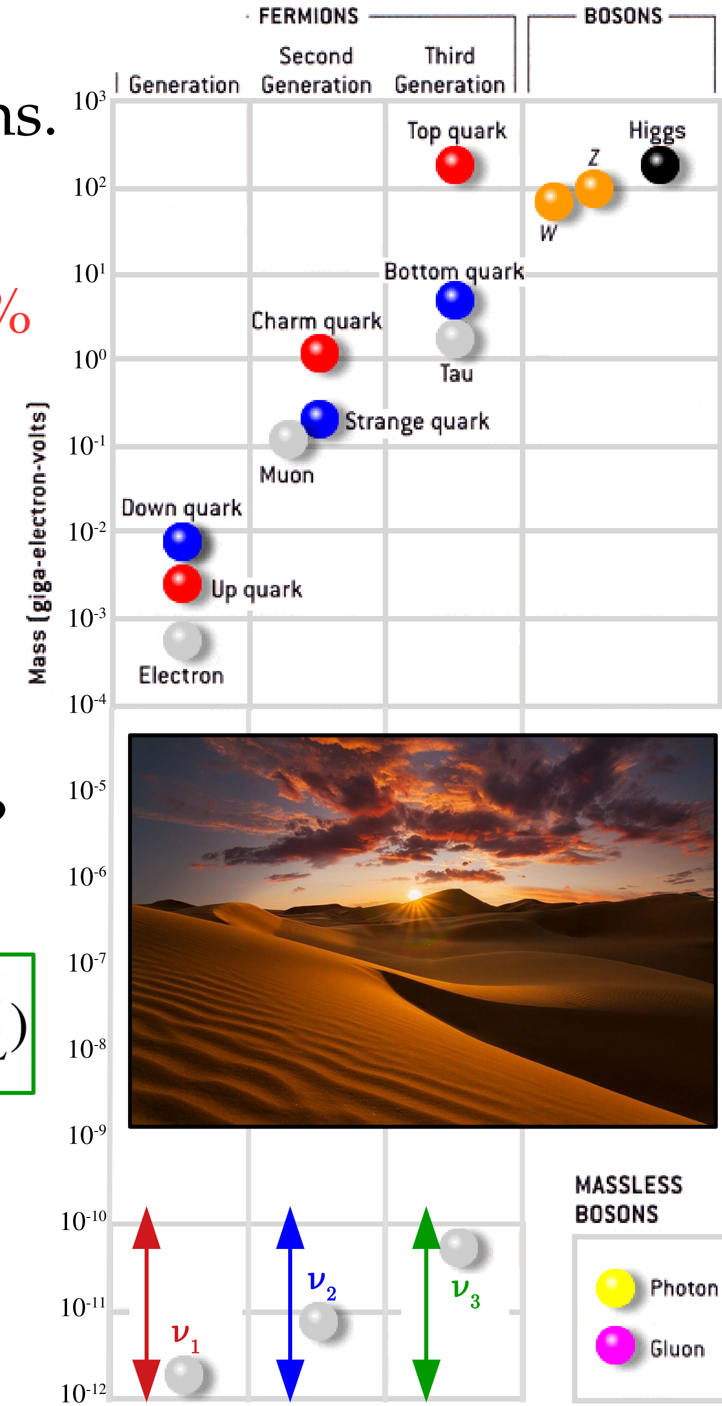
$$L^{D}_{mass} = [\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L]$$

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

3. Neutrino « oscillates » !

→ The 3 neutrino flavours can change to other ones.

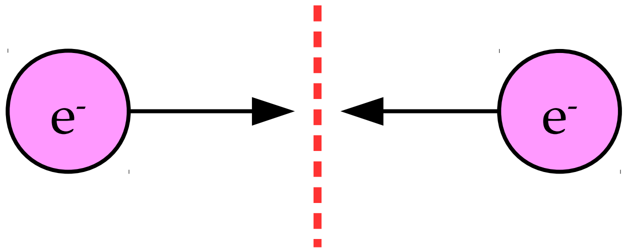




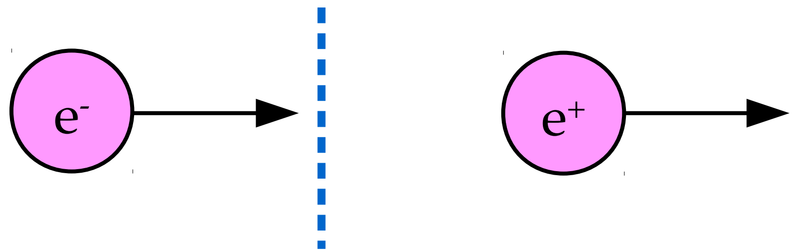
What are the possible CP violating processes ?

