Hyper-Kamiokande
Challenges in Precision Neutrino Physics

Symposium on Frontiers of Underground Physics
Chengdu, Sichuan, China
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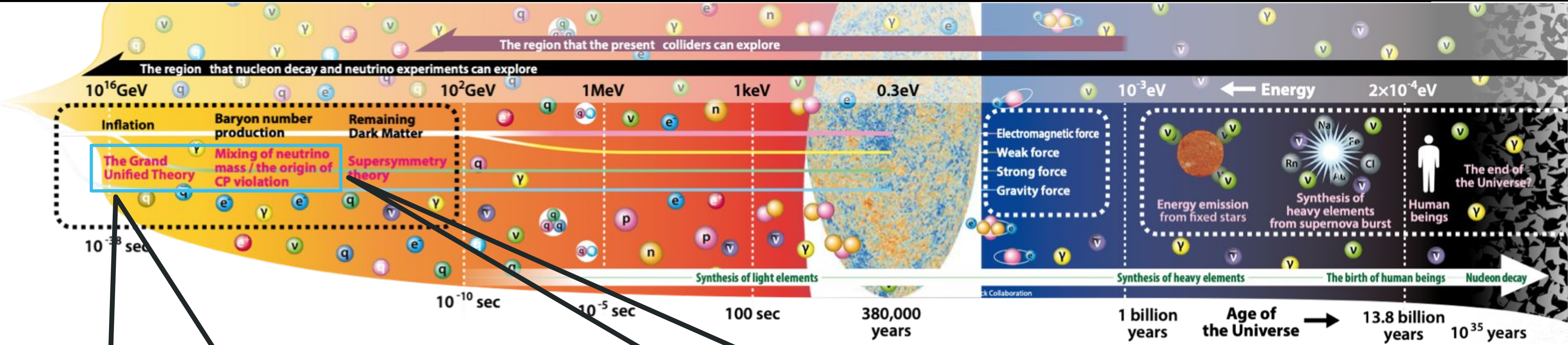
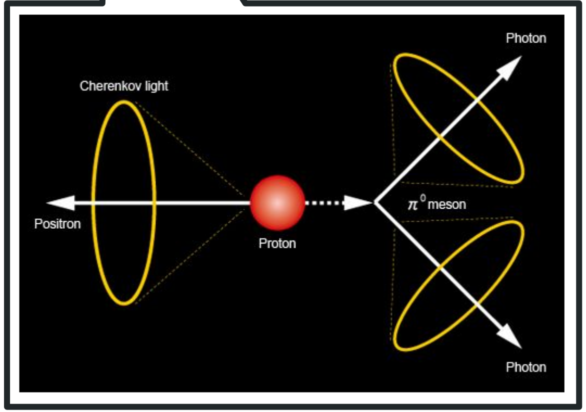
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

TRIUMF

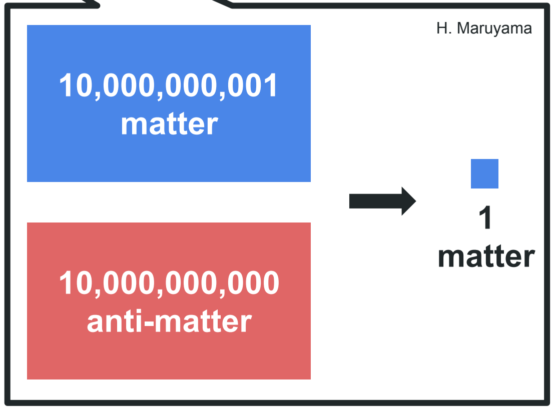
Evolution of the Universe

KAVLI IPMU

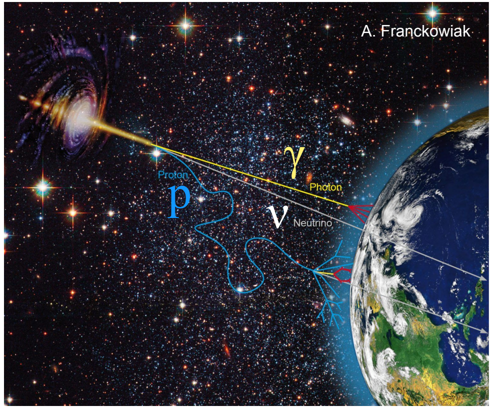




Proton Decay → GUTs



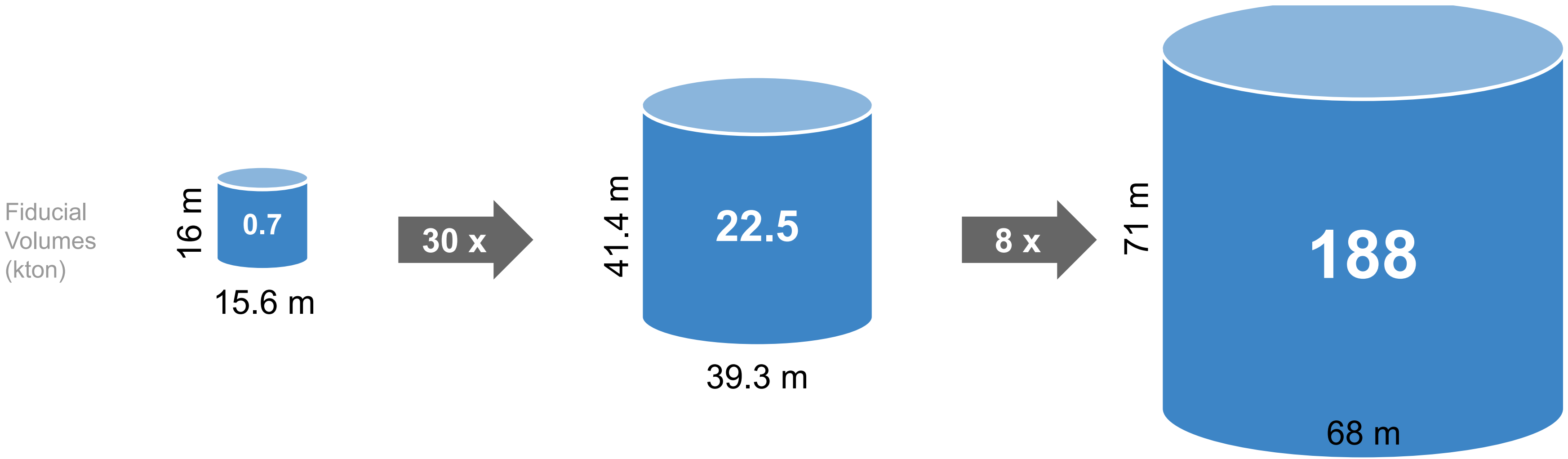
Matter - Antimatter Asymmetry



Multi-messenger astronomy

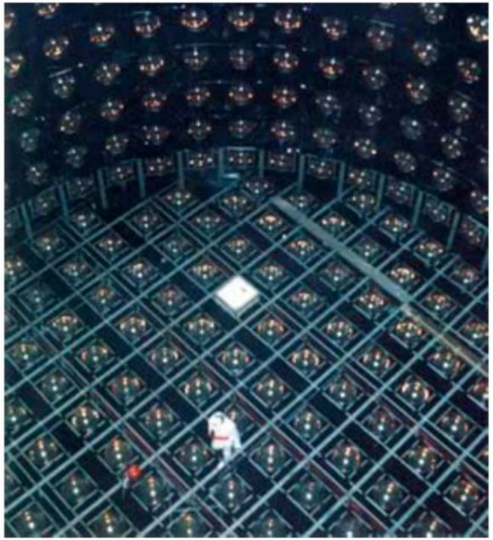
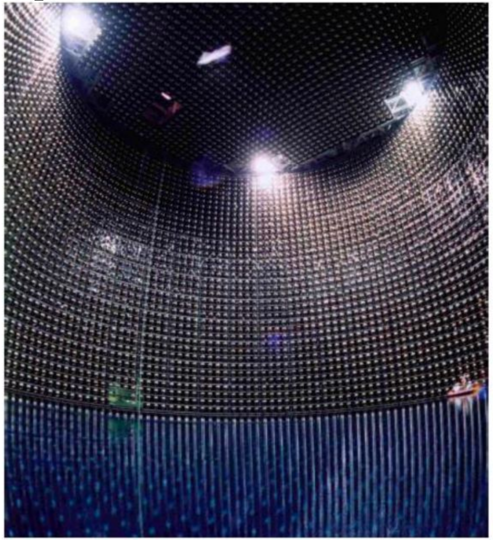
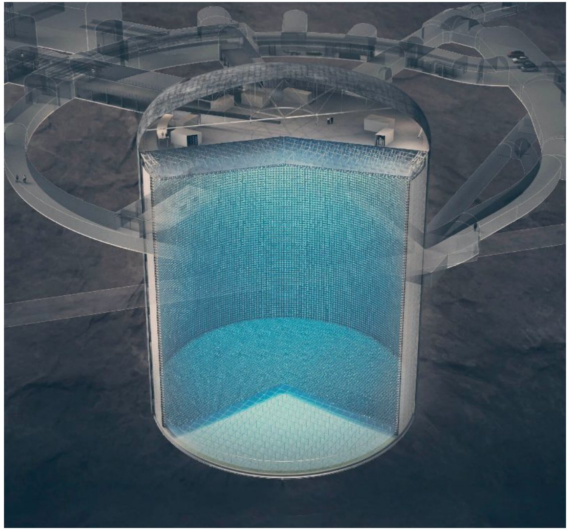
Generations of Kamiokande

Kamiokande | Super-Kamiokande | Hyper-Kamiokande



1983 - 1996	1996 - ongoing	2027 and beyond
• Atmospheric (Atm) and solar neutrino “anomaly” • Supernova 1987A ***Birth of neutrino astrophysics***	• Proton decay (world-leading limits) • Neutrino oscillation (Atm, solar, beam) ***Co-discovery of neutrino oscillations***	• Extended search for proton decay • Precision measurement of oscillations, including CP violation • Neutrino astrophysics

Generations of Kamiokande

Kamiokande	Super-Kamiokande	Hyper-Kamiokande
		
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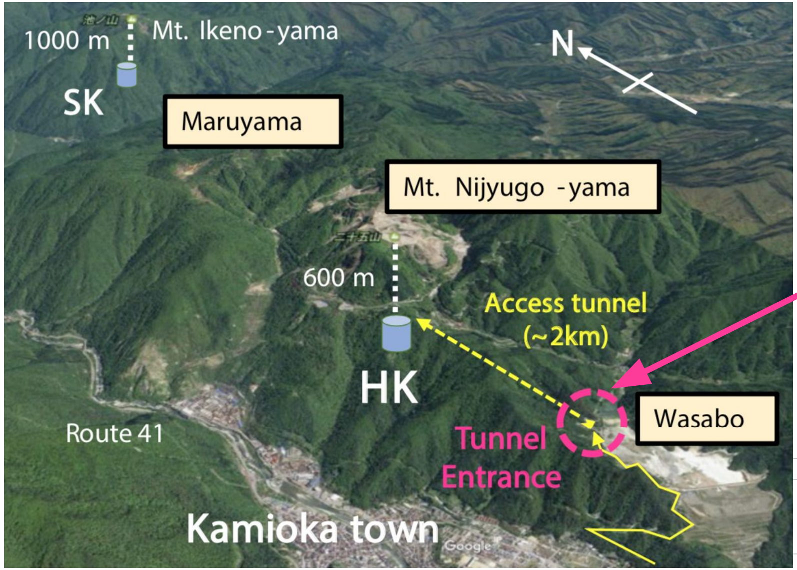
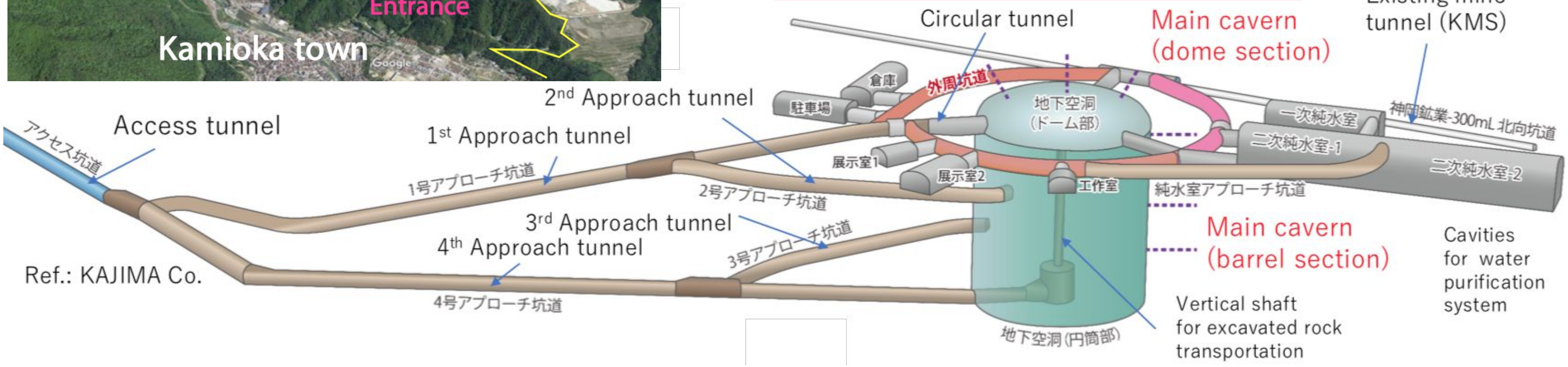
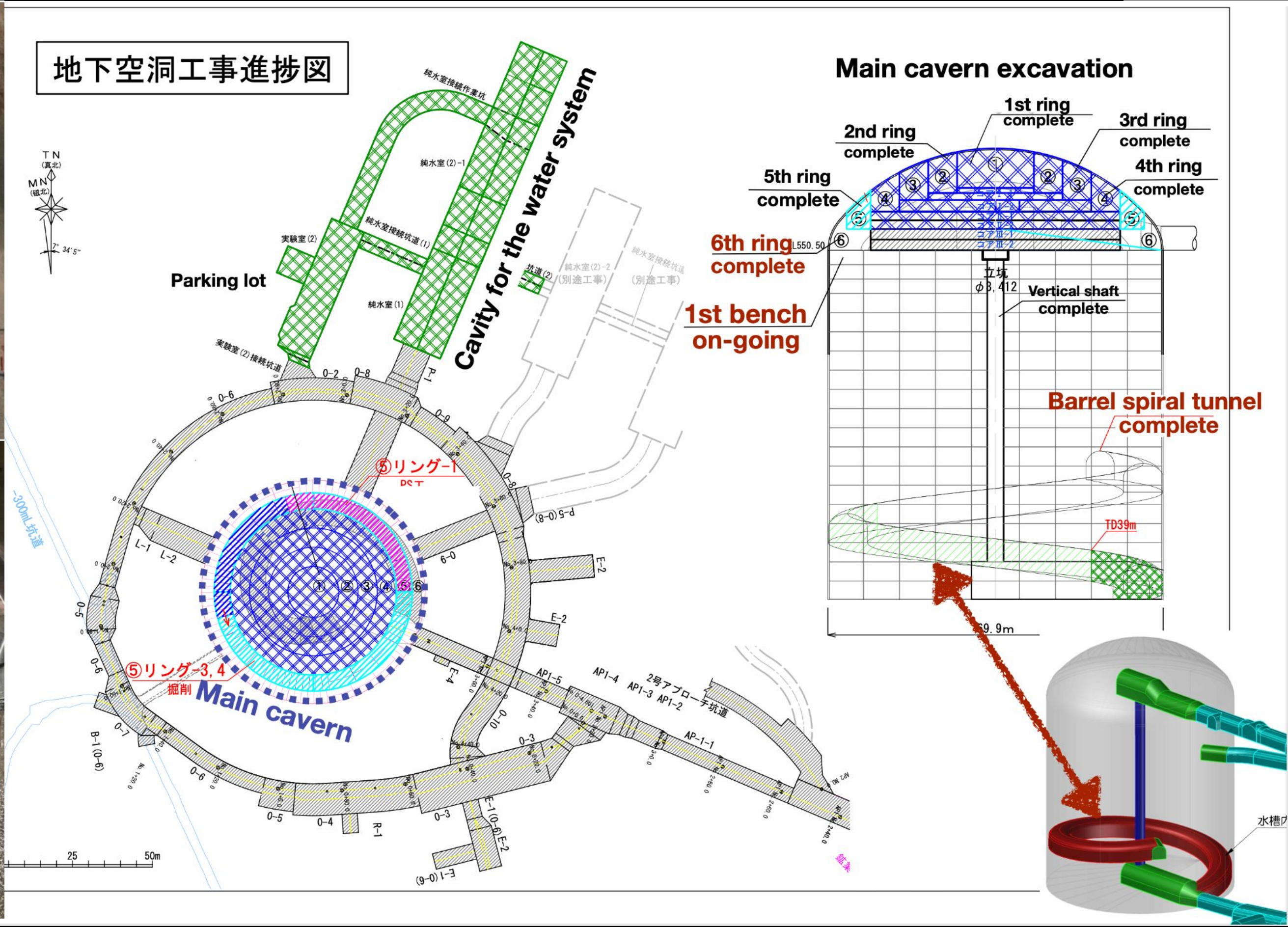
Hyper-K Far Site Overview



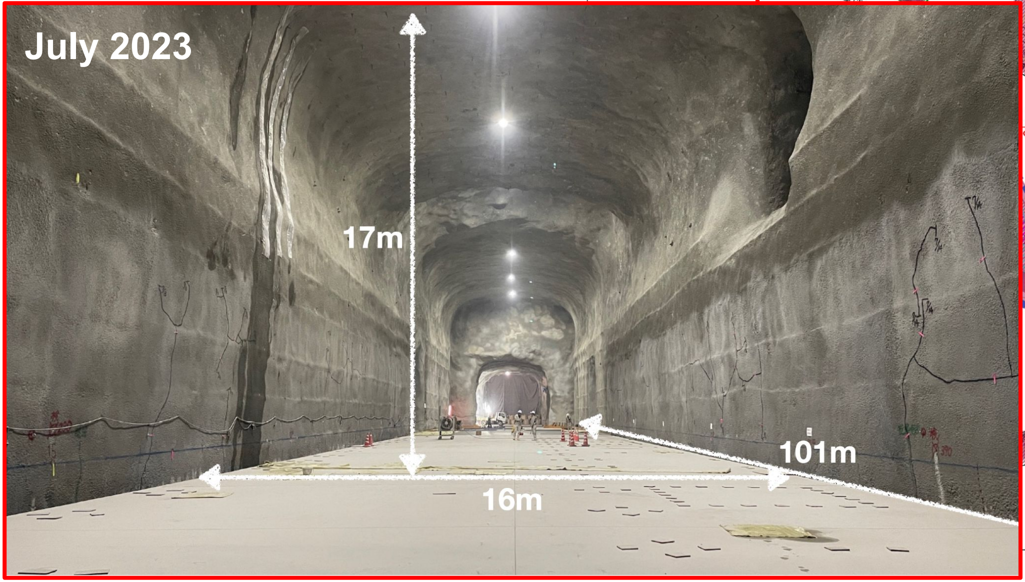


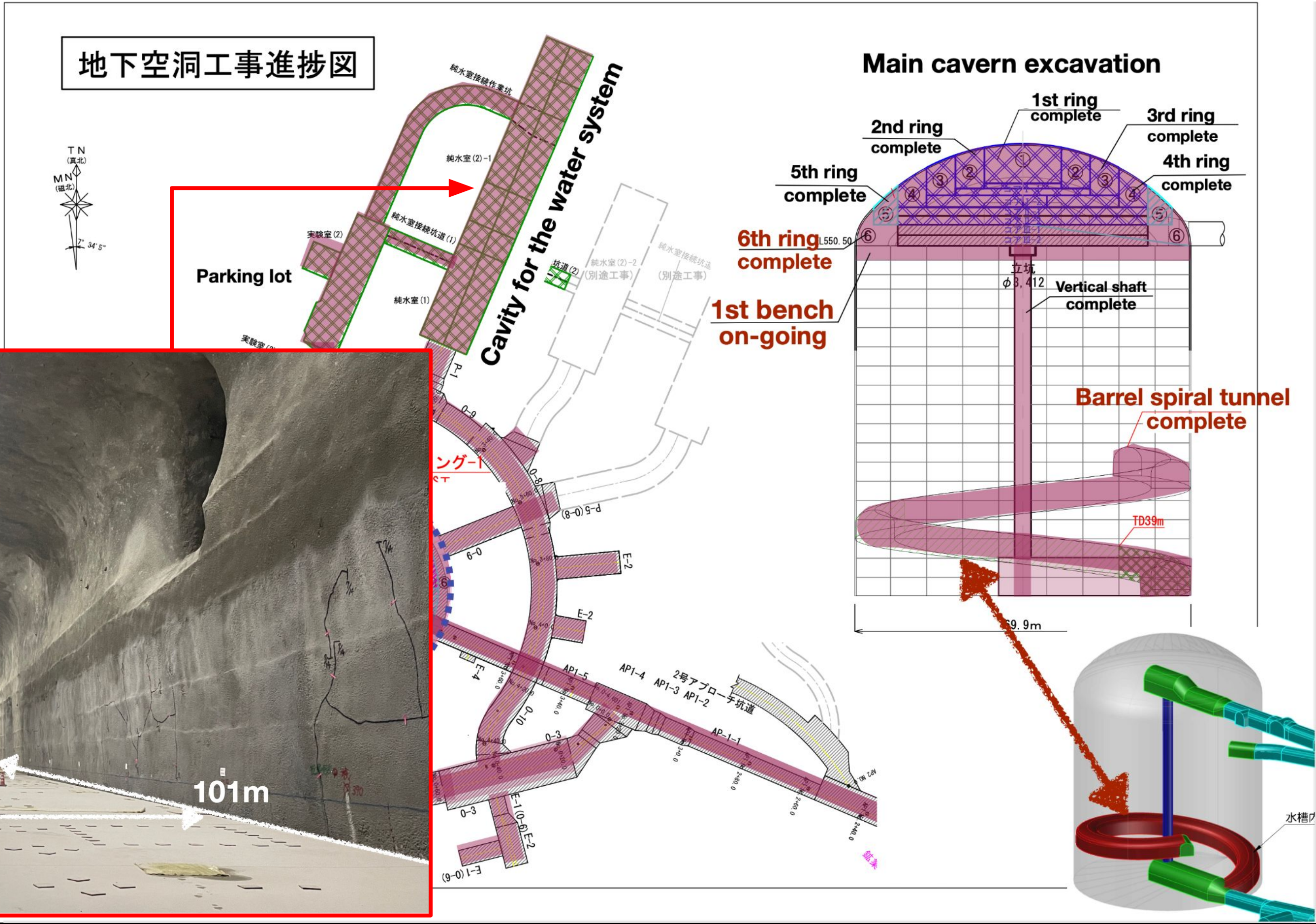
Ref.: KAJIMA Co.

