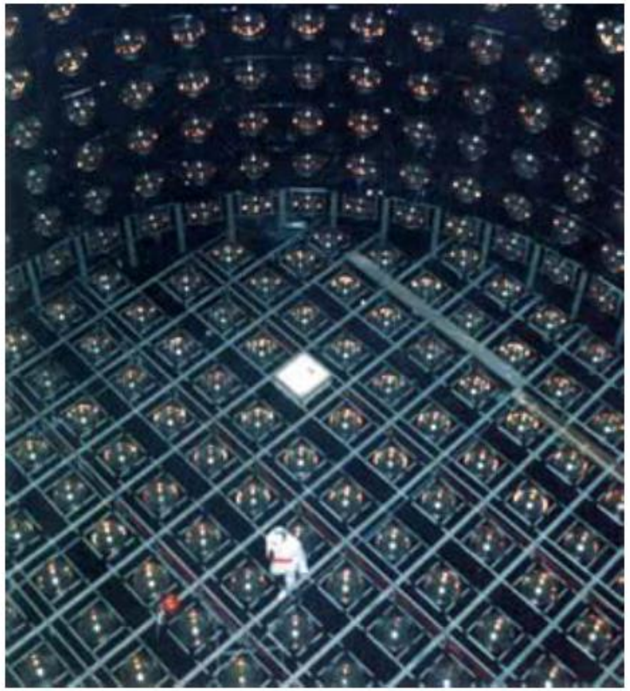
NuFACT 2023 The 24th International Workshop on Neutrinos from Accelerators
August 21 ~ 26, 2023 at Seoul National University, Seoul, Korea

Hyper-Kamiokande

NEIL MCCAULEY
UNIVERSITY OF LIVERPOOL
ON BEHALF OF THE HYPER-KAMIOKANDE COLLABORATION

NUFACT 2023

3rd generation underground water Cherenkov detector in Kamioka

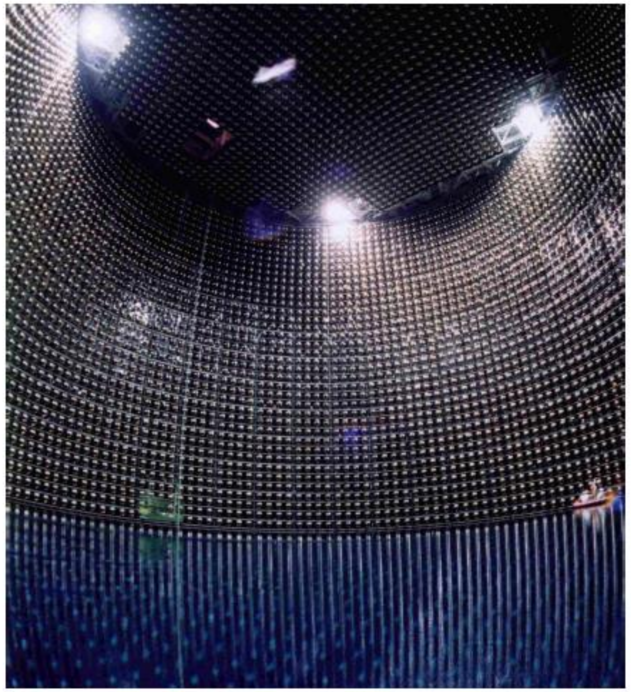


Kamiokande

(1983-1996)

- Atmospheric and solar neutrino “anomaly”
- Supernova 1987A

Birth of neutrino astrophysics

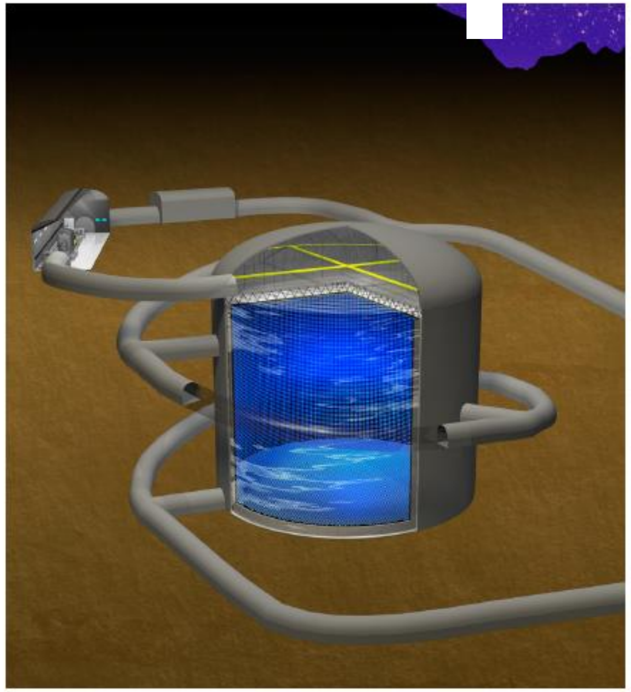


Super-Kamiokande

(1996 - ongoing)

- Proton decay: world best-limit
- Neutrino oscillation (atm/solar/LBL)
  - ➢ All mixing angles and $\Delta m^2 s$

Discovery of neutrino oscillations



Hyper-Kamiokande

(start operation in 2027)

- Extended search for proton decay
- Precision measurement of neutrino oscillation including CPV and MO
- Neutrino astrophysics

Explore new physics

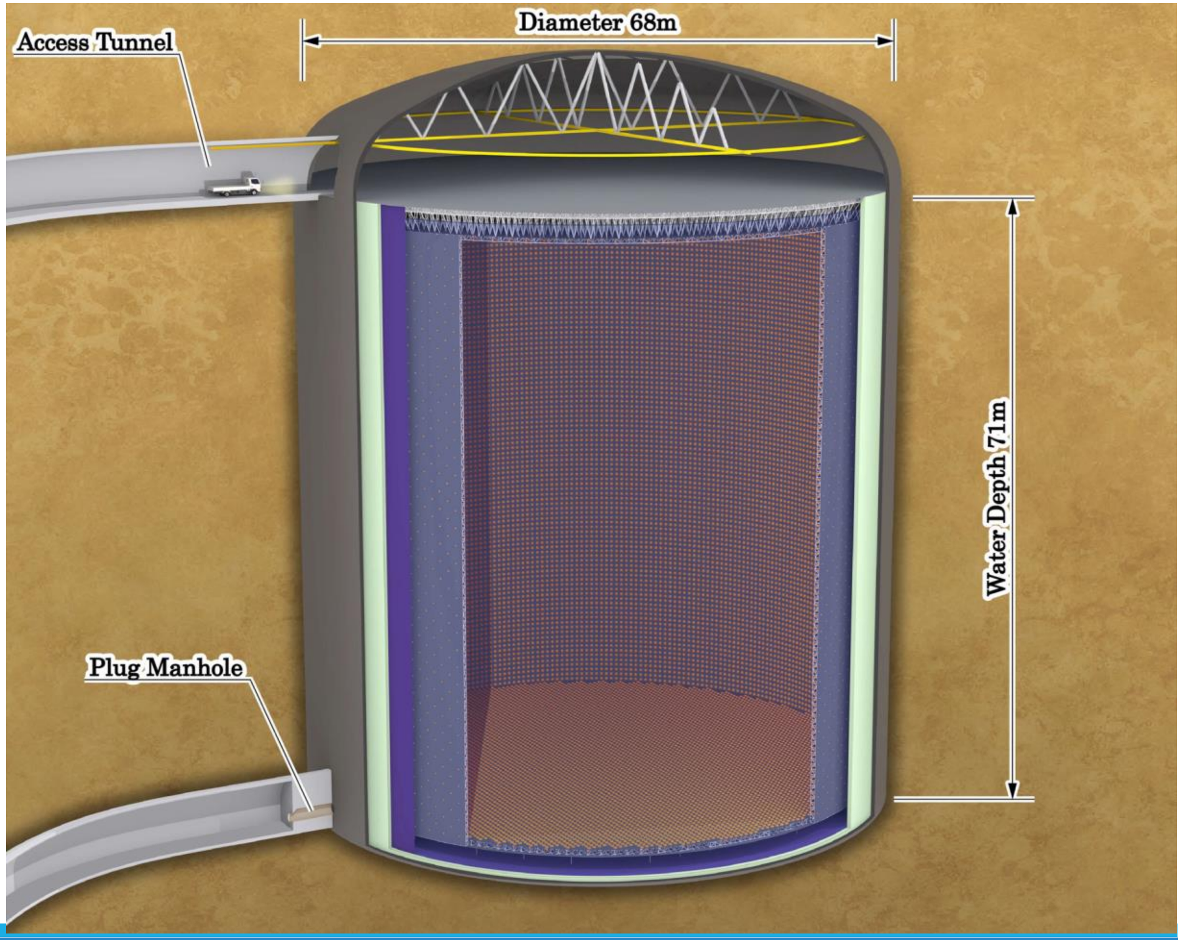
The Hyper-Kamiokande Detector

258 kton Water Cherenkov detector
- ~ 8 times larger than Super-Kamiokande

20000 50 cm PMTs

~1000 mPMTs

7200 OD units
- 8 cm PMT
- Wavelength shifting plate



A Long Baseline Experiment

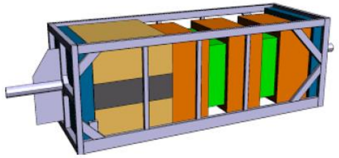
Far Detector
Oscillated Beam

Hyper K

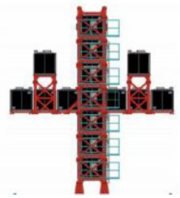
295 km

Near Detectors
Unoscillated Beam

ND280

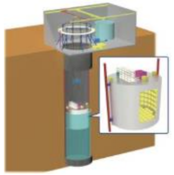


INGRID



280 m

IWCD

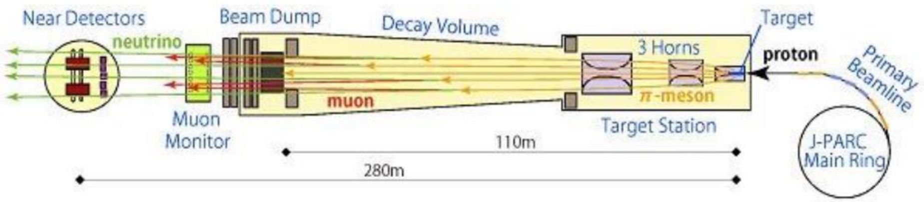


~1 km

JPARC Neutrino Beam
Upgrade 500 kW → 1.3 MW
Horn Current 250 kA → 320 kA

See T. Nakadaira’s talk on Tuesday for beam details.