- CP symmetry : P = parity, C = charge conjugation

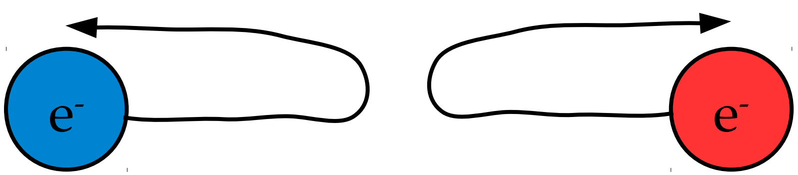
P (Parity) transformation



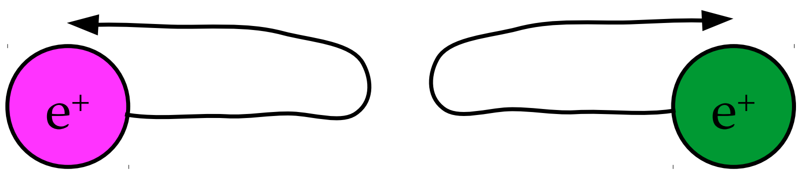
C (Charge conjugation) transformation



- Electrogmagnetic interactions preserves CP symmetry



CP :



Original process = After CP transformation

→ 2 e- : repel each other.

→ 2 e+ : repel similarly to 2 e-

- Strong interaction (in nucleus) also preserves CP symmetry.
  → Not theoretical, experimentally observed.

- Only weak interaction remains among known interactions !

