NOW 2016,
Otranto, Sep. 6, 2016

Prospects for neutrino oscillation physics at Hyper-K

Takaaki Kajita
ICRR, Univ. of Tokyo

outline

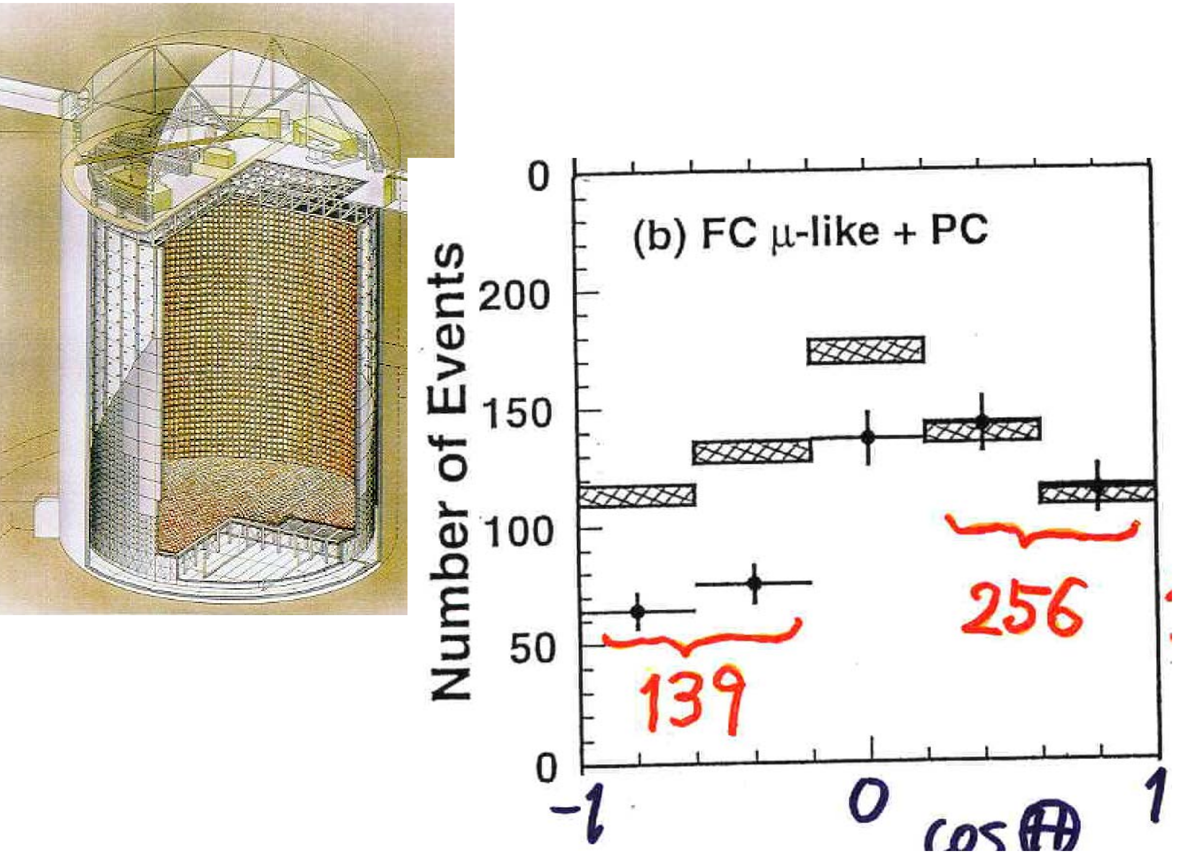
- Introduction
- Hyper-K
- Neutrino oscillation studies with the J-PARC beam
- Neutrino oscillation studies with atmospheric and solar neutrinos
- Other physics
- An interesting possibility
- Status of Hyper-K
- Summary

Introduction

Discovery of neutrino oscillations

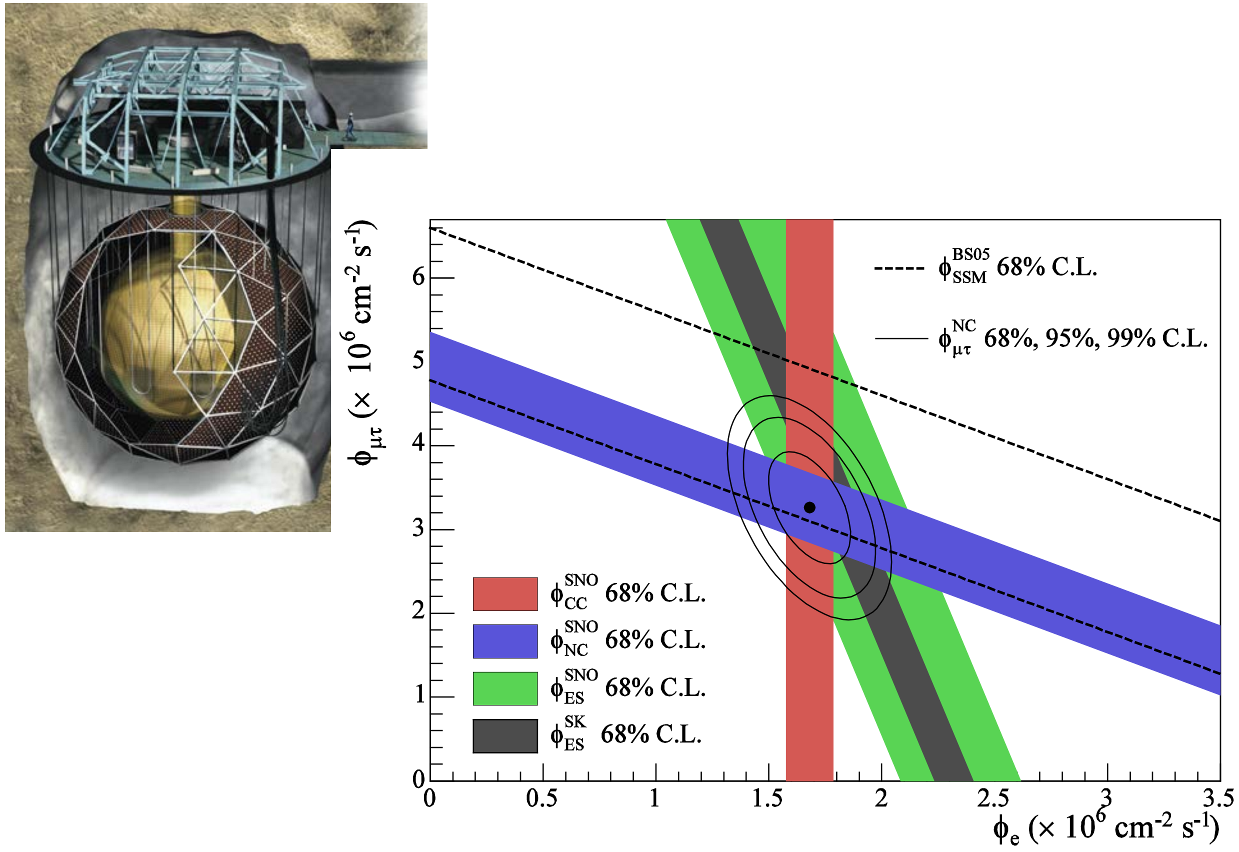
Super-K, PRL 81 (1998) 1562

Atmospheric neutrino oscillations



SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)

Solar neutrino oscillations



These discoveries opened a window to study the physics beyond the Standard Model of particle physics!

Status of neutrino oscillation studies

$\nu_\mu \rightarrow \nu_\tau$ oscillations (Δm_{23}, θ_{23})

Atmospheric: Super-K, Soudan-2, MACRO IceCube/Deepcore, …

LBL: K2K, MINOS, OPERA, T2K, NOvA, …

$\nu_e \rightarrow (\nu_\mu + \nu_\tau)$ oscillations (Δm_{12}, θ_{12})

Solar: SNO, Super-K, Borexino, …

Reactor: KamLAND

θ_{13} experiments

LBL: MINOS, T2K, NOvA, …

Reactor: Daya Bay, Reno, Double Chooz

Status (before Neutrino 2016)

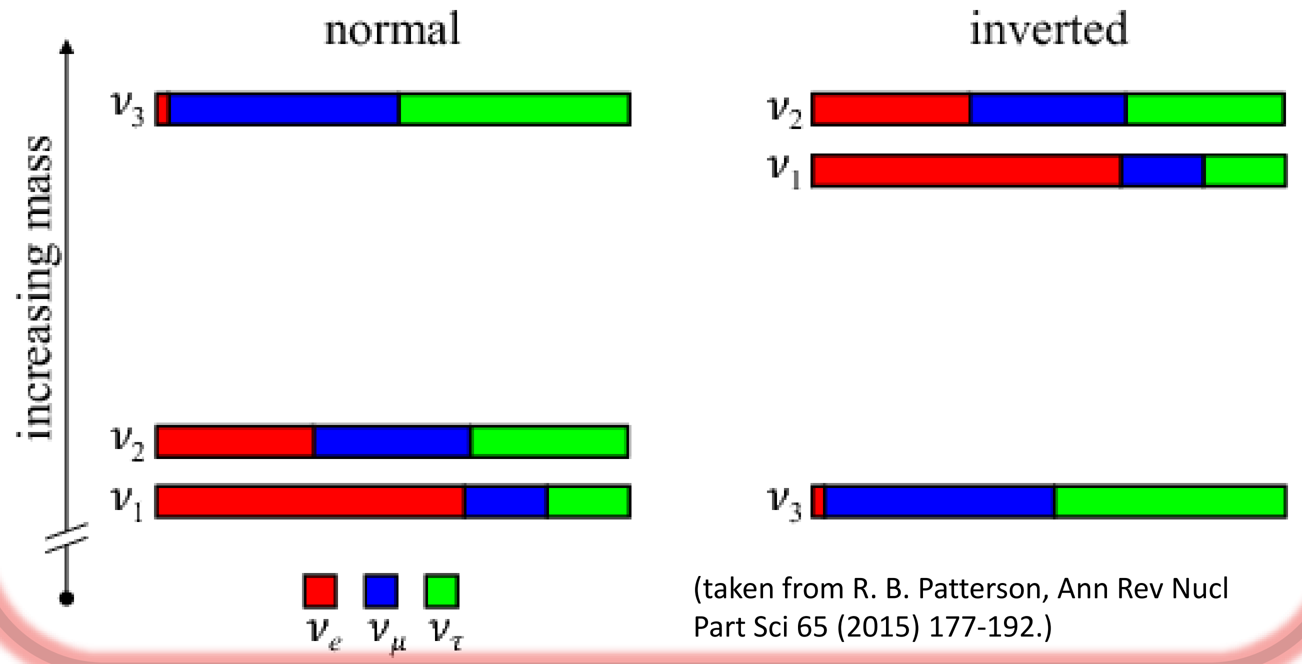
Parameter	best-fit ($\pm 1\sigma$)
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)
$\sin^2\theta_{12}$	0.308 ± 0.017
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$

K. Nakamura and S.T. Petcov, "14. Neutrino mass, mixing and oscillations"

Basic structure for 3 flavor oscillations has been understood!

Agenda for the future neutrino measurements

Neutrino mass hierarchy?



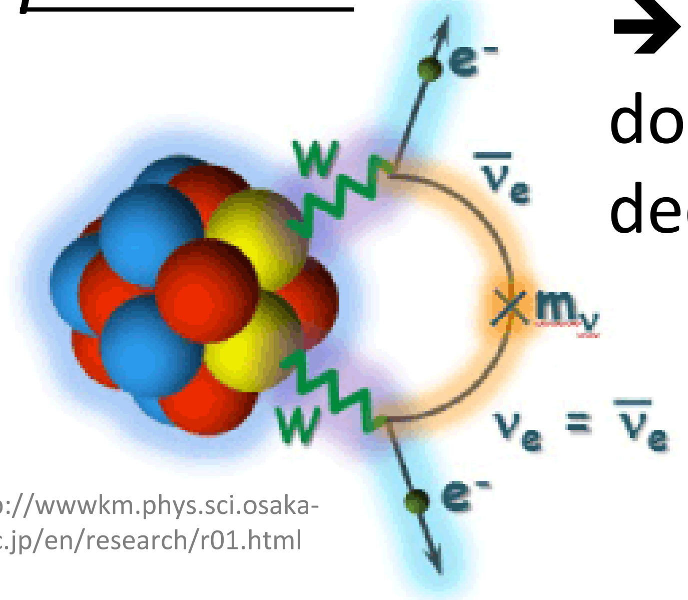
(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

CP violation?

$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta) \ ?$$

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?

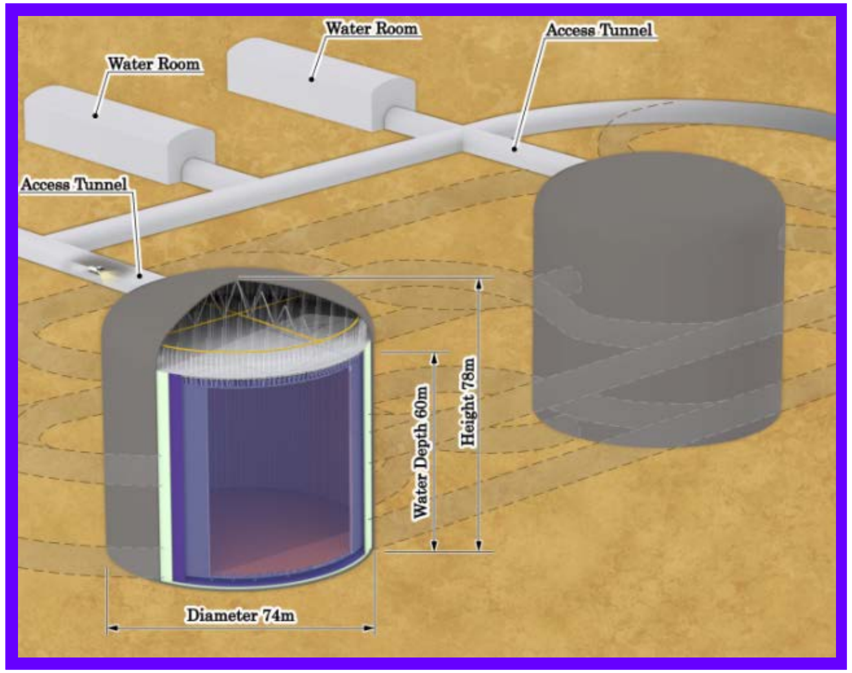


http://wwwkm.phys.sci.osaka-u.ac.jp/en/research/r01.html

➔ Neutrinoless double beta decay

Absolute neutrino mass?

