HeRALD: Dark Matter Direct Detection with Superfluid 4He

Doug Pinckney on behalf of the HeRALD collaboration

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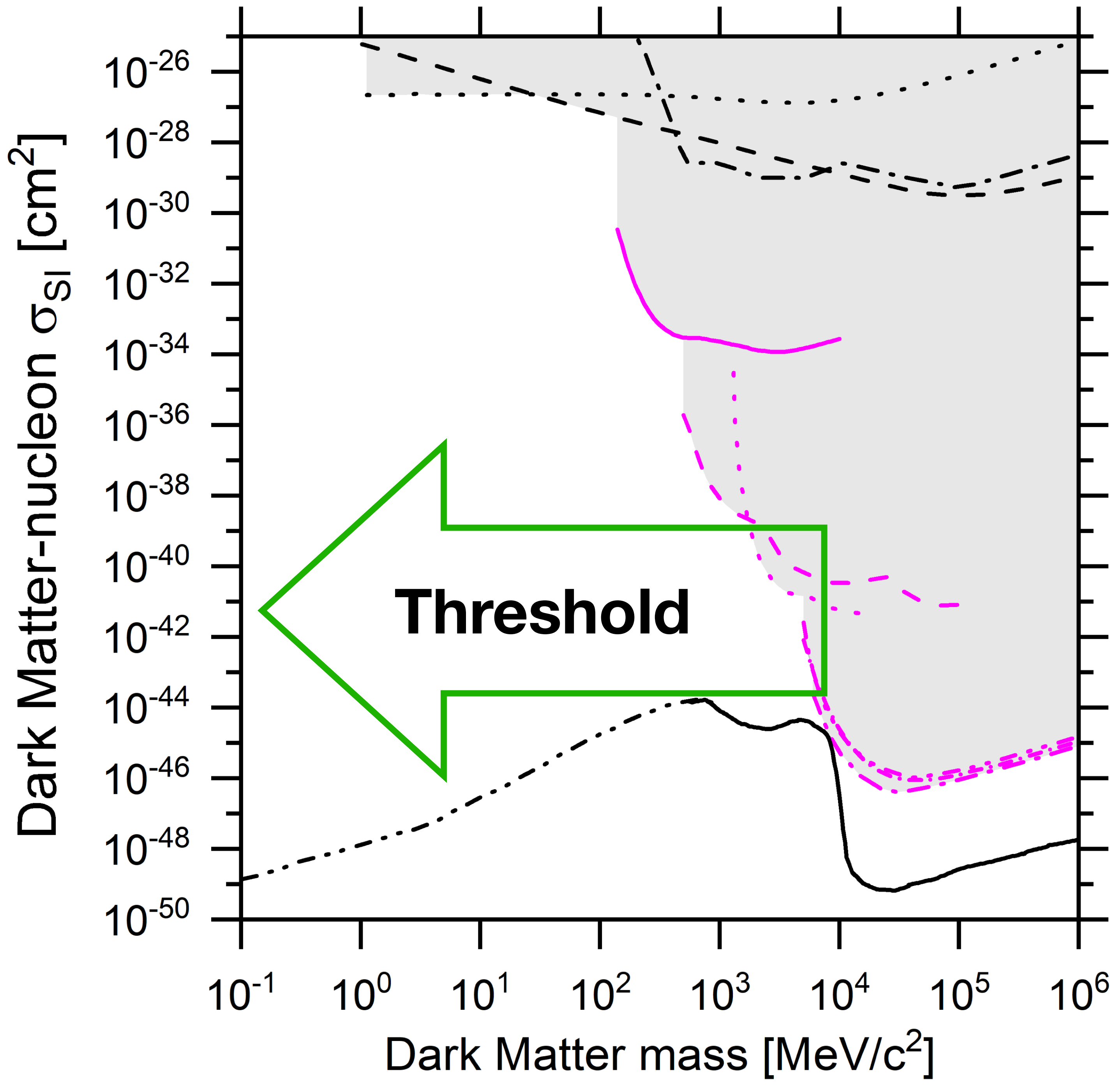
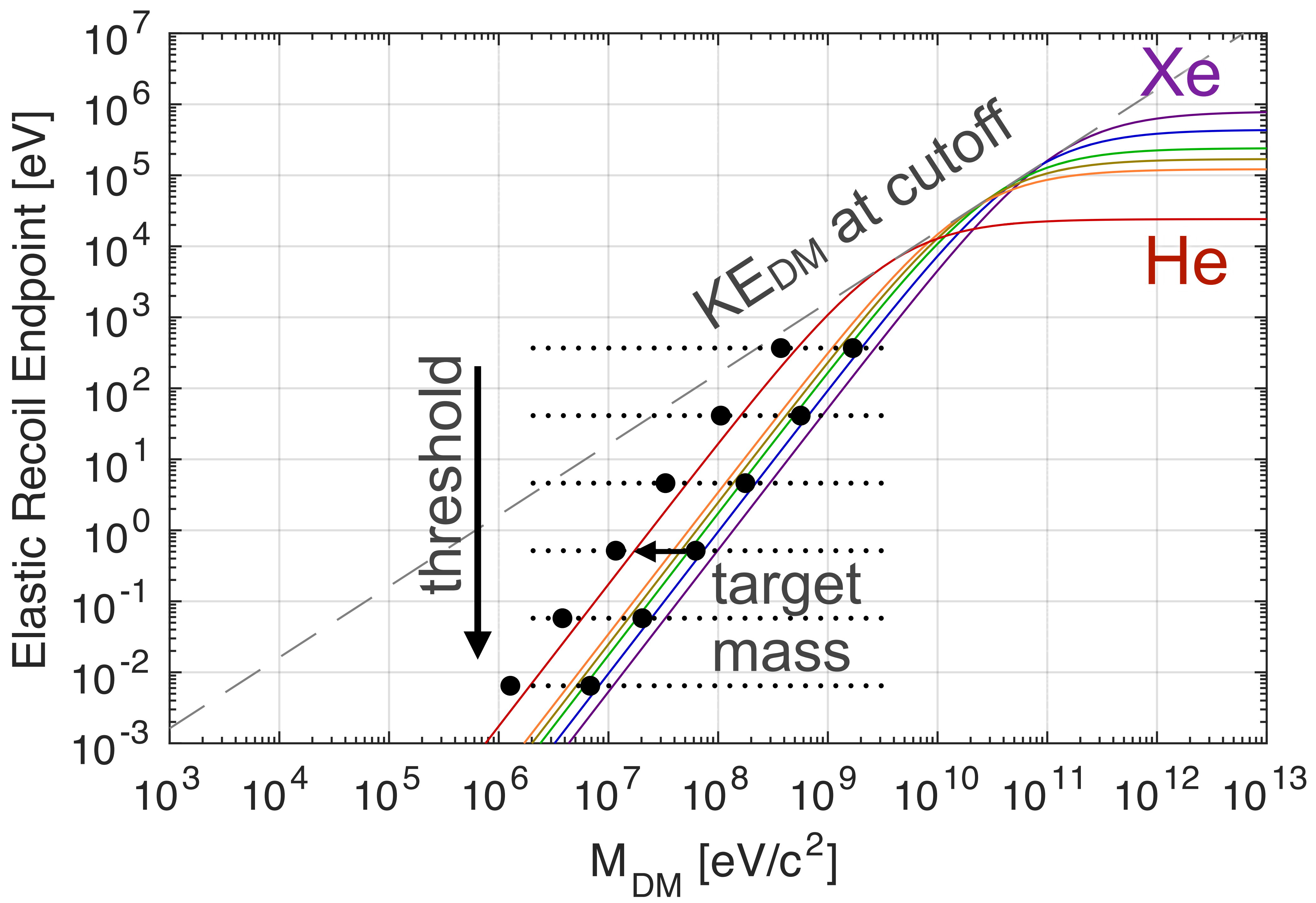
UMass Amherst

Berkeley UNIVERSITY OF CALIFORNIA

Low Mass Dark Matter Direct Detection

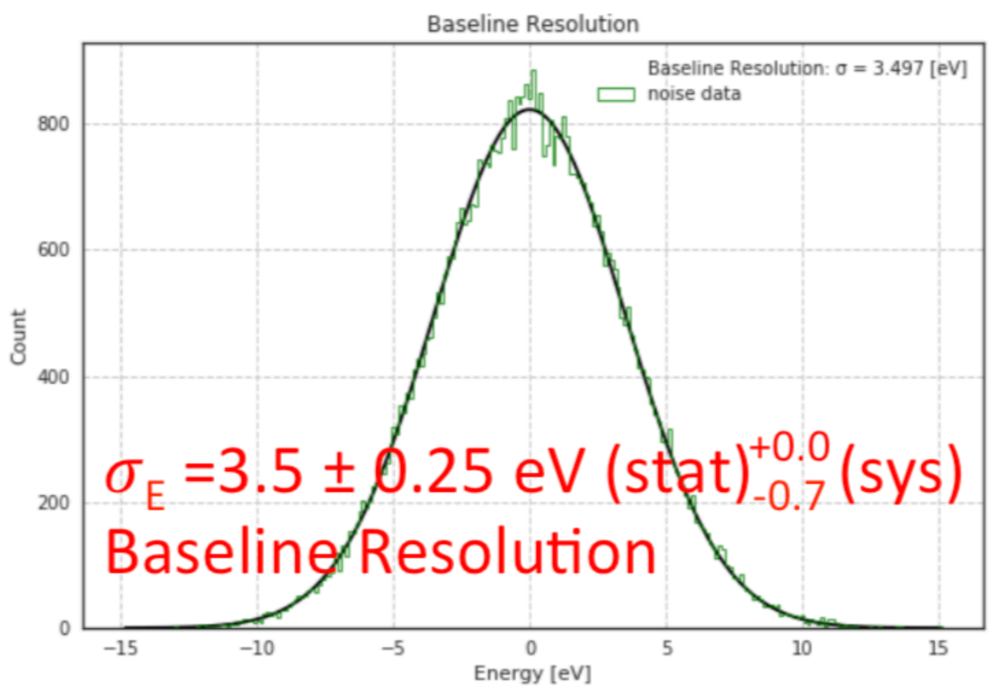
- Parameter space “wide open”, O(10 g-day) exposures set leading limits
- This space is challenging to access: for a given target mass, lower DM mass requires lower detector threshold [O(10 eV) threshold for O(100 MeV) DM]

