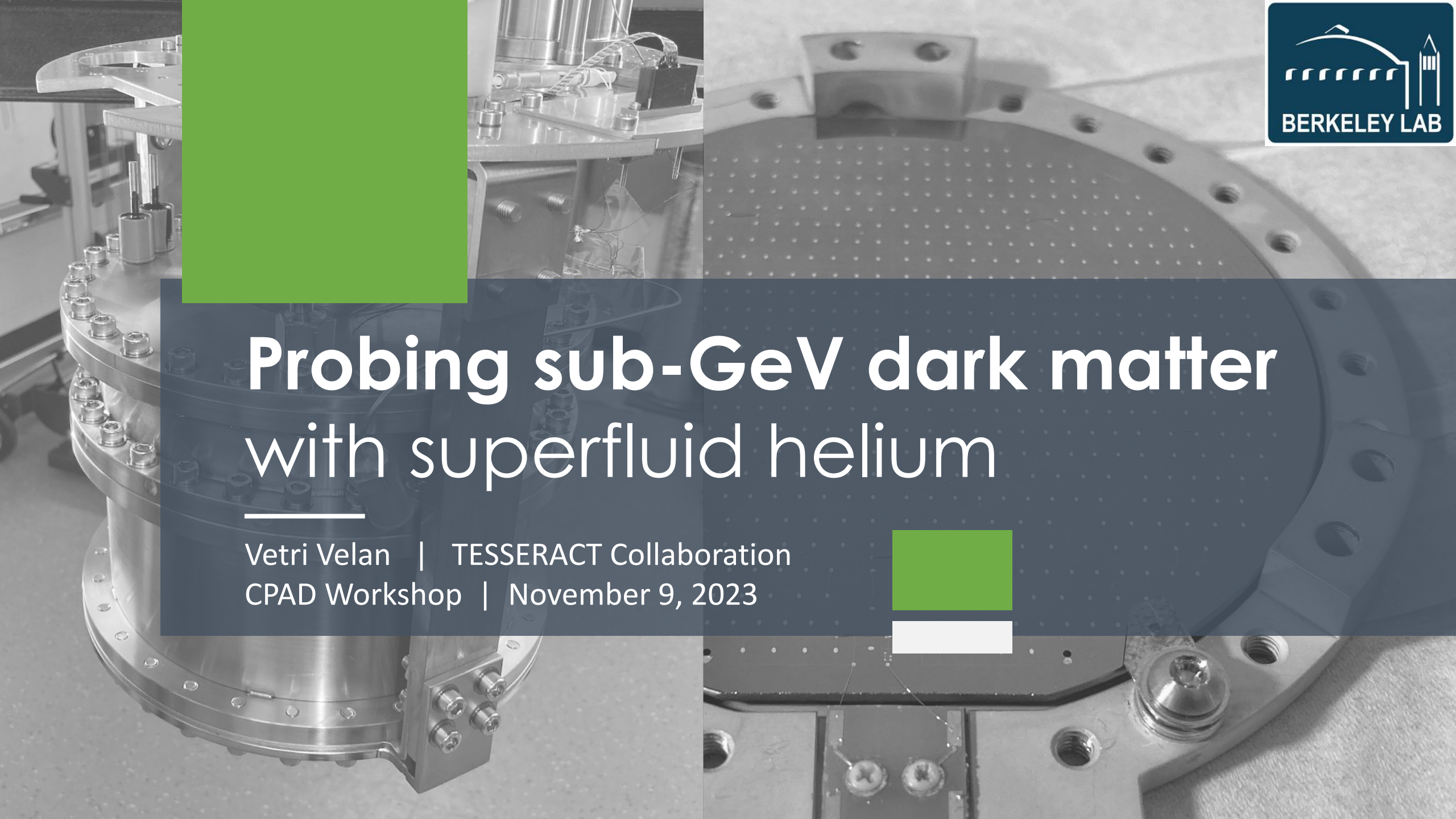


Probing sub-GeV dark matter with superfluid helium

Vetri Velan | TESSERACT Collaboration

CPAD Workshop | November 9, 2023

The Duality of Particle Detection

Targets

Noble liquids

Crystals

Liquid scintillators

Gaseous detectors

Etc.

Sensors

Photomultiplier tubes

Transition-edge sensors

Silicon Photomultipliers

SNSPDs

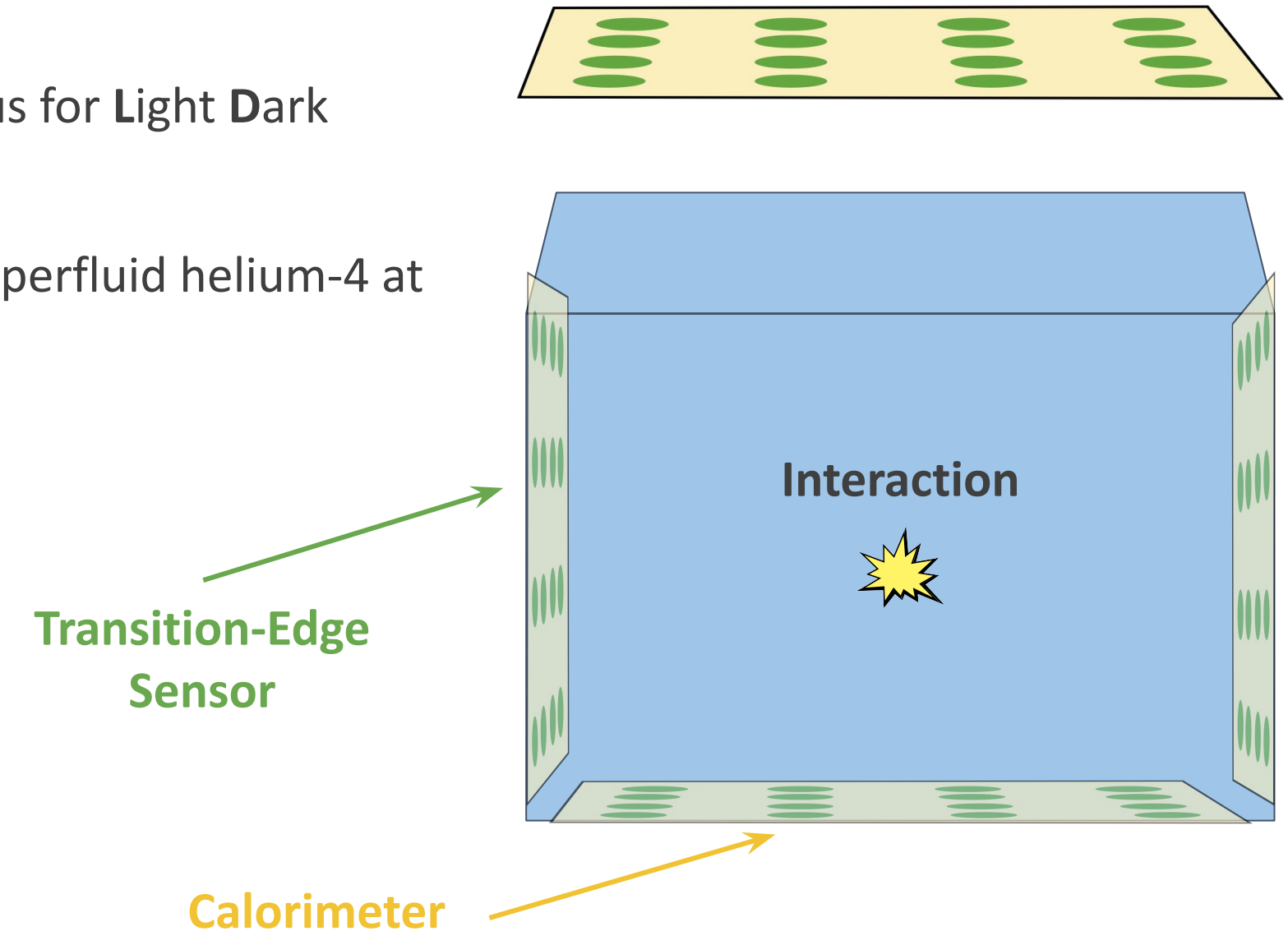
Etc.

Need <u>complementarity</u> between the target and the sensor

HeRALD: A Dark Matter Search

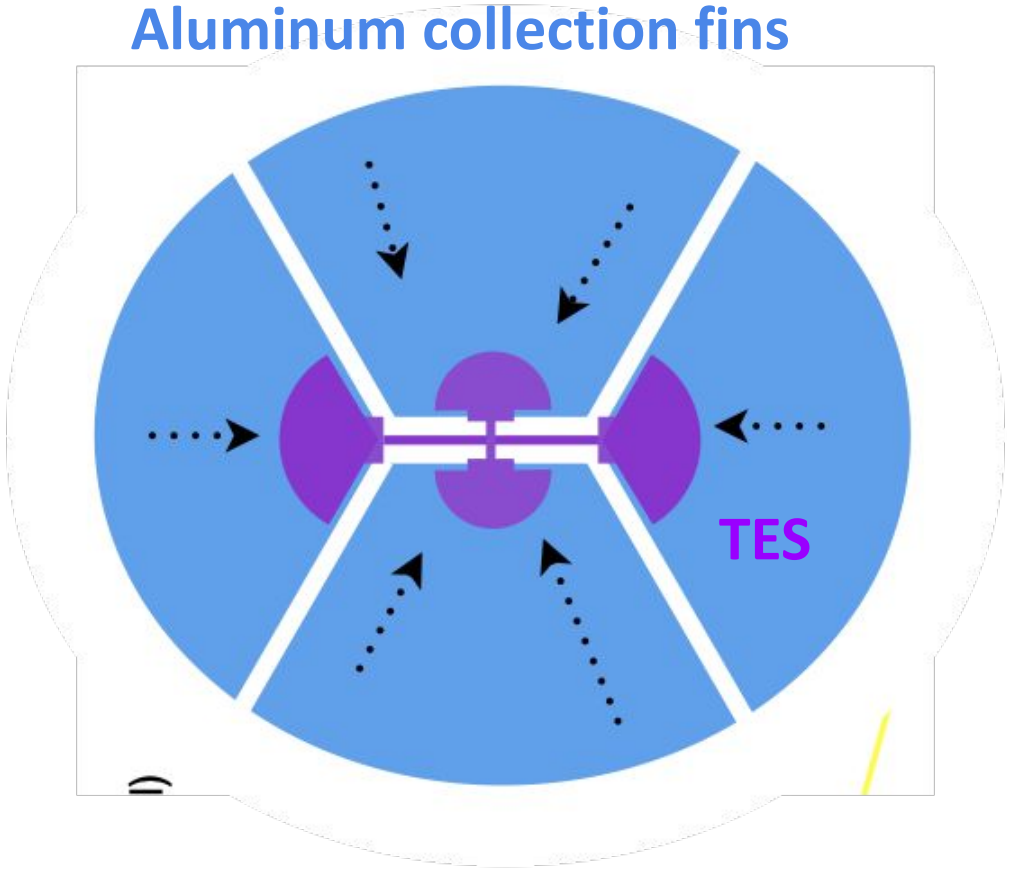
Helium **R**oton **A**pparatus for **L**ight **D**ark Matter

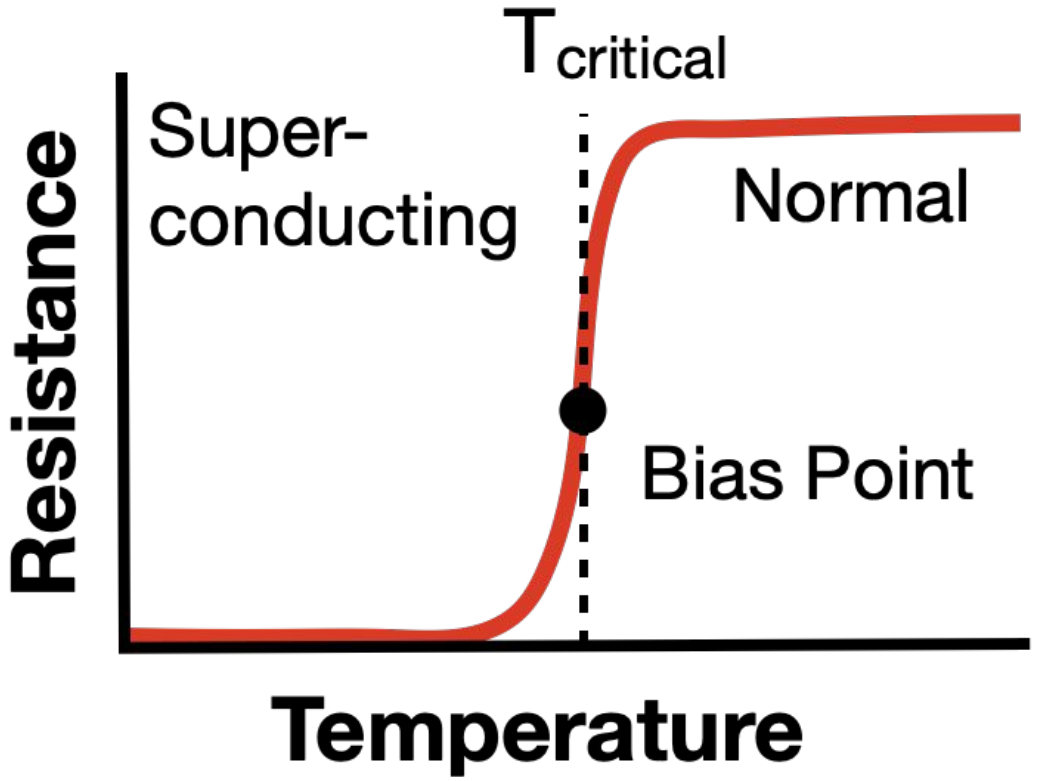
O(10-1000) grams of superfluid helium-4 at 10s of mK



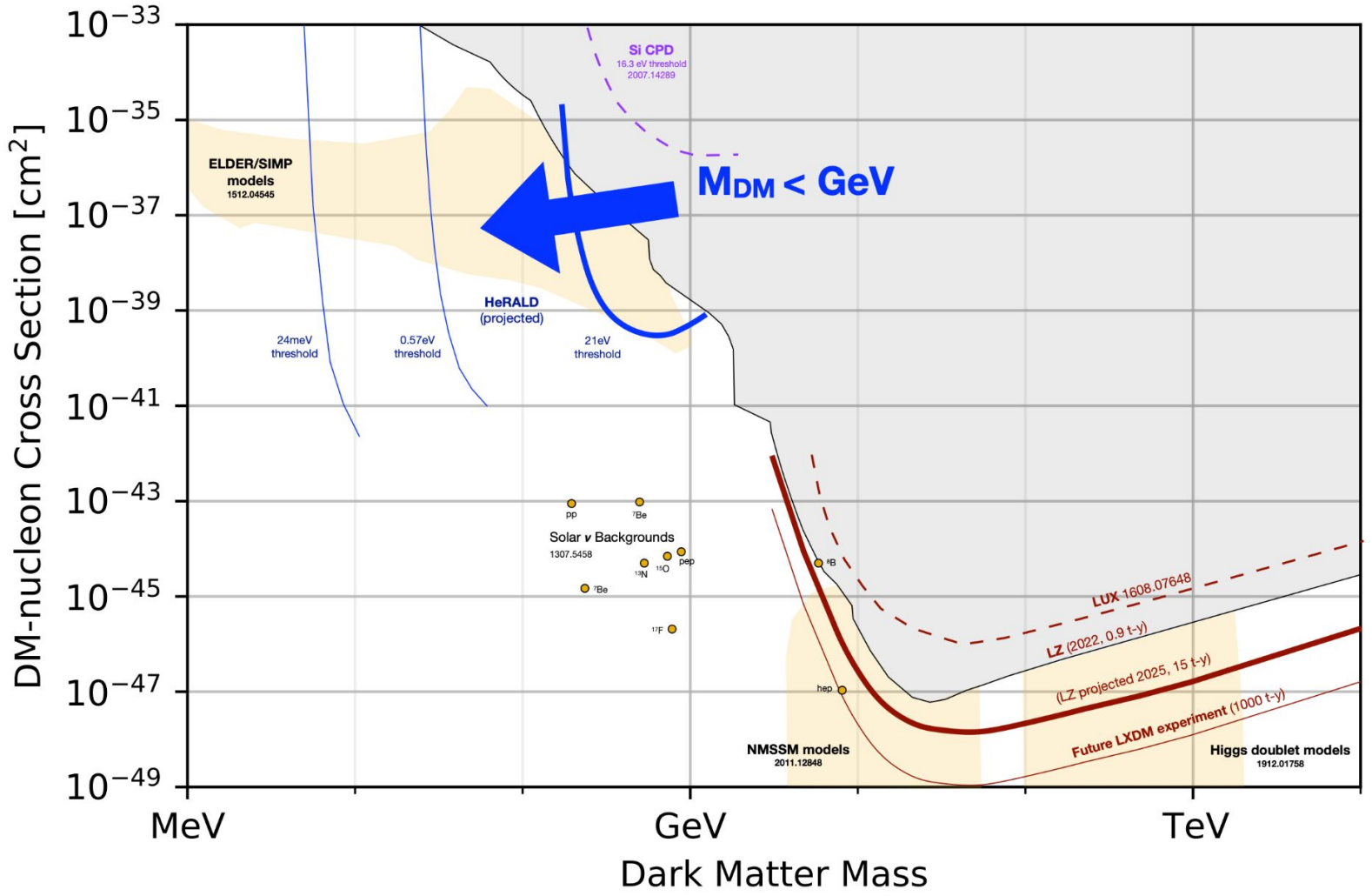
HeRALD: A Dark Matter Search

Low-temperature, small-volume sensors → better energy resolution and lower threshold





