HeRALD: Direct Detection with Superfluid 4He

Doug Pinckney on behalf of the HeRALD collaboration

1 August 2019

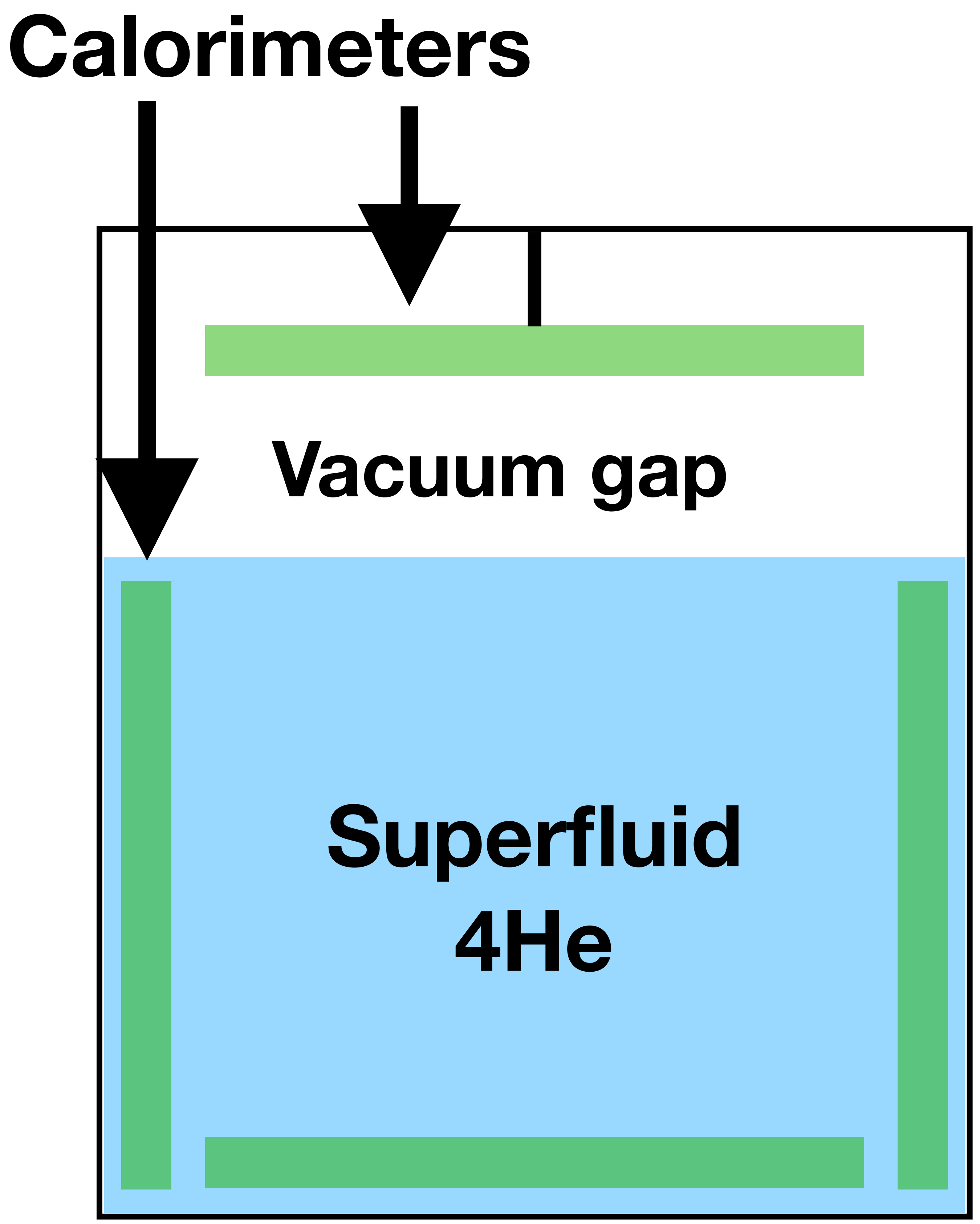
arXiv:1810.06283v1

UMass Amherst

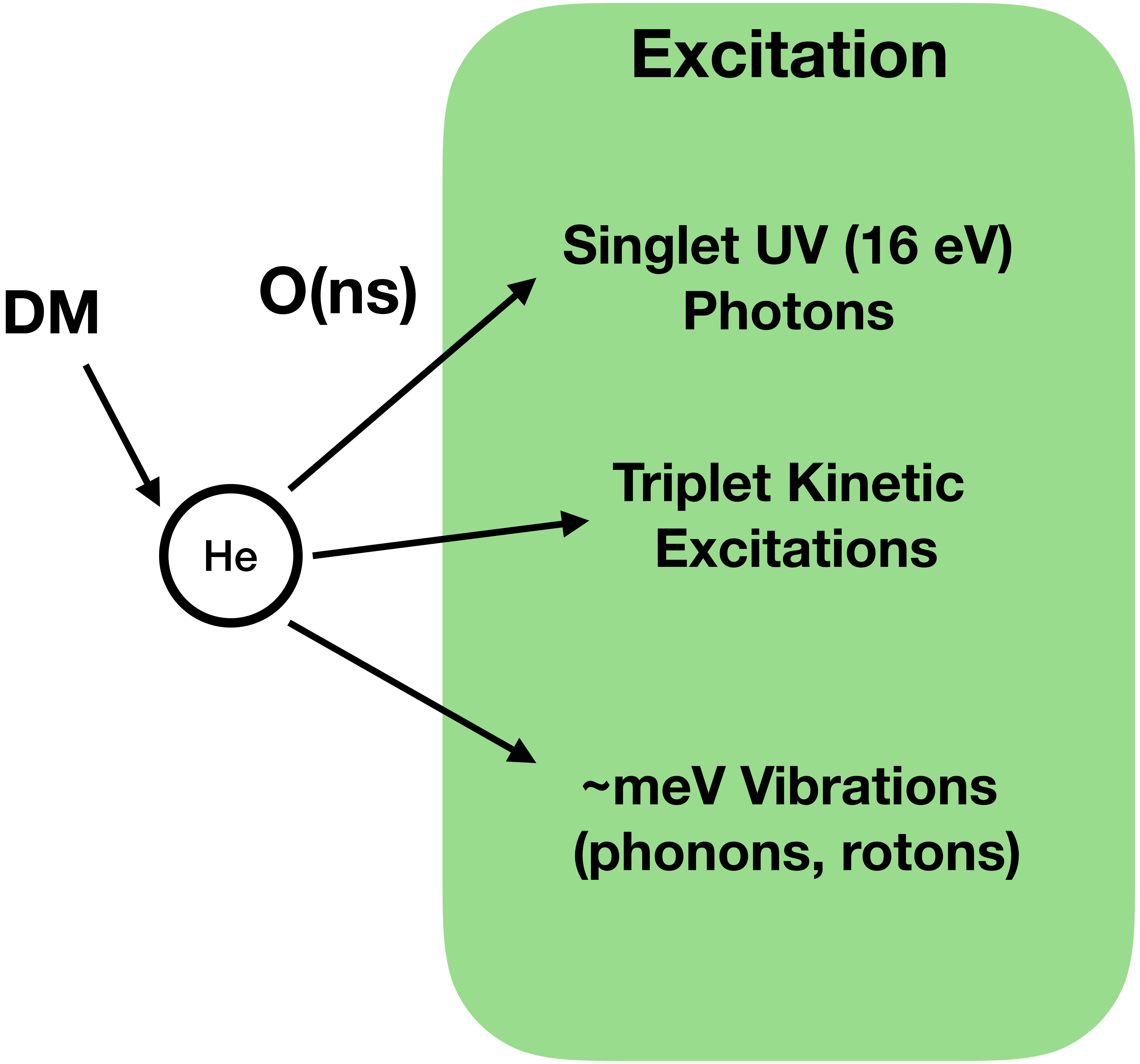
Berkeley
UNIVERSITY OF CALIFORNIA

HeRALD: Helium Roton Apparatus for Light Dark matter

- Superfluid 4He as a target material
  - Favorable recoil kinematics
  - Recoil energy can be fully reconstructed with TES calorimetry
  - Zero bulk radiogenic backgrounds
  - No Compton backgrounds below 20 eV
- HERON experiment at Brown (Seidel, Maris), proof of concept work



Excitations in Superfluid 4He



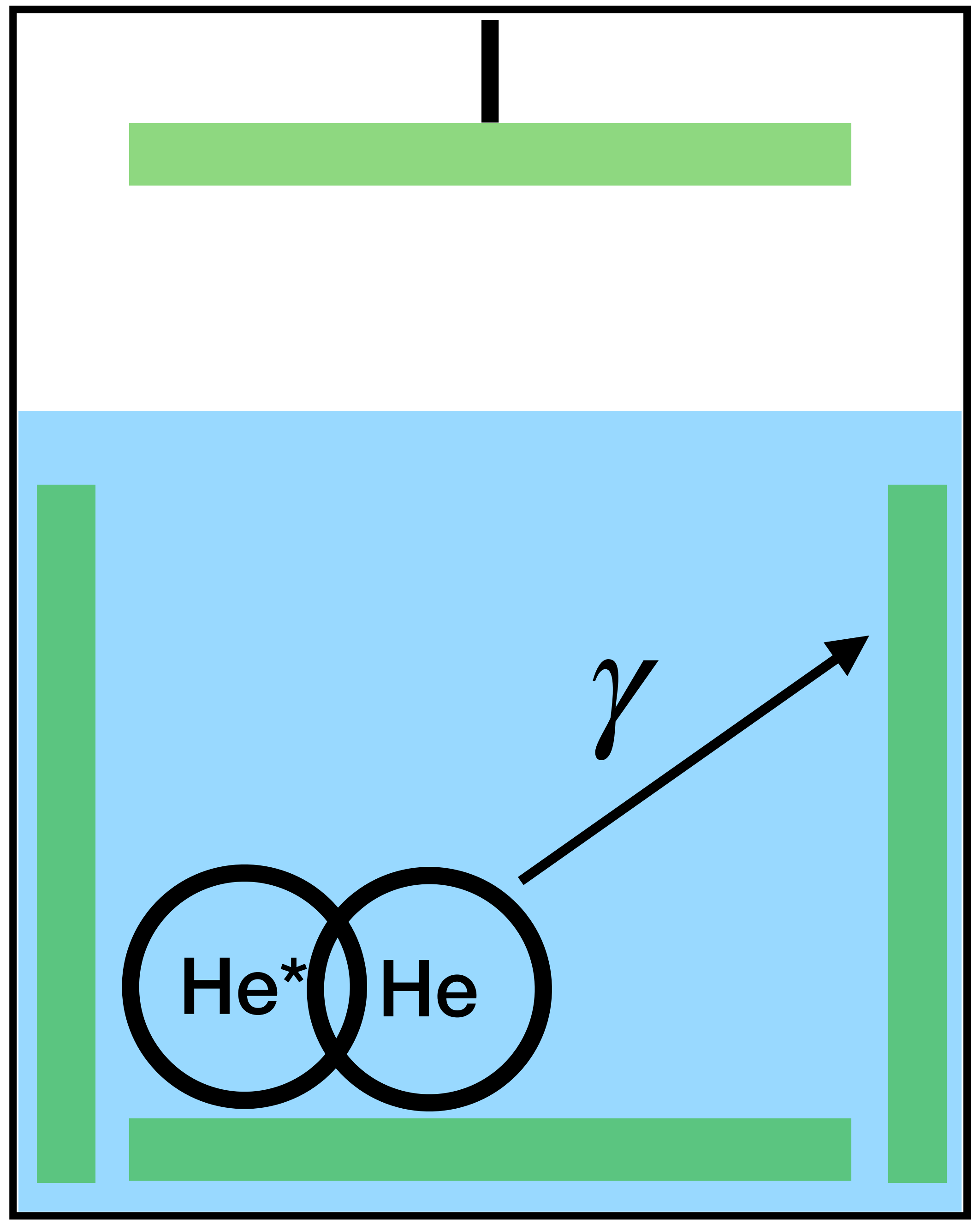
Excitations in Superfluid 4He

DM

O(ns)

He

Excitation	Detection Method
Singlet UV (16 eV) Photons	**Absorbed in calorimeters on 10 ns timescale**
Triplet Kinetic Excitations	
~meV Vibrations (phonons, rotons)	



Excitations in Superfluid 4He

DM → He

O(ns)

