Hyper-Kamiokande

Outline

1. Detector construction
2. Inner detector system
3. Outer detector system
4. J-PARC beam upgrade
5. Near detector upgrade
6. Conclusions

Teppei Katori (@teppeikatori) for the Hyper-Kamiokande collaboration
King's College London
HEP seminar, University of Zürich, Switzerland, Sept. 30, 2024

1. Detector construction

2. Inner detector system

3. Outer detector system

4. J-PARC beam upgrade

5. Near detectors

6. Conclusions

1. Hyper-Kamiokande project

Hyper-Kamiokande project includes 3 components

1. Hyper-Kamiokande detector

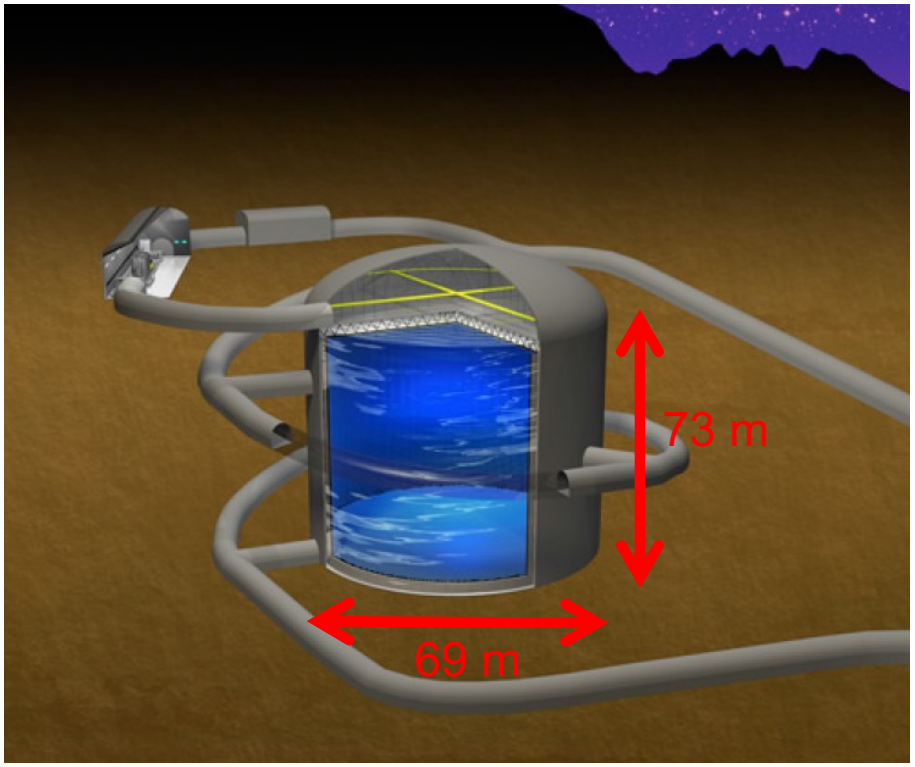
2. J-PARC beam upgrade

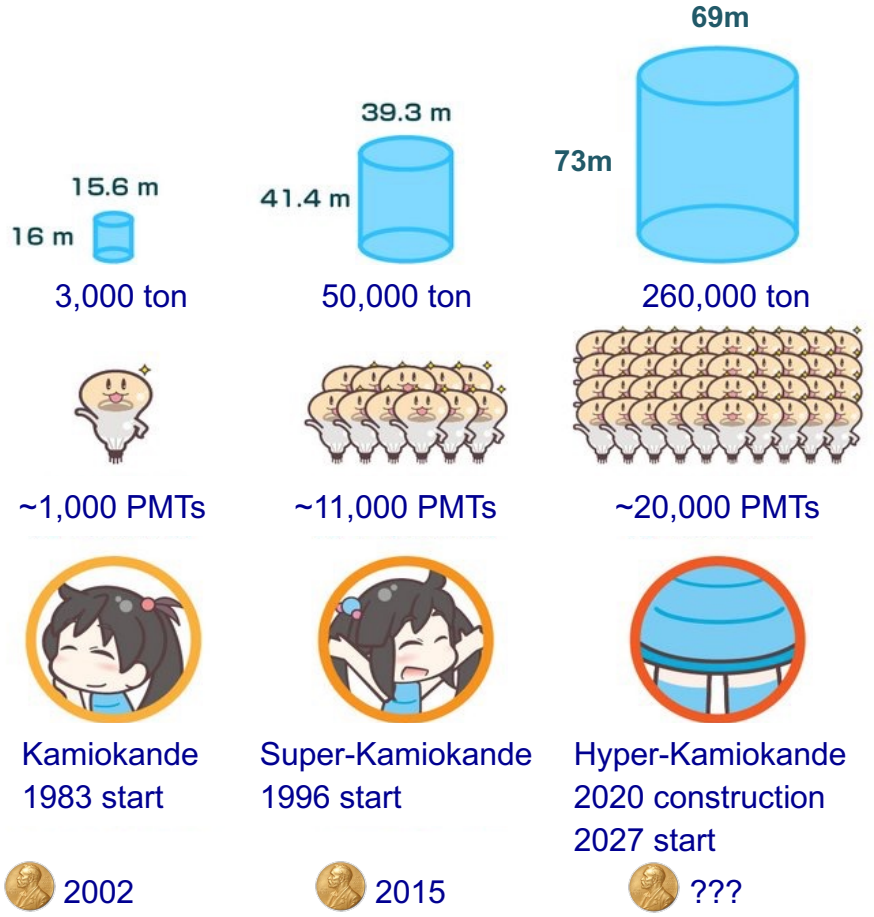
3. Near detector upgrade (ND280-upgrade, new near detectors like IWCD, intermediate water Cherenkov detector)

This talk mainly cover the status of (1)

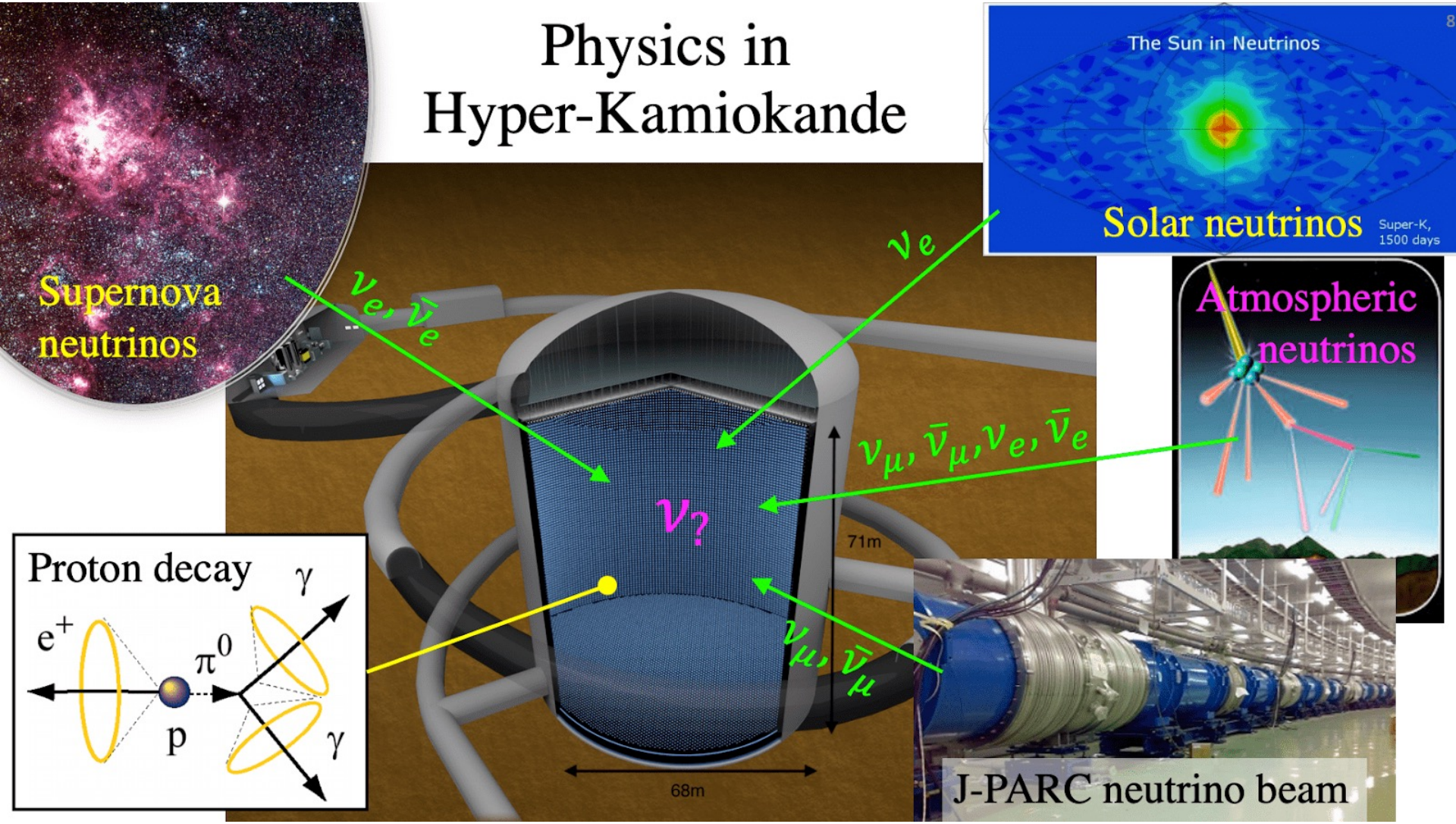
1. Hyper-Kamiokande detector

3rd generation of Kamioka water Cherenkov detector
- Inner detector volume ~220 kton, fiducial volume >188 kton
- > x8 fiducial volume of Super-K



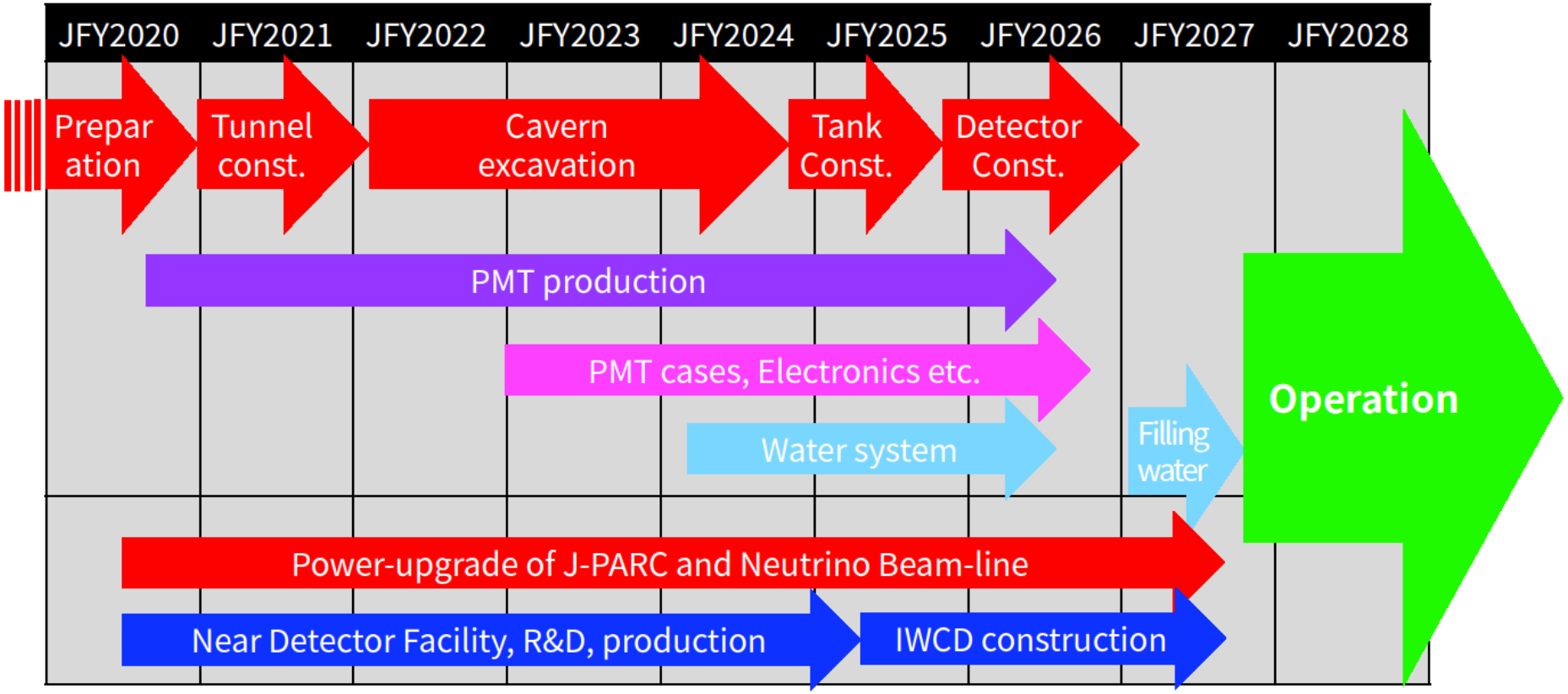


1. Hyper-Kamiokande detector



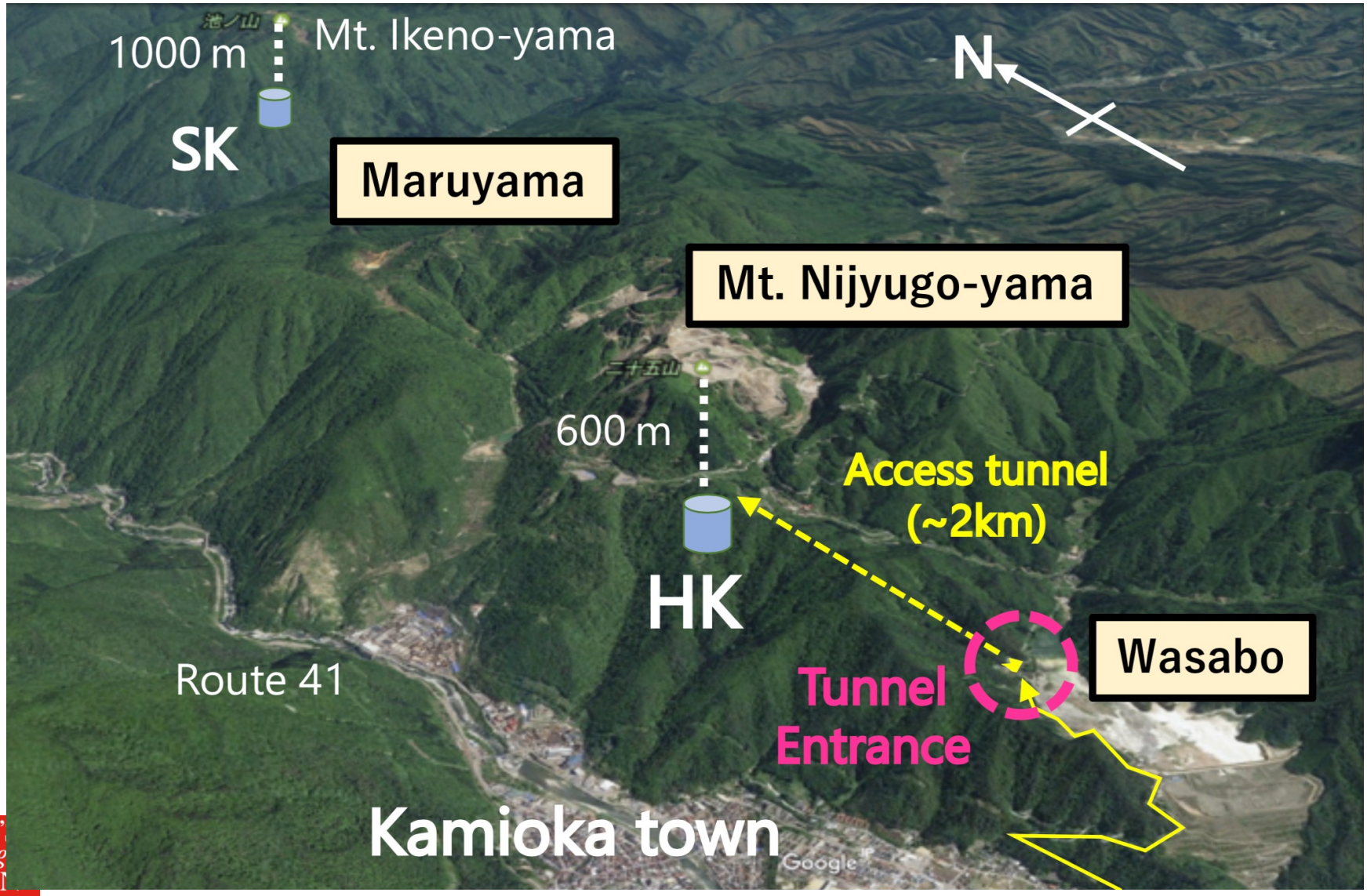
1. Hyper-Kamiokande project

2027 operation start
- R&D of all stages are finishing
- Site excavation finishing
- PMT mass production continuing (already delivered, QA finished > 10,000 PMT



1. Hyper-K site

Tochibora mine in Kamioka town



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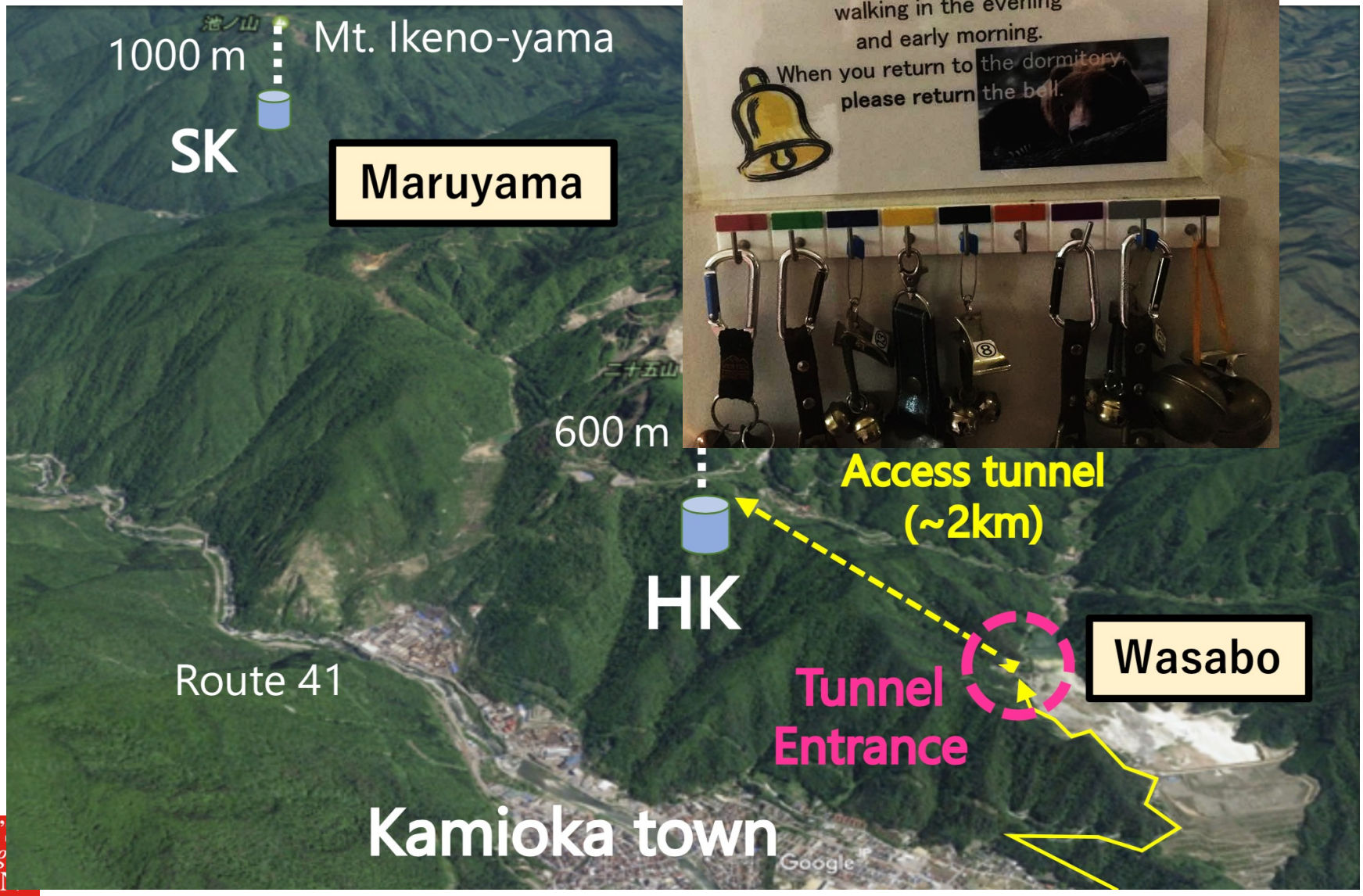
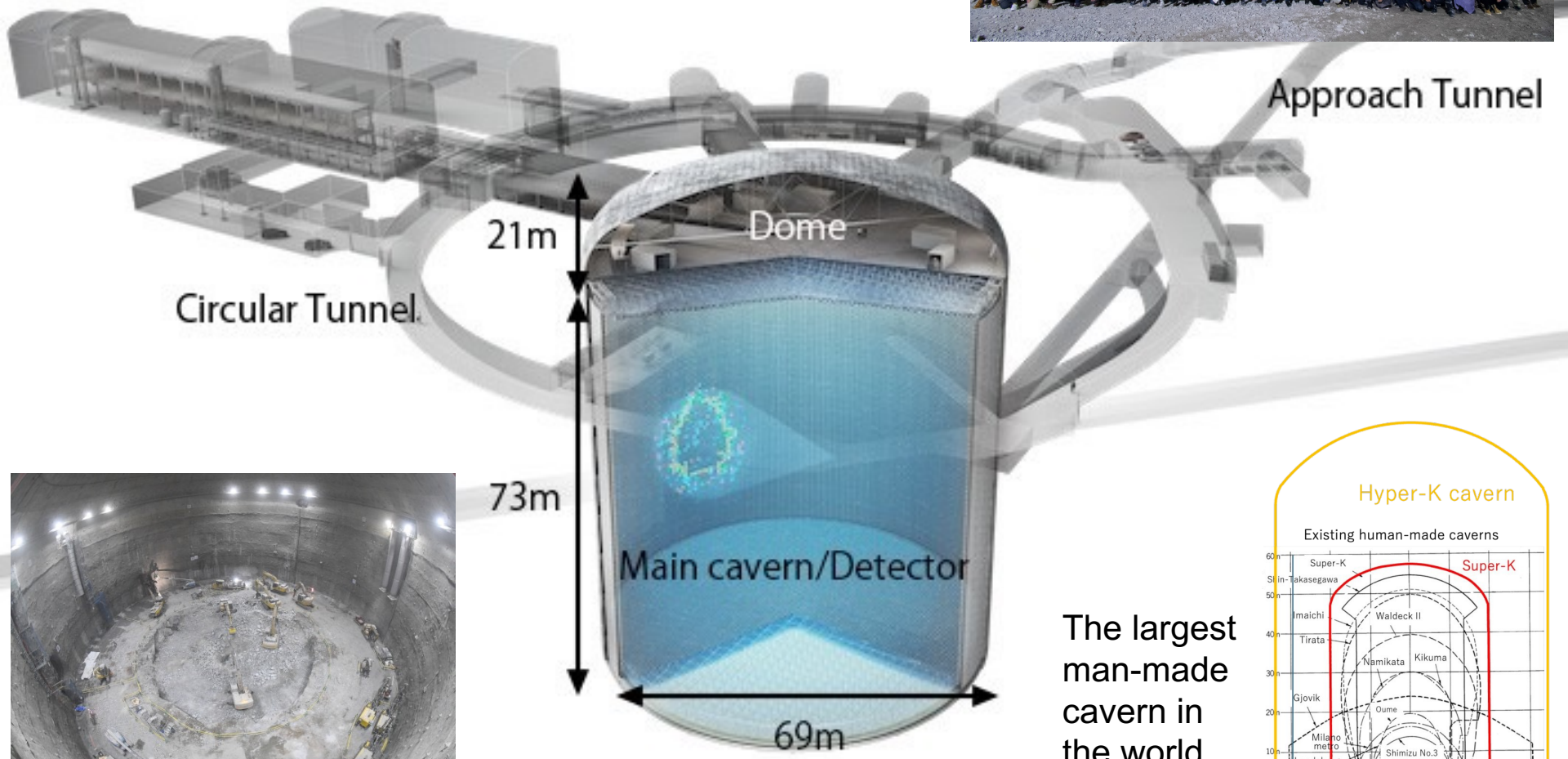


