Hyper-Kamiokande

XVII International Workshop on Neutrino Telescopes

13-17 March 2017 *Venezia, Palazzo Franchetti - Istituto Veneto di Scienze, Lettere ed Arti*

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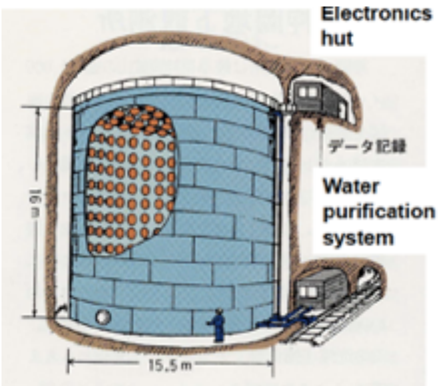
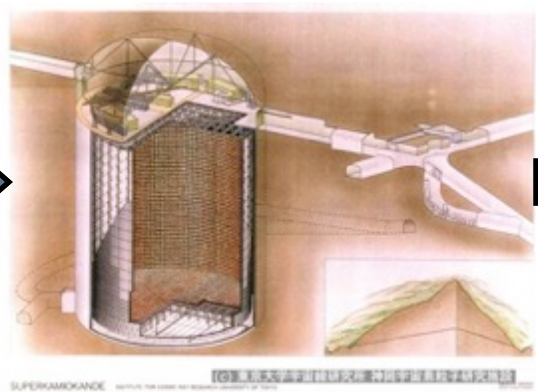
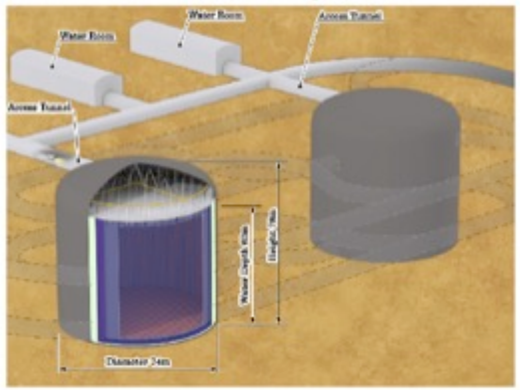
3 generations of Kamiokande family

Kamiokande (1983-1996)	Super-Kamiokande (1996-)	Hyper-Kamiokande (~2026-)







3kton	50kton	260kton×2
20% coverage with 50cm PMT	40% coverage with 50cm PMT	40% coverage with high-QE 50cm PMT

- Larger mass for more statistics
- Better sensitivity by more photons with improved sensors

Why water Cherenkov detector ?

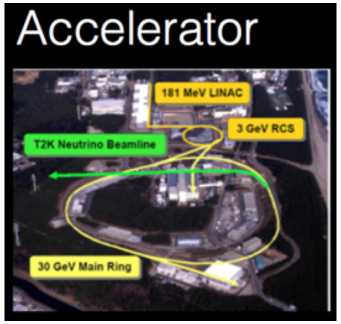
Well proven, scalable technology

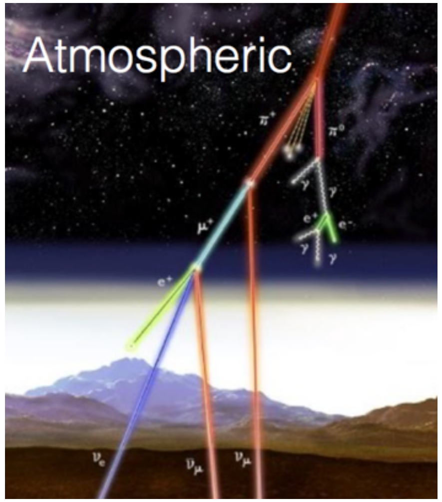
- Feasibility of ~Mton size detector confirmed by various studies over past decade
  - **20 years experience with Super-Kamiokande**
- "Ready-for-construction" design developed
- Still improving with new technology and new ideas

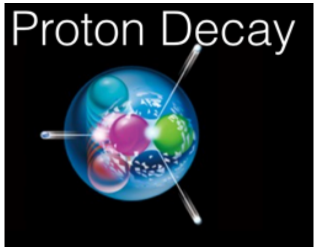
Hyper-K: a multi pourpose Experiment

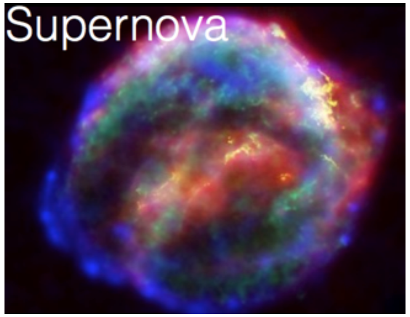
- **Neutrino oscillation physics**
  - CP violation
  - Θ_{23} octant determination
  - Mass hierarchy with beam and atmospheric ν's
- **Nucleon decay discovery potential**
  - Possible discovery with ~×10 better sensitivity than Super-K
- **Neutrino astrophysics**
  - Precisio… nts of solar ν
  - High sta… rements of SN burst ν
  - Detection and study of relic SN neutrinos
- **Unexpected….**

This talk



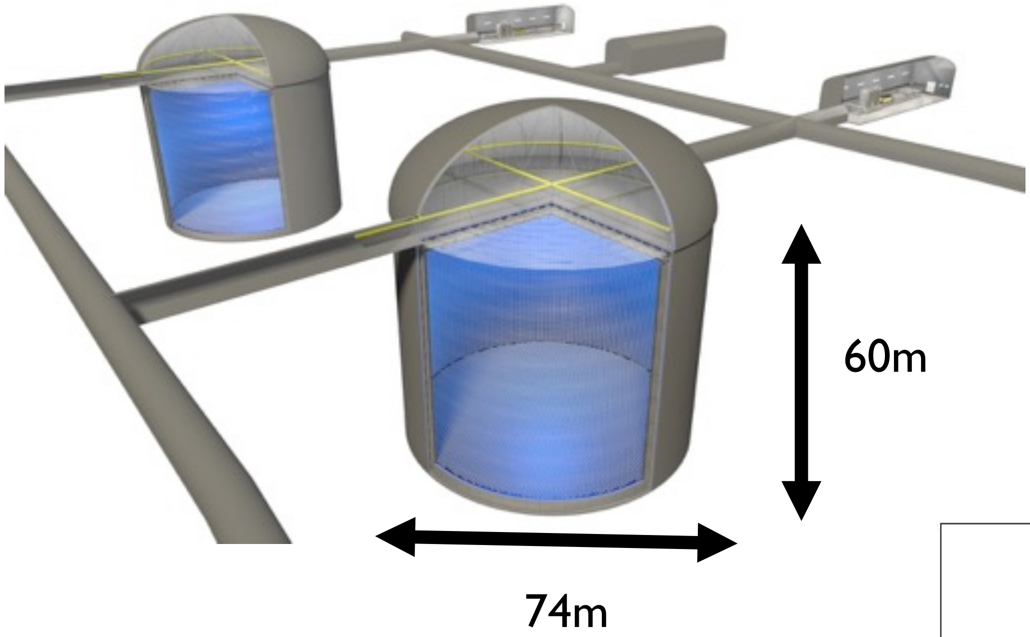






Extend highly successful program of Super-K

Hyper-Kamiokande: new design

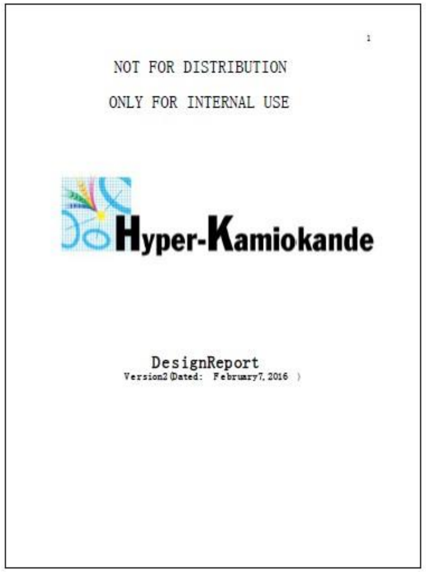


2 TANKS:

- ✓ Fiducial Volume : 2/3 of original design
- ✓ Vertical tanks
- ✓ Possibility of staging
- ✓ Significant reduction for the cost of the project

EACH TANK:

- 260 Kton total
- 10 x SK fiducial volume
- Very good PMT coverage (40%)
- 60 m height x 74 m diameter
  - ➢ 40,000 50cm ID PMTs
  - ➢ 6,700 20cm OD PMTs



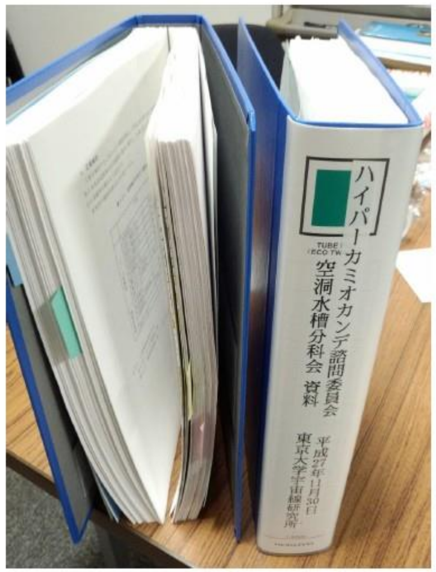
NOT FOR DISTRIBUTION

ONLY FOR INTERNAL USE

Hyper-Kamiokande

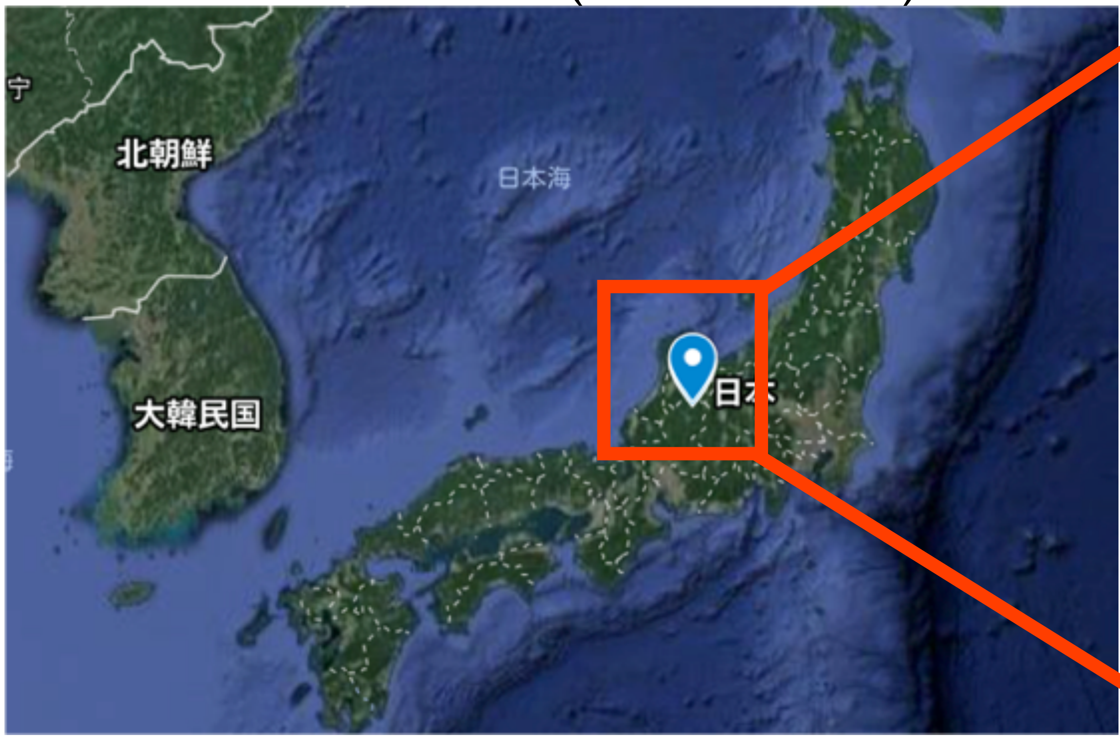
DesignReport

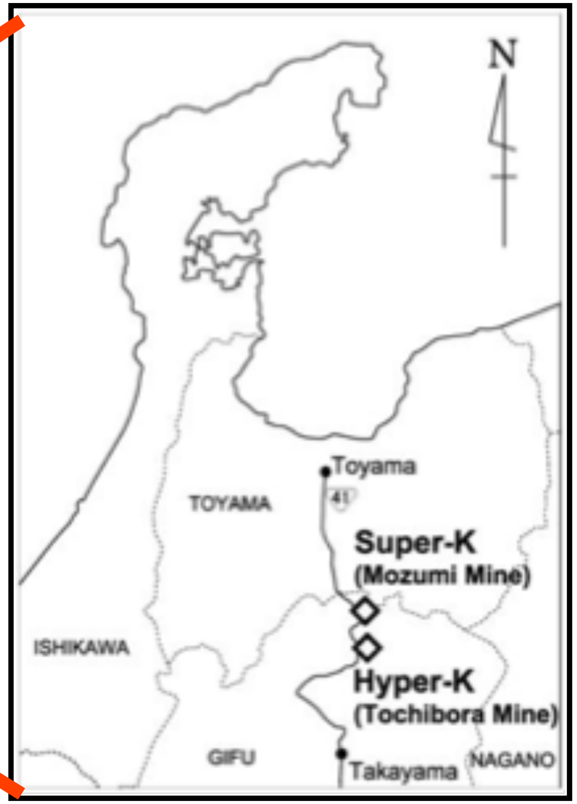
Version2 (Dated: February7, 2016)