J-PARC



ND280

ND280 upgrade is part of the T2K experiment and will still be online at start of Hyper-K

- Operational from 2024
- See T2K talks for more details

New Detectors

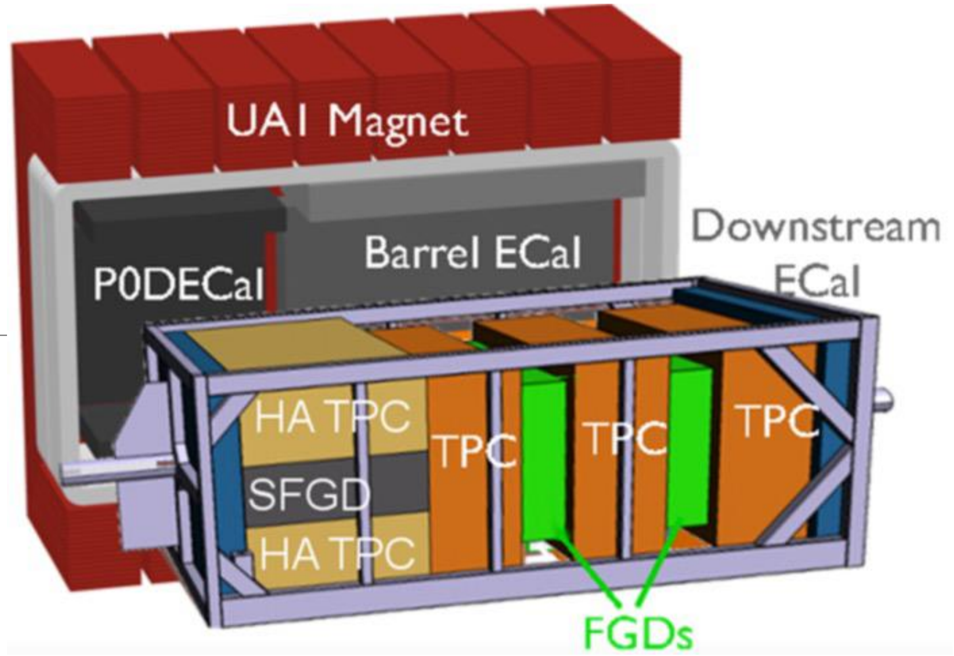
- sFGD
- hTPCs
- Time of flight

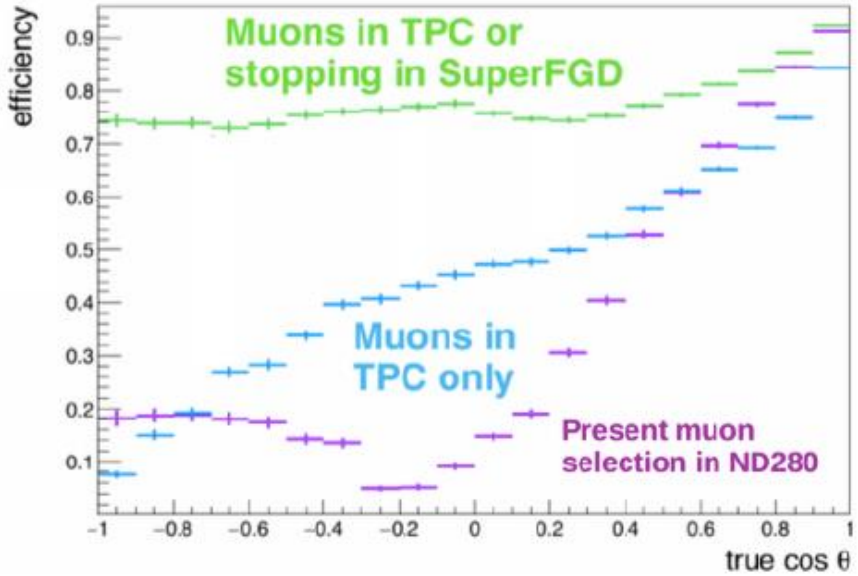
Constrain predictions for far detector

- Measure flux X cross section

Magnetised so can measure wrong sign backgrounds

Detailed kinematic measurements to constrain and develop cross section models





IWCD

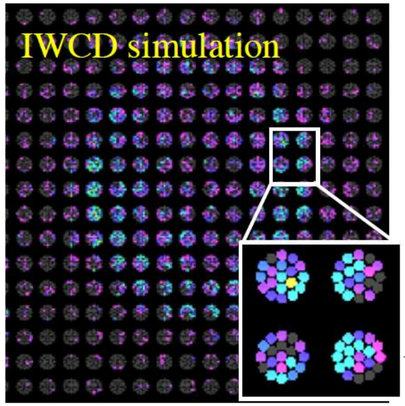
Approx 1 km from neutrino target

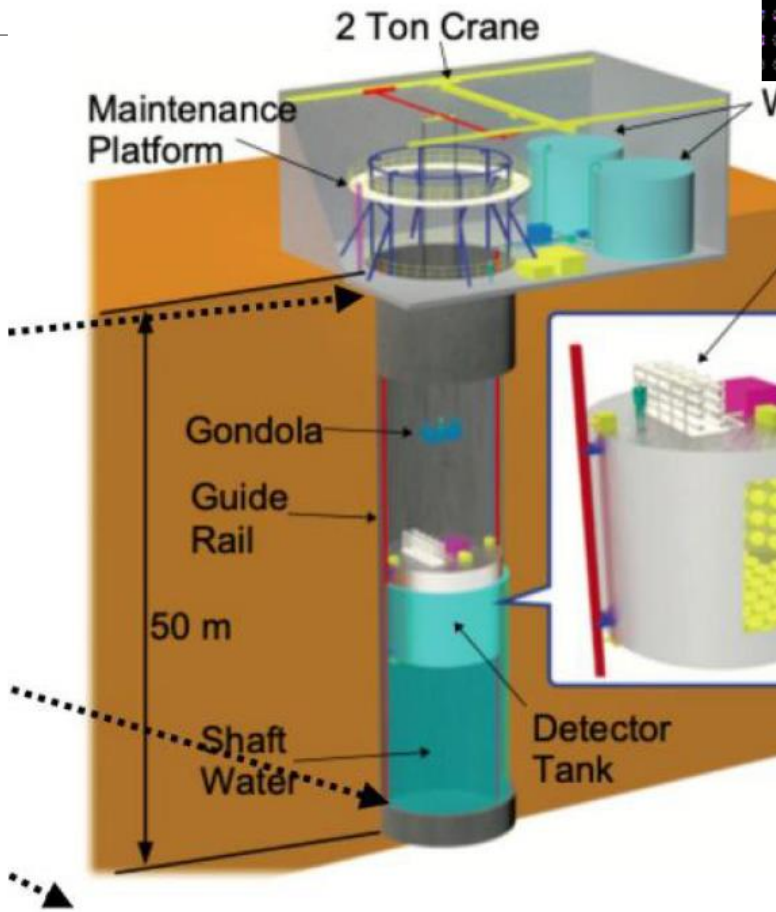
1 kton scale water Cherenkov

- Use mPMTs for readout
- Move detector up and down shaft to sample different off- axis angles

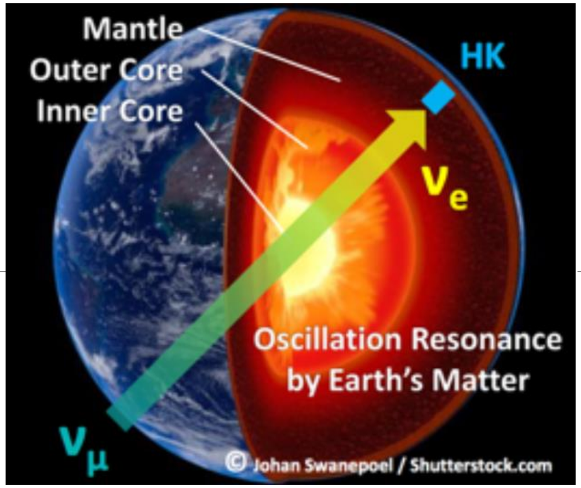
Constrain neutrino energy mis-reconstruction

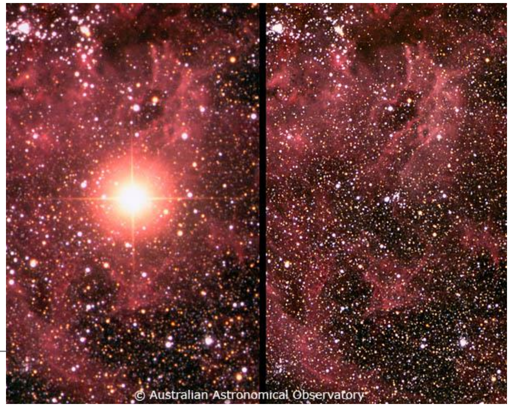
Measure electron neutrino cross sections





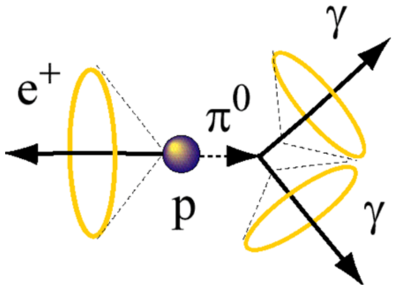
Science goals

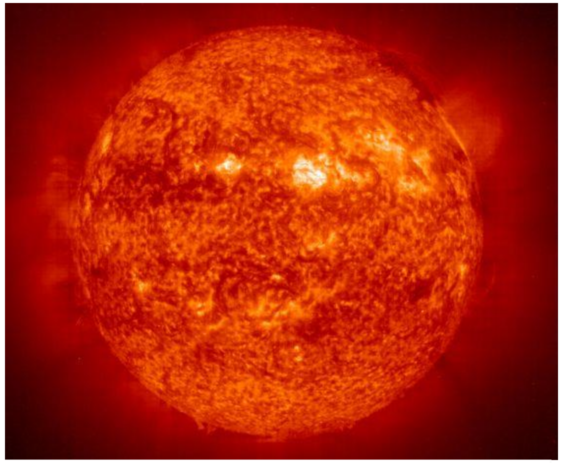




Neutrino Oscillation Physics

- Neutrino Oscillations, CP Violation, Mass Ordering, Sterile Neutrinos, Non-Standard Interactions



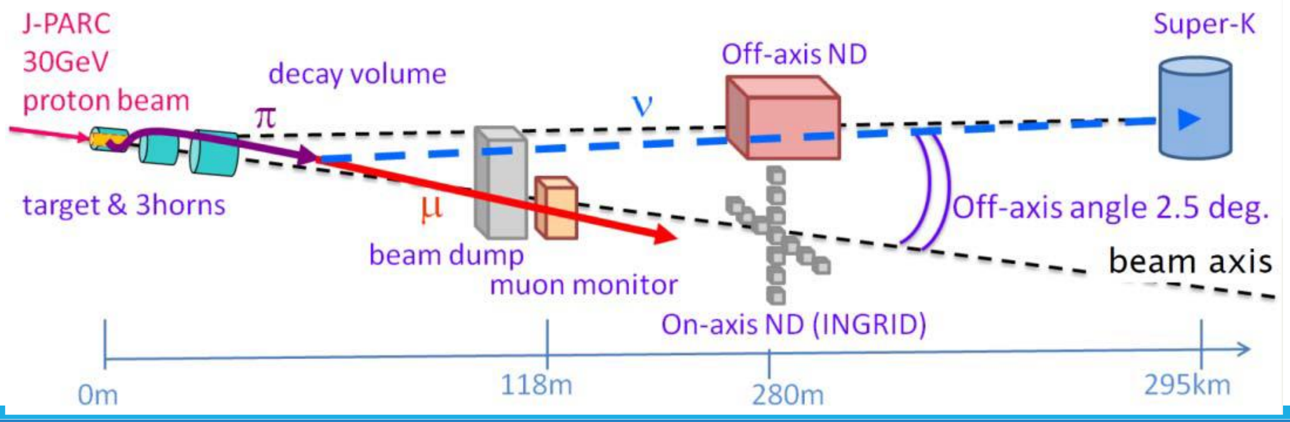


Neutrino Astrophysics

- Supernova Bursts, Pre-supernova Neutrinos, Diffuser Supernova Neutrino Background, Solar Neutrinos