1. Tunnel construction

Horizontal access to the detector by car
- All tunnels: completed
- Cavern excavation: finish in this year

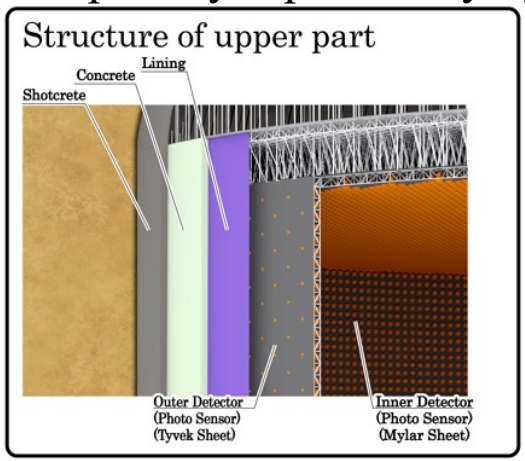


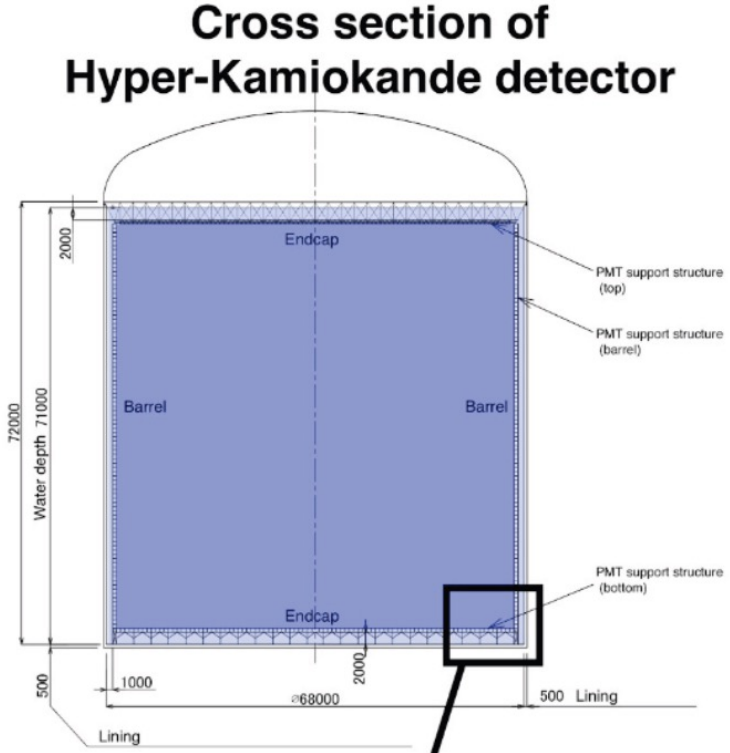
The largest man-made cavern in the world

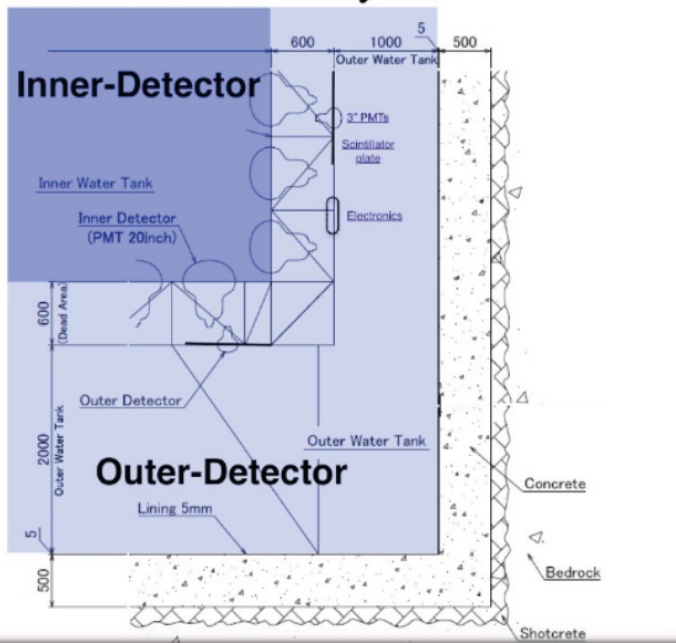
1. Hyper-K tank structure

Tank wall is protected by multiple layers

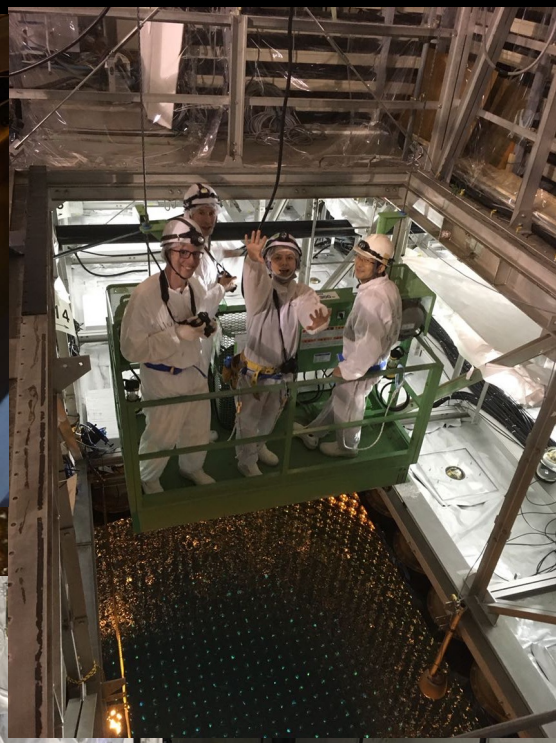
Inner detector (ID) and outer detector (OD) are optically separated by Tyvek and black sheets

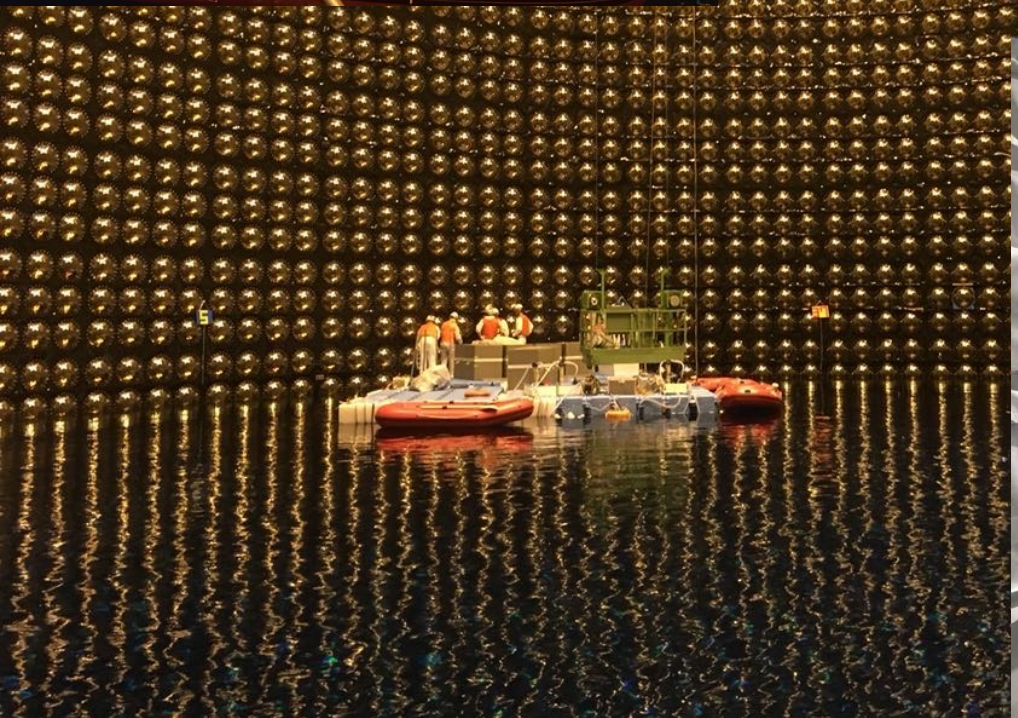






Super-Kamiokande detector refurbishment 2018





1. Detector construction

2. Inner detector system

3. Outer detector system

4. J-PARC beam upgrade

5. Near detectors

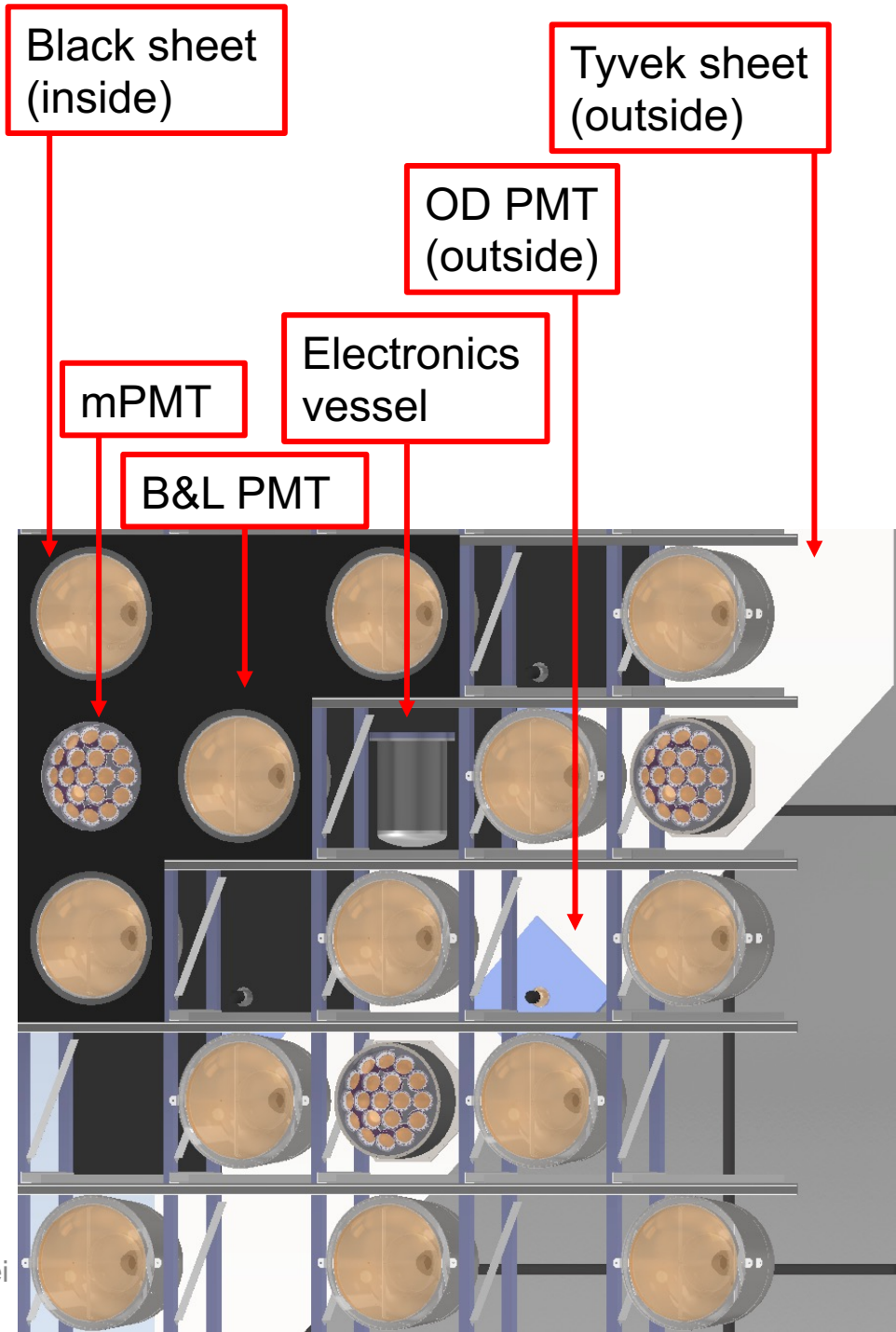
6. Conclusions

2. Hyper-K ID frame

ID PMTs, mPMTs, OD PMTs, in-water electronics, Tyvek and black sheets are all mounted on stainless streel frame

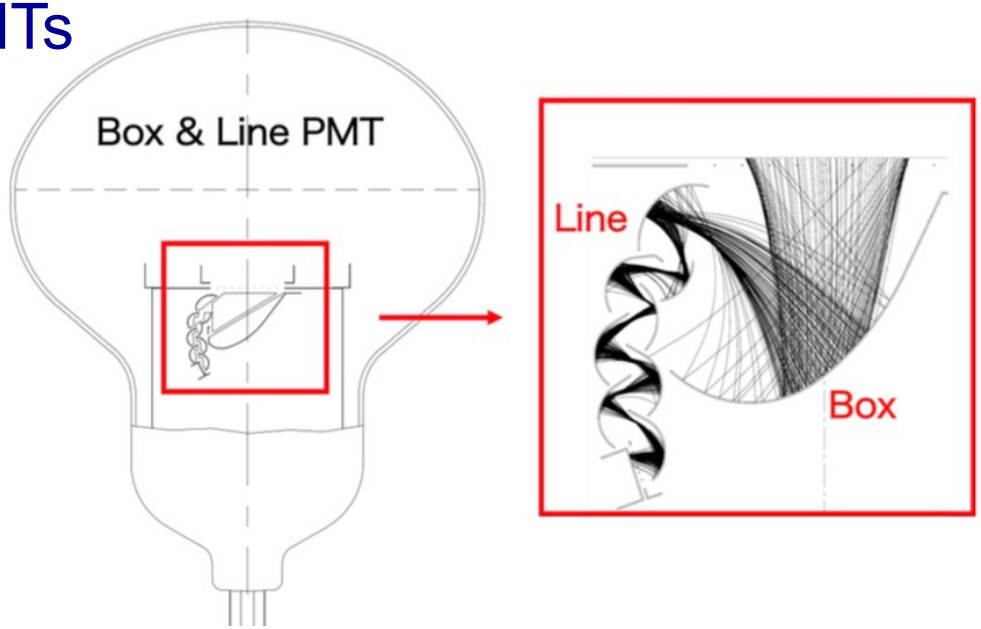
Each slot is 70cm x 70cm, and roughly 300 x 90 slots are available on barrel (70% filled)
- ~20,000 ID PMTs
- ~2,000 ID mPMTs
- ~7,000 OD PMTs

Super-K 2018 refurbishment

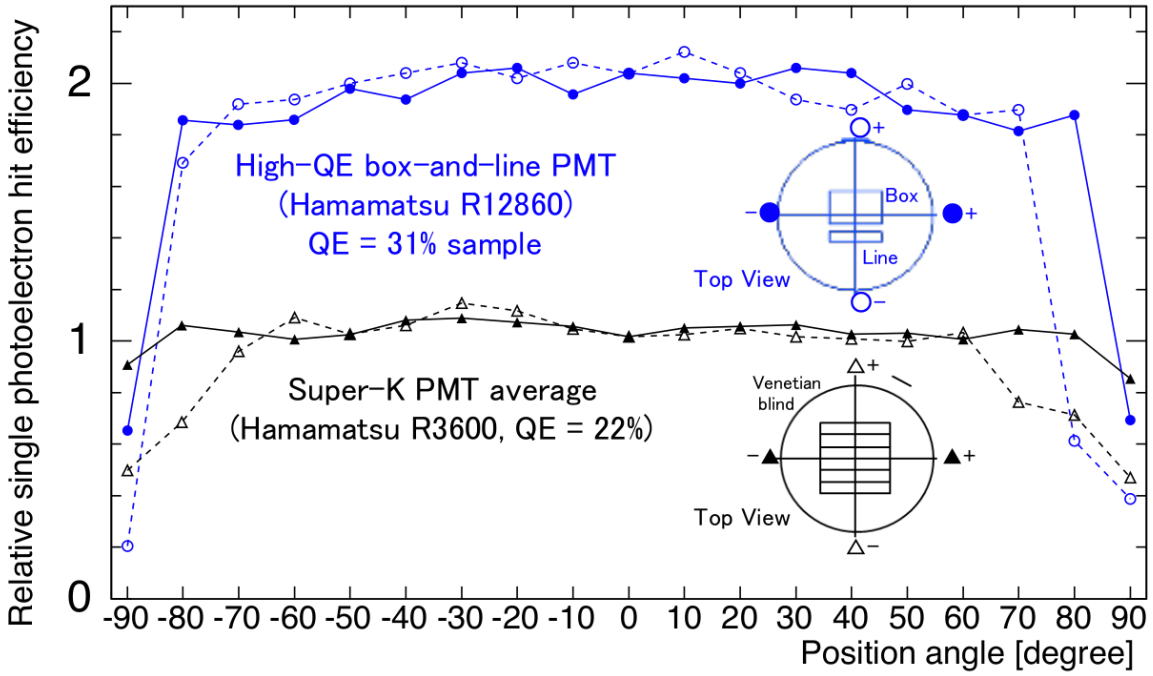


2. Hyper-K ID PMTs - B&L PMTs

R12860, new generation 50cm PMT
- Box and Line dynode structure
- 50% higher quantum efficiency (30%)
- x2 better charge resolution (30%)
- x2 better timing resolution (1.5ns)
- Stay on the same dark rate (4kHz)
- Performance tested in Super-K



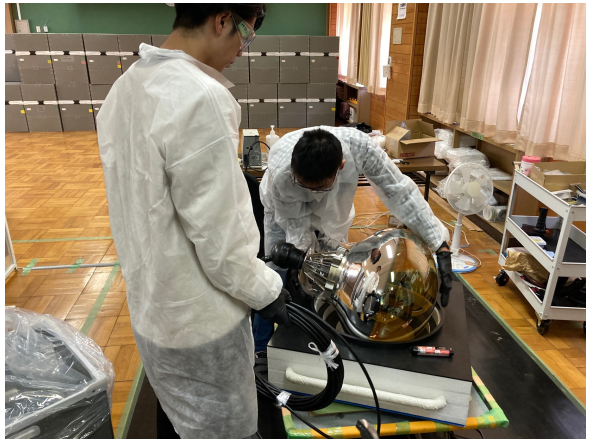
134 Hyper-K B&L PMTs are installed
(2018 refurbishment)



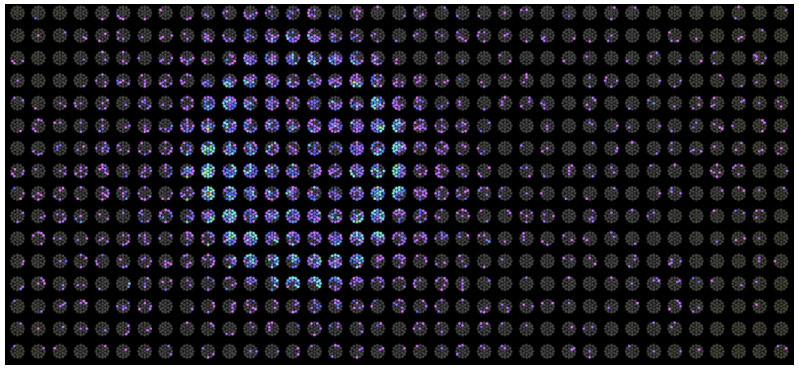
KING'S College LONDON

1. Hyper-K ID PMTs - B&L PMTs, production status

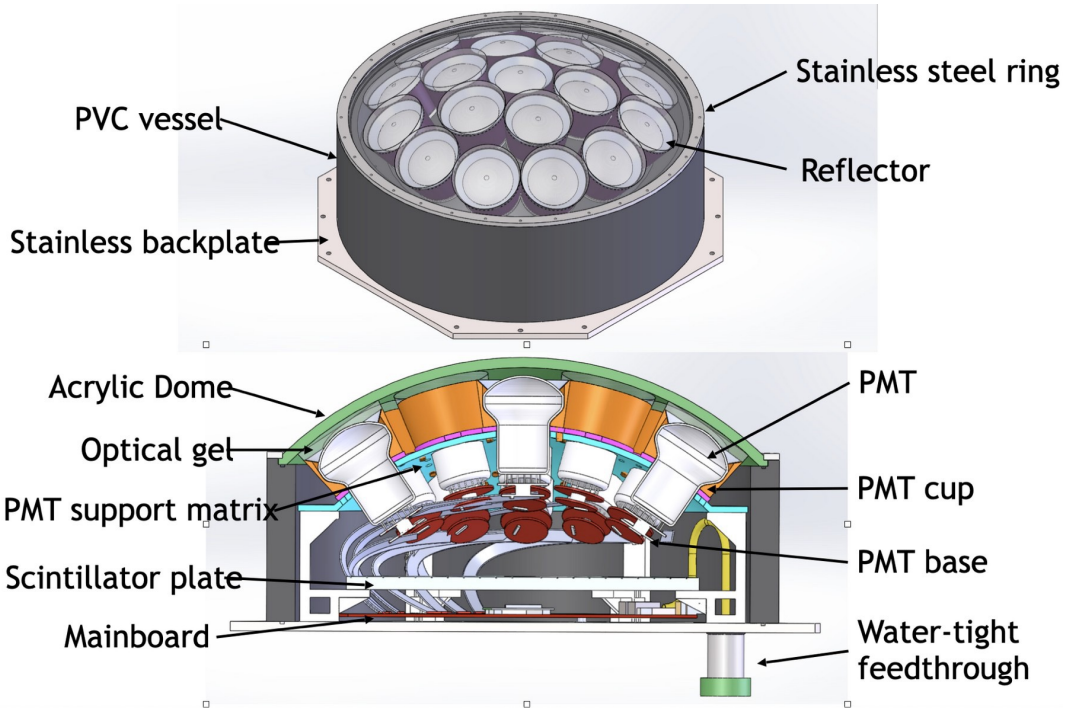
B&L PMT mass production
- So far >10,000 PMTs are delivered
- QA, Signal check + visual check
- QA shifts taken by collaborators



1. Hyper-K ID PMTs - mPMTs



KM3NeT-based design
- 19 3-inch PMTs, lower noise
- half photo-cathode coverage of B&L PMT
- C-W base and electronics
- High-granularity, photon direction information



