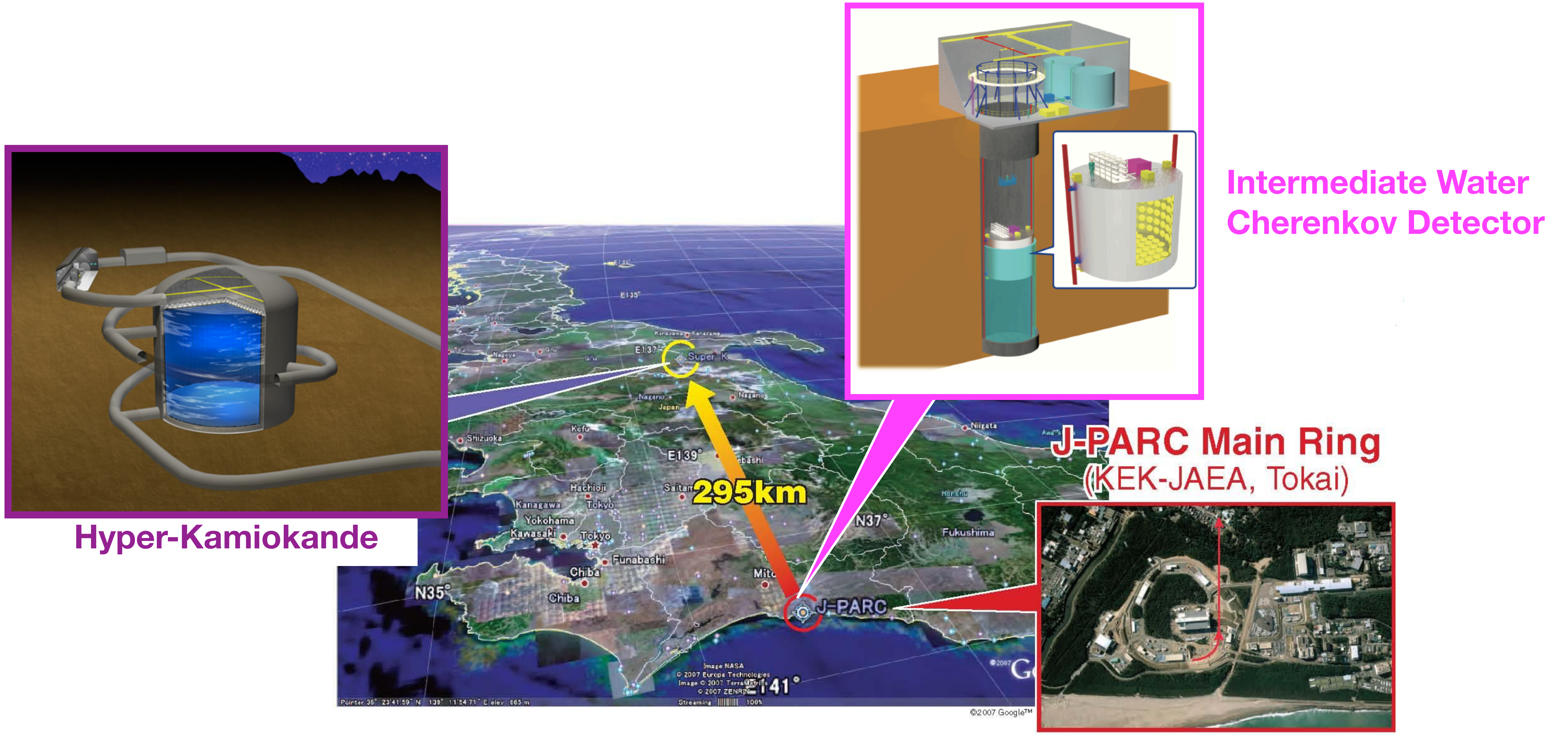
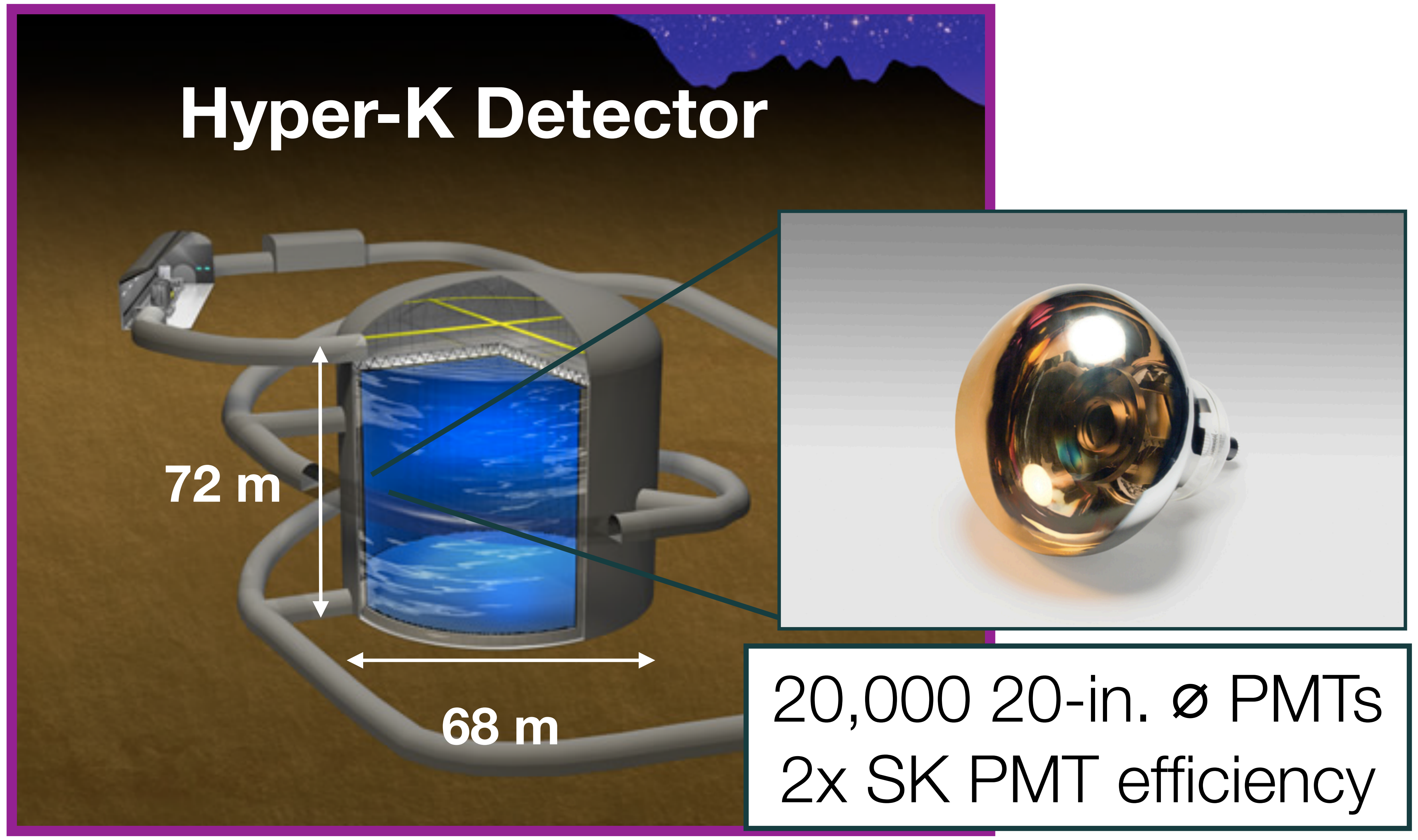
Status of the Hyper-Kamiokande Project



Mark Hartz
For the Hyper-K Canada Collaboration
IPP 50th Anniversary Symposium, May 29, 2022

Hyper-K Experiment

- 260 kton detector with fiducial mass is 8x larger than Super-Kamiokande
- Neutrino beam from J-PARC will be 2.5 times more intense (1.3 MW proton beam)
- New photon detectors and near detectors
- 20x the (anit)neutrino rate compared to T2K experiment
- Broad physics program includes
  - Accelerator neutrinos
  - Proton decay searches
  - Supernova neutrino detection
  - Atmospheric neutrino detection
  - Solar neutrino detection
  - Dark matter searches…
- Approved in 2020, planned start of operation in 2027

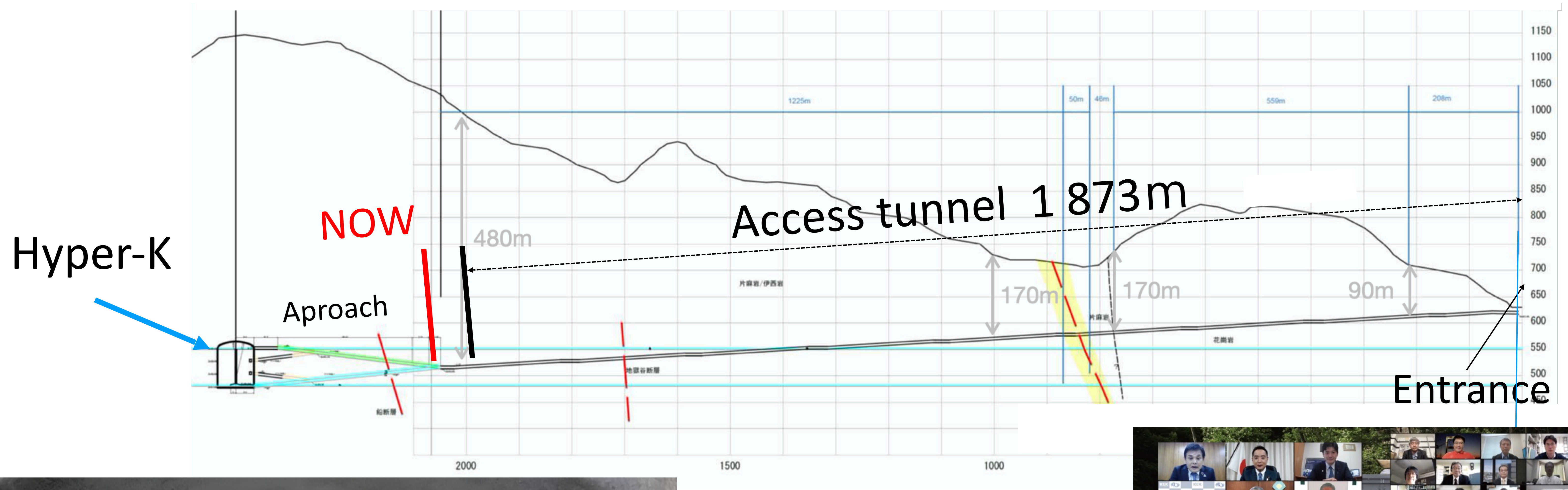


20,000 20-in. ⌀ PMTs
2x SK PMT efficiency

J-PARC upgrade to 1.3 MW beam power

Construction Progress in Japan

Hyper-Kamiokande



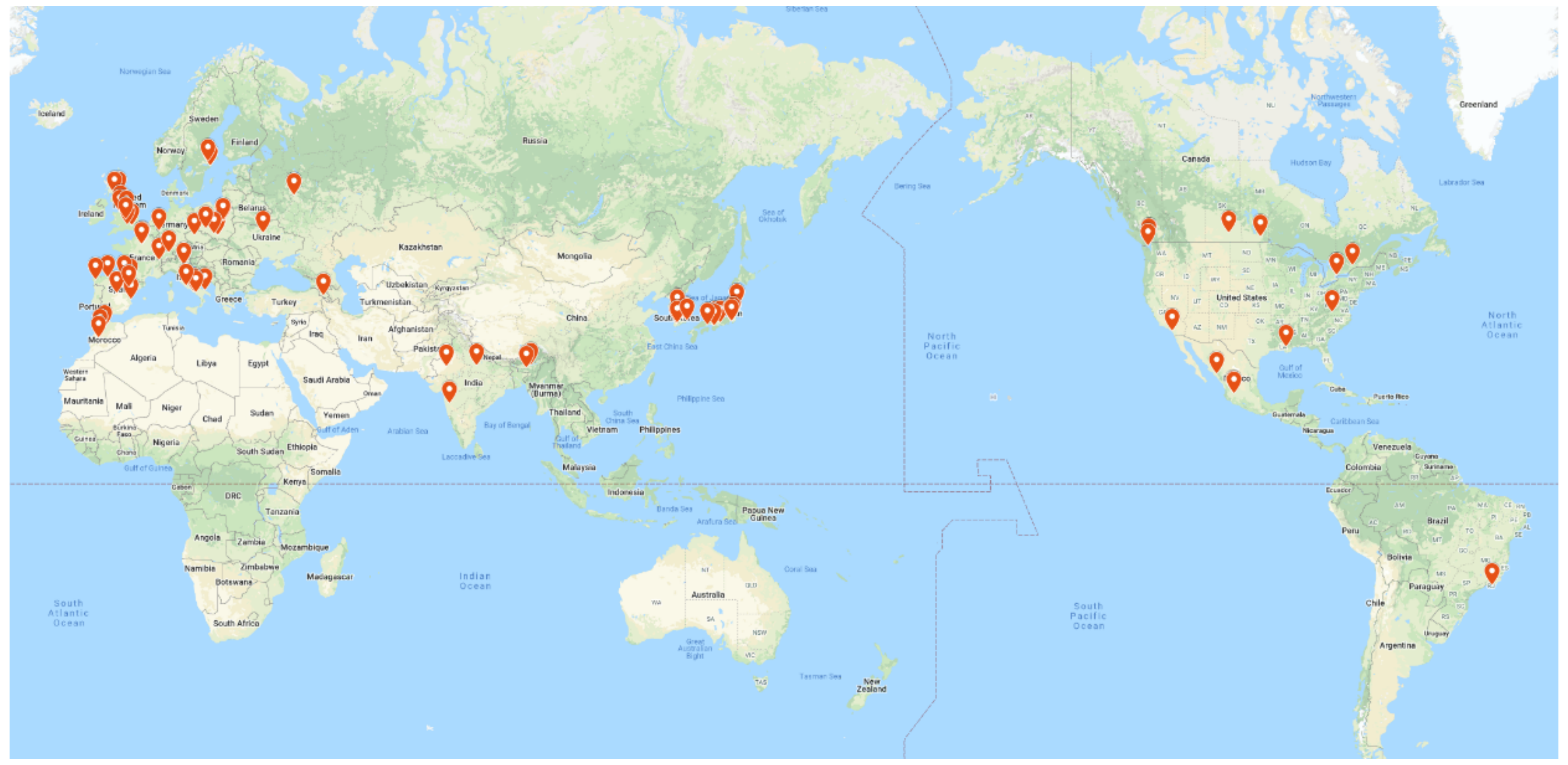
2021.5 Ground-breaking Ceremony at the Entrance

Excavation of the detector cavity, one of the world's largest underground cavities, will begin in October of this year.

Hyper-K Collaboration

Hyper-Kamiokande

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

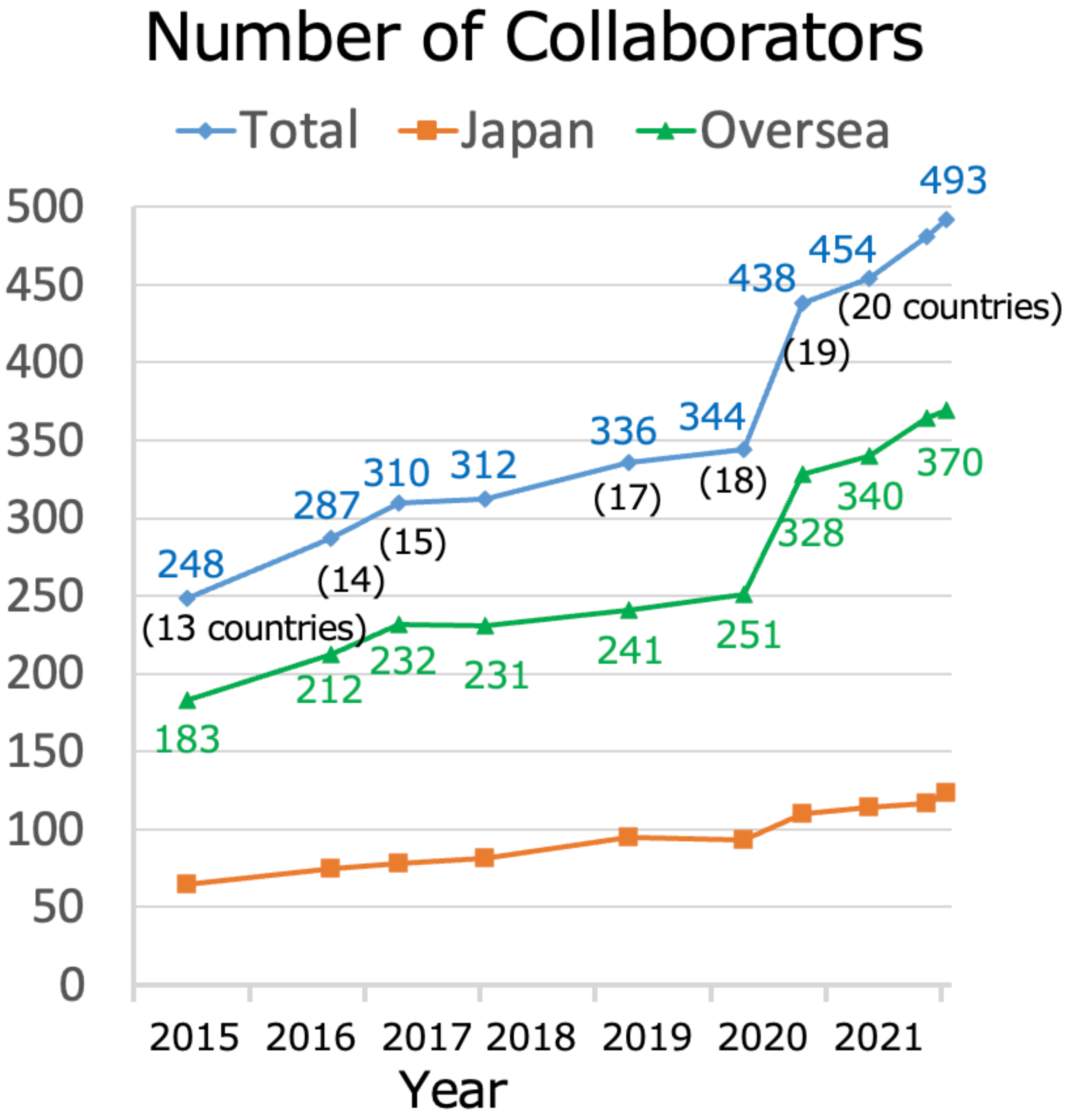


Europe	281 members
Armenia	3
Czech	4
France	27
Germany	1
Italy	55
Poland	38
Russia	22
Spain	35
Sweden	5
Switzerland	13
Ukraine	4
UK	74

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



Collaboration picture is a bit out of date. Hopefully we have a new one soon!