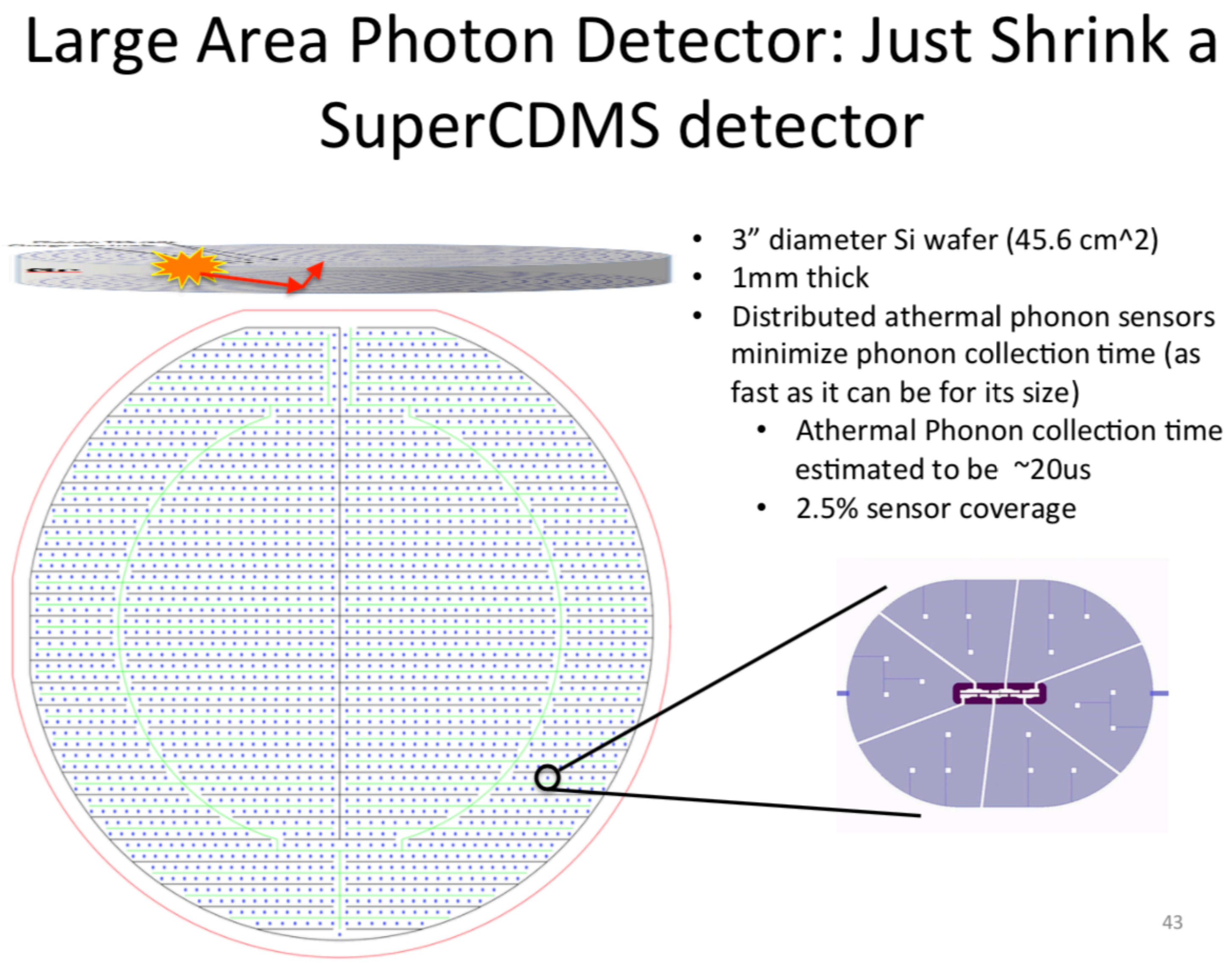


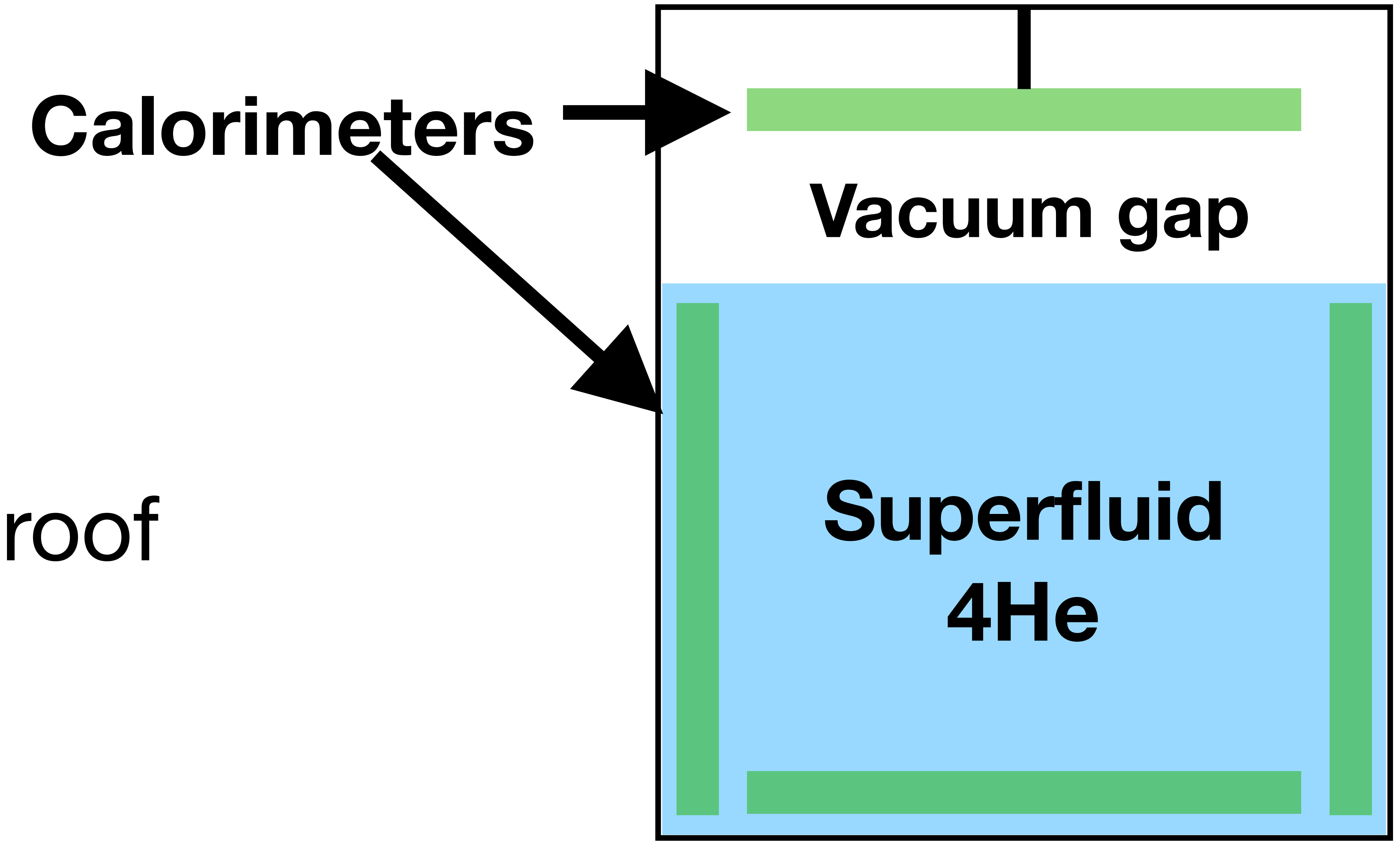


HeRALD: Helium Roton Apparatus for Light Dark matter

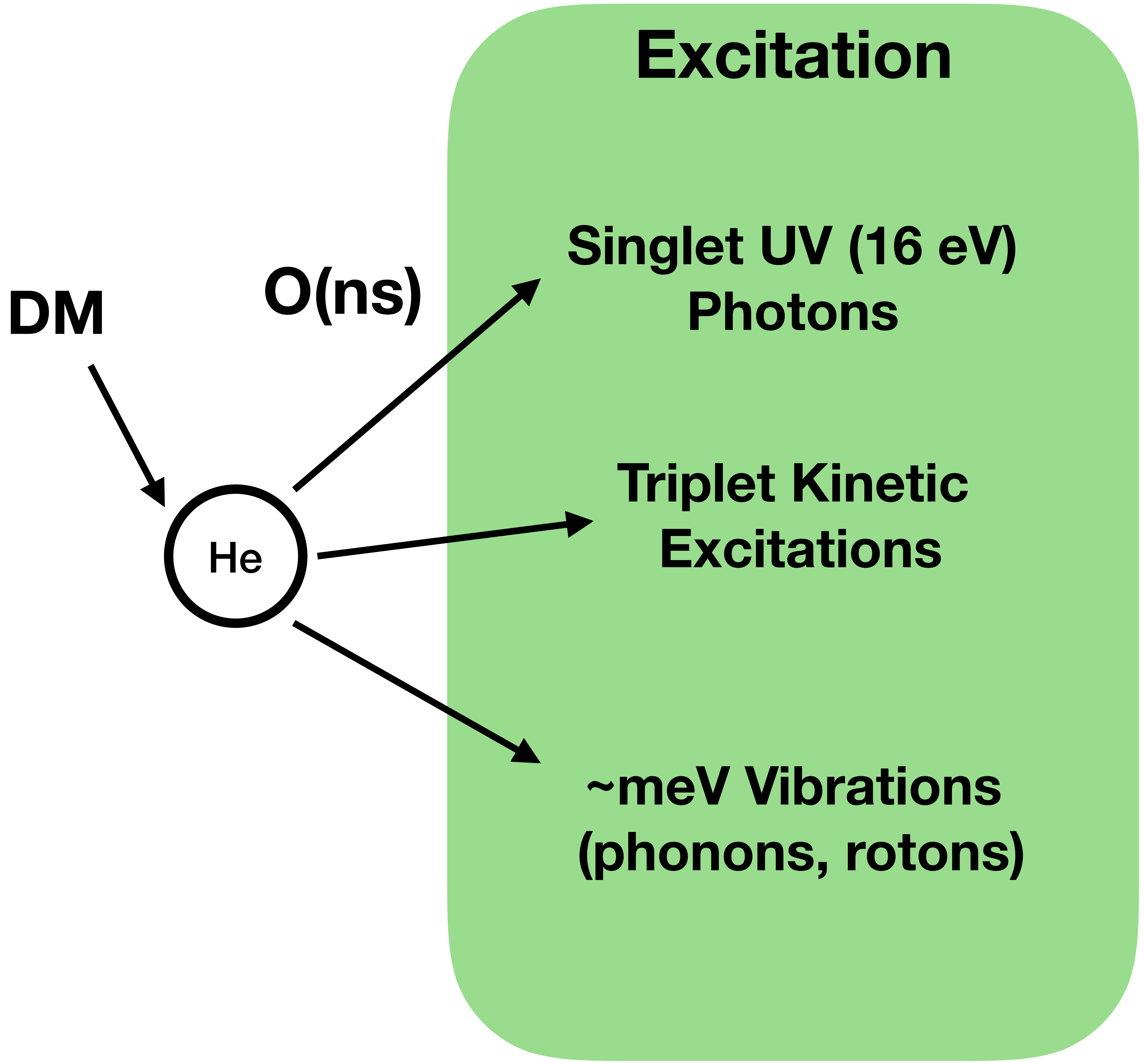
- Superfluid 4He as a target material
    - Favorable recoil kinematics
    - Recoil energy can be fully reconstructed with TES calorimetry from M. Pyle at UCB (top right taken from LBL RPM presentation)
    - Zero bulk radiogenic backgrounds
    - No Compton backgrounds below 20 eV
- HERON experiment at Brown (Seidel, Maris), proof of concept work







Excitations in Superfluid 4He



Excitations in Superfluid 4He

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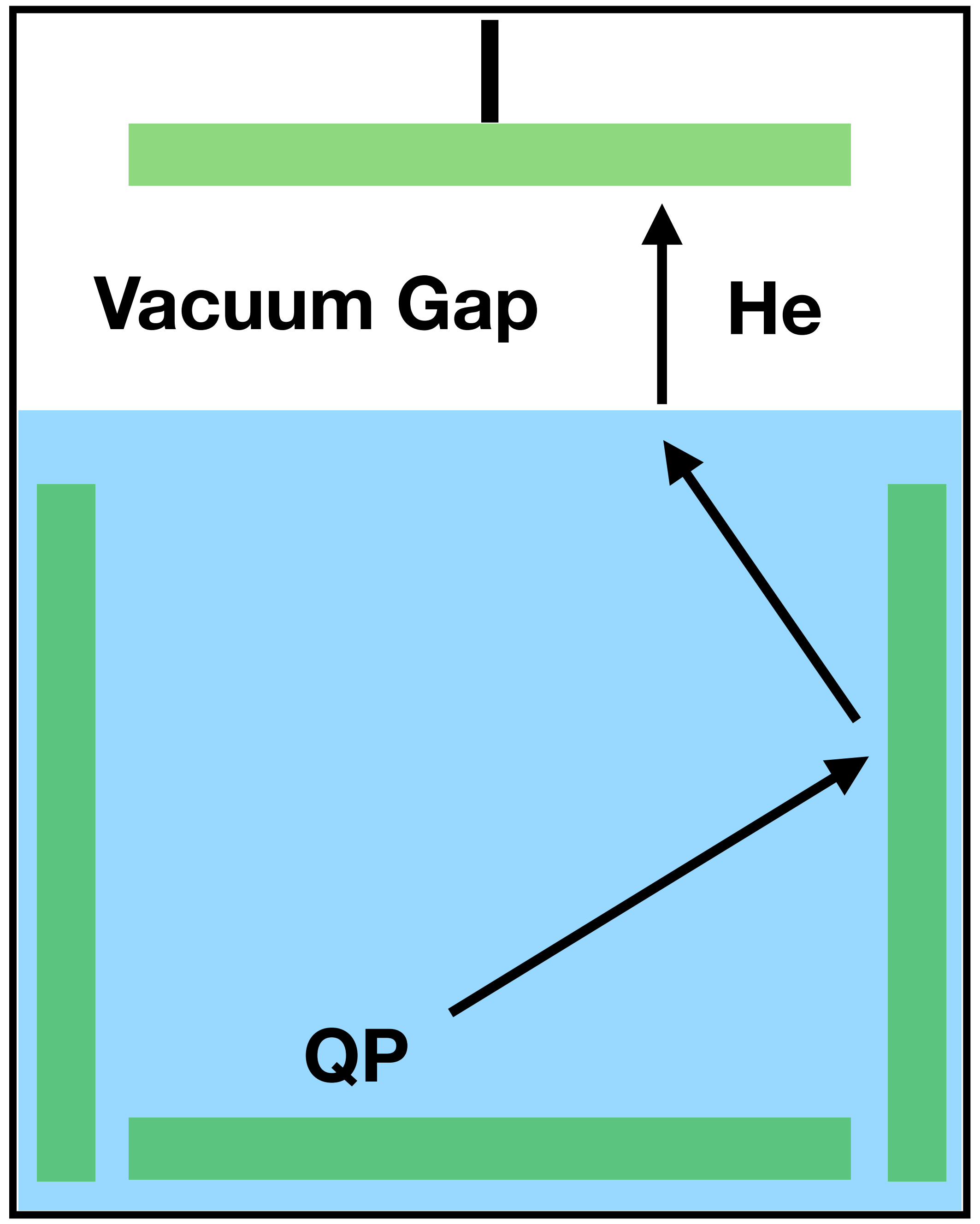
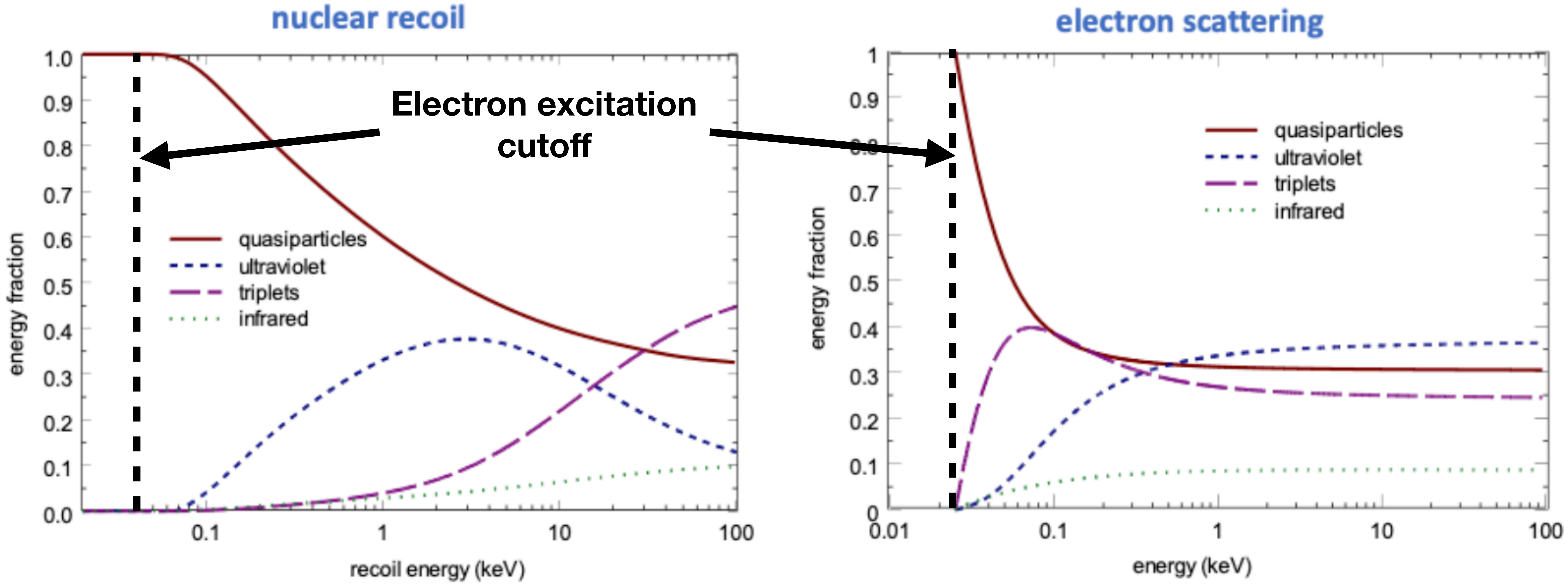
DM → He, O(ns)	Excitation	Detection Method
	Singlet UV (16 eV) Photons	Absorbed in calorimeters on 10 ns timescale
	Triplet Kinetic Excitations	Ballistic, travel at O(1 m/s), deposit energy in immersed calorimeters
	~meV Vibrations (phonons, rotons)	Adsorption of quantum evaporated He atoms on upper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



Energy Partitioning

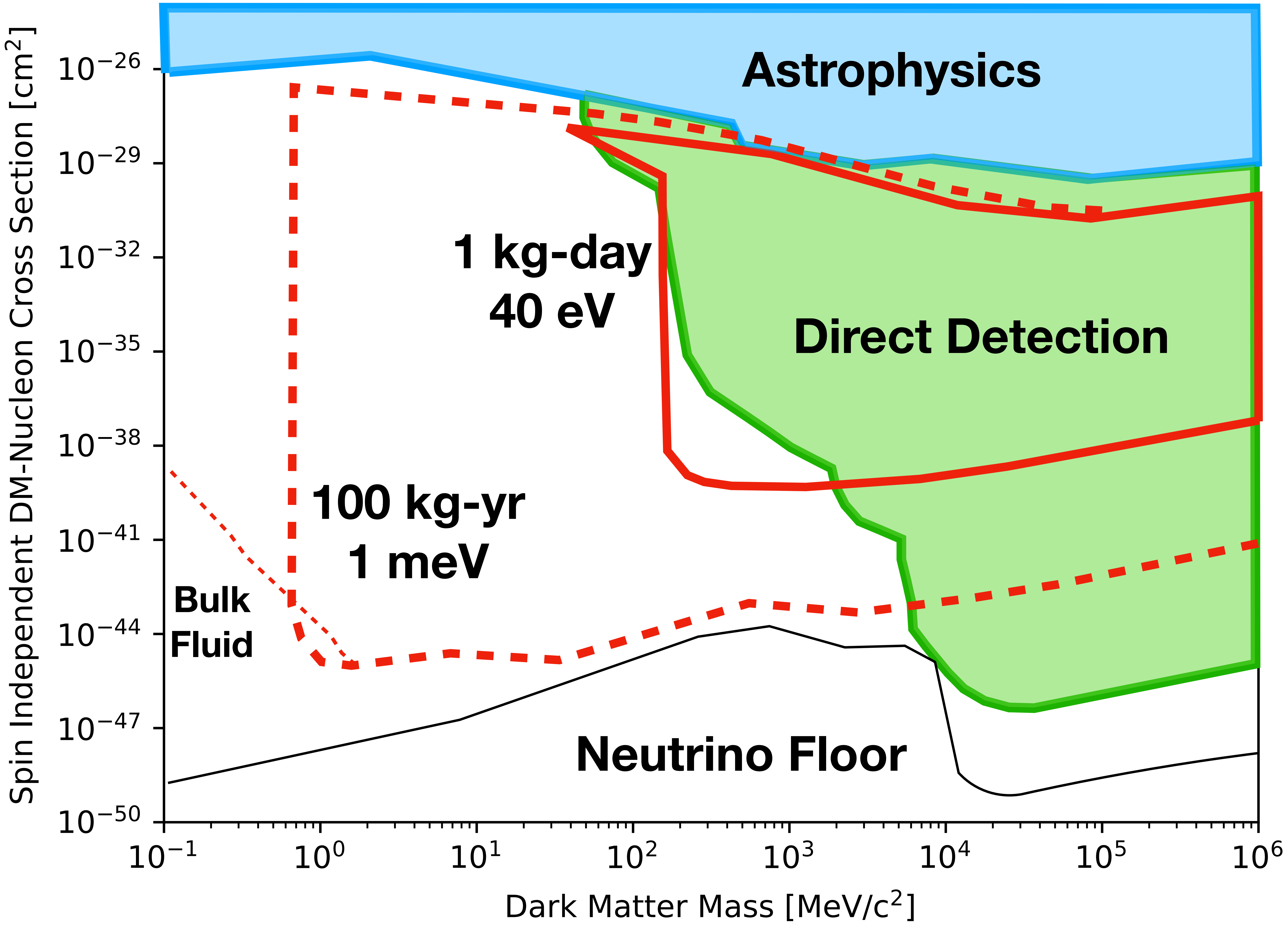
- **Nuclear and electron recoils have different energy partitioning!**
- Estimated from measured excitation/ionization/elastic scattering cross sections
- Distinguishable with signal timing



