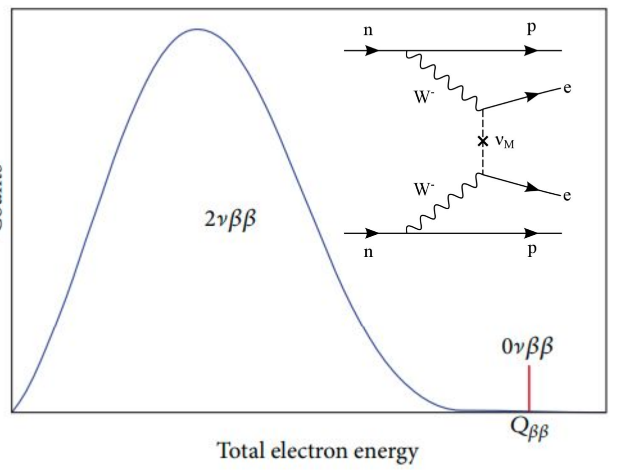
CUPID, CUPID-1T, and the DEMETER Demonstrator

E. V. Hansen for the CUPID Collaboration

Neutrinoless Double Beta Decay with CUPID



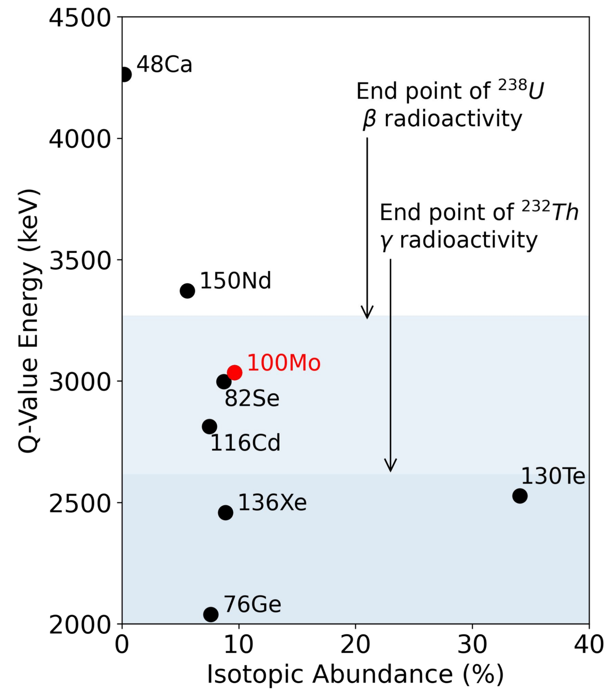
Neutrinoless double beta decay (0νββ) is a second-order rare decay which is theorized to occur if and only if neutrinos are Majorana Fermions (i.e. if neutrinos are their own antiparticle).

In CUPID, we will use the decay

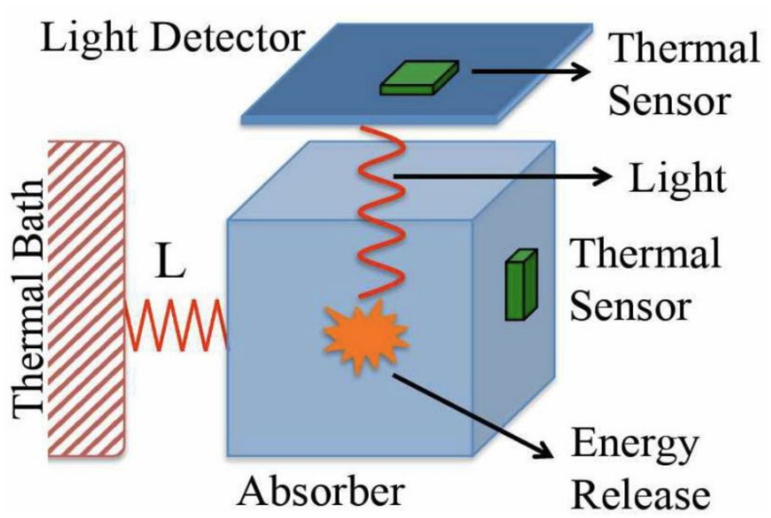
$^{100}Mo \rightarrow {}^{100}Ru + 2e^-$

to search for 0νββ in molybdenum-100. ^{100}Mo is an excellent candidate for this search, as it offers

- a high Q-value (3034 keV) above the bulk of γ environmental background,
- favorable nuclear & kinematic factors which yield an expect decay rate 10x faster than other leading isotopes, and
- ease of embedding into scintillating crystals.