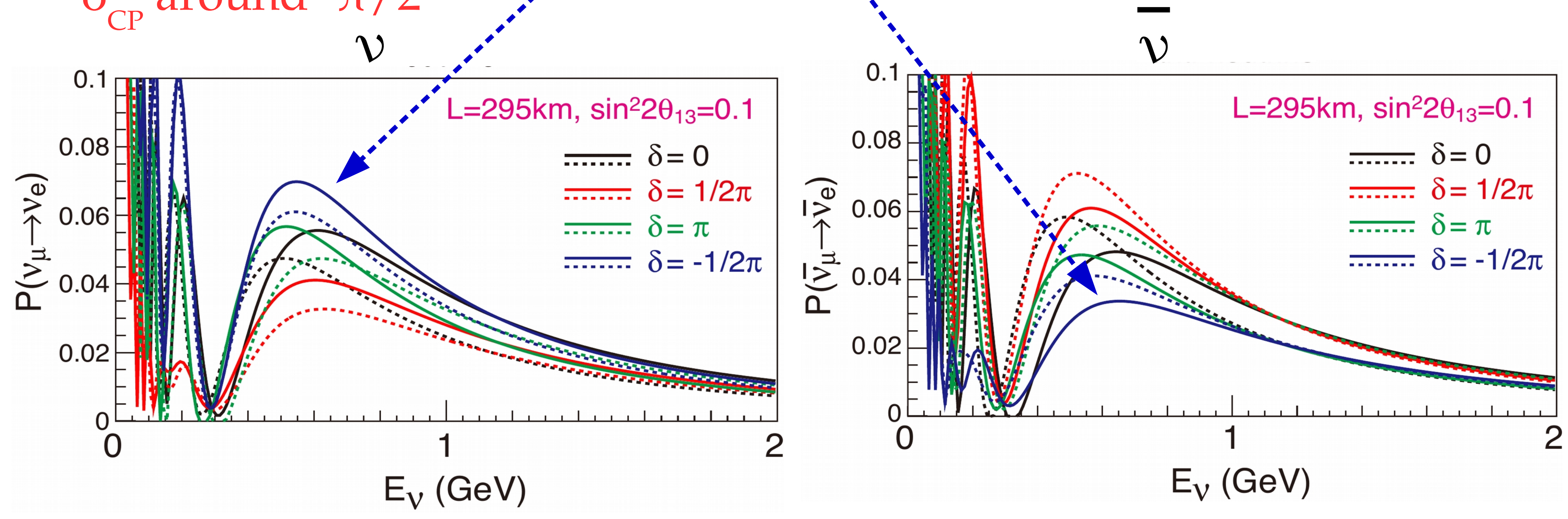
Precise measurement of δ_{CP}

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

sinδ :

- CP-odd : opposite effect for ν / $\bar{\nu}$.
- Derivative ≈ 0 for δ_{CP} ~-π/2

  → Weak sensitivity to δ_{CP} around -π/2



Precise measurement of δ_{CP}

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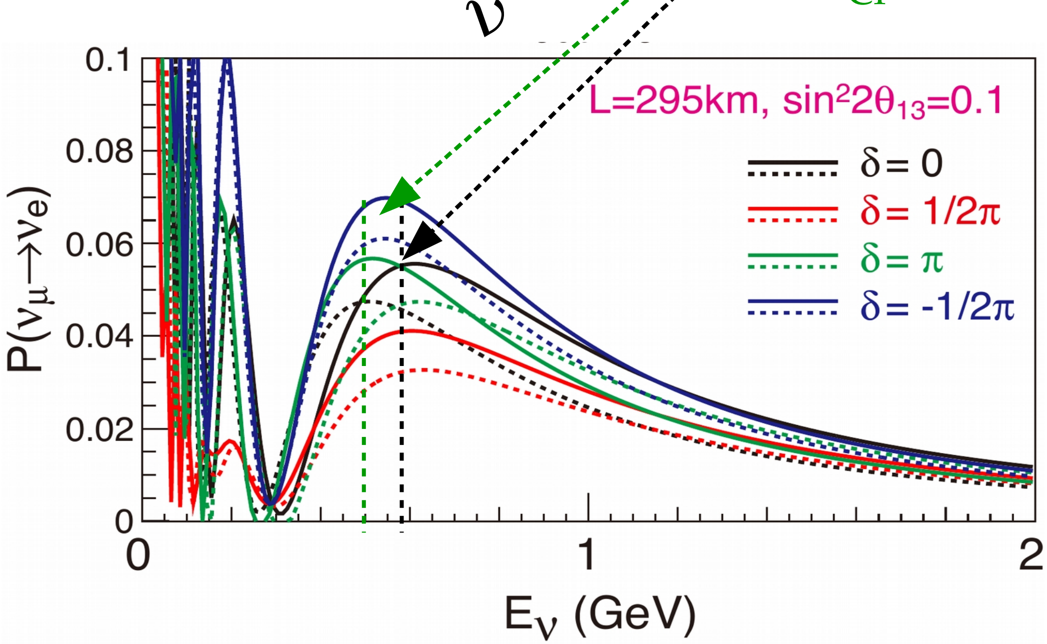
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \quad + \ldots$$

cosδ :

