Fermilab Cosmic Frontier Strategy

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PAC Meeting

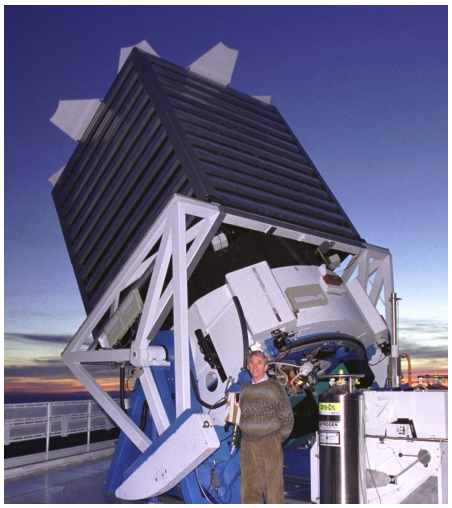
18 January 2023

Outline

- Fermilab's Cosmic History and Mission
- Our Unique Capabilities, Facilities and People
- The 2019 Strategic Plan and our Progress in Implementing It
- Impact of Snowmass 2021 and Opportunities for the Next Decade
- Summary

Fermilab's Cosmic History

- Lab Director Leon Lederman creates Fermilab Astro theory group with David Schramm, 1983. Hires Kolb and Turner.
- Rocky Kolb & Michael Turner: NASA-Fermilab theory center. Inner Space/ Outer Space conference, 1984.
- Lab Director John Peoples initiates experimental program with Sloan Digital Sky Survey beginning in late 1980s.

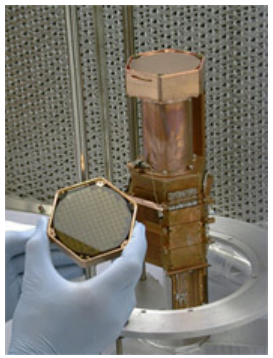


John Peoples at Apache Point w/ SDSS

***People would remind me that the A in FNAL is Accelerator, not Astrophysics**. But I always thought an accelerator is a tool. You don't say, "A carpenter is a person who uses a hammer. If you don't use a hammer, you're not doing carpentry." You know, there are other tools that you can use to get to the physics.*

- Rocky Kolb, AIP Oral History, 2020.

Rocky



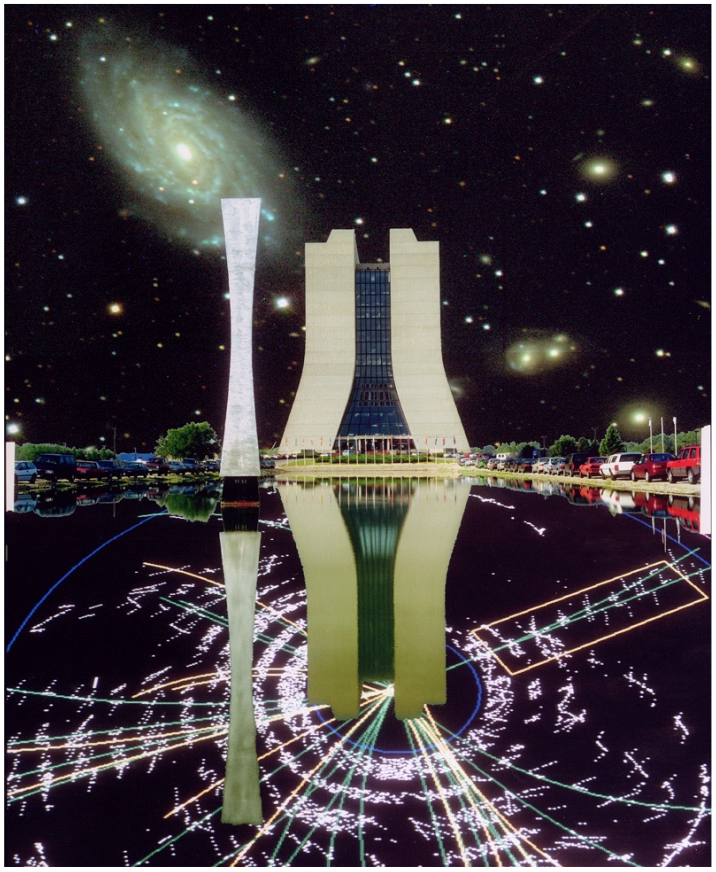
CDMS-I, mid-1990s

Fermilab's Cosmic Mission

From Fermilab's vision statement:

Our vision is to solve the mysteries of matter, energy, space and time for the benefit of all. We strive to:

- Lead the world in neutrino science with particle accelerators.
- Lead the nation in the development of particle colliders and their use for scientific discovery.
- **Advance particle physics through measurements of the cosmos.**



"About Fermilab", www.fnal.gov

Fermilab's 2019 Cosmic Strategic Plan

- Strategic planning exercise completed in 2018-2019 at request of DOE and lab directorate.
- Working group of 10 Fermilab scientists led by Josh Frieman.
- Three phase plan:
  - **Phase 1**: identify core capabilities that the laboratory provides to the OHEP Cosmic Frontier program;
  - **Phase 2**: identify the major CF activities the lab should pursue over the next 5-10 years, that exploit these capabilities, align with OHEP/P5 priorities, deliver on our commitments, and maximize scientific impact. Conclusions of planning exercise summarized in a report available at https://astro.fnal.gov/wp-content/uploads/2019/05/Cosmic-Steering-Report-public.pdf.
  - **Phase 3**: implement *focused* plan by sensibly directing effort from activities not deemed essential in the first two phases, to build our future program

  We are now (Jan 2023) ~4 years into this implementation phase.

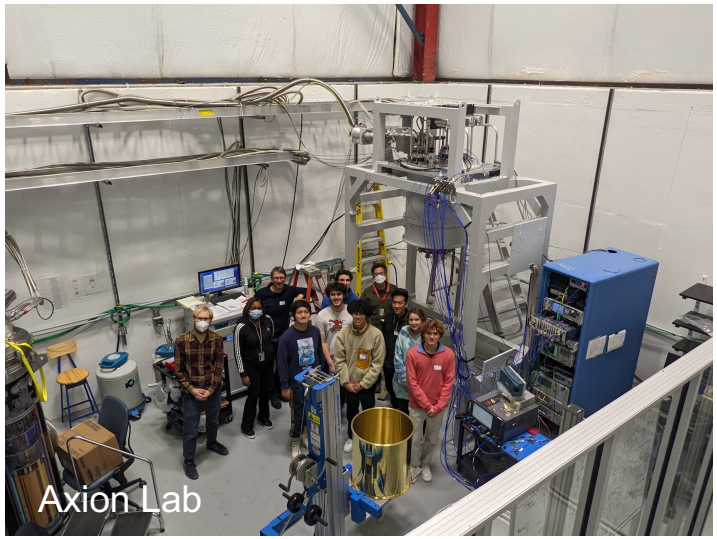
Our Unique Capabilities

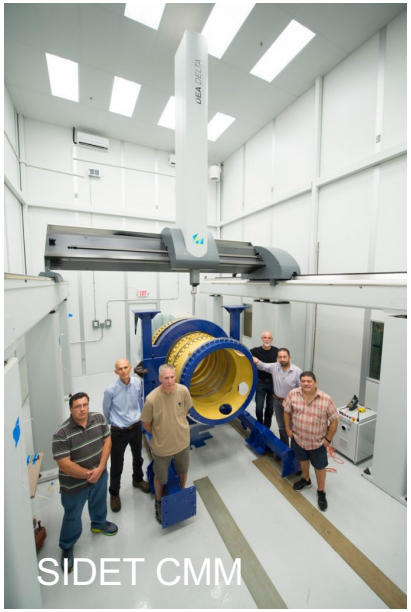
- Many capabilities created for accelerator-based program also apply to non-accelerator program.
- Largest HEP investment in detector development capabilities- a national resource available to our partners.
- Large pool of talented engineers and technician.
- Facilities and expertise are being continuously renewed.