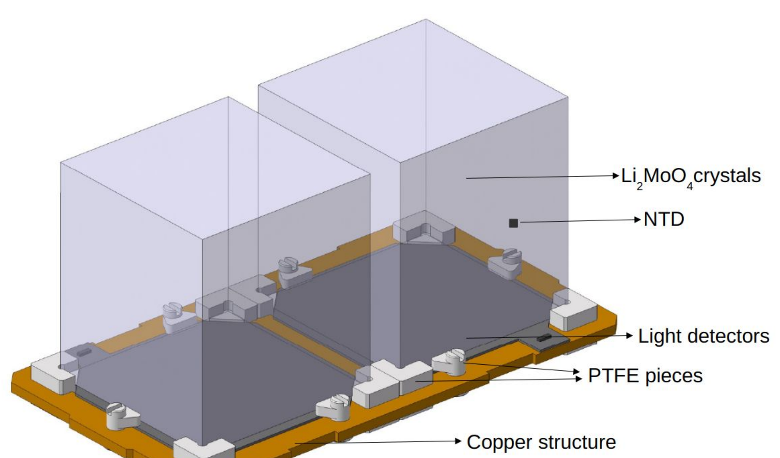


CUPID: CUORE Upgrade with Particle IDentification



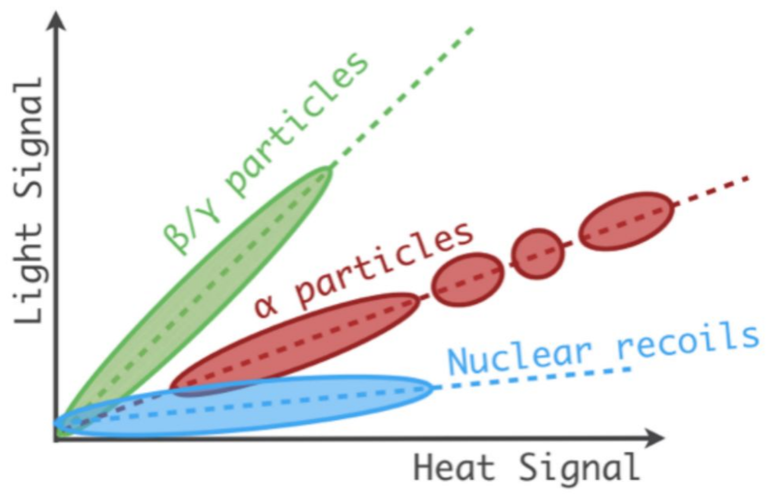
CUPID will use the same cryogenic infrastructure as CUORE at Laboratori Nazionali del Gran Sasso in Italy.

1596 Li_2MoO_4 cryogenic calorimeters will be instrumented with NTD thermistors for heat signal read out. Each crystal will be 45 x 45 x 45 mm^3, corresponding to a mass of ~280 g each and enriched to >95% ^{100}Mo for a total of 240 kg ^{100}Mo.



Each LMO crystal will also face two Ge light detectors, instrumented with NTDs (a total of 1710 light collectors).

The addition of a photon signal allows for rejection of α backgrounds — CUPID-0 [1] and CUPID-Mo [2] have demonstrated this technique with a success rate of >99%.