Seidel

Sensitivity Projections

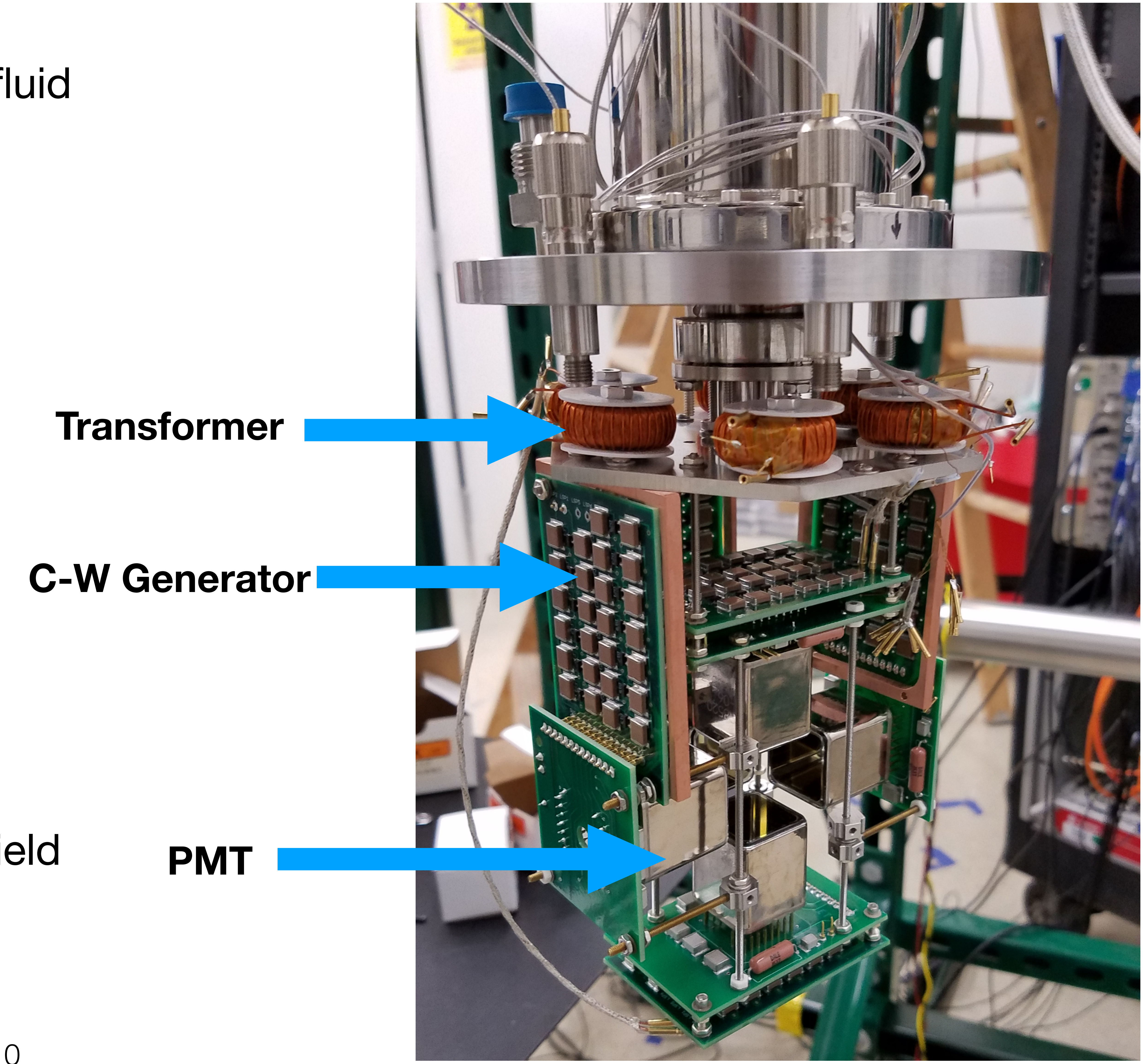
- Solid red curve, 1 kg-day @ 40 eV threshold
  - 3.5 eV (sigma) calorimeter resolution demonstrated by Pyle at UCB
  - 9x “adhesion gain”
  - 5% quasiparticle detection efficiency



Activities at Berkeley (Slides from Junsong Lin)

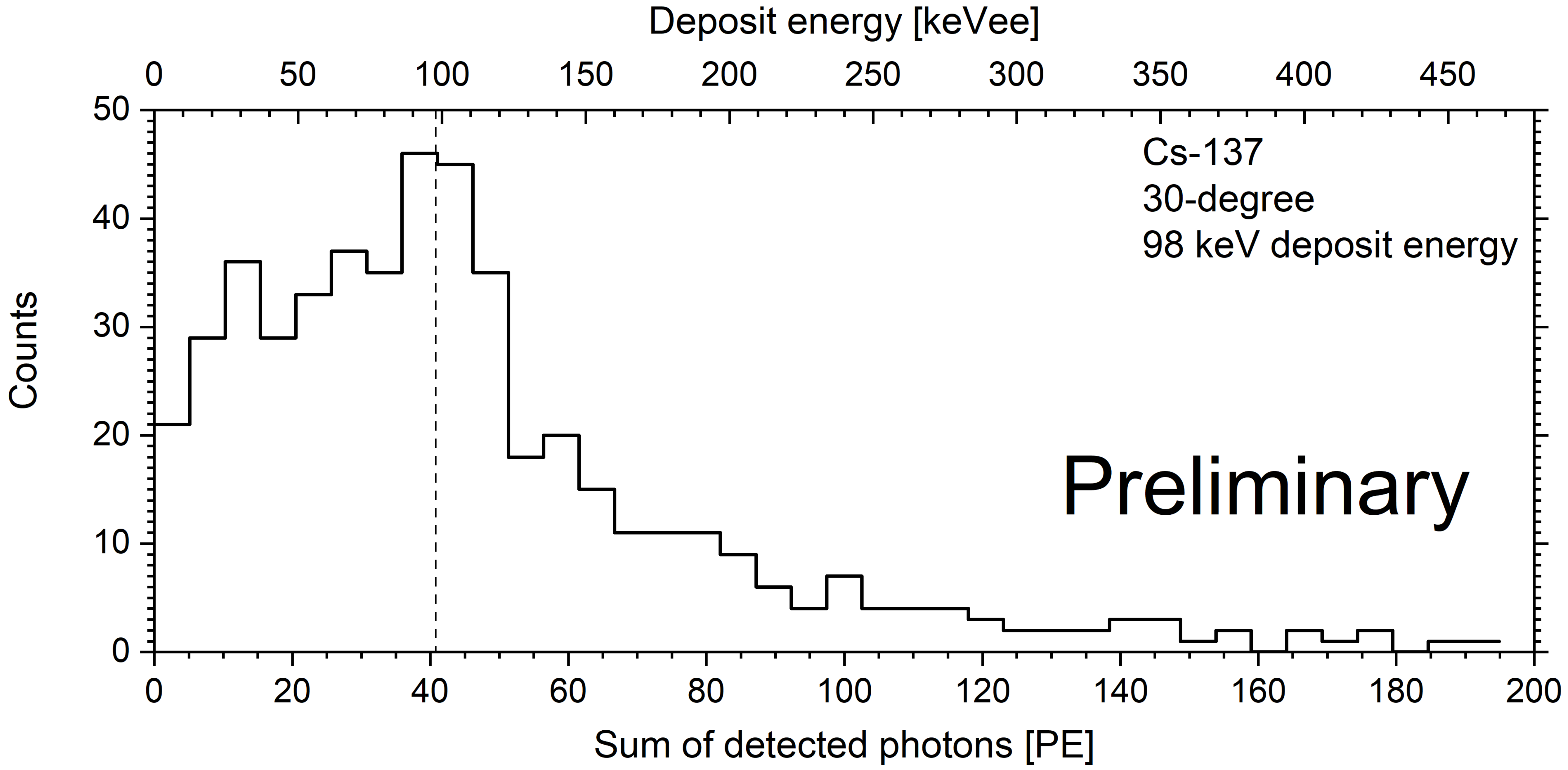
Measure nuclear recoil (NR) scintillation light yield of superfluid helium

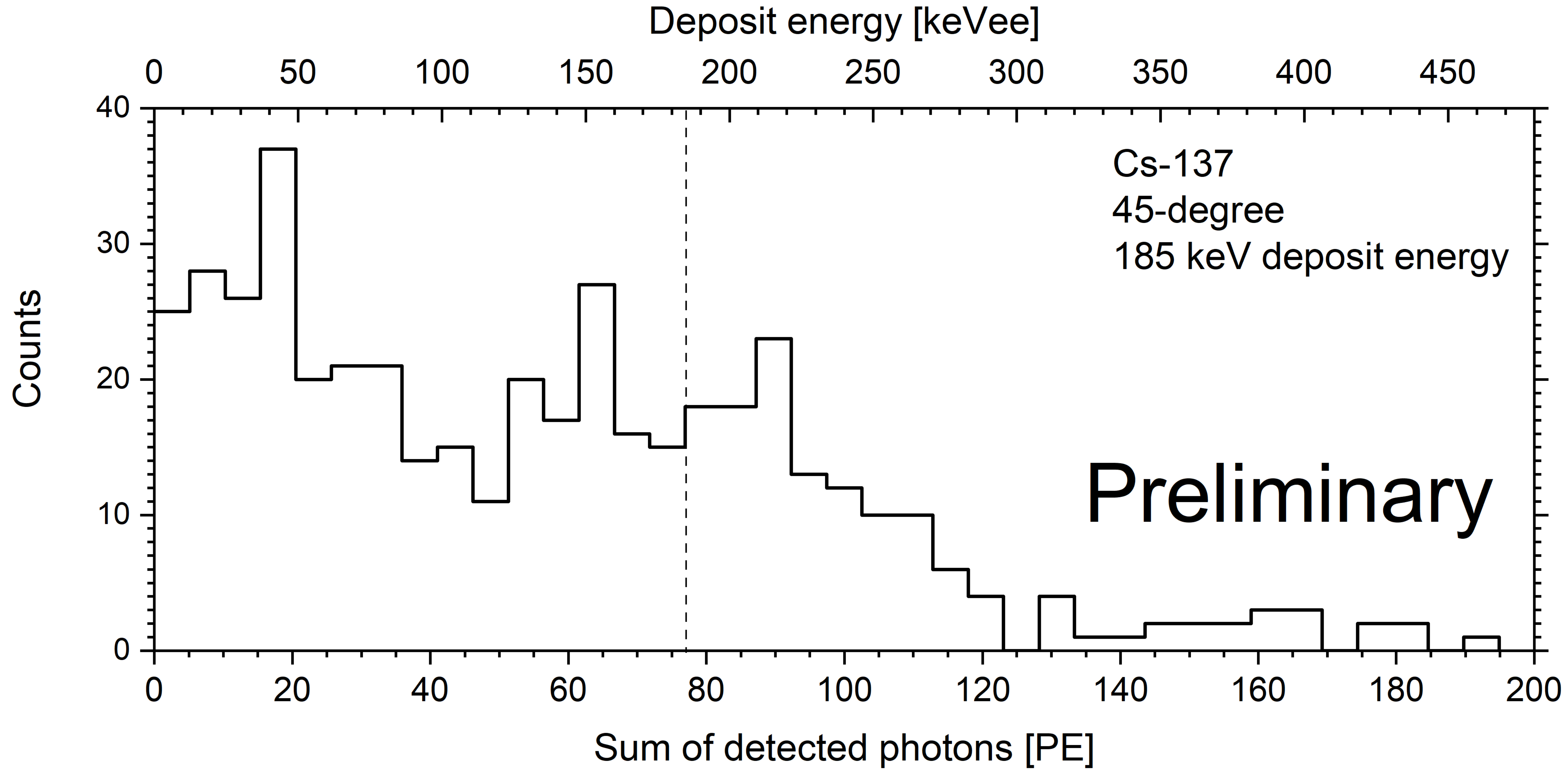
- 6 one-inch PMTs monitoring one-inch cube of LHe.
- PMTs submerged in LHe
  - Proximity leads to better light collection
- Biased by Cockcroft-Walton (C-W) generators
- TPB as wavelength shifter (LHe scintillation λ = 80 nm)
- Demonstrated single PE sensitivity at T=1.75 K
- Using Compton scattering to determine ER light signal yield
- Next step: DD generator for NR light yield



Activities at Berkeley (Slides from Junsong Lin)

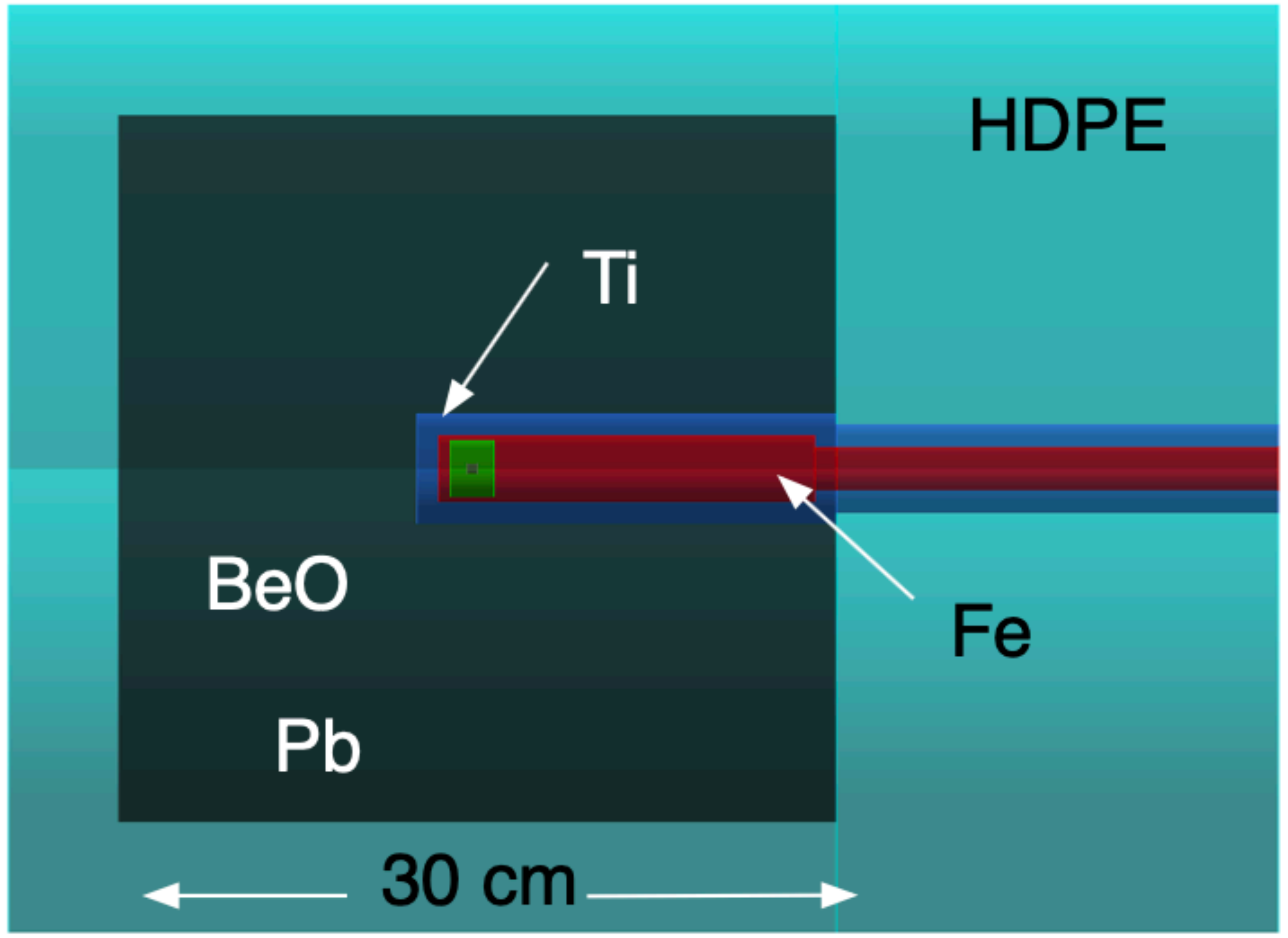
- Estimate ER light signal yield from Compton scattering peaks
- ~0.4 PE/keV_{ee} (using 3 of 6 PMTs)

