HeRALD: Direct Detection with Superfluid 4He

Doug Pinckney on behalf of the HeRALD collaboration

11-30-2018

arXiv:1810.06283v1

UMass Amherst

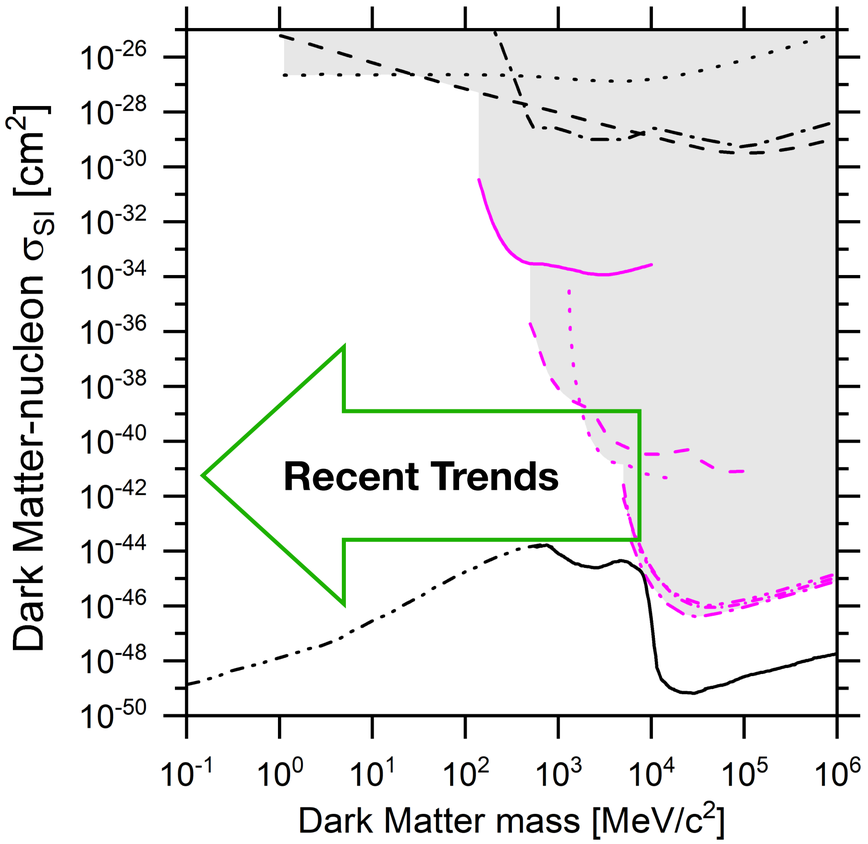
Berkeley
UNIVERSITY OF CALIFORNIA

Outline

- **Light mass dark matter recap**
- HeRALD: Helium Roton Apparatus for Light Dark Matter
  - Detector design
  - Detector simulations
  - Sensitivity
  - Activities at UMass and Berkeley

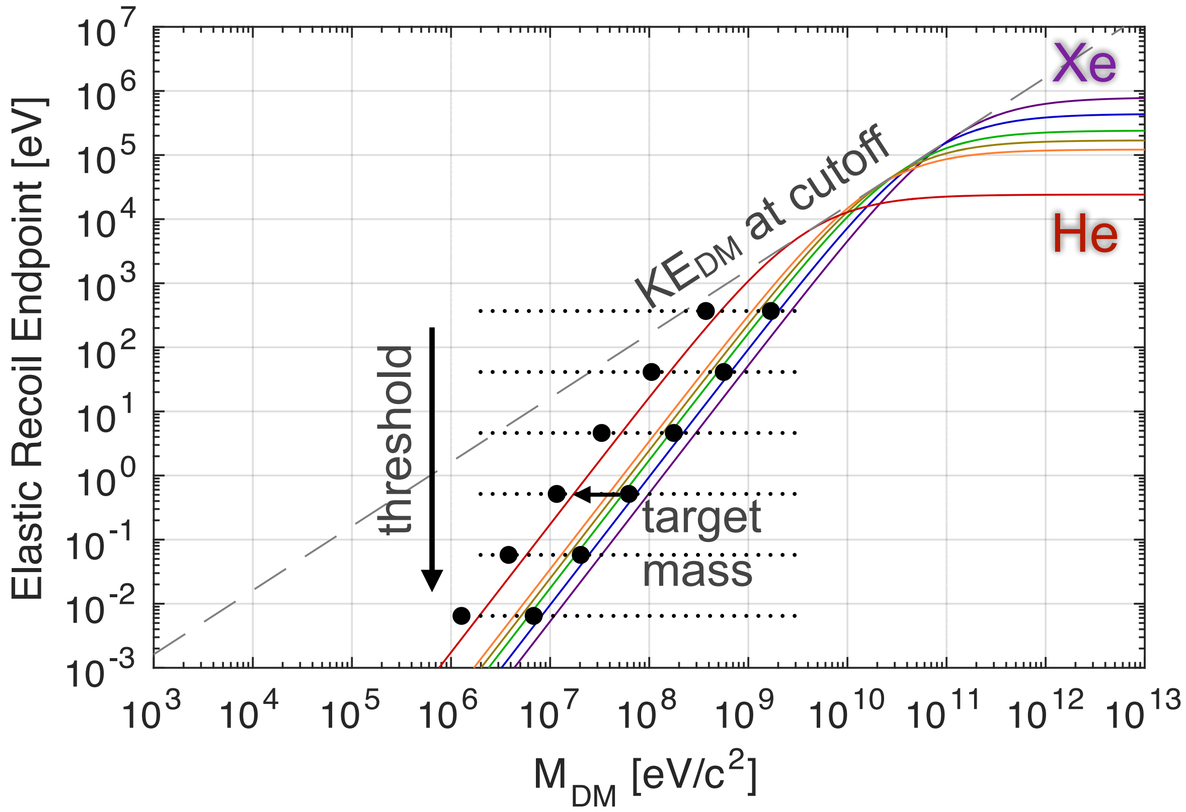
Direct Detection Searches

- Most direct detection experiments have focused on WIMPs (GeV/c^2 - TeV/c^2) and Axions (<= eV/c^2)
- If dark matter interacts through a new force it could lie between these two (keV/c^2 - GeV/c^2)
- Upper limits in “low mass” region are from CMB
- Solid pink line is CRESST, O(1 g)
  - Can test lots of parameter space with low exposure
- The focus of HeRALD to look for these “light” candidates



Challenges of Light Mass Dark Matter Detection

- As DM mass decreases relative to target particle mass, less energy is deposited in the detector
  - MeV mass requires meV threshold if using a nuclear recoil signal
- In order to test low mass hypotheses we need to maximize the signal we see!
  - Lighter target particles give us more energy to work with (electrons, light nuclei)
  - Lower energy thresholds allow us to see less energy



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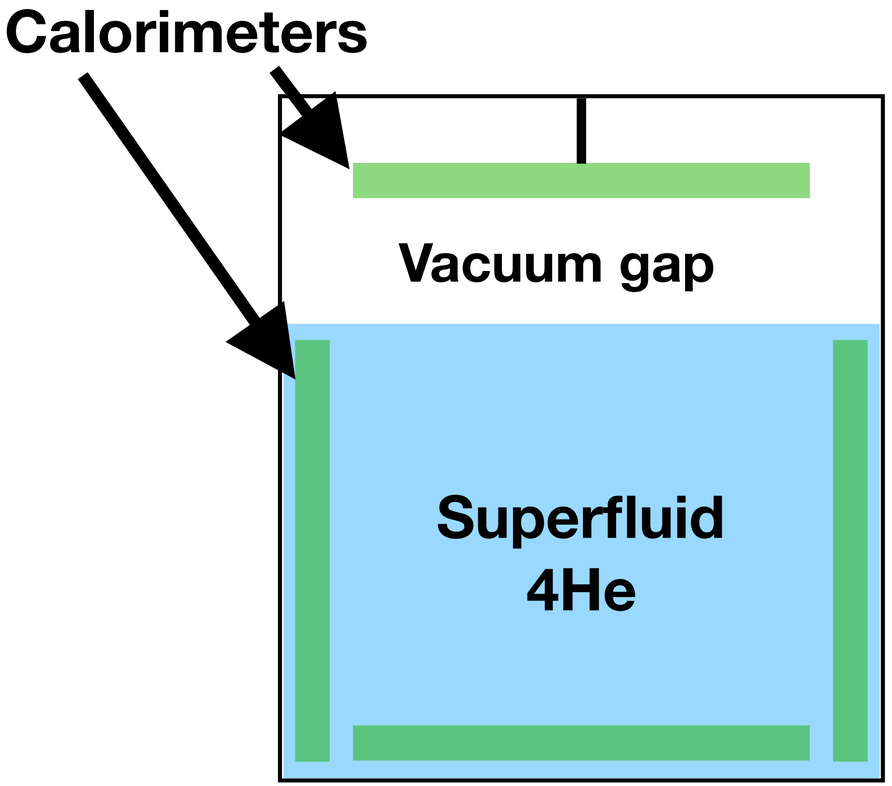
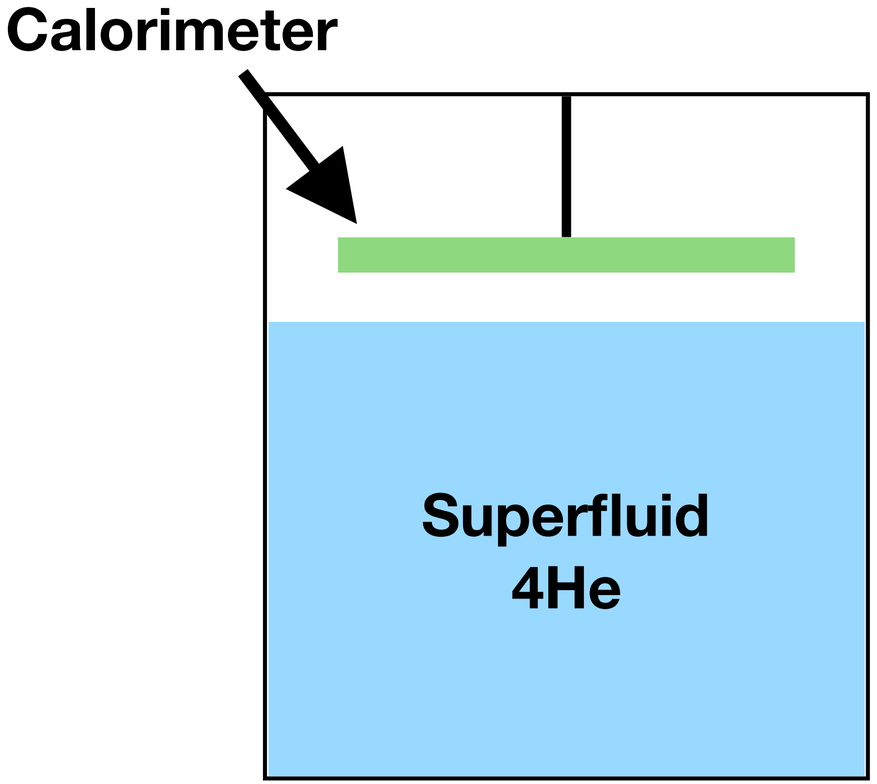
HeRALD: A Helium Based Detector

- HeRALD uses superfluid 4He as a target material
- All recoil induced excitations are observed with large area calorimetry suspended above and immersed in the liquid



HERON

- Seidel Group at Brown
- R&D to search for low energy pp solar neutrinos
- Aimed at keV threshold at ton scale
- Did a lot of the “proof of concept” work
- HeRALD has more calorimeters, aims for sub-eV threshold at sub-kg scale

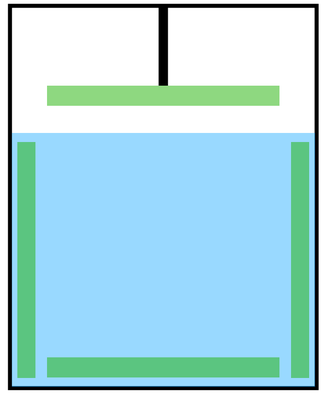


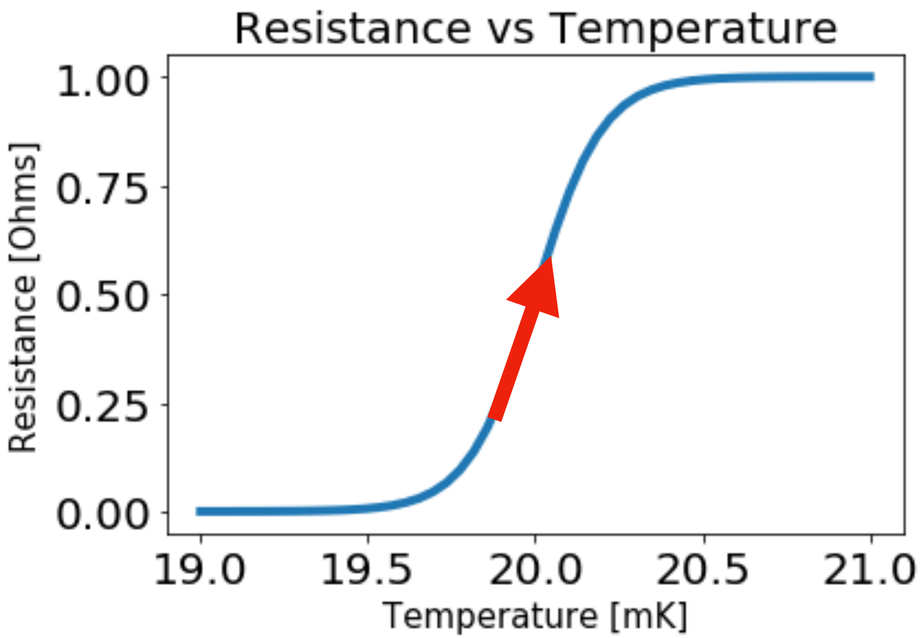
Advantages of Superfluid 4He

Advantage	Because
Favorable recoil kinematics	Light nucleus
Recoil energy can be fully reconstructed	All recoil induced excitations can be detected with calorimetry Vibrational excitations are long lived and ballistic
Low risk of radiogenic backgrounds in bulk	4He can be made very radio pure
No electron backgrounds below 20 eV	4He has no electron excitations below 20 eV
Calorimeters can be operated at arbitrarily low temperatures	4He is liquid to 0 K

The Calorimeters

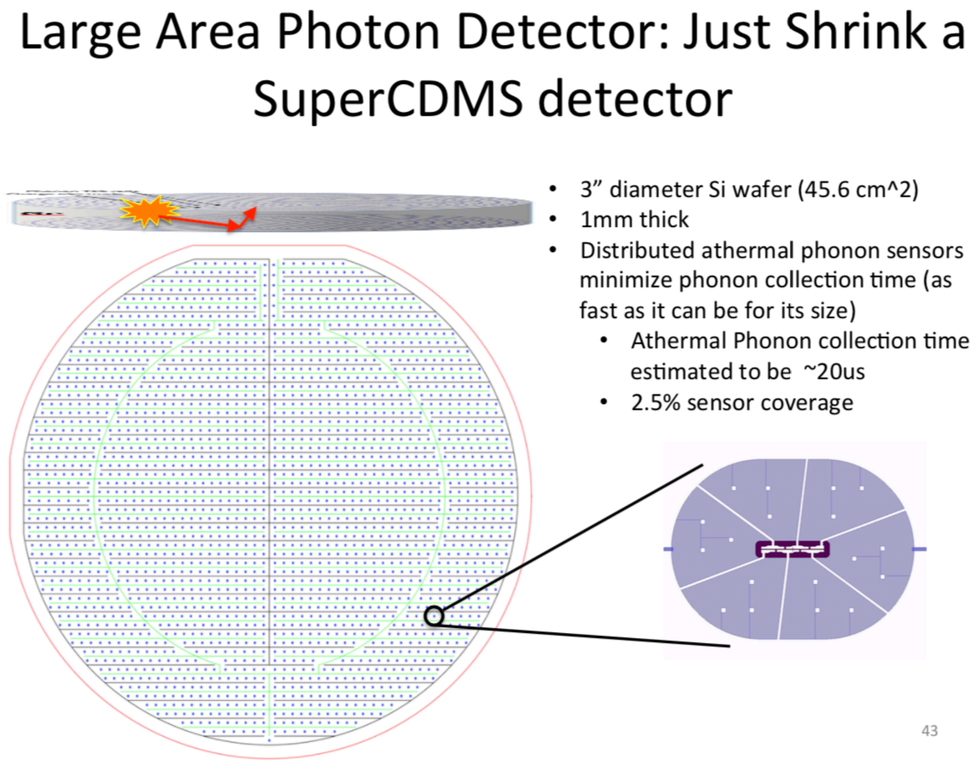
- Plans to use Transition Edge Sensor (TES) based calorimetry
- Use sharp superconducting phase transition to convert heat signals to electrical signals
- Small current signals read out by inductively coupled SQUID electronics
- You can increase sensitivity by:
  - Lowering temperature

