The Future program at Fermilab

Bonnie Fleming

11 April 2024

IOP Institute of Physics

Joint APP, HEPP and NP Conference

Fermilab at a Glance

- America's particle physics and accelerator laboratory
- Operates the largest US particle accelerator complex
- ~2,100 staff and ~$750M/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.

FNAL is an international facility

Next Generation facilities must be international to succeed!

"Now more than ever, particle physics is an international, even global, endeavor"
HEPAP P5 report, 2023

"Continue support for and actively seek engagement with international collaborations and partnerships of all sizes"
DOE International Benchmarking Report, 2023

Fermilab Science Mission – 2023 P5 Report

2023 P5 Report!

Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

Reveal the Secrets of the Higgs Boson

Explore New Paradigms in Physics

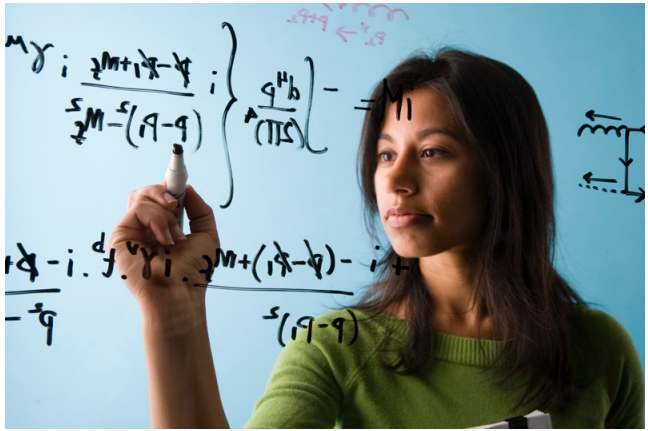
Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena

Illuminate the Hidden Universe

Determine the Nature of Dark Matter

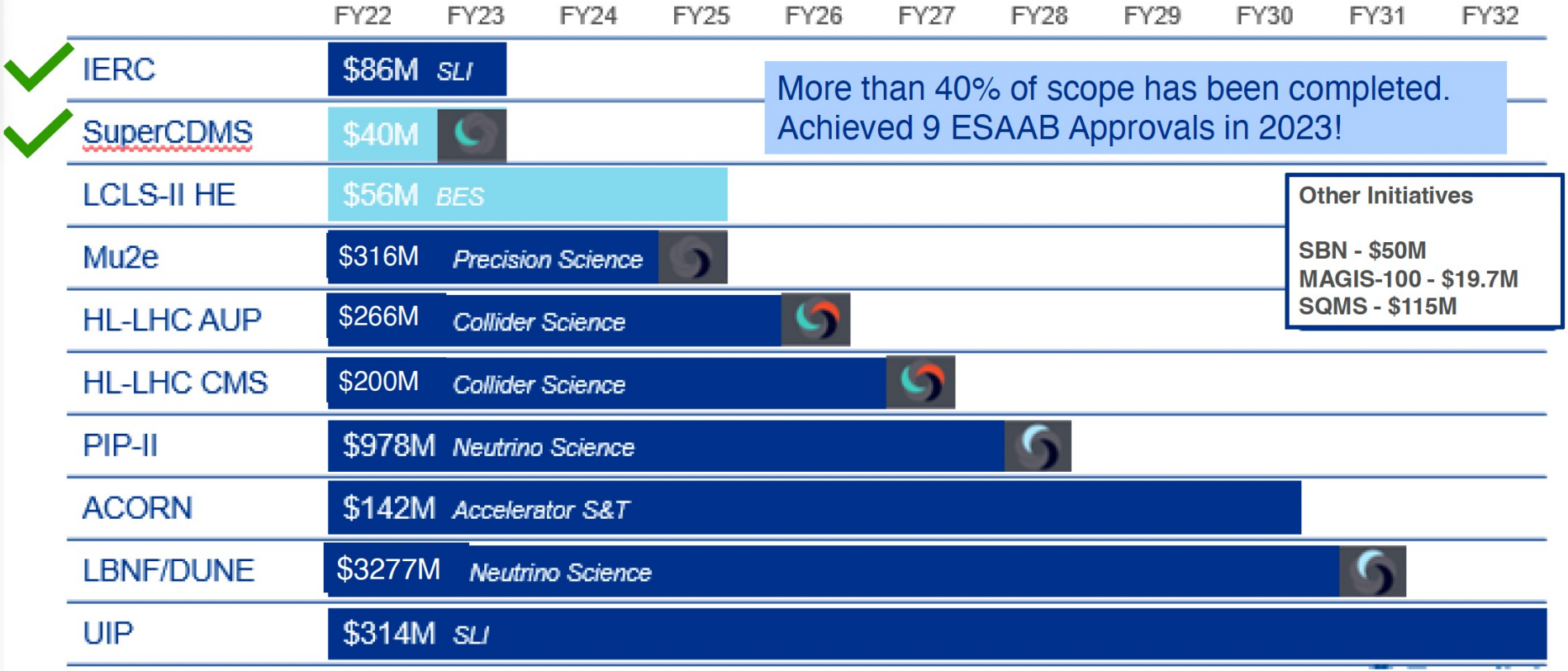
Understand What Drives Cosmic Evolution



- Support the current program! Both in running experiments and in projects underway
- Portfolio of major projects looking ahead including
  - → DUNE Phase 2 with early implementation of high intensity beam
  - → HL-LHC and off shore Higgs Factory beyond
  - → 20 year strategic plan for FNAL accelerator complex looking ahead to 10 pCM collider (Muon Collider), science along the way with a balanced program
  - → CMB-S4
  - → Portfolio of smaller projects
- Invest in workforce, broadening engagement, and ethical conduct in the field

Current program: Project portfolio

Investment
$5.6B DOE,
$1.1B International



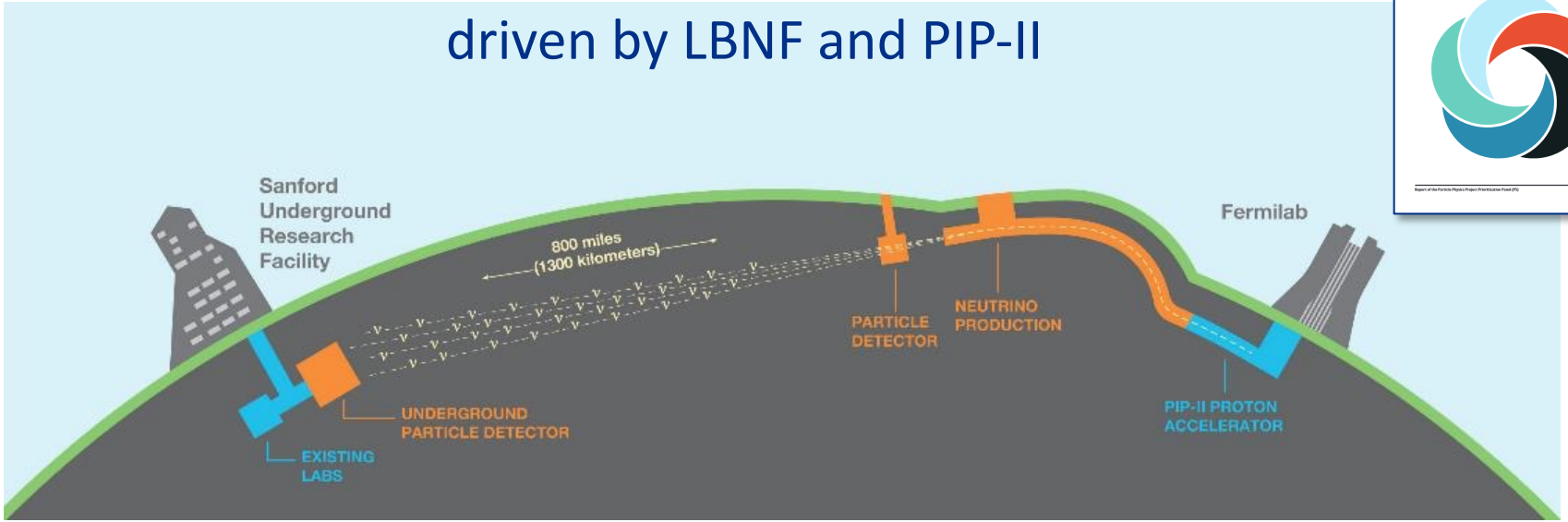
More than 40% of scope has been completed.
Achieved 9 ESAAB Approvals in 2023!

