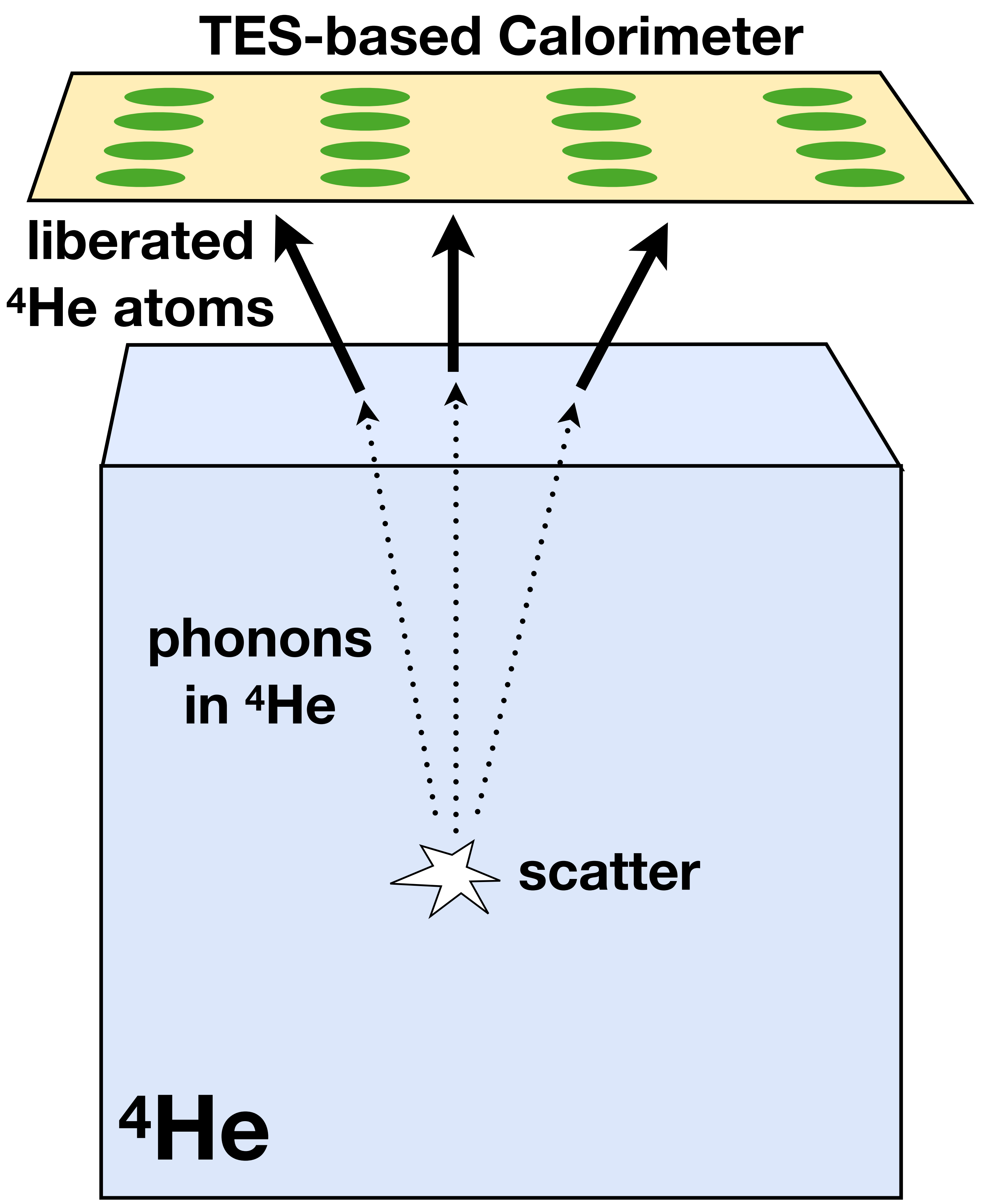
# HeRALD Progress Report:
# a Superfluid 4He Detector for Light Dark Matter

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

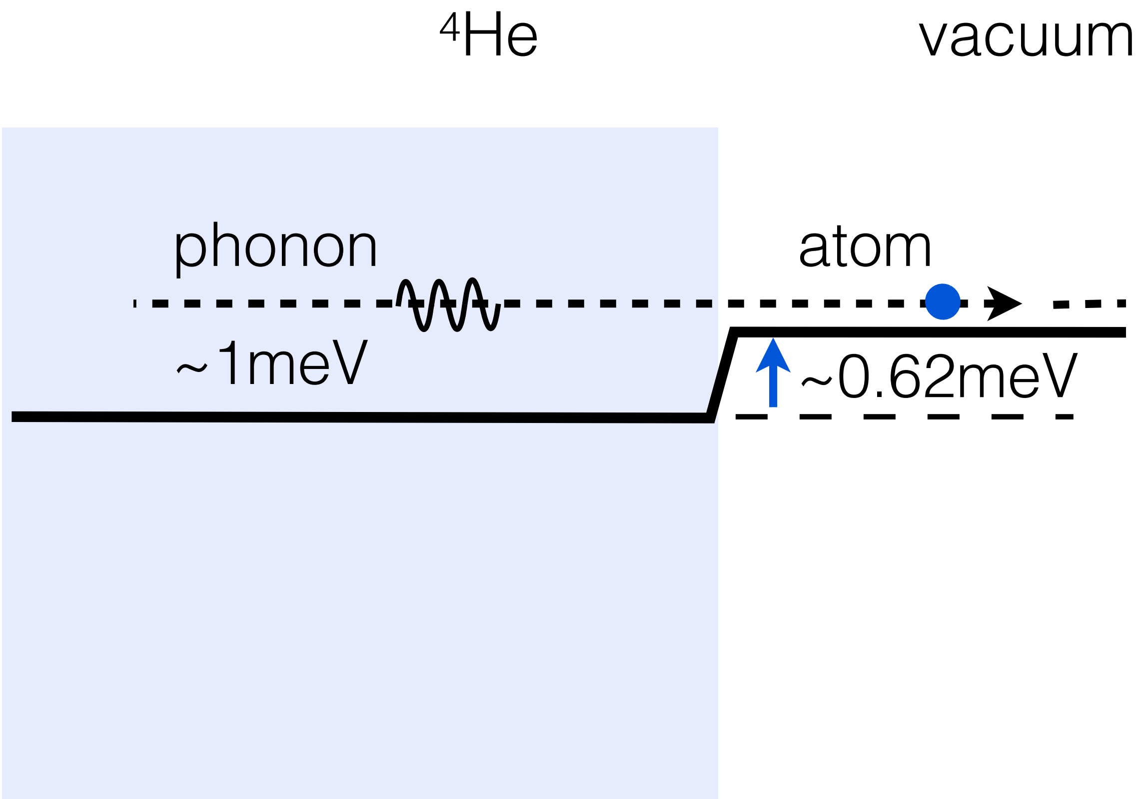
# Physics of a Superfluid $^4$He Target



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

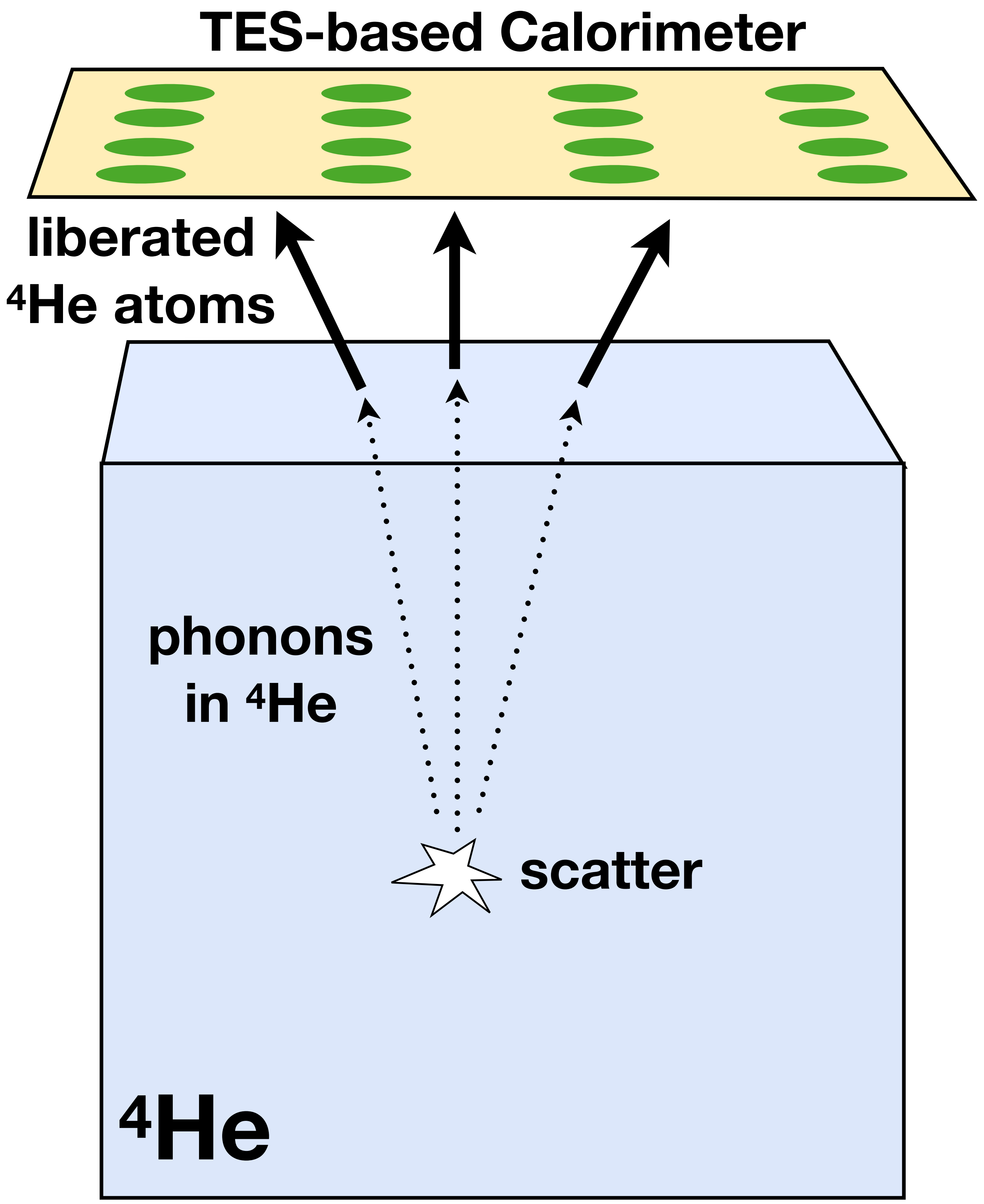
A single phonon can liberate a single atom into the vacuum

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



arXiv:1810.06283

# Physics of a Superfluid $^4$He Target



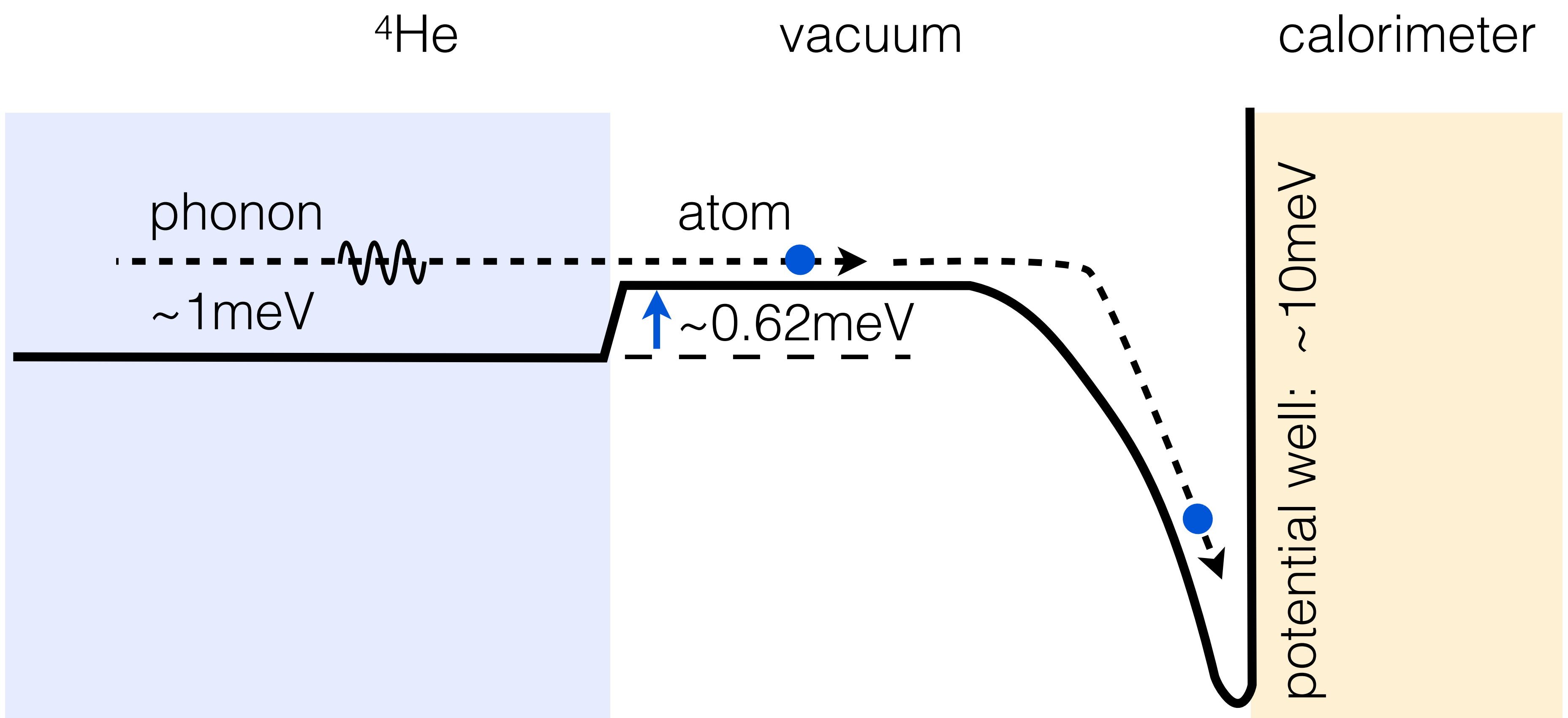
**Primary Signal Channel :** **'Quantum Evaporation'**

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**

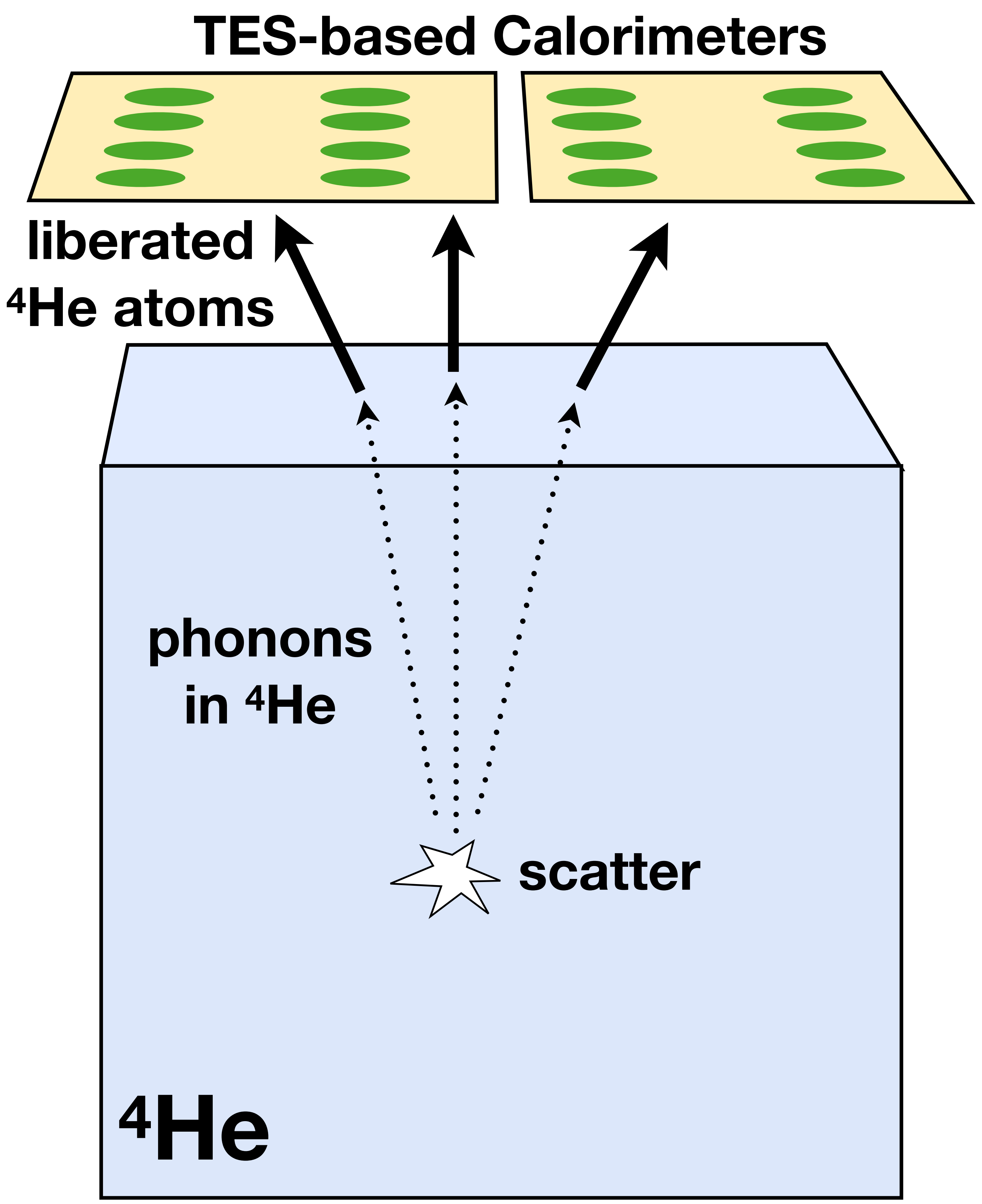
Signal: the *adsorption* of of atoms onto a calorimeter

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



arXiv:1810.06283

# Physics of a Superfluid $^4$He Target



Two advantages of Quantum Evaporation
(over standard phonon readout)

