Ongoing Projects: Neutrinos

Elizabeth Worcester (BNL)

40th Anniversary Symposium of the US-Japan Science and Technology Cooperation Program in HEP

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Overview

- Introduction and caveats
- Long-baseline neutrino oscillation experiments
- Ongoing US-Japan research efforts:
  - T2K-NOvA joint analysis
  - Liquid argon TPC R&D
  - 3D neutrino detector R&D
  - Multi-PMT photosensor R&D
  - High power neutrino beams R&D

"R&D for current & future long-baseline experiments"

KTeV

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"R&D for current & future long-baseline experiments"

Neutrino Oscillation

- Neutrinos have non-zero mass
- Mass states are not the same as the flavor states; flavor states may be written as linear combination of mass states (and vice versa) using a mixing matrix → oscillation!

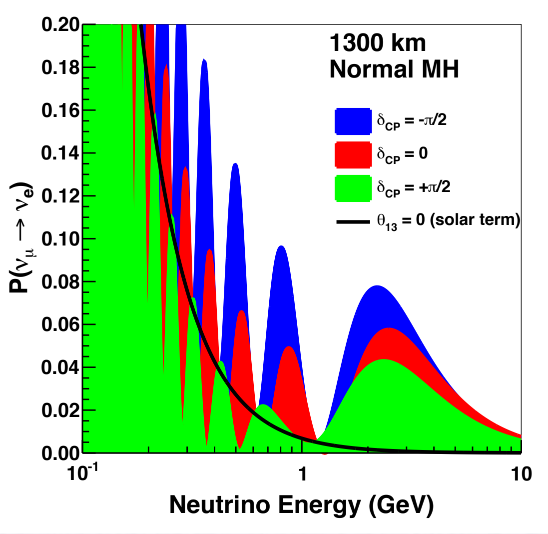
$$\boxed{\left|\nu_\alpha\right\rangle} = \sum_k \boxed{U_{\alpha k}} \boxed{\left|\nu_k\right\rangle}$$

- Open questions in 3ν model:
  - What are the neutrino masses?
  - Dirac or Majorana?
  - **How are the neutrino masses ordered?**
  - **Does $\theta_{23} = 45^\circ$ exactly? New symmetry? If not, octant?**
  - **CP violation in neutrino oscillation ($\delta_{CP} \neq 0, \pi$)?**

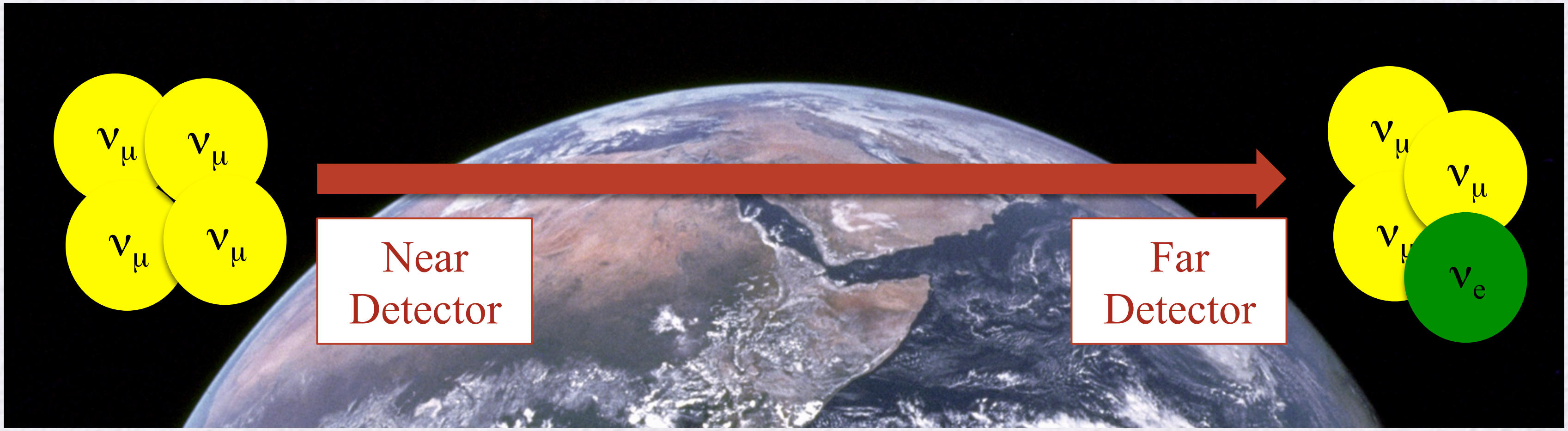
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

ν_e Appearance

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;\simeq\;& \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
&+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{\mathrm{CP}}) \\
&+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$



ν_e appearance amplitude depends on:
θ_{13}, θ_{23}, δ_{CP}, and matter effects



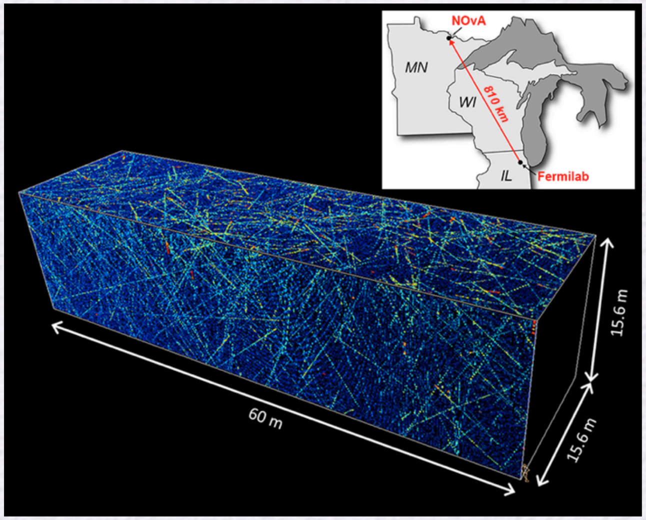
Current Long-Baseline Experiments

T2K: Tokai to Kamioka

- Beam: J-PARC (KEK)
- Far detector: SuperK
  - WCD (50 kt)
- Baseline: 295 km
- Far detector located off-axis such that observed ν flux is peaked at ~600 MeV

NOvA: FNAL to Ash River

- Beam: NuMI (FNAL)
- Far detector: segmented liquid scintillator detector (14 kt)
- Baseline: 810 km
- Far detector located off-axis such that observed ν flux is peaked at ~2 GeV

