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The Hyper-K Project

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outline

- *Introduction*
- *Hyper-K*
- *Neutrino oscillation studies with the J-PARC beam*
- *Neutrino oscillation studies with atmospheric and solar neutrinos*
- *Other physics: supernova neutrinos*
  proton decays
- *Status of Hyper-K*
- *Summary*

In many cases, the reference that is not explicitly shown is:
Hyper-Kamiokande design report, arXiv:0805.04163v1

Introduction

Strong academic relation with Soviet/Russia

- The condition that matter in the Universe survived was invented by Andrei Sakharov.
- Moreover neutrino experiments rely on the theory (of neutrino oscillations) invented by Bruno Pontecorvo.
- Principle of Kamiokande/Super-K/Hyper-K detectors is to detect Cherenkov radiation which was discovered & formulated by Cherenkov, Frank, and Tamm.
- And more …

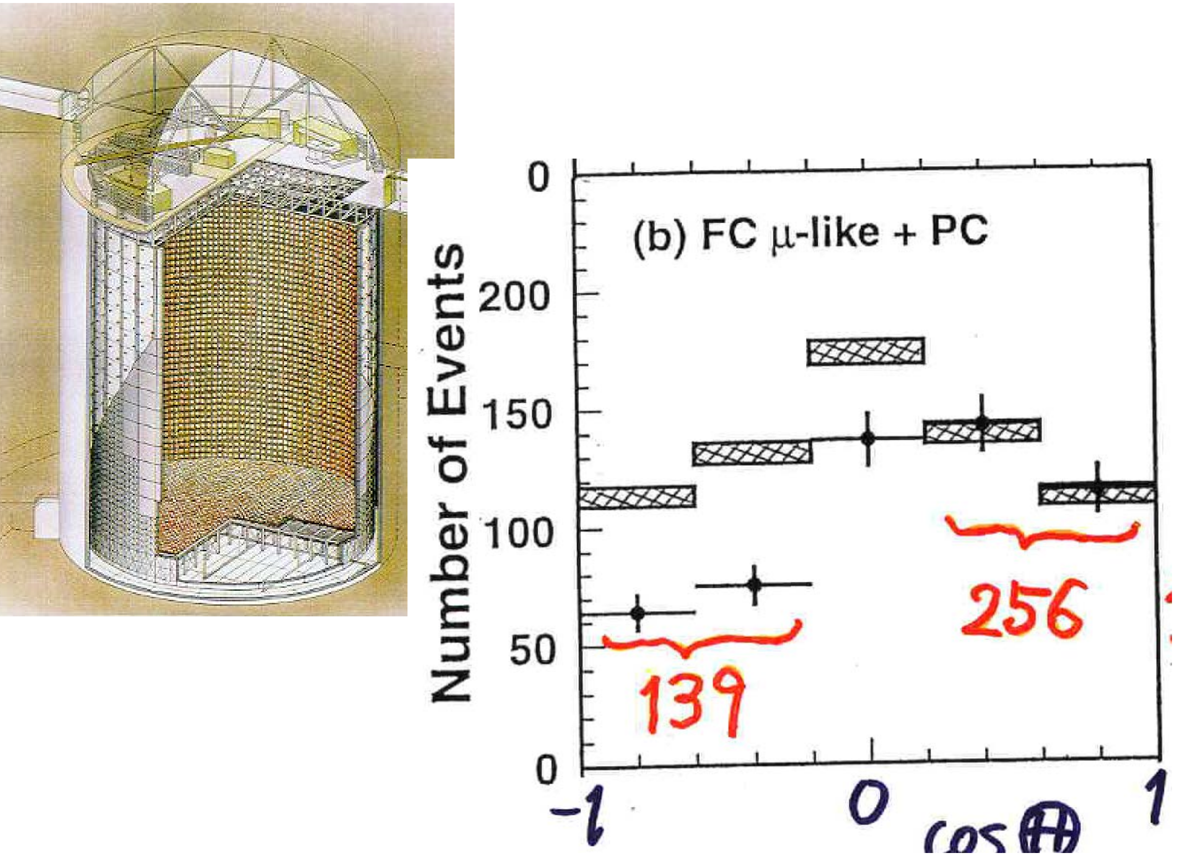




Discovery of neutrino oscillations

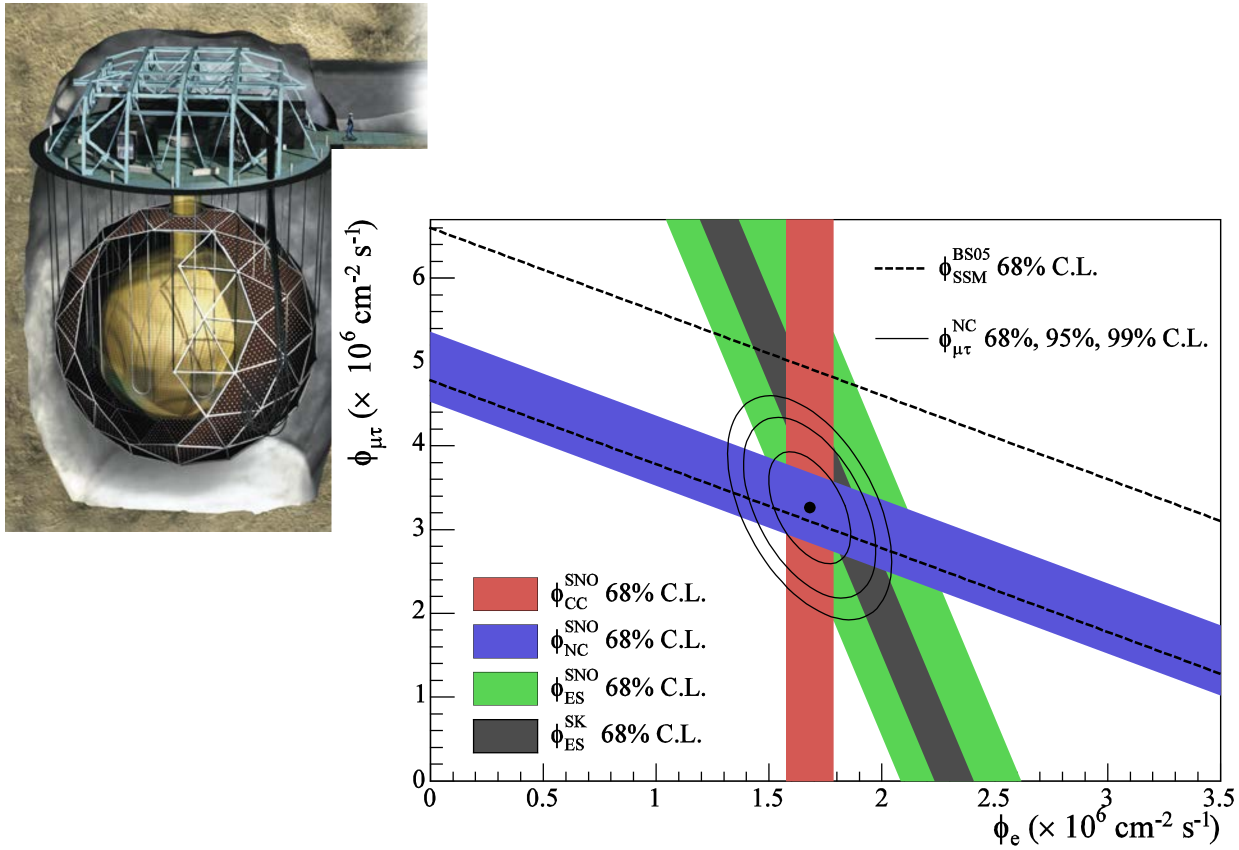
Super-K, PRL 81 (1998) 1562

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, …

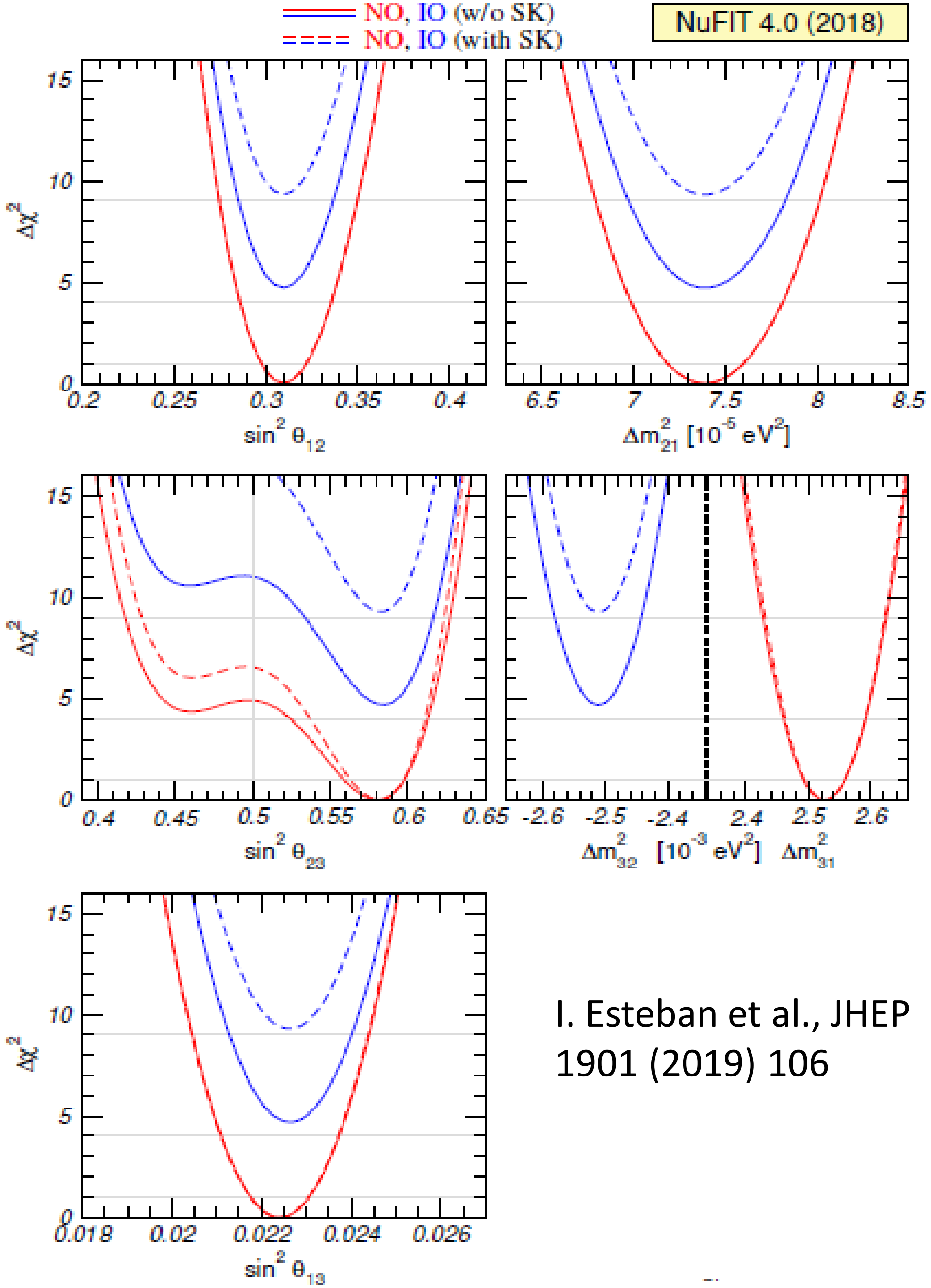
Reactor: KamLAND

θ_{13} experiments

LBL: MINOS, T2K, NOvA, …

Reactor: Daya Bay, Reno, Double Chooz

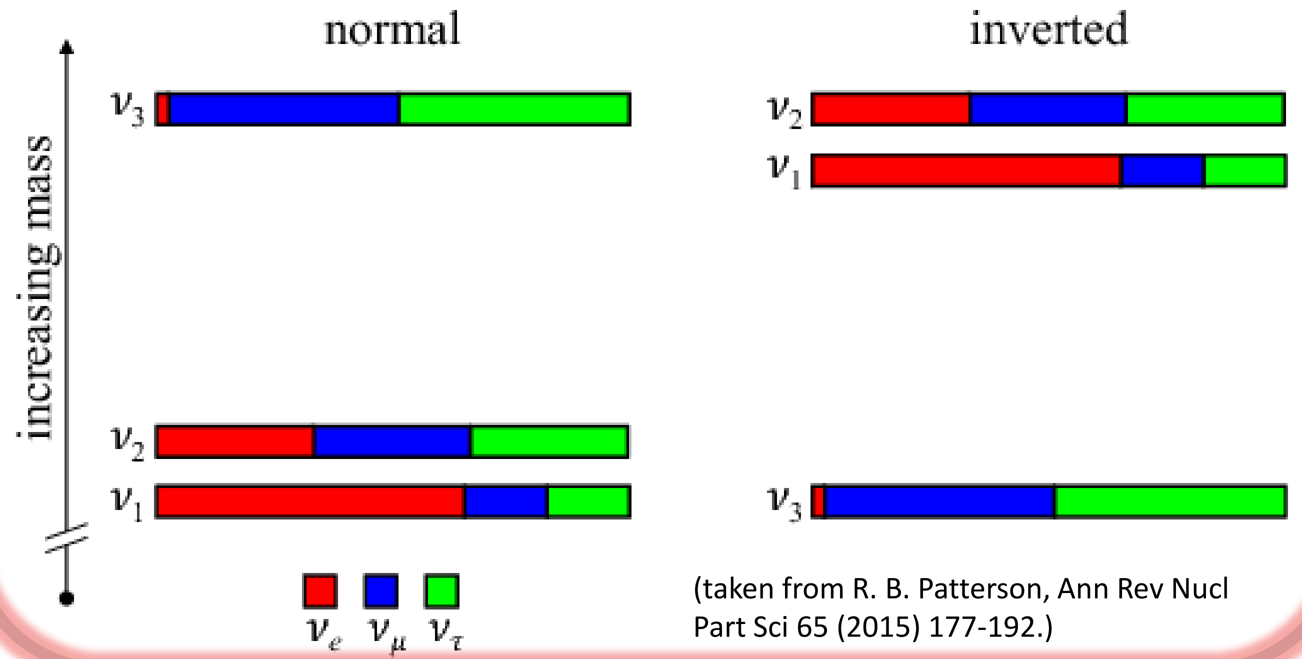
Basic structure for 3 flavor oscillations has been understood!



I. Esteban et al., JHEP 1901 (2019) 106

Agenda for the future neutrino measurements

Neutrino mass hierarchy?