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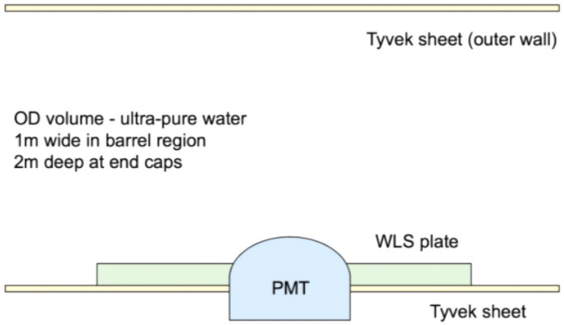
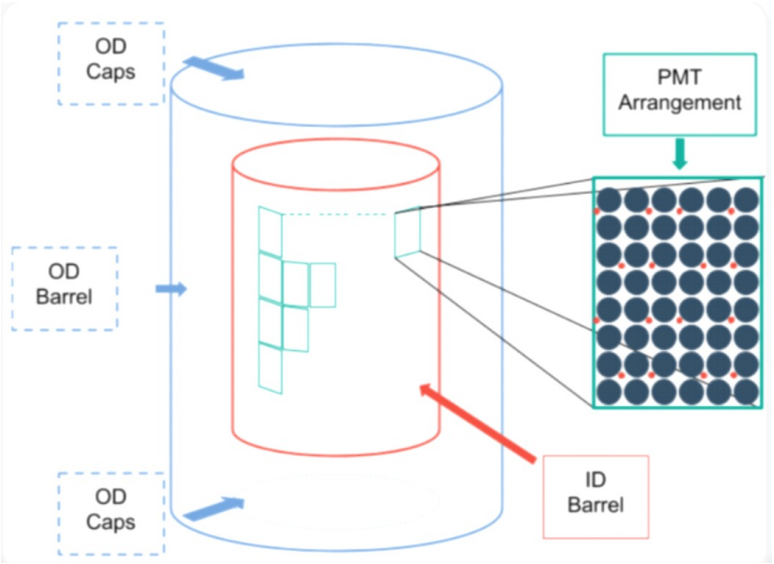
3. Hyper-K outer detector system



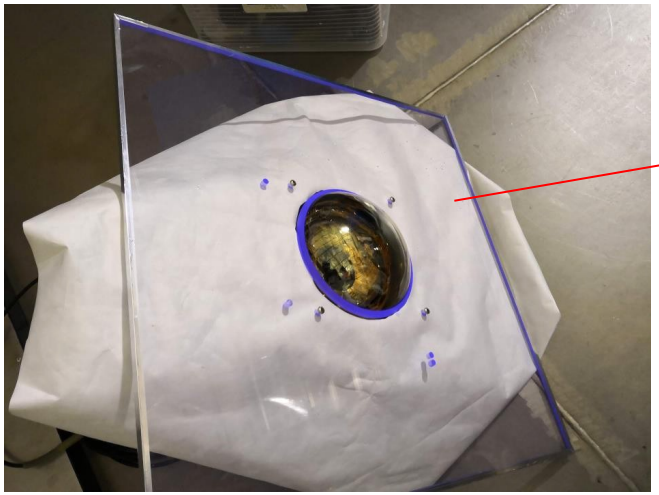


Hyper-K OD system

- 3-inch PMT
- WLS plate
- Tyvek sheet

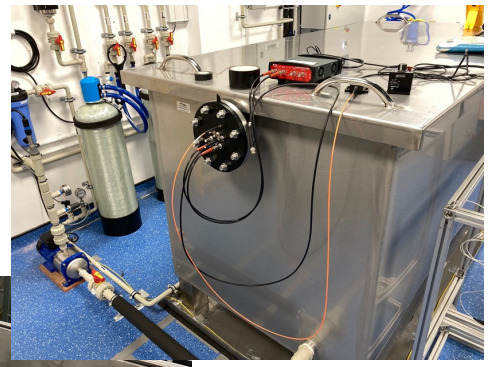
Cosmic ray rate 2Hz (SuperK) → ~45Hz (HyperK)

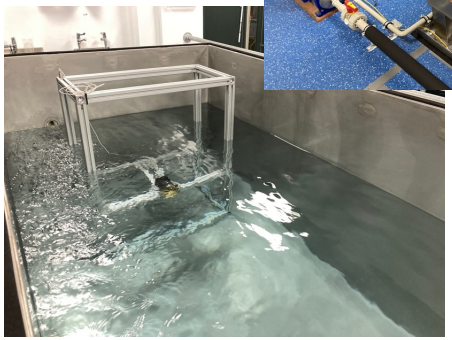
- Bigger than SuperK (50kton→260kton)
- Shallower overburden than SuperK (1000m→600m)
- Narrower barrel OD region (2m→1m)
- Baseline design → >3000 units of 3-inch PMTs + 30cm x 30cm WLS plate



3. Hyper-K outer detector system

King's ultrapure water system





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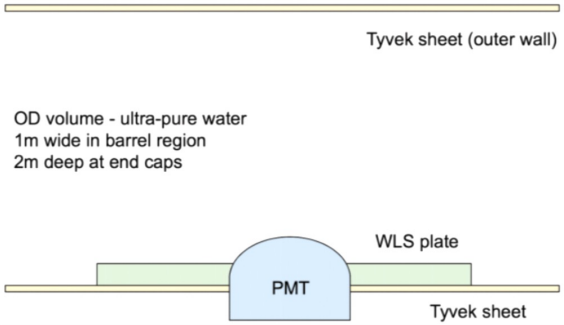


King's ultrapure water system

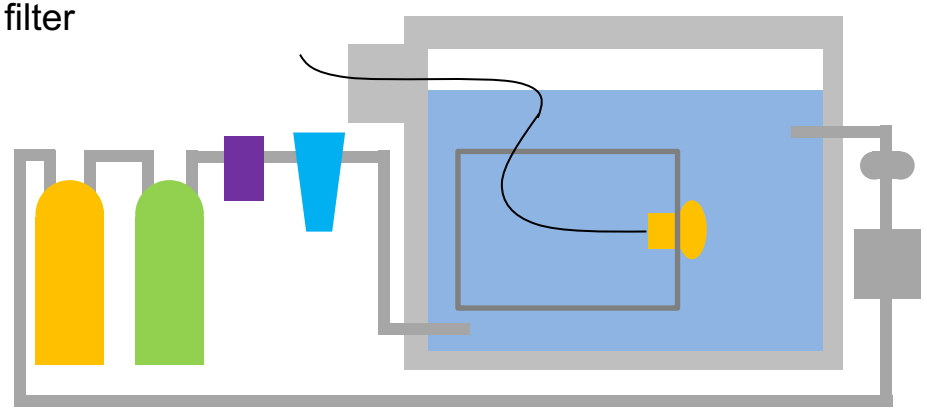
- 2000 L
- Copy of the Sheffield ultrapure system
- Purity, 16(out)-18(in) MΩ•cm
- Temperature control through heat exchanger (14°)

carbon filter

nuclear filter

UV lamp

micro filter



pump

heat exchanger

3. Hyper-K outer detector system

Hyper-K OD system
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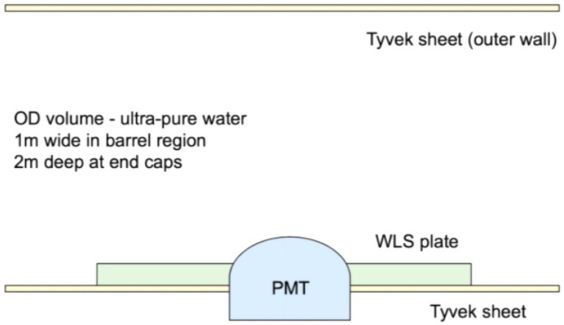
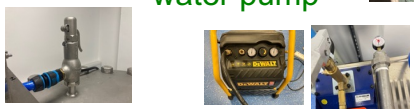
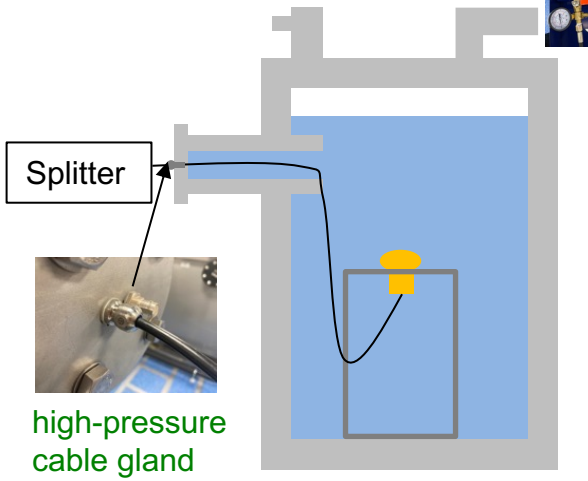


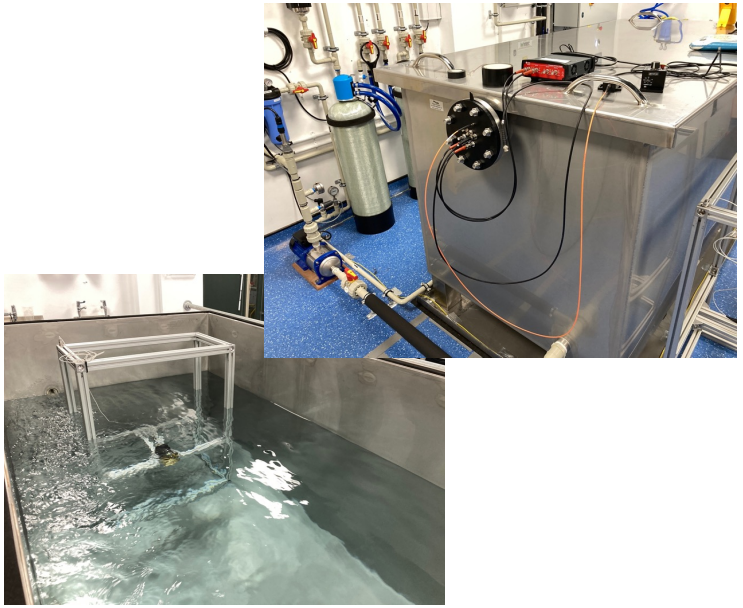
King's ultrapure water system
- 2000 L
- Copy of the Sheffield ultrapure system
- Purity, 16(out)-18(in) MΩ•cm
- Temperature control (14°)

King's pressure vessel
- 300 L
- rated 10 bar
- Pressurize with air or water

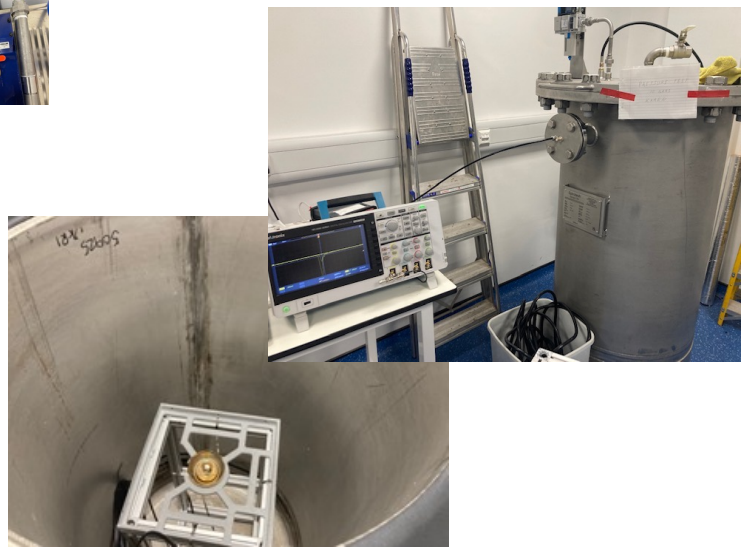




King's ultrapure water system



King's pressure vessel



3. Hyper-K outer detector system

Hyper-K OD system
- 3-inch PMT
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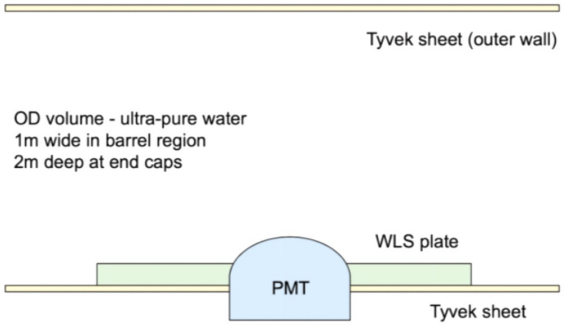
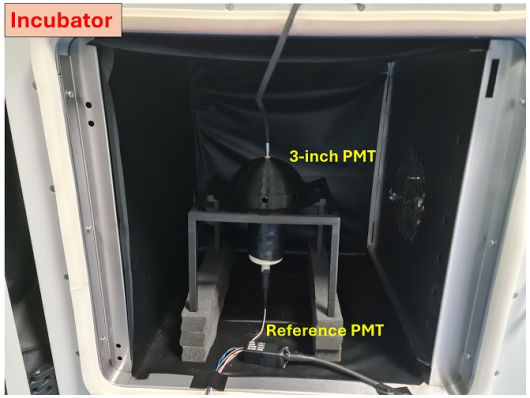
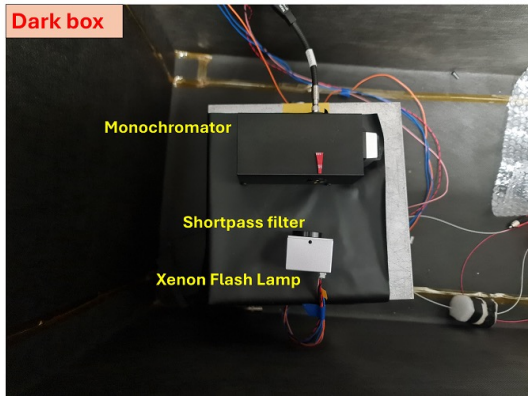
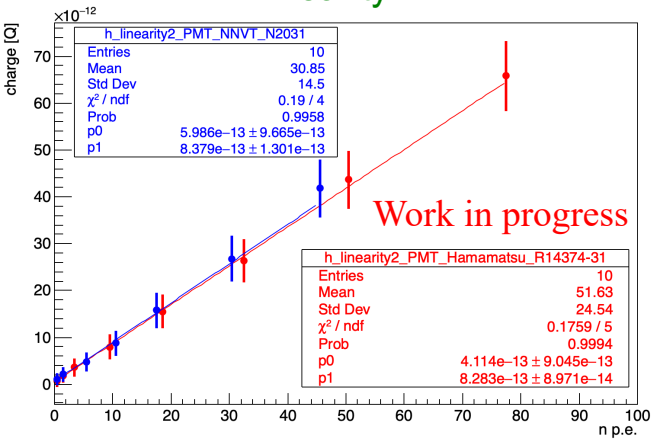




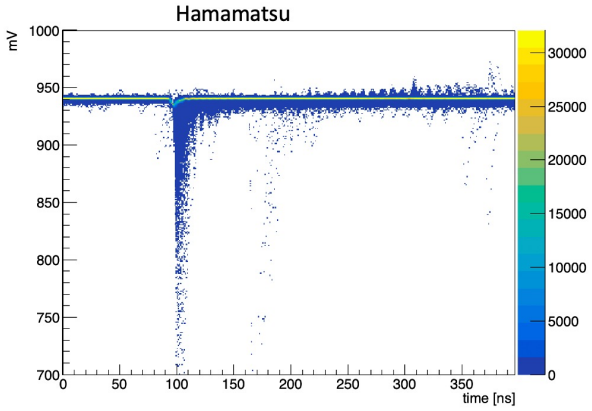
Hamamatsu vs NNVT
- 3-inch positive HV PMTs (1 cable operation)
- reasonable noise, after pulse, linearity, QE efficiency, gain
- low failure rate is the key (base, waterproof, cable, connector)

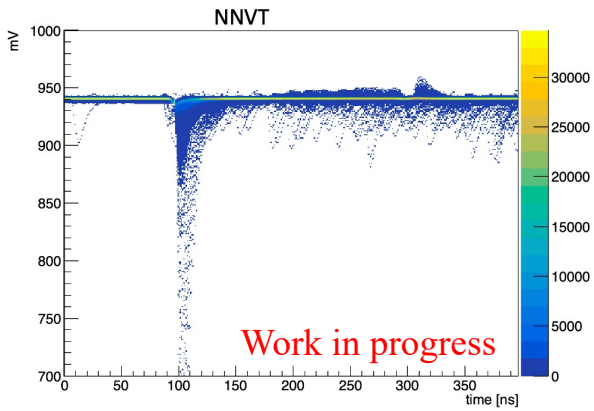


Linearity

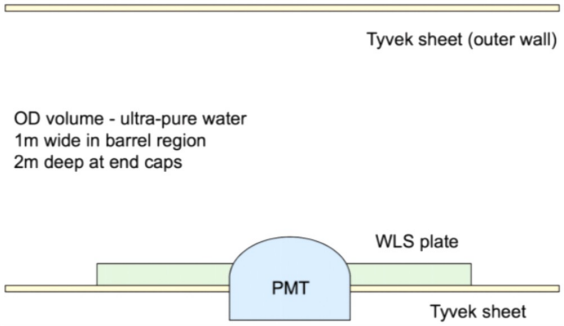


Accumulated waveform (dark rate, late pulse)



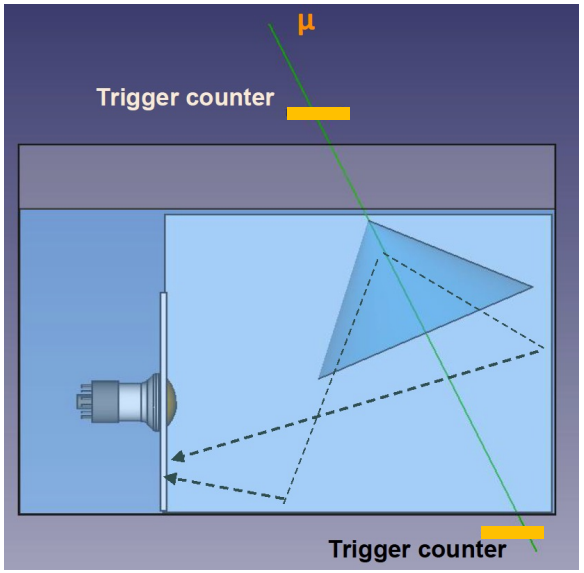


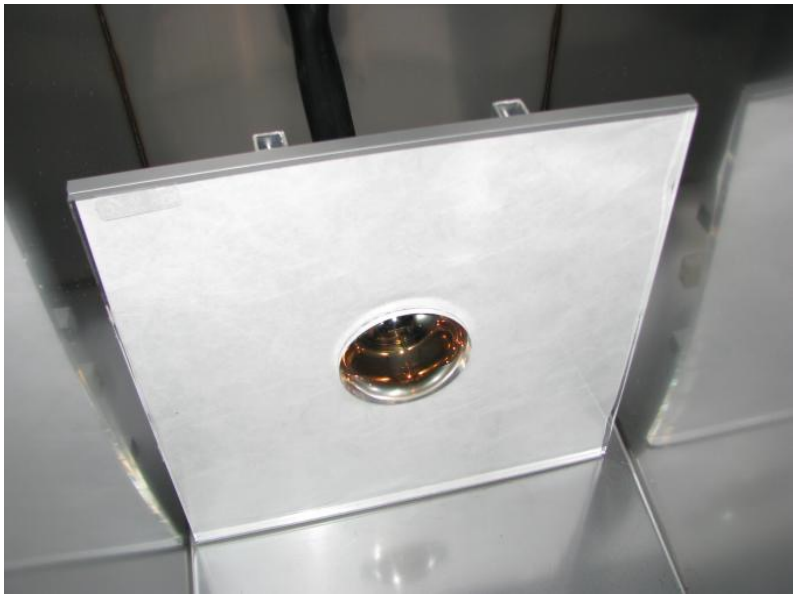
3. Hyper-K outer detector system

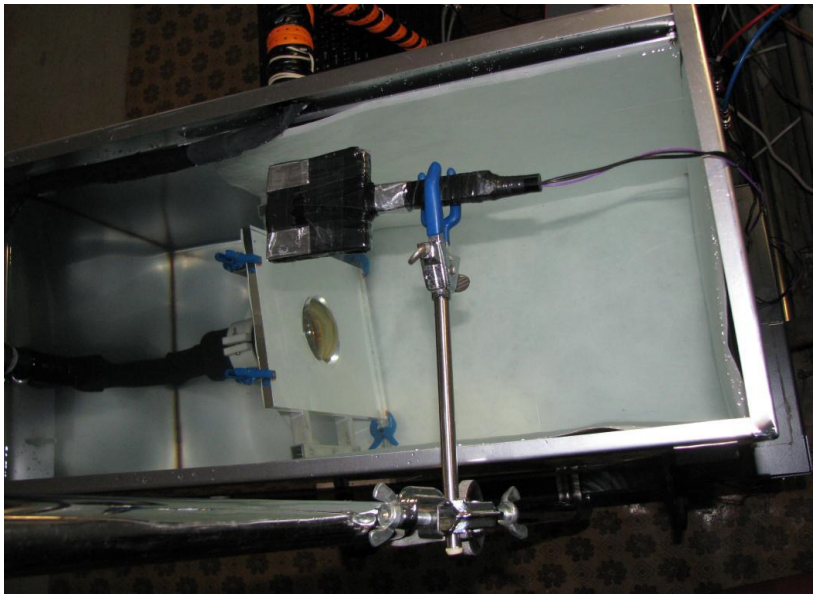


Hyper-K OD system
- 3-inch PMT
- WLS plate
- Tyvek sheet

Wave length shifting plate
-WLS plate performance is tested with cosmic rays







INR (Russia)

