Bolometer Experiments,
Underground Facilities, and Discovery Science

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Community Summer Study

SNOWMASS

July 17-26 2022, Seattle

Yale

SNOWMASS, July 19, 2022

Bolometer Experiments,

Underground Facilities, and Discovery Science

What are the underground facility needs for bolometer experiments to enable discovery science?

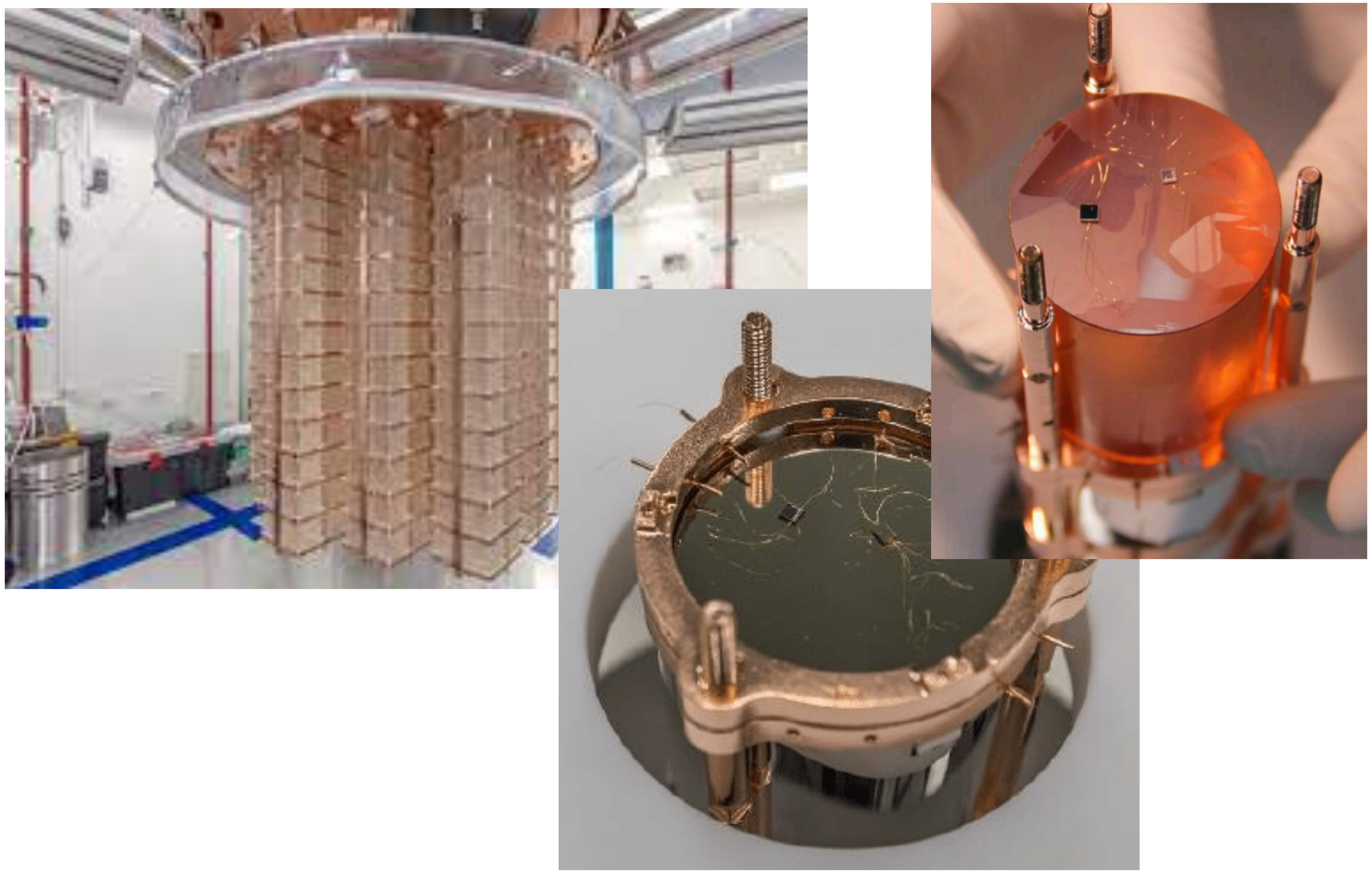
Not a complete review of all experiments

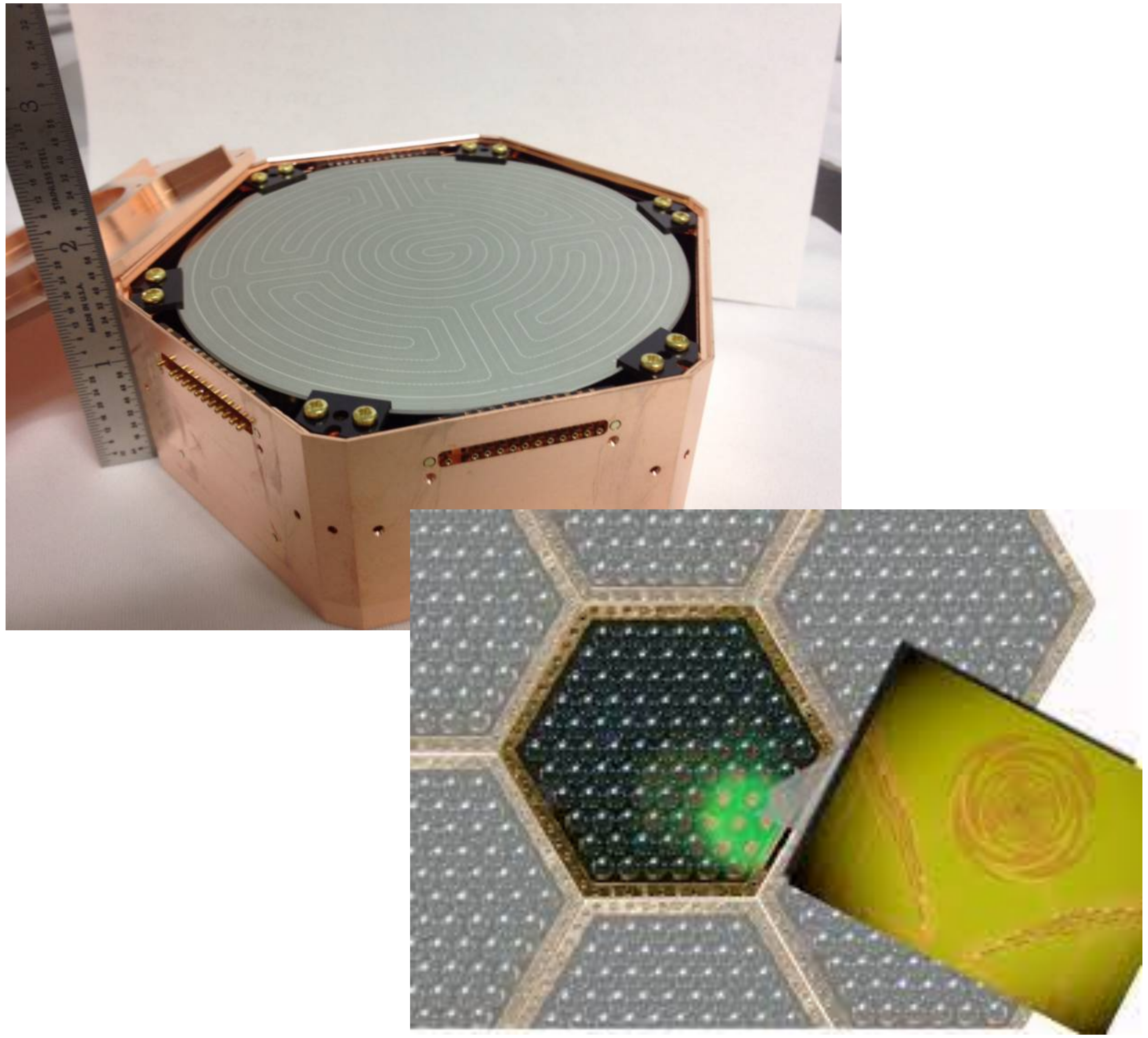
With input from Joe Formaggio, Yury Kolomensky, Ben Schmidt, and others

Yale

SNOWMASS July 19, 2022

Bolometric Detectors

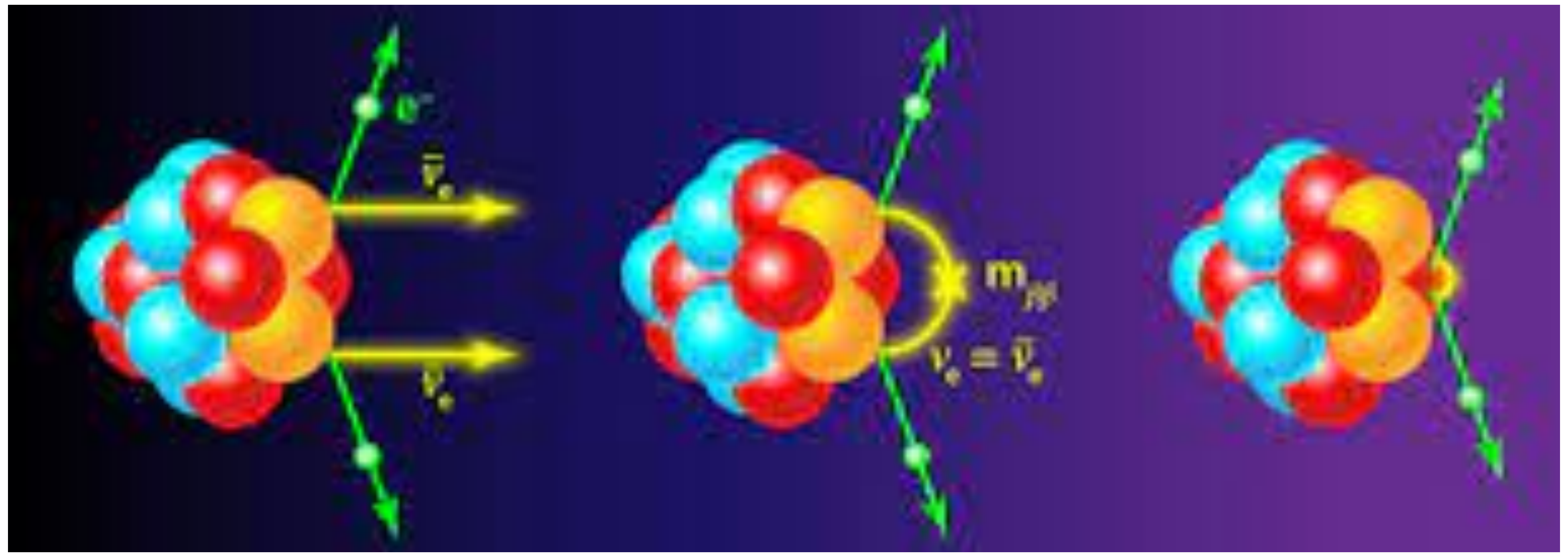


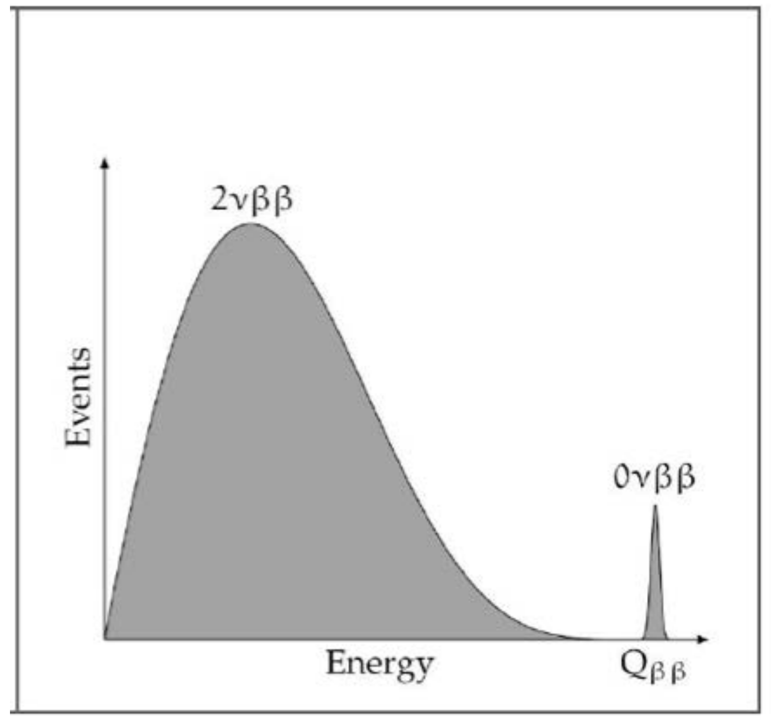


Bolometric detectors reach low thresholds with excellent energy resolution

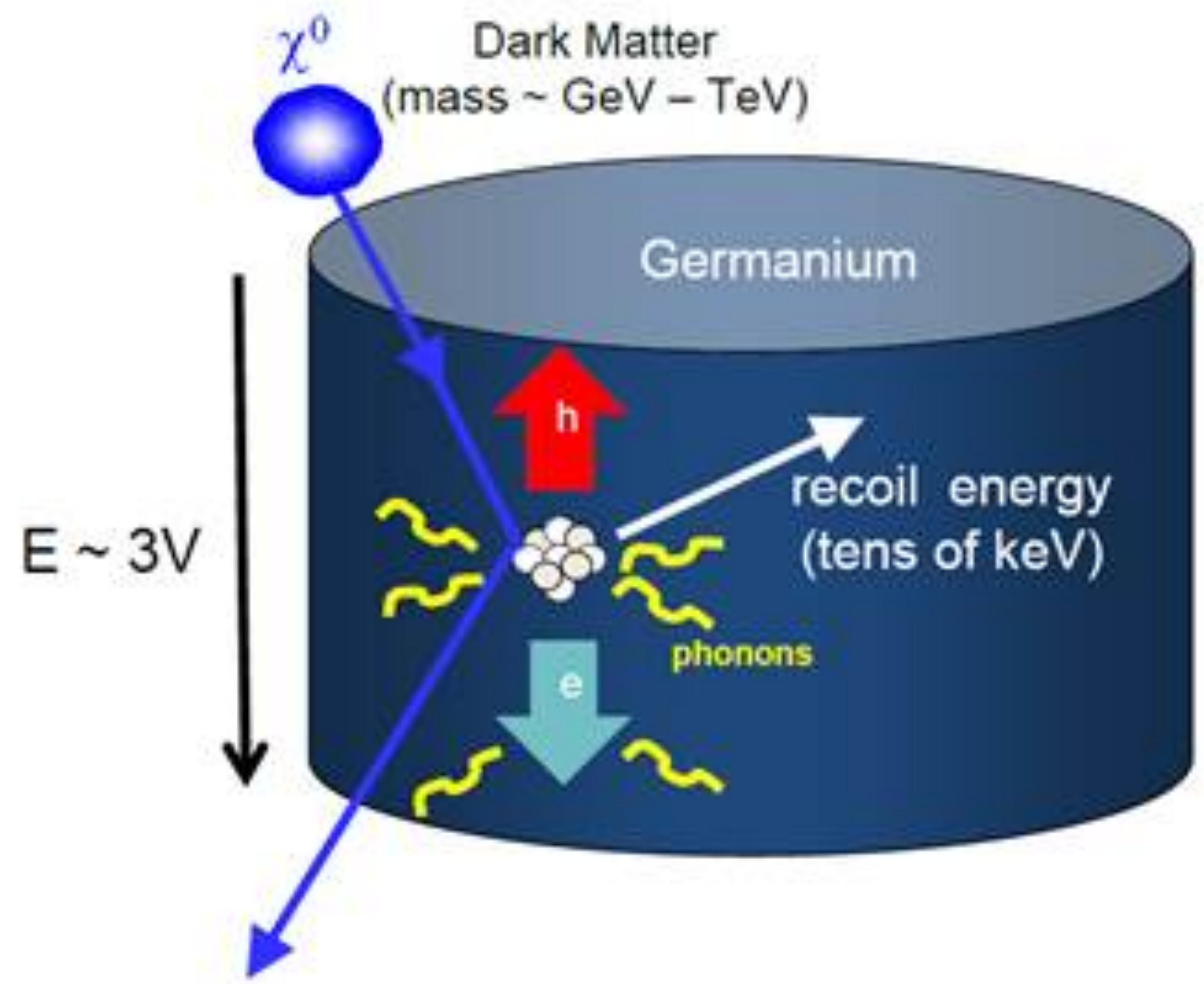
Advanced detectors benefit from developments in quantum sensing (e.g phonon and light readout)

