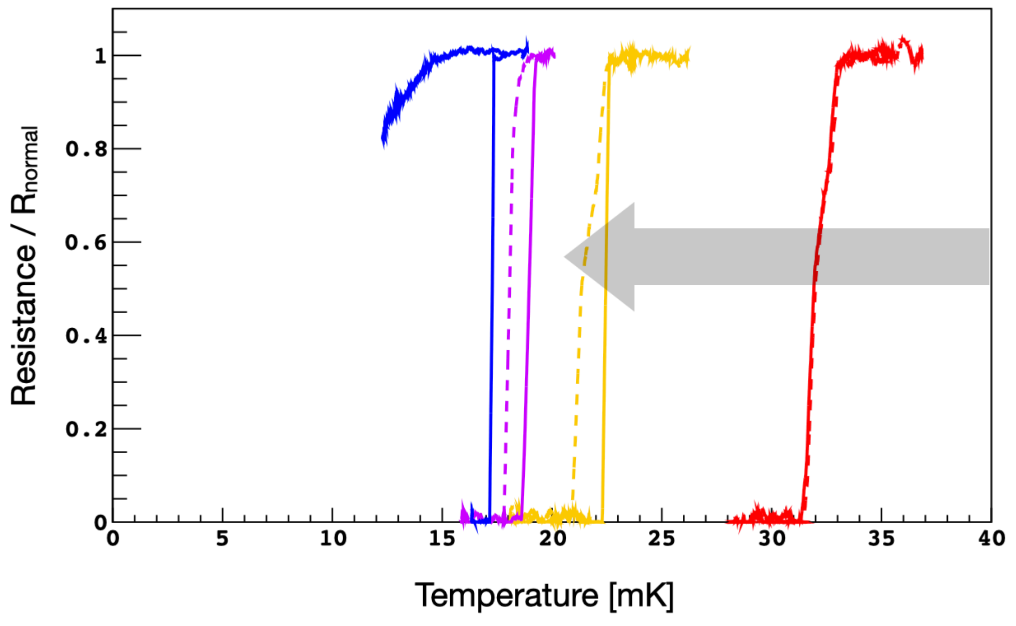
# Progress Toward a Superfluid 4He Detector for Light Dark Matter

arXiv.org:2307.11877

**Scott Hertel**
**U. Massachusetts, Amherst**
**On behalf of the SPICE/HeRALD Collaboration**

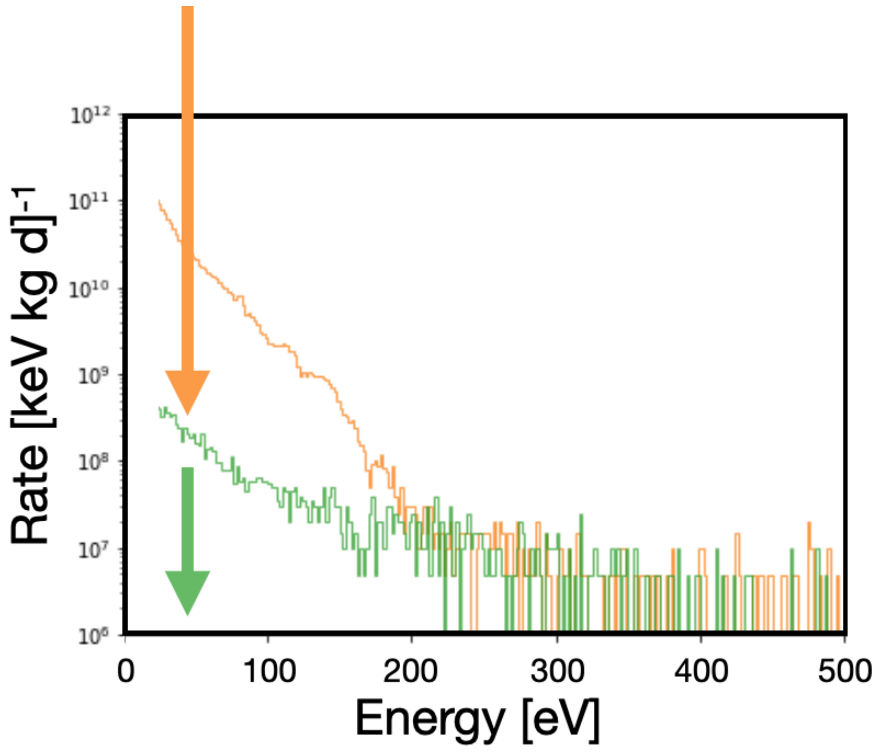
# The big-picture: SPICE and HeRALD, aka `TESSERACT'

## Core unifying R&D efforts:



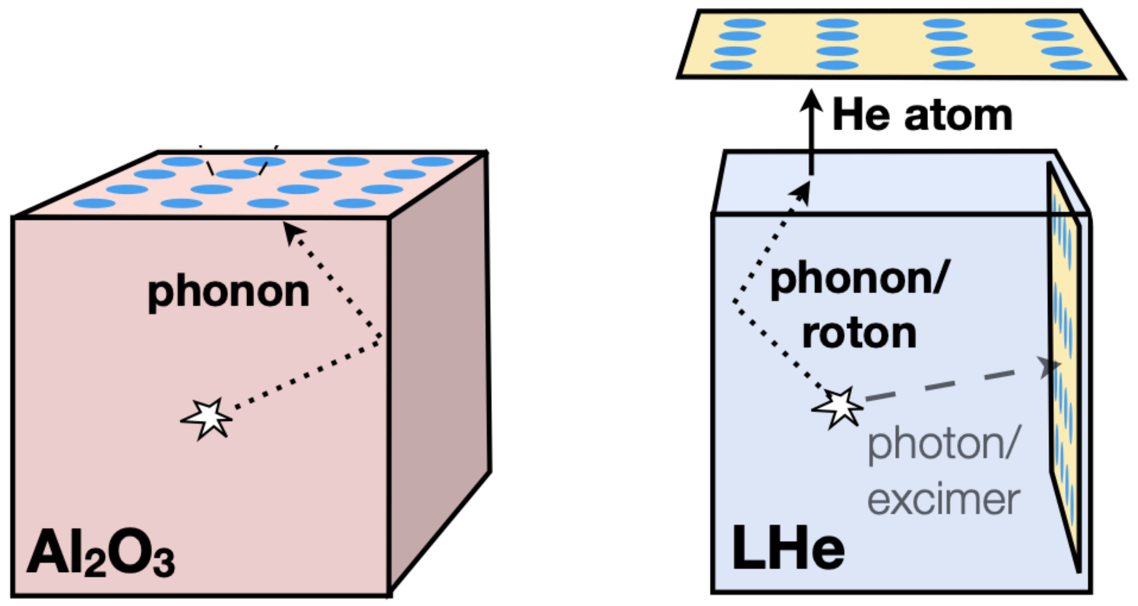

### 1. Push TESs to meV Thresholds

- ❑ Reduce $T_c$ to <20mK
- ❑ Reduce TES volume (heat capacity)
- ❑ Eliminate parasitic heat loads (IR, RF, etc.)




### 2. Minimize Low Energy Excess

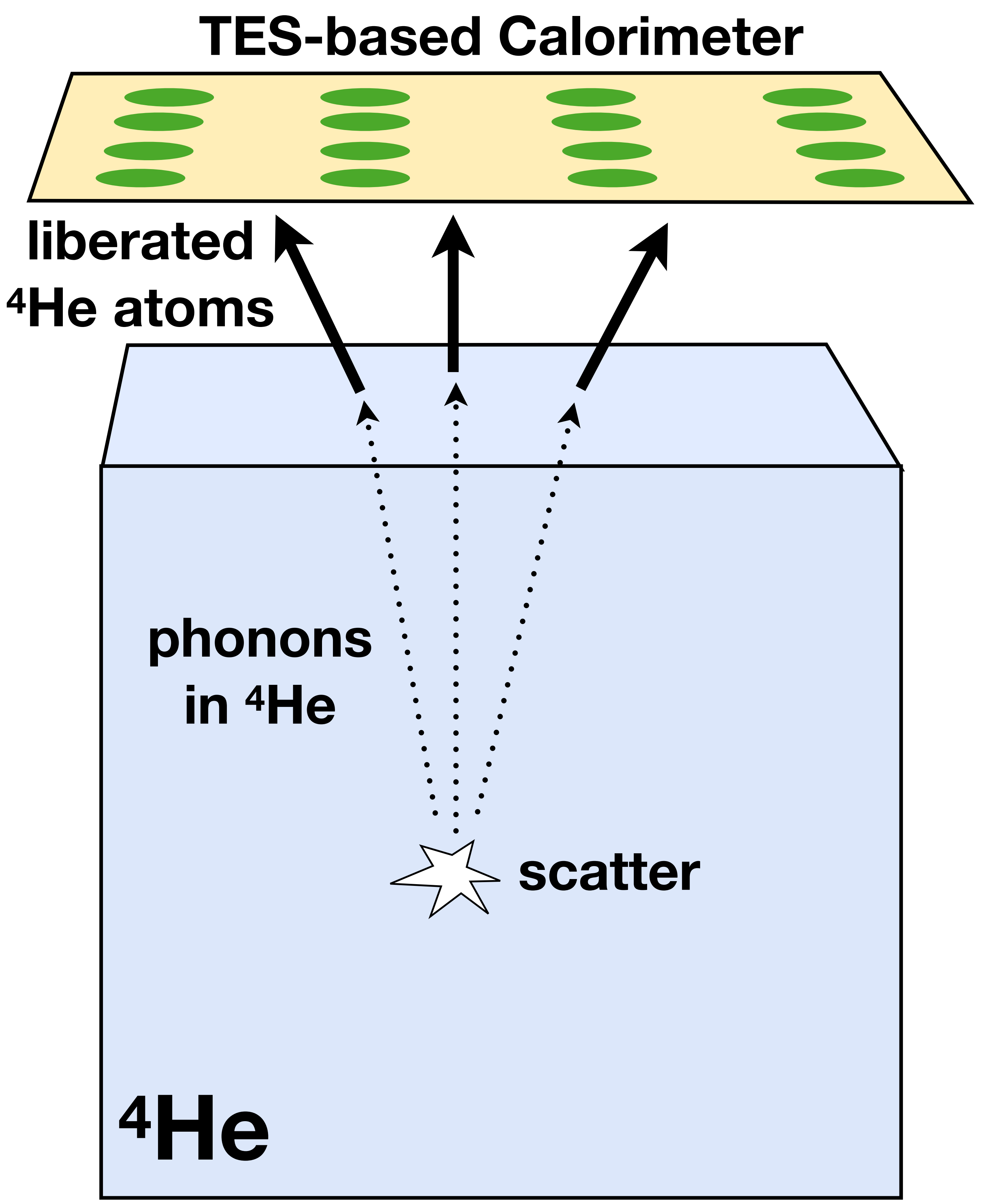
- ❑ Eliminate clamps
- ❑ Utilize multi-channel coincidence
- ❑ Optimize fabrication methods, materials, material amounts, …




### 3. Apply these meV Sensors to Diverse Target Materials

- ❑ DM coupling via optical phonons (SPICE)
- ❑ Standard NR on light nucleus with gain mechanism (HeRALD)

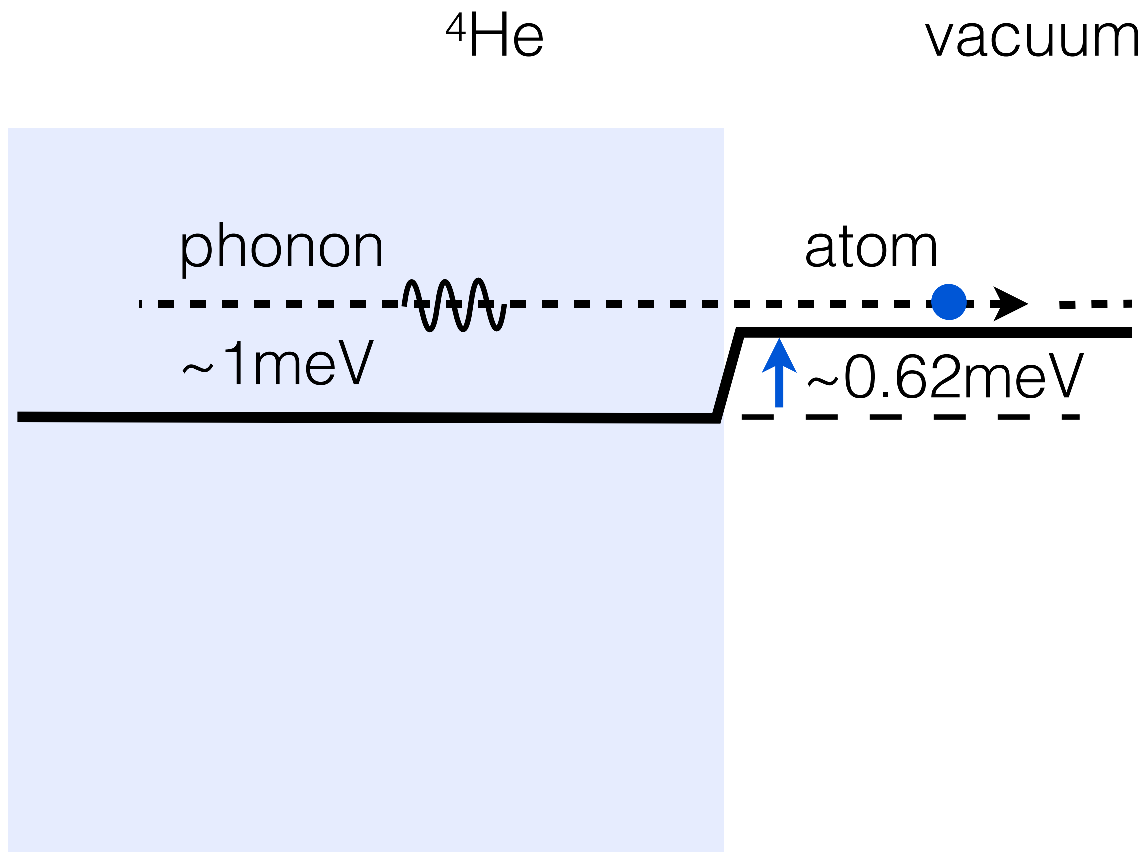
# Physics of a Superfluid $^4$He Target




**Primary Signal Channel :** **'Quantum Evaporation'**

A single phonon can liberate a single atom into the vacuum

- typical phonon energy in $^4$He: **~1meV**
- binding energy of $^4$He to the $^4$He liquid surface: **~0.62meV**



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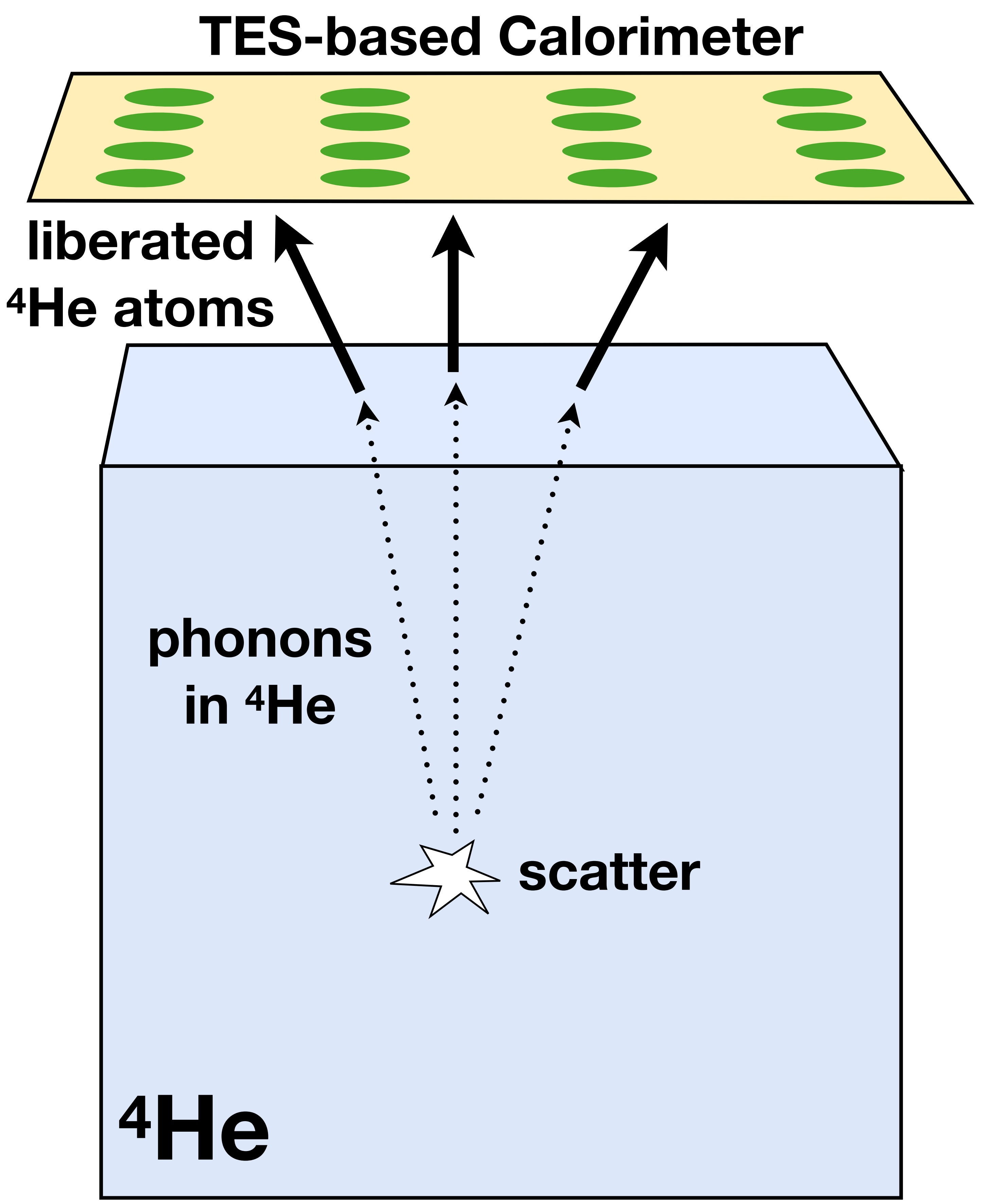


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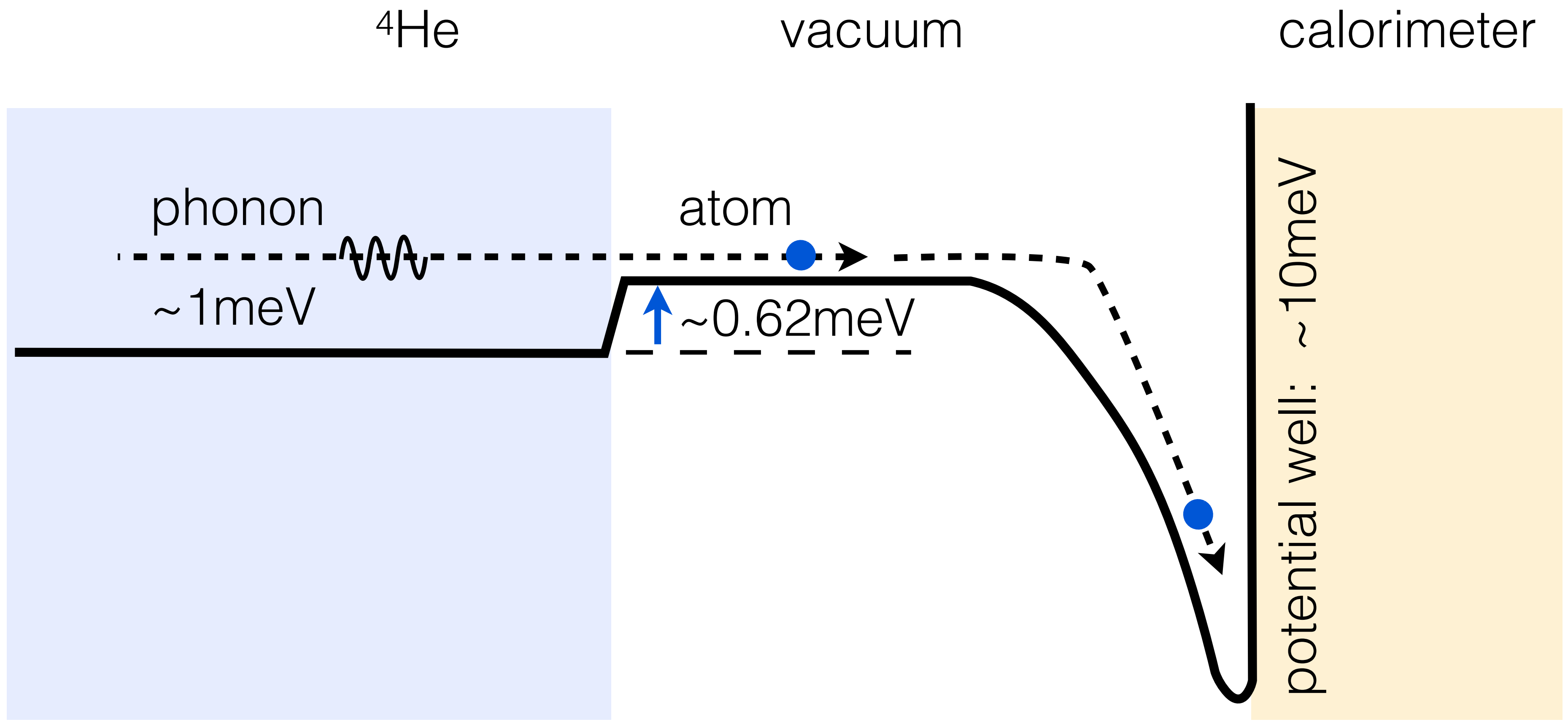
Signal: the *adsorption* of of atoms onto a calorimeter

- binding energy of $^4$He to a typical calorimeter surface: **~10meV**



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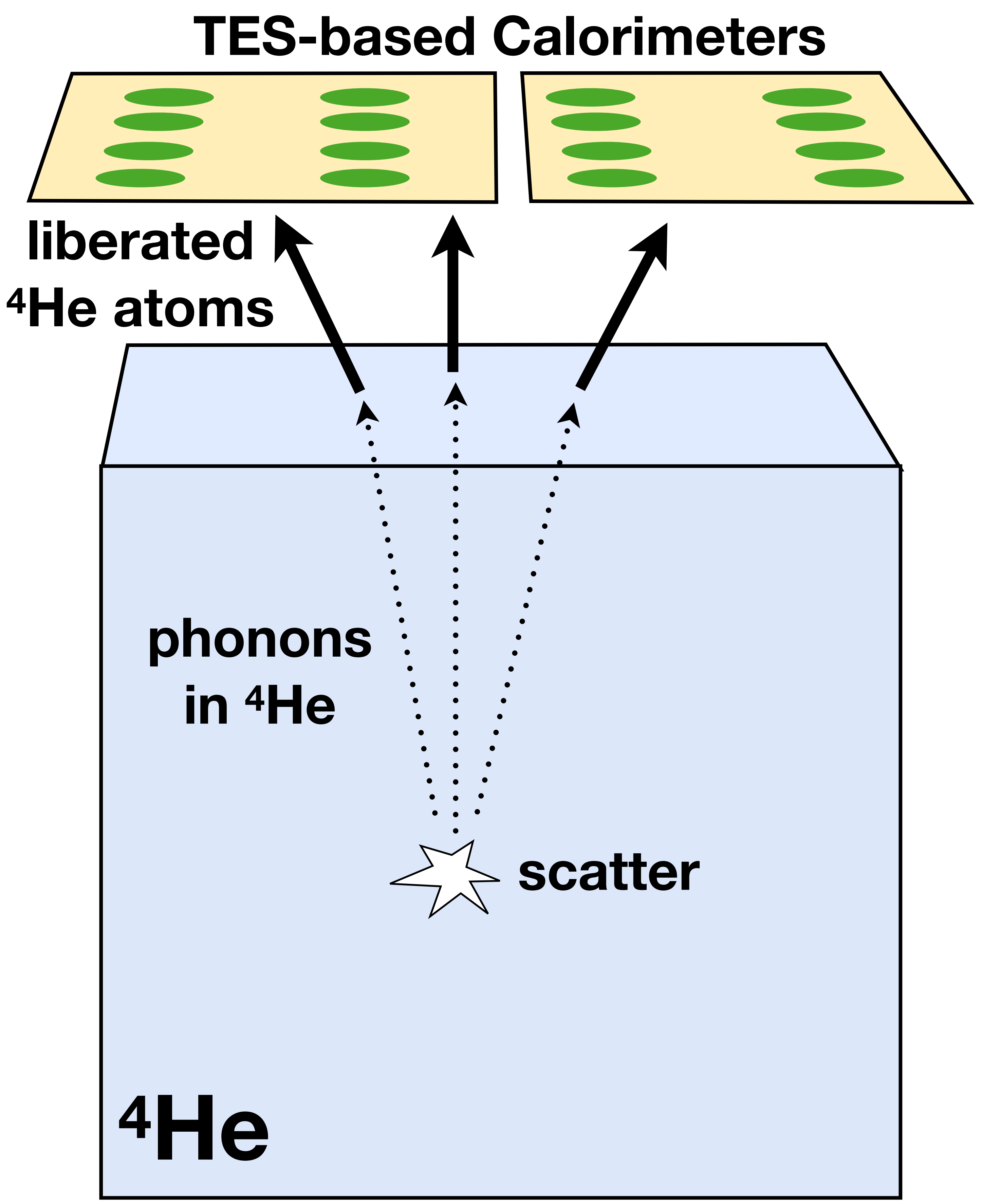


Two advantages of Quantum Evaporation
(over standard phonon readout)

**1) Gain mechanism *before* sensing**

*Route to pushing recoil threshold below calorimeter threshold*

**2) Signals from $^4$He target : strongly *multi*-channel,**
**Calorimeter backgrounds : strongly *single*-channel**

*"Low energy excess" can be excluded by enforcing multi-calorimeter coincidence (assuming calorimeter origin)*