Excitation	Detection Method
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Triplet Kinetic Excitations →	Ballistic, travel at O(1 m/s), deposit energy in immersed calorimeters
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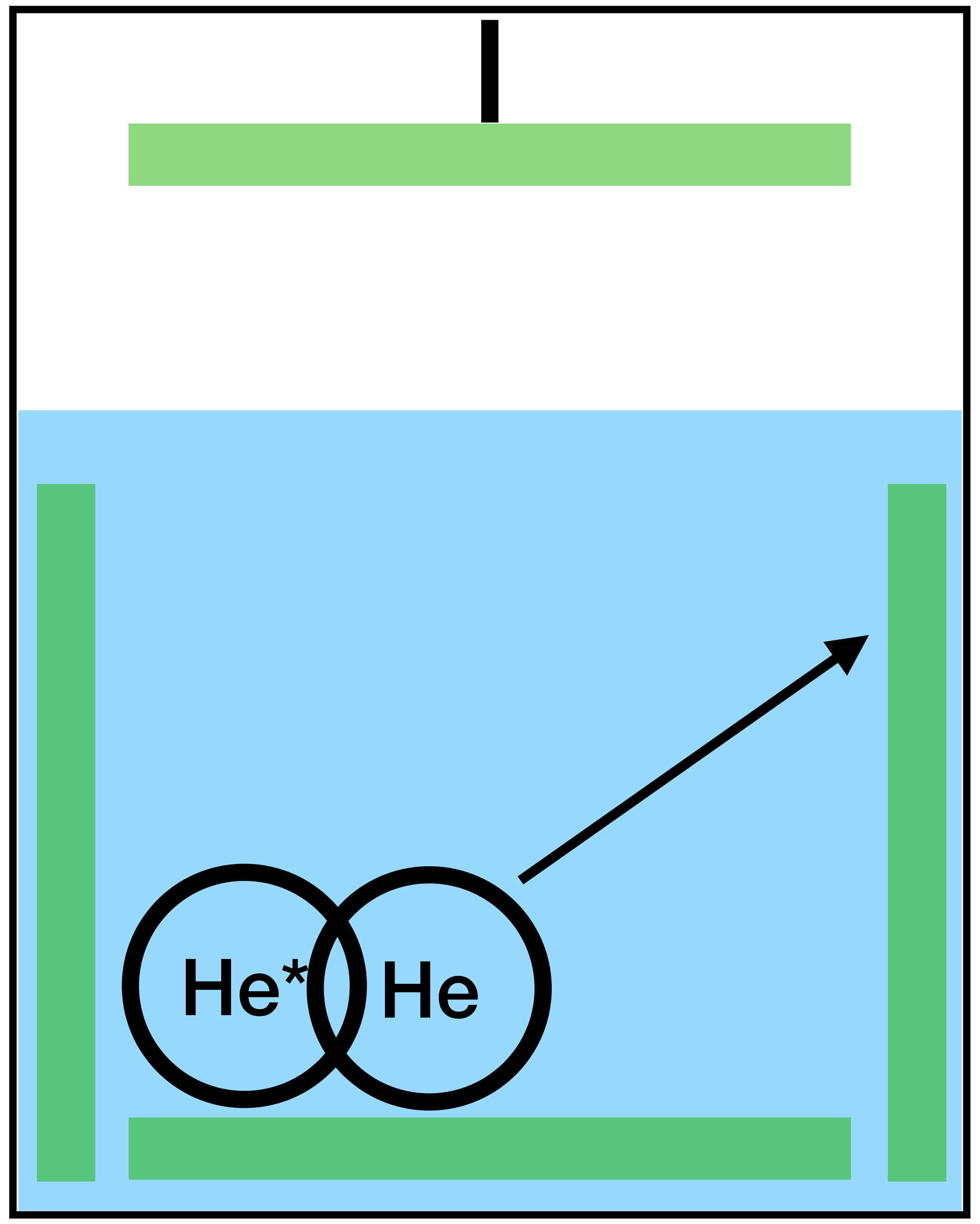
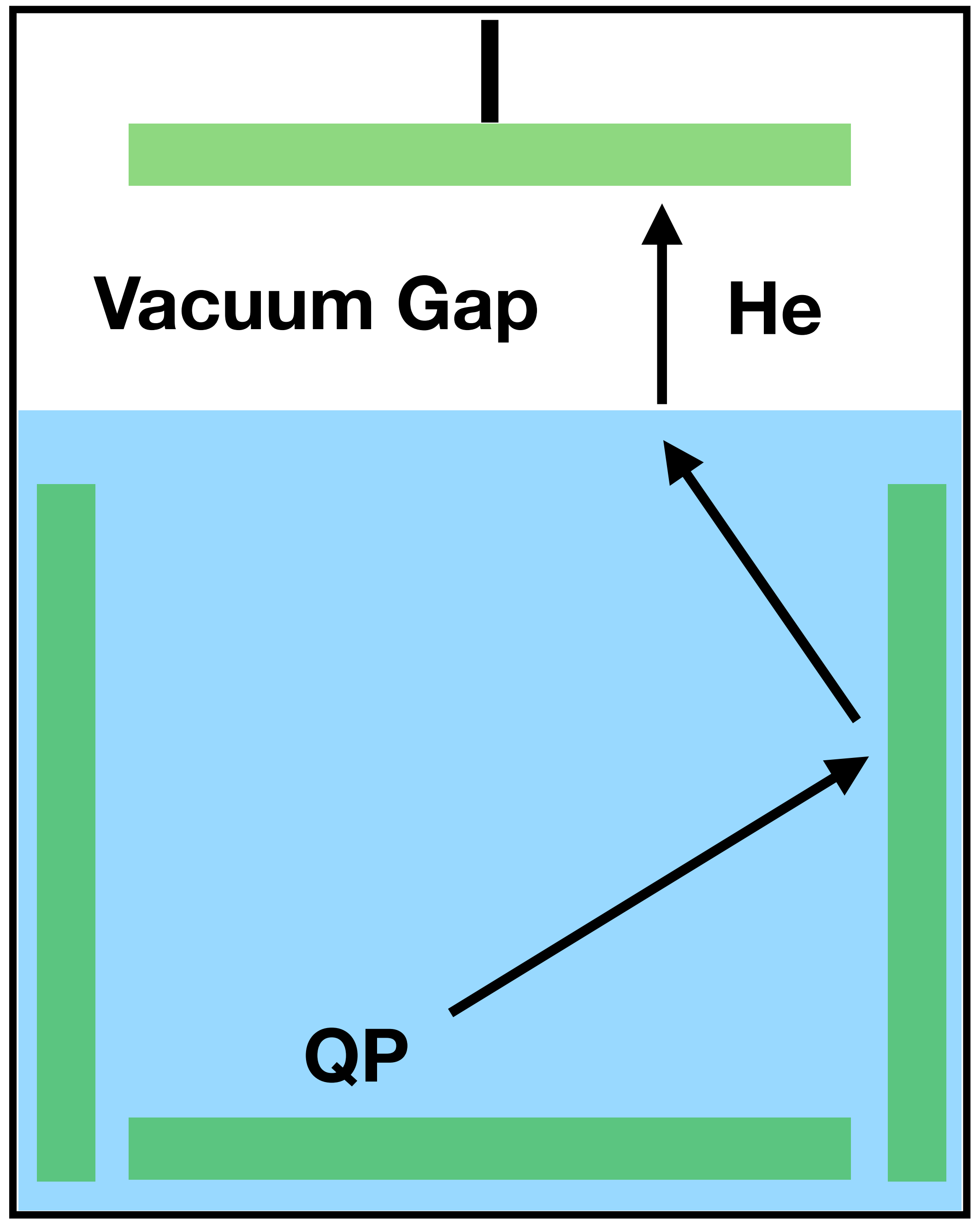


Excitations in Superfluid 4He

DM → **He** — **O(ns)**

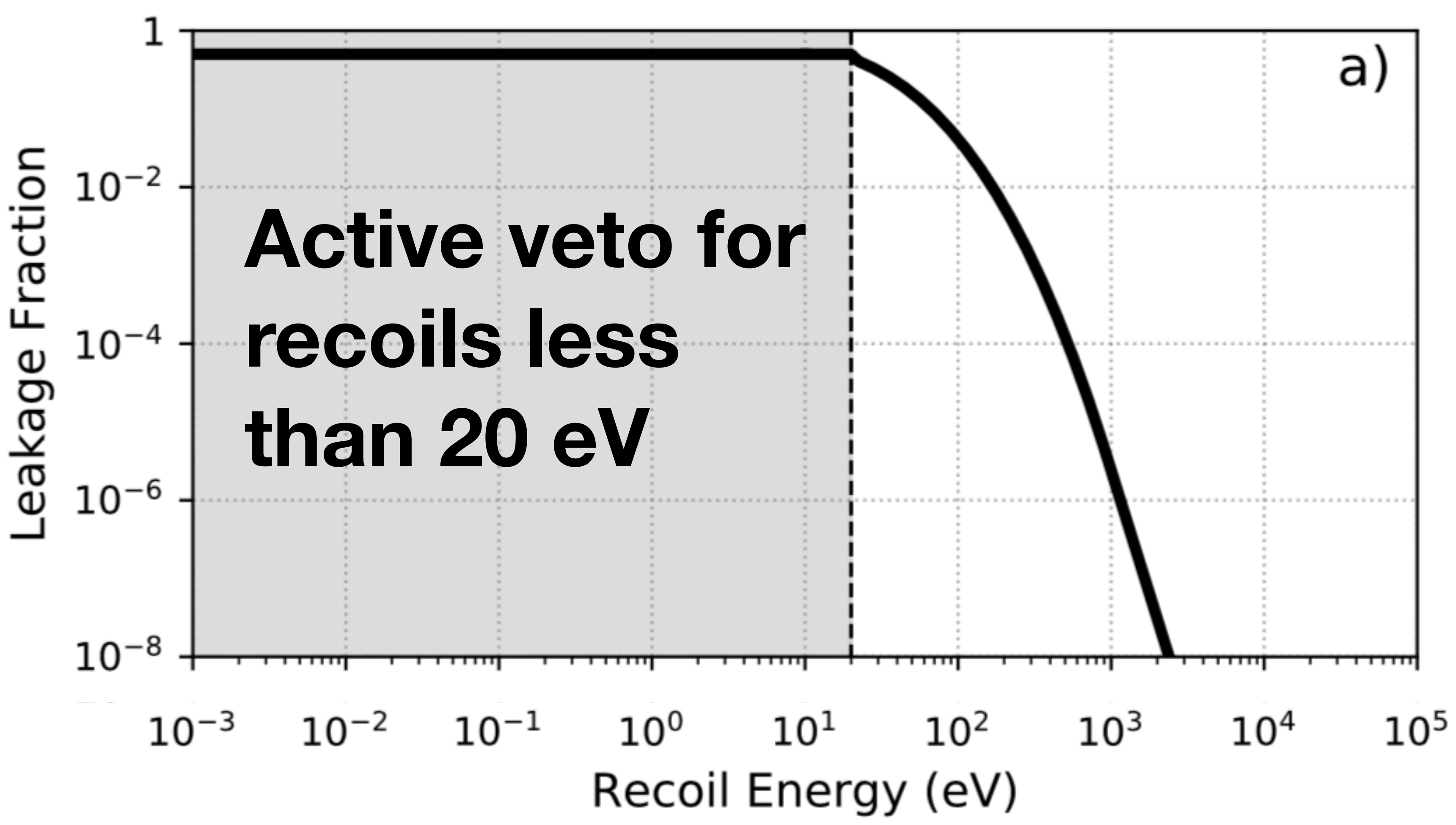
Excitation	Detection Method
Singlet UV (16 eV) Photons	Absorbed in calorimeters on 10 ns timescale
Triplet Kinetic Excitations	Ballistic, travel at O(1 m/s), deposit energy in immersed calorimeters
~meV Vibrations (phonons, rotons)	Adsorption of quantum evaporated He atoms on upper calorimeter + adhesion gain, 10-100 ms timescale

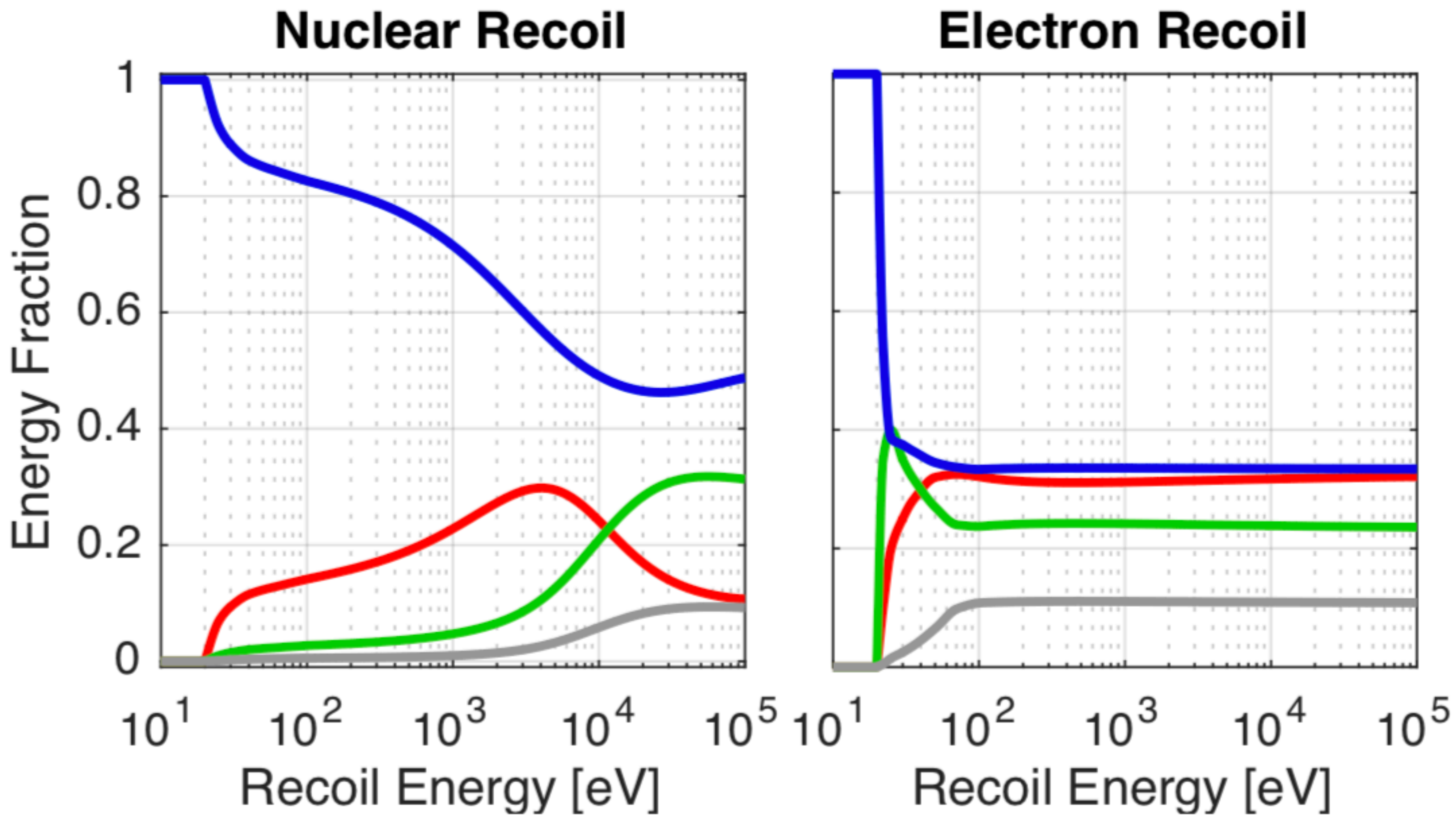


Energy Partitioning

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

- **Nuclear and electron recoils have different energy partitioning!**
- Estimated from measured excitation/ionization cross sections
- Compared to other noble elements, lots of energy goes into atomic excitations
- Distinguishable with signal timing