Hyper-K Canada Collaboration

Hyper-K Canada Collaborating Institutes

M. Barbi (URegina)
S. Bhadra (York)
R. Gornea (Carleton)
M. Hartz (TRIUMF)
B. Jamieson (UWinnipeg)
D. Karlen (UVic)
A. Konaka (TRIUMF)
N. Kolev (URegina)
T. Lindner (TRIUMF)
J. Martin (UofT)
B. Pointon (BCIT)

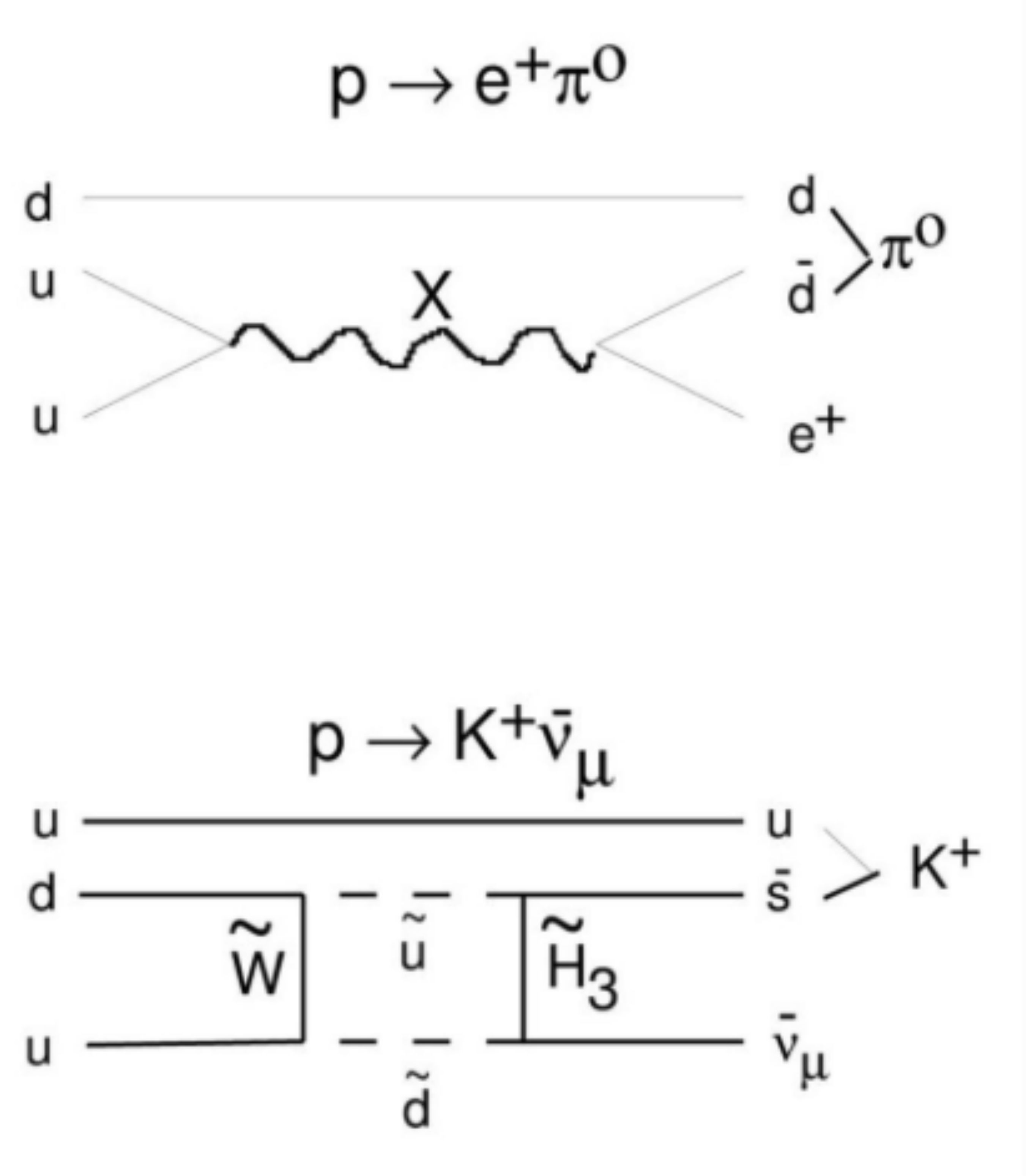
P de. Perio has moved
To Kavli IPMU, new TRIUMF
BAE hiring in progress.

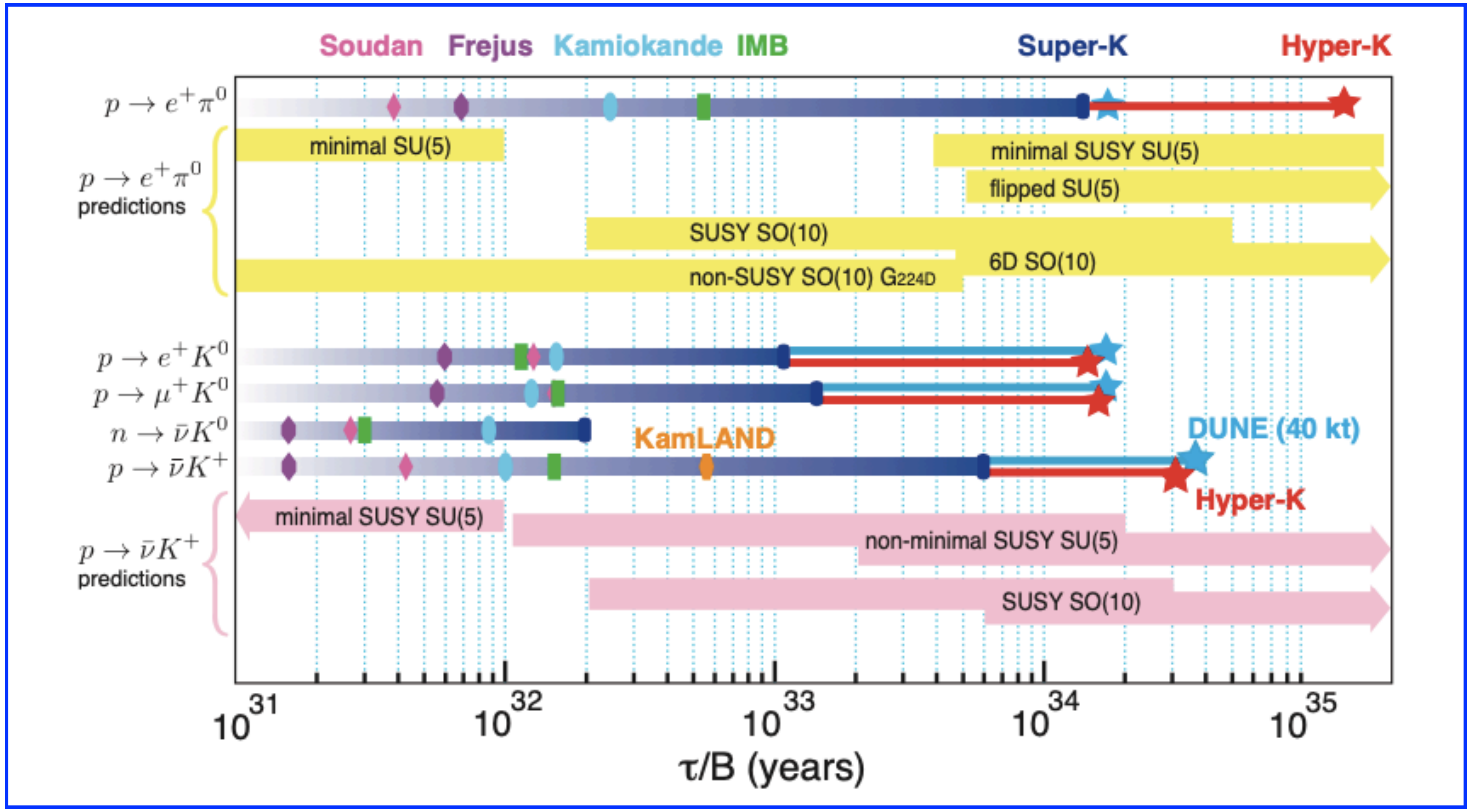
- Hyper-K Canada group formed in 2018
  - Supported by NSERC Discovery grant
- Currently 11 investigators from 8 institutes, 9 postdocs, 14 graduate students from this fall
- Funding for intermediate detector approved in 2020 CFI-IF competition
- Funding request for the Hyper-K detector contributions to be submitted in 2023 CFI-IF
- **New collaborators welcome!**

Proton Decay at Hyper-K

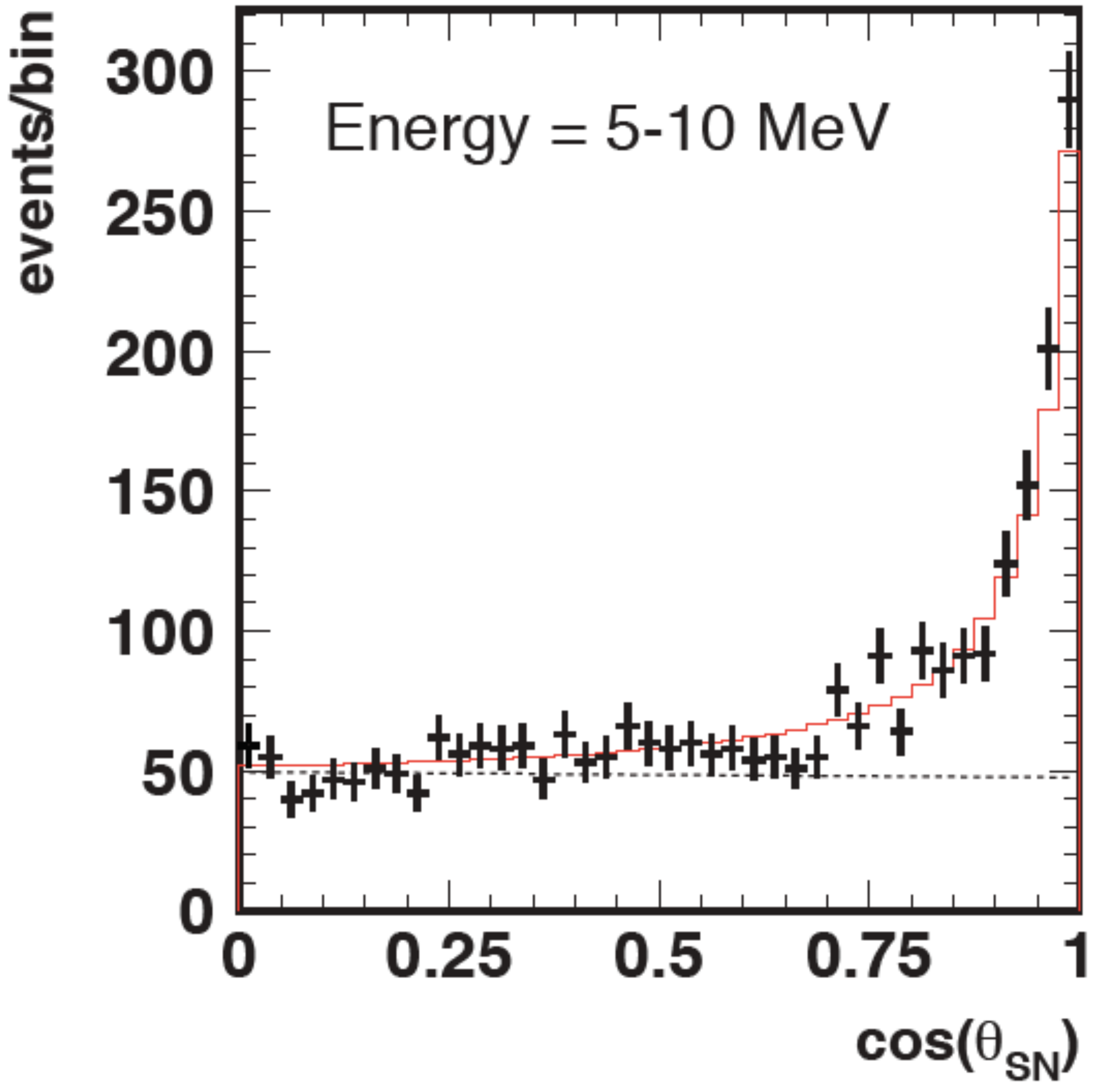
Baryon number violation is generic prediction of GUTs

With its 187 kton fiducial mass, Hyper-K will have the largest mass with sensitivity to most channels

