Dark Matter New Horizons

Fermilab Users Meeting

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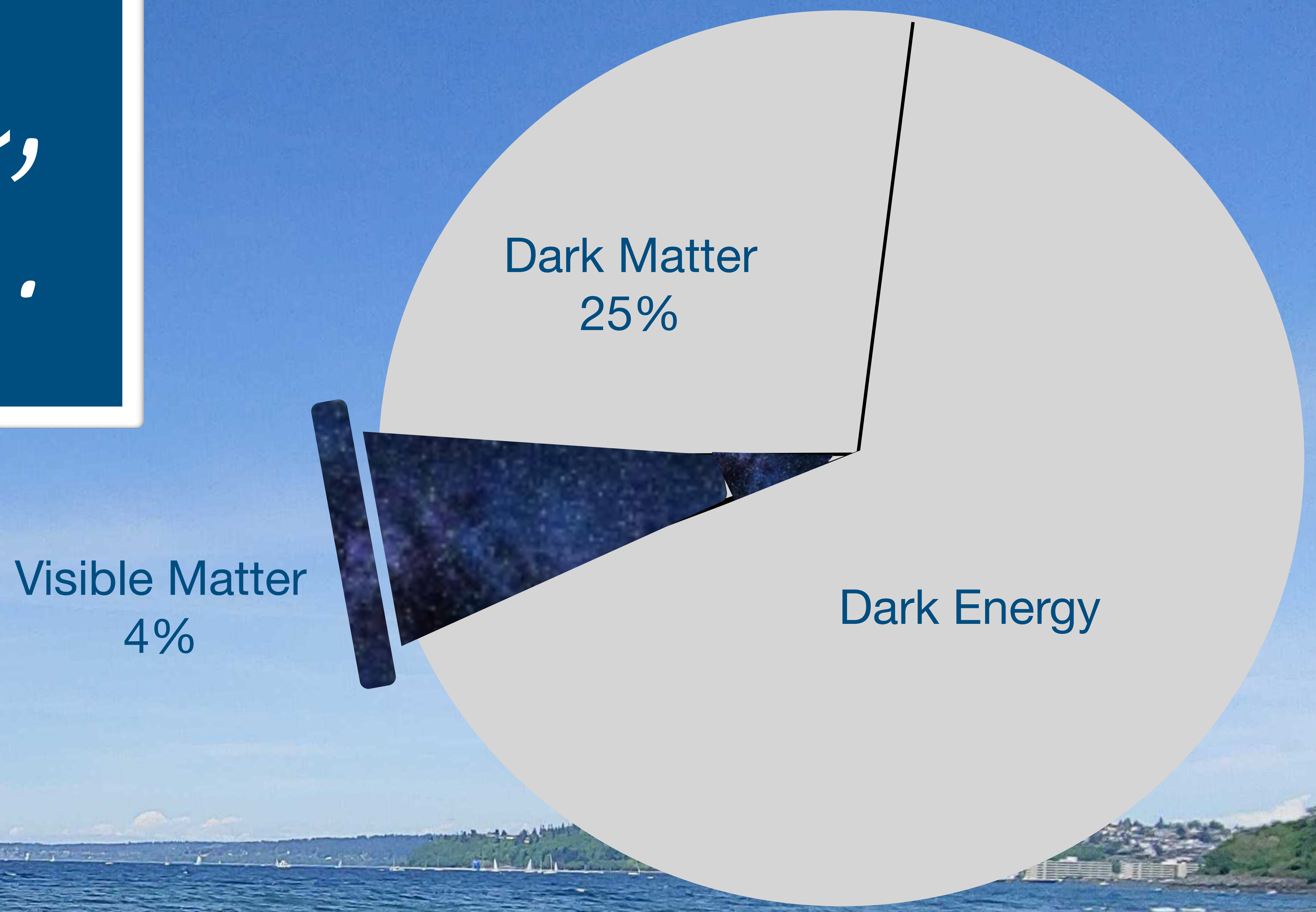
University of Washington
08/03/2021

Fermilab

Matter, matter everywhere, but not enough, we think...

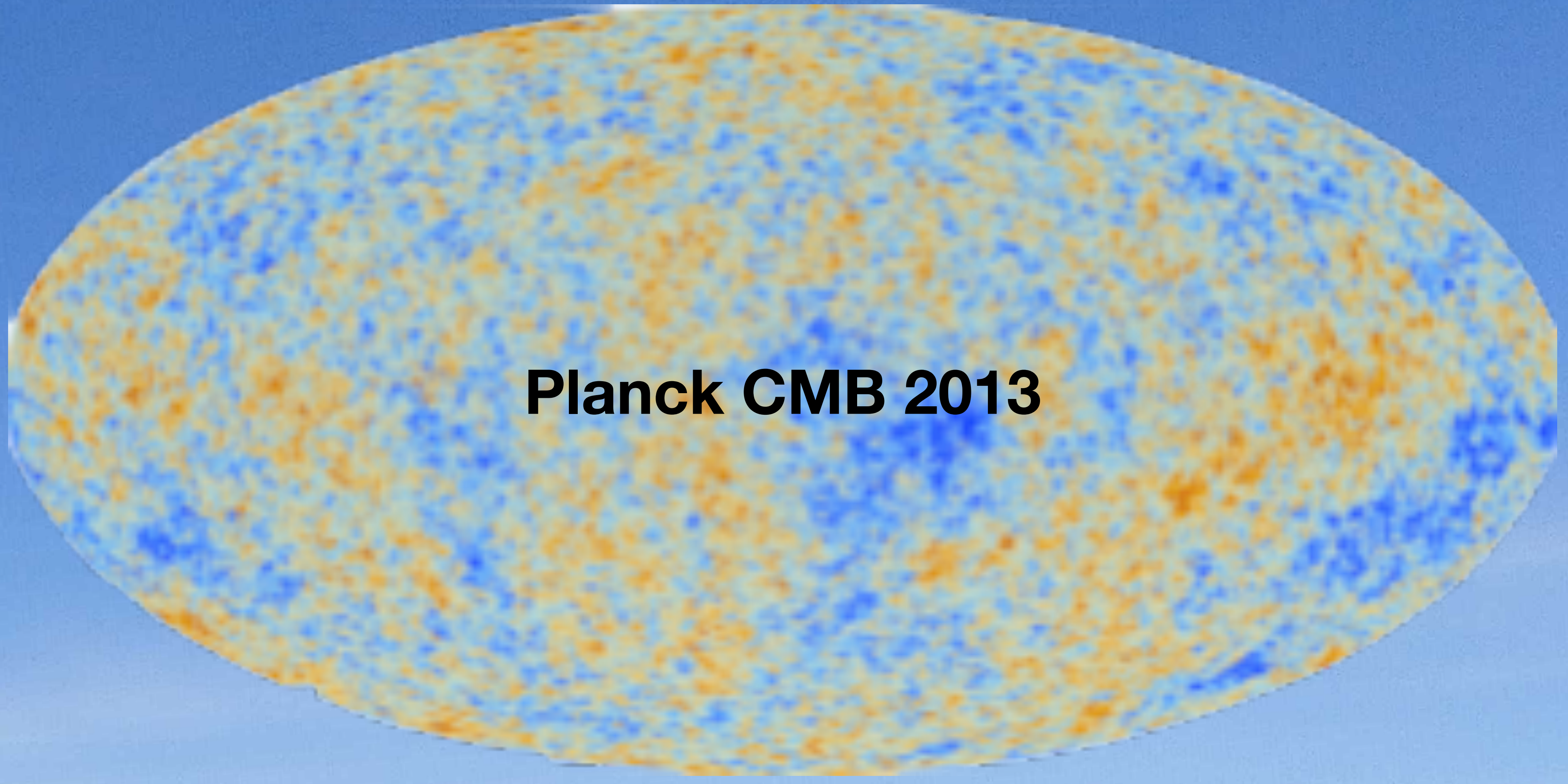
- **Indirect observations tell us:**
  - **Dark matter concentrated near galaxies**
  - **Interacts via gravity, unclear if other interactions**
  - **Cold (non-relativistic)**
  - **Feebly interacting**
  - **Very stable**
  - **Non-baryonic**

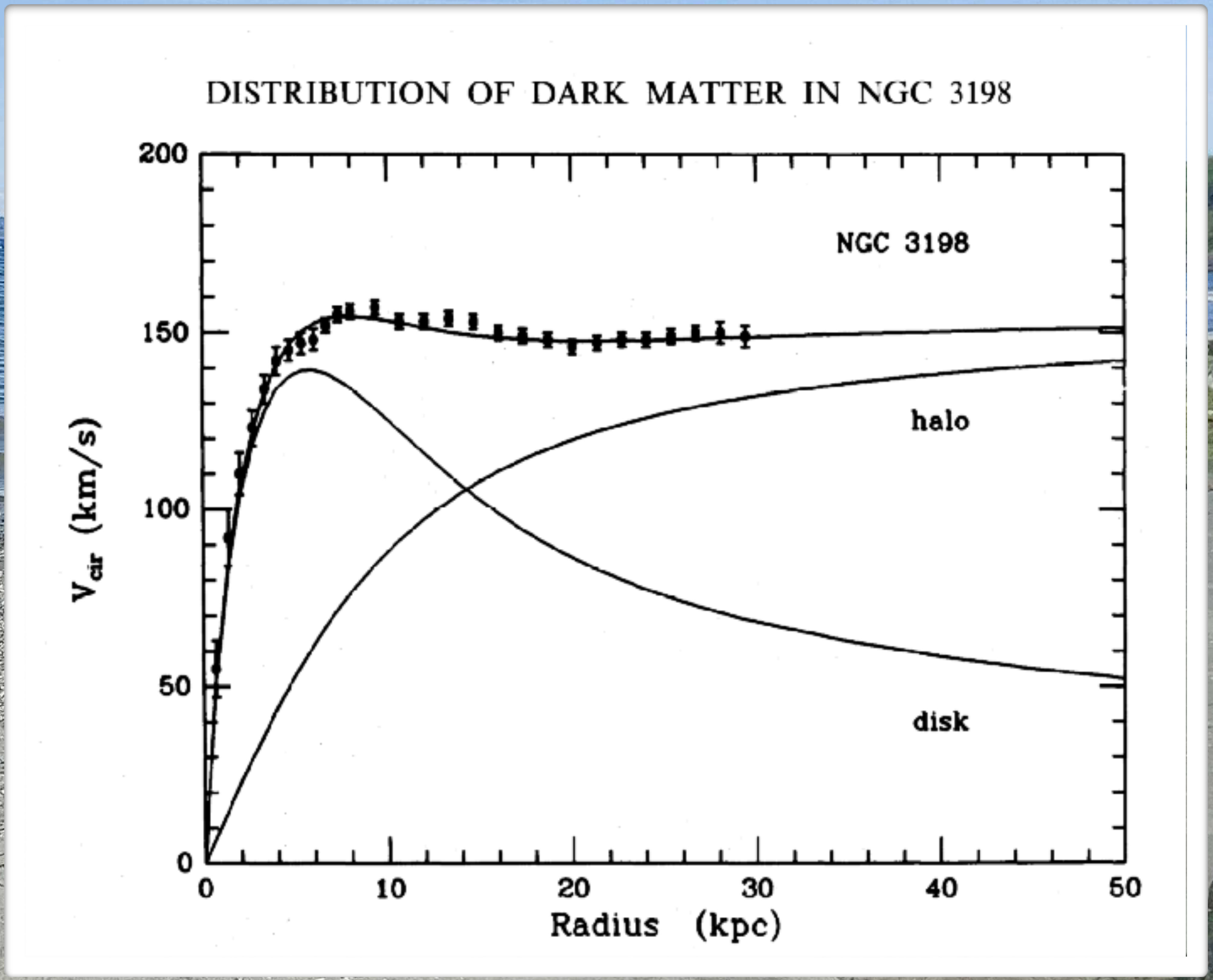


Vera Rubin at her telescope

An abundance of evidence

- Galactic rotation curves
- Gravitational Lensing
- Primordial Matter Fluctuations
- Baryon acoustic oscillations
- Matter-radiation fluctuations
- Galaxy cluster collisions
- Primordial nucleosynthesis
- Cosmic Microwave Background





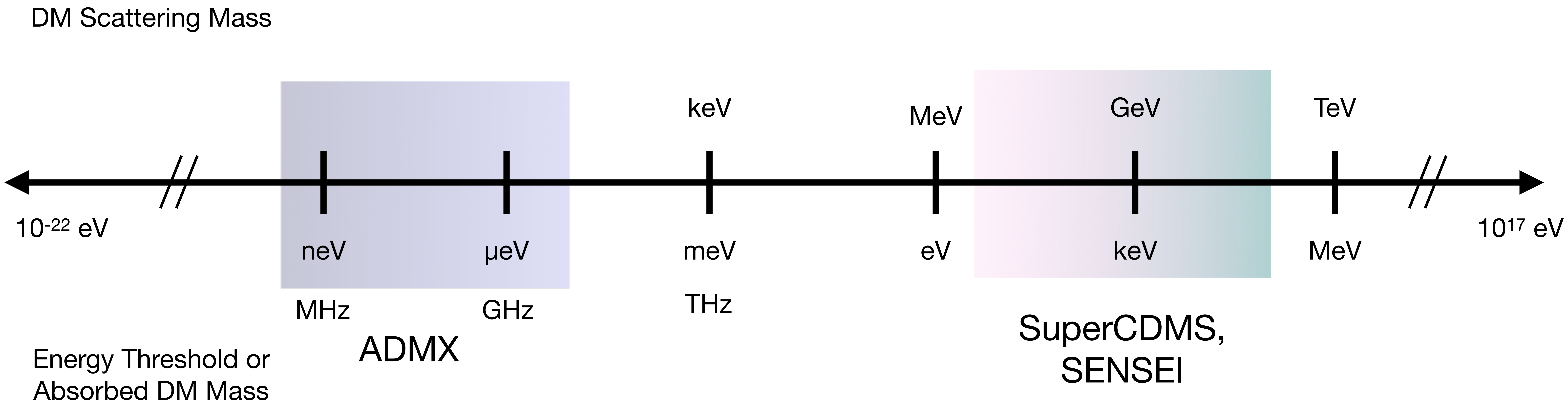
Fermilab Dark Matter Searches

ADMX

SuperCDMS

SENSEI/
OSCURA

Fermilab Dark Matter Searches



Axion, Axion-Like and Wave-like Dark Matter

Particulate Dark Matter (Weakly-Interacting Massive Particles or WIMPs)