BSM Physics

- Nucleon Decay



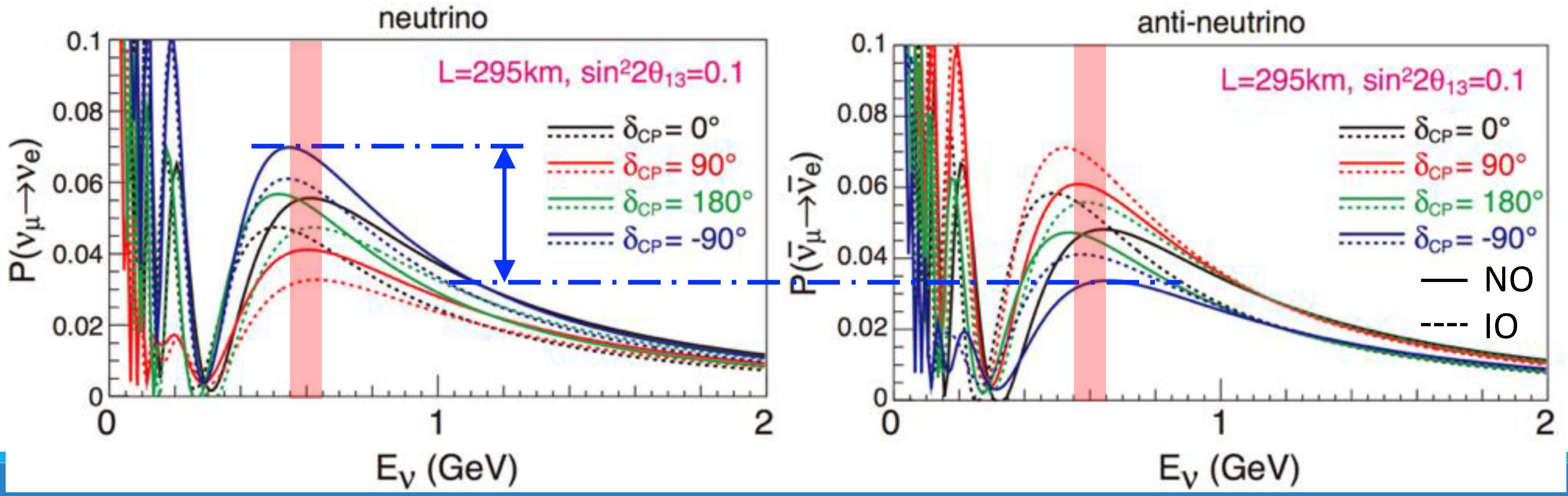
Measurement of Oscillations

Measure CP violation through υ_e appearance

Few % statistical uncertainty after 10 years operation with > 1000 υ_e and $\overline{\upsilon_e}$ signal events
- Systematics limited

Break parameter degeneracies with atmospheric neutrinos

Near detectors crucial to constrain far detector expectation



What do we see in HK?

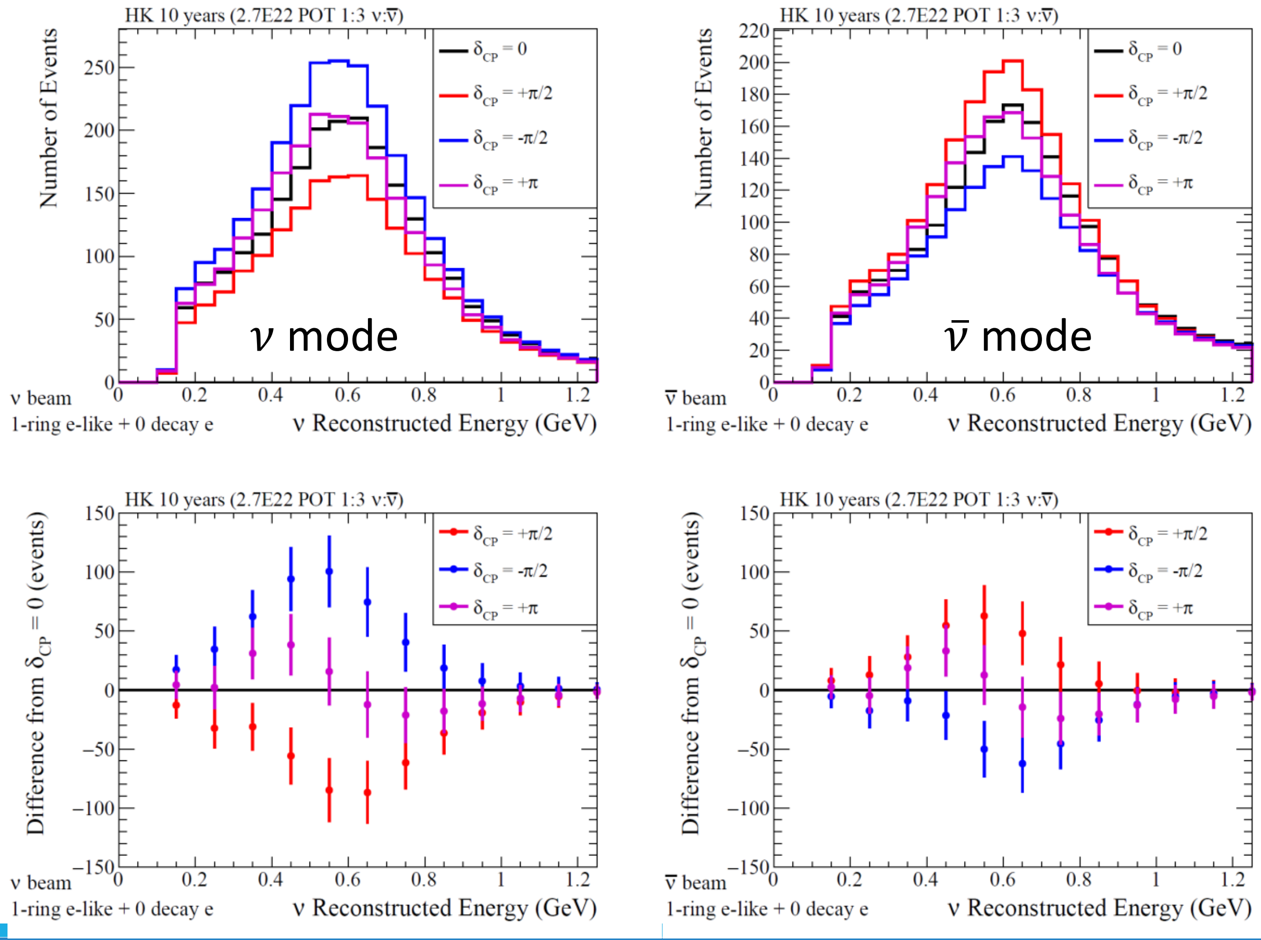
Electron and muon like rings

- Spectrum and rate
- Neutrino and antineutrino running

Rate and spectrum depend on δ_{CP}

Systematics

- Flux
- Cross Sections
- Cross section effects on neutrino energy reconstruction
- Energy Scale/Resolution
- Particle Identification
- Reconstruction

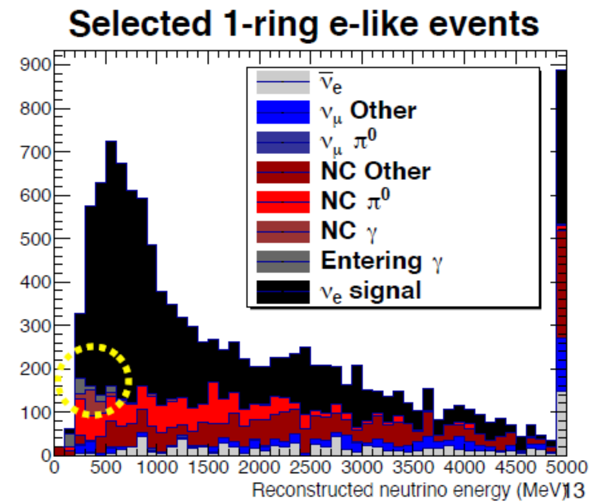


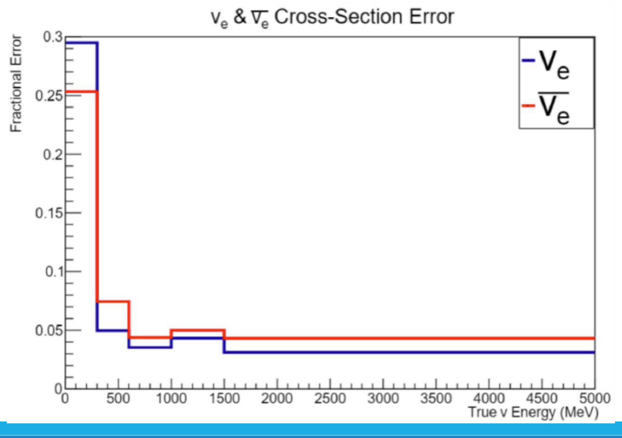
Constraints from IWCD

Neutrino flux and spectrum vary with off axis angle

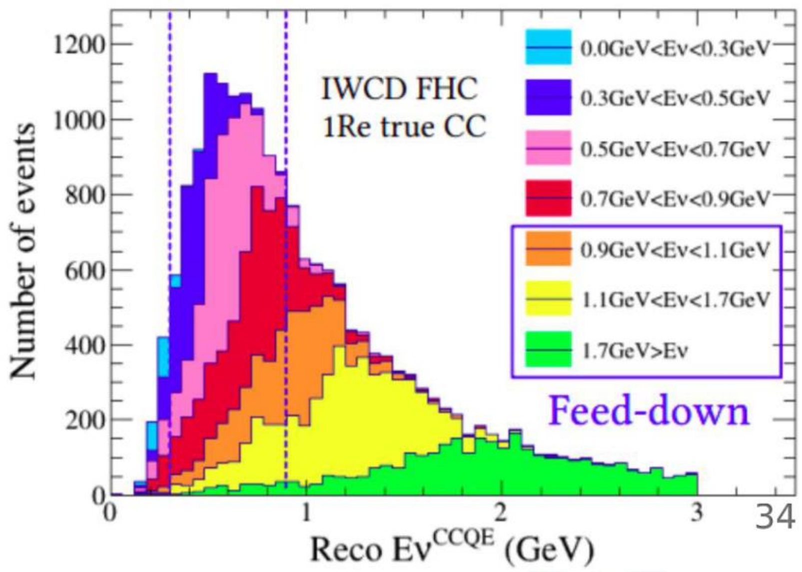
We move the detector to different angles
- Neutrino interaction constraints
- Understand neutrino energy reconstruction

