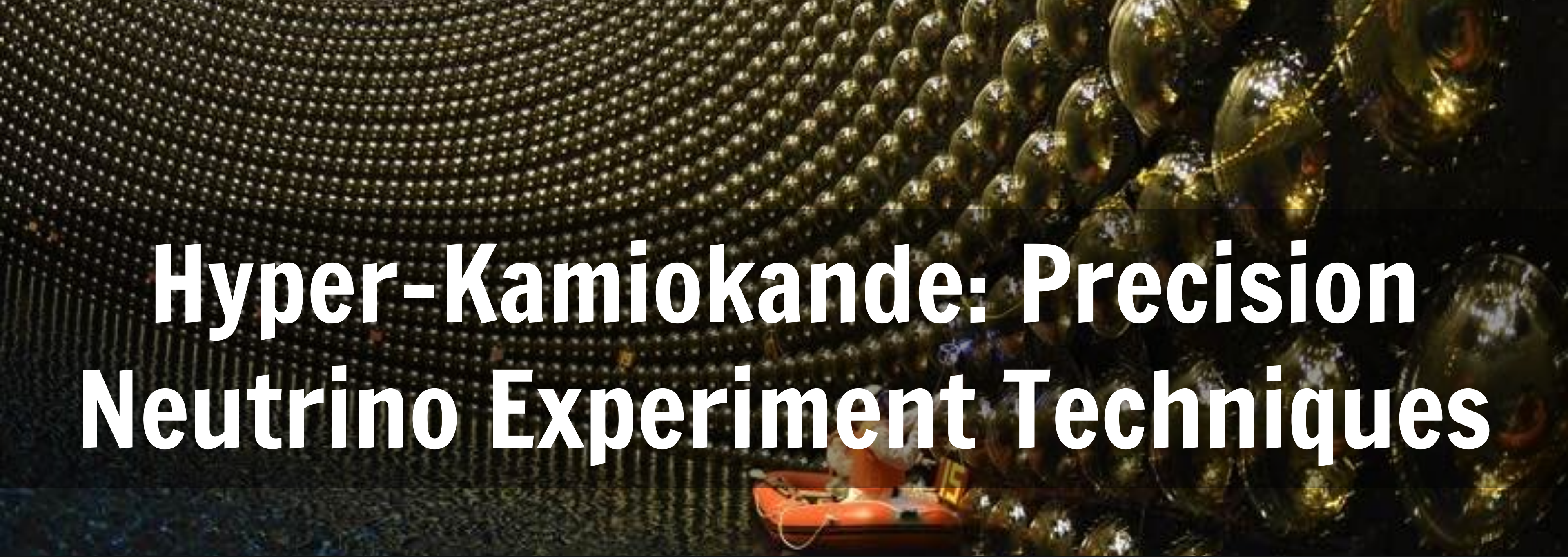


Hyper-Kamiokande: Precision Neutrino Experiment Techniques

TRIUMF SCIENCE WEEK, AUGUST 17, 2021

Patrick de Perio

pdeperio@triumf.ca

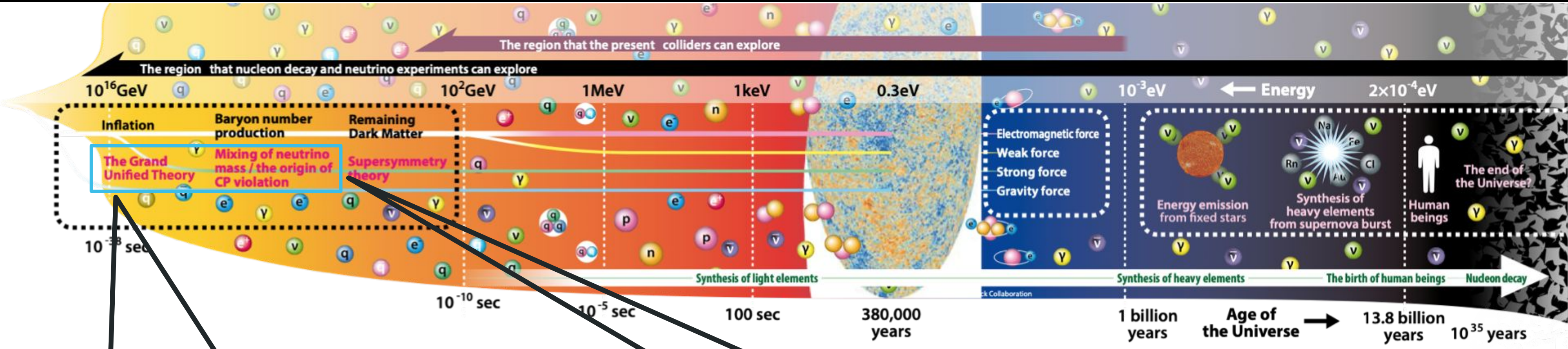
TRIUMF

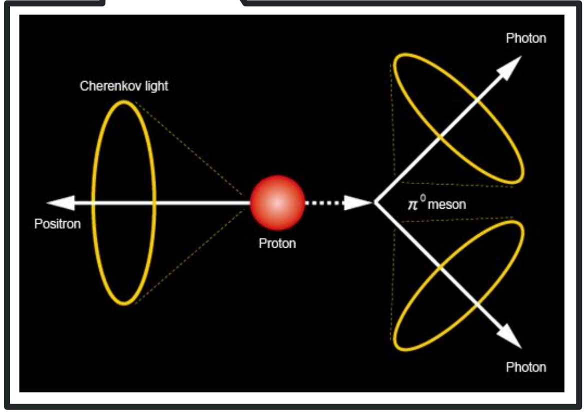
NSERC CRSNG

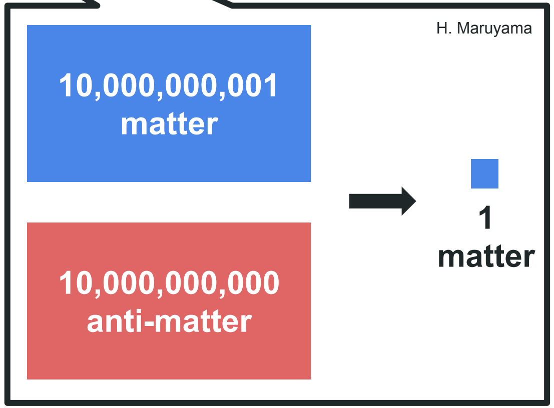
New Frontiers in Research Fund
Fonds Nouvelles frontières en recherche

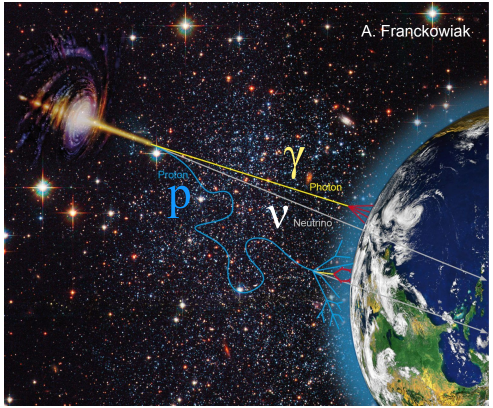
compute canada | calcul canada

Evolution of the Universe









Proton Decay → GUTs

Matter - Antimatter Asymmetry

Multi-messenger astronomy

Neutrino Oscillation Formalism

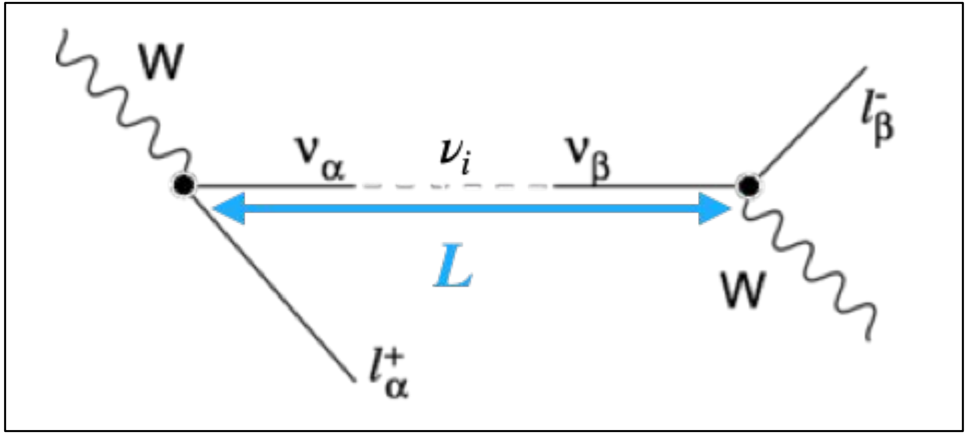
Flavor Eigenstate

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Superposition (Unitary transf.)

Hamiltonian Eigenstate ν_1, ν_2, ν_3

Produced as weak/flavour state



Interact as weak/flavour state

Propagate as mass states with relative phases

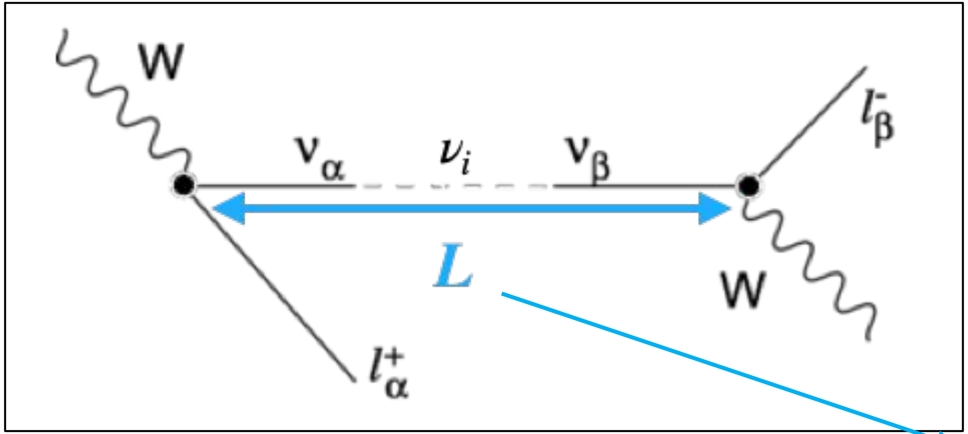
Neutrino Oscillation Formalism

Flavor Eigenstate

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Hamiltonian Eigenstate ν_1, ν_2, ν_3

Superposition (Unitary transf.)



Mixing matrix (oscillation) parameters

Including CP violating δ_{CP} terms

$$P(\nu_\alpha \rightarrow \nu_\beta) = 4 \sum Re \left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \right) \sin^2 \left[\frac{\Delta m^2_{ij}}{4} \frac{L}{E} \right] + \cdots$$

Oscillation probability

ν mass^2 differences

ν energy

Neutrino Knowns and Unknowns

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

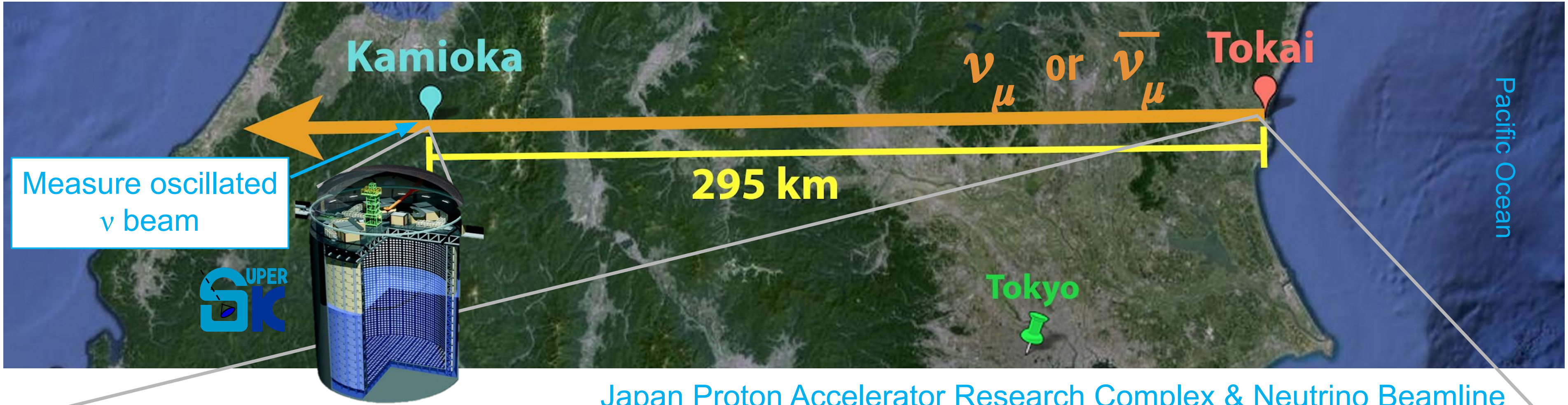
$c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$.

KNOWNS	(~1σ accuracy)
Δm^2 / eV^2 = 2.48 x 10^{-3}	(1.3%)
δm^2 / eV^2 = 7.34 x 10^{-3}	(2.2%)
$\sin^2\theta_{13}$ = 0.0225	(3.0%)
$\sin^2\theta_{12}$ = 0.303	(4.4%)
$\sin^2\theta_{23}$ = 0.545	(~5%)

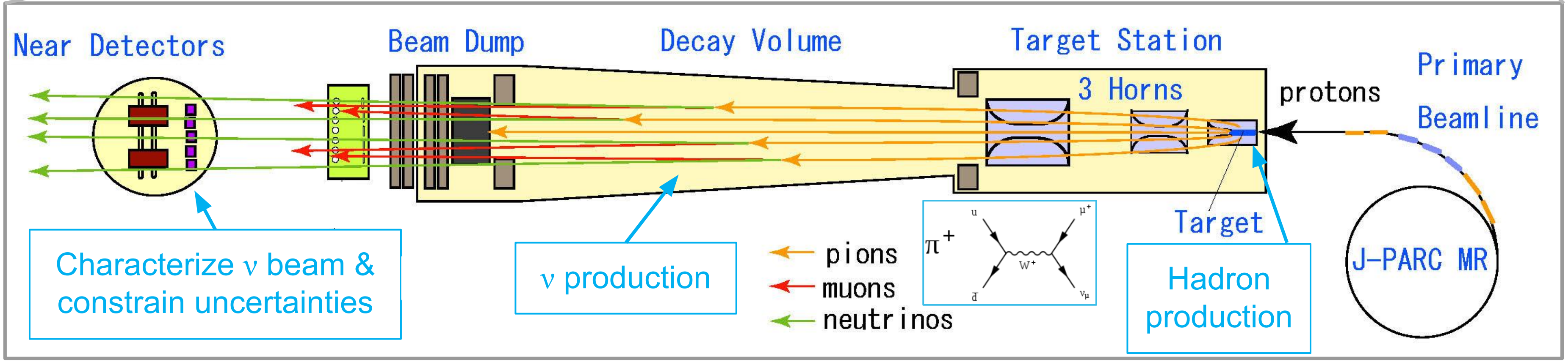
UNKNOWNS	(>1σ hints)
Dirac or Majorana	
Mass ordering	(>3σ NO)
Absolute mass	(<sub-eV)
Dirac CP phase δ_{cp}	(1.6σ CPV)
Octant of θ_{23}	

E. Lisi (TAUP2019)

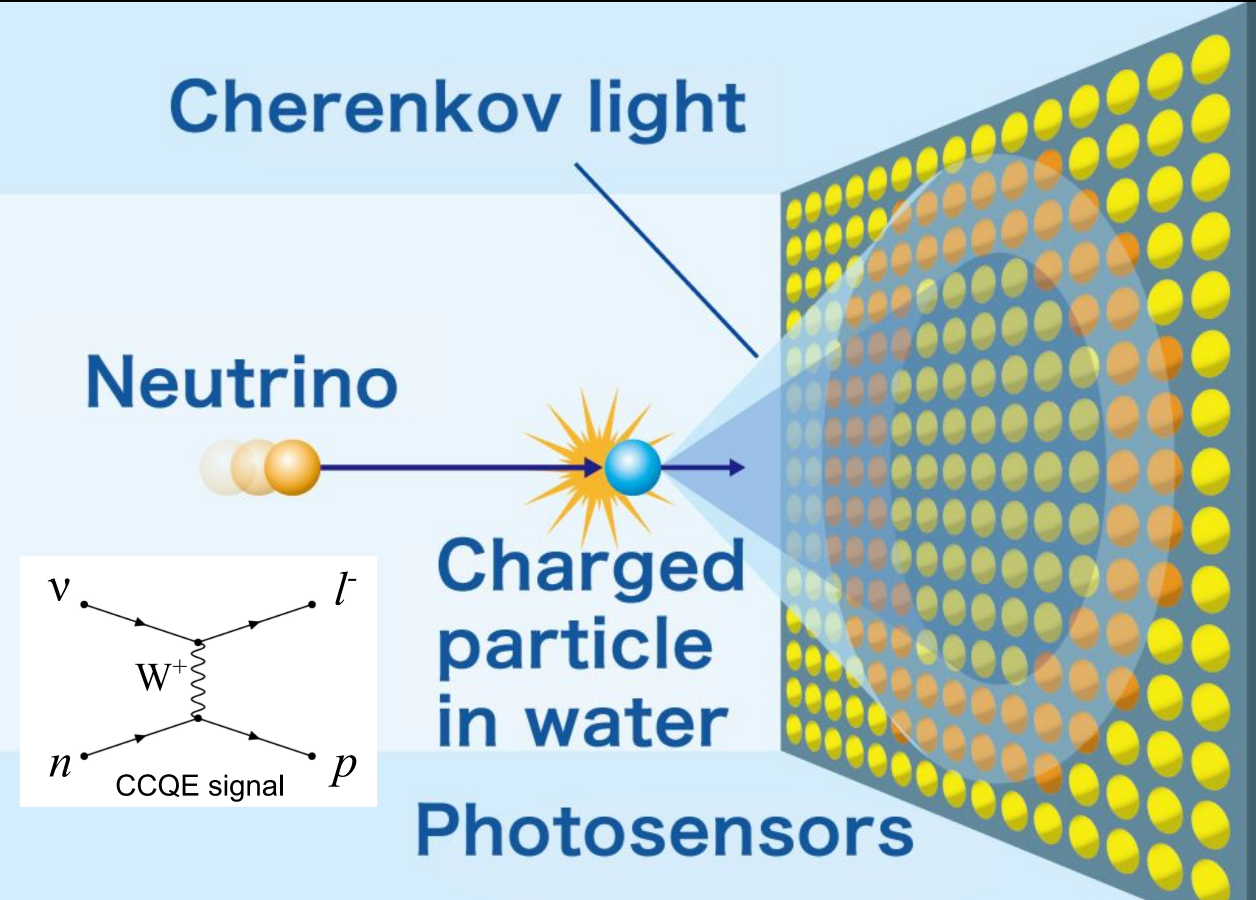
Building a Neutrino Beam (in Japan)



