Hyper-Kamiokande

Physics & status of Hyper-Kamiokande

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on behalf of the Hyper-Kamiokande collaboration

cnrs dépasser les frontières
IN2P3 Les deux infinis

LLR

ILANCE
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l'X ÉCOLE POLYTECHNIQUE
IP PARIS

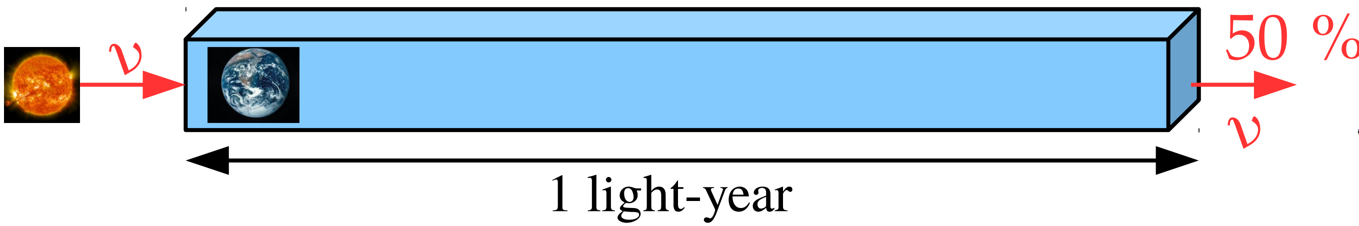
Conference of the 2 infinities, Kyoto University, 2023/03/27

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?

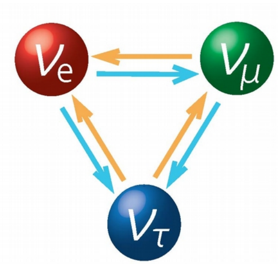
Dirac ? or/and Majorana ?

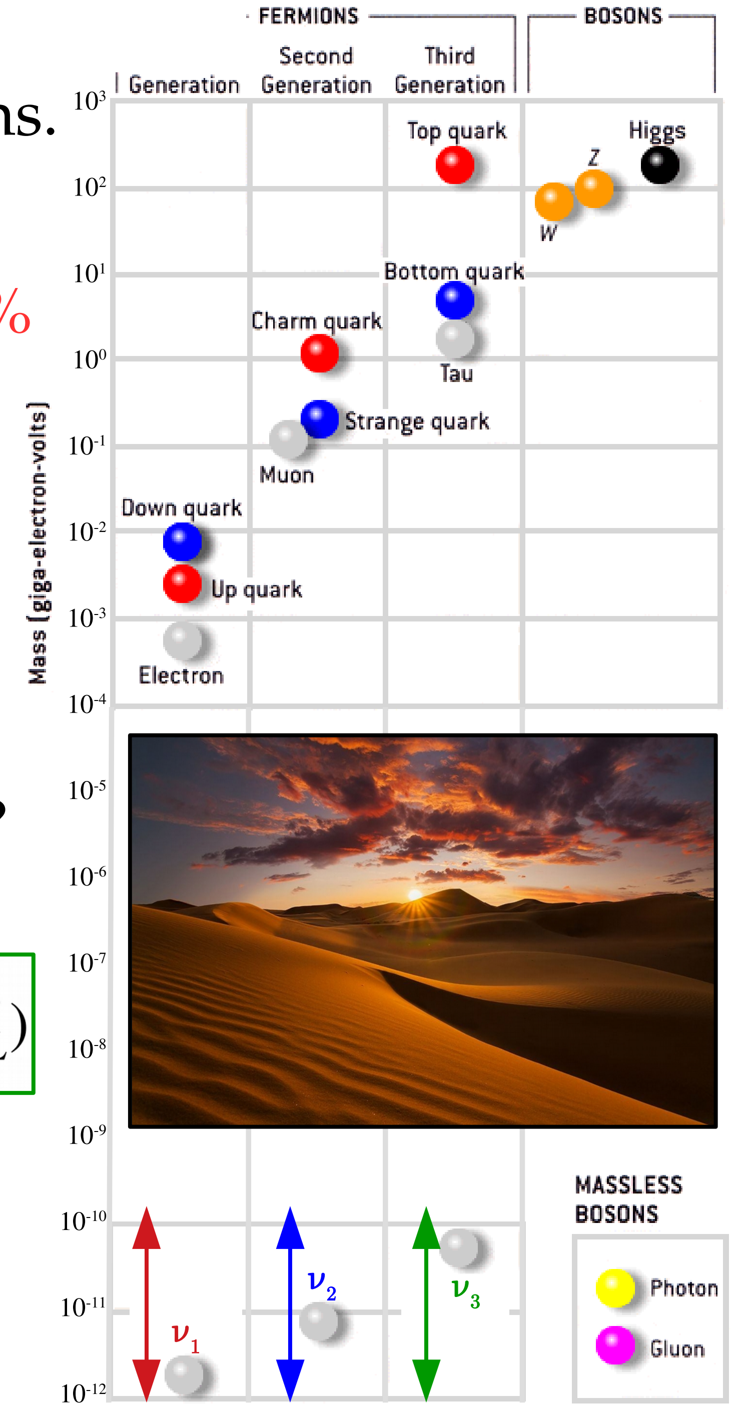
$$L^{D}_{mass} = [\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L]$$

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

3. Neutrino « oscillates » !

→ The 3 neutrino flavours can change to other ones.

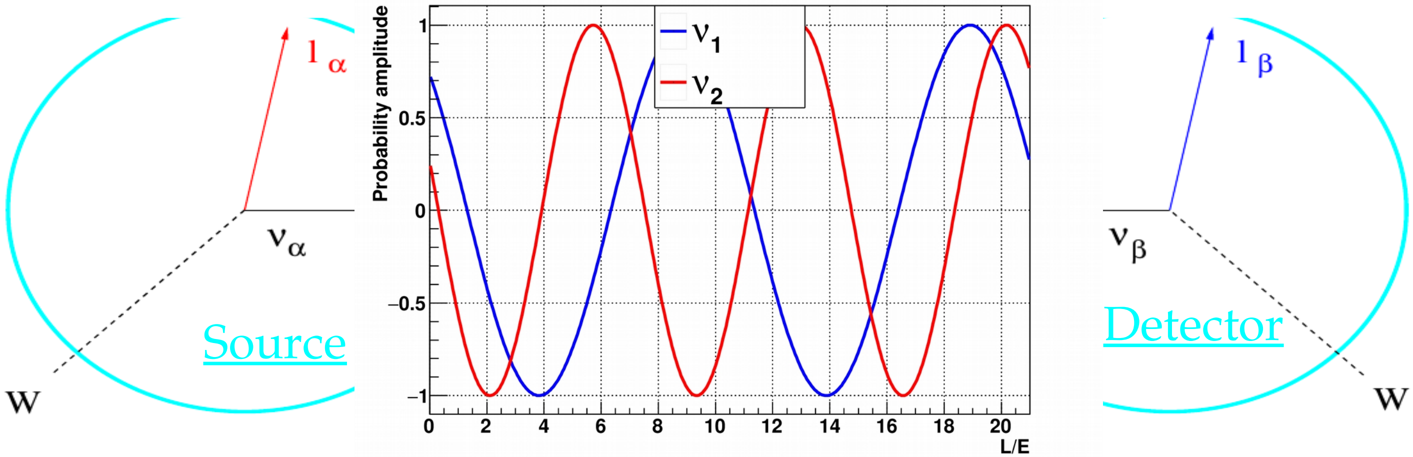




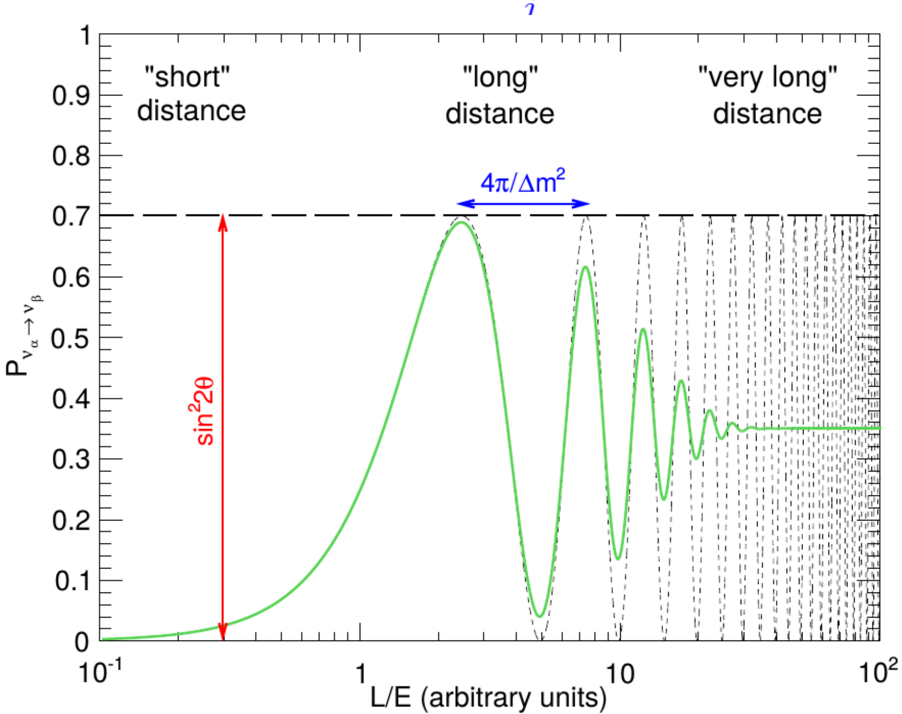
Neutrino oscillation in 2 flavour case

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

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



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



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.

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.

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

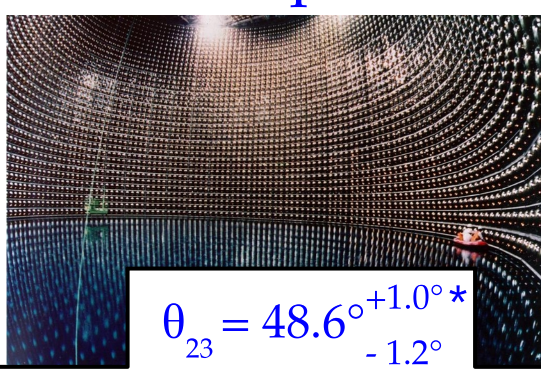
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & e^{-i\delta} s_{13} \\ & 1 & \\ -e^{i\delta} s_{13} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} &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

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}

« Atmospheric »

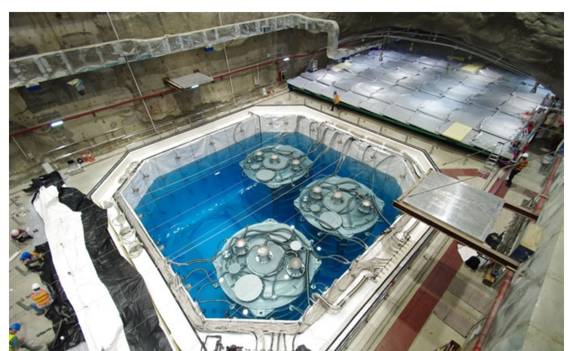


*3σ CL: [41.1° - 51.3°]

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

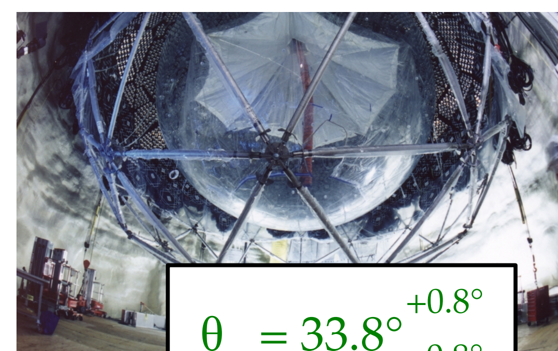
$|\Delta m^2_{32}| = (245.4^{+2.9}_{-3.1}) \times 10^{-5}$ eV²

« 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

Open issues in neutrino oscillations

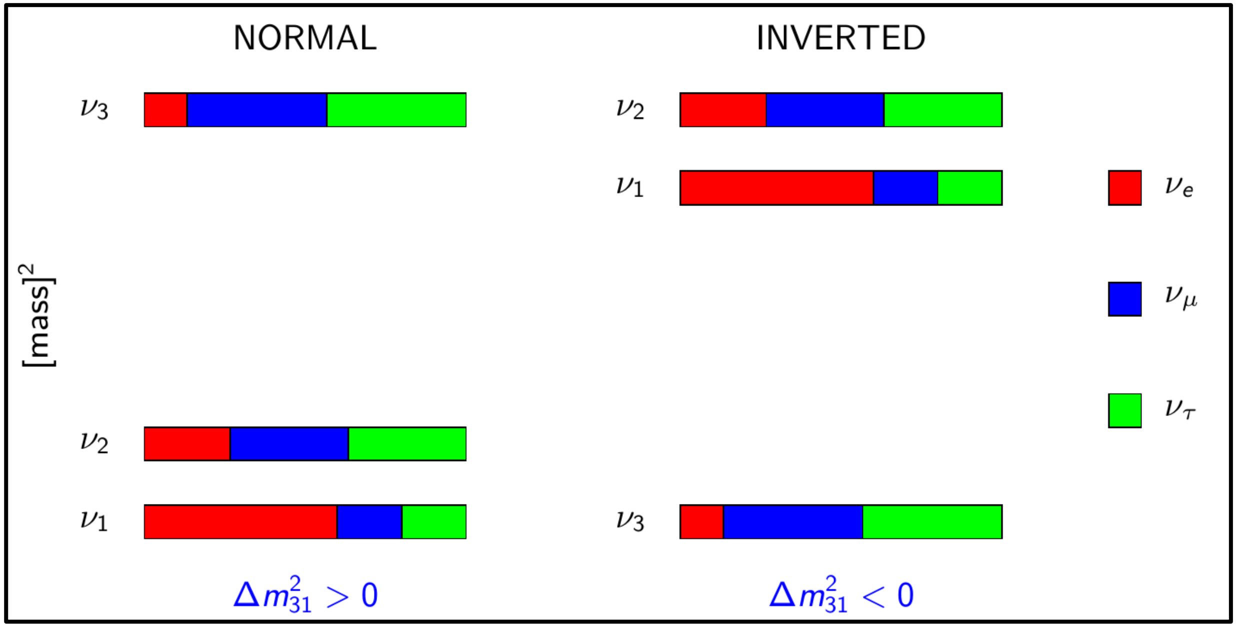
- What is ν mass ordering (MO): affect nucleosynthesis in Supernovae…

→ 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.

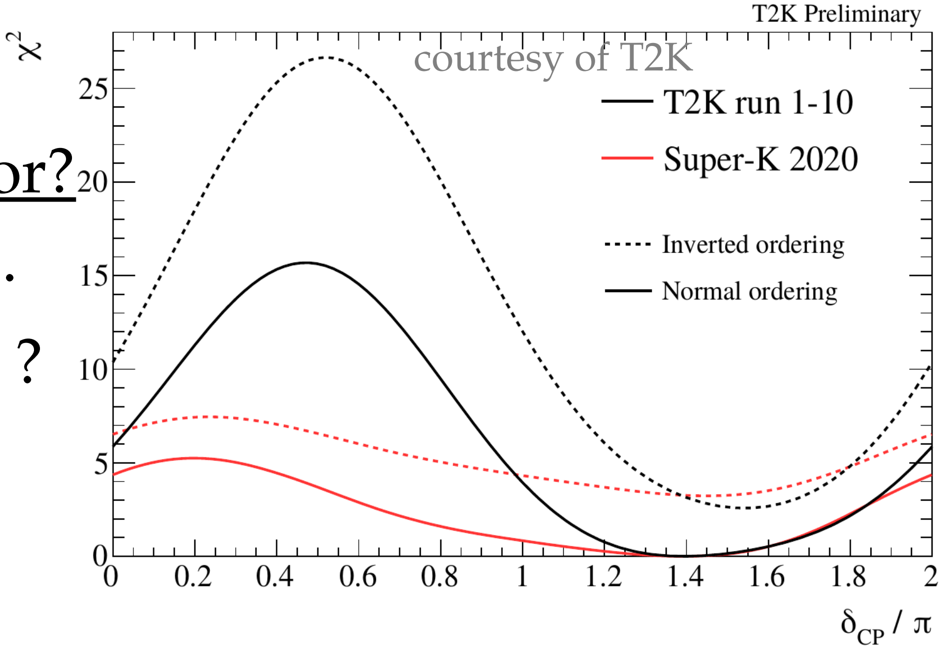


- Is CP-symmetry violated in lepton sector?