Capabilities:

Cryogenics *& vacuum technology*
Electronics*, including RF, ASICs, FPGAs,*
Superconducting detectors*, amplifiers and circuits*
Photosensors: *CCDs, SIPMs, PMTs…*
Advanced ***computing****, including management of* ***petabyte-scale*** *data sets,* ***AI/ML***
Mechanical design *and assembly, cleanrooms*
Quantum sensors*, Qubits, Superconducting resonators*
Large-scale ***optical and sub-mm focal planes***
Wire bonding and ***sensor packaging***
Magnet *engineering and operations*
Noble liquid *detectors*
Underground, ***low-background facilities***
Project and operations ***management*** *to DOE standards*

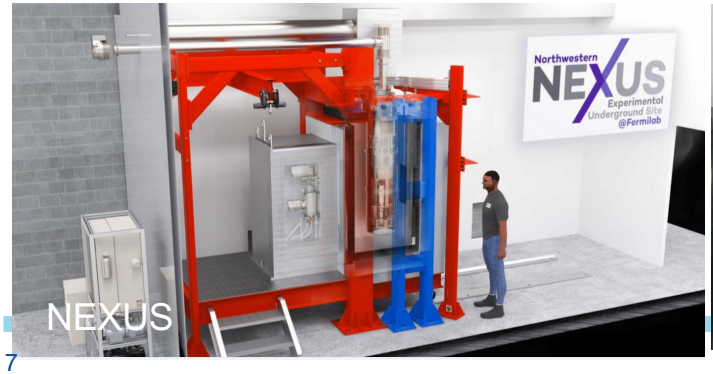
Our Unique Facilities


Axion Lab


SIDET CMM

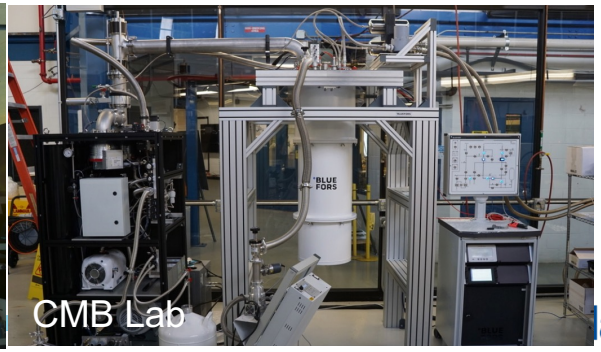

SiDET


IERC



NEXUS


SuperCDMS


CMB Lab

Award Winning Scientific Staff

- Expertise of unique scientists also creates unique lab capabilities.
- Continuous investment in hiring top scientific talent over decades.
- Recent hiring at Associate Scientist level (Junior faculty equivalent) focuses on building expertise in quantum sensing and artificial intelligence.
- A distinguished group– many DOE Early Career Awards, Wilson Fellowships.
- Breakthrough Prizes in 2020 (Benson and Rahlin) & 2021(Tiffenberg)
- Joint appointments with local universities: Chicago, IIT.

Associate Scientist Hires Since 2017

Adam Anderson
Wilson Fellow
Cosmic Microwave Background

Javier Tiffenberg
DOE Early Career Award
Dark Matter

Guillermo Fernandez Moroni
Dark Matter

Aleksandra Ciprijanovic
Wilson Fellow
Dark Energy/ AI

Dan Baxter
Dark Matter/
Quantum Sensing

Sara Simon
Wilson Fellow
Cosmic Microwave Background

Brian Nord
DOE Early Career Award
Dark Energy/AI

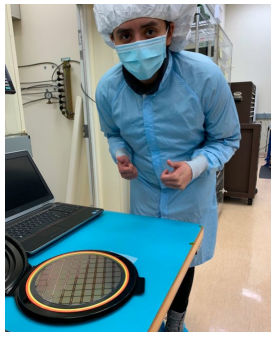
Alex Drlica-Wagner
Wilson Fellow
Dark Energy

Rakshya Khatiwada
Joint with Illinois Institute of Technology
Dark Matter/ Quantum Sensing

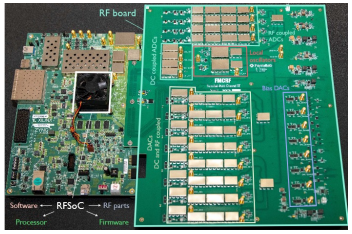
Cosmic R&D

- Cosmic sensor & experiment R&D at Fermilab is a strength.
- Very diverse, innovative and complementary to other lab programs.
- Our success is a product of creative Scientists x Facilities x Financial support.
- Financial support for R&D comes largely from outside “Cosmic Research” (KA23):
  - DOE QuantiSED program
  - Quantum Centers (SQMS, QSC)
  - DOE Dark Matter New Initiatives grants
  - DOE Microelectronics
  - DOE Generic detector R&D (KA-25)
  - Laboratory Directed R&D (LDRD)
  - Other agencies (NASA, IARPA)
  - Heising-Simons foundation

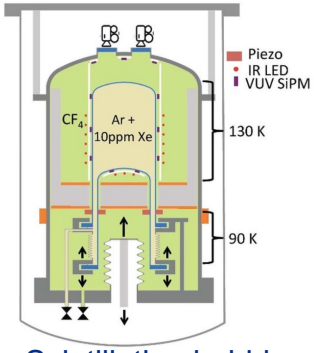
Skipper group “lowest noise” prize @ SDW2022



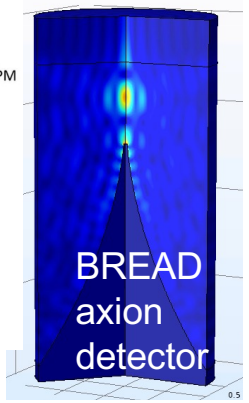
Skipper CCDs



QICK (Quantum Instrumentation Control Kit) for Astro applications



Scintillating bubble chamber dark matter detector



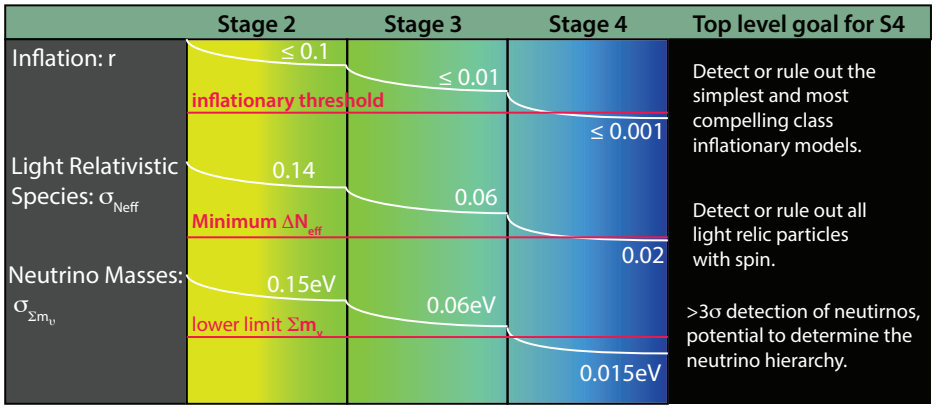
Fermilab

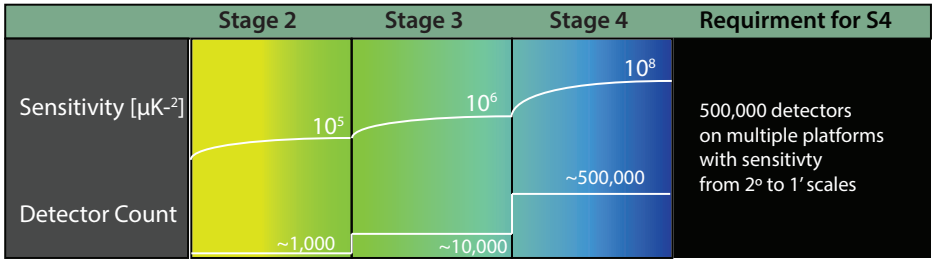
Elements of the 2019 Strategic Plan

- Cosmic Microwave Background (inflation, neutrinos)
  - Strong Fermilab contribution to CMB-S4 identified as top priority for next decade. CMB group planned to grow in size while transitioning from SPT-3G operations.
- Dark Matter Detection
  - Increase efforts to search for axion dark matter. *Exploit emergence of new techniques closely related to Fermilab's critical capabilities.* ***Develop a plan to host next generation axion search at Fermilab.***
  - Light Dark Sector Particles (sub-GeV DM). *Increasing scientific importance as heavier WIMP searches become background limited.* Deliver on SuperCDMS operations roles and develop Skipper CCD experiment (OSCURA).
- Cosmic Surveys (cosmic acceleration, dark matter)
  - Transition from DES to LSST Operations while maintaining small but critical role in DESI.
  - R&D toward future southern spectroscopic survey (LDRD)

Strategic Plan: Cosmic Microwave Background

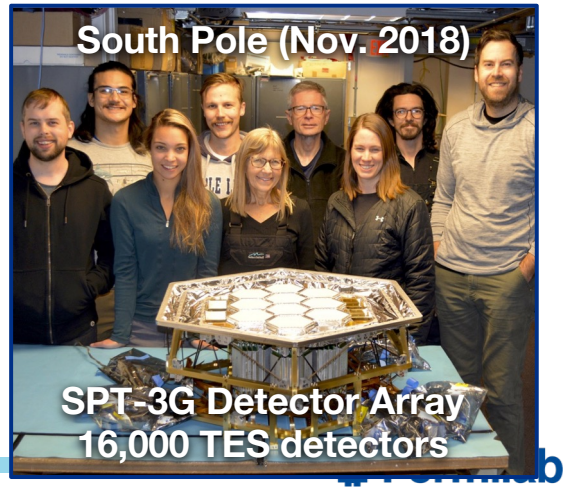
- Our 2019 Plan identified growth in CMB research at Fermilab as the top priority for next decade. **FNAL has established critical roles in CMB-S4**.
- CMB-S4 project addresses important science drivers (inflation, neutrinos) via precision measurements, also with high potential for discovery of new phenomena. Endorsed by 2014 P5, Astro 2020.
- Exploits Fermilab's strengths in Sub-Kelvin cryogenics, superconducting devices, and detector packaging.
- Expected to be DOE's largest Cosmic Frontier project in 2020s.





