Hyper-Kamiokande

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Sep. 17, 2025 @ EU Workshop on Water Cherenkov Experiments for Precision Physics

HYPER-K SUMMARY

The presentation "Hyper-K Instrumentation Highlights" by Y. Itow, along with various related activities discussed during this meeting.

1. PHYSICS;

Enhanced Physics Sensitivity Enabled by Advanced Ring-Imaging Water Cherenkov Technology:

1. The priority is to determine the leptonic *CP* phase δ_{CP} with a precision of less than 20 degrees using the J-PARC neutrino beam,
2. to extend nucleon decay search reach to a nucleon lifetime of 10^{35} years,
3. and to advance neutrino astrophysics, and more.

2. ORGANIZATION;

International Collaboration in which Europe represents the majority of participants and makes essential contributions.

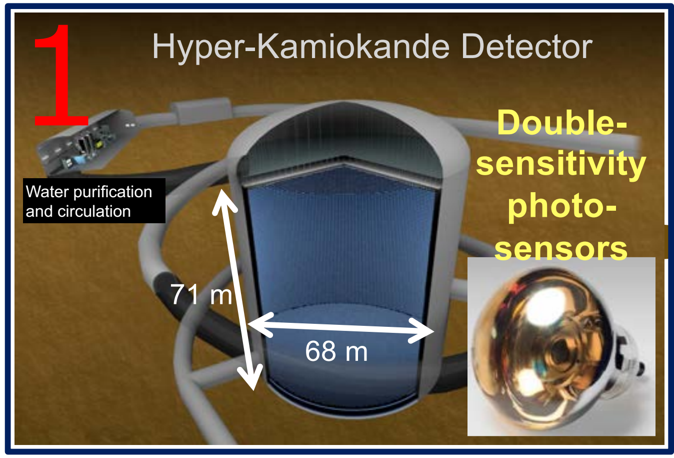
3. MILESTONES;

1. It marks major milestone: Cavern Excavation Completion in July 2025.
2. To begin full operation in 2028.

Hyper-K

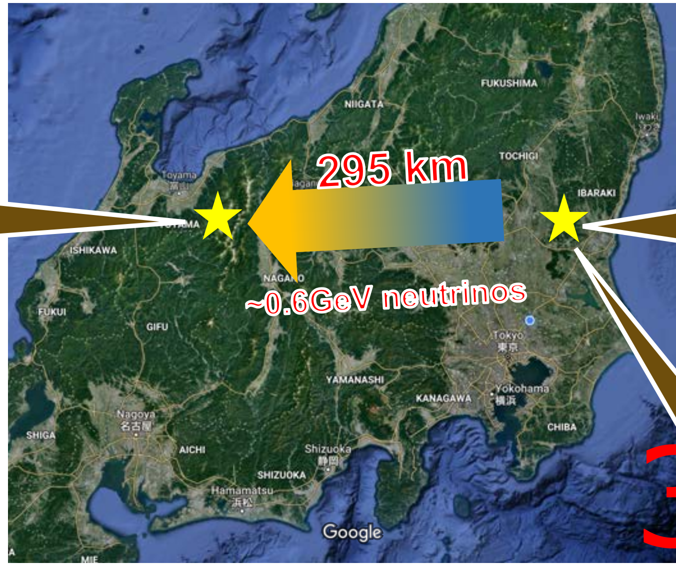
PROJECT IN A NUTSHELL:

Project started in 2020, Operation start in 2028



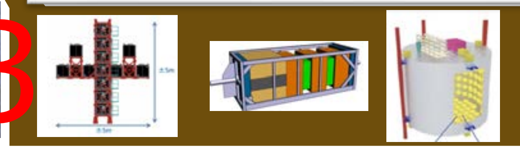
UTokyo Hyper-Kamiokande detector (hosted by the Univ. of Tokyo)

Optically separate Inner Detector and Outer Detector



KEK High power proton beams

J-PARC (hosted by KEK)



INGRID ND280 IWCD: New intermediate water cherenkov detector

1. World-largest detector for Nucleon-decay and Neutrino experiment

to be built with **8.4 times** **larger fiducial mass (190 kiloton)** than Super-K and to be instrumented with **double-sensitivity photo-sensors**

2. World most-intense neutrino beam

J-PARC neutrino beam to be **upgraded by** **a factor 2.5** **from 0.5 (as of 2019) to 1.3 Mega Watt**

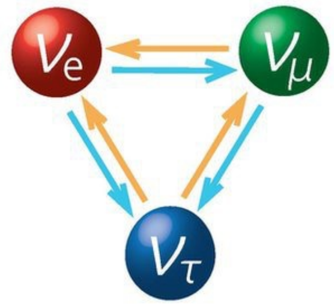
3. New and upgraded near detectors to control systematic errors

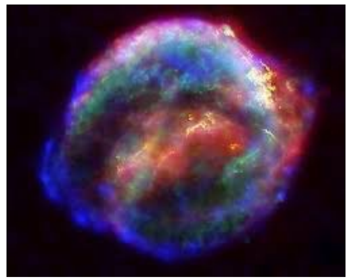
World-leading neutrino physics and astrophysics, and nucleon decay searches

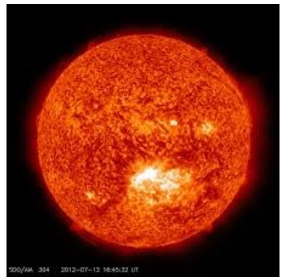
1. PHYSICS

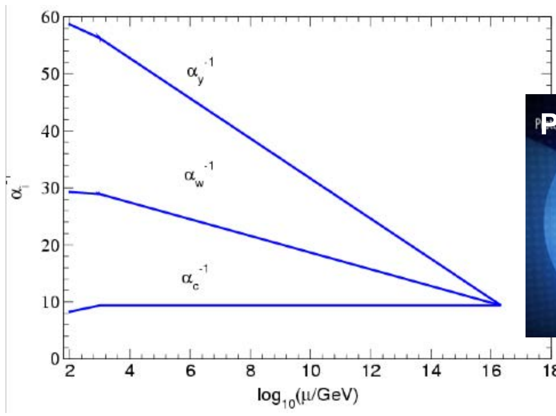
Goals of Hyper-K Physics

1. Explore full picture of neutrino oscillation including δ_{CP} and Mass hierarchy
2. Neutrino astronomy and astrophysics
3. Nucleon Decay Searches