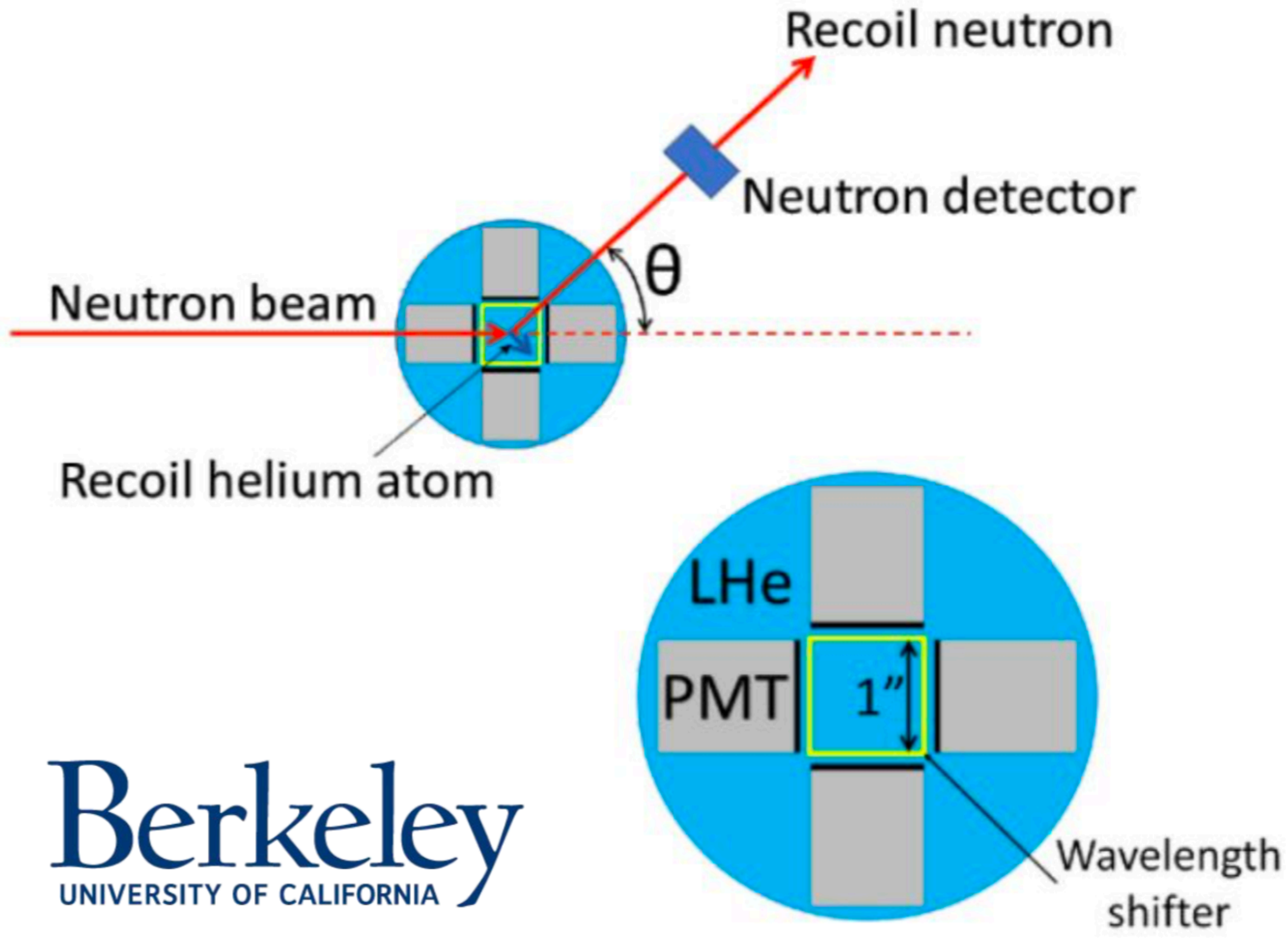


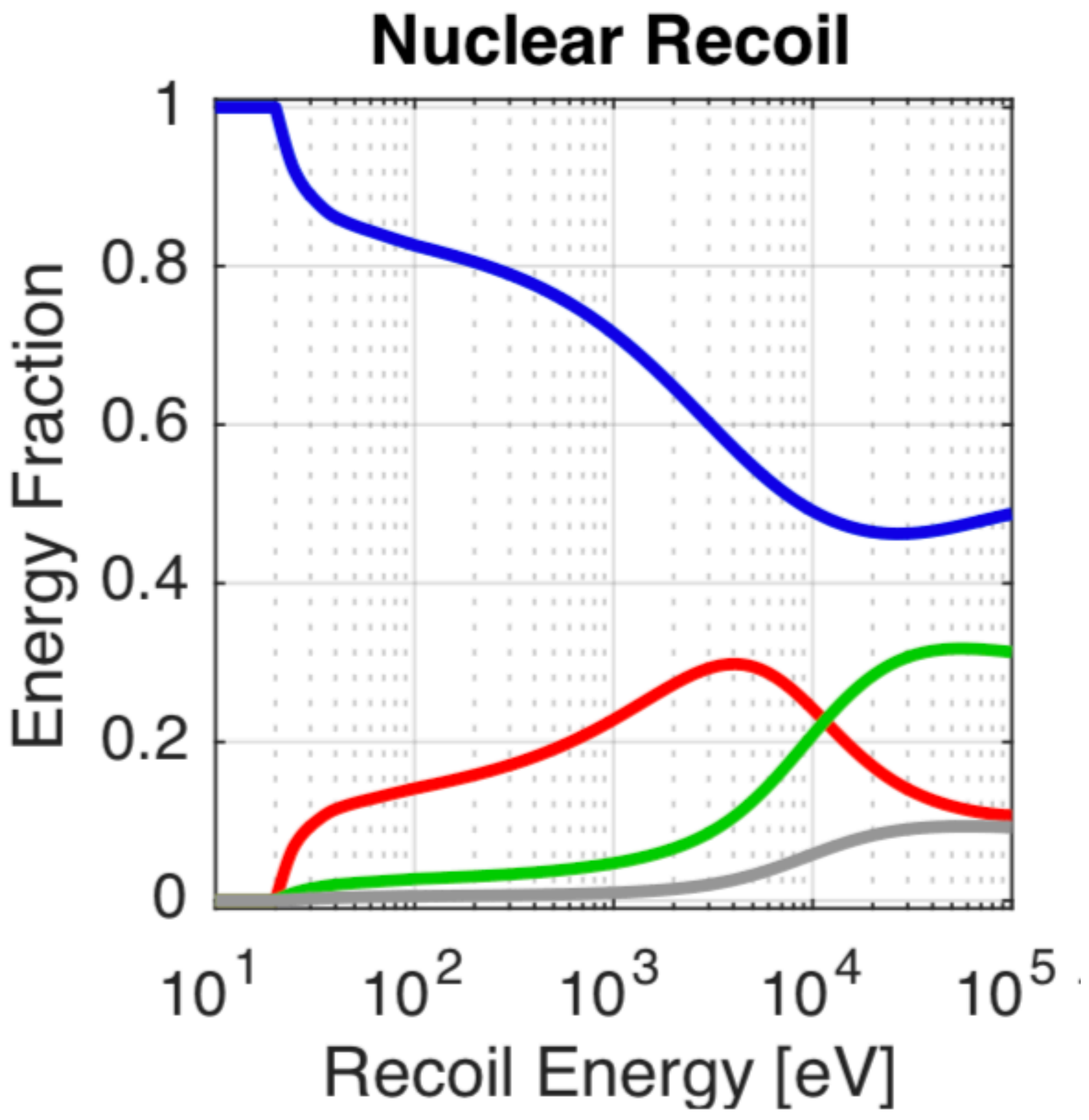


Activities at Berkeley

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

- Measuring the light yield for nuclear recoils in 4He
- Neutron scattering experiment at room and cryogenic temperatures (red curve)
    - Room temperature on arXiv: 1907.03985





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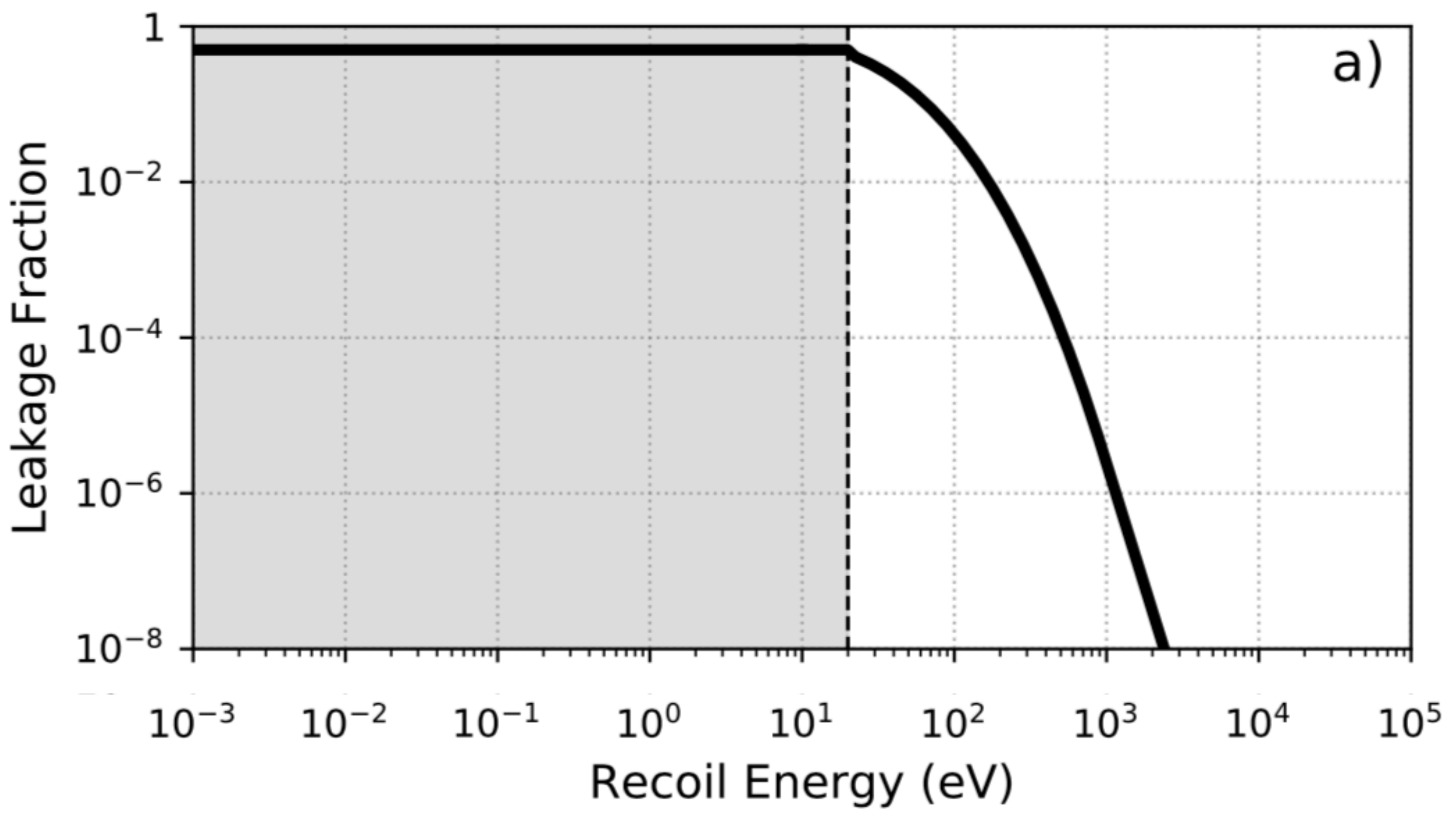
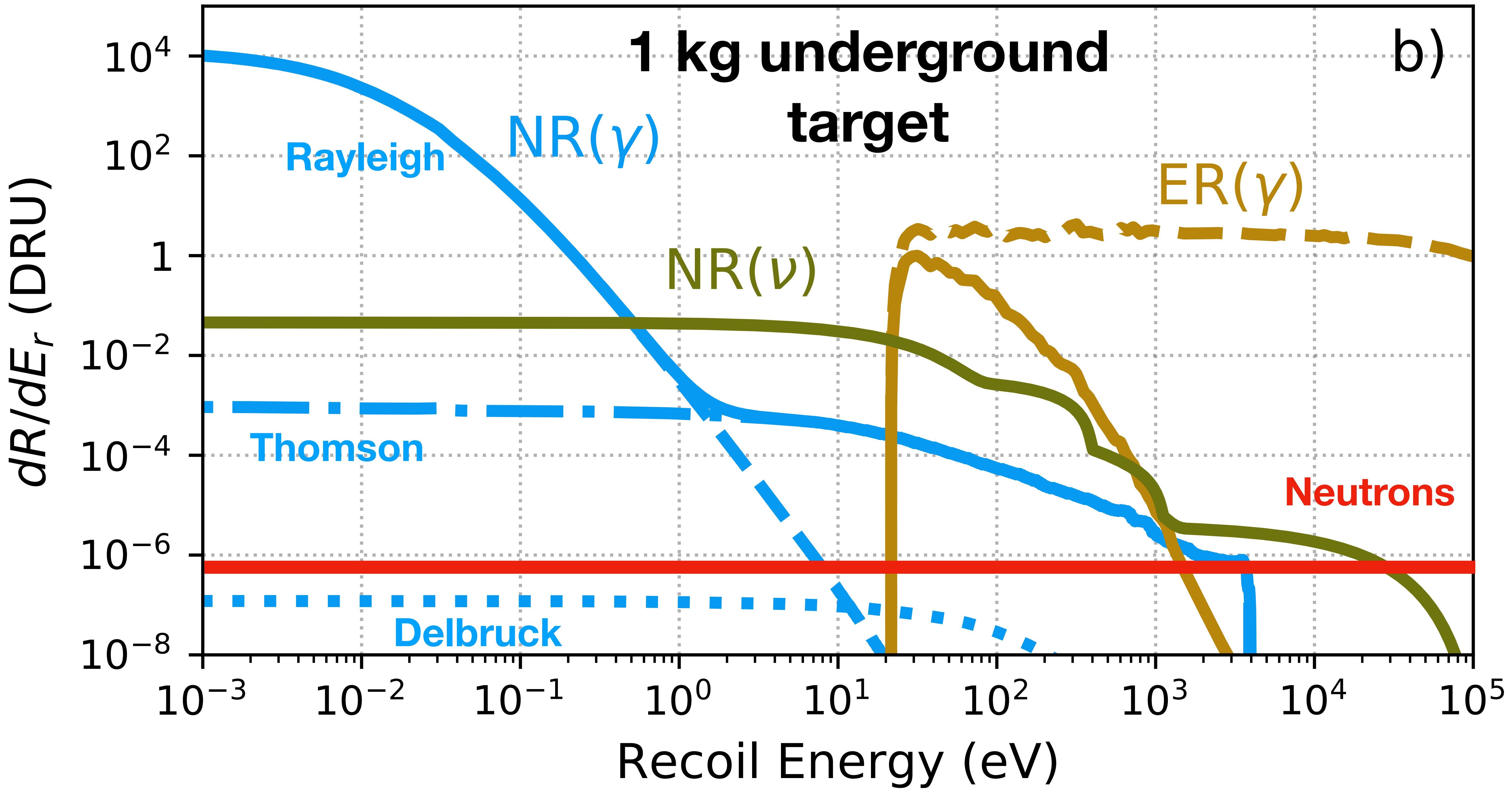
From V. Velan

Background Simulations

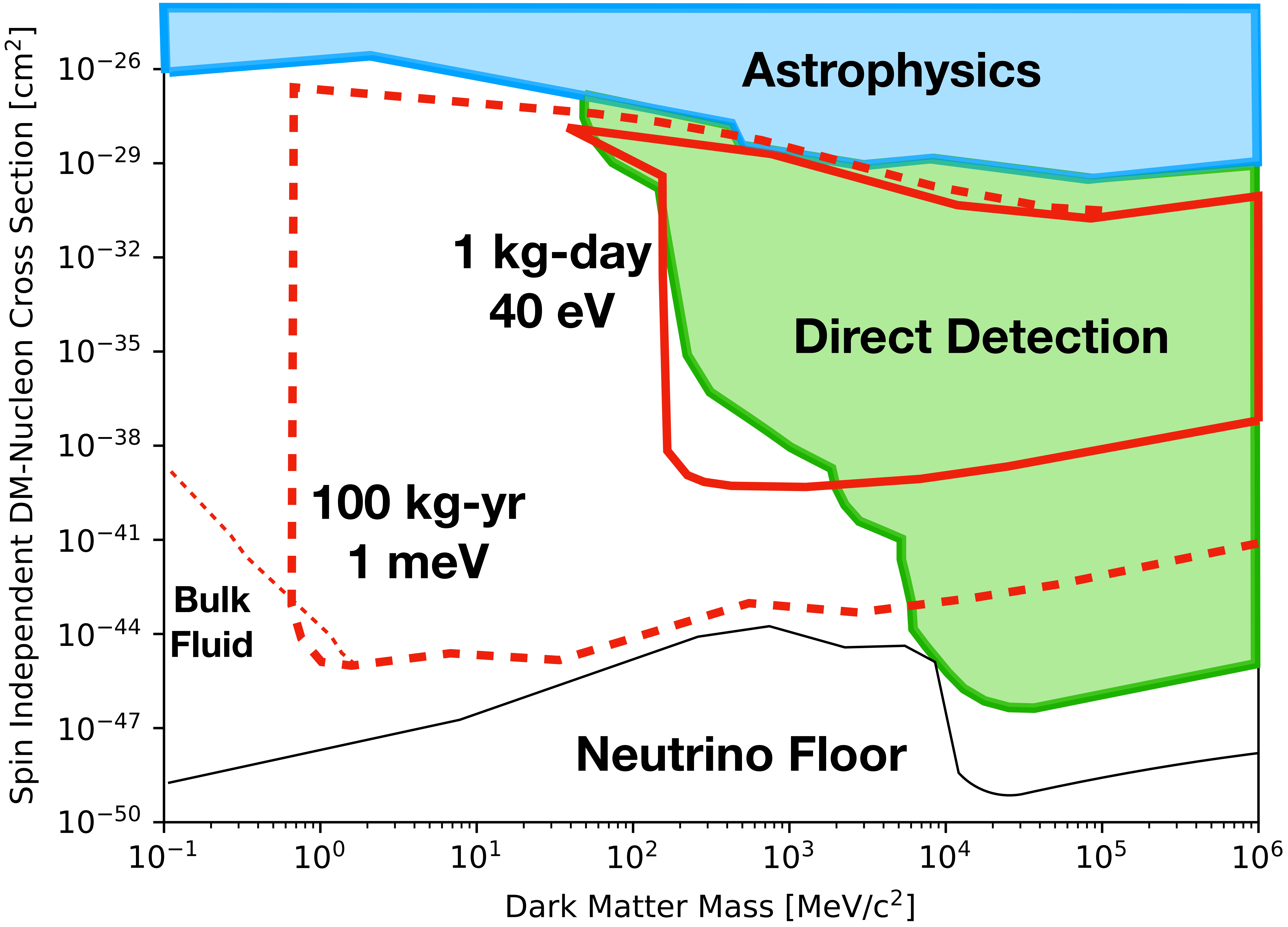
- Radon surface backgrounds not yet considered





