BERKELEY LAB

Recent Progress of the HeRALD Detector for Light Dark Matter with Superfluid Helium

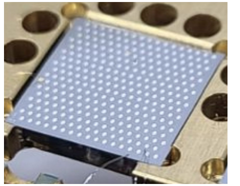
Scott Haselschwardt
LBNL

Identification of Dark Matter 2024

July 11, 2024

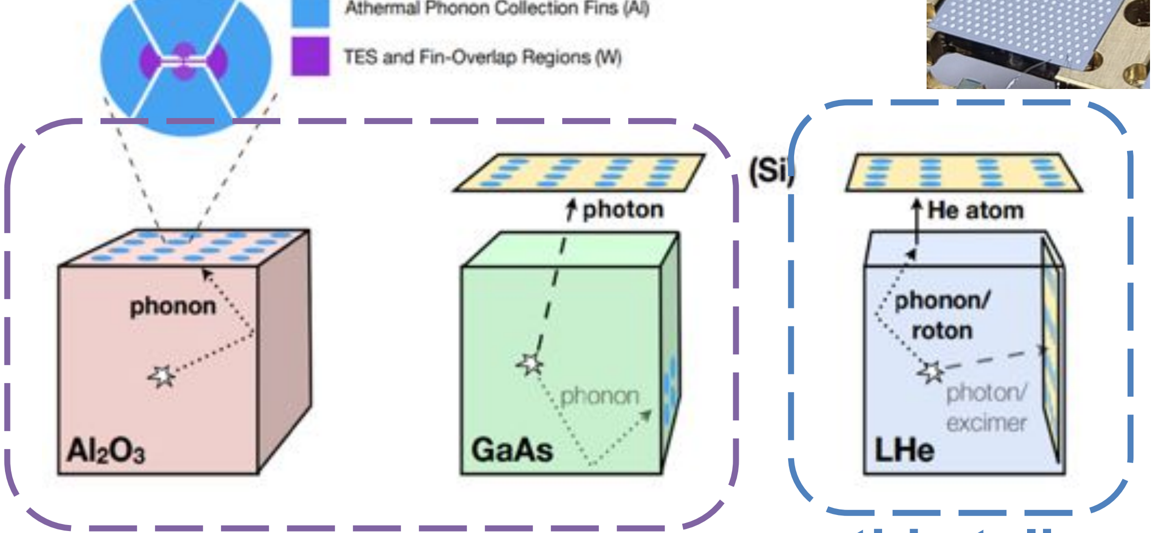
The TESSERACT project (part of the DMNI suite)

Transition **E**dge **S**ensors with **S**ub-**E**v **R**esolution **A**nd **C**ryogenic **T**argets



~40 people from 8 institutions + 3 (new!) French institutions (Lyon, Grenoble, Orsay)

Project funding from DOE-HEP and IN2P3



R. Romani's talk: SPICE

this talk: HeRALD*

* **He**lium **R**oton **A**pparatus for **L**ight **D**ark Matter

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FLORIDA STATE
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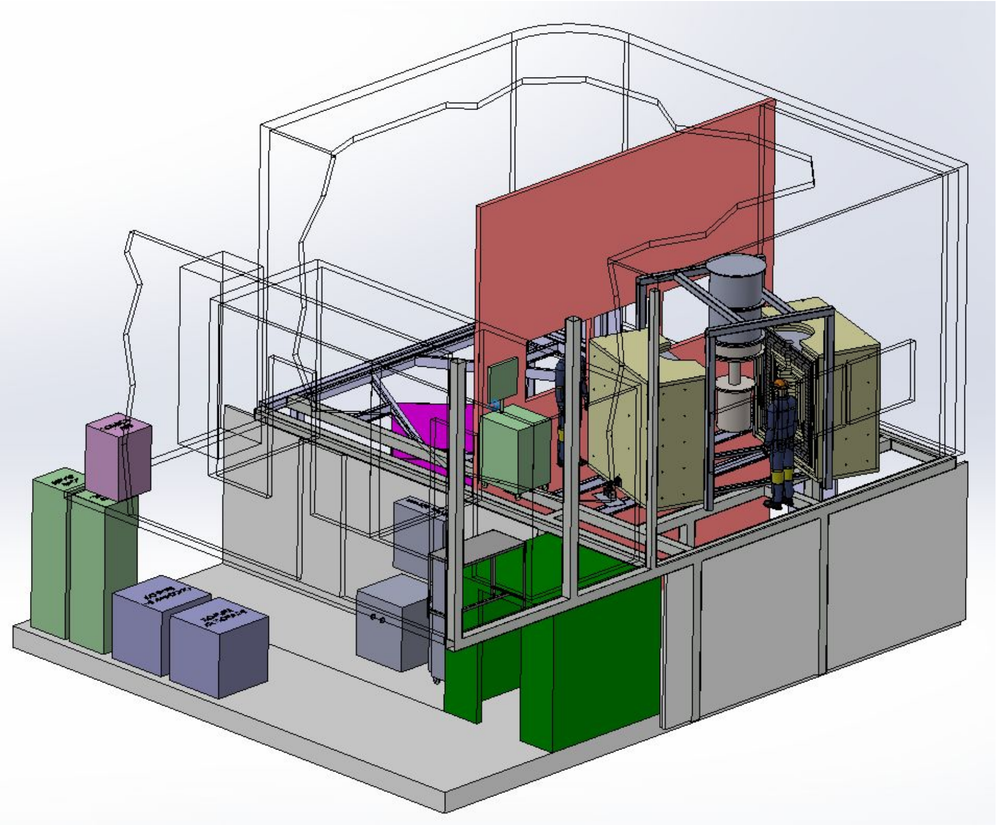
Argonne NATIONAL LABORATORY
UMass Amherst
Universität Zürich UZH