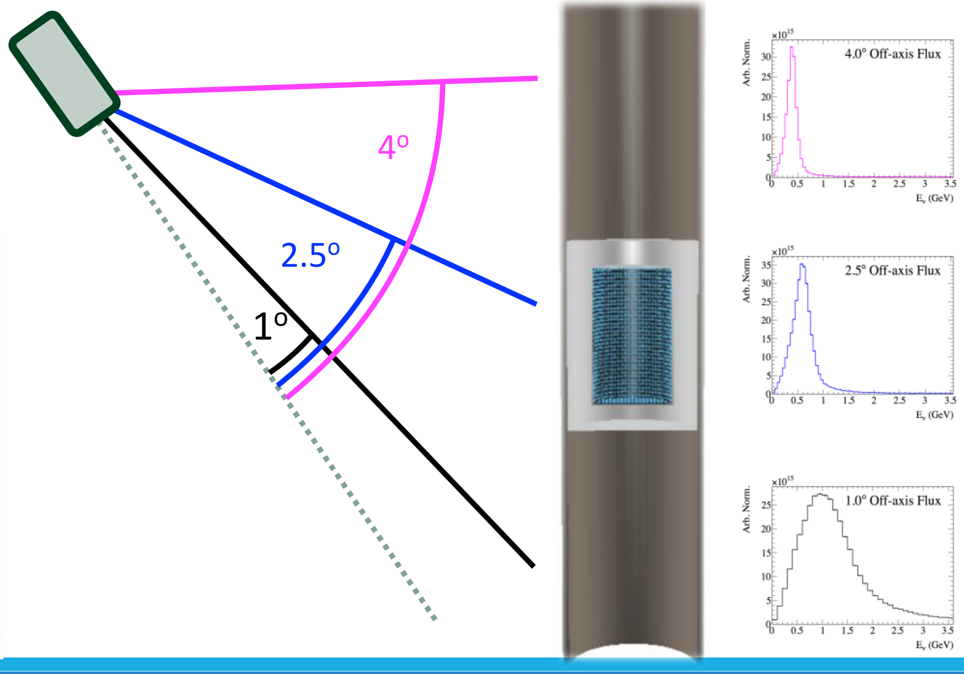
IWCD improves measurement of ν_e interactions
- Self-shielding & improved π^0 rejection
- Improved photon background compared to ND280
- Aim to significantly improve $\nu_e/\overline{\nu}_e$ cross section ratio ~4%





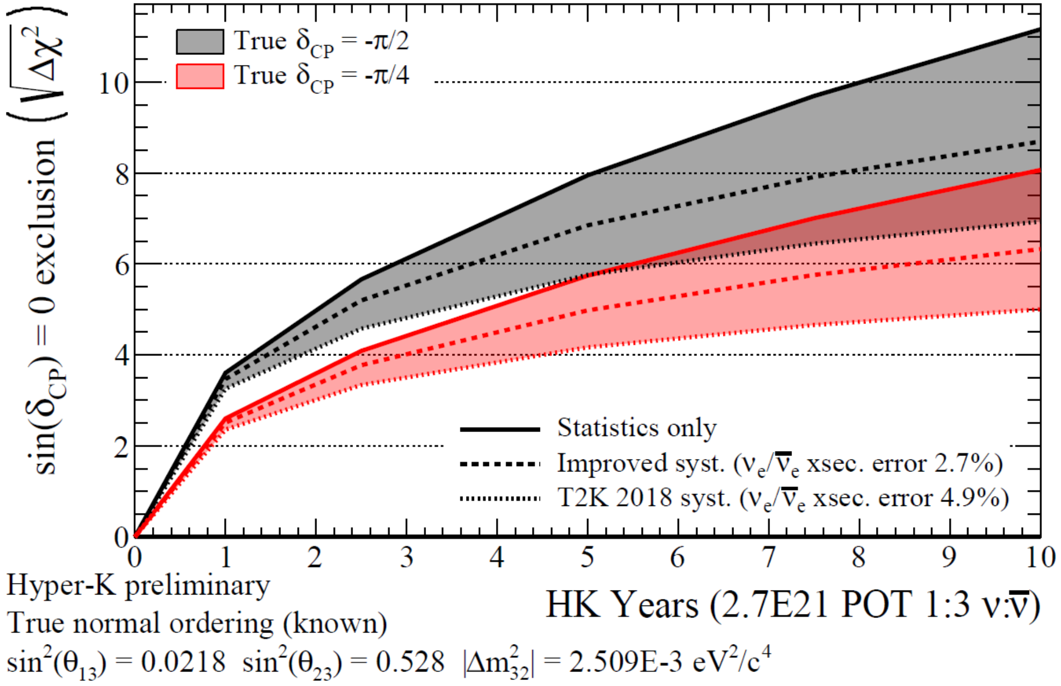
Off-axis 1°

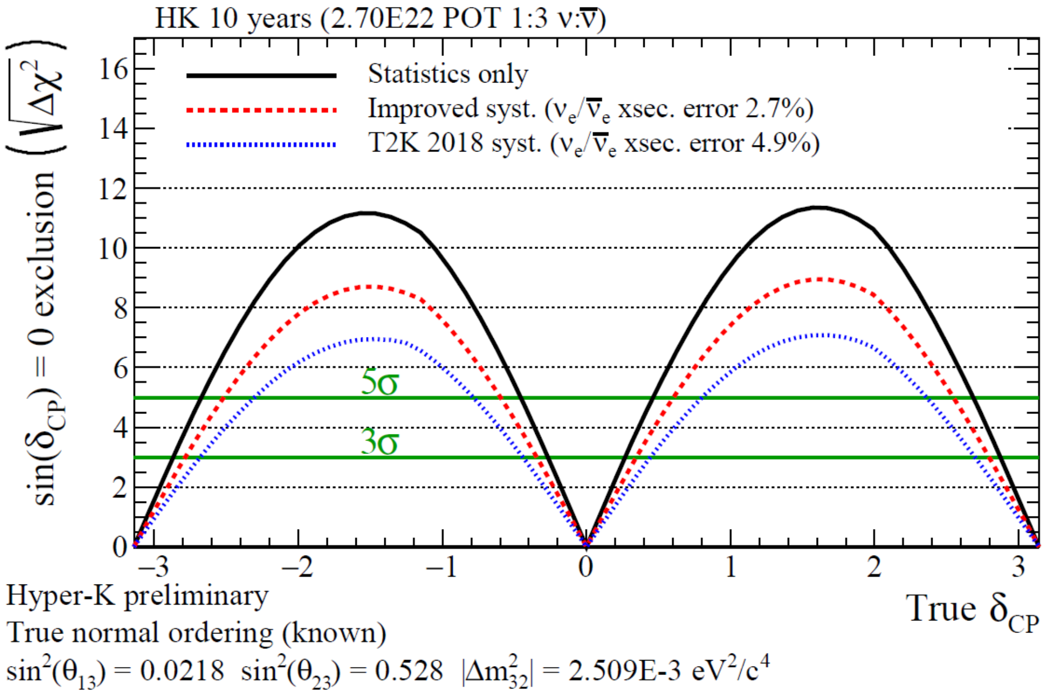




See C. Naseby's talk for more details

CP Measurement Prospects





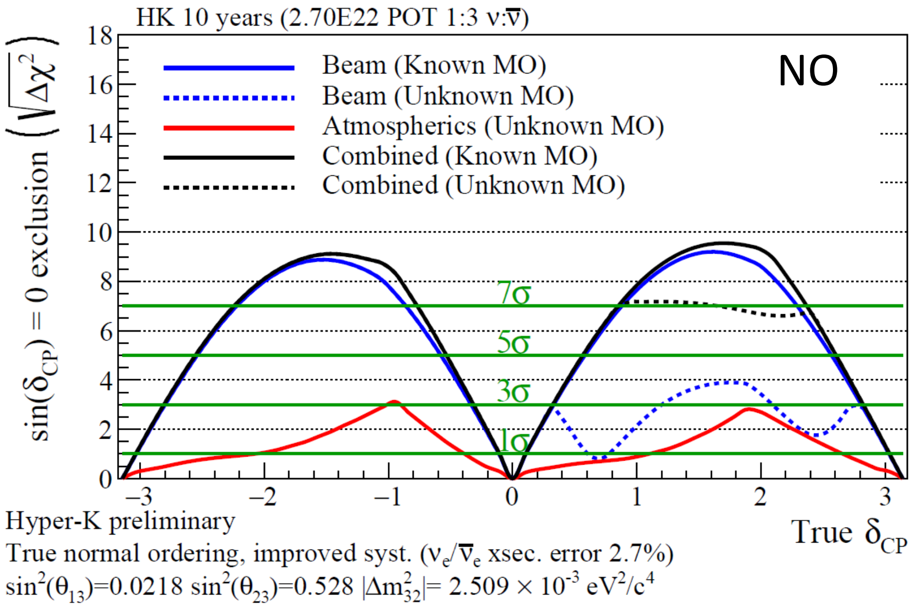
With known mass ordering can achieve 5σ CP conservation exclusion for true δ_{CP}=-π/2 in 2-3 years

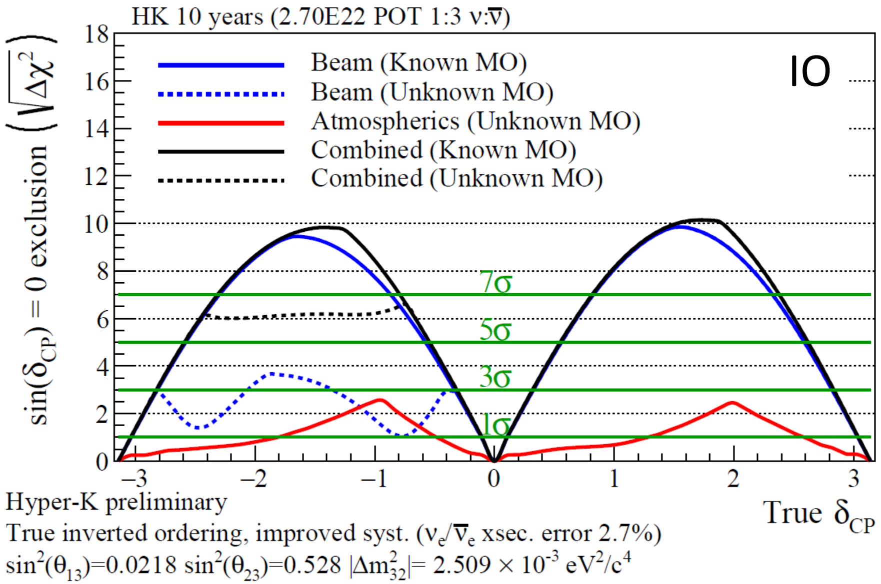
After 10 years 60% of parameter space excluded at >5σ

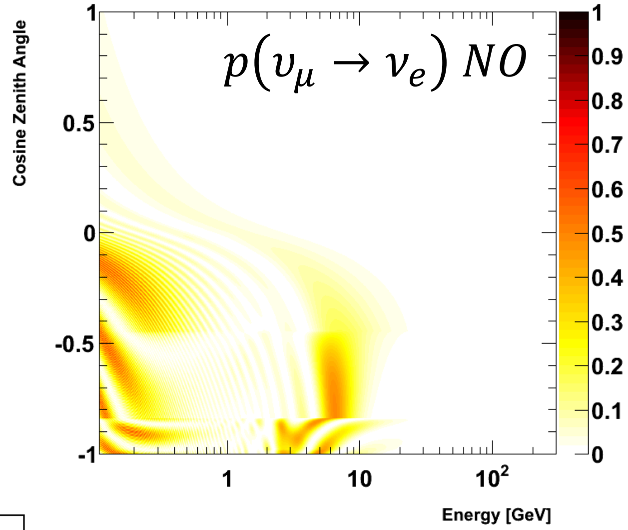
Adding Atmospheric Neutrinos

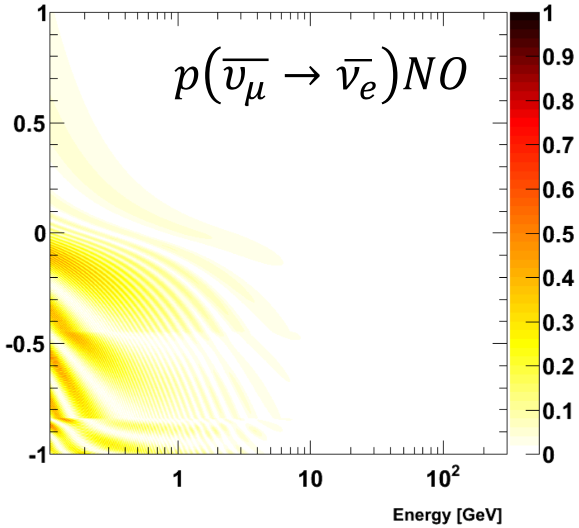
Adding atmospheric neutrinos can resolve mass ordering degeneracies

