HeRALD

A Superfluid Helium Sub-GeV Dark Matter Detector

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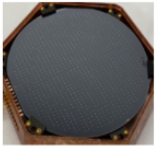
On Behalf of the SPICE/HeRALD Collaboration

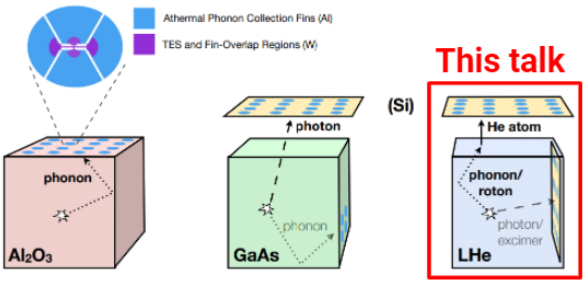
LIDINE, September 2021

Berkeley
UNIVERSITY OF CALIFORNIA

The TESSERACT Collaboration

- Project planning phase
  - Funded through DOE Dark Matter New Initiatives program
- Different targets with complimentary DM search
  - All using TES readout
- ~30 people from 8 institutes

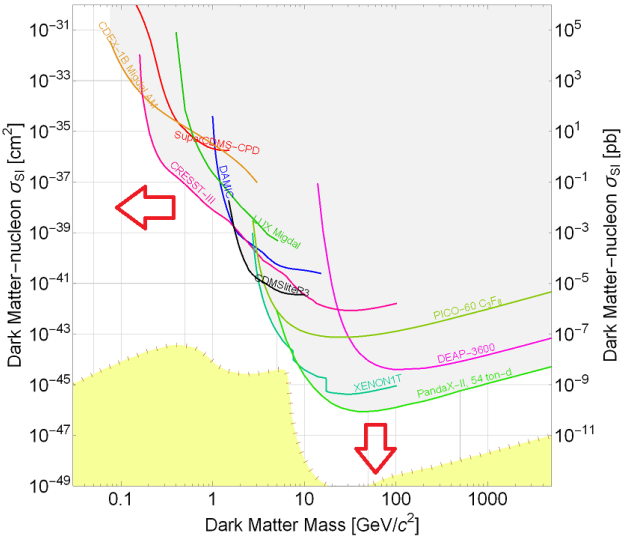




Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project

The Landscape of Direct Detection

- High mass, small cross section:
  - Large detectors, heavy nuclei
  - Low backgrounds
  - Liquid nobles (Xe) lead here
  - Hard to reduce thresholds
- Low mass, larger cross section:
  - Low thresholds, light nuclei (or electrons)
  - Backgrounds, size less important
  - Phonon based searches (semiconductors) lead here
  - Hard to increase size (exposure)



Helium: Best of Both Worlds?

"Dream" MeV scale DM target:

- Light nuclei
- Low threshold
- Easy to scale up in mass/exposure/radiopurity

Helium advantages:

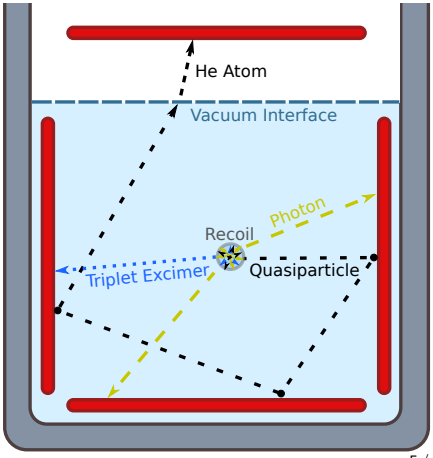
- Liquid Noble:
  - Naturally radiopure, low bulk contaiminants at low temperature
  - "Easy" to scale up
  - Multiple readout channels for NR/ER discrimination
- Quasiparticle based detection:
  - Quasiparticle excitation readout (phonon/roton, meV scale) in addition to just photons (eV scale)
  - Limited by readout technology, rather than target physics

HeRALD Overview

HeRALD: the **He**lium **R**oton **A**pparatus for **L**ight **D**ark matter

Basic schematic:

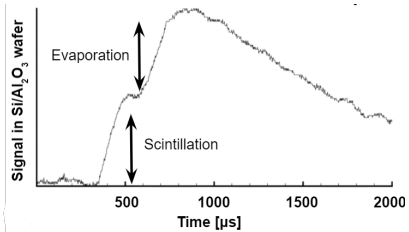
- ~1 kg of superfluid helium-4 at O(50 mk)
- TES based calorimeter readout
- 3 key readout signals:
  - "Quantum evaporation" for quasiparticle excitations
  - 16 eV singlet photons
  - 18 eV triplet molecules
- "Dry" calorimeter detects quasiparticles, photons
- Immersed calorimeter reads out triplets, photons