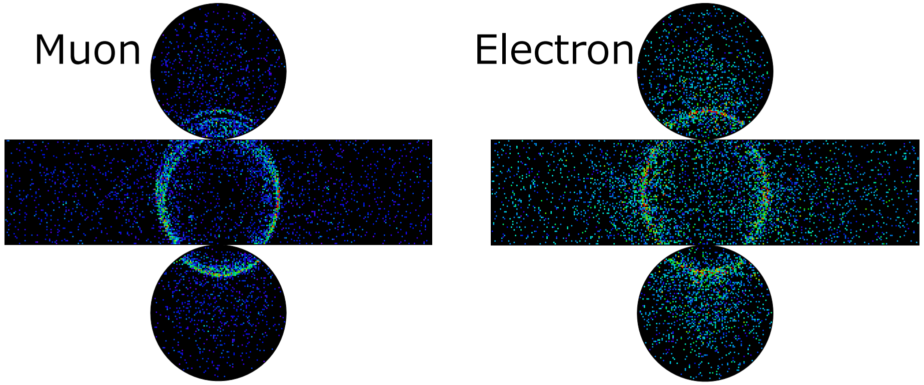


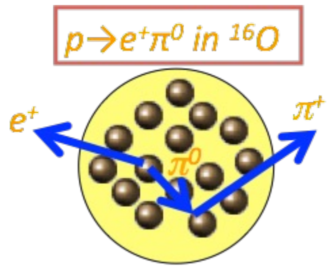
Hyper-K

The water Cherenkov detector technology that underpins Hyper-Kamiokande

- High Mass:
  - Statistics is always essential for neutrino experiments.
  - Only proposal to reach 10^{35} years of partial lifetime of protons.
- High Precision:
  - Particle identification (>99% efficiency for 1GeV μ/e separation)
  - ~3% energy resolution @ 1GeV
  - Pointing capability for neutrinos from Sun and SN
  - Neutron tagging capability, potentially enhance by Gd loading will enhance
- Unbound Protons:
  - would provide compelling evidence of proton decay.

	material	Fiducial Mass (kton)
Super-K	Water	22
Hyper-K	Water	190
Dune	Argon	40
JUNO	Liq. Scinti	20

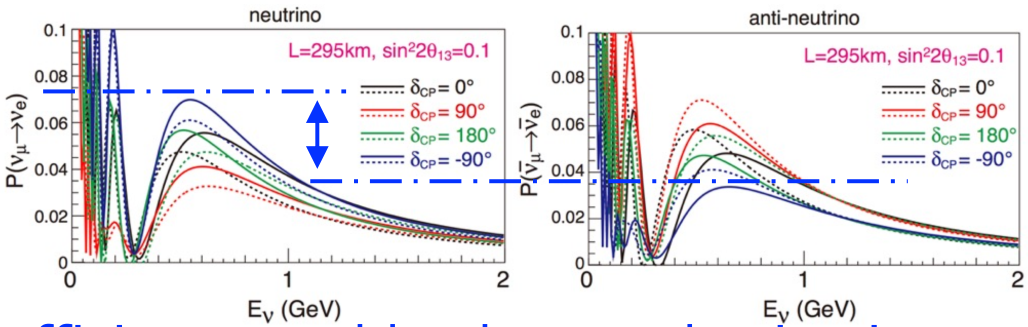




- No Fermi motion
- No π's re-scattering

J-PARC ν_μ and $\bar{\nu}_\mu$ beam, and Hyper-K

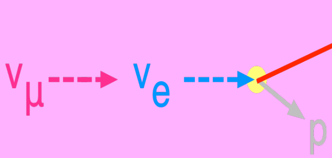
1. Intense beam (1.3 MW x 6 months/yr x 10 yrs) x High detector mass (190 kiloton)
2. Pure ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at the Hyper-K location, 295km away).
   - Measure *CP* asymmetry in neutrino by comparison of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



3. Clean signal selection by high signal efficiency and background rejection

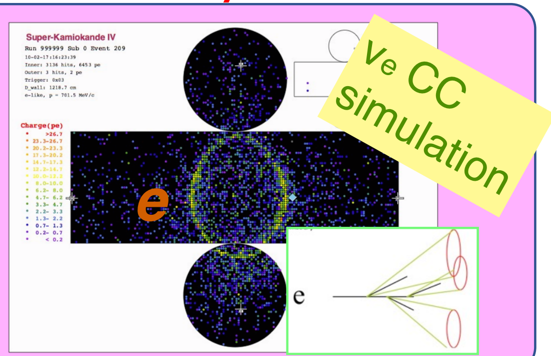
ν_e appearance signal = single e event

keeping 60% ν_e signal efficiency



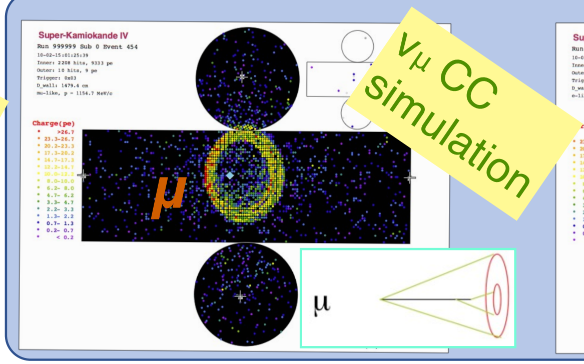
CCQE : ν_e + n → **e** + p

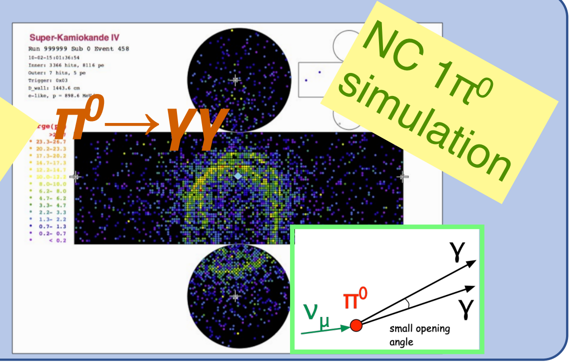
(dominant process at J-PARC beam energy)