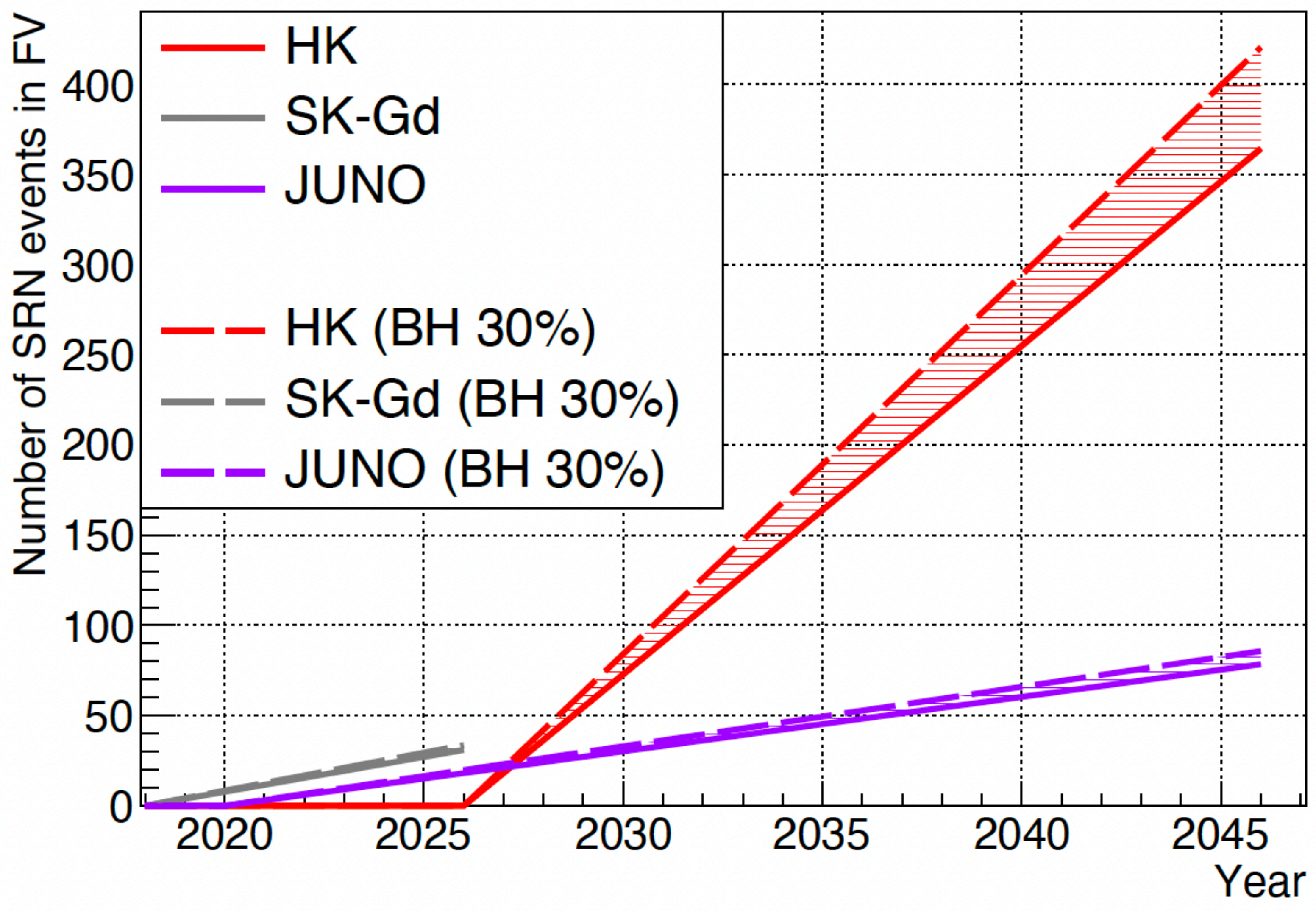




Supernova Neutrinos at Hyper-K



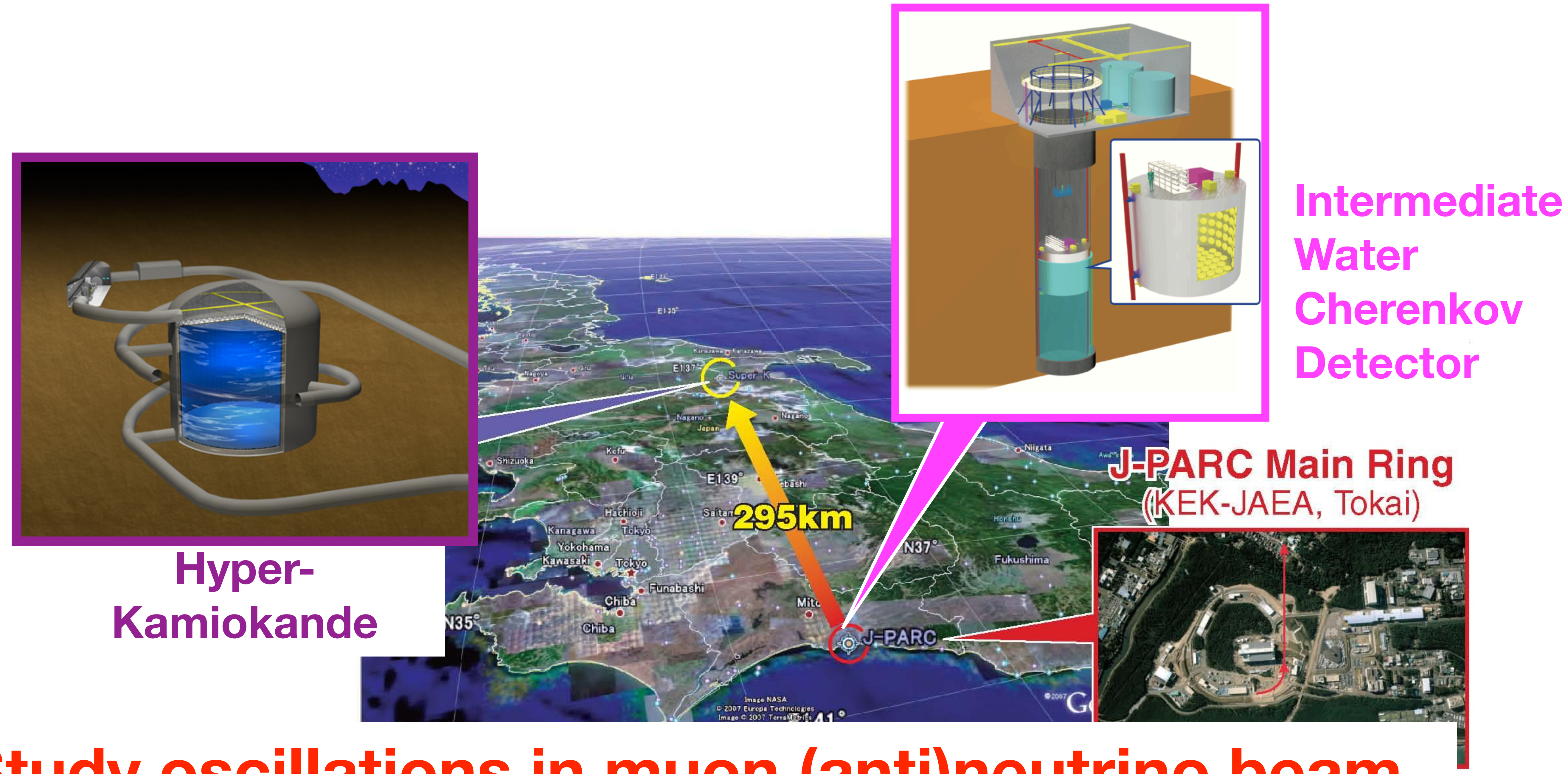
- **54k-90k events for 10 kpc distant supernova**
- ~10 neutrino events for supernova in Andromeda
- Neutrino-electron scattering introduces pointing capability
- **1.0-1.3 degree accuracy for 10 kpc distant supernova**



- There is a background of supernova neutrinos from all past supernovas
- Probes history of heavy element synthesis in stars
- Due to its large mass, Hyper-K will improve on sensitivity of SK-Gd

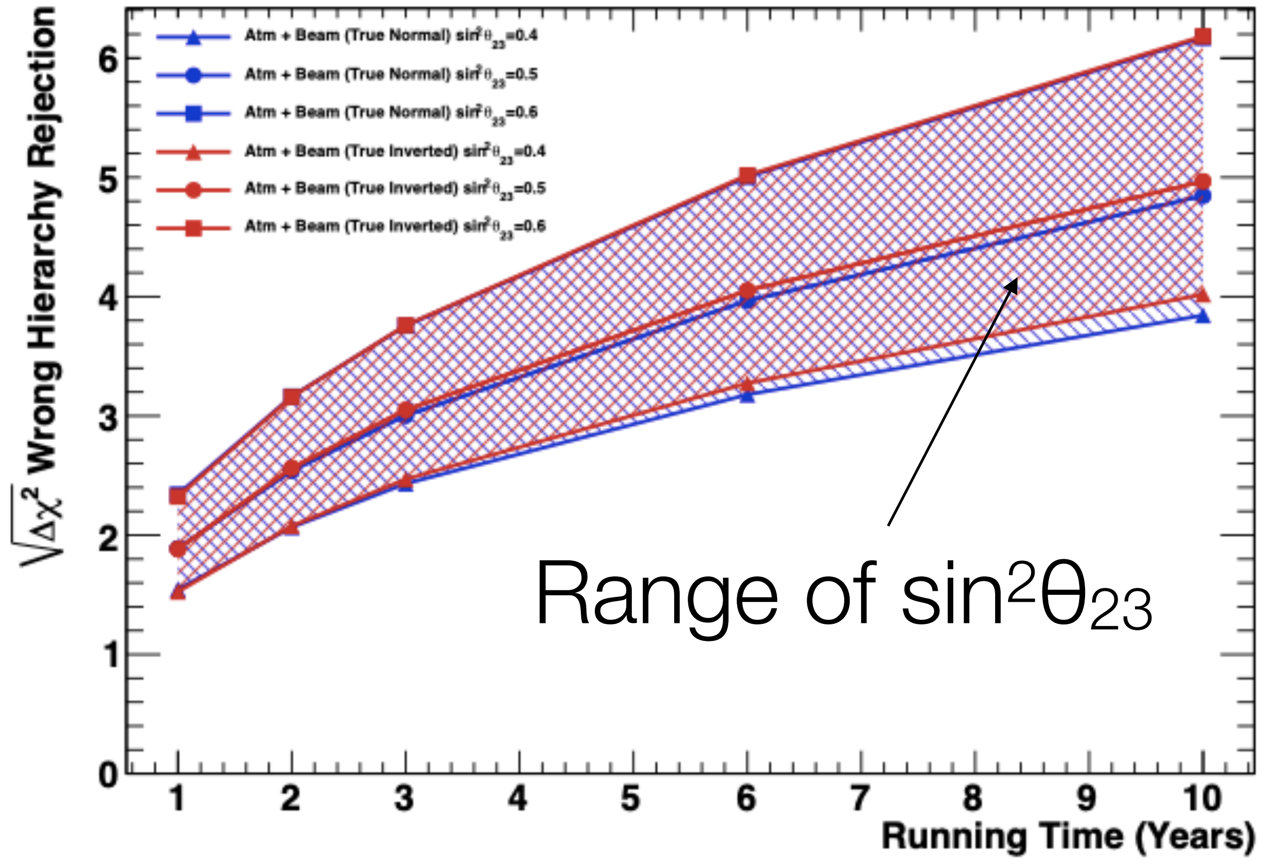
Neutrino Oscillations

Hyper-Kamiokande

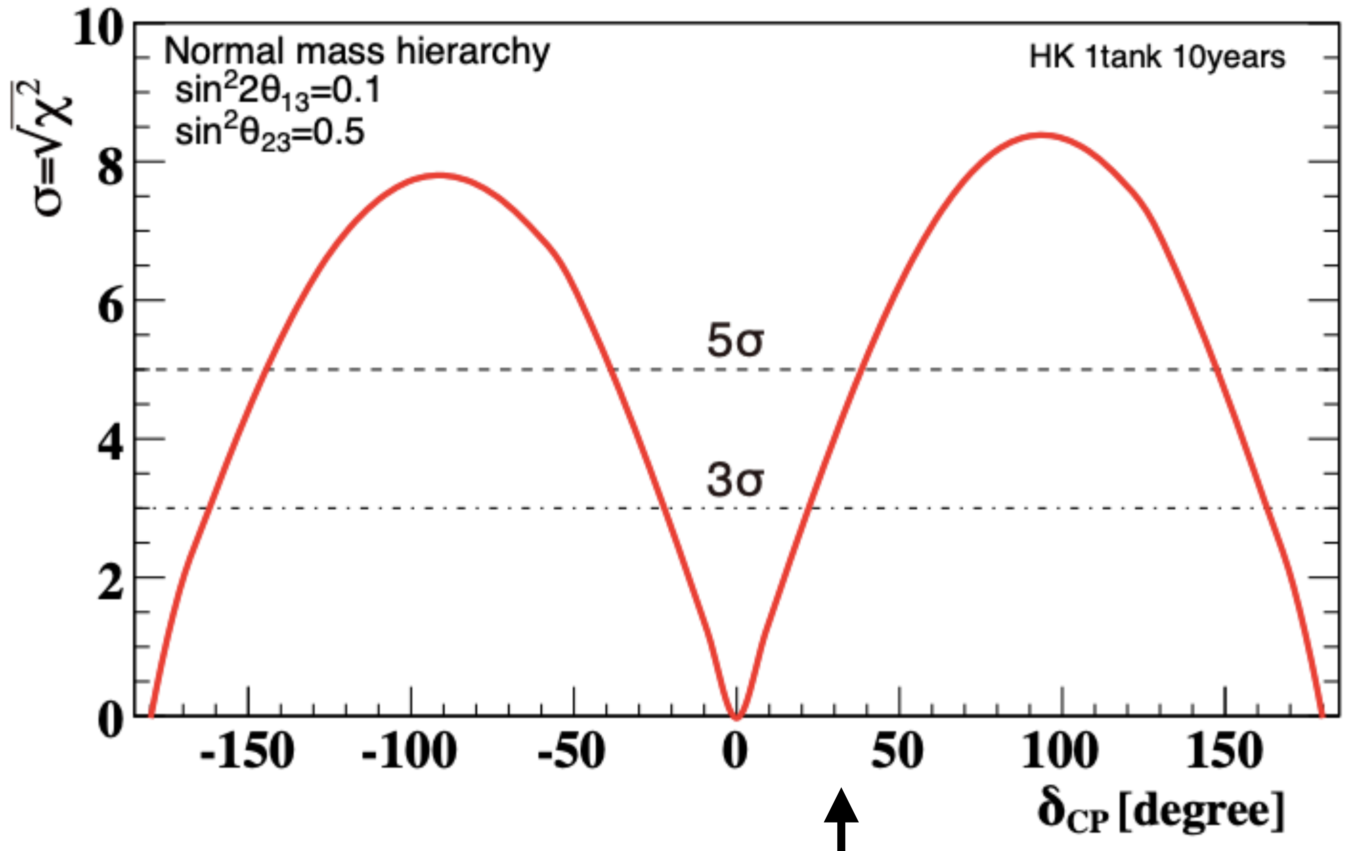


Study oscillations in muon (anti)neutrino beam, atmospheric neutrinos

Mass Ordering Determination (atmospheric ν)



CP Violation Discovery Potential



Muon (anti)neutrino survival:

$$P_{\mu\to\mu} = 1 - \left(\boxed{\sin^2 2\theta_{23}} - \sin^2\theta_{23}\cos 2\theta_{23}\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\boxed{\Delta m^2_{32}}L}{4E_\nu}\right) + \ldots$$

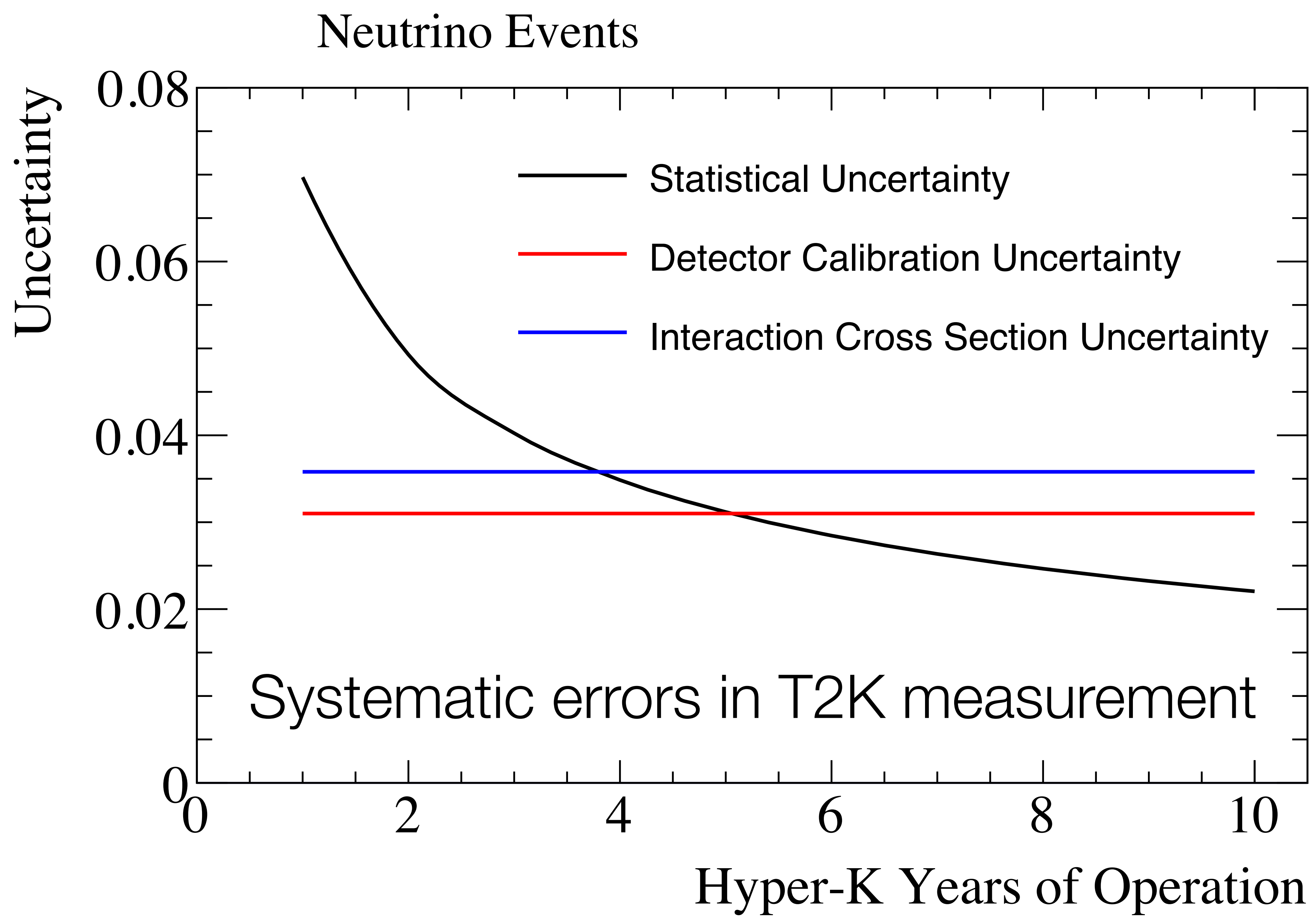
Electron (anti)neutrino appearance:

$$P_{\mu\to e} = \boxed{\sin^2\theta_{23}\sin^2 2\theta_{13}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right) \boxed{\mp} \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin^2 2\theta_{13}\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\boxed{\sin\delta_{CP}} + \ldots$$

sign flips for antineutrinos

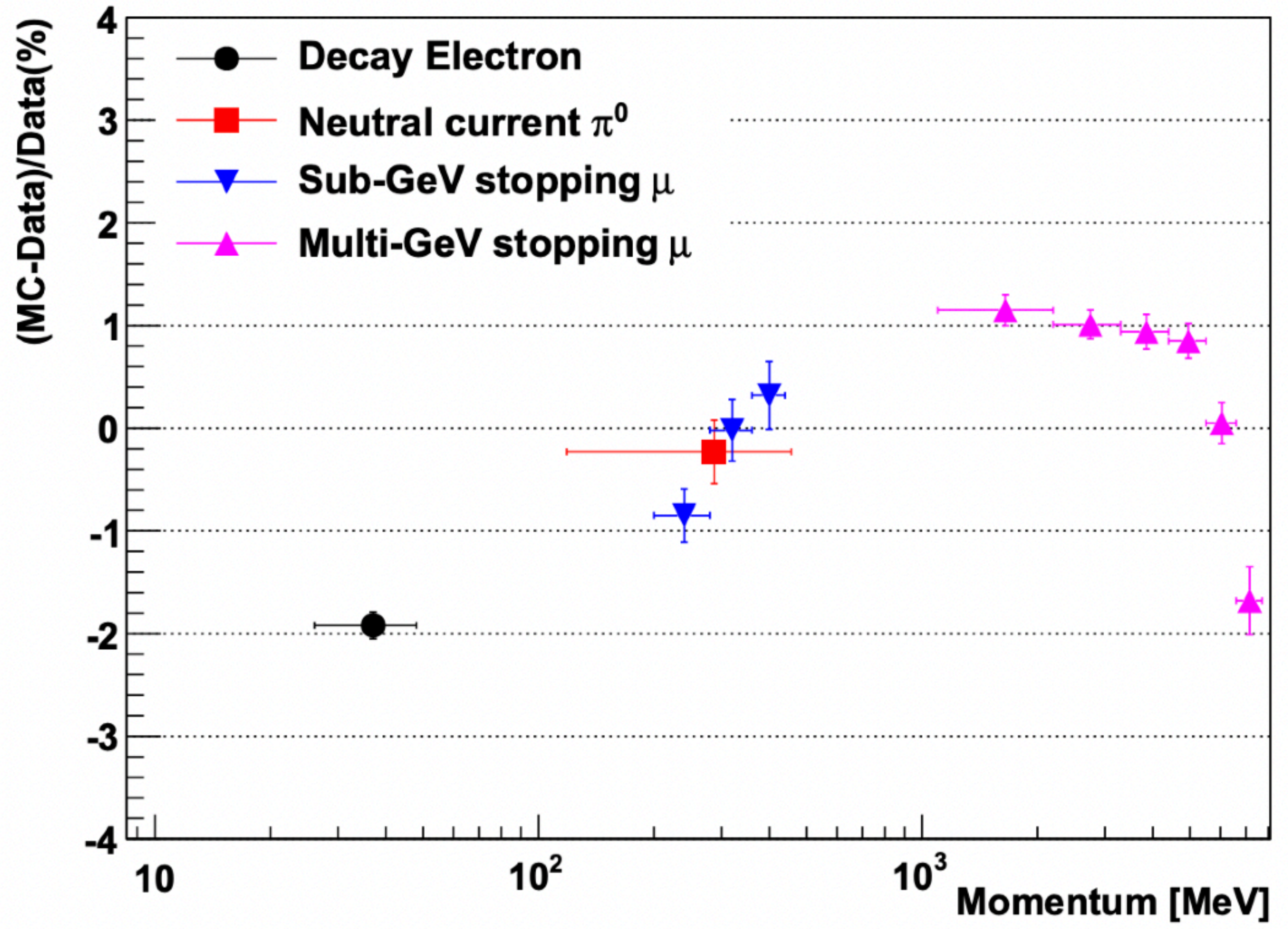
Systematic Uncertainties

- CP violation measurement quickly becomes systematic error dominated
- Uncertainty on neutrino interaction modeling to be addressed with Intermediate Water Cherenkov Detector (IWCD)
- Uncertainty on detector modeling to be addressed with new calibration systems and techniques



