Cryogenic Facility Needs for HEP*

*may include some non-standard interactions with other fields…

Enectalí Figueroa-Feliciano

Northwestern

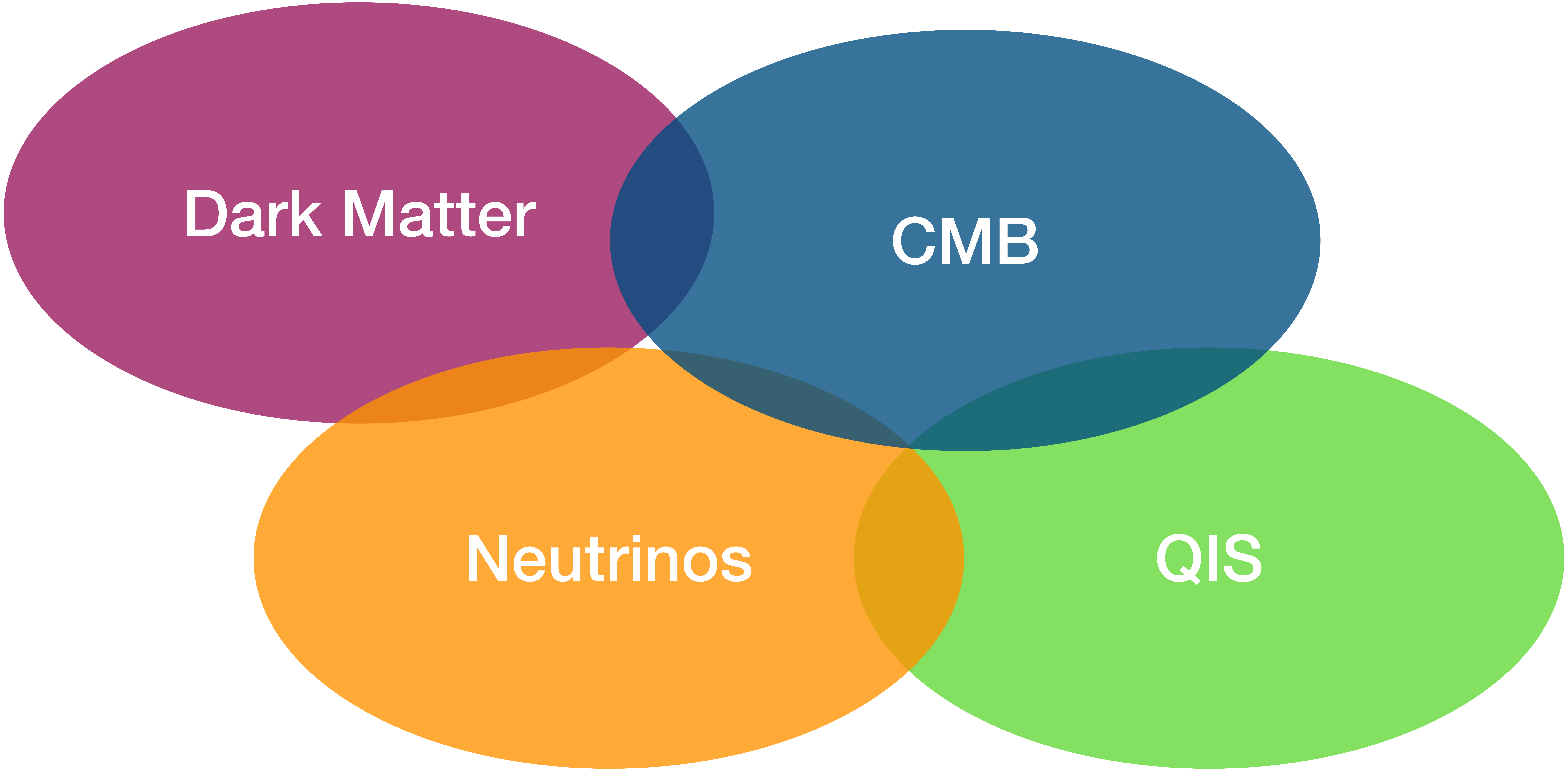
From BRN Report:

Ultra-low temperature test stands

As described in the dark matter and quantum sensor sections, these areas of research will impose exacting requirements on ultra-low temperature (mK) environments and significant testing will be required to realize future experiments. Yet, test stands for operating at these temperatures are costly and limited in number. These high value assets are dispersed throughout the community, primarily at national labs and large research universities. Some were funded by HEP while many have been funded by institutional investments and other government agencies.

The expansion of interest in such facilities is a relatively recent phenomenon, driven largely by the quickly growing HEP-QIS overlap, and thus there is not yet a consensus on the scale of community need and what siting and operating models ensure appropriately broad access and sustainable operation. Hand-in-hand with facilities supply and access is the question of what explicit efforts ought to be made to disseminate expertise in areas relevant to work that use such facilities—in particular device design and fabrication and experimental techniques—and to facilitate access. Further study by the relevant communities would clarify the situation and better define a path forward. Such study would also determine the potential impact of technical or manufacturing advances that reduce the cost of such test stands, though it is not clear that direct HEP funding for such work would substantially augment the much larger commercial and governmental interest driven by quantum computing.

Cryogenics are Everywhere!



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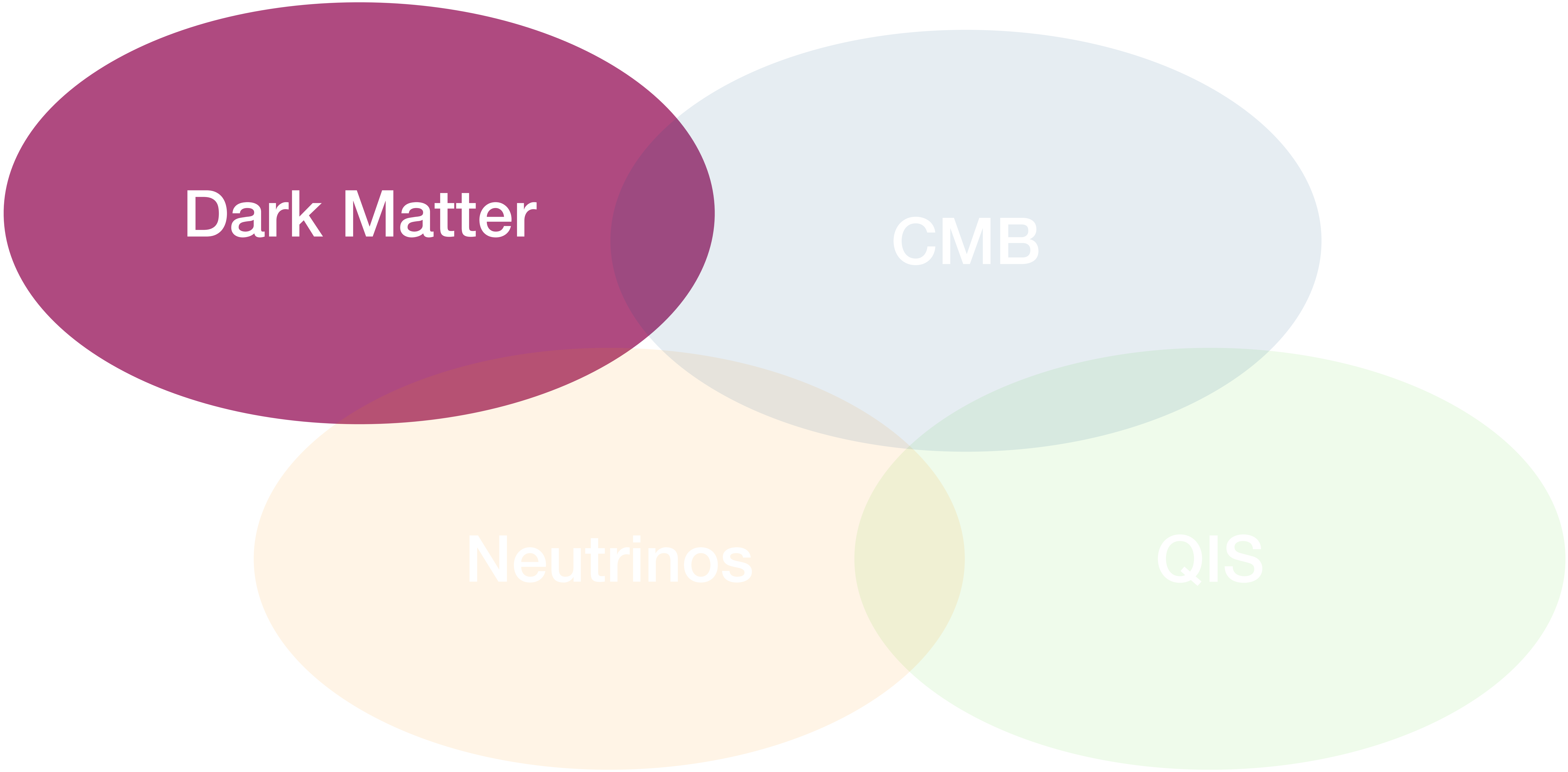
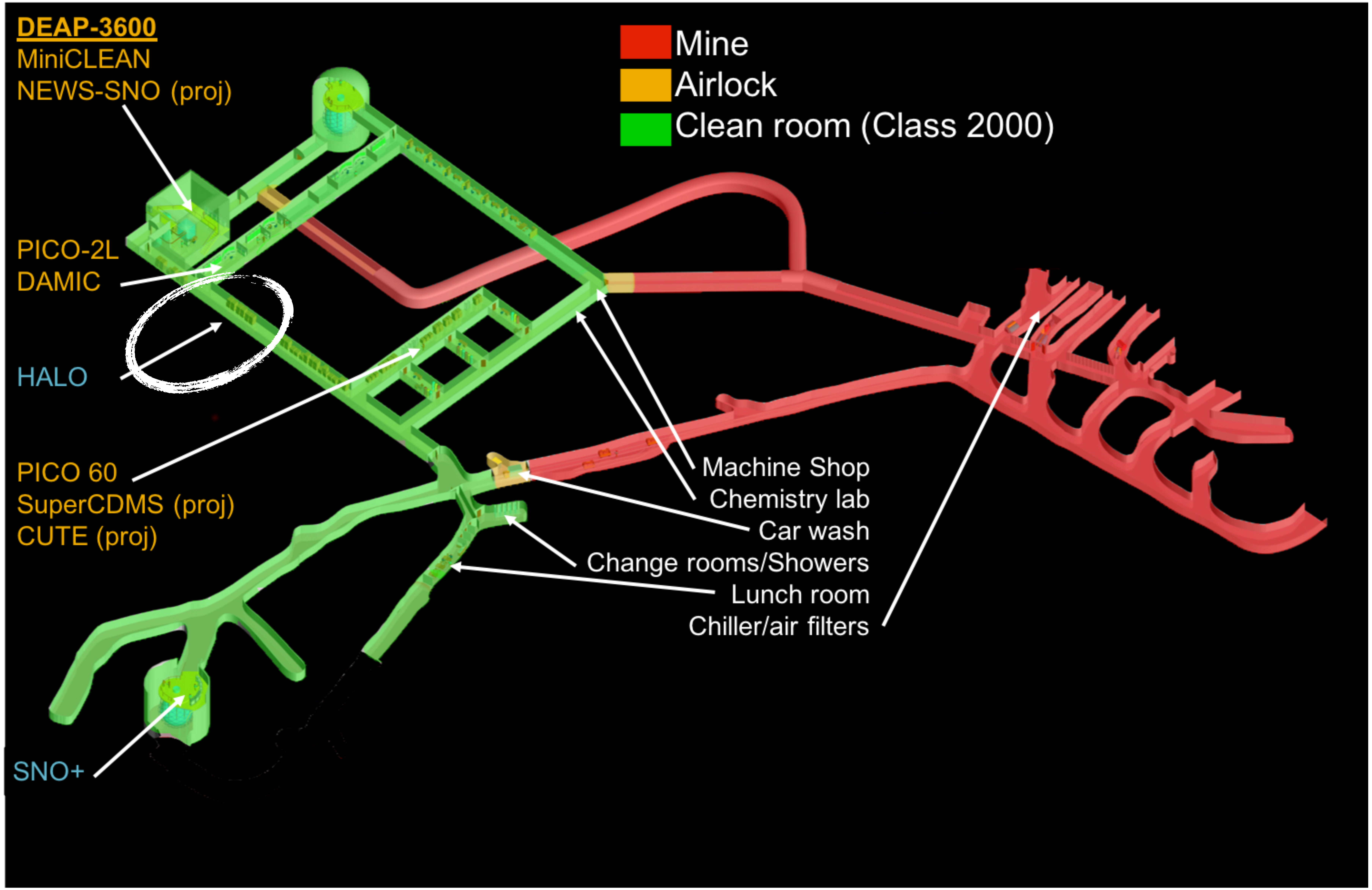
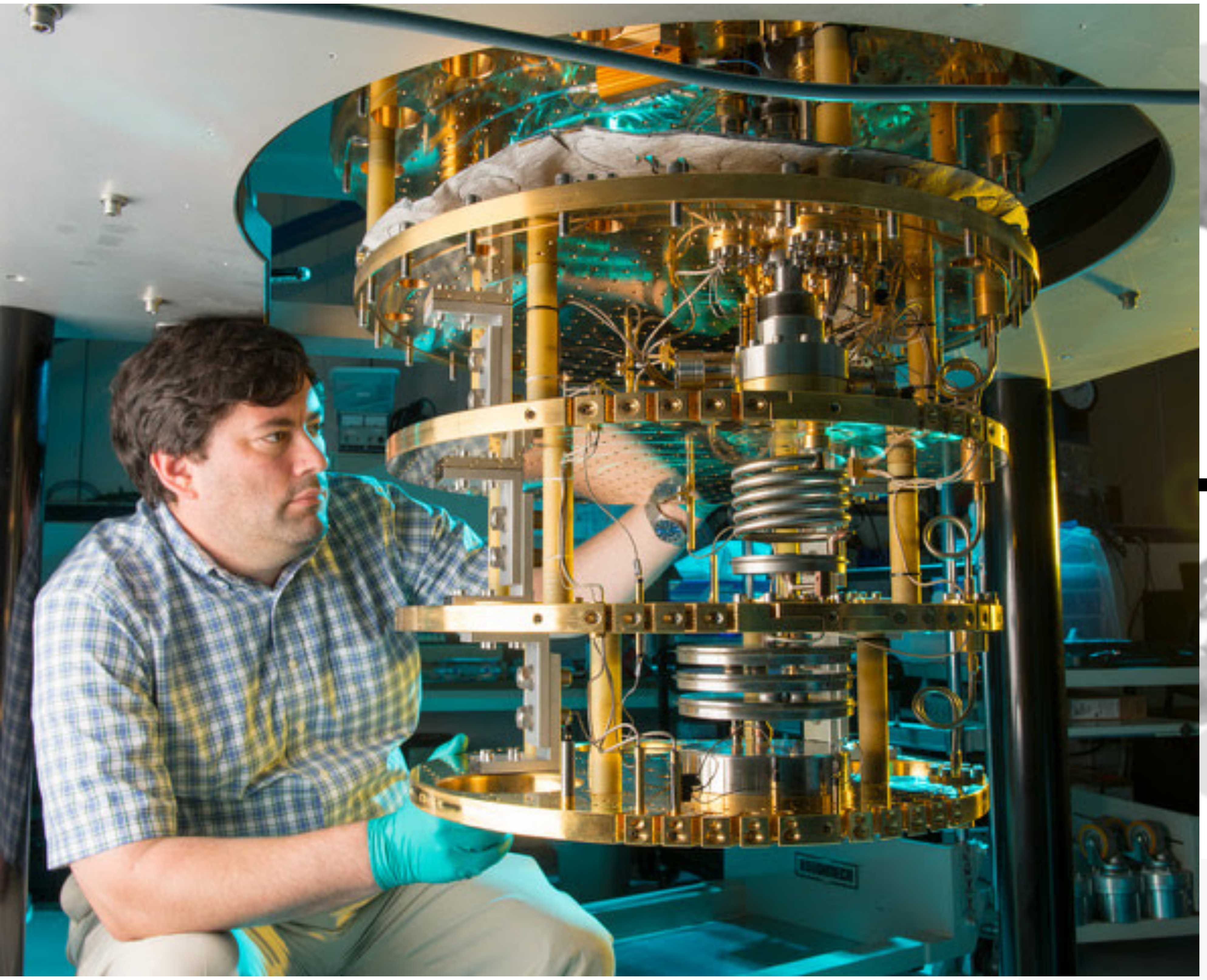
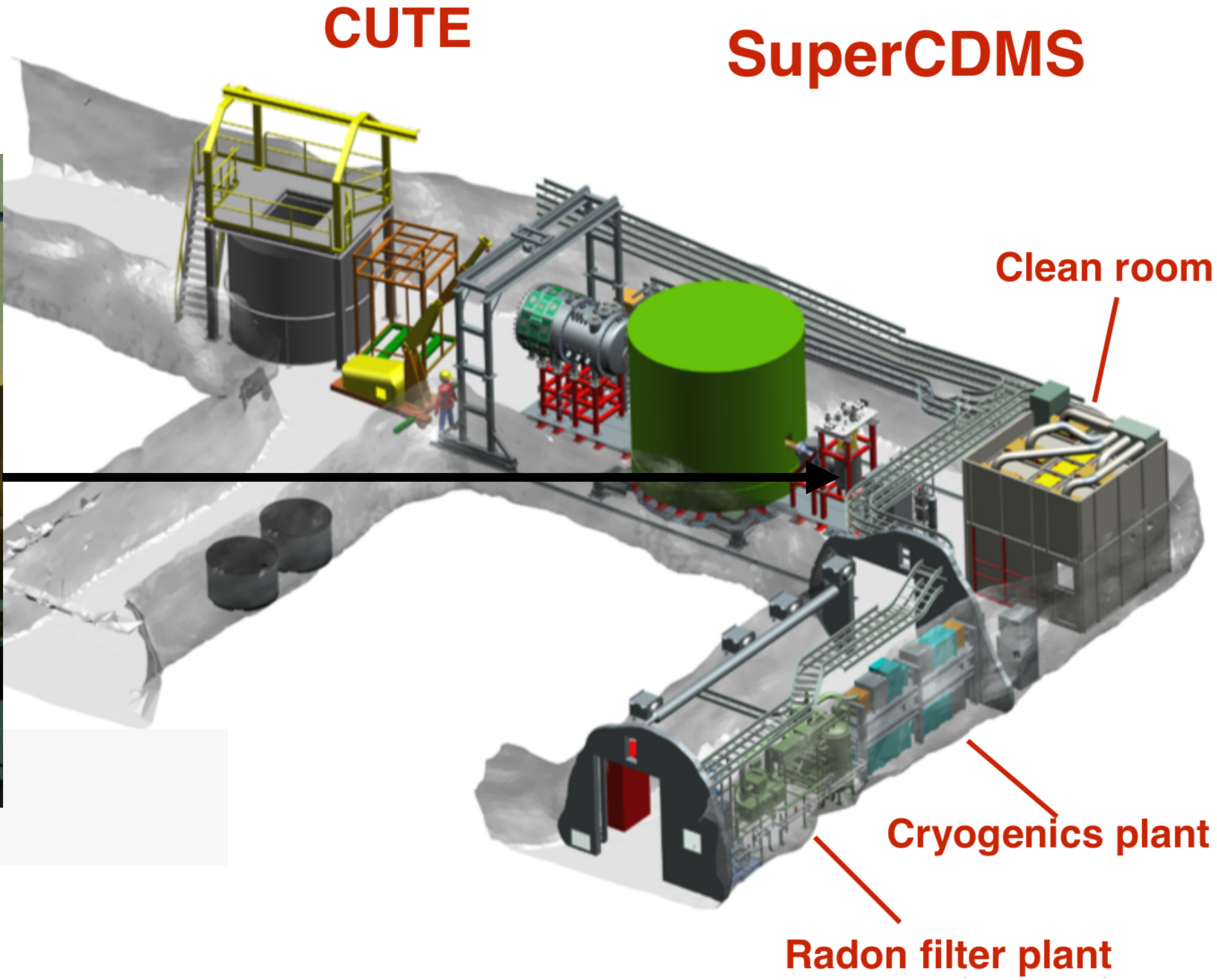