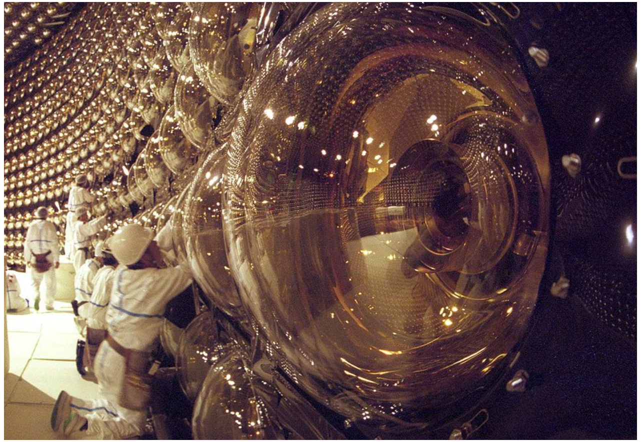
Japan Proton Accelerator Research Complex & Neutrino Beamline

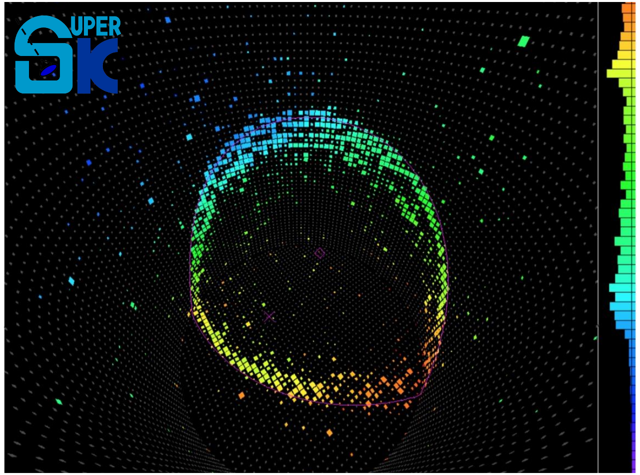


Water Cherenkov Detector Principles



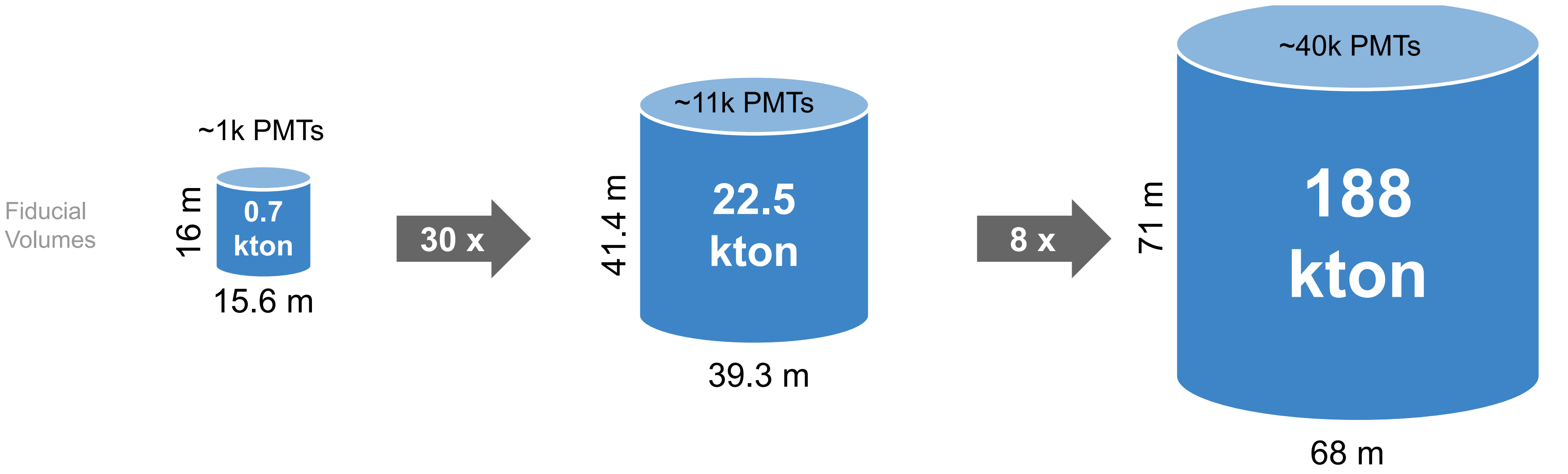
PhysicsOpenLab.org





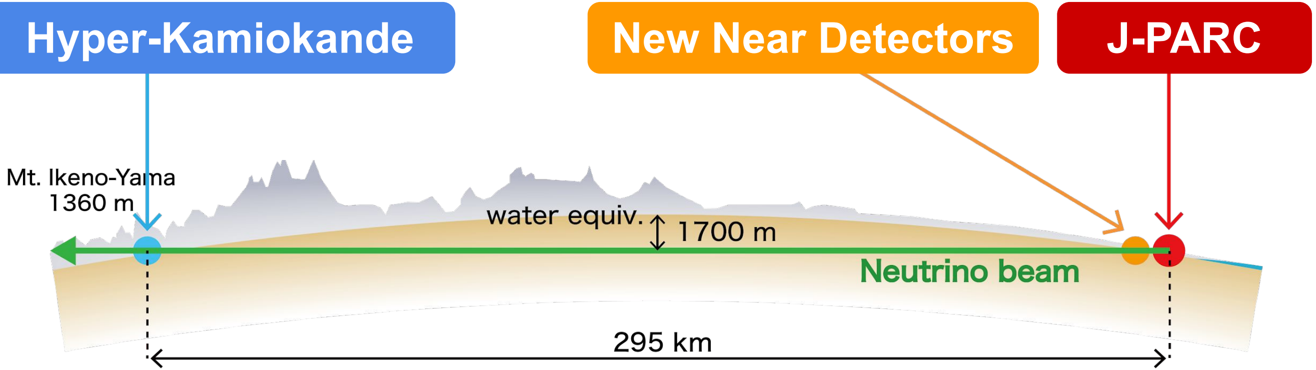
Generations of Kamiokande

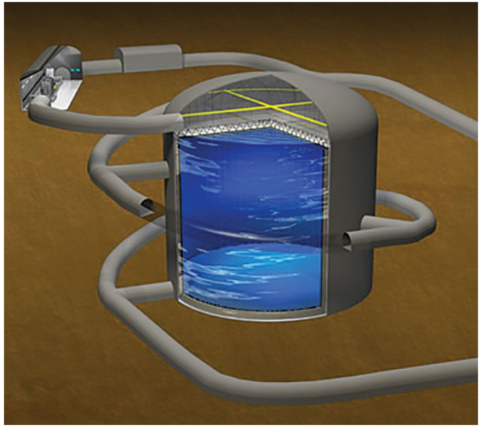
Kamiokande Super-Kamiokande Hyper-Kamiokande



1983 - 1996	1996 - today (and beyond)	2027 - (and beyond)
Supernova 1987A	Atmospheric, Solar, and accelerator (T2K) ν Oscillation	δ_{cp}, proton decay, indirect DM search, more SNs, ...

Talk Overview: Next Generation Experiment



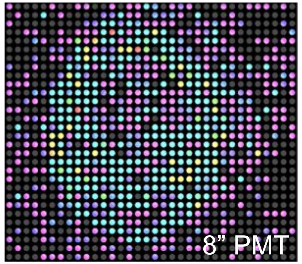


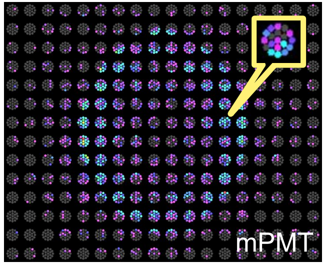
- Bigger and more sensitive than ever
  - Fiducial mass 8x Super-K
  - J-PARC beam 2.5x more powerful
    - → Neutrino rates 20x T2K
- Precise systematic understanding becomes critical to the % level
  - New near detectors and photon detectors
  - New calibration and event reconstruction techniques
  - New supporting external data from auxiliary experiments

Intermediate Water Cherenkov Detector (IWCD)

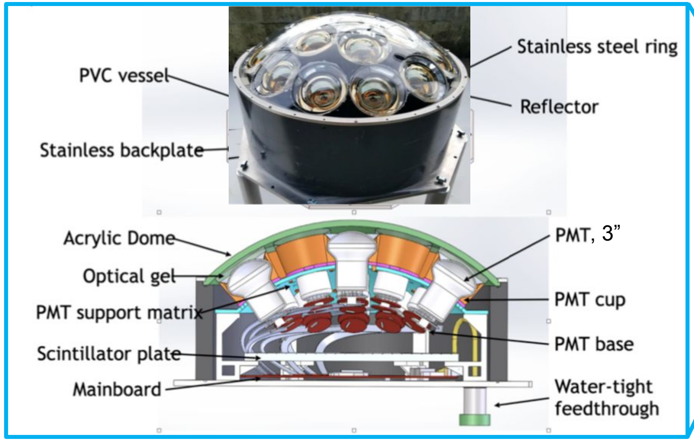
Novel off-axis spanning near detector for Hyper-K

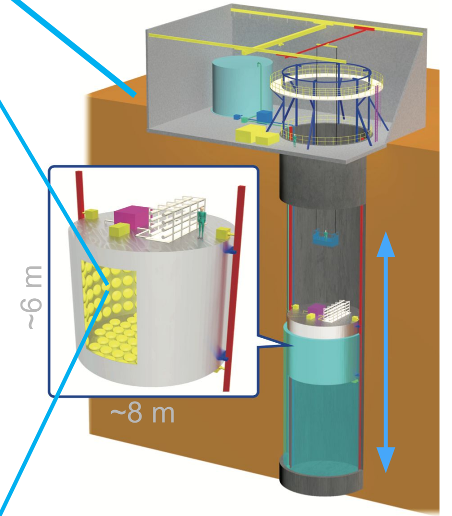
- Controlled variation of ν energy spectrum via 2-body π decay kinematics
  - Provides handle on far detector observables' dependence on ν energy
- Precise neutrino-nucleus interaction cross-section measurements on water
  - Confronting theoretical modeling





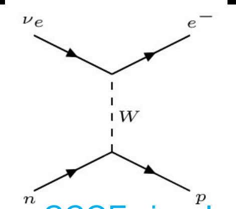
New photosensor (mPMT) development



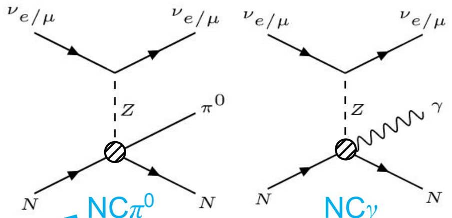


Machine Learning Event Reconstruction

- TRIUMF and Scientific Computing group leading the Water Cherenkov Machine Learning (WatChMaL) consortium
  - Towards a unified platform and knowledge base across many such detectors
- Improved particle classification and regression/reconstruction
- Massive processing speed-up enables multitudes of simulations for detector design and systematics studies
  - ~1 event/minute → ~100000 events/minute



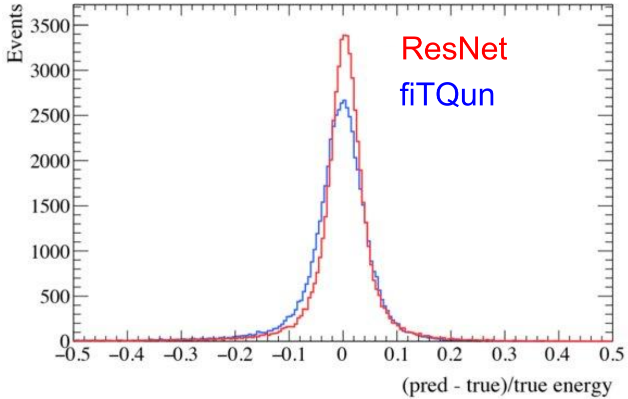
ν_e CCQE signal



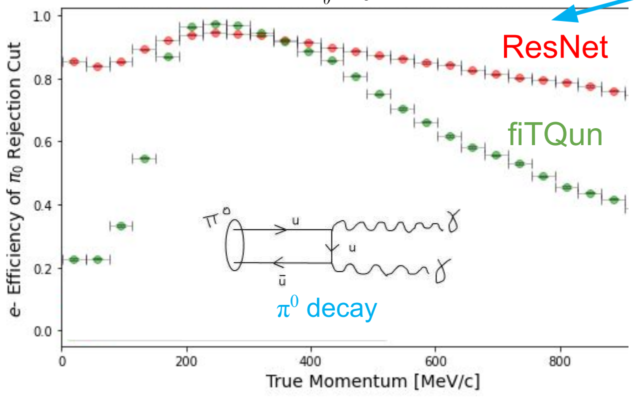
NCπ^0 NCγ
backgrounds

IWCD examples:

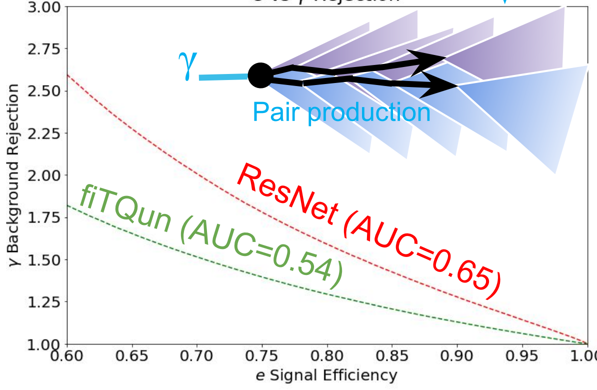
Electron energy <1 GeV reconstruction



e vs π_0 Rejection



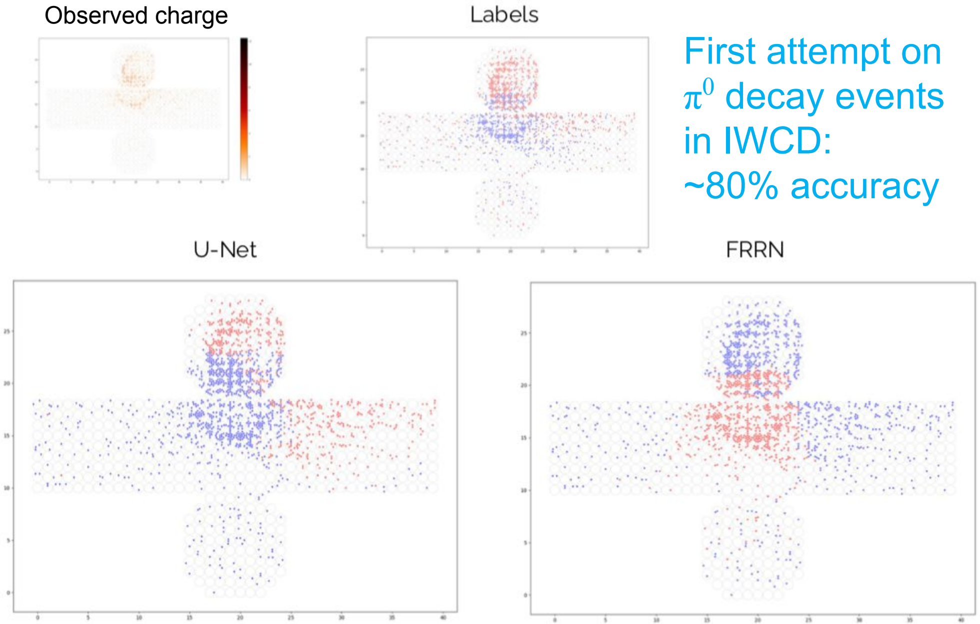
e vs γ Rejection



Multi-Ring Reconstruction in the Future

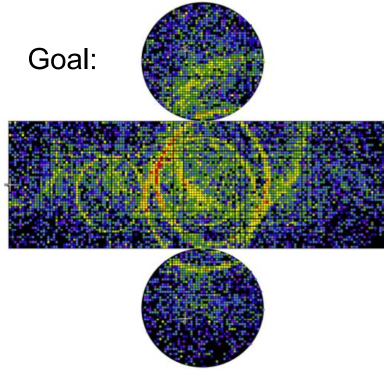
- Panoptic segmentation: separating and identifying overlapping rings
- Towards improving multi-ring & multi-GeV event classification and reconstruction
  - ν mass ordering, ν_τ appearance, δ_{CP}

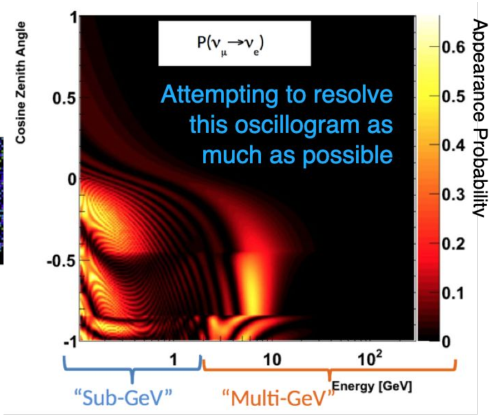
(a) image (b) semantic segmentation



First attempt on π^0 decay events in IWCD: ~80% accuracy

Goal:





