Canadian Association of Physicists
Association canadienne des physiciens et physiciennes

The T2K, Super-Kamiokande, and Hyper-Kamiokande Experiments

CAP CONGRESS, JUNE 8, 2021

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Neutrino Oscillation Formalism

Flavor Eigenstate

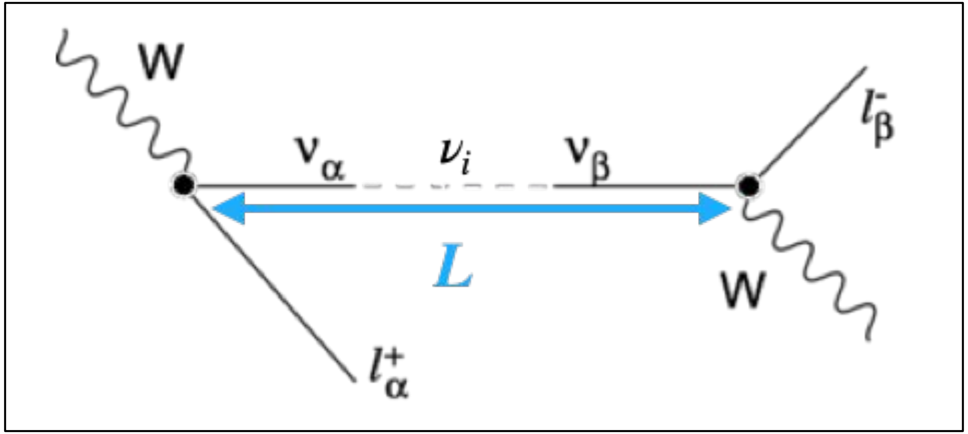
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Hamiltonian Eigenstate

ν_1, ν_2, ν_3

Superposition (Unitary transf.)

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

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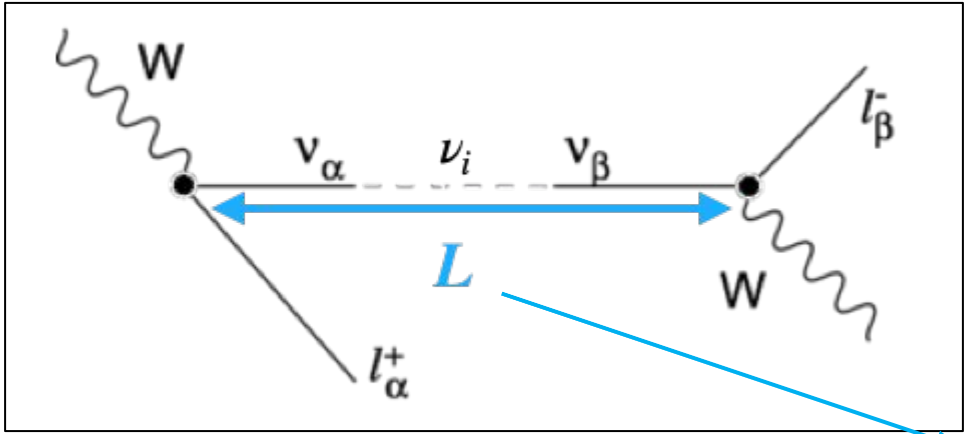


Mixing matrix (oscillation) parameters

ν mass^2 differences

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

Oscillation probability

ν energy

Neutrino Oscillation Formalism

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

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

Flavor Eigenstate

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

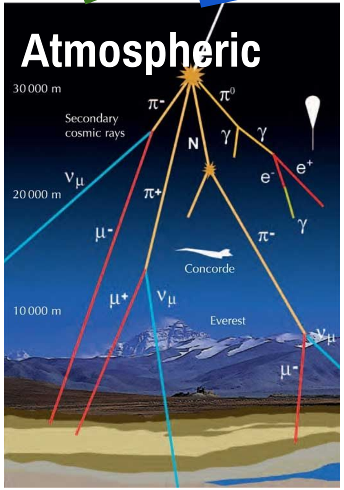
Superposition (Unitary transf.)

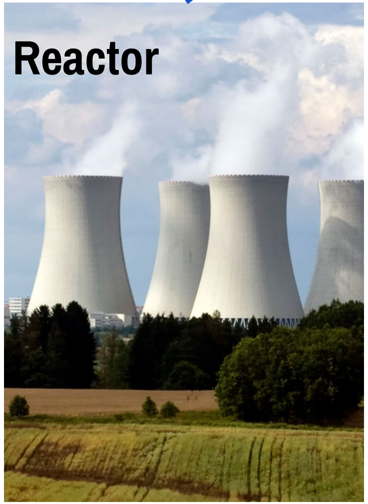
Hamiltonian Eigenstate ν_1, ν_2, ν_3

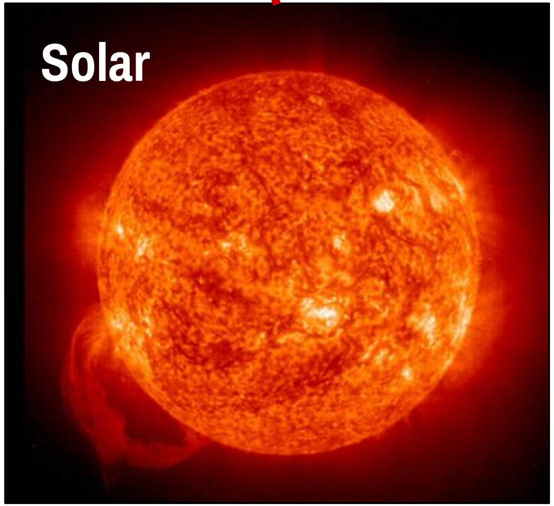
Neutrino Sources

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

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







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	($\sim 1\sigma$ accuracy)
$\Delta m^2 / eV^2 = 2.48 \times 10^{-3}$	(1.3%)
$\delta m^2 / eV^2 = 7.34 \times 10^{-3}$	(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%)

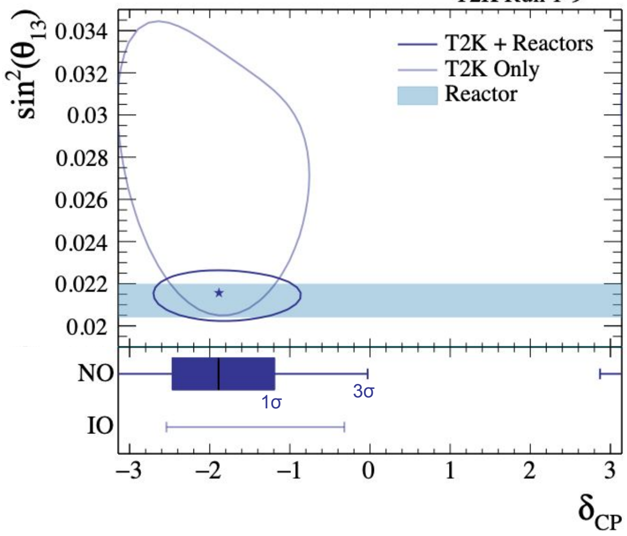
UNKNOWNS	($>1\sigma$ hints)
Dirac or Majorana	
Mass ordering	($>3\sigma$ NO)
Absolute mass	(<sub-eV)
Dirac CP phase δ_{cp}	(1.6σ CPV)
Octant of θ_{23}	

E. Lisi (TAUP2019)

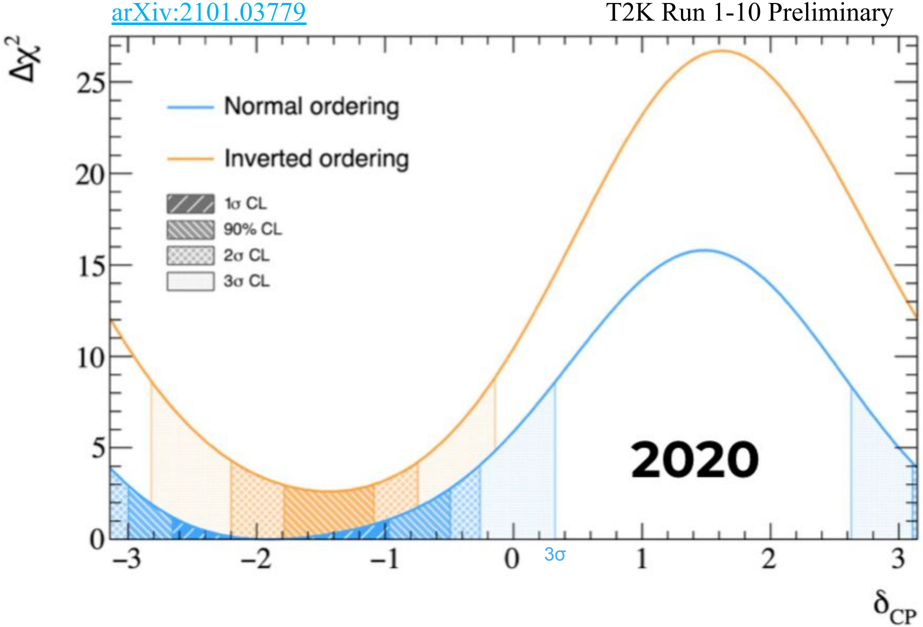
T2K CP Violation Constraints

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

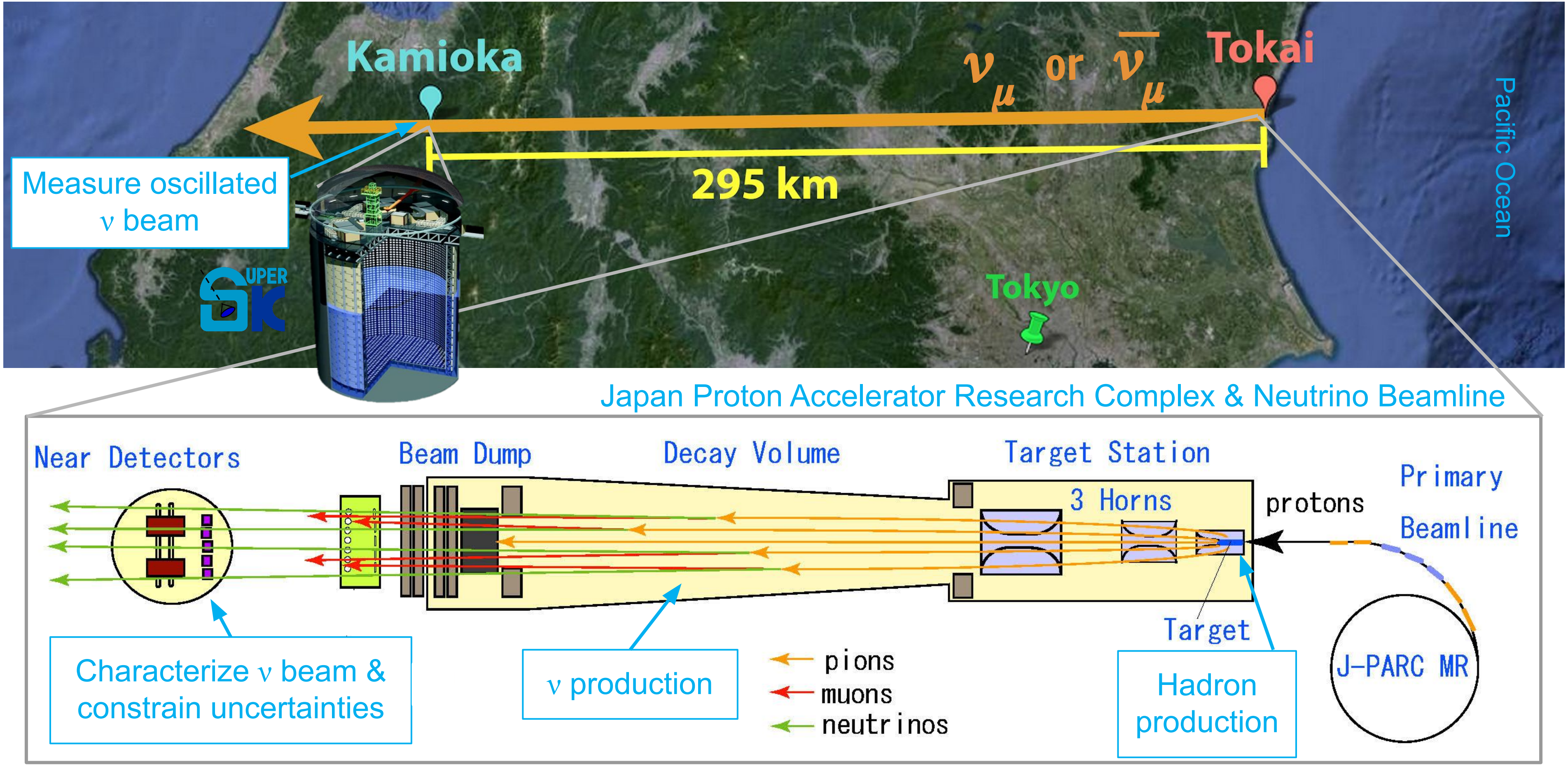
Nature 580 (2020) 7803



arXiv:2101.03779



Building a Neutrino Beam (in Japan)



T2K Beam Exposure and History

POT Total: 3.64 x 10^{21} (ν-mode : $\bar{\nu}$-mode ~ 6 : 5)

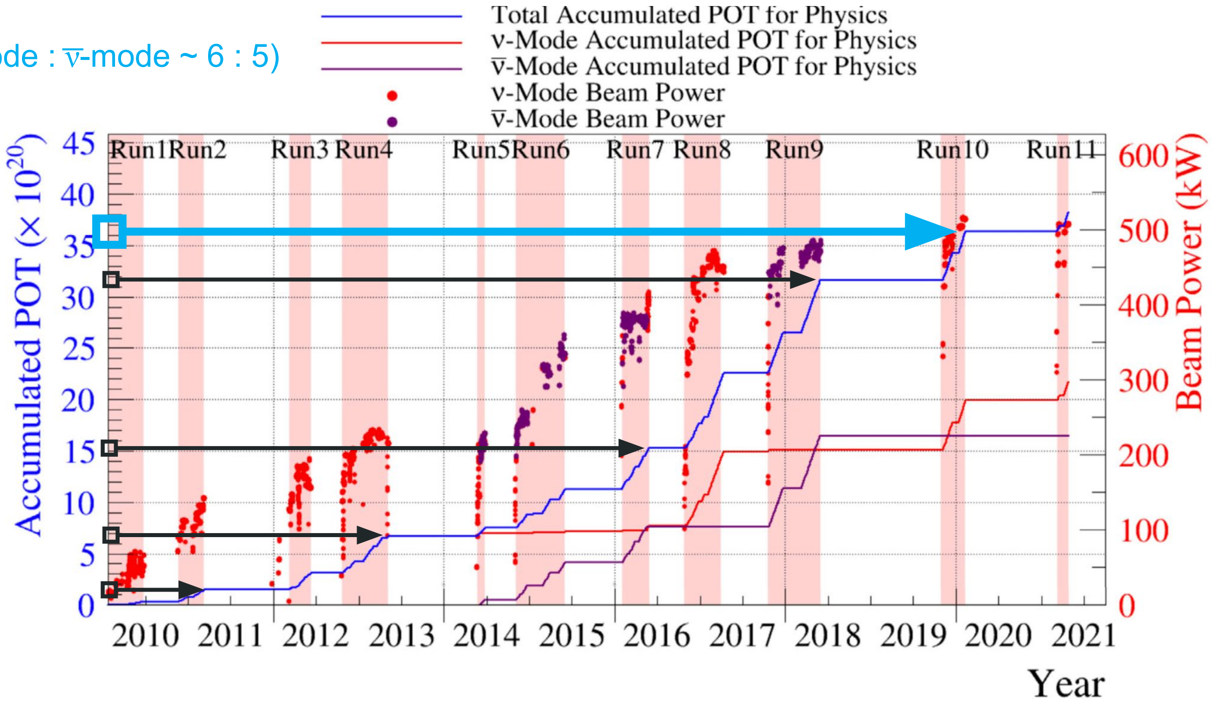
2020 Result
arXiv:2101.03779

Constraint
Nature 580, 339–344

Search for CPV
PRL 121, 171802

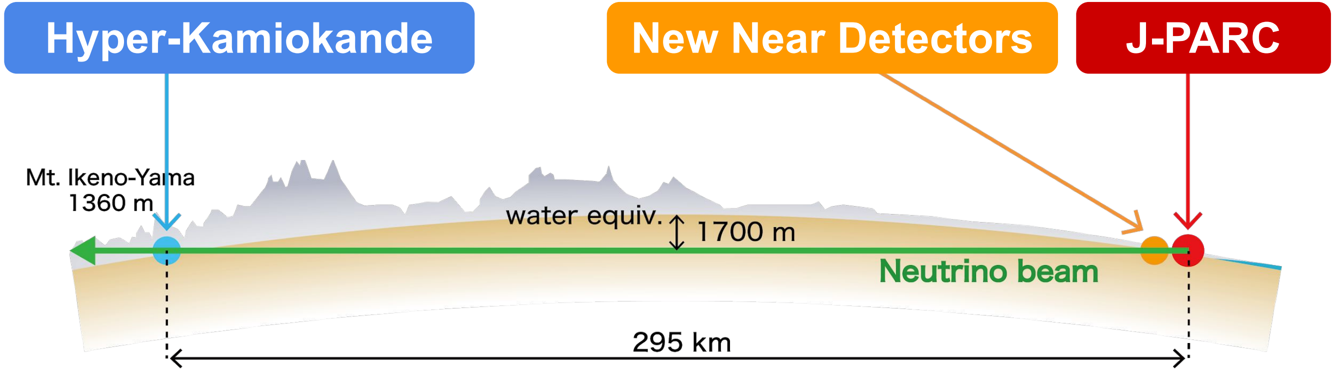
Observation of ν_e appearance
PRL 112, 061802

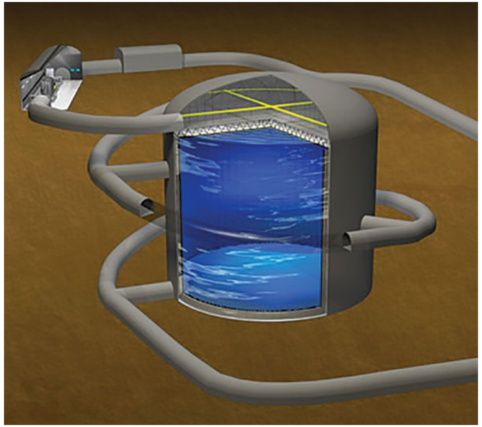
Indication of ν_e appearance
PRL 107, 041801



- **515 kW operation achieved in 2020**
- 33% increase of ν-mode data since previous analysis
- Collected Run 11 data in 2021 with SK-Gd

Overview: Next Generation Experiment

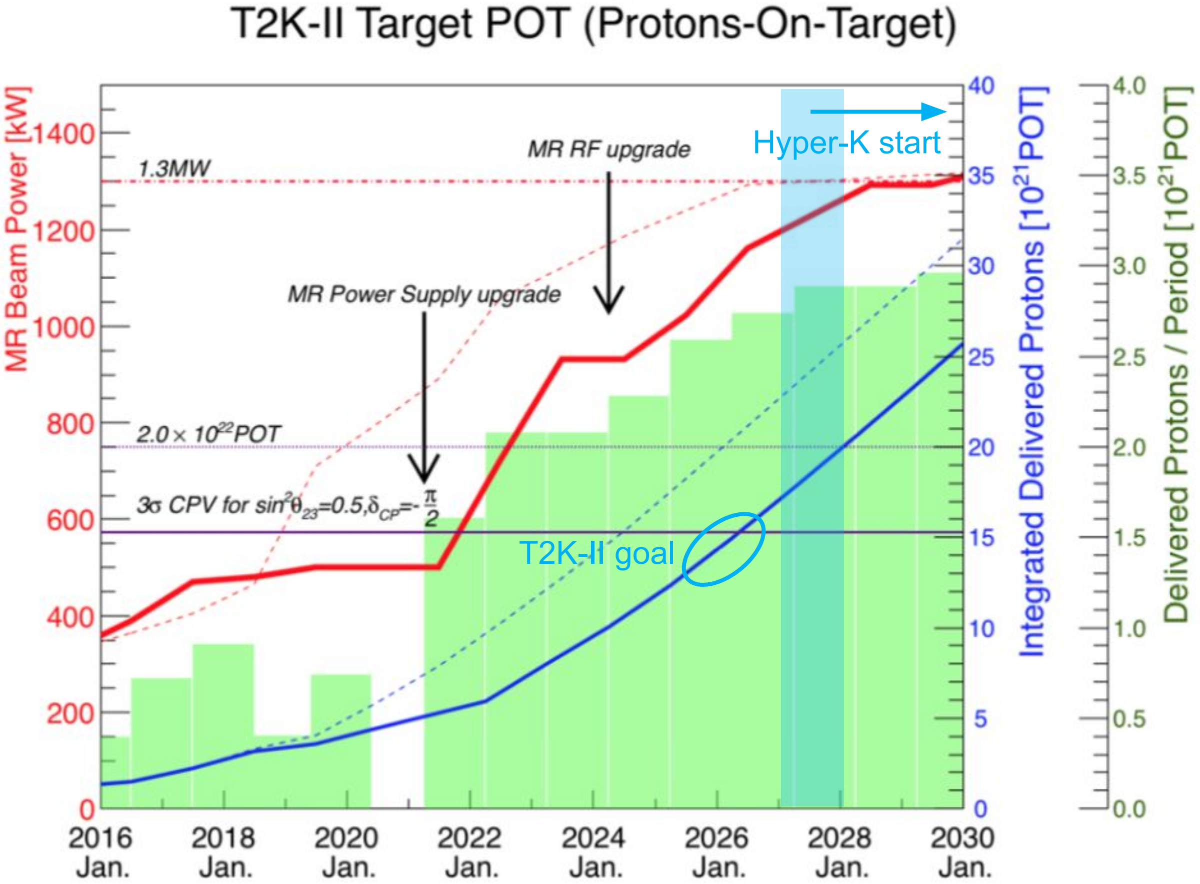




- Bigger and more sensitive than ever
  - Fiducial mass 8x Super-K
  - J-PARC beam 2.5x more powerful
    - → Neutrino rates 20x T2K
- Precise systematic understanding becomes critical to the % level
  - New near detectors and photon detectors
  - New calibration and event reconstruction techniques
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

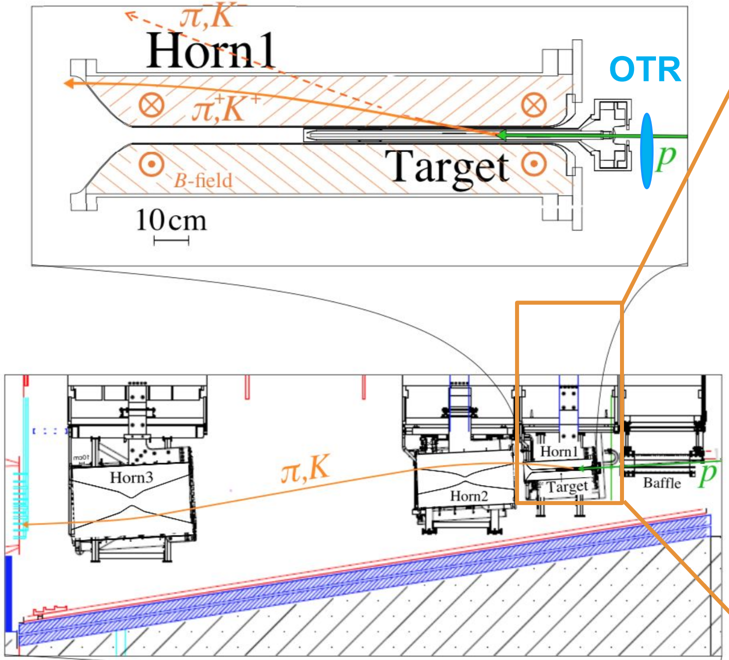
Beam Line Upgrades Towards T2K-II and Hyper-K