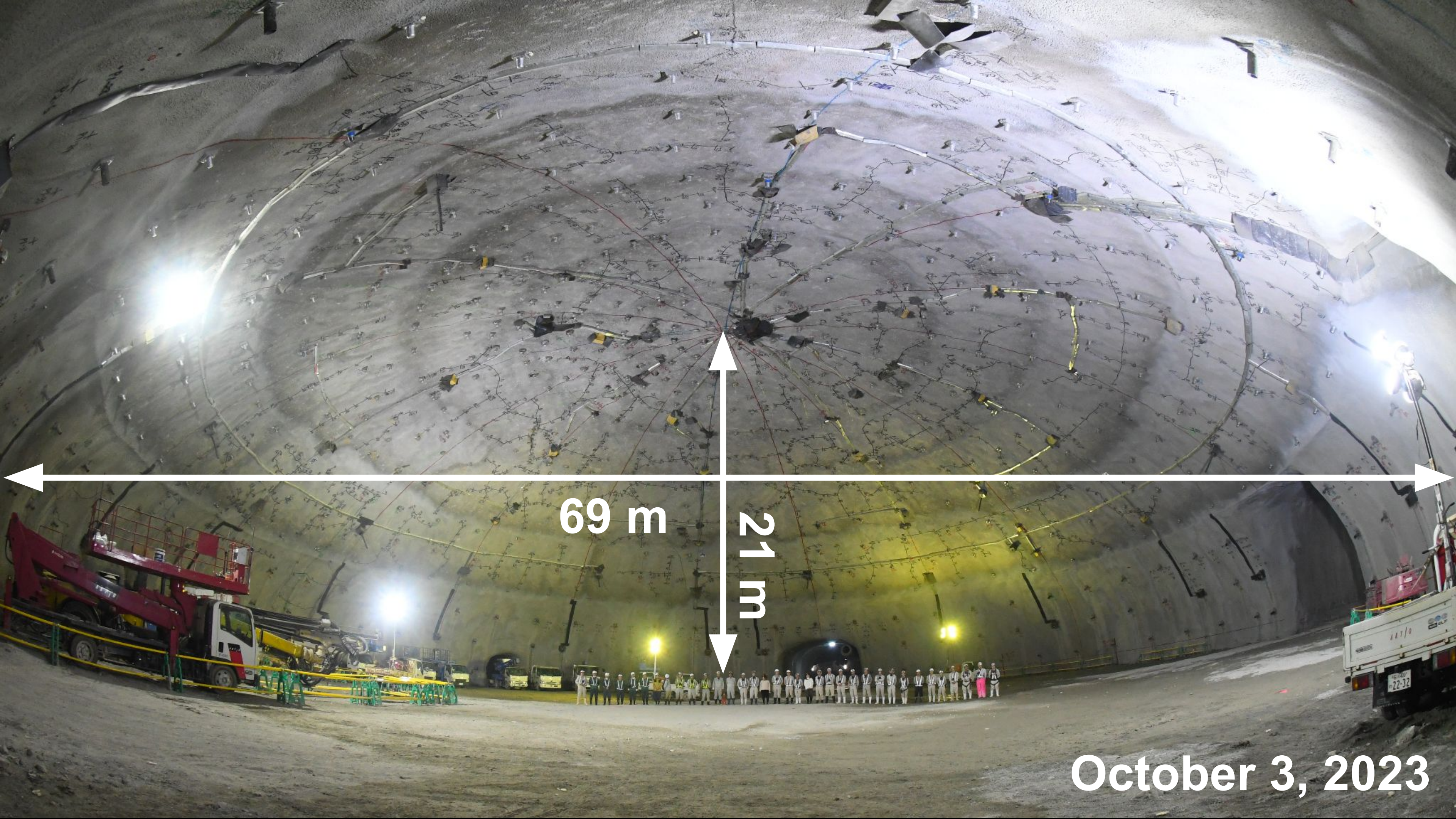
Tunnel Excavation Complete



Water System Cavity

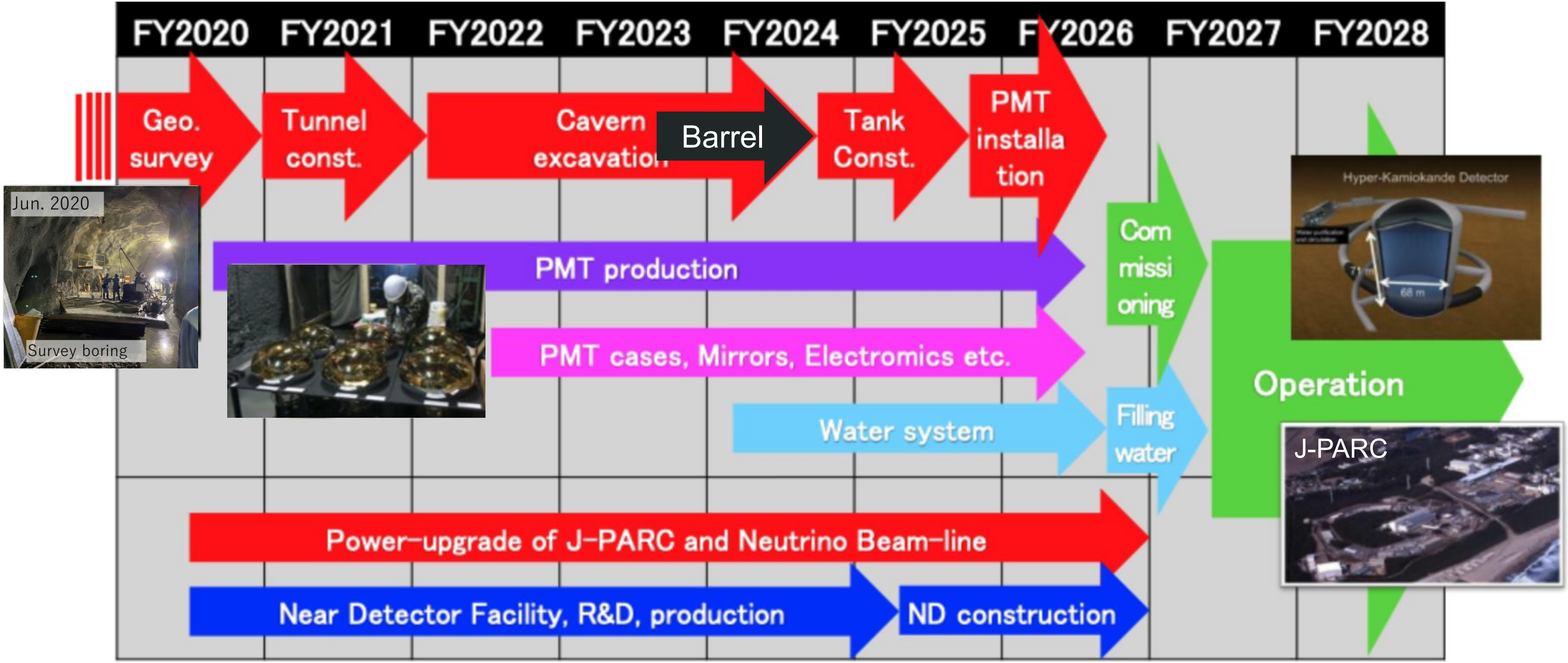




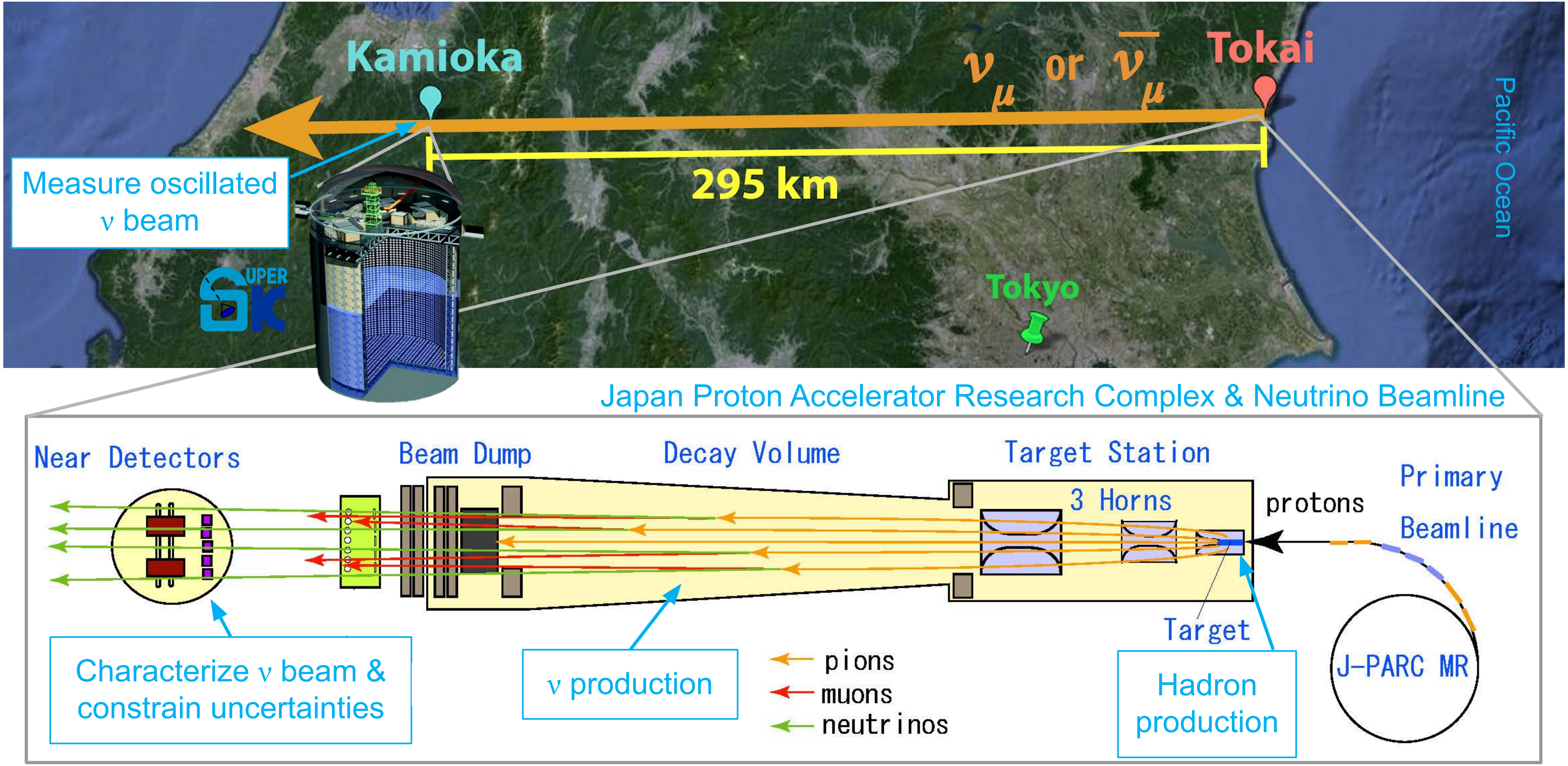

69 m
21 m
October 3, 2023

Hyper-K Schedule

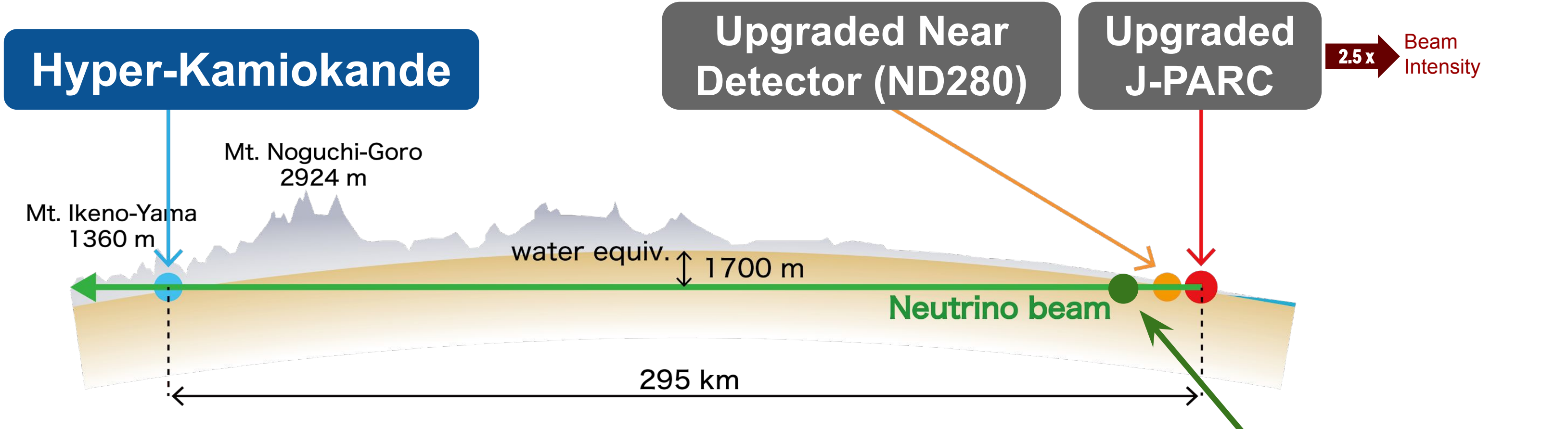
Finish all preparations within ~2 years from now for detector installation

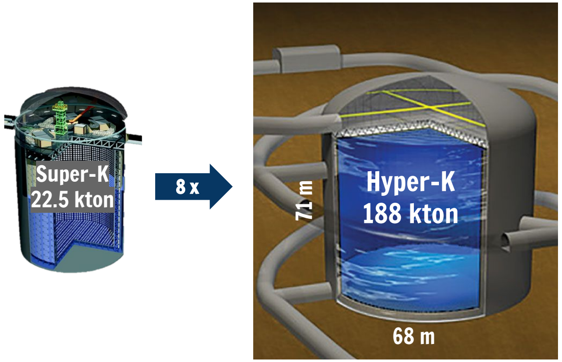


Building a Neutrino Beam in Japan

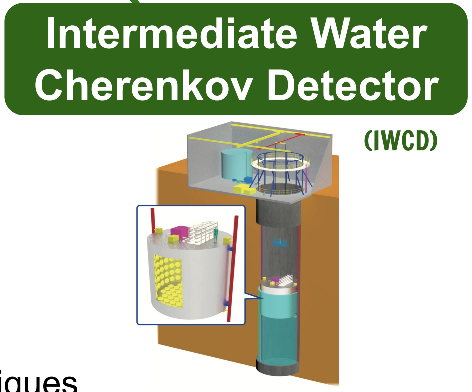


Hyper-Kamiokande: A Next Generation Experiment





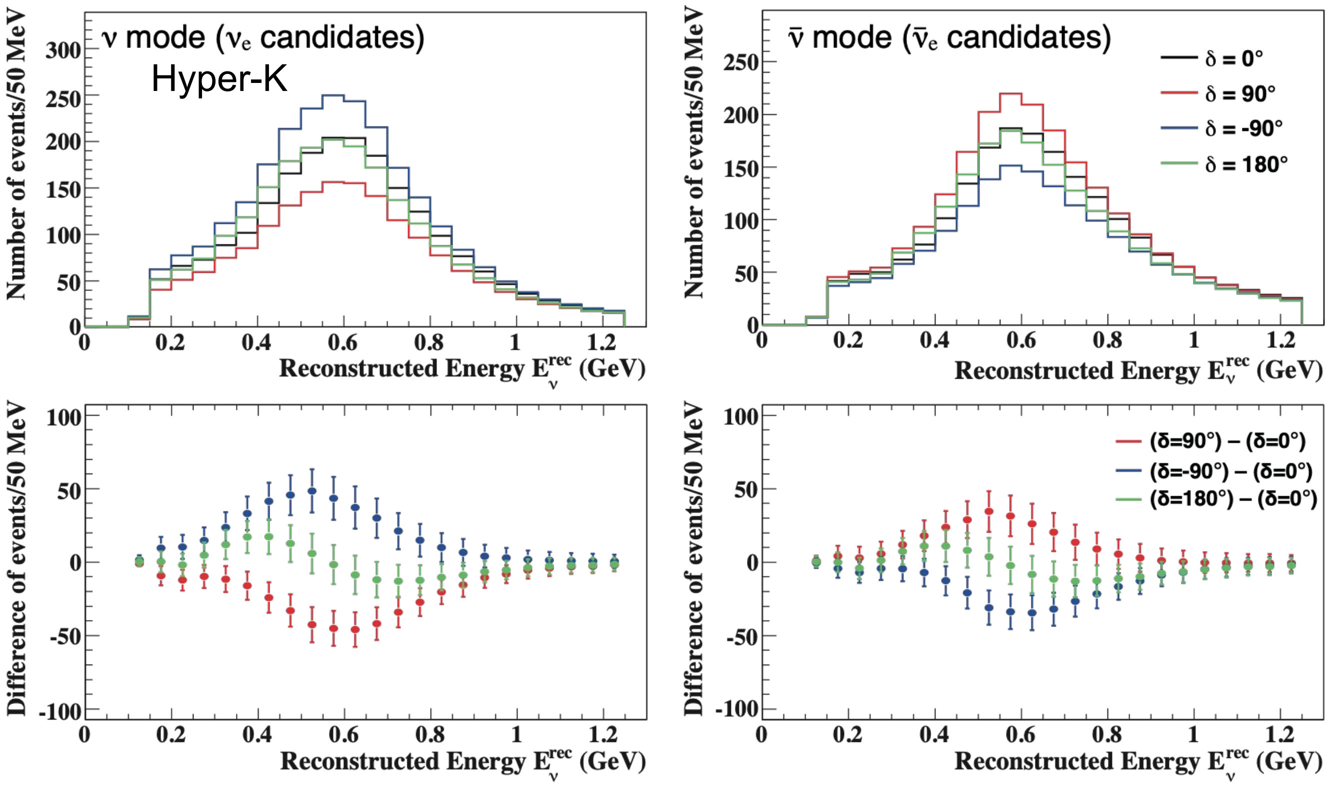
- Bigger and more sensitive than ever
  - Fiducial mass 8x Super-K
  - J-PARC beam 2.5x more powerful
    → Neutrino rates 20x T2K
- Precise systematic understanding becomes critical to the % level
  - Near detectors and photon detectors
  - Calibration and event reconstruction techniques
  - Supporting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



Unprecedented Statistical Precision

- Hyper-K aims to collect 1000s of ν_e and $\bar{\nu}_e$ appearance events
  - Can measure CP violation (CPV) with ~3% statistical uncertainty!
- Controlling systematics becomes critical!

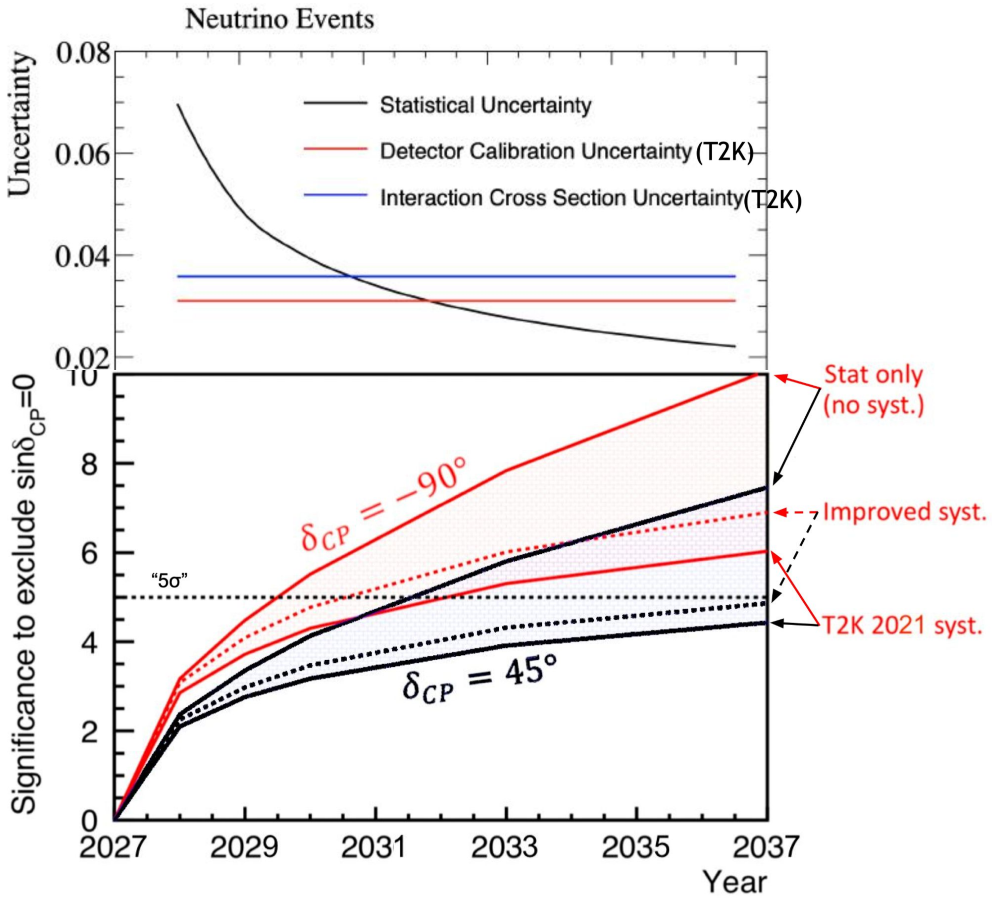
Event rates for different assumptions of true δ_{CP}



CP Violation Discovery Potential

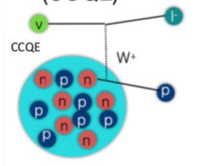
- Improved understanding of systematic errors is required for a robust and timely discovery of CPV

- Controlling systematics becomes critical!

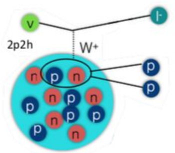


T2K Oscillation Analysis Framework

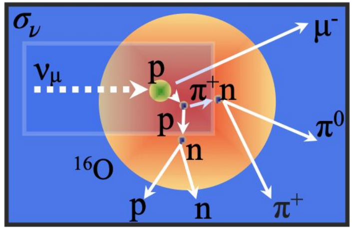
Charged current (CC) quasi-elastic (CCQE)



CC multi-nucleon knockout (2p2h)



Hadronic reinteractions



Geometry

Cherenkov physics

Water properties (light scattering, absorption)

PMT and wall reflectivity

Residual magnetic fields

PMT+electronics response

External cross section measurements

Interaction model σ_ν

External hadron production measurements, INGRID data

Flux model φ_ν

ND280 fit

ND280 detector systematics

ND280 data

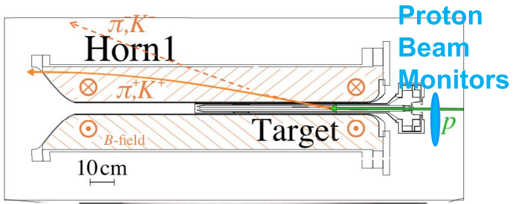
Covariance matrix

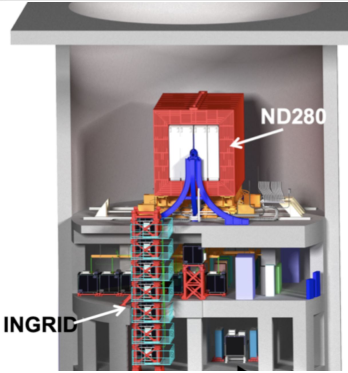
SK systematics ε_{Far}

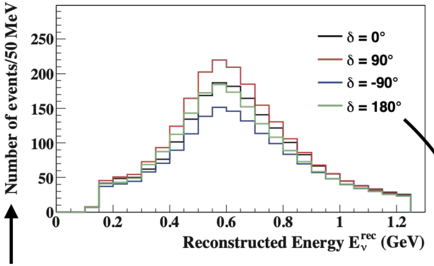
SK data

SK fit

Oscillation parameter constraints

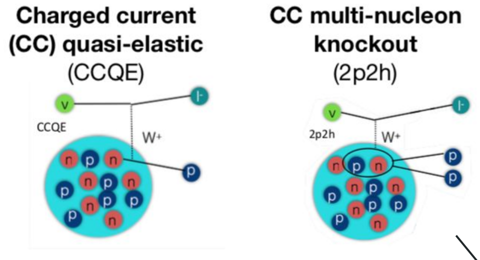


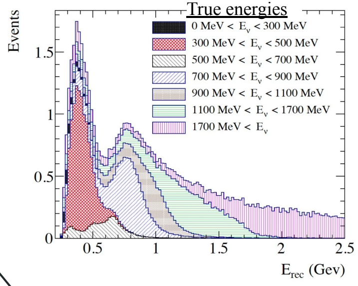




$$N_{Far} \propto \varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{Far} \cdot \boxed{P_{Osc}}$$

Neutrino Oscillation Systematic Error Budget





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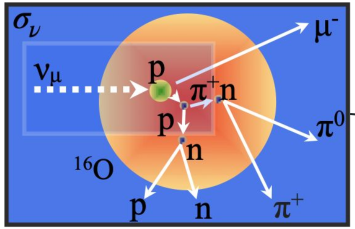
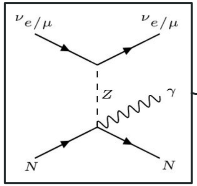
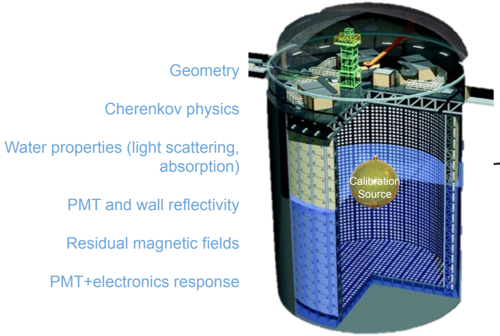


Large energy reconstruction errors and event migrations





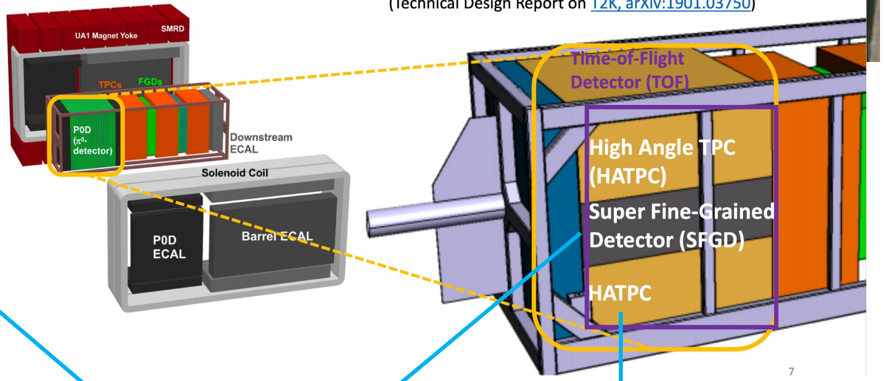
"T2K 2021 syst.": Phys. Rev. D 103, 112008

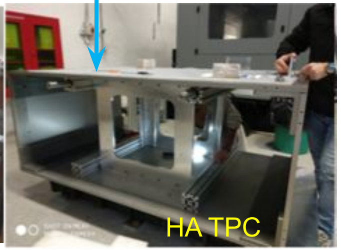
Error Source	% Error for CPV search
$\varphi + \sigma$ (ND constrained)	2.7
$\varphi + \sigma$ (ND unconstrained)	1.2
Nucleon removal energy	3.6
SK π re-interactions	1.6
Currently theoretical $\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	3.0
NC γ + other	1.5
SK detector	1.5
Total	**6.0**

Need to reduce to <3% for Hyper-K

Future of the Near Detector Suite

(Technical Design Report on T2K, arXiv:1901.03750)

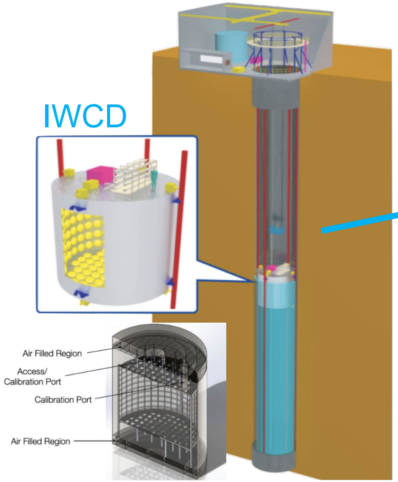


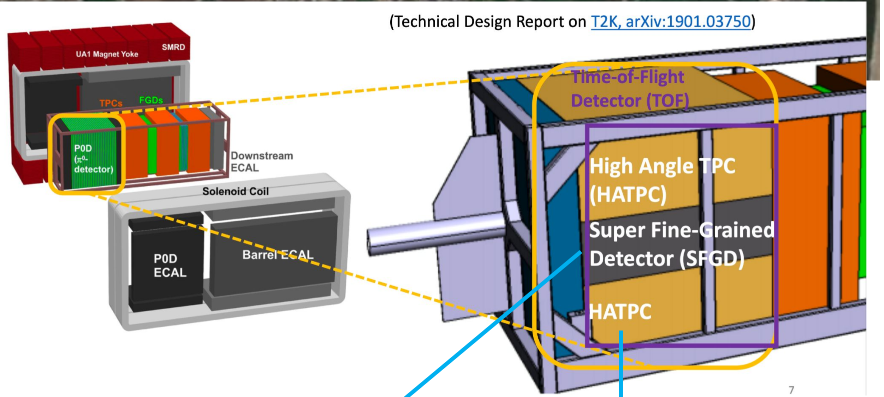


- ND280 upgrade ready for Nov. 2023 beam
  - Increase phase space coverage, similar to SK
  - Lower proton energy threshold and neutron detection capability
- *ND280++ still needs consideration for HK*