Enhancement of $p(\nu_\mu \rightarrow \nu_e)$ for NO and $p(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$ for IO







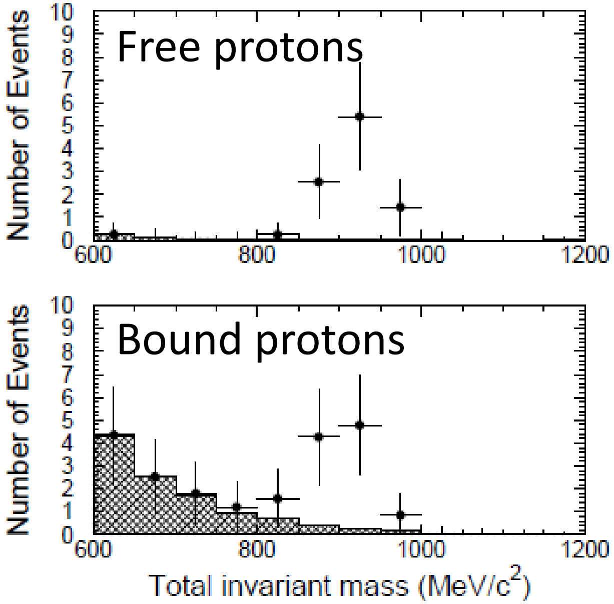


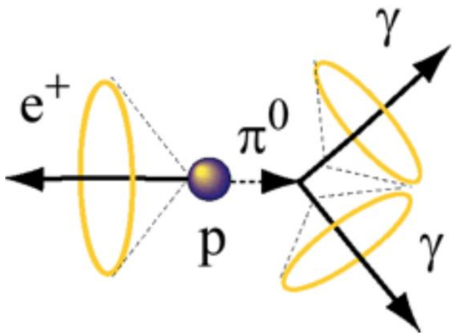
Proton Decay $p \rightarrow e^{+}\pi^{0}$

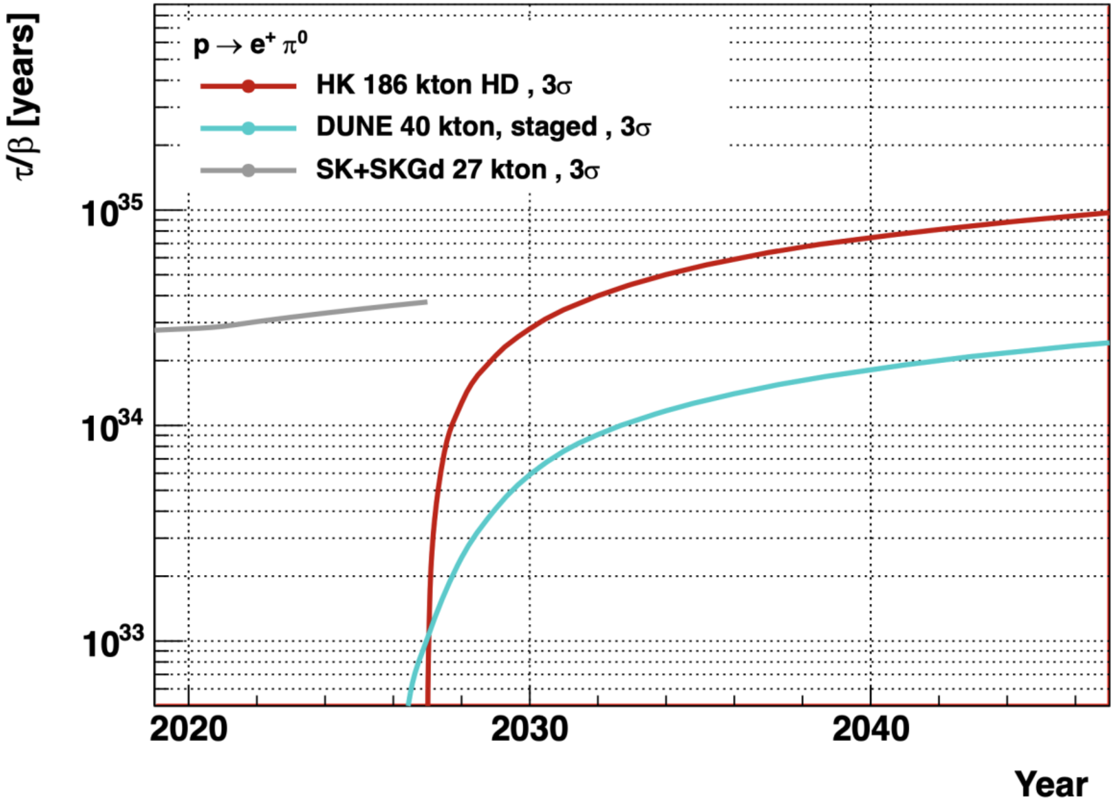
Proton decay is predicted by grand unified theories

Suppression by $^{1}/_{M_X^4}$ very long lifetimes

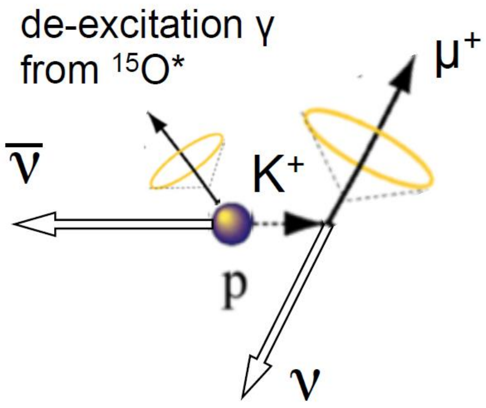
HK is only realistic option to probe 10^{35} years







Proton Decay $p \to K^+\bar{\nu}$

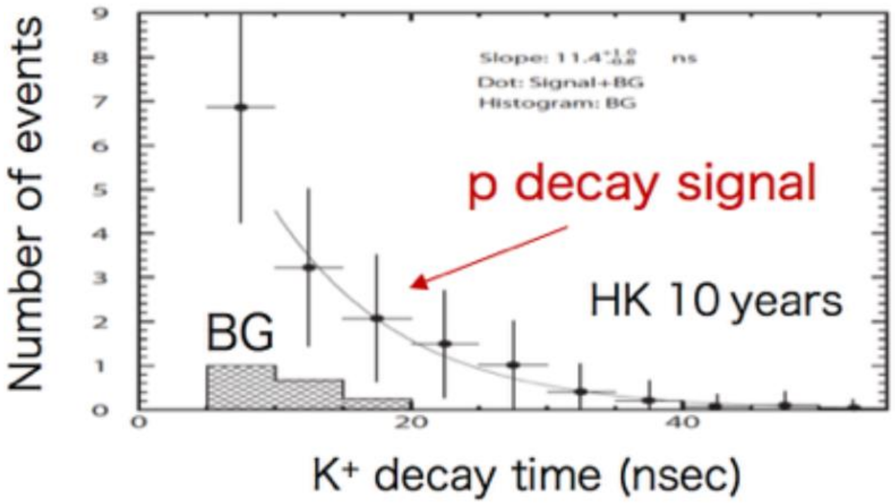


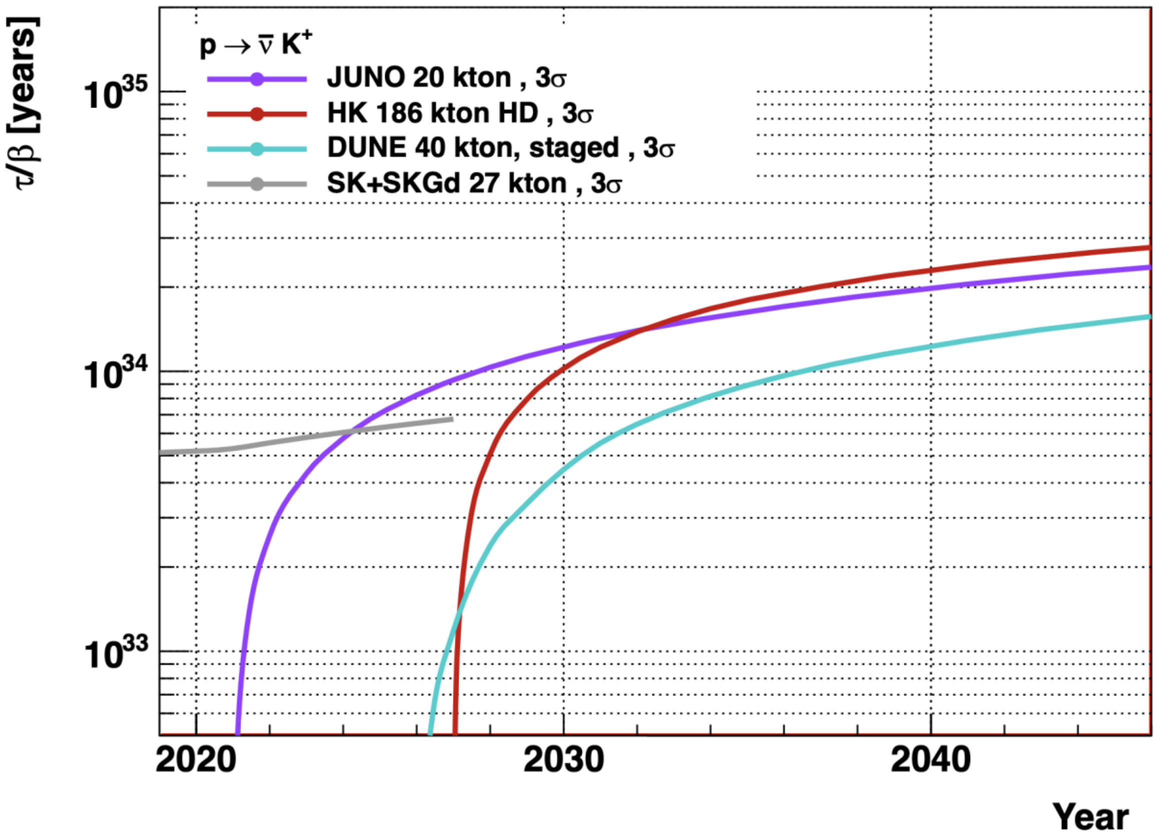
The $p \to K^+\bar{\nu}$ is an alternative decay channel

