



# Fermilab's Cosmic Program, CMB and Axion Dark Matter

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Users Meeting

11 July 2024

# 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.

*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.*

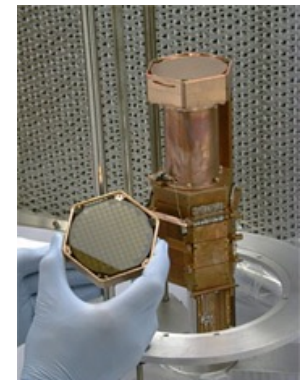
*- Rocky Kolb, AIP Oral History, 2020.*



John Peoples at Apache Point w/ SDSS



Rocky

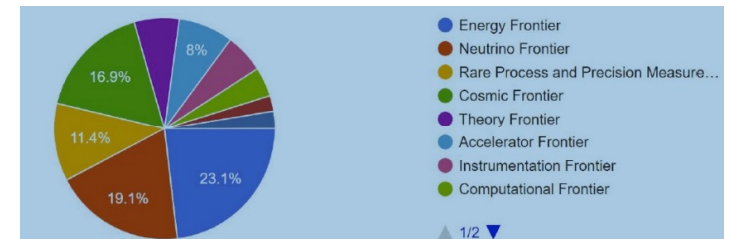


CDMS-I, mid-1990s



# Post Snowmass Vision for Cosmic Frontier

- **Dynamism and vitality of Cosmic Frontier** were on display at Snowmass:
  - Large **diversity of physics topics and methods.**
  - Opportunities to do **transformational science**, within **reasonable time frames** and at relatively **modest cost.**
- A significant fraction of HEP community is in the growing Cosmic subfield: now about the **same size as Energy and Intensity/ Neutrino** and continuing to grow.
- Shift of HEP center of gravity towards Cosmic Frontier?
- Fermilab scientists are highly engaged - **we want Fermilab to continue to have a central role** in the exciting Cosmic frontier science of the 2030s.



## P5 Cosmic Recommendations Vs Fermilab Program

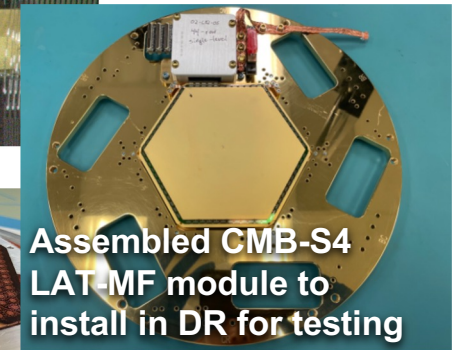
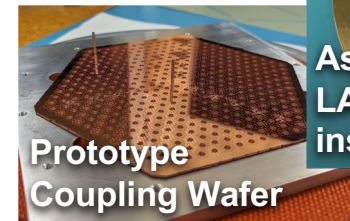
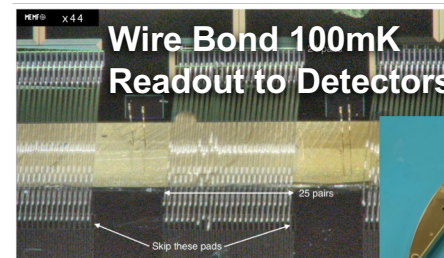
Recommended project	Fermilab Plan	Comments
CMB-S4	✓	Highest priority 2019 plan
Continued operations: ADMX-G2, DESI Rubin/LSST, SuperCDMS, SPT-3G	✓	Top near-term priority
Operations: LZ, DarkSide-20K	✗	
DESI-II and R&D for Spec-S5	✓	
DMNI and ASTAE Small Projects	✓	Opportunities for Fermilab leadership: ADMX-EFR, OSCURA and Dark Wave Lab
G3 Dark Matter	✗	
IceCube Gen 2	✗	