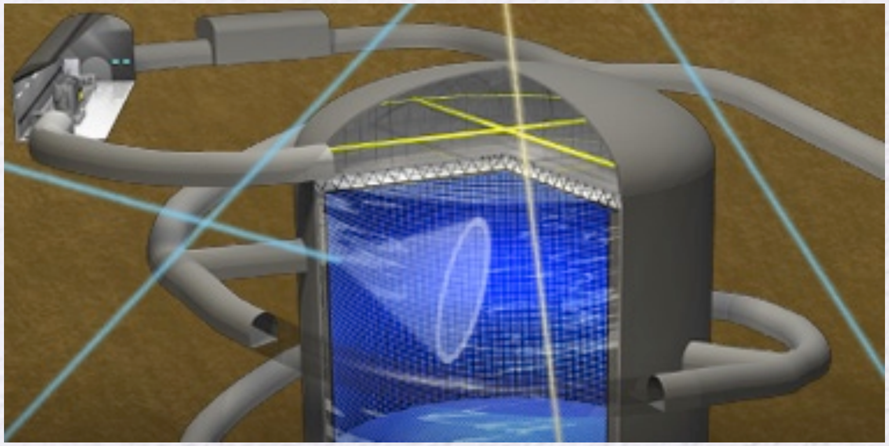


Future Experiments

c. 2026

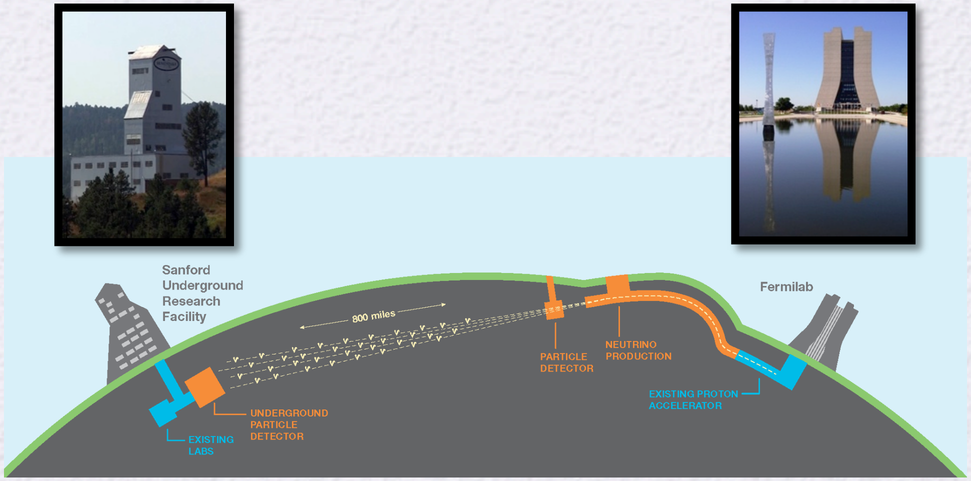
T2HK: Tokai to HyperK

- Beam: J-PARC (KEK)
- Far detector: HyperK
  - WCD (190 kt fiducial)
  - Option for 2nd tank at same baseline or in Korea
- Baseline: 295 km
- Far detector located off-axis such that observed ν flux is peaked at ~600 MeV



DUNE: FNAL to SURF

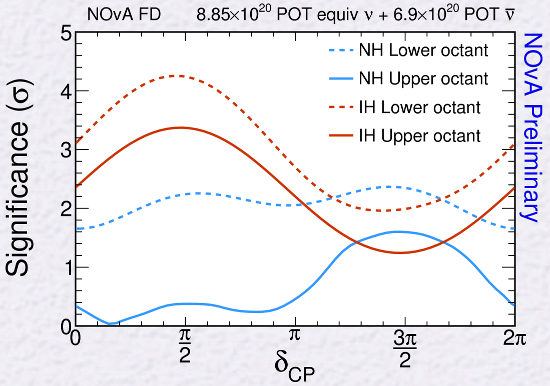
- Beam: LBNF (FNAL)
- Far detector: LArTPC
  - 40 kt fiducial
- Baseline: 1300 km
- Far detector located on-axis such that observed ν flux is a broad band spectrum

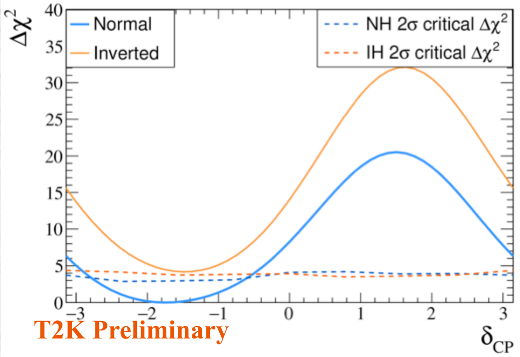


T2K-NOvA Status

NOvA and T2K – current results with ν and $\bar{\nu}$ data:

NOvA: prefers Normal Hierarchy at 1.8σ, upper θ_{23} octant at 2.4σ



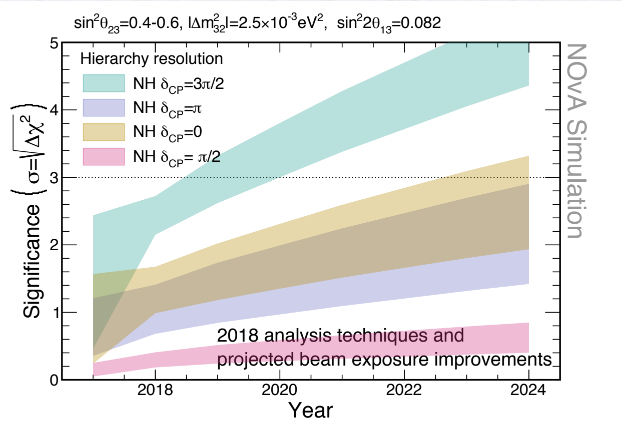


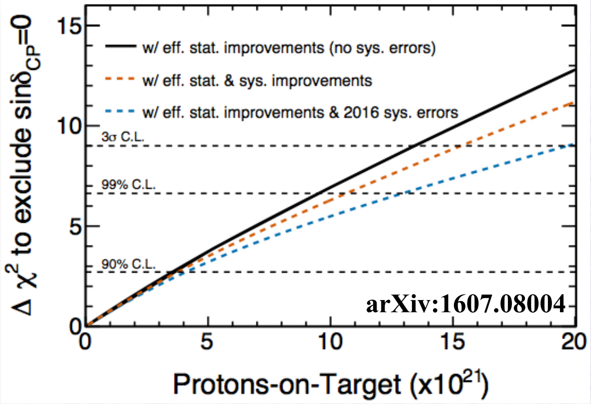
T2K: disfavors CP conservation at 2σ, prefers θ_{23} close to maximal

Compelling milestones in reach for each experiment:

Projections assuming accelerator improvements

NOvA Projected Mass Hierarchy Sensitivity (stats. only)