SuperCDMS SNOLAB

CDMS: Cryogenic Dark Matter Search

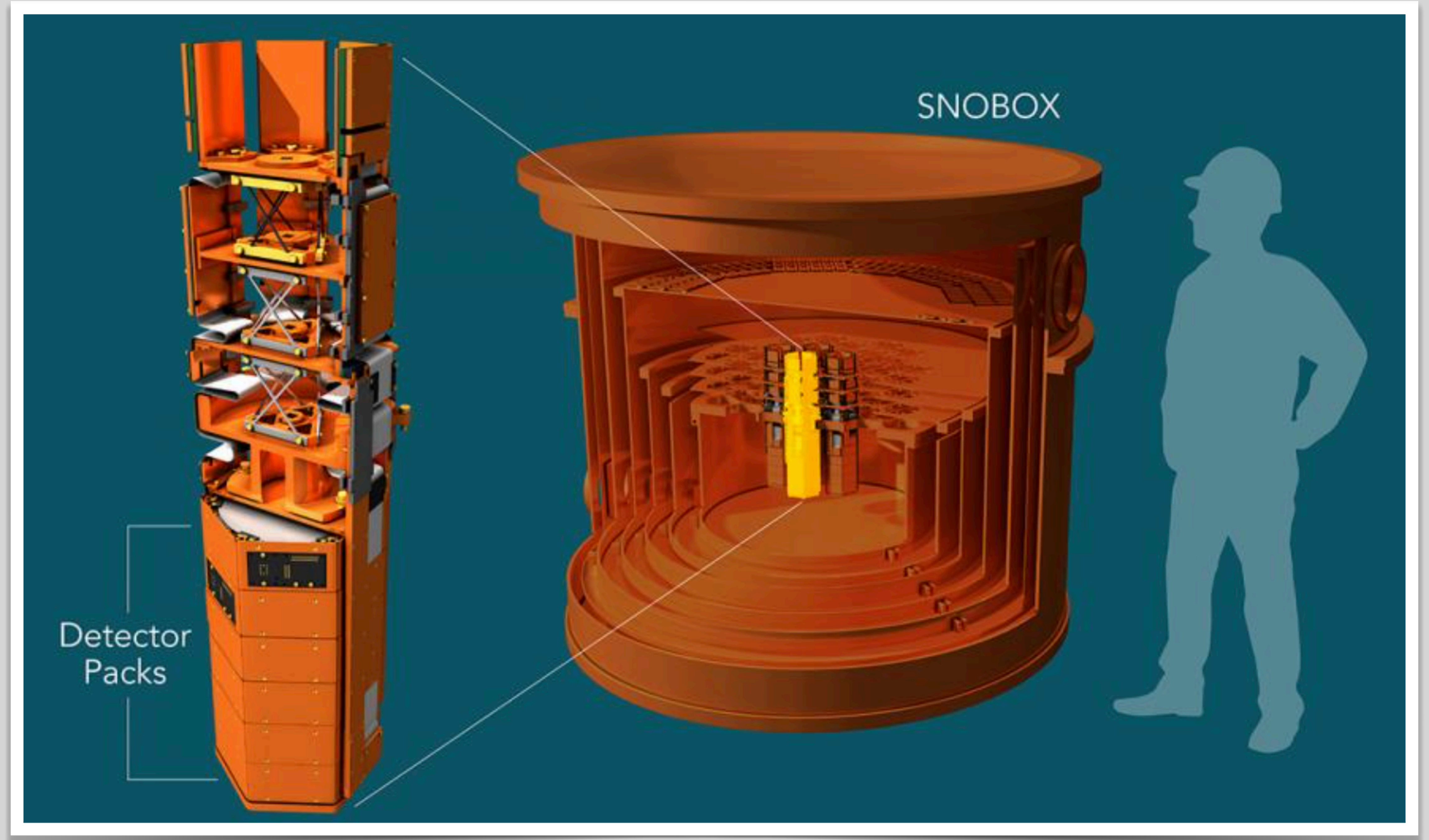
CDMS ⟶ SuperCDMS (Soudan) ⟶ CDMSlite (Soudan) ⟶ SuperCDMS (SNOLAB)

- WIMP dark matter search looking for nuclear recoil signal (spin-independent interactions).

- SuperCDMS SNOLAB will build off the success of CDMSlite (low-ionization threshold experiment)

    - Targeting low mass parameter space
    - **Mass range: 0.5—10 GeV/c²**

- SuperCDMS SNOLAB will use cryogenic Ge and Si detectors



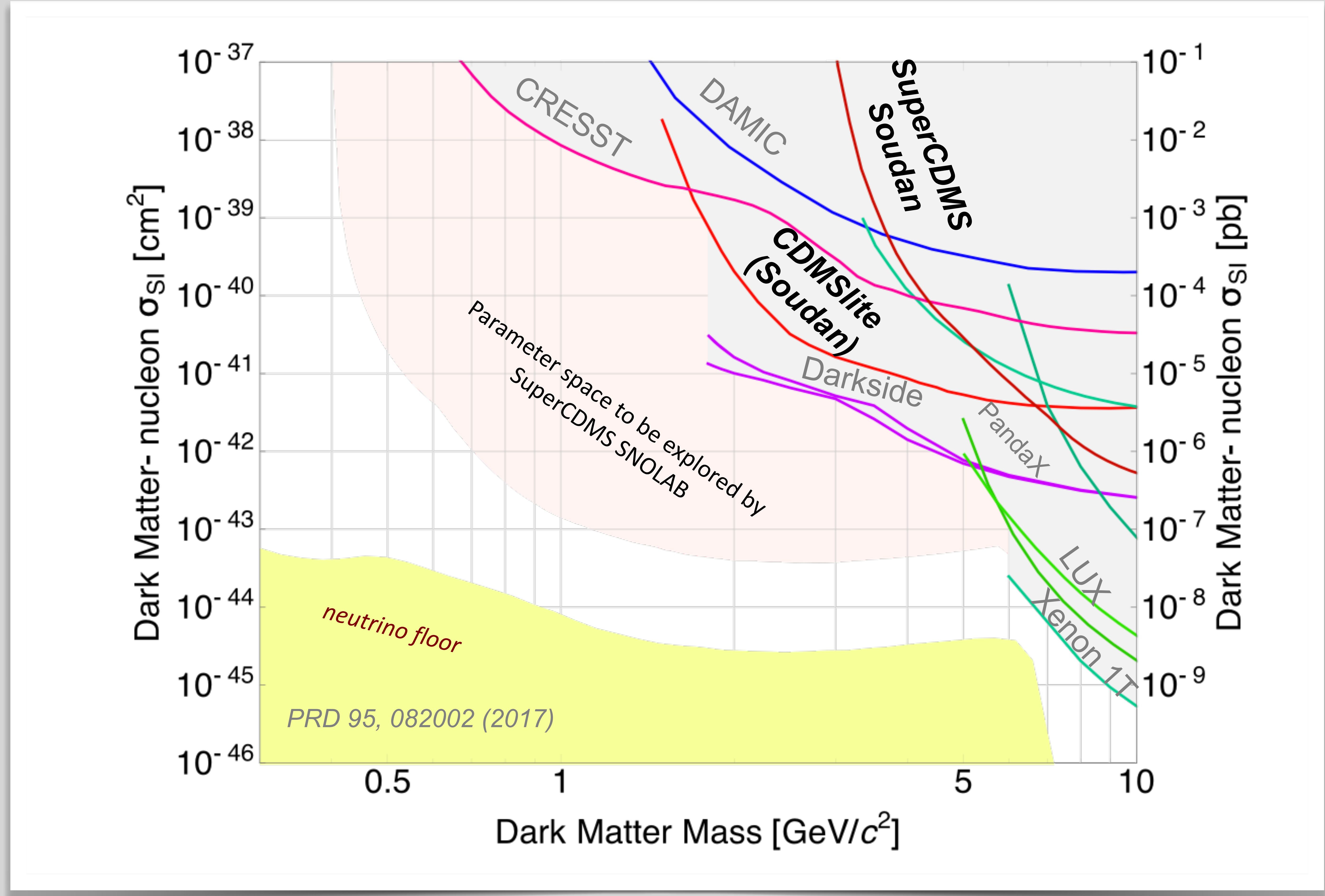
SuperCDMS SNOLAB

Building off progress by CDMS/ CDMSlite

Construction in progress
First physics results expected in 2023

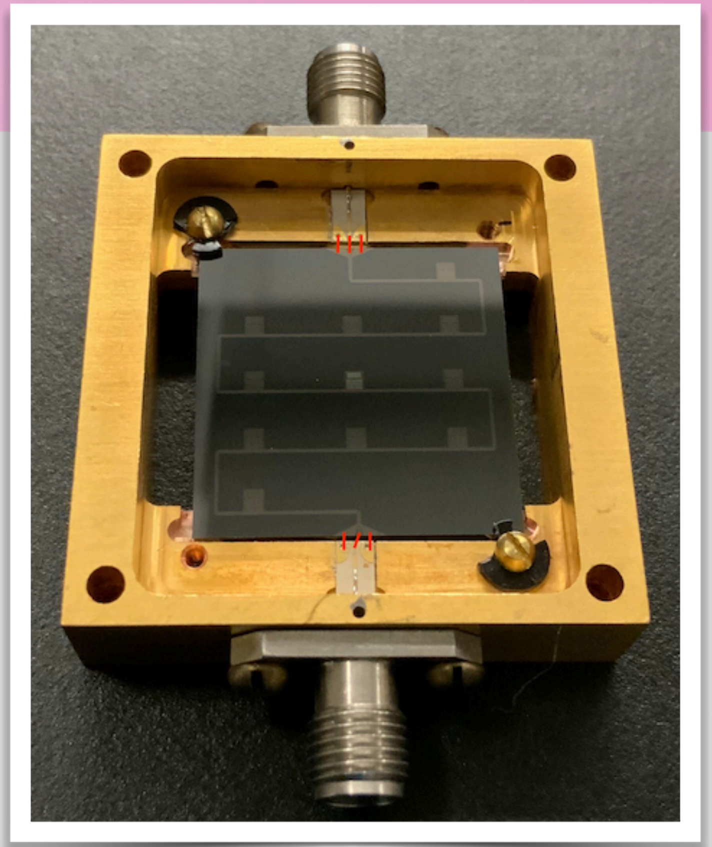
FNAL: 20 years of involvement.
Leadership roles in:

- Cryogenic design and operation
- Warm electronics design and fabrication
- Calibration system and design ops
- Infrastructure design and integration

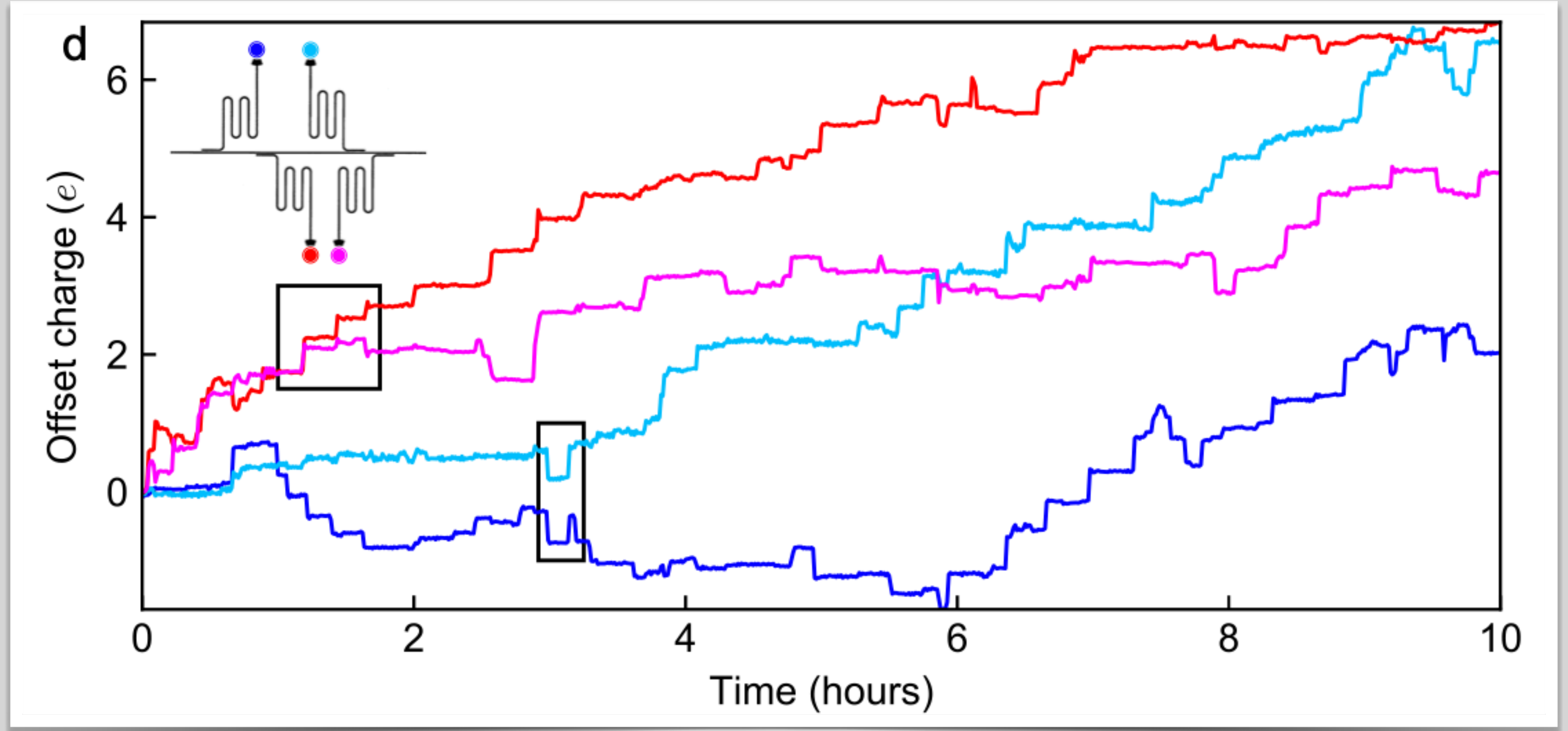


Courtesy of Lauren Hsu

Cryogenic Detector R&D



- Kinetic Inductance Detectors (KIDS) can provide sensitivity to even lower-mass dark matter than SuperCDMS or SENSEI/OSCURA
- First testing of a device by Caltech is currently underway in NEXUS
- Supported by Fermilab LDRD (Noah Kurinsky) and URA visiting scholar award (Osmond Wen)