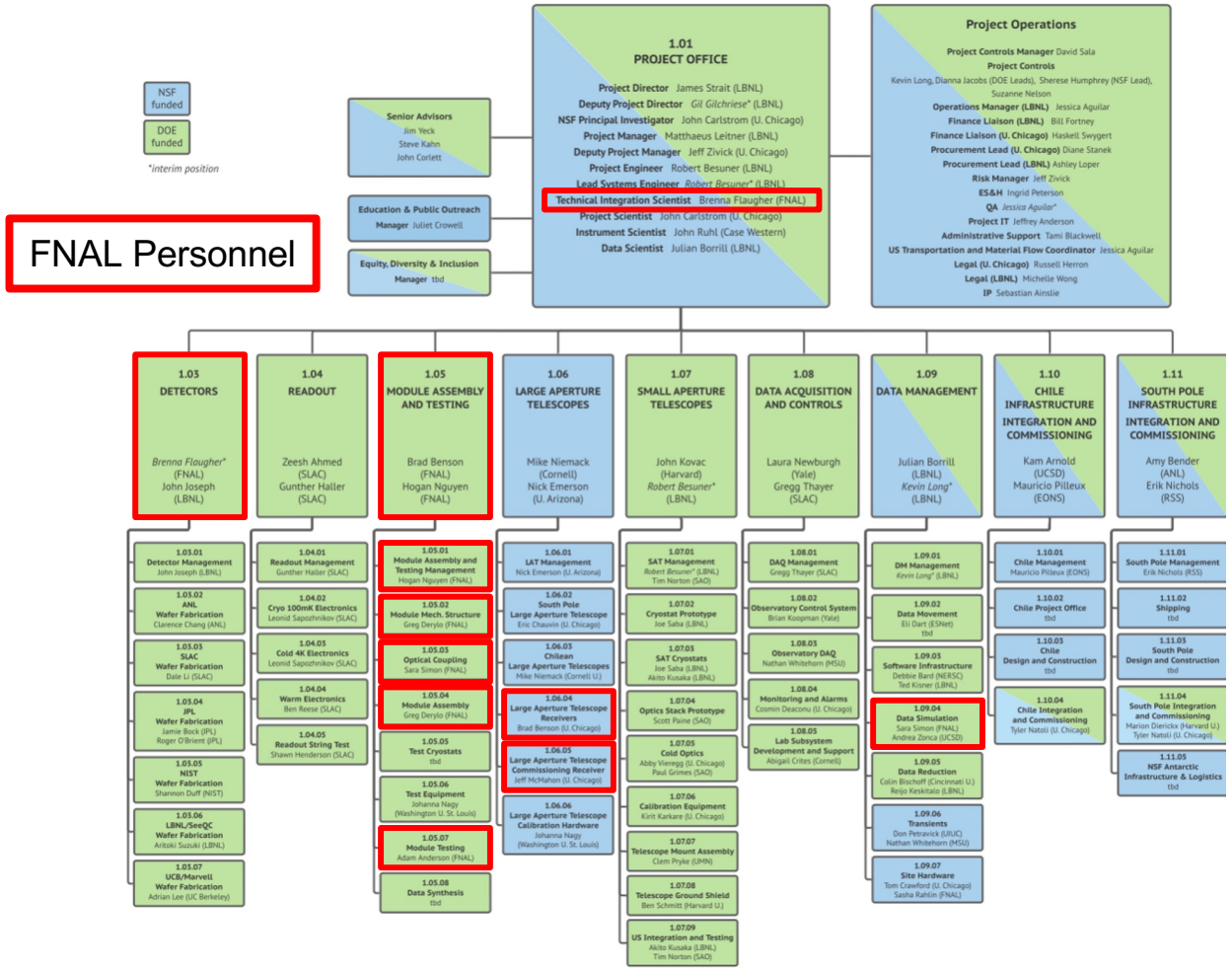
FNAL CMB Program Overview

- Very strong group with three recent Wilson Fellow hires: Benson (2013), Anderson (2019), Simon (2020), experienced senior scientists Flaugher & Nguyen, and three postdocs (~ 7 FTEs).
- Close connections to U. Chicago group (SPT & CMB-S4 NSF PI: John Carlstrom)
- Major roles in operations & data analysis for South Pole Telescope SPT-3G experiment (Assoc. Director Benson).
- Six LDRD awards since 2014.
- New IERC building will have a large CMB lab with room for 6 dilution refrigerators.
- Strengths of group: Detector assembly and testing; instrument integration; mechanical and sub-Kelvin cryogenic engineering; instrument performance modeling; scientific analysis.



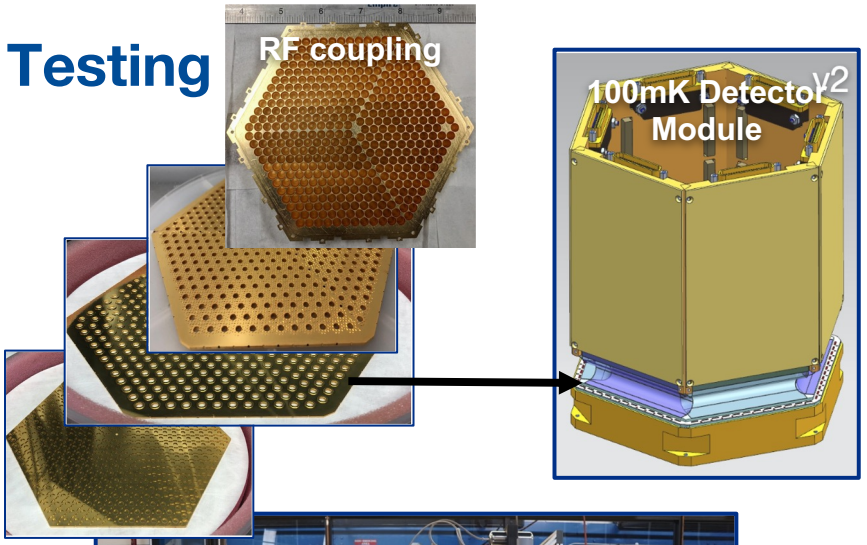
CMB-S4 at Fermilab

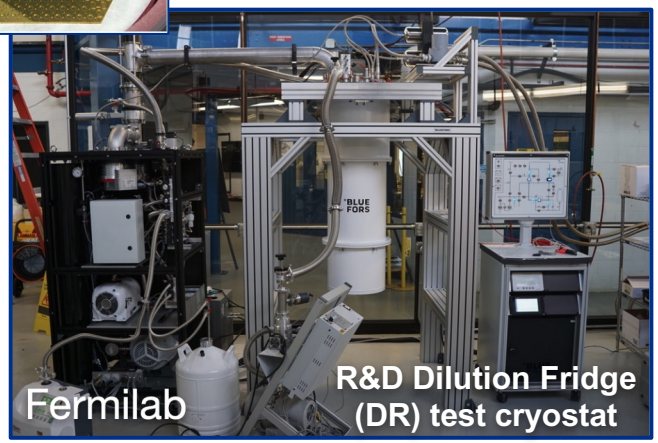
- Fermilab roles align with core capabilities and experience.
- Detector Modules Lead: Design, assembly, integration, and testing.
- Large-aperture telescope (LAT) cryostat, RF coupling.