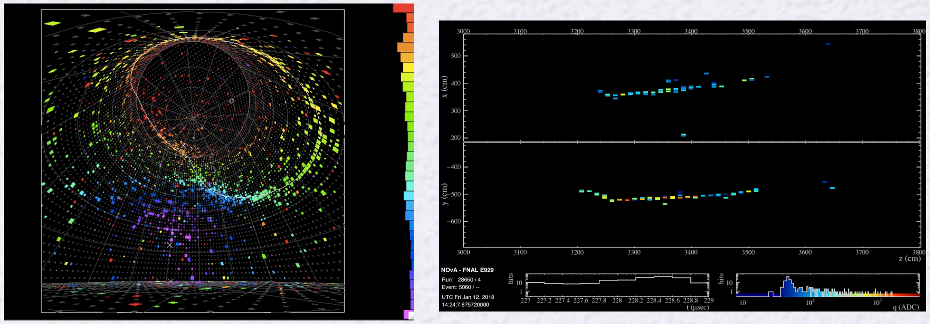
T2K Projected CP Violation Sensitivity

Assuming δ_{CP}=-π/2, $\sin^2(\theta_{23})$=0.5

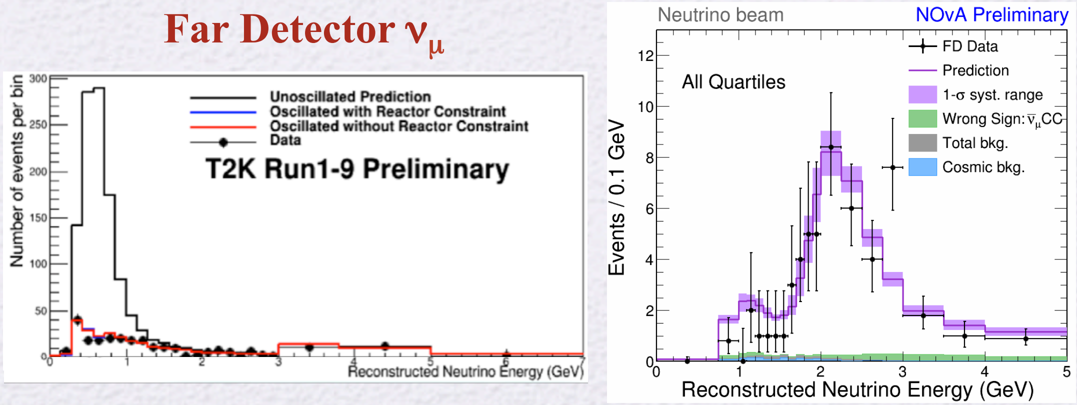
T2K-NOvA Complementarity

- Baseline: Effect of mass ordering larger in NOvA than T2K because of longer baseline
    - 810 km vs 295 km
- Detector technologies
    - Different sensitivity to final state particles
    - Different target nuclei
    - Different ND strategy
- Beam Spectrum
    - Different mix of neutrino interaction processes

ν_e CC events



Far Detector ν_μ



T2K-NOvA Joint Analysis

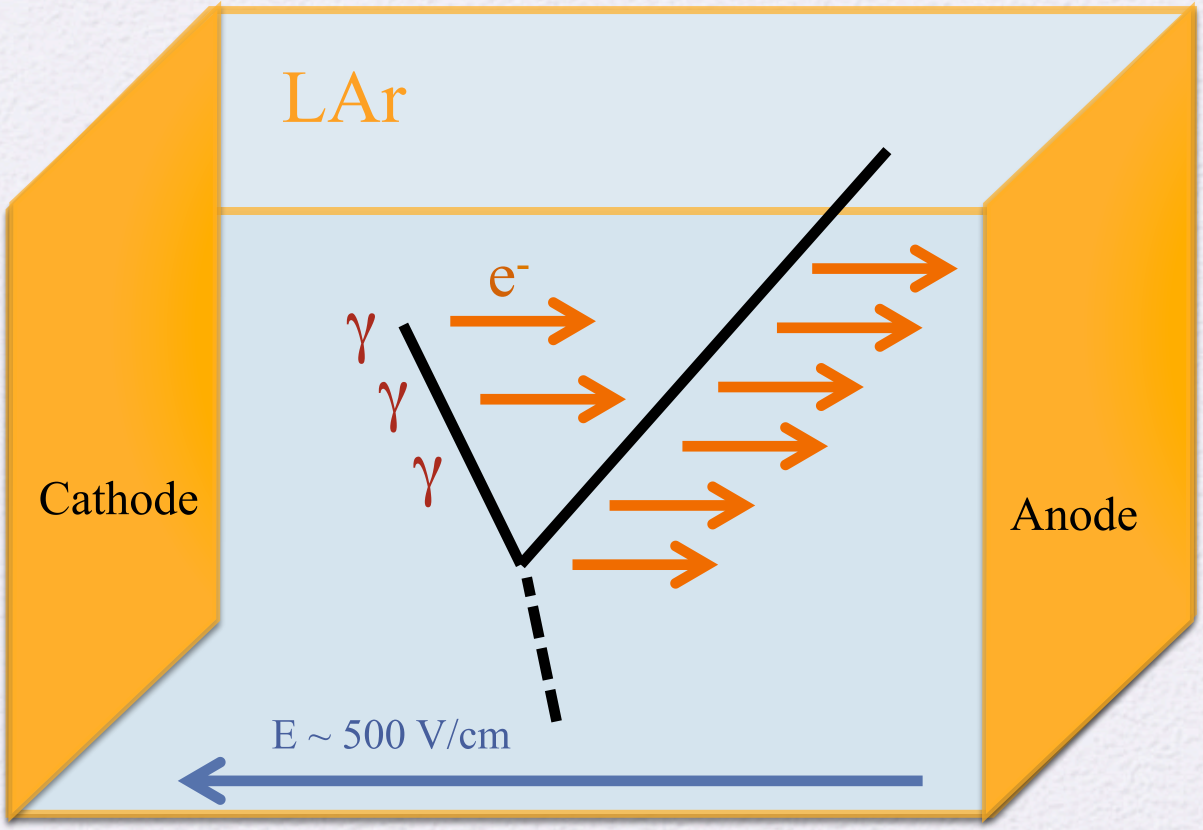
Joint effort underway to fully exploit complementarities to achieve best combined reach in current generation of experiments

- Four joint meetings since 2016
  - Increasing levels of focus and participation, and of support from US-Japan program
- First formal joint workshop in Tokai, October 2017
  - "Role of Neutrino Interaction Uncertainties in Oscillation Measurements"
- 2nd workshop at Fermilab, February 2019
  - Identify important correlations in systematic uncertainty
  - Develop means/tools to share information and study correlations

- Future Plans
  - Meet every 6-9 months to continue laying framework for joint fits
  - Targeting first joint fits in 2021; scope of fits to be defined summer 2020