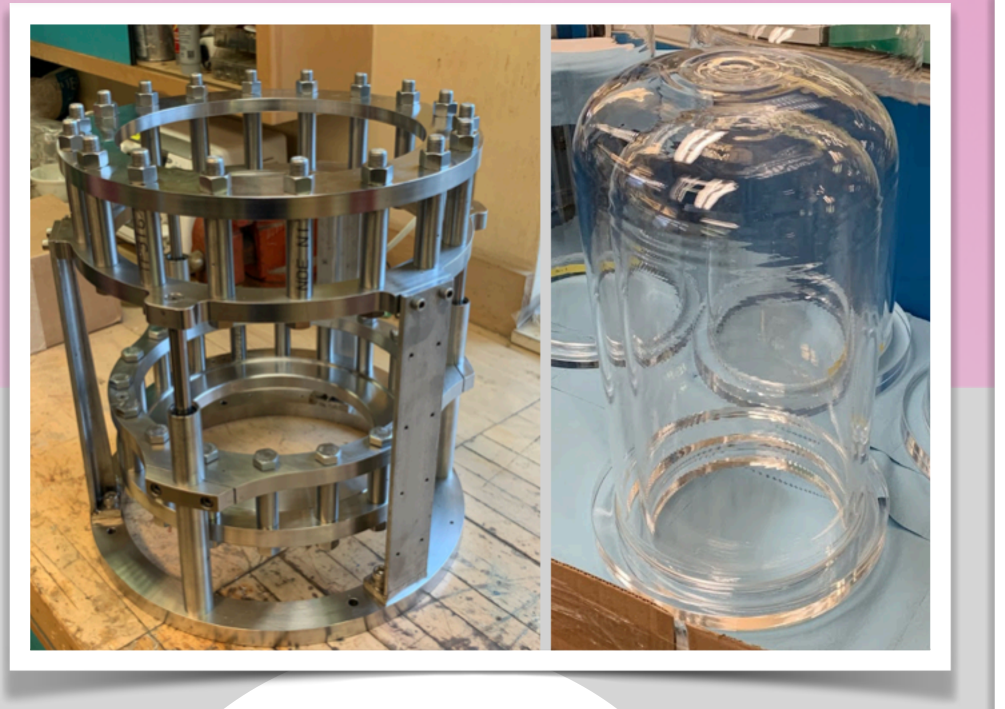


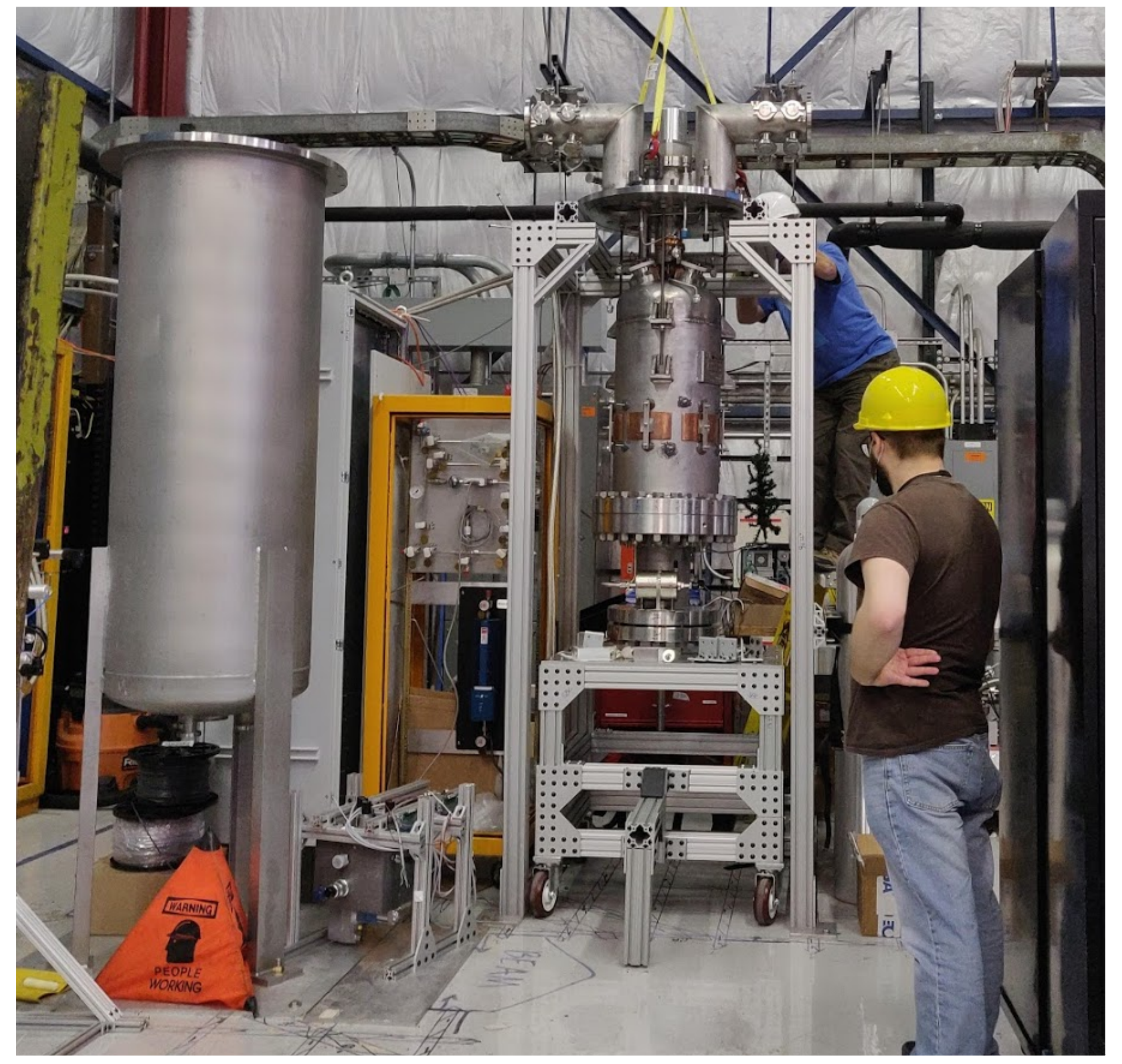
Time and spatial correlations of charge offsets on four qubits (arXiv:2012.06029)

- Fermilab is a partner in the Quantum Science Center; will build a second underground test stand (QUIET) for development of quantum devices targeting next-gen dark matter searches
- Operation of qubits underground will enable understanding of how external radiation contributes to decoherence (and dark matter backgrounds)

Courtesy of Lauren Hsu

Liquid Nobel Bubble Chambers





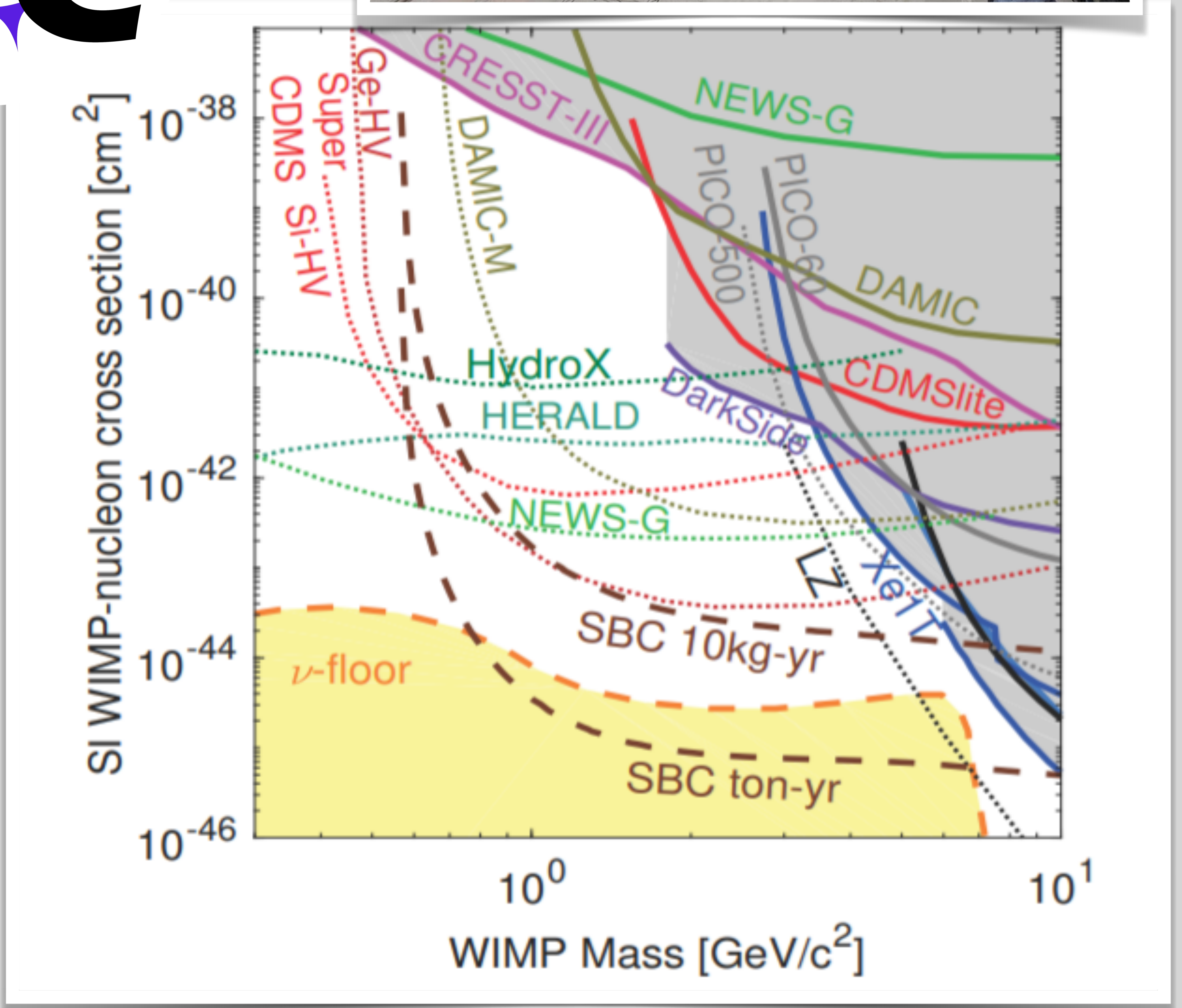
Scintillating Bubble Chamber (SBC)

Objective:
Scalable, background-free detection of sub-keV nuclear recoils

10-kg LAr Bubble Chamber at Fermilab

- Cryo/hydraulic commissioning in Lab B:
  - Summer 2021
- Complete detector assembly in Lab B/C:
  - Fall 2021/Winter 2022
- Move to MINOS:
  - Winter/Spring 2022

Threshold studies at MINOS underground hall will determine the unique dark matter and neutrino physics potential of this technique.

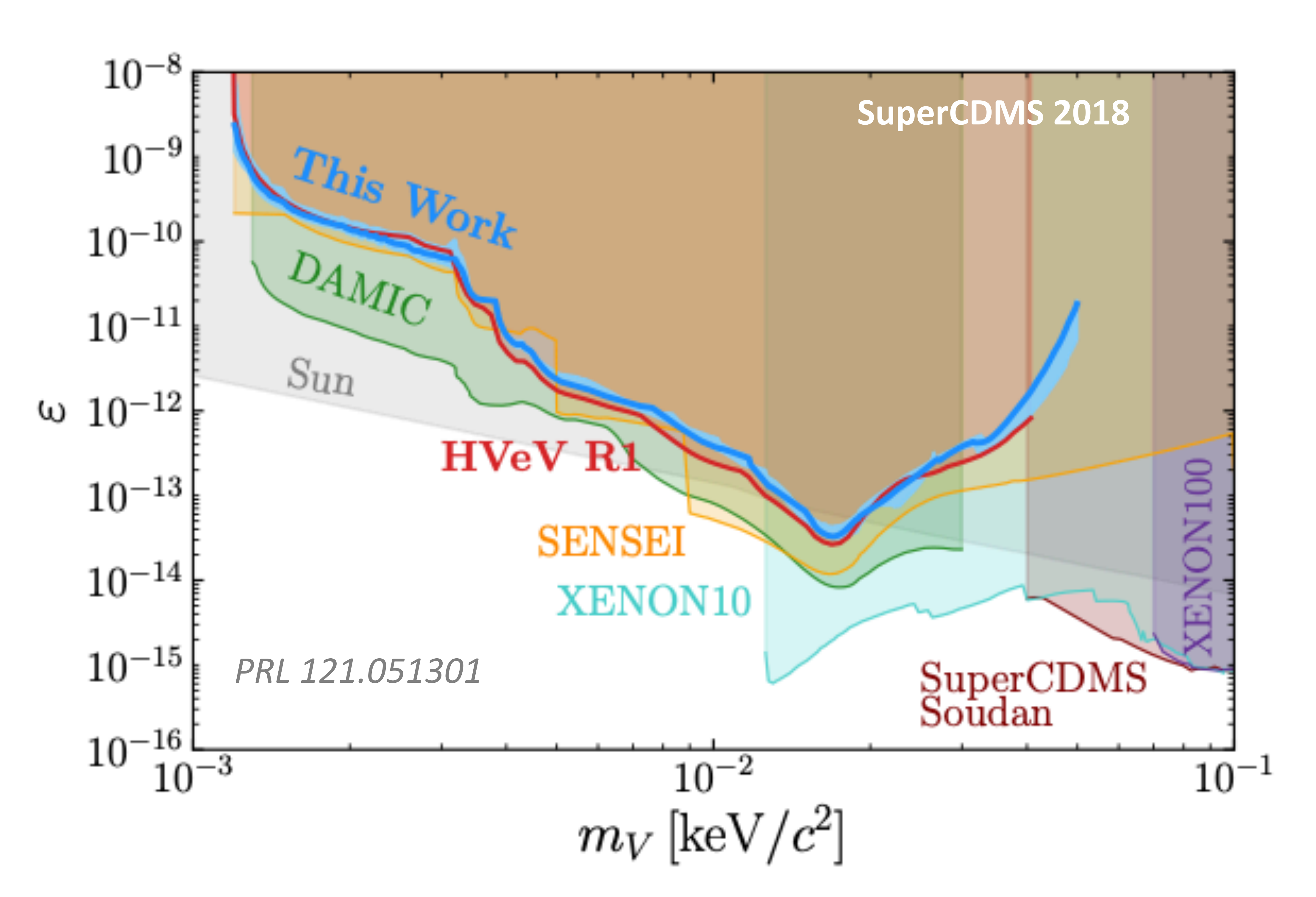


Courtesy of Lauren Hsu

NEXUS: Sub-GeV Dark Matter and Cryogenic Detector Test Facility

Operating new Fermilab/Northwestern facility (NEXUS) in MINOS hall

- Meant for low-background testing of cryogenic detectors
- Sub-GeV dark matter run in Dec/Jan with SuperCDMS “HVeV” detectors
- Neutron generator will be installed this year, along with scattered neutron “backing array” to determine nuclear recoil energy scale in SuperCDMS detectors



In 2018, SuperCDMS demonstrated world-leading sensitivity to sub-GeV dark matter with HVeV detector

- Sensitive to single e/h pairs; synergistic R&D with SENSEI/OSCURA
- Recent data taken underground at NEXUS, will yield substantial improvements in sensitivity; Results expected in 2021!