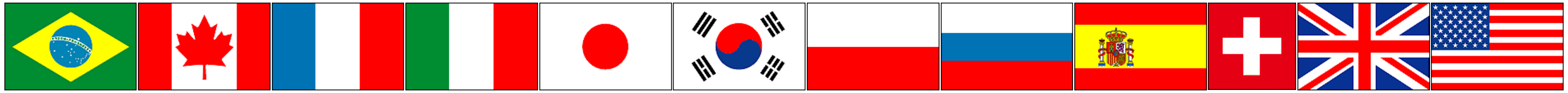
Beyond the 3 flavor framework? (Sterile neutrinos?)



Hyper-K

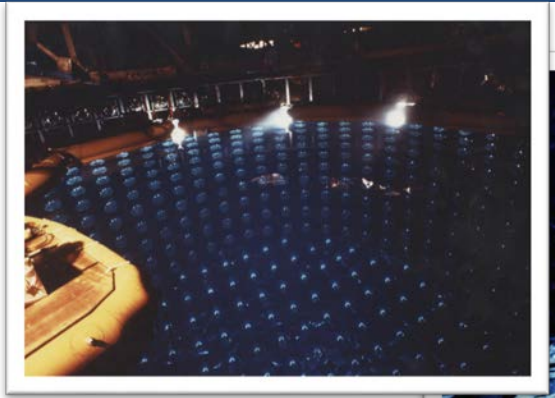
J-PARC

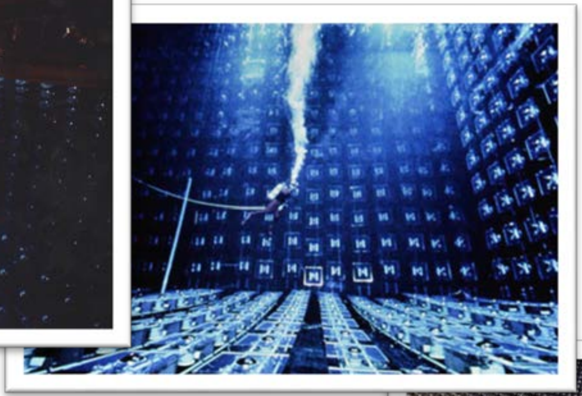
Hyper-K proto-collaboration: 12 countries, ~250 members and growing



Hyper-K

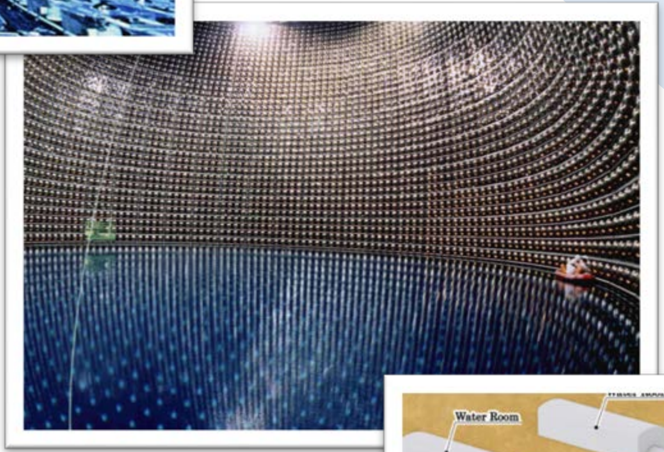
Hyper-K as a natural extension of water Ch. detectors





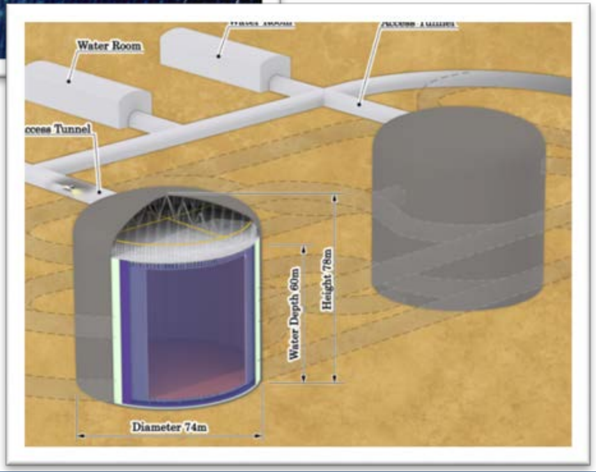
Kamiokande & IMB

- *Neutrinos from SN1987A*
- *Atmospheric neutrino deficit*
- *Solar neutrino (Kam)*



Super-K

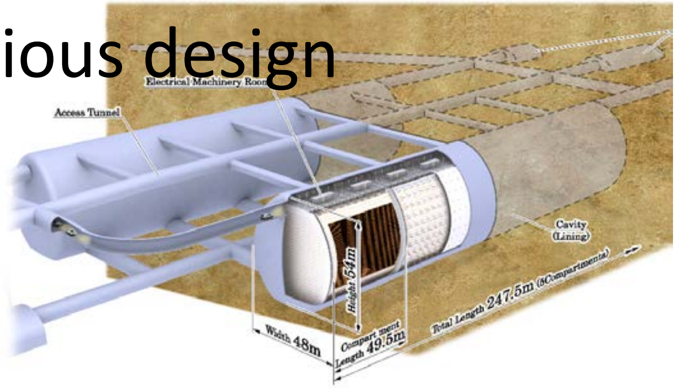
- *Atmospheric neutrino oscillation*
- *Solar neutrino oscillation with SNO*
- *Far detector for K2K and T2K*

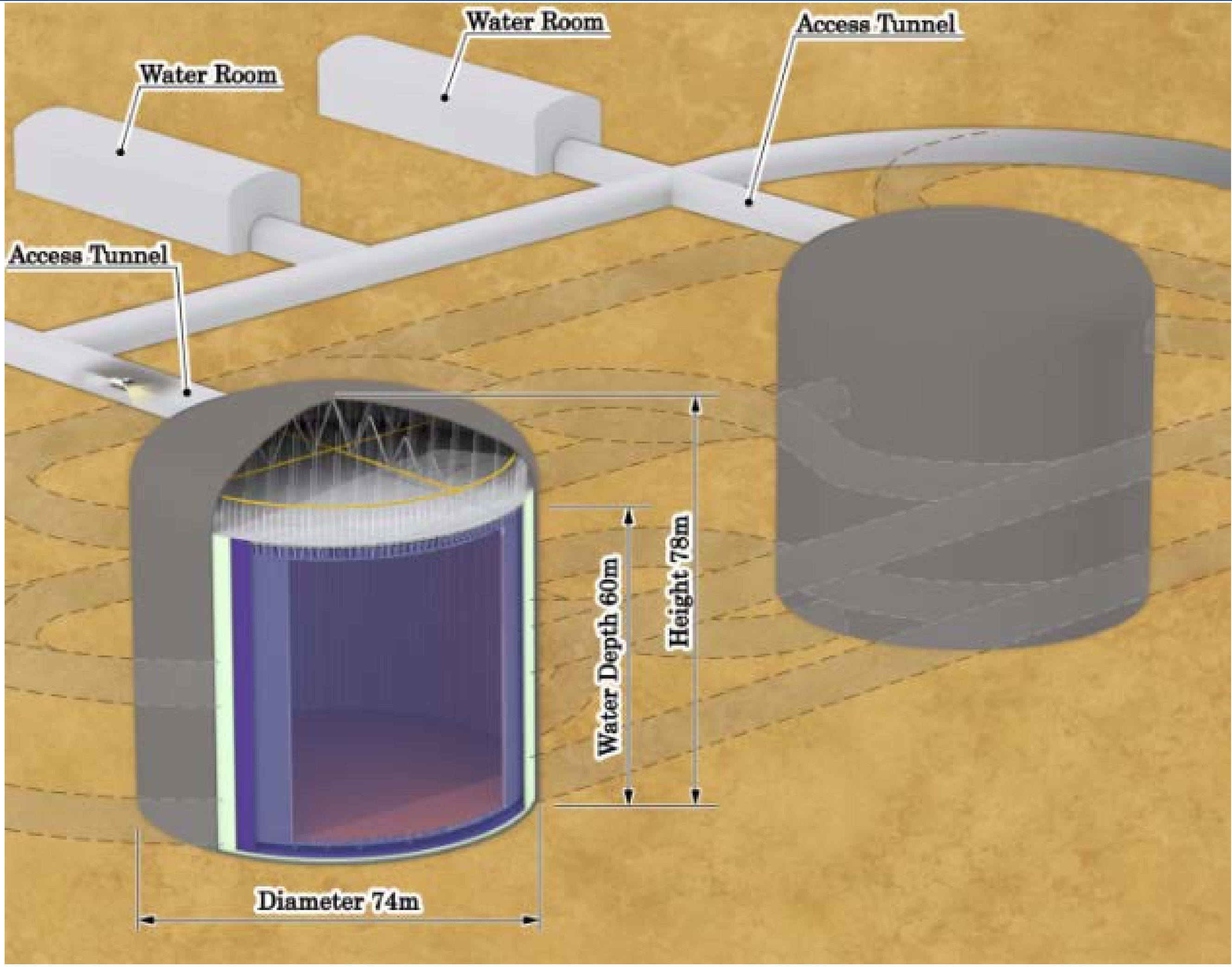


Hyper-K

Present design of Hyper-K

Previous design





✓Super-K-like structure

✓2 tanks with staging

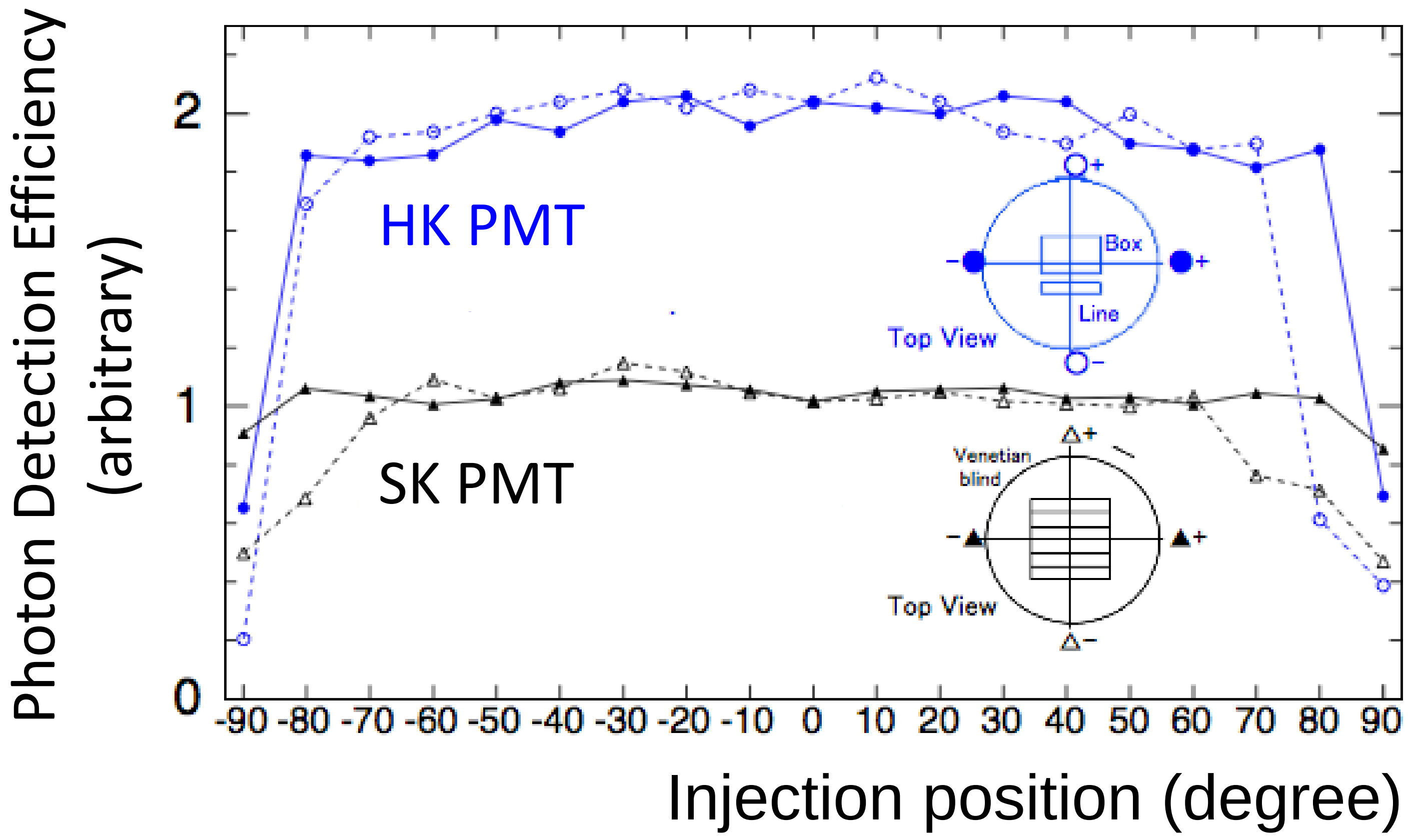
(2nd tank assumed to be ready 6 years later)

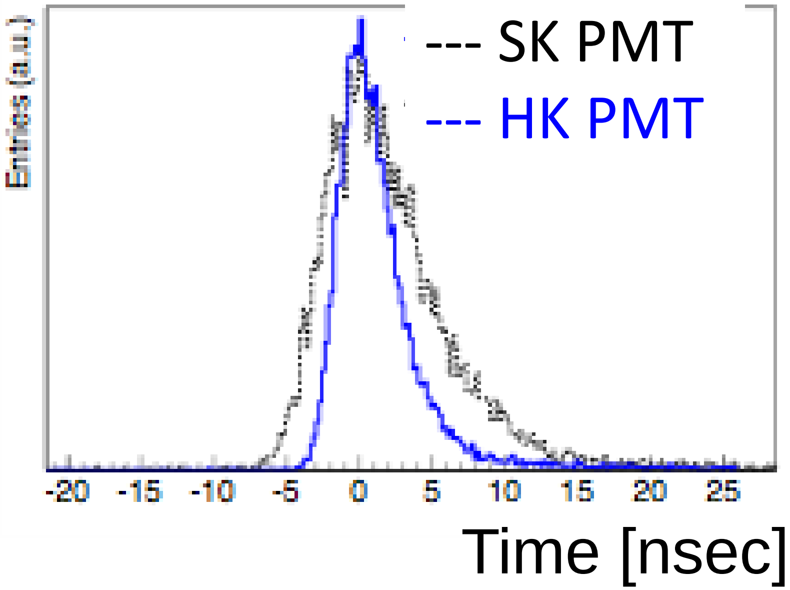
✓1 tank will be;