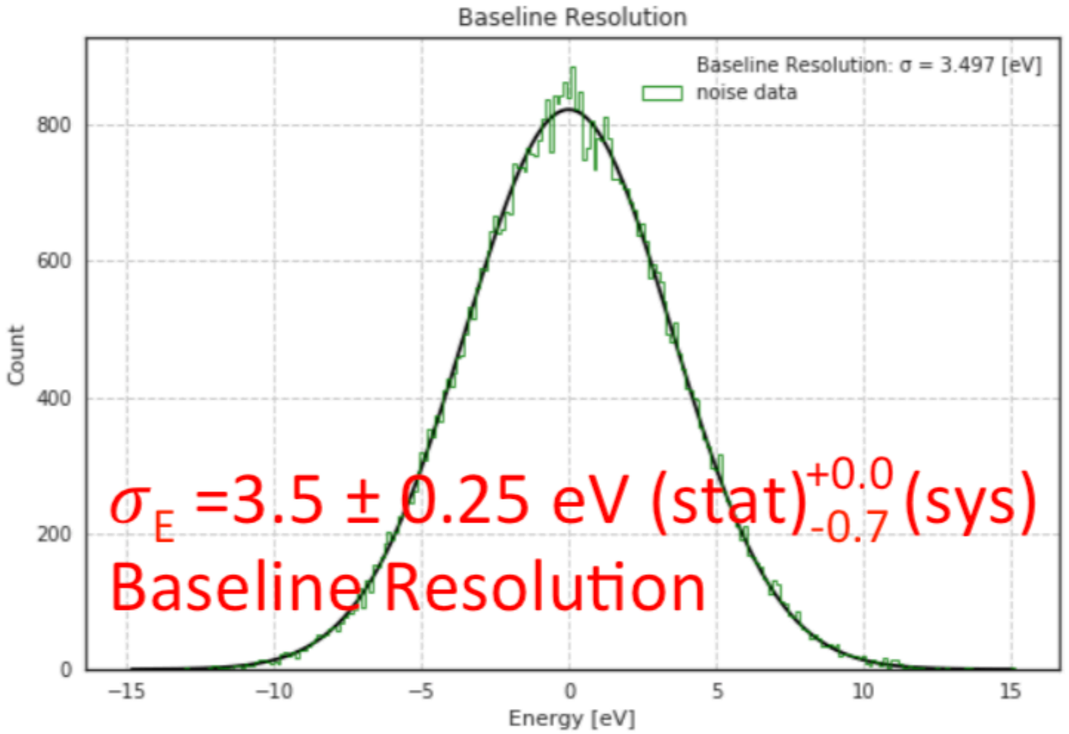




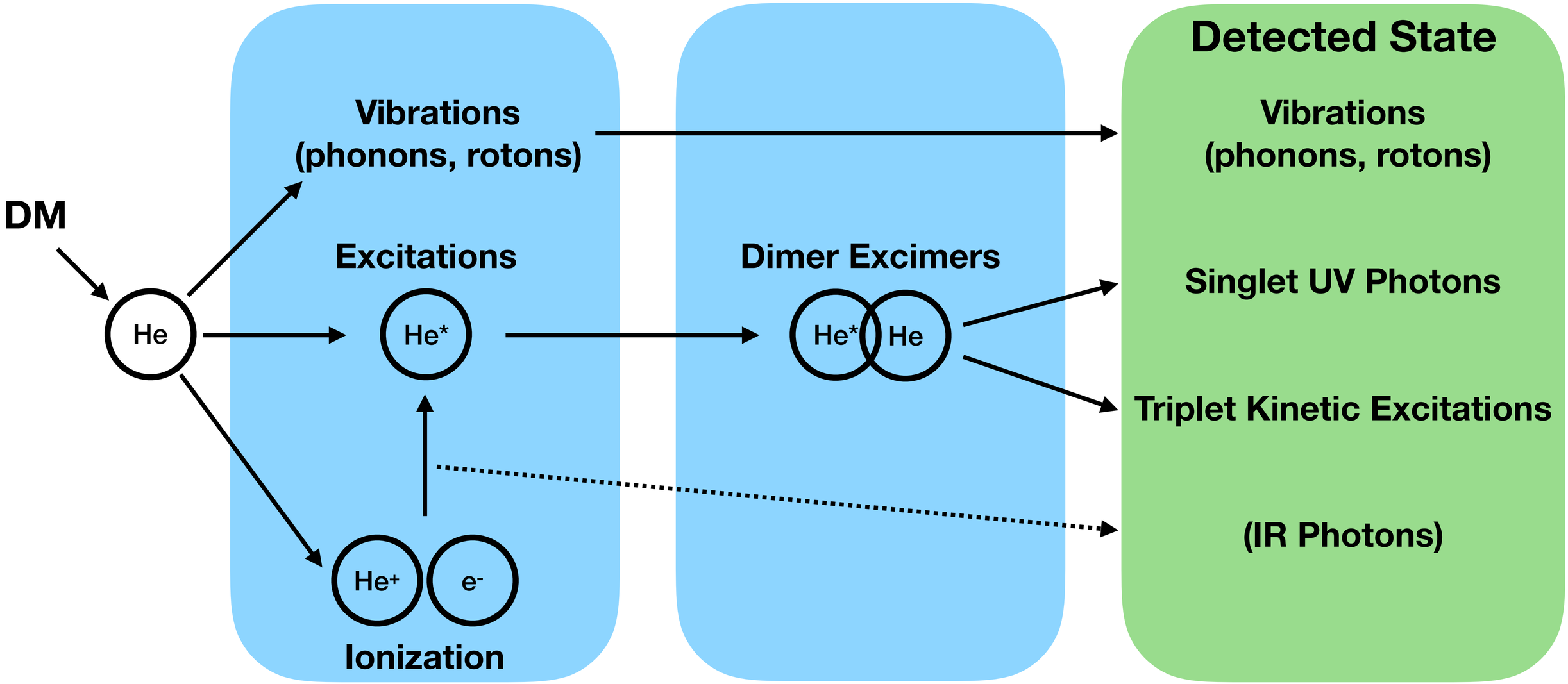
Calorimetry Continued

- Calorimetry from M. Pyle at Berkeley (below is from a recent talk)



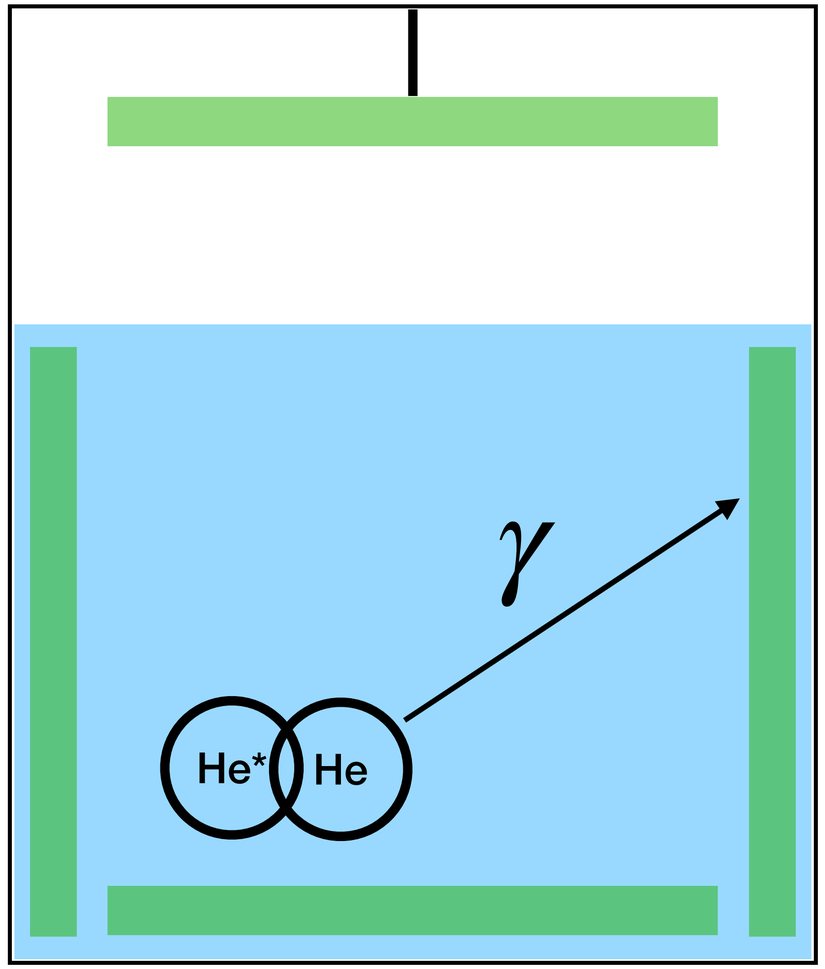


Excitations in Superfluid 4He



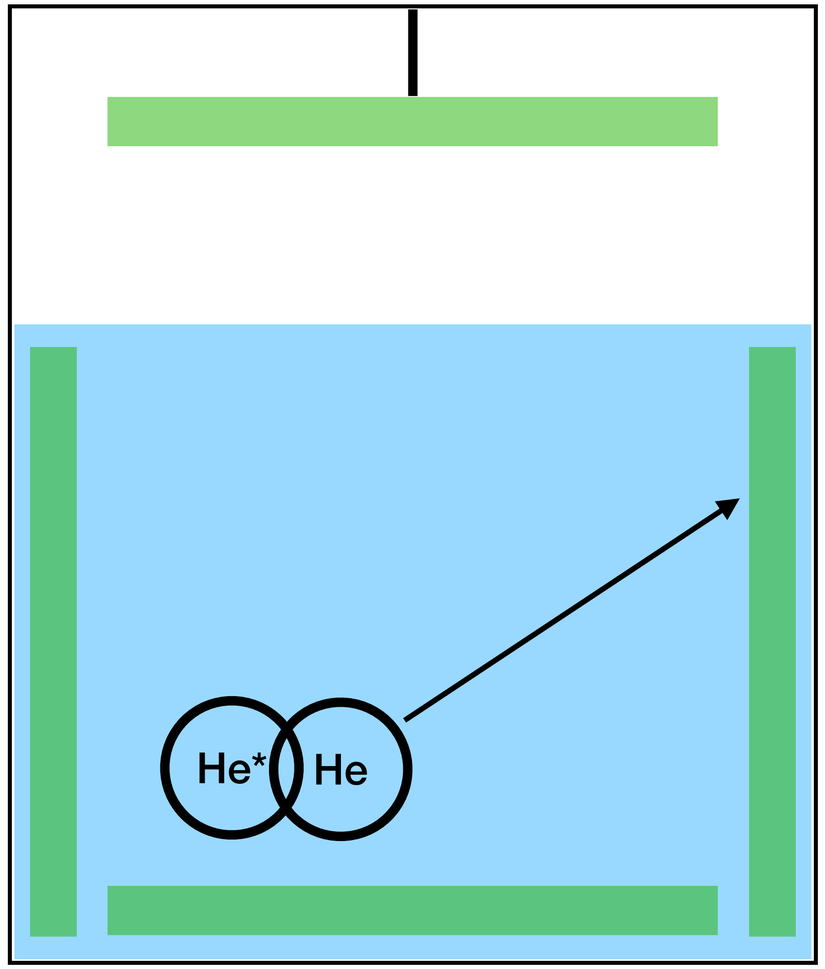
Detecting Singlet Excitations

- The singlet excimer has a half-life of 10 ns
- Decays by emitting a UV photon (~16 eV)
- Absorbed in calorimeters
- Propagates freely through liquid as there are no electronic excitations below ~20 eV
    - Similar to other noble element experiments!



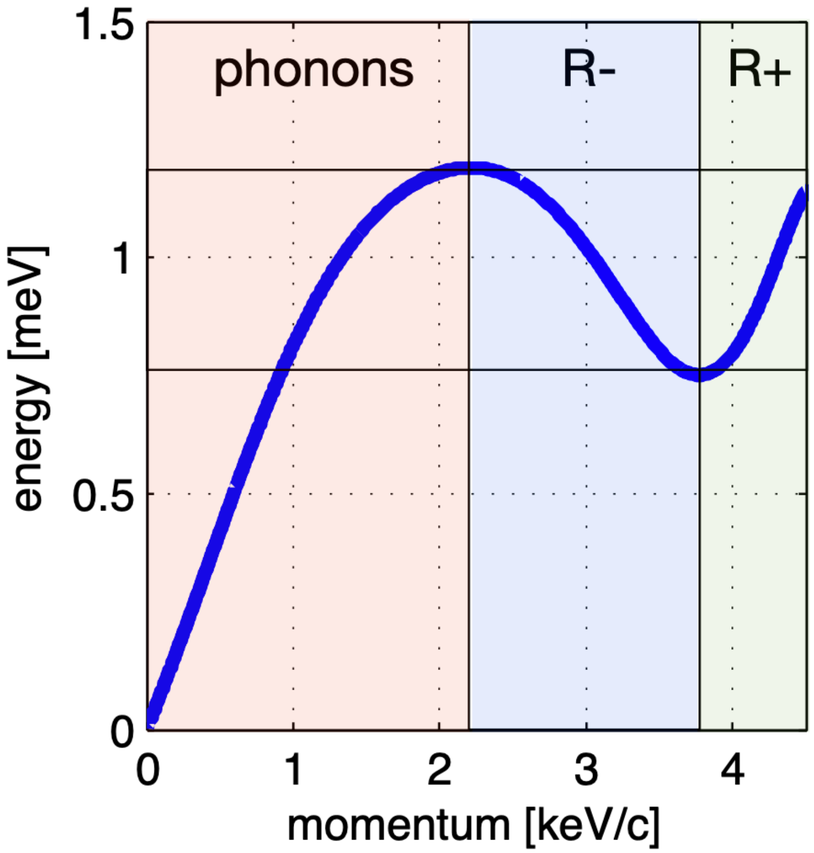
Detecting Triplet Excitations

- The triplet excimer has a long half life of 13 s
- Ballistic, velocity O(10 m/s)
- Typically releases energy in material boundaries (ie. calorimeters)



