Fermilab Progress Update

Lia Merminga, Laboratory Director

HEPAP Meeting
8-9 December 2022

Outline

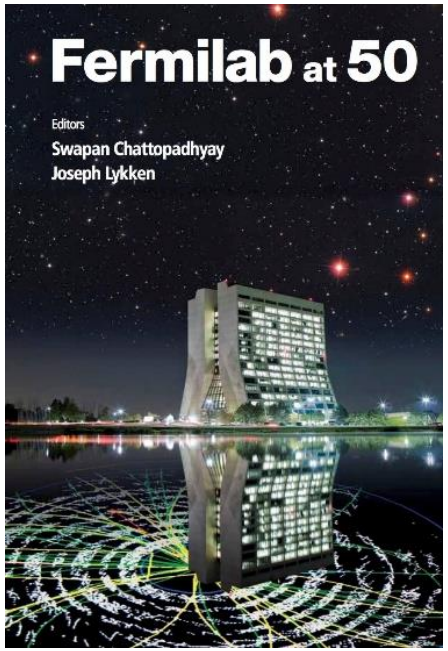
- Fermilab at a Glance
- Vision and Strategic Pillars
- Major Science & Technology Initiatives
- Emerging Science & Technology Capabilities
- International Engagements
- FY23: A Year of Change for Fermilab
- Summary

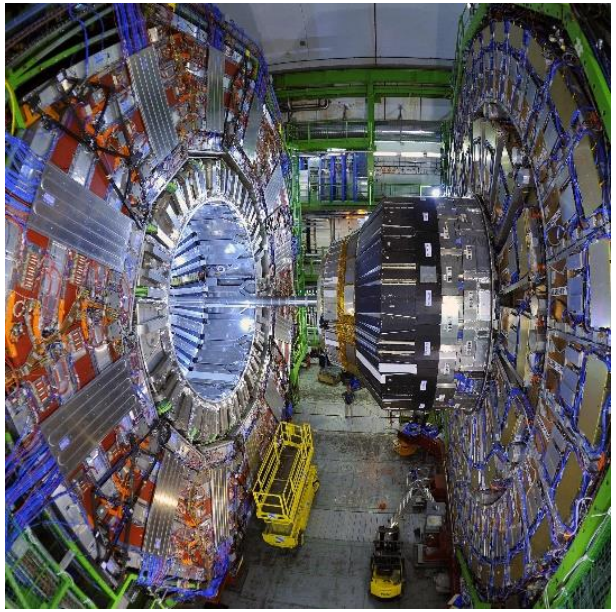
Fermilab at a Glance

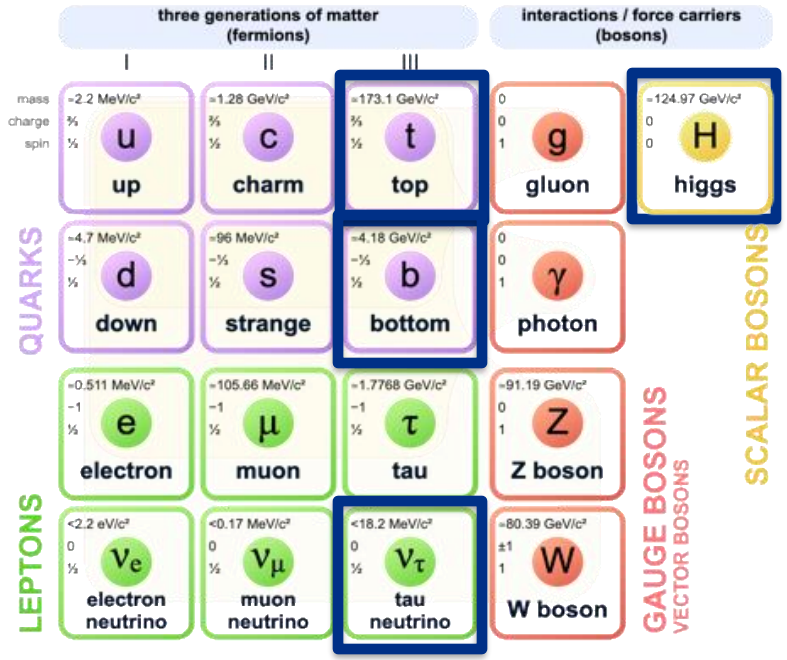
- America's particle physics and accelerator laboratory
- Operates the largest US particle accelerator complex
- ~1,900 staff and ~$600M/year budget
- 6,800 acres of federal land
- Facilities used by 4,000 scientists from >50 countries

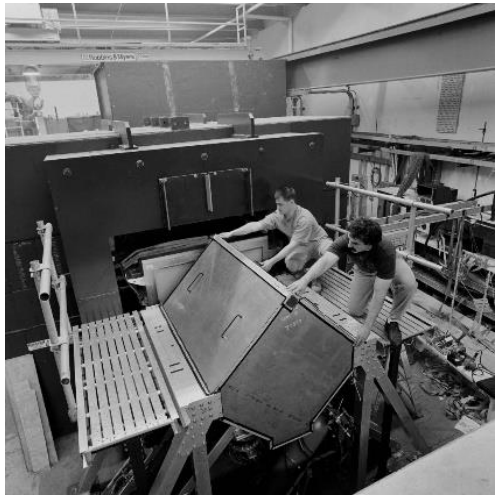
As we move into the next 50 years, our vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all.

50 Years of Discovery









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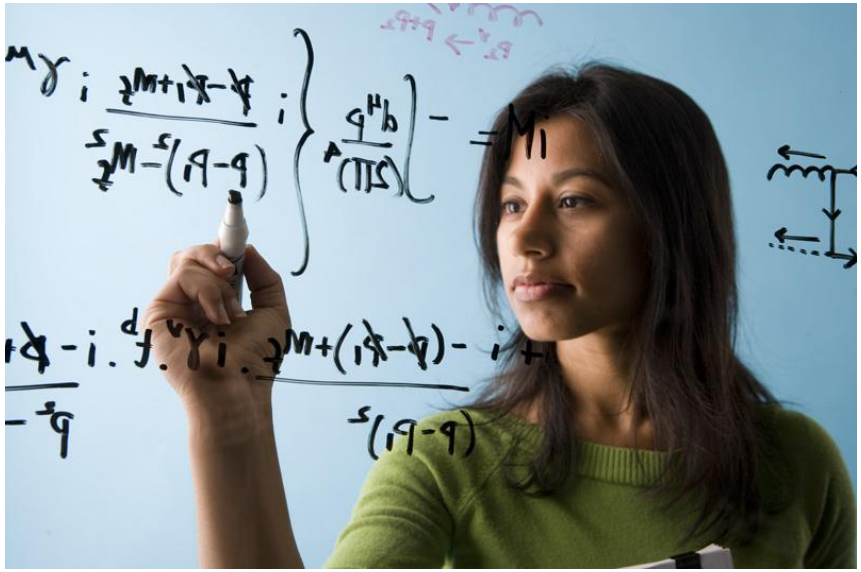
Fermilab Science Mission – P5 science drivers

- Higgs boson
- Neutrinos
- Dark matter
- Dark energy and inflation
- Exploring the unknown



Fermilab is delivering on the DOE/SC discovery science mission: Major particle physics breakthroughs from Fermilab experiments, major technology breakthroughs from Fermilab research

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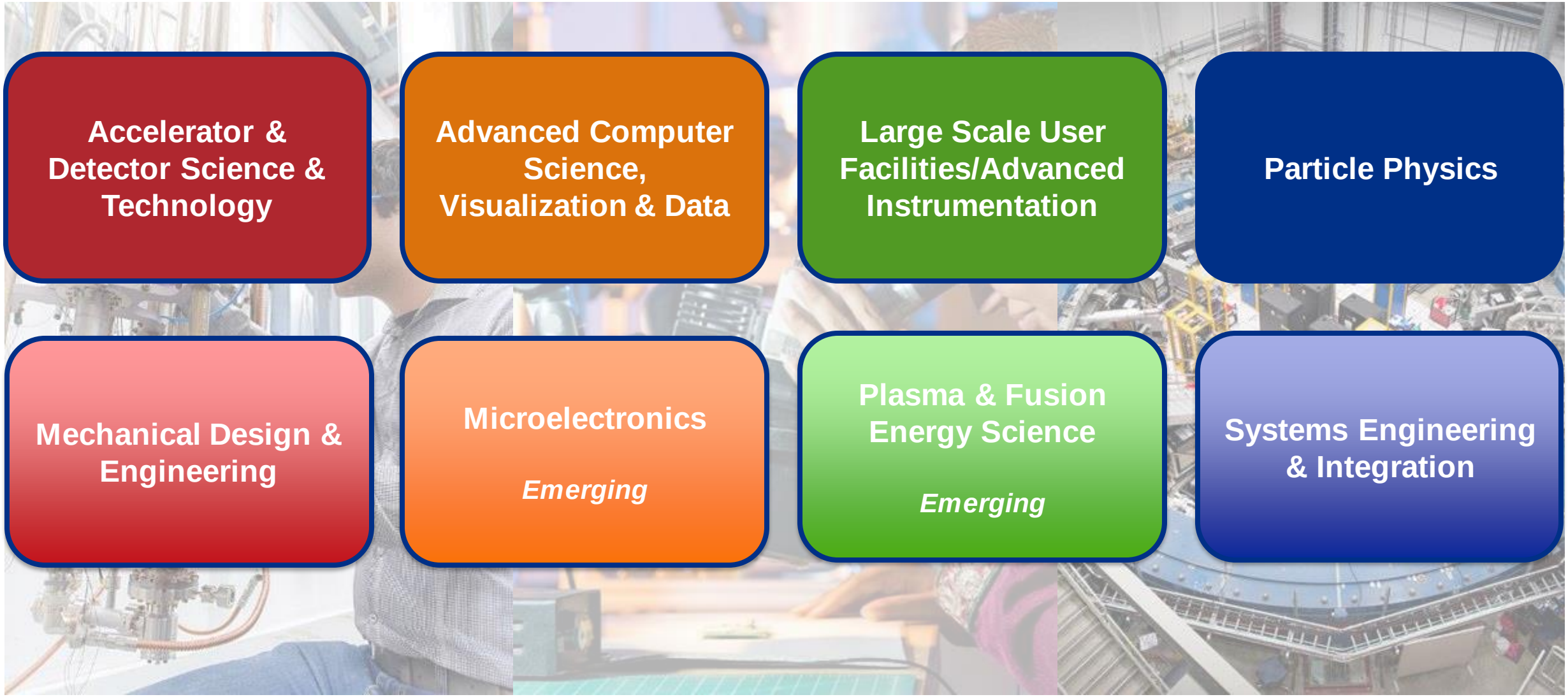
Fermilab Core Capabilities



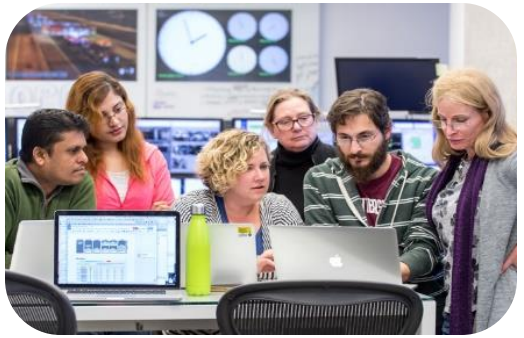
A new vision for Fermilab

Lead the world in particle and accelerator physics and technology innovation, underpinned by a *diverse* and *world-class* workforce; *transformed* business systems and operations; a renewed, sustainable campus; and *enabling regional*, national and international partnerships.

Strategic Thrusts: Pillars of our vision for Fermilab

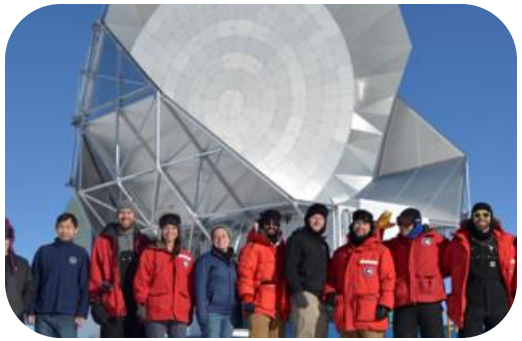
Deliver groundbreaking science and technology innovation

Building for Discovery: Project Execution



Diversify and empower our workforce

Transform business & operations, execute sustainable campus strategy integrated with science vision

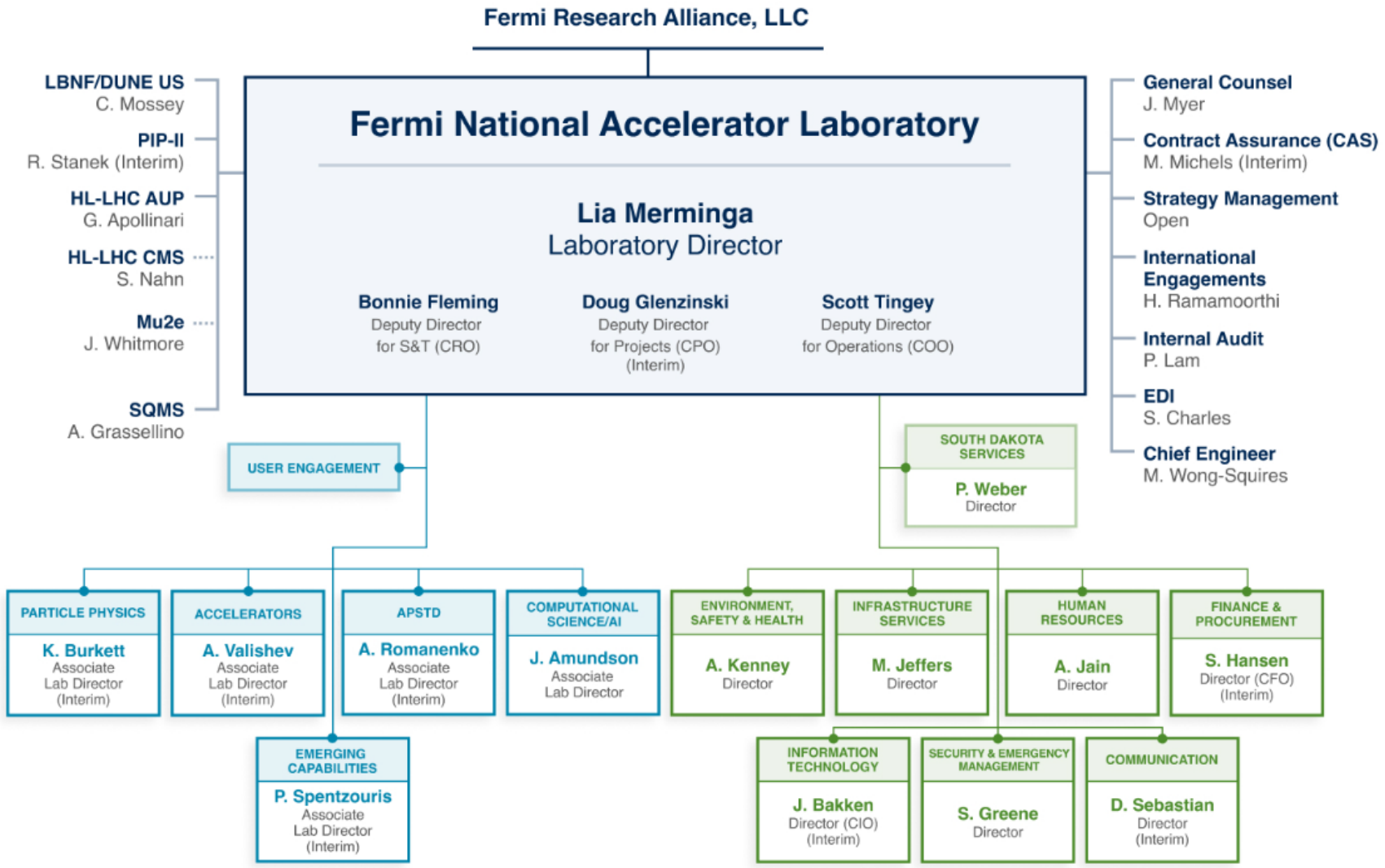


Forge strong alliances with UChicago, ANL, URA and other national/international institutions

Develop Strategic Plan for Fermilab's next 20 Years

New Organizational Structure

Last Modified: November 2022



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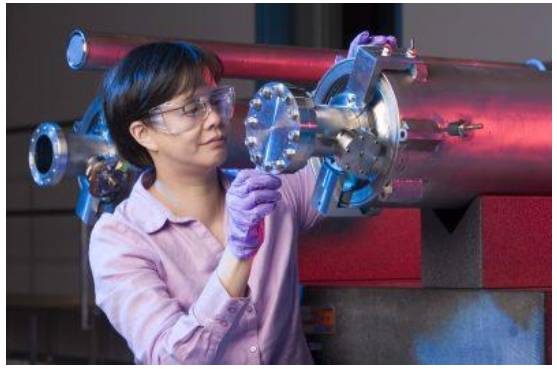
A world-class leadership team

Bonnie Fleming,
Deputy Director for
Science & Technology/CRO

Scott Tingey,
Deputy Director for
Operations/COO

Steve Gourlay
Magnets Division Director



Mayling Wong-Squires
Head of Mech. Engineering, AD
Chief Engineer

Matt Kwiatkowski, ANL
Interim CISO

Susan Simpkins
Deputy CFO

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Major Science & Technology Initiatives

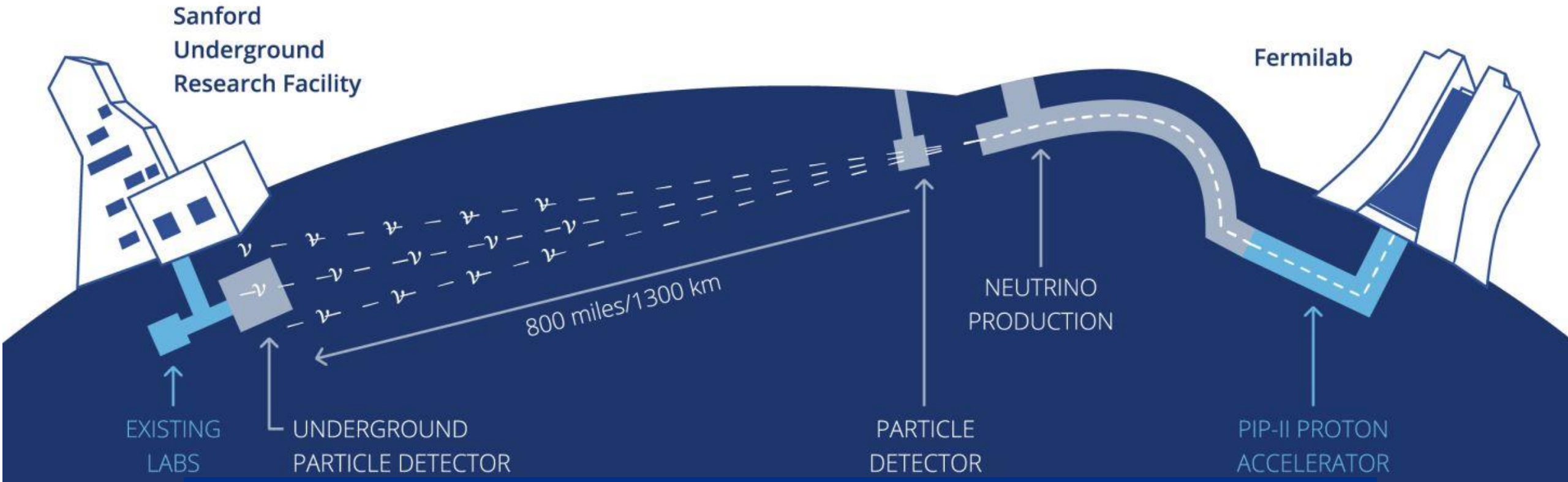
- Neutrino science and LBNF/DUNE
- Collider science
- Precision science
- Cosmic science