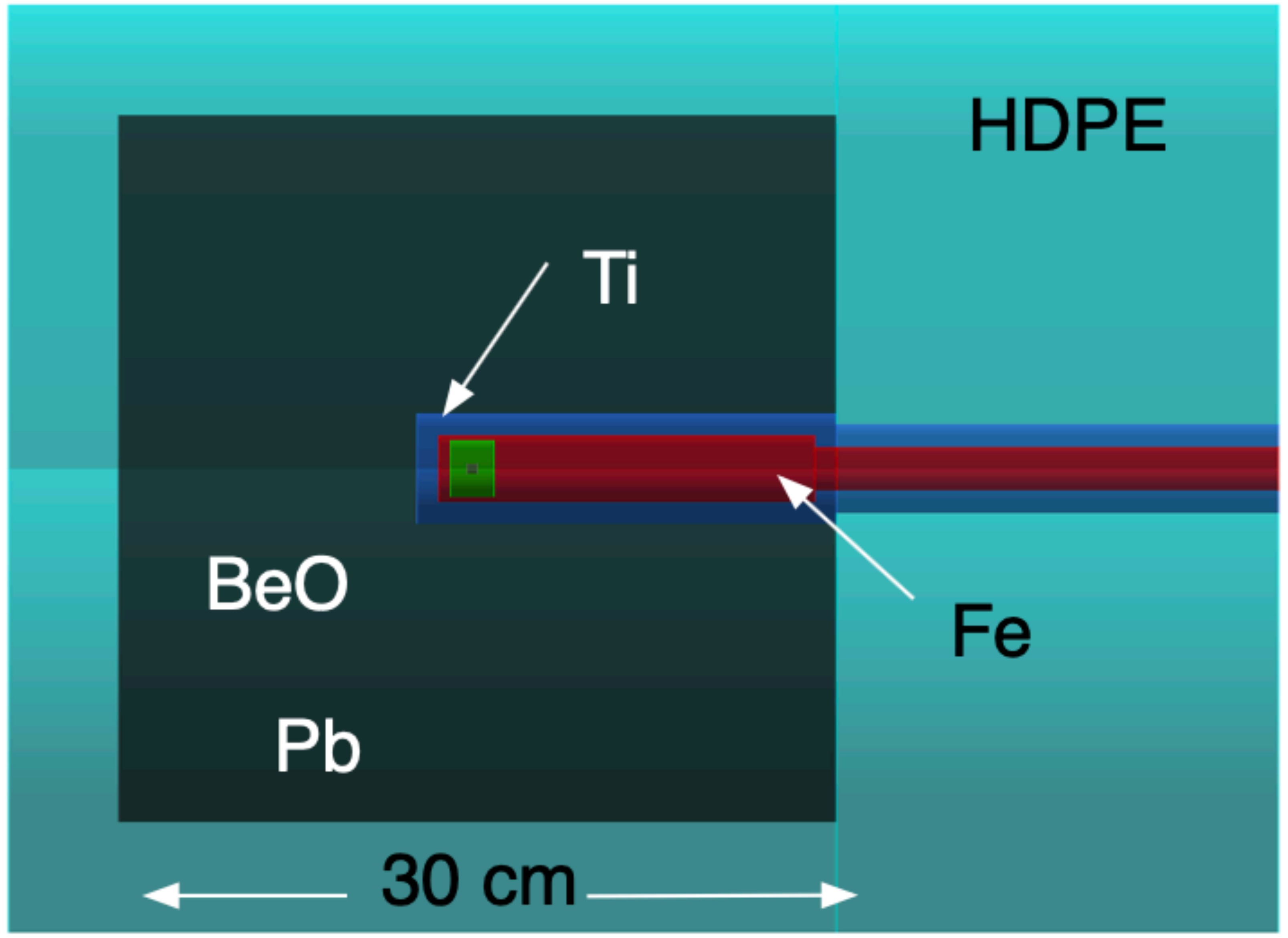
Sensitivity Projections

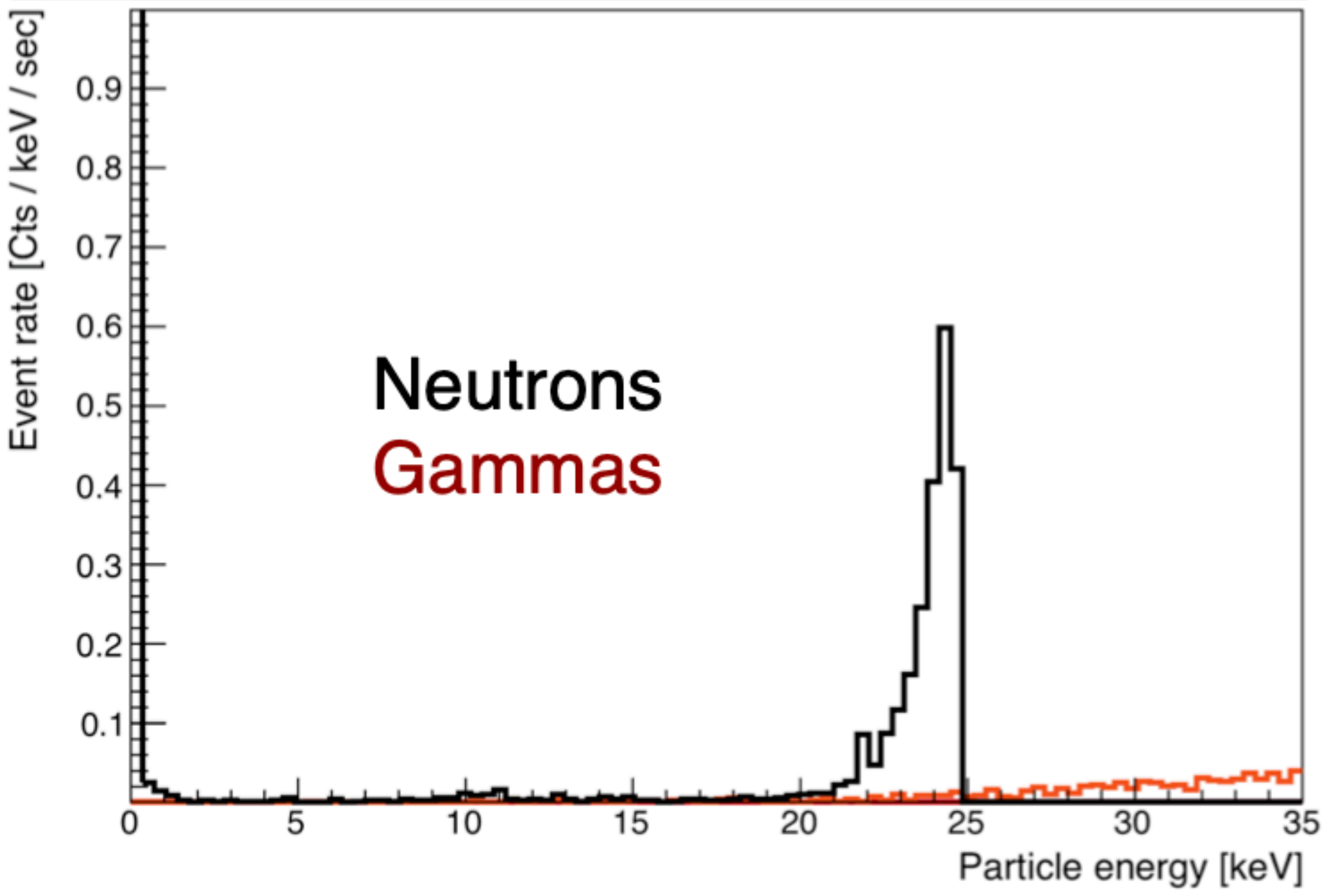
- Solid red curve, 1 kg-day @ 40 eV threshold
    - 3.5 eV (sigma) calorimeter resolution
    - 9x “adhesion gain”
    - 5% quasiparticle detection efficiency



Low Energy Neutron Calibration

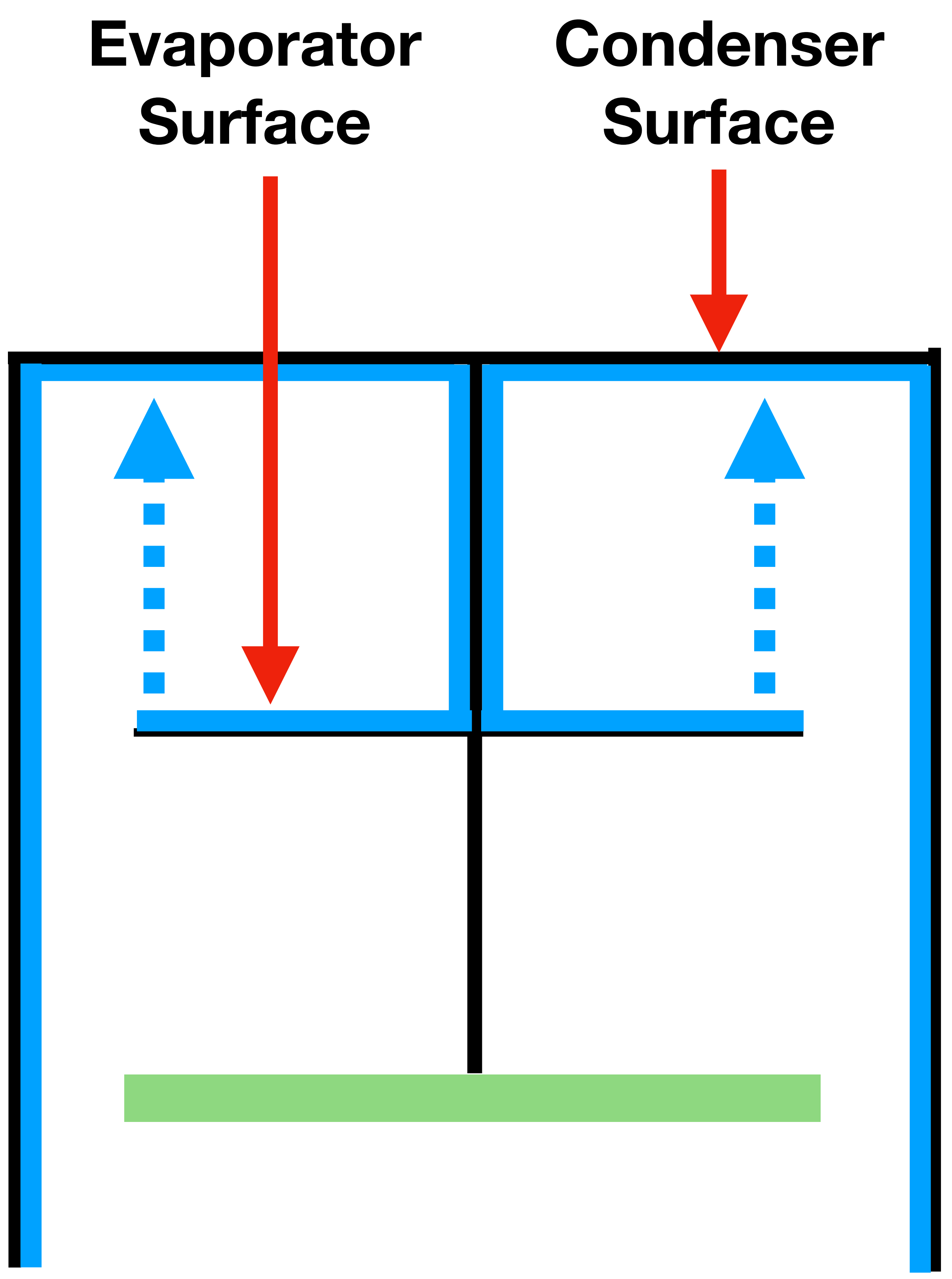
- Coincidence at 24 keV:
  - Energy of convenient photoneutron source (124SbBe)
  - Energy of 'notch' in cross section of Fe (~100 m interaction length)
  - Result: can surround a photoneutron source in material opaque to gammas but transparent to 24 keV neutrons
- Endpoint in He: 14 keV
- 1 GBq 124 Sb source (practical) results in a few n/s collimated neutrons
- Also looking into pulsed source based on pulsed filtered neutron generator, DD or DT