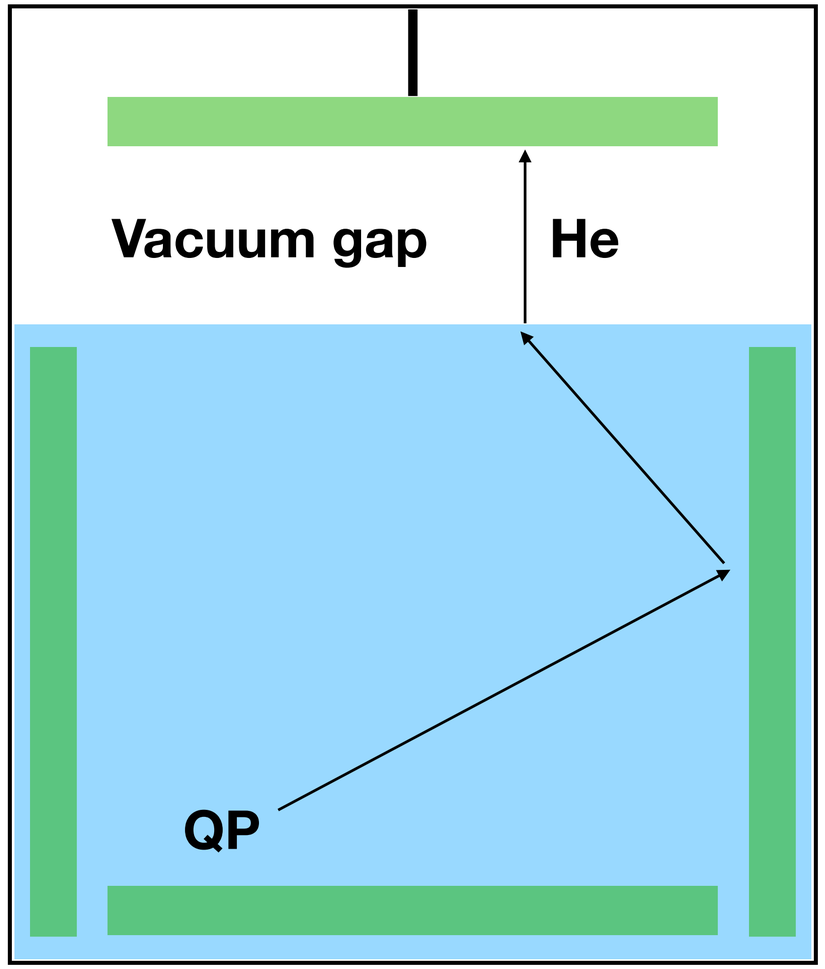
Detecting Vibrations: Vibrations in Helium

- The vibrational (“quasiparticle”, “QP”) excitations we expect to see are phonons and rotons
- Velocity is slope of dispersion relation
- Rotons ~ “high momentum phonons”
  - Just another part of the same dispersion relation
  - R- propagates in opposite direction to momentum vector



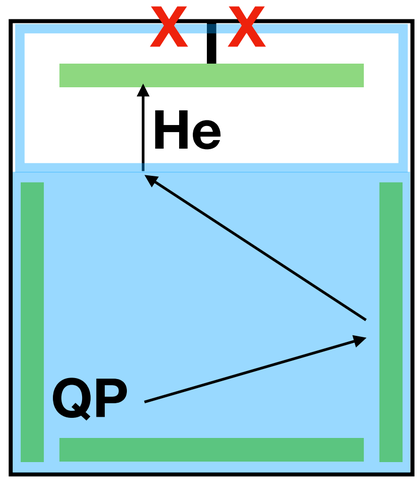
Detecting Vibrations: Method

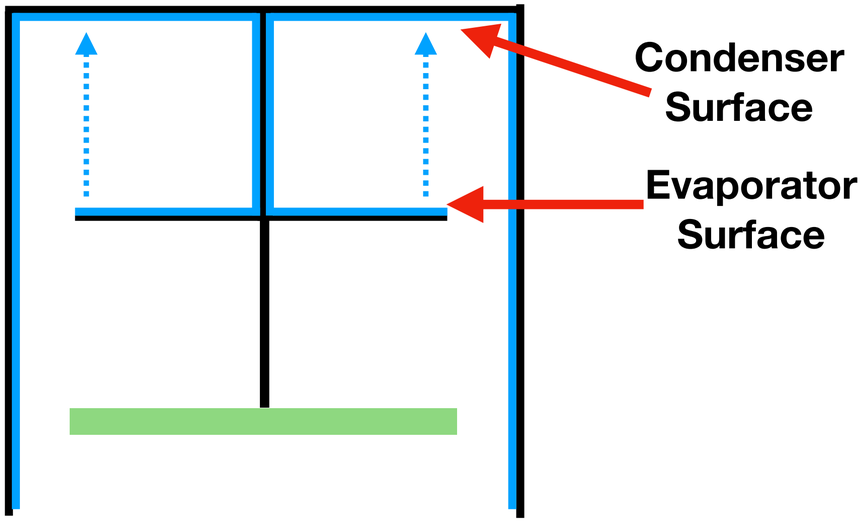
- Quasiparticles internally reflect until they find the vacuum interface
  - Some probability of changing flavor on reflection
- At the surface quasiparticles knock He atoms into the vacuum (“quantum evaporation”)
- These free He atoms adsorb onto the large area surface calorimeter



Detecting Vibrations: Adhesion Gain

- A helium free calorimeter will give an electrostatic “adhesion gain” amplifying the quasiparticle signal
- Need to stop helium film from reaching calorimeter, can be achieved with a film burner (shown with HERON but has heat load)*
- UMass is looking into low heat load options (more later)

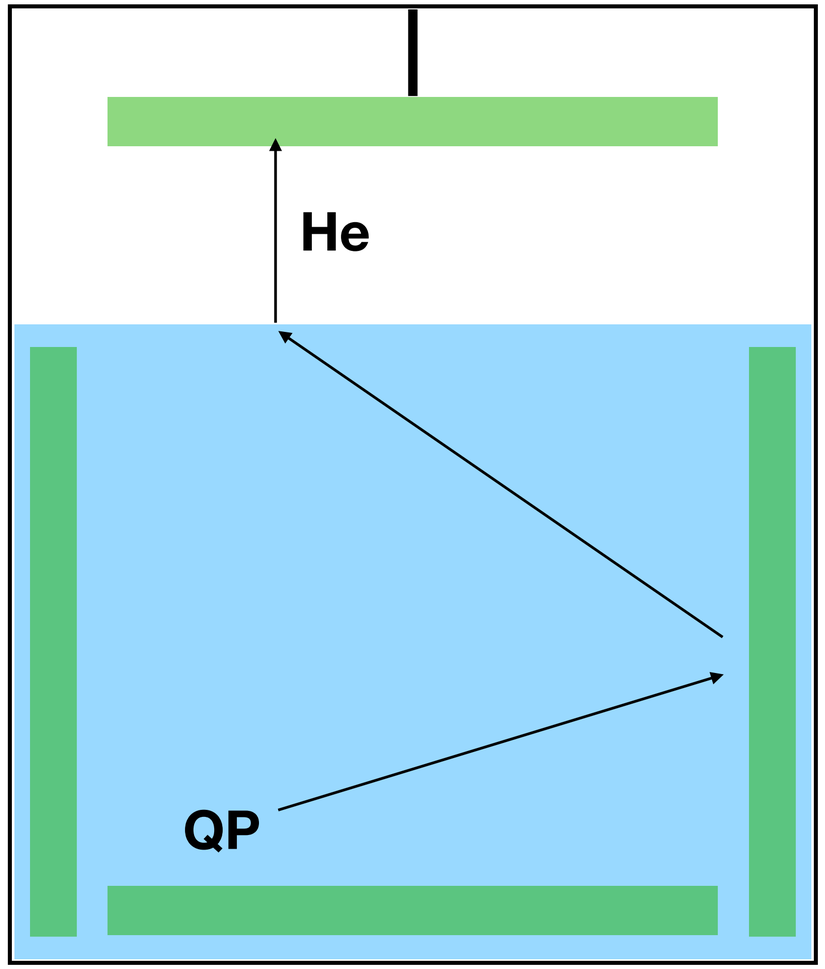




*Torii et. al., "Removal of superfluid helium films from surfaces below 0.1 K" (1992). Physics Faculty Publications and Presentations. 11.

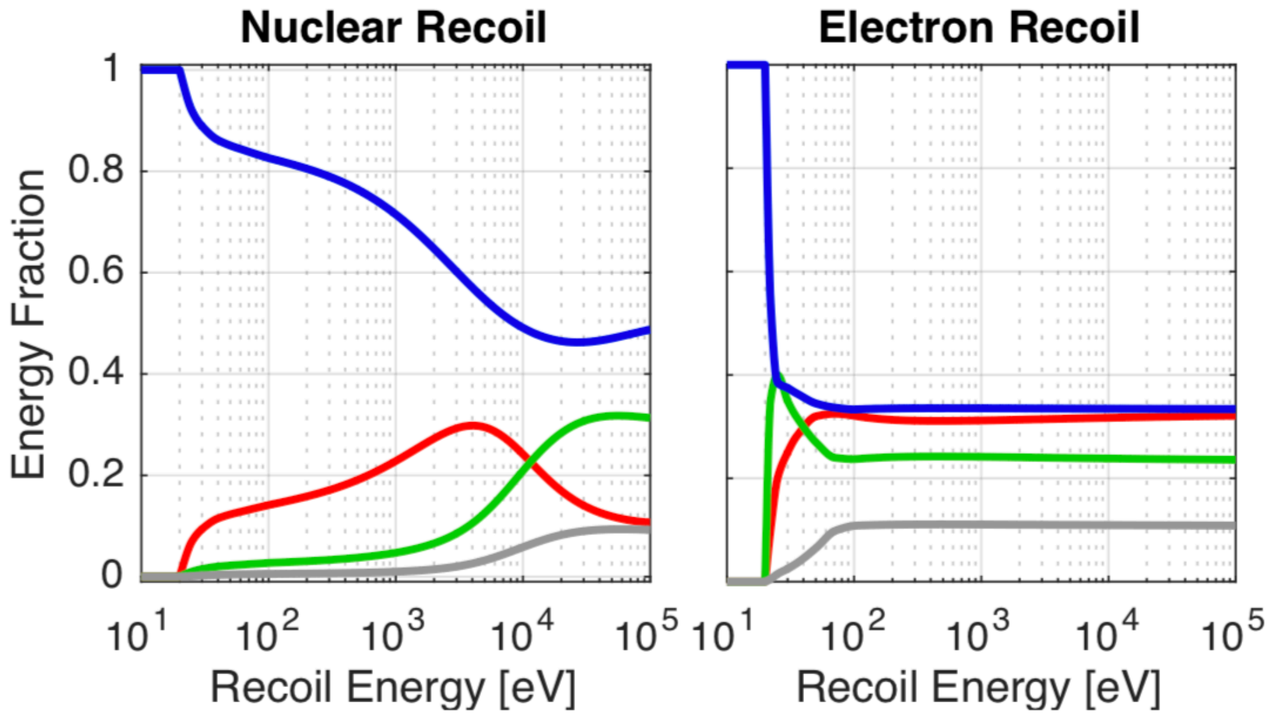
Detecting Vibrations: More Challenges

- Uncertainty in reflection efficiency
- Theory expects near perfect reflection, experiments say otherwise
  - The difference is likely due to surface roughness
  - Resonant transmission when (QP wavelength)~(surface roughness length scale)



Energy in Each Channel

- Recoil energy partitioned into the difference excitation populations
- Partitioning estimated from measured excitation/ionization cross sections
- Nuclear and electron recoils have different energy partitioning!
- Compared to other noble elements, lots of energy goes into atomic excitations



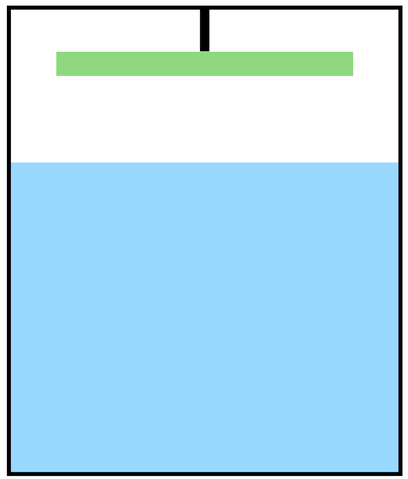
Blue = quasiparticle
Red = Singlet
Green = Triplet
Grey = IR photon

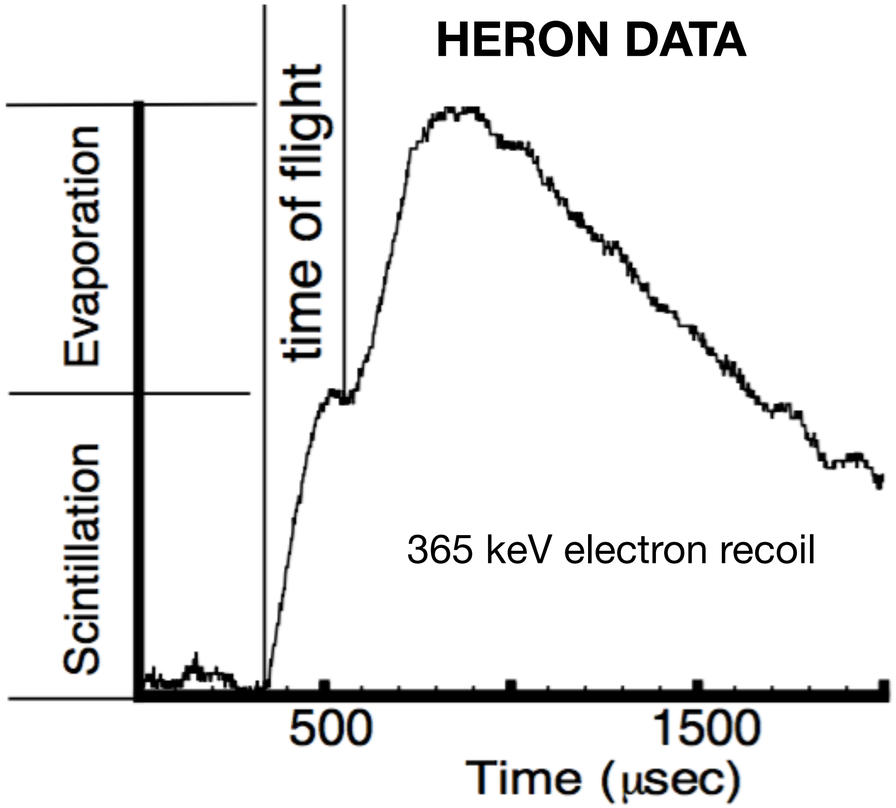
Distinguishing Quasiparticles and Excitations

- Use signal timing
  - Singlet signal expected to have O(10 ns) fall time, delta function in calorimeter
  - Triplets have O(10 m/s) velocity, observed as a delta function mostly in immersed calorimetry
  - Quasiparticles signal expected to have O(10-100 ms) fall time, mostly observed on surface calorimeter spread out

Example Waveform

- Based on HERON R&D
  - Can distinguish scintillation and evaporation based on timing



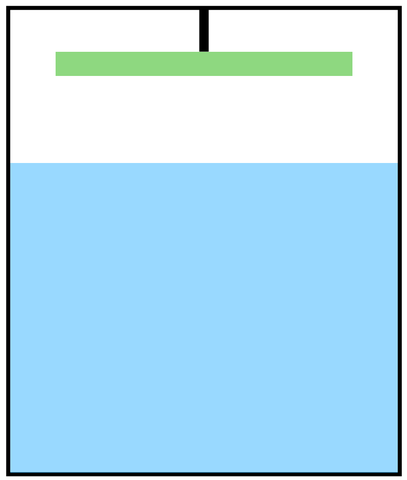


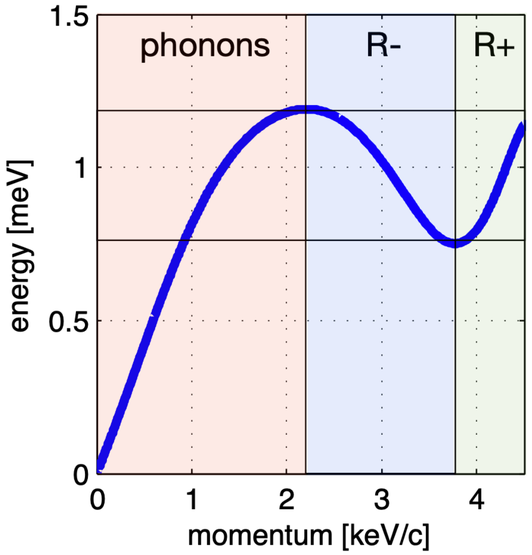
J. S. Adams et al. AIP Conference Proceedings 533, 112 (2000)