SNOLAB Cryogenic Facilities

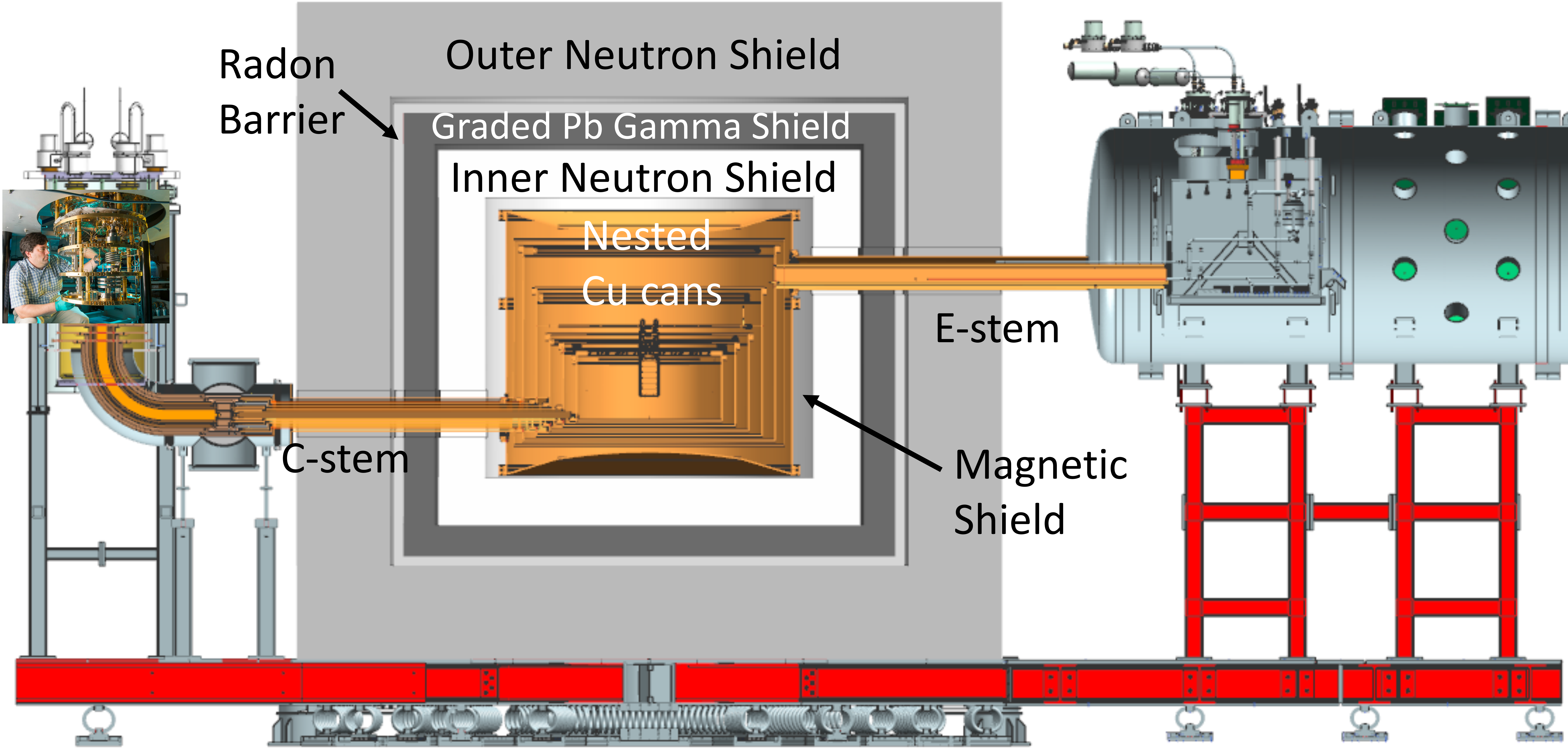


SNOLAB Cryogenic Facilities

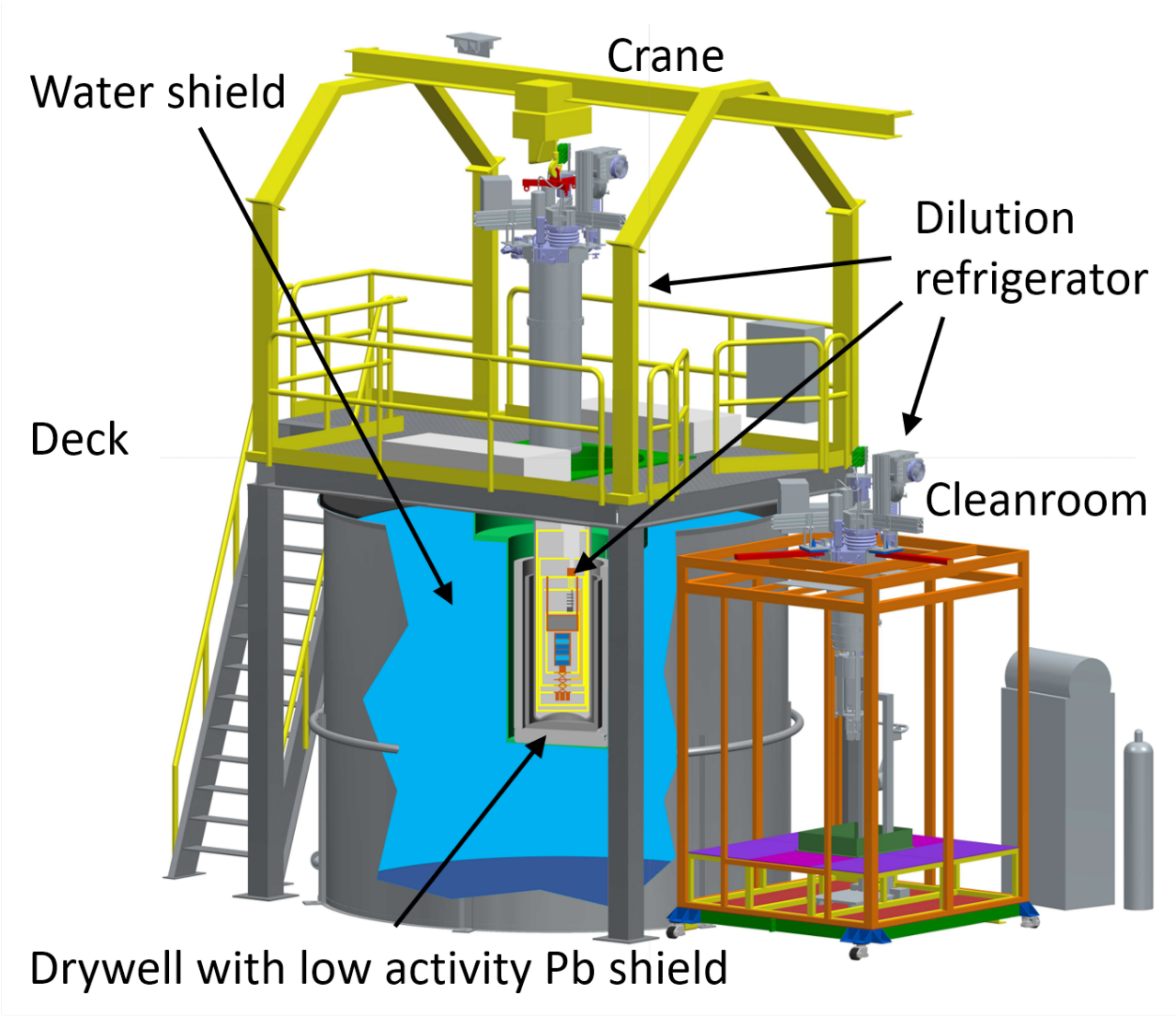




SuperCDMS SNOLAB: Premier Cryo Facility for the Future



Cryogenic Underground TEst Facility



Motivation

- Above-ground testing exposes detectors to cosmogenic radiation / activation
- Large rate at surface may lead to constant pile-up
- Discrimination power (ER/NR) measurement requires absence of neutrons

⇒ need for a well shielded underground test facility

Design

- 3.6 m water tank (n and γ shielding), w/ drywell for fridge
- ~12 cm of low-activity Pb inside drywell; 15 cm of Pb inside the fridge (between active components and detectors) to shield direct line of sight from top, 20 cm PE above cryostat
- Low-Rn purge gas expels lab air from drywell
- Clean room for payload change (filtered low Rn air)
- Cryostat mounted on soft dampers to minimize vibration transmission.
- Holds up to 6 SuperCDMS SNOLAB detectors

Cryogenic Underground TEst Facility

Status

- Completed / commissioned in 2019
- Performance validation measurements:
  - Cryogenics: Base temperature w/ detectors: 12 mK
  - Background: <10 evts/keV/kg/day above 10 keV
  - Vibration mitigation effective
- Detector testing for SuperCDMS:
  - Small devices
  - X-ray / γ calibrations (^{55}Fe, ^{133}Ba)
  - SuperCDMS Pathfinder testing upcoming
- SuperCDMS Data Challenge
  - Same DAQ system as SuperCDMS
  - Full test of data transfer/processing

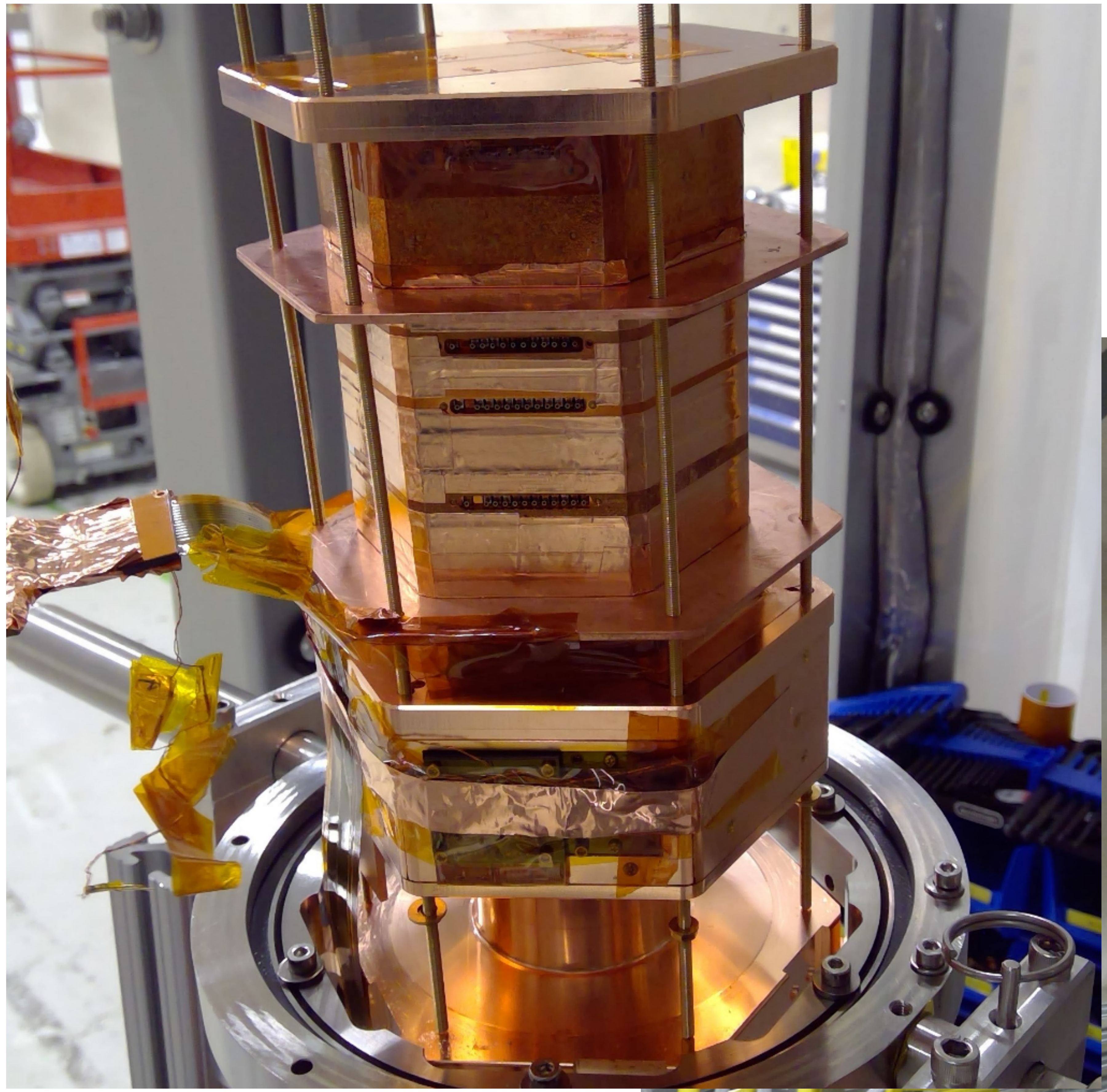
Plans

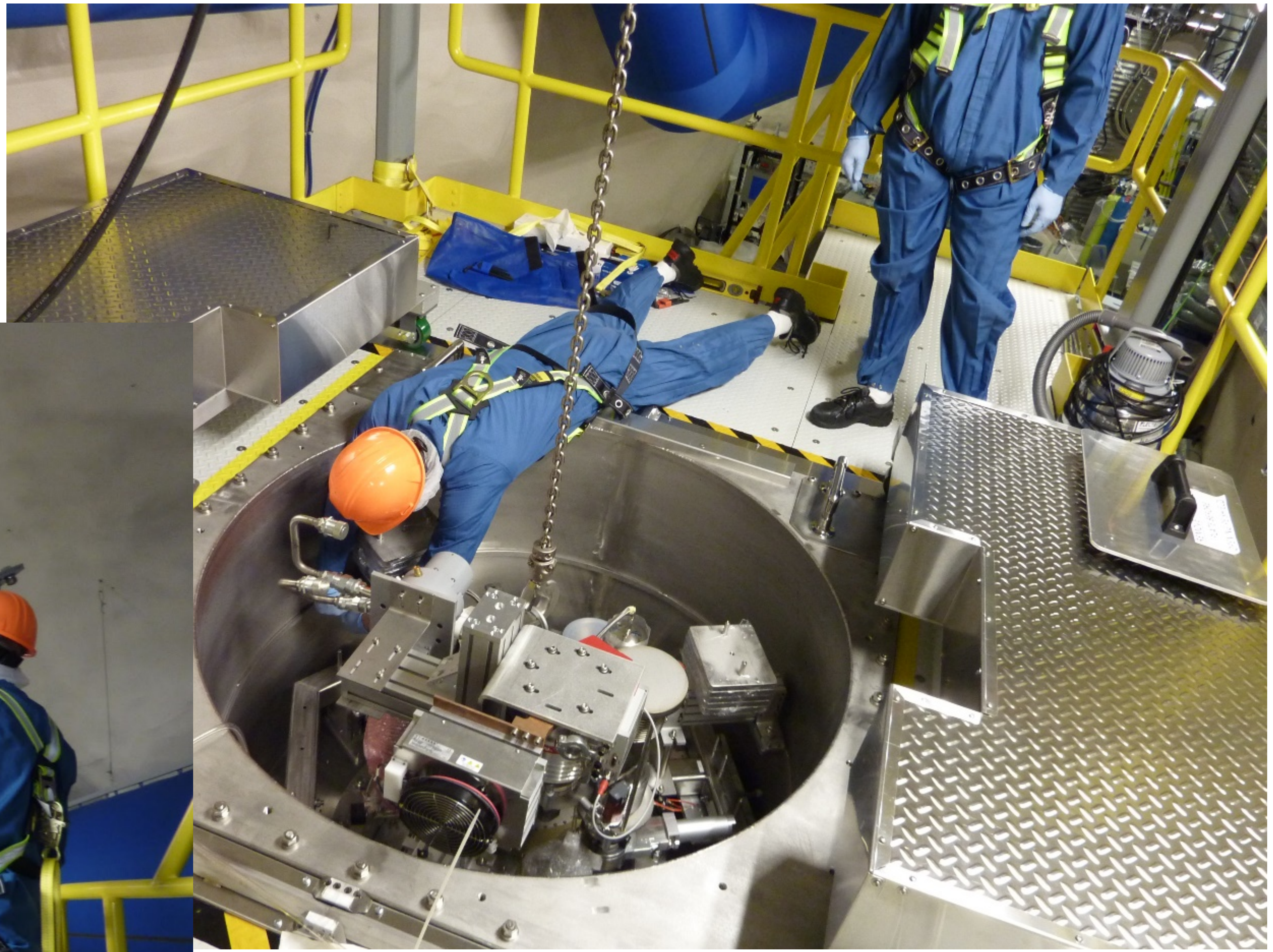
- 2021/22:
  - SuperCDMS Pathfinder and Tower testing
  - First DM search with SuperCDMS detectors as time allows
- Later: open for future projects
  - SuperCDMS upgrades
  - Cryogenic detector testing for other projects
  - Small scale rare event searches with cryogenic detectors
  - Other cryogenic low-background tests (e.g. cryogenic Q-bits)
- Continued facility improvements
  - Facility reliability / ease of operation
  - Background improvements
  - Noise reductions
  - …