Science Goals

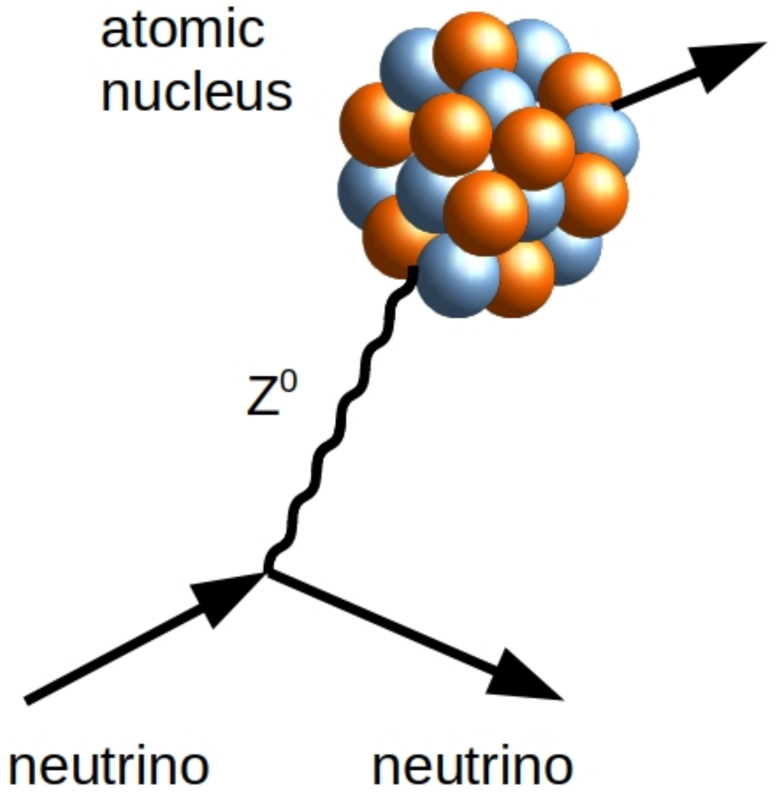




Neutrinoless double beta decay



Dark matter searches

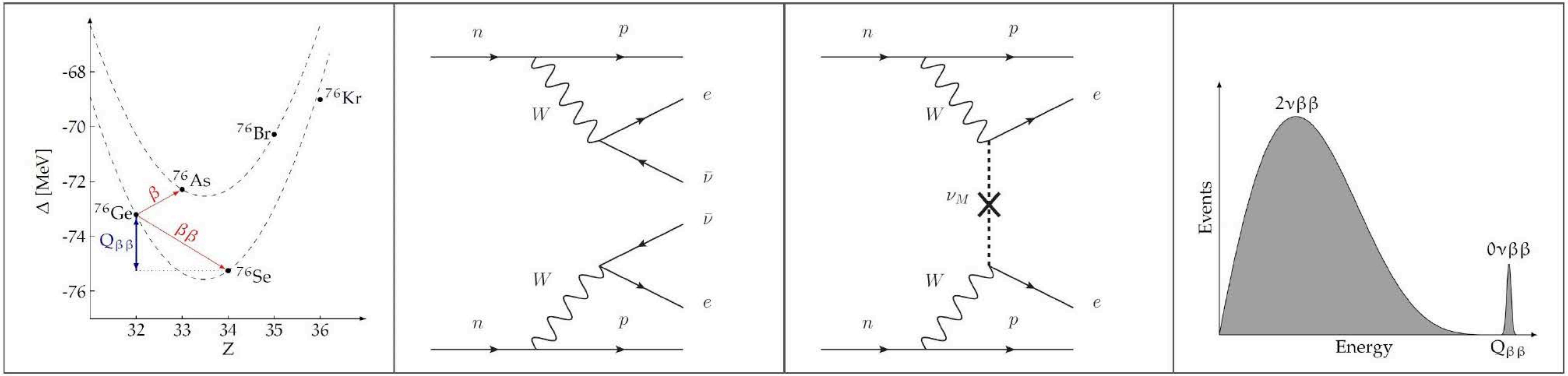


Coherent neutrino scattering

Bolometric detectors address fundamental science questions with discovery potential

Synergies between HEP and NP science

Science Goals: Search for Neutrinoless Double Beta



Are neutrinos Dirac or Majorana particles?

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu} \cdot |M_{0\nu}|^2 \cdot |f|^2 / m_e^2$$

$T^{1/2}{}_{0\nu}$ = 0νββ decay halflife
$G_{0\nu}$ = phase space (known)
$M_{0\nu}$ = nuclear matrix element (NME)
f = new physics term

0νββ Decay Signature

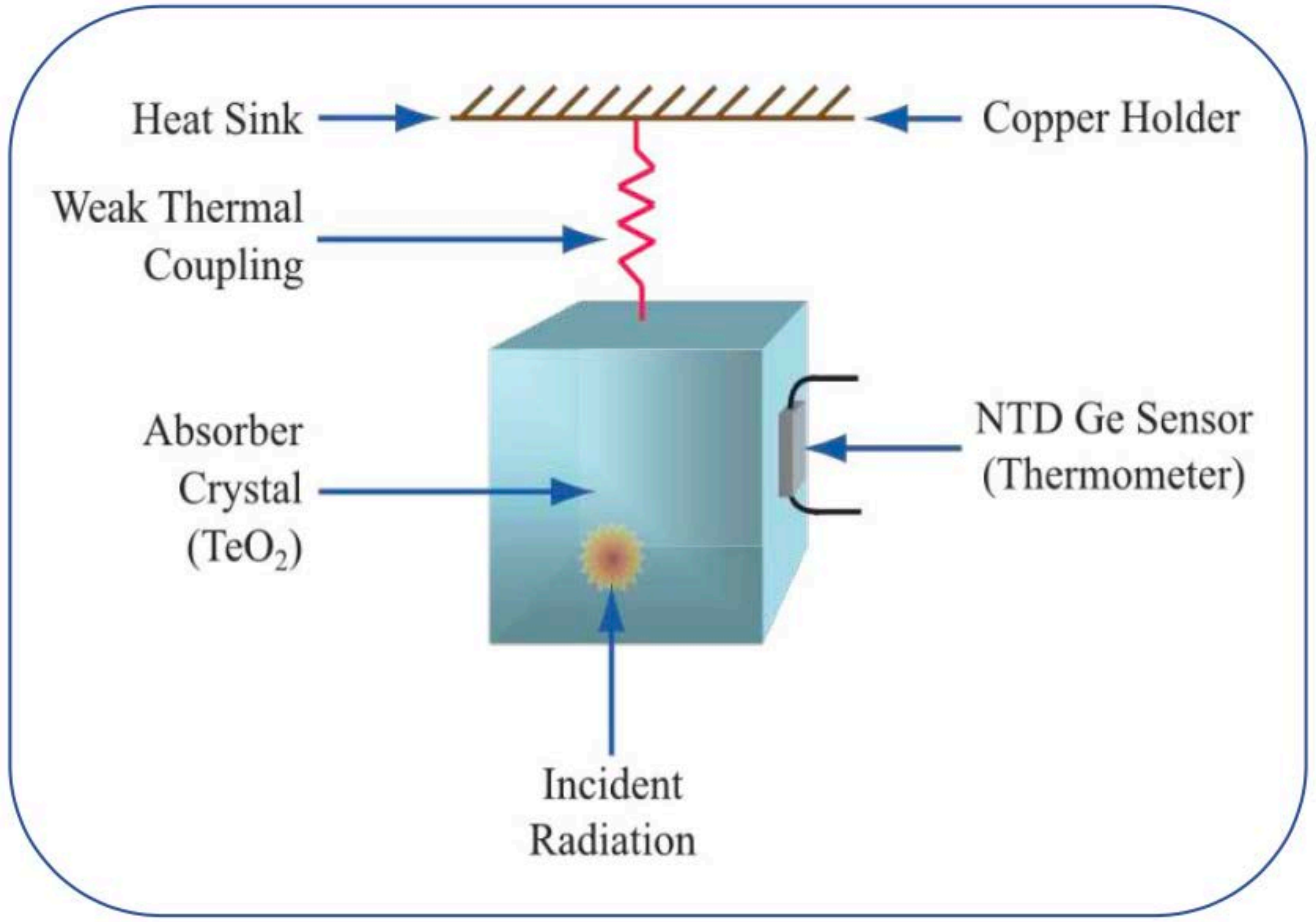
Distinguishing peak at $Q_{\beta\beta}$ for 0νββ decay from continuum **for discovery**

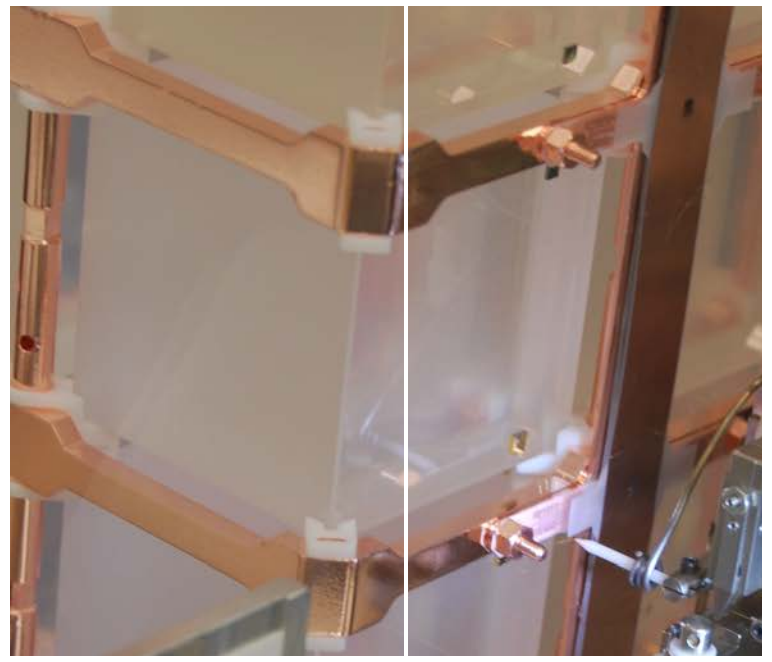
Essential to understanding the physics of neutrinos mass

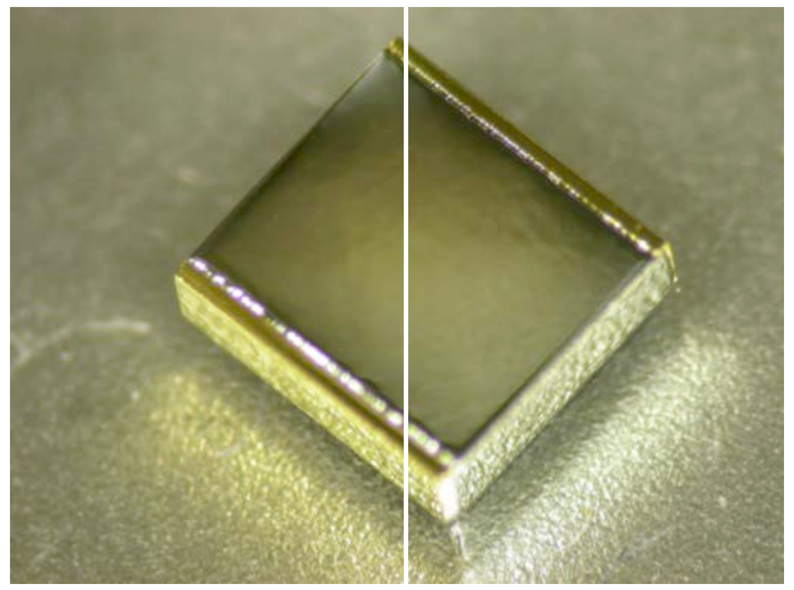
NP science

Bolometric Detectors

CUORE ^{130}Te
pure thermal detector
(bolometer)

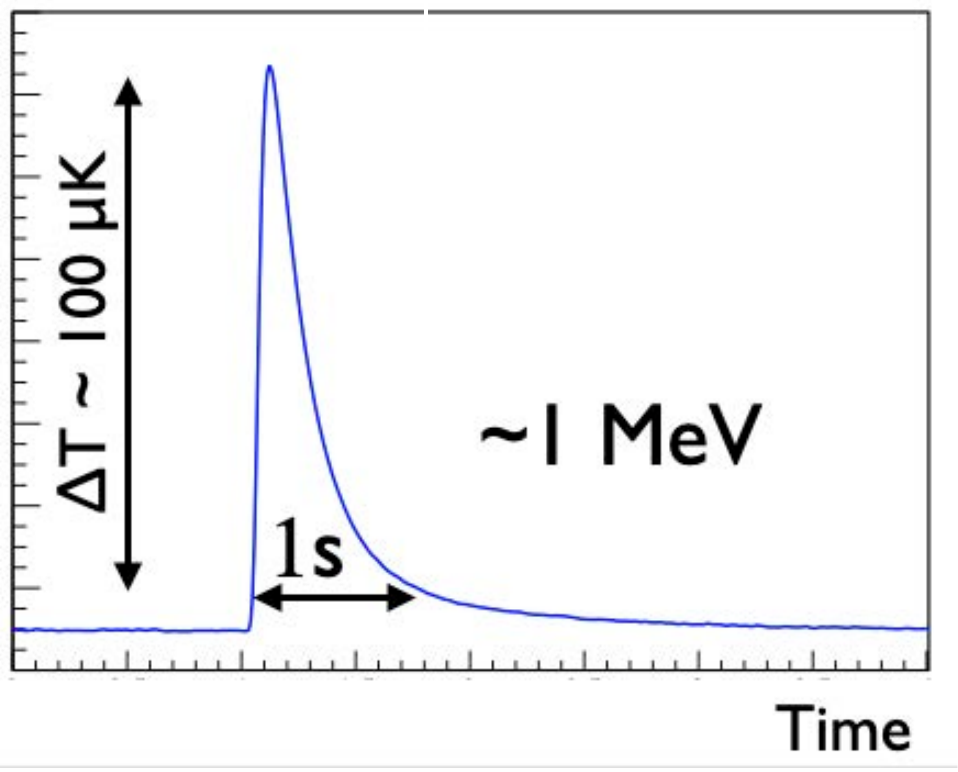






- Low heat capacity @ T ~ 10 mK
- **Excellent energy resolution** (~0.2% FWHM)
- Detector response independent of particle types
- **Flexibility in 0νββ candidate choice**
- Detector response of O(1) sec if readout with e.g. Neutron Transmutation Doped (NTD) Gesensors