3. Hyper-K outer detector system

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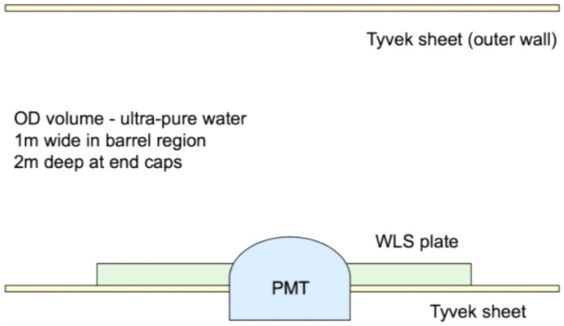
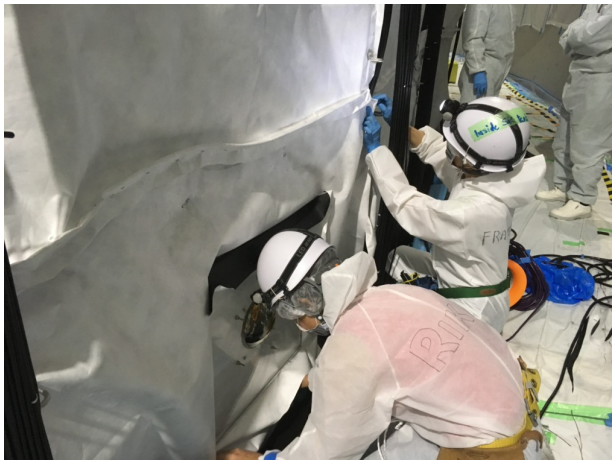
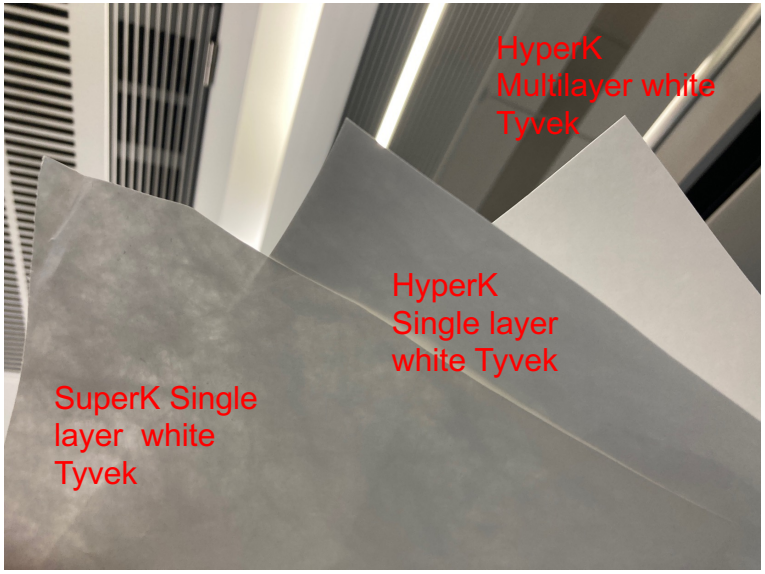
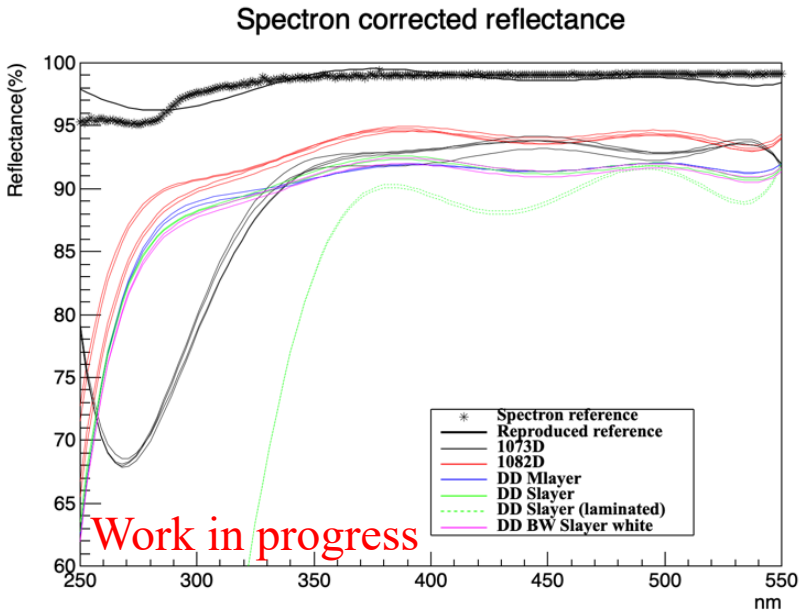




Super-K 2018 refurbishment

Requirement: >90% reflectivity





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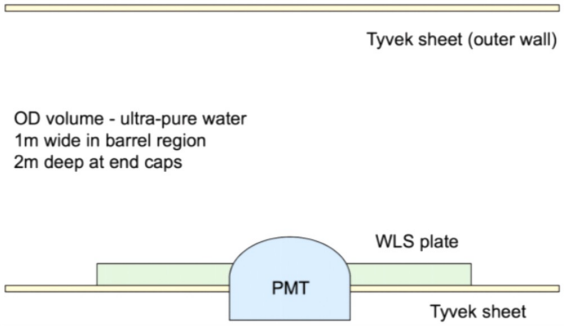
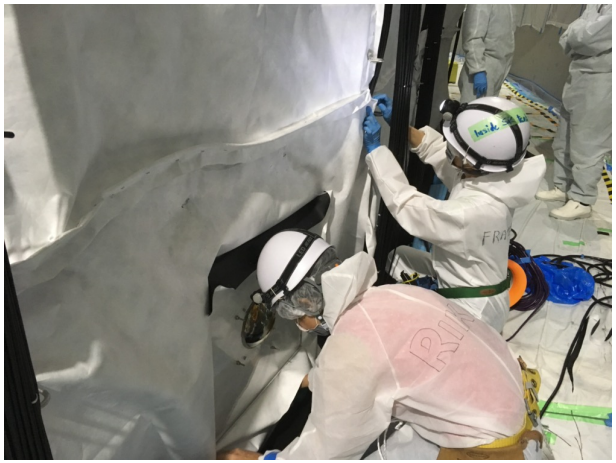


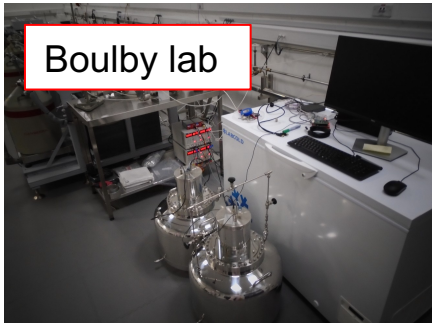


Super-K 2018 refurbishment

Requirement: >90% reflectivity
- UK installation frame for designing and practicing Tyvek installation

UK Hyper-K installation practice frame (Rutherford Appleton Lab)

3. Hyper-K material tests

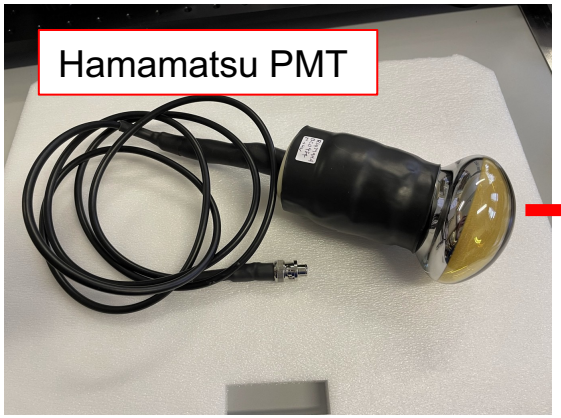


Soak tests
- UV transparency scaled to HyperK volume

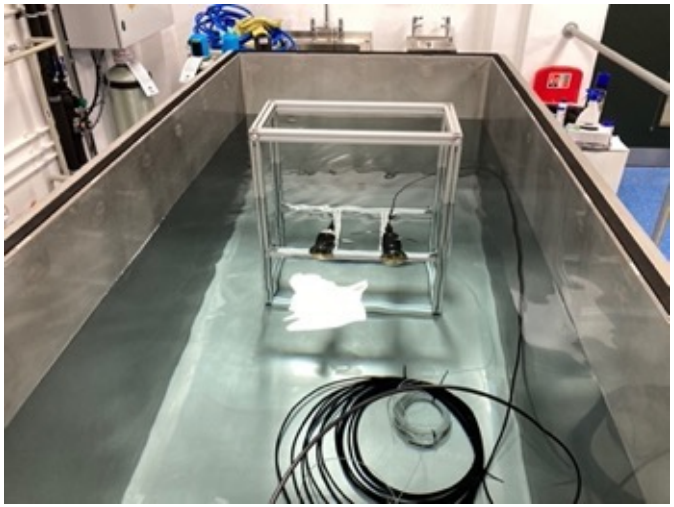
Radioactivity screening tests
- Boulby Underground Lab

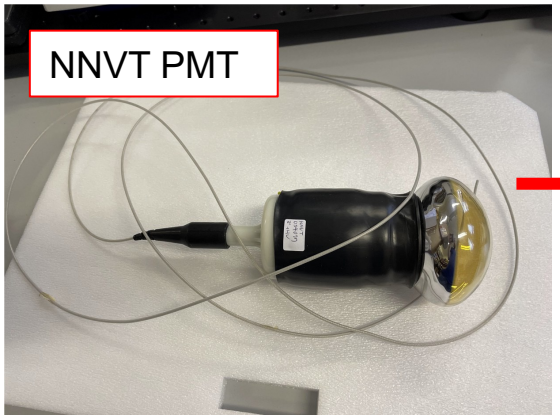
Aging test
- Ultrapure water system

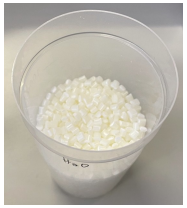
All of these shows mastic have issues but not show stopper



King's ultrapure water system







3. Hyper-K underwater connections

Underwater electronics

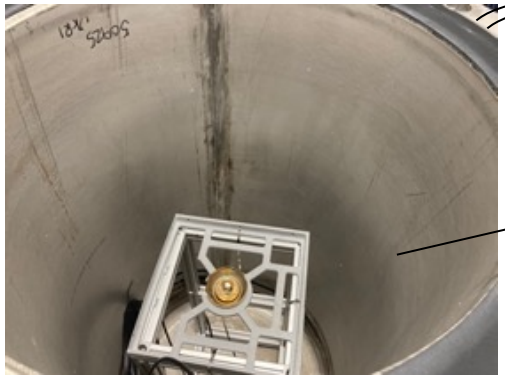
- Digitizer, HV power supply etc in electronics vessel
- Underwater cable connection, feed-through (~8 bar)

Each design is being finalized and integrated to one system

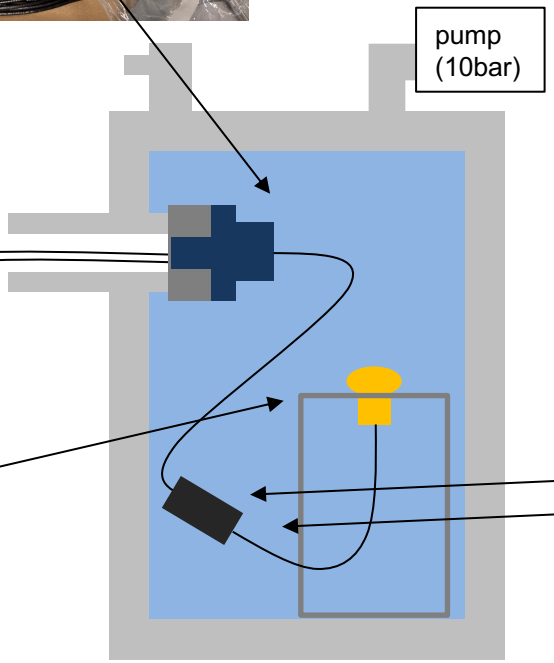
Issues, all custom-made
- Procurement
- Long lead time
- Frequent design changes

King's pressure vessel

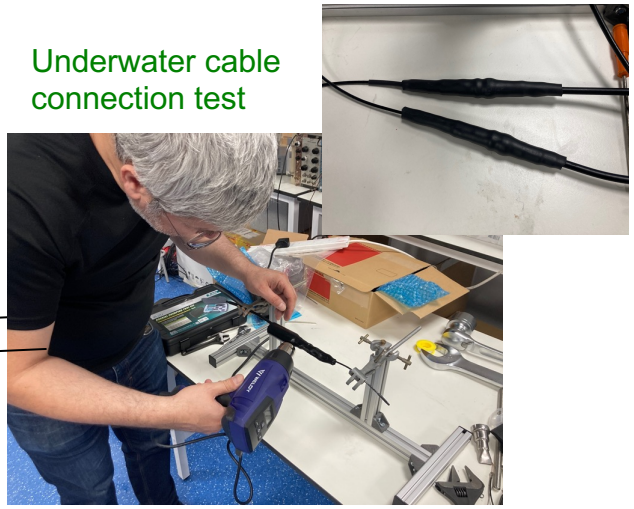
OD feedthrough test



OD PMT pressure test



Underwater cable connection test



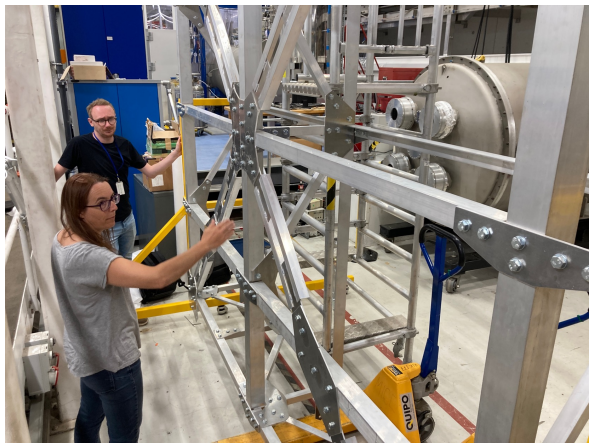
3. Hyper-K installation practice

All working group installation test (Japan)
- Raised many (minor) issues
- Second installation test soon

OD installation
- OD PMT unit (quick)
- Tyvek installation (time consuming), also it requires coordination with other groups

Optimization is necessary...

HyperK installation practice frame (ICRR, Japan)



UK installation practice frame (Rutherford Appleton Lab)

1. Detector construction

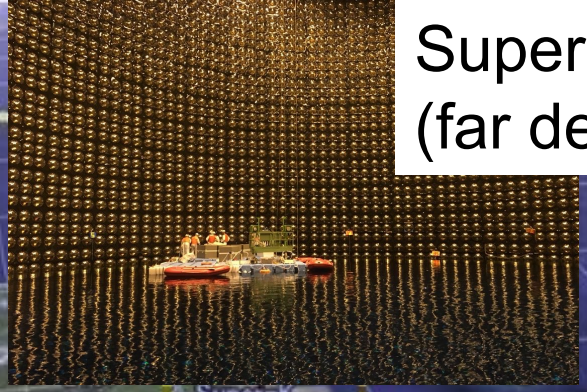
2. Inner detector system

3. Outer detector system

4. J-PARC beam upgrade

5. Near detectors

6. Conclusions



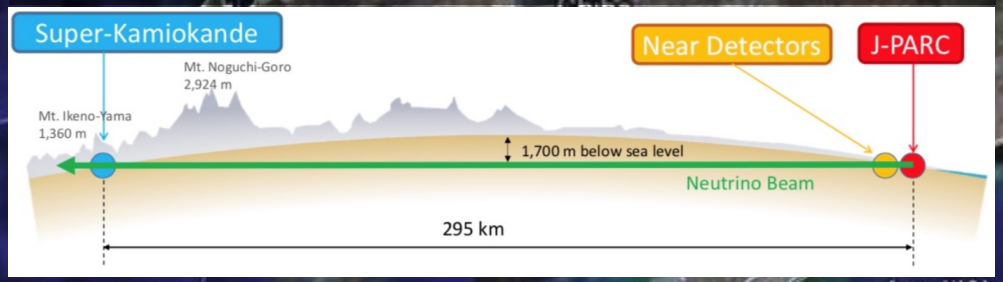
Super-Kamiokande detector (far detector)

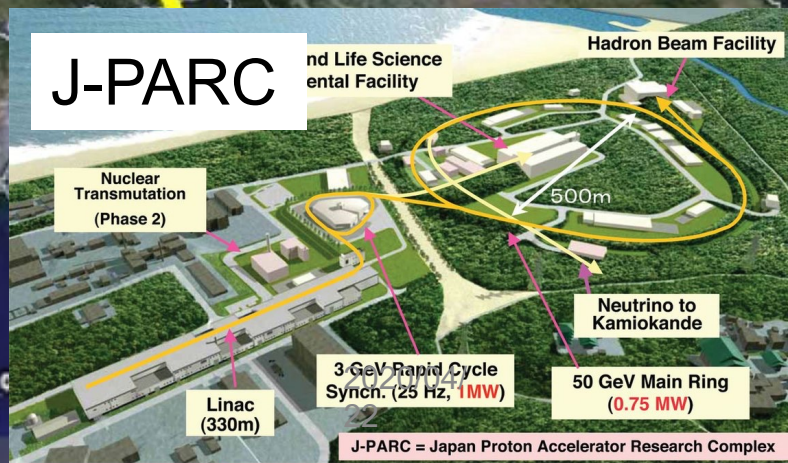
T2K

295km

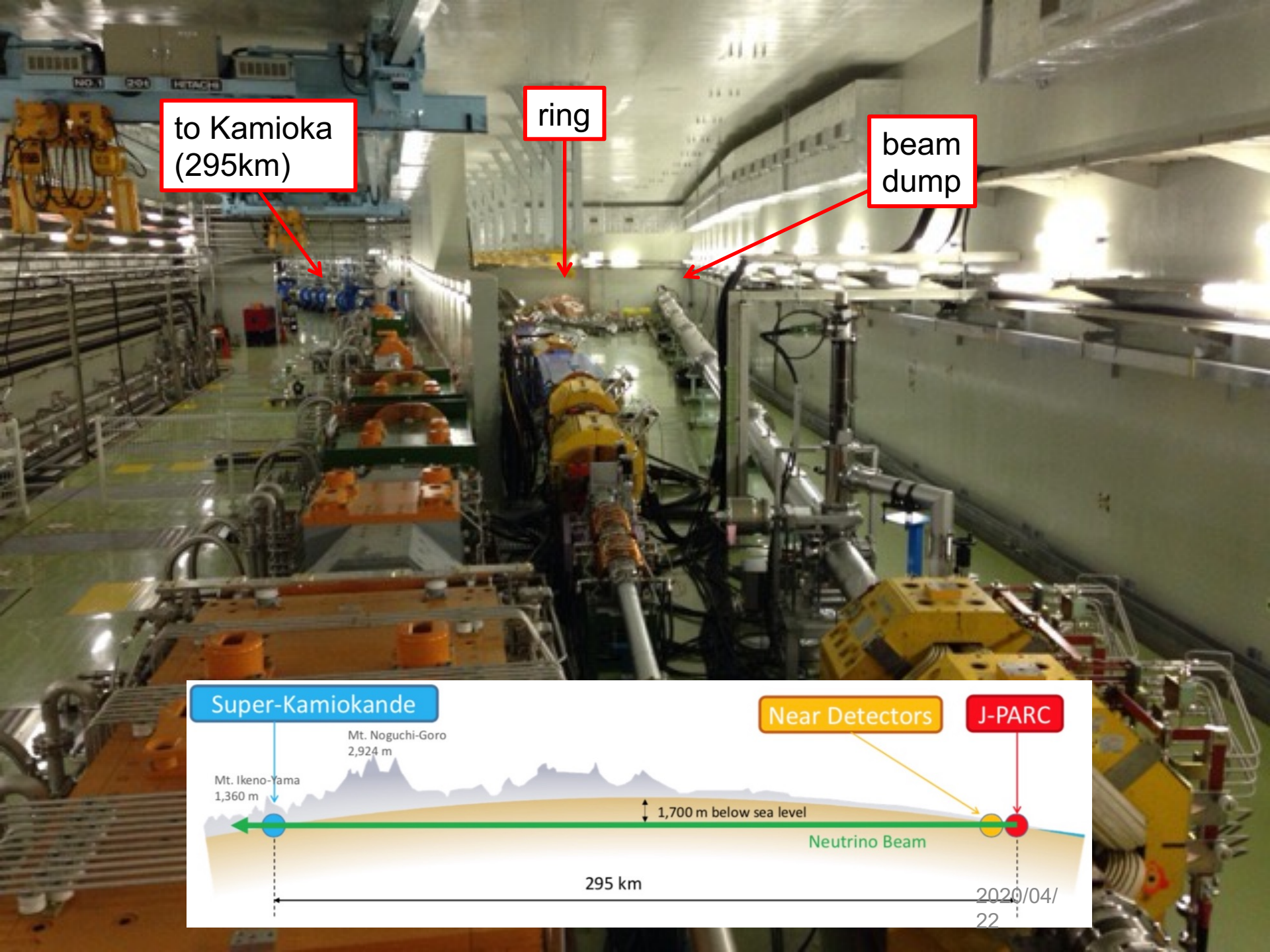
Neutrino beam

T2K (Tokai to Kamioka) experiment





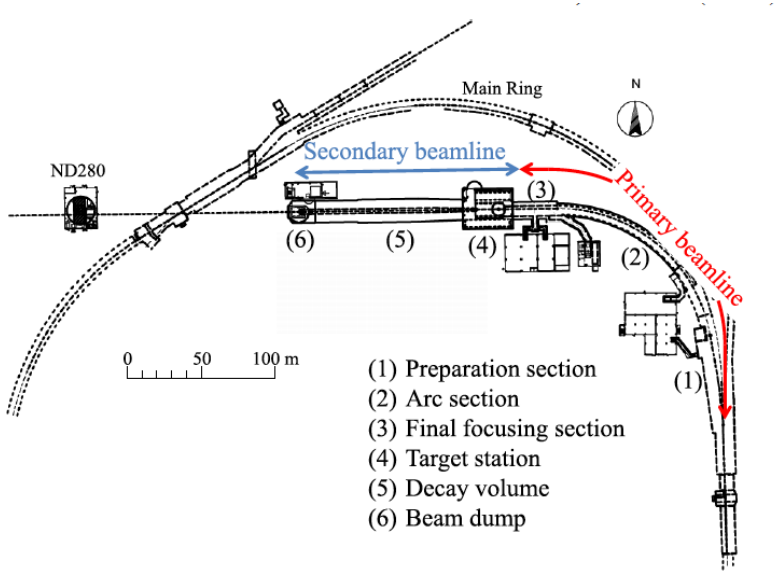

4. J-PARC
LINAC
- 400 MeV
RCS (Rapid Cycling Synchrotron)
- 3 GeV
To Kamioka
Neutrino
Main Ring
- 30 GeV

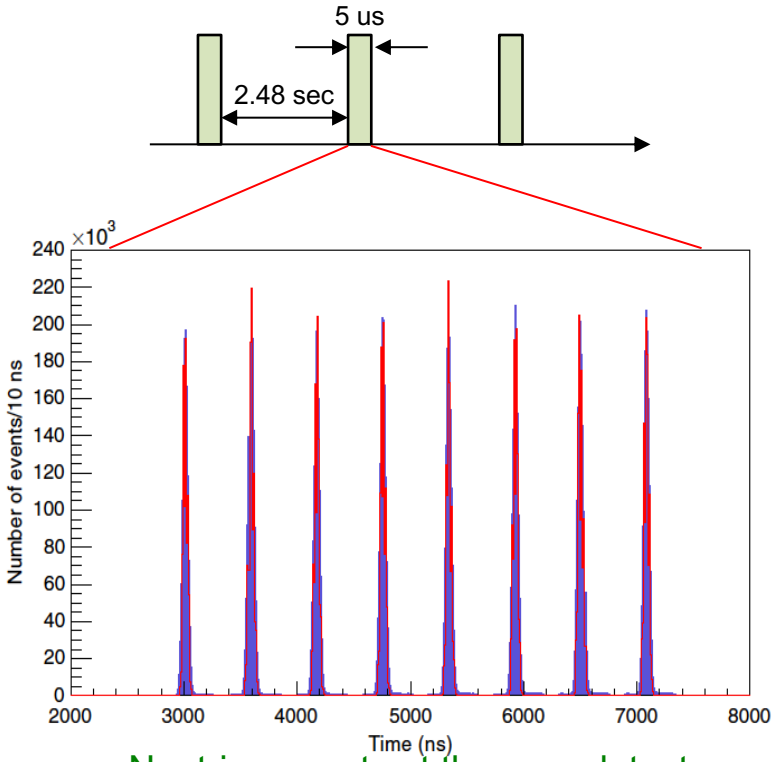

to Kamioka
(295km)
ring
beam
dump
Super-Kamiokande
Mt. Noguchi-Goro
2,924 m
Mt. Ikeno-Yama
1,360 m
1,700 m below sea level
Near Detectors
J-PARC
Neutrino Beam
295 km

4. Neutrino beamline

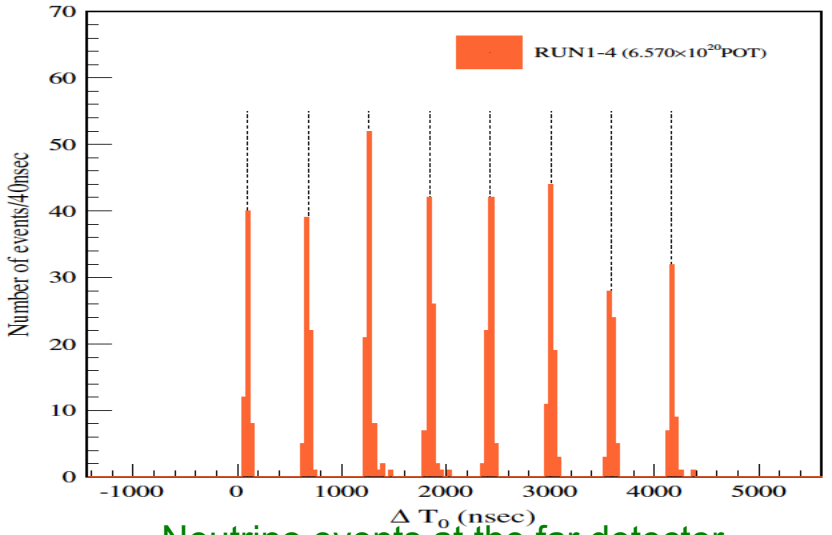
Primary beamline

- 30 GeV protons are extracted from MR
- 1 pulse = 8 bunches
- 1 bunch ~2.6E14 ppp (protons per pulse)





Neutrino events at the near detector



Neutrino events at the far detector

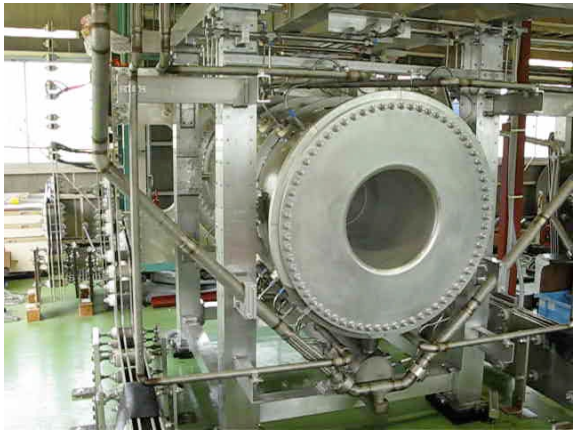
4. Neutrino beamline

Secondary beamline

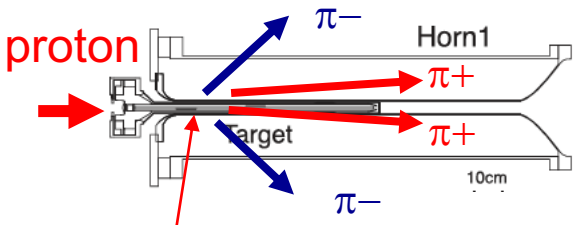
- 3 magnetic horns (flux ~x15), decay volume, beam dump
- Neutrino mode (forward horn current): focus π+, defocus π−
- Antineutrino mode (reversed horn current), focus π−, defocus π+

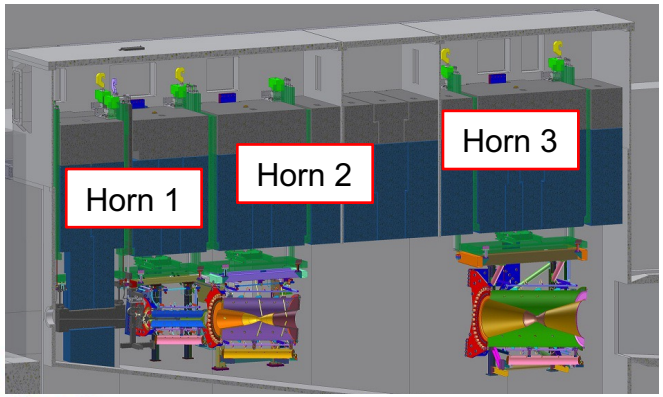
This is the sound of neutrinos!