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

*Route to pushing recoil threshold below calorimeter threshold*

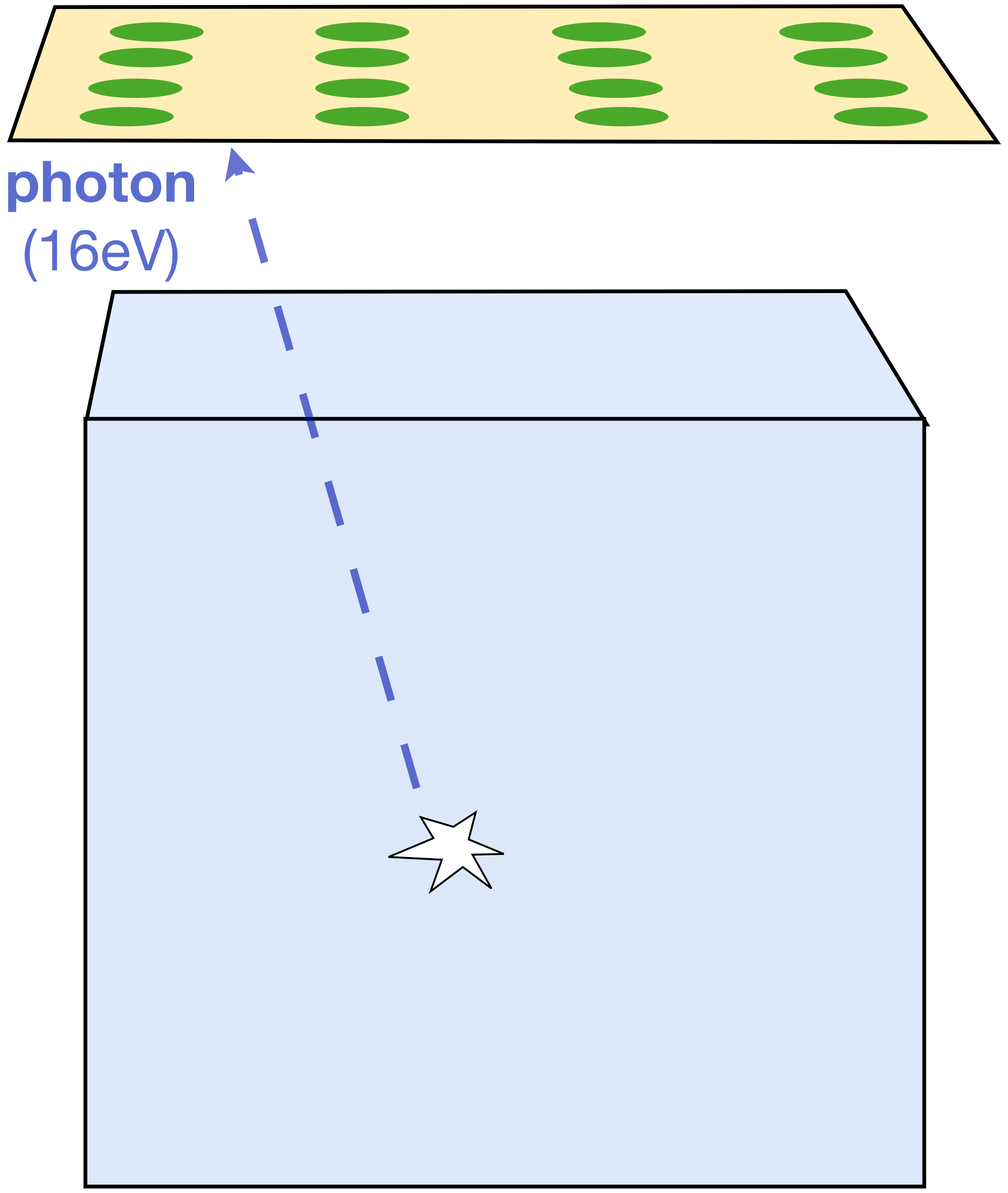
**2) Signals from $^4$He target : strongly *multi*-channel,**
**Calorimeter backgrounds : strongly *single*-channel**

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

arXiv:1810.06283

# Physics of a Superfluid $^4$He Target

**Secondary signals:   atomic excitations**

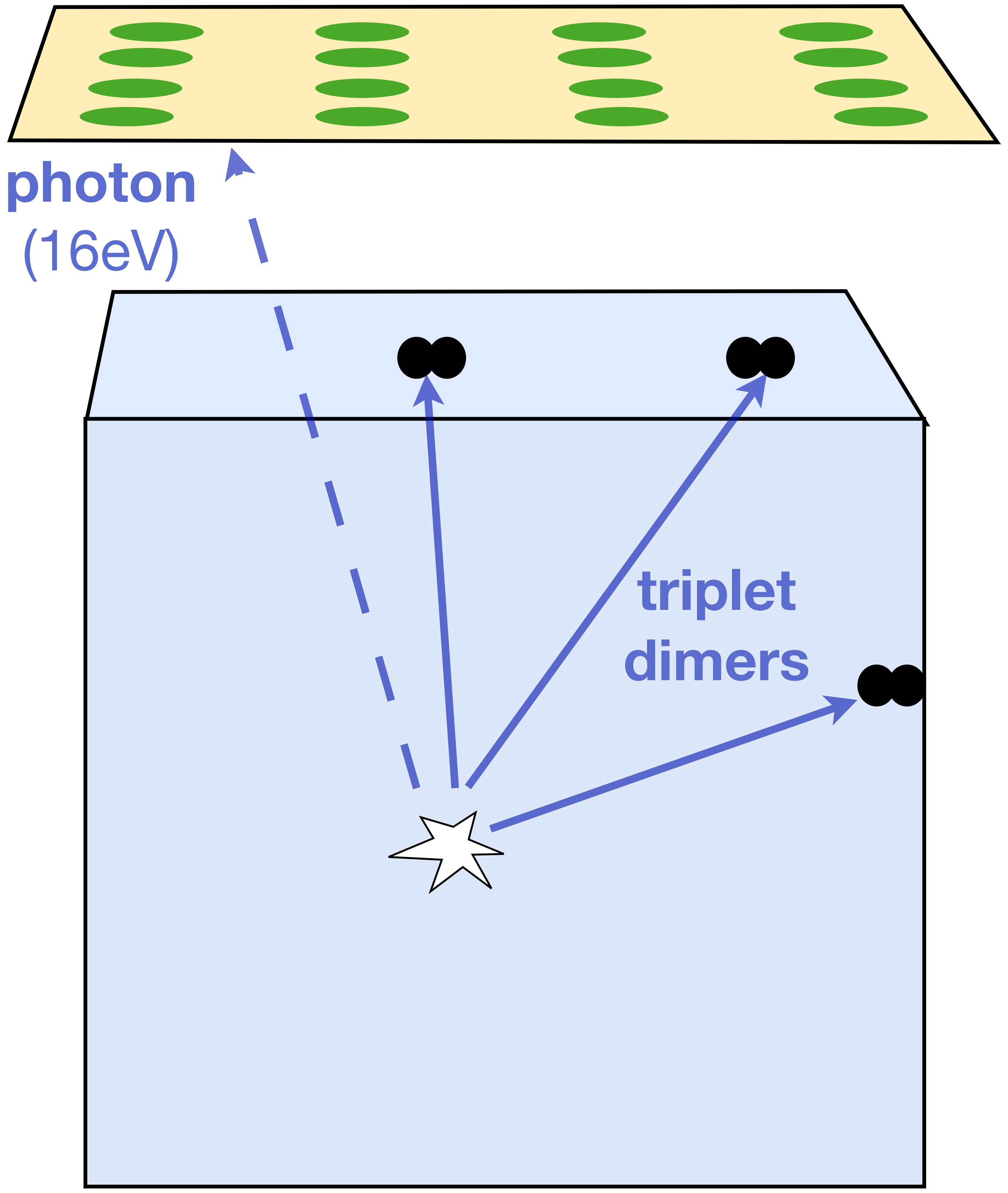


**Singlet dimers:  simple**

- Prompt decay
- Photon energy:  ~16eV

arXiv:1810.06283

# Physics of a Superfluid $^4$He Target



**Secondary signals: atomic excitations**

**Singlet dimers: simple**

- Prompt decay
- Photon energy: ~16eV

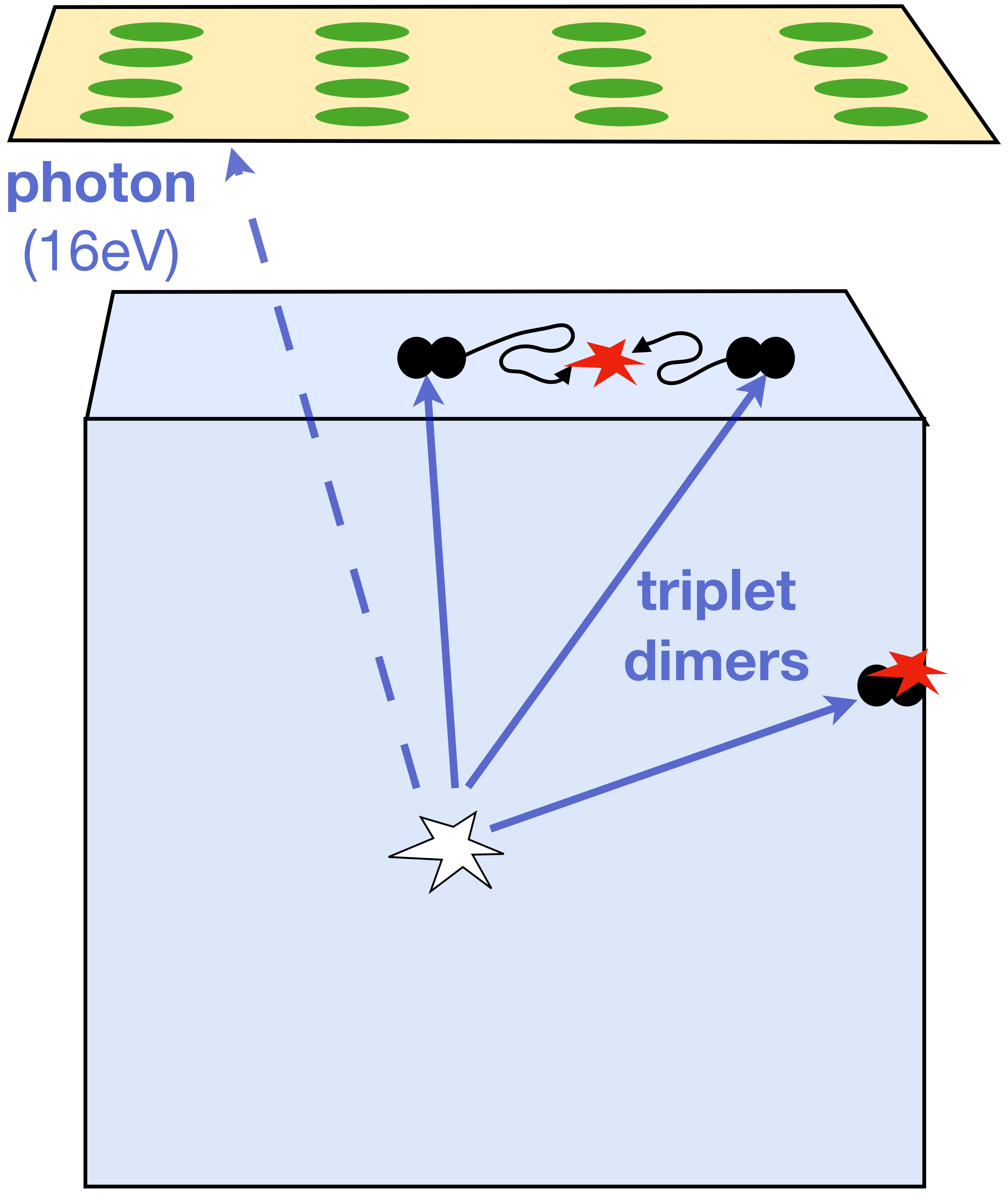
**Triplet dimers: "interesting"**

- In the bulk superfluid:
  - extremely long lifetime (13 s) DOI:10.1103/PhysRevA.59.200
  - ballistic propagation at order-m/s velocities arXiv:1207.1799

arXiv:1810.06283

# Physics of a Superfluid $^4$He Target

**Secondary signals: atomic excitations**



**Singlet dimers: simple**

- Prompt decay
- Photon energy: ~16eV

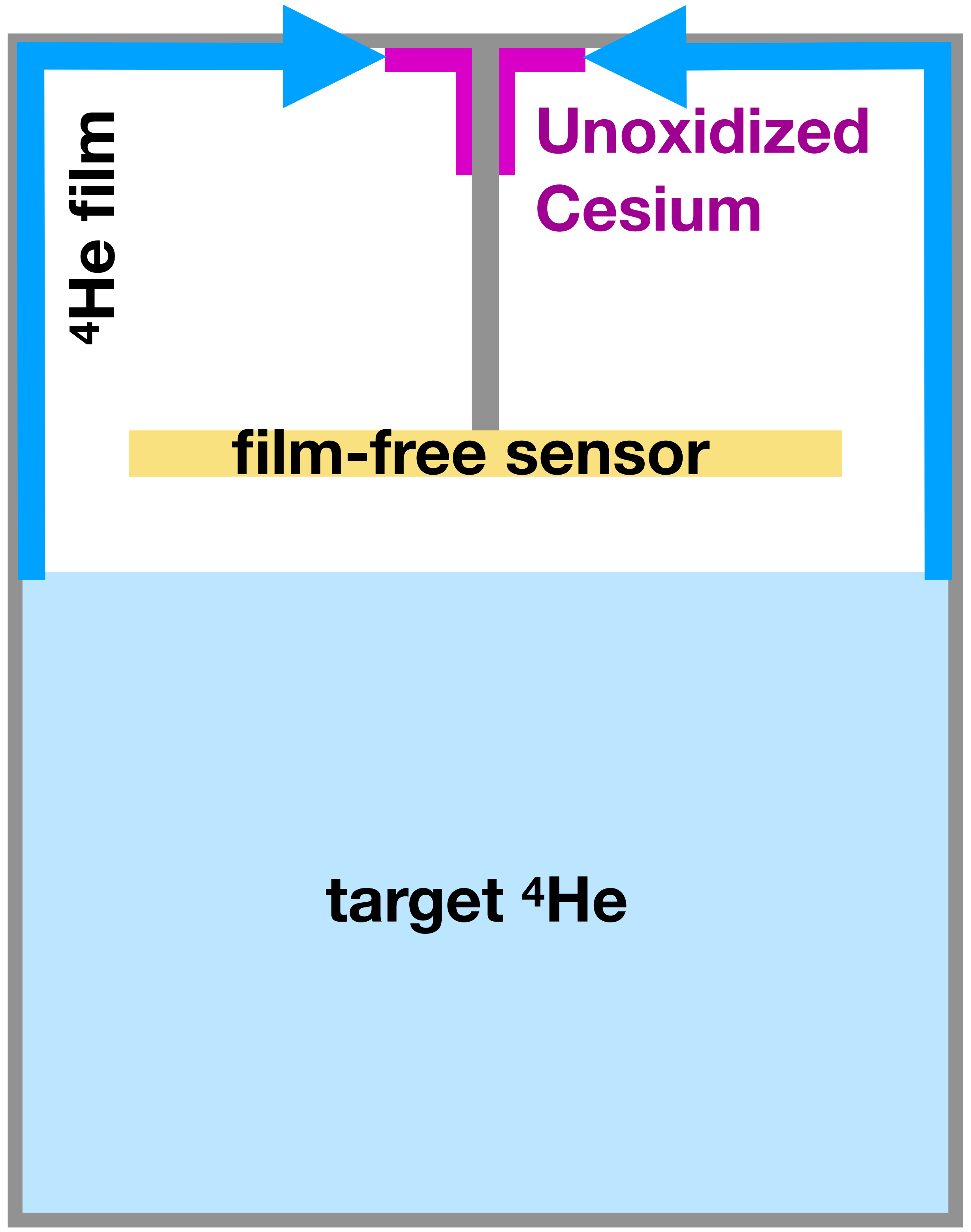
**Triplet dimers: "interesting"**

- In the bulk superfluid:
  - extremely long lifetime (13 s) DOI:10.1103/PhysRevA.59.200
  - ballistic propagation at order-m/s velocities arXiv:1207.1799
- Quench/decay occurs at ***surfaces***:
  - $^4$He/metal: exchange of electrons with surface (immediate)
  - $^4$He/vacuum: diffusion, then triplet-triplet quenching (rate~1/t )

arXiv:1810.06283

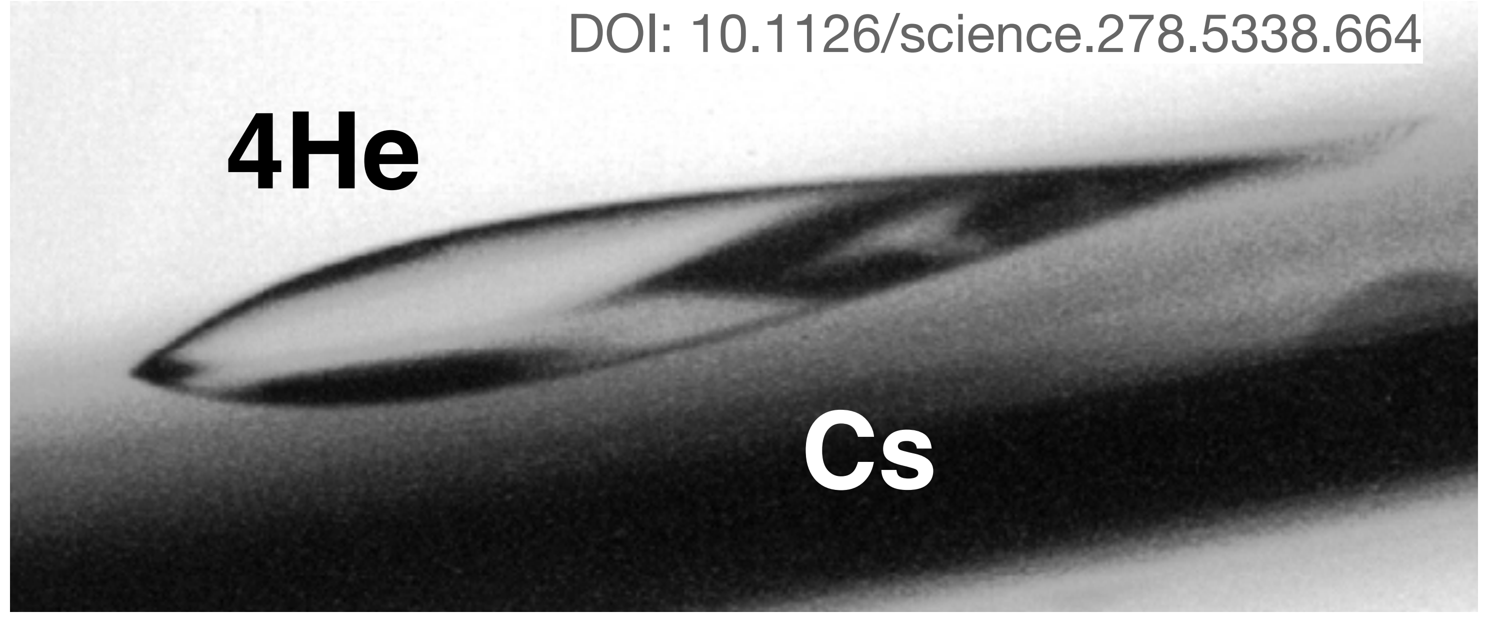
# Physics of a Superfluid $^4$He Target: Film-Stopping