## “Cosmic Day” Meeting of Cosmic Physics Center

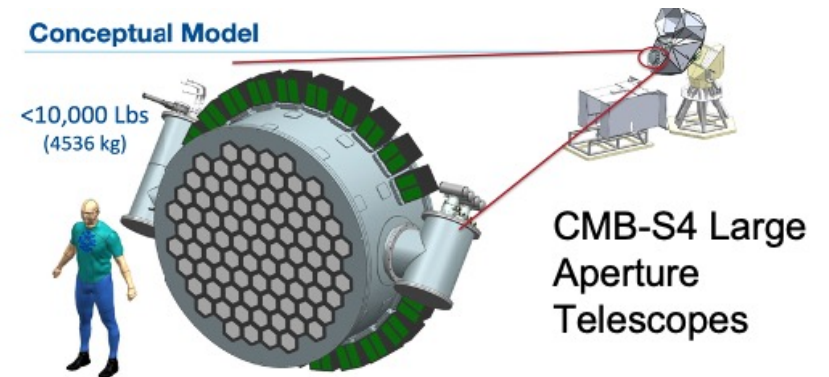
- For a more complete view of Fermilab’s program, we recommend slides from “Cosmic Day” meeting of the Cosmic Physics Center in Fall 2023.  
<https://indico.fnal.gov/event/61765/>
- We plan to repeat this in again in late 2024. **You are invited.** If you would like to be on the Cosmic Physics Center email list, please write to me  
[Sonnenschein@fnal.gov](mailto:Sonnenschein@fnal.gov).
- The rest of this talk focuses on:
  - Cosmic Microwave Background research at Fermilab, including CMB-S4
  - Axion dark matter detection, including ADMX-EFR and the Dark Wave Lab

# CMB-S4 at FNAL

- CMB-S4 will be the most sensitive CMB experiment to date, requiring 500,000 bolometer pixels in ~400 modules.
- Original plan called for arrays of small and large aperture telescopes deployed in both Chile and at South Pole.
- Fermilab's major role will production and cryogenic testing of detector modules at unprecedented scale- requires 8 large dilution fridges for 5 years.
- Team has built and tested prototype modules.



## Conceptual Model



# Delays and Restructuring of CMB-S4

- NSF decision in May 2024: Design Proposal for CMB-S4 cannot move forward with plan that involves construction at South Pole.
- Logistical and infrastructure deficiencies, no new experiments at South Pole for some time.
- DOE and NSF: CMB-S4 experiment needs to be restructured around a single site in Chile
- Starting up task force to study Chile-only option. Includes Fermilab scientists working on data simulation and observation strategy.
- DOE and NSF emphasize that they remain committed to CMB science.



Jean Cottam Allen talk at May HEPAP

# South Pole Telescope (SPT): SPT-3G Status



## • Two Primary Surveys

- **Main 1,500 deg<sup>2</sup> survey:** Advance inflation science working with the BICEP Array (or South Pole Observatory / SPO)
- **Ext-10k 10,000 deg<sup>2</sup> survey:** Will produce world-leading cosmological results, summarized in [Prabhu et al 2024](#)

## • Science and Status

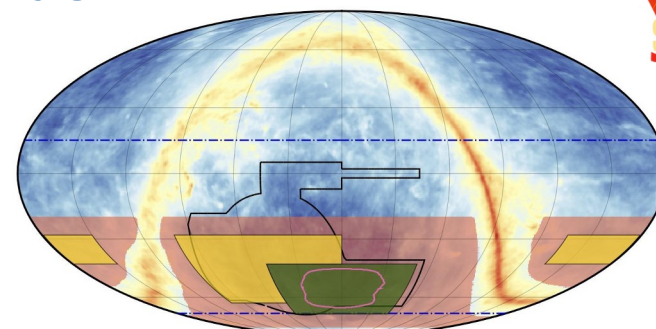
- SPT & SPT-3G camera continues to perform extremely well.
- 2024: Ext-10k survey completes, 2025: Main survey restarts.
- In past 12-mos, produced 33 publications and 5 PhD theses.