Horn 3 test (250 kA, ~1.7 T)

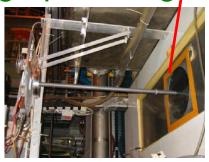


Horn 1 graphite target

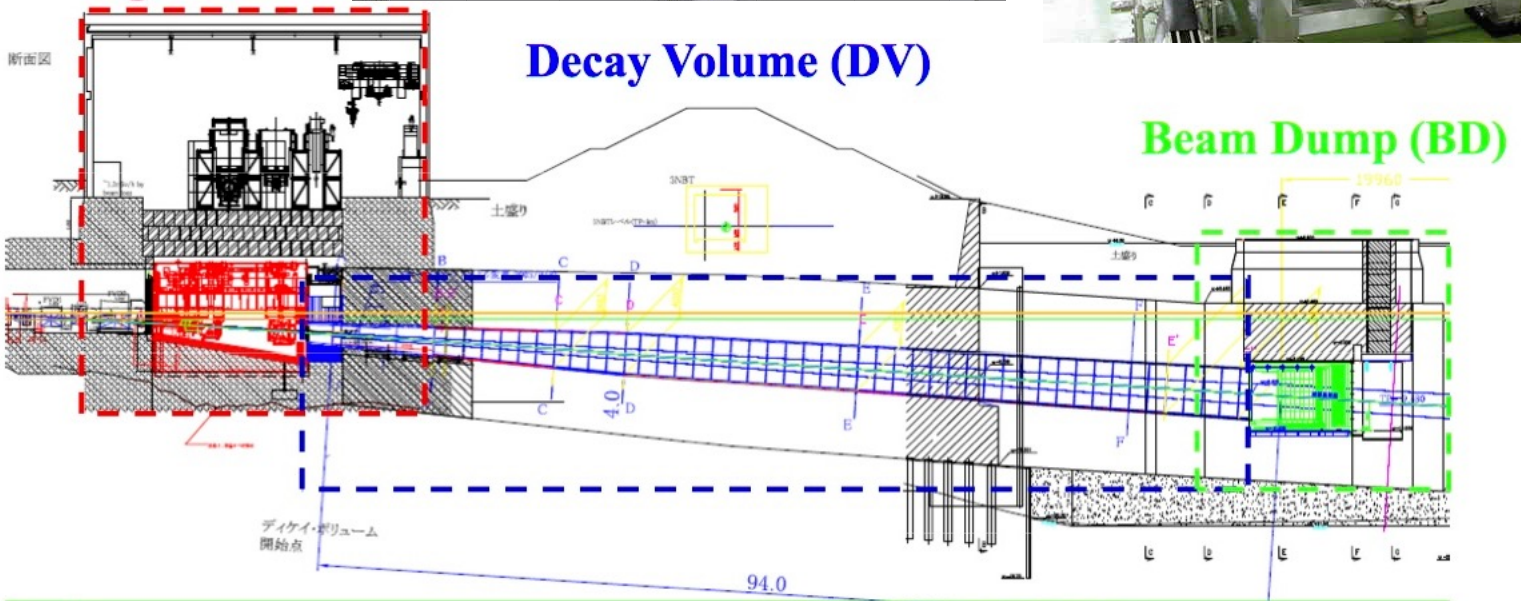




graphite target



Target Station



T2K, PRD87(2013)012001
NA61/SHINE, EPJC76(2016)84

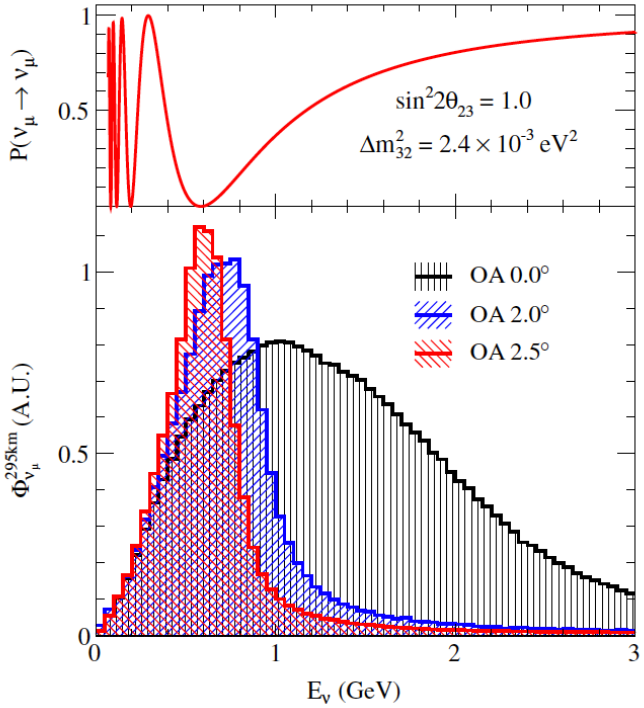
4. Neutrino beamline

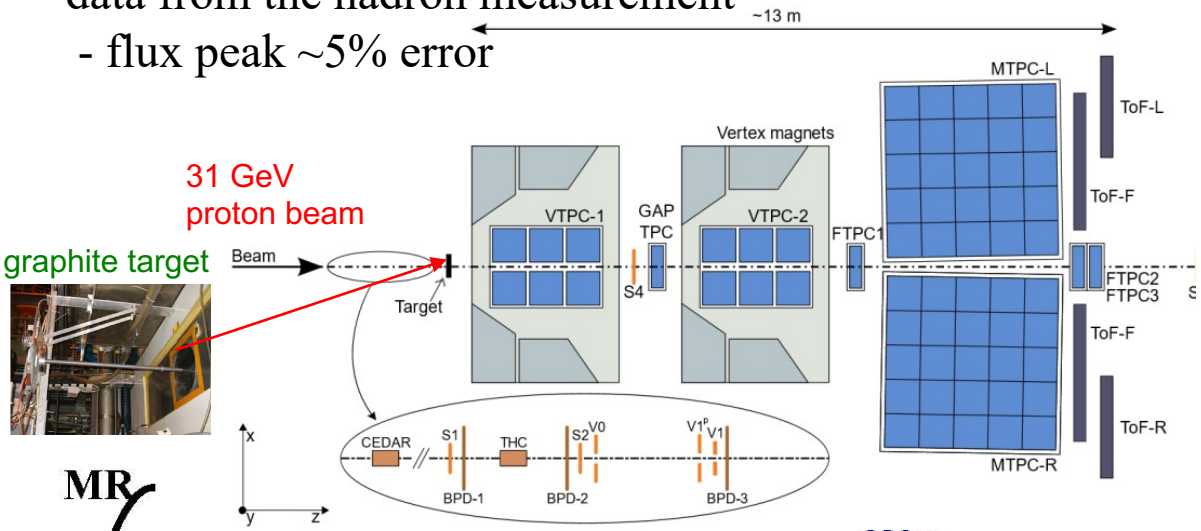
Off-axis beam

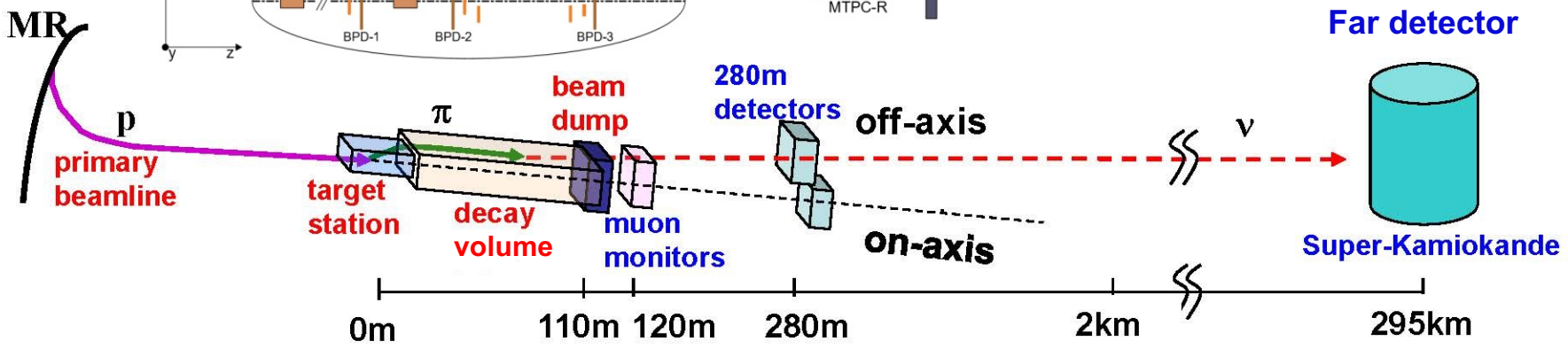
- 2.5° off-axis to make ~0.6 GeV narrow band beam

CERN NA61/SHINE

- Hadron production at the target is simulated with the data from the hadron measurement
- flux peak ~5% error







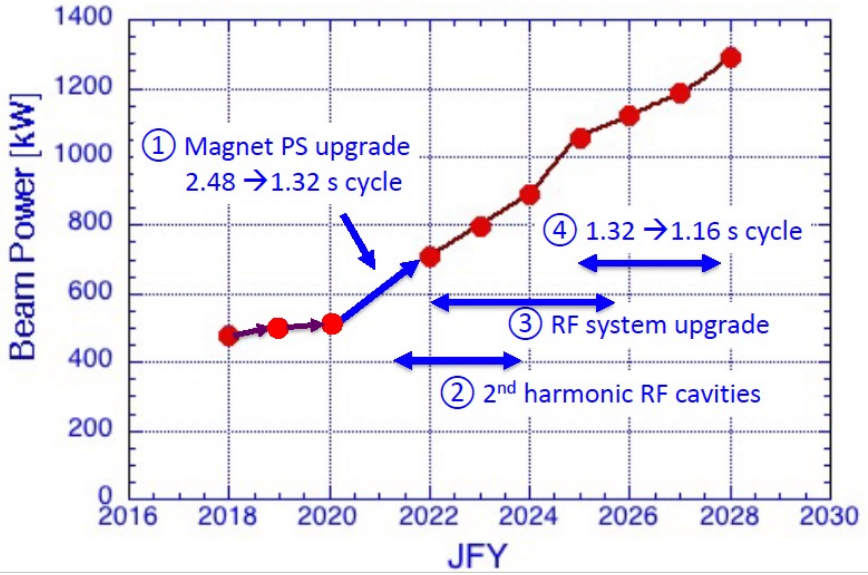
T2K, Arxiv:1908.05141

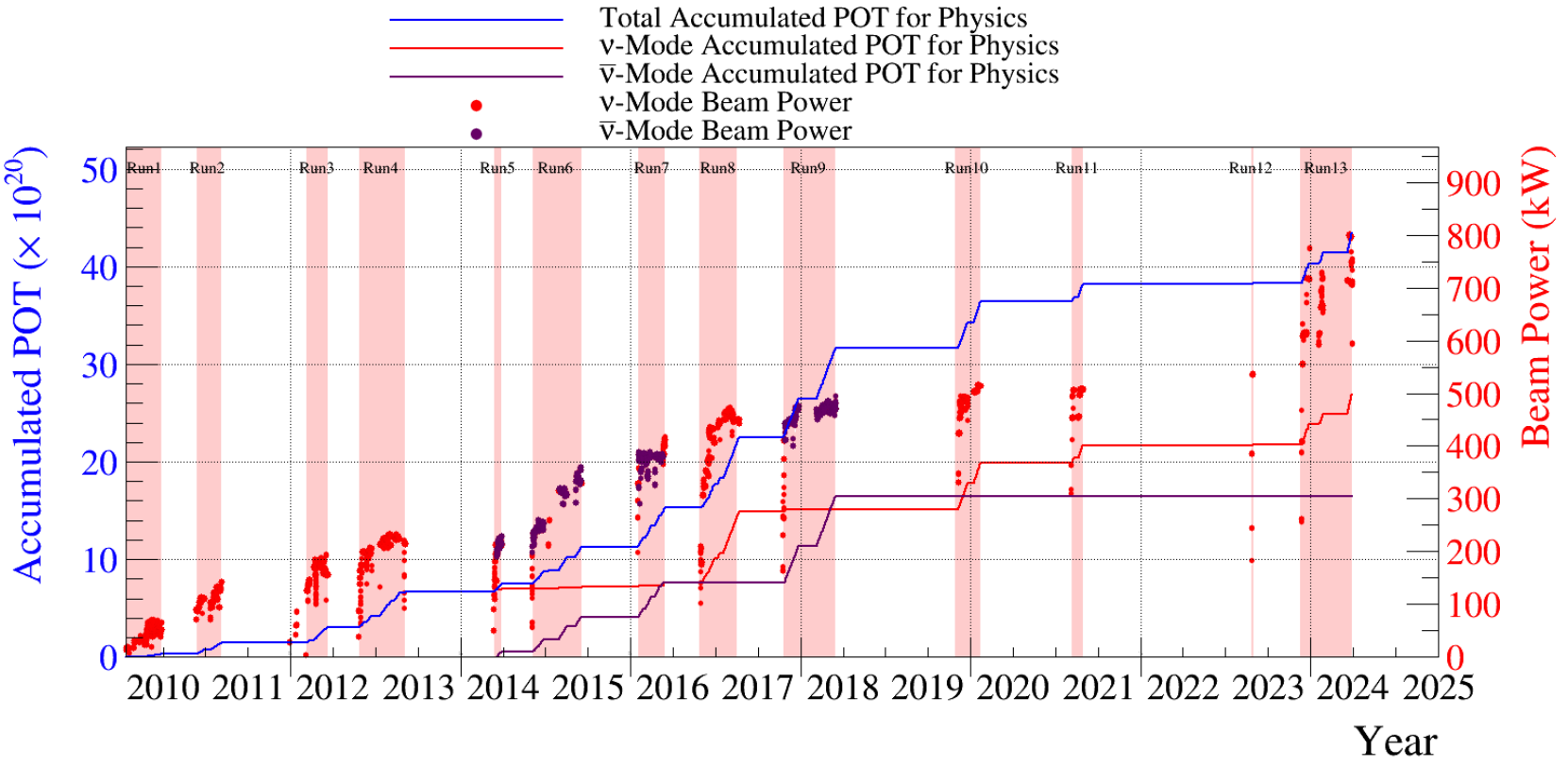
4. J-PARC Beam Upgrade

Key improvements

- Horn current 250kA → 320 kA (now)
- Cycle 2.48s → 1.36s (now) → 1.16s
- Proton per pulse 2.6E14ppp → 3.2E14ppp

Power 515kW → 800kW (now) → 1.3MW





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1. Detector construction

2. Inner detector system

3. Outer detector system

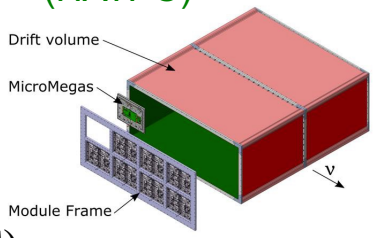
4. J-PARC beam upgrade

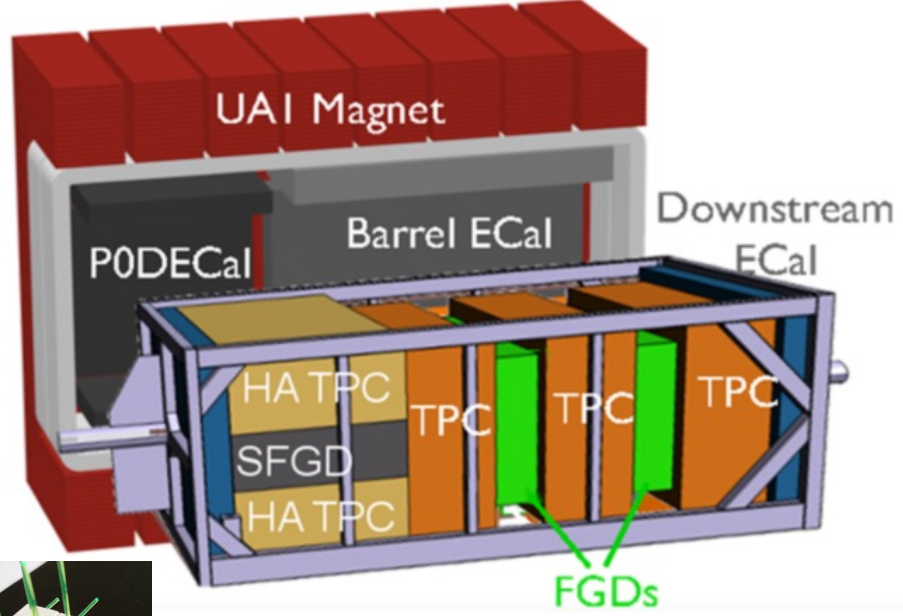
5. Near detectors

6. Conclusions

5. ND280 Upgrade

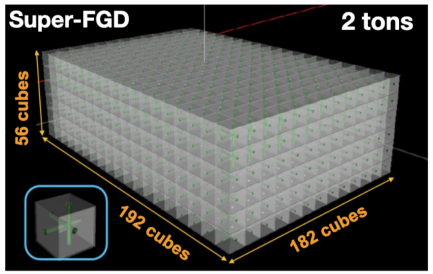
High angle TPC (HATPC)



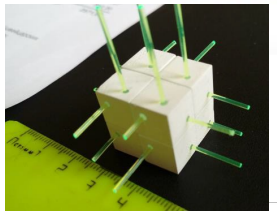


ND280 Upgrade

- Out: P0D detector
- In: High angle TPC (HATPC)
- In: SuperFGD

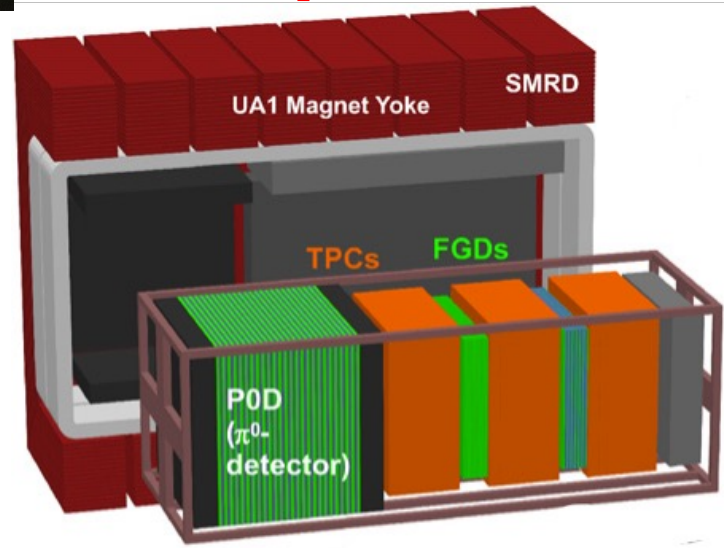


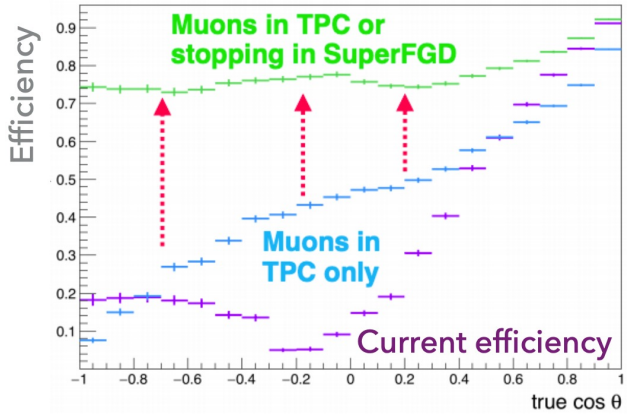
SuperFGD (SFGD)



Since Hyper-K is a 4π detector, larger acceptance of near detector is necessary

Lower proton threshold to understand nuclear effects





Physics Letters B 840 (2023) 137843
2020 JINST 15 P12003

5. ND280 Upgrade

ND280 Upgrade

- Out: P0D detector
- In: High angle TPC (HATPC)
- In: SuperFGD

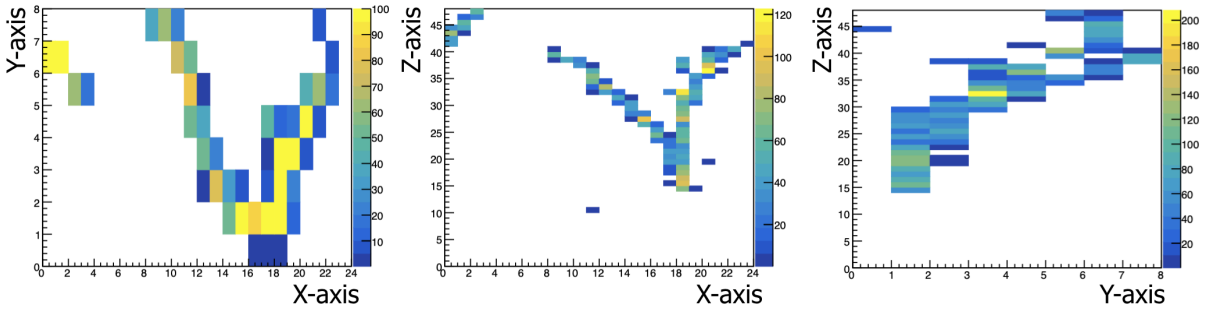
SuperFGD prototype beam test

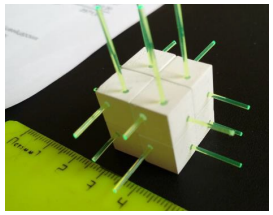
- LANL neutron cross-section measurement
- CERN track reconstruction

Installation

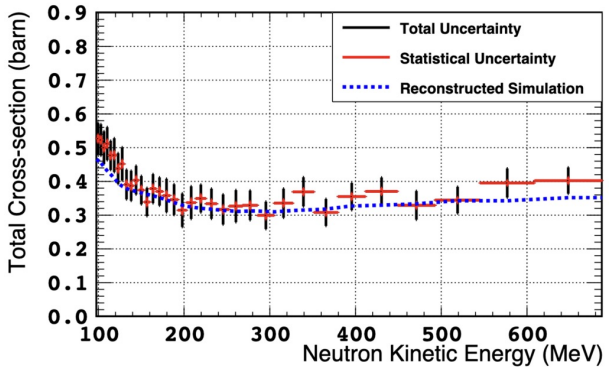
- labour-intensive assembly
- Neutrino data!