Background events

>99.9% ν_μCC, 99% NC π^0 rejection



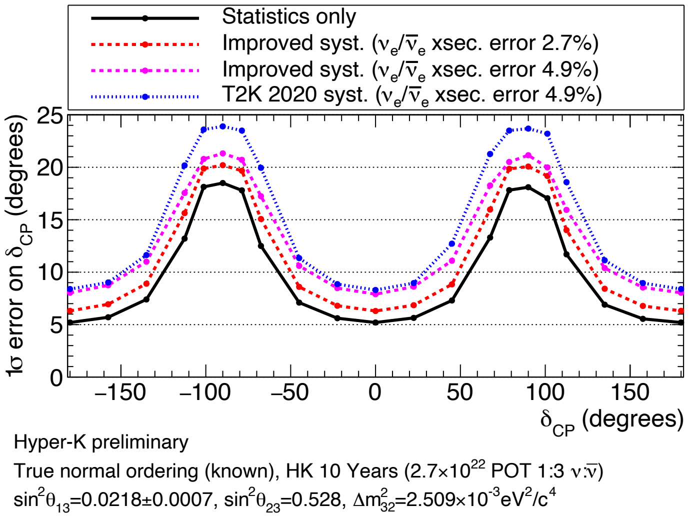


Hyper-K

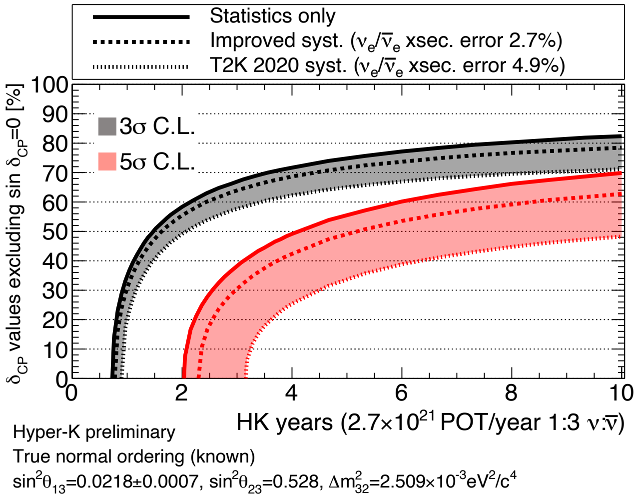
DETERMINATION OF LEPTONIC *CP* PHASE

1.3 MW x 6 months/yr x 10 yrs x 190 kiloton

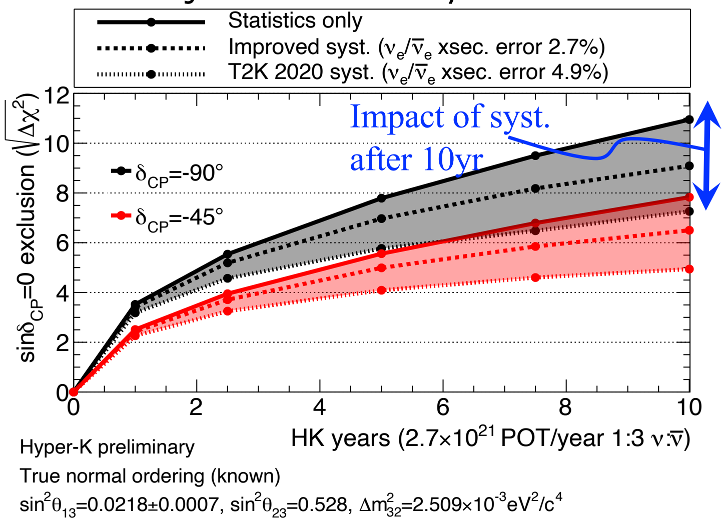
Precision of δ_{CP} measurement



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



Projected sensitivity to CPV

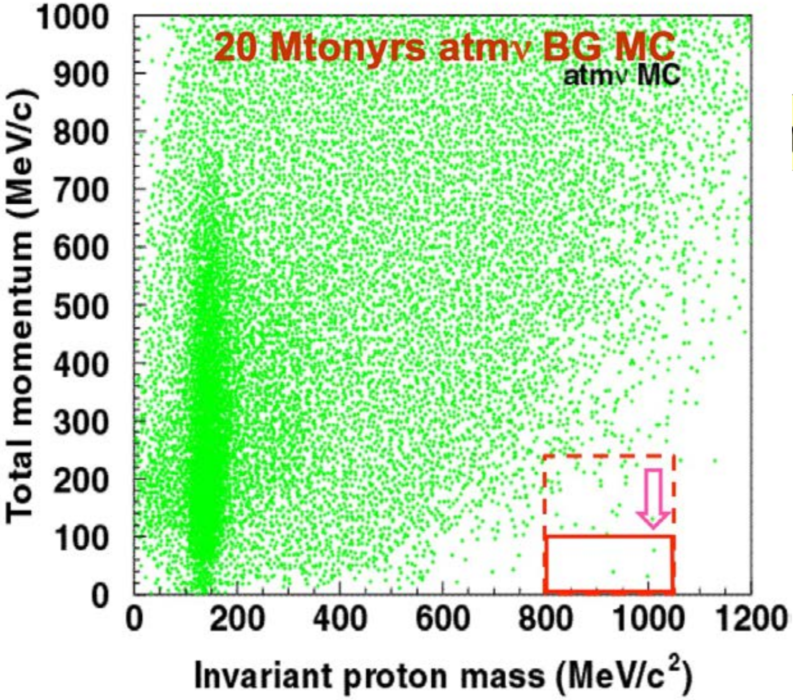


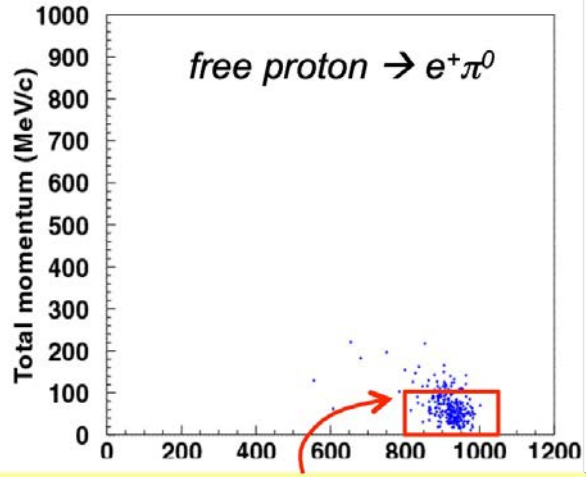
- Precision measurement of δ_{CP}
  - $\sim 20°$ for $\delta_{cp} = -90°$ / $\sim 7°$ for $\delta_{cp} = 0°$
- *CP* violation can be established with a statistical significance of $3\sigma(5\sigma)$ for 78%(63%) of the δ_{cp} parameter space.
- Reduction of systematic uncertainty has sizable impact
  - Upgrade of ND280 + 1kton scale water Cherenkov (IWCD) to maximize the sensitivity

Unbound proton decay into $e^{+}+\pi^{0}$

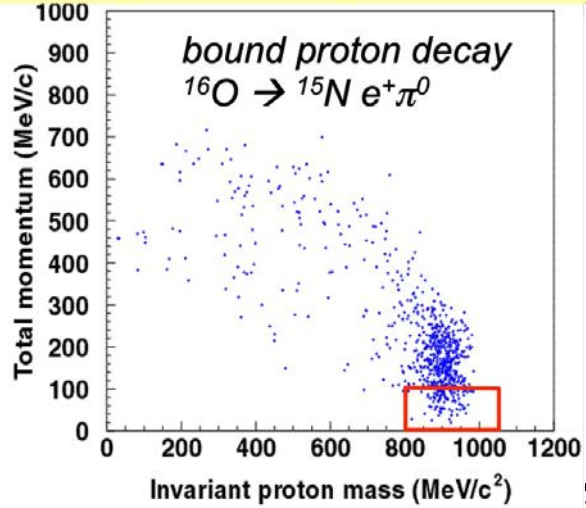
- Selection criteria includes below to largely reject ν's background events
  - Total momentum p_{tot} < 250 MeV
  - and Invariant proton mass M_{tot} ~ 938 MeV
- Tighter cut p_{tot} < 100 MeV further reduce background by one order of magnitude while keeping a half of signal thanks to unbound protons.

	p_{tot}<100MeV/c		100<p_{tot}<250MeV/c	
	Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
HK	18.7	0.06	19.4	0.62