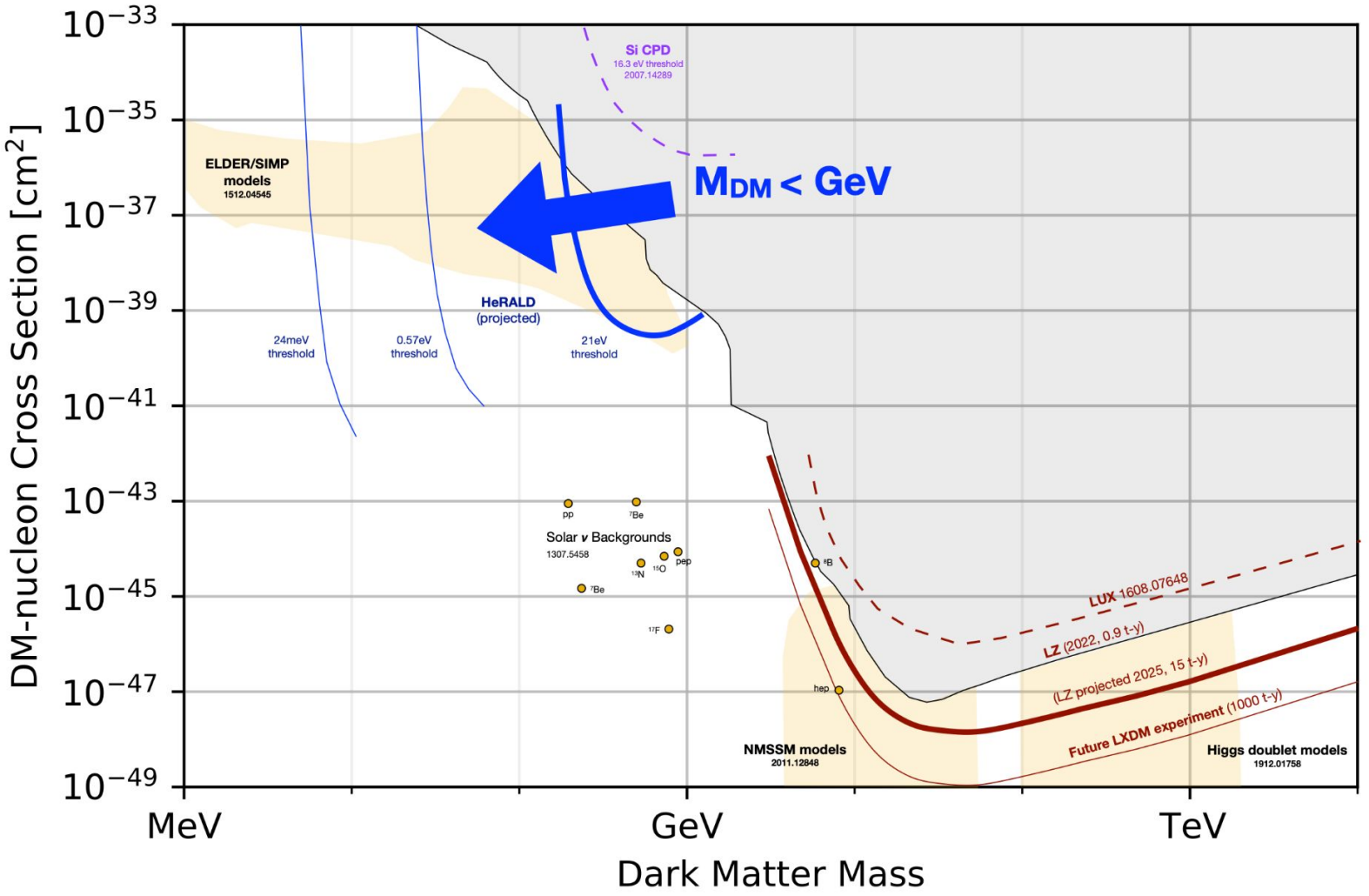
HeRALD: A Dark Matter Search



HeRALD: A Dark Matter Search

What makes helium specifically well-suited for MeV-scale dark matter detection?

1. Kinematic matching
2. Theoretical 1 meV recoil energy threshold
3. Exploit the unique way energy is absorbed in helium



TESSERACT

- TESSERACT collaboration includes ~40 scientists, advancing the use of TESs and cryogenic targets for DM searches
- Two other target materials: sapphire, GaAs (collectively called SPICE)
  - Sensitivity to dark photon mediators and absorption of bosonic DM, via direct phonon excitation
- See talks from **R. Romani** (today in Cross-Cutting), **M. Reed** (yesterday in RDC7), **M. Williams** talk (Tuesday in RDC8)!

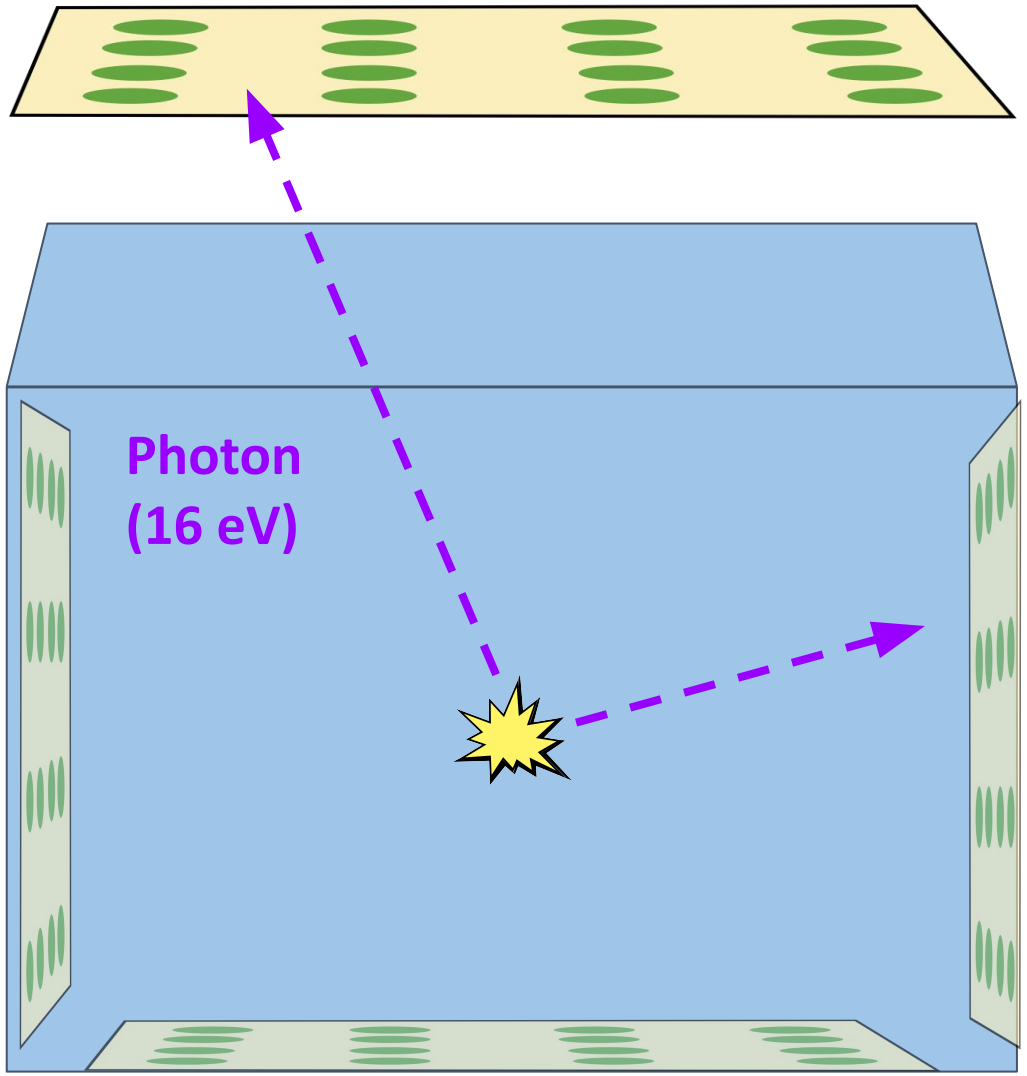
BERKELEY LAB
Lawrence Berkeley National Laboratory
Berkeley
UNIVERSITY OF CALIFORNIA
Caltech
FLORIDA STATE UNIVERSITY
FLORIDA STATE
TEXAS A&M UNIVERSITY
UNIVERSITY OF MICHIGAN
Argonne NATIONAL LABORATORY
UMass Amherst
KEK

What's special about ^{4}He?