Other Initiatives

SBN - $50M
MAGIS-100 - $19.7M
SQMS - $115M

Fermilab

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



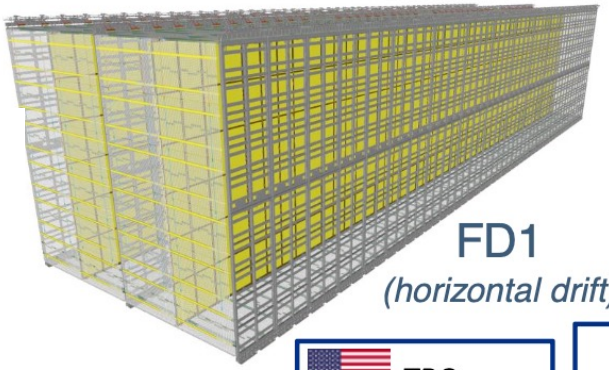
Origin of matter. Investigate leptonic CP violation. Are neutrinos the reason the universe is made of matter?

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.

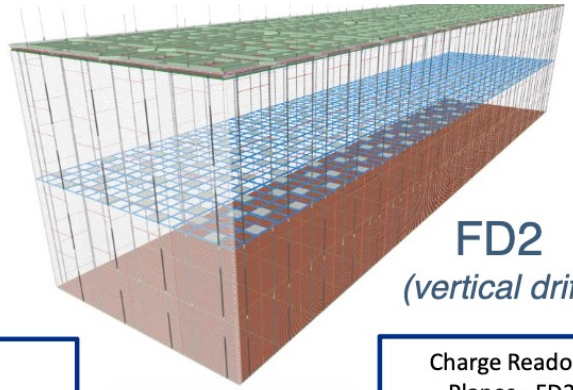
The LBNF/DUNE project will be the first internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States” – DOE

The DUNE Far Detectors – A Model of International Partnership



FD1
(horizontal drift)

High Voltage
FD1, FD2



FD2
(vertical drift)

Anode Plane
Assemblies - FD1

TPC
Electronics
FD1, FD2-B

Photon Detection
FD1, FD2

Data Acquisition
FD1, FD2

Charge Readout
Planes - FD2

CALCI
FD1, FD2

Brookhaven
National Laboratory

BERKELEY LAB

Argonne
NATIONAL LABORATORY

Fermilab

Los Alamos
NATIONAL LABORATORY

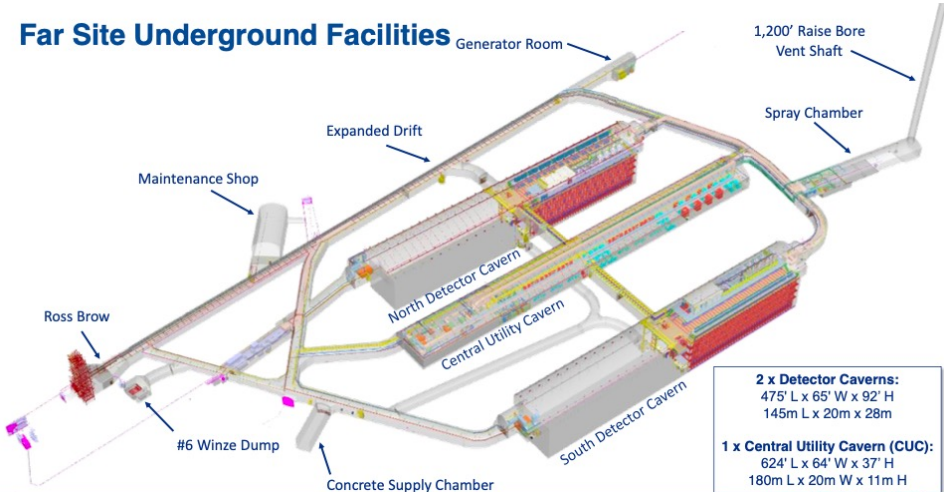
Electronics
FD2-T

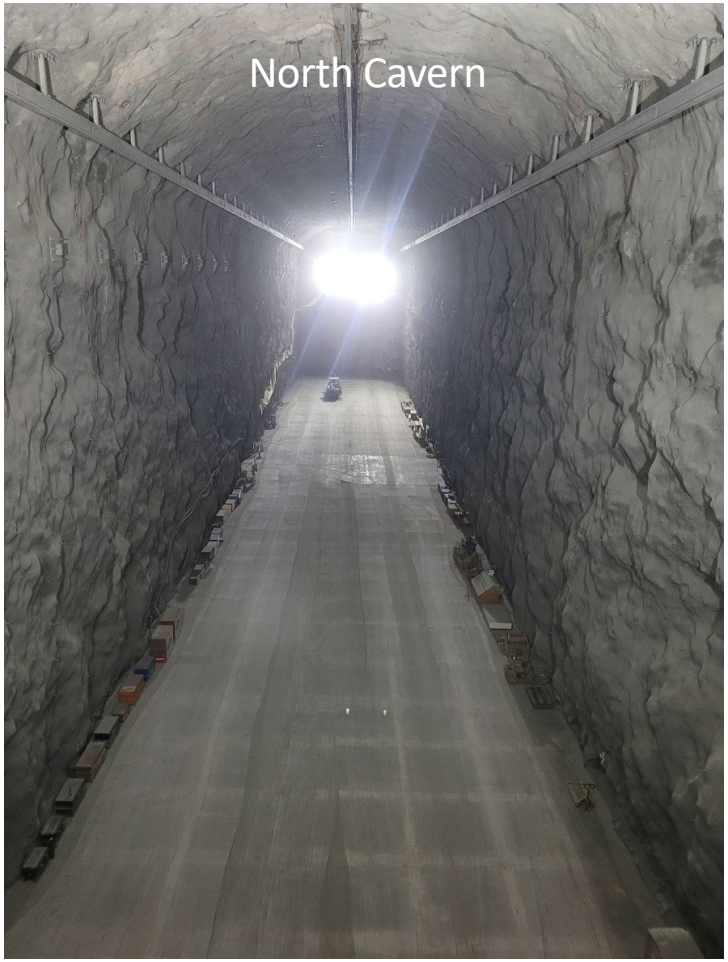
+ many Universities

Fermilab LBNF/DUNE

Excavation of Underground Facility in South Dakota is complete!