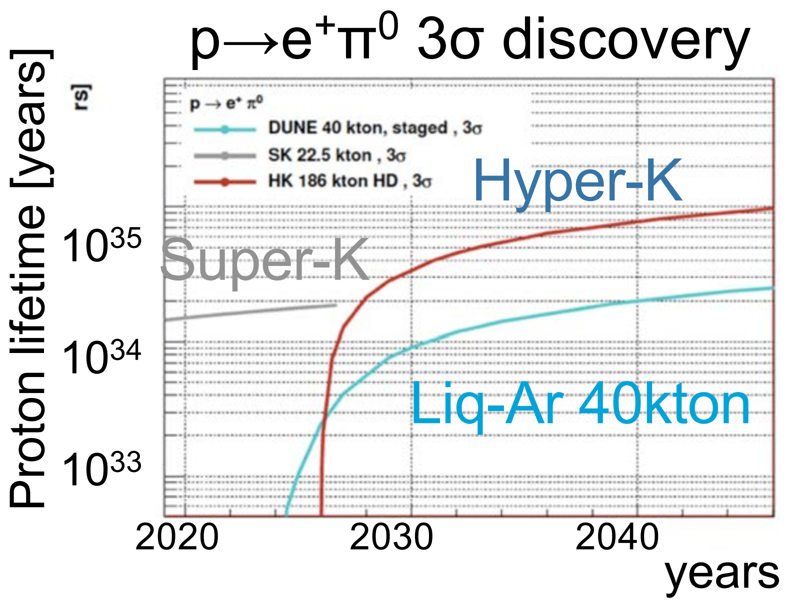
ain target is *free proton decays*

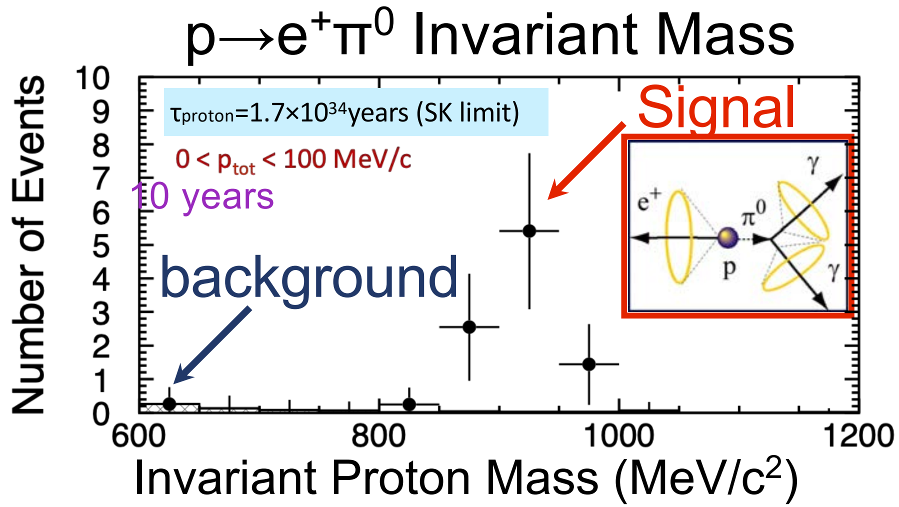


Hyper-K

$p \rightarrow e^{+}\pi^{0}$ discovery in Hyper-K

- Reach to 10^{35} yrs for $p \rightarrow e^{+}\pi^{0}$
- BG free search possible: 0.06 BG/Mton・year
- 3 ×10^{34} years for $p \rightarrow \nu K^{+}$





2. ORGANIZATION

Hyper-K

ハイパーカミオカンデ国際共同研究グループ結成記念シンポジウム
Inaugural Symposium of the Hyper-Kamiokande Proto-collaboration
平成27年1月31日（土）柏の葉カンファレンスセンター　主催 ハイパーカミオカンデ国際共同研究グループ

EB Members

Members: Di Lodovico (SP, chair), Shiozawa (SP), Moriyama (Tokyo PM), Kobayashi (KEK PM), Yokoyama (FD WGL), Radicioni (IB), Itow (LTC), Ishitsuka & Nakaya (Japanese at-large members, Nakaya also SRB chair), Konaka & Drapier & Rondio (non-Japanese at-large members).

Thanks to Labarga for his previous work in the committee!

By-weekly meetings

ORGANIZATION: HYPER-K COLLABORATION

630 collaborators from 22 countries: Armenia, Australia, Brazil, Canada, Czech Republic, France, Germany, India, Italy, Japan, Korea, Mexico, Morocco, Poland, (Russia*), Spain, Sweden, Switzerland, UK, Ukraine, and the United States.

Collaborating Institutes

Oct 21-26, 2024 Collaboration Meeting at Toyama

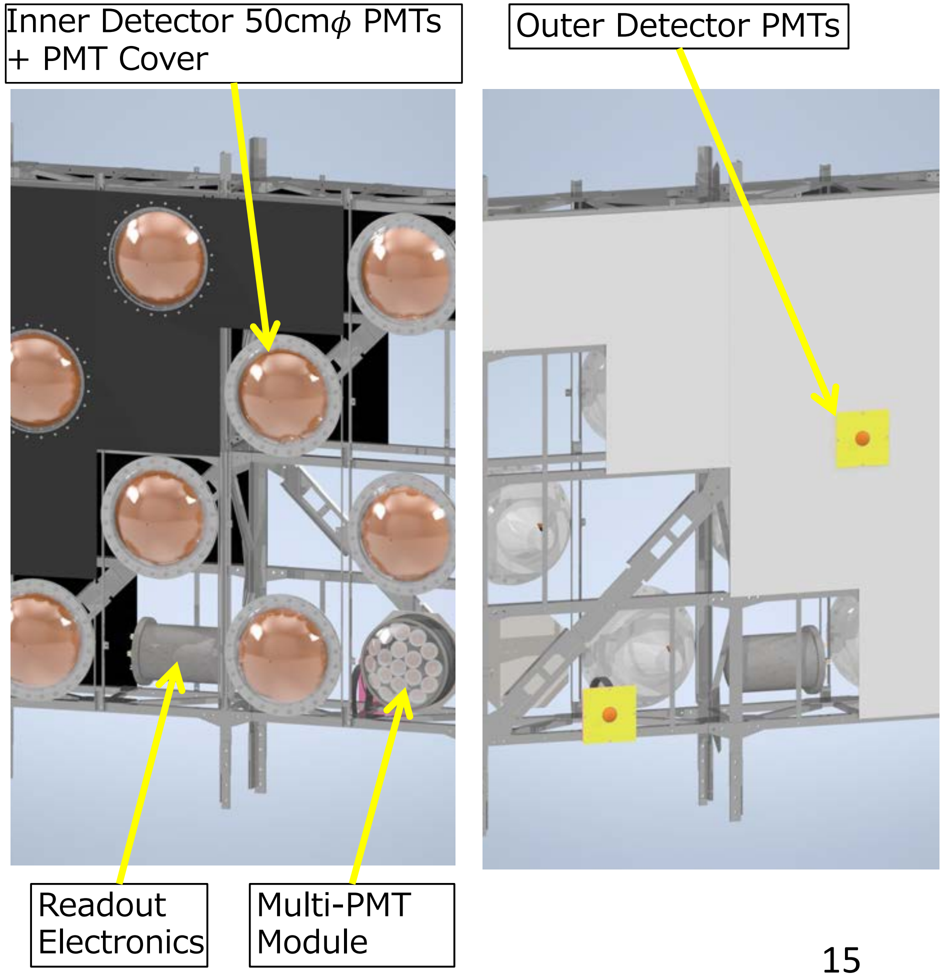
<u>Hyper Kamiokande Collaboration</u> will build, commission, operate, maintain, and analyse and publish the data.