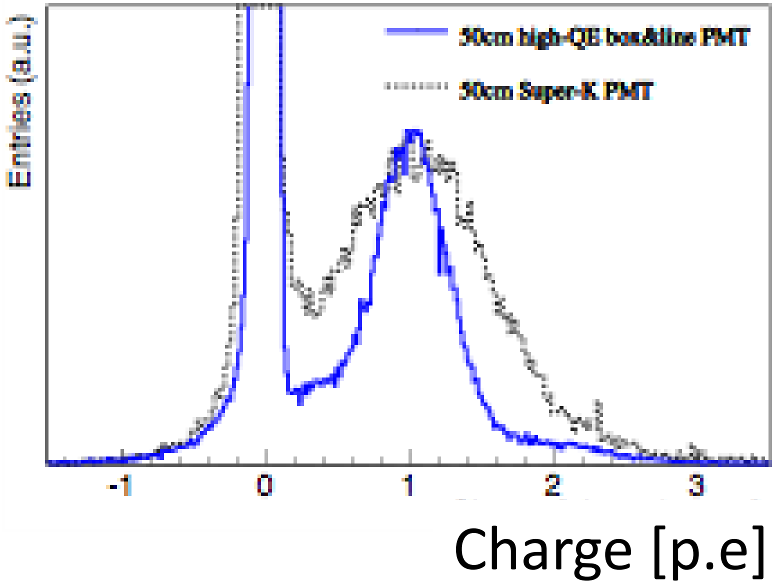
- 60m(H)×74m(D)
- Total volume: 260 kton
- Fiducial volume(FV): 190 kton
  ~10 x Super-K FV
- PMT coverage 40%, 40,000 ID-PMT, 6,700 OD-PMT

✓ The candidate site is ~8km south of SK (2.5 degree off axis beam, L=295km)

A highlight of the Hyper-K R&D: New 50cmϕ PMT





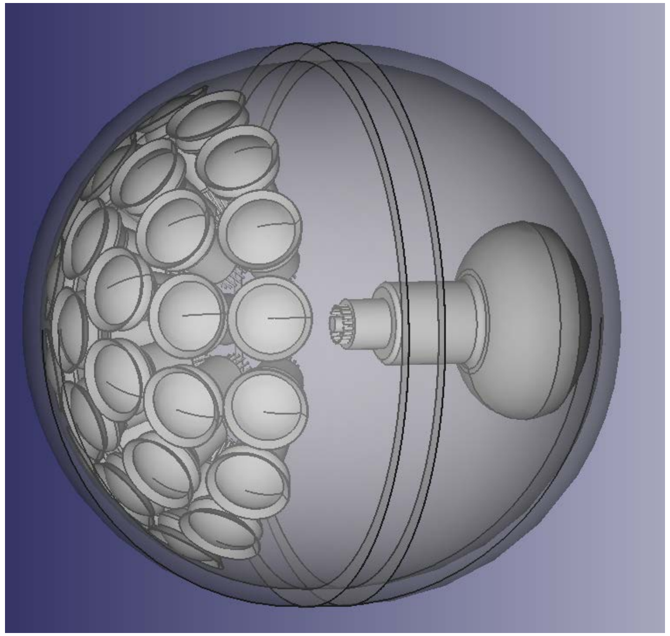


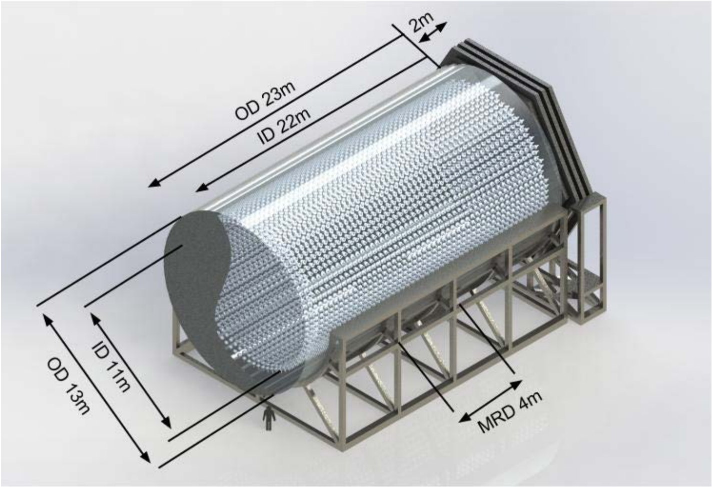
- ✓ Photon detection efficiency x 2,
- ✓ Timing & charge (@1 p.e.) resolution x 1/2
- ✓ (Pressure tolerance x 2 (>100m))

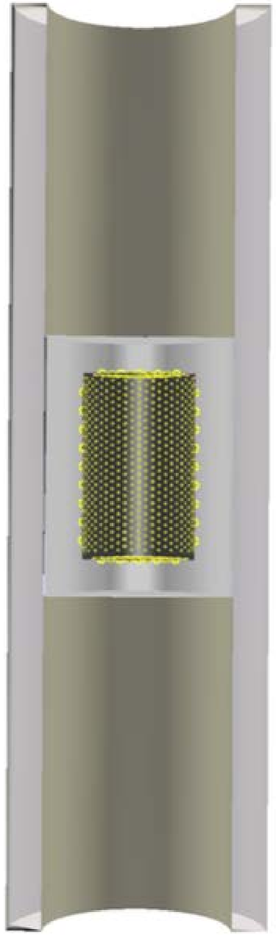
➔ Large impacts to physics

International responsibilities

- Half of photo-detection system
  - Multi-PMT module (for Inner Detector /Outer Detector)
    - Established MoU with KM3NeT to exchange knowledge on multi-PMT technology
  - or other type of photo-detector for Outer Detector
- Electronics, DAQ, calibration and others
- Near detectors for LBL
- Others …





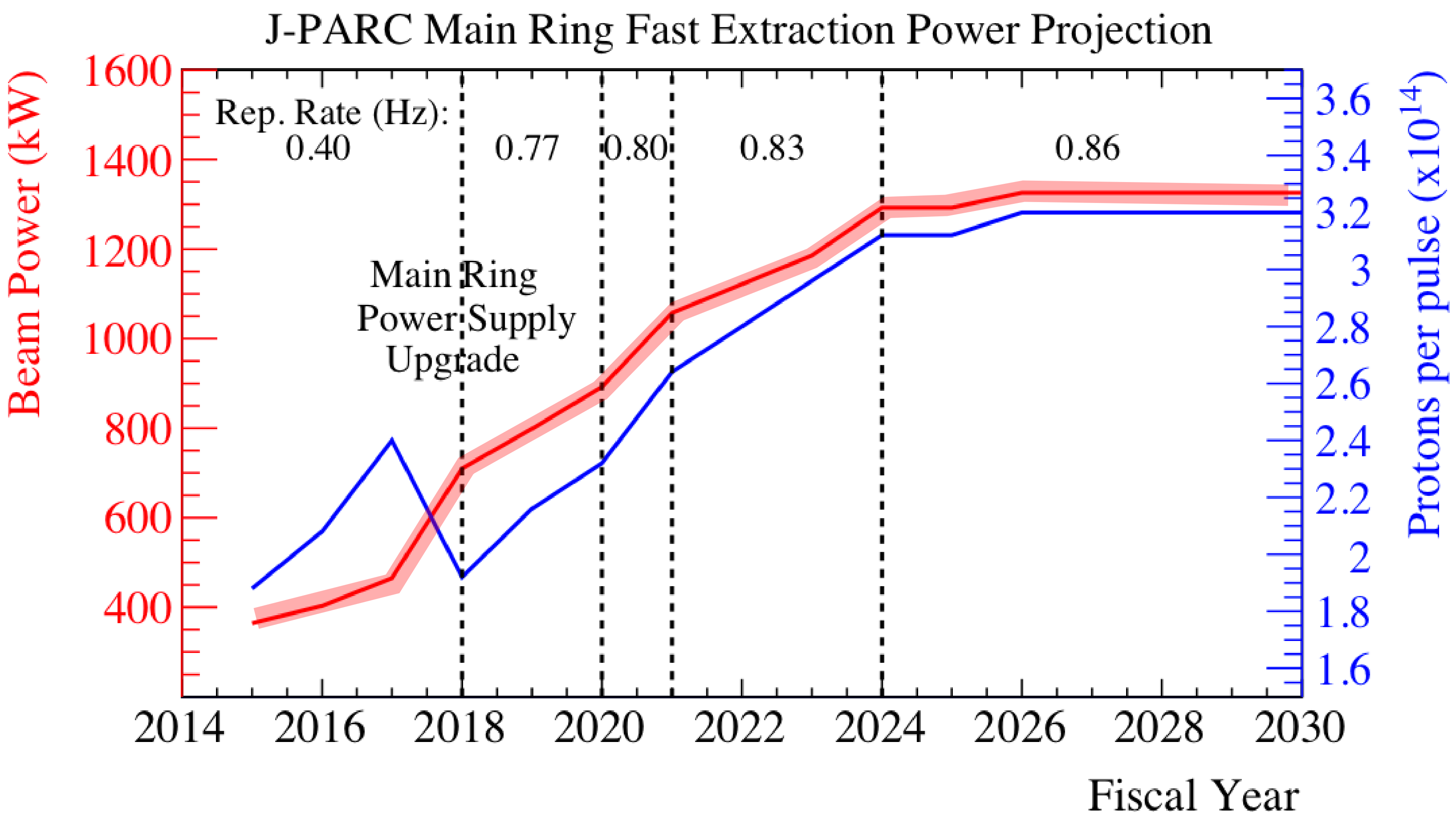


Neutrino oscillation studies with the J-PARC beam

J-PARC neutrino beam upgrade

Continuous upgrade plan of the neutrino beam

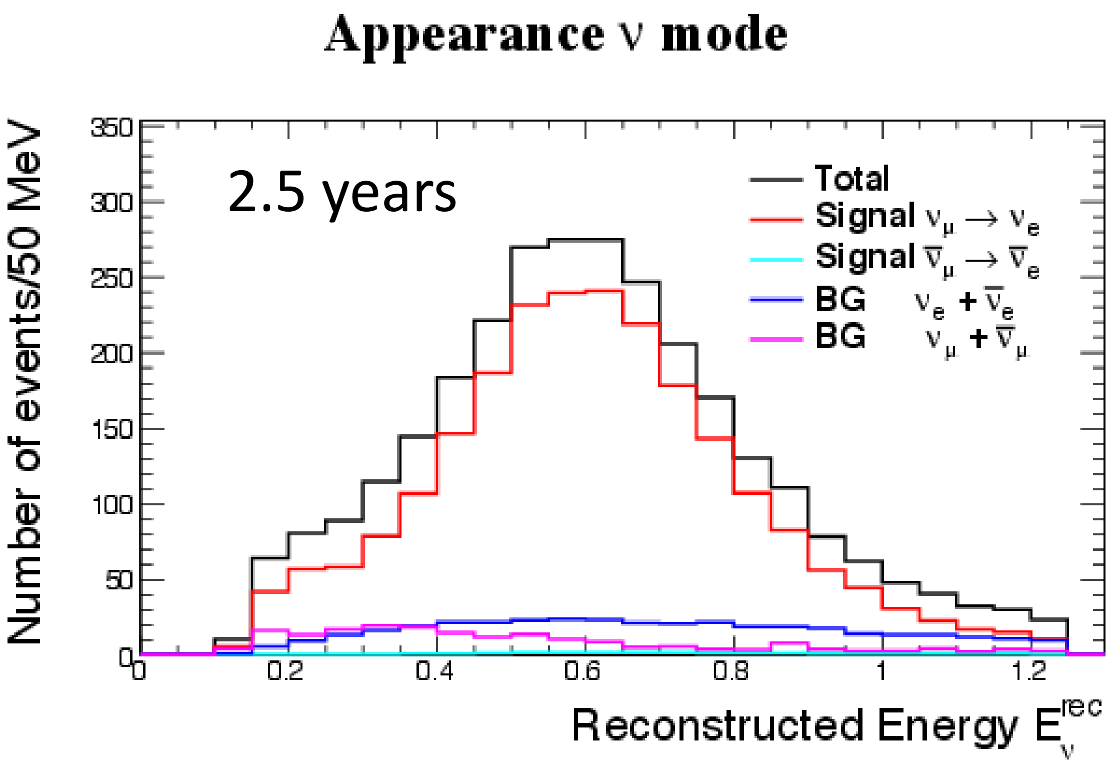
- ✓ 0.75 MW in 2018 by MR power supply upgrade
- ✓ 1.3 MW by ~2026 by increasing rep. rate to 0.86 Hz

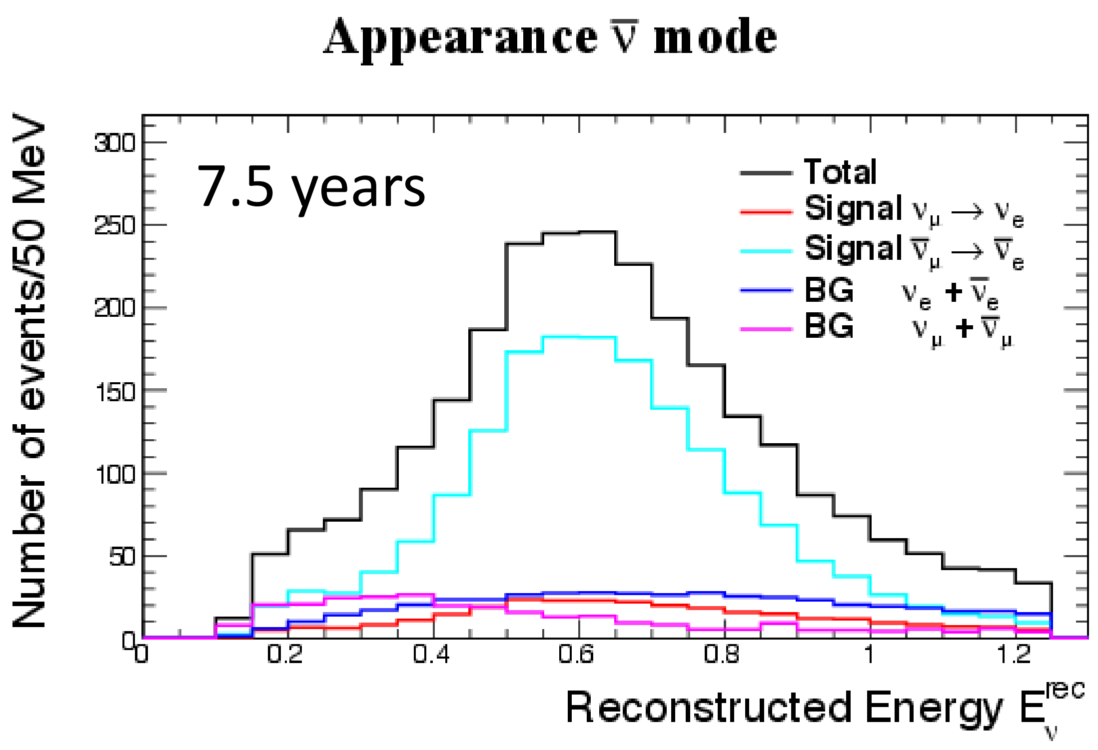


KEK Project Implementation Plan Review:

➢ PIP review concluded that "J-PARC upgrade for Hyper-K is the highest priority" (2016).