- **Excavation completed in Feb 2024!**
- > 800,000 tons of rock removed
  - equivalent of 8 aircraft carriers
- ~6500 cubic yards of concrete
- Work was done safely
  - Excavation subcontractor exceeded 1 million hours without a lost time incident. Significantly exceeded industry safety metrics.
- Cryostat installation begins in 2025

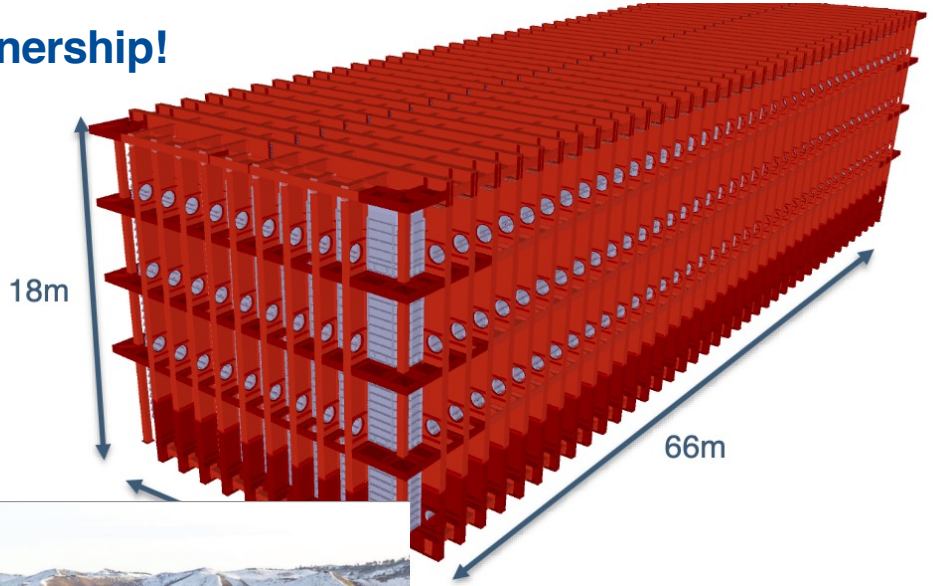



North Cavern


South Cavern

Far detector modules → International partnership!

CERN contributing the cryostats: constructed in Europe, shipped to South Dakota



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Looking ahead →

DUNE Phase 2:

- EARLY implementation of higher intensity beam (1.2 MW → 2.1 MW)
- Proceed with Far detector Module 3
- Far detector module 4: R&D now, construction in next decade
- Upgraded near detector

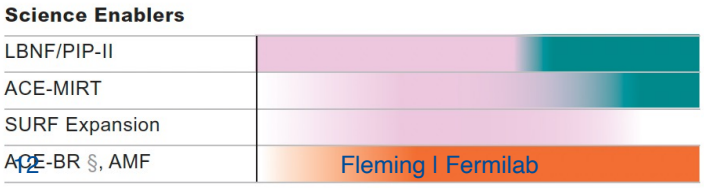


Figure 1 – Program and Timeline in Baseline Scenario (B)

Index: Operation Construction R&D, Research P: Primary S: Secondary

§ Possible acceleration/expansion for more favorable budget situations

Science Experiments	Timeline 2024–2034	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
		Science Drivers						
LHC			P	P		P	P	
LZ, XENONnT				P				
NOvA/T2K		P				S		
SBN		P				S		
DESI/DESI-II		S		S	P			P
Belle II				S		S	P	
SuperCDMS				P				
Rubin/LSST & DESC		S		S	P			P
Mu2e							P	
DarkSide-20k				P				
HL-LHC			P	P		P	P	
DUNE Phase I		P				S	S	S
CMB-S4		S		S	P			P
CTA				S				P
G3 Dark Matter §		S		P				
IceCube-Gen2		P		S				P
DUNE FD3		P				S	S	S
DUNE MCND		P				S	S	
Higgs factory §			P	S		P	P	
DUNE FD4 §		P				S	S	S
Spec-S5 §		S		S	P			P
Mu2e-II							P	
Multi-TeV §	DEMONSTRATOR		P	P		P	S	
LIM		S		P	P			P

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)
- Fermilab LHC Physics Center hosts US CMS
- 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 : CMS spokesperson

LHC Run 3 plan modified due to challenges encountered in 2023

CMS detector performed well in 2023 (92% efficiency in pp running – 29/fb recorded)

The LHC is currently in the year end technical stop (Expected start of commissioning in March 2024, physics data in April 2024)

CMS has published 1239 papers with collider data (highest # of publications from a single experiment), documenting innovative searches for new phenomena and precision SM measurements

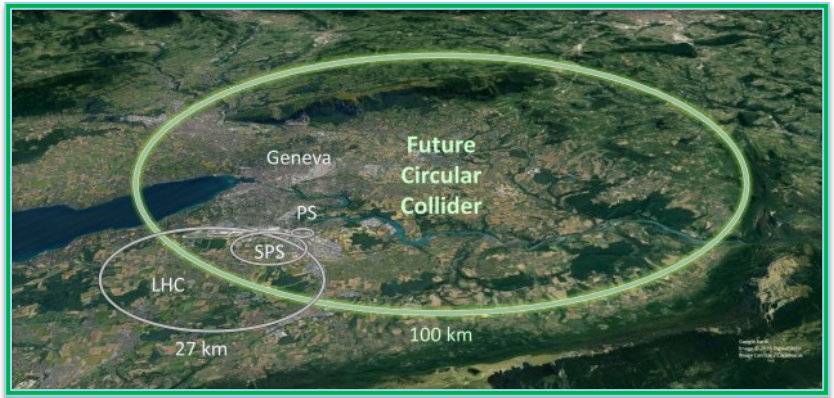
The Energy Frontier
Beyond the LHC and HL-LHC

FNALtownhall presentation to P5

Precision measurements of the Higgs boson and EW sector and BSM searches at future colliders will shed light on key open questions in particle physics.

