Exploring Neutrino Phenomenology for the Hyper-Kamiokande Project

Ponticífcia Universidade Católica do Rio de Janeiro - PUC-Rio
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WORKSHOP RENAFAE 2022
April 26 2022

Outline

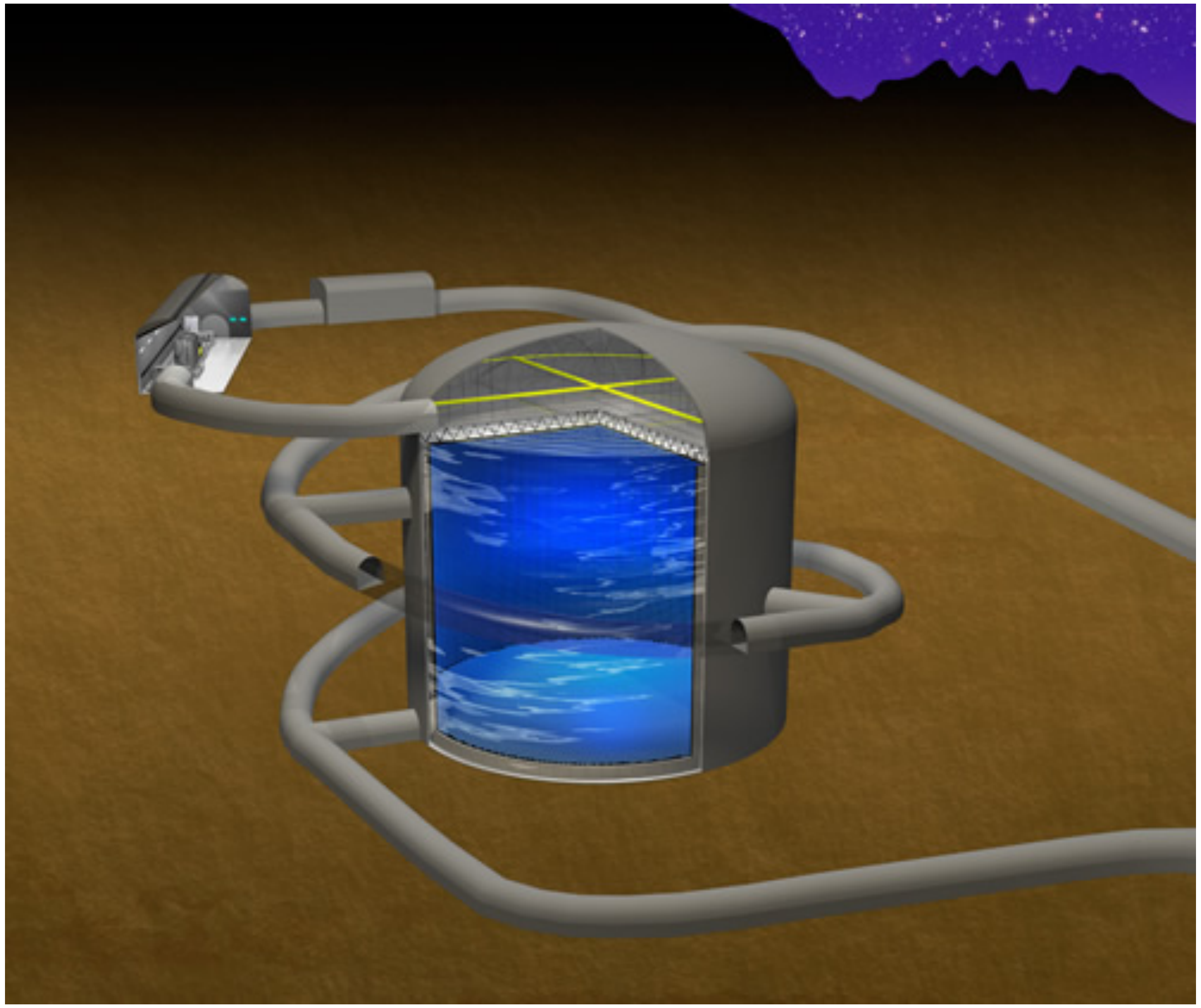
Introduction to Hyper-Kamiokande

Brief presentation of some of our recent activities related to Hyper-K

Concluding Remarks

What is Hyper-Kamiokande?

Hyper-Kamiokande is a next generation Water Chrenkov detector and also the name of the project with various physics programs to be performed by this detector



Detector Size

Diameter: 68 m
Height: 71 m
total mass: 258 kt

fiducial mass: 188 kt
(8.4 times Super-K)

Site: Under the Nijugo Mountain, with overburden of 650 m of rock close to Kamioka

Sucessor (3rd generation) of Kamiokande (fid. mass ~ 1kt) and Super-Kamiokande (fid. mass ~ 22 kt)

Current Status of Hyper-Kamiokande

Approved (funded) oficially in Japan in 2020

Currently under construction, to start data taking in 2027

20 countries, 99 institutes, ~500 people as of Jan 2022, and growing

Collaborating Institutes

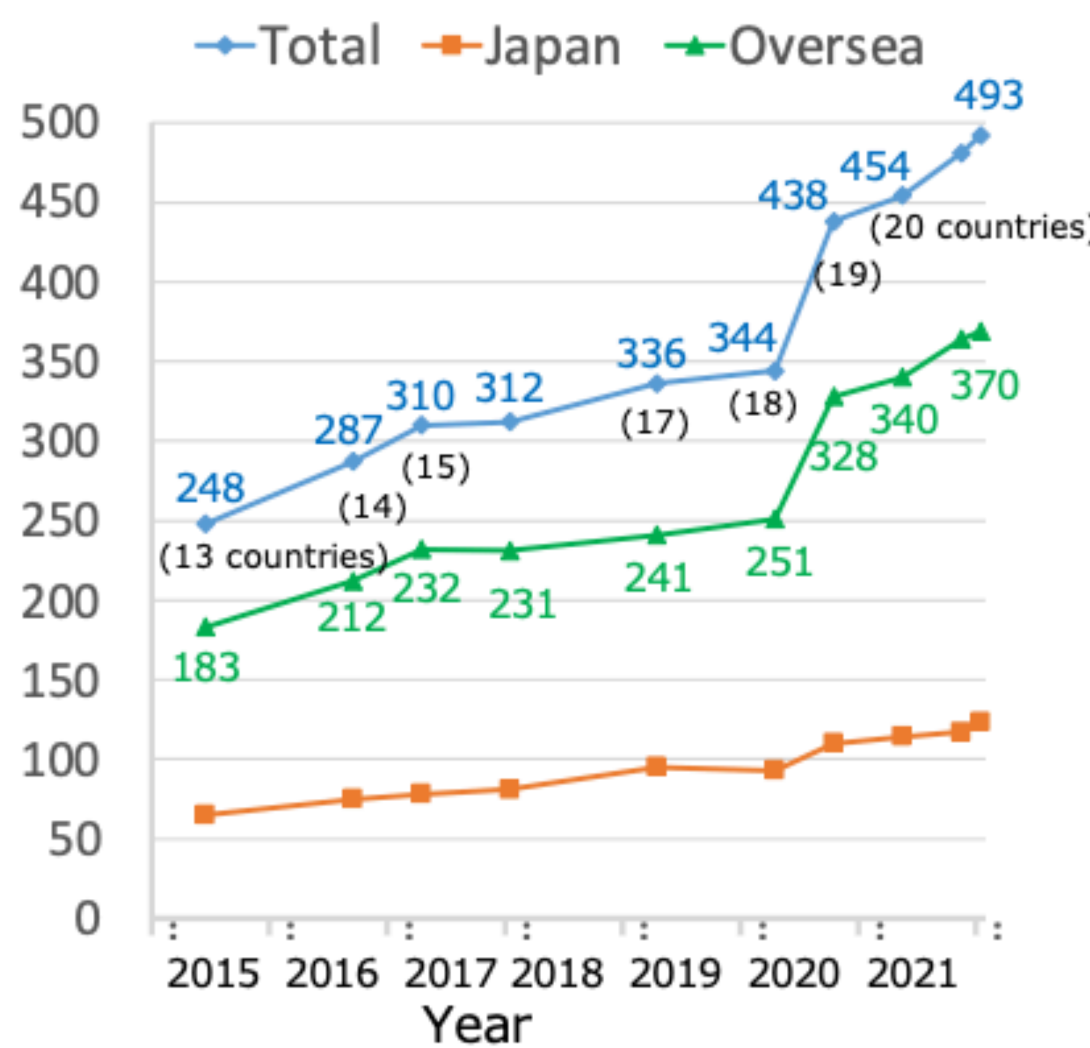
Europe	281 members
Armenia	3
Czech	4
France	27
Germany	1
Italy	55
Poland	38
Russia	22
Spain	35
Sweden	5
Switzerland	13
Ukraine	4
UK	74