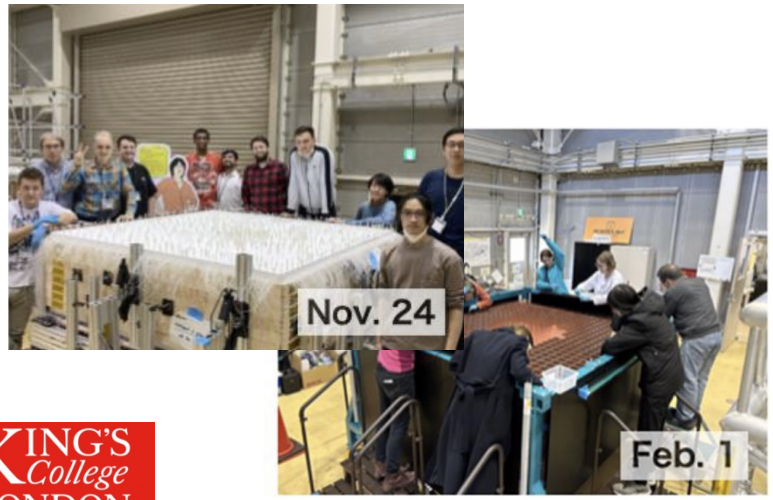
CERN beam test pair production



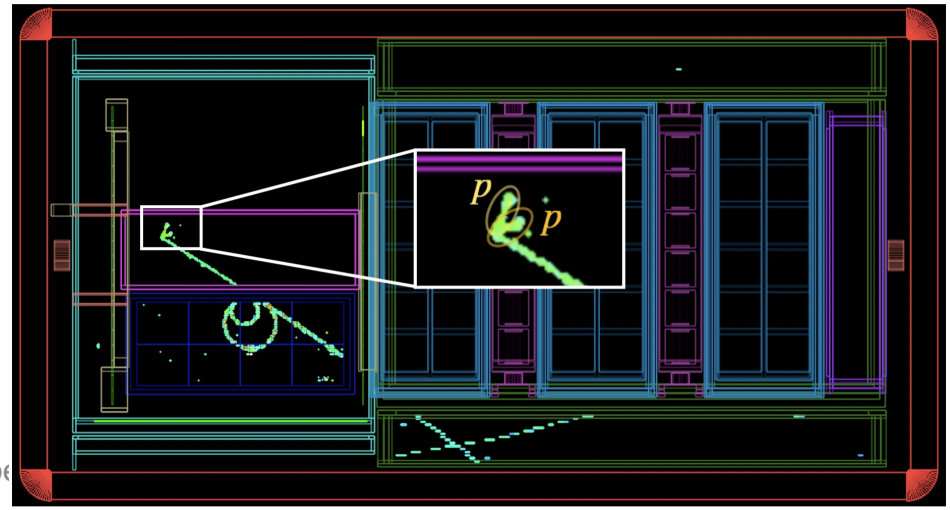


Total carbon-neutron cross-section





Neutrino even candidate



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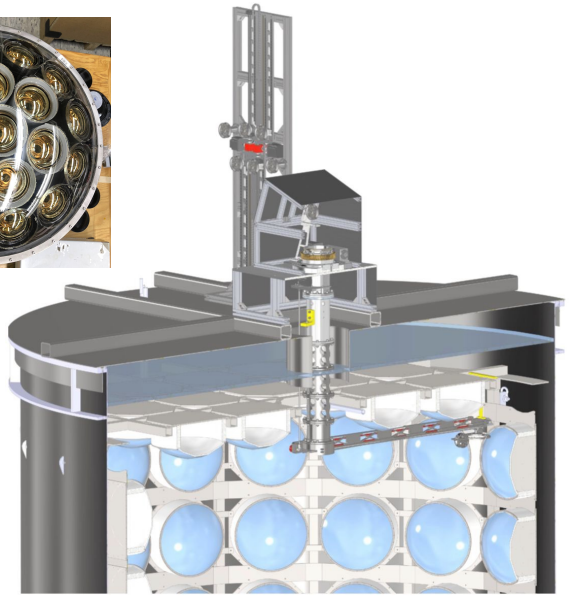
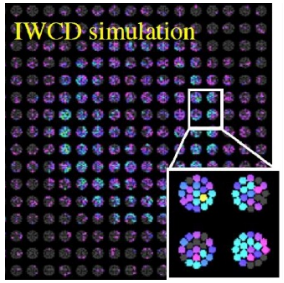
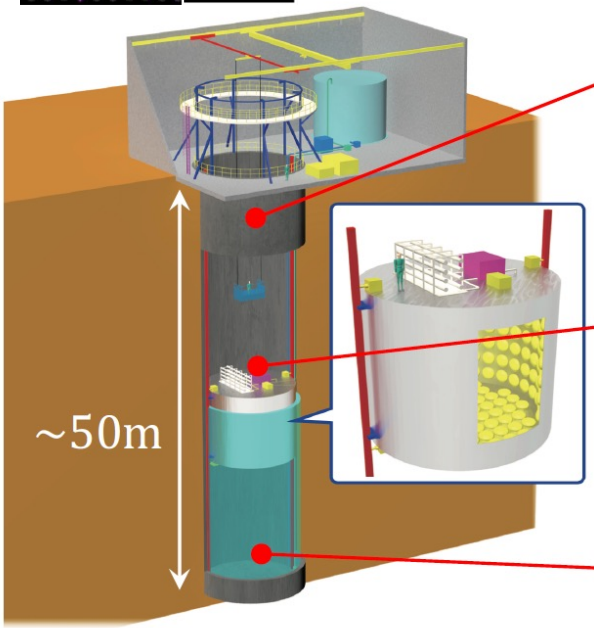
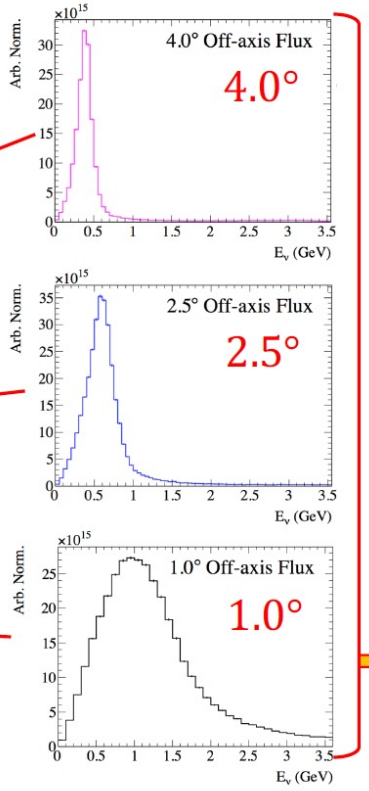
5. IWCD

Intermediate Water Cherenkov Detector
- nuPRISM concept, ~1km from the target
- mPMT units, driving force of HyperK machine learning effort





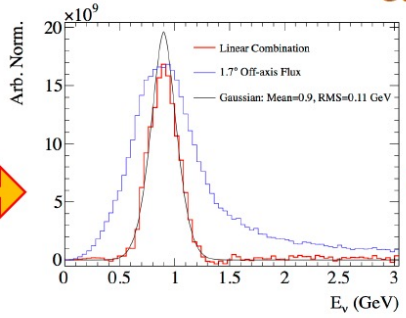




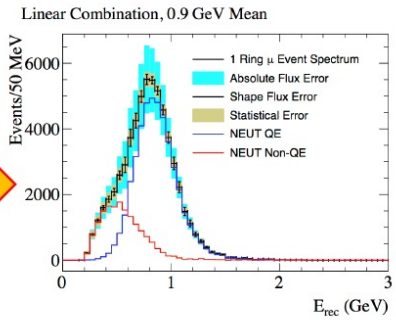
Physics target

- ν-int. measurement by off-axis scanning
- ν_e cross section (3-5% for $\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\overline{\nu}_e)/\sigma(\overline{\nu}_\mu)$
- NC and intrinsic ν_e BG measurement (3-4%)
- Neutron multiplicity with Gd loading

Linear sum to make monochromatic energy

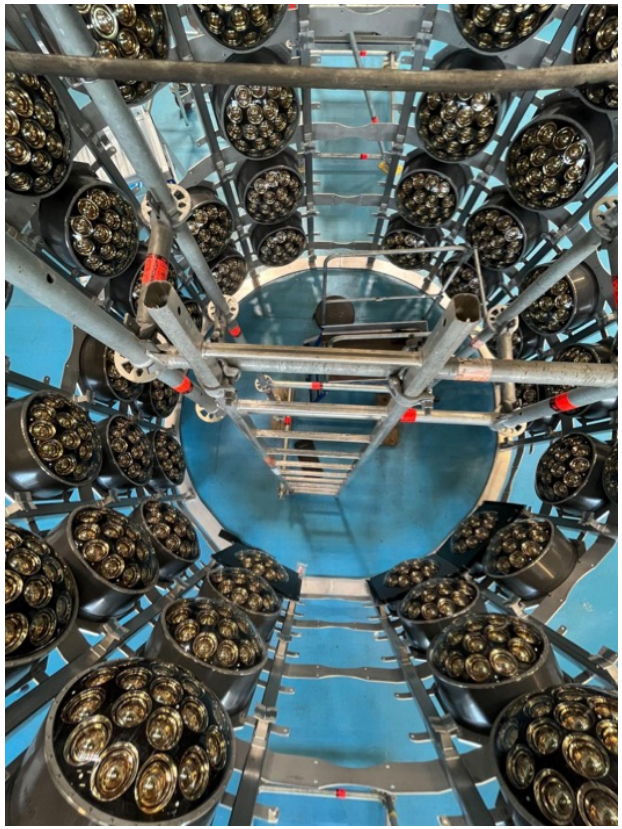


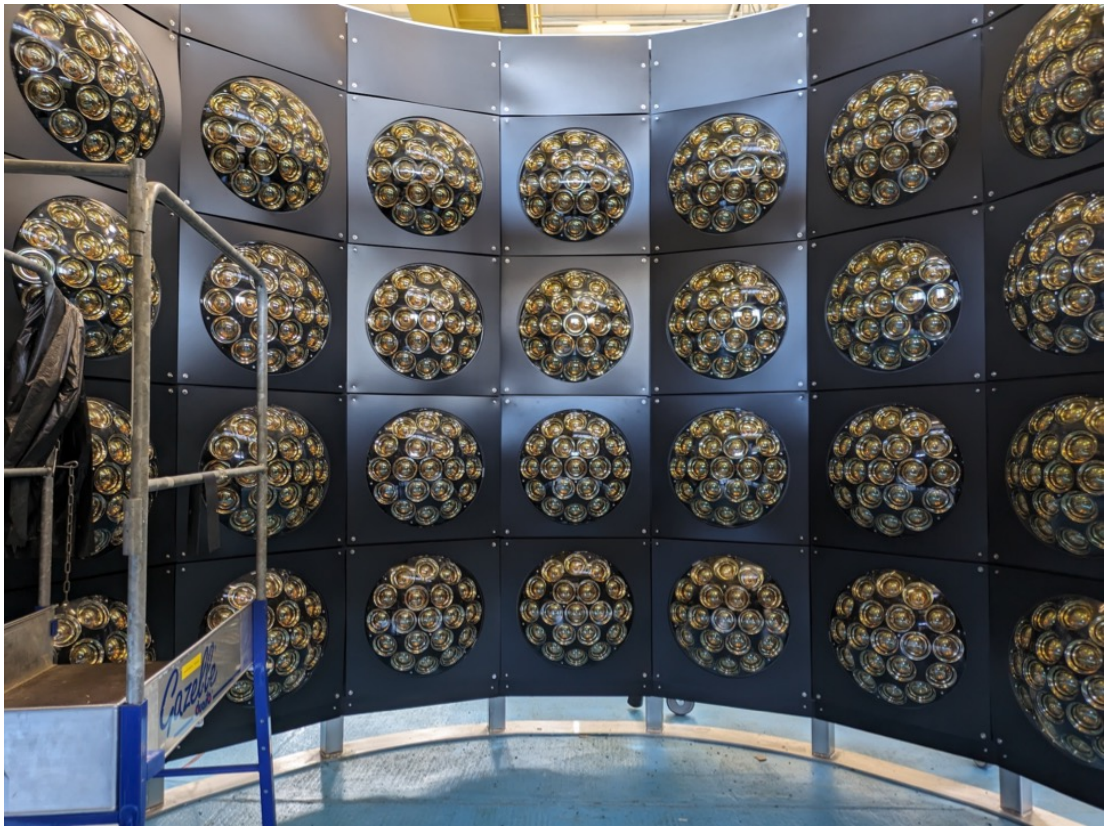
Reconstruction



5. WCTE

Water Cherenkov Test Experiment
- CERN T9 beamline, 0.1-1.1 GeV/c of e, μ, π, p
- ~100 mPMTs to test performance





1. Detector construction

2. Inner detector system

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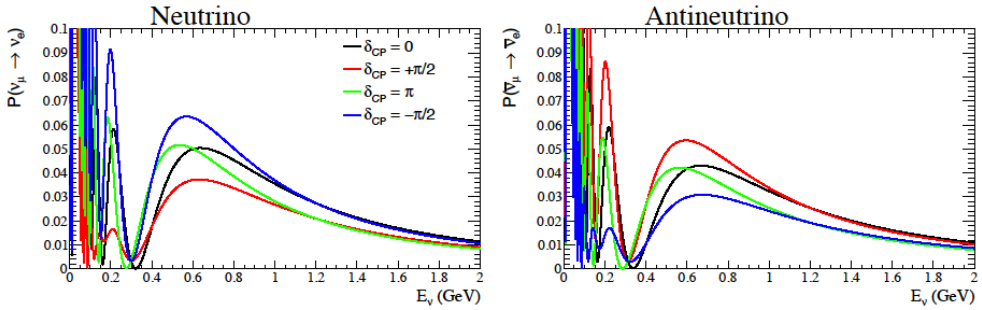
5. Near detectors

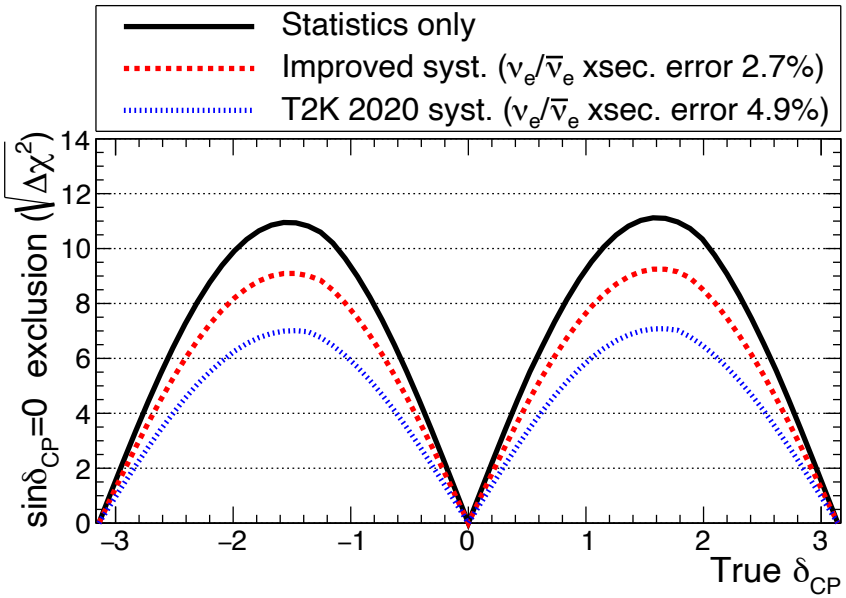
6. Conclusions

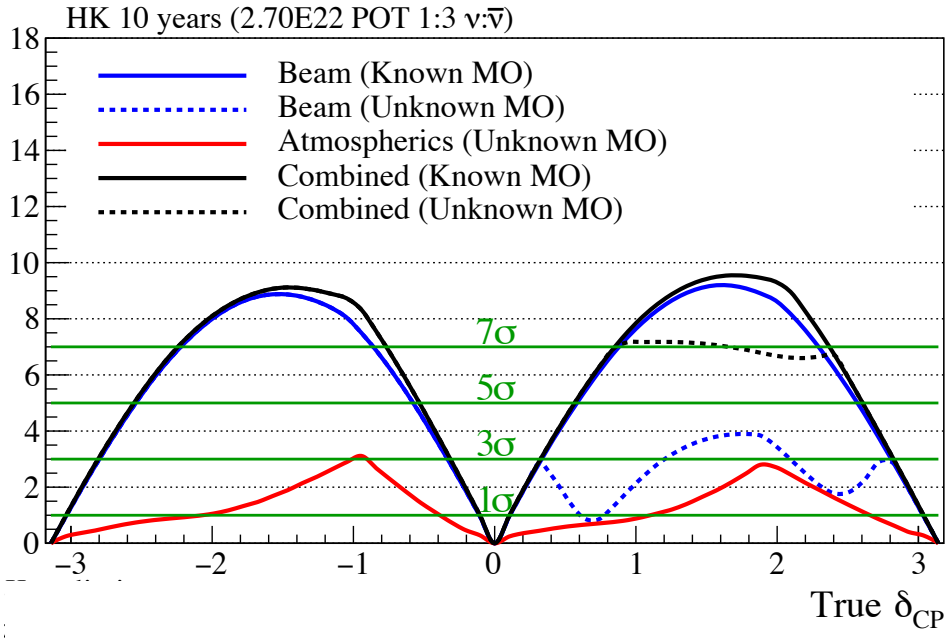
Hyper-K physics sensitivities



Oscillation physics

- ~x20 higher statistics of T2K (bigger detector, higher power beam)
- 10yrs beam data can exclude 63% of δ_{CP} values
- Combining with atmospheric neutrino data can break parameter degeneracy



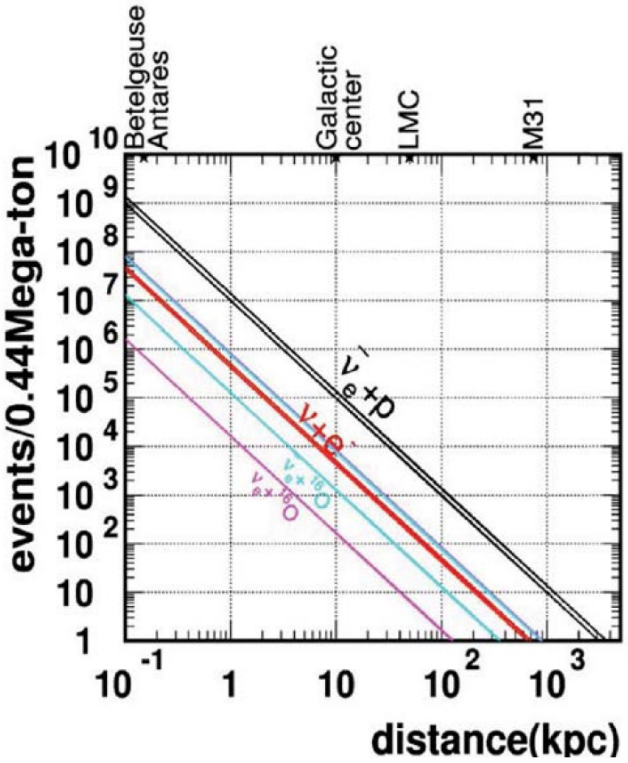


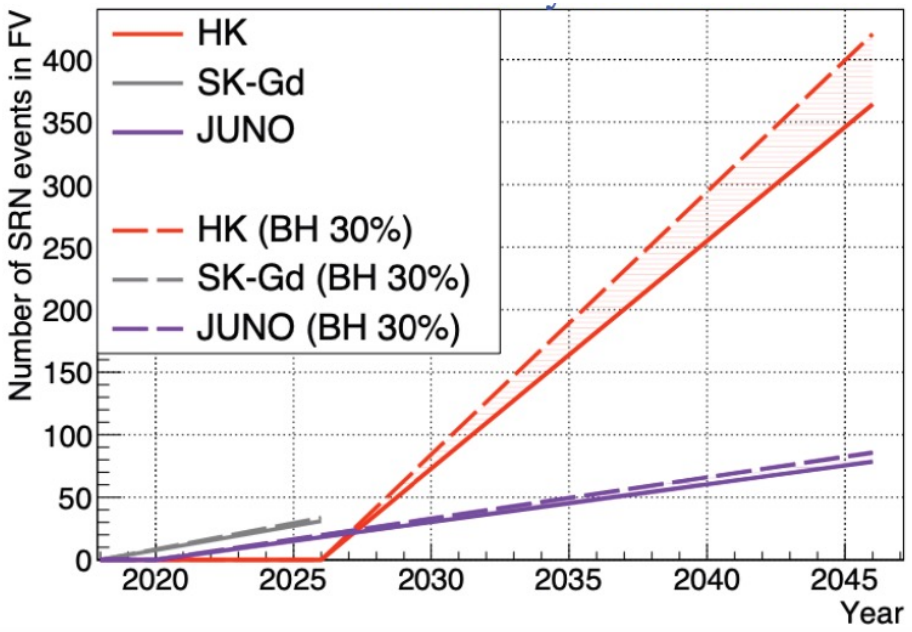
Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)

Hyper-K physics sensitivities

Supernova

- Core collapse supernova neutrinos. ~70k at 10kpc
- Andromeda is within the range
- Diffuse supernova neutrino background ~ 4 events/yr