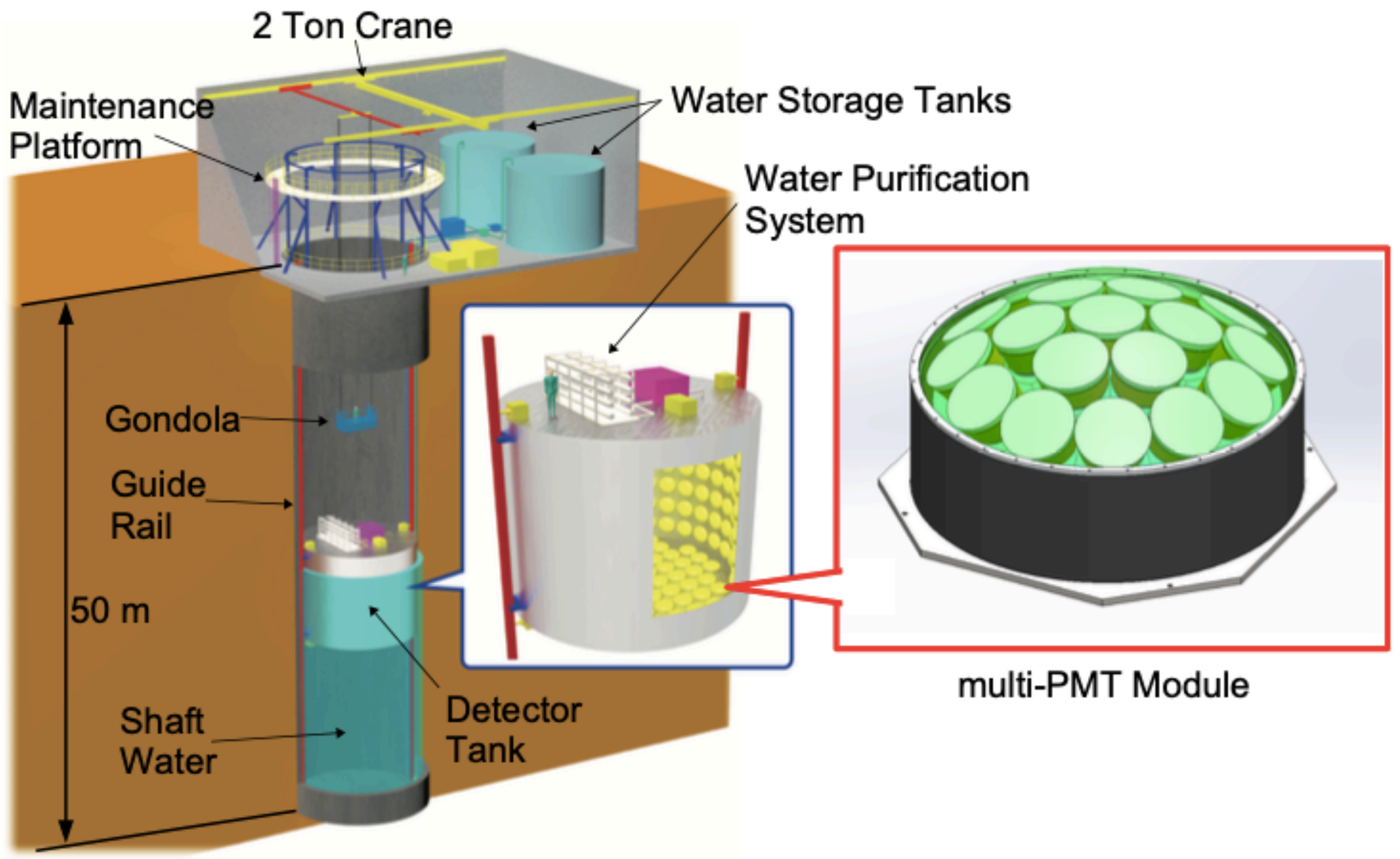
- To make precision parameter measurements, also need to know energy scale to 0.5% level
- Current error in Super-K is ~2%
  - Studies indicate this may arise from challenges in modeling water properties and PMT angular responses