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

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

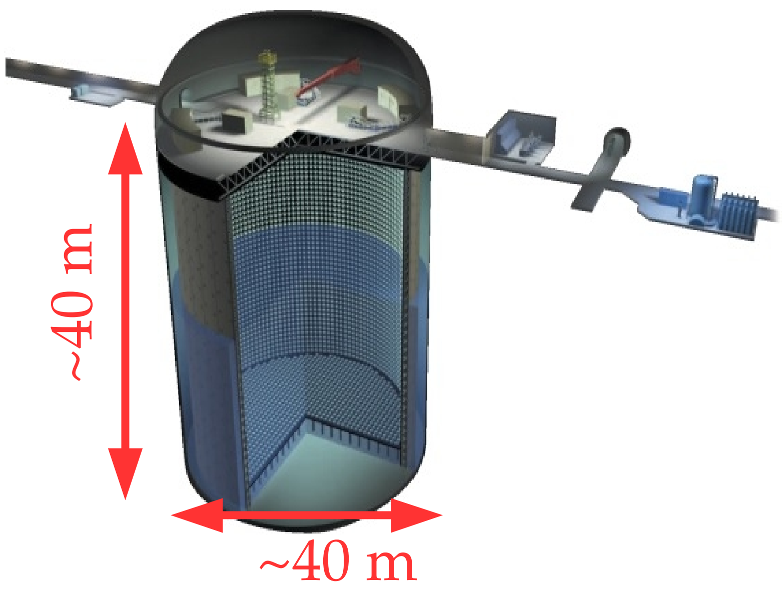
→ Could be very 1st hints towards matter-antimatter asymmetry !



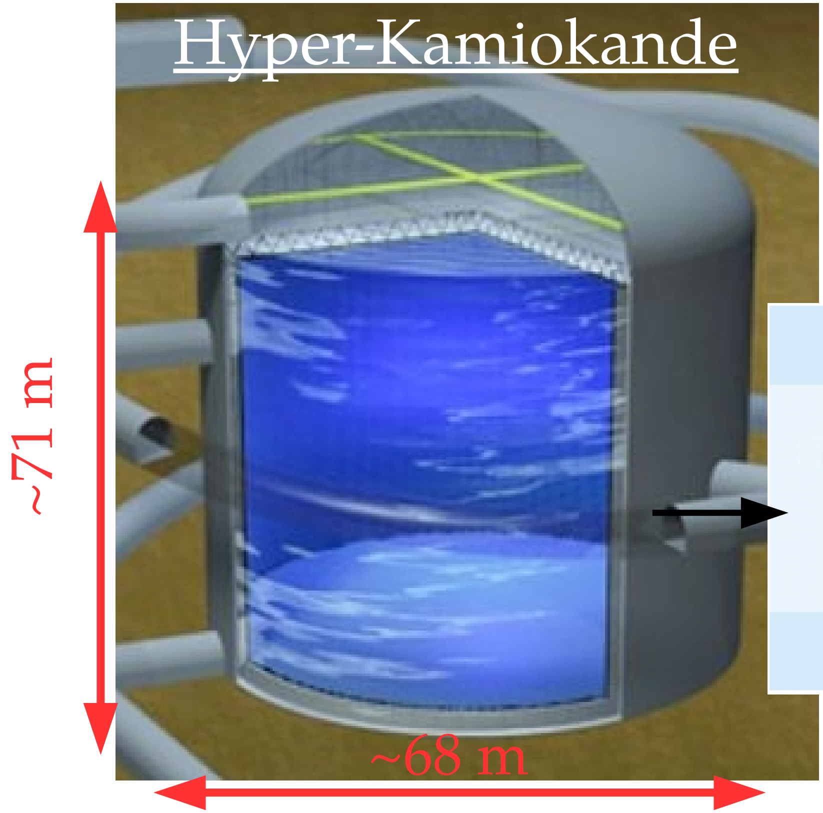
What is Hyper-K ?

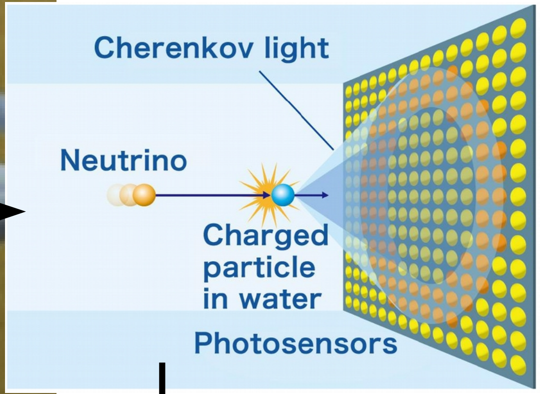
- Next generation of neutrino observatory in Japan→ construction 2020-27
  → A 260 kton water Cherenkov detector → Fiducial Mass ~ 8 x SK.

Super-Kamiokande

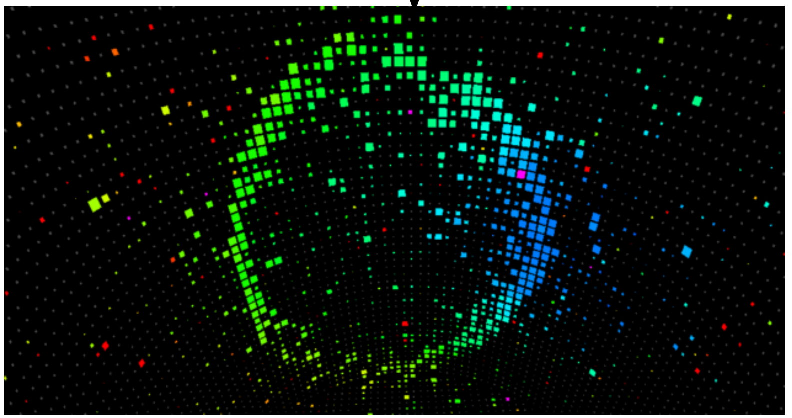


Hyper-Kamiokande

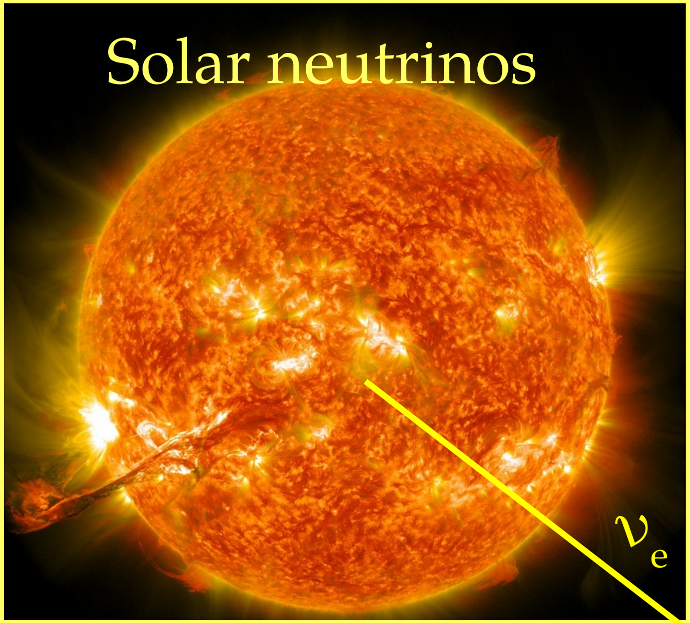




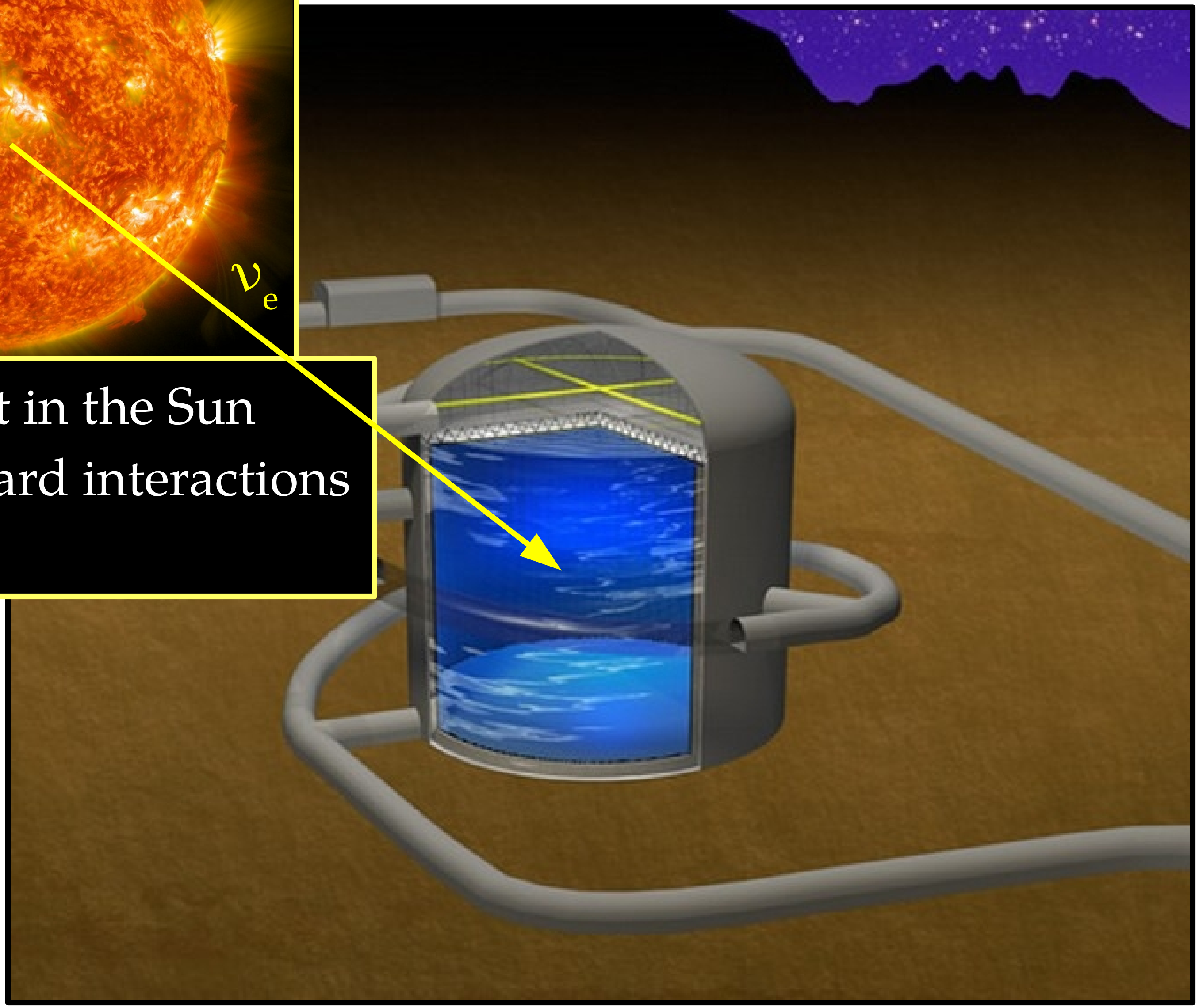
	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% (×2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton



Physics case



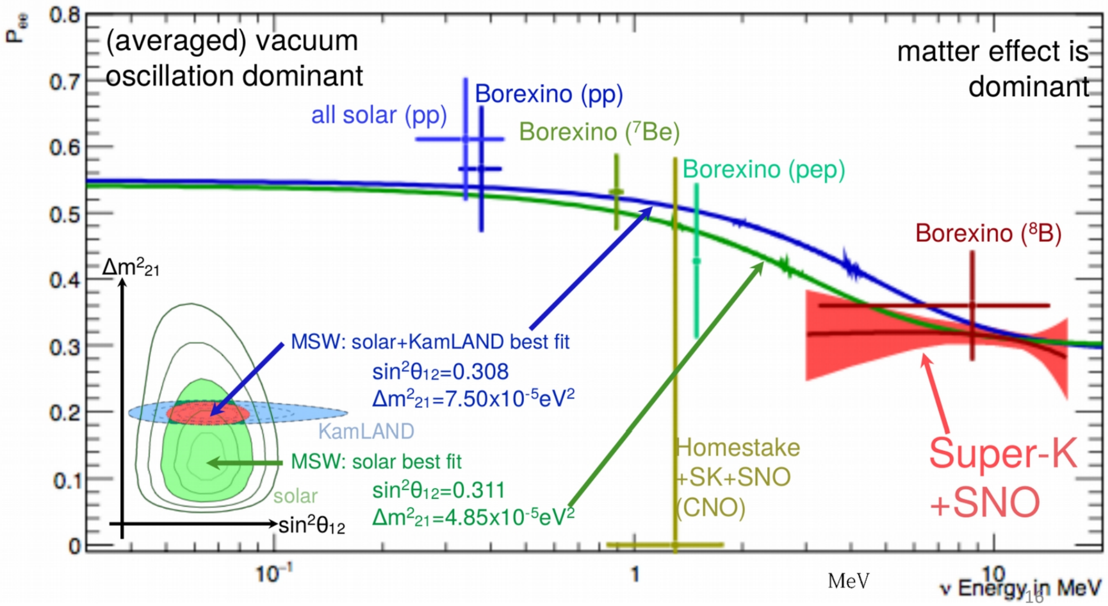
- MSW effect in the Sun
- Non-standard interactions in the Sun.