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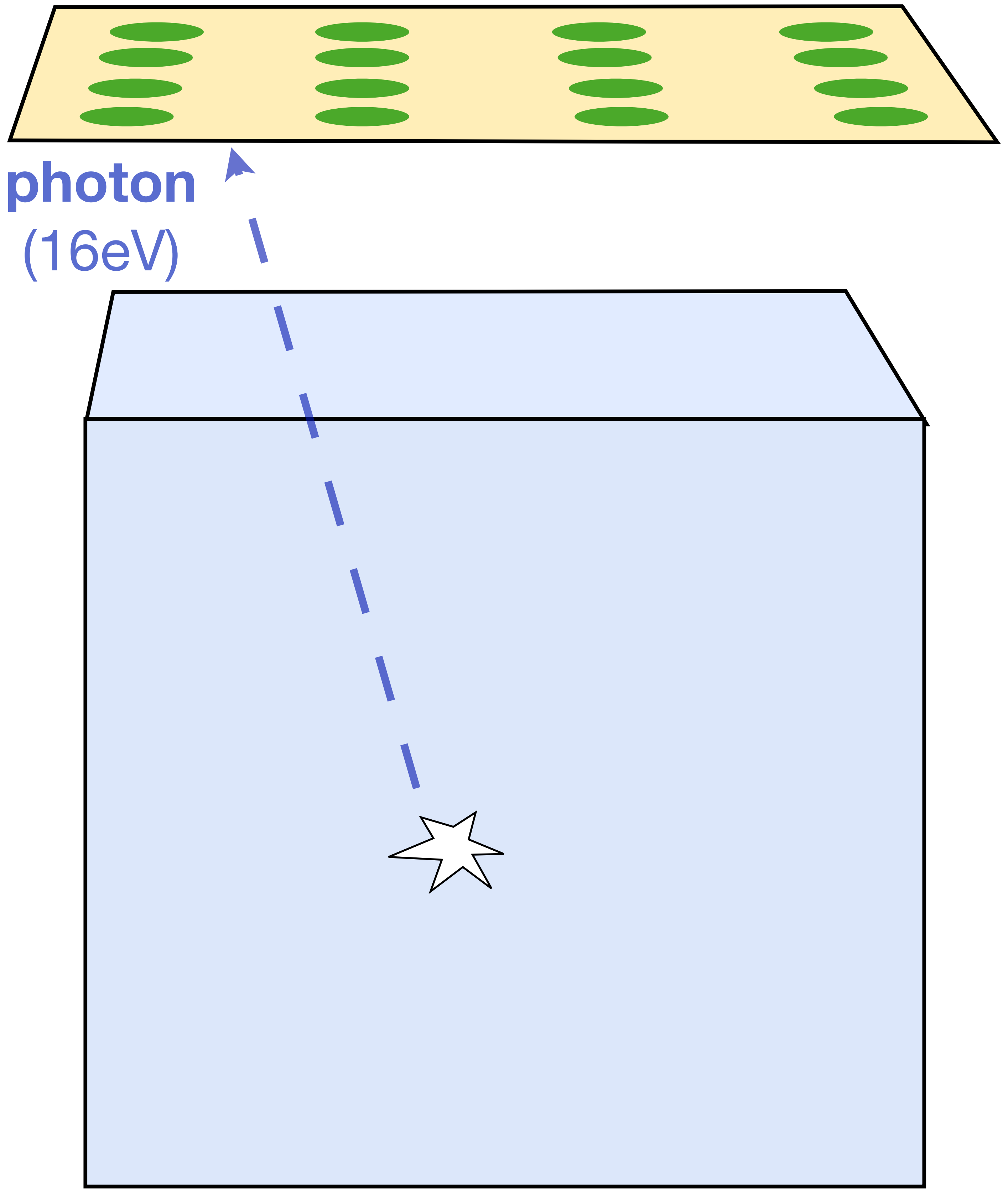


**Secondary signals: atomic excitations**

**Singlet dimers: simple**

- Prompt decay
- Photon energy: ~16eV

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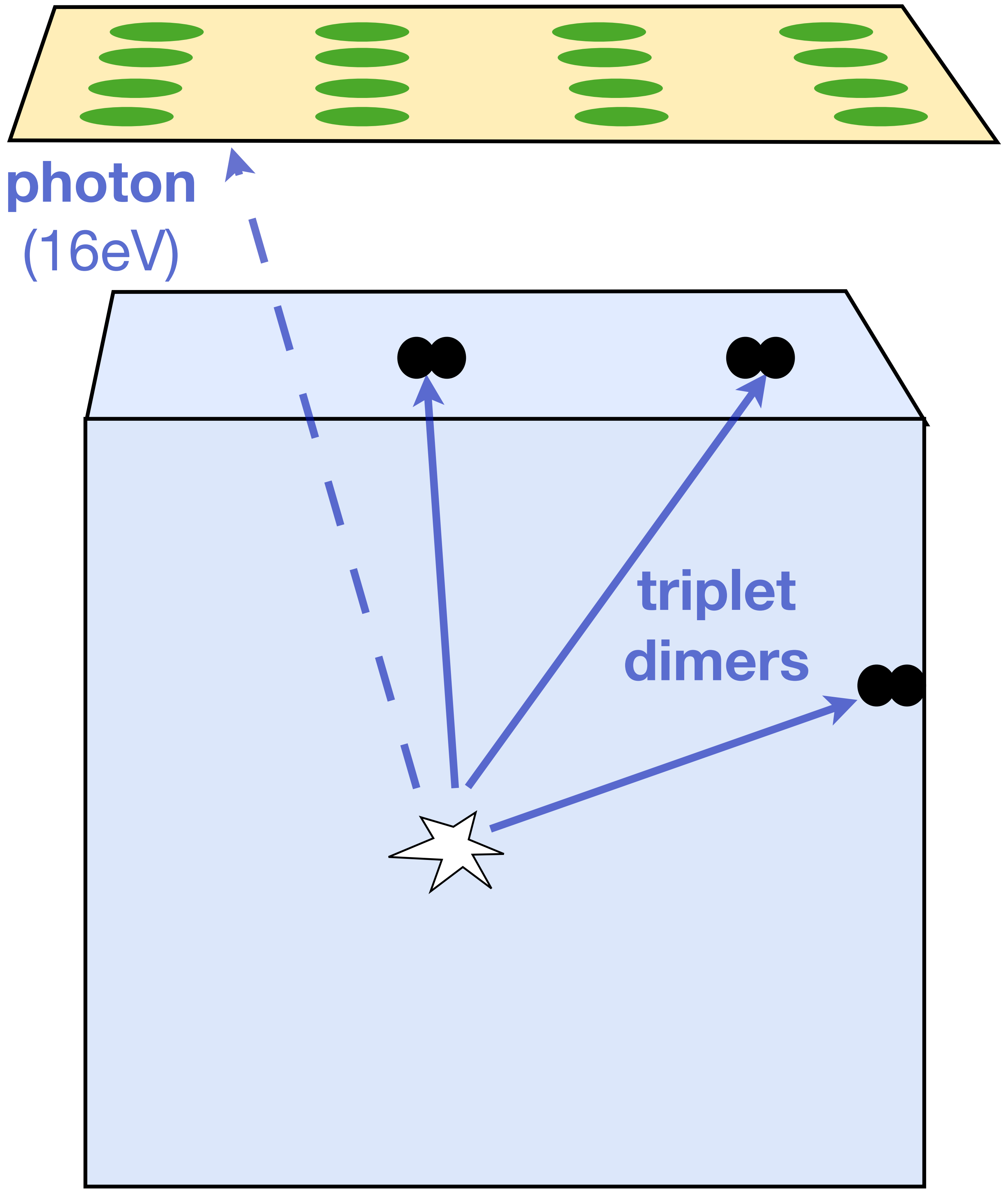


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**Triplet dimers: "interesting"**

- In the bulk superfluid:
  - extremely long lifetime (13 s) DOI:10.1103/PhysRevA.59.200
  - ballistic propagation at $\mathcal{O}$(m/s) velocities arXiv:1207.1799

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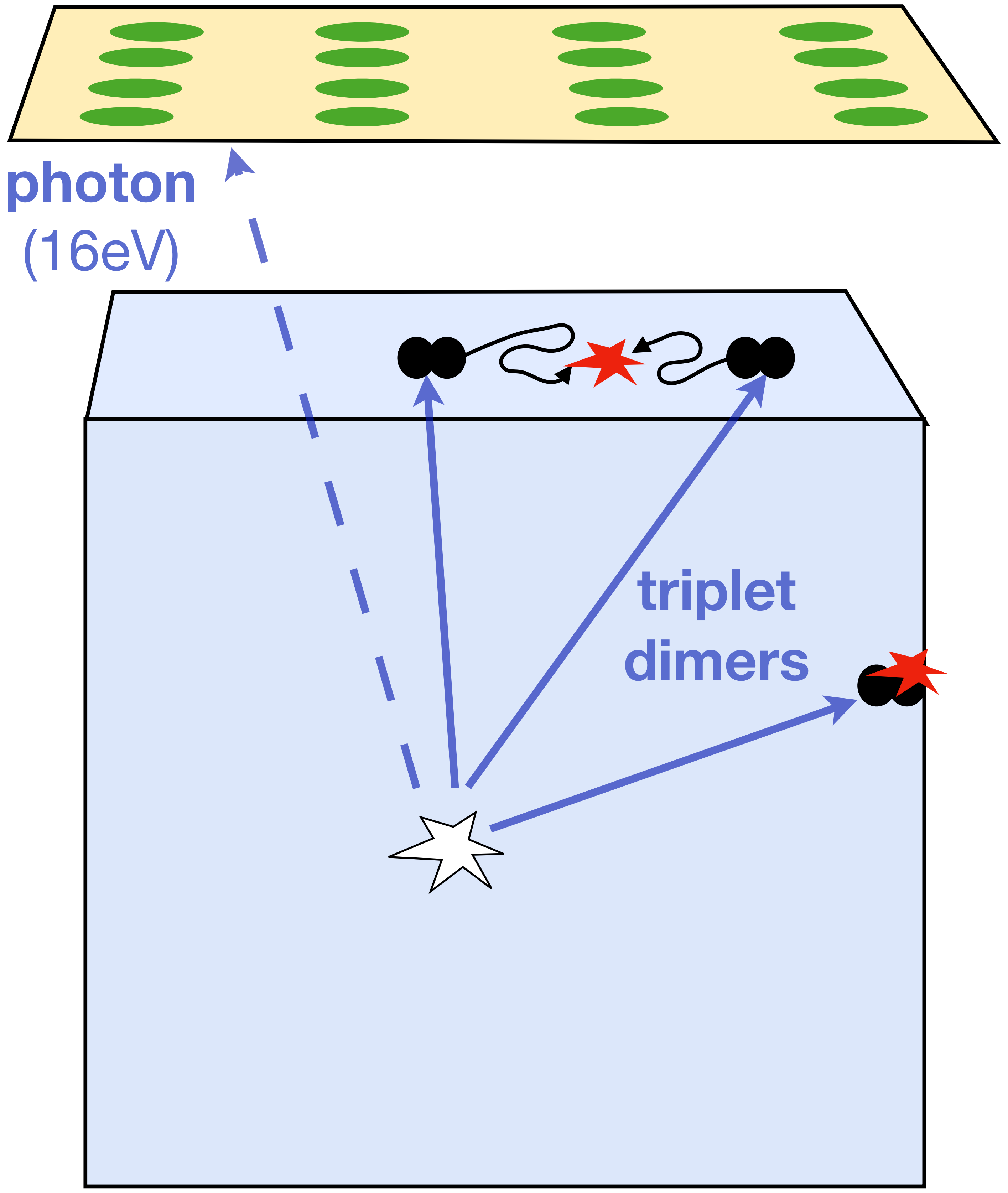


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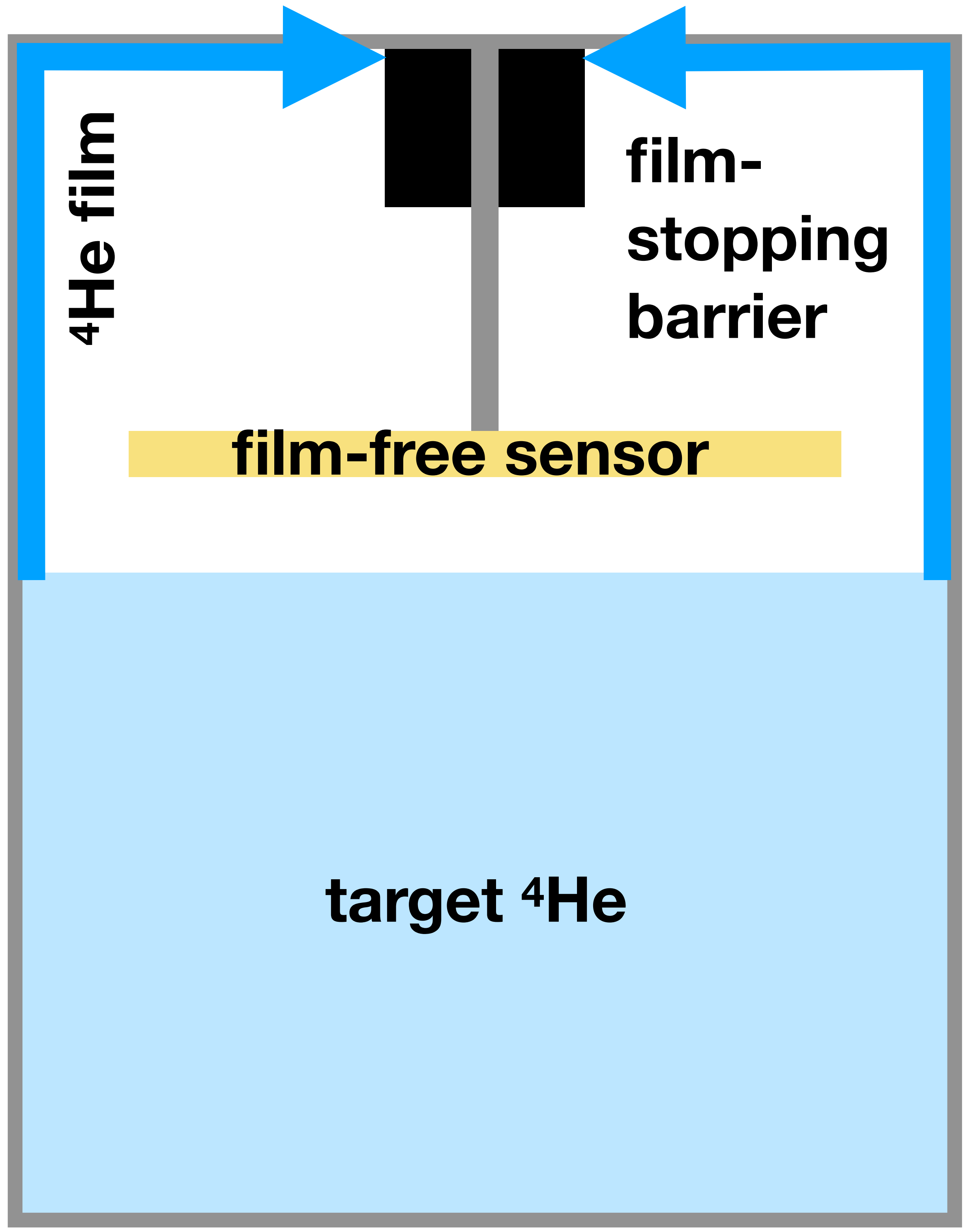
  - extremely long lifetime (13 s) DOI:10.1103/PhysRevA.59.200
  - ballistic propagation at $\mathcal{O}$(m/s) velocities arXiv:1207.1799
- Quench/decay occurs at ***surfaces***:
  - $^4$He/metal: exchange of electrons with surface (upon arrival)
  - $^4$He/vacuum: surface diffusion to quenching sites (rate~1/t )

# Physics of a Superfluid $^4$He Target: Film-Stopping

Need some **barrier** to keep $^4$He from flowing to the sensor.




**Options are few:**

1. **Film Burner**
(necessarily raises sensor temperature)

2. **Knife Edge**
(requires Å-scale radius at 10mK )

3. **…. need something new.**

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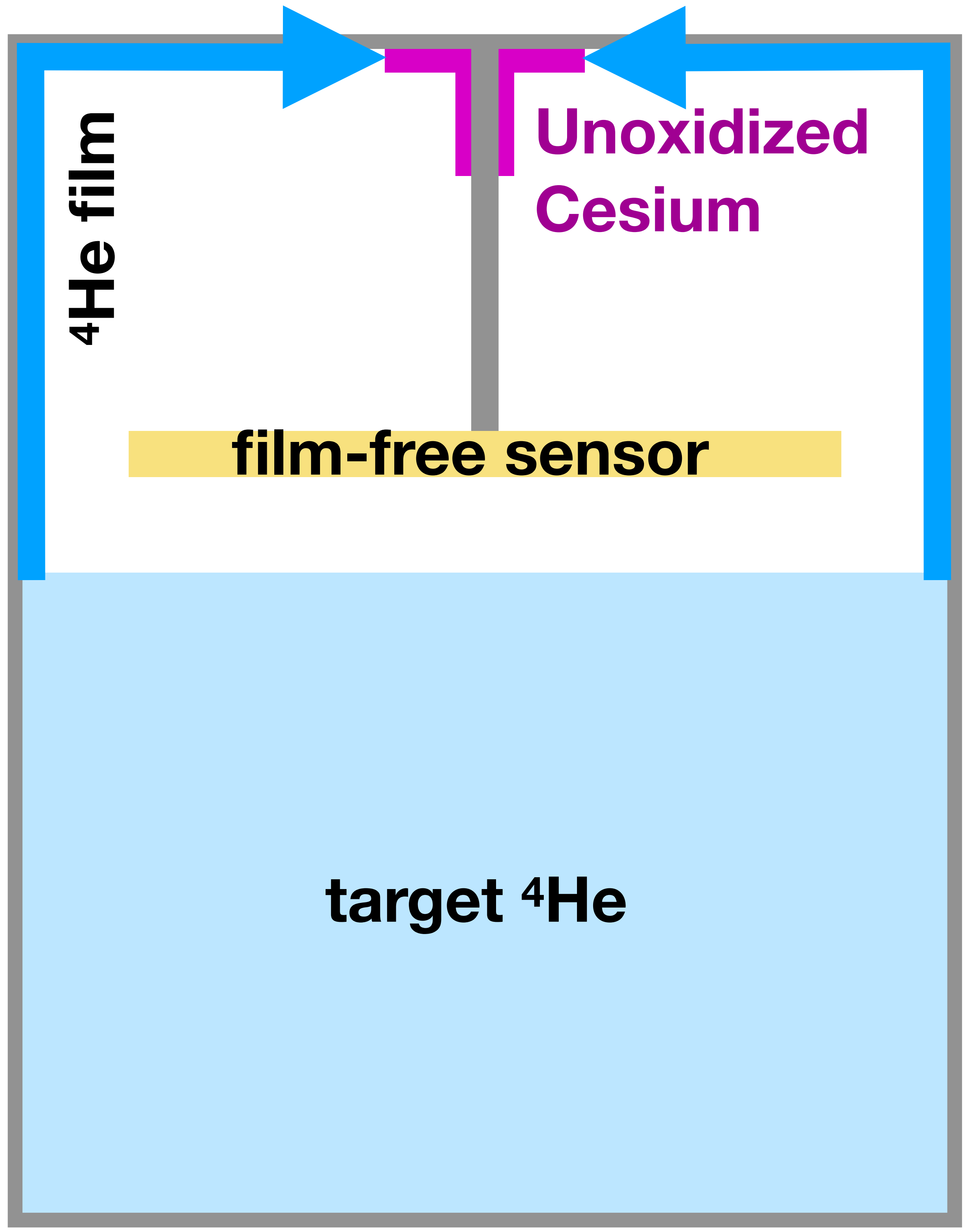


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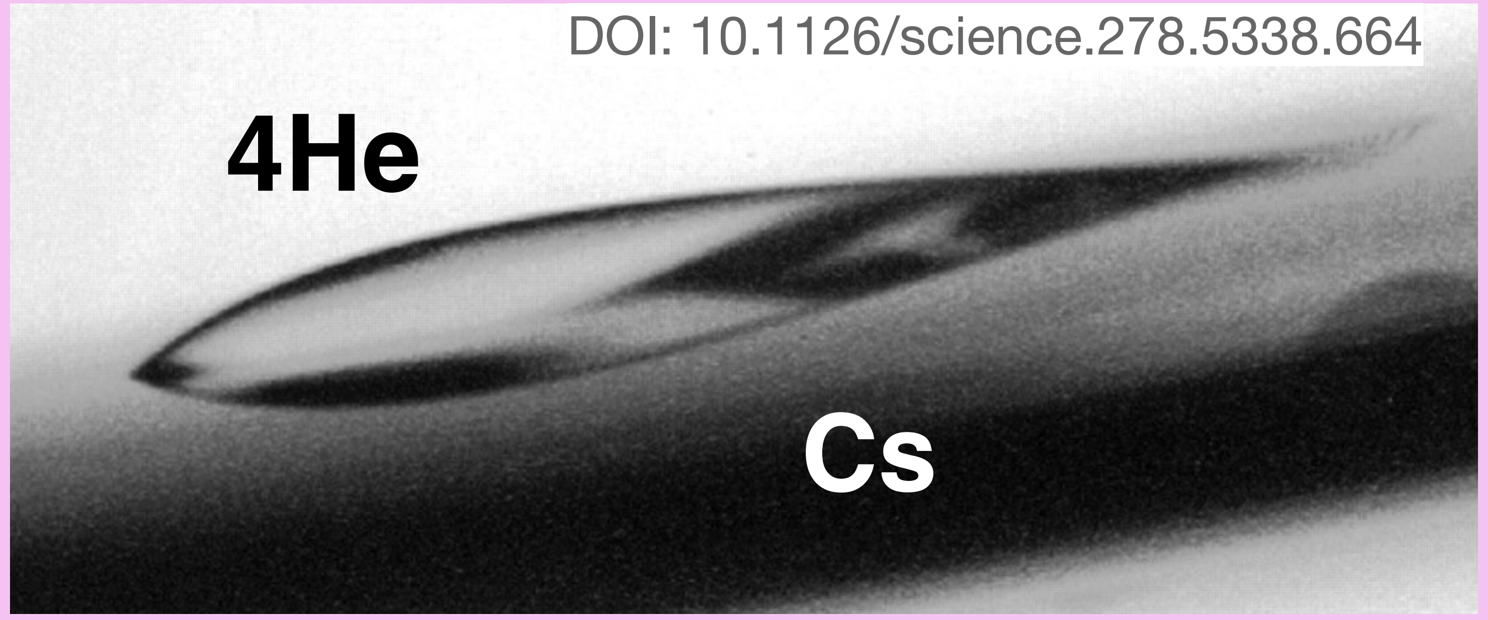
3. **Elemental Cesium**
(one of very few surfaces which $^4$He does not wet)



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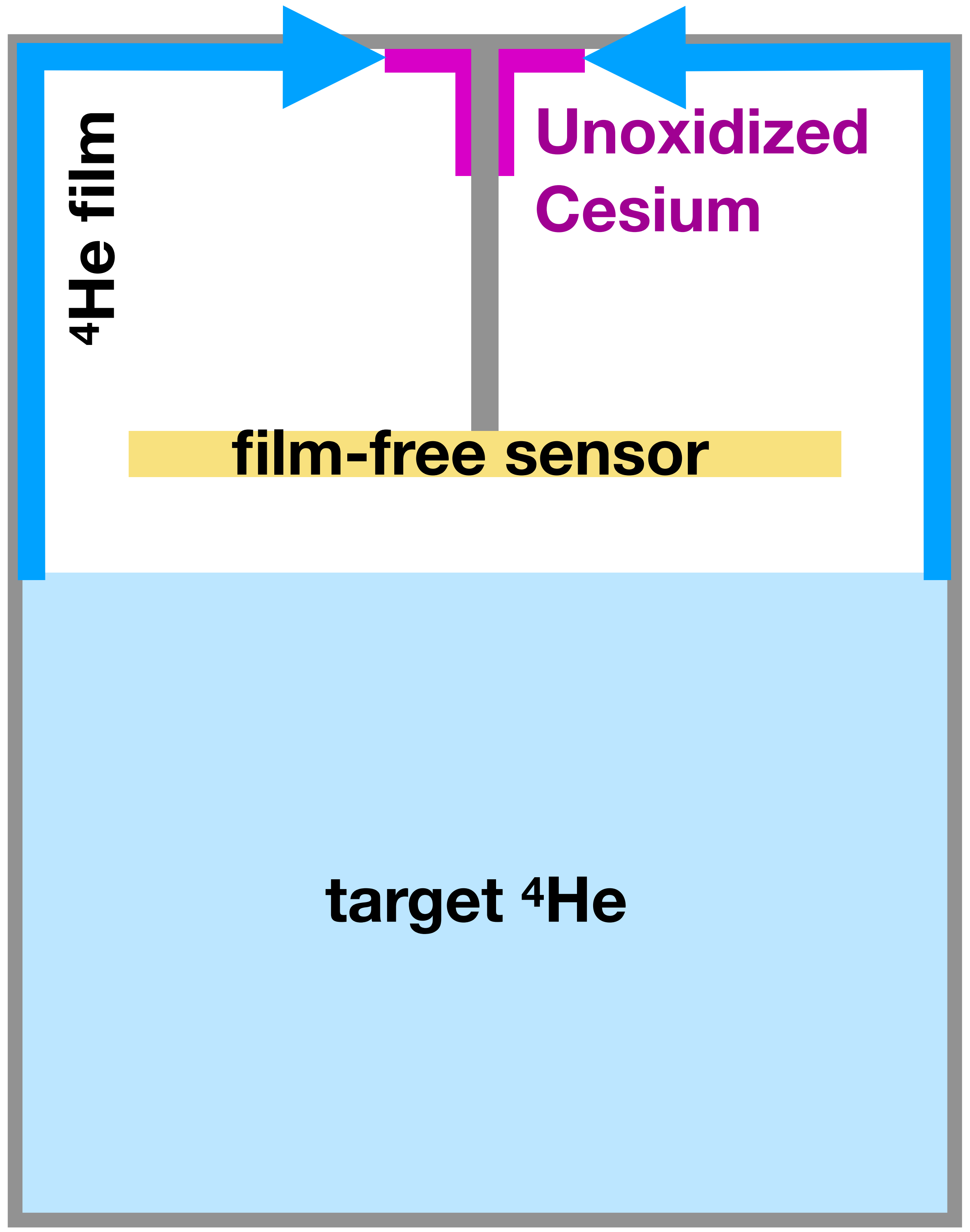


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However… Cs is a major practical challenge:

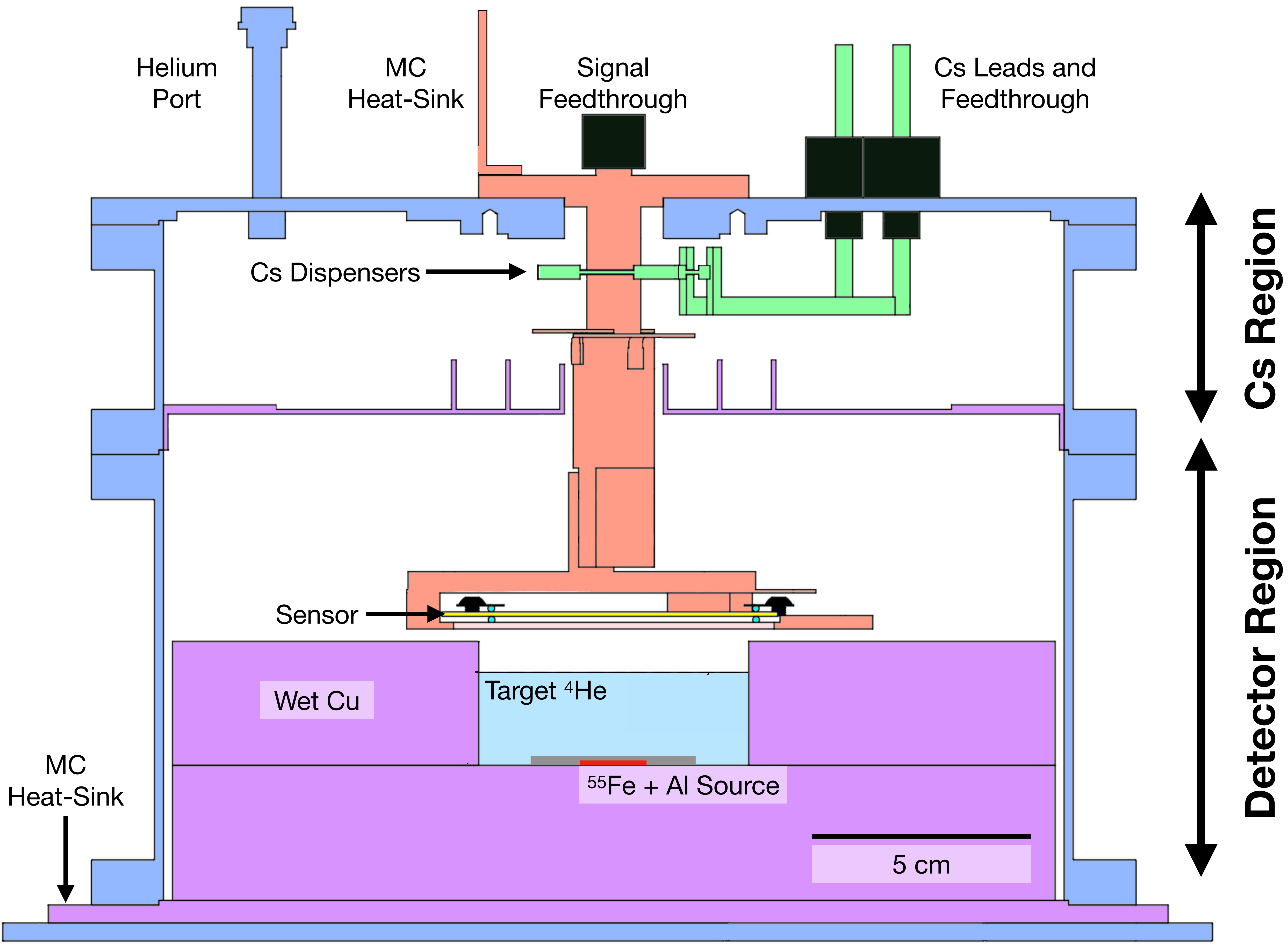
- must be unoxidized (deposited in vacuum, *in situ* )
- deposition requires ~800°C (and high current, >7A)
- significant vapor pressure at room temperature

(deposition must occur cold, and Cs must be chemically ‘fixed’ before warming up)

We are progressing now, after solving these challenges.