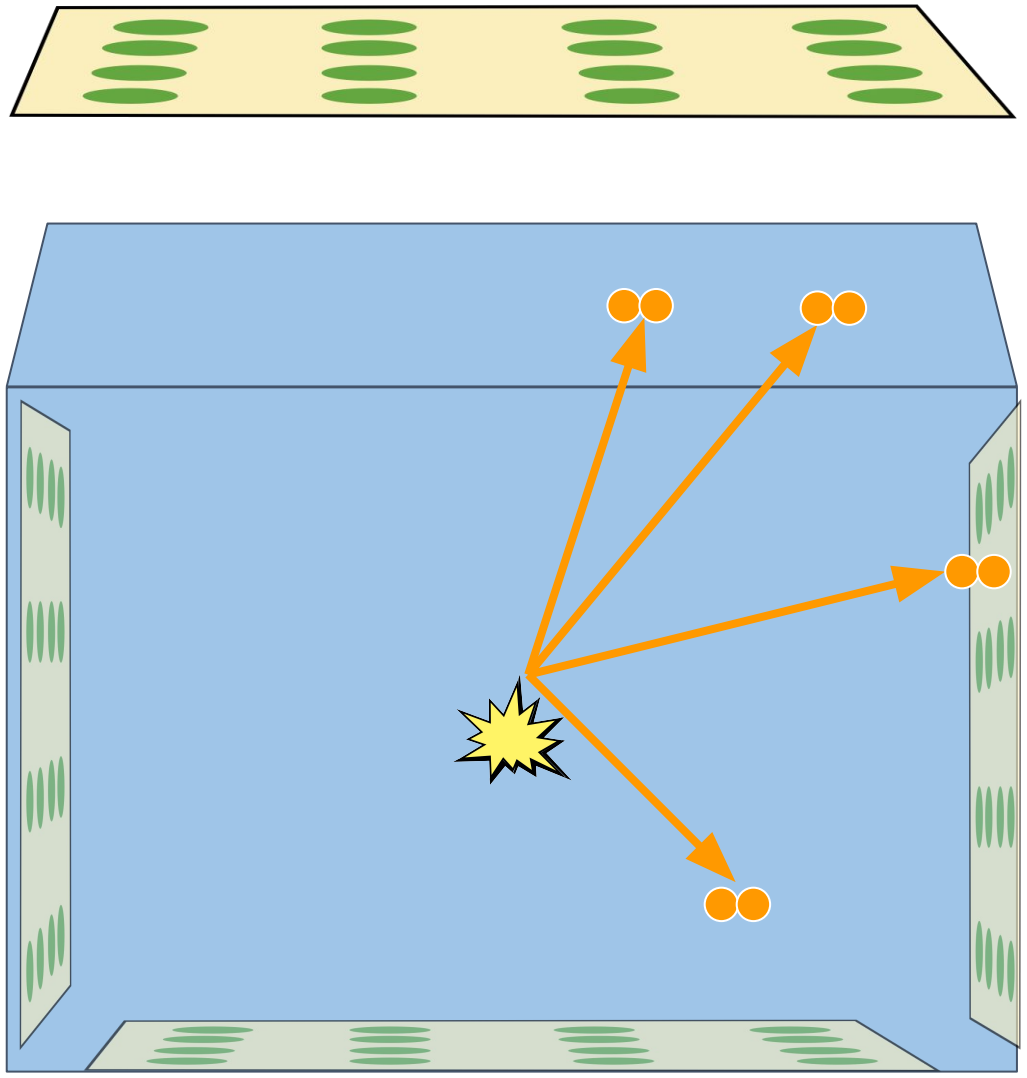
Energy Depositions in Helium

De-excitation of singlet dimer

Prompt, O(ns) lifetime



Energy Depositions in Helium

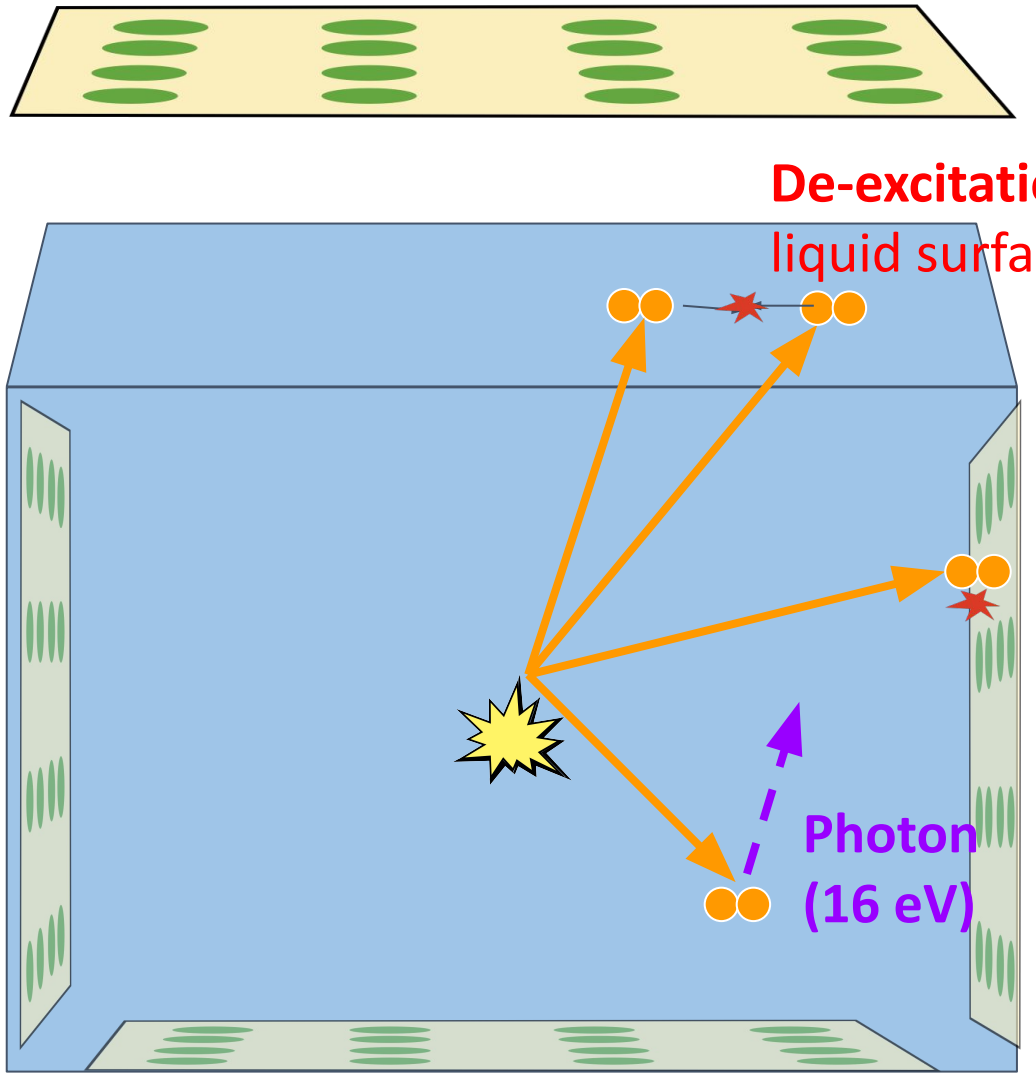


Triplet Molecules

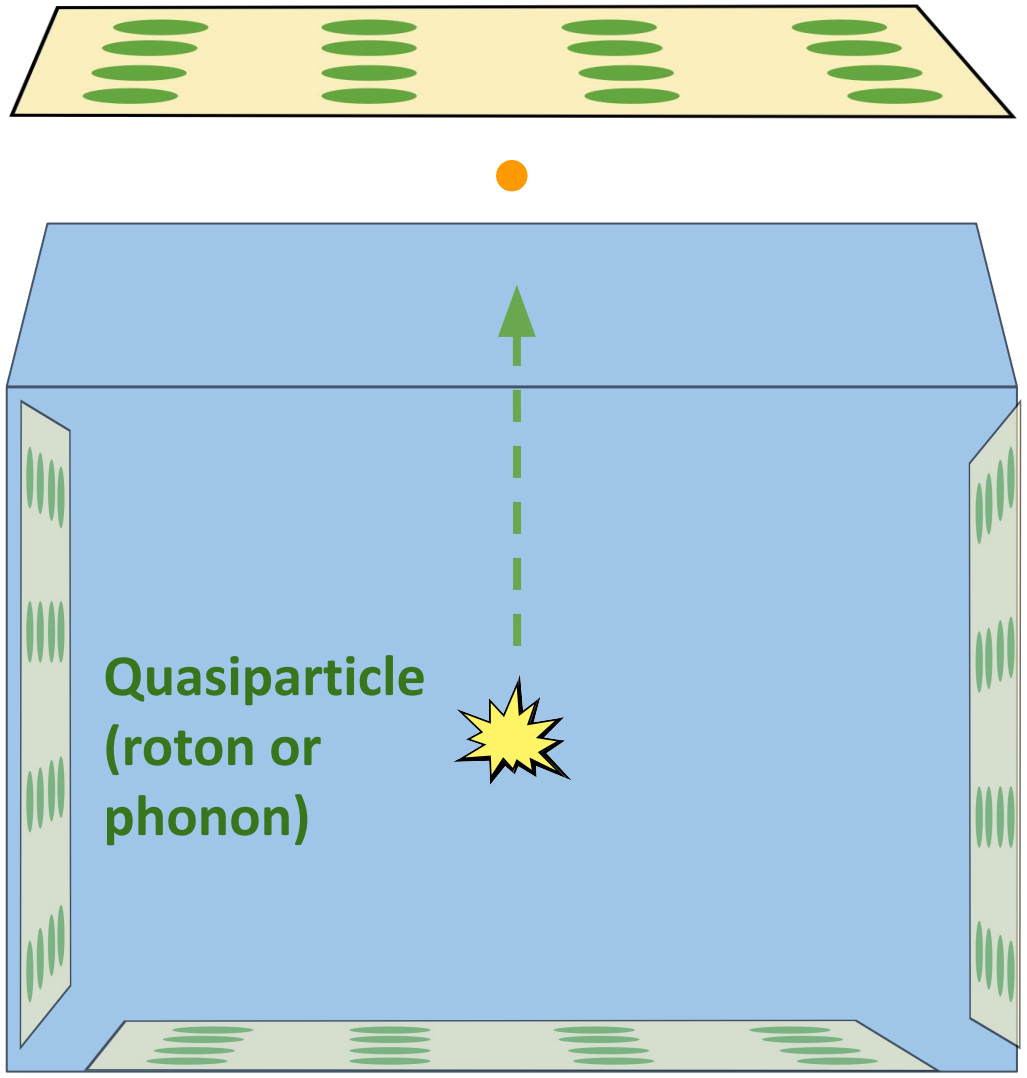
Long-lived; 13s lifetime

Propagate ballistically through the He-4

Energy Depositions in Helium



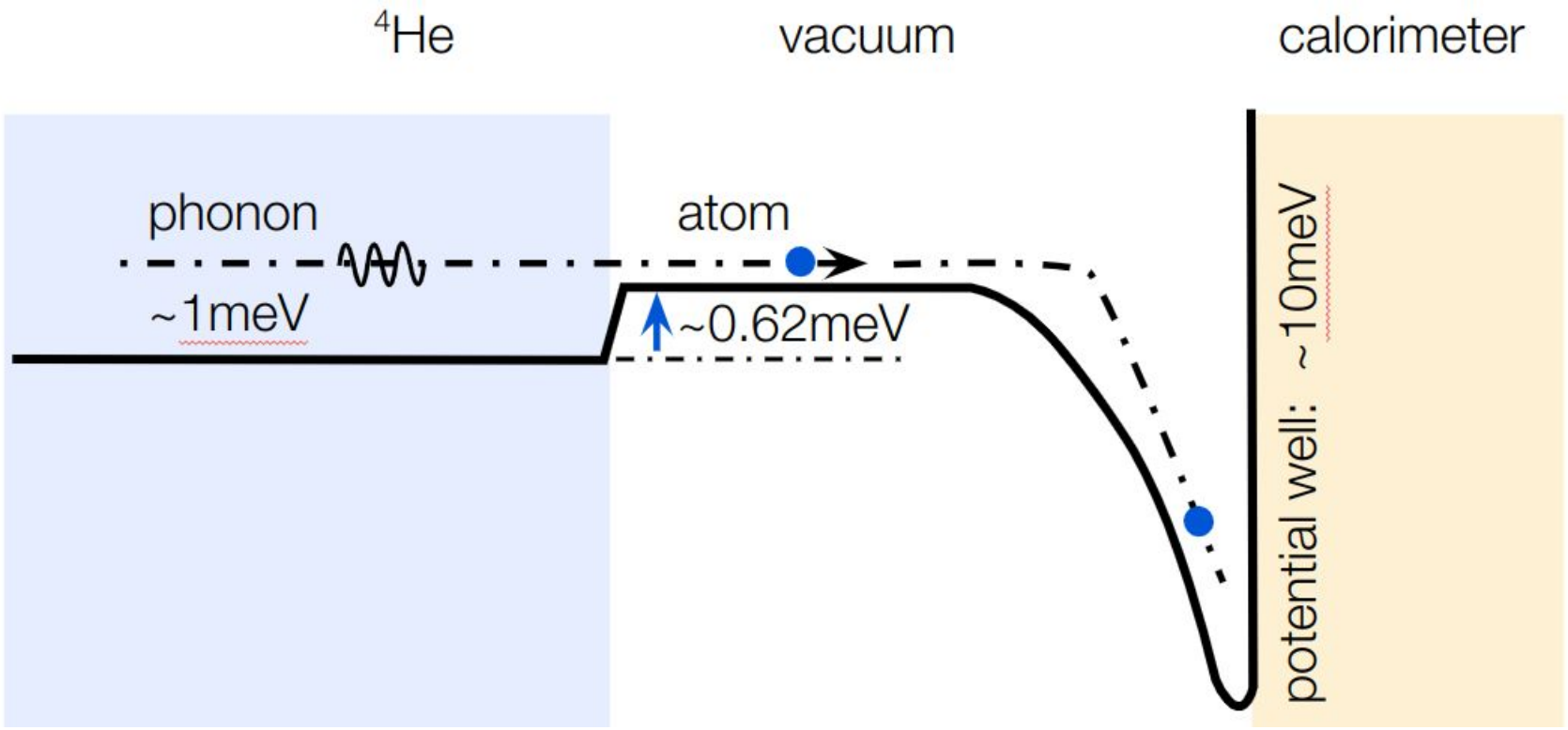
Energy Depositions in Helium



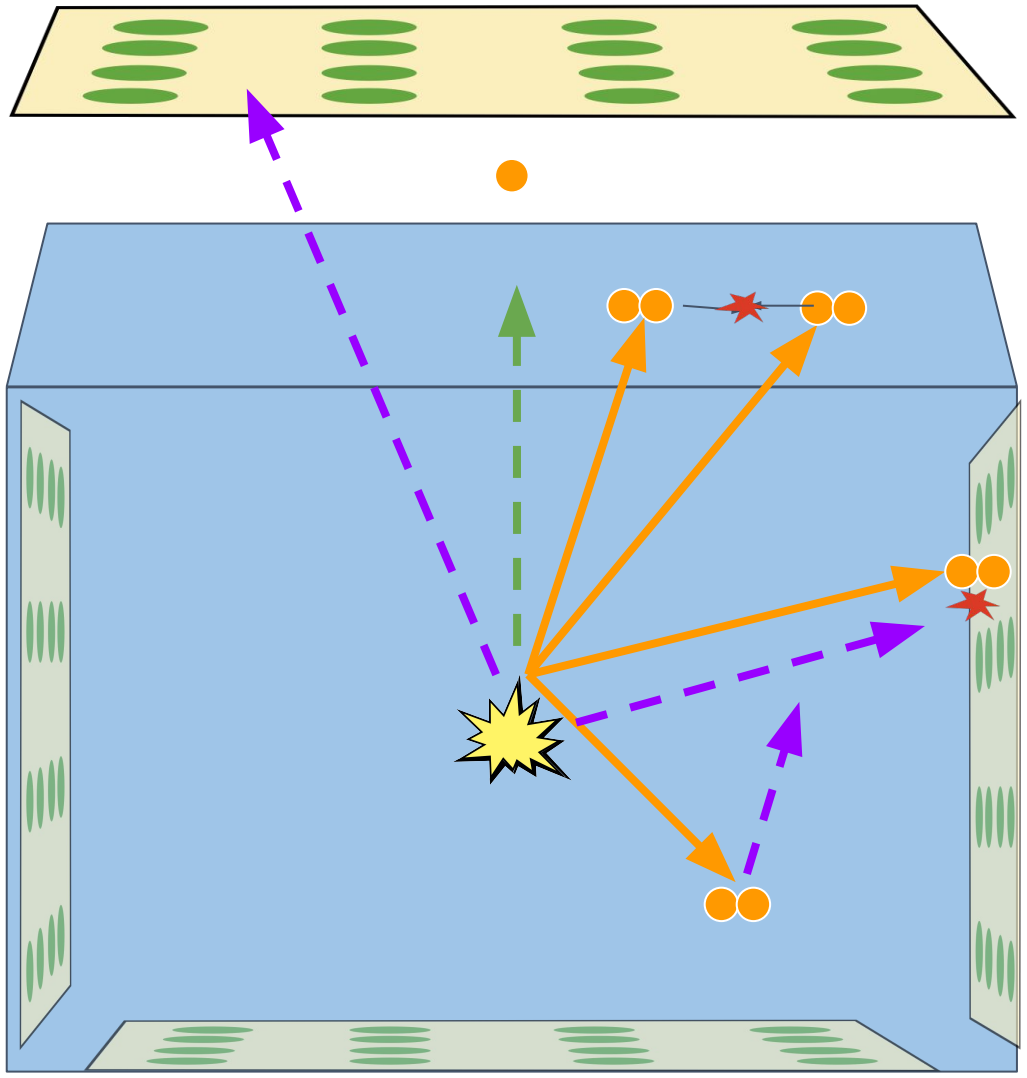
Quasiparticles are collective excitations in the superfluid, that act like ballistic particles