New: TESSERACT @ Modane (LSM)

- Plan for **two** identical setups, each able to hold any TESSERACT target:
  - sapphire
  - GaAs
  - ^{4}He
  - Si/Ge

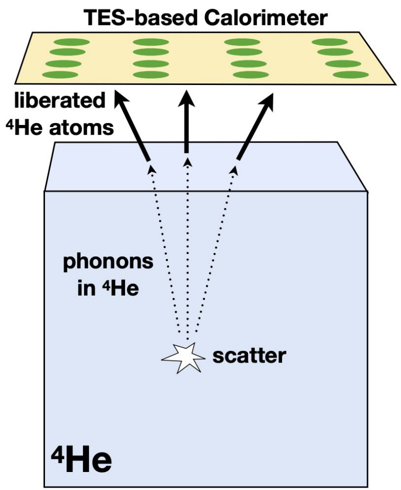
- enables fast turn around for characterization of **backgrounds** and potential **signal (ER & NR)**



HeRALD: Superfluid ^{4}He for DM detection

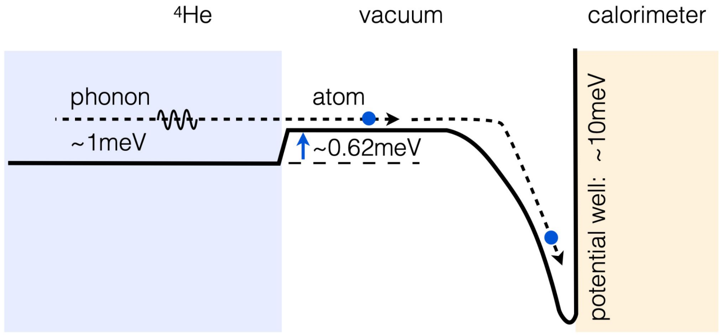
Energy deposits create:

1. **quasiparticles (phonons, rotons)**
   - ballistically propagate to surface → liberate individual 4He atoms → adsorption onto TES
2. **singlet and triplet dimers → scintillation photons**



Key advantages:

- very pure, impurities freeze out @ 10's mK
- no bulk stress/defects…it's a liquid!
- scalable
- **signal: multiple-sensors**
  LEE background: single-sensor
  → coincidence to remove backgrounds

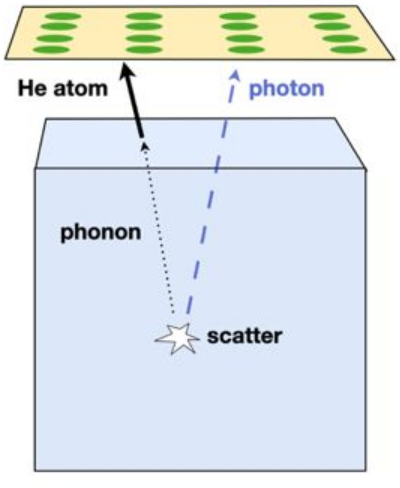


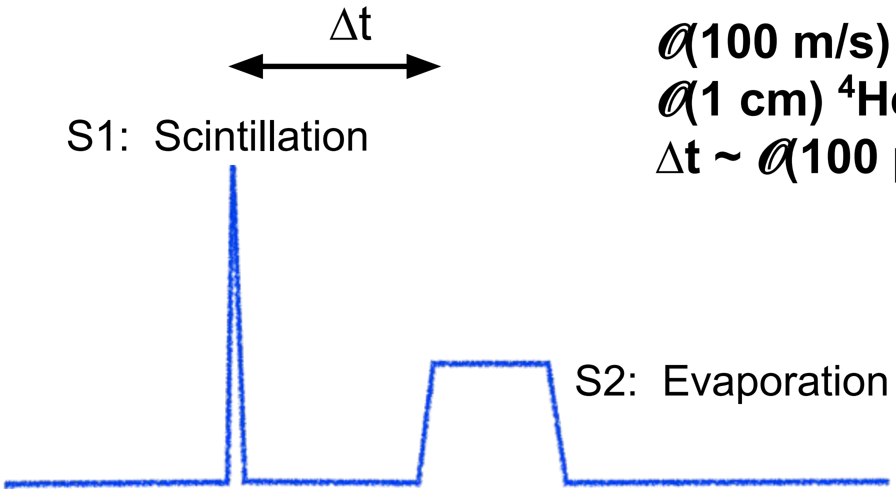
Expected Signals

"S1" - Prompt scintillation (singlets). Just like in LXe, but with 80 nm (16 eV) photons.