Clean signatures

$K^+ \to \mu^+\nu$ (64%)   236 MeV μ^+

$K^+ \to \pi^+\pi^0$(21%) 205 MeV π^+ back to back photons



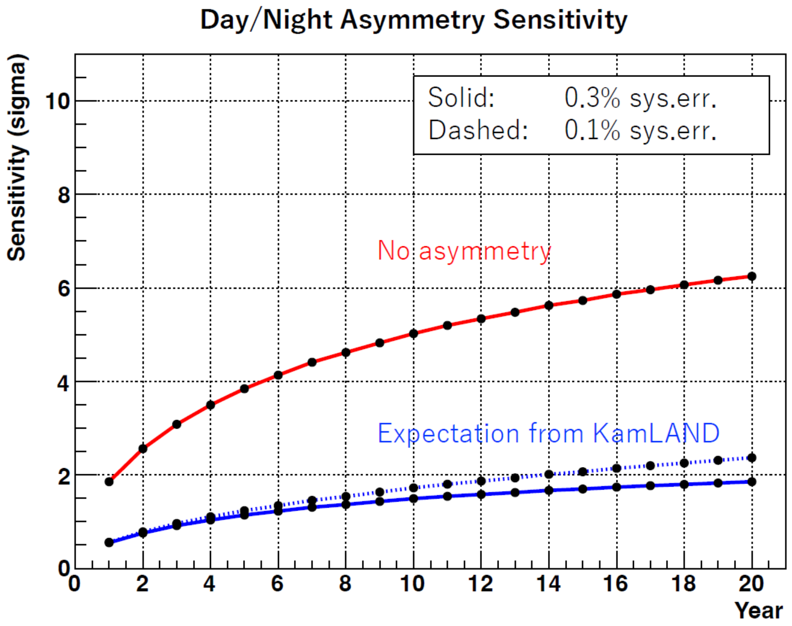


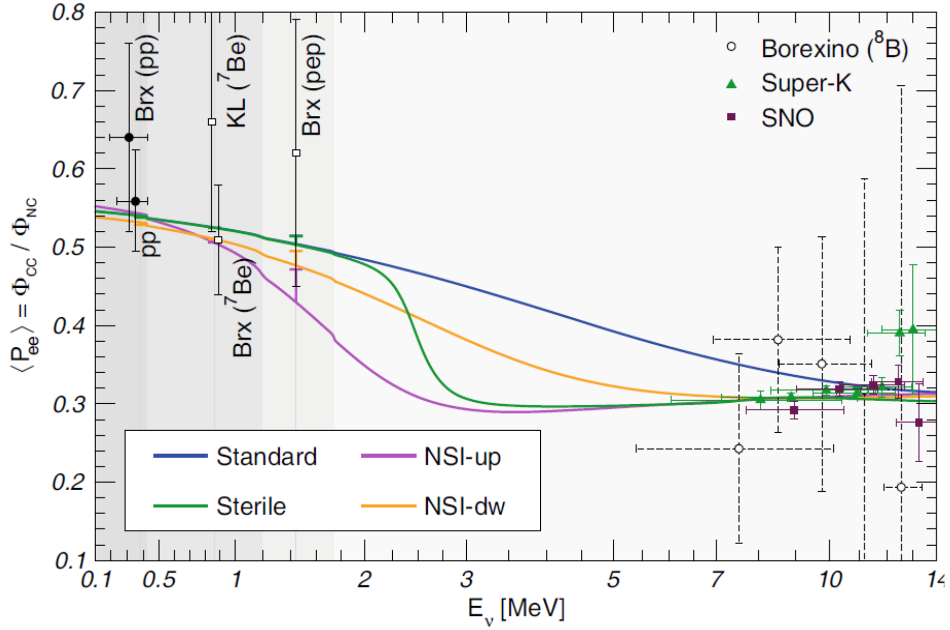
Solar Neutrinos

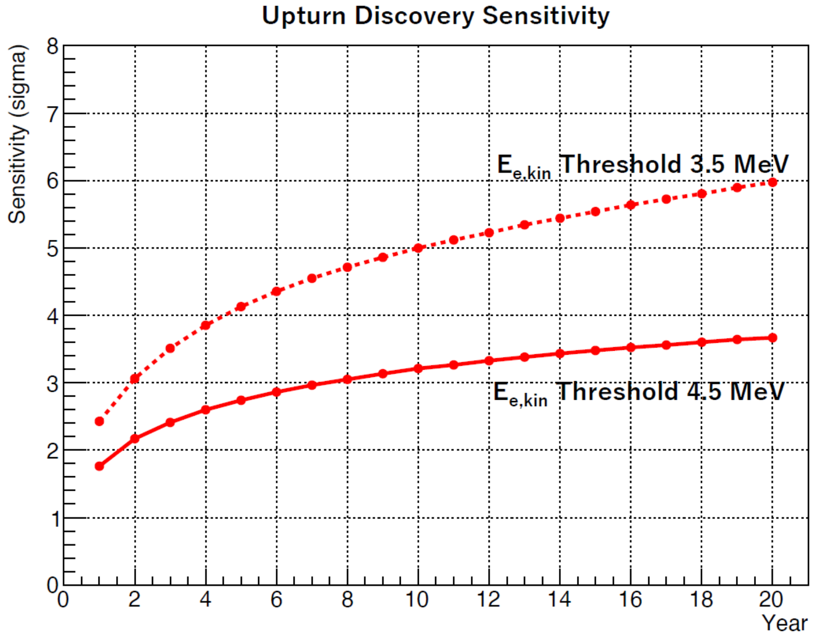
Solar neutrino survival probability strong function of energy

Sensitivity to new physics in transition region

Hyper-Kamiokande will search for the up-turn







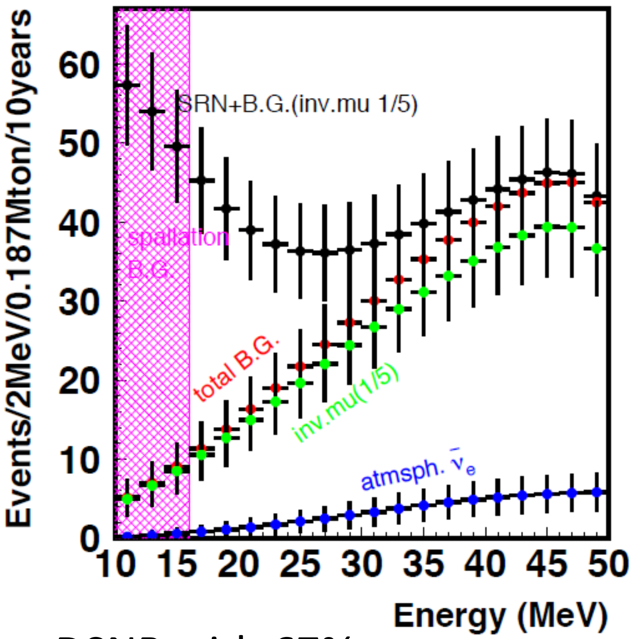
Hyper-Kamiokande will also search for the day night asymmetry

Supernova Neutrinos

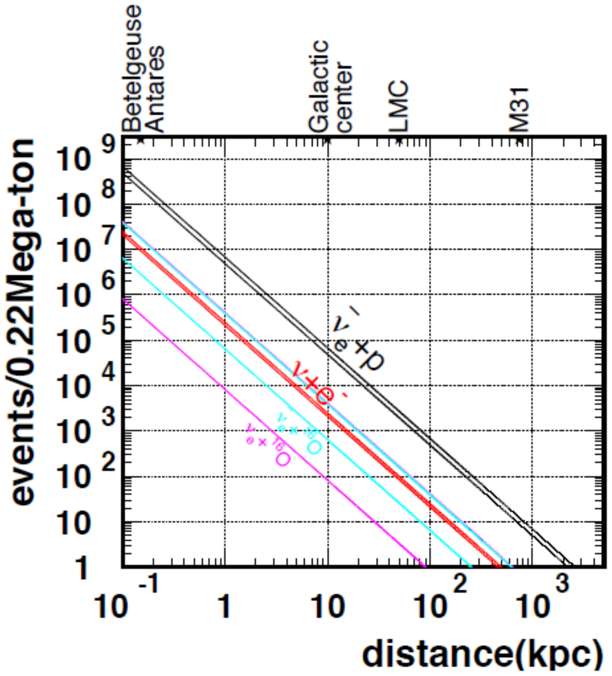
Hyper Kamiokande is sensitive to neutrinos from

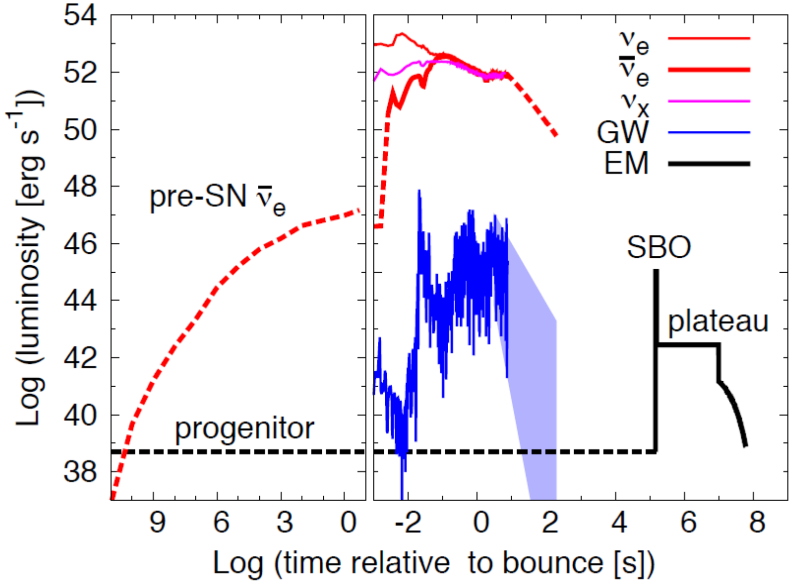
- Core-Collapse Supernova
- Pre-Supernova Si burning
- The Diffuse Supernova Neutrino Background

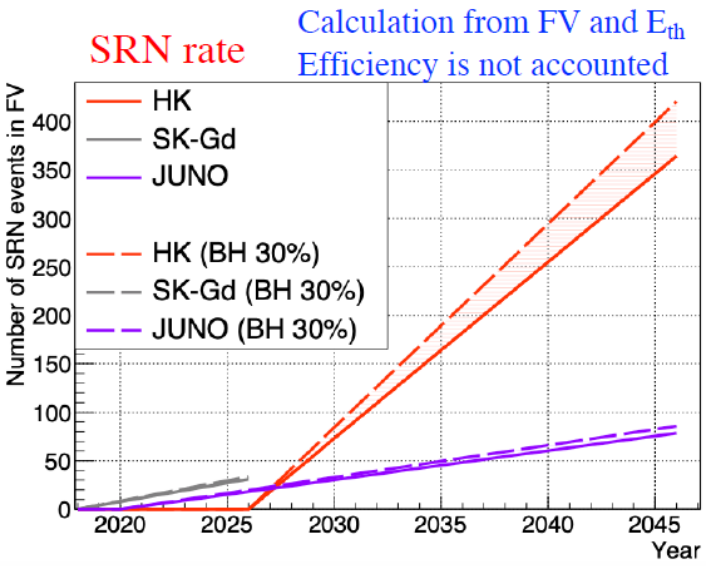
Dominant signal
$\bar{\nu}_e + p \rightarrow e^+ + n$



