Superfluid Helium for sub-GeV Dark Matter

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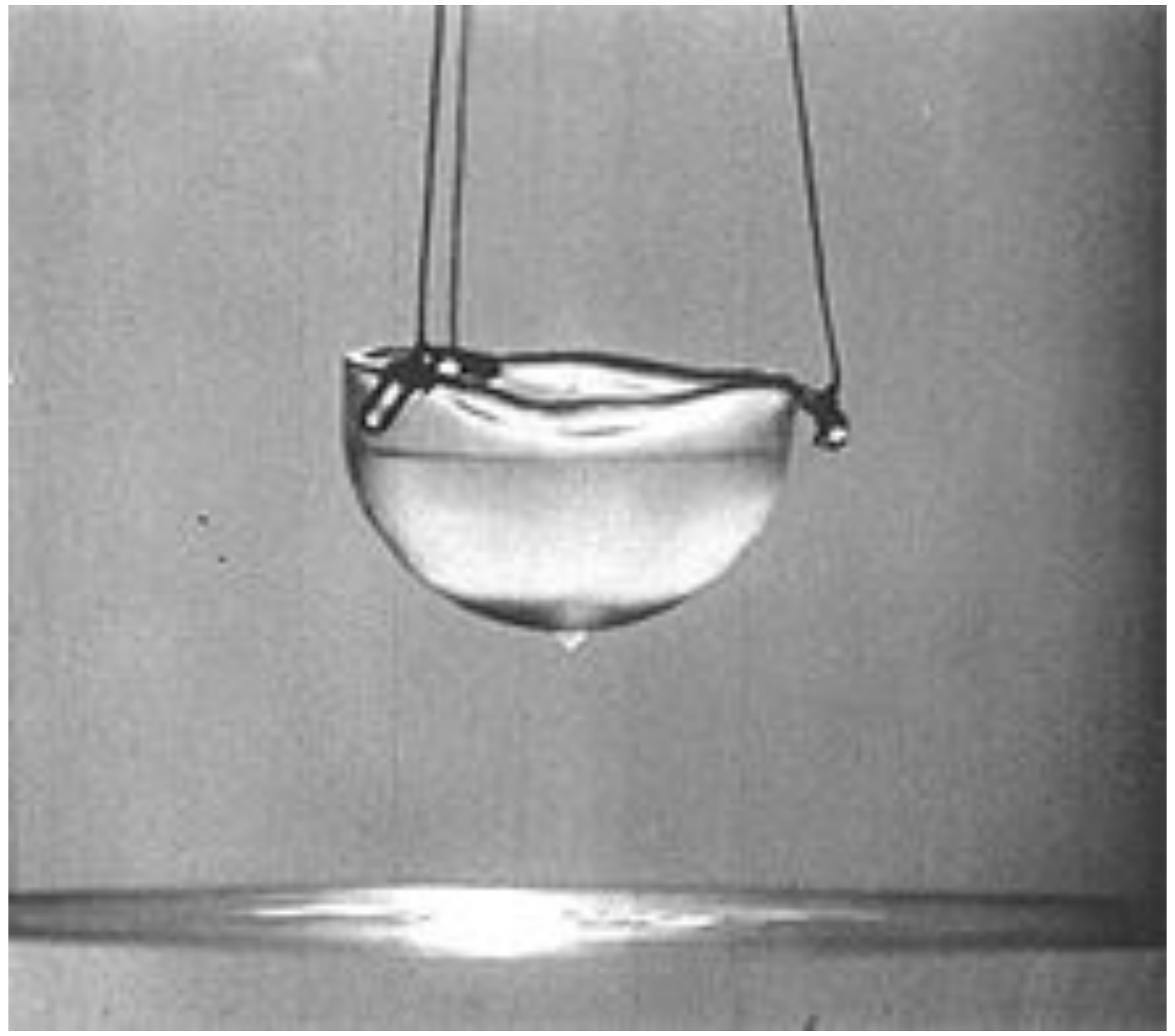
For the HeRALD Collaboration and Others

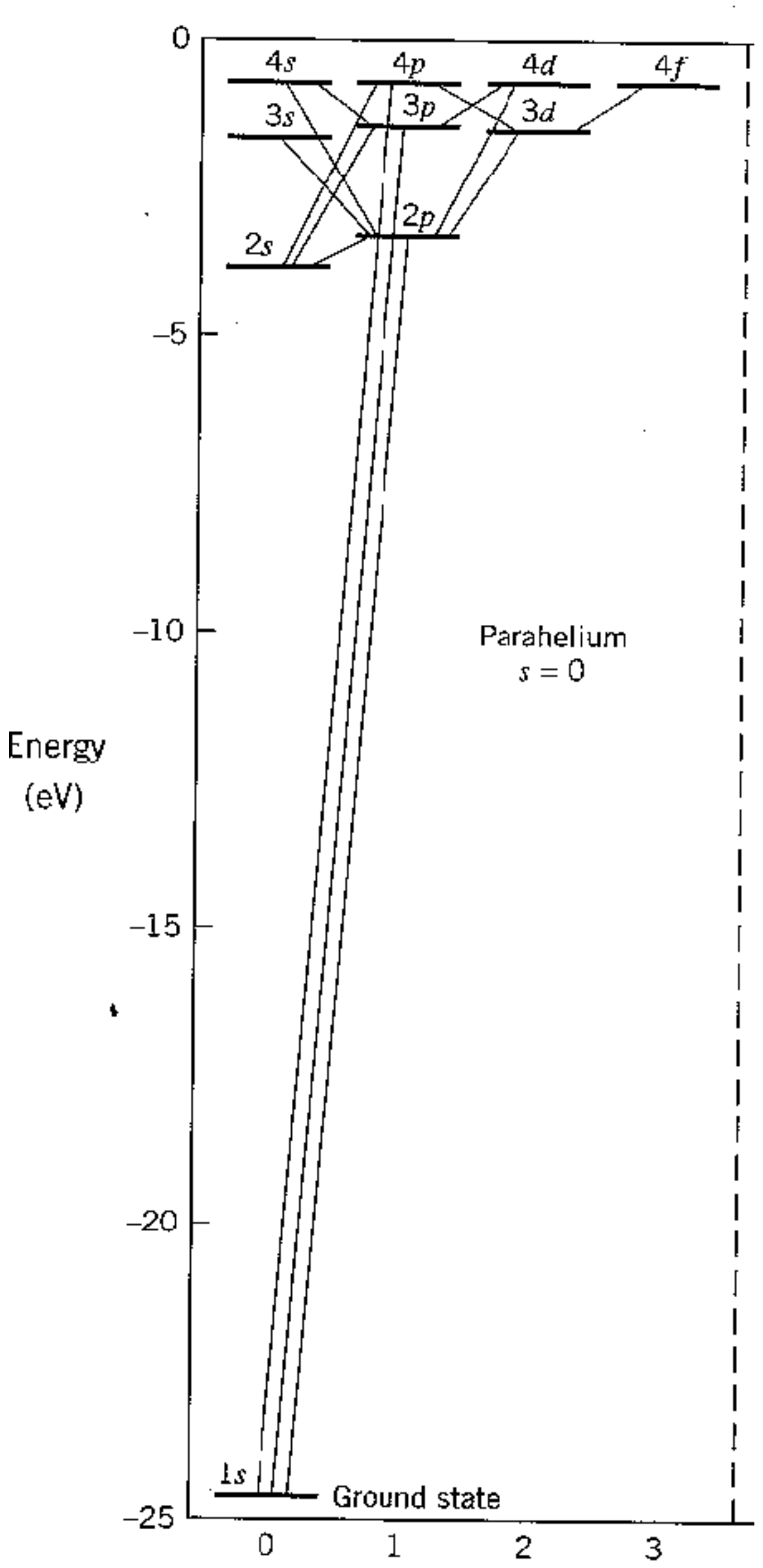
IF/SNOWMASS21-IF1_IF8-CF1_CF0_Hertel-158.pdf

Big-Picture Summary

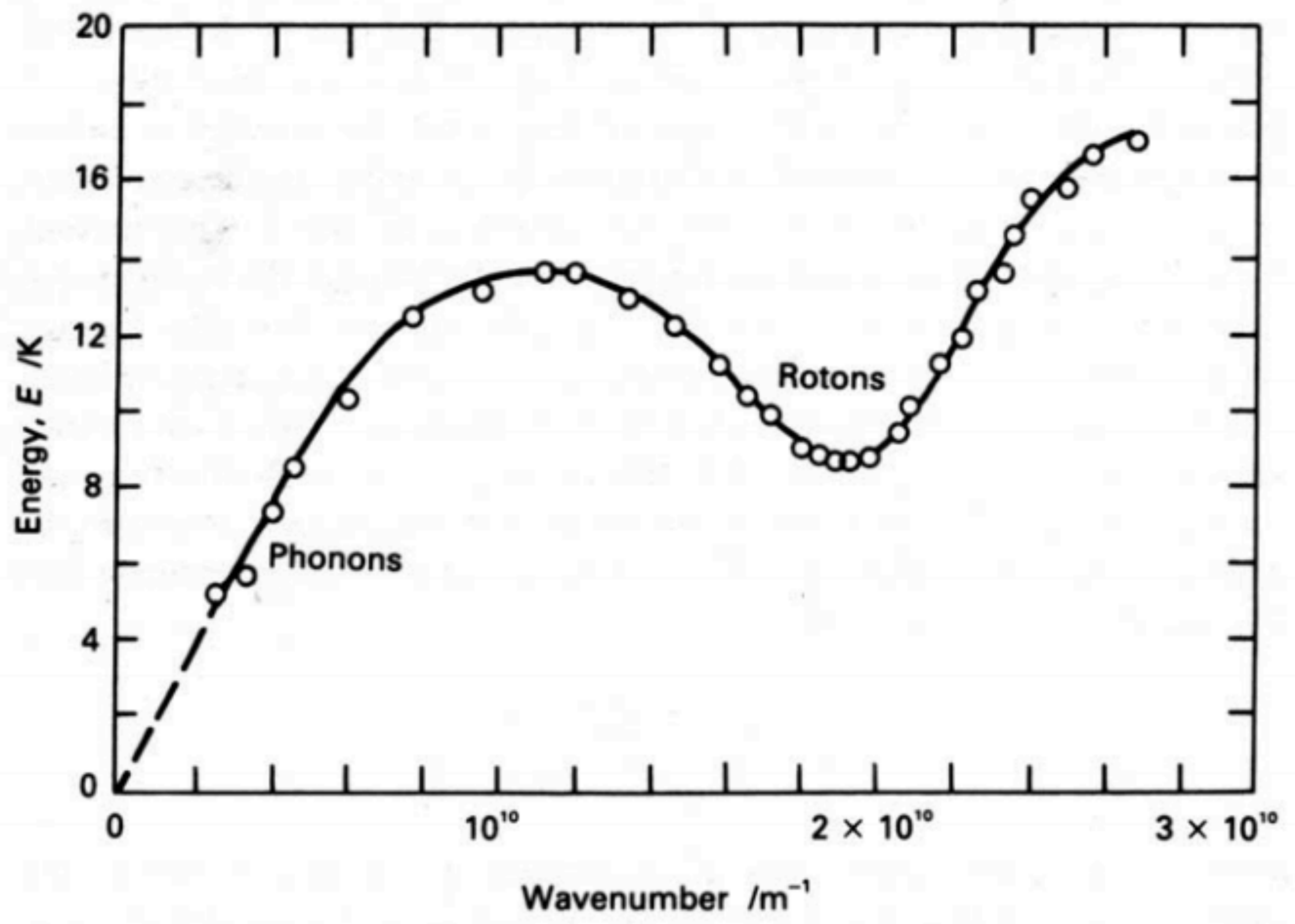
Superfluid 4He
chemically and isotopically pure
‘for free’ at mK temperatures



eV-scale
singlet and triplet atomic excitations
(dimers as in other noble liquids)