"S2" - Delayed Evaporation (rotons/phonons in LHe, causing He atoms to be evaporated from the liquid surface)

When deposited energy is < 20 eV → no scintillation, 'phonon only'



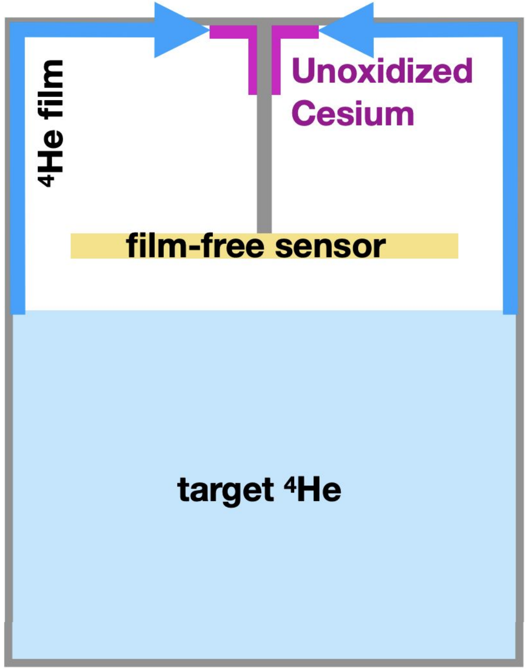


$\mathcal{O}$(100 m/s) phonon velocity
$\mathcal{O}$(1 cm) ^{4}He thickness
$\Delta t \sim \mathcal{O}$(100 μs)

First HeRALD R&D @ U. Mass (S. Hertel)

Major challenge: Superfluid ^{4}He covers all surfaces of a closed container. Do not want this on sensor!

- Empirically: superfluid on calorimeter degrades performance
- Superfluid ^{4}He does not wet Cs
  - see Ketola, Wang, Hallock *PRL* 68, 201 (1992).
- Strategy: deposit a ring of Cs between helium target and calorimeter.



See arxiv:2307.11877 (recently accepted in Phys. Rev. D)

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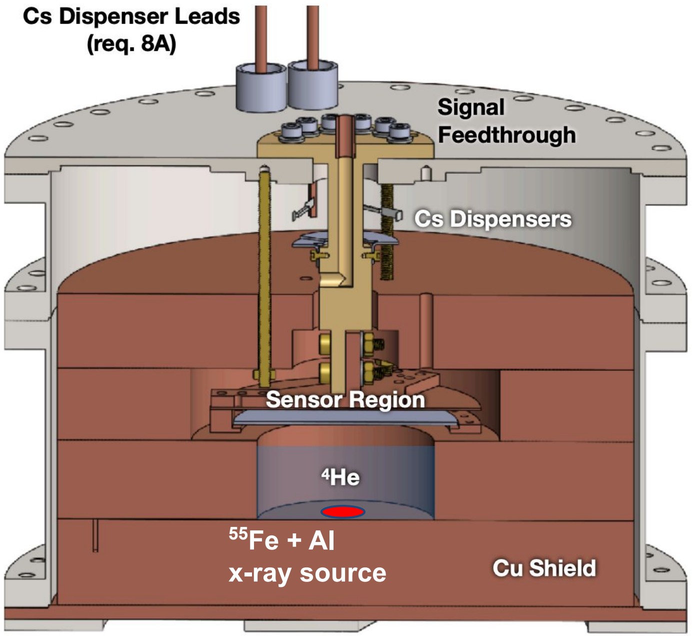
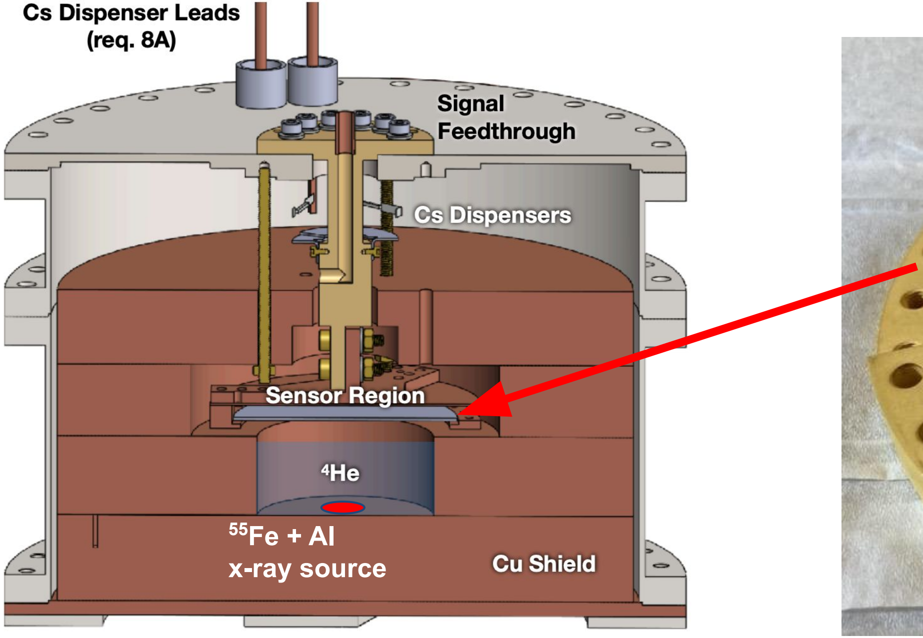
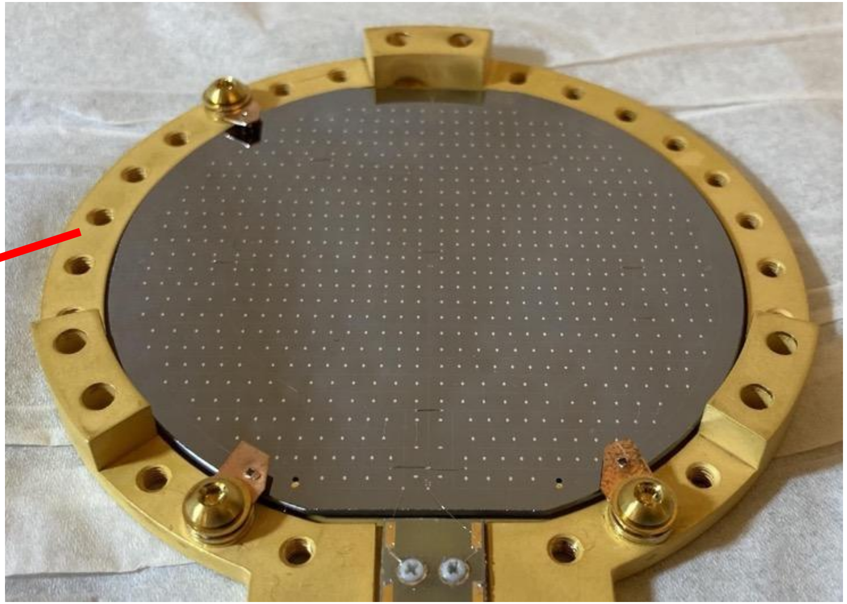