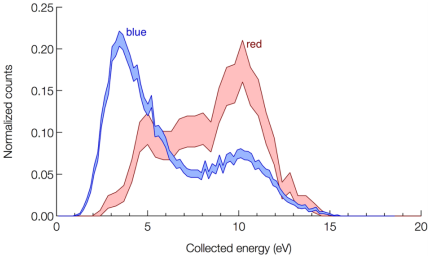


HeRALD Readout Channels

- Quantum evaporation
  - When phonons/rotons interact with superfluid surface, individual He atoms evaporated, 0.6 meV binding energy
  - Evaporated atoms impact calorimeter surface
  - Binding energy to calorimeter higher than to superfluid... energy gain!
  - Demonstrated by HERON collaboration in the 90s
- Singlet photon detection with calorimeters
- Triplet molecules
  - Long lifetime, molecules hit wall before radiative decay
  - Travel through superfluid at around 1 m/s
  - Relax on solid surfaces, such as calorimeters
  - Detection in TESs, discrimination demonstrated
- NR energy preferentially partitions into QP channel

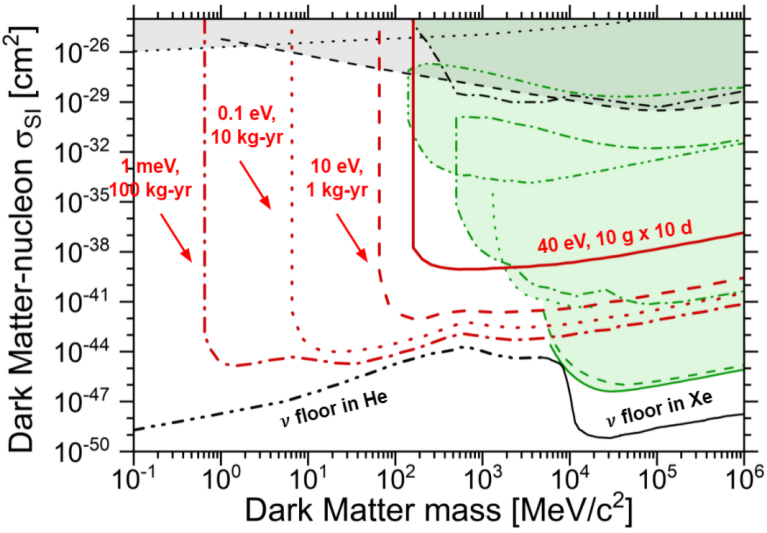
"Calorimetric Observation of Single He_2^* Excimers in a 100-mK He Bath", Carter et. al. 2017





HeRALD Reach

- Solid line: 40 eV threshold, "shovel ready"
- SPICE/HeRALD TES R&D path to reducing threshold
- Modest detector exposures approach ν floor



Limits from "Direct detection of sub-GeV dark matter using a superfluid ^{4}He target", Hertel et. al. 2019

Progress: Fridge Commissioning and TES Development

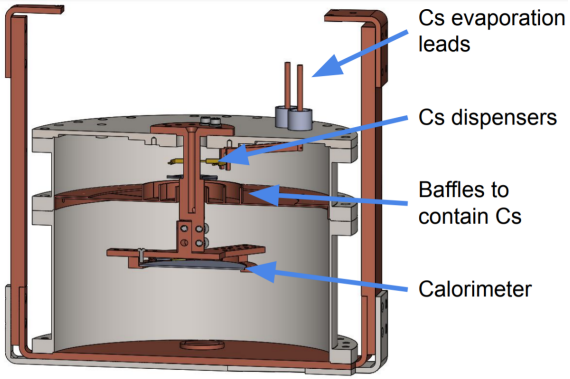
- 4 test facilities commissioned or being commissioned:
  - 4x dilution fridges (wet + dry + hybrid) at UCB, LBNL, UMass
  - 1x pumped ^{4}He fridge at UCB for light yield measurement
- CPD_v1 detector: a 3.8 σ eV energy resolution large area detector
  - Designed, fabricated, performance demonstrated
  - High performance detector for testing prototype HeRALD detectors
  - Energy resolution improvements expected with improved device design, reduced Tc
- Fabricating "Helium Specific" test devices to improve detector technology

"Performance of a large area photon detector for rare event search applications", Fink et. al. 2021
"Light Dark Matter Search with a High-Resolution Athermal Phonon Detector Operated Above Ground", Alkhatib et. al., 2021

Progress: Film Blocking

"Dry" calorimeter needs to be free of superfluid to detect quantum evaporated atoms

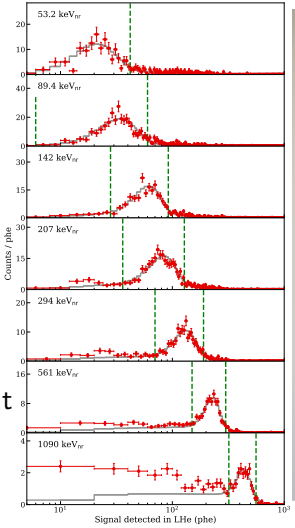
- Key technology to obtain world-leading results
- Three film blocking technologies:
  - Non-wetting cesium
  - Silicon knife edge
  - Heated film burner
- Knife edges fabricated, measured with SEM
- Preliminary Cs results:
  - Cs deposited at cryogenic temperatures
  - Film evaporated from calorimeter by heat
  - Film measured to not return on the day timescale

