Hyper-Kamiokande

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for the Hyper-Kamiokande Working Group

Remaining Issues for Large Neutrino Experiments in future

- **Neutrino Oscillation (Atmospheric ν and Accelerator ν beam (J-PARC))**
  - ***θ_{23} by SK in 1998; θ_{12} by SNO+SK in 2001; θ_{13} by T2K(SK) in 2011.***
  - ➔ CP phase, Mass Hierarchy, Octant of θ_{23}
- **Astrophysical Neutrinos**
  - Solar neutrinos
  - ➔ Upturn (Sterile?), Day/Night (Earth's Matter Effect)
  - Neutrinos from Supernovae
  - ➔ Detailed explosion mechanism (ν Burst); Past history of the Universe (Relic SN ν)
- **Proton Decay**
  - ***2012 ($\tau[e^+\pi^0] > 1.3 \times 10^{34}$ years by SK)***
  - ➔ In the region of 10^{35} years (test of GUTs)
- **Dark Matter (Neutrinos from GC, Sun and Earth)**

Hyper-Kamiokande Detector

Reference: LOI by Hyper-K WG, arXiv: 1109.3262 [hep-ex]

- **Total vol.** ~1 Megaton
  - Outer vol. 0.2 Mton
  - Inner vol. 0.74 Mton
- **Fiducial vol.** 0.56 Mton
  - (0.056 Mton x 10 comp.)

X 25 of Super-Kamiokande

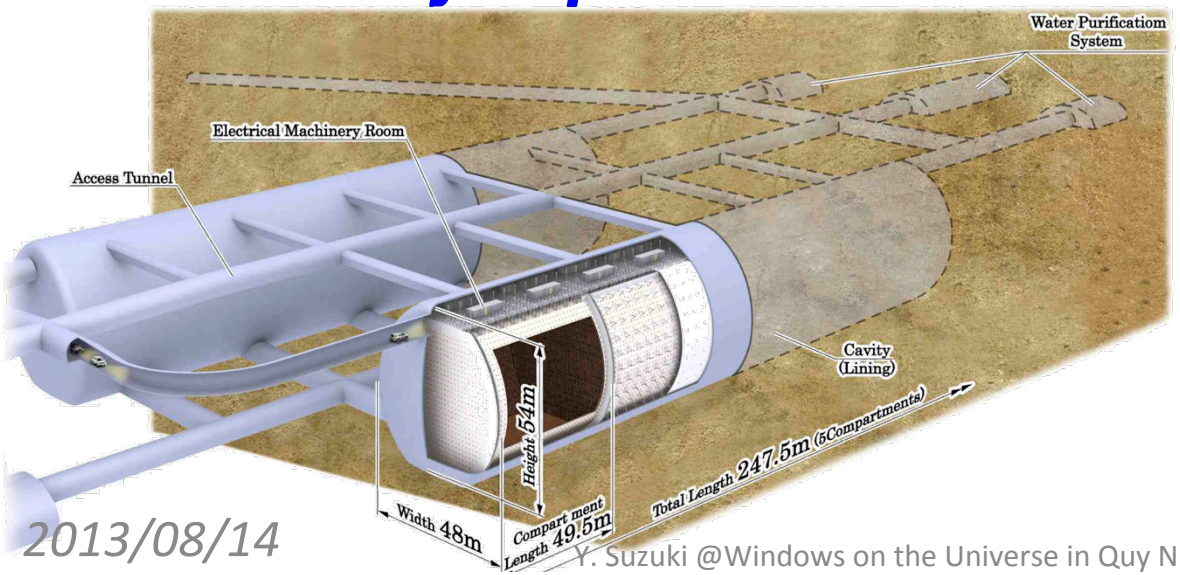
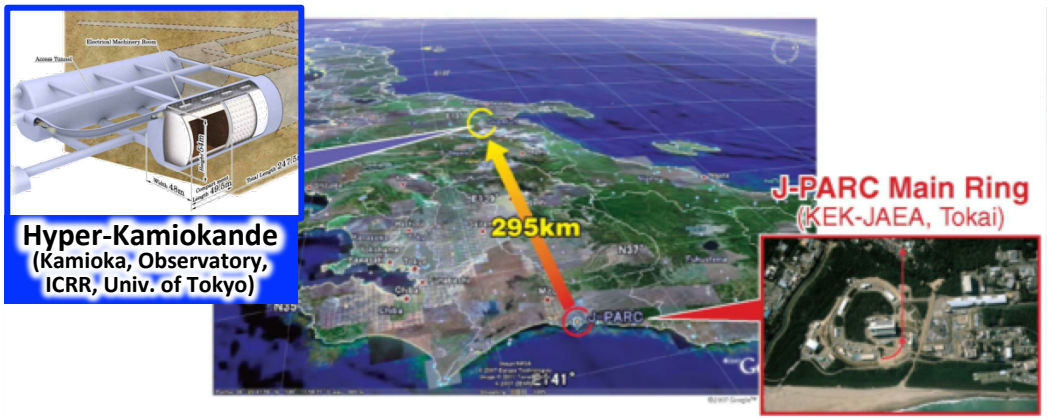


Photo-sensors

- 99,000 of 50 cm diameter light sensors for the Inner Detector (20% photo-coverage ⇔ 40% (SK))

  [May need higher sensor density compartment]
- 25,000 of 20 cm ϕ light sensors for the Outer Detector

CPV measurement w/ J-PARC ν
Extension of T2K with Hyper-K



- Distance: 295 km (short)
  - ➔ less matter effect: good for CP measurement
- 2.5 deg. Off-Axis Beam
  - ➔ low energy (~0.6 GeV) and narrow band beam