Asia	149 members
India	8
Korea	18
Japan	123

Americas	52 members
Brazil	3
Canada	32
Mexico	8
USA	9

Africa	11 members
Morocco	11

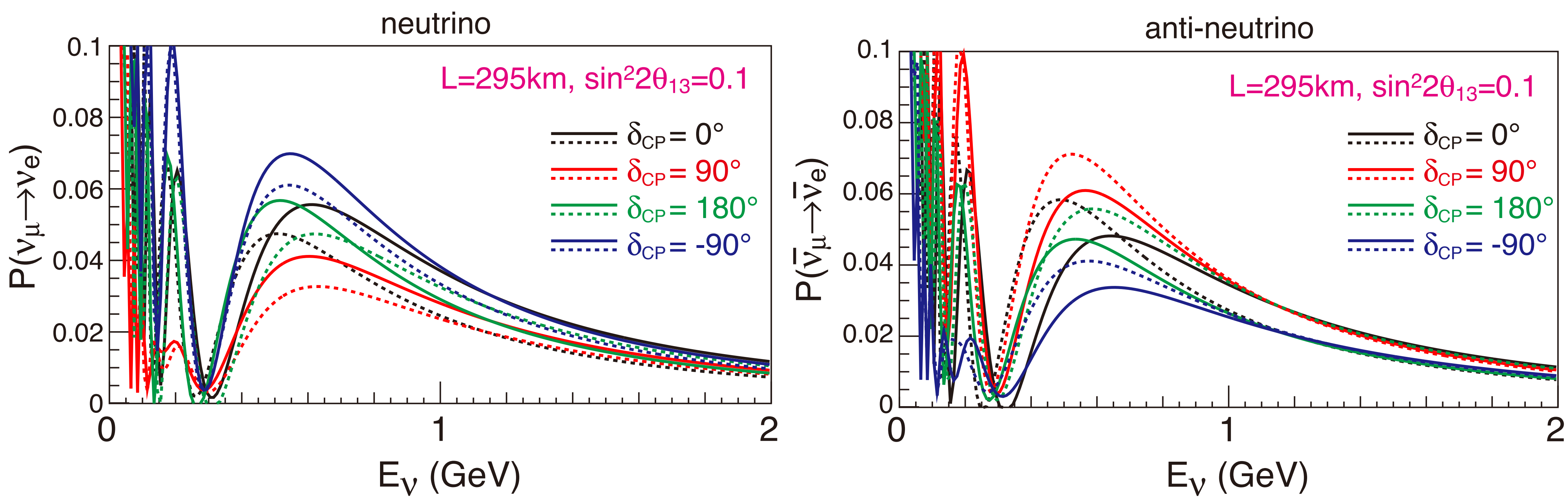
Number of Collaborators



Main Objectives of Hyper-Kamiokande

Longbaseline Oscillation Physics

Observation of CP Violation

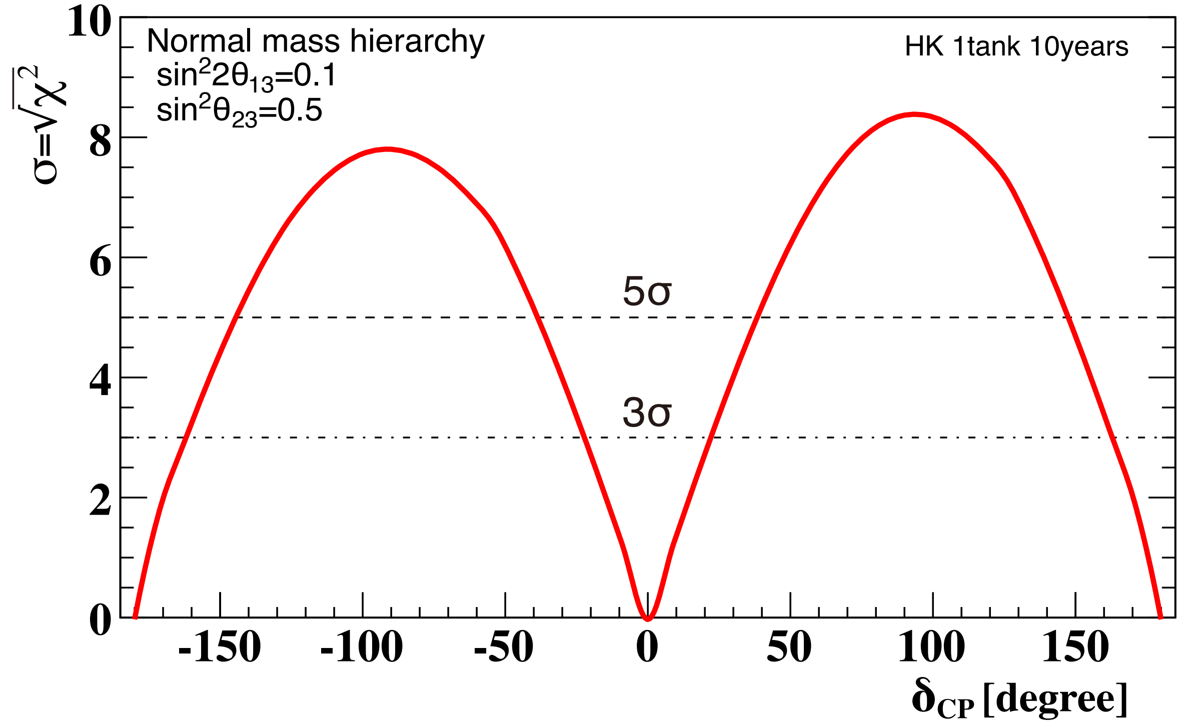


By Comparing the Oscillation Probabilities between ν and $\bar{\nu}$

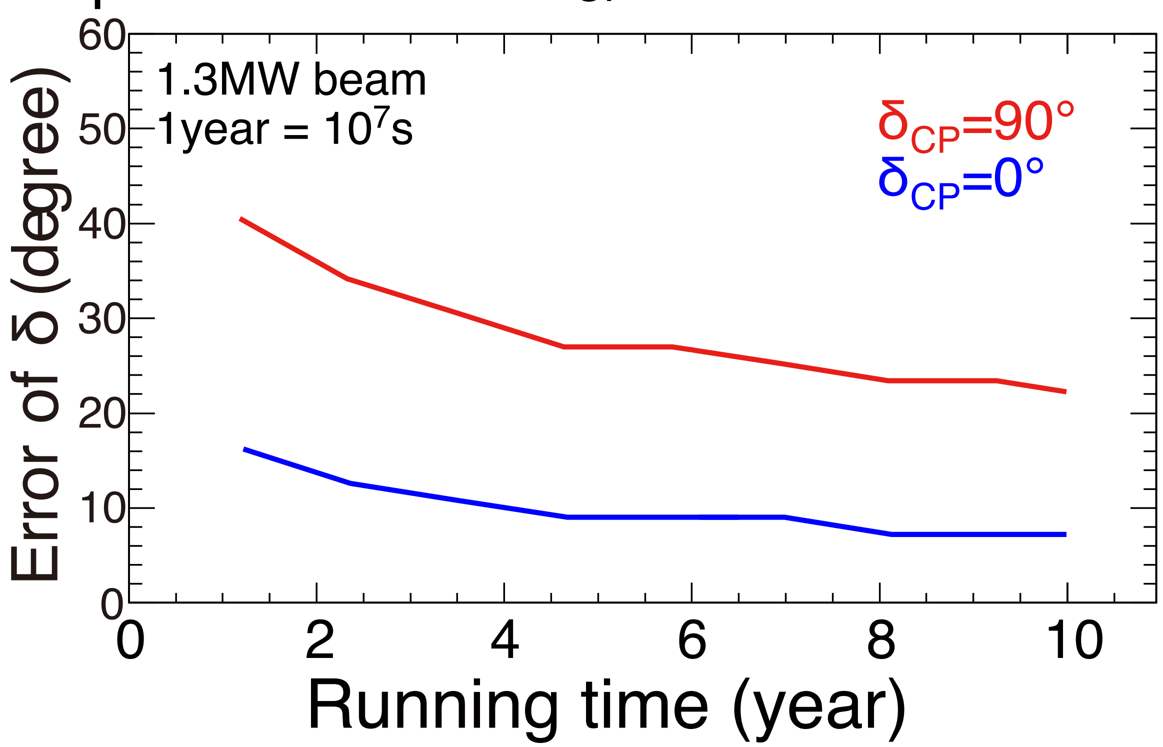
Main Objectives of Hyper-Kamiokande

Expected sensitivity for CP violation

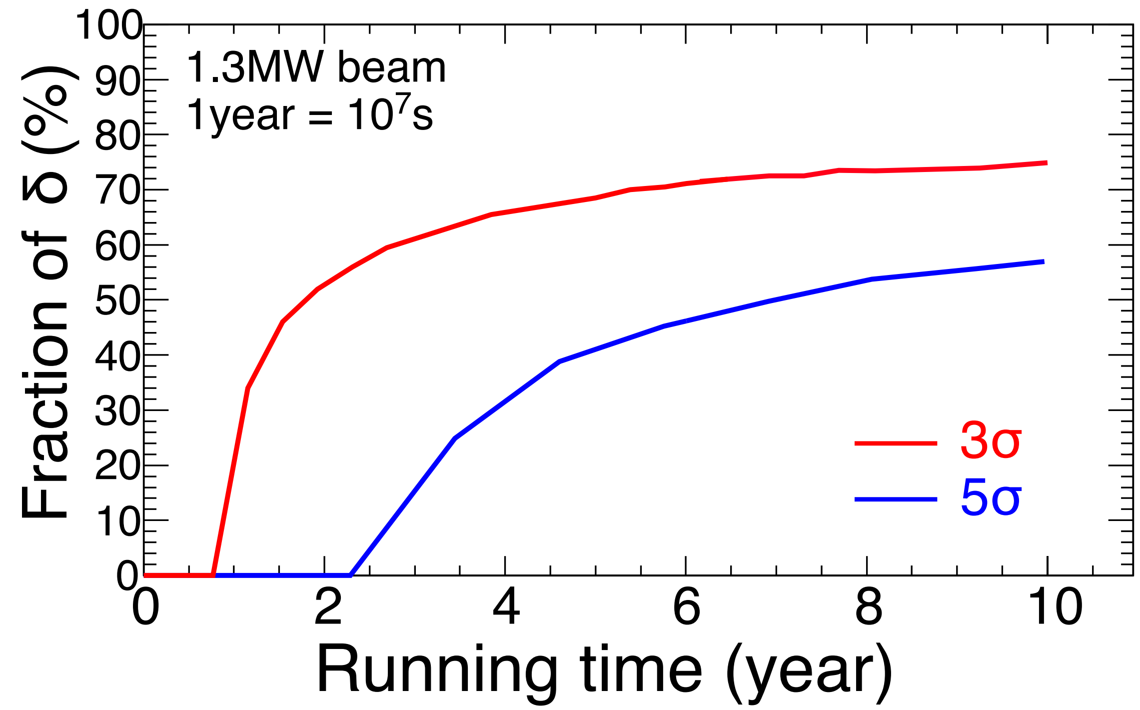
Significance to establish CP violation as a function of the true value of δ_{CP}



Expected Error of δ_{CP} as a function of time



Fraction of δ_{CP} to exclude $\sin\delta_{CP} = 0$



Hyper-K Design Report, arXiv:1805.04163v2 [hep-ex]