“HeRALD v0.1”

See arxiv:2307.11877 (recently accepted in Phys. Rev. D)

Operating TES sensors above superfluid helium

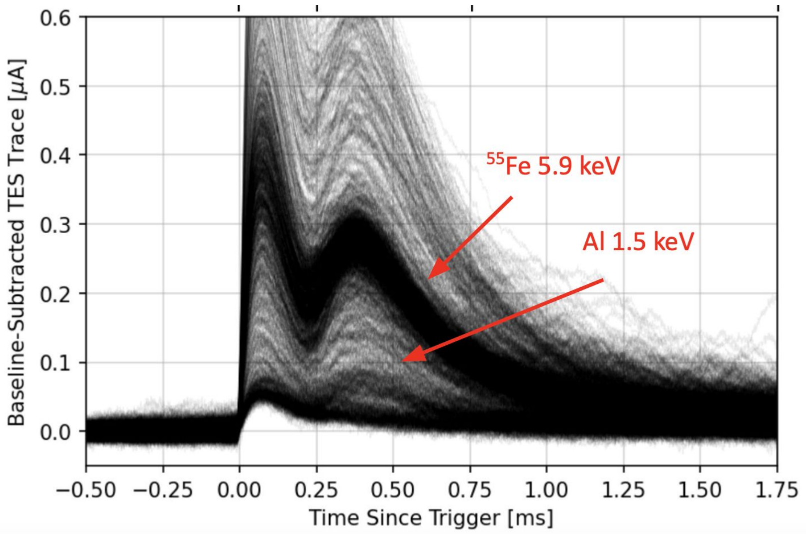


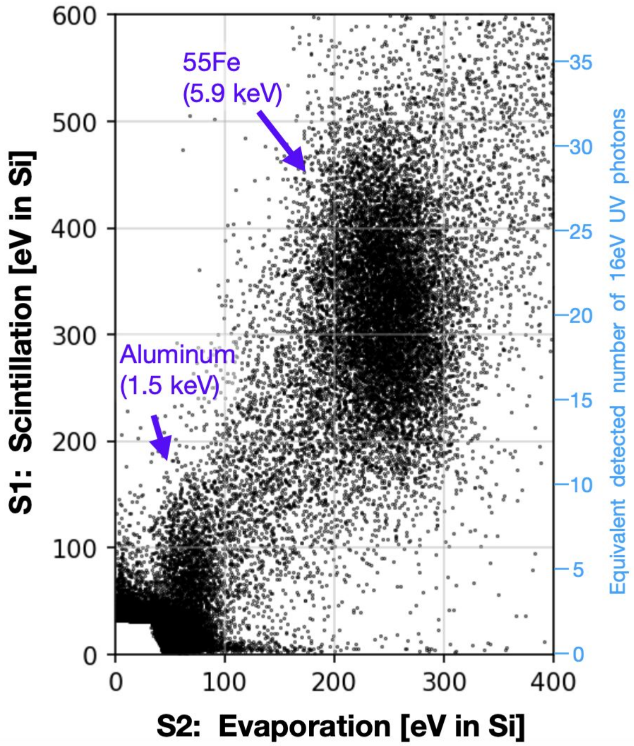


Silicon substrate, 7.6 cm diameter, 1 mm thick

Array of tungsten TESs read out in parallel: T_c = 55 mK, σ ~ 2.26 eV

Initial R&D data: signal gain





Demonstrated 'signal gain' = (sensor energy)/(He energy) ~ 0.15

Converted to [eV in He], 5σ energy threshold is ~140 eV in the evaporation channel → DM mass threshold ~220 MeV/c^2