The experiments then include the ND280 detector complex, and the other components of the WC detectors including the photo-detection system (e.g. photodetectors, covers, electronics), water systems, calibration systems, DAQ, and other software, and offsite computing and storage.

UNDER WATER COMPONENTS

PRODUCTION, INSTALLATION, AND OPERATION BY COLLABORATING COUNTRIES

Component	Responsible Countries
50cmϕ PMTs	Japan
PMT Covers	Spain
Multi-PMT Modules	Italy, Canada, Poland, Czech Republic, Mexico
Outer Detector PMTs and Tyvek	UK, South Korea, Australia
Readout Electronics	Japan, France, Italy, South Korea, Poland, Spain, Switzerland, UK
Linac and Calibration	Poland, UK, Japan, Spain, and more



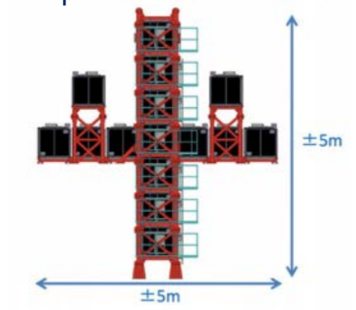
Hyper-K

NEAR/INTERMEDIATE DETECTORS

- Critical components to precisely understand J-PARC beam and neutrino interactions.

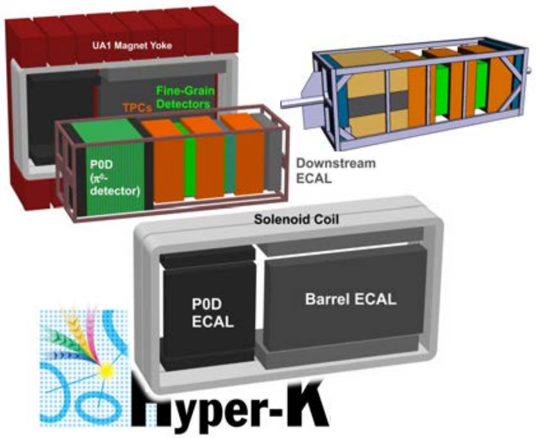
On-axis Detector

(INGRID →plans to be taken over by HK)



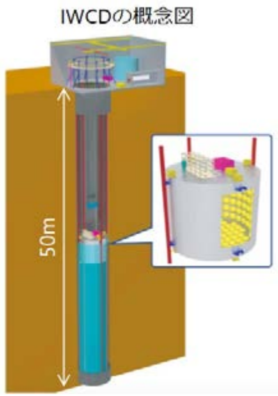
Off-axis Magnetized Tracker

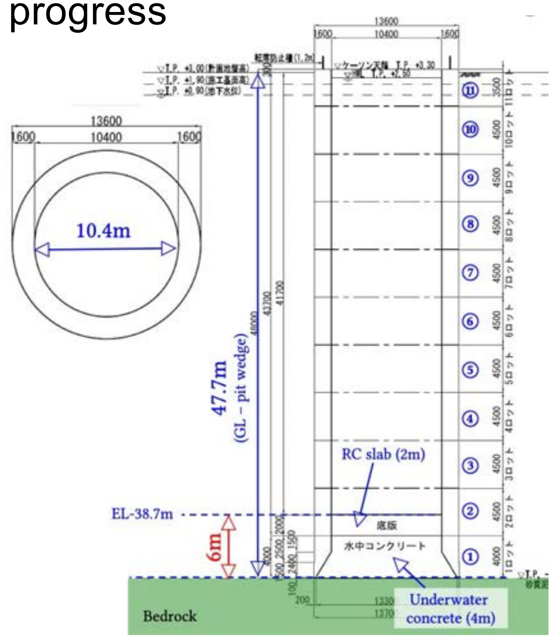
(ND280→ND280 Upgrade for T2K
→plans to be taken over by HK)

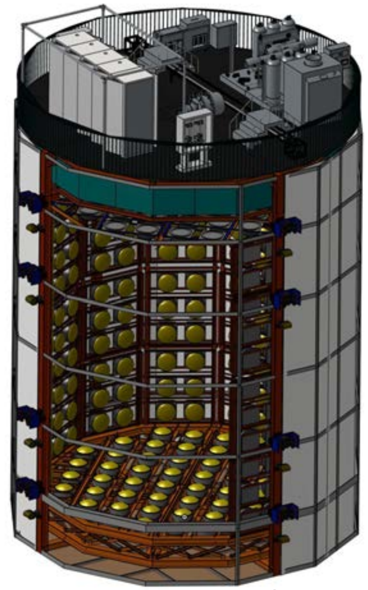


Off-axis spanning intermediate water Cherenkov detector (IWCD)

- Essential for CP asymmetry measurement by providing interaction probability of ν_e, ν_μ, $\overline{\nu_e}$, and $\overline{\nu_\mu}$ on H_2O
- New land has been officially secured, Facility construction is going on now.
- Detector design in progress