Super-K Energy Scale
PTEP, vol. 2019, no. 5, p. 053F01, 2019

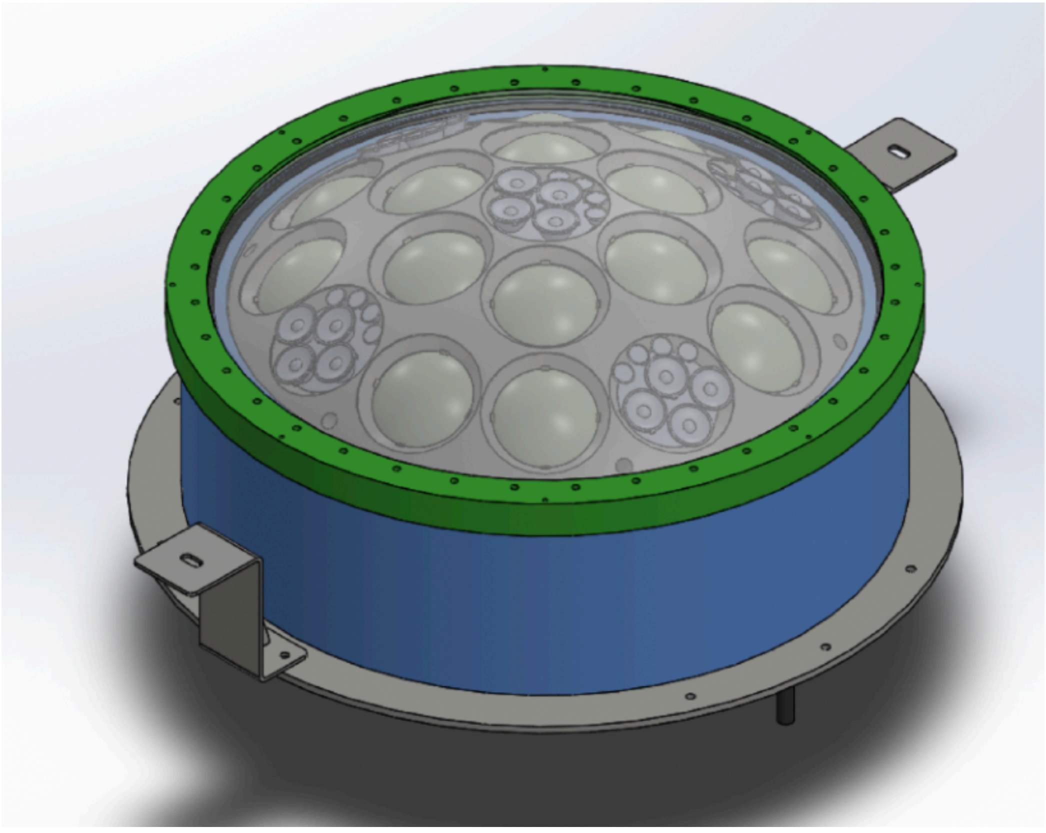


Canadian HK Program

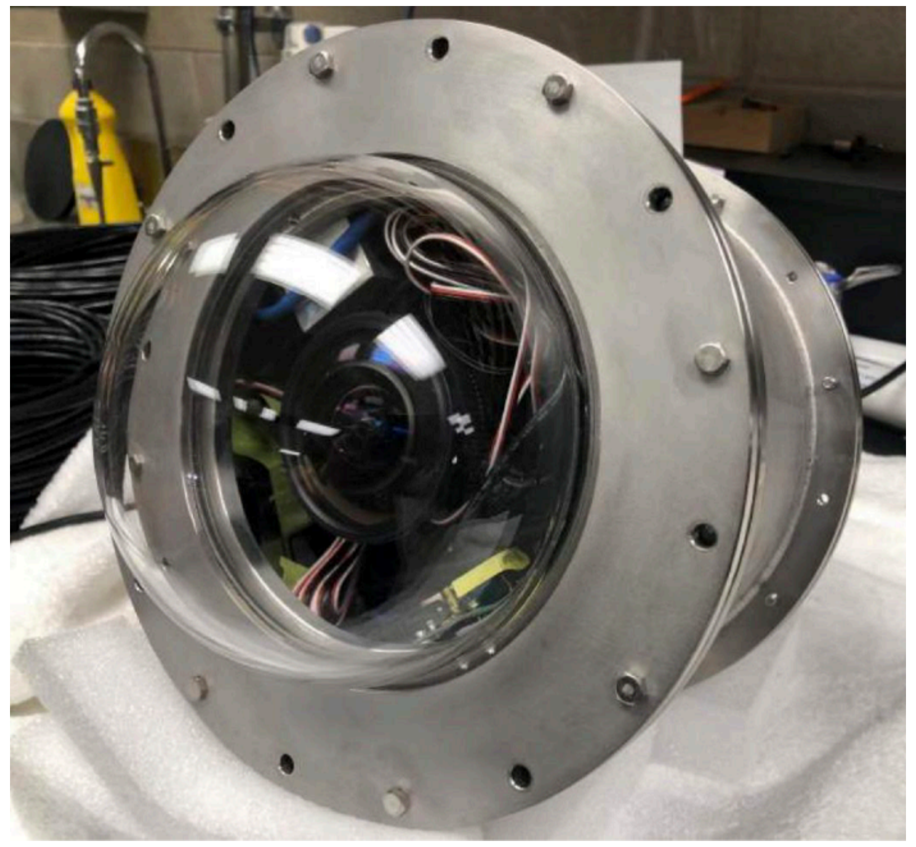
Intermediate Water Cherenkov Detector



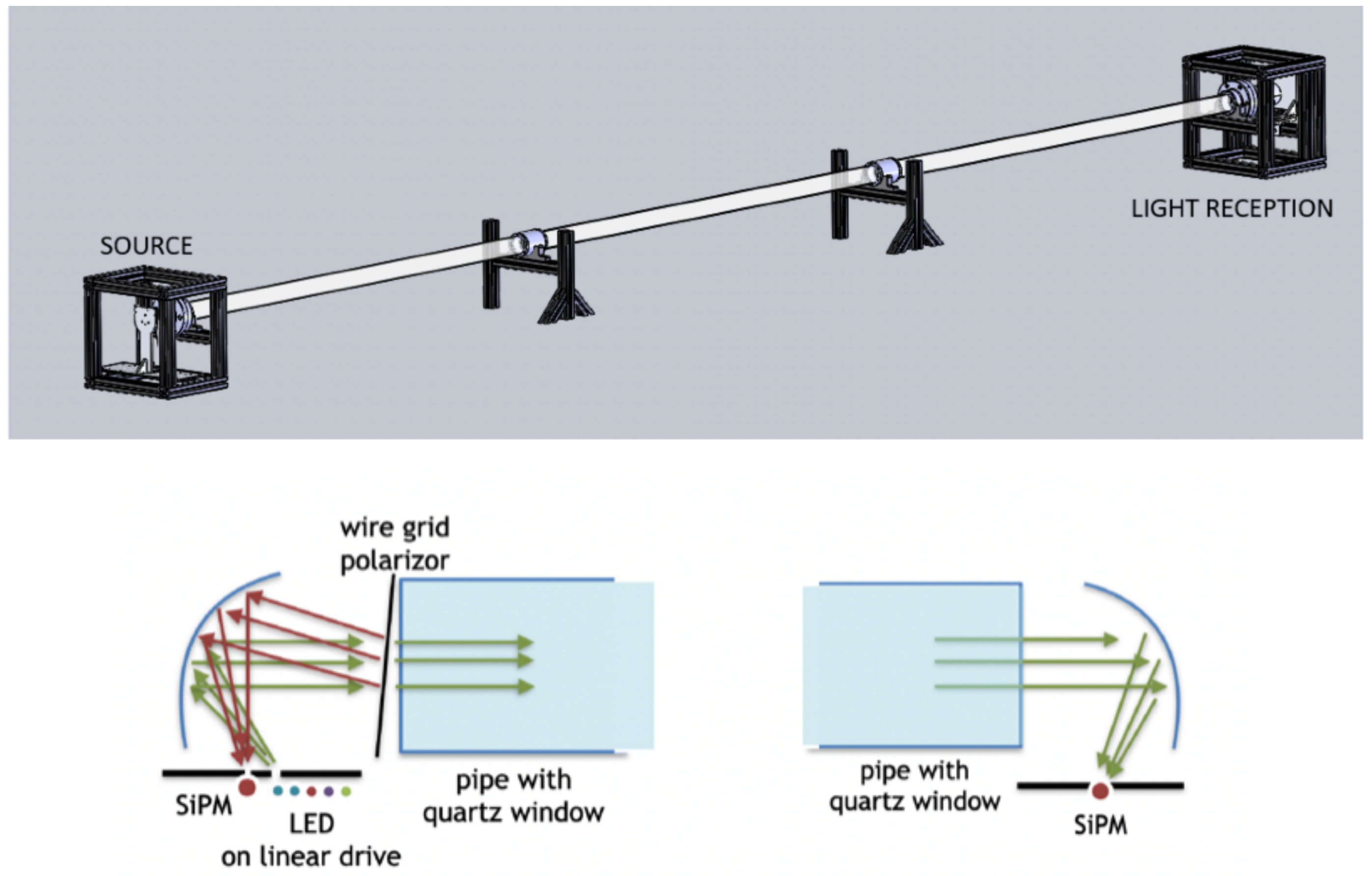
Hyper-K Style Multi-PMT



Camera for Photogrammetry



Water Scattering & Attenuation Measurement

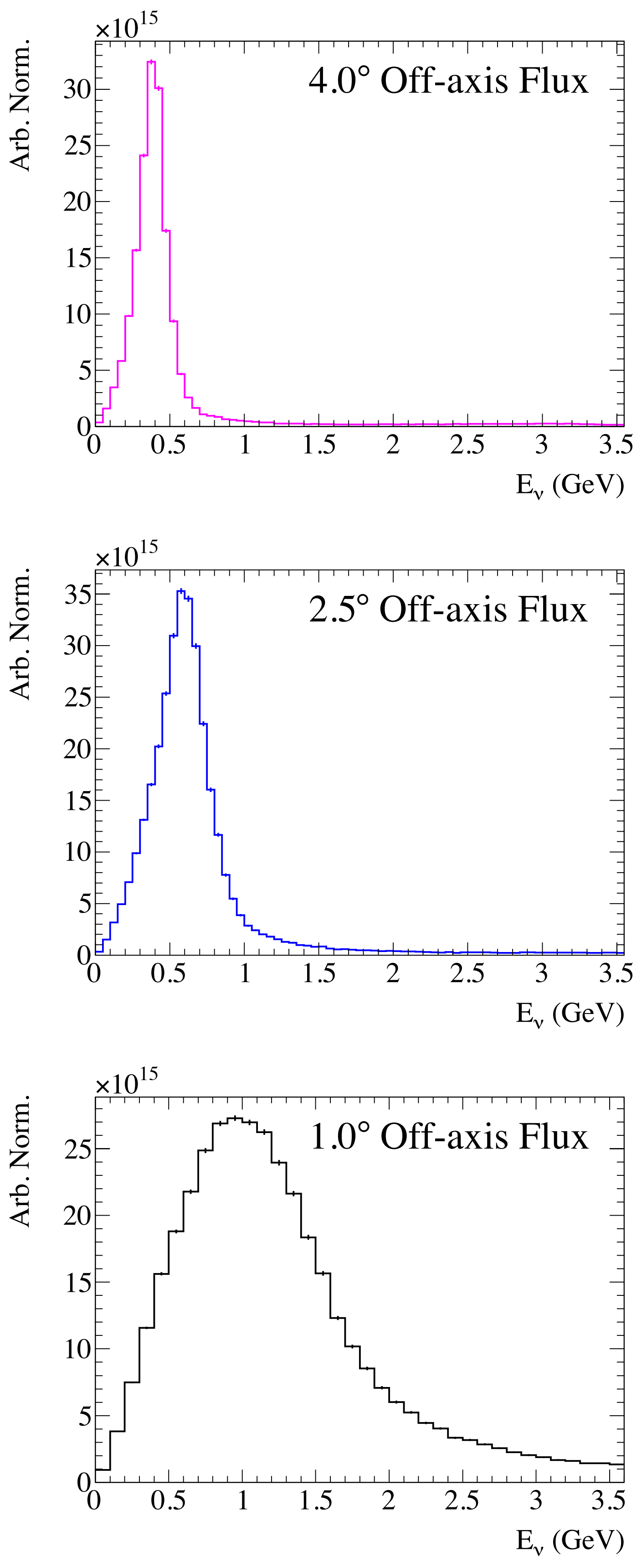


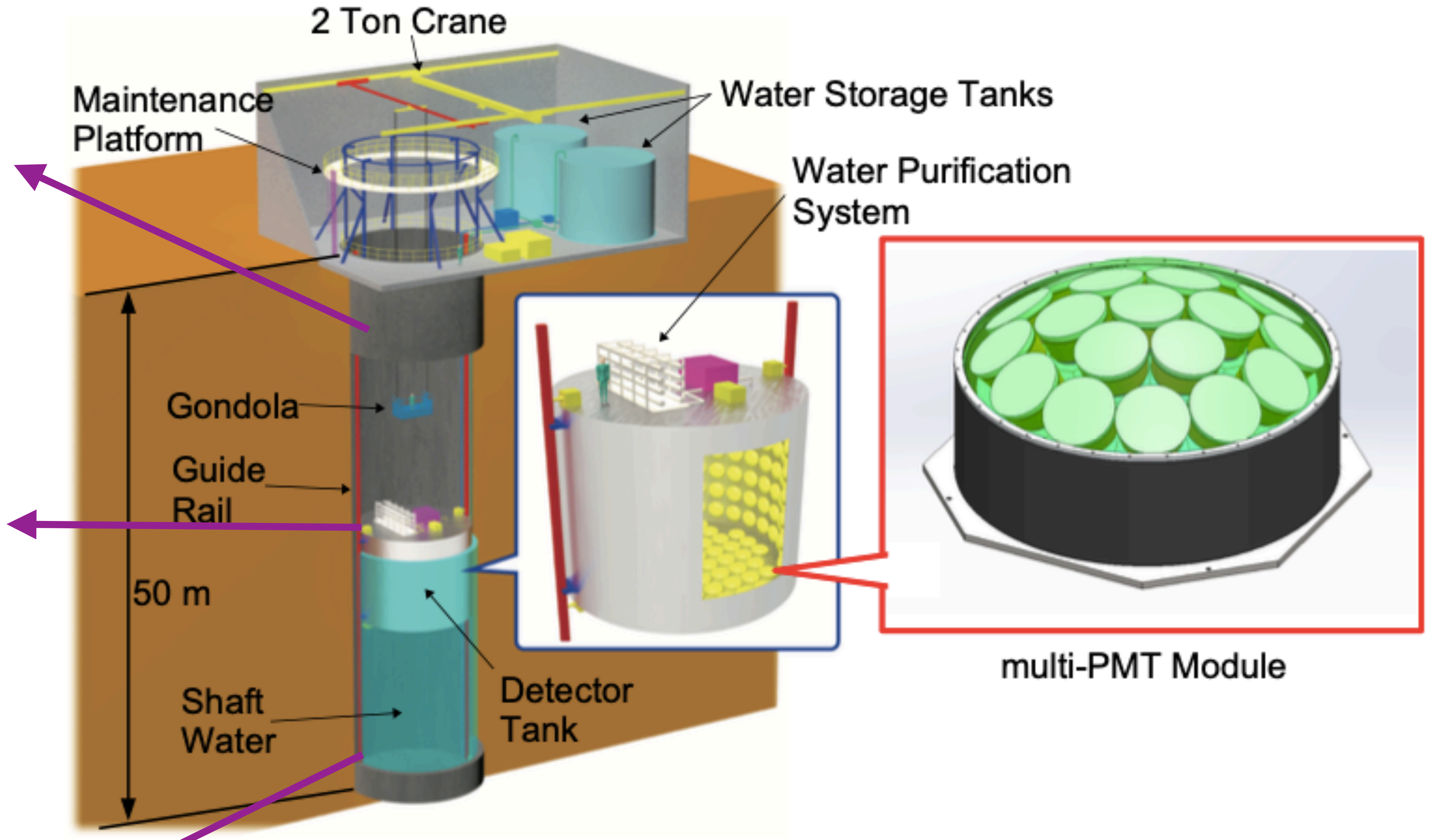
- IWCD will study important neutrino interaction properties - multi-PMT and photogrammetry contributions
- Will build 200 multi-PMT modules for Hyper-K with fine resolution photon detection and LED-based sub-ns pulse width light injection
- System of fixed cameras and remotely operated vehicles to measure the positions of PMTs and calibration sources
- Ex-situ water quality system to measure attenuation and scattering of Hyper-K water

The Intermediate Water Cherenkov Detector

Canadian led project

- Intermediate detector for Hyper-K
- Located ~1 km from neutrino source
  - Land acquisition is primary focus of host lab at this time
- 600 ton water Cherenkov detector
- Position can be moved to different off-axis angles
- Using new high resolution multi-PMT photon detectors
- Primary physics:
  - Electron (anti)neutrino interactions (with 1% of beam)
  - Measuring (anti)neutrino energy reconstruction



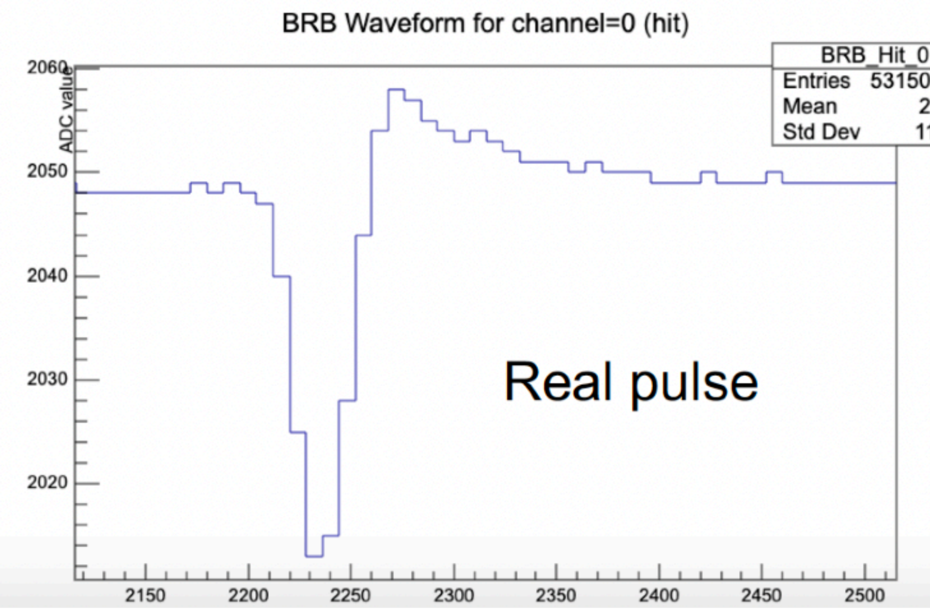


Approved Hyper-K project includes IWCD

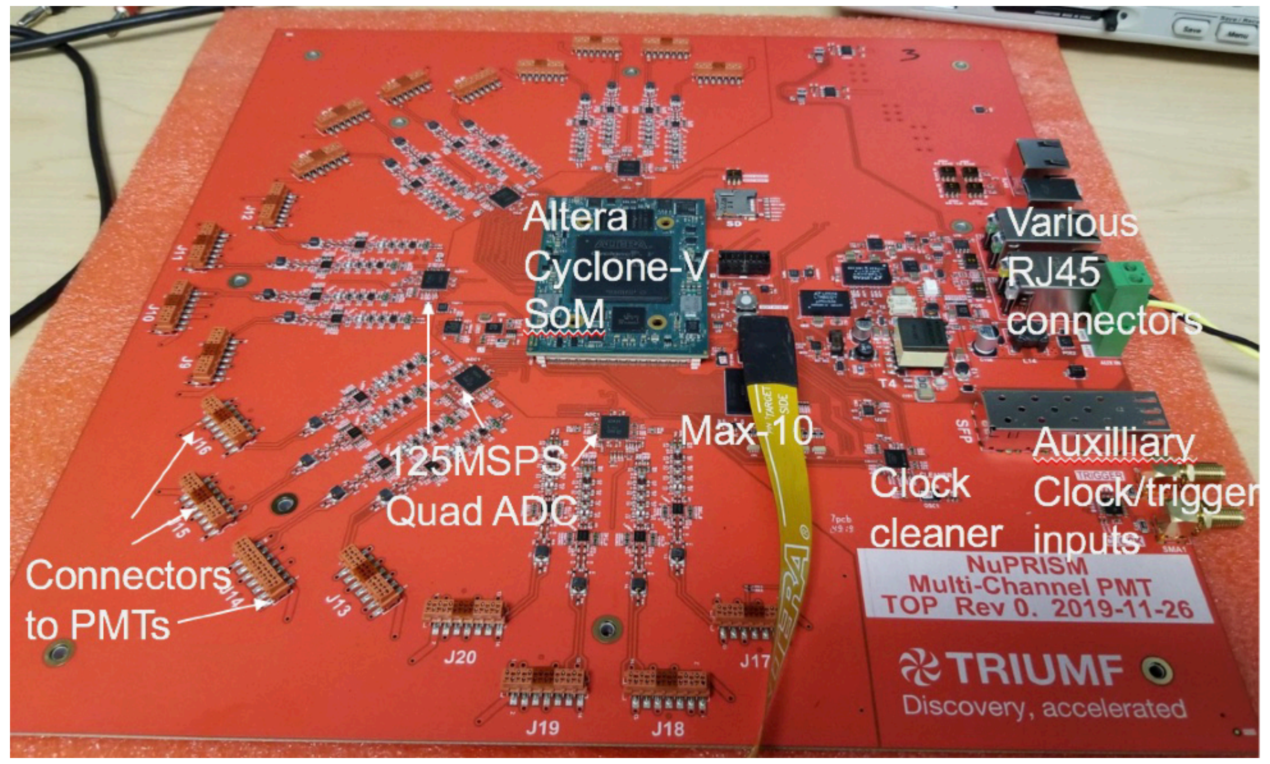
Multi-PMT (mPMT) Photosensor

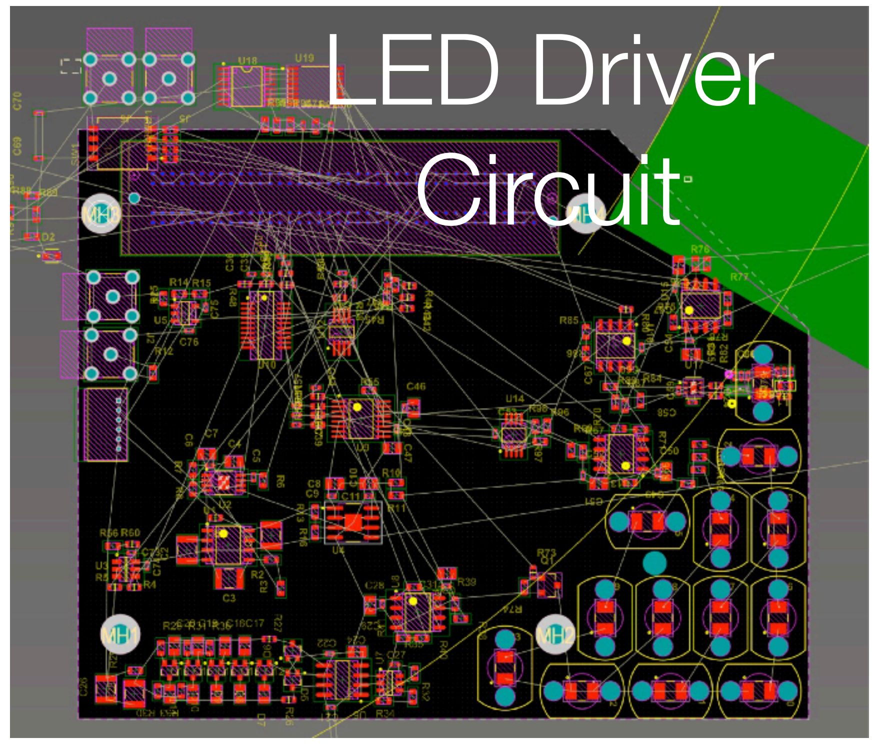
Hyper-Kamiokande

- Electronics development on 125 MSPS 20-channel FADC is well advanced
    - Working firmware for Xilinx FPGA
    - One more prototype revision planned with final decision on shaping circuit
    - Development of mezzanine care for driving of LED light injectors
- Mechanical vessel development focussed on application of optical gel for contact between dome and PMTs
    - Pre-gelling method (at TRIUMF) has produced perfect optical contact
    - Also considering applying gel after assembly (at Carleton U.)
    - Refining assembly method for mass production



Electronics main board





Prototype for ex-situ gelling

Prototype for in-situ gelling

Carleton UNIVERSITY
University of Victoria
TRIUMF
THE UNIVERSITY OF WINNIPEG
YORK UNIVERSITÉ UNIVERSITY

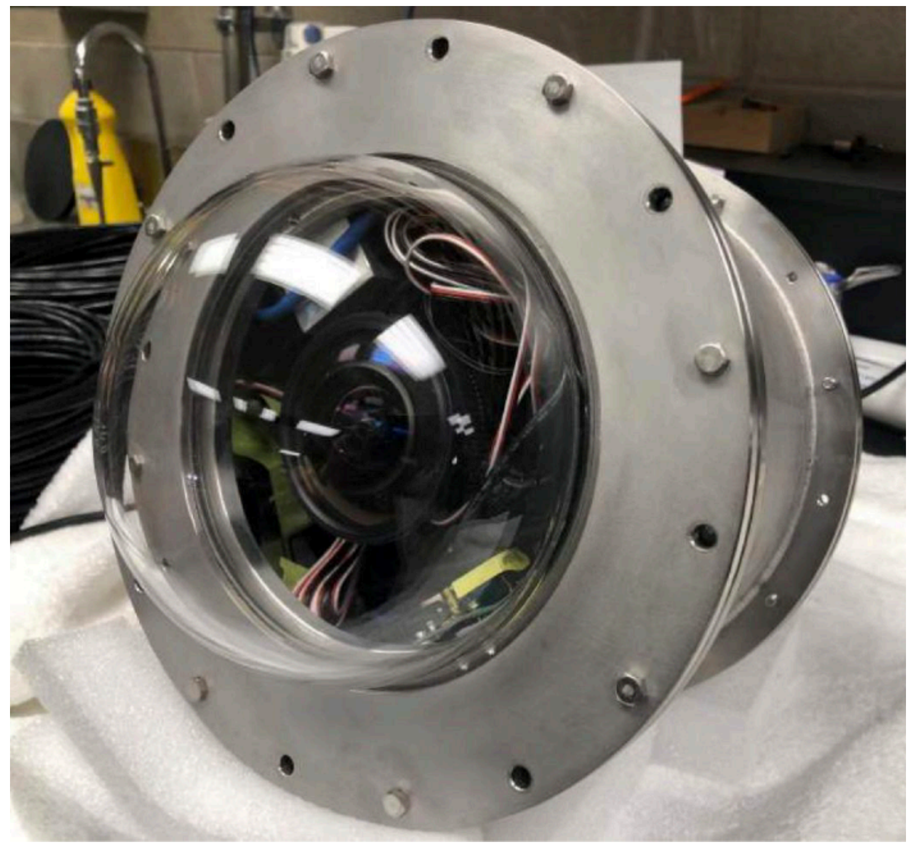
Photogrammetry Calibration

- Use standard cameras and lenses with custom-built underwater vessels for fixed cameras
- Ongoing tests at the UBC pool to characterize the optics under water
- Tests of the vessel at necessary pressures for Hyper-K detector are planned
- Prototype readout system has been developed and being tested at U. Winnipeg
- Photogrammetry simulation of detectors under development - choose the best location of cameras in detectors

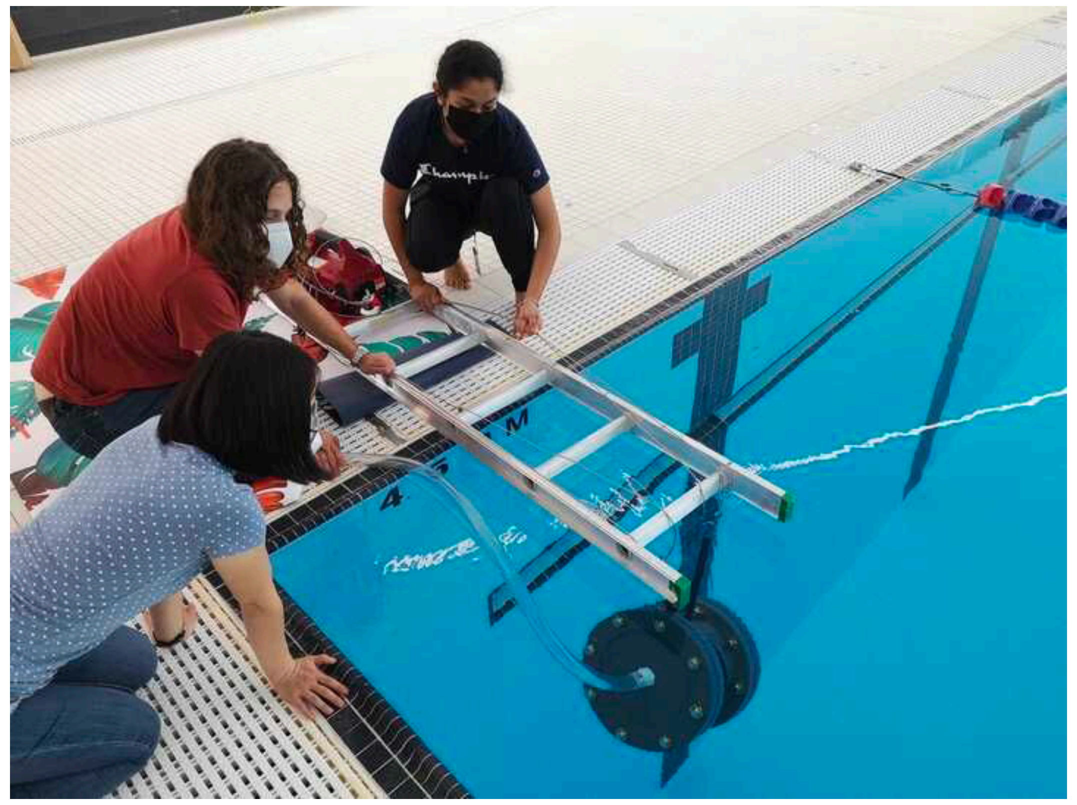
TRIUMF THE UNIVERSITY OF WINNIPEG University of Victoria