No PID
Q = 2527 keV < 2615 keV



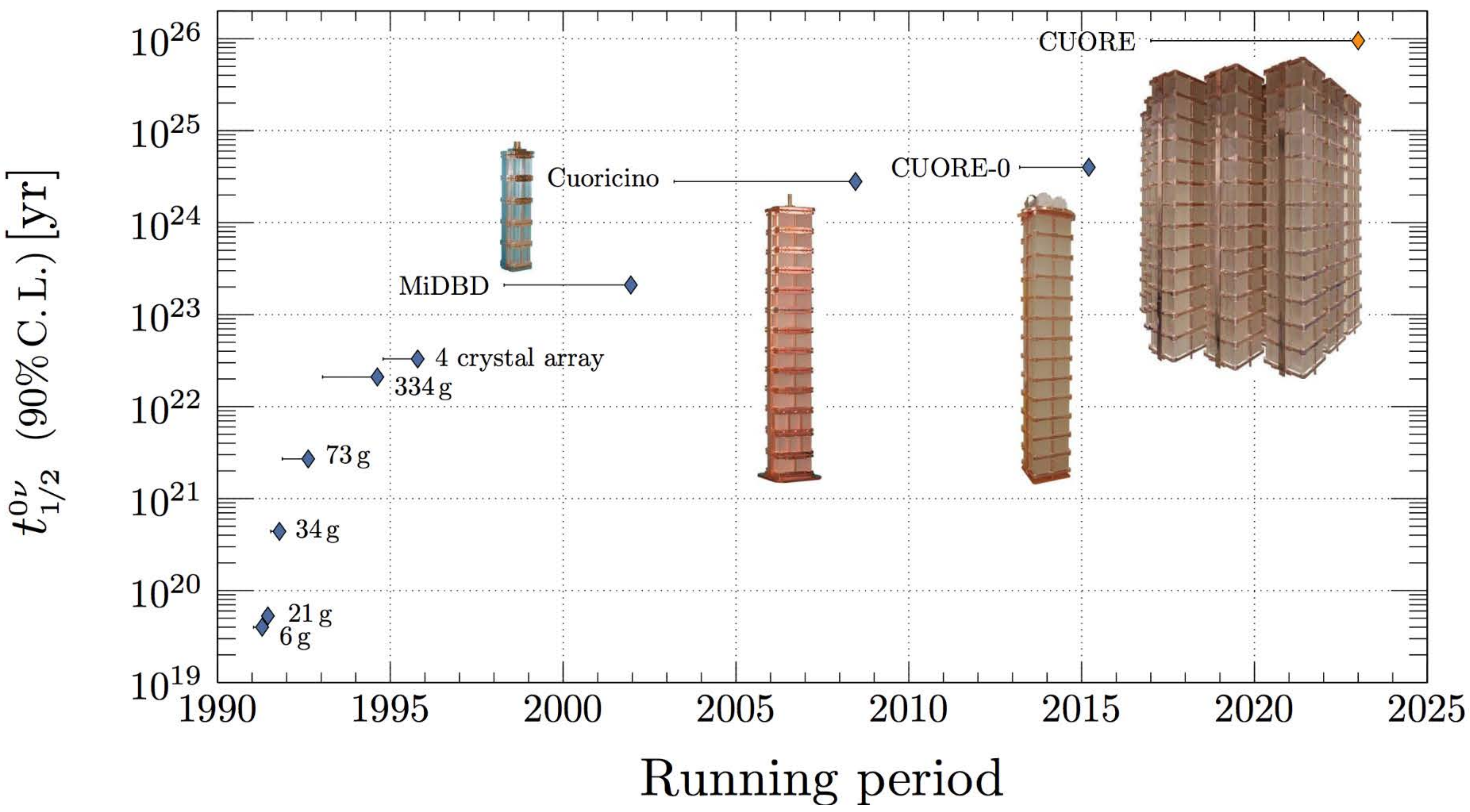
- Crystal heat capacity: C
- Conductivity of coupling to thermal bath: G
- Signal amplitude ∝ $\Delta T = E_{dep} / C$
- Decay constant: $\tau = G / C$

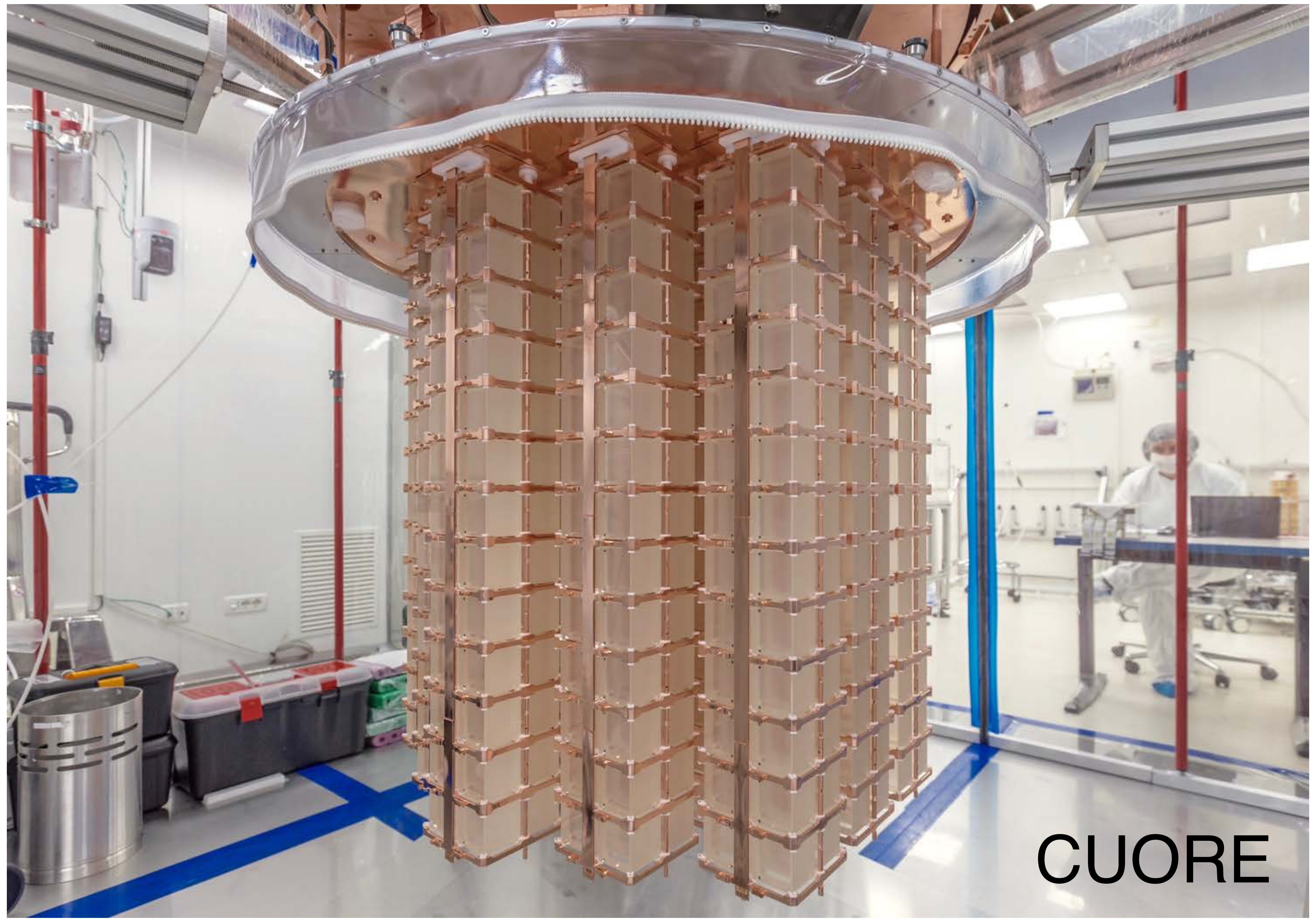
Successful History of Bolometer Experiments

30 years of experience in searching for 0νββ with cryogenic bolometers

CUORE is in a long series of experiments, from few grams to 742 kg of detector material

First tonne-scale bolometric experiment in the world





Brofferio, C. and Dell'Oro, S., Rev. Sci. Inst. 89, 121501 (2018)

CUPID builds on decades of bolometer experience at LNGS

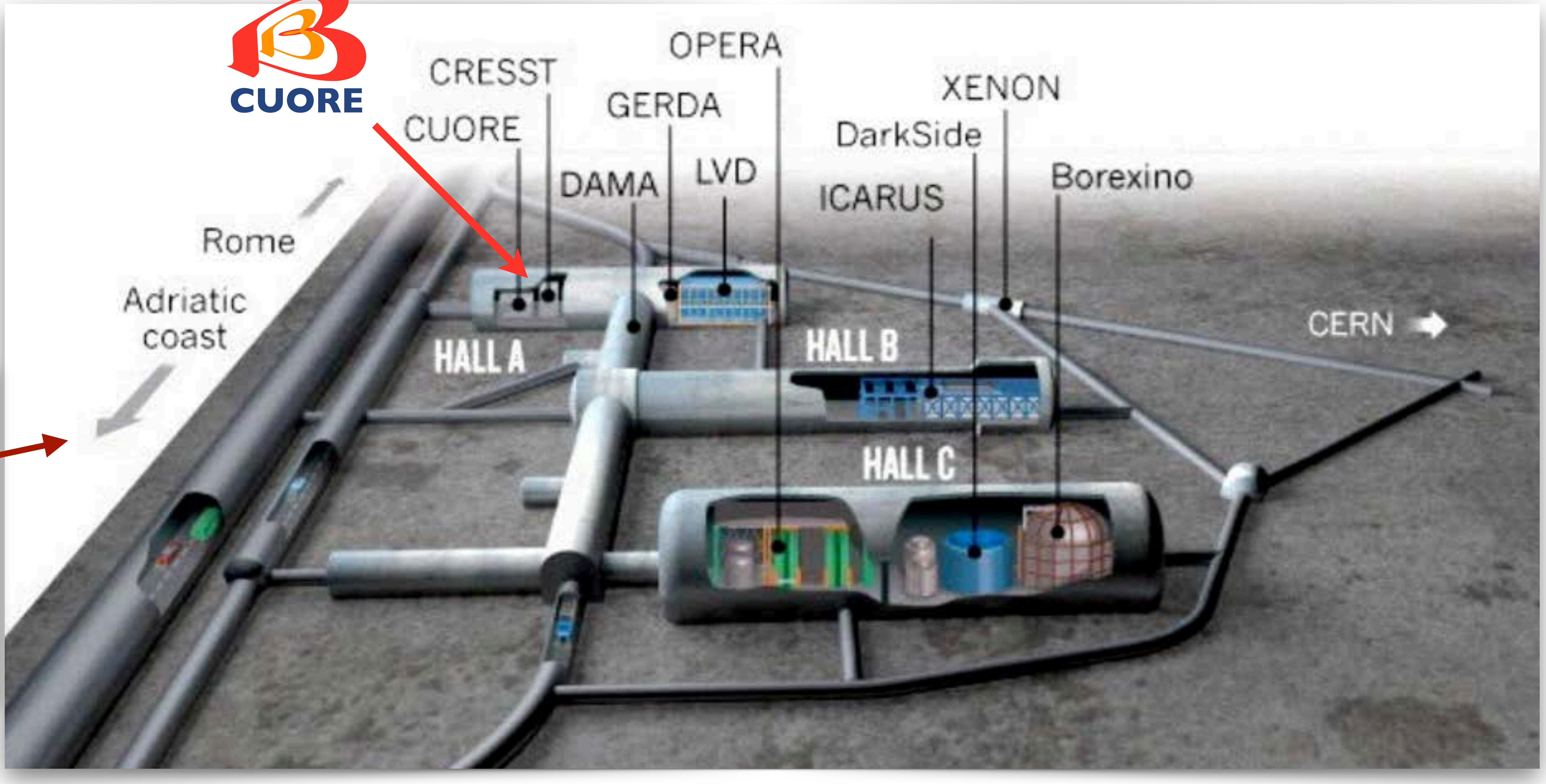
LNGS: Laboratori Nazionali del Gran Sasso

Natural shielding from cosmic rays by the mountain of Gran Sasso

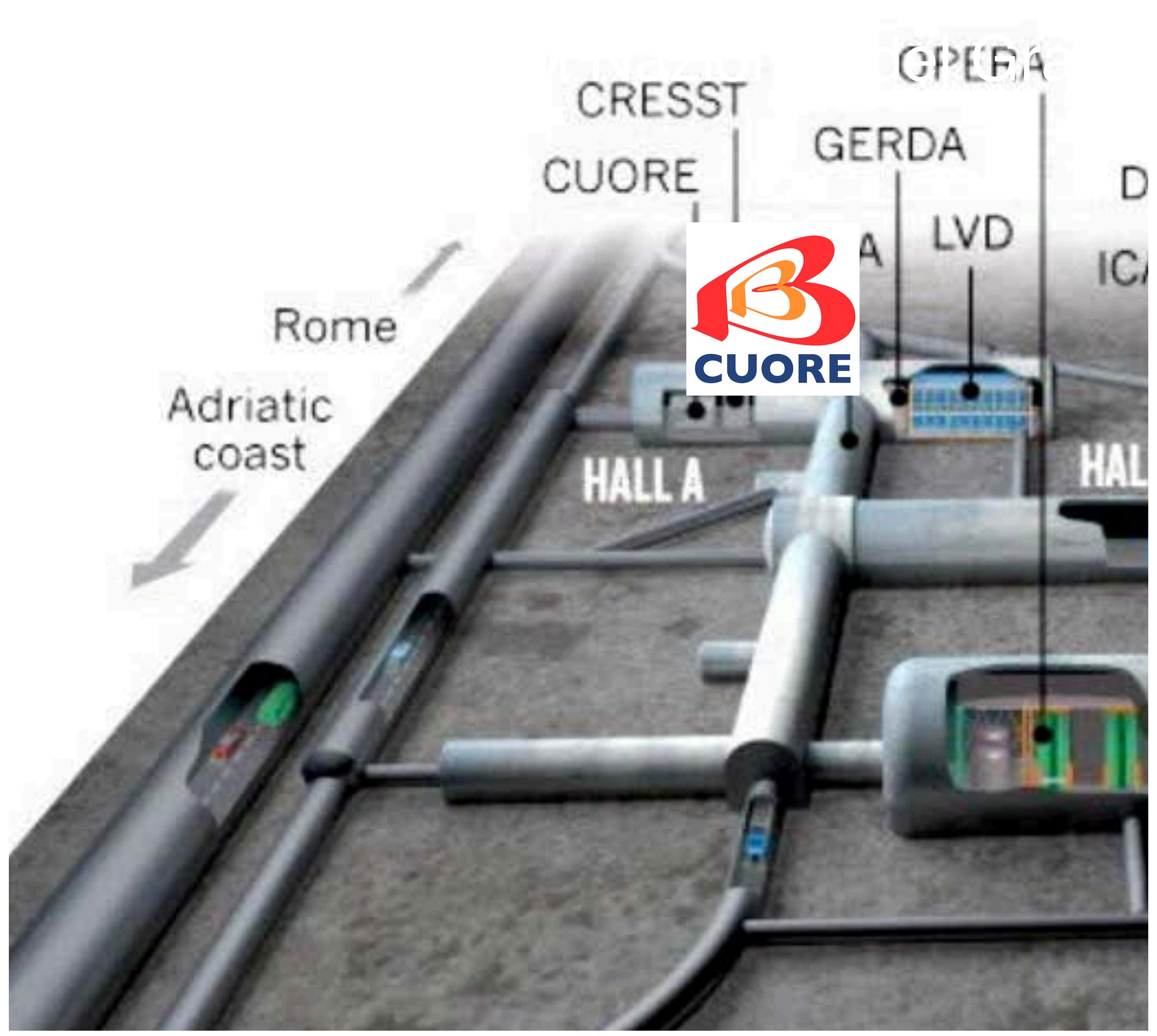
3600 meter water equivalent overburden

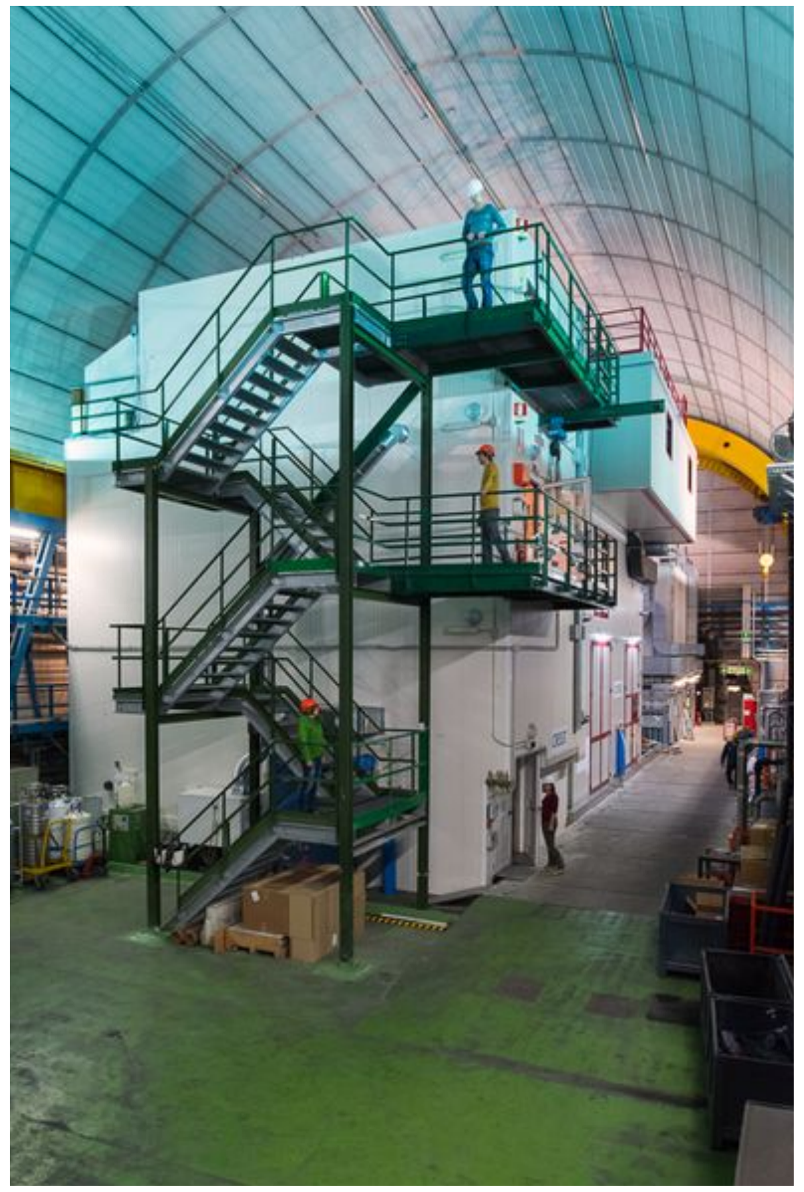
Well-established support for experiments and user access