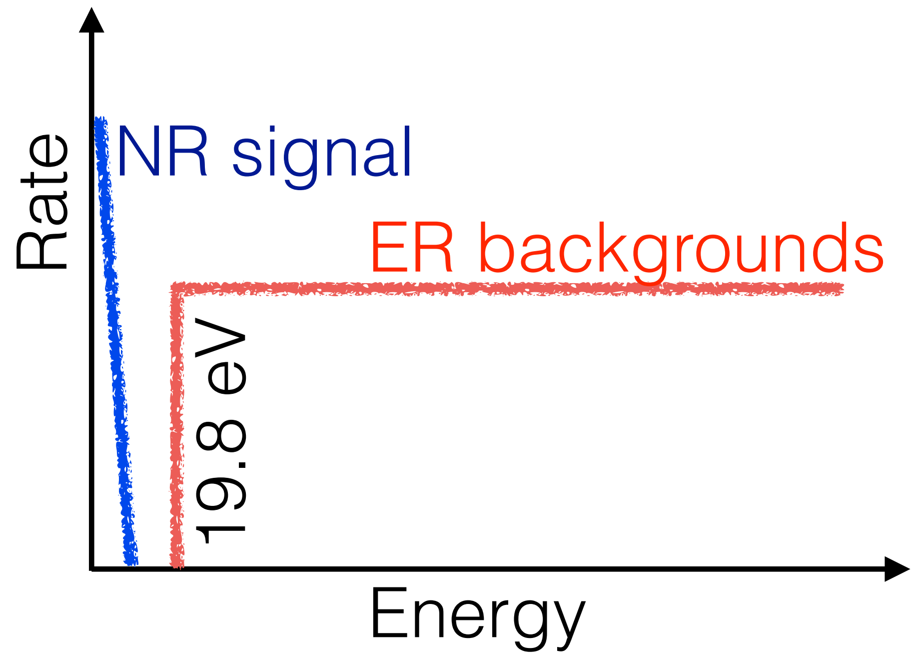


meV-scale
phonon-like excitations
(as in other crystal targets, except this
‘lattice’ is defect-free at macroscopic scales)

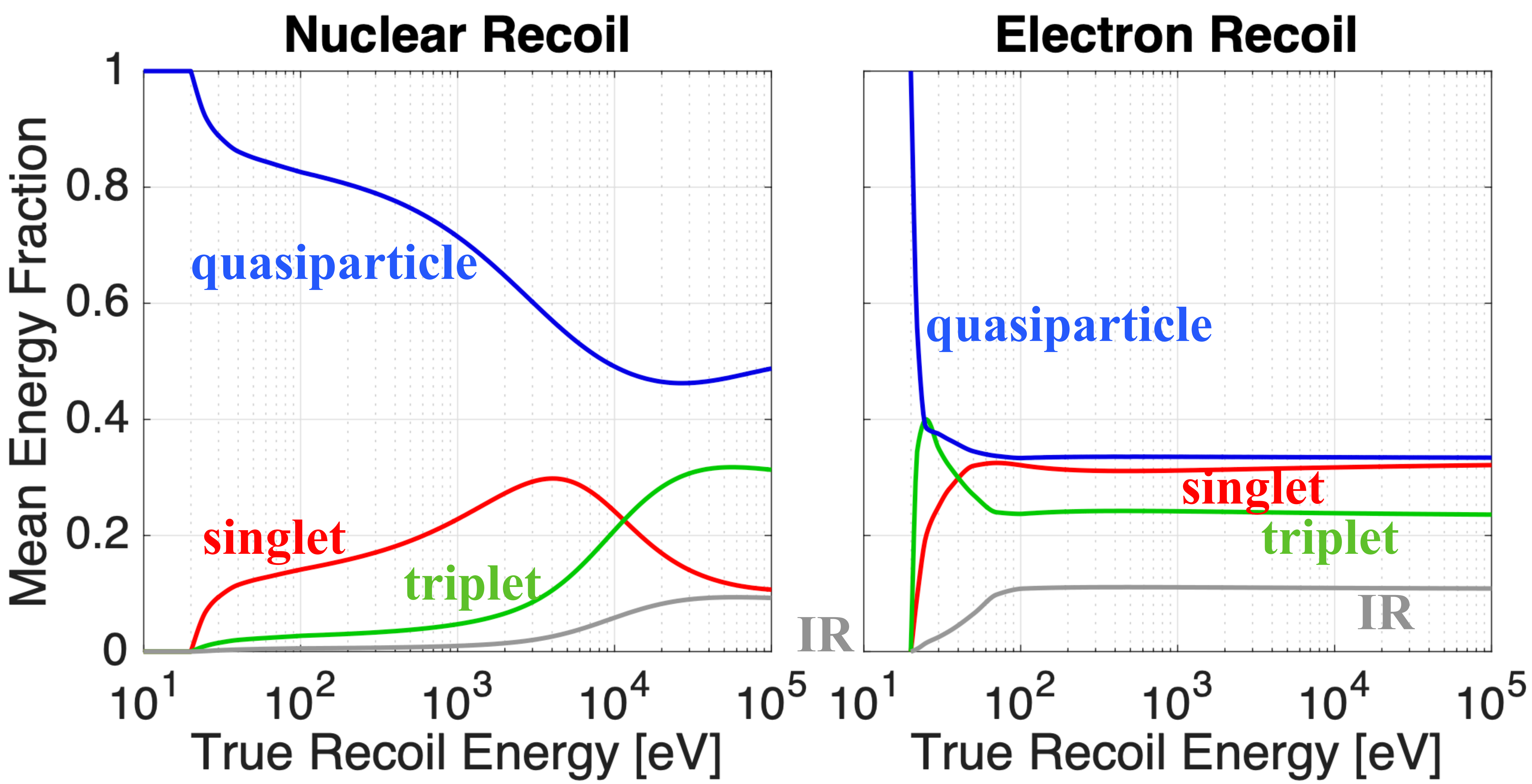


eV-scale Atomic excitations

Energy of first excited electron state: 19.8eV (large perfect ‘gap’ compared to other materials)
Excitation cross sections experimentally well-understood.

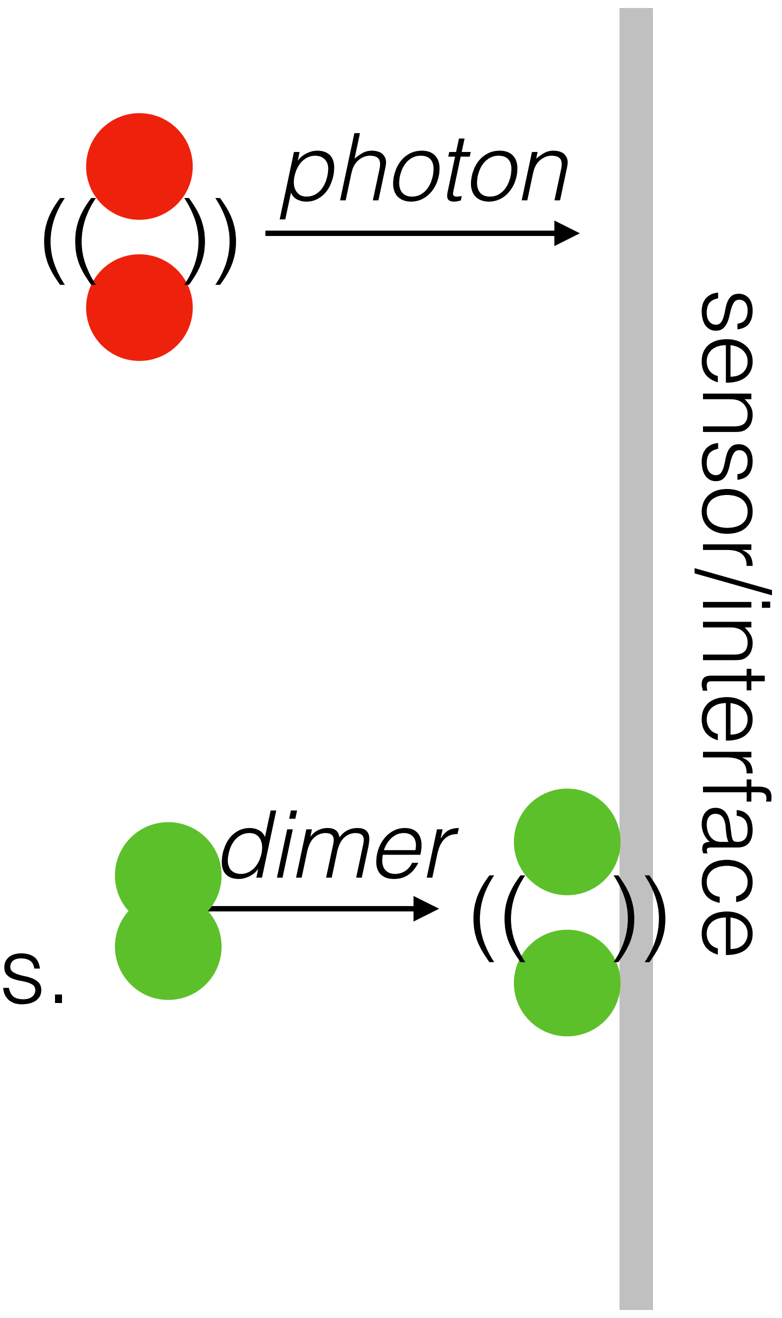


>19.8eV: robust discrimination based on atomic excitation ratios
(and robust tagging of this ‘high energy’ less interesting regime)
<19.8eV: no such thing as ‘electron recoil backgrounds’