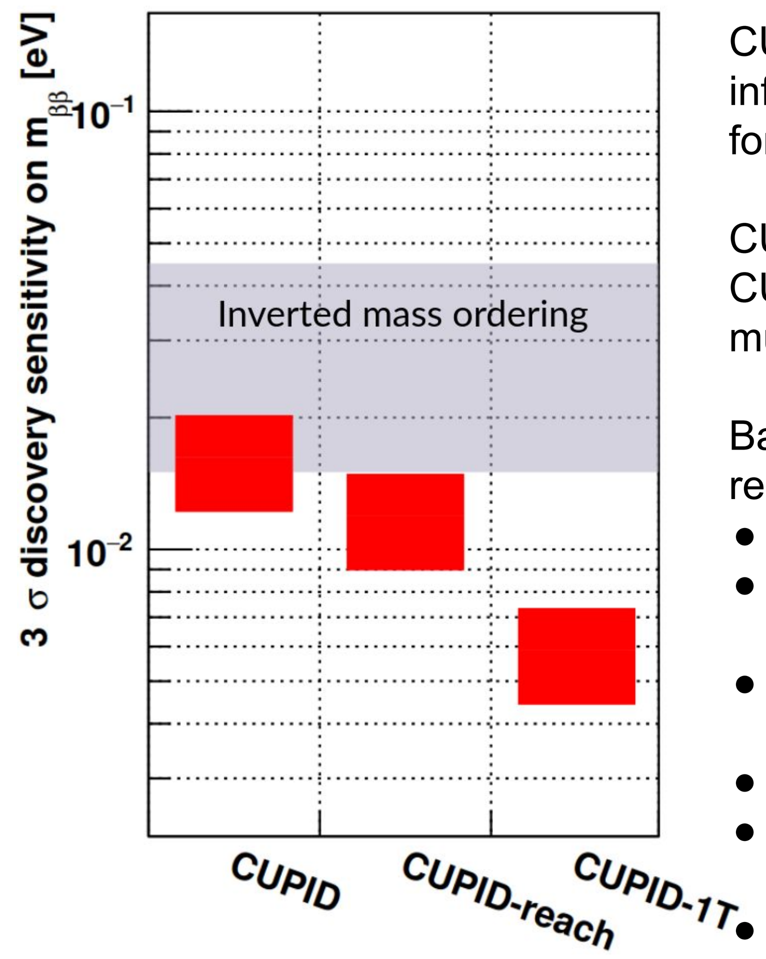


Target energy resolution (ΔE) of 5 keV at Q-value (3034 keV). Target background index of b = 10^{-4} ct/keV/kg/yr.

> Discovery sensitivity (3σ, 10 yr)
> 1 x 10^{27} year
> $m_{\beta\beta}$ < 10-17 meV

[1] Phys. Rev. Lett. 123, 032501 (2019)
[2] Phys. Rev. Lett. 126, 181802 (2021)

Research and Development towards CUPID-1T



CUPID-Reach relies on the same CUPID infrastructure with updated software tools for a 5x reduction in background.

CUPID-1T would host 4x the mass of CUPID using updated technology, including multiplexed readout for >10k channels.

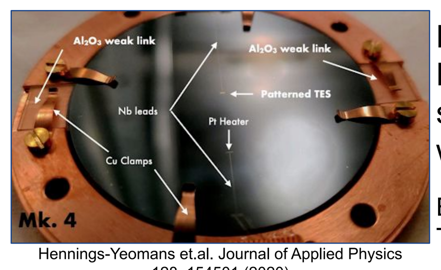
Background can be realistically 20x reduced to the level of 5 x 10^{-6} ckky by

- materials screening & radiopurity,
- improved timing resolution of TES-based detectors,
- passive reduction and active veto for elimination of surface backgrounds,
- further purification of LMO crystals,
- cleaner cryogenic shields for reduction of γ backgrounds, and
- reconstruction of 0νββ event topology.

Parameter	CUPID-Baseline	CUPID-Reach	CUPID-1T
Crystal	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$	$Li_2{}^{100}MoO_4$
Detector mass (kg)	450	450	1871
^{100}Mo mass (kg)	240	240	1000
Energy resolution FWHM (keV)	5	5	5
Background index (counts/(keV·kg·yr))	10^{-4}	2 x 10^{-5}	5 x 10^{-6}
Containment efficiency	78%	78%	78%
Selection efficiency	90%	90%	90%
Livetime (years)	10	10	10
Half-life exclusion sensitivity (90% C.L.)	1.4 x 10^{27} y	2.2 x 10^{27} yr	9.1 x 10^{27} yr
Half-life discovery sensitivity (3σ)	1 x 10^{27} y	2 x 10^{27} y	8 x 10^{27} yr
$m_{\beta\beta}$ exclusion sensitivity (90% C.L.)	10–17 meV	8.4–14 meV	4.1–6.8 meV
$m_{\beta\beta}$ discovery sensitivity (3σ)	12–20 meV	9–15 meV	4.4–7.3 meV

Superconducting Sensors

Requirements include fast timing resolution and multiplexed readout for >10k channels.



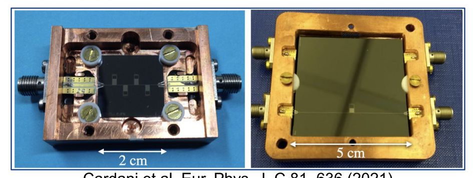
Hennings-Yeomans et.al. Journal of Applied Physics 128, 154501 (2020)

Low-impedance TES Production is easy to scale, and compatible with multiplexing.