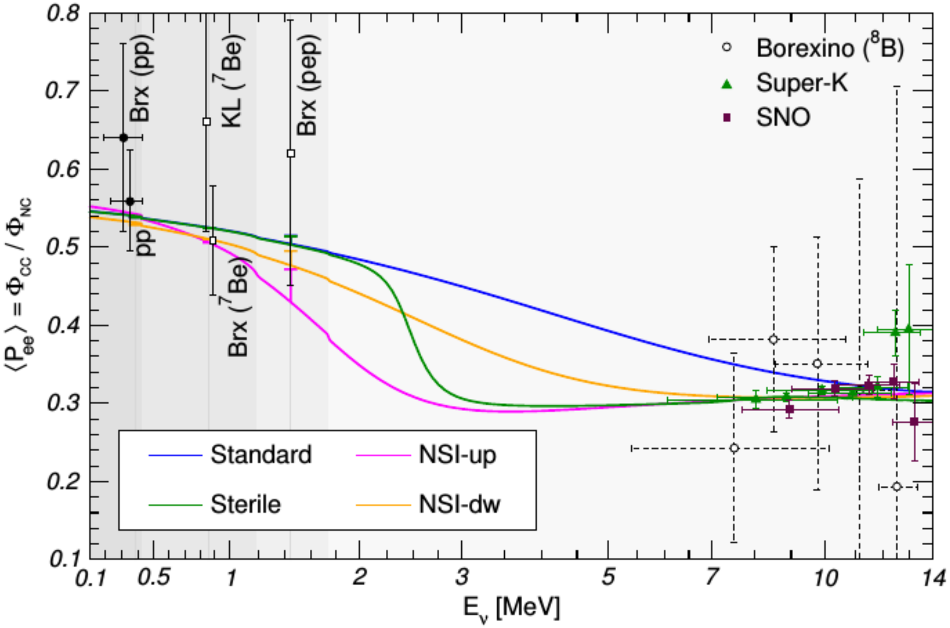
Solar neutrinos : upturn

- Probe solar ν : SK/SNO found a high matter effect in the Sun
  ↔ Solar upturn shifted to lower energies

[Ikeda M., SK, Neutrino 2018]



[arXiv:1507.0587]

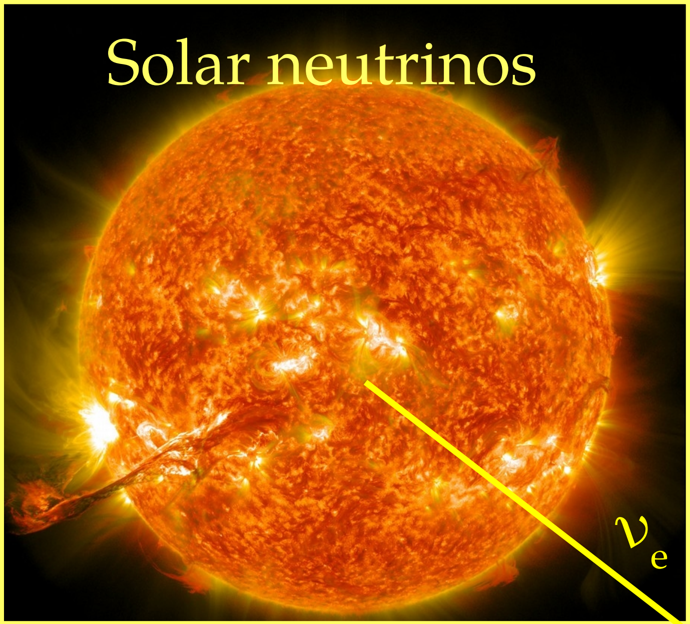


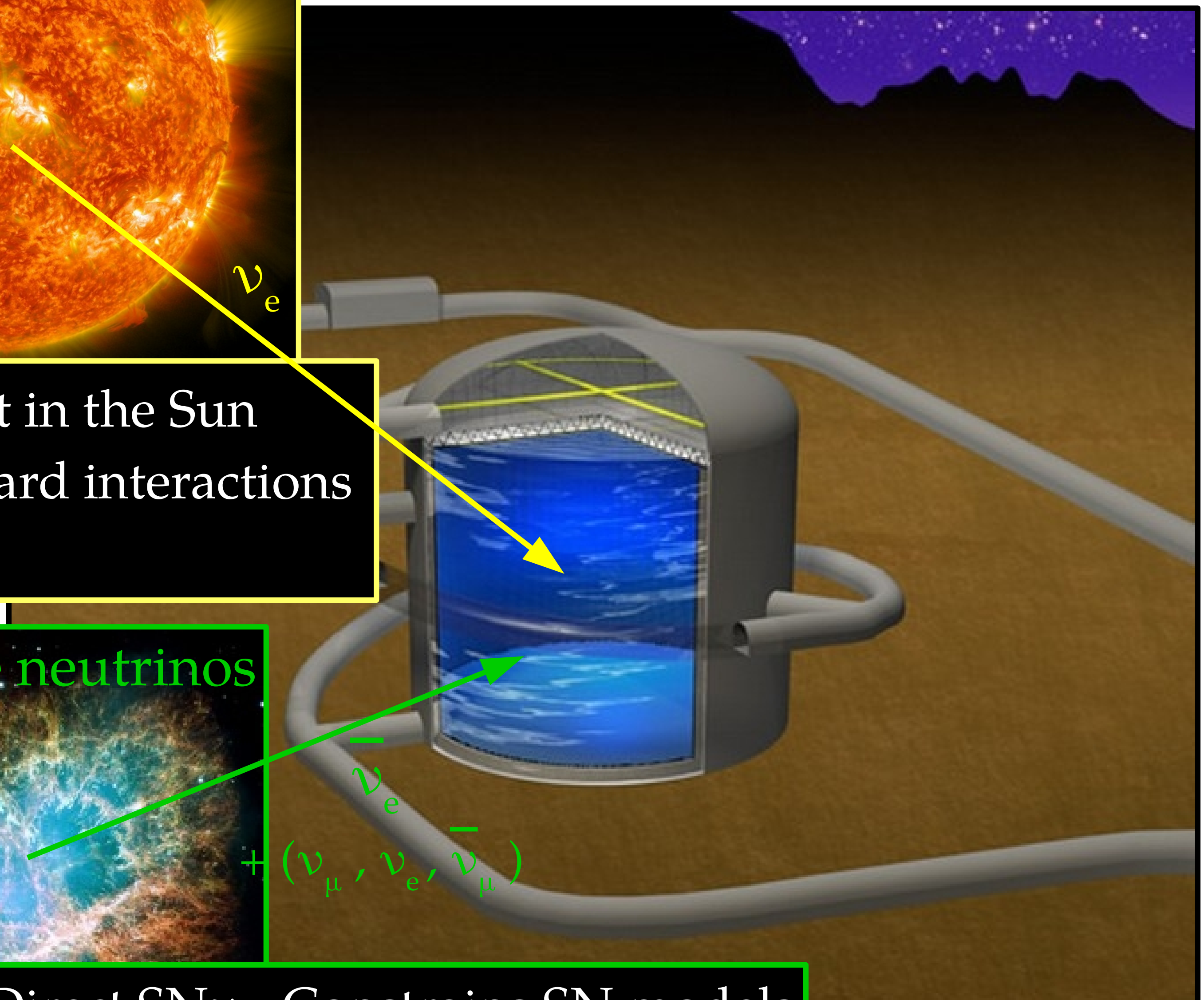
- SK deviates from standard upturn scenario > 2σ . [Moriyama S., SK, Neutrino 2016]

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

Physics case

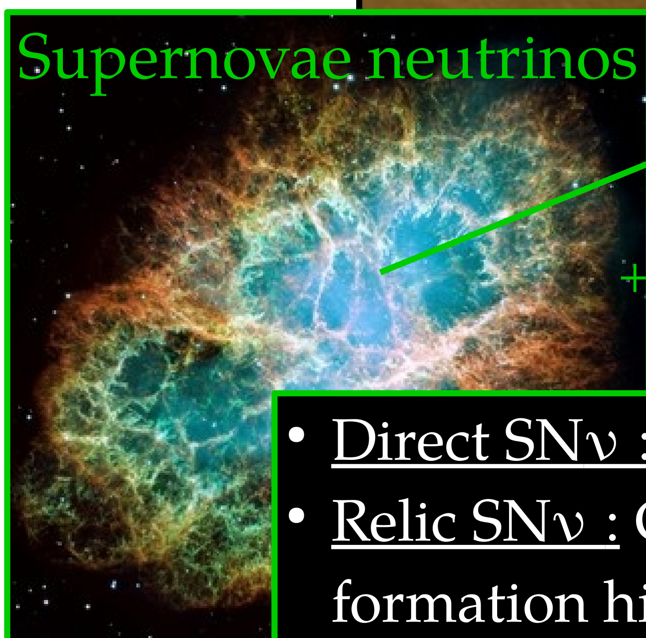
Solar neutrinos





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

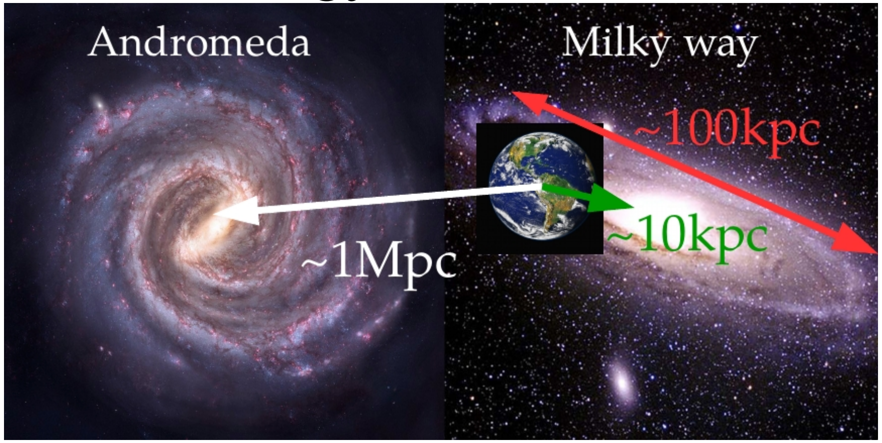
Supernovae neutrinos



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

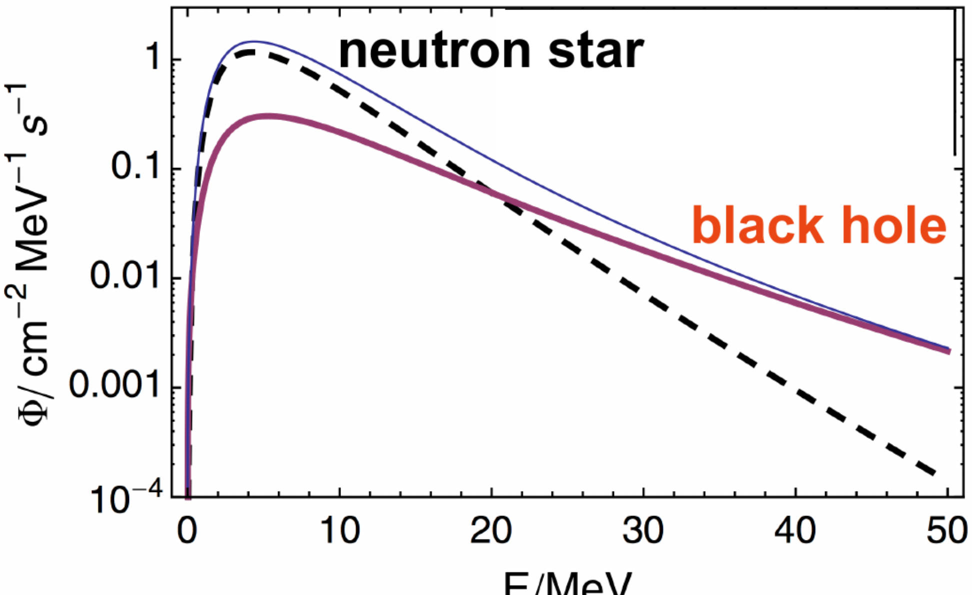
Supernovae neutrinos

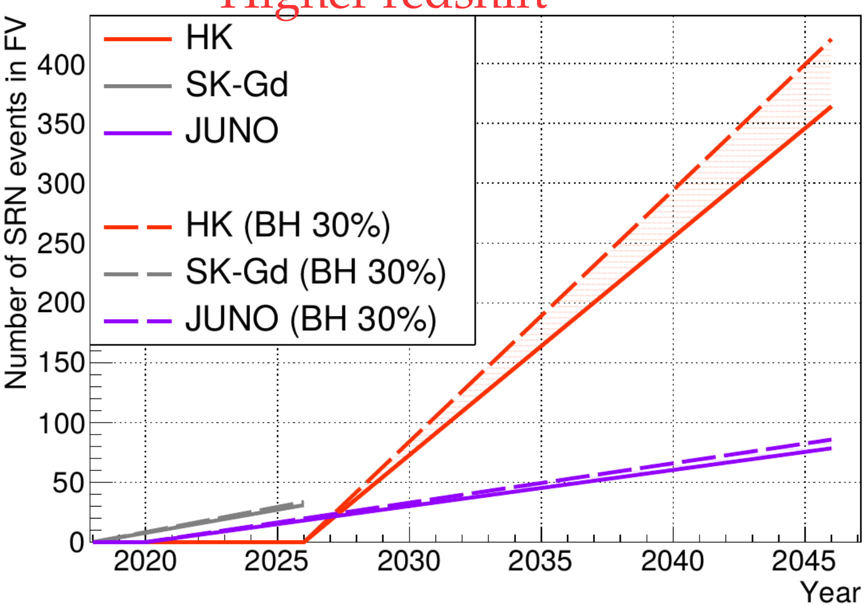
- Unique probe for supernovae ν : 99 % of SN energy → ν.
  - But direct ν detection very rare.
  - HK also sensitive to extra-galactic SNν from Andromeda !