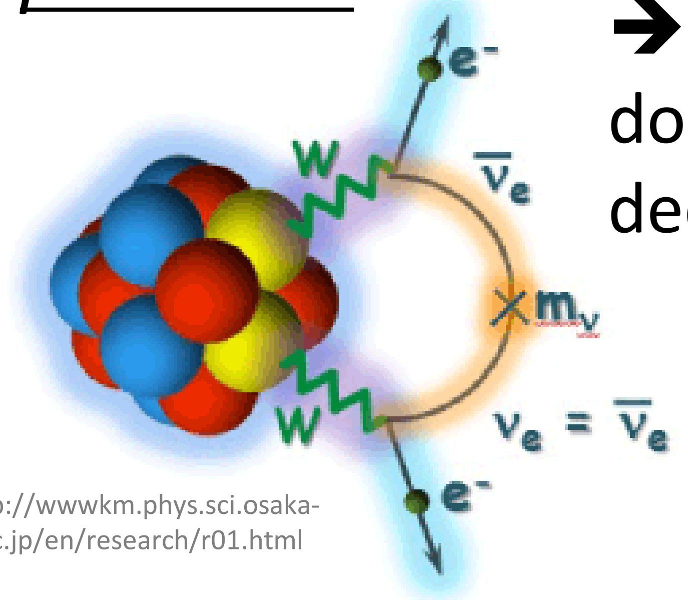
(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

CP violation?

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \ ?$$

Baryon asymmetry of the Universe?

Are neutrinos Majorana particles?



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

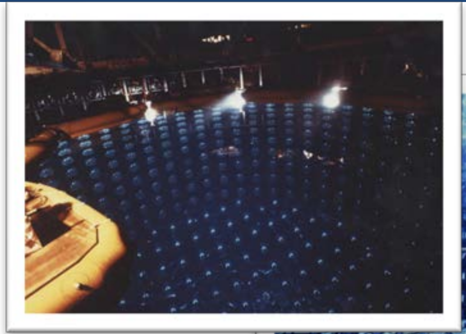
➔ Neutrinoless double beta decay

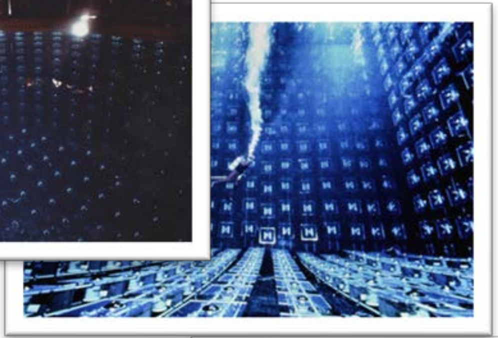
Absolute neutrino mass?

Beyond the 3 flavor framework? (Sterile neutrinos?)

Hyper-K

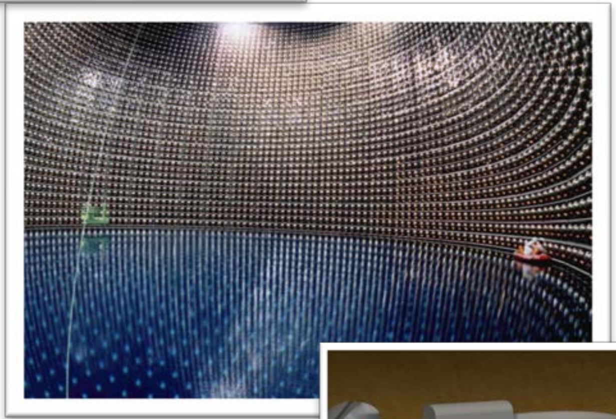
Hyper-K as a natural extension of water Ch. detectors





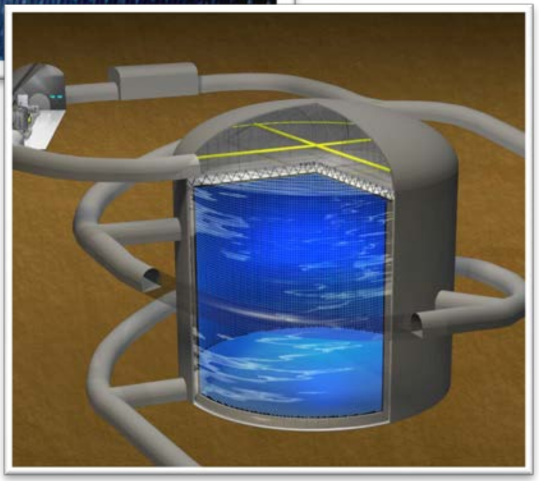
Kamiokande & IMB

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



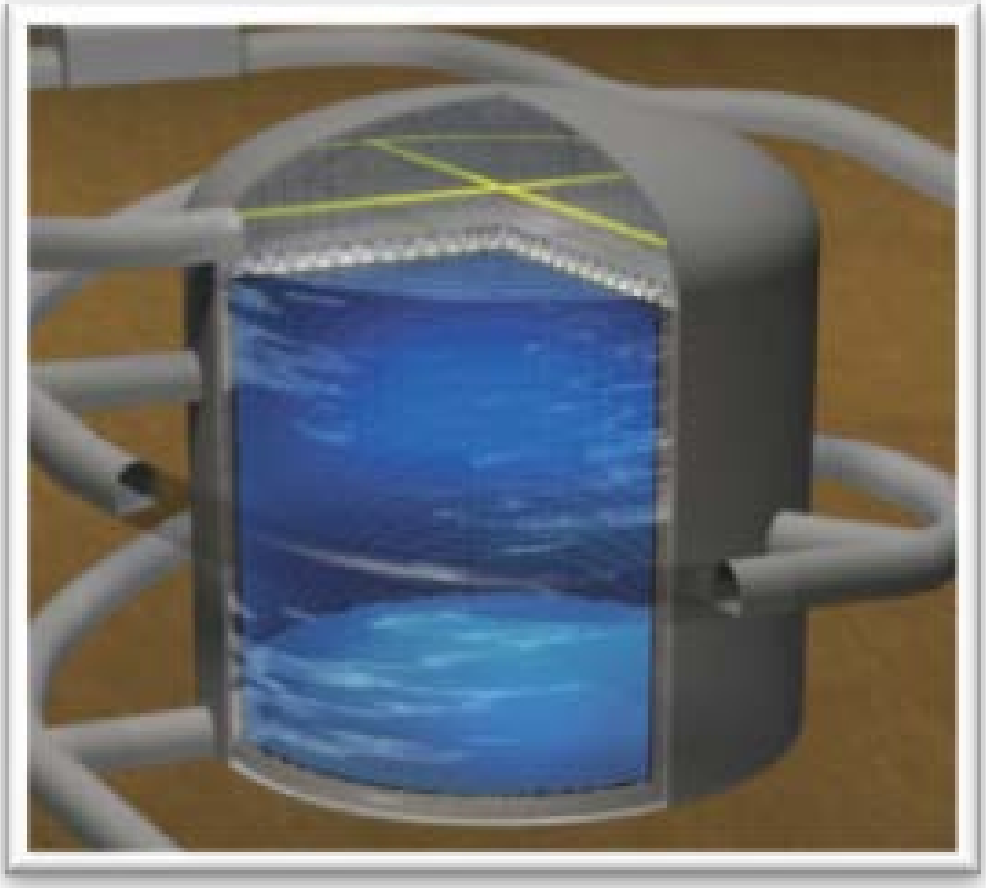
Hyper-K

KEK-PS

J-PARC

25 collaborators
from Russia in T2K

Hyper-K



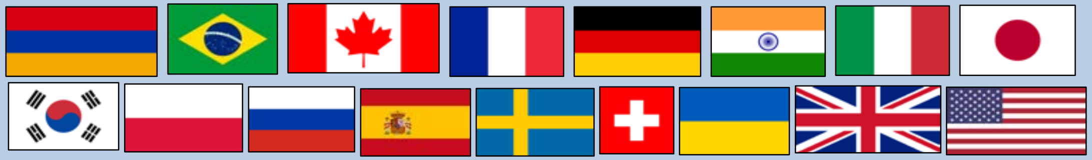
◆Φ 74 meters and H 60 meters.

◆The total and fiducial volumes are 0.26 and 0.19 M tons, respectively.

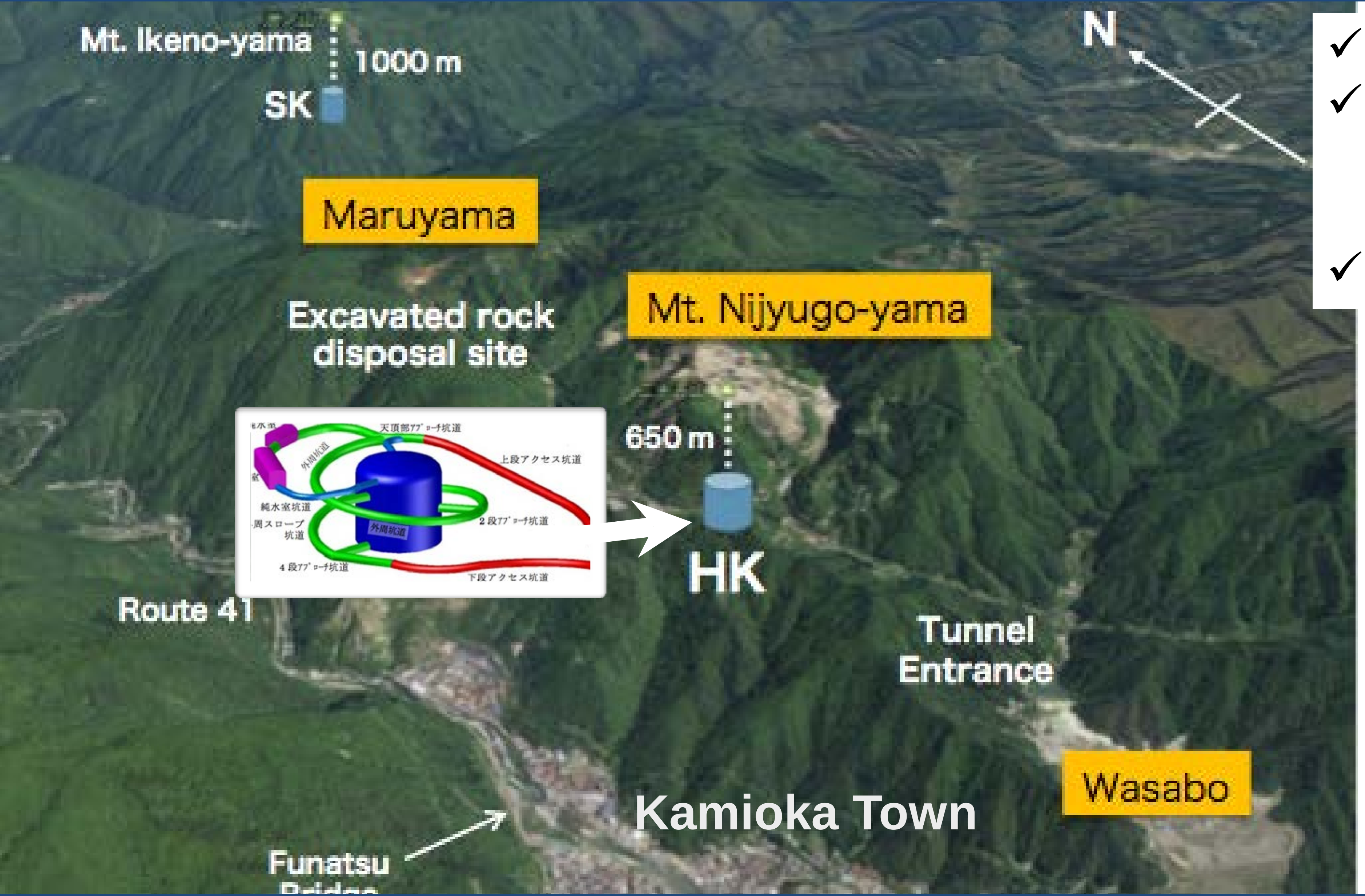
Hyper-K detector will be used to study:

- ✓ Neutrino oscillations with J-PARC neutrino beam(1.3MW beam),
- ✓ atmospheric neutrino oscillations,
- ✓ solar neutrino oscillations
- ✓ Proton decays
- ✓ Supernova neutrino burst
- ✓ Past supernova neutrinos
- ✓ ….

Hyper-Kamiokande proto-collaboration
~300 members from 17 countries
We expect about 60 collaborators from Russia will join Hyper-K.