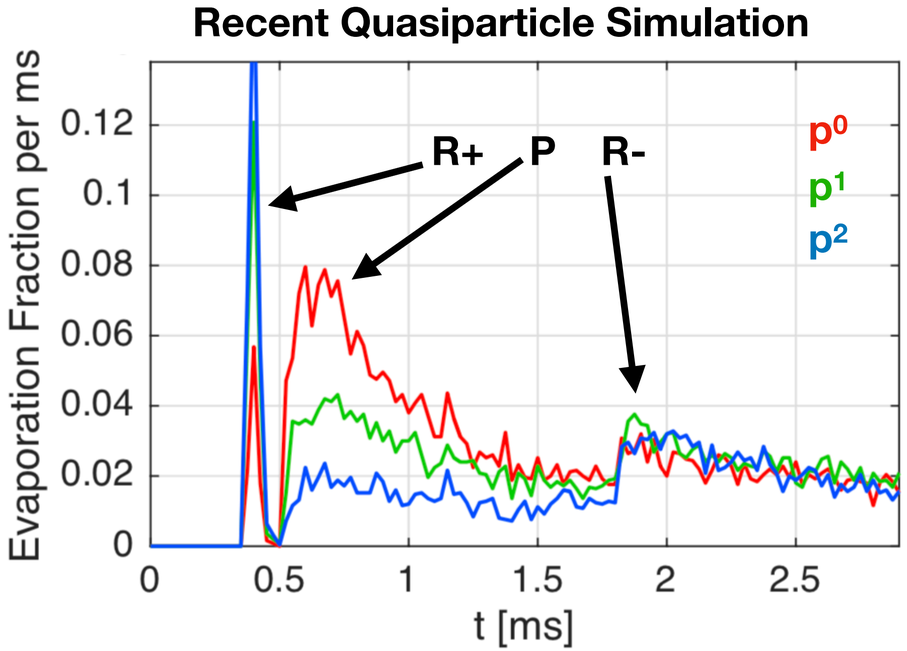
Annotations from Vetri Velan

Another Example Waveform

- Distinguish between different phonon distributions by arrival time in detector
  - R+ arrive first
  - P travel at a mix of slower speeds and arrive next
  - R- can’t evaporate directly, need reflection on bottom to convert into R+ or P







Some Uncertainties

- Uncertainty in how excitation quanta interact with surfaces:
  - Triplet excimers:
    - **Know:** decay at metal surface by exchanging electrons
    - **Don’t know:** interaction with silicon surface, vacuum surface, or wavelength shifter
  - Rotons:
    - **Don’t know:** interaction with solid surfaces

Alternate Detector Designs

- Alternate designs based on outcome of studies:
  - Calorimeters inside or outside chamber (avoid a QP sink)
  - Walls with or without wavelength shifter (convert triplet to an optical signal?)
  - Detector geometry: pancake or tall skinny (accentuate different phonon populations)
  - Wet sensors timed for fast atomic excitations or slower QP signals

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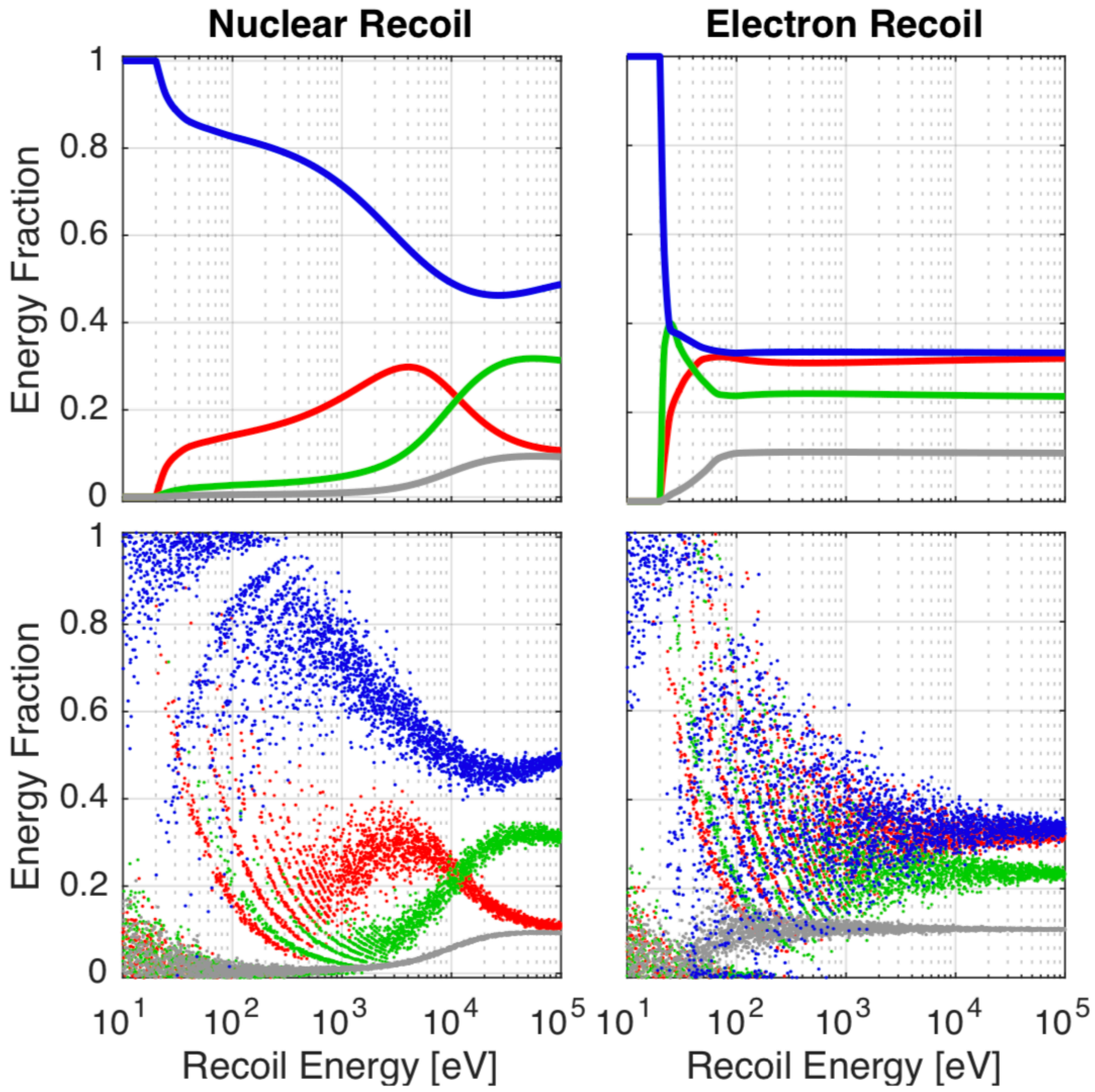
Detector Simulations

- Used a toy Monte Carlo to simulate detector
- Excitation quanta generated from energy partitioning with Poisson distribution
- Detector efficiencies modeled as a binomial distribution with efficiencies:
  - 95% for singlet and IR photons
  - 5/6 for triplet excitations (unsure of how triplets will interact with vacuum surface)
  - 5% for quasiparticle evaporation, assumes imperfect quasiparticle reflection
- Included 42.9 meV adhesion energy and 0.5 eV calorimeter noise

Detector Simulations Continued



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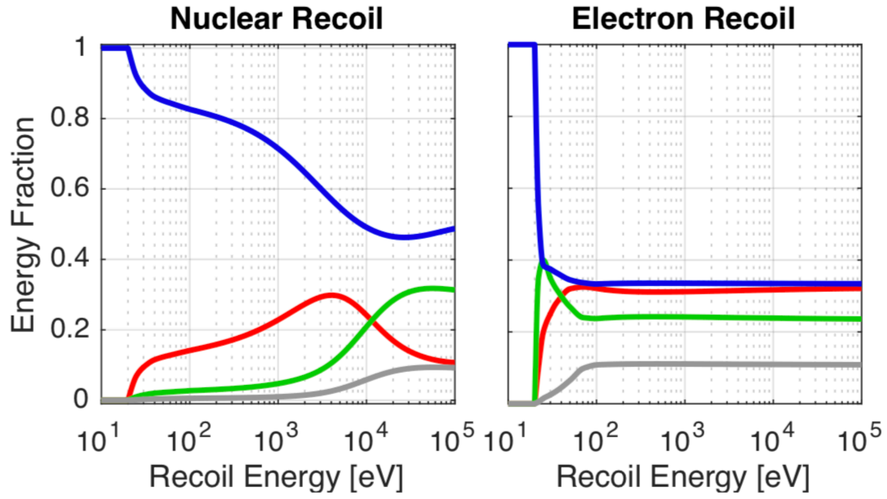
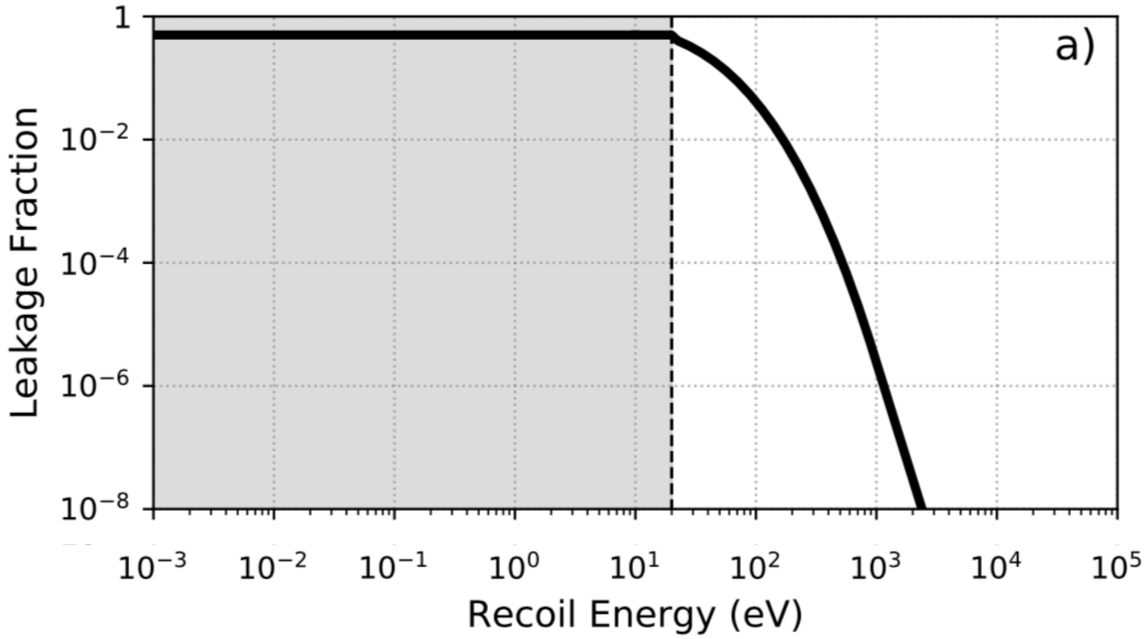
Electron Recoil Discrimination

- Nuclear and electron recoils have different amplitudes of each signal channel
  - Make electron recoil discrimination cuts
  - Powerful since such large portions of energy go to atomic excitations





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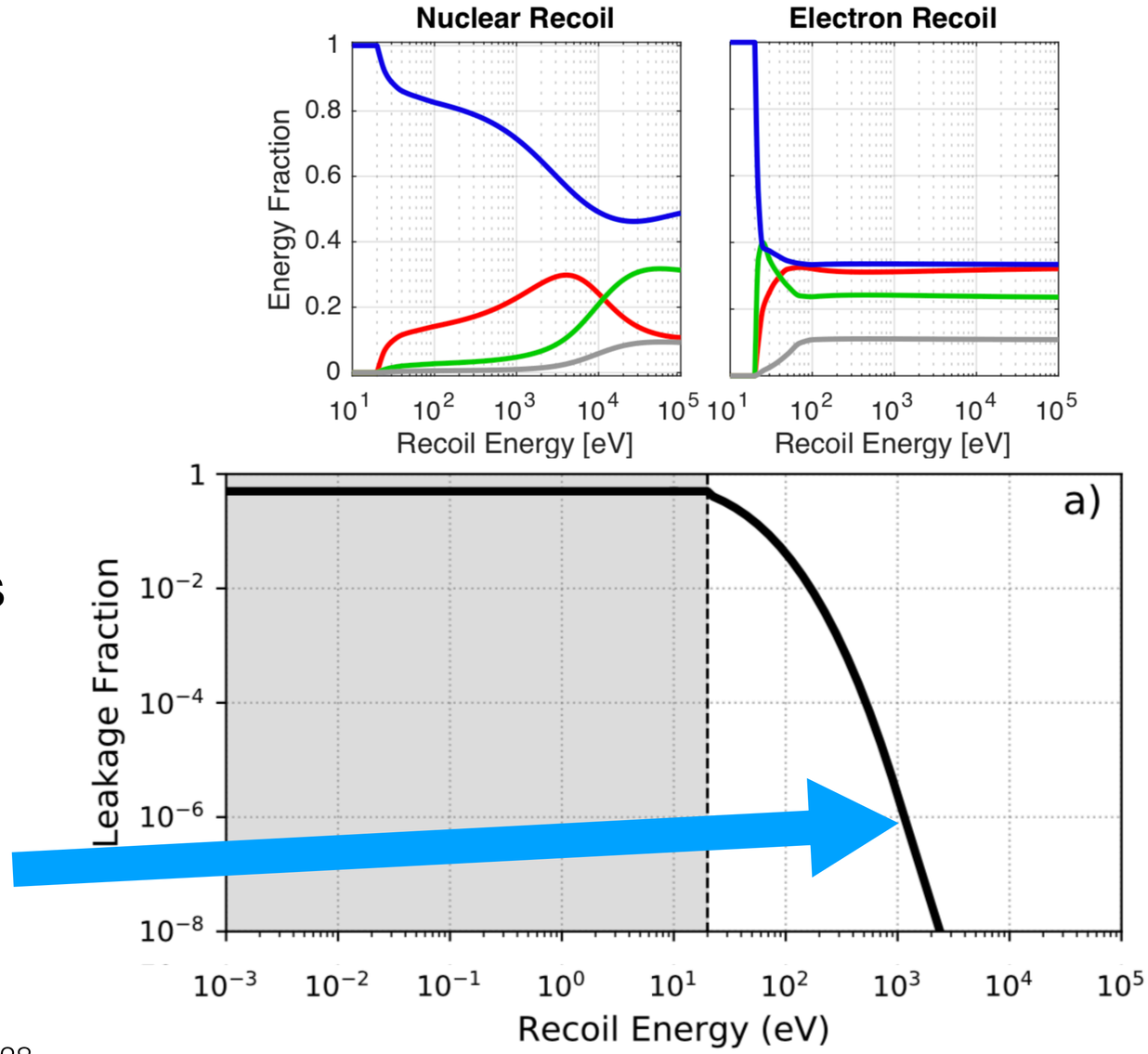
- For 1 keV recoil, O(10^{-6}) discrimination at 50% nuclear recoil acceptance