Expected number of events (10 years)

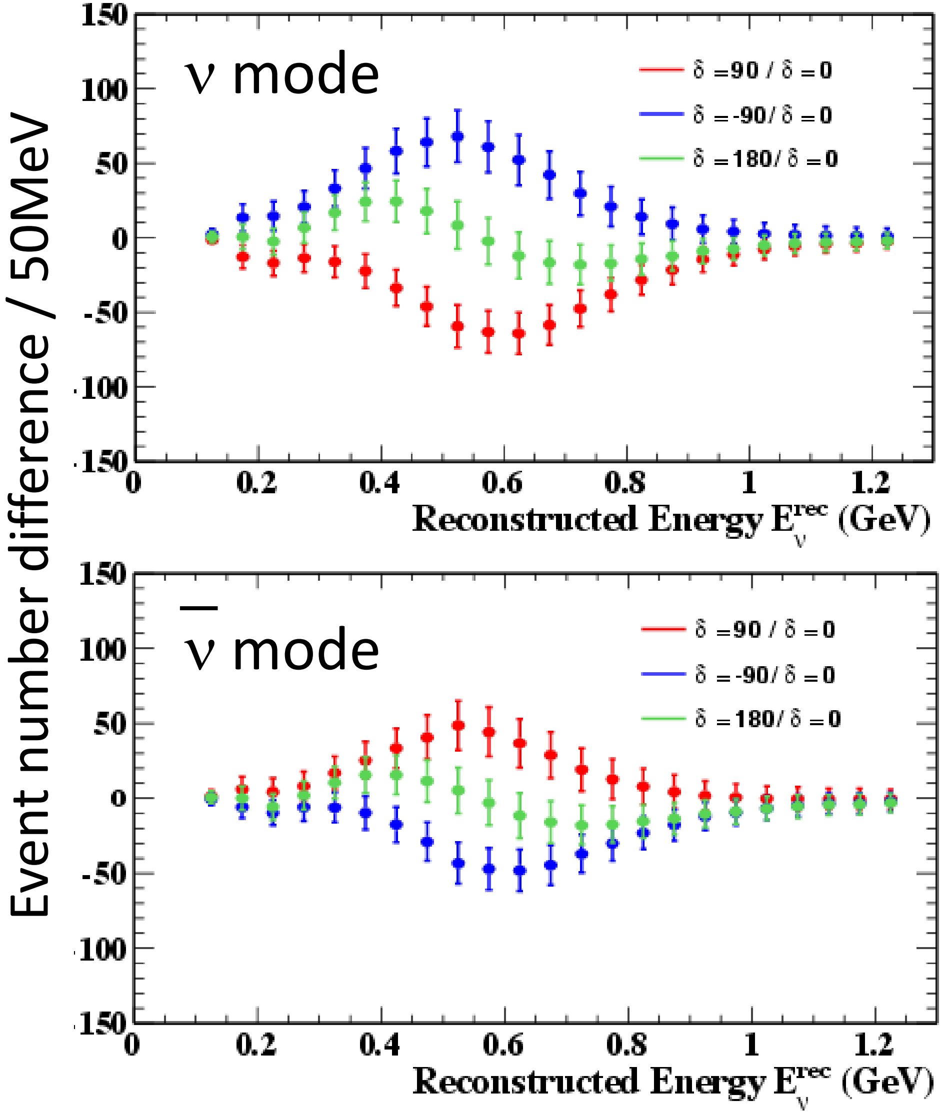


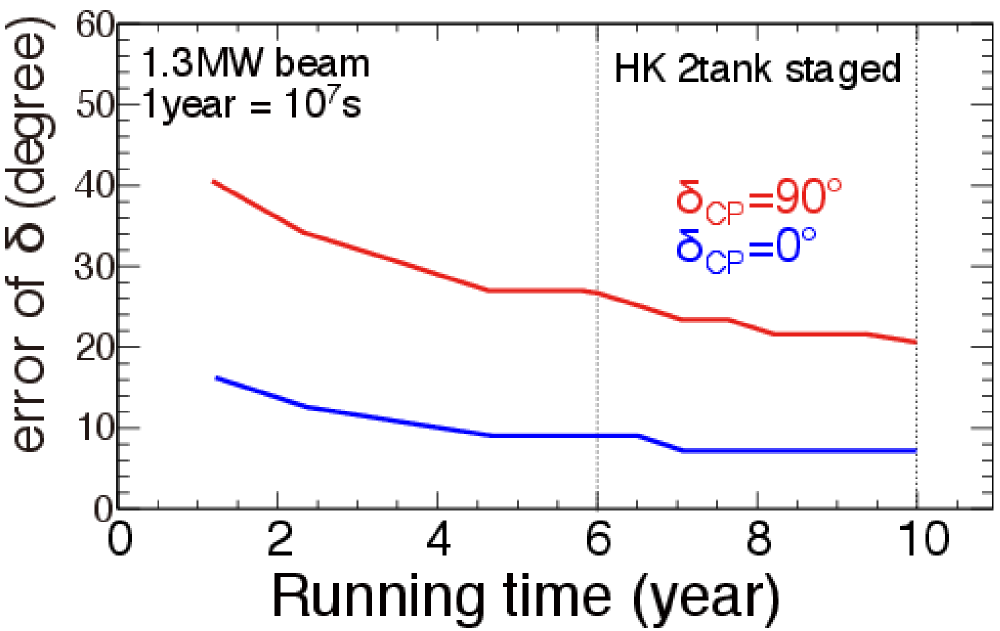


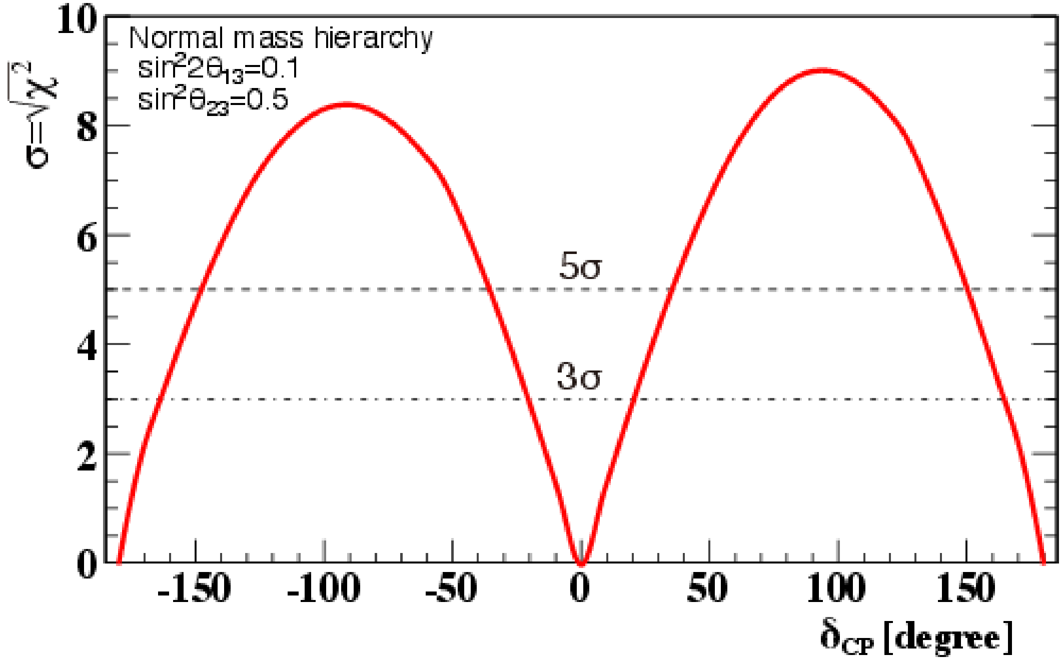
	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	ν_μ , $\bar{\nu}_\mu$ CC	Beam ν_e, $\bar{\nu}_e$ contamination	NC
ν beam (δ_{CP}=0)	2300	21	10	362	188
$\bar{\nu}$ beam (δ_{CP}=0)	1656	289	6	444	274

δ_{CP} sensitivity

Difference from δ_{CP}=0







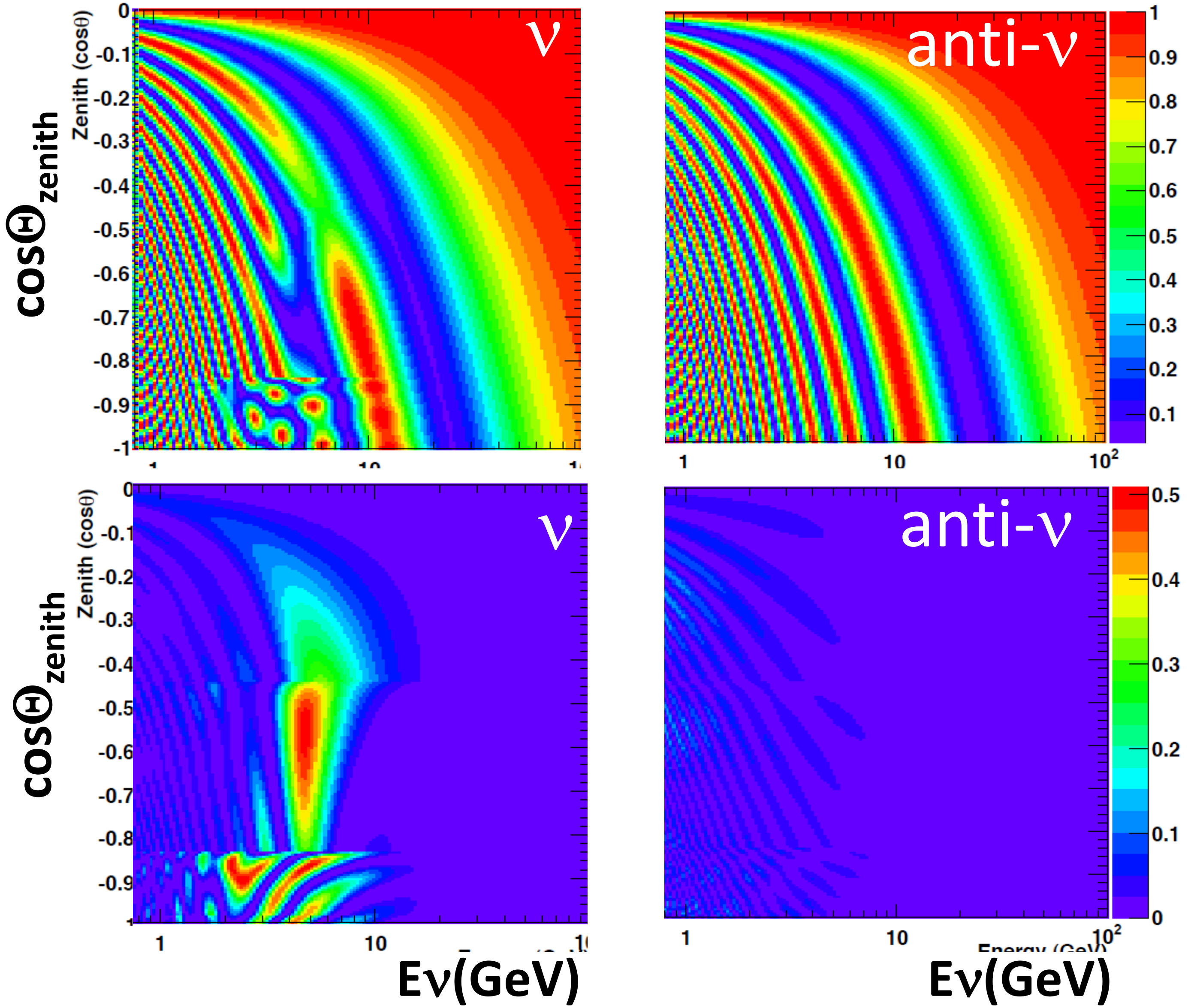
Neutrino oscillation studies with atmospheric and solar neutrinos

Oscillation probabilities

Osci. Probabilities for Normal Hierarchy

$P(\nu_\mu \rightarrow \nu_\mu)$

$P(\nu_\mu \rightarrow \nu_e)$

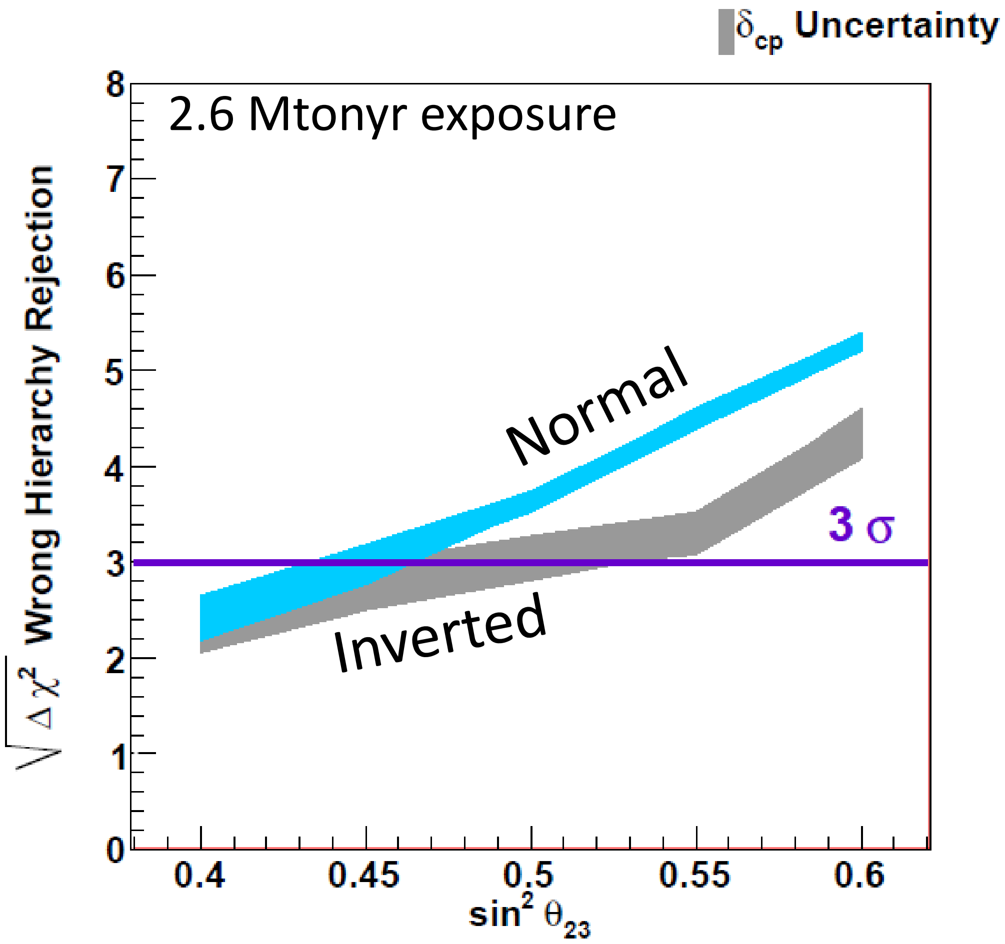


Inverted hierarchy:

ν ←→ anti-ν

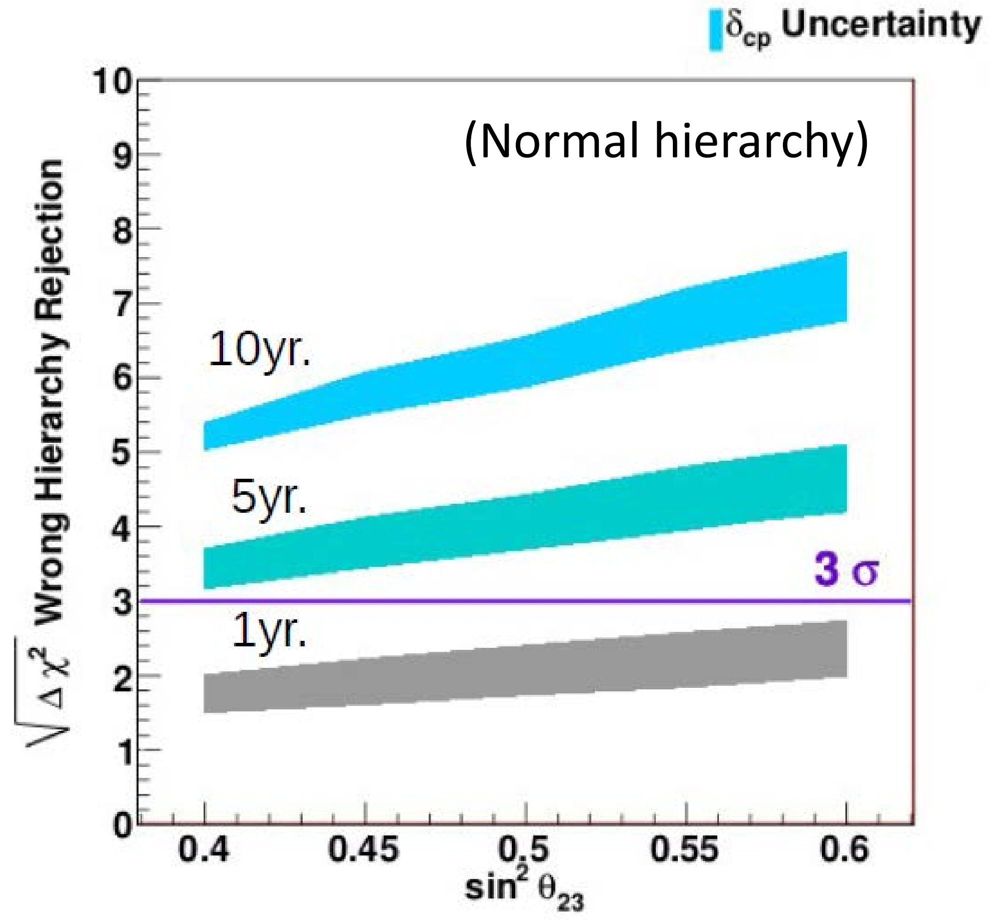
Sensitivity to mass hierarchy

Atmospheric neutrinos only



(The systematic errors: identical to those of Super-K.)

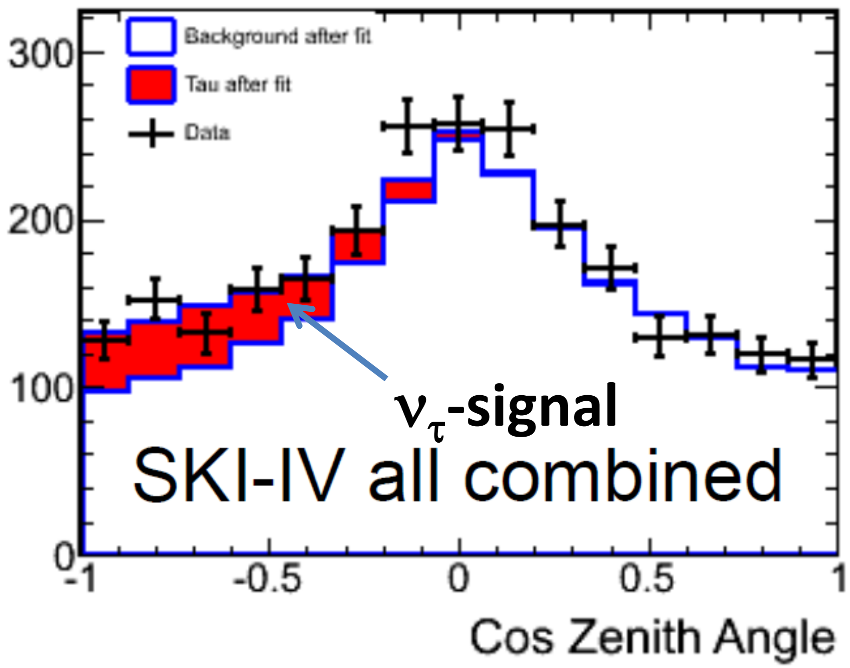
Atmospheric + beam



Tau neutrino appearance

Super-Kamiokande

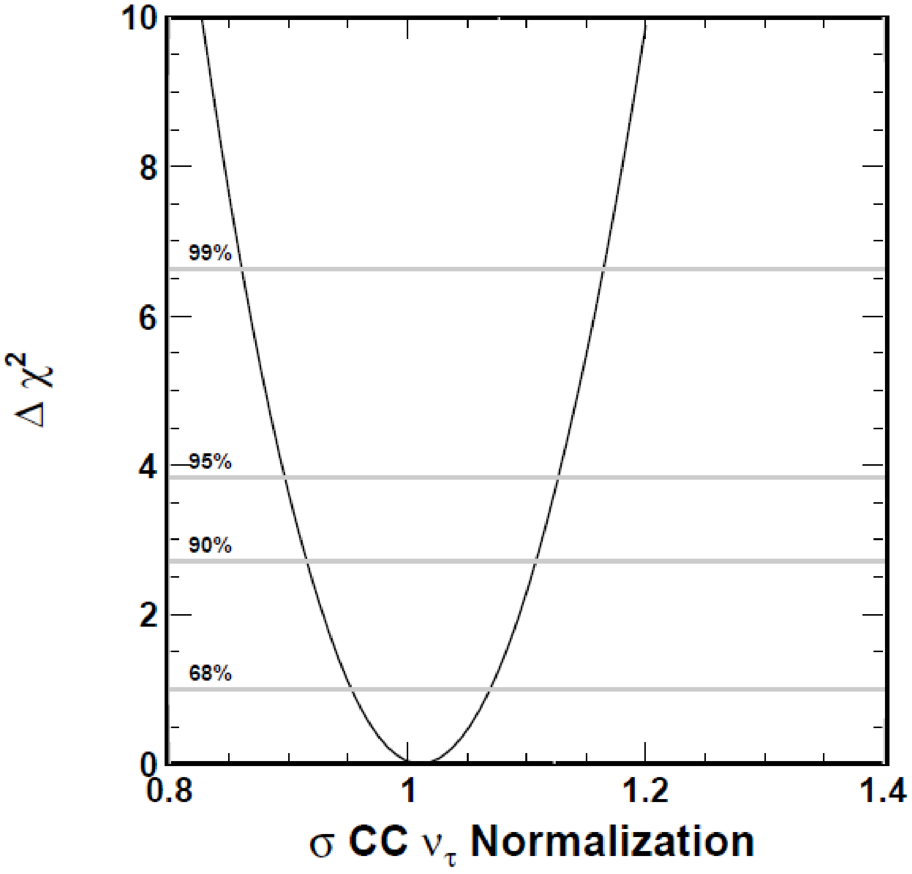
Super-K (S.Moriyama) @nu2016
See also, SK PRL 110(2013)181802



➔ τ-appearance signal at 4.6σ

- In Hyper-K, the statistical significance is no more an issue.
- the normalization of the CC ν_τ cross section (relative to CC ν_μ cross section) can be constrained to ~7% with a 5.6 Mton year exposure of Hyper-K.
- This measurement will help understand the CC ν_τ cross section near the threshold, which is known rather poorly.