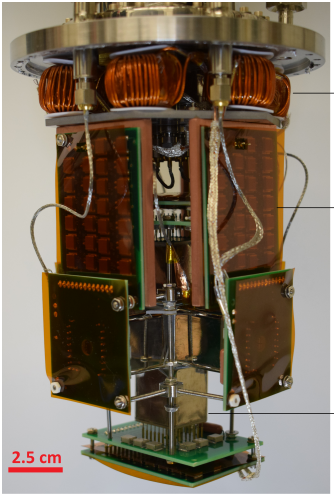


Progress: Scattering Studies

Studying NR/ER yields in He scattering experiments

- Room temperature gaseous He light yield
- Superfluid liquid helium light yield
  - See R. Smith's talk "Scintillation yield from electronic and nuclear recoils in superfluid ^{4}He"!
- Near future: TES based readout scattering studies at 50 mK



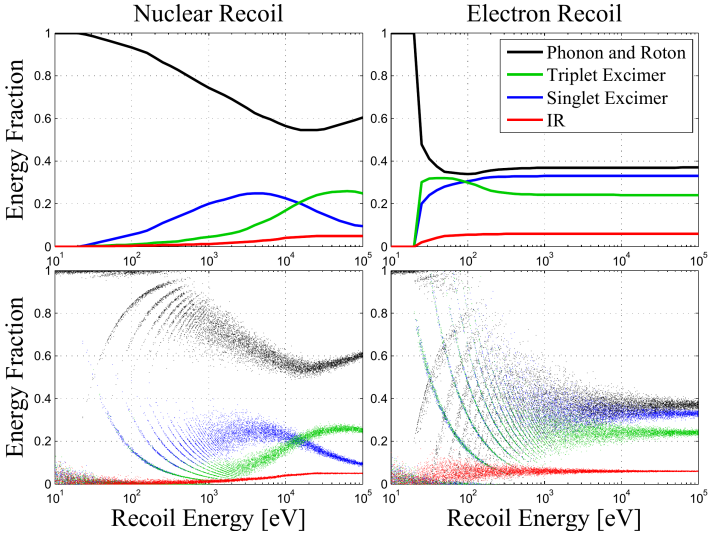


"Scintillation yield from electronic and nuclear recoils in superfluid ^{4}He", Biekert et. al, 2021
"Nuclear Recoil Scintillation Linearity of a High Pressure ^{4}He Gas Detector", Biekert et. al 2019

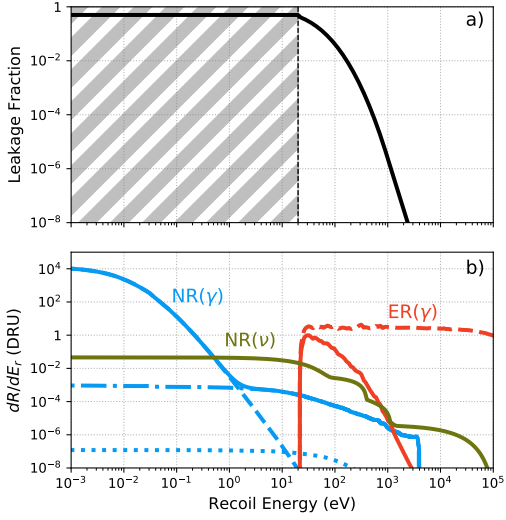
Next Steps and Conclusions

- HeRALD: a highly promising helium based light dark matter detector
- Key technologies demonstrated, prospects for near to medium term improvement strong
- Near future: the fun part!
  - Measure ER/NR photon/triplet yield with large scale immersed CPD calorimeters
  - Test quantum evaporation with integrated Cs film blocker, CPD calorimeter in one cell
  - R&D to understand the detector physics of immersed TES based calorimeters
- Opportunities for results:
  - ER/NR discrimination using quasiparticle/photon channels down to 16 eV
  - World leading NR low mass dark matter results
  - Searches for dark matter with a new target nucleus

Backup: Energy Partitioning



Backup: ER Rejection



Backup: Low Energy Neutron Calibration Sources, Detectors

- 24 keV SbBe source development at UC Berkeley
  - Photoneutron source filtered by iron rod
  - Source constructed, calibration ongoing
- Pulsed 2 keV Sc source development at UMass
  - DT neutron generator moderated, neutrons filtered through 2 keV Sc window
  - Simulation and design work ongoing
- Backing detectors become difficult at 10s of keV
  - Commercial high QE liquid scintillator detectors being tested at UCB
  - UMass investigating custom capture based backing detector