**Practical challenge : keeping the atom-sensor dry**



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

**Cesium** is one of very few surfaces which $^4$He does not wet.



DOI: 10.1126/science.278.5338.664

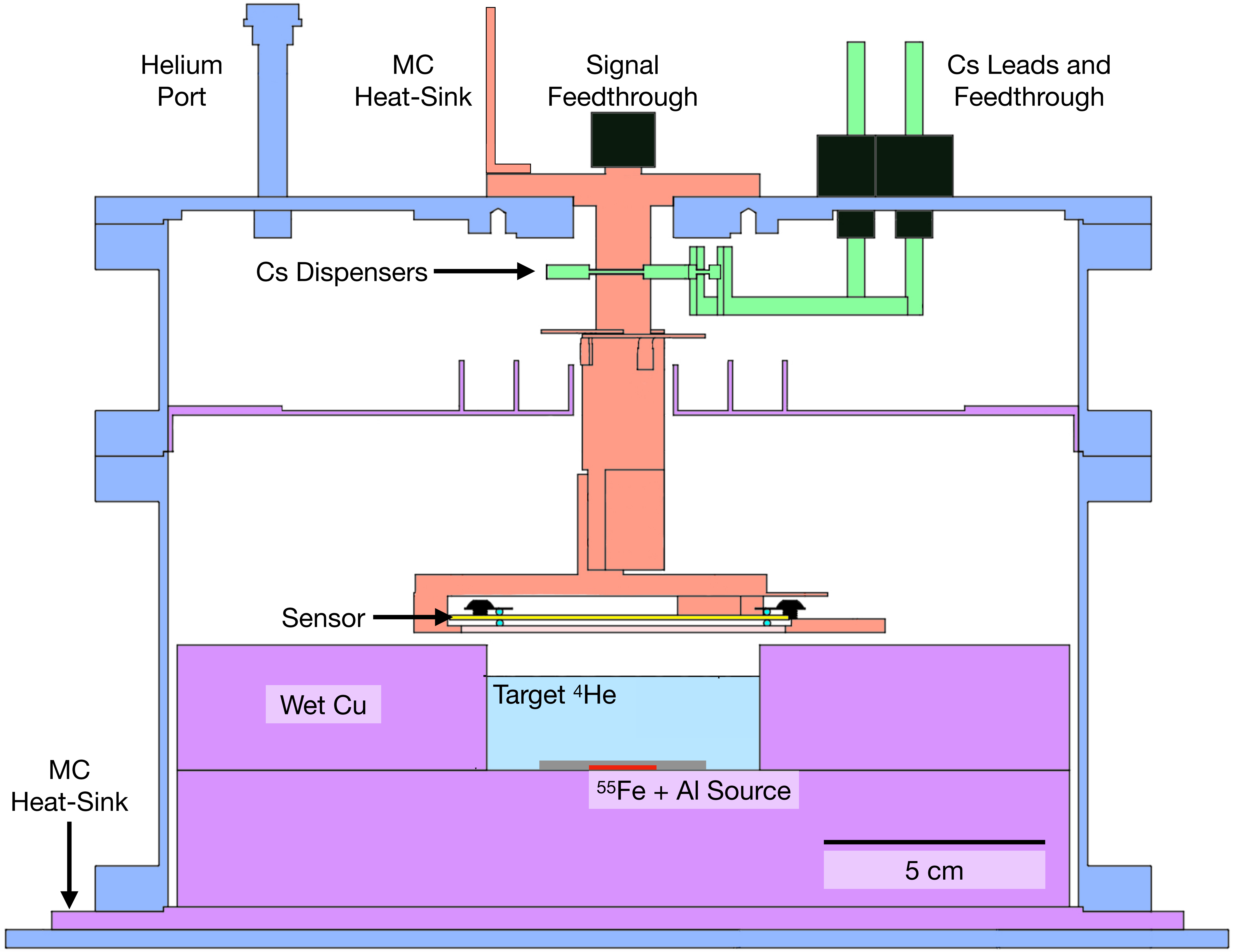
However… Cs is a major practical challenge:

- must be unoxidized (deposited *in situ* )
- deposition requires ~800°C (and high current, >7A)
- high 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.

# HeRALD v0.1



**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”

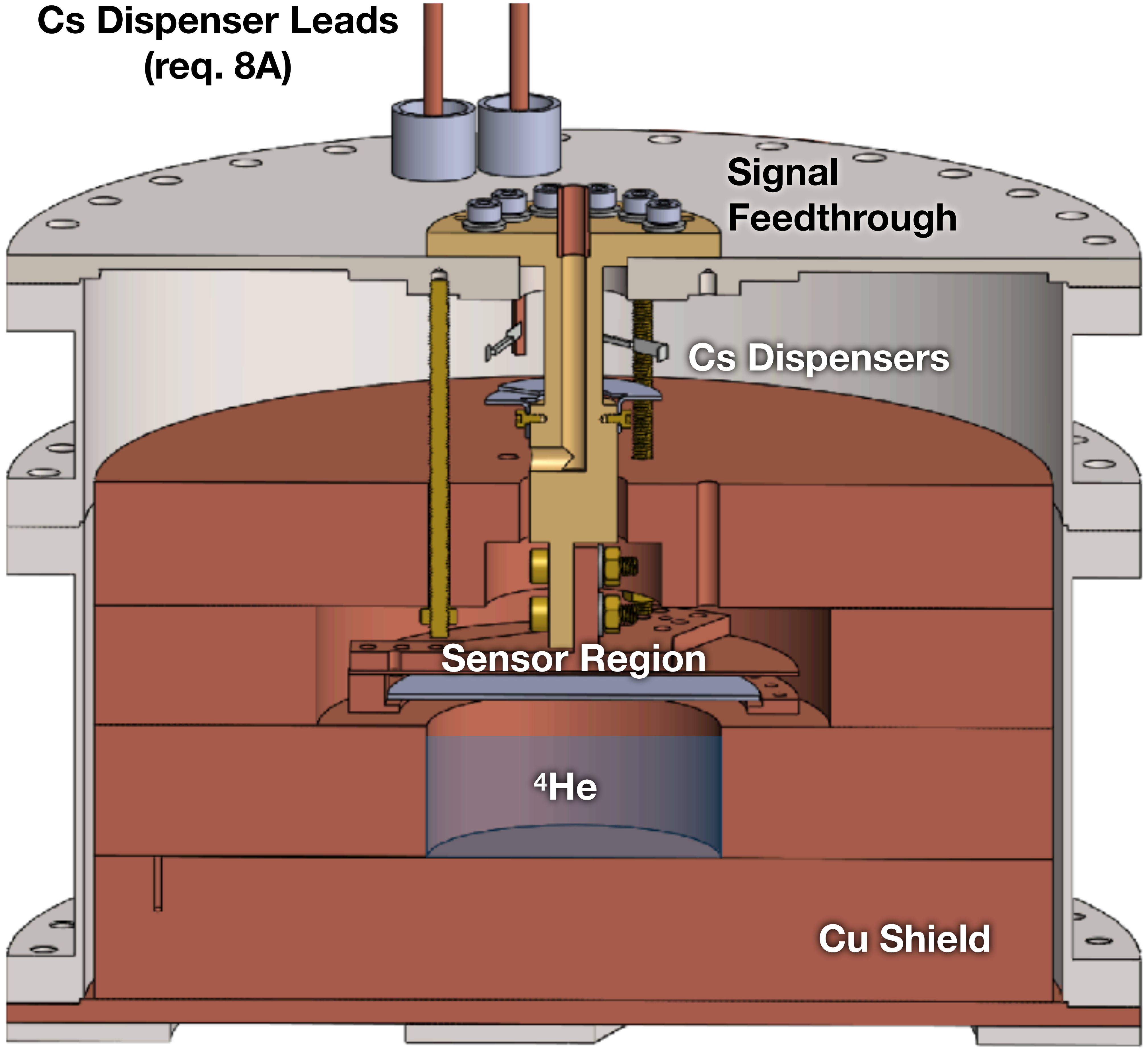
Large (20cm ⌀ ) stainless cell

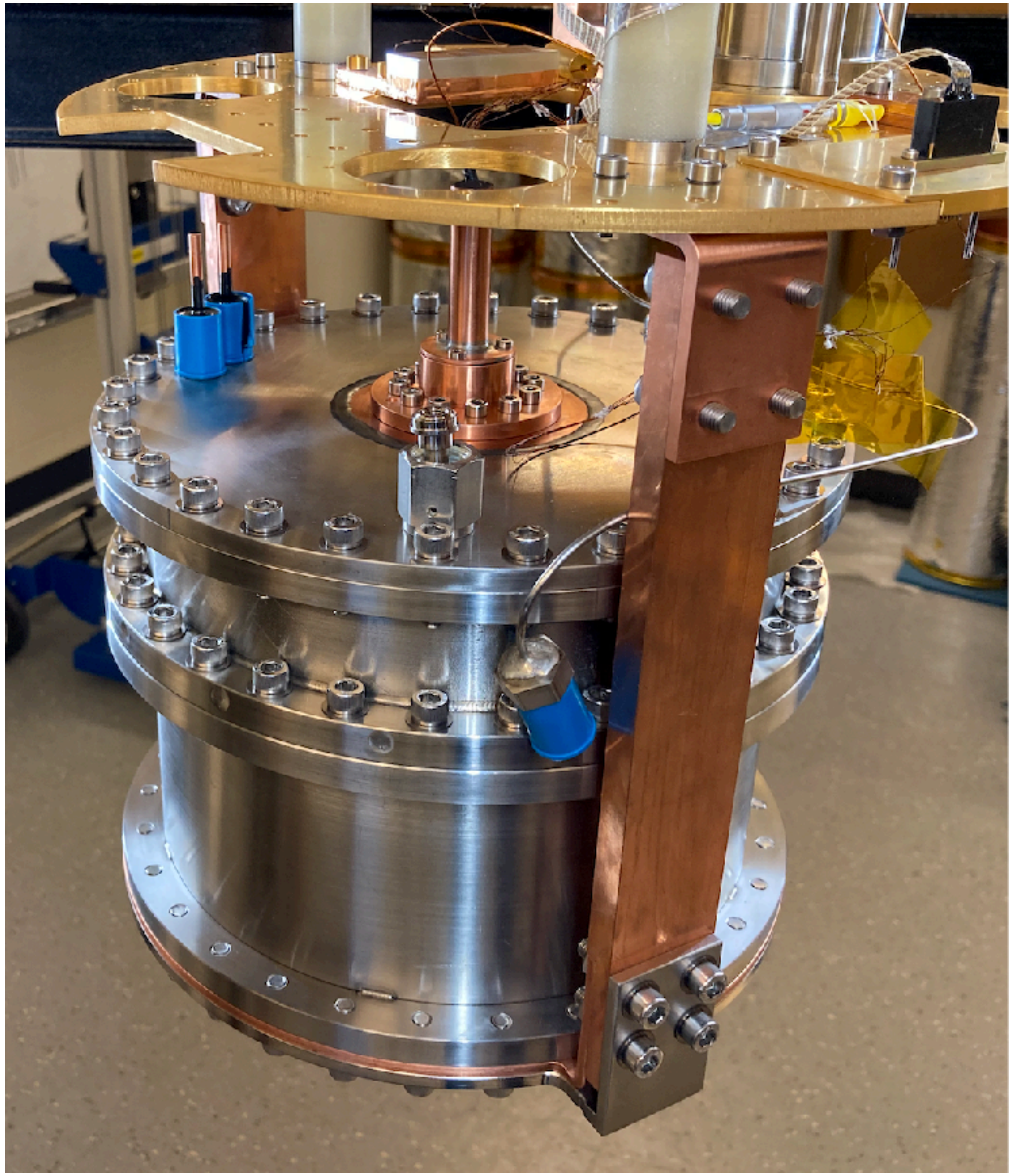
Recent $^4$He target region: 6cm diameter

Significant mass of Cu within cell (arrangements up to 27kg)

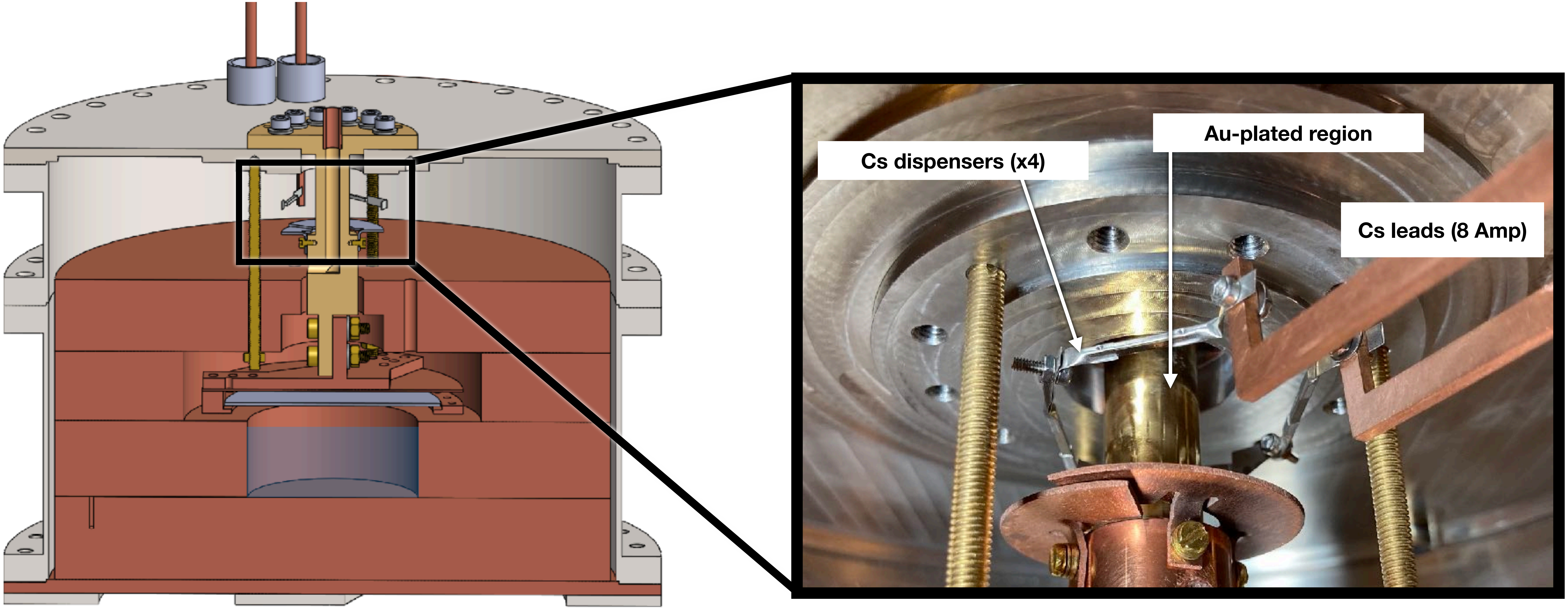
- serves as flexible ‘filler’ to shape/define the target
- $\gamma$ shield (→ 0.7 Bq in the 10g of Si)

# HeRALD v0.1

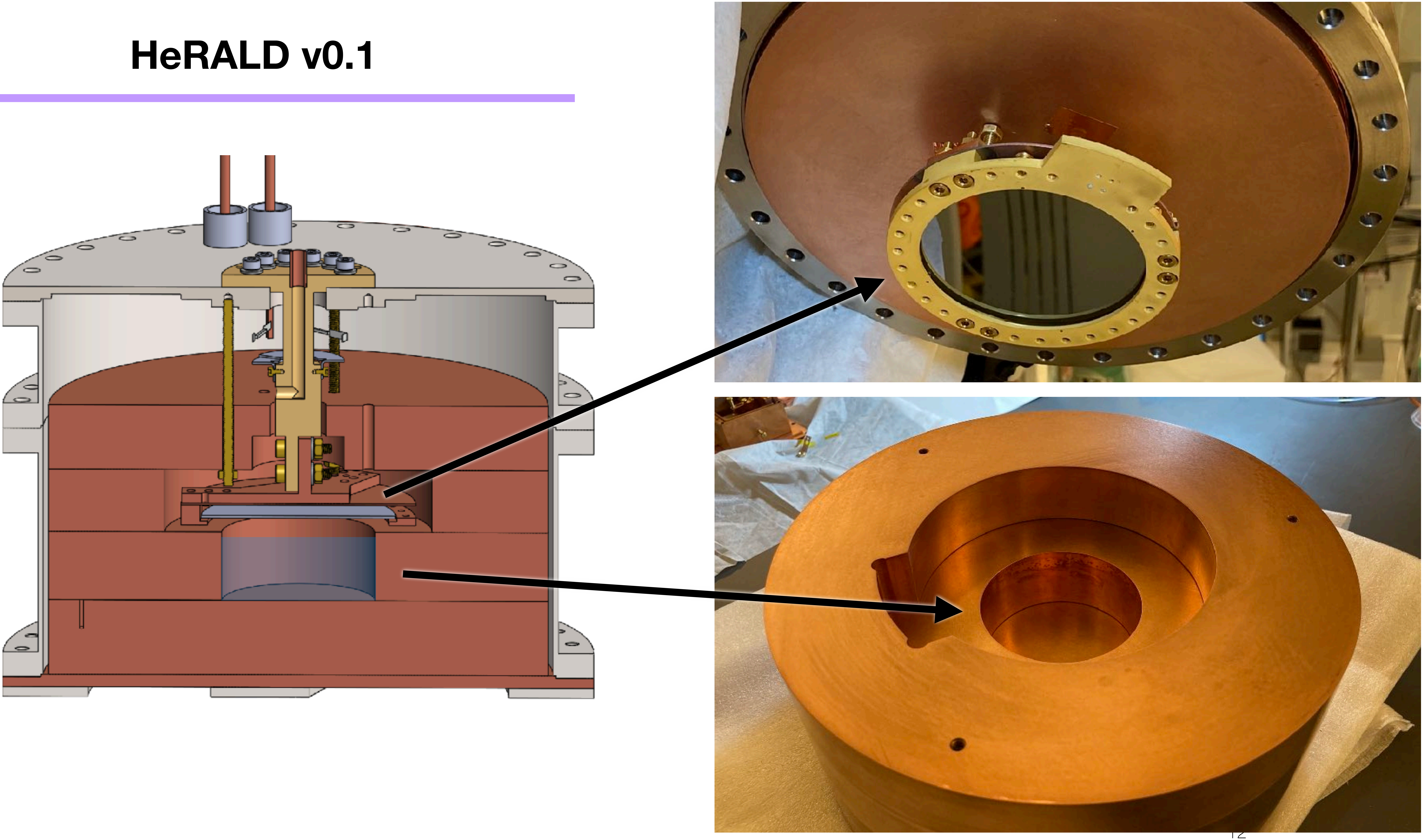

Cs Dispenser Leads
(req. 8A)
Signal
Feedthrough
Cs Dispensers
Sensor Region
$^4$He
Cu Shield