- This exploration will require an investment in accelerator technology research to
  - Contribute to the international effort to build a Higgs factory at CERN
  - Revitalize accelerator and detector R&D towards a next-generation multi-TeV energy frontier machine
- *Fermilab is poised to host a next generation multi-TeV energy frontier collider, as a global endeavor, following the completion of the full DUNE program*
- In order to make realistic progress, a substantial investment **in targeted accelerator research** as well as **associated detector research** will be required

These efforts should be organized through **national integrated accelerator R&D and detector R&D programs** that are aligned and coordinated with our international partners



International MUON Collider Collaboration

March 15, 2022
https://muoncollider.web.cern.ch

Promising Technologies and R&D Directions for the Future Muon Collider Detectors

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

The Path to a 10 TeV pCM

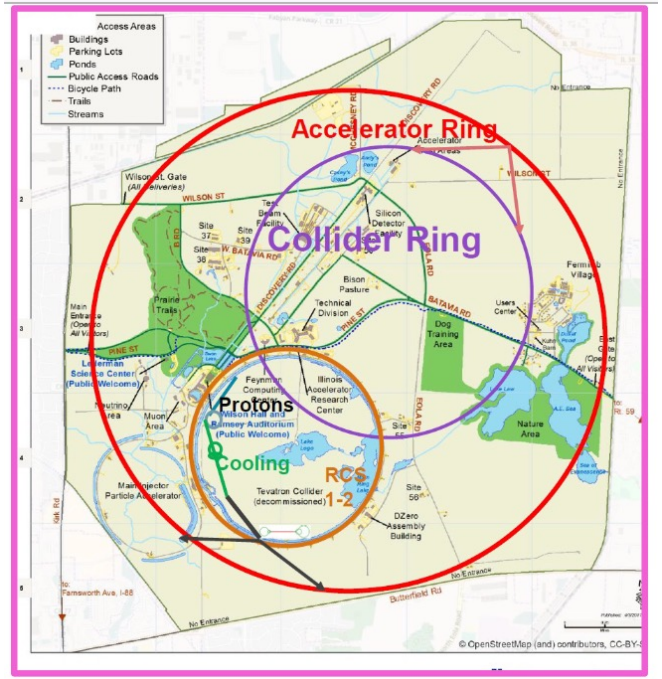
From the P5 report

"Although we do not know if a muon collider is ultimately feasible, **the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil.**
This is our Muon Shot."

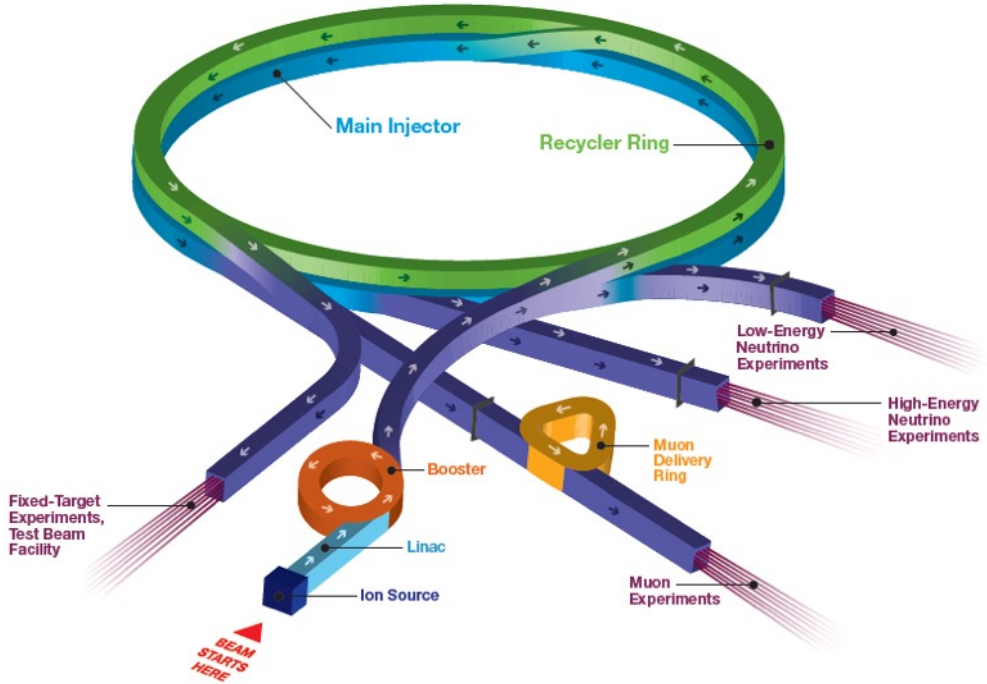
Accelerator Complex Evolution:

- **Near term beam for current and near future program**
- **Evolve as front end for Muon Collider**

Accelerator and Detector R&D along the way



AD: Fermilab Accelerator Complex – world-leading proton beam facility



Beams to Booster Neutrino beam, NuMI, muon campus, Test beams (MTA and 120 GeV), fixed target (spinquest)

120 GeV beam power – 0.895 MW

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

Operation with uptime of ~80%

Continue to ramp up MI power through cycle time reduction

Looking ahead to 20 year plan for modernization of the complex (P5 report)

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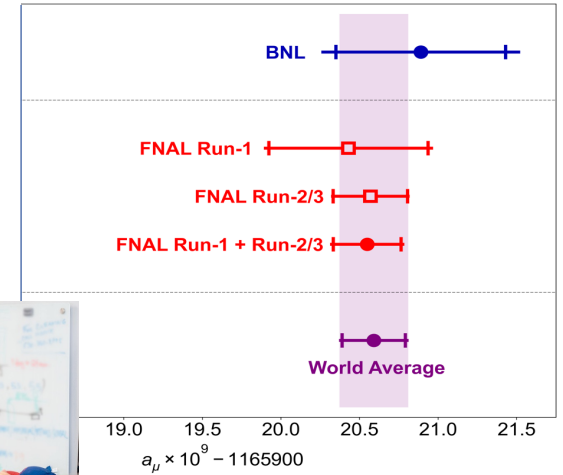
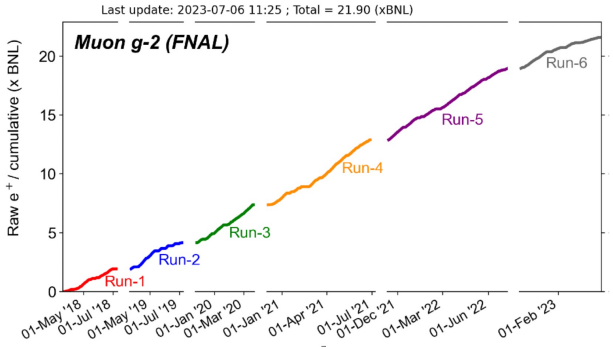
The international PIP-II accelerator project

Precision Science

Muon Science: g-2 outlook

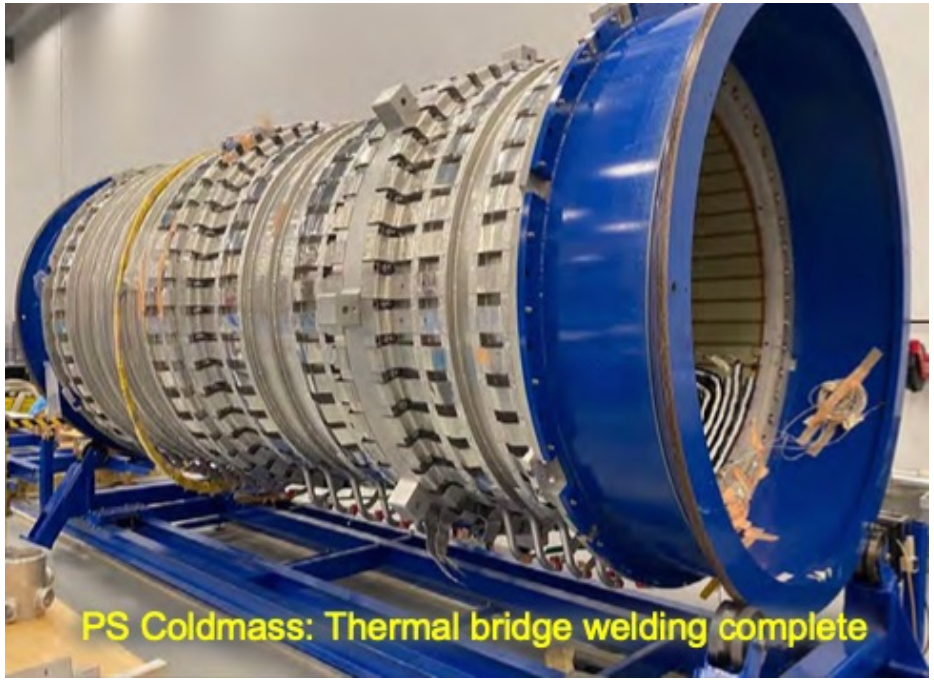
- **Second result from Run-2/3 data**
  - Second result garnered world-wide media attention with **2,000+ media mentions and 7+ billion media reach**
  - New average has **190 ppb** precision, dominated by FNAL
  - Systematic uncertainty of **70 ppb** already surpasses goal