Singlet
dimer promptly decays.
signal: VUV photon

Triplet
dimer long-lived,
ballistic propagation,~10m/s.
signal: decay at interface



Phonon and Roton `quasiparticles’

Again: *All* recoil energy is in these modes if $E_{recoil} < 19.8$ eV

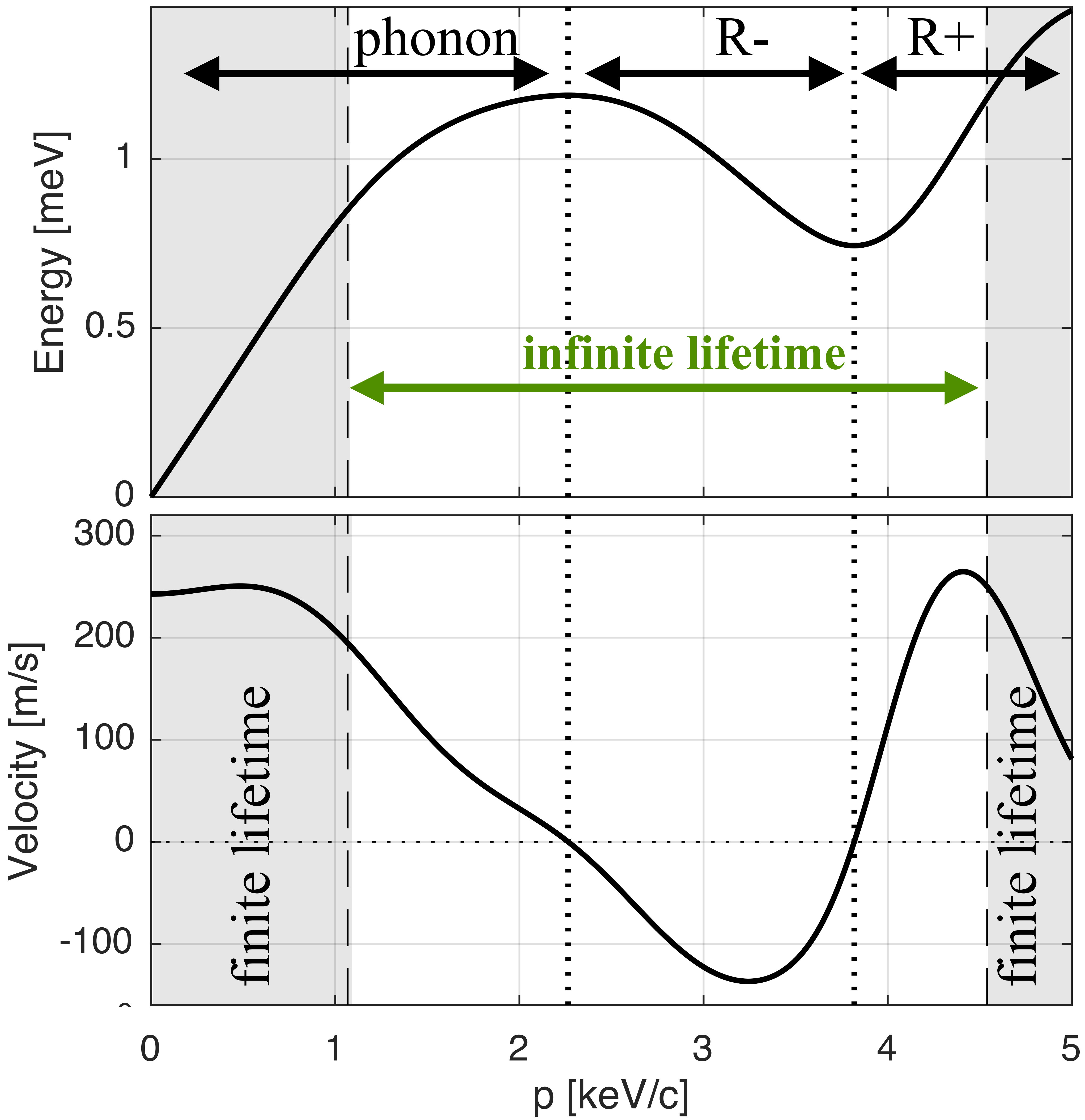
Variety of distinguishable ‘flavors’
  -different velocities (different arrival times at sensor)
  -different boundary-crossing probabilities (and critical angles)

‘Rotons’ for our purposes are just ‘phonons with high momentum’

Decay is kinematically impossible over wide momentum-range.

Dispersion relation is isotropic.

Propagation is entirely ballistic, thanks to
  -lack of lattice imperfections
  -lack of isotopic impurities
  -lack of thermal phonon population



4He quasiparticles preserve information

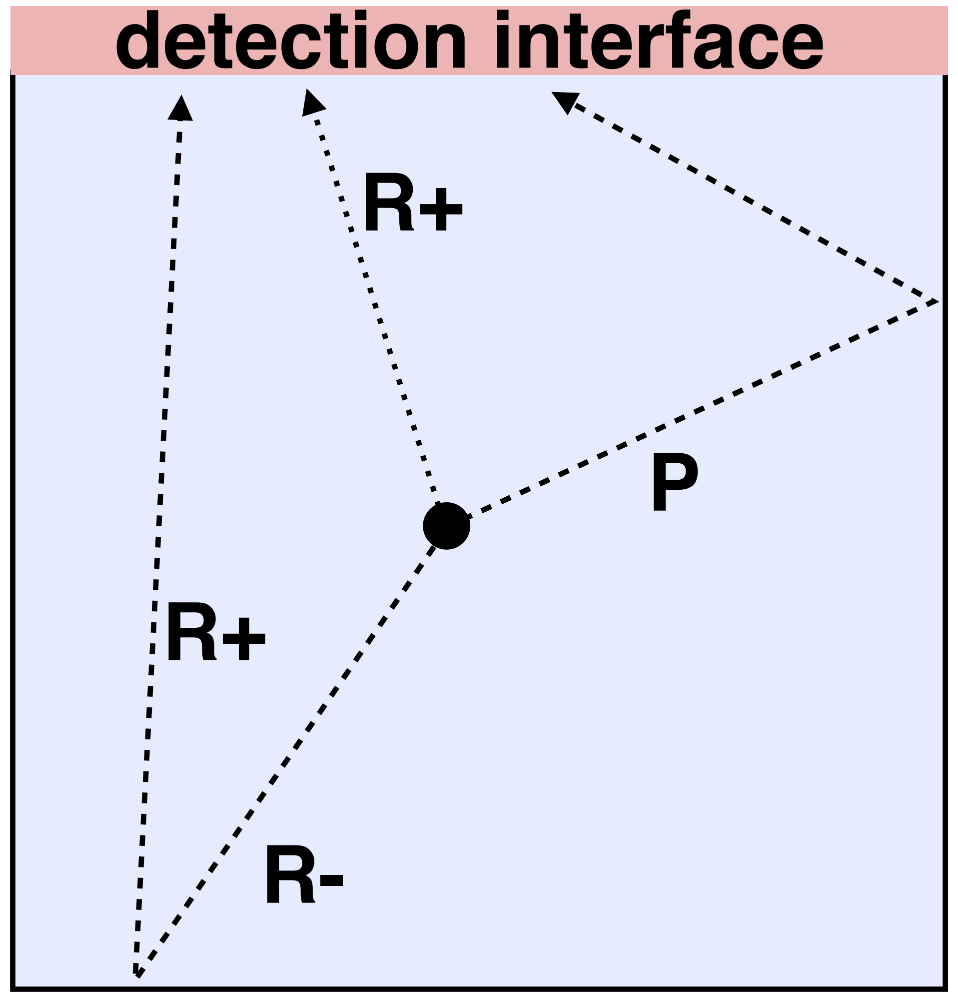
4He QPs naturally conserve a large amount of information.

To illustrate, we perform a simple toy MC:

Setup: 4He cell, 20cm scale, recoil at center

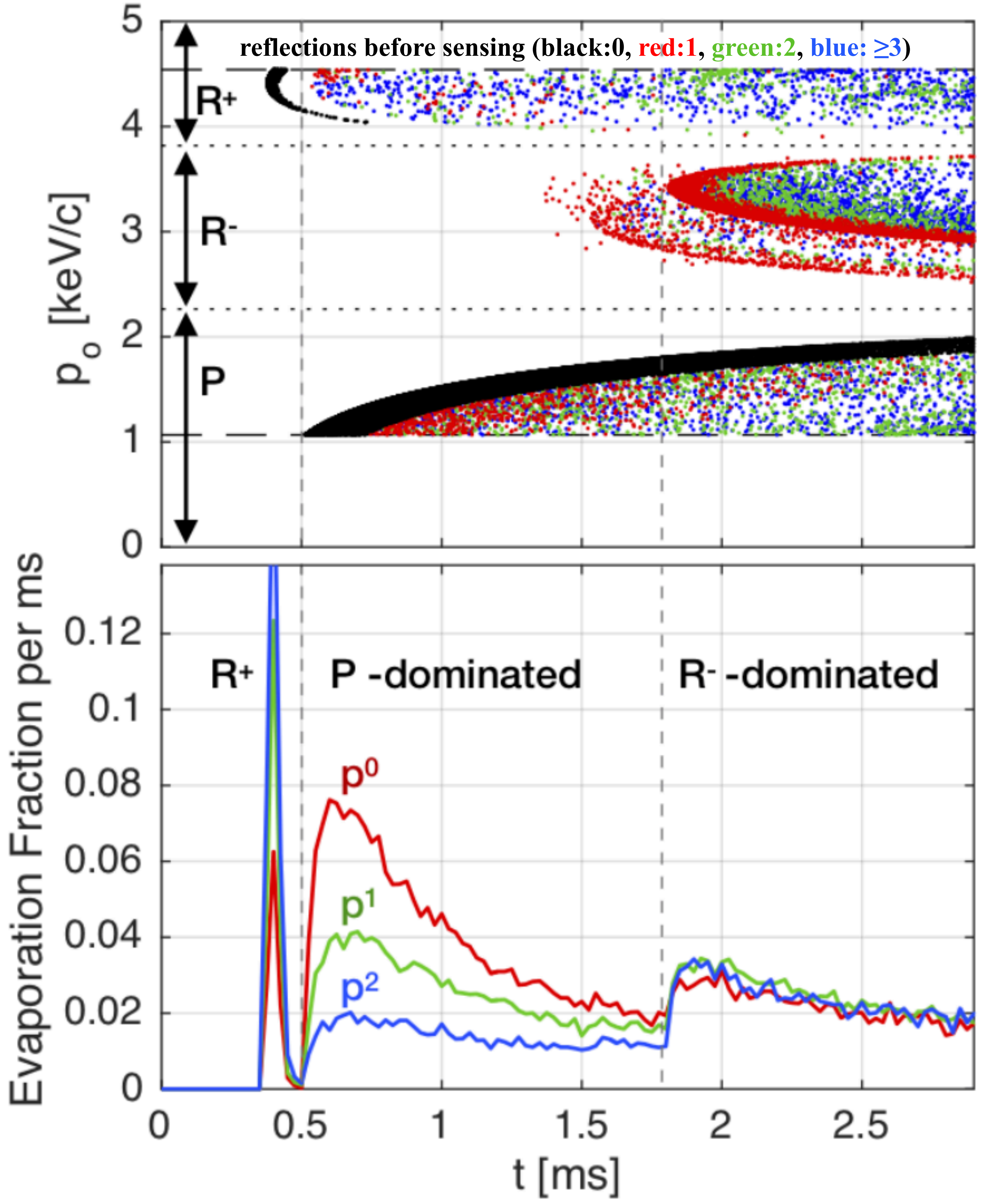
‘Detection interface’ at top
‘Reflection interfaces’ elsewhere