# HeRALD v0.1



# HeRALD v0.1



# HeRALD v0.1

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

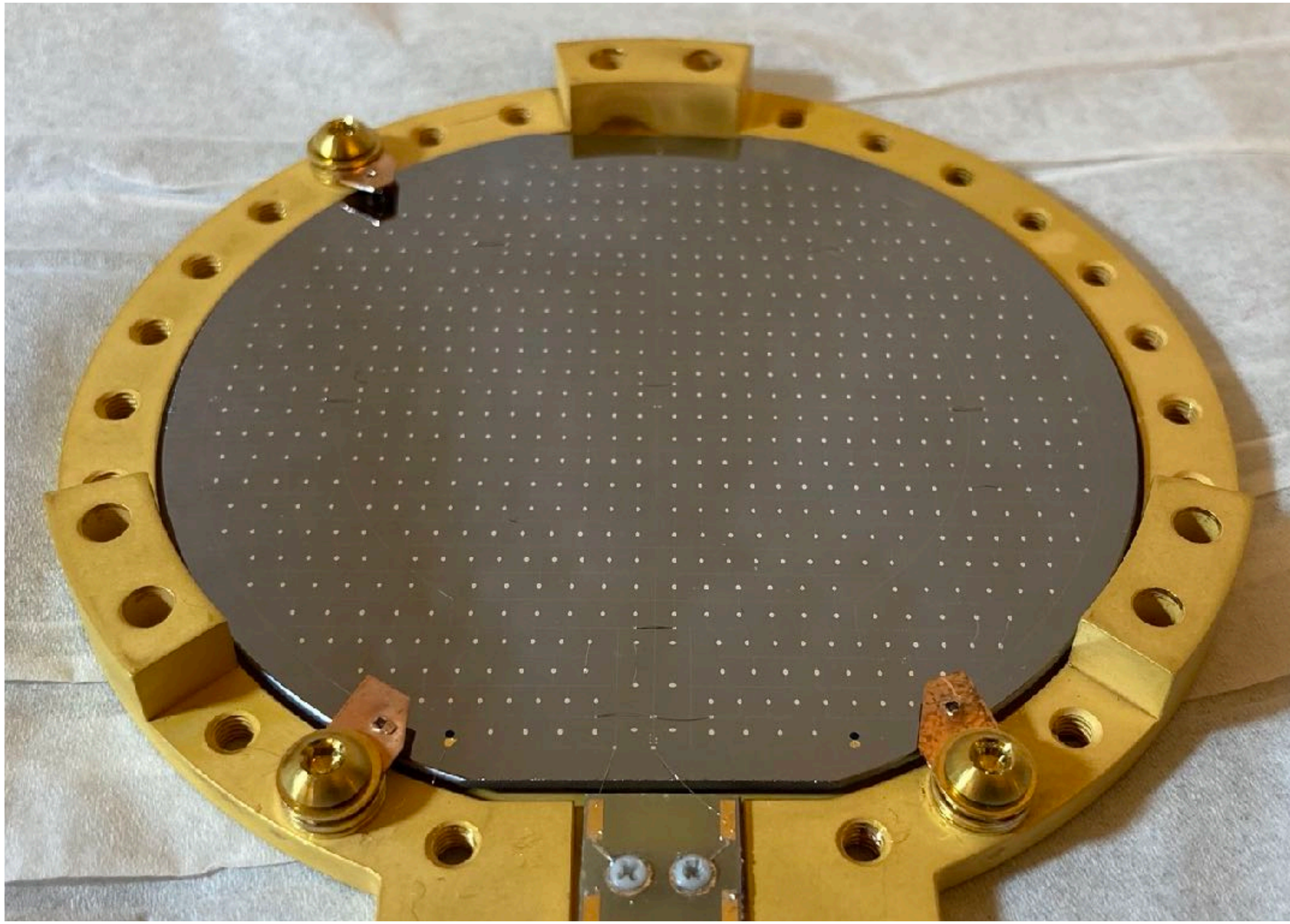
3" Si wafer (10g mass, 1mm thickness)

Array of tungsten TES's ( $T_c = 55\text{mK}$ )

~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, via Si recoils.)



# Initial R&D Data

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

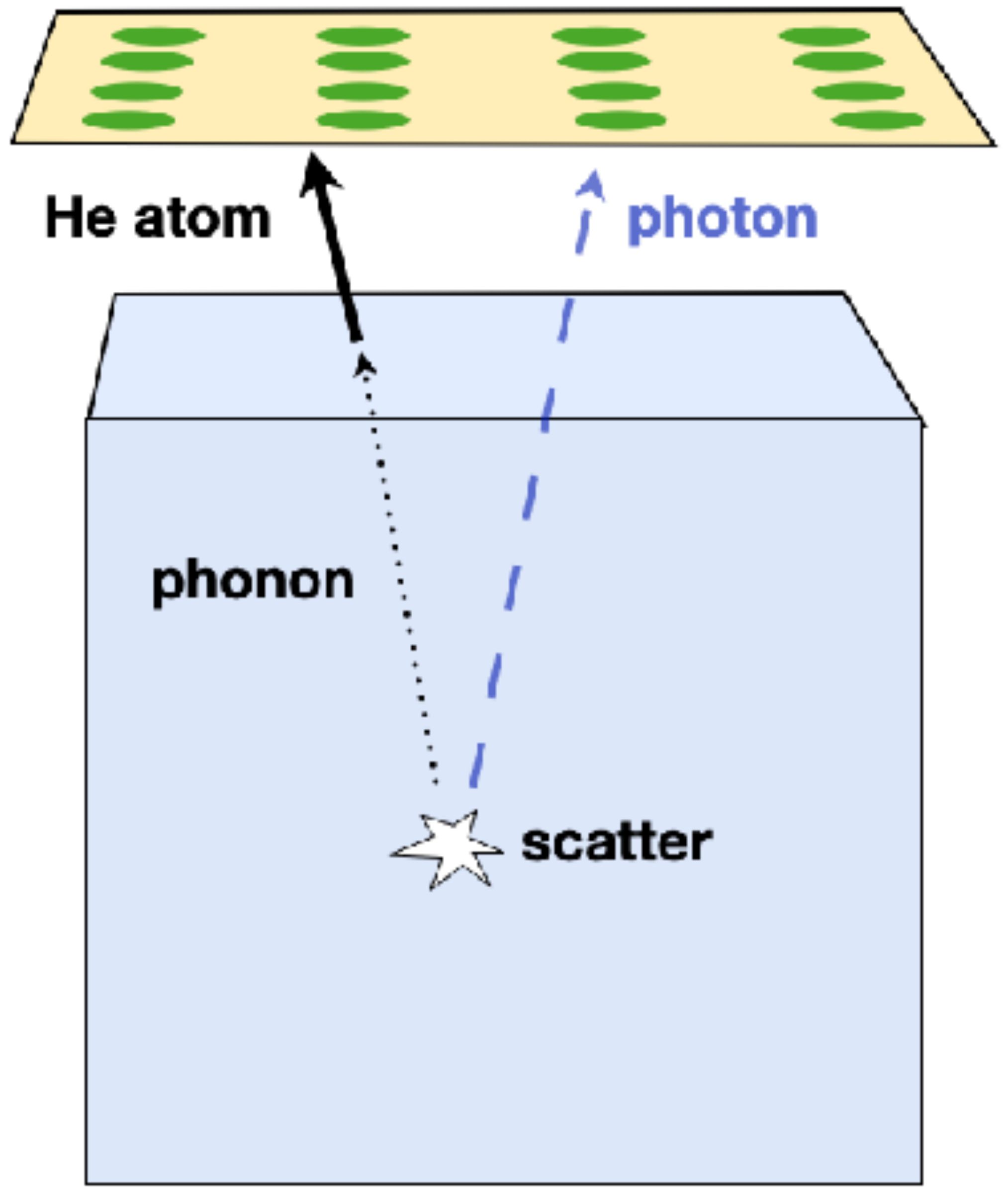
**S1: Prompt scintillation (singlets)**

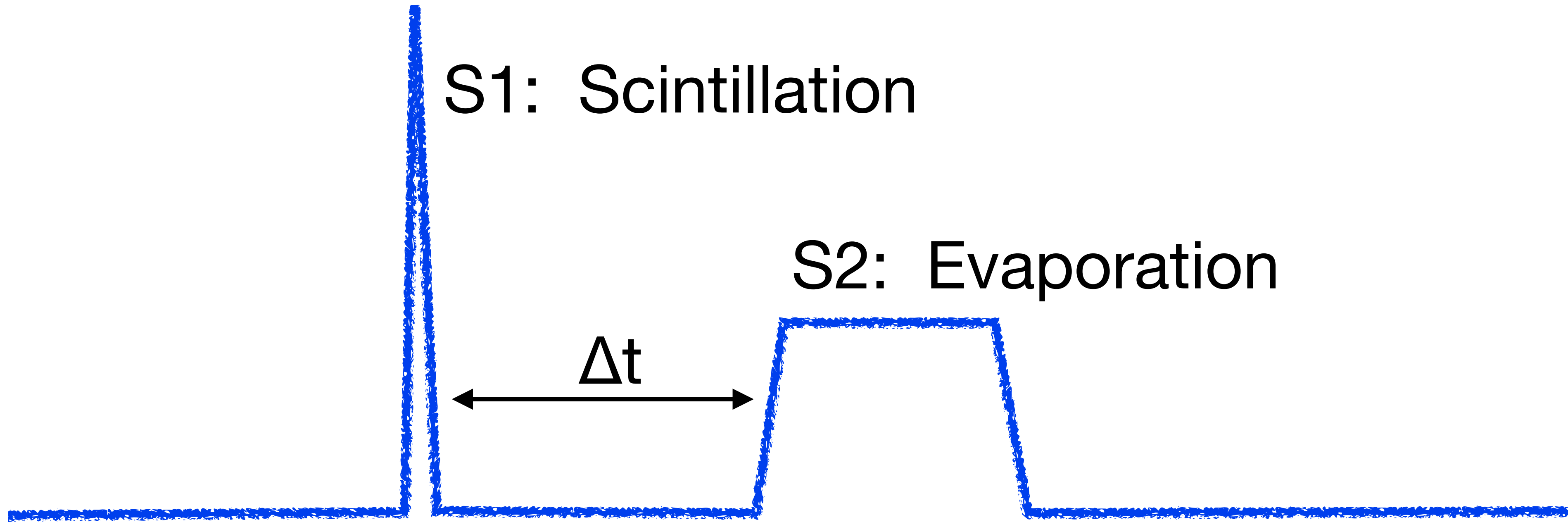
**S2: Delayed Evaporation**

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

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

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





(future DM search windows will likely be <20eV, in the phonon-only regime)

# Initial R&D Data

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

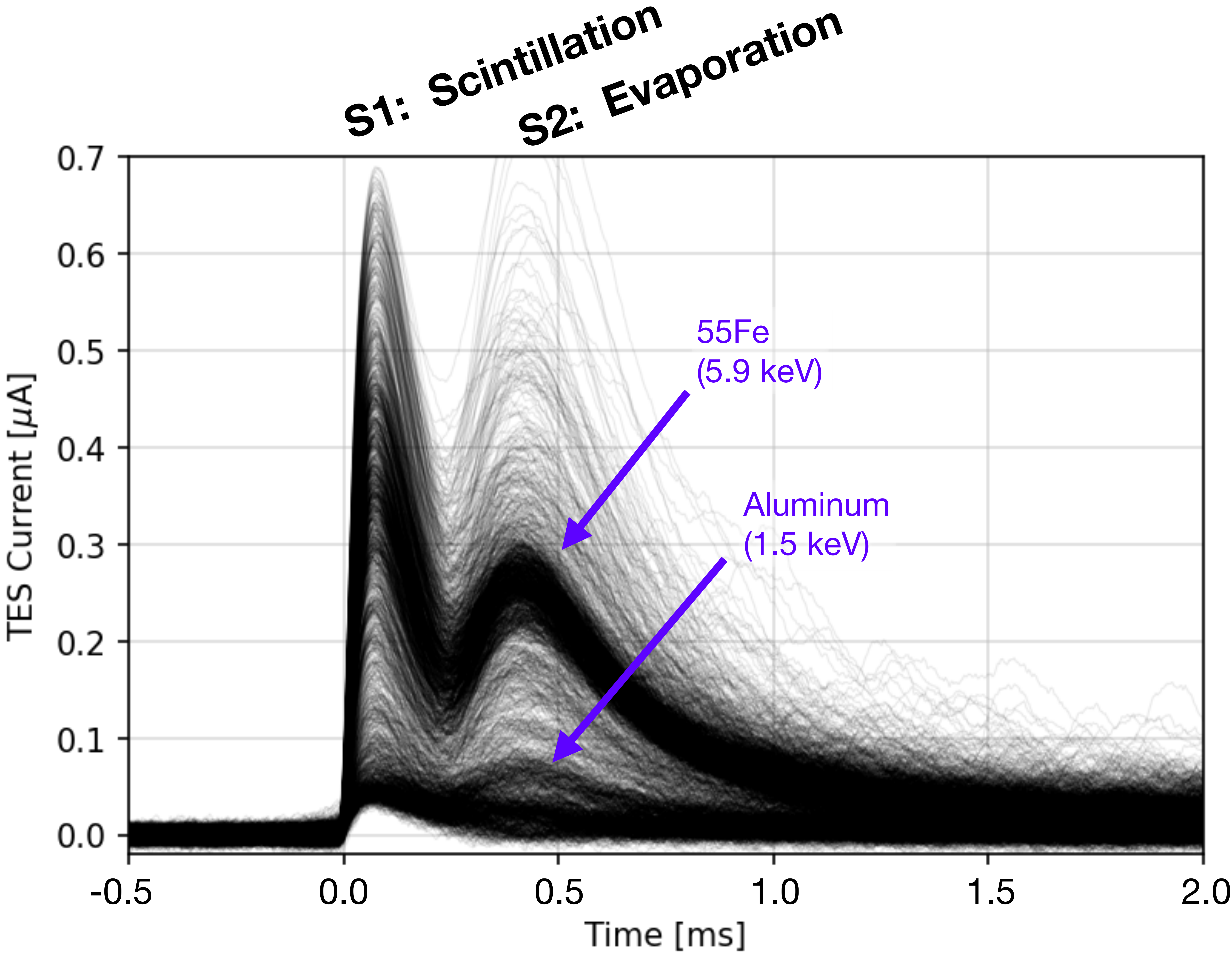
**S1: Prompt scintillation (singlets)**

**S2: Delayed Evaporation**

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

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

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



(in the future will be evaporation-only in the DM search window)

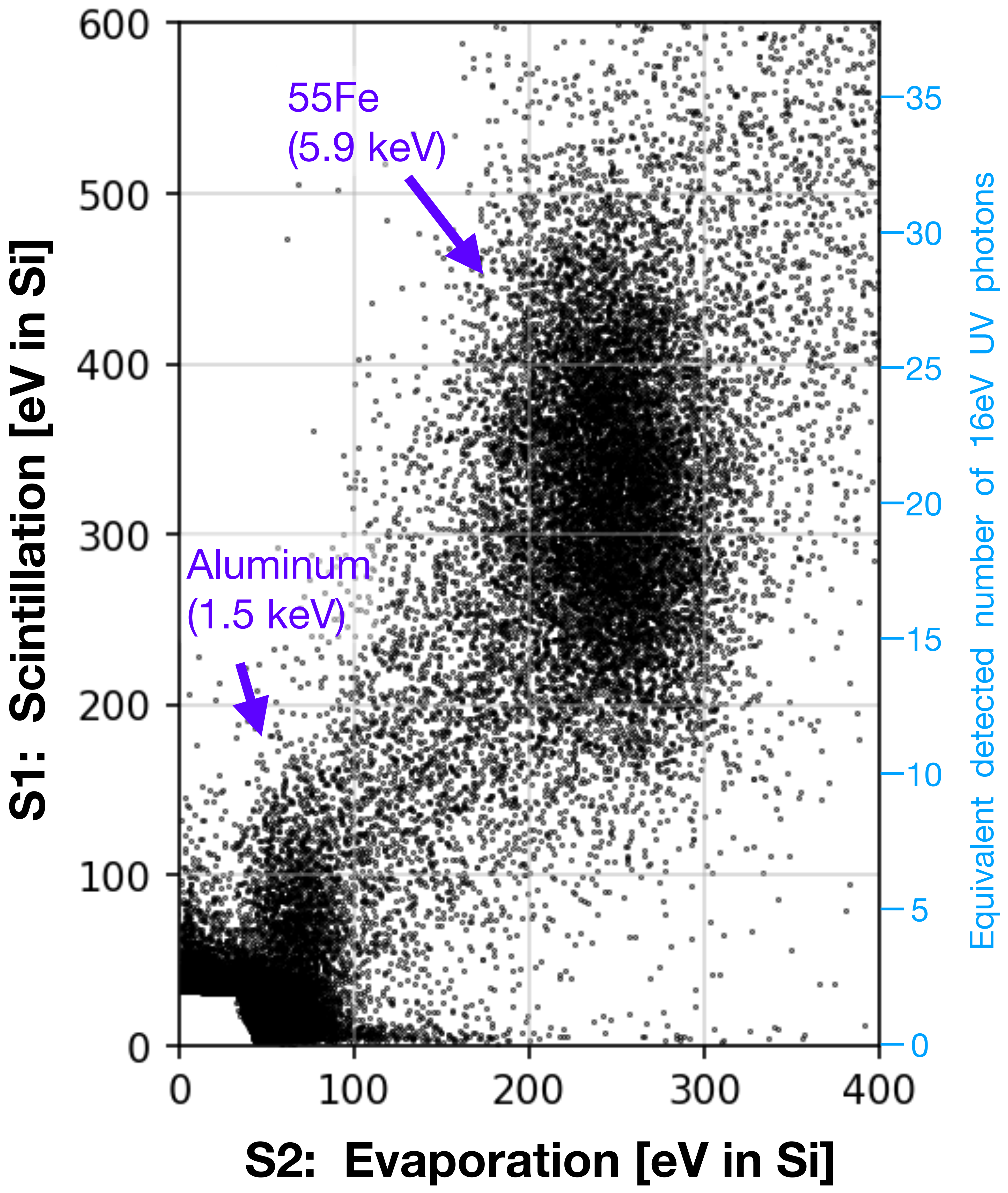
# Initial R&D Data

## Amplitudes of the two signals

*Clear populations for two calibration x-ray peaks*
*5.9keV (Fe55)*
*1.5keV (Al fluorescence)*

***Scintillation:***
*matches expectation from [light yield + solid angle]*
*smeared due to Poisson fluctuation (small photon number)*