Courtesy of Lauren Hsu

SENSEI/OSCURA

Sub-electron noise Skipper CCD Experimental Instrument (SENSEI)

Goal is to probe:

- DM Scattering off of electrons
- DM absorbed by electrons
- DM scattering off a nucleus (Migdal effect)

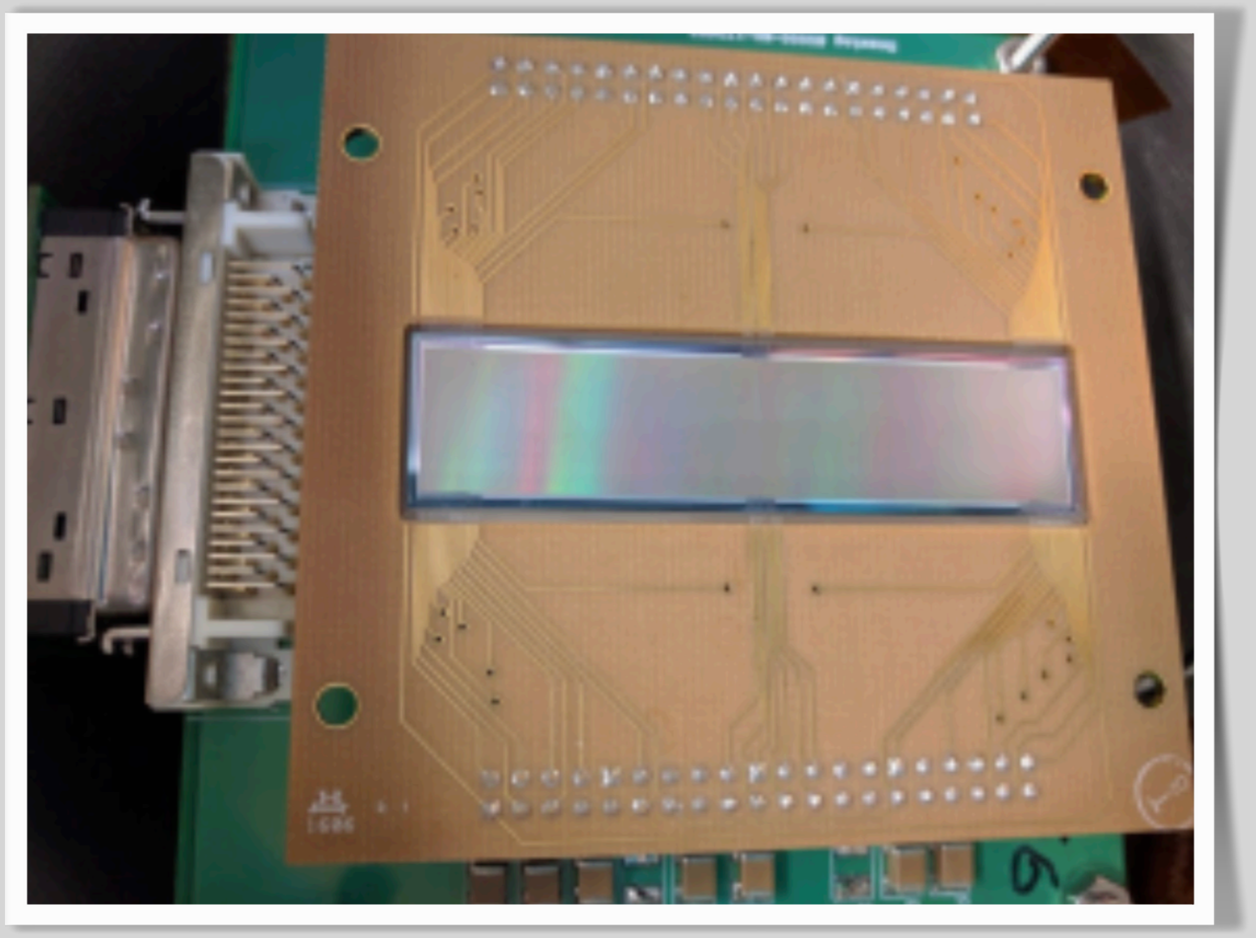
Status:

- Science coming from SENSEI now. Cutting edge low mass e-recoil dark matter thanks to new sensor development.
- Oscura in the future. 100x SENSEI and selected by DOE in the DMNI based on success of SENSEI. R&D until FY23 ($4M). Construction FY24-27 ($10M) first review in June. Operations at SNOLAB.
- Sensor R&D very active. ECA-JT, LDRDs, quantized have allowed the collaboration to keep developing new techno.ogy. Neutrion CEvNS application on the horizon.

Team: J. Estrada, G. Fernandex-Moroni (RA), J. Tiffensberg.

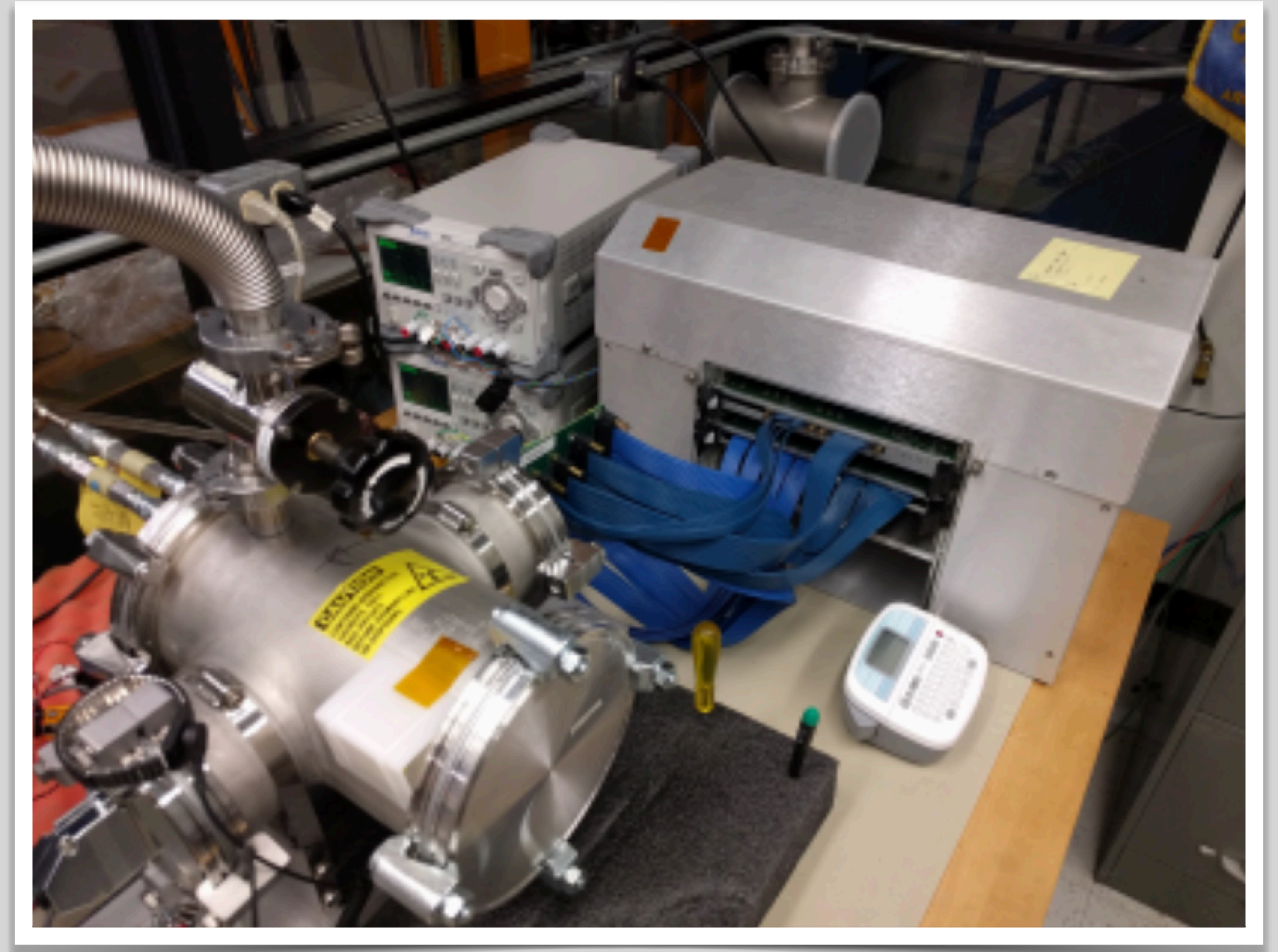
Skipper CCD (enabling technology)

Sensors



- Skipper-CCD prototype designed at LBL MSL
- 200 & 250 micron thick, 15 micron pixel size
- Two form factors (4k x 1k (0.5 g) and 1.2k x 0.7 k pixels)
- Parasitic run, optic coating and Si resistivity ~10 kΩ
- 4 amplifiers per CCD, three different RO stage designs

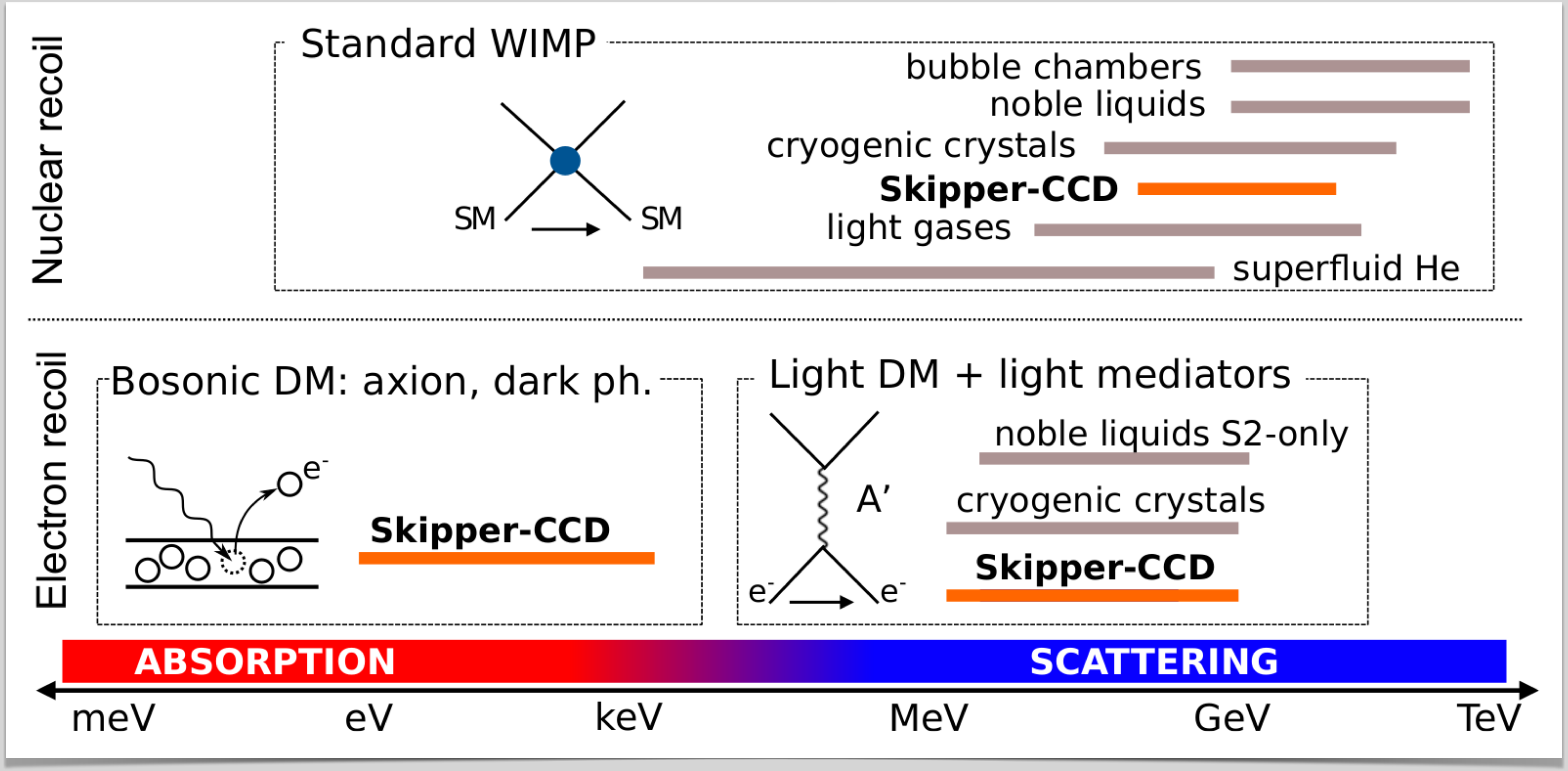
Instrument



- System integration done at Fermilab
- Custom cold electronics
- Modified DES electronics for read out
- Firmware and image processing software
- Optimization of operation parameters