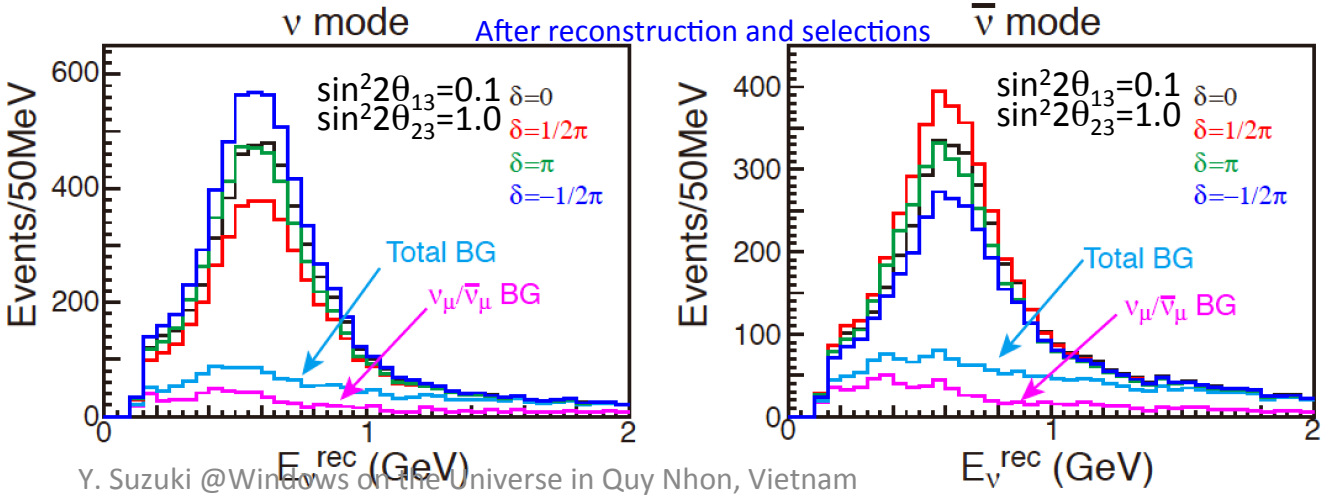
Same as T2K ⇔ LBNE, LBNO

Look for $\overset{(-)}{\nu}_\mu$ ➔ $\overset{(-)}{\nu}_e$ appearance

Assumption: Total 7.5 MW year of running

- ν mode: 0.75 MW x 3 yrs and $\bar{\nu}$ mode: 0.75 MW x 7 years

Reconstructed Neutrino Energy

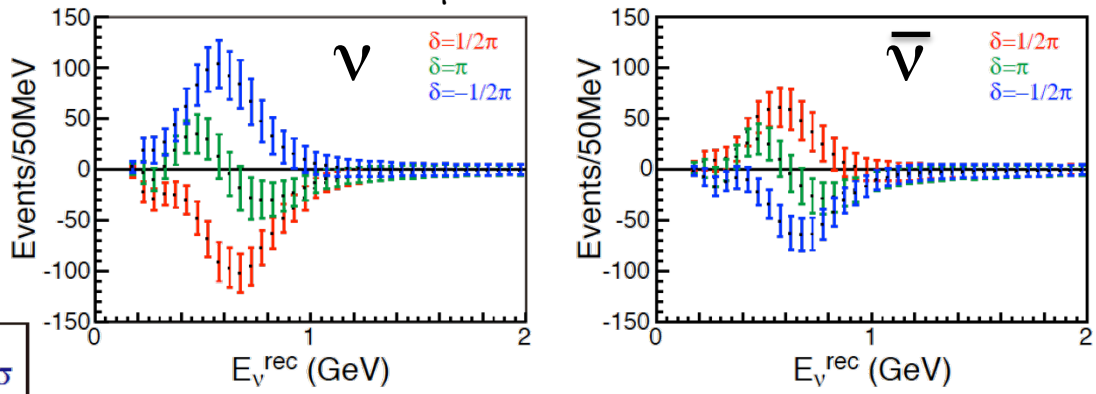


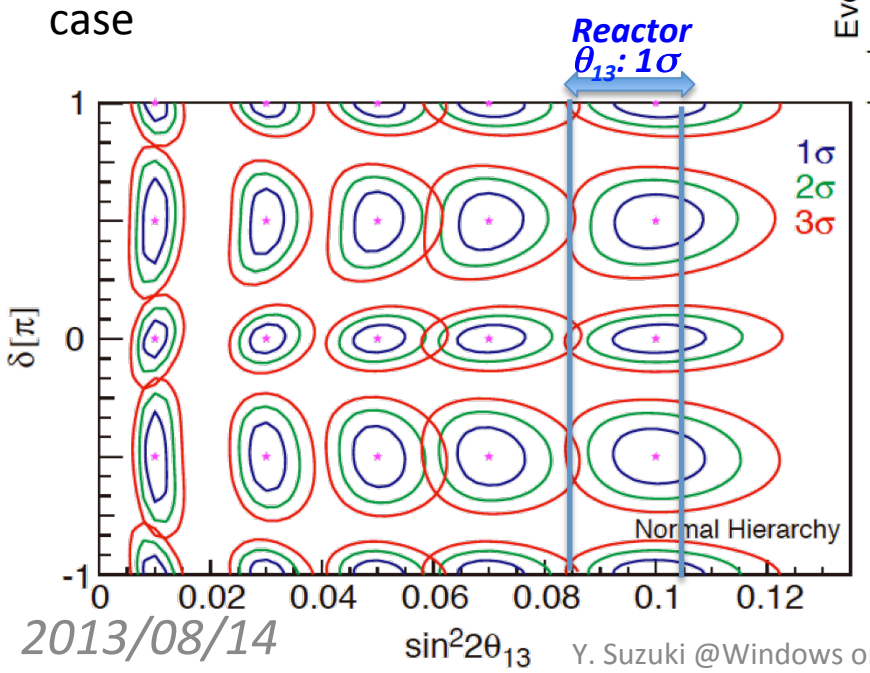
CPV measurement w/ J-PARC ν
Extension of T2K with Hyper-K

For total 7.5 MWyr of running

- ~3,500 ν_e signal (total ~1600 BG); ~2,000 $\overline{\nu}_e$ signal (Total ~2000 BG)
- Major BG: Beam $\nu_e/\overline{\nu}_e$ and NCπ^0;
  Wrong sign appearance of ν_e in $\overline{\nu}_\mu$ beam

Difference of the reconstructed neutrino energy distribution for δ_{CP} = 1/2π, π,-1/2π from δ_{CP} = 0 case





- 5% systematics on signal, $\overline{\nu}_\mu$ BG, $\overline{\nu}_e$ BG

➔

- δ_{CP} resolution < 10° (@ δ_{CP}=0)
- Fractional δ range (CP can be discovered):
  - ✧ 74% with more than 3σ (known MH)
  - ✧ 55% with more than 3σ (MH not-known)

Atmospheric neutrinos

ν_e appearance in 3 flavor oscillation

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1)$$
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin^2\theta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2)$$
$$-2\sin^2\tilde{\theta}_{13}(1 - r \cdot \sin^2\theta_{23})$$
$$-\sin^2\tilde{\theta}_{13}P_2(r - 2) + \sin^4\tilde{\theta}_{13}(1 - r\sin^2\theta_{23})(2 - P_2)$$