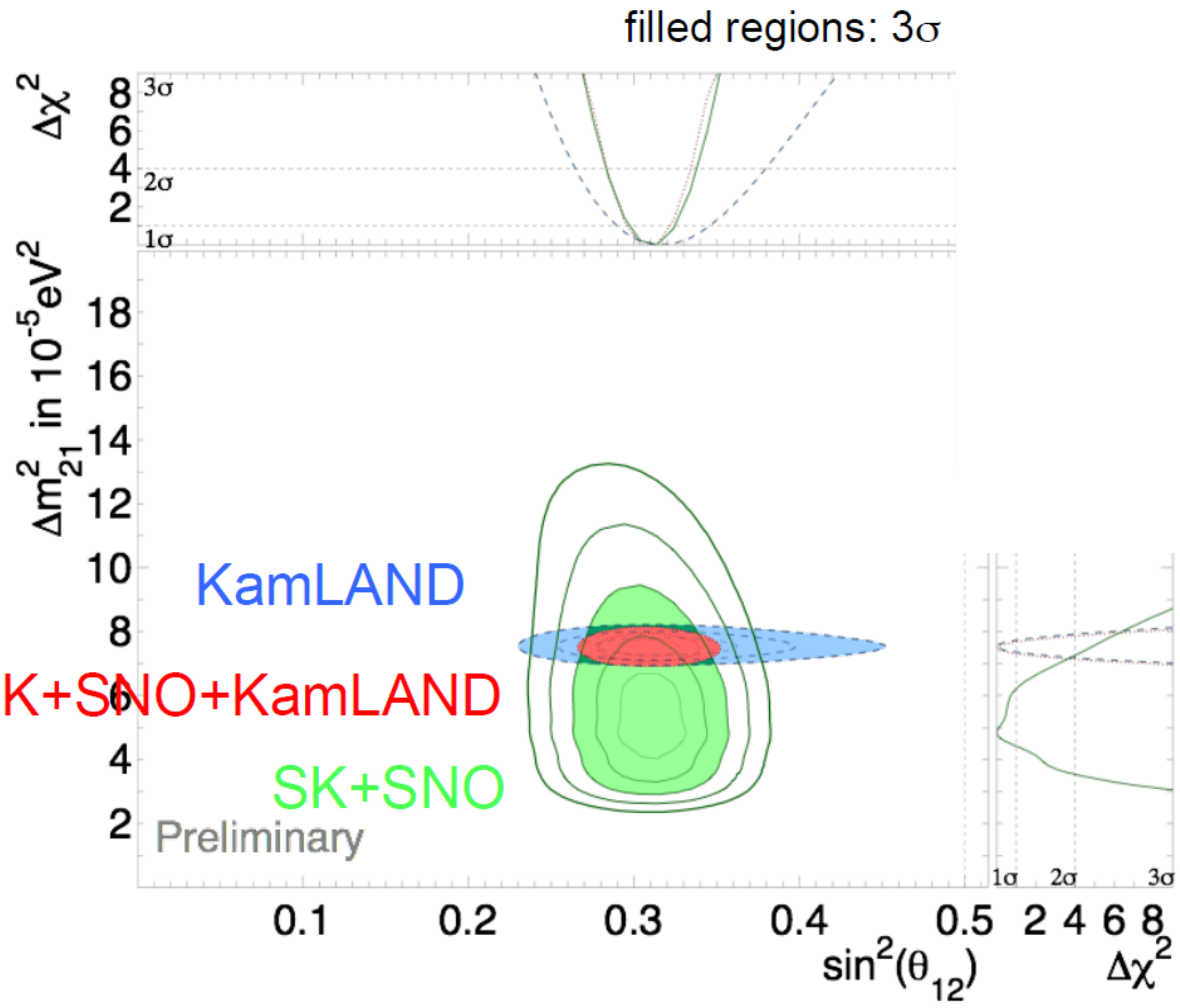
Hyper-K, 5.6 Mton yrs



Solar neutrino oscillations and day/night effect

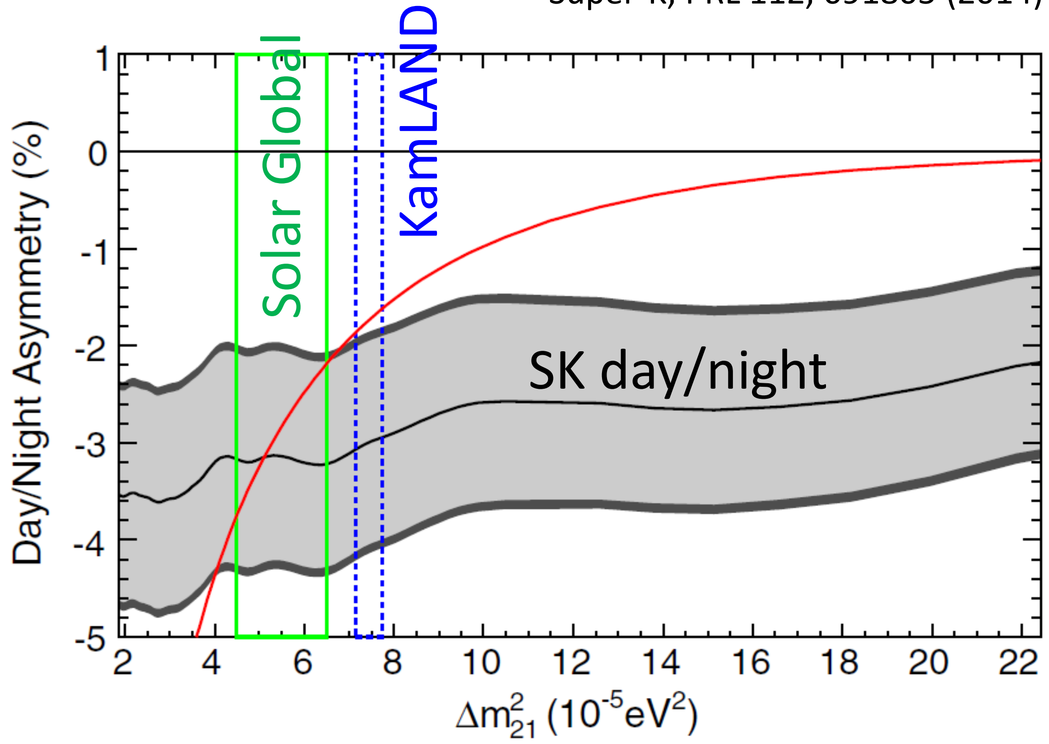
Status of the 12-parameter measurements

S. Moriyama (Super-K), Neutrino 2016



SK day/night and Δm_{12}^2

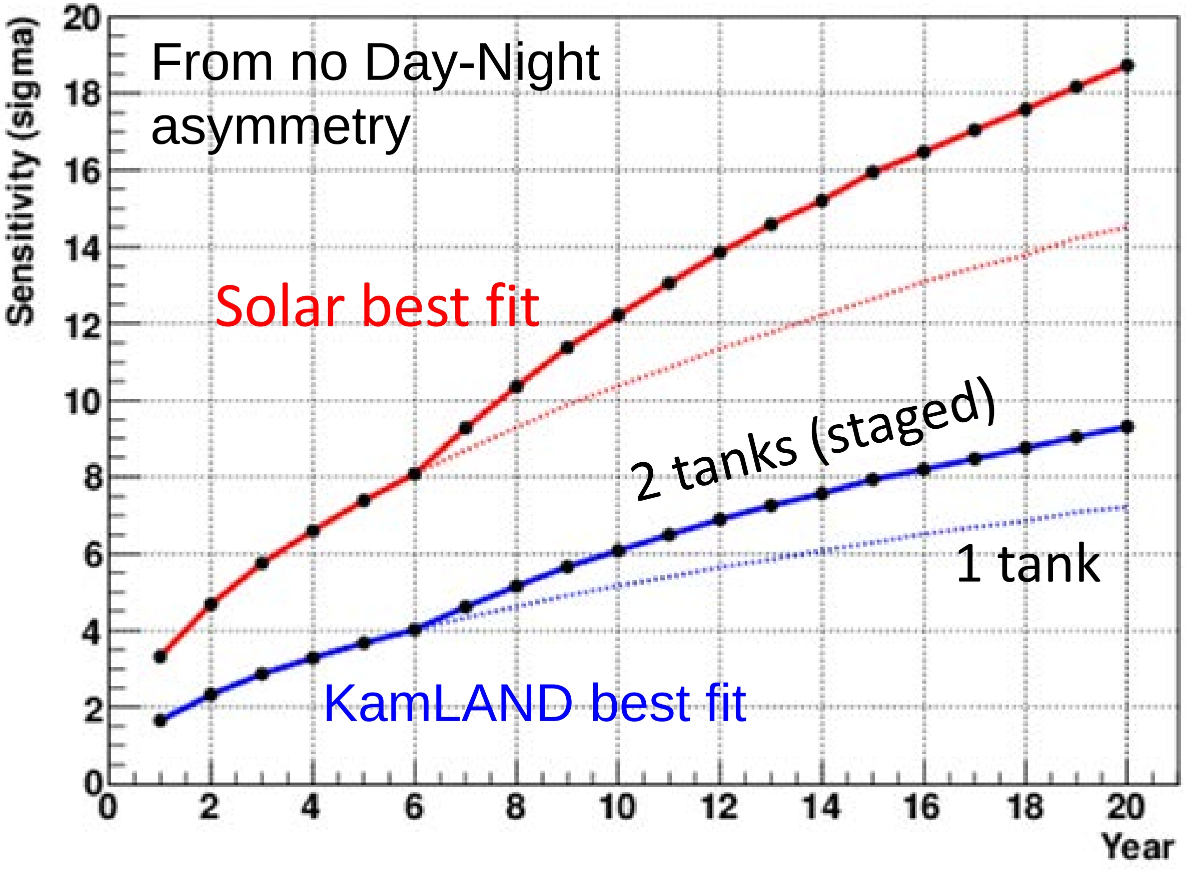
Super-K, PRL 112, 091805 (2014)



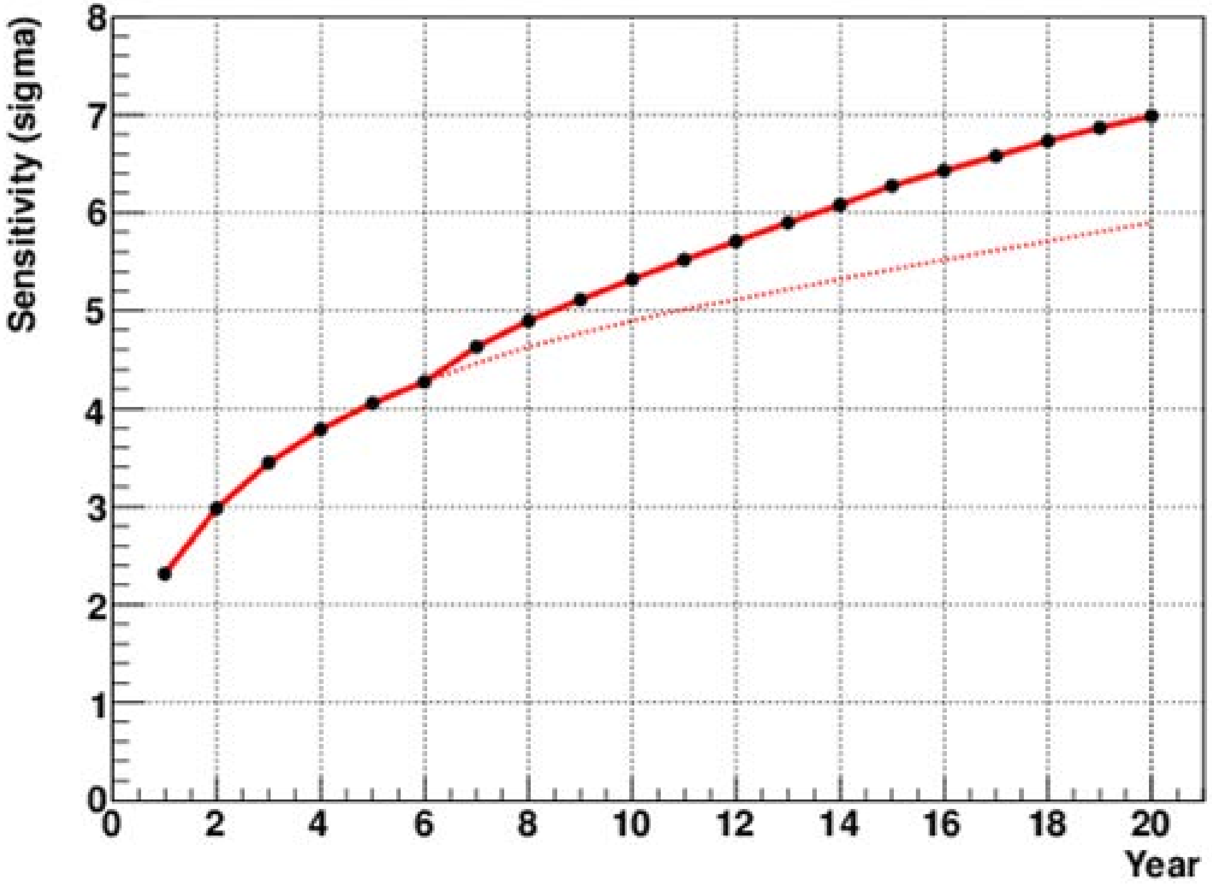
- ✓ The data might indicate that there is something interesting going on in solar neutrinos….

Hyper-K solar neutrino measurements

Day-night asymmetry sensitivity



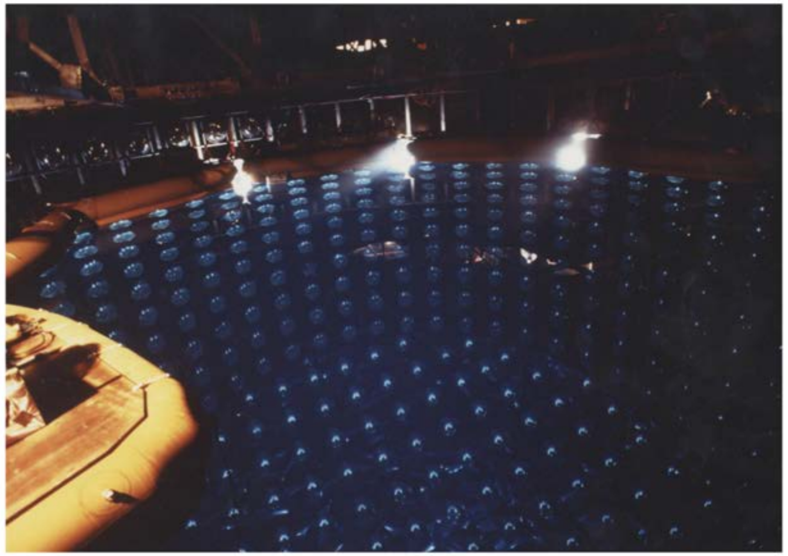
Spectrum upturn discovery sensitivity



Other physics

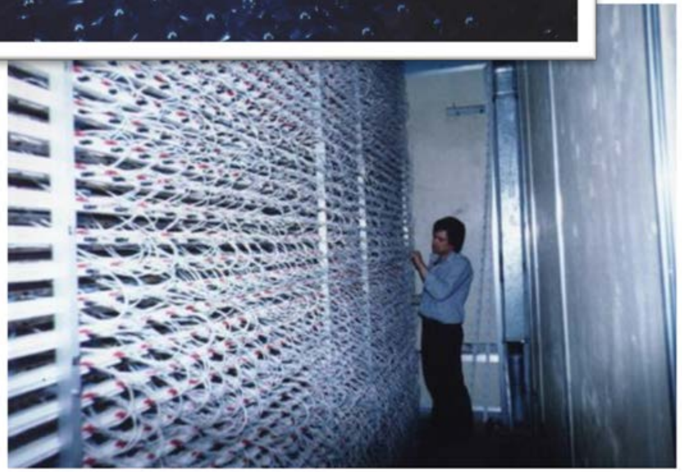
Proton decay experiments (1980's)

Grand Unified Theories
(in the 1970's)
➔ $\tau_p = 10^{30\pm2}$ years

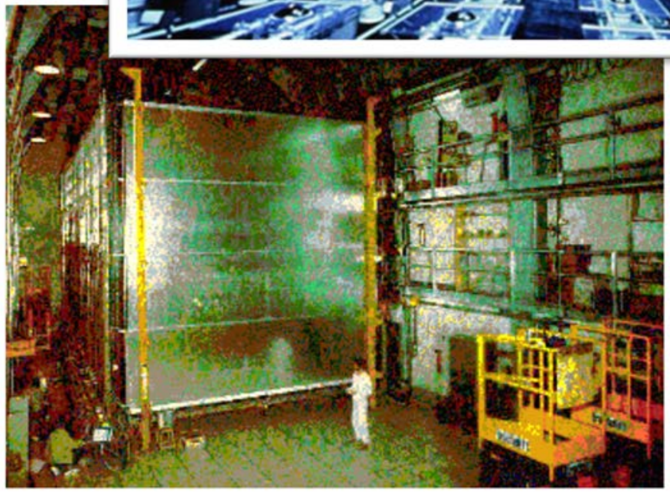


Kamiokande
(1000ton)

IMB
(3300ton)



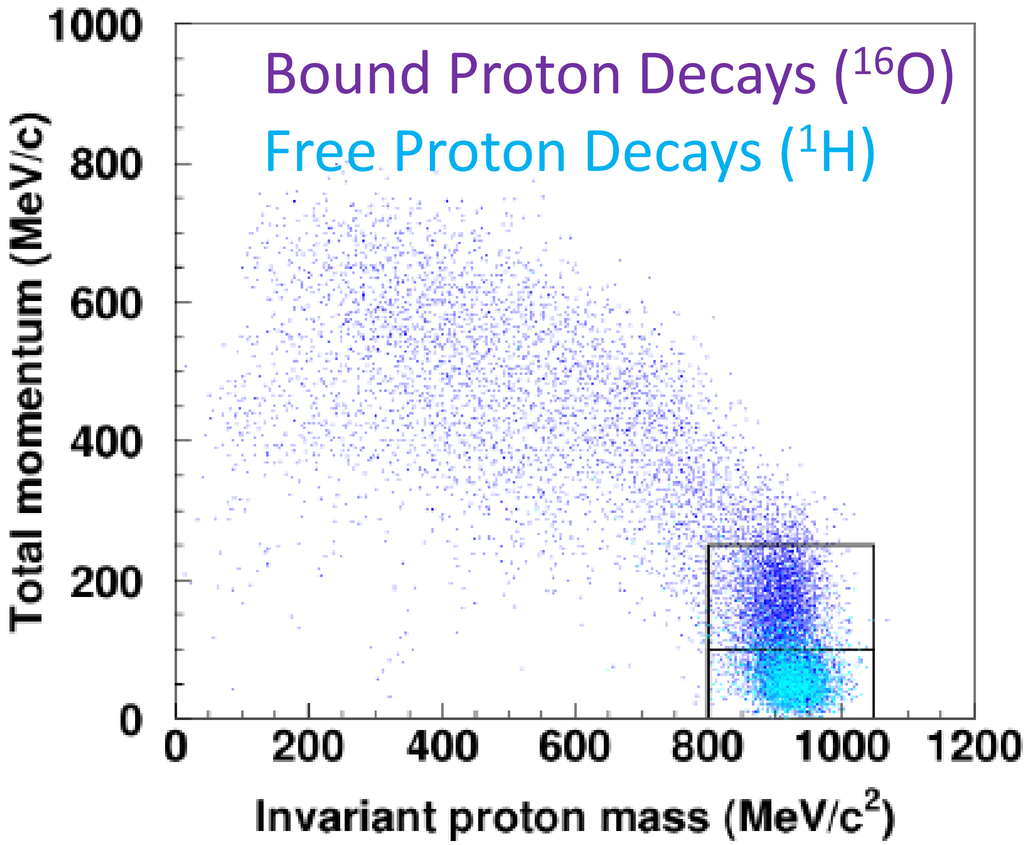
NUSEX
(130ton)