Cryogenic Underground TEst Facility

Moving fridge between
drywell and cleanroom

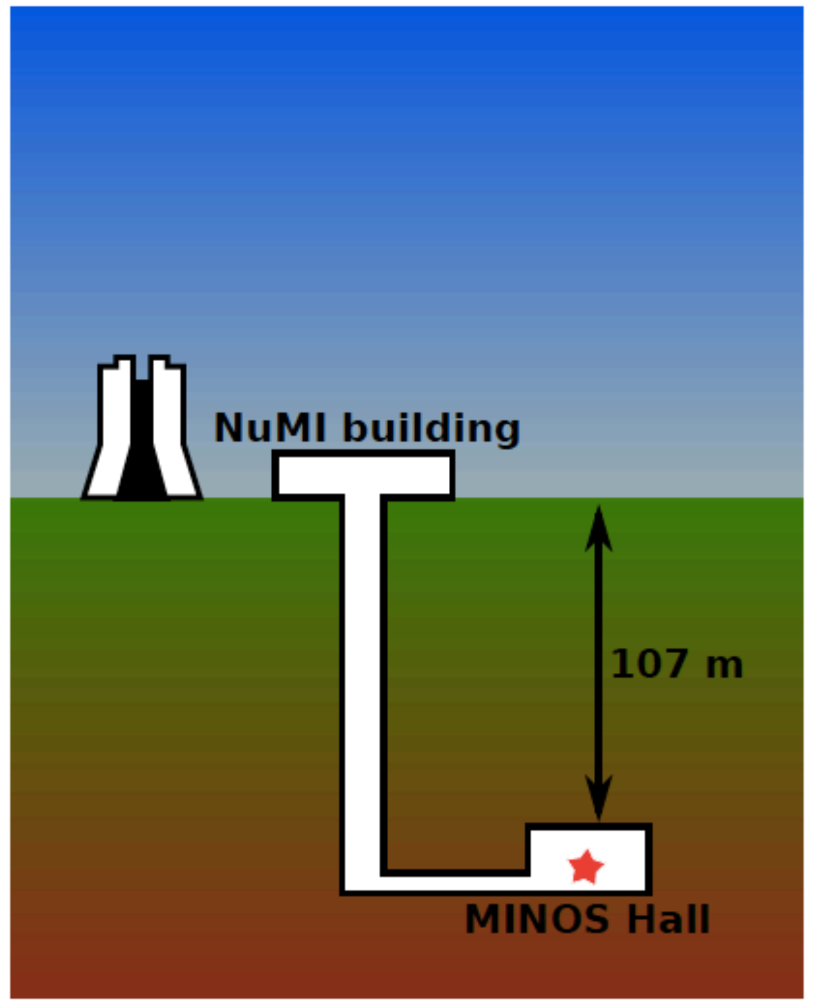
Cryogenic Underground TEst Facility

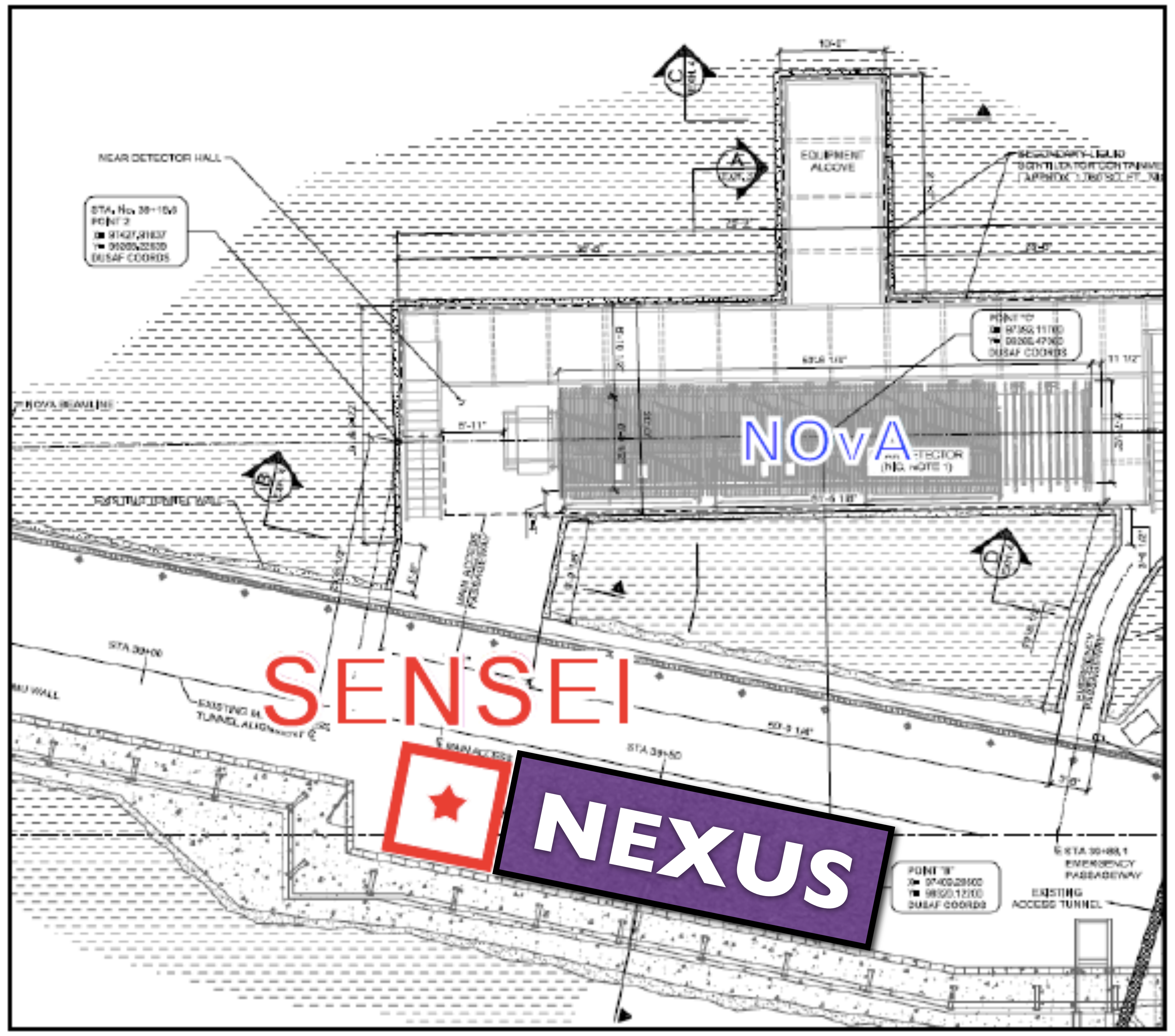




NEXUS@FNAL Facility

- Northwestern Experimental Underground Site at Fermilab
- Underground cryogenic facility in class 10,000 clean room
- Vibration-isolated dry dilution refrigerator with 8mK base temperature
- 107 m depth (300 meters water equivalent) + lead shielding
    - Design background < 100 events/keV/kg/day
- Optical fiber, neutron, gamma calibration sources



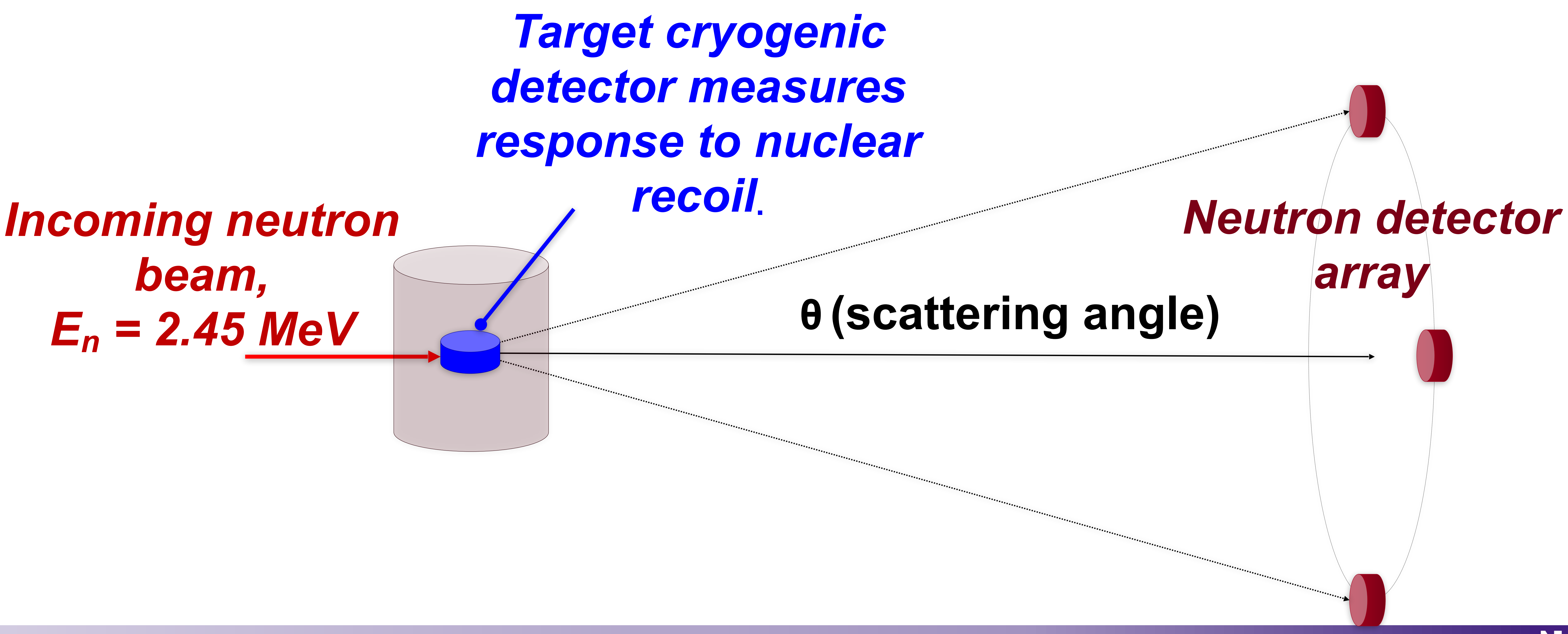



Northwestern
NEXUS
Experimental
Underground Site
@Fermilab
DD
Generator
Dilution
Refrigerator
Location for
Backing Array

Detector Calibration via Scattering Angle Measurement

- A standard way characterize detector response to nuclear recoils is with a neutron scattering setup
- Precise knowledge of the scattering angle provides the recoil energy in the detector
- The detector signal can then be calibrated as a function of neutron recoil energy

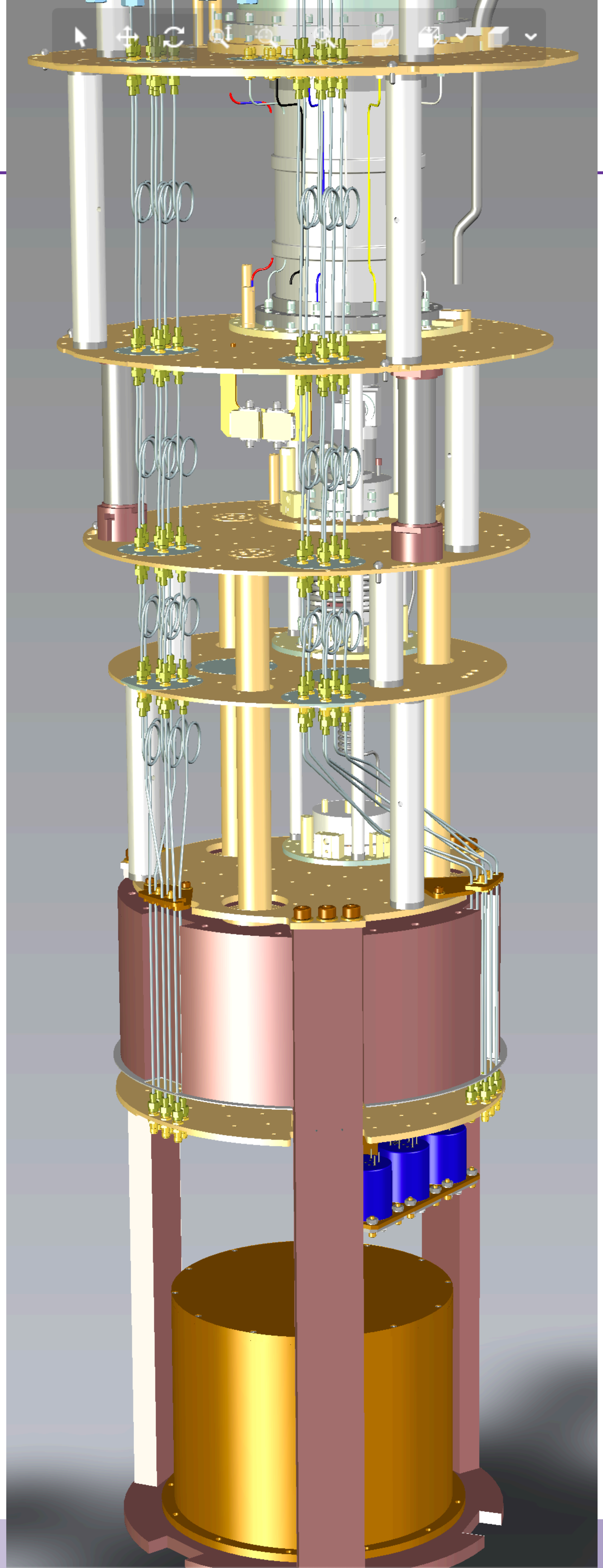
$$E_{\text{recoil}} = 2E_n \frac{M_n^2}{(M_n + M_T)^2} \left(\frac{M_T}{M_n} + \sin^2\theta - \cos\theta \sqrt{\left(\frac{M_T}{M_n}\right)^2 - \sin^2\theta} \right)$$



Experimental Space

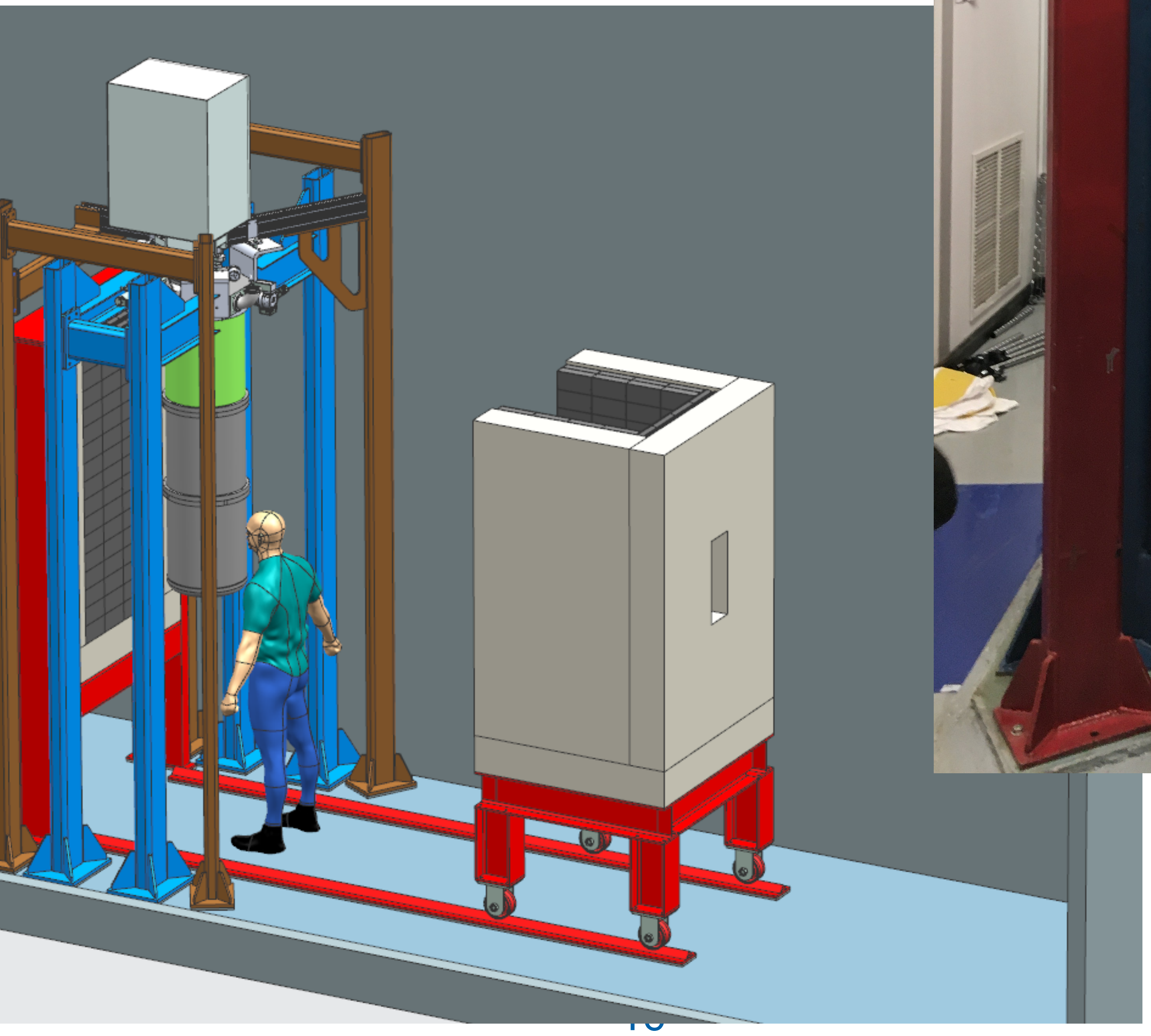
Northwestern NEXUS Experimental Underground Site @Fermilab

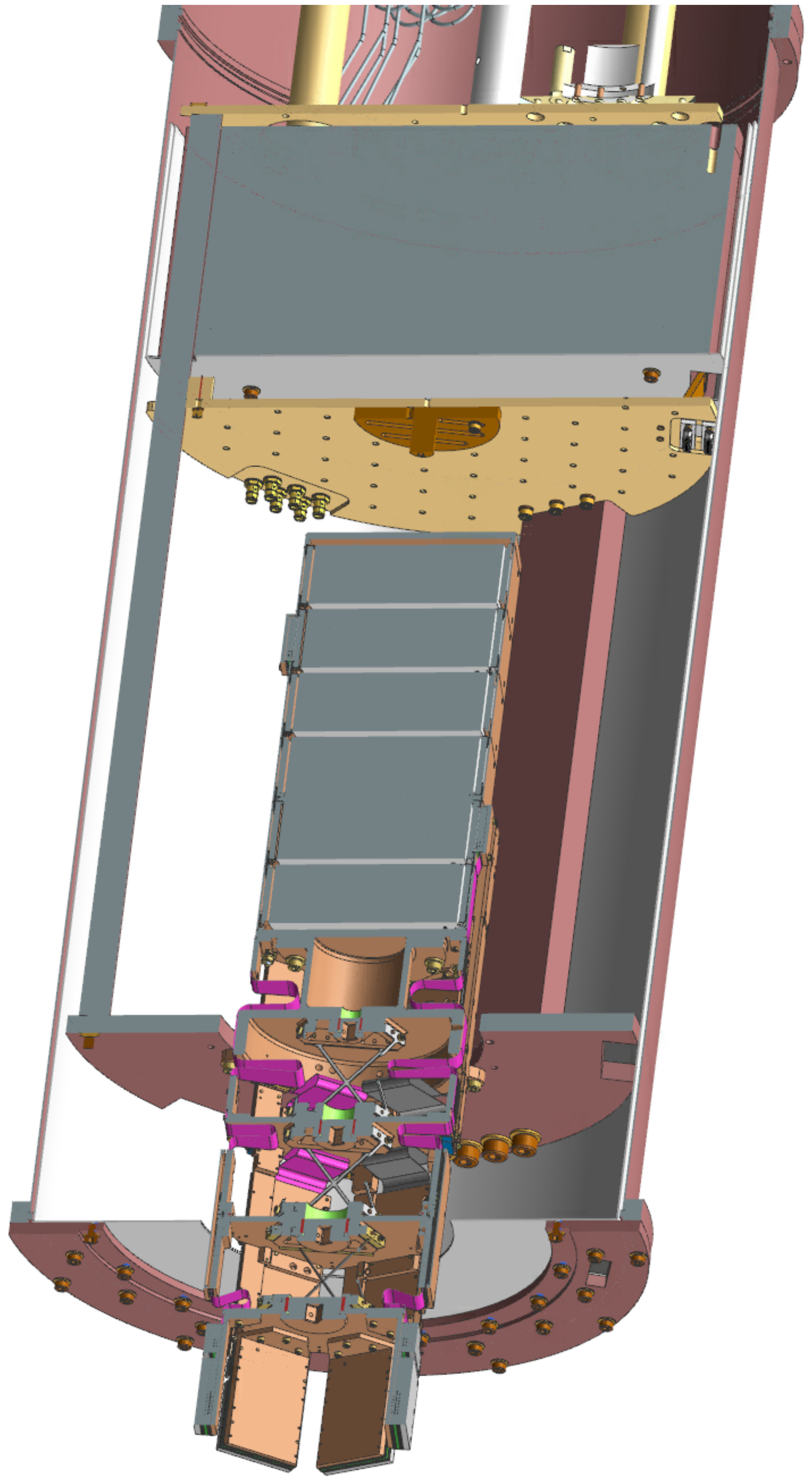
- Experimental space: 500 x 300 mm
- Readout: 8 DC SQUID channels (expanding to 12)
- 6 4-wire measurement channels
- 10 RF channels being installed right now!