(anticipating a natural question: Cs has no long-lived radioisotopes)

# "HeRALD v0.1"   R&D Hardware




**Primary goal:   demonstrate/practice Cs film-stopping**

Ring of Cs dispensers, deposit Cs on central pillar

Everything on pillar (below Cs) remains film-free

Baffles separate "film-stopping region" from "detector region"

Large (20cm ⌀ ) stainless cell

$^4$He target region:  6cm diameter

Up to 27kg of Cu within cell

- serves as flexible 'filler' to define the target during R&D
- $\gamma$ shield      (→ 0.7 Bq in the 10g of Si)

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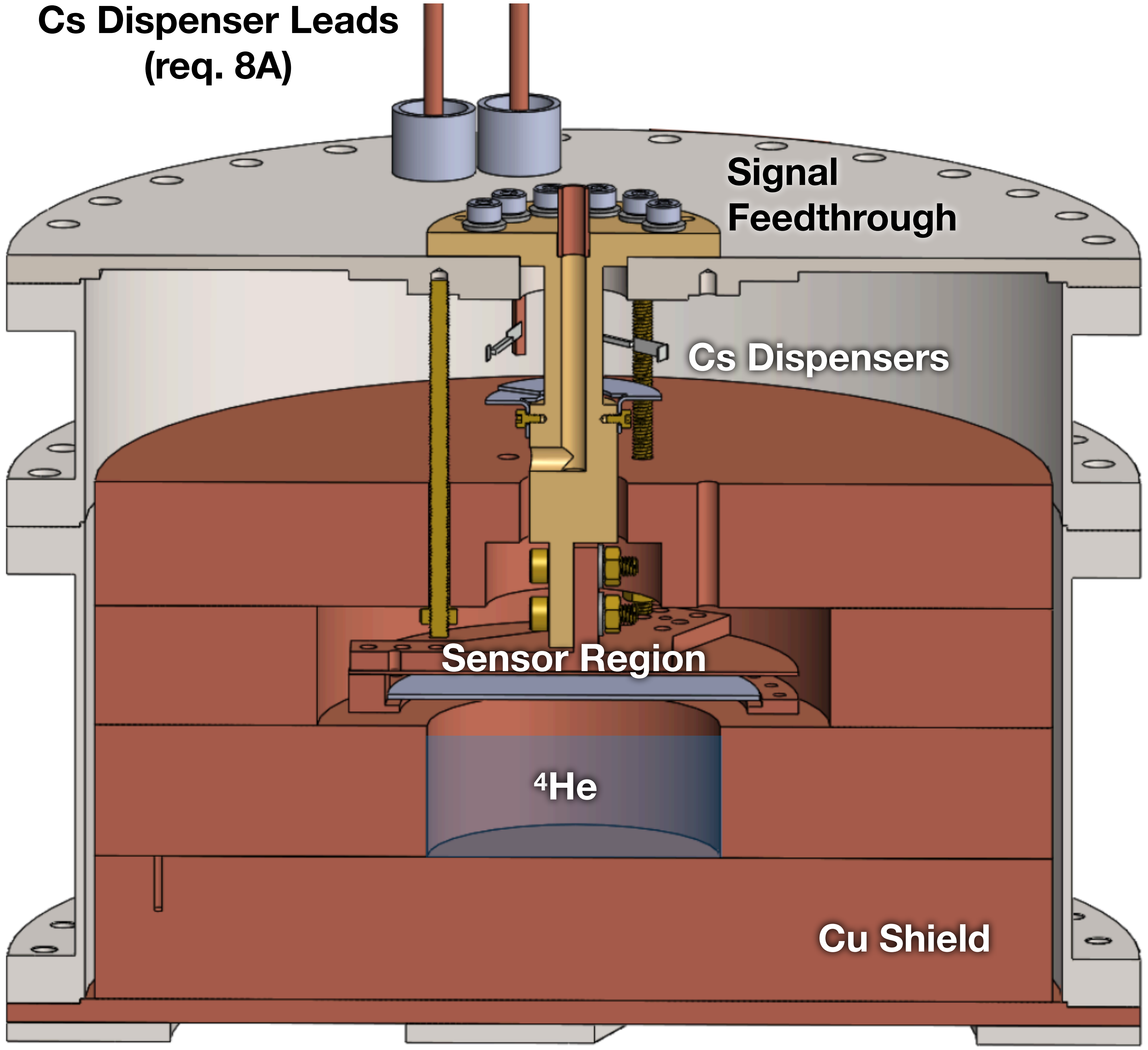


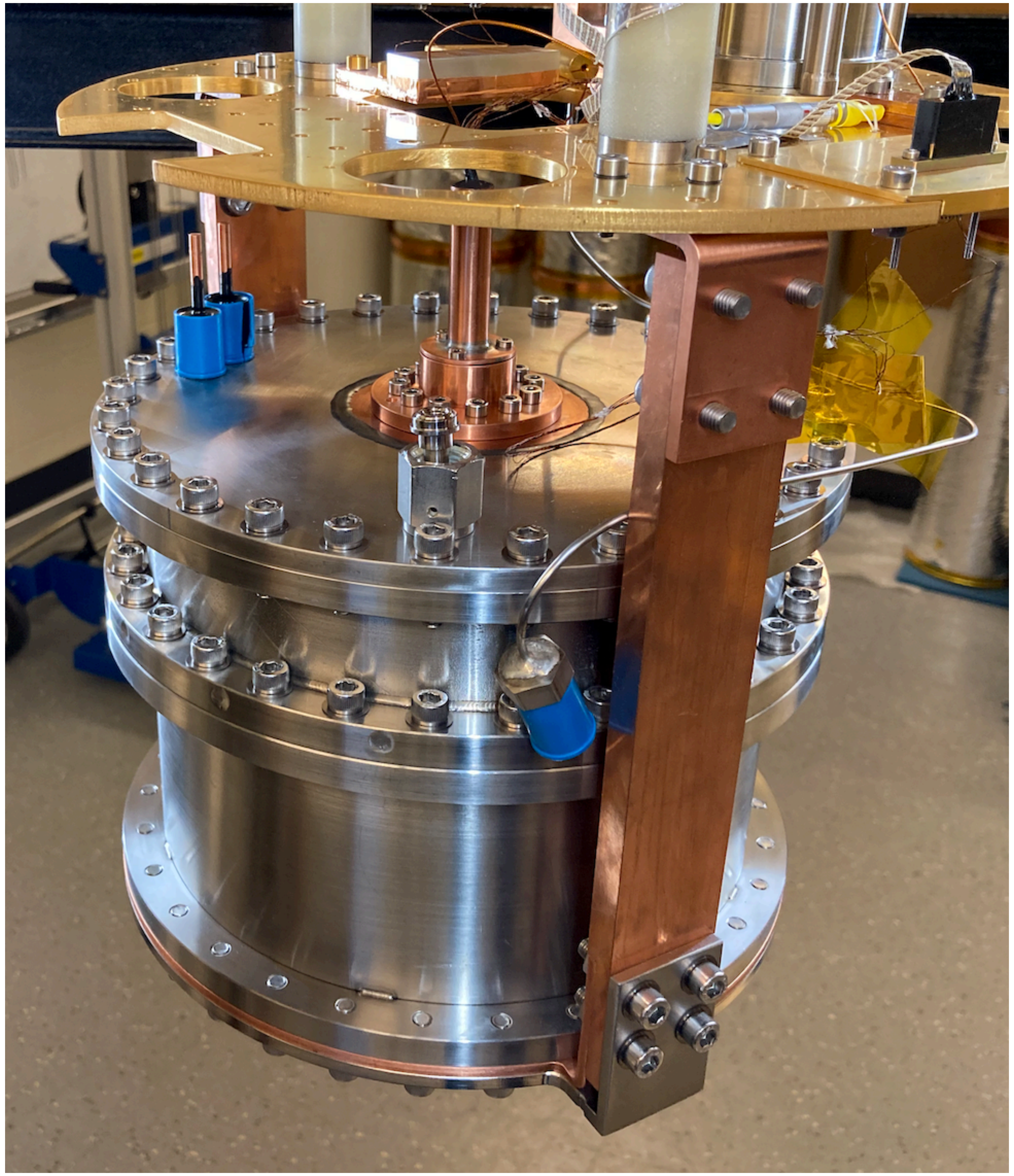

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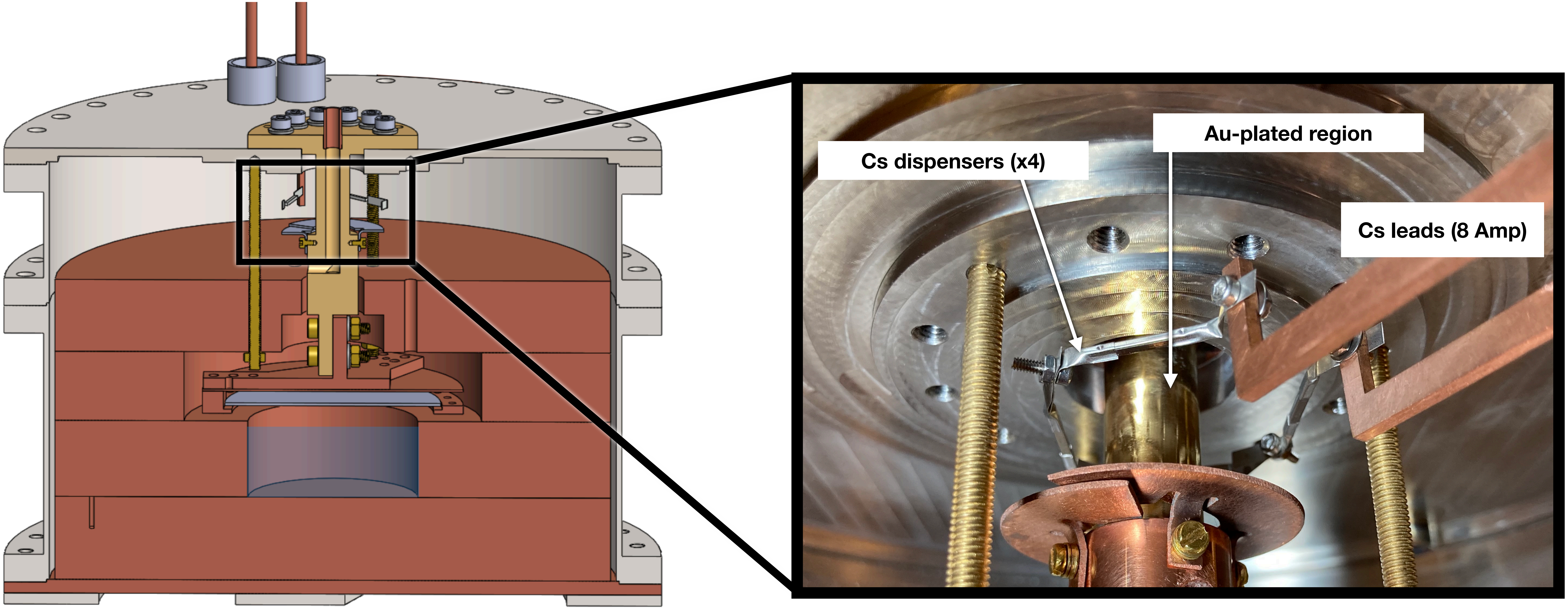

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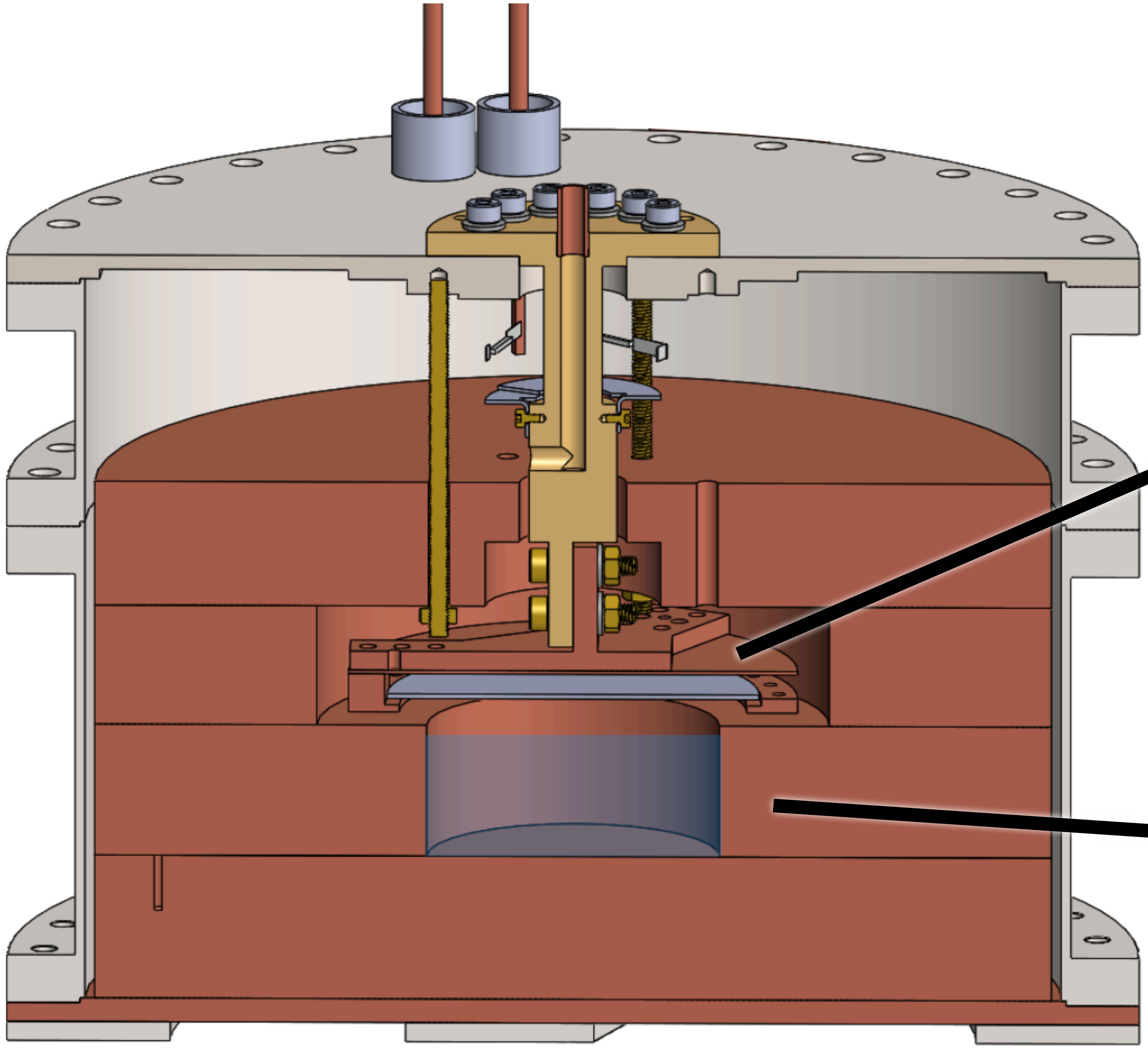
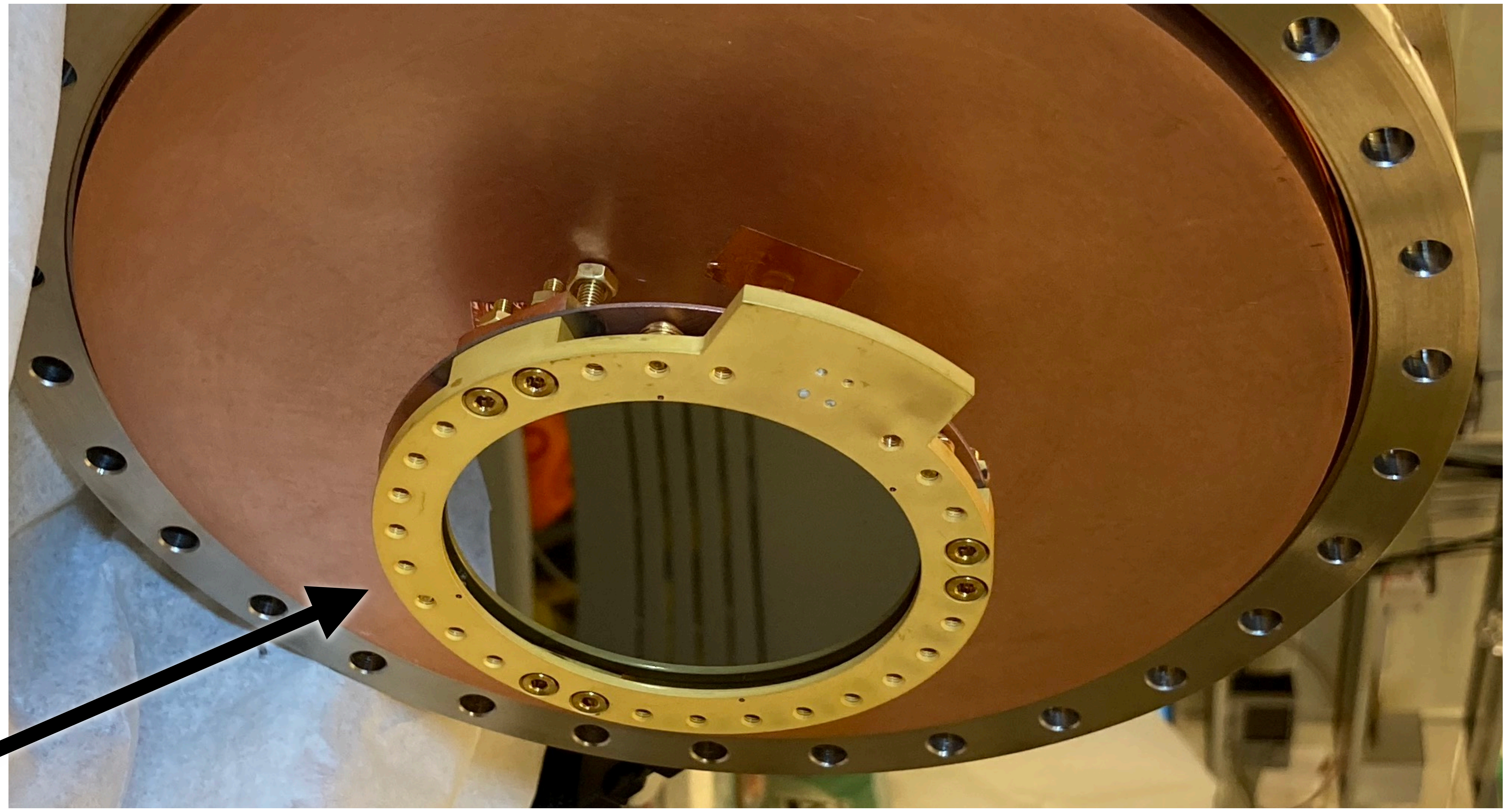
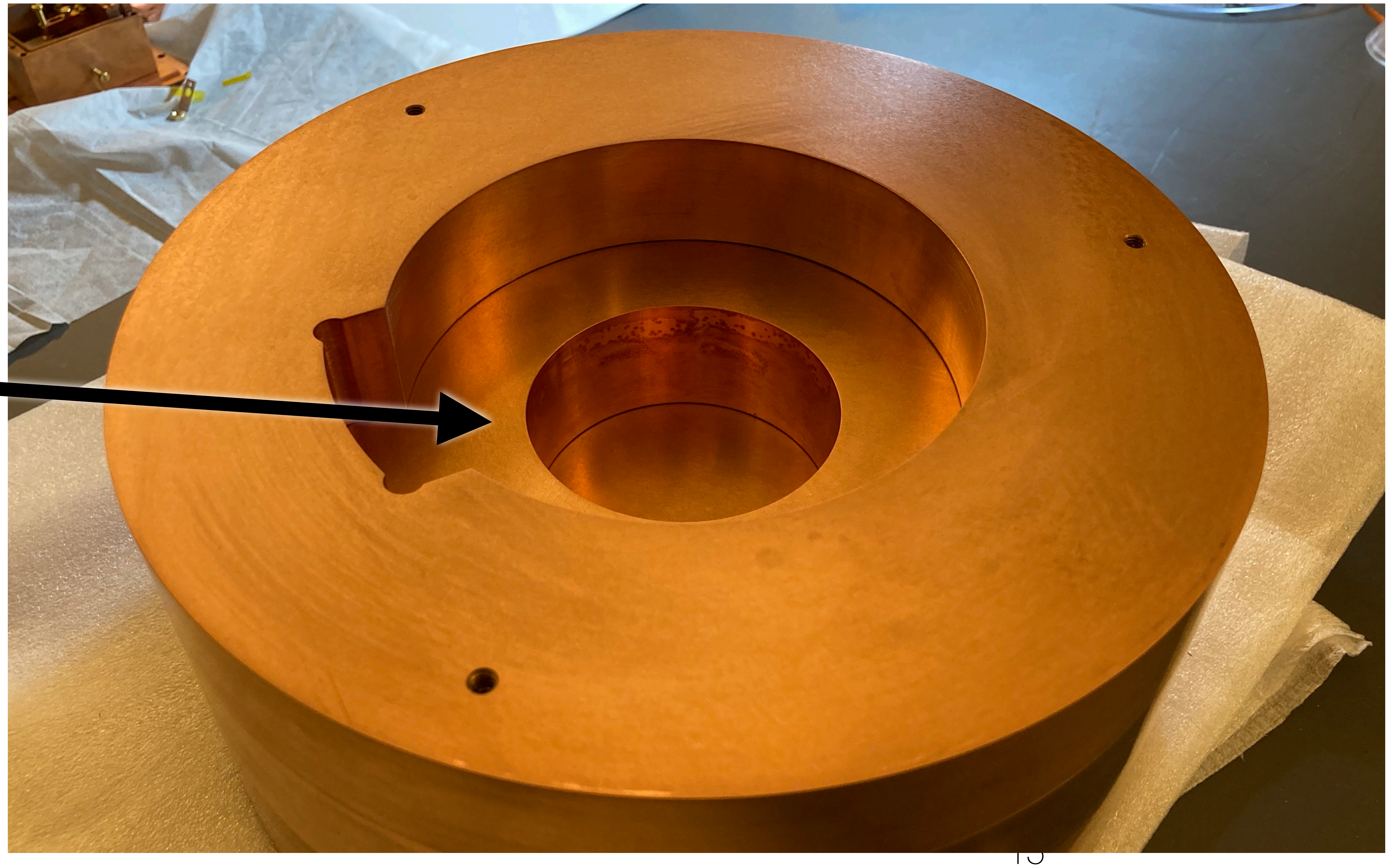






# "HeRALD v0.1"   R&D Hardware

**The calorimeter for the data you'll see today:**

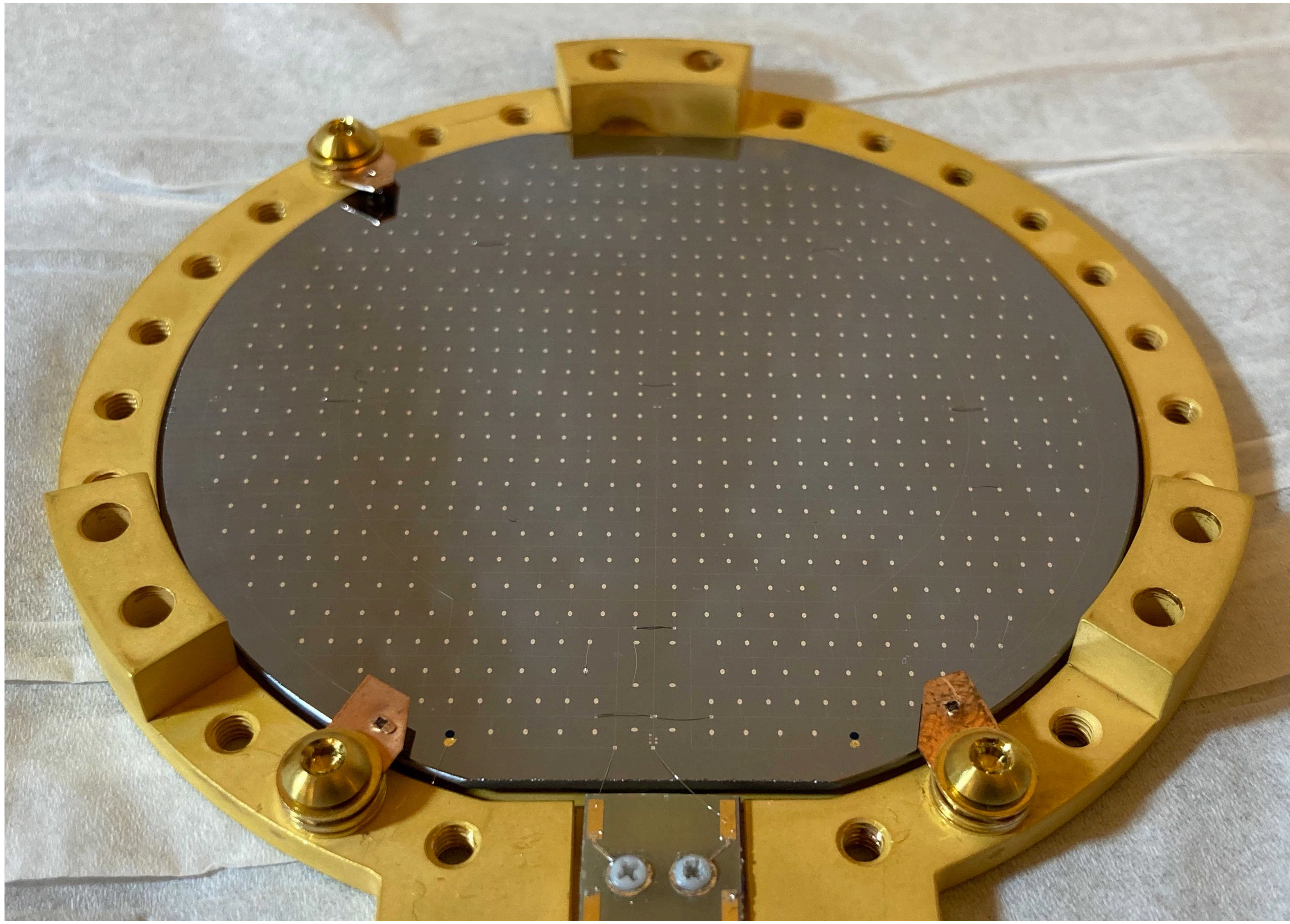
3" Si wafer     (10g mass,  1mm thickness)

Array of tungsten TESs
( $T_c$ = 55mK, plenty of room for reduction)

~2.26eV resolution (σ) for energy in Si

An evolution of the 'Cryogenic Photon Detector' described in arXiv:2009.14302

Aside:  Few-eV resolution is useful in its own right!
(Working on a DM search analysis, using simple Si recoils.)