Liquid Argon TPC

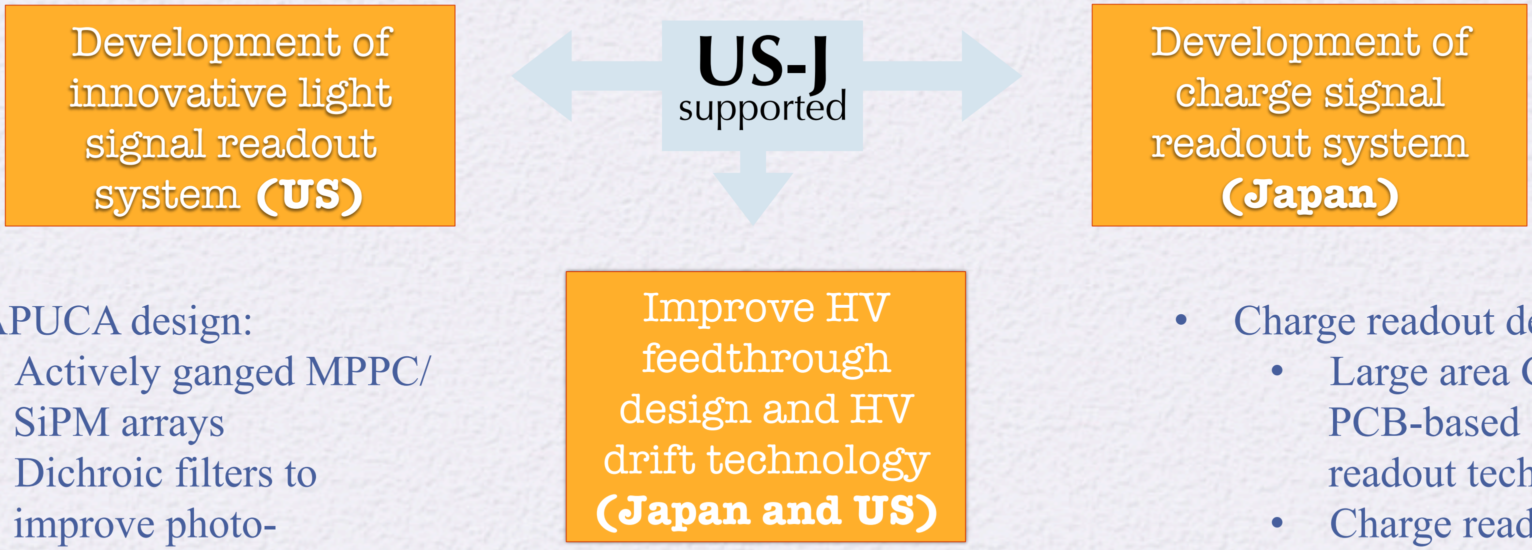
(Far detector technology for DUNE)



- Prompt scintillation light (128 nm) observed by photon detectors
- Ionization electrons drift to anode

LArTPC R&D

JFY2018-19 Plan



Development of innovative light signal readout system **(US)**

US-J
supported

Development of charge signal readout system **(Japan)**

Improve HV feedthrough design and HV drift technology **(Japan and US)**

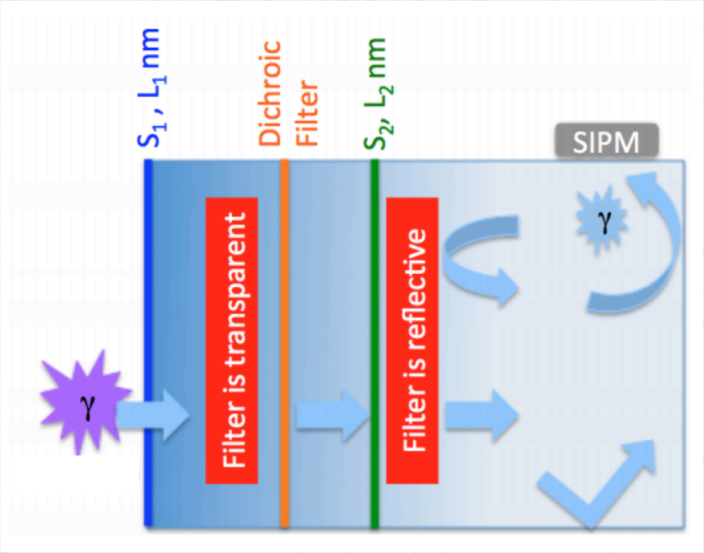
- ARAPUCA design:
    - Actively ganged MPPC/SiPM arrays
    - Dichroic filters to improve photo-collection efficiency
    - Prototype tests

- New materials for HV feedthrough fabrication
- Improvements to HV design to reduce risk of discharge

- Charge readout design:
    - Large area GEM and PCB-based anode readout technology
    - Charge readout electronics
    - Charge signal feedthrough

ARAPUCA Light Detection

ARAPUCA: light is trapped using wavelength shifters and a dichroic filter; trapped light read out by SiPMs

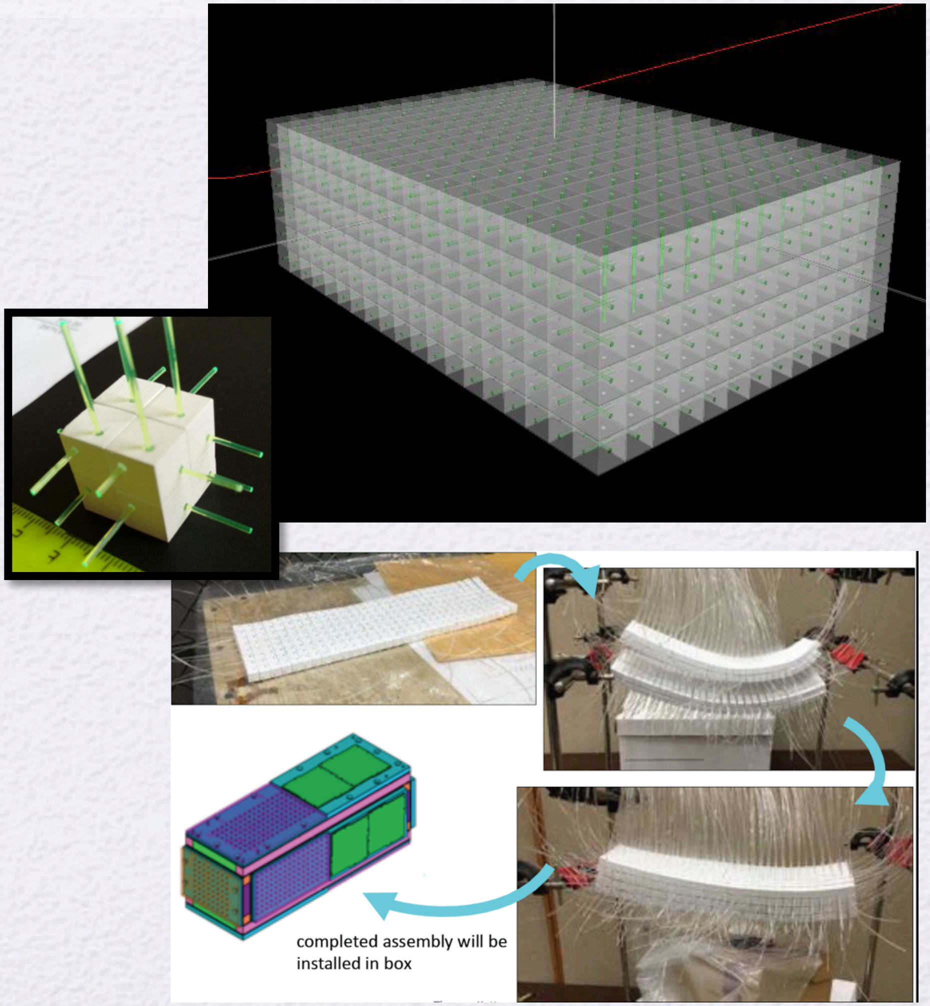


protoDUNE:

3D-projection Scintillator Tracker (3DST)

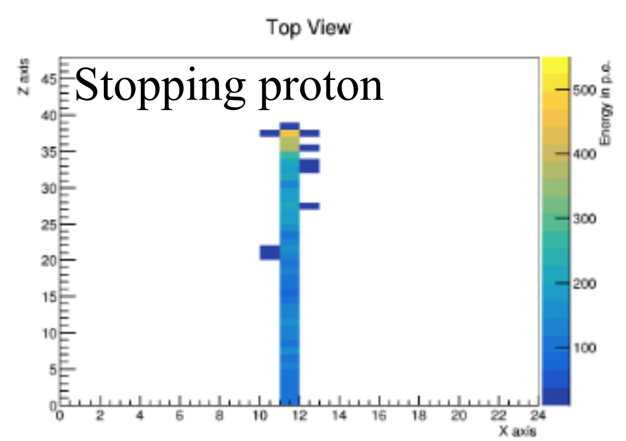
(ETW is US PI)

- Fully active detector
- Plastic scintillator + WLS fiber + MPPC
- 1x1x1 cm^3 scintillator cubes assembled in rows and columns
- Provide 3D projected views w/ fine segmentation
- 4π acceptance w/ low momentum threshold for protons (~300 MeV)
- Neutron detection and energy measurement



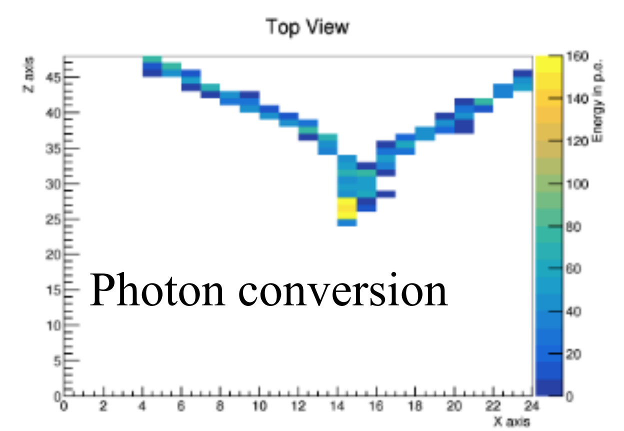
3DST R&D

- CERN beam tests
  - 5x5x5 cm^3 array (2017)
  - 8x24x48 cm^3 array (2018)
- US-Japan prototype
  - 8x8x32 cm^3 supported by US-Japan program
  - BNL, CERN, Geneva, INR, LSU, KEK, Penn, Pitt, Rochester, Stony Brook, Tokyo
- Proposed neutron beam test at LANL (2019)
  - CERN prototype + US-Japan prototype
  - Proposal submitted March 2019



Stopping proton

CERN prototype

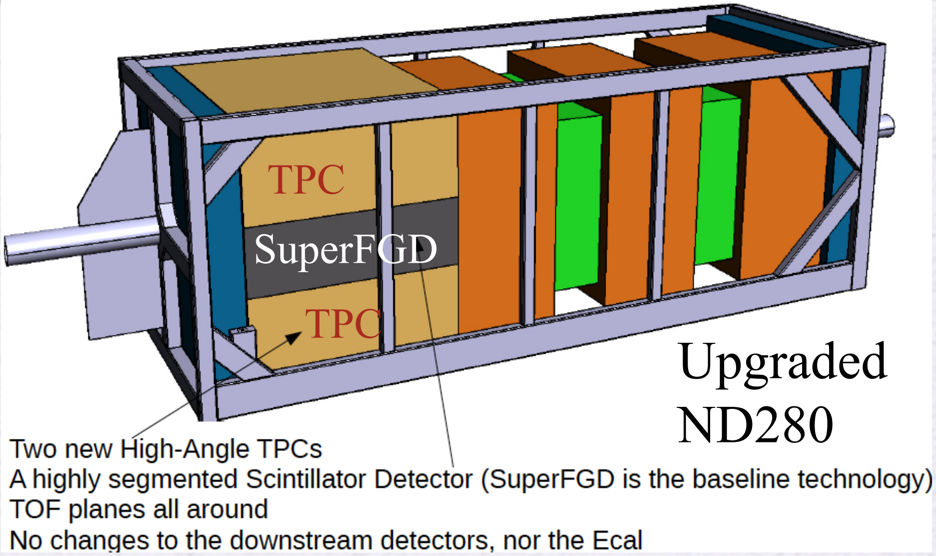


Photon conversion

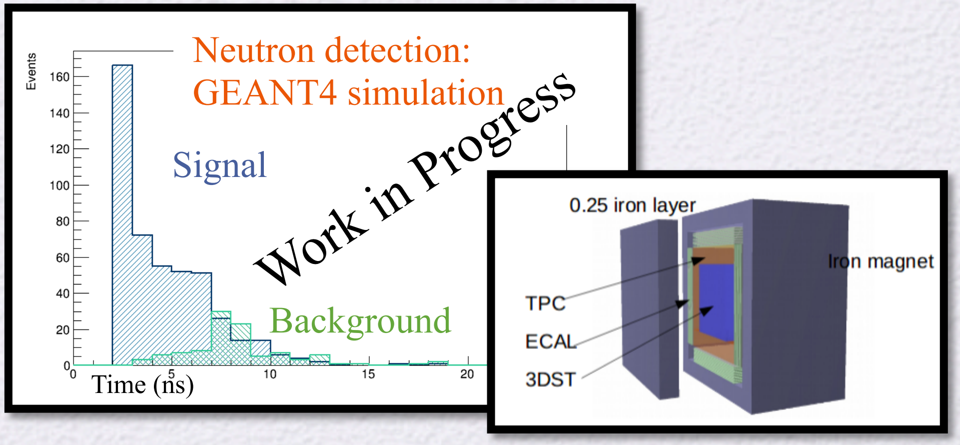
CERN prototype

3DST Applications

- T2K near detector upgrade
  - ND280 being upgraded to reduce systematic uncertainties in T2K oscillation analysis
  - Improve angular acceptance, increase target mass, improve efficiency for short tracks
  - “SuperFGD” is a 3DST detector
- DUNE near detector design concept
  - Modular LArTPC
  - Magnetized multipurpose detector (HPgTPC+ECAL)
  - 3DST spectrometer
  - Design concept → conceptual design in progress
- Measurements of neutron spectrum