Energy resolution ~ 100 eV
Timing resolution = 10 μsec

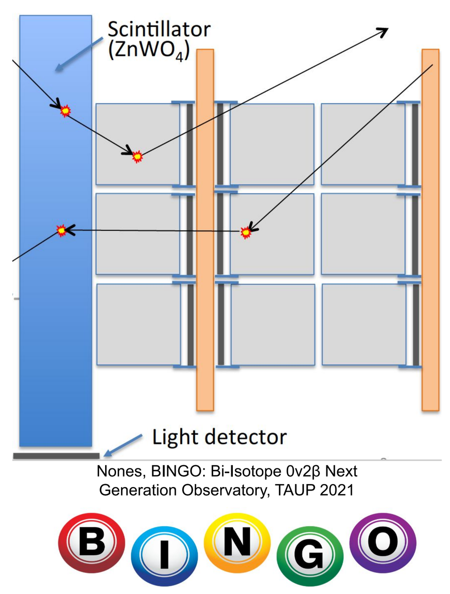
MKIDs: Natively pairs with frequency MUX through tuning of individual devices.

Ongoing work of CALDER.
Noise RMS = 90 eV (vibration dominated)
Risetime = 120 μsec



Cardani et.al. Eur. Phys. J. C 81, 636 (2021)

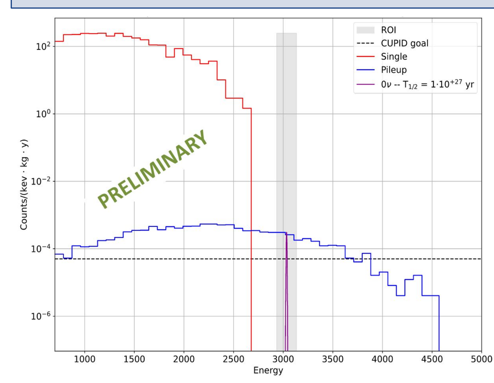
Active γ Veto



Nones, BINGO: Bi-Isotope 0ν2β Next Generation Observatory. TAUP 2021

BINGO (Bi-Isotope 0ν2β Next Generation Observatory) is a demonstrator experiment which developed an internal cryogenic active shield based on $ZnWO_4$ or BGO scintillators. Encouraging results for both LMO and TeO_2 source crystals.

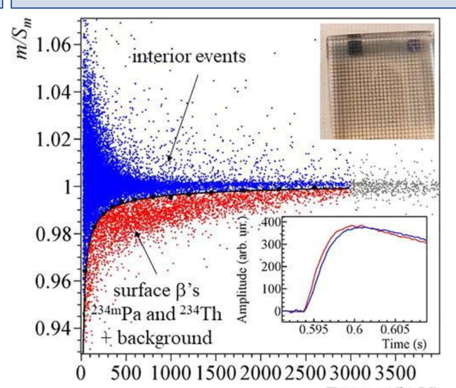
2νββ Pileup



Slow thermal pulses and fast ^{100}Mo 2νββ decay rate means simultaneous 2νββ events will occur in the same crystal.

CUPID crystal geometry optimized for this, but applications in progress for simulating & filtering pulses, as well as rejection using CNN (see poster by C. Capelli)