Energy Depositions in Helium

Amplification of evaporation signal via Van der Waals acceleration



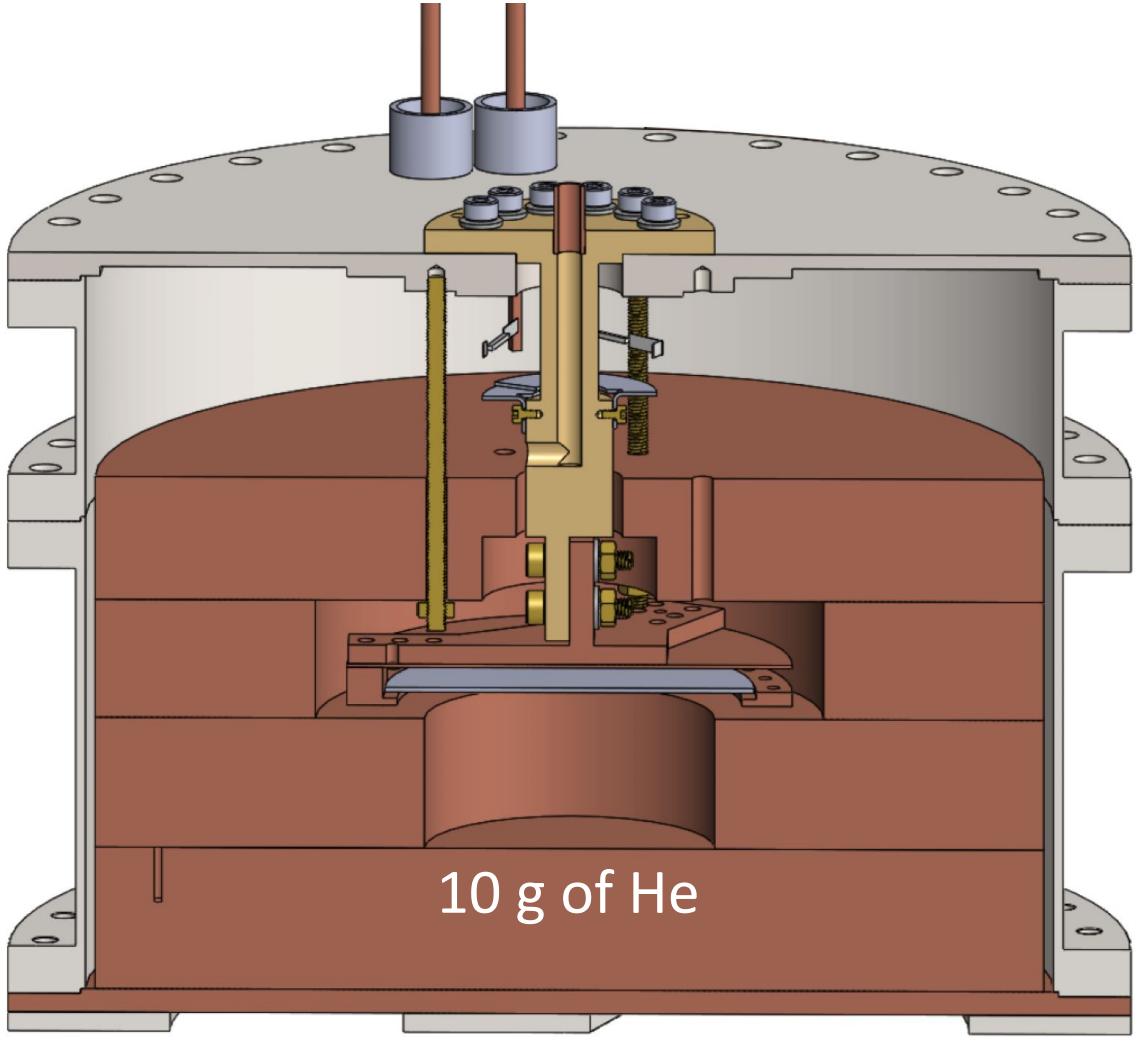
Energy Depositions in Helium

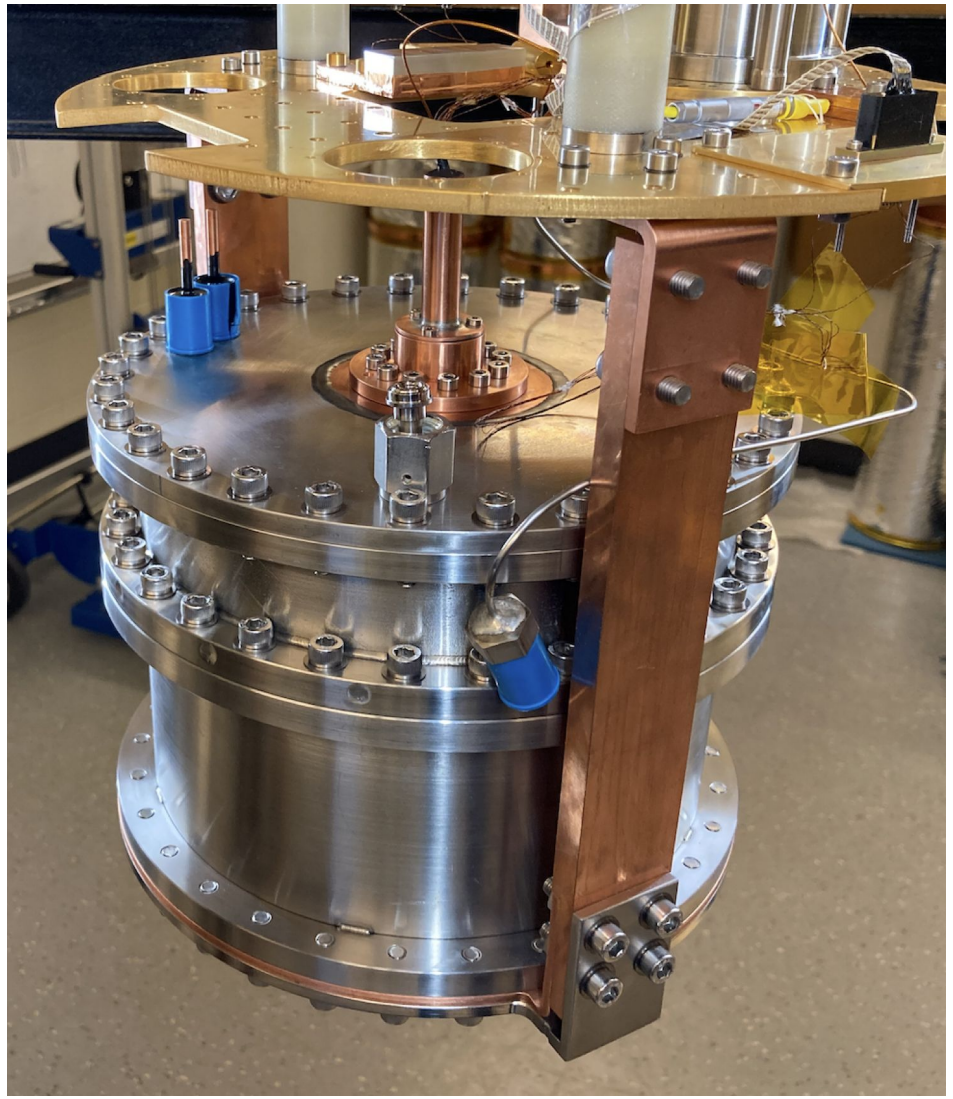


Three signals to detect

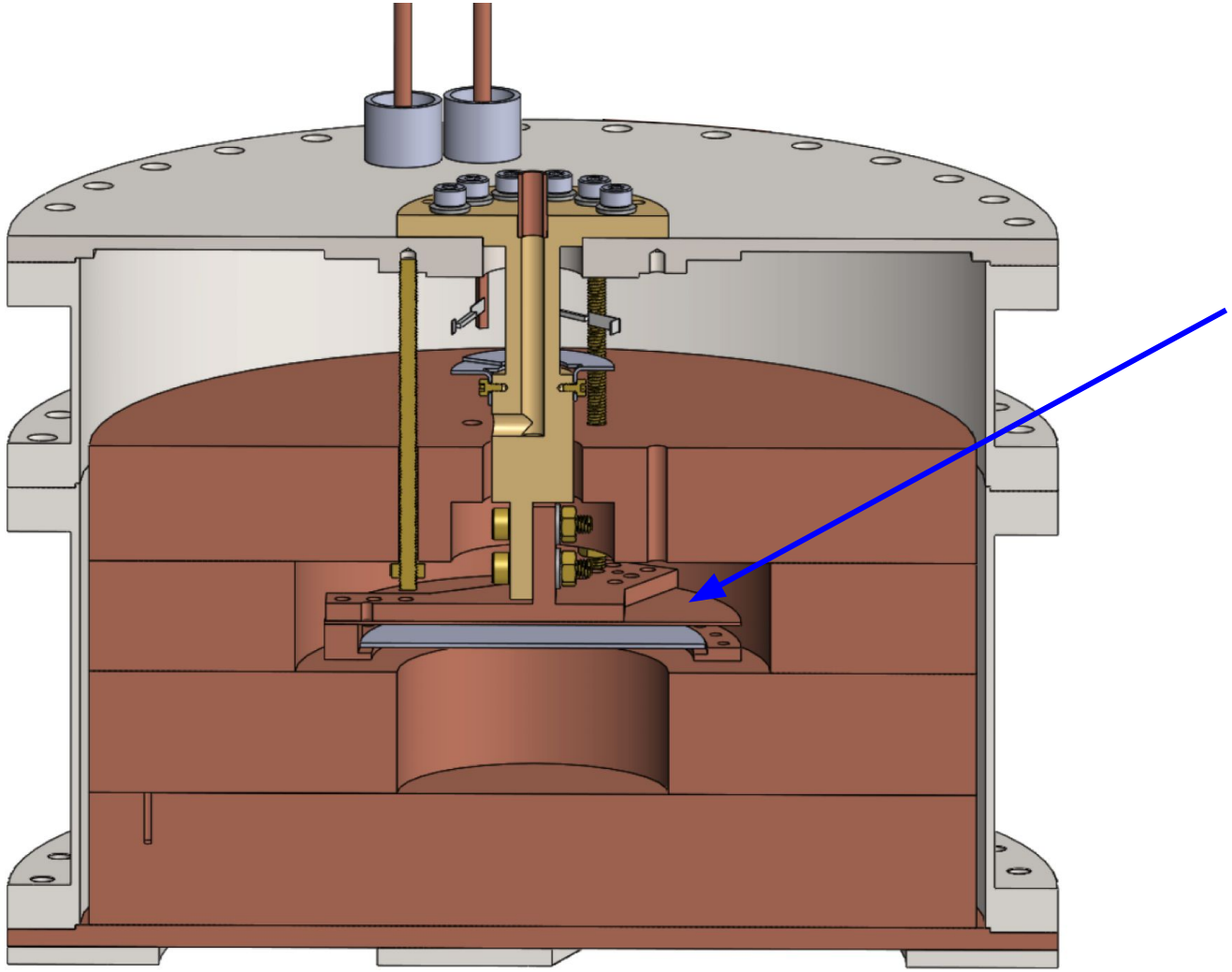
Ongoing Progress

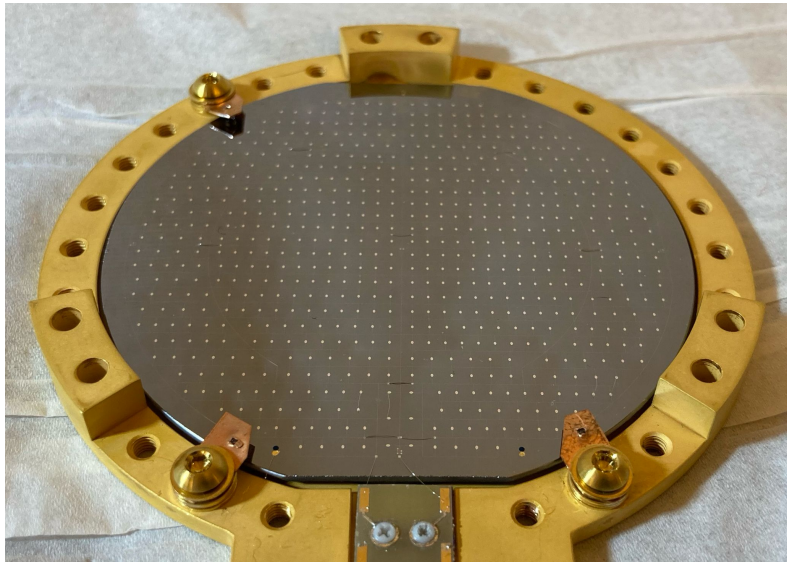
HeRALD at UMass Amherst (2307.11877)





HeRALD at UMass Amherst (2307.11877)



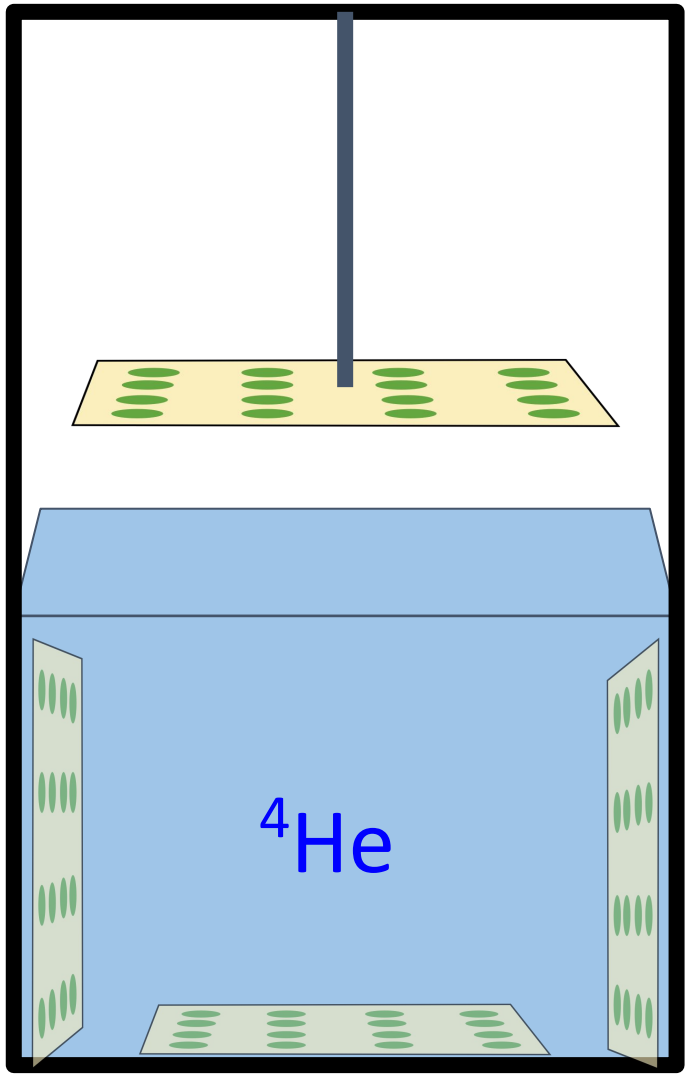


3” Si wafer, 1mm thickness

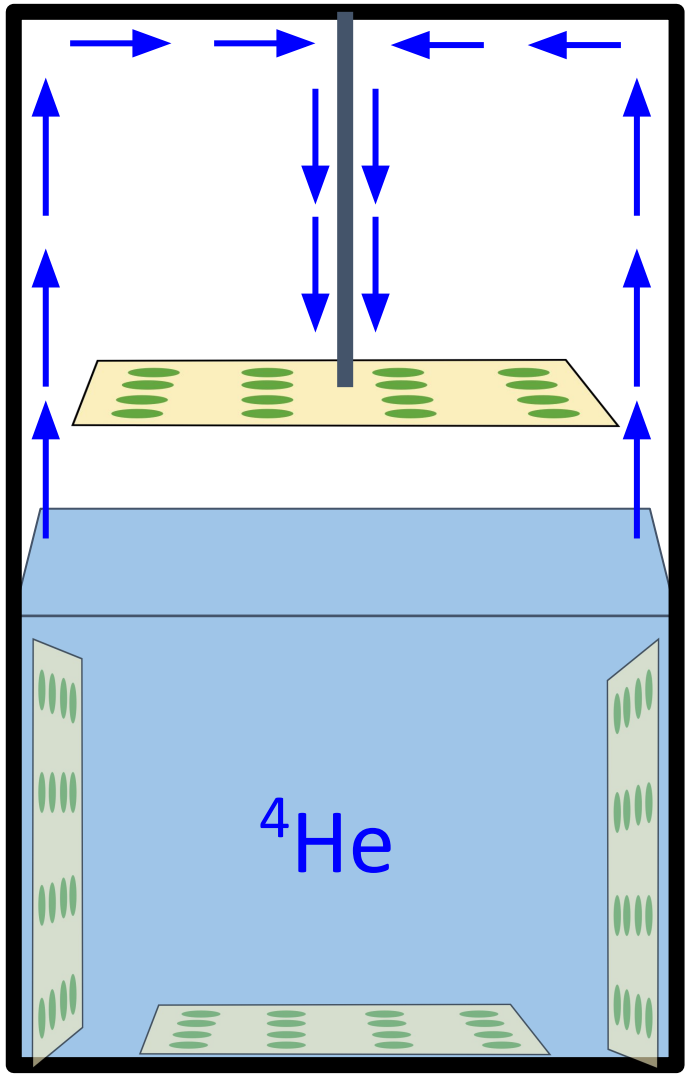
Instrumented with TESs, Tc = 55mK

~2.26 eV resolution in Si

Film Blocker

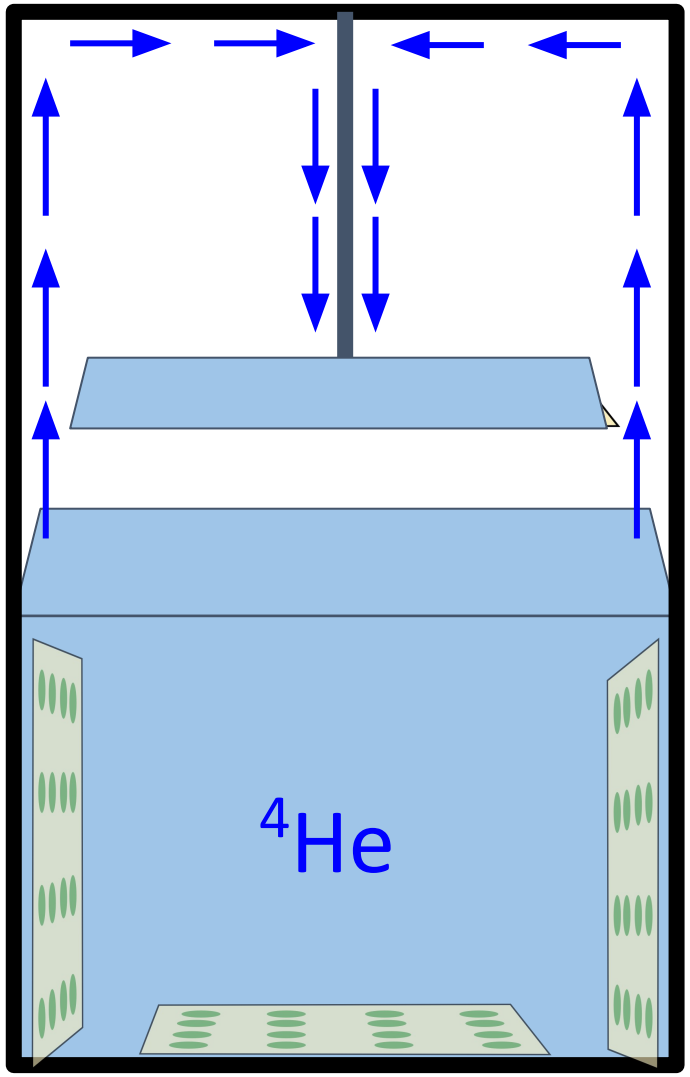


Film Blocker



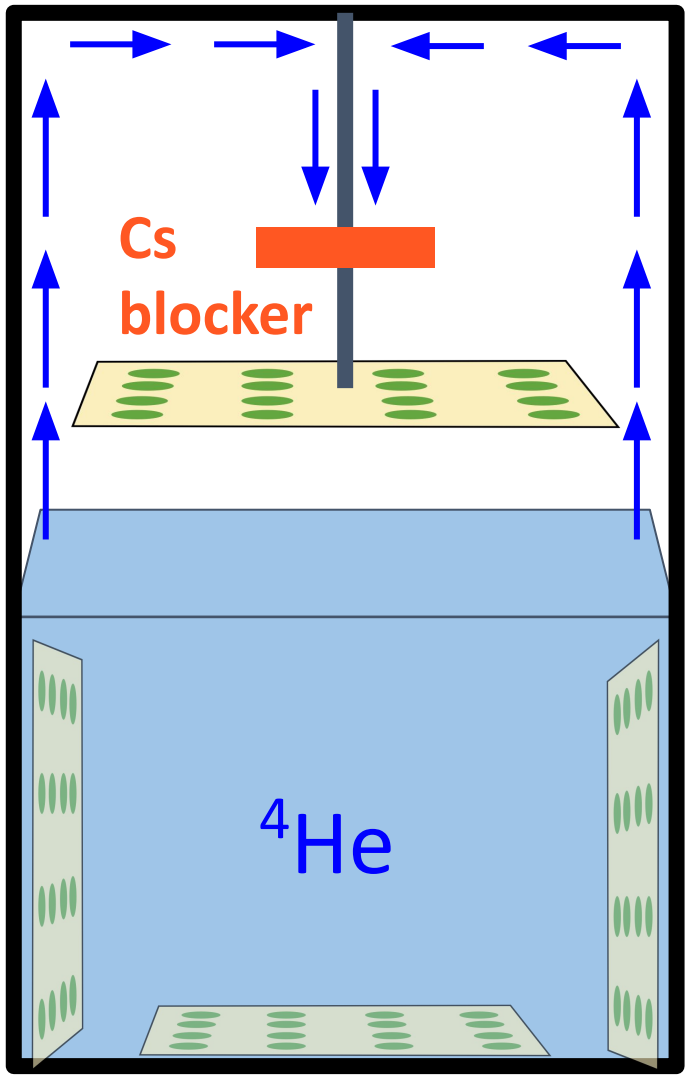
Challenge: Superfluid helium will attach to nearly any surface it can find, including the sensor