Initial QP distribution: p^0, p^1, p^2 (thermal)



Result: Distinct waves of QP arrival

Amplitude and timing of waves encode
- recoil energy
- initial QP distribution
- recoil position (xy, depth)
- recoil direction (more on this is a sec)



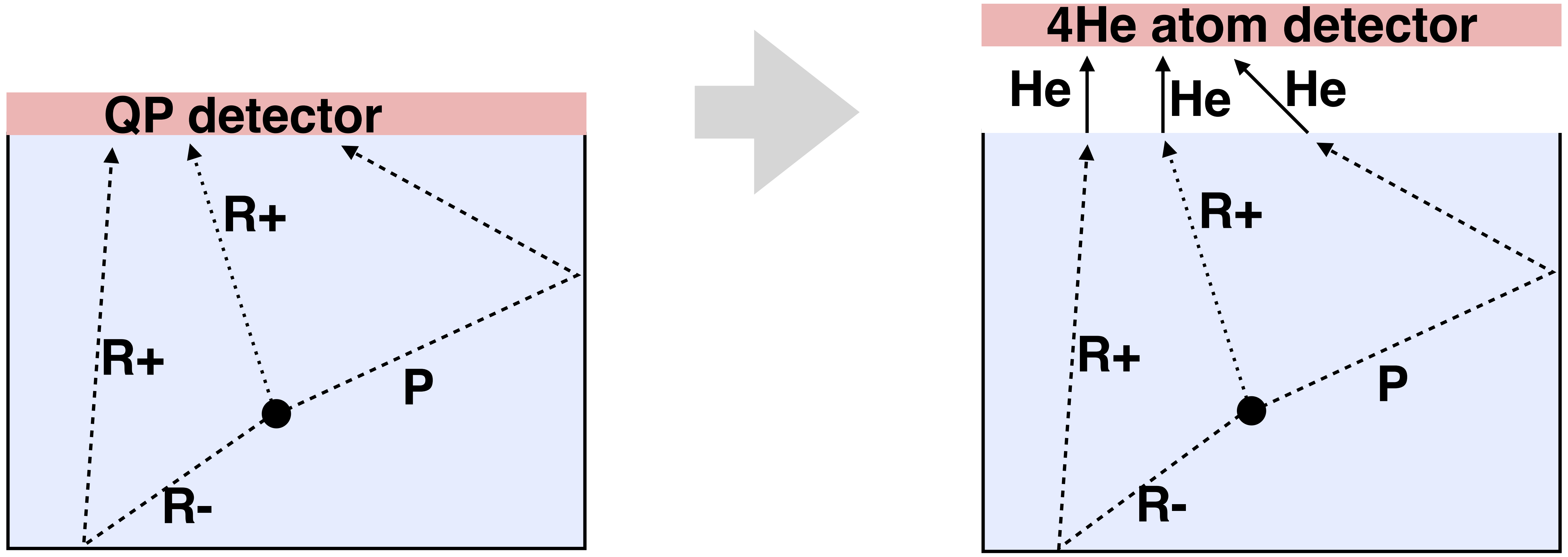
4He quasiparticles are detectable as ‘quantum evaporation’

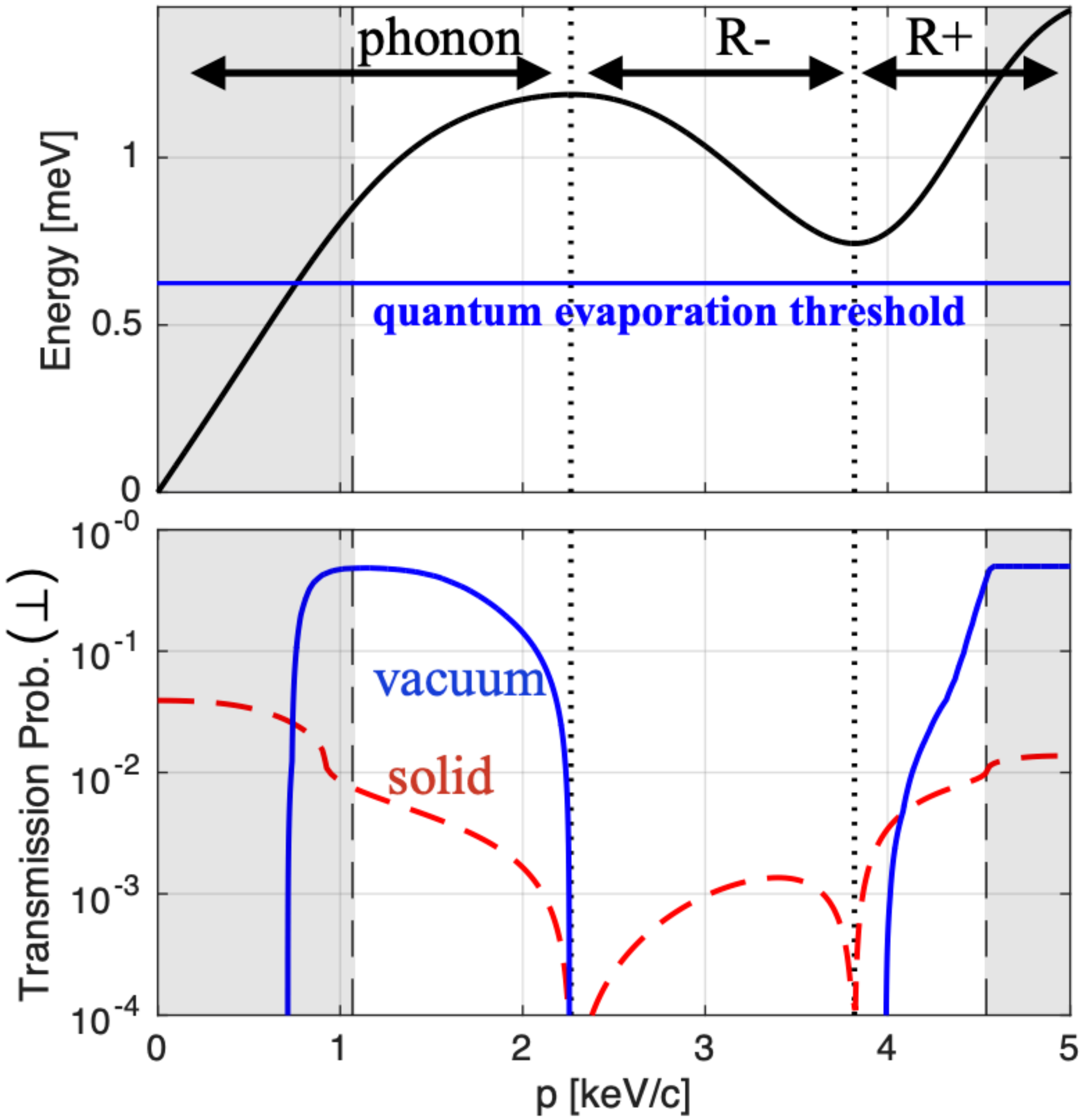
1-to-1 conversion: one QP liberates one 4He atom into vacuum.

Most QPs are above the evaporation threshold (0.62meV)

Quantum evaporation characteristics/probability well understood.
(theory-experiment agreement to factor of ~2)

Not all QP ‘flavors’ can trigger evaporation,
but ‘flavor’ changes on reflections (giving 2nd, 3rd, chances etc.)





HERON

HERON (1987-1999) demonstrated several key principles.