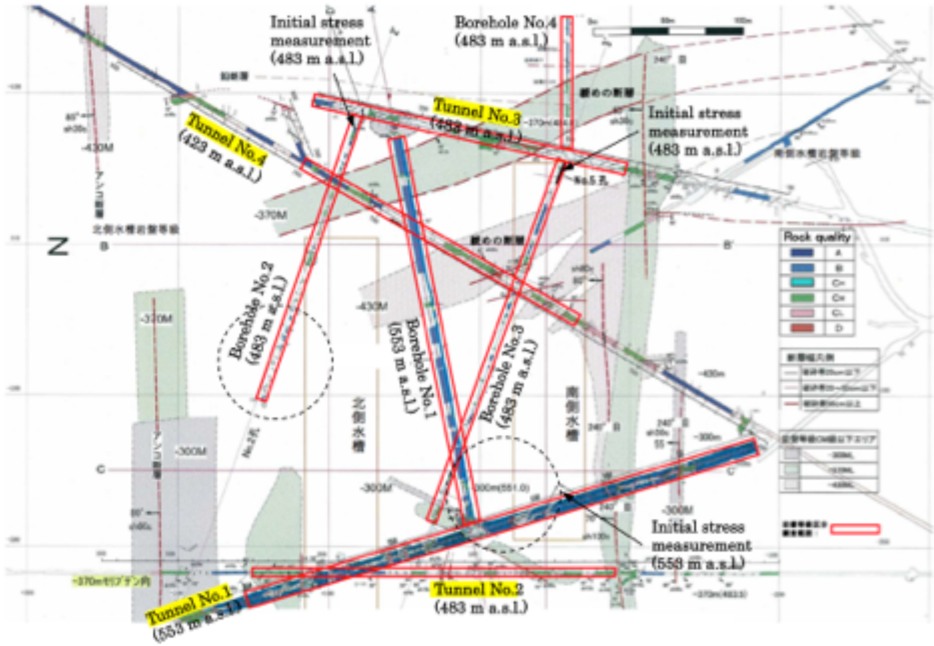
Detector location @ Kamioka, Japan

- The candidate site locates under Mt. Nijugo-yama
  - ~8km south from Super-K
  - Identical baseline (295km) and off-axis angle (2.5deg) to T2K
- Overburden ~650m (~1755 m.w.e.)



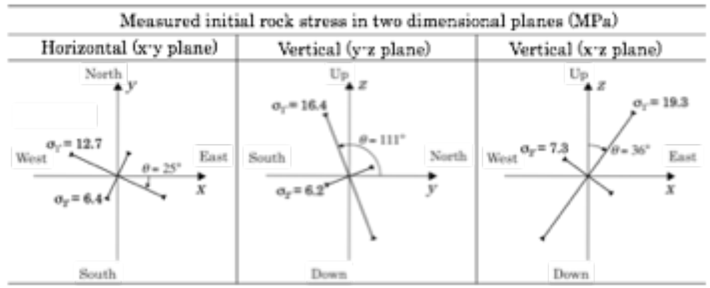


Geological condition: confirmed



Surveyed area around candidate position

Initial rock stress



Making huge (74mD×60mH) caverns is not trivial

Detailed geological surveys at the candidate site

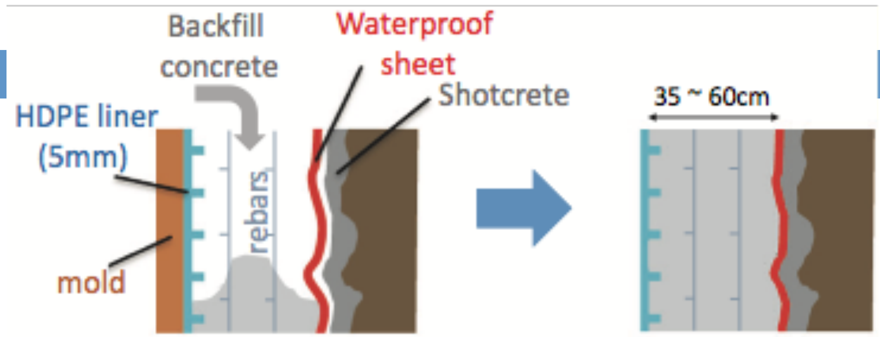
Rock core sampling, initial stress of bedrock, etc.

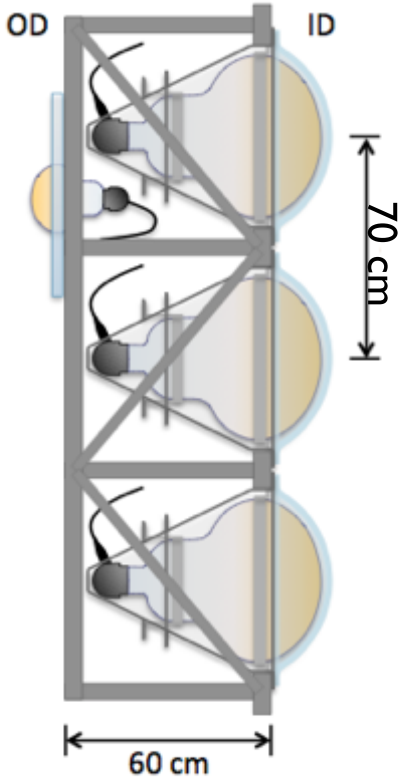
Bedrock condition confirmed for HK cavern construction

Tank design: ready

Water containment system and PMT support structure have been designed

3 layer lining design

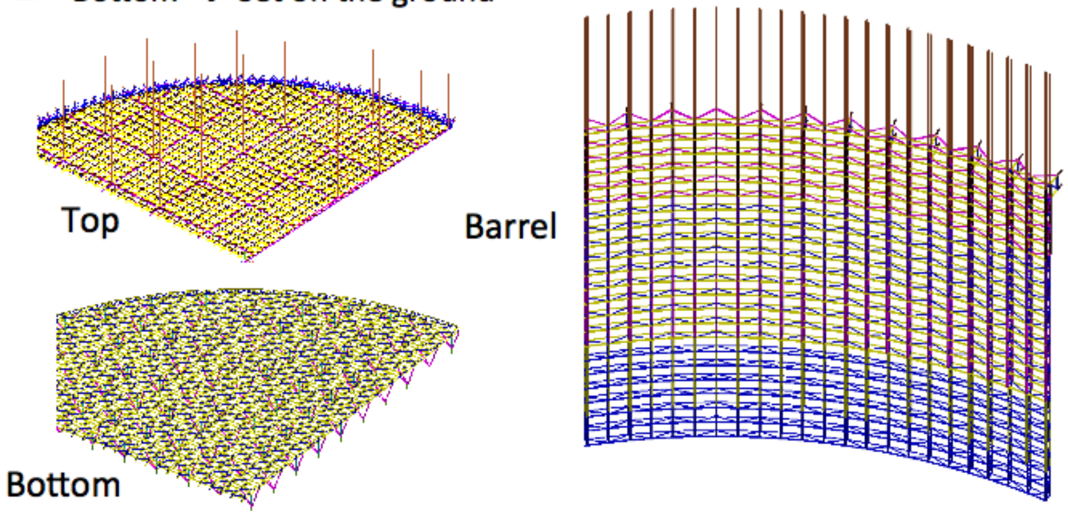




Support structure design

Truss structure made of shaped stainless steel (SUS304)

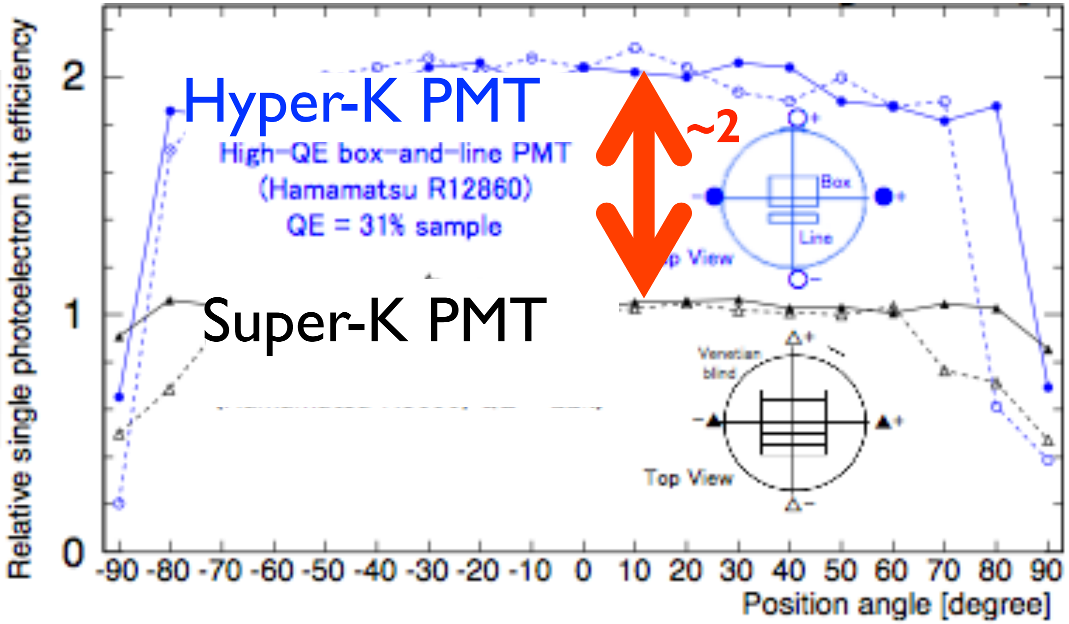
- Top/Barrel → Hung from the ceiling
- Bottom → Set on the ground



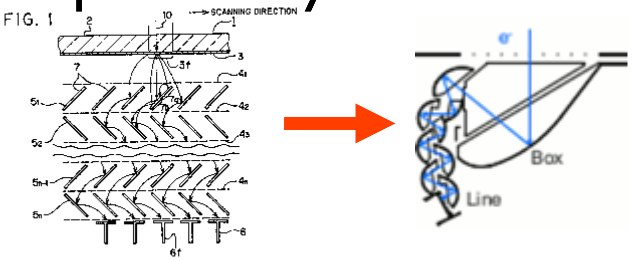
Newly developed 50cm PMT

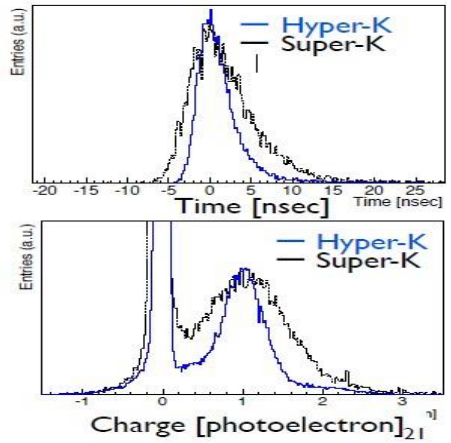
Super-K PMT

New PMT



Improved dynode



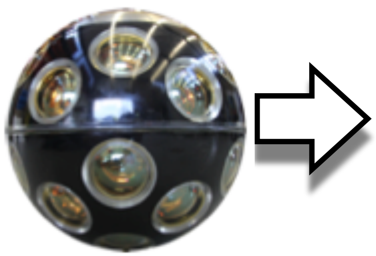


- ×2 better photon efficiency and timing resolution
  - Enhance physics potential (neutron tagging, low energy events)
- Higher pressure tolerance (> 80m)