# What do we expect?

**We expect two primary signals per event, with a delay proportional to depth:**

**S1: Prompt scintillation (singlets)**

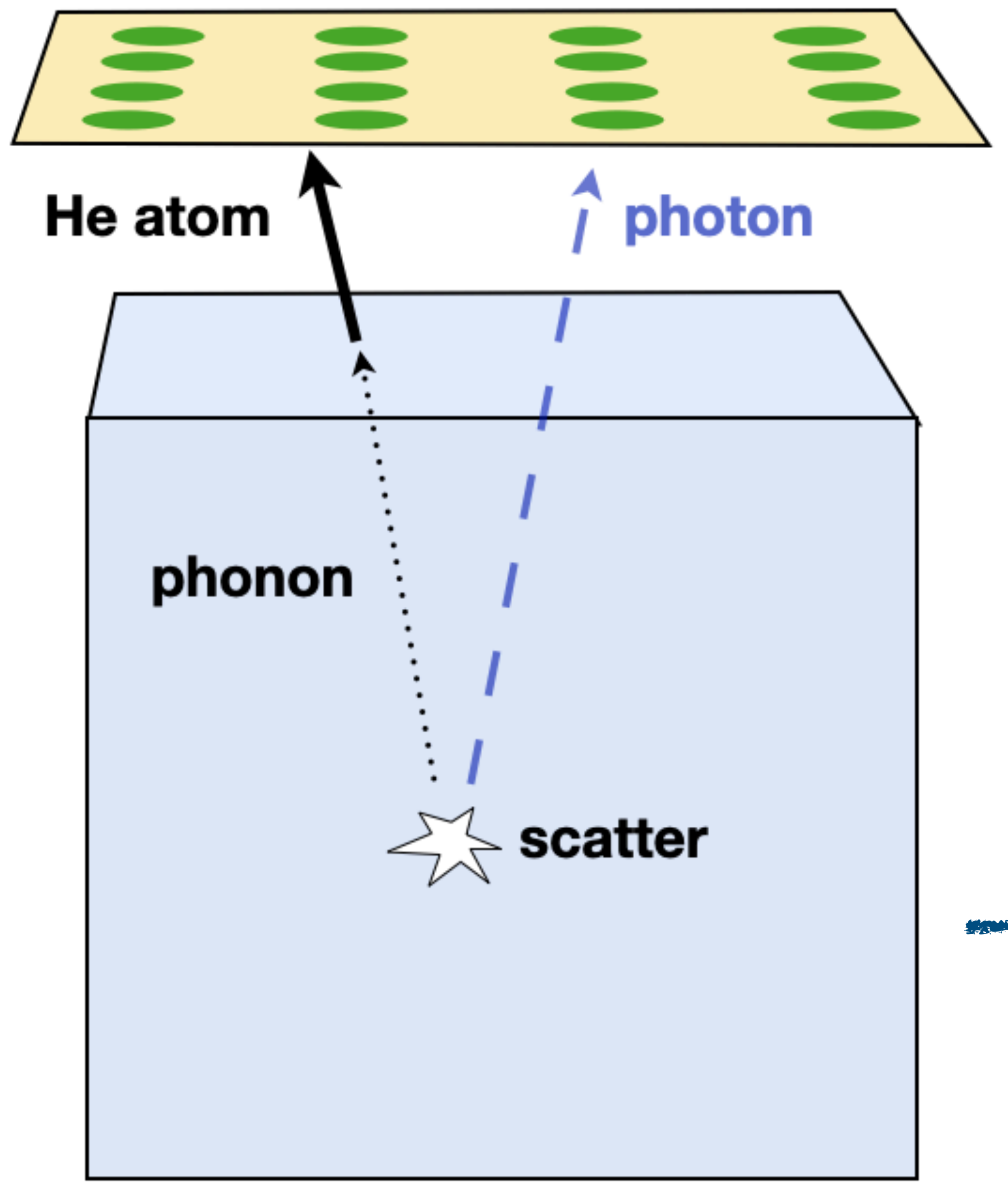
Note: coming DM searches will be “phonon-only”, below the 20eV electron excitation threshold

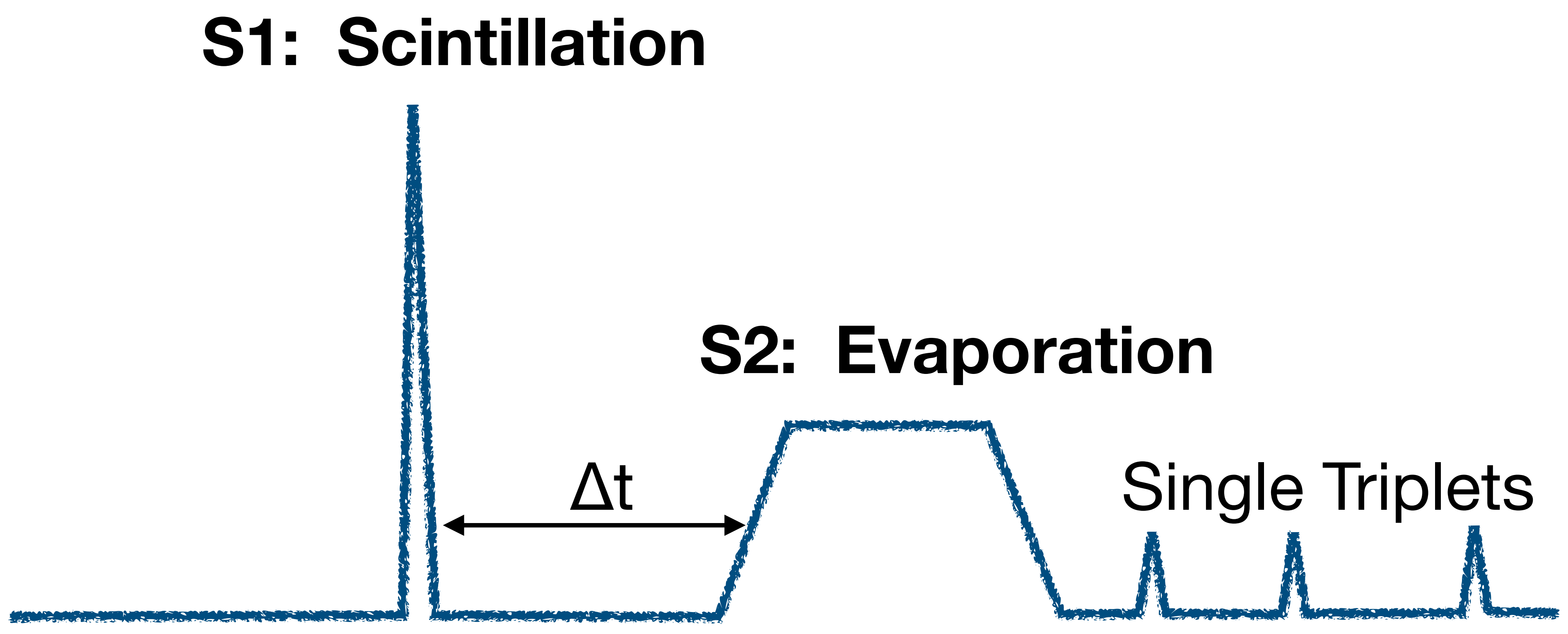
**S2: Delayed Evaporation**

$\mathcal{O}$ 100m/s phonon velocity

$\mathcal{O}$ 1cm $^4$He thickness

→ expect delay times $\mathcal{O}$ 100μs



# Raw Waveforms

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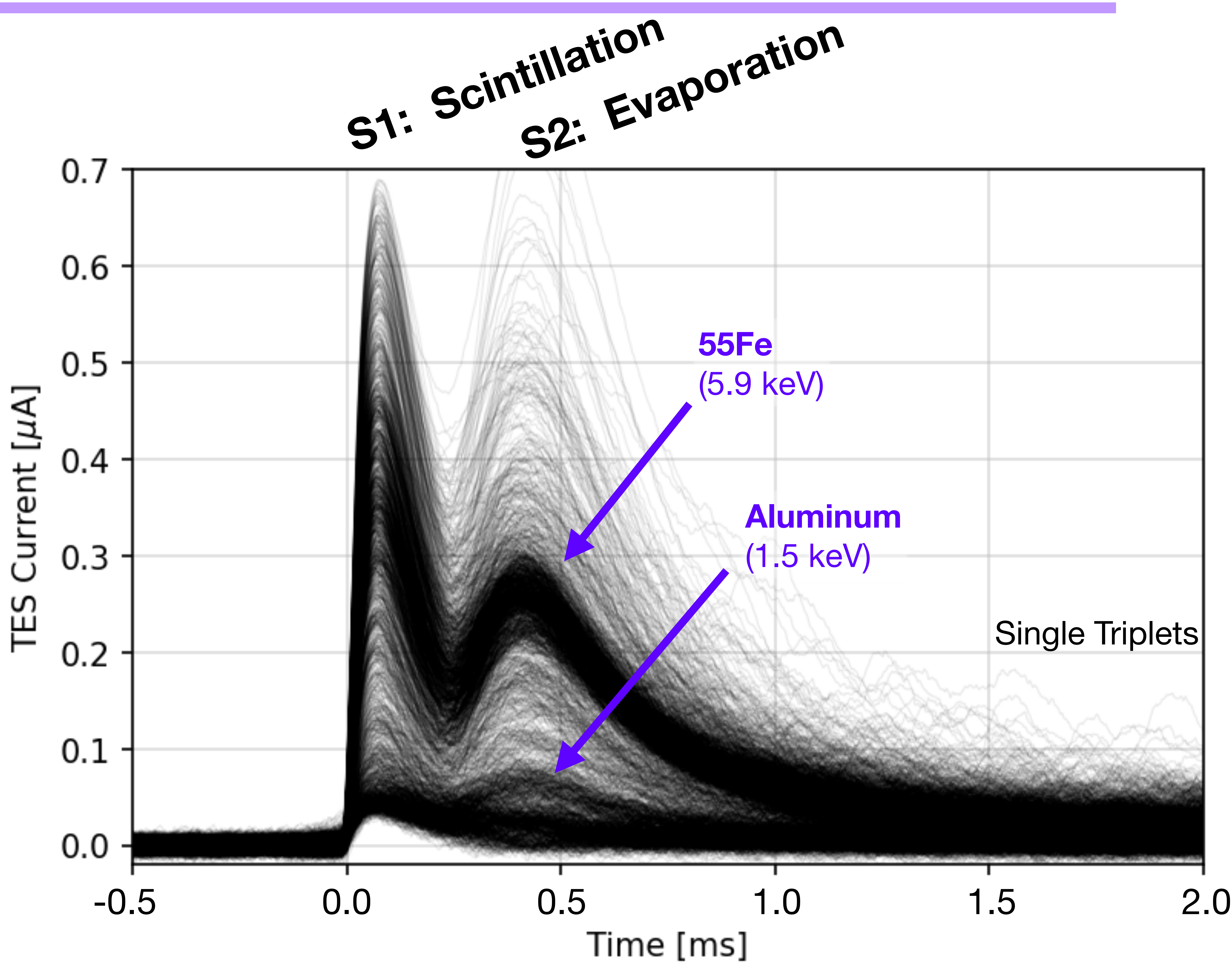
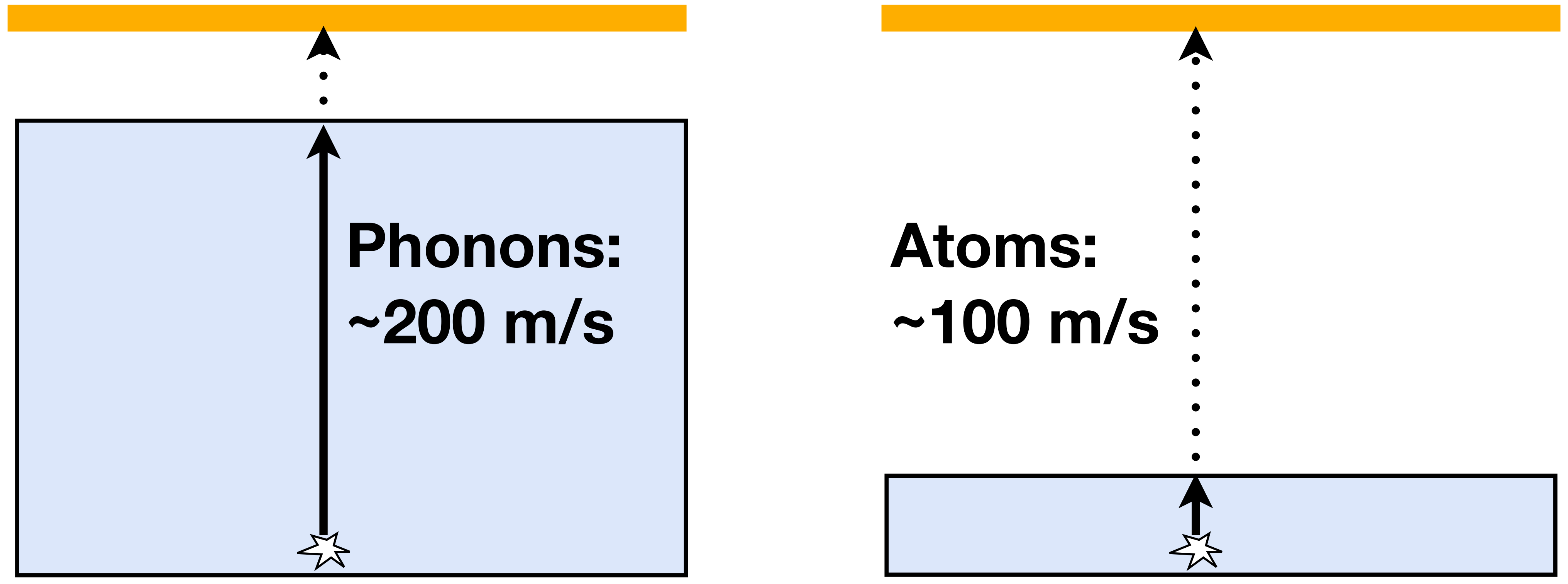
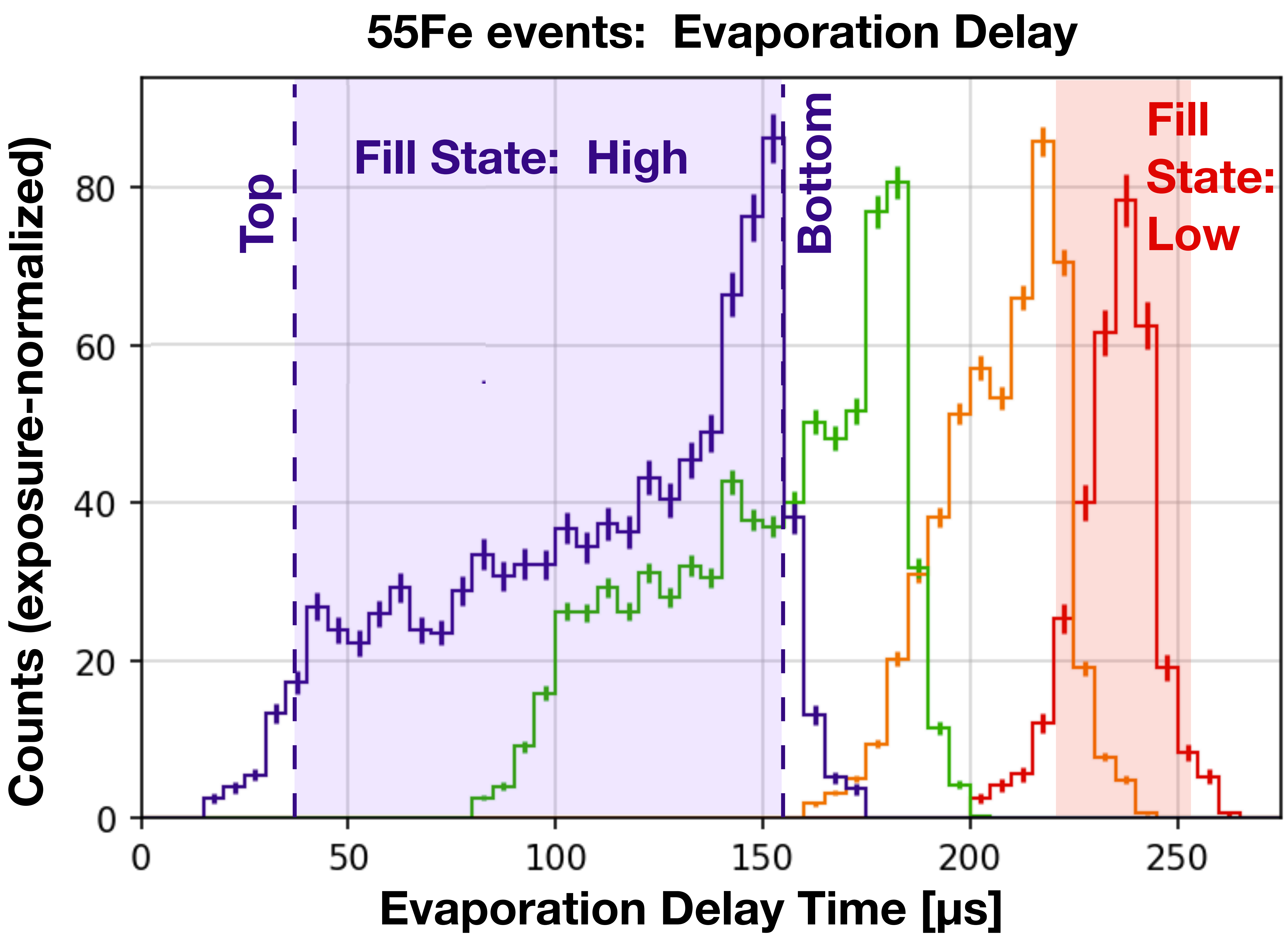


# Evaporation Timing

Evaporation delay is sum of two terms: phonon + atomic

We can vary the 4He fill state to understand velocities.
(with total propagation distance: 2.7cm)



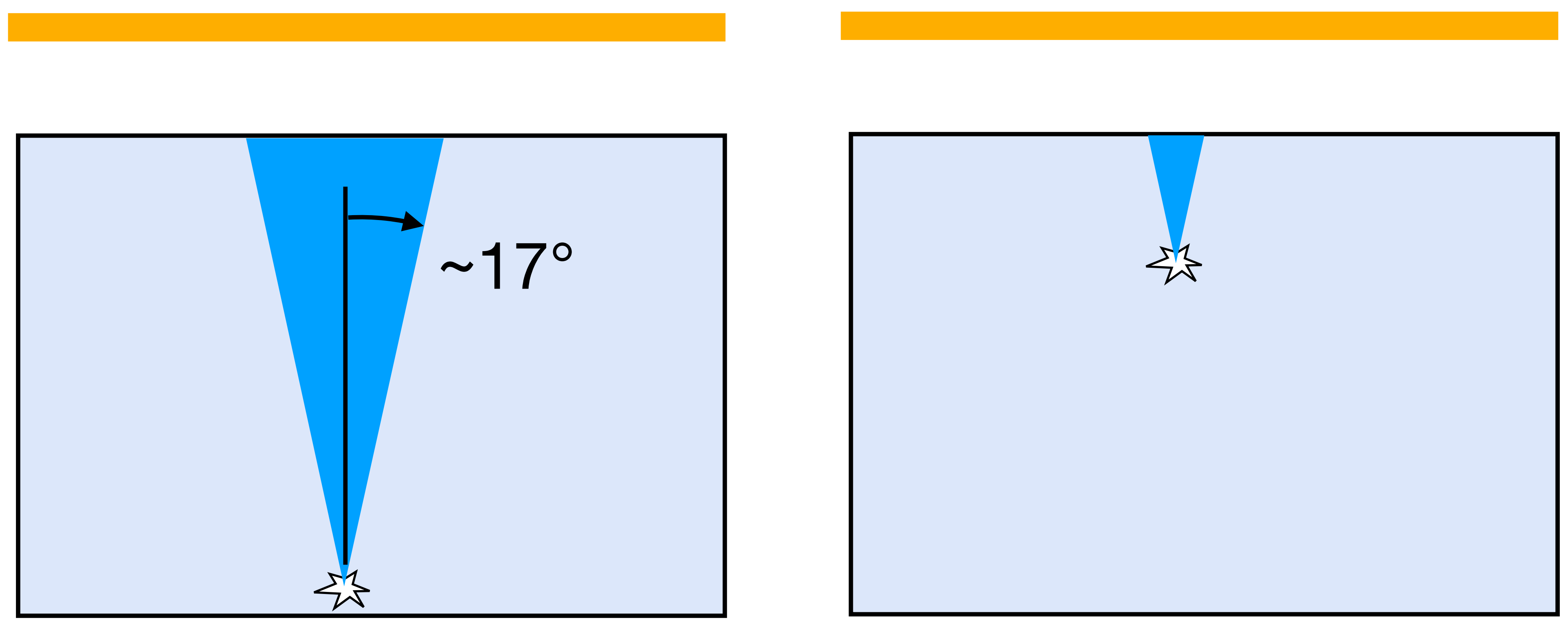



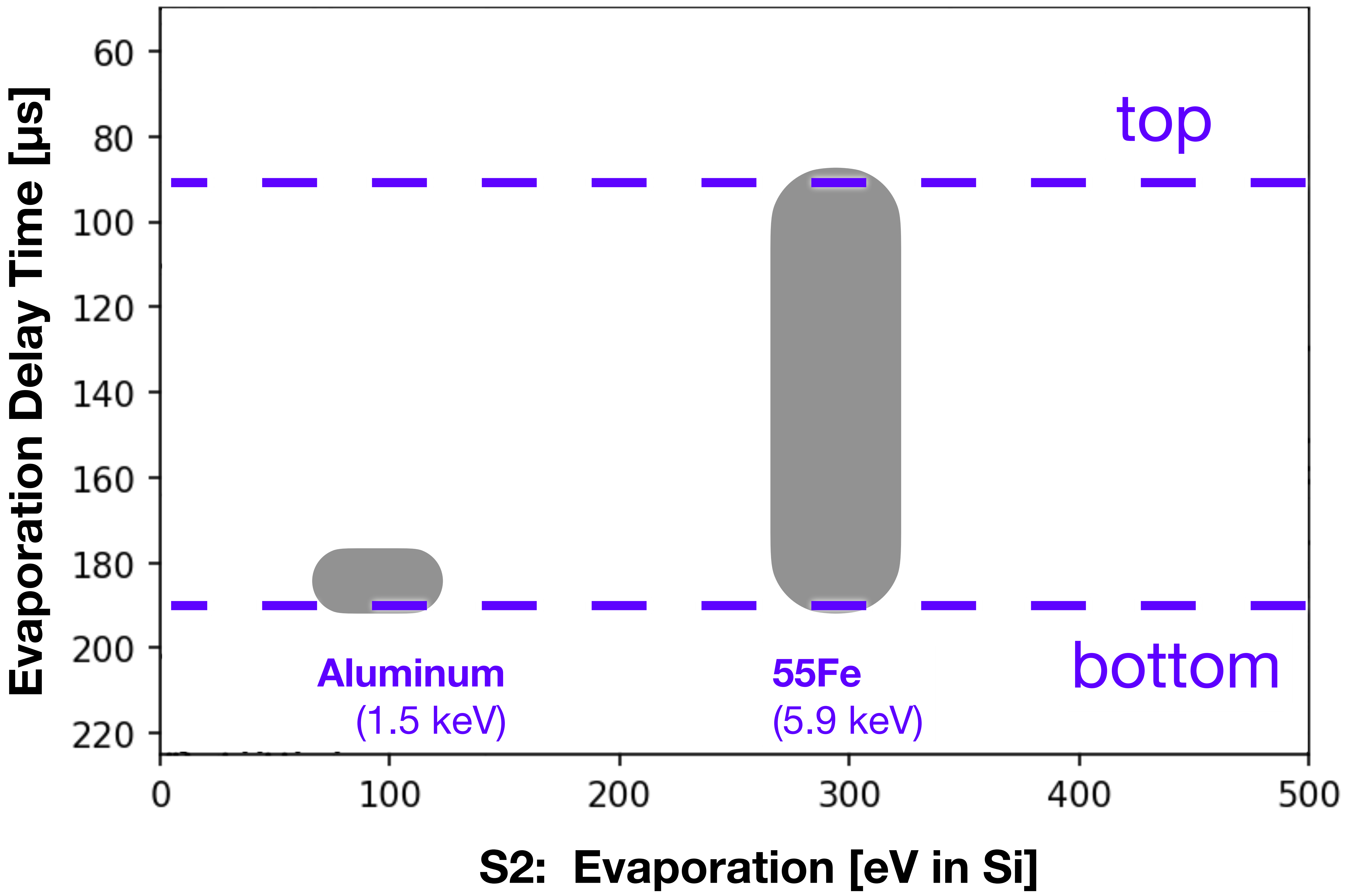
# Evaporation Amplitude vs Depth

**Naive expectation:**

$^{55}$Fe (5.9keV) roughly uniform in 4He
Al (1.5keV) only near bottom

Negligible variation of evaporation signal with depth
(narrow cone of phonons within evaporation critical angle)