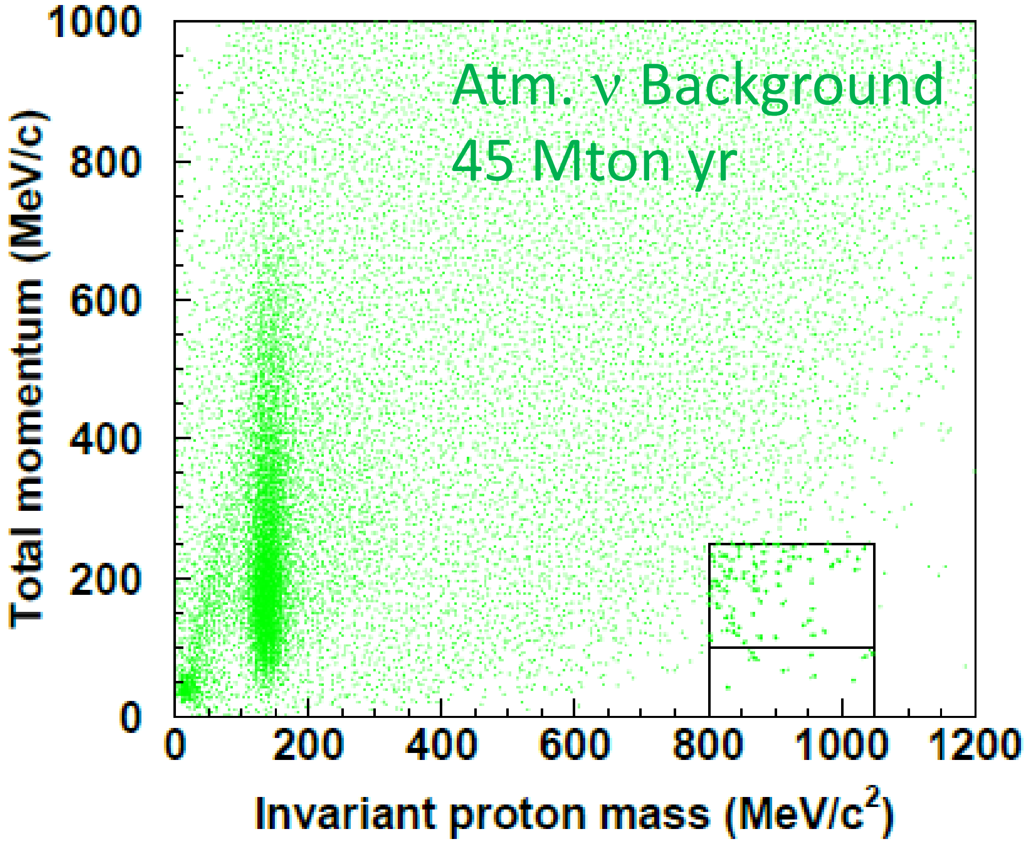


Frejus
(700ton)

These experiments did not observe proton decays and excluded the original GUTs.
However, we should not forget about the importance of proton decays!

Proton decay ($p \rightarrow e^{+} \pi^{0}$)

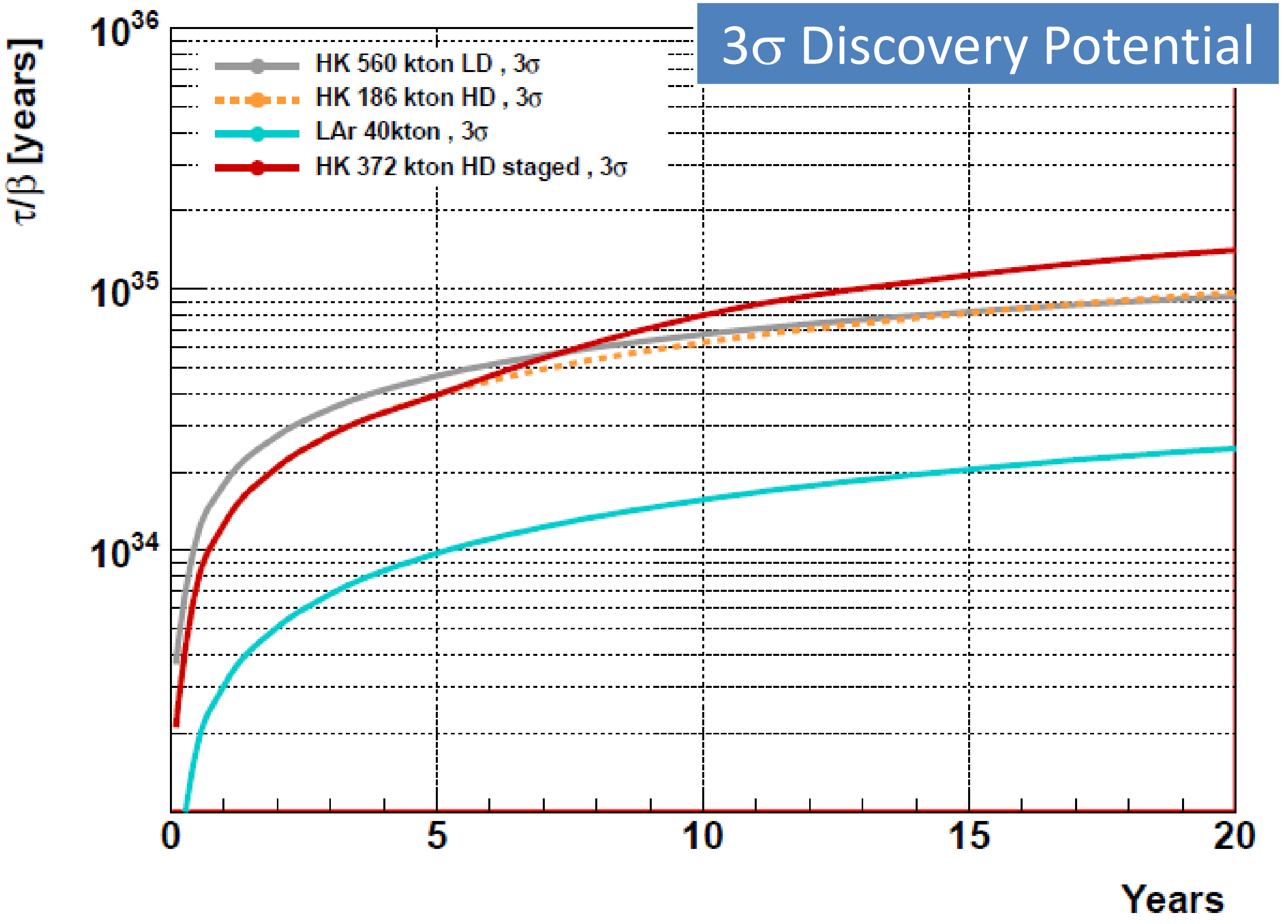


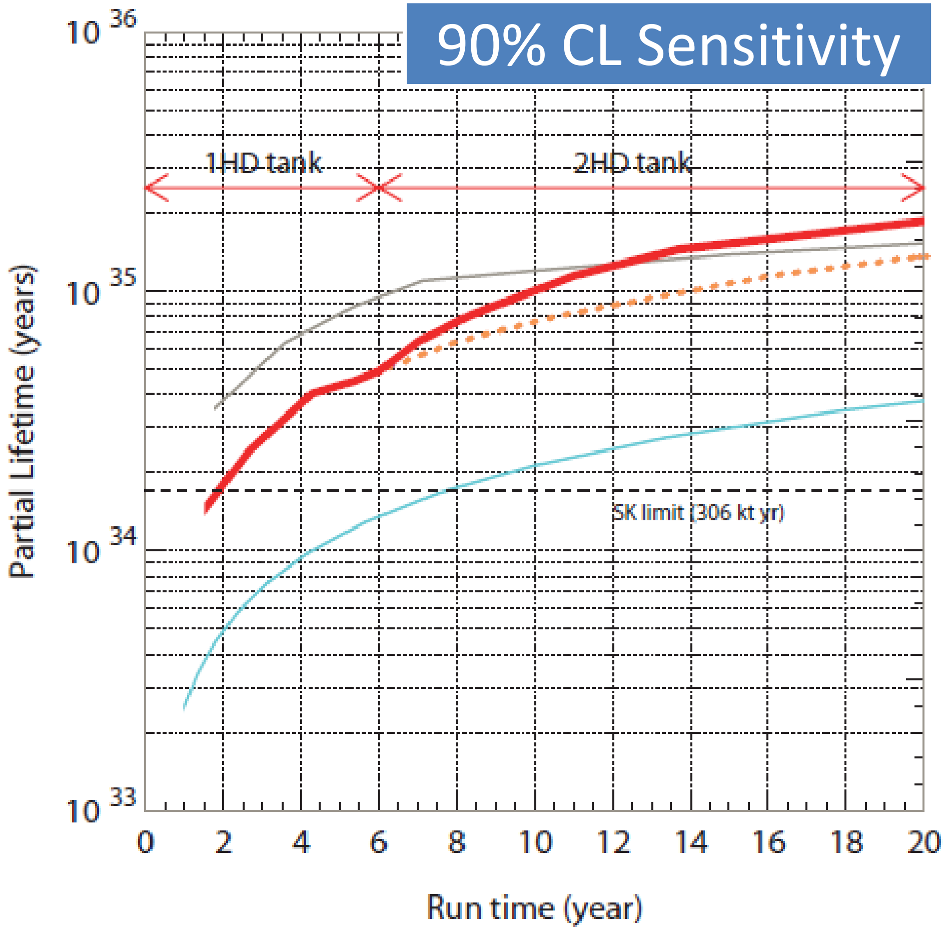


	P_{total}< 100 MeV/c		P_{total} < 250 MeV/c	
	efficiency	Background (/Mtonyr)(*)	Efficiency	Background (/Mtonyr)(*)
Hyper-K	18.7%	0.06	38.1%	0.68

(*) Neutron tagging included to reduce the background

$P \rightarrow e^+ \pi^0$: sensitivity

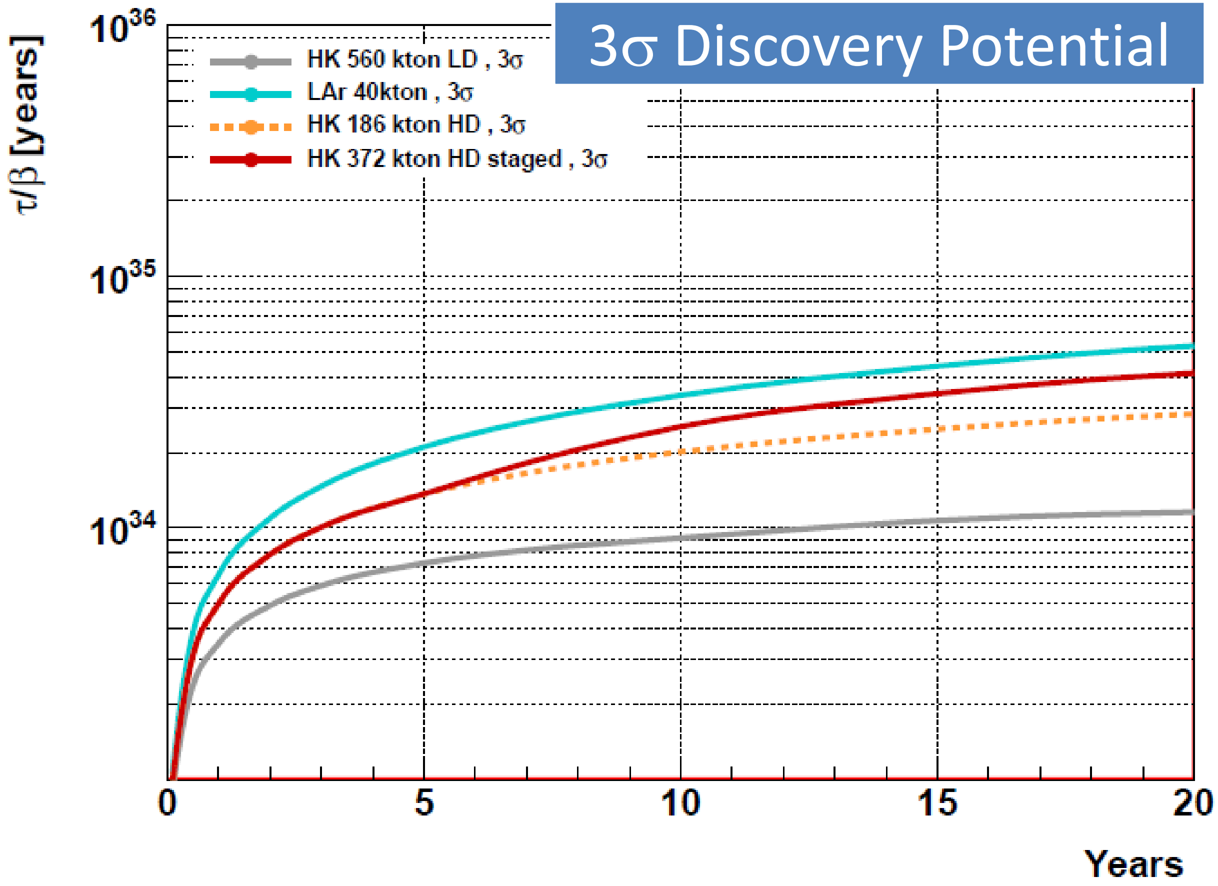


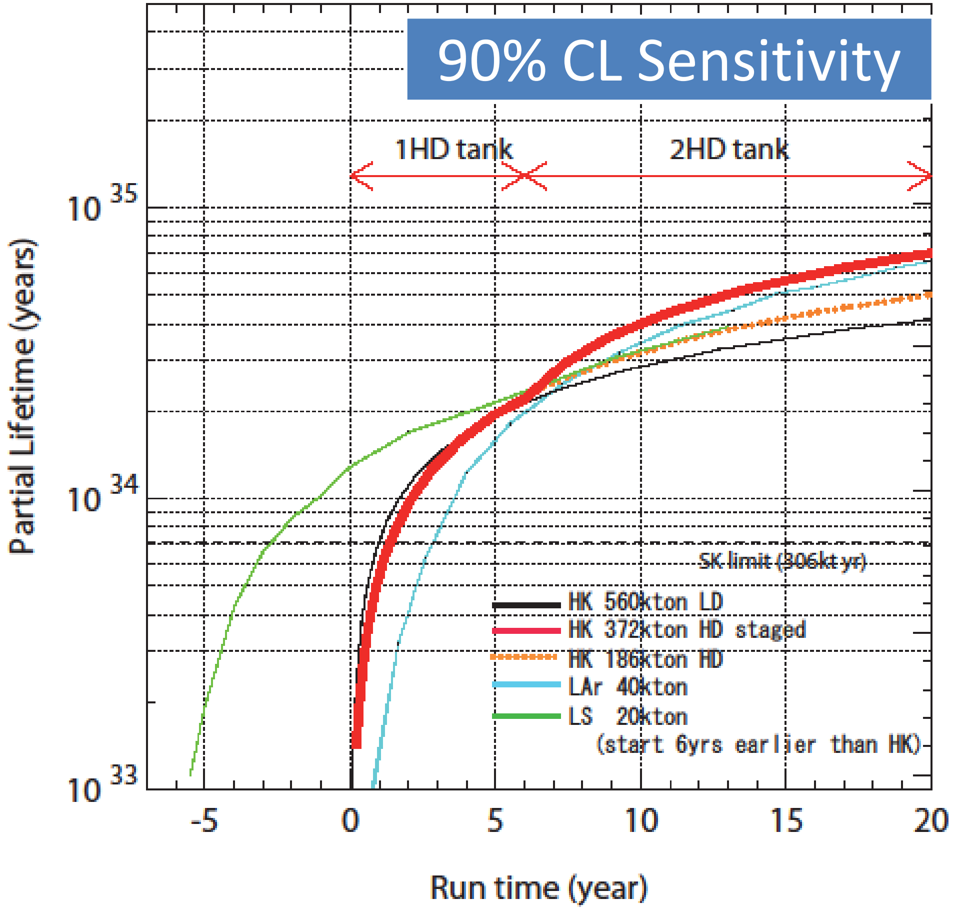


- > 1×10^{35} years after 2.7 Mton yr (90%CL) or 3σ discovery with 4.0 Mtonyr.
- If proton lifetime is near the current Super-K limit of 1.7×10^{34} years Hyper-K will observe a positive signal at 8.9σ in 2.7 Mtonyr exposure.

