Status of the Hyper-Kamiokande experiment

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(for Hyper-Kamiokande proto-collaboration)

PANIC 2017
Beijing, 1 Sep. 2017

東京工業大学
Tokyo Institute of Technology

Neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata)

ν_e, ν_μ, ν_τ : flavor eigenstates.

ν_1, ν_2, ν_3 : mass eigenstates of $m = m_1, m_2, m_3$.

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{23}=\cos\theta_{23}$, etc.

3 mixing angles (θ_{12}, θ_{23}, θ_{13}) + 1 complex phase (δ) ←CP violation

Neutrino oscillation

IF $\theta \neq 0$ AND $\Delta m^2 \neq 0$, flavor transmutation occurs.

$P(\nu_i \rightarrow \nu_j) = \sin^2 2\theta_{ij} \times \sin^2(1.27 \Delta m^2 L/E)$ (2 flavor approx.)

Δm^2 in (eV^2), L/E in (km/GeV or m/MeV)

- 3 mixing angles
  θ_{12}, θ_{23}, θ_{13}
- 2 (independent) mass^2 differences
  $\Delta m^2_{32} = m_3^2 - m_2^2$
  $\Delta m^2_{21} = m_2^2 - m_1^2$
  ($\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$)
- 1 complex phase (CPV) δ

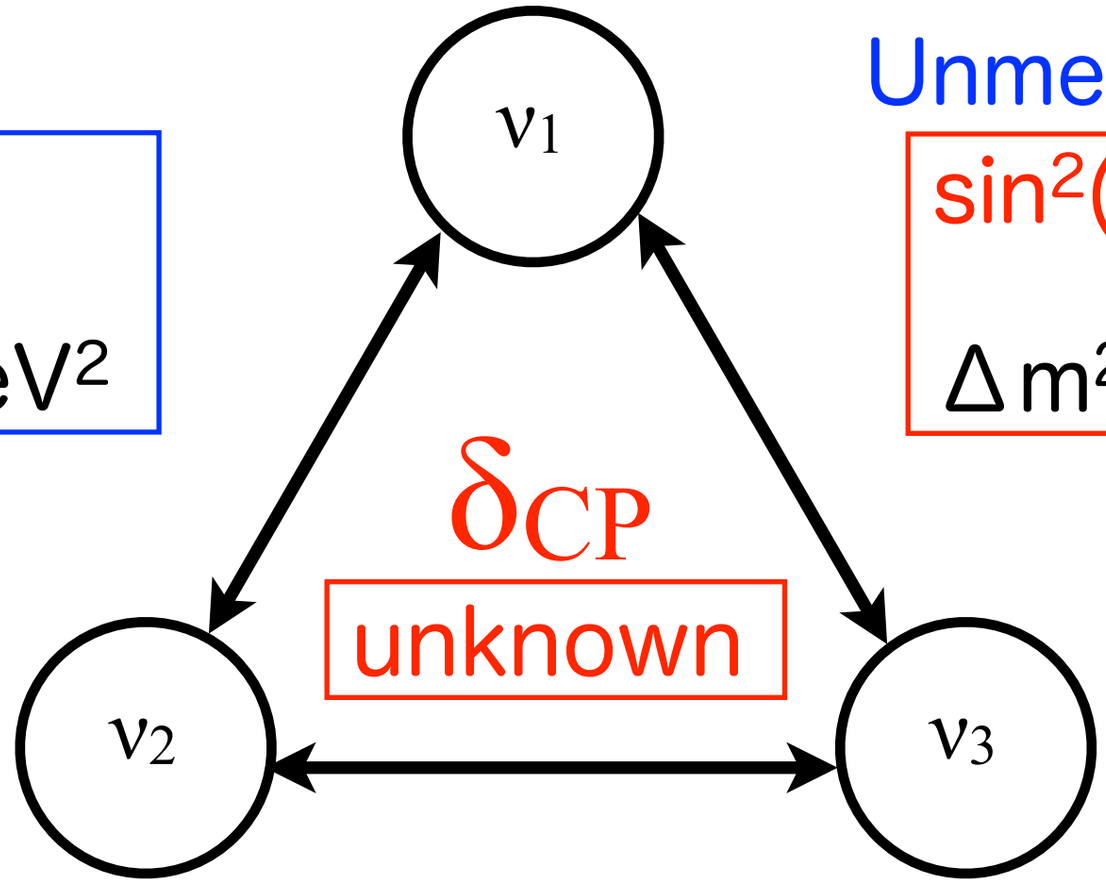
Oscillation parameters

$\sin^2(2\theta_{12}) \sim 0.8$

$\Delta m^2_{21} \sim 8\times10^{-5}\mathrm{eV}^2$

Solar-ν

Reactor-ν



Unmeasured <2011

$\sin^2(2\theta_{13}) \sim 0.1$

$\Delta m^2_{31} \sim \Delta m^2_{32}$

Reactor-ν

Acc-ν

Atm-ν

Acc-ν

$\sin^2(2\theta_{23}) \sim 1.0$

$|\Delta m^2_{32}| \sim 2.5\times10^{-3}\mathrm{eV}^2$

unknown

mass ordering:

$m_3 >> m_2 > m_1$ or

$m_2 > m_1 >> m_3$

- $\theta_{12} \sim 33^\circ$, $\theta_{23} \sim 45^\circ$, but $\theta_{13} \sim 9^\circ$
- $|\Delta m^2_{32}| >> |\Delta m^2_{21}|$ (by factor ~30)

Outstanding issues in neutrino physics

- PMNS matrix:

  All 3 mixing angles θ_{ij} are measured.

  Octant of θ_{23} not yet known (> 45° or < 45°)

  CP violation phase δ_{CP} is unknown.

- Neutrino masses:

  Both mass^2 differences Δm^2_{32} and Δm^2_{21} measured.

  Sign(Δm^2_{32}) still unknown - Mass Hierarchy (Mass Ordering)

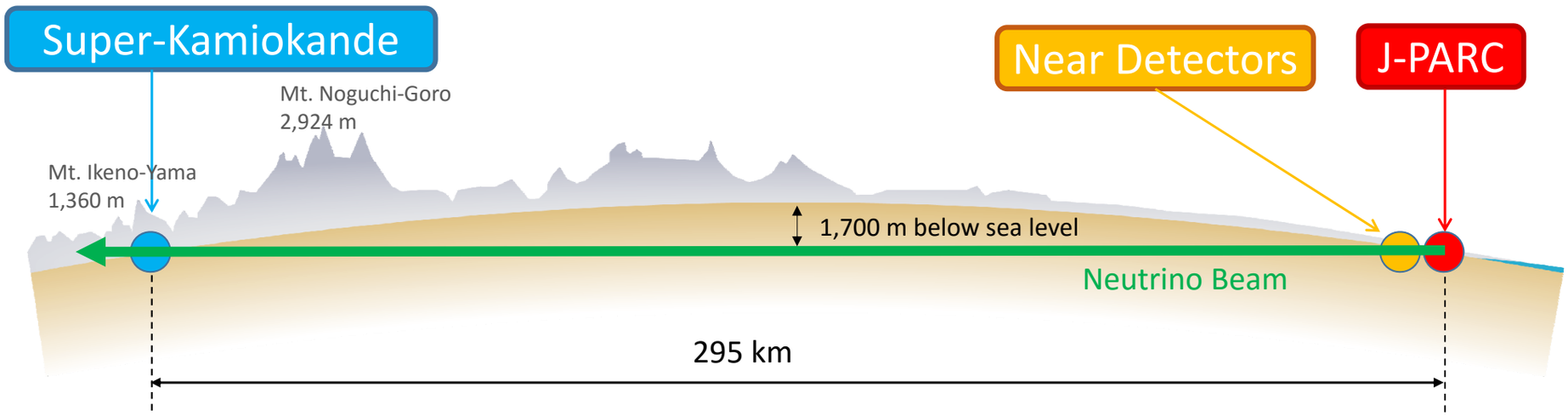
  $m_3 >> m_2 > m_1$ (normal) or $m_2 > m_1 >> m_3$ (inverted)

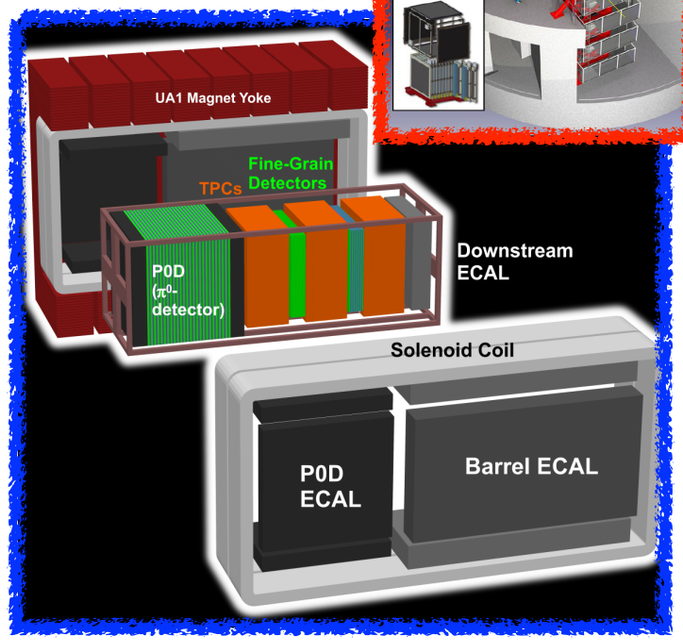
  Absolute m_ν not measurable with ν oscillation

  → $0\nu2\beta$ (if Majorana)／direct β measurement (KATRIN) and cosmological constraints on Σm_ν (ν osc.→ $\Sigma m_\nu > 0.05$ eV)

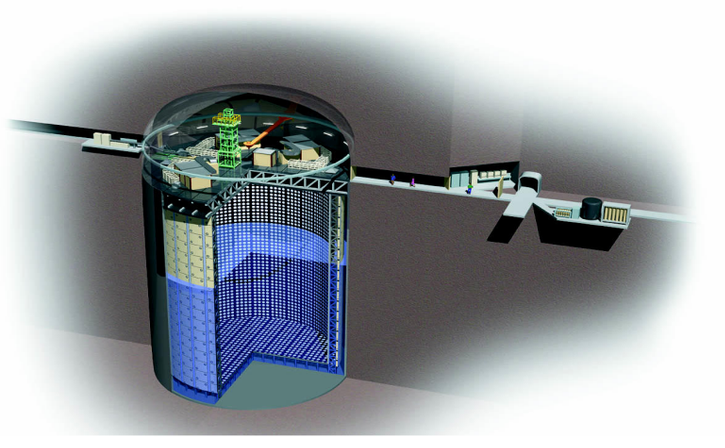
T2K experiment in Japan

- Tokai (J-PARC) to Kamioka (SK)
  Long-BaseLine accelerator ν exp.