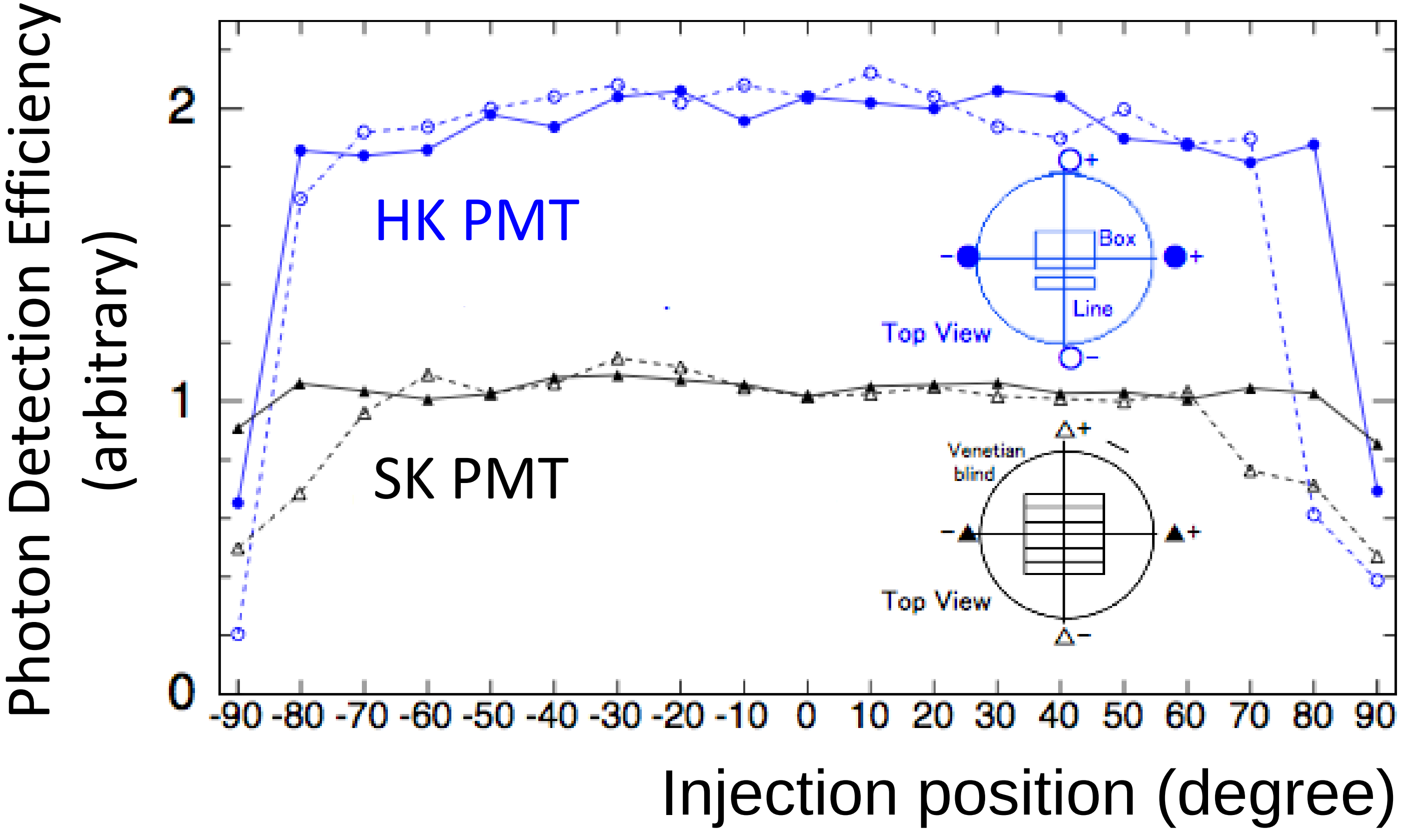


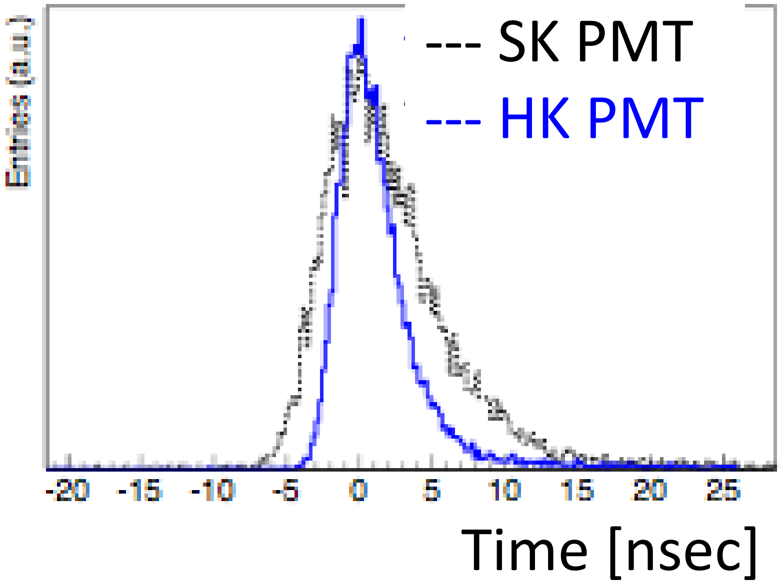
Hyper-K location

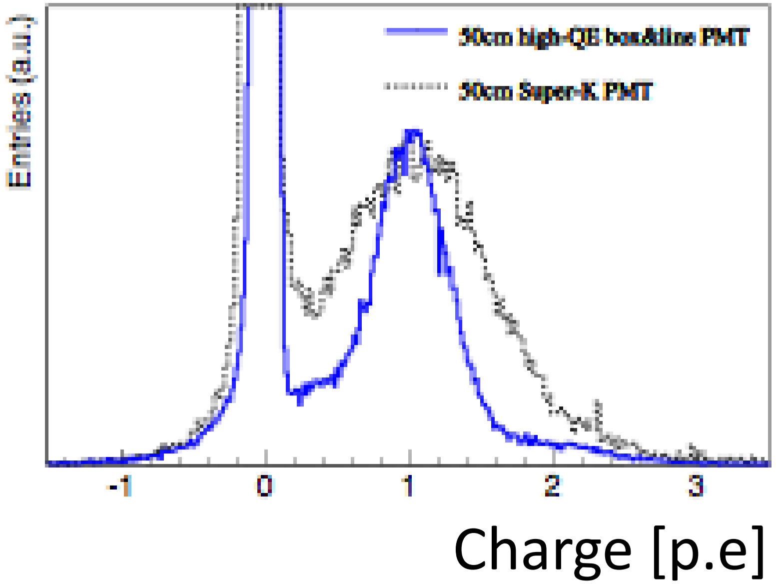


- ✓ ~8km south of Super-K.
- ✓ 295km from J-PARC and 2.5 deg. Off axis beam (same as Super-K)
- ✓ 650 m rock overburden

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





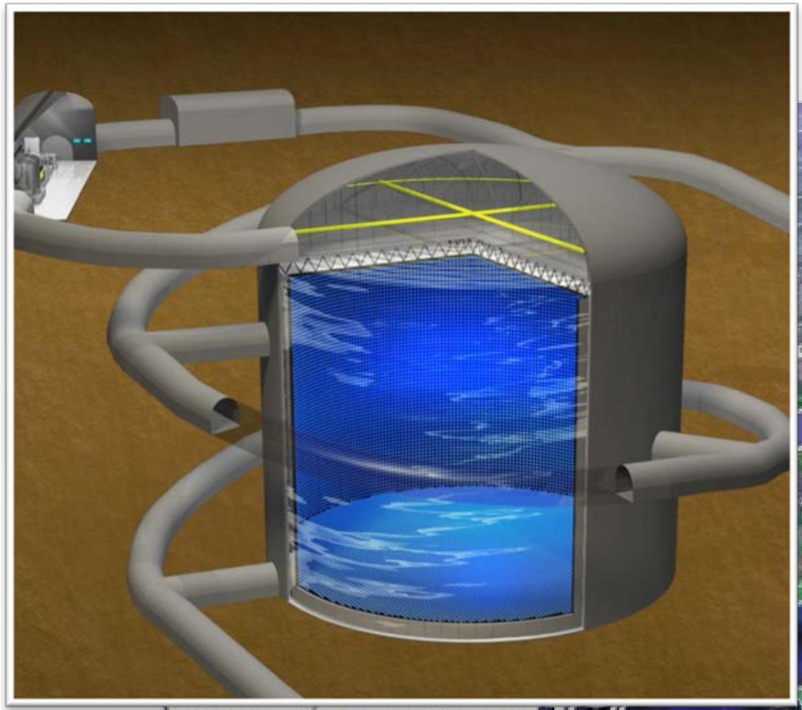


- ✓ Photon detection efficiency x 2,
- ✓ Timing & charge (@1 p.e.) resolution x 1/2
- ✓ (Pressure tolerance x 2 (>100m))

➔ Large impacts to physics

Neutrino oscillation studies with the J-PARC beam

Hyper-K with J-PARC neutrino beam



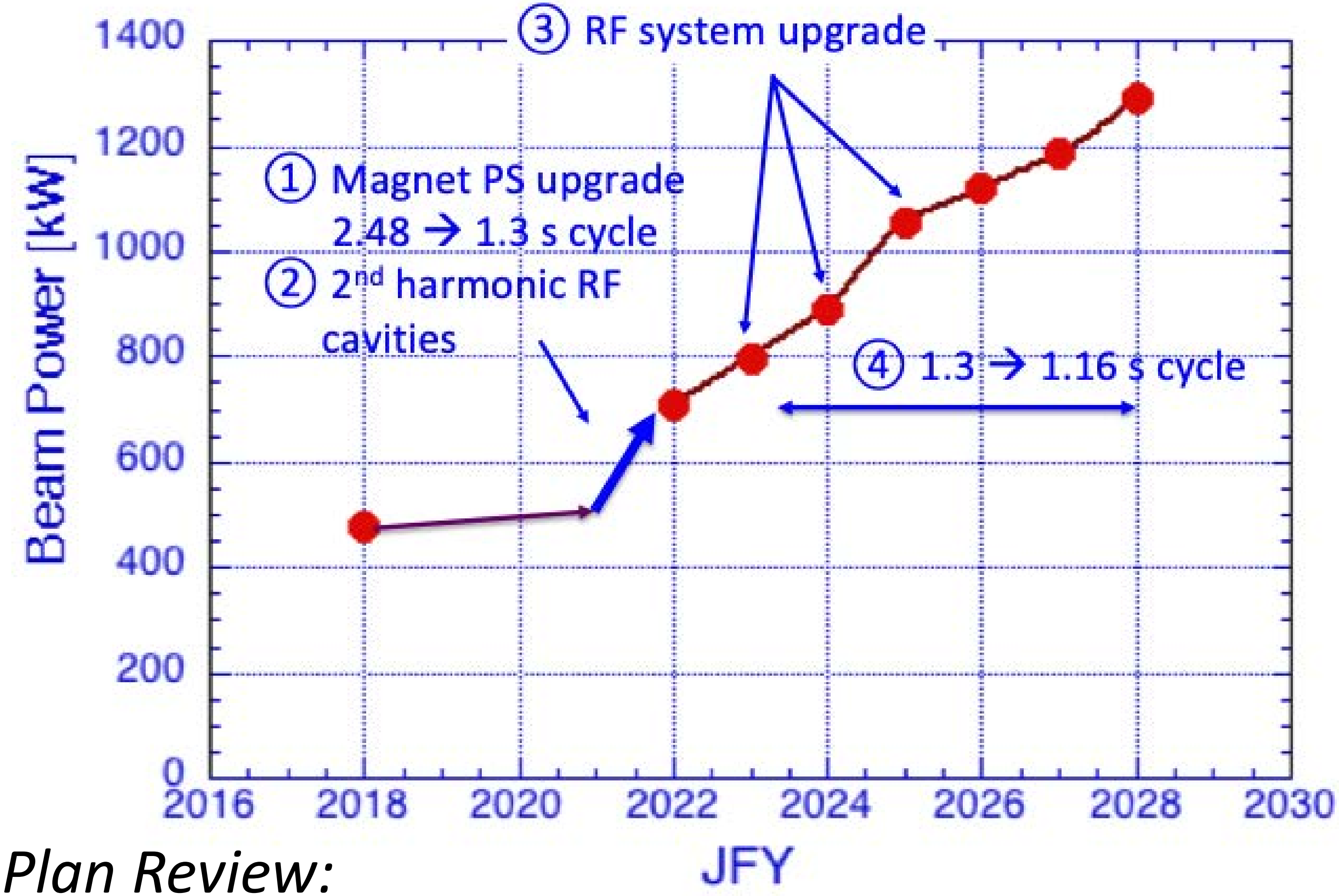
Hyper-K

J-PARC

J-PARC neutrino beam upgrade plan

Continuous upgrade plan of the neutrino beam

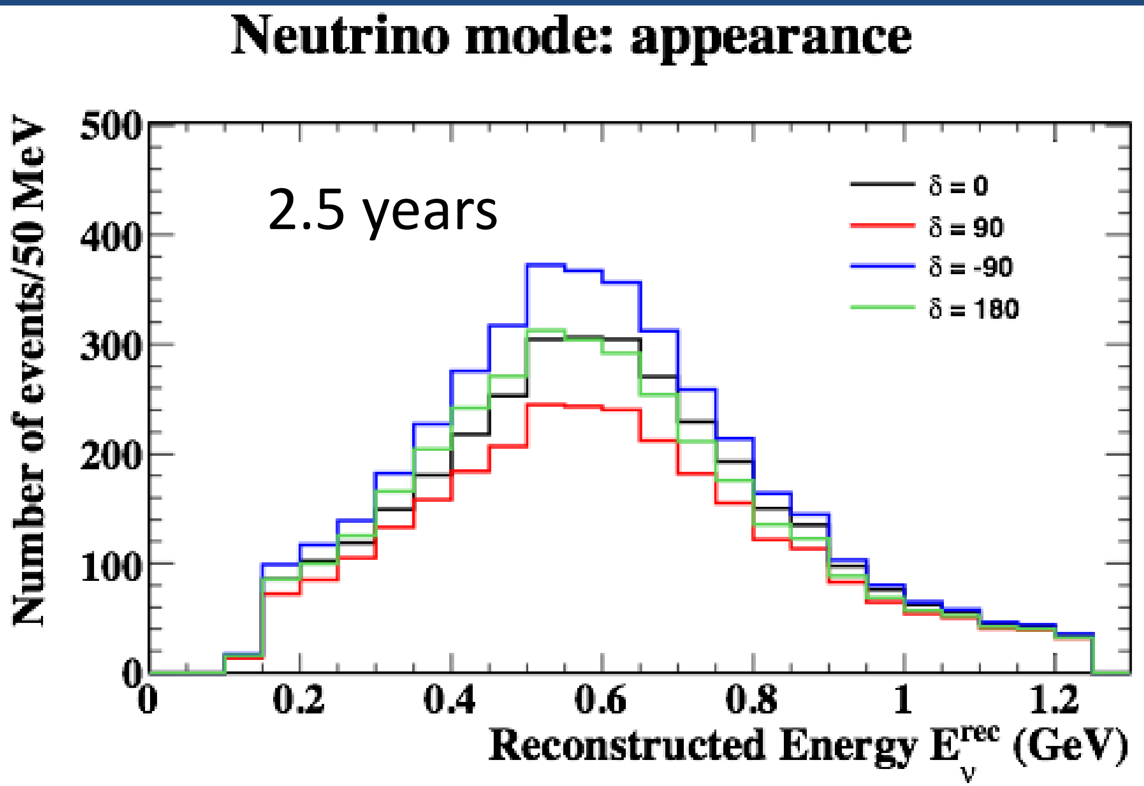
✓ 1.3 MW in ~2028

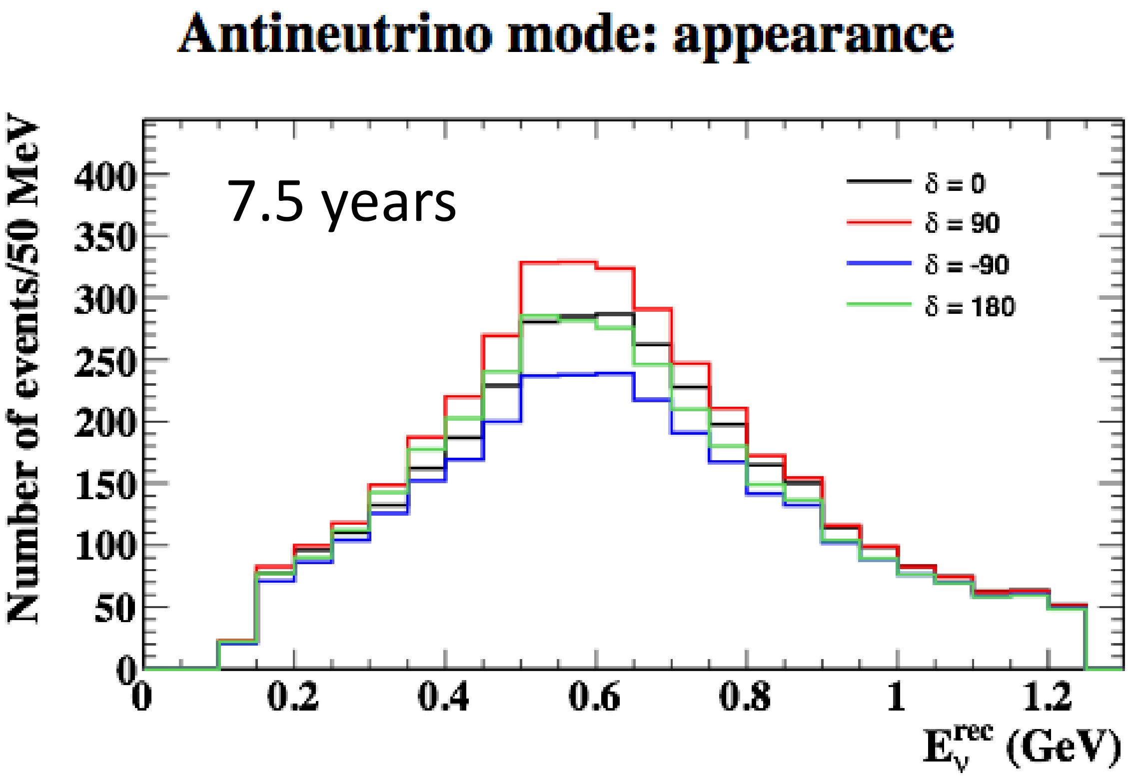


KEK Project Implementation Plan Review:

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

Expected number of events (10 years)

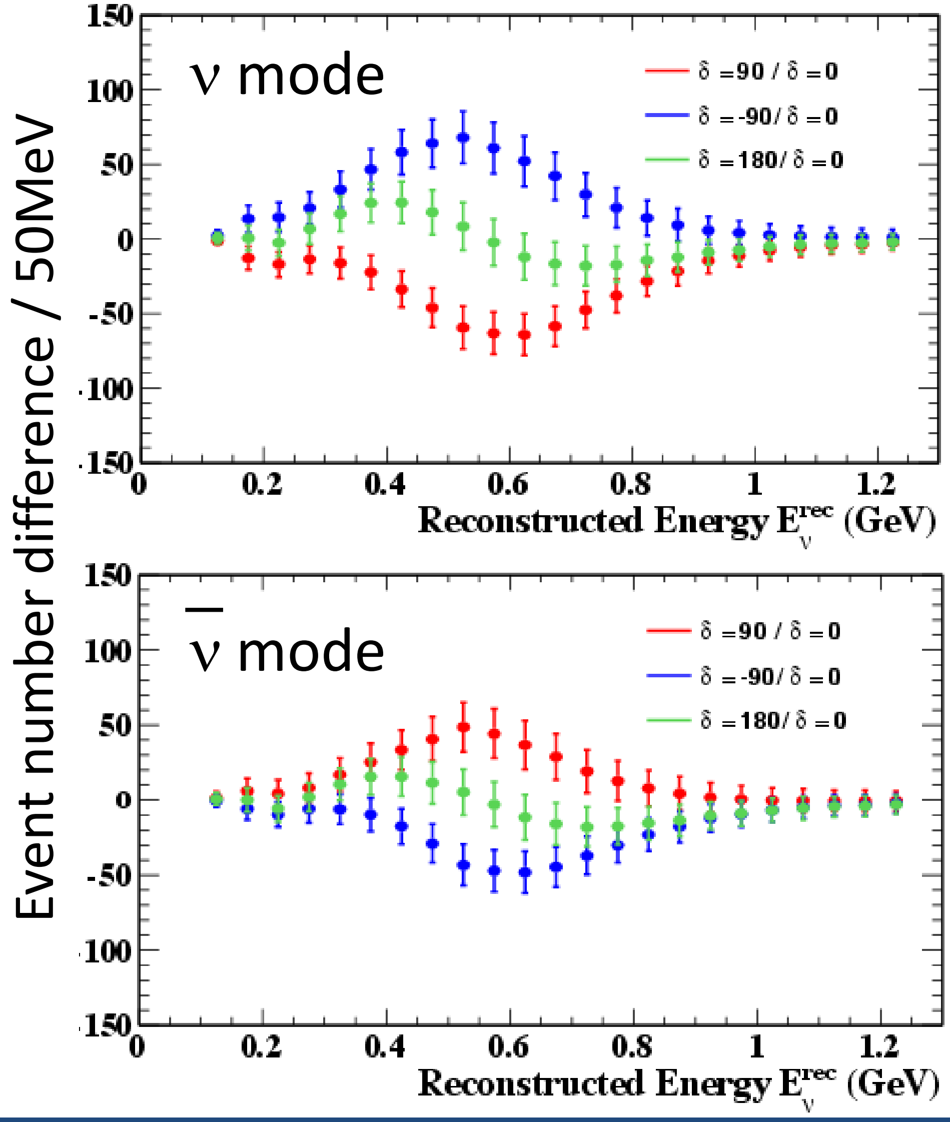


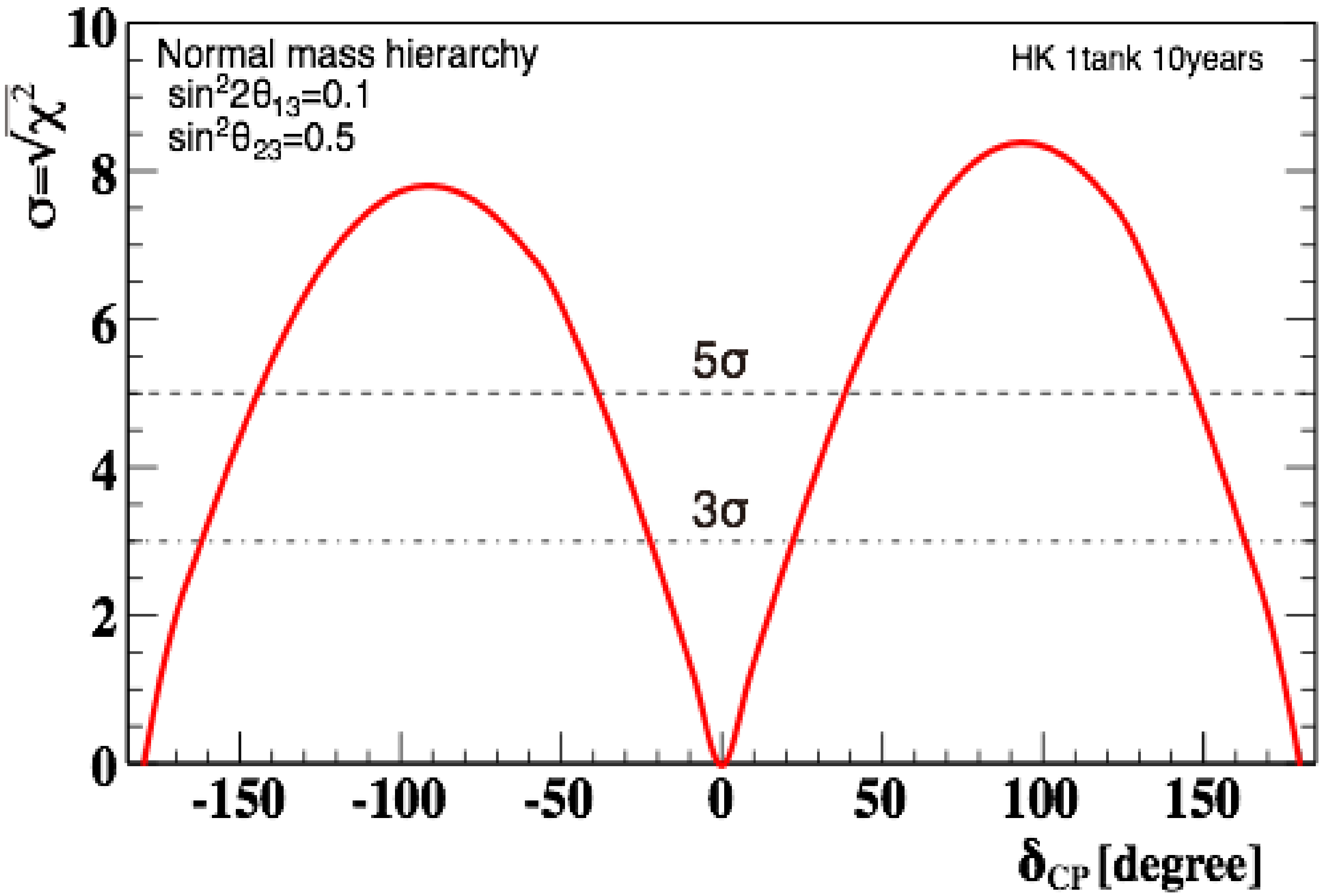


	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	ν_μ , $\bar{\nu}_\mu$ CC	Beam ν_e, $\bar{\nu}_e$ contamination	NC
ν beam (δ_{CP}=0)	2300	21	10	362	188
$\bar{\nu}$ beam (δ_{CP}=0)	1656	289	6	444	274

δ_{CP} sensitivity

<u>*Difference from δ_{CP}=0*</u>

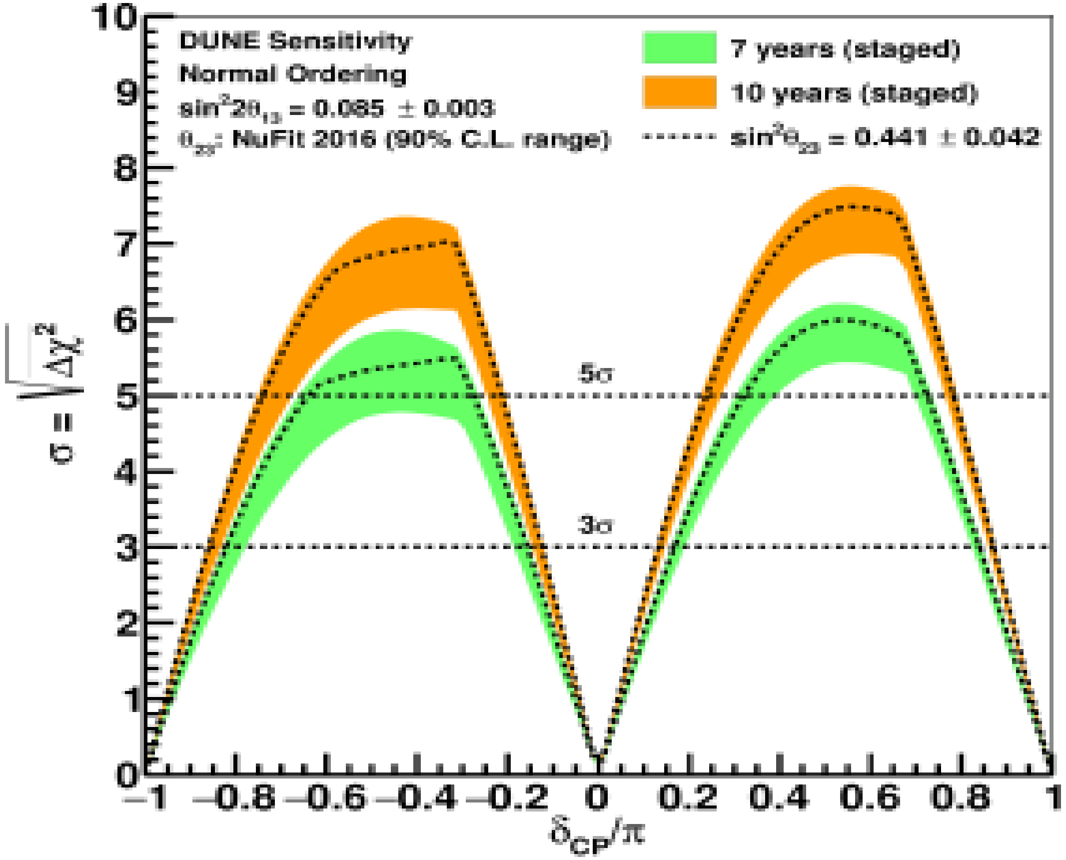


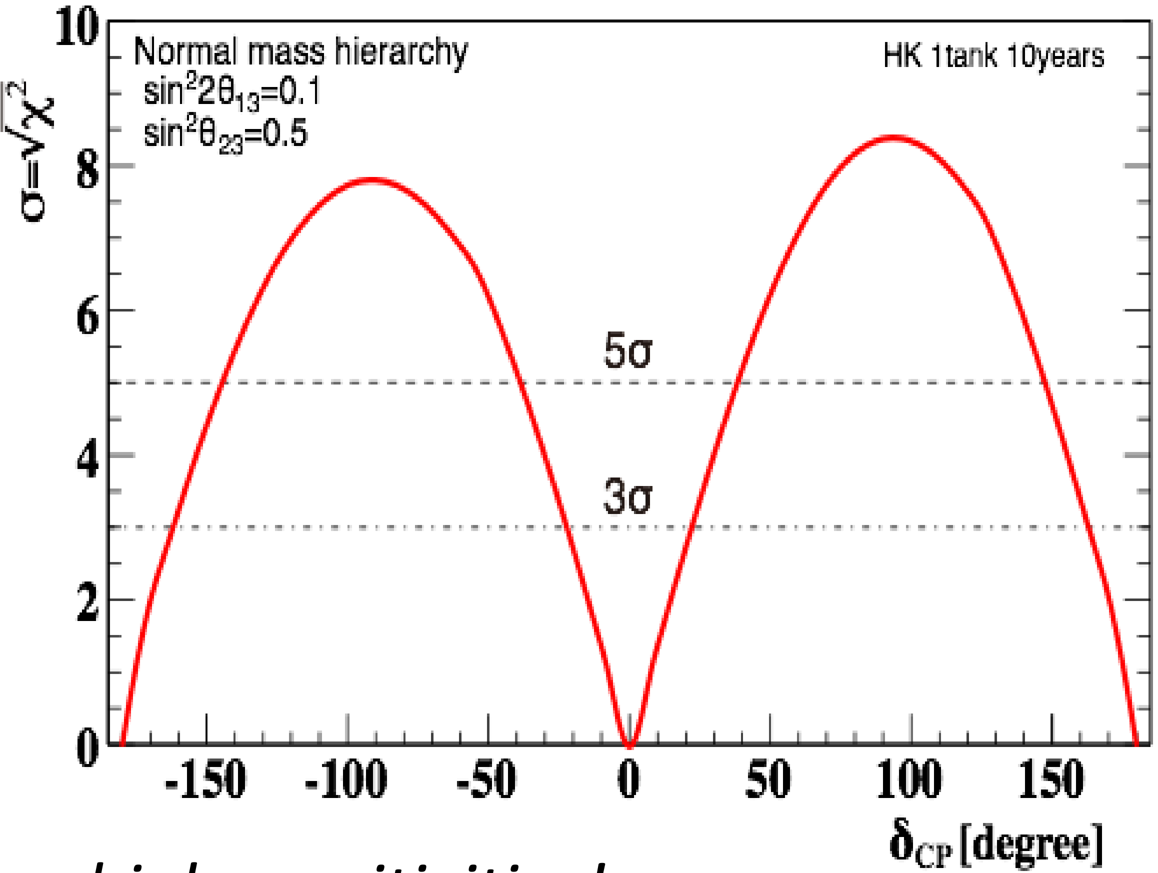


Comparison

DUNE
(Nu2018, E. Worcester)