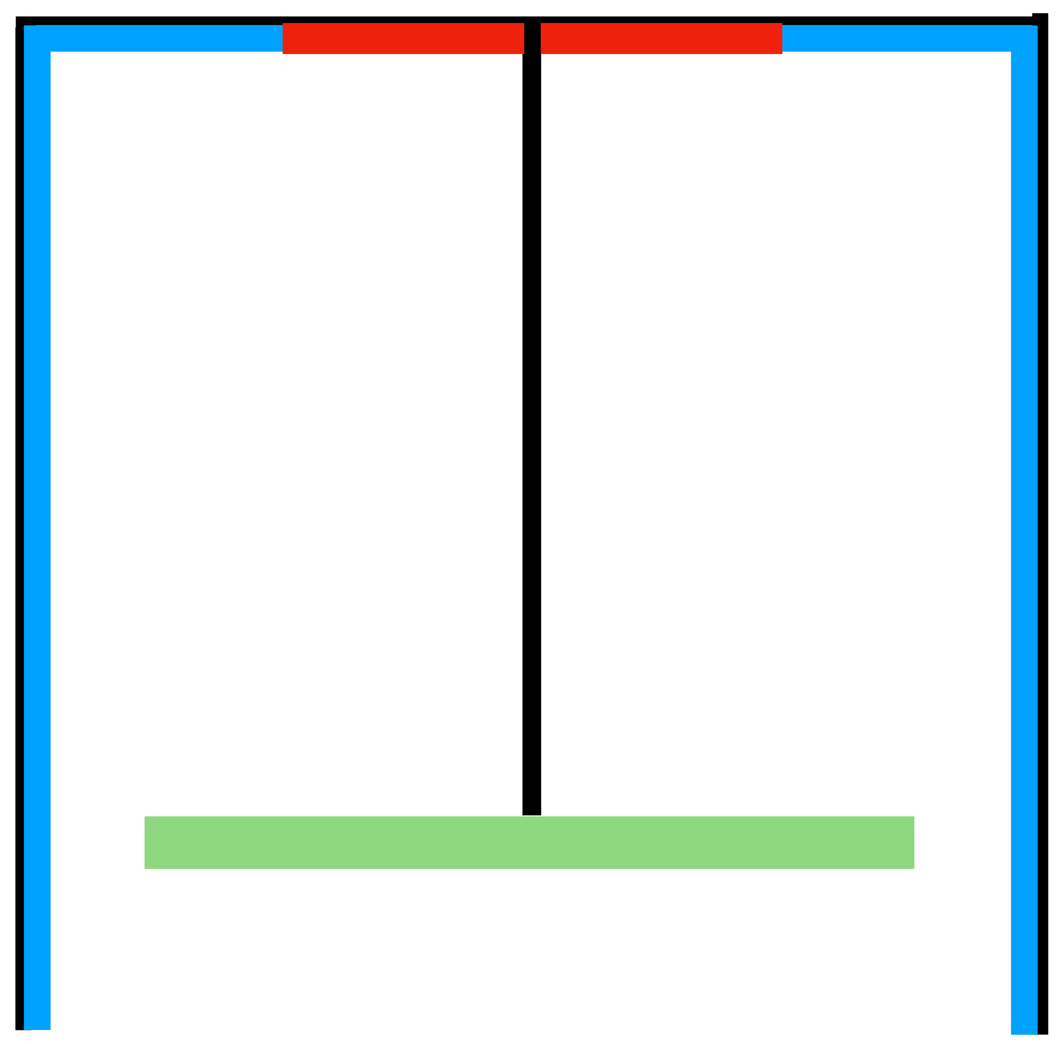
Activity at UMass

- Characterizing dilution refrigerator
- Uncertainty in how quasiparticles, triplet excitations interact at surfaces
- Adhesion gain: use materials with higher van der waals attraction, keep calorimeter dry
    - Adapting the HERON film burner design, demonstrated but **heat load problematic**



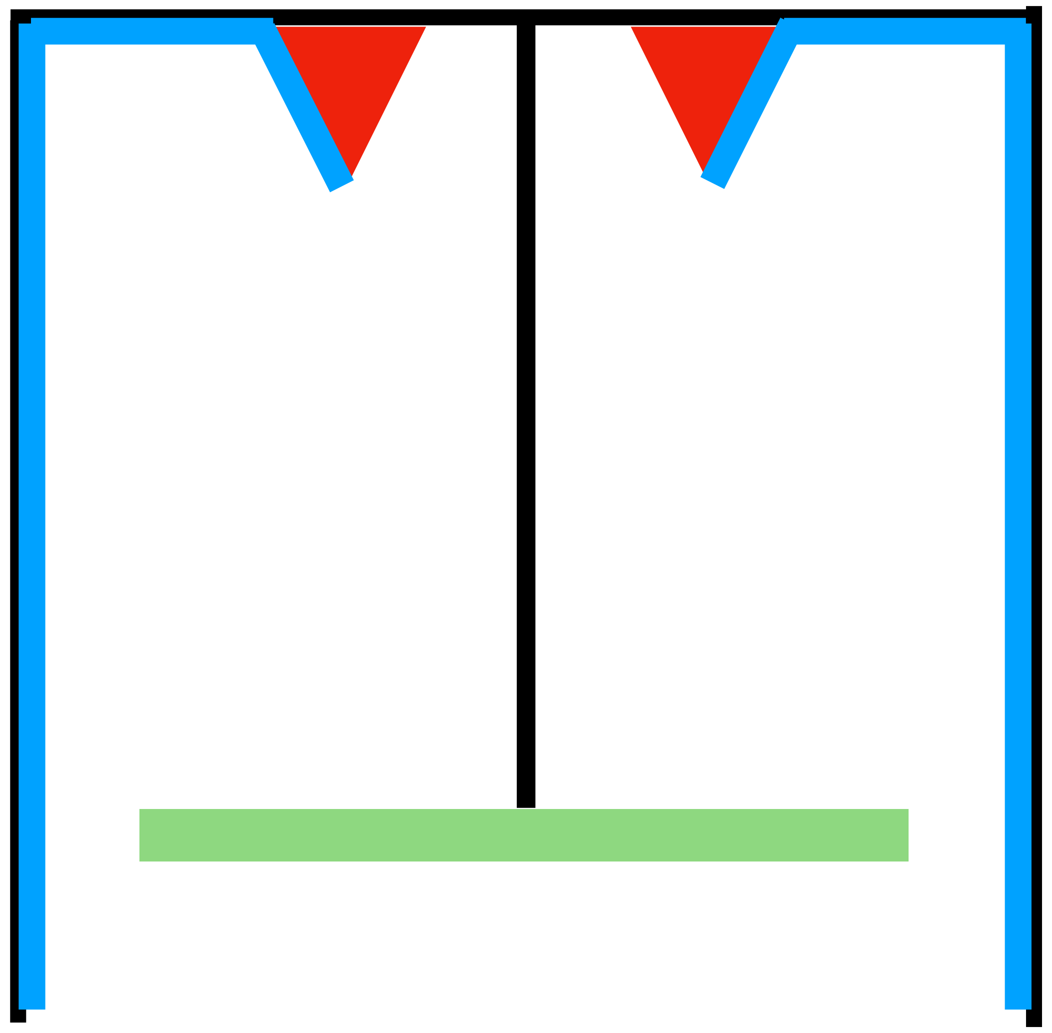
Heat Load Free Film Stopping: Cesium

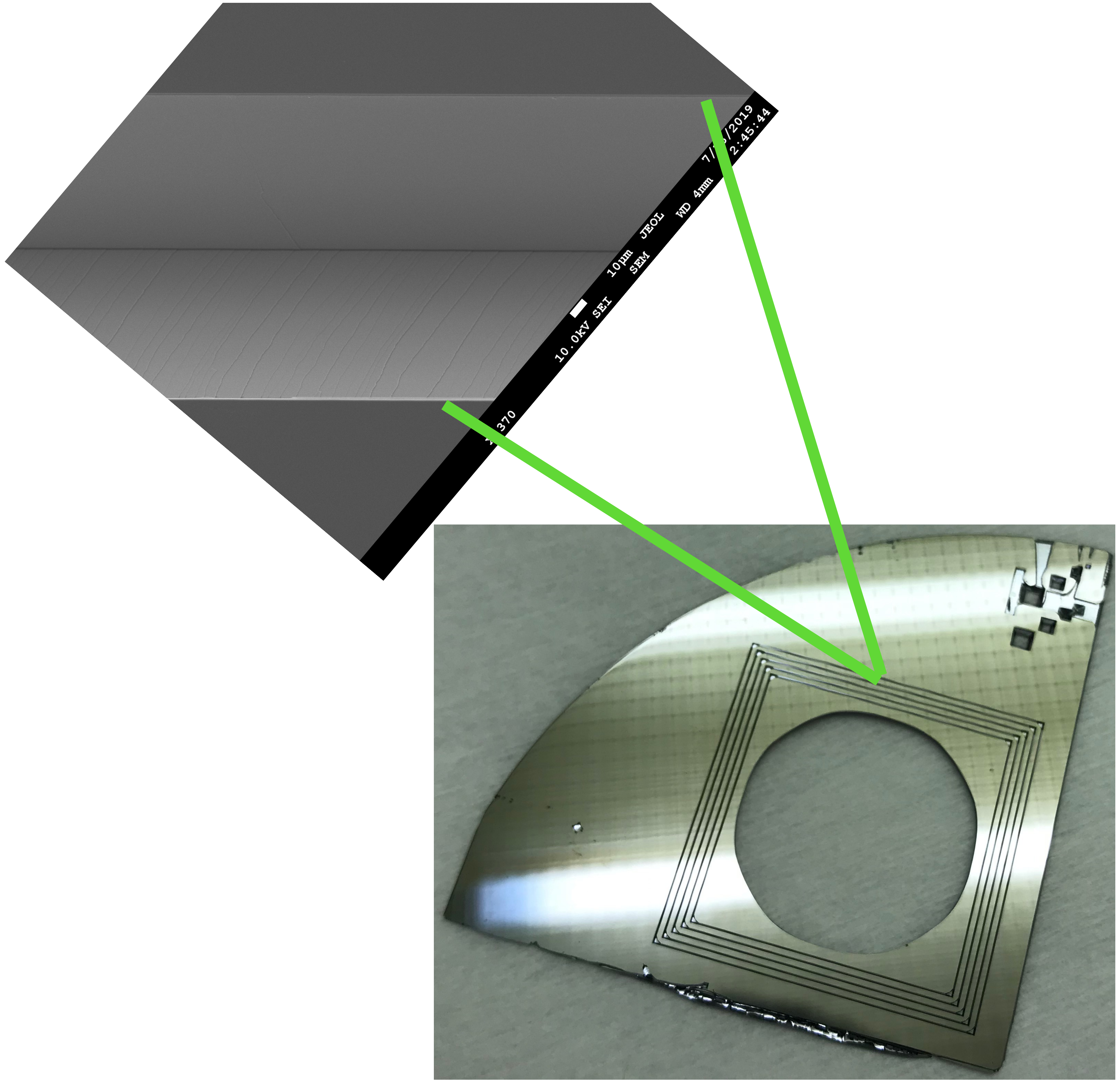
- Cesium coated surfaces, demonstrated but technically difficult
    - Nacher and Dupont-Roc, PRL 67, 2966 (1991)
    - Rutledge and Taborek, PRL 69, 937 (1992)



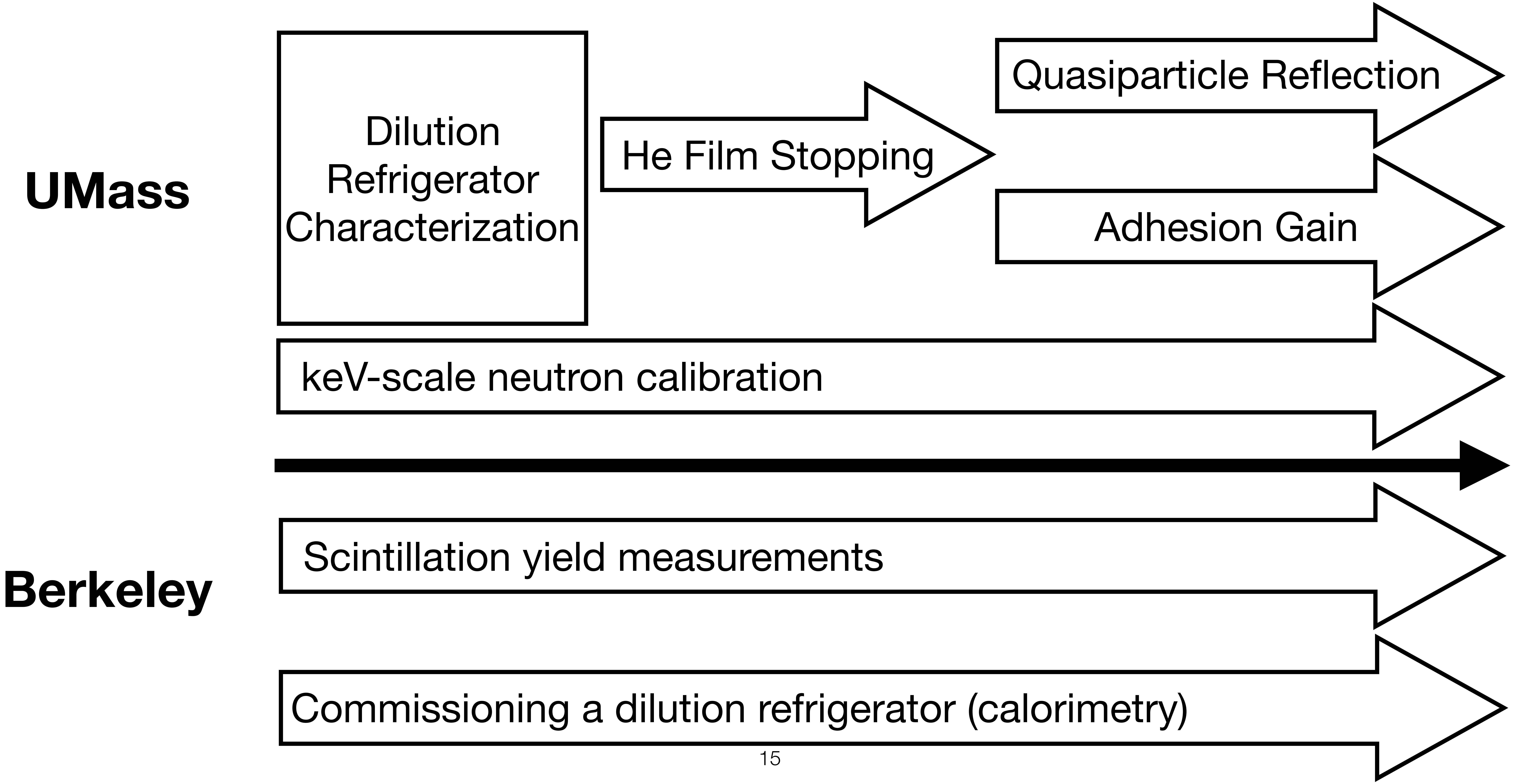
Heat Load Free Film Stopping: Geometry

- Atomically sharp knife edges, used by x-ray satellites at higher temperatures, has yet to be conclusively demonstrated
  [Y. Ezoe et al J. Astron. Telesc. Instrum. Syst. 4(1) 011203 (27 October 2017)]