(Lines for the liquid argon experiment have been generated based on numbers in the literature (efficiency: 45% bkg: 1 event/Mtonyr).)

P→ ν K⁺: sensitivity



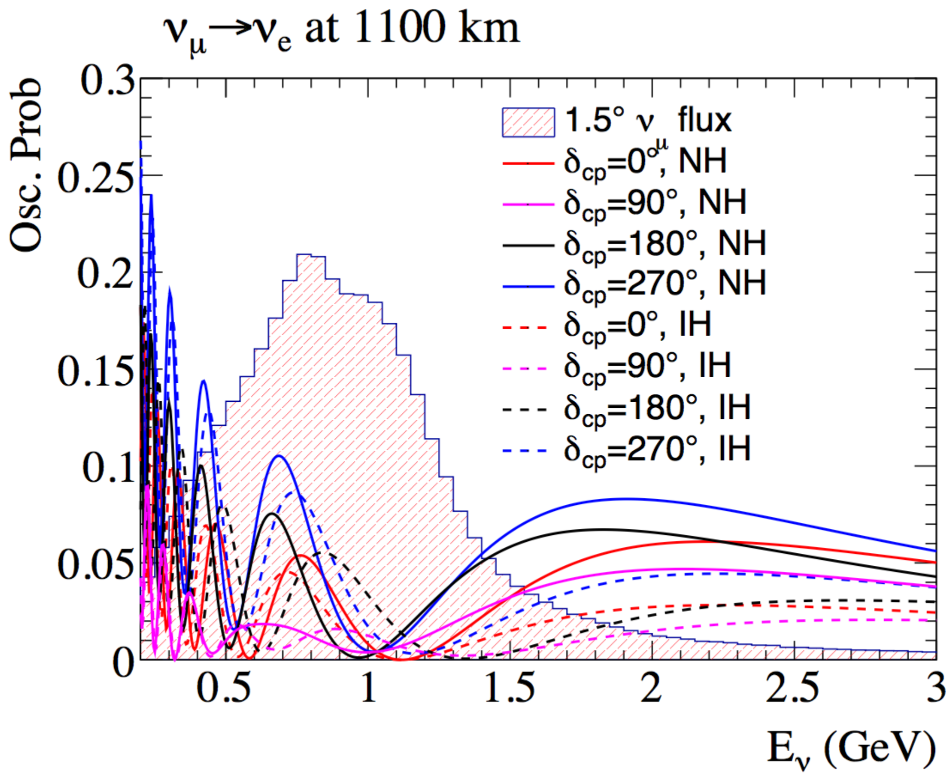


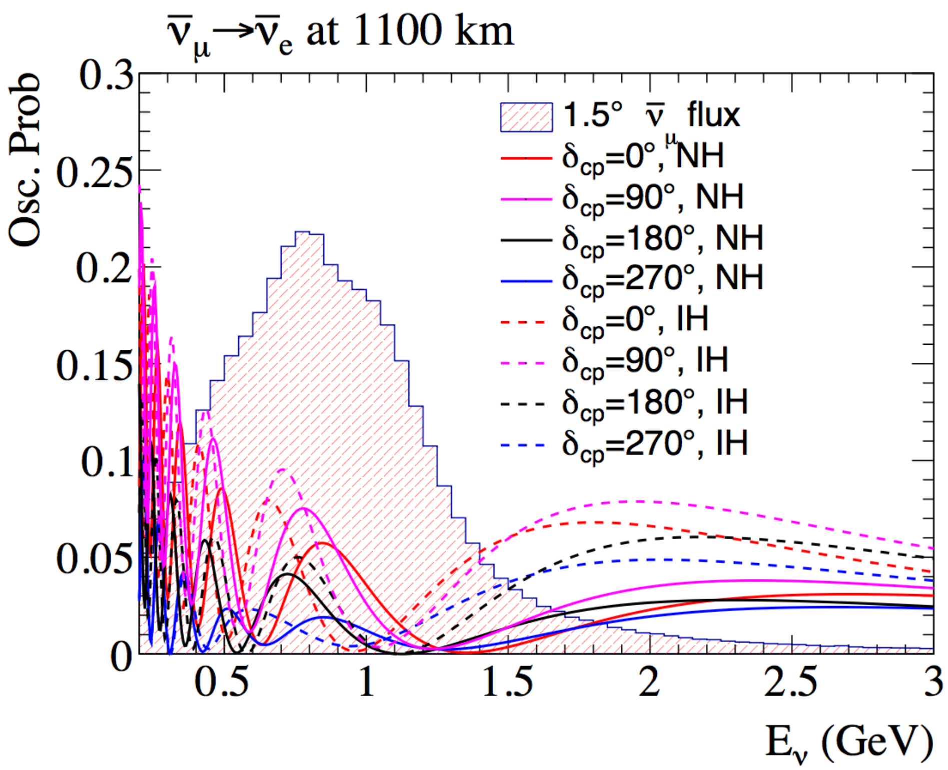
- Discovery potential higher in Liq. Ar. (Hyper-K will be slightly better for 90%CL limit.)
- If proton lifetime is near the current Super-K limit of 6.6×10^{33} years Hyper-K will observe a positive signal at 8.6σ in 2.7 Mton yr.

(Discovery potential for the Lar experiment has been generated based on numbers in the literature (efficiency: 97%, bkg: <1 event/Mton year).

An interesting possibility

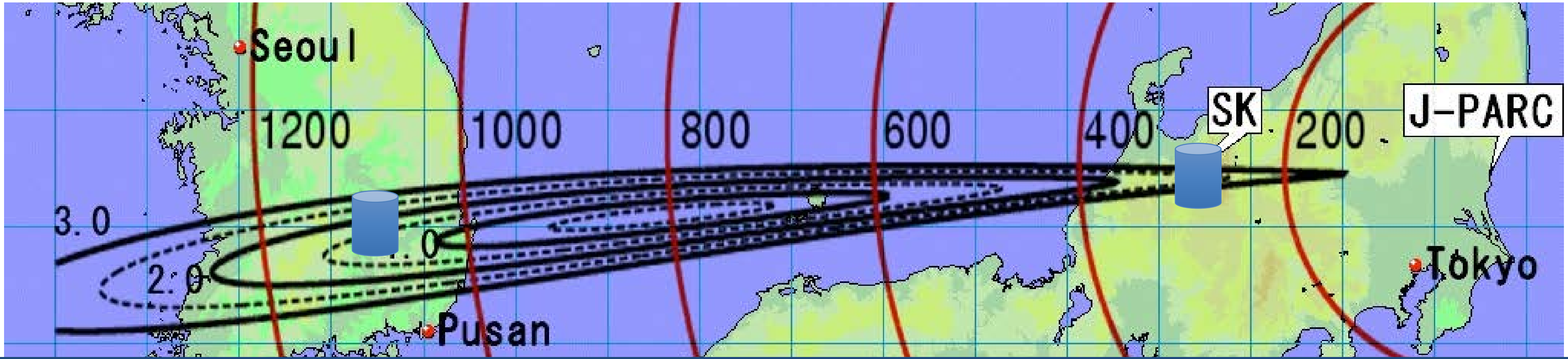
2^{nd} Hyper-K detector in Korea ?





Phys.Rev.D72:033003,2005
Phys.Lett.B637:266-273,2006
Phys. Rev. D81, 093001, 2010

- The 2^{nd} HK tank can be located some other place.
- About 10 years ago, this possibility was discussed.
- Now this possibility is revisited...



2nd Hyper-K detector in Korea ?

Announcement of The 1st T2HKK International Workshop

- When : Nov. 21 - 22
- Where: Seoul National Univ., Korea

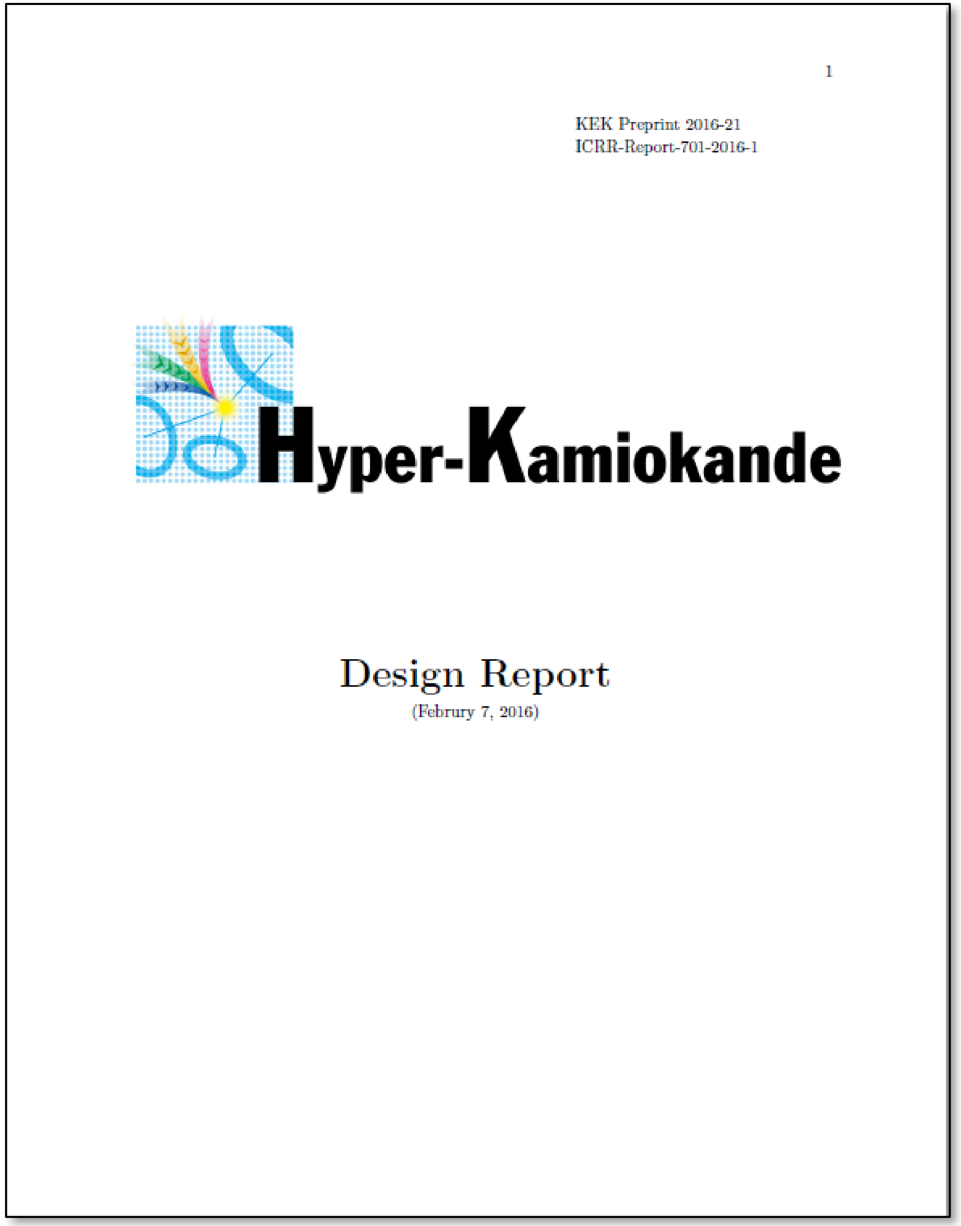
We invite all of you !

"Anyone" is very welcome to join this workshop !

Status of Hyper-K

Status of Hyper-K

- ✓ The design report has been written and reviewed by the Hyper-K Advisory Committee.
- ✓ The plan of Hyper-K was submitted to the Science Council of Japan (SCJ). If things goes well, Hyper-K will be listed as one of the "Master Plan Projects" of SCJ.
- ✓ Then, Hyper-K will be reviewed by the Ministry of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2017. If it is evaluated highly, it will be listed in the MEXT "Roadmap".
- ✓ Then, …



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KEK Preprint 2016-21
ICRR-Report-701-2016-1

Hyper-Kamiokande

Design Report
(Februry 7, 2016)

Summary

- Thanks to the successful development of the new PMTs, the physics potential is essentially unchanged in spite of the smaller fiducial volume in the new design.
- The neutrino oscillation experiment between J-PARC and Hyper-K will have a very high sensitivity to the CP violation and the other measurements.
- Atmospheric neutrinos will help the oscillation studies.
- Solar neutrino measurements might be very interesting. (There is a small tension between solar and KamLAND allowed parameter region.)
- Hyper-K will contribute to other physics, in particular to proton decays, as well.

Hyper-K is advancing towards realization!