Two new High-Angle TPCs
A highly segmented Scintillator Detector (SuperFGD is the baseline technology)
TOF planes all around
No changes to the downstream detectors, nor the Ecal



3DST Global Strategy

- Synergy between T2K ND280 upgrade (SuperFGD) and DUNE ND (3DST)
  - Use US-Japan support to seed international effort on both

- US-Japan 2018 proposal
  - Approved in April 2018
  - Build a US-Japan prototype for neutron beam test
  - Develop US expertise/experience with this detector technology

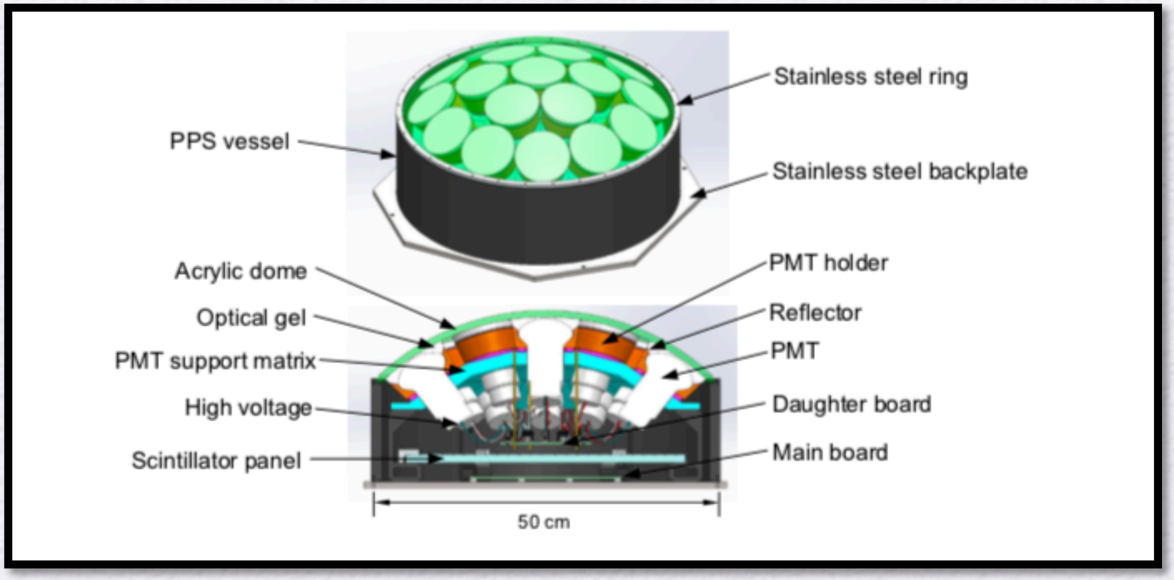
- 2018 US HEP Portfolio Review
  - T2K upgrade (including SuperFGD) received highest priority classification

- DUNE Near Detector
  - Design concept including 3DST adopted by DUNE Executive Board (2018)
  - Design concept → Conceptual Design in progress

- US contribution to T2K SuperFGD proposal (~$1M US) submitted to DOE in January 2019

- US contribution to DUNE ND proposal being developed; to be submitted in 2019

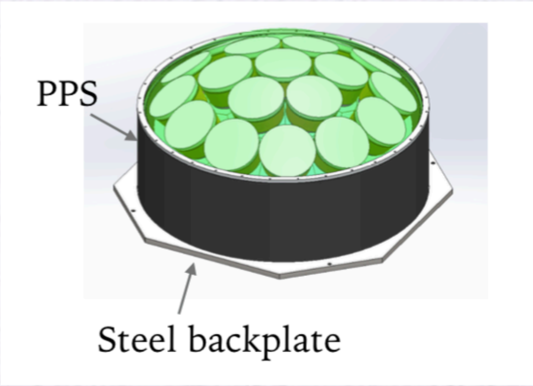
Multi-PMT Detector (mPMT)

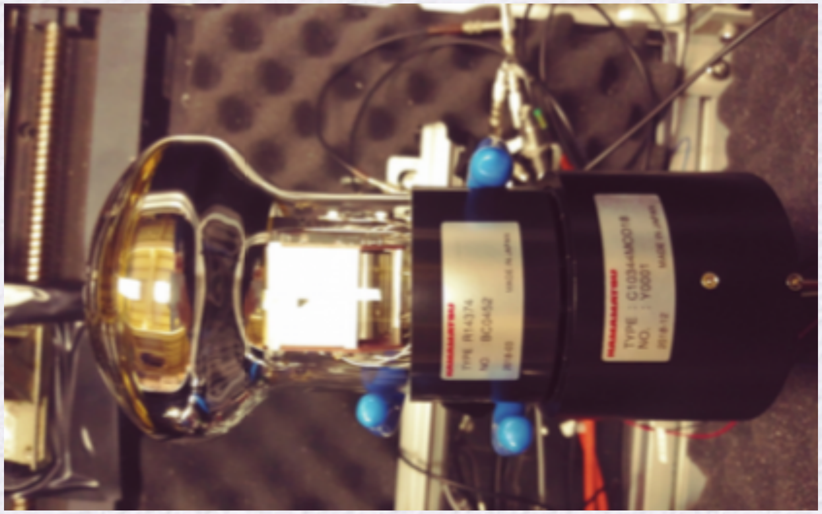


- Single module containing 19 3-inch-diameter PMTs
  - Improved spatial and timing resolution
  - Improved S/N compared to SuperK PMTs
- Readout electronics and high voltage circuits contained in the module
- Water-tight vessel must be compatible with ultra-pure water and pressure tolerant