Solar term

Interference term; δ_{CP}

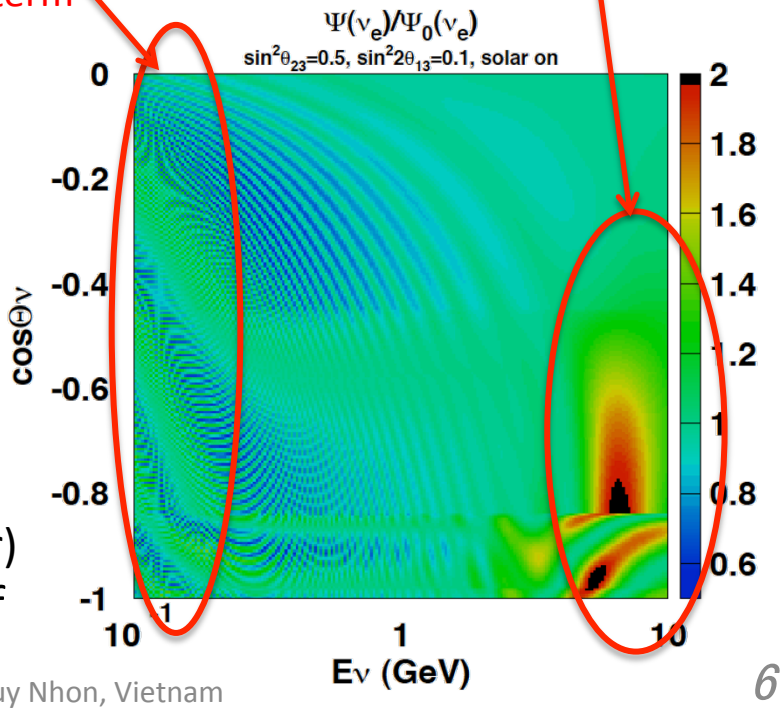
Ue3 term; matter enhancement

Negligible Ue3 term

- ~ : mixing angle in matter
- $P_2 = |A_{e\mu}|^2$: $\nu_\mu \rightarrow \nu_e$ in matter
- $R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$, $I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

- **Mass hierarchy**
  - Ue3 matter enhancement
    - $\Delta m_{13}^2 = 2.4\times10^{-3}$ eV^2 ➔ ~10GeV
  - Resonance condition ($\pm V \sim \Delta m^2$)
    - NMH ➔ ν undergoes resonance, but not $\bar{\nu}$
    - IMH ➔ $\bar{\nu}$ undergoes resonance, but not ν
- **Octant of θ_{23}**
  - Many places: different ways to show up for different samples
- **CP-phase**
  - Interference term (Higher resonance eff is better)

➔ Atmospheric neutrinos have a clear signature of those effects



Atmospheric neutrinos

ν_e appearance in 3 flavor oscillation

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2\theta_{23} - 1) \quad \text{Solar term}$$

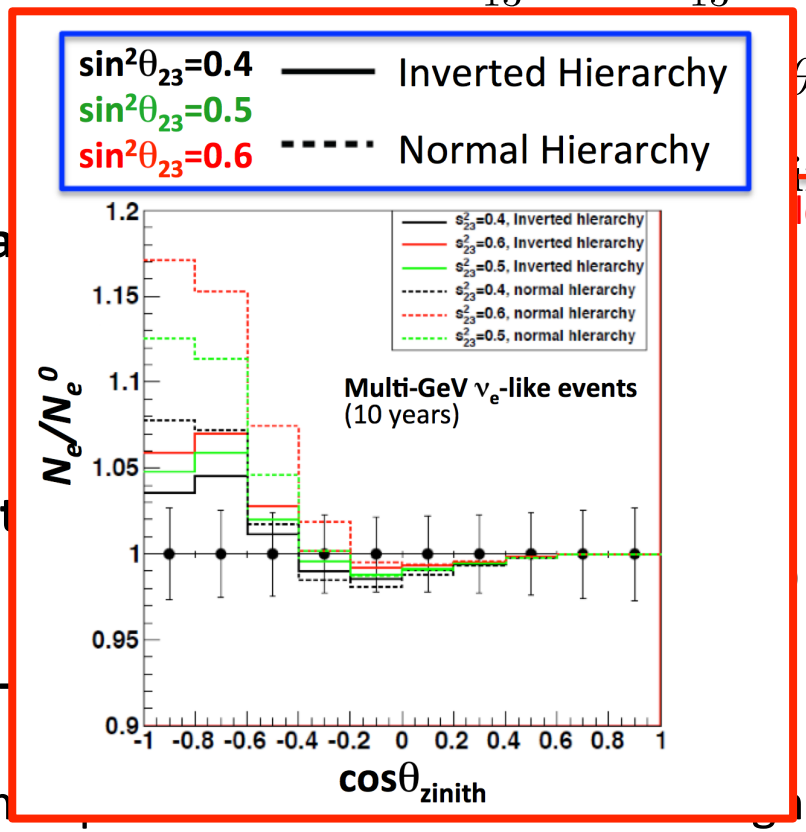
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin^2\theta_{23}(\cos\delta_{CP} \cdot R_2 - \sin\delta_{CP} \cdot I_2) \quad \text{Interference term; } \delta_{CP}$$

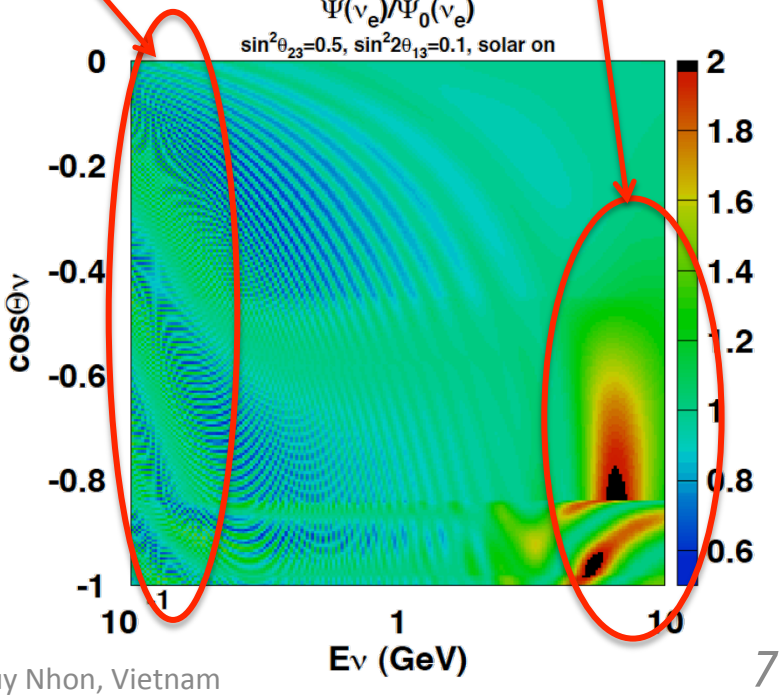
$$\sin^4\tilde{\theta}_{13}(1 - r\sin^2\theta_{23})(2 - P_2) \quad \text{Ue3 term; matter enhancement}$$