1) Demonstrated readout of singlet+evaporation signals

2) Significant characterization of QP behaviors (reflection and evaporation)

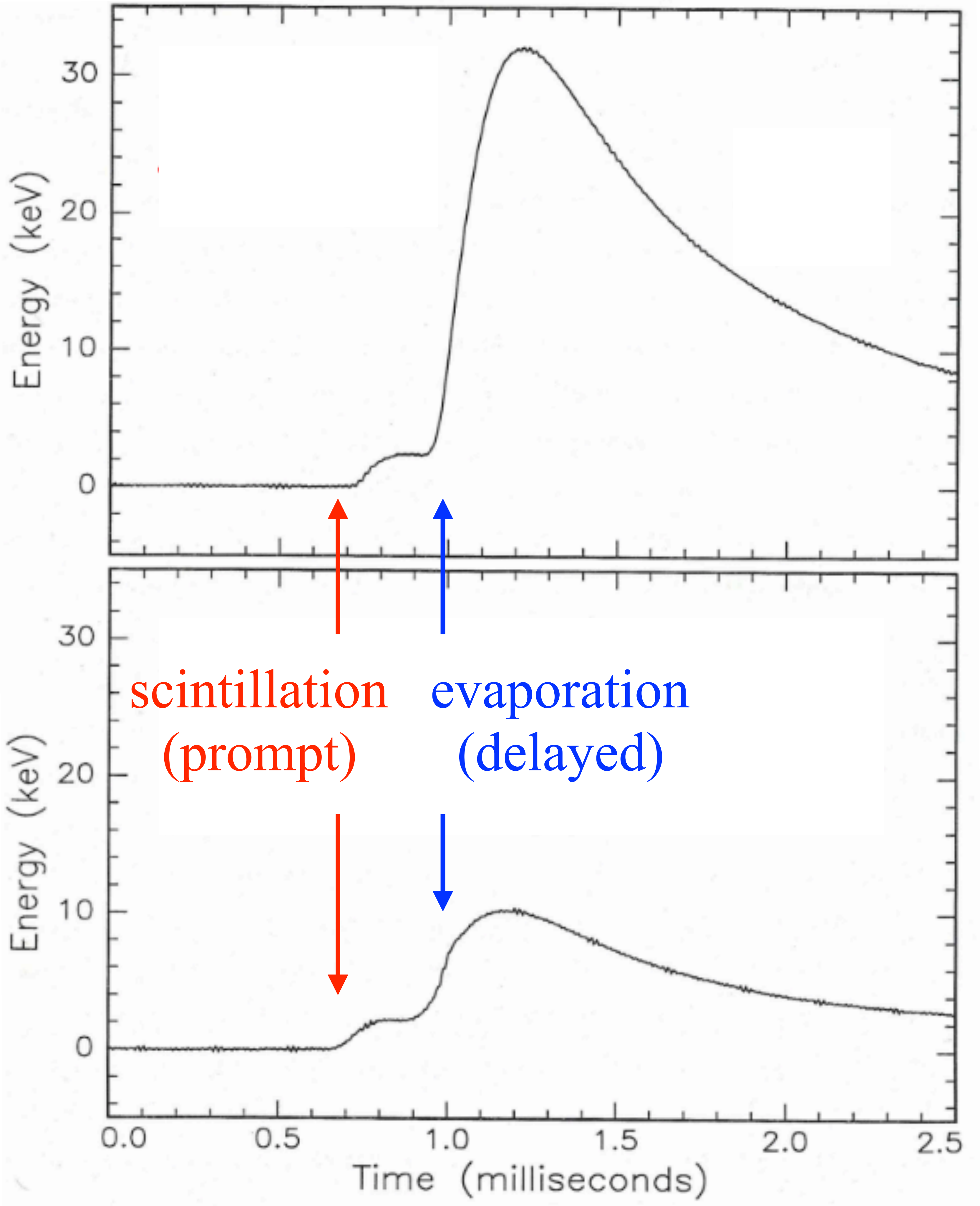
3) Observed significant directionality in QP signal

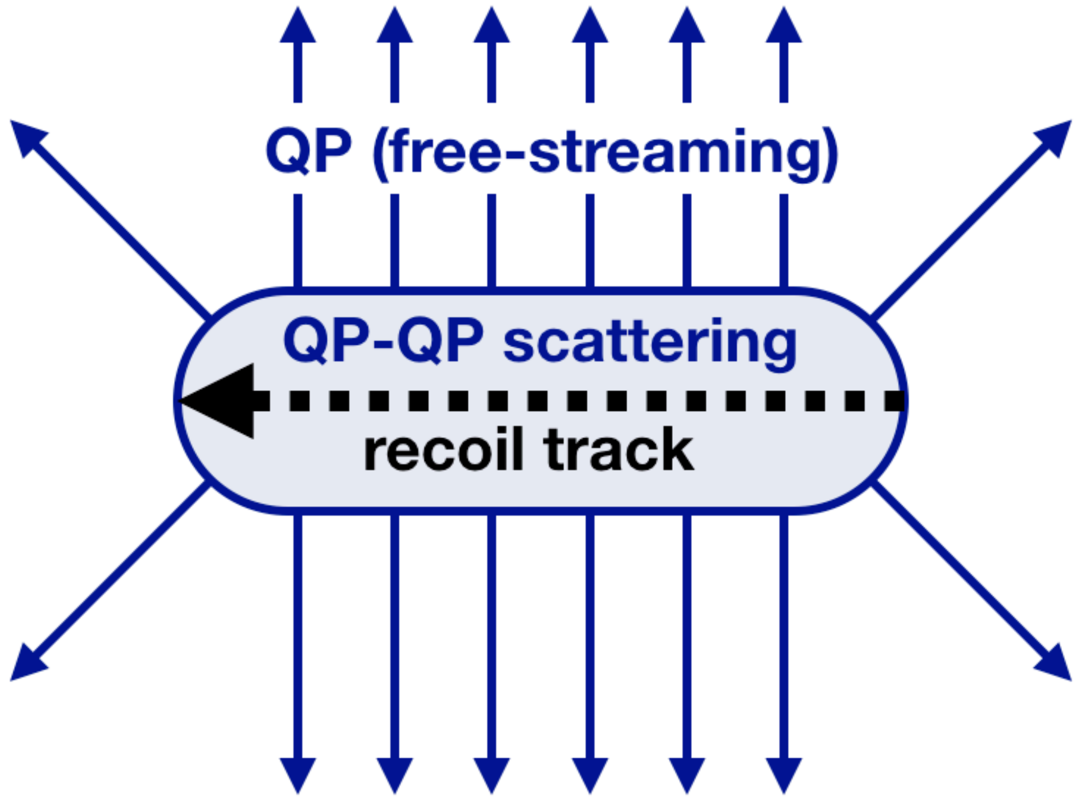
***parallel* to liquid surface**

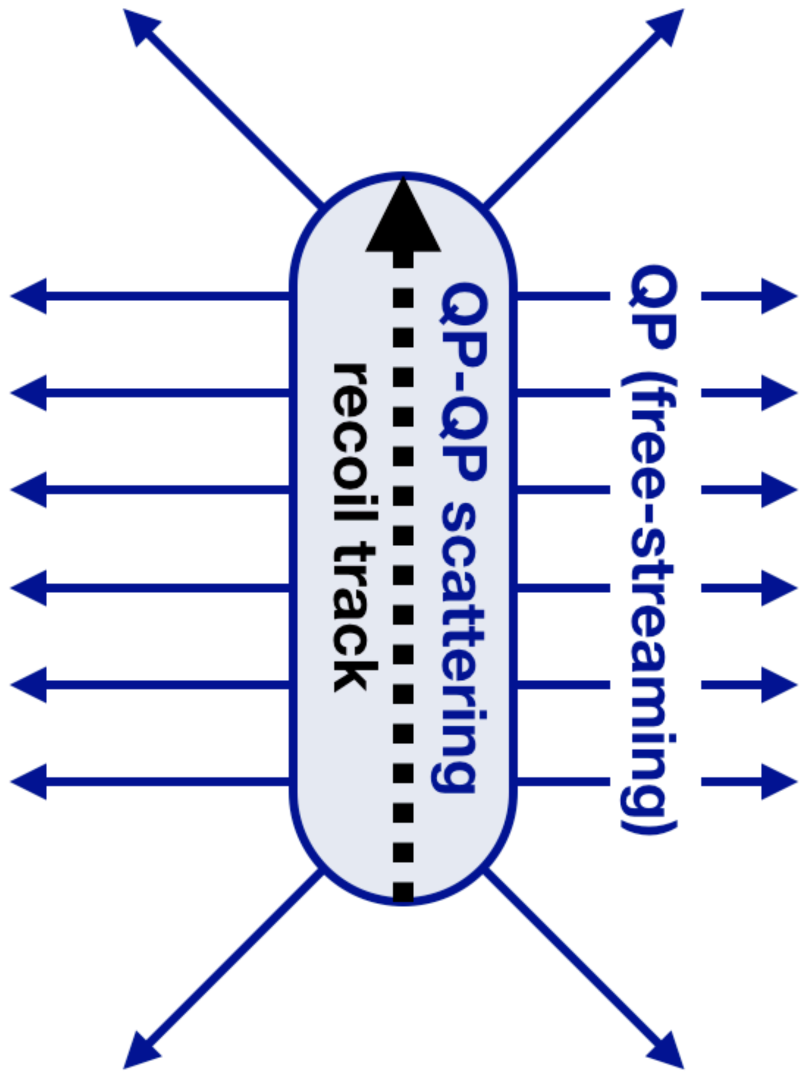
***perpendicular* to liquid surface**

Punchline: a DM detector is a small step from HERON

Collimated Alpha Source (*data*)