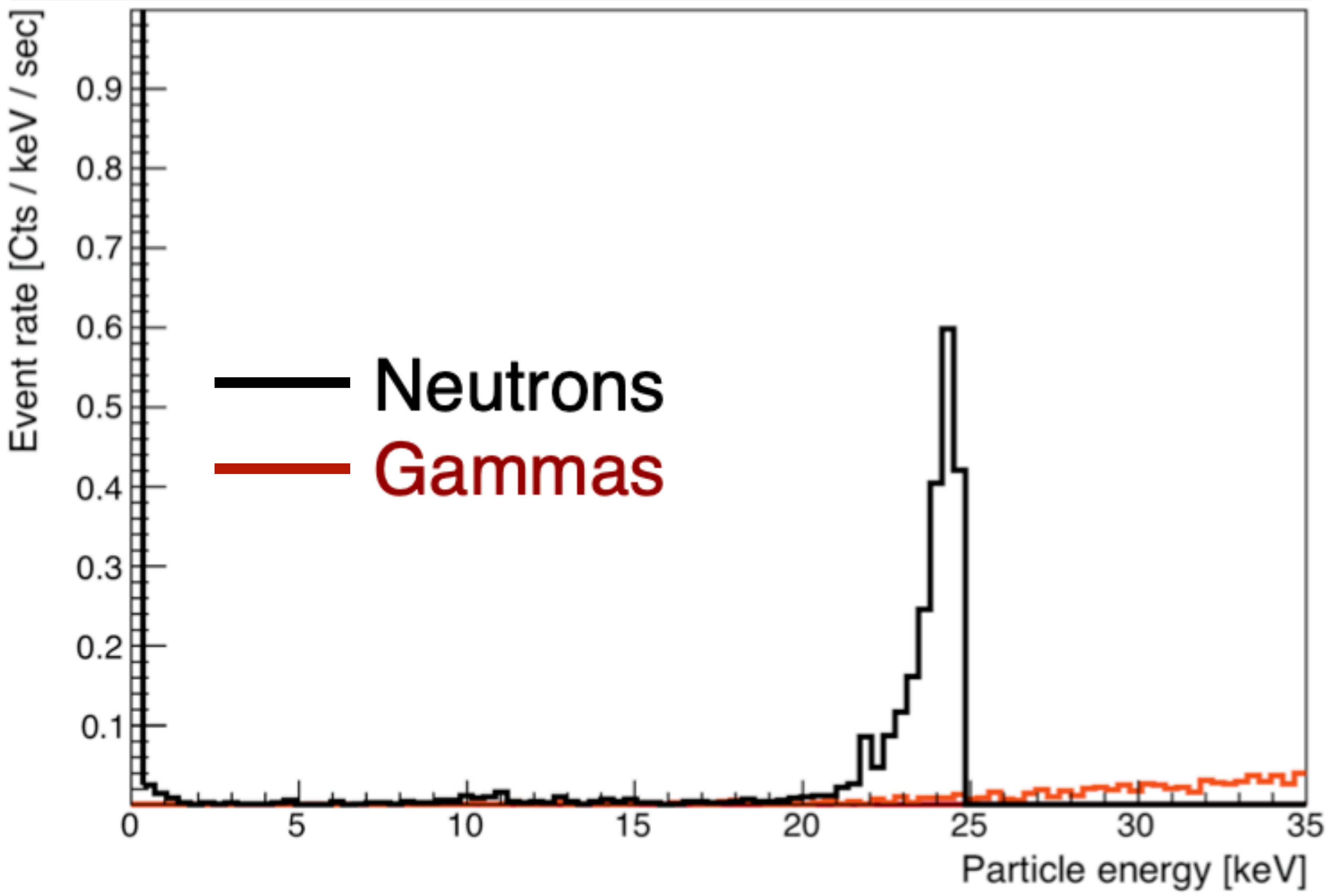




Calibration via 24keV neutrons: Photoneutron

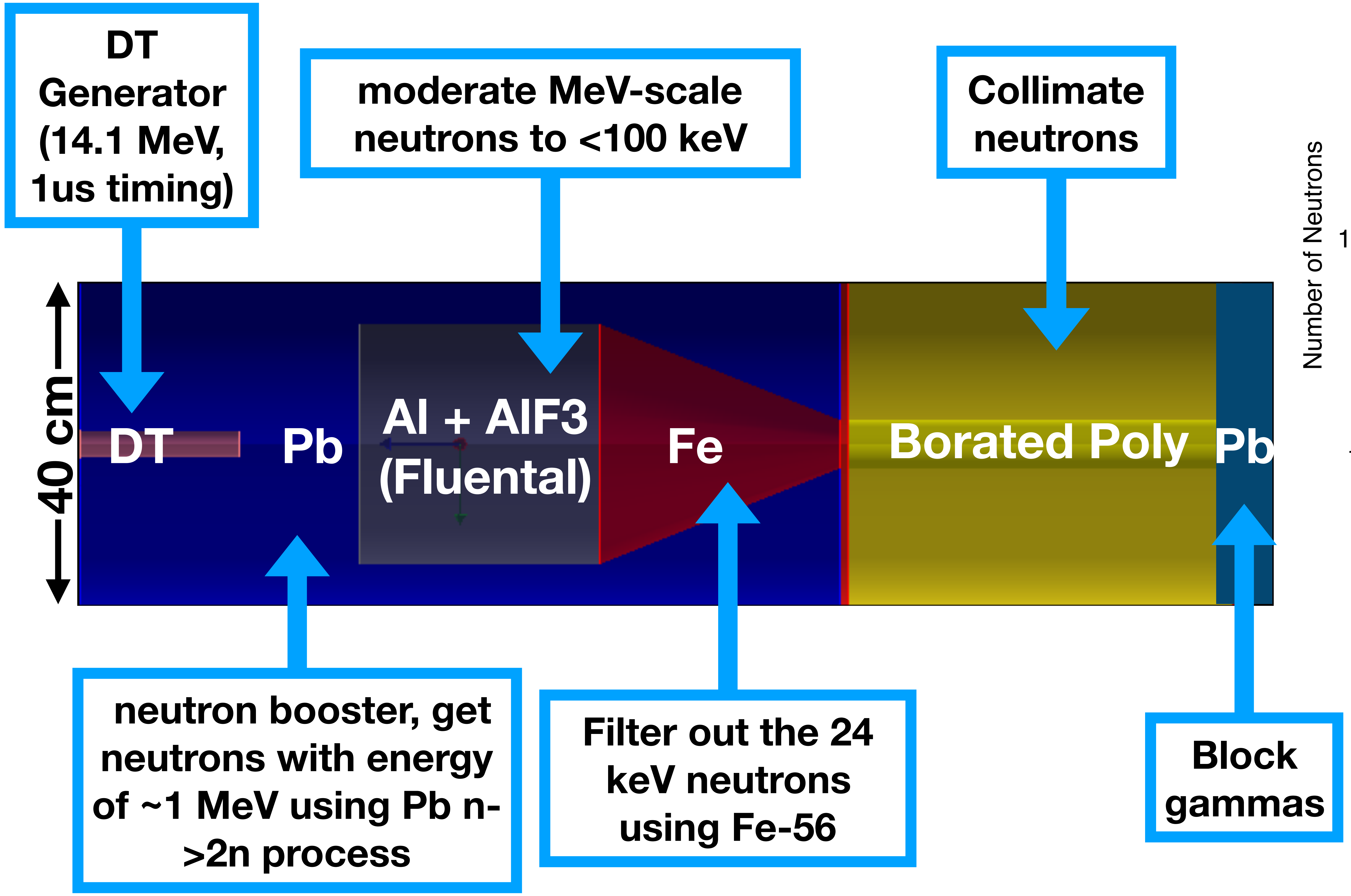
- Coincidence at 24 keV:
  - Energy of convenient photoneutron source (124SbBe)
  - Energy of ‘notch’ in cross section of Fe (~25 m interaction length)
  - Result: can surround a photoneutron source in material opaque to gammas but transparent to 24 keV neutrons
- Endpoint in He: 14 keV
- 1 GBq 124 Sb source (practical) results in a few n/s collimated neutrons

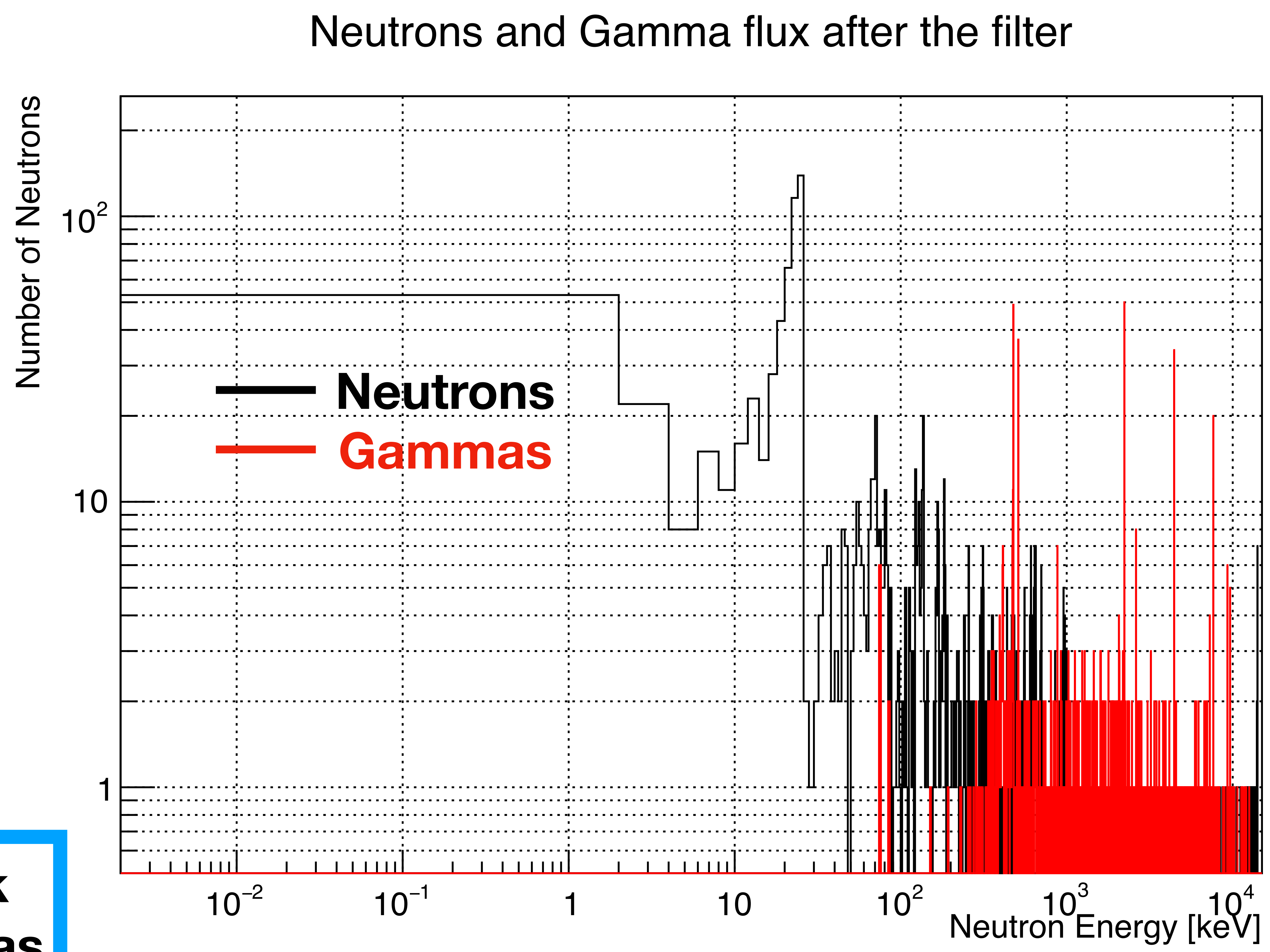




Calibration via 24keV neutrons: Pulsed

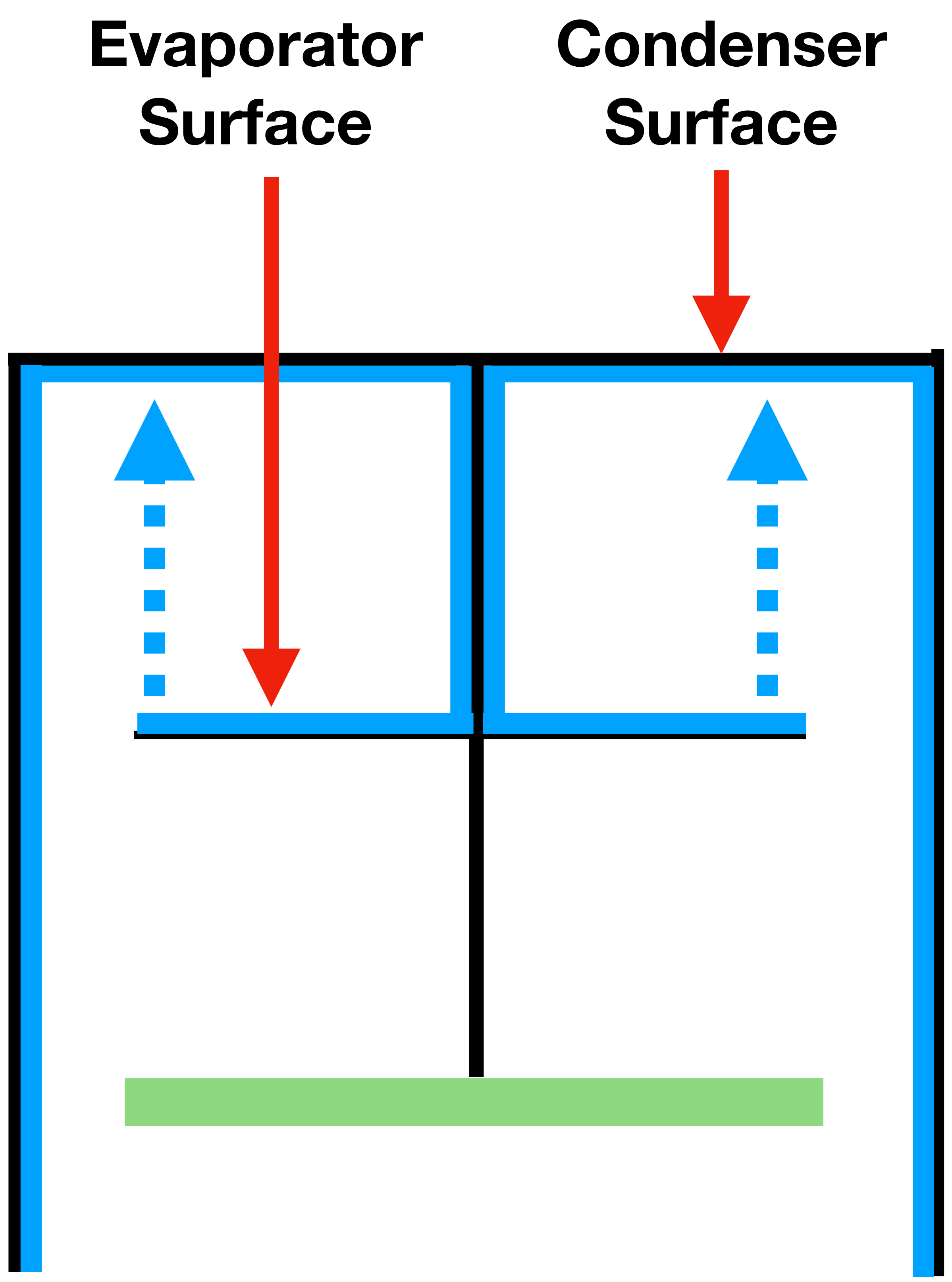
- Also looking into pulsed source based on filtered DT neutron generator