- ~ : mixing angle in matter
- $P_2 = |A_{e\mu}|^2$: $\nu_\mu \rightarrow \nu_e$ in matter
- $R_2 = \mathrm{Re}(A^*_{ee}A_{e\mu})$, $I_2 = \mathrm{Im}(A^*_{ee}A_{e\mu})$

- **Ma**
  - –
  - –
- **Oct**
  - – for
- **CP-**
  - –

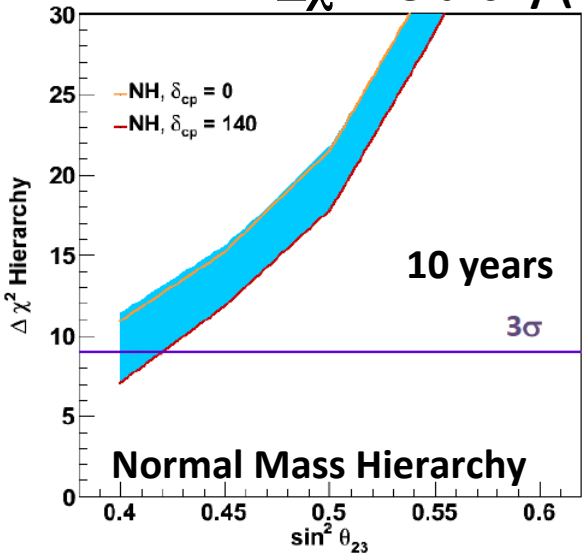
➔ Atn ature of those effects

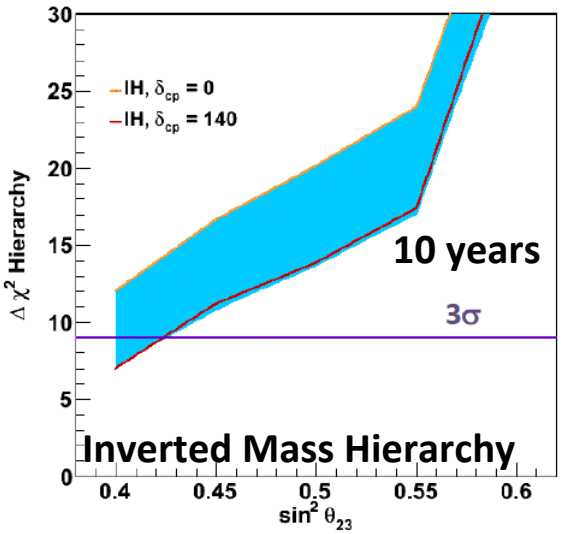




Atmospheric neutrinos

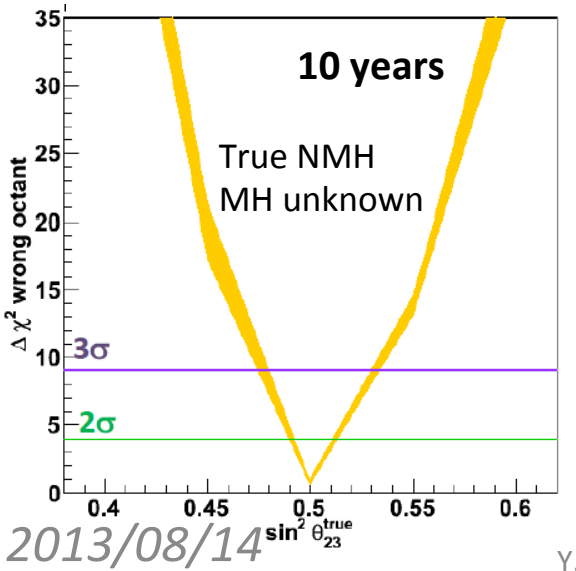
$\Delta\chi^2$ hierarchy (wrong hierarchy rejection)

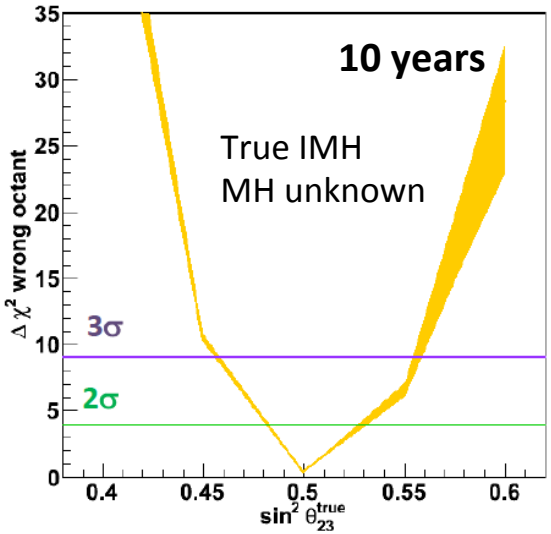




Mass hierarchy determination

- $\sin^2 2\theta_{13}$=0.10 fixed
- Thickness of band: range of CP
- Sensitivity depends on θ_{23}
- Mass Hierarchy will be determined @>3σ for $\sin^2\theta_{23}$ > 0.42 (0.43) [normal(inverted)]