Future of the Near Detector Suite

- 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





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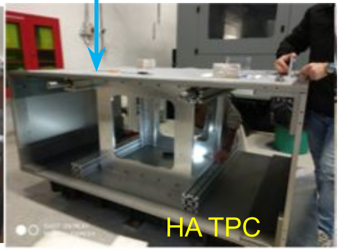
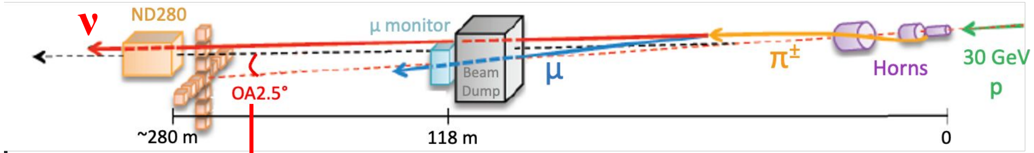


The NuPRISM Concept

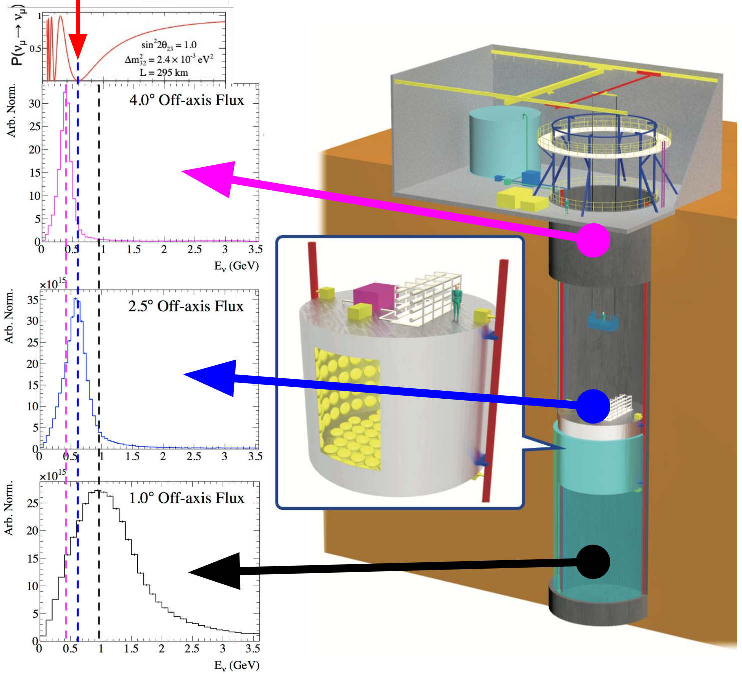


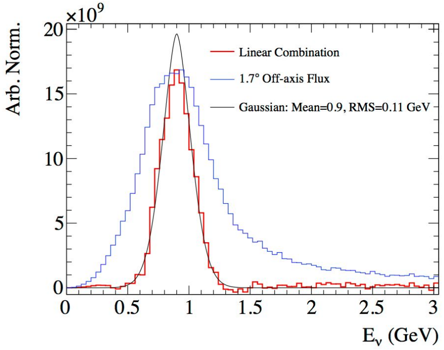
Neutrino energy spectrum depends on **off-axis angle (OOA) to the neutrino beam source.**

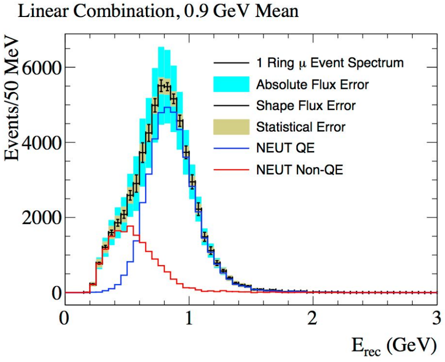
Moving IWCD vertically → varying off-axis angle → measurements with differing energy spectra.

Linear combinations of measurements at off-axis angles can mimic **a monochromatic beam**, or the **far-detector spectrum** effectively *bypassing neutrino interaction modeling deficiencies*…

OAA Nominally tuned to oscillation maximum



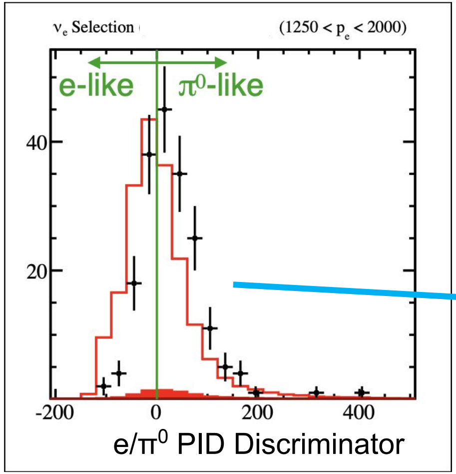




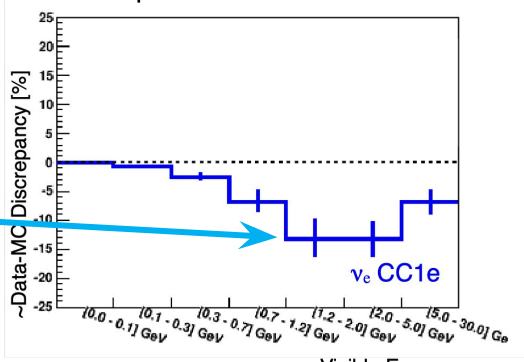
Water Cherenkov Detector Systematics

… Then understanding the detector becomes more important

"T2K 2021 syst.": Phys. Rev. D 103, 112008



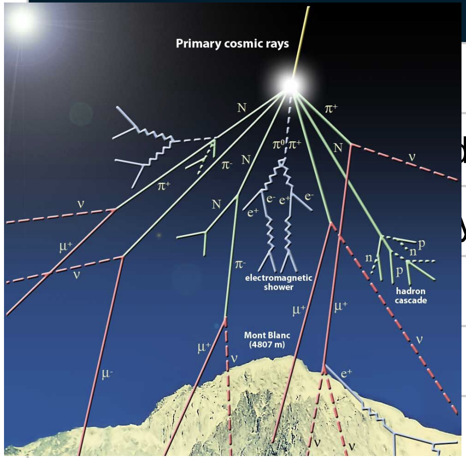
Effective parameterization of PID discriminators, fitted to atmospheric neutrino data



Assumed spatially uniform and same for ν and $\bar{\nu}$;
Also, Atm-ν non-existent for IWCD!

Systematic errors in event selection and energy scale assigned from data/MC discrepancies in cosmic ray and atmospheric ν data

Error Source	% Error for CPV search
	2.7
d)	1.2
y	3.6
	1.6
	3.0
	1.5
SK detector	1.5
Total	**6.0**



Need to reduce to <3%

Water Cherenkov Detector Systematics

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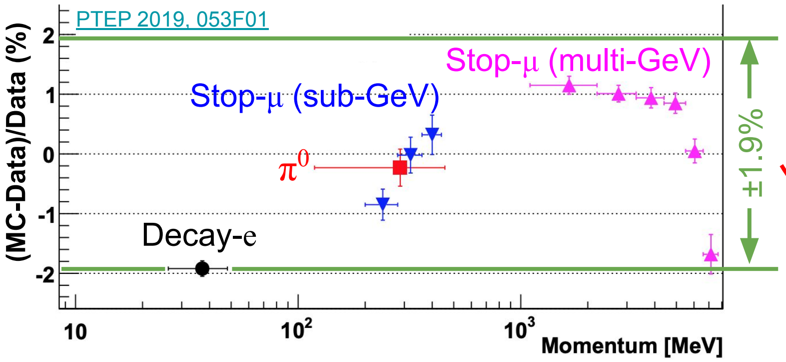
Super-K Control Samples for Energy Scale



Aiming for 0.5% in Hyper-K

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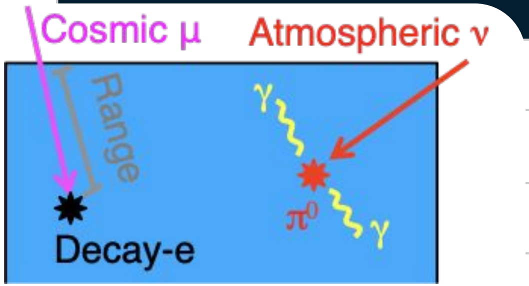
"T2K 2021 syst.": Phys. Rev. D 103, 112008



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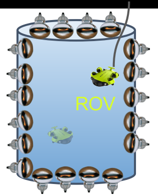
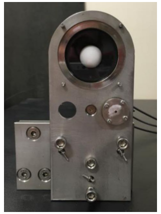


Photogrammetry



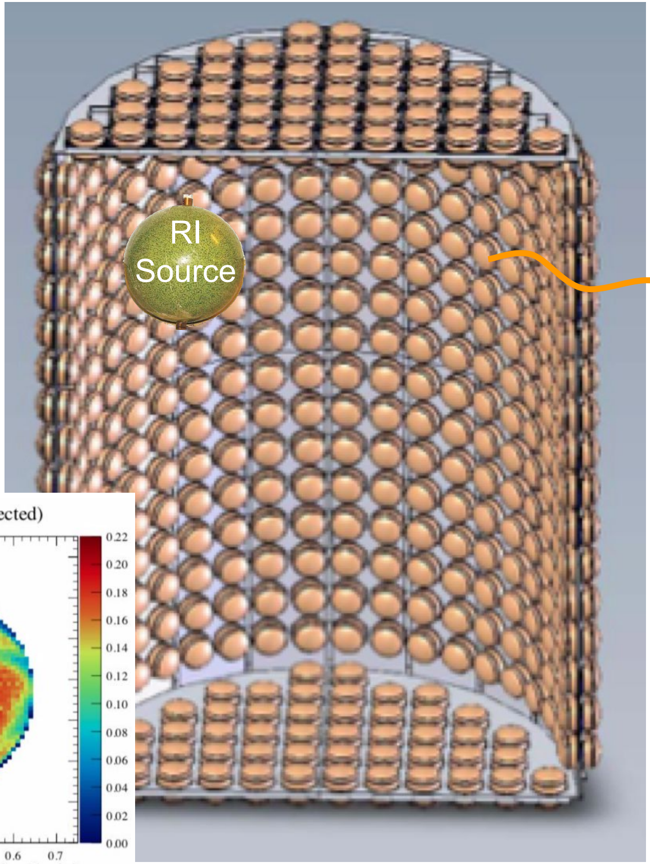
Light injectors

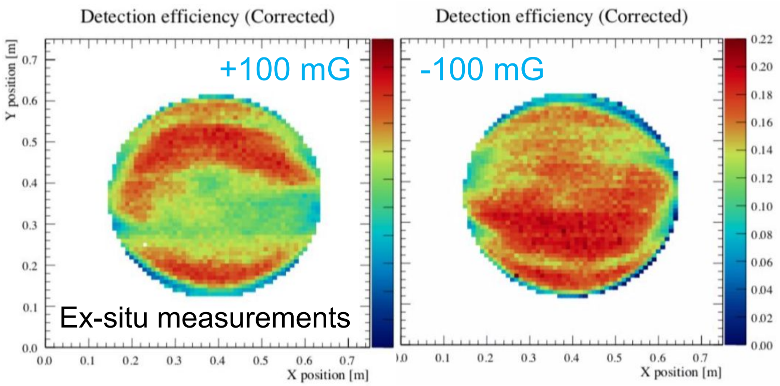
Geometry (detector and calibration devices)

Water quality (light scattering, absorption)

PMT and wall reflectivity

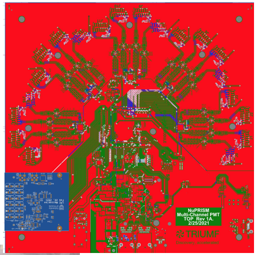
Residual magnetic fields





Cherenkov physics

γ



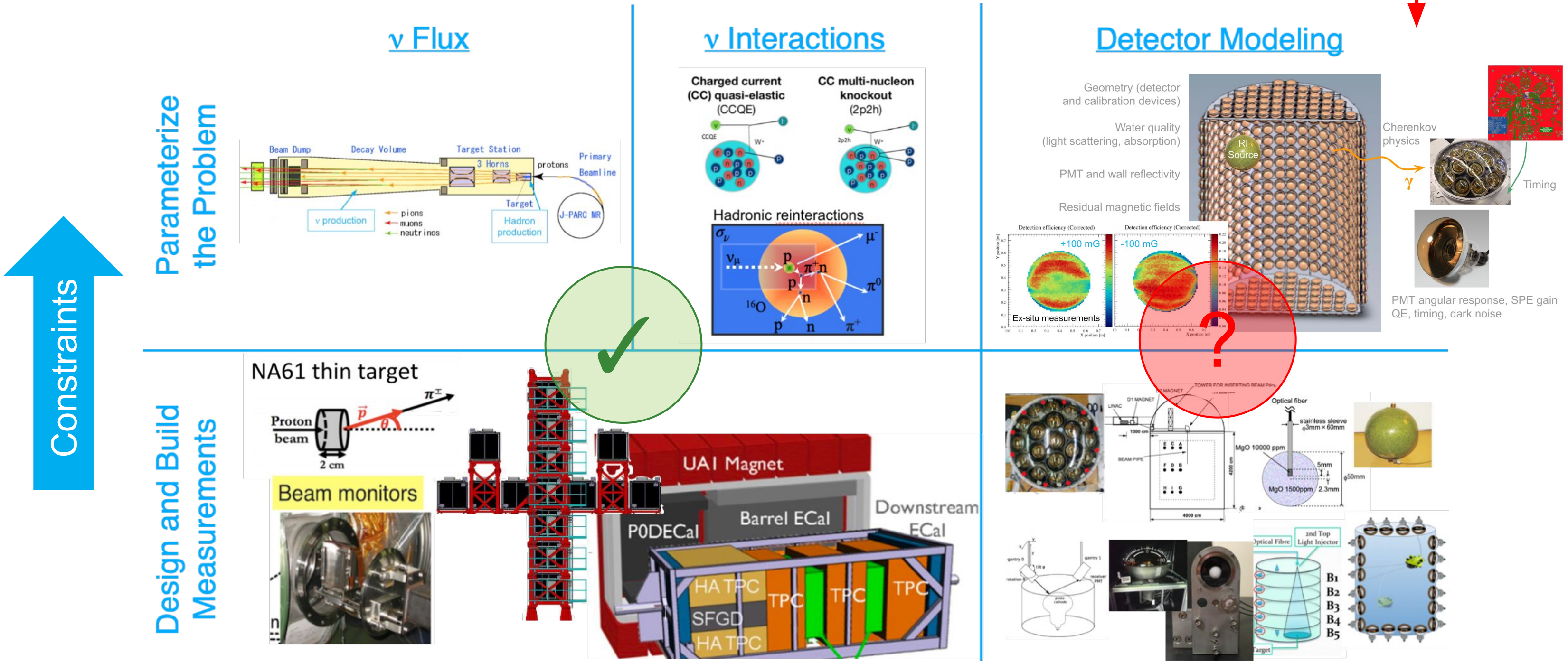
Timing

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

Constrained Modeling of the Experiment

- A coherent method exists for constraining (degenerate) fundamental physics parameters of the neutrino flux and interactions with comprehensive measurements

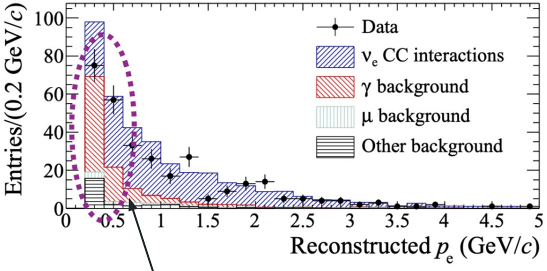
- This still needs to be developed for complex detector parameters

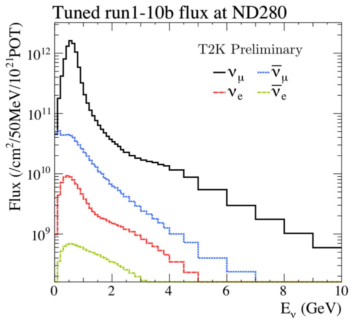


The Need for IWCD and New Event Reconstruction

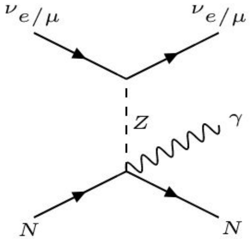
- Constrain $\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$ using **1% intrinsic ν_e ($\bar{\nu}_e$) in beam**

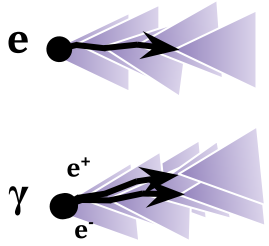
T2K (ND280): Phys. Rev. Lett. 113, 241803 (2014)

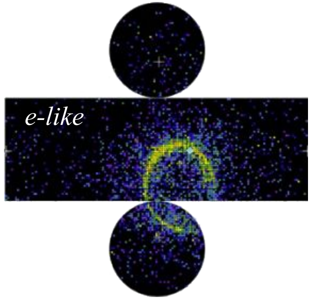




- Need data driven constraints on γ backgrounds







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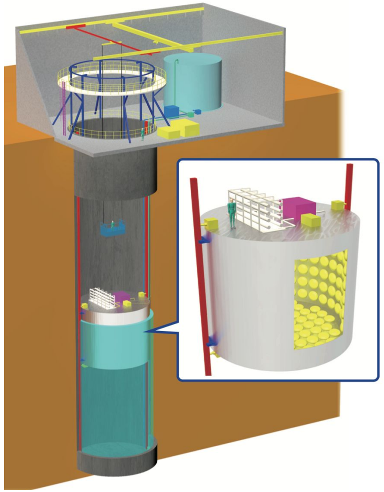
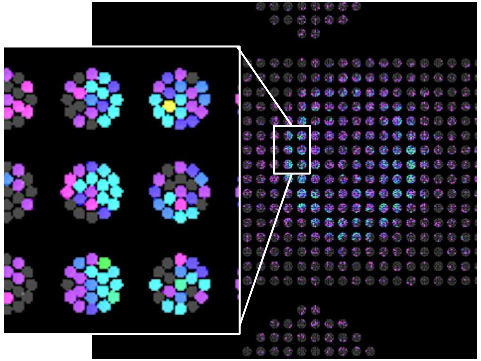
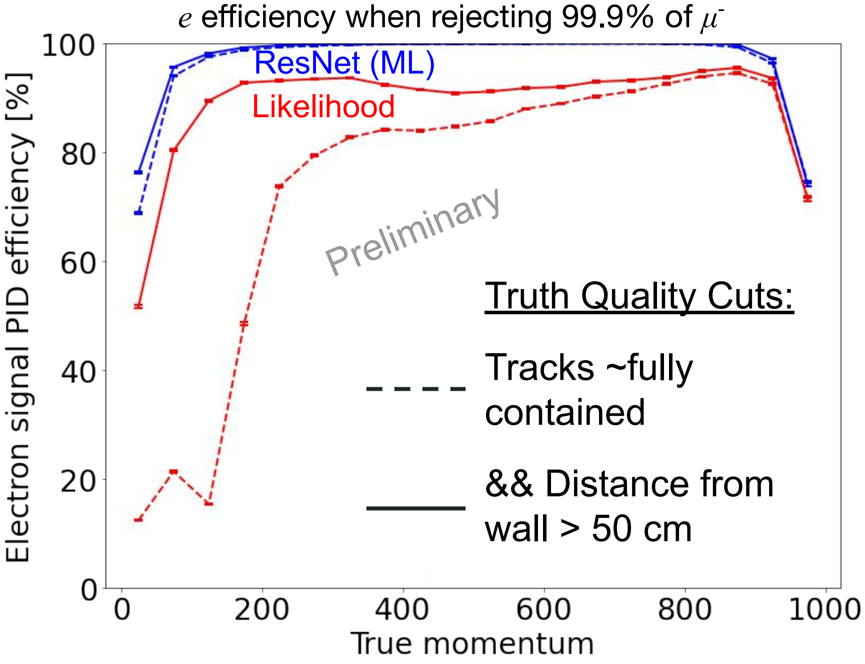
Need to reduce to <3%

e / μ Classification in IWCD

- Constrain $\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$ using **1% intrinsic ν_e ($\bar{\nu}_e$) in beam**
- Need >~1000 in μ rejection (>99.9%)
- Can be achieved in IWCD with machine learning (ML)
    - Further prospects of expanding fiducial volume

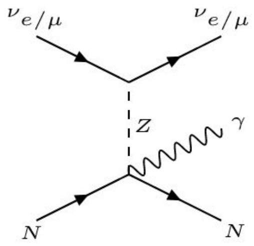


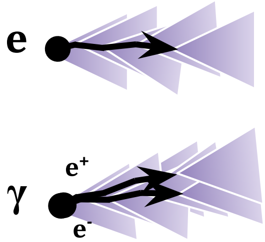


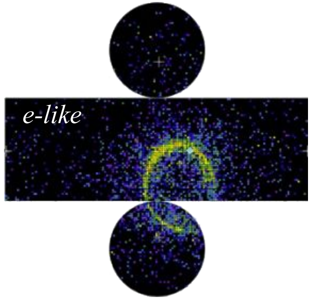


Gamma (γ) Identification

- Need data driven constraints on γ backgrounds

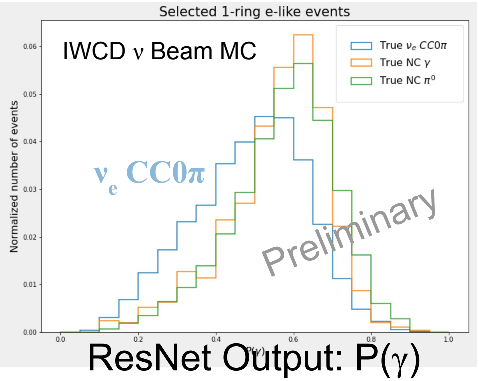


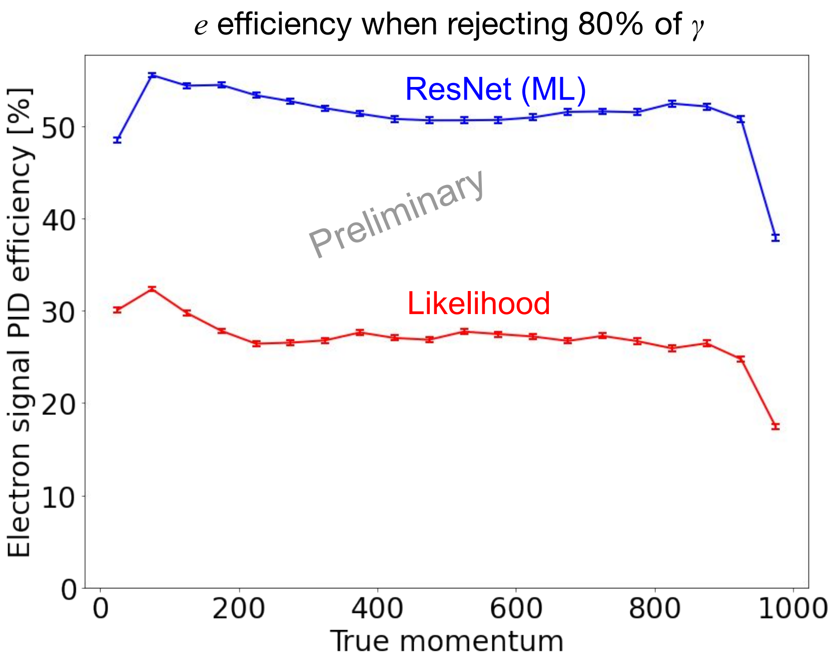




- γ and e almost indistinguishable in water Cherenkov detectors
  - Potential discrimination shown for the first time

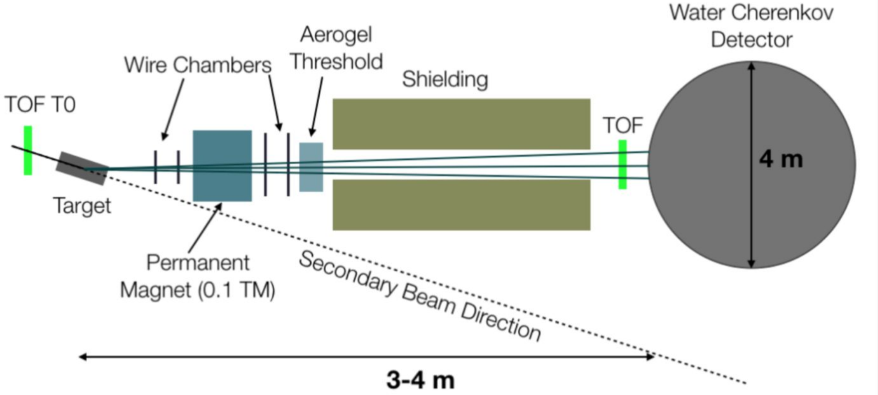
- ML shows promise with at least some statistical separation