UBC Capstone

Water Cherenkov Detector Systematics

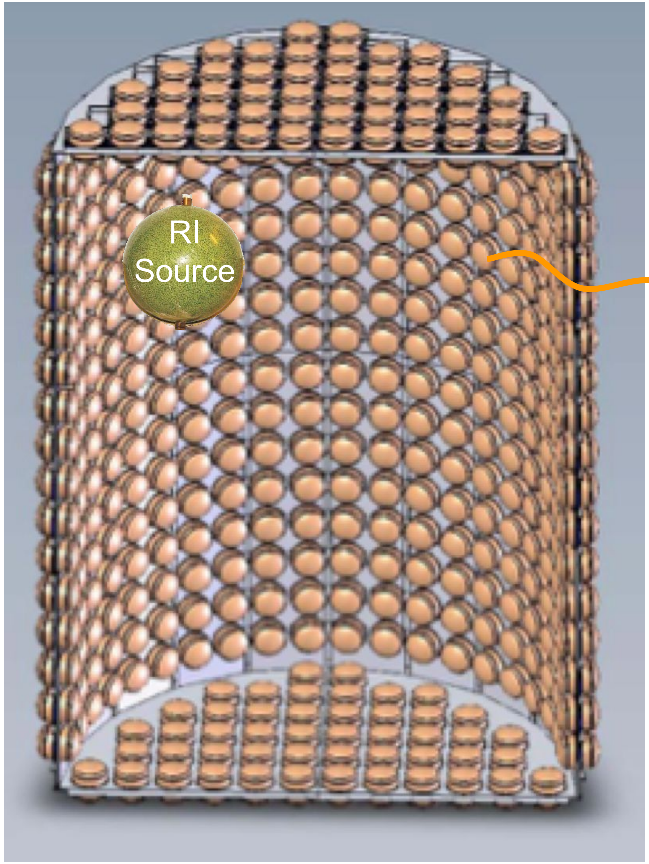
Higher detail of information from ML and precision measurement of CP violation requires <1% level understanding of detector

Geometry (detector and calibration devices)

Water quality (light scattering, absorption)

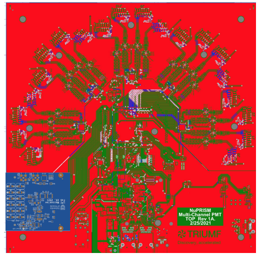
PMT and wall reflectivity

Residual magnetic fields

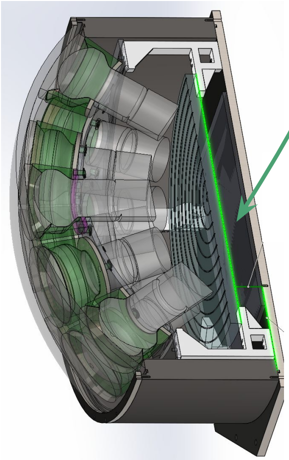


Cherenkov physics

γ



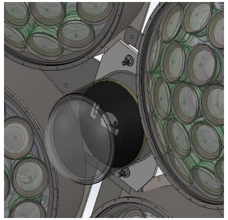
Timing

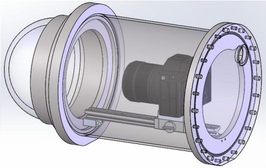


PMT angular response, SPE gain QE, timing, dark noise

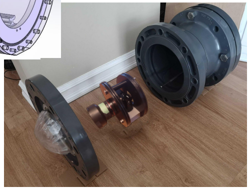
Novel Detector Geometry Calibration

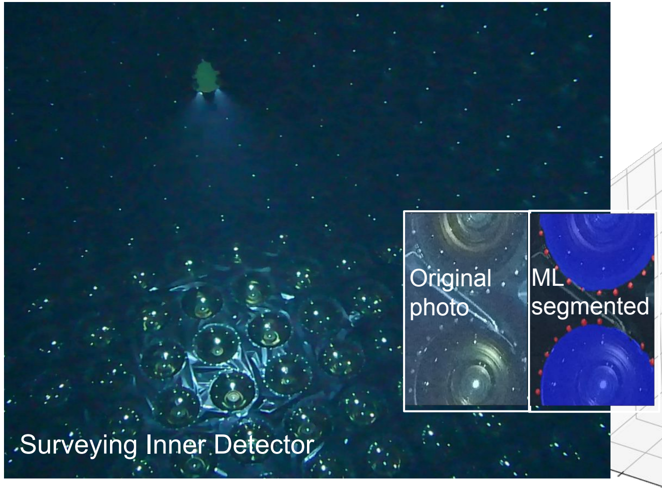
- First underwater survey of Super-K detector geometry
- Challenging photogrammetry analysis ongoing
  - Demonstrated with a ring of barrel PMTs
- Developing new systems for Hyper-K and IWCD



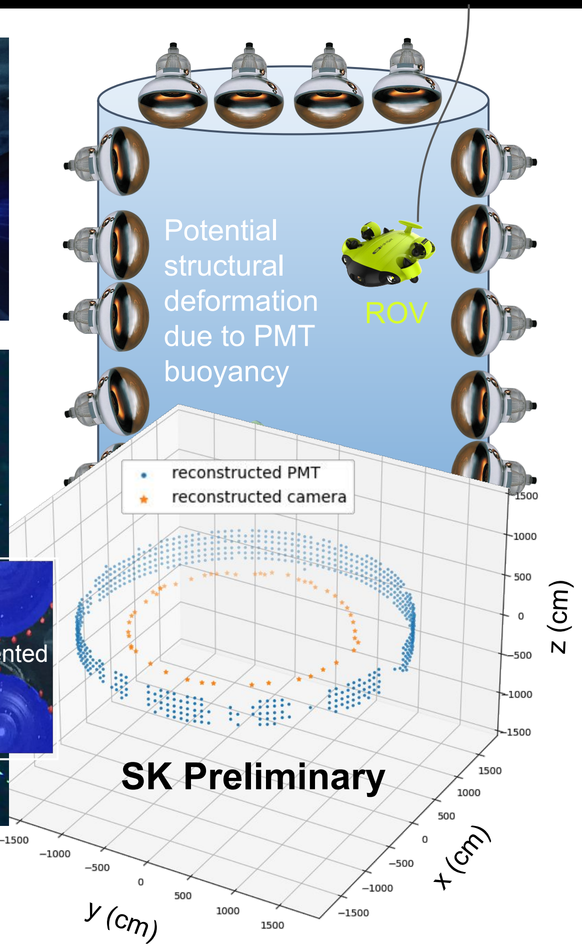


TRIUMF SciTech





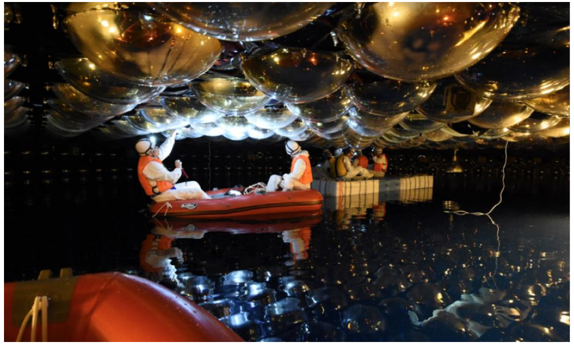
UBC Capstone

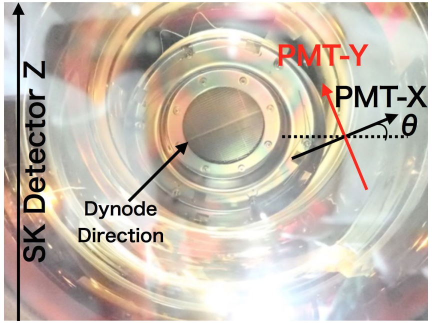


Precise and Comprehensive PMT Characterization

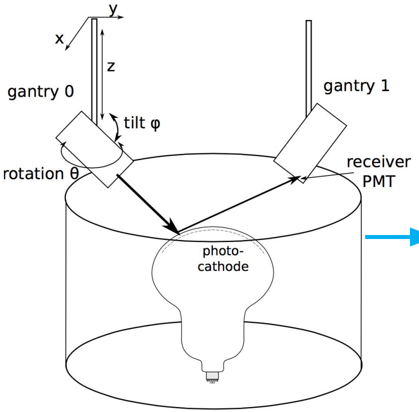
- Uncertainties in PMT response is a major systematic in water Cherenkov detectors
- (Re)Building a photosensor test Facility (PTF) at TRIUMF for Super-K and Hyper-K/IWCD

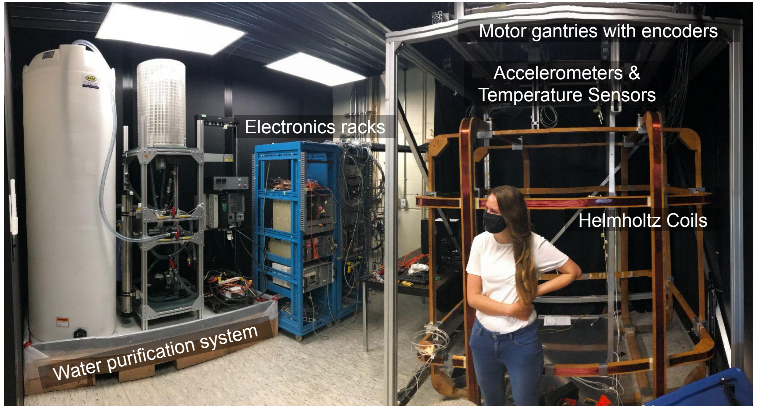
Magnetic field and PMT orientation survey throughout Super-K





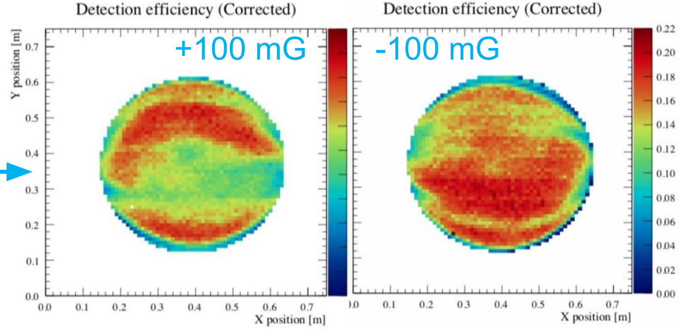
Renovated MHESA Dark Room





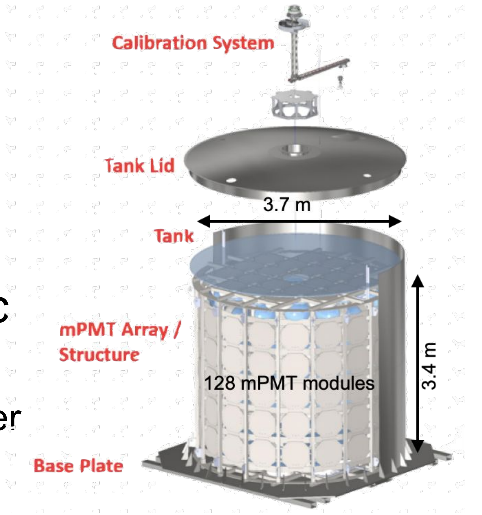
TRIUMF SciTech

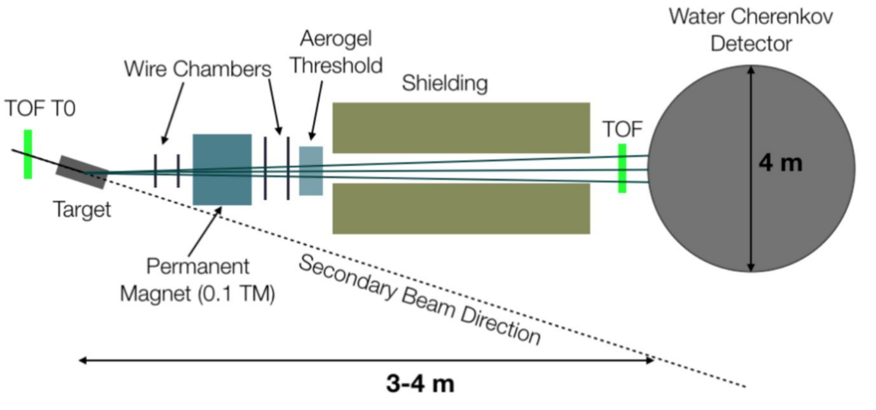
Super-K PMT

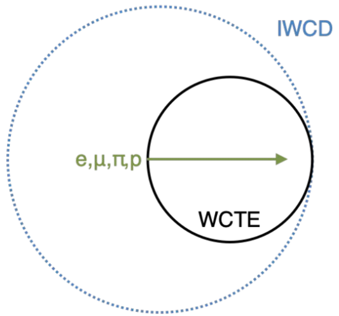


The Water Cherenkov Test Experiment (WCTE)

- Prototype detector for beam test at CERN in 2023
- mPMT pilot run and test-bed for precision calibration and ML
  - Opportunity to improve systems prior to IWCD and Hyper-K
- Well-understood p, e, $\pi^{\pm}$, $\mu^{\pm}$ particle beam from 140-1200 MeV/c
  - Control samples to constrain neutrino experiment modeling, e.g. Detector response: Cherenkov light emission; $\pi^{\pm}$ re-interactions in water
  - Immediate impact to existing experiments (T2K, Super-K)

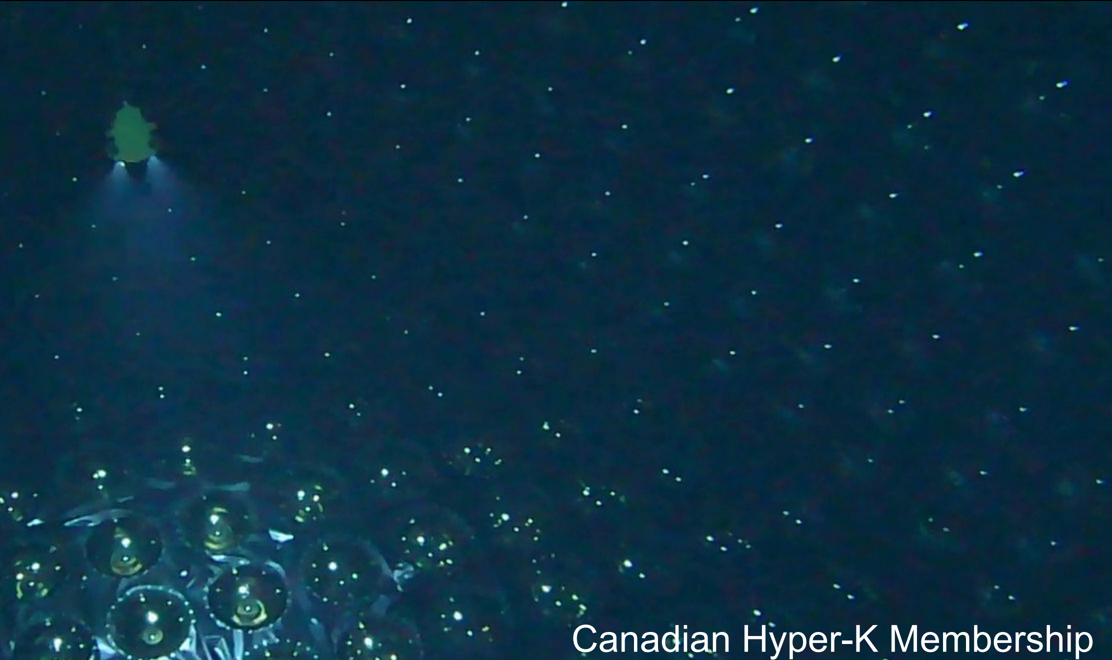






Summary

- Broad physics with many ν sources and proton decay in Super-K and Hyper-K
- New developments towards realizing maximal sensitivity
  - Photosensors (mPMTs)
  - Detector calibration
    - Photogrammetry
    - Photosensor characterization
  - Machine learning event reconstruction
- Near term auxiliary projects to enhance all of the above:
  - e.g. WCTE @ CERN



Canadian Hyper-K Membership

TRIUMF
University of Toronto
University of Victoria
York Université University
The University of Winnipeg
BCIT British Columbia Institute of Technology
Carleton University
University of Regina

Appendix

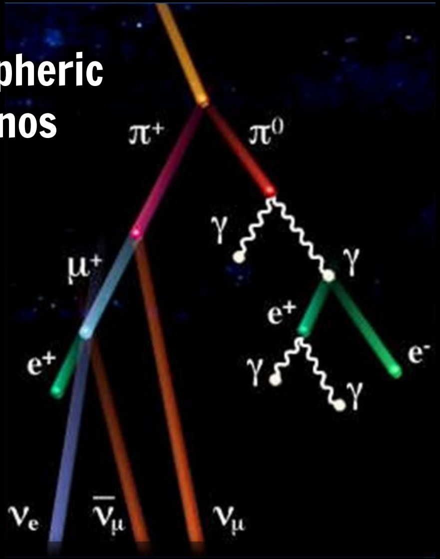
Rich Science with Hyper-Kamiokande

Design report: arXiv:1805.04163

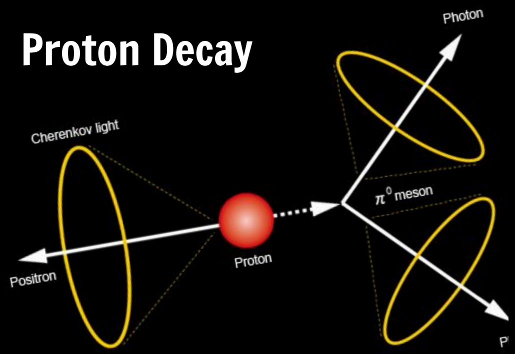
Multi-Messenger: Supernova, GW, ...