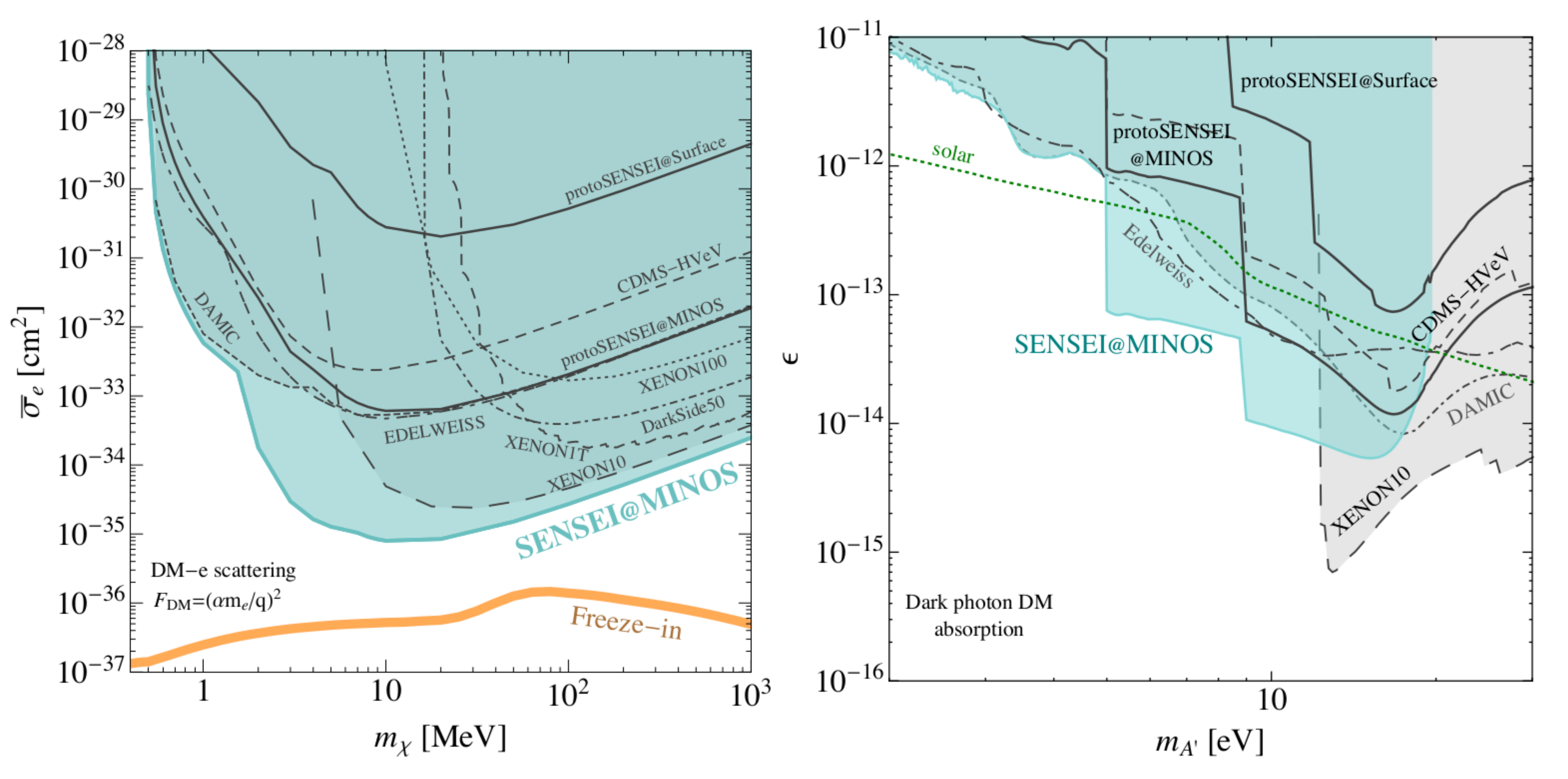
Courtesy of Juan Estrada

Skipper CCDs and Dark Matter



Courtesy of Juan Estrada

SENSEI in 2020



World leading result & PRL editors suggestion (PhysRevLett.125.171802)

New Horizons in Physics Award from the Breakthrough Foundation

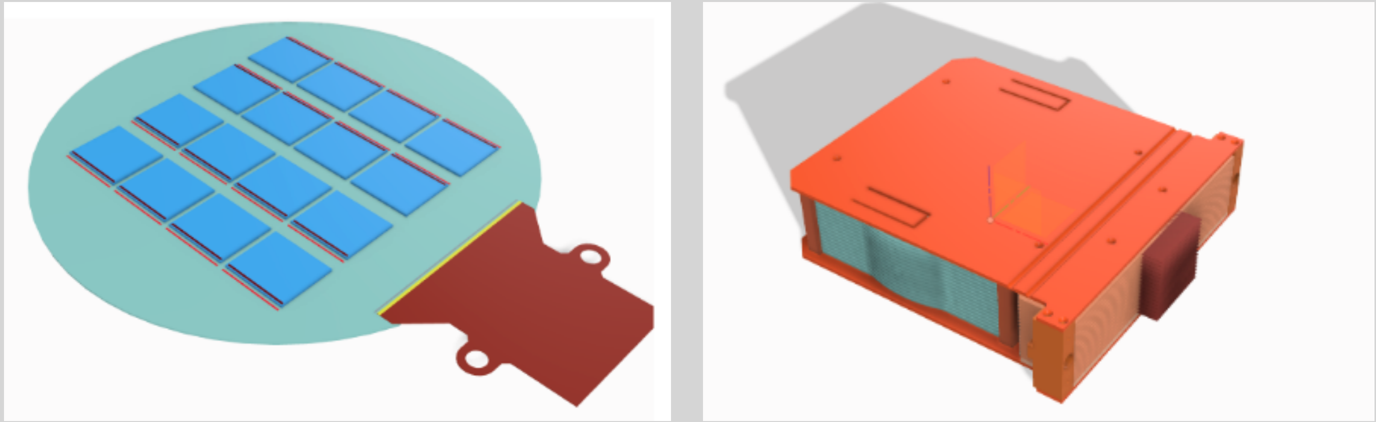
Courtesy of Juan Estrada

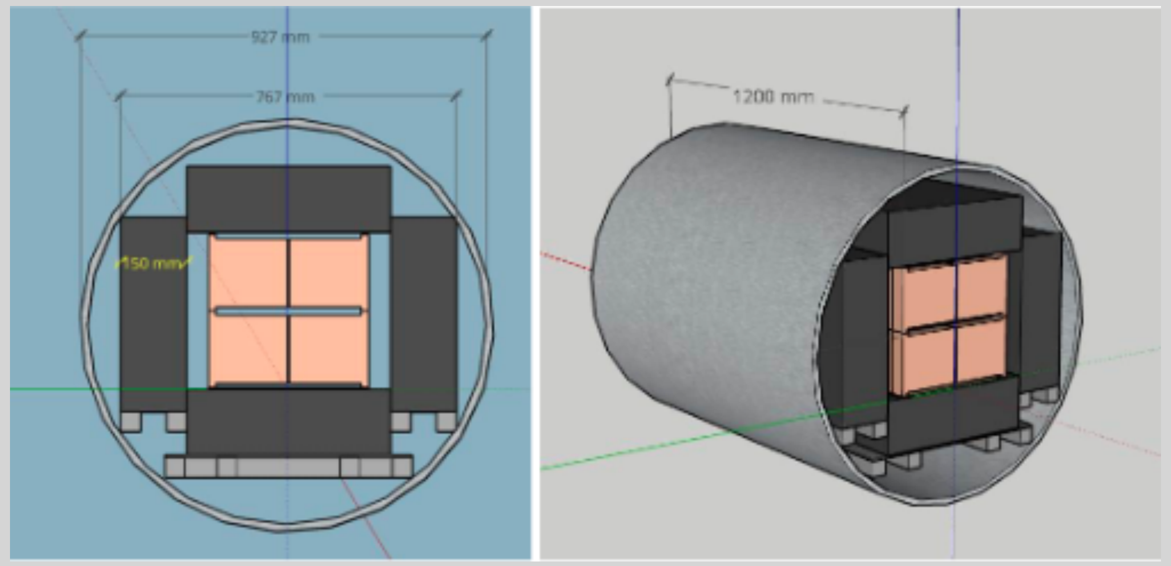
OSCURA: 10-kg skipper ccd experiment

Goal: e-recoil low mass direct dark matter search (1 MeV —> 1 GeV)

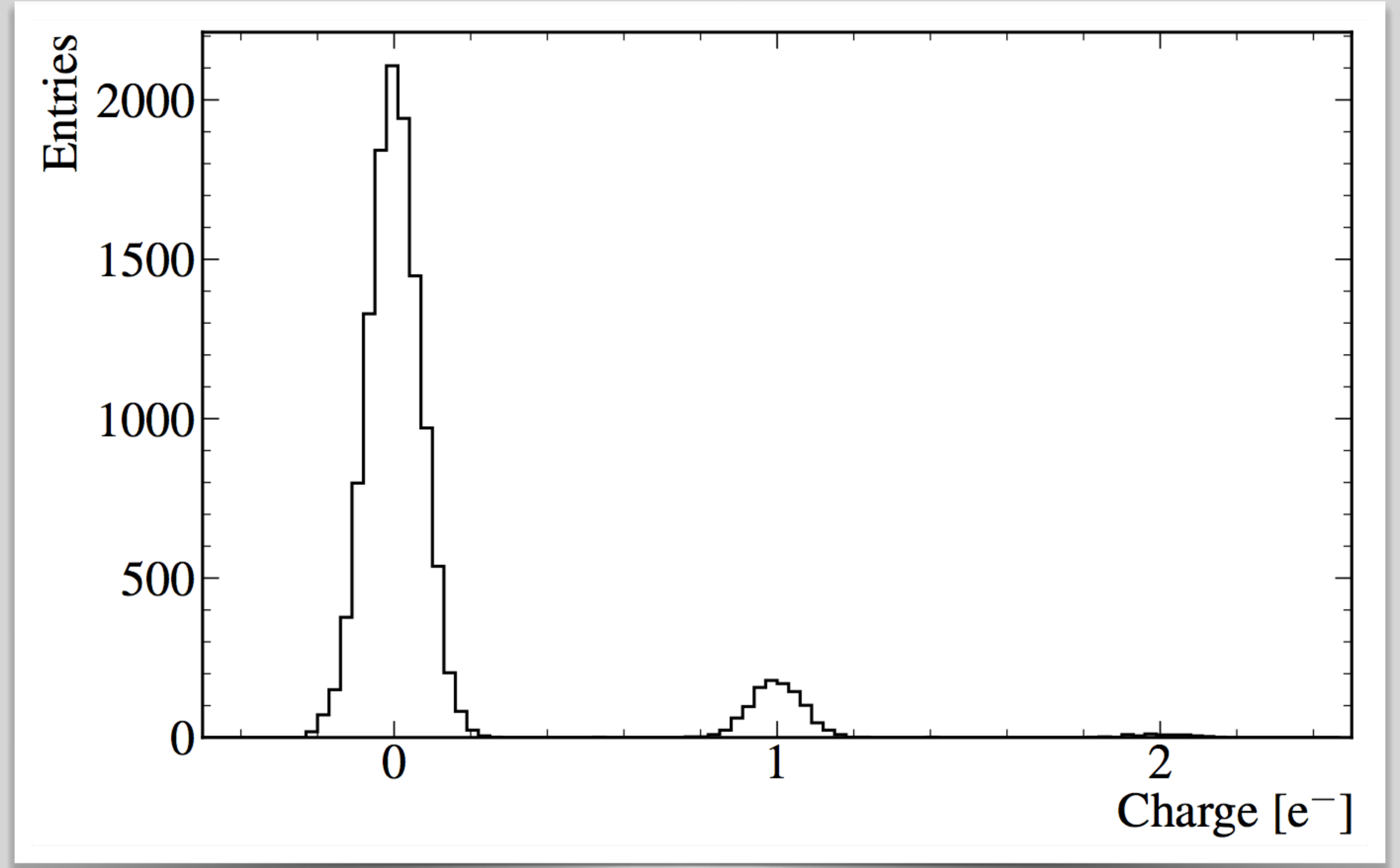
- Technology: skipper-ccd array (sub-electron noise) at underground lab (SNOLAB, SURF, other)
- R&D: scale the existing technology towards a 10 kg experiment
- Cost: $4M R&D + design, $10M execution
- Schedule: small project execution plan completed in 2023