## • Future

- Impact of NSF's CMB-S4 decision on SPT-3G: *"NSF is committed to cosmic microwave background science and will continue to support current CMB activities at the South Pole and in Chile"*
- See next slide

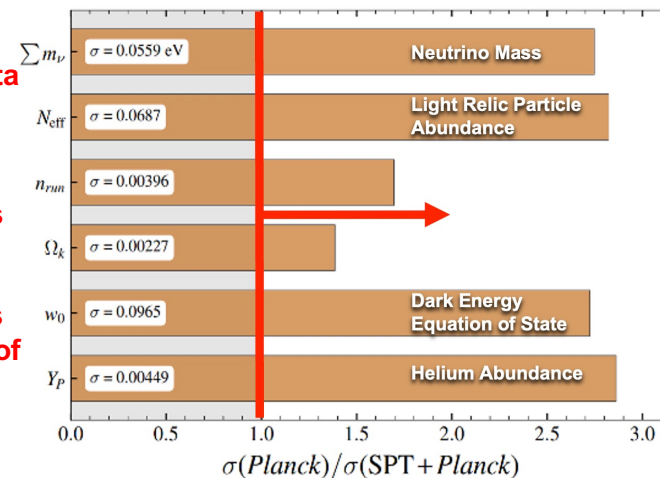
## • FNAL Roles

- Benson (Director of Operations, NSF Co-PI). Anderson (PI: SPT-SLIM). Postdocs: Saunders, Sobrin, Young, Zebrowski leading (or major roles) in several SPT-3G science analyses.



■ SPT-3G Main    ■ SPT-3G Summer    ■ SPT-3G Wide  
--- SO/LSST    --- BICEP3    --- DES

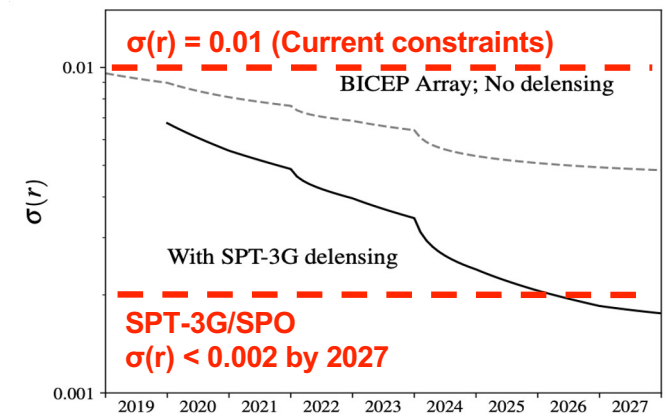
**SPT-3G data improves CMB cosmology constraints on many individual parameters by factors of ~2-3**





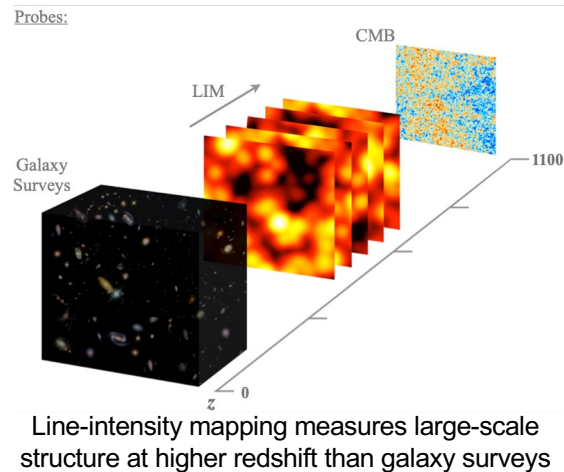
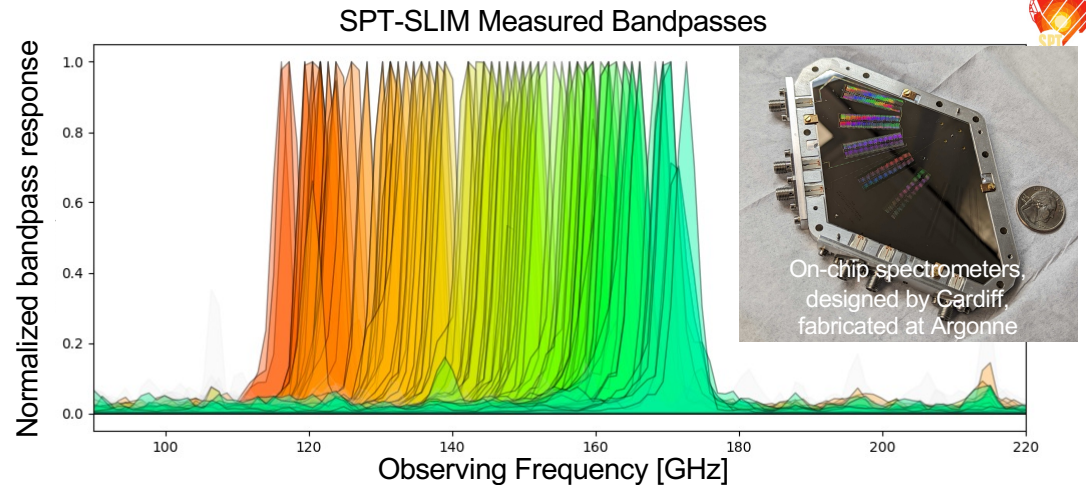
# SPT Future Plans