Dark Matter

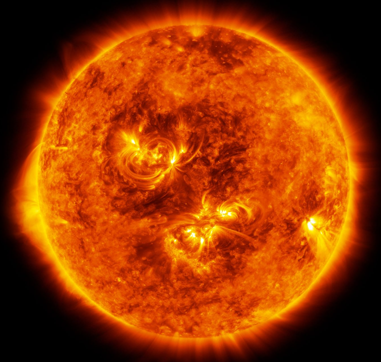
Atmospheric Neutrinos



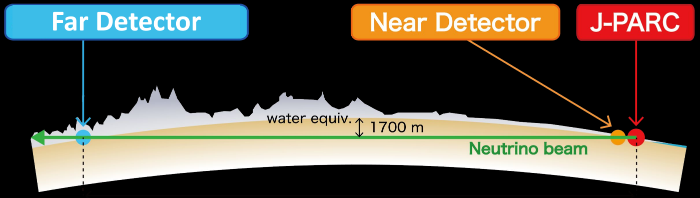
Proton Decay



Solar Neutrinos



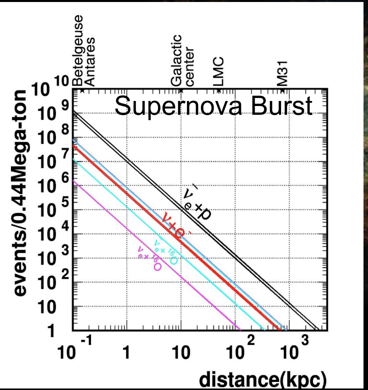
Accelerator Neutrinos



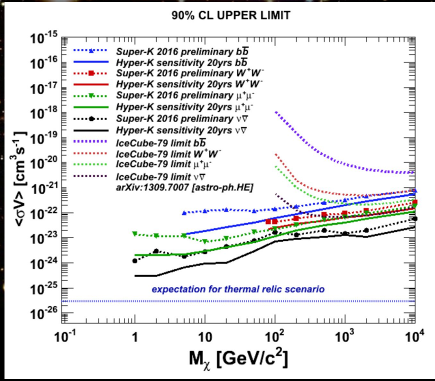
Rich Science with Hyper-Kamiokande

Design report: arXiv:1805.04163

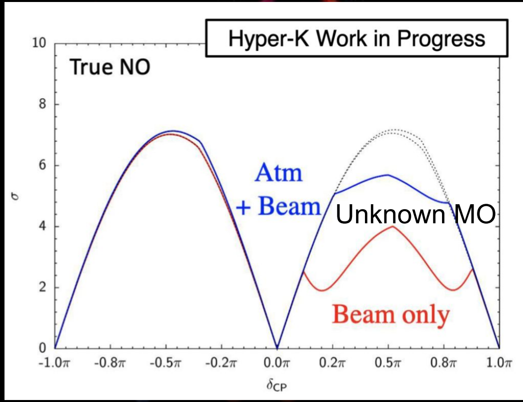
Multi-Messenger
[arXiv:2101.05269]



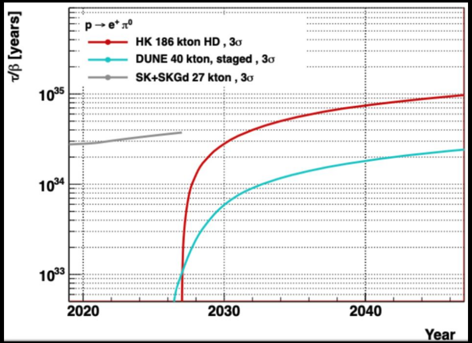
Dark Matter



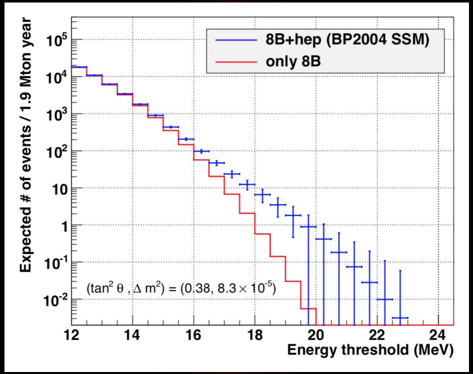
Atmospheric Neutrinos



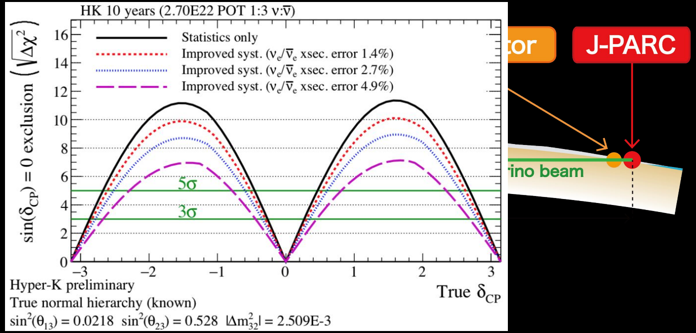
Proton Decay



Solar Neutrinos



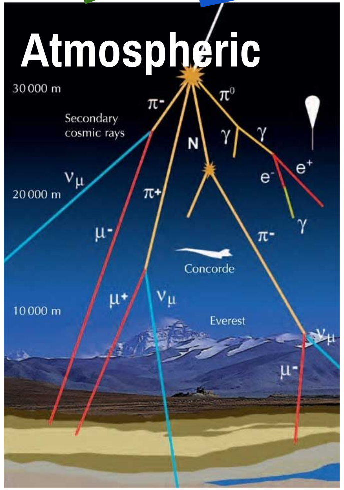
Accelerator Neutrinos

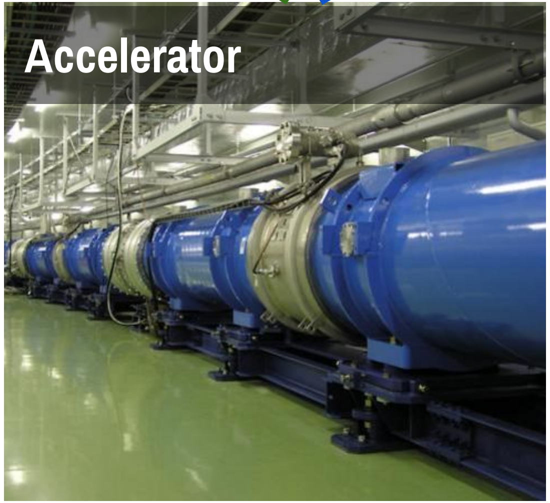


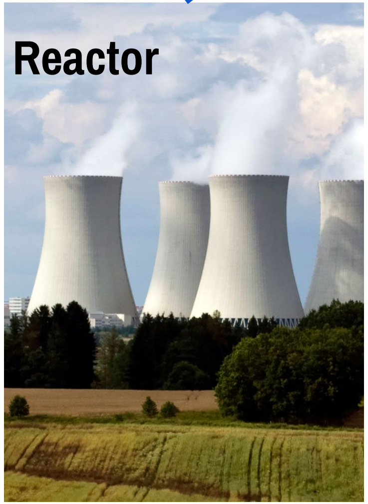
Neutrino Sources

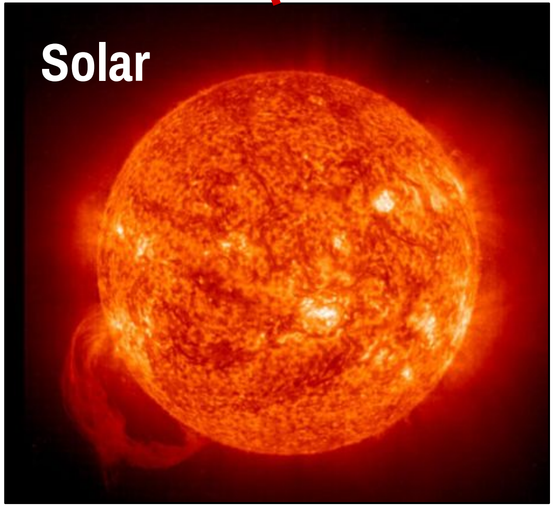
$c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





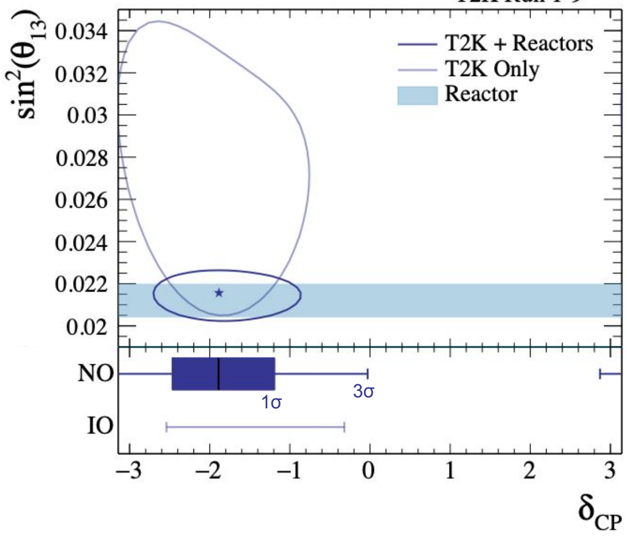




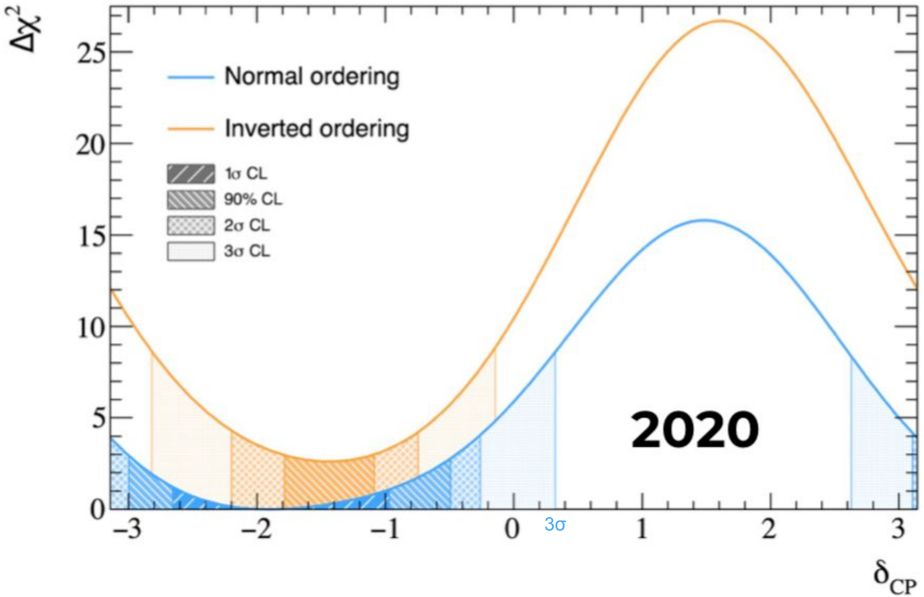
T2K CP Violation Constraints

- 2019 analysis:
  - Disfavored δ_{CP}= 0 at 3σ
  - Disfavored IO at 1σ
- 2020 analysis slightly looser constraints

Nature 580 (2020) 7803

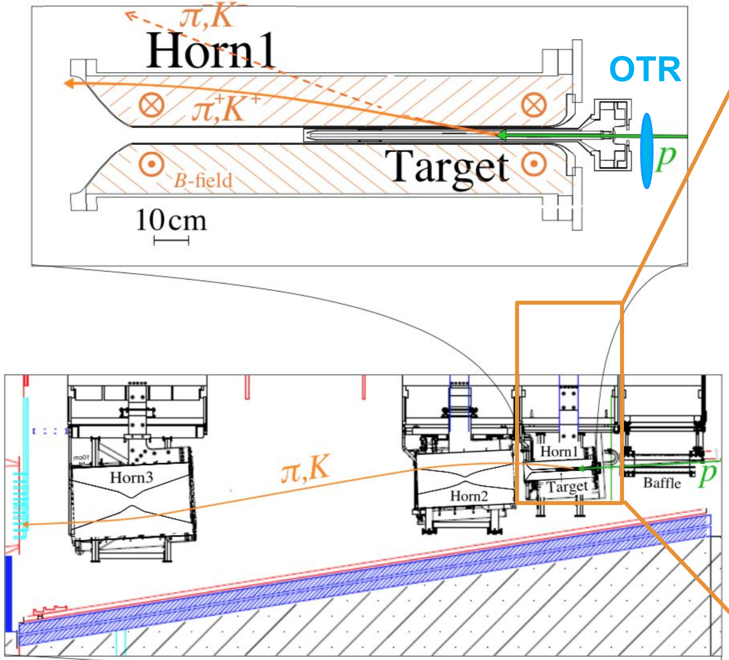


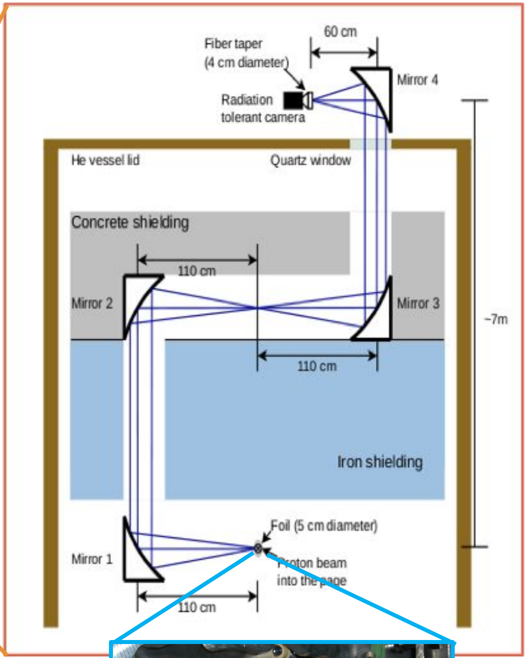
arXiv:2101.03779

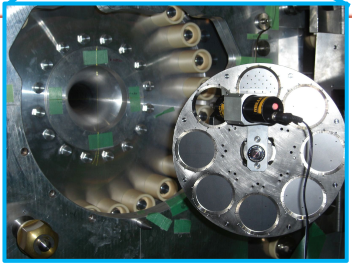


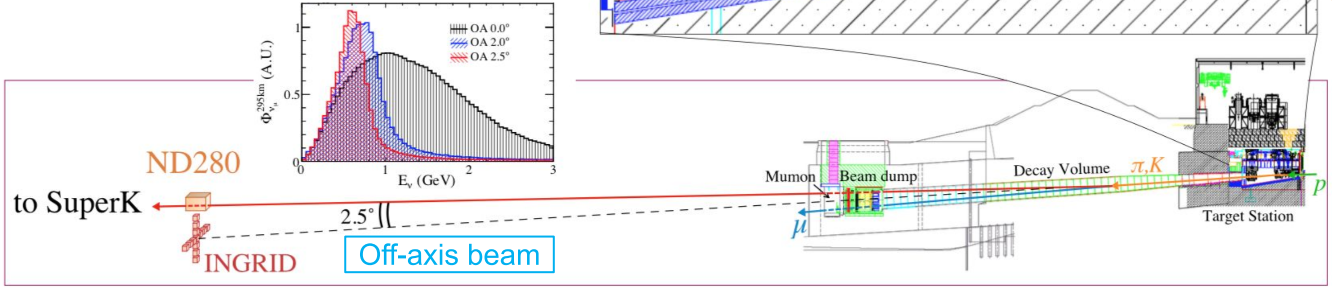
Proton Beam Monitoring: Optical Transition Radiation

- Crucial proton beam monitoring and ν beam constraints
- New OTR installation in spring 2022 for T2K-II era and beyond
  - Improving calibration systems
  - New simulations
  - Stress testing new foils





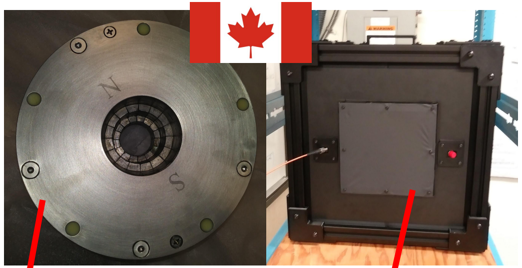


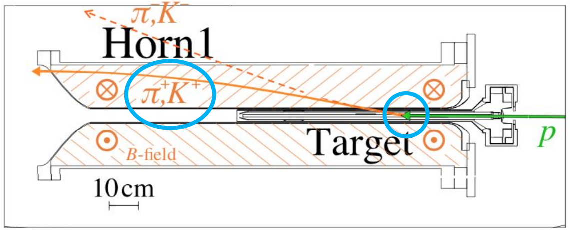


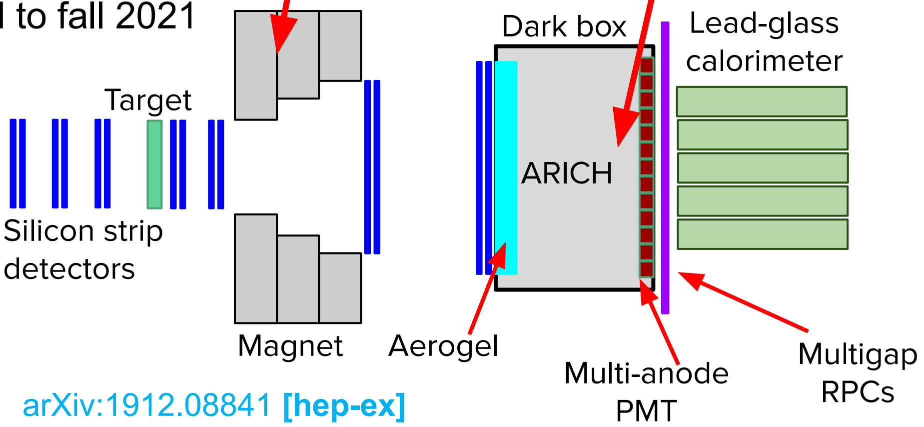
Hadron Production for Neutrino Flux Modeling: EMPHATIC

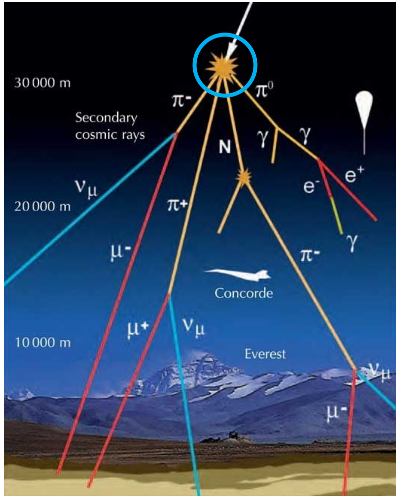
- **E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**estbeam **I**n **C**hicagoland
- Constraints on beam and atmospheric ν flux predictions
  - For T2K, SK, HK, NOνA, DUNE
- At Fermilab Test Beam Facility
  - **2018**: Pilot run, paper finished collaboration review
  - **2020**: Phase I (limited acceptance 150 mrad) → postponed to fall 2021
  - **2022**: Phase II, full acceptance 400 mrad