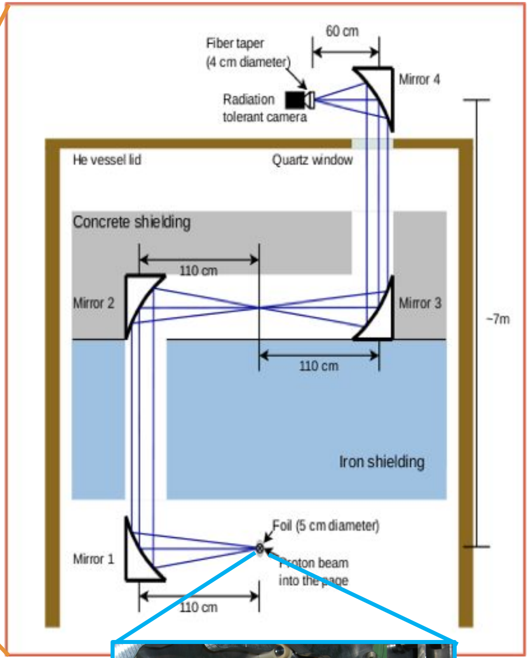
- Increase beam power from ~500 kW to 1.3 MW
- Many upgrades to neutrino beamline components
  - Target, beam monitors, etc.
- Increase horn current from 250 → 320 kA
  - 10% more neutrinos and reduced wrong-sign background

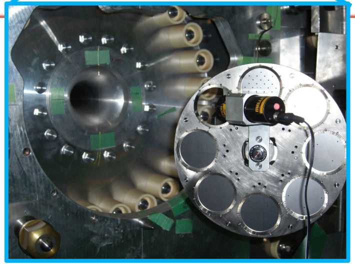


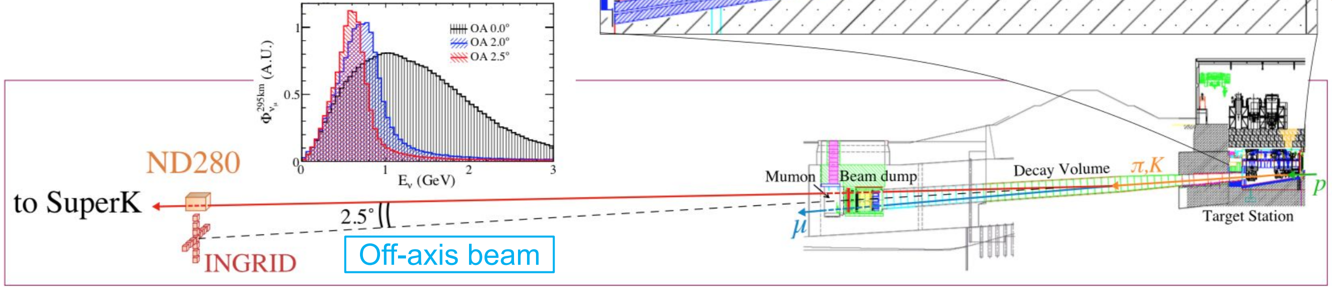
Proton Beam Monitoring: Optical Transition Radiation

- 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





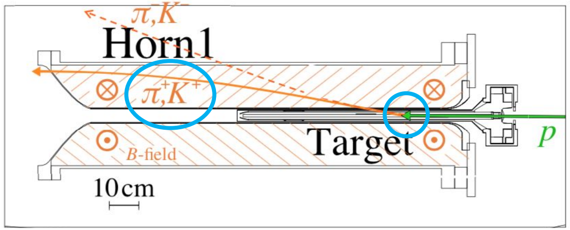


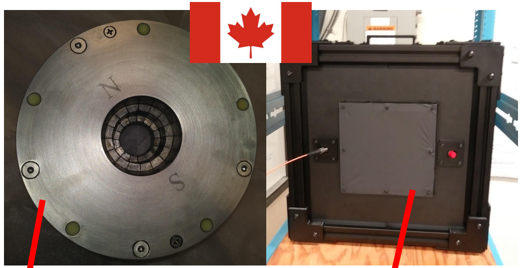


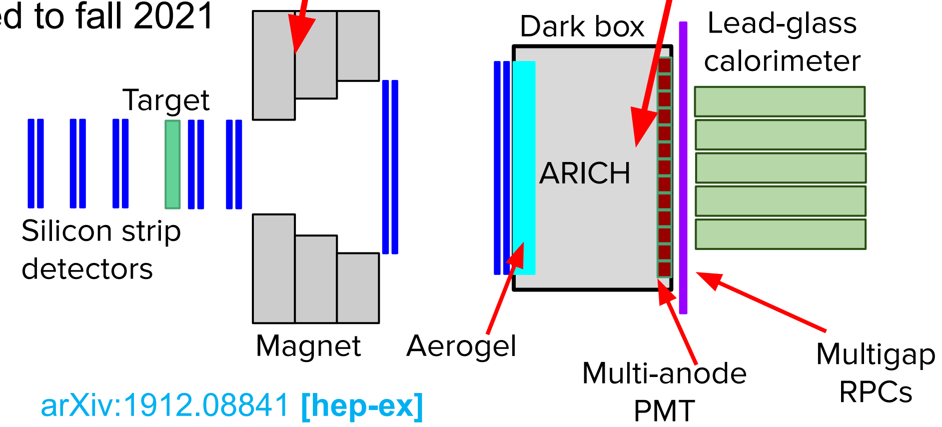
Hadron Production for Neutrino Flux Modeling: EMPHATIC

- **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
- See poster by [Bruno Ferrazzi (Regina)]()

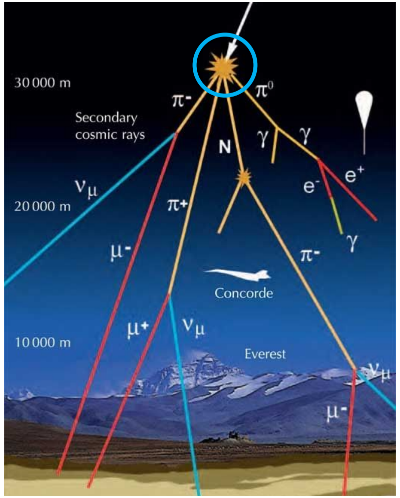
π and K elastic and QE interactions (< 10 GeV/c)
Important systematic uncertainty







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

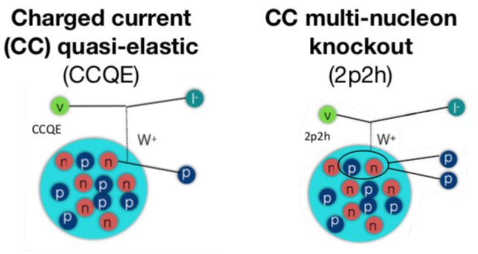


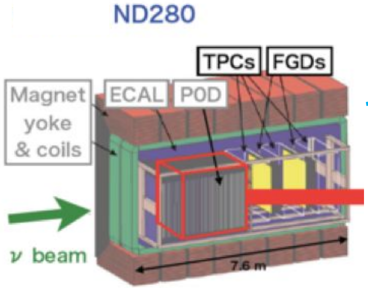
T2K-ND280 ν Cross-Section Measurements

- ν-nucleus interactions: a theoretical challenge that must be met by rich experimental measurements

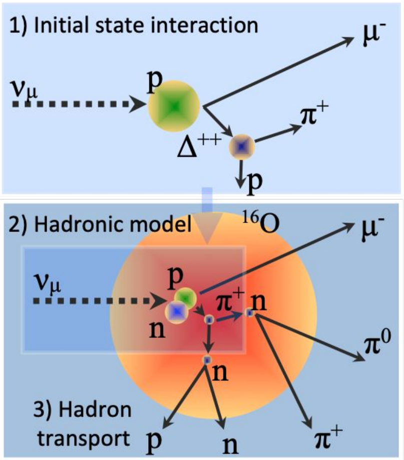
- Many recent T2K xsec papers, e.g.:
  - CC0π on C+O (PRD 101, 112004 (2020))
  - $\nu_\mu/\bar{\nu}_\mu$ CC0π (PRD 101, 112001 (2020))
  - $\nu_e/\bar{\nu}_e$ CC - First $\bar{\nu}_e$ in 43 years! (JHEP 2020, 114 (2020))
  - CC1π+p - Nuclear effects (arXiv:2102.03346 [hep-ex])

- See also talk by Mitchell Yu (York):
  - $\nu_\mu/\bar{\nu}_\mu$ CC coherent π production

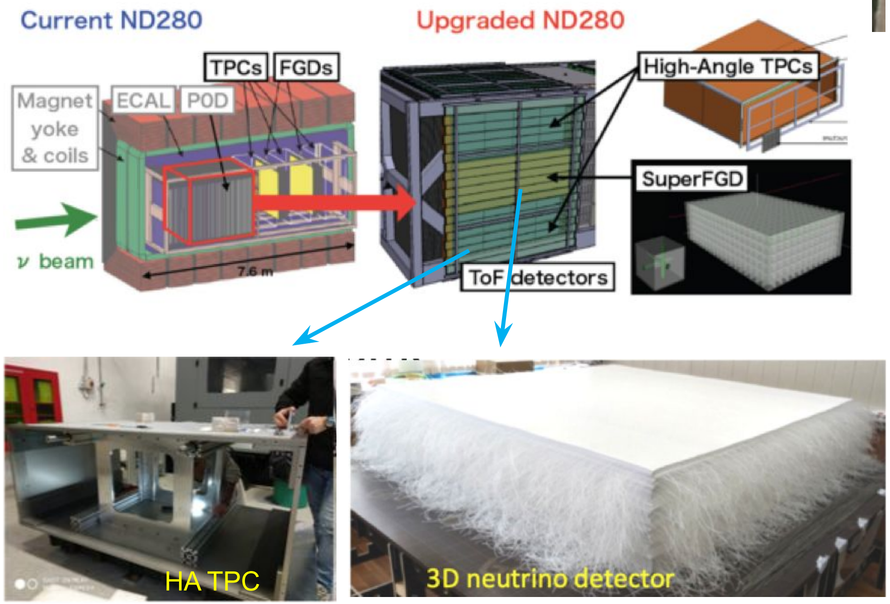




ND280 off-axis detector
- Active scintillator + passive water targets
- Tracking with time projection chambers
- Magnetized for charge & momentum measurement



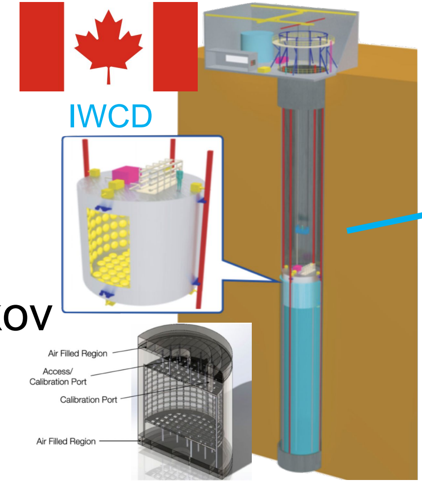
Future of the Near Detector Suite



- ND280 upgrade in 2022
  - Increase phase space coverage, similar to SK
  - Lower proton energy threshold and neutron detection capability

Future of the Near Detector Suite

- Canada-led, novel off-axis spanning **I**ntermediate **W**ater **C**herenkov **D**etector for Hyper-K
  - Handle on far detector observables' dependence on neutrino energy
  - Precise cross-section measurements on water
  - See [Mark Hartz's (TRIUMF) talk at TIPP]



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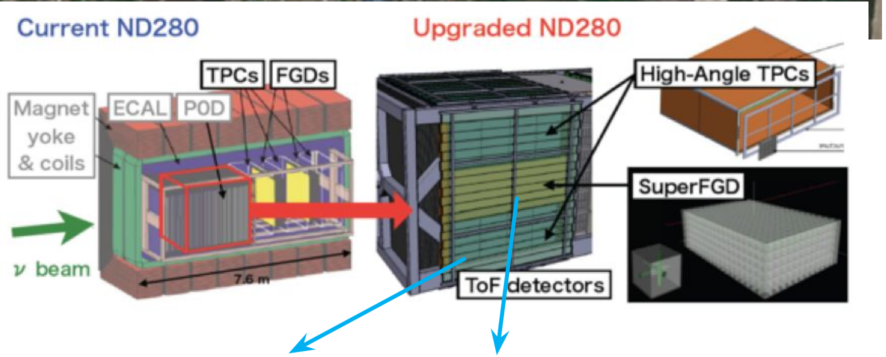
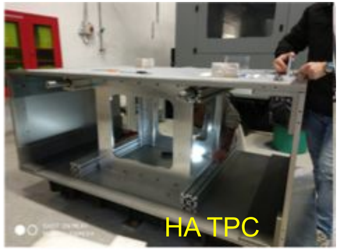
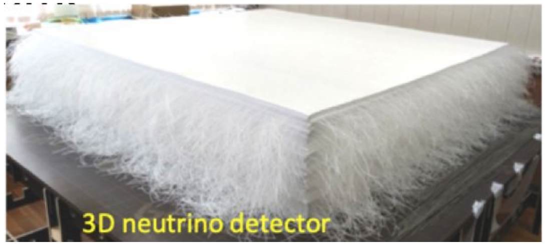
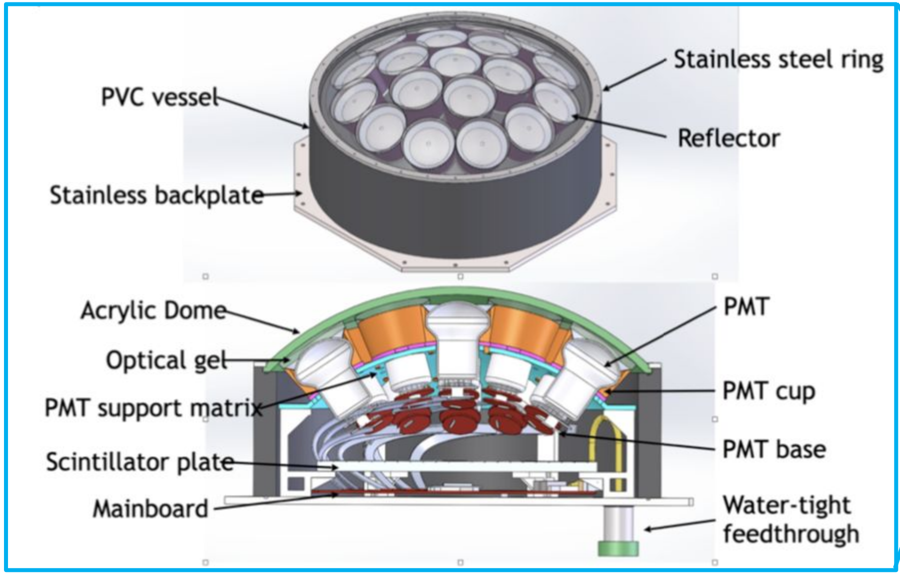


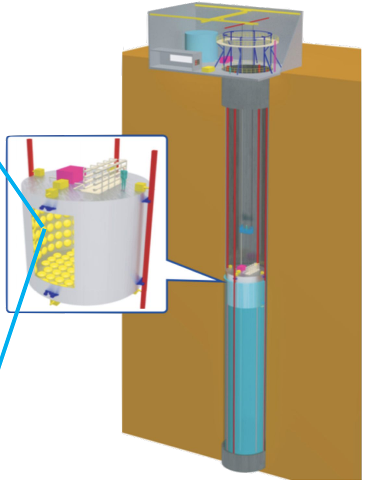




IWCD & Hyper-K Photosensor Development

- Multi-PMT:
  19 x 3” diameter PMTs in a water-tight vessel with HV and electronics



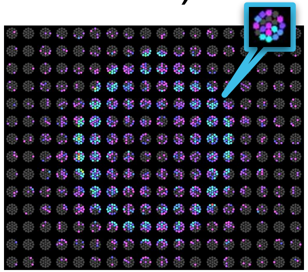


- Canadian contribution to the IWCD
  - ~250 out of 480 mPMTs
  - Aiming for 400 from CFI 2023 for Hyper-K far detector contribution

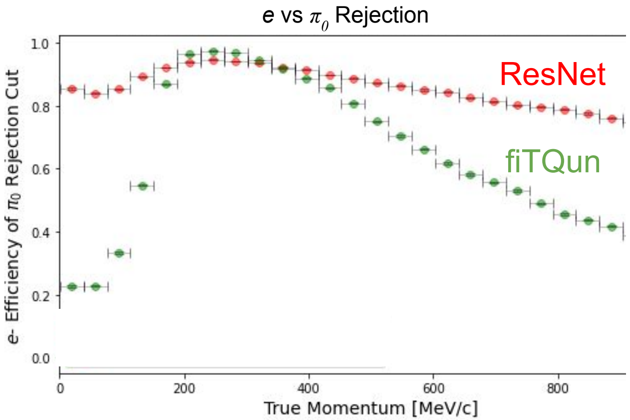
- See talk by [Luan Koerich (Regina)]

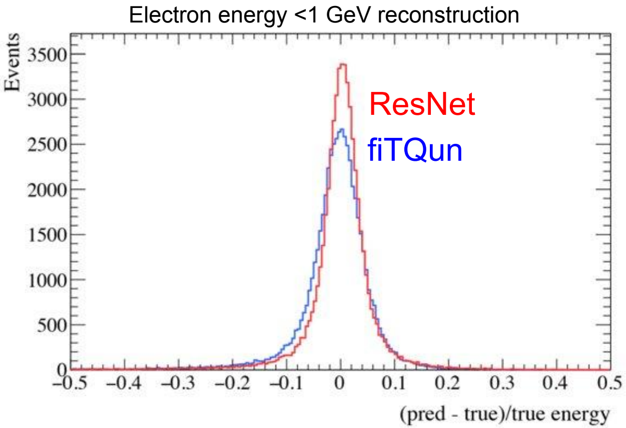
Machine Learning Event Reconstruction

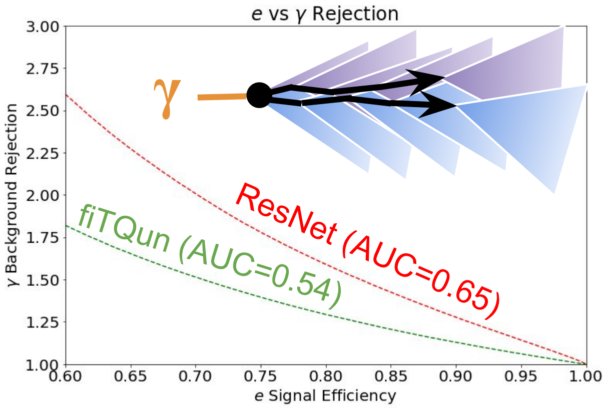
- Canada leading the Water Cherenkov Machine Learning (WatChMaL) consortium
  - Towards a unified platform and knowledge base across many such detectors
- Improved particle classification and regression/reconstruction (in IWCD below)
- Massive processing speed-up enables multitudes of simulations for detector design and systematics studies



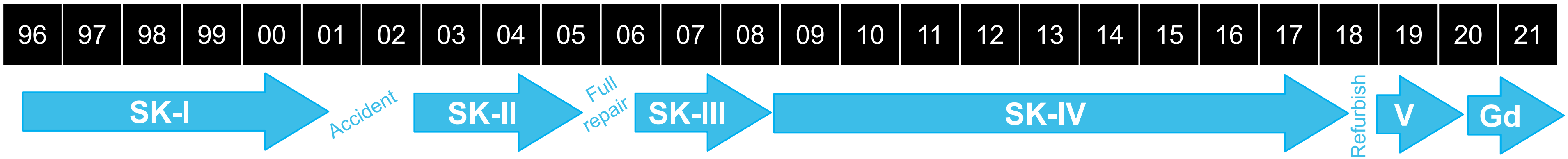
- See talk by [Nick Prouse (TRIUMF)]



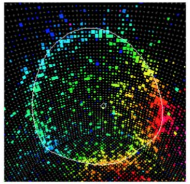


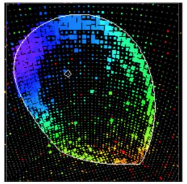


Super-Kamiokande - 25 Years of ν and Astrophysics

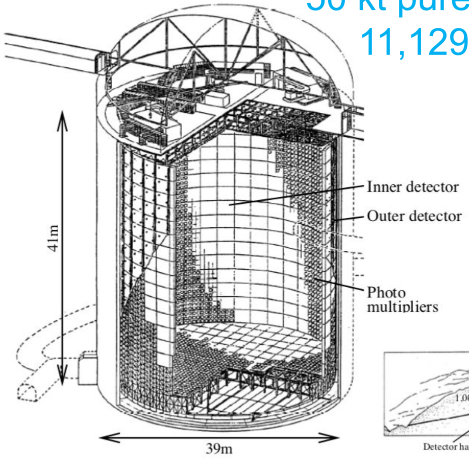


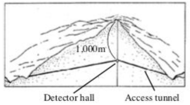
- 1998: discovery of atmospheric ν flavor transformation
- 2001: discovery of solar ν flavor transformation with SNO
- 2004: confirmation of atmospheric ν oscillation by K2K
- 2012: first evidence for τ appearance
- 2013: first direct indication of ν osc. matter effects
- Ongoing searches for nucleon decay, DM, supernovae...