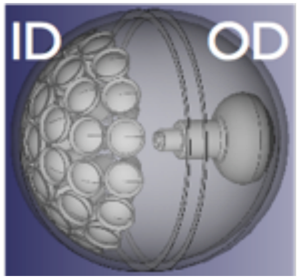
Photo-sensor R&D

- International efforts for further improvement:
  - 50cm Hybrid Photo-detector (HPD)
  - 20-30cm photo-sensors for OD / ID
- "Multi-PMT" module
  - Being developed based on KM3NeT optical module
  - MoU with KM3NeT to exchange knowledge
- PMT housing to prevent chain implosion
  - Confirmed functionality at 80m under water

HPD



KM3NeT

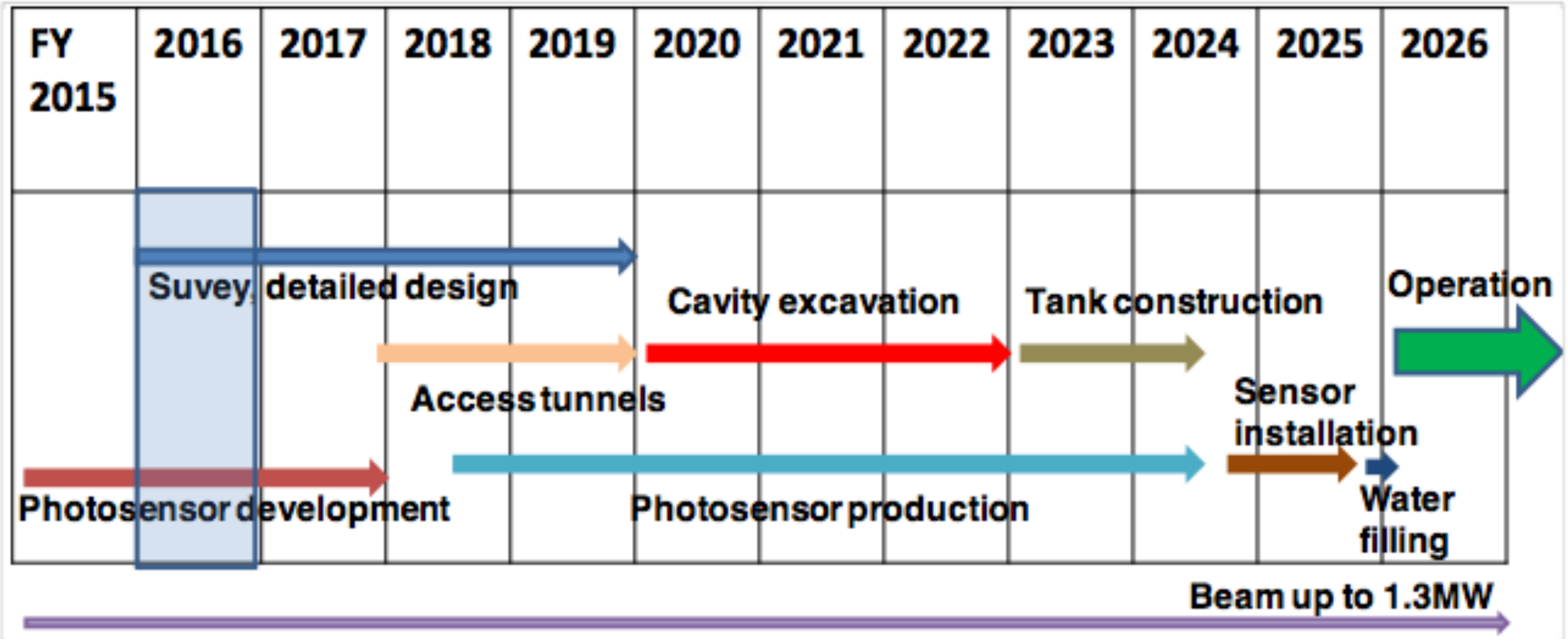


Multi-PMT

8cm (3") PMT

28cm (11") PMT

Hyper-K construction timeline



- Assuming funding from 2018
- The 1st detector construction in 2018~2025
  - Cavern excavation: ~5 years
  - Tank (liner, photosensors) construction: ~3 years
  - Water filling: 0.5 years

Hyper-K proto-collaboration

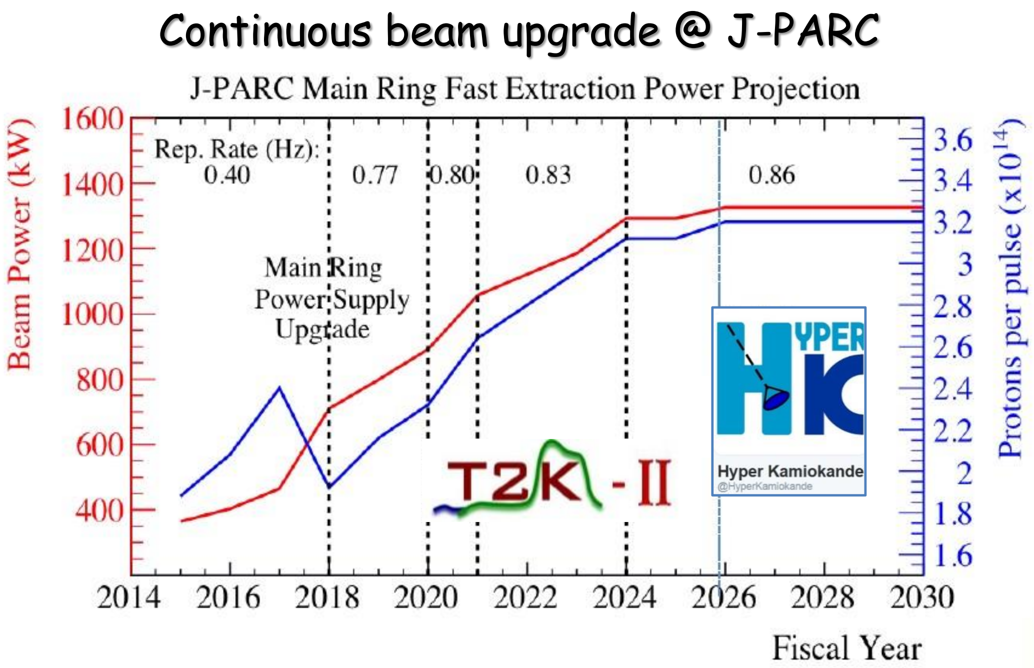
- International proto- collaboration formed on January 2015
- Reviewed by an International HK Advisory Committee
- New proposal submitted in March 2016 selected as one of important large scale projects by Science Council of Japan.
- J-PARC upgrade for Hyper-K is top priority in KEK Project Implementation Plan (KEK-PIP)
- Budget request for detector construction in preparation
- 15 countries, ~300 members and growing

Tokai to Hyper-K (T2HK)

- Long baseline oscillation using the J-PARC neutrino beam-line (as T2K)
- Same off-axis angle (2.5°) as Super-K
- Improved Neutrino Beam (1.3 MW)

J-PARC neutrino beam upgrade

- Continuous upgrade of neutrino beam up to 2030
- Present beam power ~470 kW
- New MR power supply for 750kW by 2019
- Repetition rate increase to 0.86 Hz for 1.3MW by 2026

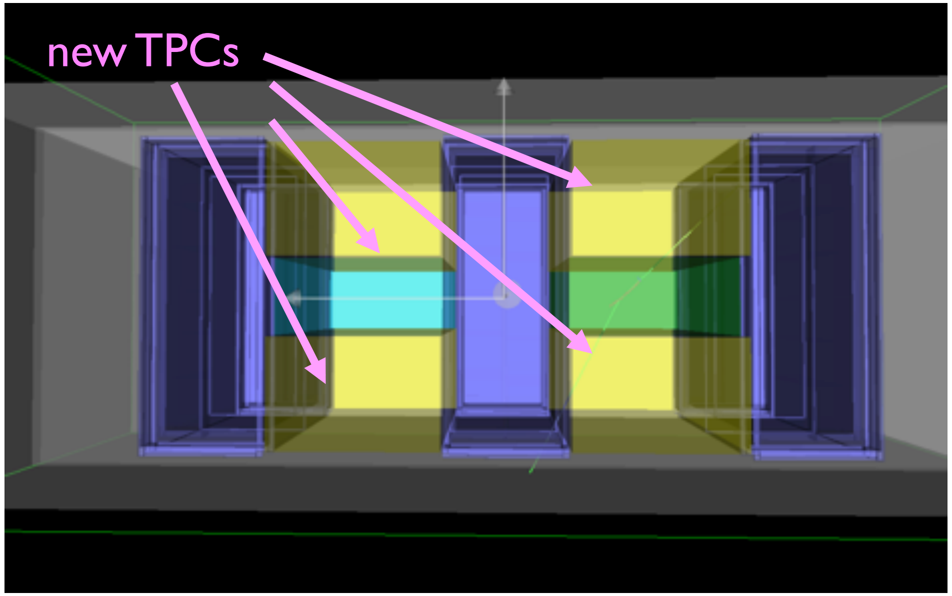


- J-PARC upgrade for Hyper-K is top priority in KEK Project Implementation Plan (KEK-PIP)

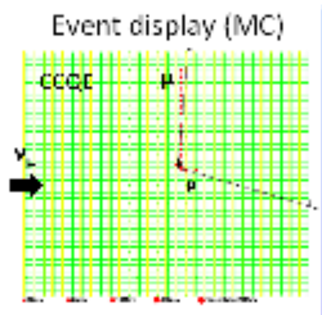
- **Strong commitment for future neutrino program**

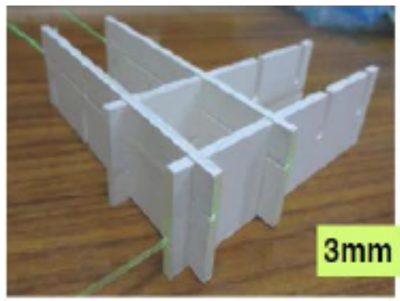
Near Detector upgrade

- Under consideration by T2K
  - Goal: systematics reduction in T2K-II era
    - Expand angular acceptance with new TPCs and new target detectors
- LoI "*Neutrino Near Detectors based on gas TPCs*" @CERN (Neutrino Plat.)
- Technical design in ~2017, aim for installation around 2020/21
- Operation foreseen to continue in HK (possibly further improvement)



※ Configuration under optimization





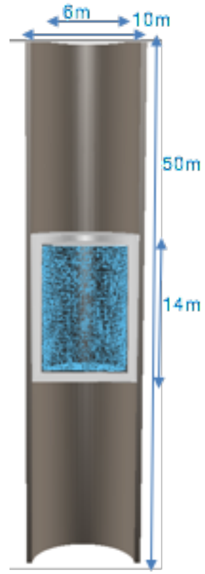
Large angular acceptance detector with plastic scintillator grid (WAGASCI)

Intermediate Detectors

- Water Cherenkov detectors at ~1-2 km distance being investigated for HK (or possibly before).
- The same technology as the far detector
  - Further reduction of systematic uncertainties
- Two proposals:
  - Off-axis angle spanning orientation.
  - Gd loading, magnetized μ range detector.
  - Will merge in unique detector/ collaboration.