- Accelerator science & technology
- Detectors & Microelectronics
- Computing, AI/ML
- Quantum science & technology
- Theory

DUNE: “Best in Class” neutrino experiment, driven by LBNF and PIP-II

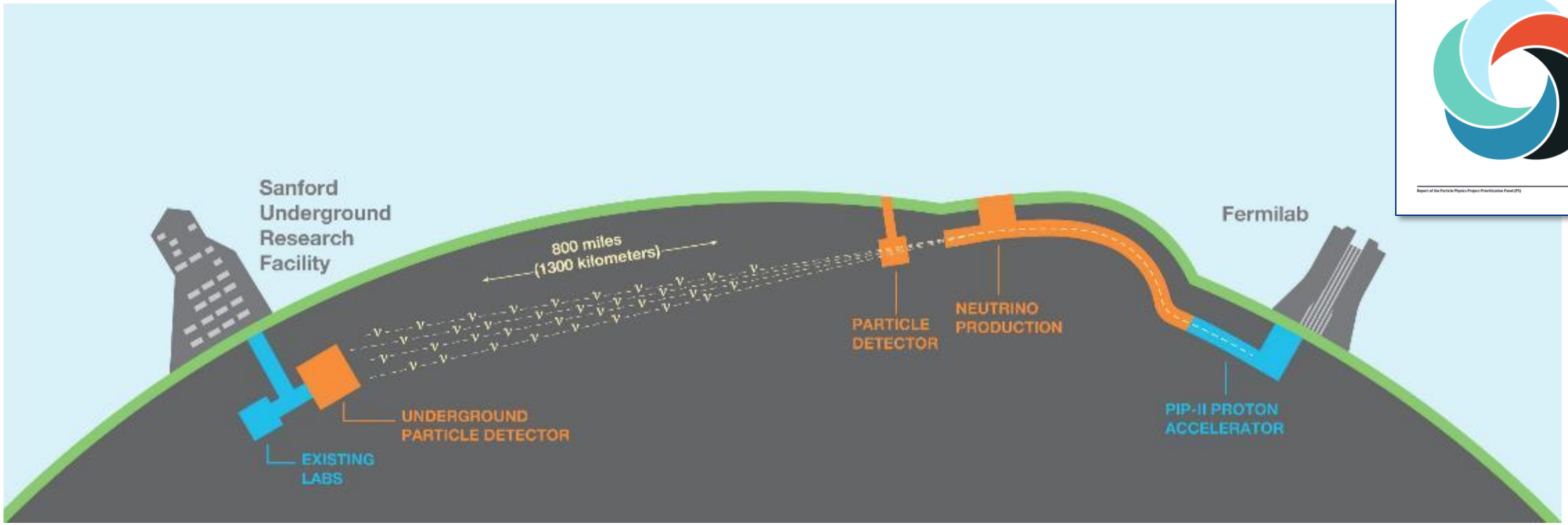
Vision for Neutrino Science

U.S. is universally acknowledged as the world leader in neutrino science for decades to come



Delivering on LBNF/DUNE is Fermilab’s highest priority

Science Objectives



Origin of matter. Investigate leptonic CP violation. Are neutrinos the reason the universe is made of matter?

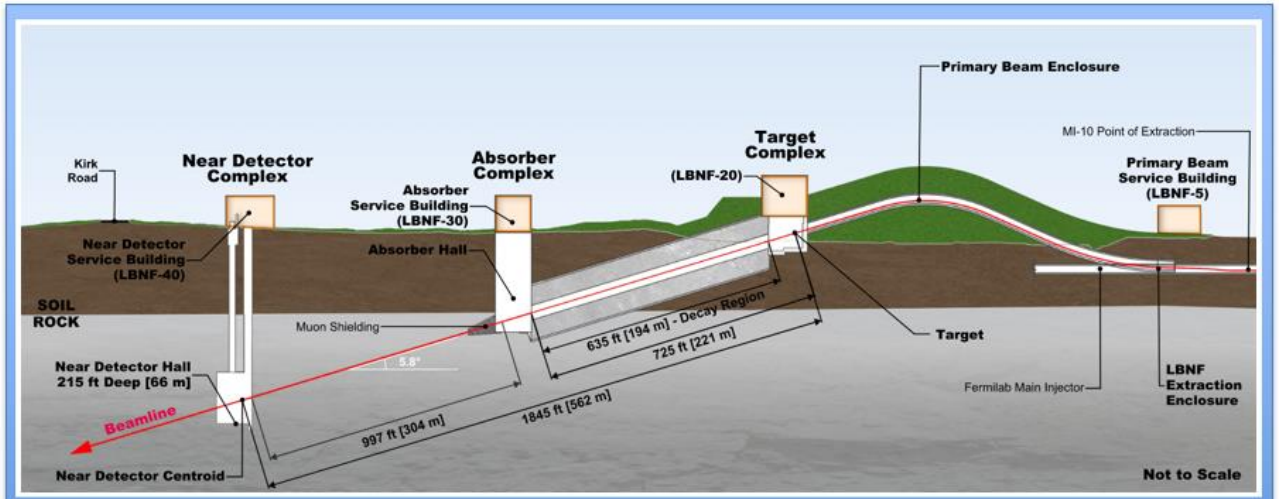
Neutron star and black hole formation. Ability to observe neutrinos from supernovae events and perhaps watch formation of black holes in real time.

Unification of forces. Investigate nucleon decay, advance unified theory of energy and matter.

The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States" – DOE

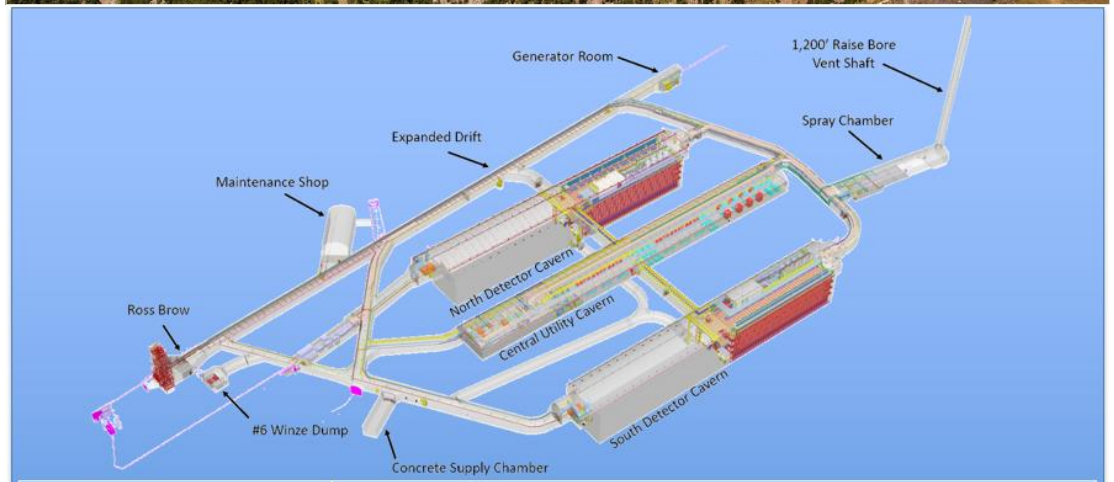
LBNF/DUNE-US Project Scope

Near Site – Batavia, IL



WBS/Subproject	Scope
131.NSCFB/NSCF + Beamline	1.2MW primary and neutrino beam, upgradable to 2.4MW; facility to support 1.2MW upgradable beamline and ND Complex
131.ND/Near Detector	DUNE-US contributions to Phase 1 Near Detector; LAr and LHe systems to support ND; installation and integration for detector and cryogenic systems.

Far Site – SURF, Lead, SD



WBS/Subproject	Scope
131.FSCFEXC/FSCF-Excavation	Project management, preliminary and final design, reliability/infrastructure upgrades, pre-excavation systems, and excavation work to support 4 detector modules.
131.FSCFBSI/FSCF-Building & Site Infrastructure	Project management, preliminary and final design, and construction of surface and underground utilities, and infrastructure outfitting of spaces for detector modules.
131.FDC/Far Detectors and Far Site Cryogenic Infrastructure	DUNE-US contributions to two DUNE detector modules; two cryostats & associated liquid argon; cryogenic systems to support two detector modules; installation and integration for two detector modules and cryogenic infrastructure

Over 50% of scope is at final design maturity; project at 85% design maturity overall

Planned Critical Decision Timeline Summary

9 Dec 2022

Subproject	CD	Q3 2022	Q4 2022	Q1 2023	Q2 2023	Q3 2023	Q4 2023	Q1 2024	//	Q3 2024	//	Q2 2025	//	Q4 2025
All	CD-1RR	✓ **IPR 11-15 Jul**		ESAAB										
FSCF-EXC[1]	CD-2/3	✓ **ESAAB 19 Aug**												
FSCF-BSI	CD-2/3		✓ **IPR 15-17 Nov**	ESAAB										
FDC	CD-3a		✓ **IPR 8 Nov**	ESAAB										
	CD-2/3					**IPR 11-14 Jul**		ESAAB						
NSCFB	CD-3a		✓ **IPR 6 Dec**	ESAAB										
	CD-2/3					IPR TBD		ESAAB						
ND[2]	CD-2							IPR TBD		ESAAB				
	CD-3											IPR TBD		ESAAB

DOE critical milestone review

DOE critical decision (ESAAB) timeframe

Notes

Quarters shown are calendar year

Bolded dates are set

1: FSCF-EXC CD-2/3 IPR was held in January 2022

2: ND critical decision timeline is under development

Each subproject will also have a CD-4 milestone review (not shown).

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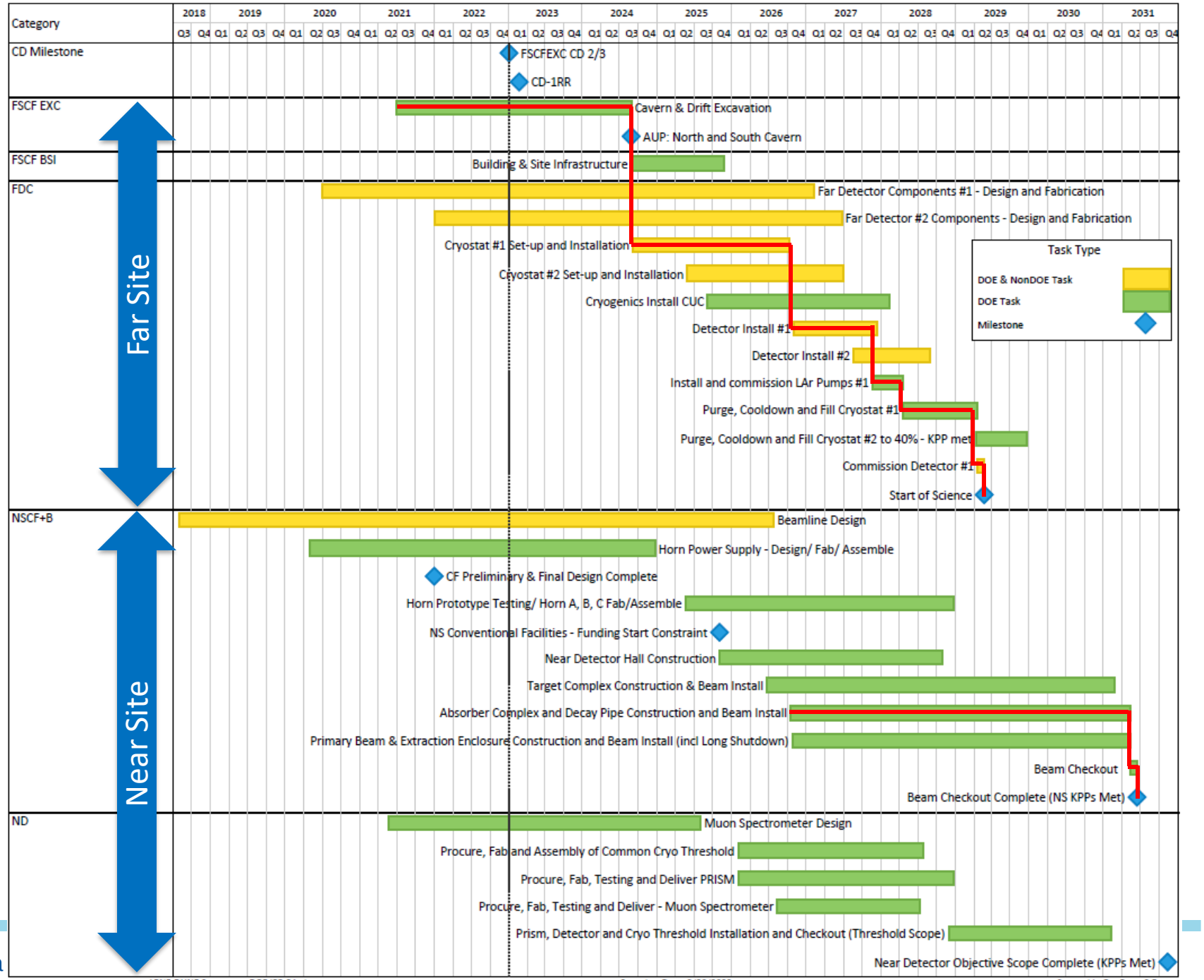
LBNF/DUNE-US: Status and recent achievements

- The excavation work in South Dakota is proceeding safely, on budget and on schedule, with the caverns at almost 50% excavated.
  - Detector installation begins 2024; CERN and partners ready for production
- The project received a favorable new funding profile in March from the Office of Science. Additionally, LBNF/DUNE-US was allocated $125M from the Inflation Reduction Act.
- CERN formally agreed to provide the second membrane cryostat via ceremony in September.
- DOE HEP provided a cost cap ($200M) for the U.S. contribution to the Near Detector. The project, collaboration, international partners, and national laboratory partners are currently working together to finalize a plan to deliver the needed capability from this project component.

Summary Schedule with Critical Paths through Start of Science (FD1) and Beam-on



Notes:

- Fiscal Year display
- Sep 2022 reporting cycle
- Based on “CD-1RR ESAAB” funding profile

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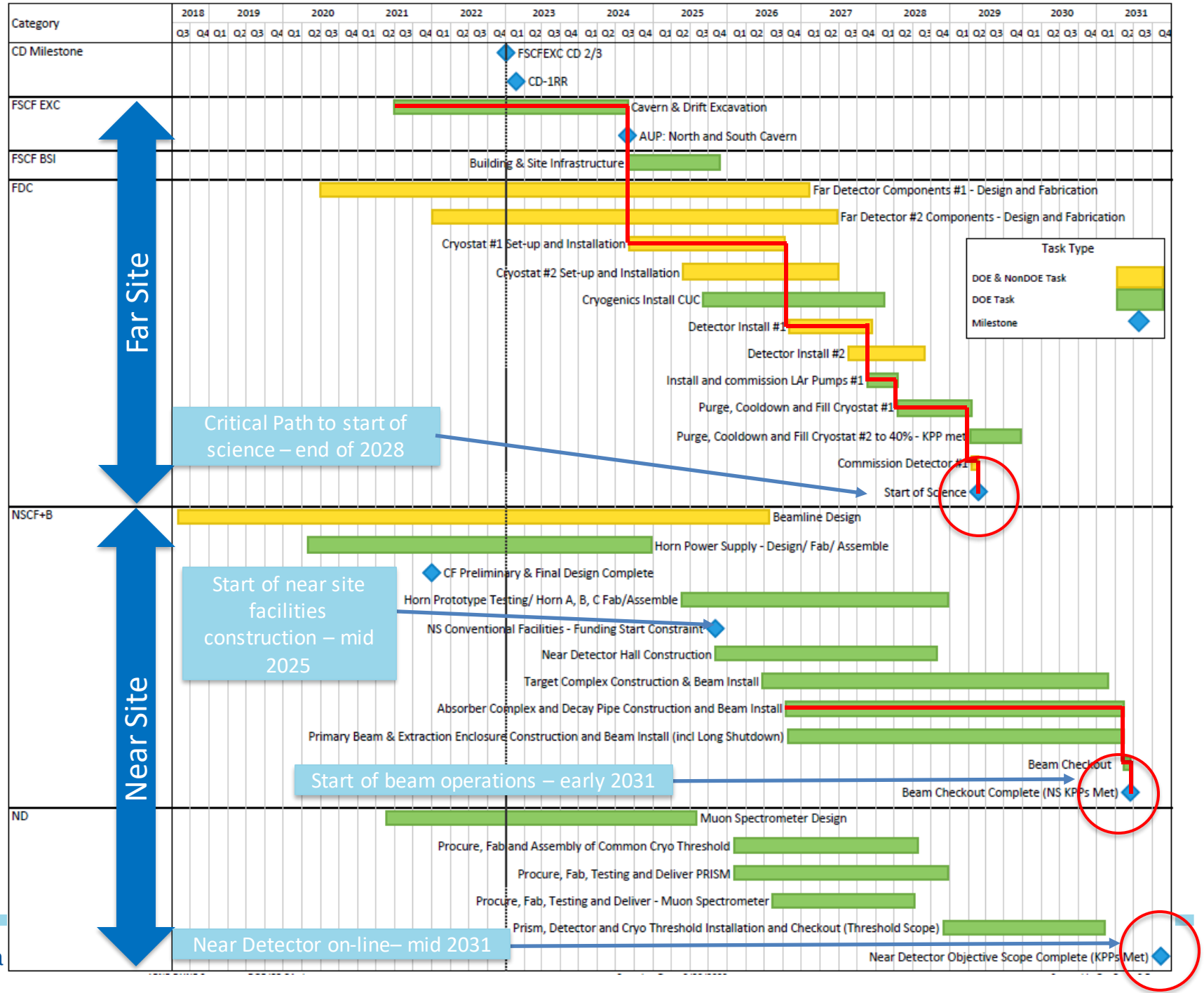
Summary Schedule with Critical Paths through Start of Science (FD1) and Beam-on



Notes:

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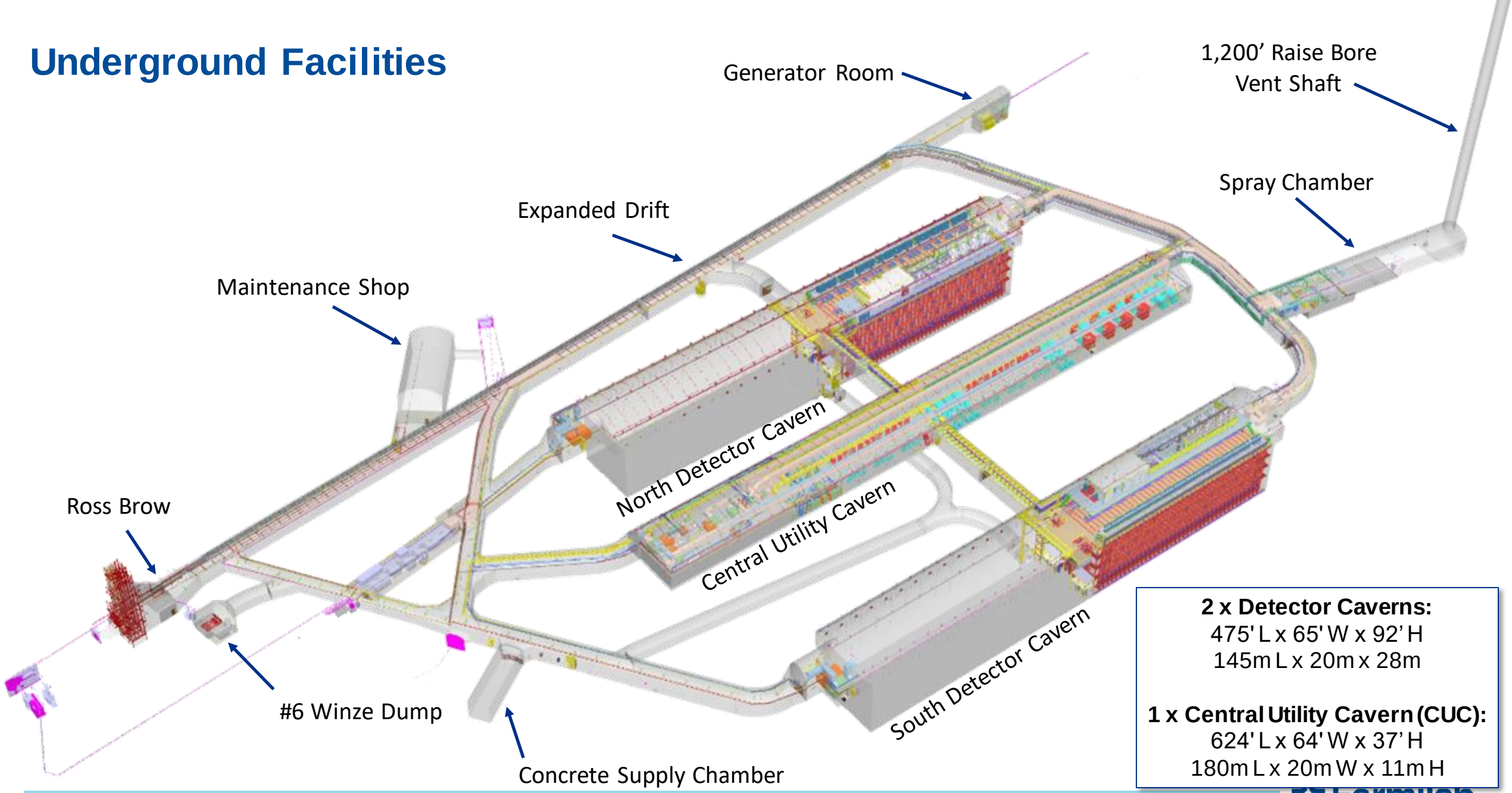
Underground Facilities



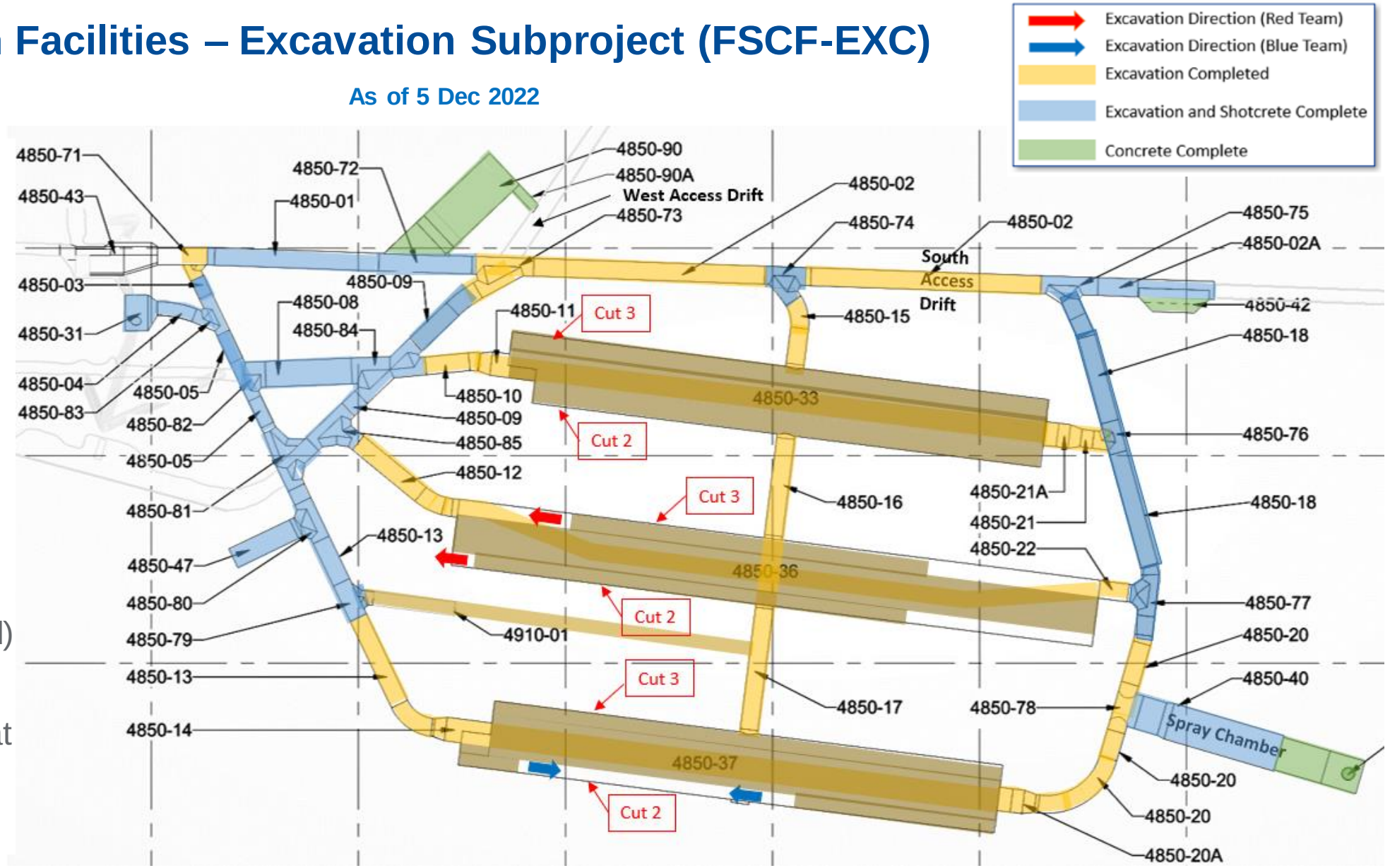
2 x Detector Caverns:
475' L x 65' W x 92’ H
145m L x 20m x 28m

1 x Central Utility Cavern (CUC):
624' L x 64' W x 37’ H
180m L x 20m W x 11m H

Far Site Convention Facilities – Excavation Subproject (FSCF-EXC)

As of 5 Dec 2022

- ✓ "Reliability projects" completed (e.g., refurbish Ross shaft) completed.
- ✓ "Pre-excavation projects" completed (e.g., systems to move excavated rock to the surface)
- ✓ The 1200' ventilation shaft was completed (reamed and shotcreted) on 28 March 2022
- Excavation of caverns at **47% complete** as of 5 December.



Excavation Progress Photos – North Cavern

View in North cavern near midpoint, looking west.
Overhead (in protective wrapping) in the central monorail (bridge crane).

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Location of photo in North Cavern

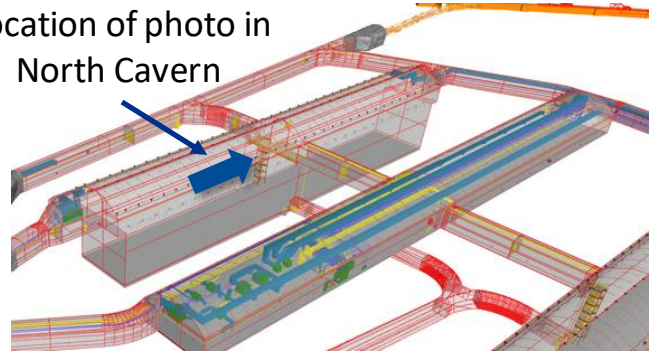
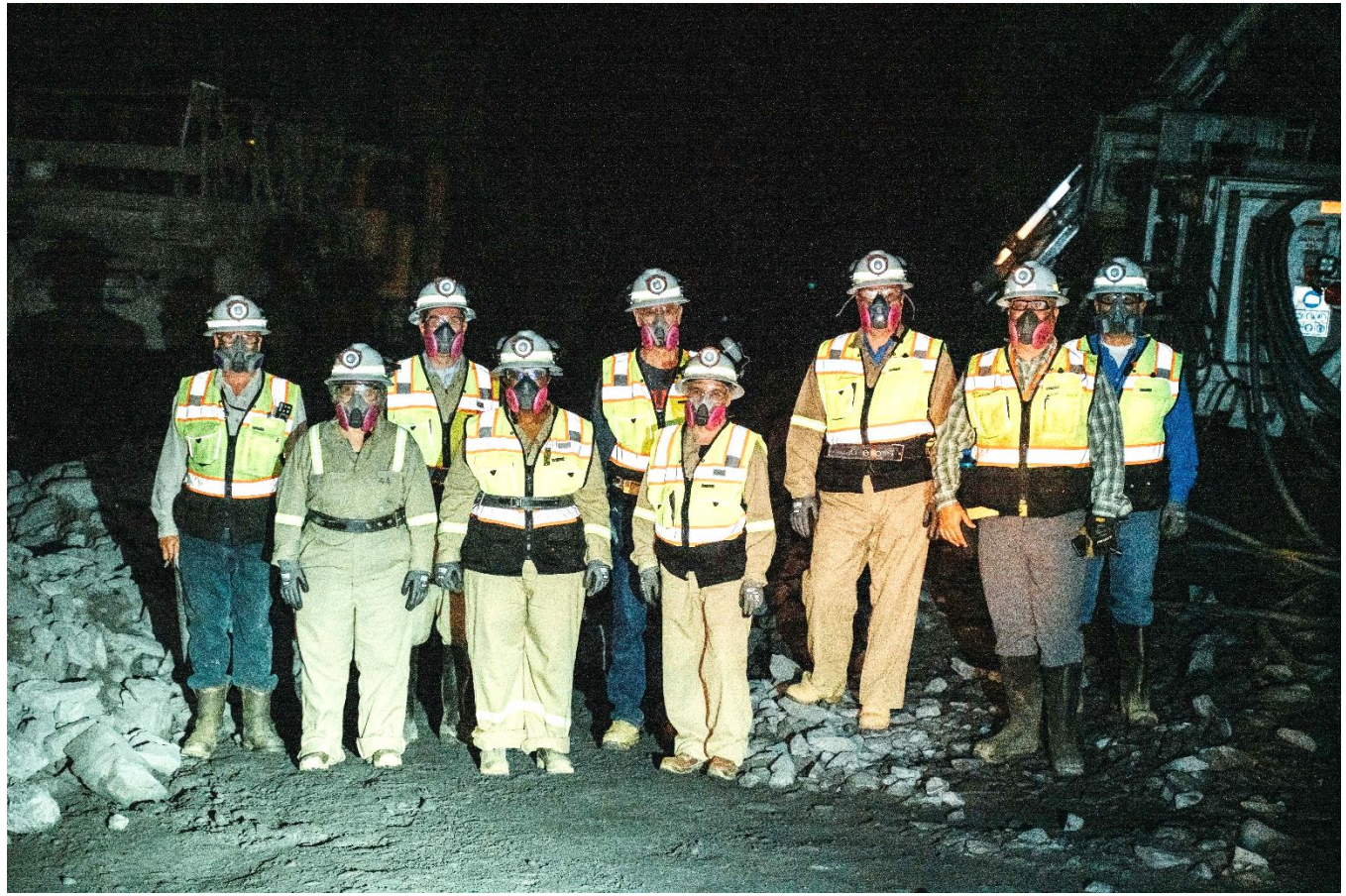


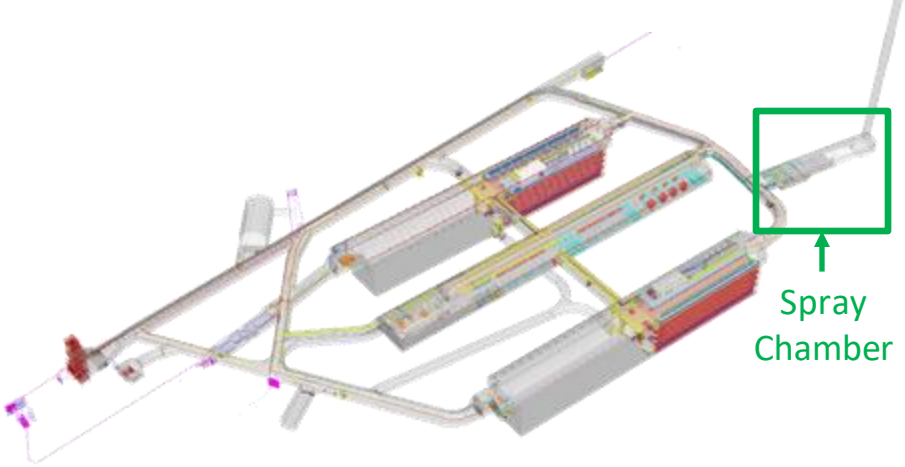
Photo taken about half-way point of the north detector cavern looking east (see blue arrow)

Visit by Dr. Berhe, DOE Director of the Office of Science, in July 2022

Ross Shaft area on 4850L
Lia Merminga (L), Asmeret Berhe (R)



North Cavern
Front row: L. Merminga, A. Berhe, M. Convery



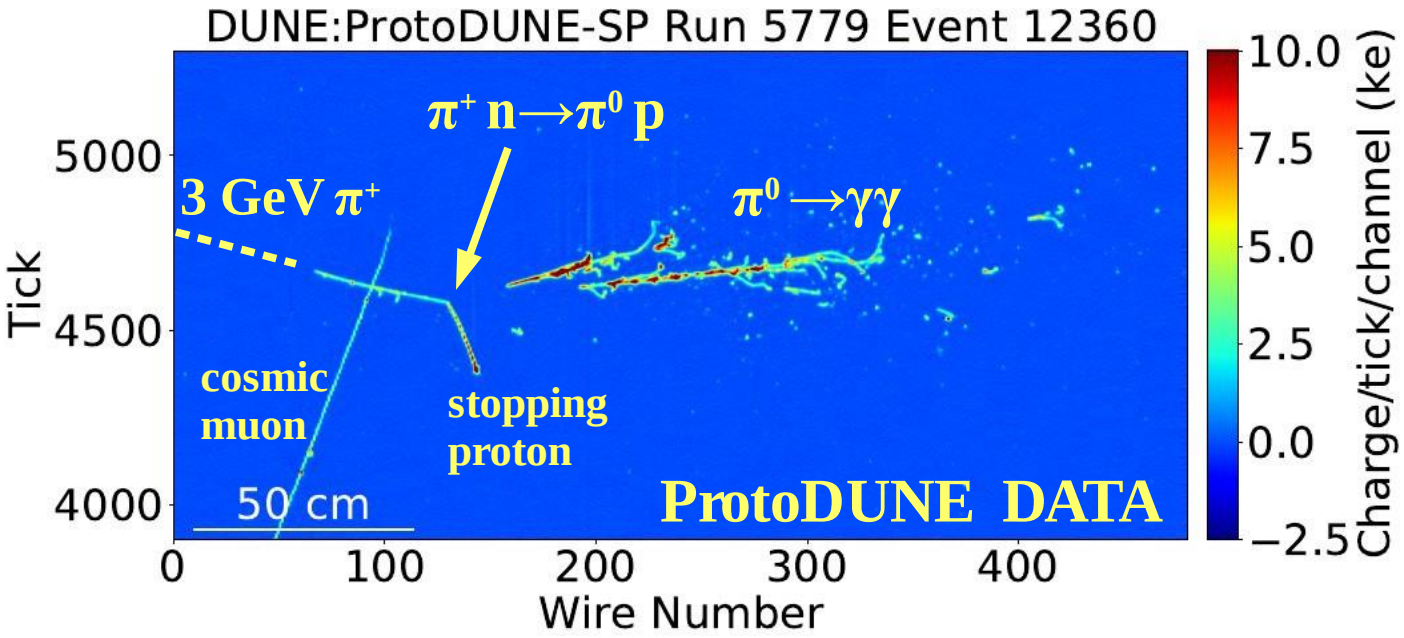
Photos taken in Spray Chamber (facility to reject heat from cryogenics systems and transfer up the raise bore)

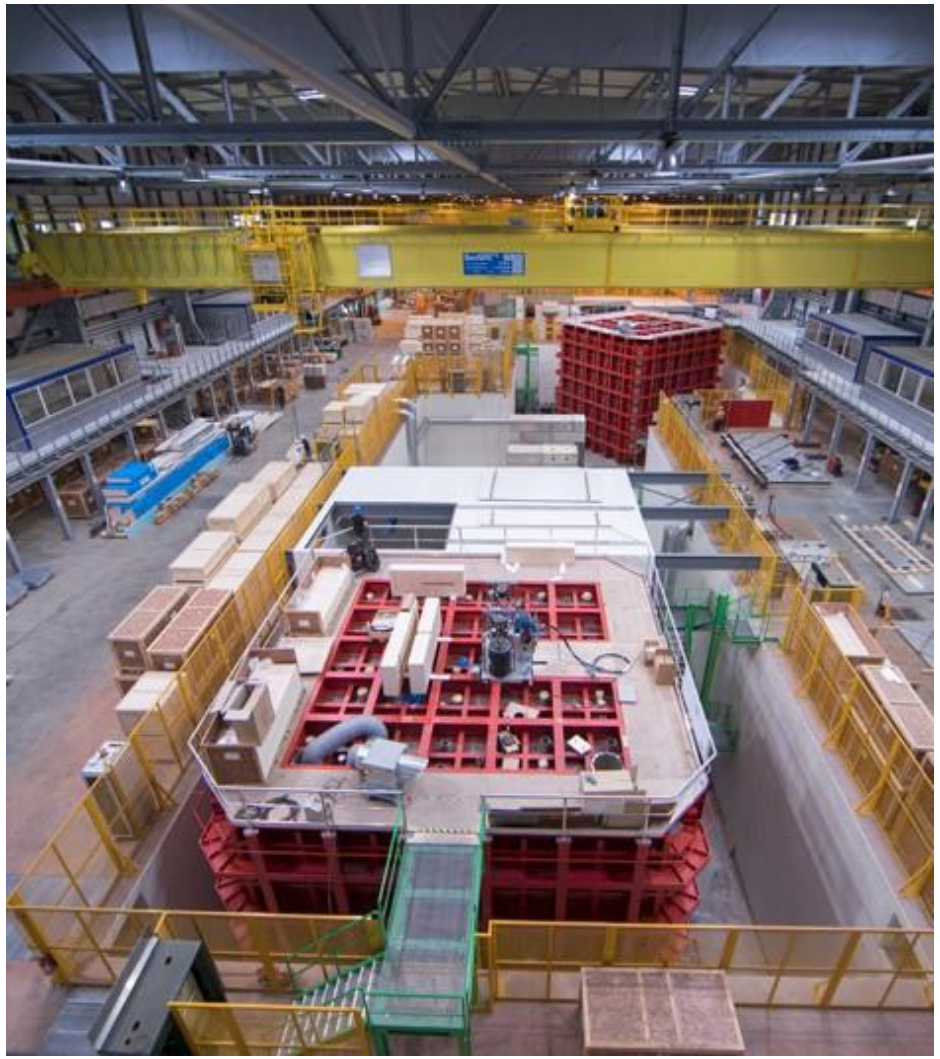
Signature Ceremony - Agreement for CERN to Provide Second Cryostat