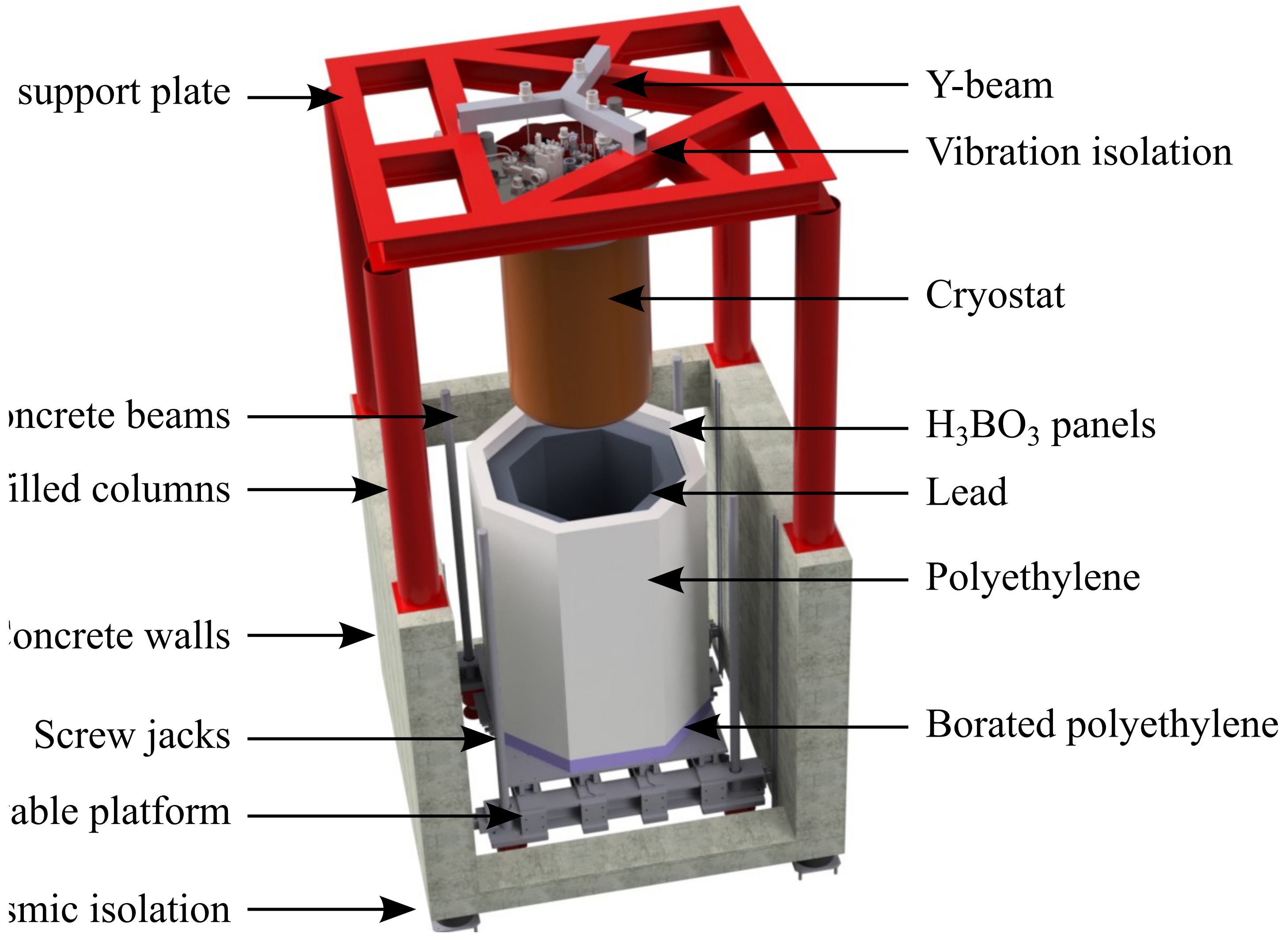
CUORE



Established Site and Infrastructure







CUPID leverages on many years of work and investment from INFN and LNGS

Existing experimental site, unique cryogenic infrastructure.

LNGS provides

- technical, user support
- R&D facilities for detector development and testing

Prototype Demonstrators: Precursors to CUPID

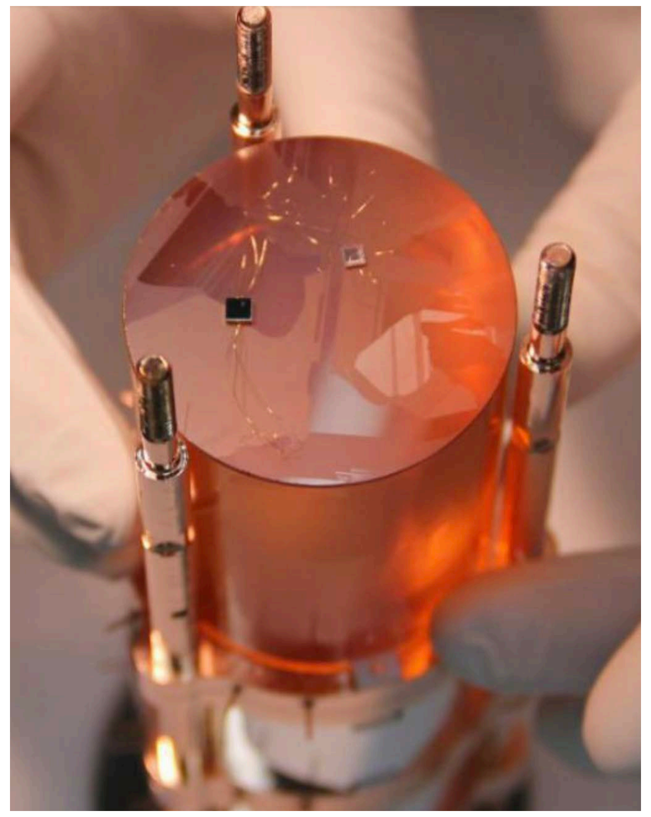
CUPID-0

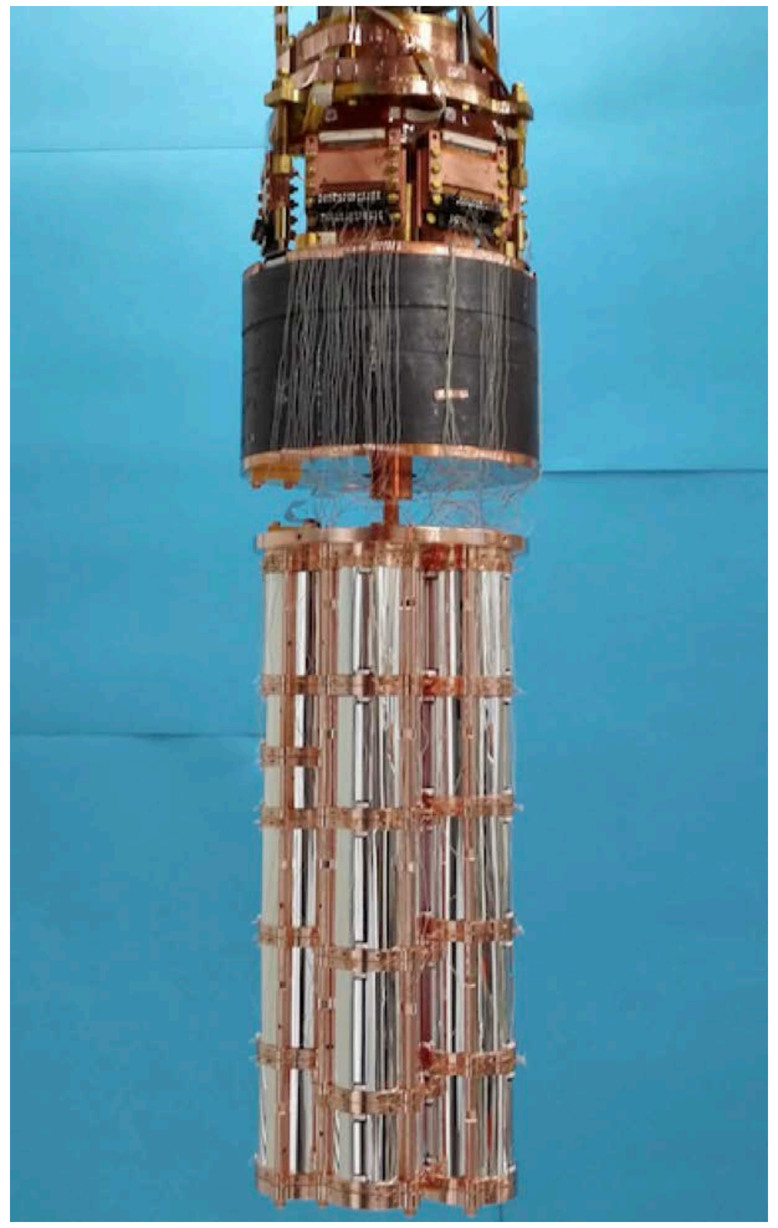
- Located in the CUORE-0 cryostat at LNGS, Italy
- 24 Zn^{82}Se (95% enrichment) +2 Zn^{nat}Se crystals
  - 5.17 kg of ^{82}Se
- Ge light detectors and NTD thermistors

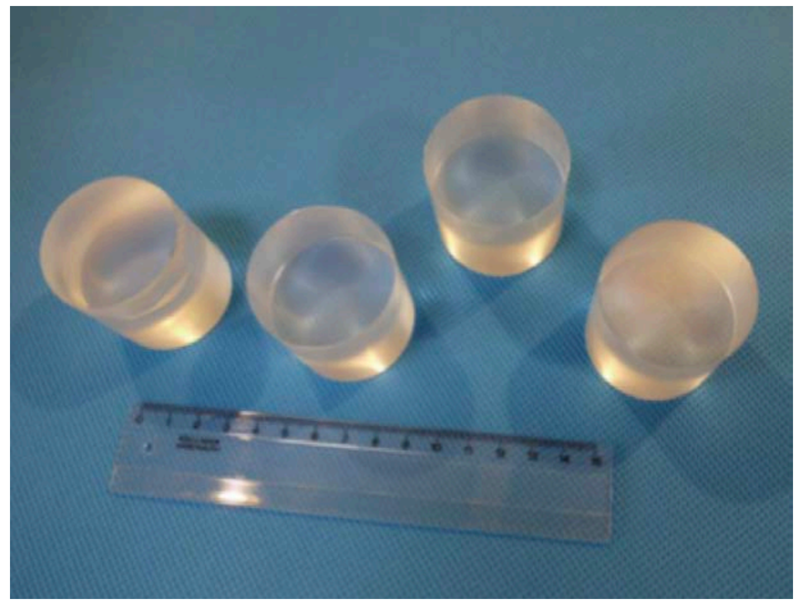
CUPID Mo

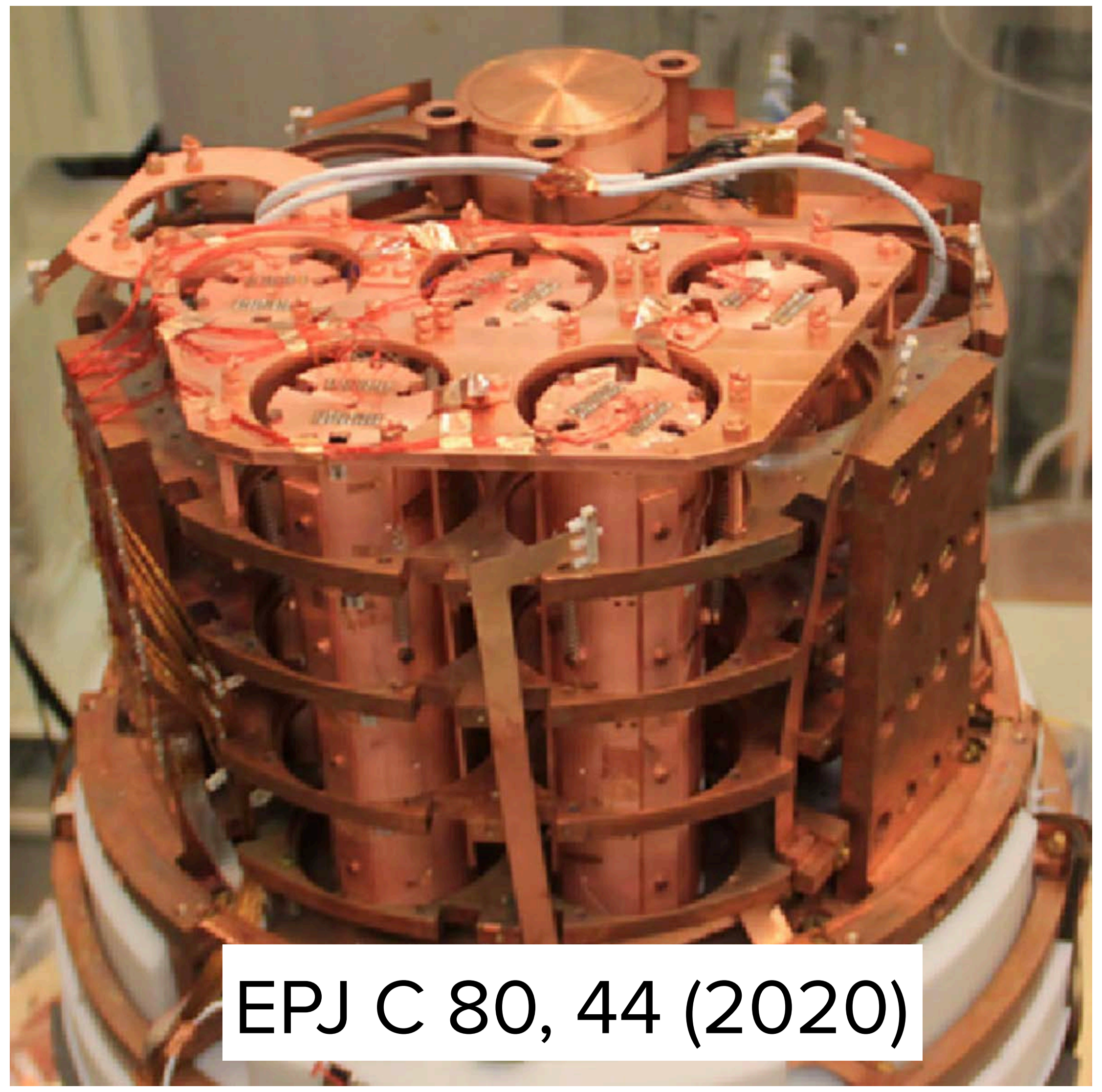
- Located in the LSM, France
- 20 enriched $Li_2{}^{100}MoO_4$ (97% enrichment) crystals
  - 2.26 kg of ^{100}Mo
- Ge light detectors and NTD thermistors