π and K elastic and QE interactions (< 10 GeV/c)
Important systematic uncertainty









arXiv:1912.08841 **[hep-ex]**

The IWCD detector

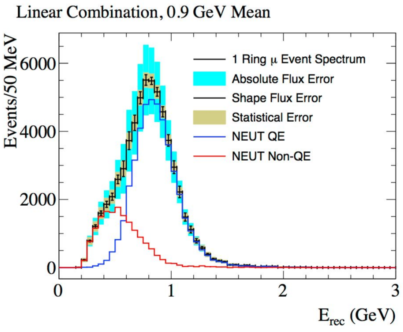
Off-axis spanning detector

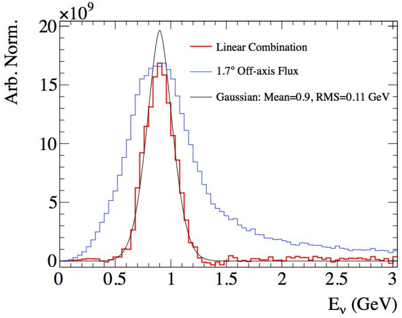
ν energy spectrum depends on angle off-axis to the neutrino beam

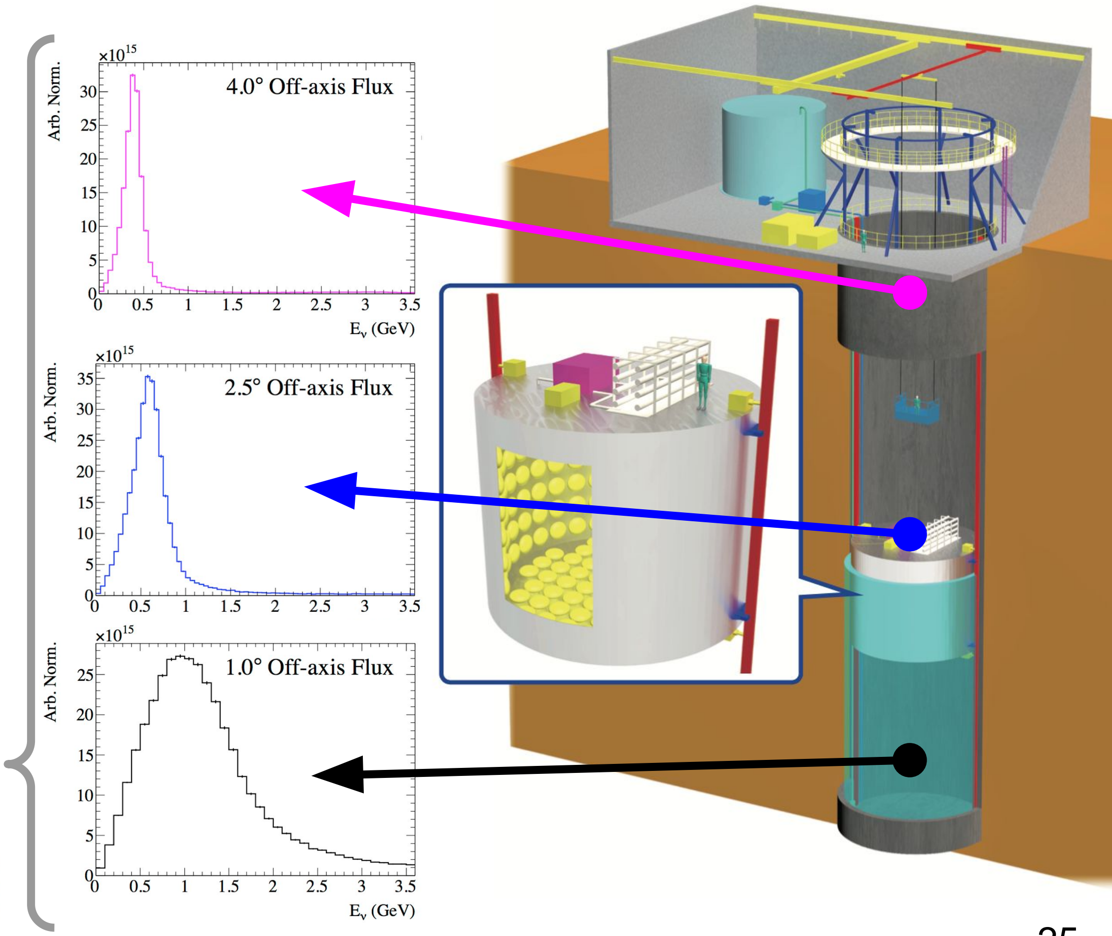
Far detector @ 2.5° for peak at ~600 MeV

Moving IWCD varies angle, allowing measurements at different energies

Linear combinations allows mimicking mono-chromatic beam or far-detector spectrum



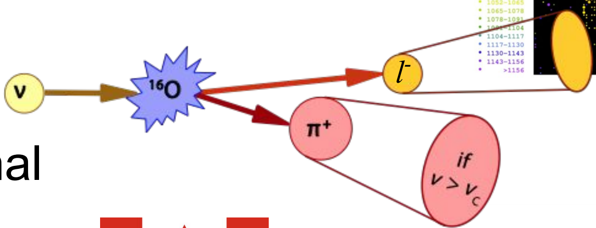


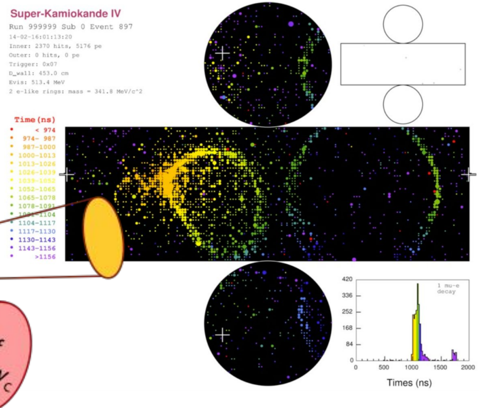


T2K-SK Multi-Ring Datasets for Future Analyses

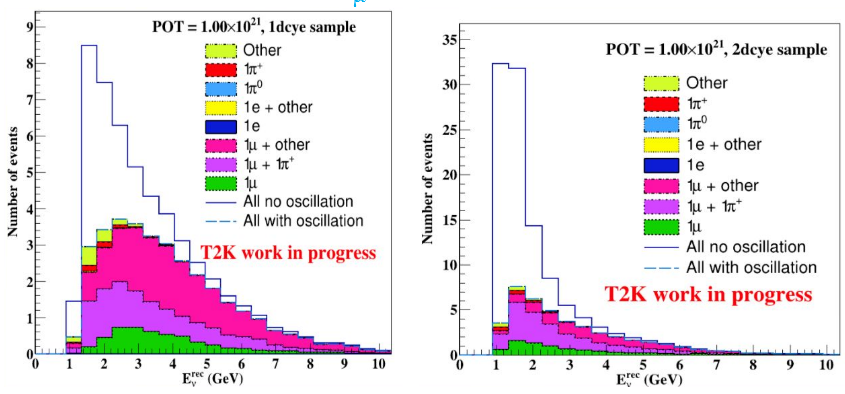
- Second dominant interaction channel: resonant 1π production
- Expected to improve oscillation parameter measurements
  - E.g. ~12% increase in ν_e signal statistics
- New BDT pushing the limits of traditional likelihood reconstruction algorithm

$$\overset{(-)}{\nu}_l\, p \rightarrow l^{\mp} p \pi^{\pm}$$
$$\overset{(-)}{\nu}_l\, n \rightarrow l^{\mp} n \pi^{\pm}$$

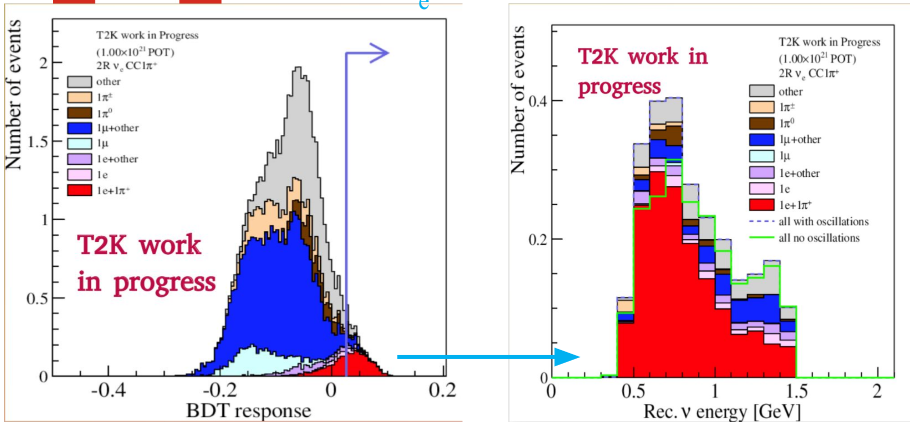




νμ CC1π⁺



νe CC1π⁺



Systematic Uncertainties

- Extrapolation of constraint from near detector isn't perfect - neutrino spectrum is different because no oscillation
- Additional errors from modeling non-quasi- elastic scattering (pion production, multi-nucleon knockout
- Electron (anti)neutrino cross section is not constrained at near detector with 99% muon (anti)neutrino beam
- Neutral current backgrounds can fake electron (anti)neutrino candidates

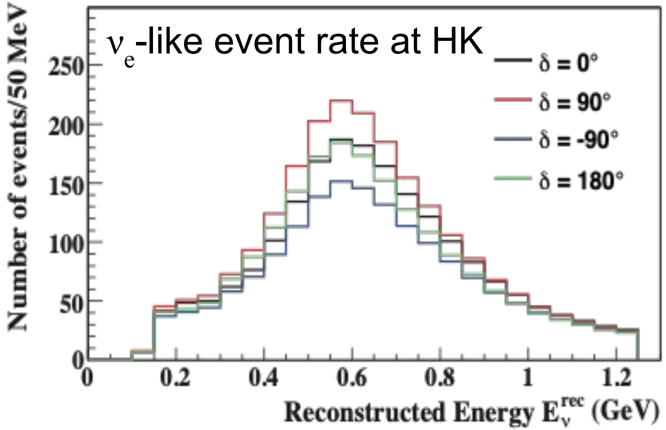
Systematic Error Source	Uncertainty on $\nu_e/\bar{\nu}_e$ Candidates (%)
Super-K Detector Model	1.47
Pion Reinteractions	1.58
Near Detector Constrained Parameters	2.31
Nuclear Binding Energy	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	3.03
NC1γ Production	1.49
Other NC Interactions	0.18
Total	5.87

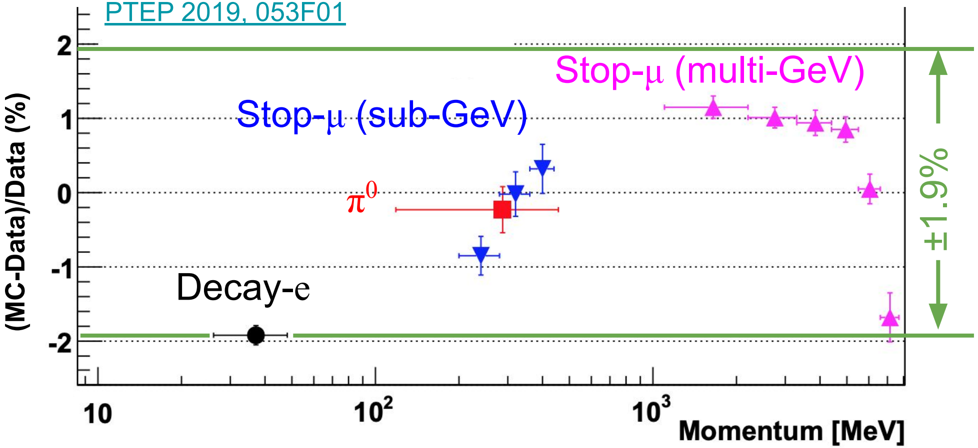
Error Source	% Error for CP Violation search
Error from near detector constraint	1.7
Modeling of events that aren't quasi-elastic scattering	2.1
Electron (anti)neutrino cross section error	3.0
Neutral current background error	1.0
Total cross section model error	**4.1**

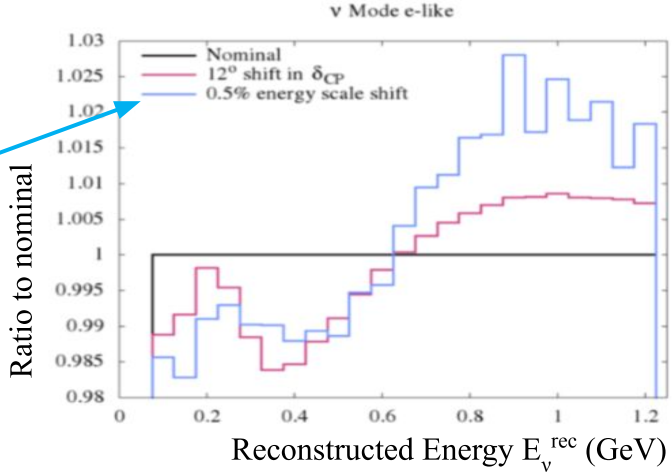
Aim to reduce total error to **<3% for Hyper-K**

Impact of Systematic Detector Uncertainties

- Energy scale control samples in Super-K show residual 2% MC/data discrepancy
  - Assigned as systematic error in ν oscillation analysis
- Degeneracy observed with CP violation parameter, δ_{CP}
  - Need to understand detector to the <1% level





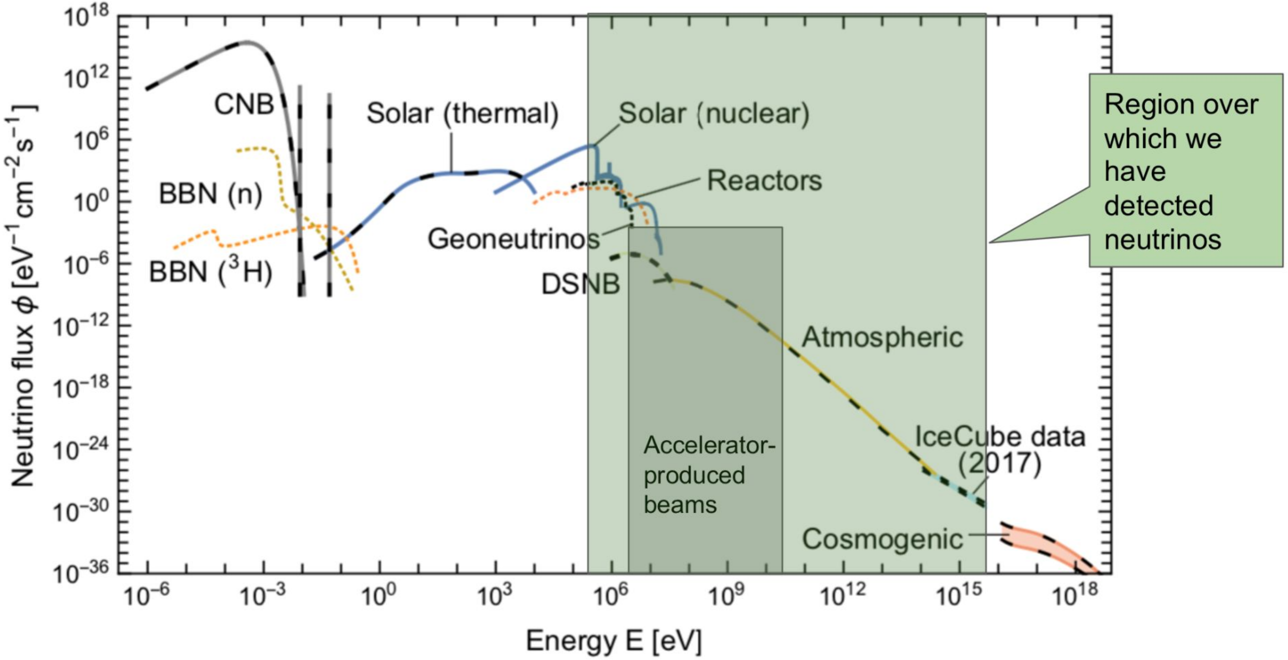


Neutrino Flux Spectra

[Kate Scholberg (Duke), TIPP 2021](#)

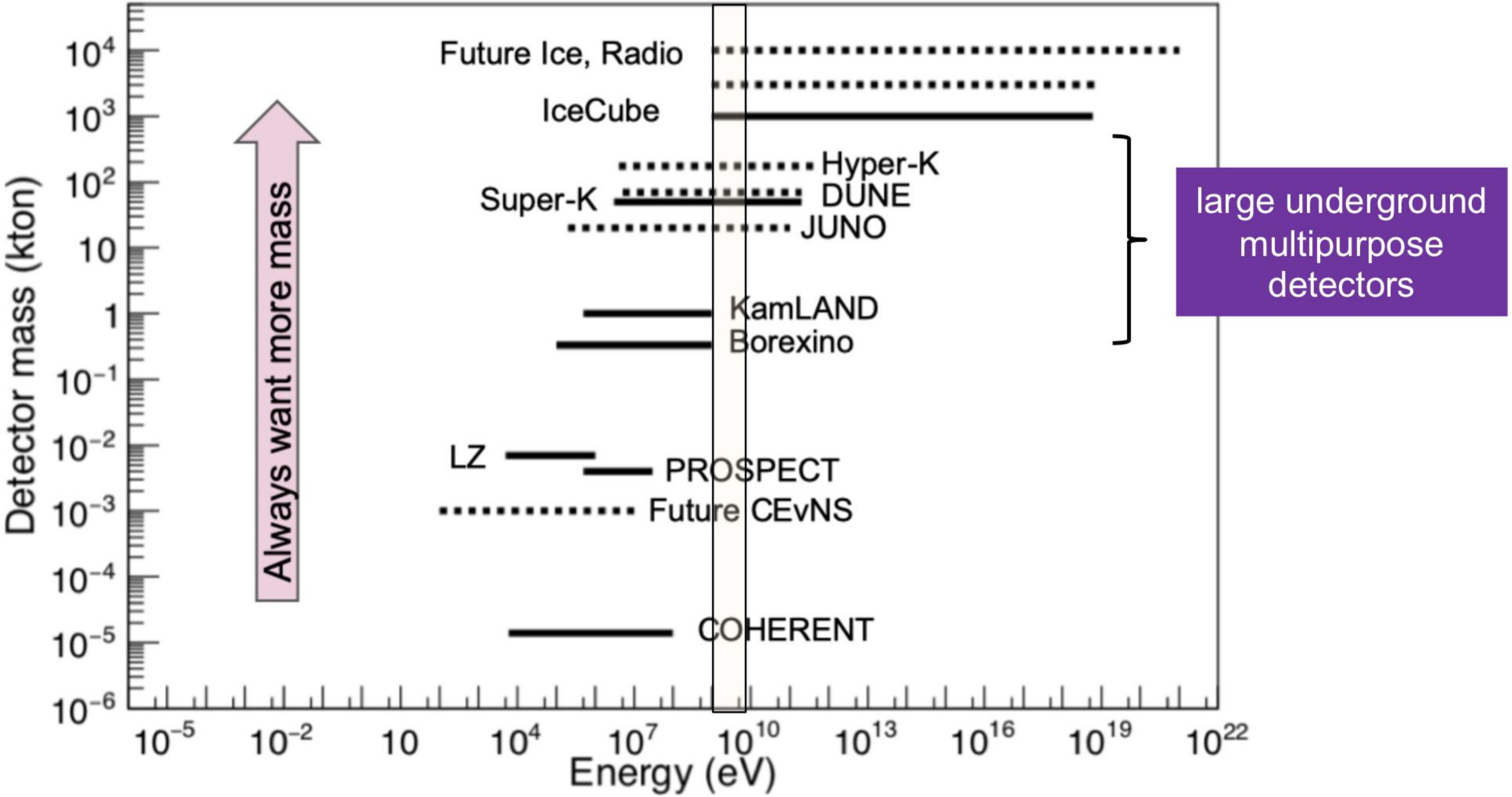
Information comes from neutrinos
over ~25 orders of magnitude in energy!