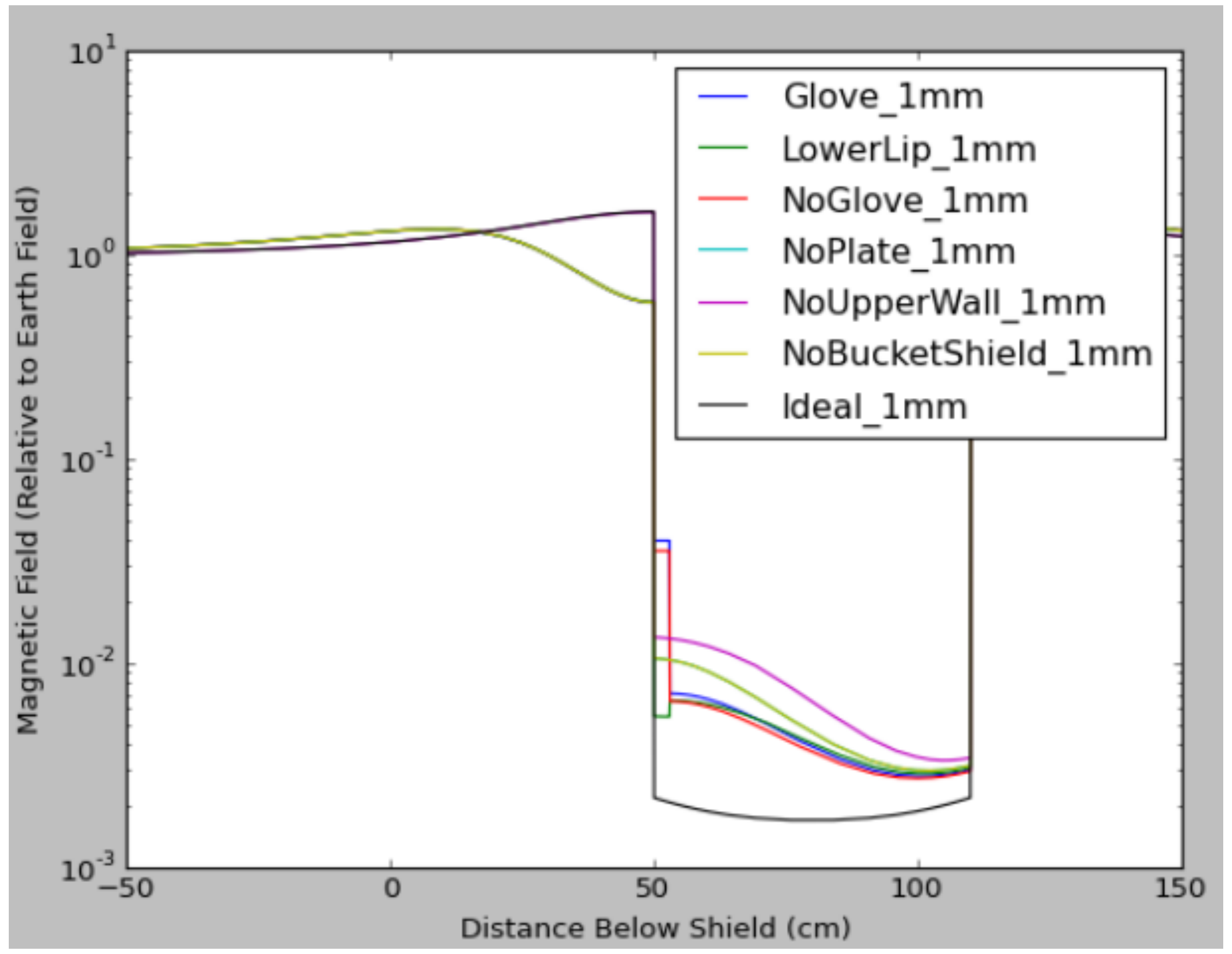


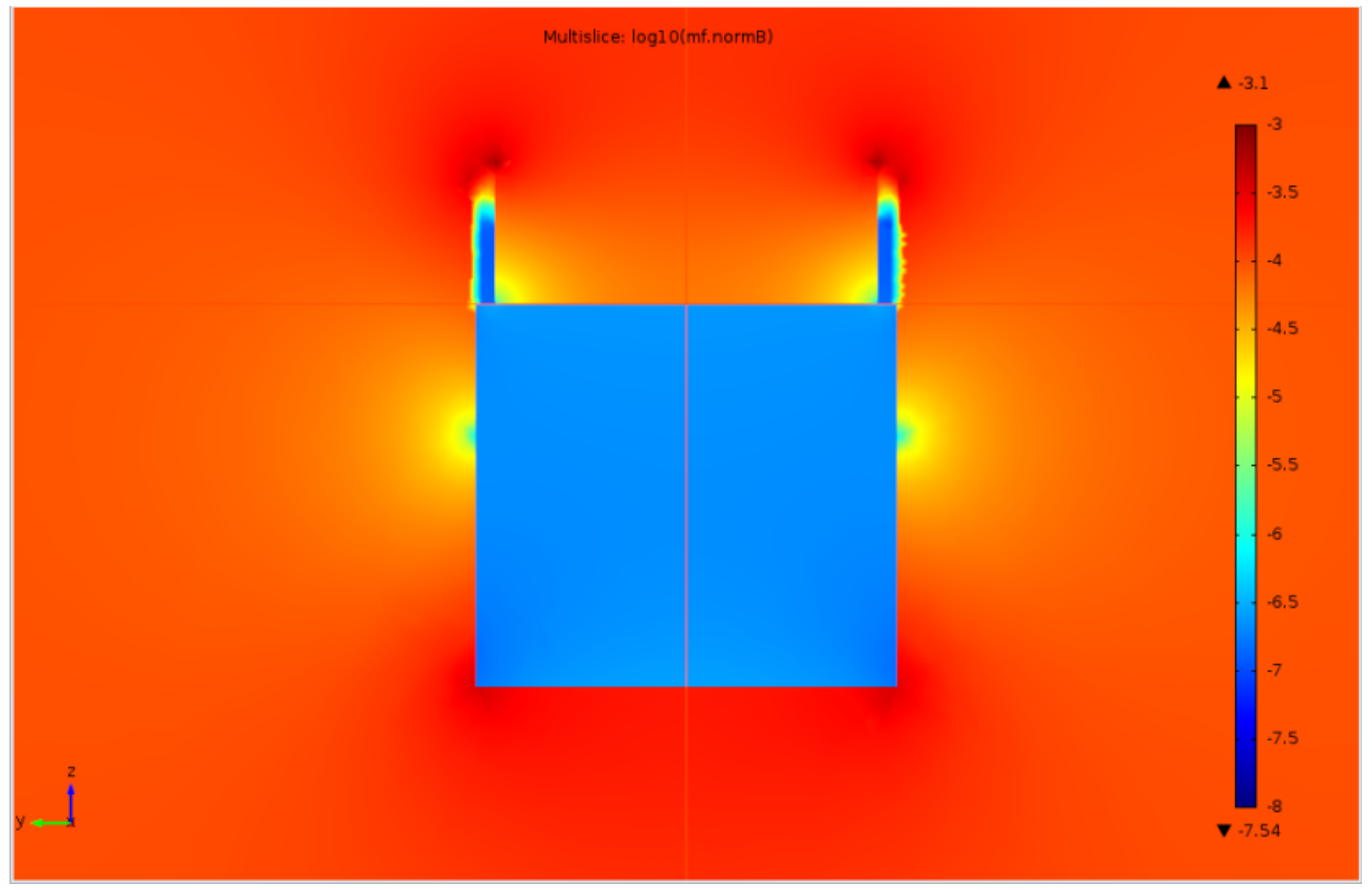
NEXUS Gamma and Magnetic Shielding

Northwestern NEXUS Experimental Underground Site @Fermilab







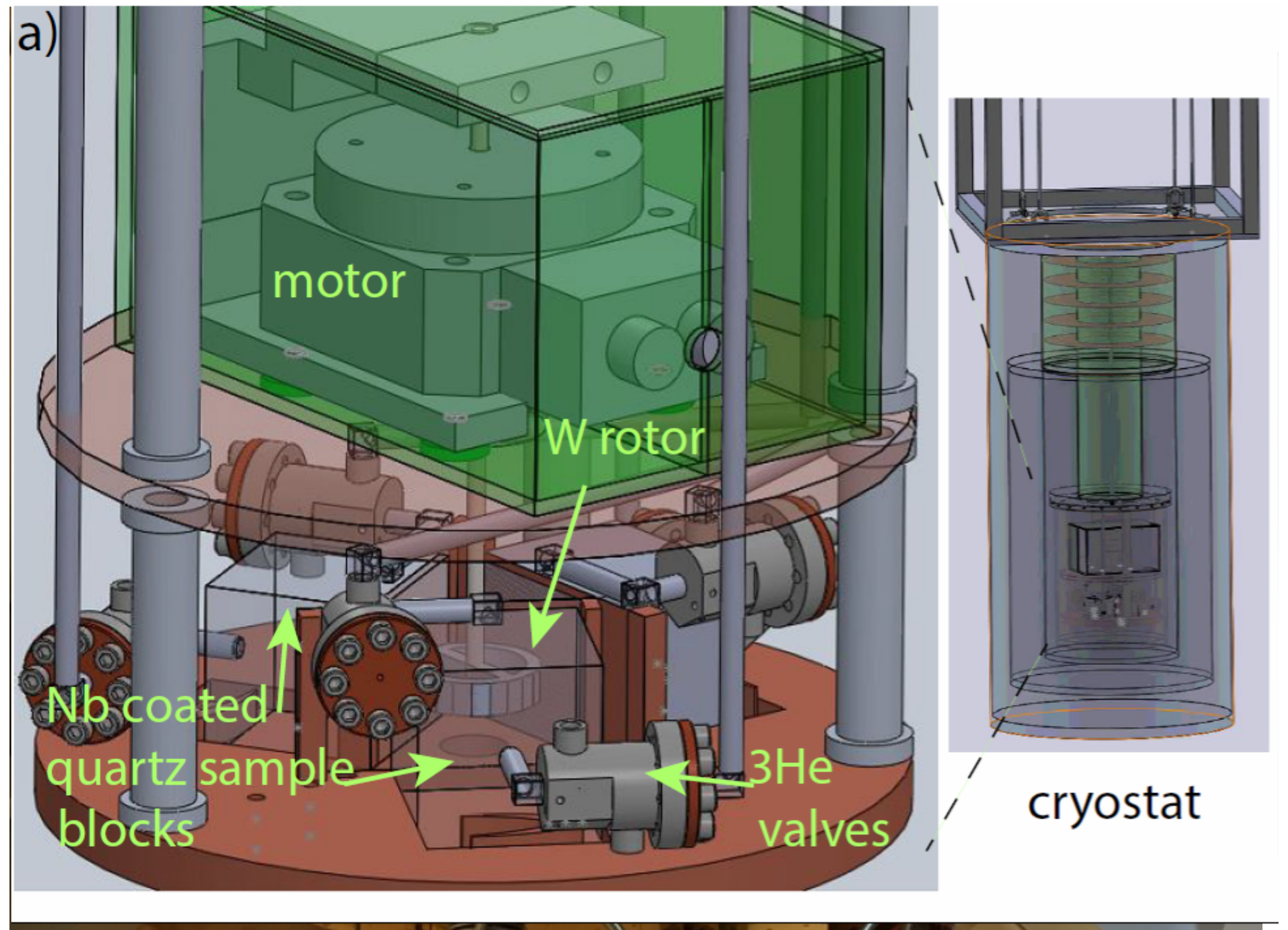


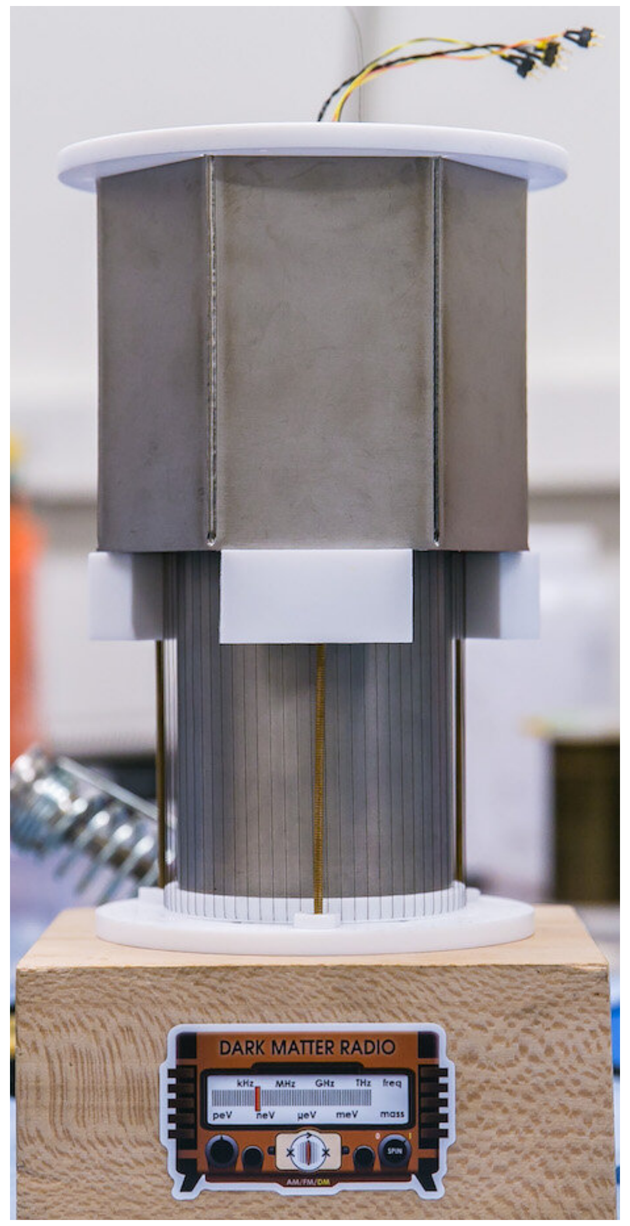
Other Particle Dark Matter Experiments Using Cryogenics

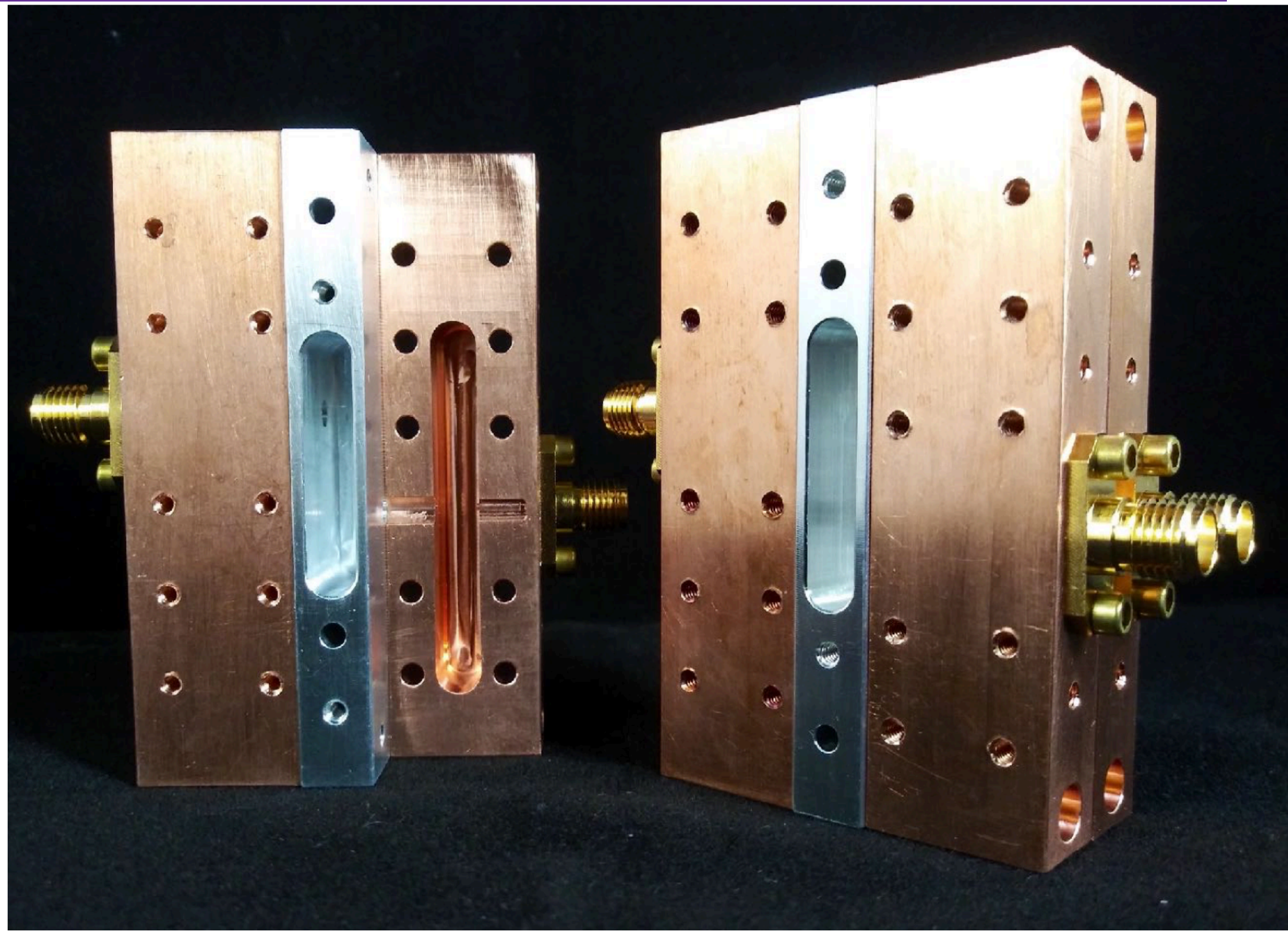
- EDELWEISS (Ge) / CRESST (CaWO+)
- SPICE (Polar Crystals) / HeRALD (Superfluid He)
- Cryogenic needs:
  - Volume and cooling power are adequate with current existing designs.
  - Vibration Isolation from Dry Dilution Refrigerators is key!
  - RF shielding important as well

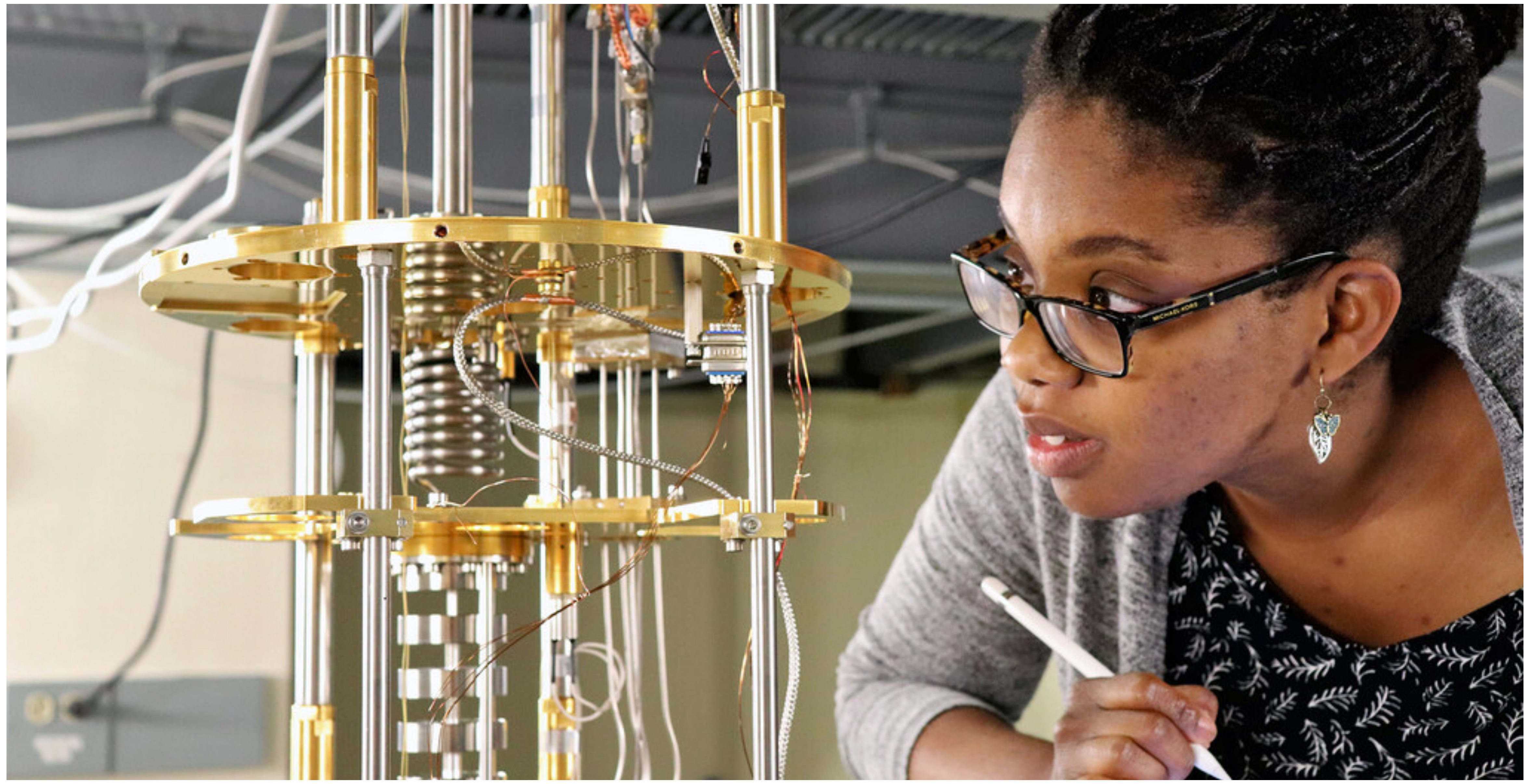
Wave-like Dark Matter Searches using Cryogenics