This will improve with:

- Sensors with better energy resolution
- Higher evaporation signal gain
- Higher phonon/roton reflectivity on surfaces

Initial R&D data: particle ID

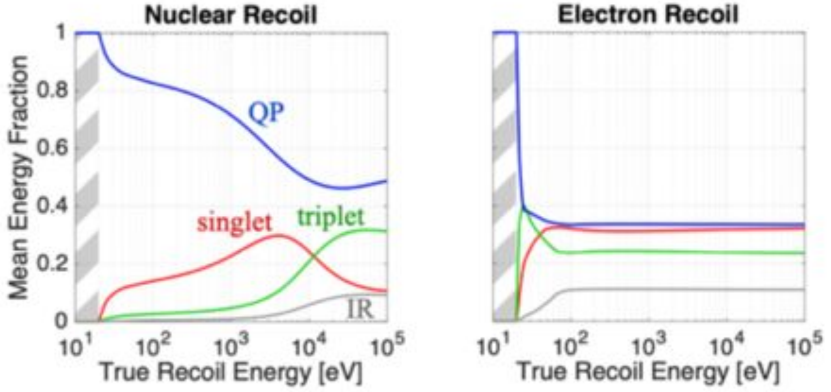
Comparing ER and NR response

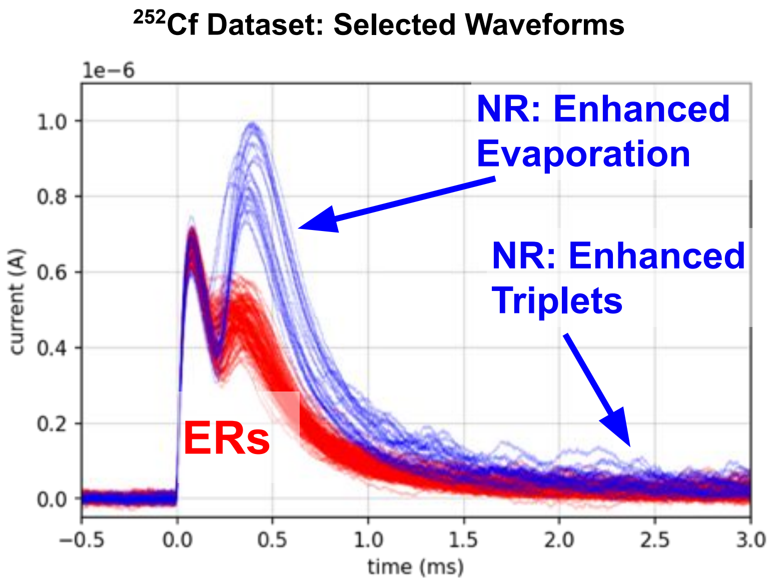
Intended signal region is mostly <20 eV (phonon-only)

Can still look at ER/NR differences above 20 eV

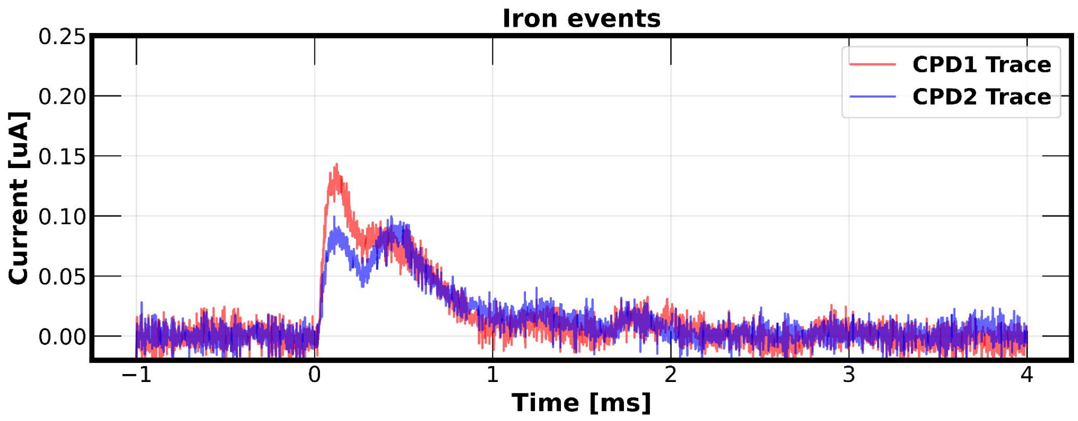
Preliminary observations w/ ^{252}Cf source:

- Larger evaporation:scintillation ratio (at all energies)
- Larger triplet fraction (above ~10 keV)