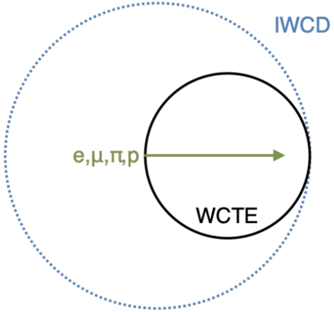


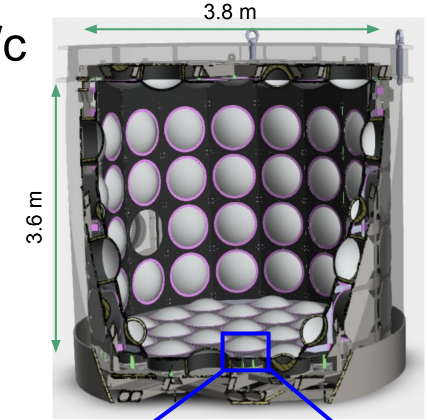


The Water Cherenkov Test Experiment (WCTE)

- Prototype for IWCD at CERN in 2024
- Well-understood p, e, $\pi^{\pm}$, $\mu^{\pm}$, γ particle beam from 140-1200 MeV/c
  - Control samples to constrain neutrino experiment modeling:
    - Detector response: Cherenkov light emission; $\pi^{\pm}$ interactions
    - Neutrino flux & interactions: lepton scattering and hadron production
  - Immediate impact to existing experiments (T2K, Super-K)
- Demonstration of these new ML simulation and calibration techniques for WC, and optimization towards Hyper-K/IWCD

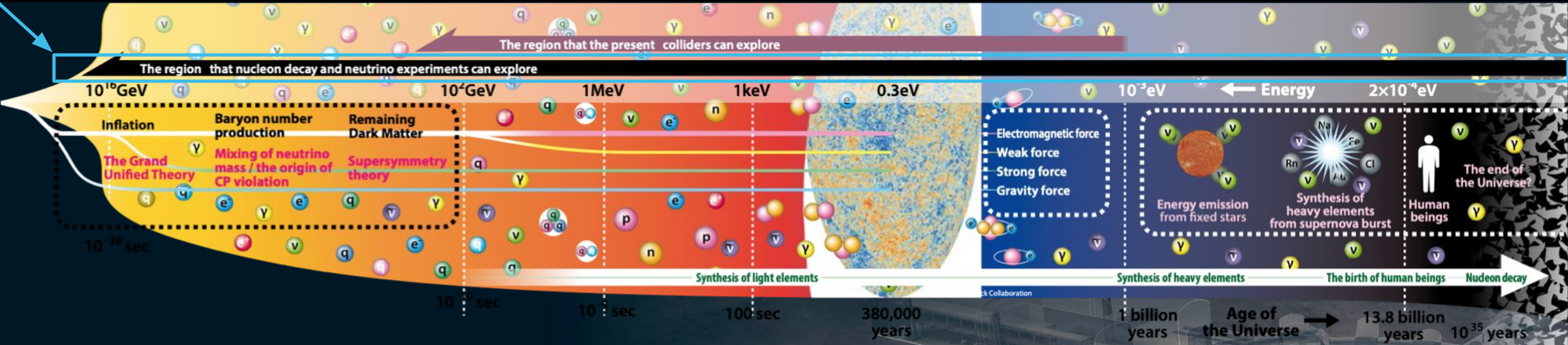




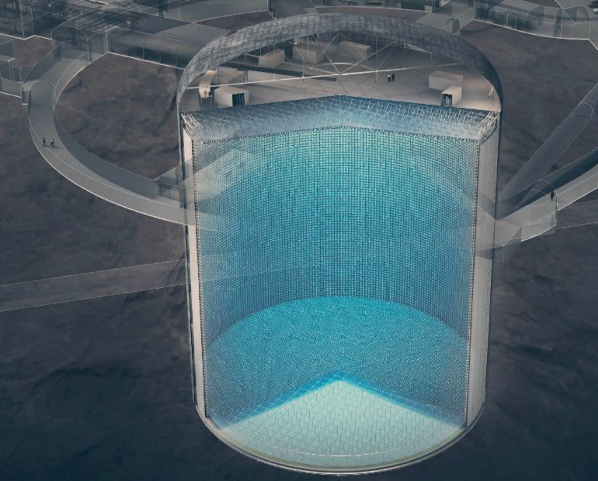


~102 mPMT modules
x19, 3” PMTs each

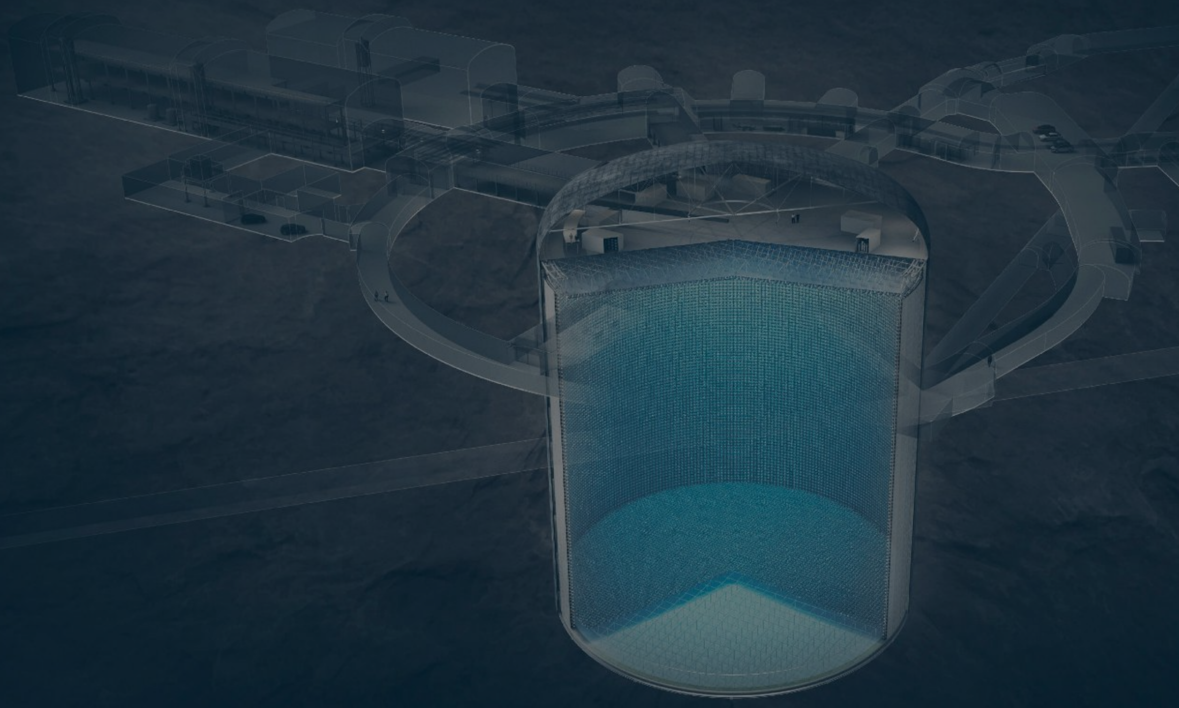
Summary



- Exciting physics program in Hyper-Kamiokande
  - CP violation, proton decay, multi-messenger astronomy, and more!
- Low level developments required to achieve full potential
  - WCTE → IWCD, calibration, and machine learning
- *Seeking new collaborators and contributions!*
  - Components of far detector, IWCD, and ND280++



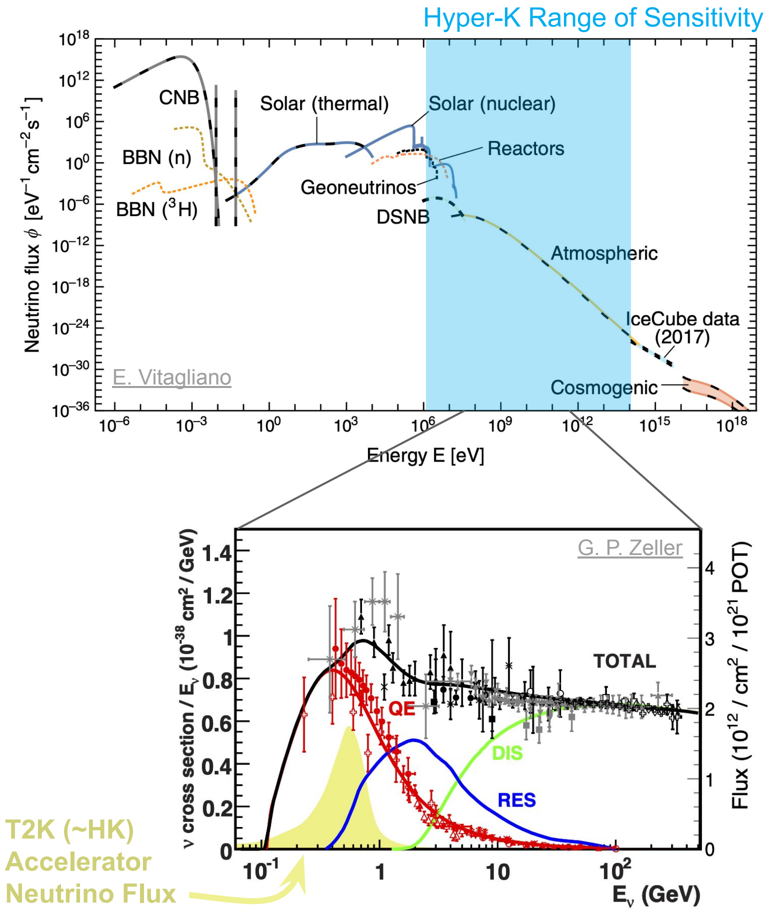
Thank you!

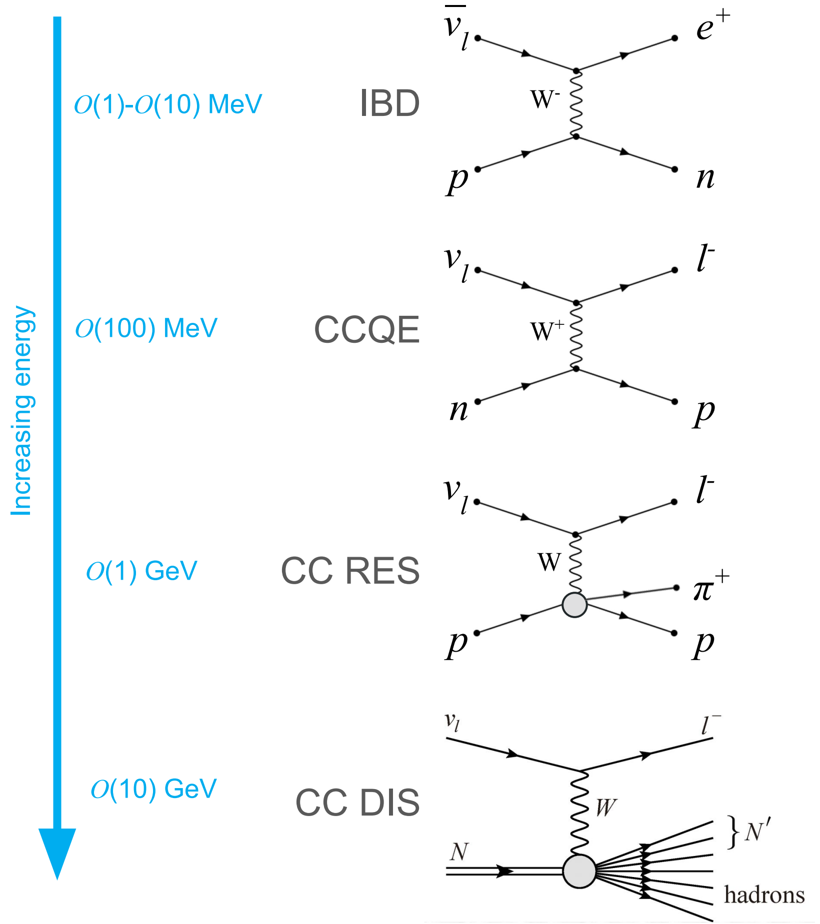


Appendix

Neutrino Interactions

KAVLI IPMU

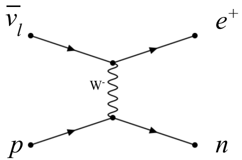


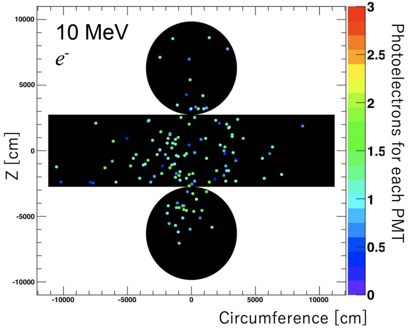


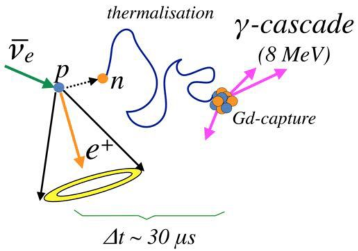
Event Topologies

KAVLI IPMU

IBD







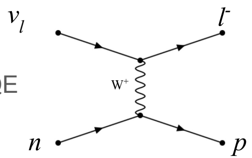
LowE

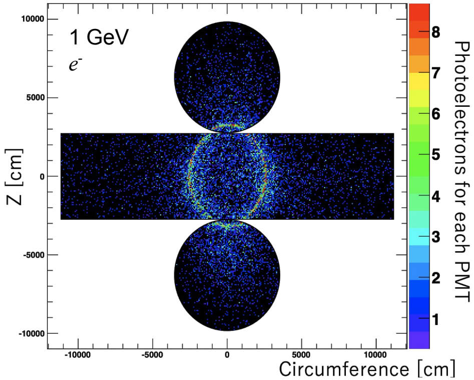
A rich problem for event reconstruction

- Particle identification
  - Sig/bkg discrimination
- Kinematics determination
- Multi-particle separation

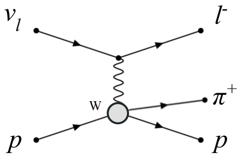
HighE

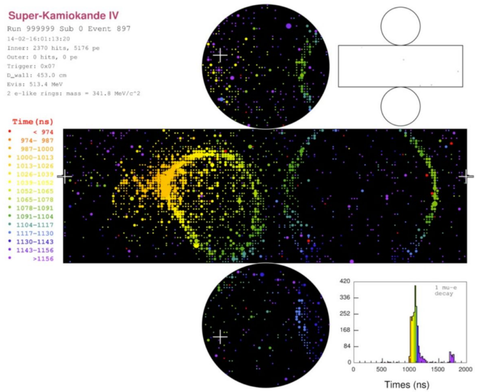
CCQE



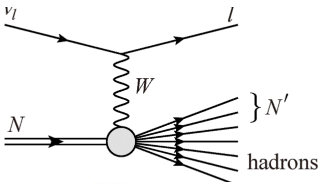


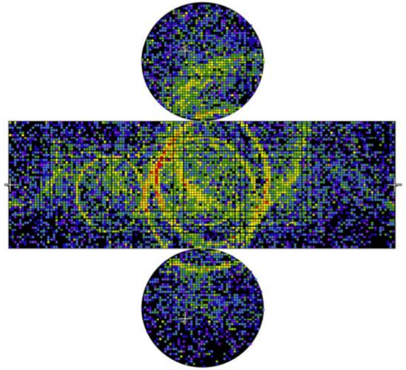
CC RES





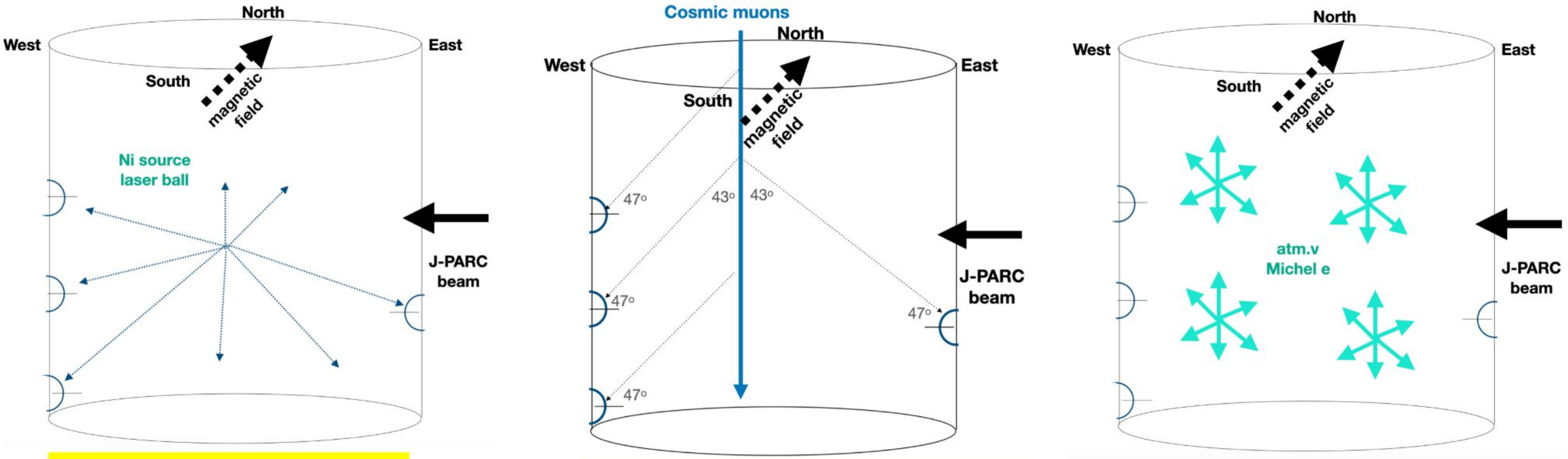
CC DIS





Super-K Calibration Concepts

- Incident angles and hit distribution of the light are different for calibrations
  - PMT angular response can create systematic uncertainty
    - main systematic uncertainty in SNO even with the spherical detector



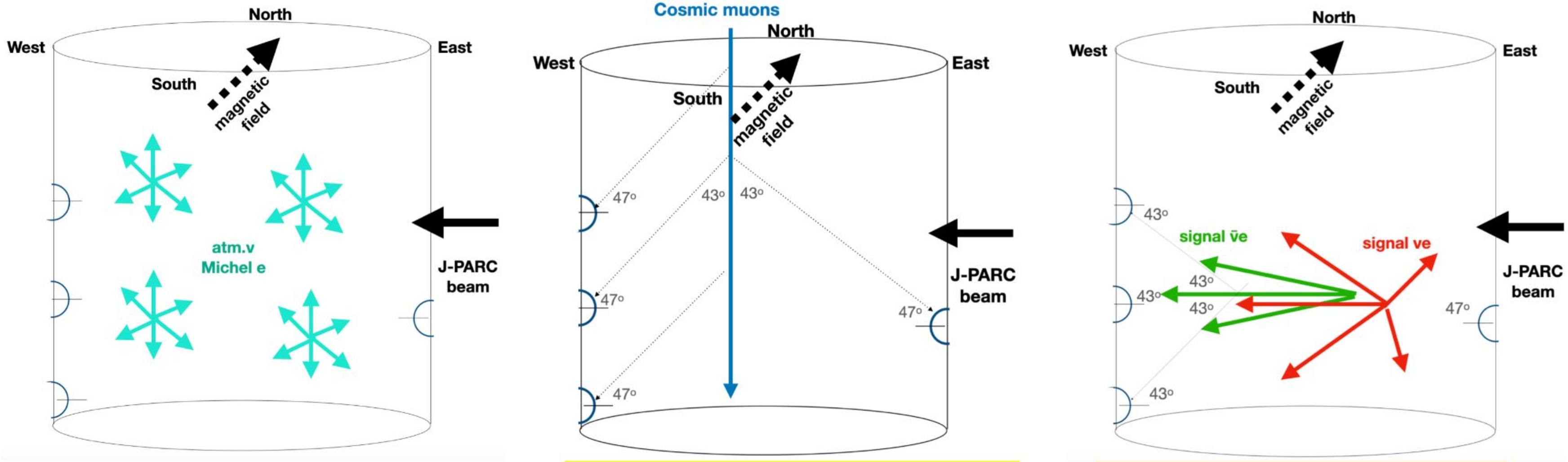
Ni source (QE):
- fixed angle on each PMT

cosmic μ (E scale, stop μ check):
- near 47deg for barrel
- less hit on the top cap

Decay e and π^0 mass checks:
- uniformly distributed

Super-K Calibration Concepts

- Particle identification and Ring counting systematics from atm. ν and cosmic μ
  - Data fit and Data-MC comparison of the likelihood distributions
  - The J-PARC signal is going west and this check even may not cover the uncertainty
    - $\bar{\nu}$ is more forward (west direction) than ν [this understanding is critical for CP violation]



Atmospheric ν checks:
- uniformly distributed

cosmic μ (E scale, stop μ check):
- near 47deg for barrel
- less hit on the top cap

J-PARC beam signal:
- hit on west wall at ~40deg
- difference between ν and $\bar{\nu}$

The fiTQun Reconstruction Algorithm

$$\boxed{L}(\boxed{\mathbf{x}}) = \prod_{j}^{unhit} \boxed{P_j\left(unhit|\mathbf{x}\right)} \prod_{i}^{hit} \boxed{P_i\left(hit|\mathbf{x}\right)} \boxed{f_q\left(q_i|\mathbf{x}\right)} \boxed{f_t\left(t_i|\mathbf{x}\right)}$$

Likelihood to maximise

Candidate track hypothesis

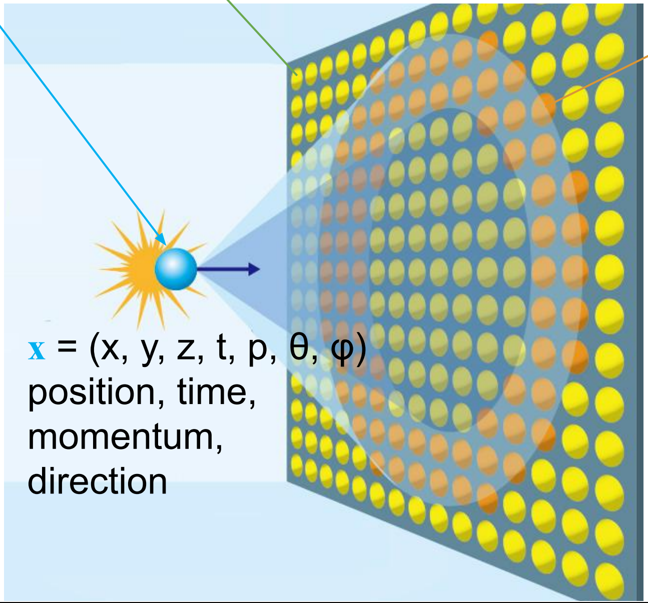
Probability of no hit at PMT

Probability of hit at PMT

Hit charge probability density

Hit time probability density

- Simultaneous fit of all 7 track parameters



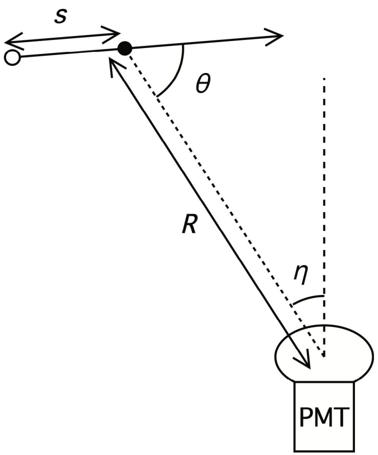
- For a given $\mathbf{x}$, a charge and time PDF is produced for every PMT

S. Tobayama (2016)

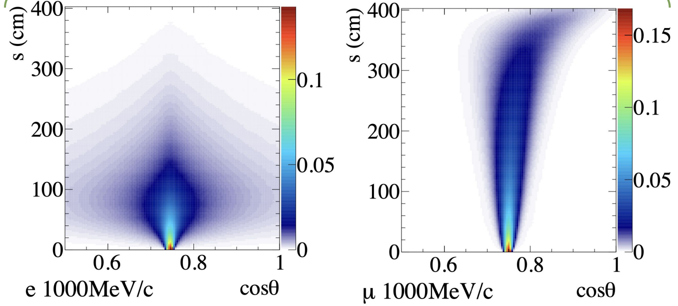
The fiTQun Reconstruction Algorithm

$$L(\mathbf{x}) = \prod_j^{\text{unhit}} P_j(\text{unhit}|\mu_j) \prod_i^{\text{hit}} \{1 - P_i(\text{unhit}|\mu_i)\} f_q(q_i|\mu_i) f_t(t_i|\mathbf{x})$$

- In practice, "predicted charge" is first calculated: $\mu = \mu^{dir} + \mu^{sct}$ which is used in the likelihood evaluation, where the direct light contribution is:

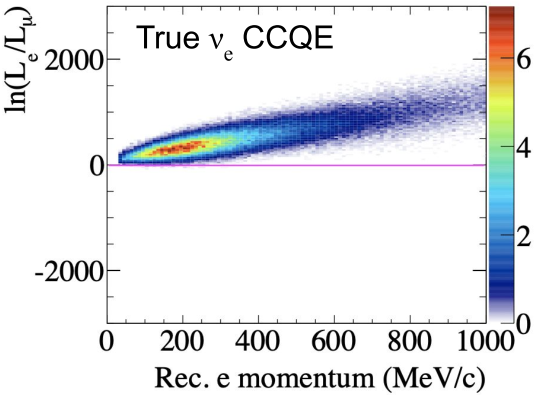


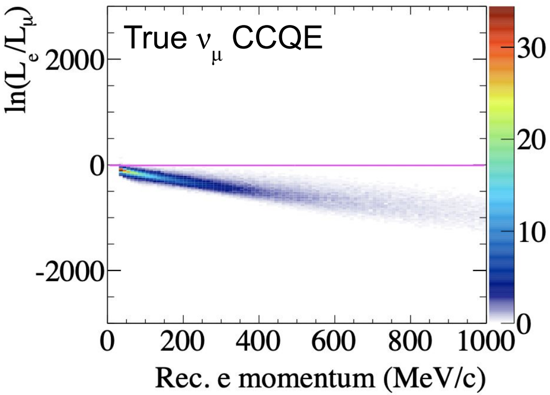
$$\mu^{\text{dir}} = \underbrace{\boxed{\Phi(p)}}_{\text{Light yield}} \overbrace{\boxed{\int ds}}^{\text{Integral over track length}} \underbrace{\boxed{g(p, s, \cos\theta)}}_{\text{Cherenkov emission profile}} \overbrace{\boxed{\Omega(R)}}^{\text{PMT solid angle}} \underbrace{\boxed{T(R)}}_{\text{Light Attenuation}} \overbrace{\boxed{\epsilon(\eta)}}^{\text{PMT angular response}}$$

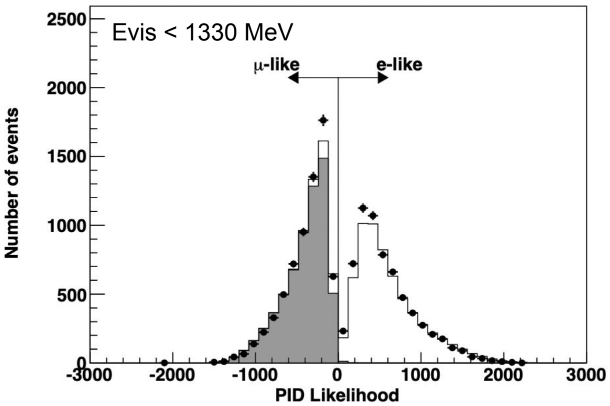


- Particle ID information encoded here and extracted from likelihood comparison of different hypotheses

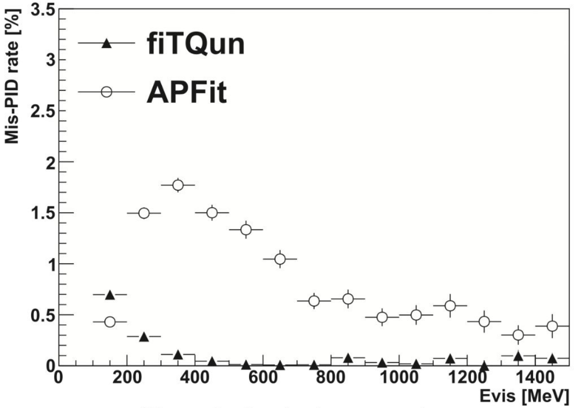
Classification Performance on Super-K Atmospheric ν



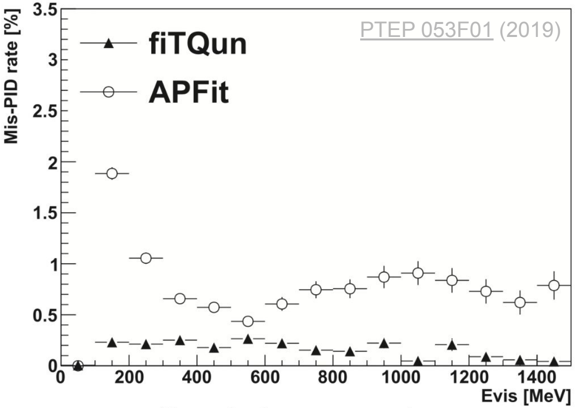




- Particle ID by cut in likelihood ratio
- <1% mis-PID achieved



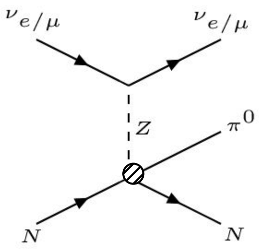
True single-electron events.