- ADMX / HAYSTAC
- DM Radio
- ABRACADABRA
- CASPEr
- ARIADNE
- Qubit searches
- Others…







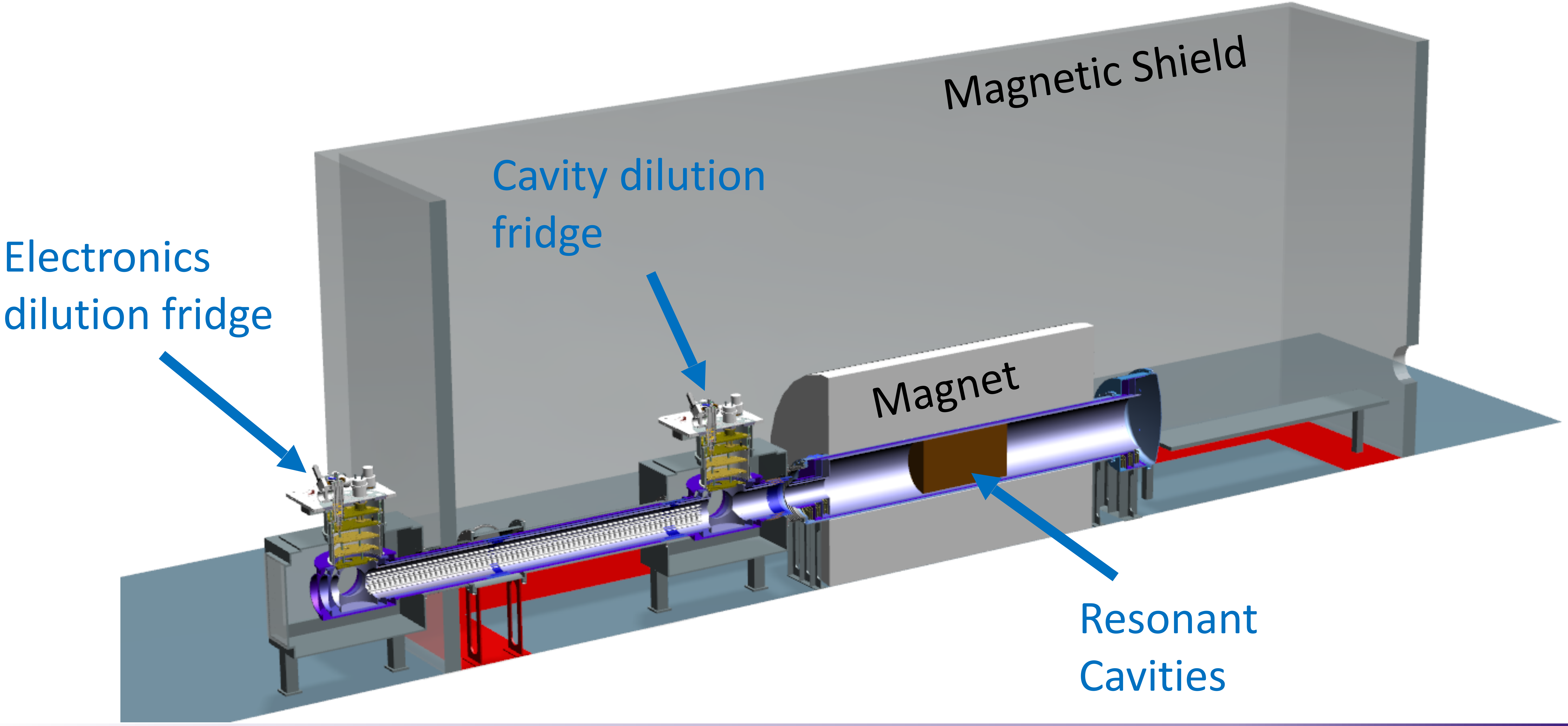


Wave-like Dark Matter Searches using Cryogenics

- ADMX / HAYSTAC
- DM Radio
- ABRACADABRA
- CASPEr
- ARIADNE
- Qubit searches
- Others…

- Need to build expertise and best practices in integrating pulse tubes, fast cooling, and dilution units with custom thermal shields and vibration isolation.
- Need to build expertise in custom high field large volume superconducting magnets.
- Facility contribution could be millikelvin cryogenic engineering expertise at the labs.
- Perhaps a very large volume magnet facility that multiple axion experiments could utilize?

ADMX 2-4 GHz Cryogenics



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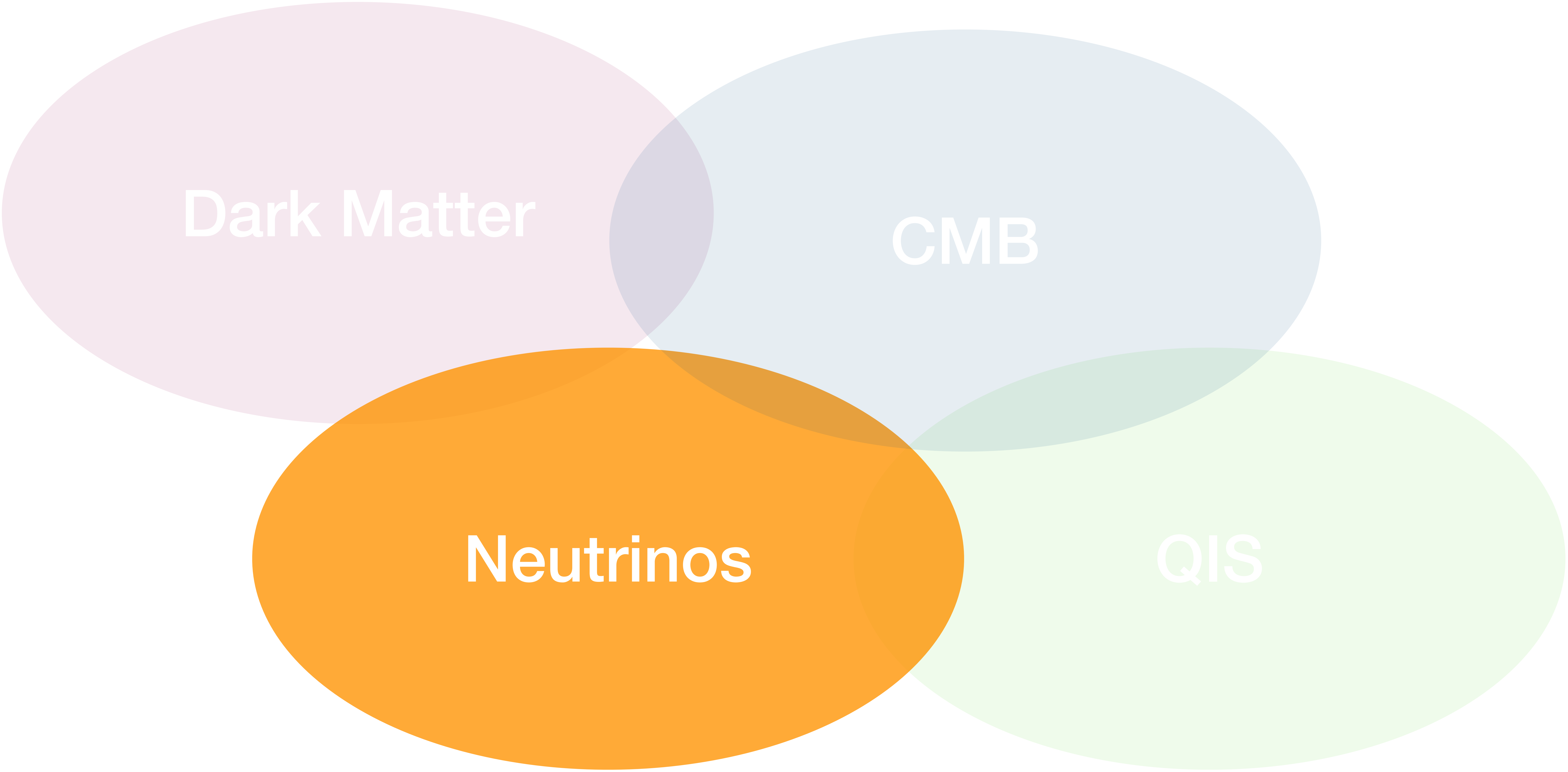
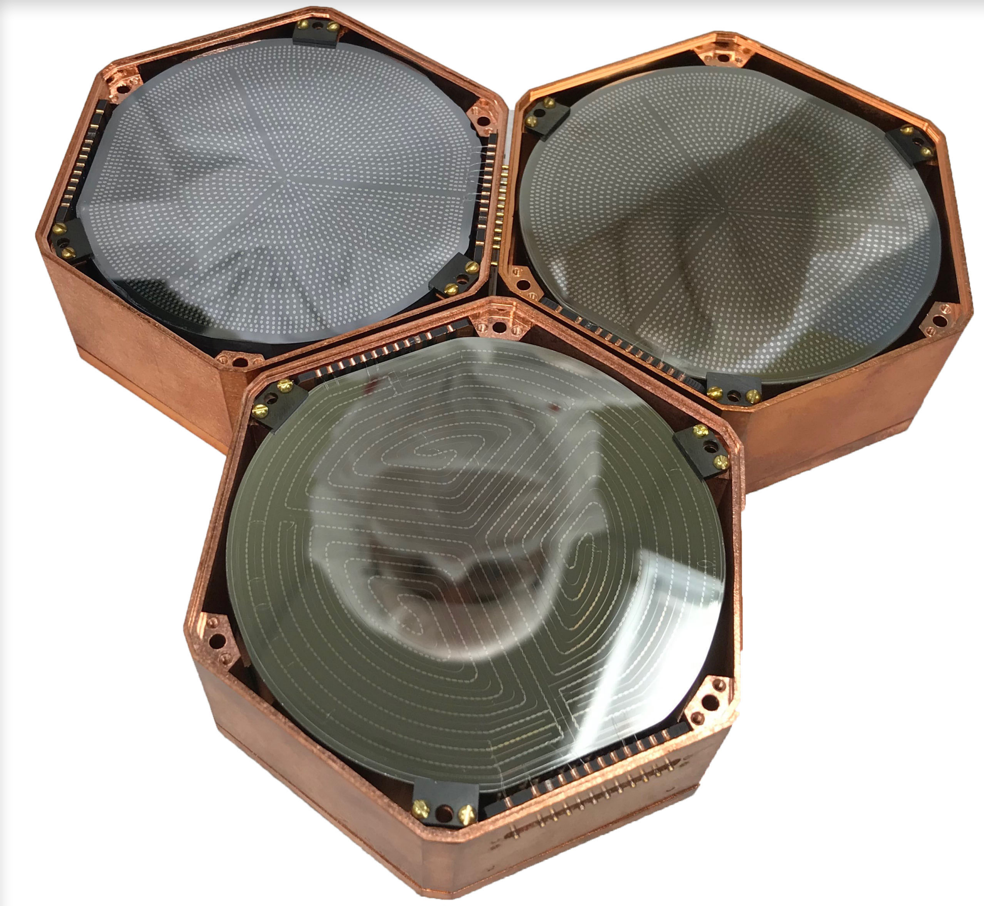
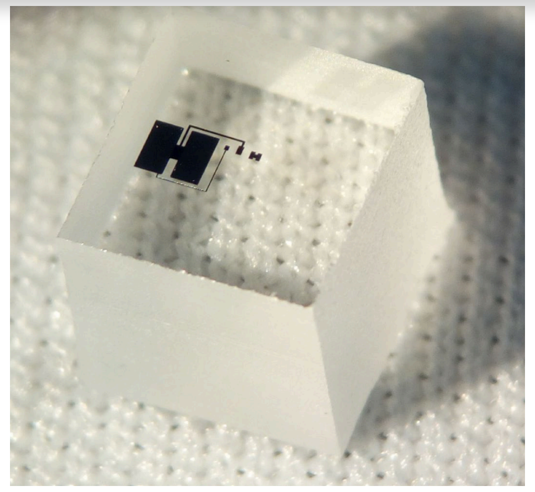
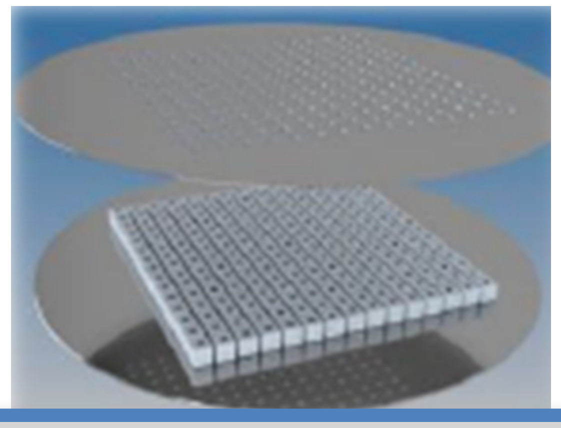
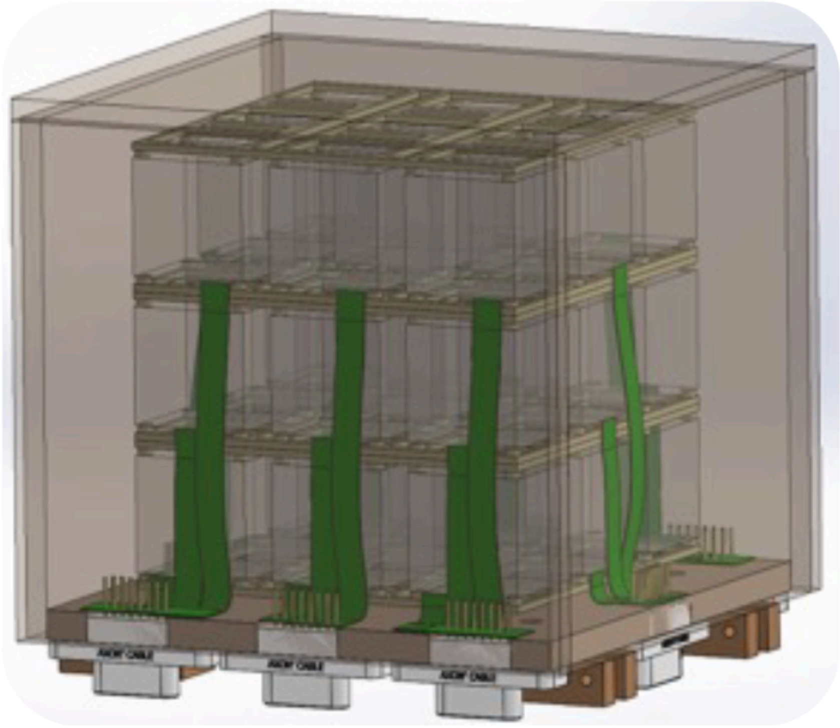
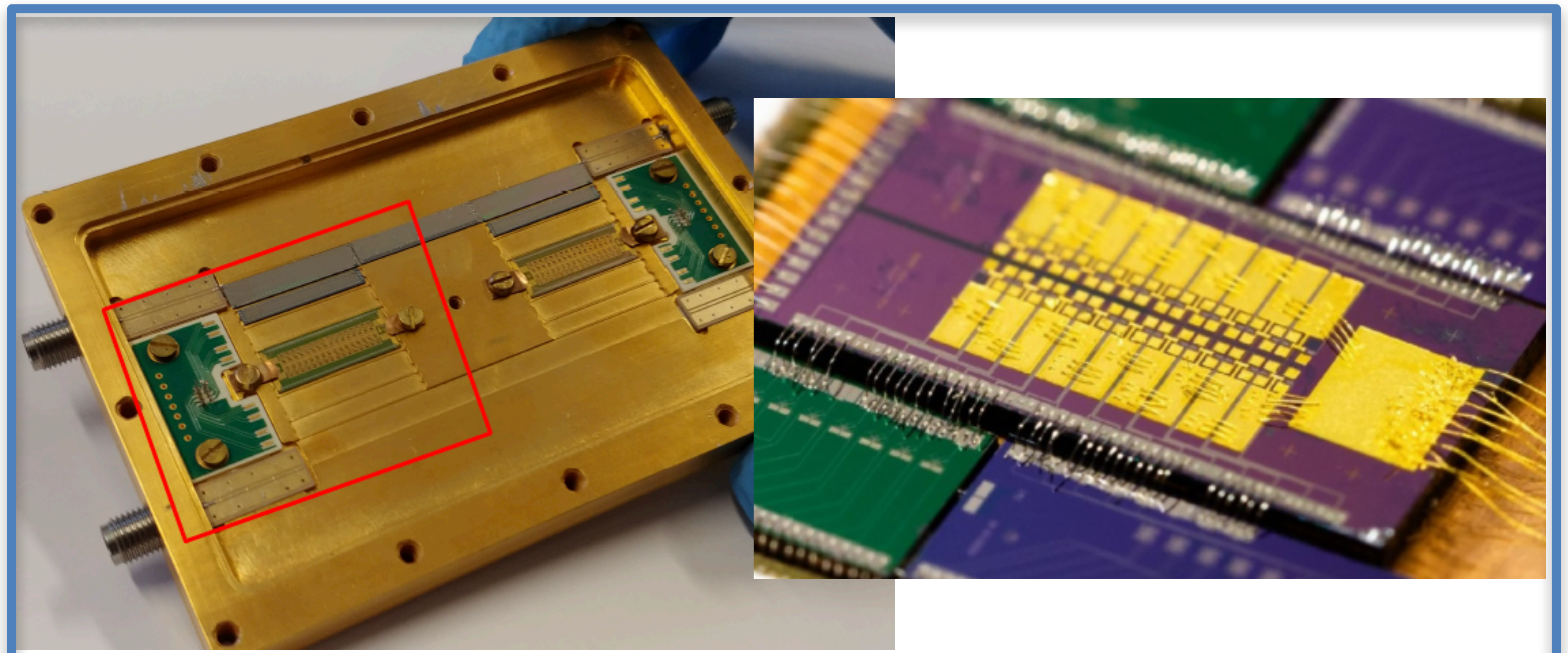
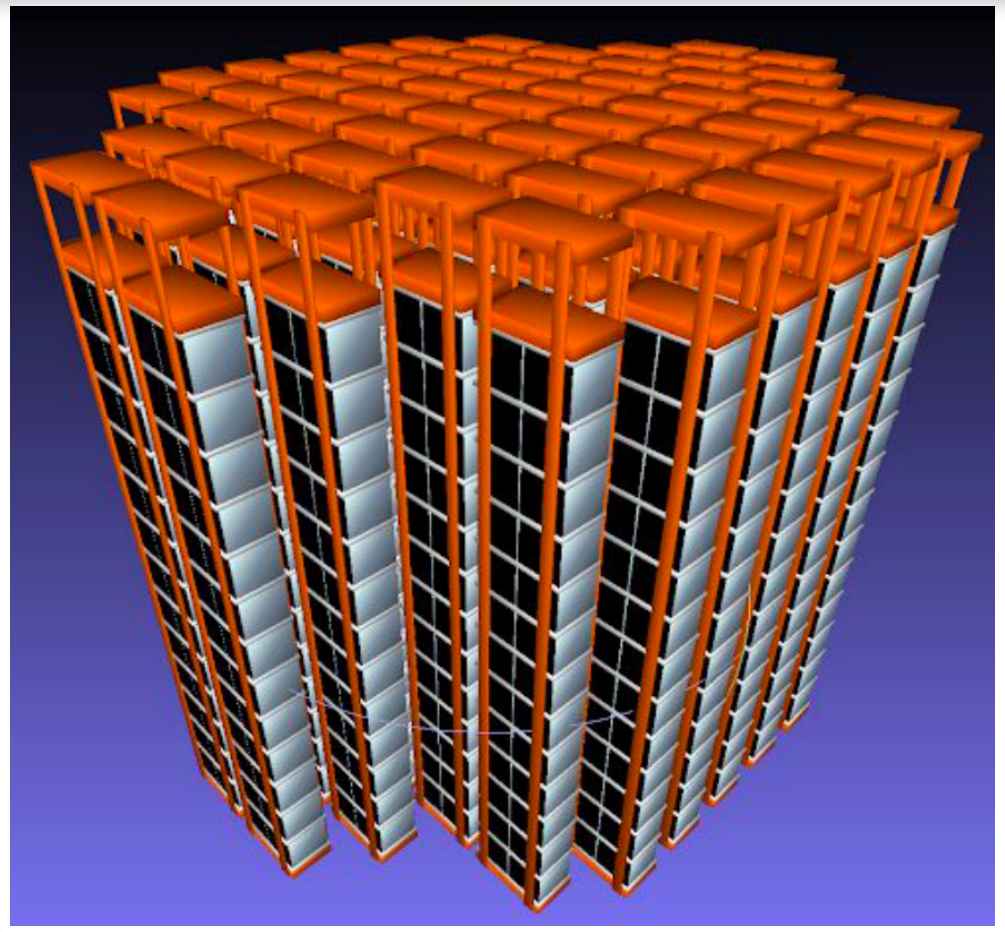
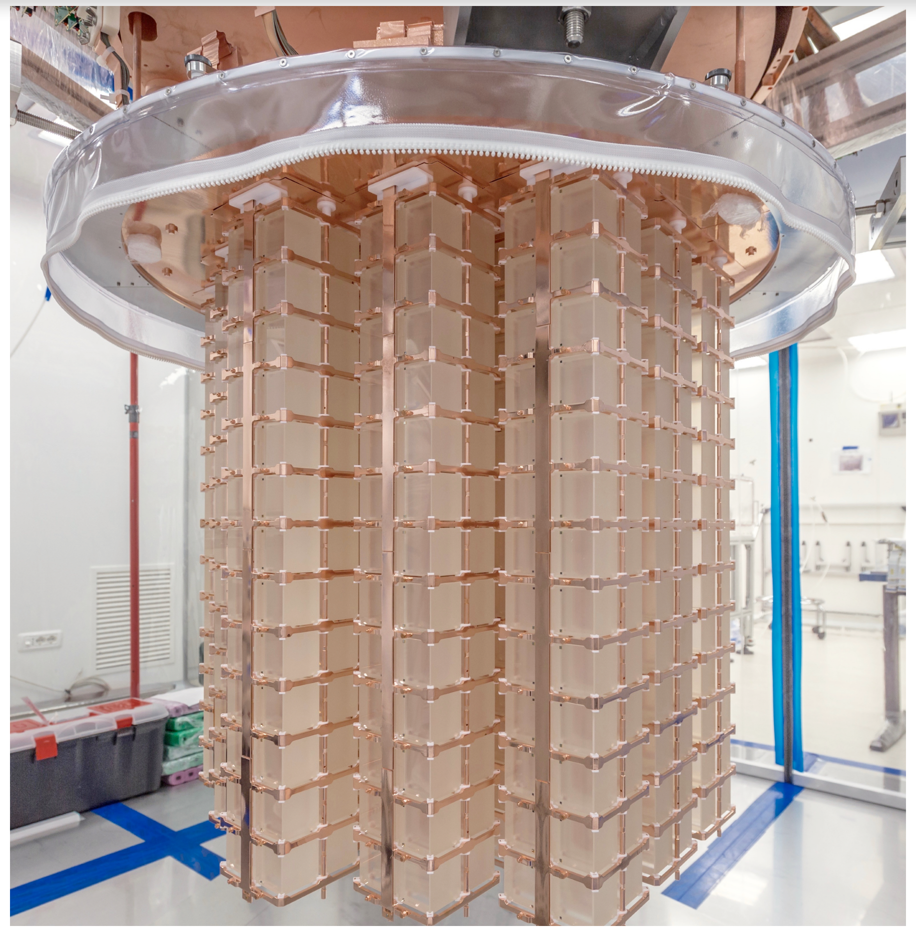
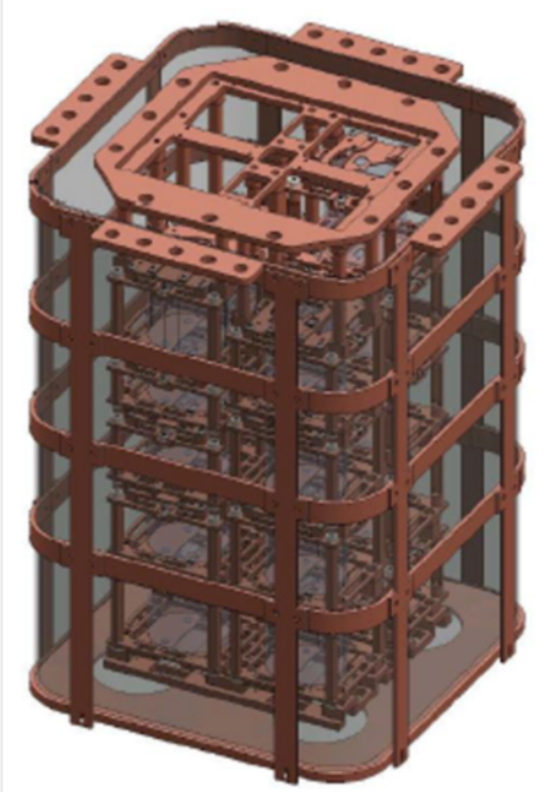