Phys. Rev. Lett. **123**, 032501





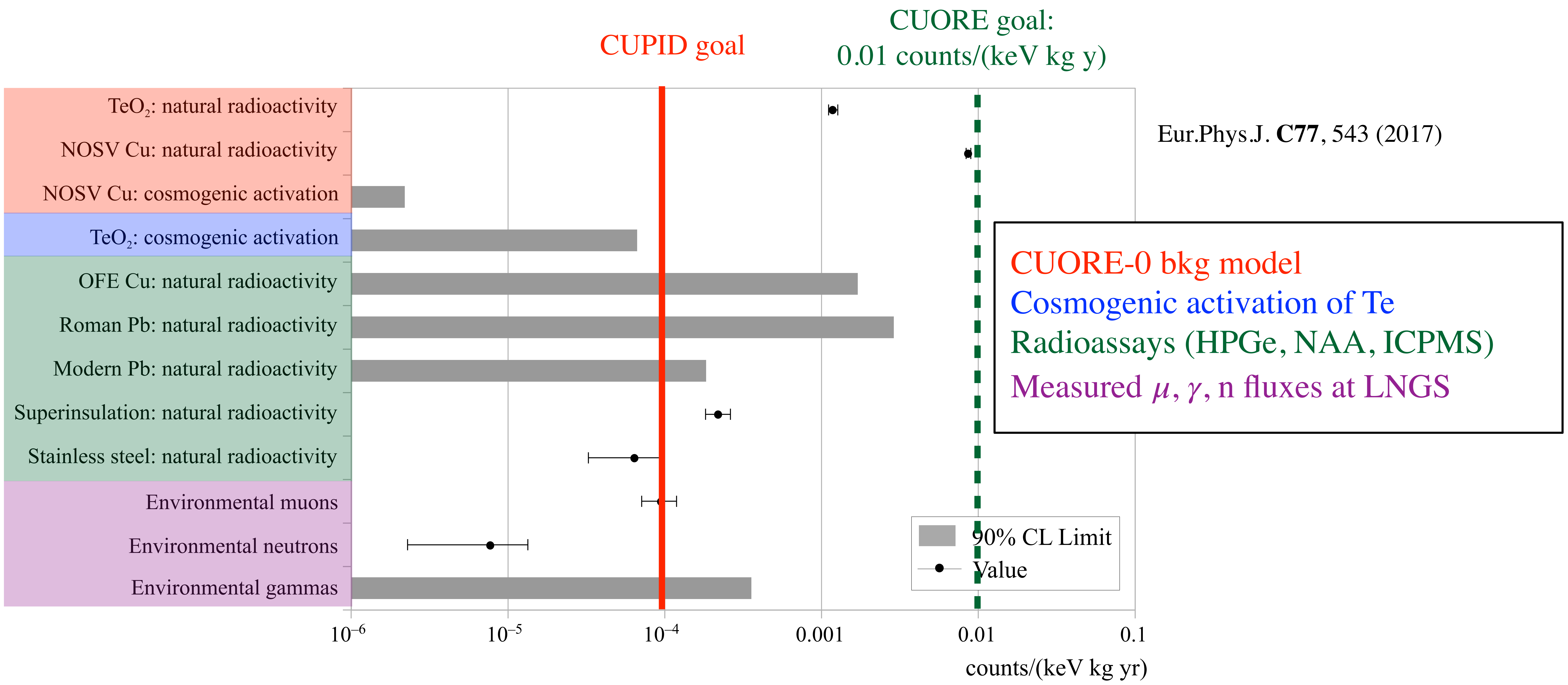




EPJ C 80, 44 (2020)

Underground facilities around the world have enabled R&D towards CUPID

CUPID Background Goal



Eur.Phys.J. **C77**, 543 (2017)

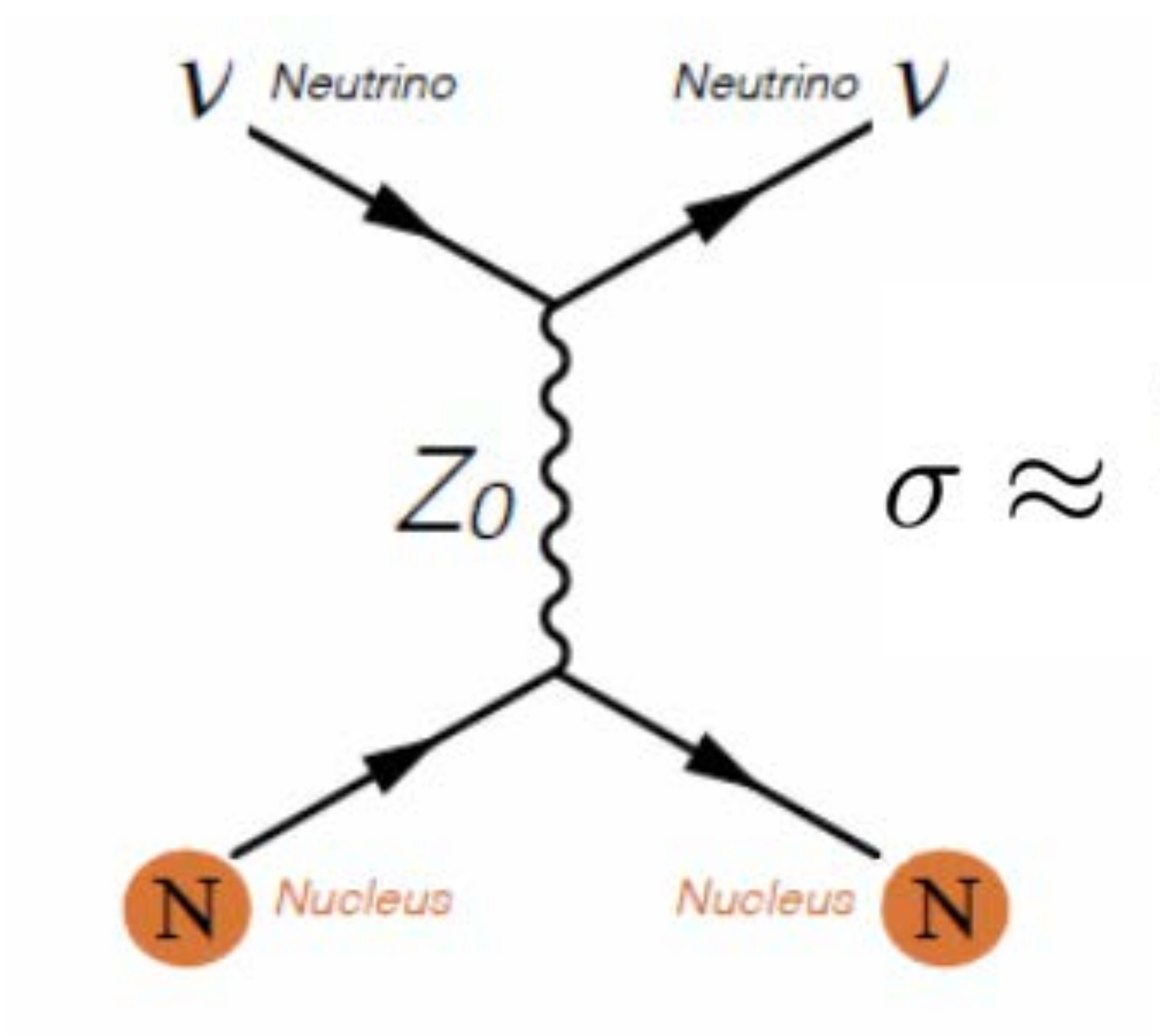
Means for background reduction

- Depth of experimental site
- radioassay of all components
- Advanced detectors (phonon and scintillation light readout)

Similar needs for $0\nu\beta\beta$ and dark matter experiments

Synergies with QIS

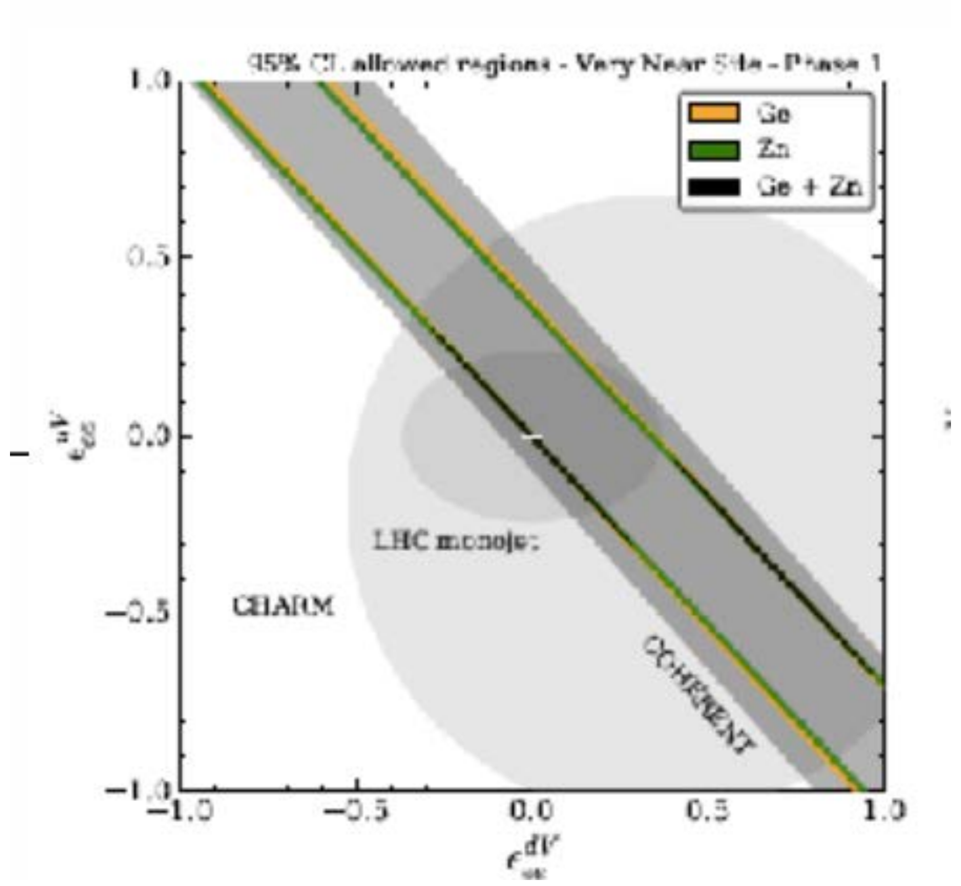
Science Goals: Coherent Nuclear Scattering



$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_\nu^2$$

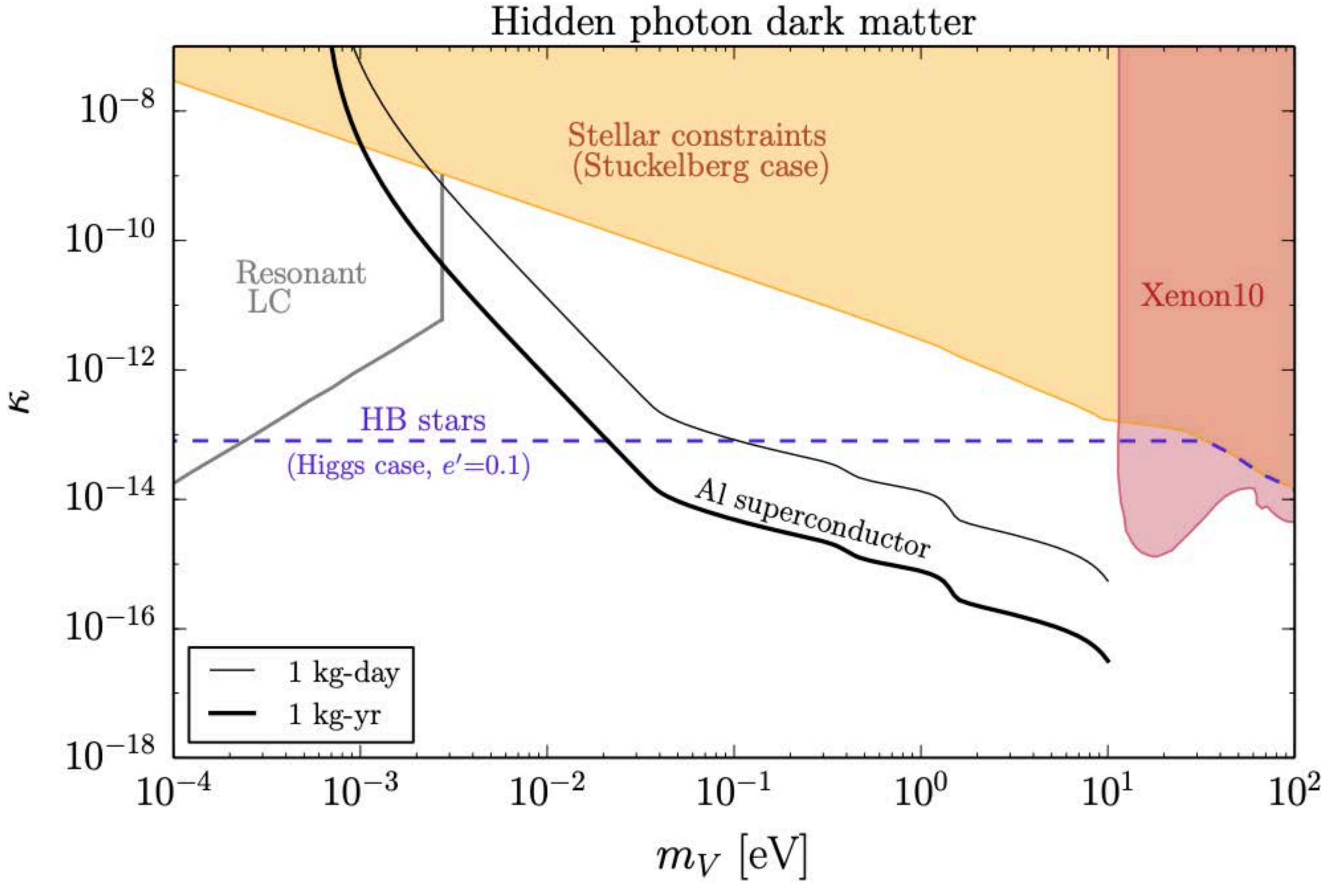
Fundamental coherent interactions

Is there BSM physics?



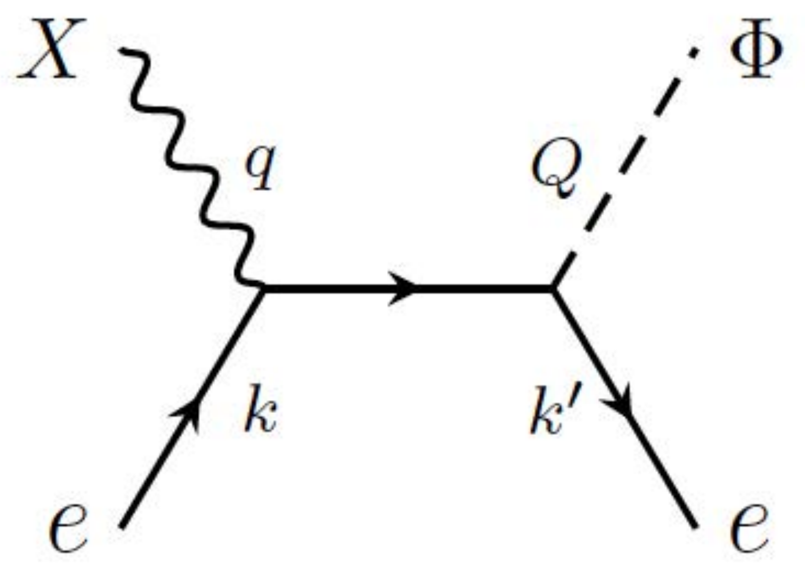
New forces?

J. Billard, J. Johnston, B. J. Kavanagh, arXiv:1805.01798



R.Hochberg et al arXiv:1604.06800v1 [hep-ph]

New particles?