- SPT-SLIM deployment in 24-25 Austral summer:
  - SPT-SLIM is a pathfinding millimeter wave line intensity mapping (LIM) experiment, aiming to take to demonstrate the mm-wave LIM technique, detectors, and instrumentation (see next slide).
- SPT “South Pole Telescope Operations and Data Products” (M&O) NSF proposal is pending (funds SPT through 2029):
  - **SPT-3G**: Proposes to continue SPT-3G observations and support EHT observations on SPT through at least end of 2026.
  - **SPT-3G+**: Proposes SPT-3G+ camera upgrade in 2027 at the earliest.
- **SPT-3G+ NSF MRI proposal is pending**:
  - Hardware proposal to support camera upgrade to SPT-3G+, including an initial focal plane to extend SPT frequency coverage (~300 GHz)
  - SPT-3G+ camera will be an adaptable platform for future focal planes, expanding on either: a) SLIM intensity mapping or b) Inflation/delensing science with SPT-3G / South Pole Observatory (SPO)
  - Related detector and readout development also supported by DOE KA25 at FNAL.



# SPT-SLIM

- Demonstrate the mm-wave Line Intensity Mapping (LIM) technique with on-chip spectrometers.
- Detect CO emission line over redshifts 0.5-2.
- Applications to measuring inflation model parameters from observations of large-scale structure.
- World's most advanced mm-wave on-chip spectrometer array using kinetic inductance spectrometer array using kinetic inductance detectors (KIDs) with 1024x multiplexing KID readout electronics.
- *Deployment in Nov 2024* – Fermilab postdocs and scientists preparing to deploy to South Pole this fall!
- Support from Fermilab LDRD (PI: Adam Anderson), KA-25 and NSF through U. Chicago grant.



Line-intensity mapping measures large-scale structure at higher redshift than galaxy surveys

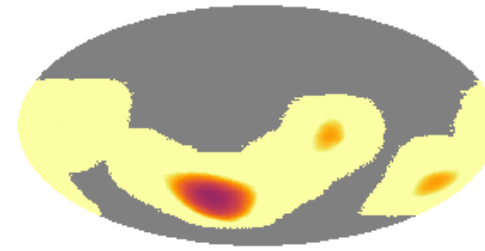


# CMB-S4 at FNAL: Data Simulation



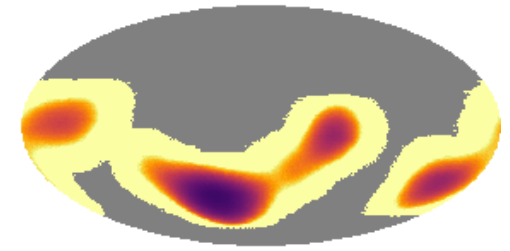
- **Key role in task force focused on re-optimizing design for Chile-only configuration + previous Analysis of Alternatives tiger team (L3 Simon)**
  - Lead of observation strategy group that will develop survey strategies and efficiencies for optimized Chile design
  - Codify instrument configuration into simulation framework and provide common simulations for forecasting
- **Reducing survey time in Chile will likely require additional systematic risk**
  - Developing next-generation calibration equipment and improved systematic simulations for mitigation of systematic effects in CMB experiments via LDRD (PI Simon)