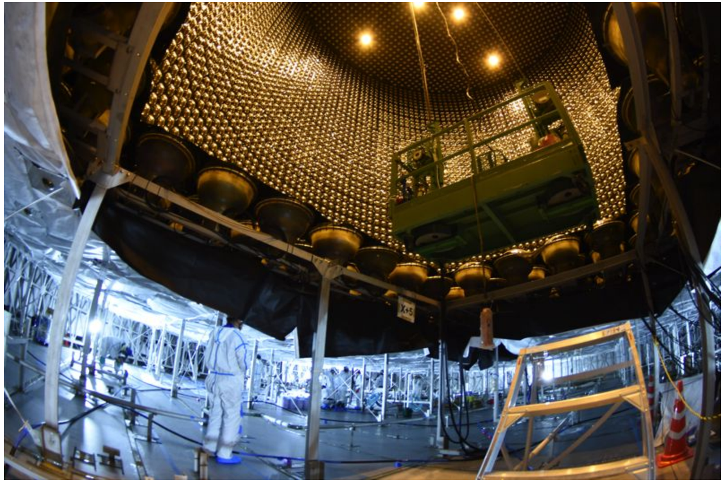

ν_e-like


ν_μ-like

50 kt pure water
11,129 PMTs

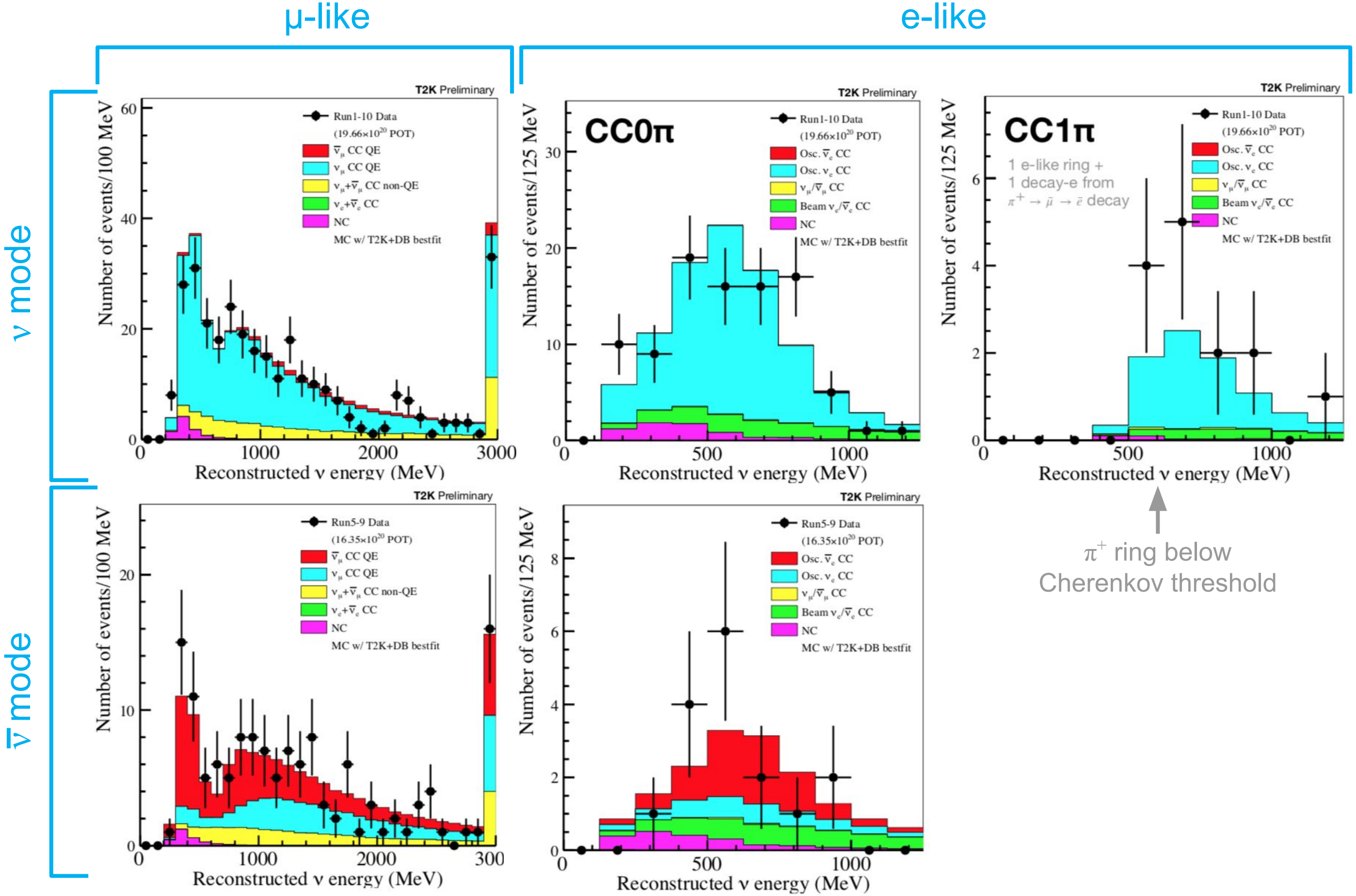






T2K-SK Single-Ring Datasets for CPV Analysis

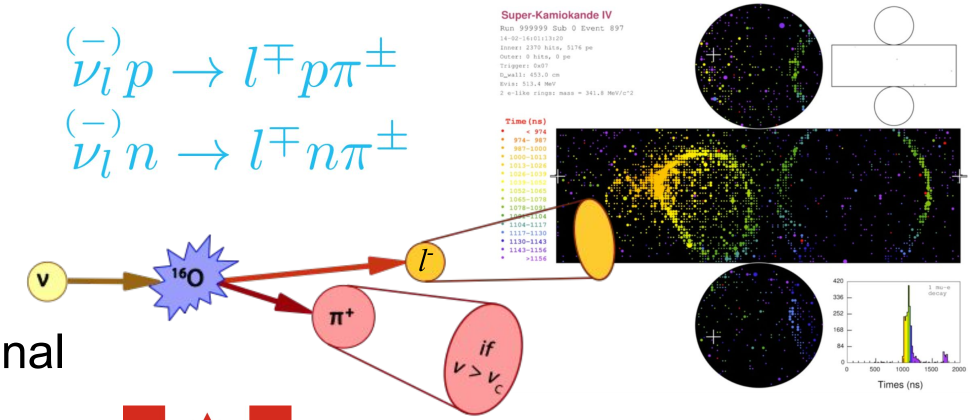
- Updated Super-K datasets used for 2020 CPV analysis
  - ν_μ disappearance
  - ν_e appearance
  - Only one visible Cherenkov ring
- Event reconstruction (fiTQun) and detector systematic analyses developed in Canada 🇨🇦



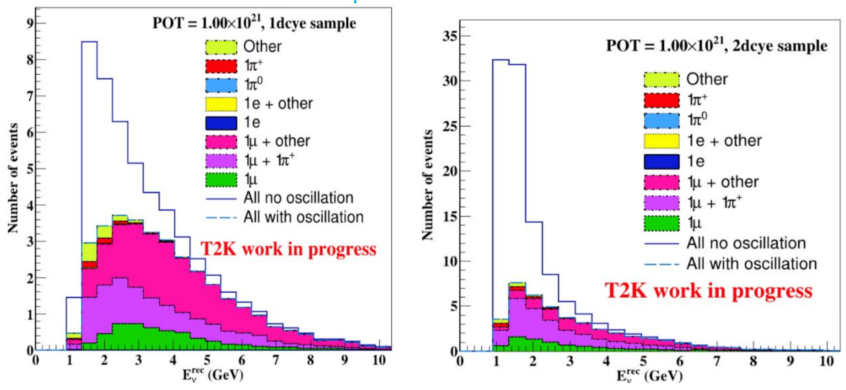
T2K-SK Multi-Ring Datasets for Future Analyses

- 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

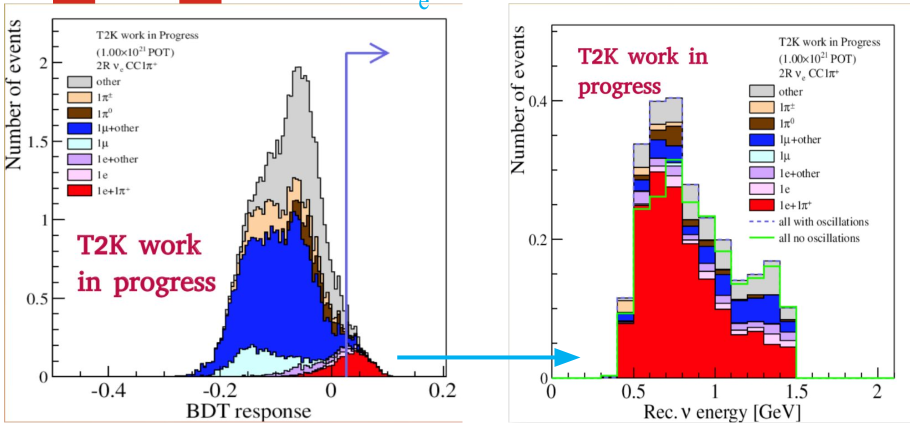
$$\overset{(-)}{\nu}_l\, p \rightarrow l^{\mp} p \pi^{\pm}$$
$$\overset{(-)}{\nu}_l\, n \rightarrow l^{\mp} n \pi^{\pm}$$



ν_μ CC1π^+



ν_e CC1π^+

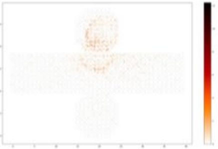


Multi-Ring Reconstruction in the Further Future

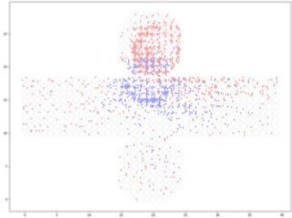
- More machine learning: panoptic segmentation
- Towards improving multi-ring & multi-GeV event classification and reconstruction
    - ν mass ordering, ν_τ appearance, δ_{CP}
- See talk by [Wojtek Fedorko (TRIUMF)]
    - Machine Learning Applications in Particle Physics: Present and Future

(a) image (b) semantic segmentation

Observed charge

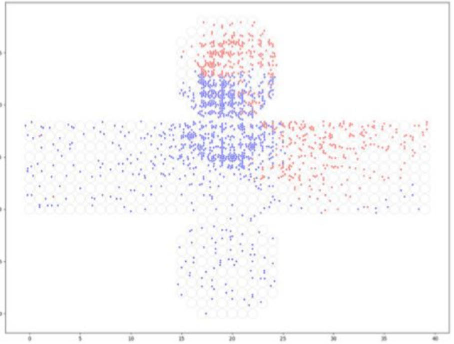


Labels

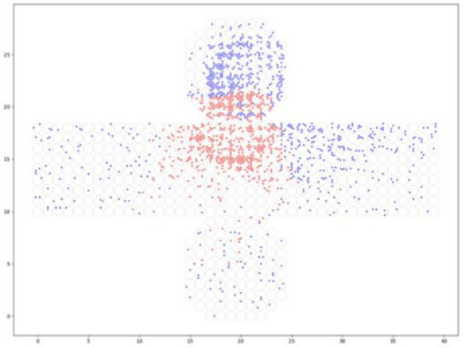


First attempt on π^0 decay events in IWCD: ~80% accuracy

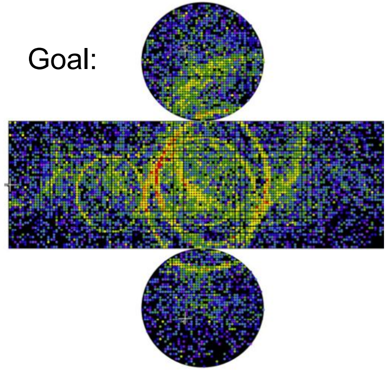
U-Net

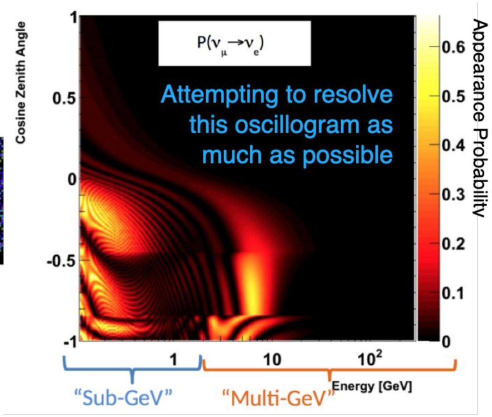


FRRN



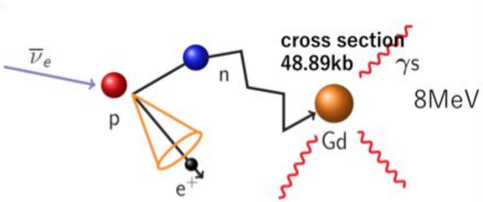
Goal:

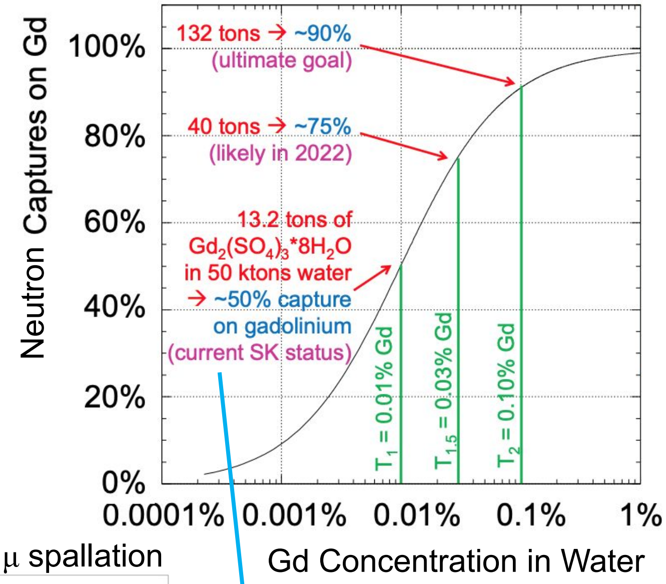


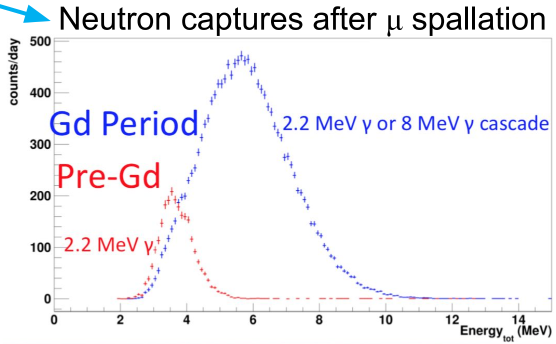


Super-K Gadolinium Upgrade

- Improved neutron detection
- More physics potentials:
  - Search for solar antineutrinos
  - Background reduction for proton decay
  - Diffuse supernova neutrino background (DSNB)
  - Improved $\nu/\bar{\nu}$ discrimination → δ_{CP}, mass ordering
- Detector refurbished in 2018 to prepare for $Gd_2(SO_4)_3$ loading in 2020
- Gd neutron captures observed!
- T2K Run 11 in March brings first beam events with Gd
  - Run 12 expected after $T_{1.5}$
- See also [Ryosuke Akutsu's talk](#):
  - Study of neutrons associated with neutrino interactions in water with the IWCD

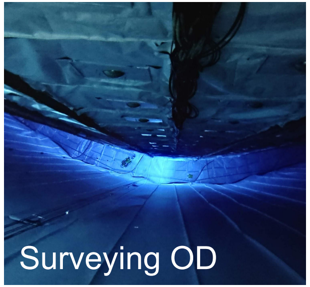


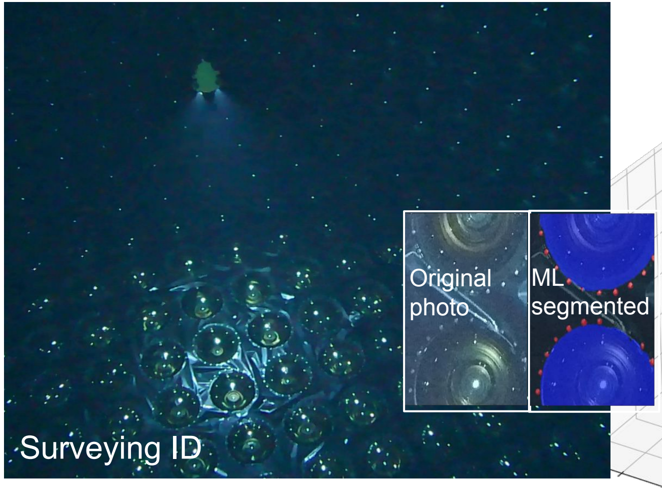


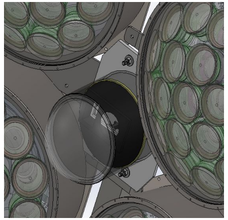


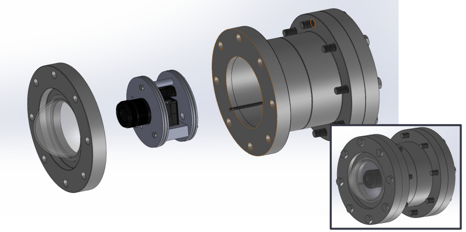
Novel Detector Geometry Calibration

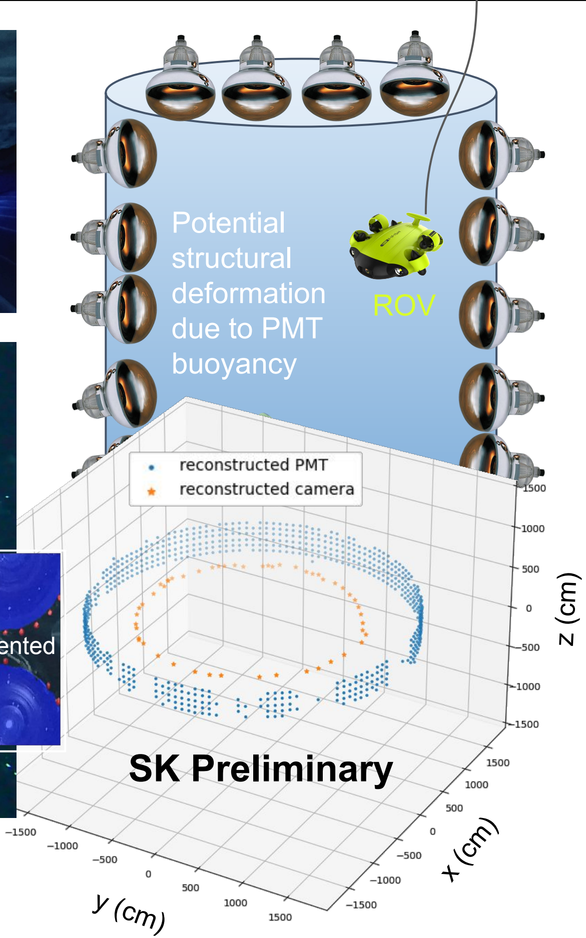
- First underwater survey of Super-K detector geometry
- Challenging photogrammetry analysis ongoing
  - Demonstrated with a ring of ID barrel PMTs
- Developing new systems for Hyper-K and IWCD
  - Critical for a moving detector









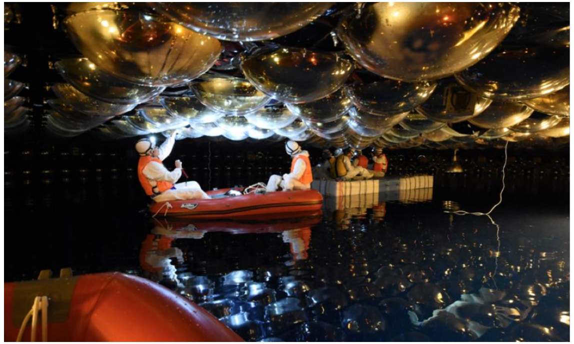


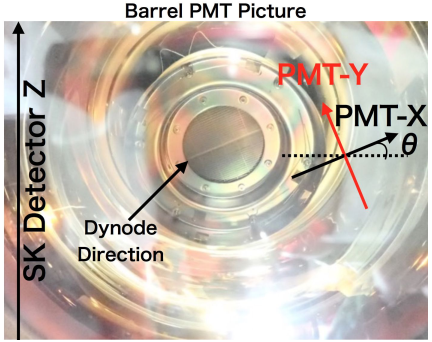
- See talk by [Blair Jamieson (Winnipeg)]() and poster by [Michael Sekatchev (TRIUMF/UBC)]()

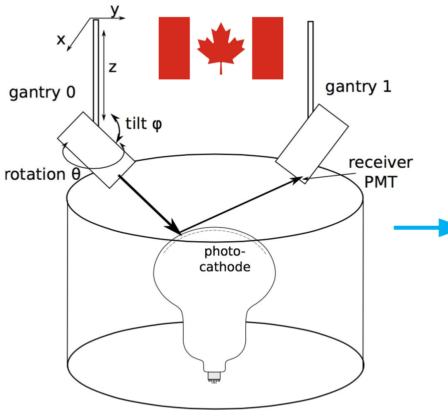
Precise and Comprehensive PMT Characterization

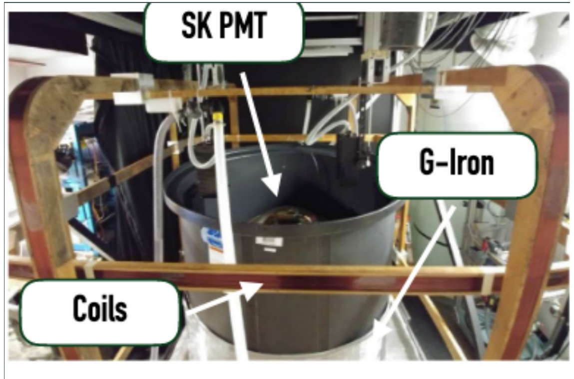
- Uncertainties in PMT response is a major systematic in water Cherenkov detectors
- (Re)Building a photosensor test facility at TRIUMF for Super-K and Hyper-K/IWCD
- See talk by V. Gousy-Leblanc (UVic) and poster by S. Wingfelder (TRIUMF)

Magnetic field and PMT orientation survey throughout Super-K

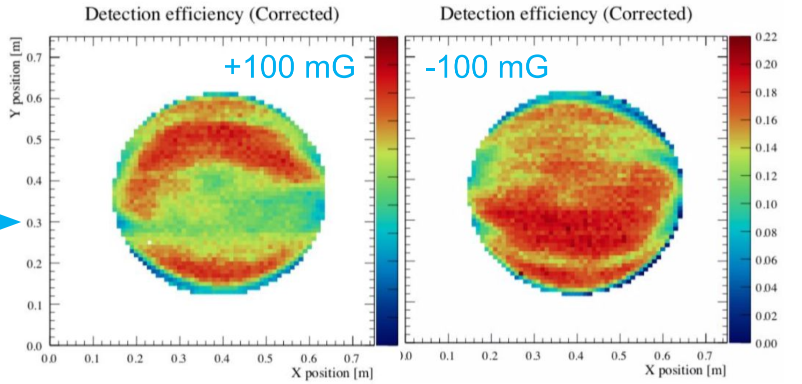




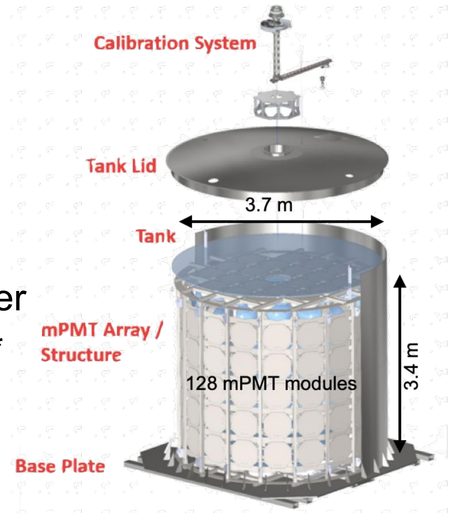


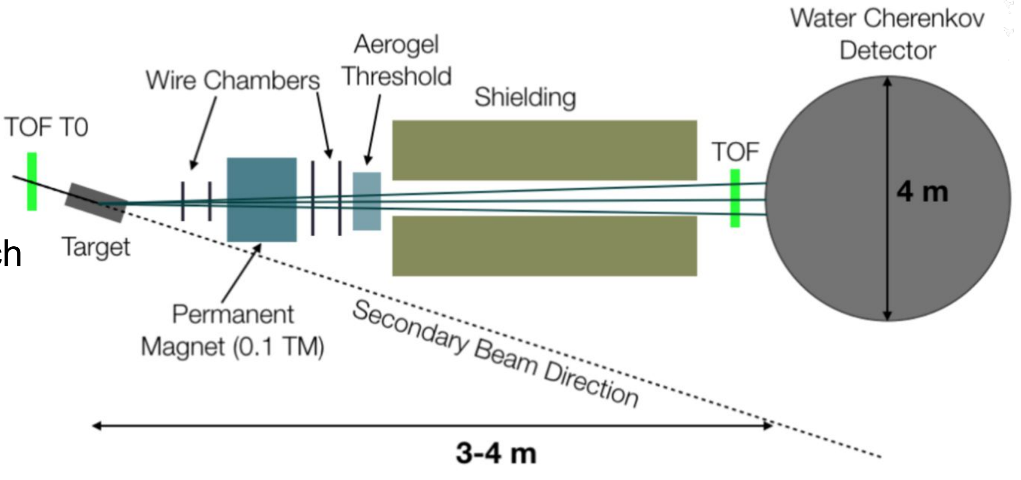


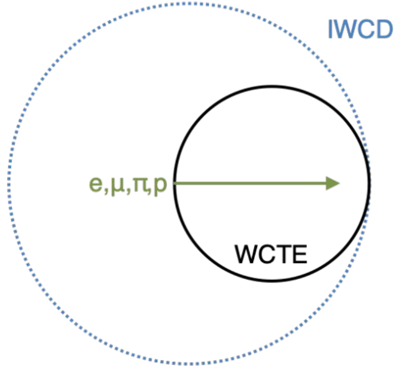
PTF setup



- Prototype detector for beam test at CERN in 2023
- mPMT pilot run and test-bed for precision calibration and ML
- Well-understood $\mathrm{p}, \mathrm{e}, \pi^{\pm}, \mu^{\pm}$ particle beam from 140-1200 MeV/c
  - Control samples to constrain neutrino experiment modeling:
    - Detector response: Cherenkov light emission; $\pi^{\pm}$ re-interactions in water
    - Neutrino flux predictions: hadron production (including K not at FTBF)*
- See talk by Matej Pavin (TRIUMF)
- Proposal:
  - CERN-SPSC-2019-042 ; SPSC-I-254
  - Will be recommended to CERN Research Board by SPSC
- *EOI submitted
  - CERN-SPSC-2021-021 ; SPSC-EOI-021