Pressure & HV Testing

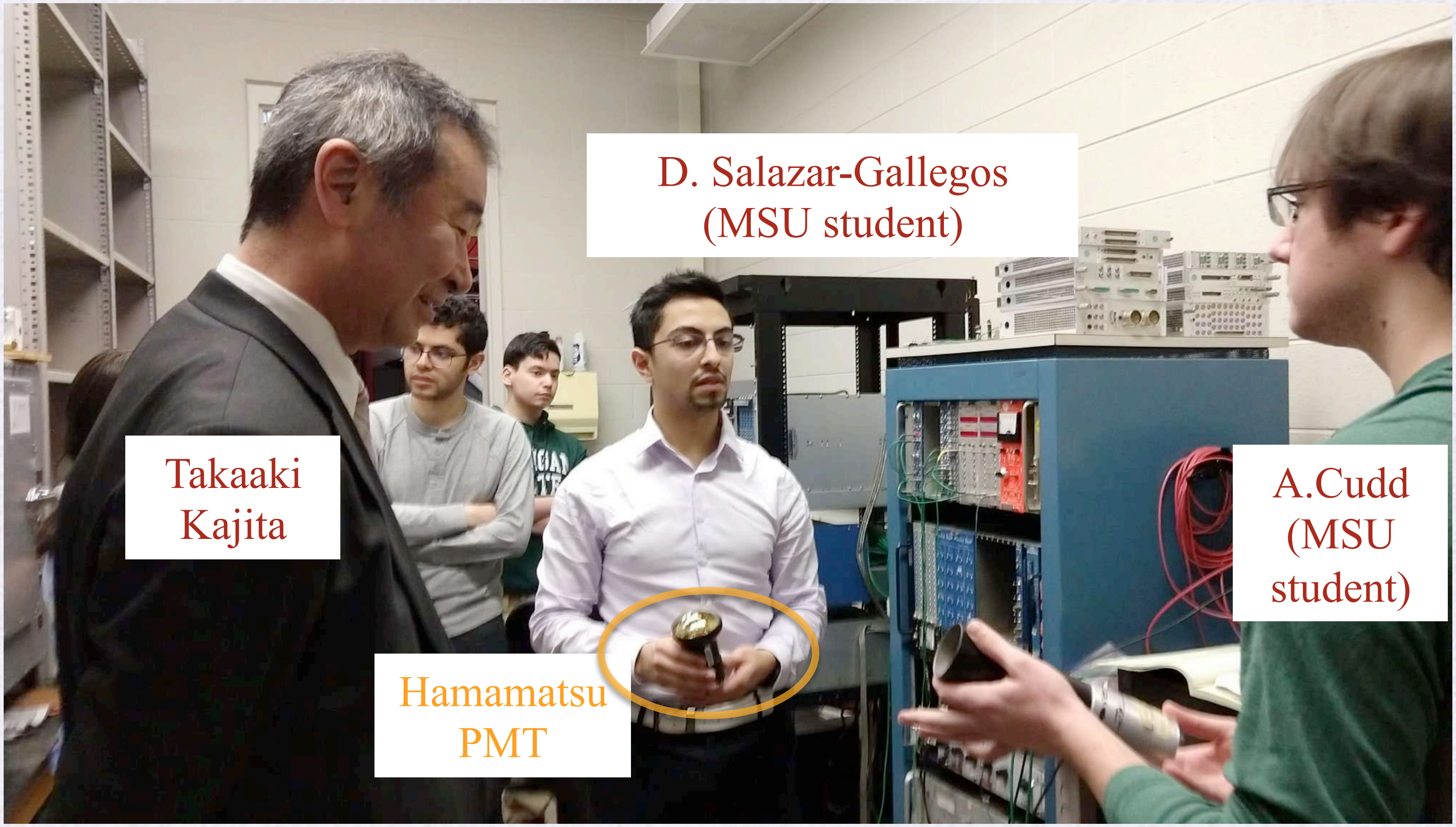
- Hydrostatic pressure test in Kamioka up to 1.7 Mpa
  - No damage to acrylic dome
  - Strain gauge data collected and being analyzed
- Second pressure test with full design for module vessel
  - 3D-printed PPS cylinder
  - Stainless steel backplate
- Working with Hamamatsu to design positive HV Cockcroft Walton base
  - Gain measurements in progress





Dark & Flashing Rate Tests

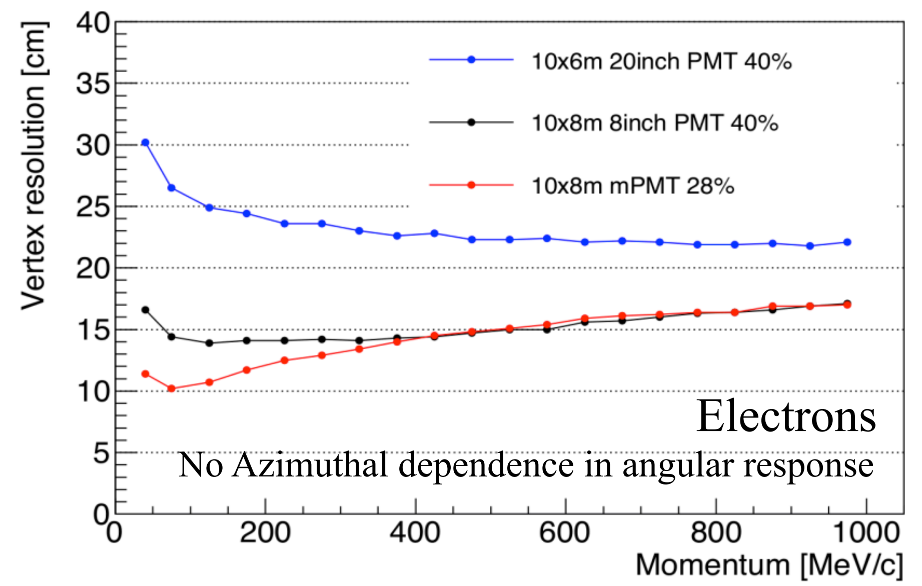
MSU Test Stand:



Tests with positive and negative polarity bases confirm dark noise rate & flasher rate
(Work ongoing)

Reconstruction for mPMTs

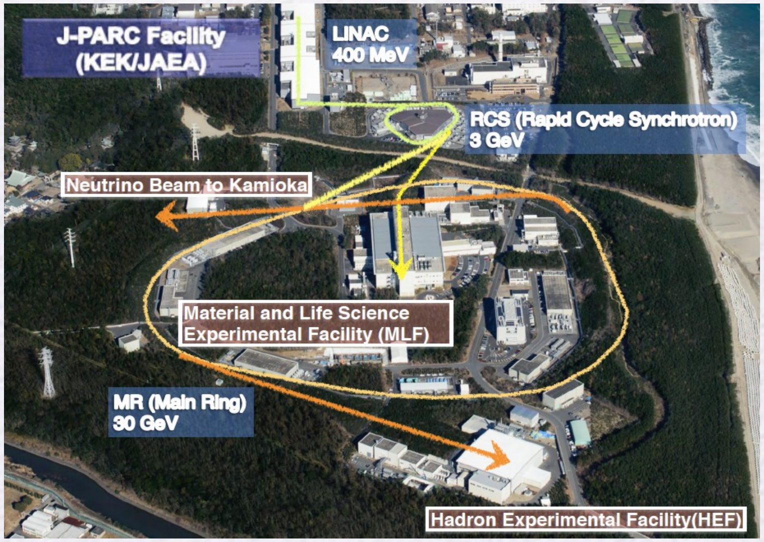
- Vertex resolution improvement seen in small water Cherenkov tank populated with mPMTs compared to 8” PMTs