- **Outlook**
  - Plan to **publish result of the full dataset in 2025** with twice improved statistical precision.
  - Jury is still out on theory predictions…

Mu2e Project: Looking for muon to electron conversion – if we see it – new physics at highest mass scales



Production Solenoid Cold Mass Assembly

1st Calorimeter disk instrumented

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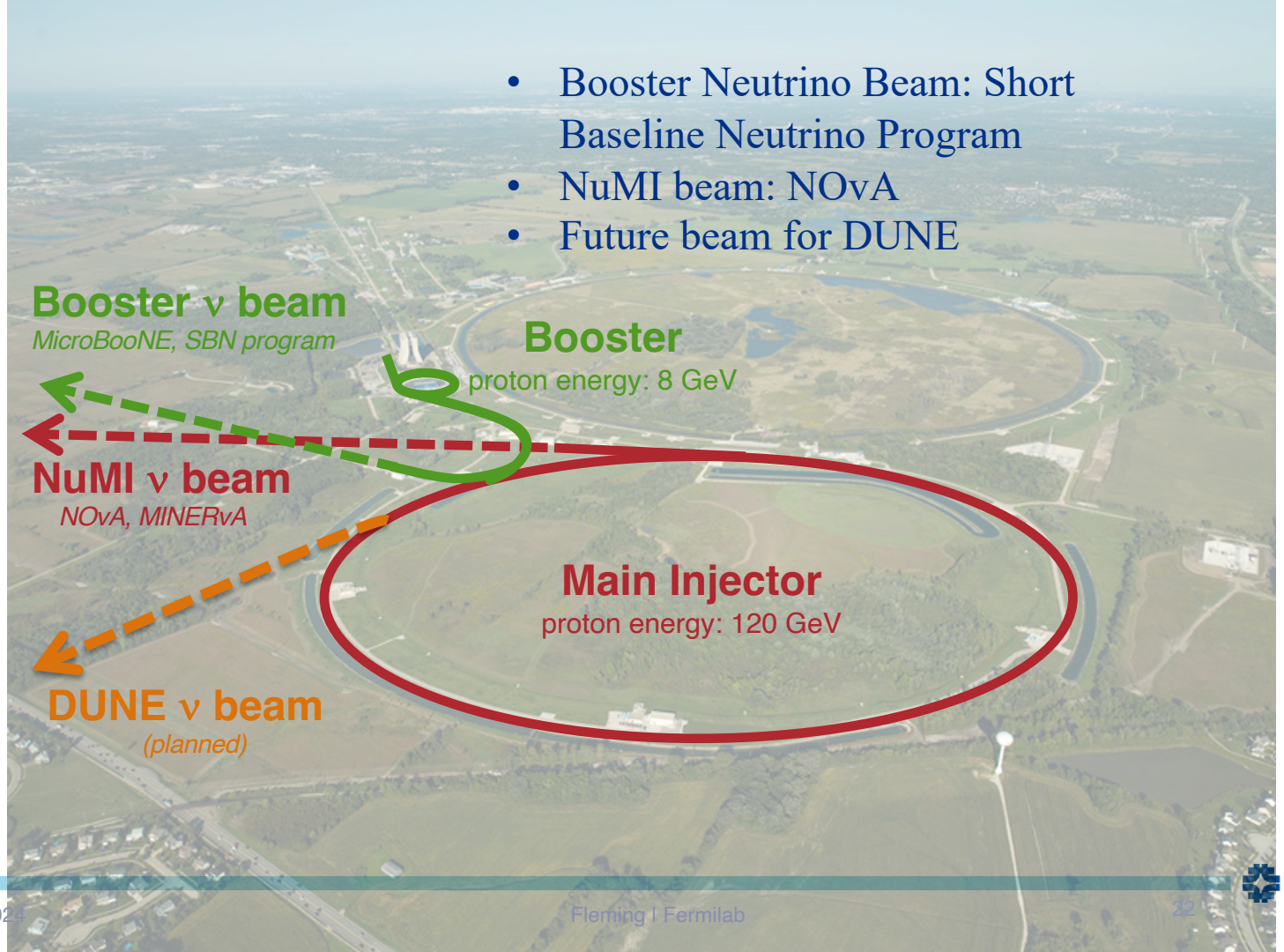
Neutrinos at Fermilab

- Booster Neutrino Beam: Short Baseline Neutrino Program
- NuMI beam: NOvA
- Future beam for DUNE



Neutrino Science: NOvA

- Doubled (1.96x) FHC(v) dataset at the end of FY23 accelerator run. Returning to RHC (anti-v) running in FY24
- 2024: Operations start in March

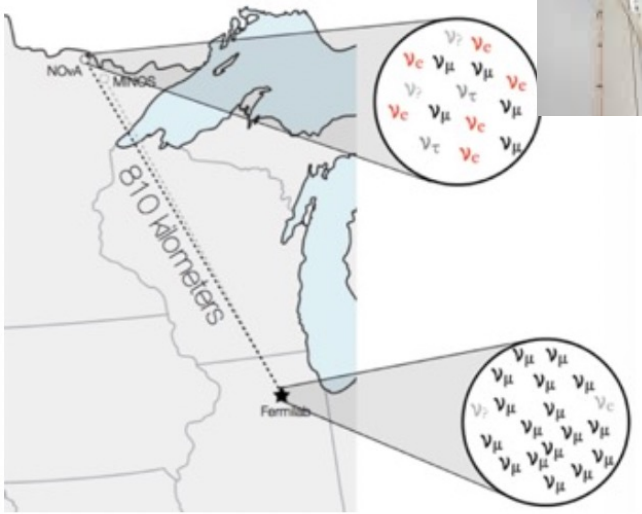
  New 3-flavor oscillation results with double the FHC data.