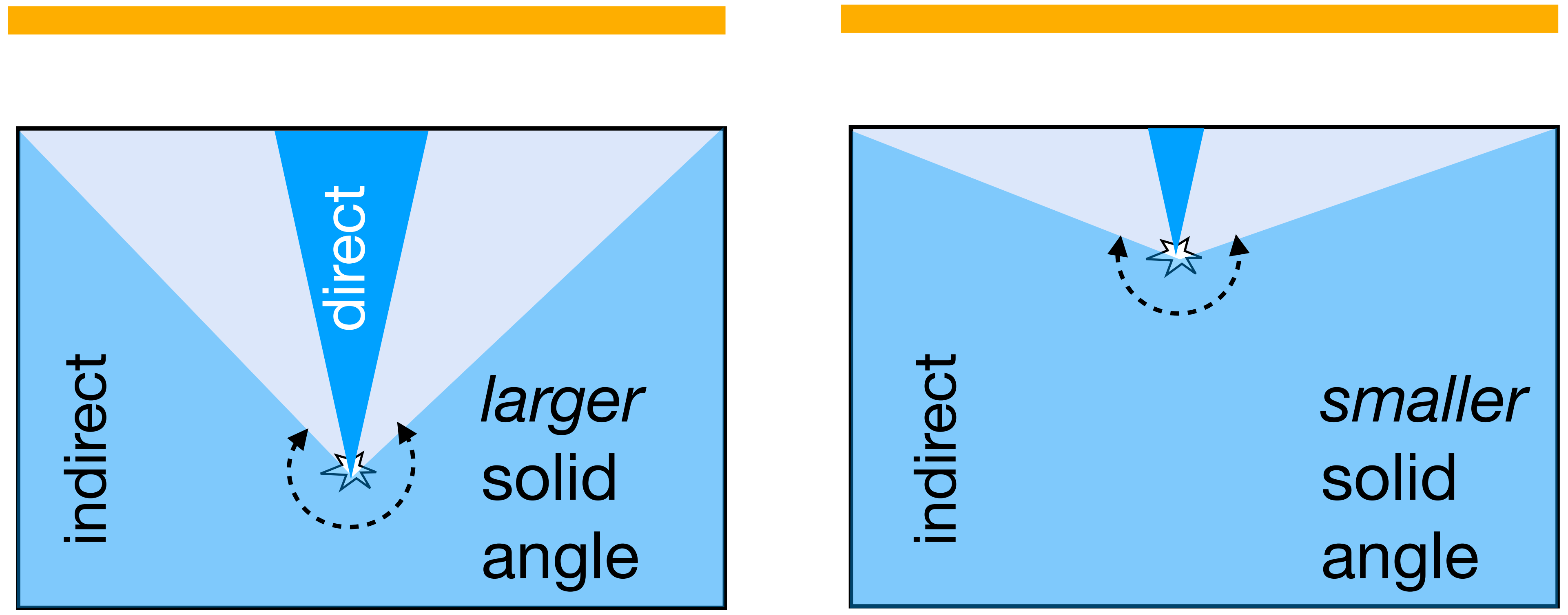



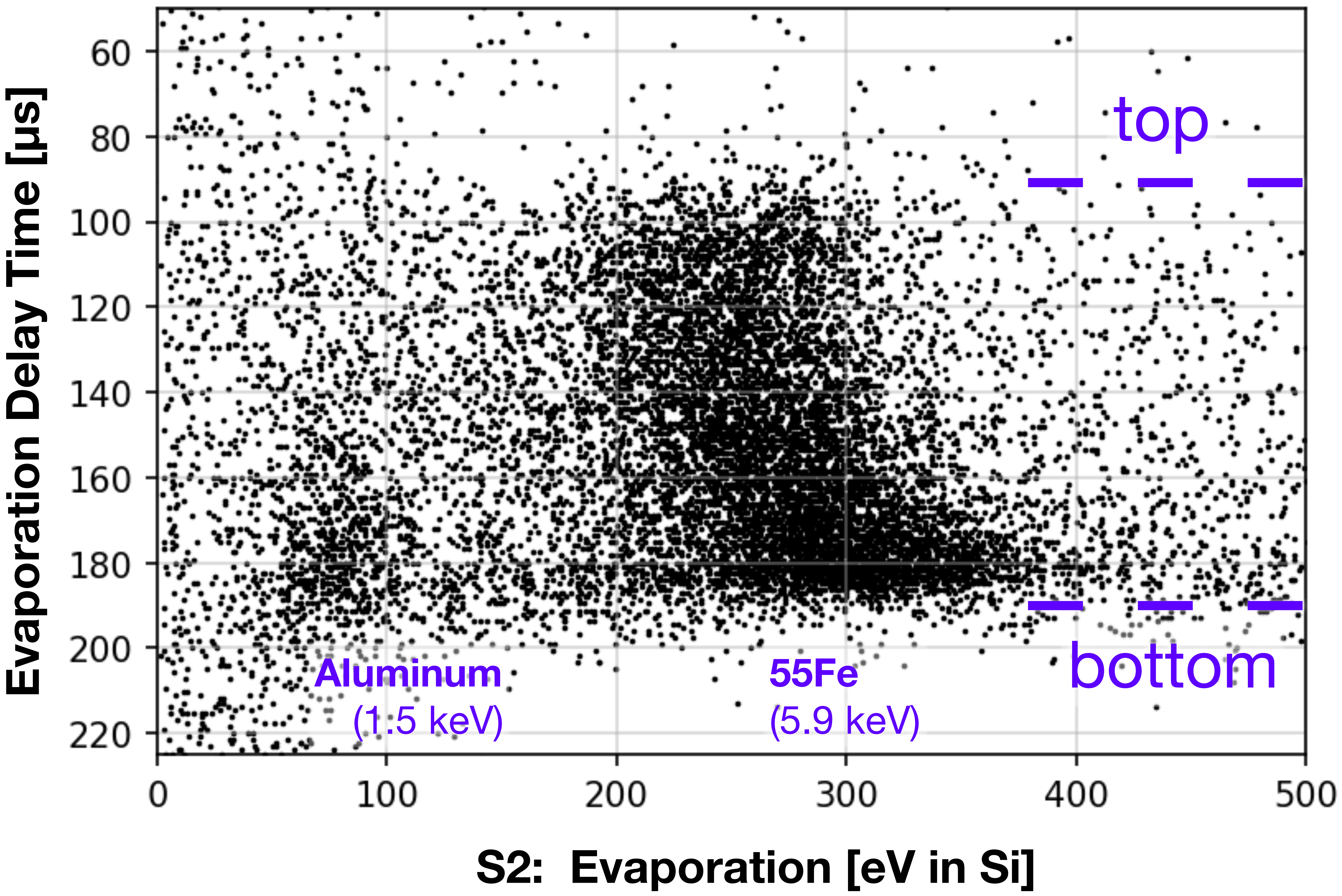
# Evaporation Amplitude vs Depth

**Distributions in Z:   as expectated**

**Surprise:  Evaporation signal boosted near cell bottom.**

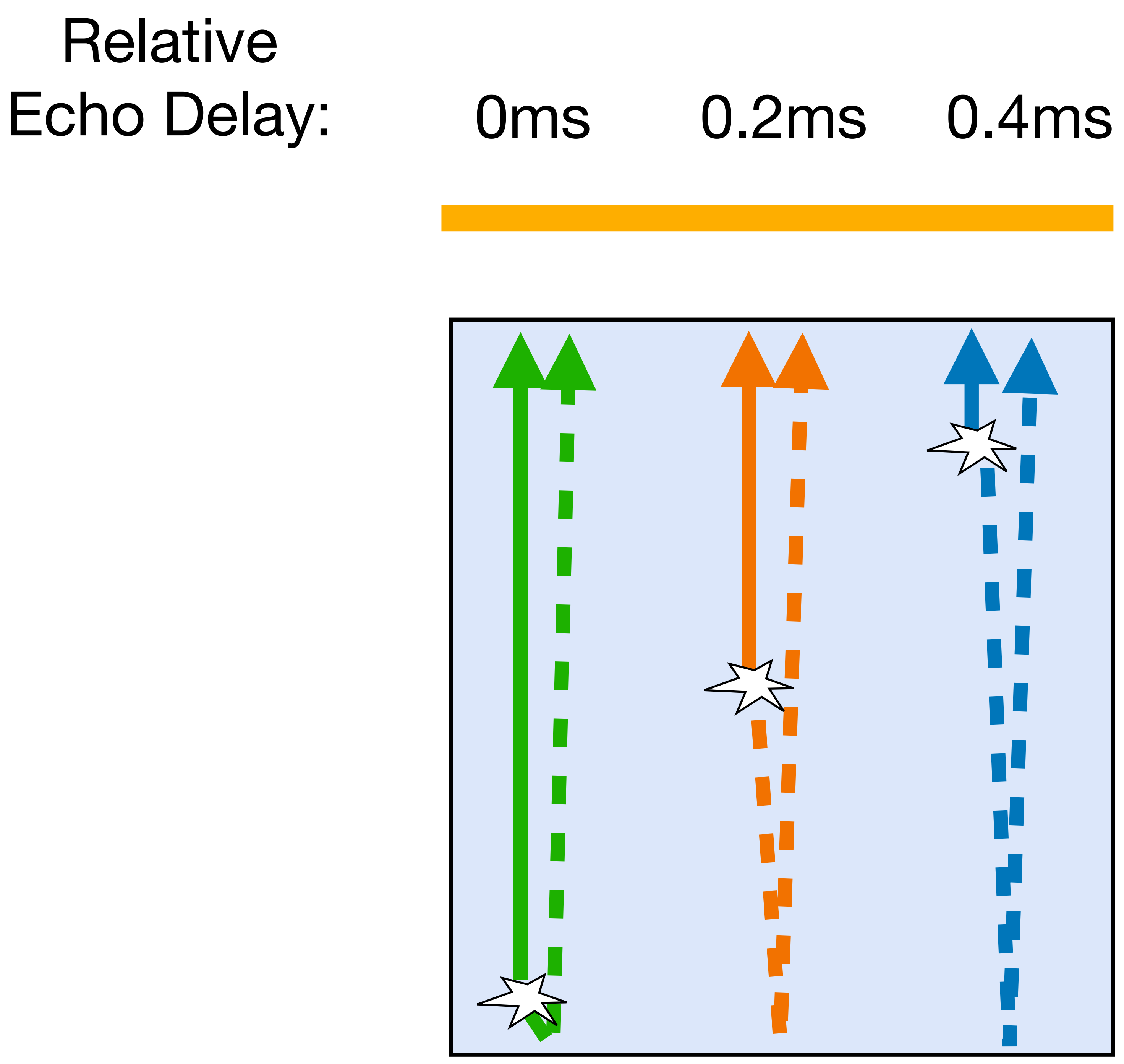
→Consistent with ~30% probability of diffuse reflection.
(Events near bottom: larger solid angle for reflection)

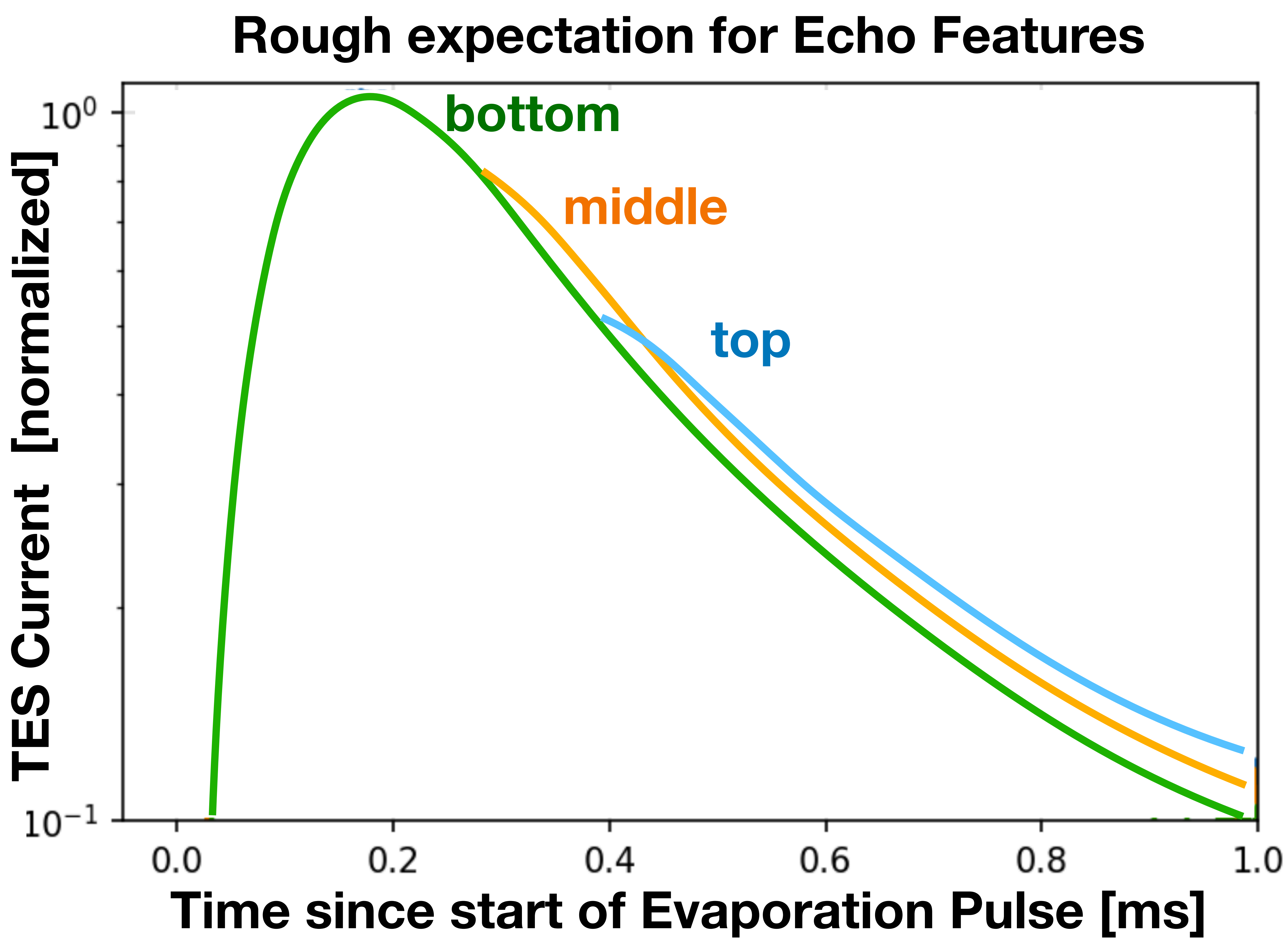


# Hints of Phonon `Echos' in Evaporation Waveforms

***We can see features echos at the expected delays (just barely)***



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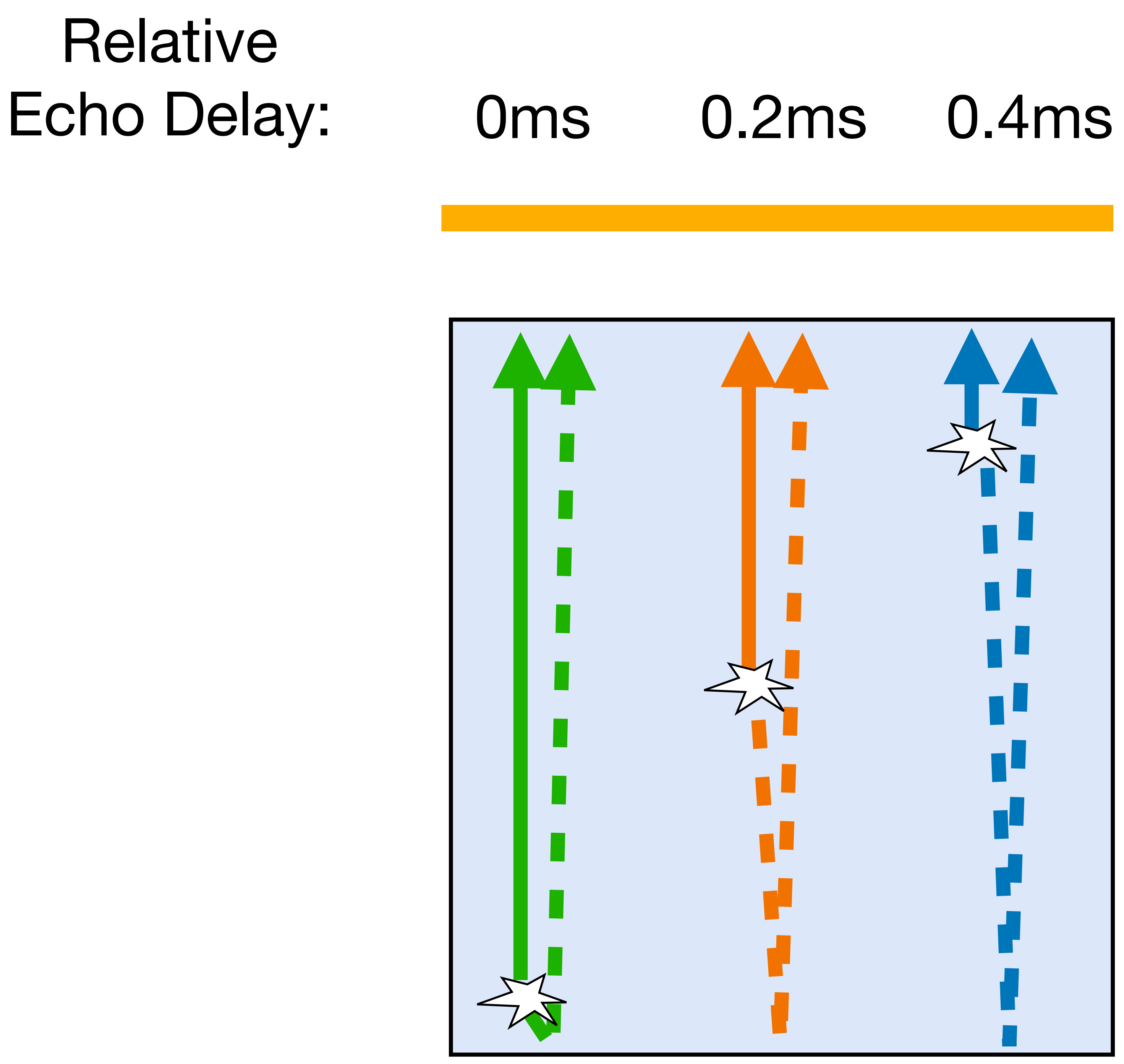
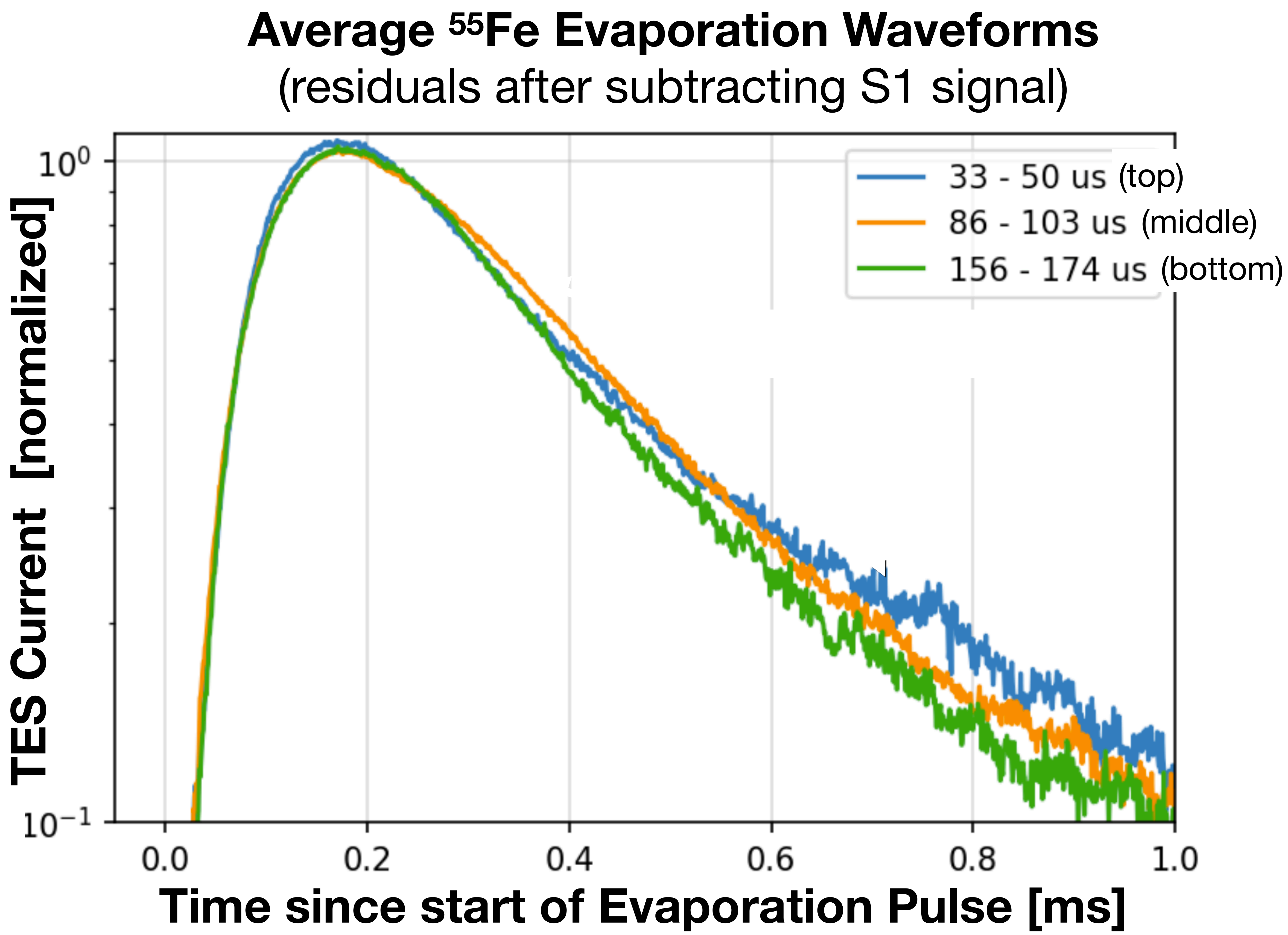
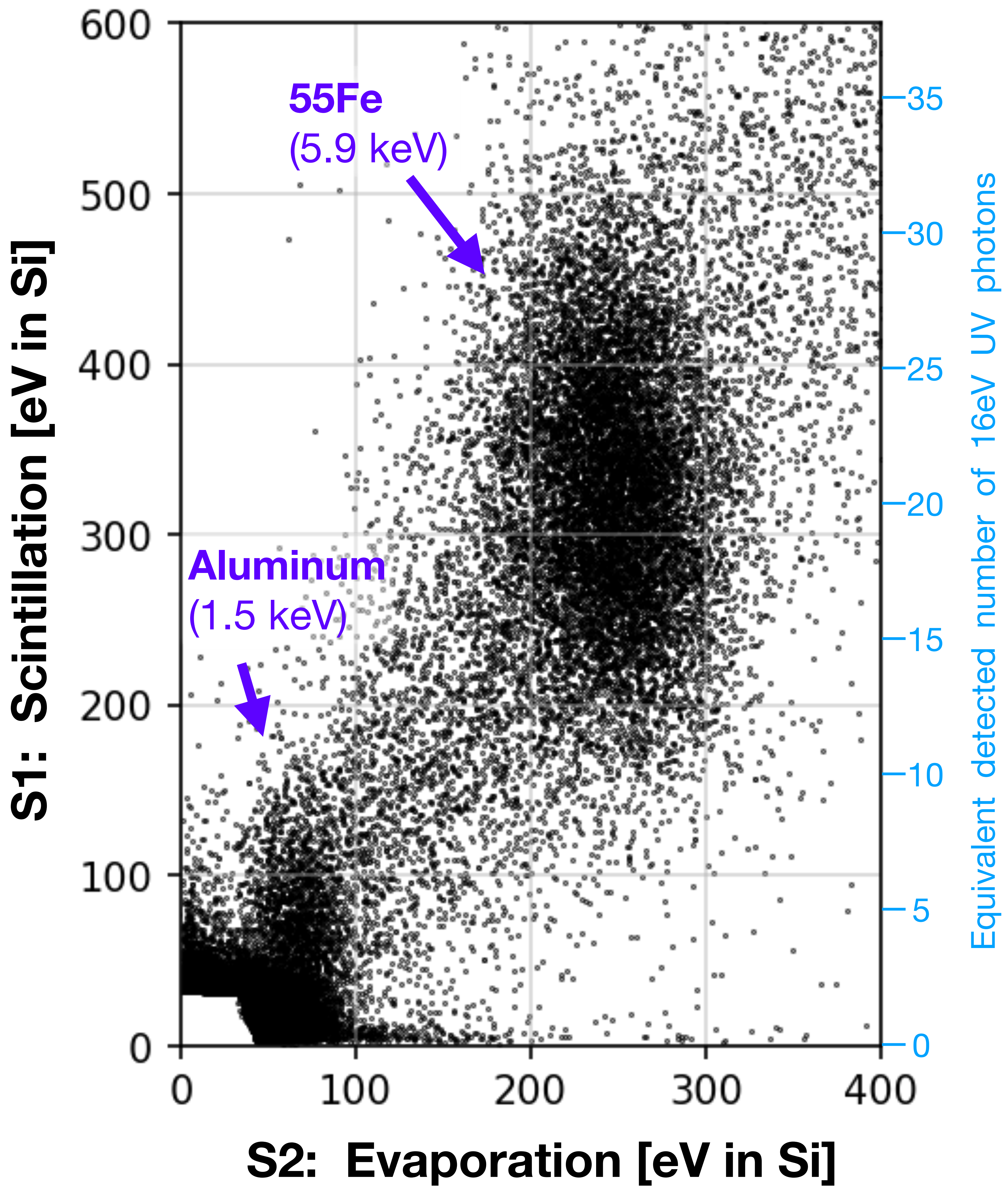


# Evaporation Signal: Gain Factor

We can plot Scintillation vs Evaporation
on an event-by-event basis.