- 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

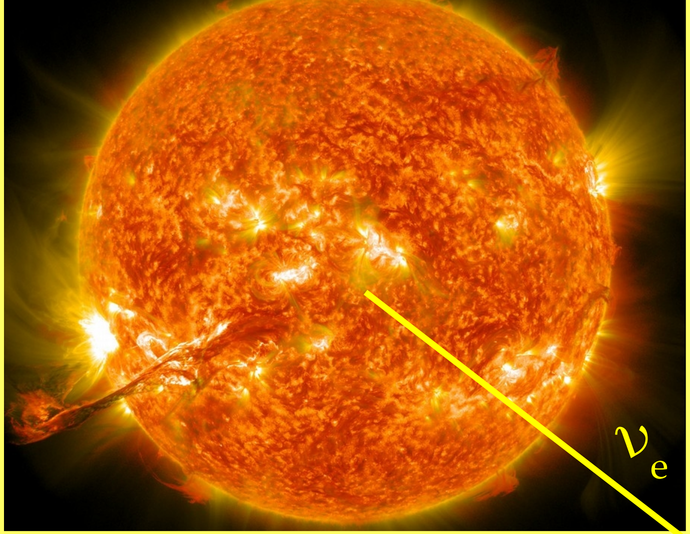
Higher redshift





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

Physics case

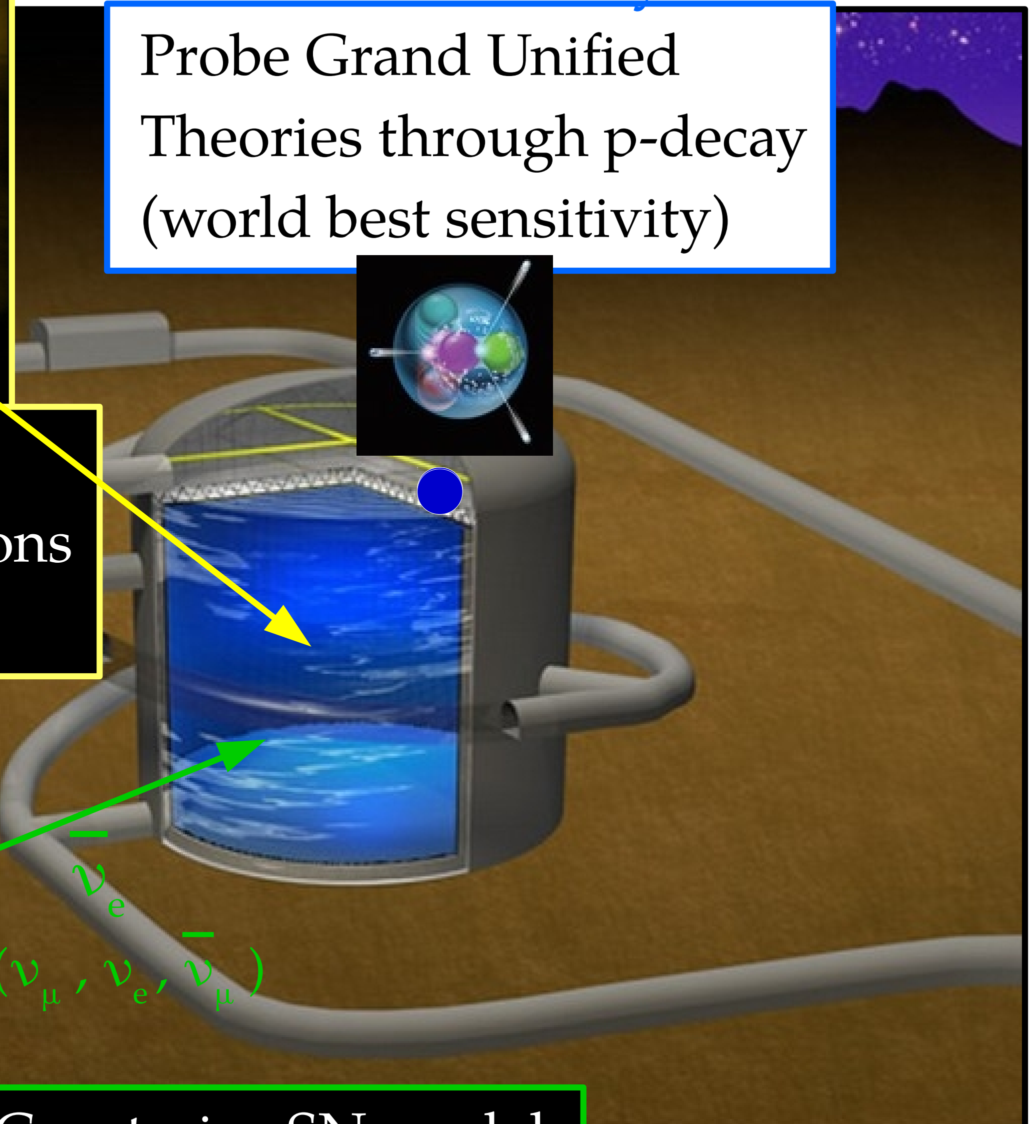


Solar neutrinos

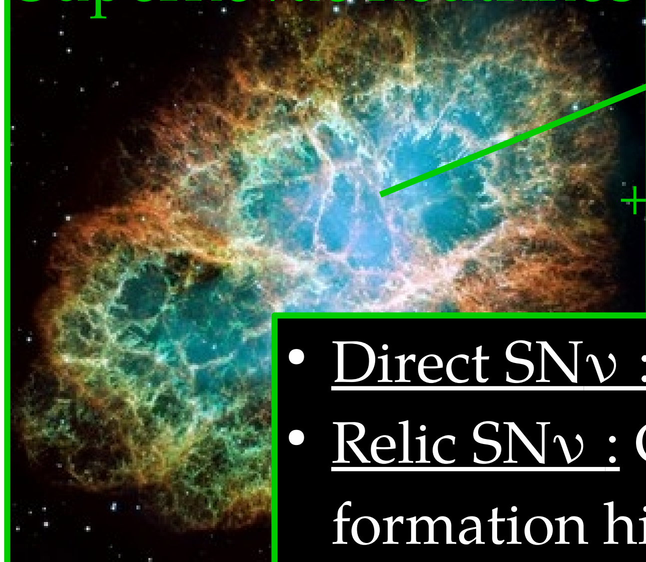
- MSW effect in the Sun
- Non-standard interactions in the Sun.

Proton decay

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



Supernovae neutrinos

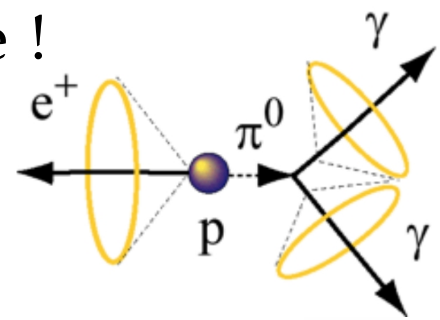


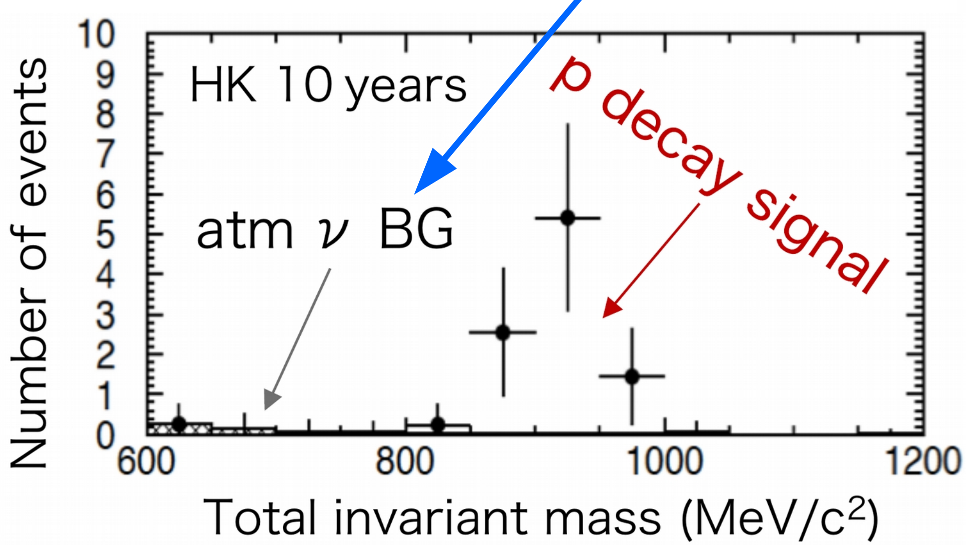
- Direct SNν : Constrains SN models.
- Relic SNν : Constrains cosmic star formation history

GUT and proton decay

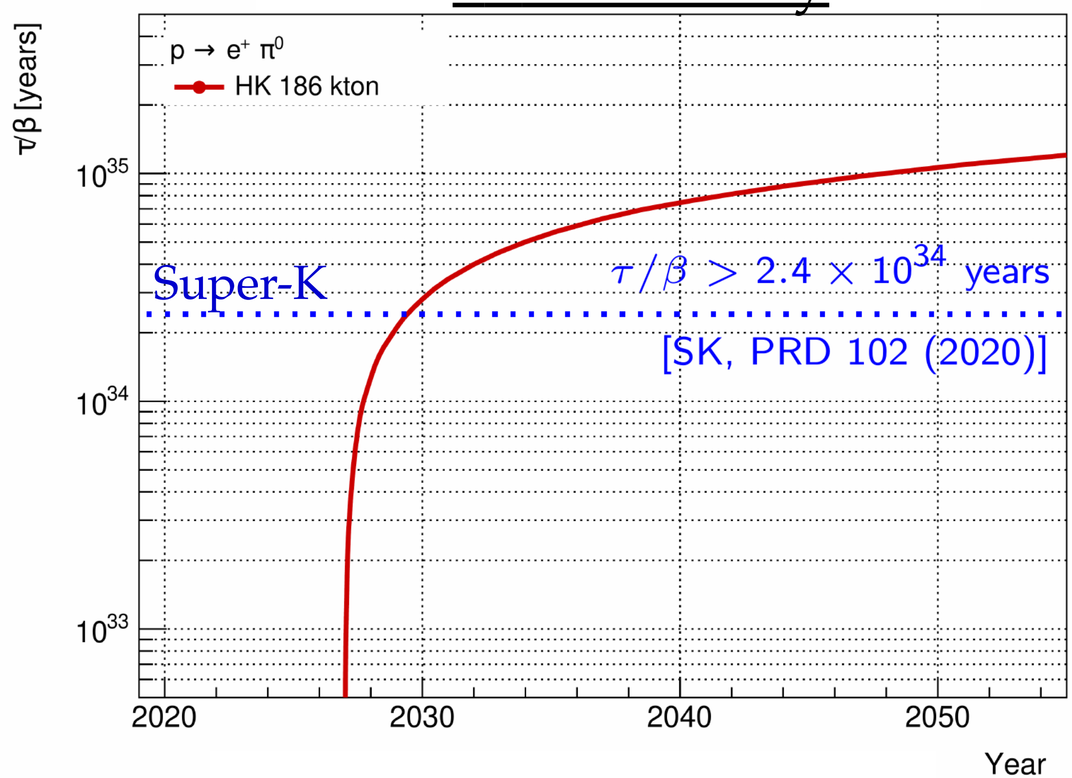
- Probe Grand Unified Theories at a new scale through proton decay.

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





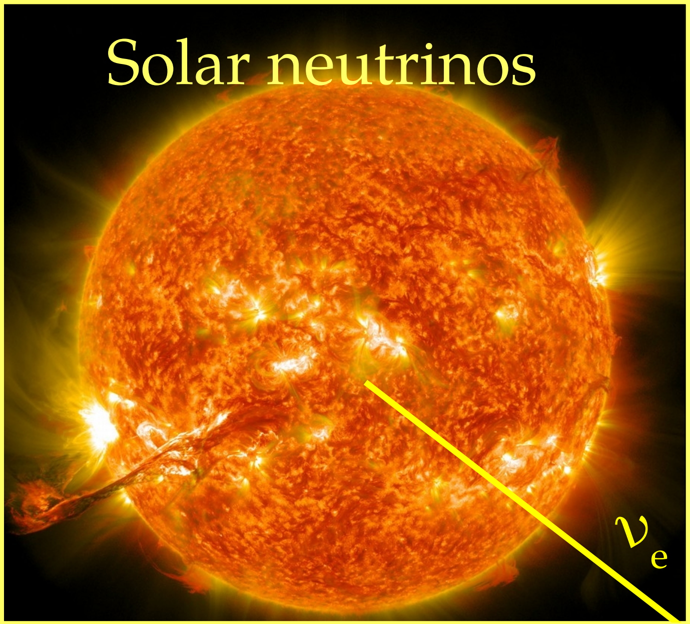
3σ sensitivity



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

Physics case

Solar neutrinos



- MSW effect in the Sun
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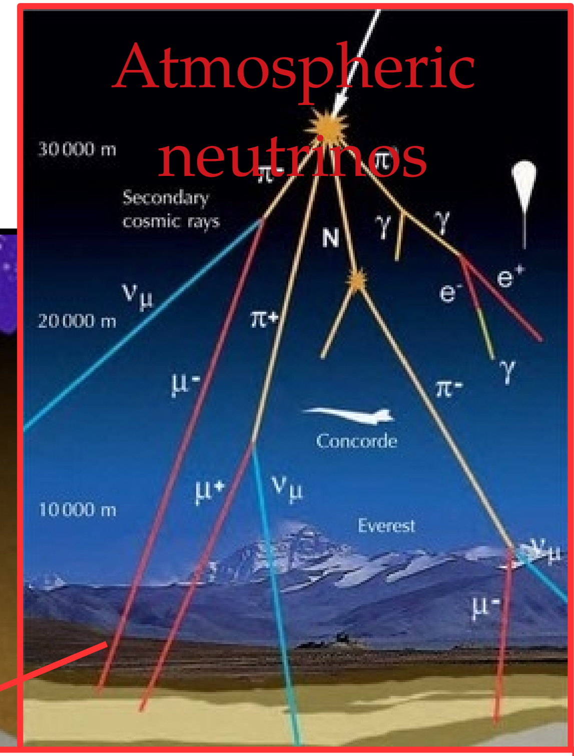
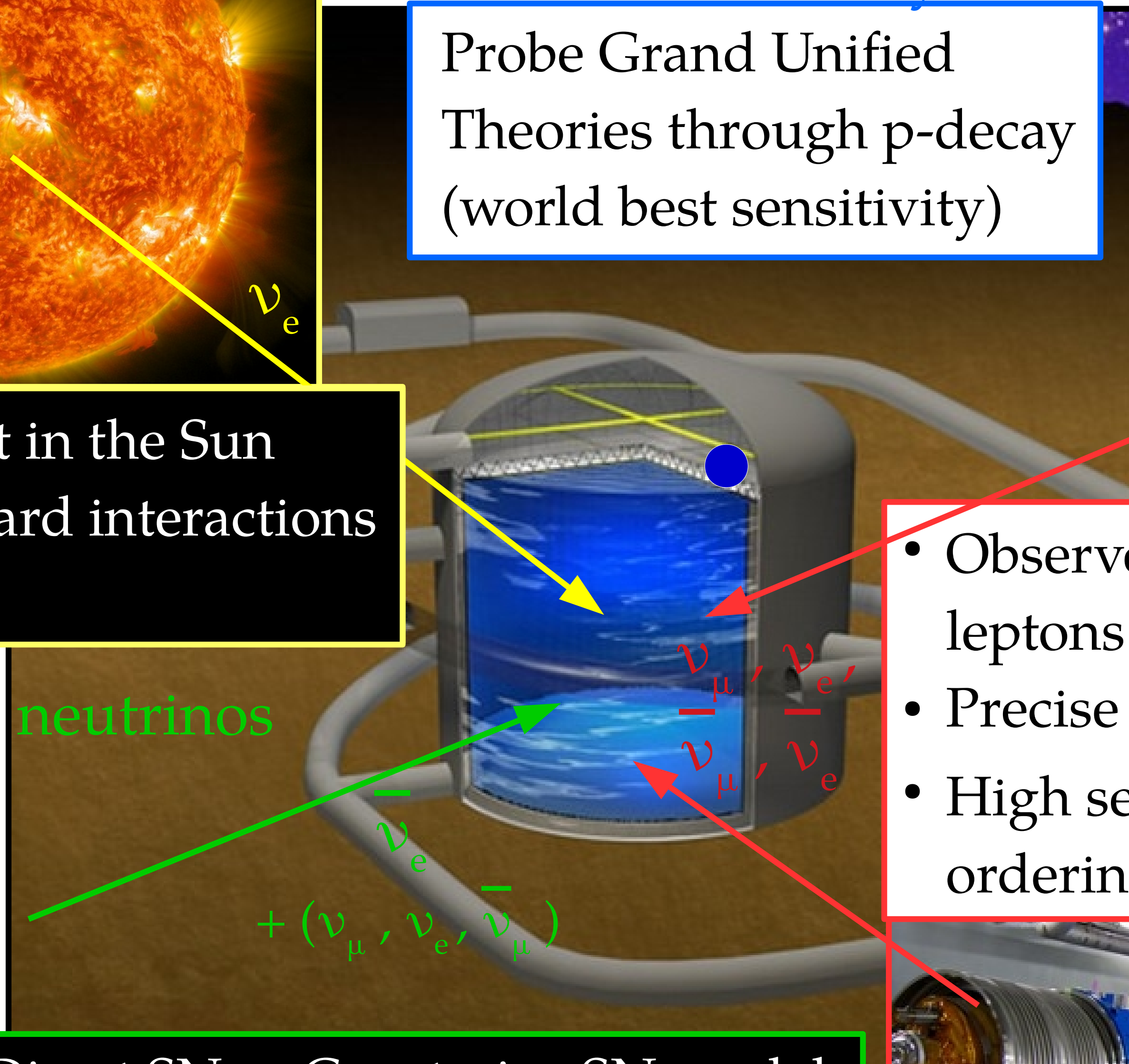
Proton decay