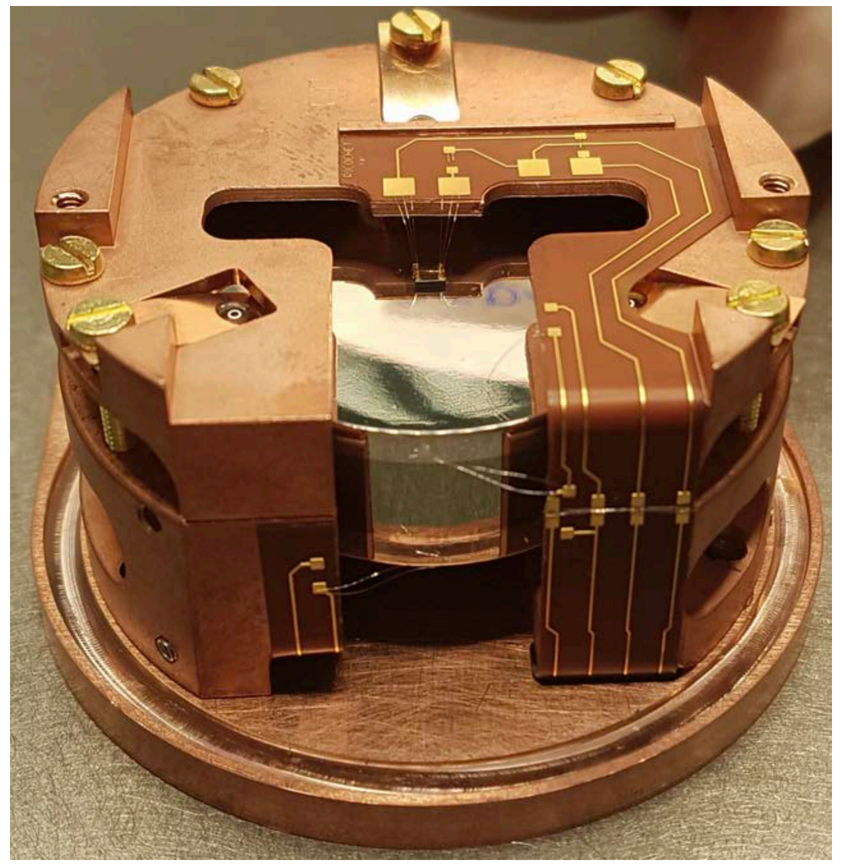
Boson dark matter at low mass scales?

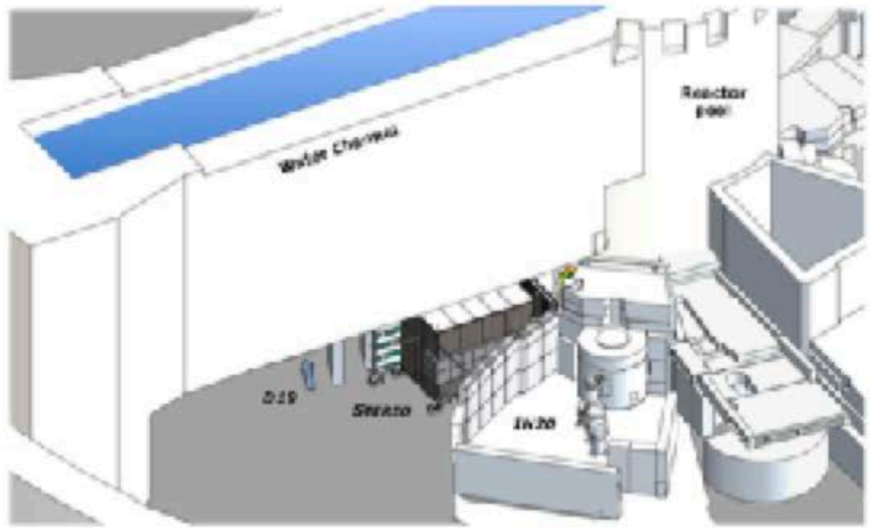
Special (Shallow) Sites with Shielding

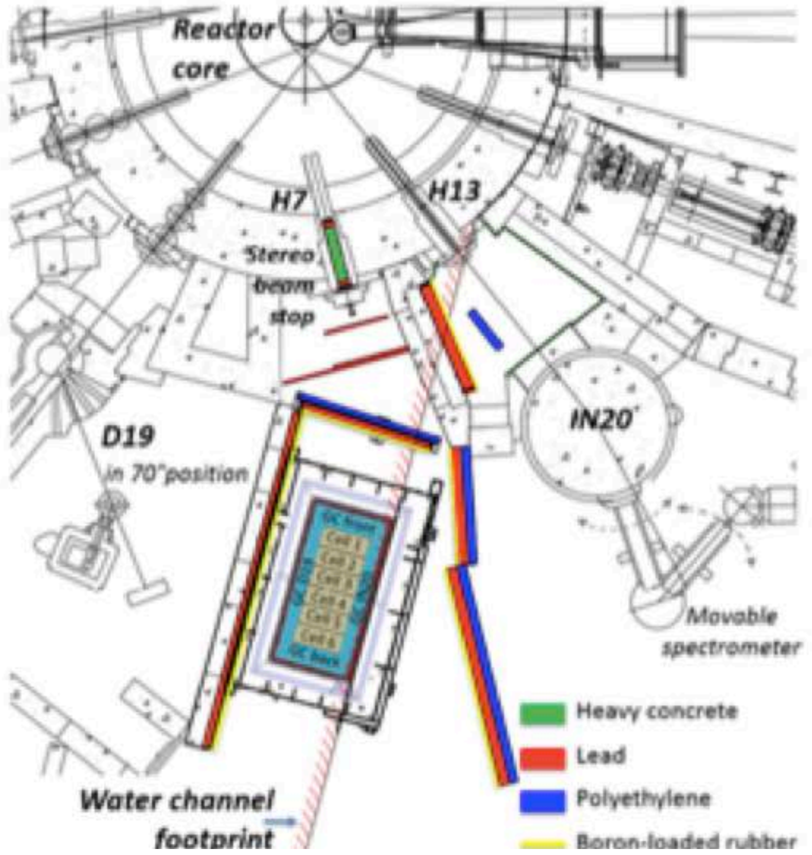
Example: Ricochet at ILL

ILL Reactor Site

- 58 MW thermal power
- 20 events/day/kg at 7m from core
- Reactor on/off
- 15 mwe overburden for background reduction

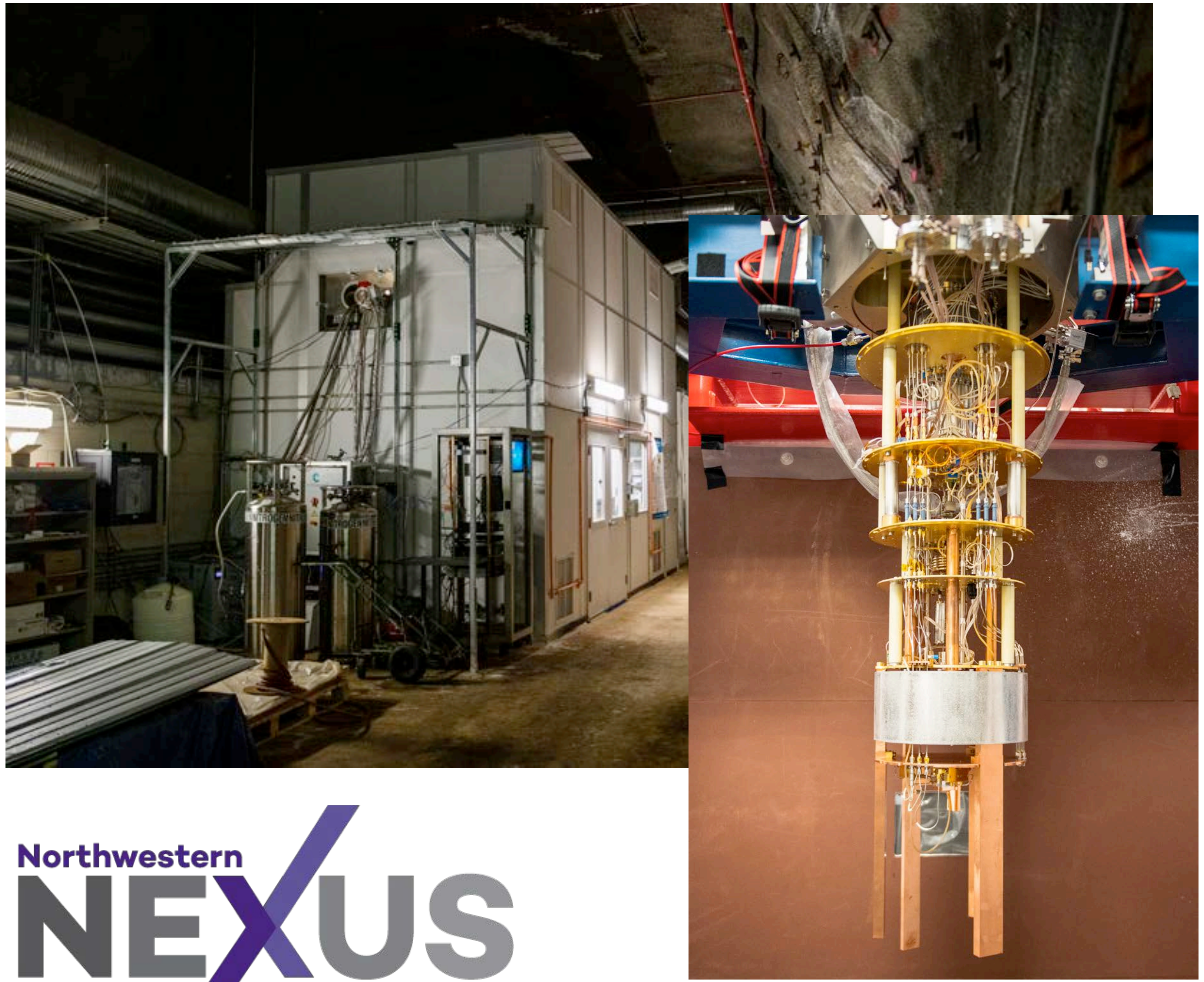






from Joe Formaggio

Underground R&D Facilities - Examples



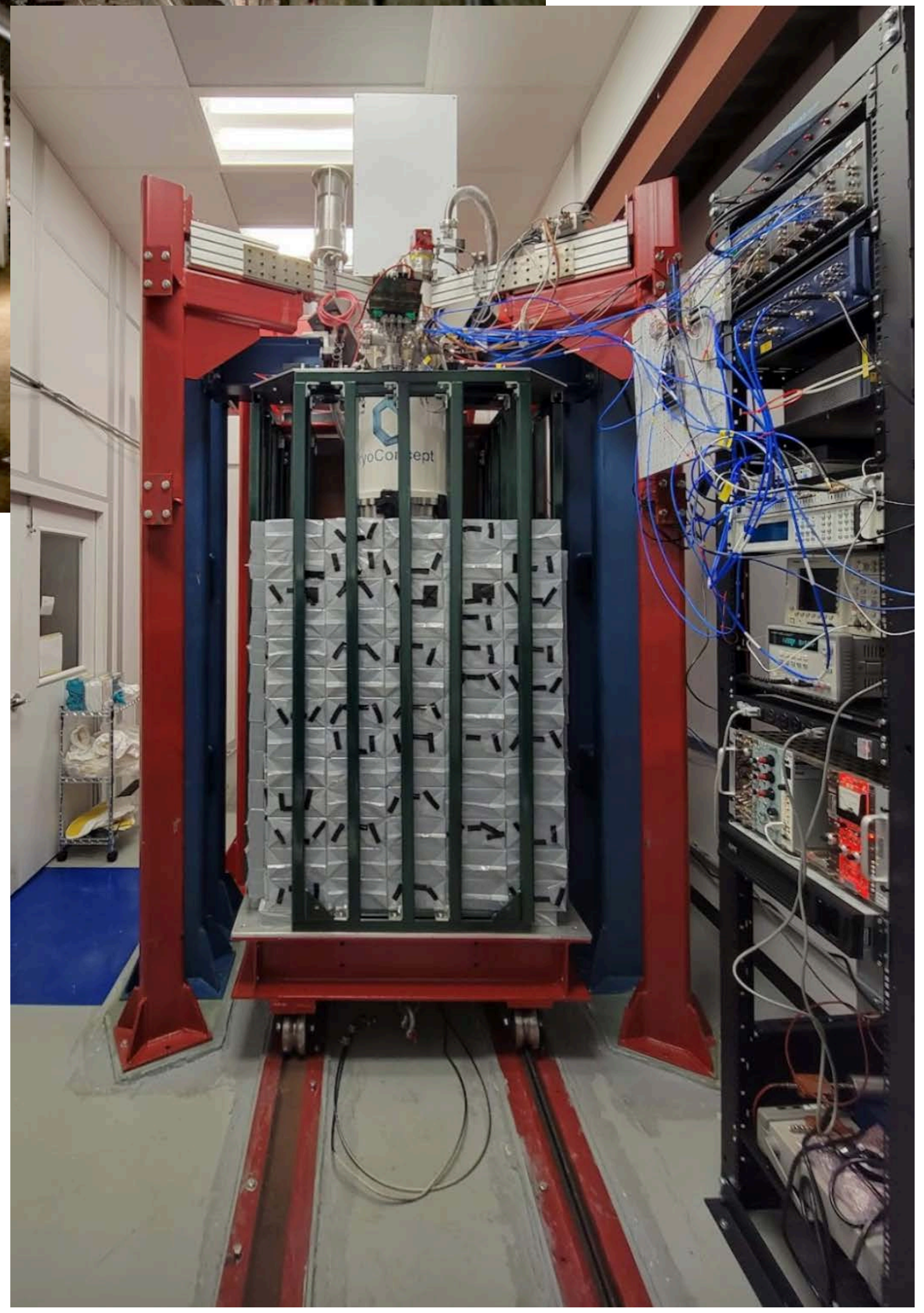
Northwestern NEXUS Experimental Underground Site @Fermilab

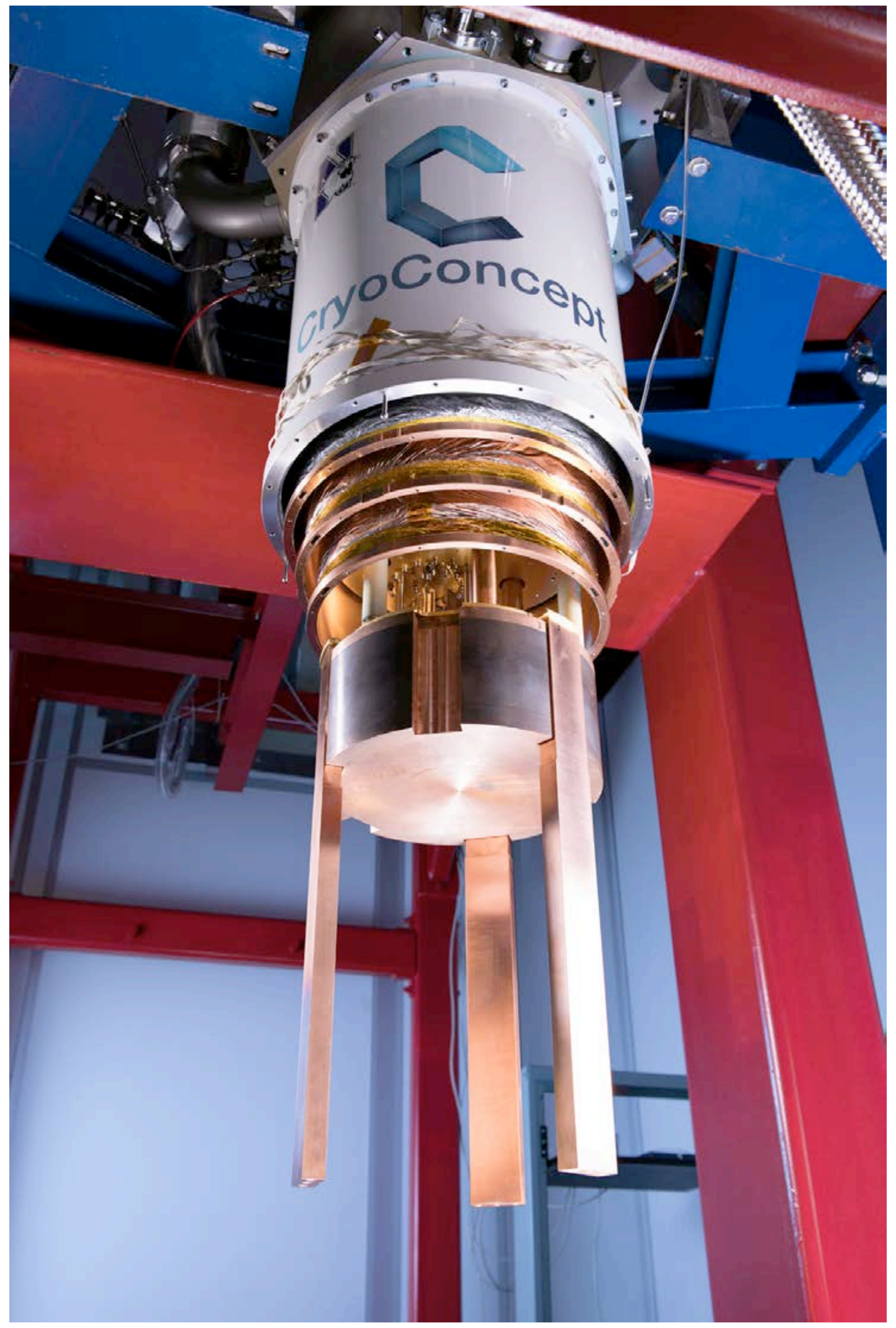
NEXUS multi-purpose low radioactivity cryogenic detector test facility