CHSAT-S4 baseline+HWP



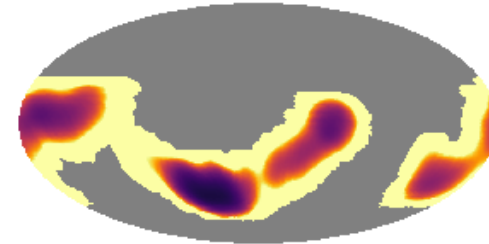
0.3  $\mu\text{K}\cdot\text{arcmin}$  2.4

CHSAT-S4 aggressive+HWP



0.3  $\mu\text{K}\cdot\text{arcmin}$  2.4

CHLAT-S4 delensing

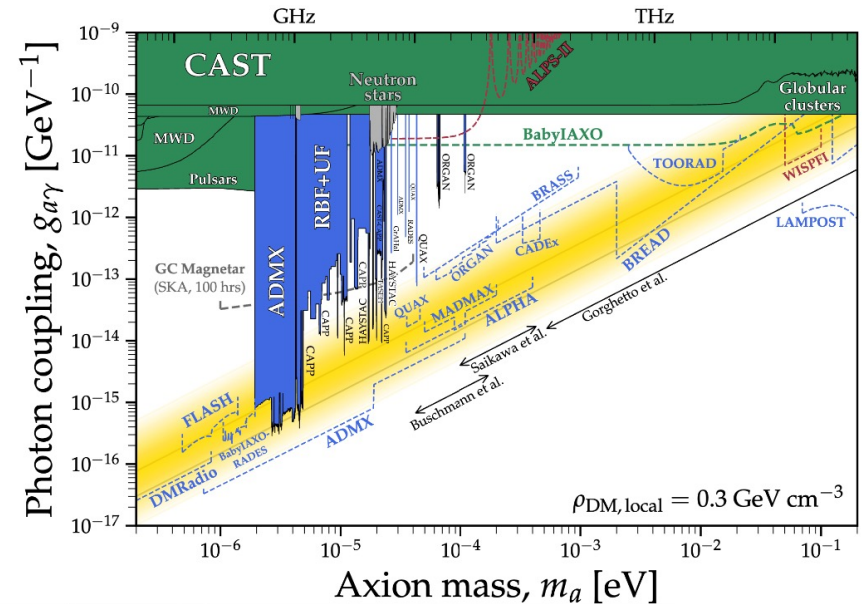


0.3  $\mu\text{K}\cdot\text{arcmin}$  2.4

Simulated Chilean Performance from  
Analysis of Alternatives Study

# Emerging Scientific Opportunity: 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.



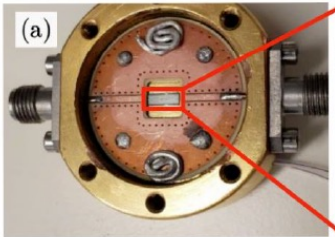
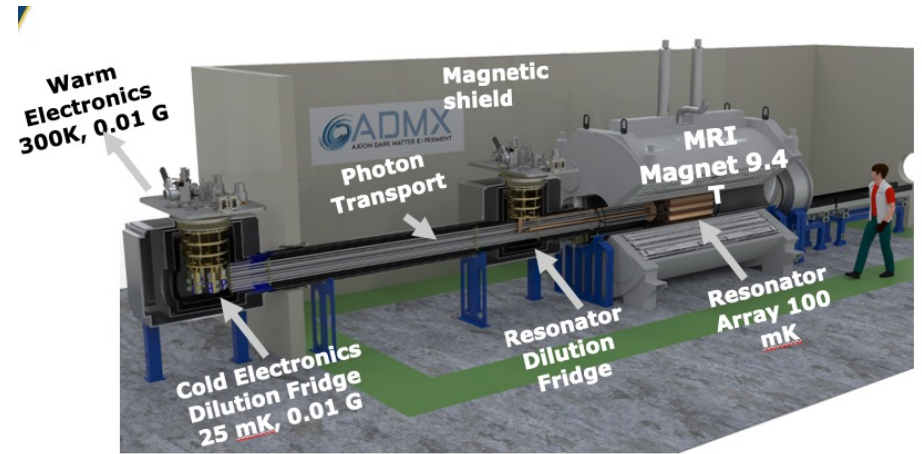
*Proposed detection techniques span allowed mass range for QCD axion dark matter.*