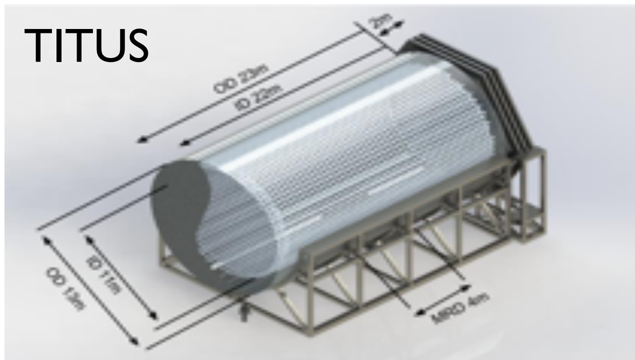
Final goal:
Reduce systematic uncertainties from 5-6% (T2K) to 3-4%

NUPRISM



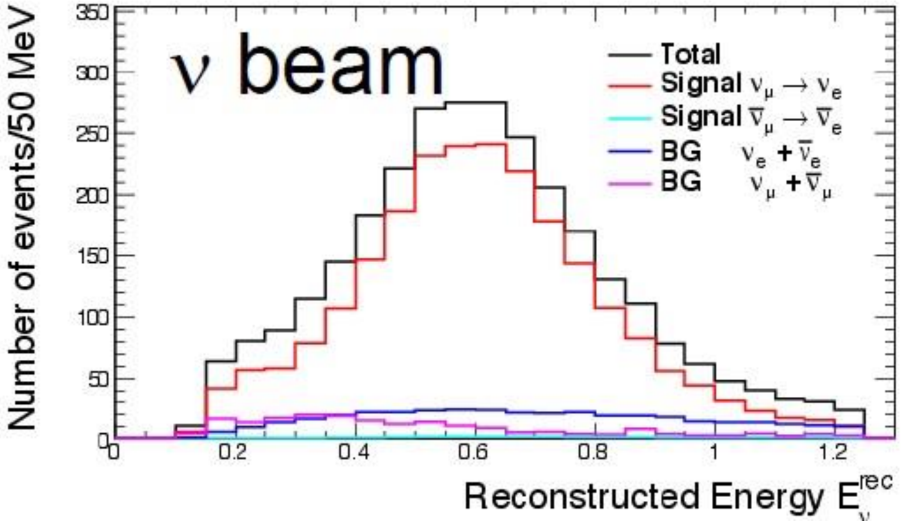
arXiv:1412.3086 [physics.ins-det]

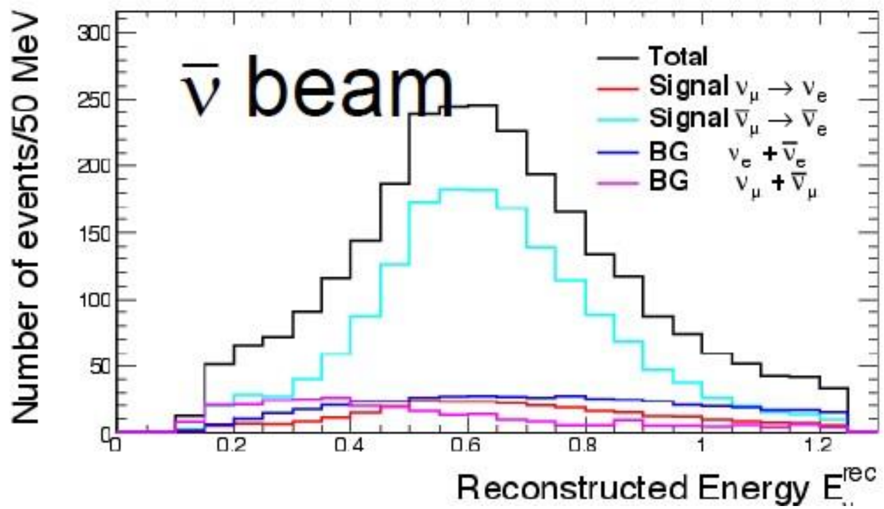
TITUS



arXiv:1606.08114 [physics.ins-det]

Physics performance for oscillation studies: ν_e appearance

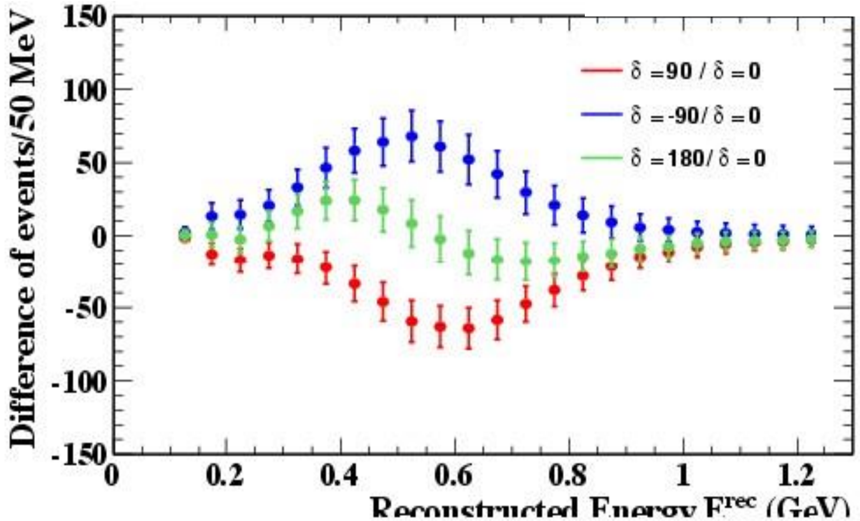


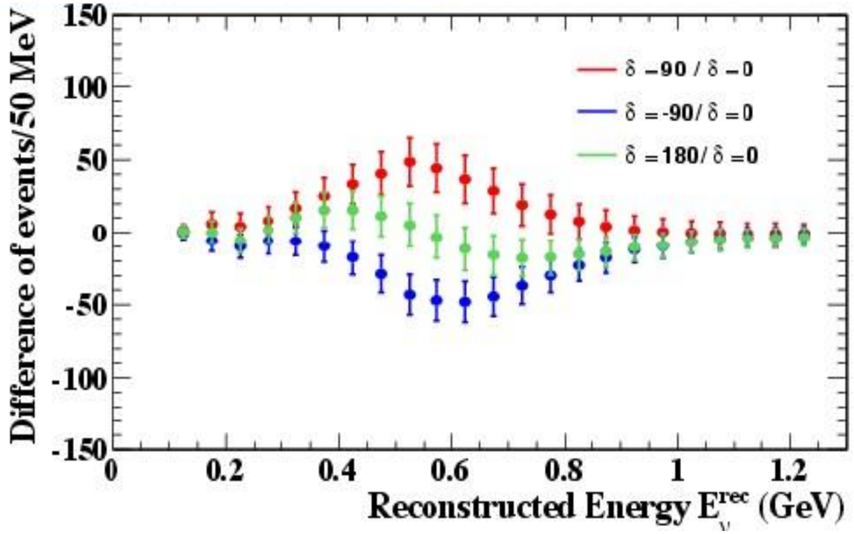


δ=0	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	$\nu_\mu, \bar{\nu}_\mu$ CC	Beam $\nu_e, \bar{\nu}_e$ contamination	NC
ν beam	2300	21	10	362	188
$\bar{\nu}$ beam	1656	289	6	444	274

- 10 years of running
- 1.3 MW for JPARC proton beam
- 1 tank then 2 tanks
- ~ 40% PMT coverage in HK
- 3-4% systematic uncertainties

Physics performance for oscillation studies: ν_e appearance



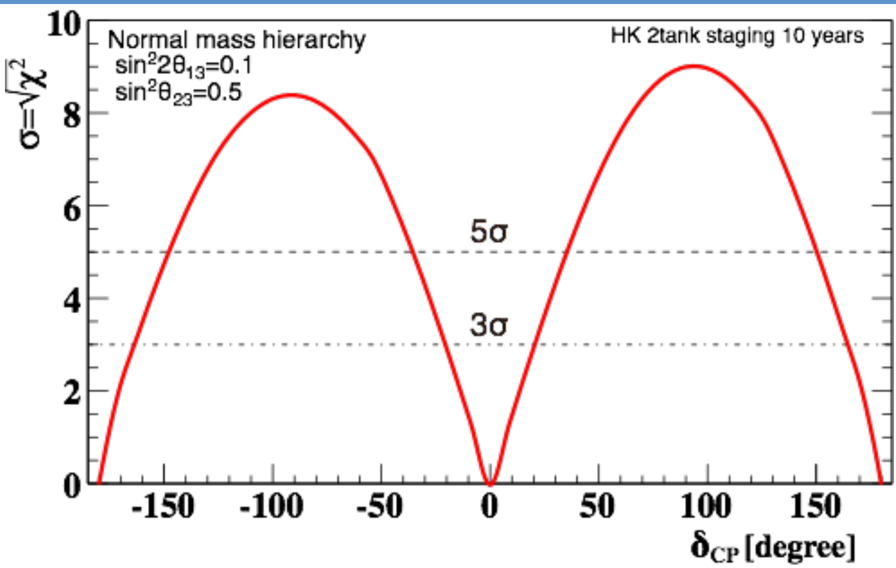


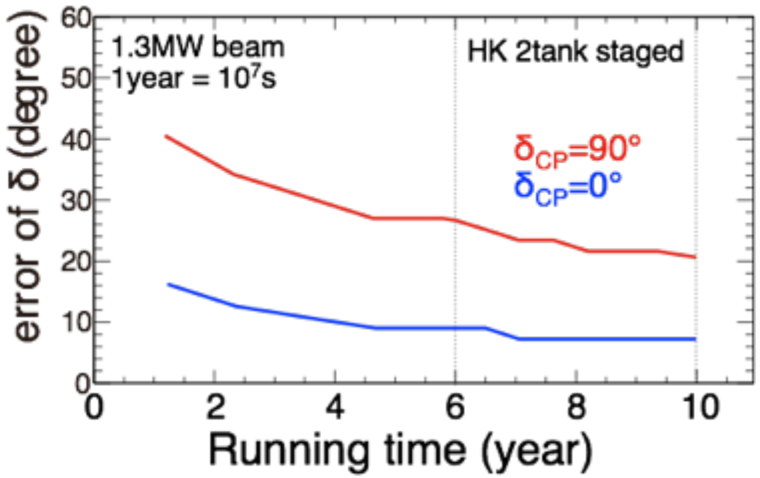
Possibility of using shape information in energy to distinguish different values for δ (CP)

- 10 years of running
- 1.3 MW for JPARC proton beam
- 1 tank then 2 tanks
- ~ 40% PMT coverage in HK
- 3-4% systematic uncertainties

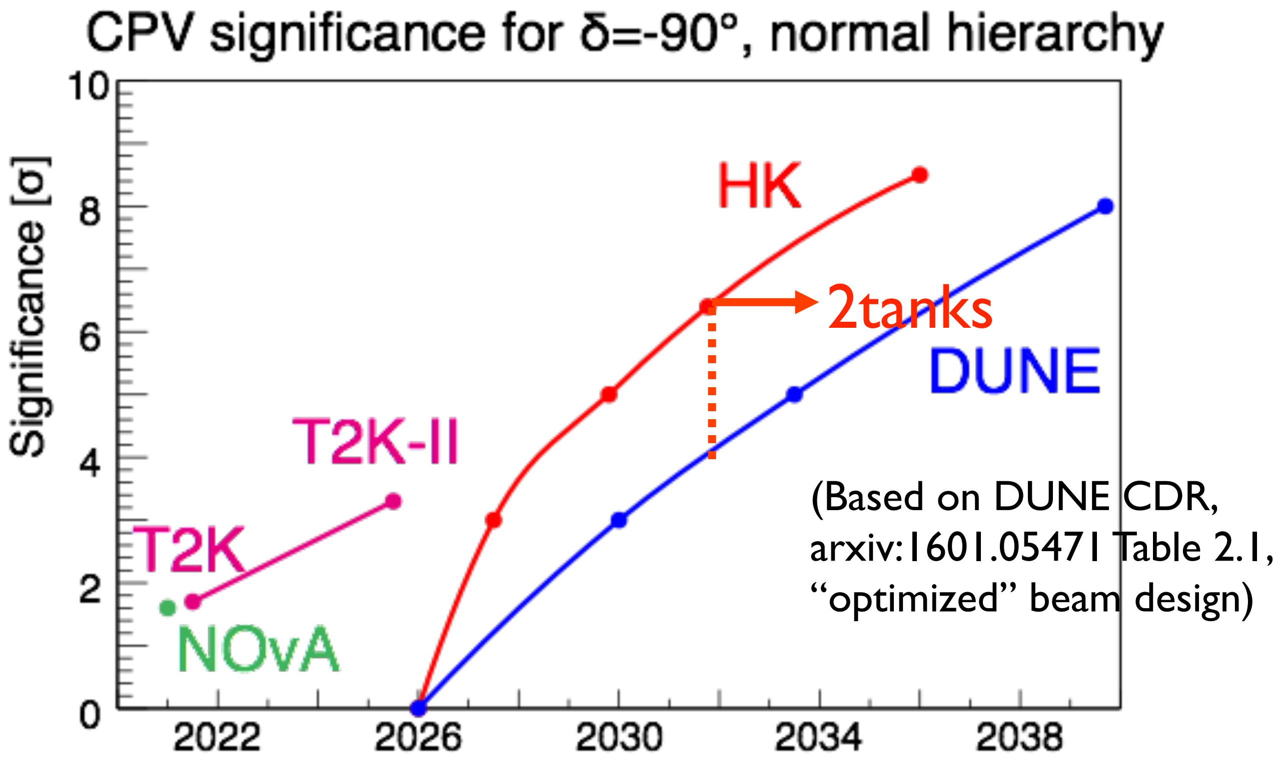
CPV sensitivity

- With 10 years exposure, can exclude sin δ_{CP}=0 and demonstrate CP violation:
  - >8 σ if δ_{CP} = ±90°
  - >5 σ for 62% of δ_{CP} values
  - >3 σ for 78% of δ_{CP} values
- δ_{CP} resolution:
  - 21° precision at δ_{CP}=90°
  - 7° precision at δ_{CP}=0°