  Results from the joint fit with T2K

  New cross section measurements

  New BSM search

Long baseline neutrino oscillation experiment



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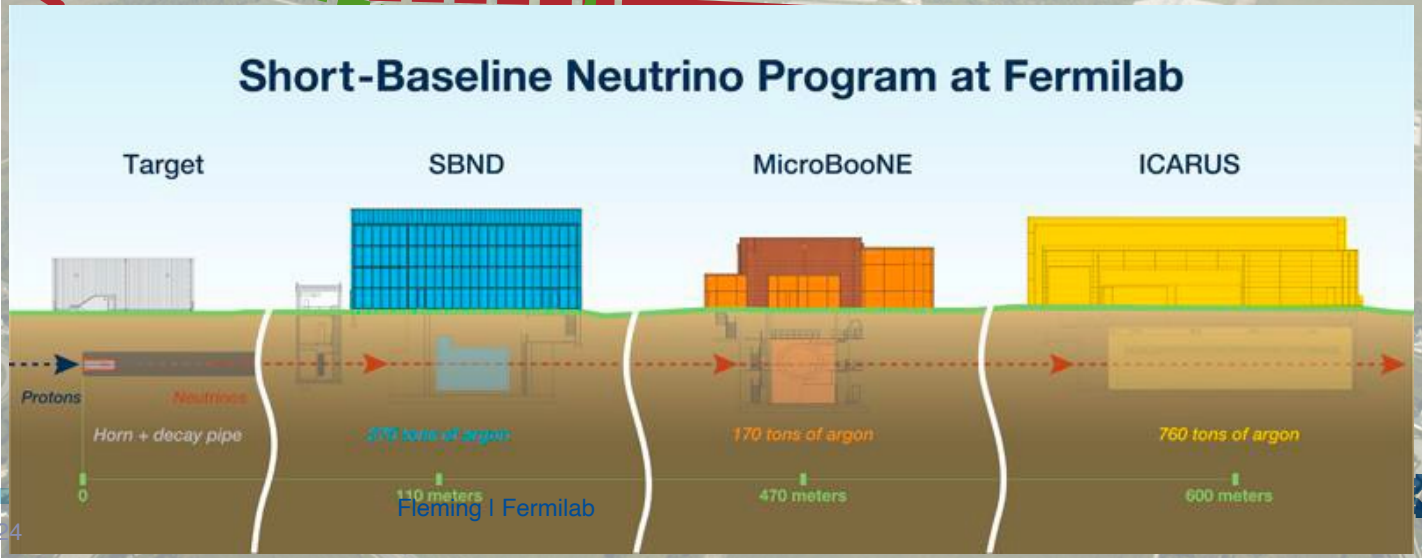
SBL program: Series of detectors addressing anomalies at short baseline and developing technology for DUNE

Booster ν beam
MicroBooNE, SBN program

Booster
proton energy: 8 GeV



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Neutrino Science: SBN Operations start in March 2024

- MicroBooNE continues to publish papers (>60 peer reviewed papers to date)
- ICARUS taking data and looking ahead to first results
- SBND commissioning now!
  - Looking ahead to first physics data this year

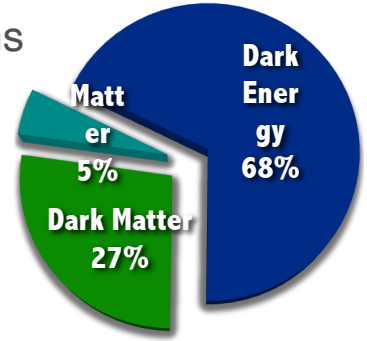
Detector rigging into the cryostat

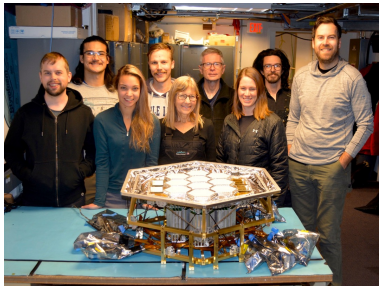
CRT north wall installation

Cabling and cryogenic connections

Cosmic Science

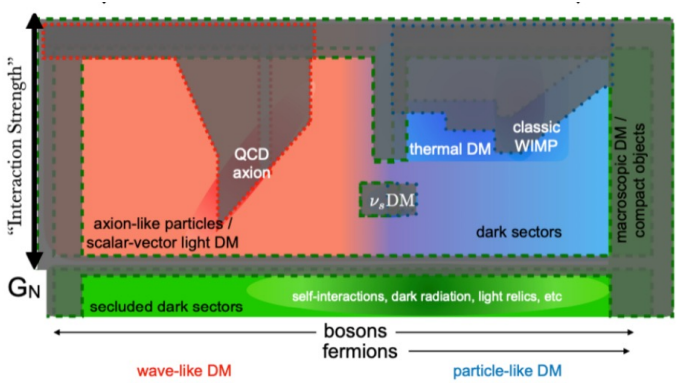
- The Cosmic Frontier addresses fundamental questions by connecting the very small to the very large:
  - **What is the dark matter?**
  - **What is dark energy?**
  - **What is the physics of inflation?**





SPT-3G Focal Plane at the South Pole

Aim high, search wide, delve deep



Dark Matter Parameter Space

Fermilab roles capitalize on unique strengths, core infrastructure, detector development support, facilities, and large talent pool

- Technical capabilities built up from accelerator program are applicable to cosmic experiments, including the **largest HEP investment in detector development**
- **Large pool of engineers and technicians**, all available to the user community

Fermilab

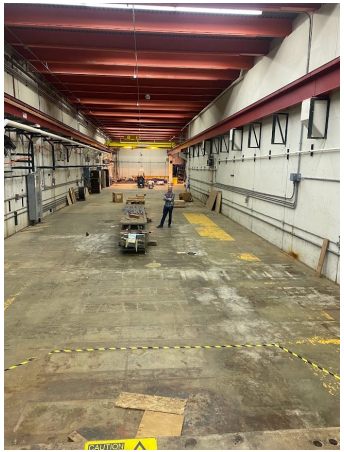
Dark Wave Lab (Axion Center for Dark Matter)

→ Build on facility for ADMX-EFR axion dark matter search
→ User facility for pathfinder experiments: prototypes to first measurements

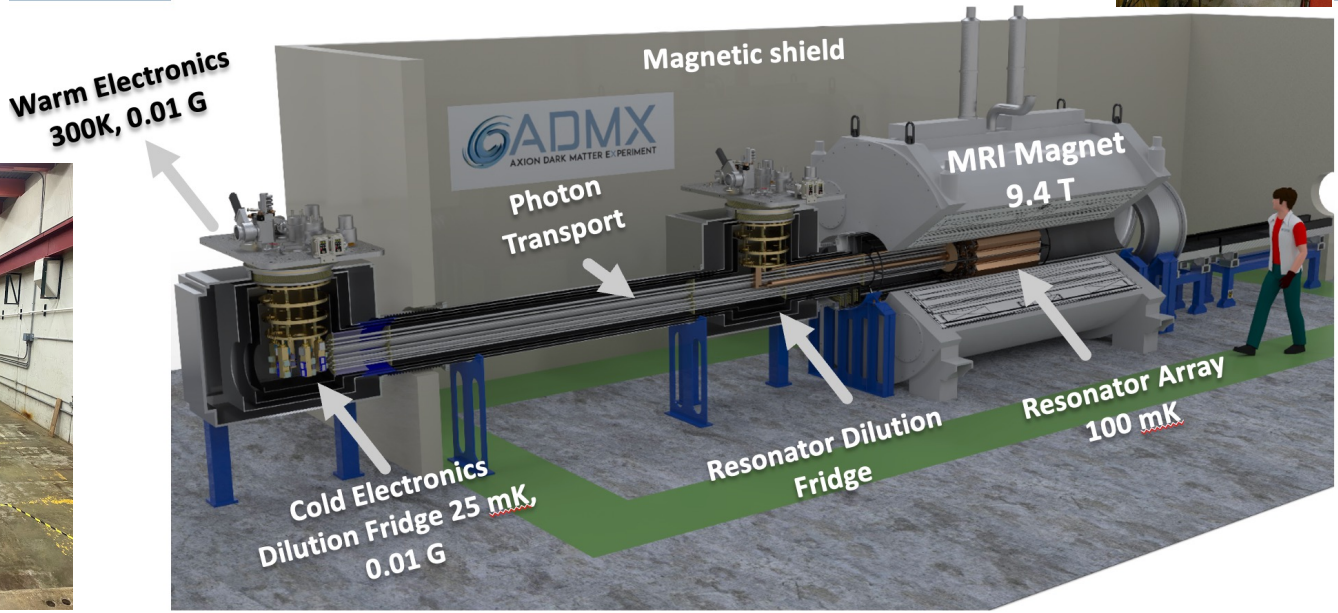
PW8/HIL at FNAL: Large, shallow underground hall with adjacent surface building. Total 13,000 square ft.