Ceremony at CERN on 16 September 2022; Agreement signed by Fabiola Gianotti (CERN DG) and Dr. Asmeret Berhe (DOE Director of Office of Science)
Photo by Jacques Fichet, CERN

FDC Subproject - LArTPC technology is demonstrated @ ProtoDUNE at CERN

- ProtoDUNE is full scale in the drift direction
- Successful operation at CERN: low noise, stable HV, high purity → has demonstrated LArTPC technology and DUNE design





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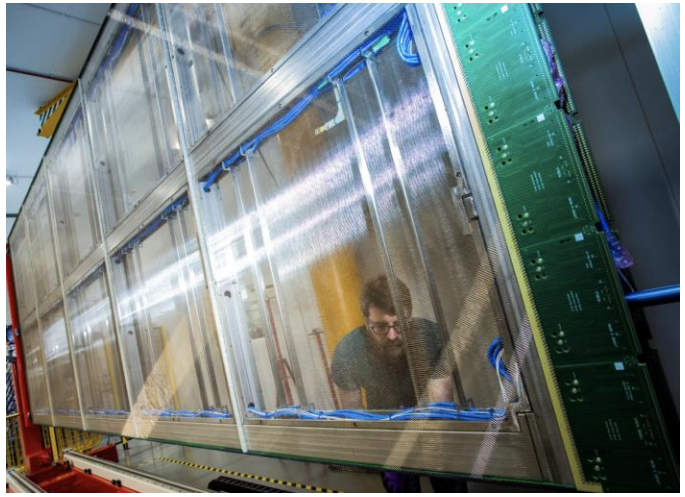
Far Detector/Cryogenic Infrastructure Subproject (FDC) Status

- FD1: Technical Design Report completed
  - Module 0 (2nd round of prototyping) under construction at CERN
- FD2: Preliminary Design Reviews completed
  - Successful cold box testing of full-scale components
  - Module 0 prototype is also under construction at CERN
- Cryogenic Infrastructure:
  - Major procurement for the nitrogen refrigeration system is under DOE review for approval to award.
  - CERN signing ceremony officially committing to provide second cryostat occurred in September.
- CD-3a IPR successfully completed in November, CD-22/3 DOE IPR is scheduled in mid-July 2023
- APA test lift successfully completed at SURF between 1 - 2 Nov; proves the largest detector components can be successfully moved to 4850L.

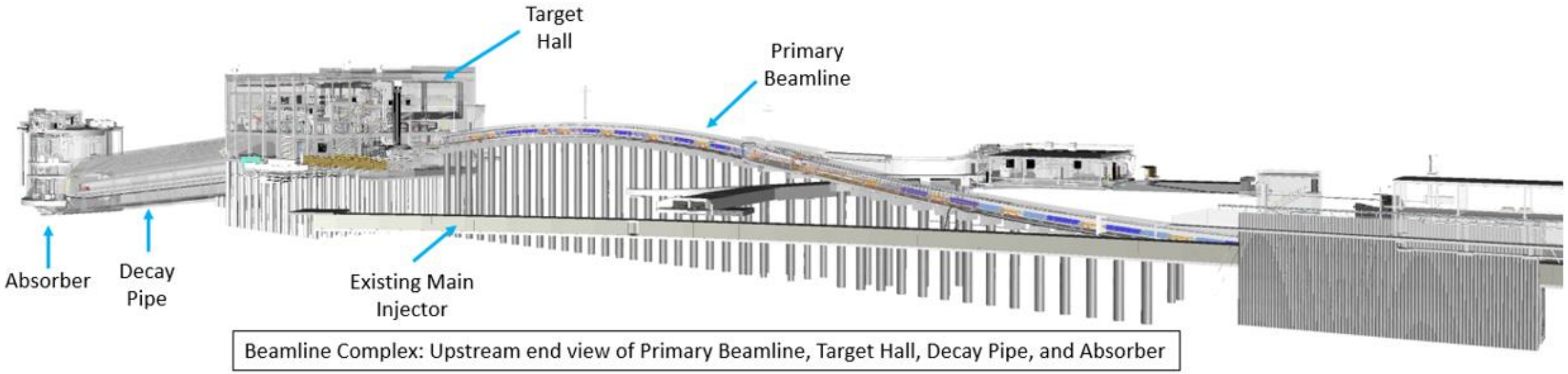


DUNE Far Detector Anode Plane Assembly (APA) at Daresbury Lab, UK, to be installed at CERN in NP04, Horizontal Drift ProtoDUNE Module 0

Shipping container, holding two APAs, is moved into the Ross Shaft at SURF to be lowered to the 4850L

Near Site Conventional Facilities + Beamline Subproject (NSCF+B)

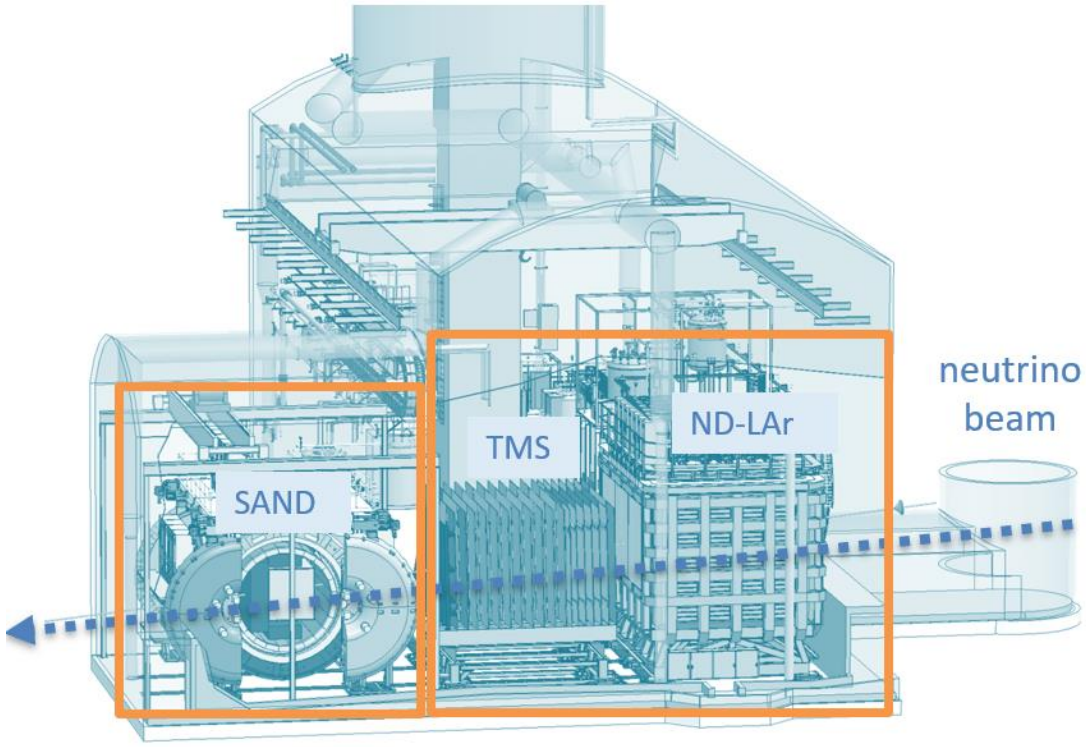
- Beamline design is at ~70% final design status and on track
- Conventional facilities design is at 100% final design status. Independent cost estimates recently updated.
- Current schedule for this subproject is funding limited, plan contact awards in 2025.
- DOE CD-3a review successfully competed on 6 December for long lead items.



Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

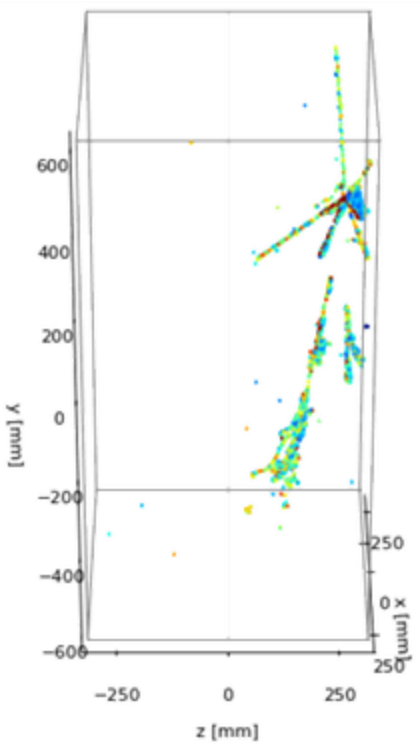
Note: ND Hall facilities is part of NSCF+B Subproject

DUNE Near Detector



Two main Near Detector components:
ND-LAr+TMS (moveable) and SAND (stationary)

- The Near Detector is a critical element to control systematic measurements in DUNE



- A fully instrumented 20% scale ND-LAr prototype has been successfully operated at LHEP/University of Bern.
- A 2x2 modular detector to be tested in Fermilab neutrino beam in 2023.

Swiss State Secretary for Education, Innovation, and Research, Martina Hirayama, visits Fermilab with Swiss delegation on October 20, 2022. Photo credit: Ryan Postel.

Fermilab is preparing to host the international DUNE Collaboration

- Fermilab is preparing to provide the array of services that will provide critical support for:
  - Execution of detector subprojects
  - Operations of DUNE experiment
  - Hosting of an international science collaboration

- The DUNE Host Lab Task Force, led by the Chief Research Officer (CRO) and Chief Operations Officer (COO) has been working since August. These organizations will provide key support in the following areas:
  - **CRO**:
    - Interface with DUNE collaboration, Int'l funding agencies, physics community
    - Organizes and coordinates oversight bodies, including LBNC, NSG, and RRB
  - **COO**:
    - Organizes and coordinates support through laboratory mission support organizations (eg; legal, facility, property, safety, HR, financial, procurement, project support services, etc)

- Draft task force report, addressing critical issues, is due by end of year.

Collaboration statistics

1,402 collaborators, 47% U.S./53% non-US

206 institutions from 37 countries including CERN

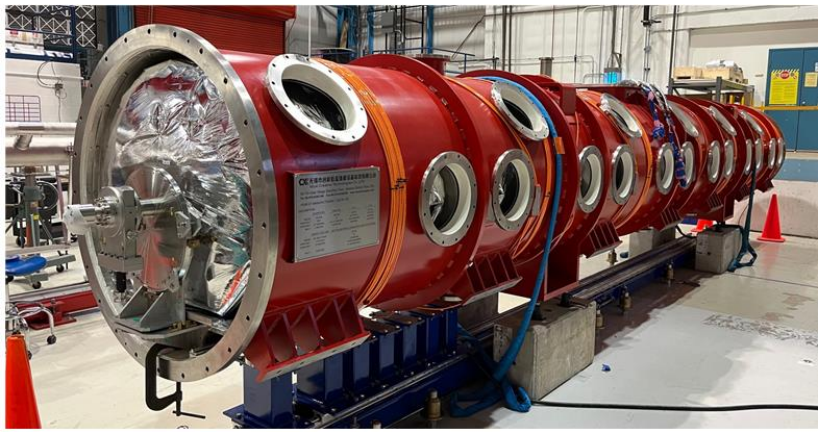
Support of the LBNF/DUNE enterprise is a lab-wide effort

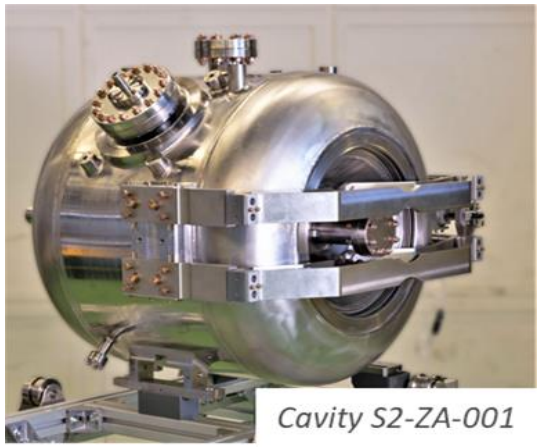
Proton Improvement Plan – II (PIP-II)

PIP-II Project construction has begun!

- PIP-II received DOE CD-3 approval for start of construction/project execution on April 2022
  - Linac complex construction contract award is imminent
- PIP-II team, including all International Partners, is fully engaged
  - UKRI has placed contract for all HB650 production cavities
  - INFN is finalizing the procurement for the production quantity of LB650 Niobium
- Front end of PIP-II linac constructed and successfully tested with beam
- PIP-II cryoplant building 99% complete. Site work is complete
  - Cryoplant is an in-kind contribution from India/DAE - final design review for cold box held in Nov 2022
- Initial tests of LB650 cavities exceeded specifications; SSR2 cavities are in production/initial testing
- HB650 prototype cryomodule (first of its kind) will be tested in Jan 2023

✓	CD-2/3 ECF	Jul 2020
✓	CD-2	Dec 2020
✓	CD-3a	Mar 2021
✓	CD-3	Apr 2022



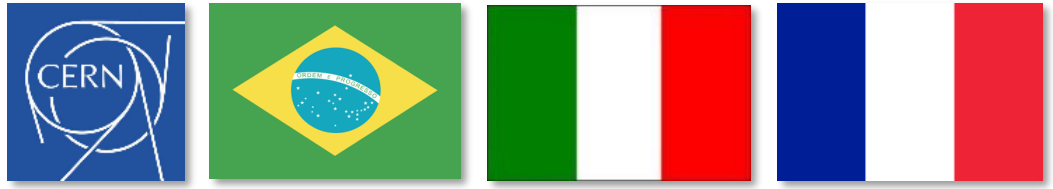


PIP-II is the first particle accelerator built in the U.S. with significant international contributions

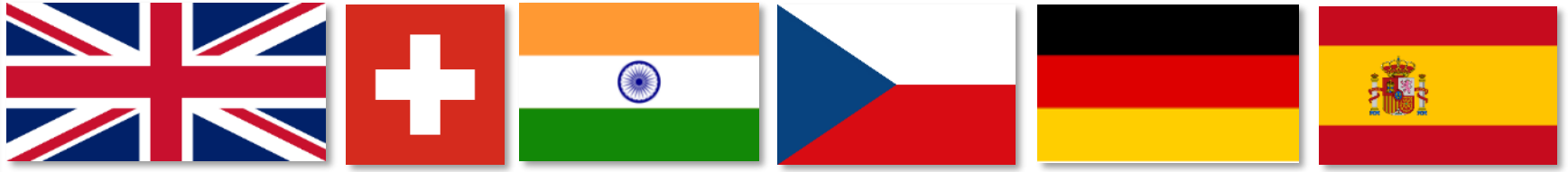
PIP-II Cryogenic Plant Building

LBNF/DUNE/PIP-II in-kind contributions $1.1B with growth potential

- LBNF/DUNE-US
  - $262M in-kind contributions to LBNF (does not include private @ $70M or State of SD @ $93M to support SURF)
  - $310M in contributions to DUNE detectors
  - $84M in CERN contributions to protoDUNE efforts (does not include French contributions to protoDUNE R&D)
- Additionally, LBNF powered by PIP-II, which has secured $310M in international contributions



- All in-kind contributions are expressed in DOE TPC units
- Numbers do not include other IKCs received in support of Fermilab's short-baseline neutrino program



In-kind contributions supported by 10 Government-to-Government agreements and 17 I-CRADAS

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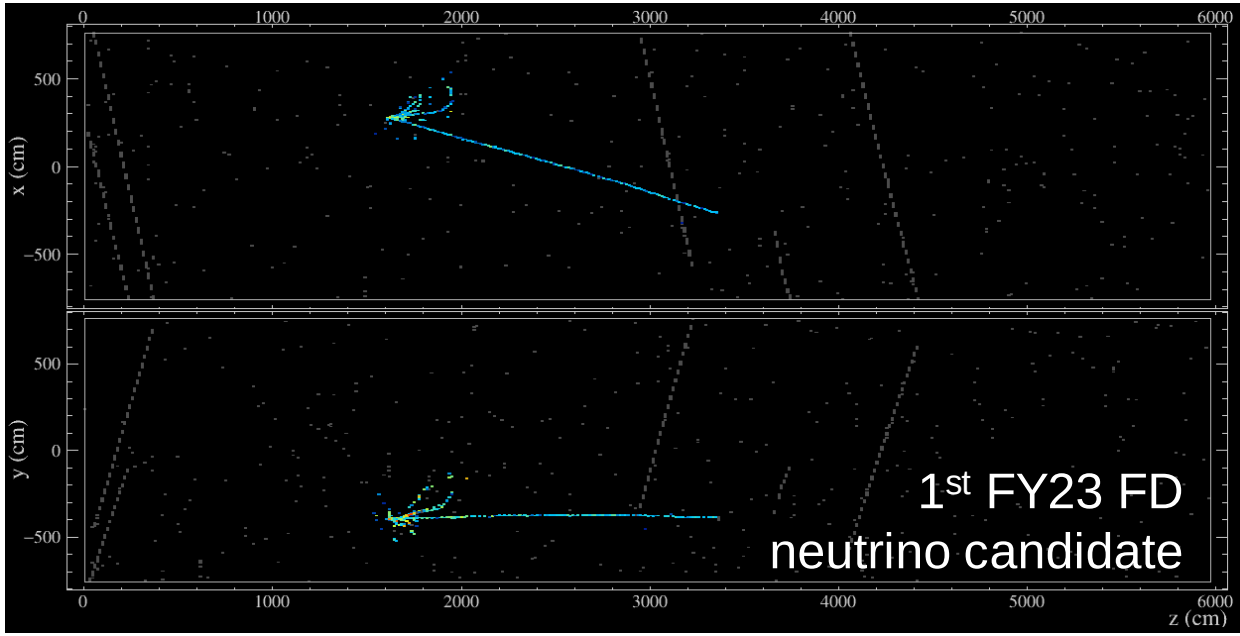
NOvA Experiment Highlights

- FY22 was a record year for NuMI
  - 897 kW, power record, 5.7×10^{20} POT total
  - Far Detector live for 99.5% of beam

- 2 new papers:
  - "Improved measurement of neutrino oscillation parameters by the NOvA experiment" highlighted with a Viewpoint in PRD
  - "Measurement of the Double-Differential Muon-neutrino Charged-Current Inclusive Cross Section in the NOvA Near Detector" just accepted by PRL

- 5 new conference results:
  - 2 multi-nucleon scattering constraints
  - New limits on light sterile neutrinos
  - New limits on non-standard interactions
  - A Bayesian re-analysis of the 2020 3-flavor results