Film Blocker



Challenge: Superfluid helium will attach to nearly any surface it can find, including the sensor

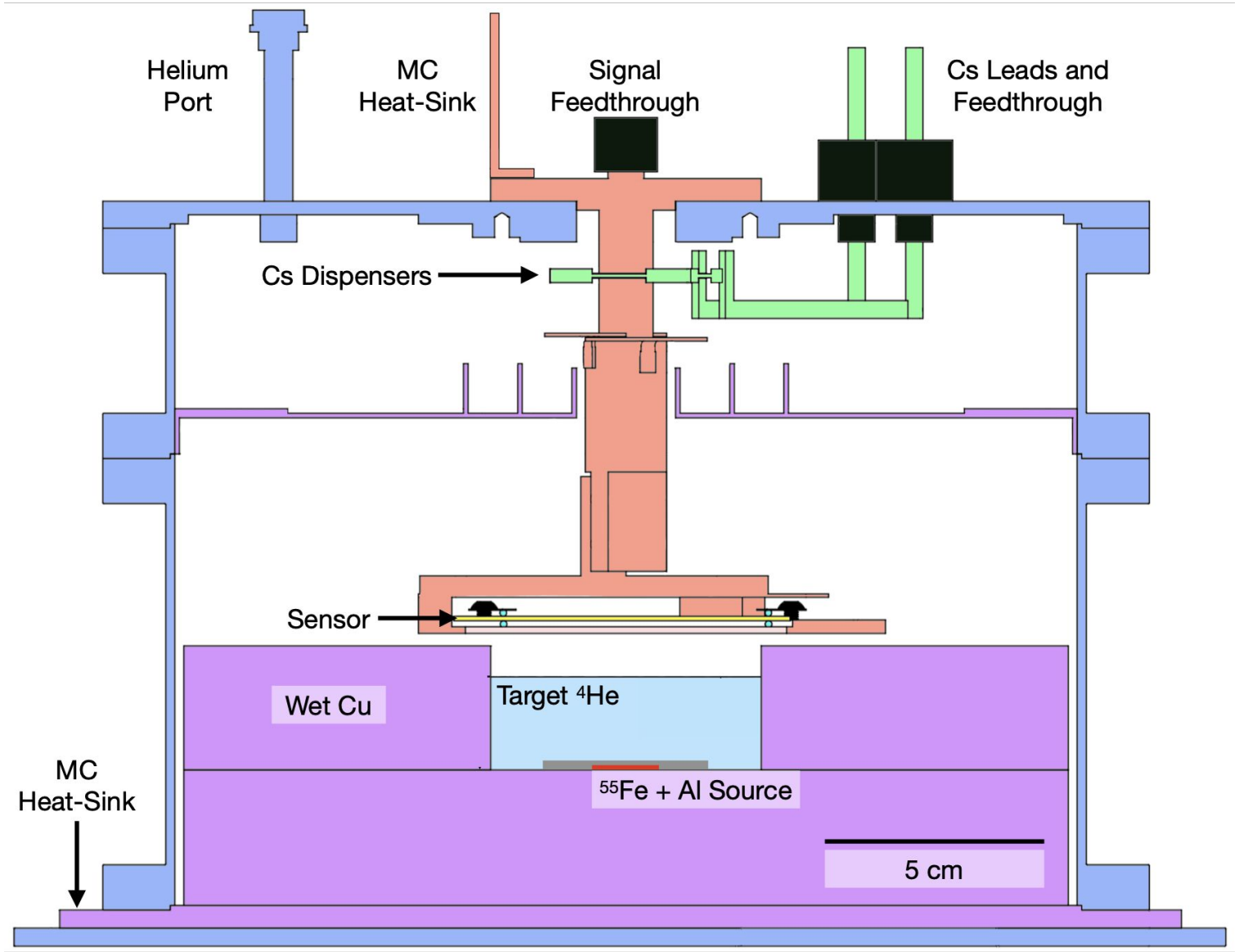
Film Blocker



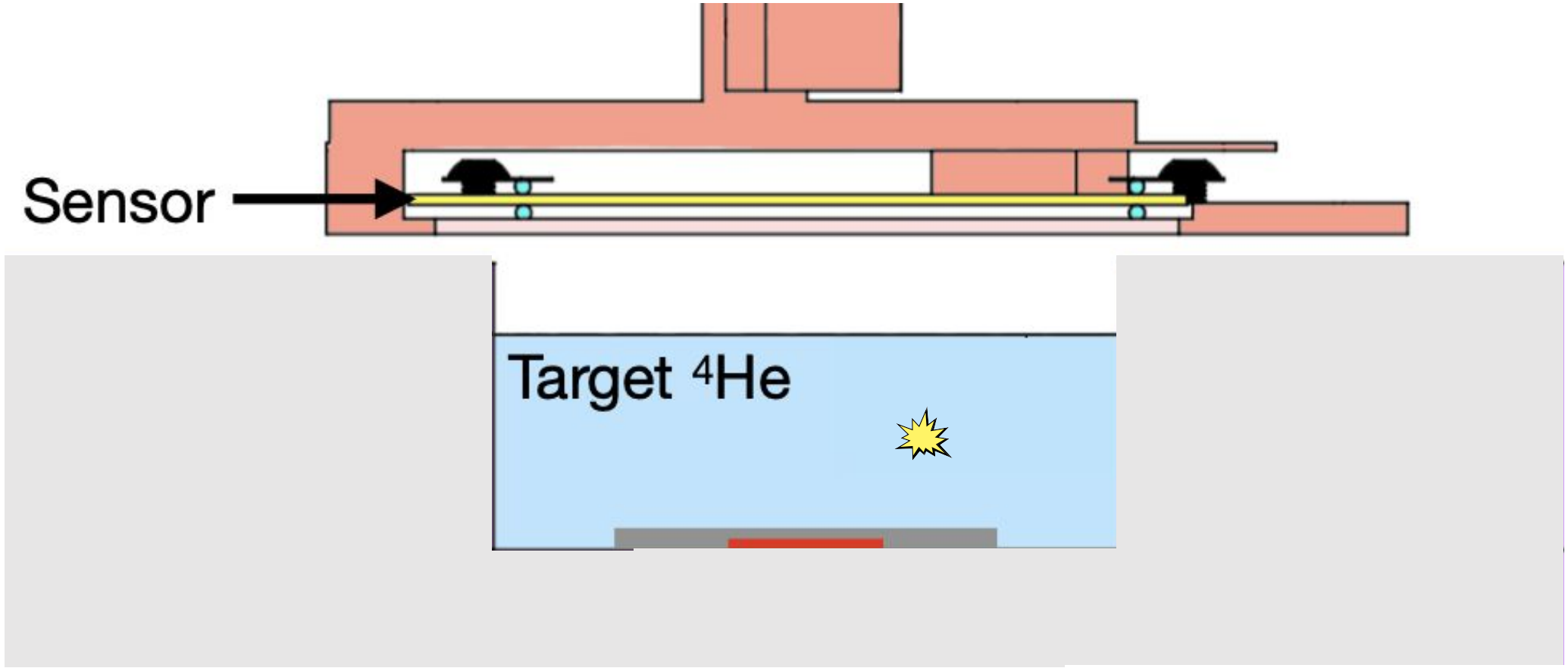
Challenge: Superfluid helium will attach to nearly any surface it can find, including the sensor