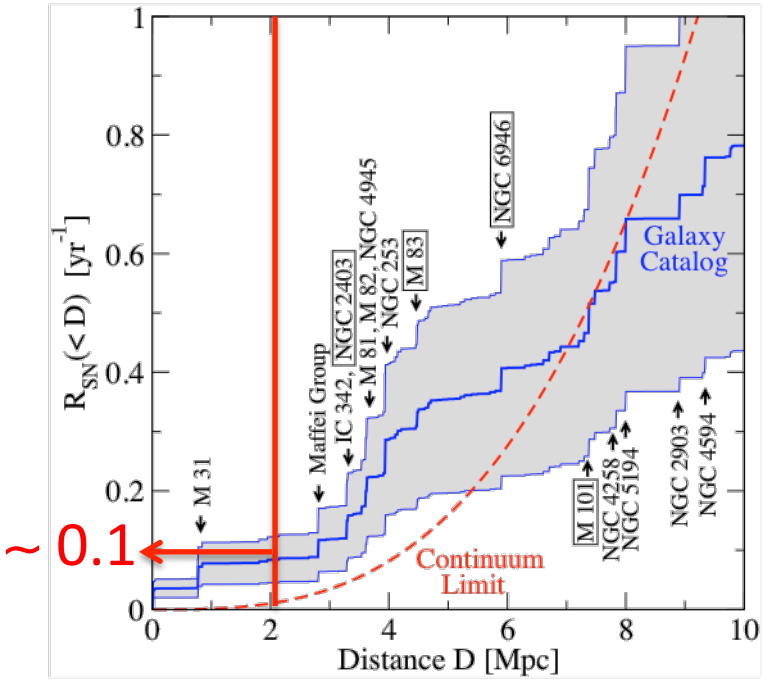
θ_{23} Octant determination

- $\sin^2 2\theta_{13}$=0.10 fixed
- Octant can be determined @ >3σ if $\sin^2\theta_{23}$ < 0.47 (0.45) and $\sin^2\theta_{23}$ > 0.53 (0.56) for normal (inverted) mass hierarchy