Neutrino Experiments using Cryogenics

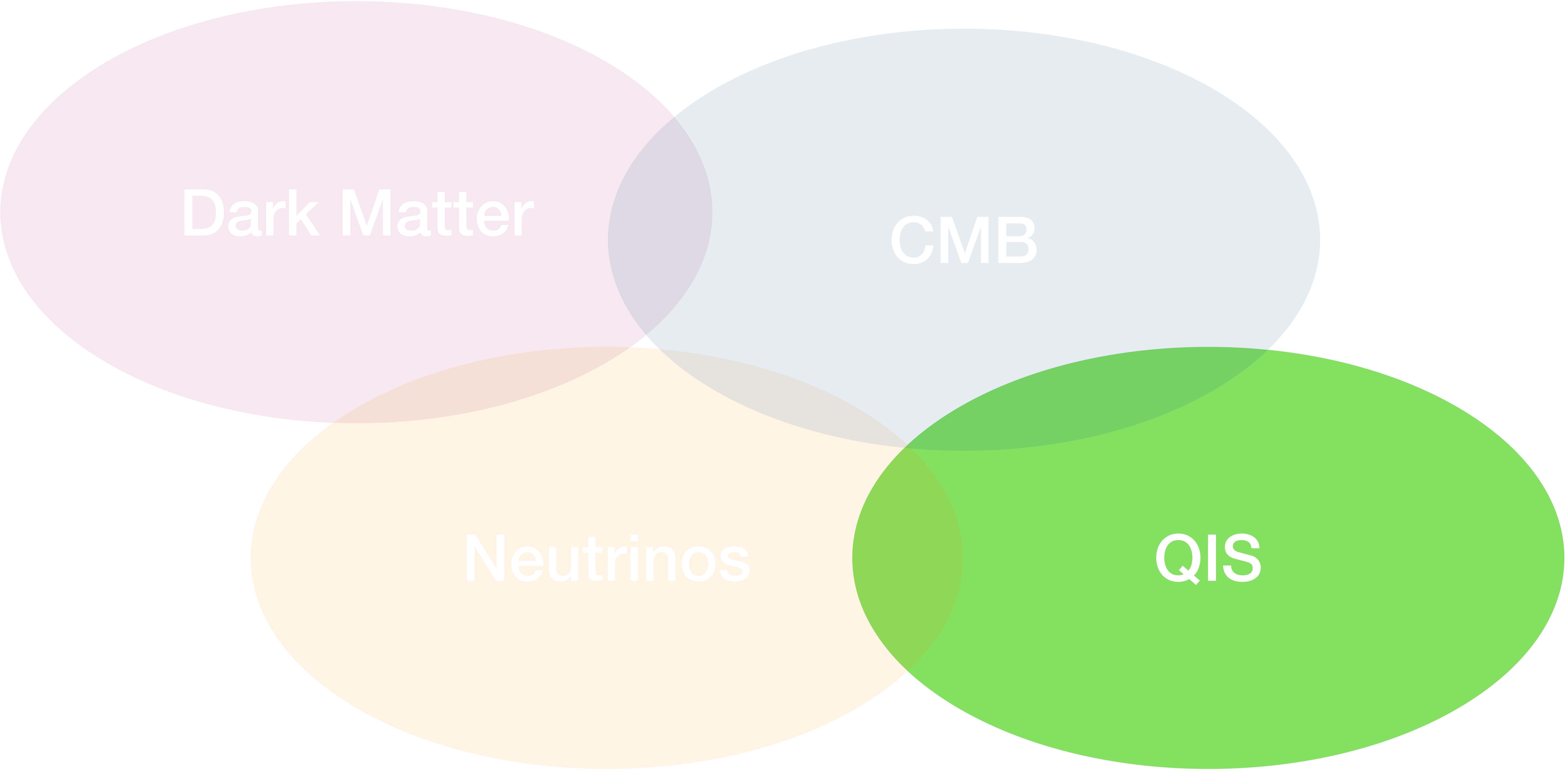
CEvNS
- MINER 100-g scale Ge detectors
- NUCLEUS 1-g scale absorbers ($CaWO_4$, Al_2O_3 - TES) 10 g total,
- Ricochet 40-g scale absorbers (Ge - NTD/TES, Zn with TES readout chip) ~1 kg at ILL reactor 2023

Neutrino Mass
- HOLMES 300 Bq Ho/Au absorber on array of microMUX TESs
- ECHo-1k 1 kBq Ho implanted in a microMUX array of Au/Er Magnetic microCalorimeters (MMCs)

Neutrinoless double beta decay (0nbb)
- CUORE ~750 kg TeO_2, 988 crystals NTD,
  CUPID ~500 kg Li_2MoO_4 ~1600 crystals NTD/TES
  -> CUPID-1ton 1 ton of ^{100}Mo, 2 ton of Li_2MoO_4 TES,
- AMoRE 6 kg (AMoRE I) - 200 kg in ~400 crystals MMC

Cryogenics are Everywhere!



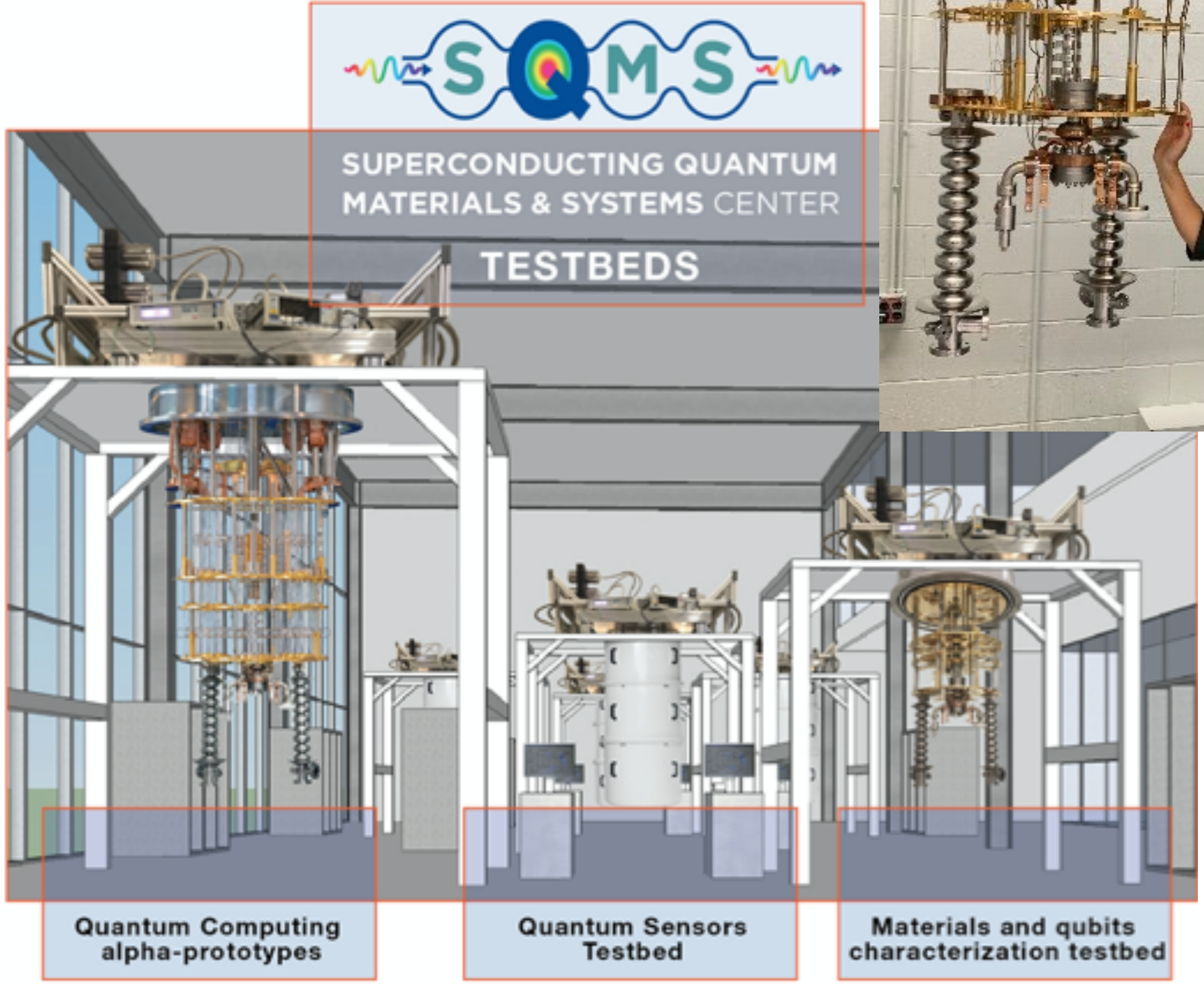
QIS Facilities

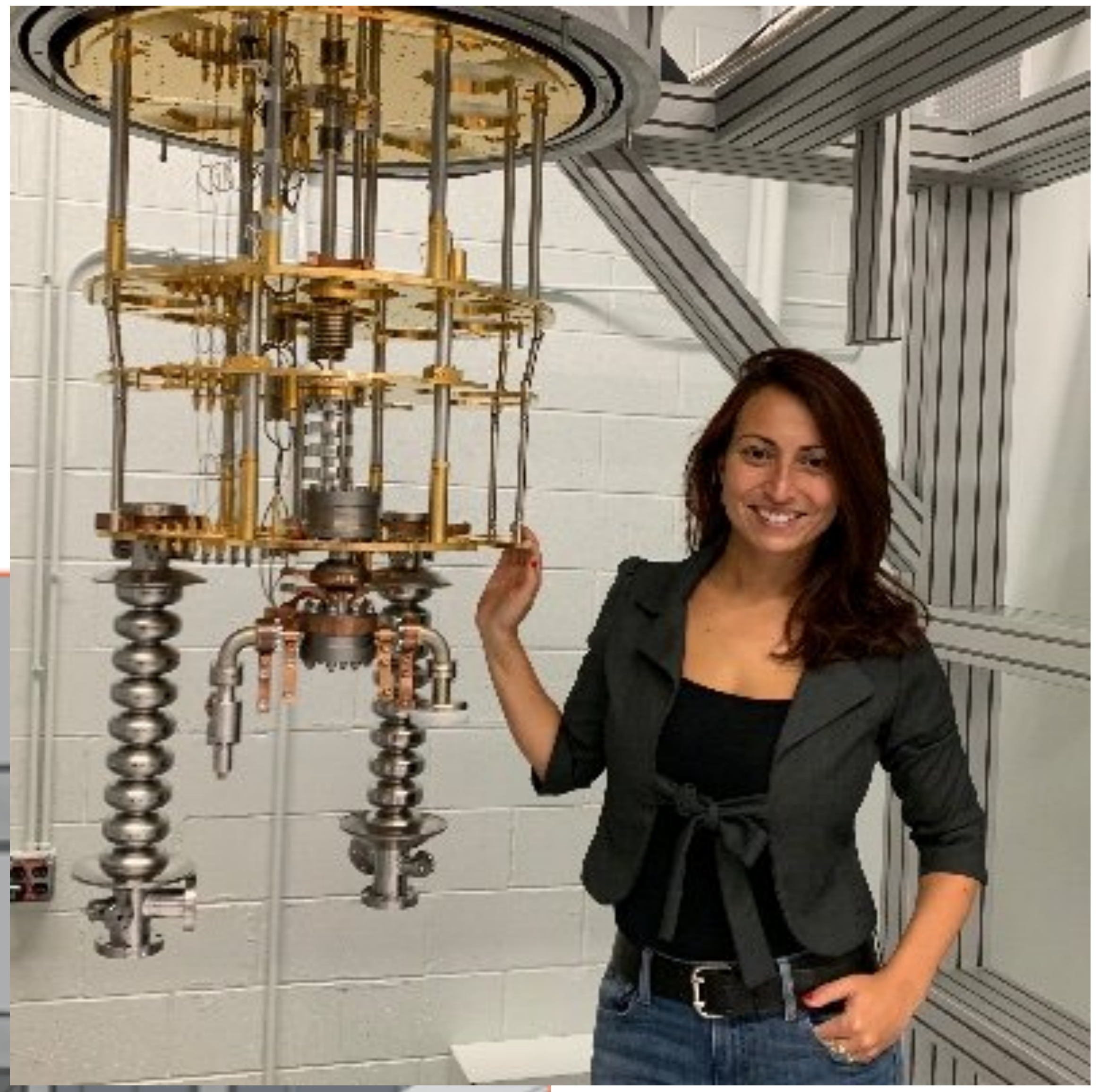
QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem

C²QA
Co-design Center for
Quantum Advantage

Q-NEXT
NEXT GENERATION QUANTUM
SCIENCE AND ENGINEERING

$625 million over five years





Northwestern
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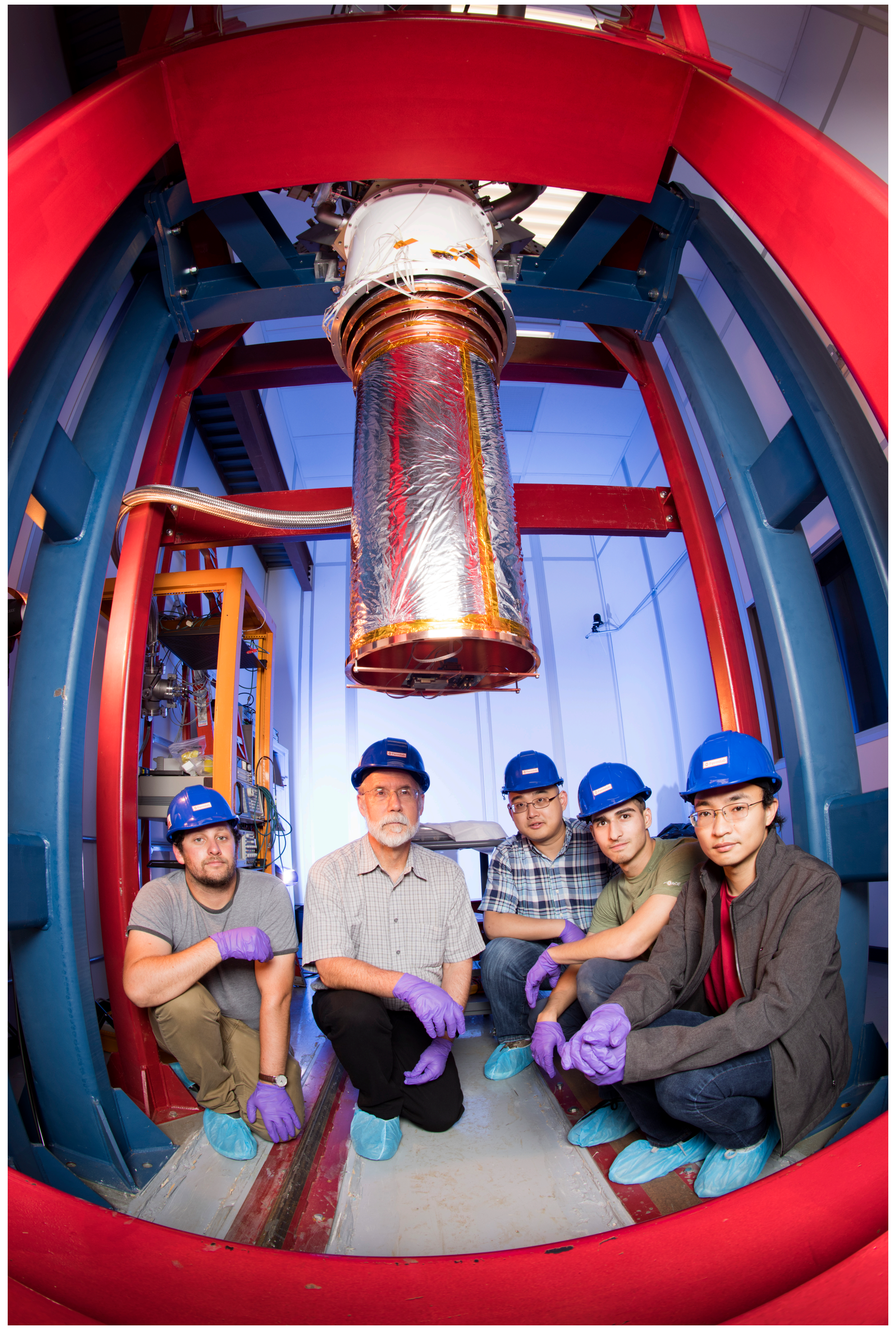
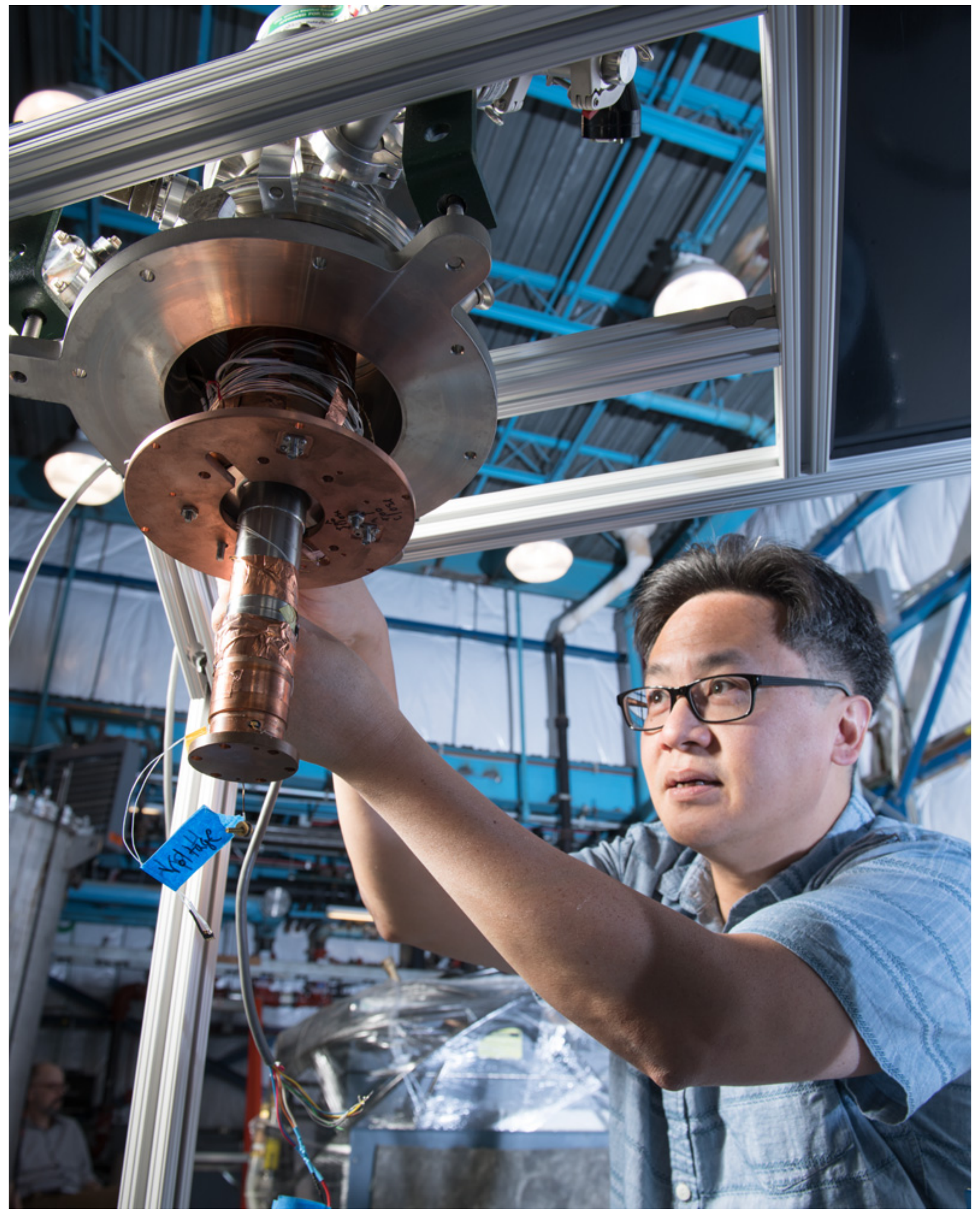


QUANTUM℠
SCIENCE
CENTER



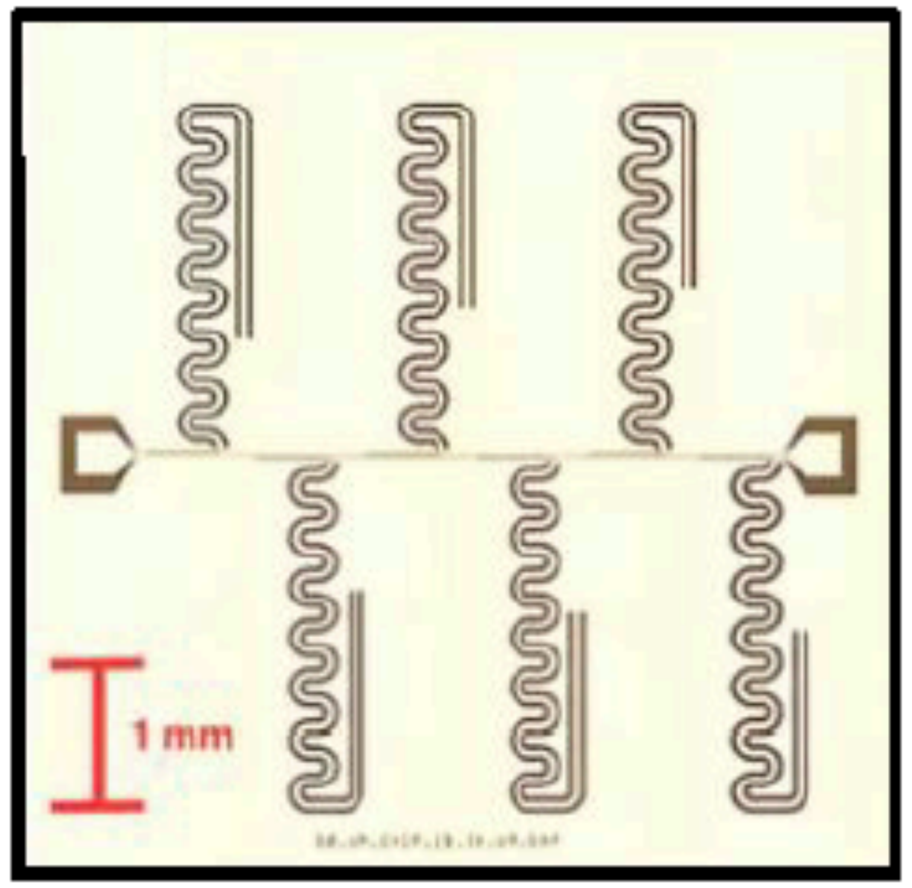
SQMS @ FNAL, QSA @ LBNL, C²QA @ Brookhaven, Q-NEXT @ Argonne, QSC @ Oakridge

Quantum Information Science

QUANTUM SCIENCE CENTER

Northwestern NEXUS Experimental Underground Site @Fermilab

- Collaboration with R. McDermott (UW-Madison), D. Bowring (FNAL), et al.
  - Study Quasiparticle Poisoning in **Superconducting Microwave Resonators** (1610.09351)
- Quantum coherence improved underground (2005.02286)
- Will use NEXUS to study coherence time in **low background environments**
- Fridge upgrades (2020 FNAL LDRD, Bowring DOE ECA)
  - Superconducting coax wiring for RF signals
  - Additional MC plate
  - Magnetic shielding (@ 1K stage)
  - Improved light and EMI shielding
  - Vibration reduction



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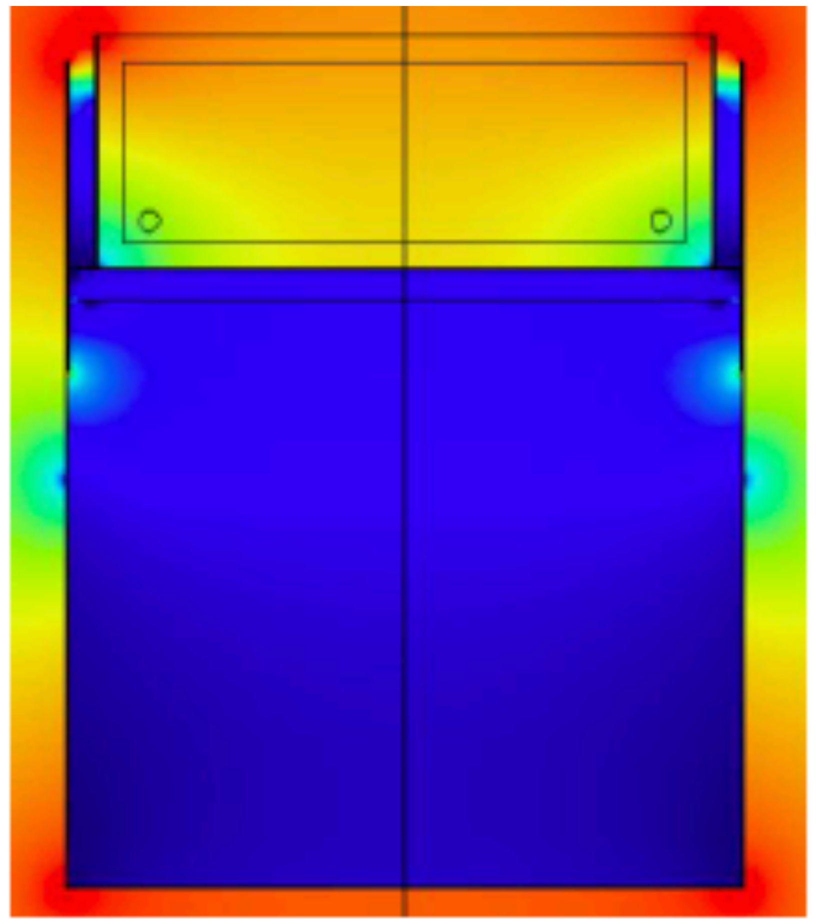
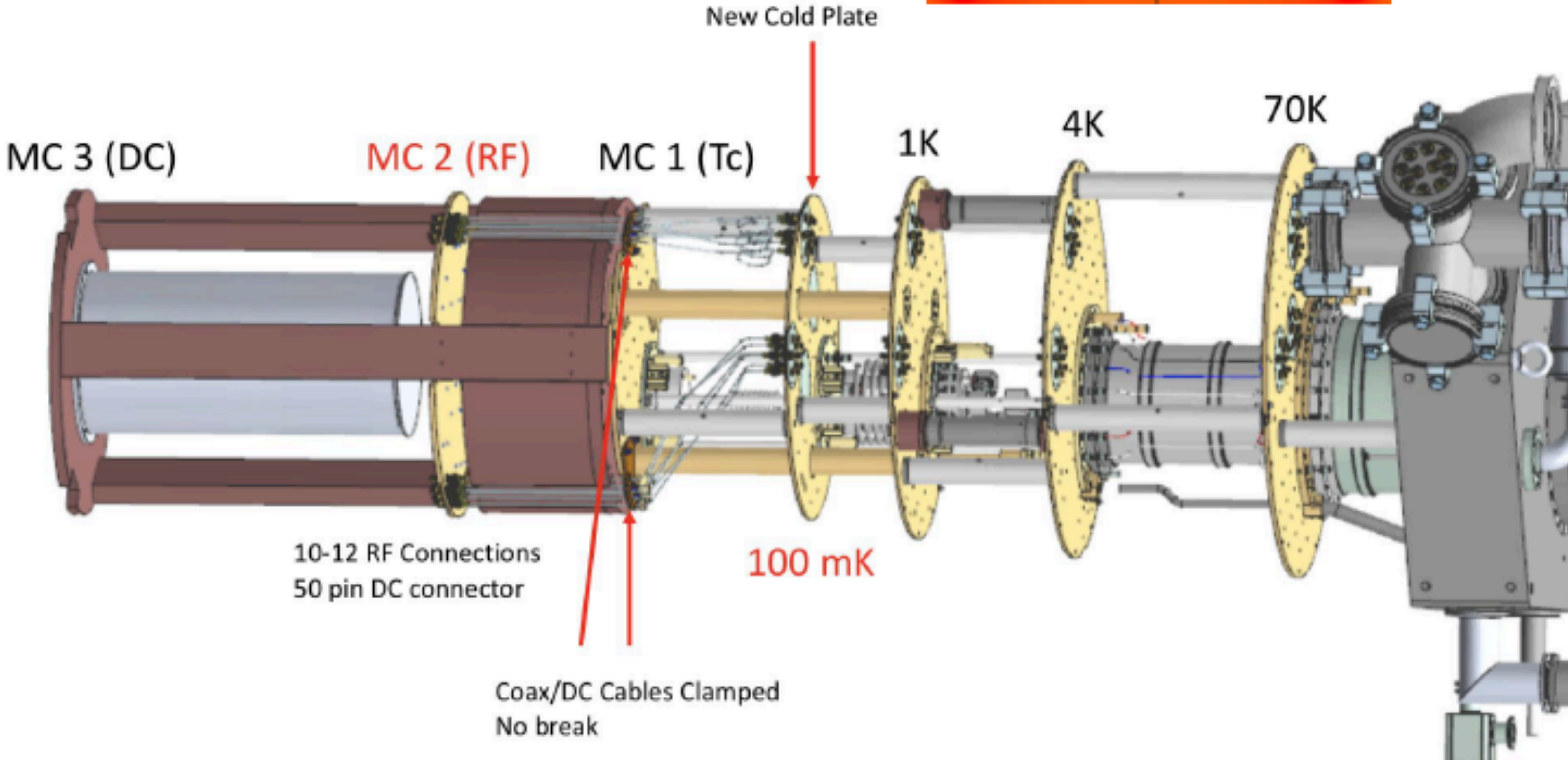


Mag. Shielding Sims
C. Bathurst



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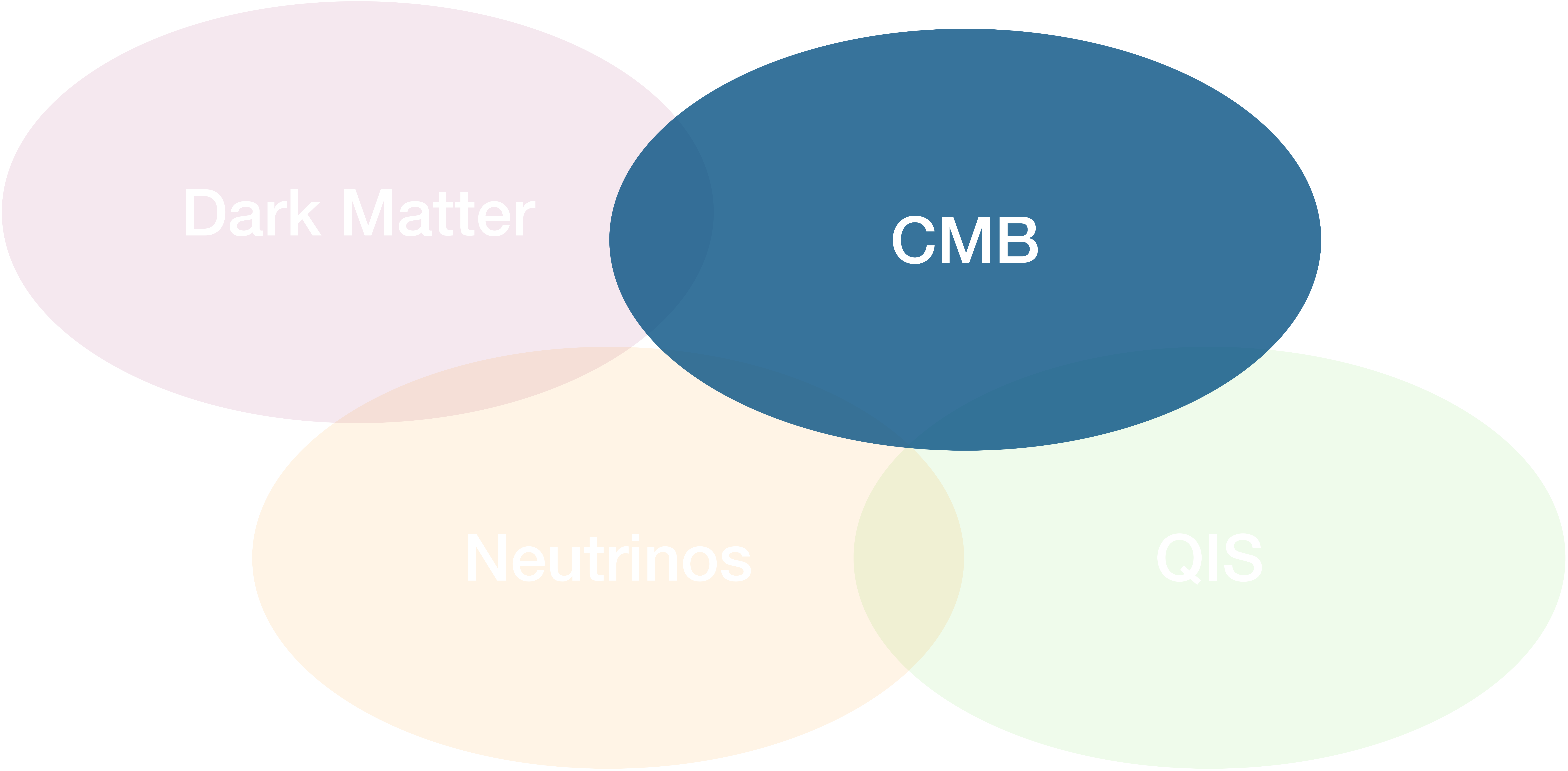
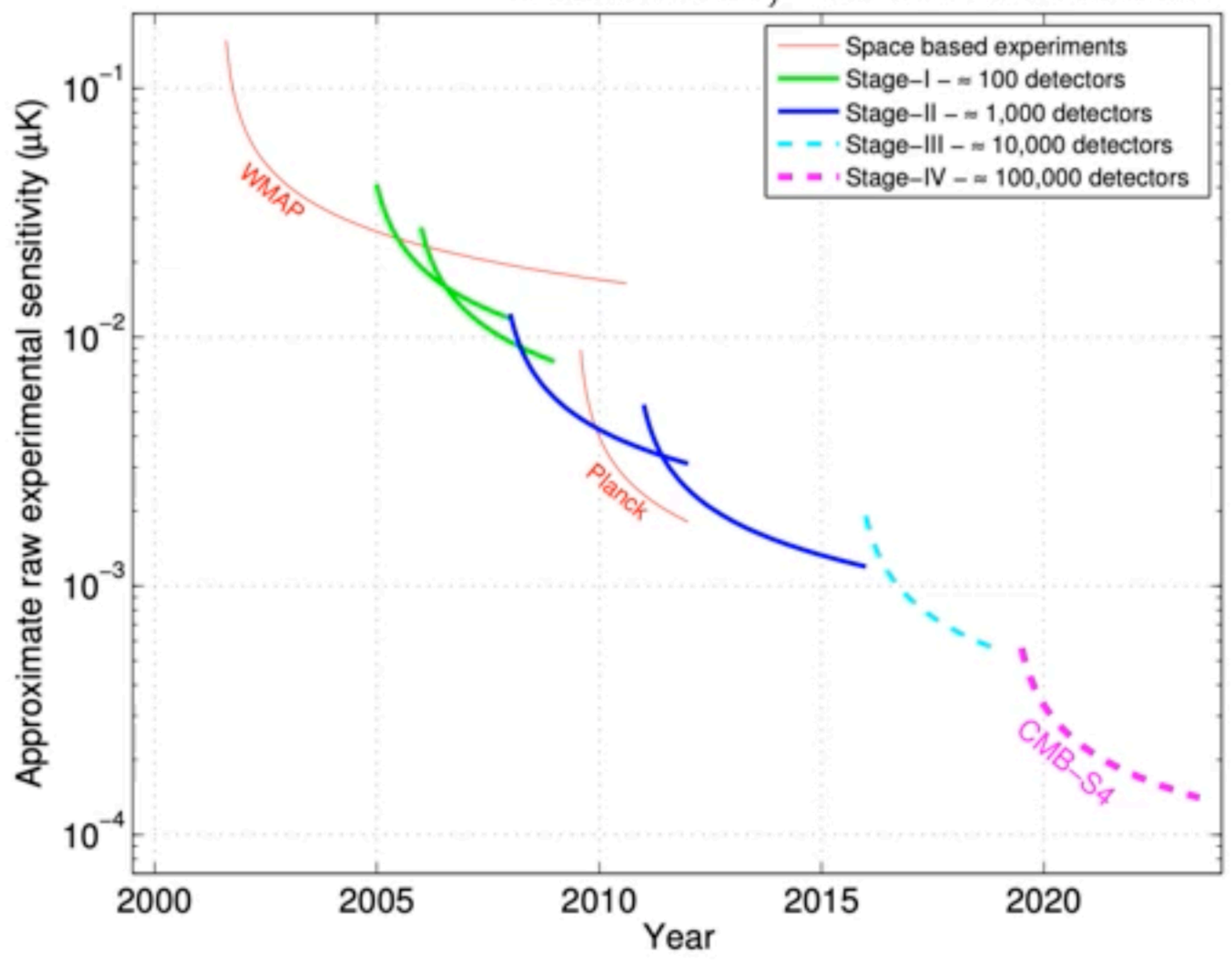


CMB-S4

CMB-S4 scales up **proven** existing technology to unprecedented levels.