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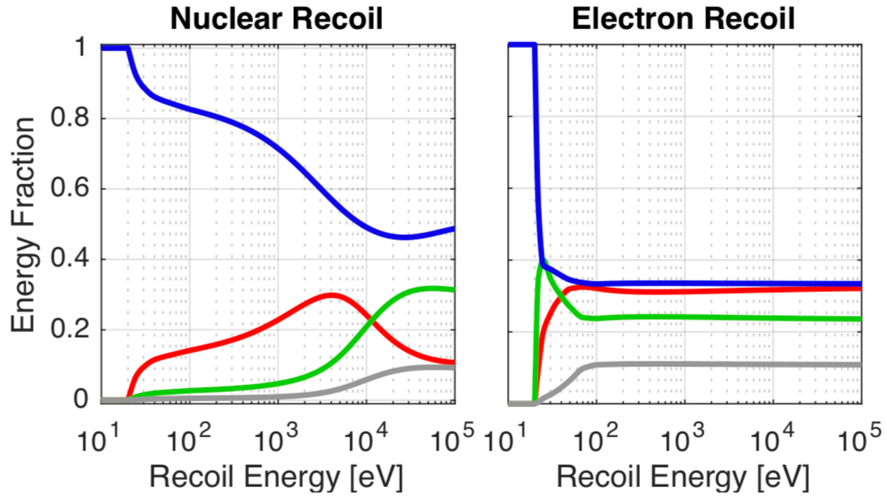
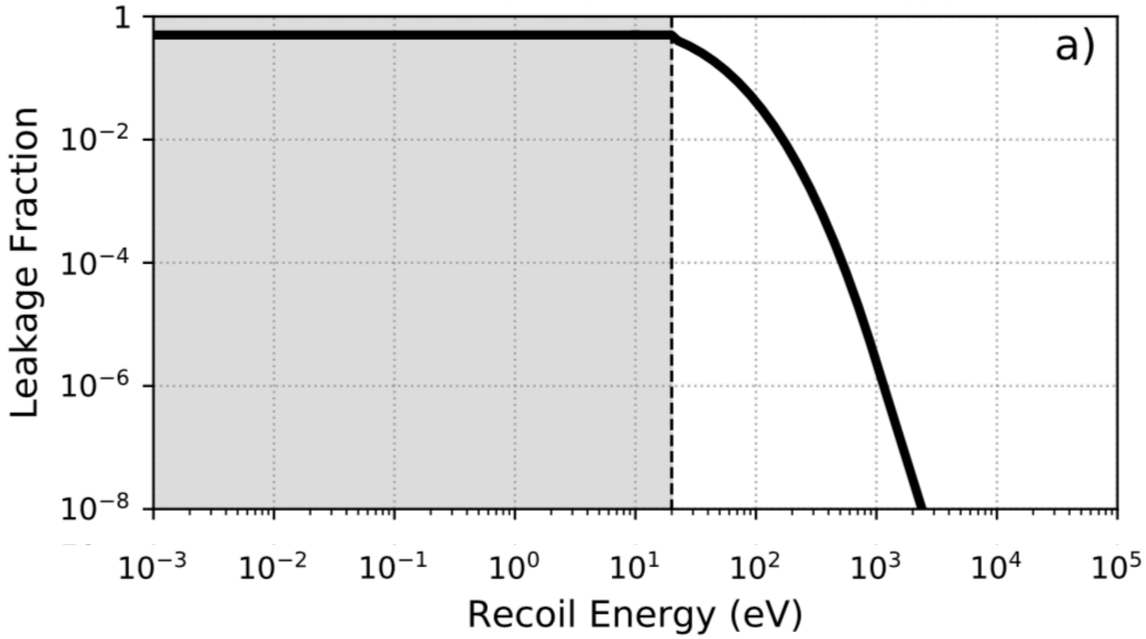
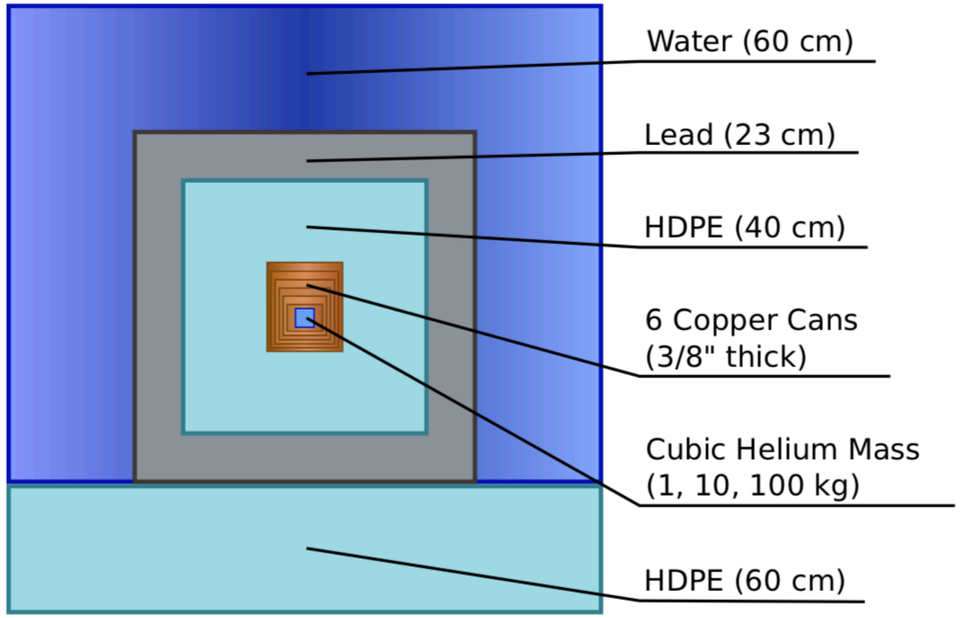
- **Active veto for recoils less than 20 eV**





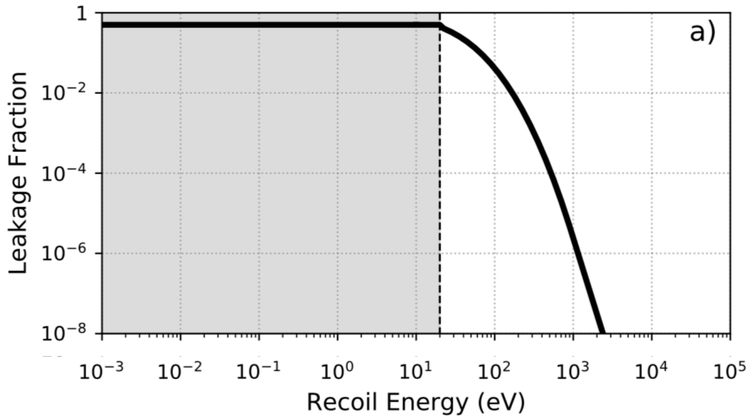
Background Simulations: Shielding

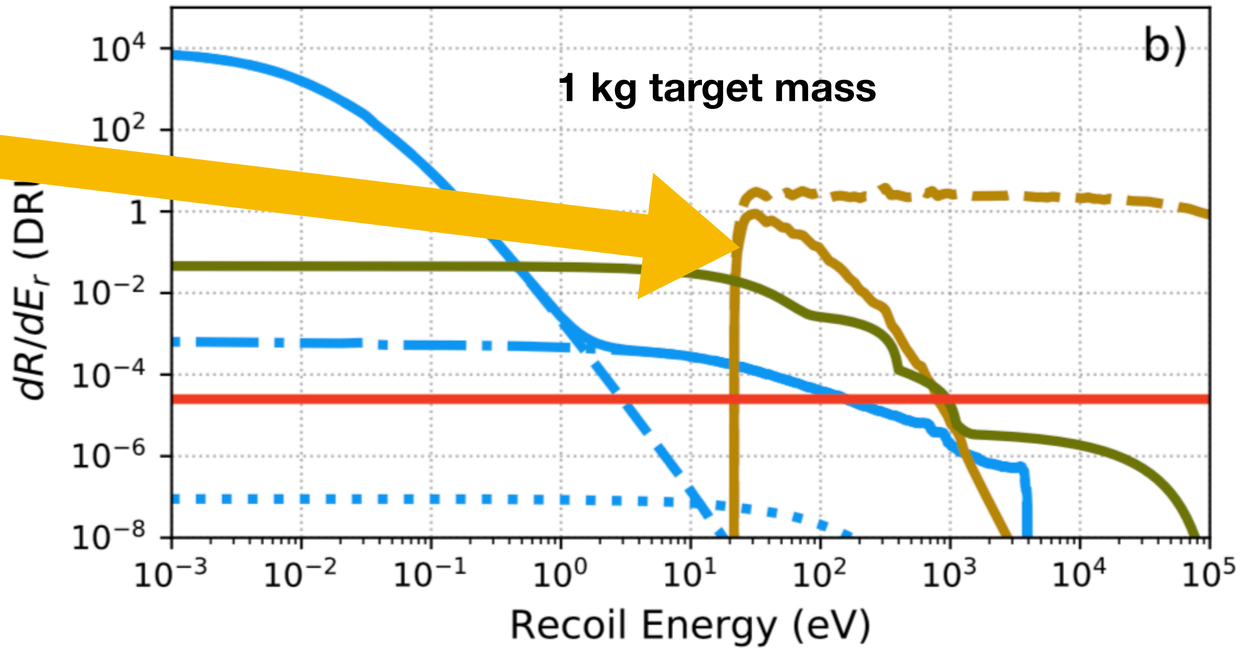
- Experimental shielding fairly standard
- Contamination was taken from SuperCDMS projections
- Assume underground



Background Simulations: Rates

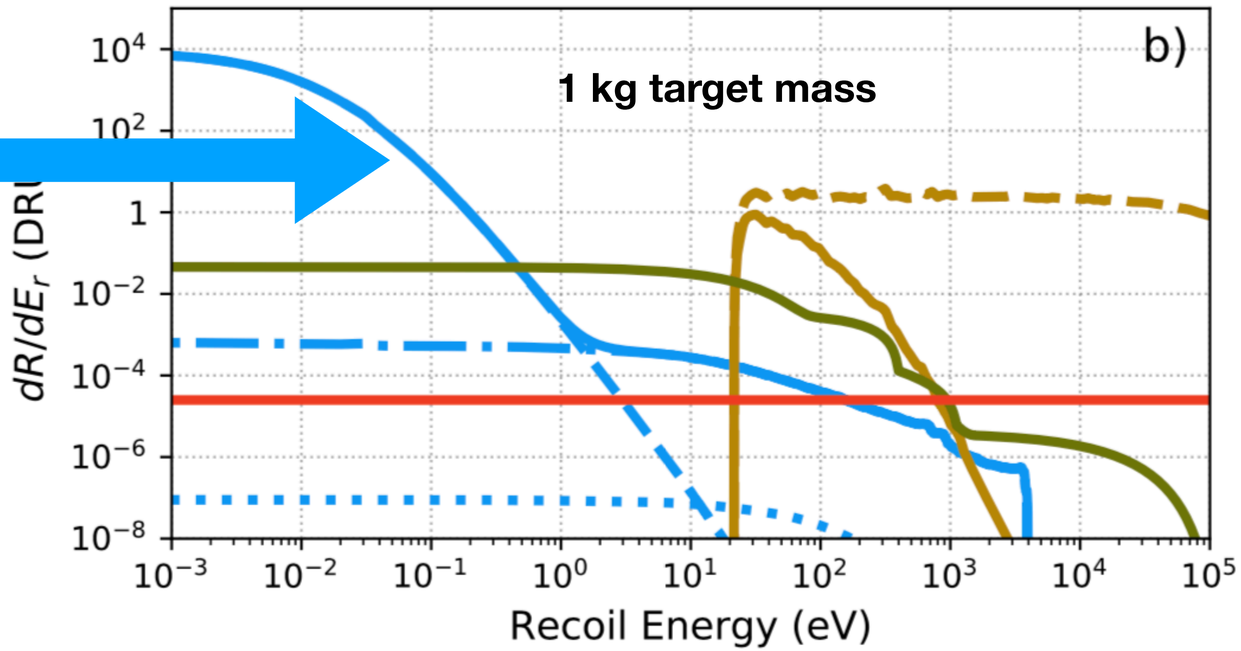
- Use GEANT4 simulation to find:
  - Electron recoil spectrum in detector (Compton scattering) (dashed yellow)
    - Multiplied by discrimination power (solid yellow)
  - Gamma energy spectrum entering detector





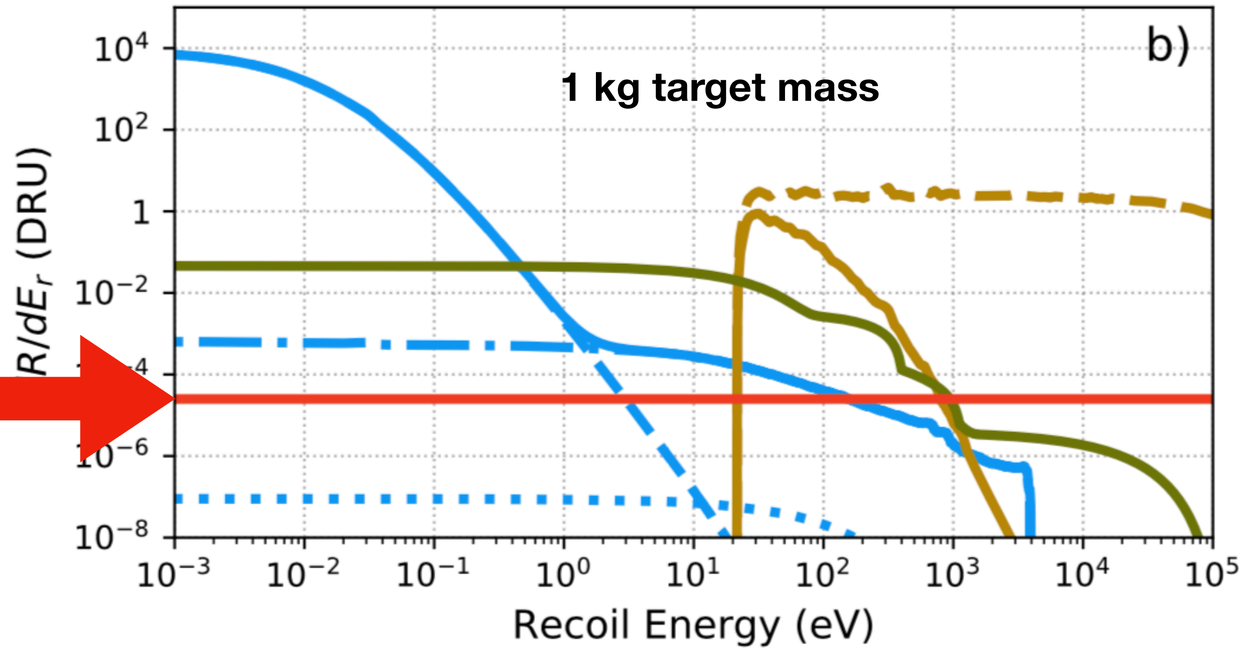
Background Simulations: Rates

- Used gamma energy spectrum to calculate coherent scattering rate (Blue) from:
  - Rayleigh Scattering (dashed)
  - Thompson Scattering (dot dashed)
  - Delbrück Scattering (dotted)