<https://cajohare.github.io/AxionLimits/>

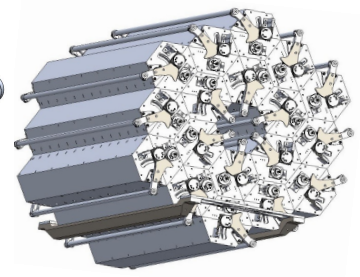
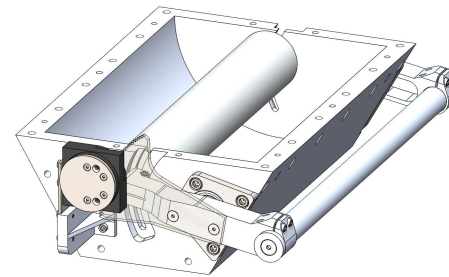
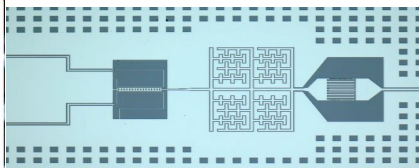
- Important strategic opportunity- progress will be driven by technologies closely related to Fermilab capabilities in quantum sensors, cryogenics, magnets.

# The Next Generation ADMX-EFR Axion Search at Fermilab

- 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 arrived on June 24<sup>th</sup>!

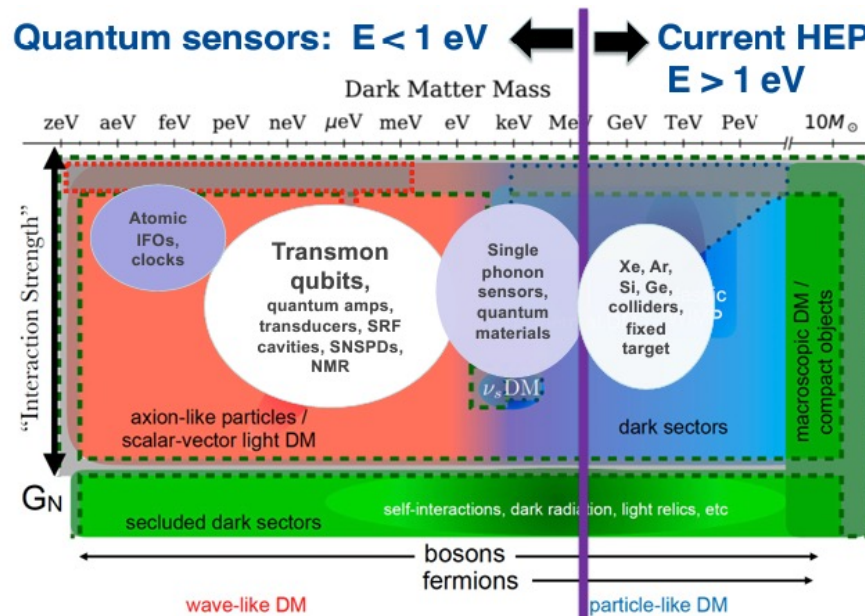


Josephson Parametric Amplifier

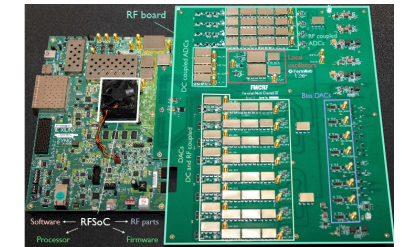
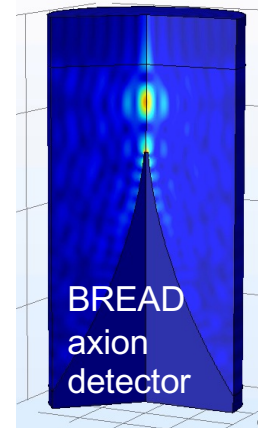