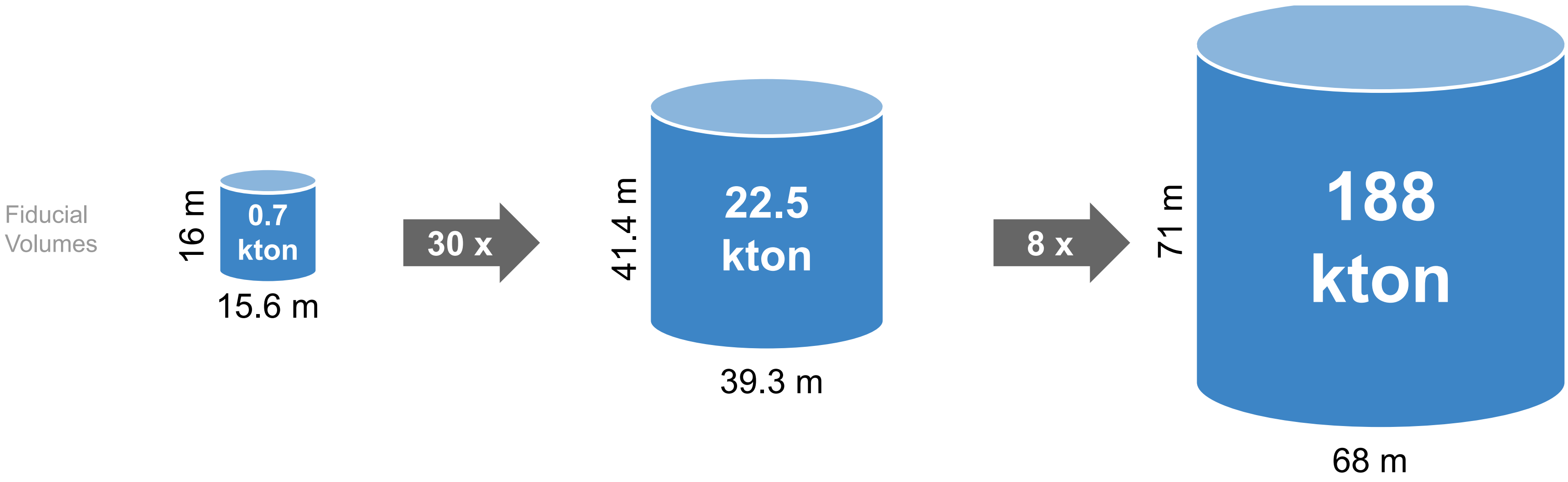






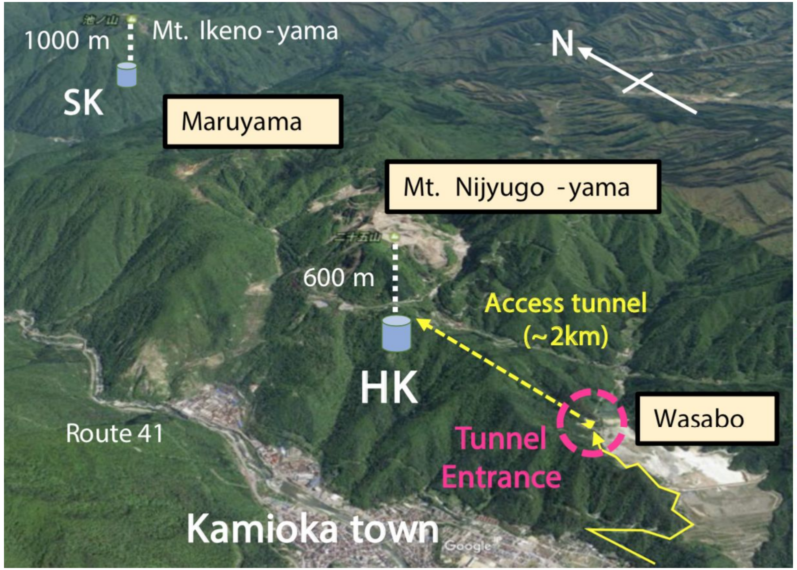
Generations of Kamiokande

Kamiokande | Super-Kamiokande | Hyper-Kamiokande



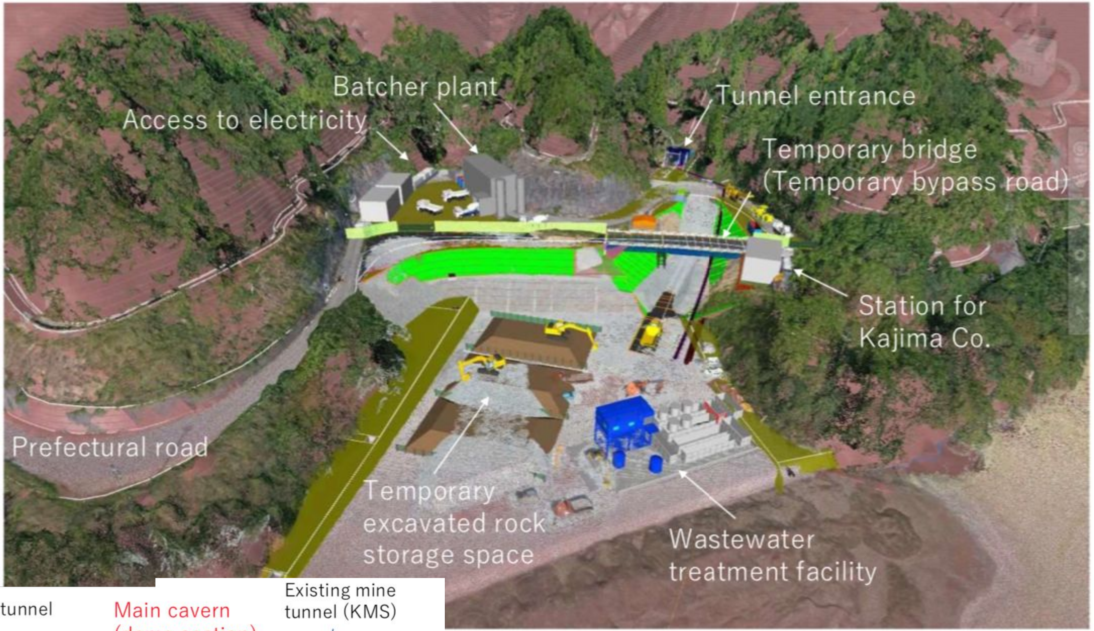
1983 - 1996	1996 - today (and beyond)	2027 - (and beyond)
Supernova 1987A  *2002 Physics*	**Atmospheric ν Oscillation**  *2015 Physics*	**δ_{cp}, proton decay, indirect DM search, more SNs, ...**

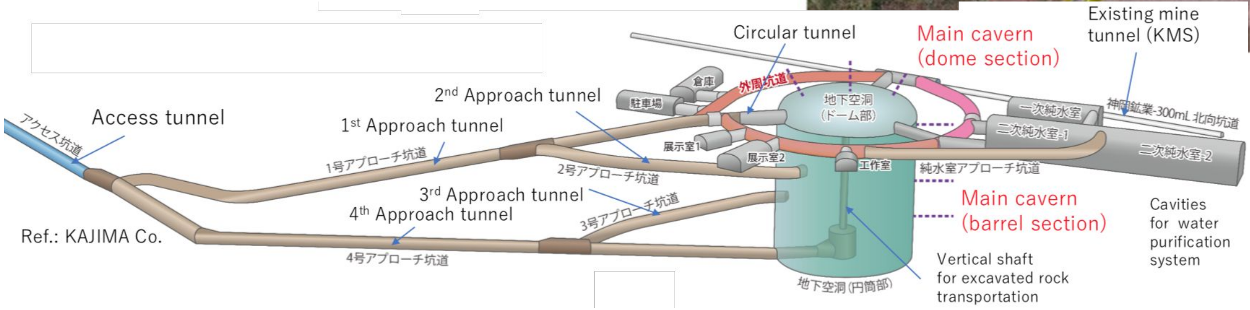
Hyper-K Far Site Overview



Overall plan of the entrance yard

Jan 28, 2021, Kajima Corporation.

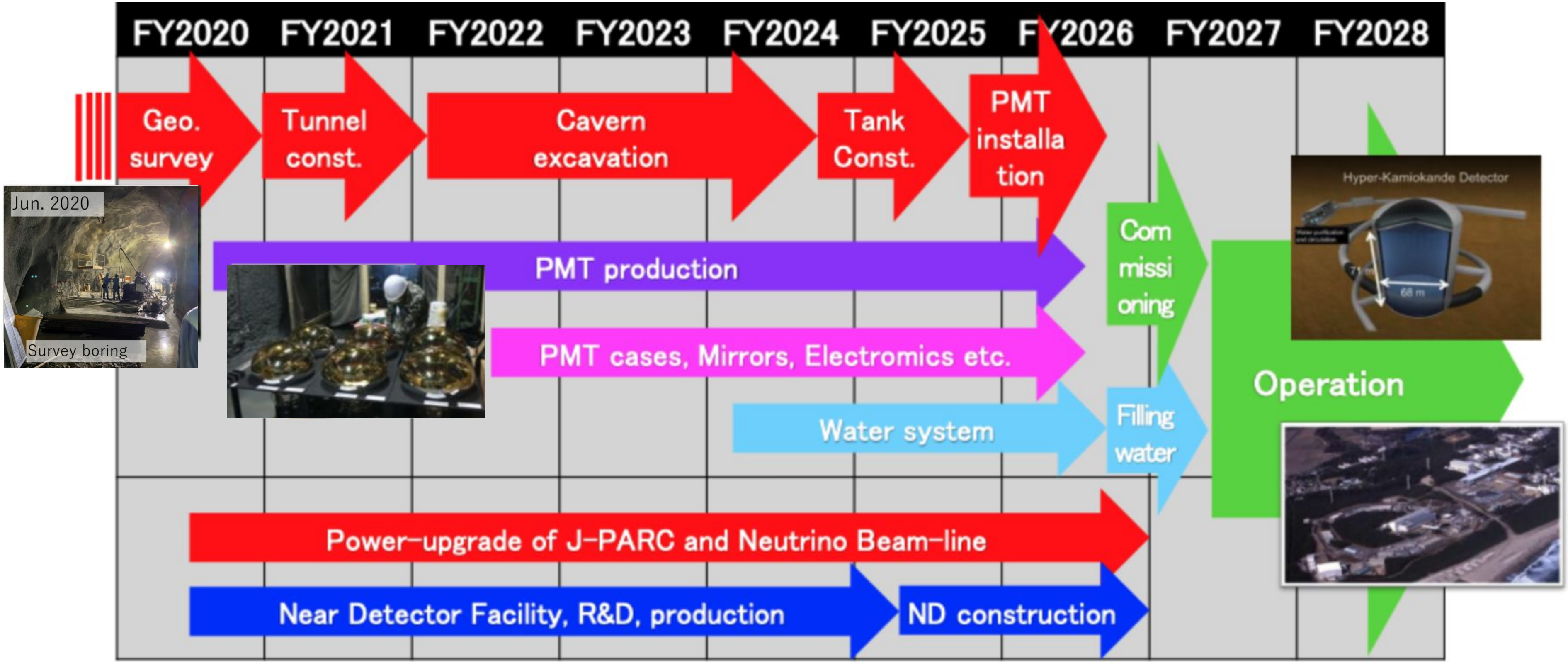




- Entrance yard, tunnel, and cavern conceptual designs

Hyper-K Schedule

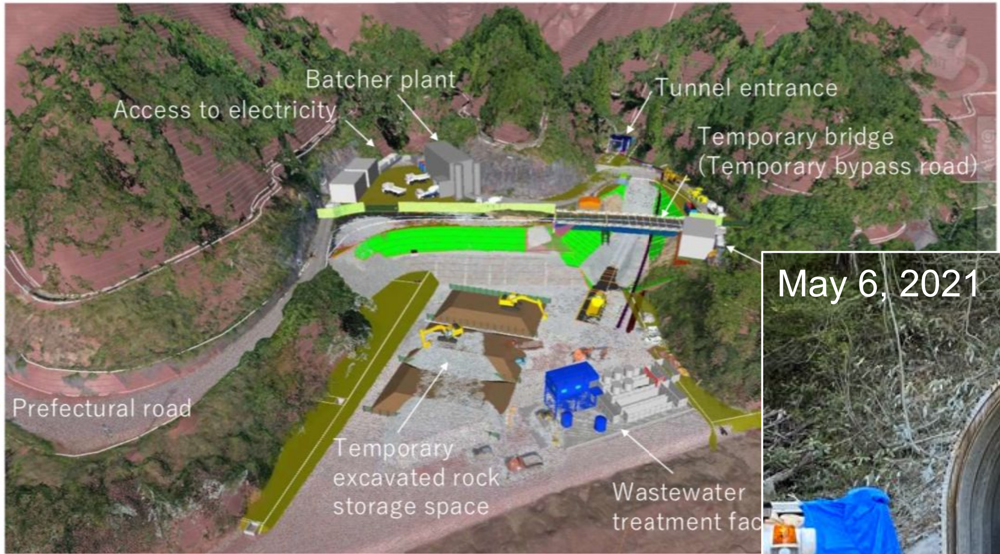
Finish all preparations within ~4.5 years from now for detector installation



Hyper-K Concept Becoming Reality

Overall plan of the entrance yard

Jan 28, 2021, Kajima Corporation.



- Entrance yard and tunnel/cavern excavation progressing on schedule

May 28, 2021: Groundbreaking Ceremony

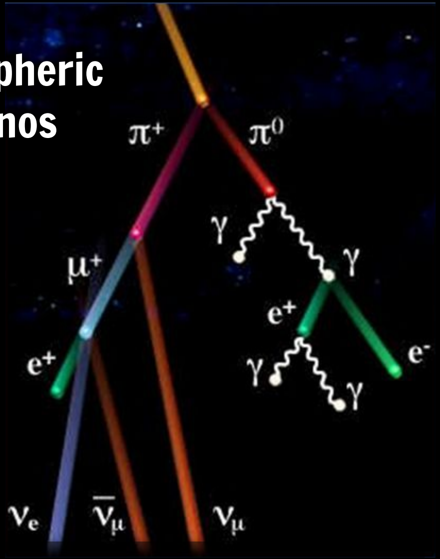
Rich Science with Hyper-Kamiokande

[Design report: arXiv:1805.04163](https://arxiv.org/abs/1805.04163)

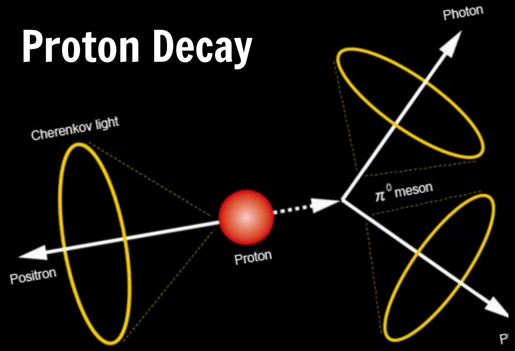
Multi-Messenger: Supernova, GW, ...

Dark Matter

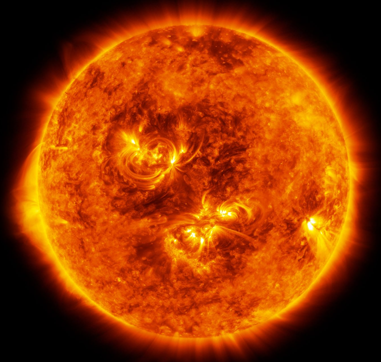
Atmospheric Neutrinos



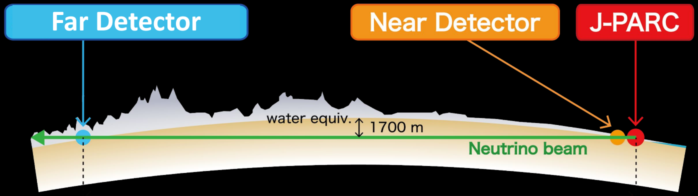
Proton Decay



Solar Neutrinos



Accelerator Neutrinos

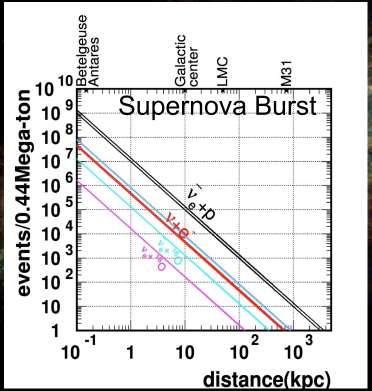


Rich Science with Hyper-Kamiokande

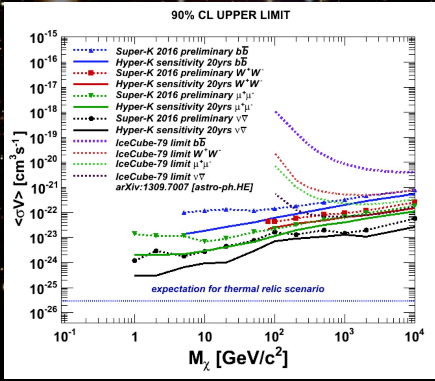
[Design report: arXiv:1805.04163]

Multi-Messenger

[arXiv:2101.05269]

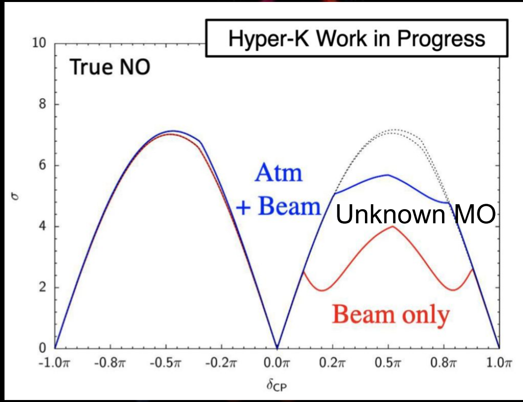


Dark Matter

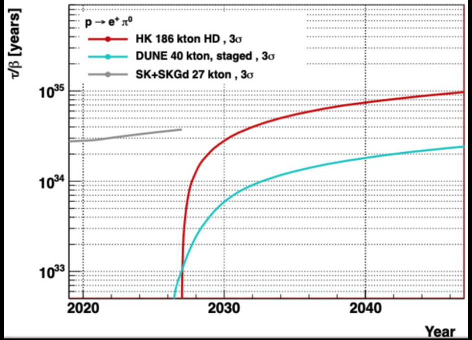


Atmospheric Neutrinos

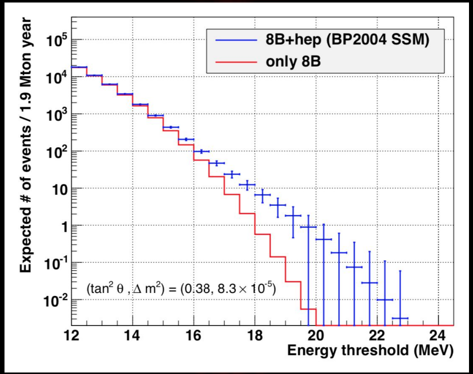
π^+ π^0



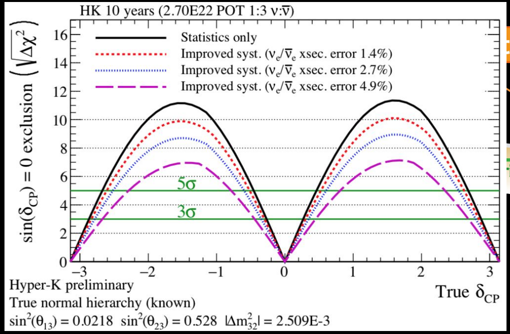
Proton Decay

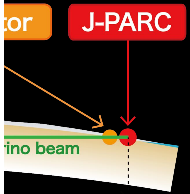


Solar Neutrinos

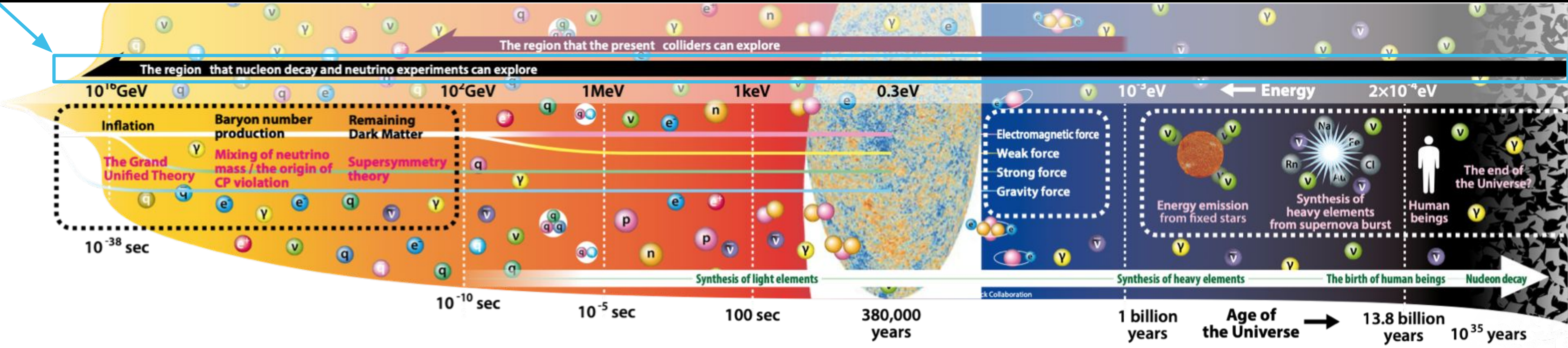


Accelerator Neutrinos





Summary



- Ongoing breadth of rich, world-leading physics: T2K(-II), SK-Gd, Hyper-K
- Near term auxiliary efforts to enhance all of the above:
  - WatChMaL, WCTE, EMPHATIC
- Canadian involvement on all fronts
  - *New collaborators welcome and encouraged!*

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

+ ··· ?