Main Objectives of Hyper-Kamiokande

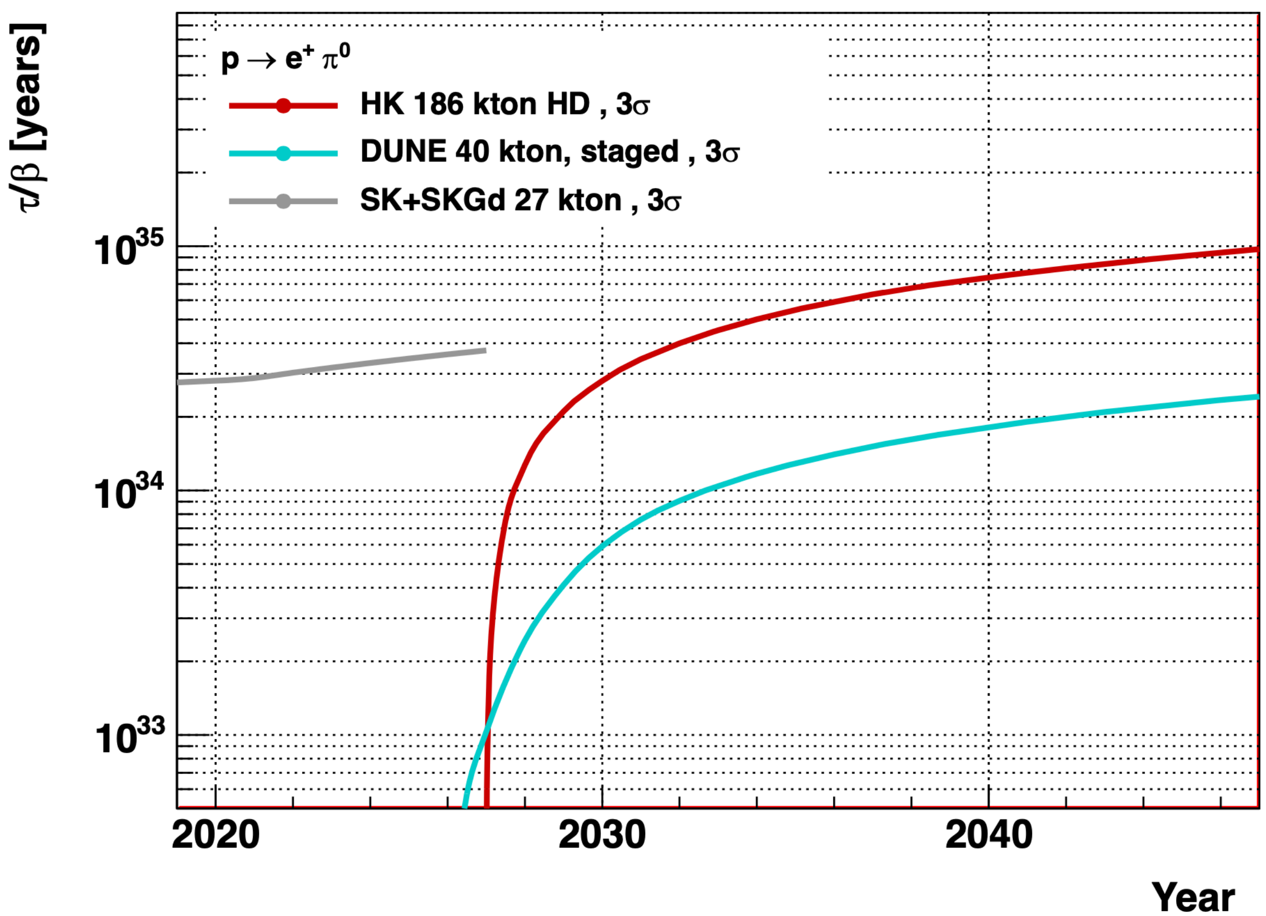
Search for Nucleon Decay

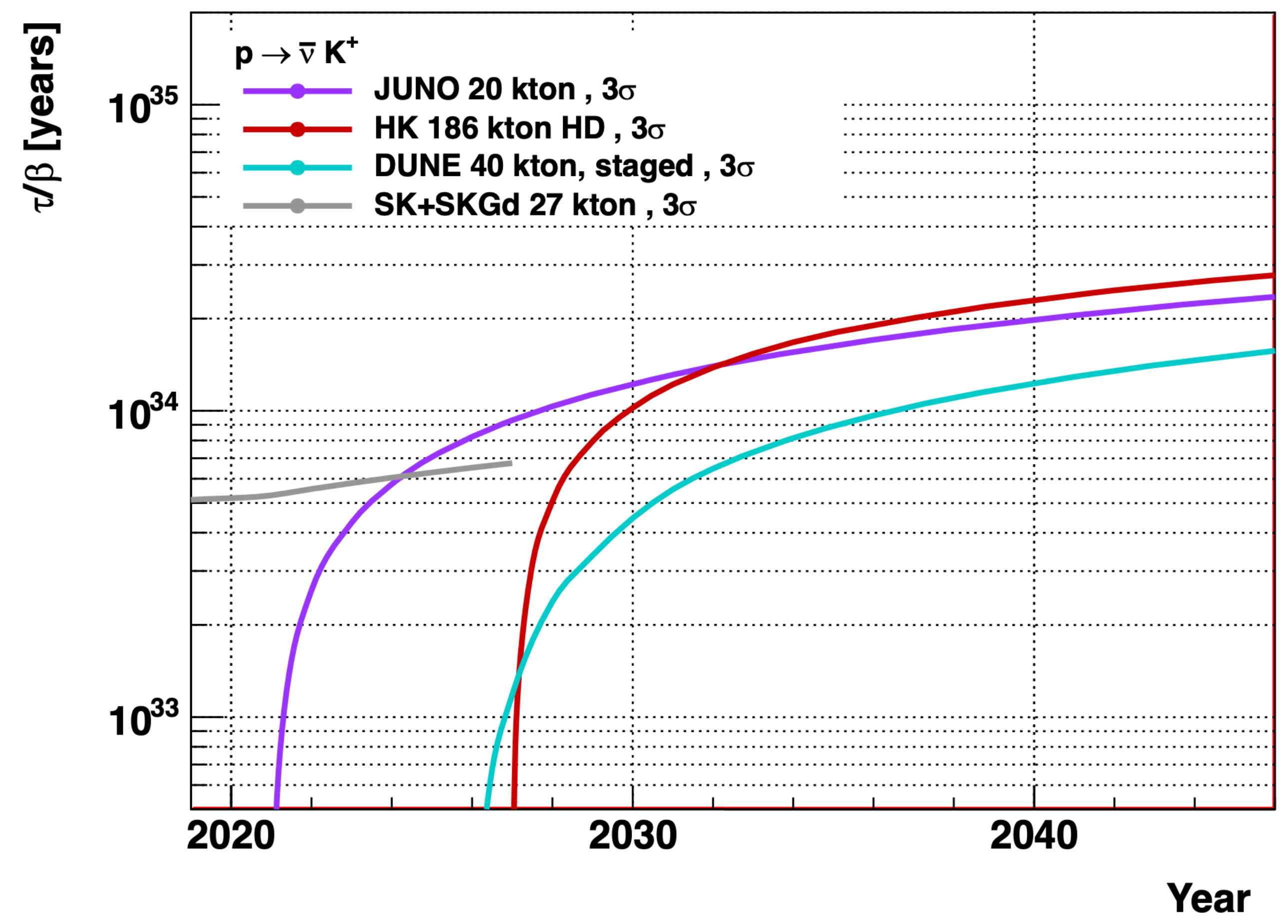
Study stability of nucleons probing new physics related to GUT/SUSY

Because of the larger detector size, ~ 8 times larger than Super-K, we can improve significantly the current limits

examples of 2 decay modes expected in various models beyond SM

$$p \to e^+ + \pi^0 \qquad\qquad p \to \bar{\nu} + K^+$$





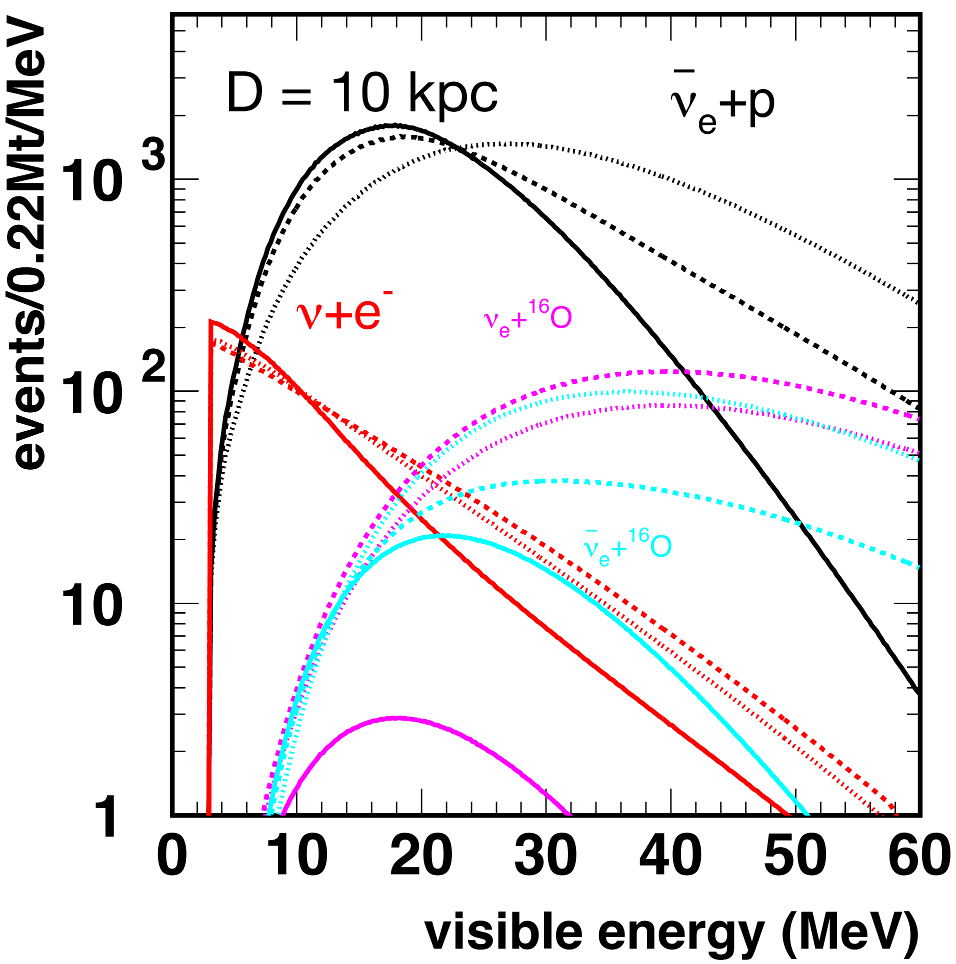
Hyper-K Design Report, arXiv1805.04163v2 [hep-ex]