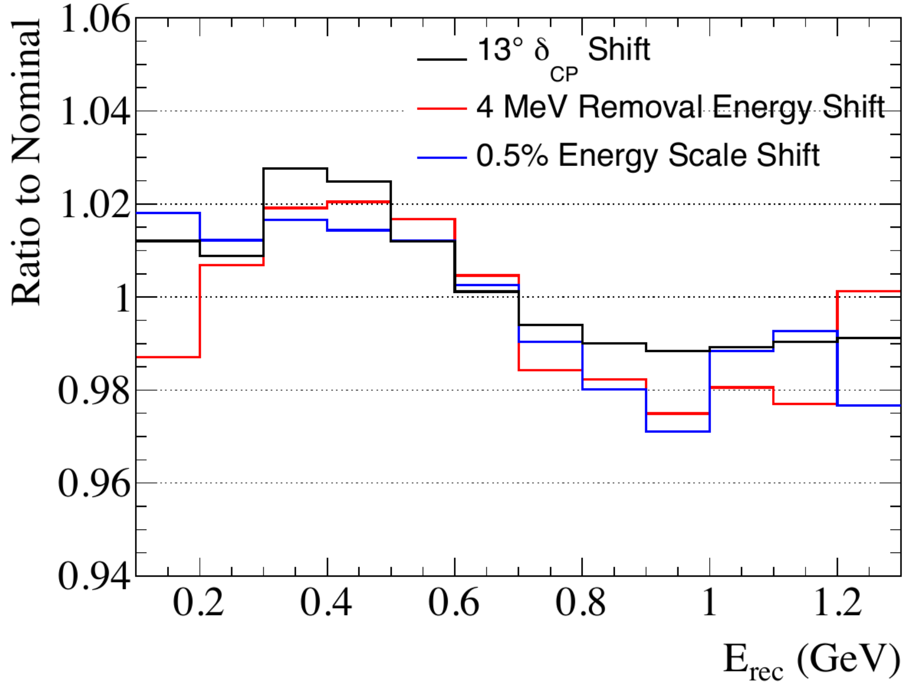
- CP-event : same effect for ν / $\bar{\nu}$.
- Large derivative for δ_{CP} ~-π /2

→ Large sensitivity to δ_{CP} .

→ Ideal term to measure δ_{CP} .



cos δ ≈ E spectrum shift (L fixed).



- Need to step-up in spectrum systematics control

→ New complex of near detectors to reach these accuracies.

Matter/antimatter asymmetry

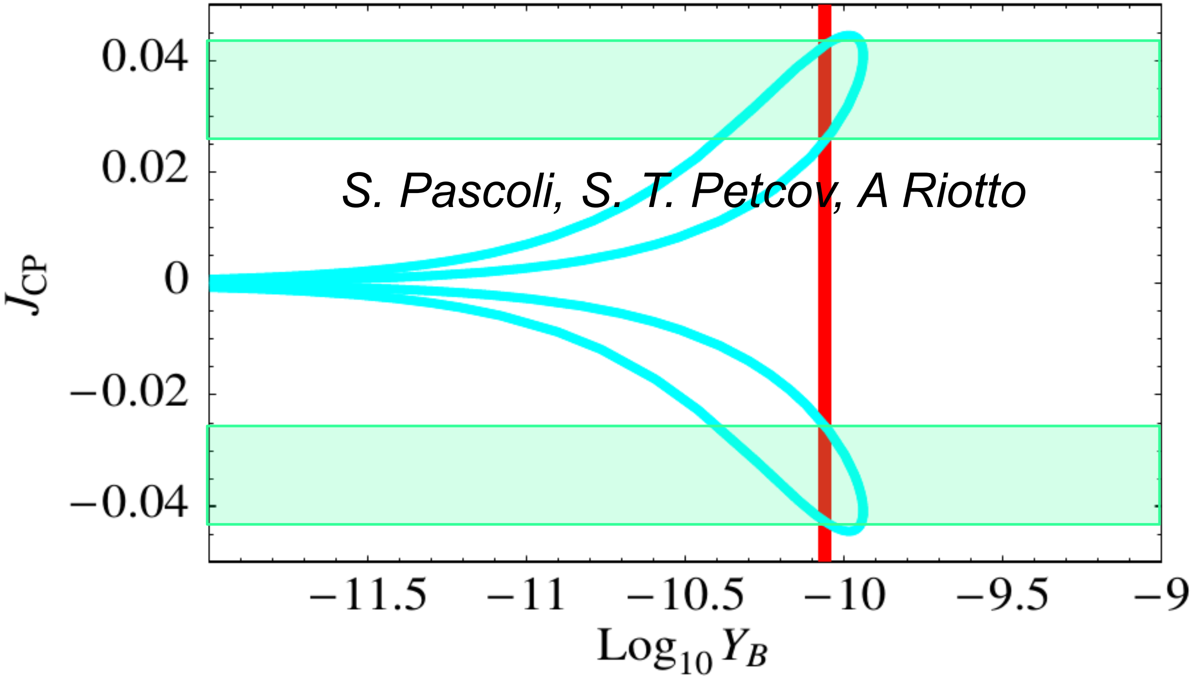
- ν CP violation at low E maybe the key to matter/antimatter asymetry
  → Class of theories directly link low E δ_{CP} to matter/antimat. asymetry.