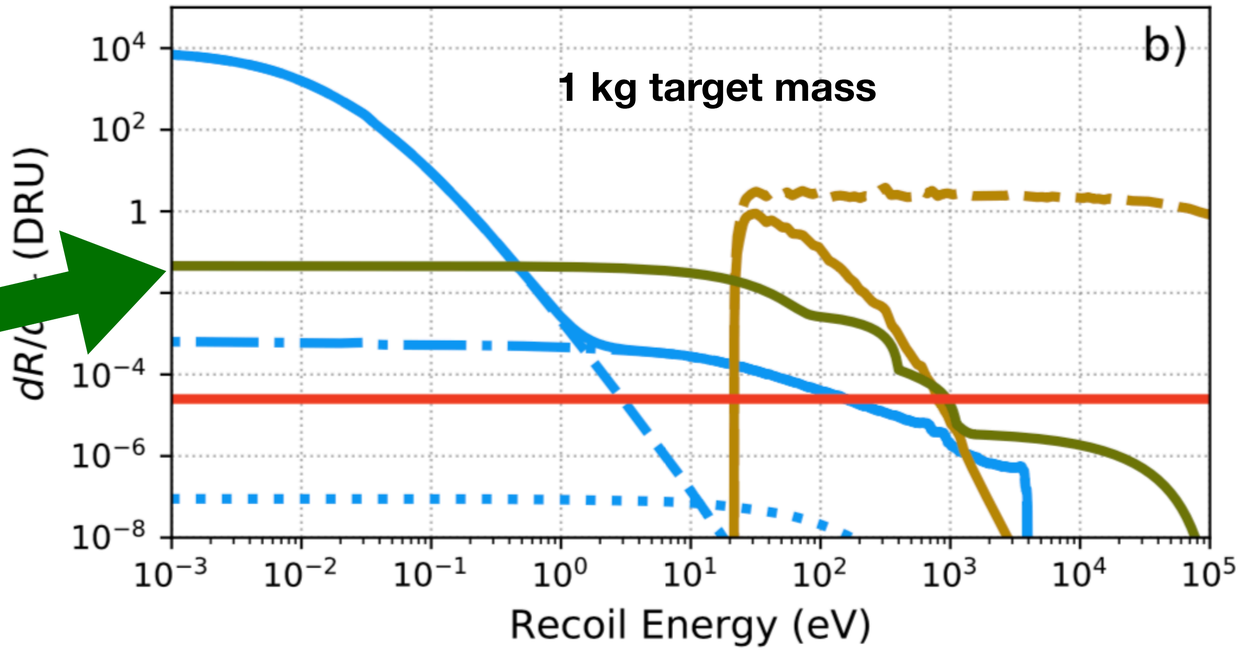
Background Simulations: Rates

- Assumed flat neutron spectrum (Red)
  - SuperCDMS prediction



Background Simulations: Rates

- Included coherent scattering from solar neutrinos (Green)



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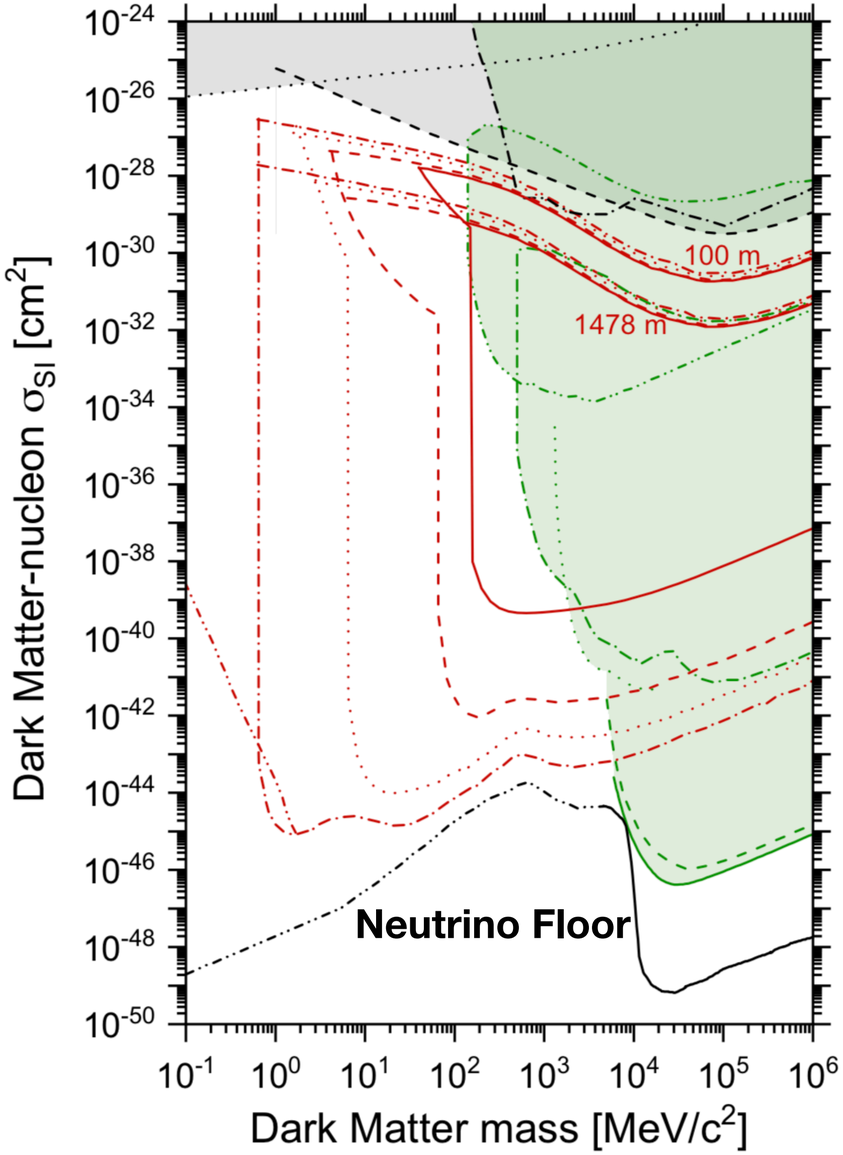
  - **Sensitivity**
  - Activities at UMass and Berkeley

Sensitivity Projections

- Used Profile Likelihood Ratio (PLR)
- Upper limits from earth scattering
- Solid red curve can be built with existing technology
  - 1 kg-day at 40 eV threshold

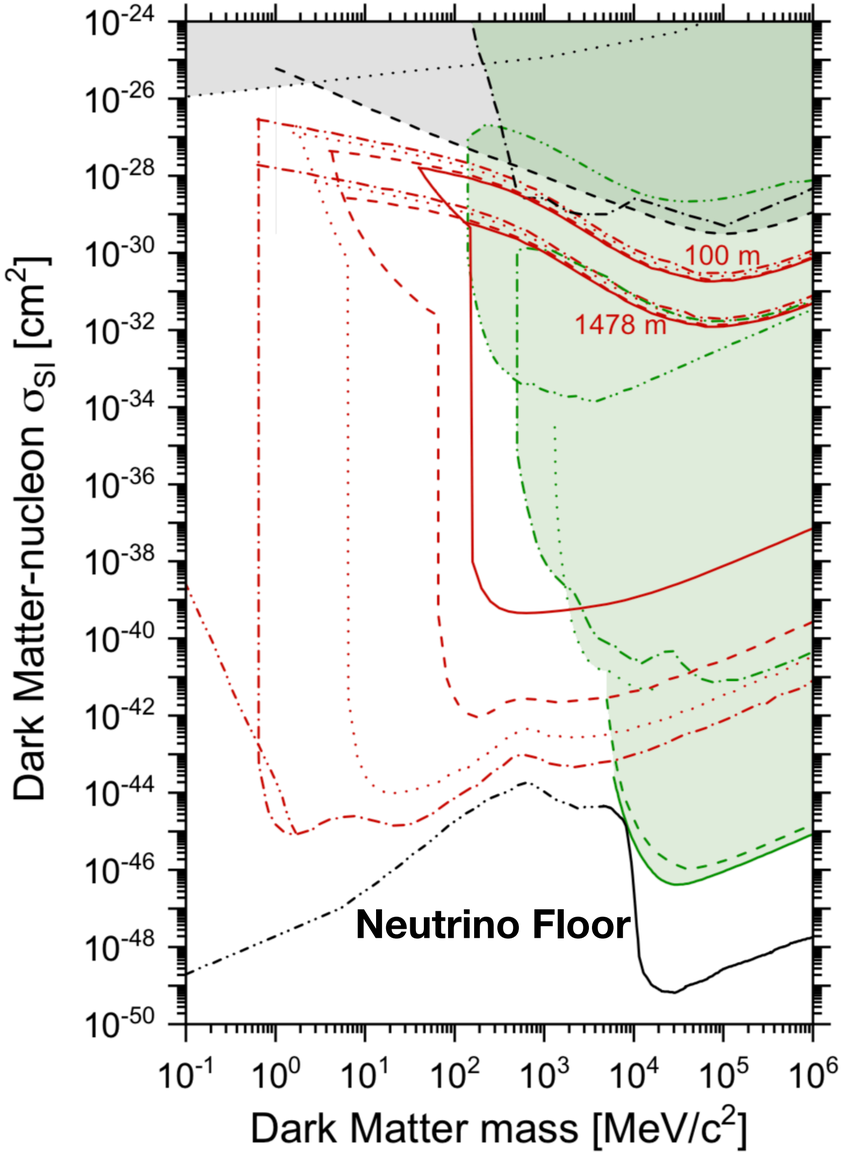


Threshold

- Where does 40 eV threshold come from?
  - 3.5 eV (sigma) resolution demonstrated by M. Pyle on large area calorimeter
  - 9x “adhesion gain” demonstrated by HERON R&D
  - 5% quasiparticle detection efficiency demonstrated by HERON R&D
- (3.5 eV)*(5 sigma)/(9x adhesion gain)/(0.05 QP detection) = 39 eV threshold

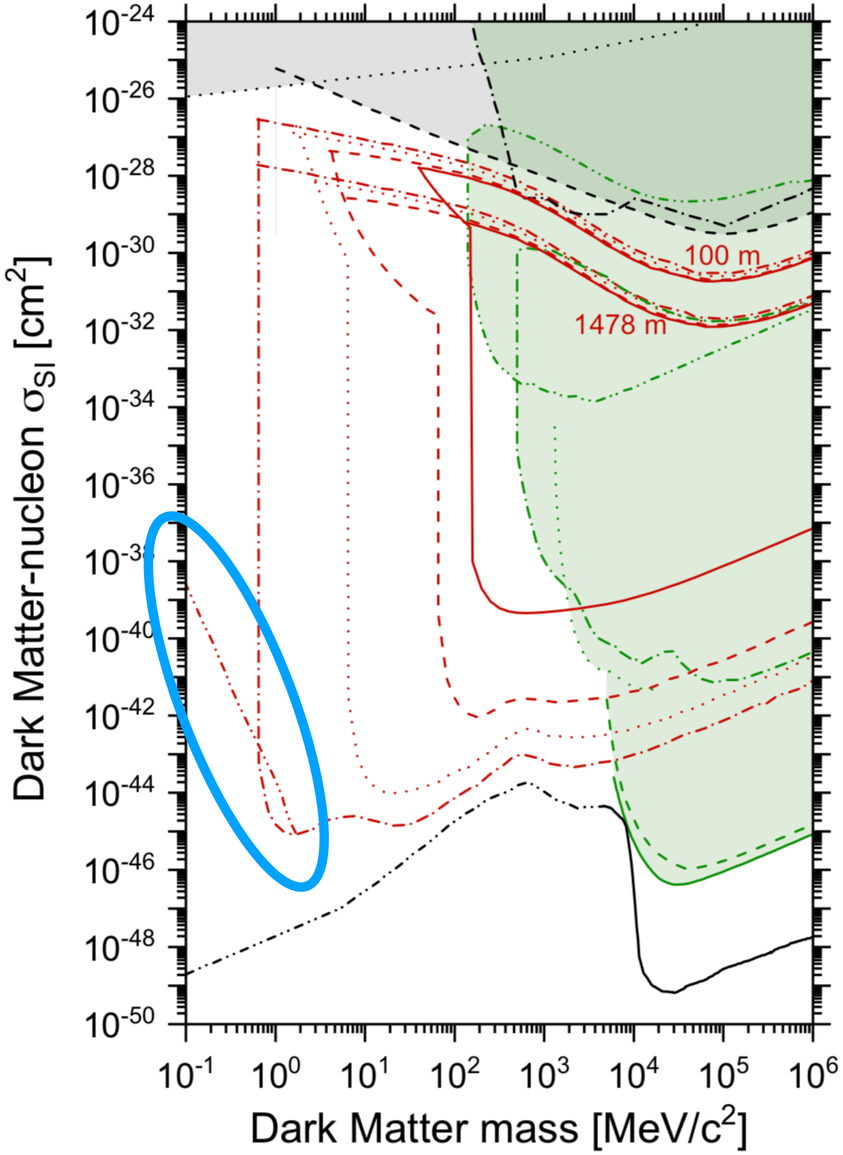
Sensitivity Projections Continued

Curve	Exposure	Threshold	
Solid Red	1 kg-day	40 eV	
Dashed Red	1 kg-yr	10 eV	
Dotted Red	10 kg-yr	0.1 eV	
Dashed-Dotted Red	100 kg-yr	1 meV	
Dashed-Dotted-Dotted Red	100 kg-yr	1 meV	**+ off shell phonon sensitivity**



Extending Sensitivity with Off Shell Interactions

- The 0.6 meV evaporation threshold limits nuclear recoil DM search to m_{DM} >~ 1 MeV
- Can be avoided if we find an excitation with an effective mass closer to the DM mass, allow DM to deposit more energy in the detector
  - In helium this could be recoiling off the bulk fluid and creating off shell quasiparticles



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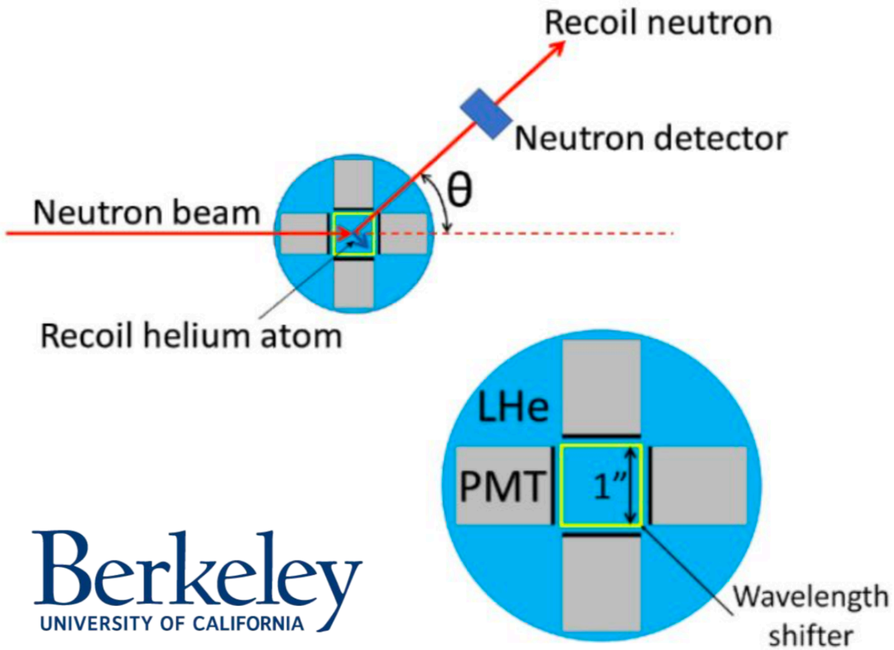
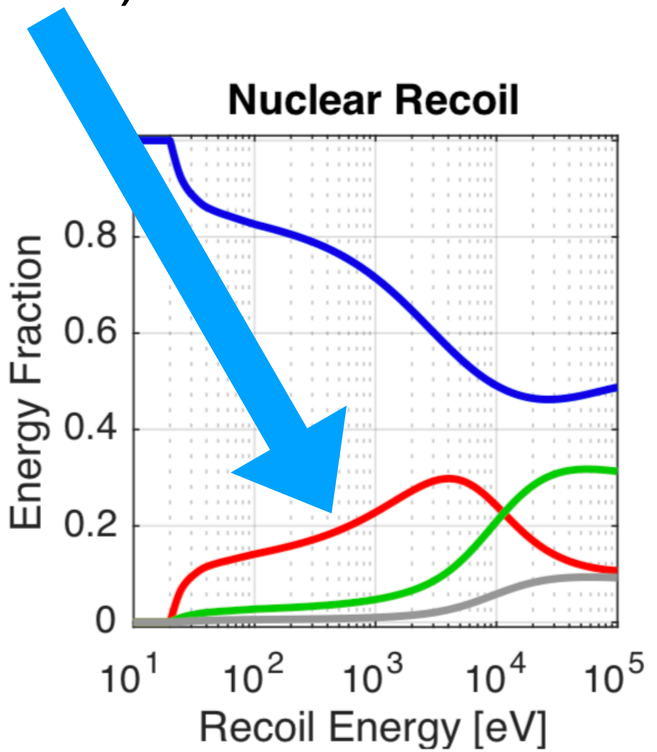
Activities at Berkeley