Note the large statistical fluctuations in Scintillation
(small number of photons, large number of atoms

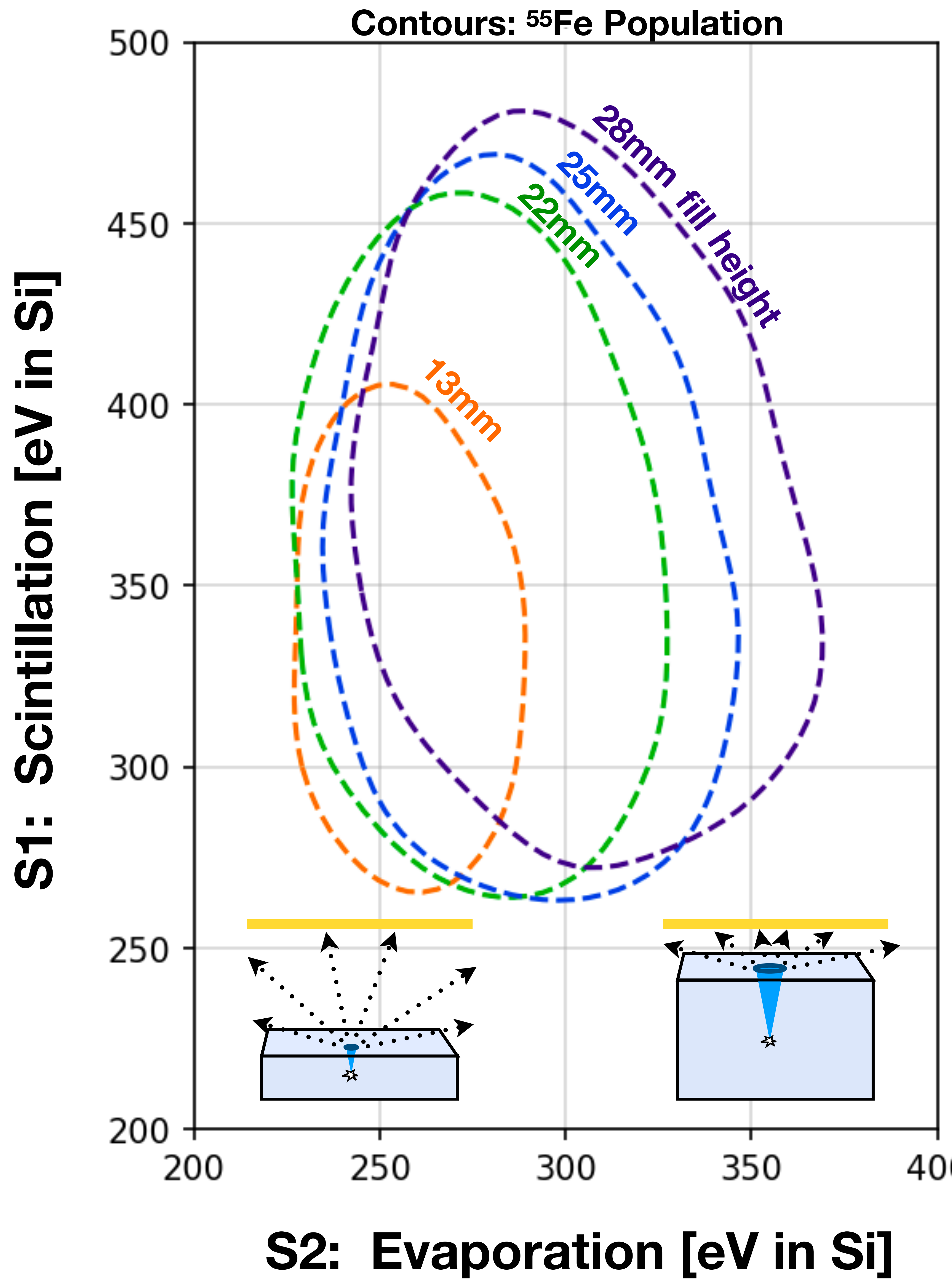


# Evaporation Signal: Gain Factor

$$\text{'Gain Factor'} = \frac{\text{Energy Sensed (in Calorimeter Substrate)}}{\text{Energy Deposited (in 4He QP System)}}$$

Gain folds together many effects:

- *QP propagation/reflection*
- *evaporation efficiency*
- *atomic sticking probability*
- *van der Waals energy per atom*
- *etc etc etc.*



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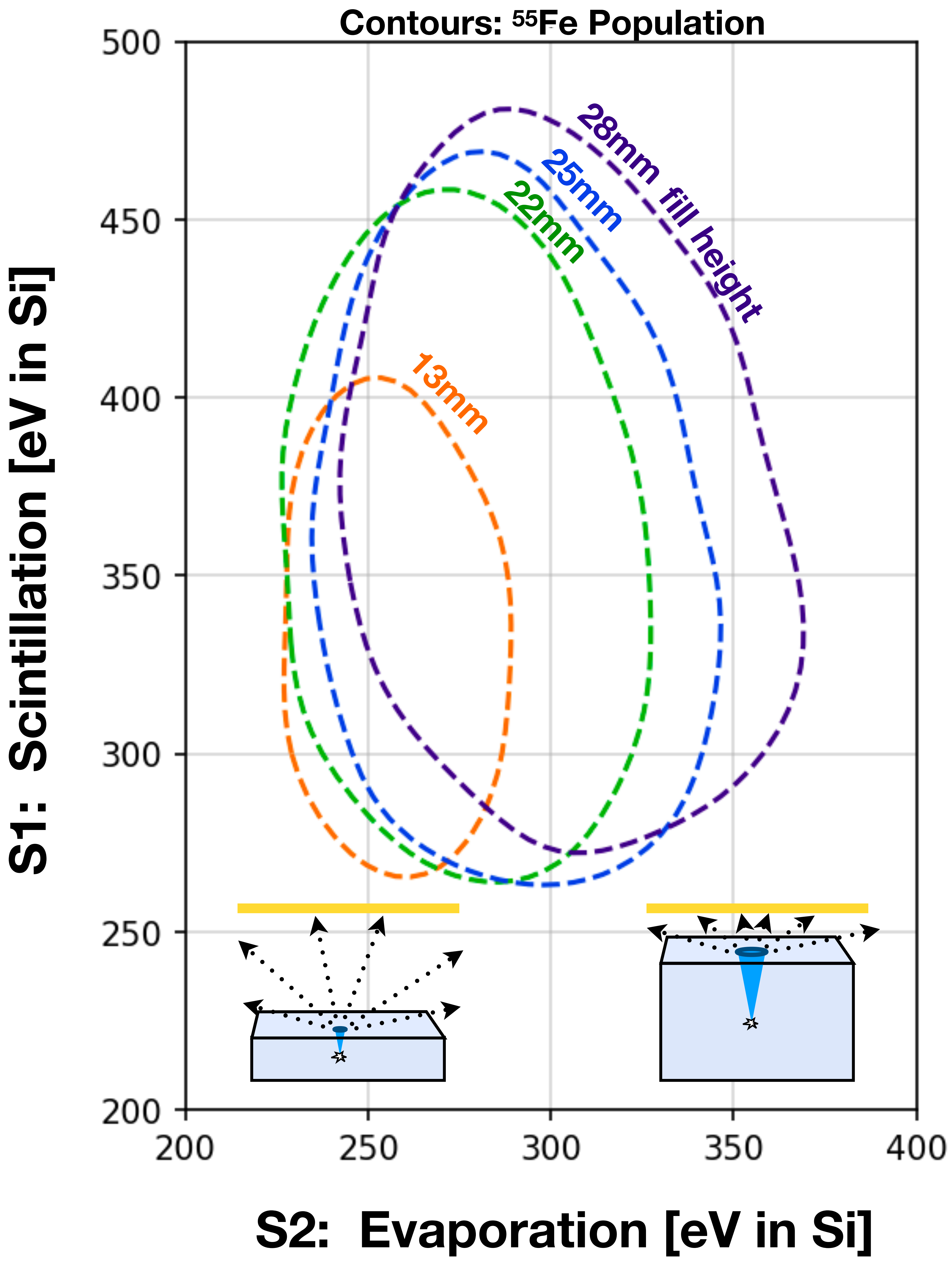
**Using $^{55}$Fe X-rays:**
(average of all positions,
using highest fill state)

$$\textbf{Gain} = \frac{300\text{ eV}}{2000\text{ eV}} = \sim 0.15$$



# Recoil Energy Threshold

## More appropriate figure of merit: *Mass* threshold

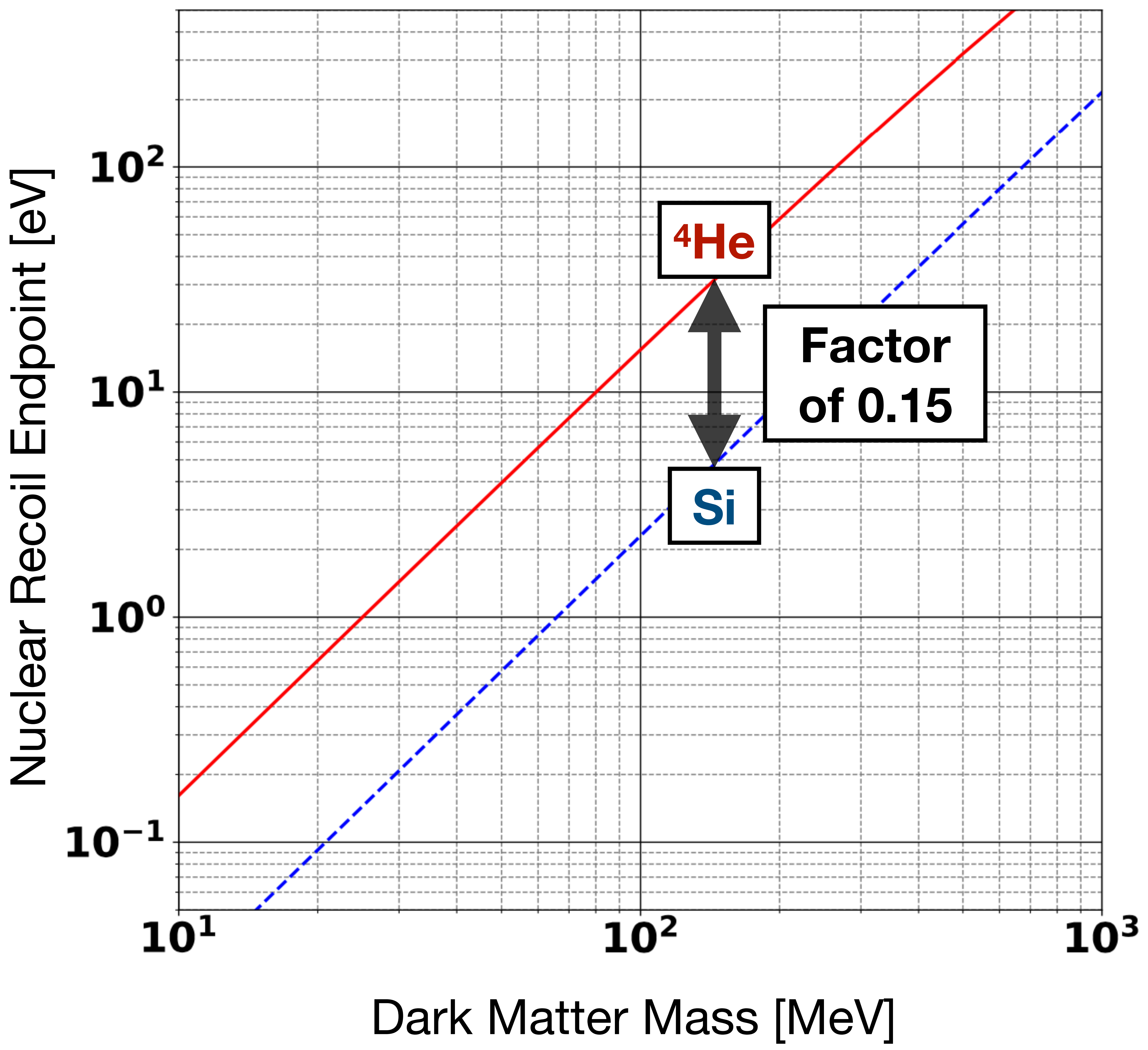
A coincidence:

Gain factor ***suppresses*** evaporation signal: **x 0.15**

Low 4He mass ***boosts*** endpoint energy: **x $0.15^{-1}$** (relative to Si)

→ **0.15 is the 'break even' at gain factor**
(similar mass threshold in 4He and the Si sensor)

→ **Expect to surpass 'break even' with R&D**

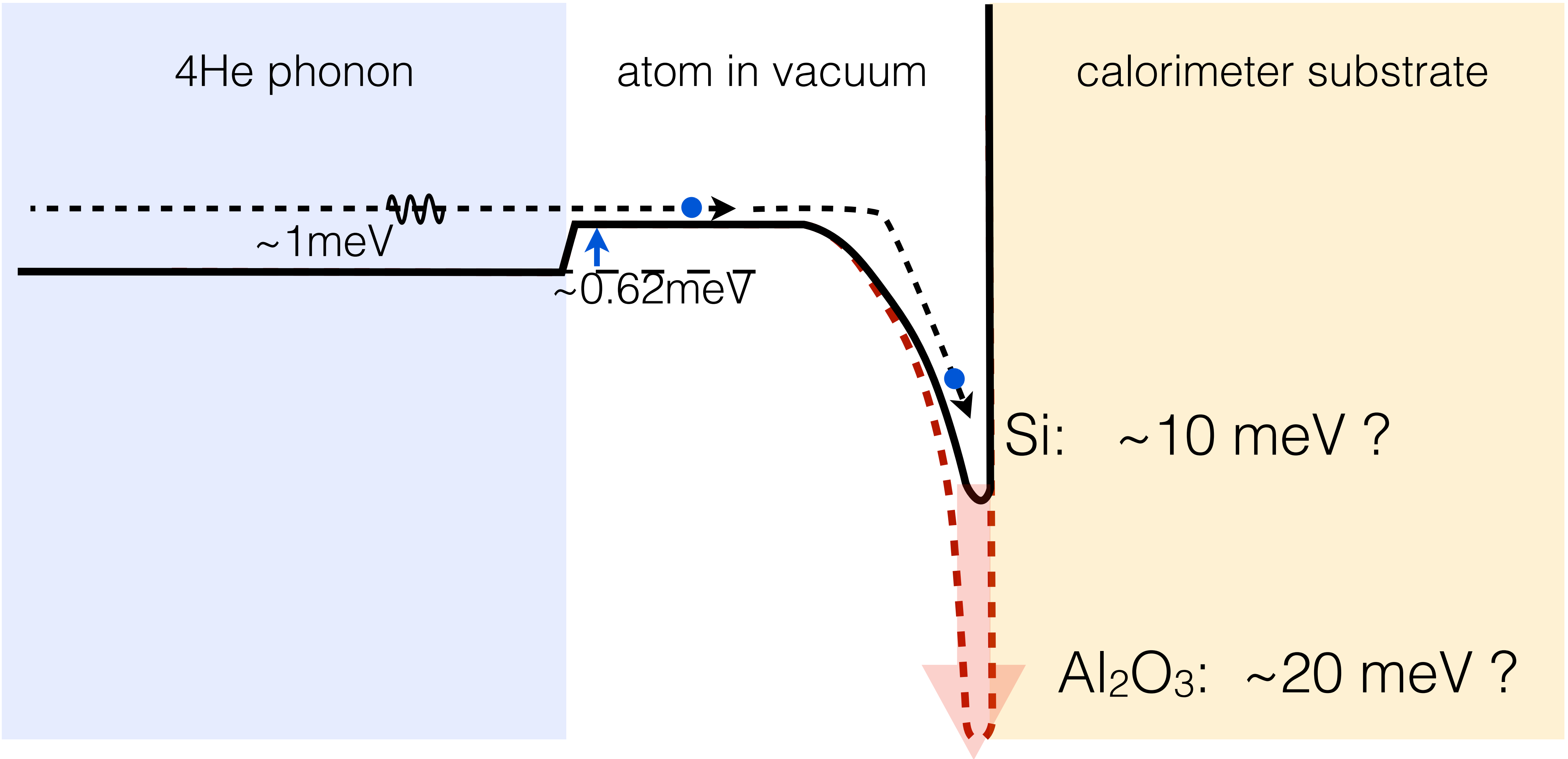


# Next Steps: Pushing the Gain

## 1. Higher van der Waals gain per atom

- Depends on the calorimeter surface
- ~10meV/atom is *typical* of many surfaces
- Expect higher energies from polar lattices/surfaces

→ Near-term plan to test $Al_2O_3$ calorimeter
Expect 20-30meV/atom (based on condensed matter sim)
(Improvement by factor of a few)



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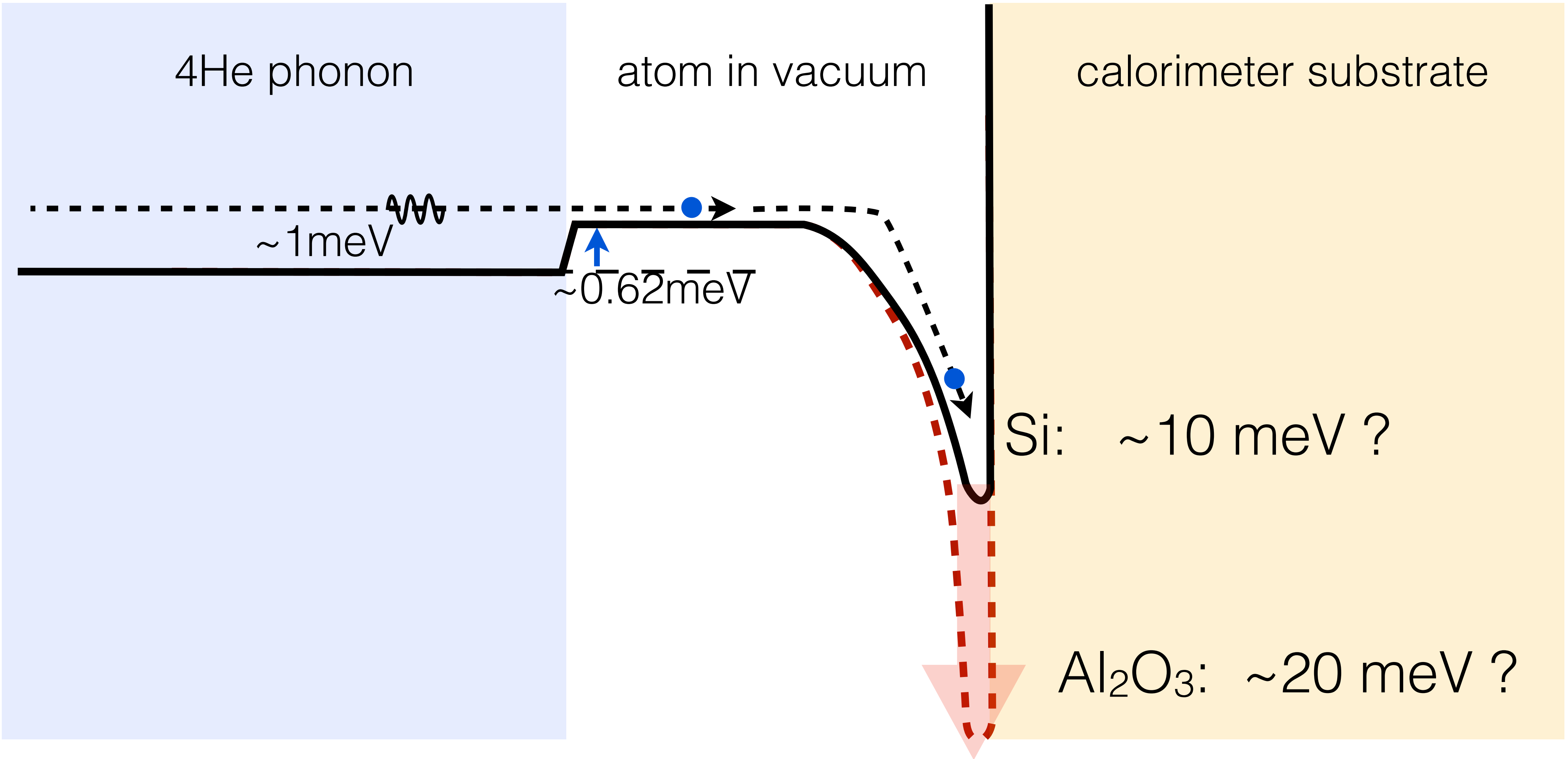
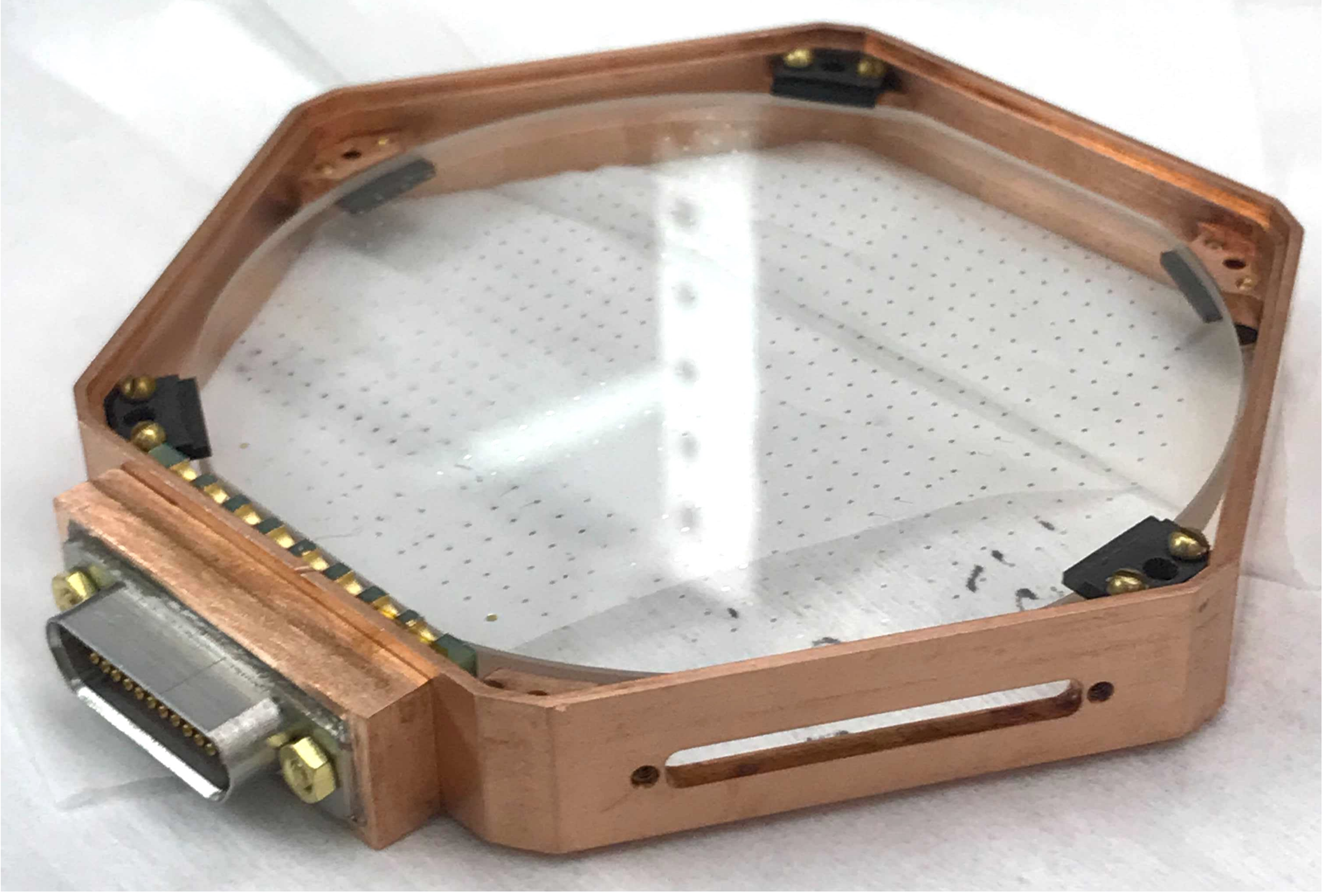