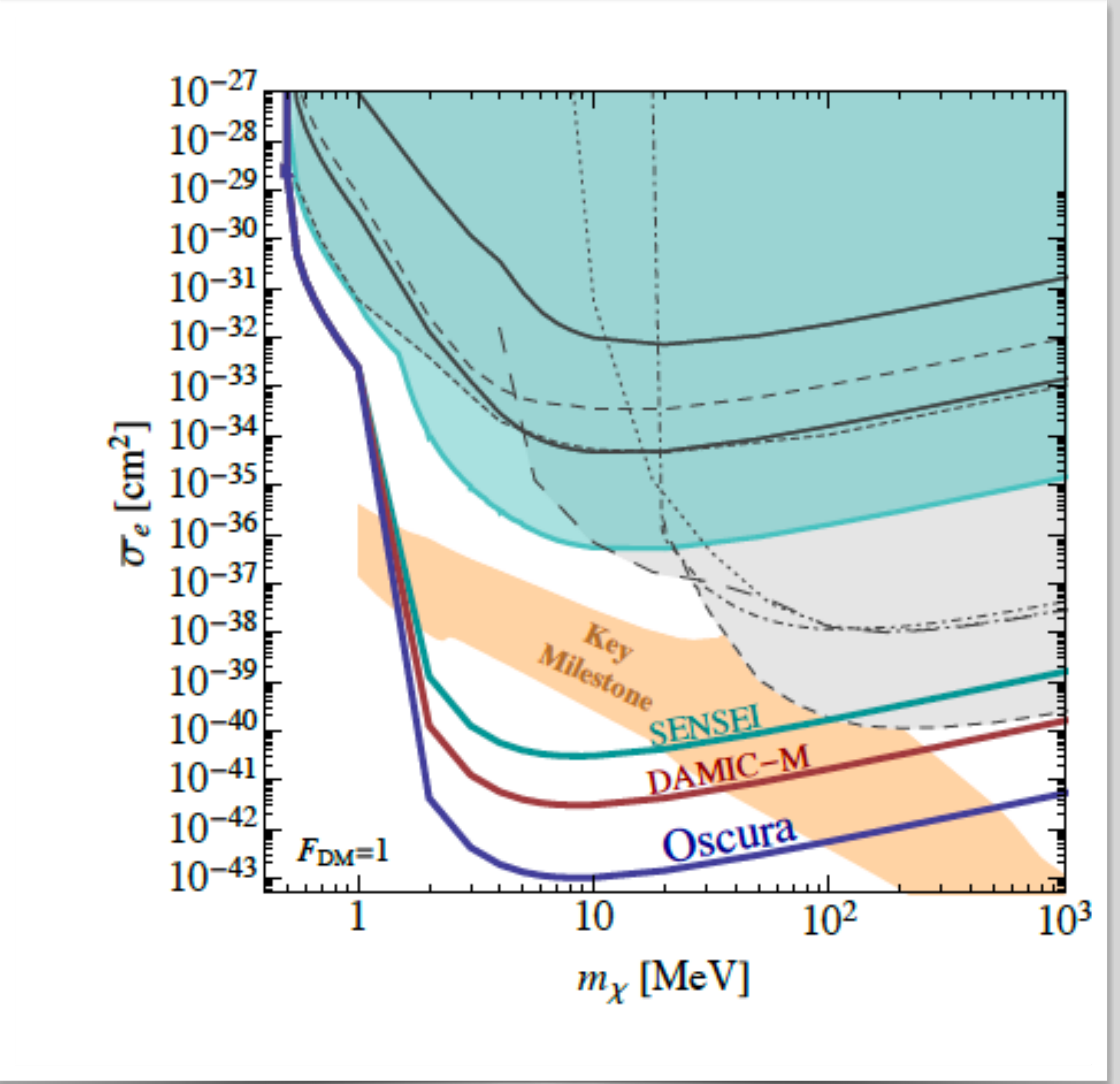
- R&D: FY19, FY20, FY21
- Design: FY22, FY23
- Execution: FY24-27
- Operations: FY28-30





detector concept



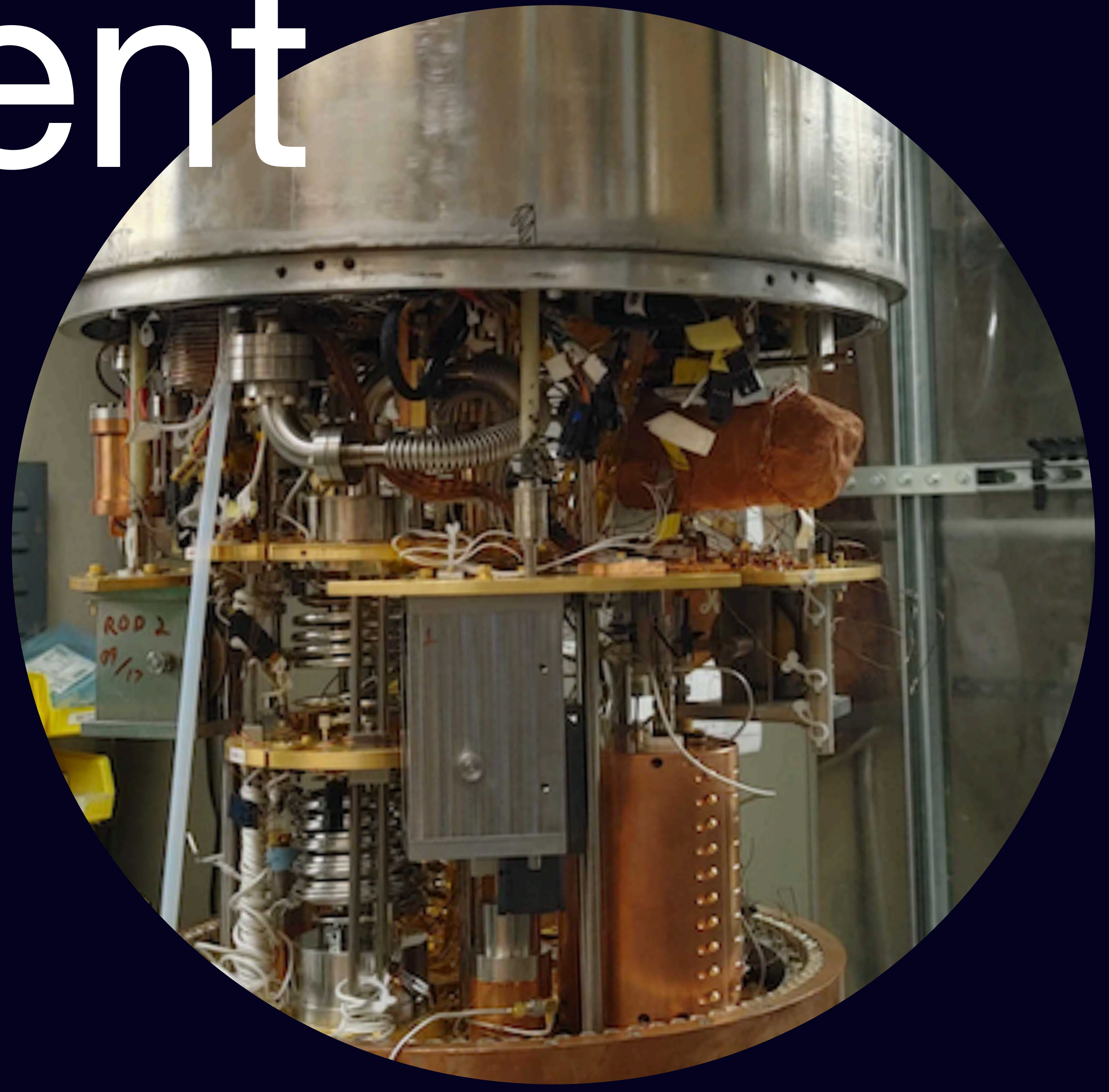


scientific reach

30 kg-yr

Courtesy of Juan Estrada

Axion Dark Matter eXperiment



- Resonant cavity in a magnetic field (‘haloscope’ as first proposed by Pierre Sikivie)
- Relying on inverse Primakoff effect
- High-Q —> Higher probability of axion to photon conversion
- Have reached DFSZ benchmark sensitivity with the ADMX detector

University of Washington 1861 · The University of Western Australia · Washington University in St. Louis 1853 · Pacific Northwest National Laboratory

Funding Agencies: Department of Energy · NSF · Heising - Simons Foundation

Lawrence Livermore National Laboratory · UF University of Florida · Georg-August-Universität Göttingen

The University Of Sheffield. · Fermilab · Los Alamos National Laboratory · Berkeley University of California

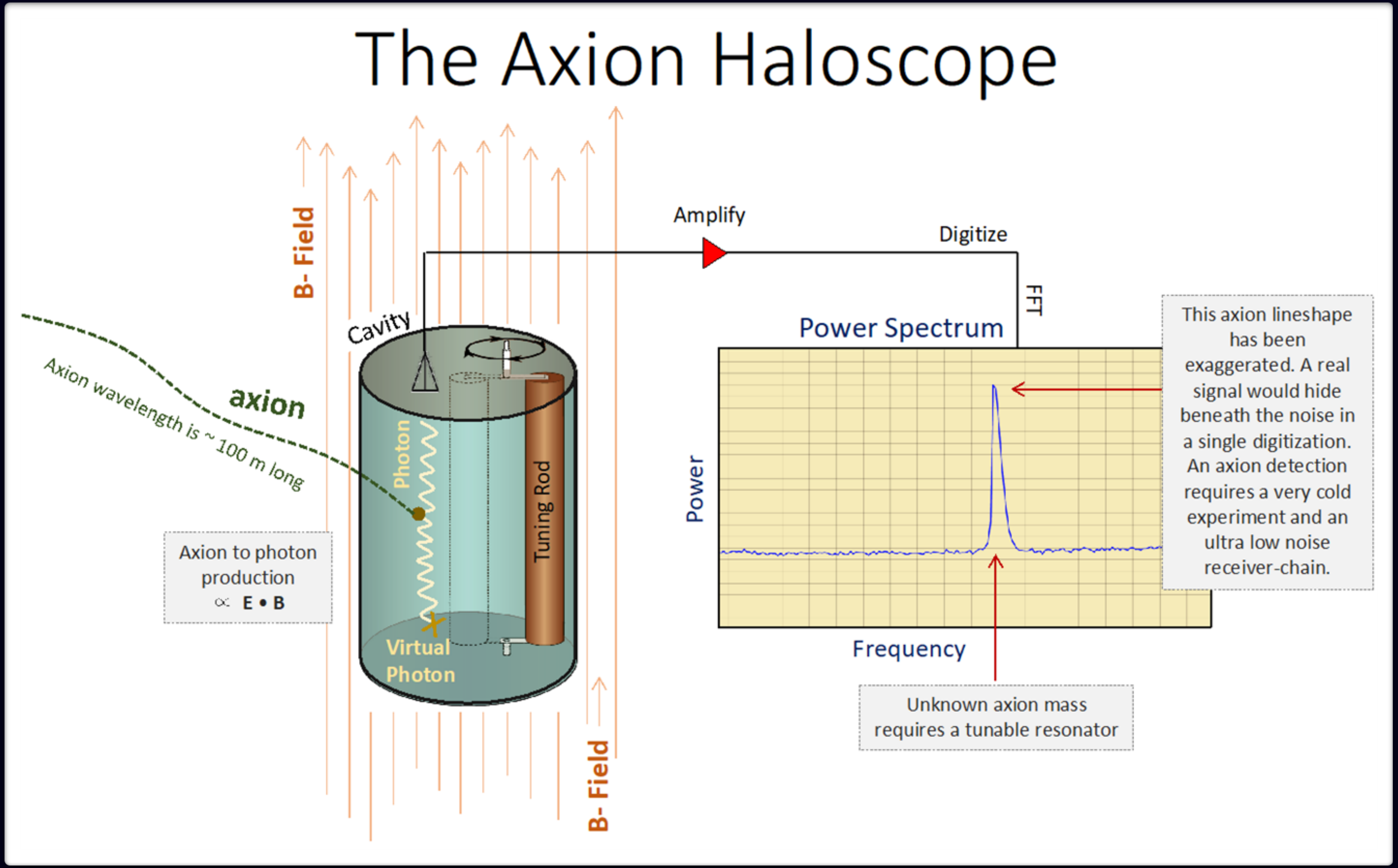
Guided by the QCD Axion

- 1-100 μeV mass range can constitute all the dark matter.
- Can also solve the strong CP problem.