Hyper-K





➔ *Both experiments have very high sensitivities!*

Complementarity

	DUNE	Hyper-K
Baseline	1300km ➔ Large matter effect (Good for Mass Ordering determination)	295km ➔ Small matter effect (Smaller effect of matter density uncertainty in δ_{CP})
Beam energy	~ Multi-GeV	~ Sub-GeV
Detector technology	Liq. Ar TPC	Water Cherenkov

- ✓ ***We would like to be convinced the CP violation by the consistent results from these 2 experiments with very different systematics.***
- ✓ ***We hope that these 2 experiments will carry out the experiments in a similar timeline.***

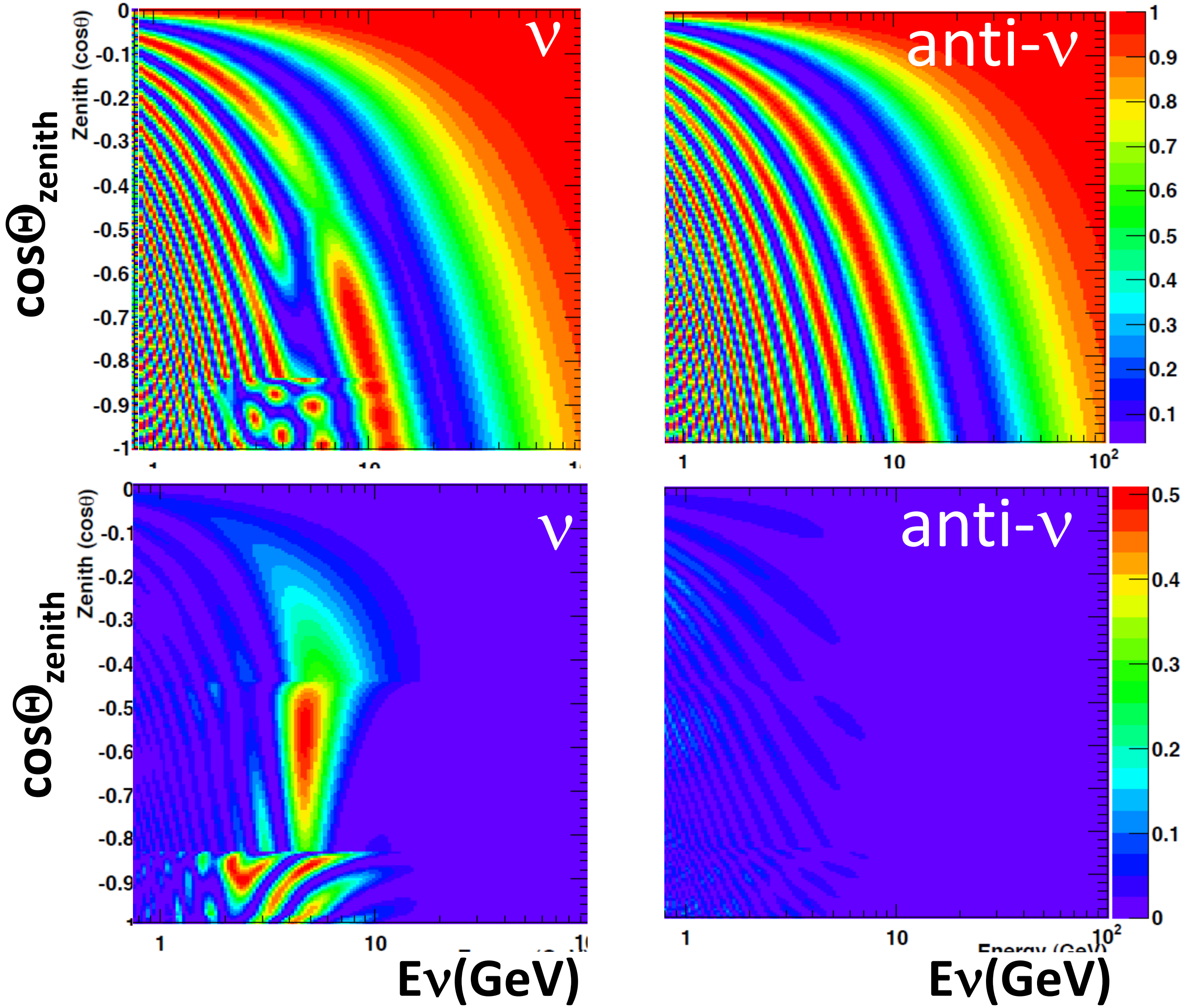
Neutrino oscillation studies with atmospheric and solar neutrinos

Oscillation probabilities

Osci. Probabilities for Normal Hierarchy

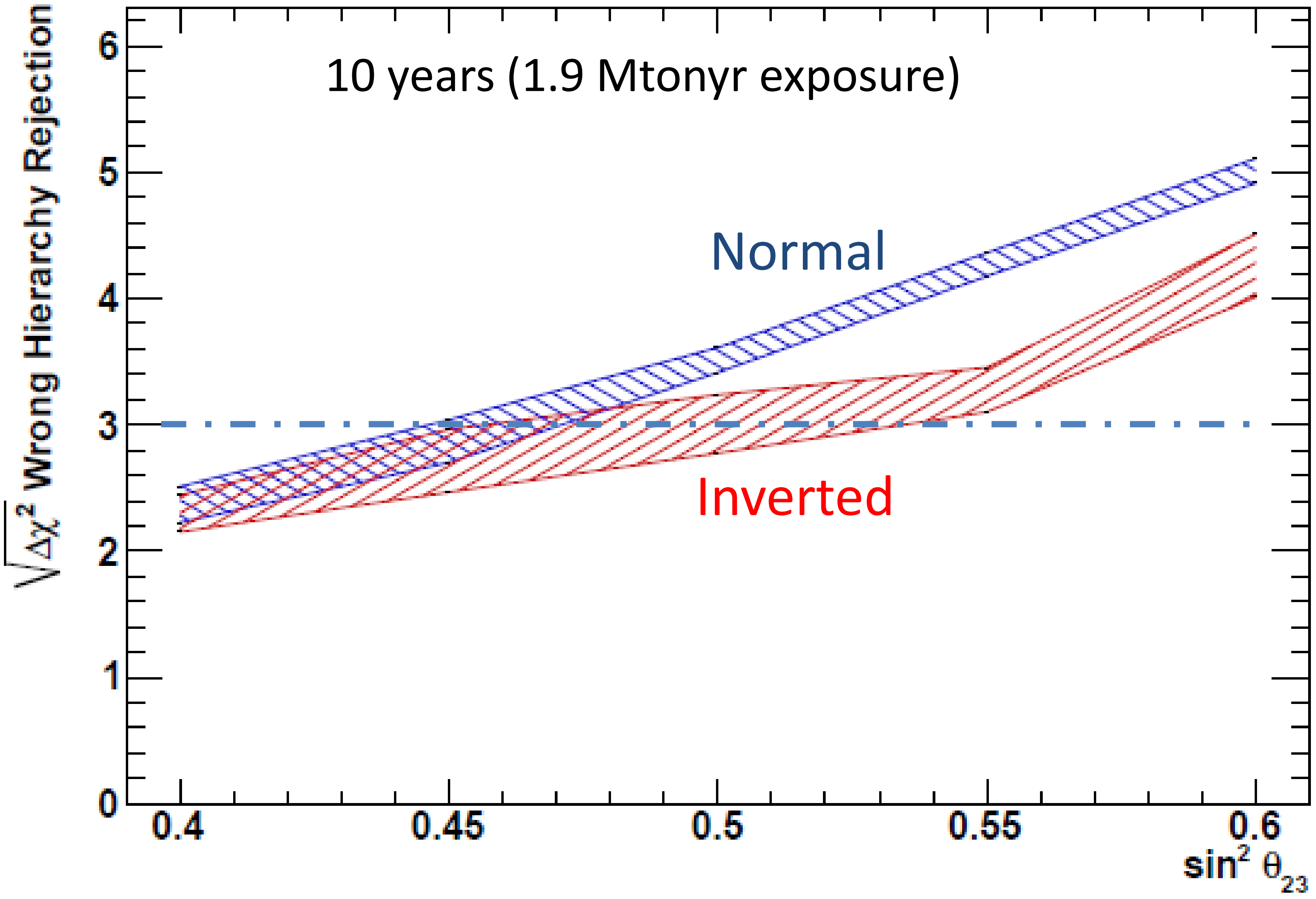
$P(\nu_\mu \rightarrow \nu_\mu)$

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

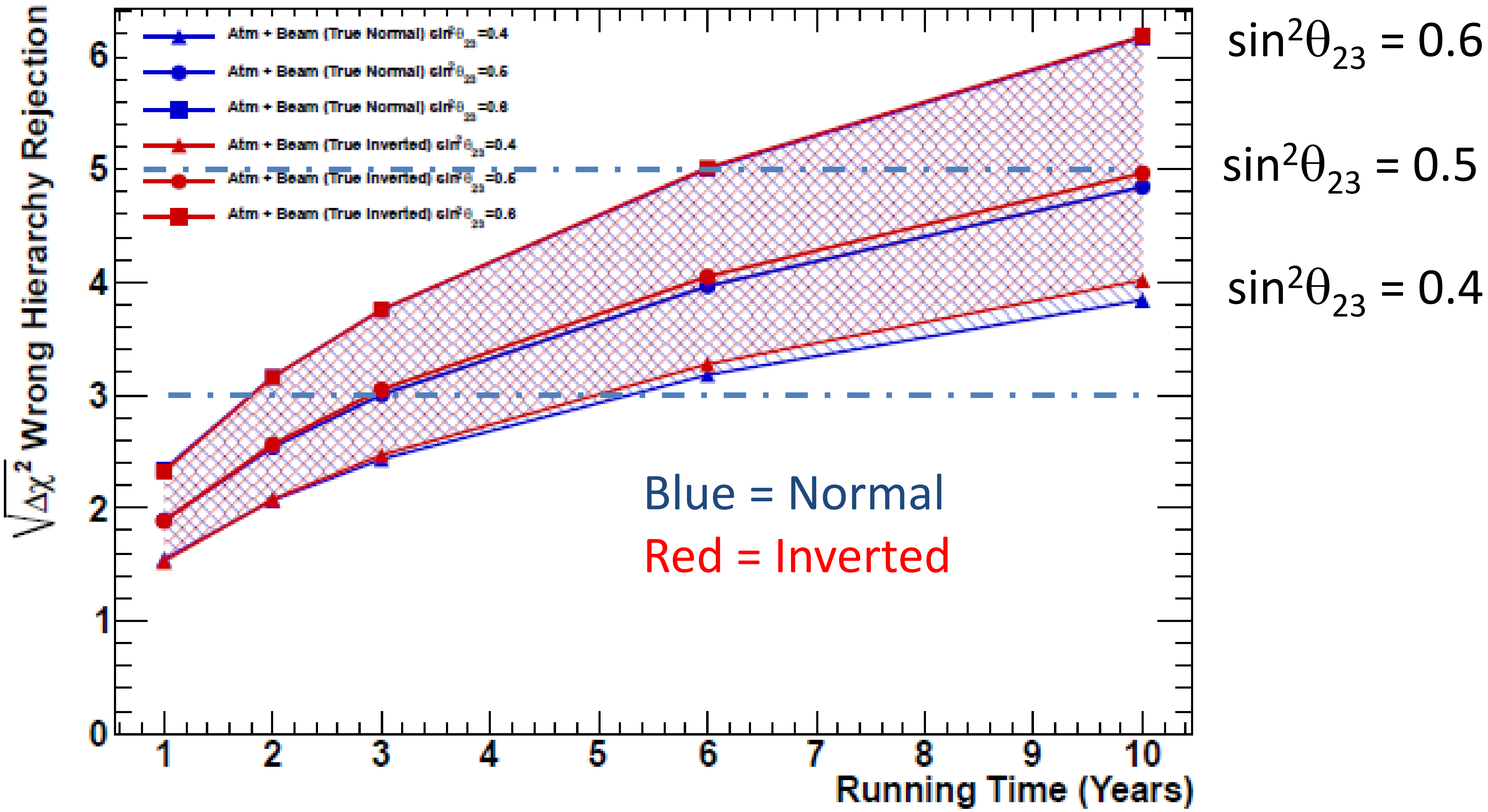


Inverted hierarchy:
ν ←→ anti-ν

Sensitivity to mass ordering (atmospheric only)



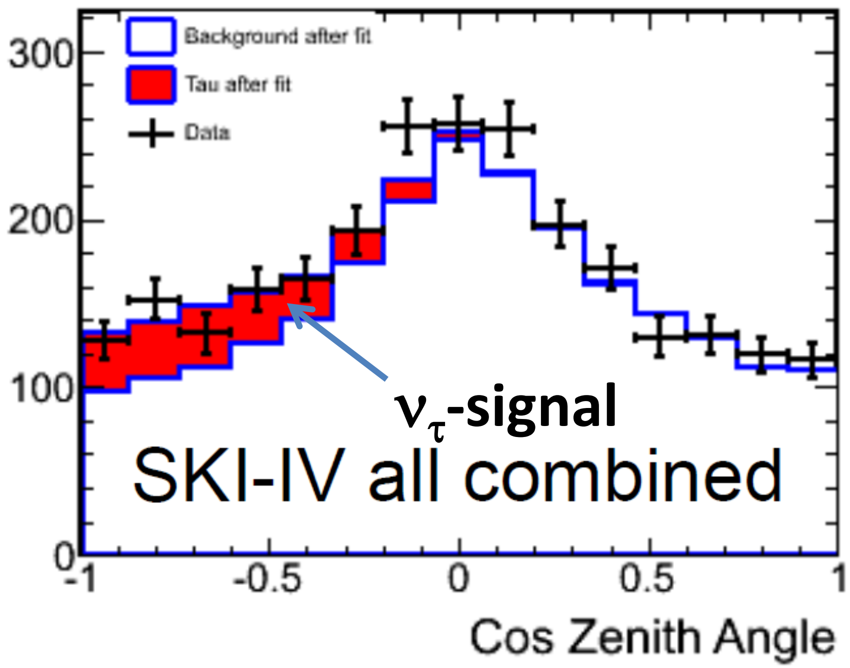
Sensitivity to mass ordering (atmospheric + LBL)