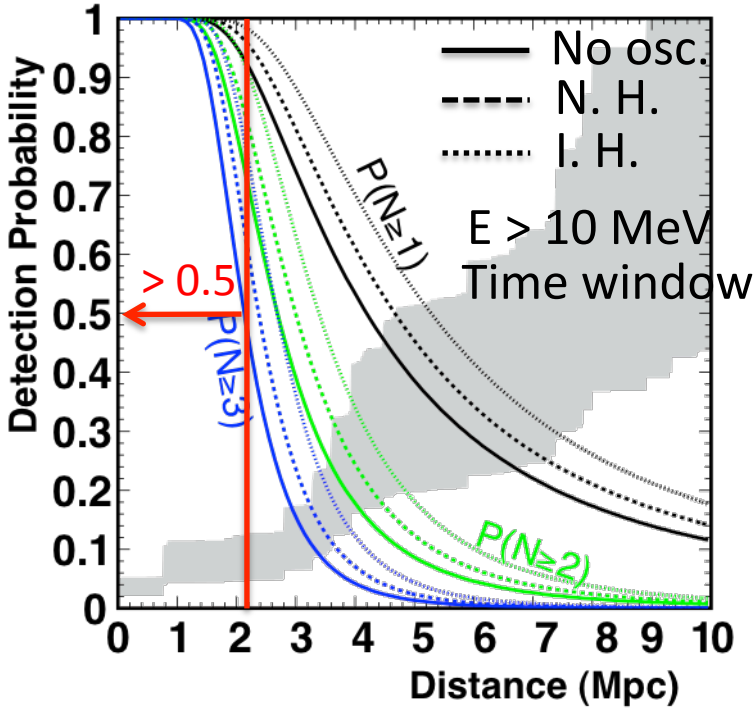
Supernova neutrinos

- Supernovae in nearby galaxies

Cumulative supernova rate



Hyper-K detection probability

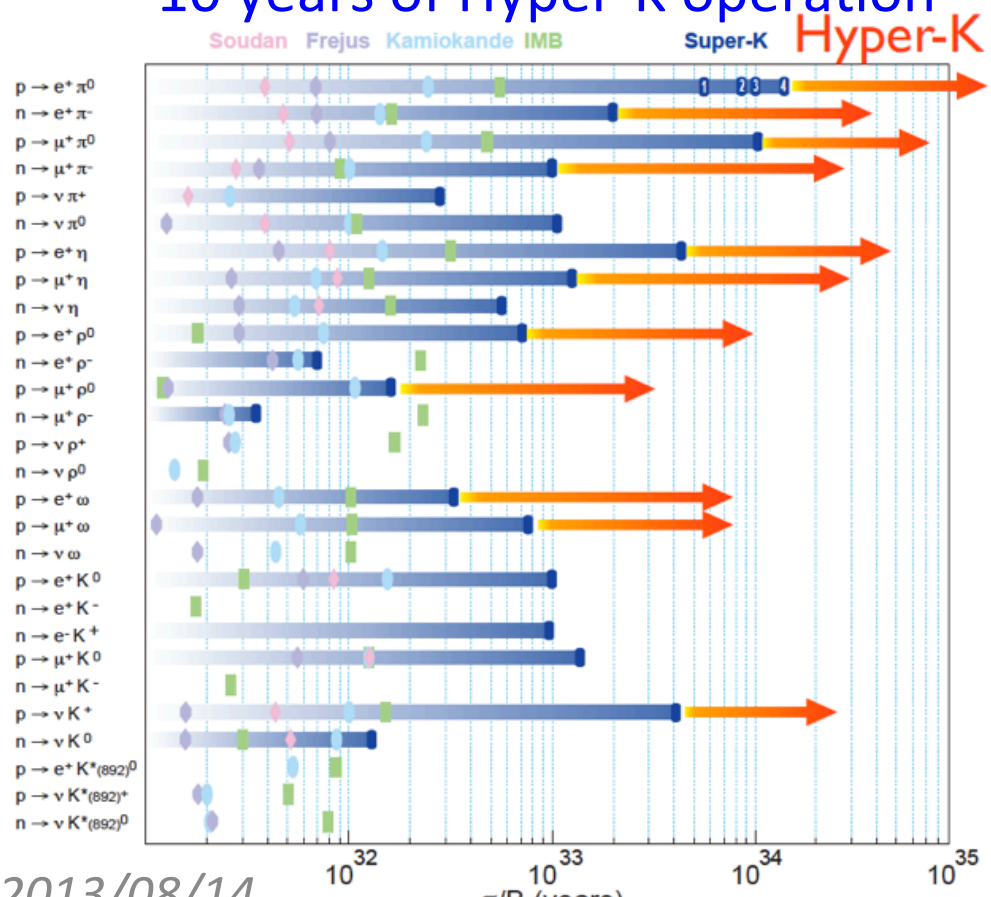


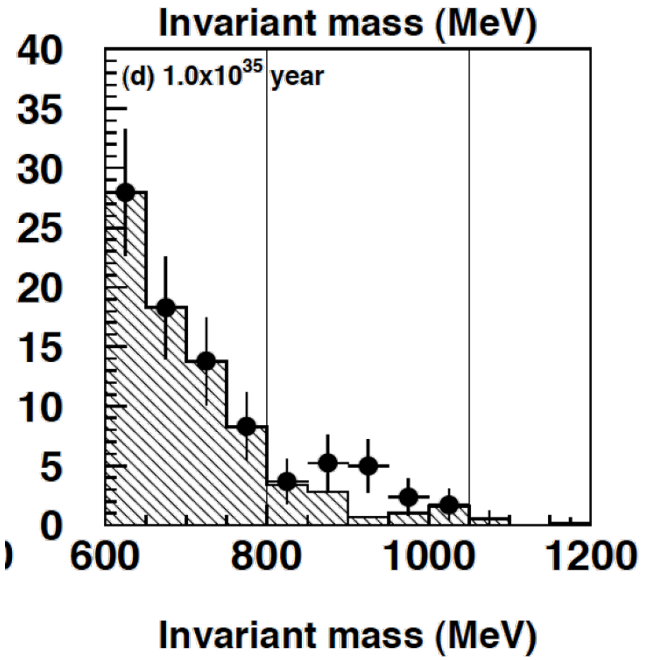
- >50% efficiency is estimated for required signal multiplicity of 3 for SN at 2 Mpc distance.
- 1 SN about every 10 years is expected within 2 Mpc.

Nucleon decay

- 10 times better sensitivity than Super-K.
  - Only realistic plan to go beyond 10^{35} years for $p \rightarrow e^+\pi^0$

10 years of Hyper-K operation





$e^+ + \pi^0$

- 1.3×10^{35} years (90% C.L.)
- 5.7×10^{34} years (3σ discovery)

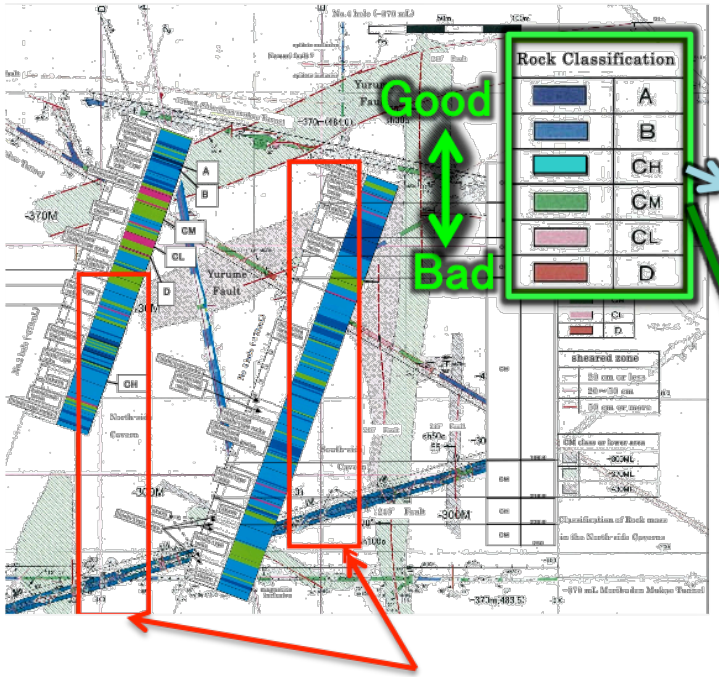
$\nu + K^+$ (SUSY favored)

- 3.2×10^{34} years (90% C.L.)
- 1.2×10^{34} years (3σ discovery)

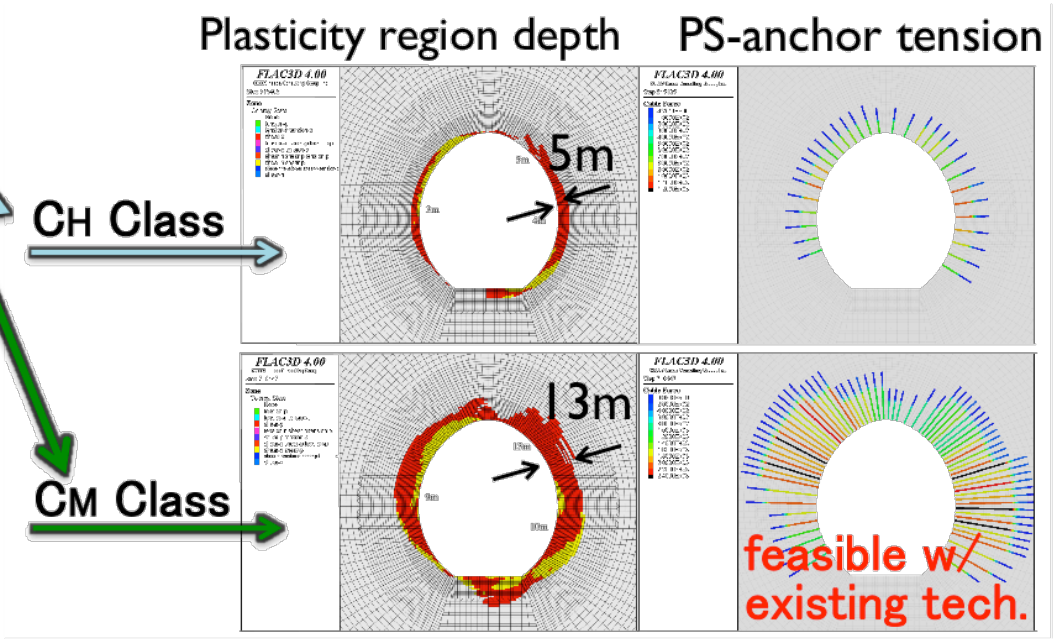
A candidate site and Cavern stability analysis

- Candidate site
  - 8 km south from Super-K
  - 648 m of rock overburden (1,750 m.w.e)