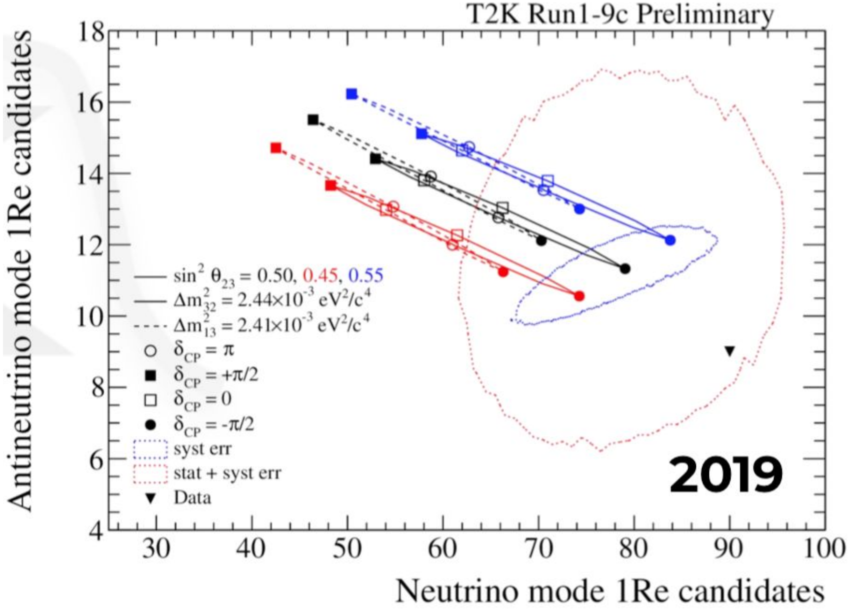
Overview of T2K / SK / HK Contributions at CAP Congress

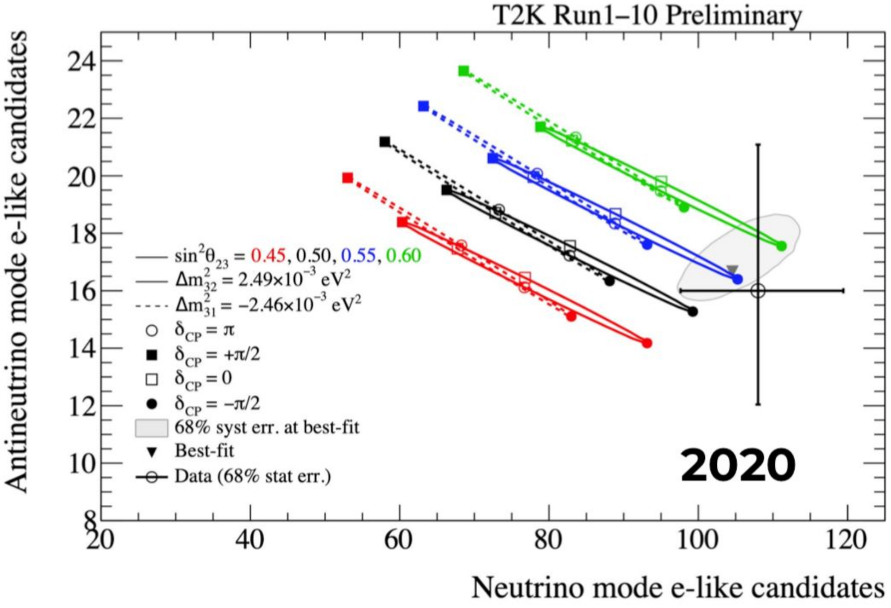
Name	Title	Date	Time (PDT)
Nick Prouse	Machine learning techniques for improving water Cherenkov event reconstruction	June 7	9:45
Luan Koerich	A Multi-Photomultiplier Photosensor Module for IWCD/Hyper-K	June 9	10:05
Michael Sekatchev	Automated Feature Detection and Camera R&D for Photogrammetry in Super-K and Future Water Cherenkov Neutrino Detectors	June 9	10:45
Skylar Wingfelder	Hyper-Kamiokande Photosensor Test Facility Recommissioning and System Upgrades.	June 9	10:55
Bruno Ferrazzi	Optical reflectors in an ARICH detector for a hadron production experiment	June 9	11:19
Vincent Gousy-Leblanc	Super-Kamiokande PMT characterizations using artificial magnetic field and robotic laser-equipped arms	June 10	8:45
Ryosuke Akutsu	Study of neutrons associated with neutrino interactions in water with the IWCD detector	June 10	9:55
Mitchell Yu	Measuring the muon (anti-)neutrino induced charged-current coherent pion production cross sections on carbon using the off-axis T2K near detector	June 10	10:05
Wojtek Fedorko	Machine Learning Applications in Particle Physics: Present and Future	June 10	12:45
Matej Pavin	Water Cherenkov Test Experiment	June 10	12:45
Blair Jamieson	Photogrammetry in Water Cherenkov Neutrino Detectors	June 10	13:15

Appendix

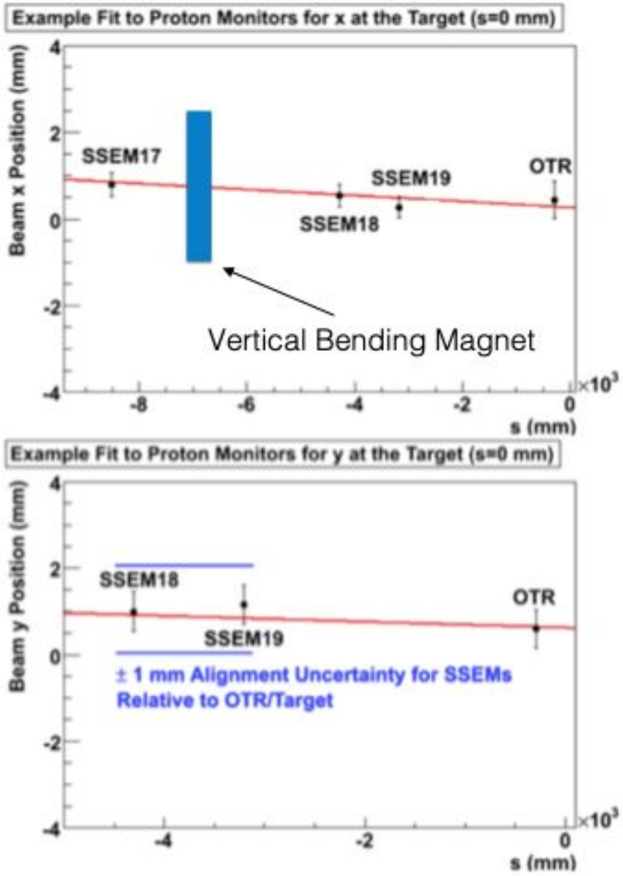
T2K CP Violation Constraints

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





OTR Impact



asurements are used to extrapolate the beam position

to reduce uncertainties

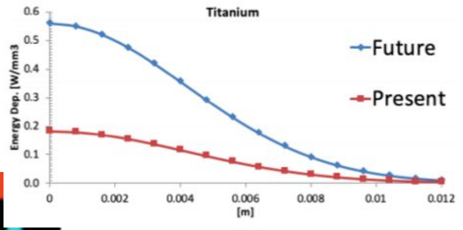
-position uncertainty:

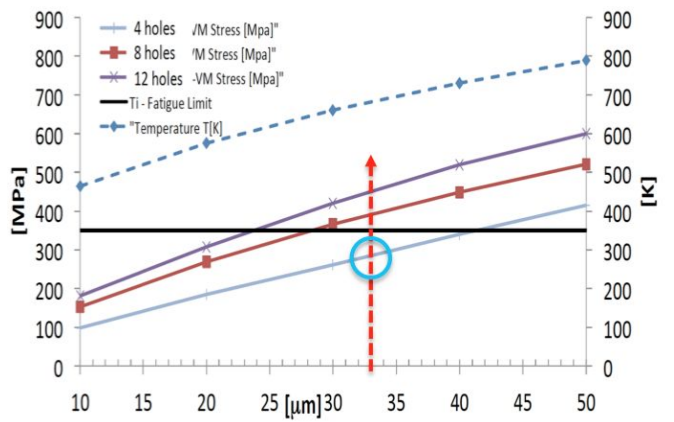
	Extrapolation uncertainty	
	Without OTR	With OTR
Pos. X (mm)	0.5	0.5
Pos. Y (mm)	2.3	0.5
Angle X (mrad)	0.08	0.08
Angle Y (mrad)	0.5	0.3

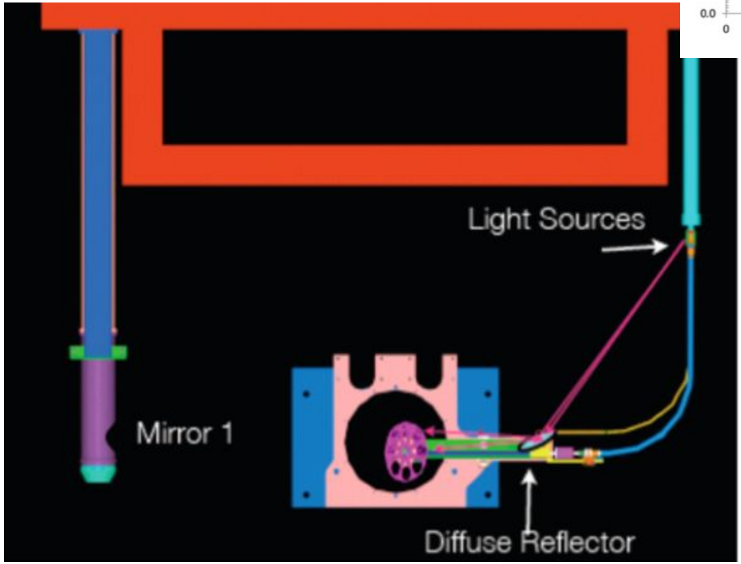
New OTR System for T2K Upgrade

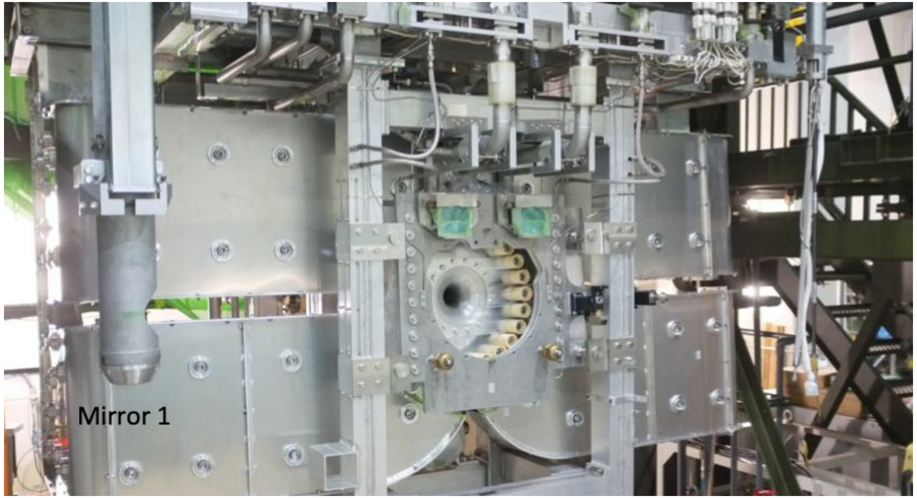
- New horn for T2K upgrade era
  - New OTR installation in spring 2022
- Improving calibration systems
  - Including new simulations
- Stress test of new foils

Beam Conditions	Present	Upgrade
Nb. Protons 30 GeV	2.5e14	3.2e14
Repetition Time [s]	2.2	1.16
Beam Energy [MW]	0.545	1.32



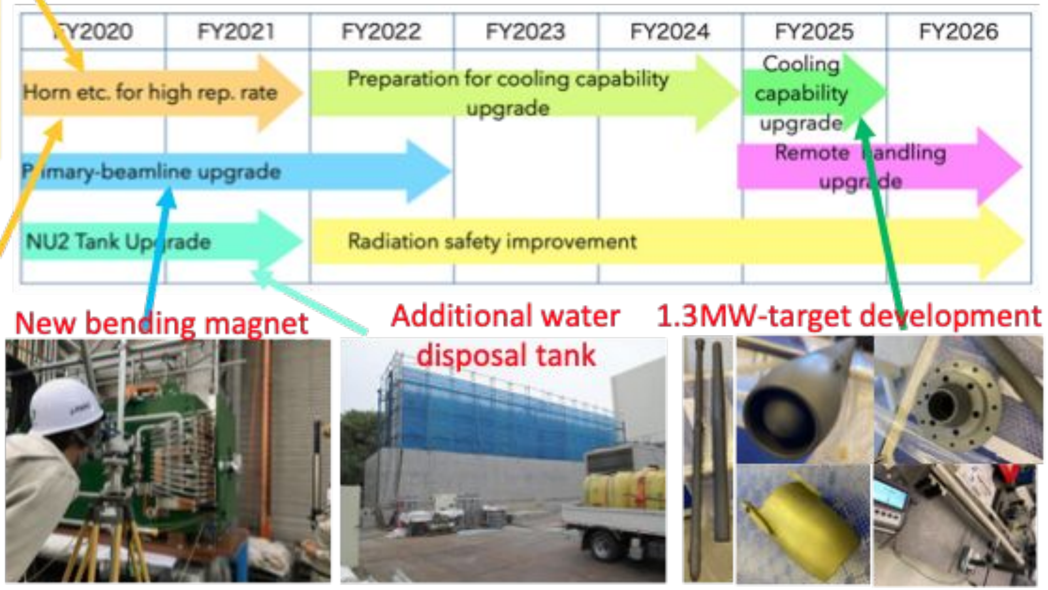






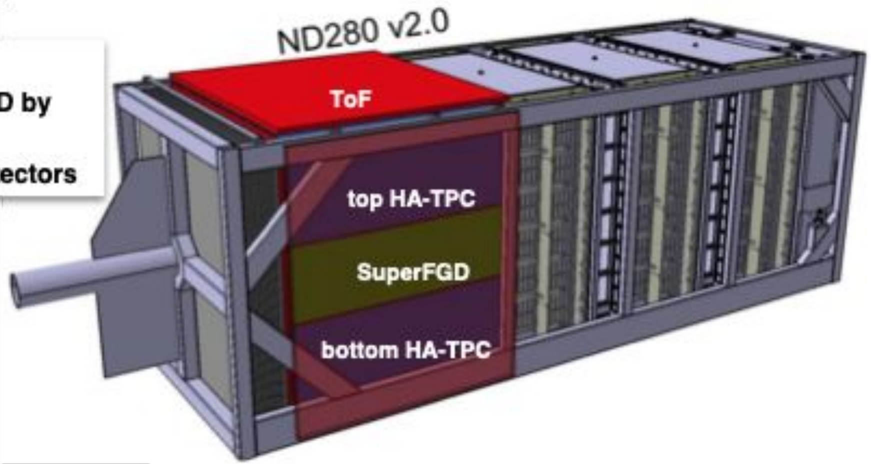
J-PARC and Neutrino Beamline Upgrades

- Major upgrade will be planned in FY2021-2022 long shutdown
- Budget allocation by MEXT as requested in FY2021
- Many beamline components already produced or under production



T2K ND280 Upgrade

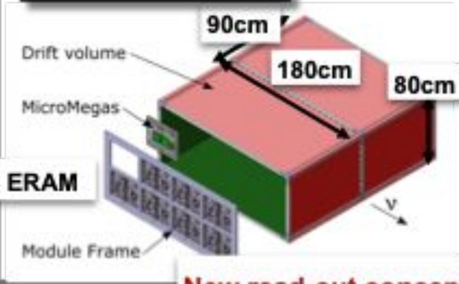
Replace P0D by new subdetectors



Milestones

- 2018 → TDR arXiv:1901.03750
- 2021/22 final modules
- 2022 installation

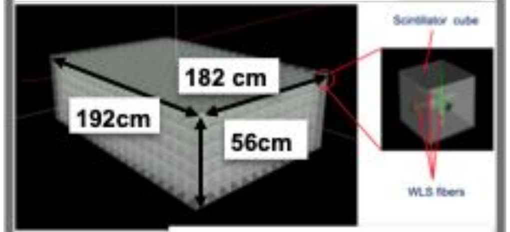
2 High Angle TPCs



New read-out concept

NIM A 957 163286 (2020)

1 SuperFGD



Novel detector concept

JINST 13, P02006 (2018)

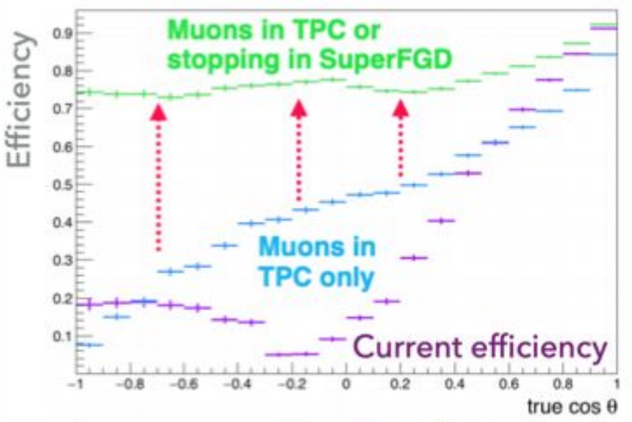
6 ToF panels

150 ps time resolution

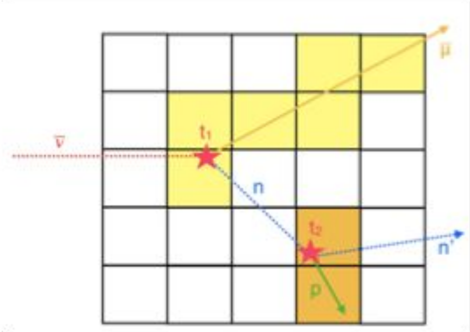
JPS Conf. Proc. 27, 011005 (2019)

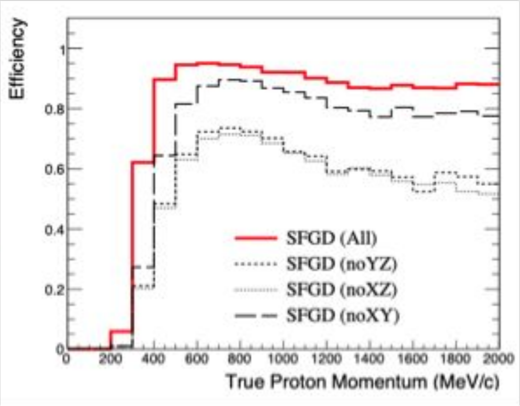
T2K ND280 Upgrade

- Upgraded ND280 covering similar phase space coverage as Super-Kamiokande
- Significant lower energy threshold
- Neutron detection capability

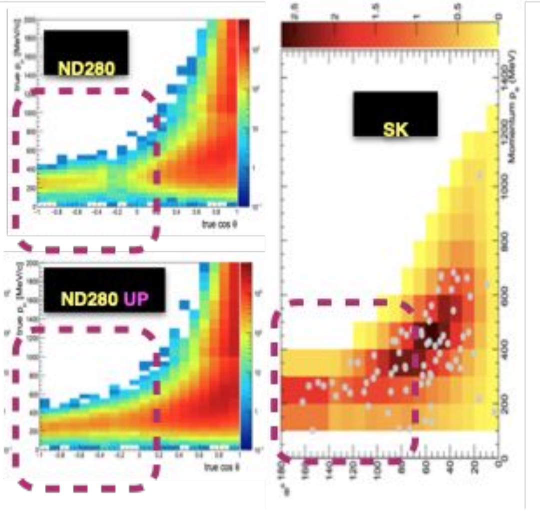


Much better constraint on beam and better cross section measurements!

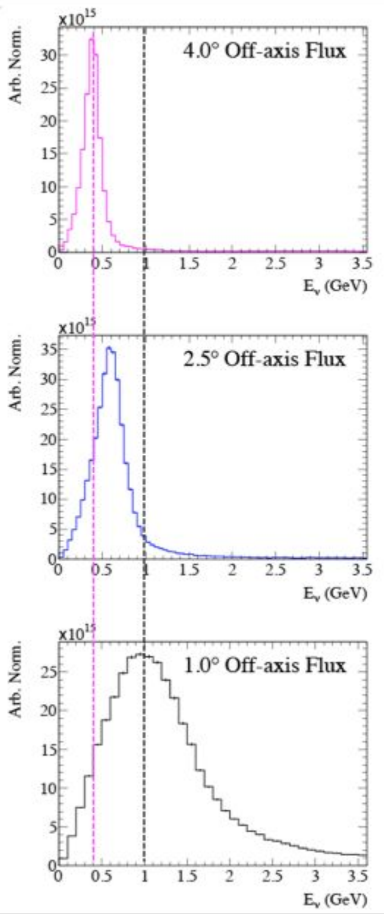


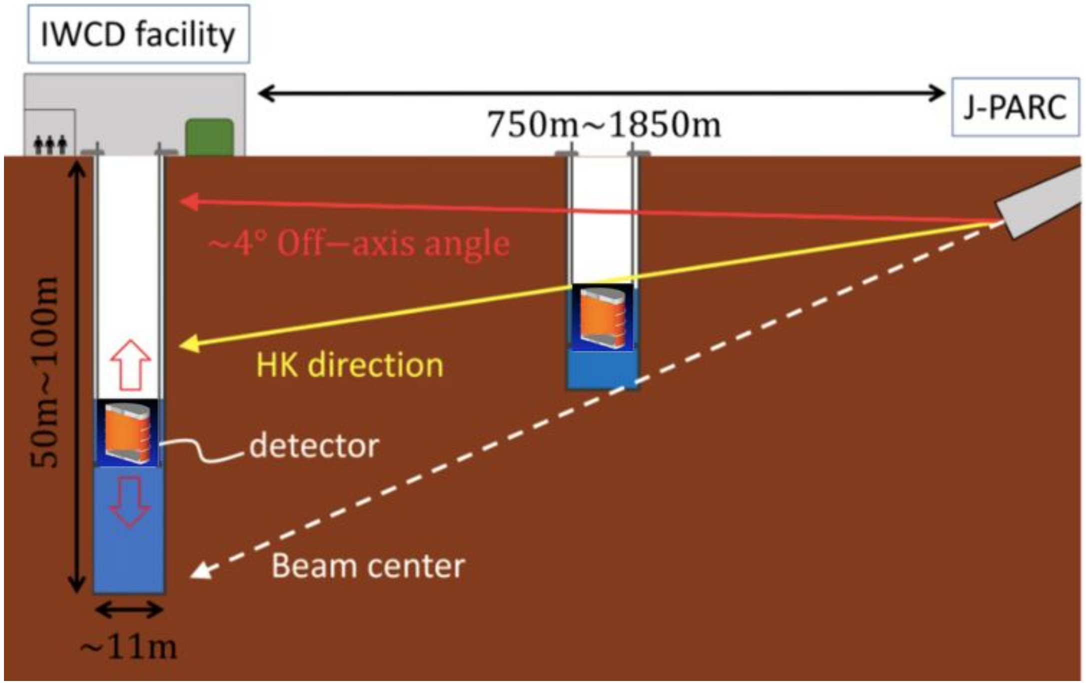


Current ND280 threshold: ~500MeV/c



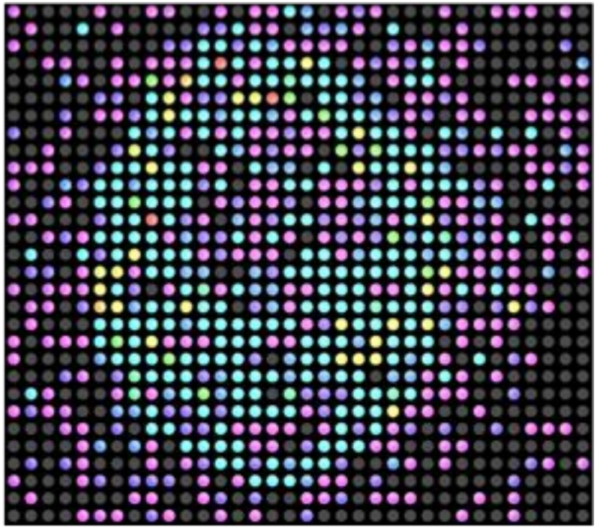
NuPRISM Off-axis Spanning Concept



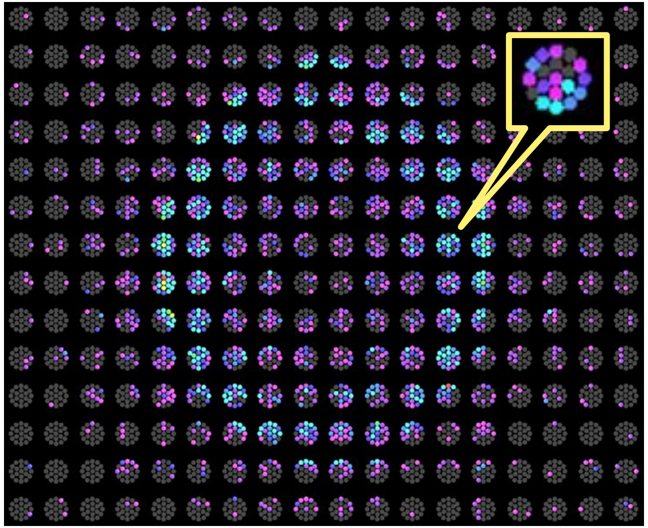


Multi-PMTs

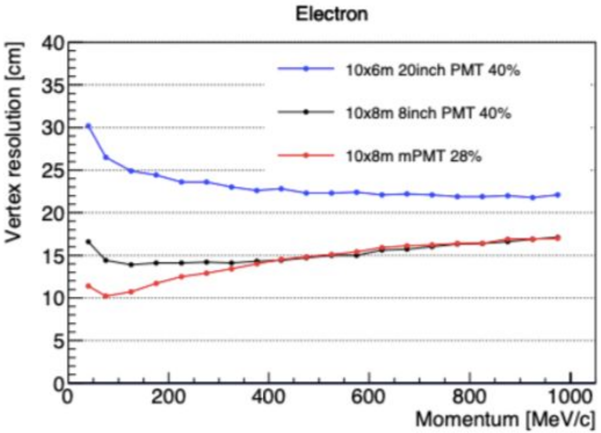
Improved spatial granularity and timing resolution (1.7 ns FWHM)