Super-K@Kamioka

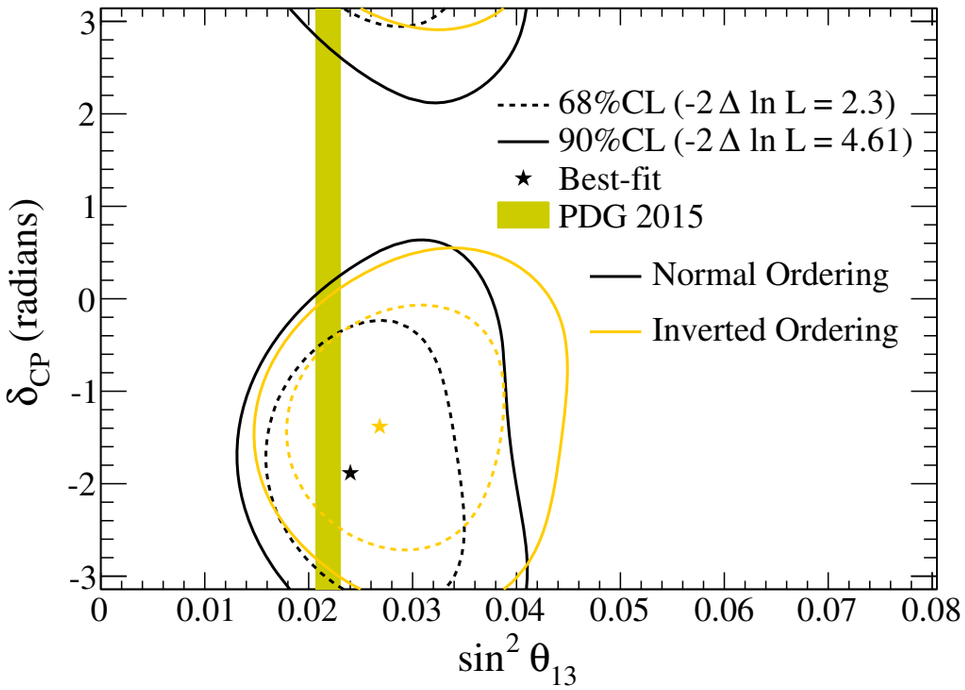


ND280 @Tokai

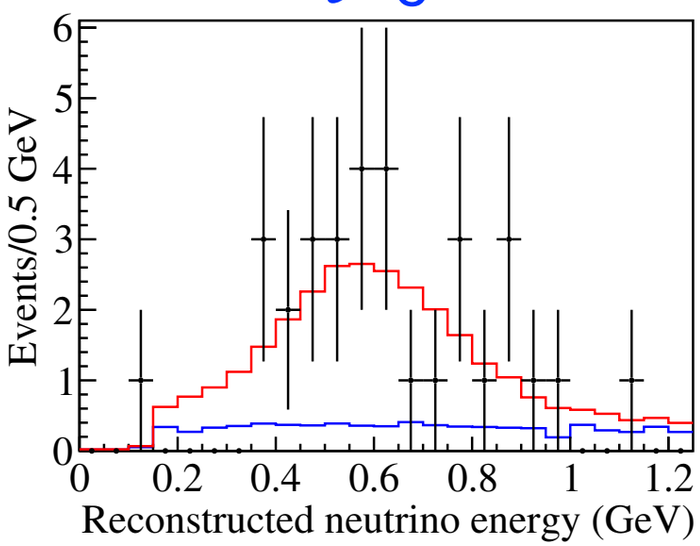
T2K results on δ_{CP}

- Note: results from up to 2016 data (Run 1-7)
- See talks by T. Kobayashi today and by X. Lu tomorrow for latest results (Run 1-8)
- δ=0 or π excluded at 90% C.L.

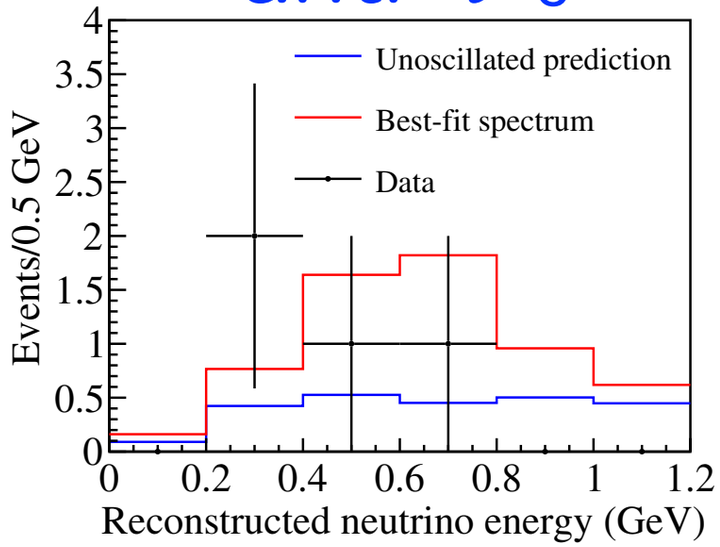
Use reactor θ_{13} constraint



ν_e

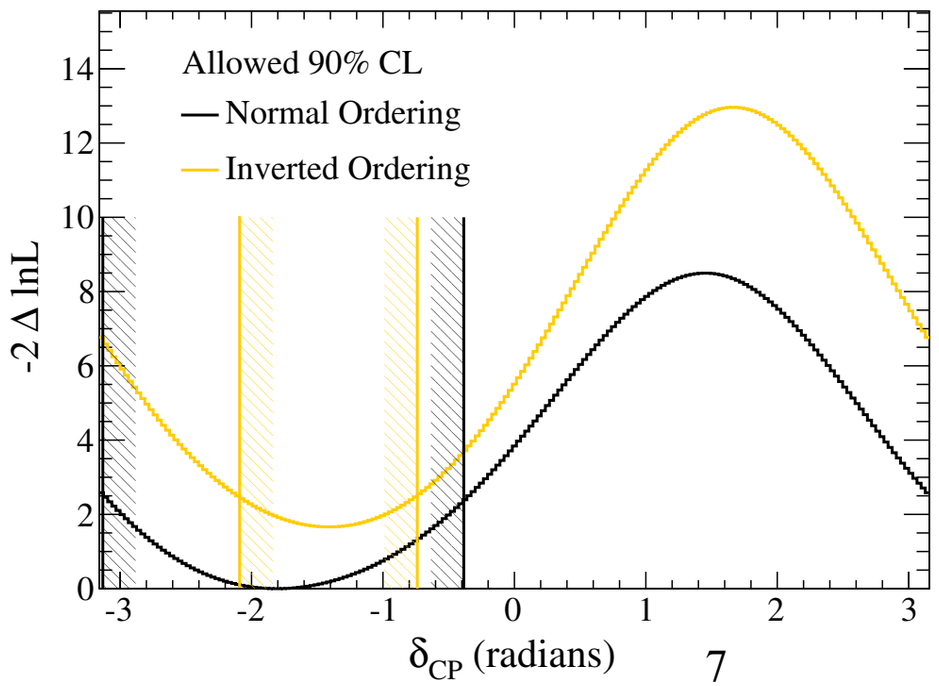


anti-ν_e



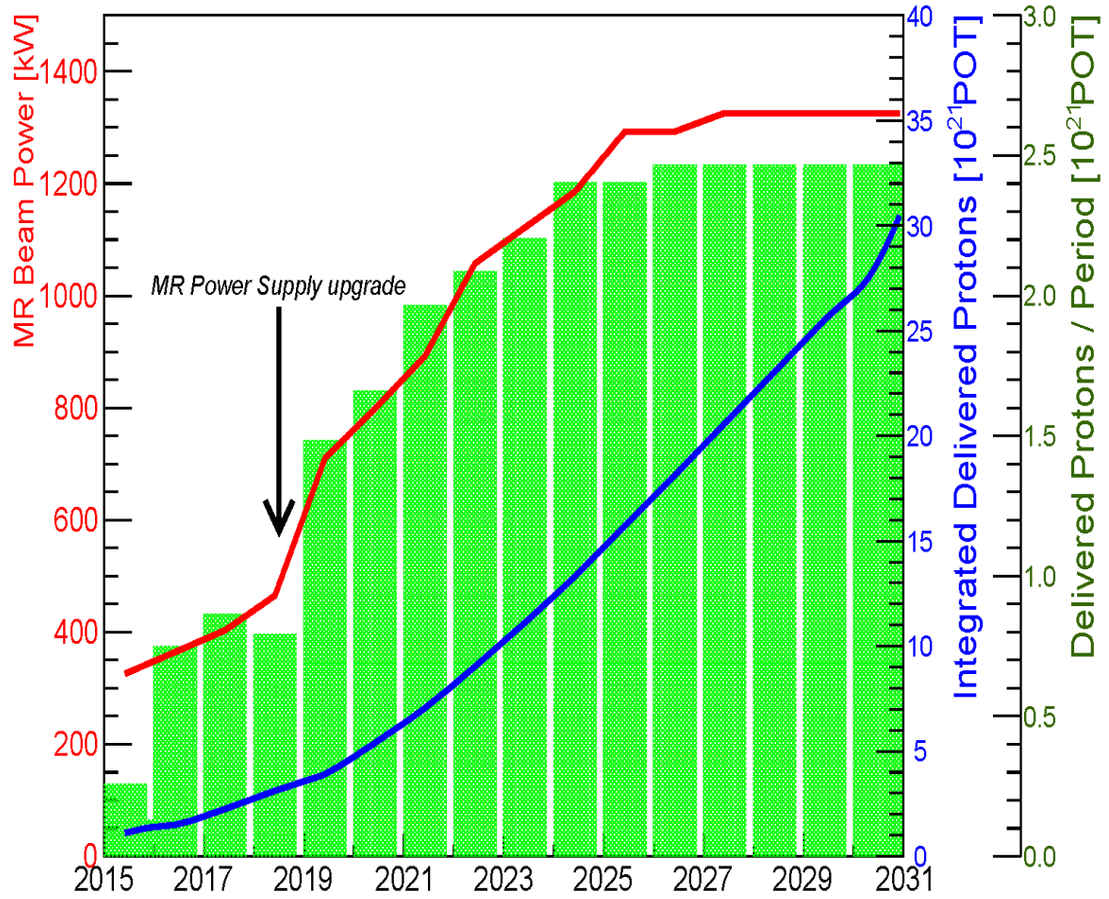
Normal	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4
Inverted	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\bar{\nu}_e$	6.5	7.4	8.4	7.4	4

PRL118, 151801 (2017)