Solution: use unoxidized cesium, which is not wetted by superfluid helium

Film Blocker

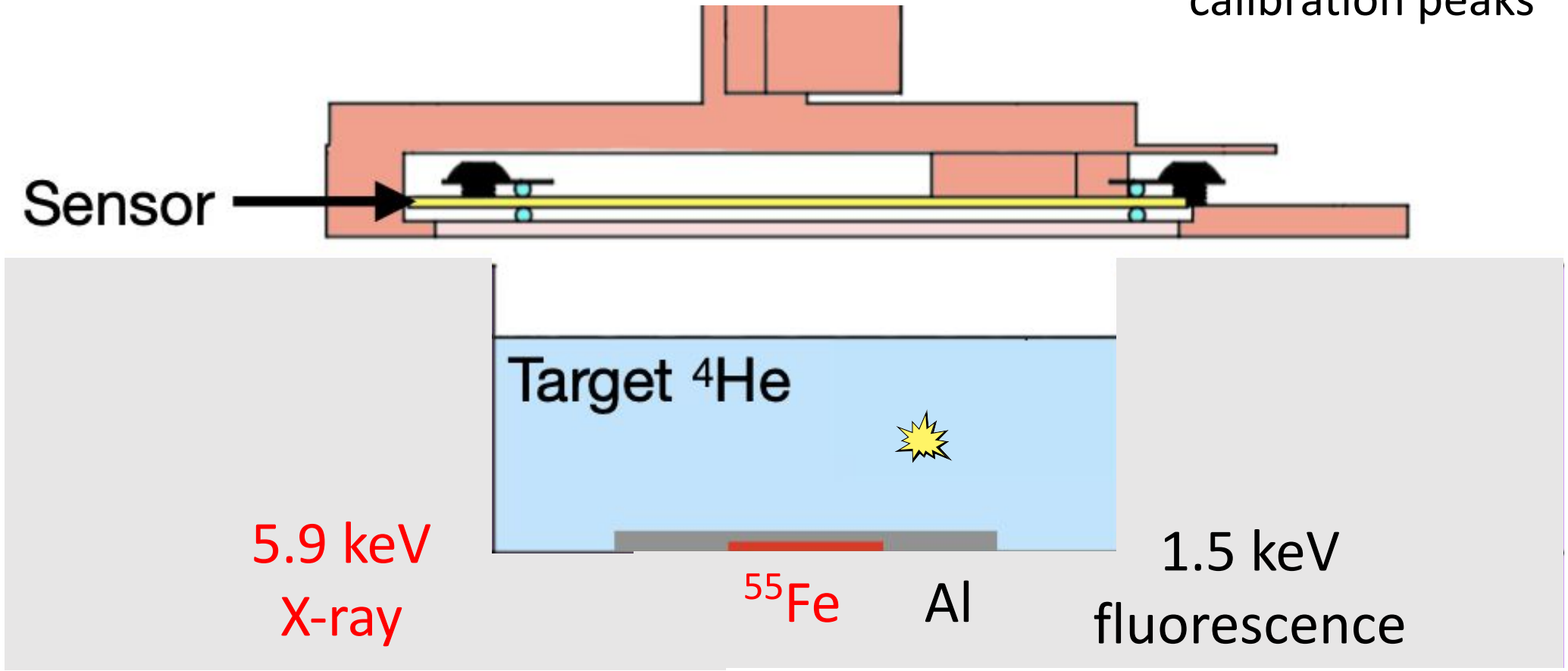


Data Collection



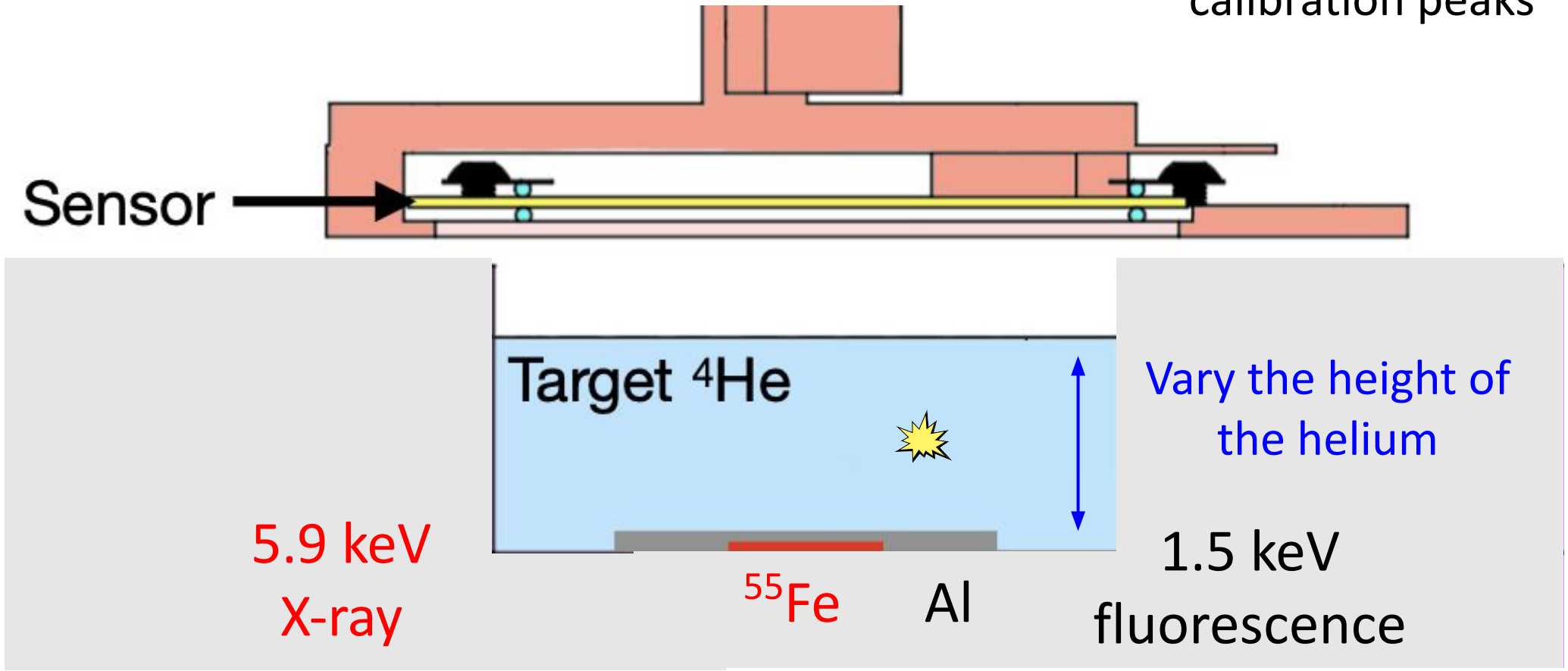
Data Collection

Two low-energy mono-energetic calibration peaks

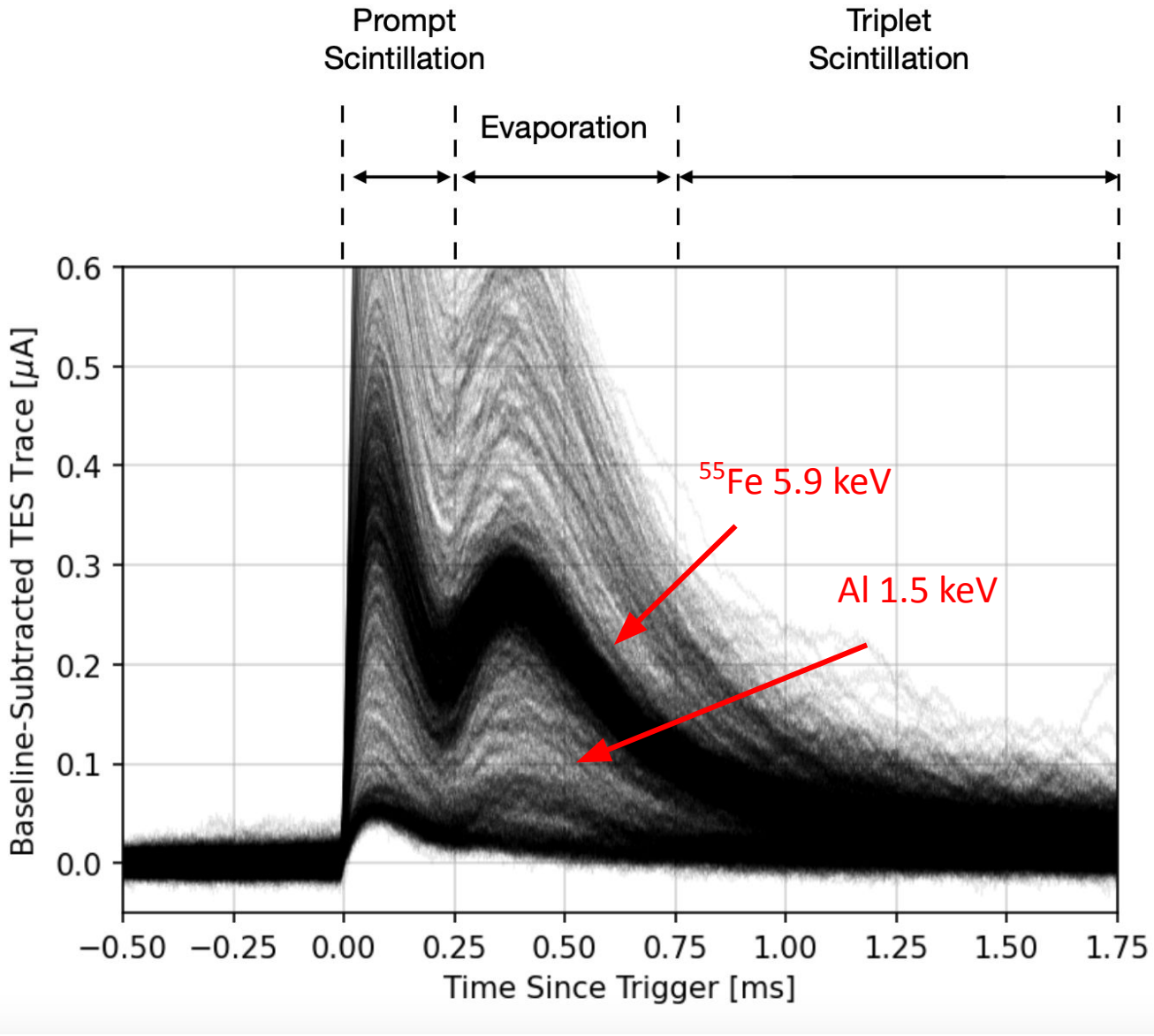


Data Collection

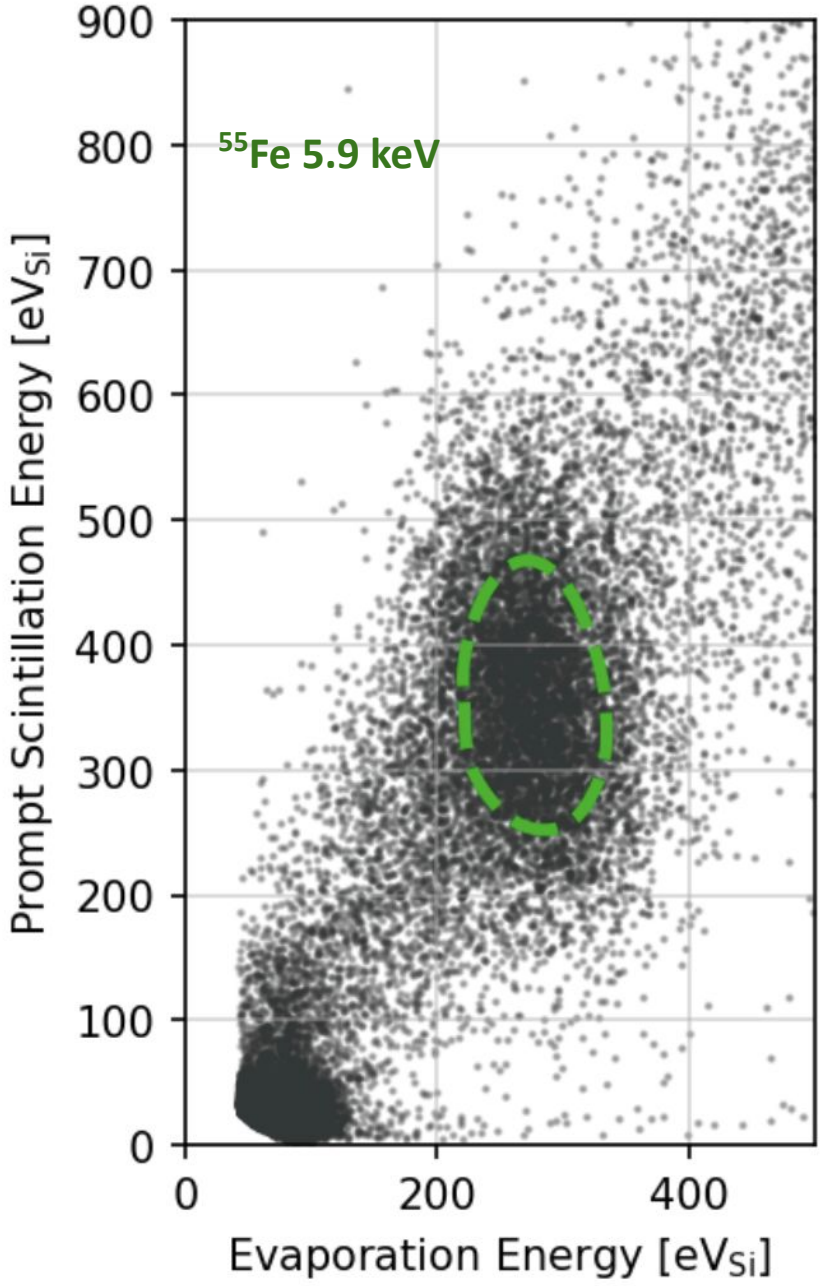
Two low-energy mono-energetic calibration peaks



Three-signal Observation



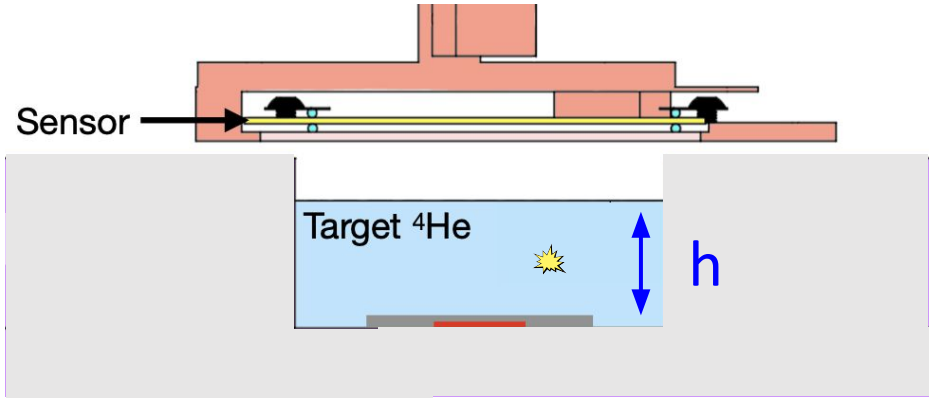
Photons and **Phonons**

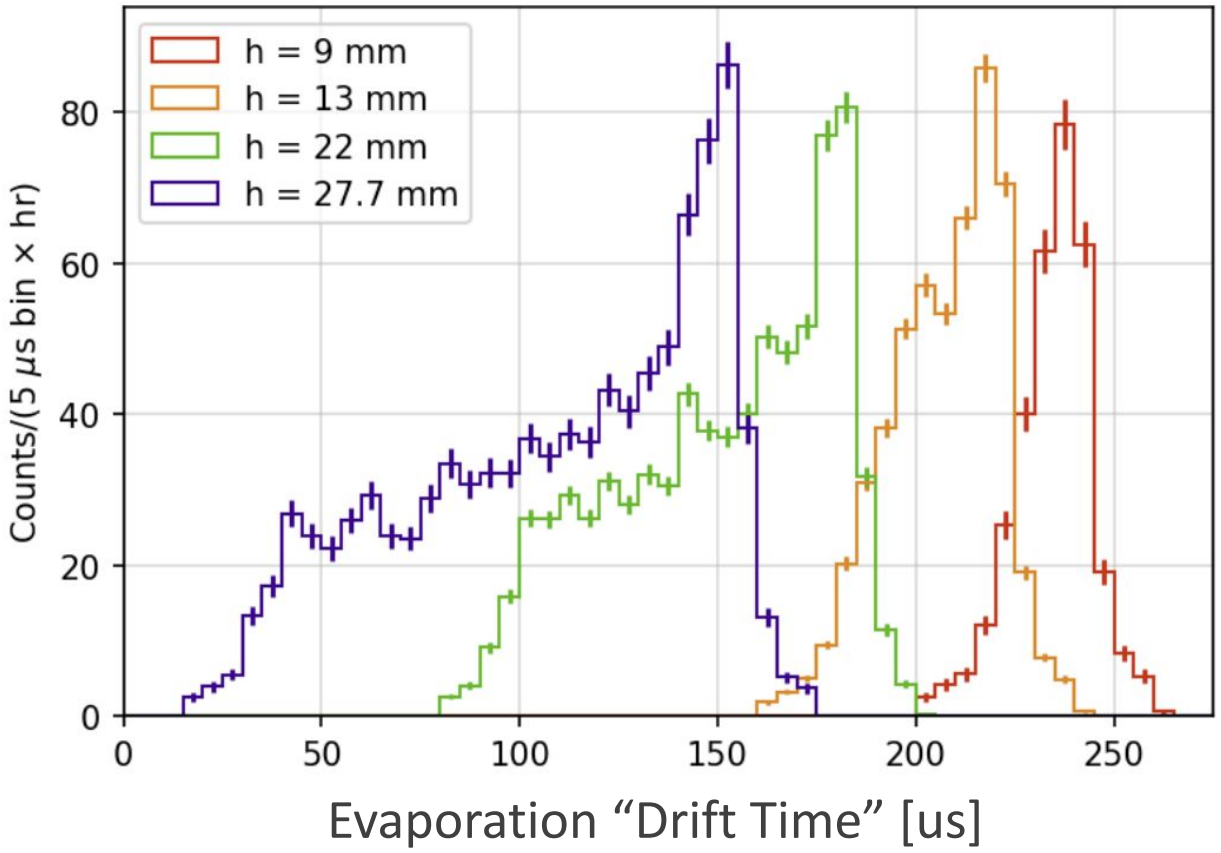


Photons and **Phonons**

Vary the helium fill-level

Get a rough estimate of
quasiparticle velocity ~200 m/s
evaporated atom velocity ~100 m/s

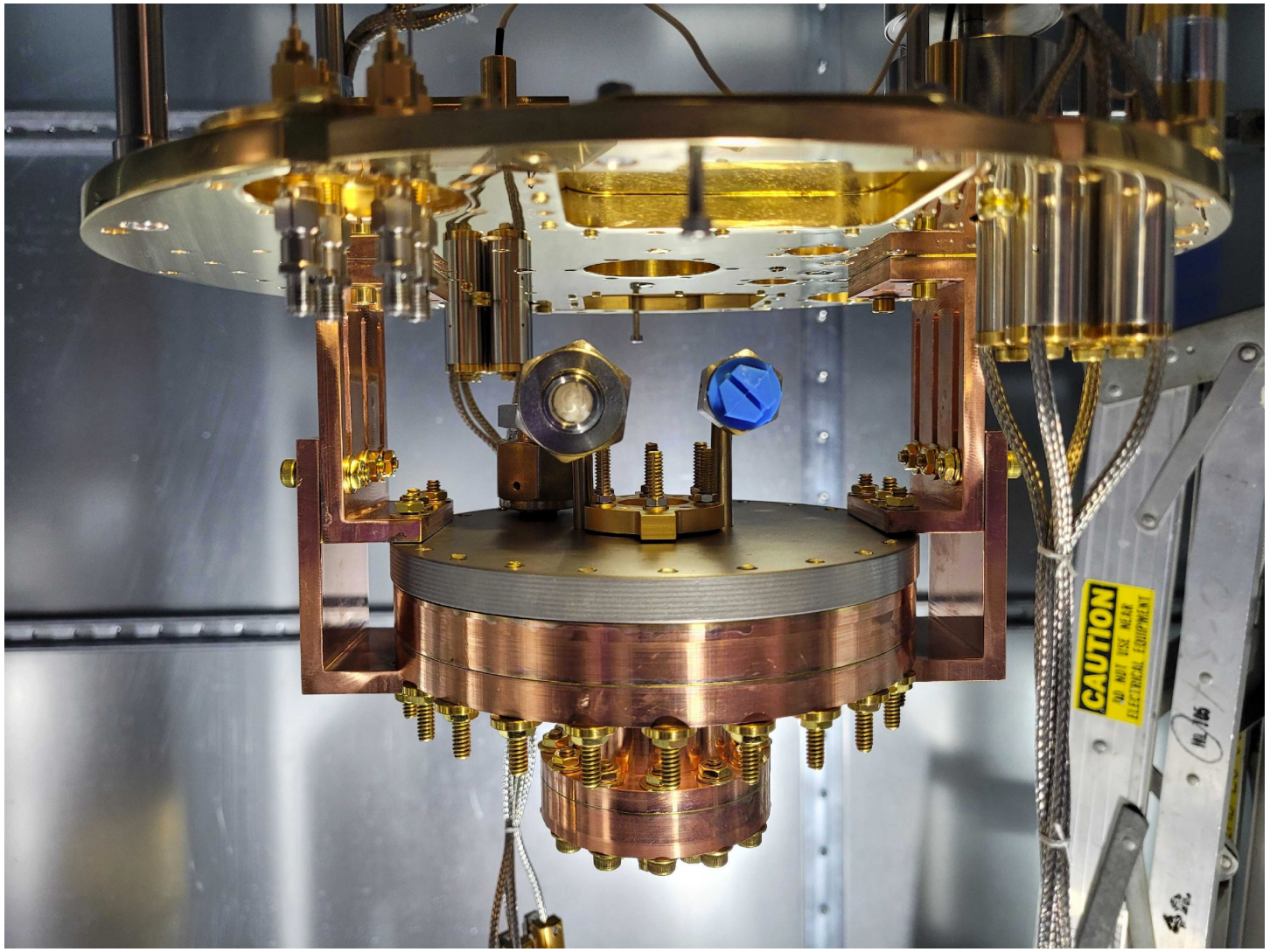




Takeaways from Amherst R&D

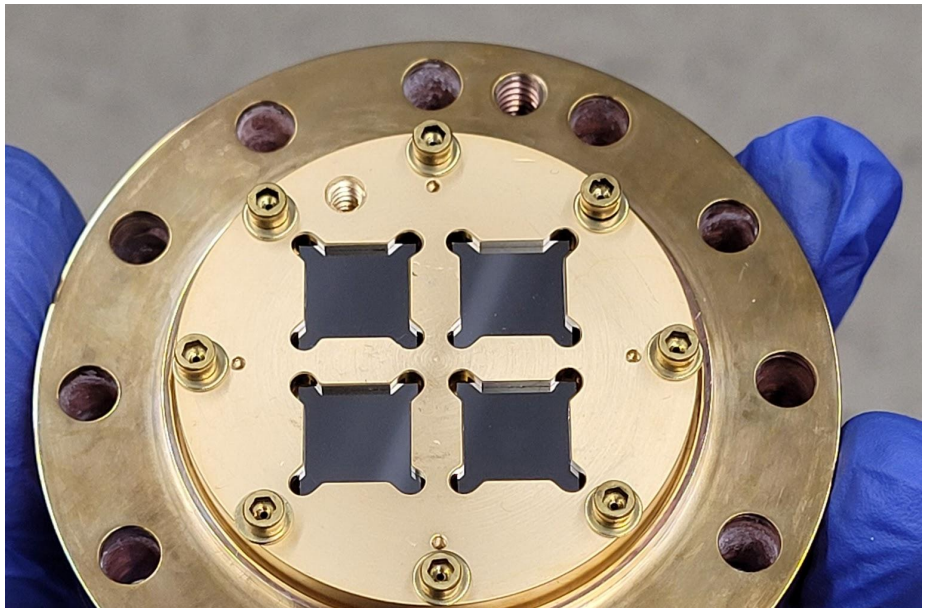
- Achieved 145 eV nuclear recoil energy threshold, corresponding to DM sensitivity >220 MeV
- Evaporation signal gain of ~0.15
- Measured quasiparticle and evaporated atom velocities
- Results are consistent with quasiparticle-metal reflection probability of ~0.3
- More work ongoing!