CMB-S4 at Fermilab: Modules and Testing

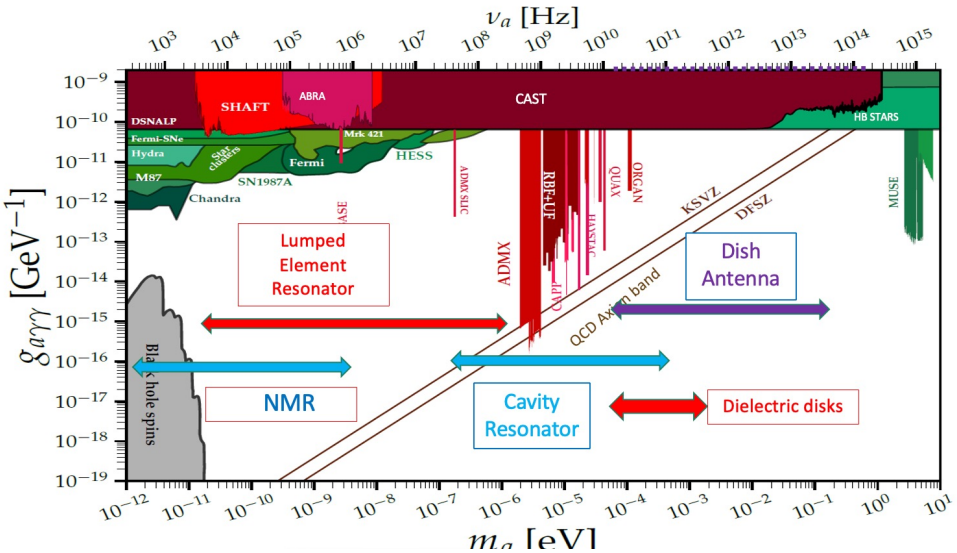
- Fermilab leading 100mK Detector Module Assembly and Testing.
  - **FNAL roles:** L2 **Benson**, separate L3 roles for **Anderson**, **Simon**, mech. eng. **Derylo**
  - Scope includes microwave coupling elements (horn arrays and interface wafers) that couple microwaves onto the detectors (L3 **Simon**)
  - Scope includes 100 mK detector module testing and characterization (L3 **Anderson**)
  - Current phase is enabled by Fermilab LDRD investments in DR cryostat (PI **Anderson**), and RF equipment for feedhorn development (PI **Simon**)
- ***>2024:*** Begin mass production and testing of modules and components for CMB-S4
  - IERC space for Dilution Fridges starts becoming available in Winter 2023





Strategic Plan: Axion Dark Matter

- QCD axion was identified as a compelling dark matter candidate in the 1980s. It would solve both strong CP problem and dark matter problem.
- Experimental progress in last 40 years has been modest, ***but that's changing now.***
- Many new ideas in this field, most motivated by progress in low noise superconducting electronics and quantum sensors. E.g. ability to detect single photons across the electromagnetic spectrum.



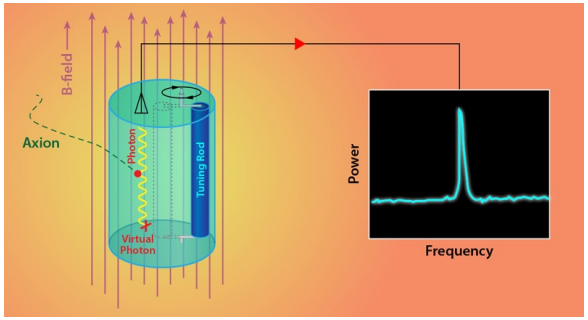
Proposed detection techniques span allowed mass range for QCD axion dark matter.

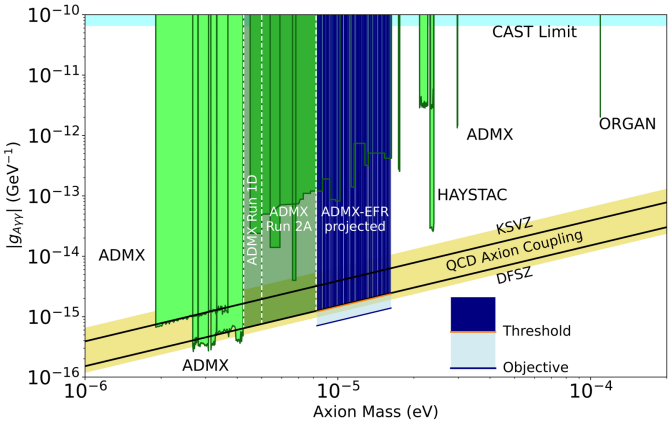
- Important strategic opportunity- progress will be driven by technologies closely related to Fermilab capabilities in quantum sensors, cryogenics, magnets.

Fermilab

Axion Group Overview

- Three senior scientists (Sonnenschein, Chou, Tesarek), Khatiwada (Joint appointment IIT) and a postdoc (2 FTEs total).
- Lead lab for operations of current generation DOE experiment, ADMX-G2. Located at U. Washington.
- Dark Matter New Initiatives project: **ADMX-Extended Frequency Range (ADMX-EFR) will be located at Fermilab.**



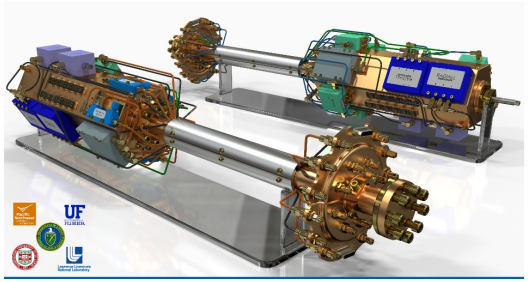


Fermilab

ADMX-G2

- ADMX-G2 is DOE's current generation axion search installed at U. Washington. Fermilab joined in 2017.
- First experiment to reach sensitivity required to test most important axion models (KFVZ, DFSZ)
- Fermilab roles in current experiment:
  - Operations management
  - Analysis coordination
  - Resonator testing
  - Cryogenic, mechanical and controls engineering.

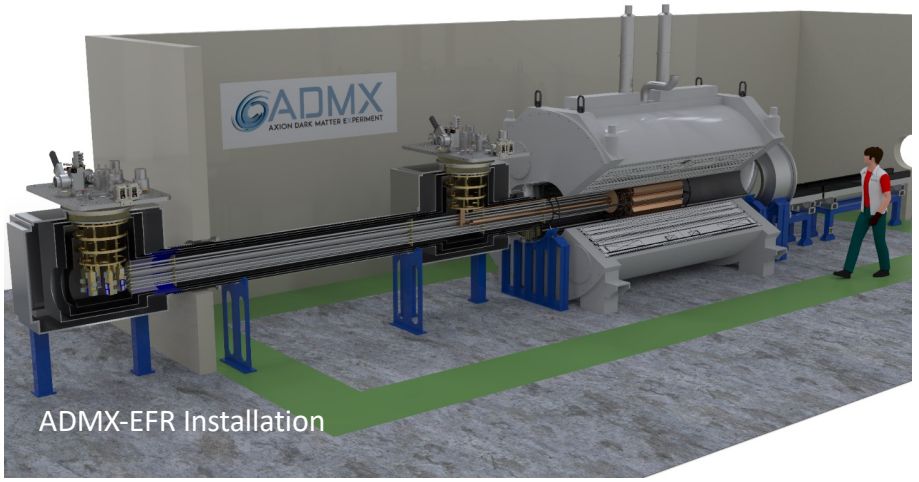
Fermilab-designed cryo electronics packaging



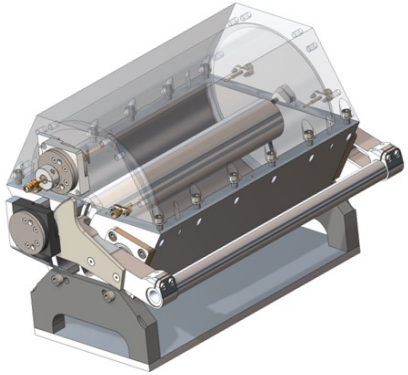
ADMX-G2 Resonator Testing in Fermilab's axion lab at SiDet

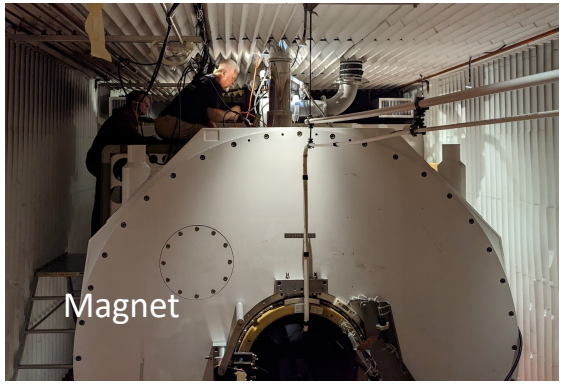
ADMX-EFR

- Design phase funded in 2020-2022 under DOE Dark Matter New Initiatives (DMNI)
- Based on an existing 9.4 Tesla MRI magnet being donated by U. Illinois Chicago– order of magnitude more stored energy than ADMX-G2.
- Array of 18 resonant cavities at 150 mK read out with Josephson Parametric Amplifiers– near quantum limited noise.
- Status– magnet to be installed this year. Preparing for cost and schedule review in Summer 2023.