About half the space will be used by ADMX-EFR.

Expand for full Dark Wave Lab



ADMX-EFR Experiment Layout



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

Inauguration of Quantum Garage at SQMS last November

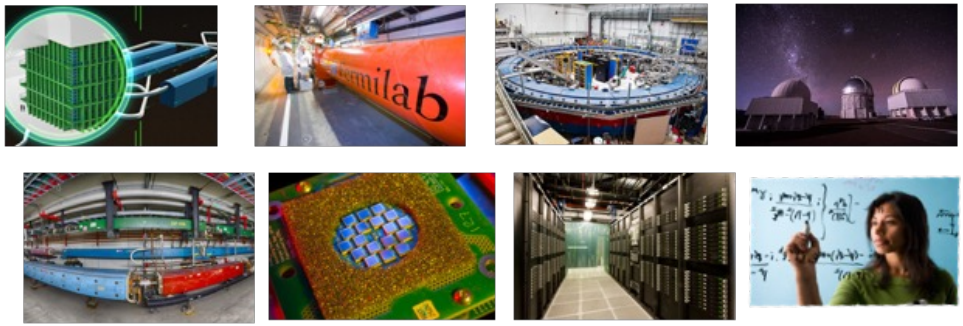
→ newly commissioned, large dilution refrigerators

→ fridges host platforms developed by SQMS collaborations for quantum computation, sensing, metrology and communications.

Fermilab and Emerging Technologies

NEW DIRECTORATE!

HEP science with neutrinos, the LHC, muons, and the cosmos



Underpinned by strong competencies in accelerator and detector science and technology, computing, and theory

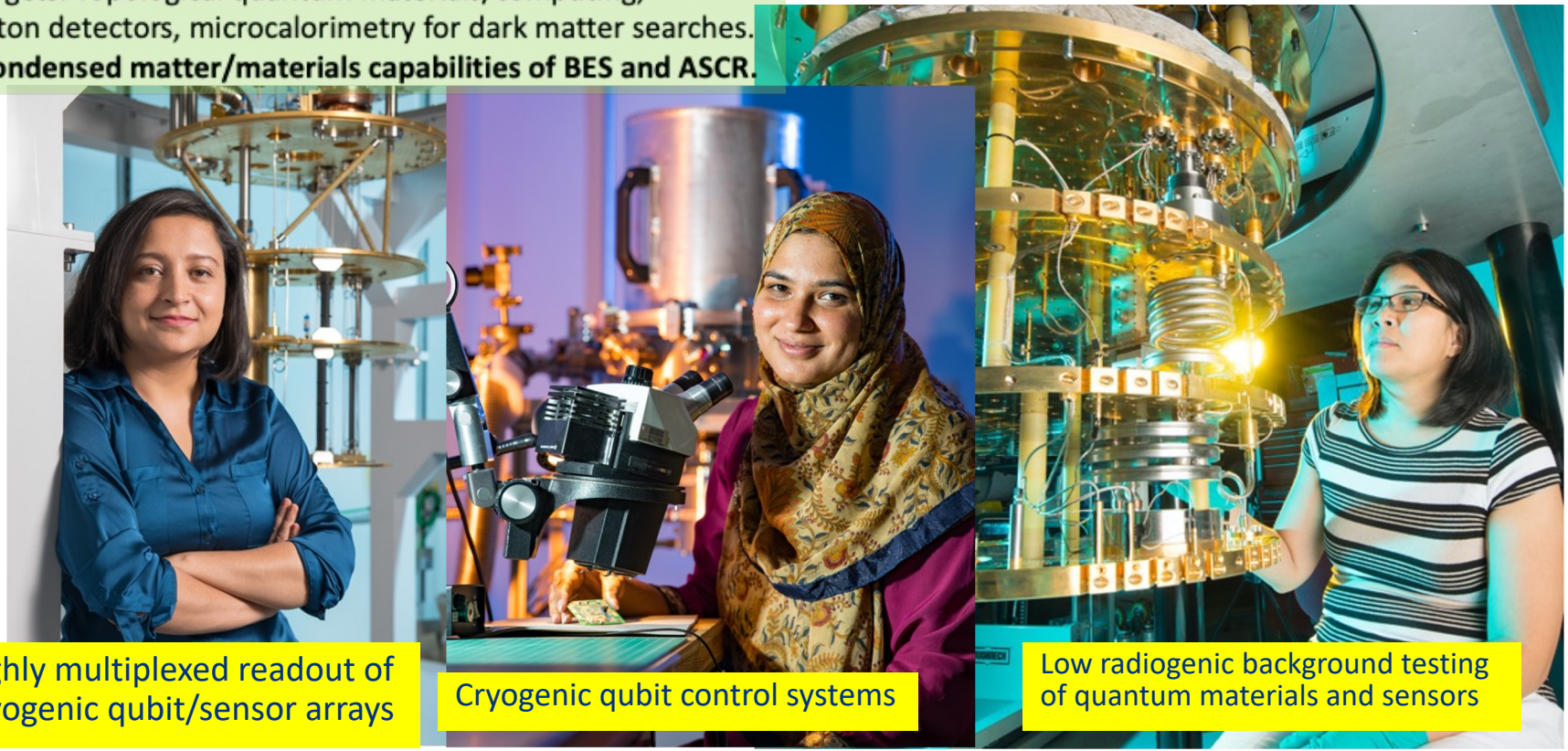
Our **science goals** demand ever increasing precision instruments, driving the need for **innovative techniques and technologies**

Many fundamental **HEP** research areas can **benefit** from emerging technology **applications** and many **HEP competencies** can help **advance new technologies**

Establishing new and rapidly advancing programs in **QIS** and **microelectronics**, leveraging national programs and initiatives. Continue to pursue **partnerships** to apply Fermilab **accelerator** and other technologies to new applications.