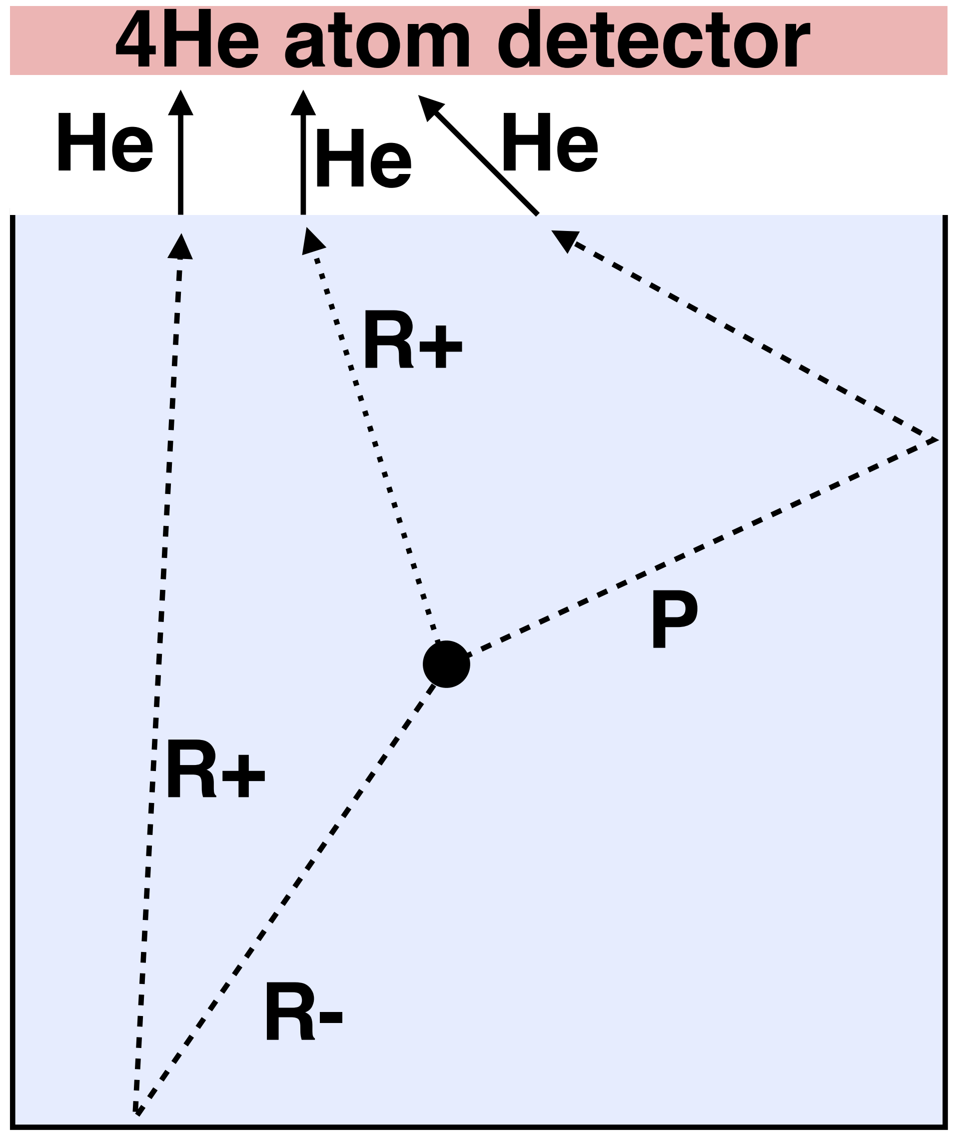


Evaporation Sensor

The evaporation sensor is all-important, setting the threshold and the DM mass reach.

What is the ideal sensor technology for this unusual signal?

Are there technologies which can reach the single-atom limit, while keeping the dark rate low?

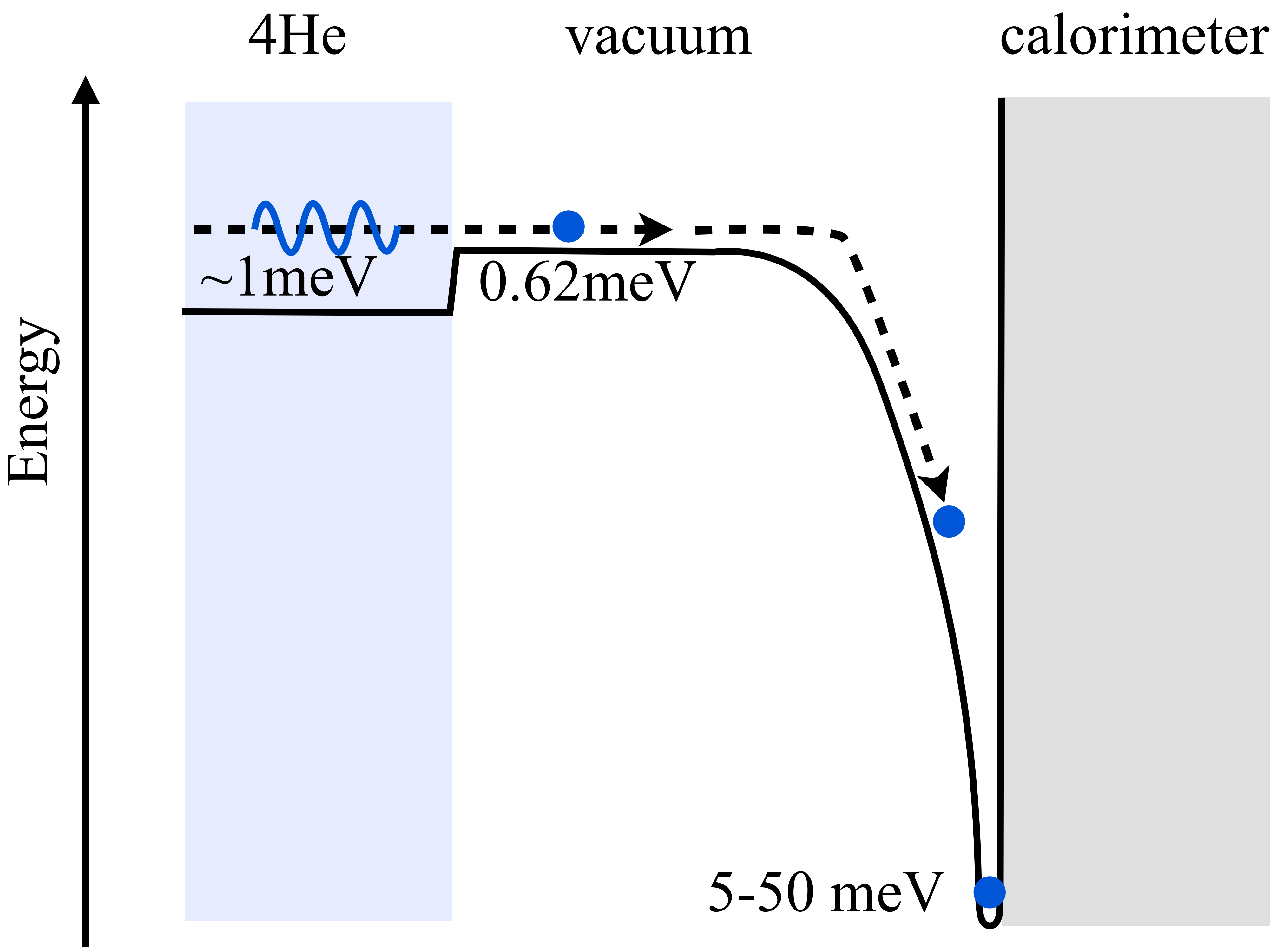


Evaporation Sensor Option 1: low-temperature calorimetry

The ‘standard’ demonstrated method (by HERON and others).

Signal received is NOT the atom’s kinetic energy,
instead dominated by 4He-calorimeter adsorption energy
(5-50 meV per atom, meaning a ~5-50x gain factor).

Additional benefit: evaporation sensor also senses photons



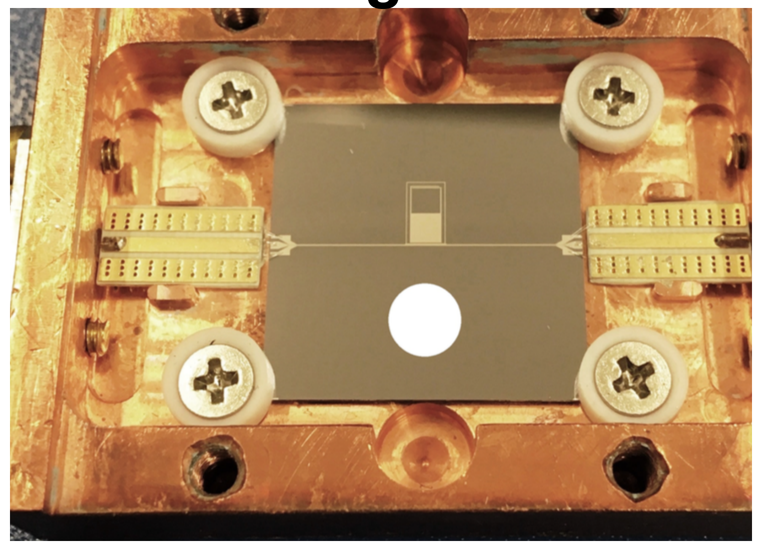
Today’s thresholds: $\mathcal{O}$ 10 eV
(with 5-50x gain: $\mathcal{O}$ 1 eV of QP evaporation)

Clear path forward for threshold reduction.
(rich and separate topic of research)

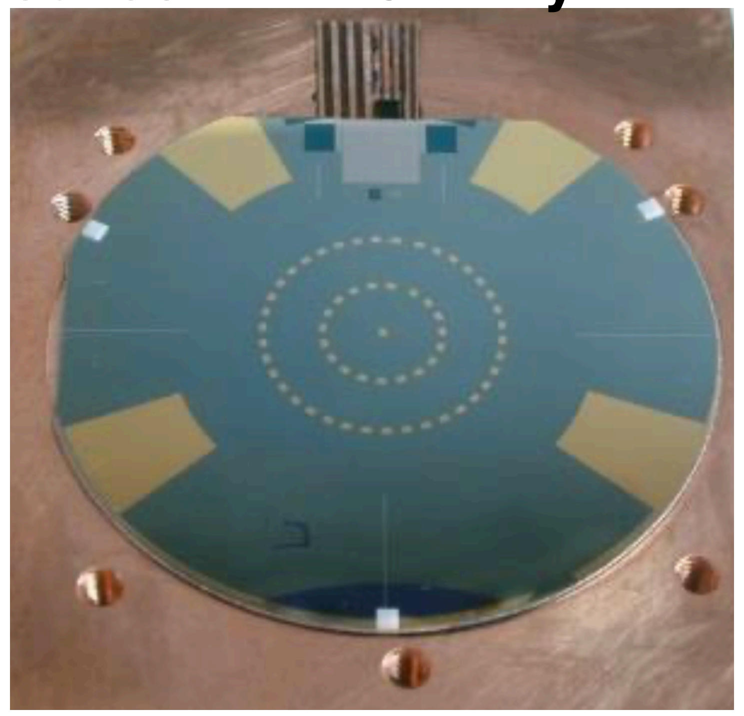
Dark counts: plausibly low thanks to evaporation ‘gap energy’ and distinct evaporation pulse shapes.