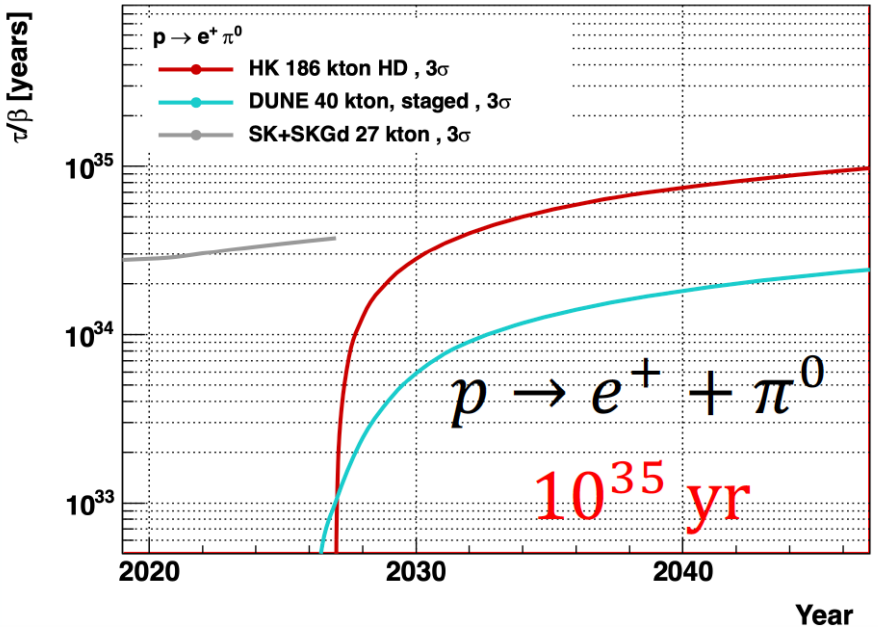


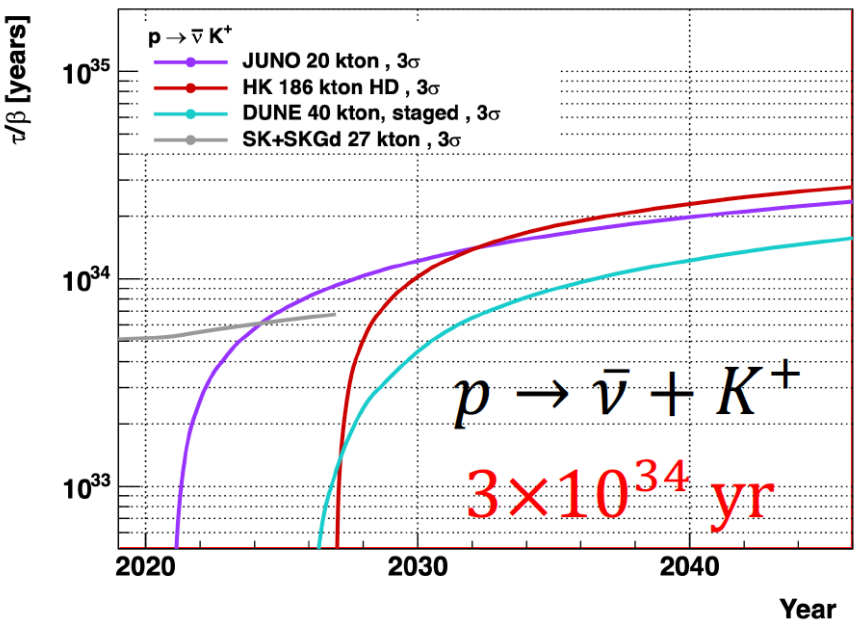


Hyper-K physics sensitivities

Proton decay

- $p \to e + \pi^o$: ~6×10^{34} yr (10yr)
- $p \to \bar{\nu} + K^+$: ~2×10^{34} yr (10yr)
- A lot more channels





How to discover unknown unknowns???

Path forward to unknown unknowns 1 - Machine Learning

WatChMaL

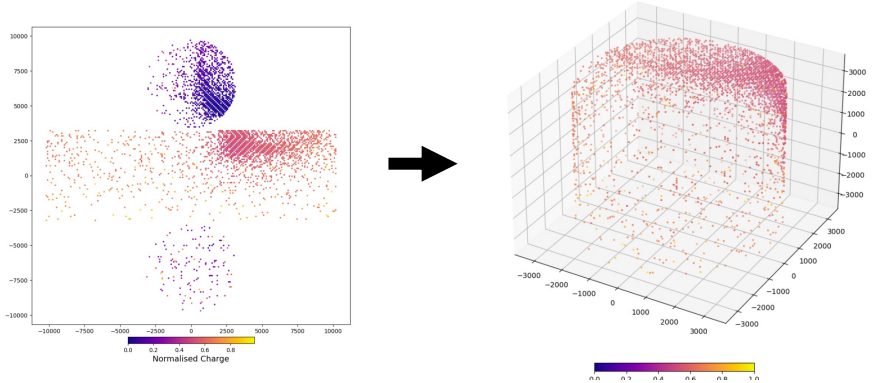
- International working group to develop Machine learning for water Cherenkov detector
- Kinematic reconstruction, particle identification
- Faster, higher background rejection, better reoncstruction resolution
- Suitable for mPMT reconstruction

fiTQun

- Likelihood based reconstruction

(LSND→MiniBooNE→SuperK)

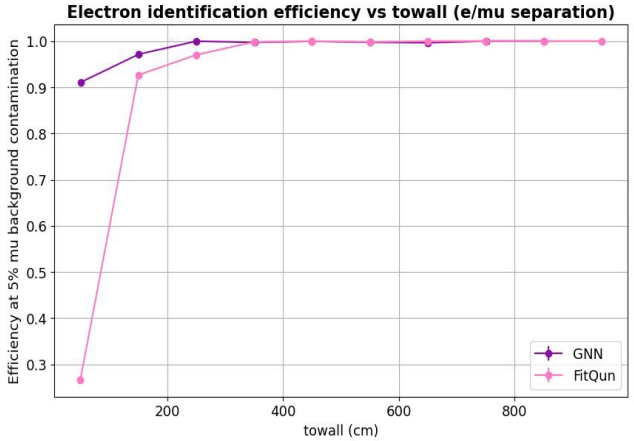
- T2K analysis main tool
- ~1 event/min (CPU)



Machine learning

- CNN is x100 (CPU) or x10000 (GPU) faster
- 2-d (CNN etc) → 3-d (GNN etc)
- Better reconstruction resolution
- Good efficiency & resolution near the wall

Electron PID efficiency with 95% muon rejection

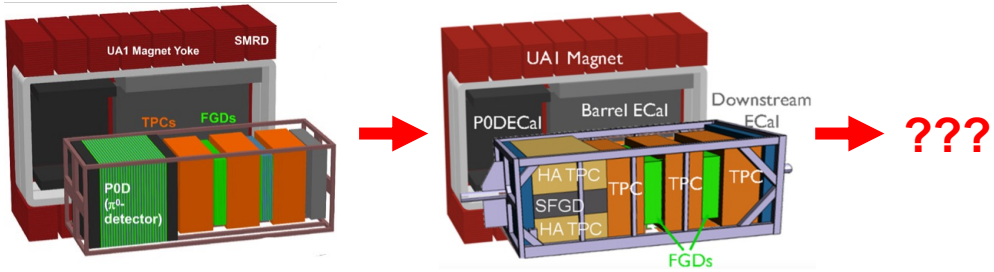


https://physicsworld.com/a/quantum-dot-liquid-scintillator-could-revolutionize-neutrino-detection/
Zhao et al, JINS19(2024)P07014

Path forward to unknown unknowns 2 - New new near detector

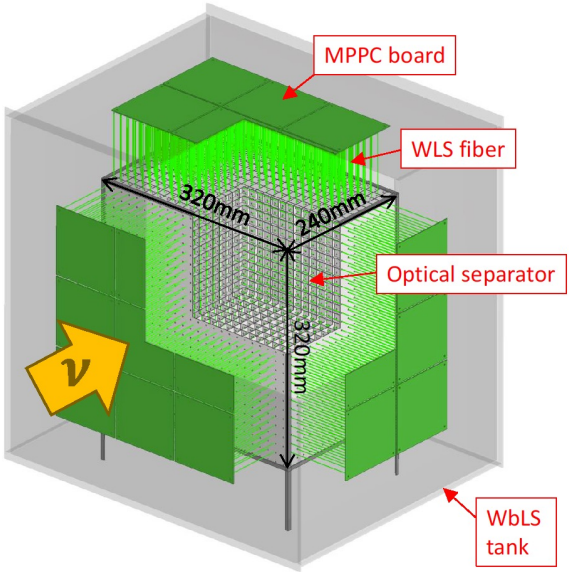
ND280++

- T2K near detector ~17yrs old (2027)
- Oldest component, UA1 magnet!



Inorganic liquid scintillator

- Established surface modification, encapsuling
  → choice of solvent (=water based liquid scintillator)
- high-light output, tuneable spectrum
- safe, sustainable materials & productions
- 3-d fiber reading



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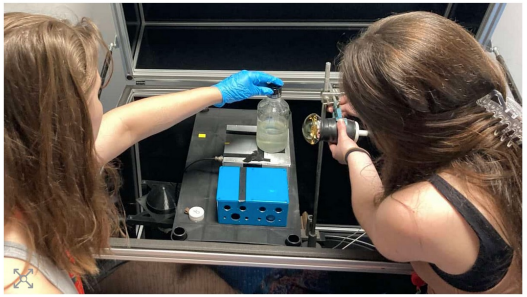
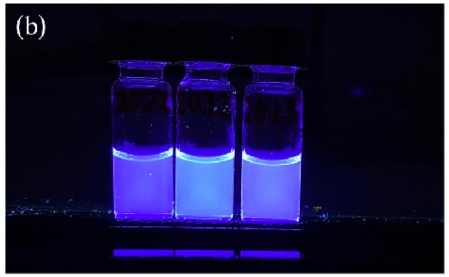
Quantum dot liquid scintillator could revolutionize neutrino detection

19 Aug 2024





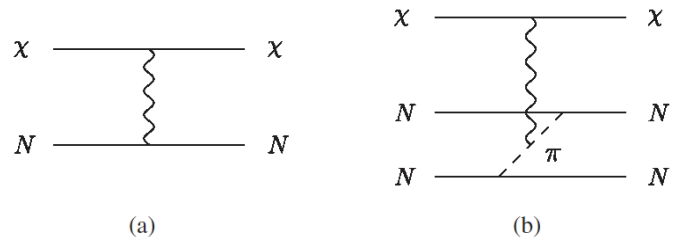
Path forward to unknown unknowns 3 - Nuclear physics

Next generation neutrino experiments are systematically limited
- Nucleon correlation can change neutrino cross-sections up to 30%
- The same idea works for EMC effect, g_A quenching, WIMP search, etc
- NuSTEC: Neutrino Scattering Theory-Experiment Collaboration https://nustec.fnal.gov

ECT* workshop (Oct. 21-25, 2024)
"Measuring neutrino interactions for next-generation oscillation experiments"
https://www.ectstar.eu/workshops/measuring-neutrino-interactions-for-next-generation-oscillation-experiments/

PHYSICAL REVIEW LETTERS **122,** 071301 (2019)

First Results on the Scalar WIMP-Pion Coupling, Using the XENON1T Experiment



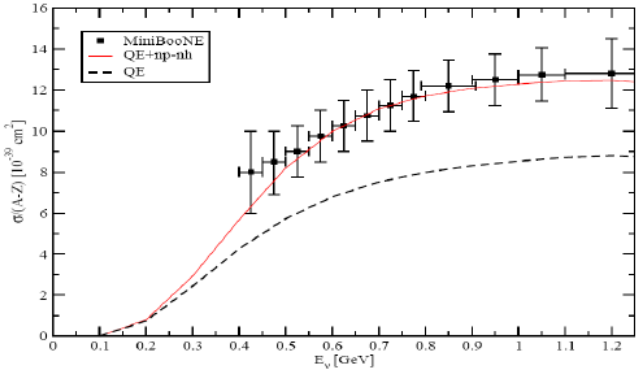
XENON1T, PRL122(2019)071301

WIMP-pion interaction

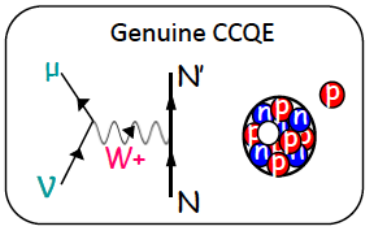
An explanation of this puzzle

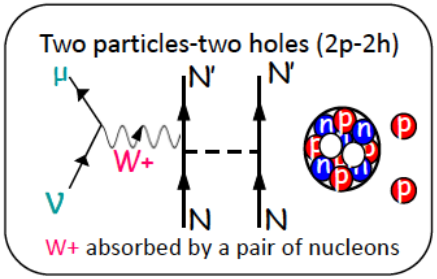
2p2h effect

Inclusion of the multinucleon emission channel (np-nh)



Martini et al,PRC 80(2009)065501





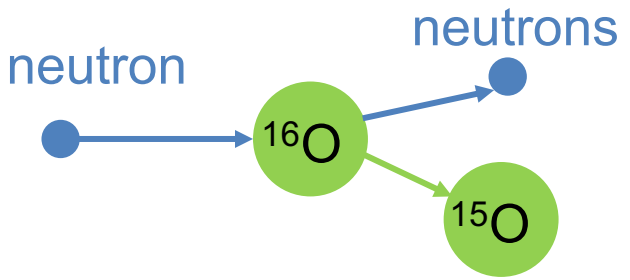
KING'S College LONDON

Path forward to unknown unknowns 4 - Neutron physics

Neutron tagging

- Supernova neutrinos, reactor neutrinos
- SK-Gd has ~75% tagging efficiency now (0.03%)
- 17% tagging efficiency in water fiducial volume

n+p→d+g (2.2 MeV)



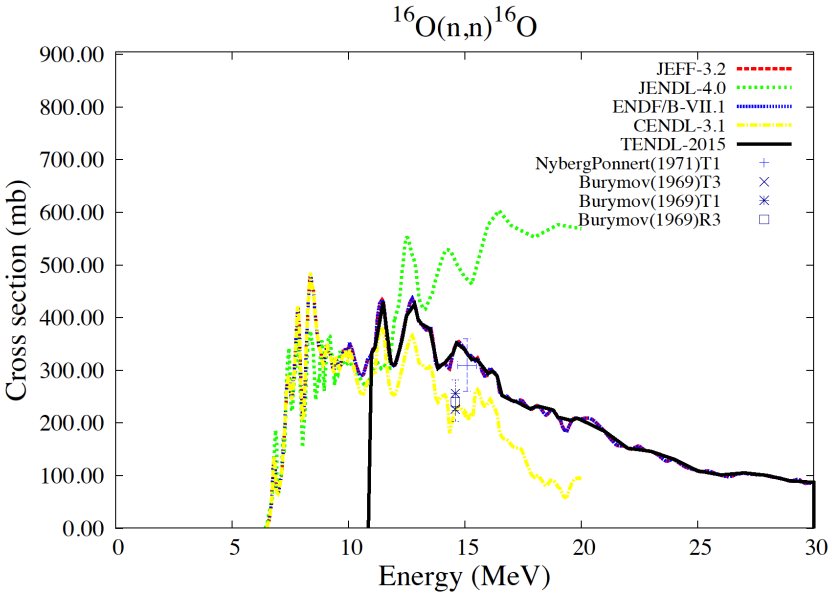
Nucleon multiplicity is a dream parameter!

$$\nu_e + n \rightarrow e^- + p$$
$$\bar{\nu_e} + p \rightarrow e^+ + n$$

- Charge separation
- Channel separation (baryonic resonance etc)
- Kinematics reconstruction, etc

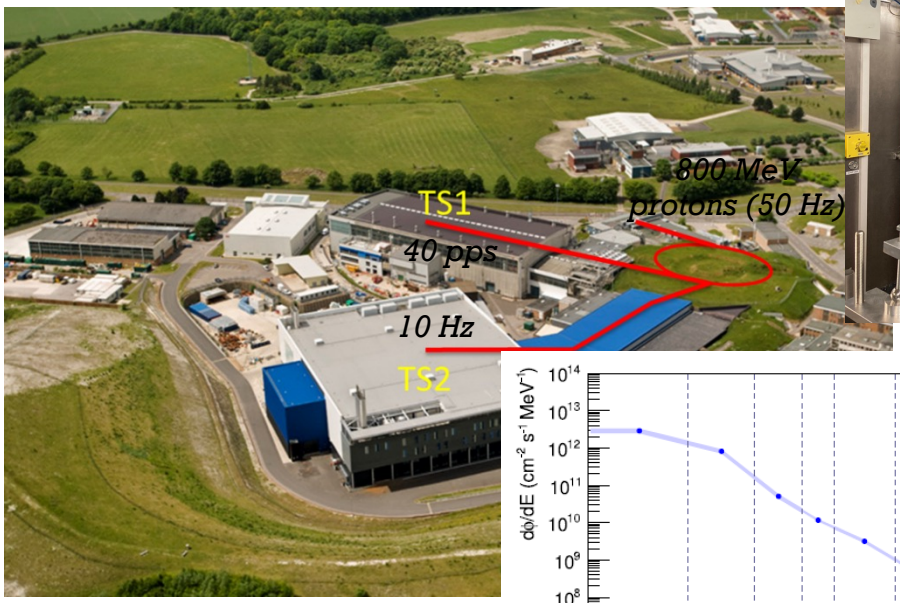
However, neutron multiplicity is not easy to predict

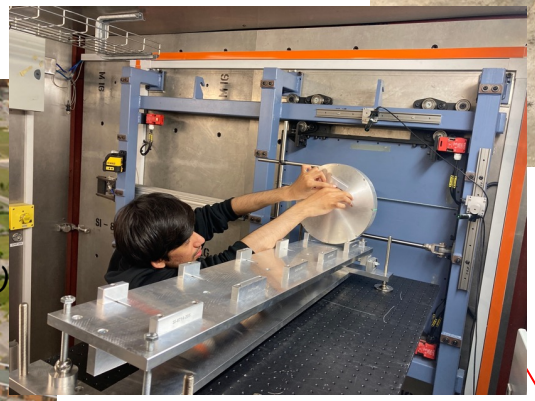
- Primary interaction
- Final state interactions in target nucleus
- Neutron propagation in media



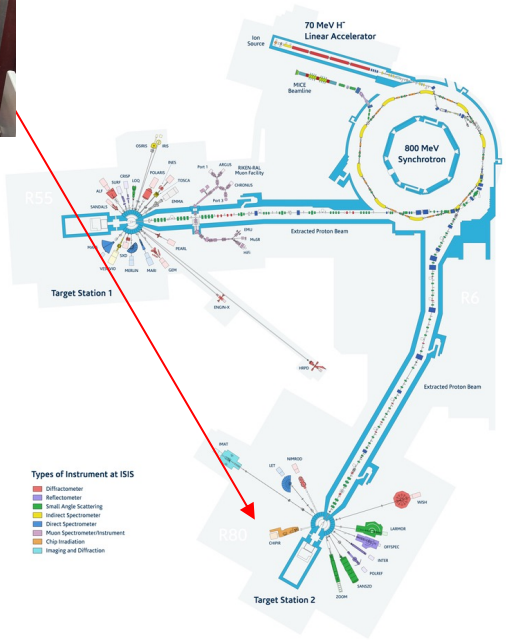
Neutron cross-section measurements

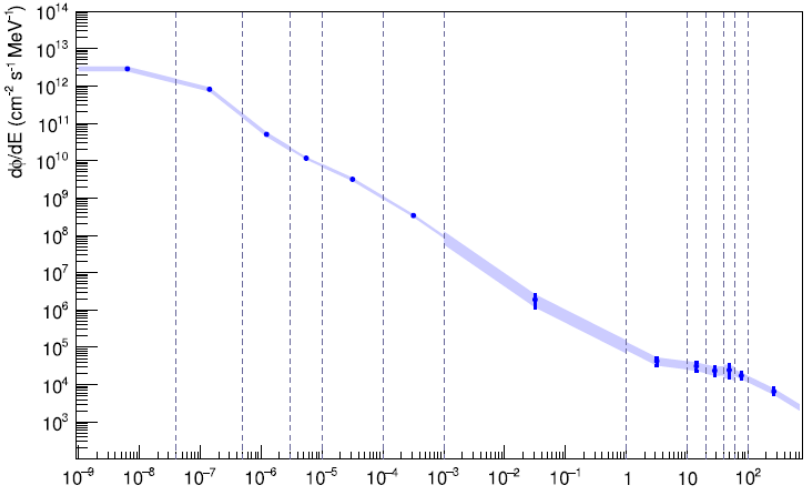
ISIS neutron source at Rutherford Appleton Laboratory (UK)
- Target station 2, ChipIr, up to several hundreds MeV
- Beam data taken (2023)





ChipIr

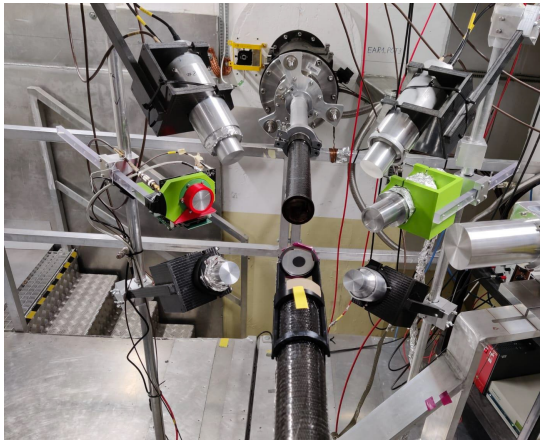




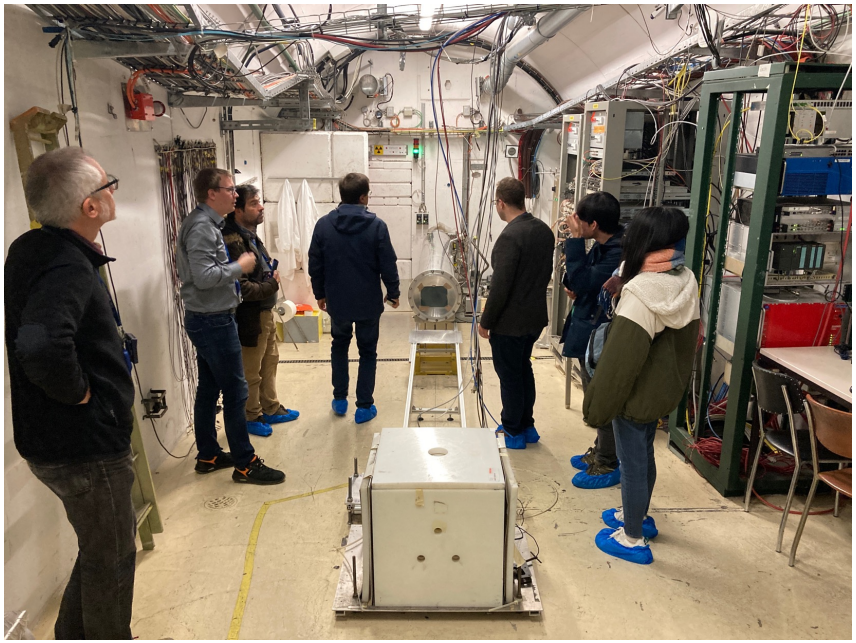
Activation foil data unfolded neutron flux

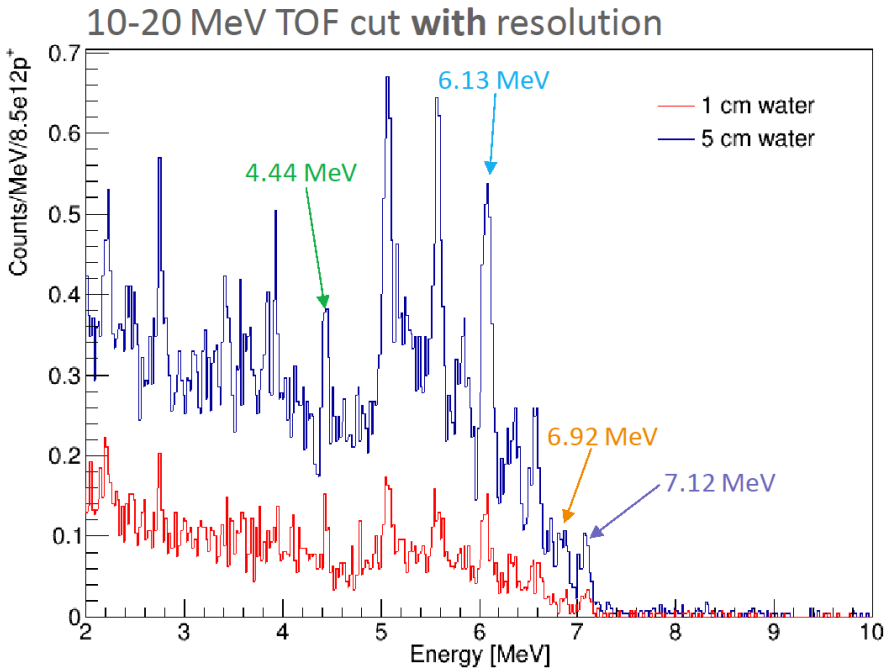
Neutron cross-section measurements

n_TOF at CERN
- Beam time approved
- up to a few hundreds MeV
- first beam data taking, Sep 2-22



cross-section measurement setup





Conclusions

HyperK construction is on the right track

Growing collaborations (~600 people, ~100 institutions, ~22 countries)

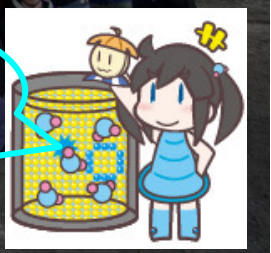
There is no “red carpet”, the project takes risks and challenges, but we try to solve one by one

There are many guaranteed physics results, but HyperK also have many exciting topics of “unknown unknowns”

Hyper-Kamiokande collaboration (2023)

Thank you for your attention!