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

Atmospheric neutrinos





Supernovae neutrinos

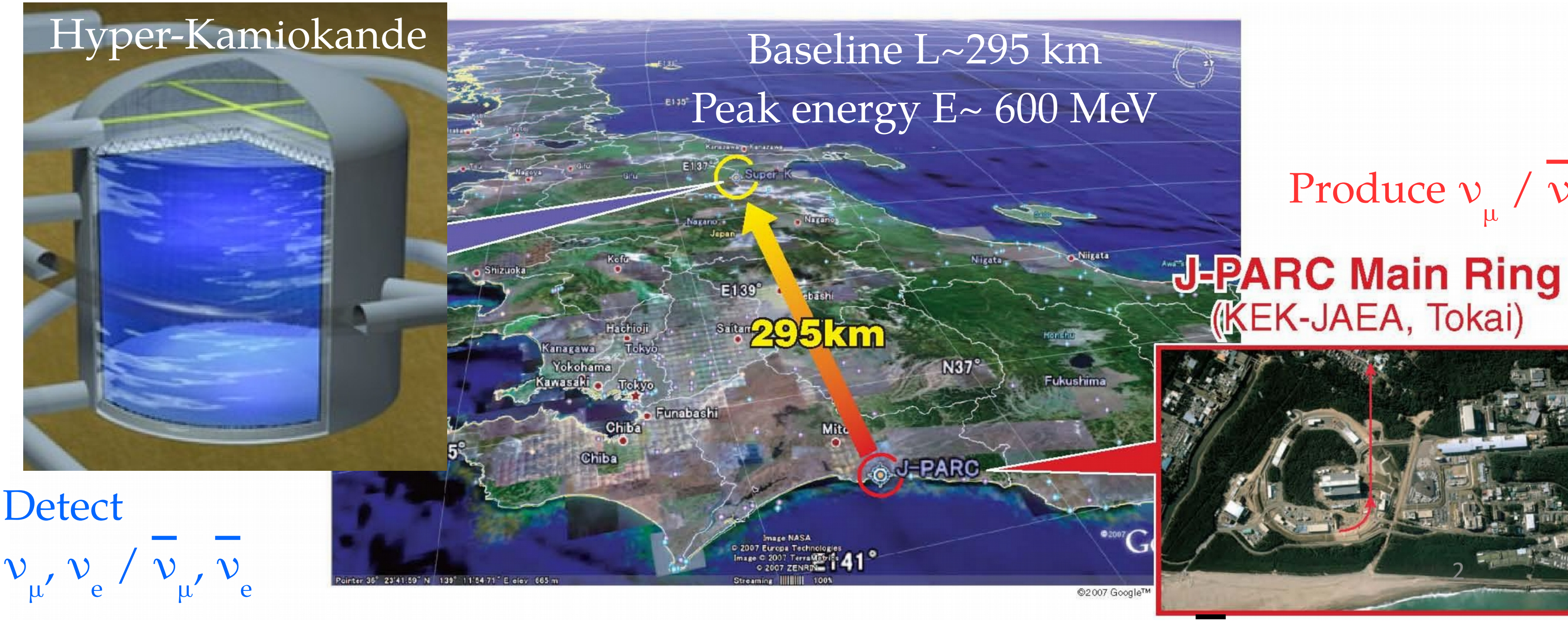
- Observe CP violation for leptons at 5σ
- Precise measurement of δ_{CP} .
- High sensitivity to ν mass ordering.

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

JPARC accelerator neutrinos

Focus on CP violation

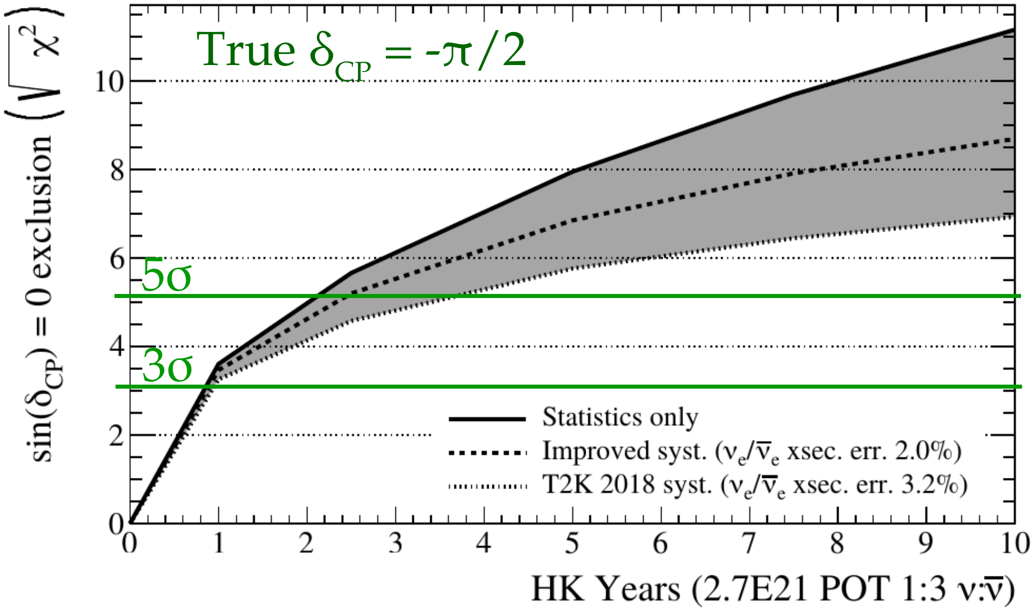
- CP violation search essentially based on accelerator ν : T2HK

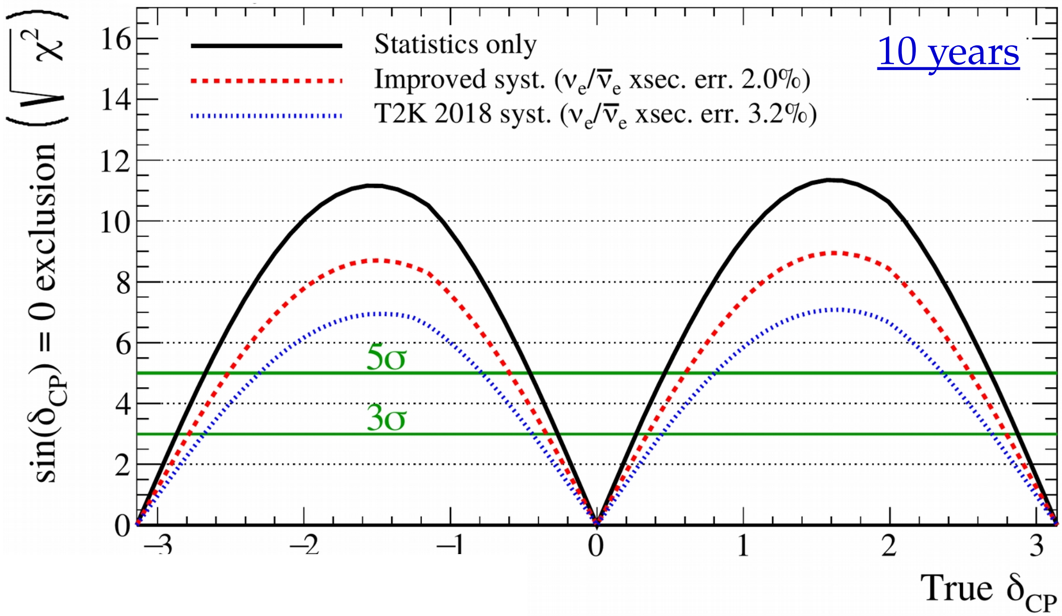


- ν_e appearance in a ν_μ beam and ν_μ disappearance & $\bar{\nu}$ equivalents.
- Compare $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$: ideal probe to CP-violation !
- Use T2K beamline : $\Longrightarrow$ Quick start ! Which relies on 2 milestones.
  1. ↓ time to accumulate 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).





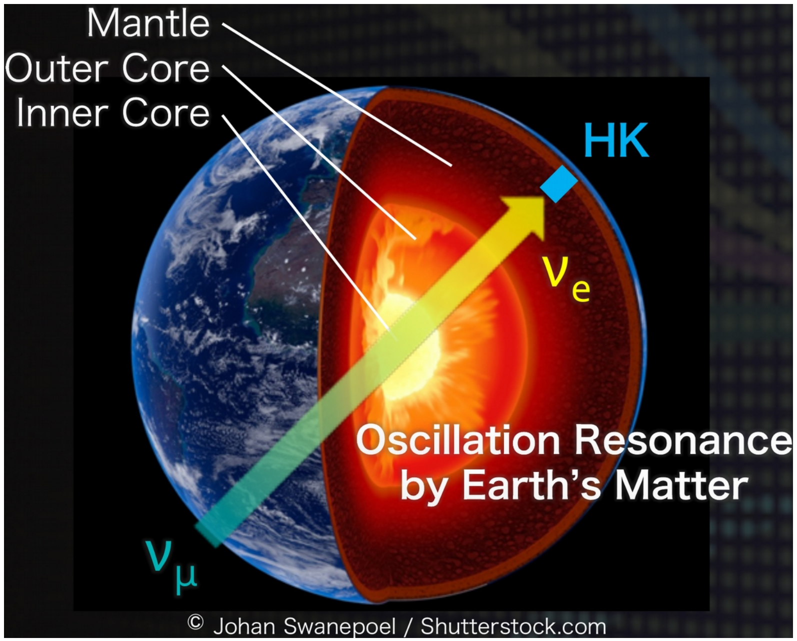
- δ_{CP} = -π/2: 5σ after 2-3 years of data taking : known in 2029-2030 !
  → Independent from ↓ systematic uncertainties.

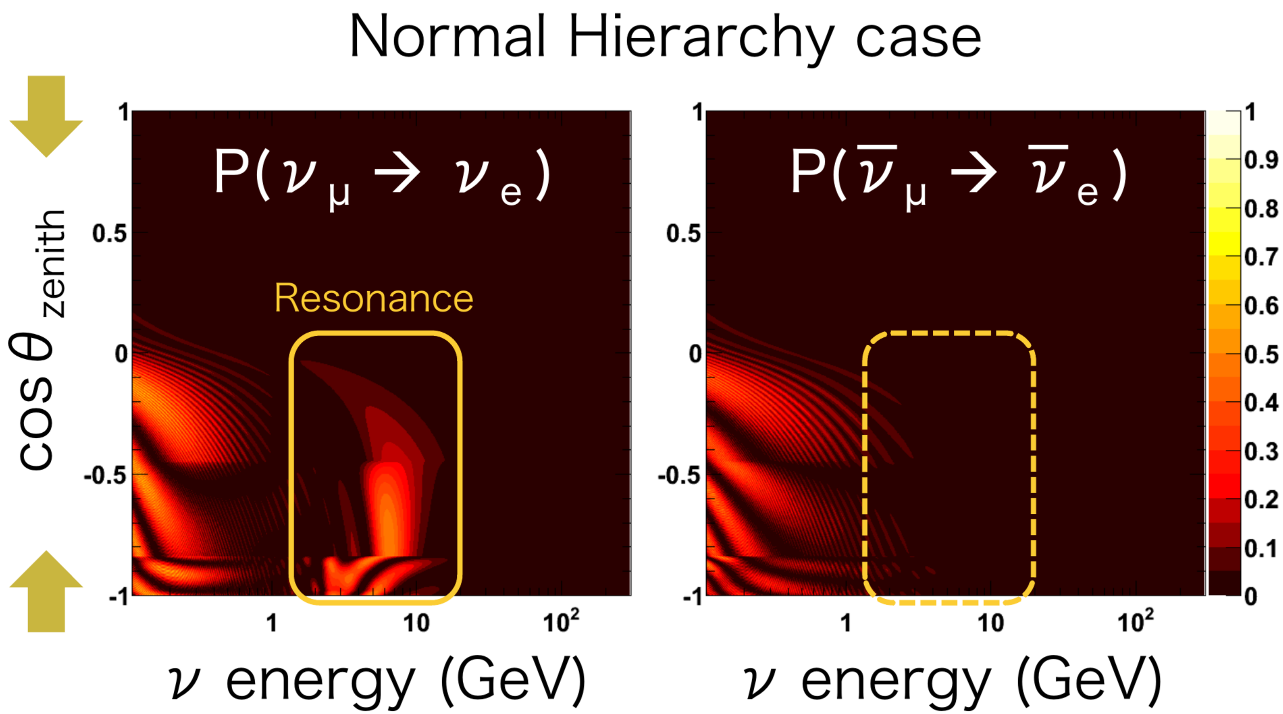
- HK 10 years : 5σ sensitivity on 60% of δ_{CP} values.

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

Atmospheric neutrinos

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





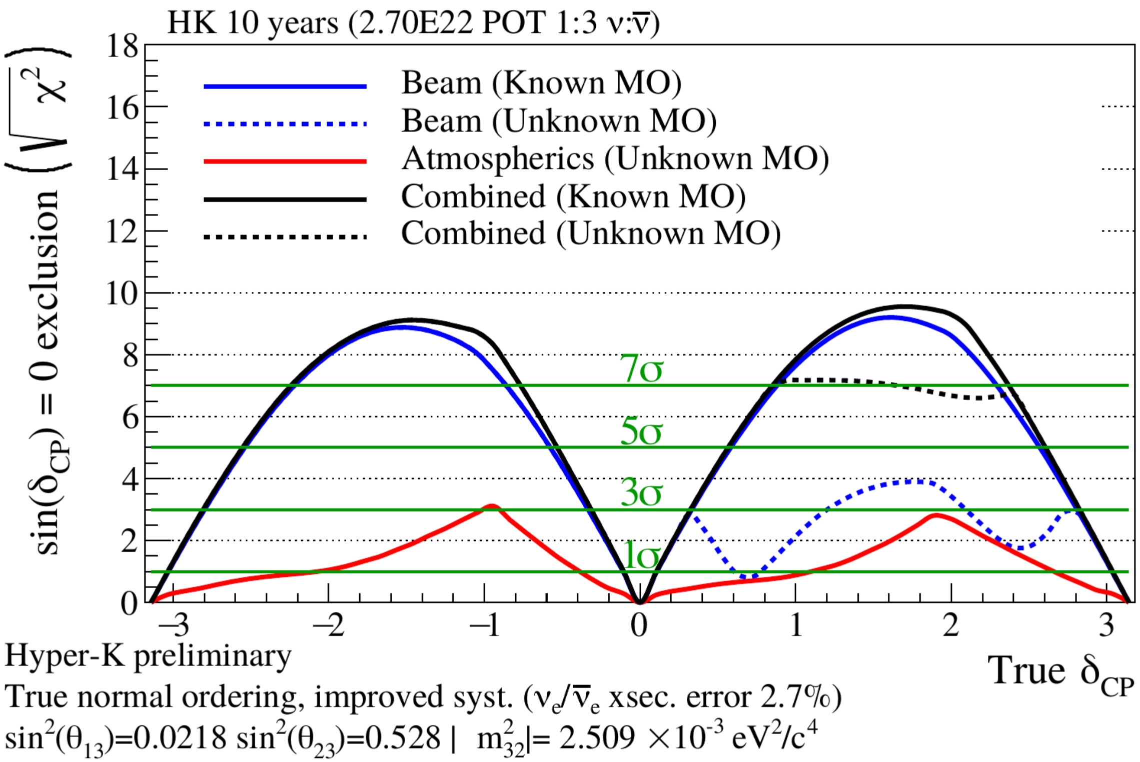
- Mass ordering determined with upward-going multi-GeV ν_e sample :

atm. baseline ≤ 13000 km ≫ 295 km accelerator baseline

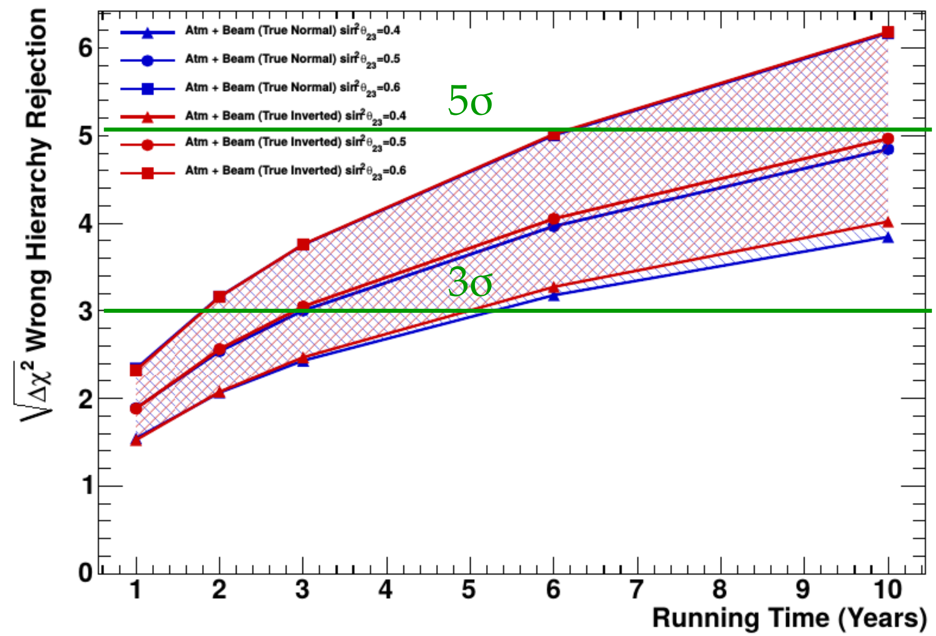
  - <u>Normal hierarchy :</u> enhancement of $\nu_\mu \to \nu_e$.
  - <u>Inverted hierarchy :</u> enhancement of $\bar{\nu}_\mu \to \bar{\nu}_e$.