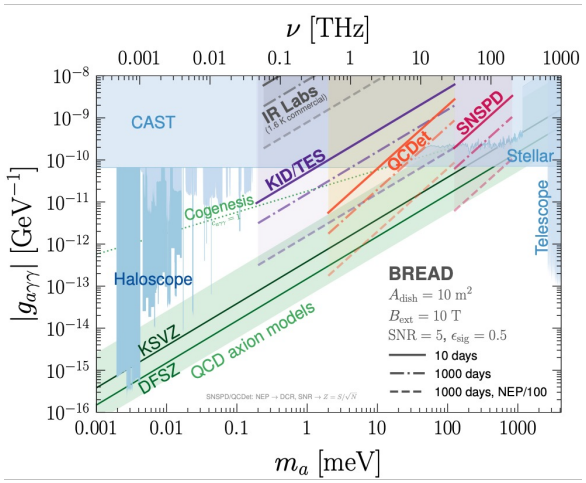
ADMX-EFR Installation

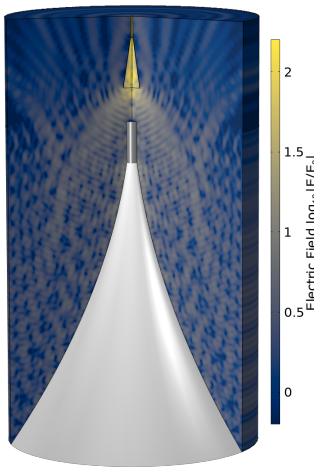

Resonators

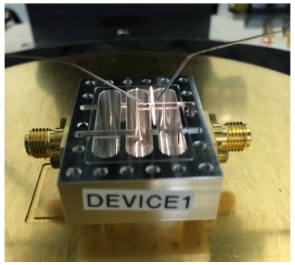

Magnet

Future Axion Program

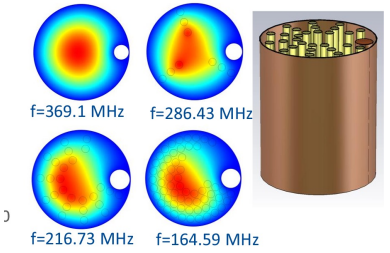
- New Fermilab-led experiment concepts would probe higher and lower mass ranges beyond reach of ADMX-EFR.
  - Superconducting cavities in high magnetic field (SQMS, APS-TD, LLNL)
  - BREAD broadband axion antenna for high frequency.
  - SQUAD qubit based single photon detection
  - Dielectric-loaded cavities for low frequency.
- Support from QuantiSED, quantum centers and LDRD.
- We want to host a series of small projects covering different axion mass ranges.







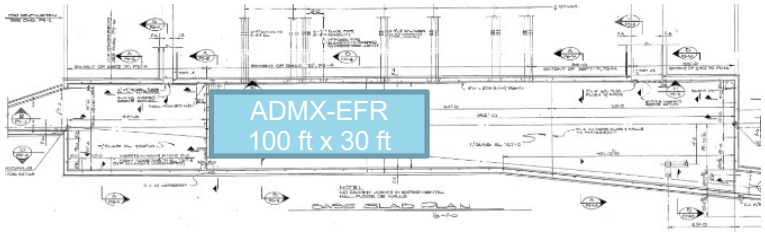
SQUAD Qubit GHz photon counter



Dielectric-loaded low-frequency cavities

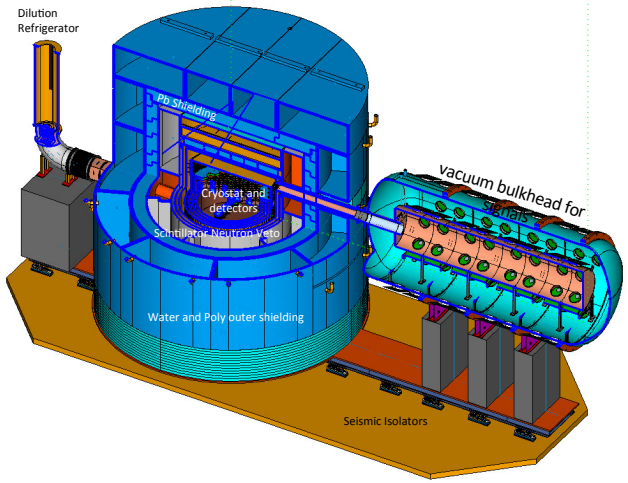
Dark Wave Laboratory

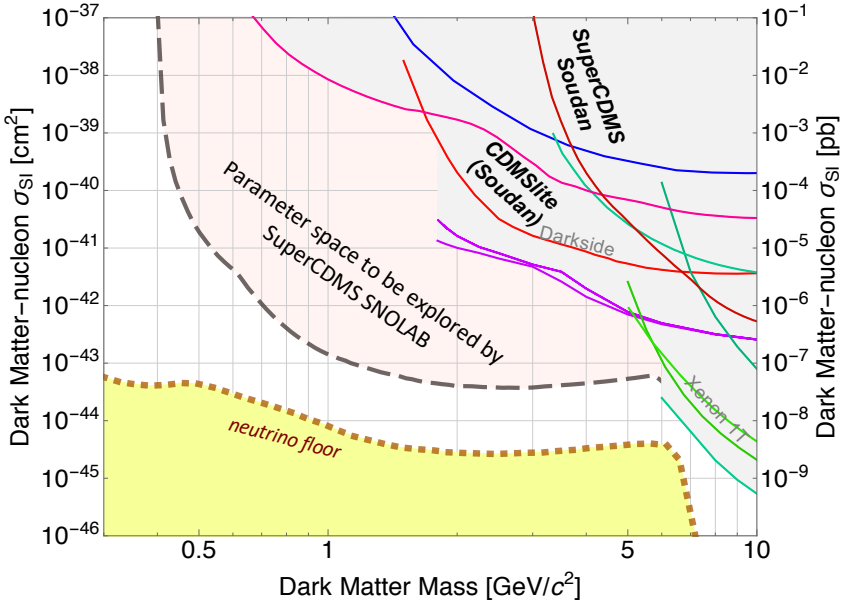
- ***Vision: host several experiments which could support a new dark matter program over the next decade, with many students/postdocs potentially being stationed at Fermilab***
- Will convert an underused 7000 sq. ft high-bay facility + 6500 sq ft of shop and office space into a dedicated “Dark Wave Quantum Sensor Laboratory” .
  - Good place to run large magnets – will have helium recovery and other cryo infrastructure, magnetic shielding.
  - Initially will install ADMX-EFR in half the space.
  - Renovation of this space has been proposed as General Plant Project (GPP)



Light Dark Matter- SuperCDMS

- Unparalleled sensitivity to dark matter with masses in the range of 0.5-10 GeV/c^2
- Construction underway, with commissioning in 2023-24
- Fermilab designed and will deliver major components of the experiment

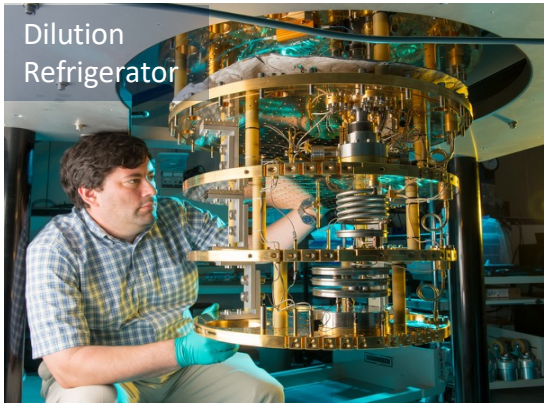


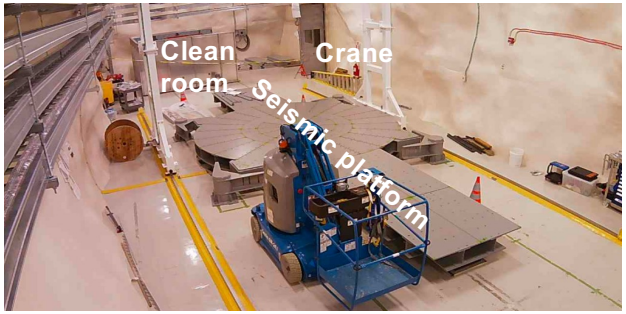


First year of operation with HV Ge and Si detectors will probe substantial new territory in the few GeV/c^2 mass range