8” PMT



mPMT (3”)

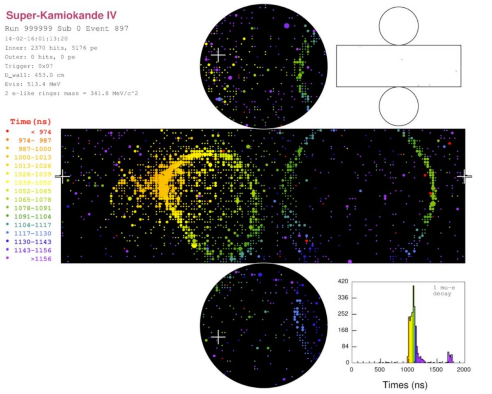


T2K-SK Multi-Ring Datasets for Future Analyses

ν_μ

1.00×10^{21} POT	ν_μ CCQE	ν_μ CC1π^+	ν_μ CC other	$\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$CC	NC	Signal Purity
1R μ like	143.34 (Signal)	18.41	7.45	11.43	0.05	5.49	76.99%
Signal Efficiency	83.84%						
MR 1 decay e	8.93	11.15 (signal)	9.26	2.38	0.088	1.83	33.14%
Signal efficiency		52.02%					
MR 2 decay e	2.85	23.97 (signal)	11.86	0.732	0.011	1.76	58.20%
Signal efficiency		86.28%					

T2K work in progress



$$\nu_l\, p \rightarrow l^-\, p\, \pi^+ \,;\; \bar{\nu}_l\, p \rightarrow l^+\, p\, \pi^-$$
$$\nu_l\, n \rightarrow l^-\, n\, \pi^+ \,;\; \bar{\nu}_l\, n \rightarrow l^+\, n\, \pi^-$$
$$\nu_l\, n \rightarrow l^-\, p\, \pi^0 \,;\; \bar{\nu}_l\, p \rightarrow l^+\, n\, \pi^0$$

ν_e

1.00×10^{21} POT	ν_e CCQE	ν_e CC1π^+	ν_e CC other	$\bar{\nu}_e$ CC	$\nu_\mu+\bar{\nu}_\mu$ CC	NC	Signal purity
Existing 1 ring elike 0 dcye sample	39.892 (signal)	3.347	0.884	0.482	0.201	2.771	83.85%
Signal efficiency	76.65%						
MR e like BDT sample	0.027	1.647	0.134	0.007	0.328	0.388	65.07%
Signal efficiency		9.64%					

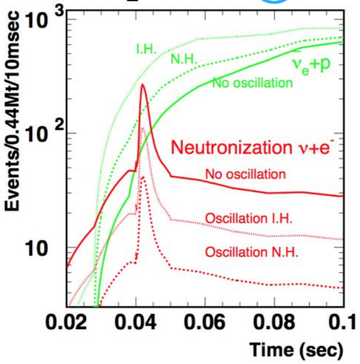
T2K work in progress

Super-K Gadolinium Upgrade Physics Potentials

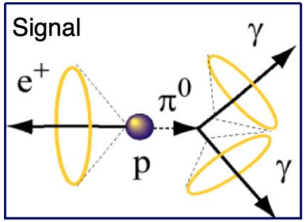
- Supernova burst and relic ν
  - Separating IBD from elastic scattering for better direction resolution
  - Reduction of invisible μ decay-e bkg

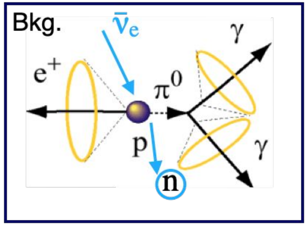
Inverse β decay

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

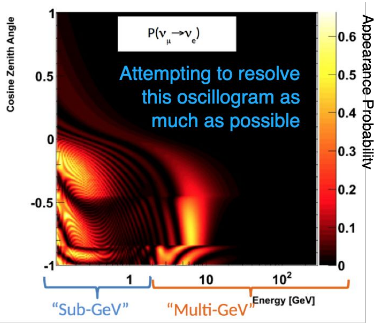


- Proton decay
  - Removal of atmospheric ν backgrounds
  - Towards background-free measurement

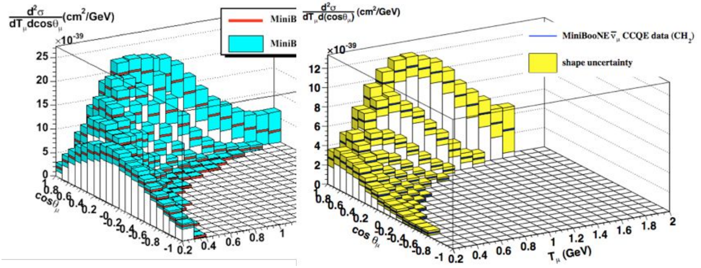




- Neutrino oscillation
  - Improved separation of $\nu/\bar{\nu}$
    - Reduction of beam wrong-sign bkg.
  - New probe of sub-GeV oscillogram
    - Directionality: $\bar{\nu}$ are forward Peaked
    - Full 2-body ν energy and direction reconstruction

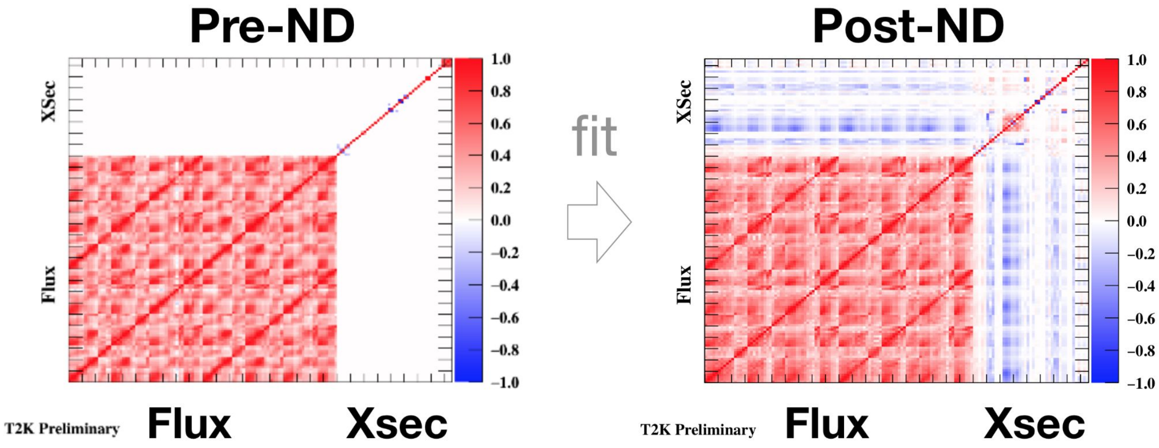


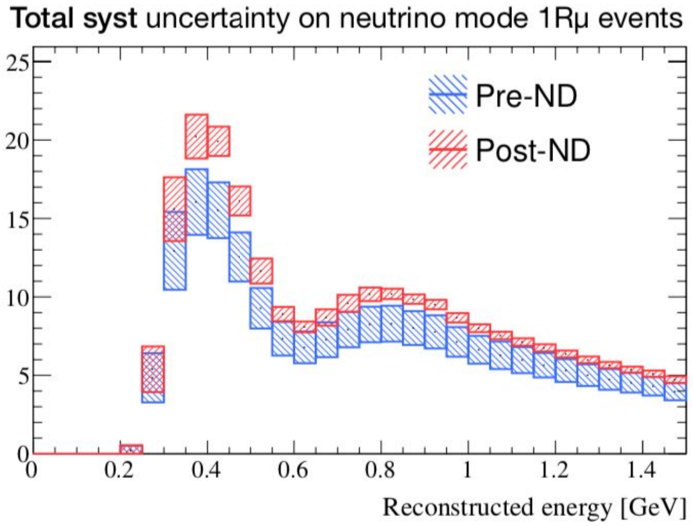
$\nu_\mu\, n \rightarrow \mu^- p$ $\qquad$ $\bar{\nu}_\mu\, p \rightarrow \mu^+ n$



Near Detector Constraint of Systematic Uncertainties

- Neutrino flux and cross section models simultaneously constrained by near detector fit
- Priors from external hadron production and neutrino interaction data, beam monitors, and theory





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

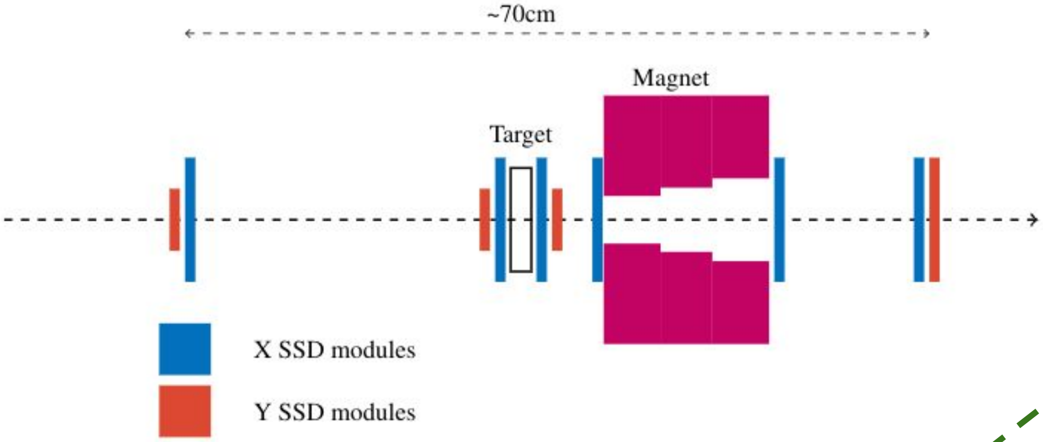
Systematic Error Source	Uncertainty on $\nu_e/\bar{\nu}_e$ Candidates (%)
Super-K Detector Model	1.47
Pion Reinteractions	1.58
Near Detector Constrained Parameters	2.31
Nuclear Binding Energy	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	3.03
NC1γ Production	1.49
Other NC Interactions	0.18
Total	5.87

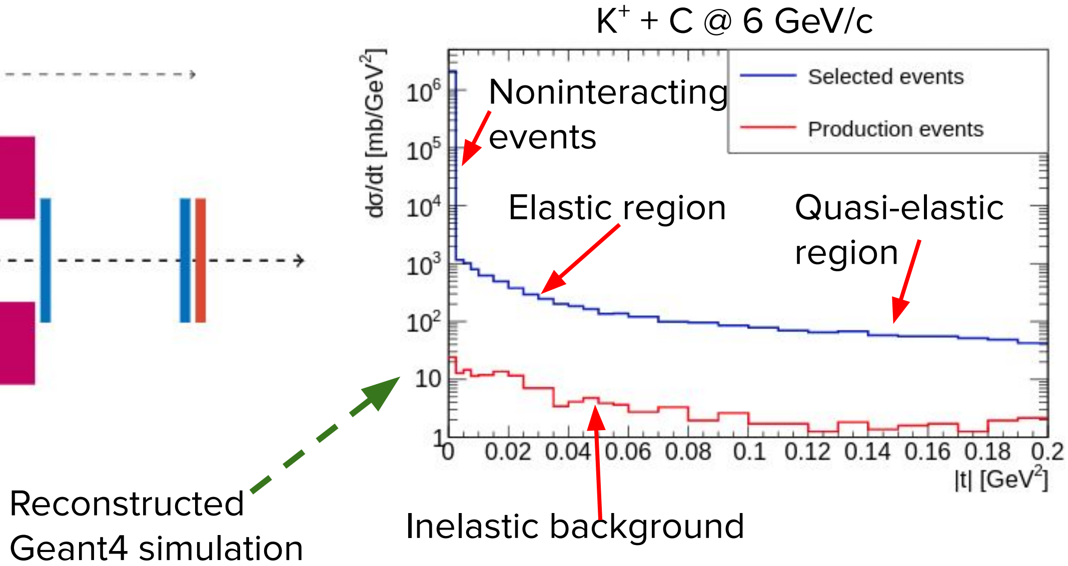
Error Source	% Error for CP Violation search
Error from near detector constraint	1.7
Modeling of events that aren't quasi-elastic scattering	2.1
Electron (anti)neutrino cross section error	3.0
Neutral current background error	1.0
Total cross section model error	**4.1**

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

Hadron Interaction Measurements in the WCTE Facility

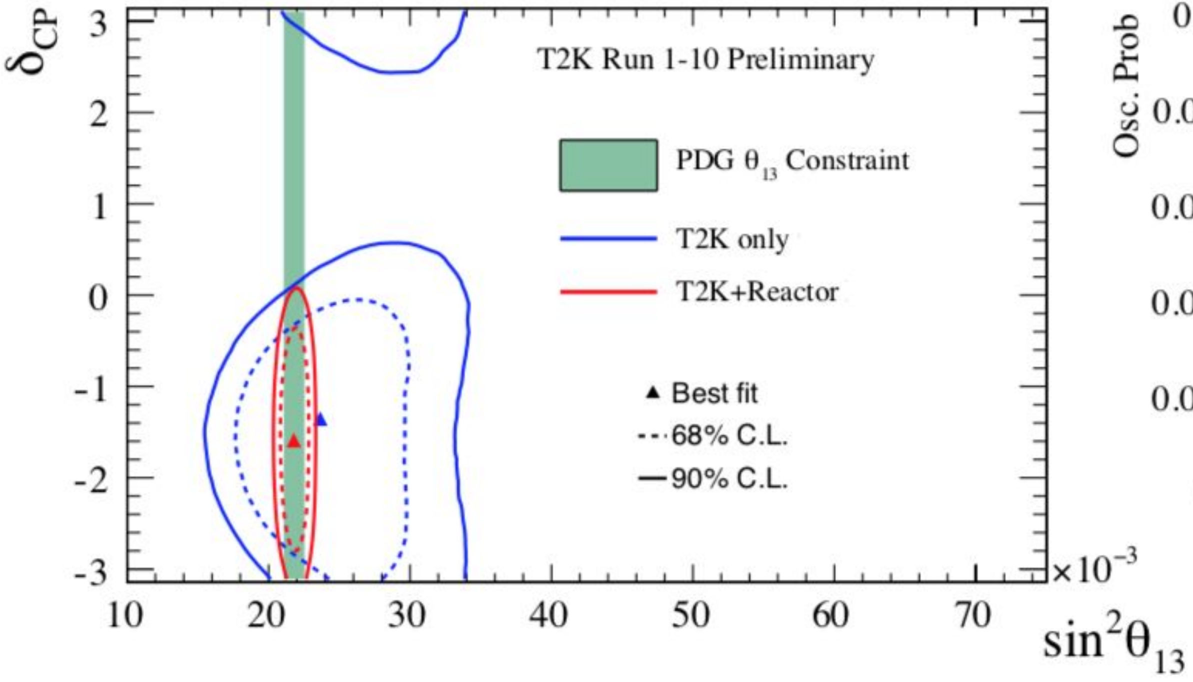
- Pion and kaon elastic and quasi-elastic interactions (< 10 GeV/c) are important source of systematic uncertainty in the HyperK neutrino flux prediction → **no existing data**
- Reconfiguring WCTE tertiary beam spectrometer for hadron interaction measurements → similar to EMPHATIC, but kaon beam < 10 GeV/c not possible at FTBF
- Water tank can be used to identify pions and muons in the secondary beam
- Expression of interest: http://cds.cern.ch/record/2771386

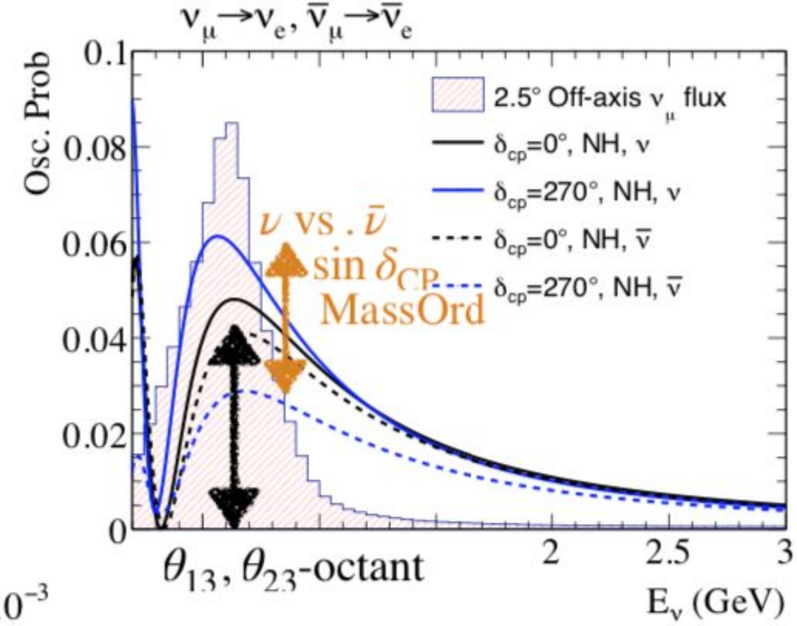




Constraints on θ_{13}

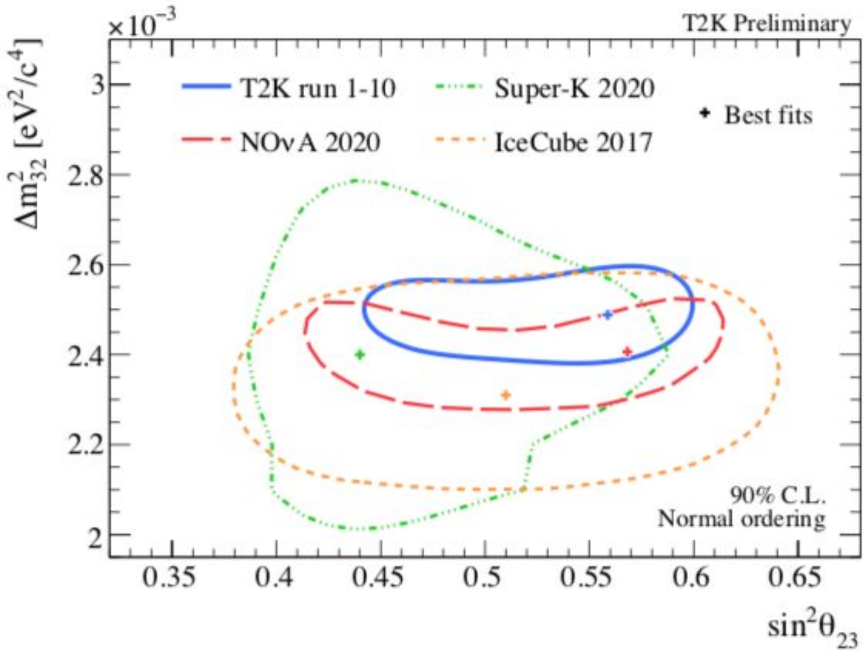
T2K's θ_{13} constraint ($\nu_\mu \rightarrow \nu_e$ appearance) consistent with the much stronger constraint from reactor experiments ($\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance)



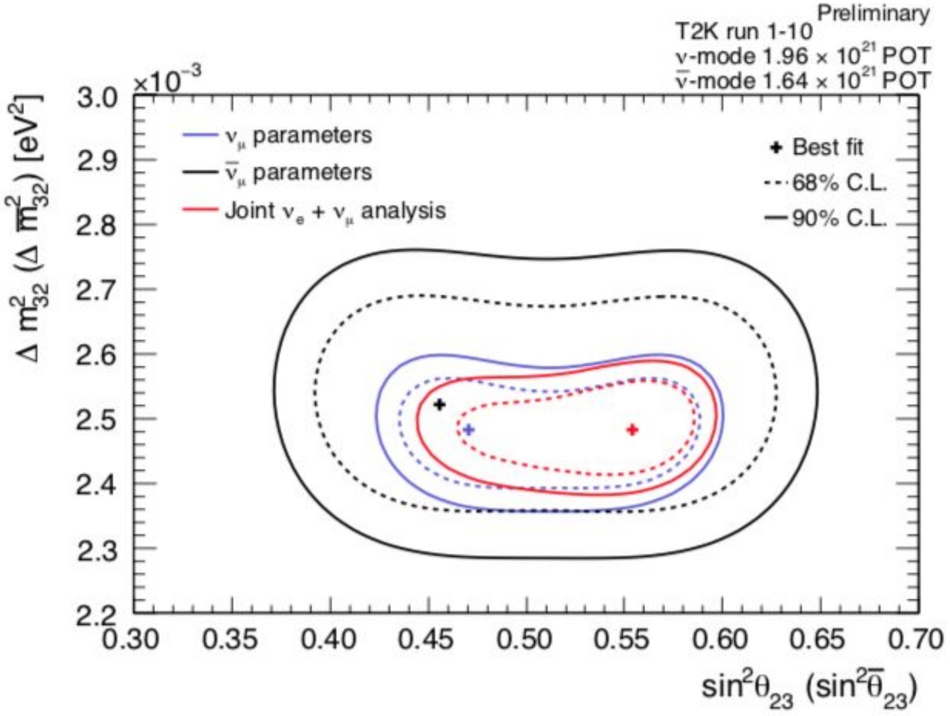


Atmospheric Mixing Parameters

- World-leading measurement of atmospheric parameters
  - Slight preference for $\sin^2\theta_{23}$ in upper octant

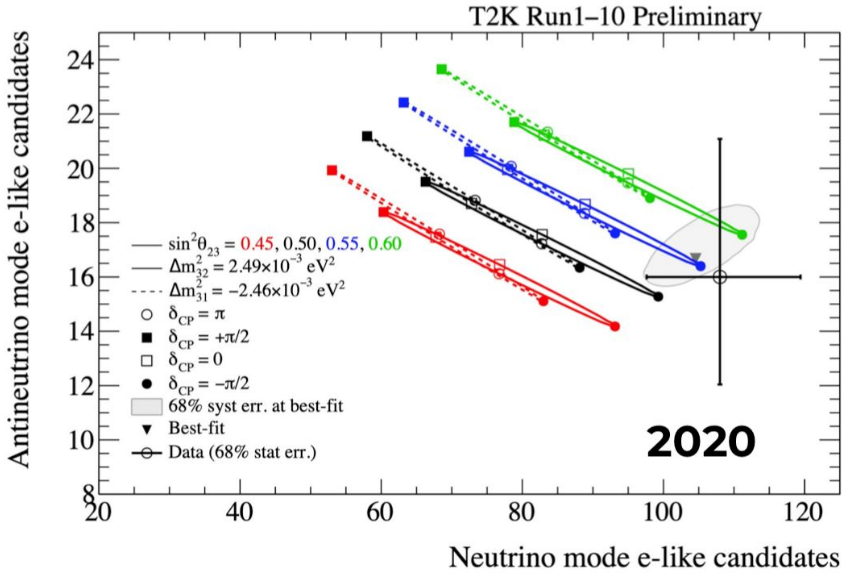


- Fit with separate parameters for $\nu_\mu/\bar{\nu}_\mu$ shows consistent results
  - Expected from CPT symmetry



ν_e vs $\bar{\nu}_e$ Appearance

- Bi-event plot illustrates origin of data constraints
- Best-fit δ_{CP} around maximal CP-violation $-\pi/2$
- Weak preference for Normal ordering with Bayes factor 4.2
- Weak preference for upper octant with Bayes factor 3.4