Towards leptonic CP asymmetry



~3 σ indication with T2K→T2K-II,

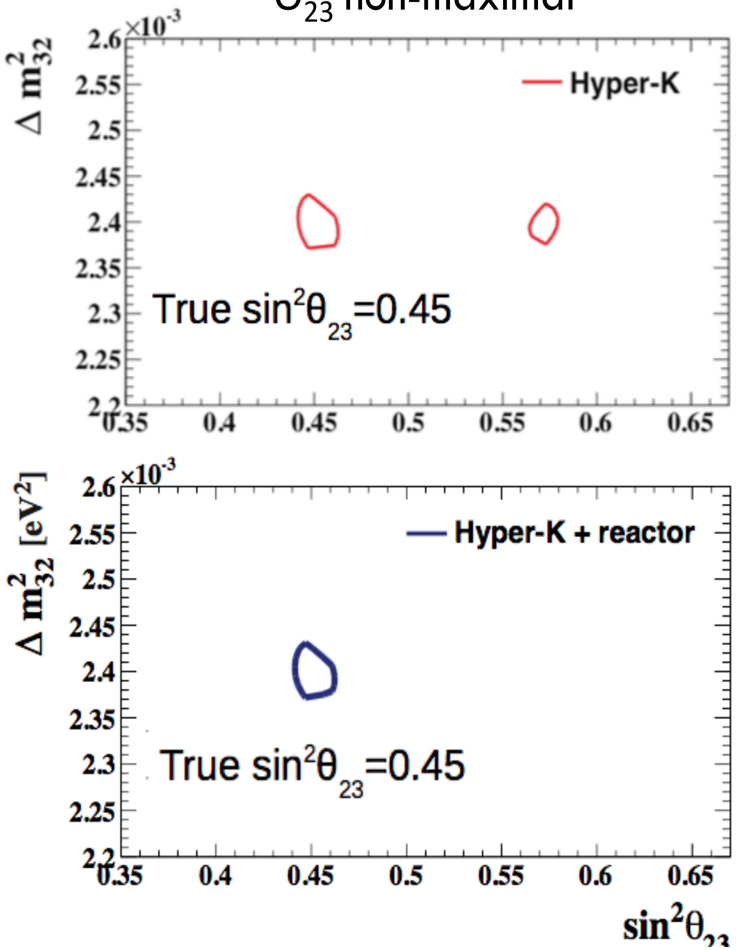
>5 σ discovery and measurement with HK

Note: "exact" comparison sometimes difficult due to different assumptions

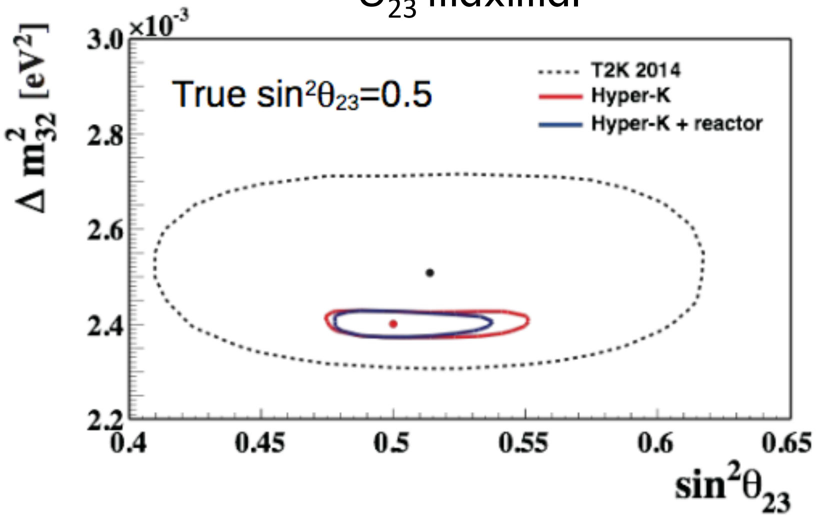
Precision measurements of Θ_{23}

- Large improvements in $\sin^2\Theta_{23}$ measurements
  - ~0.015 precision at $\sin^2\Theta_{23} = 0.5$
  - ~0.006 precision at $\sin^2\Theta_{23} = 0.45$
- For non-maximal Θ_{23}, reactor constraint breaks octant degeneracy

Θ_{23} non-maximal



Θ_{23} maximal

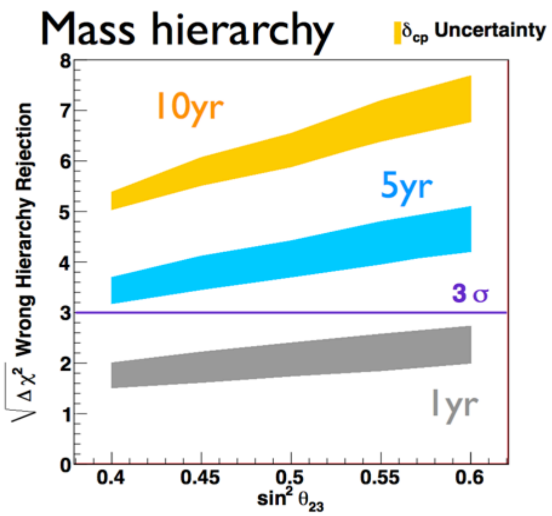


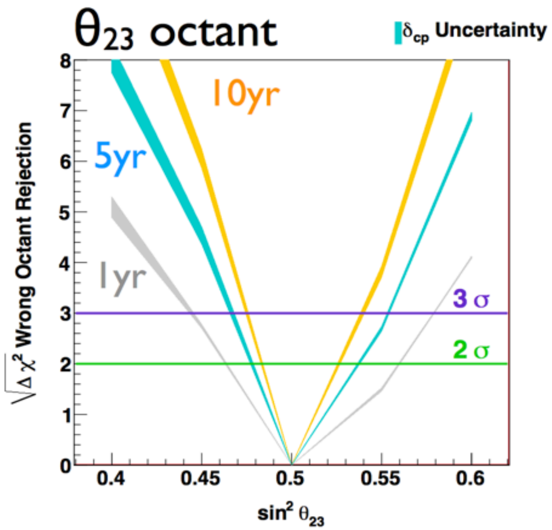
T2K

$\sin^2\theta_{23}$	$0.532^{+0.044}_{-0.060}$

Beam and atmospheric neutrinos

- Atmospheric neutrinos data has sensitivity to mass hierarchy and Θ_{23} octant
- Sensitivity is enhanced by combining atmospheric and beam neutrinos
  - $>5\sigma$ determination of the mass hierarchy (10 years)
  - Improved performance for octant determination



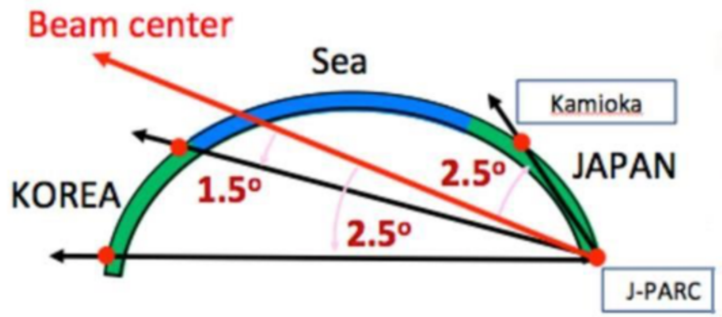


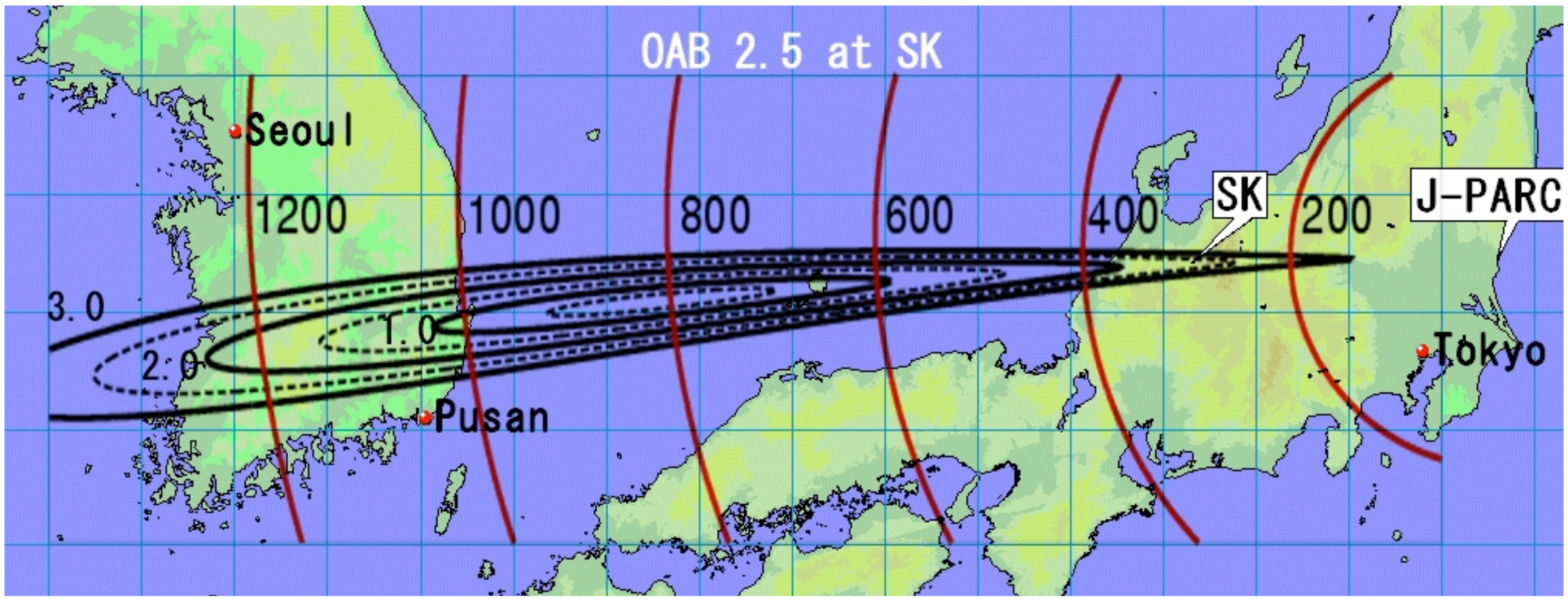
10 yrs NH		Mass Hierarchy (σ)	
		Atm	Atm+Beam
2Tanks	θ_{23}=0.4	2.2	5.3
	θ_{23}=0.6	5.2	6.9