- Measuring the light yield for nuclear recoils in 4He (red curve)
- Neutron scattering experiment

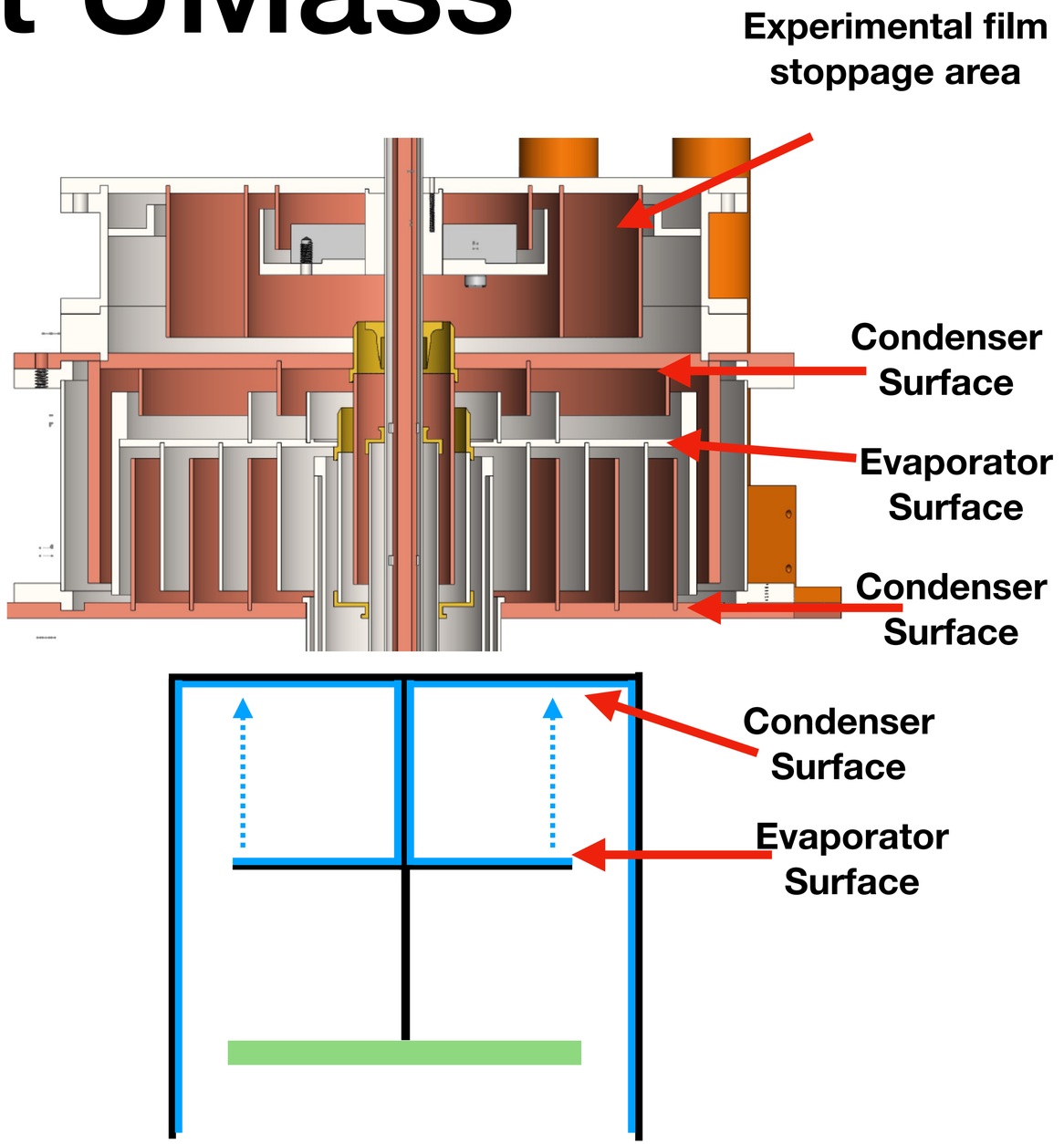




From V. Velan

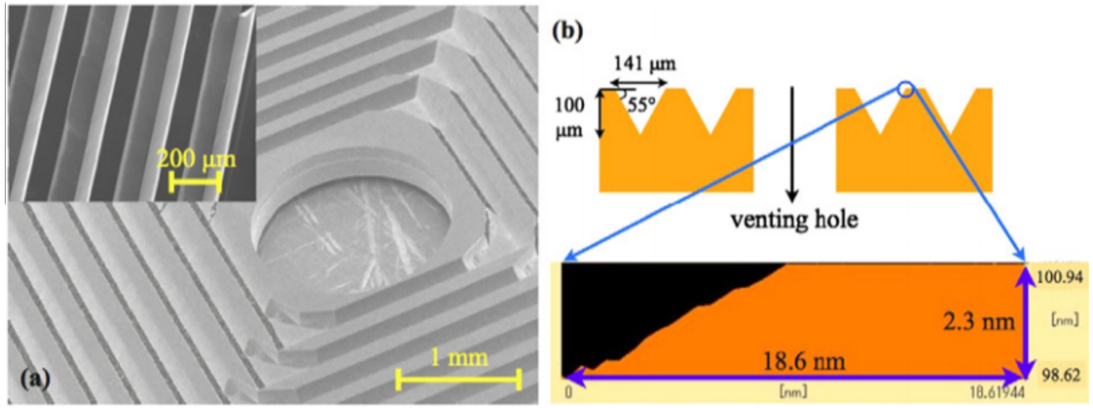
Activities at UMass

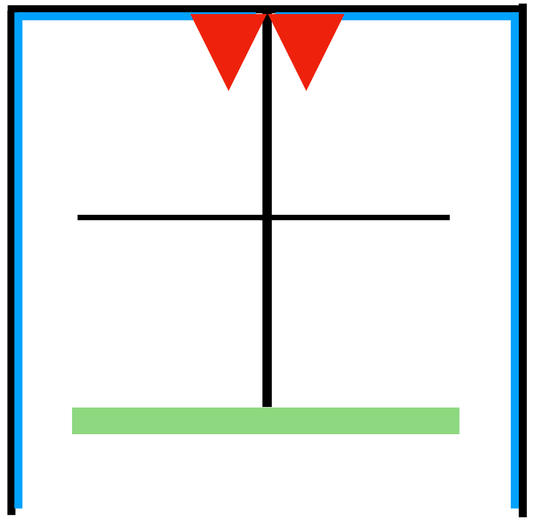
- Purchased a dilution refrigerator to conduct R&D
- First task: keep the surface calorimeter dry
  - Adhesion gain (read as: sensitivity)
  - Adapting the HERON film burner design
    - Problem: heat load, makes calorimeters less sensitive



More Activities at UMass

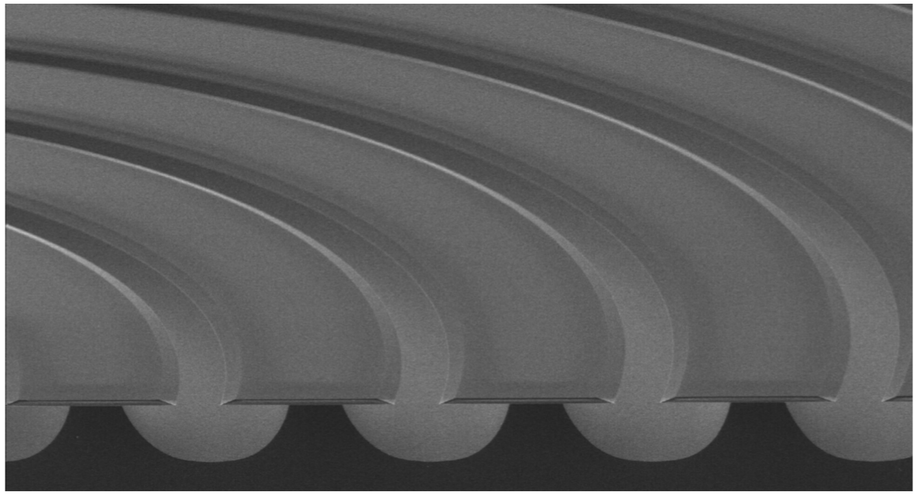
- Want a low (or no) heat load film suppressor
- Idea: unwettable surface? Cs, Rb
  - Demonstrated. Resistor-like evaporation sources for Cs are commercially available
  - Practicalities would be difficult
- Idea: knife edge device (a la XRS)
  - film thins as it passes over a sharp corner (surface tension vs Van Der Waals)
  - Try and thin the film enough that it becomes a normal fluid





More knife edge details

- XRS and others have achieved ~10nm scale radius of curvature by etching silicon planes (Cryogenics 50 (2010) 507–511)
- Since we are operating much colder, thinner films can be superfluid, may need even sharper edges, nm scale
  - Graphene overhang?



SiO2 overhangs, Chen Thesis: https://thesis.library.caltech.edu/7470/

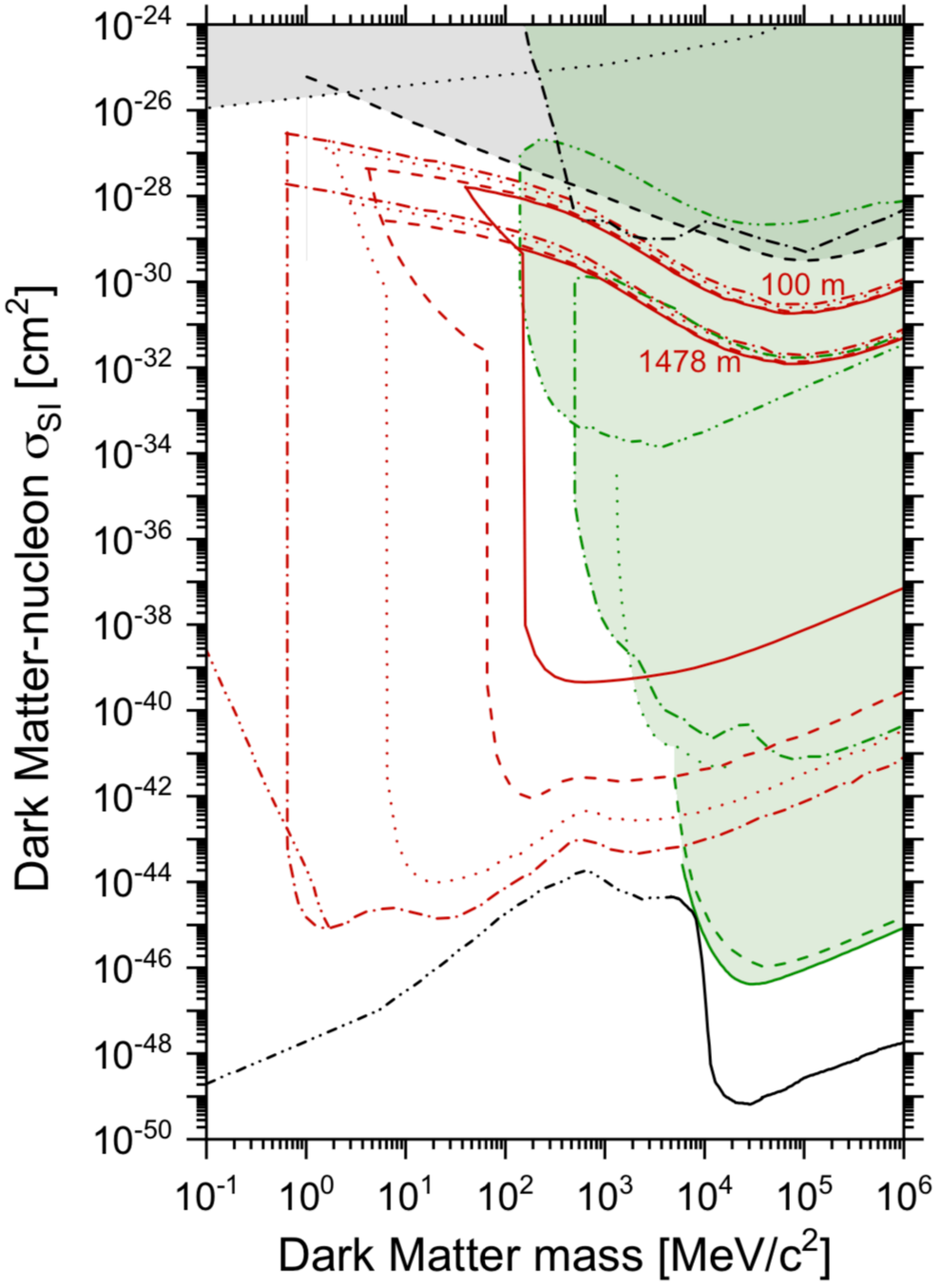
Summary

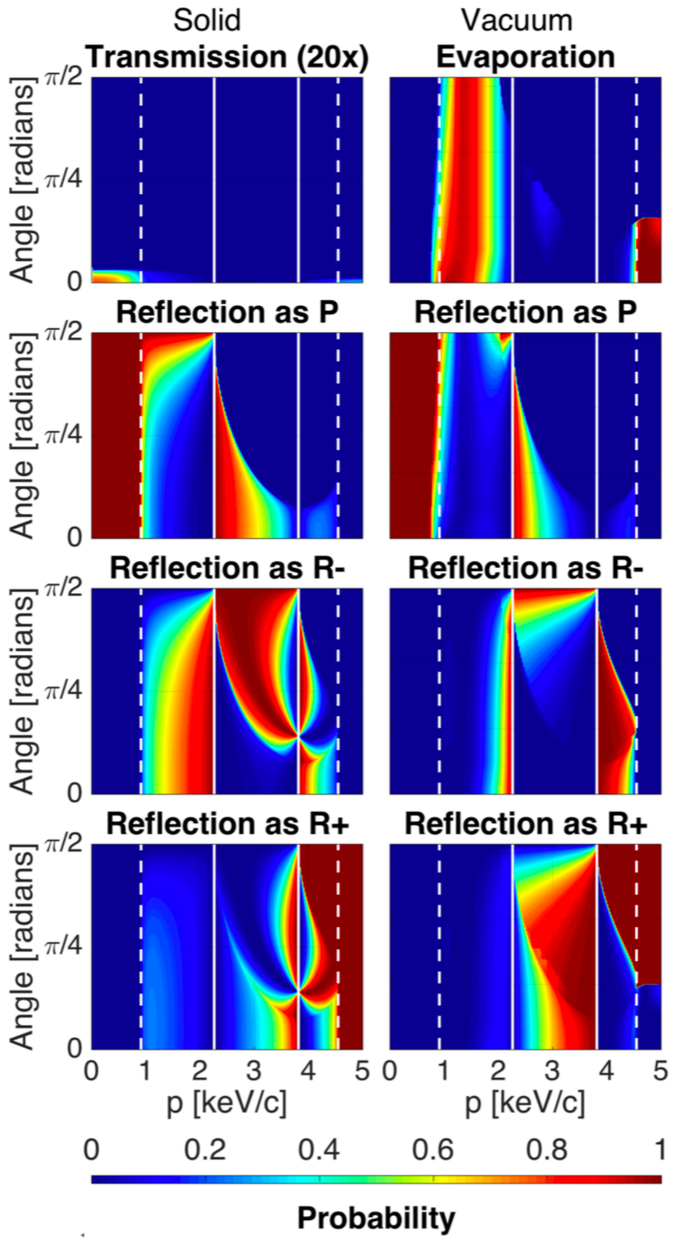
- HeRALD proposes to search for “light” (sub-GeV) dark matter candidates using a superfluid helium target mass
- A design based on existing technology could test new parameter space

Questions/Discussion

Backups

FIG. 9. Projected sensitivity of the helium detector to DM-nucleon SI interaction with 90% confidence level, through detection of elastic scattering and Bremsstrahlung emission [103]. Four combinations of exposure and energy threshold have been investigated: 1 kg-day with 40 eV(solid red), 1 kg-yr with 10 eV (dashed red), 10 kg-yr with 0.1 eV (dotted red), and 100 kg-yr with 1 meV (dashed dotted red). The label 100 m and 1478 m refers to the experiment site depth, related to the limit curves due to the earth shielding effect discussed in the main text. The dashed dotted dotted red curve corresponds to limit taking off-shell phonon sensitivity into account, assuming a massive mediator with 100 kg-yr exposure and 1 meV energy threshold, extrapolated from Knapen *et al.* [18]. The dashed dotted dotted black curve corresponds to the neutrino floor calculated for helium, as discussed in the main text. Some other limits are also plotted for comparison: the neutrino floor for xenon (solid black) [87], cosmic Microwave Background anisotropy (dotted black) [90, 91], galaxy gas cooling (dashed black) [98], XQC experiment (dashed dotted black) [96], CRESST surface (dashed dotted dotted green) [97], CRESST-II (dashed dotted green) [93], CDMS-Lite (dotted green) [92], XENON-1T (solid green) [95], and LUX (dashed green) [94]. The earth shielding limits for CRESST surface and CRESST-II are also shown [99]. The green and grey shaded region correspond to parameter space that has been excluded by direct detection experiments and astronomy, respectively.