Rock Classification

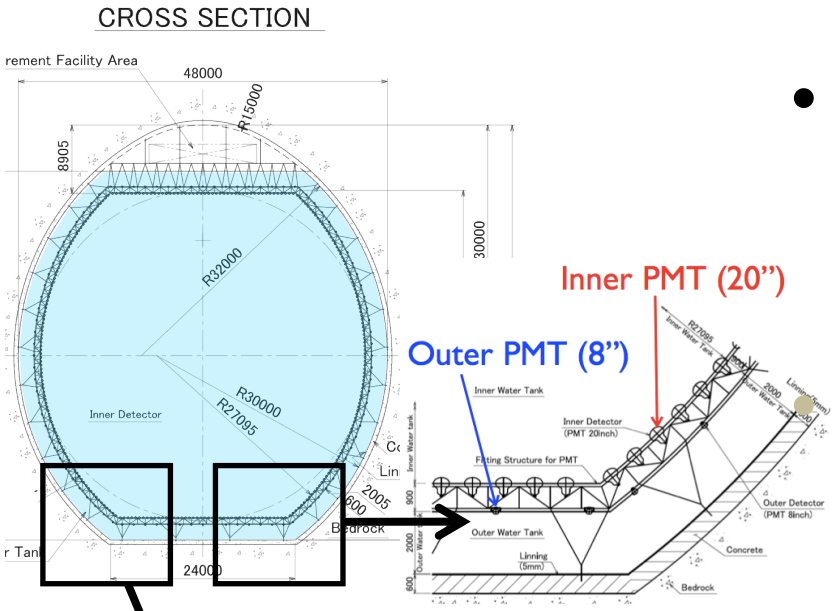


Required Pre-Stressed (PS) anchors



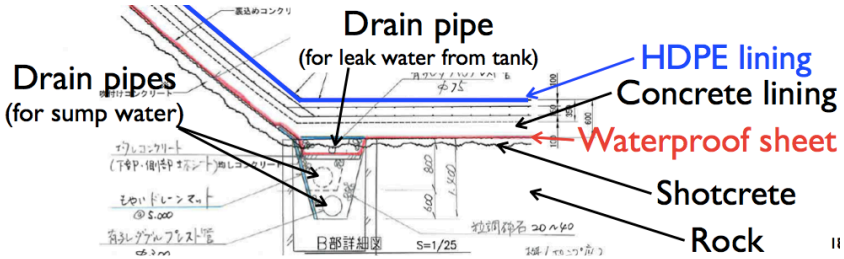
For all rock mass classes ➔ B, CH, CM
HK caverns can be constructed.

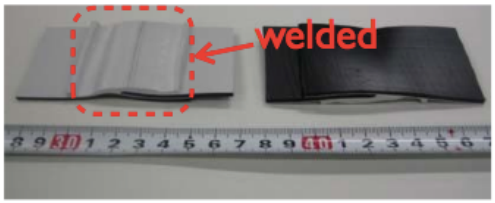
Tank and photo-sensor support



- Baseline design of the water containment system and photo-sensor support are ready
- Build a prototype detector (1kt)
  - Funding request approved

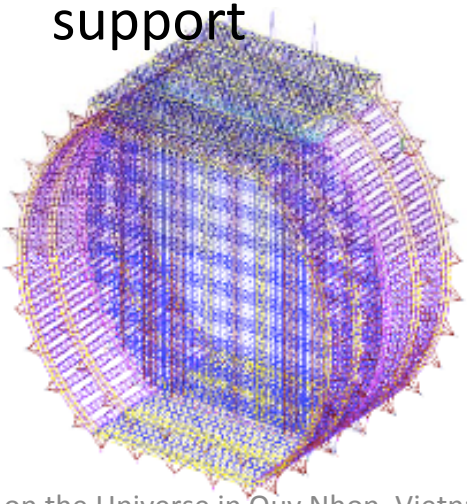
Lining & drain system



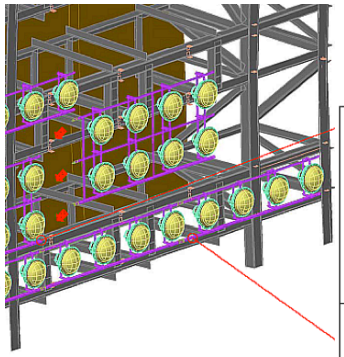


Polyethylene sheet

Photo-sensor support



Mounting Photo-sensor



Housing

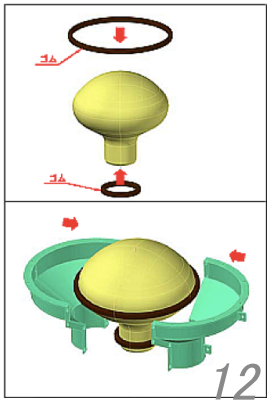
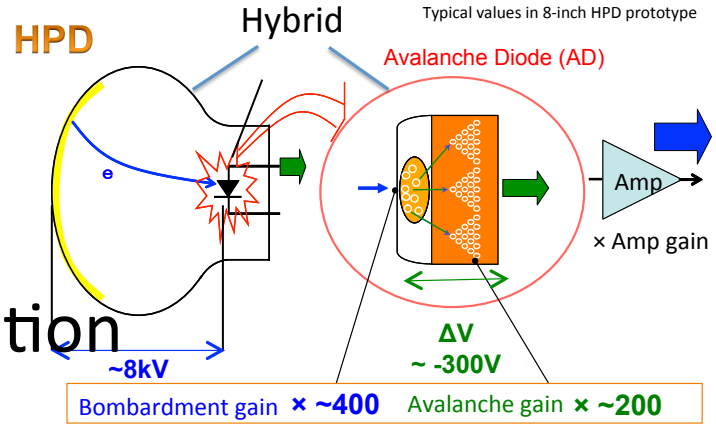
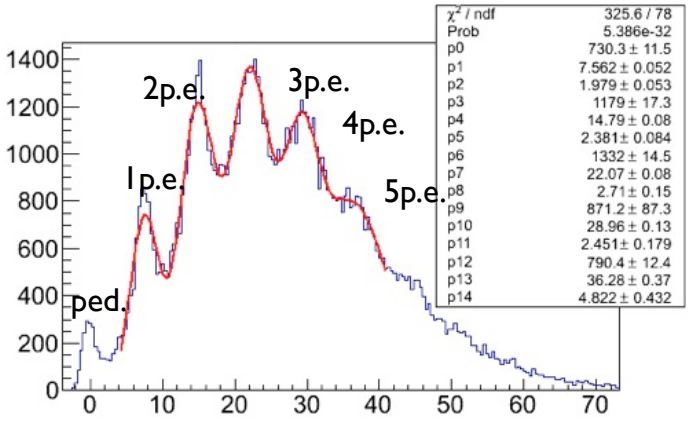
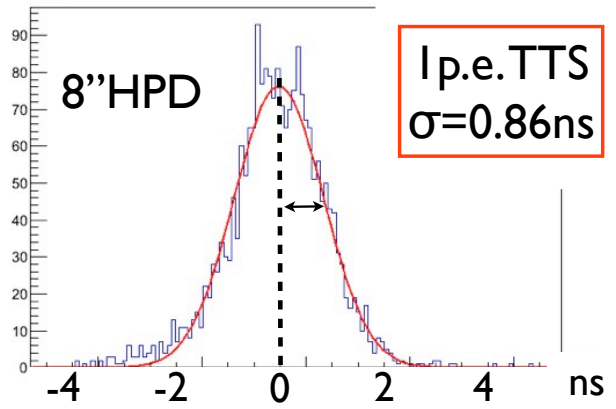