10 yrs NH	Octant (σ)	
	Atm	Atm+Beam
θ_{23}=0.45	2.2	5.8
θ_{23}=0.55	1.7	3.7

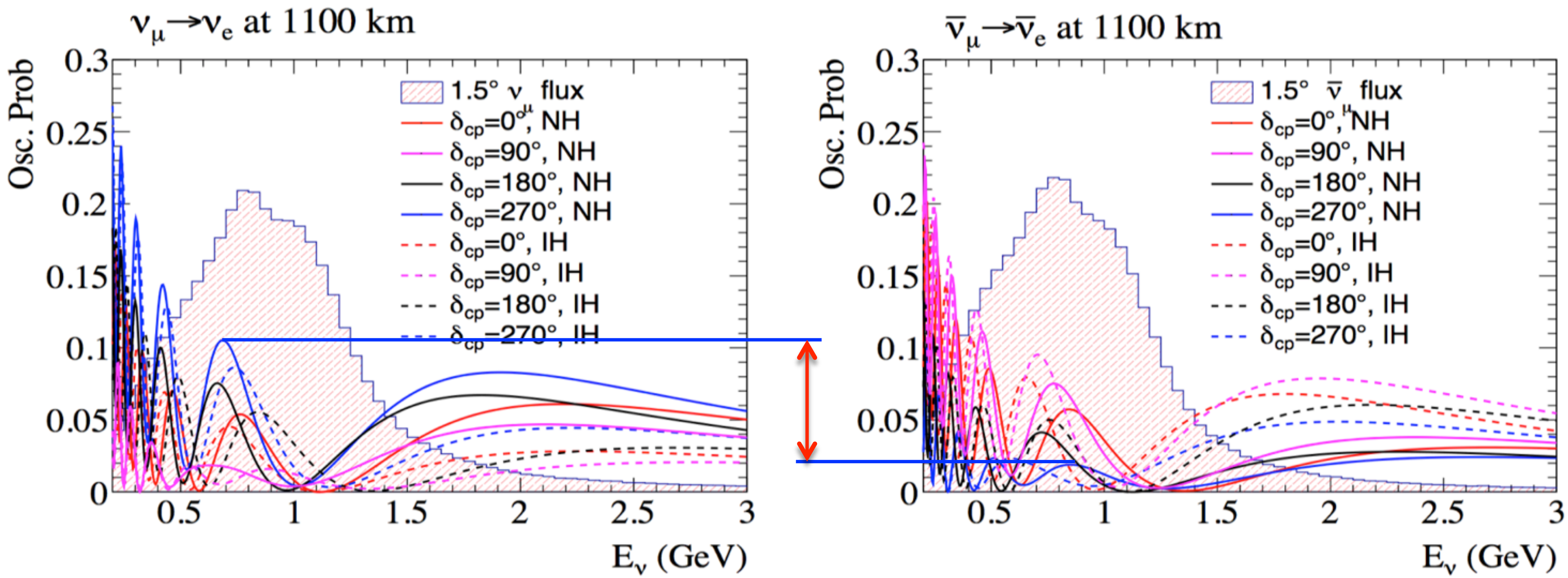
T2HKK: Tokai to Hyper-K and Korea

- Build second tank in Korea to enhance mass hierarchy and δ_{CP} sensitivities
  - 1000 – 1200 km baseline
  - $1.3^0 – 3.0^0$ off axis beam direction





ν_e appearance at the Korean site

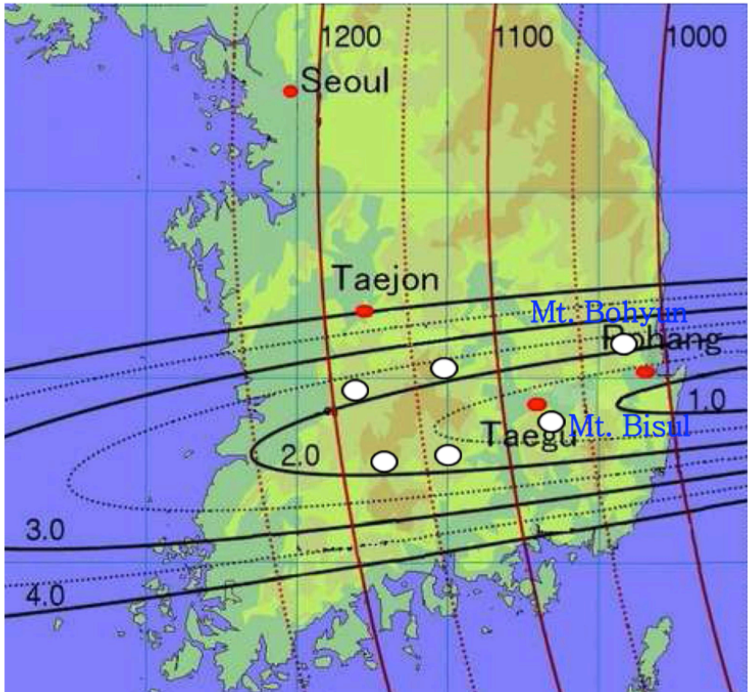


- Covers the 2nd oscillation maximum where the CP asymmetry between ν and anti-ν is 3 times larger than the 1st oscillation maximum
- Less sensitive to systematics errors due to larger CP effect
  - Lower statistics due to flux reduction
- Longer baseline(1100km) leads to larger matter effects
  - MH better determination

Additional benefits of the Korean site

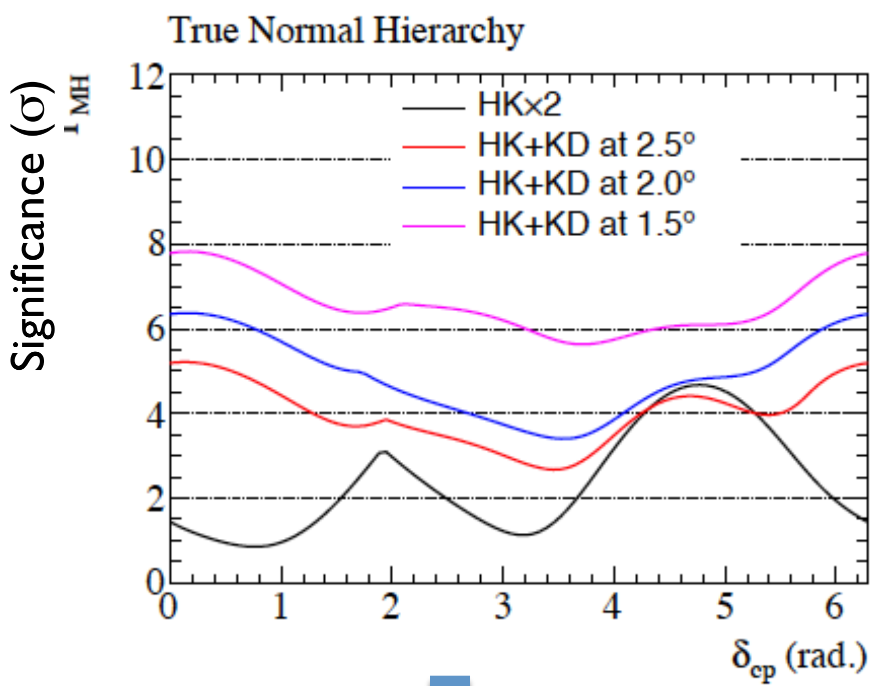
- >1000 m high mountains with hard granite rocks
- Smaller background due to its larger overburden (> 800m)
- Improved sensitivity in solar neutrino physics
  - Day/night asymmetry due to MSW matter effect in Earth
  - HEP solar neutrinos
  - Energy spectrum upturn
- Supernova relic neutrino detection capability below 20 MeV improves
  - Detection efficiency is more than twice HK site in16-18 MeV range

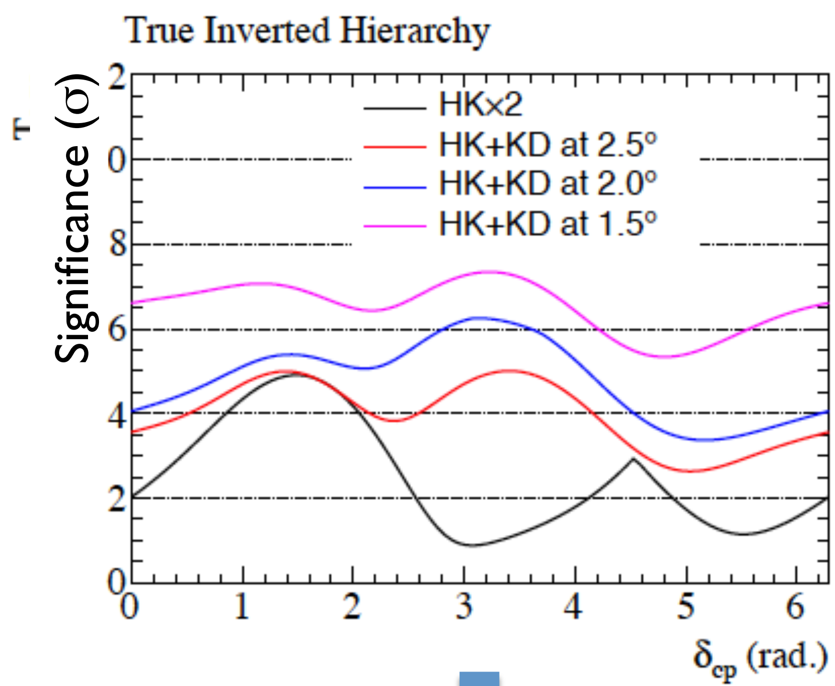
Site	OAB	Baseline [km]	Height [m]
Mt. Bisul	~1.3°	1088 km	1084 m
Mt. Hwangmae	~1.8°	1140 km	1113 m
Mt. Sambong	~1.9°	1180 km	1186 m
Mt. Bohyun	~2.2°	1040 km	1126 m
Mt. Minjuii	~2.2°	1140 km	1242 m
Mt. Unjang	~2.2°	1190 km	1125 m



K. Abe *et al.*, "Physics Potentials with the Second Hyper-Kamiokande Detector in Korea", November 2016, arXiv:1611.06118

Mass Ordering Sensitivities





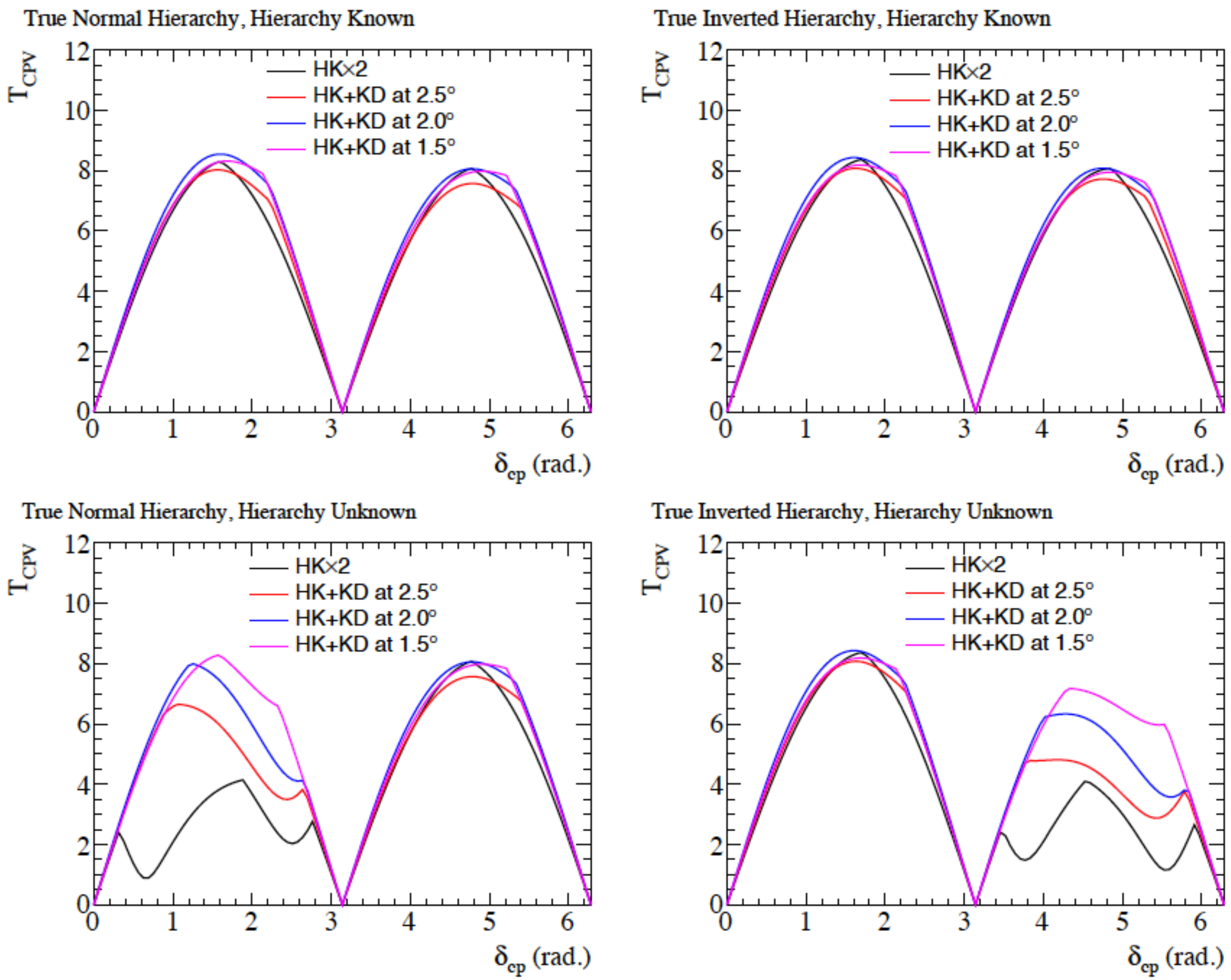
HK+KD 1.5°: 6 ~ 8 σ for all δ_{CP}
HK x2 : 1 ~ 4.5 σ for all δ_{CP}
(< 3 σ for most cases)