***Evaporation:***
*matches rough expectation… but lots to study!*



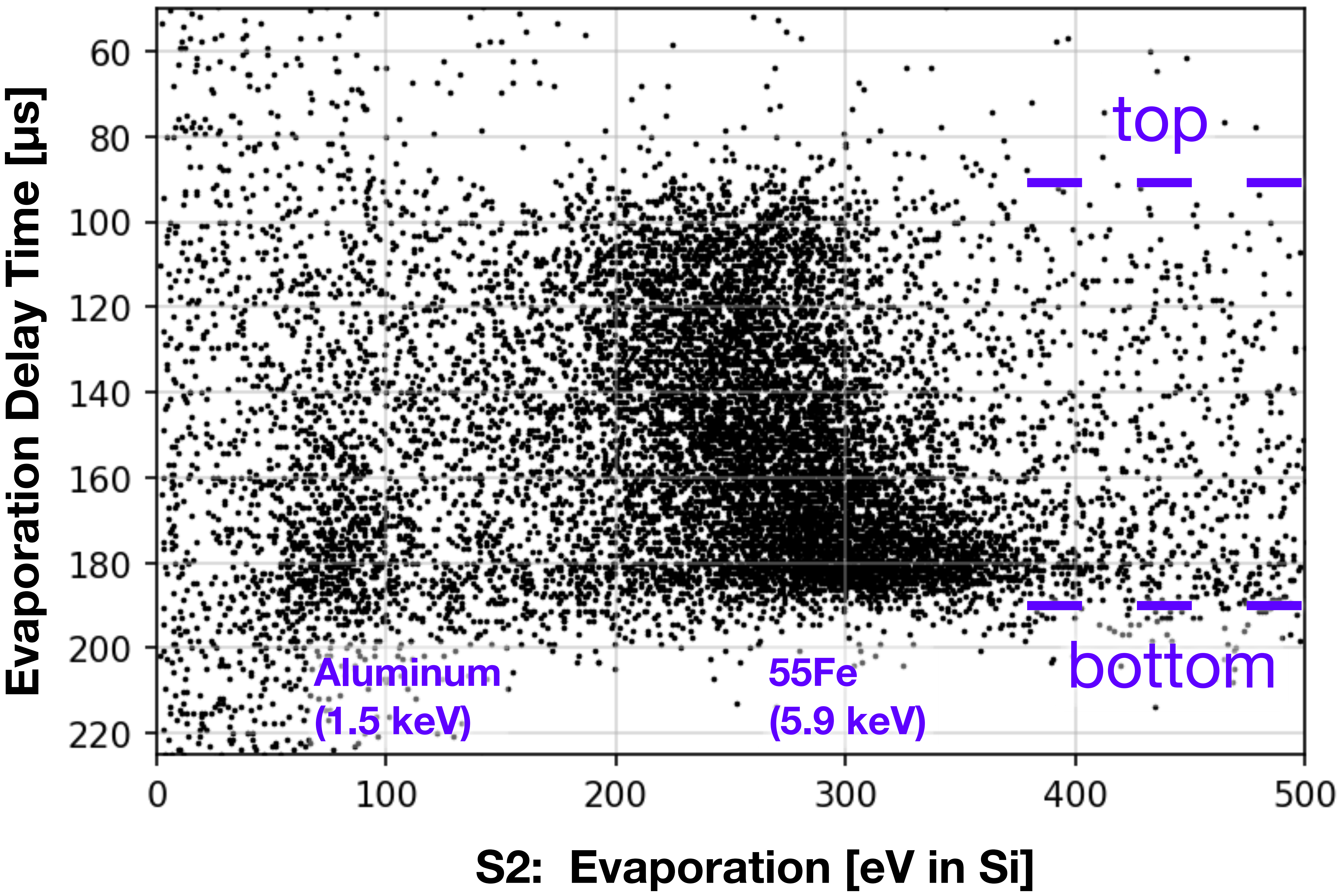
# Initial R&D Data

## Position from phonon propagation time

*The phonon delay time (after scintillation) corresponds to event distance from the liquid surface.*

***As expected:*** *$^{55}$Fe (5.9keV) is ~uniform*
*Al (1.5keV) only near bottom*

***Surprise:*** *Evaporation signal boosted near cell bottom.*
*→Consistent with 30% probability of diffuse reflection.*
*(Events near bottom: larger solid angle for reflection)*



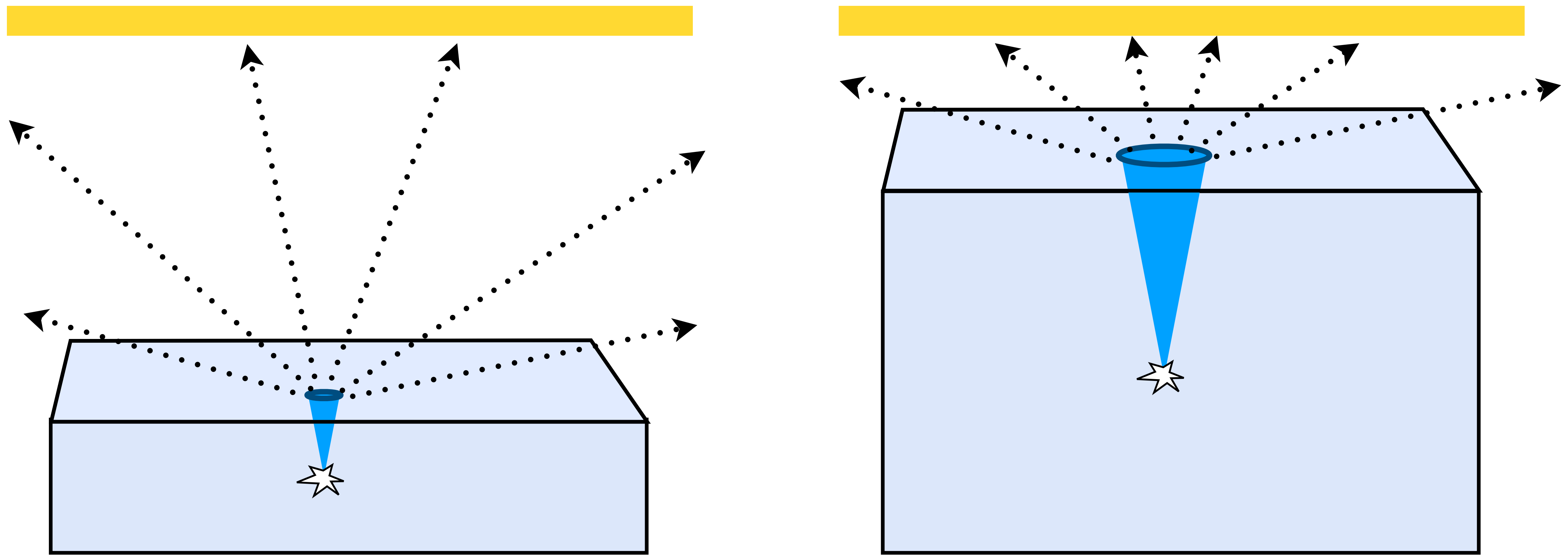
# Initial R&D Data

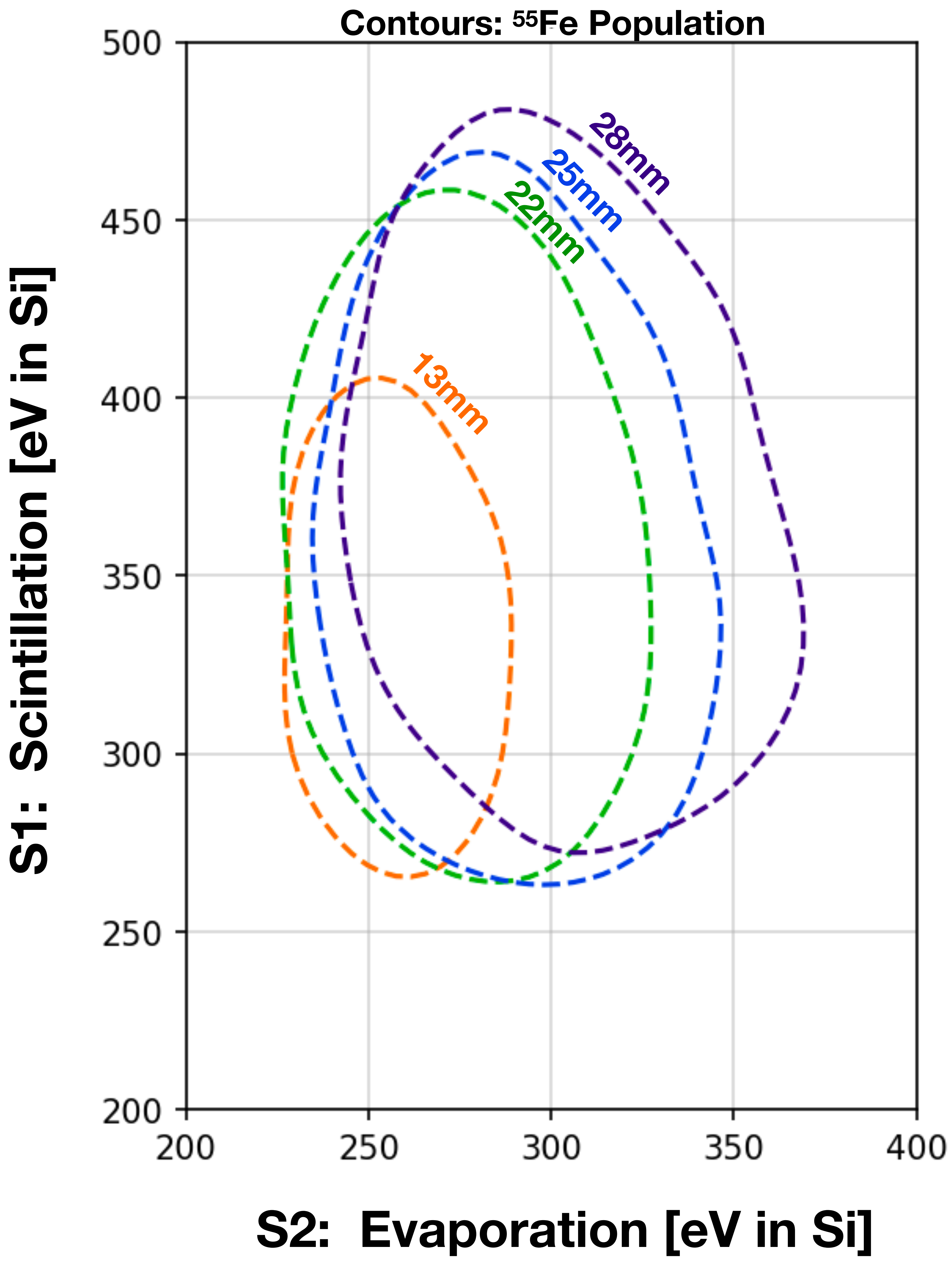
## Varying 4He Fill Level

Easy to change the target geometry, just condense a bit more $^4$He.

The higher the level, the larger the detector solid angle.

(Particularly for evaporation, due to critical angle at surface.)





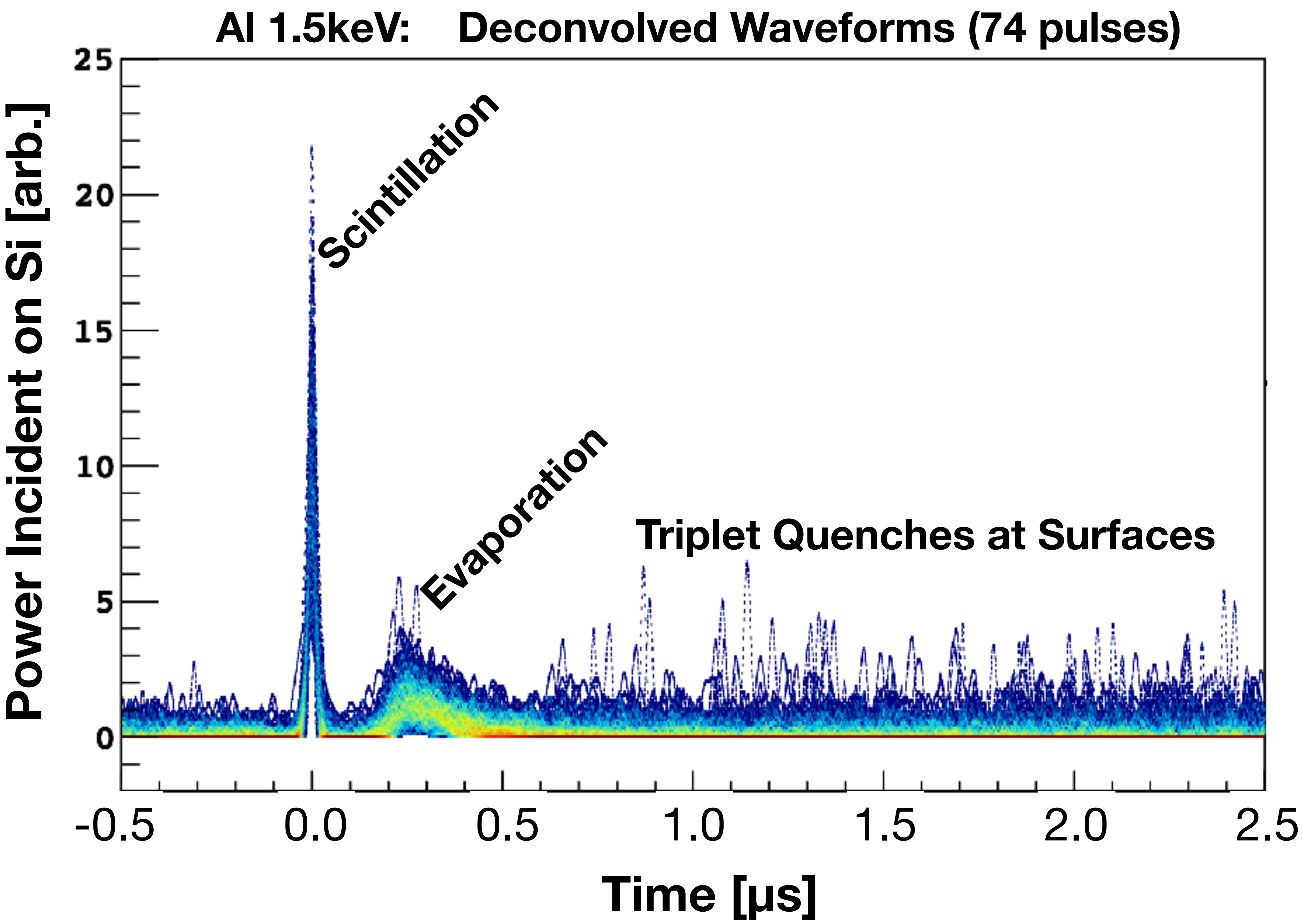
# Initial R&D Data

## Understanding Pulse shape via Deconvolution

To better understand 4He physics timescales,
we remove sensor timescales (Si phonon physics, TES physics, etc.).

Observations:

- Scintillation consistent with delta-function, as expected
- Evaporation signal is spread over ~300 μs
- Small delta-functions at late times (*triplet quenches*)



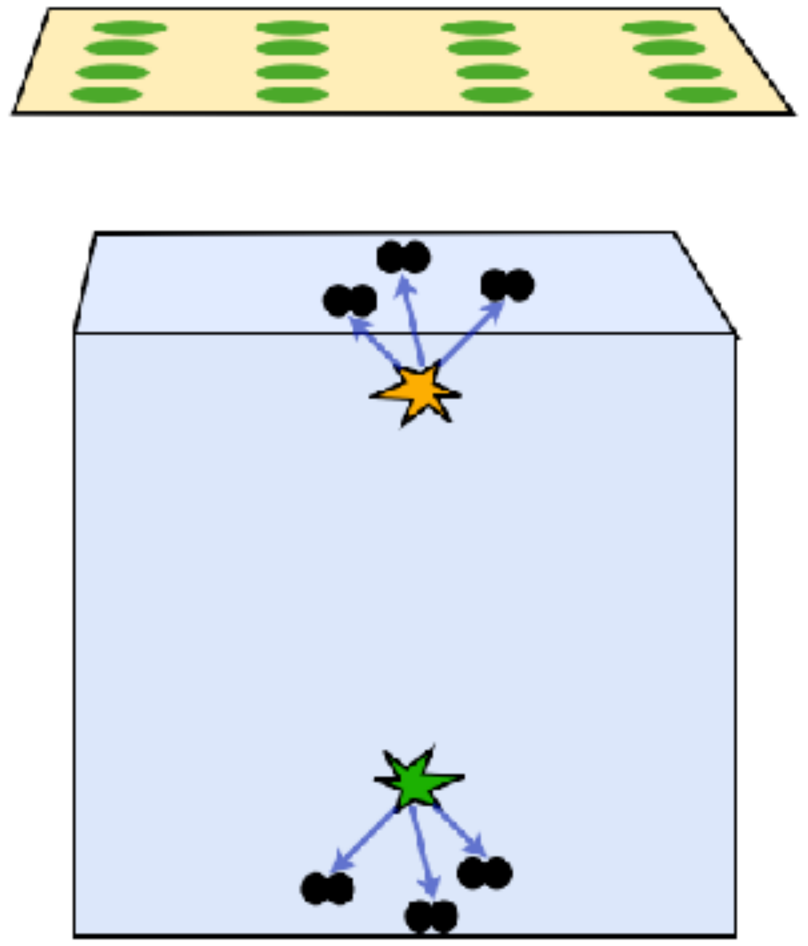
# Initial R&D Data

## Triplet Quenching Timescales

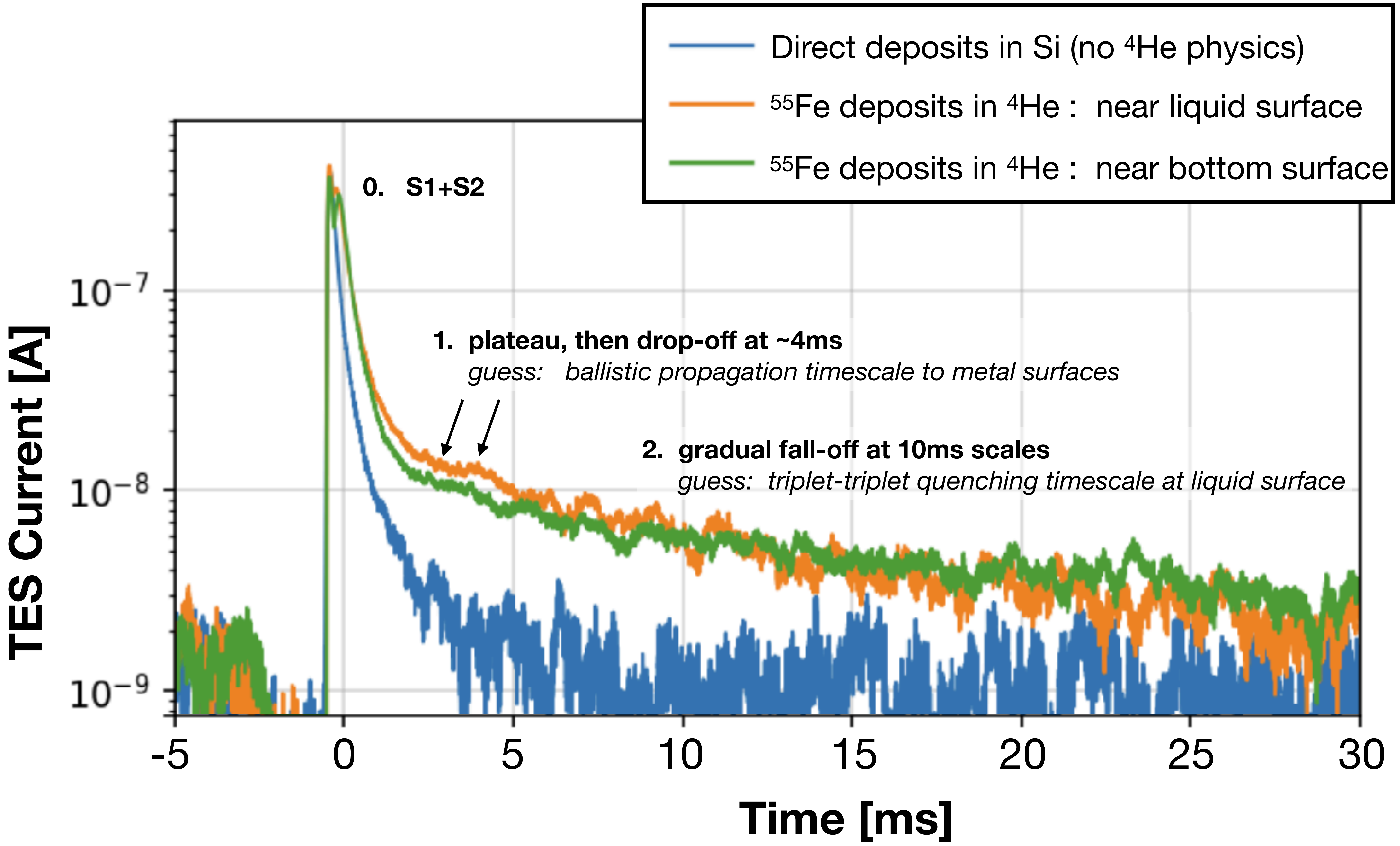
Triplet dimers represent a potential source of dark counts
(few-eV energies stored for significant timescales)