Tau neutrino appearance

Super-Kamiokande

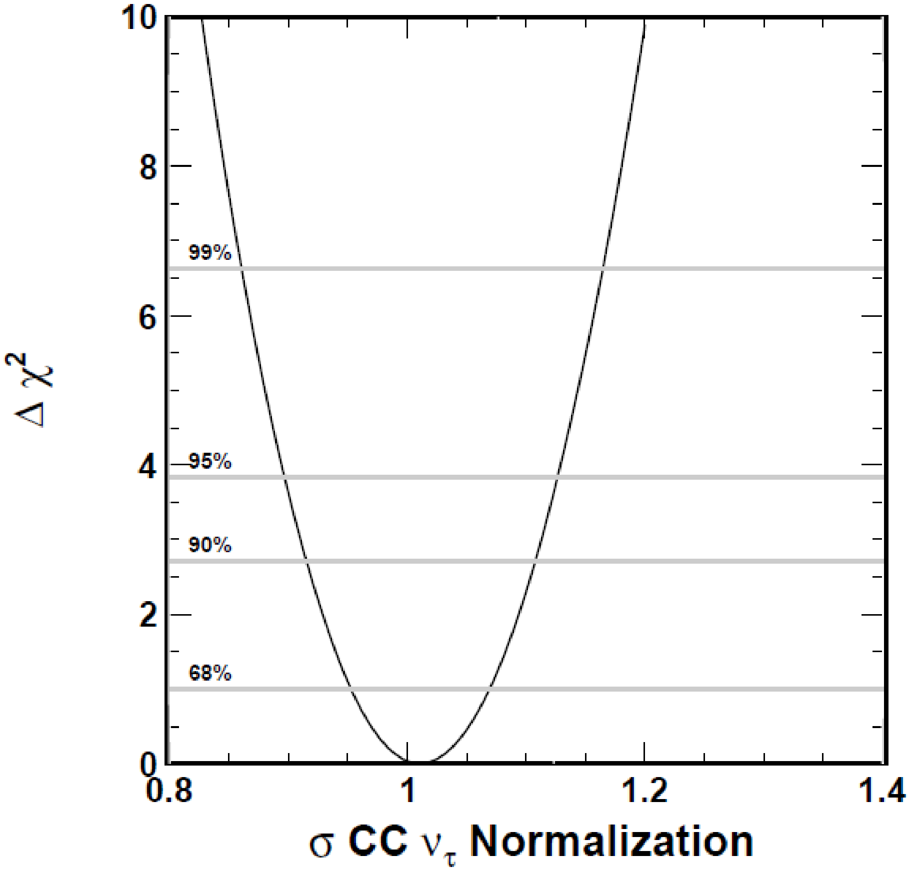
Super-K (S.Moriyama) @nu2016
See also, SK PRL 110(2013)181802



➔ 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.

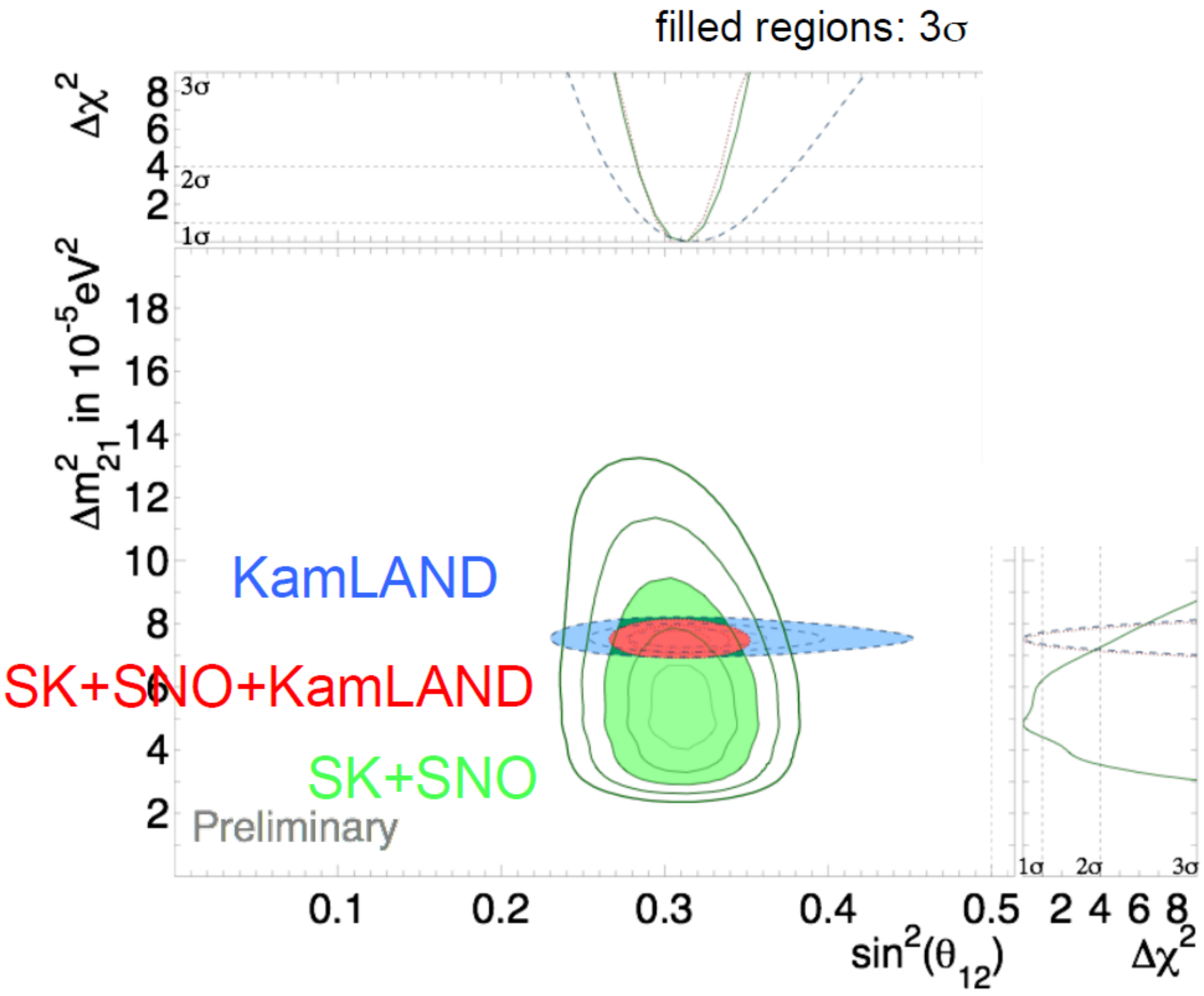
Hyper-K, 5.6 Mton yrs (30 years)



Solar neutrino oscillations and day/night effect

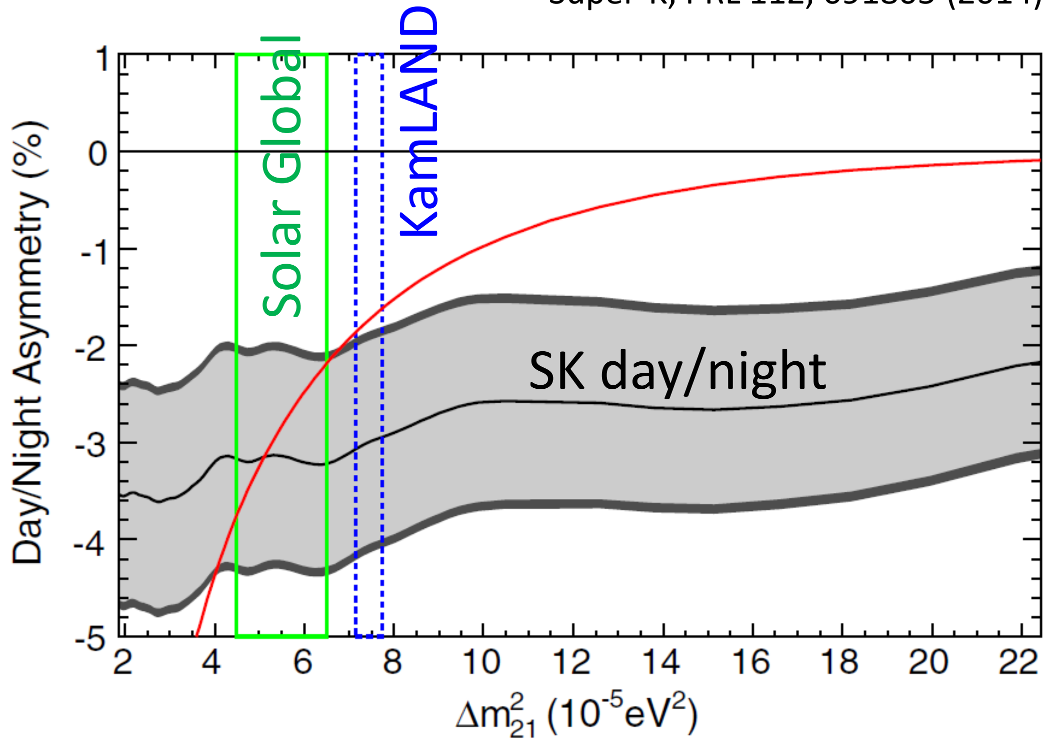
Status of the 12-parameter measurements

S. Moriyama (Super-K), Neutrino 2016



SK day/night and Δm_{12}^2

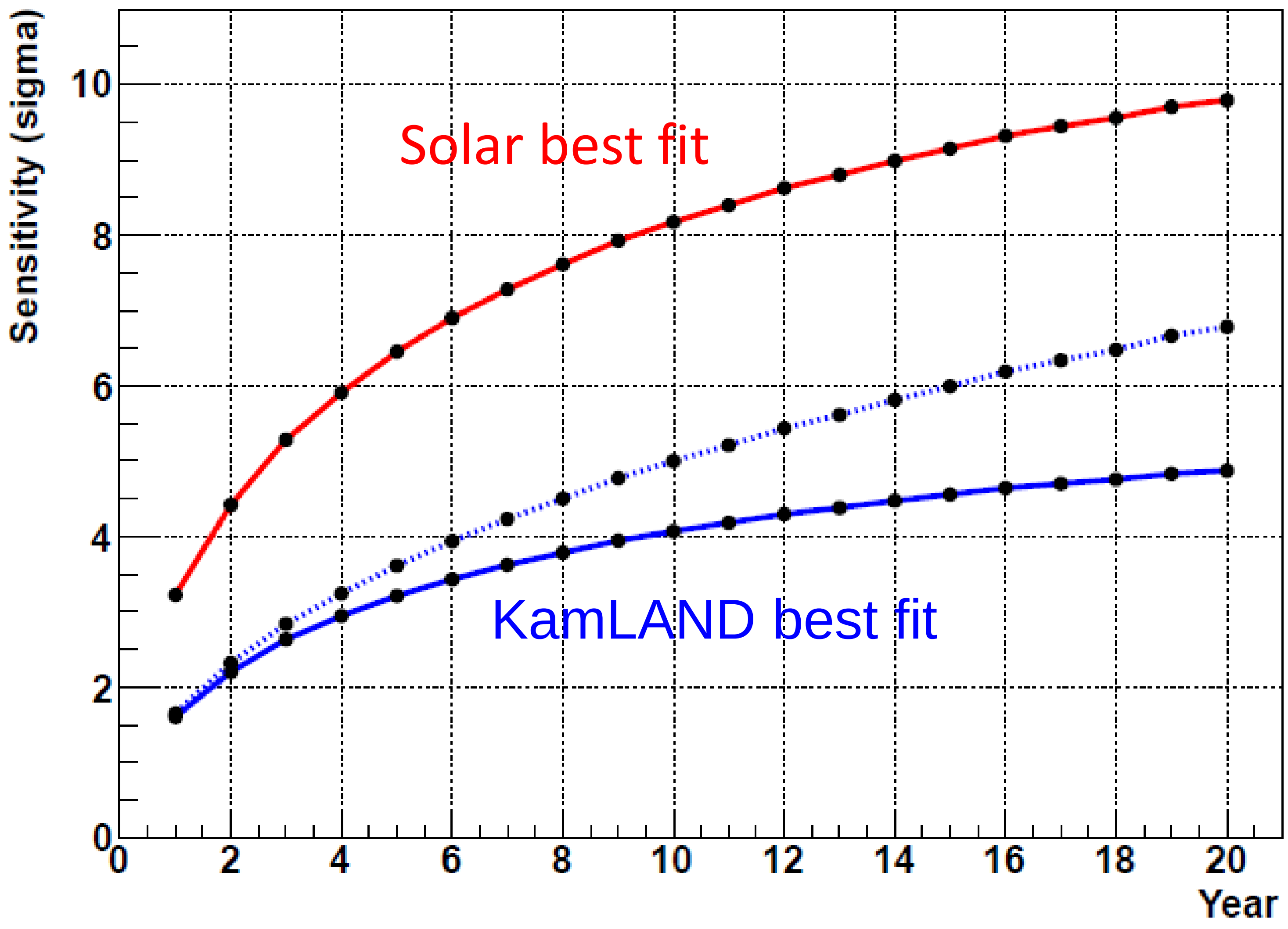
Super-K, PRL 112, 091805 (2014)



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

Hyper-K solar neutrino measurements

Day-night asymmetry sensitivity (From no Day-Night asymmetry)



(BG syst. 0.1%)