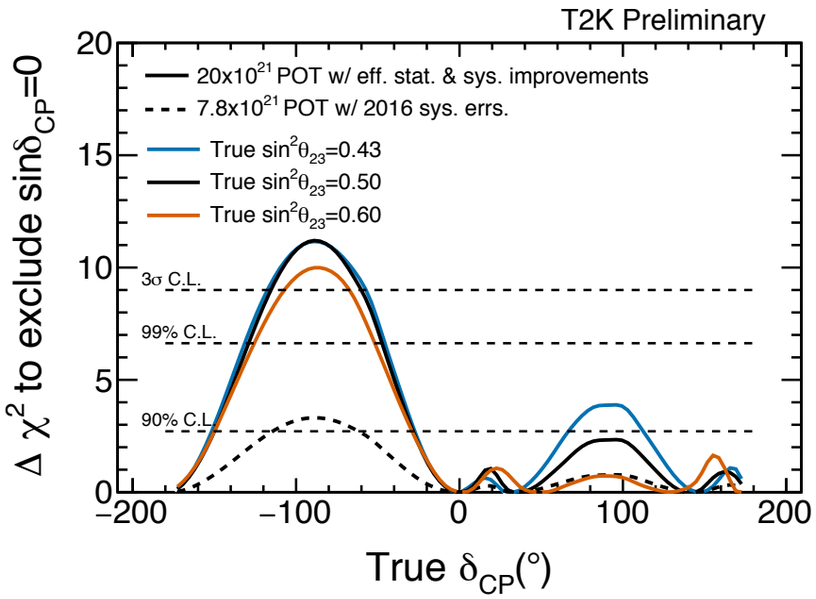


T2K→T2K-II→T2HK

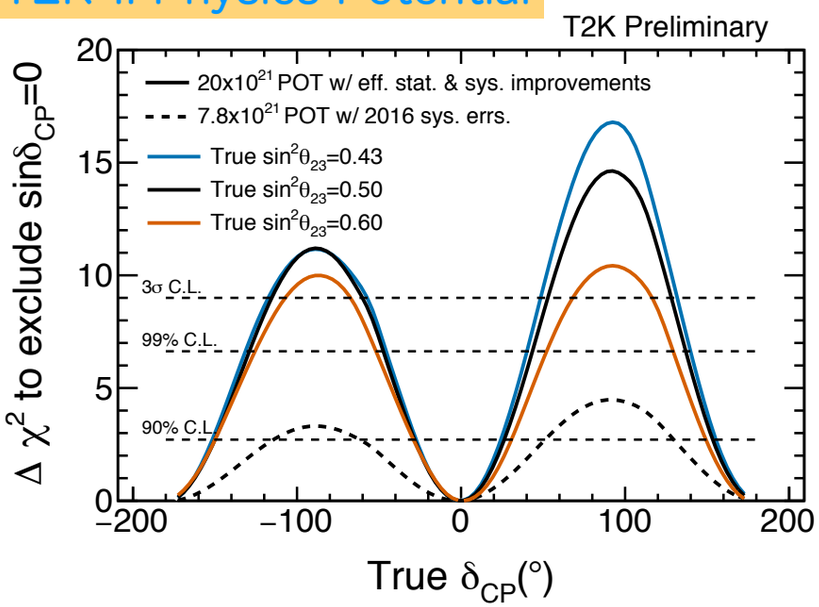
- T2K was proposed with 7.8E20 POT
  - So far accumulated 1.5E20
- T2K-II (till ~2026) to collect 20E20
  - MR Power Supply upgrade (>750kW)
  - ~3σ evidence if δ ~ -90deg
- T2HK (from ~2026) with 1.3MW beam
  - Hyper-K as the Far Detector
  - Definite observation of CP violation



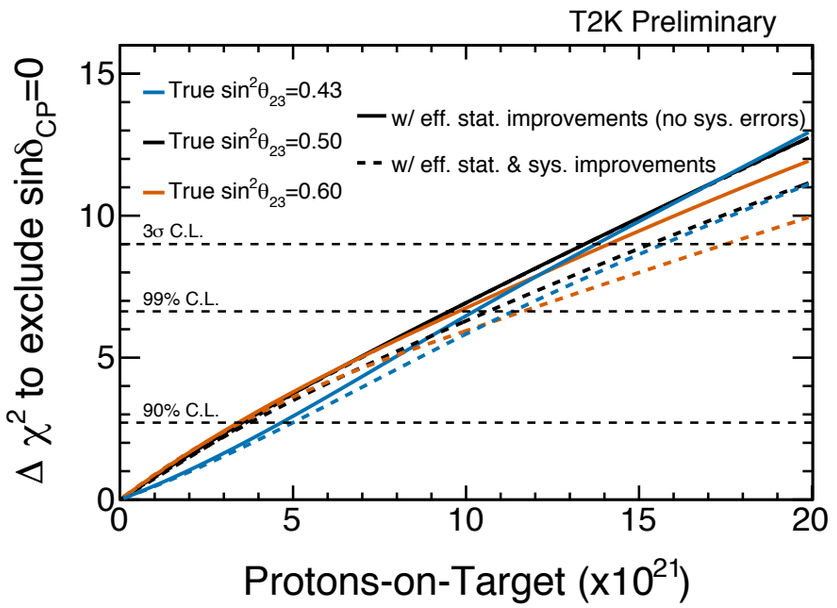
T2K-II Physics Potential



hierarchy unknown



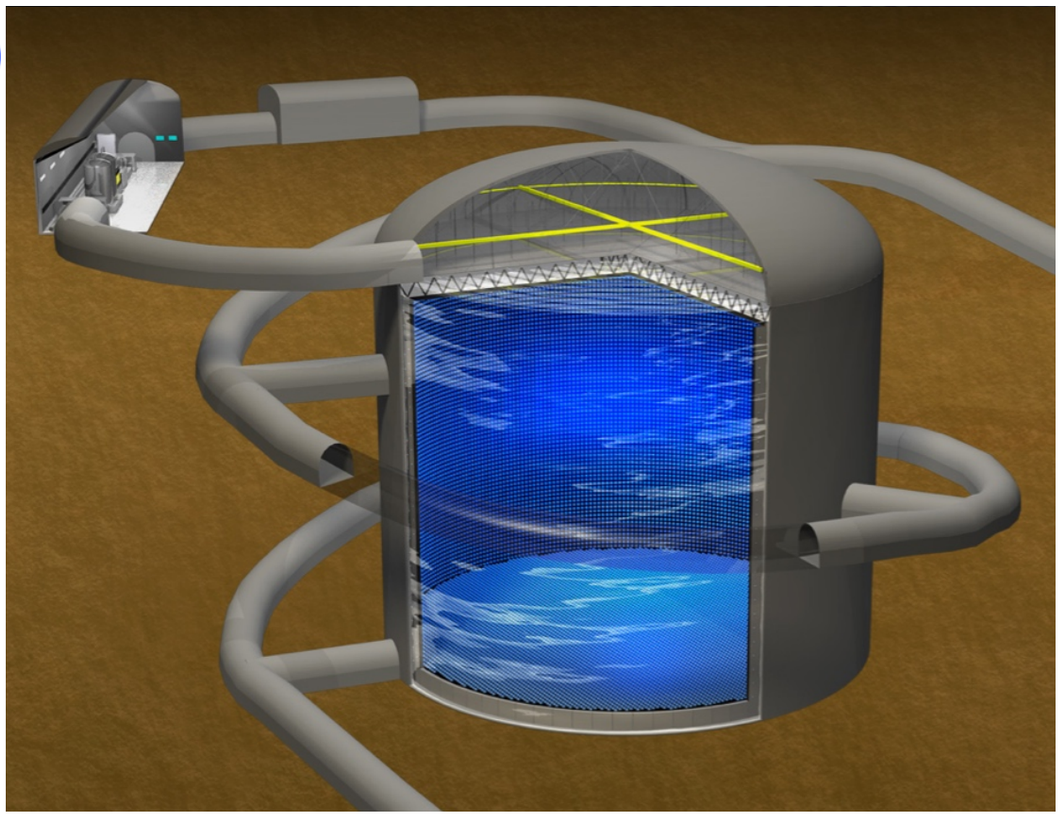
external hierarchy input



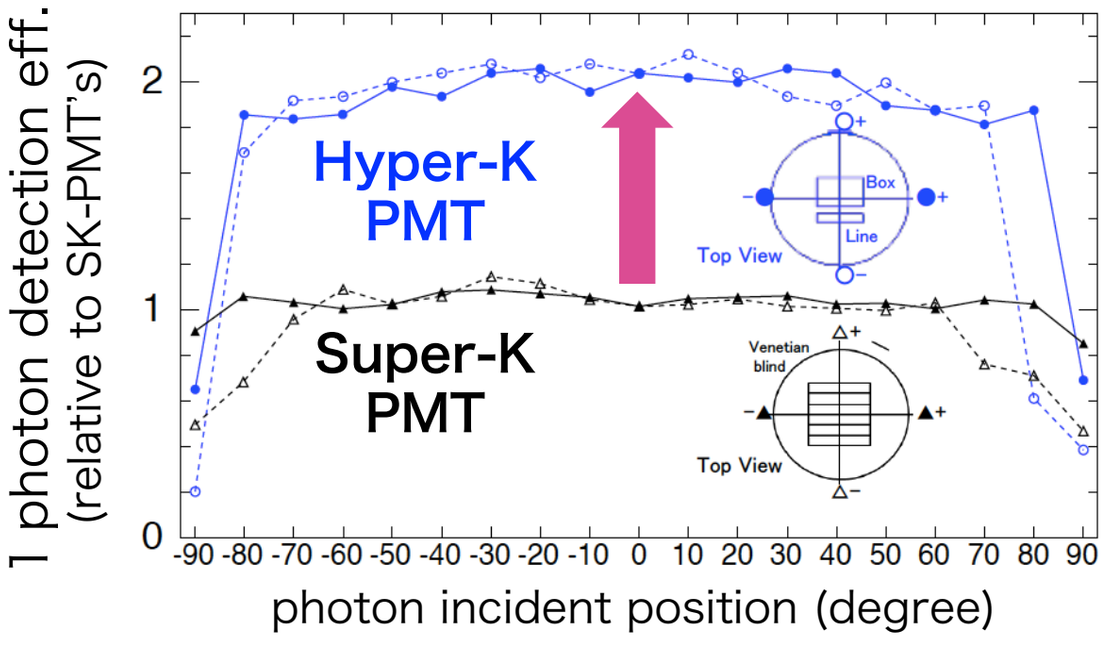
H.A. Tanaka, Neutrino 2016

Hyper-Kamiokande

- 2x260 kton tank (D74m×H60m)
- 190 kton fiducial mass/tank (~×10 of Super-K)
- Aim for quick <u>start w/ 1 tank</u>
- 40,000 PMTs with 2x eff.