DSNB with 67% neutron tag

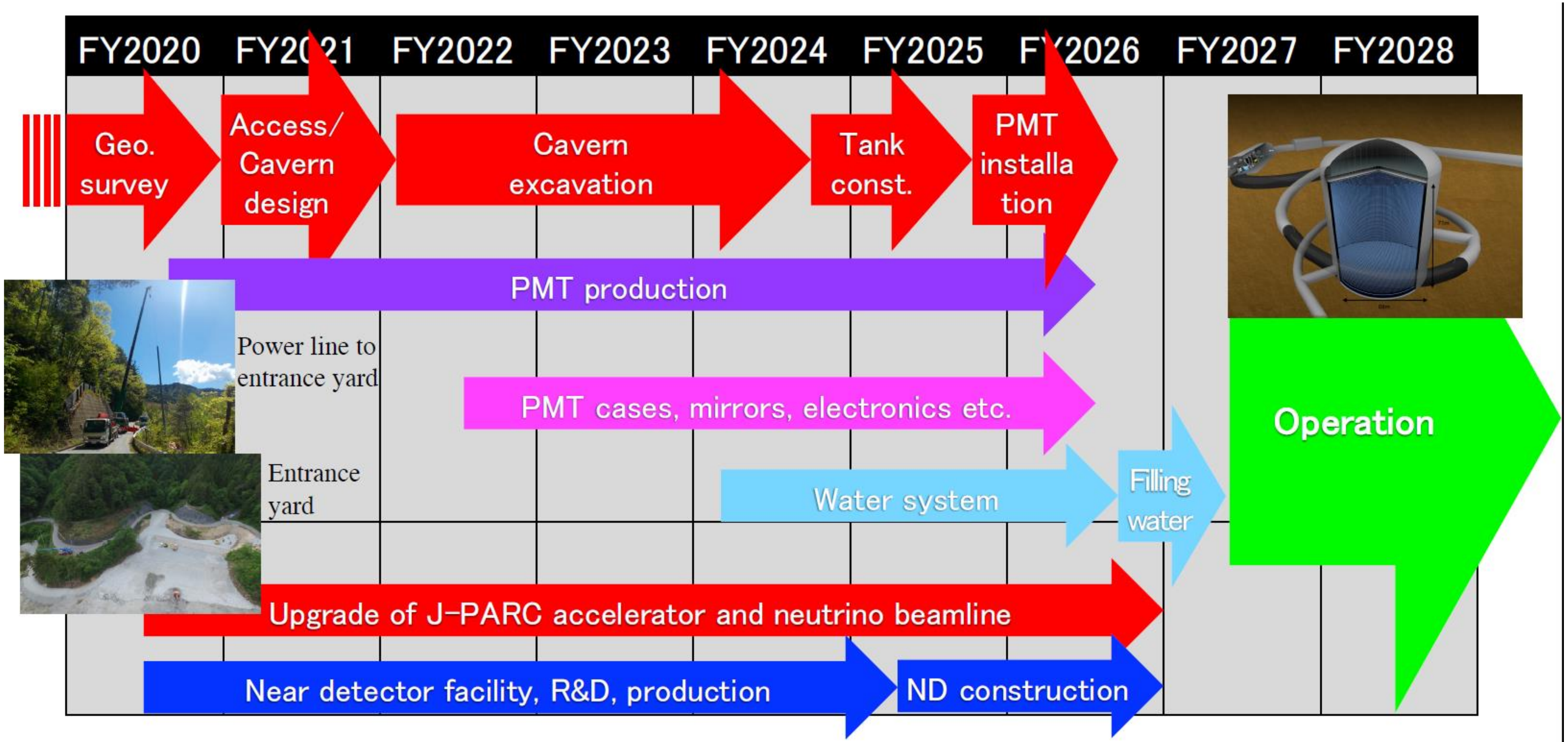




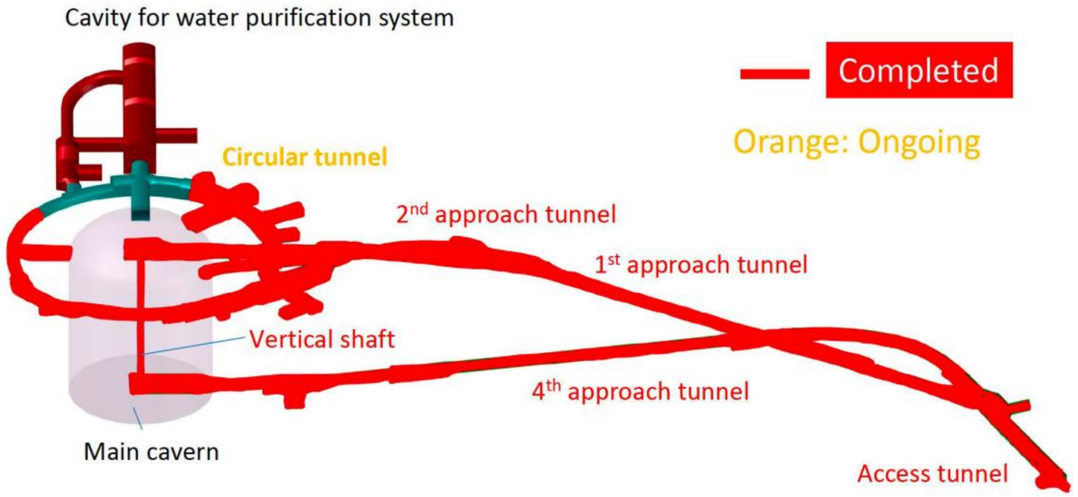


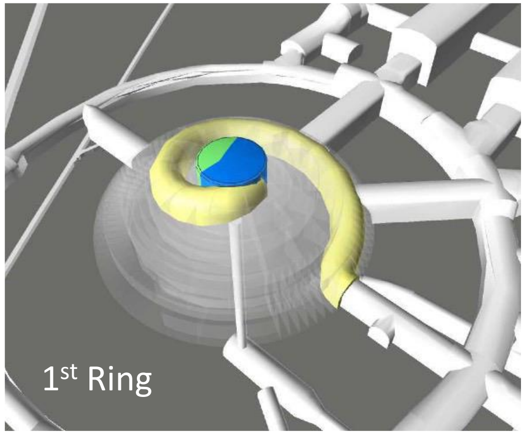
MNRAS, 461, 3296 (2016)

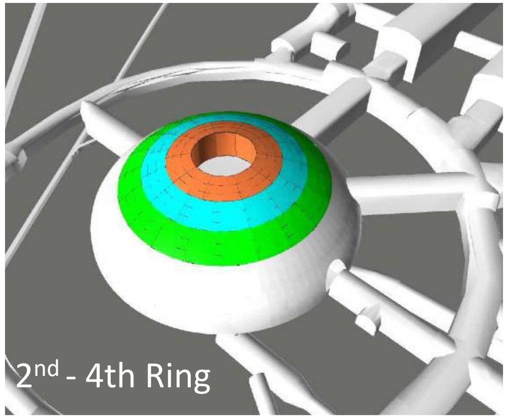
Construction Timeline

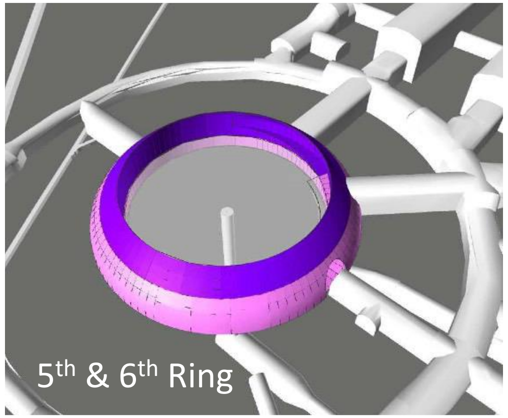


Underground Facility









Access tunnels completed

Centre of dome reached June 2022

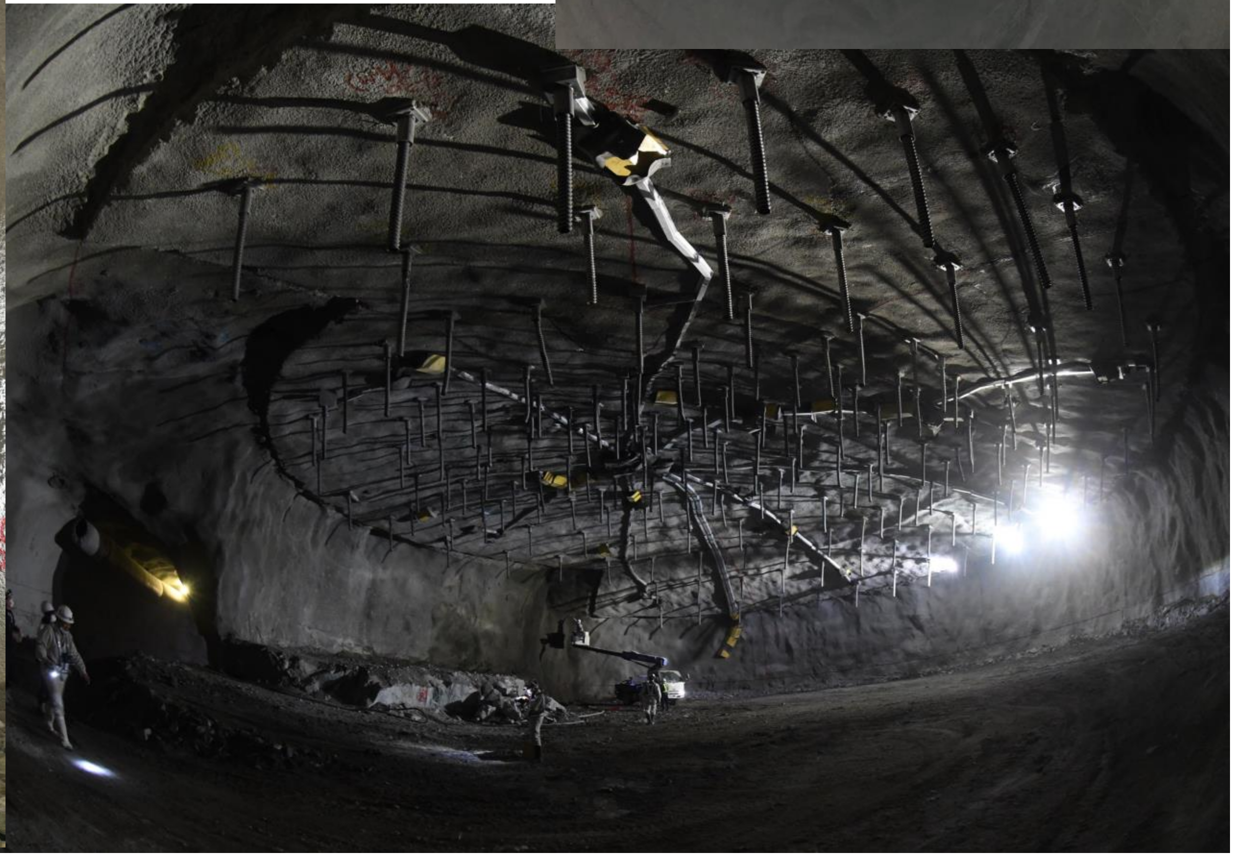
Cavern dome constructed through consecutive rings

Currently excavating 5th ring

Construction on track!