BG syst. 0.3%

Other physics: supernova neutrinos

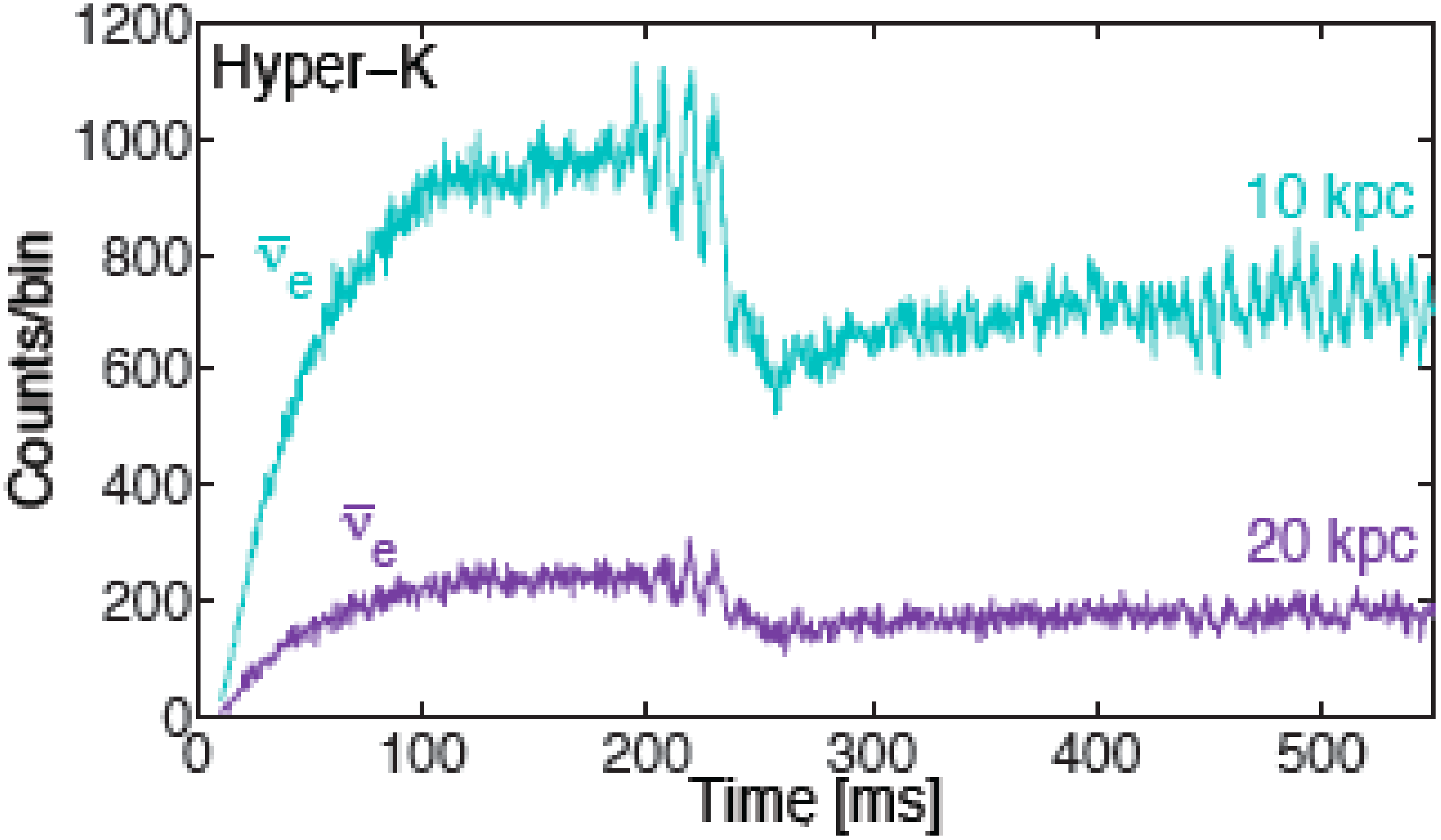
Supernova neutrino burst

(M. Shiozawa, Neutrino 2018)

✓50-80 k events / SN @10 kpc
- Dynamics of SN central engine,
- Explosion mechanism,
- NS/BH formation
- ~1º pointing for SN alert for Multi-messenger study (w/ GW, Optical, …)

✓ Hyper-K can detect neutrino burst for SNe in Andromeda (~10 events).

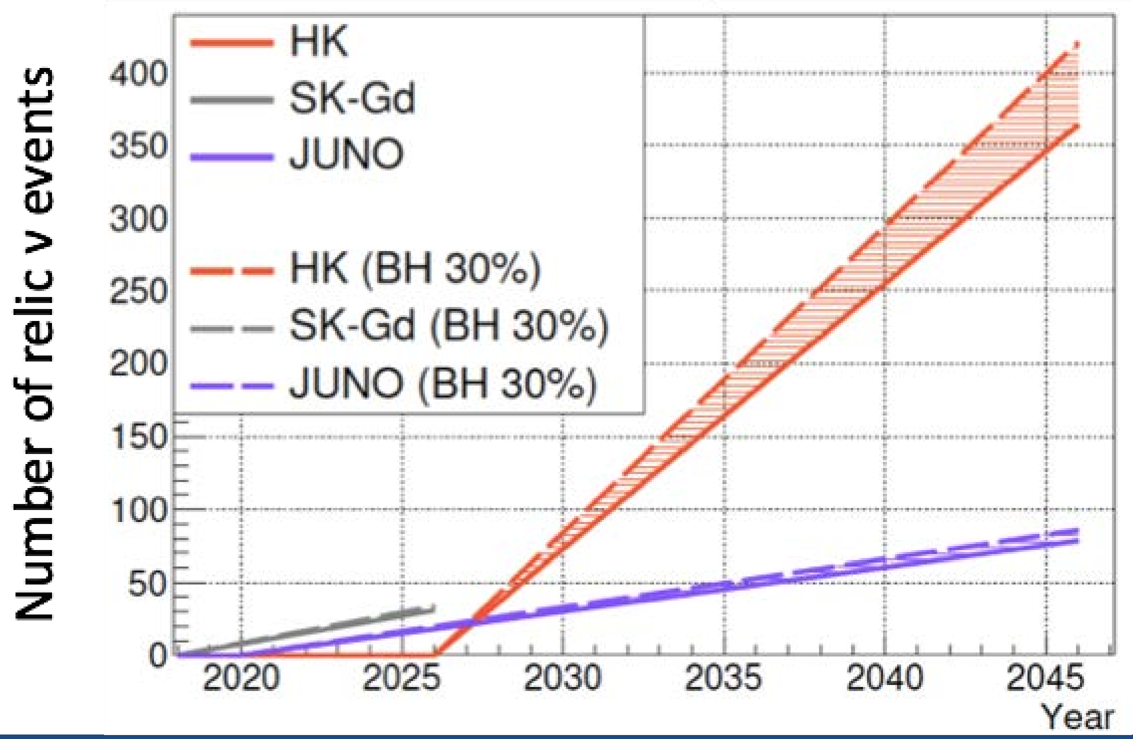
SASI (standing accretion shock instability)

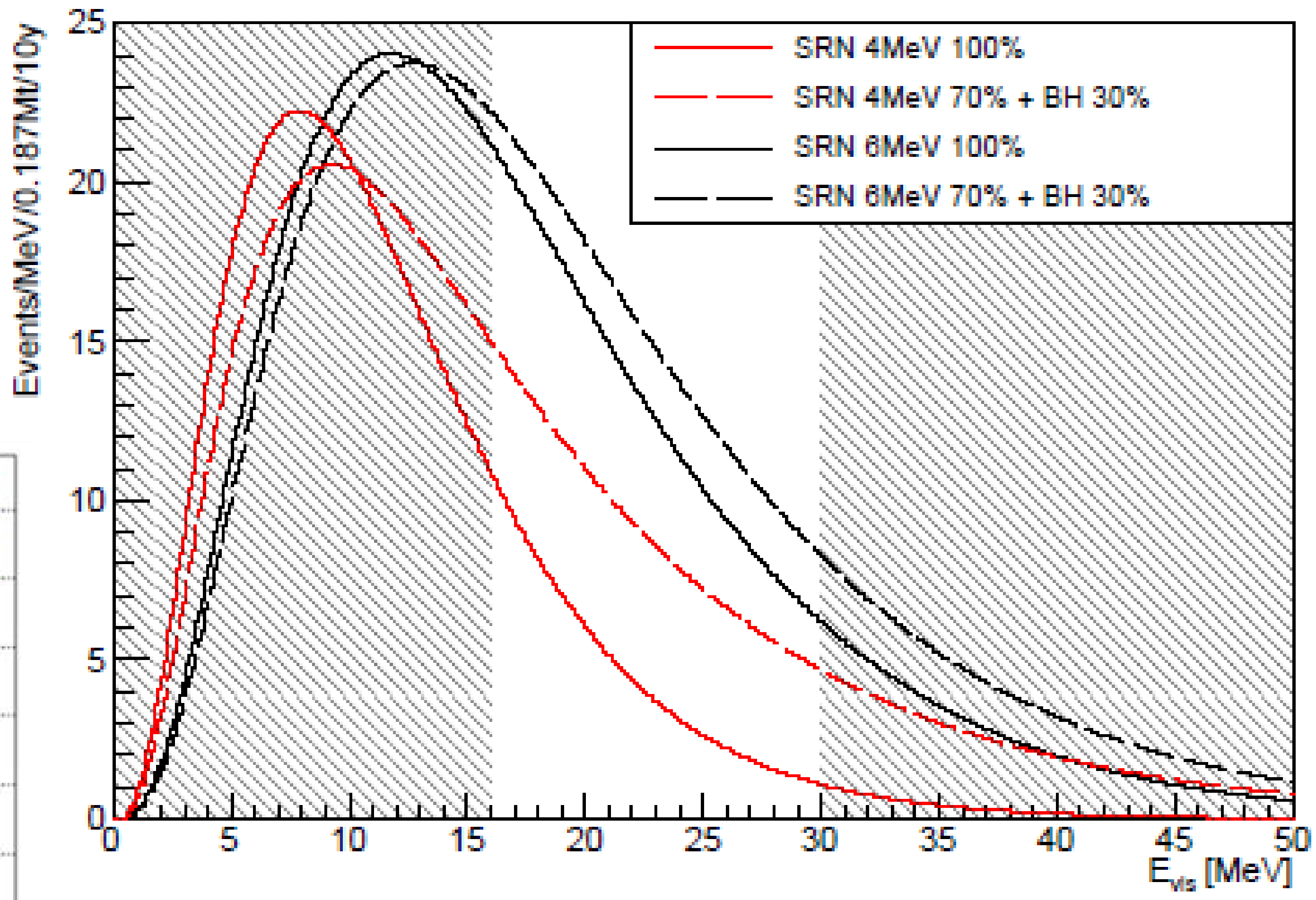


Relic supernova neutrinos

- ✓ Neutrinos that were produced by past SNe should be observed.
  - History of SN explosions in the Universe.
- ✓ SK-Gd and Juno will discover them.

efficiency not considered





✓ Hyper-K will measure the spectrum
➔ History and average behaver of SNe

Other physics: Proton decay

Motivation

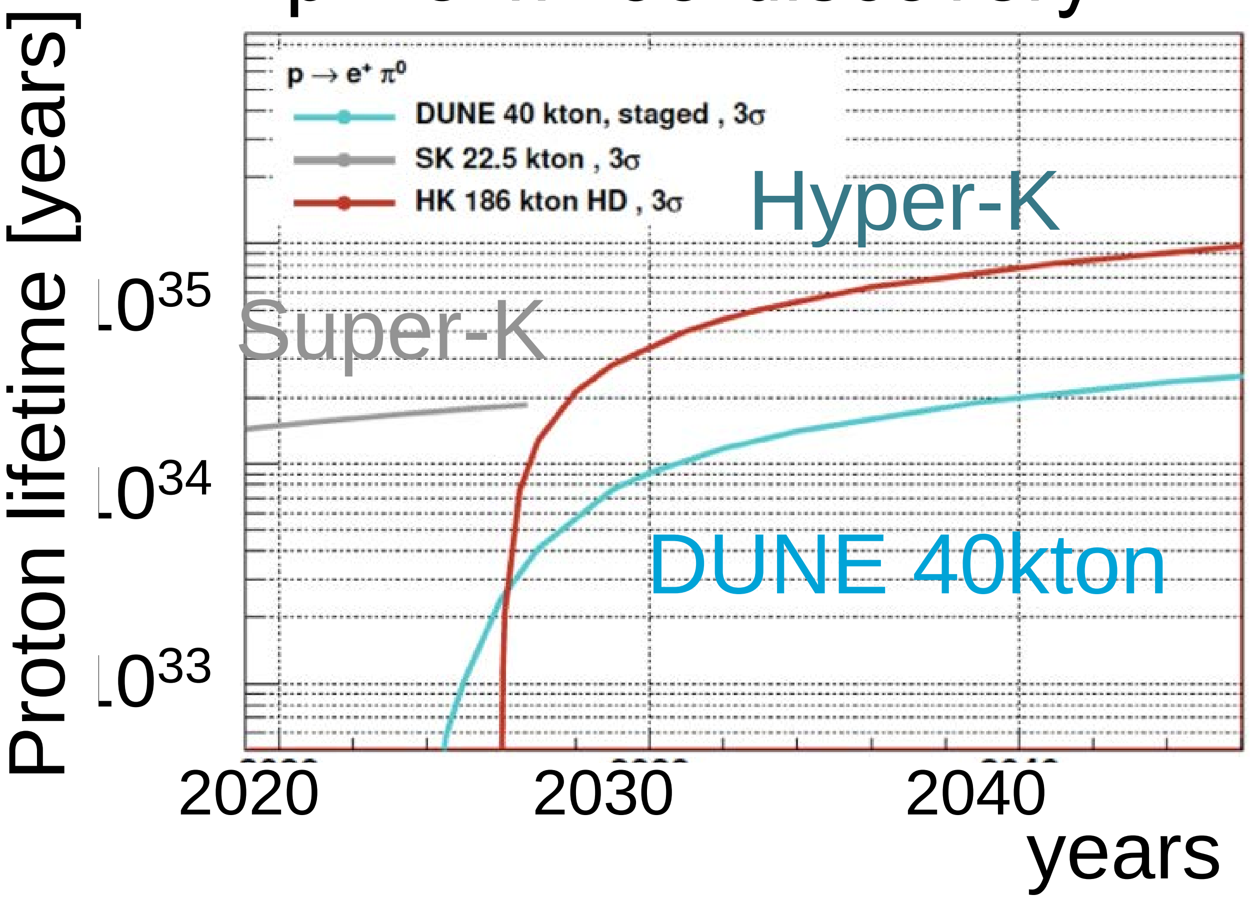
- ✓It is clear that proton decay is very important for understanding of physics at the very high energy scale (GUTs).
- ✓Neutrino masses/mixings and proton decays might be related to the physics at very high energy scale.

- ✓We are in an extremely interesting era. New large neutrino detectors (JUNO, DUNE and Hyper-K) will (or are planed to) begin the operation in the near future. These detectors are also very good proton decay detectors.
- ✓Therefore, we should not forget the proton decay searches in the next generation “neutrino experiments”.