- Acc. ν : δ_{CP} measurement
- Atm. ν : mass hierarchy
- Astronomical ν : Supernova and solar ν
- Observe nucleon decay

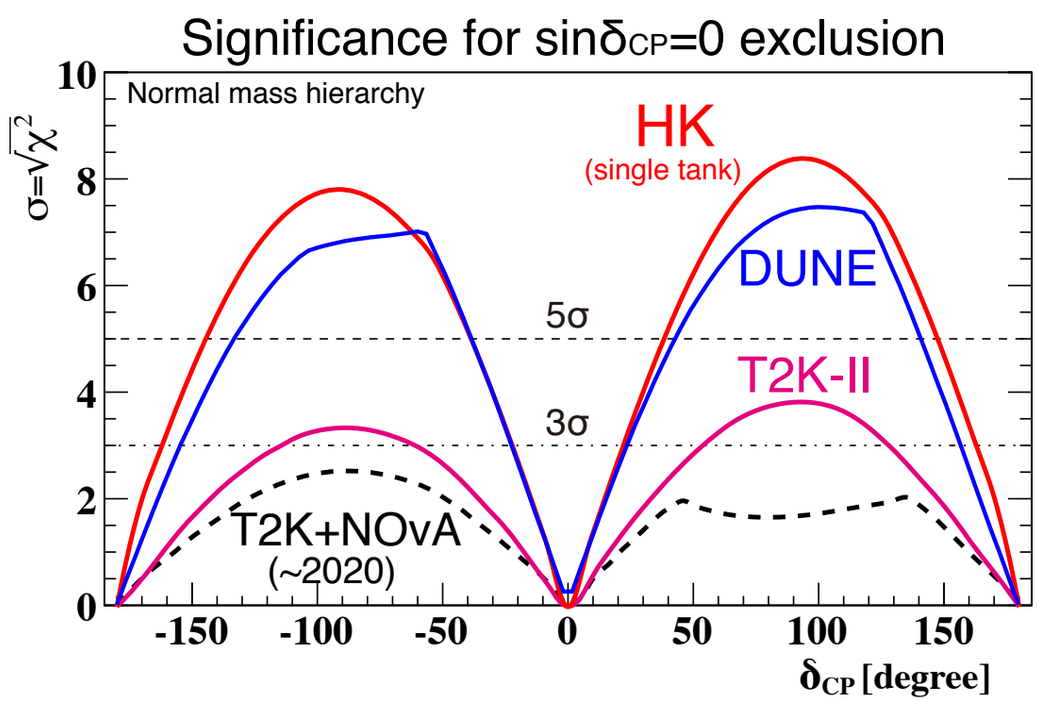


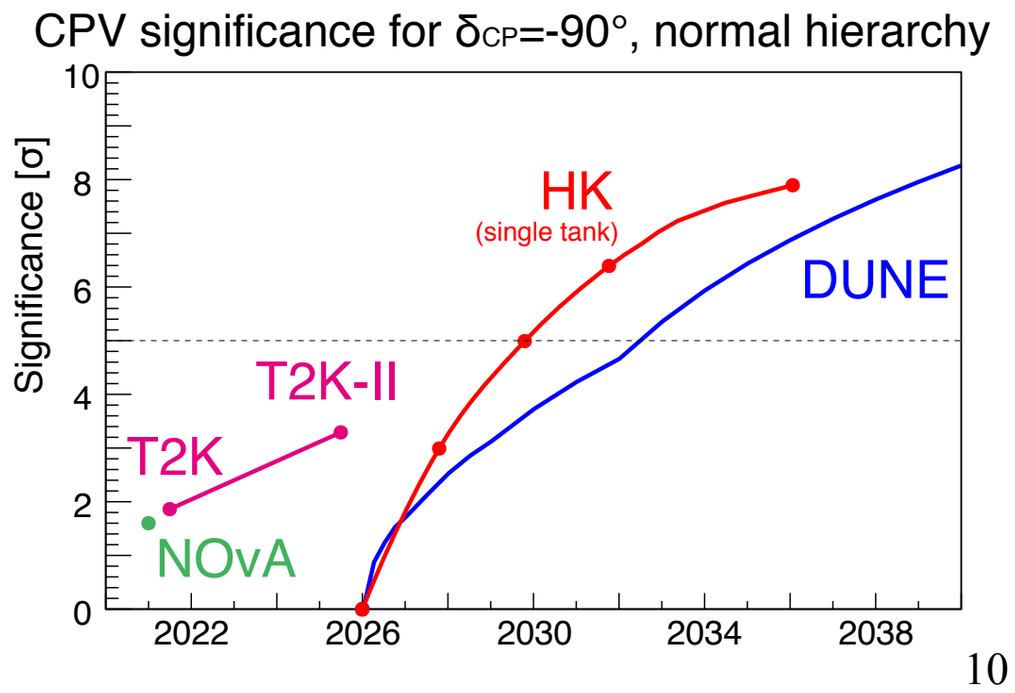
CP violation with T2HK

- Compare $\nu_\mu \rightarrow \nu_e$ appearance for ν and anti-ν
- High statistics: no need to rely on reactor θ_{13}

Number of signal candidate events, 1.3 MW × 10 years (10^8 sec), $\nu : \bar{\nu} = 1:3$

for $\delta_{CP} = 0$	**Signal $\nu_\mu \rightarrow \nu_e$ CC**	Wrong sign appearance	$\nu_\mu / \bar{\nu}_\mu$ CC	Beam $\nu_e / \bar{\nu}_e$ contamination	NC
ν beam	1,643	15	7	259	134
$\bar{\nu}$ beam	1,183	206	4	317	196

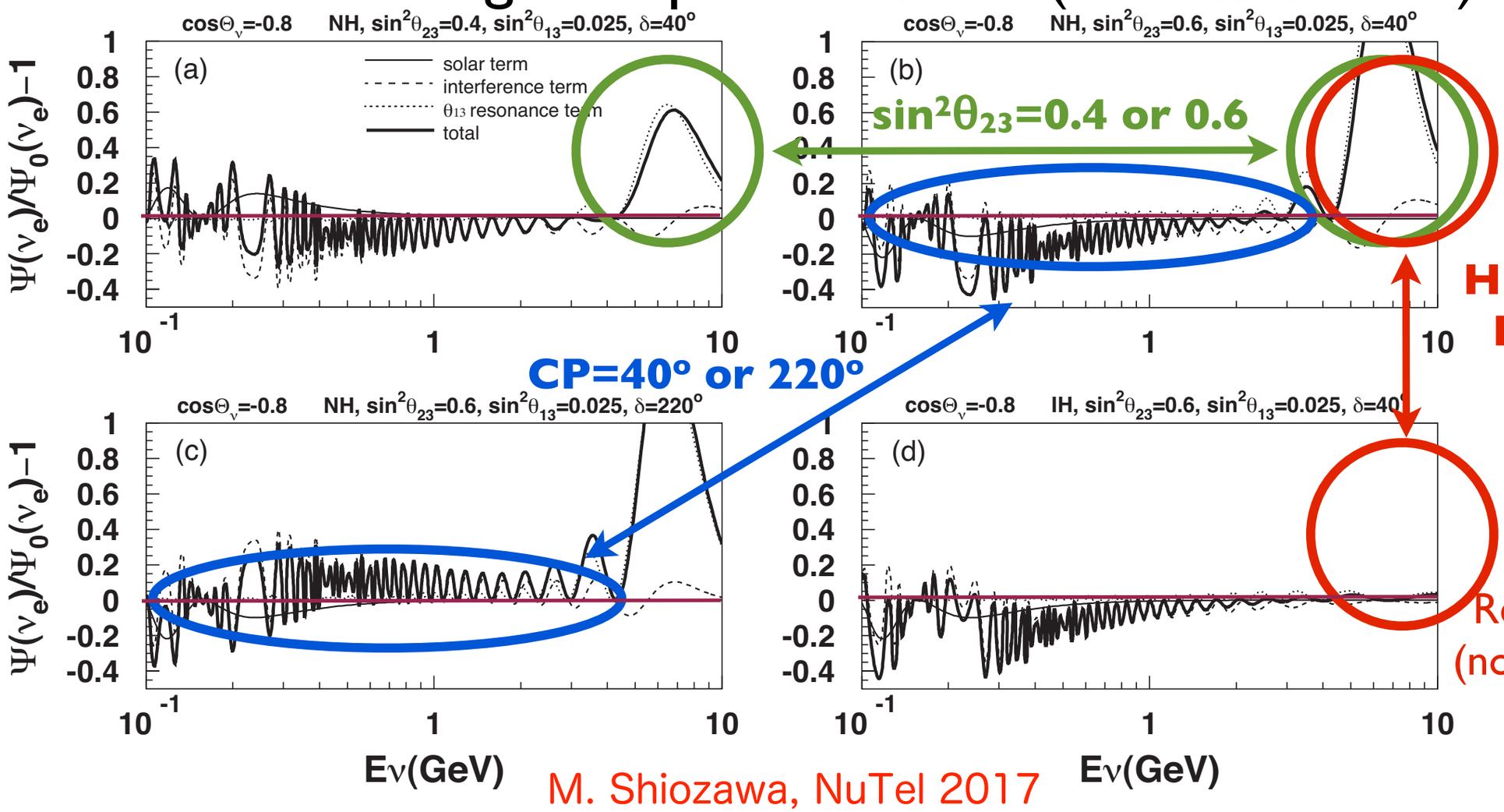




Accessing M.H. by atm-ν

- Matter effect: resonant enhancement of ν_e oscillation at certain energy/zenith-angle
- Effect reverses for Normal and Inverted H.

"Fractional change of upward ν_e flux ($\cos\Theta_{zenith}$=-0.8)"