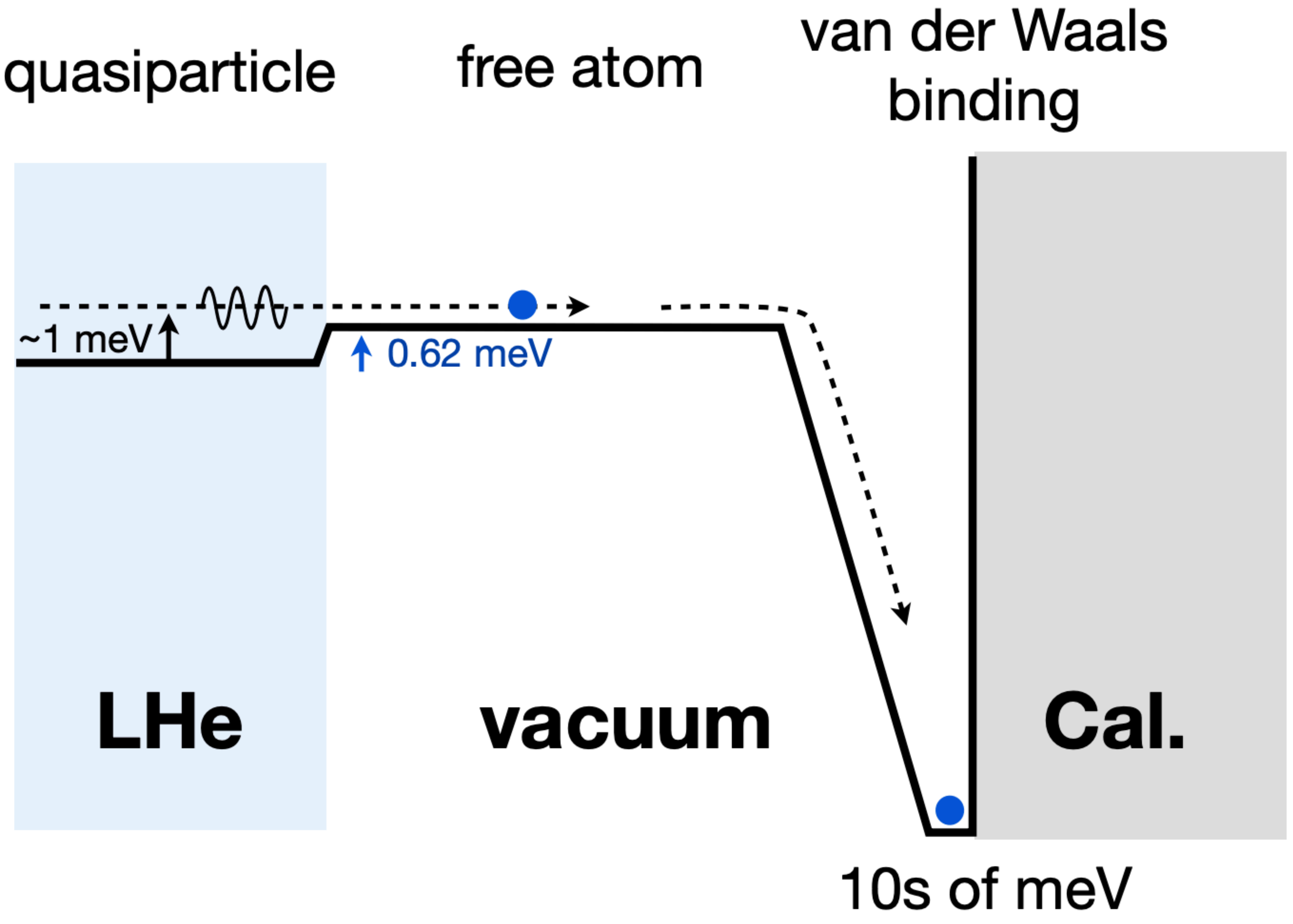


Next Steps

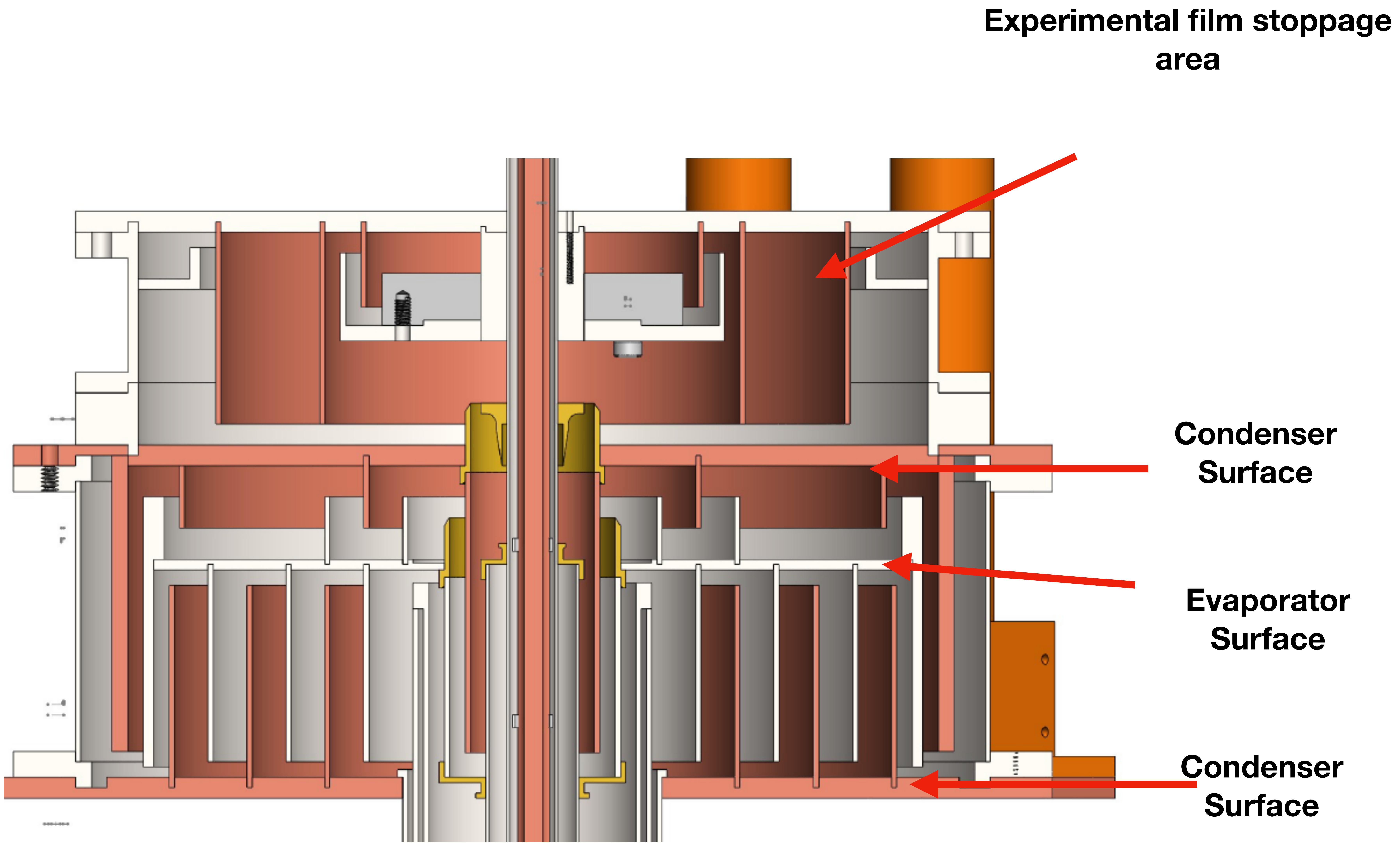

UMass
Dilution Refrigerator Characterization
He Film Stopping
Quasiparticle Reflection
Adhesion Gain
keV-scale neutron calibration
Berkeley
Scintillation yield measurements
Commissioning a dilution refrigerator (calorimetry)

Extras

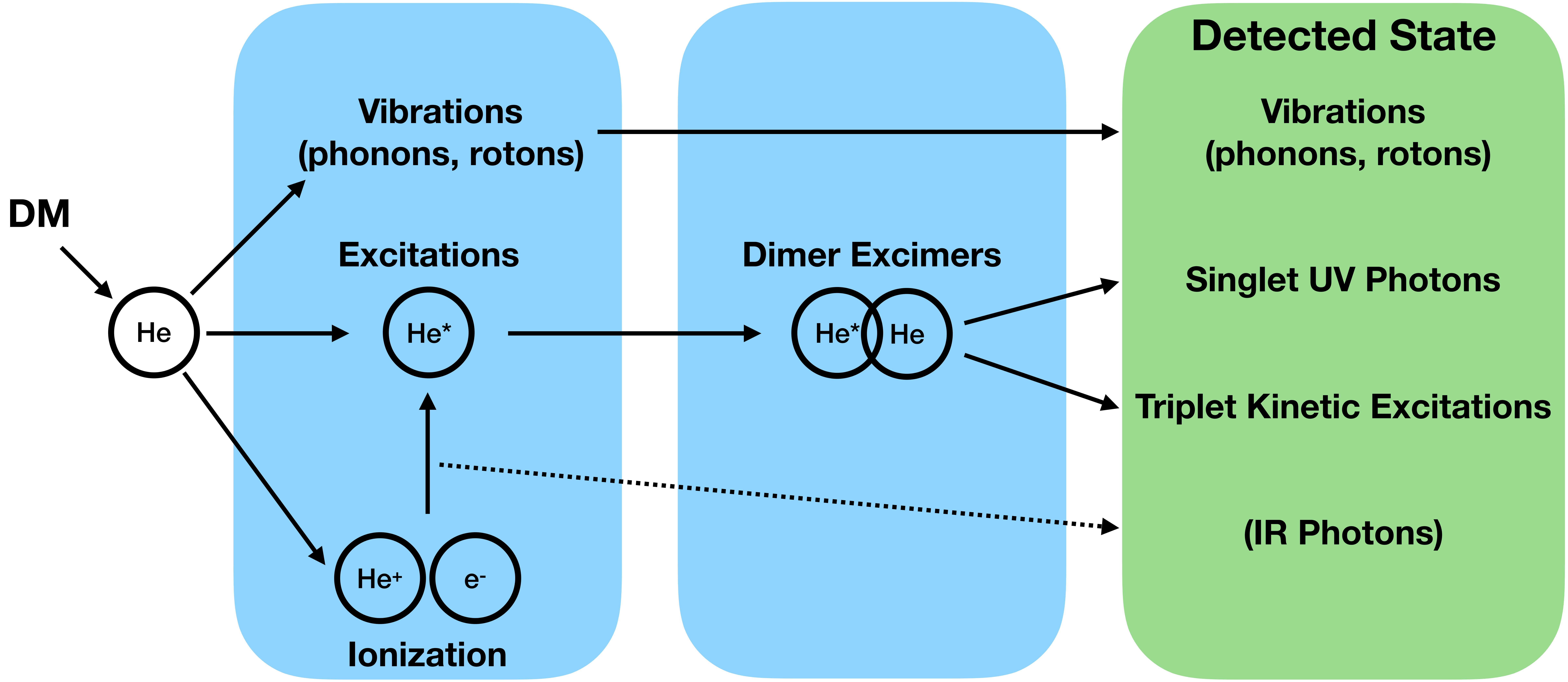
From Scott Hertel



Film Burner Model

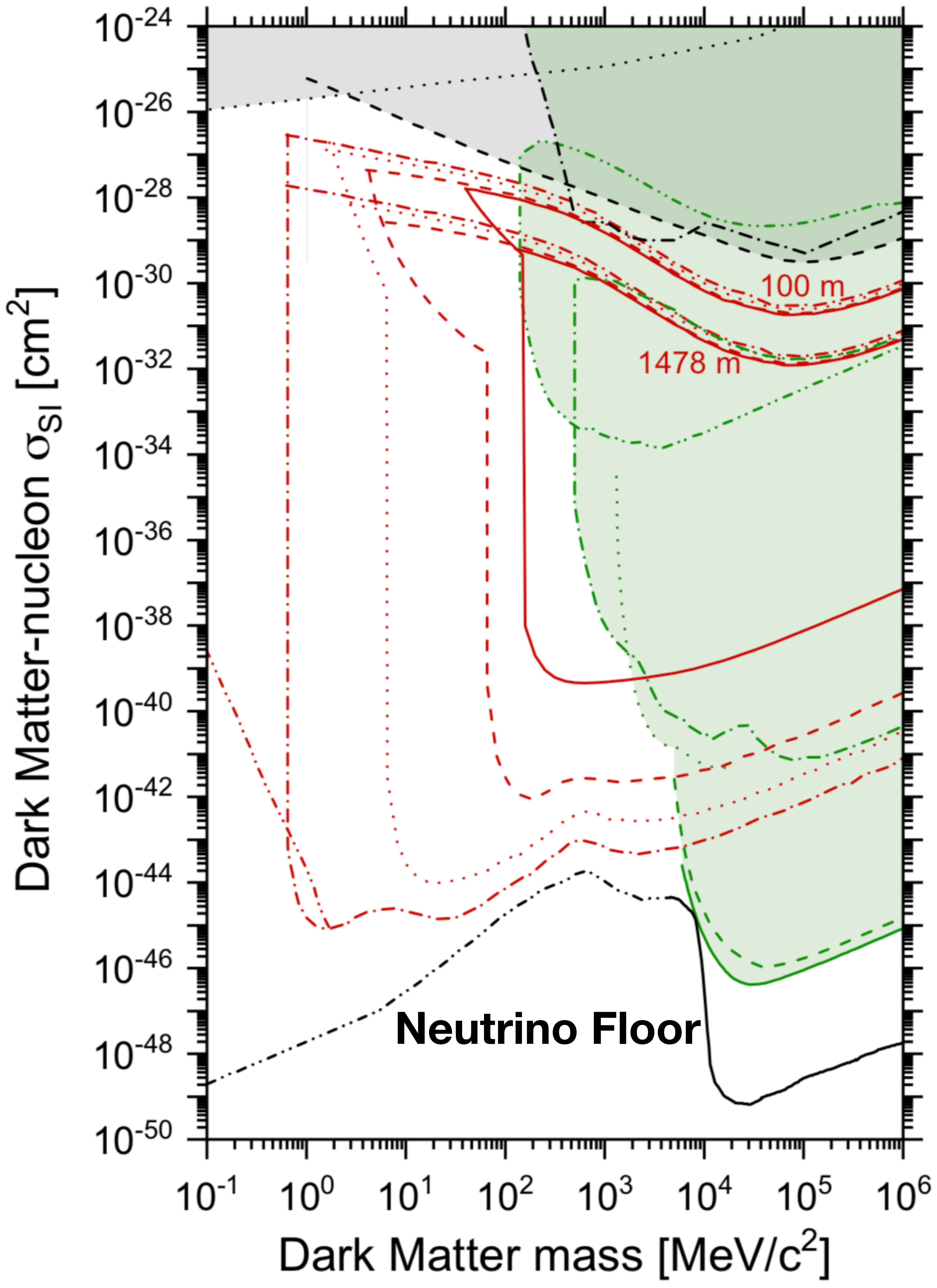


Excitations in Superfluid 4He



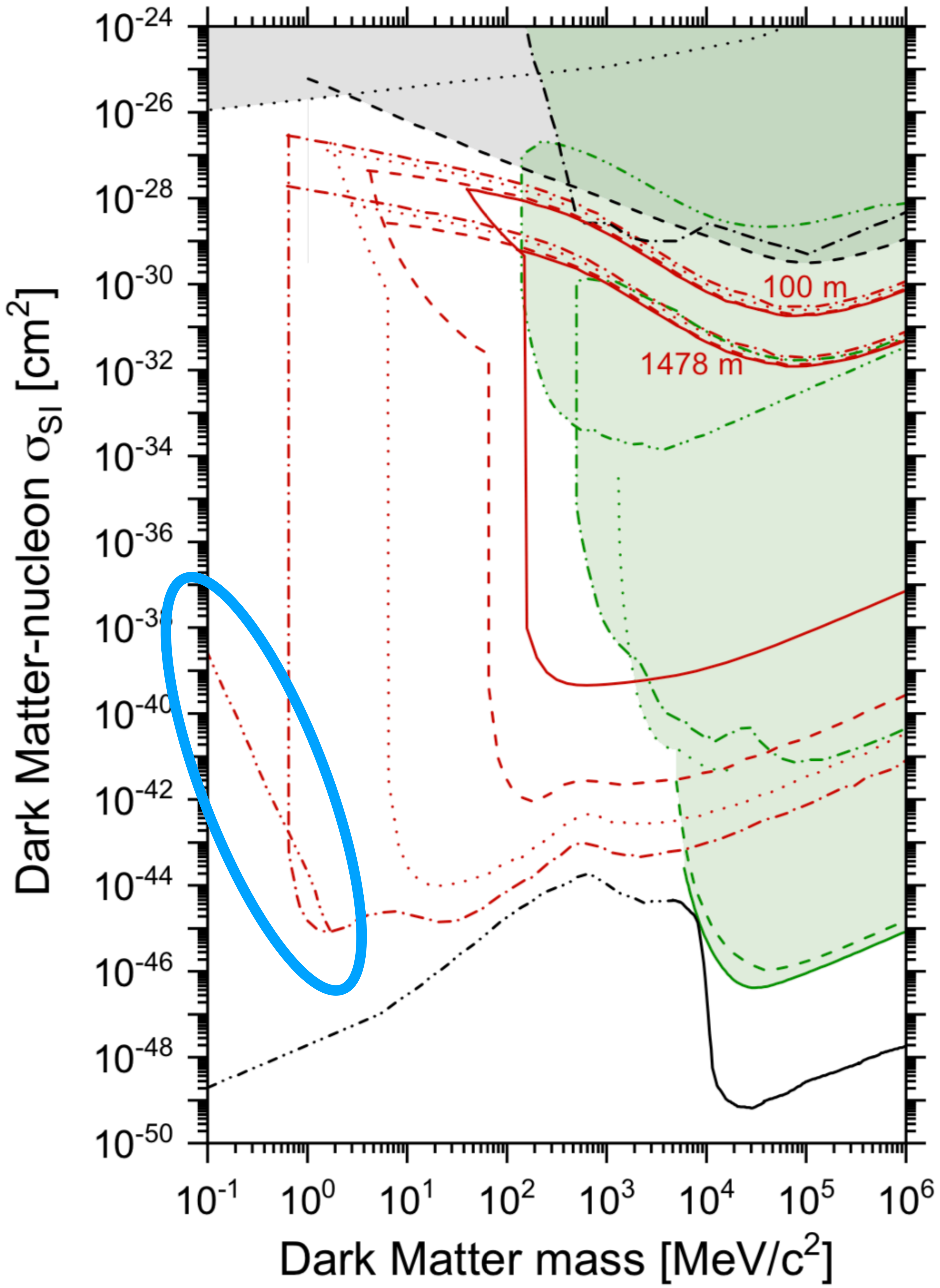
Sensitivity Projections Cont.