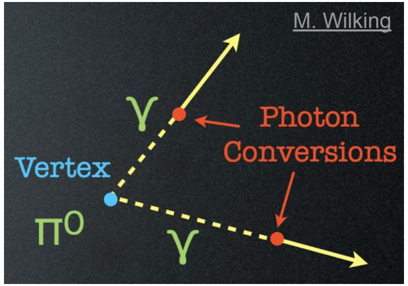
True single-muon events.

Neutral Pion (π^0) Identification

NCπ^0 background



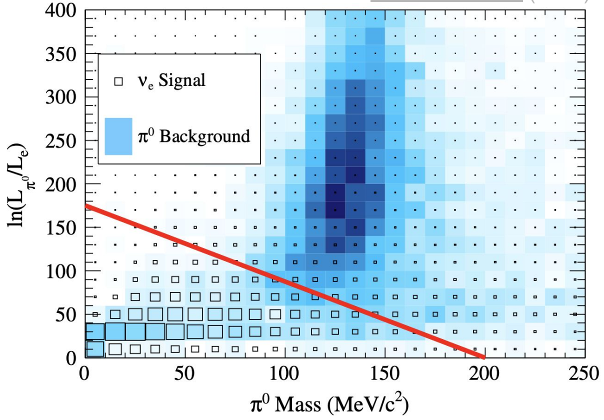
fiTQun Hypothesis

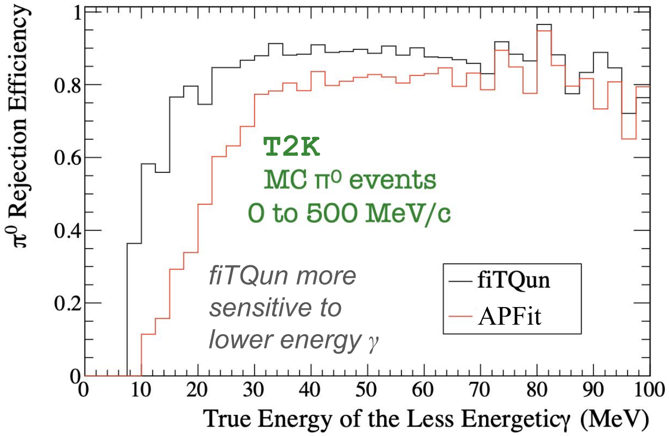


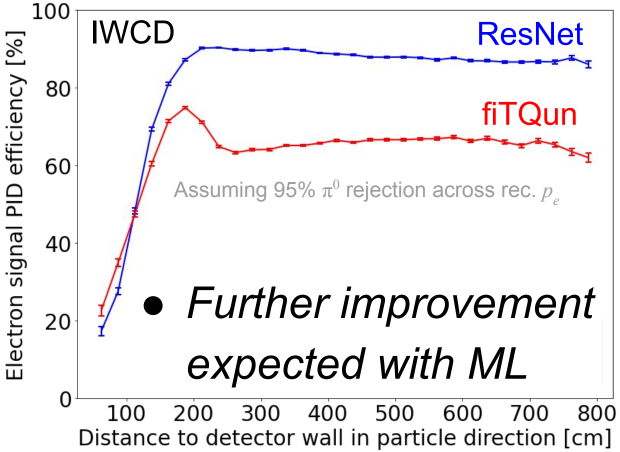
12 parameter fit

- fiTQun hypothesizes two electron tracks from 1 vertex
  - Including new γ conversion length parameters, in addition to previous single track parameters
- 65% background reduction with ~6% signal loss
  - ~Twice more than APFit

PRL112 061802 (2014)







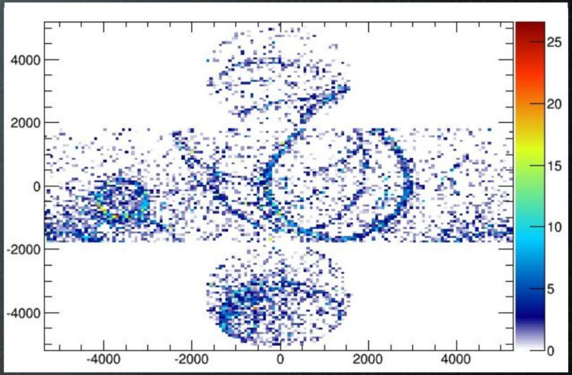
- *Further improvement expected with ML*

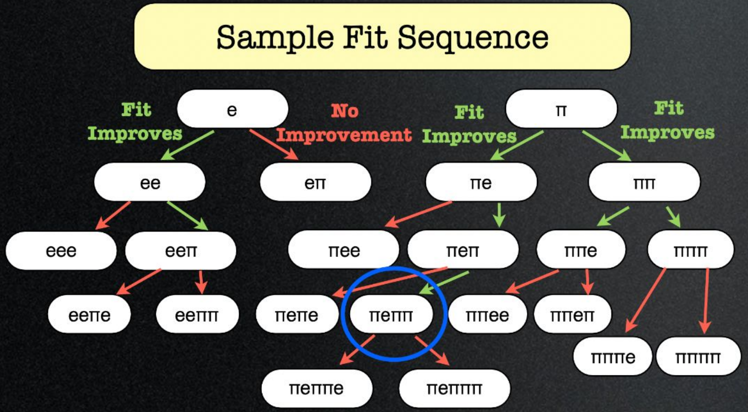
Multi-ring Reconstruction

M. Wilking

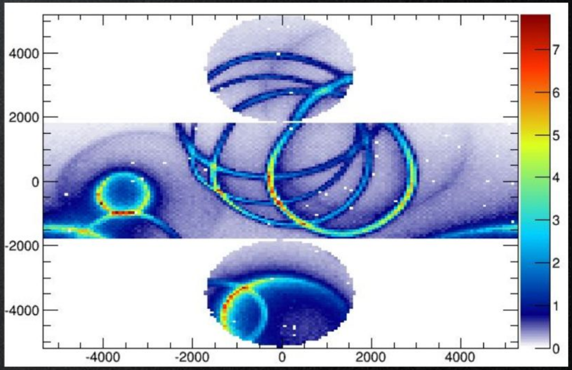
- FiTQun can currently reconstruct up to 6 rings in a staged approach
  - Each step sequentially adds a "track-like" (π^+) or "shower-like" (e) ring
  - The chain terminates when adding a ring does not sufficiently improve the fit
- Ring counting & PID are significantly improved

Hit Charge Distribution

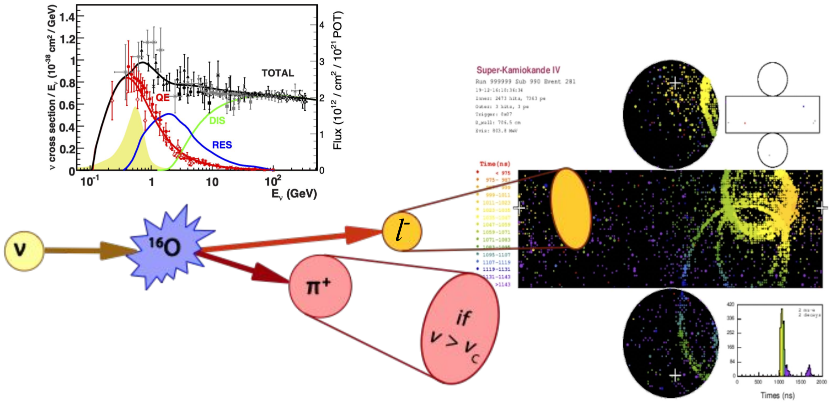


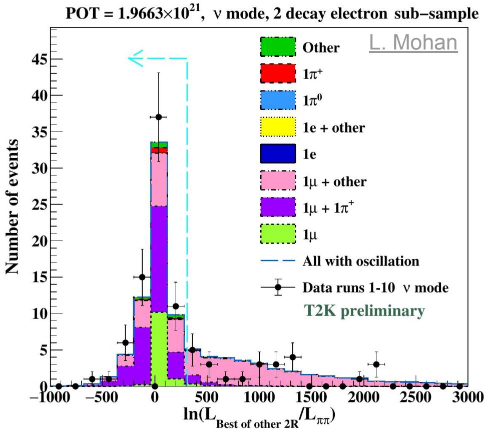


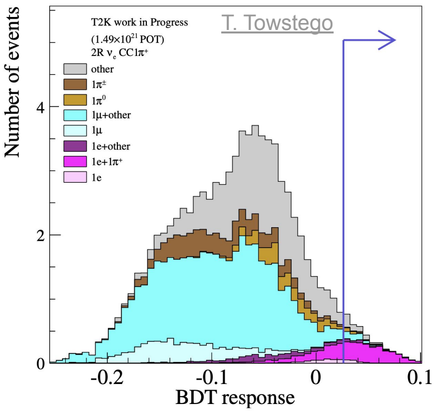
Reconstructed "Mean" Charge



ν Multi-ring (Lepton + π±) Samples





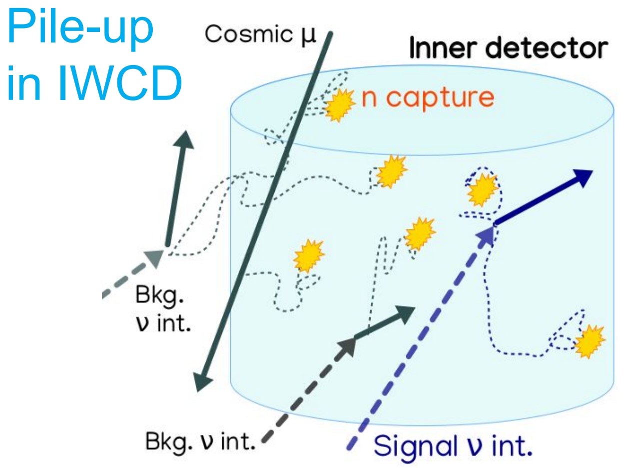


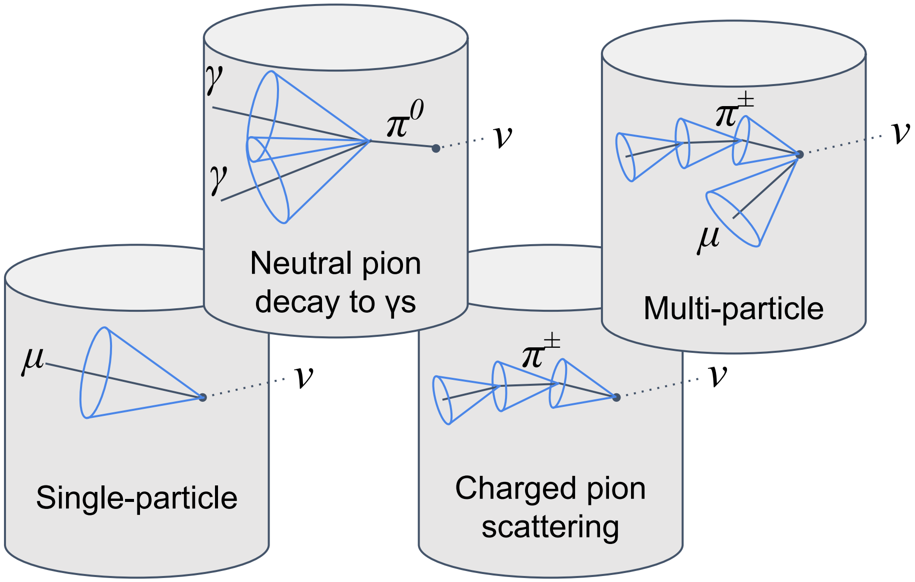
- Various combinations of multi-ring likelihoods can be used to explicitly reconstruct final states
- *Can further improvements come from ML?*

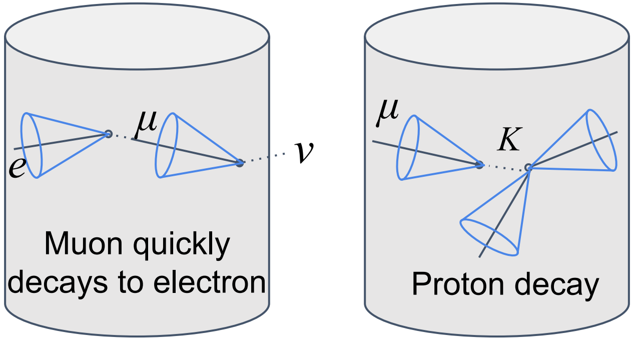
T2K work-in-progress	ν_μ ($\mu + \pi^\pm$)	ν_e ($e + \pi^\pm$)
Efficiency (%)	83 to 93	60 to 70
Purity (%)	30 to 48	50 to 60
Increase in oscillation sample statistics (%)	30	4 to 12

Multi-Vertex Event Topologies

- So far have considered only single-vertex events
- Need to consider multi-vertex events too
  - Application of ResNet ongoing

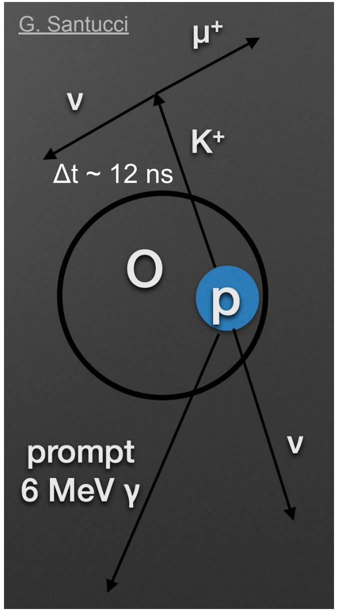


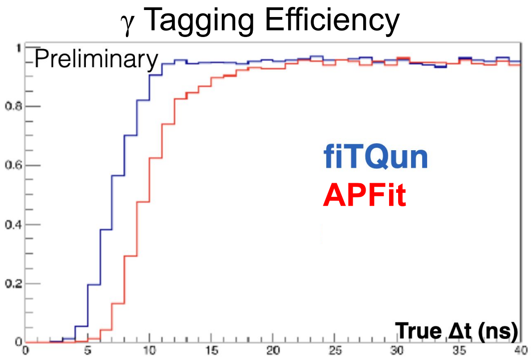




- Design dedicated fiTQun hypotheses based on the signal event topology

- Fit $\mu + \gamma$ tracks, assuming same vertex but different times

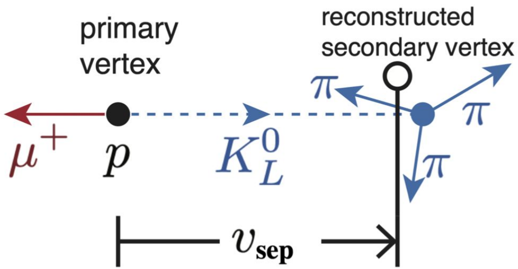




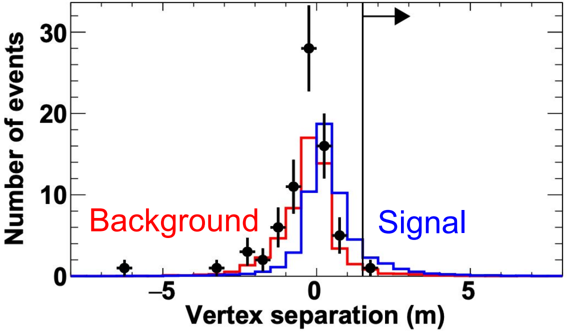
- 9.4% → 13.9% (1.5x) efficiency gain with similar background

arXiv:2208.13188

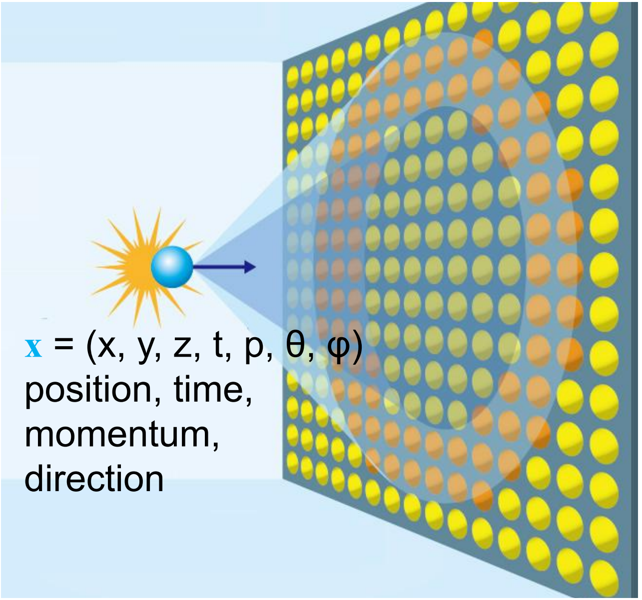
- Assume second vertex for additional rings after the first



- Improved background rejection (~⅓) with similar efficiency (~90%) compared to APFit

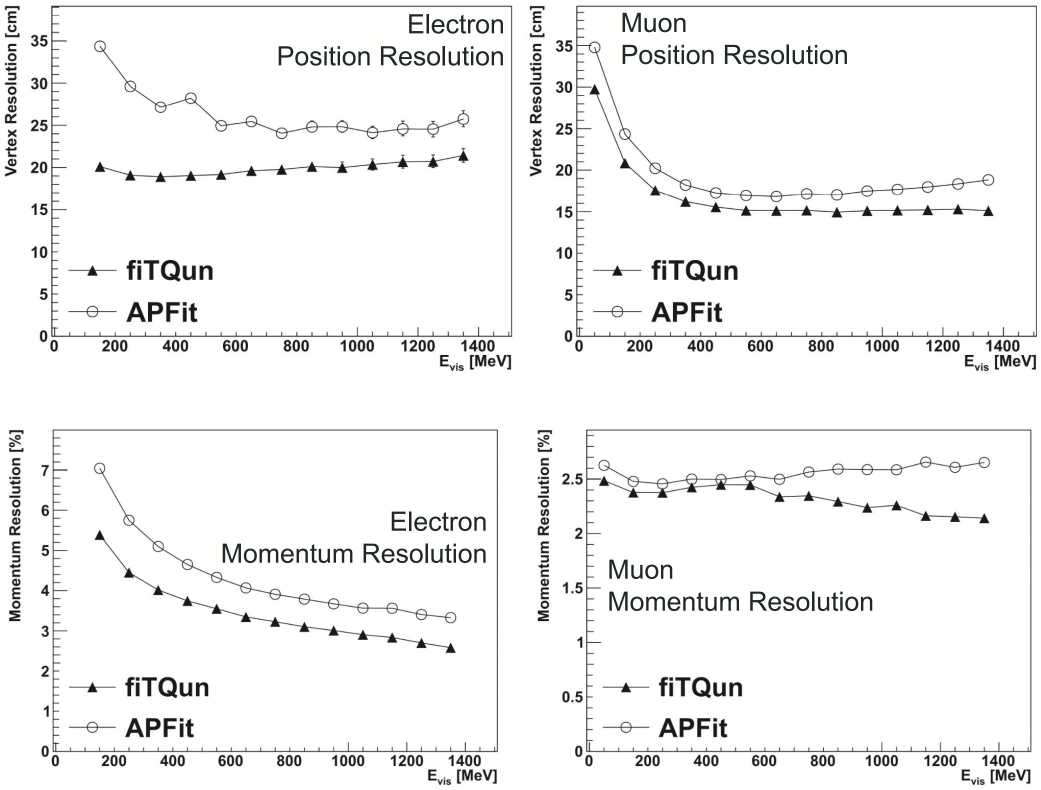


- fiTQun vertex position, momentum, and direction reconstruction improved relative to APFit



True CCQE (1-ring) Events

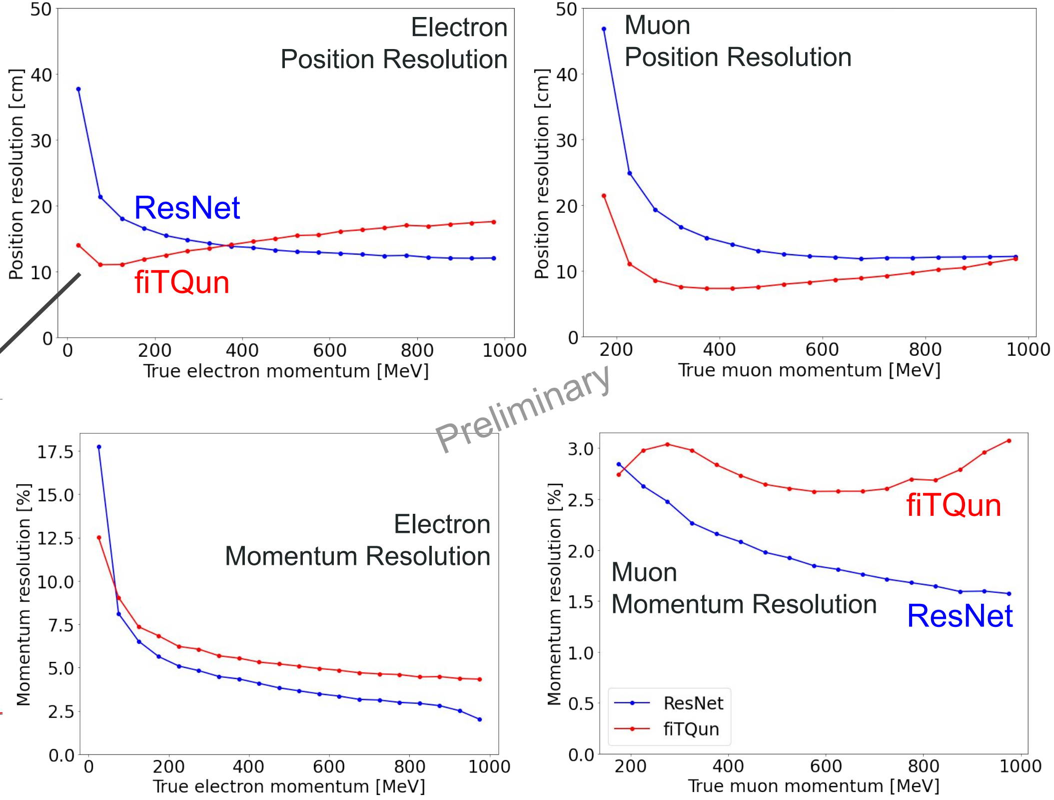
PTEP 053F01 (2019)

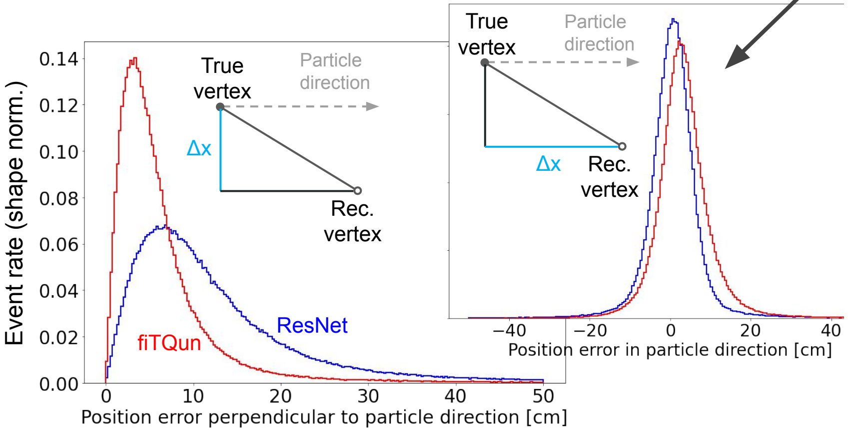


Reconstruction Performance with DL in IWCD

- Using same ResNet network as classification
  - Output reconstructed quantities instead of PID variables
- Momentum resolution improved, but position reconstruction lacking perpendicular to particle direction
  - Likely since ResNet is not yet using hit timing information

Particle Gun Events





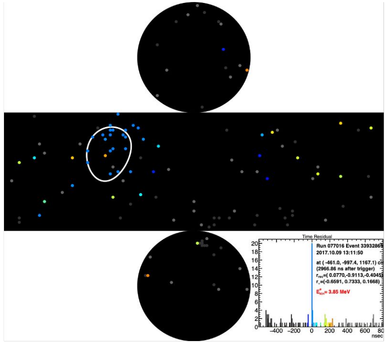
Computing Time Improvement

- Growing MC (and data) sample sizes in high precision era
- Event reconstruction becoming a computing time limiting factor
  - Especially in systematic error studies varying a large number of detector parameters
- fiTQun: ~90 seconds per event on CPU (for e, μ, $\pi 0$ hypotheses in IWCD)
  - Multi-ring events >~5 minutes
- ResNet: ~6 ms per event on GPU (for classification and e, μ regression)
- Factor of 10^5 speed-up
  - But actual throughput will depend on how many GPUs you can afford
- Assuming the size and cost of the small CPU and GPU clusters at IPMU:

  ~ 5000x more throughput with the $ spent on GPUs instead

Low Energy (2.5 - 8 MeV) Applications

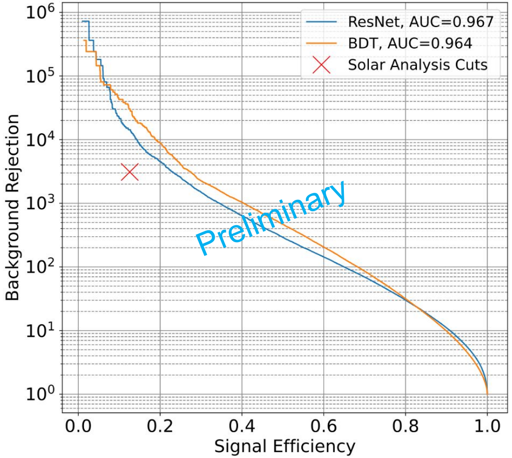
- Sparser images → CNNs tend to perform less well
  - e.g. ResNet below is susceptible to noise model



Typical low energy data event with PMT relative times.
Reconstructed Cherenkov cone in white.