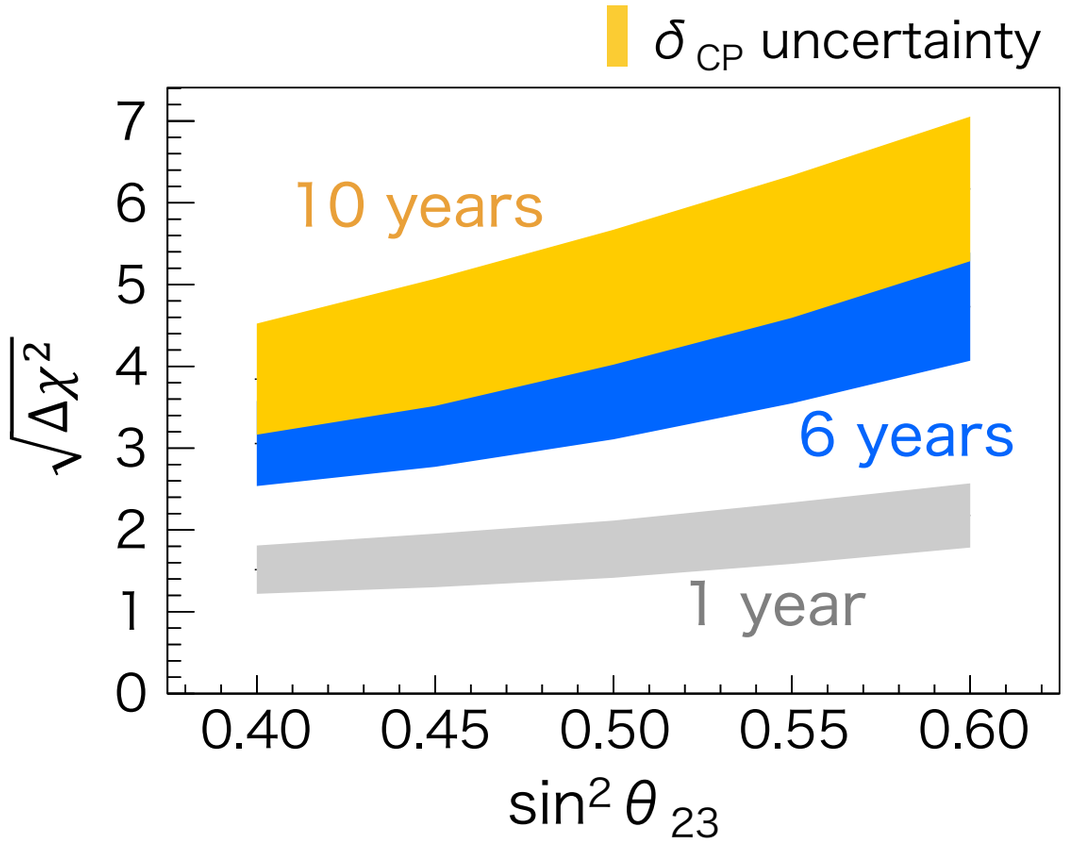


M. Shiozawa, NuTel 2017

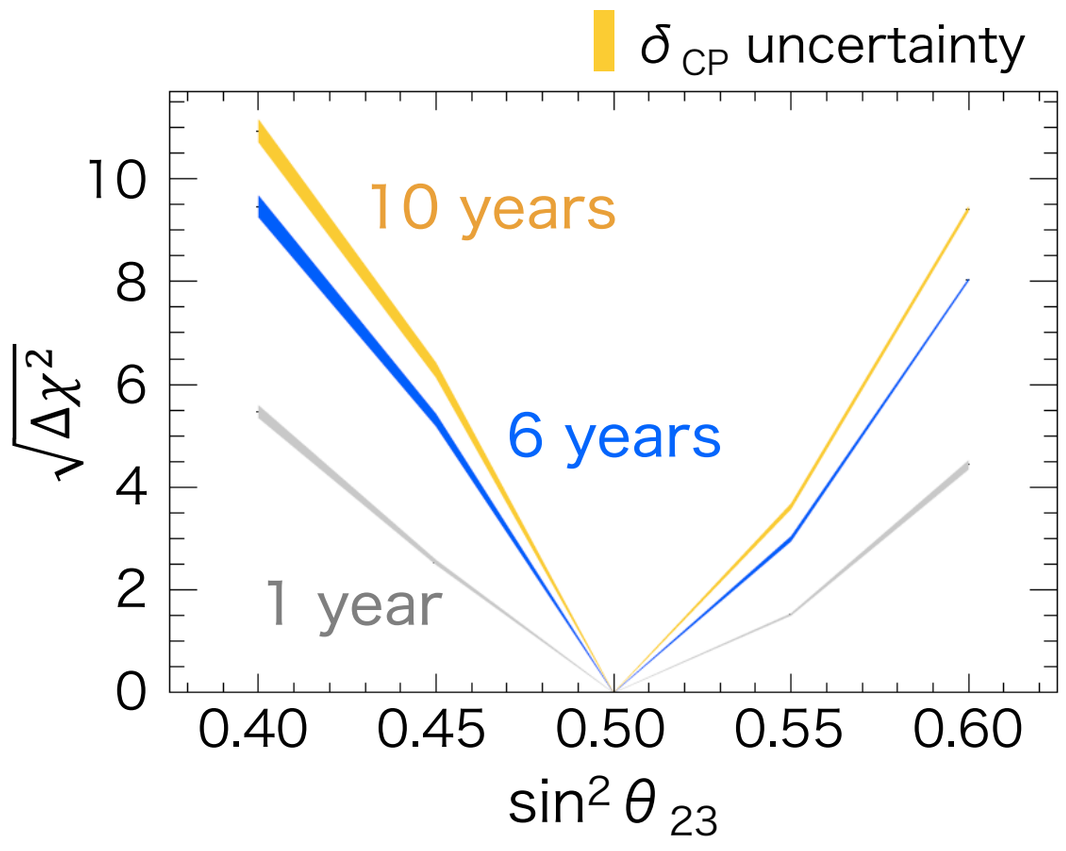
Atmospheric ν in Hyper-K

- Combining Atm-ν and Acc-ν data

wrong MH rejection



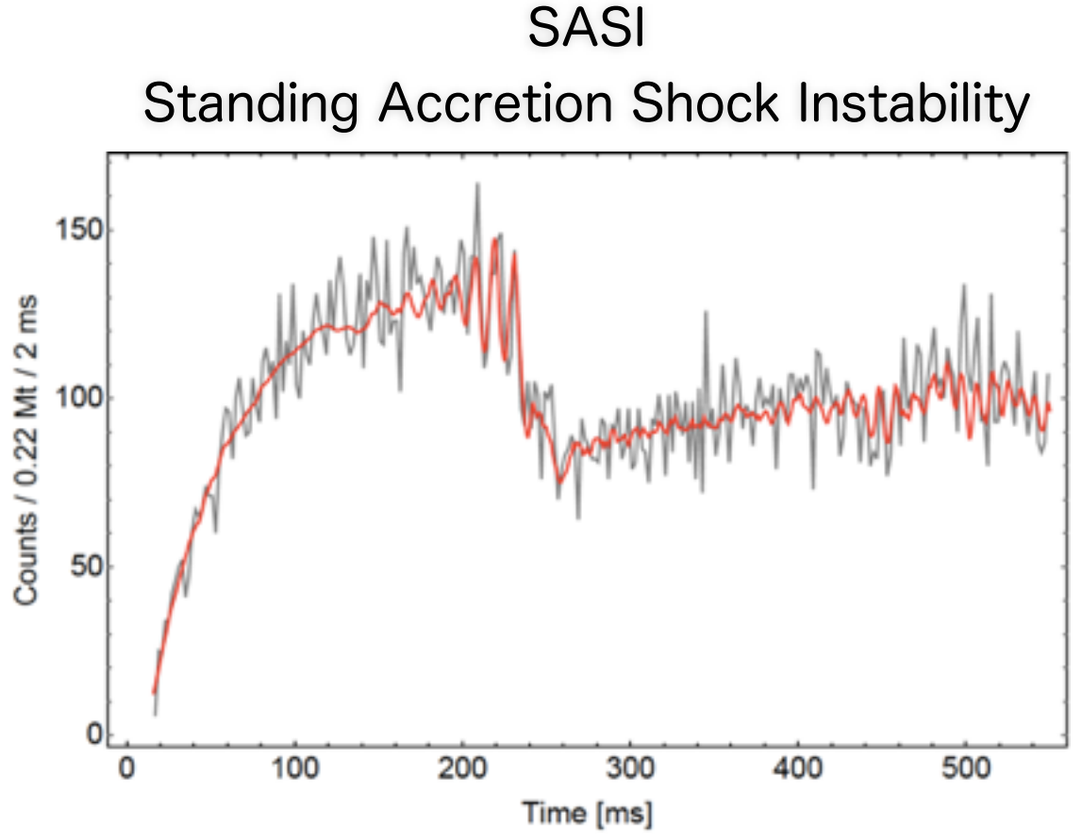
wrong octant rejection



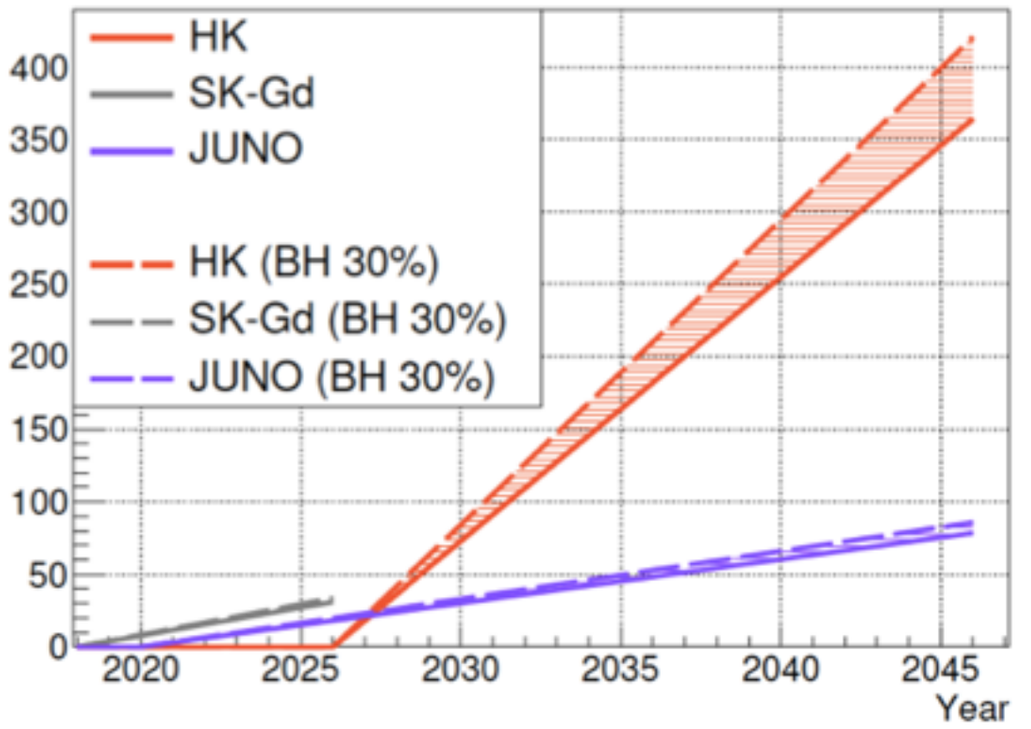
- $> 3\sigma$ determination for any θ_{23}
- Good chance to determine θ_{23} octant

Neutrino Astrophysics with HK

- Supernova burst ν
  - For SN@10kpc, 50-80k evts
  - 1deg. pointing resolution
  - Study detailed mechanism

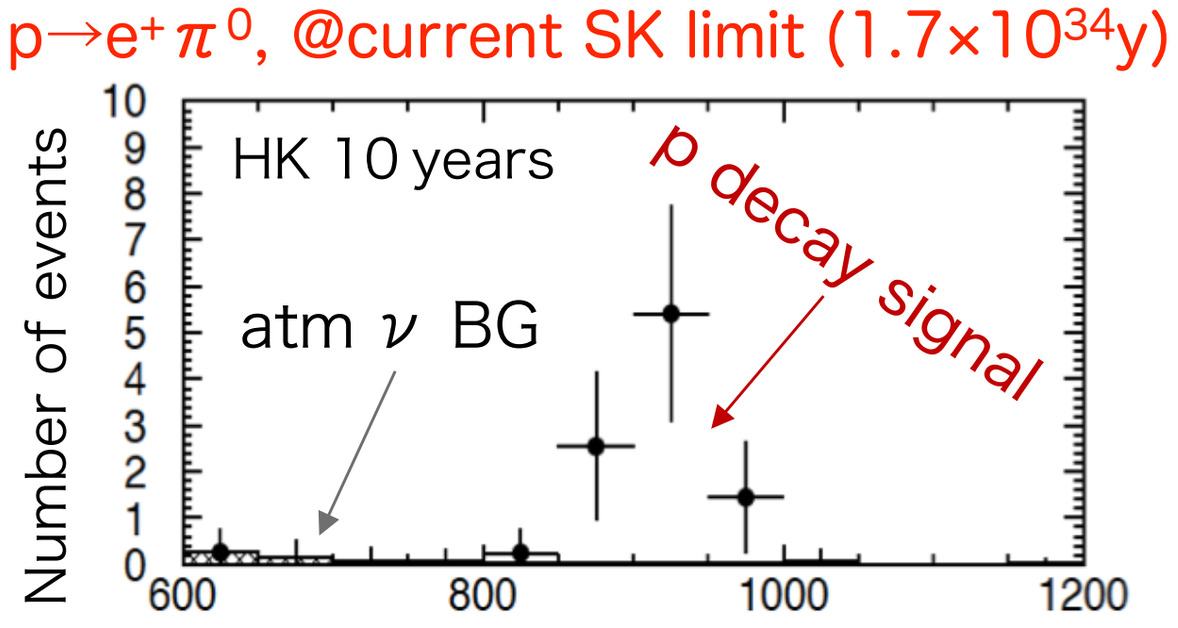


- Supernova Relic Neutrinos
  - Expect SK-Gd to discover 1st
  - High-stat measurement by HK
  - History of star/BH formation