HK+KD 1.5°: 5.5 ~ 7 σ for all δ_{CP}
HK x2 : 1 ~ 5 σ for all δ_{CP}
(< 3 σ for most cases)

δ_{CP} Sensitivities

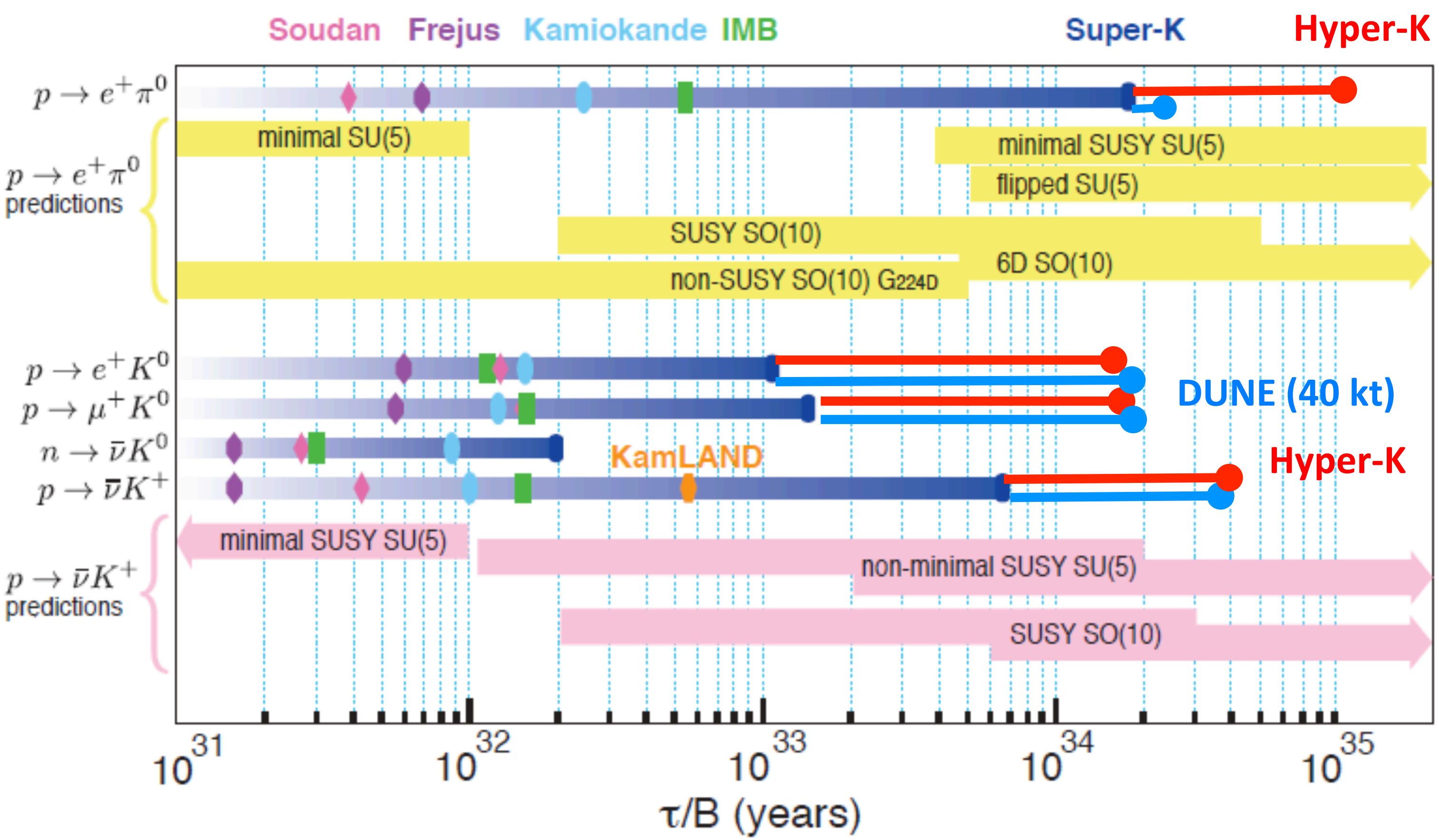
Known MO

Unknown MO



an Hyper-Kamiokande primary goal: nucleon decay

status & next generation expectations (10 y exposure), most important modes:

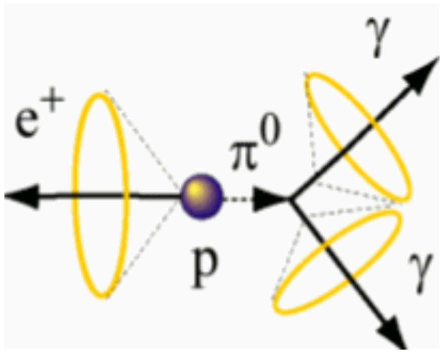


design emphasizes **p → e$^+$π^0**, **p → ν K$^+$** while keeping sensitivity to many other

$p \rightarrow e^{+}\pi_{o}$

favored by non super-symmetric GUTs
a nearly model independent reaction

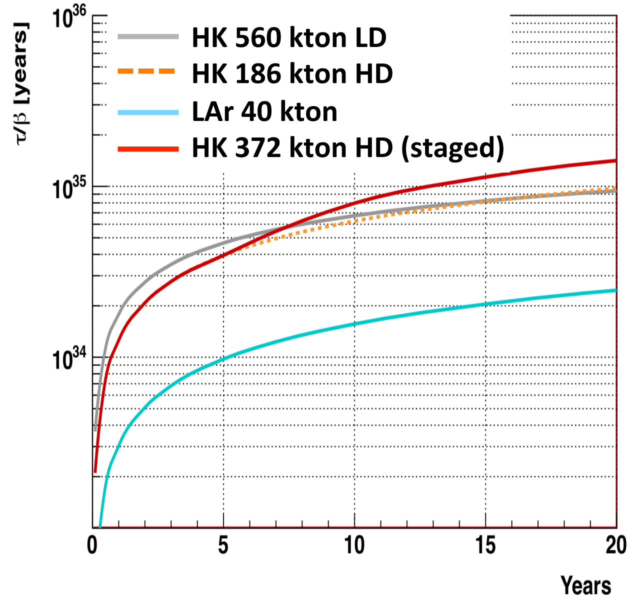
used $\tau_p = 1.7 * 10^{34}$(SK limit)
10 years exposure



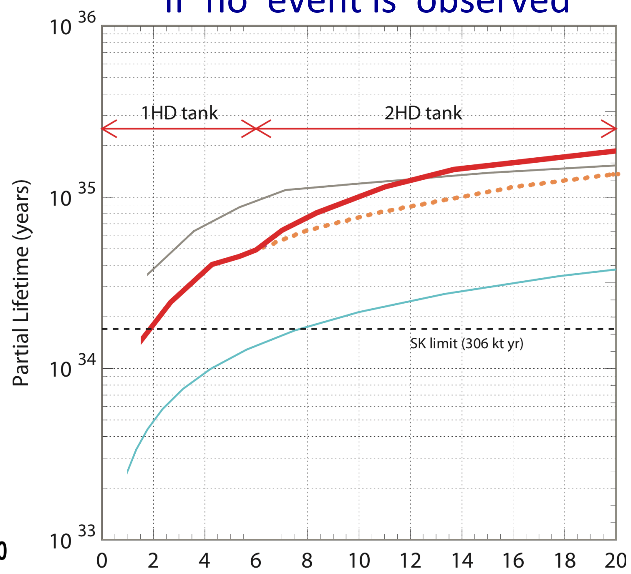
back-to-back e^+, π^0 (459 MeV)
e^+, $\pi^0 \rightarrow \gamma\,\gamma$ are detected

fully final state reconstructed
in Water Cherenkov detectors

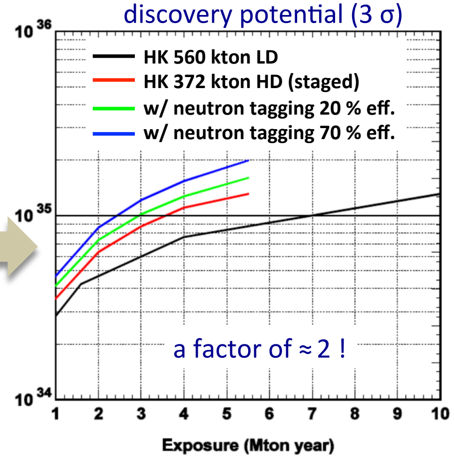
discovery potential (3 σ)



90% C.L. limits achievable
if no event is observed



discovery potential (3 σ)



Some of the benefits from increased photon yield :

- Neutron tagging (veto)

* *LAr discovery potential computed using numbers from DUNE CDR 2015: signal efficiency: 97%, background: 1 event Mton/year, no systematic errors*

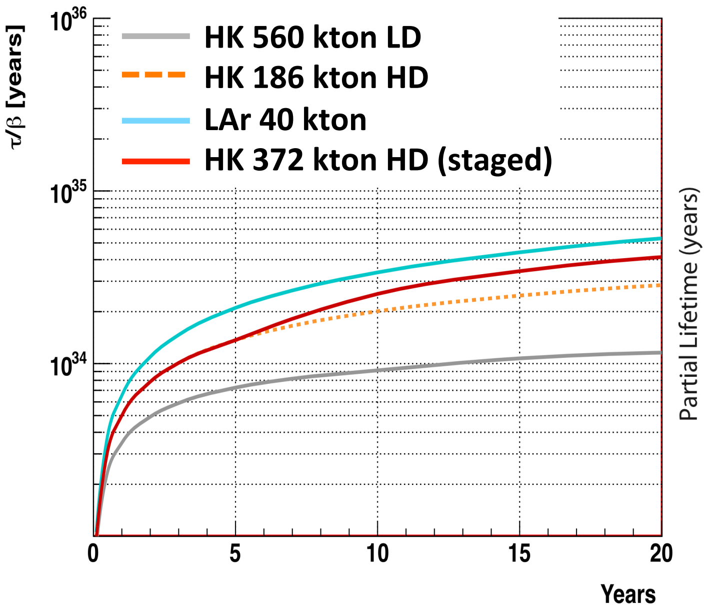
$p \rightarrow \bar{\nu} K^+$

feature of super-symmetric GUTs

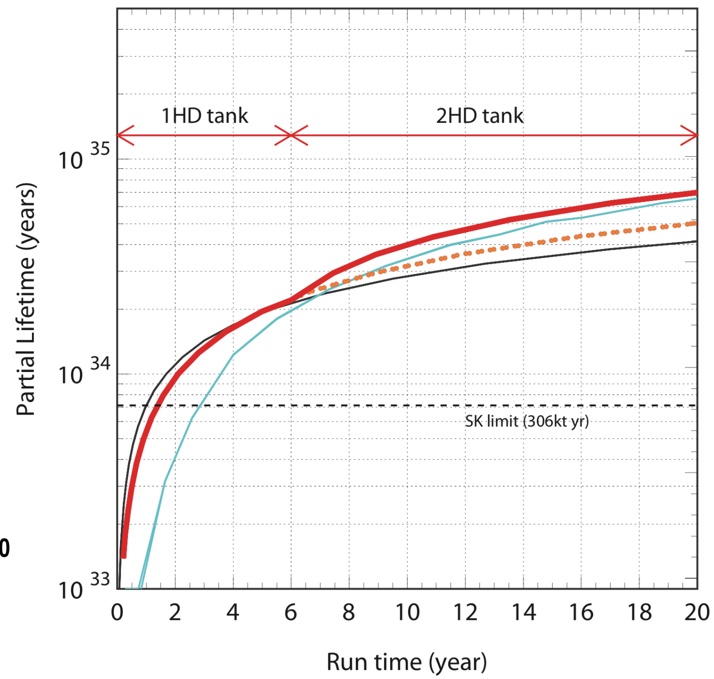
decay mode rather interesting but difficult to reconstruct

at decay $p(K^+)$= 340 MeV, K^+ light threshold: 749 MeV → reconstruct K^+ from its decay products $K^+ \rightarrow \nu\, \mu^+$ *(64%)*, $K^+ \rightarrow \pi^+\pi^0$ *(21%)*

discovery potential (3 σ)