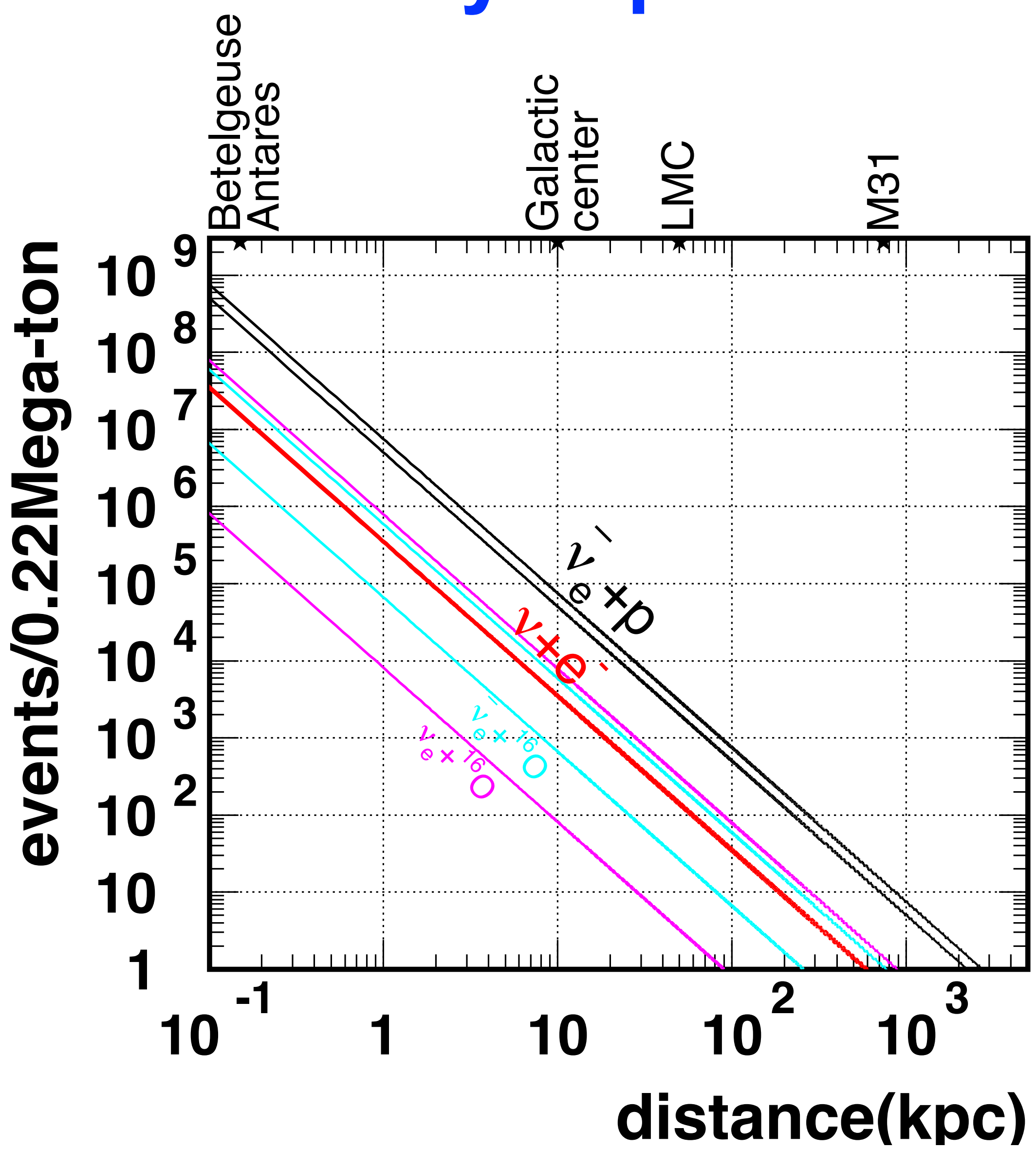
Main Objectives of Hyper-Kamiokande

Programs for Neutrino Astrophysics

For example,

Observation of Neutrinos coming from nearby supernova





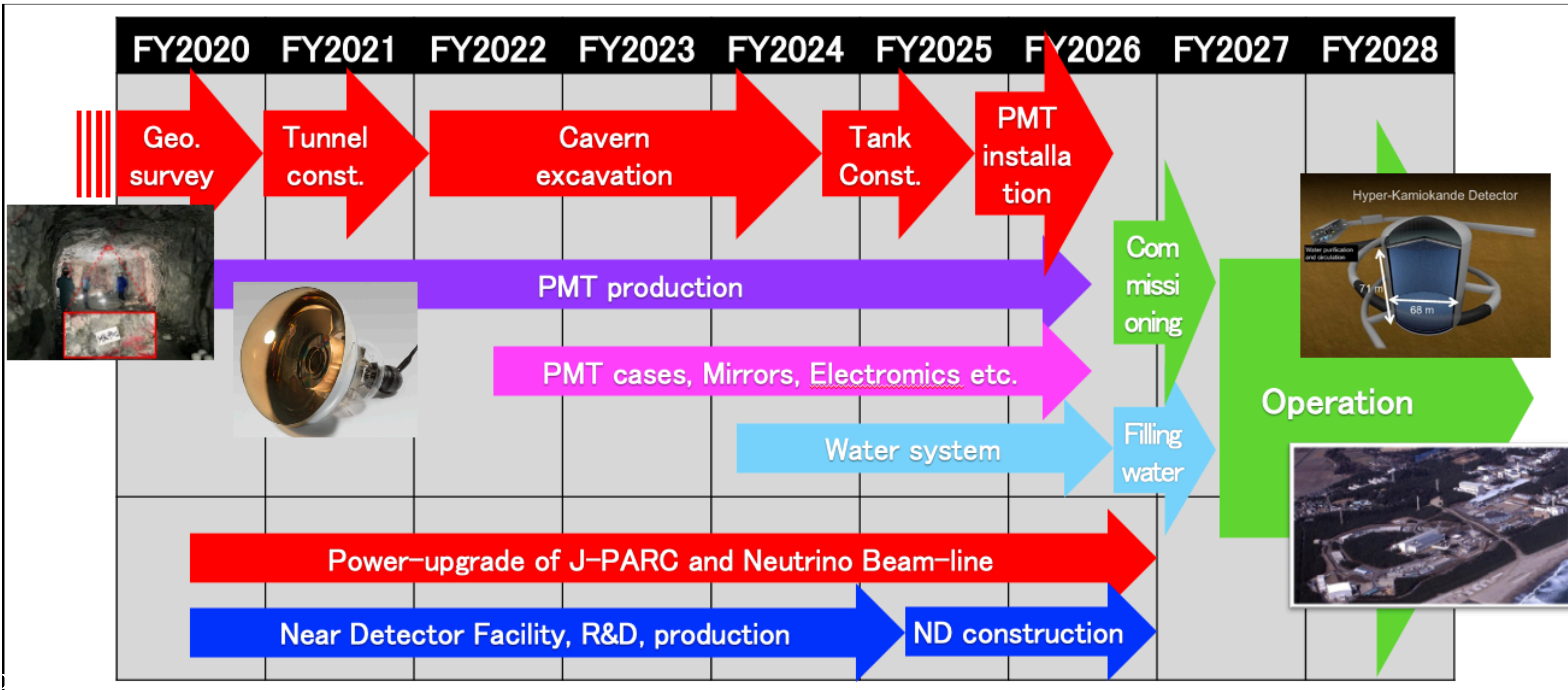
For more detailed understanding of the explosion mechanism of supernova, formations of neutron stars and black holes

Hyper-K Design Report, arXiv:1805.04163v2 [hep-ex]

Time Schedule of Hyper-Kamiokande

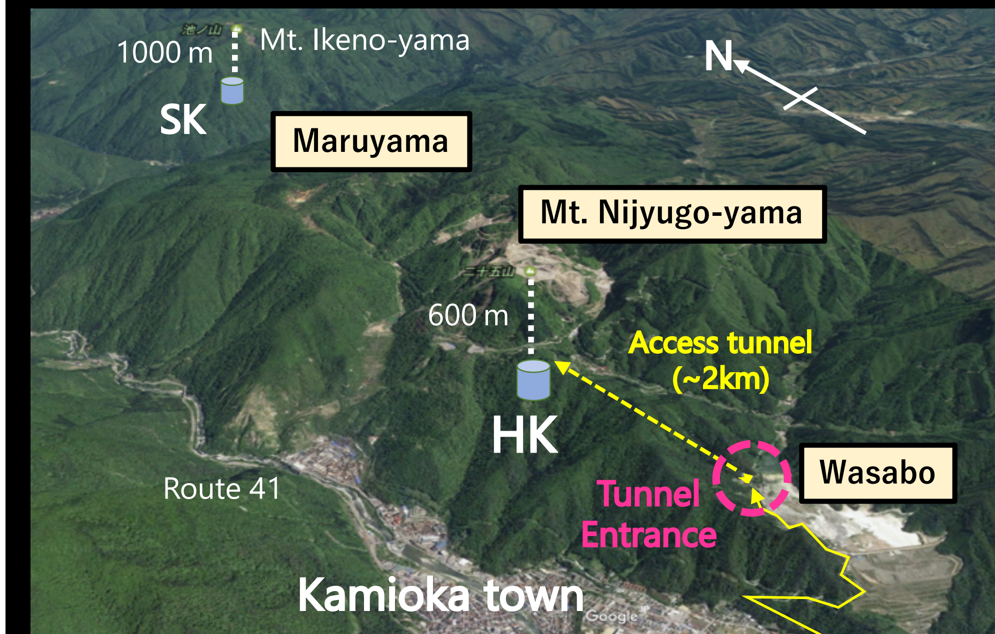
~7 years of construction from 2020, 5 years of excavation + 2 years of detector construction