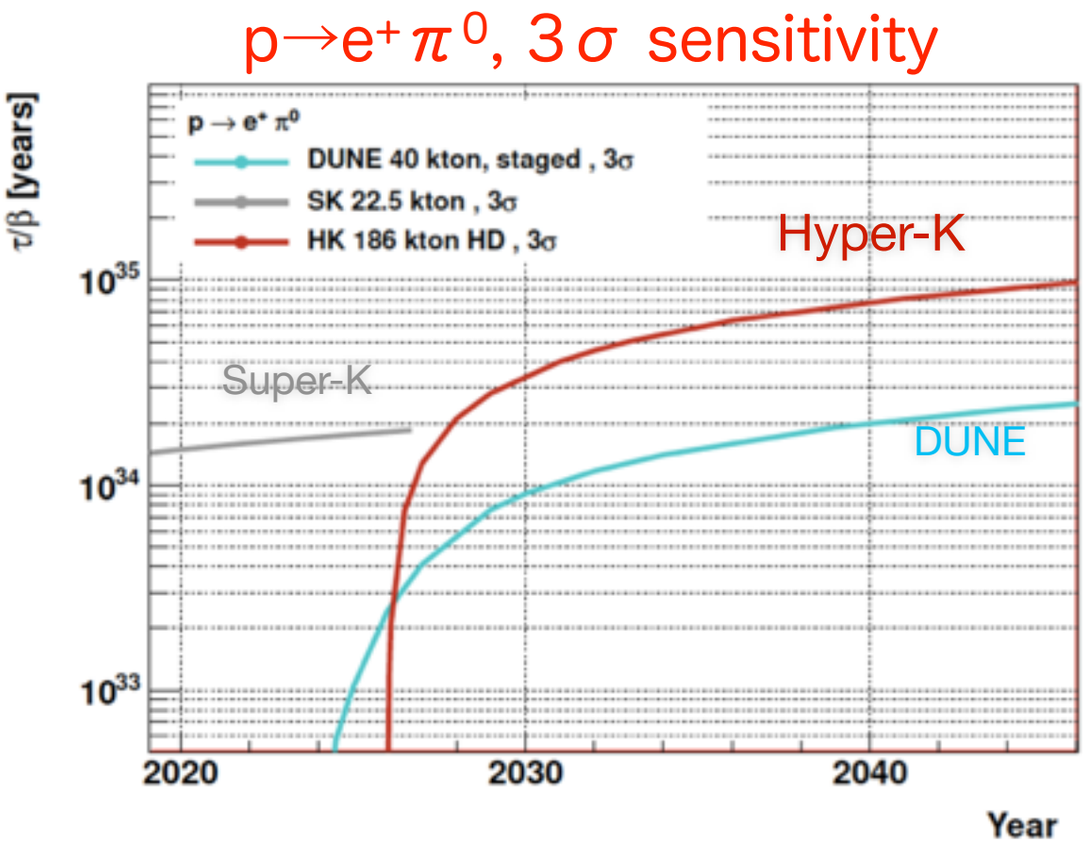


- Solar ν and more ...

Proton decay in HK



- Great potential for $e^+\pi^0$ mode, reaching 10^{35} years sensitivity
- Almost BG free
- Complementary to DUNE, who is good at νK mode



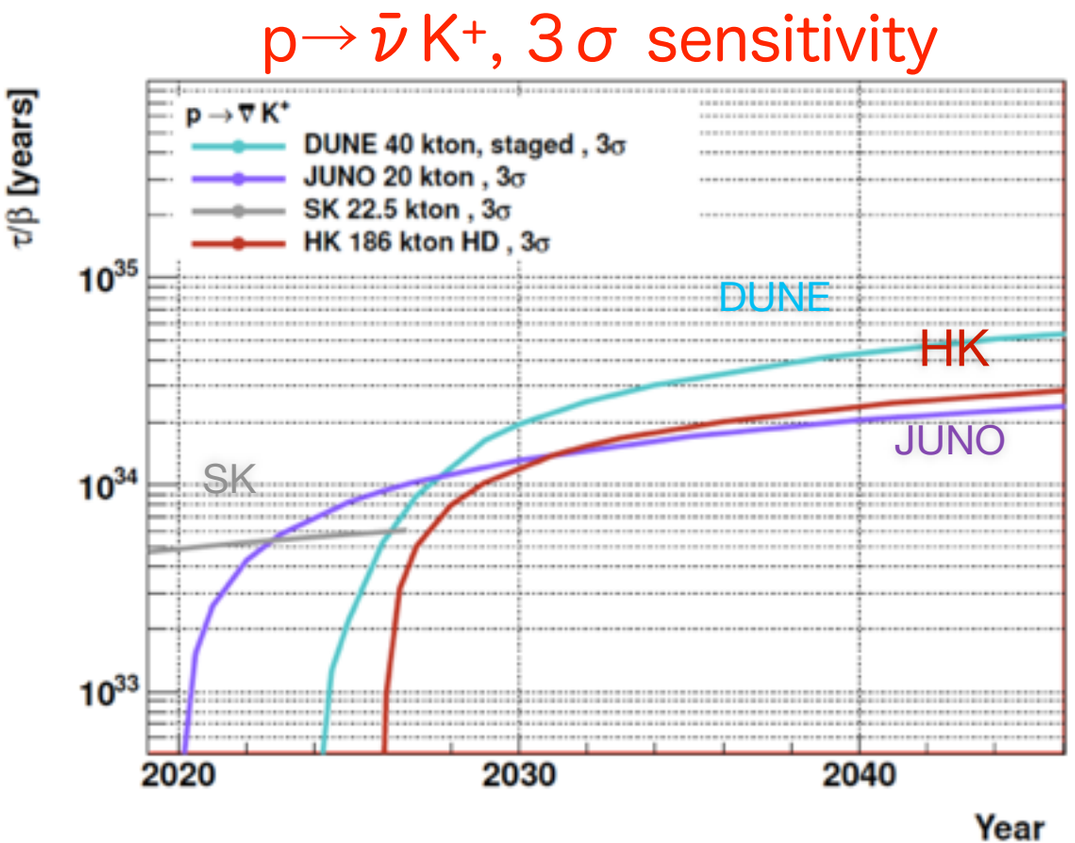
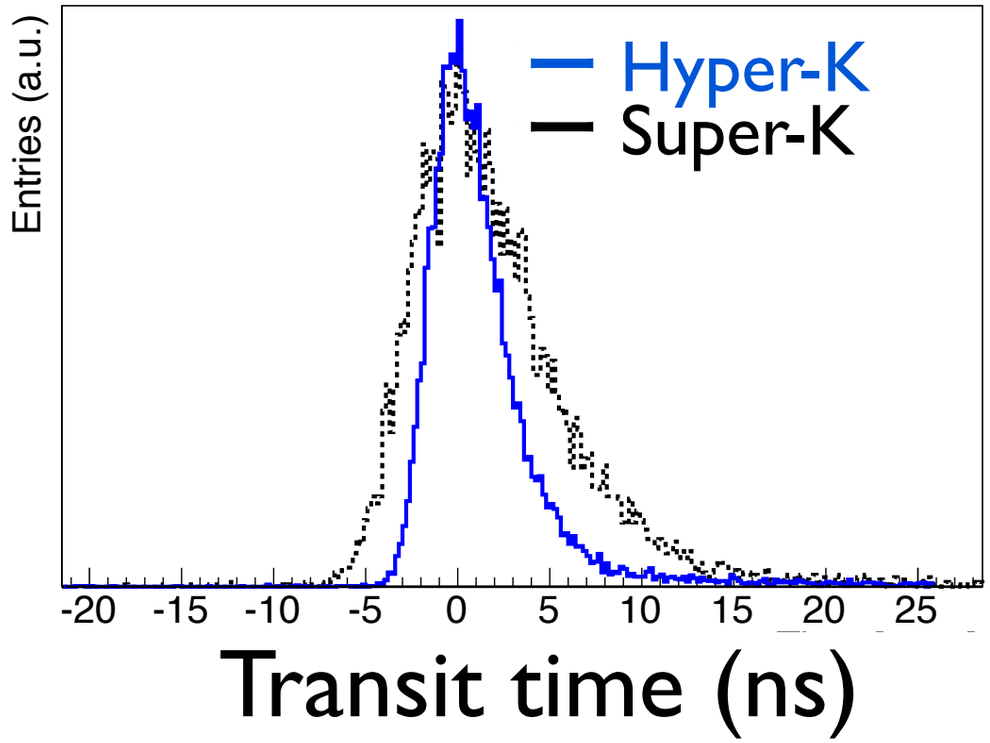
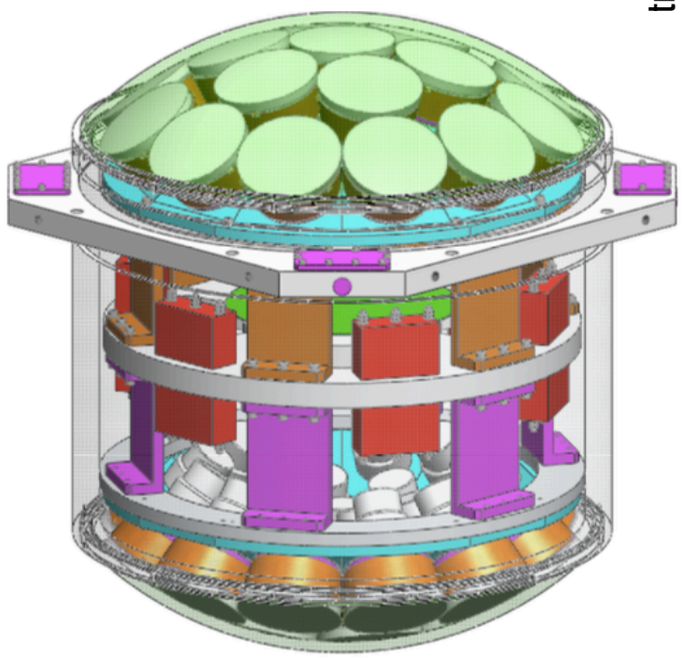