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**



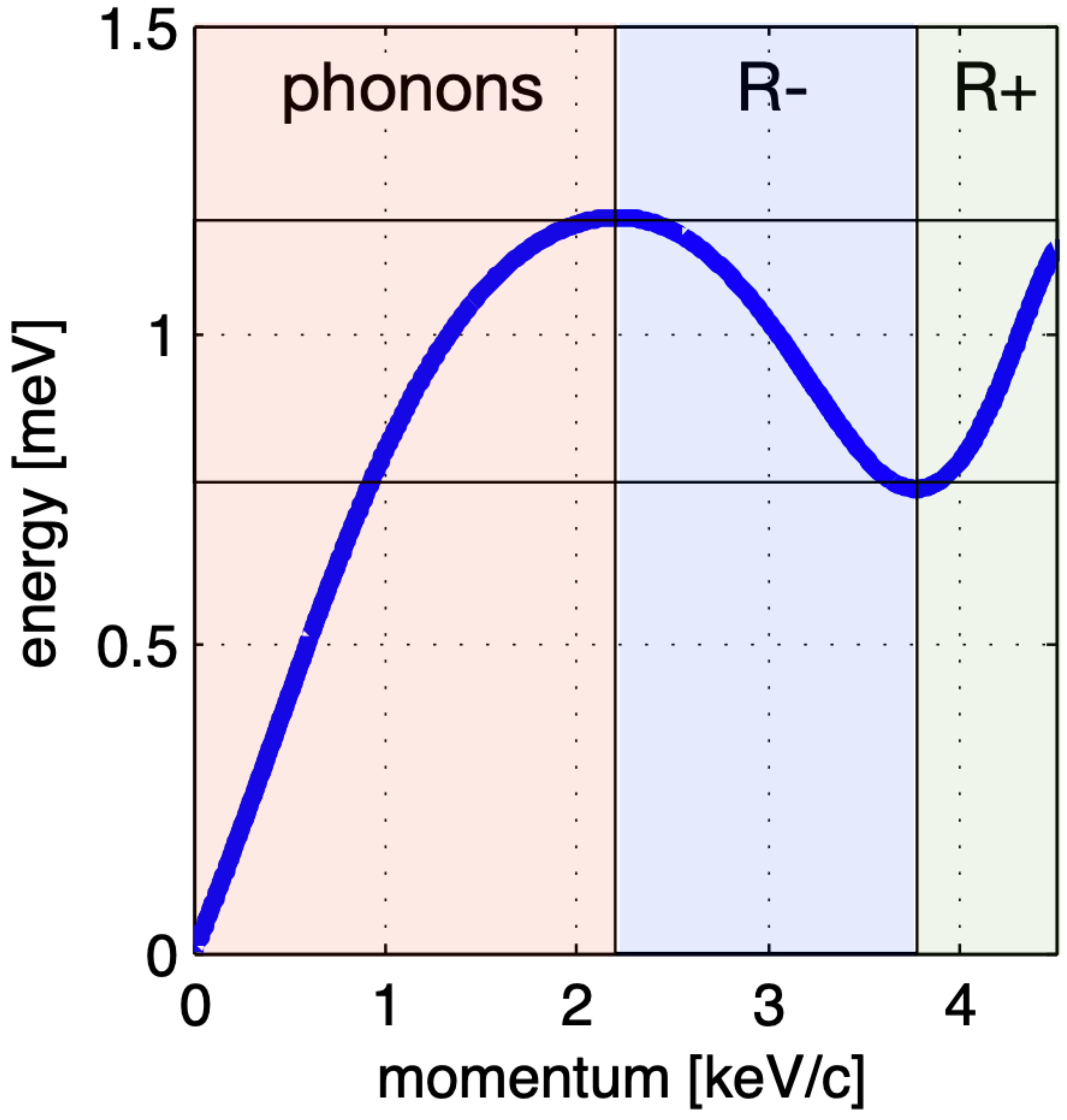
Extending Sensitivity with Off Shell Interactions

- 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



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

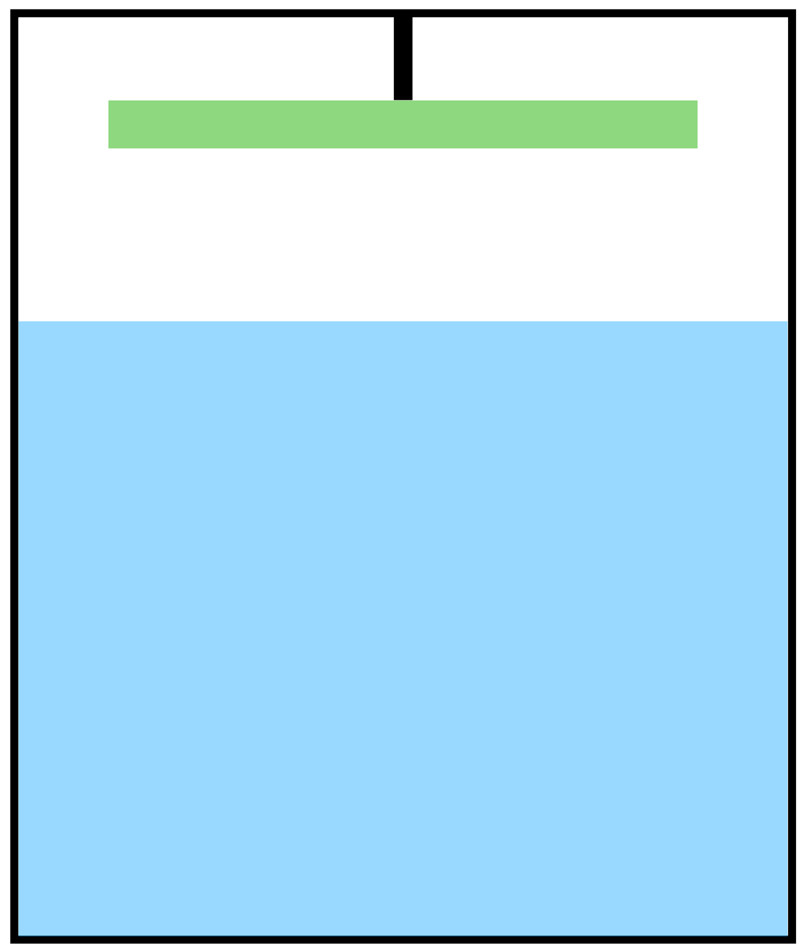


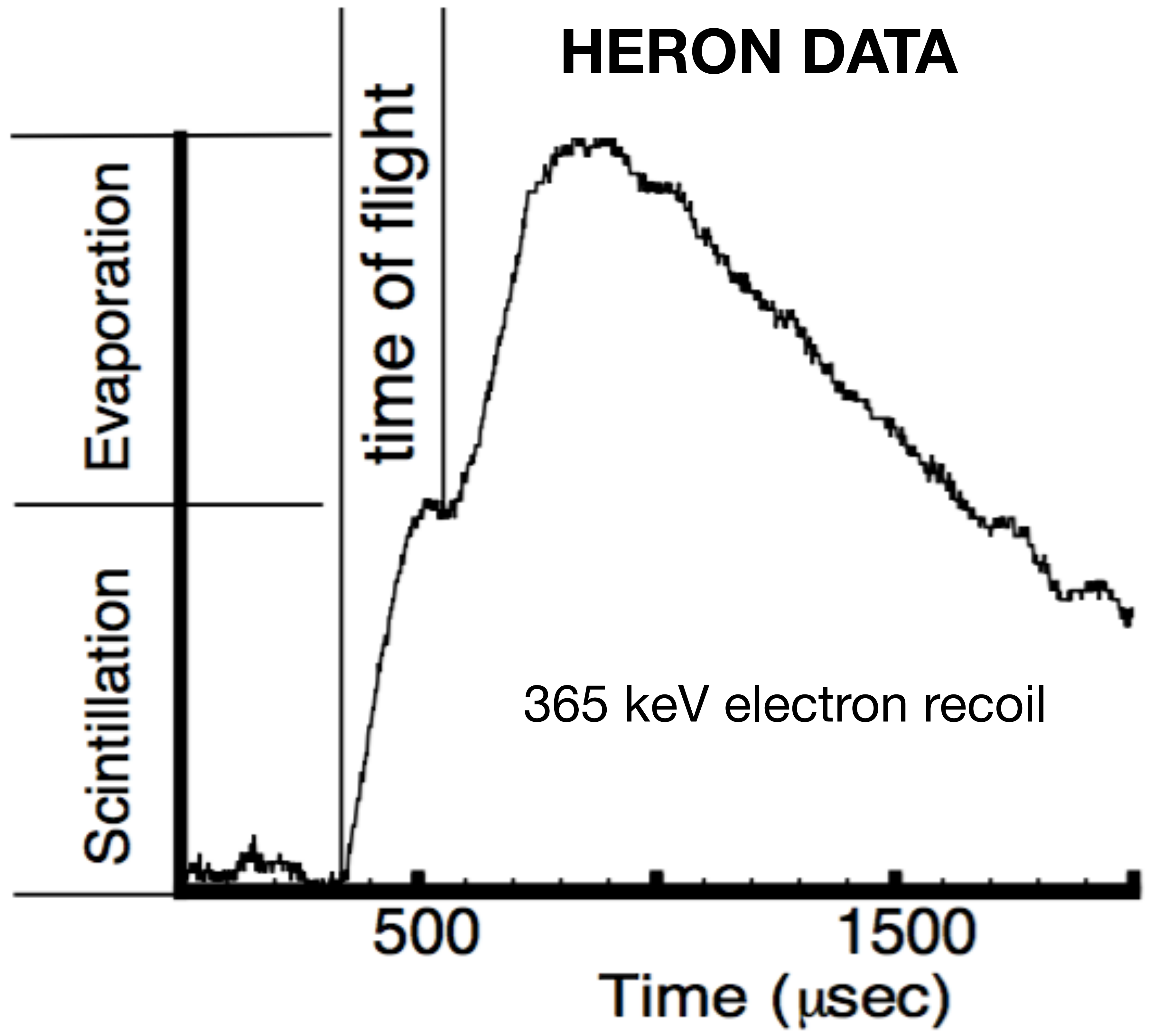
Distinguishing Quasiparticles and Excitations

- Use signal timing
  - Singlet signal expected to have O(10 ns) fall time, delta function in calorimeter
  - Triplets have O(1 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