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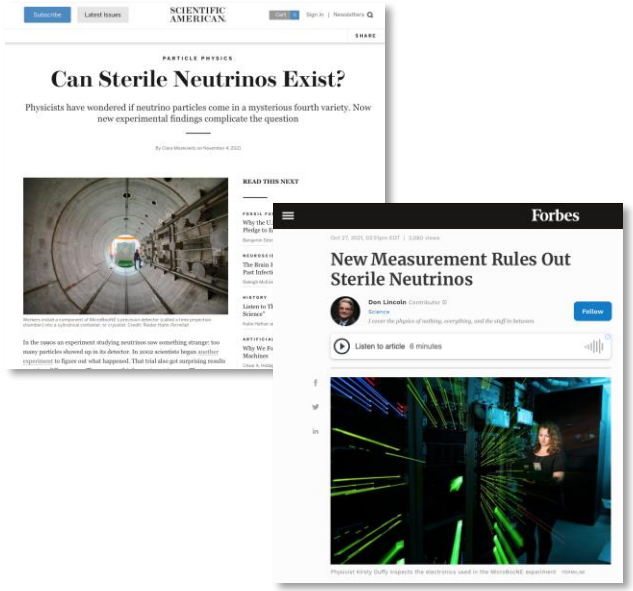
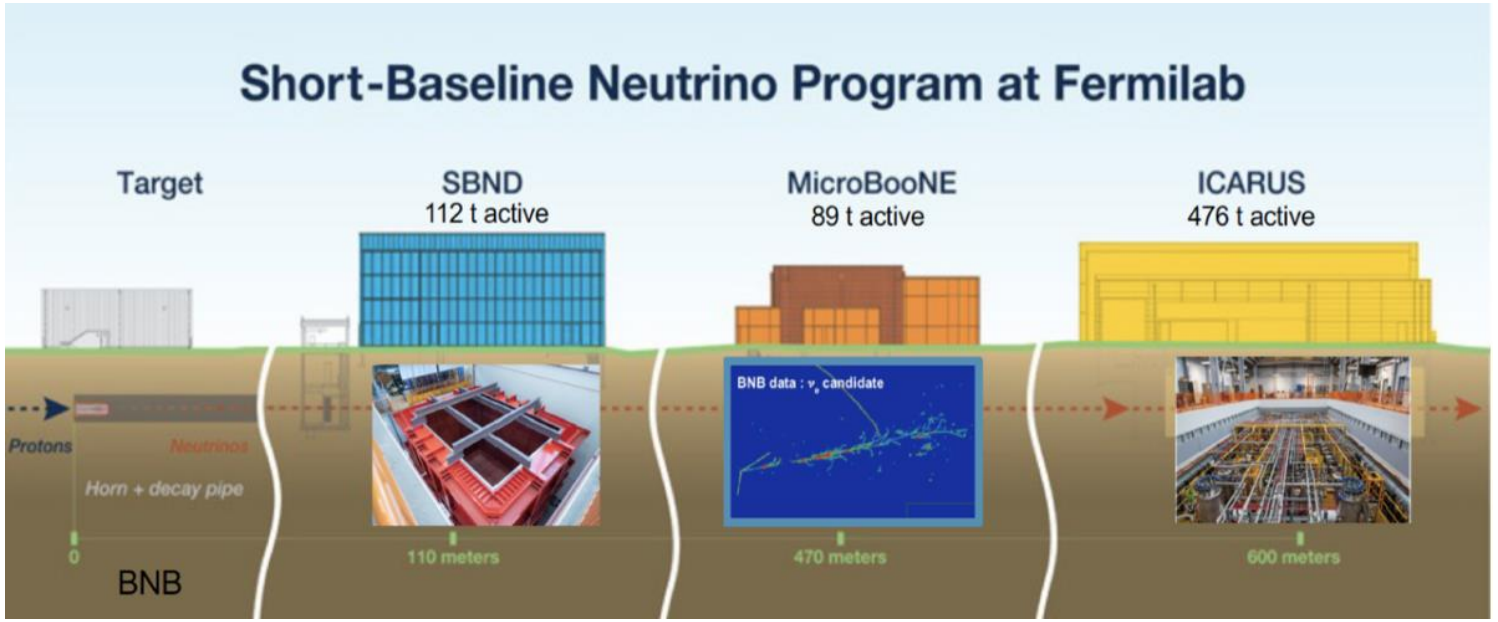
Short Baseline Neutrino (SBN) program

The SBN program is a P5 report recommendation:
Pursue an exciting accelerator-based short baseline neutrino program at Fermilab, SBN

- to attract national and international neutrino community to Fermilab
- perform experiments using liquid argon detector technology – basis of DUNE
- establish and train diverse community of researchers needed for DUNE era





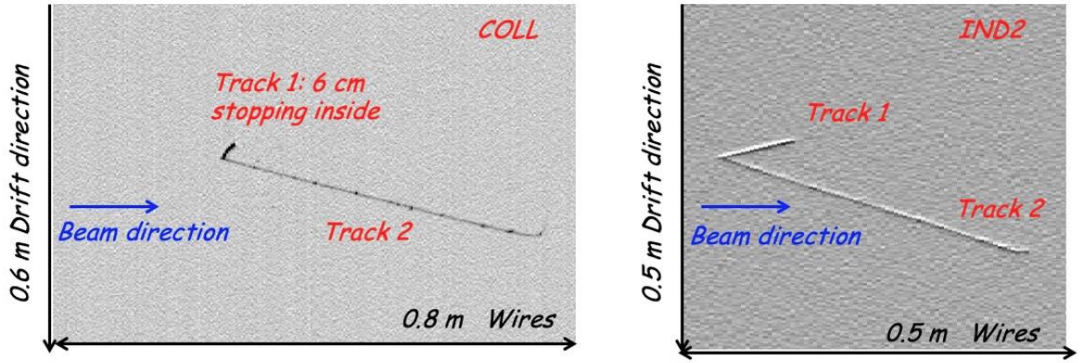
MicroBooNE made a big splash with its flagship results:

- Liquid argon technology works extremely well, good news for DUNE
- Seven papers released simultaneously

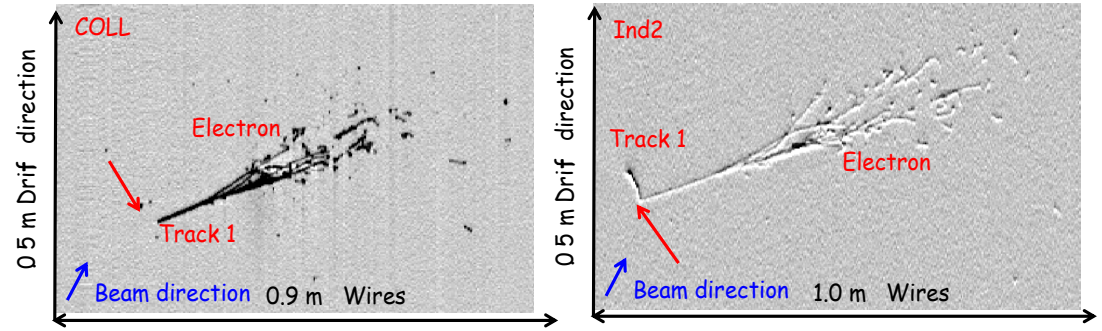
Science target: resolve the 4.8σ MiniBooNE low energy excess, with the possibility of discovering sterile neutrinos or other exotic neutrino physics

ICARUS Operations Status

- Completed detector installation and commissioning in June 2022
- Physics run with ν's from BNB and NUMI June-July 2022
  - 44.1E18 P.O.T. (BNB) + 73.1E18 P.O.T. (NUMI)
  - 93% collection efficiency
- Summer shutdown:
  - Improved TPC power supplies to reduce coherent noise
  - Improved trigger efficiency for cosmics
  - Regenerated LAr filters for west cryostat; improved electron lifetime from 3ms to >6ms
- Now collecting physics data with ν's from BNB and NUMI
- First paper on initial operation in preparation



Candidate ν_μ C.C. Event



Candidate ν_e C.C. Event

Fermilab

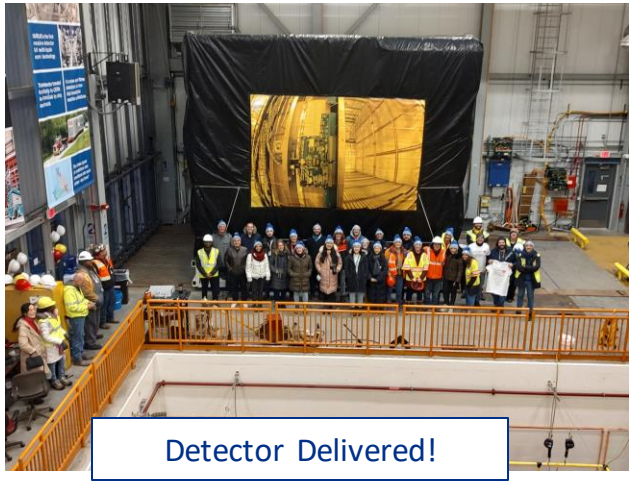
SBND Detector Assembly and Installation on Track

- Detector assembled at the DZero Assembly Building (DAB) by collaboration with FNAL technician support
- Membrane cryostat installed by Gabadi (CERN sub-contractor) with FNAL and CERN technicians
  - Final prototype of LBNF/DUNE design
- Cryostat top cap assembled by FNAL and CERN technicians
- Detector transported from DAB to SBN ND building on Dec 1

Assembled SBND Detector

Cryostat Installation Team

SBND Cryostat + Top Cap



Detector Delivered!

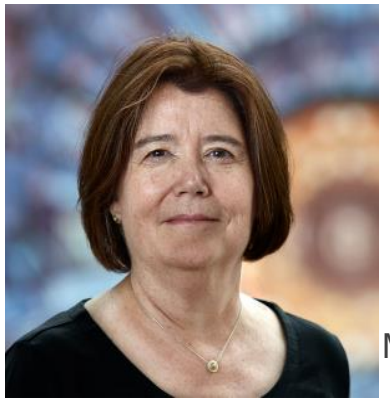
Fermilab


Collider Science and
the US CMS Collaboration

Collider Science

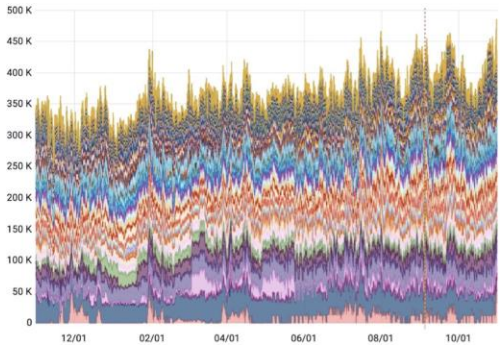
Vision: Fermilab continues to be the leading U.S. center for CMS and second leading center in the world after our partner CERN

- Fermilab is host lab for US CMS (27% of CMS)
- CERN LHC CMS experiment resumed collisions for Run 3
  - ROC is back in Operations!
- Execute HL-LHC AUP and CMS Detector Upgrade Projects
- **CERN is our European sister laboratory and our strong partner in many areas**

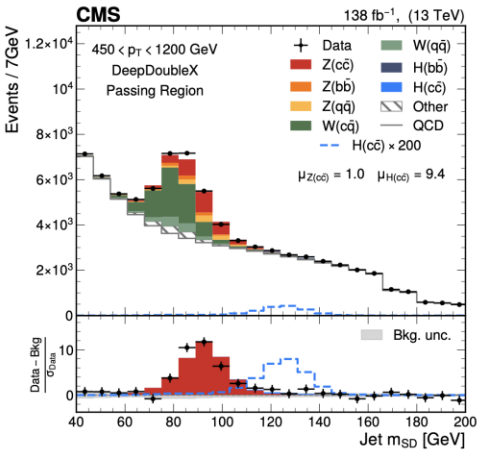


Fermilab's Patty McBride elected next CMS spokesperson

CMS Experiment



- The **2022 LHC run ended on November 29th** with 38/fb recorded by CMS
  - Fermilab and USCMS played a key role in detector operations at CERN and through the Remote Operations Center (ROC) at the laboratory.
  - Fermilab Tier1 and computing infrastructure maintained excellent performance, including critical exploitation of HPC (bringing to a record 248k USCMS cores out of - a record - 485k for CMS).
- **CMS submitted 1172 collider data papers** as of November 30th
  - including the Fermilab-led first search for the H → cc decay at the LHC (Phys. Rev. Lett.)
- The **Energy Frontier at the lab (including the LHC Physics Center) reviewed very positively** at the DOE National Laboratory HEP Research Review (09/22)
- The Fermilab CMS group directly contributed to **46 White Snowmass papers and to the Frontiers' reports**.
- **Wilson Fellow Jennifer Ngadiuba** received the Artificial Intelligence Research for High Energy Physics Award and was selected as a AI2050 Early Career Fellow at Schmidt Futures.



Fermilab

HL-LHC AUP Upgrade

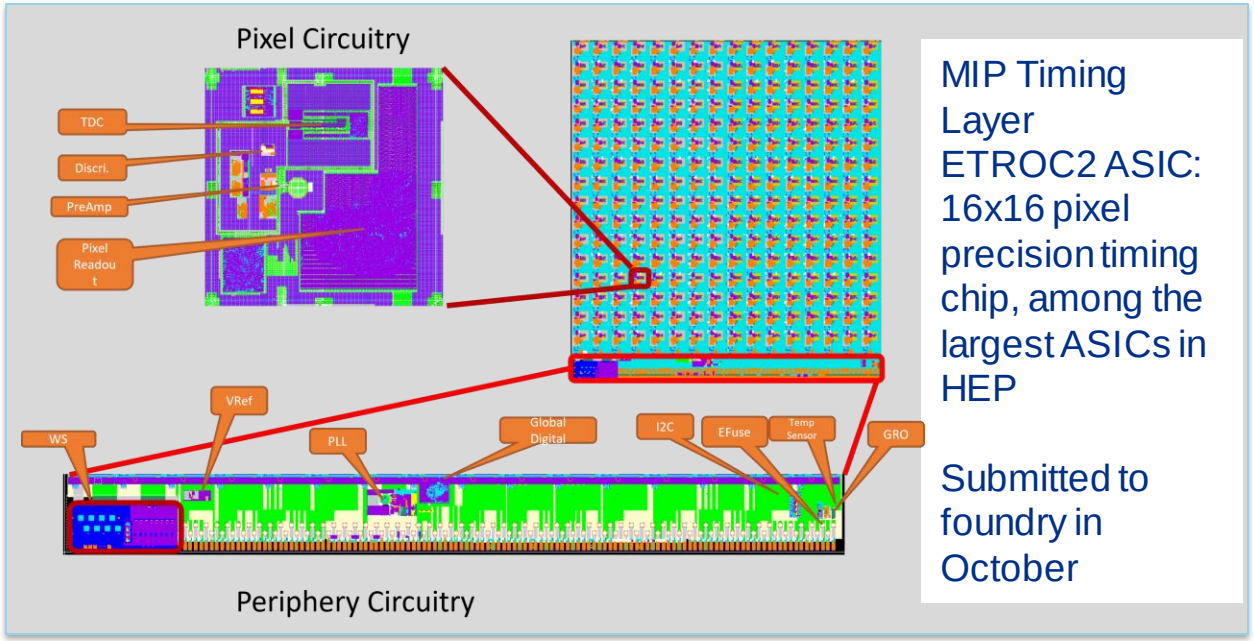
- HL-LHC AUP is a critical in-kind contribution to the HL-LHC Upgrade
  - HL-LHC Goal: deliver 3000-4000 fb^{-1} to CMS/ATLAS
- FNAL hosts HL-LHC AUP which drives a consortium of 5 US Labs and Universities to deliver:
  - 10 Q1/Q3 Cryo-assemblies with 20 Final Focusing Quads in Nb_3Sn
    - 1st Nb_3Sn application to Accelerators
  - 10 Dressed RFD Crab Cavities
- AUP received CD-3 in 2020 (TPC 242M$), now in execution
  - Magnet production line at full speed
  - First cryoassembly successfully assembled. Cold testing starting in December
  - Construction of two pre-series SRF cavities going well at vendor
- Ready for DOE review for rebaseline request scheduled 13-15 December!

Q1/Q3 Cryo-assembly with two 4.2m long Magnets


RFD Crab Cavity

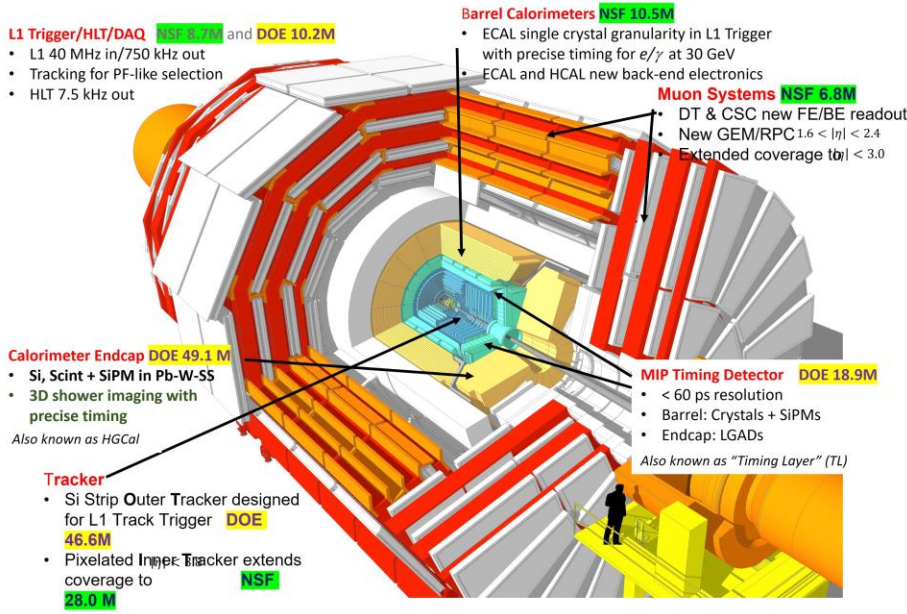
HL-LHC CMS Upgrade

- **HL-LHC CMS** is the U.S. Contribution to the CMS Detector Upgrade
- FNAL and ~45 U.S. Institutes deliver substantial portions of detector
- HL-LHC CMS moving into Production Phase in 2023
  - DOE (TPC $200M): successful Director's Review Nov 2022 leading to CD-2/3c DOE IPR Jan 2023
  - NSF (TPC $77M): re-baselining review Mar 2023
- Progress ensues across all technical areas



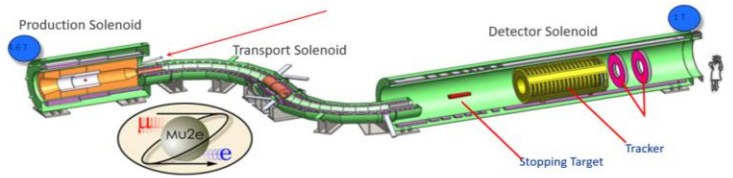
MIP Timing Layer ETROC2 ASIC: 16x16 pixel precision timing chip, among the largest ASICs in HEP

Submitted to foundry in October



Calorimeter: Extruded Scintillator Tile fabrication at Fermilab

Precision Science



Vision: Fermilab is a world center for accelerator-based Charged-lepton flavor violation (CLFV) and Dark Matter experiments, driven by intense particle beams and PIP-II/Booster Replacement

The Muon g-2 and Mu2e experiments use muons, particles that we can produce and control, as a probe of possible new forces or quantum phenomena beyond the Standard Model.