Quenching timescales therefor quite important to DM search viability

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



**Average $^{55}$Fe Waveforms: Triplet Quenching Timescales**

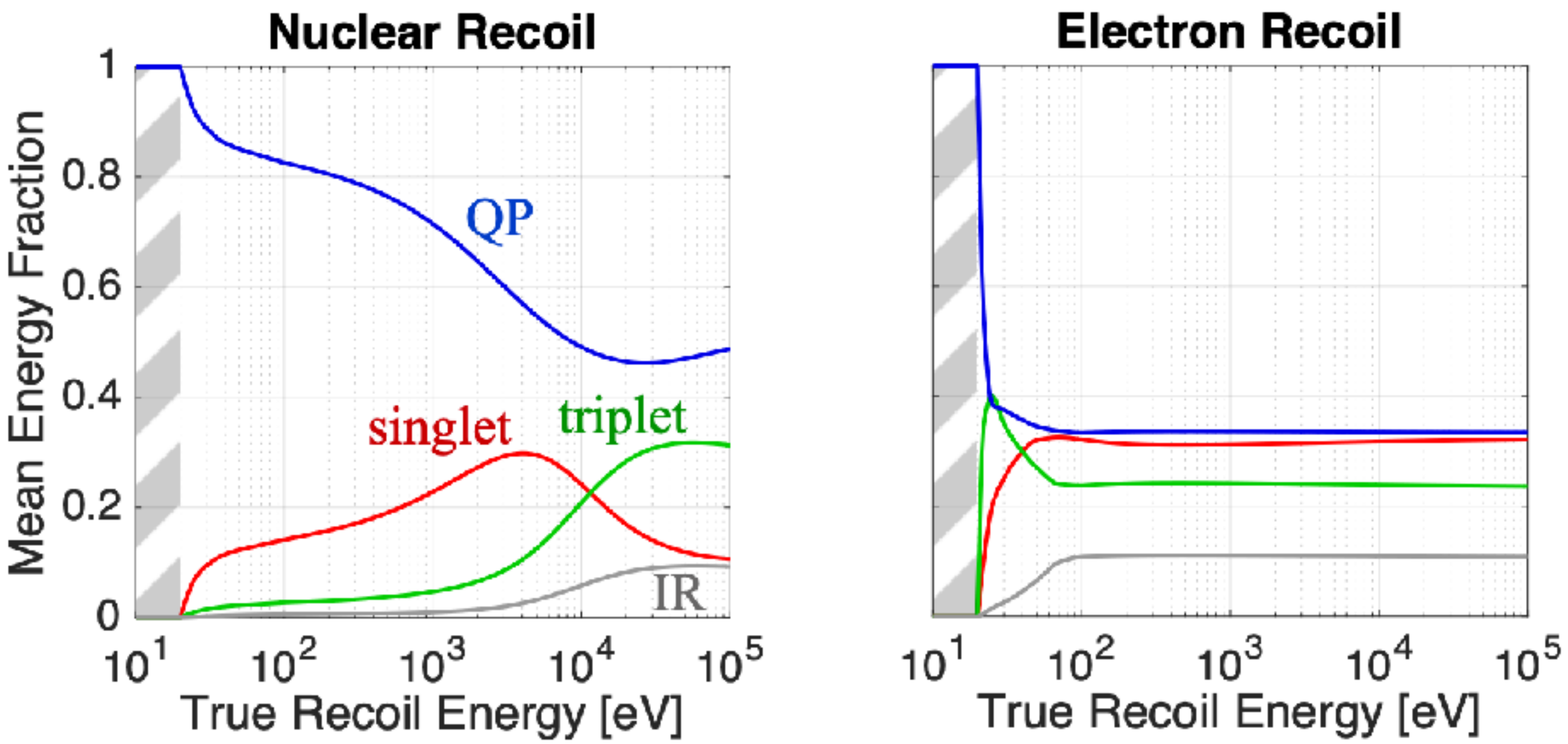


# Initial R&D Data

## 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)

21

# Initial R&D Data

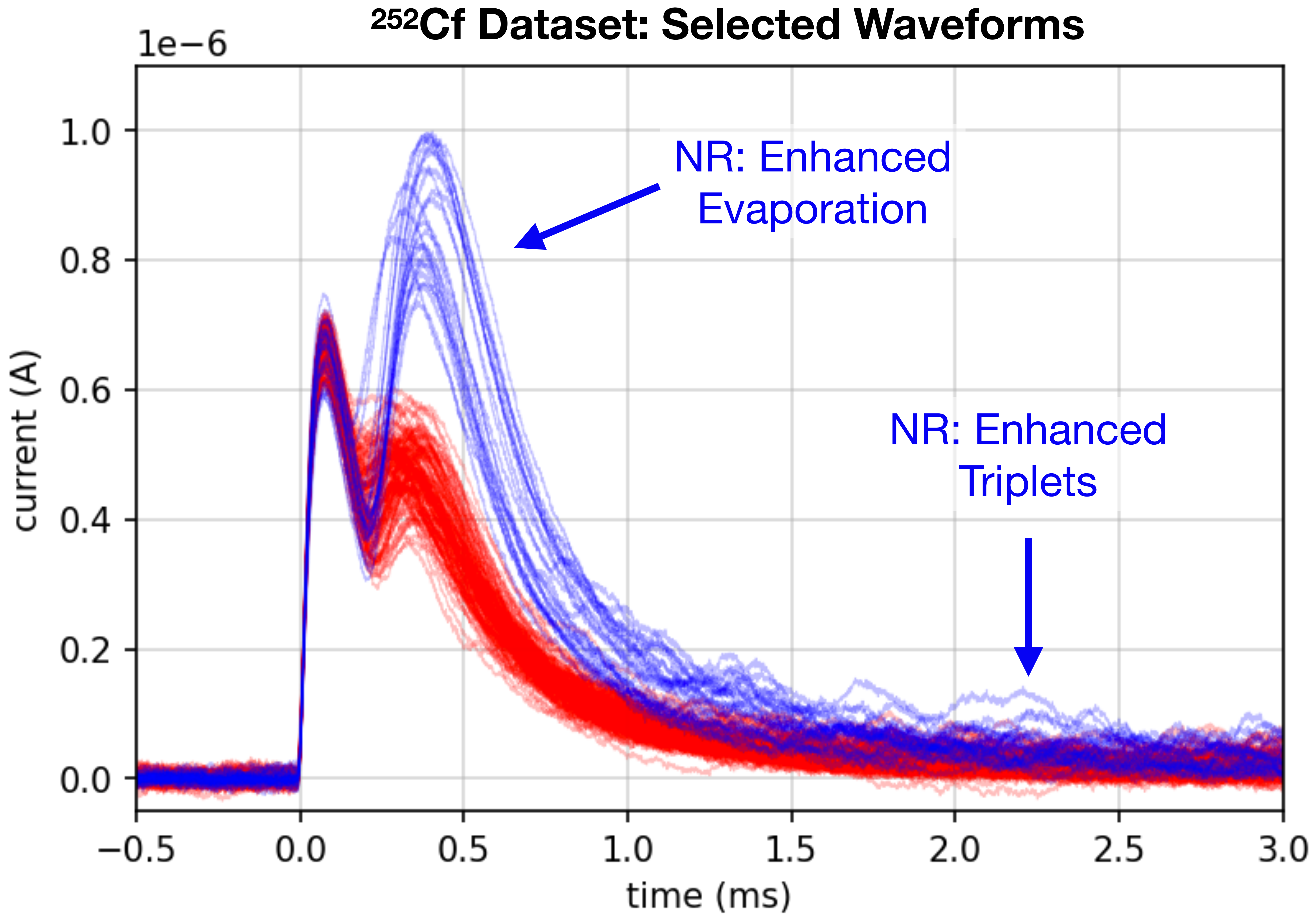
## Comparing ER and NR response

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

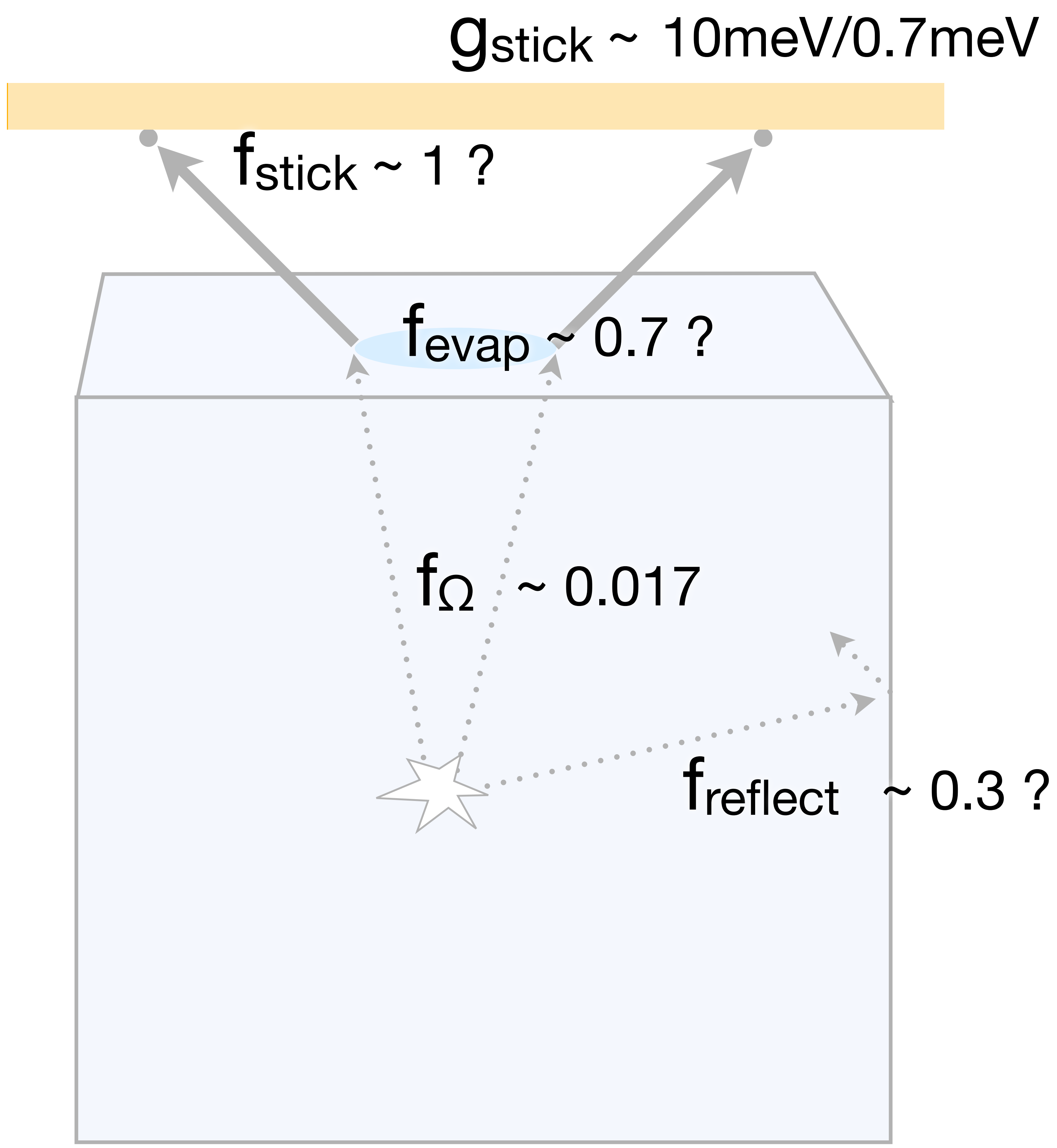
But we can still look at ER/NR differences above 20eV

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

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



# Recoil Energy Threshold



## Efficiency and Gain in the Evaporation Channel

The data shows an overall ‘gain factor’ in the evaporation channel of ~0.15

(An $^{55}$Fe x-ray produces ~2000 eV of $^{4}$He phonons which appears as ~300 eV in the calorimeter Si)

The gain factor combines several effects each with large uncertainties:

- Solid angle over which evaporation is kinematically allowed: **$f_{\Omega}$ ~ 0.017** ?
- Fraction of those allowed phonons which do trigger evaporation: **$f_{evap}$ ~ 0.7** ?
- Fraction of those evaporated atoms which stick to sensor: **$f_{stick}$ ~ 1** ?
- Adsorption energy per adsorbed atom: **$g_{stick}$** [ **~10 meV** ? ]/[0.7 meV phonon]

Total : $f_{\Omega}$ $f_{evap}$ $f_{stick}$ $g_{stick}$ ~ 0.15

These reasonable guesses match our observed gain value.

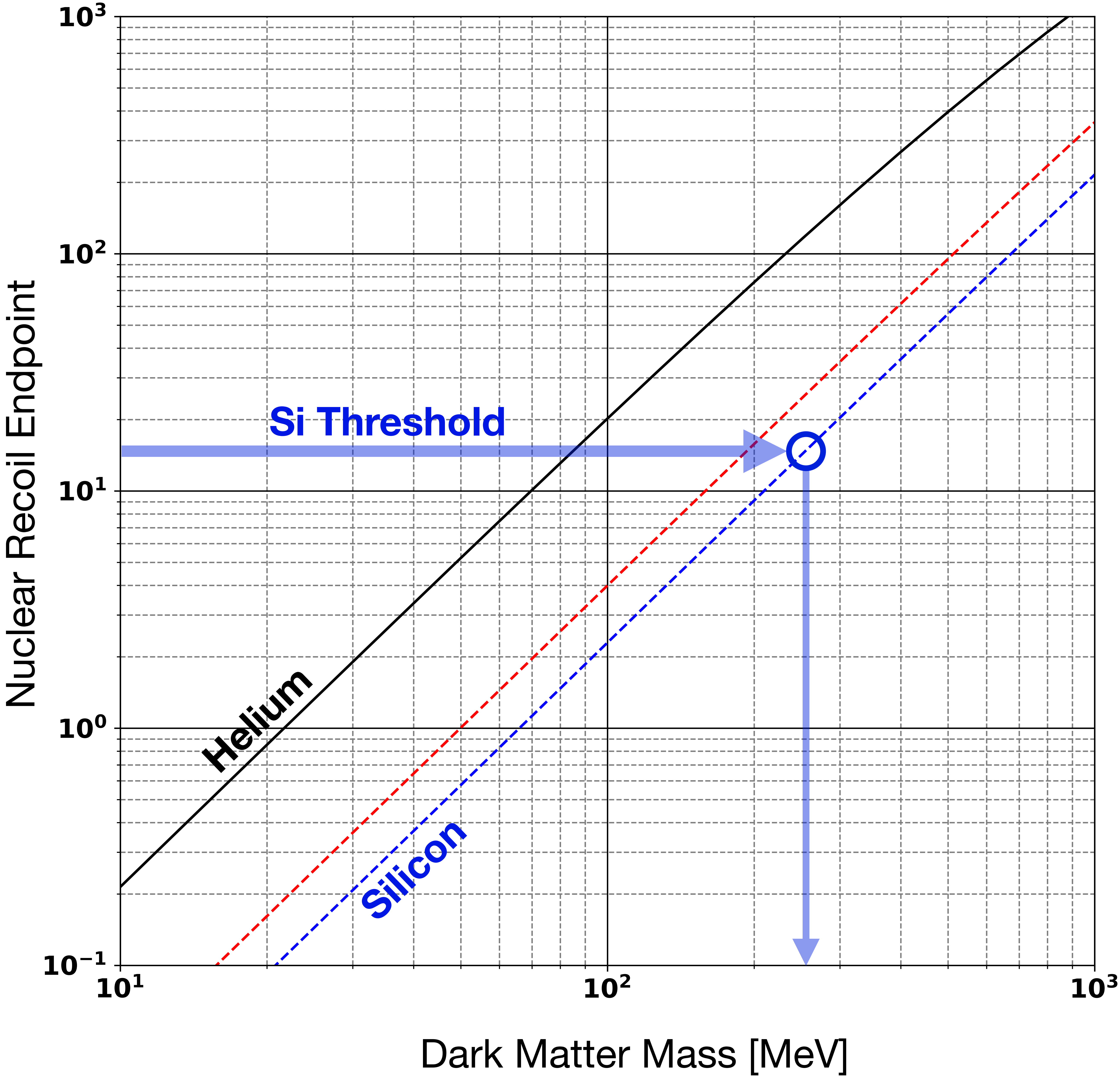
Separately: Reflected phonons contribute some portion of the signal.