SuperCDMS SNOLAB: Fermilab Roles & Status

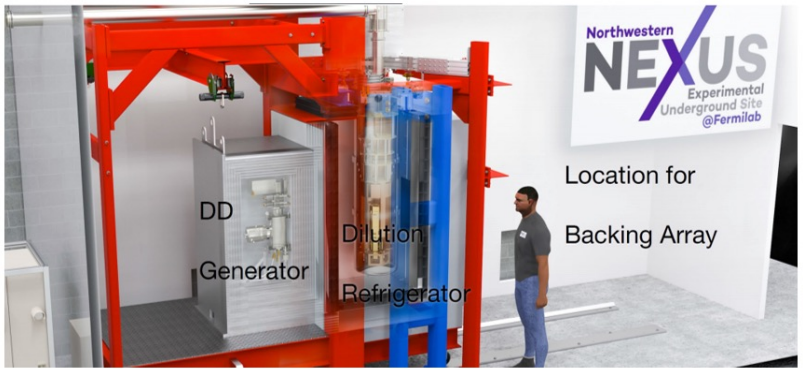
- **Fermilab continuing 20 years of involvement in SuperCDMS:**
  - Cryogenic system design and operation
  - Warm electronics design and fabrication
  - Calibration system design and operation
  - Infrastructure design and Integration
- **Recent Milestones:**
  - Dilution Refrigerator commissioned at Fermilab, delivered to SNOLAB
  - Copper cryostat (SNOBOX) is under construction.
  - Electronics, Calibration fabrication and testing completed
- **Infrastructure installed at SNOLAB:**
  - Seismic platform, cleanroom, crane, utilities - all designed by Fermilab

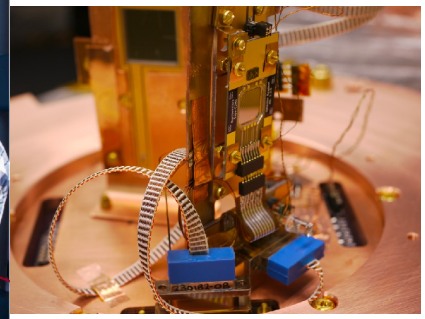




NEXUS: A Unique Test Facility at Fermilab

- Heavily shielded dilution refrigerator in clean room 106 meters underground in MINOS tunnel.
- Much easier access than deep underground sites like SNOLAB– perfect for sensor R&D and small experiments. *Small sensor packages (grams) typically cannot benefit from a site any deeper than this.*
- Wide applications to future light DM program- e.g. next-generation SuperCDMS detectors, novel quantum sensors, MKIDs
- Underground limits from SuperCDMS HVeV detectors.
- Neutron generator will be used for nuclear recoil calibrations.
- NEXUS is over subscribed- a second setup is under construction by Quantum Science Center.

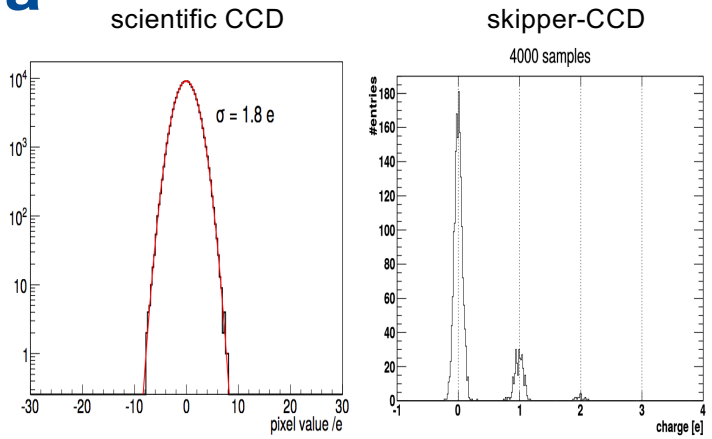




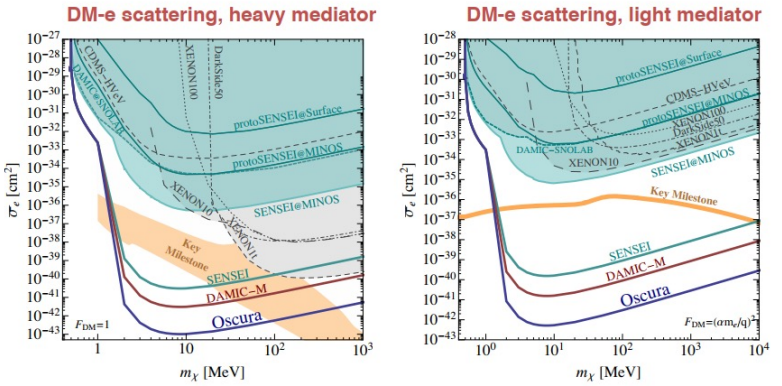
Fermilab

Light Dark Matter– SENSEI/ Oscura

- Fermilab pioneered use of CCDs for WIMP searches starting with DAMIC in 2008.
- More recently adapted LBNL's Skipper CCD technology to reduce the energy threshold for detection of dark matter scattering to the single electron level.



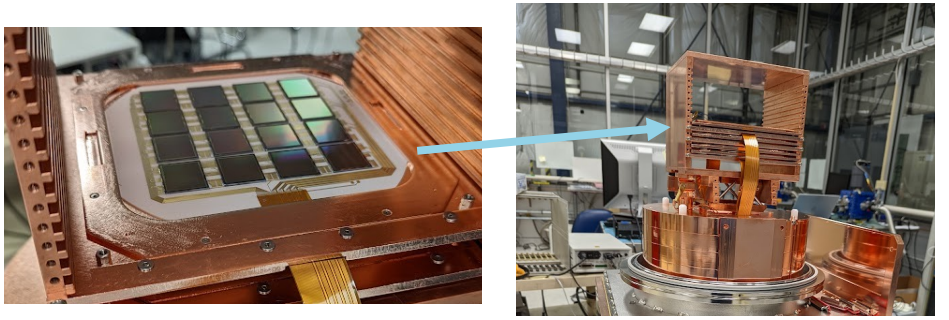
- SENSEI: a 100 g Skipper experiment now operating at SNOLAB. **Sensei won 2021 Breakthrough Prize New Horizon Award.**
- OSCURA: 10 kg Dark Matter New Initiatives project. Operations in FY29.

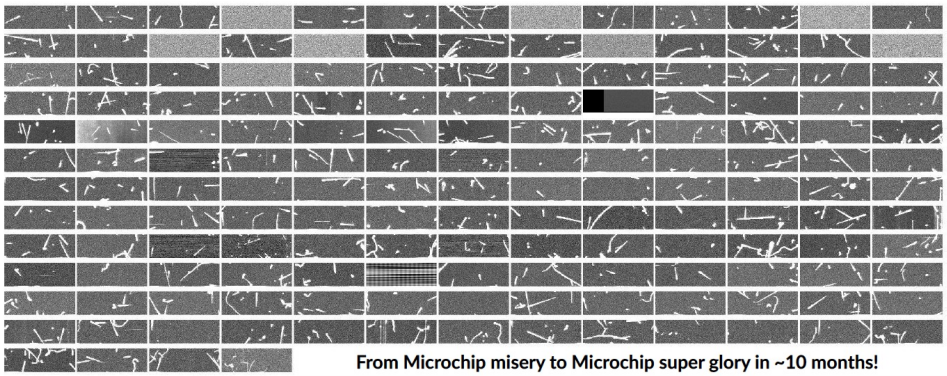


Fermilab

From Sensei to OSCURA

- Active R&D program for OSCURA electronics sensors and cryogenics at Fermilab SiDet lab. A larger facility is planned for Fermilab's IERC building to be completed soon.
- From 50 CCDs in SENSEI to 24,000 in OSCURA. Major effort for sensor packaging, cooling and readout. Electronics per channel cost reduction. Will use ASICs.
- Three orders of magnitude background reduction needed. Limit cosmic ray exposure during packaging and assembly.