Mass ordering / Octant

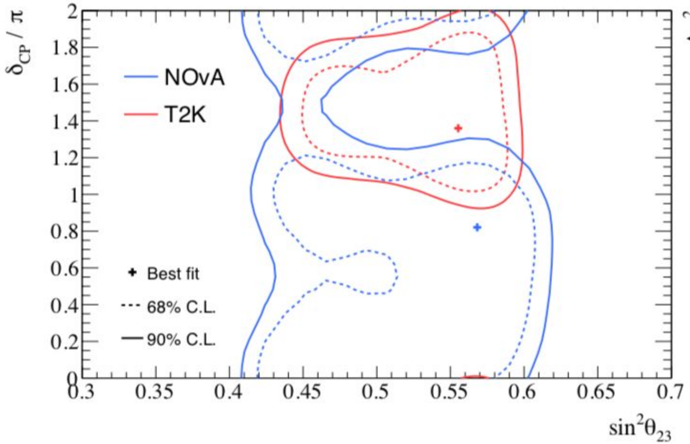
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.195	0.613	0.808
IO ($\Delta m^2_{32} < 0$)	0.034	0.158	0.192
Sum	0.229	0.771	1.000

NOvA + T2K   Ongoing joint fits   SK + T2K

atmospheric + accelerator

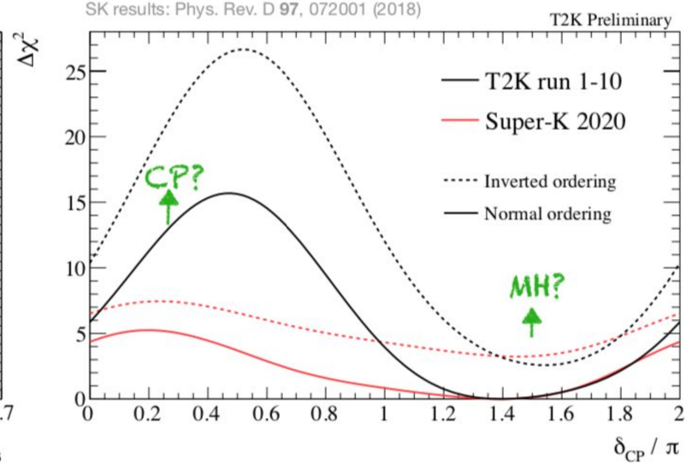
Comparison of released contours (not joint fit)

NOvA results: A. Himmel (2020) Zenodo, T2K Preliminary



Comparison of released contours (not joint fit)

SK results: Phys. Rev. D **97**, 072001 (2018)



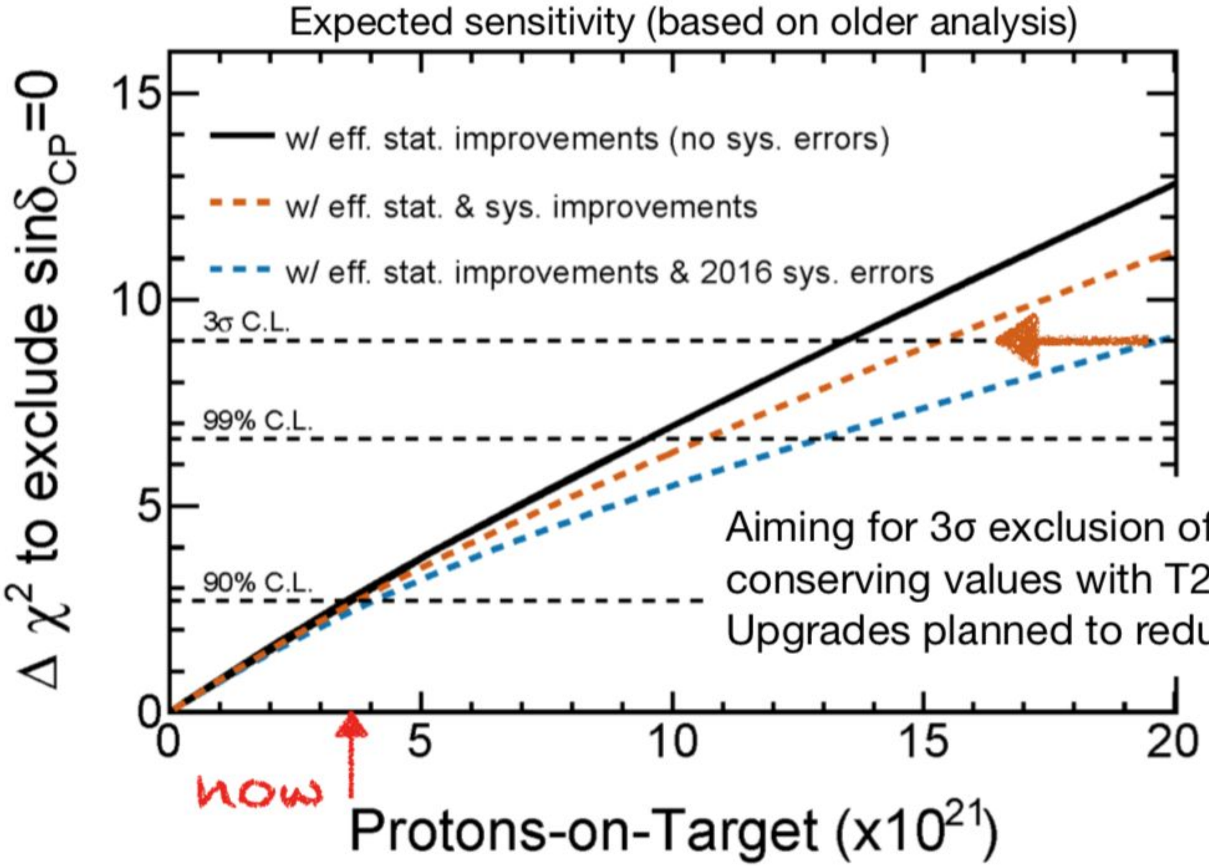
- Joint fits between experiments with different oscillation baselines/energies and detector technologies

→ expect increased sensitivity in δ_{CP}, mass ordering, θ_{23} octant **beyond** stats increase from resolved degeneracies and syst constraints

- important to understand potentially non-trivial syst. **correlations** between experiments

Agreements are signed between experiments and joint work ongoing. Stay tuned!

T2K Toward 3σ Evidence of CP Violation



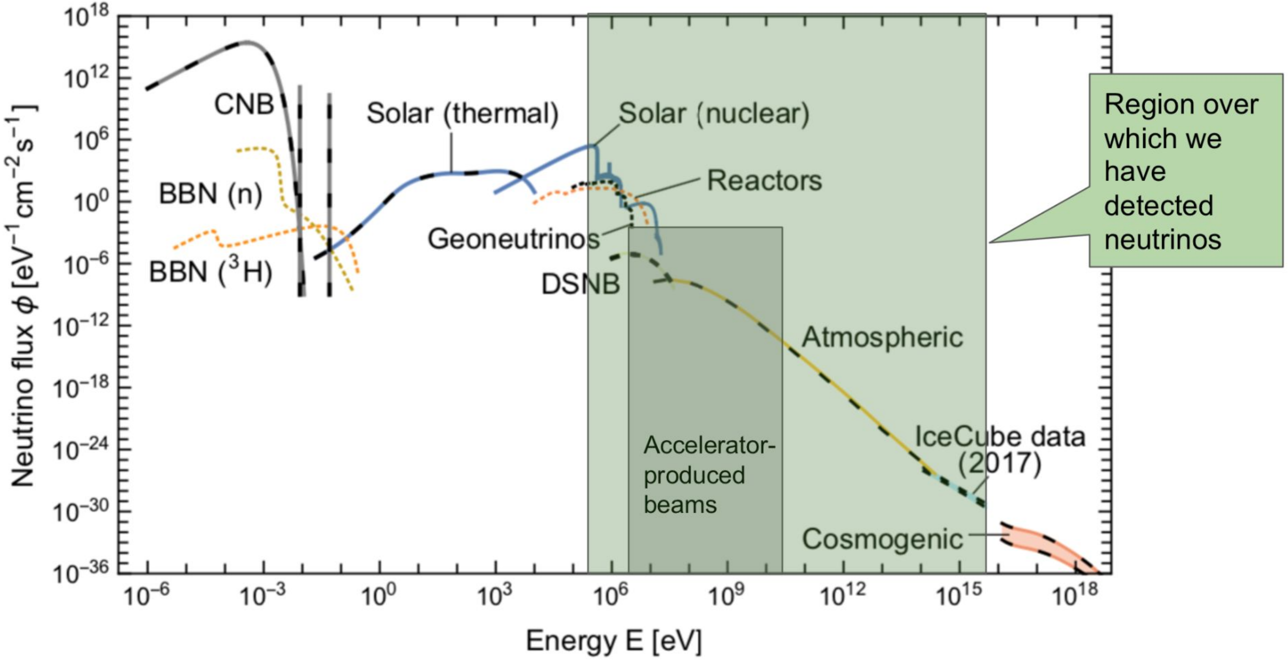
Aiming for 3σ exclusion of CP conserving values with T2K-II. Upgrades planned to reduce syst.

Neutrino Flux Spectra

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

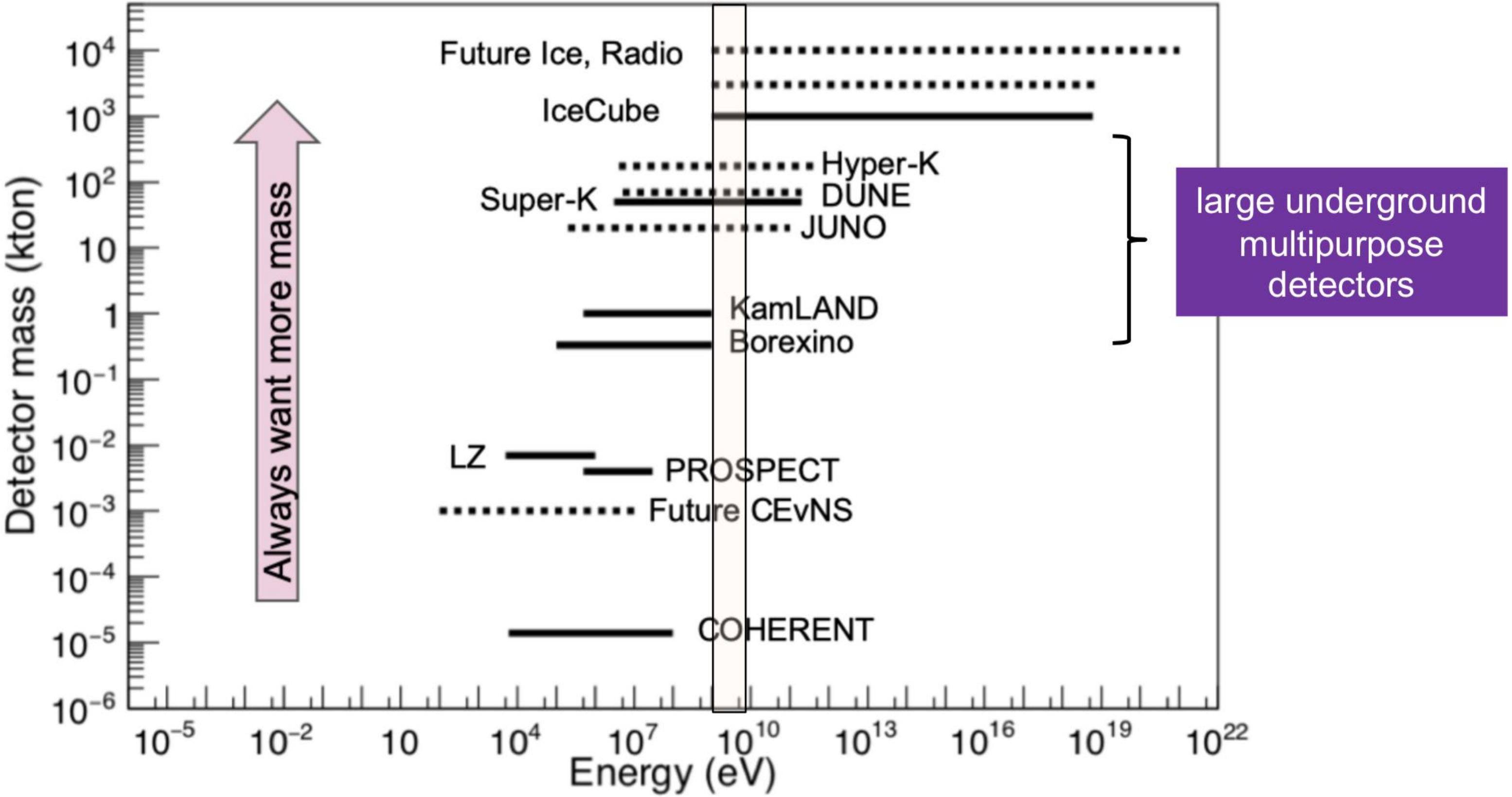
Information comes from neutrinos over ~25 orders of magnitude in energy!

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

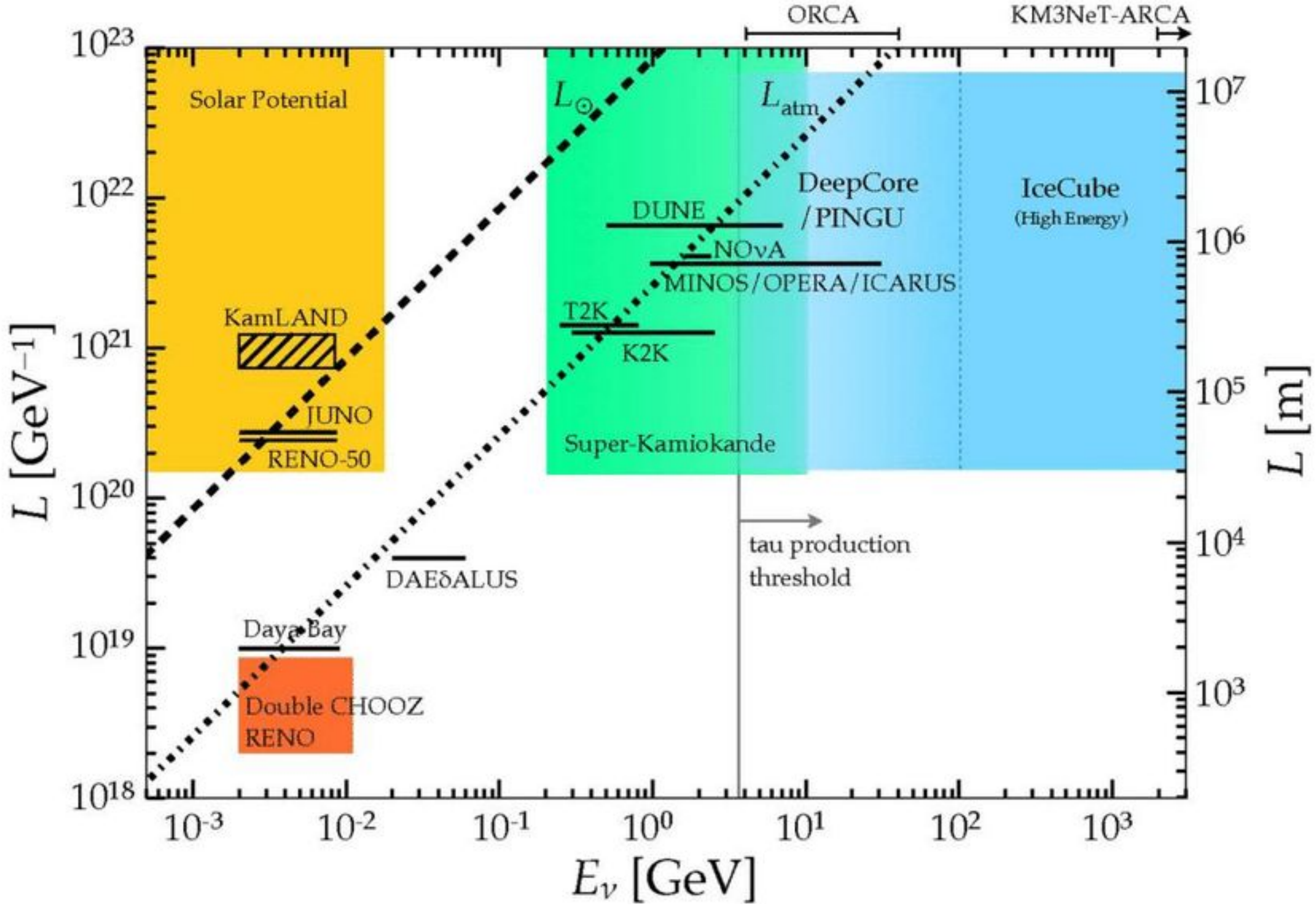


Neutrino detector masses and sensitive energy ranges

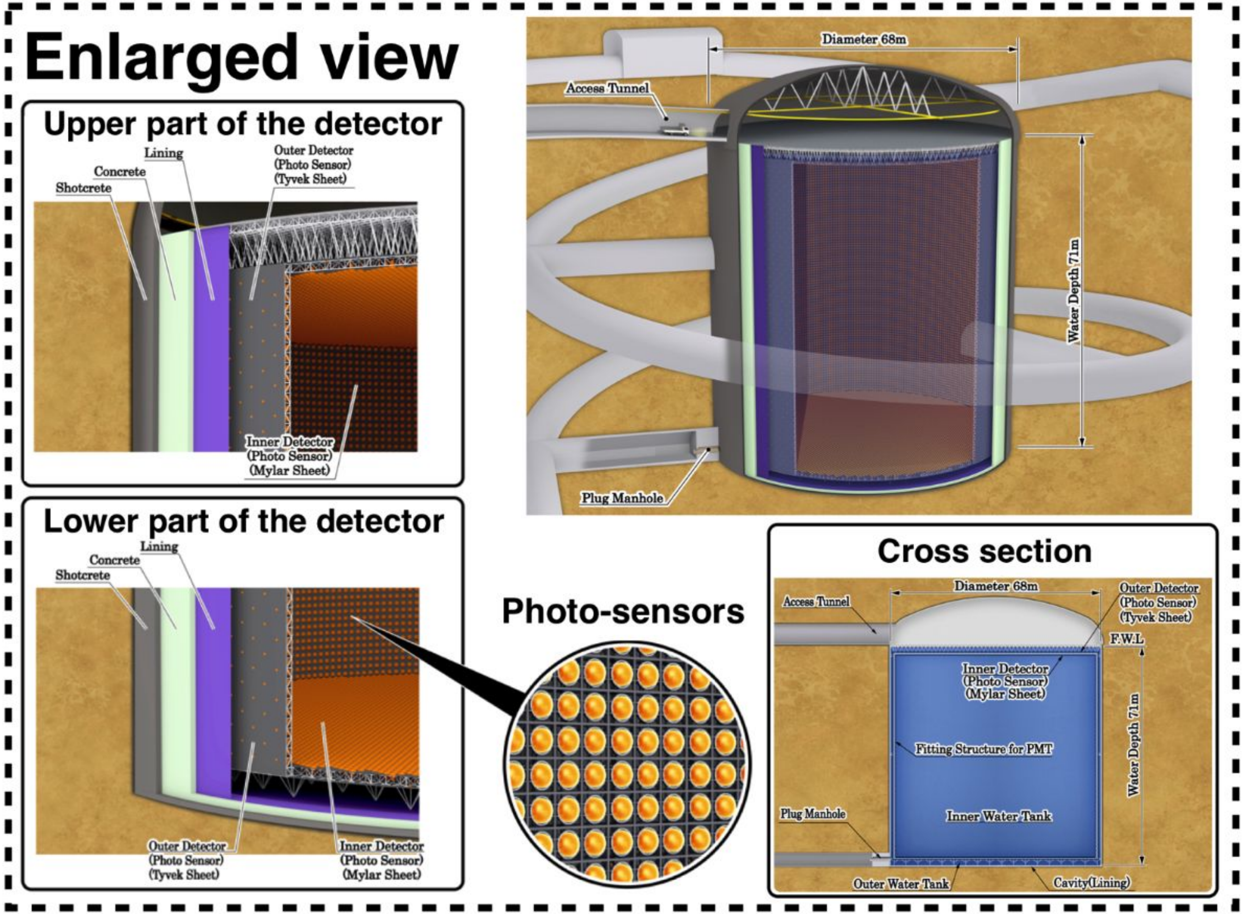
Kate Scholberg (Duke), TIPP 2021



Neutrino Oscillation L/E Scales

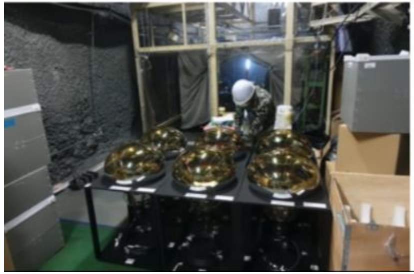


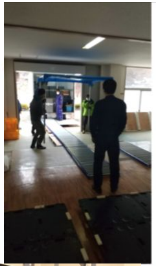
Hyper-K Far Detector Concept



Hyper-K PMT Progress

HK PMTs were checked according to the pre-calibration manual to install HK PMTs in 2018 for SK.