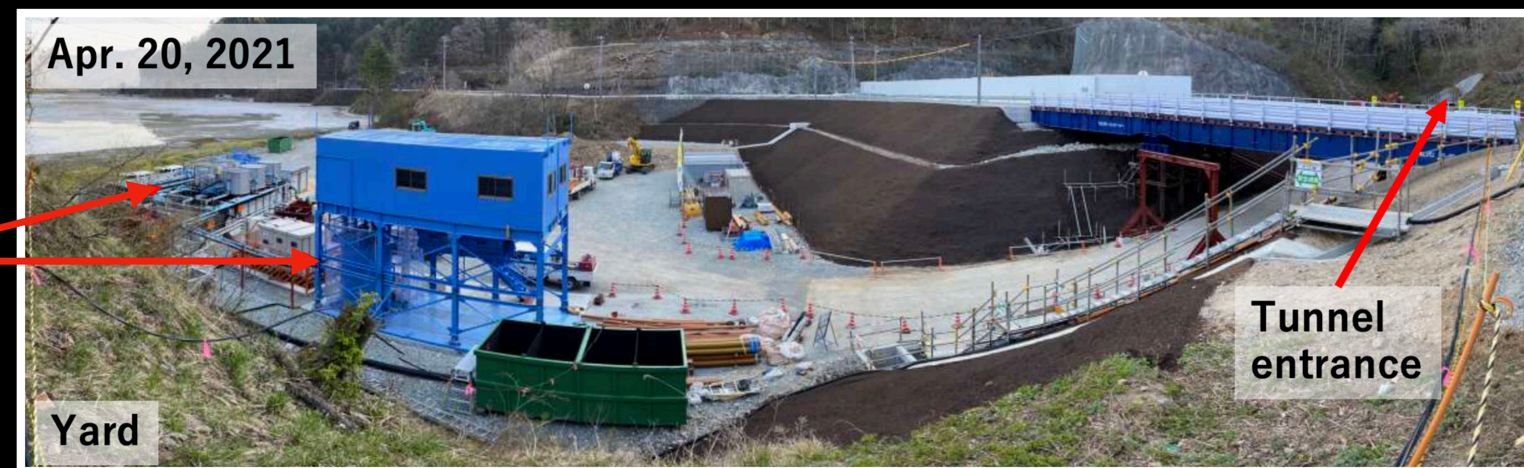
Data taking expected from 2027



Current Status

Entrance Yard Construction





- Access tunnel (1873m) completed in February 2022.
- Approach tunnel started.

21/Mar/2022

Presente by Francesca Di Lodovico (HK co-spokes person) @
First Pan-African Astro-Particle and Colider Physics Workshop, 21 March 2022

Current members of Hyper-K group in Brazil

3 oficial HK members (theorists) from PUC-Rio

Hiroshi Nunokawa (faculty)

Arman Esmaili (faculty)

Alexander A. Quiroga (pos-doc)

+ Some Students

Ana Maria Garcia Trzeciak (PhD)

Emilse Cabrera Capera (PhD)

+ Some External Collaborators

Our Contributions to HK

Currently, our efforts are theory/phenomenogy oriented

Neutrino Phenomenology related to Hyper-K

We are interested to explore Physics Potential of Hyper-K experiment

- Prob new physics beyond Standard Model, beyond minimum extension of the νSM (SM + neutrino masses/mixing)

- For example, neutrino decay, non-standard interactions, violation of unitarity, sterile neutrinos, decoherence, large extra dimensions, etc, for accelerator, solar, atmospheric and supernova neutrinos

Our Contributions to HK

Neutrino Phenomenology related to Hyper-K

We are also interested to explore possible synergies between Hyper-K and other experiments such as JUNO, DUNE, IceCube, Gravitational Wave detectors, etc

Some examples of our recent activities

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Probing neutrino decay scenarios by using the Earth matter effects on supernova neutrinos

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Abstract. The observation of Earth matter effects in the spectrum of neutrinos coming from a next galactic core-collapse supernova (CCSN) could, in principle, reveal if neutrino mass ordering is normal or inverted. One of the possible ways to identify the mass ordering is through the observation of the modulations that appear in the spectrum when neutrinos travel through the Earth before they arrive at the detector. These features in the neutrino spectrum depend on two factors, the average neutrino energies, and the difference between the primary neutrino fluxes of electron and other flavors produced inside the supernova. However, recent studies indicate that the Earth matter effect for CCSN neutrinos is expected to be rather small and difficult to be observed by currently operating or planned neutrino detectors mainly because of the similarity of average energies and fluxes between electron and other flavors of neutrinos, unless the distance to CCSN is significantly smaller than the typically expected one, $\sim 10\,\mathrm{kpc}$. Here, we are looking towards the possibility if the non-standard neutrino properties such as decay of neutrinos can enhance the Earth matter effect. In this work we show that invisible neutrino decay can potentially enhance significantly the Earth matter effect for both ν_e and $\bar{\nu}_e$ channels at the same time for both mass orderings, even if the neutrino spectra between electron and other flavors of neutrinos are very similar, which is a different feature not expected for CCSN neutrinos with standard oscillation without the decay effect.

Keywords: neutrino properties, supernova neutrinos

ArXiv ePrint: 2109.02737

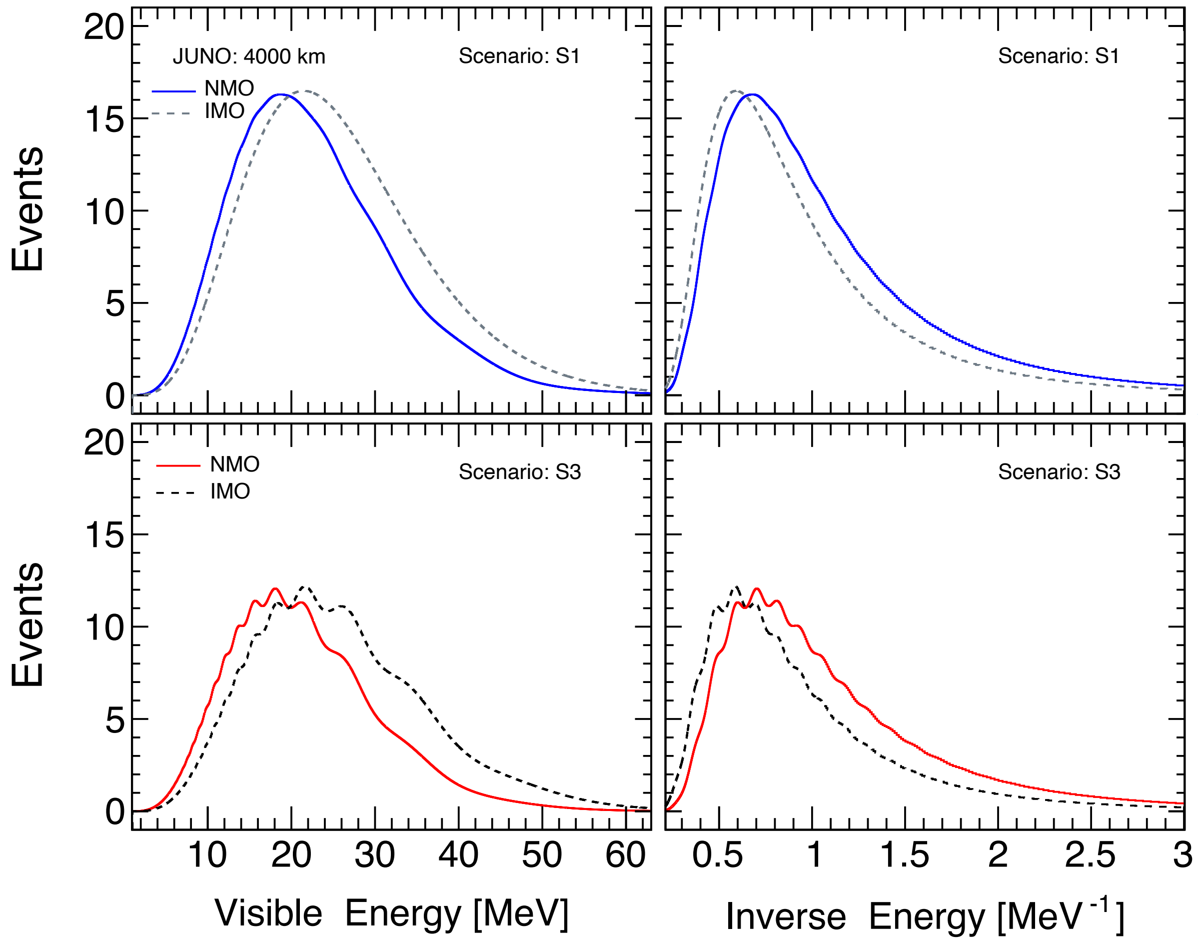
JCAP01(2022)003

Recently, we showed that effect of neutrino decay can be manifested at Hyper-K, JUNO and DUNE simultaneously through the Earth matter effect

this can be possible if neutrino life time divided by mass is given by

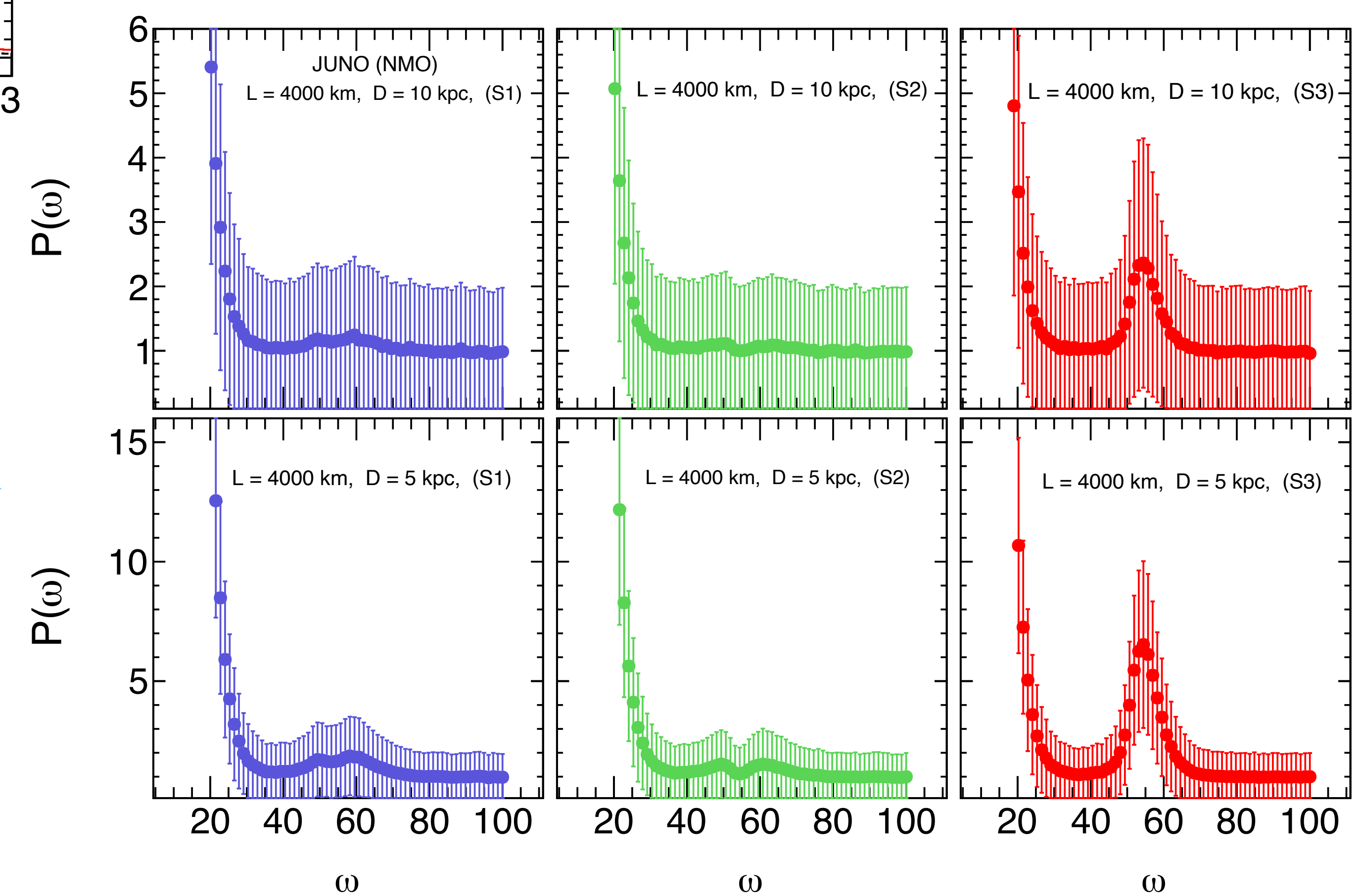
$$\frac{\tau}{m} \sim \frac{D}{E} \sim 10^5 \left[\frac{D}{10\,\mathrm{kpc}}\right]\left[\frac{E}{10\,\mathrm{MeV}}\right]^{-1} \frac{\mathrm{s}}{\mathrm{eV}}.$$