Activity at UMass

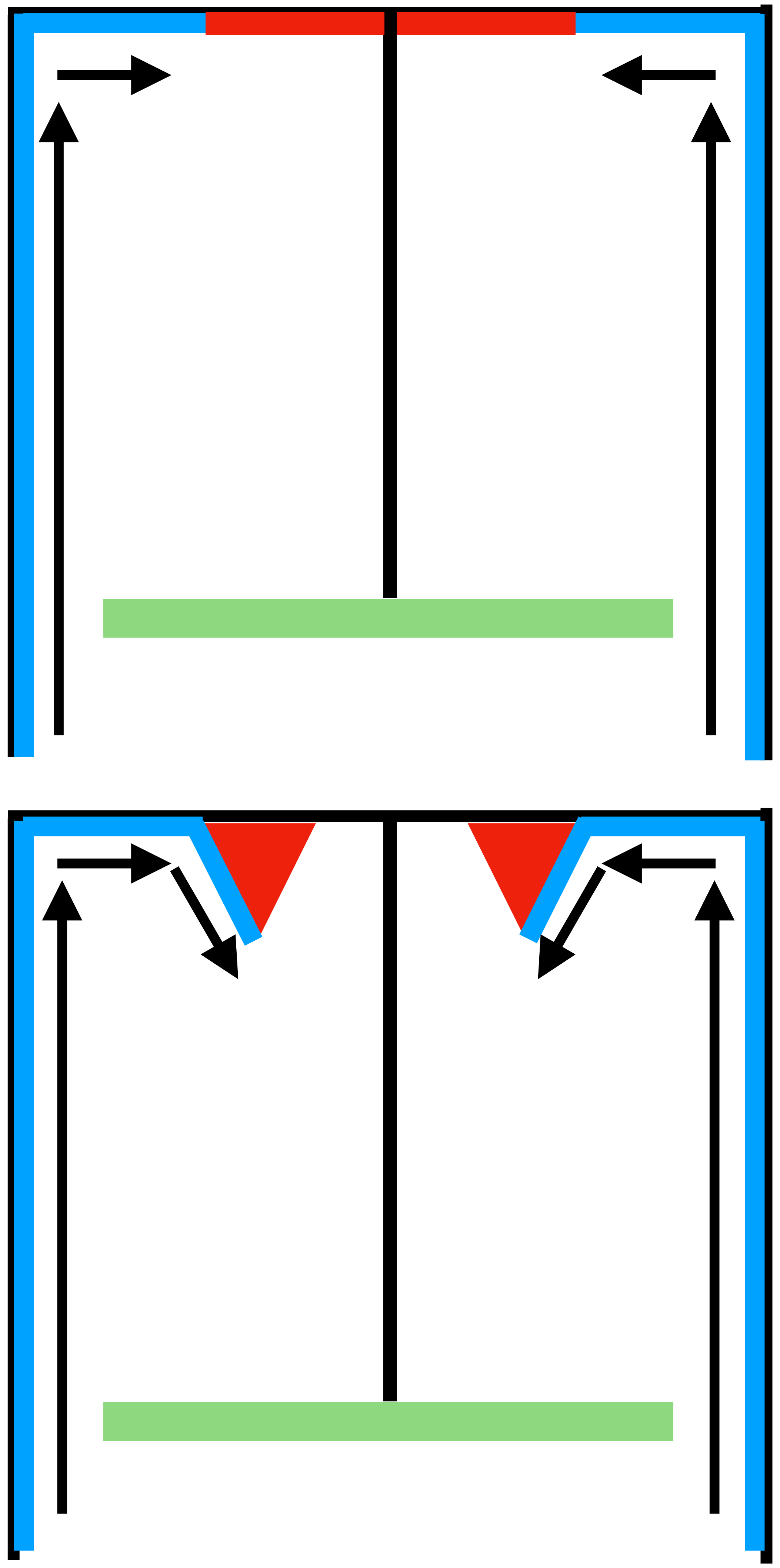
- Characterizing dilution refrigerator
- Uncertainty in how quasiparticles, triplet excitations interact at surfaces
- Achieve and enhance adhesion gain: keep calorimeter dry, use materials with higher Van der Waals attraction
    - Adapting the HERON film burner design, demonstrated but **heat load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

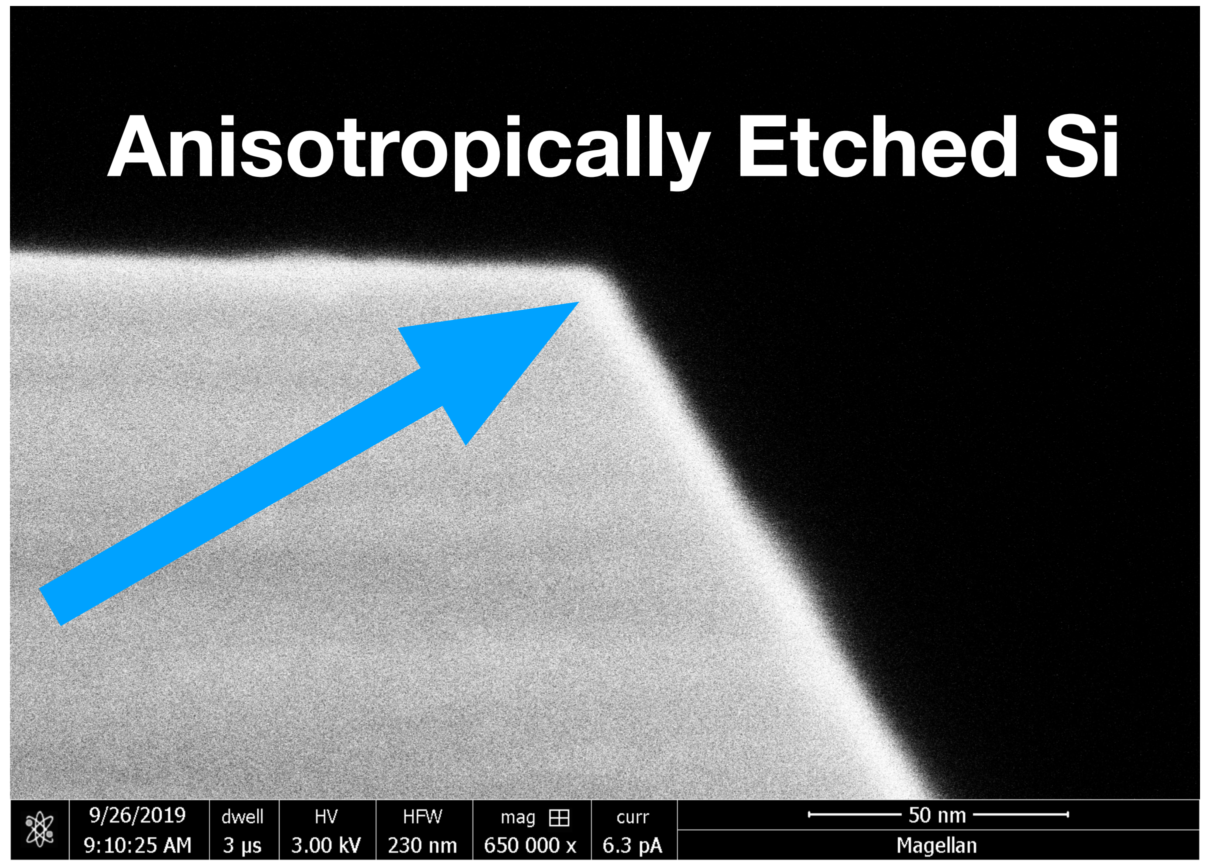


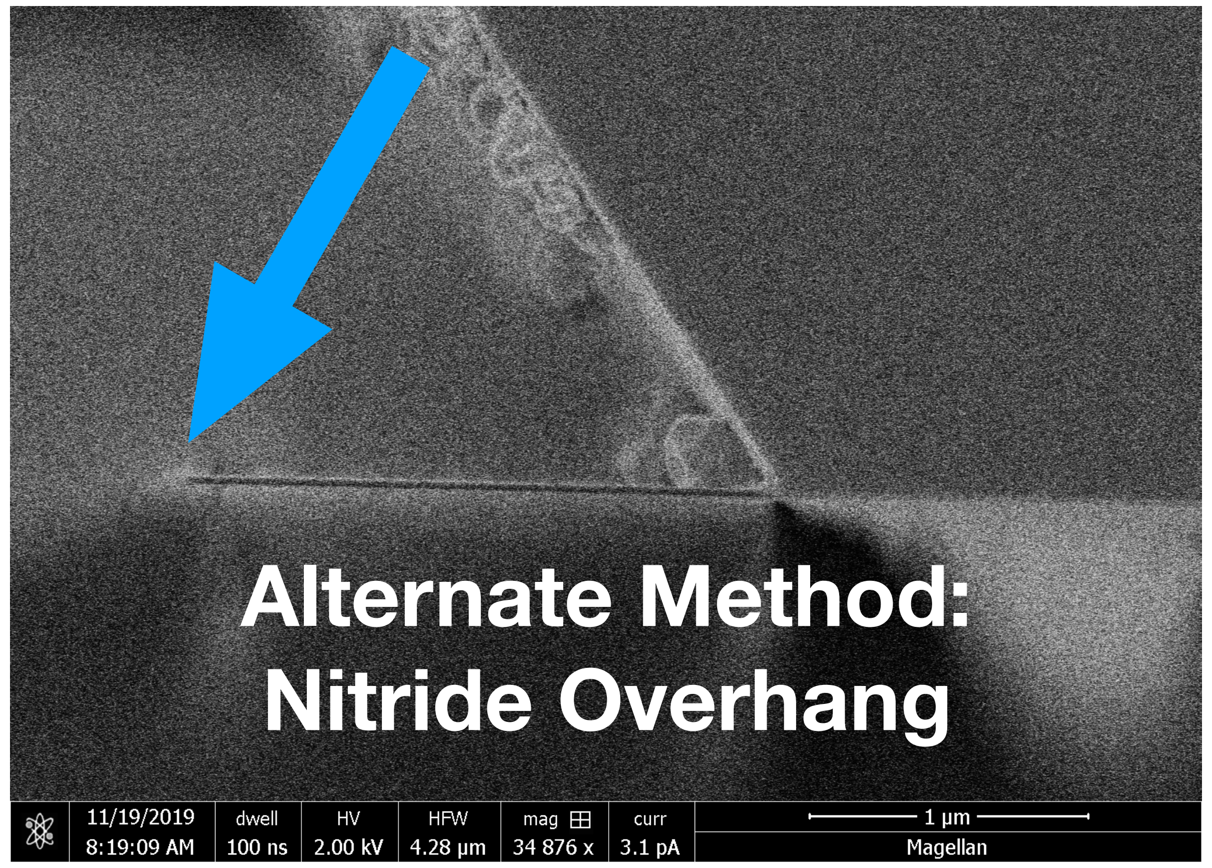
Heat Load Free Film Stopping

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

- Geometry of 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)]