90% C.L. limits achievable if no event is observed



Benefits from increased photon yield and better timing resolution

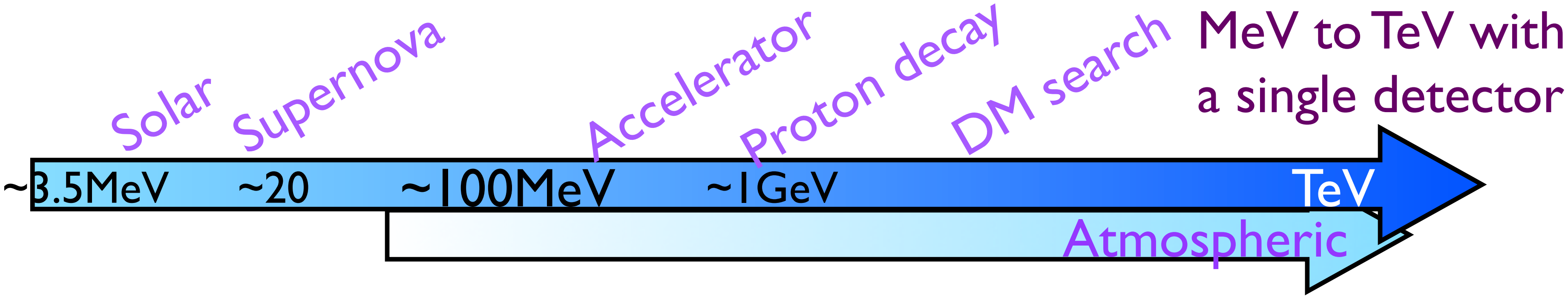
Summary of physics potential

		HK (2TankHD w/ staging)
LBL (13.5MWyr)	δ precision	7°-21°
	CPV coverage (3/5 σ)	78%/62%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MH determination	>5.3 σ
	Octant ($\sin^2\theta_{23}$=0.45)	5.8 σ
Proton Decay (10 years)	$e^+\pi^0$ 90%CL	1.2×10^{35}
	ν K 90%CL	2.8×10^{34}
Solar (10 years)	Day/Night (from 0/from KL)	6 σ / 12 σ
	Upturn	4.9 σ
Supernova	Burst (10kpc)	104k-158k
	Nearby	2-20 events
	Relic (10 yrs)	98evt/4.8 σ

** for DM search see backup slides

Conclusion

- Hyper-Kamiokande will have a rich program with world-leading science output
  - Technology established with past/ongoing experiments
  - Fast and robust approach to lepton CPV
    + long term program with a wide range of science
  - Multi-purpose approach crucial (huge investment)
    new design optimized with better sensors



- Project being accelerated towards an early approval
  - International collaboration open for new groups

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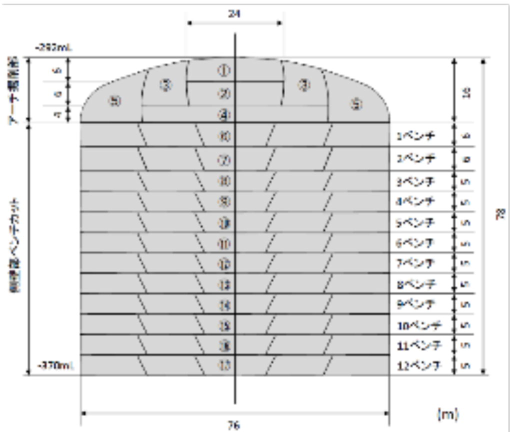
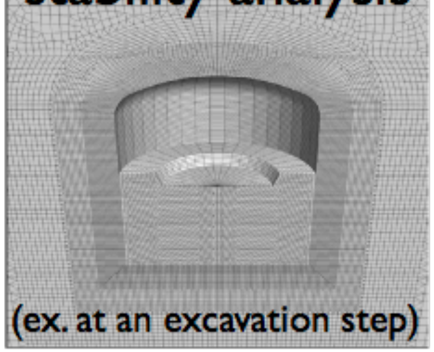
Backup

Cavern stability analysis

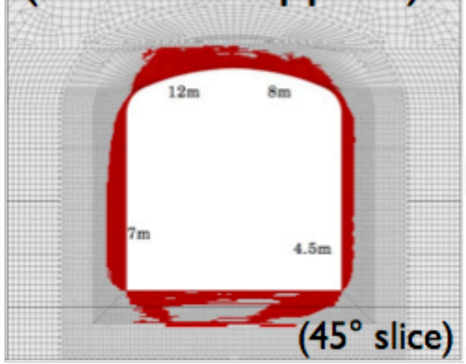
Excavation steps



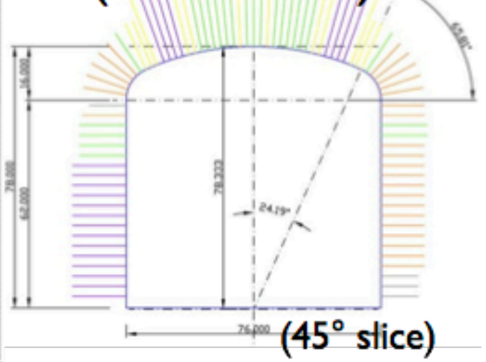
3D model for stability analysis



Plastic region depth (without support)



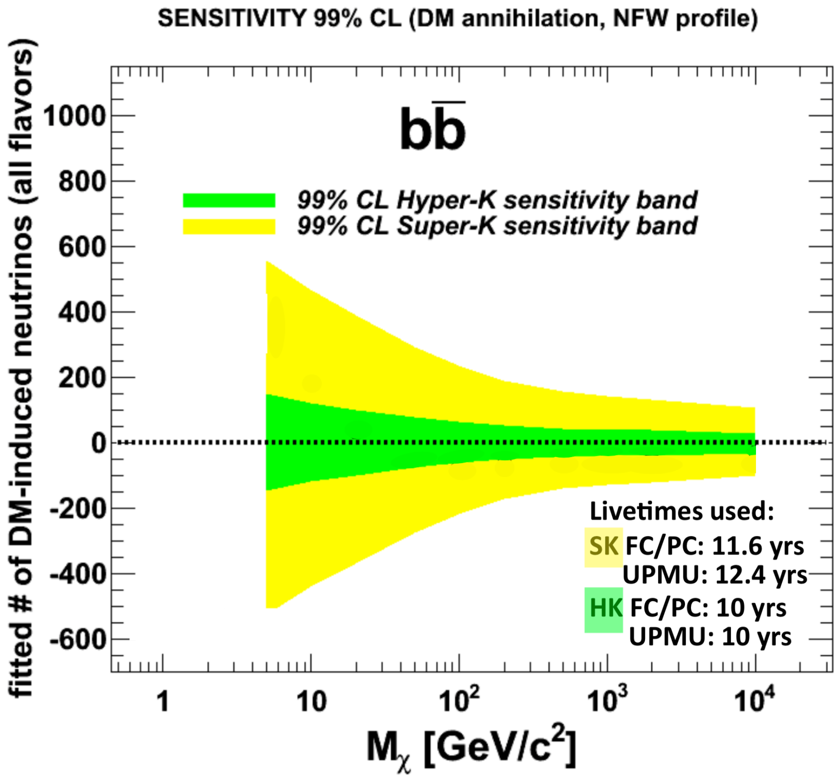
Cavern support (PS-anchors)



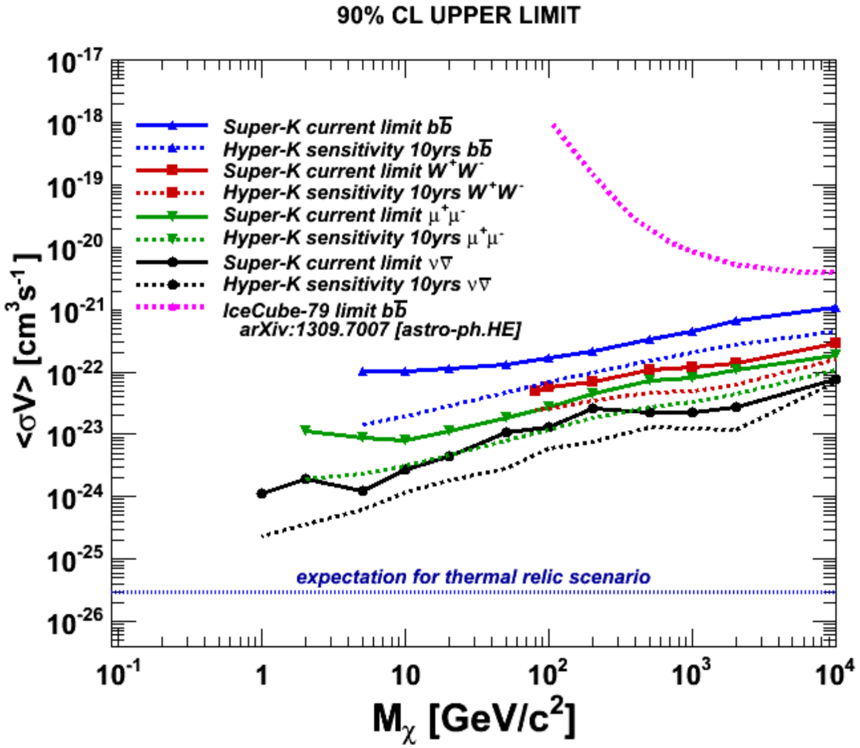
- Cavern stability analyses based on geol. survey results
  - 3D finite element analysis
  - Excavation steps taken into account in stability analysis
  - Evaluate plastic region depth and design cavern support
- Confirmed the Hyper-K cavern can be constructed with the existing technologies
  - Detailed construction timeline established

DM WIMP-induced neutrino **searches** at the Galactic Center

DM induced event excess for χχ → bb̲



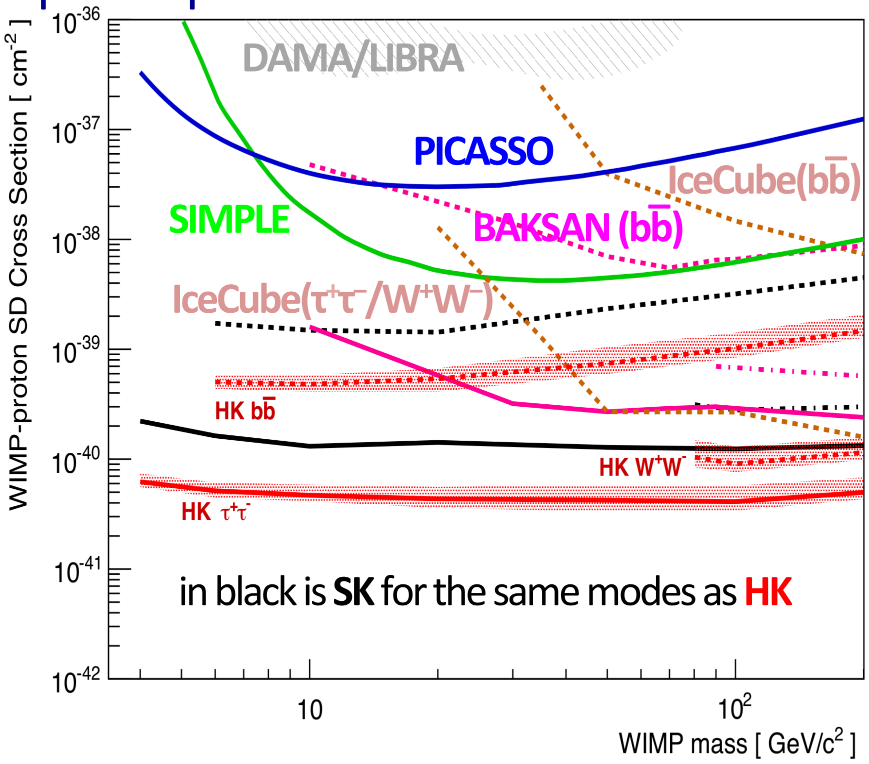
WIMP velocity averaged annihilation cross-section



DM WIMP-induced neutrino **searches** the Sun

90% CL limits on WIMP nucleon scattering cross-section

spin dependent



spin **in**dependent