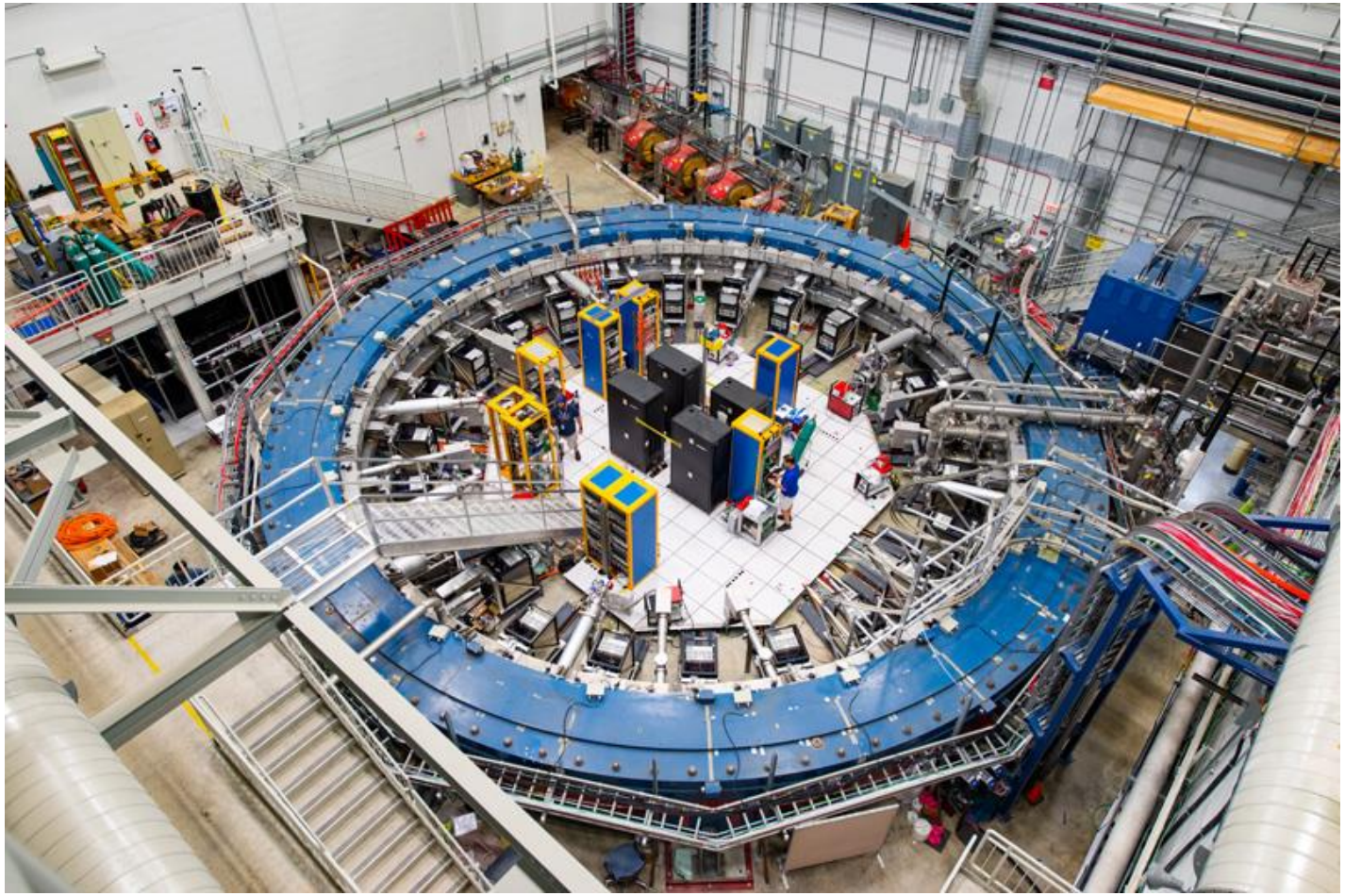
Major goals

- Muon g-2: Complete data production, analysis, theory to achieve 5σ
- Complete Mu2e project in 2025 and start science

Fermilab

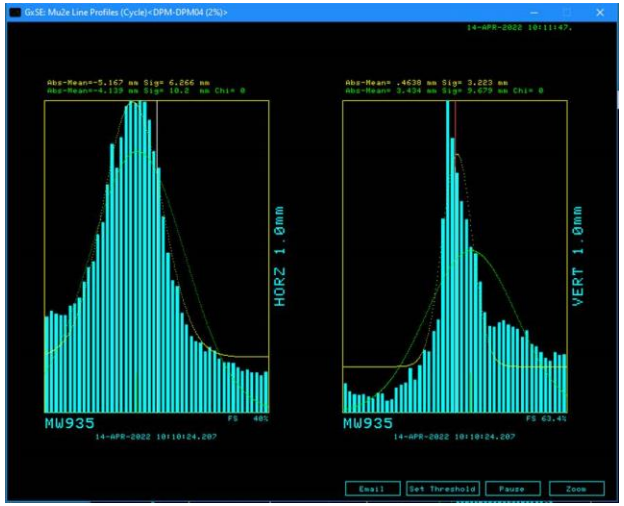
Muon g-2

- Experiment will reach its statistics goal of 21x the BNL data set this year
- New result based on 2019-2020 data expected this Spring with approximately half the uncertainty of the previous result
- Final result based on 2021-2023 data expected in 2025
- Updates from the Muon g-2 Theory Initiative expected on the same timescales
- Collaboration is exploring possibilities for future running in different configurations



Mu2e Project

- Project is on track to rebaseline in Dec 2022
- Mu2e Project is 85% complete
- Project achieved its first Key Performance Parameter on April 14, 2022!
  - First beam from Delivery Ring to M4 Diagnostic Absorber
- Production Solenoid coils complete, cold mass assembled, installing thermal shields.
- Transport Solenoid cryostating nearly complete.
- Tracker, Calorimeter, Cosmic detector subsystems 94% complete.



Production Solenoid Cold Mass Assembly

1st half of Transport Solenoid cryostated

1st Calorimeter disk instrumented

Cosmic Science

Vision: Fermilab is both a leader and essential partner in cosmic science experiments investigating the connections between phenomena on the very largest and smallest scales of the universe. Our scientists play key roles in all stages of experiment development, from initial conception, through construction, operations and data analysis.

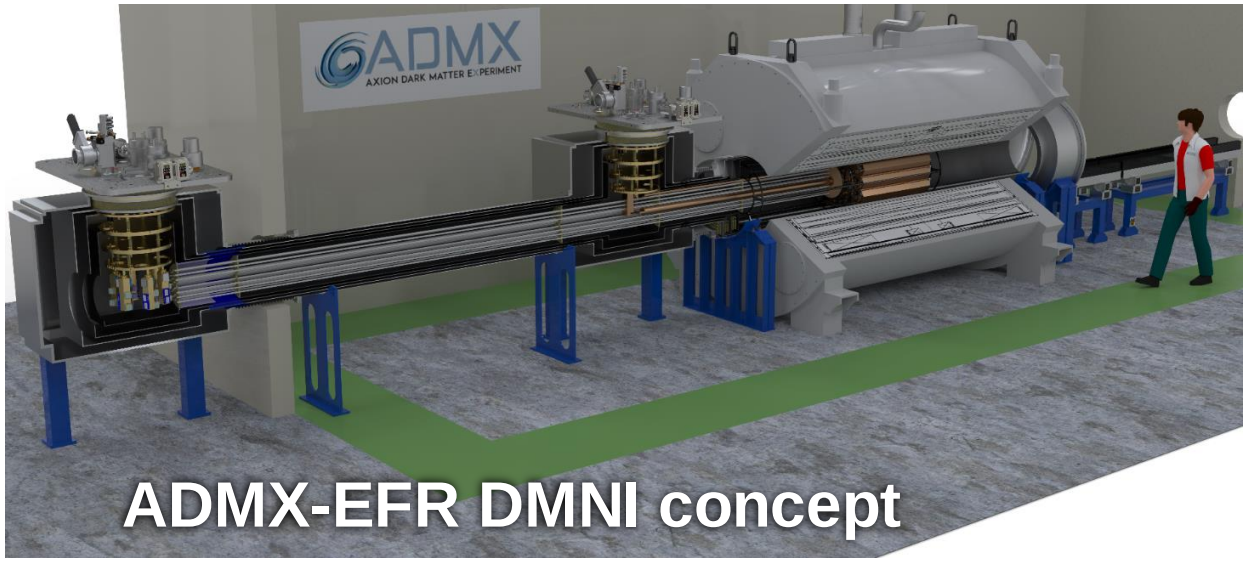
Discovery Potential:

Surveys of galaxies and cosmic background radiation use precise measurements of cosmic structure to learn about cosmic acceleration, new forms of matter, and properties of cosmic neutrinos. A coordinated campaign of experiments seek to directly detect and study the properties of dark matter particles in the laboratory.

South Pole Telescope during 2022 Austral winter survey observations (Credit: Aman Chokshi)

World-Leading Capabilities and Projects


New CCD & CMB R&D facilities



ADMX-EFR DMNI concept


Sub-Kelvin Cryogenics


SPT-3G operations


Skipper CCDs

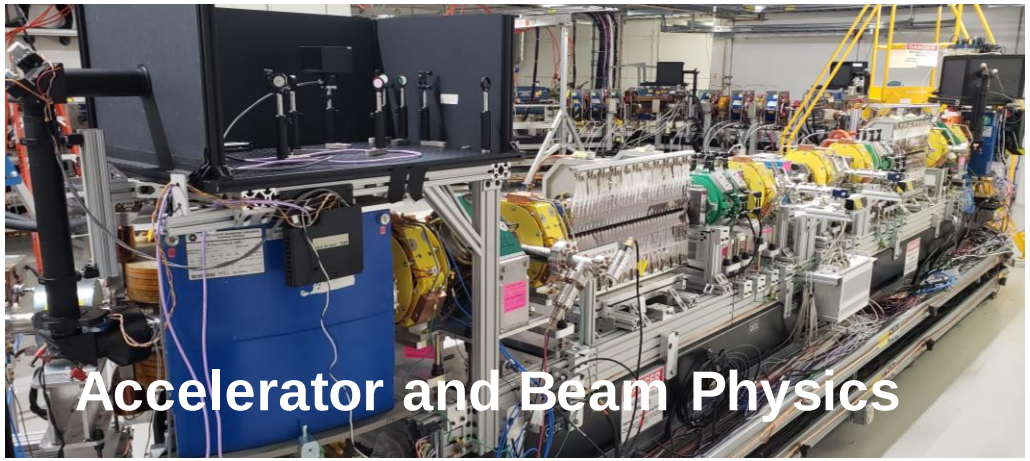
Fermilab

Cosmic Frontier Progress

- **Cosmic surveys**: DES & LSST/Rubin
  - Fermilab scientists led the use of the Rubin cloud data reduction system to convert a simulated dataset into Rubin catalogs.
  - Fermilab DES scientists and collaborators completing final 6-yr Weak Lensing Shape Catalogs.
- **Cosmic Microwave Background**
  - Designed, fabricated and started testing first prototype CMB-S4 detectors and readout.
  - Finished 4th full season of observations at South Pole. New cosmology results next week!
- **Dark Matter Detection**
  - ADMX
    - Improvements in noise and stability of operations in ADMX-G2.
    - Preparing to install 9.4 Tesla x 80 cm bore solenoid for ADMX-EFR.
  - OSCURA Dark Matter New Initiatives project
    - Demonstration of Skipper CCD production at Microchip and MIT-Lincoln Labs.
    - Completed studies of cosmogenic tritium production in silicon and removal by baking.
- **SuperCDMS**
  - SuperCDMS dilution fridge shipped to SNOLAB.

Accelerator Science & Technology

Vision: Fermilab is a world-leader in Accelerator Science & Technology R&D that enables the next generation of particle accelerators and advances the HEP and Office of Science mission. Fermilab is an essential partner of choice to future large-scale accelerators.



Fermilab is addressing the needs of many SC program offices

Fermilab

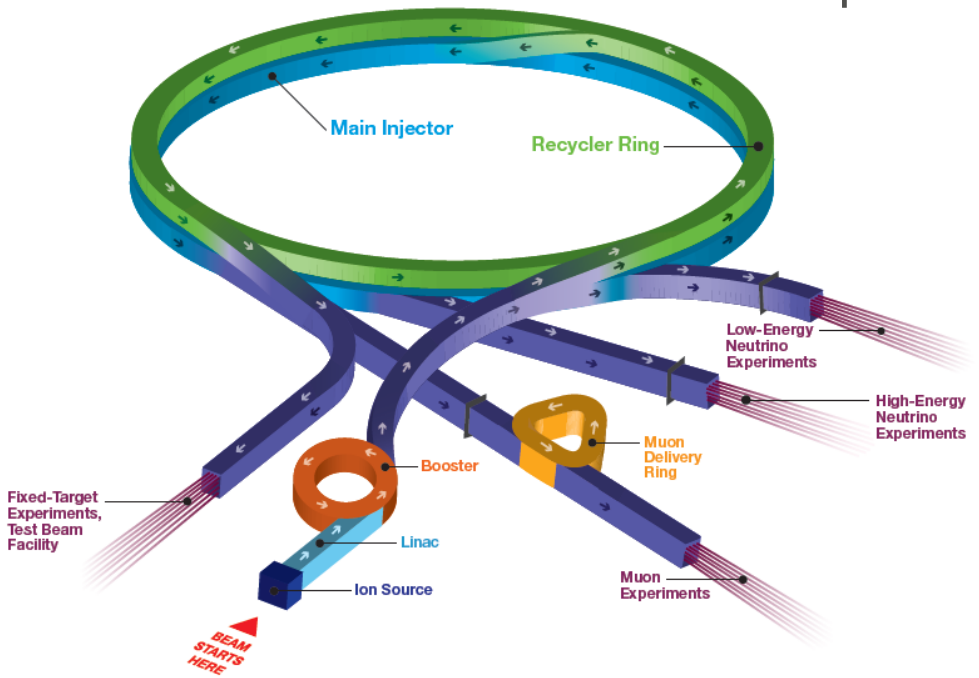
Fermilab Accelerator Complex – delivering beams for groundbreaking science

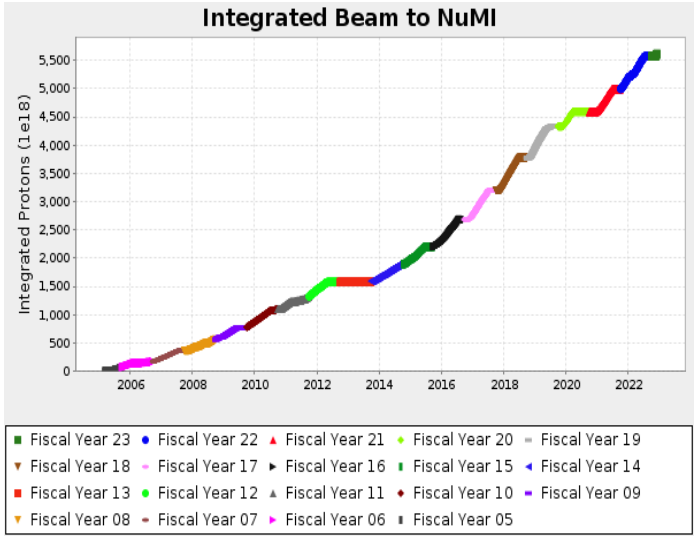
- Proton Source
  - 400 MeV Linac @ 805MHz.
  - 8 GeV Proton Synchrotron Booster 15Hz
- Recycler
  - 8 GeV fixed energy
- Main Injector
  - 120 GeV, 1.2 s cycle
- Beam lines
- Target stations
- Expert workforce

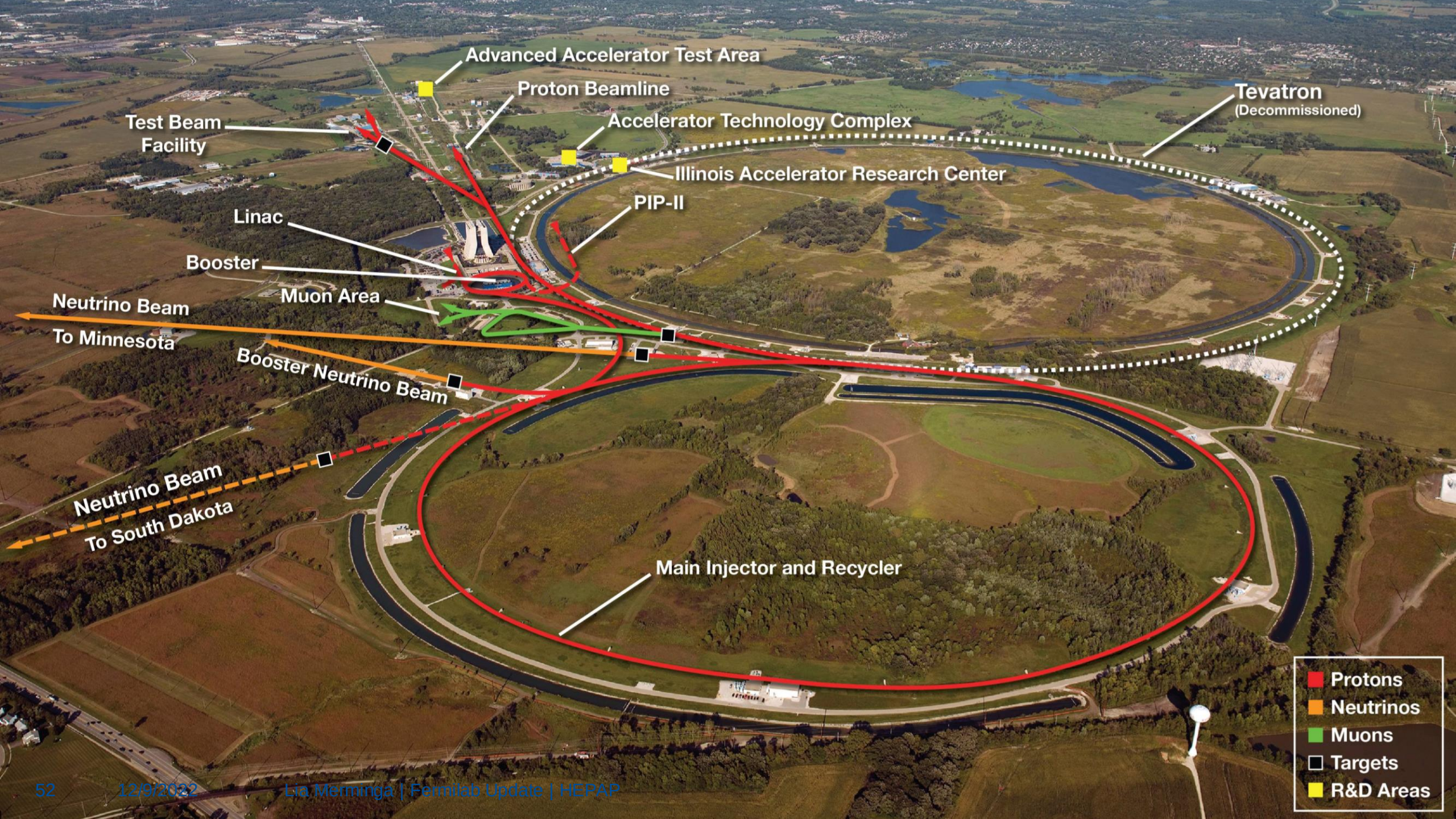
895 kW beam power at 120 GeV– in 7/2022

Over 5 years power increased by 30% while beam loss reduced by factor 2

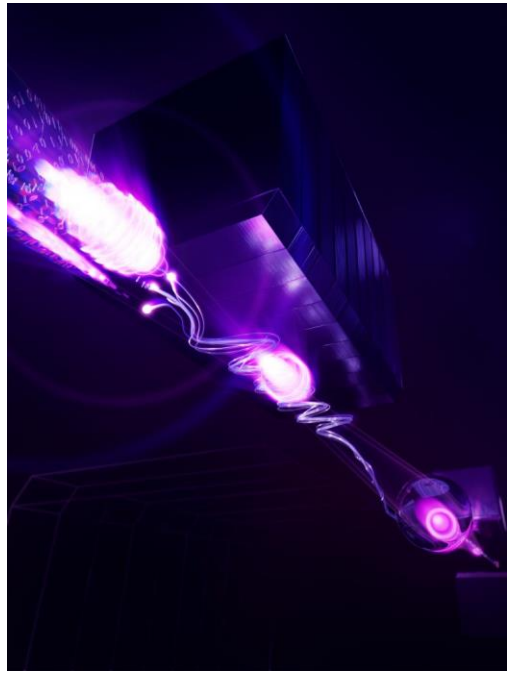
Operation with uptime of ~80%






Advanced Accelerator Test Area
Proton Beamline
Test Beam Facility
Accelerator Technology Complex
Tevatron
(Decommissioned)
Illinois Accelerator Research Center
PIP-II
Linac
Booster
Muon Area
Neutrino Beam
To Minnesota
Booster Neutrino Beam
Neutrino Beam
To South Dakota
Main Injector and Recycler
Protons
Neutrinos
Muons
Targets
R&D Areas