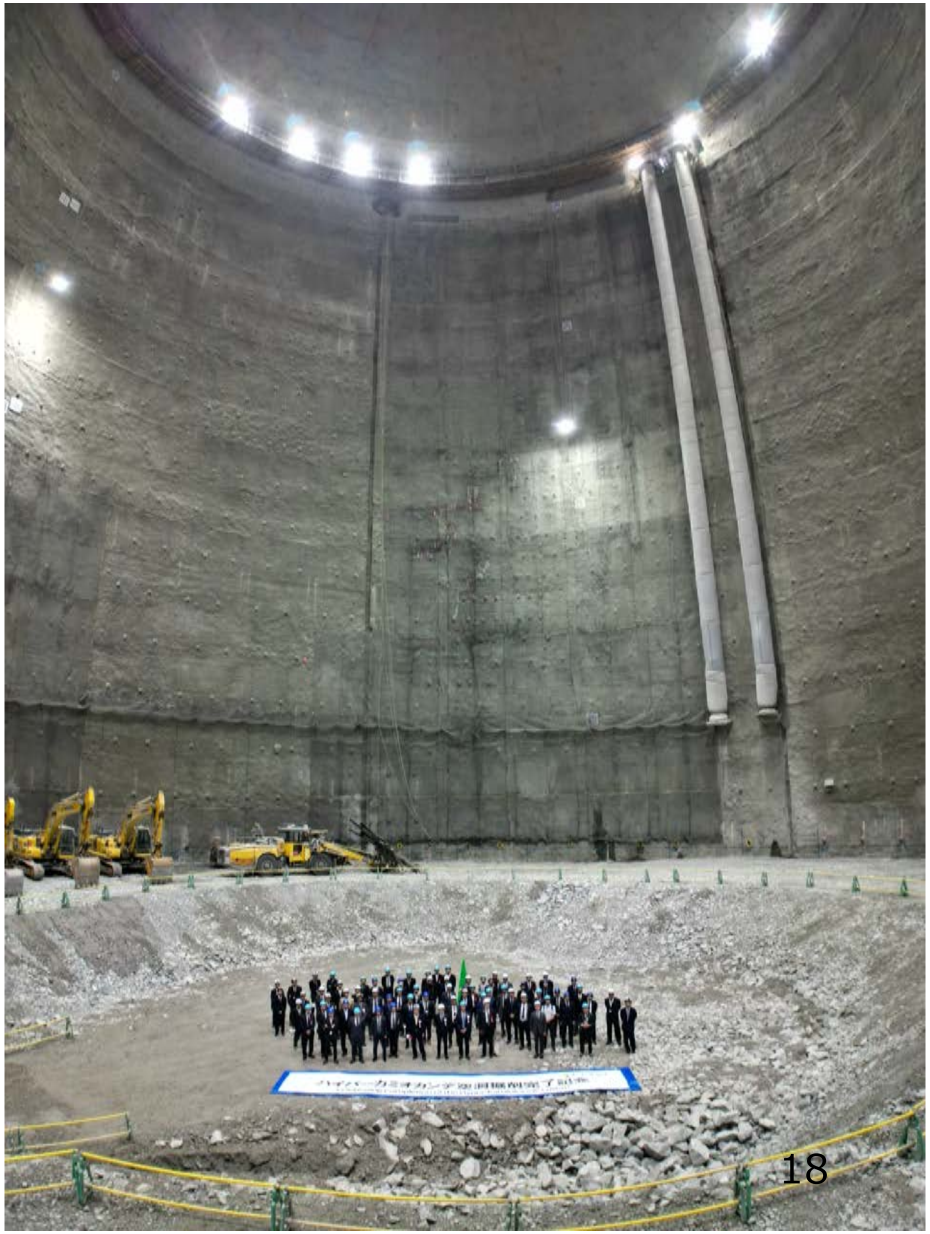




3. MILESTONES

2025.7 Completion of the detector cavern

- It marks a major milestone.

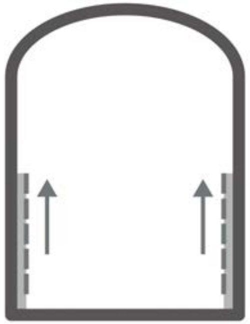


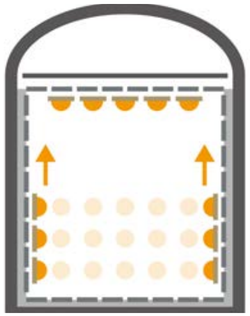
The next phase of construction has already begun

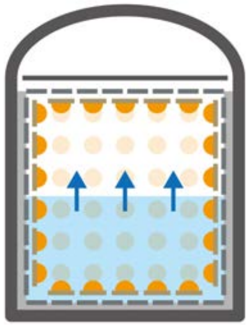
Hyper-K

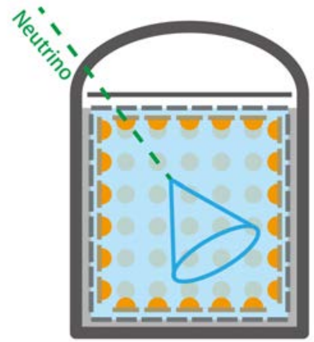
PROJECT SCHEDULE

- 2025:
  Tank Liner Construction,
  Water system Construction,
  Production of detector components
  (in participating countries)
- 2026/8~2027/11:
  Detector Construction incl. Installation of PMTs,Electronics,others
  (all collaborators will join the detector construction (shift work))
- 2027/11~ Filling detector water and Detector commissioning
- 2028/6~ Full-scale Operation









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3. MILESTONES;

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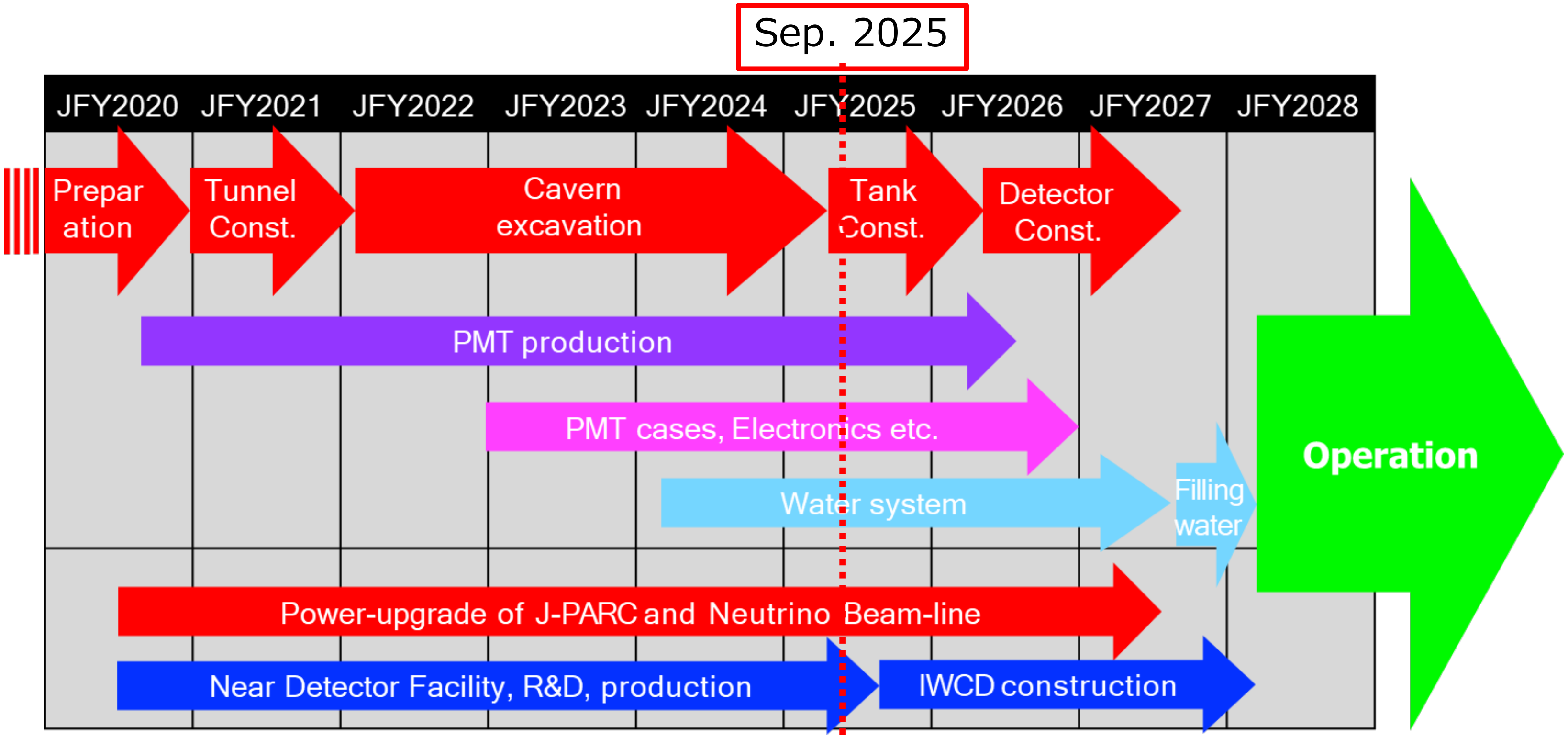
Hyper-K