Impact of neutrino decay for supernova neutrino observation



Periodic modulations in the observed spectra due to the Earth matter + decay effect

This can be identified by Fourier Analysis



E. Delgado et al, JCAP01 (2022)003, arXiv: 2109.02737 [hep-ph]

Some examples of our recent activities

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scientific reports

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Synergies and prospects for early resolution of the neutrino mass ordering

Anatael Cabrera[1,2,4], Yang Han[1,2], Michel Obolensky[1], Fabien Cavalier[2], João Coelho[2], Diana Navas-Nicolás[2], Hiroshi Nunokawa[2,8], Laurent Simard[2], Jianming Bian[3], Nitish Nayak[3], Juan Pedro Ochoa-Ricoux[3], Bedřich Roskovec[7], Pietro Chimenti[5]✉, Stefano Dusini[6]✉, Mathieu Bongrand[2,9], Rebin Karaparambil[9], Victor Lebrin[9], Benoit Viaud[9], Frederic Yermia[9], Lily Asquith[10], Thiago J. C. Bezerra[10], Jeff Hartnell[10], Pierre Lasorak[10], Jiajie Ling[11], Jiajun Liao[11] & Hongzhao Yu[11]

The measurement of neutrino mass ordering (MO) is a fundamental element for the understanding of leptonic flavour sector of the *Standard Model of Particle Physics.* Its determination relies on the precise measurement of Δm^2_{31} and Δm^2_{32} using either neutrino *vacuum oscillations*, such as the ones studied by medium baseline reactor experiments, or *matter effect modified oscillations* such as those manifesting in long-baseline neutrino beams (LBνB) or atmospheric neutrino experiments. Despite existing MO indication today, a fully resolved MO measurement ($\geq 5\sigma$) is most likely to await for the next generation of neutrino experiments: JUNO, whose stand-alone sensitivity is $\sim 3\sigma$, or LBνB experiments (DUNE and Hyper-Kamiokande). Upcoming atmospheric neutrino experiments are also expected to provide precious information. In this work, we study the possible context for the earliest full MO resolution. A firm resolution is possible even before 2028, exploiting mainly vacuum oscillation, upon the combination of JUNO and the current generation of LBνB experiments (NOvA and T2K). This opportunity is possible thanks to a powerful synergy boosting the overall sensitivity where the sub-percent precision of Δm^2_{32} by LBνB experiments is found to be the leading order term for the MO earliest discovery. We also found that the comparison between *matter* and *vacuum* driven oscillation results enables unique discovery potential for physics beyond the Standard Model.

The discovery of the *neutrino* (ν) *oscillations* phenomenon has completed a remarkable scientific endeavor lasting several decades changing forever our understanding of the leptonic sector's phenomenology of the *standard model of elementary particles* (SM). The new phenomenon was taken into account by introducing massive neutrinos and consequently neutrino flavour mixing and the possibility of violation of charge conjugation parity symmetry or CP-violation (CPV); e.g., review[1].

Neutrino oscillations imply that the neutrino mass eigenstates (ν_1, ν_2, ν_3) spectrum is non-degenerate, so at least two neutrinos are massive. Each mass eigenstate (ν_i; with $i = 1, 2, 3$) can be regarded as a non-trivial mixture of the known neutrino flavour eigenstates (ν_e, ν_μ, ν_τ), linked to the three (e, μ, τ) respective charged leptons. Since no significant experimental evidence beyond three families exists so far, the mixing is characterised by the 3×3 so called *Pontecorvo-Maki-Nakagawa-Sakata* (PMNS)[2,3] matrix, assumed to be unitary, thus parameterised by three independent mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$) and one CP phase ($\delta_{CP}$). The neutrino mass spectra are indirectly known via the two measured *mass squared differences*, indicated as $\delta m^2_{21} (\equiv m^2_2 - m^2_1)$ and Δm^2_{32} ($\equiv m^2_3 - m^2_2$),

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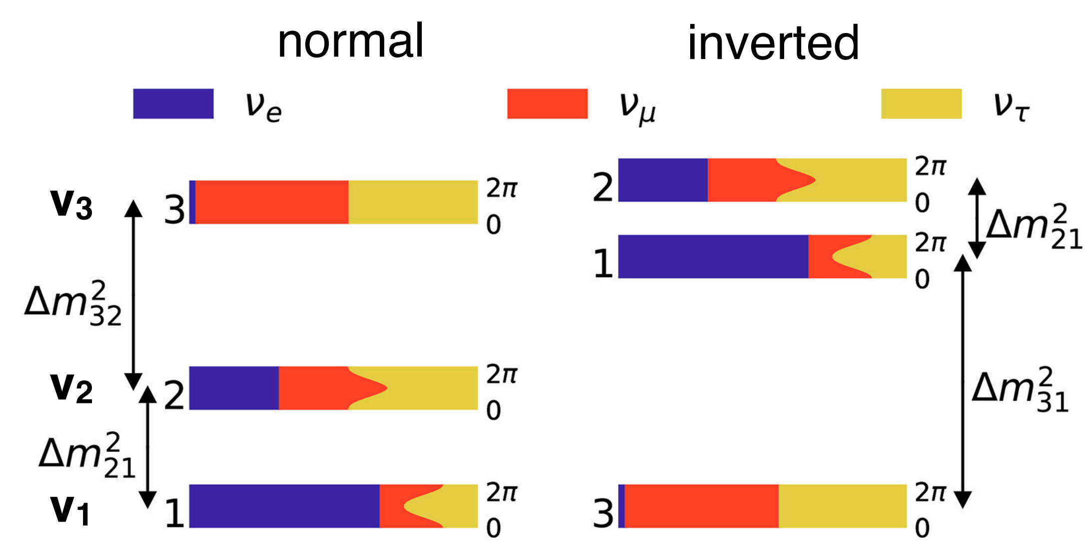
Scientific Reports | (2022) 12:5393 | https://doi.org/10.1038/s41598-022-09111-1 nature portfolio 1

Using the current best fitted neutrino mixing parameters, we have updated the effect of strong synergy between reactor (JUNO) and accelerator (T2K, NOvA, HK and DUNE) experiments for the determination of the neutrino mass ordering



Δm^2_{31}(or Δm^2_{32}) > 0 — Salas et al, FASS 5, 36(2018) — Δm^2_{31}(or Δm^2_{32}) < 0

The key idea: We can know the mass ordering if we know if

$$|\Delta m^2_{31}| > |\Delta m^2_{32}|$$ **normal**

or

$$|\Delta m^2_{31}| < |\Delta m^2_{32}|$$ **inverted**

need to be measured very precisely!