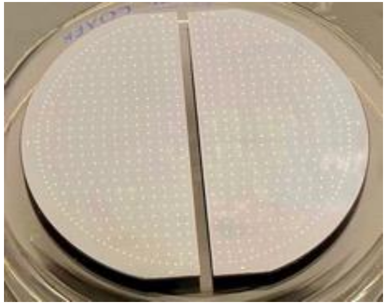


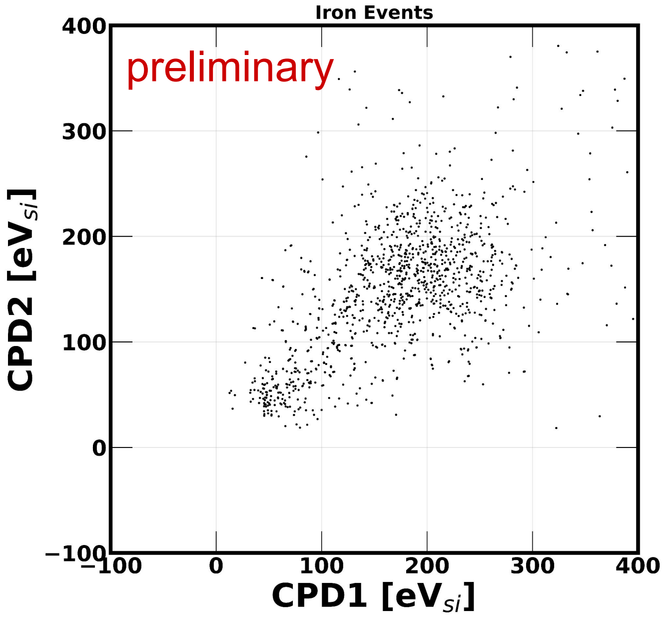


Moving to exploit coincidence @ U. Mass



2-channel array

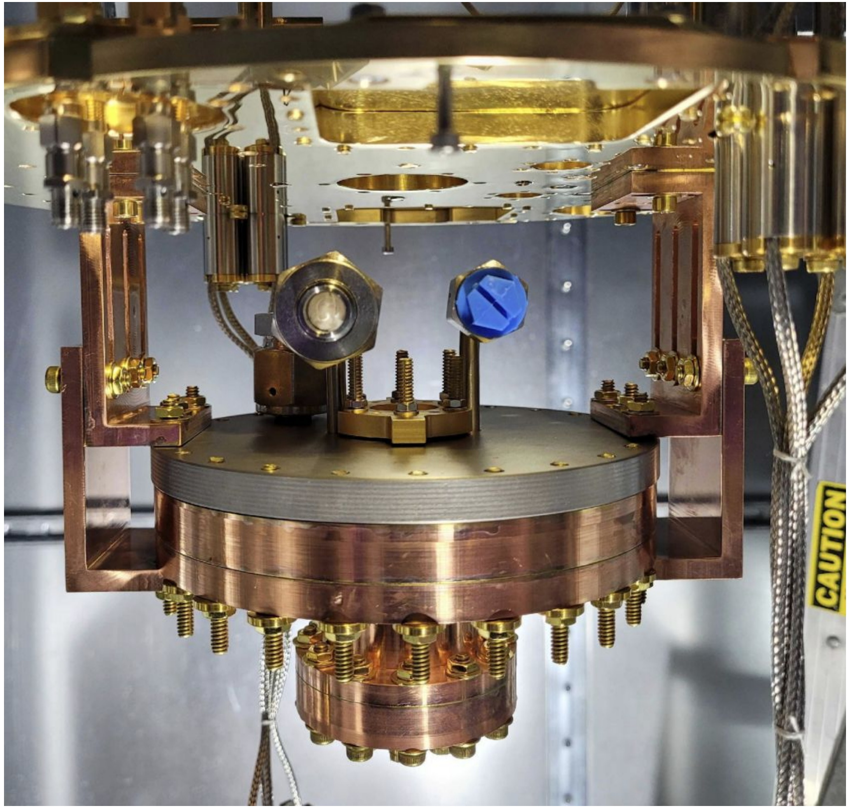




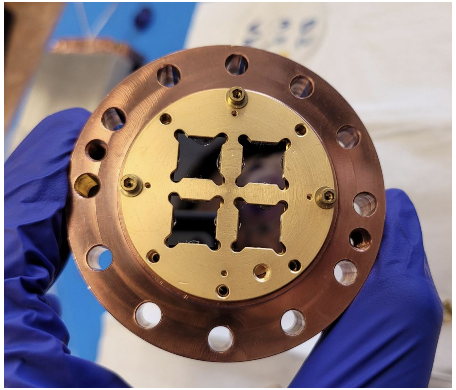
Observing coincidence in both the scintillation and evaporation (phonon) channels!

HeRALDv0.2 @ LBNL

- Further study of multi-channel coincidence w/smaller (better energy res.) sensors
- Develop low-energy ER+NR calibration techniques