Helen Quinn

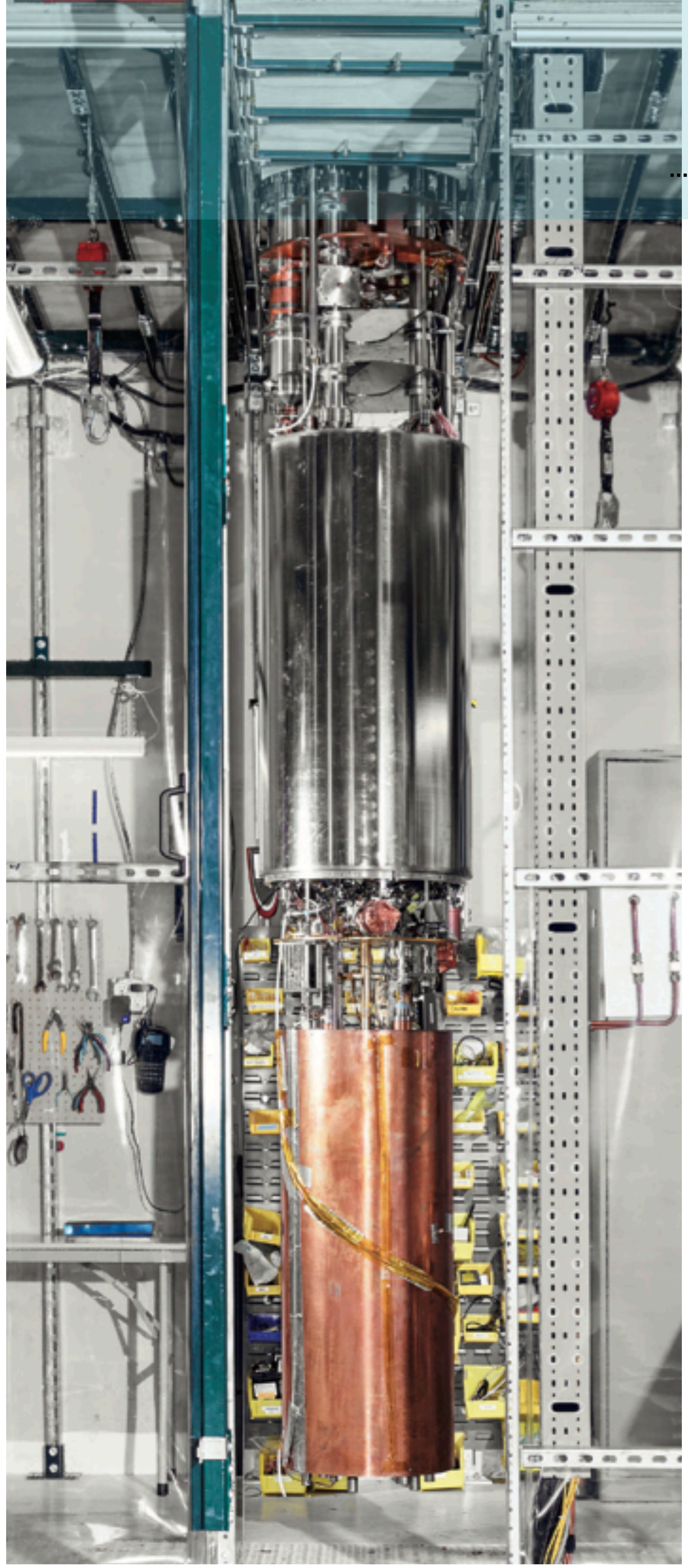
Roberto Peccei
1942-2020

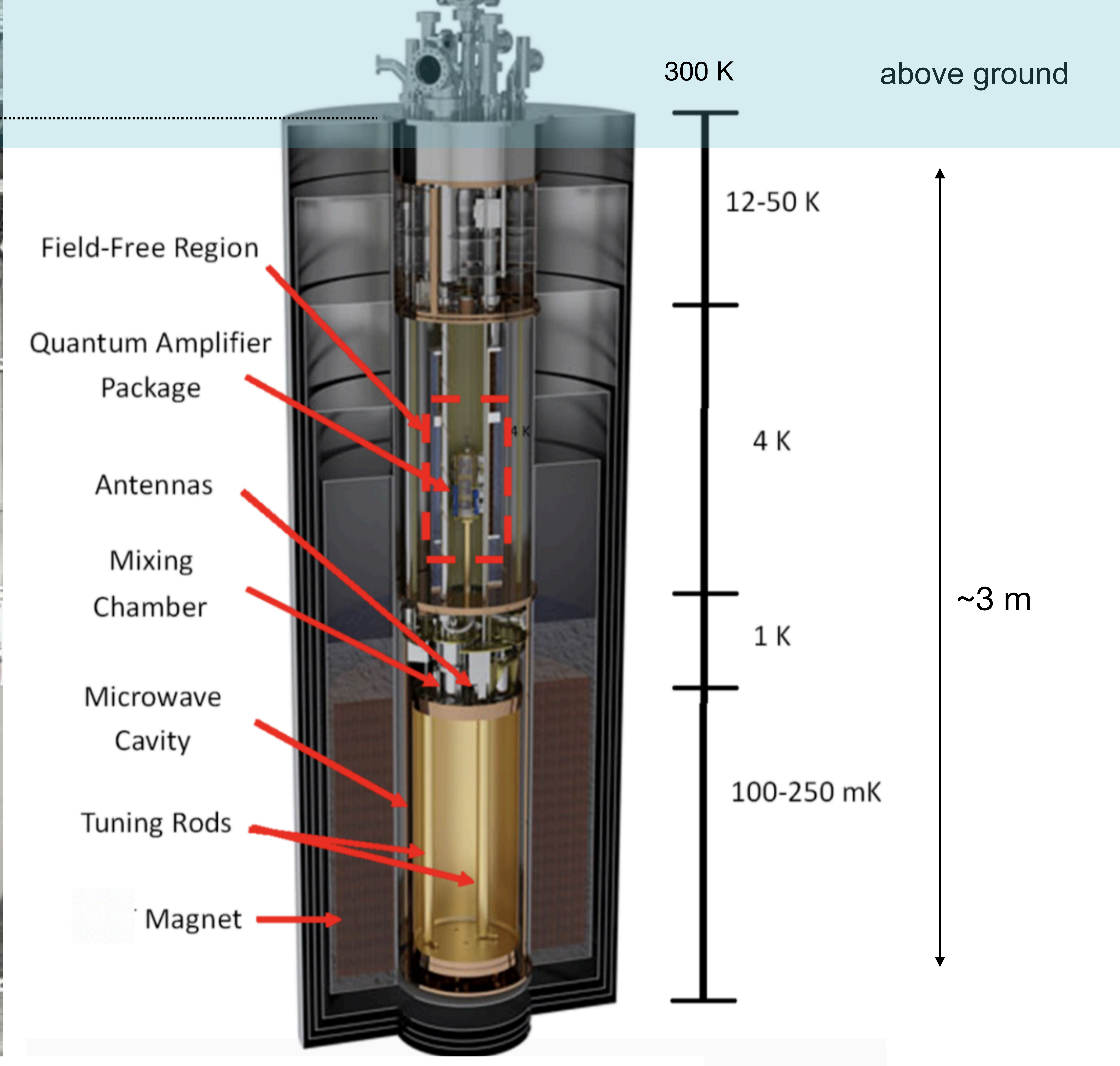
- Two classes of models: KSVZ, DFSZ



ADMX

- Dil Fridge: Reaches ~100 mK
- Superconducting magnet:
  ~can reach up to 8 T
- Quantum electronics: Josephson Parametric Amplifier (JPA)
- Field cancellation coil
- Microwave cavity and electronics



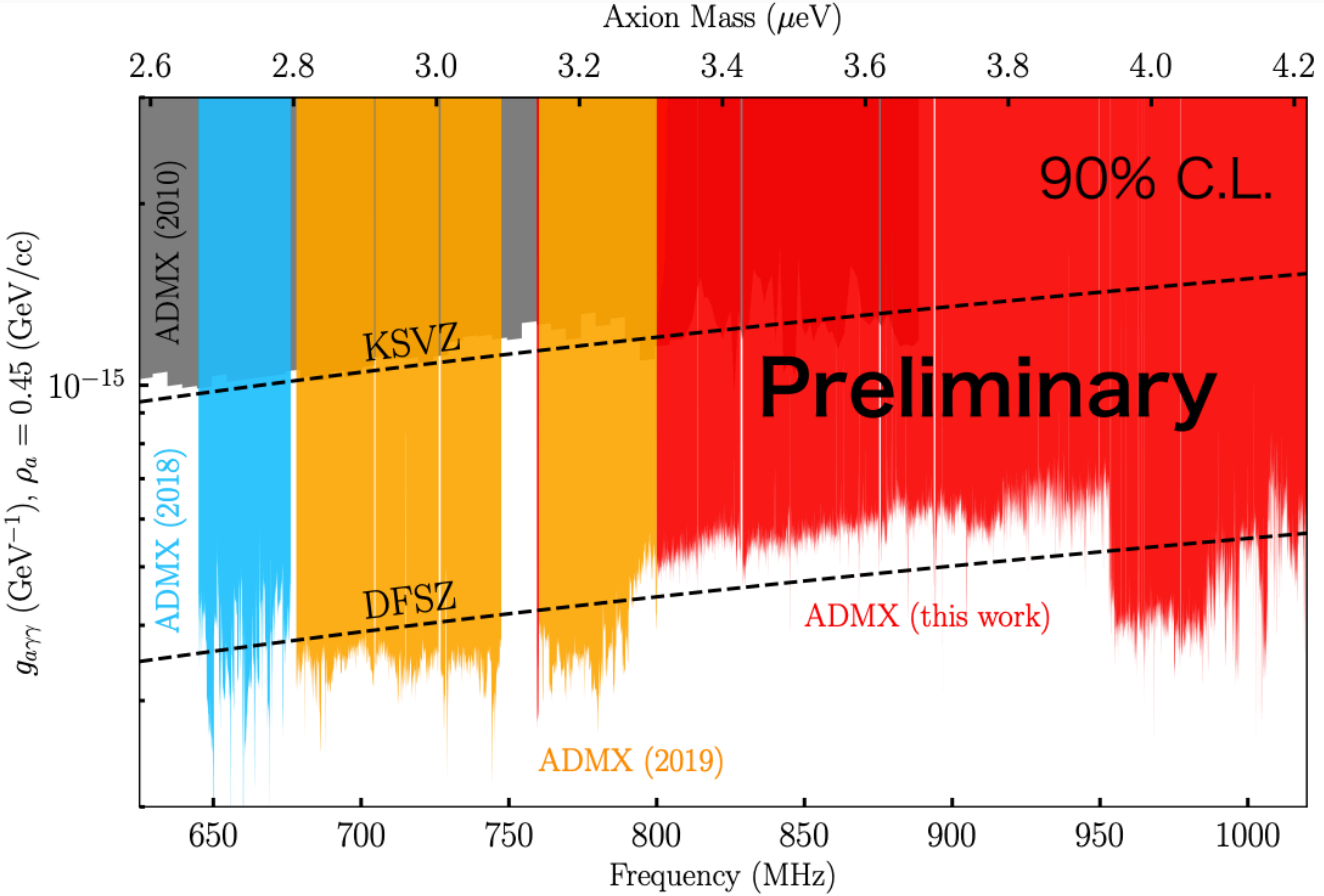


Run 1C Sensitivity

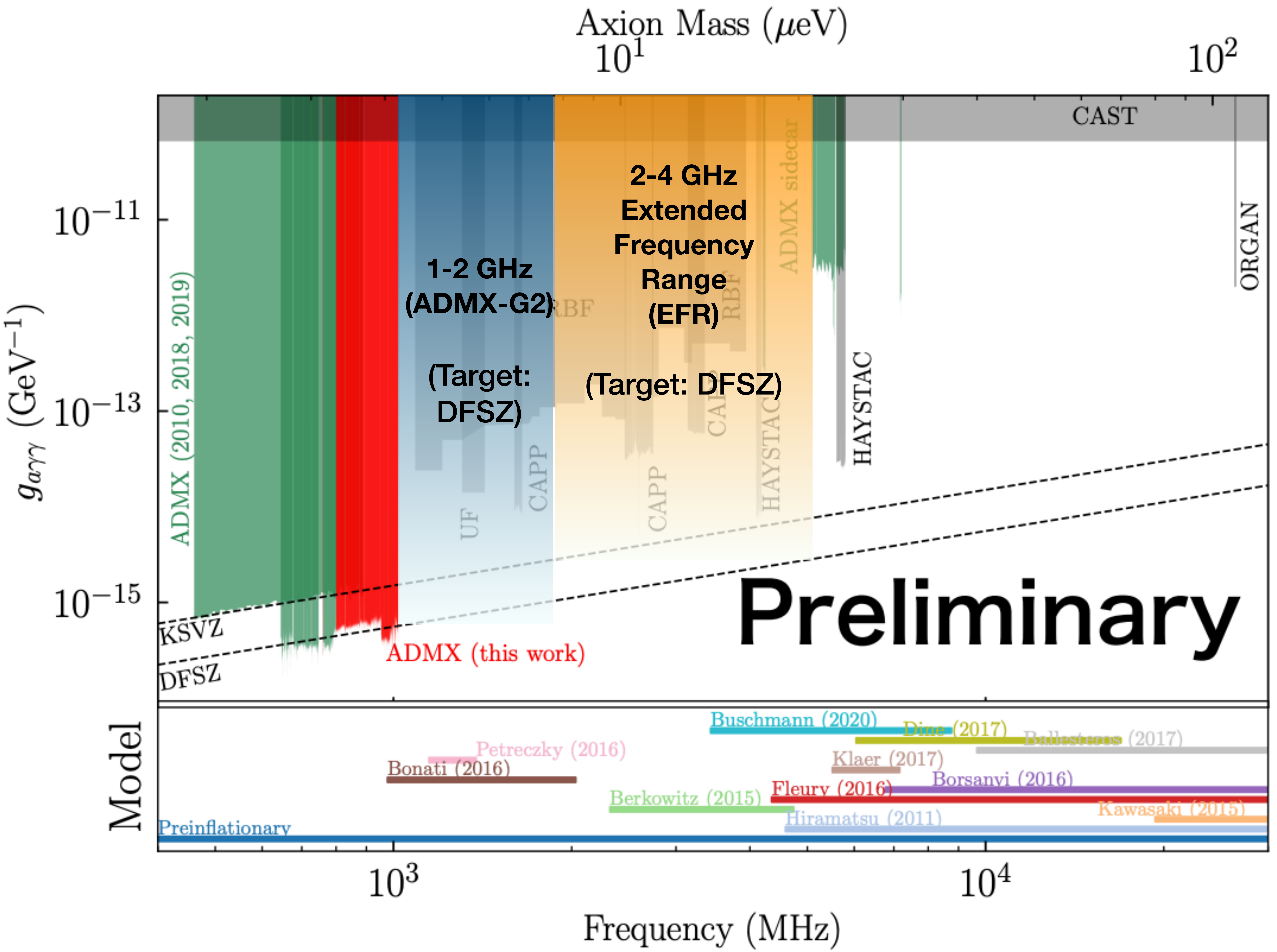
- Sensitive to KSVZ: 800-970 MHz
- Sensitive to DFSZ 970-1020 MHz
- Covered 2x prior frequency range

For analysis details

- Prior paper: Bartram, Chelsea, et al. "Axion dark matter experiment: Run 1B analysis details." *Physical Review D* 103.3 (2021): 032002.
- Results for Run 1C Forthcoming