Combination of atmospheric + beam ν

Impact on CPV sensitivity



Sensitivity to mass ordering



- Even if MO is not known when HK starts

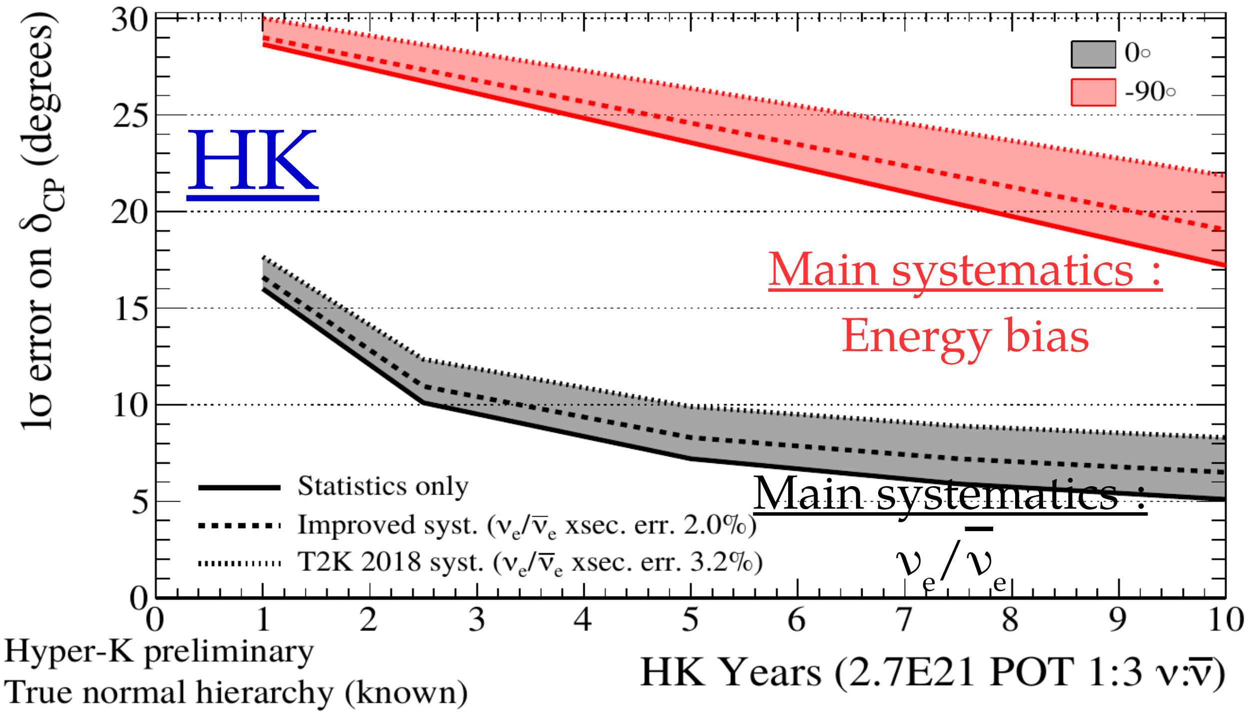
→ Sensitivity to CPV is little affected if we add atmospheric ν.

- MO would be determined by :

  → HK after ≥ 6-10 years via atmospheric.

Precise measurement of δ_{CP}

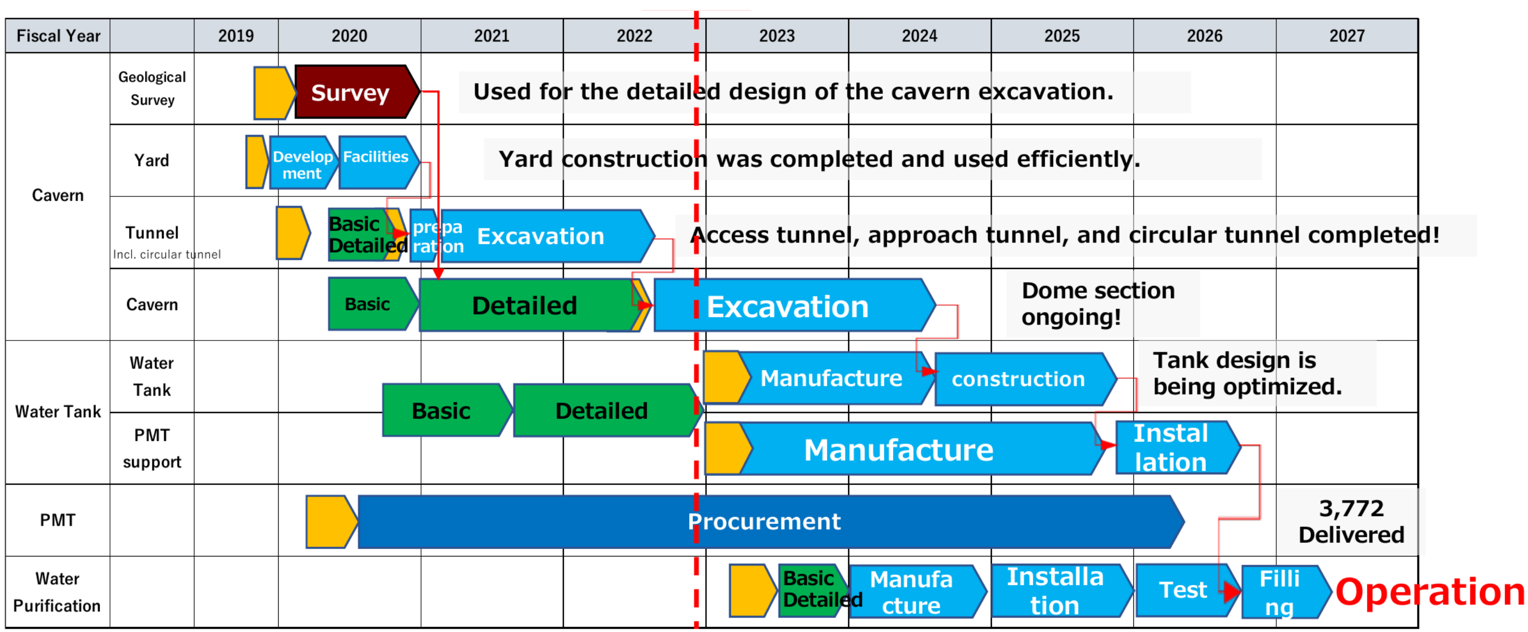
- After CPV is determined, accurate measurement of δ_{CP} will be crucial
  → Maximal CPV, leptogenesis, symetries of lepton's generations ...



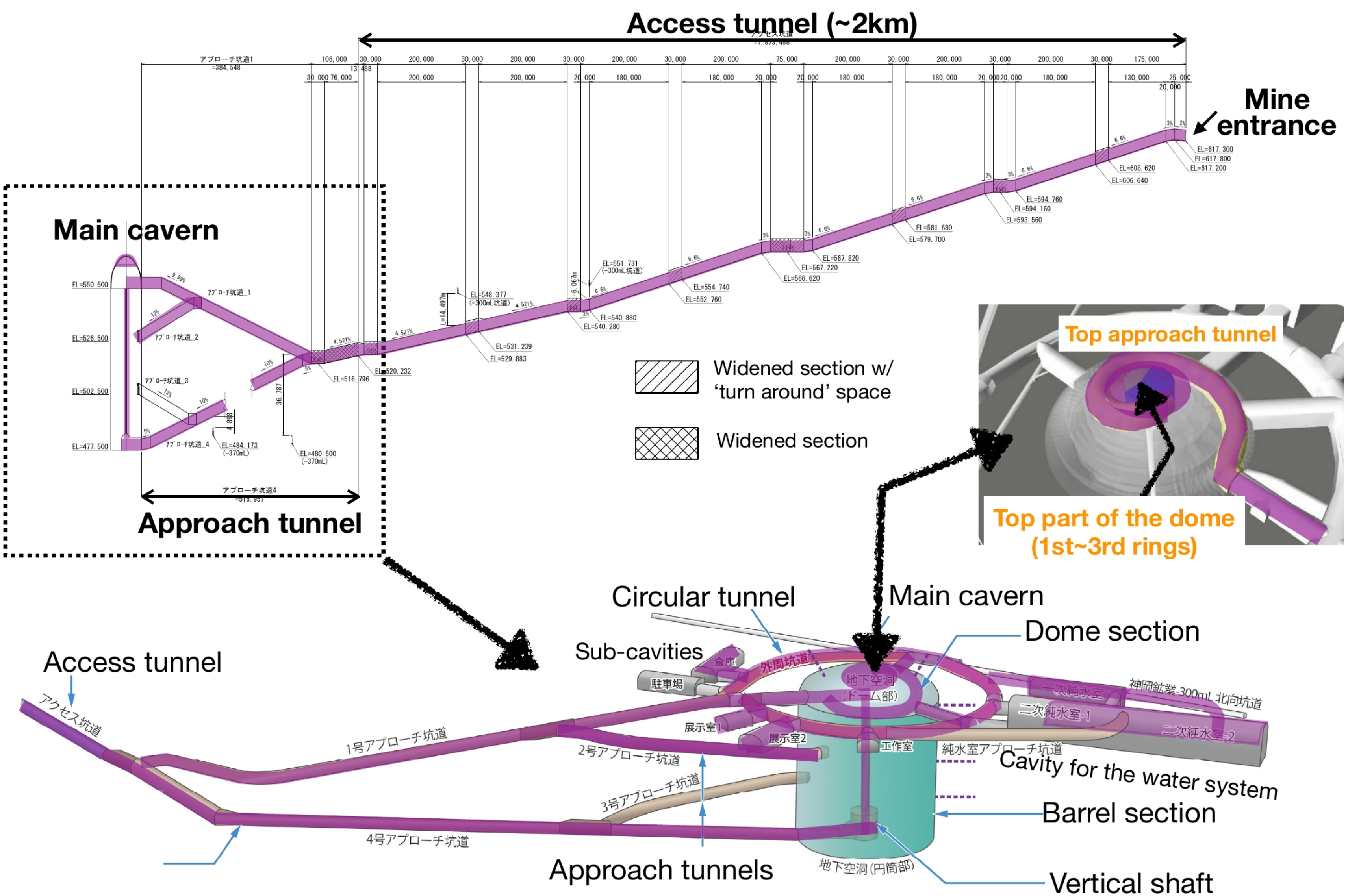
	5 years	10 years
CP conserved ($\delta_{CP} = 0$)	8°	6°
Max XPV ($\delta_{CP} = -\pi/2$)	25°	19°

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

Hyper-K schedule



Hyper-K caverns excavation



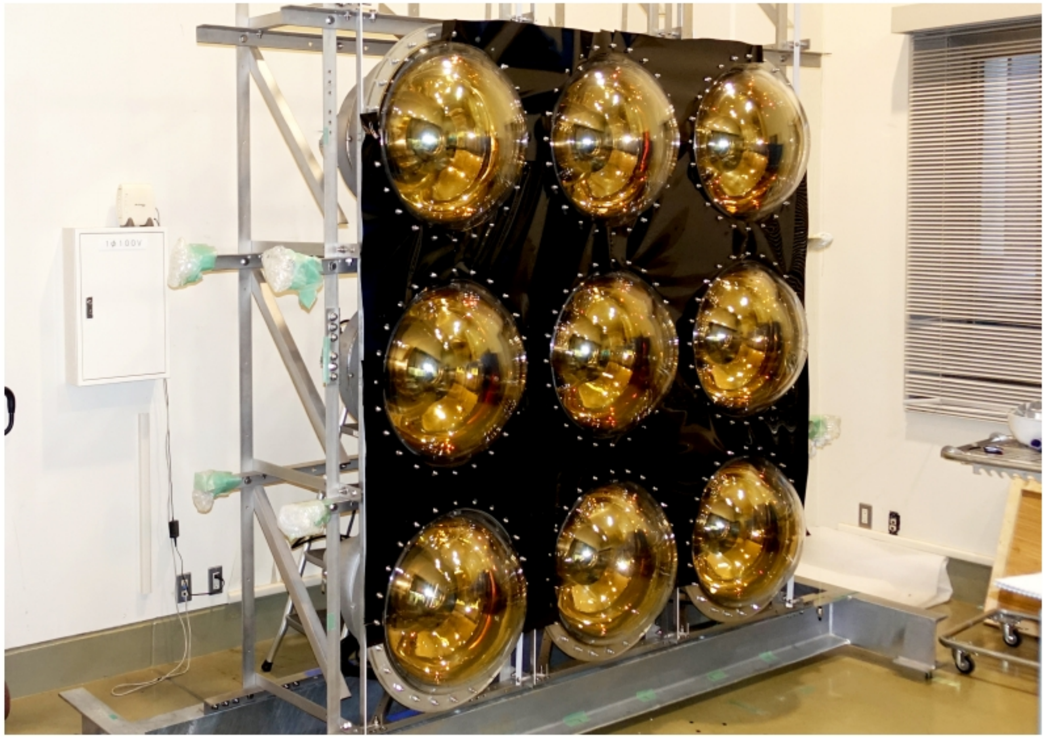
- Excavation of the access tunnel (2 km) finished the 25/02/22.
- Approach & circular tunnel excavation is over.
- Main cavern excavation has started ! → On-time !

Hyper-K construction !


Tunnel entrance


Reaching the top of HK

PMT production & delivery



- > 3700 PMTs / 20,000 delievered as of May 2022.
- <u>Constant quality inspection :</u> visual, measurements …
- No delay so-far.

The Hyper-K collaboration

The Hyper-K collaboration :

~550 members located in 102 institutes from 21 countries

March 2023 : our very 1st collaboration meeting in person after Covid !