Photo-sensor

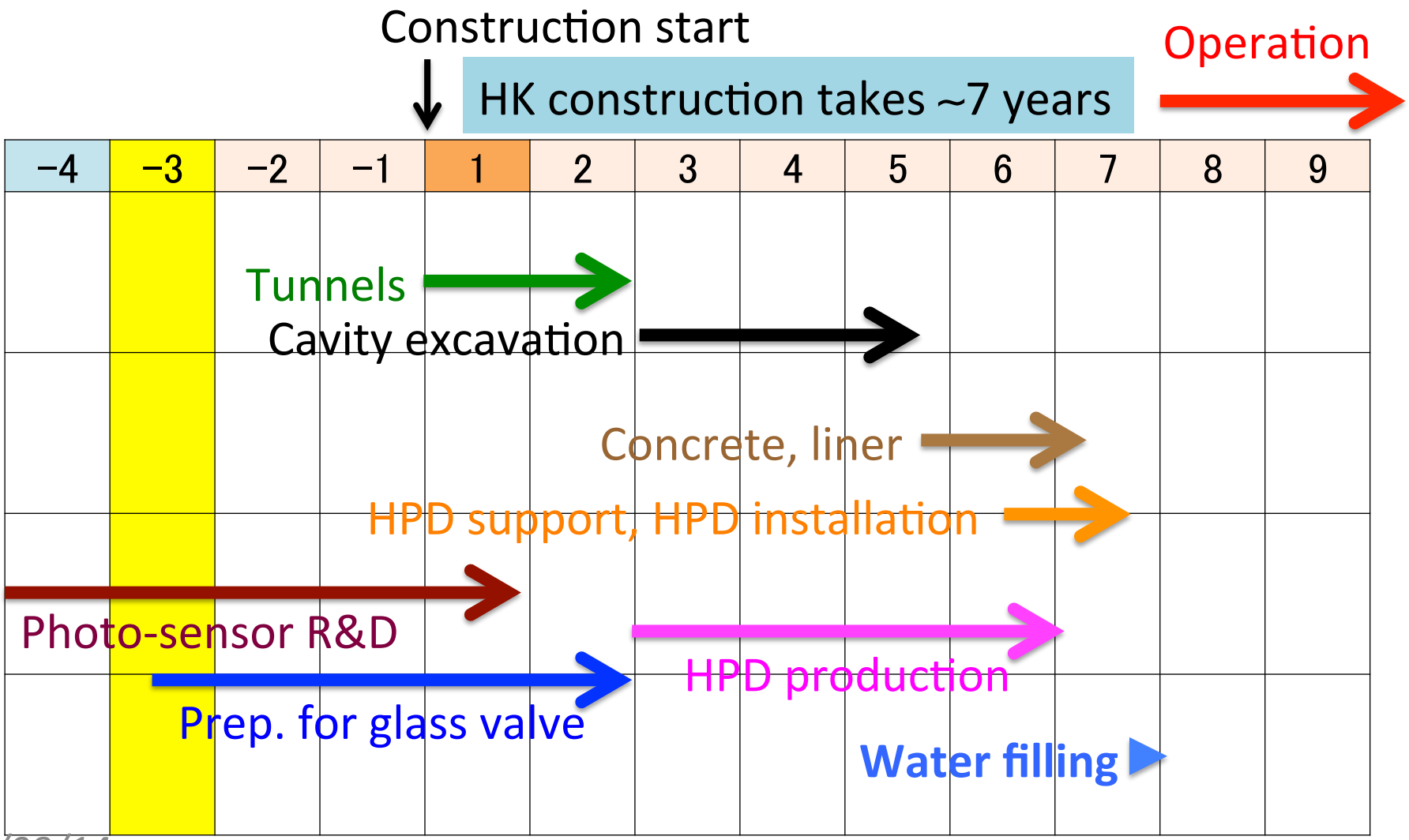
- Candidates for ID sensor
  - 50 cm Hybrid Photo Detector (HPD)
  - (New 20" PMT as backup)
- 20 cm HPD prototype under evaluation
  - Showing good basic performance.
  - Proof test in a water tank (EGADS 200 ton) from this summer.
- 50 cm HPD prototype is expected in a few month







Schedule


Construction start
HK construction takes ~7 years
Operation
−4
−3
−2
−1
1
2
3
4
5
6
7
8
9
Tunnels
Cavity excavation
Concrete, liner
HPD support, HPD installation
Photo-sensor R&D
HPD production
Prep. for glass valve
Water filling

International Hyper-K Meetings

- Hyper-K is open to the international community.
- Three Hyper-K Open meetings @ Kavli IPMU, Kashiwa, JAPAN
  - Aug. 2012 (1st), Jan.2013 (2nd), Jun. 2013 (3rd)

Group photo
@ 3rd meeting

  - ~100 participants (~50% from abroad)
- International Working Group was formed.
- Next meeting: **Jan. 27-28, 2014 @ Kavli IPMU**, Kashiwa, JAPAN
  - Open to anyone interested in Hyper-K Project

Summary

- Hyper-K has great potential for wide range of physics
  - Discovery potential of CPV (δ_{CP}) for 74% of the region with 3σ.
  - Determine Mass hierarchy and θ_{23} octant with 3σ
  - Proton decay: Sensitivity for $e+p^0$ mode in $O(10^{35}$ yrs)
  - Supernovae
    - Bursts: 200 k for a SN at 10kpc
    - Sensitivity to 2 Mpc with $N_\nu \geq 3$
    - Relic SN ν:
  - Solar neutrinos
    - 200 ν /day: Upturn (Sterile?), D/N (Earth's matter effect)
  - Others and unexpected
- Preparation works are in progress
  - HK caverns are proved to be constructed at the candidate site.
  - 20 cm HPD prototypes show good performance.
  - 50 cm HPD prototypes will arrive in a few month.