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF

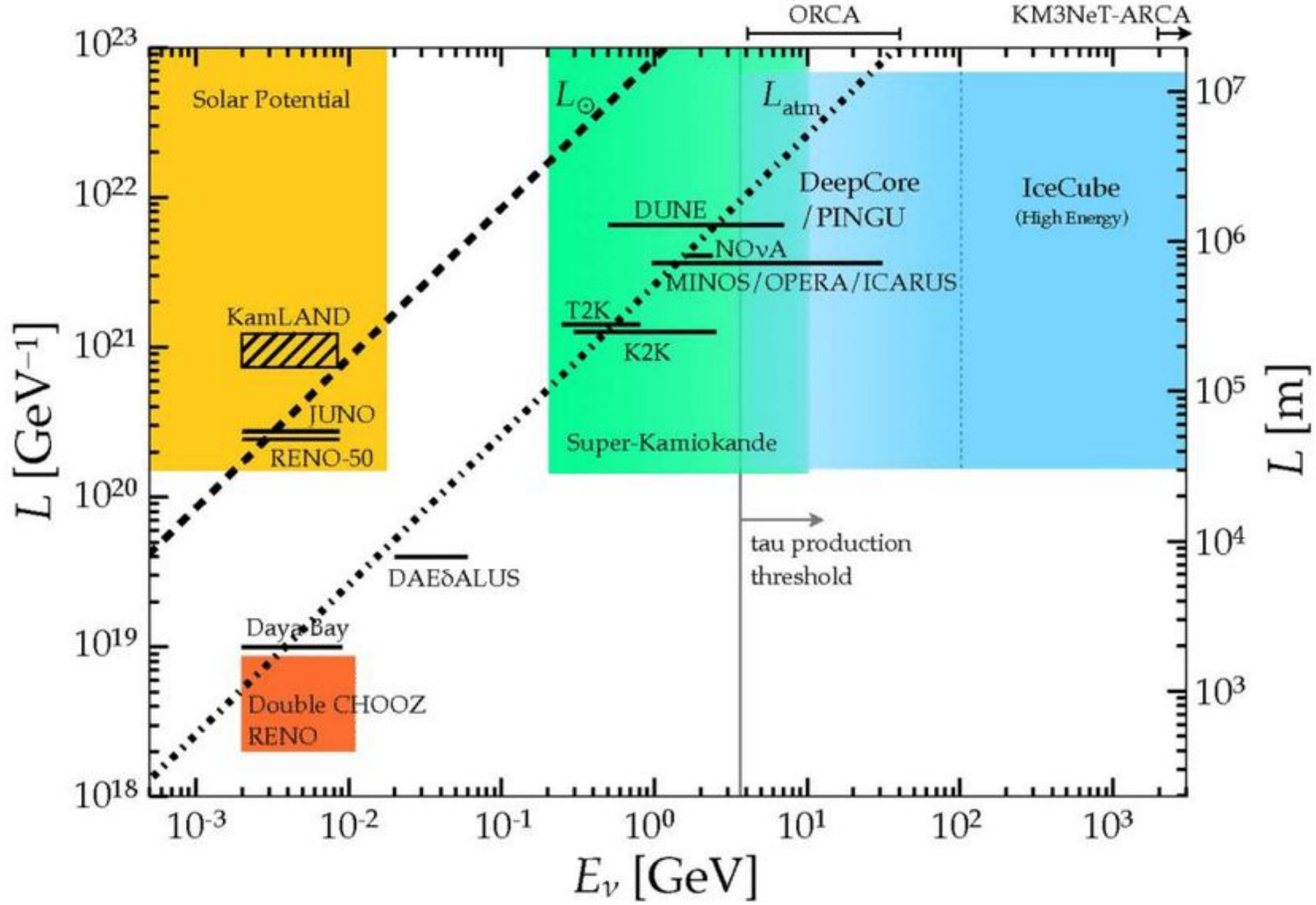


Neutrino detector masses and sensitive energy ranges

Kate Scholberg (Duke), TIPP 2021

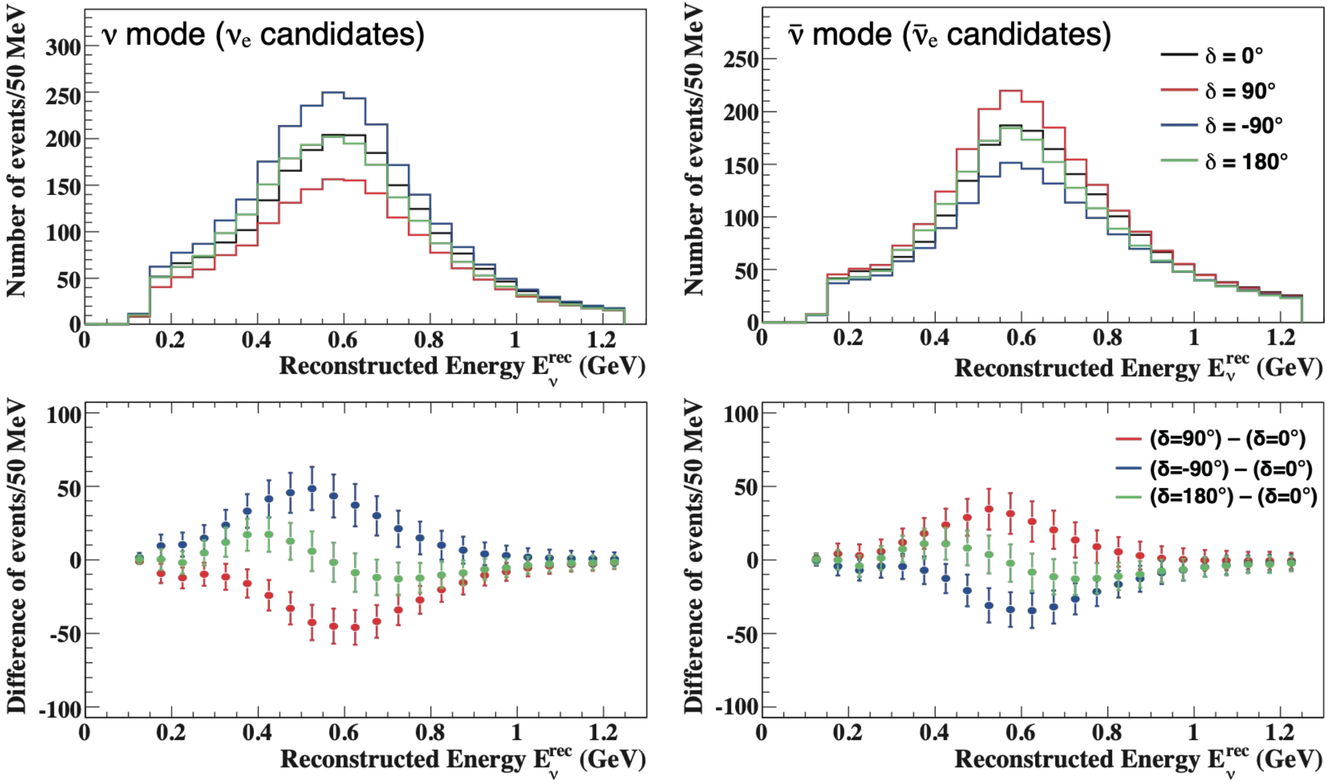


Neutrino Oscillation L/E Scales

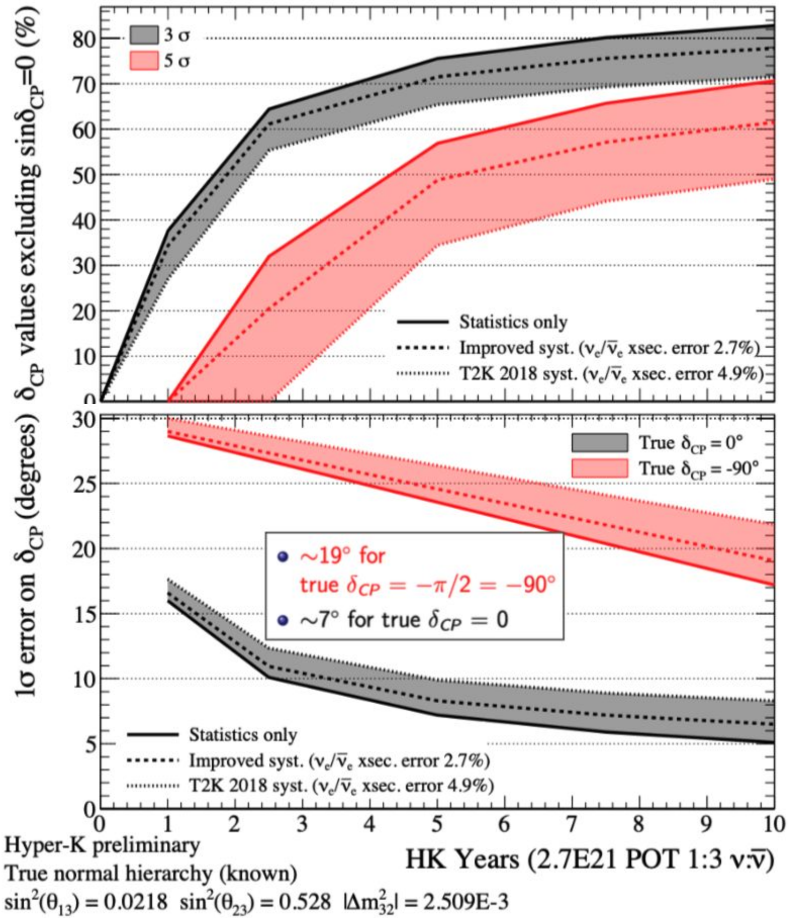


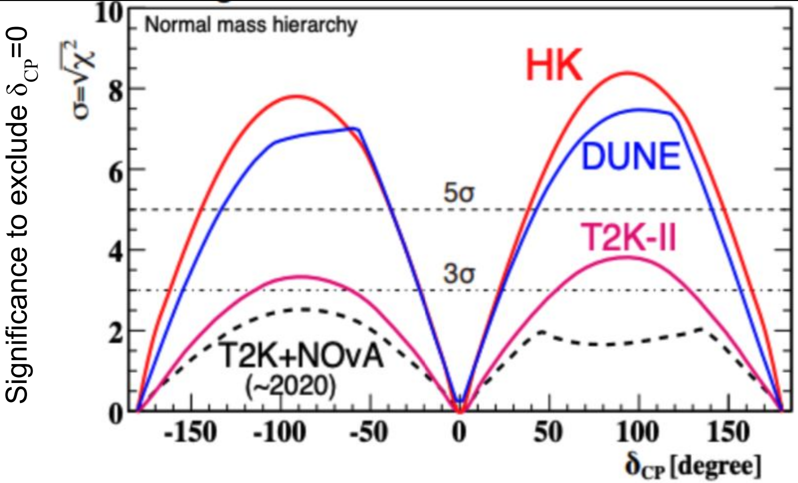
Hyper-K Expected Event Rates

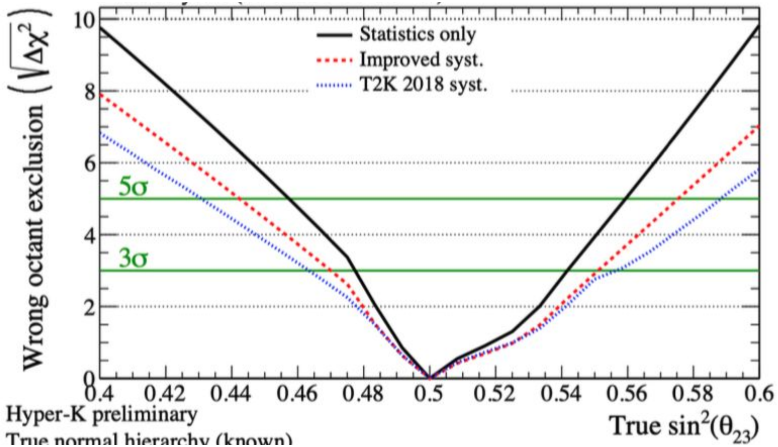
- Aim to collect ~2000 ν_e and $\bar{\nu}_e$ appearance events in 10 years
  - Will measure CPV with 3% statistical uncertainty!
- Controlling systematics becomes critical!