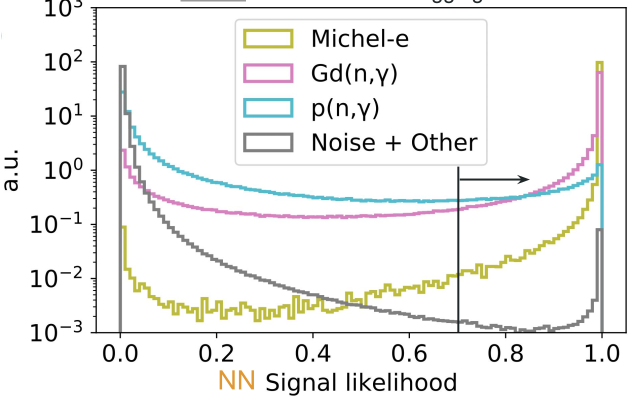
- Investigating alternative networks, e.g. DGCNN
- Though simpler BDT/NN using input features showing similar performance

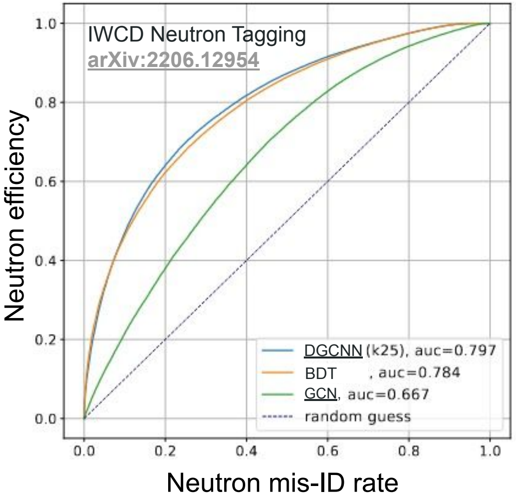
A. Yankelevich: Super-K Solar ν Classification



1/FPR vs Signal Efficiency. All events 2.49 MeV < E_{kin} < 3.49 MeV.

S. Han: SK-Gd Neutron Tagging

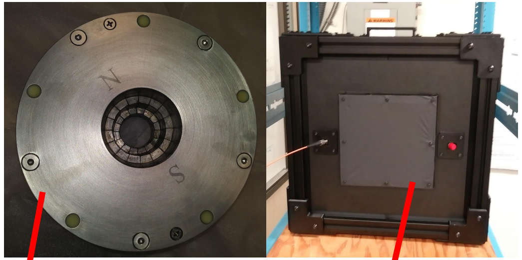


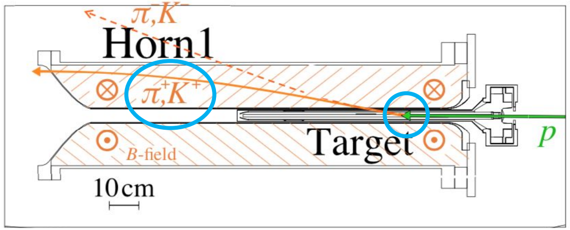


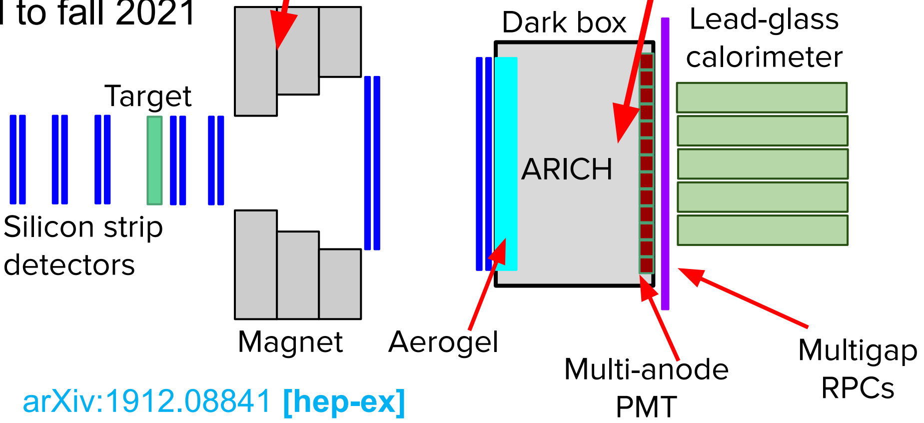
Hadron Production for Neutrino Flux Modeling

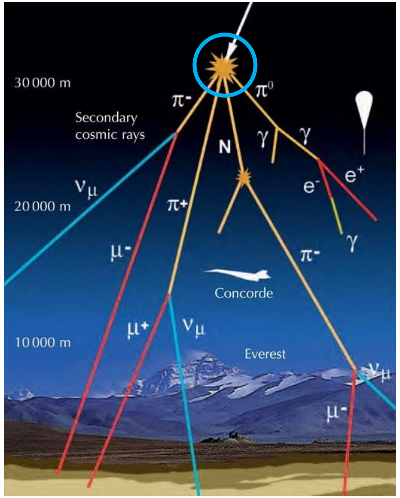
- **E**xperiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**estbeam **I**n **C**hicagoland
- Constraints on beam and atmospheric ν flux predictions
  - For T2K, SK, HK, NOνA, DUNE
- At Fermilab Test Beam Facility
  - **2018**: Pilot run, paper finished collaboration review
  - **2020**: 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





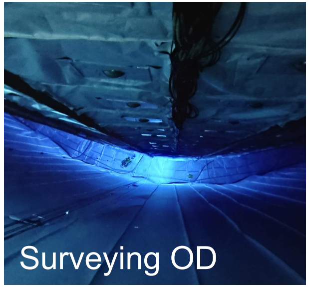


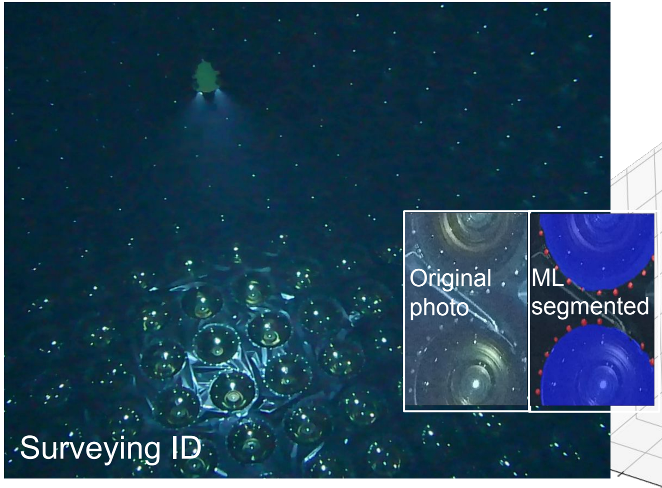


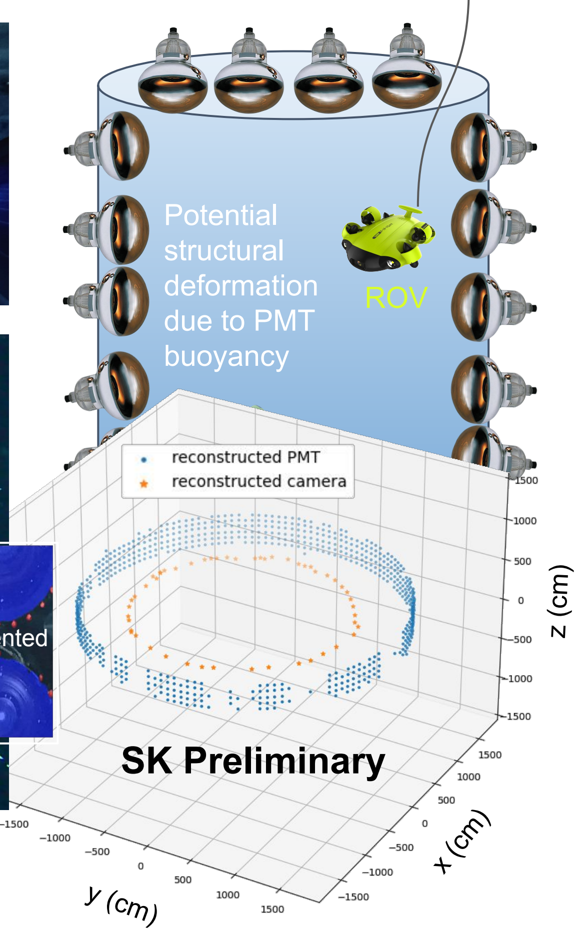
arXiv:1912.08841 **[hep-ex]**

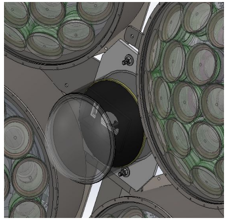
Novel Detector Geometry Calibration

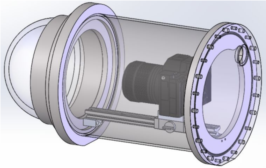
- First underwater survey of Super-K detector geometry
- Challenging photogrammetry analysis ongoing
  - Demonstrated with a ring of ID barrel PMTs
- Developing new systems for Hyper-K and IWCD
  - Critical for a moving detector

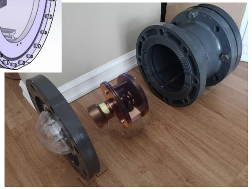








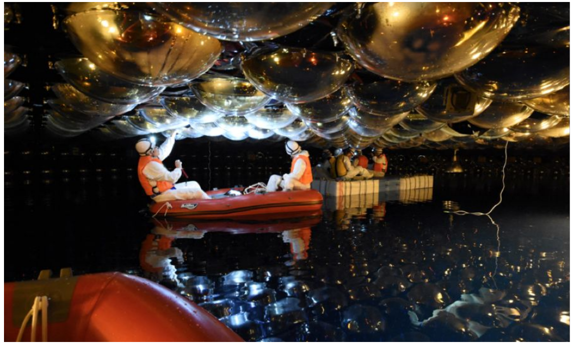


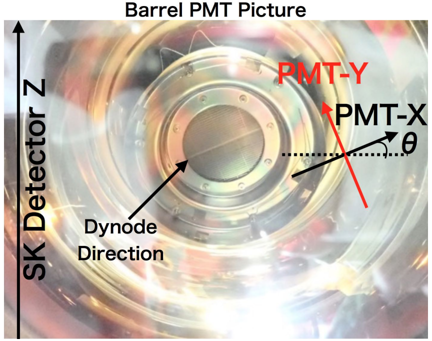


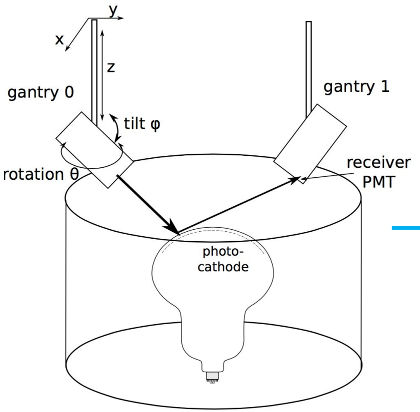
Precise and Comprehensive PMT Characterization

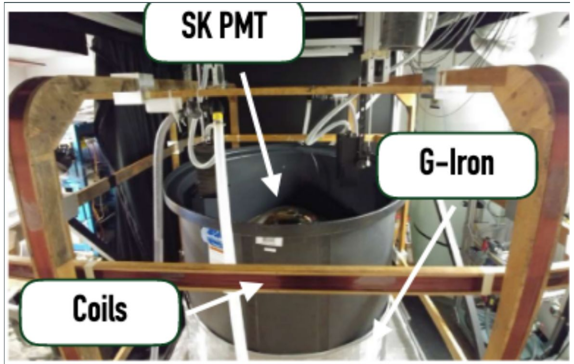
- Uncertainties in PMT response is a major systematic in water Cherenkov detectors
- Preparing ex-situ facilities for campaign of pre-calibration measurements

Magnetic field and PMT orientation survey throughout Super-K

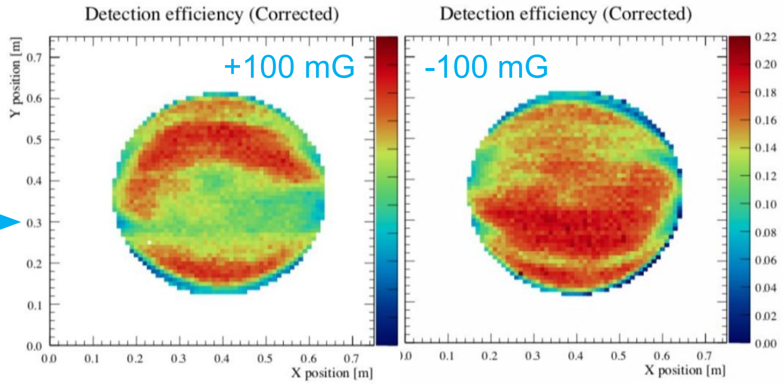








PTF setup



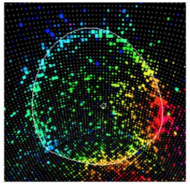
Super-Kamiokande - 25 Years of ν and Astrophysics

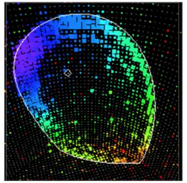
KAVLI IPMU

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21

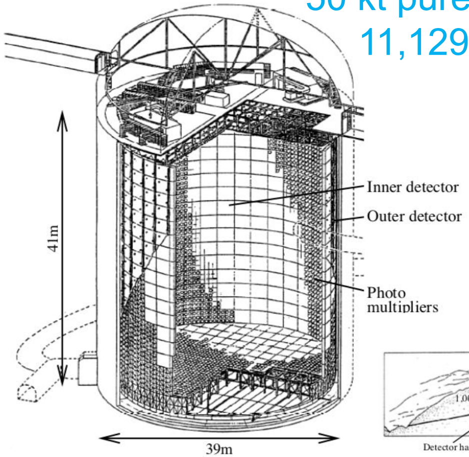
SK-I → Accident → SK-II → Full repair → SK-III → SK-IV → Refurbish → V → Gd

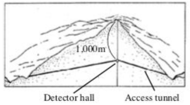
- 1998: discovery of atmospheric ν flavor transformation
- 2001: discovery of solar ν flavor transformation with SNO
- 2004: confirmation of atmospheric ν oscillation by K2K
- 2012: first evidence for τ appearance
- 2013: first direct indication of ν osc. matter effects
- Ongoing searches for nucleon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

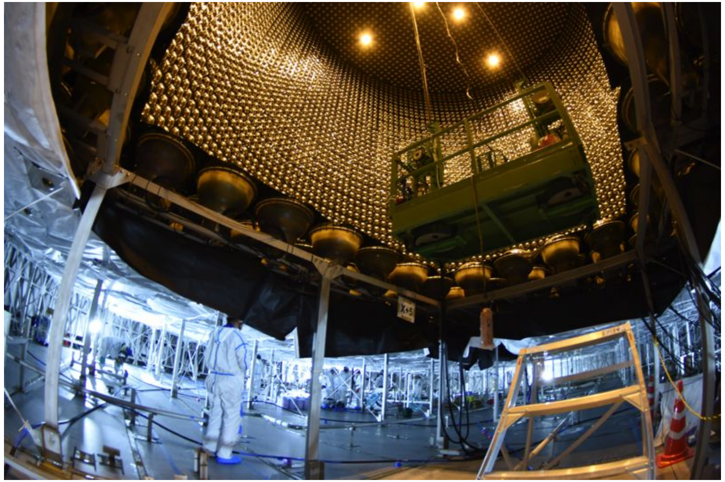

ν_e-like


ν_μ-like

50 kt pure water
11,129 PMTs

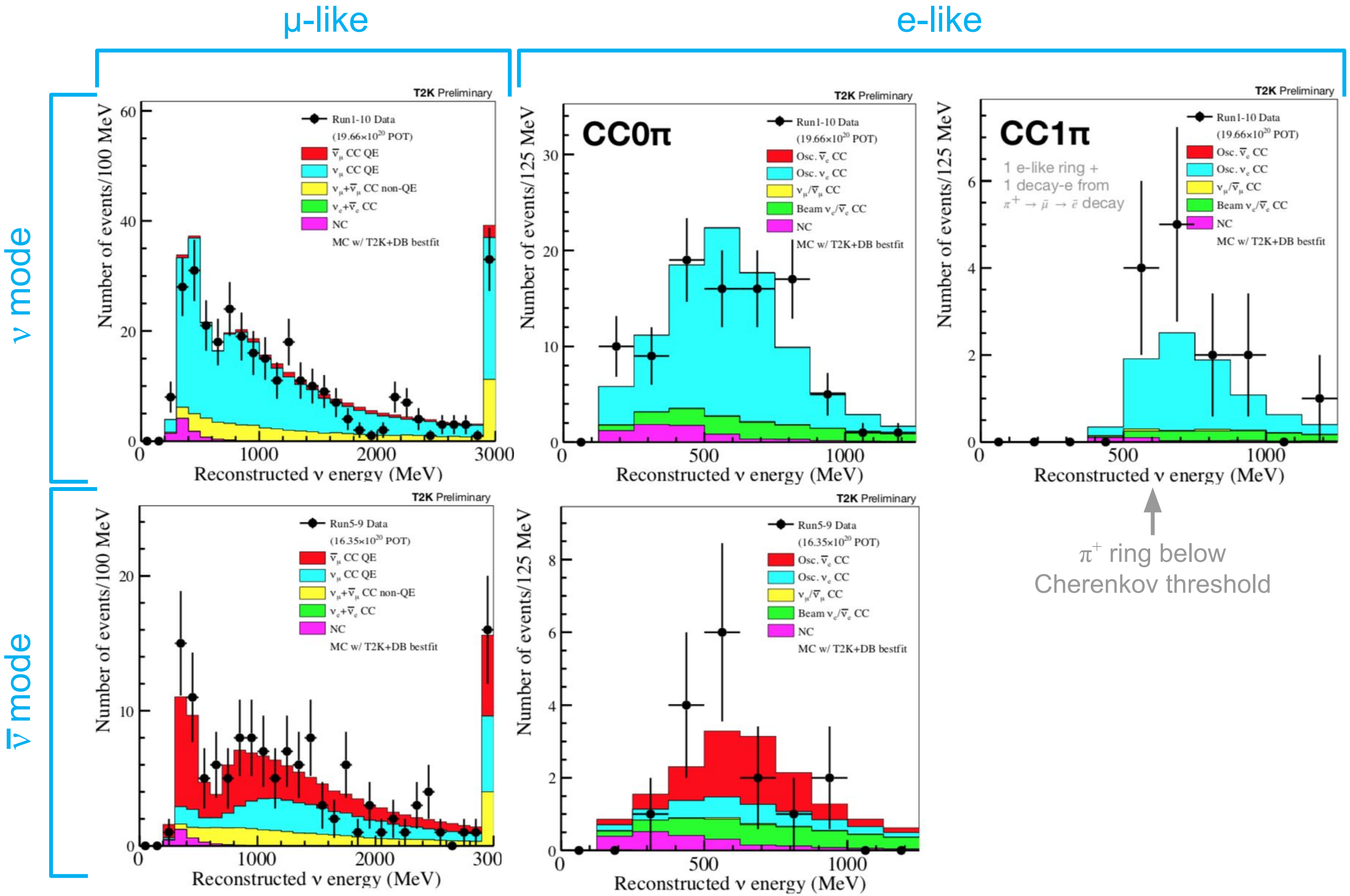






T2K-SK Single-Ring Datasets for CPV Analysis

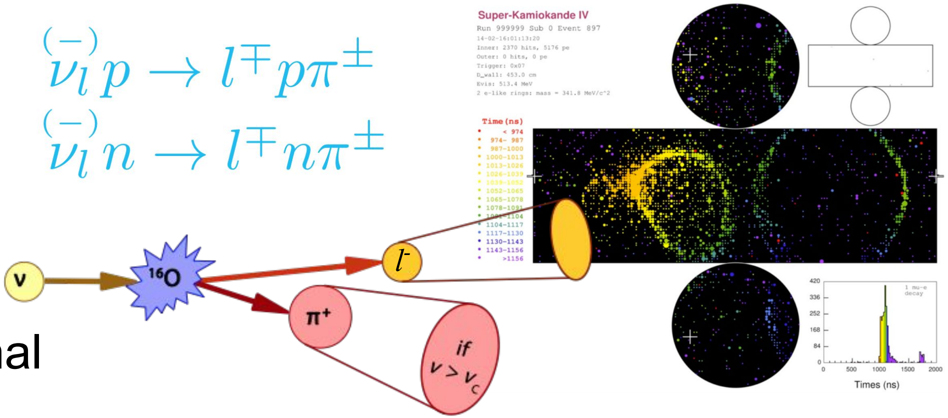
- Updated Super-K datasets used for 2020 CPV analysis
  - ν_μ disappearance
  - ν_e appearance
  - Only one visible Cherenkov ring



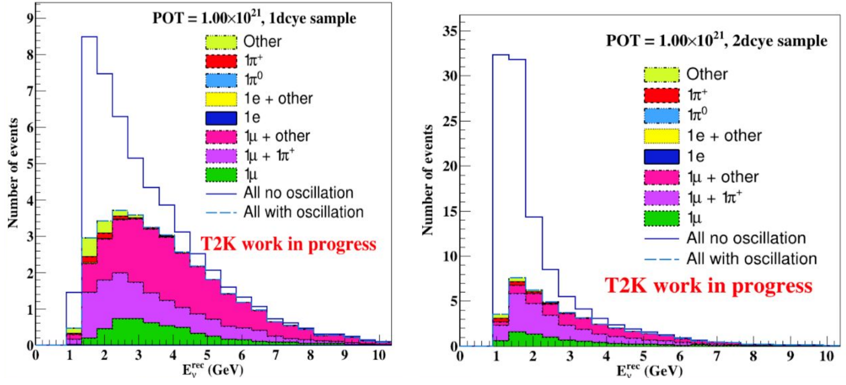
T2K-SK Multi-Ring Datasets for Future Analyses

- 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

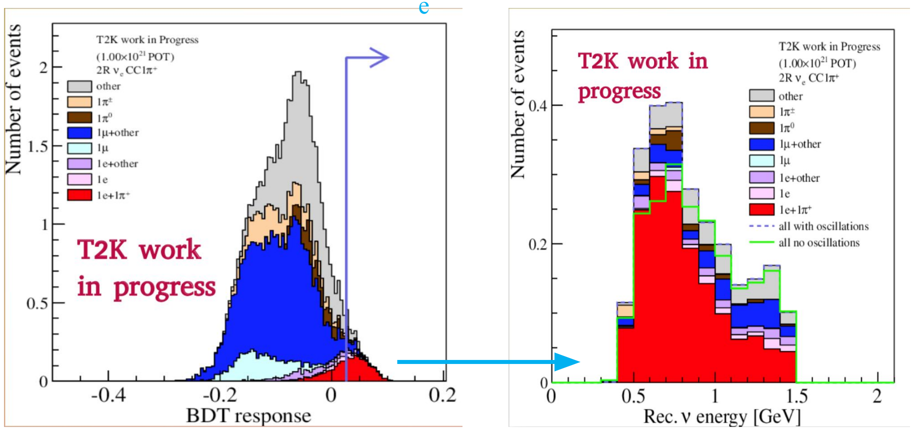
$$\overset{(-)}{\nu}_l\, p \rightarrow l^{\mp} p \pi^{\pm}$$
$$\overset{(-)}{\nu}_l\, n \rightarrow l^{\mp} n \pi^{\pm}$$



ν_μ CC1π^+



ν_e CC1π^+



Rich Science with Hyper-Kamiokande

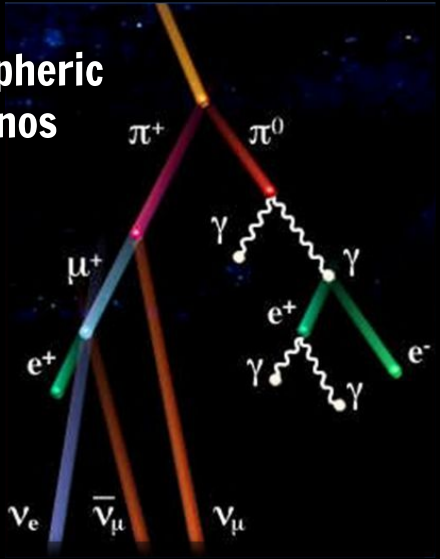
Design report: arXiv:1805.04163

KAVLI IPMU

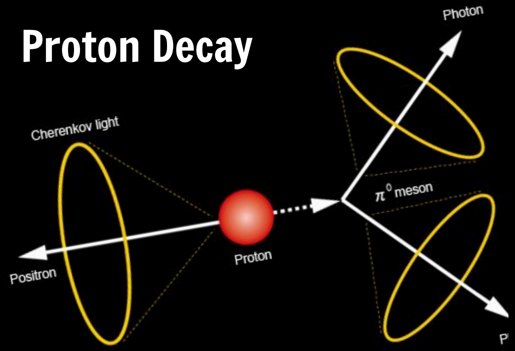
Multi-Messenger: Supernova, GW, ...