SUPPLEMENTS

Hyper-K

OVERALL SCHEDULE



Hyper-K

2020

2020.1 Before construction of the entrance yard

2021

2021.4 Construction of the entrance yard

2021.5 The access tunnel excavation starts.

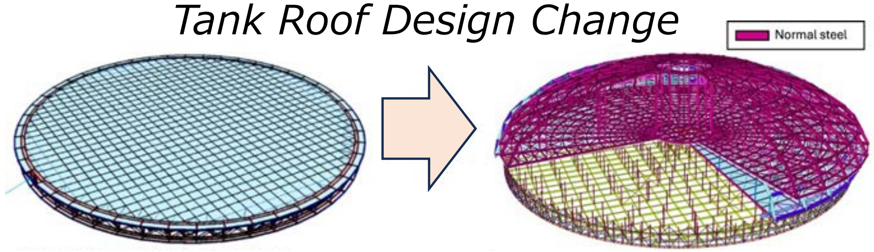
Hyper-K

ONE YEAR EXTENSION

Data taking is scheduled to begin in 2028 as its construction schedule has been extended due to two major reasons below:

- **Cavern Excavation :**
  - Safety measures, including additional support, are expected to extend the cavern excavation by 6 months.
- **Tank Design Change :**
  - Mainly due to changes in the roof design, the construction period is expected to be further extended by 5 months.

Tank Roof Design Change



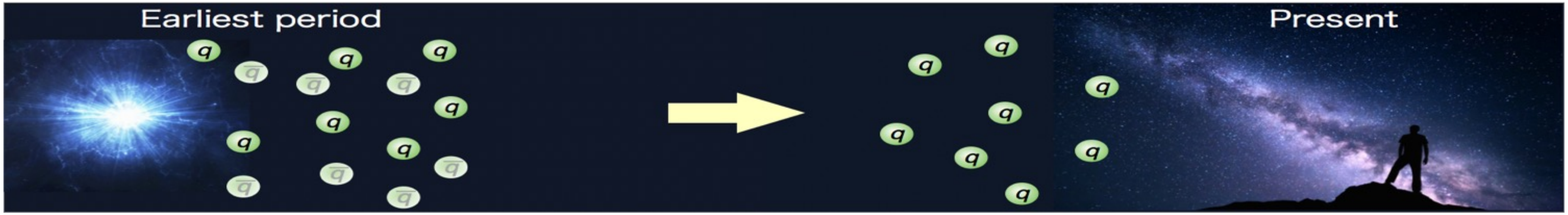
(Original design in Left) The roof plate and the PMT support structure below it are all made of stainless steel.
(New design in Right) The dome-shaped structure (in purple) is made of relatively inexpensive iron. The roof plate and the PMT support structure below it (stainless steel) are simplified.

Hyper-K

SCIENTIFIC GOALS

- By sending neutrino and anti-neutrino beams from J-PARC to Hyper-Kamiokande, the difference, if any, between the oscillation nature of those two (*CP* violation) can be measured.
- Prove the grand unification of three forces by discovering the proton decays.
- Precision measurements of neutrino oscillation phenomena through the observation of solar and atmospheric neutrinos.
- Reveal the mechanism of the supernova explosion by observing large number of neutrinos emitted from them.
- Reveal the history of supernova explosions by observing remnant of neutrinos from supernova explosions that occurred during the history of the evolution of the Universe.
- Others

WHY ANTI-MATTER DISAPPEARED IN THE HISTORY OF UNIVERSE?



- Key may be *CP* asymmetry of neutrinos (*CP* asymmetry in quark sector is not enough large).
- Leptogenesis scenario only with ν's Dirac *CP* phase δ_{CP} requires

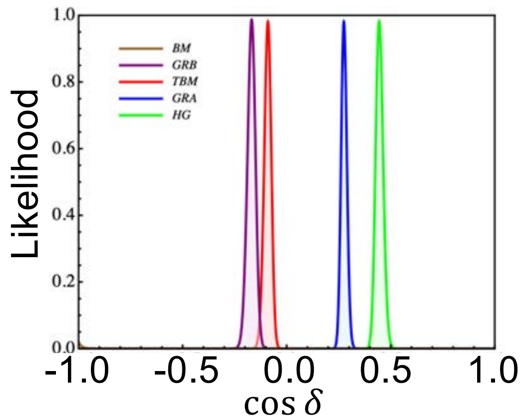
$$\left|\sin\delta_{CP}\right| > \sim 0.6$$

S. Pascoli et al., PRD 75, 083511 (2007)
PDG review 2014

- Flavor symmetry prediction on δ_{CP}

  e.g. Petcov 1504.02402v1 (right plot)

- Priority is to experimentally determine δ_{CP}.

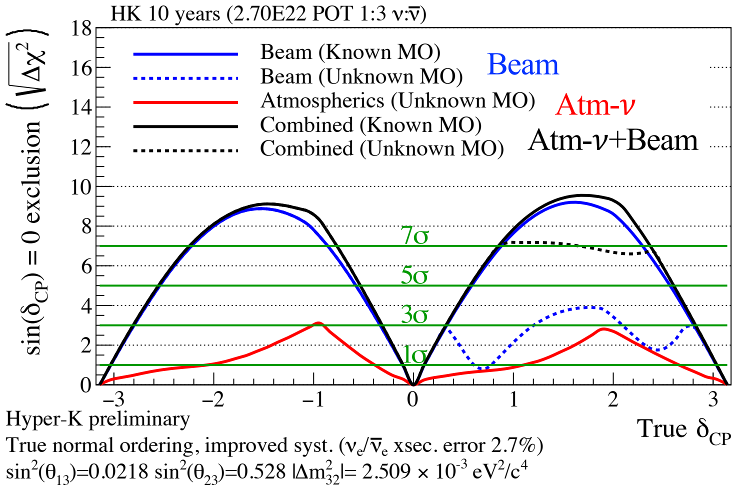


Strategy of oscillation measurement at Hyper-Kamiokande

Combination of long-baseline and atmospheric neutrino observations
⇒ Resolve parameters degeneracy

	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ
θ_{23} octant	0.45	2.2 σ	→ 6.2 σ
	0.55	1.6 σ	→ 3.6 σ

10 years with 1.3MW, normal mass ordering is assumed

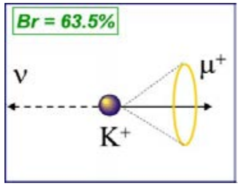


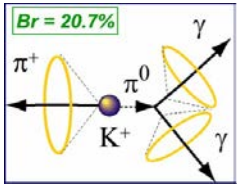
Atmospheric neutrino: sensitive to mass ordering by Earth's matter effects
→ Constraints on mass ordering enhance sensitivity to CP violation by long-baseline