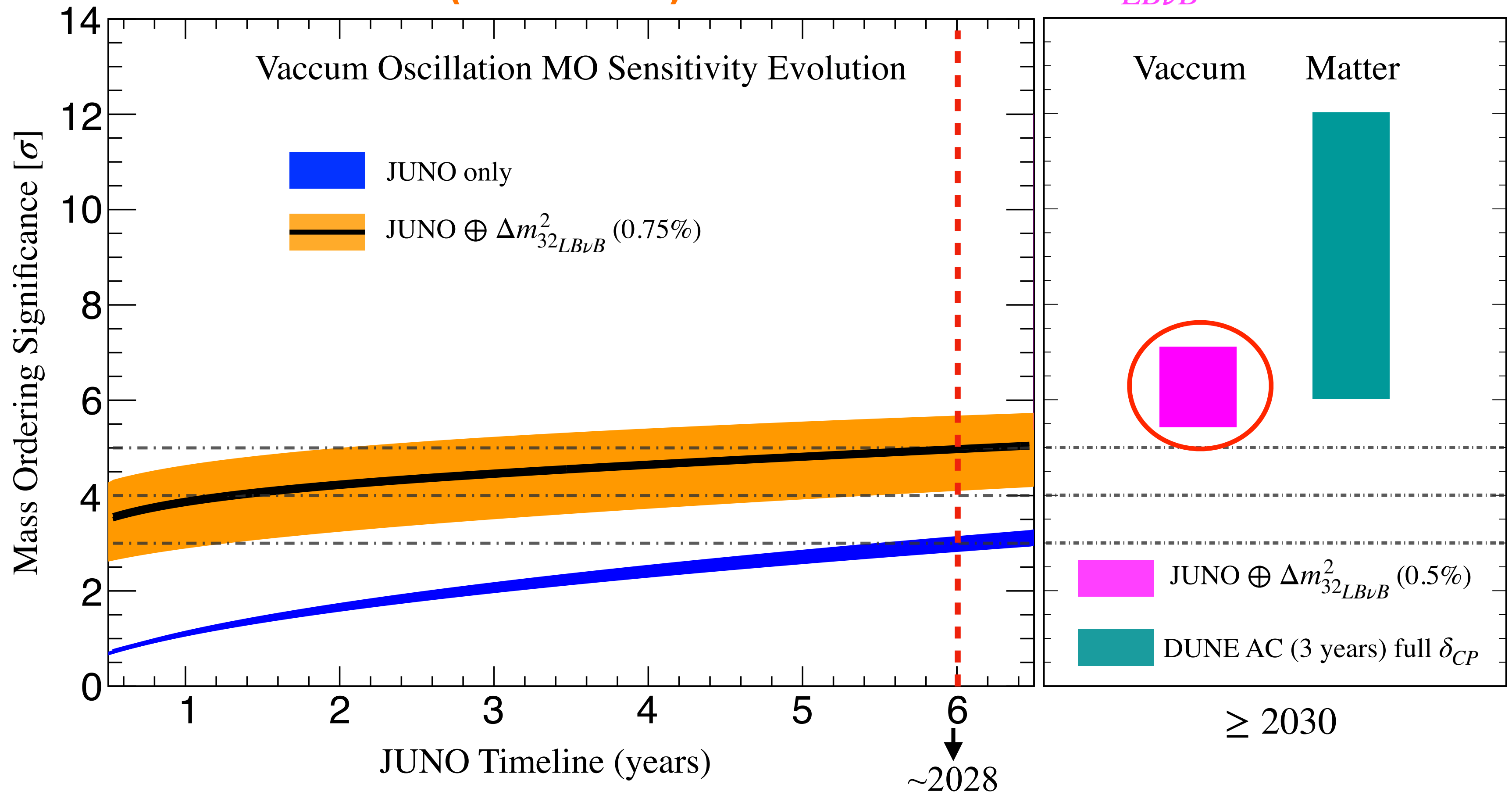
Nunokawa et al, PRD 72, 013009 (2005)

Strong synergy/complementarity between JUNO and HK/DUNE

By comparing $|\Delta m^2_{32}|$ measured by reactor and accelerator experiments, we can determine the neutrino mass ordering (because for the wrong ordering they do not agree with each other) - vacuum oscillation

Boosted JUNO with $\Delta m^2_{32_{LB\nu B}}$ (0.75%) (T2K&NOvA)

Boosted JUNO with $\Delta m^2_{32_{LB\nu B}}$ (0.5%) (HK/DUNE)



DUNE 3 years MO sensitivity [5]

DUNE NMO is shown. DUNE IMO is roughly ~2σ worse.

JUNO alone ~3σ to JUNO+HK/DUNE (osc. in vacuum) with more than 5σ

If the 2 results (vacuum vs matter) do not agree ⟶ New Physics

A. Cabrera et al, Scientific Reports 12, 5393 (2022), arXiv: 2008.11280 [hep-ph]

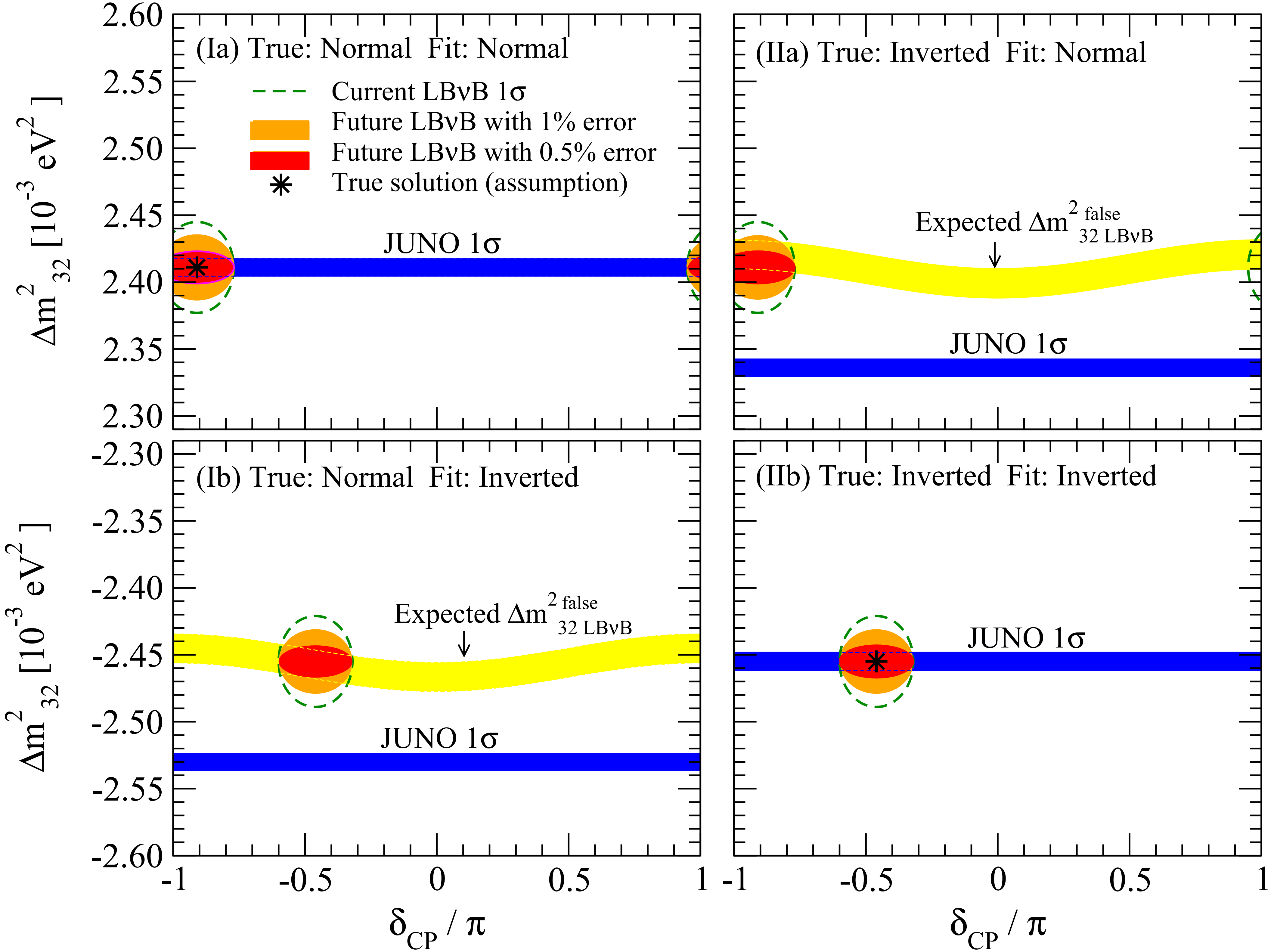
Concluding Remarks

We believe that the Hyper-K project has strong and good scientific motivations and expect to make some important contributions to the physics community

Interactions/collaborations between theorists and experimentalists can benefit both sides

It is interesting to consider and explore complementarity/synergy between Hyper-K and different experiments such as JUNO, DUNE, IceCube, etc, to strengthen the significance of expected results and also maximize the opportunity which can lead to some new discovery of new physics beyond SM!

Backup



A. Cabrera et al, Scientific Reports 12, 5393 (2022), arXiv: 2008.11280 [hep-ph]

Hyper-K related publications

K. Abe et al. Physics potential of a long-baseline neutrino oscillation experiment using a J-PARC neutrino beam and Hyper-Kamiokande, PTEP2015, 053C02 (2015) [arXiv:1502.05199 [hep-ex]].

K. Abe et al. Physics potentials with the second Hyper-Kamiokande detector in Korea, PTEP2018, no.6, 063C01 (2018) [arXiv:1611.06118 [hep-ex]].

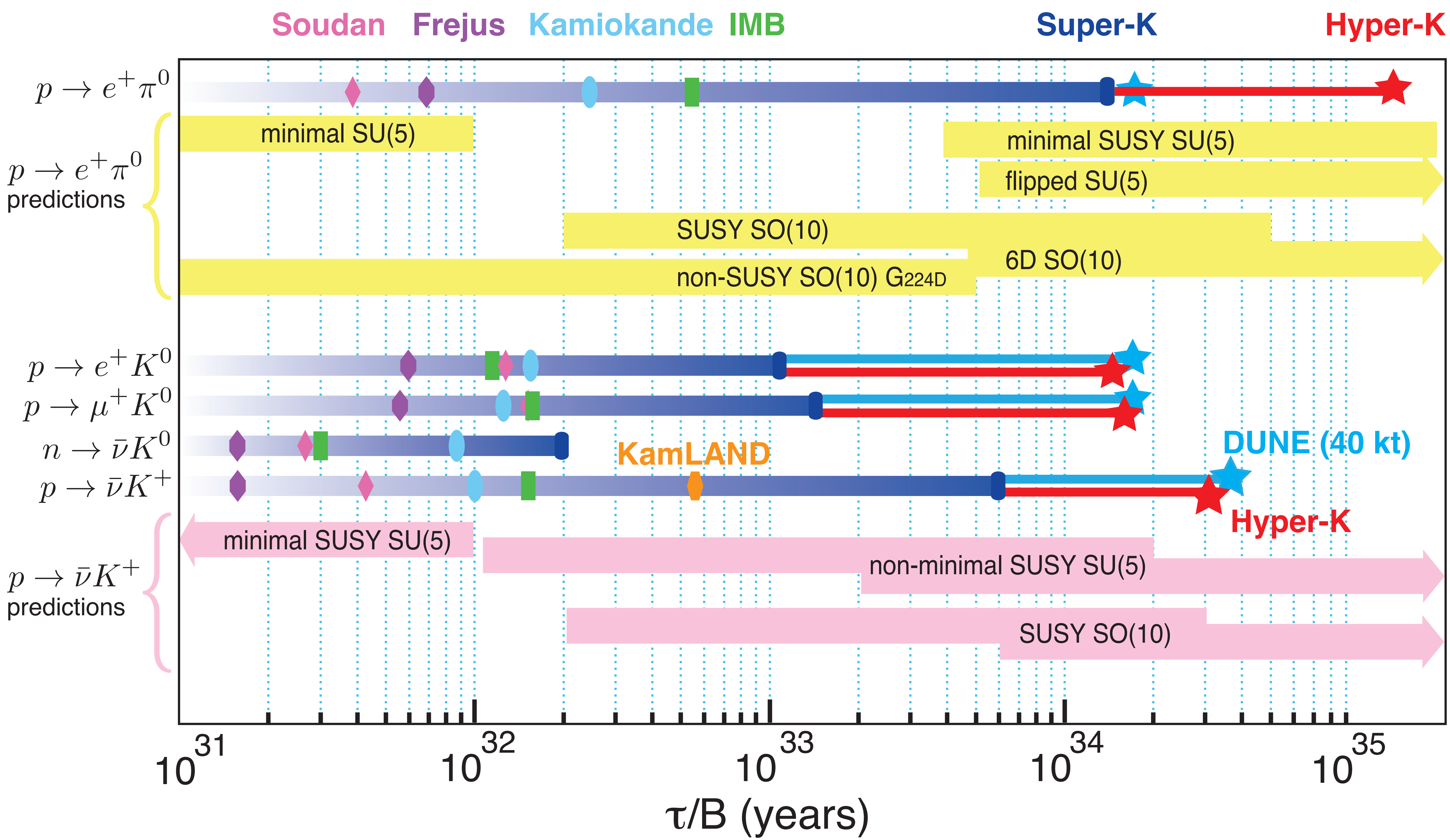
K. Abe et al. Supernova Model Discrimination with Hyper-Kamiokande Astrophys. J. 916, 15 (2021) [arXiv:2101.05269 [astro-ph.IM]].