Hyper-Kamiokande

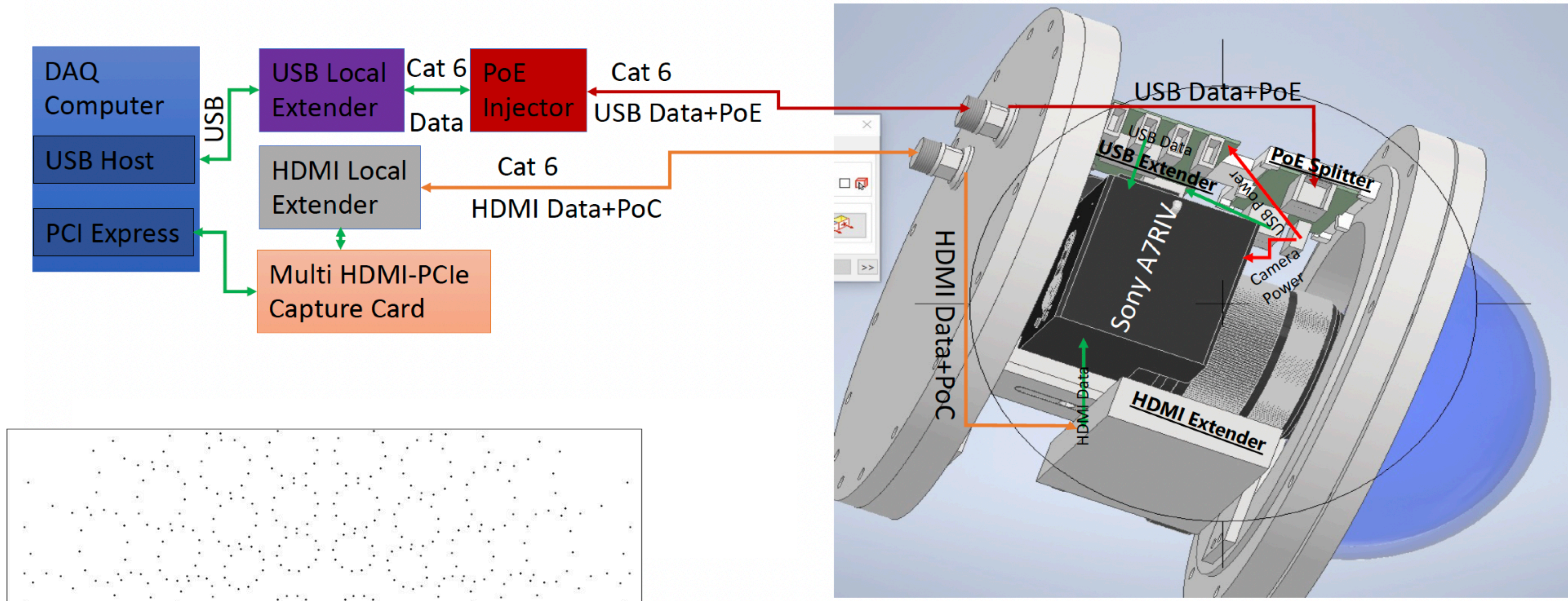
Prototype camera housing

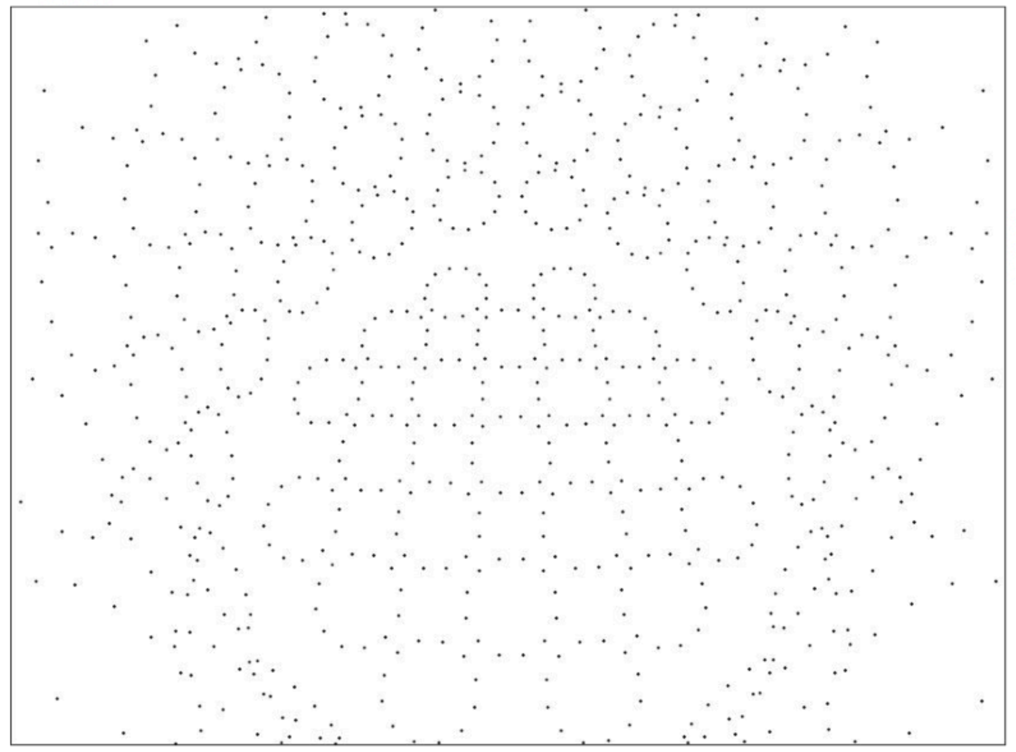


Measurements at UBC Pool



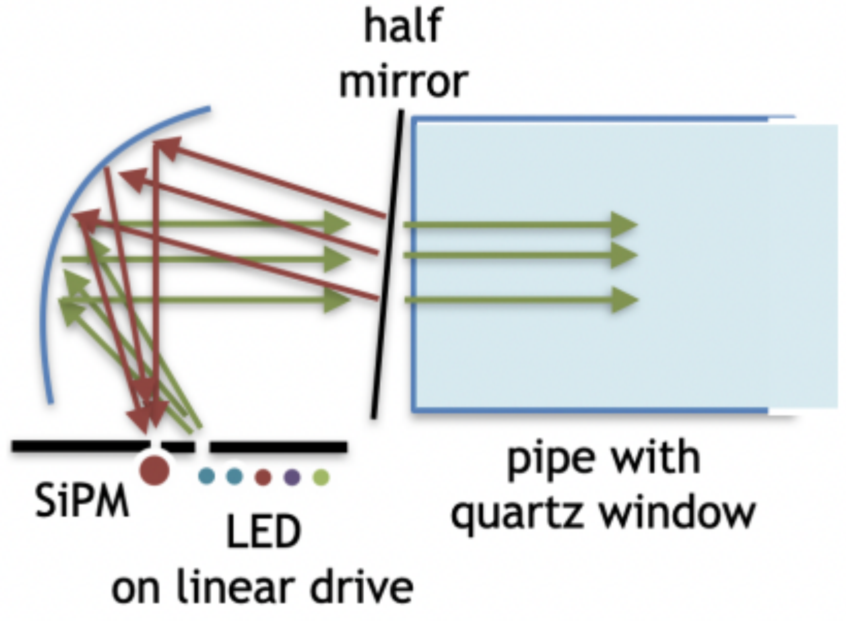
Camera readout (under development)