# Recoil Energy Threshold

**Energy threshold → *Mass* threshold**

For this particular run with this particular calorimeter:

| | | |
|---|---|---|
| Si threshold (5σ): | ~16eV | (in Si) |
| DM mass threshold in Si: | ~250 MeV | |



# Recoil Energy Threshold

## **Energy threshold → *Mass* threshold**

For this particular run with this particular calorimeter:

Si threshold (5σ): ~16eV (in Si)

DM mass threshold in Si: ~250 MeV

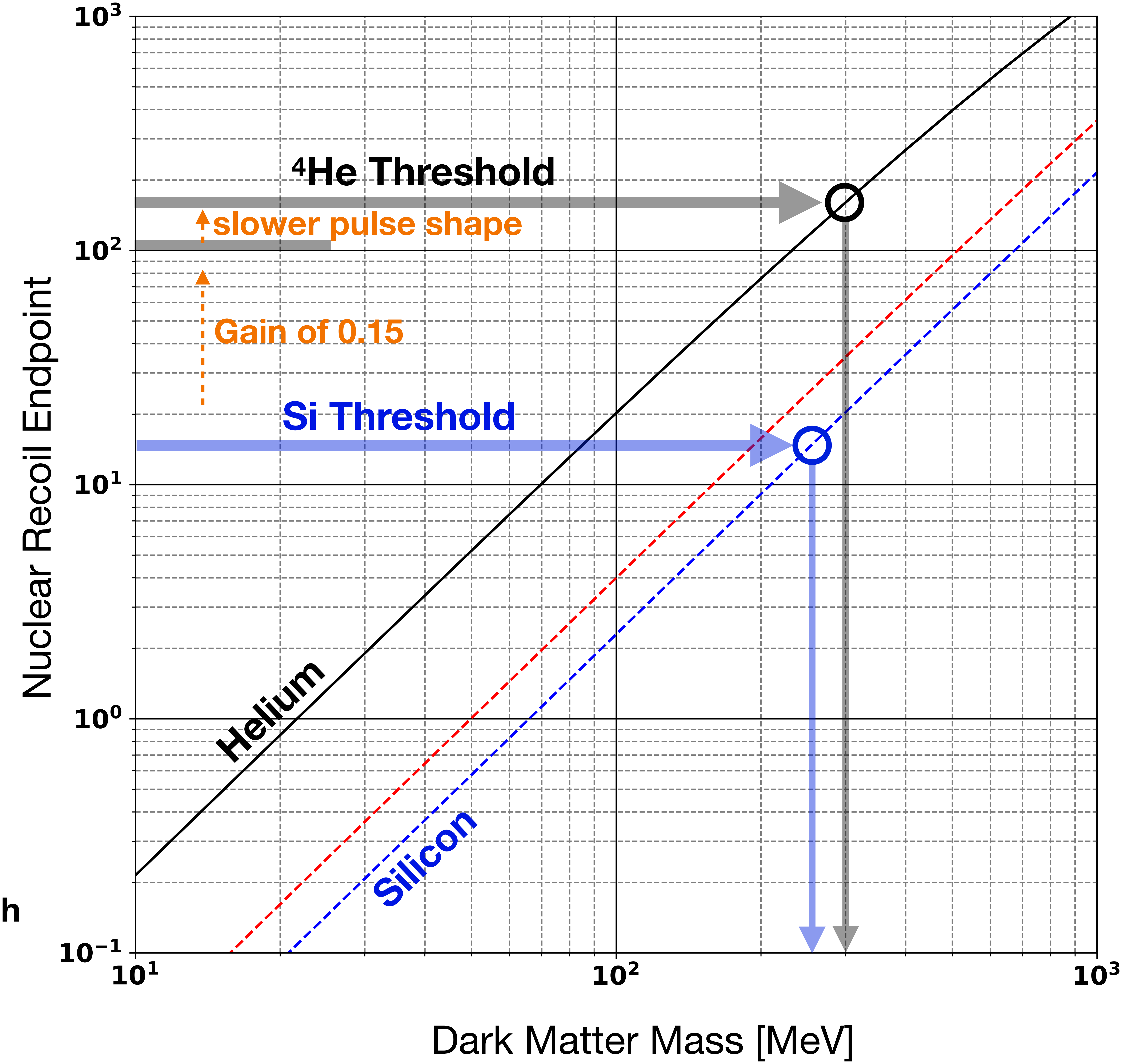
$^4$He recoil threshold (5σ) : ~25eV / 0.15 = ~170eV
( in Si ) ( in $^4$He )

DM mass threshold in $^4$He: ~300 MeV

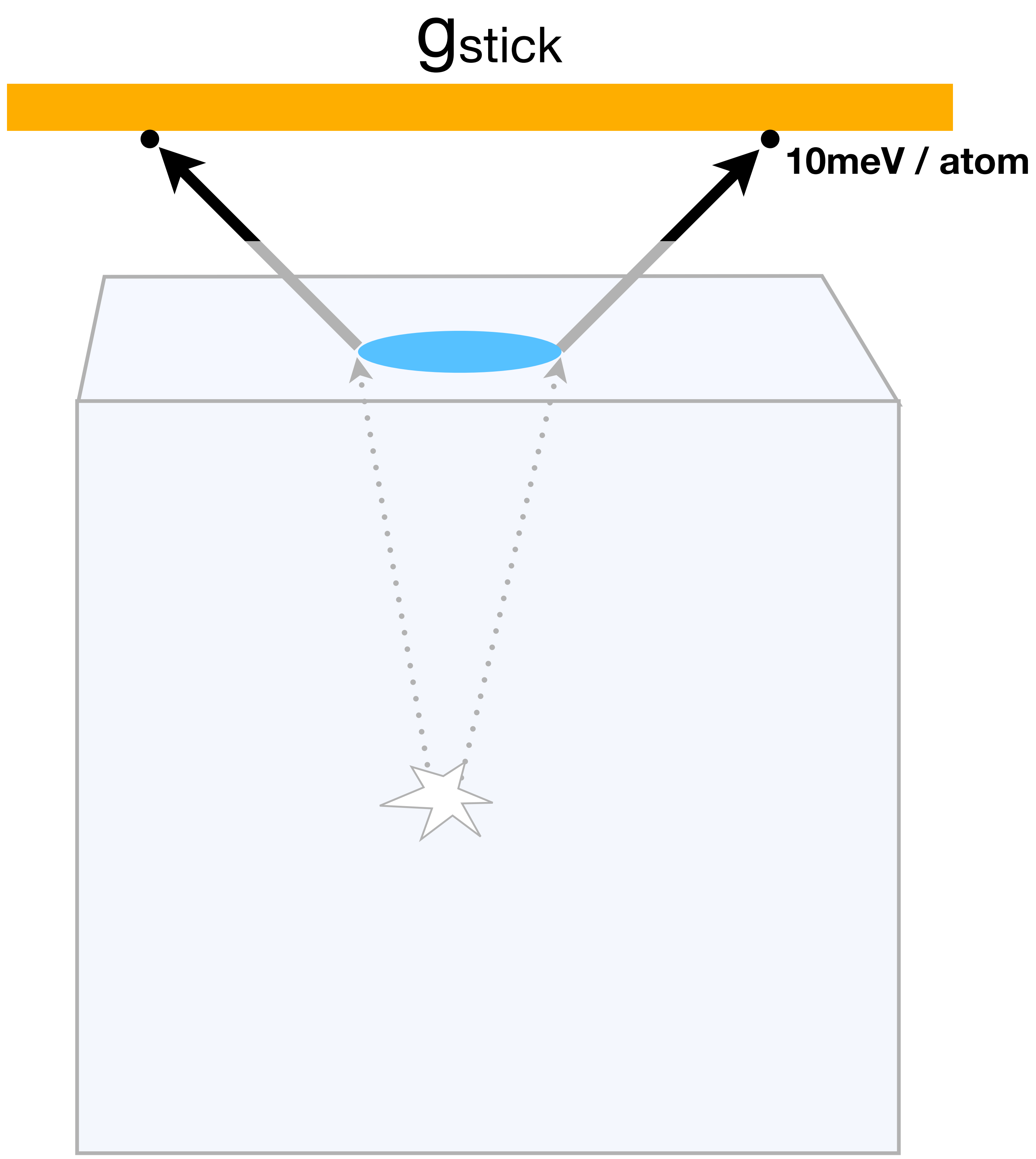
Punchline:

**Gain of 0.15 → nearly "break even" in $^4$He/Si DM mass reach**

(if we can push to gain>0.15, then He reaches DM masses Si can't reach)



# Recoil Energy Threshold

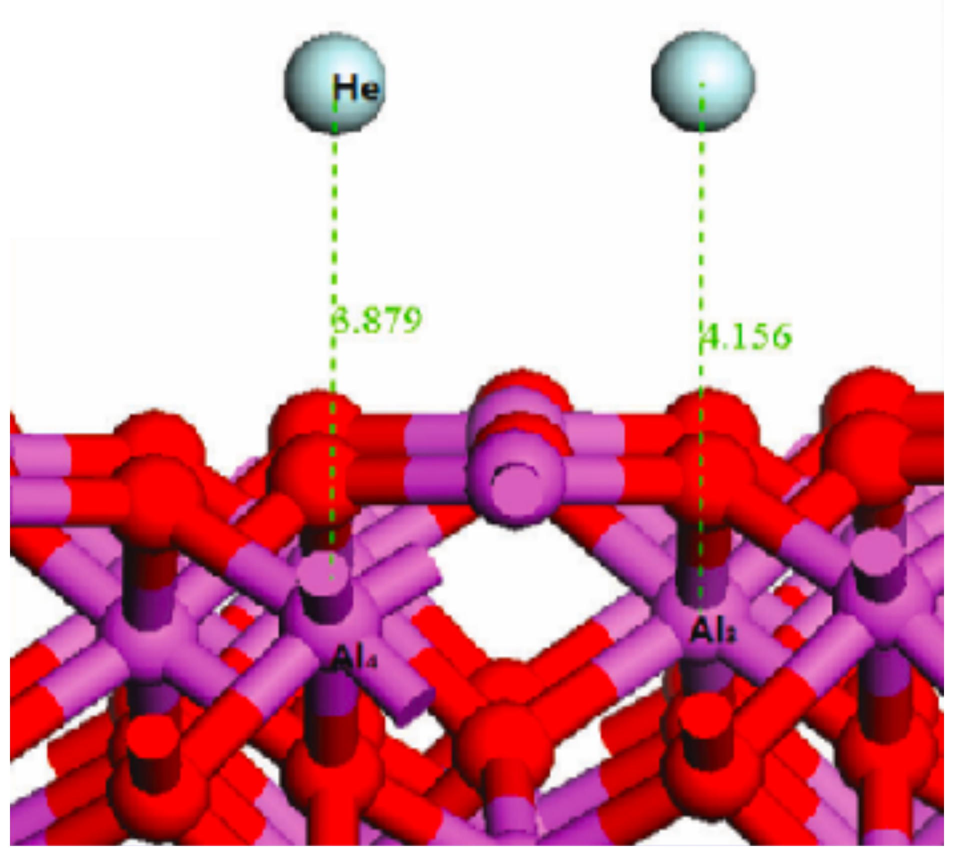


## Pathways to higher gain factors

1. **$g_{stick}$**
   - 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)

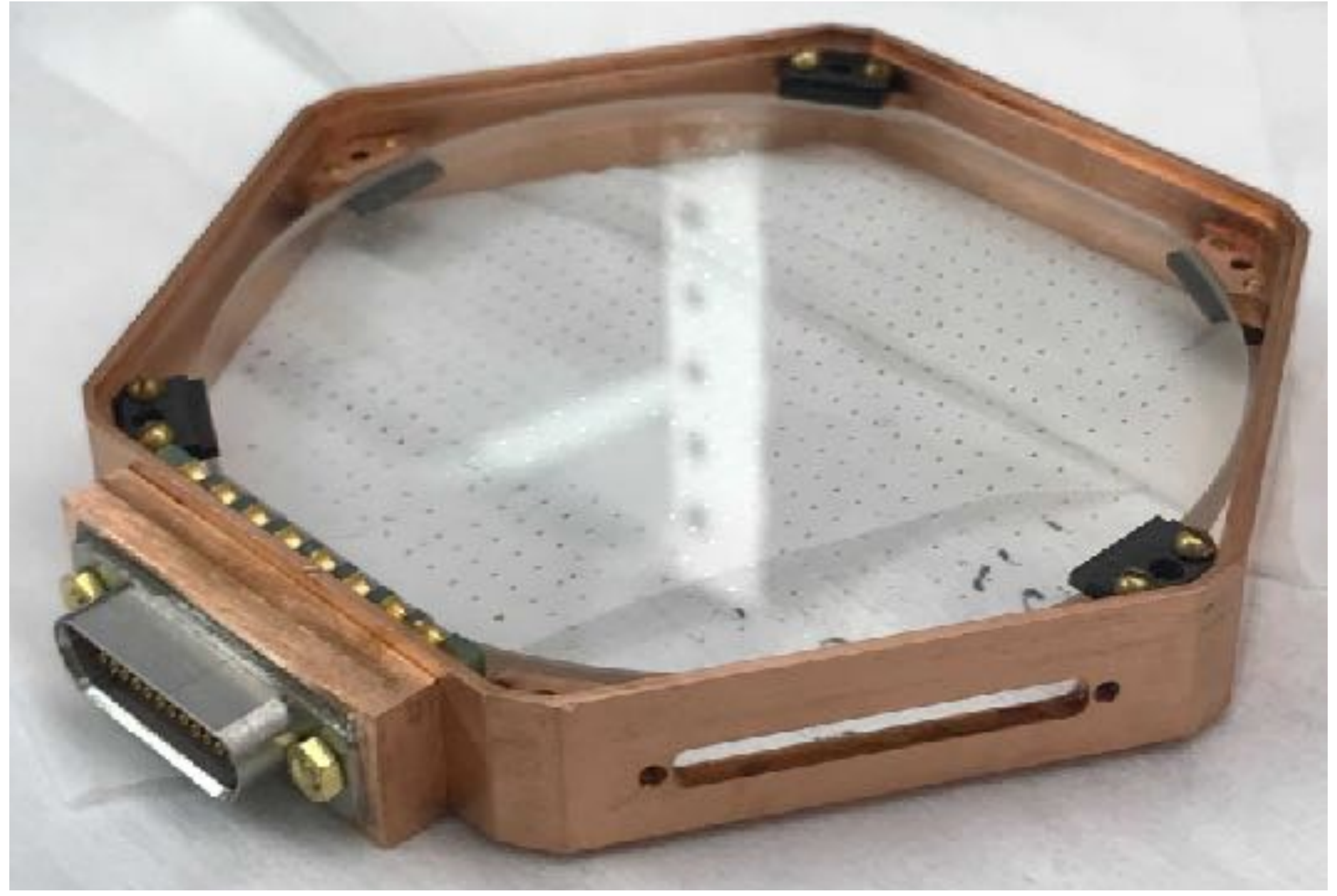
***Theory estimates of of $^4$He adsorption energy***



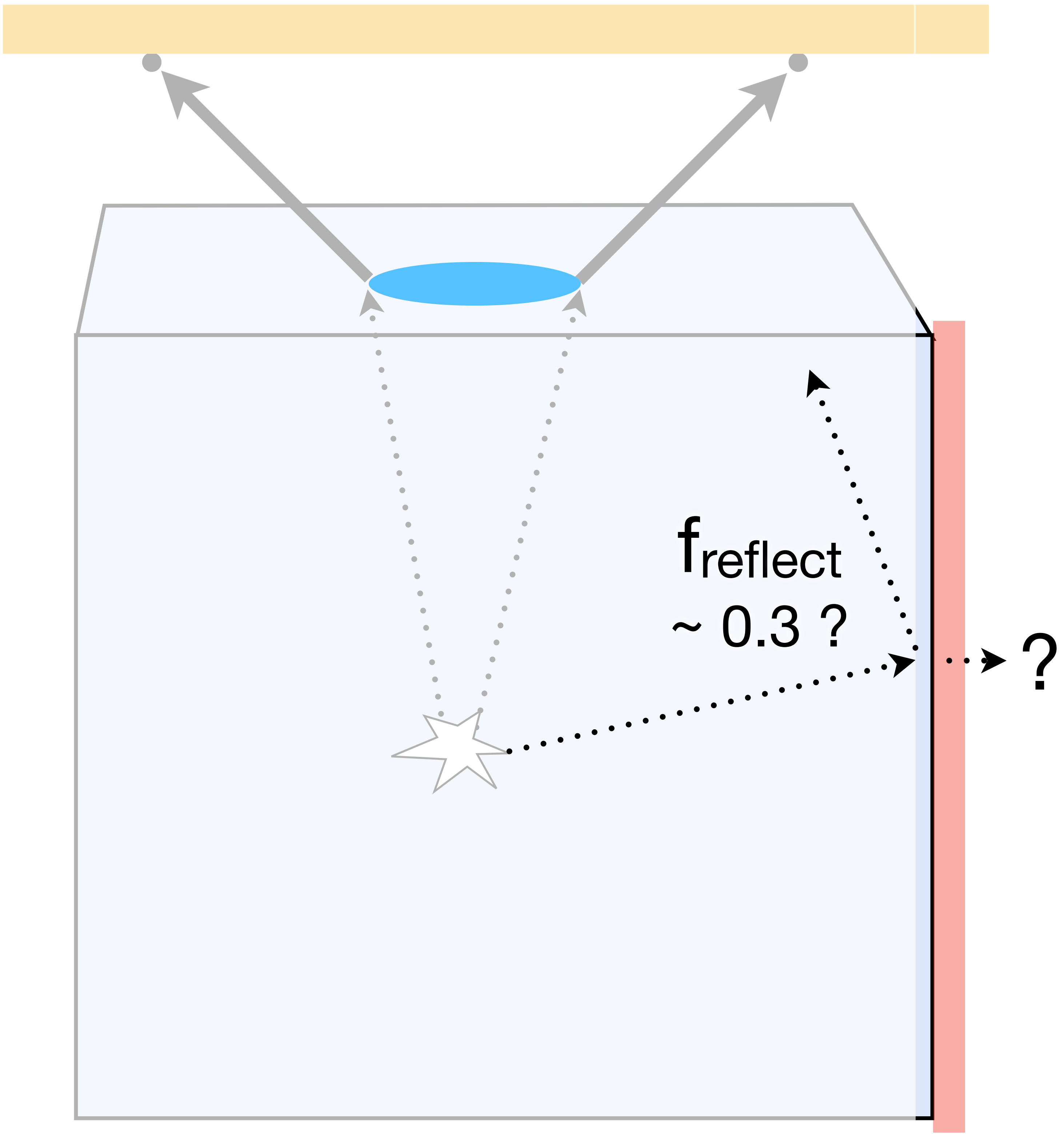
**First principles investigation of helium physisorption on an α-$Al_2O_3$(0001) surface**

Guikai Zhang,* Xin Xiang, Feilong Yang, Lang Liu, Tao Tang, Yan Shi and Xiaolin Wang

***Existing demonstration of SPICE/HeRALD fab on $Al_2O_3$***



# Recoil Energy Threshold



## Pathways to higher gain factors

1. **$g_{stick}$**

- 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)

2. **$f_{reflect}$**

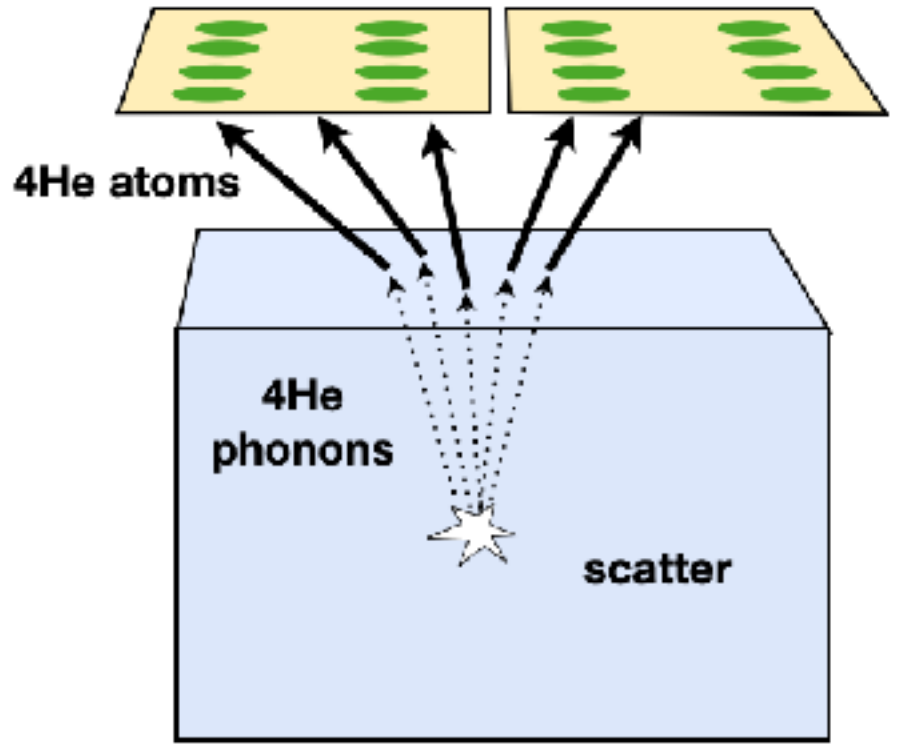
- So far consistent with very roughly $f_{reflect} = 0.3$, and fully diffuse
- What happens to the other 70%? Transmission into the metal? Downconversion?