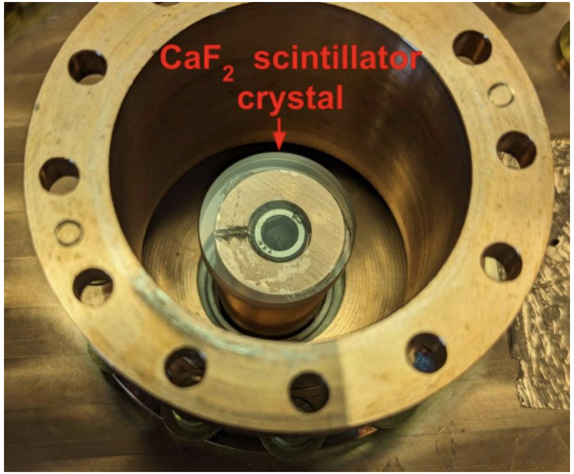


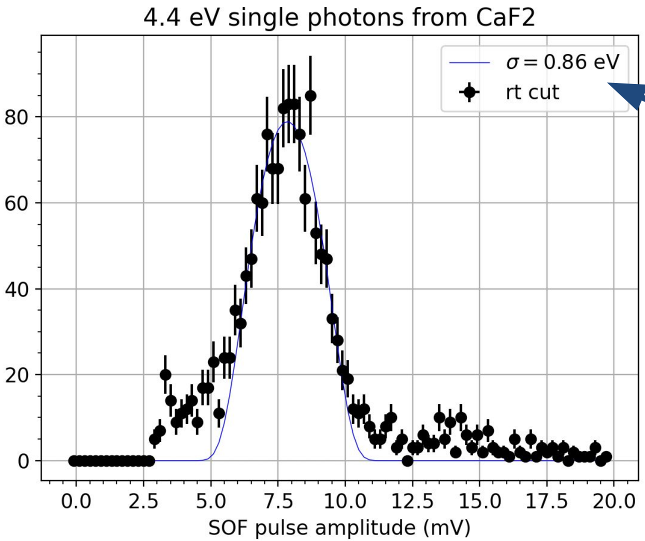
4-channel array of 1 cm^2 devices



HeRALDv0.2 @ LBNL - calibration with CaF_2

- Commissioning of Cs deposition and helium systems
- Initial sensor calibrations with CaF_2 crystal
- Expect He running soon!





single photon peak width combines sensor width & CaF_2 scintillation spectrum

V.B. Mikhailik, *NIM* 566 (2006) 522-525

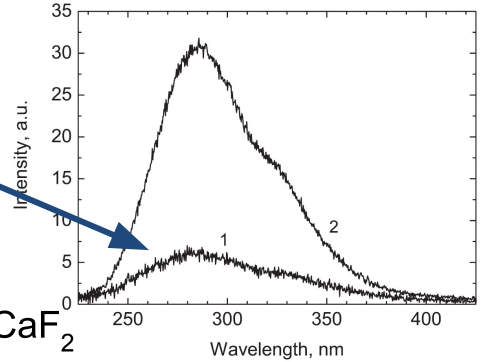


Fig. 1. Luminescence spectra of CaF_2 measured under excitation with 31 eV photons at 300 (1) and 9 K (2).

Summary

TESSERACT

TESSERACT is newly funded by DOE-HEP+IN2P3. Preparing for underground installation at LSM.

HeRALD is a superfluid helium-based light dark matter detector that will be sensitive to nuclear recoil interactions, while having unusual ability to mitigate phonon emission backgrounds.

Successful HeRALD demonstrations:

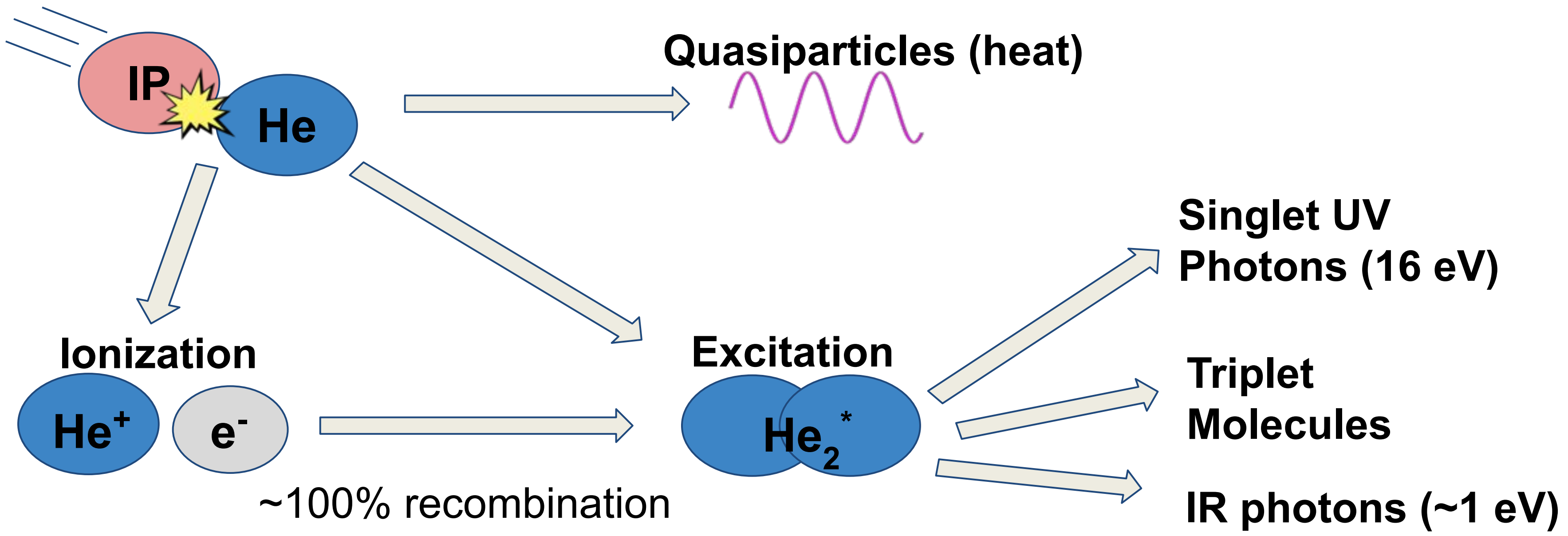
- Heat-free stopping of ^{4}He films via *in-situ* Cs deposition
- Scintillation+evaporation readout at few-photon limit.
- Initial phonon channel gain of ~0.15 (similar DM mass threshold in ^{4}He and Si calorimeter)