Excavation - Tunnels

Excavation – Cavern & Dome



Photomultiplier Tubes

20 000 Hamamatsu 50 cm box-and-line PMTs

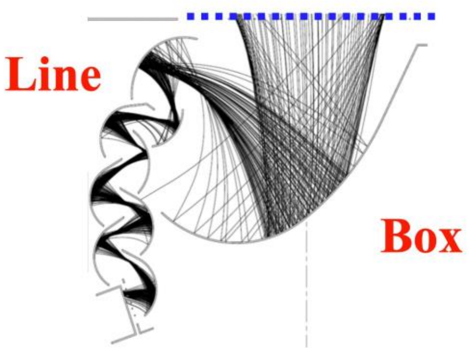
- Production, delivery and QA ongoing

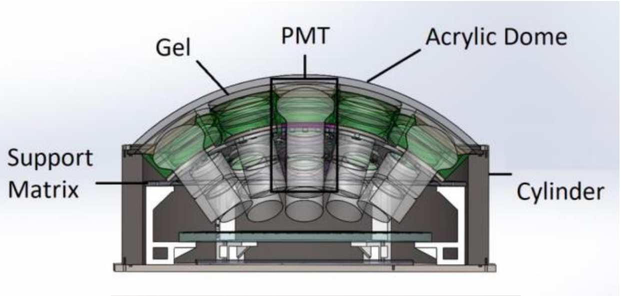
~1000 multi PMT modules

- 19 3 inch PMTs
- Improved detector calibrations

~7200 8 cm OD PMTs with wavelength shifting plate

OD studies underway to assess veto using OD & ID. OD channel number reduction



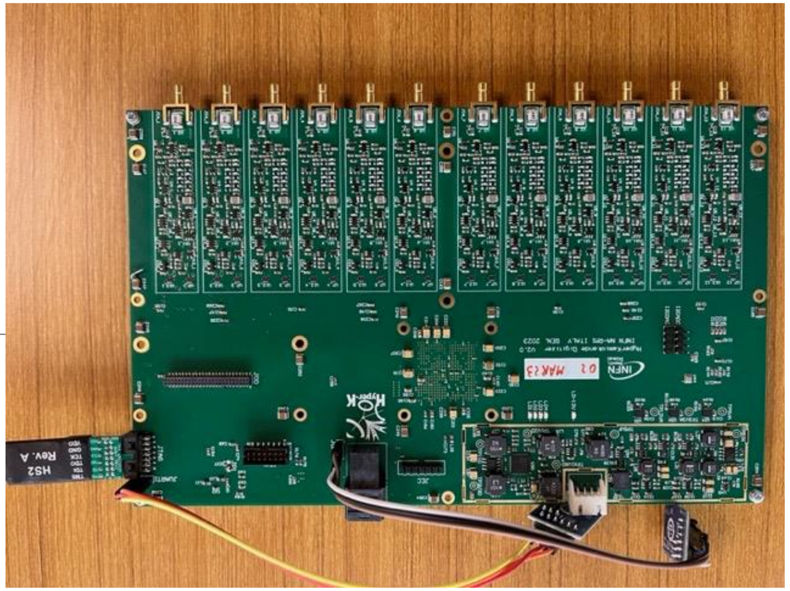


Electronics

Front-end electronics in underwater vessels

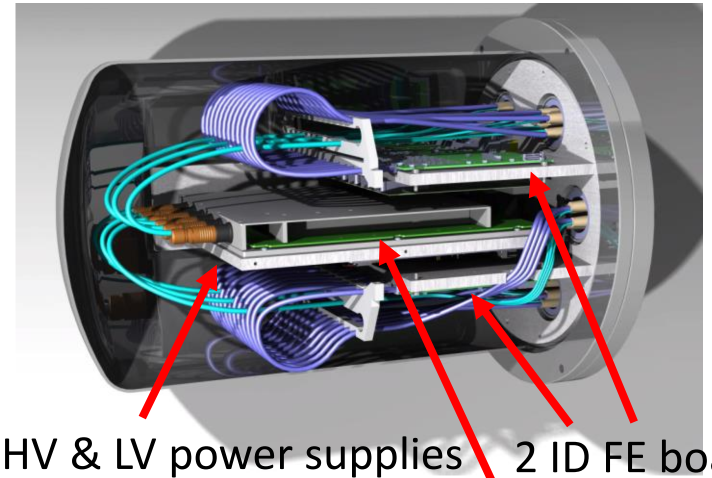
Two vessel types

- ID vessels: 24 channels read out by 2 PCBs
- Hybrid ID + OD: 20 ID & 12 OD channels



ID 12 channel-front end board

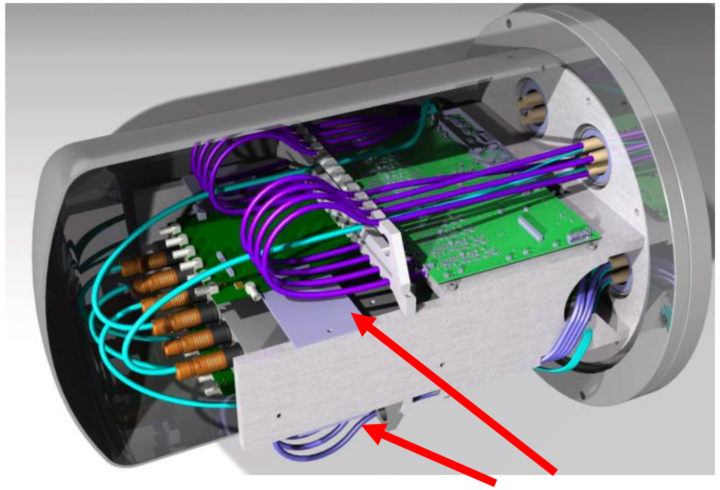
Preliminary



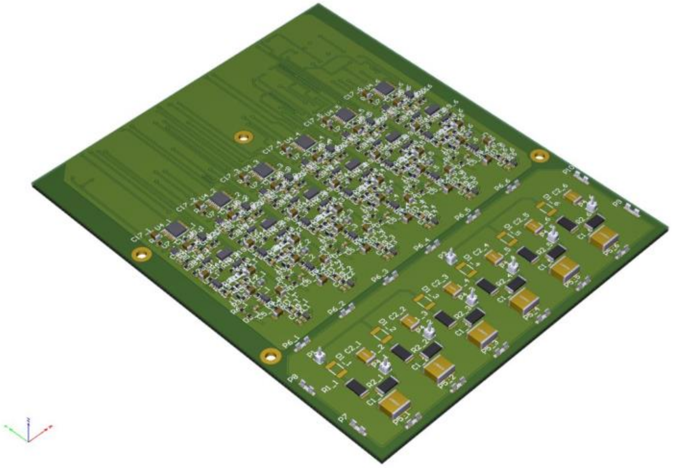
HV & LV power supplies

2 ID FE boards

Data processing and timing boards



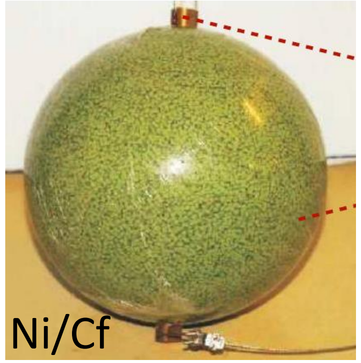
2 OD FE boards



OD 6 channel-front end board

Calibration

Photogrammetry Testing



Ni/Cf

Optical Sources, radioactive sources and control samples

Determine detector parameters and measure systematics

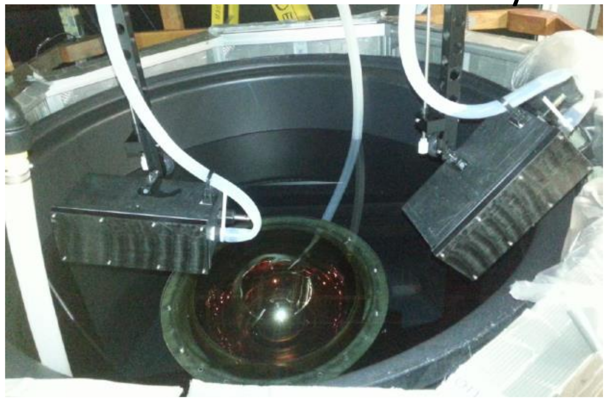
Precalibration Programme & Photogrammetry

Light Injection
- Diffusers and collimators
- mPMT system
- OD injectors

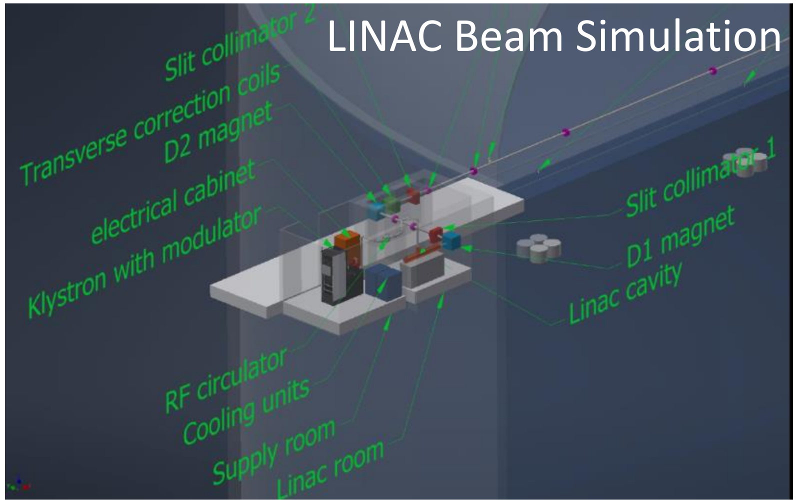
Electron Linac
- 3-24 MeV electrons

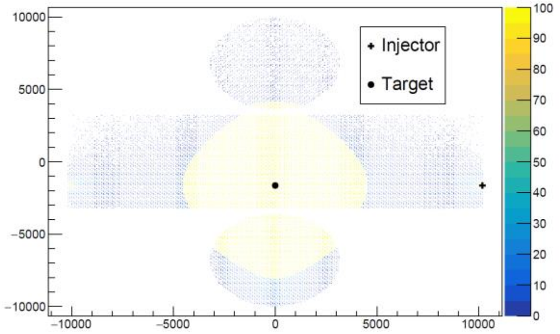
Radioactive Sources
- DT Source - ^{16}N
- AmBe + BGO – tagged neutrons
- Ni/Cf - 9 MeV γ cascade

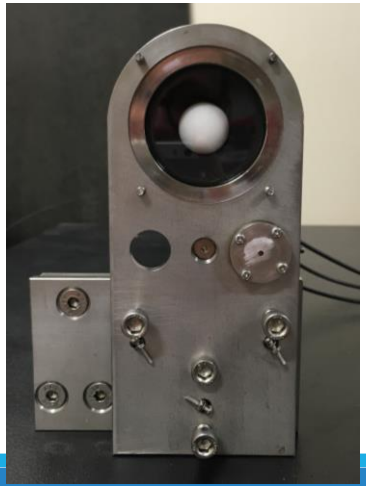
PhotoSensor Test Facility



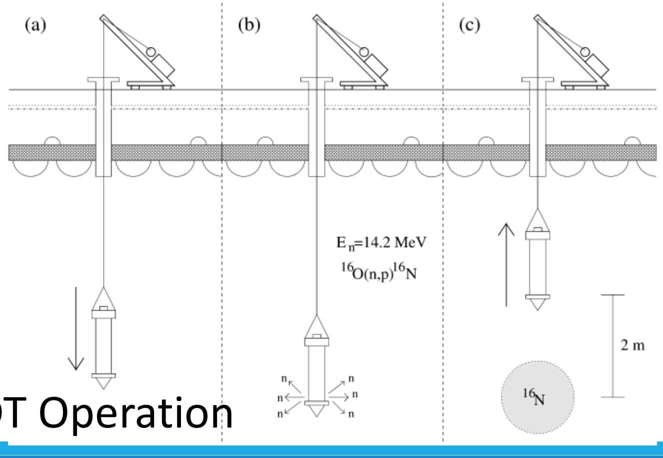
LINAC Beam Simulation







Light Injectors



DT Operation

Summary

Hyper Kamiokande is a world leading neutrino detector due to start in 2027

- World's Largest underground facility – 260 kton Water Cherenkov Detector
- Tunnels completed
- Dome construction close to completion
- PMT delivery ongoing
- Design being finalised for electronics, calibration systems, PMT support structure

It will produce world leading results in

- CP Violation - 60% of parameter space excluded at >5σ after 10 years
- MO sensitivity through combination with atmospheric neutrinos
- Nucleon Decay - > 10^{35} years for $p \rightarrow e^+\pi^0$
- Supernova Neutrinos – Bursts, Diffuse Supernova Neutrino Background, PreSN neutrinos
- Solar Neutrinos – Upturn and Day-Night Asymmetry