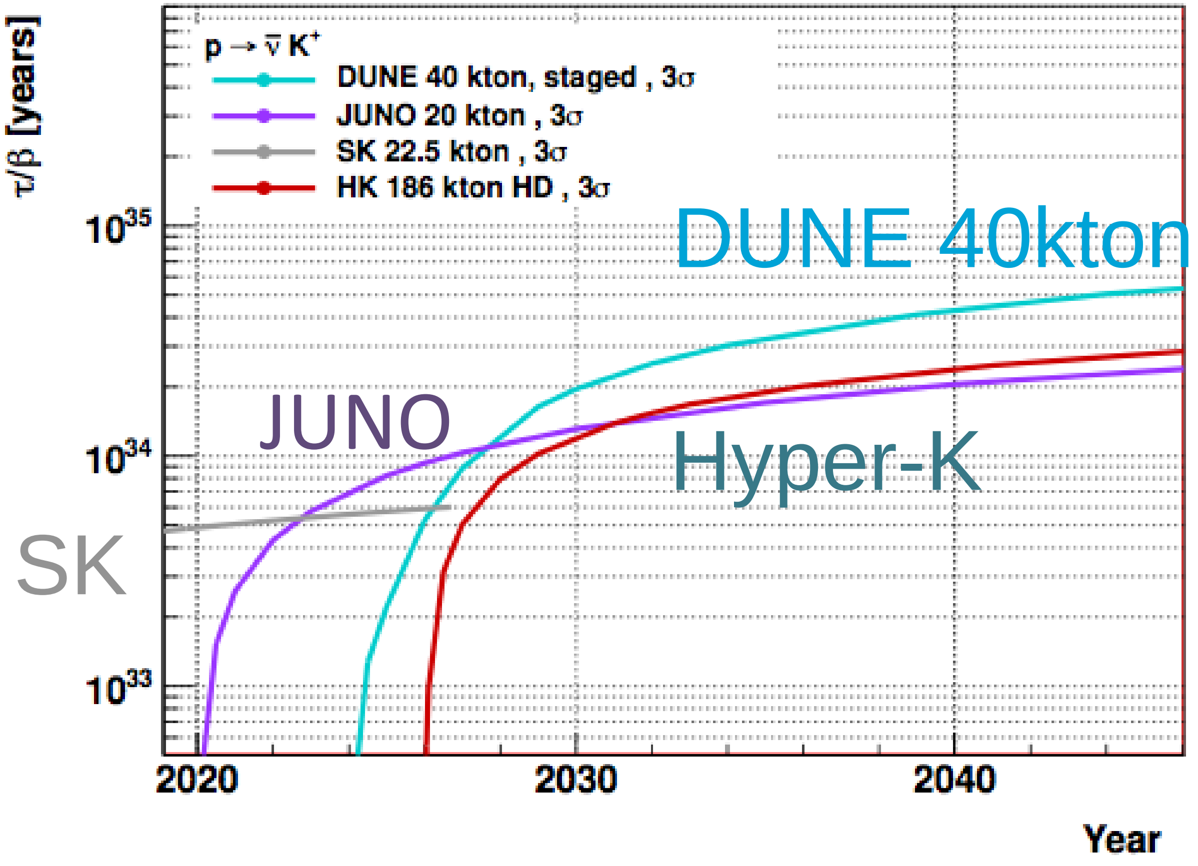
Sensitivities

DUNE arXiv:1601.05471
HK arXiv:1805.04163v1
JUNO arXiv:1507.05613

p→e$^+\pi^0$ 3σ discovery



p→νK$^+$ 3σ discovery

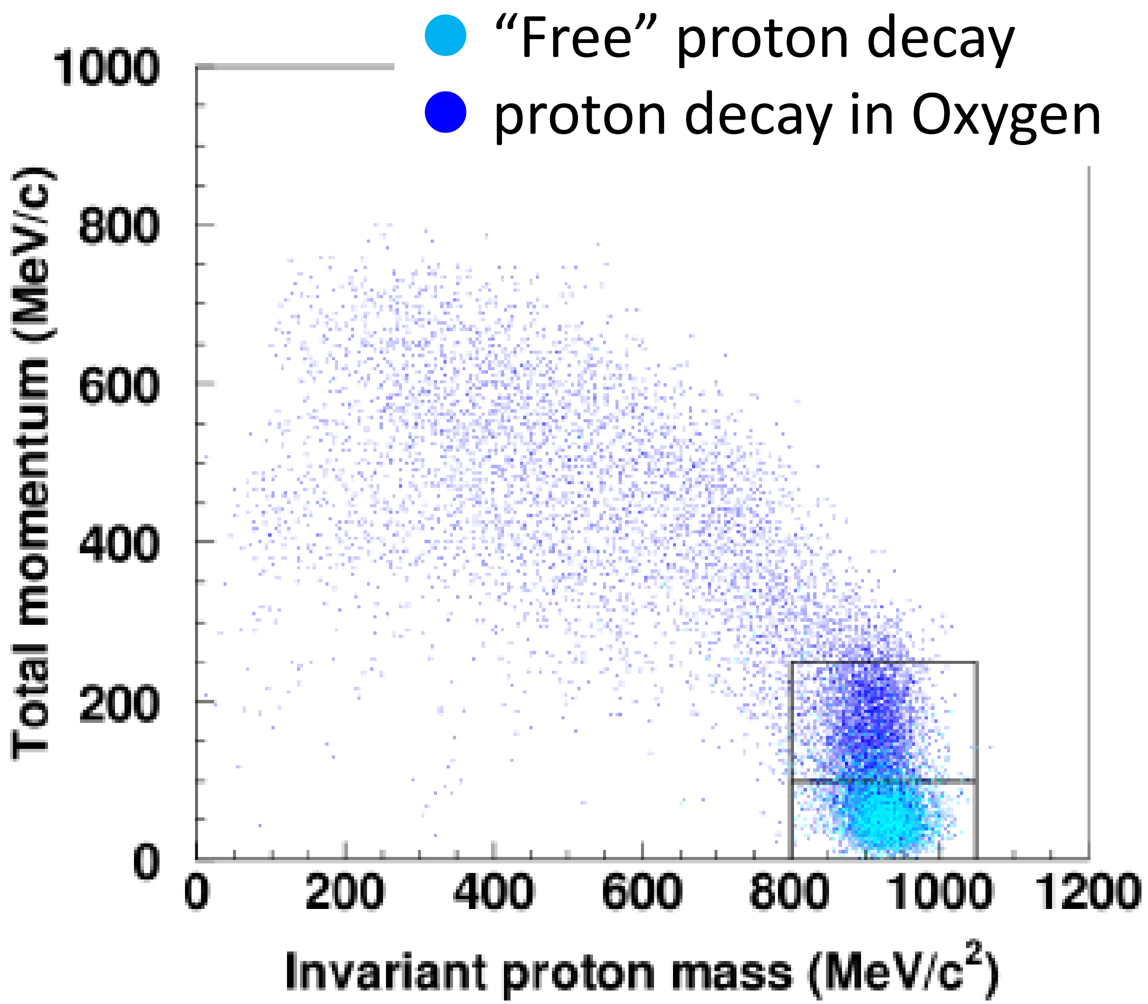


3σ discovery potential, if $\tau_p < 10^{35}$ years ($e\pi^0$) or < $5*10^{34}$ years (νk^+)

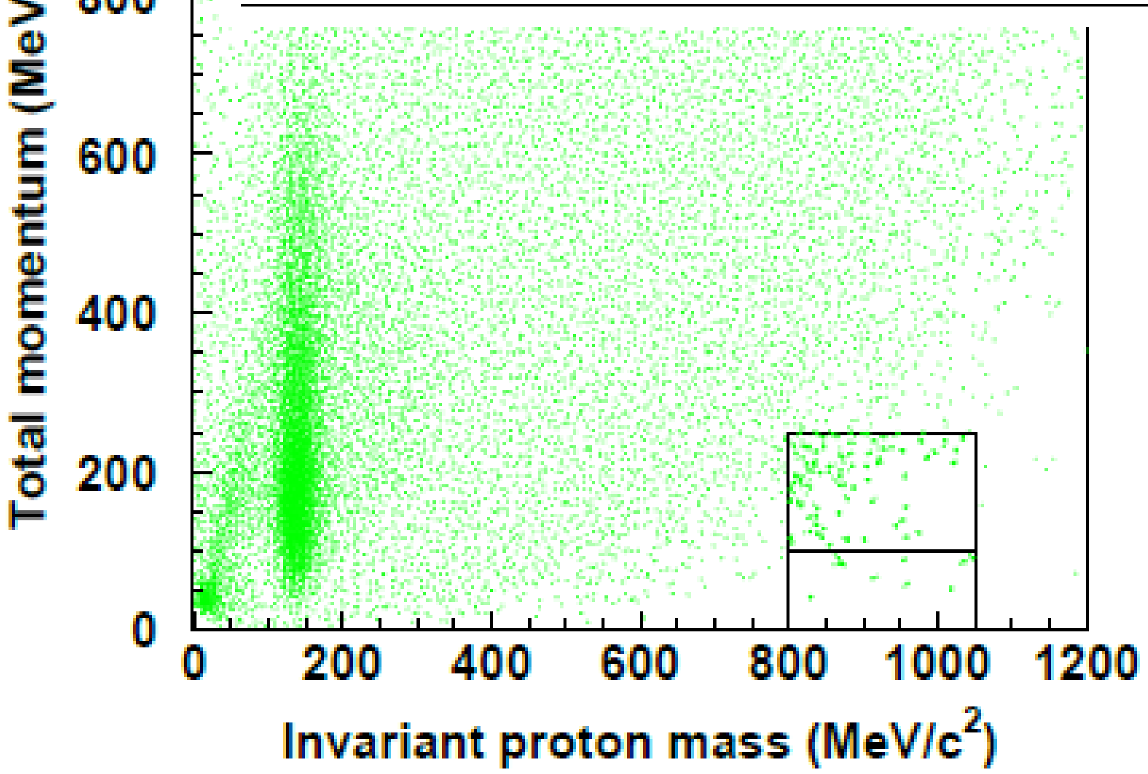
(Lines for DUNE and JUNO experiment have been generated based on numbers in the literature.)

Key plots for confirming p → e π^0

(Hyper-K, arXiv:1805.04163v1)



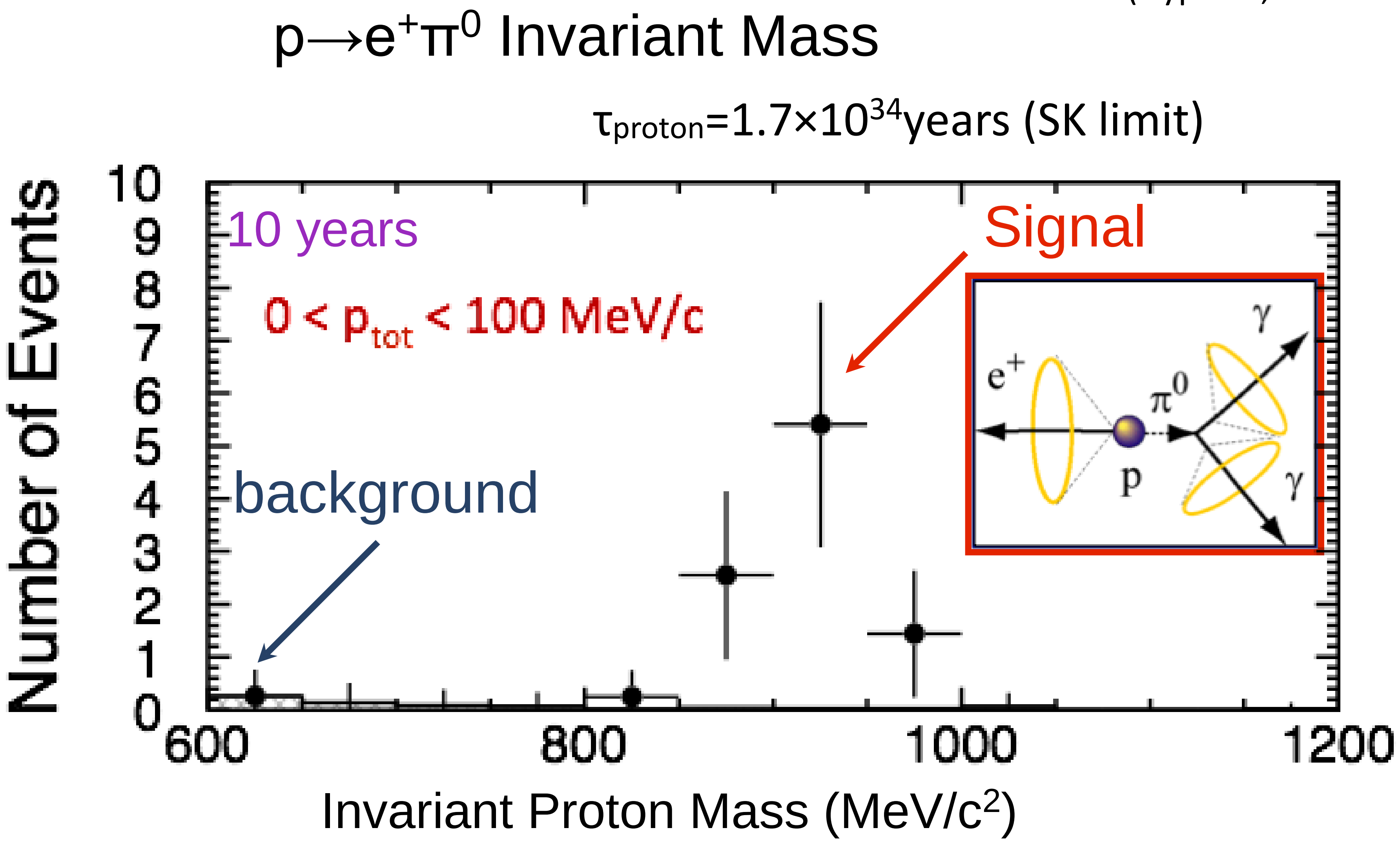
$0 < p_{tot} < 100$ MeV/c		$100 < p_{tot} < 250$ MeV/c	
ϵ_{sig} [%]	Bkg [/Mton·yr]	ϵ_{sig} [%]	Bkg [/Mton·yr]
18.7 ± 1.2	0.06 ± 0.02	19.4 ± 2.9	0.62 ± 0.20



In order to reach 10^{35} years, "free" proton decay (from Hydrogen) is very important!

Key plots for confirming p → e π^0

(Hyper-K, arXiv:1805.04163v1)



Status of Hyper-K

Status of Hyper-K

- ✓ Hyper-K has been selected as one of the 7 large scientific projects in the Roadmap of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2017.
- ✓ Since then, we have been discussing intensively with MEXT.
- ✓ In the FY2019 Japanese budget (April 2019 - March 2020), “funding for feasibility study” for Hyper-K is included. This budget is equivalent to “seed funding” in some other countries. This funding is usually for 1 year (or 2 years).
- ✓ The President of the Univ. of Tokyo, in recognition of both the project's importance and value both nationally and internationally, pledged to ensure construction of the Hyper-Kamiokande detector commences in April 2020.

Hyper-K construction will begin in April 2020!
(The construction will take 7-8 years!)
Russian participation and contributions to Hyper-K are most welcome!

Summary

- Hyper-K is a next generation, multi-purpose neutrino experiment: CP violation with the J-PARC neutrino beam, solar, atmospheric and supernova neutrino studies. Also we should not forget proton decays.
- Hyper-Kamiokande is now very seriously considered as a next generation large research infrastructure in Japan in our funding agency.
- We should not miss this great opportunity. We would like to work together with the Russian and international colleagues for the success of the Hyper-K project.