HeRALD at Berkeley Lab



Commissioning a detector at LBNL with 4 immersed and 4 suspended calorimeters

Plan to study multi-channel readout; ER and NR calibrations



Conclusions

Why use helium-4 for particle detection?

A particle detector needs:

- Particle ID

- High signal fidelity

- Low backgrounds

- Scalable

Why use helium-4 for particle detection?

A particle detector needs:

- Particle ID
- High signal fidelity
- Low backgrounds
- Scalable

Helium:

- Three signal channels, allowing discrimination between nuclear and electronic interactions
- Amplification of quantum evaporation signal
- Radiopure; chemically pure; no stress fractures
- Liquid down to 0K

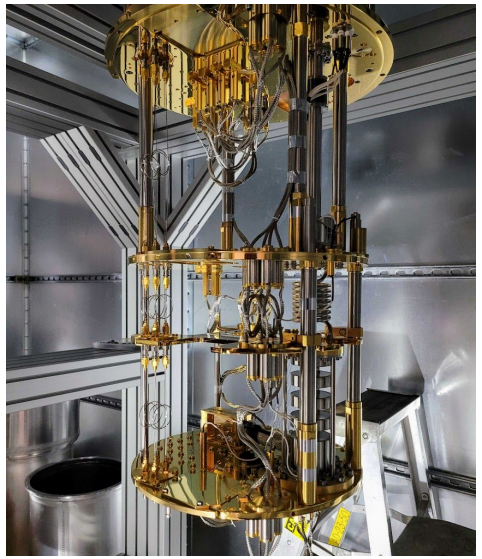
What to remember

- Superfluid ^{4}He is an excellent target for *dark matter detection* at the MeV-to-few-GeV mass scale
- The HeRALD experiments and the TESSERACT collaboration are making rapid progress towards a world-leading dark matter search
- Informed by recent advancements in sensor technologies and target dynamics

Backup

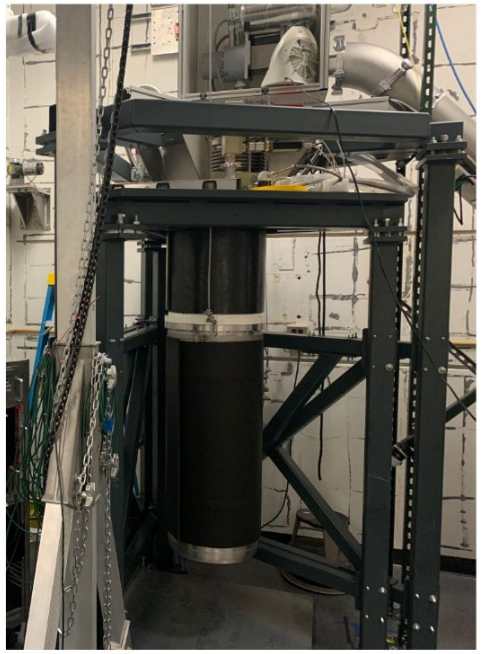
TESSERACT
R&D Stands

And a sixth
stand at KEK!

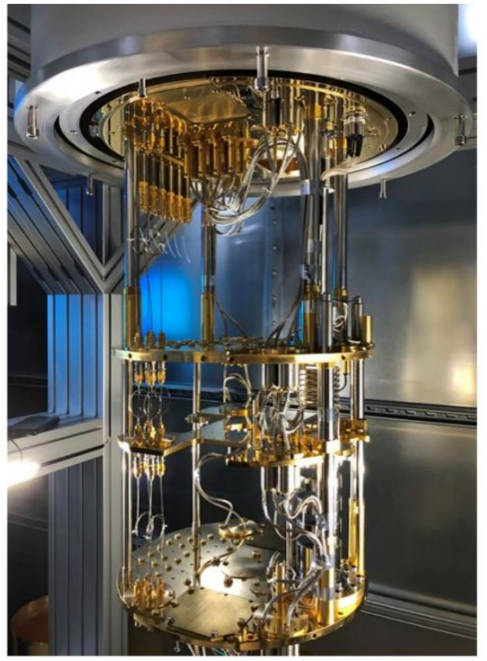


BlueFors
LD-400
LBNL

Leiden
MNK126-500
UC Berkeley



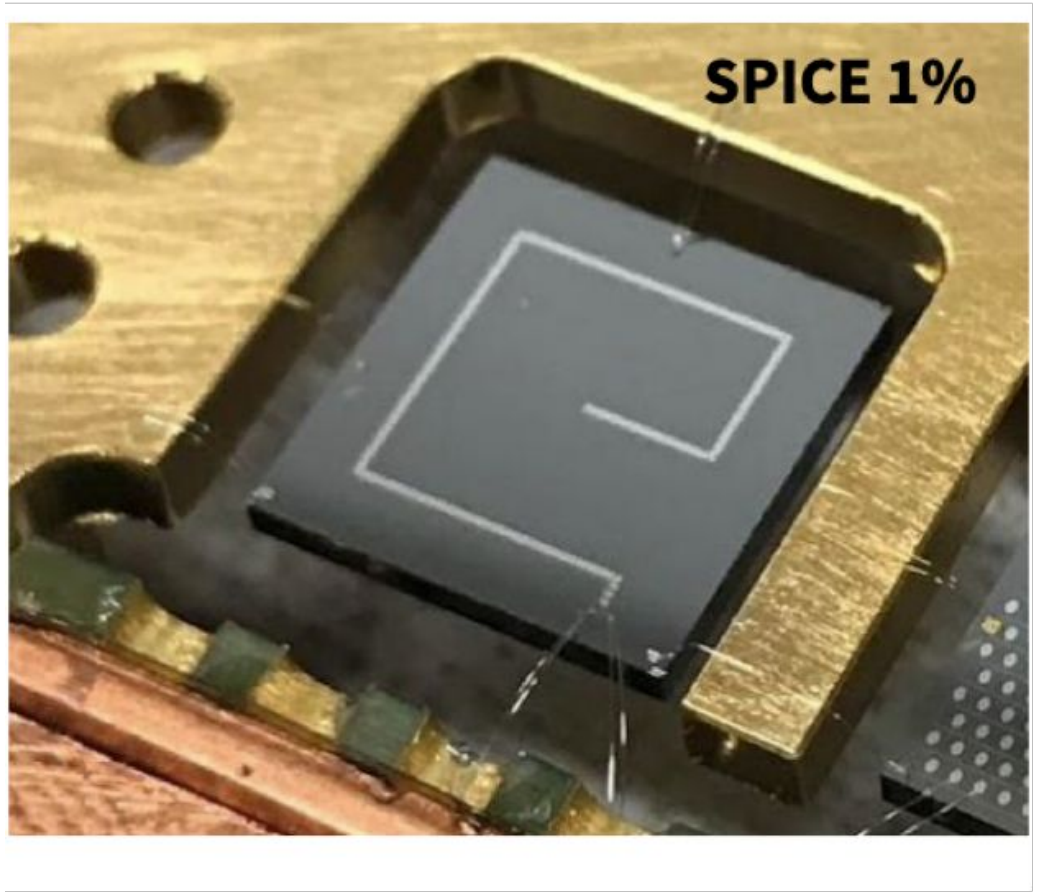
CryoConcept
UQT-B 200
UC Berkeley

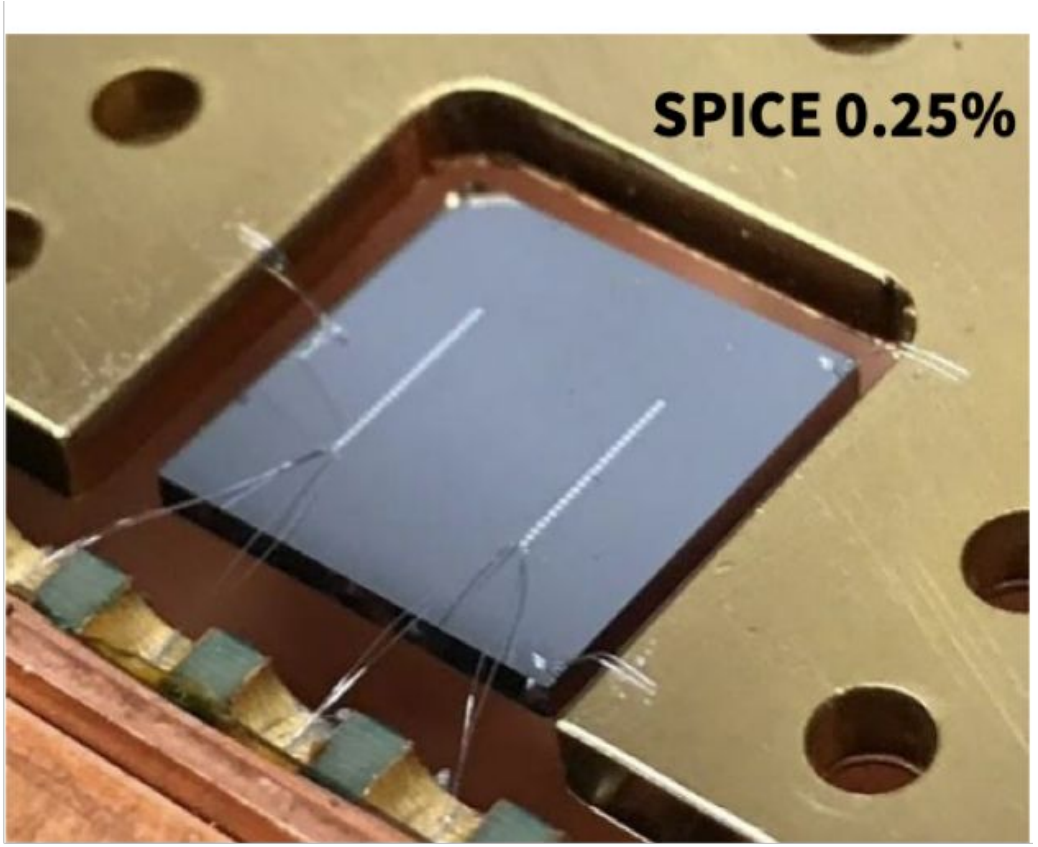


BlueFors
LD-400
LBNL

CryoConcept
UQT-B 400
UMass

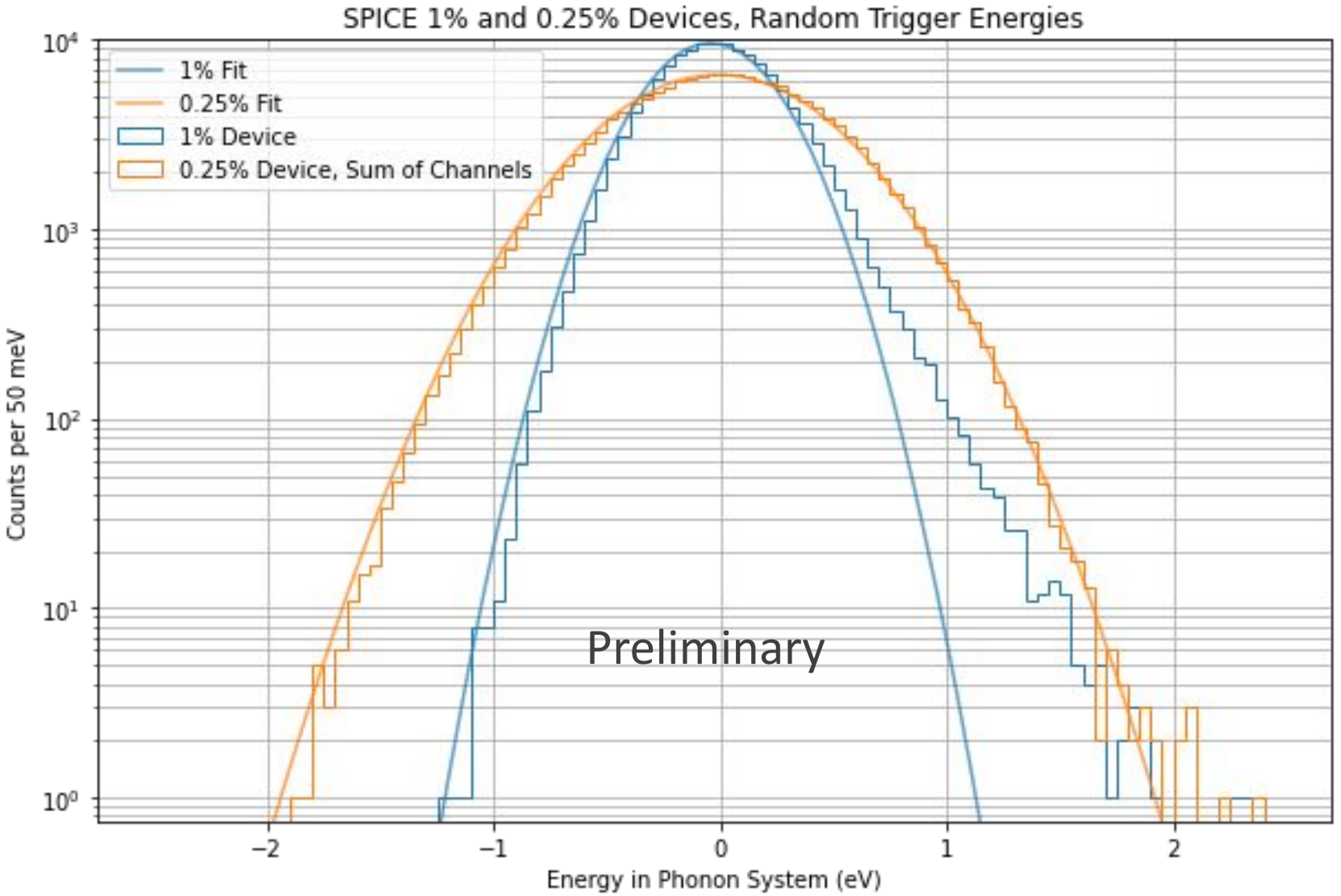
TESSERACT Sensors





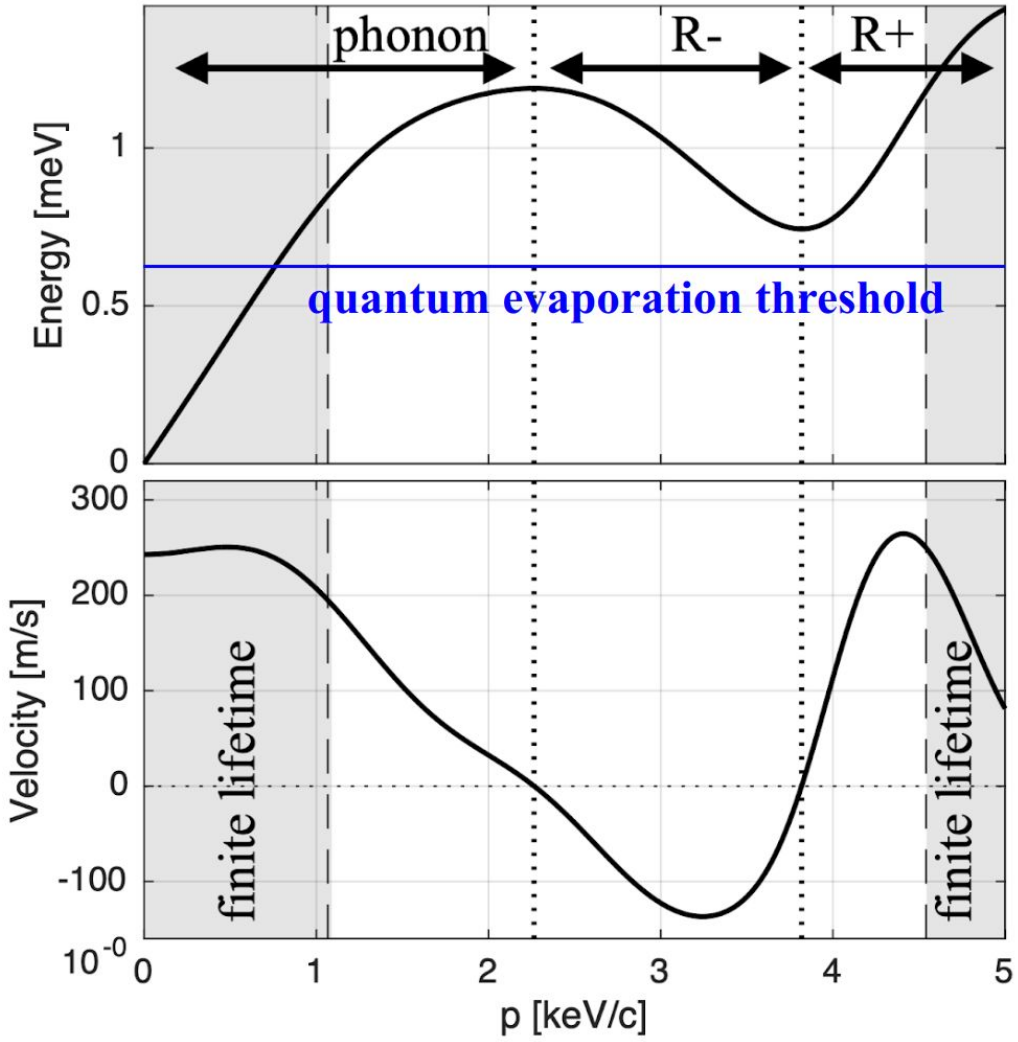
TESSERACT Sensors

- 273 and 460 meV resolution achieved with tungsten film on silicon substrate, Tc = 50 mK