Dark Matter

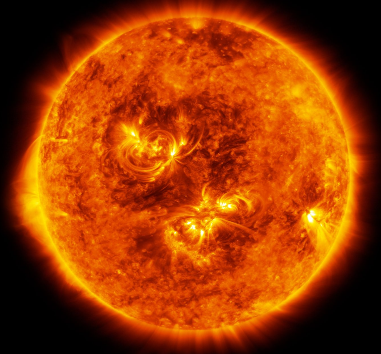
Atmospheric Neutrinos



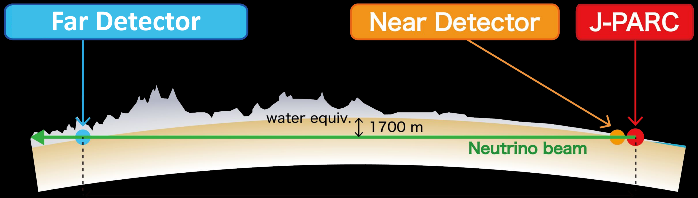
Proton Decay



Solar Neutrinos



Accelerator Neutrinos

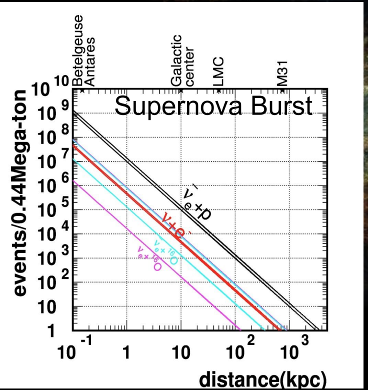


Rich Science with Hyper-Kamiokande

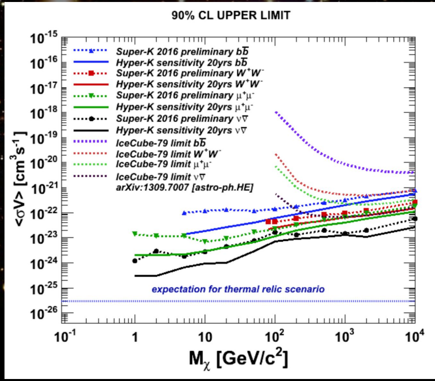
Design report: arXiv:1805.04163

KAVLI IPMU

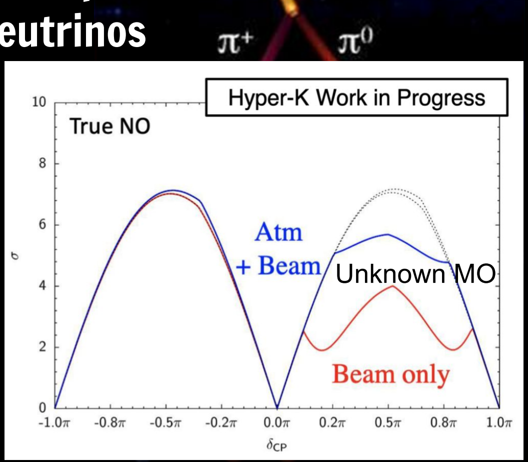
Multi-Messenger
[arXiv:2101.05269]