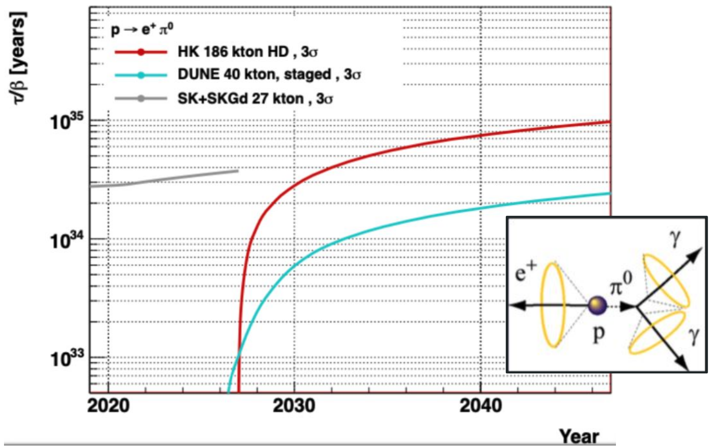
Hyper-K Long-Baseline Physics

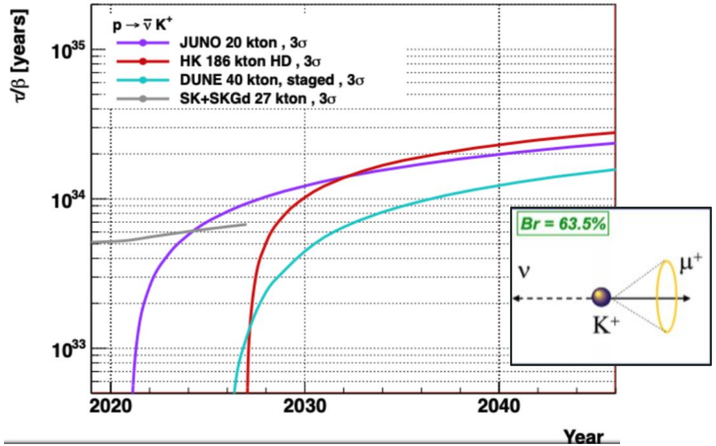


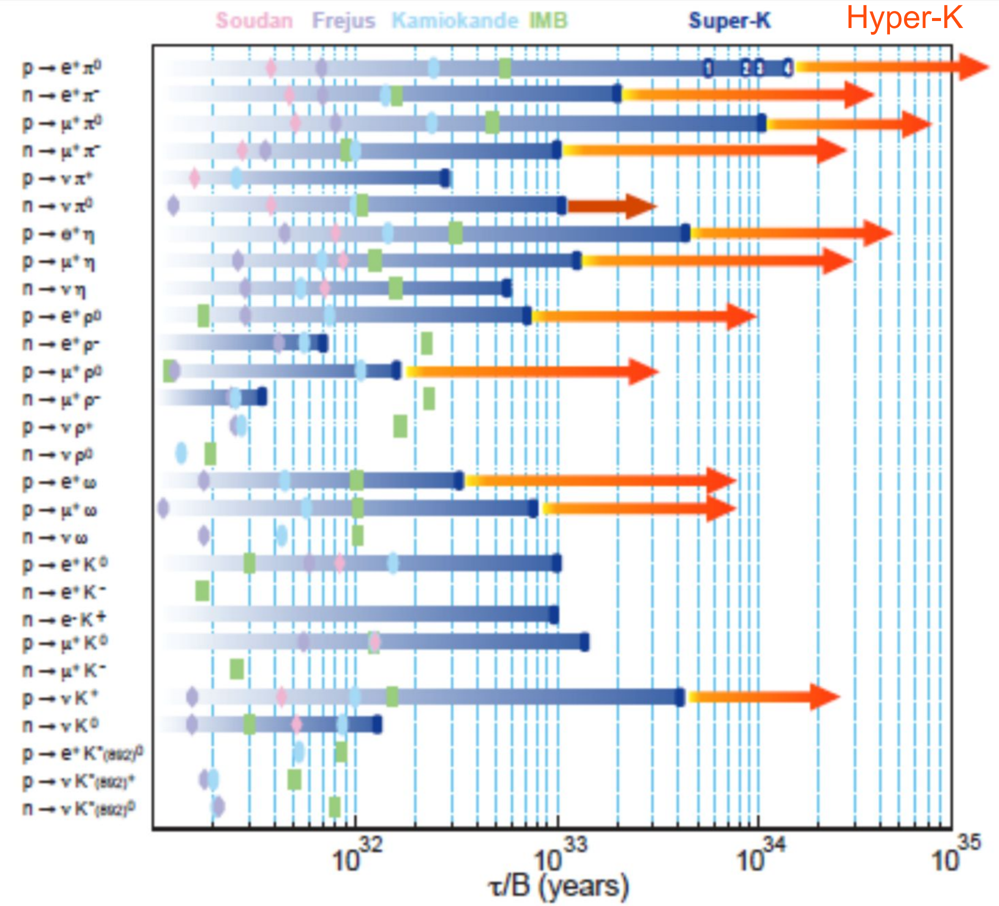




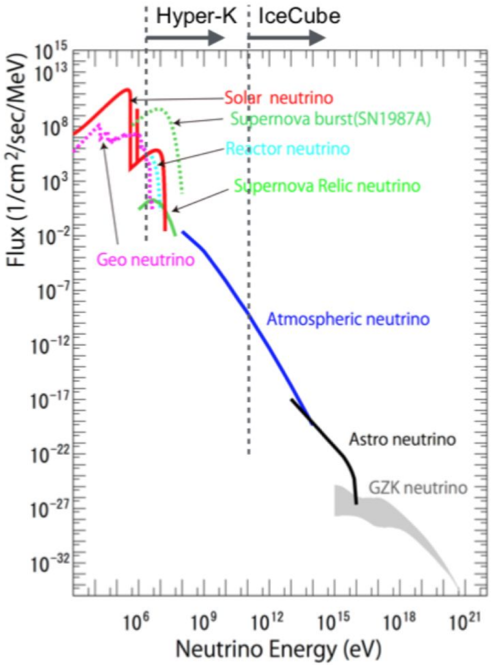
Hyper-K Proton Decay



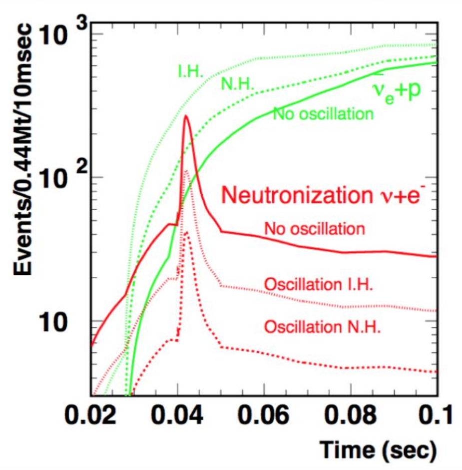


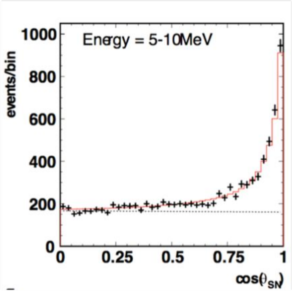


Supernova Burst in Hyper-K



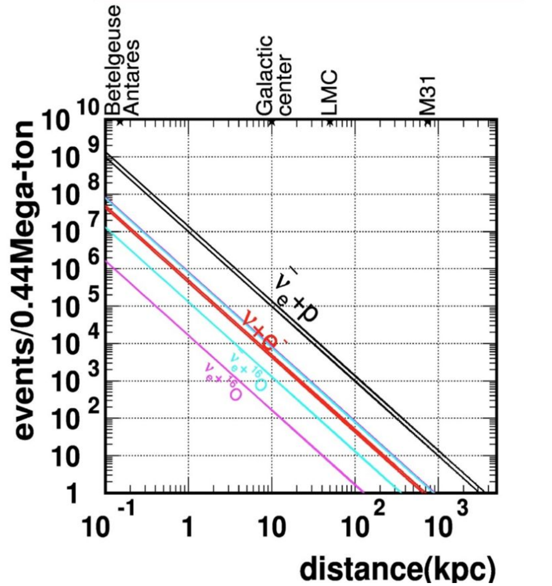
Neutrino carries information of explosion





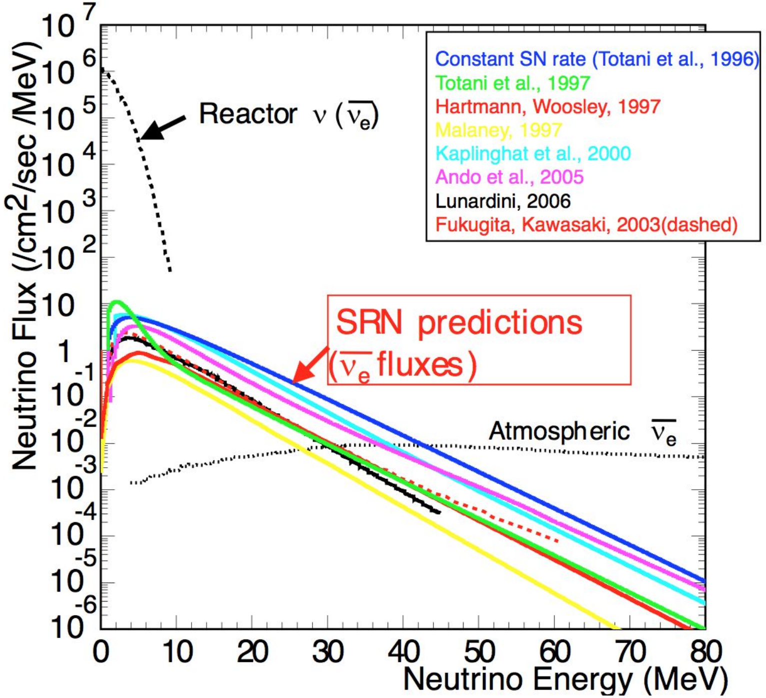
Direction alert for optical measurements (ν_e elastic)

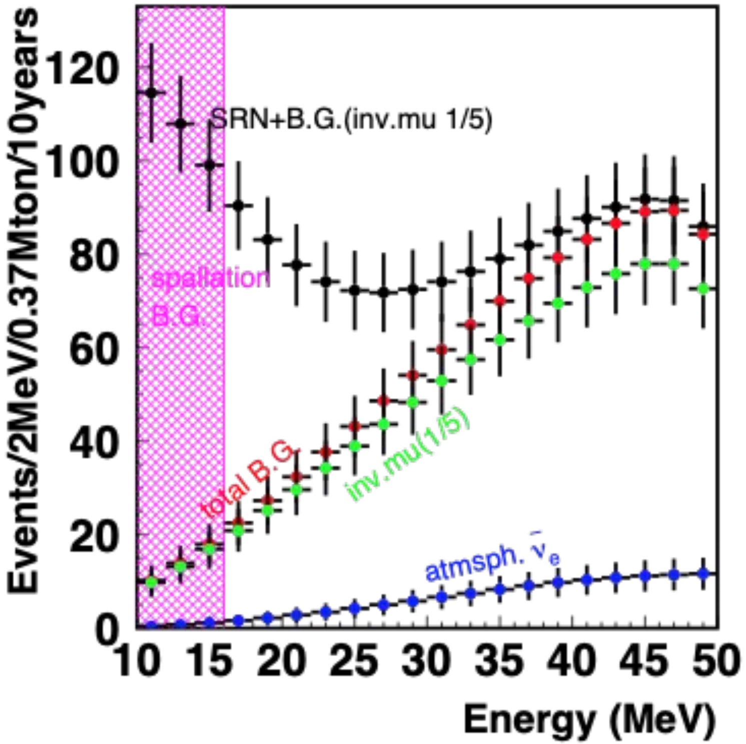
Reaching Andromeda galaxy



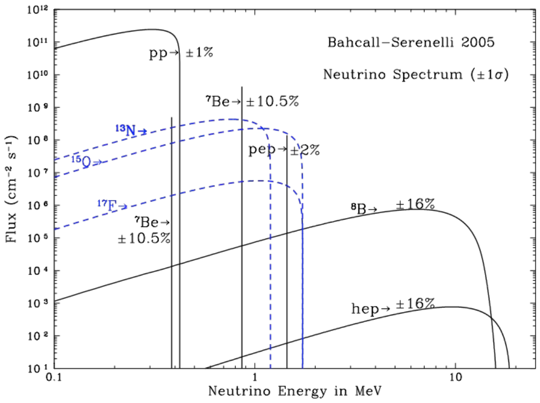
Hyper-K Supernova Relic Neutrinos

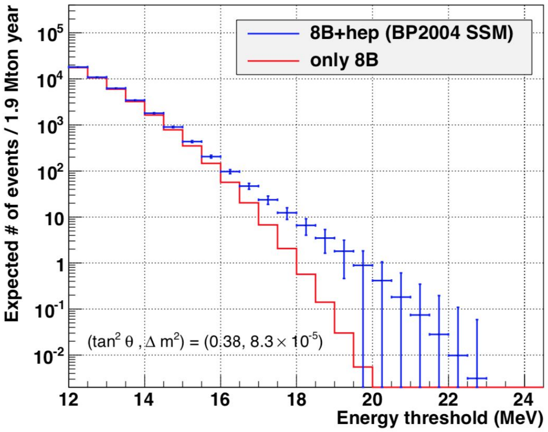
SRN can be observed by HK in 10y with ~70±17 events. It is > 4σ for SRN signal.

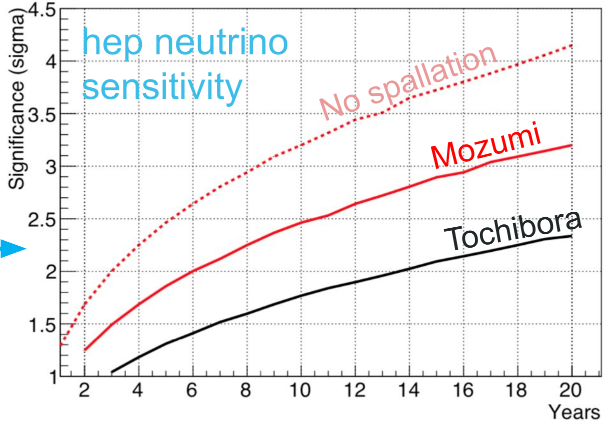


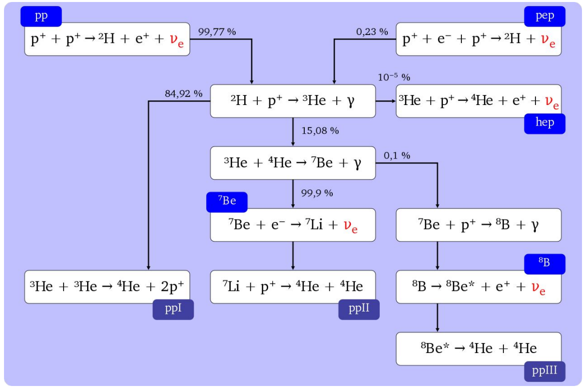


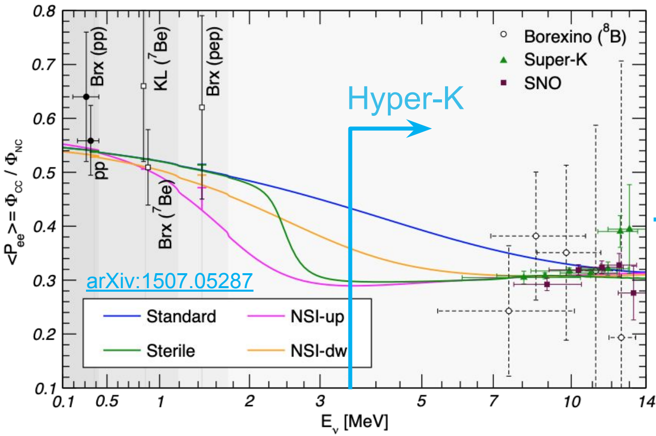
Hyper-K Solar Neutrinos

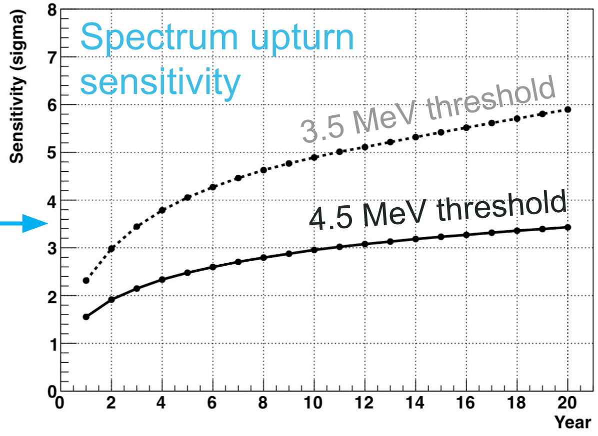












Hyper-K Collaboration Membership

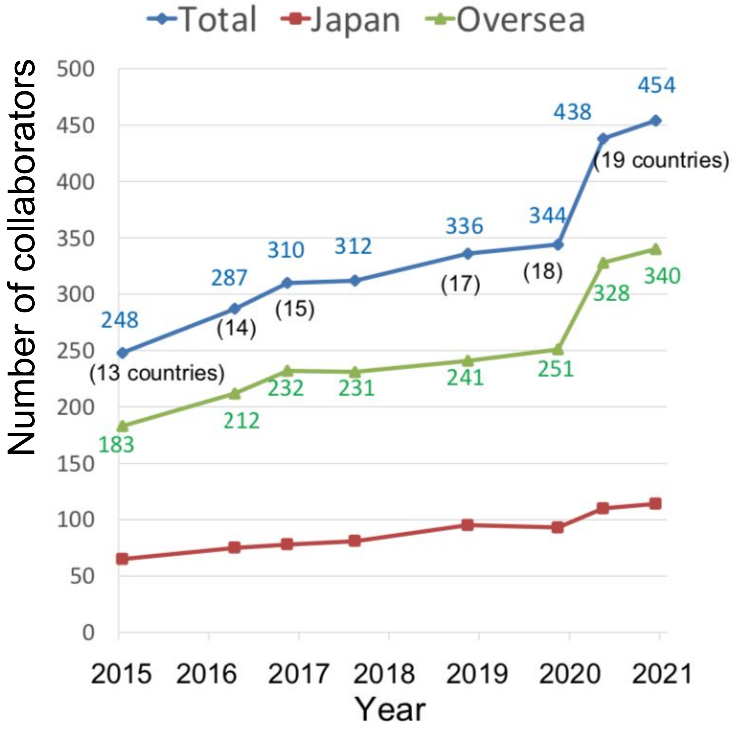
- 19 countries, 93 institutes, ~450 people as of May 2021, growing

Collaborating Institutes

Europe	260 members
Armenia	3
Czech	3
France	28
Germany	1
Italy	53
Poland	37
Russia	21
Spain	26
Sweden	5
Switzerland	5
Ukraine	4
UK	74

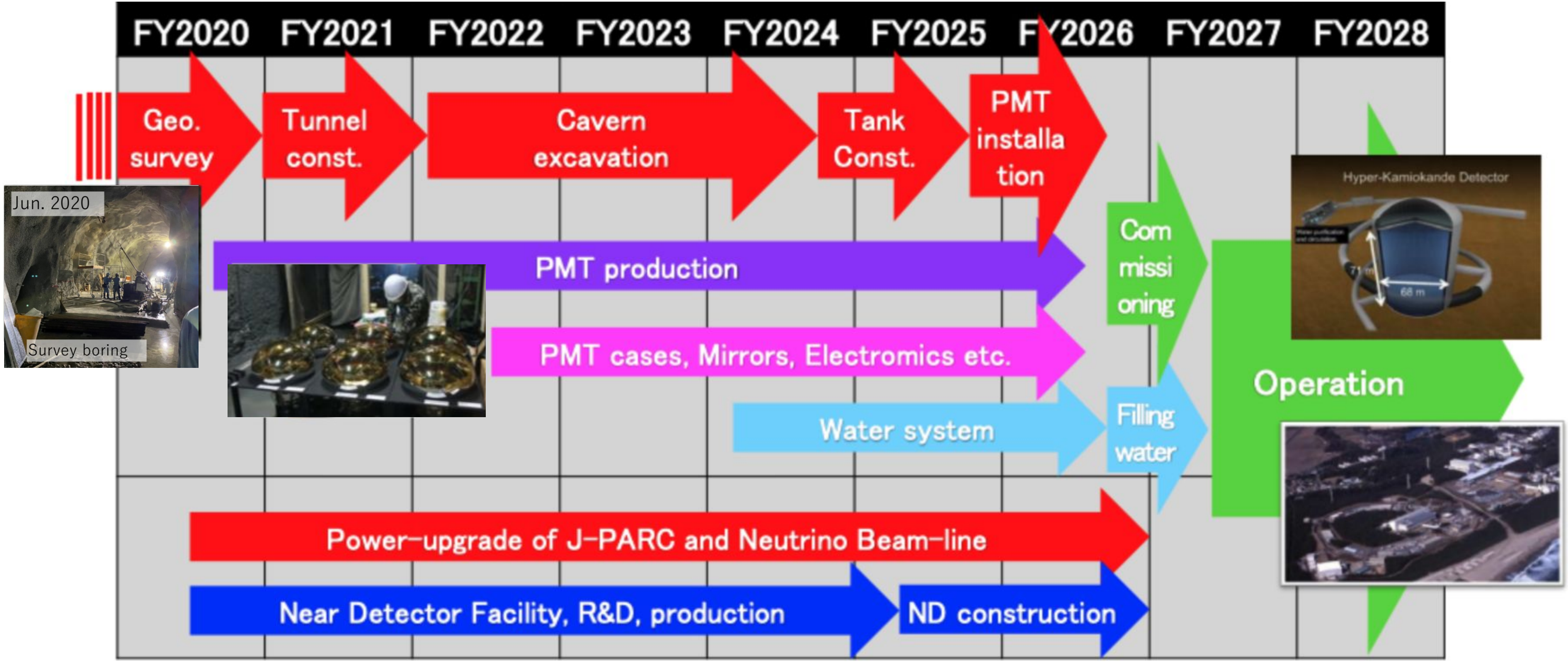
Asia	142 members
India	10
Korea	18
Japan	114