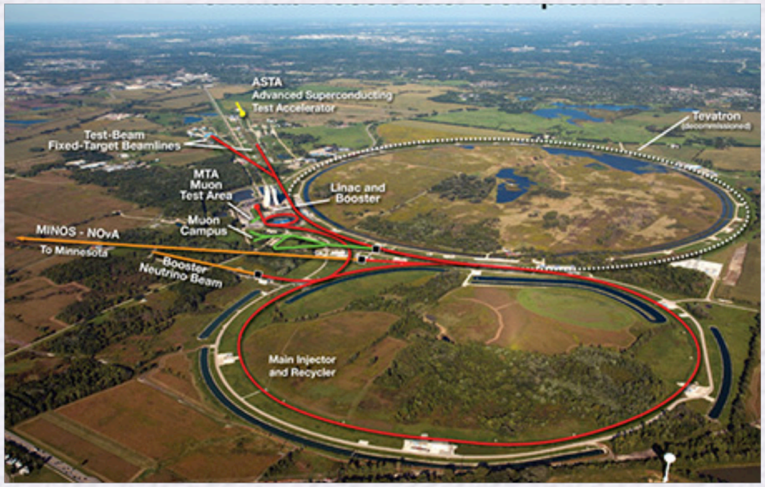


- Work is ongoing to more precisely incorporate directional information provided by mPMTs into advanced reconstruction algorithms (eg: FiTQun)

High-Power Neutrino Beams

- Next-generation facilities being designed to accommodate MW scale beam power in the DUNE/HyperK era
  - Minimize beam loss in the accelerator ring to keep radiation effects manageable
  - Increase capacity of neutrino production facility (robustness of target/horn, radioactive equipment/waste handling)
- Consortium includes Colorado, FNAL, KEK, SLAC
  - Grew out of existing areas of research of mutual interest to FNAL and J-PARC
  - In-person meetings Tokai 2018, FNAL 2019, several technical visits 2018-2019





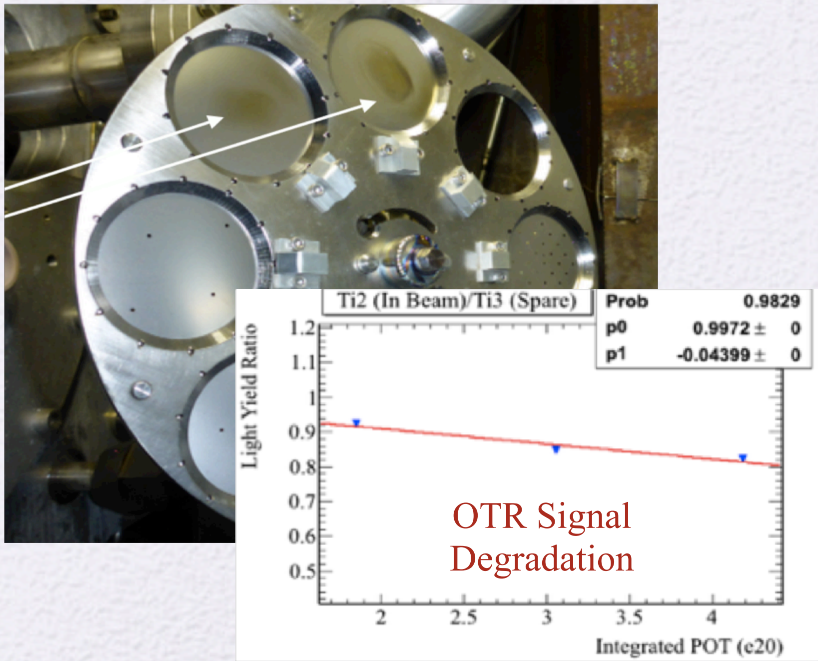
Seven Core Research Areas

- Beam dynamics studies for beam loss reduction
  - New approaches to linac and synchotron lattice optimization and measurements to decrease high-intensity beam loss
- Electron cloud studies
  - Measurements and simulation of beam instability caused by free electrons in beam pipe (new 2019)
- Gated ionization profile monitor
  - IPM measures beam width. Research into gating would allow much longer lifetime in accelerator, and thus greater ability
- Laser manipulation of H- beams
  - Stripping of beam in linac and at injection. Enable flexible beam patterns and eliminate a loss source. Develop options for beam shaping and instrumentation (A. Seryi)
- BPM Data Acquisition System
  - New system to rapidly acquire large amounts of data. Will allow a new level of precision and feedback to the J-PARC Main Ring, exploiting Fermilab expertise (new 2019)
- Extracted beam monitoring
  - Allow spill-to-spill beam profile measurements in extraction lines, and allow long lifetime of the devices and minimal radioactivation. Present work on multiwire SEMs and OTR foils. Interest in gaseous devices.
- High-power target facility issues
  - Radiation-resistant materials to seal the gas volumes around the beamlines. Sealed and cools stripline for horn current conductors and feedthroughs.Recombination of water and hydrogen from hydrolysis.

Joint KEK-FNAL Beam Monitor R&D

- Essential to continuously monitor the proton beam to protect beamline equipment and understand the proton beam parameters for flux prediction
- Profile monitors may degrade quickly at 1.3 MW

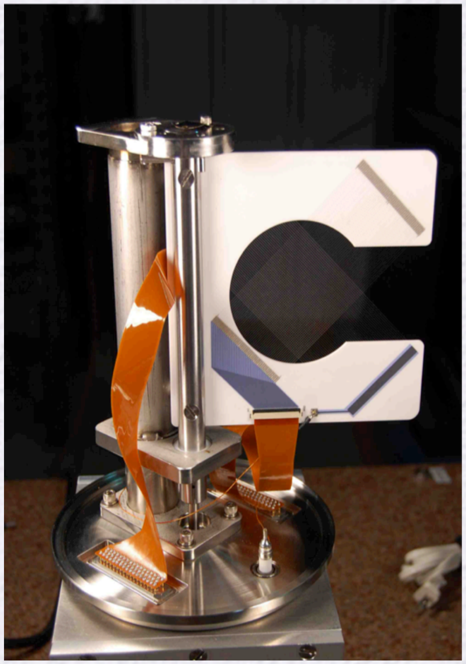
Irradiated OTR monitor (T2K)



OTR Signal Degradation

- Design more robust SSEMs using less material
  - Reduced beam loss/irradiation
  - (FNAL) C ribbons may be more robust than (T2K) Ti foils
- Collaborative work to modify FNAL SSEM design to fit T2K beam

FNAL Ti wire c-frame SEM



Summary

- US and Japan have very exciting current and planned experimental programs to make (complementary) precision measurements of parameters governing long-baseline neutrino oscillation
    - T2K and NOvA producing great results
    - Effort for combined analysis underway
    - HyperK and DUNE coming soon!

- US-Japan program facilitating analysis efforts and detector/accelerator R&D that will benefit programs in both countries
    - mPMTs: HyperK
    - LArTPC: DUNE
    - 3DST: T2K & DUNE
    - High-power beams: All experiments

Thank you!

Slides provided by:

- Steve Brice
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- Kendall Mahn
- Peter Shanahan
- Mike Wilking
- Bob Zwaska