sensor: TES array

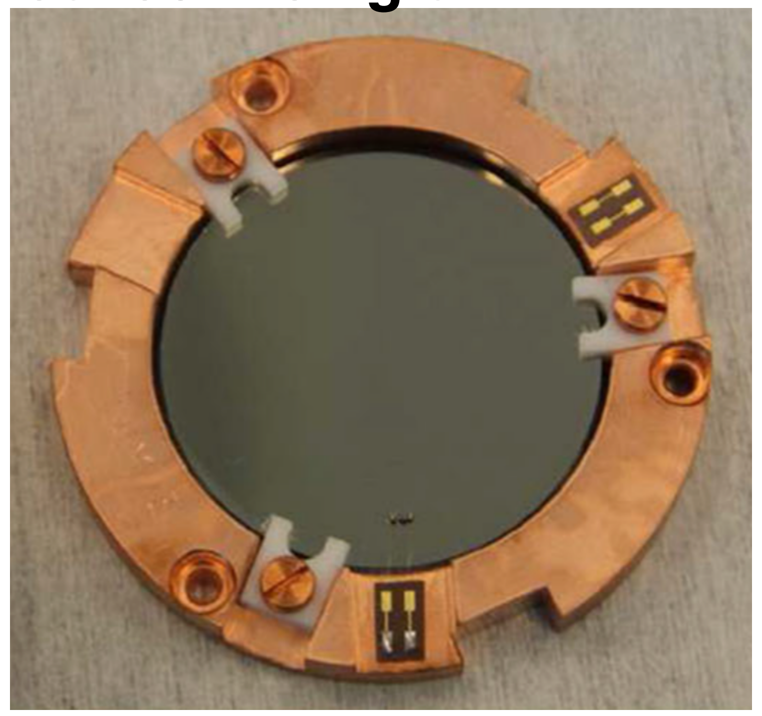
sensor: single KID



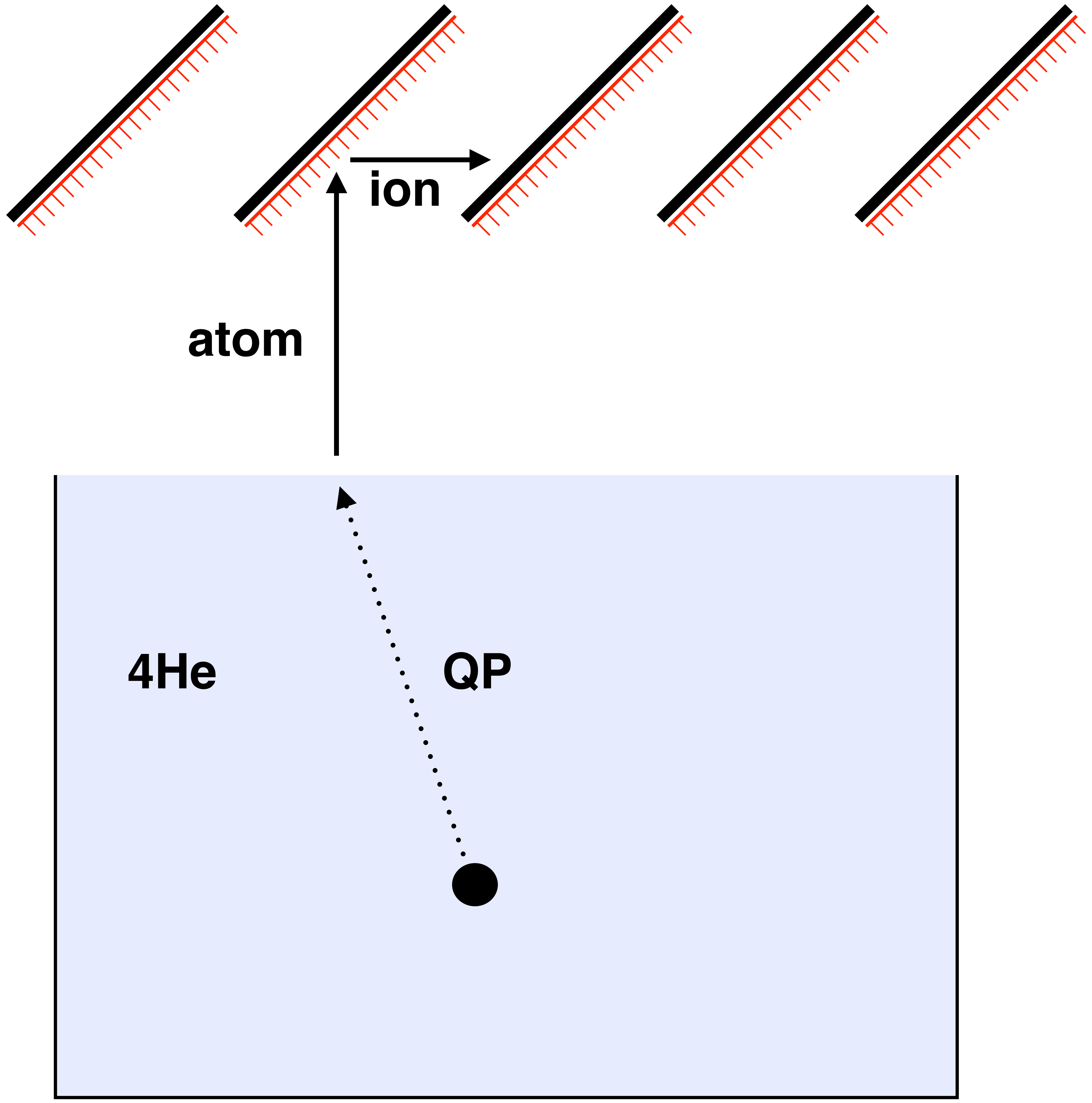
sensor: MMC array



sensor: single NTD



Evaporation Sensor Option 2: ionization of of 4He

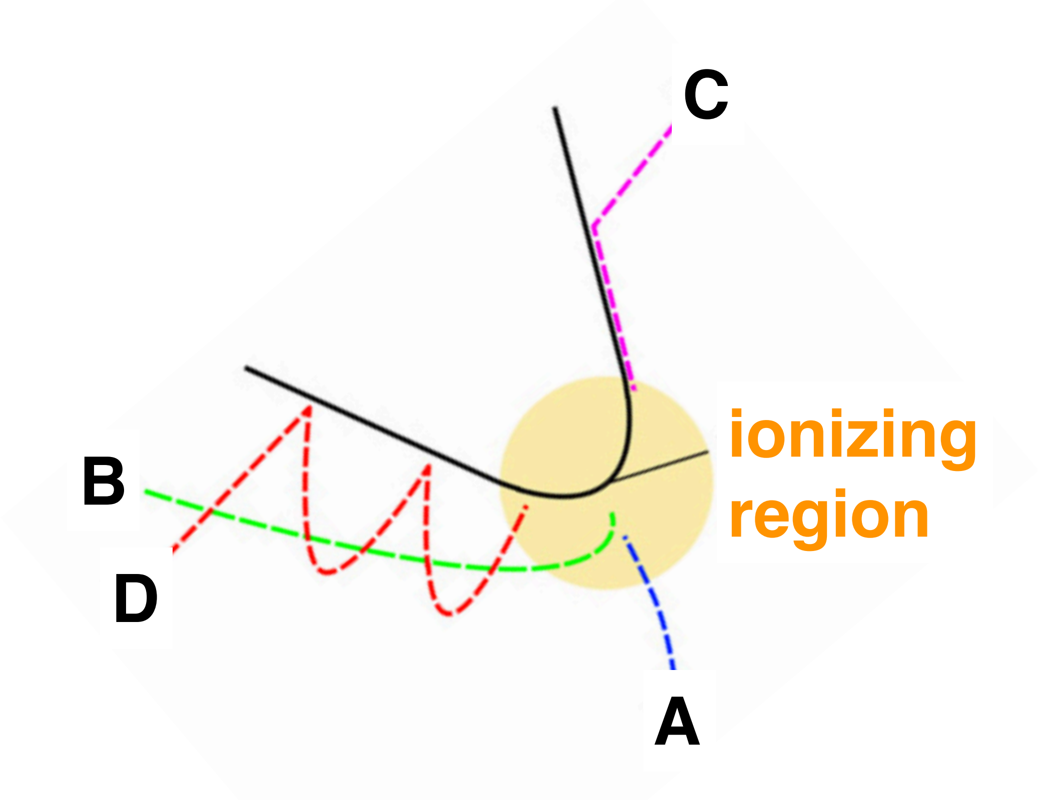


Possibility to leap-frog calorimetry to the single-evaporated-atom limit.

A charged particle (ionized 4He atom) is readily sensed.

Ionization is hard but possible:
- large-area arrays of tips
- nm-scale tip radii
- kV-scale applied voltages

Dark counts: stray atoms get stuck/ delayed in various ways. Experimental question.

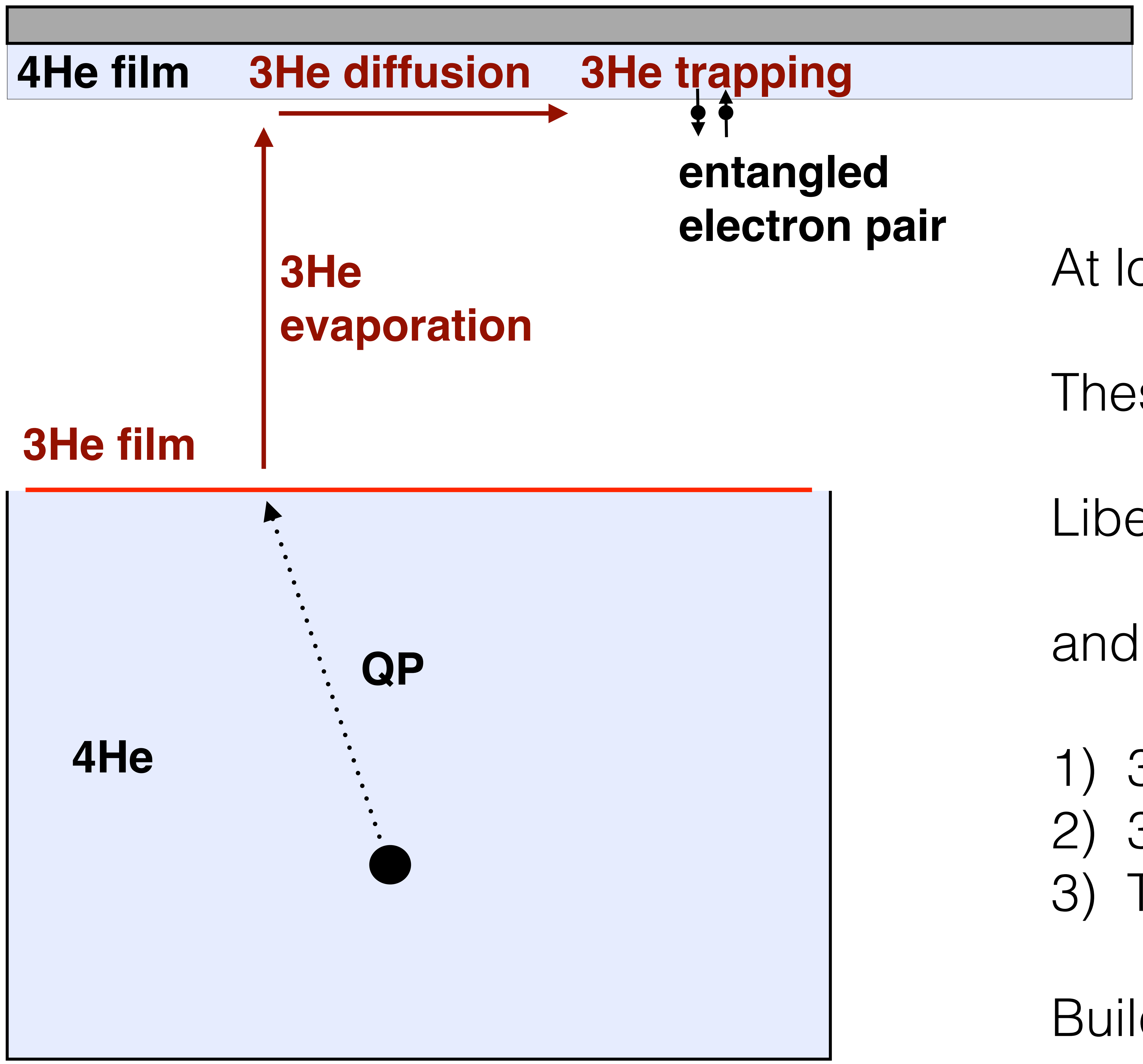


- **A.** **Direct impact**
- **B.** **Orbital capture**
- **C.** **Surface diffusion**
- **D.** **Bouncing**

Maris, Humphrey J., George M. Seidel, and Derek Stein. PRL 119.18 (2017): 181303.