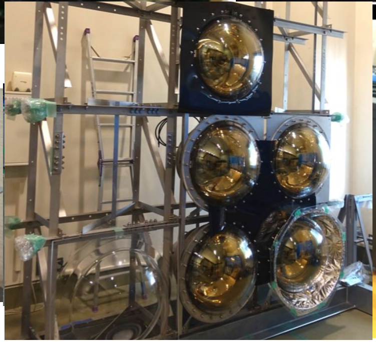
- Initial delivery of 20,000, 50cm PMTs in Dec. 2020; expect ~300 PMTs per month
- Inspection and long-term calibrations starting in Kamioka

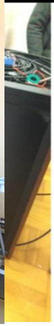
PMTs for the Inner Detector

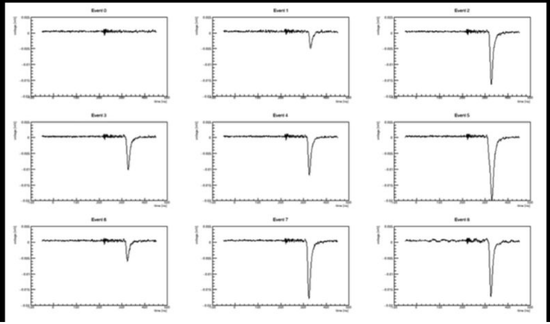
	Super-K	Hyper-K
Number of PMTs	11,129 50cm PMTs	20,000 50cm PMTs (JPN) (+ additional PDs (Oversea))
Photo-sensitive Coverage	40 %	20 %
Single photon efficiency /PMT	~12%	~24%
Dark Rate /PMT	~4 kHz (Typical)	4 kHz (Average)
Timing resolution of 1 photon	~3 nsec	~1.5 nsec

Visual inspection

- Cover production by Spain ~2022

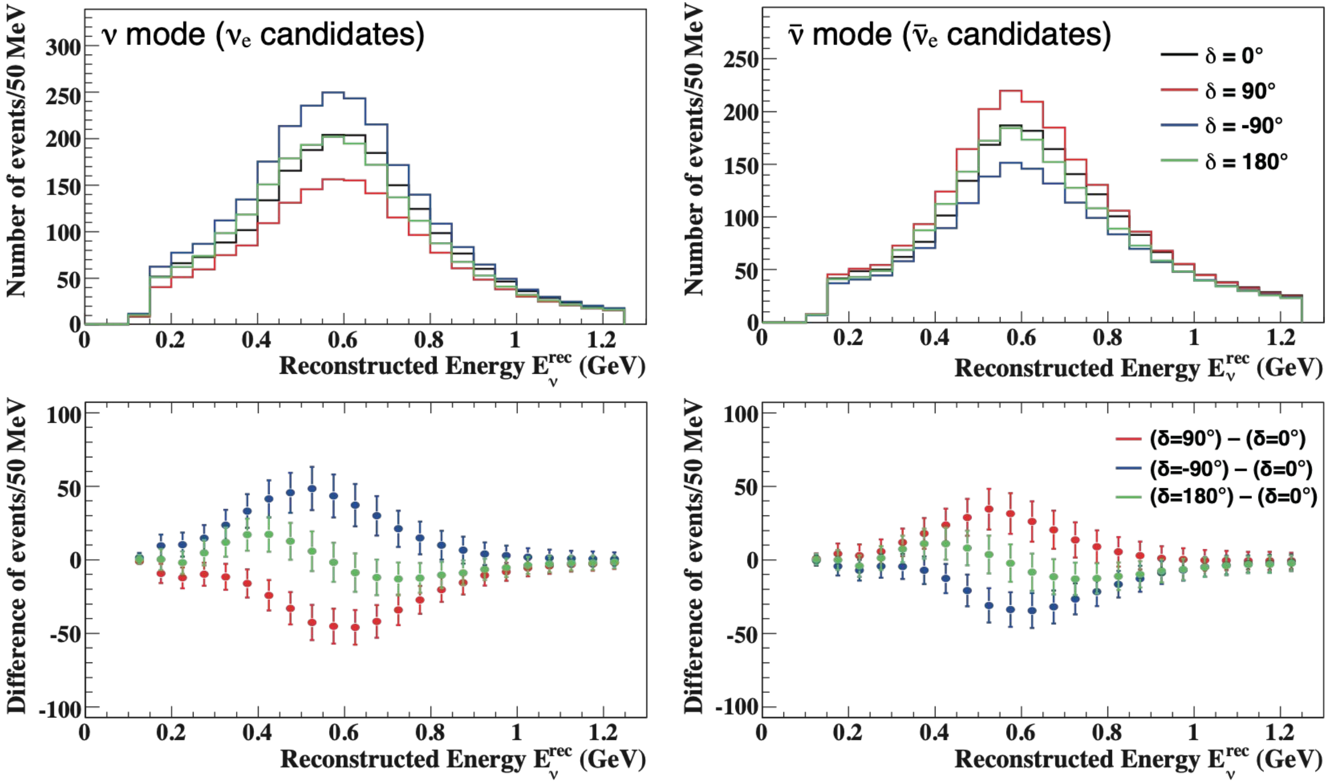




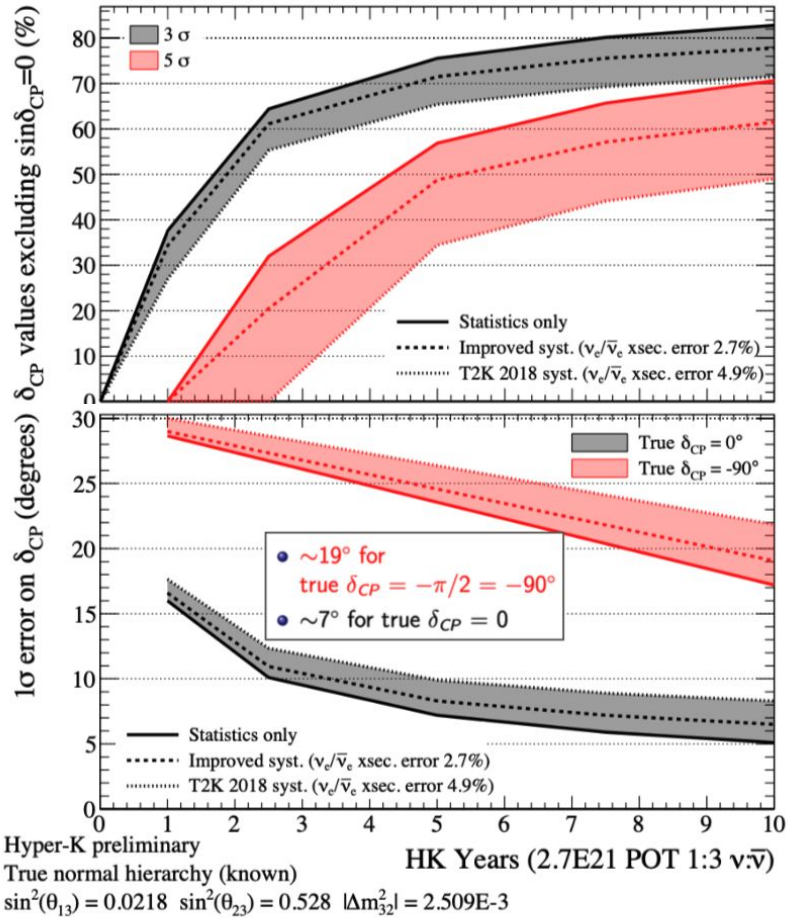


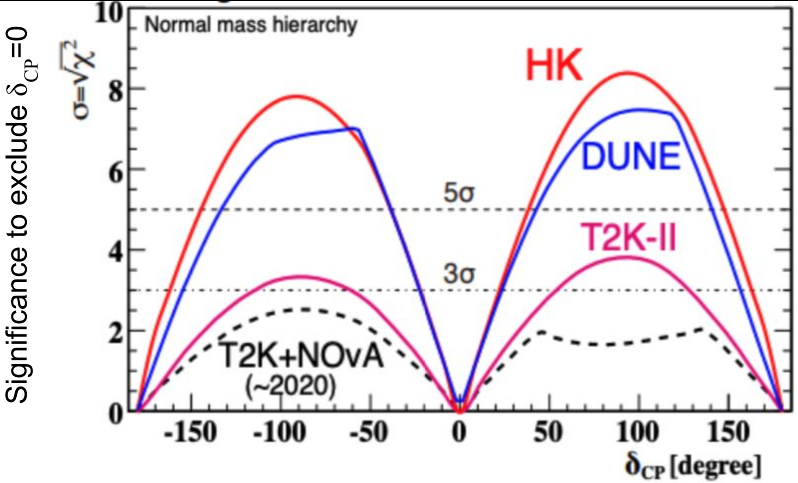
Hyper-K Expected Event Rates

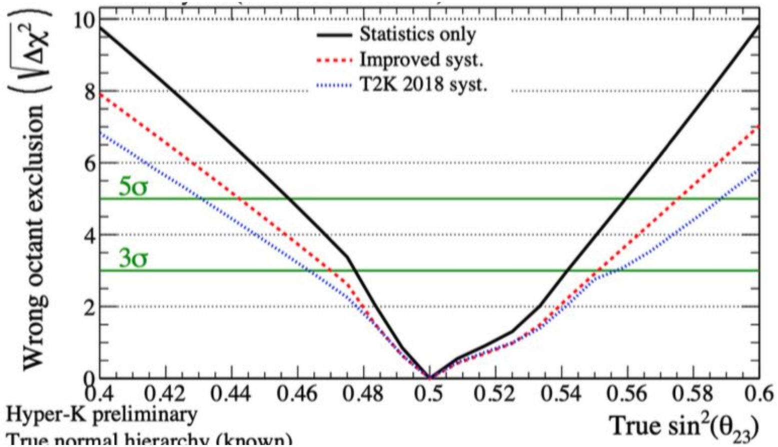
- Aim to collect ~2000 ν_e and $\bar{\nu}_e$ appearance events in 10 years
  - Will measure CPV with 3% statistical uncertainty!
- Controlling systematics becomes critical!



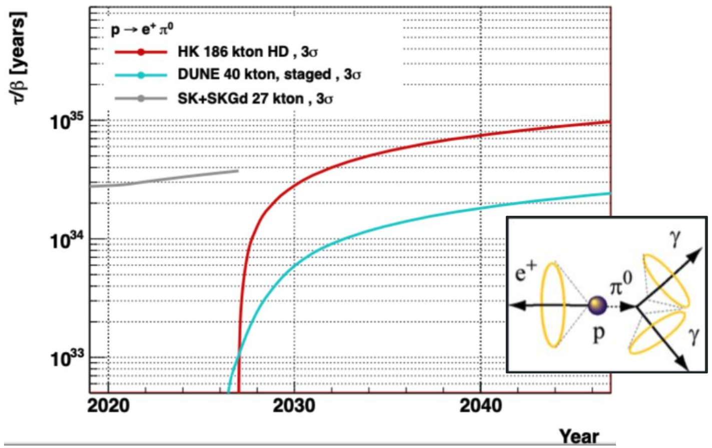
Hyper-K Long-Baseline Physics

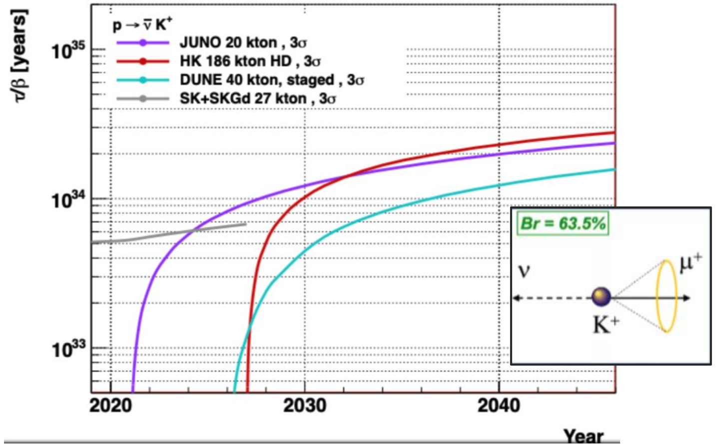


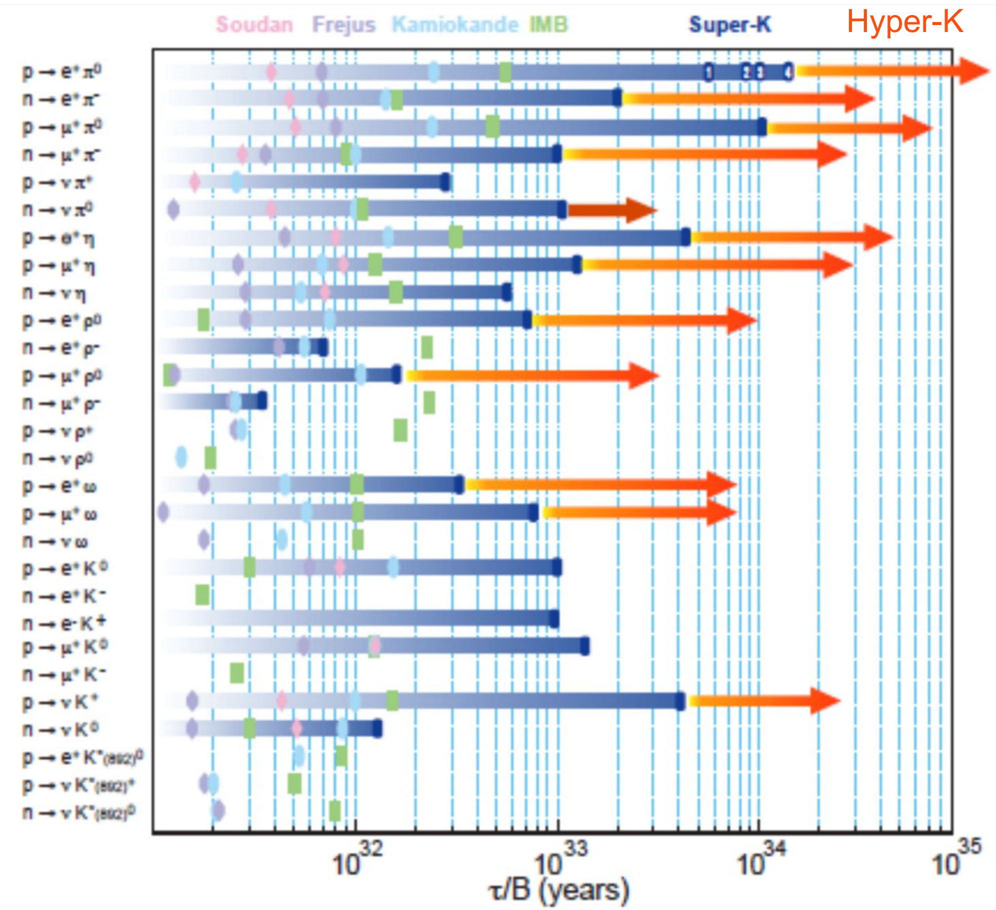




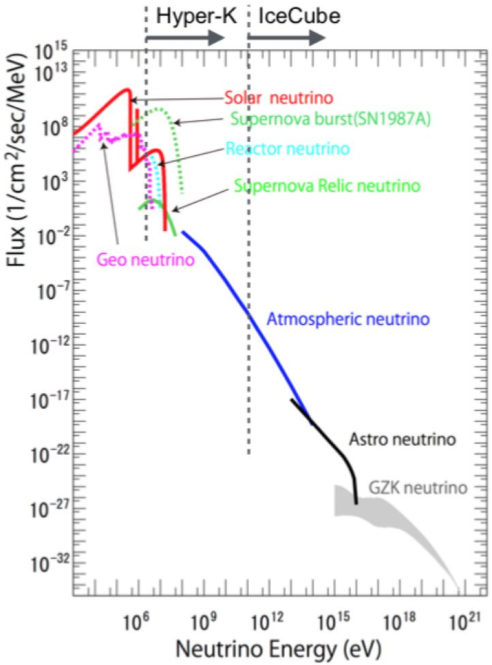
Hyper-K Proton Decay



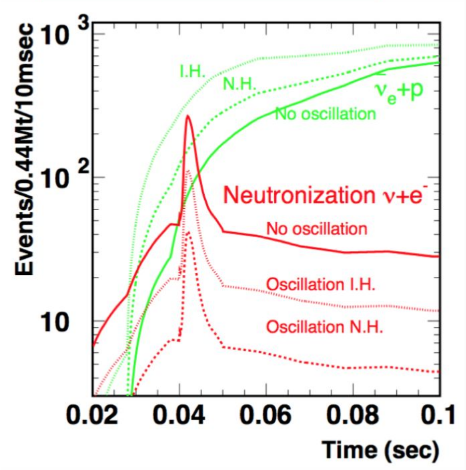


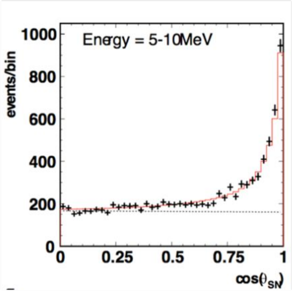


Supernova Burst in Hyper-K



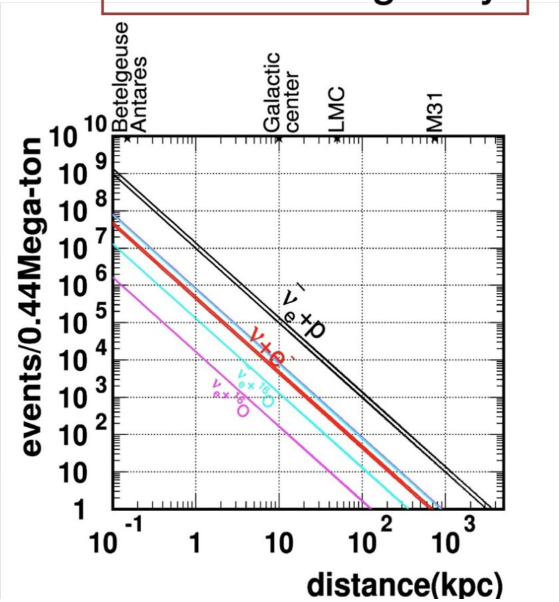
Neutrino carries information of explosion





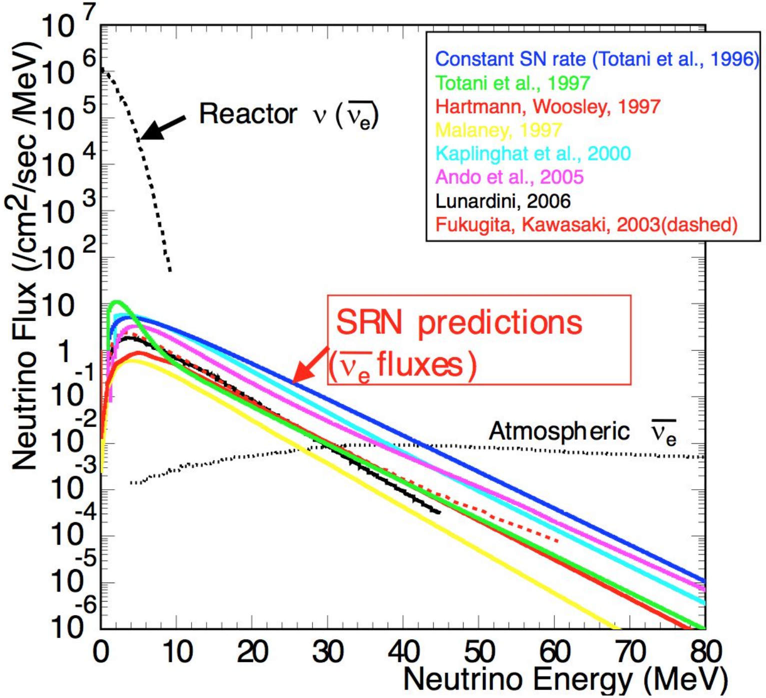
Direction alert for optical measurements (ν_e elastic)

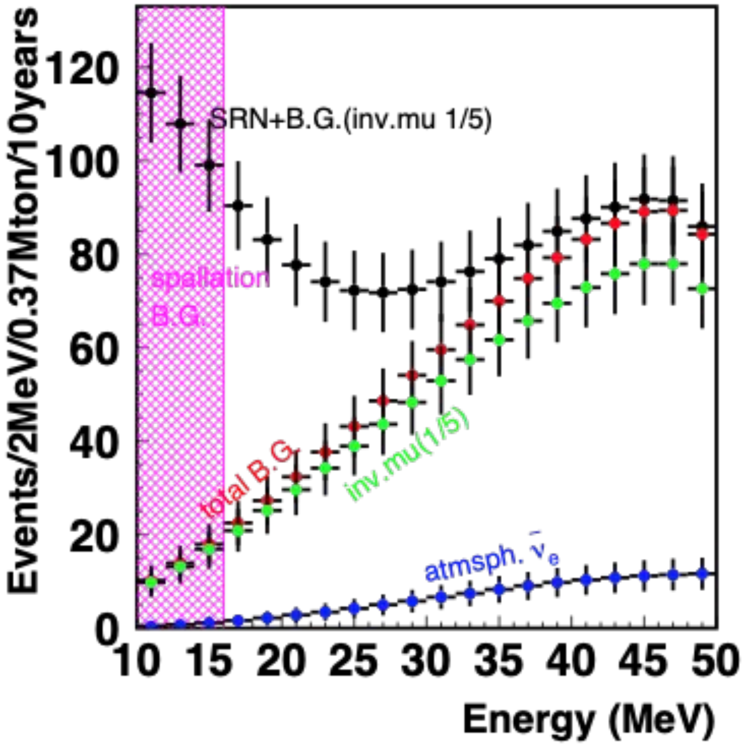
Reaching Andromeda galaxy



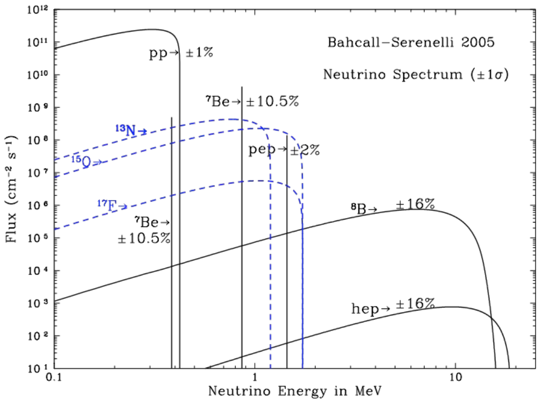
Hyper-K Supernova Relic Neutrinos

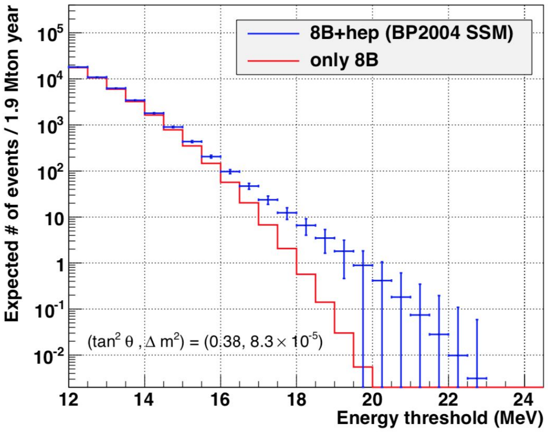
SRN can be observed by HK in 10y with ~70±17 events. It is > 4σ for SRN signal.

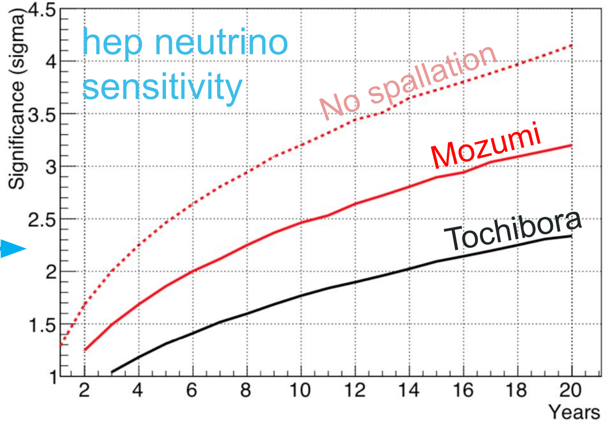


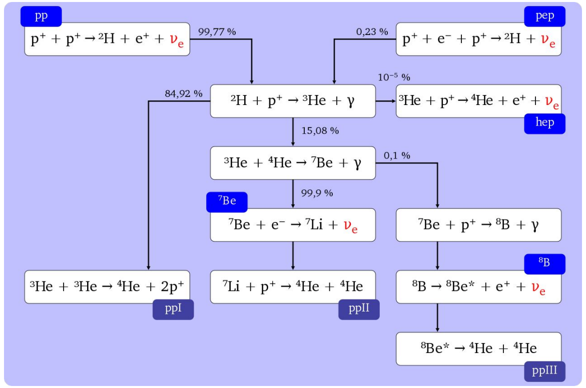


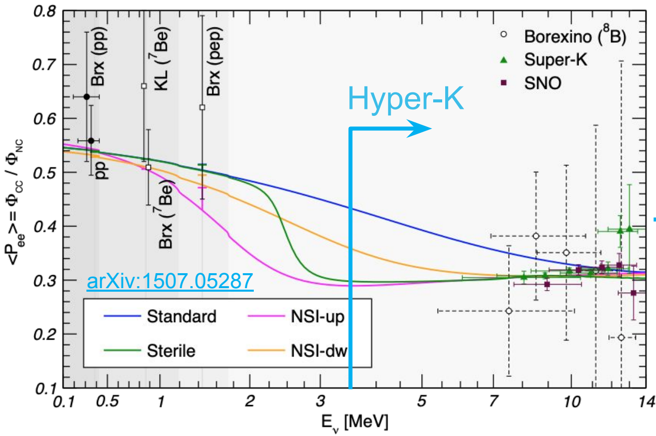
Hyper-K Solar Neutrinos

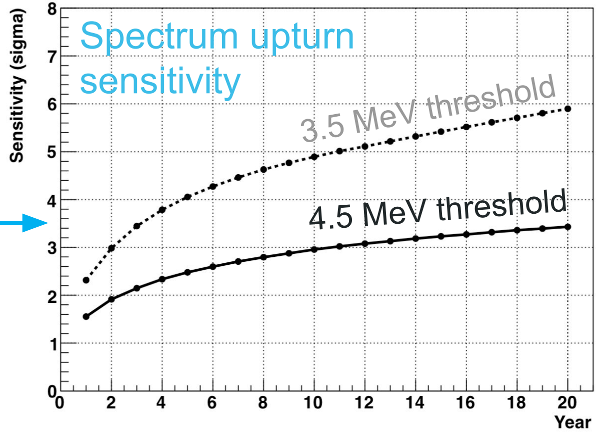












Hyper-K Collaboration Membership

- 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