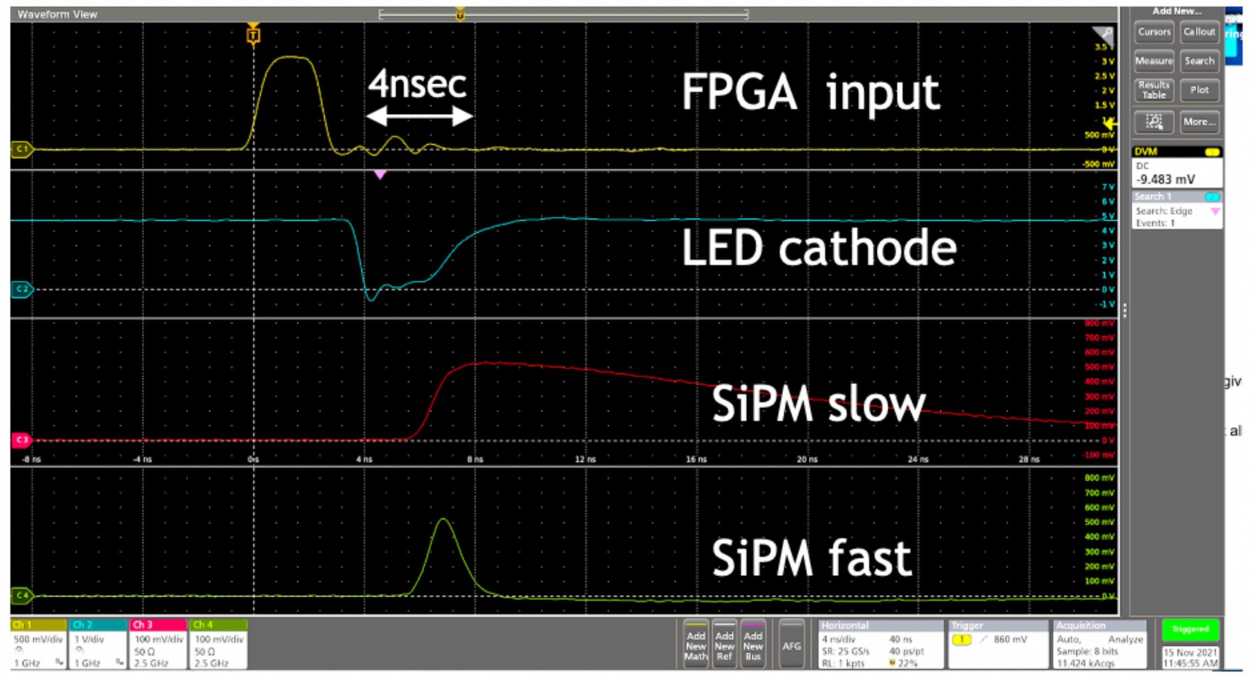




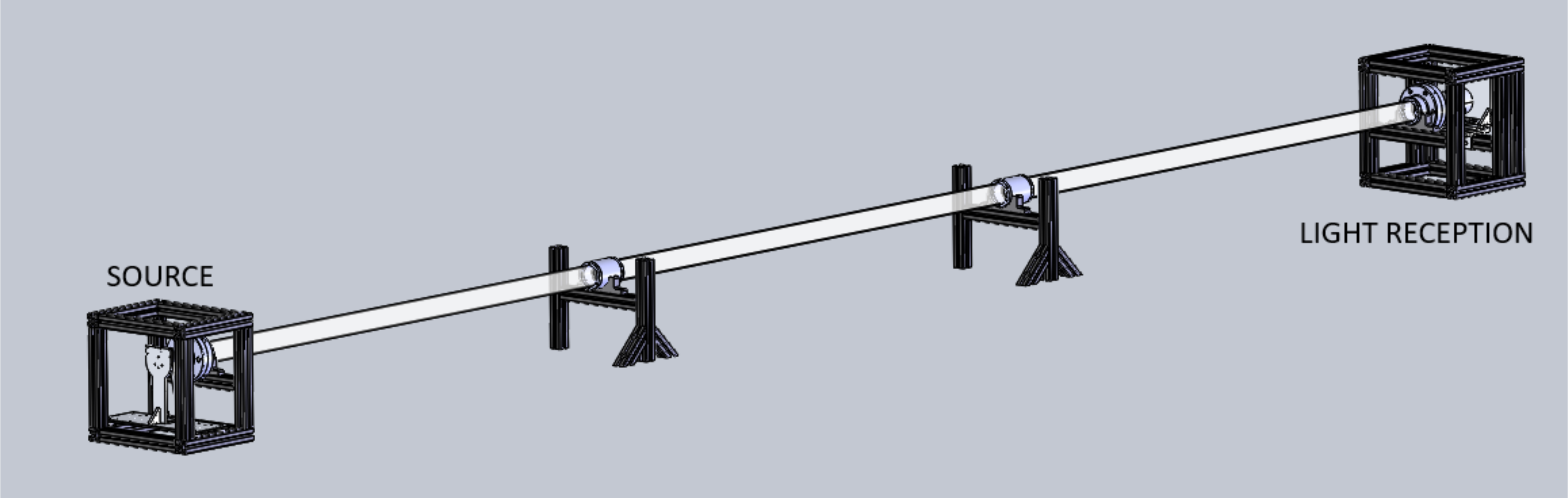
LED beacons from simulation

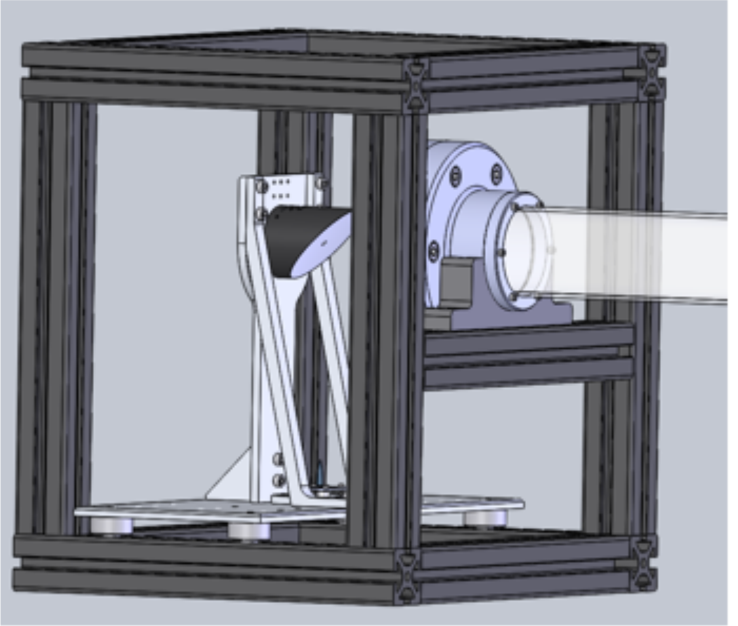
Water Quality Monitoring



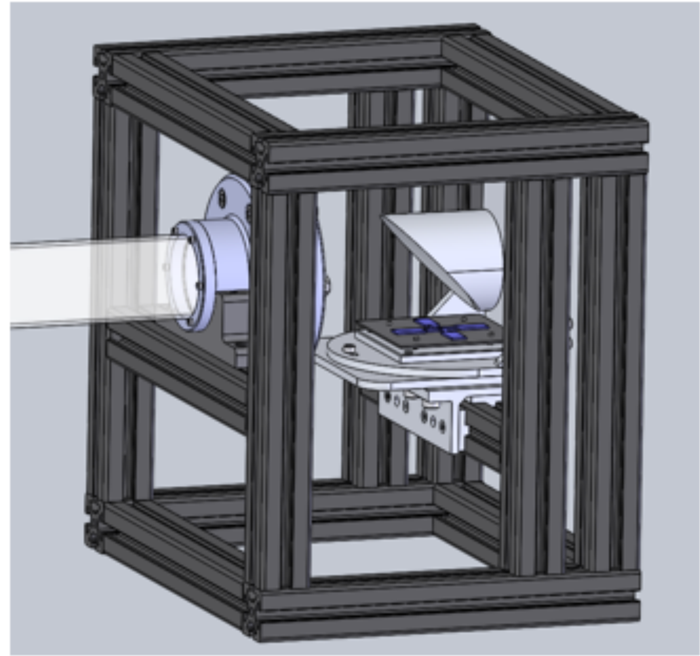


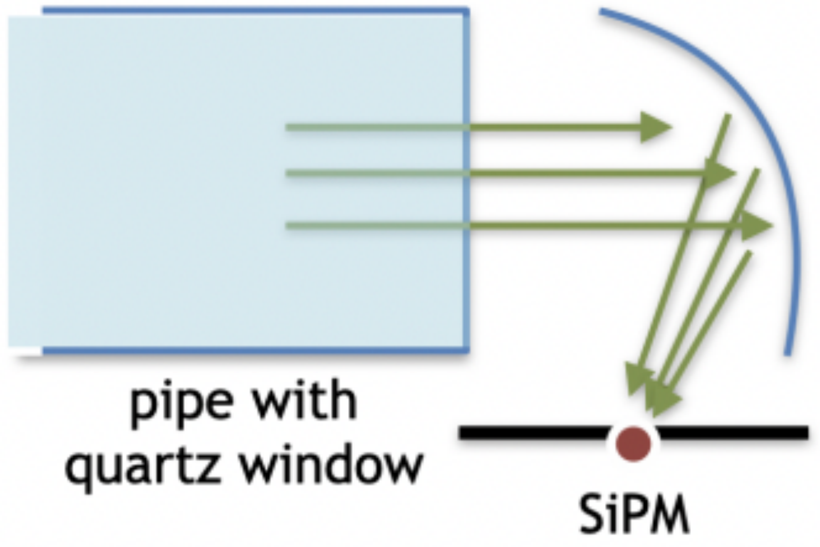
Fast LED

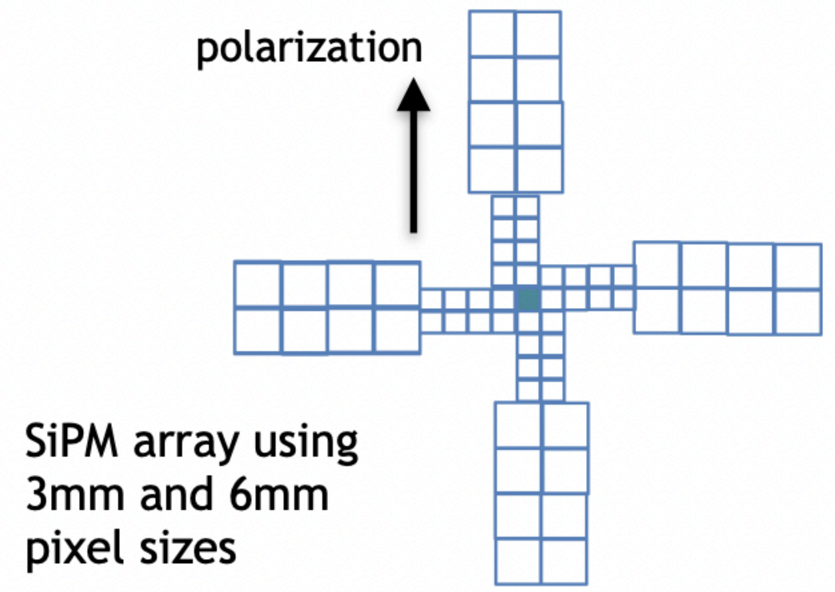




Shorter pipe for scattering measurement







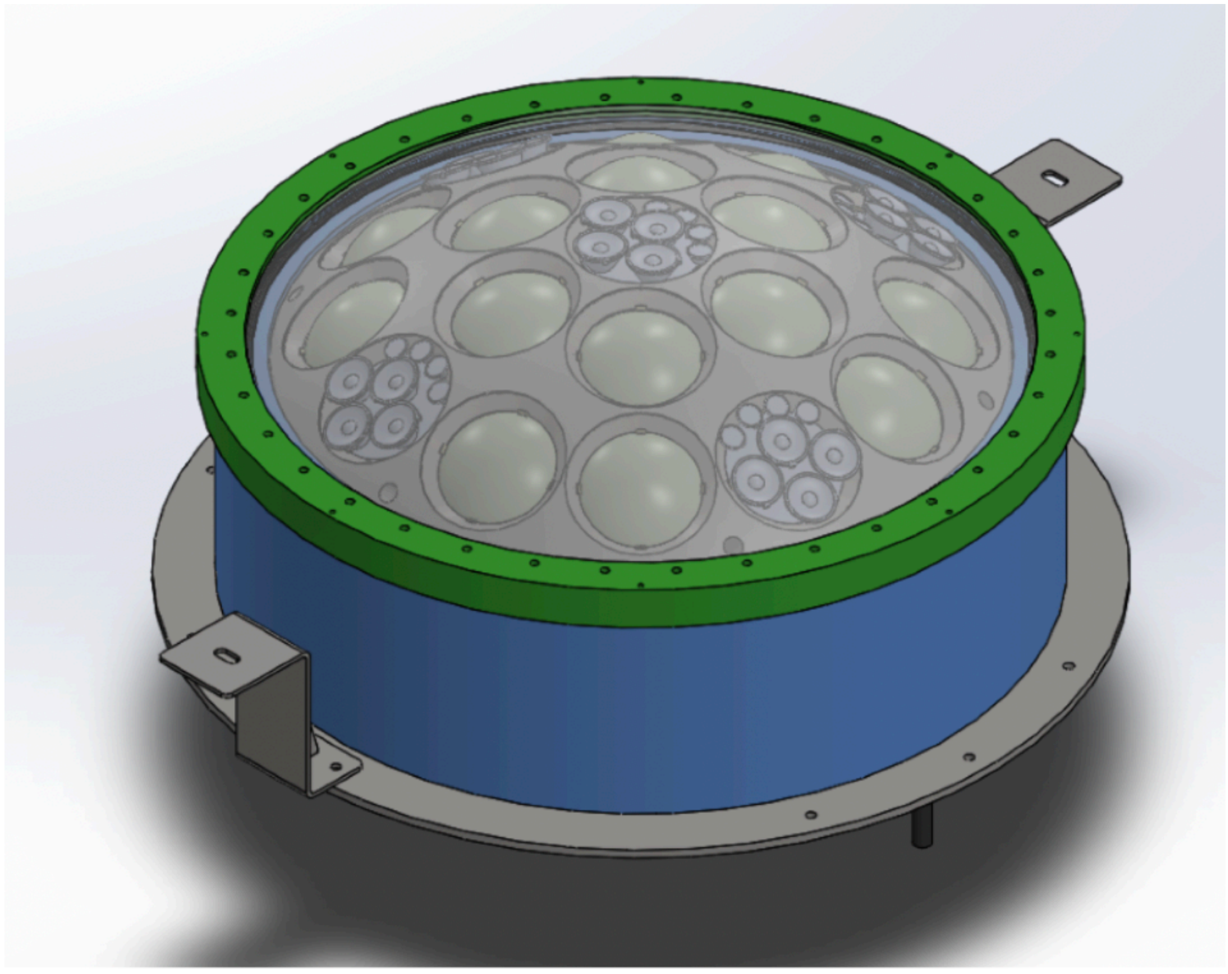
Larger SiPM array for scattering measurement

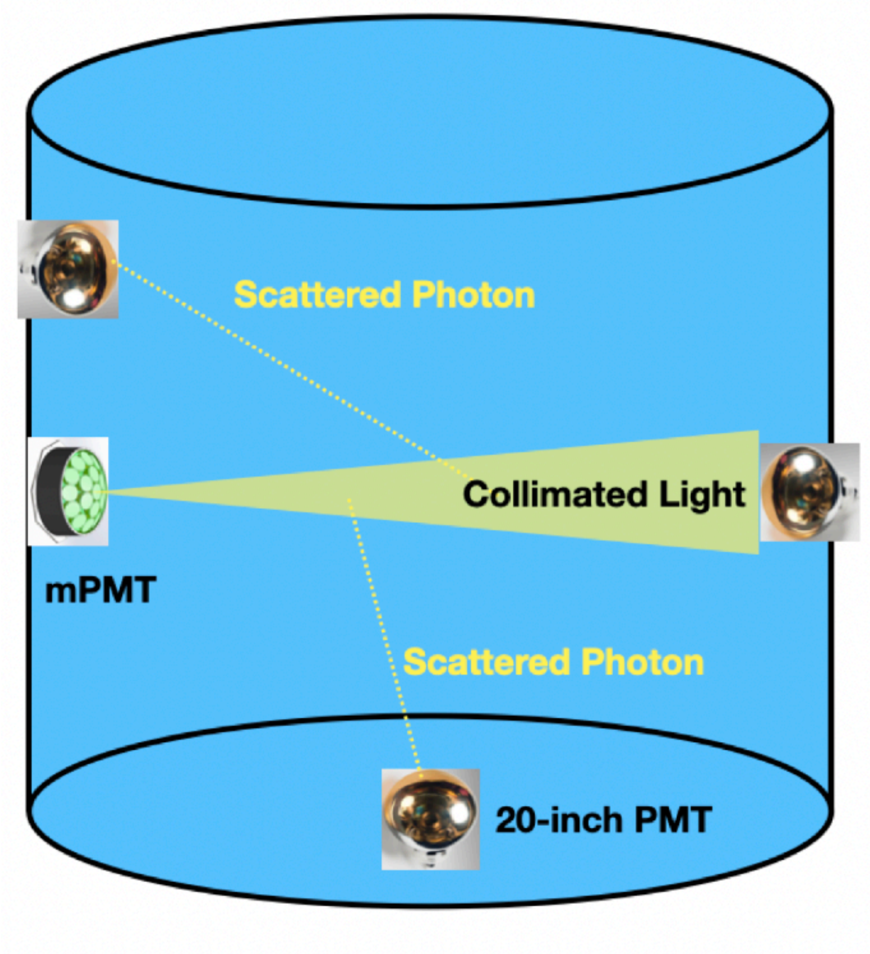
- Measure light attenuation and scattering in water samples
- Use low-cost sub-ns LED driver being developed at University of Victoria
  - LEDs down to ~270 nm allow for study of Raman Scattering
- Applications for environmental monitoring - NSERC alliance grant working with First Nations University of Canada (FNUniv), Cowessess First Nation, Ahtahkakoop Cree Nation, Weyburn Water Treatment Facility, water treatment engineering faculty at U.Regina

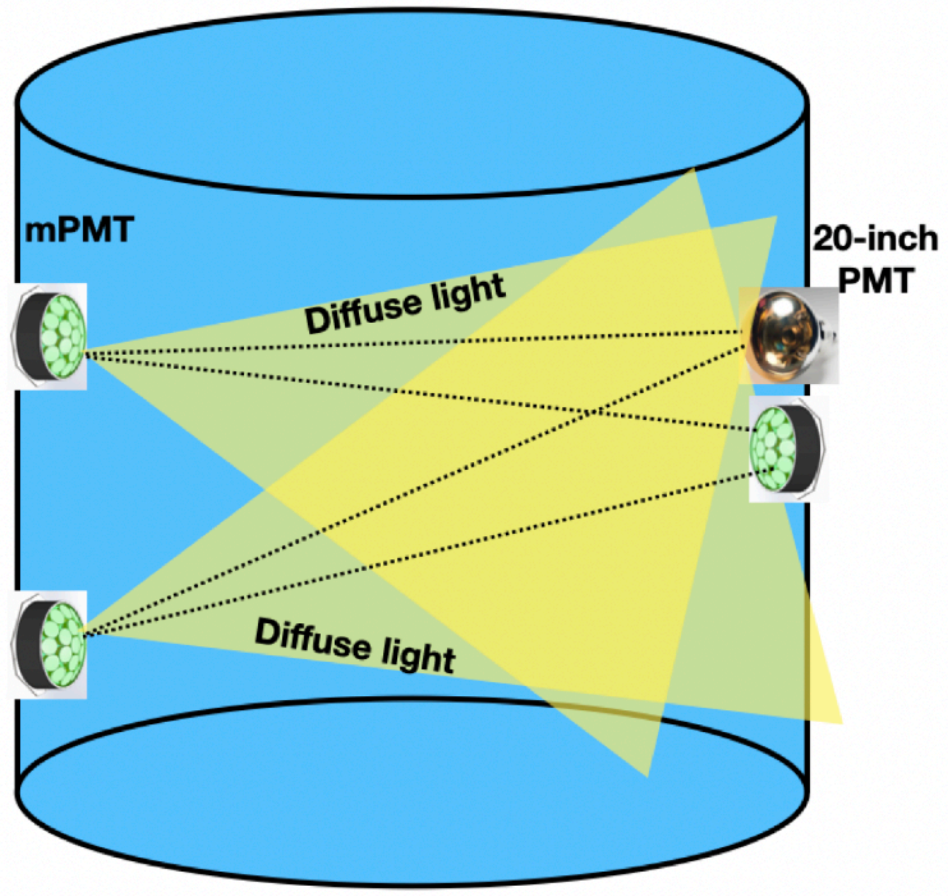
Multi-PMT for Hyper-K

- Replace 5 PMTs with LED light injector boards
- LED driver PCB with commercially available collimators/ diffusers can be mounted is under development at UVic
- Collimated light with varying wavelengths, including UV to study Raman scattering
  - 278nm - Raman scattering
  - 365nm - Peak Cherenkov intensity
  - 415nm - Peak quantum efficiency
  - 470nm - Tail of light distribution
- Sub-ns LED driver+sub-ns PMT resolution+collimated light = reconstruction of scattering position
- Diffuse light used to characterize in-situ angular response of 20-inch PMTs
  - Large 20-inch PMTs are sensitive to residual magnetic field
  - Nearby multi-PMTs provide relative normalization

Hyper-K mPMT Design



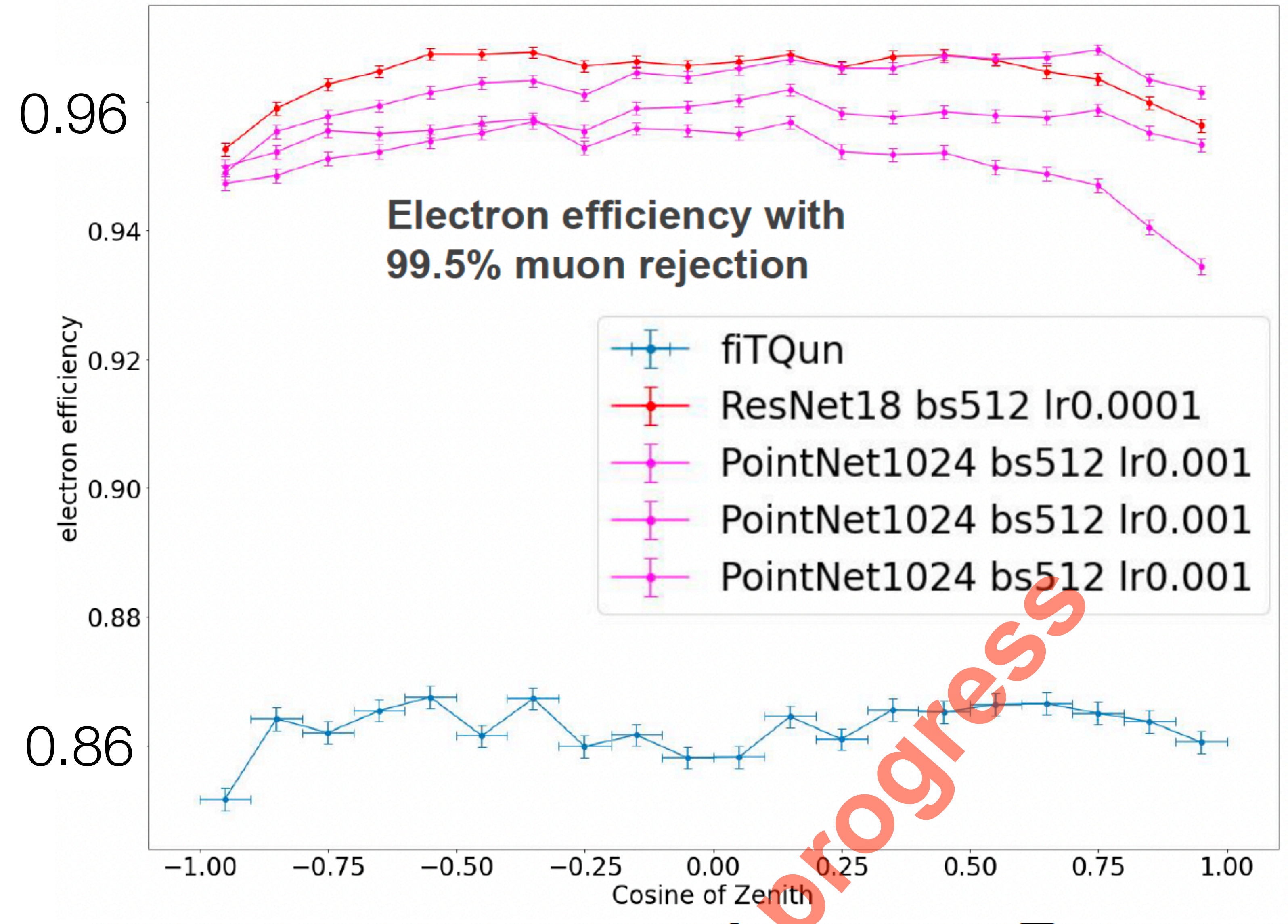


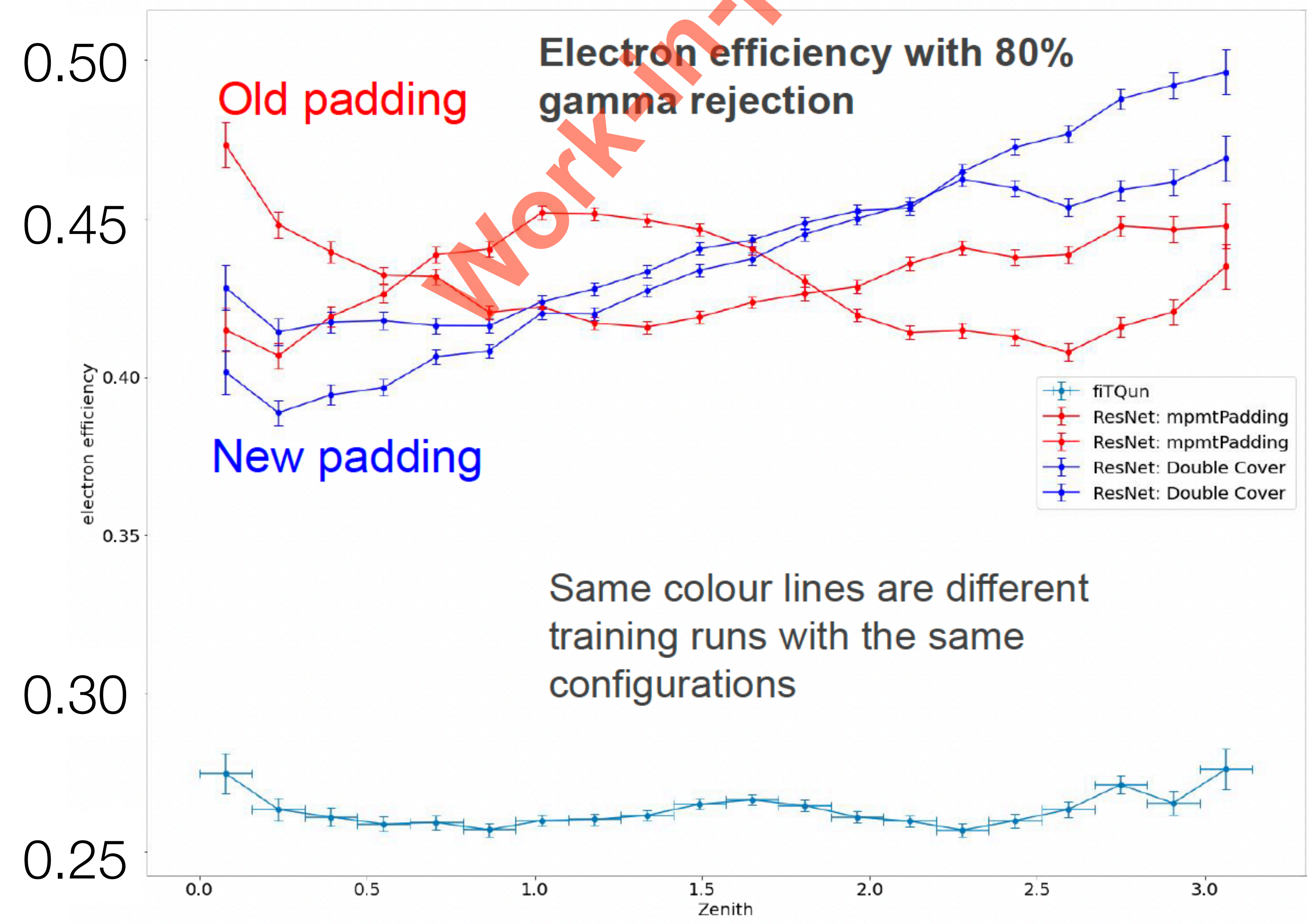


Machine Learning Event Reconstruction

Hyper-Kamiokande

- Machine learning plays a key role in the Canadian analysis strategy
  - Use all of the information provided by fine resolution measurements of mPMTs in IWCD
  - Very fast event reconstruction allows for quick study of systematic parameter variation in detector calibration
- WatchMal group started by Hyper-K Canada leads studies of machine learning applications for water Cherenkov detectors across the globe
- Generally seeing significant improvements in areas such as classification compared to the likelihood-based fiTQun reconstruction