Evaporation Sensor Option 3: 3He-triggered electron decoherence

Another concept for leapfrogging calorimetry to the single-atom limit.



At low temperatures, 3He naturally segregates to the surface.

These 3He atoms can evaporate in the same way.

Liberated 3He atom sticks to surface of a pure 4He film,

and then….

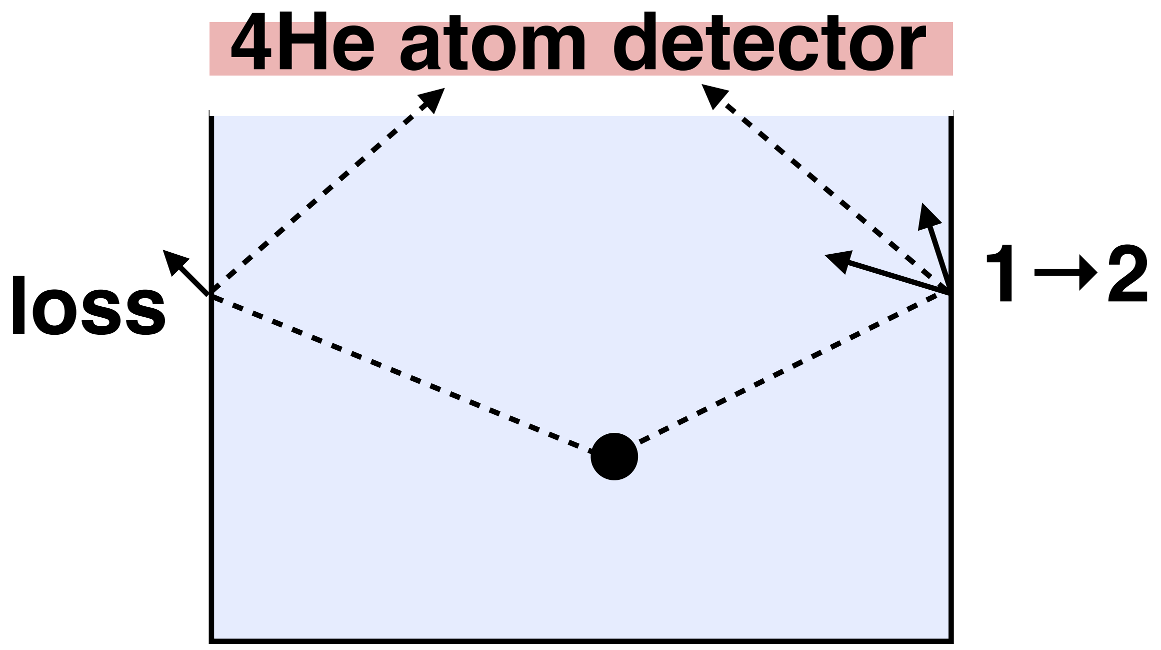
1) 3He diffuses over 4He film surface
2) 3He falls into the ‘well’ formed by a bound electron
3) That electron loses coherence (if initially in an entangled state)

Builds on existing significant QIS R&D on bound electrons.

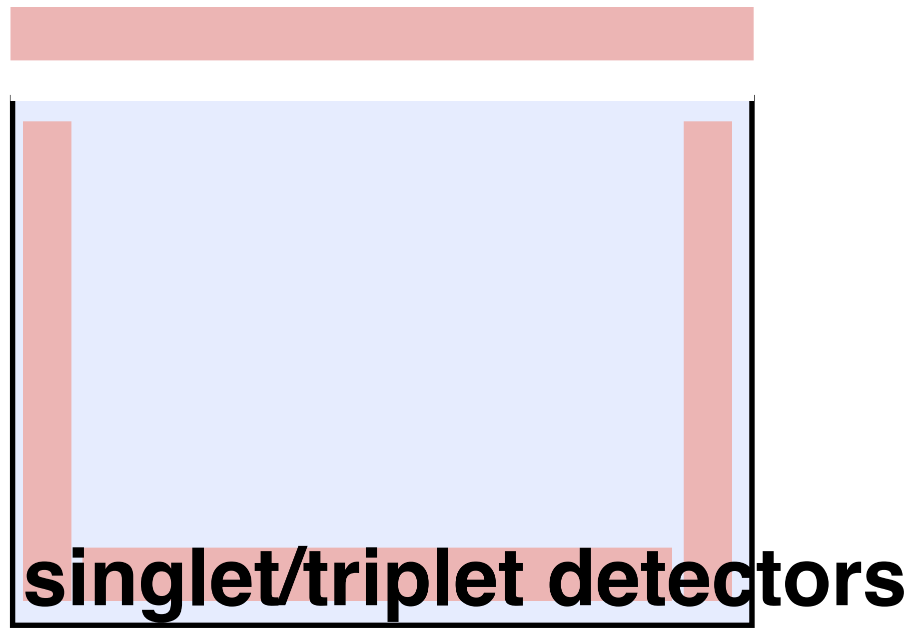
See LOI: IF/SNOWMASS21-IF1_IF0-RF3_RF0-CF1_CF2_Steve_Lyon-055.pdf, Lyon & Schenkel

R&D path

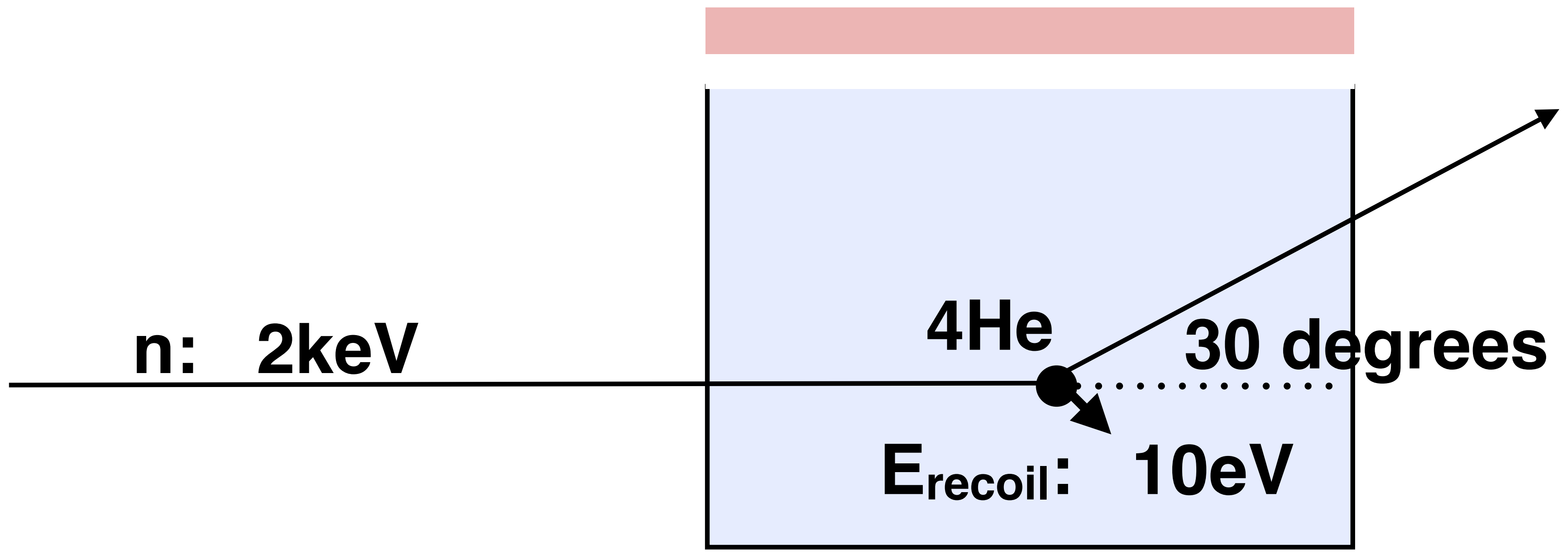
1) Push evaporation calorimeter threshold as low as possible.
   $\mathcal{O}$ 10 eV → $\mathcal{O}$ 1 eV → $\mathcal{O}$ 0.1 eV → goal: 10meV, the single-atom limit



2) Study QP reflection and loss to increase evaporation fraction.
   (swept this under the rug till now: only ~5% of QPs survive multiple reflections and contribute to evaporation signal)



3) Measure atomic excitation yields, and test immersed detectors with ~4π coverage.



4) Requires new calibration methods (including keV & sub-keV neutrons)

Summary points

4He is a promising target for testing MeV-scale DM via hadronic interactions.

clean <20eV window in which only NR is possible

complementary to electronic searches in earlier talks today

some sub-MeV sensitivity via direct QP excitation (not the main selling point)

Material properties make quasiparticle signal especially useful and especially practical.

QPs preserve recoil information (not just energy)

QPs visible as liberated atoms, a well-demonstrated technology.

Calorimeter physically separated from target, no thermal connection.

Path is clear for low evaporation thresholds via calorimetry. (plus, other technologies under development).