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Next Steps

UMass

He Film Stopping

Quasiparticle Reflection

Adhesion Gain

Both

keV-scale Neutron Calibration

Dilution Refrigerator Characterization

Berkeley

Scintillation Yield Measurements

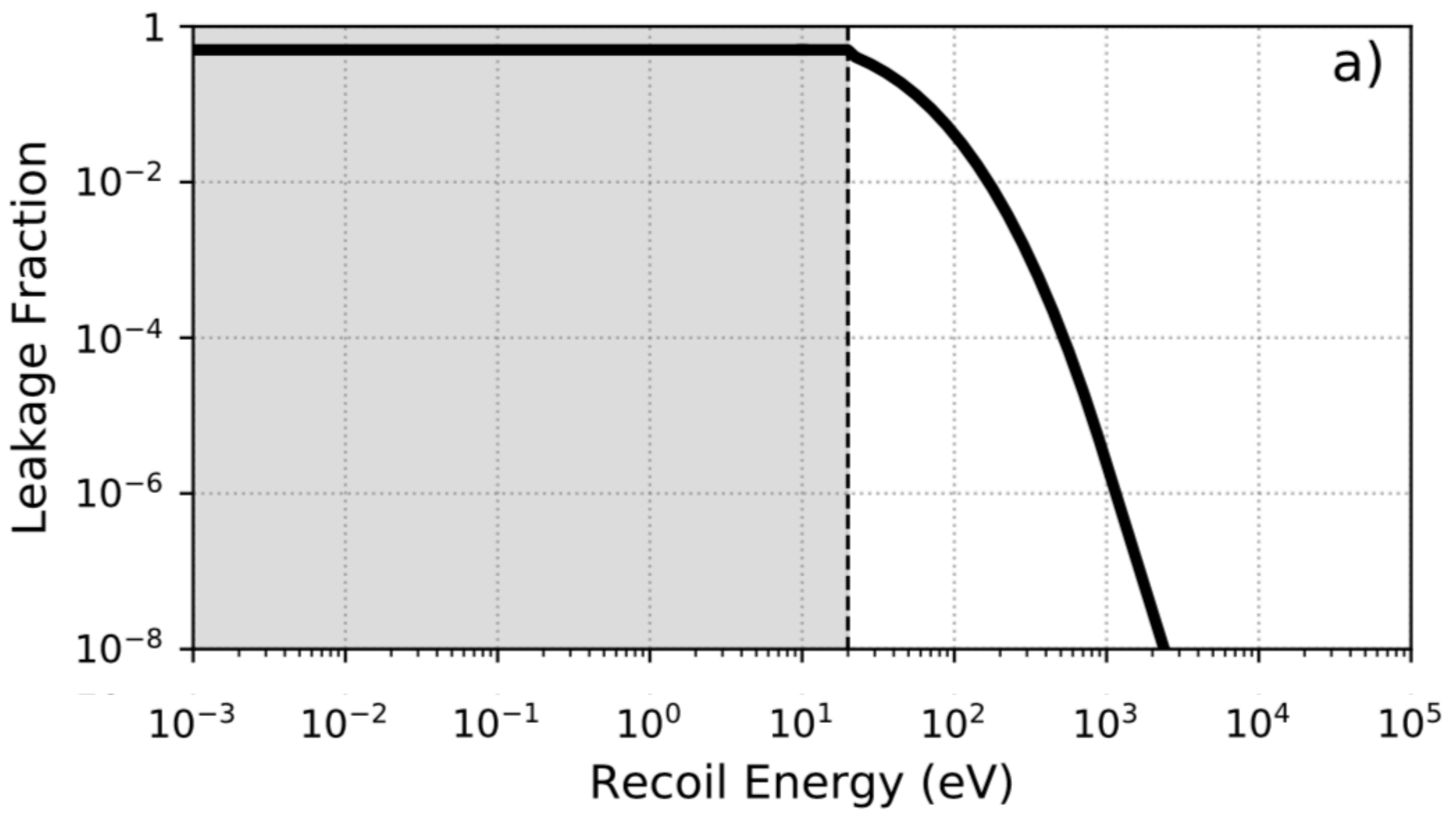
Calorimetry Testing

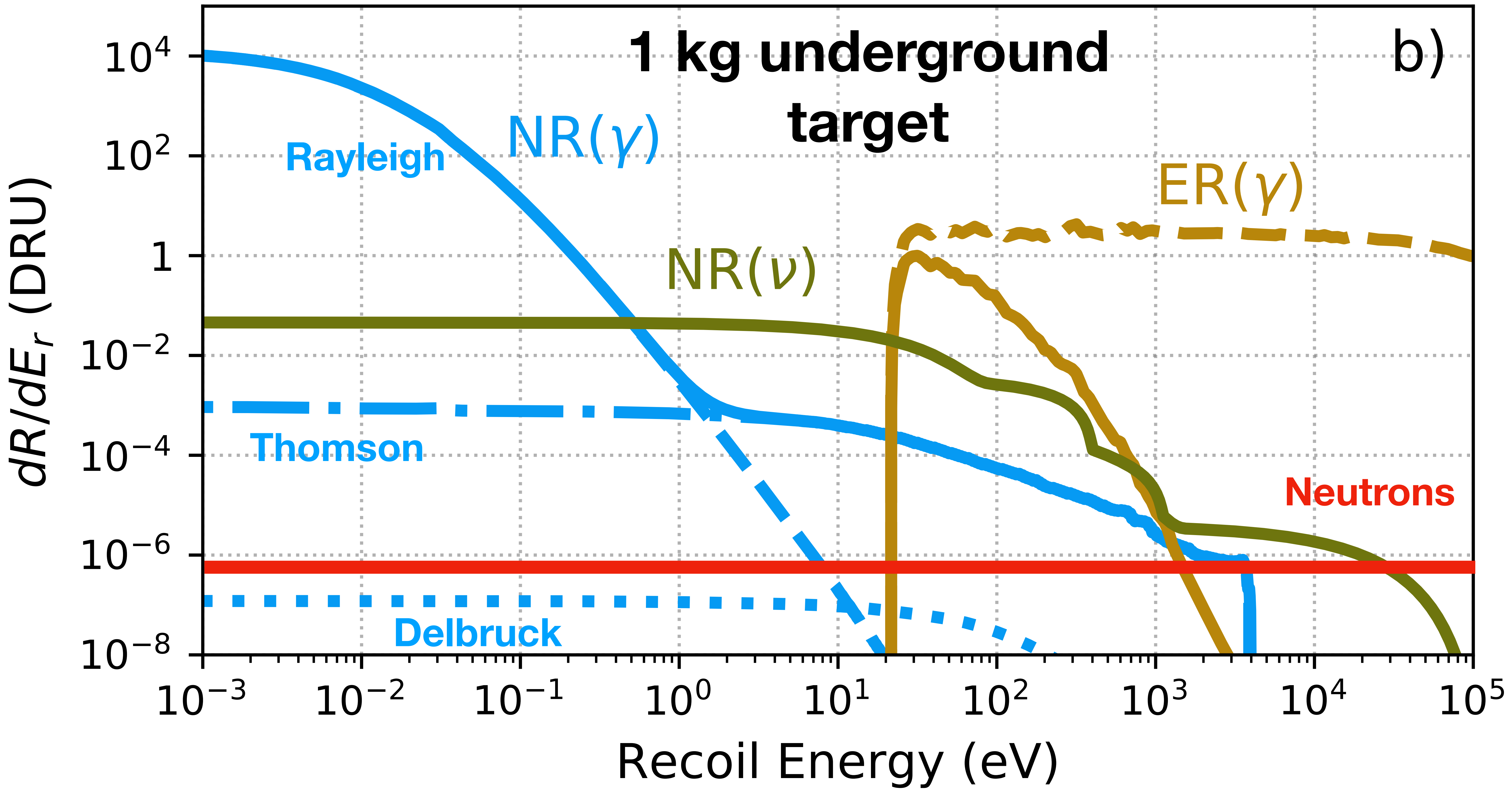
Data taking with optimized designs

Extras

Background Simulations

- Radon surface backgrounds not yet considered





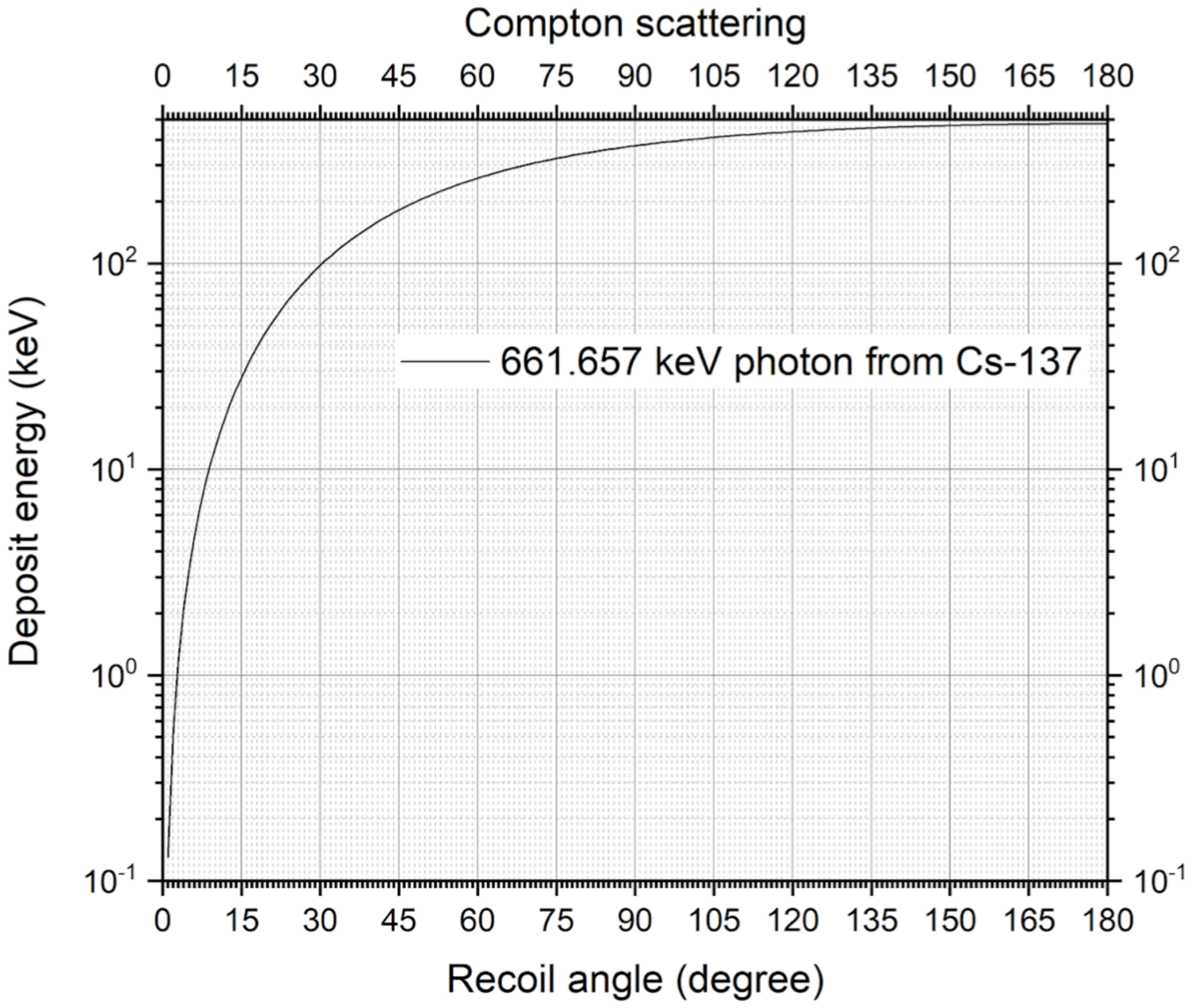
Scintillation Yield Measurement Details

- PMTs are Hamamatsu R8520-06-MOD (platinum underlay for cryogenic usage)
- PMTs and biasing system previously demonstrated to work at ~15 mK temperature vacuum in an earlier project by Junsong & co.
- Cockcroft-Walton (CW) generator directly generates the different individual voltages needed by different dynode stages of the PMT. So no voltage-divider resistor circuit needed.
- Only a few volts AC needed from room temperature, no need for high-voltage cryogenic feedthrough

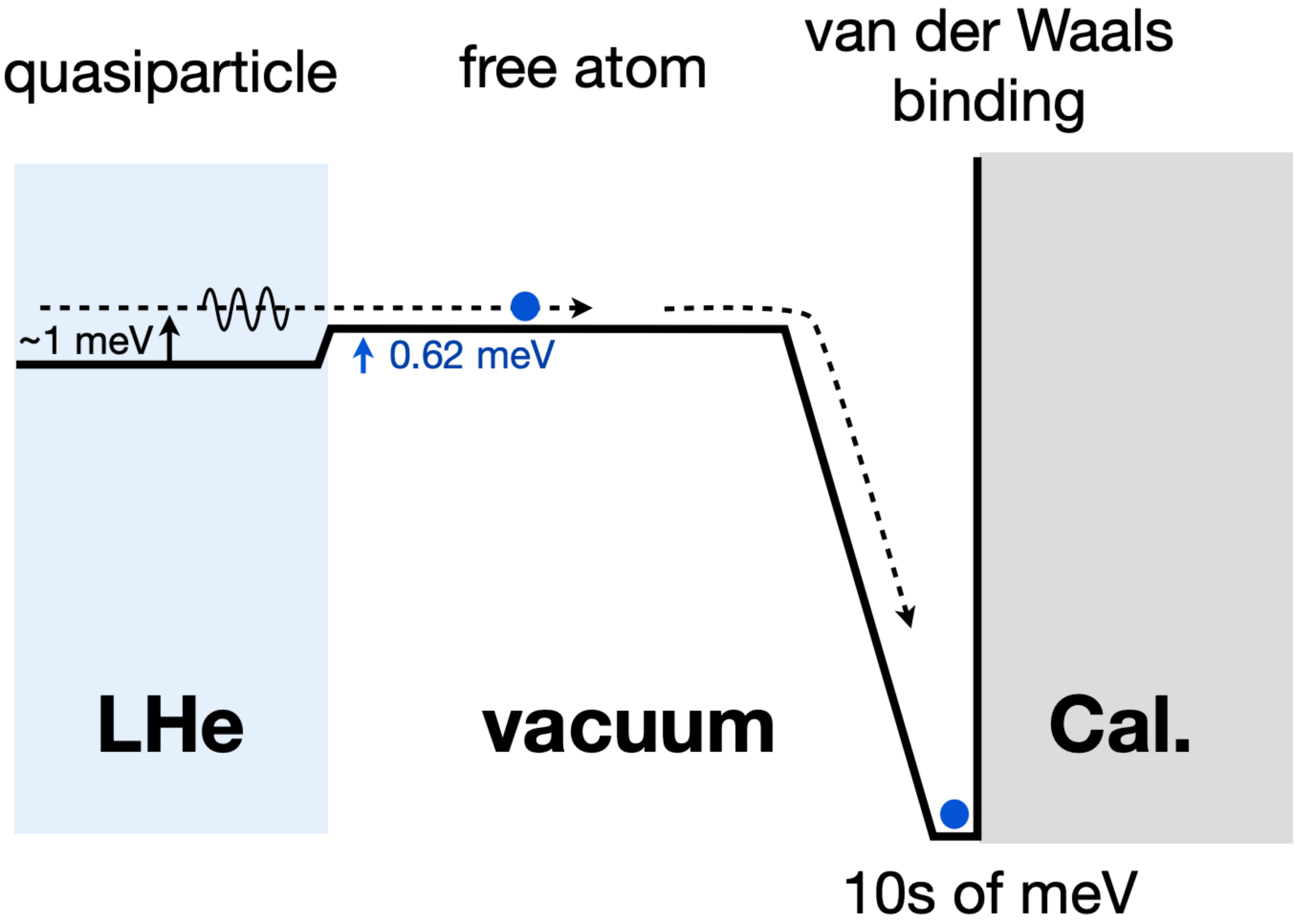
More Scintillation Yield Measurement Details

- For Compton scattering, we used a 2” diameter by 2” height NaI detector as far side detector to determine the recoil angle.
- For DD generator, we will use a 5” diameter by 5” height BC-501A liquid scintillator detector as far side to determine the recoil angle.
- For both cases, coincidence is used to select true events.
- Currently, I only understand the single PE area from 3 of the 6 PMTs well to sum up their area