Conclusions

- Hyper-K will be the world-leading experiment in many aspects of neutrino physics for the next 20 years.
  → Measure CP-violation for the first time in lepton sector & probe leptogenesis model to explain matter-antimatter asymmetry.
  → Constrain star formation rate & supernovae models.
  → Probe Grand Unified theories in still unknown landscapes …

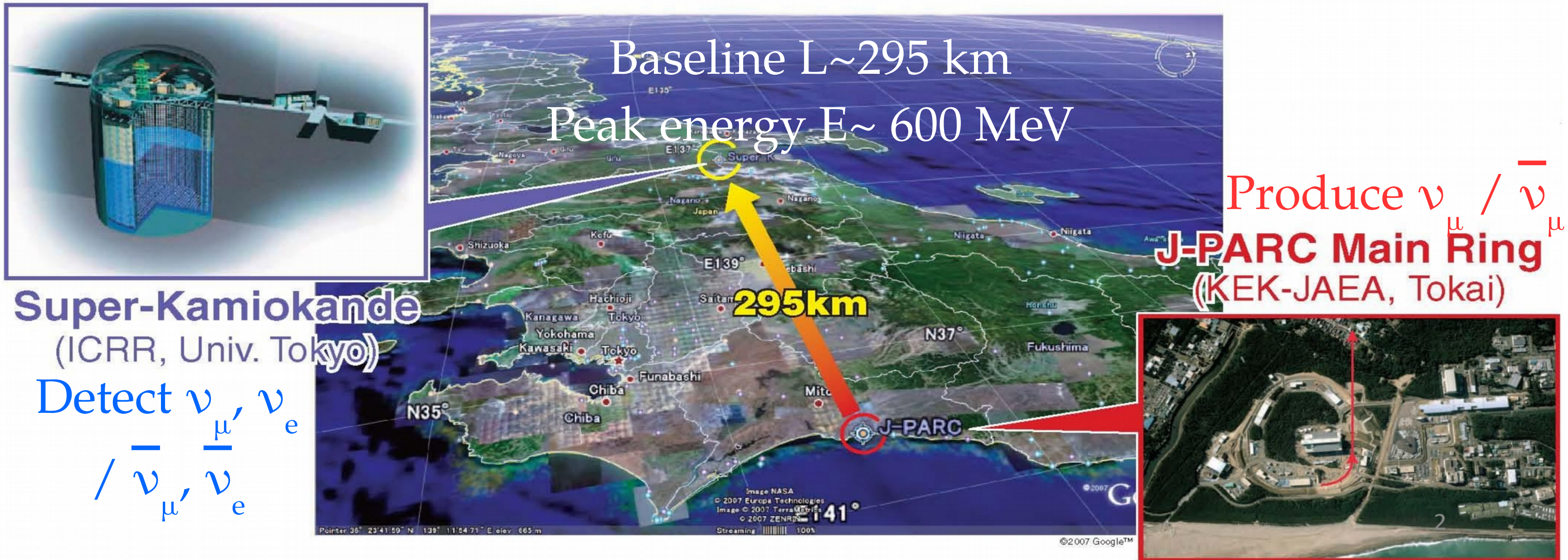
- Construction & production are on-time, no delay since the start
  → HK will take its first data in 2027.
  → Rely on well-proven technologies and analyses.

- You are very welcome to jump on-board of this adventure and join us !

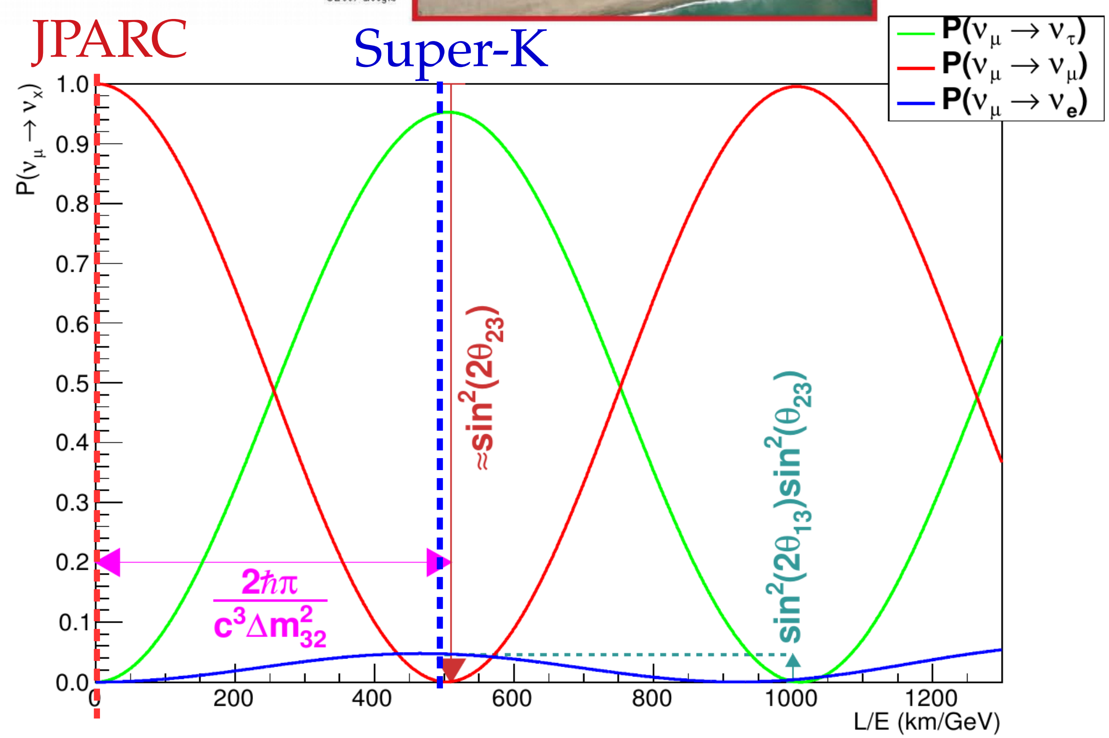
Additional slides

The long-baseline experiments

- <u>All uses same method :</u> focus on the T2K experiment in Japan.



- Intense ν_μ beam.
- Observe ν_μ disappearance and ν_e appearance.
- Can select ν or $\bar{\nu}$.



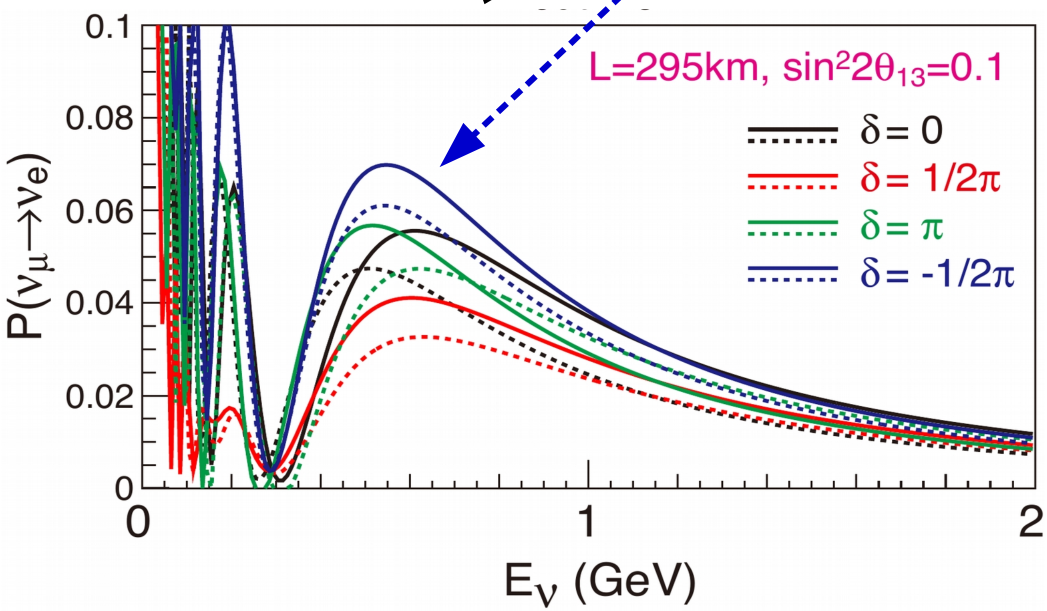
Precise measurement of δ_{CP}

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

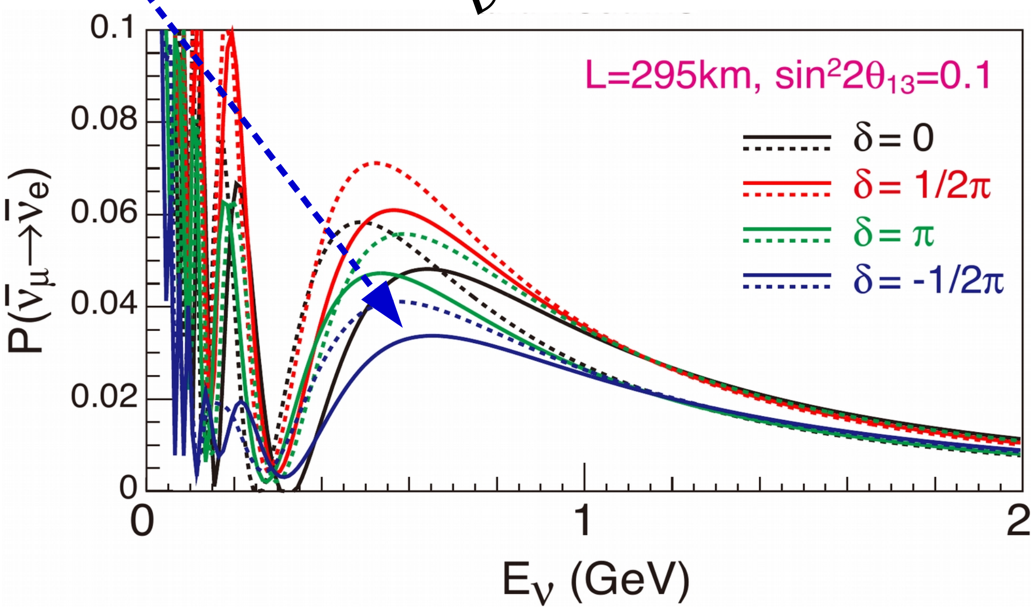
<u>sinδ :</u>

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

ν



$\bar{\nu}$

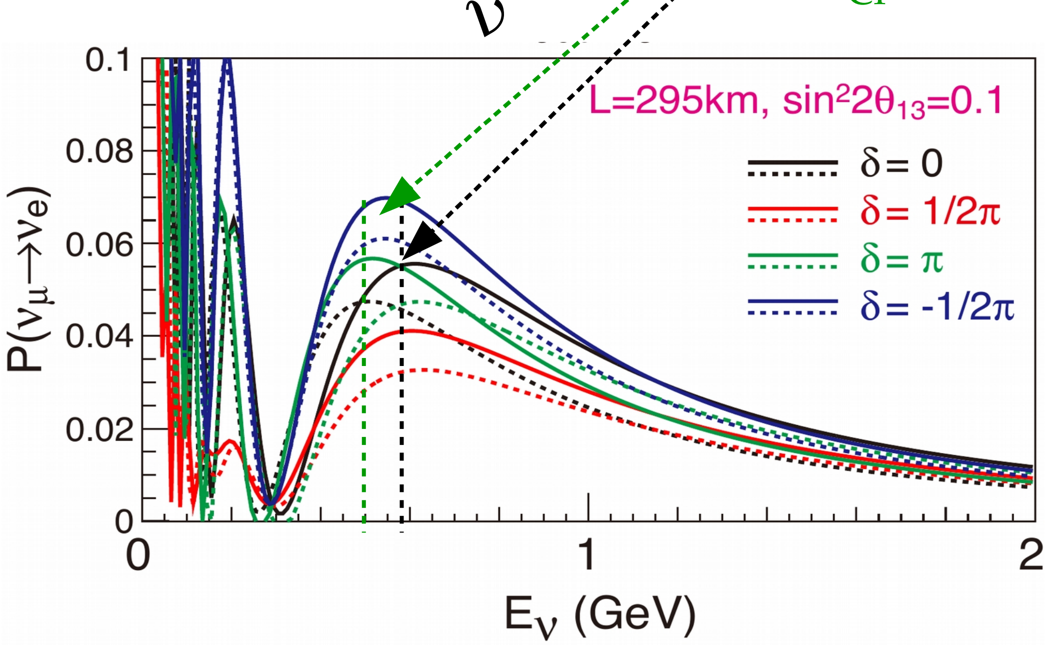


Precise measurement of δ_{CP}

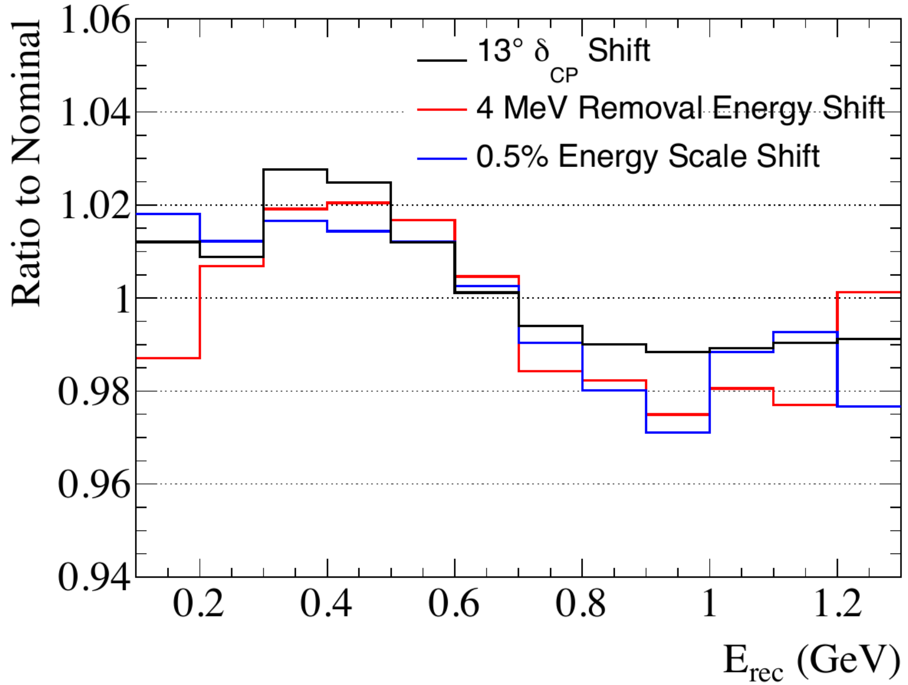
$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$
$$+8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \quad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

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

- <u>ν CP violation at low E maybe the key to matter/antimatter asymetry</u>

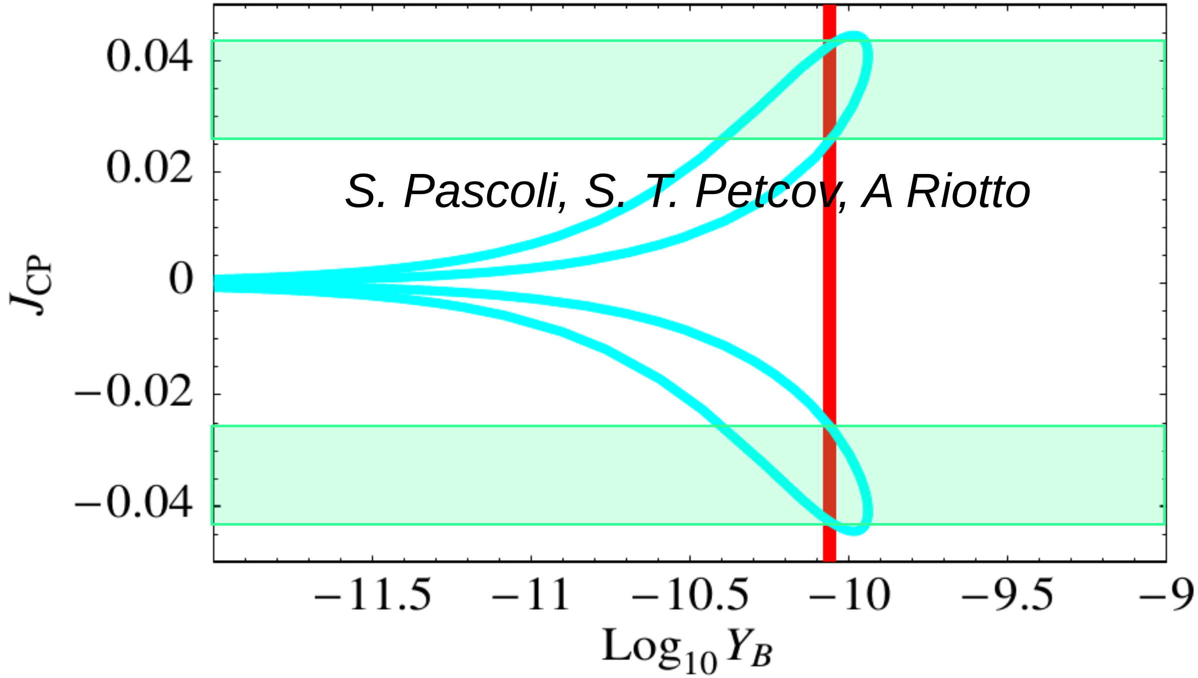
  → Class of theories directly link low E δ_{CP} to matter/antimat. asymetry.