- Multiple cameras and telescopes distributed across two sites
  - each site has unique advantages and logistical challenges
- High-throughput telescope optical designs & elements
  - includes cryogenic optics
- 500,000 superconducting detectors operated at a temperature of 100 mK distributed across all the receivers
  - multiplexed readout
- Large cosmological simulations for improved theoretical modeling
- Computational methods for analysis of the resulting data

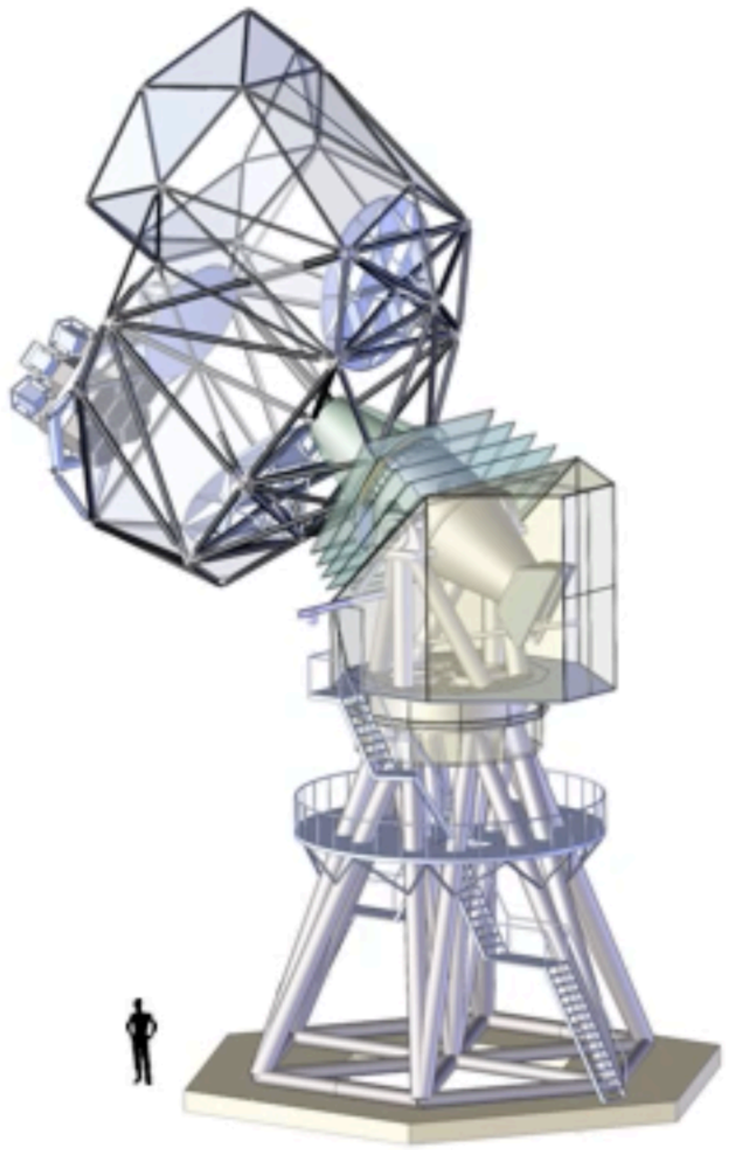
Snowmass; arXiv:1309.5383



CMB-S4

Ultra-deep survey: observe ~3% of the sky with 150,000 detectors in SATs & a de-lensing LAT with 120,000 detectors.

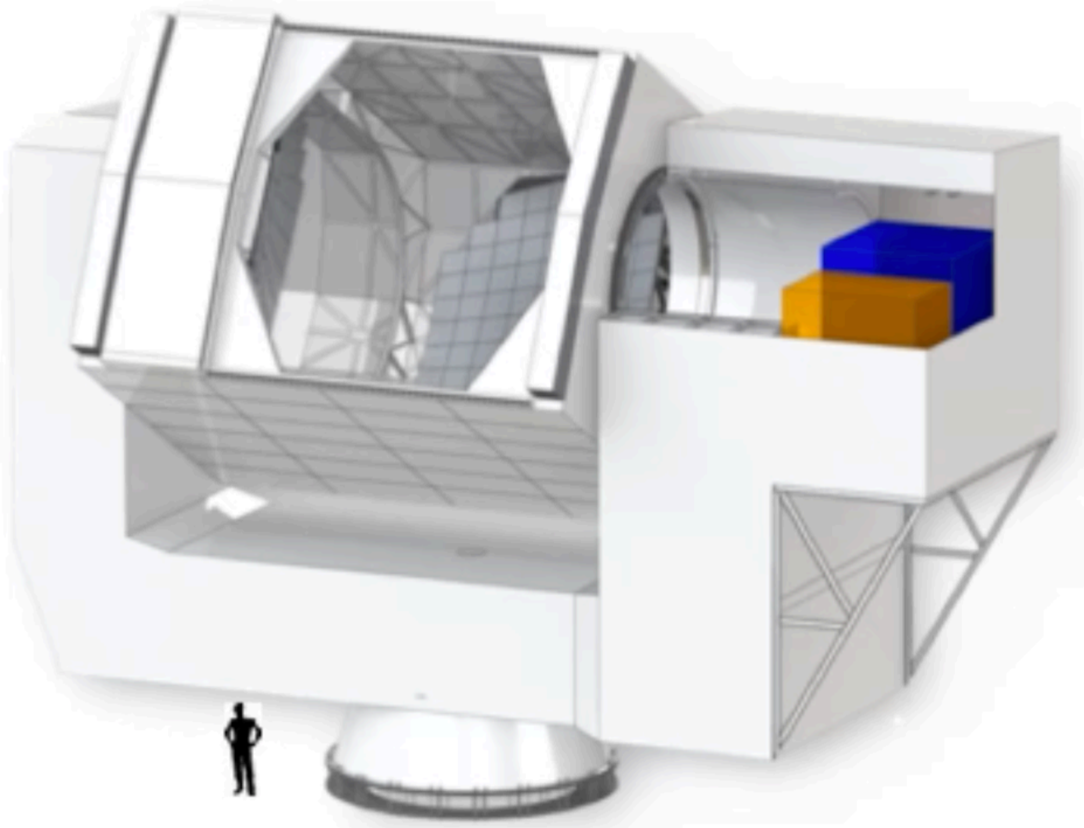
Large Aperture Telescope (LAT)



Small Aperture Telescopes (SATs)

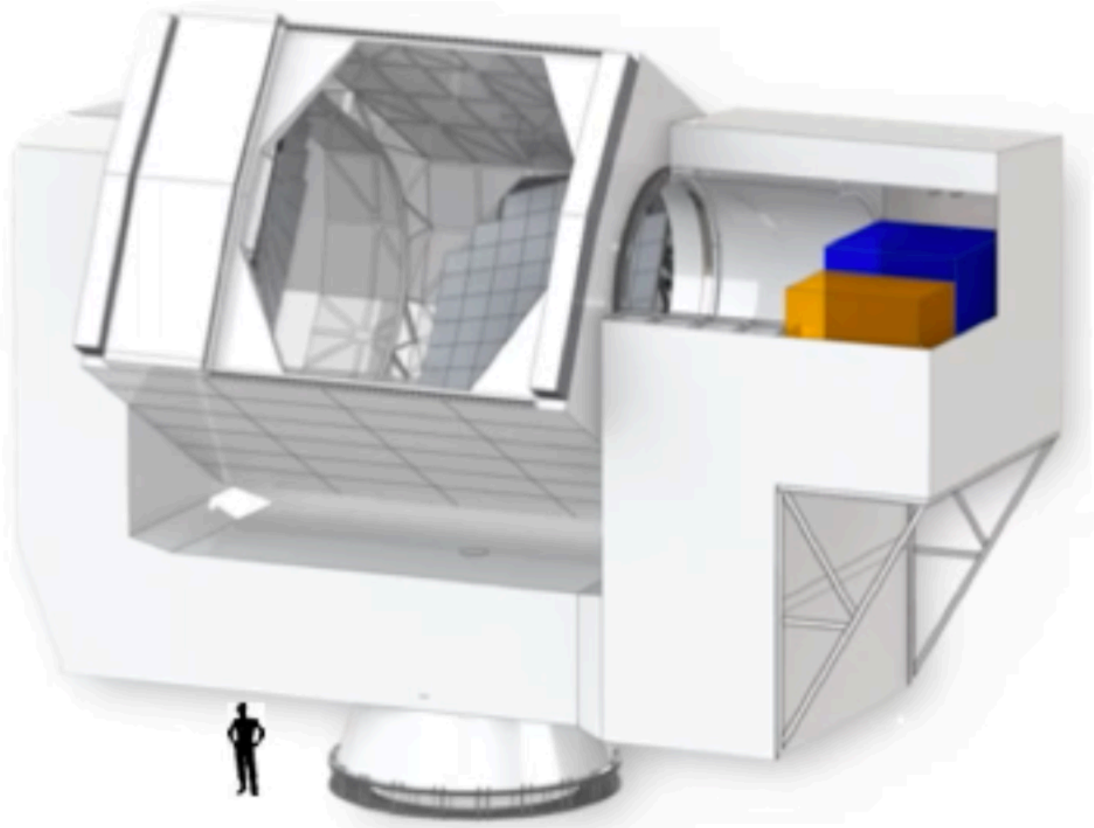
18 x 0.55m small telescopes (3 per cryostat), e.g., like BICEP Array

Deep-wide survey: Two LATs observing ~60% of the sky with 240,000 detectors.



LAT

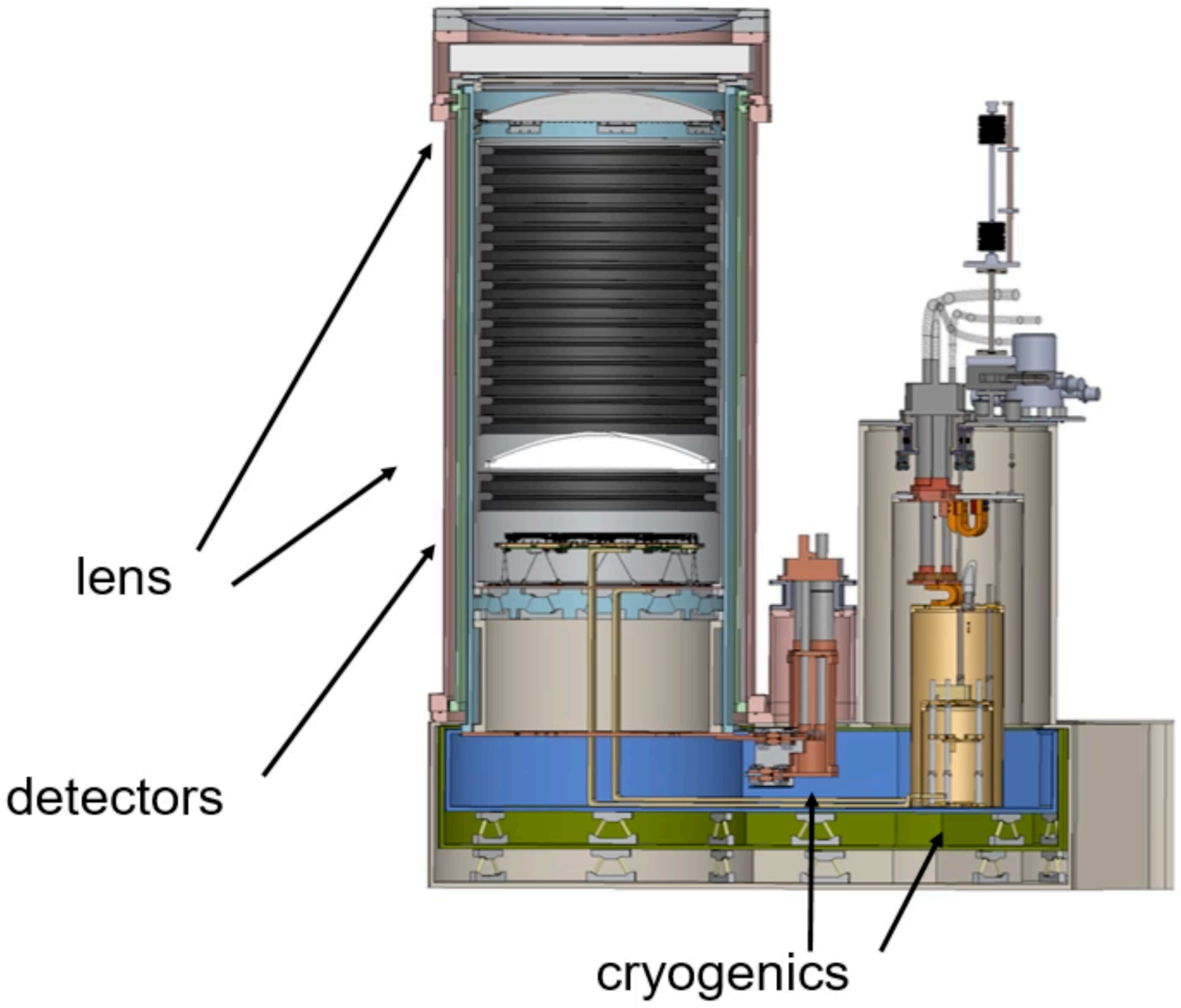
6m large telescopes, e.g., like Simons Obs.



LAT

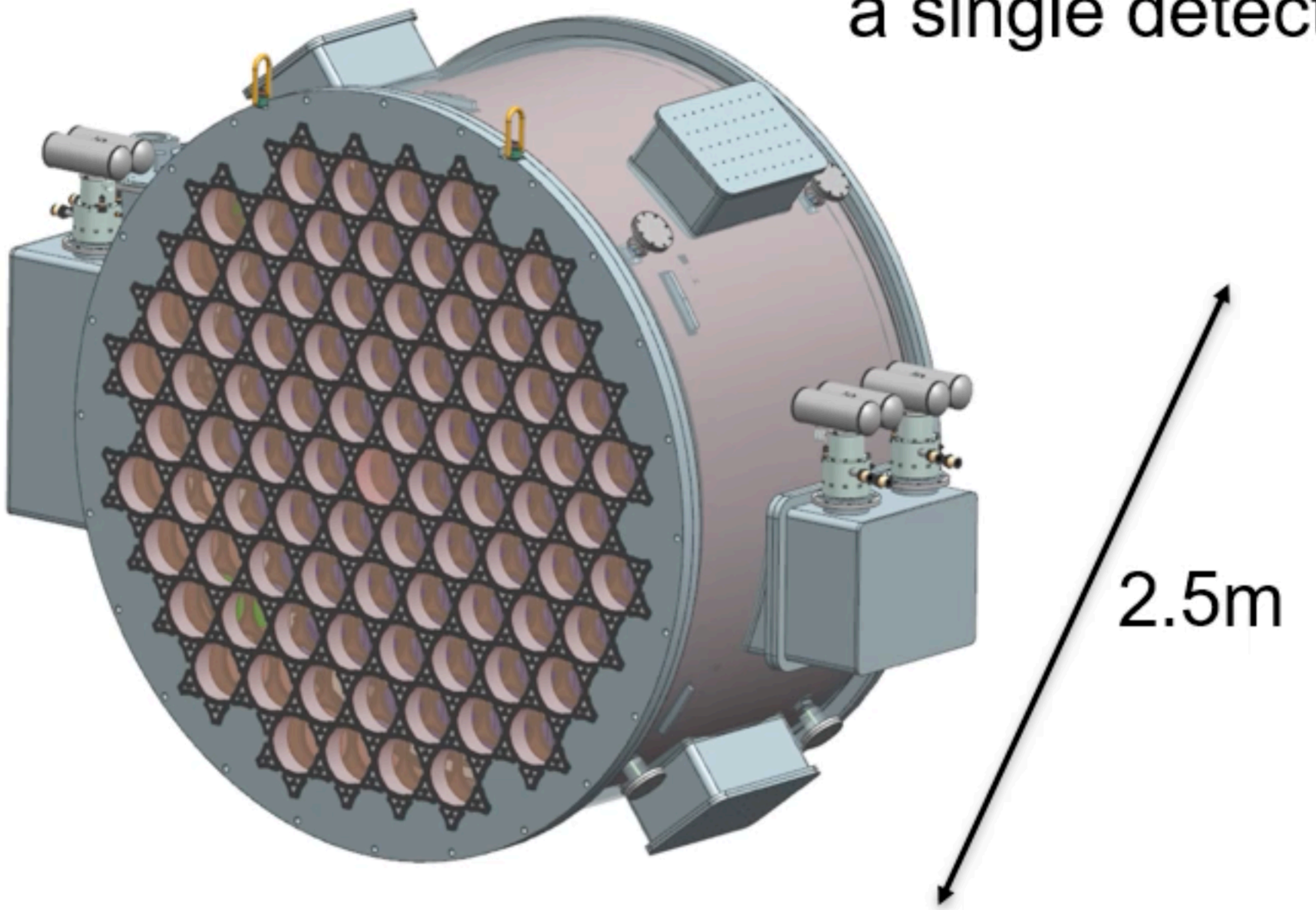
CMB-S4

Small Area Telescope



Large Area Telescope Detector

85 optics tubes each with a single detector wafer



Conclusions

- Cryogenics Facilities necessarily carry over the design requirements of each experiment - there is no one-size-fits-all approach.
- CUTE and NEXUS are currently open for business and are planning their future as DM/neutrino/QIS all-purpose facilities, but capability and throughput will be limited. Other facilities (like a large-magnet axion lab) might be useful.
- The large number of experiments using cryogenics, superconducting magnets, multiplexed readouts, and RF circuits provides an opportunity by the national labs to provide expertise in these areas.