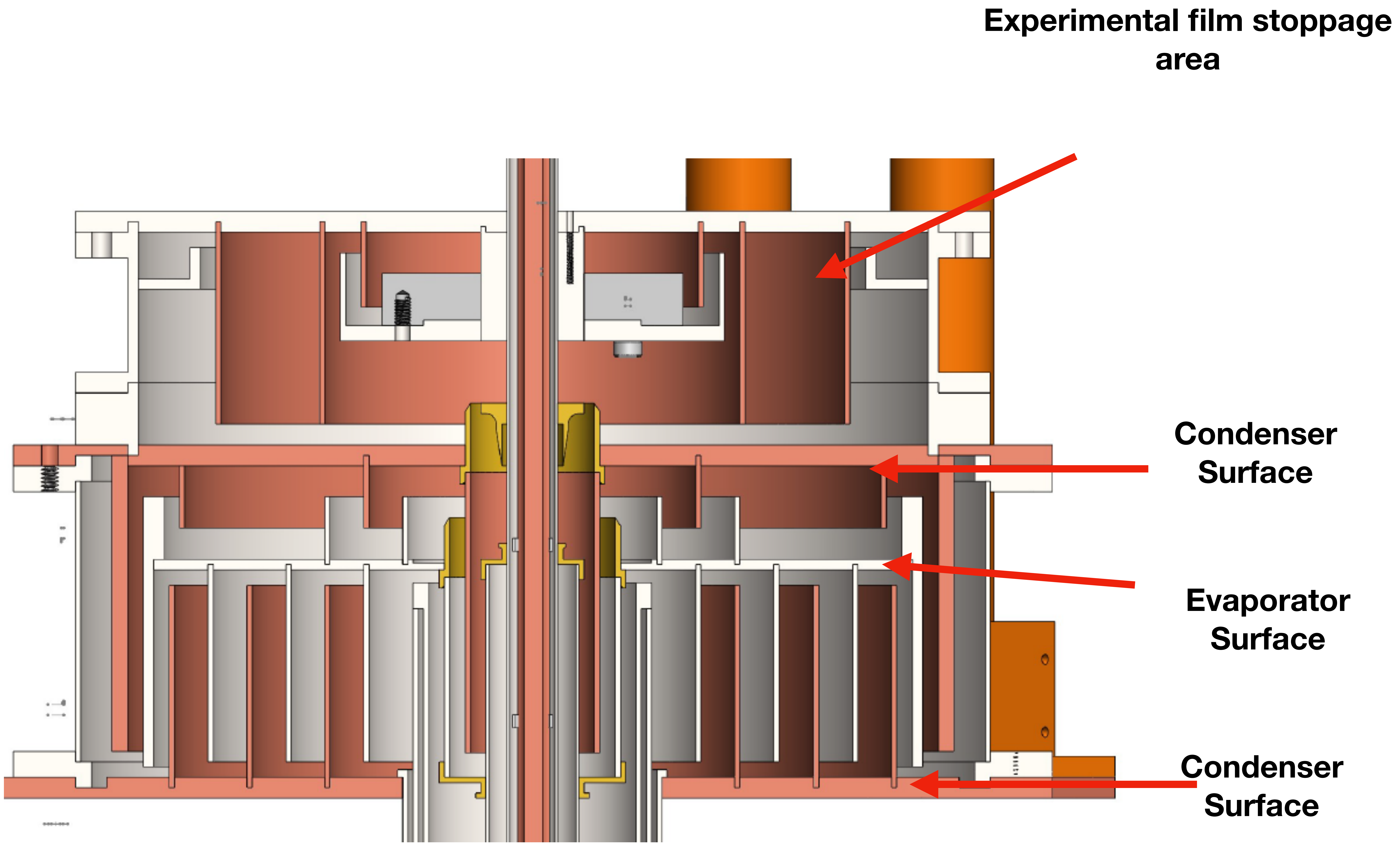
Helium Compton Scattering



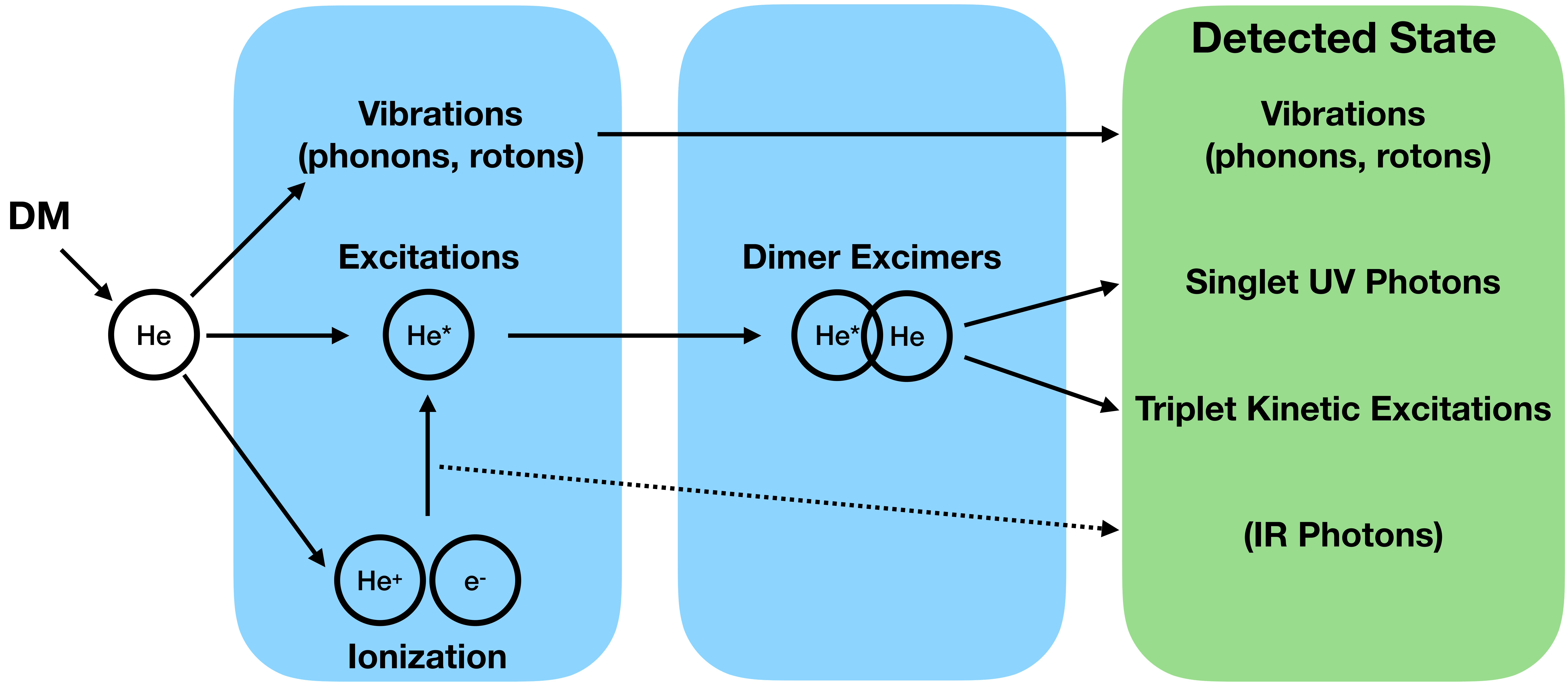
From Scott Hertel



Film Burner Model

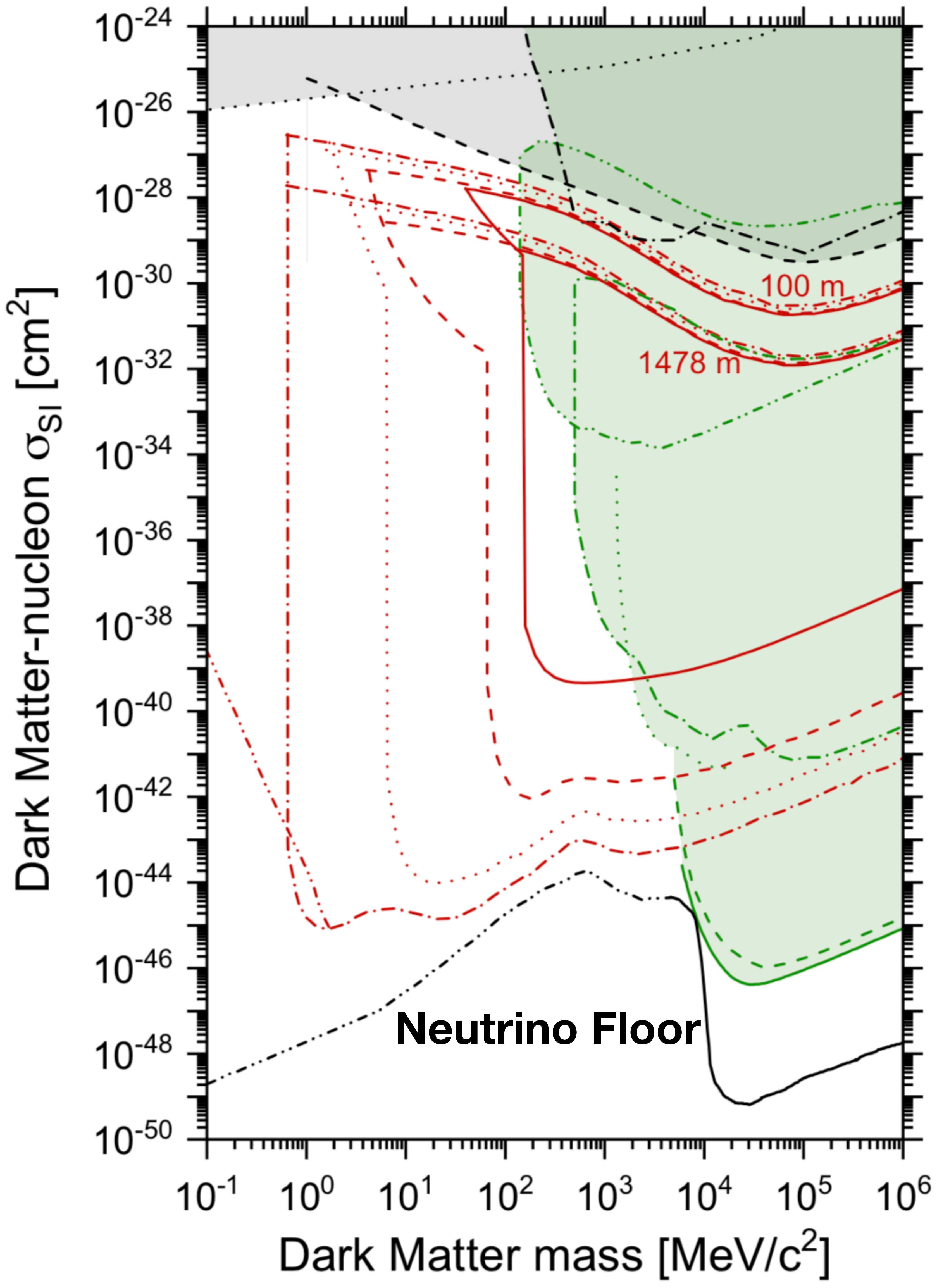


Excitations in Superfluid 4He



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**

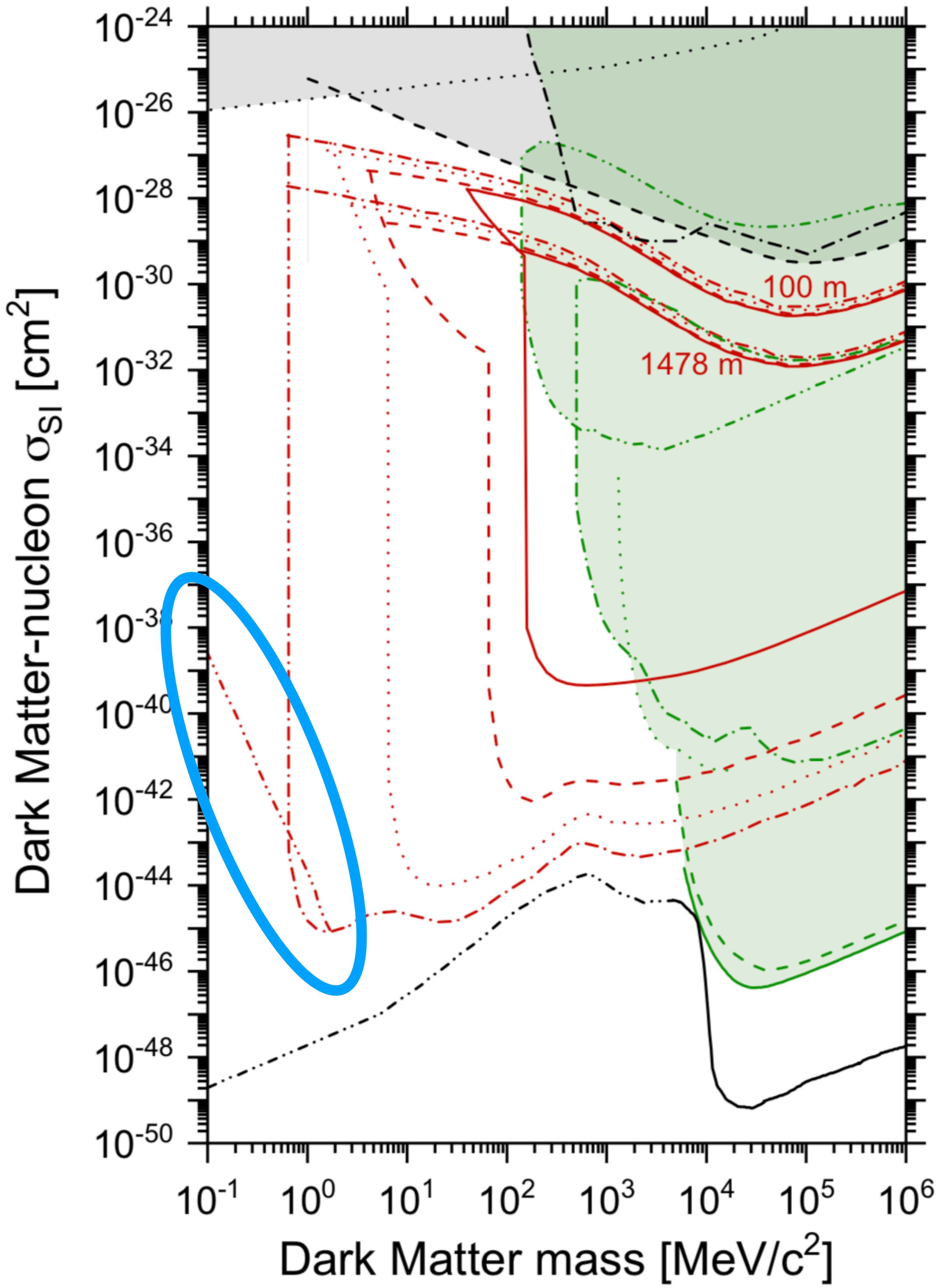


Extending Sensitivity with Off Shell Interactions

- The 0.6 meV evaporation threshold limits nuclear recoil DM search to m_{DM} >~ 1 MeV

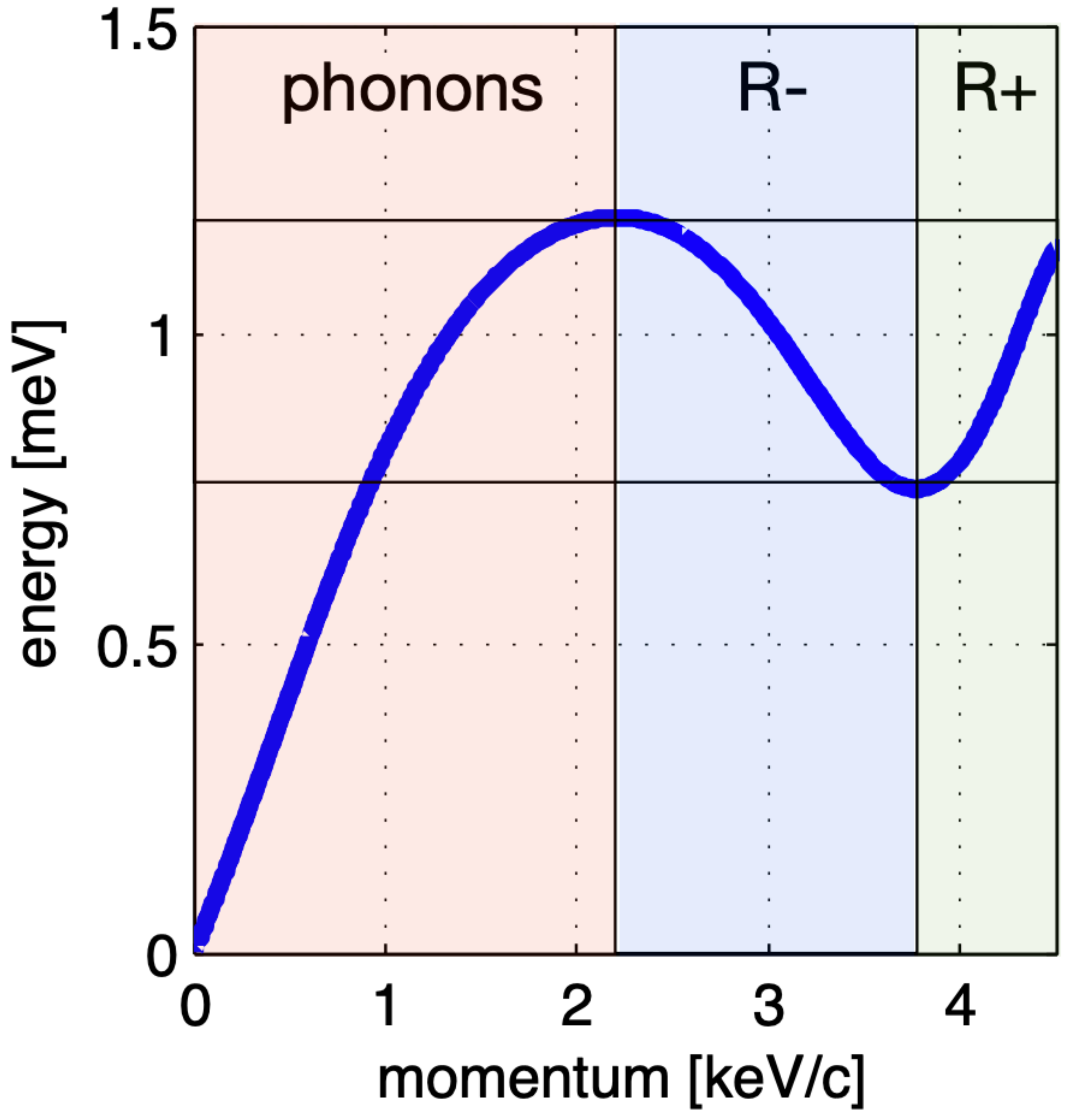
- Can be avoided if we find an excitation with an effective mass closer to the DM mass, allow DM to deposit more energy in the detector

    - In helium this could be recoiling off the bulk fluid and creating off shell quasiparticles



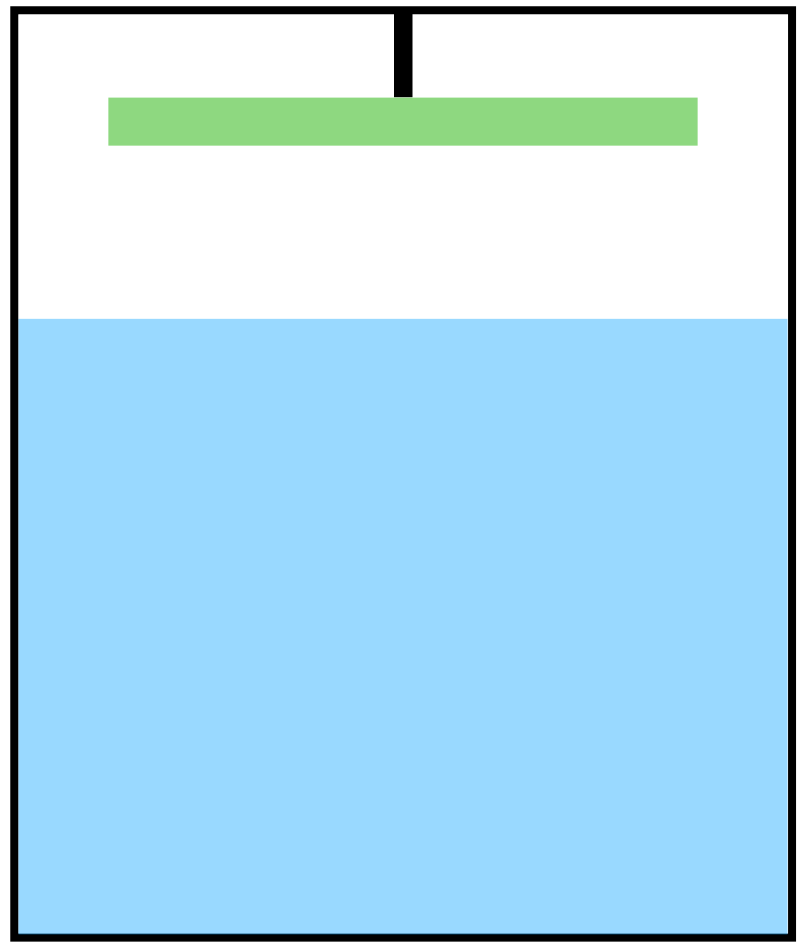
Detecting Vibrations: Vibrations in Helium