CUTE FACILITY at SNOLAB

NEXUS - US R&D Facility

Fermilab





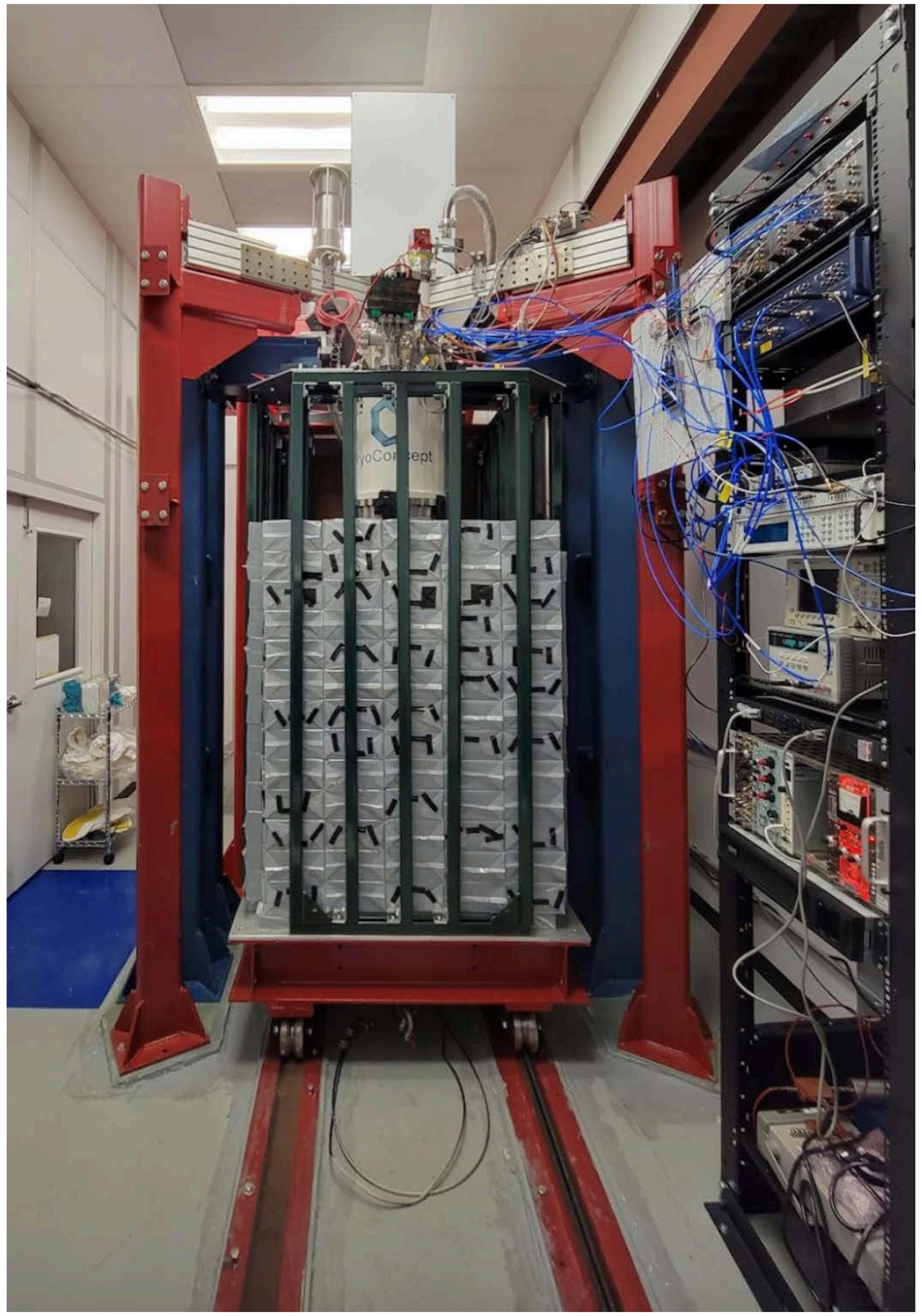
- Located in MINOS experimental hall at Fermilab
  - 107 m underground (300 m.w.e)

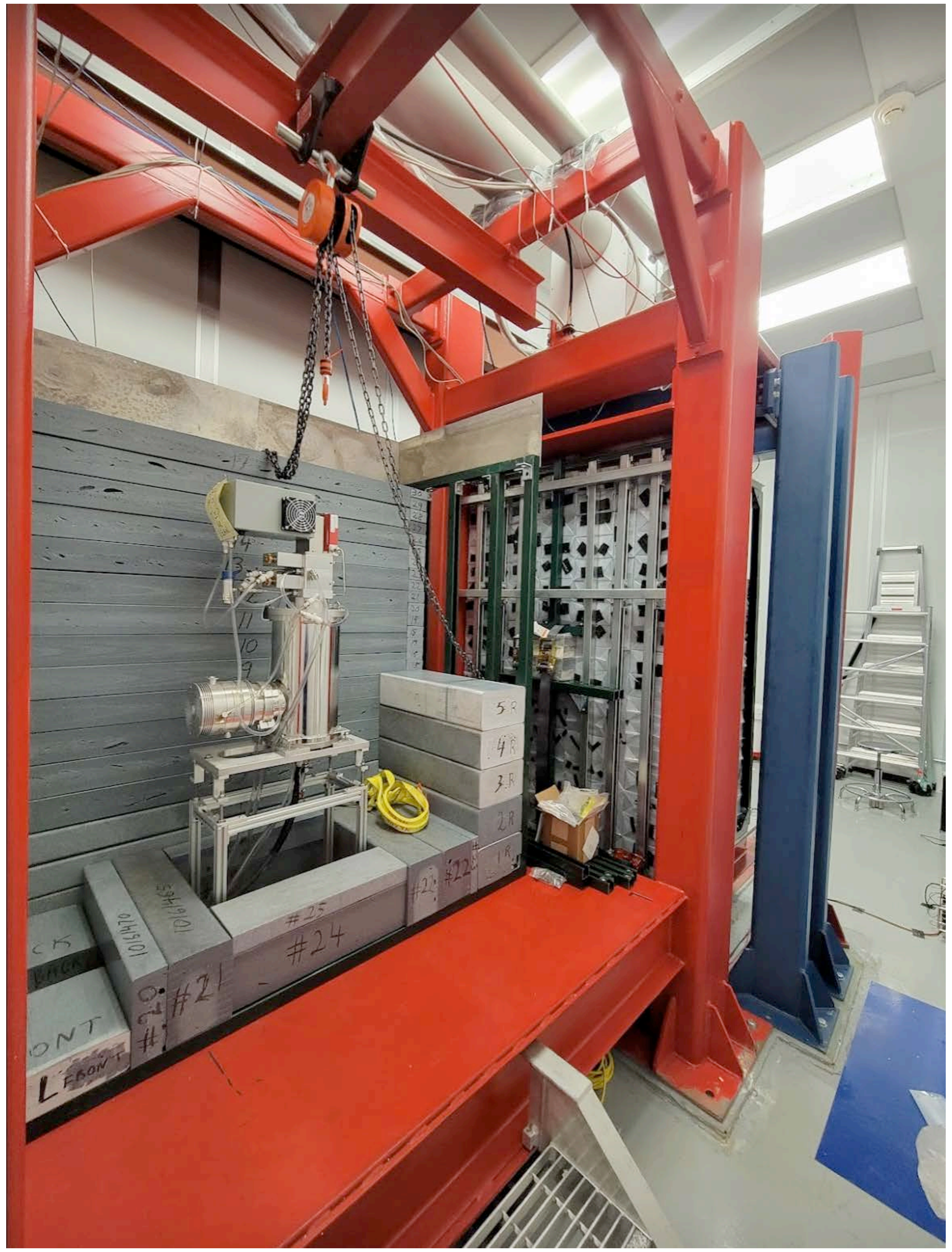
Multi-purpose low-background cryogenic test facility

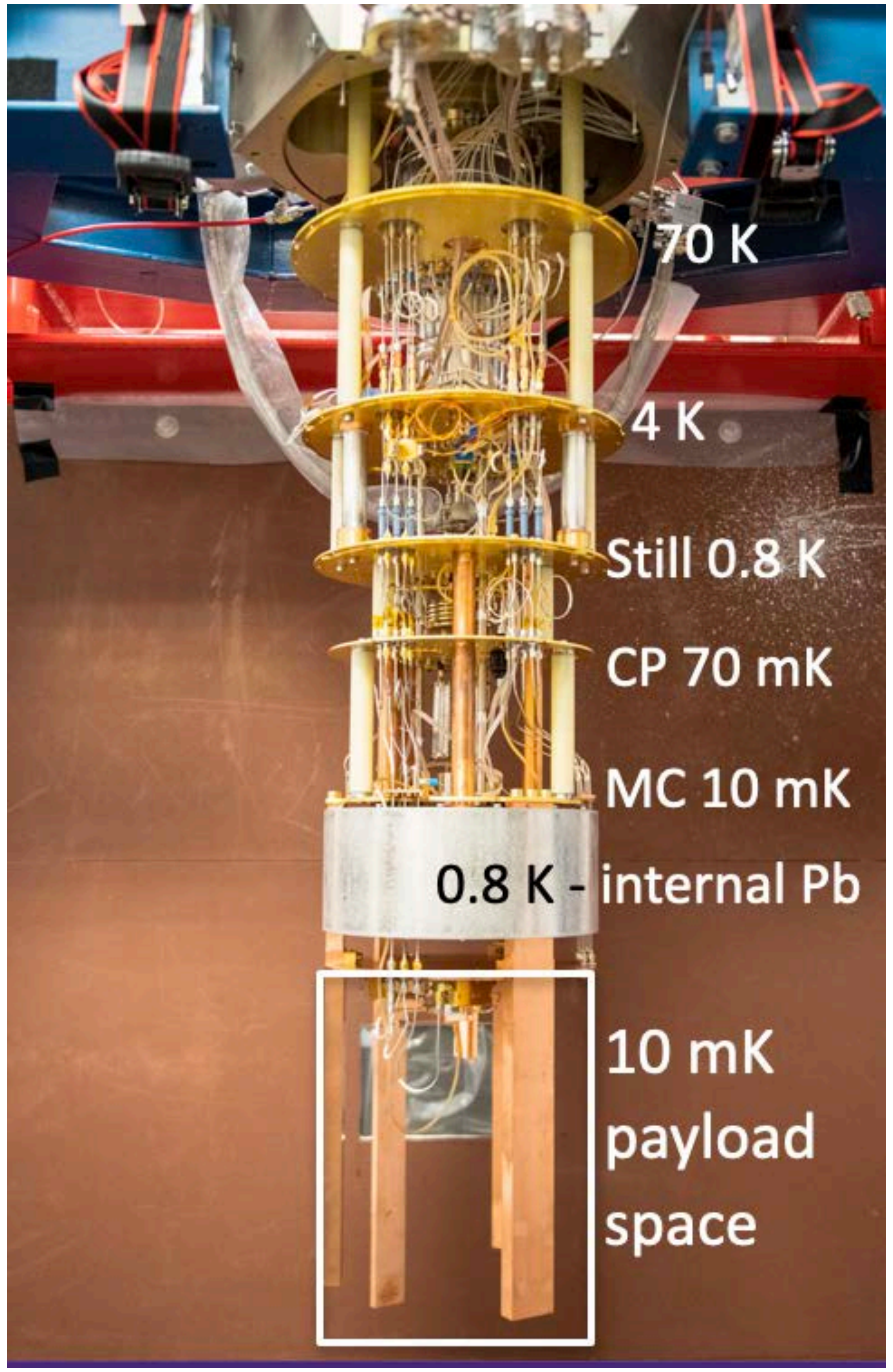
- Hosting at present
  - SuperCDMS Transition Edge Sensor based dark matter search detectors
  - Kinetic inductance detectors
  - Qubits