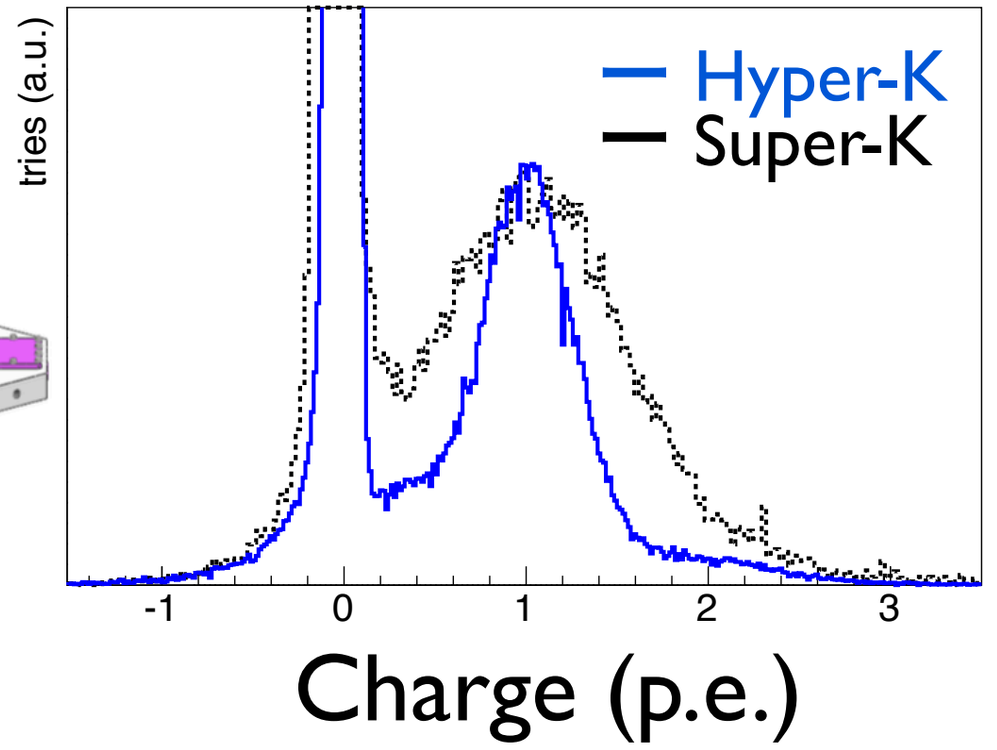
Photo-sensor R&D

- New “Box & Line” dynode PMT developed with Hamamatsu
- 2x efficiency, timing resolution, pressure tolerance
- New PMT cover developed



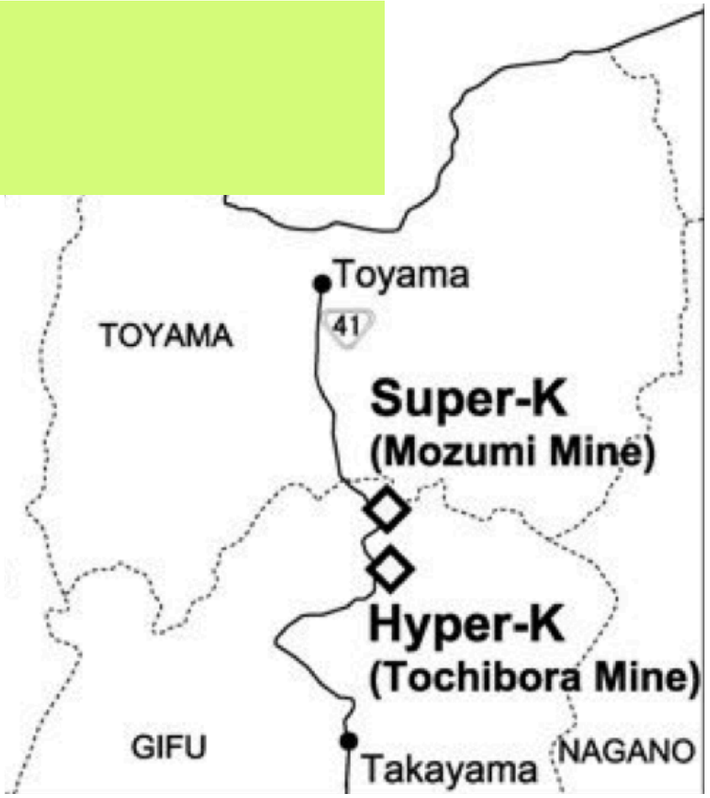
- As overseas contribution, also multi-PMT modules are in R&D



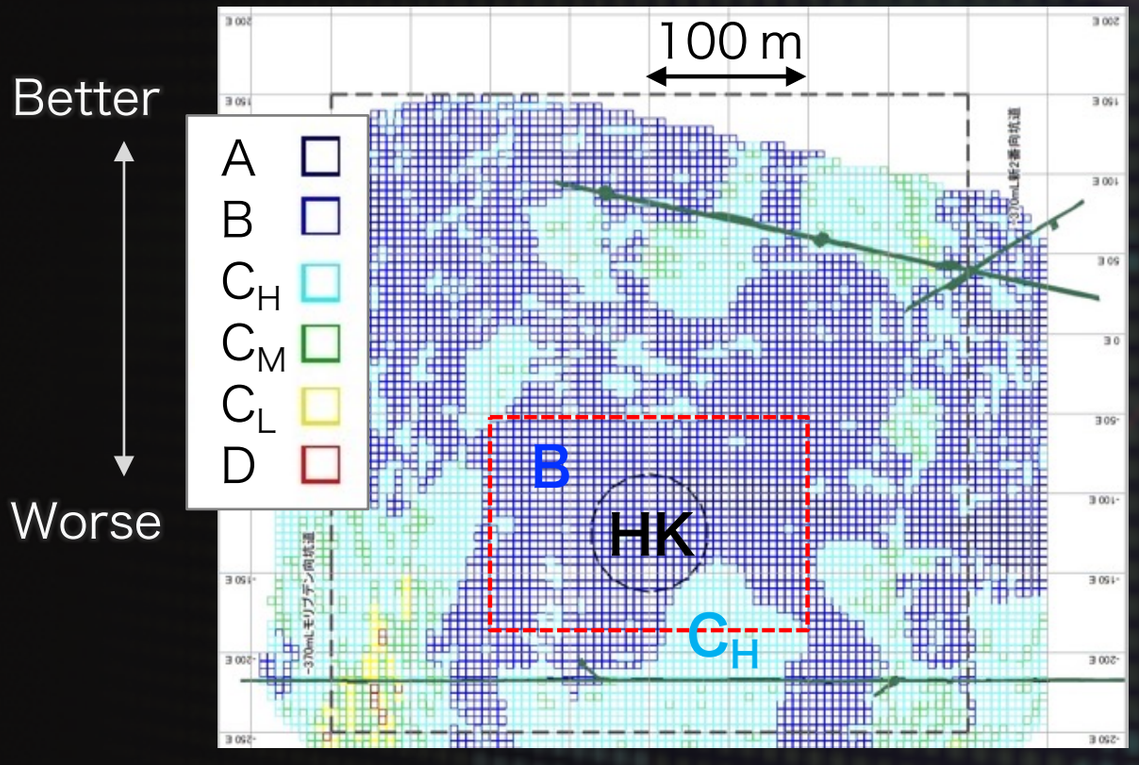


Candidate site

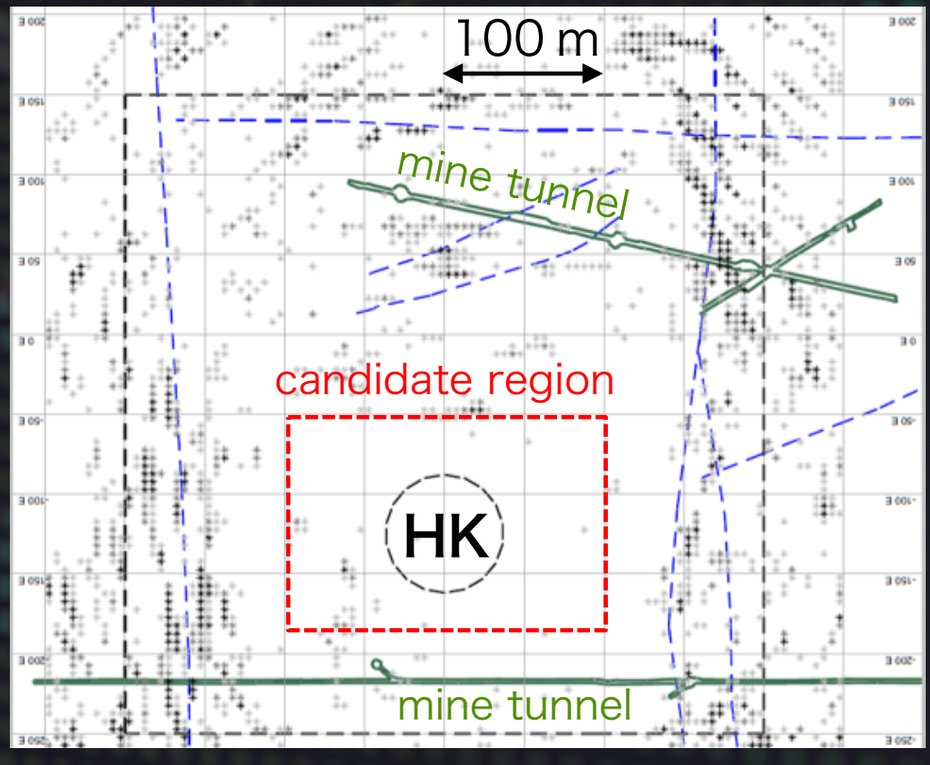
- 8 km south of Super-K
- Geological surveys with boring and seismic wave analysis



Rock grade (color)



Fracture zones (grayscale dots)