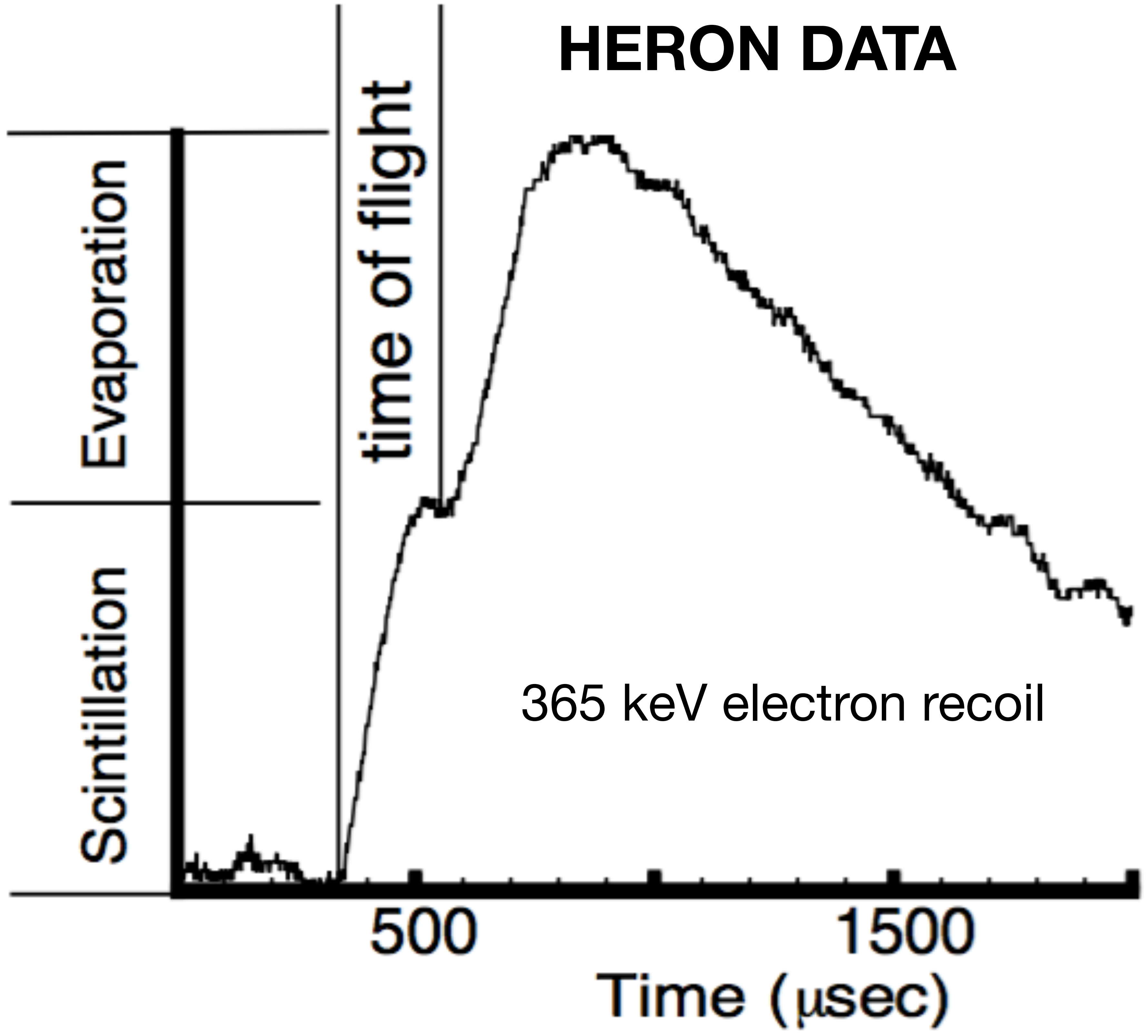
- The vibrational ("quasiparticle", "QP") excitations we expect to see are phonons and rotons
- Velocity is slope of dispersion relation
- Rotons ~ "high momentum phonons"
  - Just another part of the same dispersion relation
  - R- propagates in opposite direction to momentum vector



Example Waveform

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



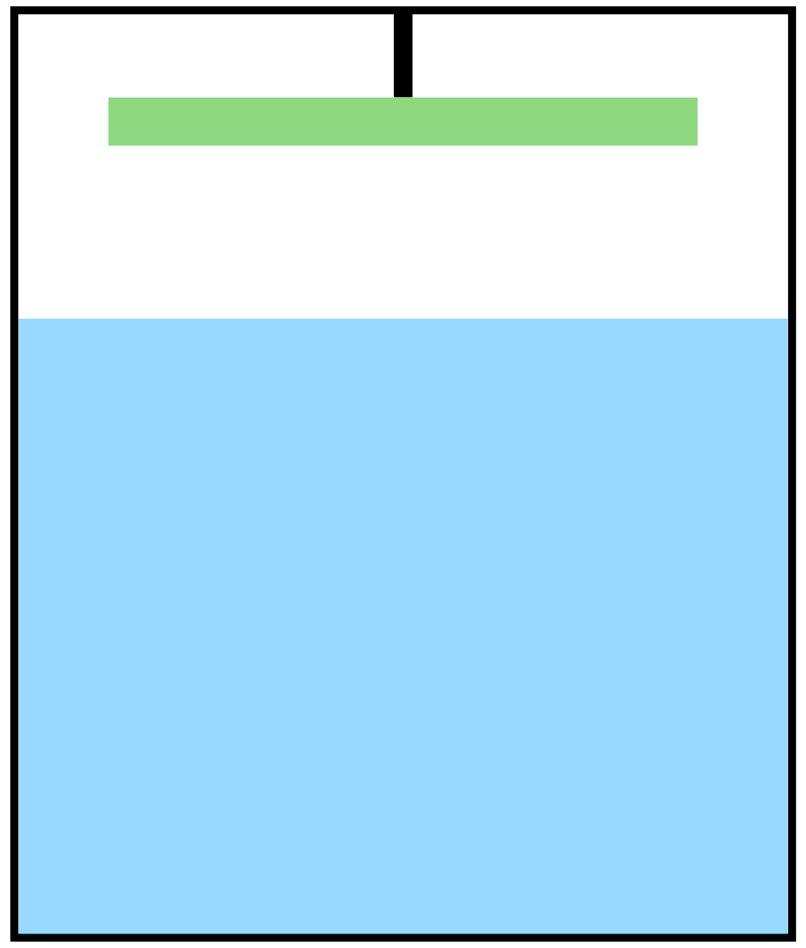


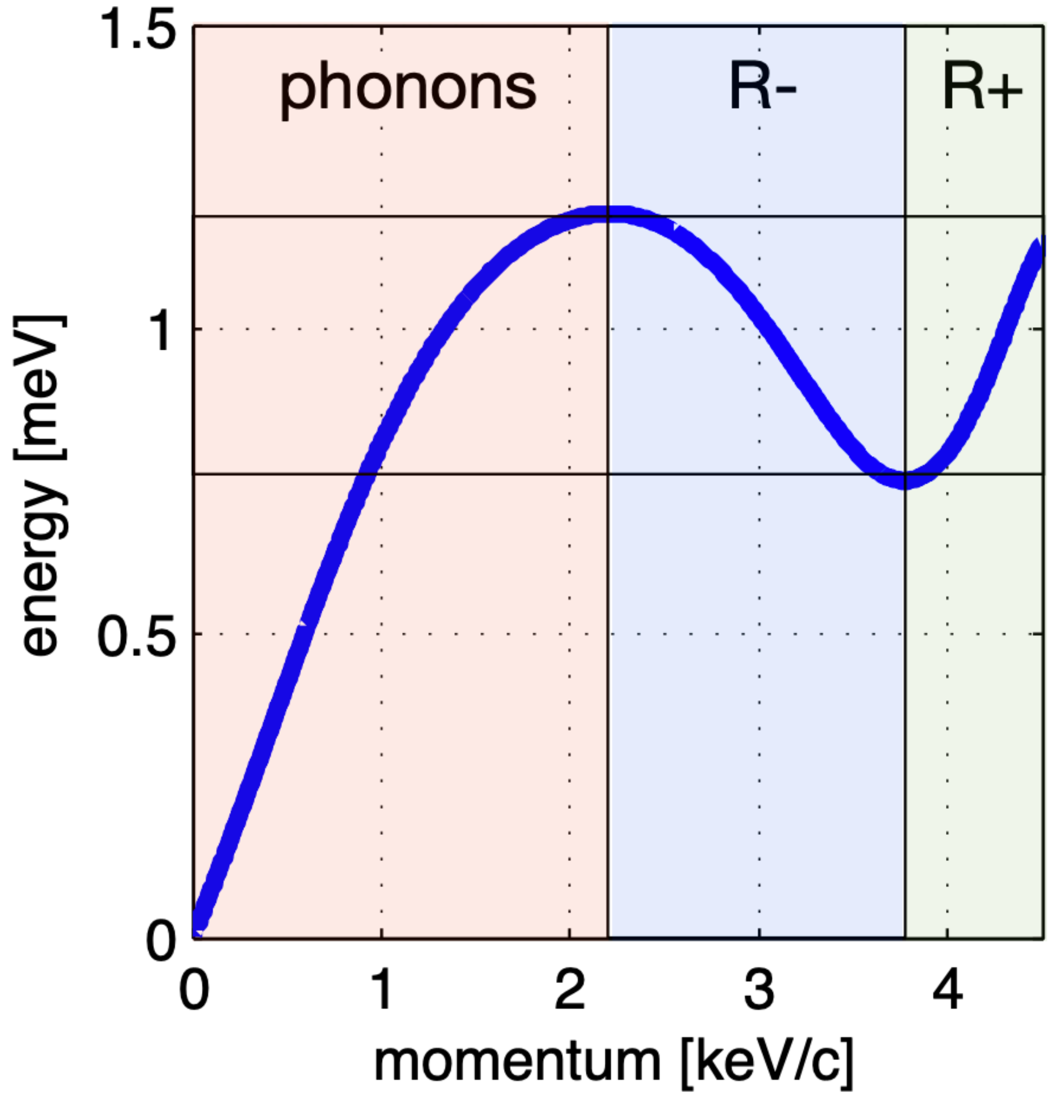
J. S. Adams et al. AIP Conference Proceedings 533, 112 (2000)

Annotations from Vetri Velan

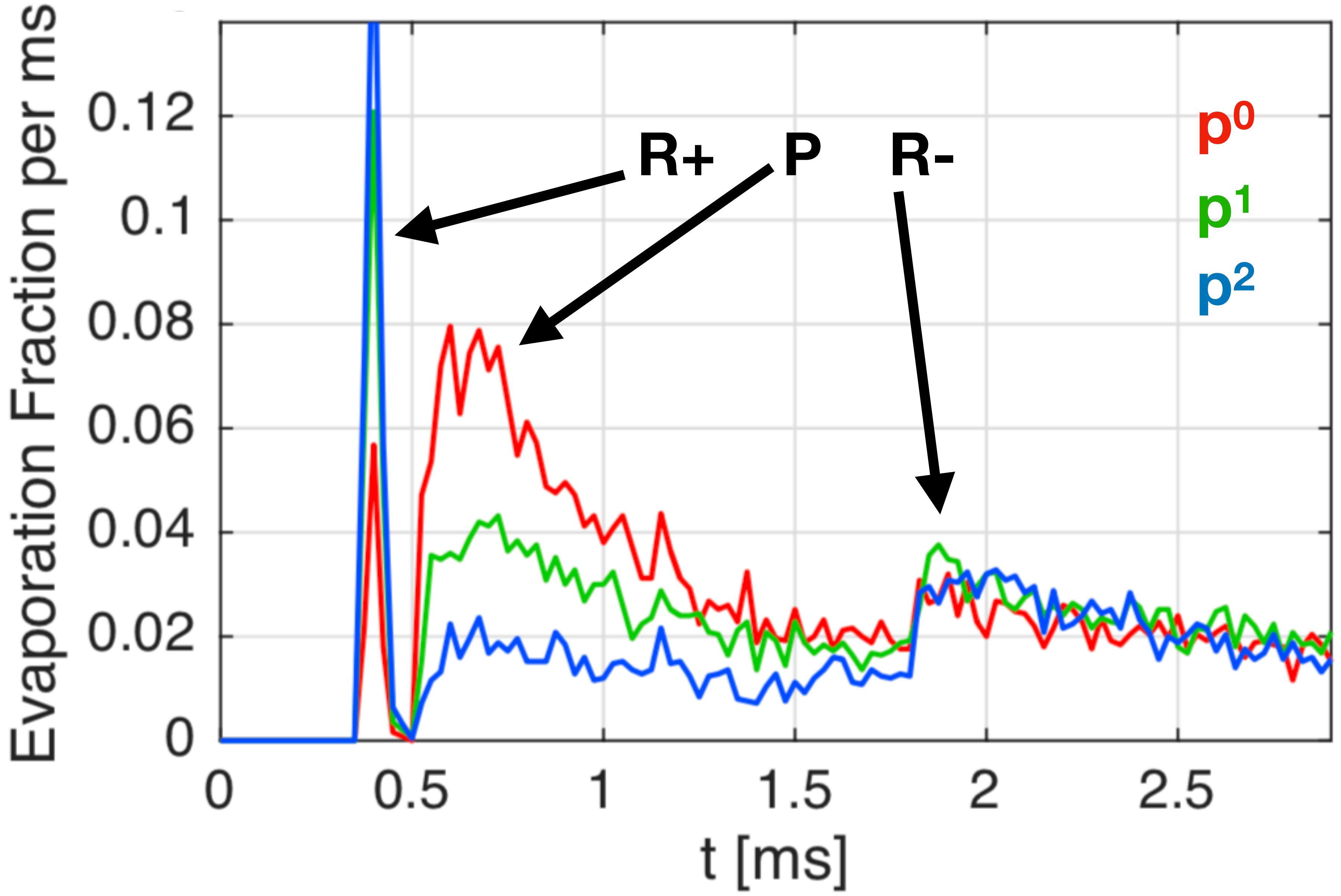
Another Example Waveform

- 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



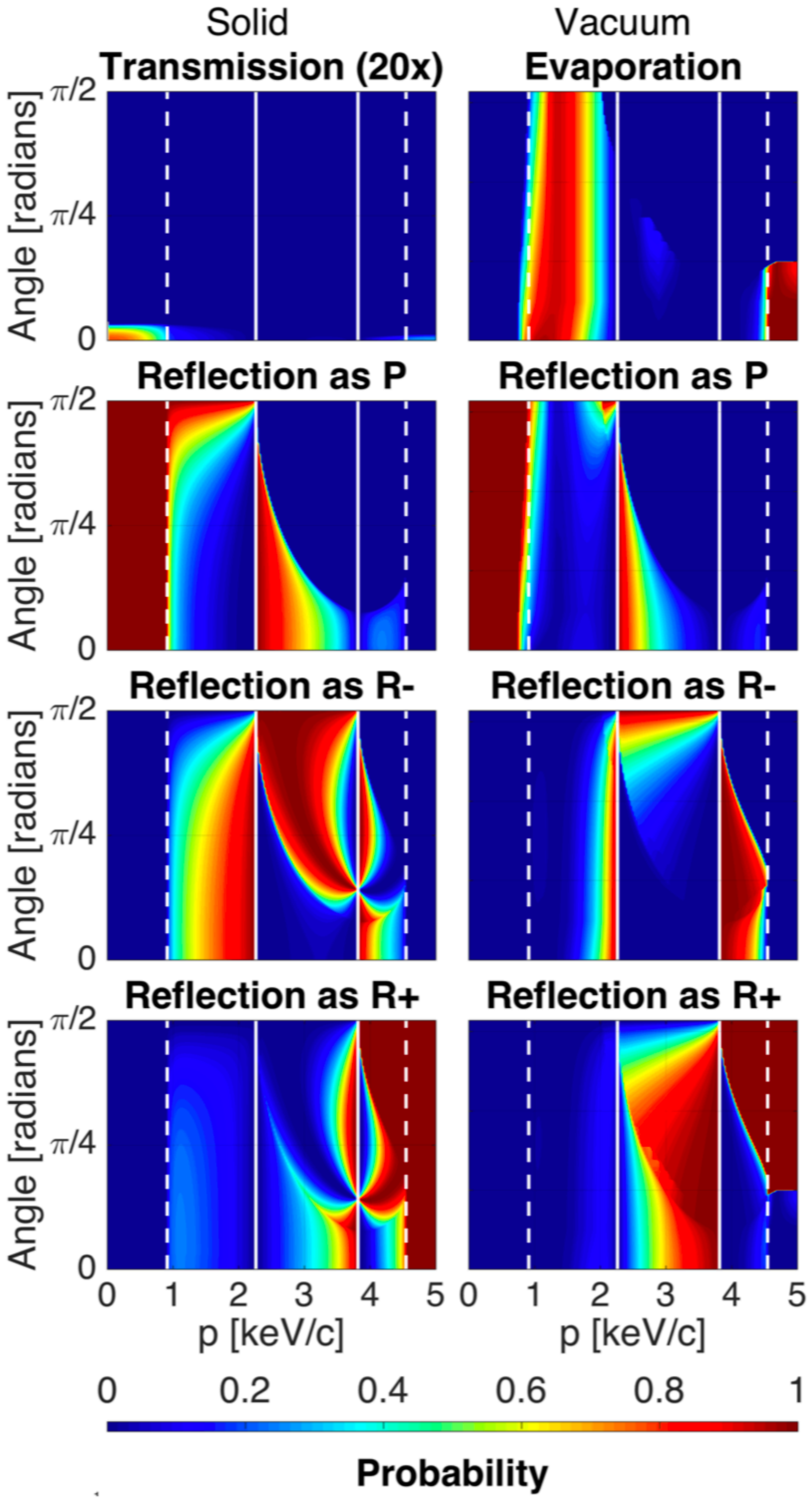

Solid
Transmission (20x)
Vacuum
Evaporation
Reflection as P
Reflection as P
Reflection as R-
Reflection as R-
Reflection as R+
Reflection as R+
Angle [radians]
π/2
π/4
0
0 1 2 3 4 5
p [keV/c]
0 0.2 0.4 0.6 0.8 1
Probability

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.