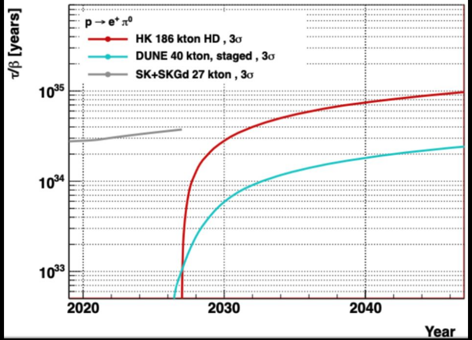
Dark Matter



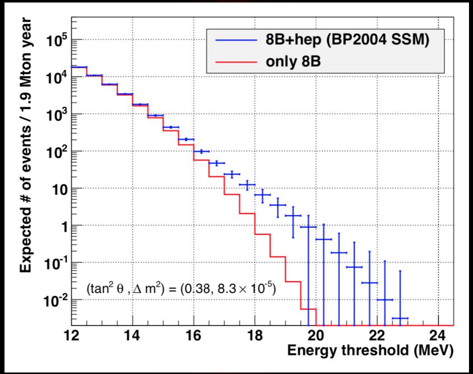
Atmospheric Neutrinos



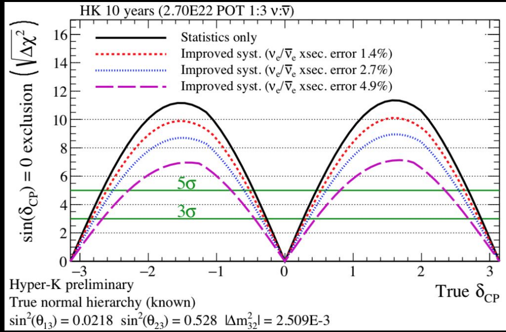
Proton Decay

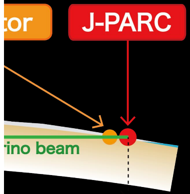


Solar Neutrinos



Accelerator Neutrinos



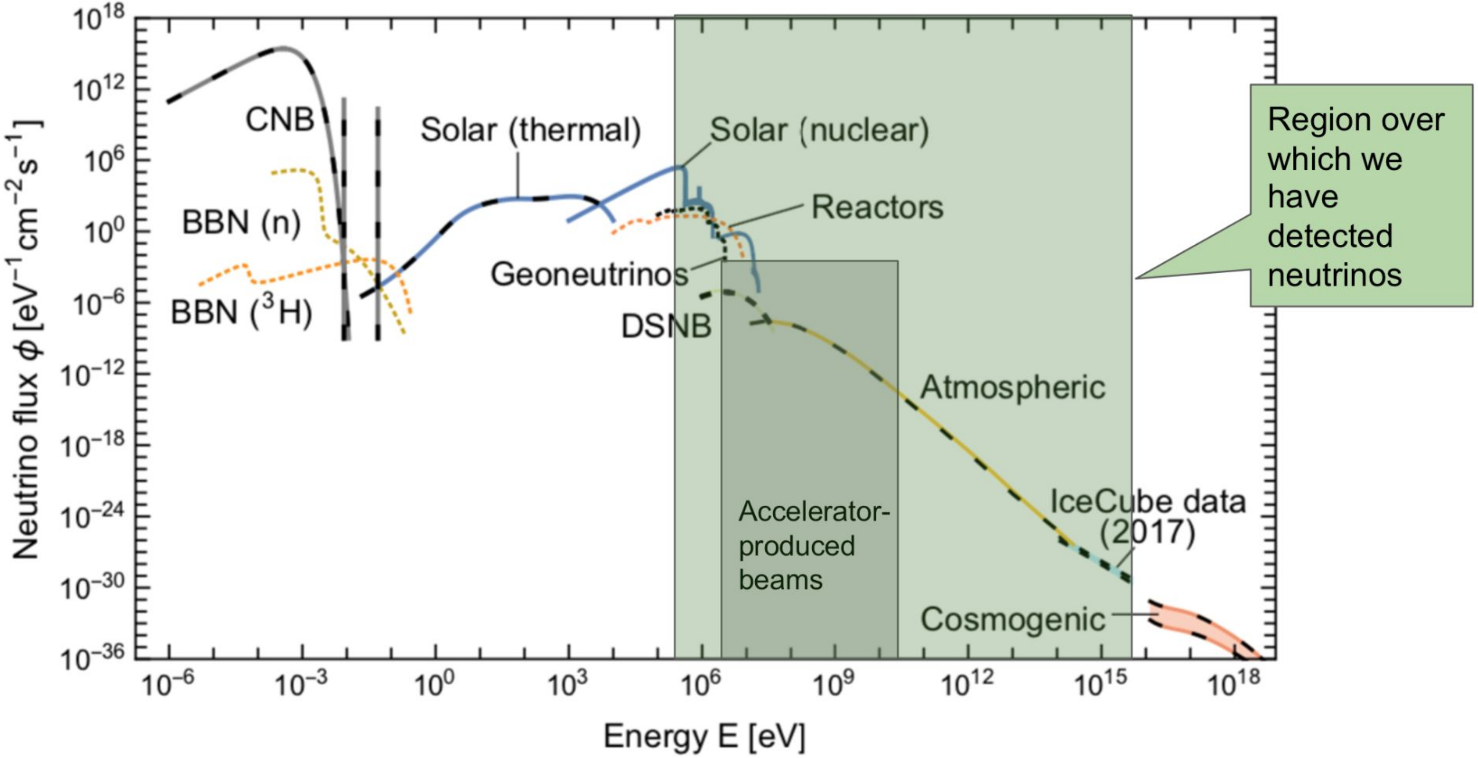


Neutrino Flux Spectra

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

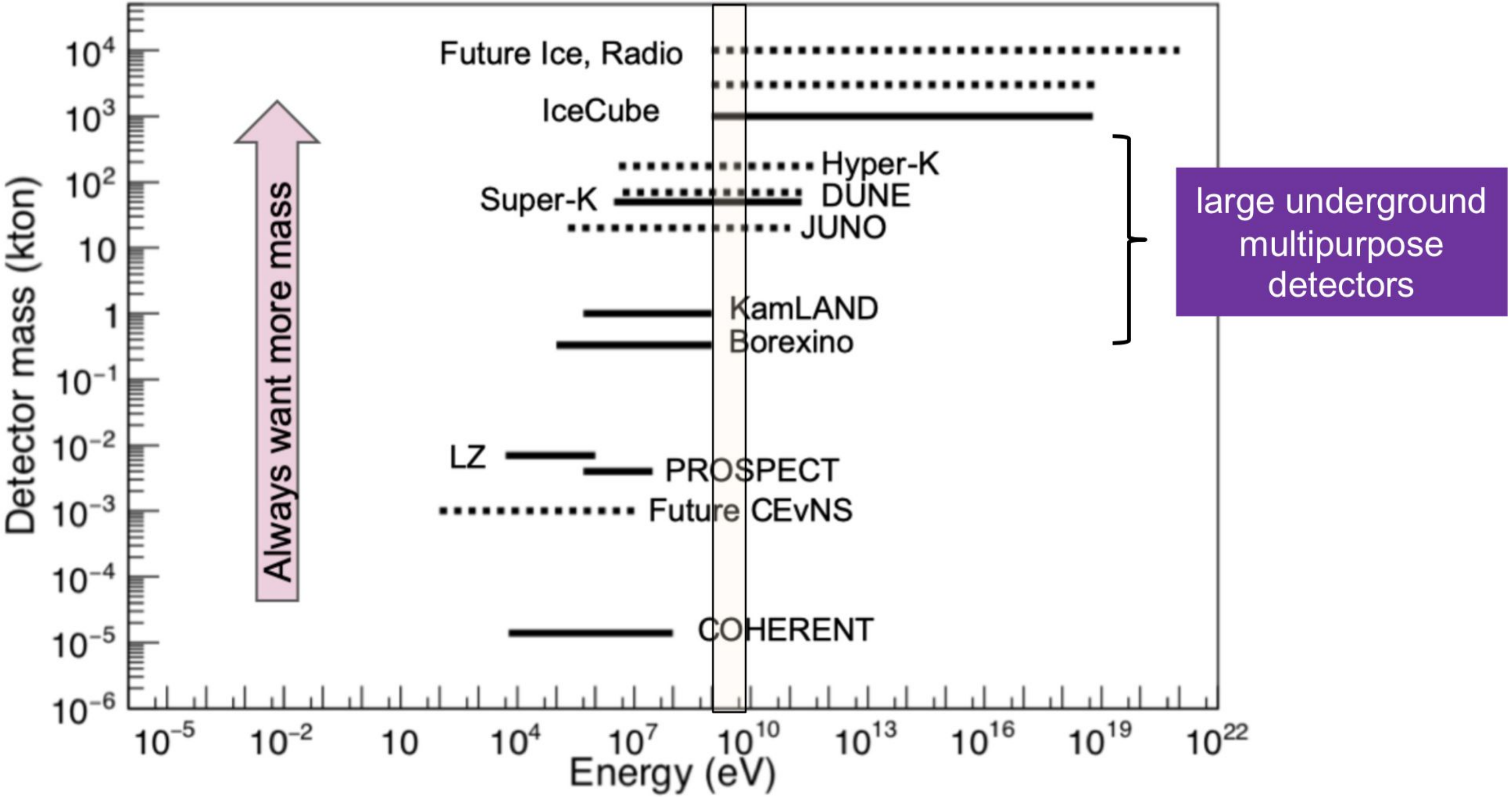
Kate Scholberg (Duke), TIPP 2021

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

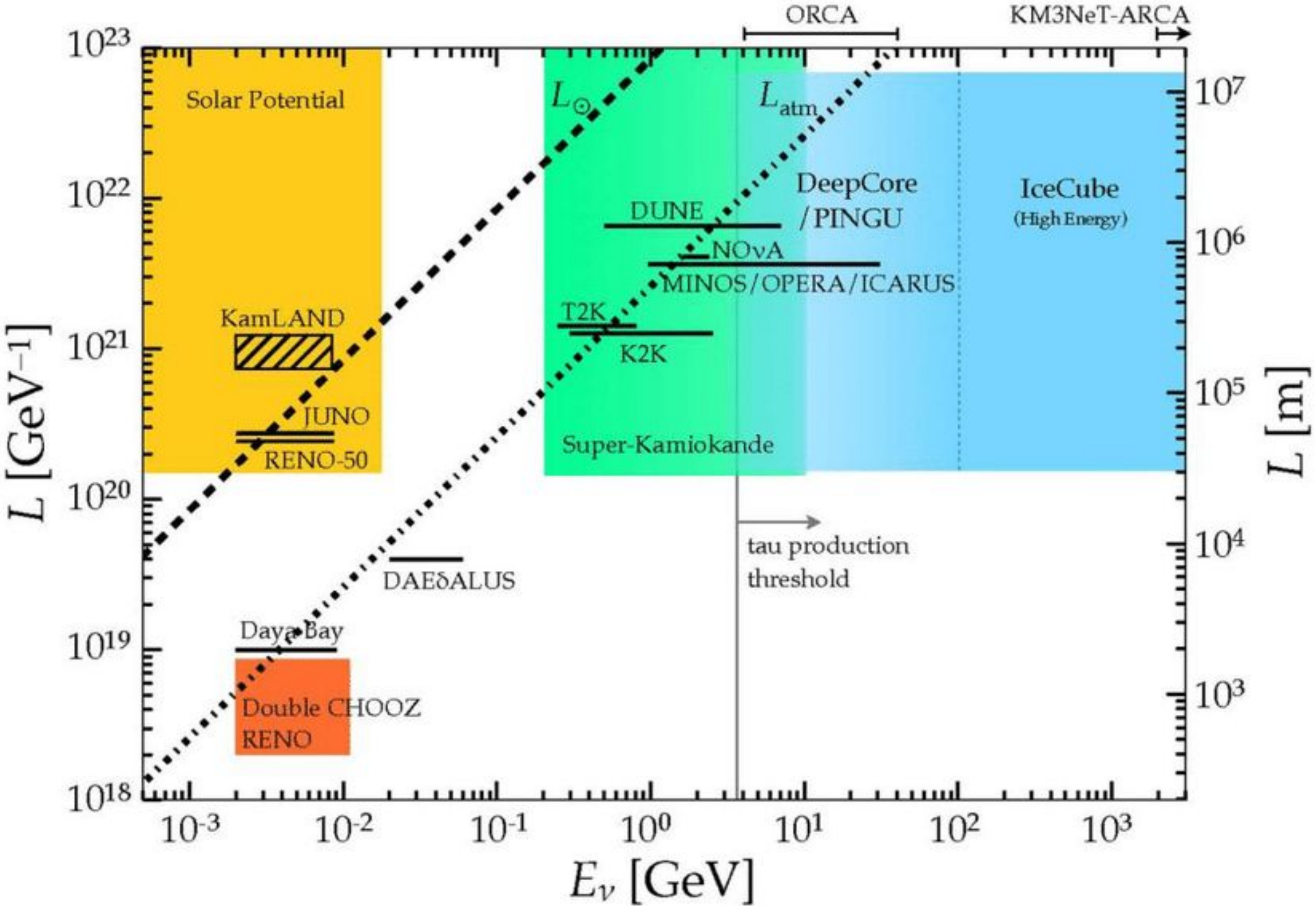


Neutrino detector masses and sensitive energy ranges

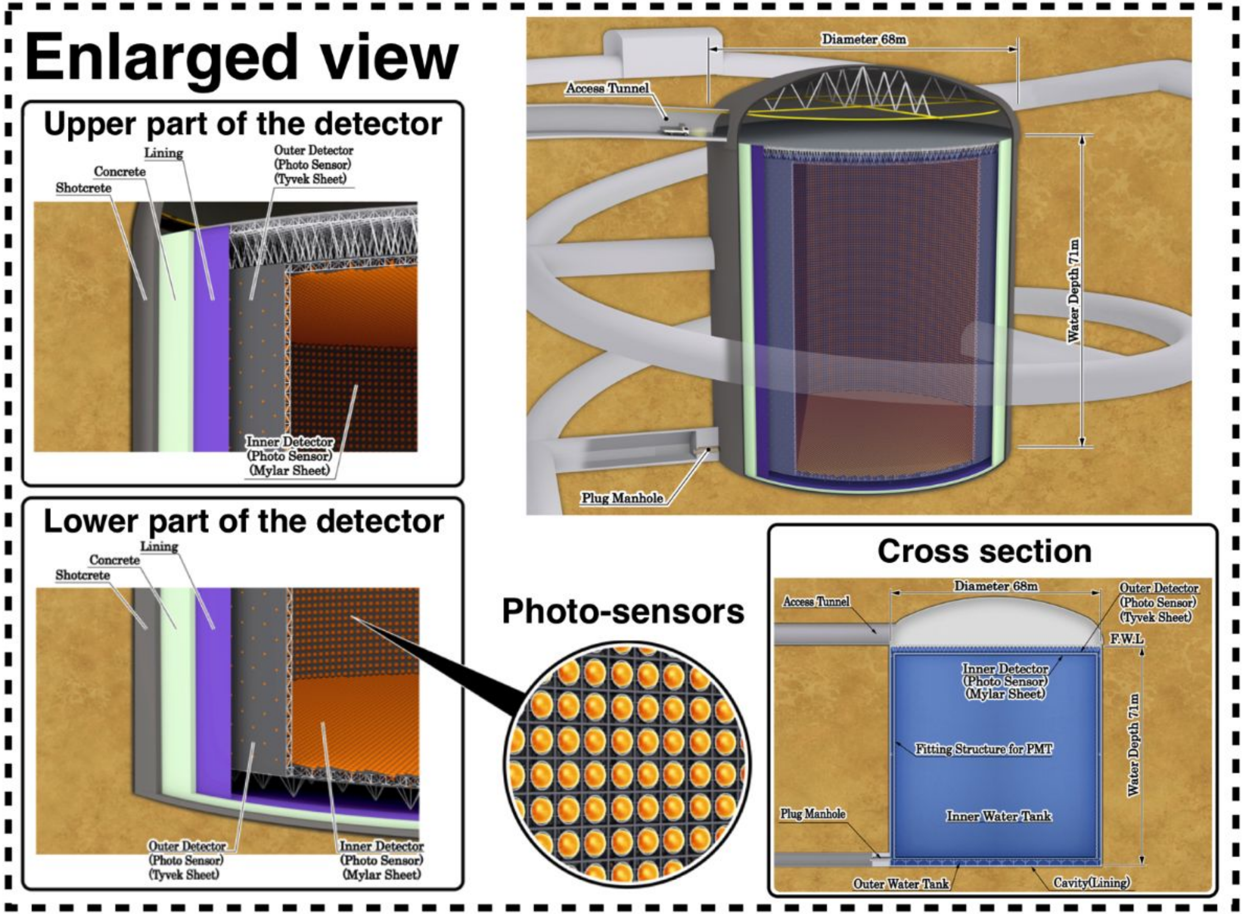
Kate Scholberg (Duke), TIPP 2021



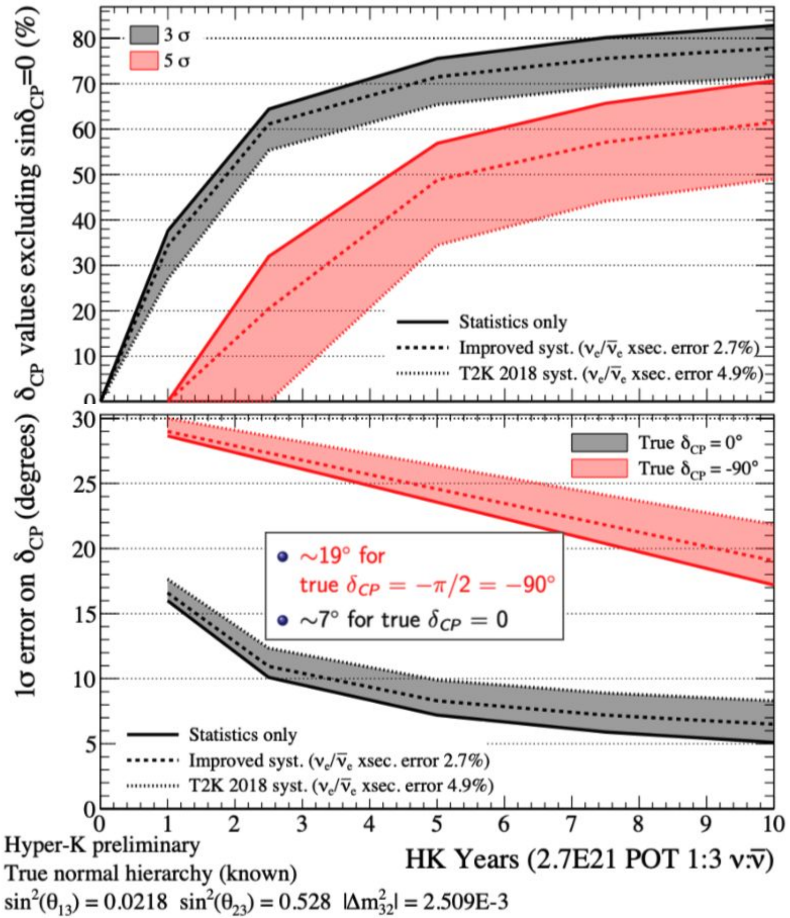
Neutrino Oscillation L/E Scales

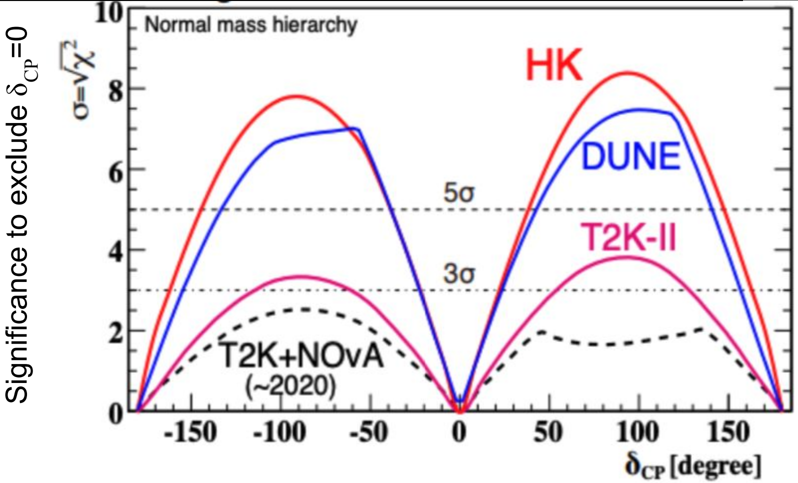


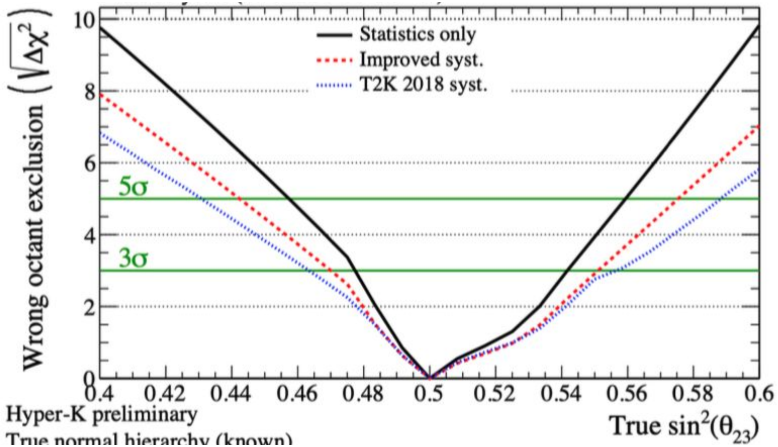
Hyper-K Far Detector Concept



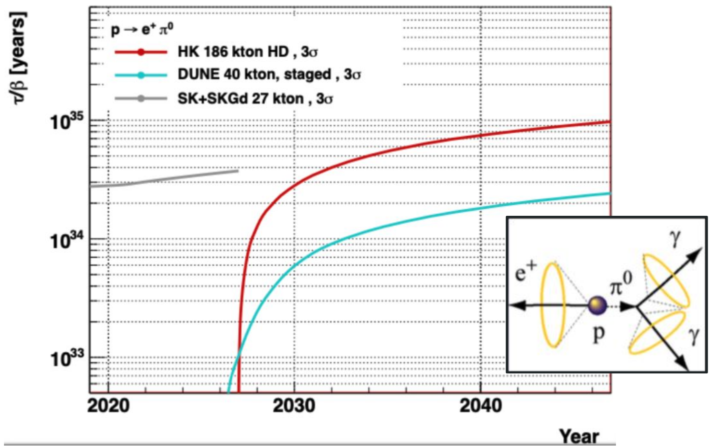
Hyper-K Long-Baseline Physics

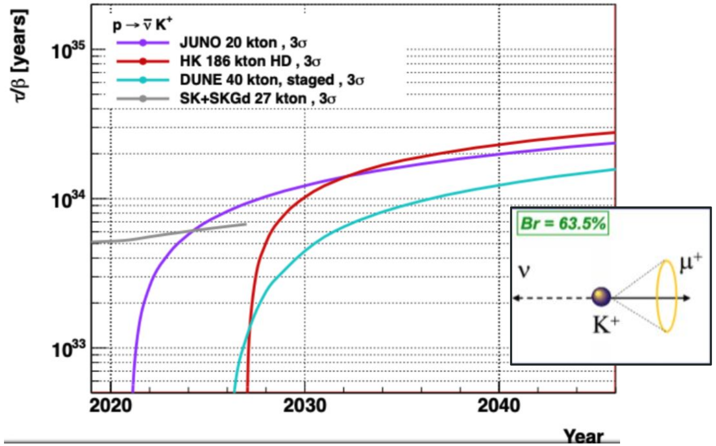


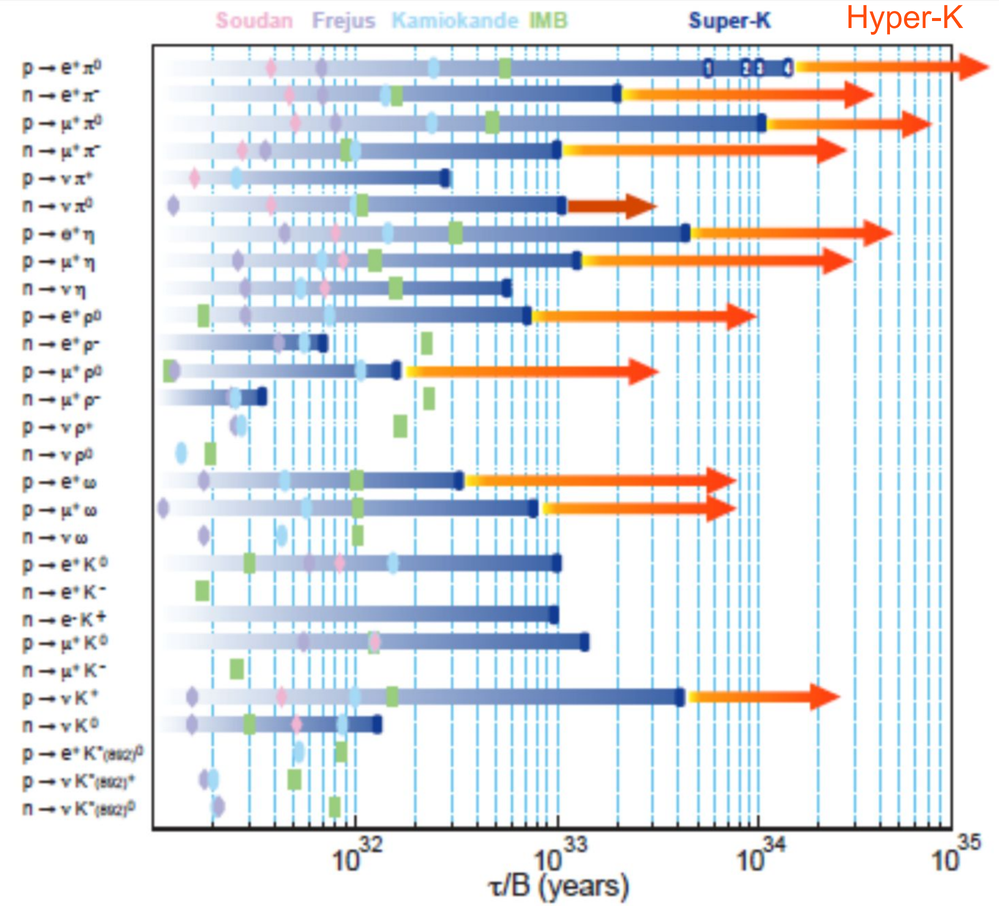




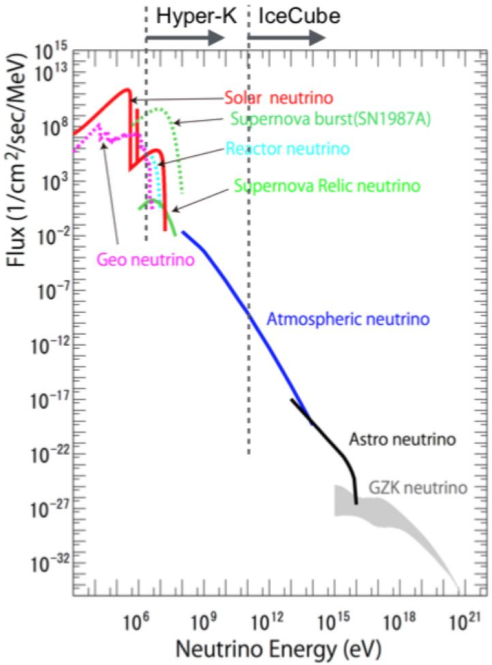
Hyper-K Proton Decay



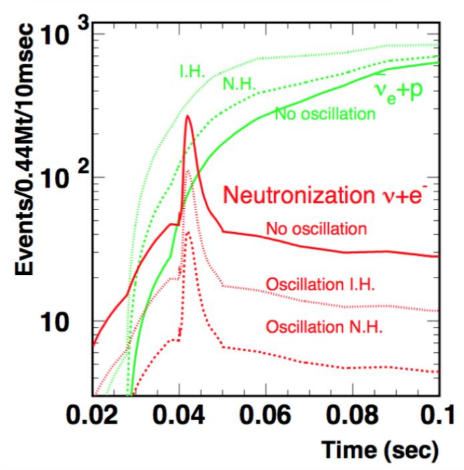


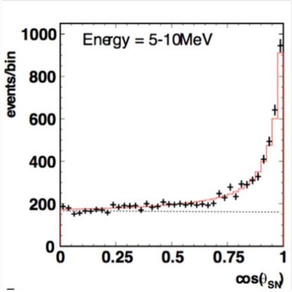


Supernova Burst in Hyper-K



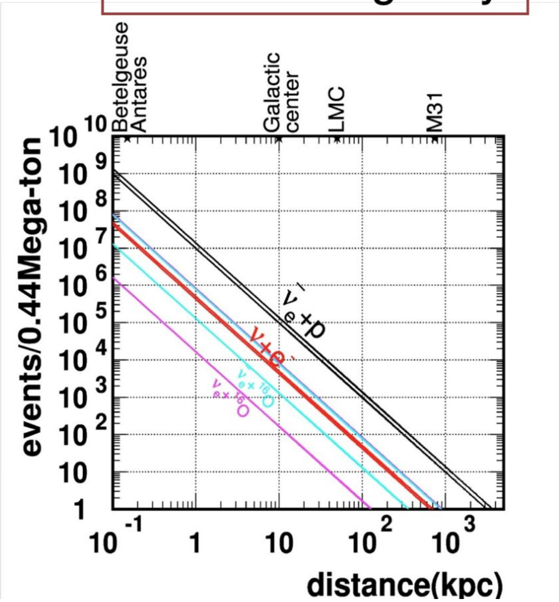
Neutrino carries information of explosion





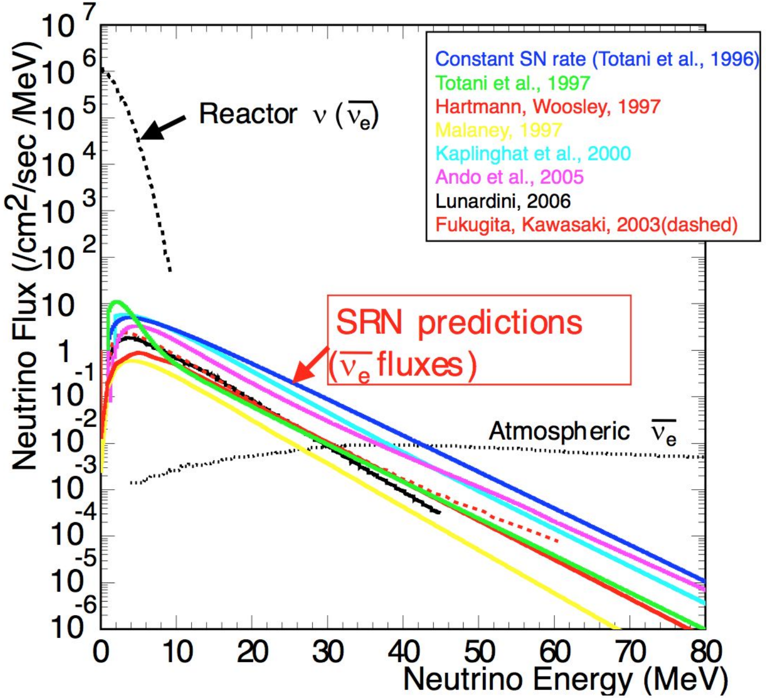
Direction alert for optical measurements (ν_e elastic)

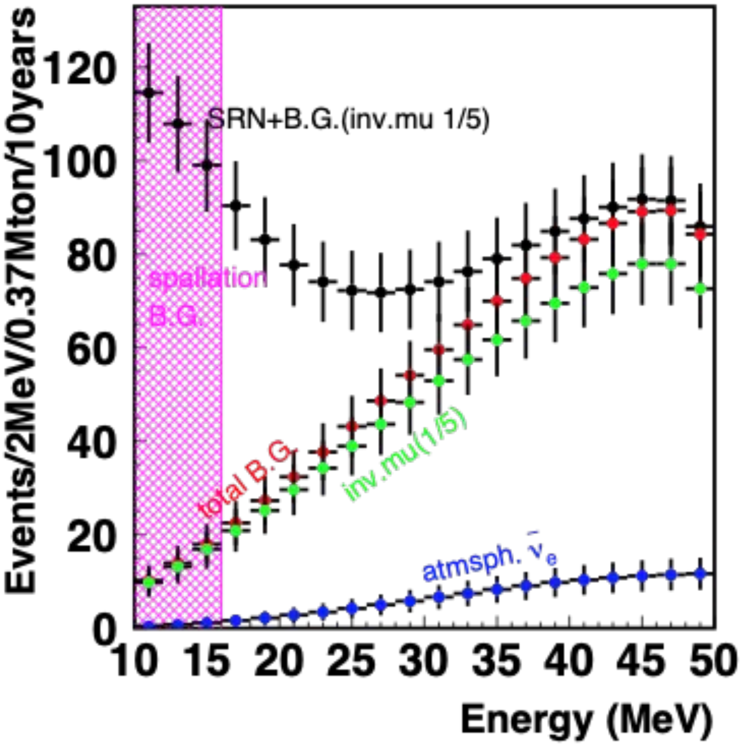
Reaching Andromeda galaxy



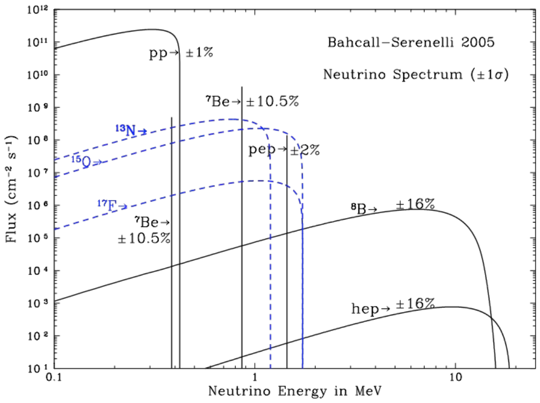
Hyper-K Supernova Relic Neutrinos

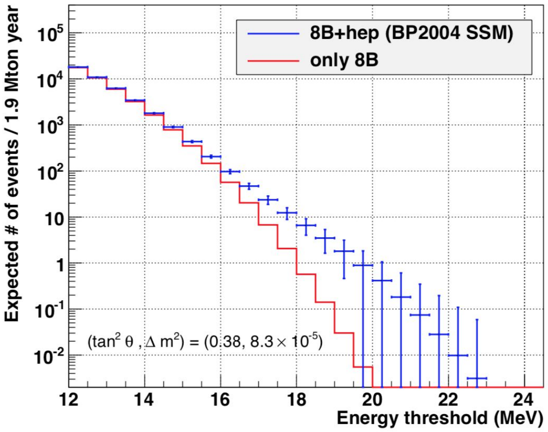
SRN can be observed by HK in 10y with ~70±17 events. It is > 4σ for SRN signal.

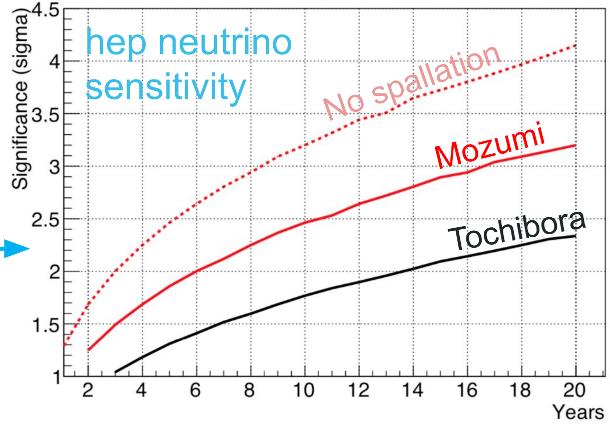


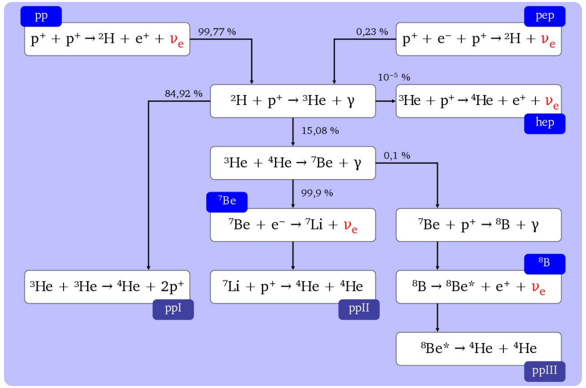


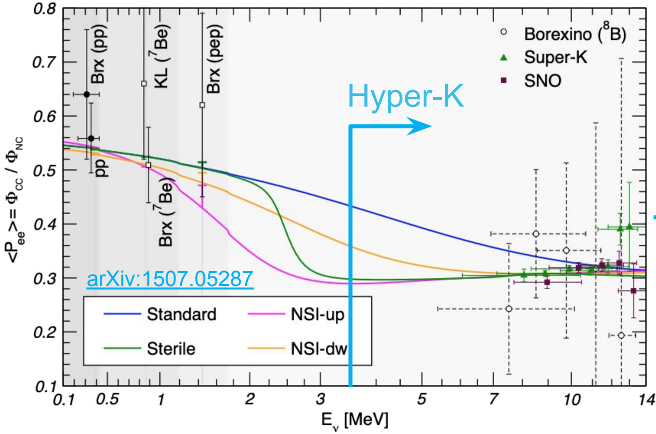
Hyper-K Solar Neutrinos

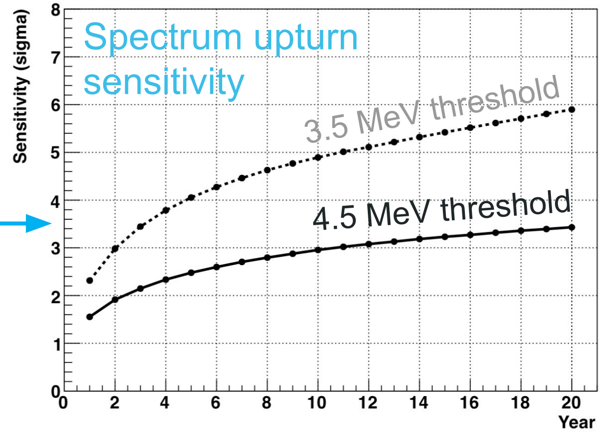








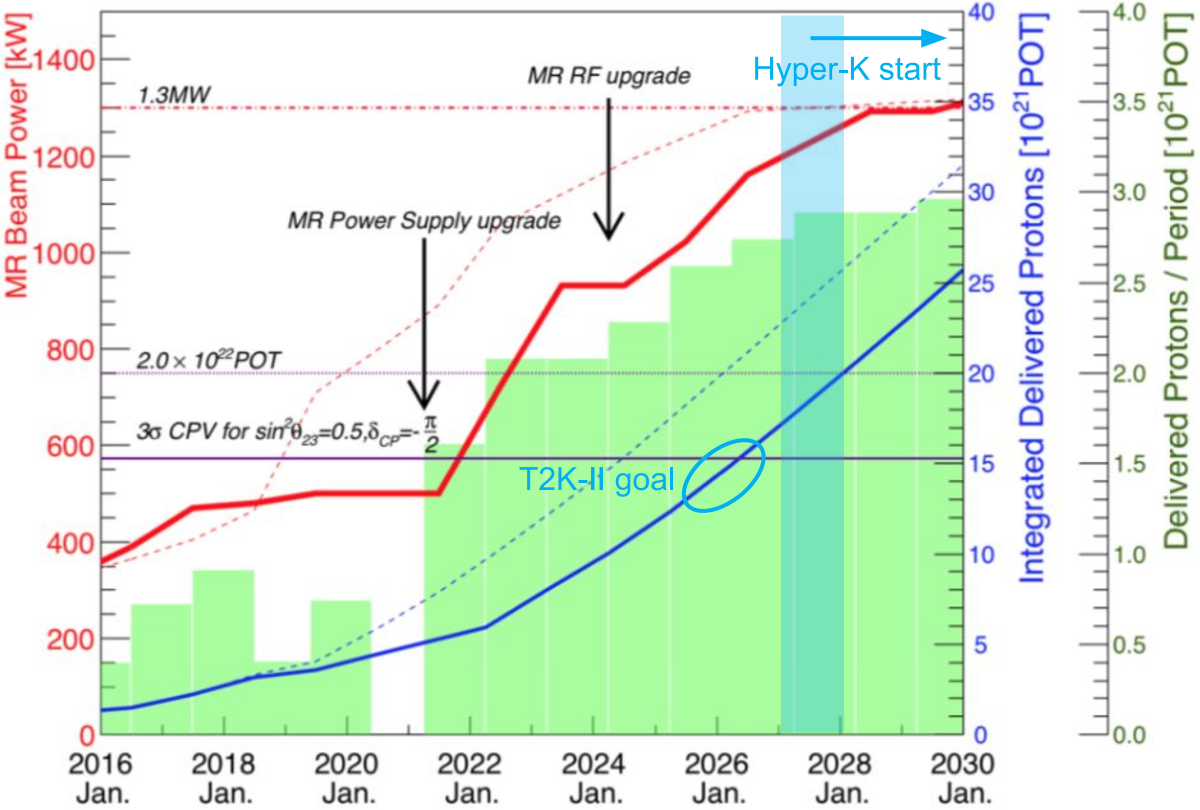




Beam Line Upgrades Towards T2K-II and Hyper-K

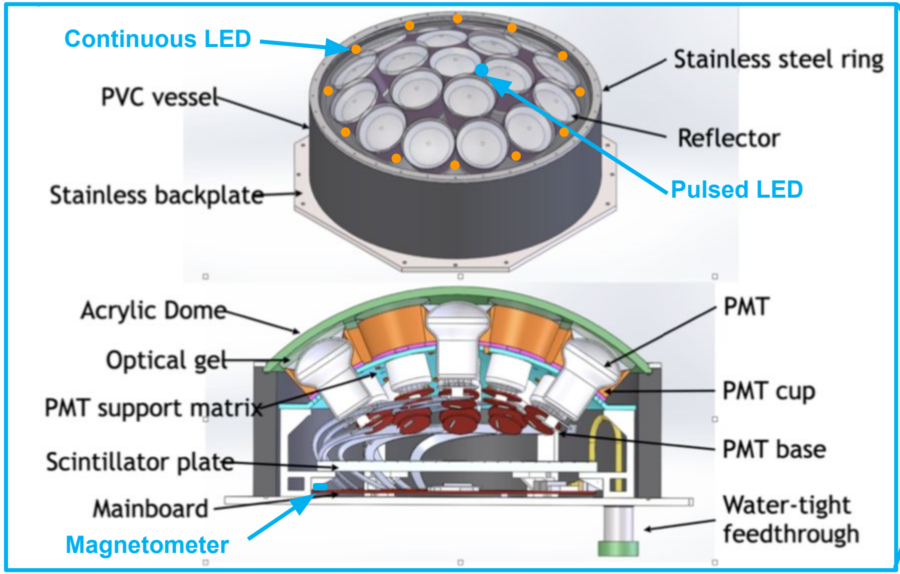
- Increase beam power from ~500 kW to 1.3 MW
- Many upgrades to neutrino beamline components
  - Target, beam monitors, etc.
- Increase horn current from 250 → 320 kA
  - 10% more neutrinos and reduced wrong-sign background

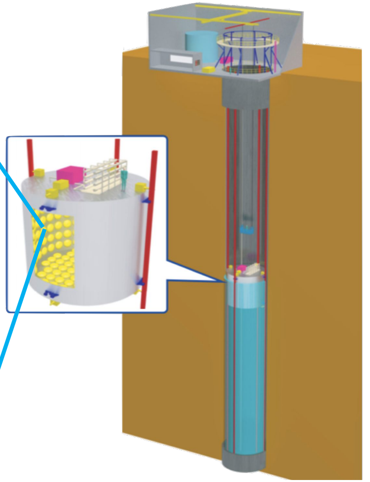
T2K-II Target POT (Protons-On-Target)

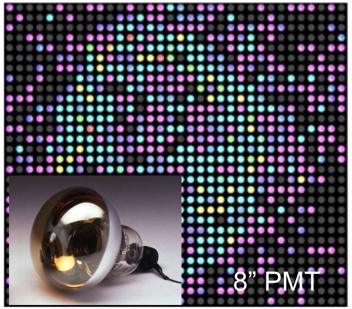


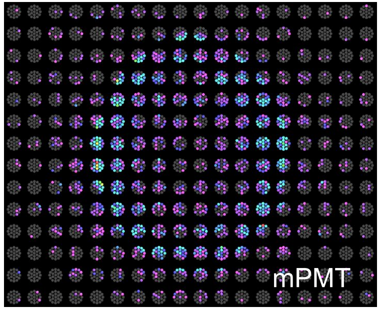
IWCD & Hyper-K Photosensor Development

- Multi-PMT (mPMT): 19 x 3” diameter PMTs in a water-tight vessel with HV and electronics
- Pulsed and continuous LEDs for calibration:
  - PMT timing
  - Water properties
  - Detector geometry
- Sensors for magnetic field monitoring



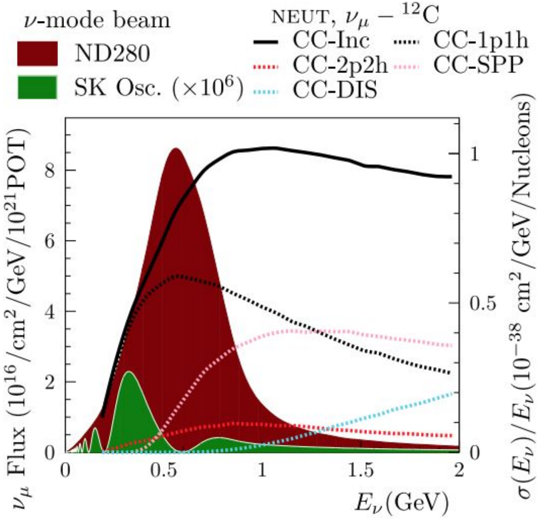






The Need for a New Near Detector

Imperfect extrapolation of neutrino flux & cross-section from near detector to Super-K



Differing energy spectra between near and far detectors

"T2K 2021 syst.": Phys. Rev. D 103, 112008

Error Source	% Error for CPV search
φ + σ (ND constrained)	2.7
φ + σ (ND unconstrained)	1.2
Nucleon removal energy	3.6
SK π re-interactions	1.6
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	3.0
NC γ + other	1.5
SK detector	1.5
Total	**6.0**

Need to reduce to <3% for Hyper-K

IWCD Measurement of ν_e ($\bar{\nu}_e$)

Constrain $\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}$ using **1% ν_e ($\bar{\nu}_e$) contamination in beam**

γ background mostly mitigated by water Cherenkov active shielding