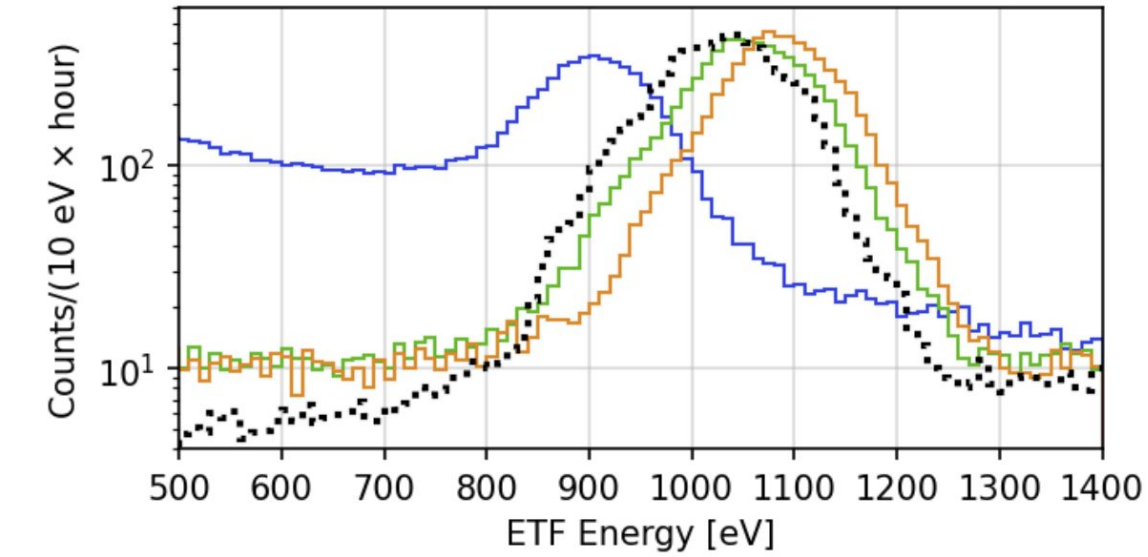


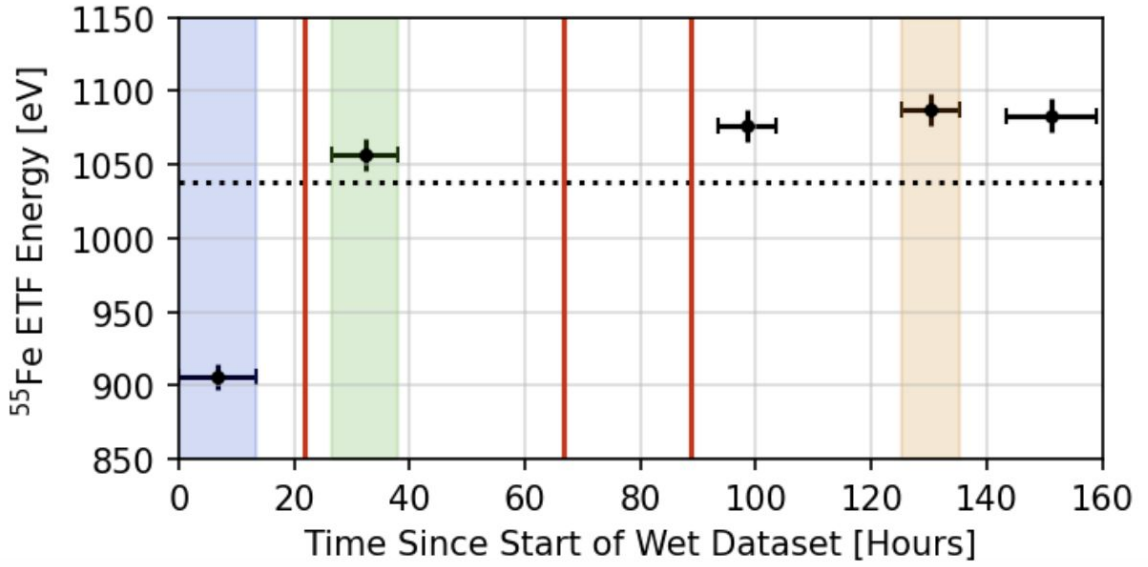
Energy Partitioning in Helium

- Three flavors of quasiparticles: Phonons, R+ rotons, R- rotons
- Different regions of the same dispersion curve
- In the bulk, we have athermal quasiparticles with infinite lifetime and ballistic propagation

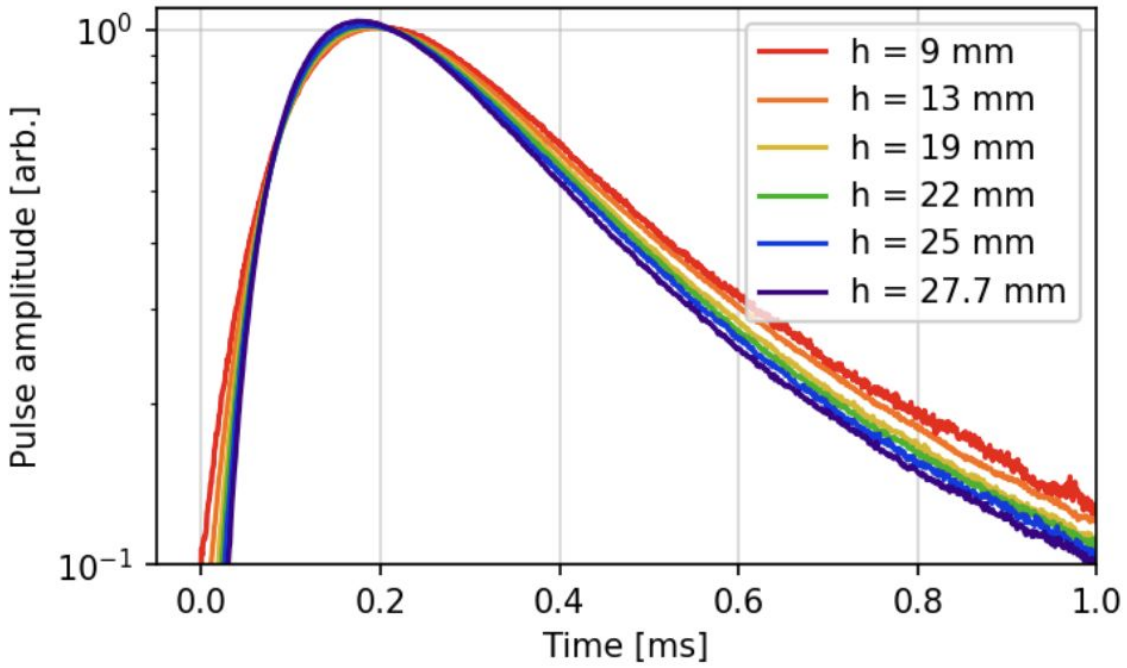


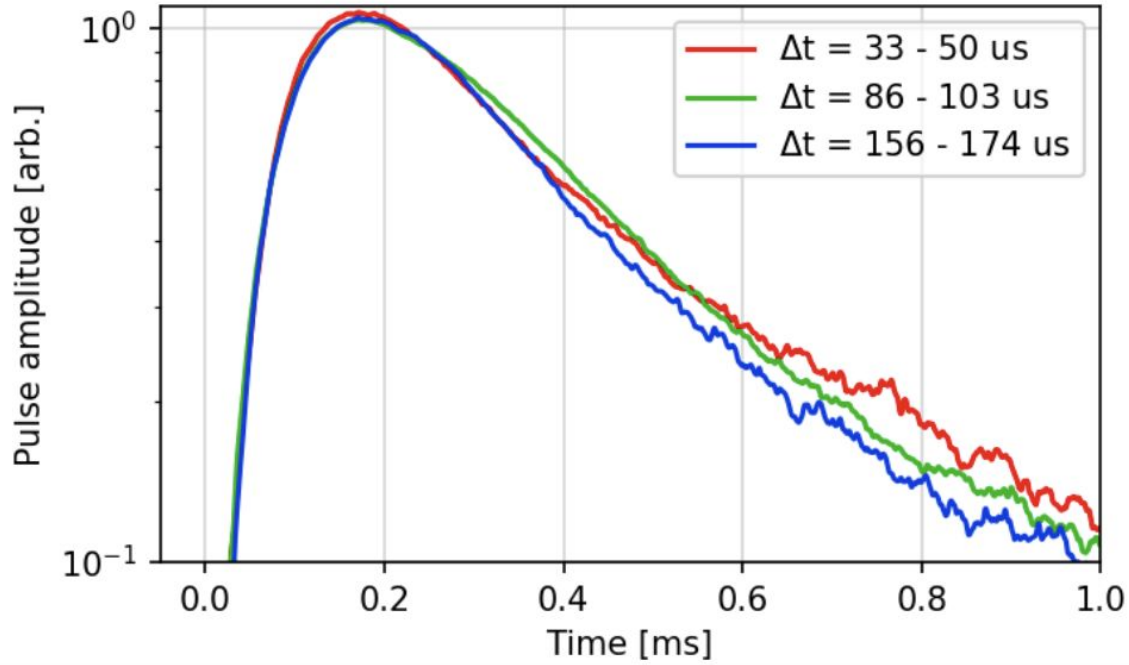
Cesium Film Blocker Efficacy



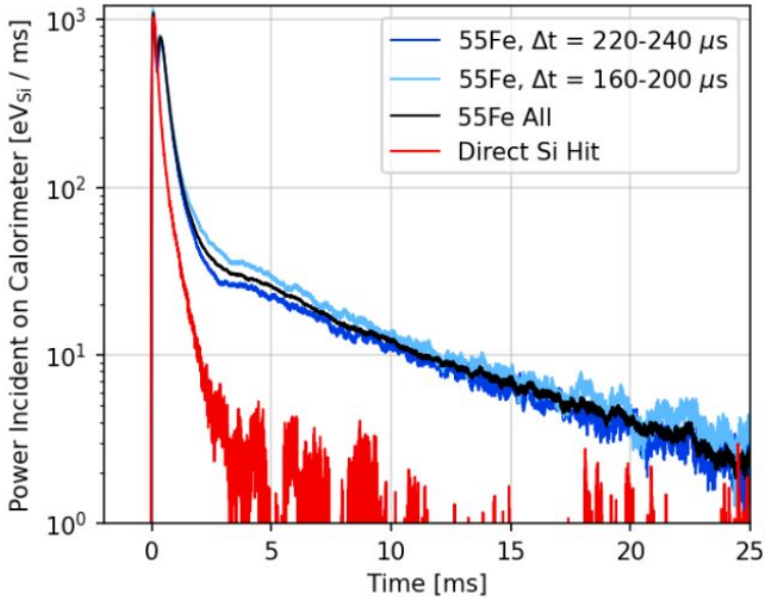


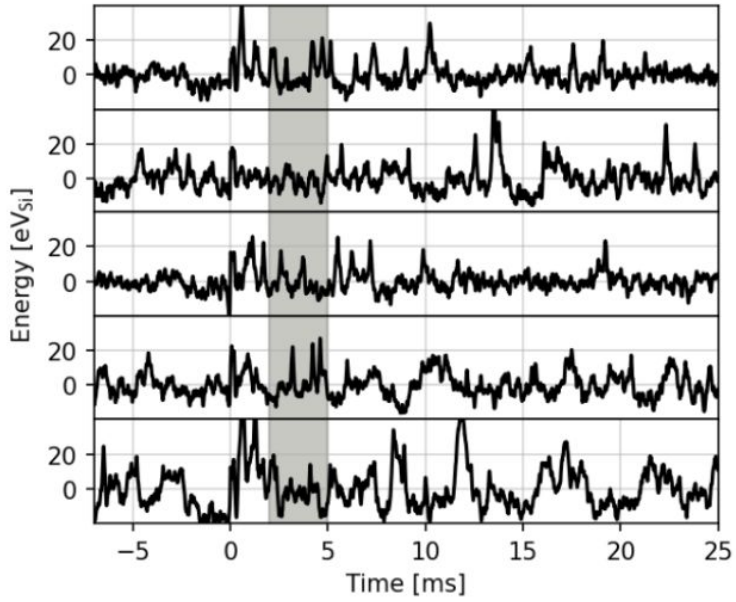
Evaporation Pulse Shape

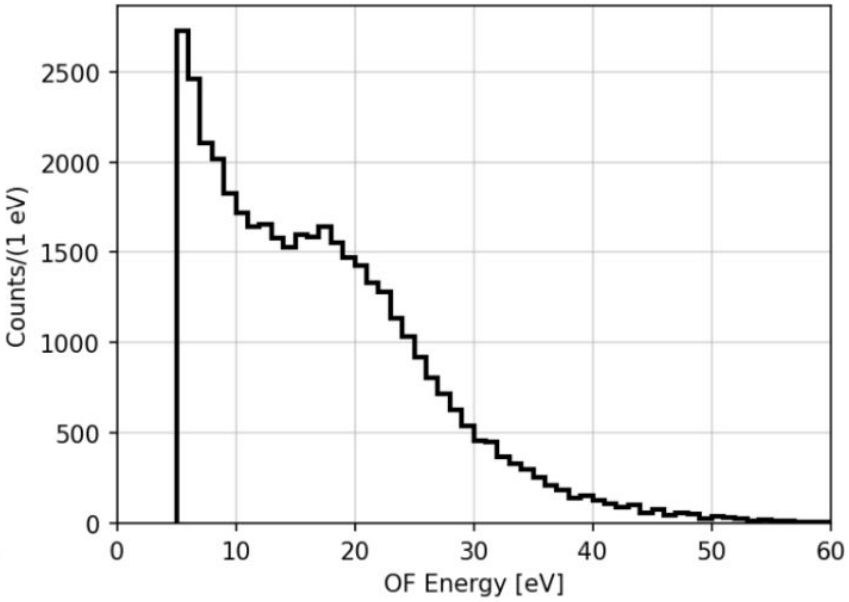




Triplet Pulse Shape







Electronic vs. **Nuclear** Recoil Discrimination