**Fabrication on $Al_2O_3$**
already practiced
and demonstrated



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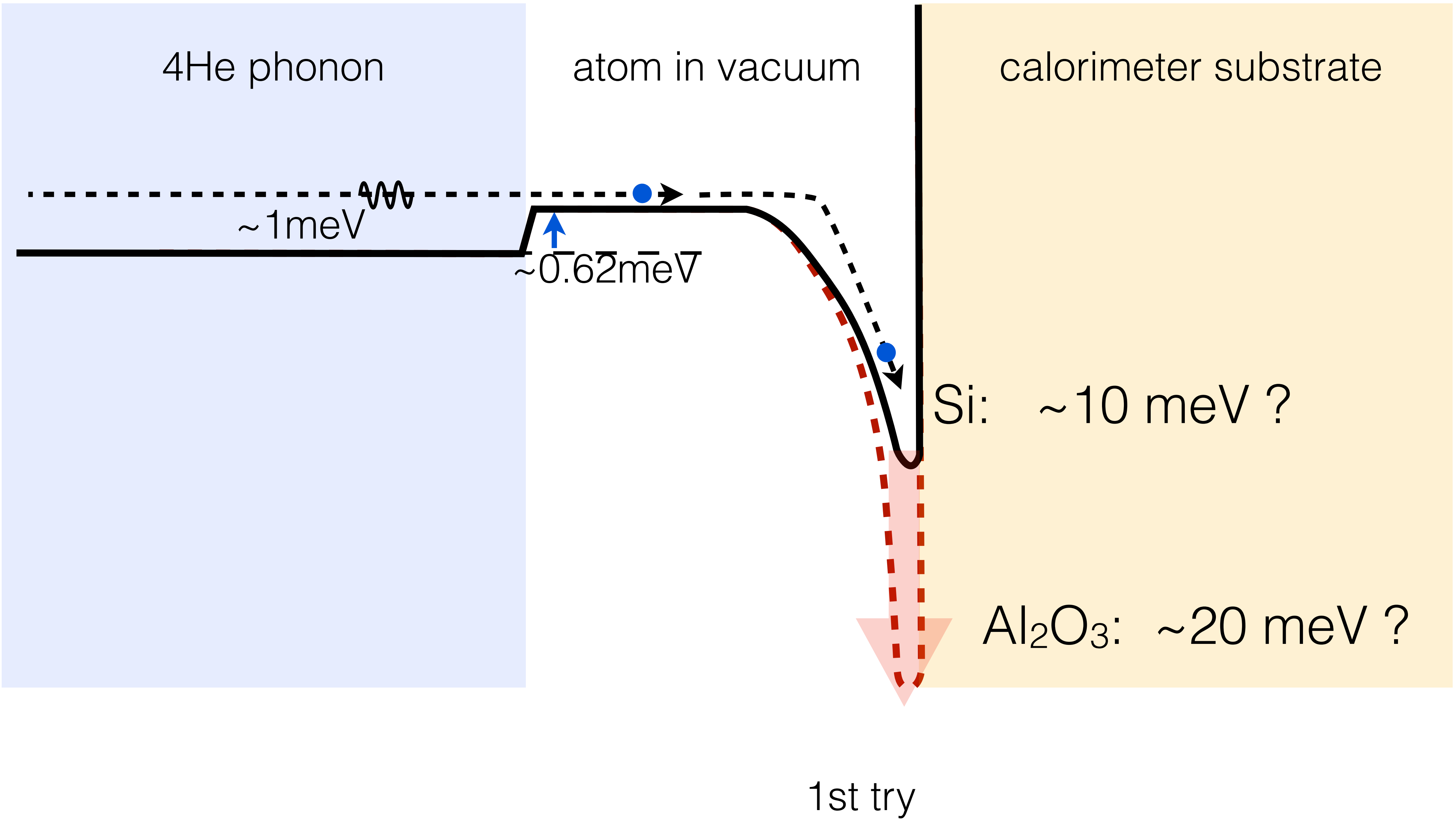
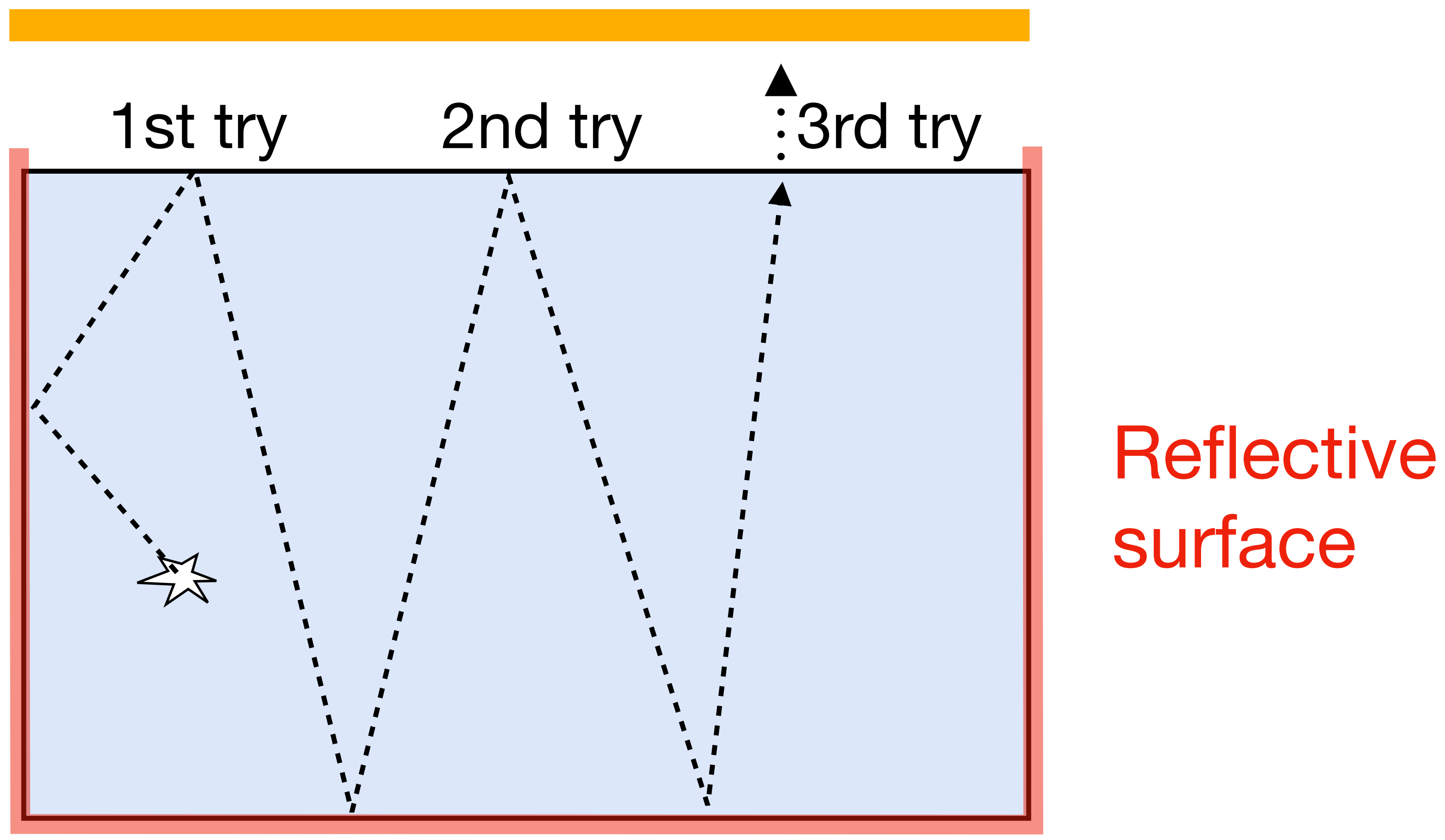



## 2. Higher phonon reflection probability

- With 30% probability, get at most "one more chance" at evaporation
- Higher reflection probabilities → more evaporation "chances" per phonon
  (emphasizing: nonlinear signal increase with $P_{evap}$ )
- Planning a campaign of testing materials/surfaces

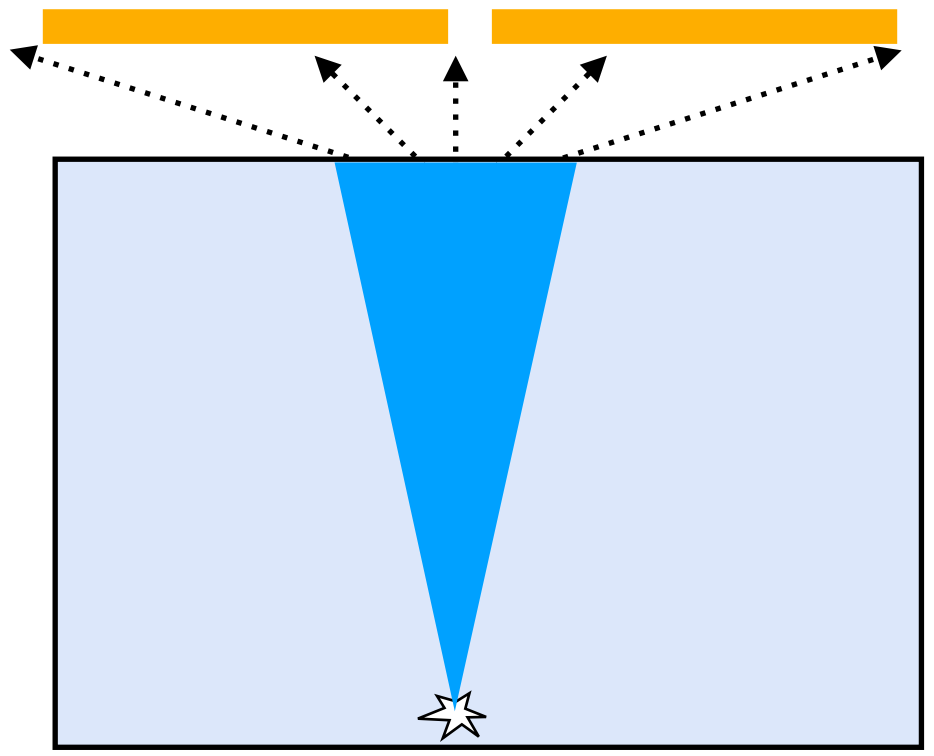


# Next Steps: Rejecting Low-Energy Excess via Coincidence

$^4$He is uniquely situated:

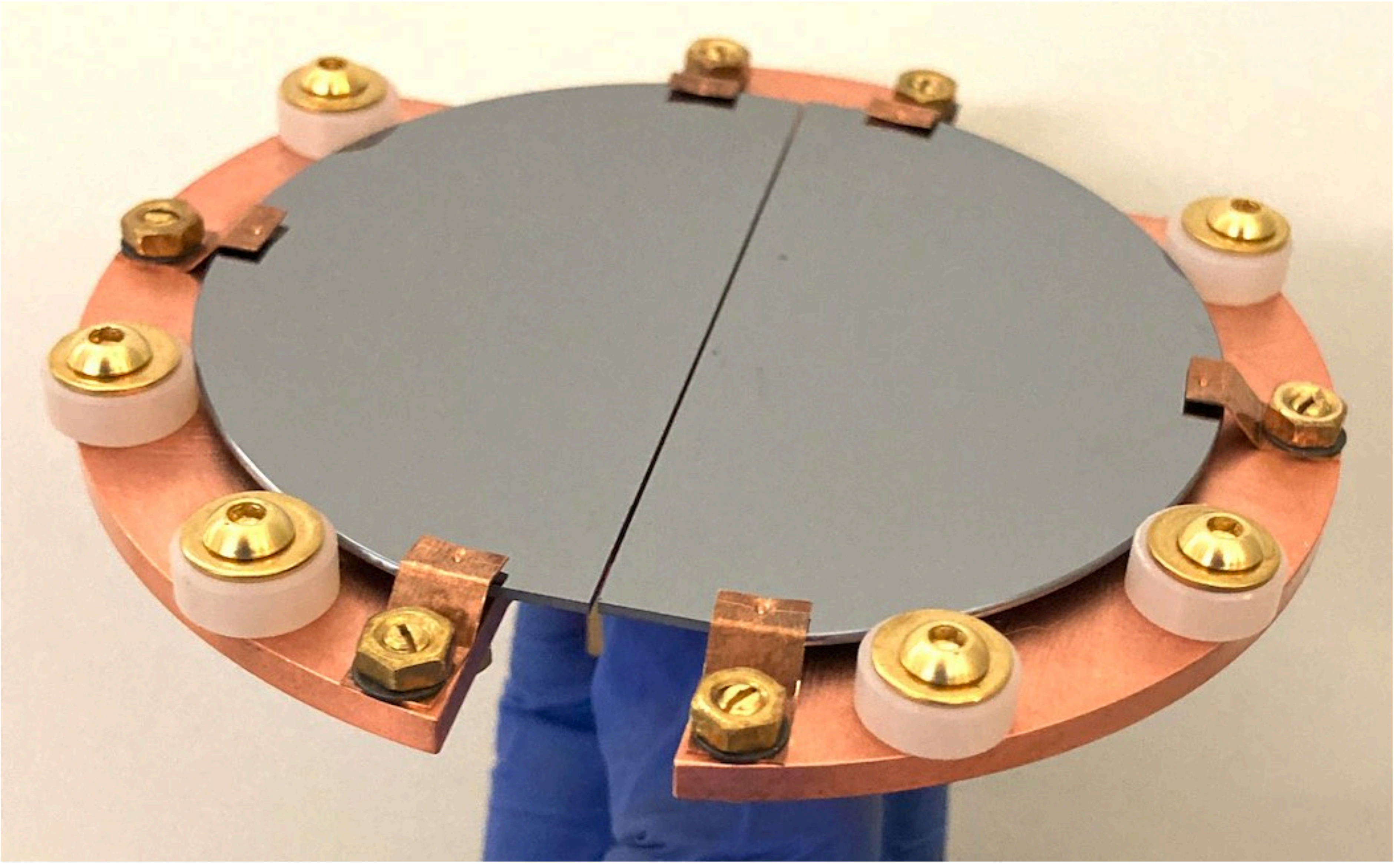
1. **The vacuum gap allows for `perfect' tagging of single-channel sensor backgrounds**
   (low-energy excess: spontaneous relaxing of Aluminum and Tungsten films?)

2. **The target is in a superfluid state, not far from a quantum ground state**
   (with no 'lattice defects' or stress, superfluid 4He may be a naturally excess-free material)

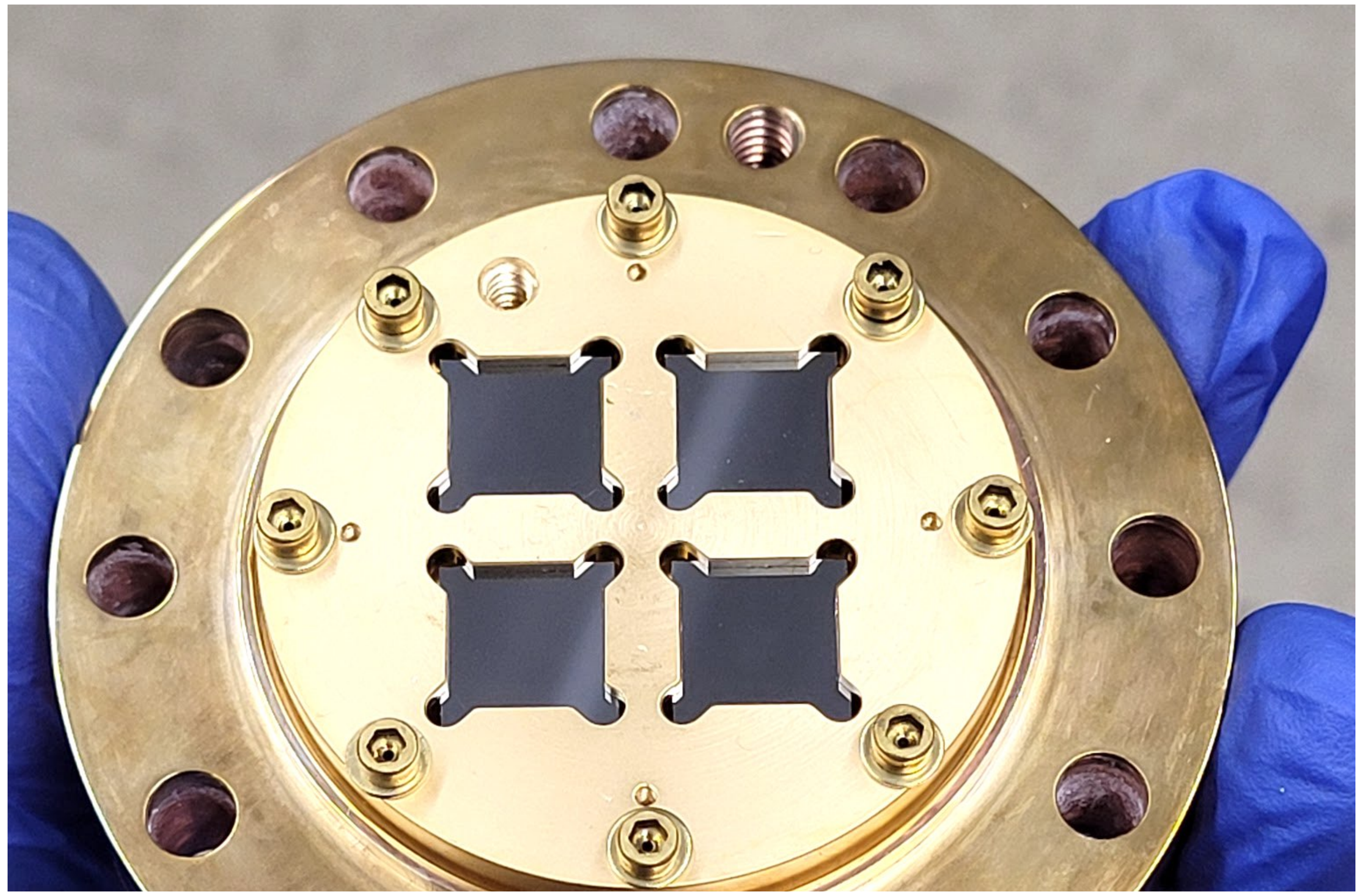


→ Near-term HeRALD R&D will test multi-channel evaporation readout for excess rejection

**2-Channel Array for HeRALD v0.1 @UMass (3-inch)**



**4-Channel Array for HeRALD v0.2 @LBNL (4x 1cm$^2$ )**



# Summary

## Succesful Demonstrations

arXiv.org:2307.11877

- Heat-free and practical stopping of $^4$He films
- Scintillation+evaporation readout at few-photon limit.
- Initial evaporation signal gain of 0.15 (already at 'break even' DM mass threshold)

## Exciting next steps

- Lowering threshold via three separate/independent/multiplying strategies:
  1. Calorimeter threshold eV ➞ meV
  2. Adsorption energy per atom ~10 ➞ ~30 meV ?
  3. Phonon reflectivity ~1.2x boost ➞ 2x boost? 10x boost?

  gain (items 2–3)

- Lowering the low-energy excess via multi-detector coincidence

  4He with evaporation *may* be uniquely powerful

# Extra Slides

# Physics of a Superfluid $^4$He Target

**Phonons in Superfluid $^4$He:**

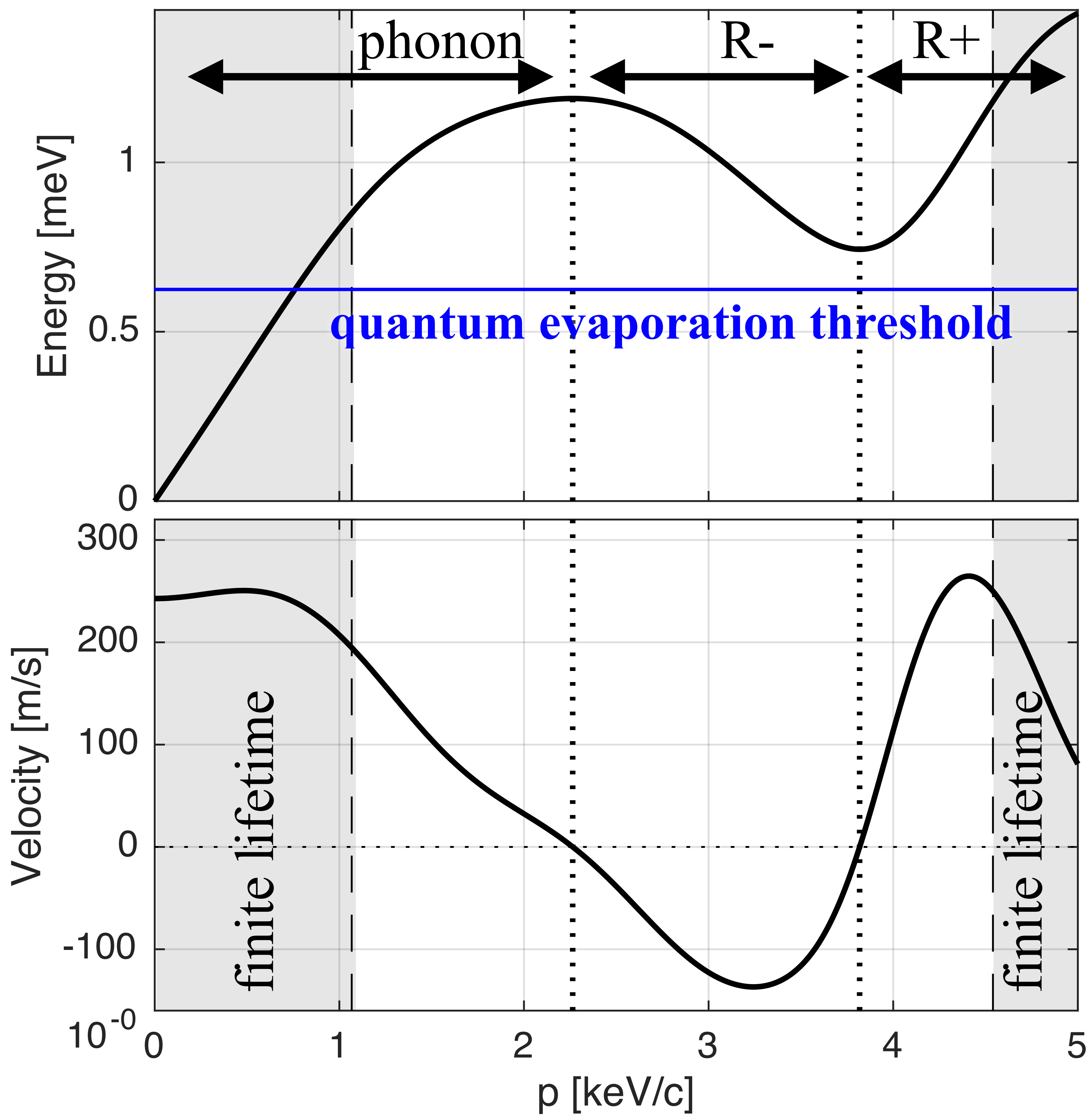
Three flavors: "phonon" , "R- rotons" , "R+ rotons"

- just names for different regions of the same dispersion curve
- R- are nonintuitive: momentum points opposite to group velocity

Bulk behavior is 'perfect'

- infinite lifetime (no 1→2 or 1→n process is possible)
- ballistic (if T<100mK and low $^3$He concentration)

Density of states favors ~7meV energies (near 'roton minimum')



# Physics of a Superfluid $^4$He Target

**Above 20eV:**

Large fraction of recoil energy goes into dimers (in both ER and NR cases)

Can estimate fraction directly from measured atomic excitation cross sections.

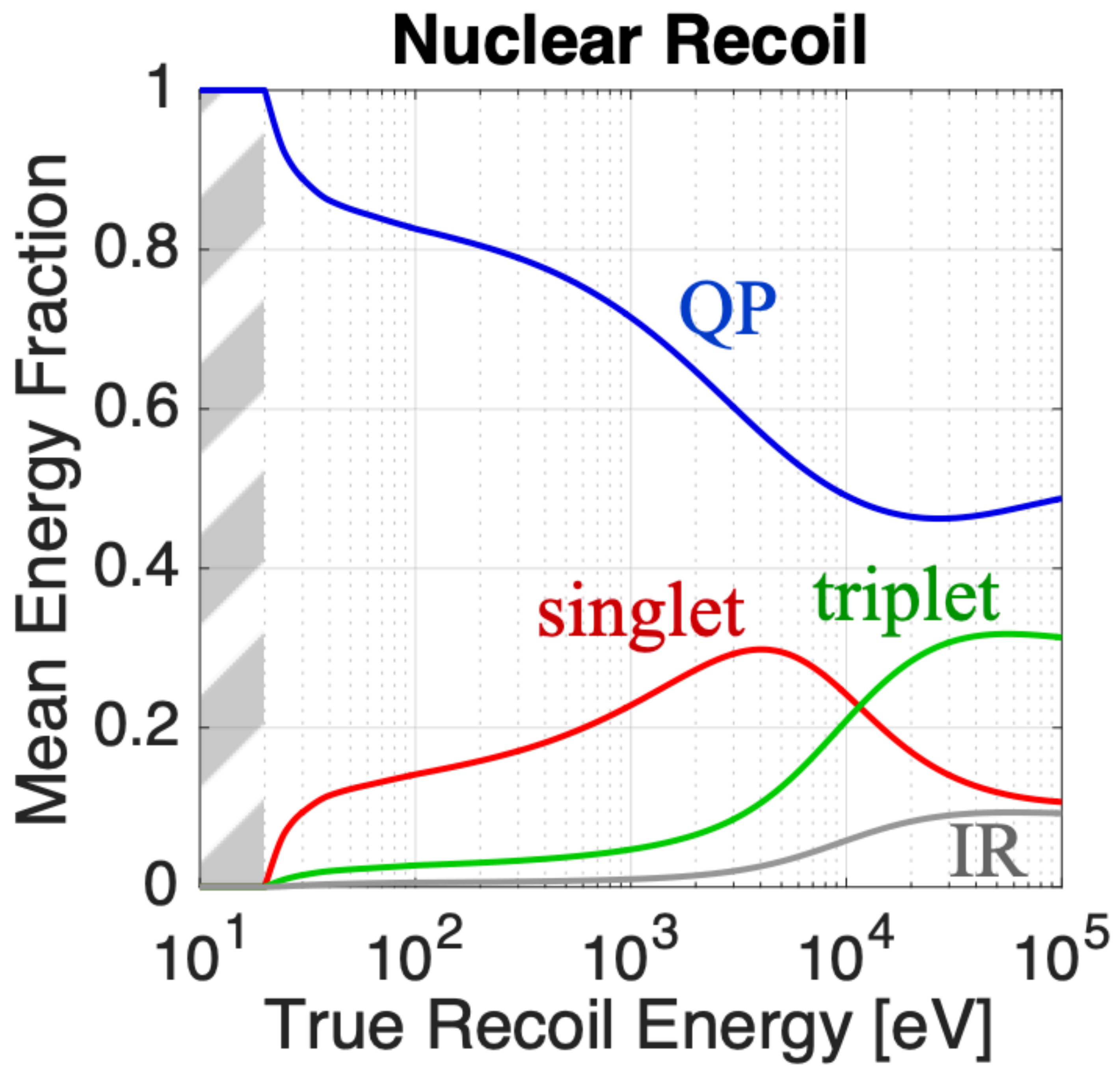
So far ER and NR calibrations agree with expectation arXiv:2108.02176