K. Abe et al. Hyper-K Design Report, arXiv:1805.04163v2

Main Objectives of Hyper-Kamiokande

Search for Nucleon Decay

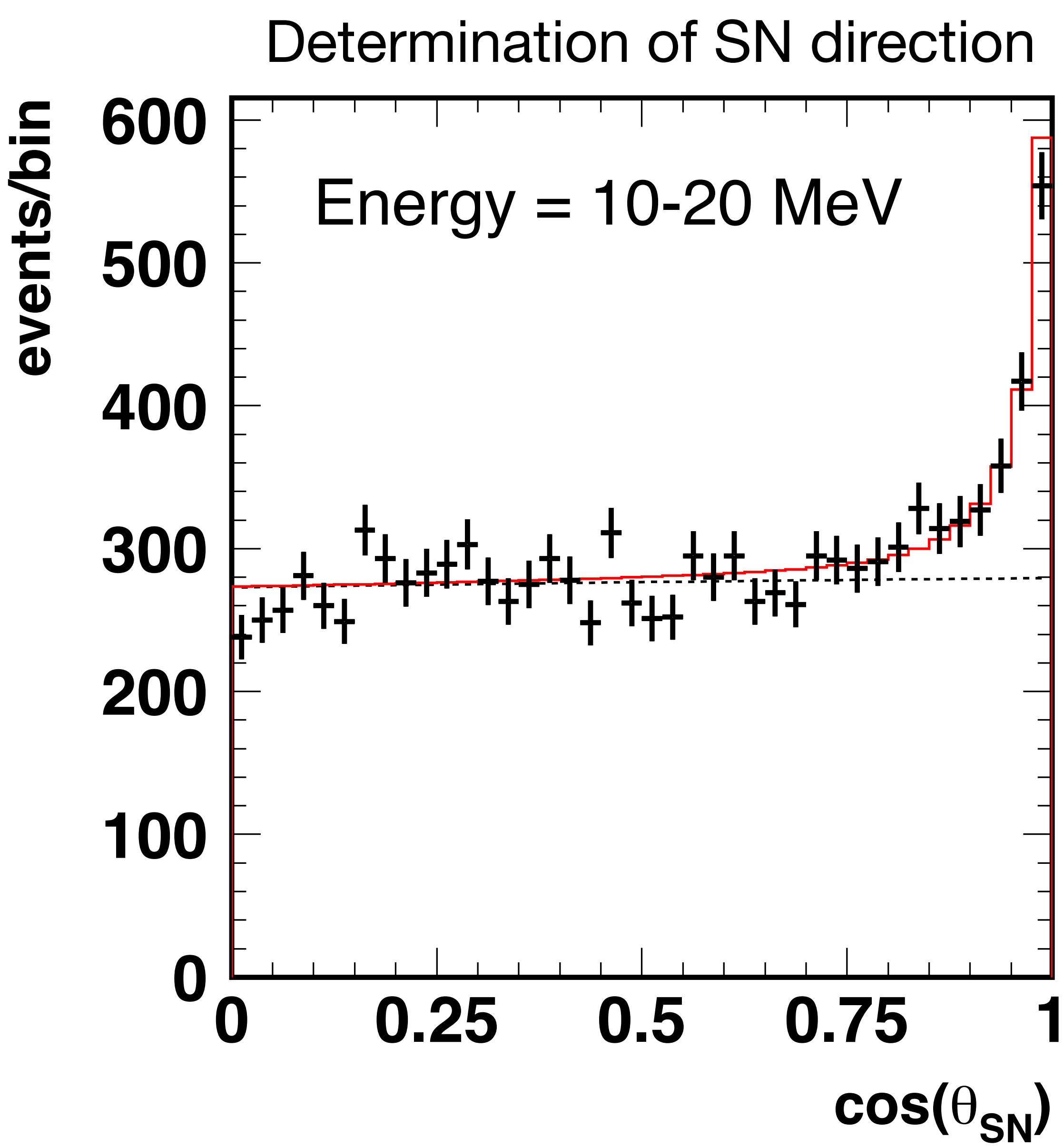
Comparison with the current limits

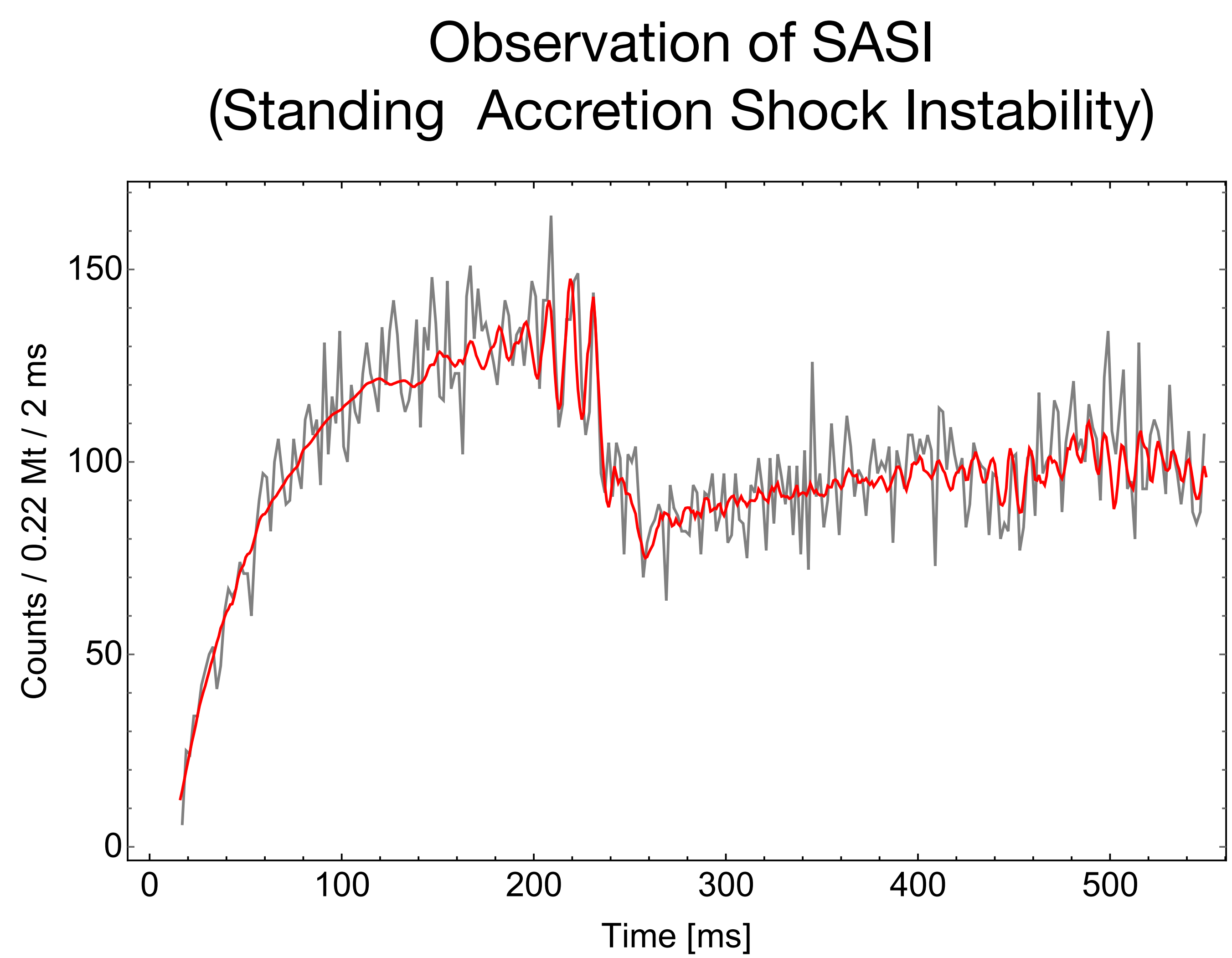


Main Objectives of Hyper-Kamiokande

Programs for Neutrino Astrophysics

Observation of Neutrinos coming a galactic supernova





Hyper-K Design Report, arXiv:1805.04163v2 [hep-ex]

Hyper-K Detector Construction has Started

PMTs for the Inner Detector		
	Super-K	Hyper-K
Number of PMTs	11,129 50cm PMTs	20,000 50cm PMTs (JPN) (+ additional PDs (Oversea))
Photo-sensitive Coverage	40 %	20 %
Single photon efficiency /PMT	~12%	~24%
Dark Rate /PMT	~4 kHz (Typical)	4 kHz (Average)
Timing resolution of 1 photon	~3 nsec	~1.5 nsec

2020/12 First six PMTs delivered to Kamioka

- Production has started on time for the 50cm PMTs with Box&Line dynode.
- 300 PMTs by March, 20,000 PMTs in total by 2026 according to the Japanese budget profile.

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Presente by Francesca Di Lodovico (HK co-spokes person) @
First Pan-African Astro-Particle and Colider Physics Workshop, 21 March 2022