CP violation at low energy for ν → **Leptogenesis** → Matter/antimatter asymetry

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

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

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



Precision on sin δ_{CP}

↔ Precision on leptogenesis models

Lower limit for leptogenesis :

$|\sin\theta_{13} \sin\delta_{CP}| \geq 0.11$

→ $|\sin\delta| \geq 0.78$

Flavour symmetries

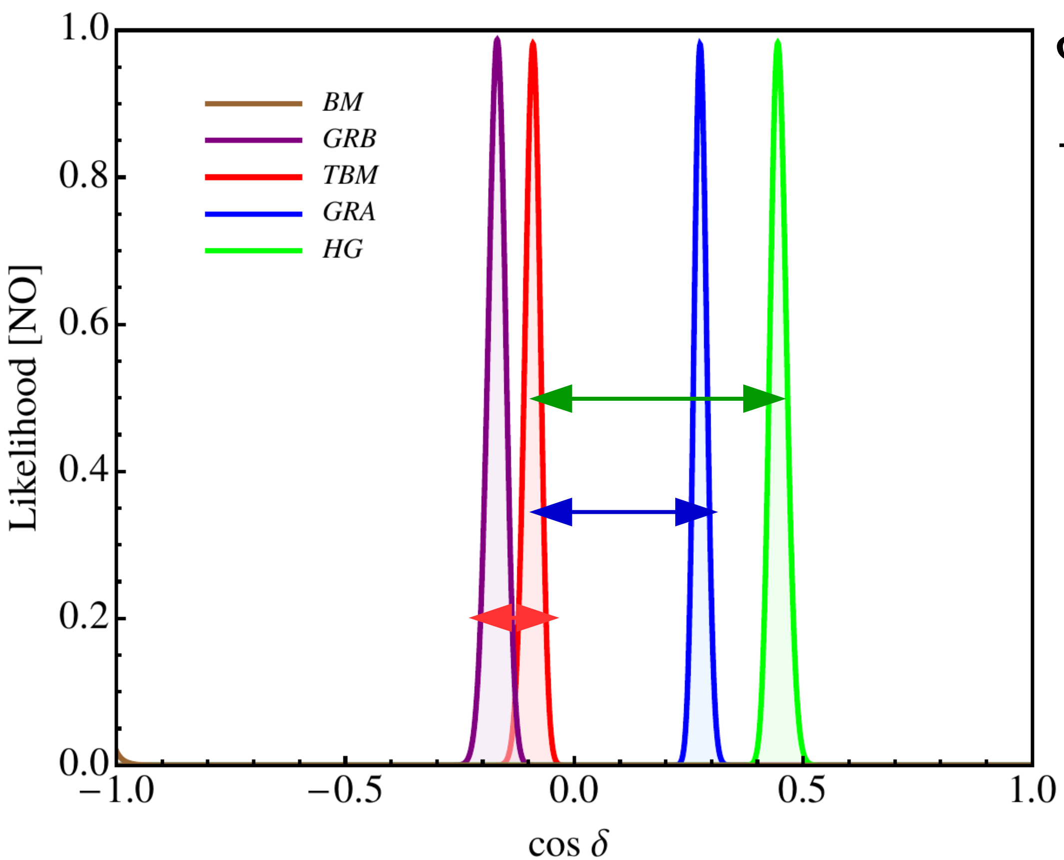
- Models of lepton flavour symetries could be also tested

$e \leftrightarrow \mu \leftrightarrow \tau$

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

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

Lepton generation symetric models → Links PMNS parameters



δ_{CP} = less well-known parameter

→ Limits the model constraints.