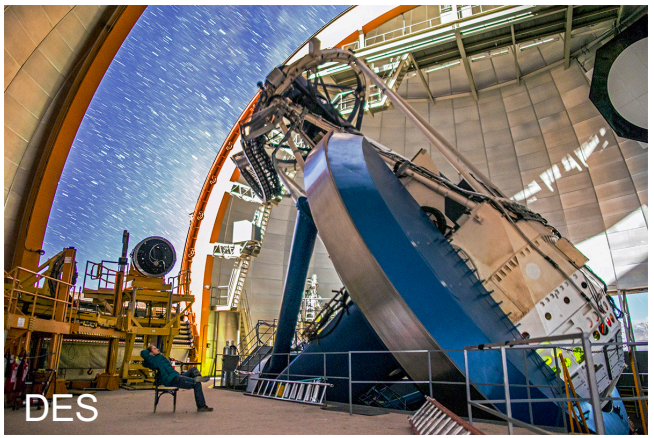


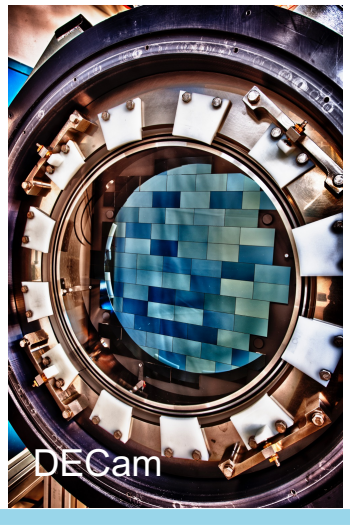
From Microchip misery to Microchip super glory in ~10 months!

- Demonstrated readout of 160 CCDs in 2022.
- Largest Skipper array ever, comparable to LSST camera in scale (189 CCDs)

Dark Energy/ Cosmic Surveys

- Historically, largest Cosmic Frontier group at Fermilab beginning with SDSS. Currently 11 people/ 6 FTEs
- Lead Lab for Dark Energy Survey, now completing analysis of its 6-year, 5100 square degree data set.
- Dark Energy Spectroscopic Instrument (DESI)– major fabrication and installation effort is complete. 5-year survey is underway. Remaining Fermilab effort on spare CCDs, Science Operations, Analysis (~2 FTEs)
- Effort of scientists and computing professionals on DES, DESI is in transition to work on LSST/ DESC. Responsibilities for data processing & analysis leadership.


DES


DECam


DESI

Dark Energy Survey: World Leading Cosmology

With DES survey operations completed in 2019, Dark Energy Camera remains in operation as a user instrument on Blanco telescope and the 500 TB Y6 data set is being processed and analyzed. More than 416 publications to date from Year-3 and Year-6 DES data sets.

- Growth rate of structure and Expansion History:
  - **Galaxy Clustering & Weak Lensing**: FNAL contributes to pipelines for weak lensing shear calculation, for Data Quality efforts, has main responsibility for "Balrog" (a hybrid MC that derives the galaxy detection efficiency), and star/galaxy catalogs , galaxy cross correlations with SPT
  - **Galaxy Cluster Abundances and Mass:** FNAL leads the current Y3 effort to produce the Y3 cosmology results using GPU's.
- Expansion History:
  - **SN1a (standard candles)**: FNAL SCD computing professionals contribute & make calibrated light curves for Hubble Diagram , systematic studies of SN host galaxies
  - **Baryon Acoustic Oscillations (standard rulers)**: FNAL contributes to catalog construction and Data Quality
  - **Optical Counterparts to Gravitational waves (standard sirens) & Detection and follow-up of lensed SN and Quasars (standard clocks)**. FNAL scientists have most leading roles

Top 12 DES Publications by # citations

https://inspirehep.net/ search in literature with text "cn DES" as of Jan 14, 2023. This is also every one with > 250 cites.

1) Many collaborations including DES, "Multi-messenger Observations of a Binary Neutron Star Merger", *Astrophys.J.Lett.* 848 (2017), 2709 citations.
2) DES Collaboration, "Dark Energy Survey year 1 results: Cosmological constraints from galaxy clustering and weak lensing", *Phys.Rev.D* 98 (2018), 043526, 997 citations.
3) A few collaborations including DES, "A gravitational-wave standard siren measurement of the Hubble constant", *Nature* 551 (2017) 85, 876 citations.
4) Fermi-LAT & DES Collaborations, "Searching for Dark Matter Annihilation in Recently Discovered Milky Way Satellites with Fermi-LAT", *Astrophys.J.* 834 (2017) 2, 541 citations.
5) **B. Flaugher, H. T. Diehl** et al., "The Dark Energy Camera", *Astron.J.* 150 (2015) 150, 505 citations.
6) M. A. Troxel et al., "Dark Energy Survey Year 1 results: Cosmological constraints from cosmic shear", *Phys.Rev.D* 98 (2018), 043528, 505 citations.
7) DES Collaboration, "The Dark Energy Survey: more than dark energy – an overview", *Mon.Not.Roy.Astron.Soc.* 460 (2016), 1270, 492 citations.
8) DES Collaboration, "Dark Energy Survey Year 3 results: Cosmological constraints from galaxy clustering and weak lensing", *Phys.Rev.D* 105 (2022), 023520, 388 citations.
9) **M. Soares-Santos** et al., "The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera", *Astrophys.J.Lett.* 848 (2017), L16, 380 citations.
10) K. Bechtol, **A. Drlica-Wagner** et al., "Eight New Milky Way Companions Discovered in First-Year Dark Energy Survey Data", *Astrophys.J.* 807 (2015), 50, 330 citations.
11) DES Collaboration, "The Dark Energy Survey Data Release 1", *Astrophys.J.Suppl.* 239 (2018), 18, 320 citations.
12) **A. Drlica-Wagner** et al., "Eight Ultra-faint Galaxy Candidates Discovered in Year Two of the Dark Energy Survey", *Astrophys.J.* 813 (2015), 109, 273 citations.

Sample of 12 DES Papers from 2022 FNAL scientists

E. Zaborowsky, A. Drlica-Wagner et al., "**Identification of Galaxy-Galaxy Strong Lens Candidates in the DECam Local Volume Exploration Survey Using Machine Learning",** https://arxiv.org/abs/2210.10802

DES Collaboration, "Dark Energy Survey Year 3 results: Constraints on extensions to ΛCDM with weak-lensing and galaxy clustering", https://arxiv.org/abs/2207.05766

DES Collaboration, "**Joint analysis of DES Year 3 data and CMB lensing from SPT and Planck III: Combined cosmological constraints",** MNRAS 518, 5340 (2023), https://arxiv.org/abs/2206.10824

C. Meldorf, A. Palmese et al., "**The Dark Energy Survey Supernova Program results: Type Ia Supernova brightness correlates with host galaxy dust",** MNRAS 518, 1985 (2023) , https://arxiv.org/abs/2206.06928

R. Morgan, B. Nord et al., "**DeepZipper II: Searching for Lensed Supernovae in Dark Energy Survey Data with Deep Learning"**, accepted by ApJ, https://arxiv.org/abs/2204.05924

J. Sanchez et al., "**Mapping gas around massive galaxies: cross-correlation of DES Y3 galaxies and Compton-*y*-maps from SPT and** *Planck",* https://arxiv.org/abs/2210.08633

A. Drlica-Wagner et al., "**The DECam Local Volume Exploration Survey Data Release 2**", ApJS 261, 38 (2022), https://arxiv.org/abs/2203.16565

S. Mau et al., "**Milky Way Satellite Census. IV. Constraints on Decaying Dark Matter from Observations of Milky Way Satellite Galaxies",** ApJ 932, 128 (2022), https://arxiv.org/abs/2201.11740

Z. Zhang, H. Wu, Y. Zhang et al., "**Incorporating galaxy cluster triaxiality in stacked cluster weak lensing analyses",** https://arxiv.org/abs/2202.08211

R. Morgan, B. Nord et al., "**DeepZipper: A Novel Deep Learning Architecture for Lensed Supernovae Identification**", ApJ 927, 109 (2022), **https://arxiv.org/abs/2112.01541**

J. H. O'Donnell, R. D. Wilkinson, H. T. Diehl et al., **"The DES Bright Arcs Survey: Candidate Strongly Lensed Galaxy Systems from the Dark Energy Survey 5,000 Sq. Deg. Footprint**", ApJS 259 (2022), 27, https://arxiv.org/abs/2110.02418

V. R. Chintalapati, G. Gutierrez, M. H. L. S Wang, "**A Systematic Study of Projection Biases in Weak Lensing Analysis**", PRD, 105 (2022), 043515, https://arxiv.org/abs/2108.11518