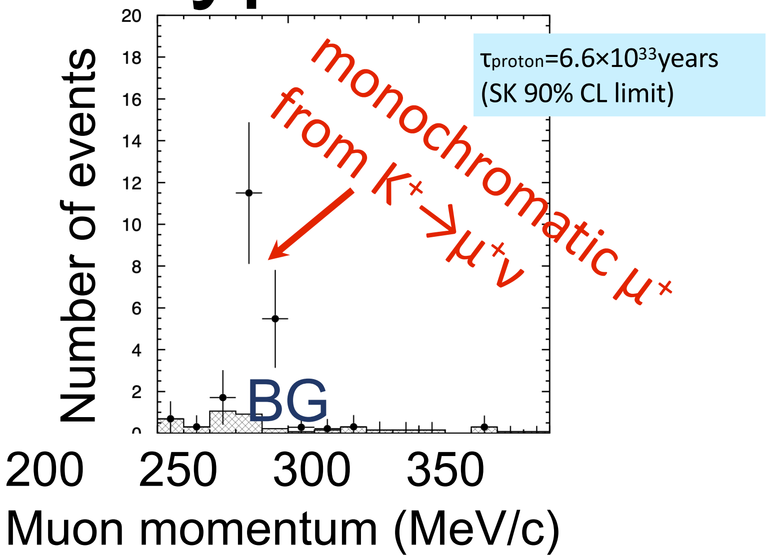
p→νK⁺ discovery in Hyper-K

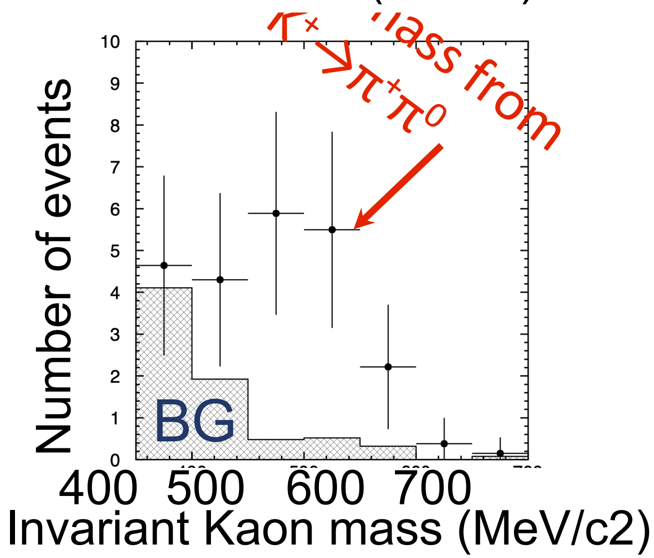
arXiv:1805.04163

- K+ is invisible so signal signature are:
  - 236 MeV/c muon
  - $\pi^+\pi^0$
- Discovery reach to 3×10^{34} years







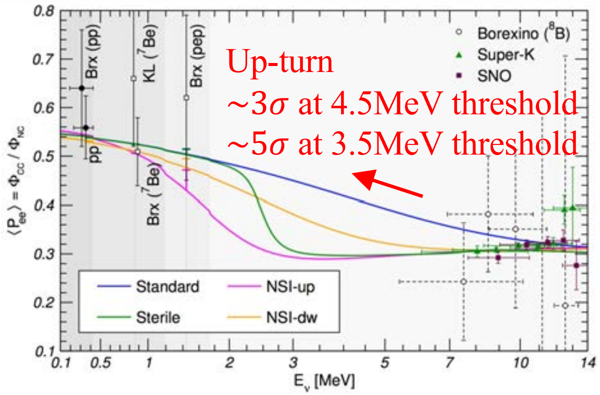


	prompt-γ & $K^+\to\mu^+\nu$		$K^+\to\pi^+\pi^0$	
	Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
HK	12.7	0.9	10.8	0.7

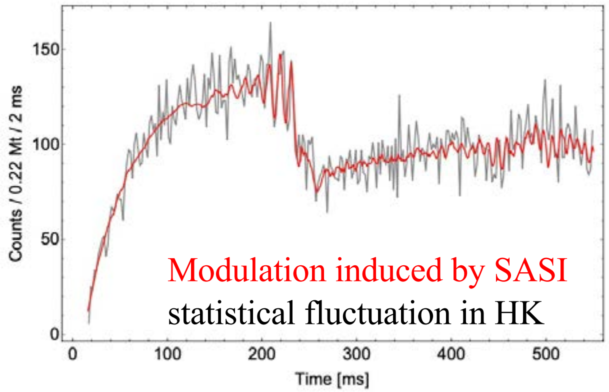
Hyper-K

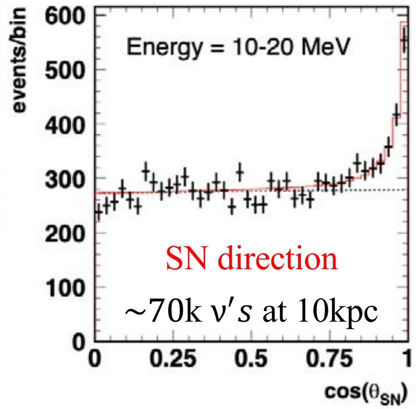
Neutrino astrophysics

- Observation of ~10 MeV neutrinos with the time, energy and direction
  - ➢ Unique role in multi-messenger observation
  - ➢ Sensitivities depend on the energy thresholds
- Solar neutrinos (~130/day): up-turn at vacuum-MSW transition region, D/N, hep ν
- Supernova burst (~50k/burst): explosion mechanism, BH/NS formation, alert with 1° pointing



M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)





Hyper-K

J-PARC UPGRADE

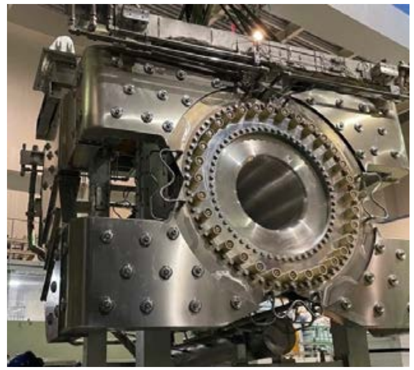
- **As parts of HK project J-PARC MR & neutrino beam-line upgrade towards 1.3MW are being conducted.**
  - **J-PARC MR:** magnet power supply upgrade, RF upgrade, Fast Extraction Kicker upgrade, …
  - **Neutrino beam-line:** Upgrade of target, horn (250kA to 320kA), beam monitors, …
  - **Facility upgrade:** cooling, radiation protection, …
- **Progress is proceeding according to plan.**
  - Shortening the repetition cycle from 2.48 seconds to 1.36 seconds.
  - Successful continuous operation at 800 kW and beyond
  - Moving forward, further equipment upgrade will be made to achieve an even higher repetition rate (1.16-second cycle) and to increase the number of beam particles, aiming for 1.3 MW.
- **J-PARC accelerator team and Beam WG are advancing beam tuning and studies related to increasing beam power and delivery of stable beams.**

Hyper-K

Beam Power Upgrade Schedule

RF Acceleration Cavity

PS Upgrade work for RF Cavity



Upgraded horns for neutrino beamline