Join us!



Backup

Reference

Overview
“Hyper-Kamiokande”, Shigetaka Moriyama (Neutrino 2024)
https://agenda.infn.it/event/37867/timetable/#20240616
“Hyper-Kamiokande Status”, Christophe Bronner (NuFact 2024)
https://indico.cern.ch/event/949705/contributions/4555521/

PMT
“PMT development for Hyper-Kamiokande”, Christophe Bronner (NuFact2021)
https://indico.cern.ch/event/855372/contributions/4366117/
“Multi-PMT photodetector system for the Hyper-K experiment”, Gianfranca De Rosa (ICHEP2020)
https://indico.cern.ch/event/868940/contributions/3814071/

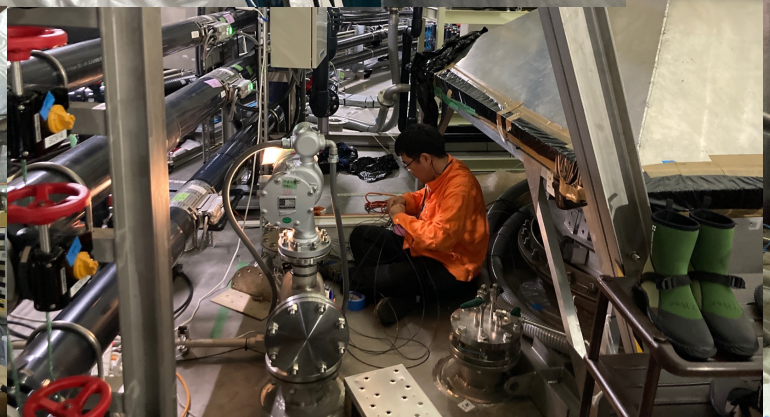
Beam
“Upgrade of J-PARC magnetic horn system towards 1.3 MW beam ”, T. Sekiguchi (NuFact2024)
https://indico.fnal.gov/event/63406/contributions/297564/
“NA61/SHINE measurements for neutrino experiments”, Laura Fields (NuFact2024)
https://indico.fnal.gov/event/63406/contributions/297872/

Electronics
“The Hyper-Kamiokande Experiment Status and Prospect”, Umut Kose (Tau2023)
https://indico.cern.ch/event/1303630/contributions/5620874/

Near detector
“A new near neutrino detector SuperFGD for the T2K experiment”, Tristan Doyle (NuFact2024)
https://indico.fnal.gov/event/63406/contributions/297834/

Machine learnng
“Enhancing Event Reconstruction with Machine Learning for Water Cherenkov Detectors of Hyper-K”, Nick Prouse (ICHEP2024)
https://indico.cern.ch/event/1291157/contributions/5892379/

Super-Kamiokande detector refurbishment 2024

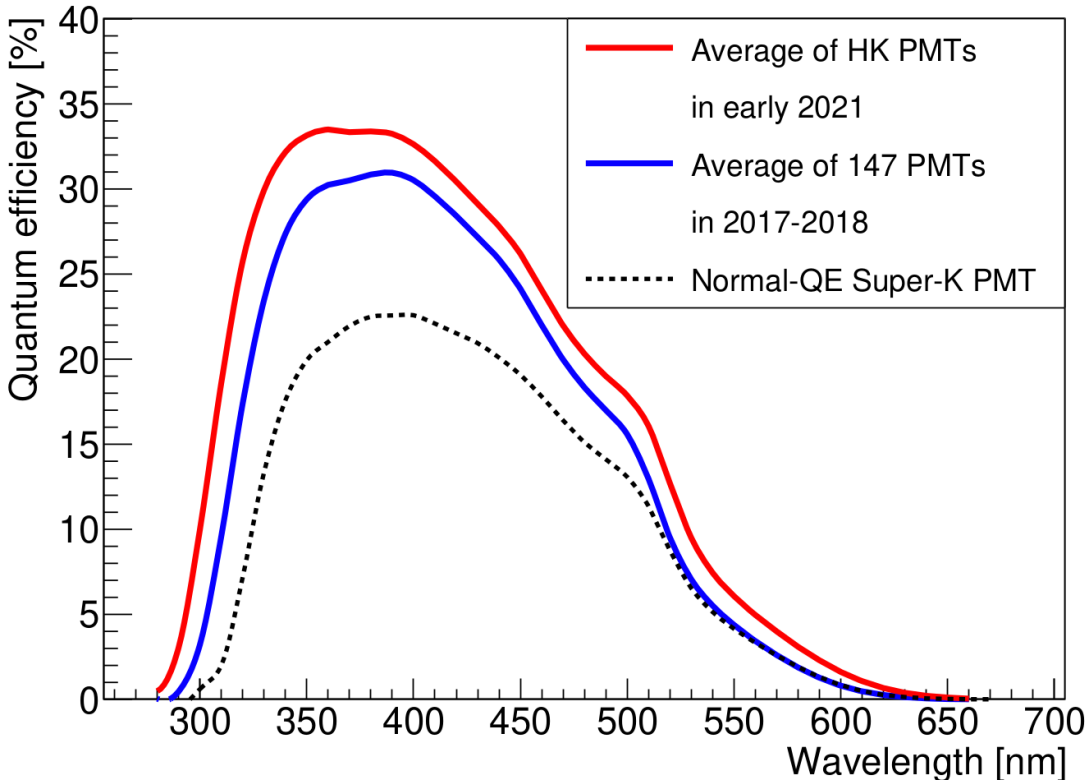


2. Hyper-K ID PMTs - B&L PMTs

Radio-isotopes in glass window are the major sources of dark current (scintillation)
- After meticulous researches, people found the origin of them
- R12860 finally achieved the 4kHz target goal!
- QE is further improved for short wavelength region

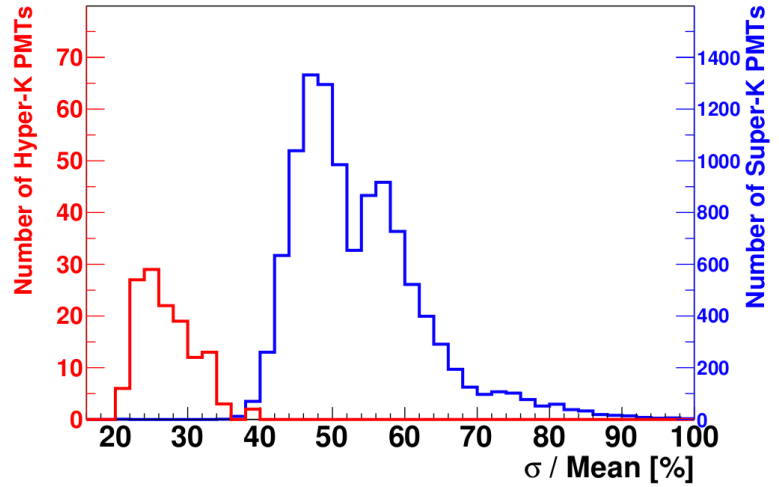
Radio isotopes in glass (Bq/kg)

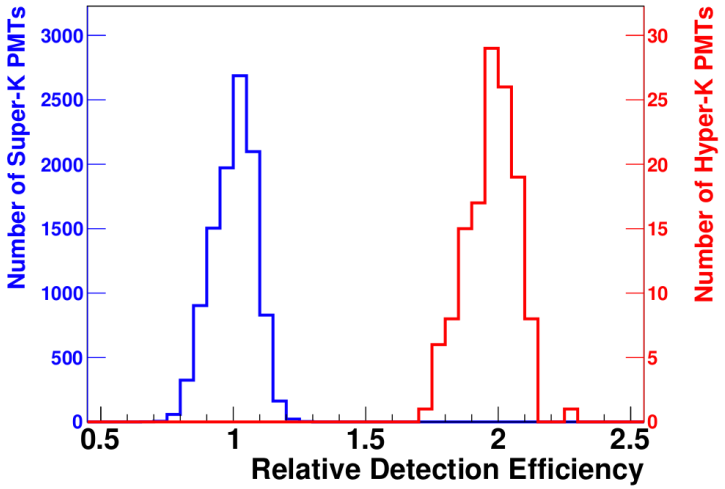
	Super-K (R3600)	R12860 (before)	R12860 (after)	R12860 (2021)
U	5.5	5.4	2.9	2.5
Th	1.8	1.8	0.95	0.7
^{40}K	18.2	1.6	2.0	1.0

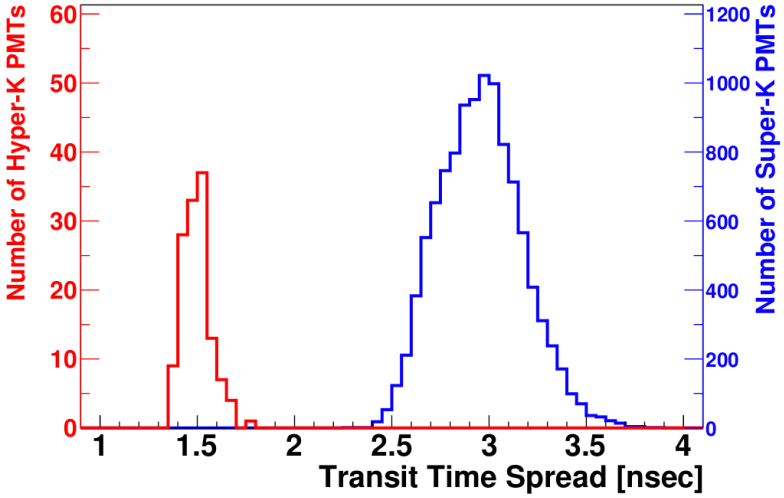


2. Hyper-K ID PMTs - B&L PMTs, in SuperK

134 of B&L PMTs were installed in SuperK (2018). Performance was confirmed in the ultra-pure water environment







3. Hyper-K underwater electronics

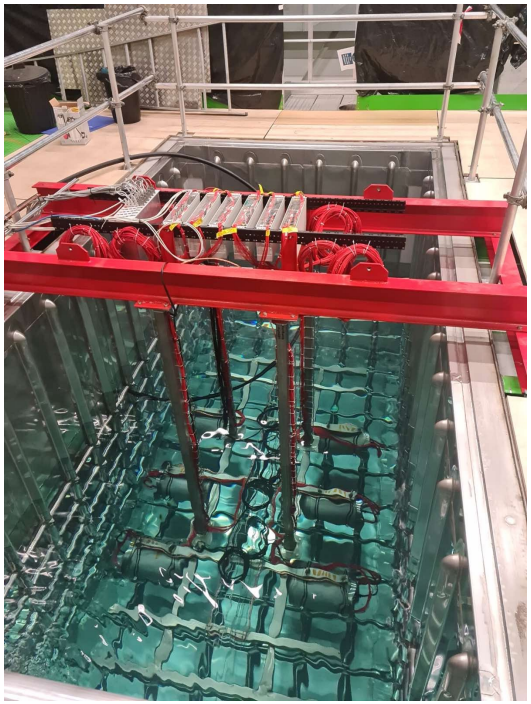
ETH zürich

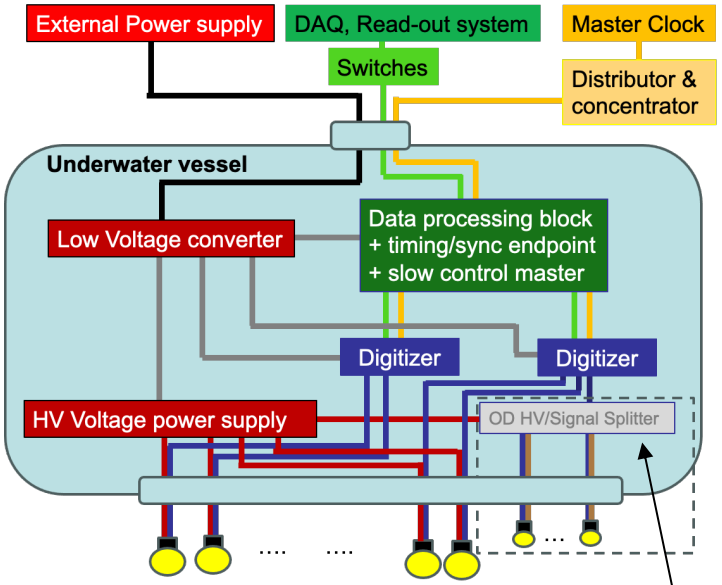
Underwater electronics

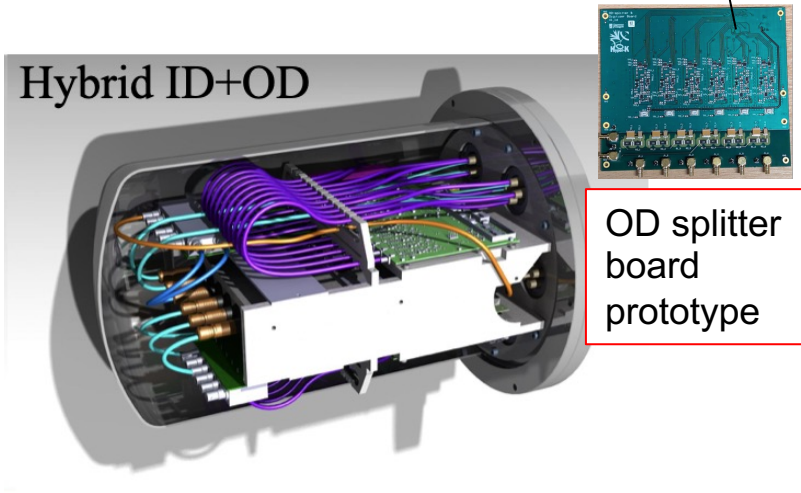
- Digitizer, HV power supply etc in electronics vessel
- Underwater cable connection, feed-through (~8 bar)

King's pressure vessel

CERN electronics vessel underwater test





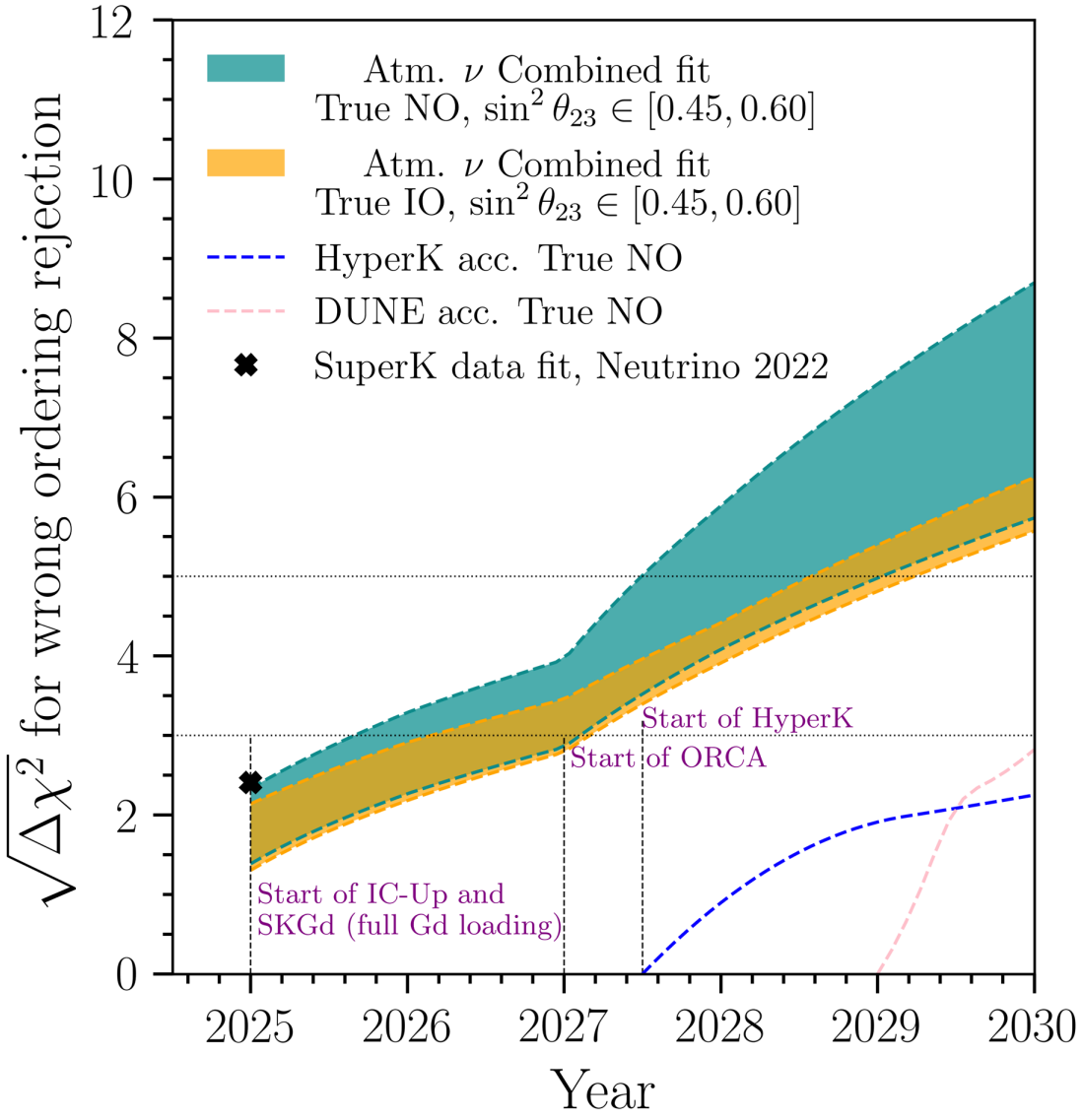


OD splitter board prototype

Argüelles, Fernández, Martínez-Soler, Jin, PRX13, 041055 (2023)

6. Global mass hierarchy sensitivities

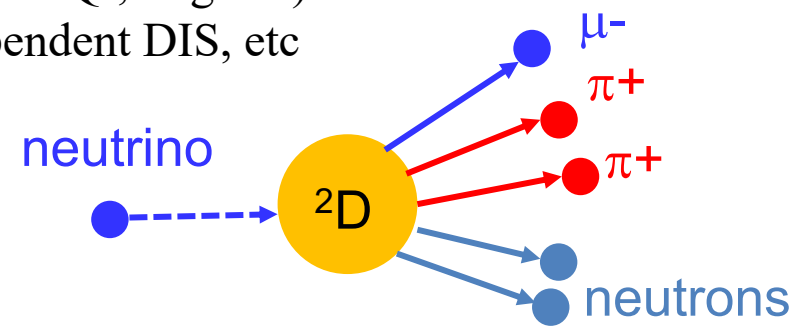
Hyper-K with IceCube-Upgrade and/or KM3NeT-ORCA and/or JUNO can reach 5-sigma neutrino mass hierarchy discovery before 2030

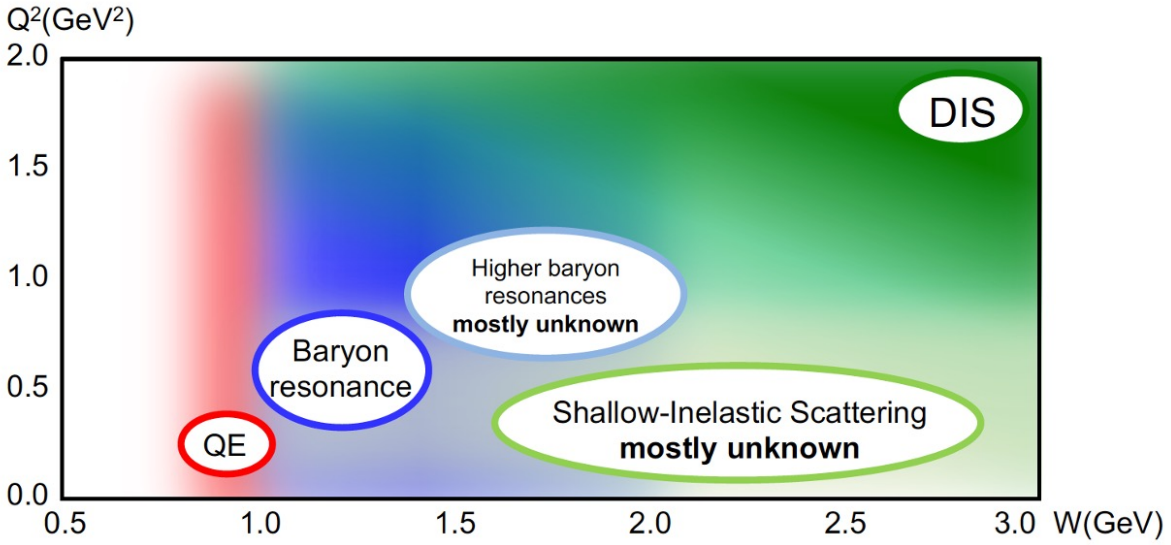


Path forward to unknown unknowns - hadron physics

Next generation neutrino experiments are systematically limited

- Current focus of oscillation experiment, around 1 GeV (T2K, NOvA)
- Next generation experiments, around 3 GeV (DUNE, ORCA, IceCube-Upgrade)
- Significant fraction of shallow-inelastic scattering (low Q^2, large W)
- Higher resonance, quark-hadron duality, nuclear dependent DIS, etc





Neutrino induced 2-pion production