Reduction in Surface Events



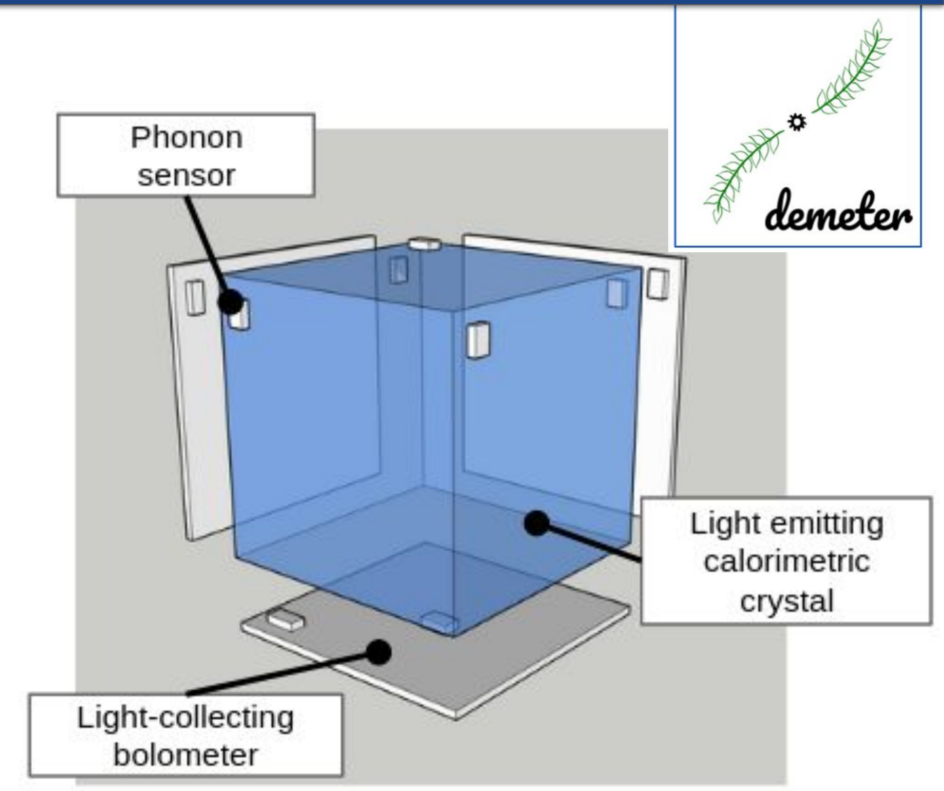
Appl. Phys. Lett. 118, 184105 (2021);

The CROSS project seeks to discriminate surface from bulk events through the use of grid coatings on the LMO crystals. (Left) Al-Pd grid coating, with U source. Surface β rejection efficiency 93(10)%

BINGO (see above) also seeks to reduce surface backgrounds passively, by exposing crystals to only active elements.

DEMETER: Demonstrator Experiment with Multiplexed Event Topology and Energy Reconstruction

CUPID's ability to collect a combination of heat and light signals provides excellent particle discrimination, but there's not yet sensitivity to topology (energy / position reconstruction) at the single-crystal level.

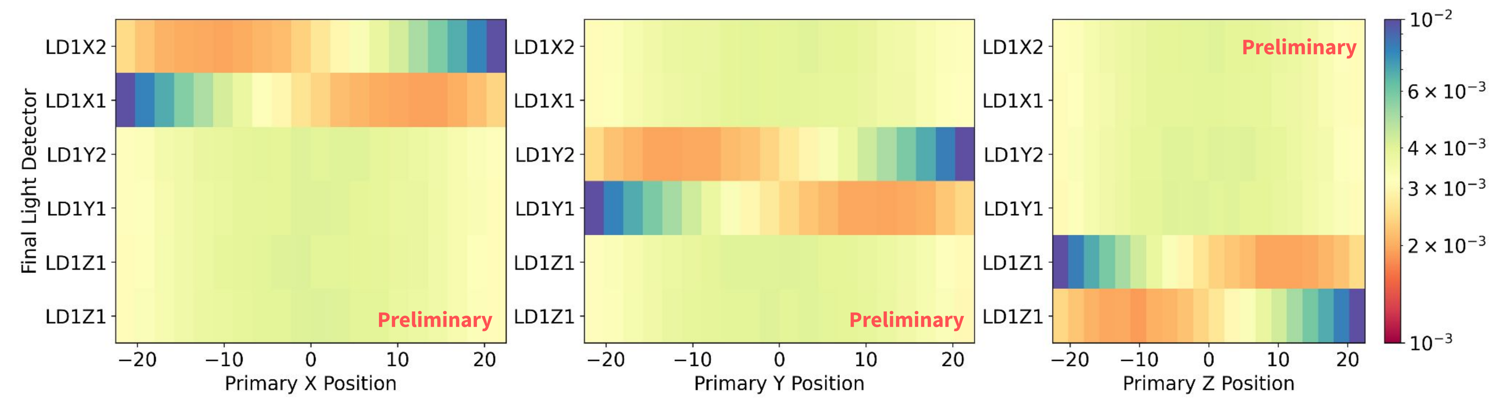


The ability to reconstruct topology of the event would add a breakthrough capability to calorimetric detectors. We could distinguish between one- and two-electron events for a truly background-free measurement, as well as sensitivity to DBD mechanism in case of discovery.