18-cavity resonator array

# Fuzzy Boundary Between Quantum and Cosmic Research



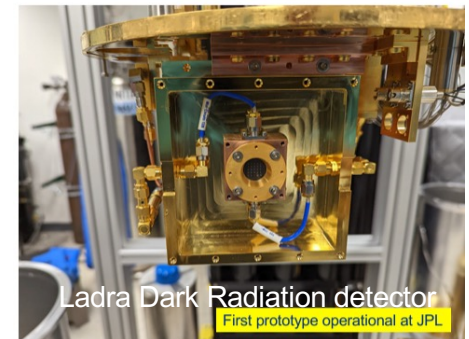
Cartoon from Snowmass  
Aaron Chou



QICK (Quantum Instrumentation Control Kit) for Astro applications



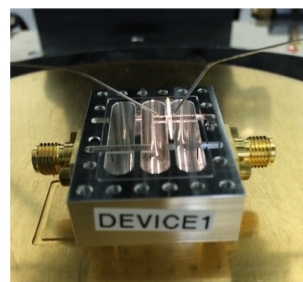
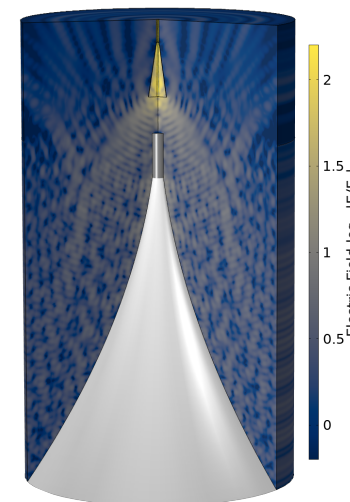
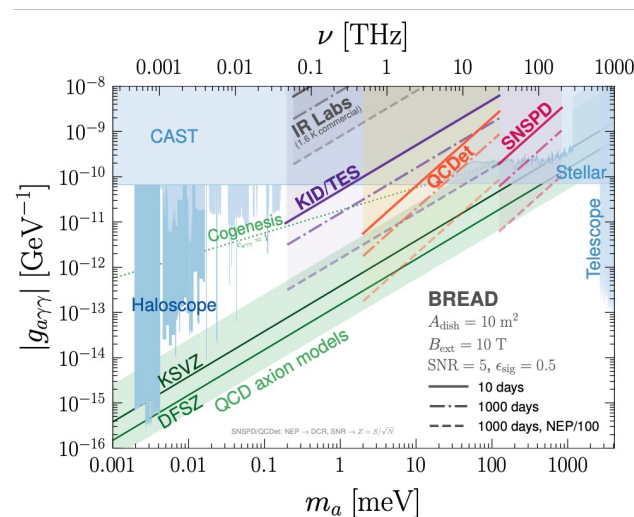
SQUAD axion detector with qubits



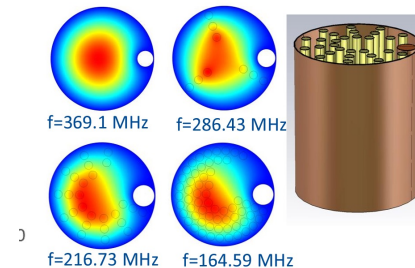
Ladra Dark Radiation detector

# 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

## Proposal: Dark Wave Laboratory at Fermilab

- We propose to provide a facility able to host several small scale and at least one larger scale axion search experiment.
- We will begin by installing the 9.4 Tesla MRI magnet selected for the ADMX-EFR experiment. This magnet is significantly larger than needed for the ADMX-EFR detector alone and, with careful planning, may host one or more smaller additional experiments.
- The cryogenic system and magnetic shielding will also be planned to allow for additional experiments.
- The Dark Wave Lab will include shop, assembly and testing areas and will have robust, reliable infrastructure for operating cryogenic equipment.
- A mechanism will be put in place for proposal of new experiments to share space in the magnet.
- Over time, responding to identified needs, additional magnets and cryostats will be installed in the Dark Wave Lab.