BCIT BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY

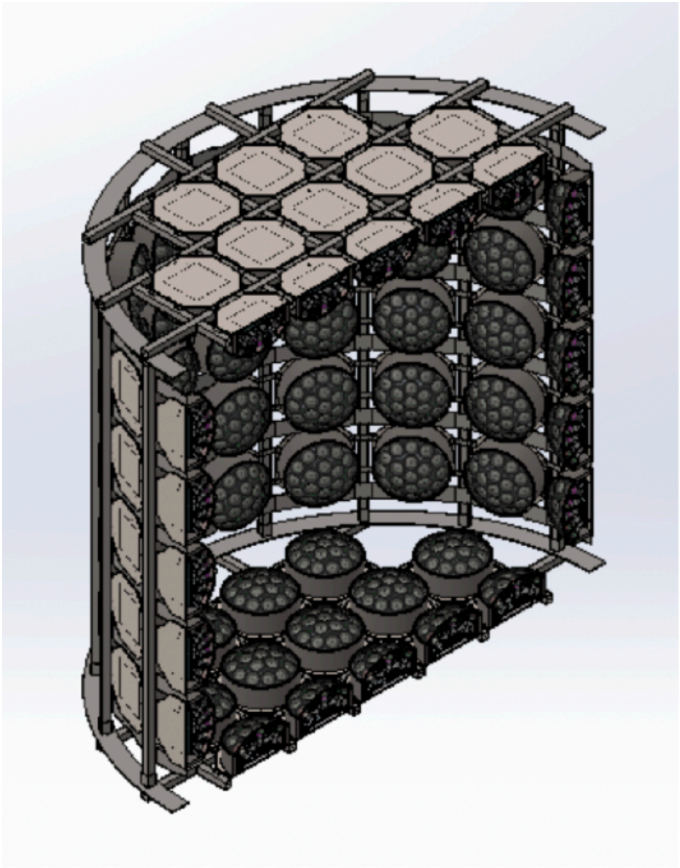
TRIUMF

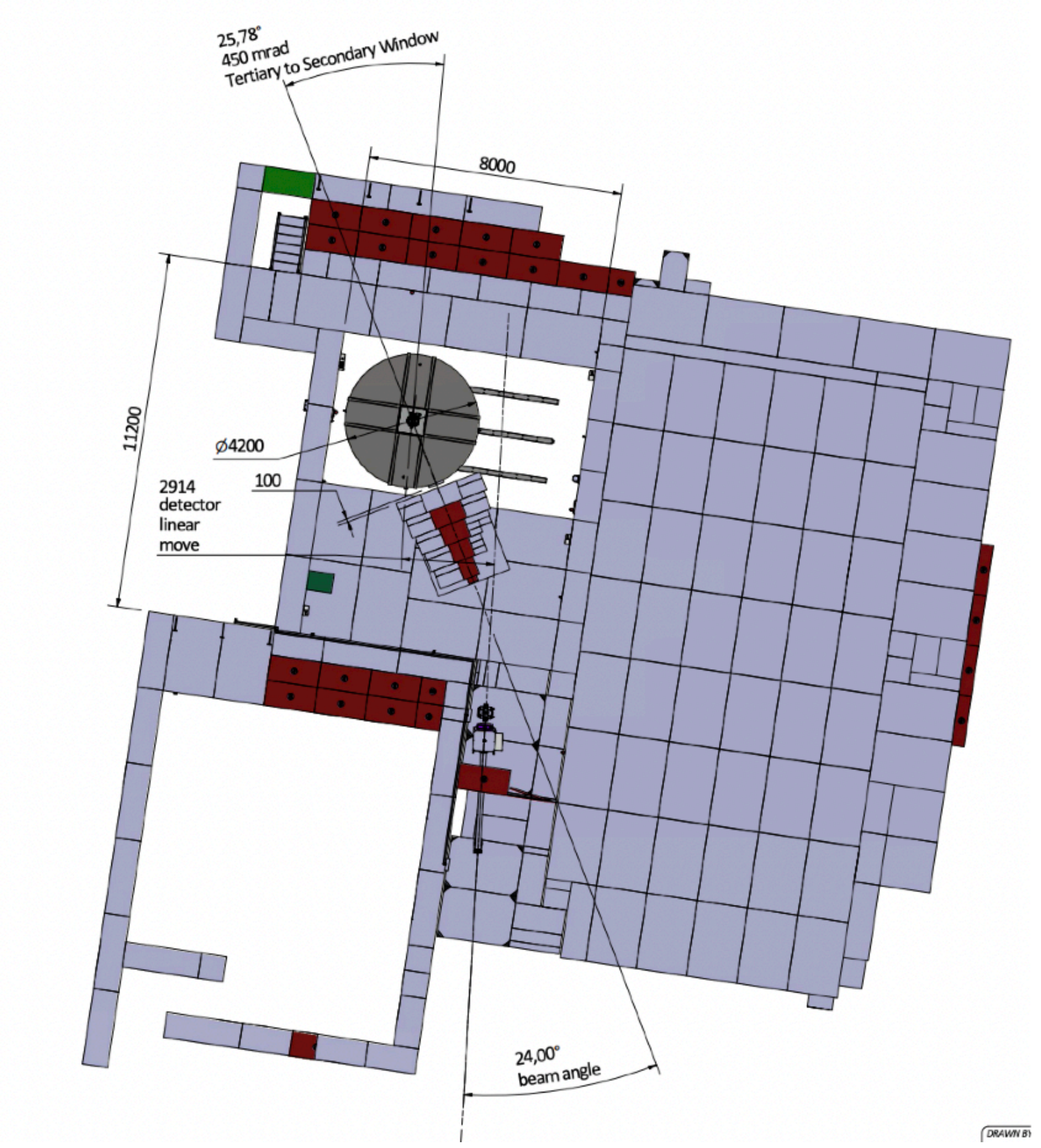
THE UNIVERSITY OF WINNIPEG

Test Experiment at CERN

- Operation of IWCD prototype called WCTE in CERN test beam (T9) in 2024
- Study detector calibration and response with known particle fluxes of 0.2-1.1 GeV/c π, p, e, μ
- Beam test data in 2022 to determine if secondary particle fluxes at low momenta are sufficient
    - Test muon/pion separation with Aerogel Cherenkov Threshold detector (ACT)
    - More data collection in low momentum beam configuration in July
- Have received recommendation from the CERN SPSC and Research Board Approval

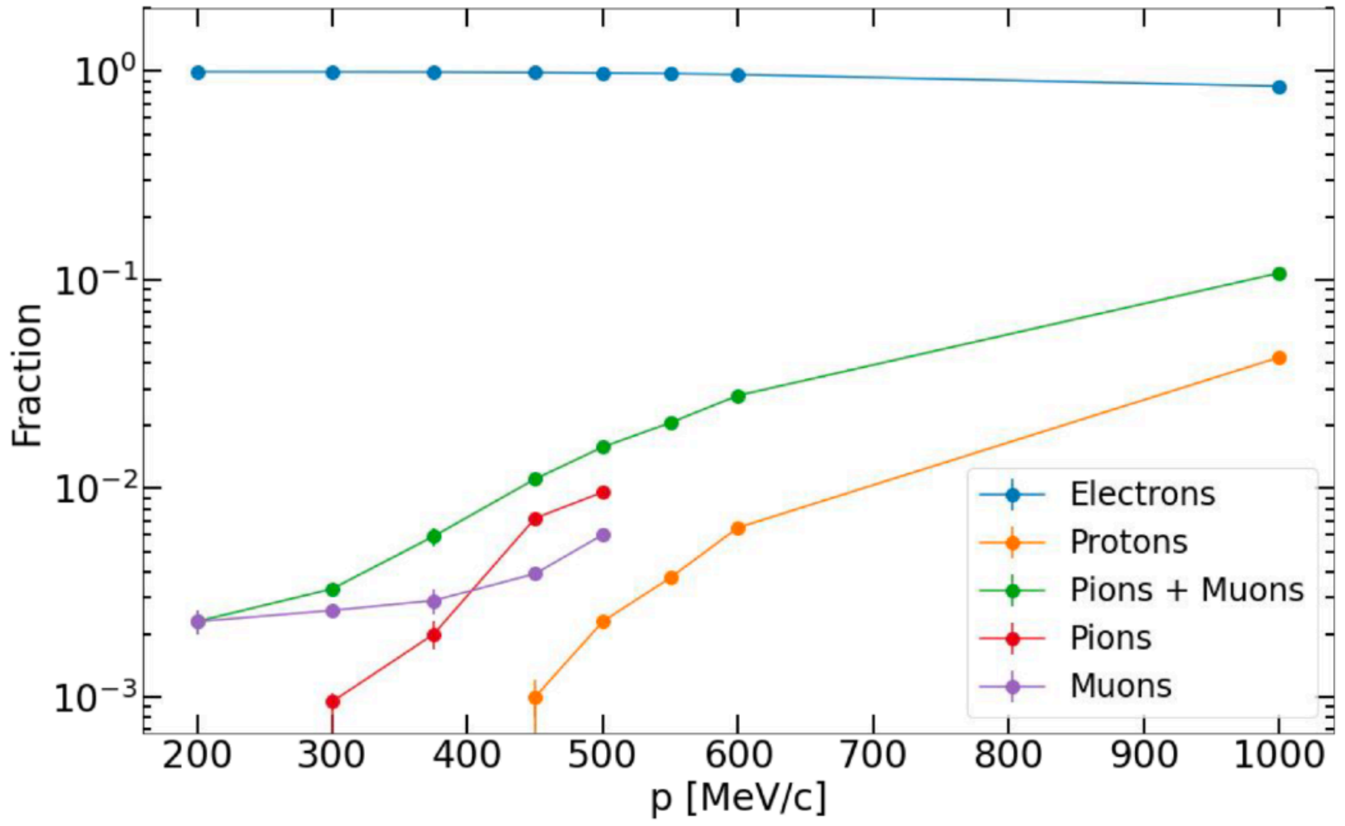
CERN-SPSC-2020-005; SPSC-P-365:
http://cds.cern.ch/record/2712416?ln=en





ACT Detector

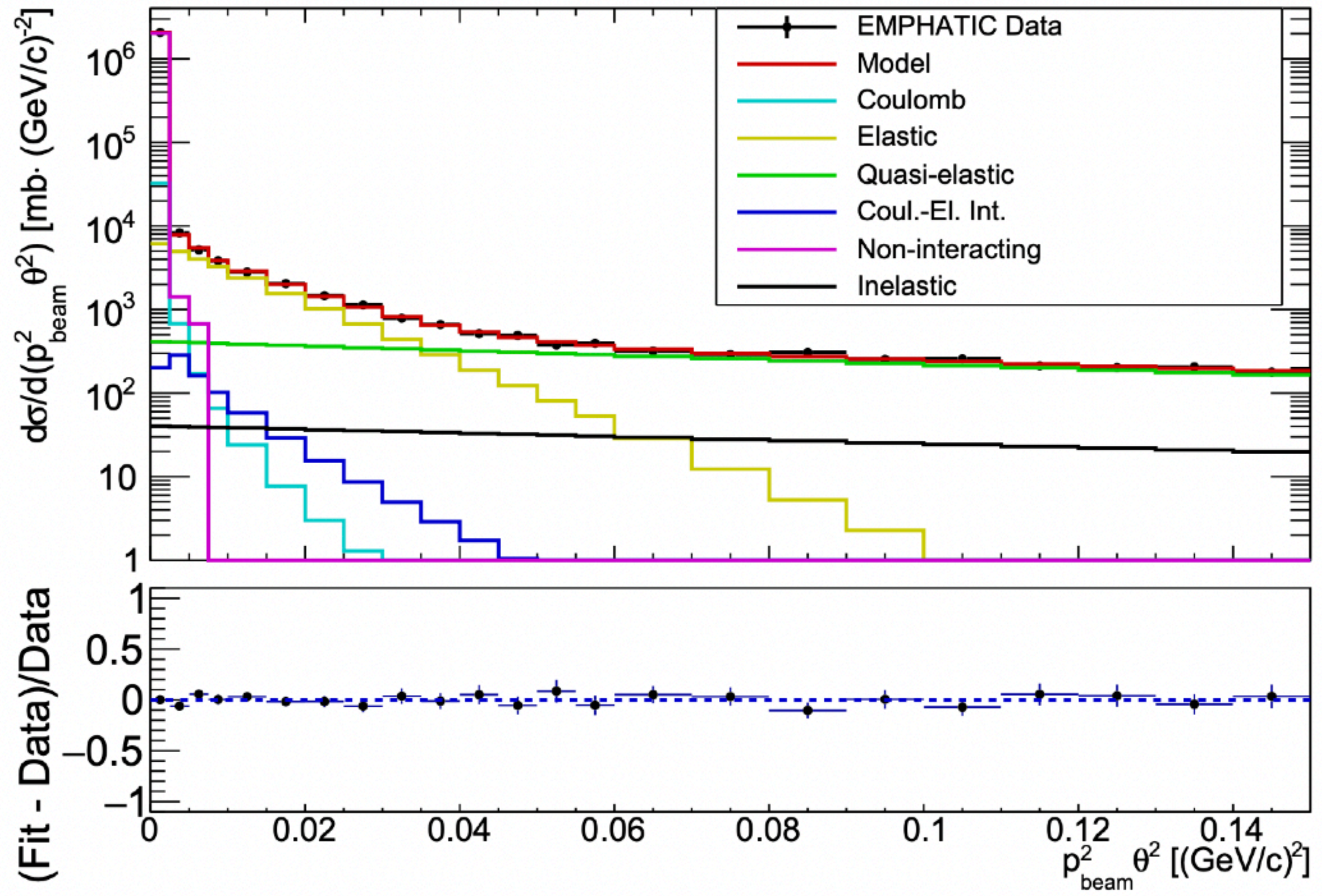
Initial Beam Composition Measurement



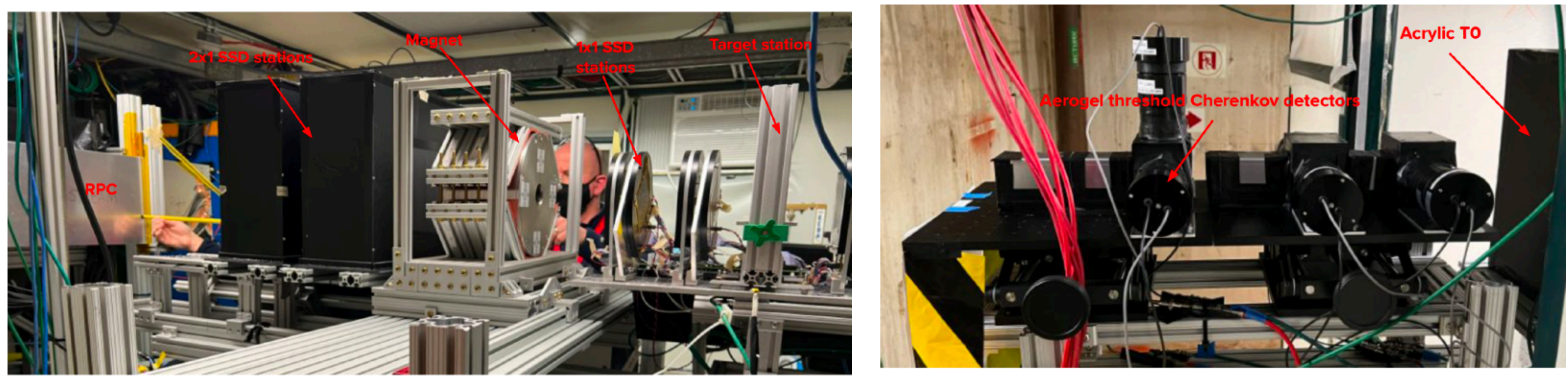
EMPHATIC

- Collaboration on EMPHATIC hadron production experiment at Fermilab
- Pilot run in 2018 to measure p+C forward scattering
  - Analysis led by postdoc M. Pavin, submitted to PRC (arXiv:2106.15723)
- Phase-1 run with spectrometer delayed due to COVID-19
  - Initial Phase-1 operation in January, but Canada could not participate due to COVID situation
  - Second Phase-1 run in June with Canadian Aerogel Ring Imaging Cherenkov (ARICH) detector for PID

Model fit to forward scattering data



Phase-1 Experimental Configuration



ARICH detector

Summary

- The Hyper-Kamiokande experiment will allow us to probe neutrino properties with unprecedented precision amongst a broad physics program
- Construction of the experiment is proceeding on schedule in Japan. Start of detector cavity excavation soon!
- Canada is focussed on contributions to Hyper-K in order to meet the requirements for systematic uncertainty reduction
  - IWCD contribution funded through 2020 CFI-IF competition
  - Hyper-K detector contribution to be requested in 2023 CFI-IF competition
- Many areas of development in Canada to realize multi-PMT, photogrammetry calibration, water quality monitoring systems
- Exciting time for the Hyper-K project in Canada and overall. We are always looking for opportunities to grow the effort in Canada.

Thank you