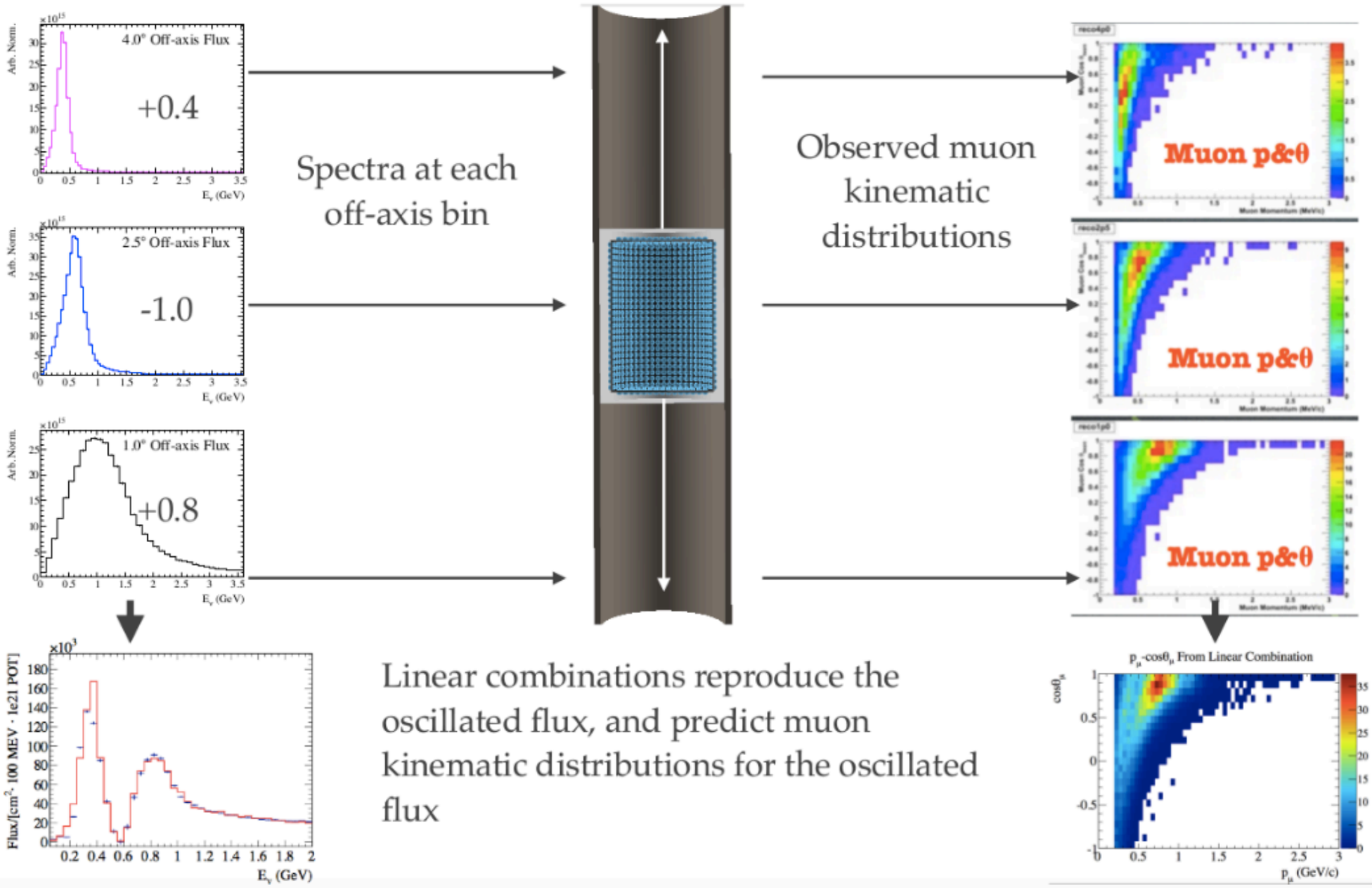


Confirmed that the rock condition is good enough.
Pinned down the candidate tank potion.

S. Nakayama
WIN 2017

Intermediate water detector

- Measure ν+H_2O events at varying off-axis angles (i.e. varying known ν spectra) @1~2 km, reducing systematics together with ND280 upgrade
- Superpose and predict interaction at Hyper-K (after oscillation!)
- Proposed as J-PARC E61 with international collaboration



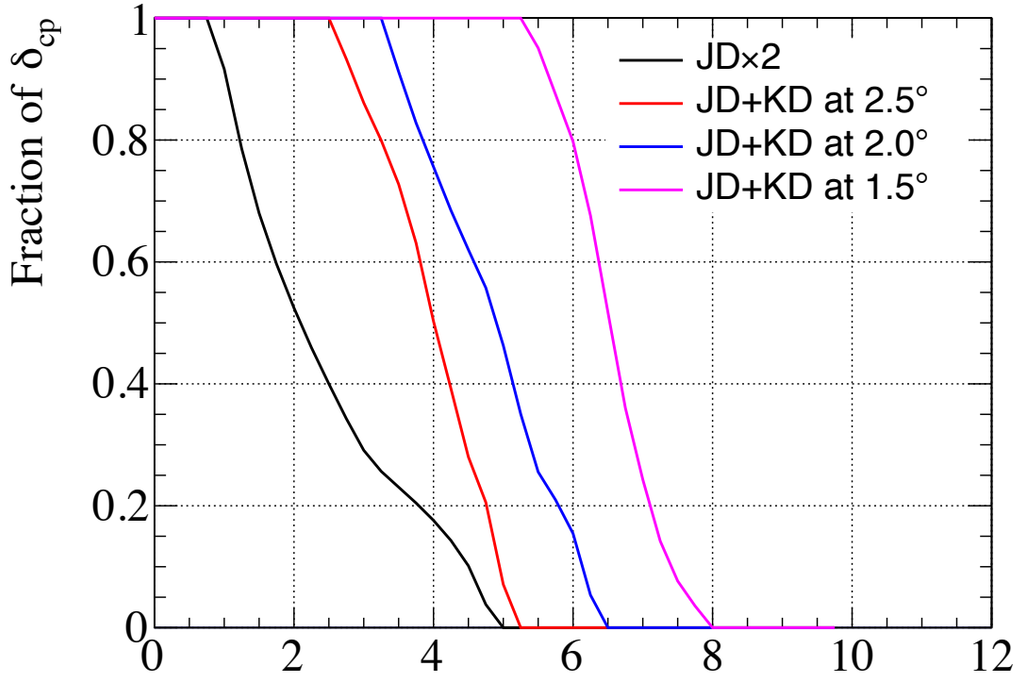
Project status

London, July 2016

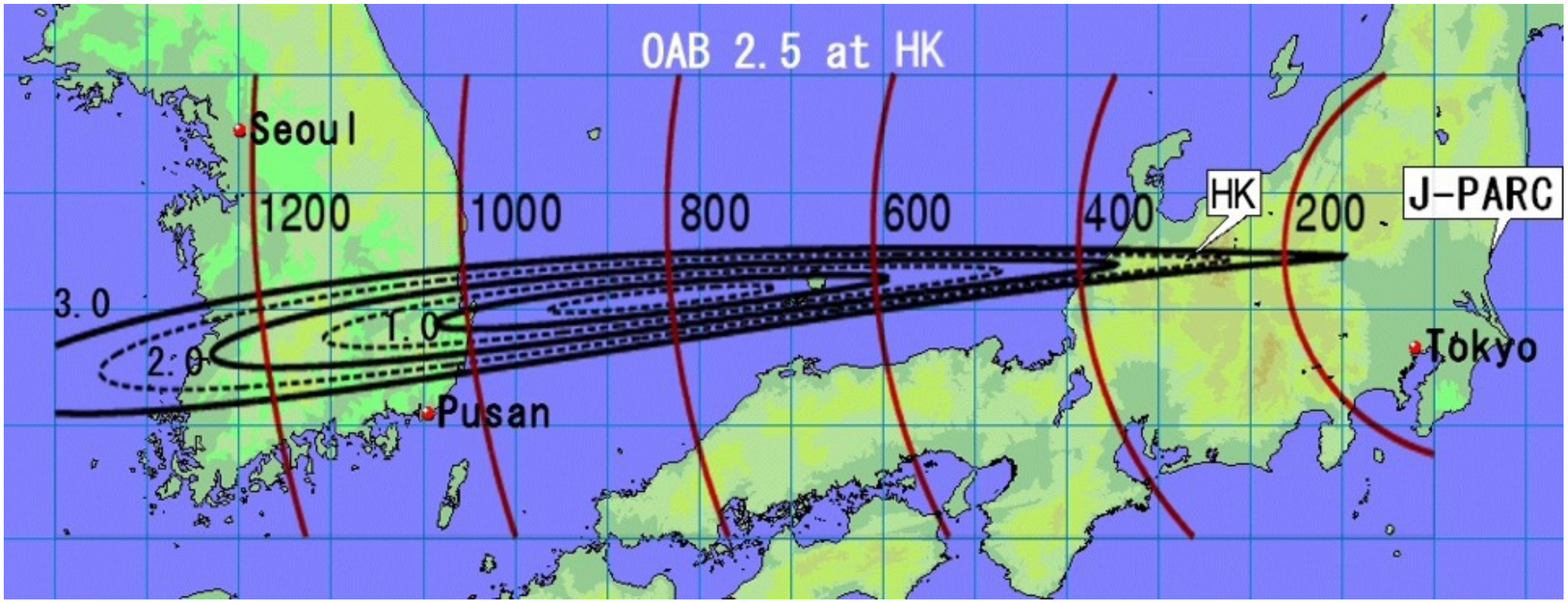
- Proto-collaboration formed since 2015
  - 300 members from 15 countries (70% overseas)
- Selected by Science Council of Japan as a top-priority large-scale project (Master Plan 2017)
- Selected by MEXT in Roadmap 2017 on promotion of large research projects
- Budget request submission being prepared

T2HKK (Tokai 2 HK & Korea)

- Idea to build a 2nd tank in Korea ("another" Off-Axis beam reaches Earth surface in Korea)
- L ~1100 km → large matter effect
  → Mass Hierarchy sensitivity
- > 5σ for any δ_{CP} value
- Also δ_{CP} precision improves



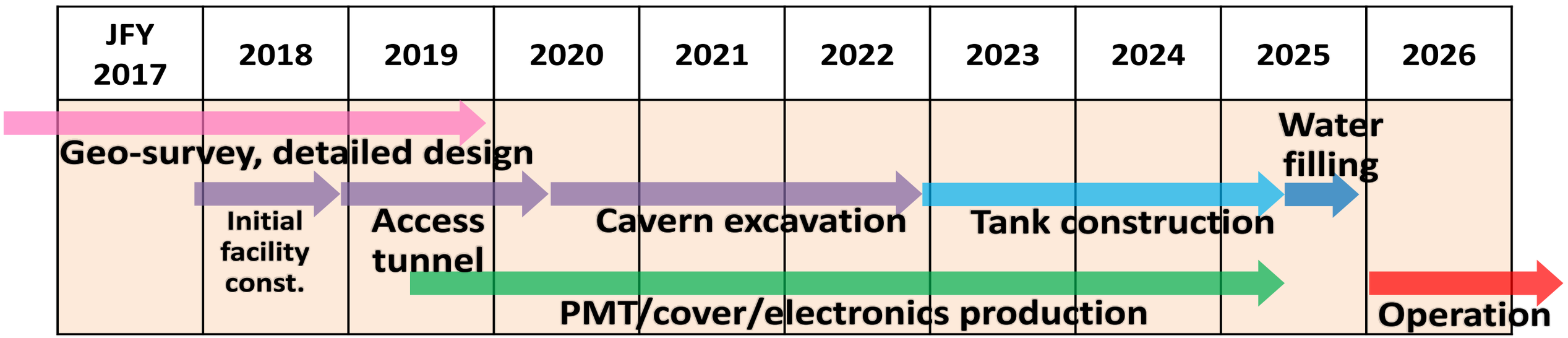
T2HKK White Paper
1611.06118



PLB 637(2006)266
PRD 76(2007)093002

Timeline and Summary

H.-K. Tanaka, TAUP 2017



- With x10 volume and x2 photo efficiency, Hyper-K will lead neutrino physics in the next generation.
- Proven technology of Water Cherenkov promises fastest physics.
- Very good chance to observe leptonic CP violation, further precise measurement to explore new physics.
- Rich physics programs with acc.-, atm.- astro- neutrinos and nucleon decay search.
- Please join!