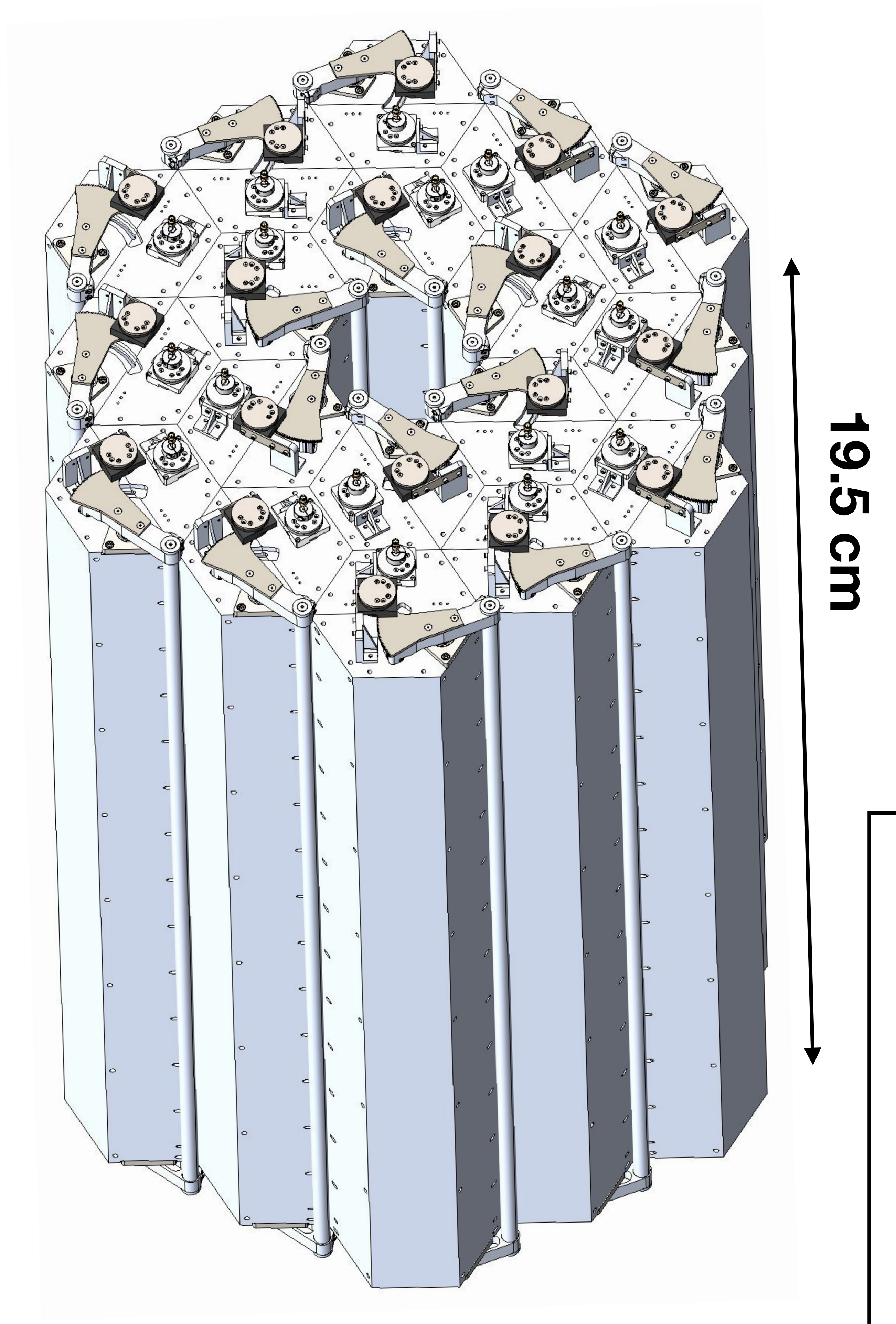
Sensitivity Plot

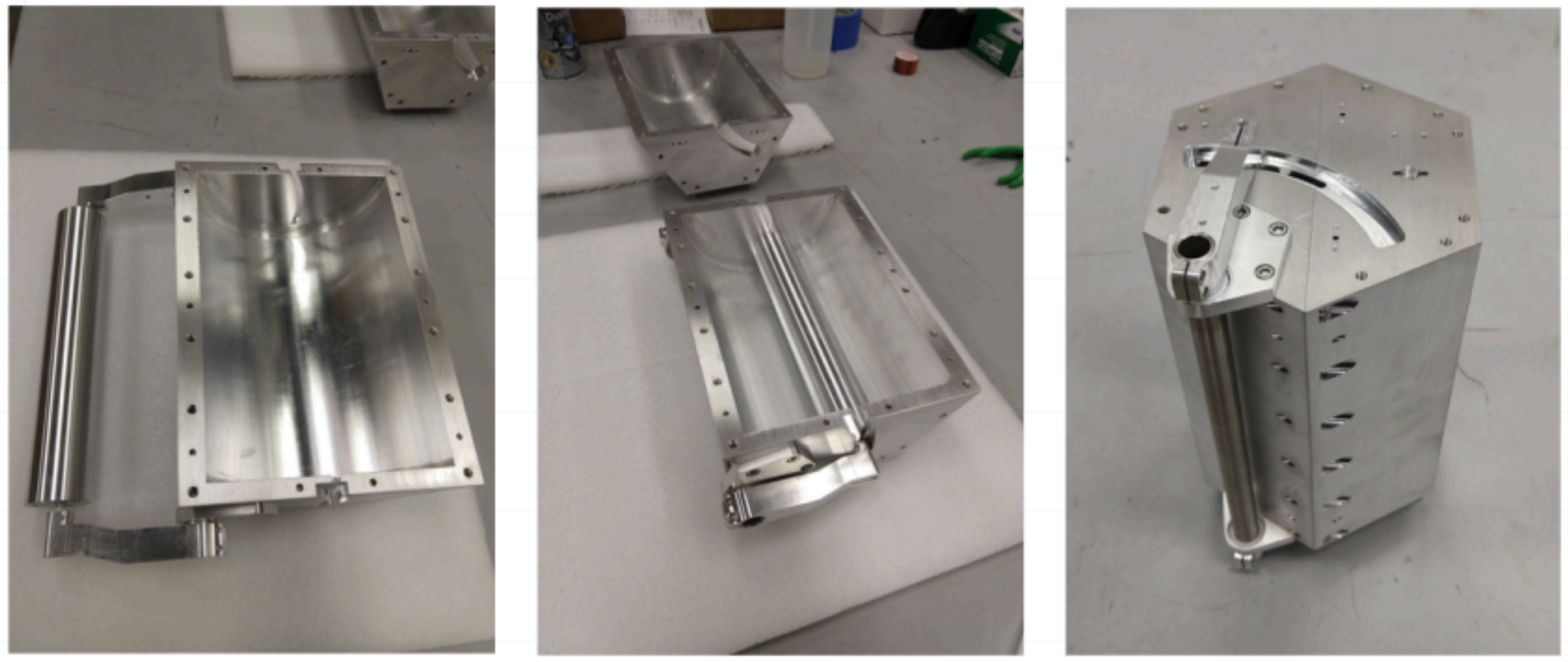


Axion Mass (μeV)
10^1
10^2
CAST
ORGAN
HAYSTAC
ADMX sidecar
2-4 GHz
Extended
Frequency
Range
(EFR)
(Target: DFSZ)
1-2 GHz
(ADMX-G2)
(Target:
DFSZ)
RBF
UF
CAPP
HAYSTAC
ADMX (2010, 2018, 2019)
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-11}
10^{-13}
10^{-15}
KSVZ
DFSZ
ADMX (this work)
Preliminary
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Fleury (2016)
Berkowitz (2015)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)

ADMX Extended Frequency Range

- 2-4 GHz prototype cavity assembly at University of Florida
- Cylindrical cavity formed from two clamshell halves
- Possibly ~18 cavities
- Simulations Underway
- Large-bore 9.4 T Magnet
- Room for R&D Work



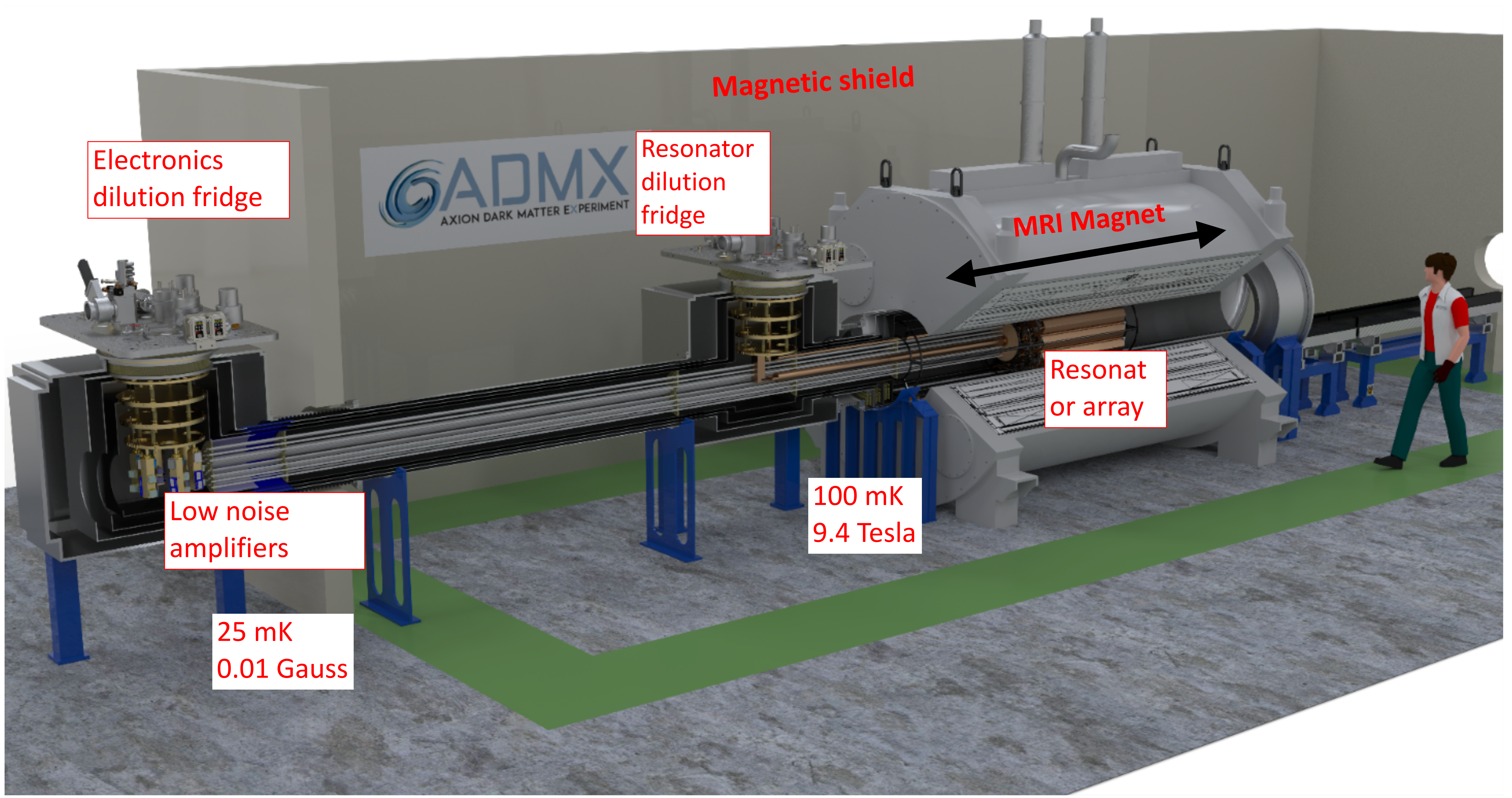


UF UNIVERSITY of FLORIDA

ADMX Extended Frequency Range (EFR)

New Features

- Horizontal magnet bore
- Extra modularity: cavity electronics are separate from magnet bore
- Large magnet volume: 258 liters
- Preferred site for ADMX-EFR: PW8 Hall at Fermilab
- Other: Squeezing? Superconducting cavities?



(ADMX EFR Design)

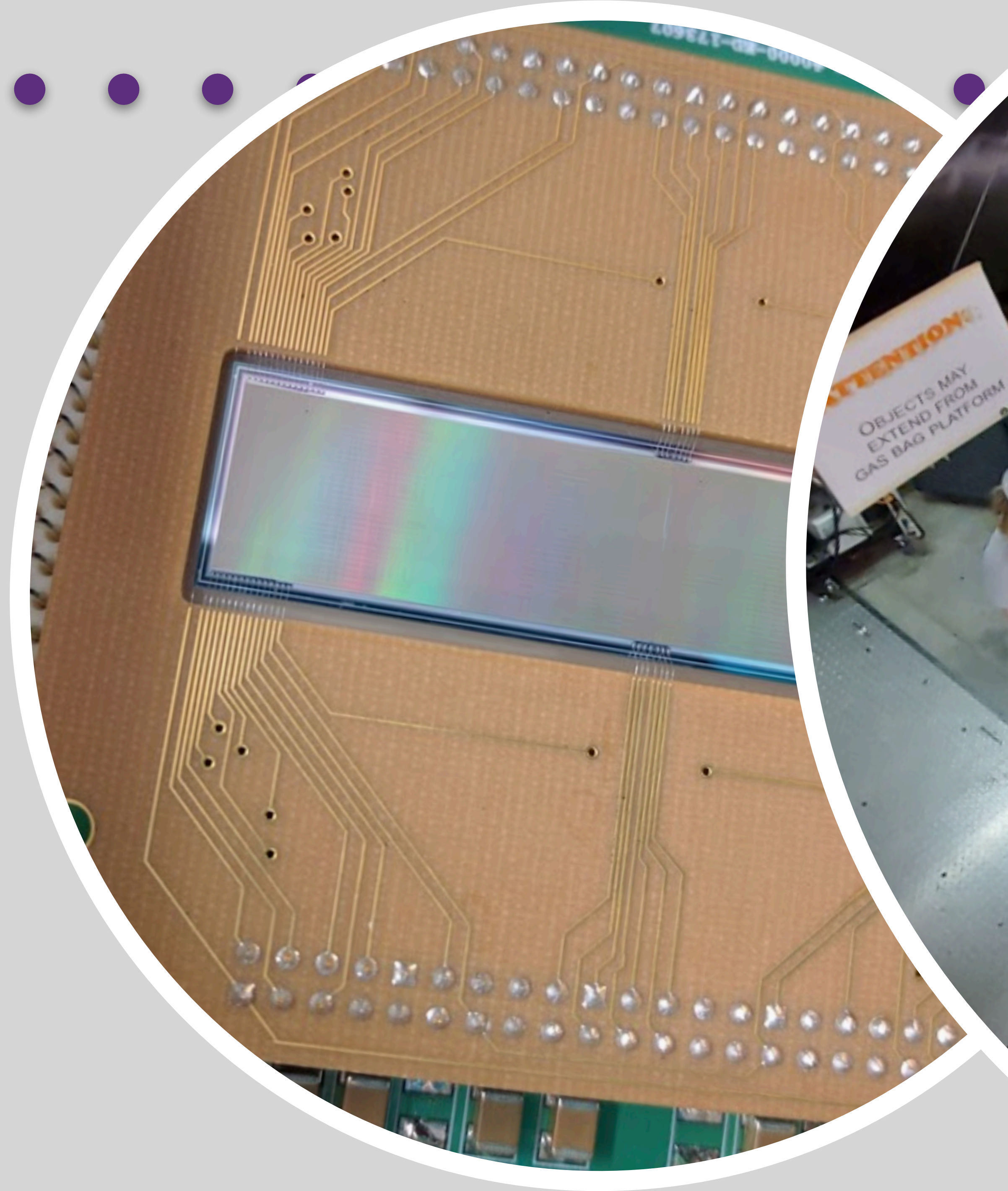
Conclusions

Fermilab is a world leader in dark matter searches.

Leadership in 3 ongoing dark matter searches + future dark matter endeavors over a wide mass range:

- Axion Dark Matter eXperiment
- SENSEI/OSCURA
- SuperCDMS

Dark matter discovery on the horizon!



Fermilab