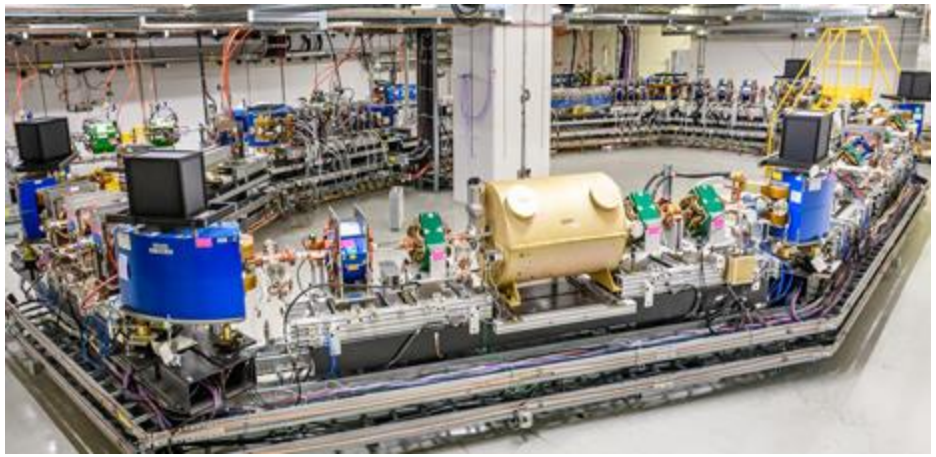
Accelerator physics R&D to enable future accelerators



FAST/IOTA facility Fermilab's center for beam physics research

2017 World-record beam acceleration by ILC-type CM: >**31.5MV/m** – relevant for linear colliders such as ILC

2020 Demonstration of nonlinear integrable optics and improved beam stability in nonlinear lattice – important for future high-intensity circular accelerators



2021 First experimental demonstration of 6D Optical Stochastic Cooling – novel tool for increasing beam brightness, published in *Nature* in August 2022

Successful educational and personnel development effort

Fermilab Accelerator Technology Enables BES Mission

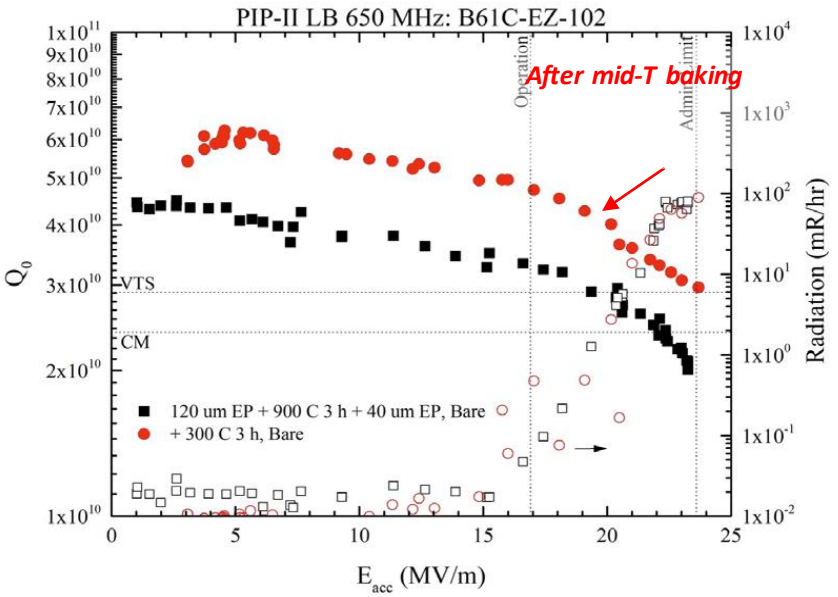
- Fermilab played major roles in SRF and cryo aspects of SLAC's **Linac Coherent Light Source II (LCLS-II)** including R&D, design, production, and participation in linac commissioning
- Record high Q in linac enabled by Fermilab SRF technology

- While LCLS-II is commissioned, the **LCLS-II-HE** upgrade is underway. Fermilab is assembling 14 even more advanced SRF cryomodules.
- First 3 FNAL HE cryomodules successfully qualified

- Fermilab is building advanced normal conducting magnets for ORNL's **Proton Power Upgrade (PPU)** project for the Spallation Neutron Source
- First magnet complete, undergoing measurements

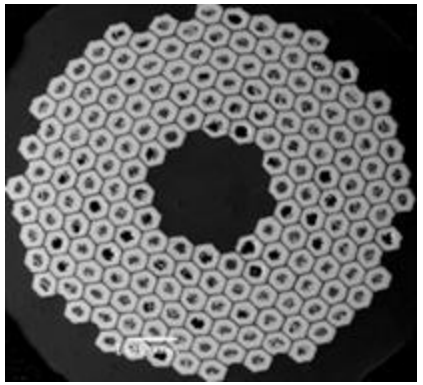
Recent Developments in SRF and Superconducting Magnets

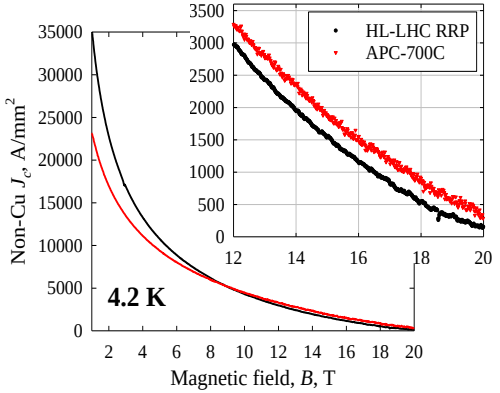
- Recent results from a PIP-II 650 MHz cavity show an improved performance after treatment with **mid-T bake**, developed at Fermilab, providing significant increase in margin for Q during operation – optimization program is in progress – Synergy with FCC



New 2022 APC wires w/ 217 filaments

- **Nb_3Sn wire R&D** can help realize future hadron collider and muon collider (X.Xu ECA)
- New 2022 Nb_3Sn wires with artificial pinning centers simultaneously achieve critical current J_c at the FCC-hh specification and also have stability at low magnetic field – crucial for applications.
- Also developing high-C_p wires which have larger energy margin against quench and are promising to reduce training in Nb_3Sn magnets.



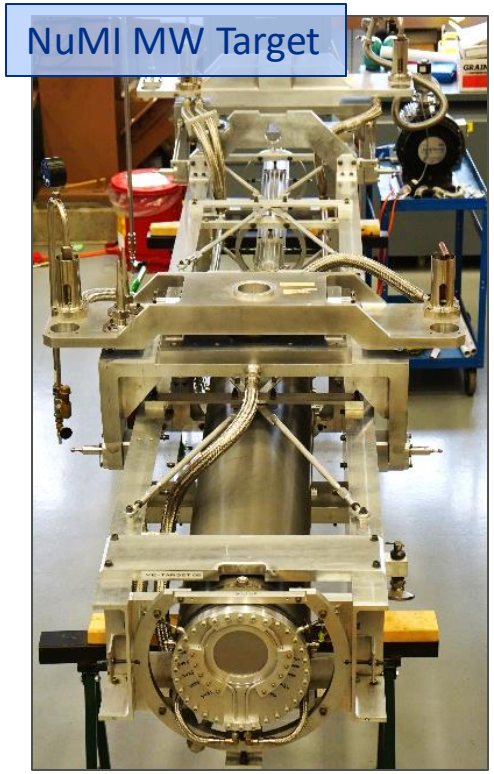


Fermilab High Power Target Development

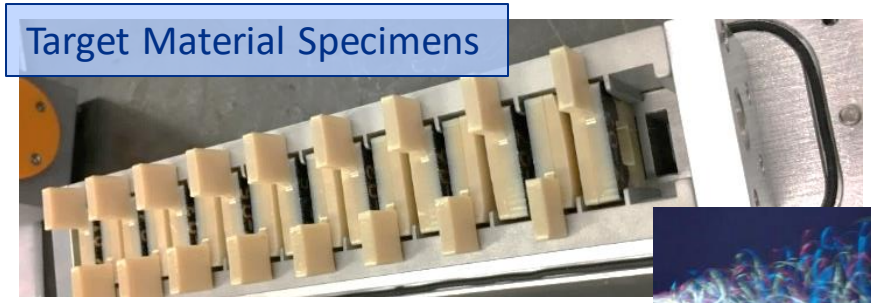
- Operation of MW Target Stations
  - NuMI 1 MW target and horn produced, and operated up to 900 kW
  - Also: BNB, Muon g-2, Mu2e
- High-Power Targetry R&D
  - Accumulate statistics of material response to extensive irradiation, thermal shock, and fatigue
  - Development of novel materials
- Multi-MW Target Station Designs
  - LBNF to 1.2 MW, and then 2.4 MW
  - PIP-II 1+ MW capability

NuMI MW Horn

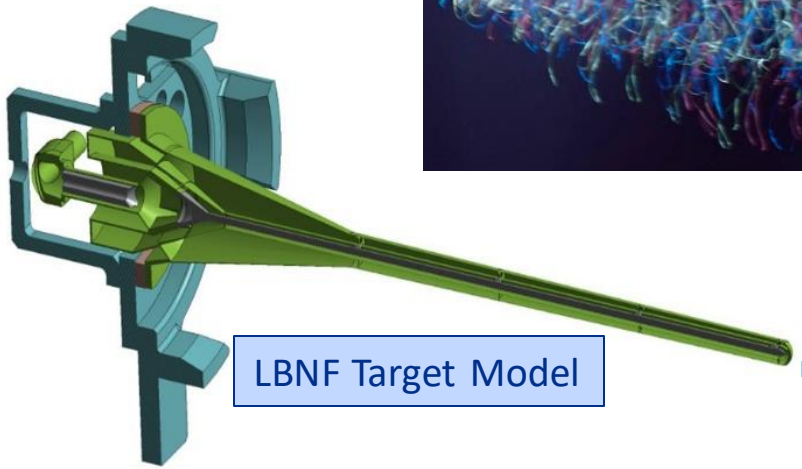
NuMI MW Target



Target Material Specimens



Sinuous Target Fabrication



LBNF Target Model

Fermilab

Fermilab Accelerator Complex User Facility Modernization

Vision/Goals

- Highly effective, efficient accelerator operations with a modernized control system, work and lab spaces and integration of emerging technologies like robotics and AI/ML for accelerators

Key Initiatives

- **ACORN**: DOE O413 project to modernize the accelerator control system and replace end-of-life power supplies; partnership with INL for user interface and human factors expertise
- **Robotics Initiative**: Motivated by need to increase worker safety and efficiency for accelerator and target operations
- **CAST**: Proposed building to potentially include updated Main Control Room, co-located controls and instrumentation staff and space for USPAS, visiting scientists and engineers

Recent Achievements

- Completed Accelerator Operations Requirements Workshops – broad labwide participation; documented requirements for AI/ML for accelerator operations, cybersecurity, ES&H, software development, etc.
- Completed Robotics Strategic Plan and initiated partnership with National Robotics Engineering Center (NREC) at Carnegie Mellon

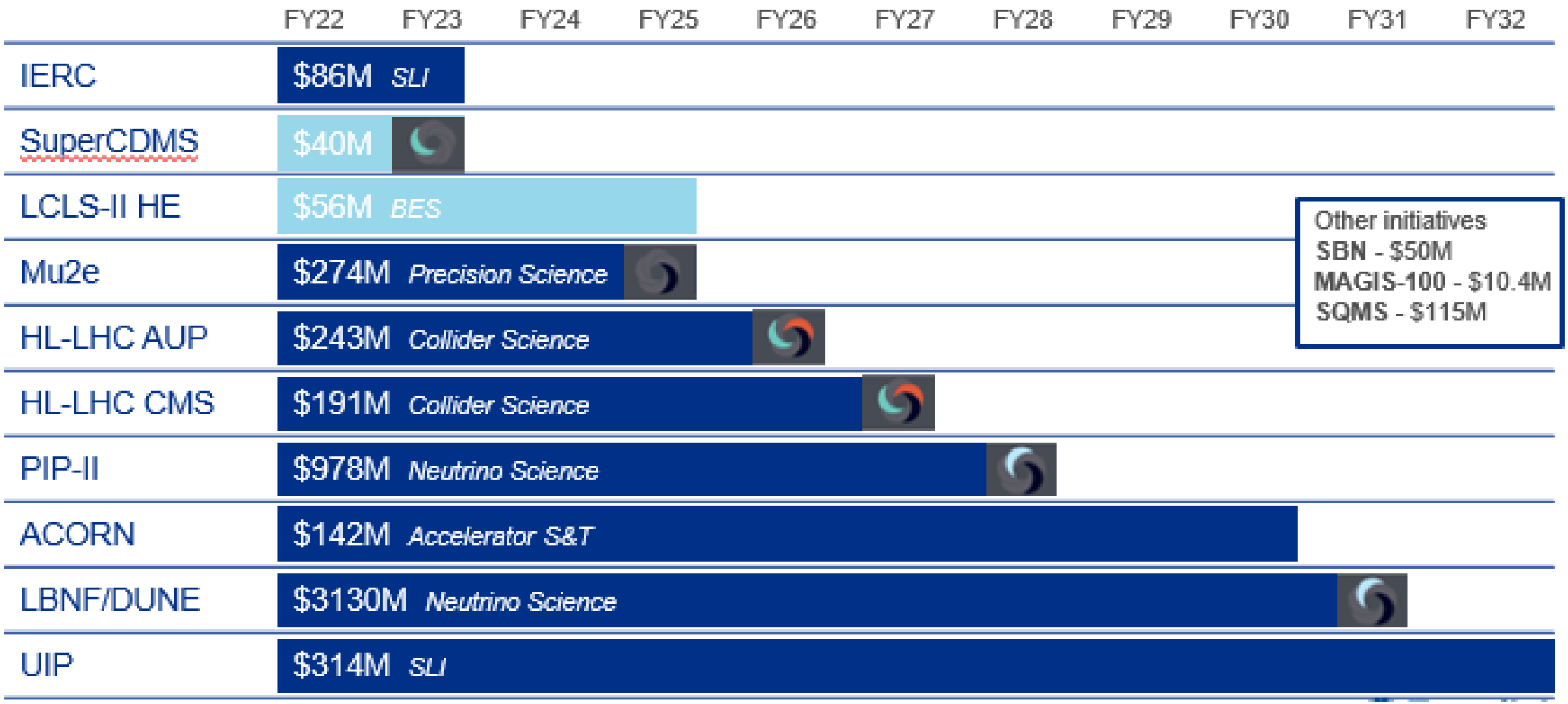
Fermilab visitors Tia Miceli, Adam Watts, and Mayling Wong-Squires with CHIMP (CMU Highly Intelligent Mobile Platform) at NREC

ACORN is the key to enabling future accelerator operations capabilities

Fermilab

Fermilab executes the P5 plan

Investment
$5.6B DOE,
$1.1B International



Other initiatives
SBN - $50M
MAGIS-100 - $10.4M
SQMS - $115M

IRA funding of $260M in FY22 "forward funded" our major construction projects

Fermilab

IERC → The Helen Edwards Engineering Research Center

On Dec 1 U.S. Senators Durbin and Duckworth, and U.S. Representatives Foster and Underwood introduced legislation to rename Fermilab's Integrated Engineering Research Center (IERC) after Dr. Helen Edwards.

Helen Edwards
1936-2016
Master Builder of Accelerators

"…Not only is renaming the Integrated Engineering Research Center after her well-deserved, I think it tells generations of girls interested in science that they belong at the table." Senator Tammy Duckworth

Emerging Science & Technology Capabilities

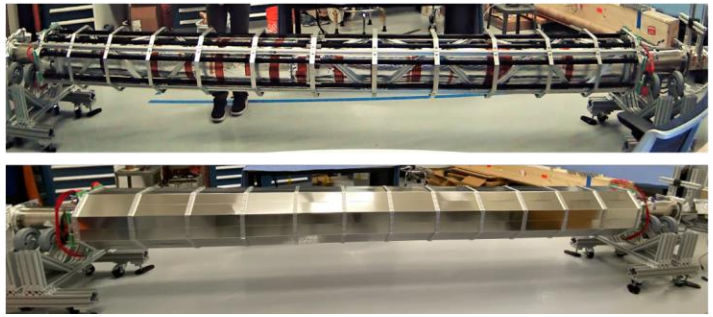
Quantum Information Science & SQMS
Artificial Intelligence / Machine Learning
Microelectronics

S&T Quantum Information Science

Vision: Fermilab, together with Chicagoland partners, is a major US quantum center; hosts national facilities for Quantum Science, developing innovative approaches that enable HEP discovery.