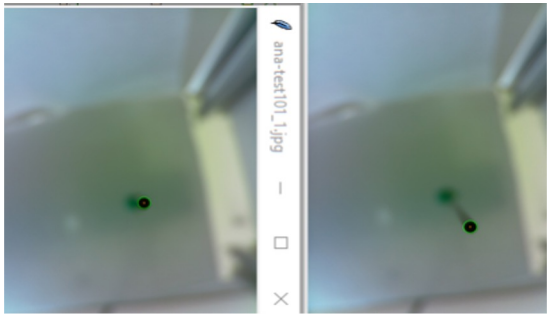
Transition of DES Effort to Rubin/DESC

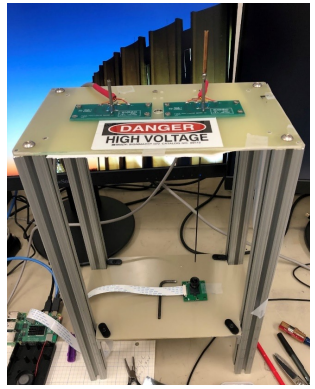
- Carry forward DES expertise to Rubin Operations and Science.
- Fermilab roles in Rubin & DESC Science and Operations
  - Data production and release scientists (Yanny, Lin, Paterno)
  - System Performance Scientists (Nord, Drlica-Wagner, Annis)
  - Science working group leadership (Drlica-Wagner, Annis, Tucker)
  - DESC Pipeline Scientist roles (Lin, Paterno, Buckley-Geer)
  - Machine learning (Nord, Ciprijanovic)
  - DESC Operations committee, Publication Board infrastructure (Drlica-Wagner)
- FY23: ~2 scientists FTEs + 6 FTE computing professionals (data production team)
- Plan to complete rollover of staff from DES to Rubin/ DESC by FY25.

Beyond LSST: Stage 5 Spectroscopic Survey

- Spectroscopic galaxy survey with order of magnitude larger throughput than DESI.
  - Measure 100 Million galaxy redshifts.
  - Achieved with larger telescope, larger number of fibers and spectrometers.
  - Infrared photosensors may extend sensitivity to Z~5.
- Fermilab R&D towards spectrometer components (fiber positioners, Skipper CCDs)
- **New--** Participation with Carnegie Observatory, LBNL, Berkeley Space Science in 2023 NSF proposal to design "**Megamapper**".

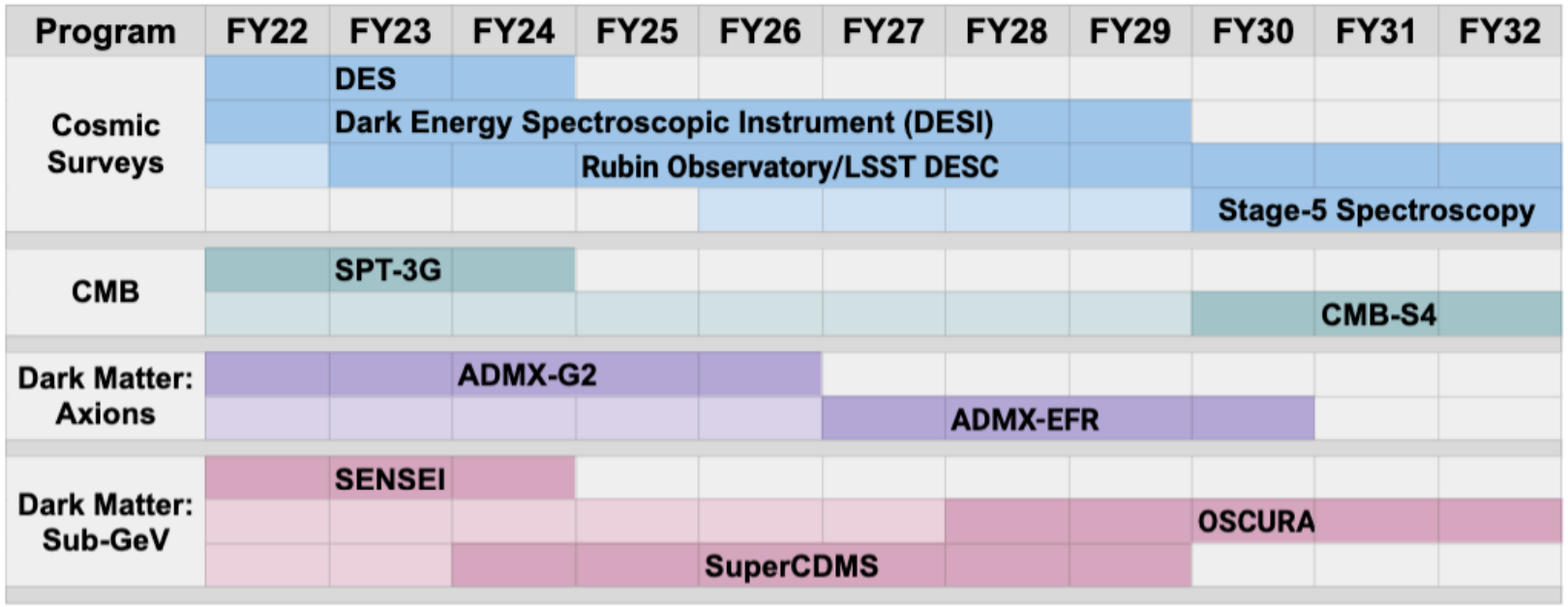
Parameter	DESI-II	MegaMapper	MSE	SpecTel
Telescope aperture diameter (m)	4	6.5	11.25–14	11.4
Field-of-view (deg^2)	8.94	7.06	1.52	4.91
Number of fibers	5000	20000	4332–21000	15000–60000
Spectral resolution $\lambda/\delta\lambda$	3000	4000	5000/20000	4000/40000
Wavelength range (μm)	0.36-1.0	0.36-1.0	0.36-1.8	0.36-1.3
Site location	US/Arizona	Chile	US/Hawai'i	Chile
Total project cost	low	medium	high	high
Expected US contribution	low	medium	medium	unknown
Timescale	near	medium	medium	long





Piezoelectric "tilting spine" fiber positioner LDRD (PI: Tom Diehl)

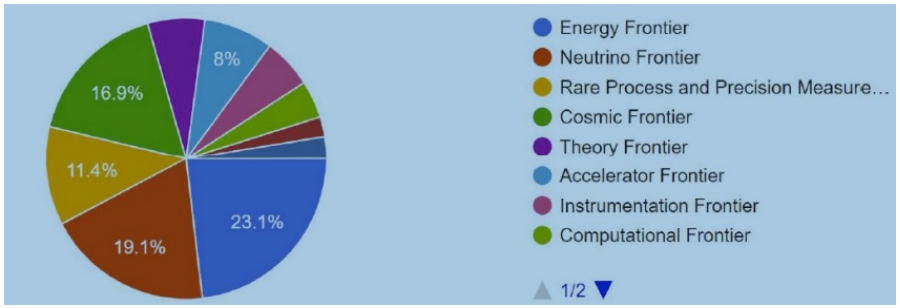
Summary Timeline for Fermilab's Cosmic Projects



Fermilab

Snowmass 2021

- Vitality of Cosmic frontier subfield was evident: Many attendees, white papers, presentations.
- Large number of science opportunities.
- Fermilab scientists highly engaged– Five cosmic frontier scientists were topical group convenors.
- Fermilab Scientist Aaron Chou was Co-Convenor of Cosmic Frontier with Marcelle Soares-Santos and Tim Tait.
- Snowmass summary reports show a close alignment between Fermilab's current strategic priorities and the priorities of the larger community.



Three Opportunities Highlighted by Snowmass

- Stage 5 spectroscopic galaxy survey in 2030s.
  - Broad community interest in a spectroscopic survey with order of magnitude larger throughput than DESI.
- Wide ranging direct searches for wave-like and particle-like dark matter.
  - Fermilab aims to be at the forefront in exploration of new quantum technologies for dark matter searches, including searches for the QCD axion over a wide mass range and particle-like dark matter with masses below that of a proton. The Dark Wave Lab would be a new central focus for this work at Fermilab.
- WIMP search to neutrino floor provides an opportunity to re-engage.
  - Fermilab possesses unique expertise and testing facilities for the development of liquid noble TPCs and bubble chambers. Participation in current generation experiments was curtailed due to budget shortfalls and loss of key personnel. We would consider a strategic re-engagement our program if such a search is prioritized by P5.

Summary

- Cosmic program capitalizes on Fermilab's unique strengths and deep talent pool.
- We made a good start on implementing our 2019 strategic plan, including:
  - Creation of a strong CMB group and development of critical project roles in CMB-S4 based on our areas of technical strength.
  - Advancement of plan to host next generation axion experiment (ADMX-EFR)
  - Completion of R&D for 10 Kg OSCURA experiment.
  - Development of roles in LSST/ as staff transition from DES, DESI.
- Quantum sensors funding has grown at a rate far exceeding what we expected in 2019. May be transformative for dark matter searches.
- High level of engagement in Snowmass. Fermilab program is very closely aligned with community goals.