→ Medium-term plan to test varied surface coatings at $^4$He-metal interfaces
Potential high reward in gain (evaporation signal increases exponentially )

# Heat-only background?

The primary background in all phonon efforts at eV energies: ***Spontaneous phonon emission by materials***

$^4$He is unique in two ways:

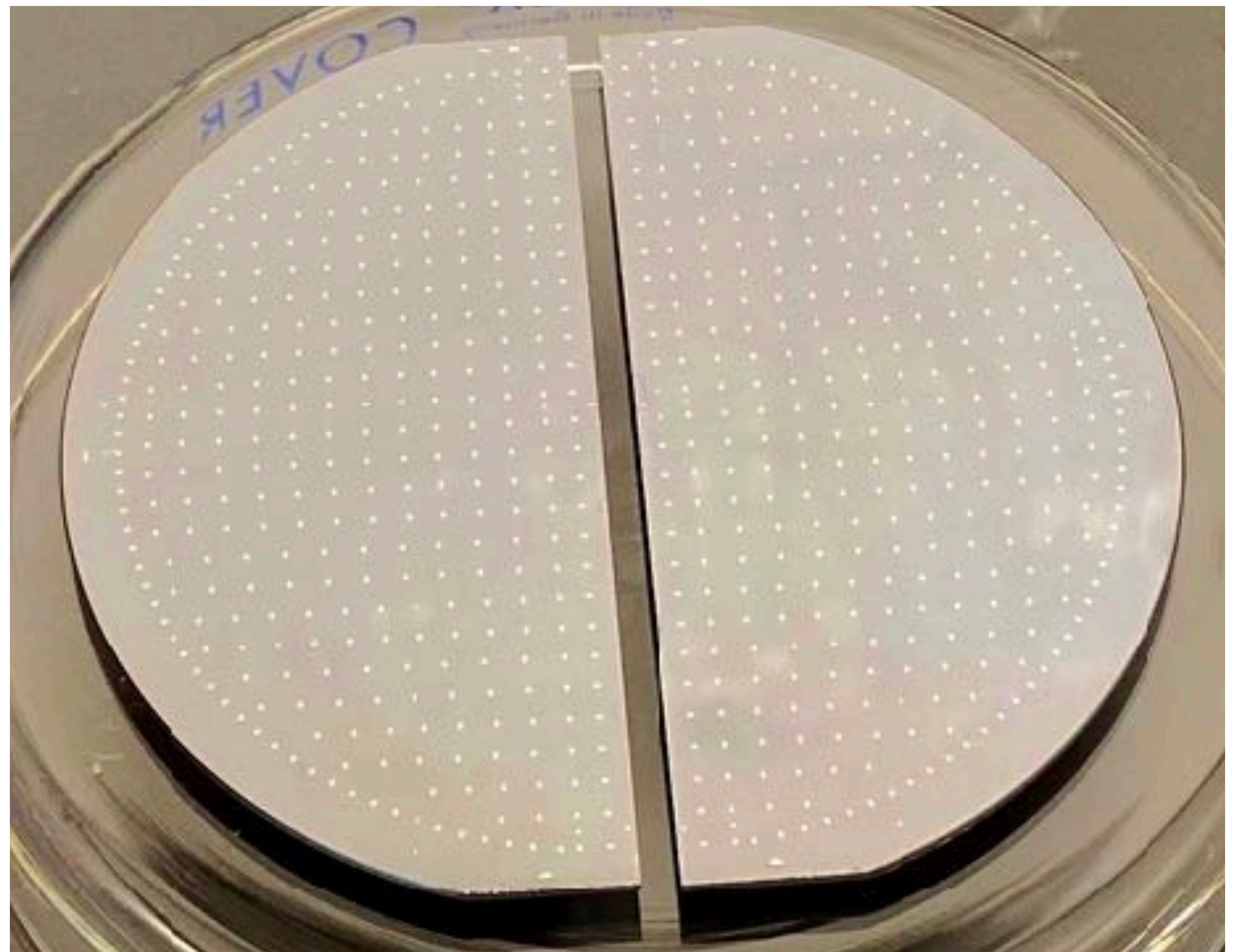


1. **Quantum evaporation allows for robust coincidence requirements**
   Heat-only events in Si or metal films: single-channel (vacuum gaps mean no shared phonons)

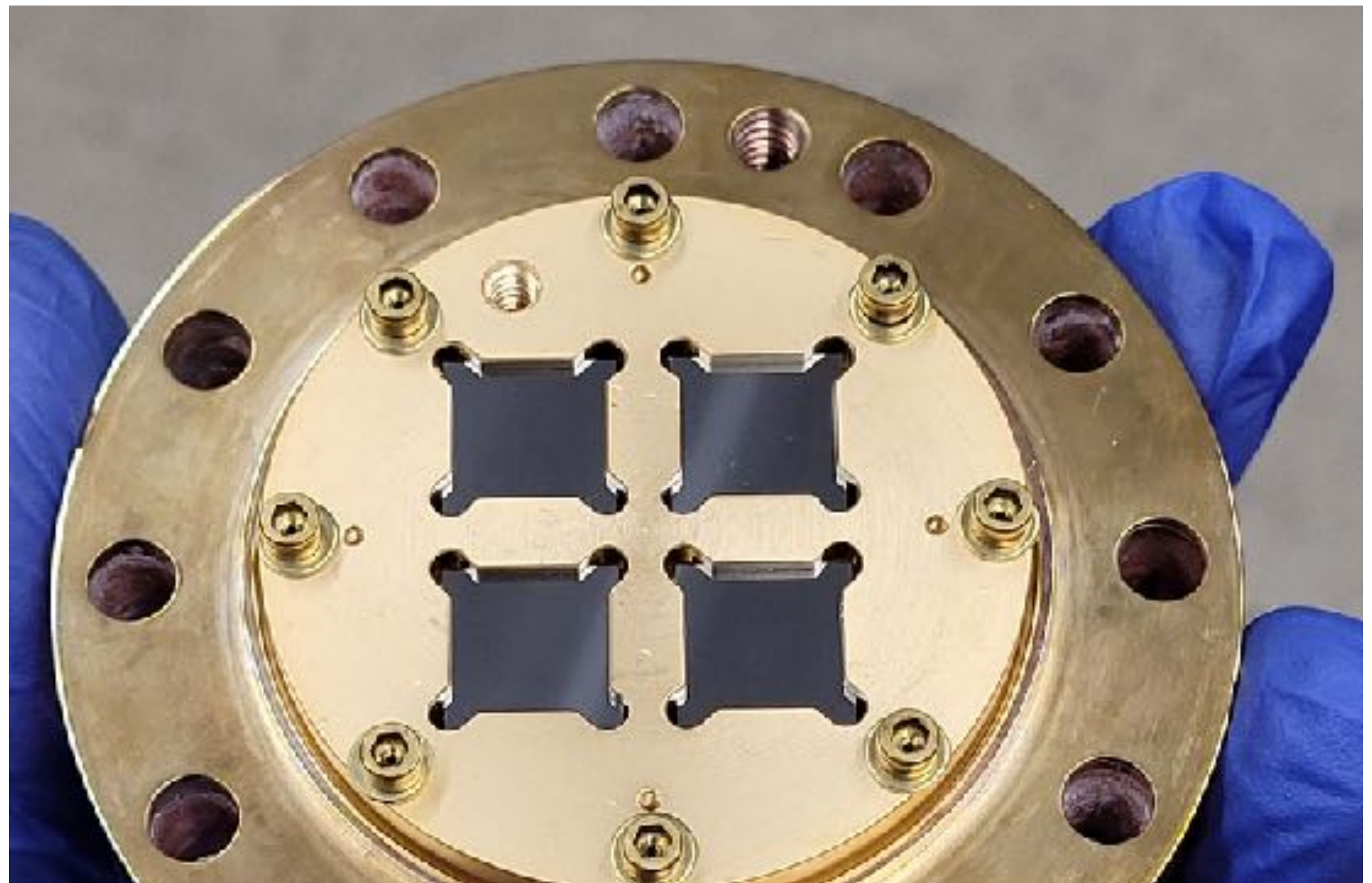
2. **Target material in a macroscopic ground state, with no defects/stress/etc.**
   Superfluid is unique among obtainable bulk materials in this regard

→ Near-term plans all involve multi-channel evaporation readout

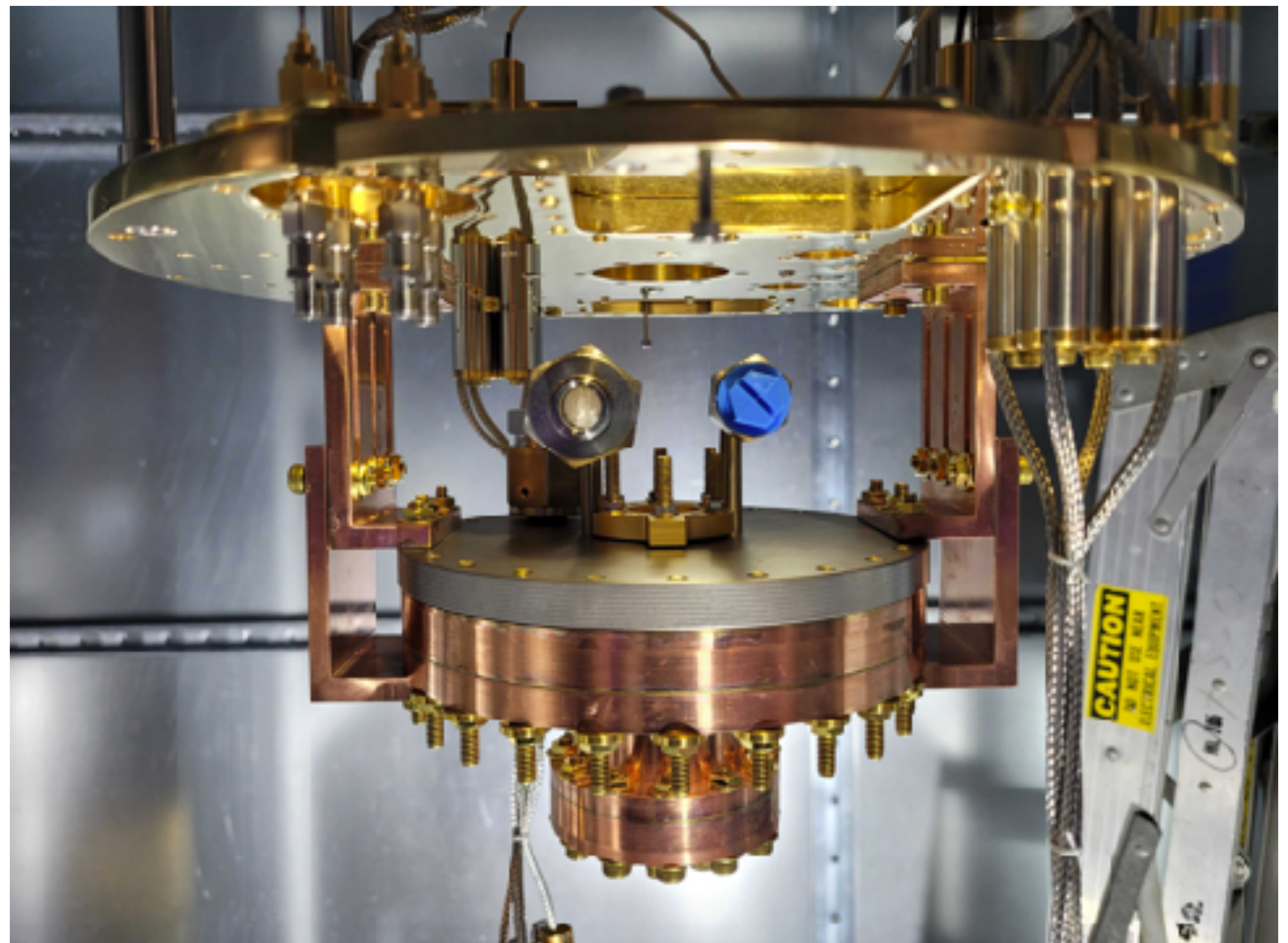
**2-Channel Array for HeRALD v0.1 (3-inch)**



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



**HeRALD v0.2, installation underway LBNL**



# Summary

**Succesful Demonstrations:**

- Heat-free stopping of $^4$He films
- Scintillation+evaporation readout at few-photon limit.
- Order 10ms timescales for triplet quenching
- Initial phonon channel gain of ~0.15 (Similar DM mass threshold in $^4$He and calorimeter)

**Exciting next steps:**

- Lowering threshold via separate paths (effects multiply)
    1. Calorimeter threshold eV → meV
    2. Adsorption energy ~10 → ~30 meV
    3. Phonon reflectivity ~1.2x boost → 2x boost? 10x boost?
- Attacking the low-energy excess via multi-detector coincidence

  Quantum evaporation a uniquely powerful tool in this battle

**Lots of exciting progress on all fronts!**

# Physics of a Superfluid $^4$He Target

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

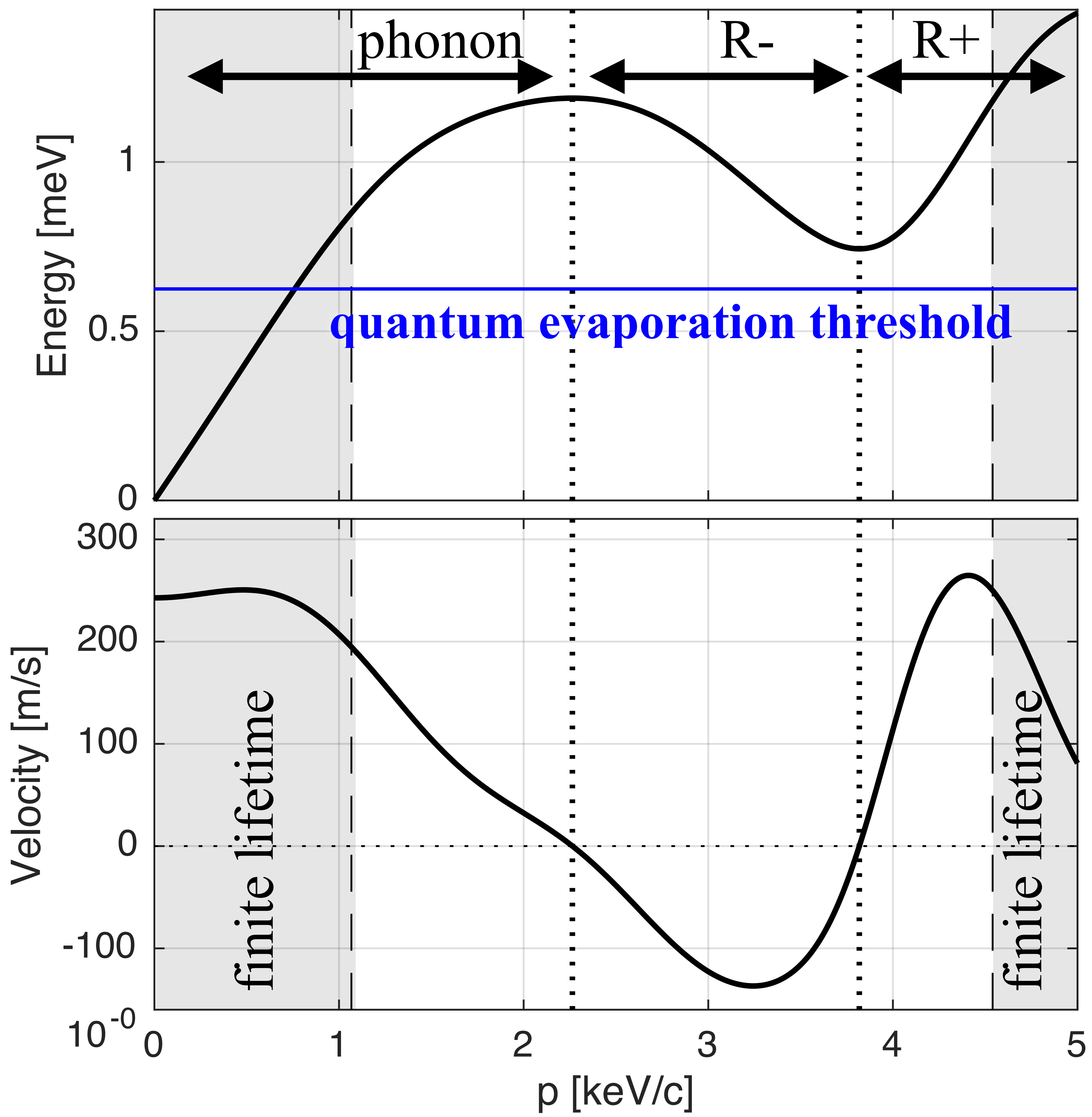
Three flavors: “phonon” , “R- rotons” , “R+ rotons”

- 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’)



arXiv:1810.06283

# 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