Americas	52 members
Brazil	3
Canada	29
Mexico	11
USA	9

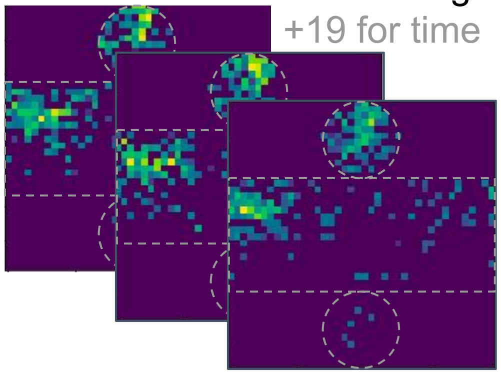


Hyper-K Schedule

Finish all preparations within ~4.5 years from now for detector installation



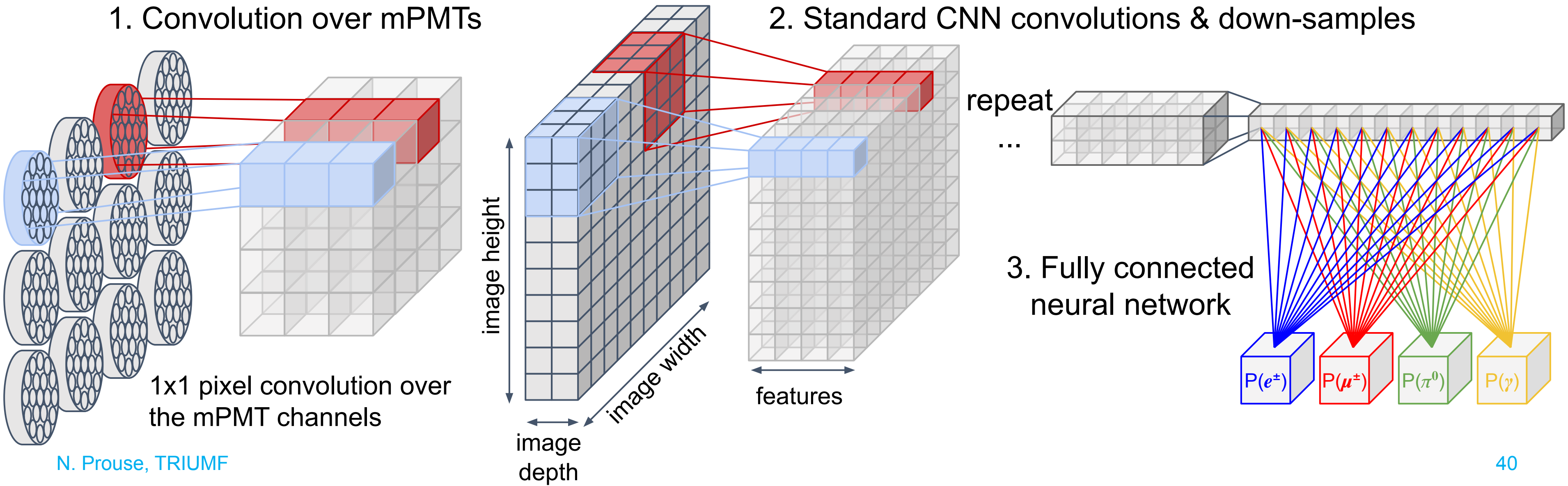
CNN architecture



Full cylinder of mPMTs is unwrapped onto flat image

- One pixel per multi-PMT
- Charge (& time) of 19 PMTs per mPMT
- No special treatment at barrel / end-cap boundary
    - Alternative projections from cylinder to grid have also been explored

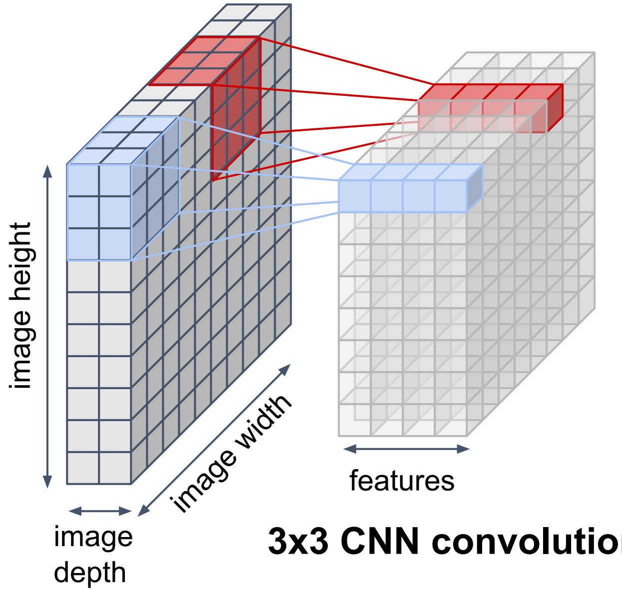
Network based on ResNet-18 CNN architecture[arXiv:1512.03385]



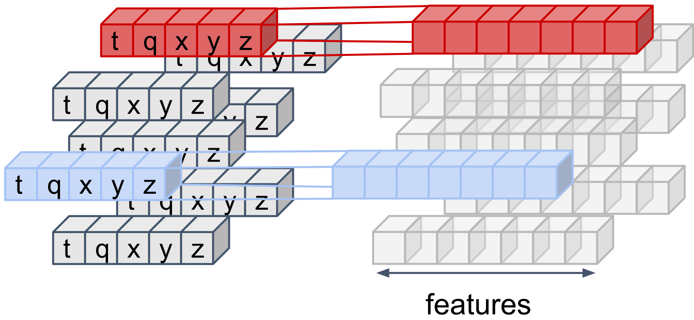
PointNet architecture

PointNet is designed to work on ‘point clouds’ rather than images

- Each hit PMT is a ‘point’ with time, charge & position, not fixed to grid
    - CNN learns translation-invariant functions on image
    - PointNet learns symmetric functions on point clouds
        - Symmetric: ordering of points cannot affect outcome
- Convolution-like operations act on each point’s charge, time and position
- Information flows between points by learning global transformations applied to all points
- Can apply to any detector geometry



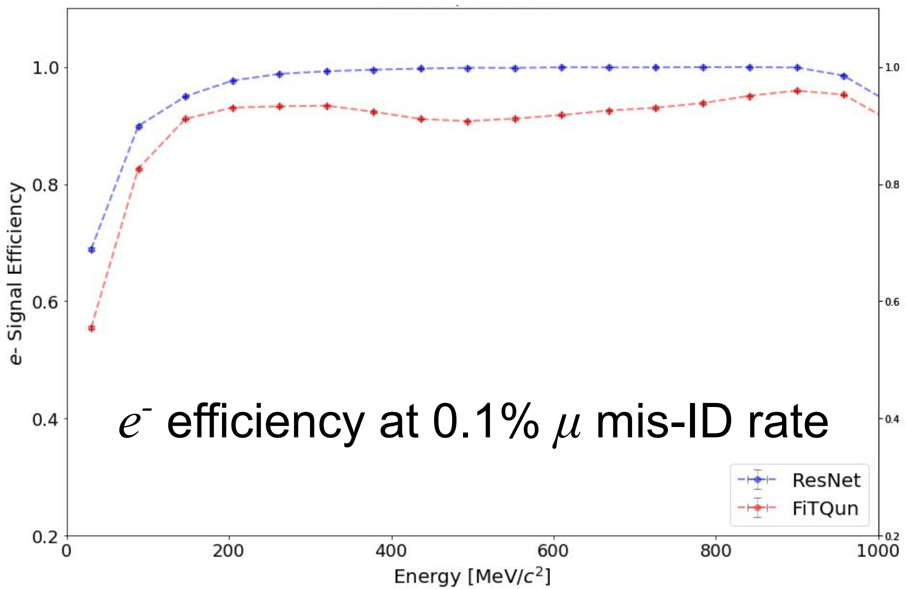
3x3 CNN convolution

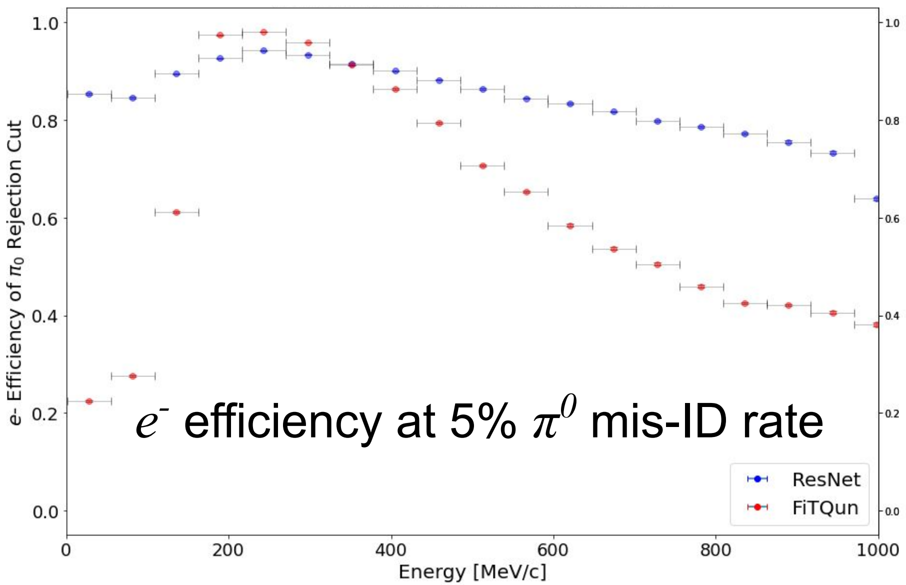


PointNet MLP (1x1 convolution on point cloud)

Classification results

Comparison of ResNet to traditional maximum-likelihood method (fiTQun)



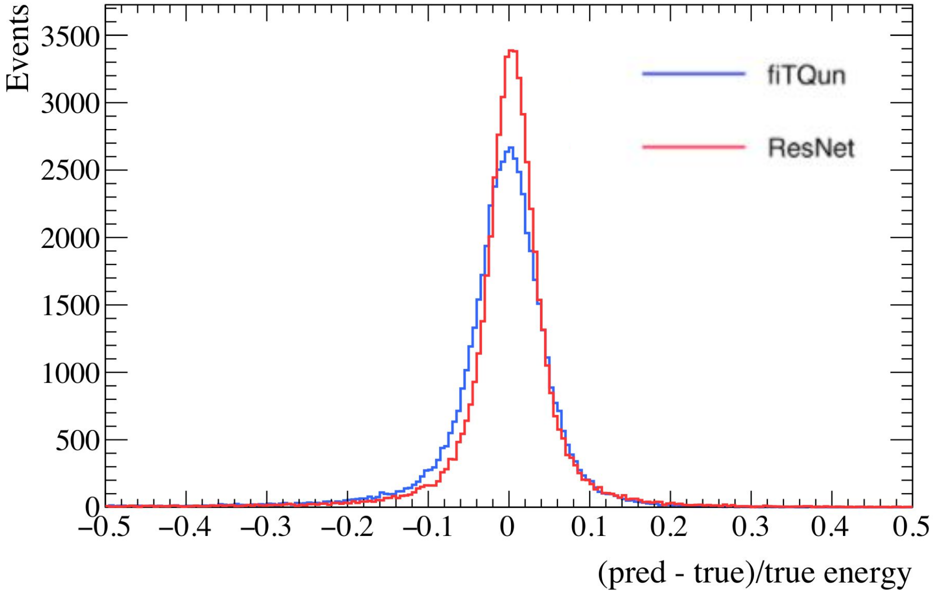


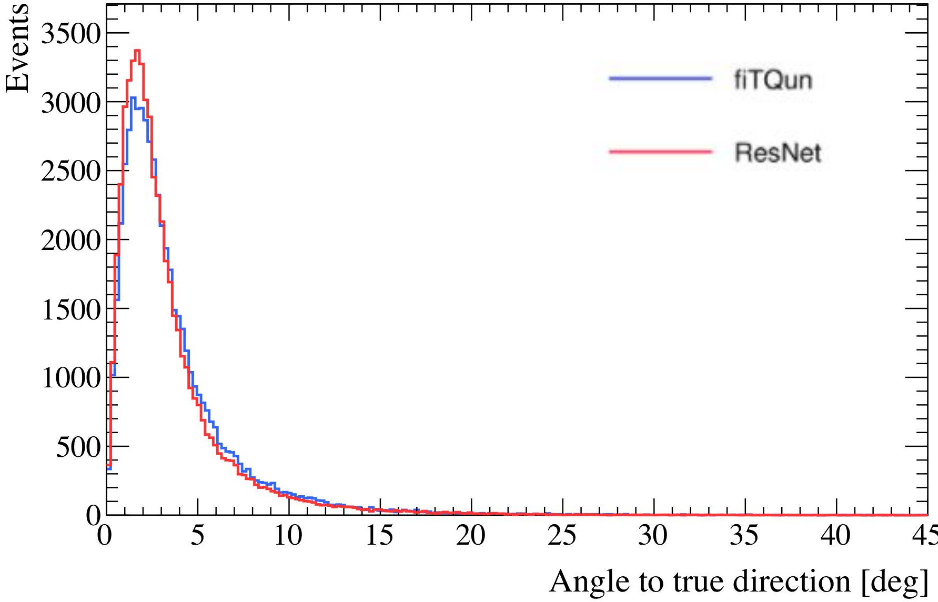
- ν_μ beam produces mostly μ, need rejection factor of 1000 for ν_e measurement
- Increased e^-/μ discrimination across energies
- π^0 is significant background to e^- signal
- Increased e^-/π^0 discrimination, particularly at challenging energies

Position, direction, energy reconstruction

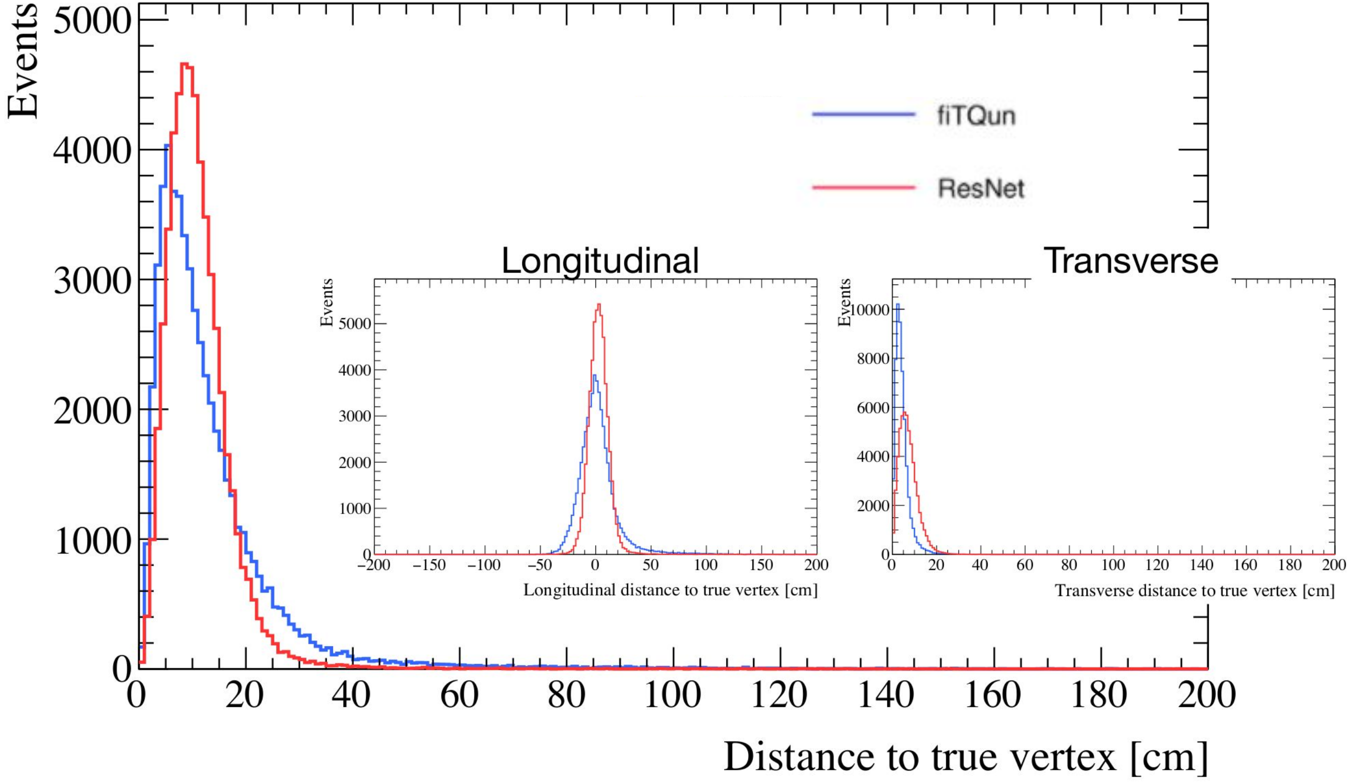
Similar ResNet architecture as used for classification

- Output reconstructed quantities instead of classification variables
- Use Huber loss to minimise true-reconstructed residuals
- ResNet is outperforming fiTQun at energy and direction reconstruction





Position, direction, energy reconstruction



- ResNet is outperforming fiTQun overall at position reconstruction
  - Better in longitudinal direction (along direction of particle track)
  - But worse in transverse direction