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

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

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

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



Precision on sin δ_{CP}

↔ Precision on leptogenesis models

<u>Lower limit for leptogenesis :</u>

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

$\to |\sin\delta| \geq 0.78$

Flavour symmetries

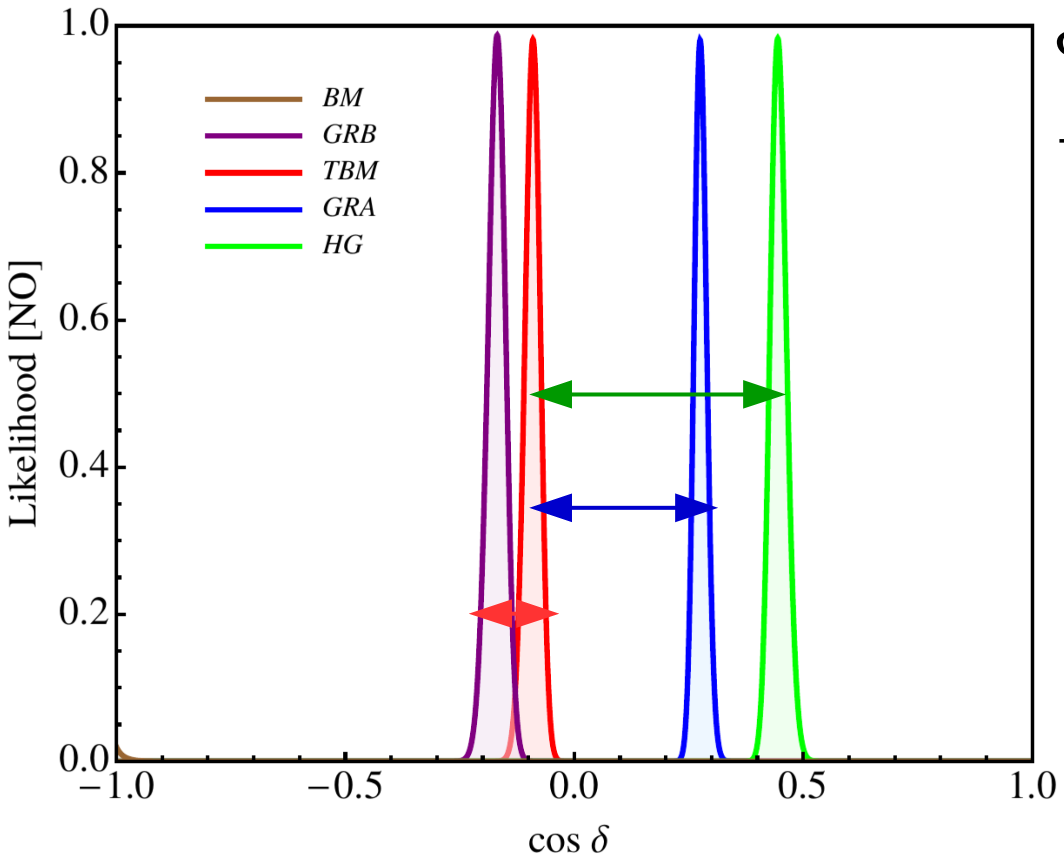
- Models of lepton flavour symetries could be also tested

$e \leftrightarrow \mu \leftrightarrow \tau$

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

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

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 ?

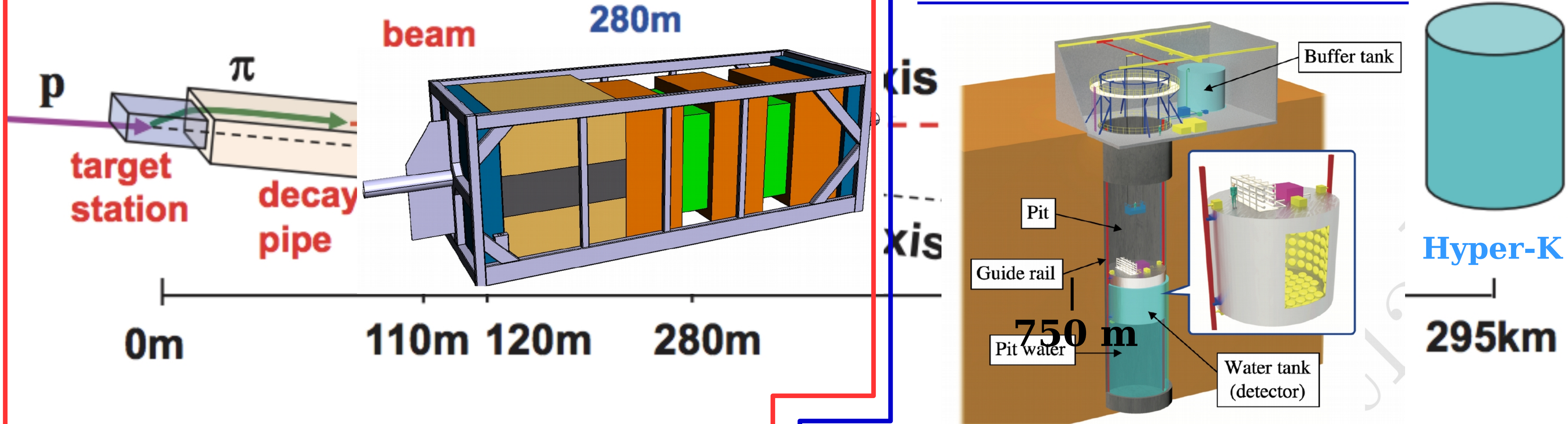
Updated systematic uncertainties

New

• 2 very complementary near detectors :

Upgraded ND280

Intermediate Water Cherenkov Detector



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.

Target & acceptance ~ far detector.

• Cancel detector uncertainties & precise measurement of ν_e / ν_μ

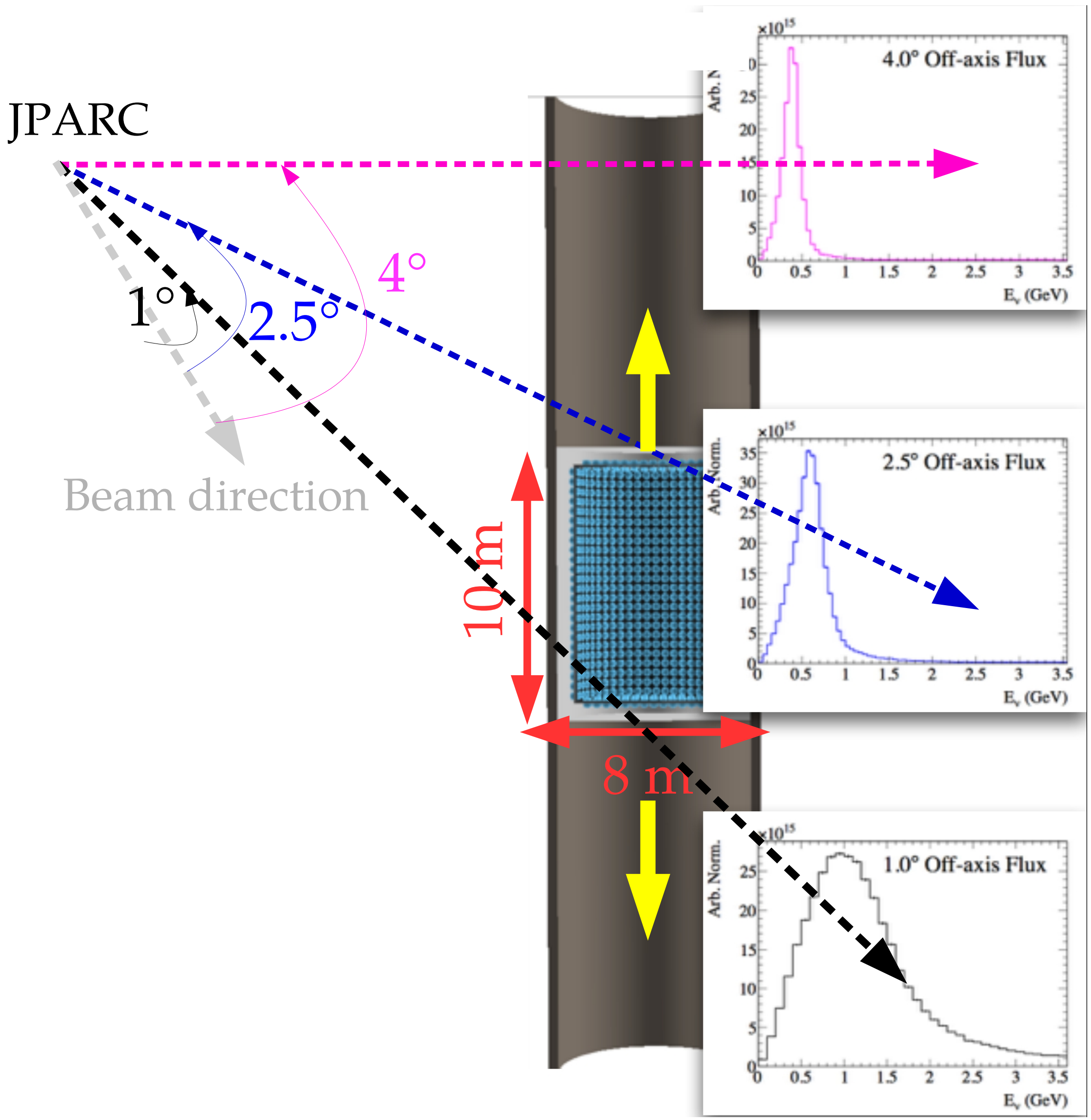
• Here from 2028.

• Contributions still open

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

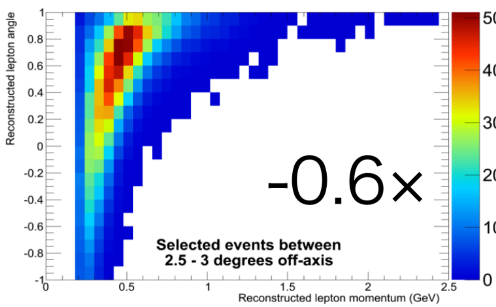
The IWCD

- New Intermediate Water Cherenkov detector (E61):



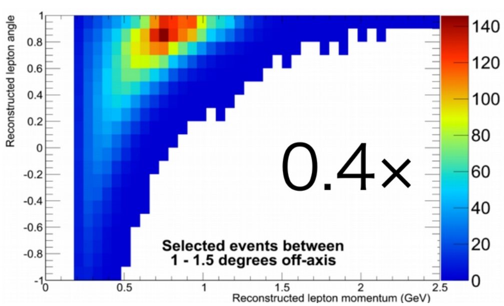
1. HK flux = linear combination of different off-axis angles.

2. Take same combination of



reconstructed number of neutrinos (e.g. in p_μ/θ_μ)

→ Drastically reduce use of cross-section models !



The IWCD

- Water Cherenkov : Excellent ν_e / ν_μ separation

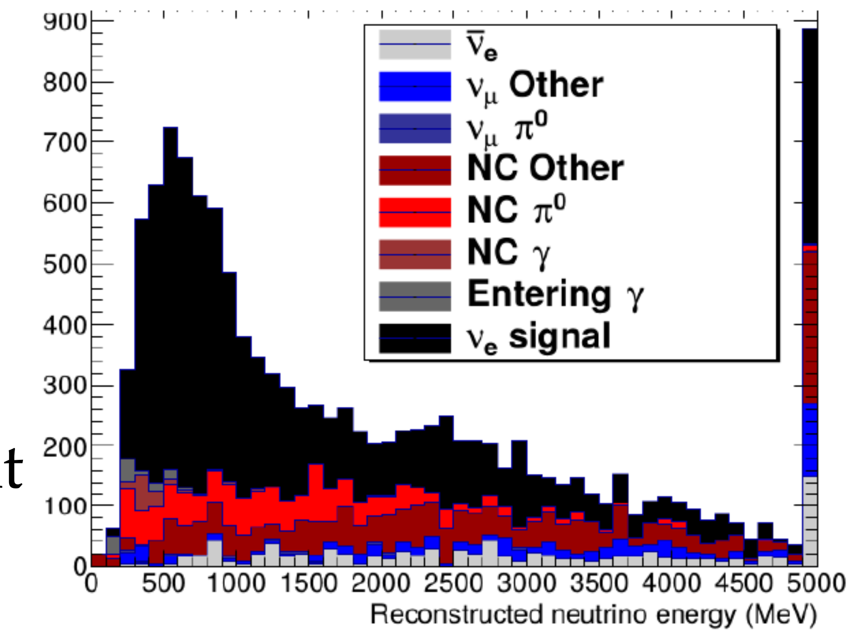
  → Extremely precise measurement o f $(\nu_e / \nu_\mu) / (\bar{\nu}_e / \bar{\nu}_\mu)$.

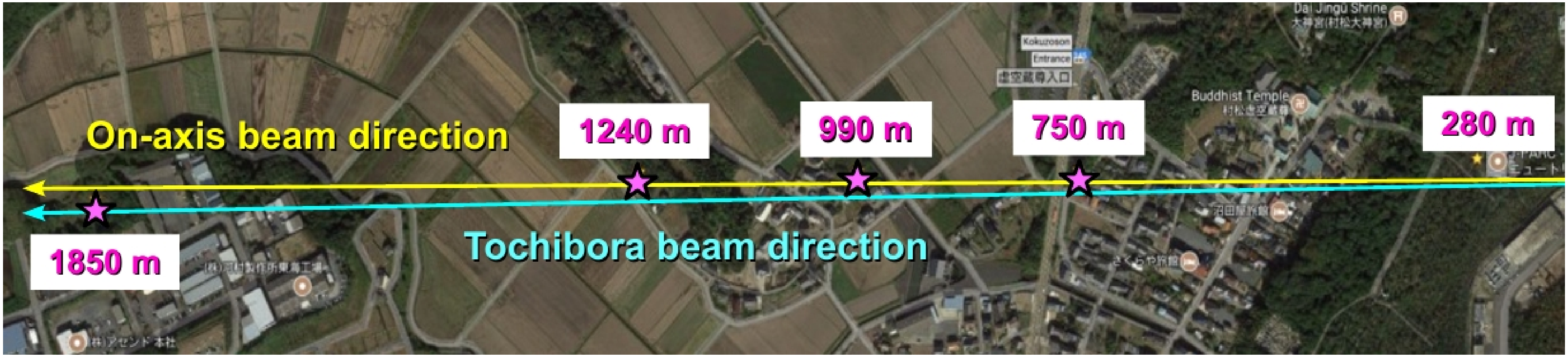
- Loaded with Gd for n-tagging

  → Enhanced $\nu/\bar{\nu}$ separation.

  → Measure n-multiplicy

- Sites under survey (balance between event rate / pile-up vs pit depth)





- ND280 + IWCD totally complementary to reach systematics ≤ 3 %.