Model separation requires :

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

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

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

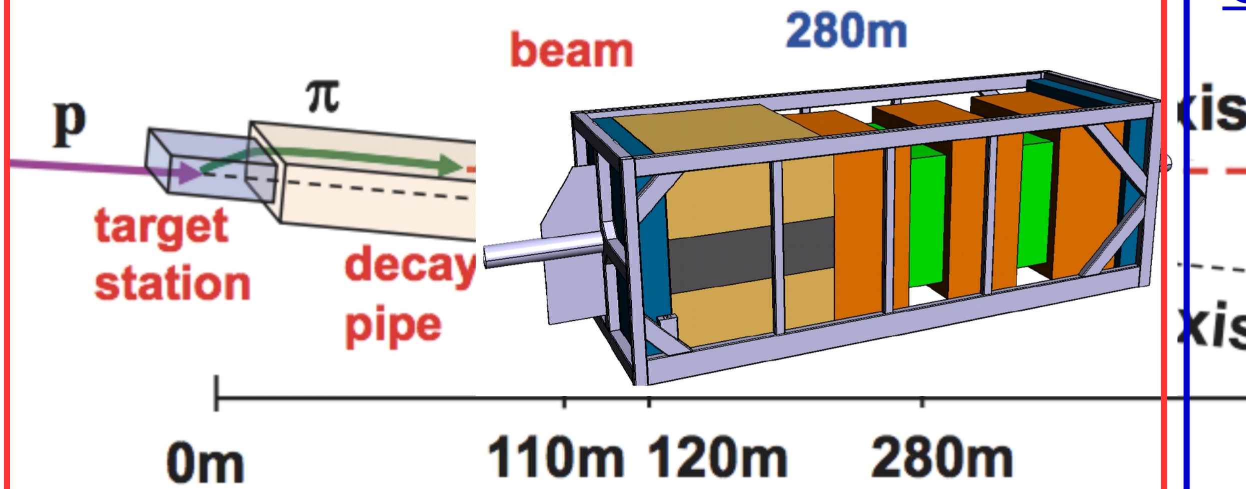
→ Precision of our experiments ?

Updated systematic uncertainties

- 2 very complementary near detectors :

New

Upgraded ND280



Ideal to measure cross-section

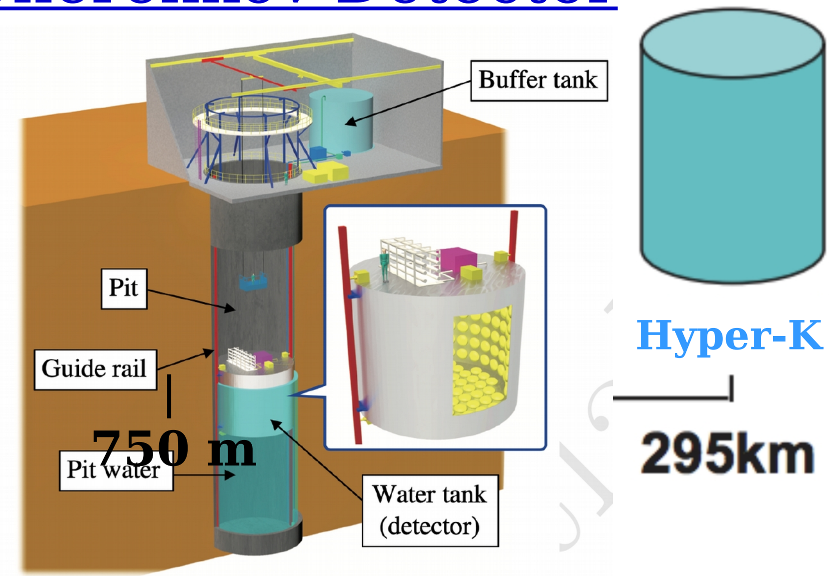
- Very low E-threshold, 2 π angular acceptance

→ CC0π, CC1π, CCNπ separation.

→ Measure of hadronic effects.

- Here from 2023→ Great control from day 1 of HK.

Intermediate Water Cherenkov Detector



Target & acceptance ~ far detector.

- Cancel detector uncertainties & precise measurement of ν_e / ν_μ
- Here from 2028.
- Contributions still open

→ Great opportunity to join HK & synergy with far detector.