from Ben Schmidt

NEXUS - US R&D Facility





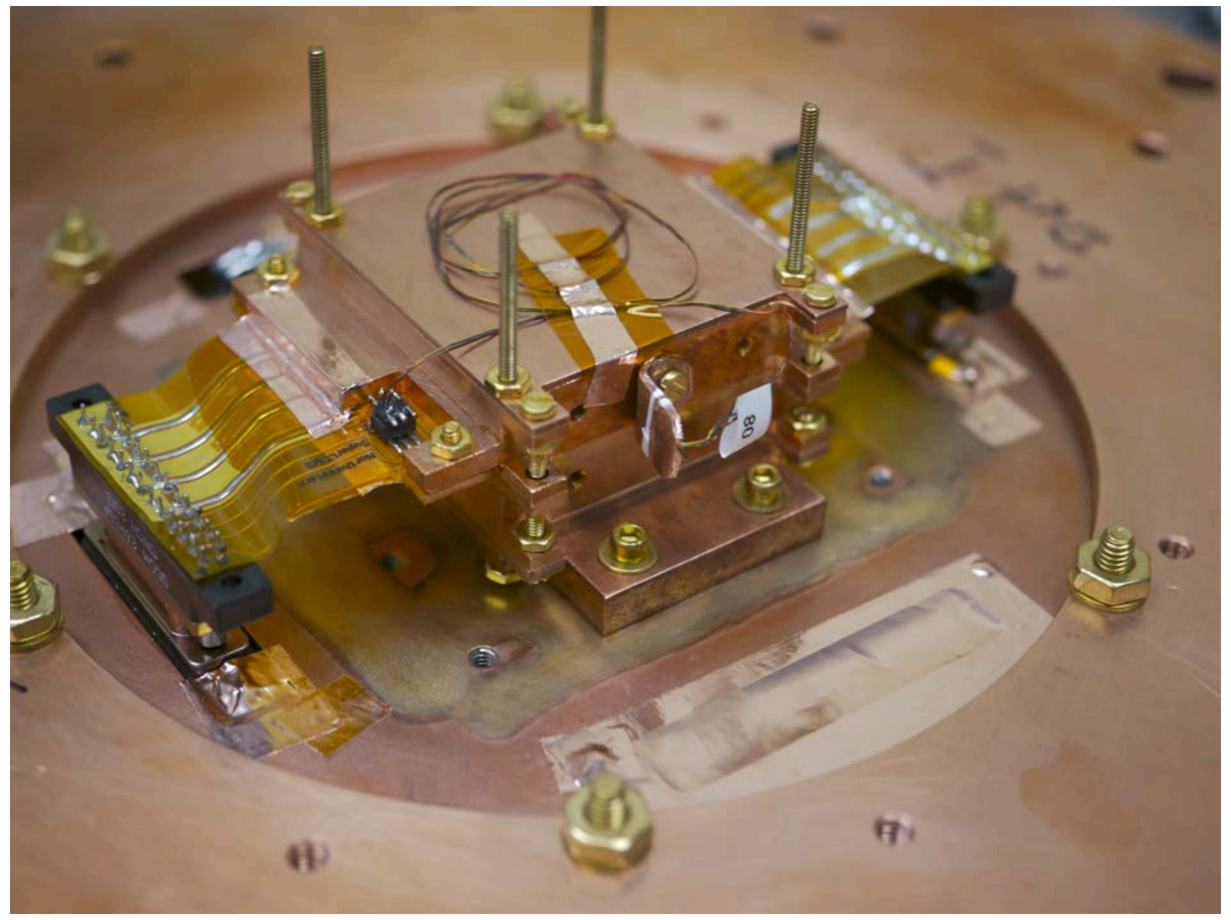


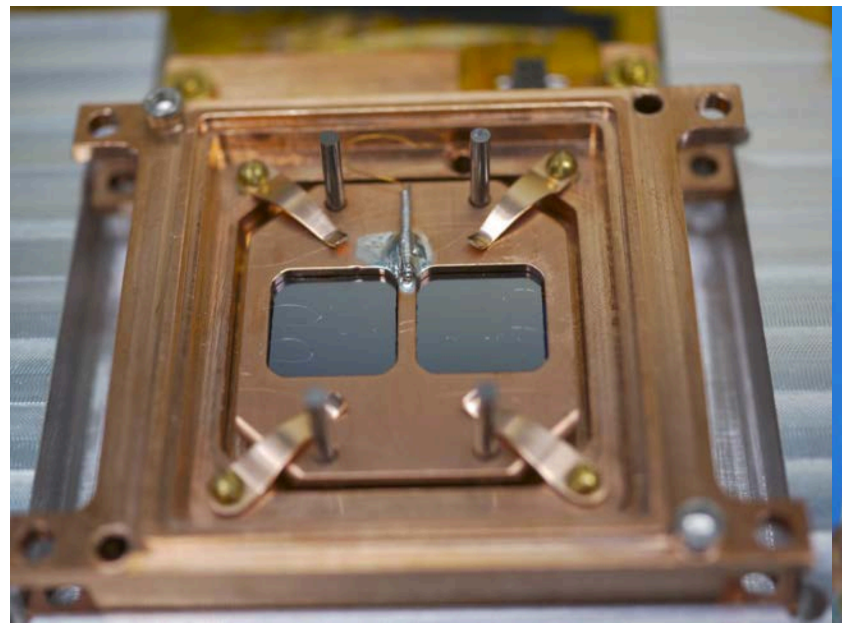
from Ben Schmidt

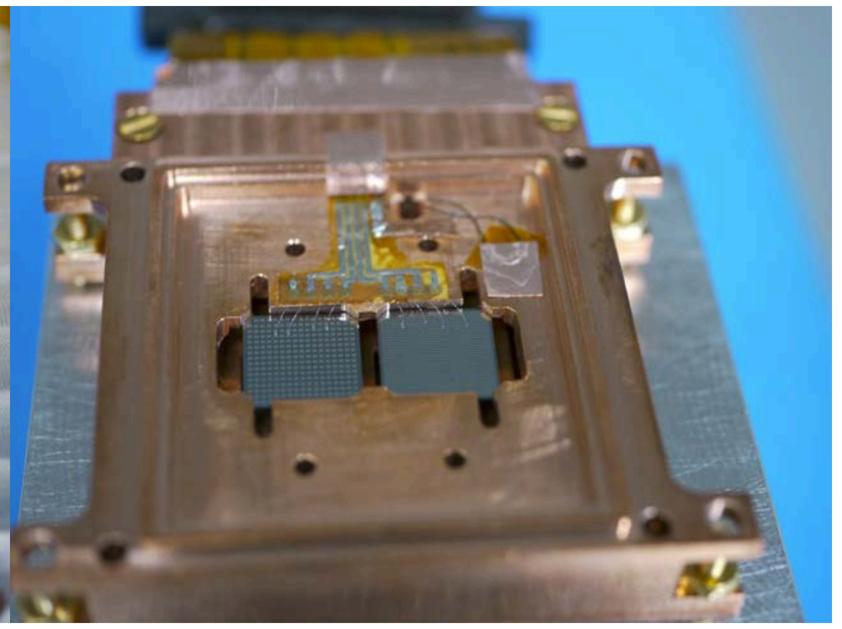
NEXUS - A Multi-Purpose Test Facility

Enables Broad Range of Experiments

SuperCDMS HVeV

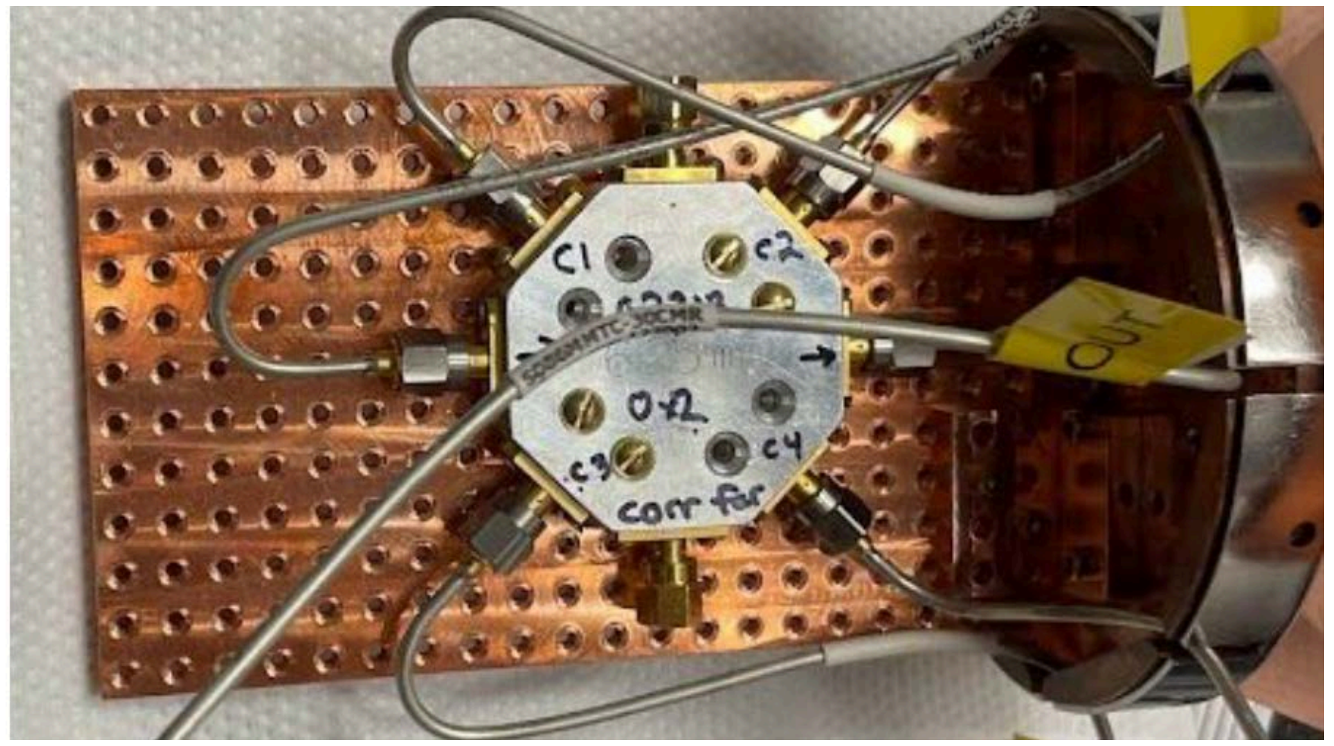


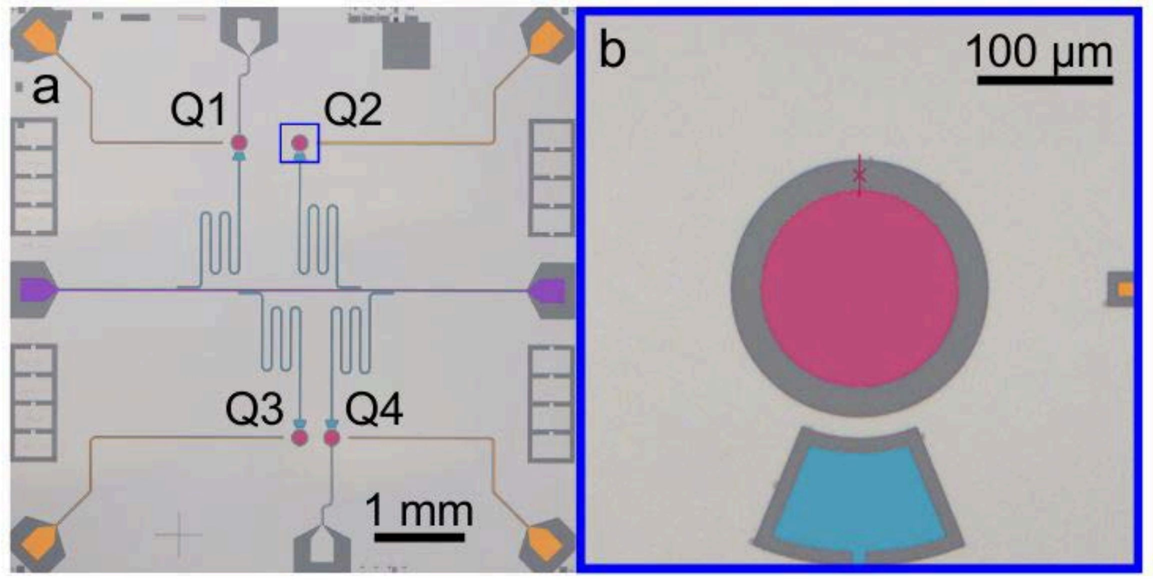




Detector and prior results from above ground operation:
Ren et al., Phys. Rev. D 104, 032010
Albakry et al., Phys. Rev. D 105, 11206

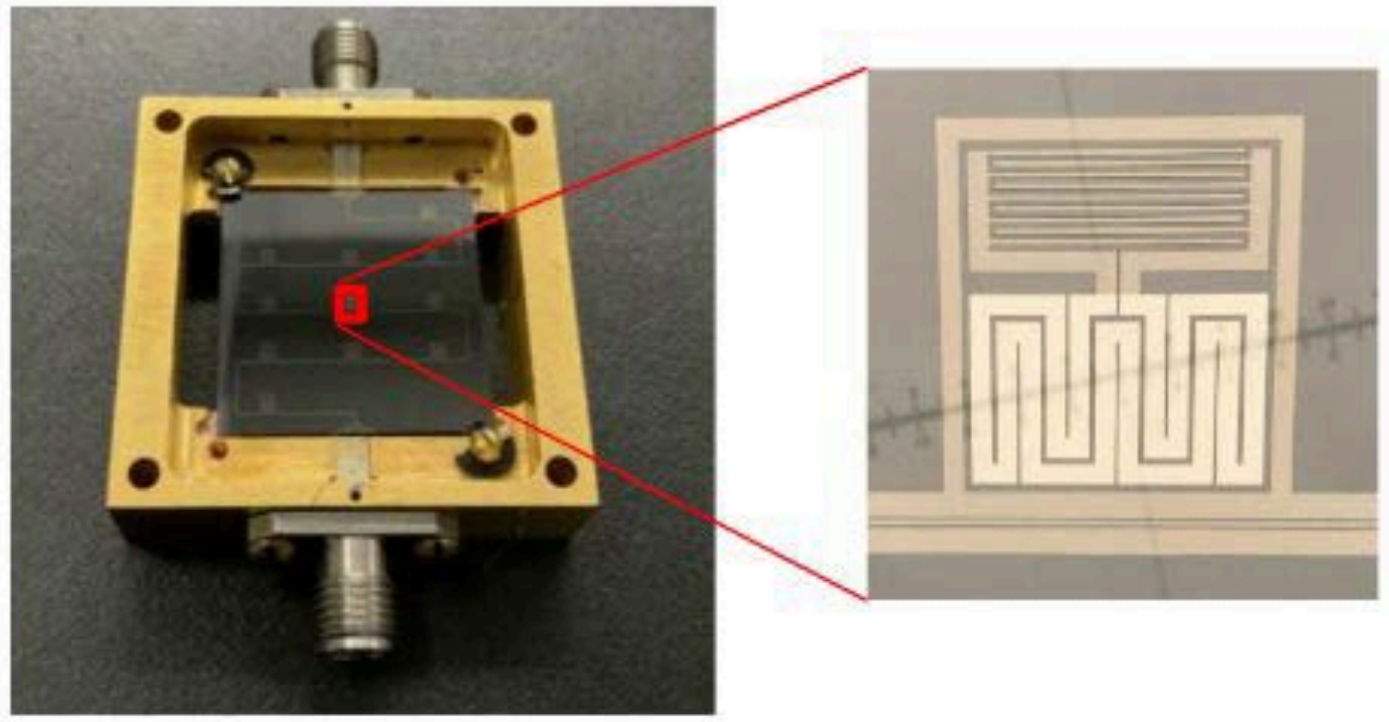
Qubit Array

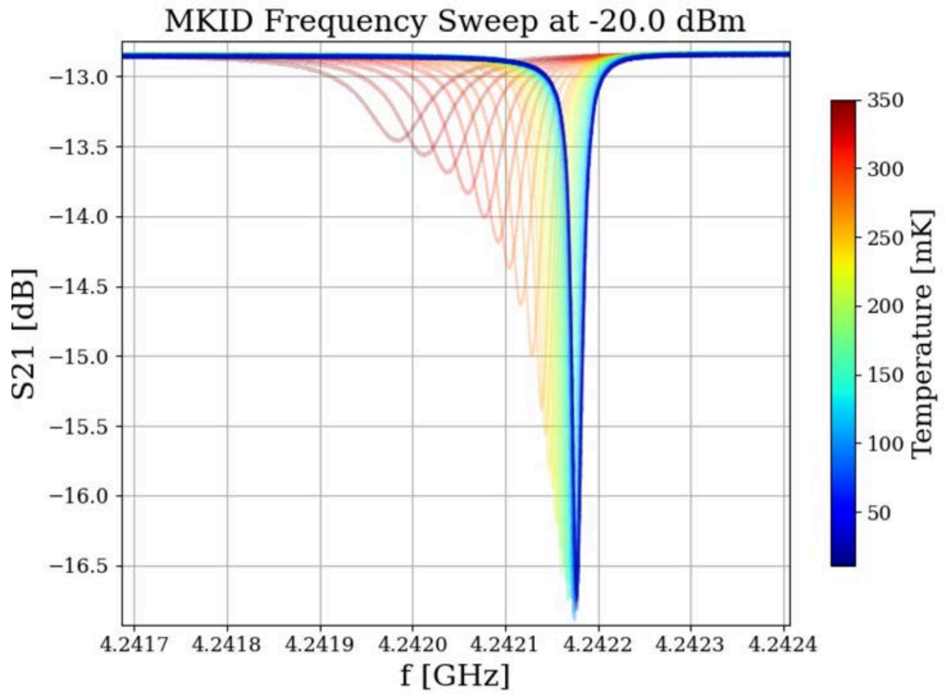




Wilen, et al, Nature 594, 369--373 (2021)

Kinetic inductance Detector Array





Plan to do crystal verification tests for CUPID

from Ben Schmidt

Underground Facility Sites for Bolometer Experiments

Search for $0\nu\beta\beta$, dark matter and CEνNS remain high priorities of the field.

Experiments with discovery potential.

- Bolometer experiments are done at facilities worldwide. International collaboration and coordination is important.
- Infrastructure is complex, takes time to develop. Need to understand and characterize site-specific backgrounds.

- **Deep underground locations** are needed for searches for double beta decay and dark matter (LNGS, Modane, SNOLAB, SURF, etc…..)
- **Underground sites with shielding enable R&D** and detector development, modest to good overburden essential for R&D on large bolometers.
- **Special sites at reactors** enable the study of other physics, e.g. coherent scattering.

Underground Facility Needs for Bolometer Experiments

R&D is critical for leadership in the field. Underground R&D facilities with general user access enable development of detector technology for next-generation experiments.

R&D Facilities

- Next-generation dark matter and $0\nu\beta\beta$ experiments need R&D facilities to test detectors at modest to good overburden.
- NEXUS is currently the only cryogenic facility in the US, SNOLab has CUTE

Radio-Assays/Low Background Counting

- Low-background counting often oversubscribed. Available at SURF, SNOLAB, and other labs.
- Current capacity and sensitivity of existing facilities will need to be further developed for next-generation $0\nu\beta\beta$ and dark matter experiments.

Shared Data/Simulations

- Useful to develop common tools for evaluation of cosmogenic and environmental backgrounds

HEP, NP and QIS benefit from underground test facilities for bolometric detectors.