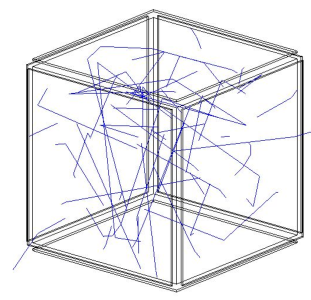
DEMETER also provides a test stand for development of multiplexing applications, which will be required for CUPID-1T >10k channels. Collaboration with LBNL CMB researchers is ongoing.

> DEMETER focuses on both phonon and photon reconstruction at the crystal scale to provide physics information & background identification to large scale detectors like CUPID-1T.

> **Potentially transformative technology:** Modular TeO_2 calorimeters with topological reconstruction and PID (Cherenkov and phonon imaging) could mitigate the need for enriched detectors.

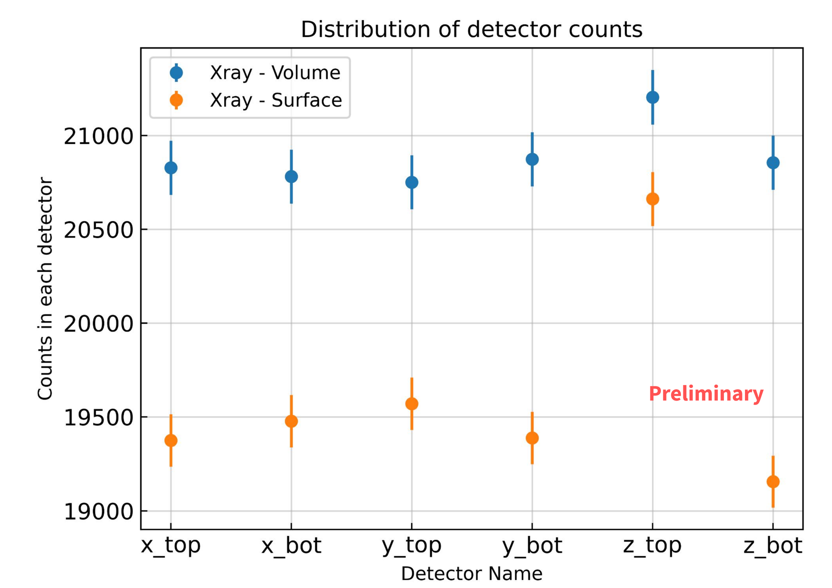


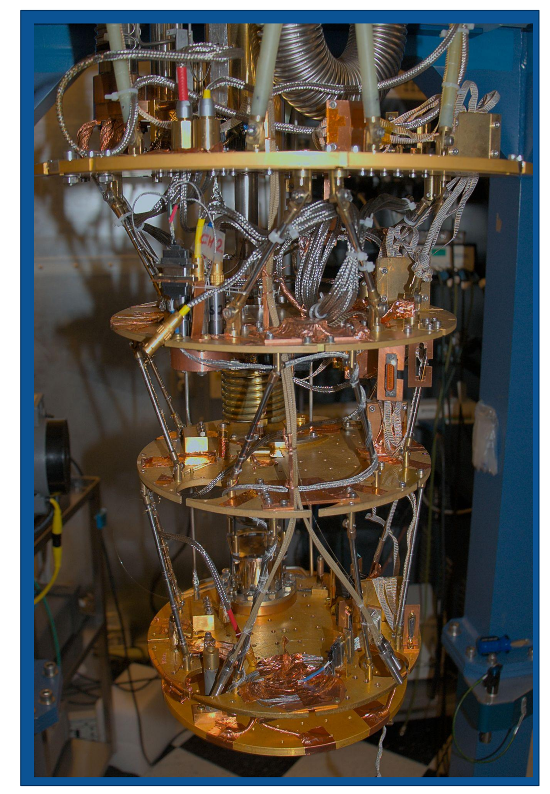
(Above) *Preliminary* optical photon simulation with LMO crystal surrounded by Ge light detectors. OP generated uniformly in LMO, final signal demonstrates preference for near LDs.



(Left) Simplified model of optical photon simulation with DEMETER-like geometry

(Below) *Preliminary* phonon simulation with TES instrumentation. Events near LD "z_top" appropriately deposit more energy in that LD.





(Above) Local dilution refrigerator where DEMETER development is underway

Acknowledgements

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