Quantum Science Center (QSC): Fermilab leads sensor and controls R&D

Science targets: Topological quantum materials/computing, single photon detectors, microcalorimetry for dark matter searches.
Engages condensed matter/materials capabilities of BES and ASCR.



highly multiplexed readout of cryogenic qubit/sensor arrays

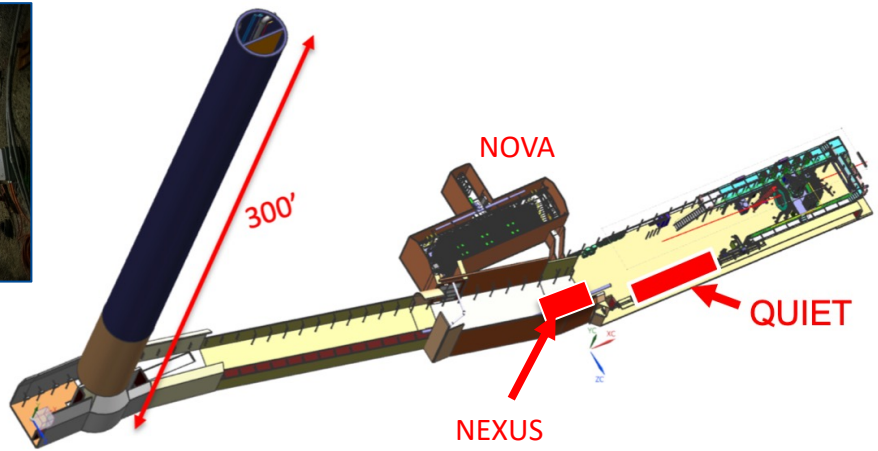
Cryogenic qubit control systems

Low radiogenic background testing of quantum materials and sensors

Fermilab

Quantum Underground Instrumentation Experimental Testbed

- Located in the MINOS Near Detector Hall at FNAL
- 300 foot rock overburden reduces cosmic showers by 99%
- Identical surface facility (LOUD) for rapid testing of devices before underground deployment

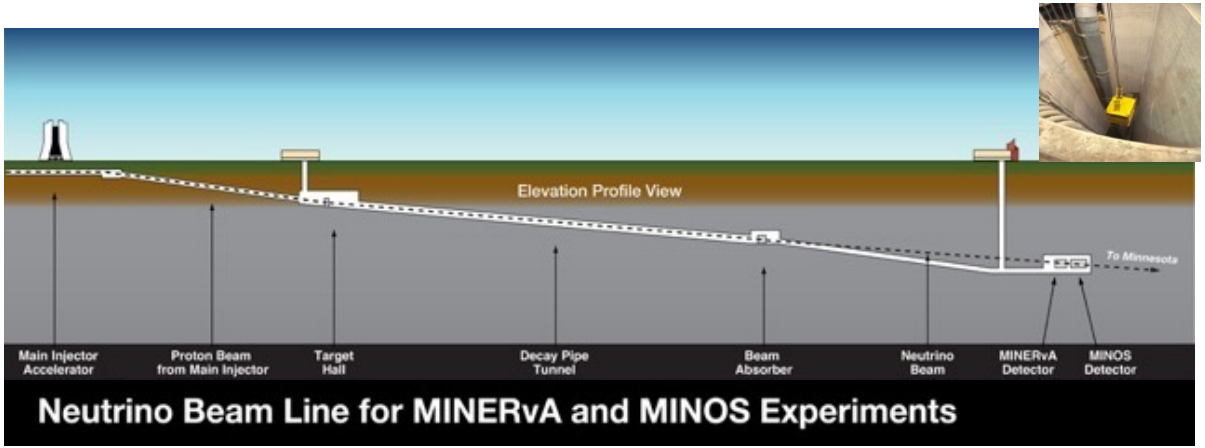


LOUD Run Coordinator: Ryan Linehan

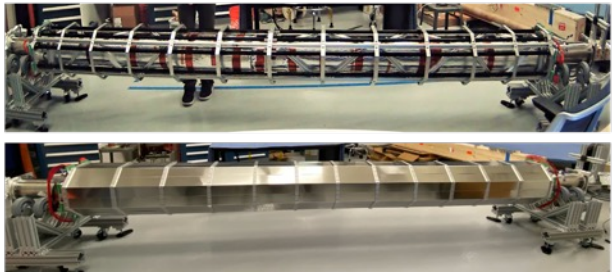
From Dan Baxter

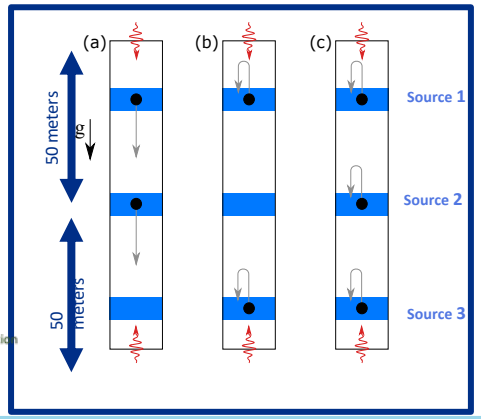
MAGIS-100 experiment at Fermilab

MAGIS-100 will explore fundamental physics using clock atom interferometry across a 100-meter vertical baseline.



Assembled prototype MAGIS module with horizontal bias coils and magnetic shield



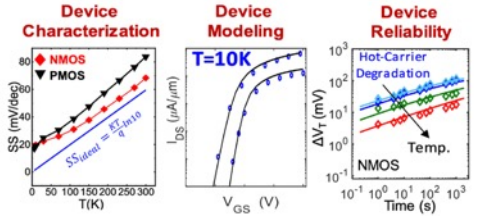


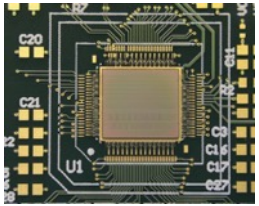
- Major **technological advance** for studying very **low mass dark matter.**
  - 100 m baseline – order of magnitude better than current state-of-the-art
  - Uses ultra-precise Strontium clock transition.
- **Pathfinder** for longer baselines, sensitive to **~1 Hz gravitational waves.**

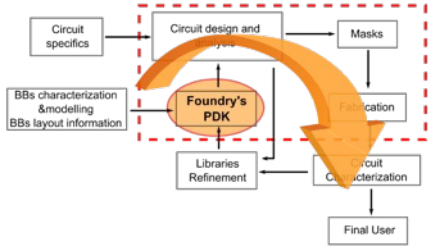
Fermilab

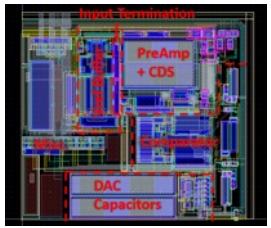
Microelectronics at Fermilab

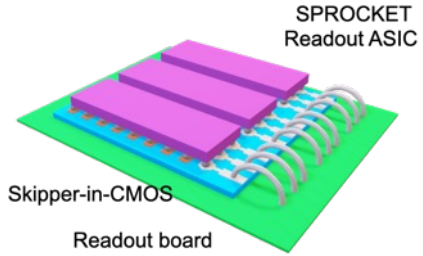
- Support ASIC design for extreme environments
- Perform R&D to underpin the success of CMS and DUNE and the next generation HEP detectors and experiments
- R&D for new technology capabilities (CMOS, hybrid)











Skipper-CCD-in-CMOS pixel detectors are a highly attractive platform for HEP/quantum imaging and dark matter detection because of their low noise.

Pursue new partnerships for DOE, DOD and DOC projects (CHIPS act) to advance our capabilities to support HEP science

Fermilab facilities are key to Particle Physics Program

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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