Solid
Vacuum
Transmission (20x)
Evaporation
Reflection as P
Reflection as P
Reflection as R-
Reflection as R-
Reflection as R+
Reflection as R+
Angle [radians]
π/2
π/4
0
0 1 2 3 4 5
p [keV/c]
0 0.2 0.4 0.6 0.8 1
Probability

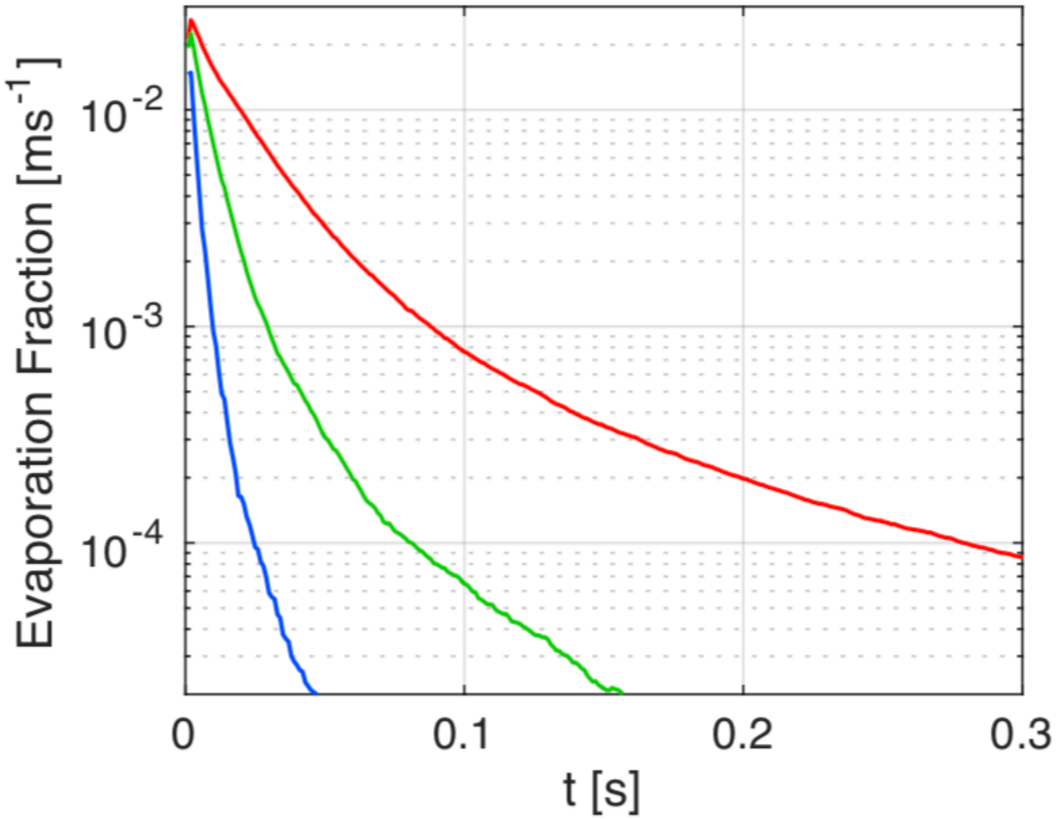


FIG. 5. Simulated pulses from a helium evaporation channel, showing the pulse decay timescales given several distinct quasiparticle loss probabilities per interaction with solid surface (blue: 0.7, green: 0.1, red: 0.01). The pulse cannot be described using a single exponential falltime; the exponential time constant increases at late times in each case due to the survival of slow-moving excitations.

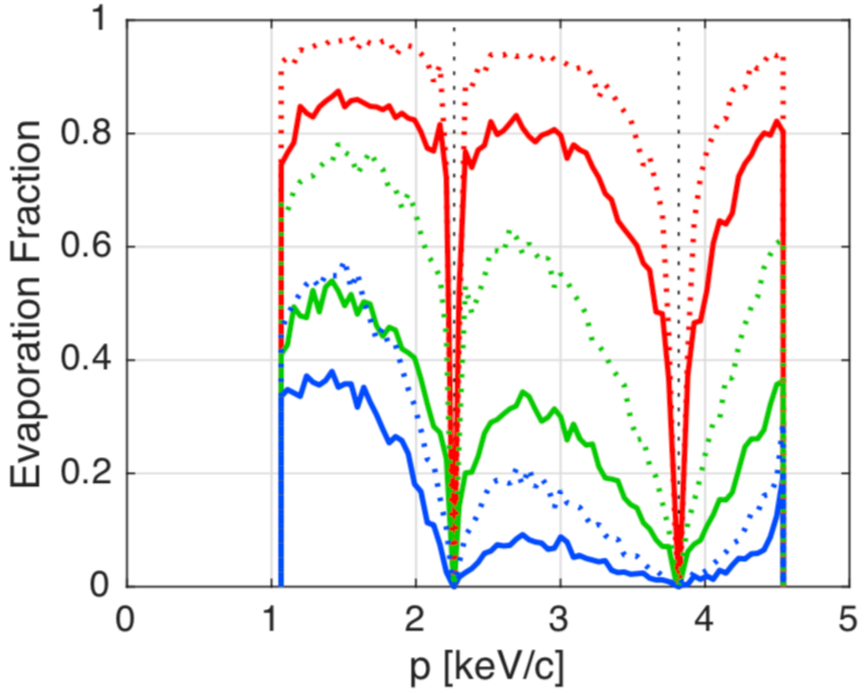
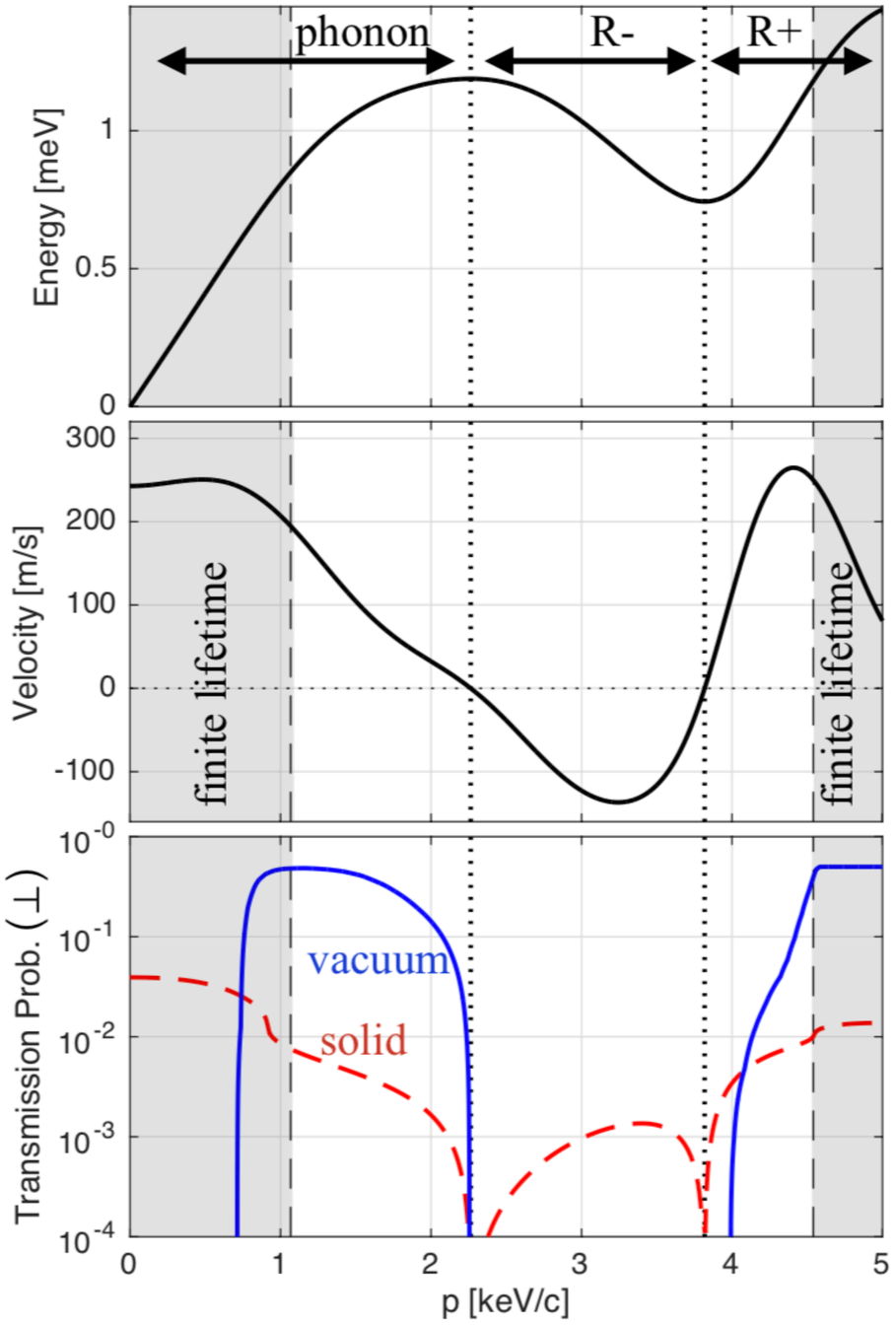
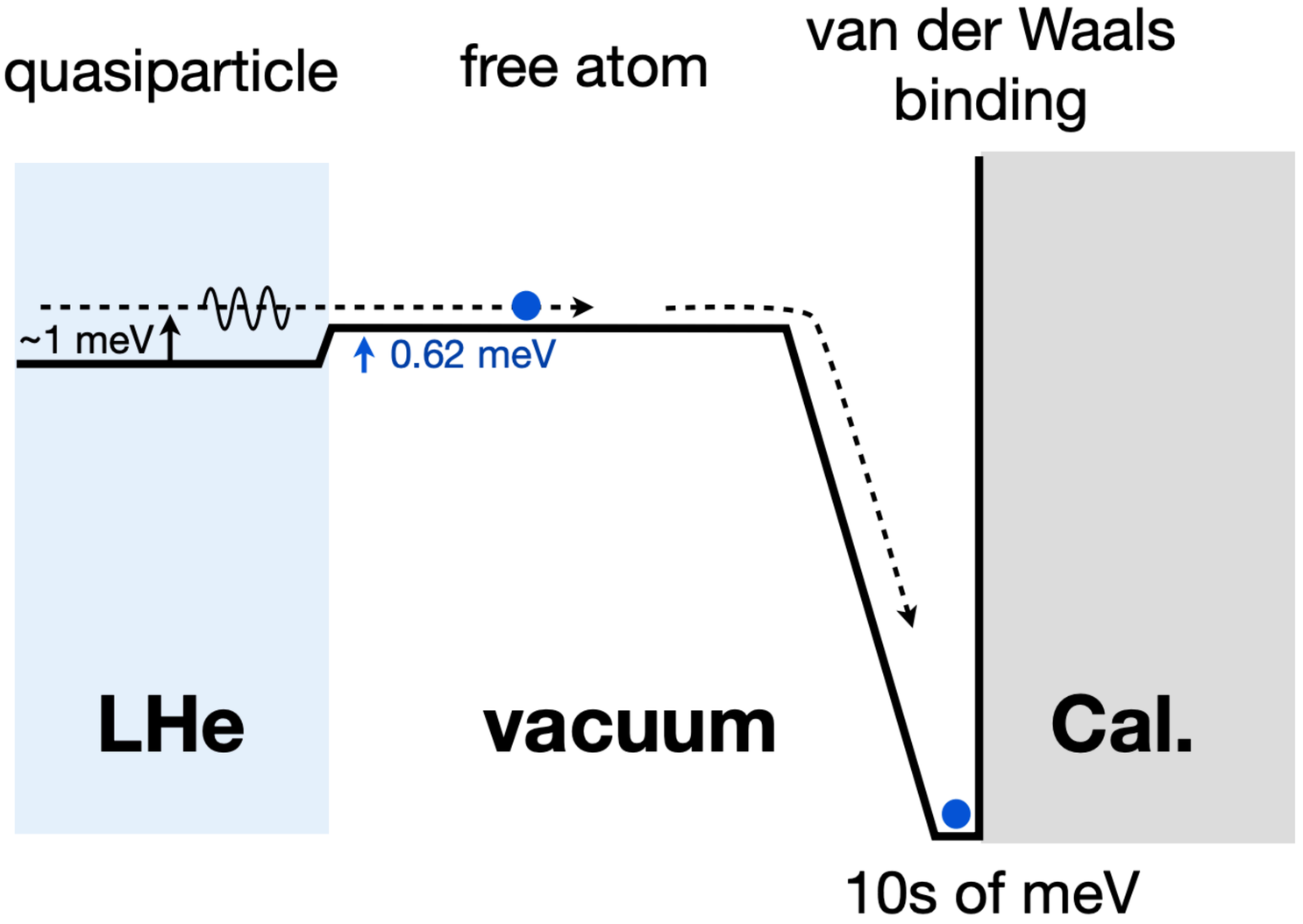


FIG. 6. Probabilities for eventual evaporation after many reflections (including times up to one second after recoil), as a function of initial quasiparticle momentum. As in Figure 5, color represents different probabilities of loss per solid surface interaction (blue: 0.7, green: 0.1, red: 0.01). It can be seen that the loss probability has a strong effect on eventual evaporation probability, given the many expected reflections. The geometry of the simulated liquid volume is also varied: Solid lines are for a cylindrical volume of equal height and diameter (20 cm), while dashed lines are for a 'pancake' geometry in which the depth is much less than the diameter (20 cm depth, infinite diameter). It can be seen that a pancake geometry enhances the evaporation probability by boosting the fraction of boundary interactions occurring on the vacuum interface.

FIG. 3. Several fundamental characteristics of superfluid ^{4}He quasiparticles are here illustrated. TOP: the dispersion relation. MIDDLE: the group velocity. BOTTOM: transmission probabilities at normal incidence in two cases, incident on a ^{4}He-solid interface with solid phonon outgoing state (red dashed) and incident on a ^{4}He-vacuum interface with outgoing state a ^{4}He atom (blue solid). At both high and low momentum quasiparticles are of finite lifetime, and unlikely to reach an interface before decay.



From Scott Hertel