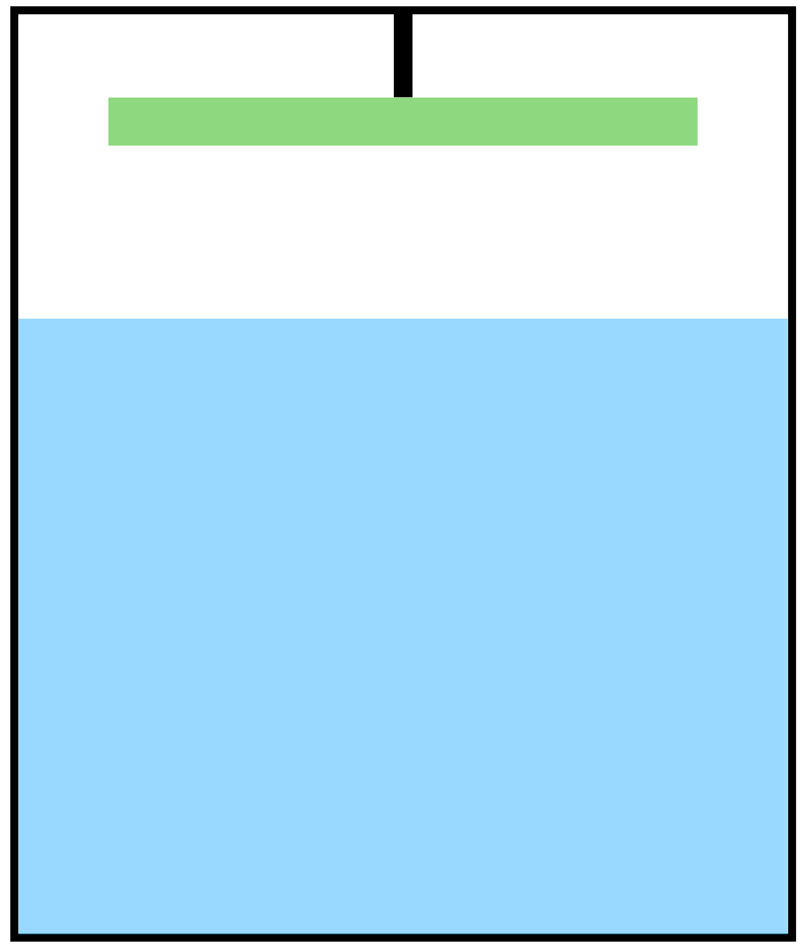


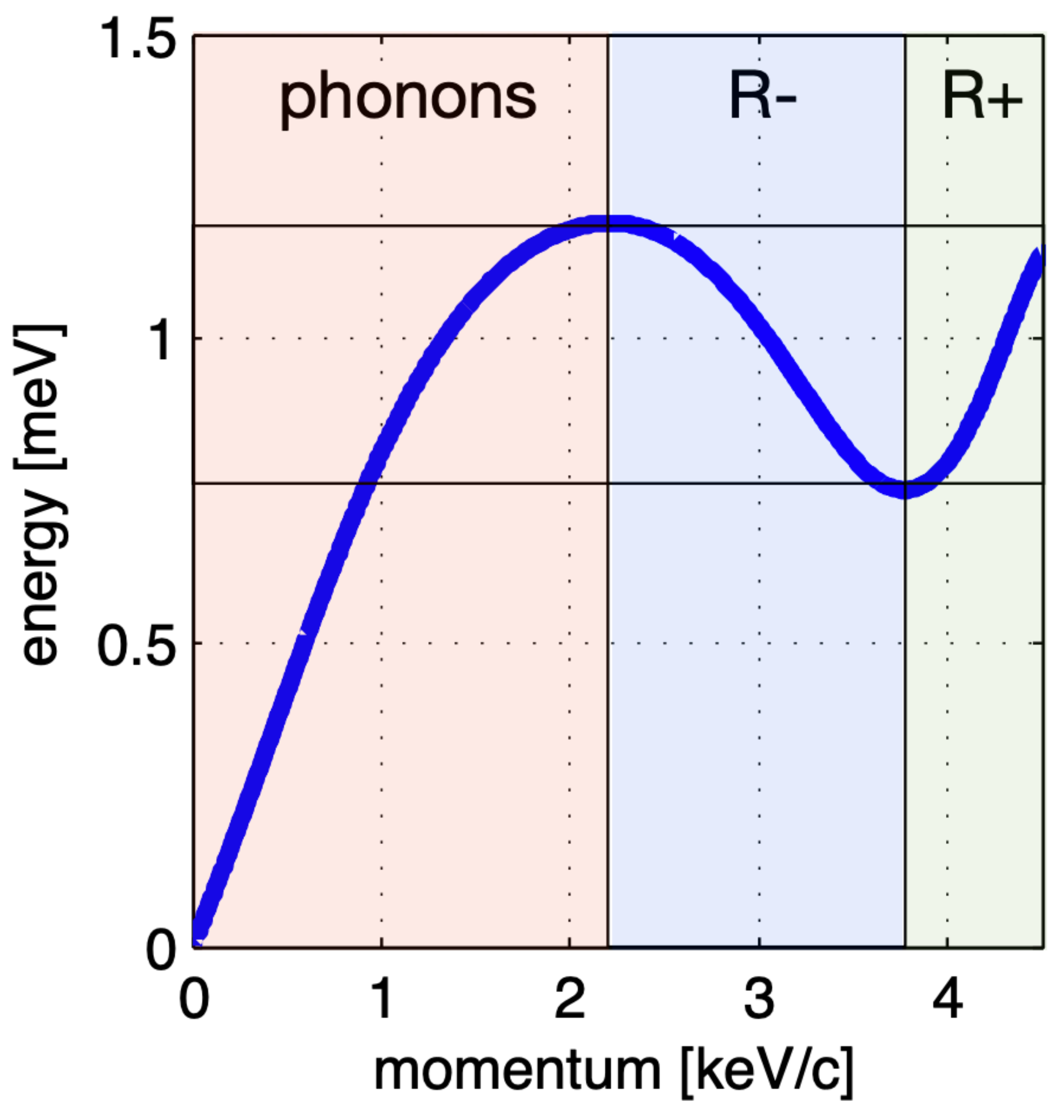
J. S. Adams et al. AIP Conference Proceedings 533, 112 (2000)

Annotations from Vetri Velan

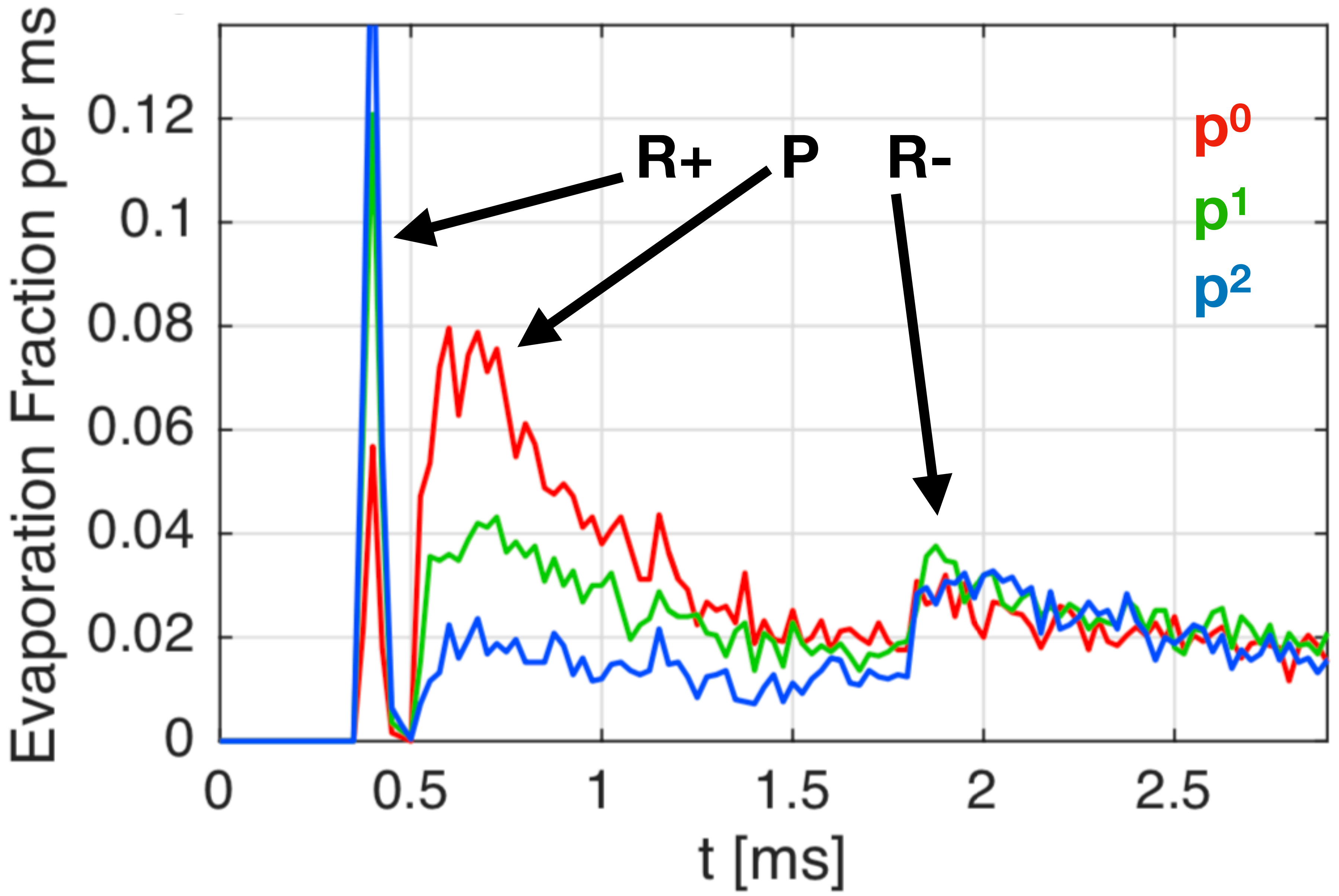
Another Example Waveform

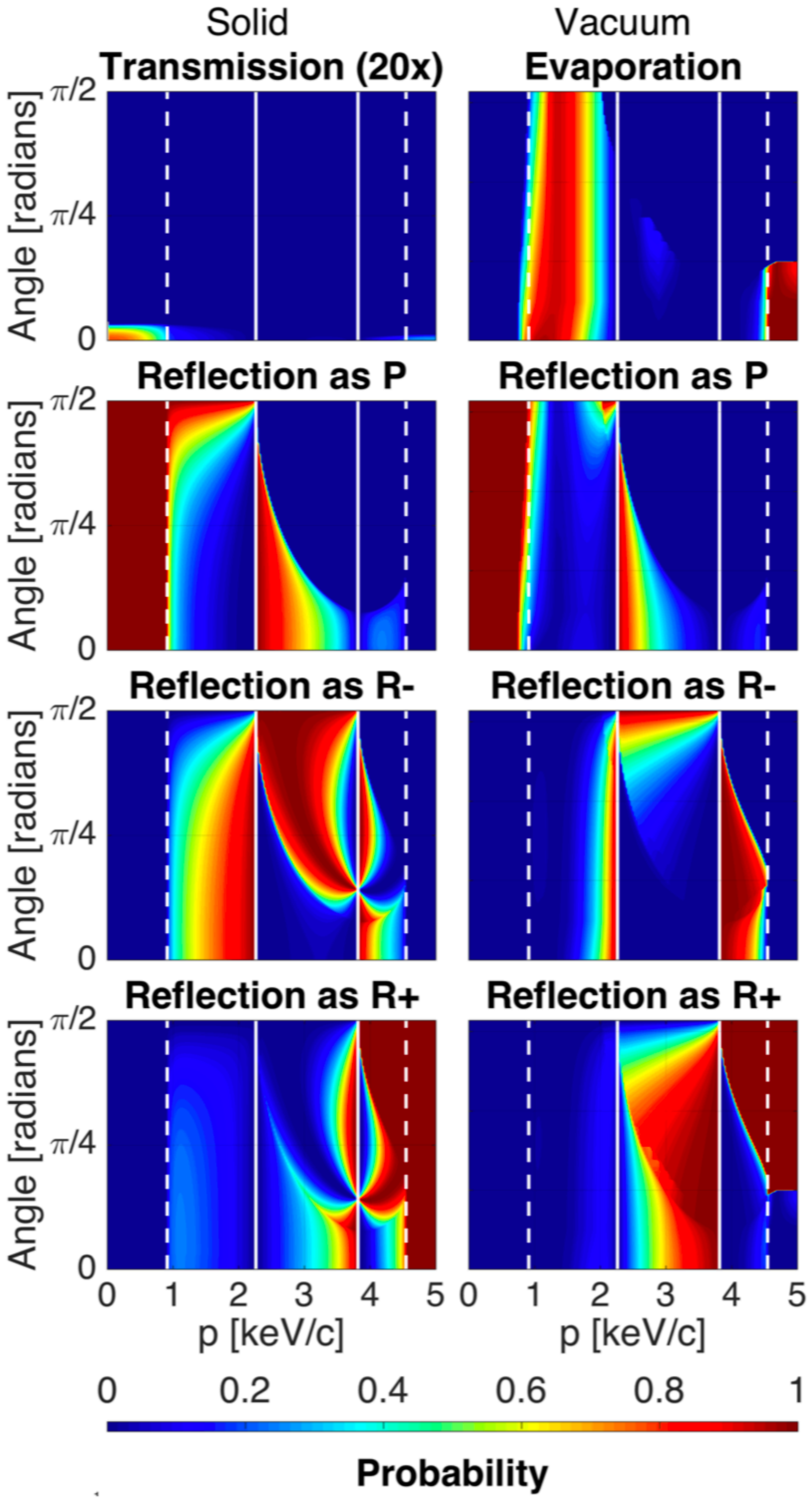
- Distinguish between different phonon distributions by arrival time in detector
    - R+ arrive first
    - P travel at a mix of slower speeds and arrive next
    - R- can't evaporate directly, need reflection on bottom to convert into R+ or P





Recent Quasiparticle Simulation




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

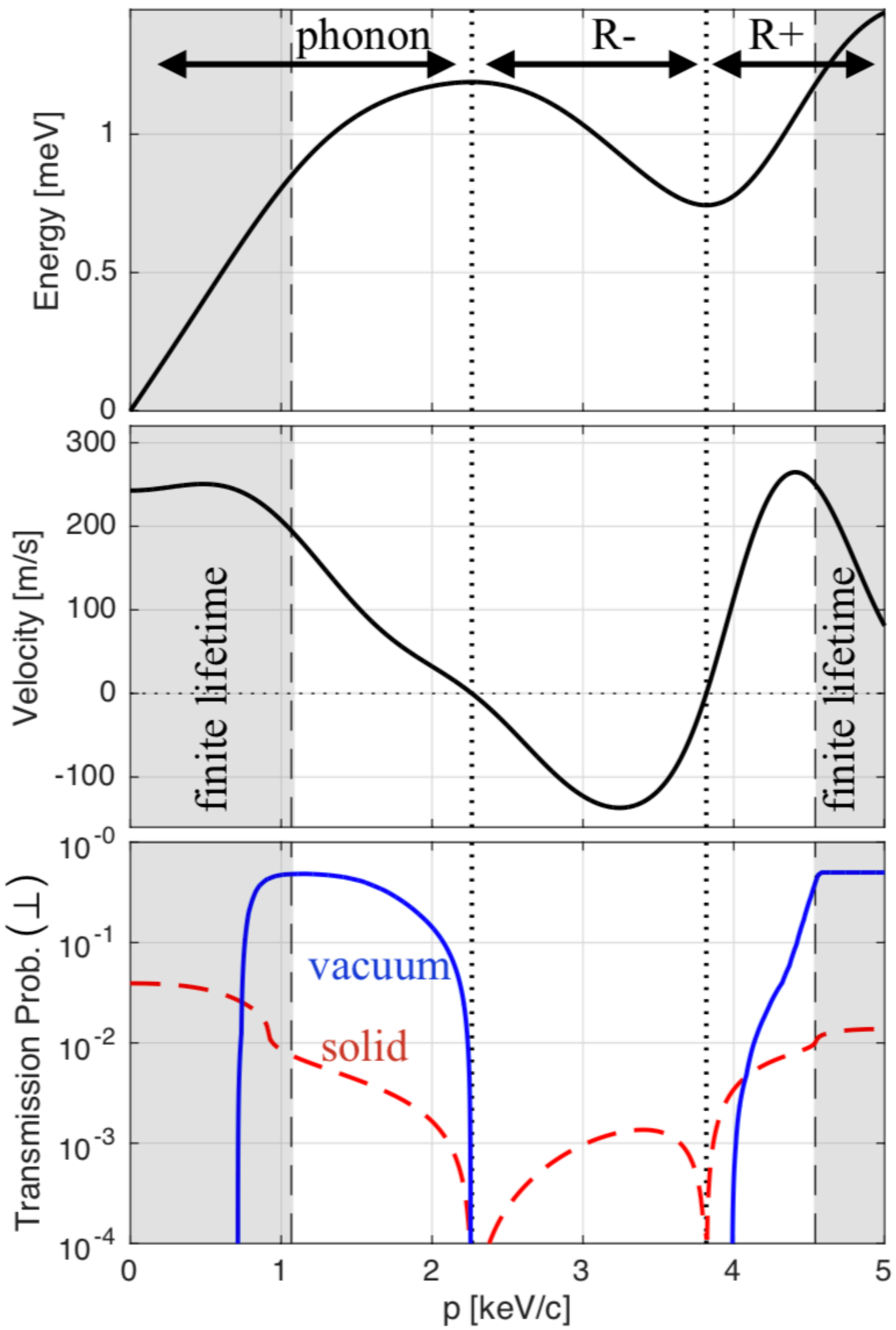


FIG. 3. Several fundamental characteristics of superfluid ^{4}He quasiparticles are here illustrated. TOP: the dispersion relation. MIDDLE: the group velocity. BOTTOM: transmission probabilities at normal incidence in two cases, incident on a ^{4}He-solid interface with solid phonon outgoing state (red 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.