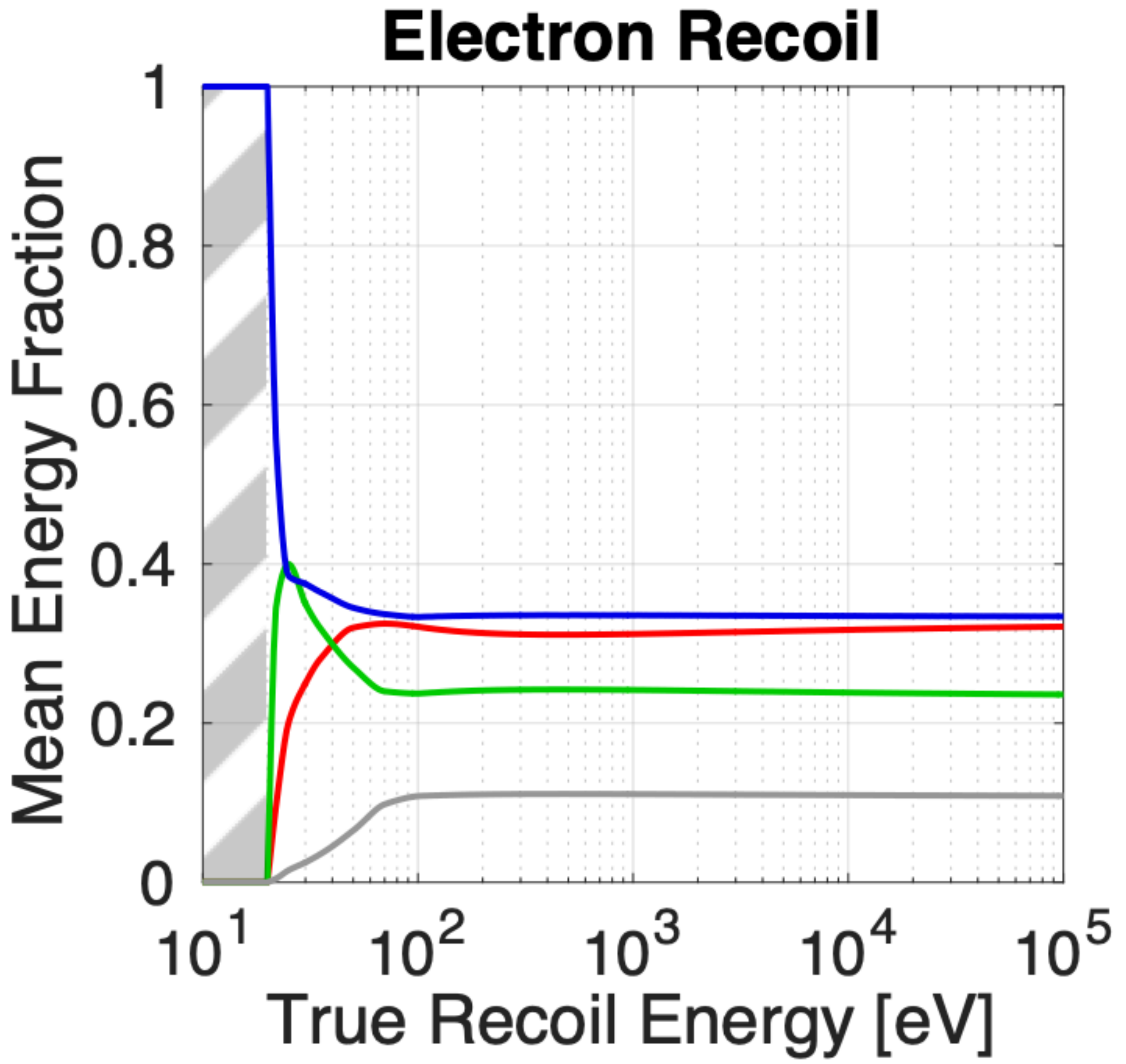
**Below 20eV:**

All recoil energy appears as phonons
(Hard cutoff on any of electronic excitation)

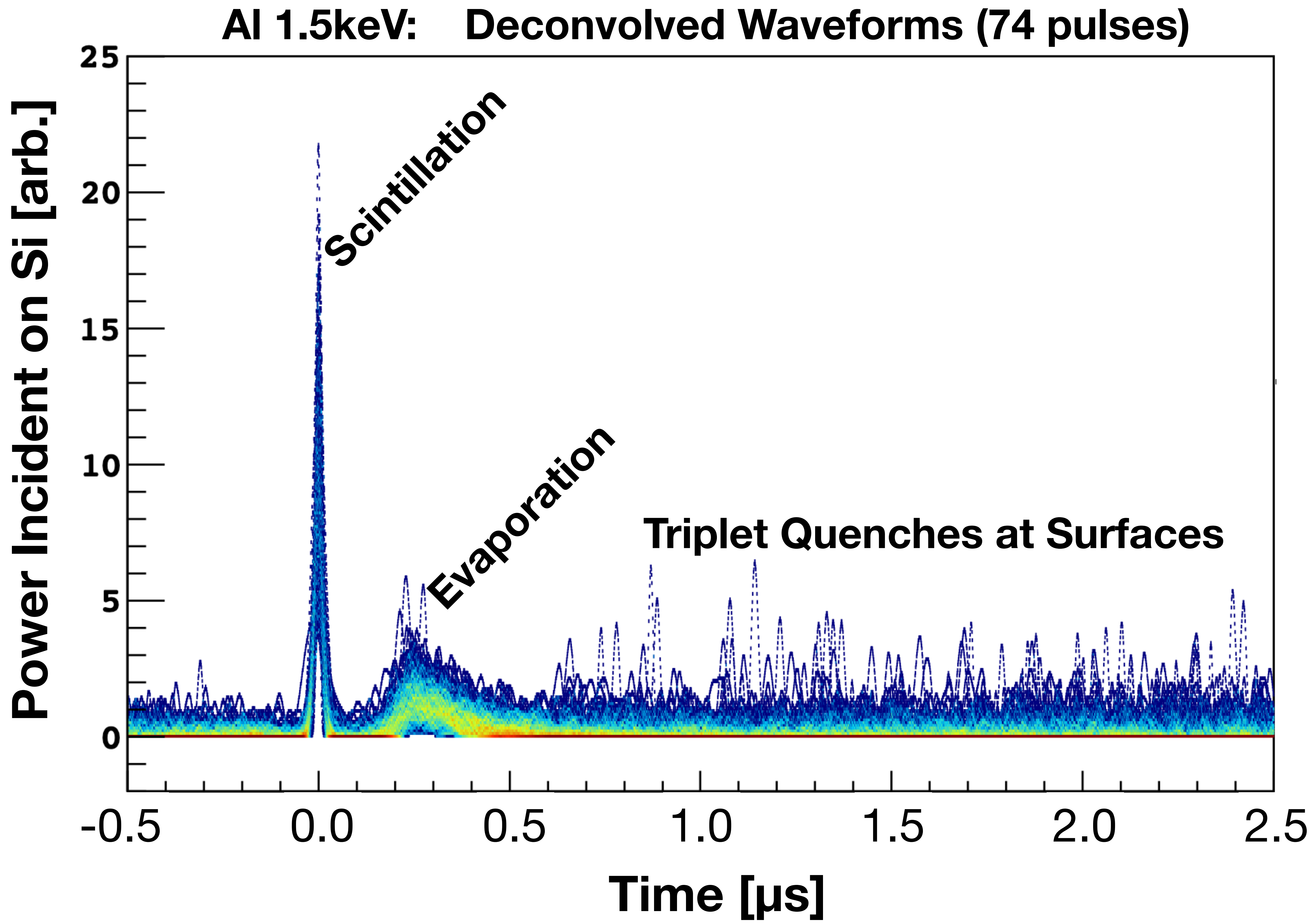
Compton scattering backgrounds highly suppressed

If the goal is E<20eV recoils, then dimers can act as a veto, tagging E>20eV recoils

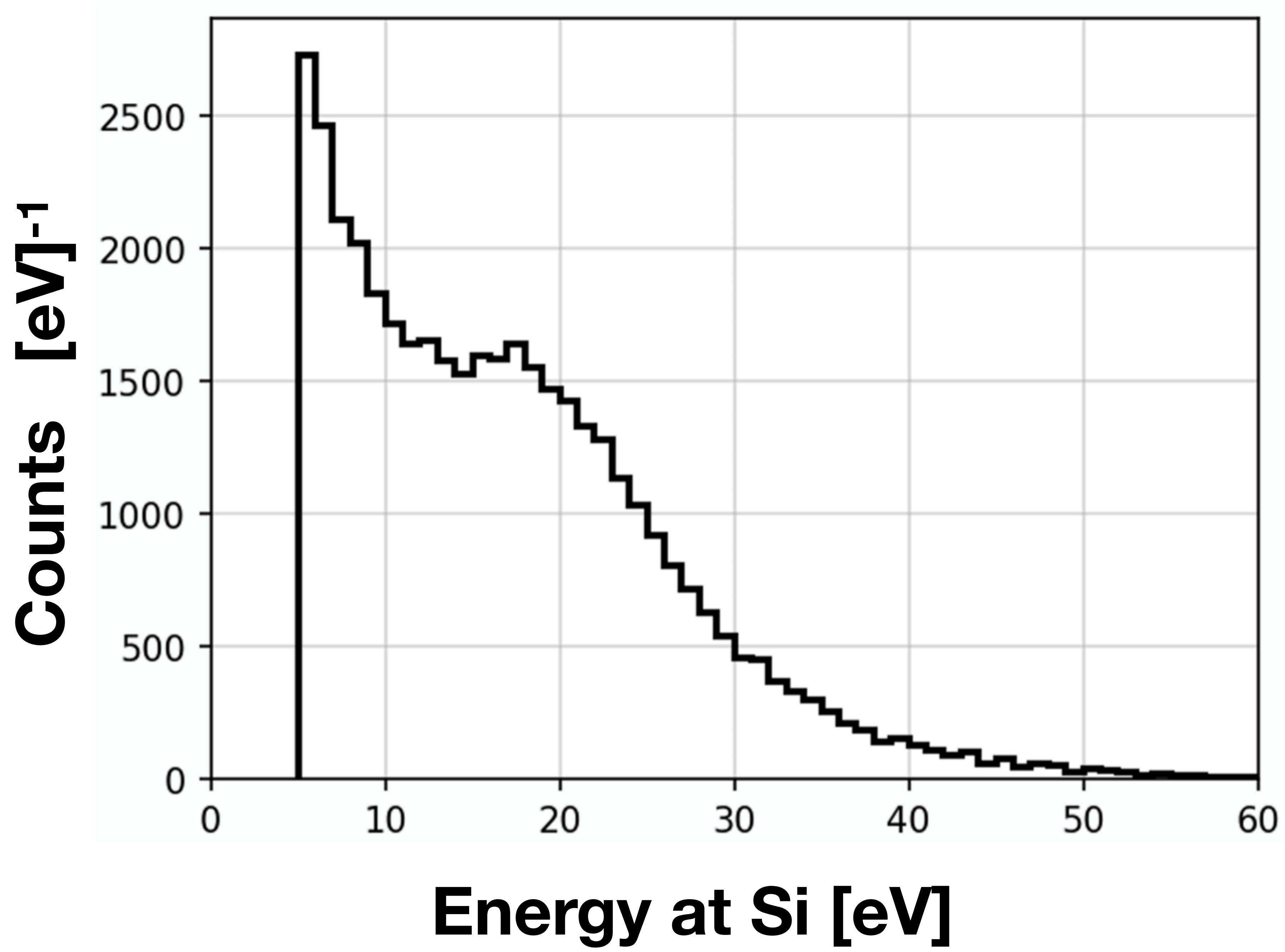


# Triplet Quenching at Late Times




Amplitude of single triplet quench pulses
(looking in 2-5ms time window)

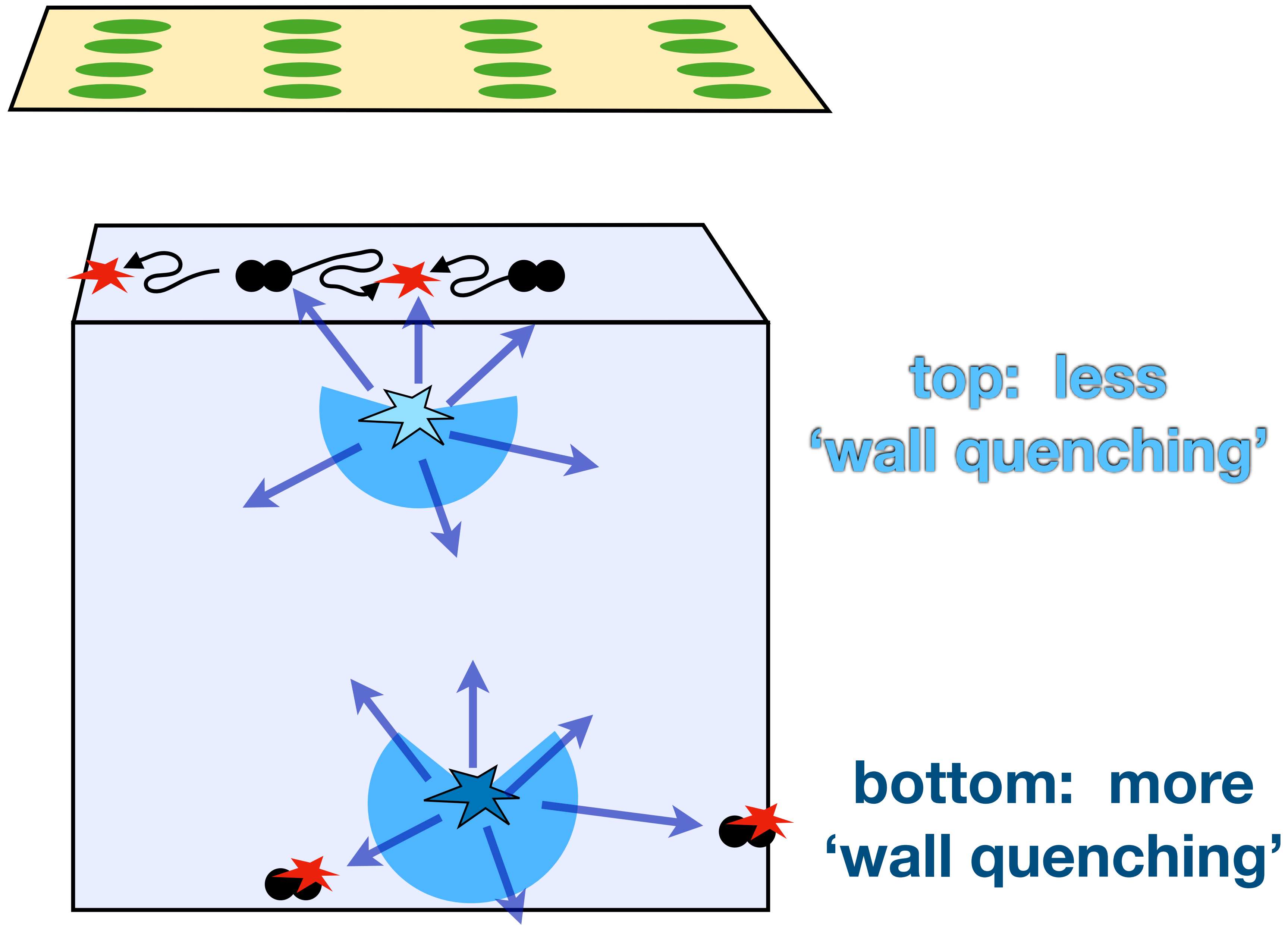


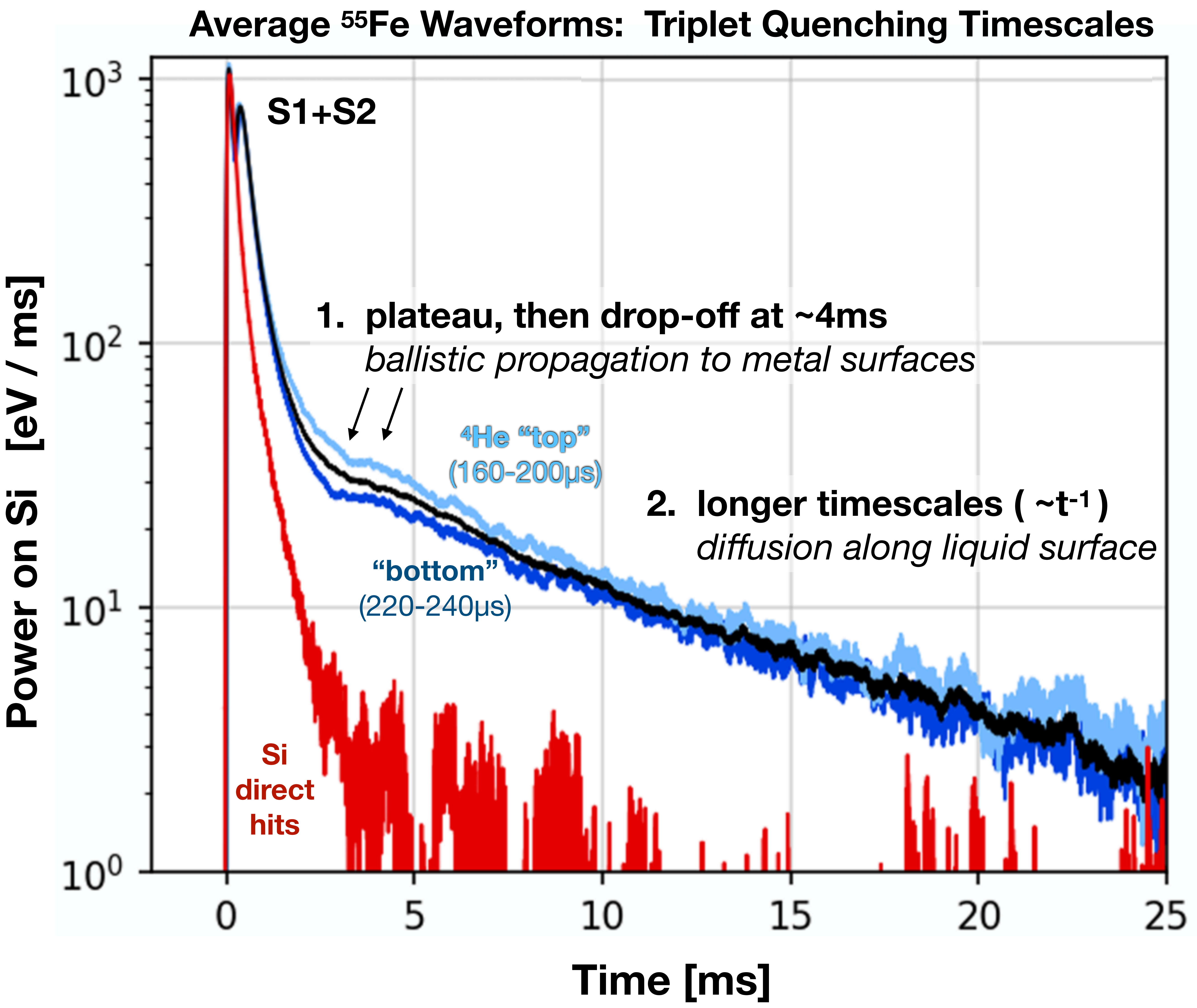
# Triplet Quenching at Late Times

## Triplet Quenching Timescales

Triplets represent a *potential* source of dark counts
(few-eV energies stored for significant timescales)

**Preliminary observations: order-10ms timescales**
**(low dark count risk)**



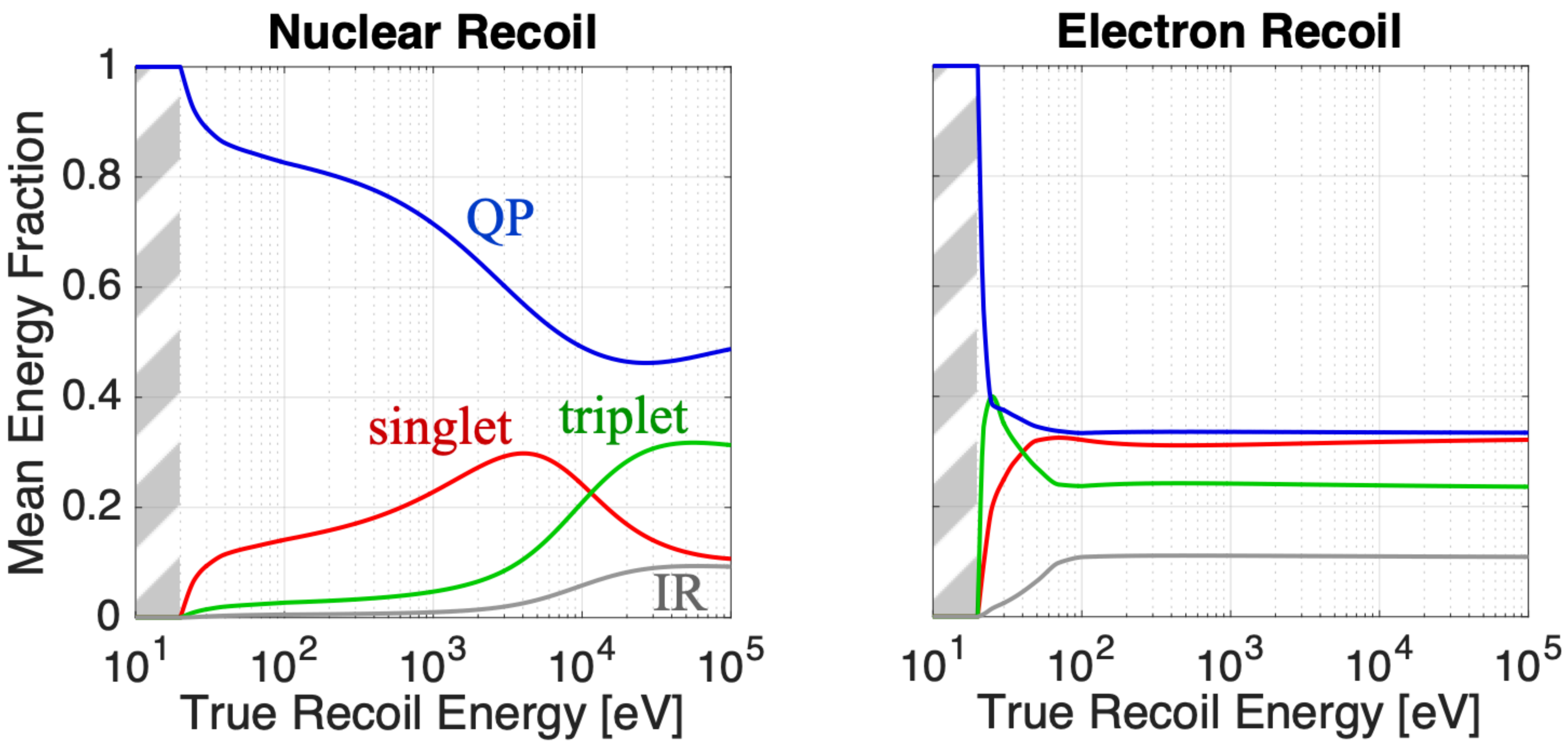



# Initial R&D Data

## Comparing ER and NR response

Our intended signal region is mostly <20eV (phonon-only)

But we can still look at ER/NR differences above 20eV




**Nuclear Recoil Expectation:**

- ☐ Larger evaporation:scintillation ratio (at all energies)
- ☐ Larger triplet fraction (above ~10keV)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# Initial R&D Data

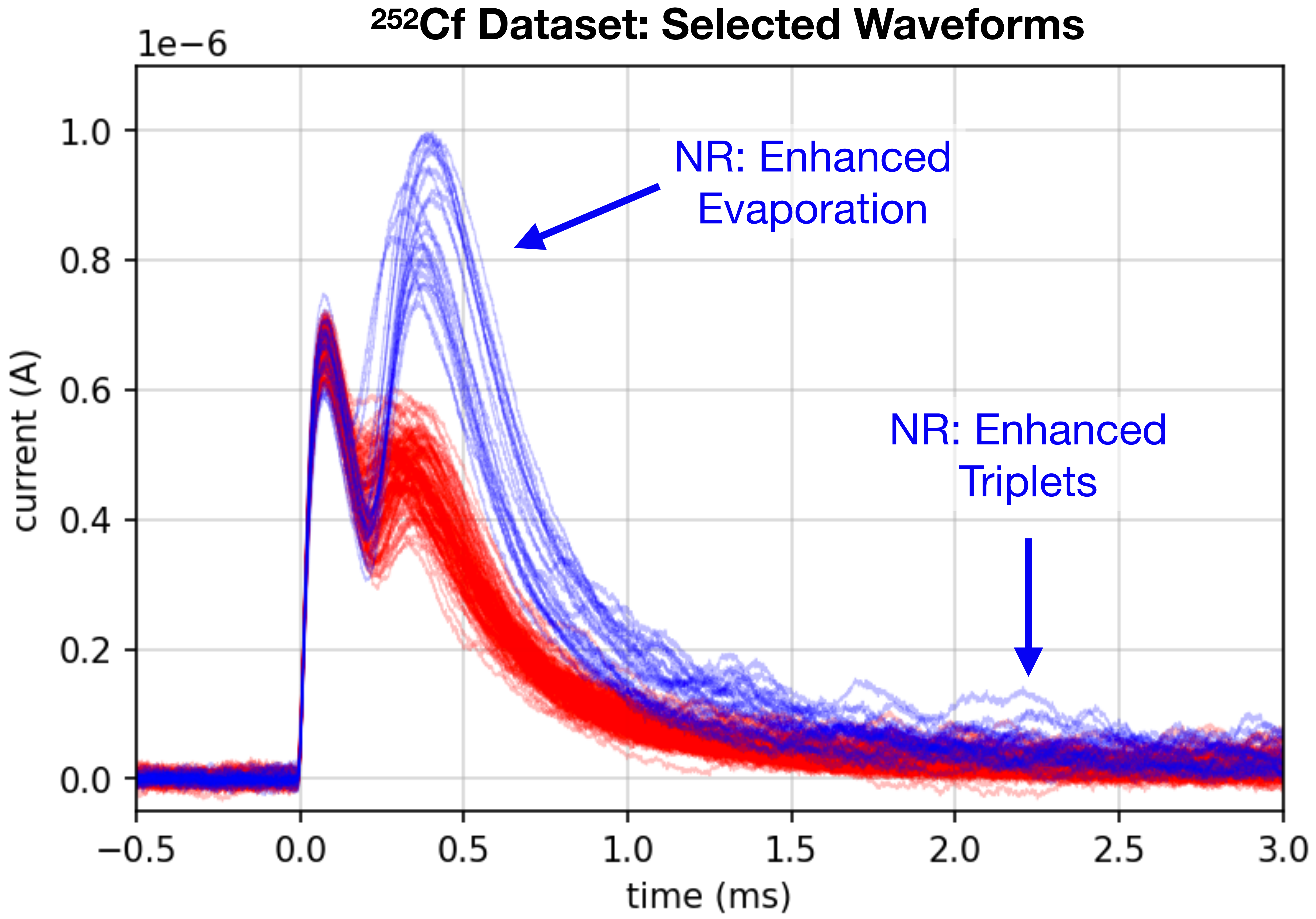
## Comparing ER and NR response

Our intended signal region is mostly <20eV (phonon-only)

But we can still look at ER/NR differences above 20eV

**Preliminary Observations using $^{252}$Cf Source:**

- ☑ Larger evaporation:scintillation ratio (at all energies)
- ☑ Larger triplet fraction (above ~10keV)



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