## 9.4 Tesla MRI Magnet from University of Illinois, Chicago

- ADMX-EFR will reuse a 45-ton, 9.4 Tesla, 800 mm bore MRI magnet currently at University of Illinois Chicago medical center. Was world's highest field whole-body MRI magnet when installed in 2003.
- Arrived at Fermilab on June 23.
- Will install and commission over next year.

	ADMX-G2 Magnet	ADMX-EFR Magnet
Peak Field	7.6 T	9.4 T
Bore diameter	530 mm	800 mm
Magnet length	1117 mm	3100 mm
Cryostat diameter	1295 mm	2580 mm
Stored Energy	16.5 MJ	140 MJ
Weight	6 tons	45 tons
Helium consumption	3 liters/ hour	0.35 liters/hour
Current	204 Amps	220 Amps
Persistent current	No	Yes
Orientation	Vertical	Horizontal
Manufacturer	Wang NMR	GE Medical Systems
Manufacture date	1993	2003



Magnet arrives at PW8



# Dark Wave Lab Workshop April 15-16 2024

- We held a very successful workshop in April <https://indico.fnal.gov/event/63051/>
- Goals:
  - Assessment of community interest in common facilities.
    - What experiments would likely be proposed and what facilities are needed for them?
    - Gather material for White Paper and presentation to Fermilab Physics Advisory Committee.
  - Identify best near-term uses (2025- 2028) for 9.4 Tesla MRI magnet with bore at room temperature or 4 kelvin.
  - Form new experiment collaborations & expand the field of potential Dark Wave Lab users.



~80 participants from US and international labs and universities

## Early projects for Dark Wave Lab

- We identified ~10 projects that could go into the 9.4 Tesla MRI magnet before the start of ADMX-EFR.
- Most not sensitive to QCD axion band but would search for ALPs while developing detector technologies.
- Significant interest in tests with room temperature magnet bore– could start as soon as 2025.
- Some groups are ready now– have room temperature prototypes operating without a magnetic field.
- 4 Kelvin experiments beginning in 2027.
- 100 mK experiments in parallel with ADMX-EFR as soon as 2028– depends on DMNI funding timeline.

Experiment	Collaboration	Type	Room Temp ?	4 Kelvin
ADMX-EFR	ADMX	Cavity	✓	✓
<u>GigaBREAD</u>	BREAD	Dish	✓	✓
ADMX-SLIC	Florida + ?	LC	✓	✓
ADMX-VERA	Stanford, Washington, LLNL	Cavity	✓	✓
Orpheus	Washington	Dielectric Disc	✓	✓
MADMAX prototype	MADMAX	Dielectric Disc	✓	✓
ORGAN	<u>UWa</u> , Swinburn	Reentrant cavity	✓	✓
TBD	Florida + <u>UWa</u> + Swinburne?	Reentrant cavity	✓	✓
SC Cavities 2-10 GHz	SQMS, CAPP?	Cavity		✓
Large 300 MHz Cavity	ADMX?	Cavity	✓	✓

## Conclusion

- Cosmic frontier is very exciting right now– includes small and medium sized projects that can address fundamental physics issues within reasonable time and budget envelopes.
- I highlighted work on CMB and Axion searches. Apologies that I was not able to cover the whole program here.
- Sho Uemura is covering searches for dark matter other than axions.
- Excellent talks from "New Perspectives" on Dark Energy Survey, CMB, AI/ML applications to cosmology.
- "Cosmic Day" meeting has a more comprehensive set of talks.