Fermilab quantum research

Assembled prototype MAGIS module with horizontal bias coils and magnetic shield



Before shield

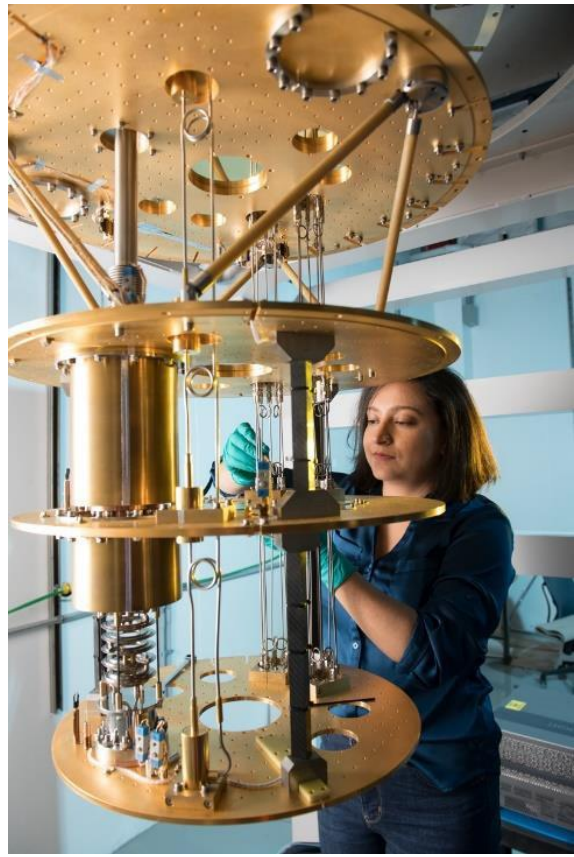
With shield

QIS for HEP

- MAGIS-100 cold atom interferometers
- Qubit-based sensors for dark matter detection
- Dark SRF cavity-based sensors for dark photon detection
- Quantum computers to simulate HEP quantum dynamics

HEP for QIS

- Better qubits from Fermilab's expertise in superconducting devices and materials
- Ionizing radiation effects on qubits characterization leveraging Fermilab infrastructure
- Control and readout systems for quantum processors
- Picosecond synchronization for quantum communications (system now operates between FNAL and ANL)



Fermilab leads one of five NQI Centers (SQMS), has a major role in the ORNL led NQI Center (QSC), and a portfolio of other QIS projects

Fermilab

Led by FNAL, $115M
Awarded August 2020

Superconducting Quantum Materials and Systems Center

A DOE National Quantum Information Science Research Center

24 Institutions
> 400 Researchers
> 100 students/postdocs

Fermilab · rigetti · Northwestern University · Ames Laboratory, Creating Materials & Energy Solutions, U.S. Department of Energy · NASA Ames Research Center

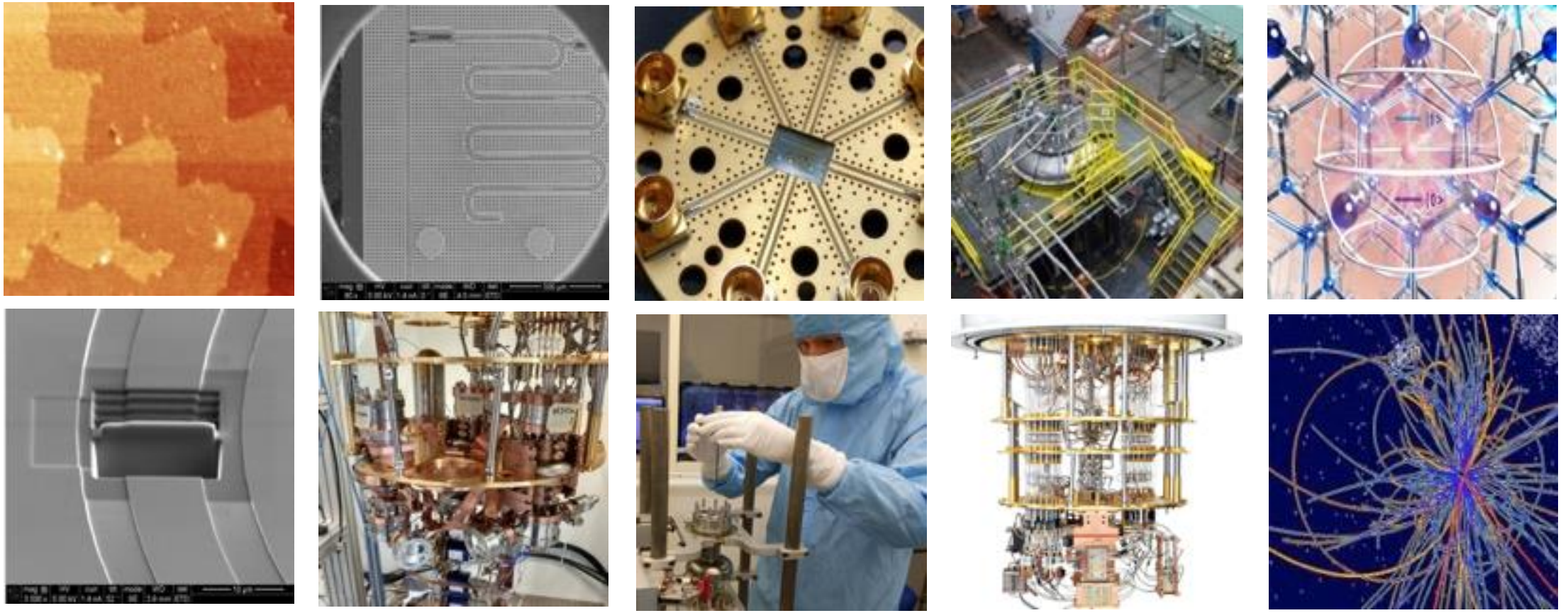
NIST · INFN Istituto Nazionale di Fisica Nucleare · Stanford University · University of Illinois Urbana-Champaign · Rutgers · Università di Pisa

University of Colorado Boulder · Illinois Institute of Technology · Johns Hopkins University · Temple University · Colorado School of Mines · The University of Arizona

University of Minnesota · NYU · Goldman Sachs · LSU · Lockheed Martin · JANIS · Unitary Fund

SQMS Roadmap: from materials to systems to applications

Materials Discovery → High Coherence Devices → Systems Integration → New quantum computing and sensing platforms → Quantum Advantage



Synergy with HEP science goals and technological strengths at every step of the chain:
Bi-directional value “HEP for QIS and QIS for HEP”

Fermilab

SQMS summer internships

SQMS summer schools

SQMS

Quantum workforce development

200+

External students & postdocs engaged

10 weeks

Paid training, education & research for undergraduate students

~50%

Female & URM interns

2021 Virtual summer school

Quantum Computing and Sensing

100+ registered students

2022 Hybrid summer school
Florence (Italy)

Quantum Simulations for Field Theory

70 students

Carolyn B. Parker

first African American woman to earn a postgraduate degree in physics

Postdoctoral Fellowship

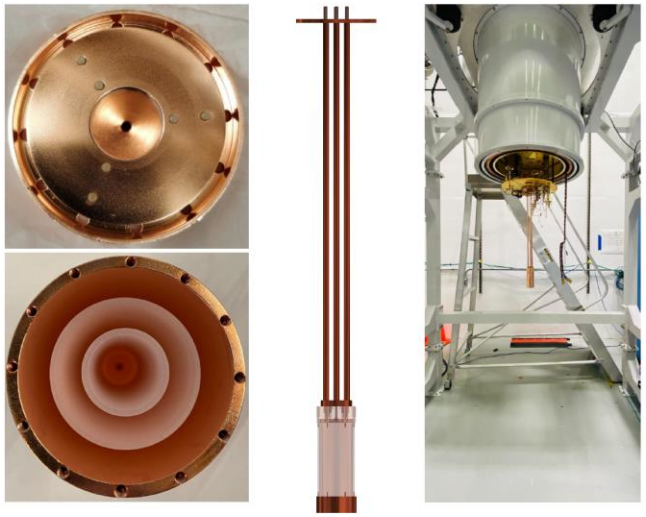
increase representation and inclusion of URM individuals

Quantum Sensing for Dark Matter

QuantISED: nested sapphire photonic band gap cavity for dark matter axion detection

Achieved Q>10^6, when operated in with B=14 T magnet used for dark matter axion searches.

Sapphire cylinders form ¼ wave stack to reflect microwaves back into center of cavity



Quantum Science Center: cryogenic test stands

Develop multiplexed qubit sensor arrays and study detector response to ionizing radiation and dark matter

SiDet Lab G

QSC dark matter group

NuMI underground

Foundational physics studies using QIS

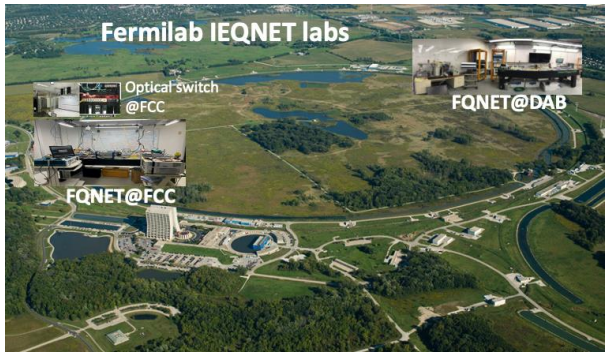
- Use a Quantum Computer (QC) as an experimental apparatus to probe connections between spacetime and quantum entanglement
    - Utilize a highly entangled quantum system and implement a protocol to **measure properties consistent with descriptions of a traversable wormhole** (in a very simple model)
- Demonstrate for the first-time the potential of quantum-scale experiments that could probe fundamental physics and could be possible as quantum technology evolves.
    - Future experiments with better QC and with QCs connected through quantum networks, such as those under development at Fermilab, could provide better insight through better resolution and adding non-trivial spatial separation of the two systems

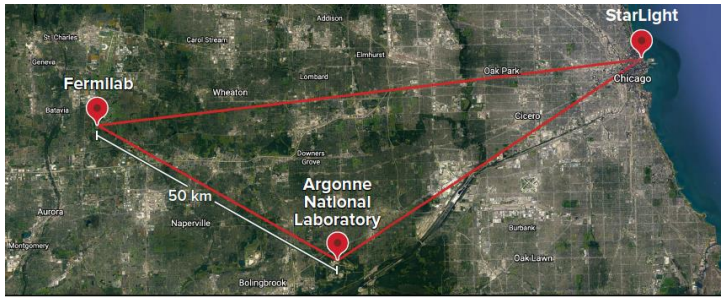
Harvard, Caltech, MIT, Google, and Fermilab

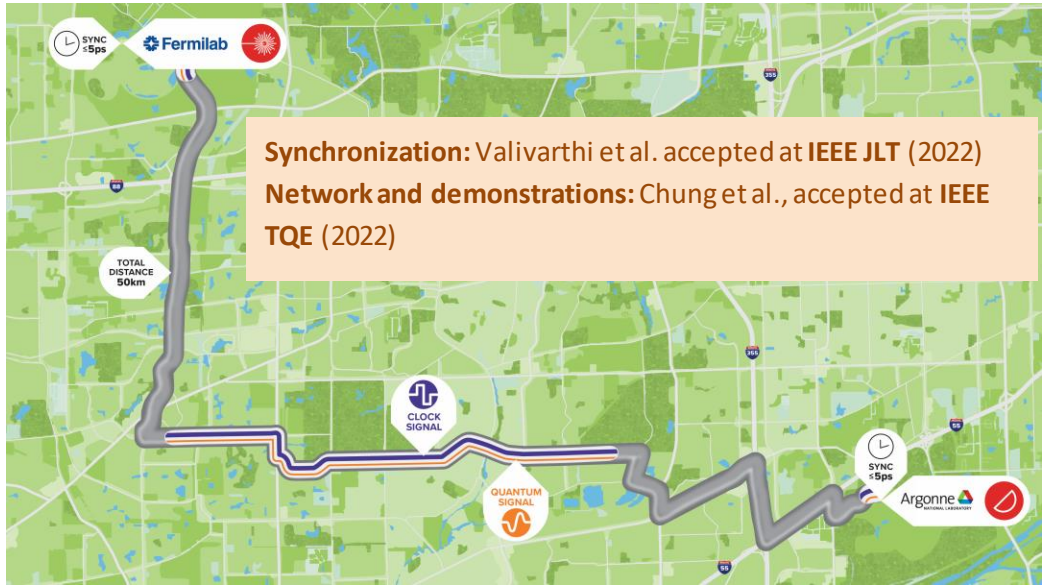
Quantum Network R&D toward a Quantum Internet

- **Fermilab together with Chicagoland and other collaborators is working to deploy a multi-node, multi-user metropolitan scale quantum network in the greater Chicago area.**

Demonstrated entanglement distribution with picosecond precision synchronization between nodes at Fermilab and Argonne and co-existence with classical (synchronization) information on the same optical fiber







Synchronization: Valivarthi et al. accepted at **IEEE JLT** (2022)
Network and demonstrations: Chung et al., accepted at **IEEE TQE** (2022)

The IEQNET collaboration

Fermilab, Argonne, Caltech, Northwestern University, HYPERLIGHT, NuCrypt

The network could integrate cutting edge quantum systems under development at the NQI centers of the Chicagoland QIS&T ecosystem

Fermilab

Fermilab AI/ML research

Fermilab has identified focus areas where our mission needs overlap with AI/ML special expertise :

- Real-time fast AI integrated into sensor for HEP experiments, includes FPGAs and “AI on a chip”
- AI/ML for optimal operations of accelerators and experiments - real-time controls with continuous and autonomous learning and calibration systems
- Robust models with uncertainty quantification; essential for reducing biases, detecting anomalies, and adaptation across broad HEP applications
- Physics-inspired data & models, e.g. graphs, generative modeling - tailoring AI to our data representations and integrating our physics knowledge

Nhan Tran
2019 DOE Early Career Research Award
Deep Learning Acceleration of the Boosted Higgs Program and HEP Computing

Brian Nord
2021 DOE Early Career Research Award
Simulation-based inference for cosmological parameter estimation and discovery

Alexandra Ćiprijanović
Wilson Fellow, AI/ML principal investigator

Jennifer Ngadiuba,
Wilson Fellow,
AI/ML principal investigator
Designing Efficient Edge AI with Physics Phenomena

Microelectronics and Detector R&D

Fermilab led Microelectronics co-design team

(Partnership with SLAC, ANL, JPL, NIST, Caltech, MIT, Synopsys)

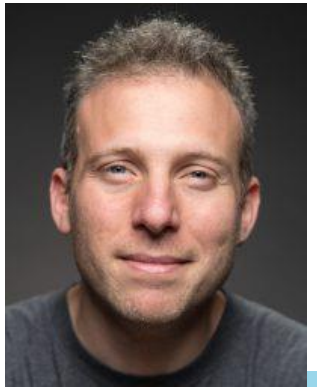
- Development of novel, ultrafast 3D Skipper CCD-in-CMOS
- Integrated Cryogenic readout ASIC with picosecond timing for Superconducting Nanowire detectors (4K)

Strong Industry **partnership** in Microelectronics for advancing semiconductor innovation for **QIS & AI**

- Microsoft for joint development of deep cryogenic electronics
- Global Foundries and Tower Semiconductor (Intel) to support specialized CMOS fabrication for HEP
- Member of the **IBM** led American Semiconductor Innovation Consortium

Fermilab's **Detector R&D Strategic Plan** identified two other focus areas

- Picosecond timing for advanced particle detectors
- Advances in detectors using liquid argon/xenon



Javier Tiffenberg
2018 DOE Early Career Research Award
Towards table-top neutrino detectors: A 10 kg Skipper-CCD experiment

Artur Apreysan
2018 DOE Early Career Research Award
Exploring the Lifetime Frontier with New Detectors and New Searches

Farah Fahim
2021 DOE Early Career Research Award
Front-end implementation of AI/ML neural networks for on-detector radiation-hard edge compute

Davide Braga
Microelectronics co-design Principal Investigator

Fermilab

National and international partnerships

UK delegation

IN2P3 delegation

Austrian delegation

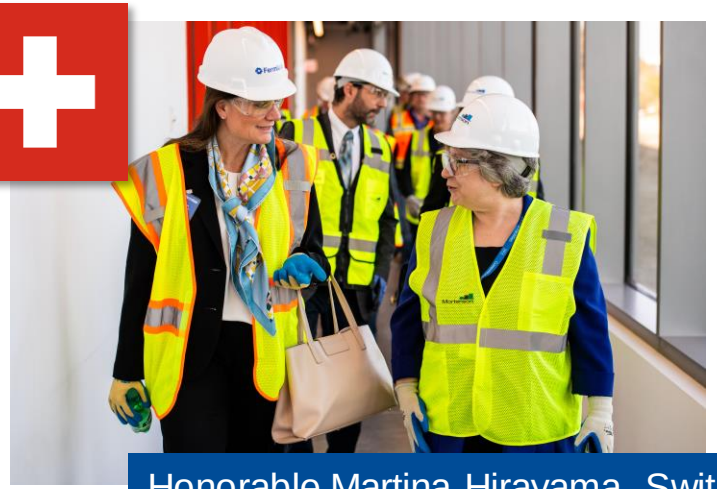
Fermilab delegation visits DAE labs

Fermilab

National and international partnerships

BARC Director and PIP-II technical coordinators from BARC and RRAT delegation visits Fermilab November 7-9

National and international partnerships



Honorable Martina Hirayama, Switzerland's state secretary of education, research and innovation, October 20

A visit by Charles Tahan Assistant Director for Quantum Information Science, Director, National Quantum Coordination Office, OSTP, October 21

Fermilab

Dr. Berhe visits Fermilab on July 8, 2022

FY23: A year of change for Fermilab

- Deliver groundbreaking science & technology on all P5 science drivers
- Execute LBNF/DUNE-US and all construction projects on time and on budget
- Complete our world-class leadership team
- Achieve excellence in business & operations
  - Restore the intellectual vitality and open and inclusive culture of Fermilab that are essential for the health of our field
- Engage in the next P5 process

"In order to position Fermilab to meet future success and deliver on mission, FY2023 must be a year of cultural and functional change."

A Culture of Safety

- At Fermilab, we are committed and strive to establish a **Culture of Safety** in all its manifestations: **physical and psychological**

- **Safety, both physical and psychological, is our top priority and supersedes every other priority**.

- As an institution, we have the moral and ethical obligation to provide our employees/users/community a safe, respectful, inclusive, welcoming working environment.

- In this environment there is **zero tolerance** for disrespectful, disparaging, discriminatory behavior, bullying, harassment of any kind, and any form of unethical behavior.
  - Must preserve vigorous debates centered on ideas!

- This cultural change must be accompanied by a formal system for practical consequences for violations, accountability, and fair and transparent enforcement procedures resulting in appropriate actions for those who are detrimental to the health of our community, up to and including suspension or termination of a member.
  - All supervisors are stewards of our message.

Summary

- Fermilab is delivering world-class science and executing the P5 plan
- Steady progress on multiple focus areas: building leadership team, advancing construction projects, seeking excellence in operations, building relationships with key stakeholders
- FY23 is a year of change for Fermilab and we are positioning ourselves for success
- It is imperative we ensure that Fermilab's role in the HEP Community is an integral part of our mission:
  - as the nexus for US HEP
  - as a resource for co-located expertise and capabilities and *intellectual vitality*
  - as an International User Facility, dedicated to a diverse workforce and collaborative culture, and to enabling world-class scientific discovery
- By defining a bold yet realistic vision and a new P5 strategic plan, together we can ensure that US remains a global leader in High Energy Physics

We are grateful to the DOE Office of Science and HEP for tremendous support and growth and to our community of users and international partners!

Thank you!

Wilson Hall and IERC at dawn. The sloped roof on IERC is intended to mimic the curve of Wilson Hall rotated 90 degrees; this is especially evident when the image of IERC is doubled in the reflecting pond. Photo credit: Brian Rubik