Exciting next steps:

- Photon calibration using 16 eV scintillation of the LHe itself
- **Attack LEE via multi-detector coincidence, exploit quantum evaporation channel**

Backup

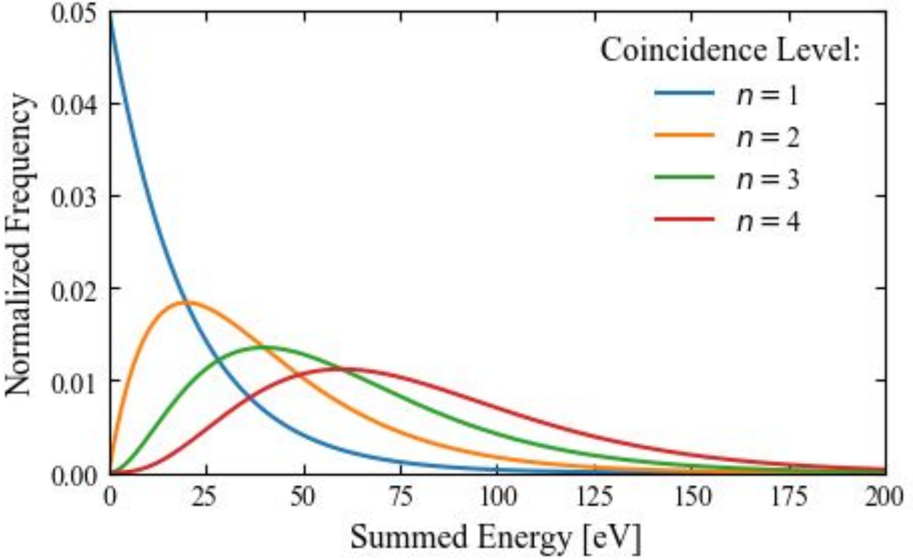
Recoils in Helium (generic incident particle IP)



TESSERACT will use coincidence to suppress LEE

If rate in each sensor is **R**, requiring **n-fold** coincidence with **m total sensor** in a **time window T** gives rate of pile-up rate:

$$R_{\text{pile-up}} = \frac{m!}{(m-n)!} R^n T^{n-1}$$



Spectrum of pile-up events **shifts away from low-mass DM energy region of interest** with higher coincidence level

Quasiparticles in ^{4}He

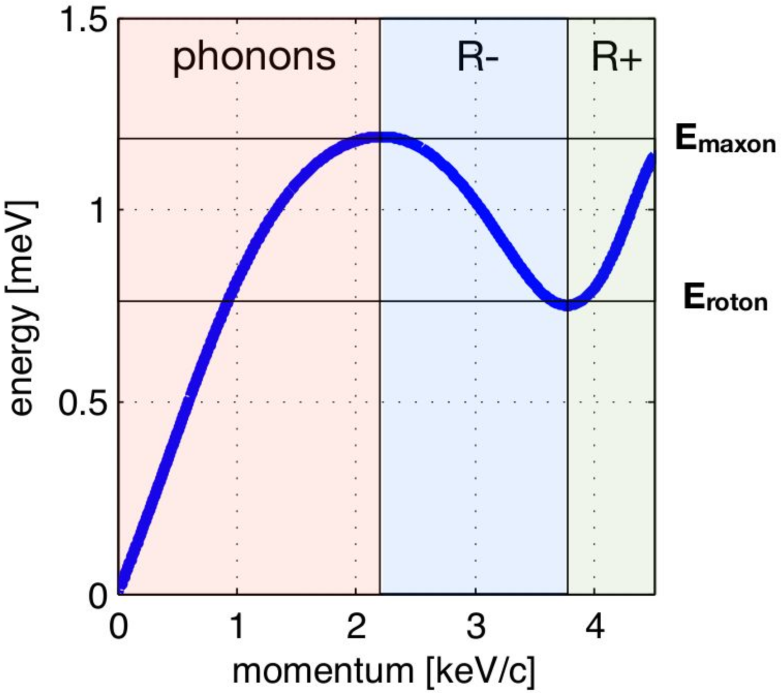
Quasiparticles: collective excitations in superfluid helium

Long-lived, speeds of ~100 m/s

Classified based on momentum:
Phonons, **R-** rotons, **R+** rotons
(roton ≈ high-momentum phonon)

At interface, can transform from one type to another if energy conserved

An eV scale recoil produces thousands of quasiparticles!



SbBe neutron source with iron filter

- 24 keV photo-neutrons from ^{124}Sb-^{9}Be
- Iron cross-section dip at 24 keV neutrons
- 3-GBq Sb produced in nuclear reactor
- See arXiv:2302.03869 (accepted to JINST)