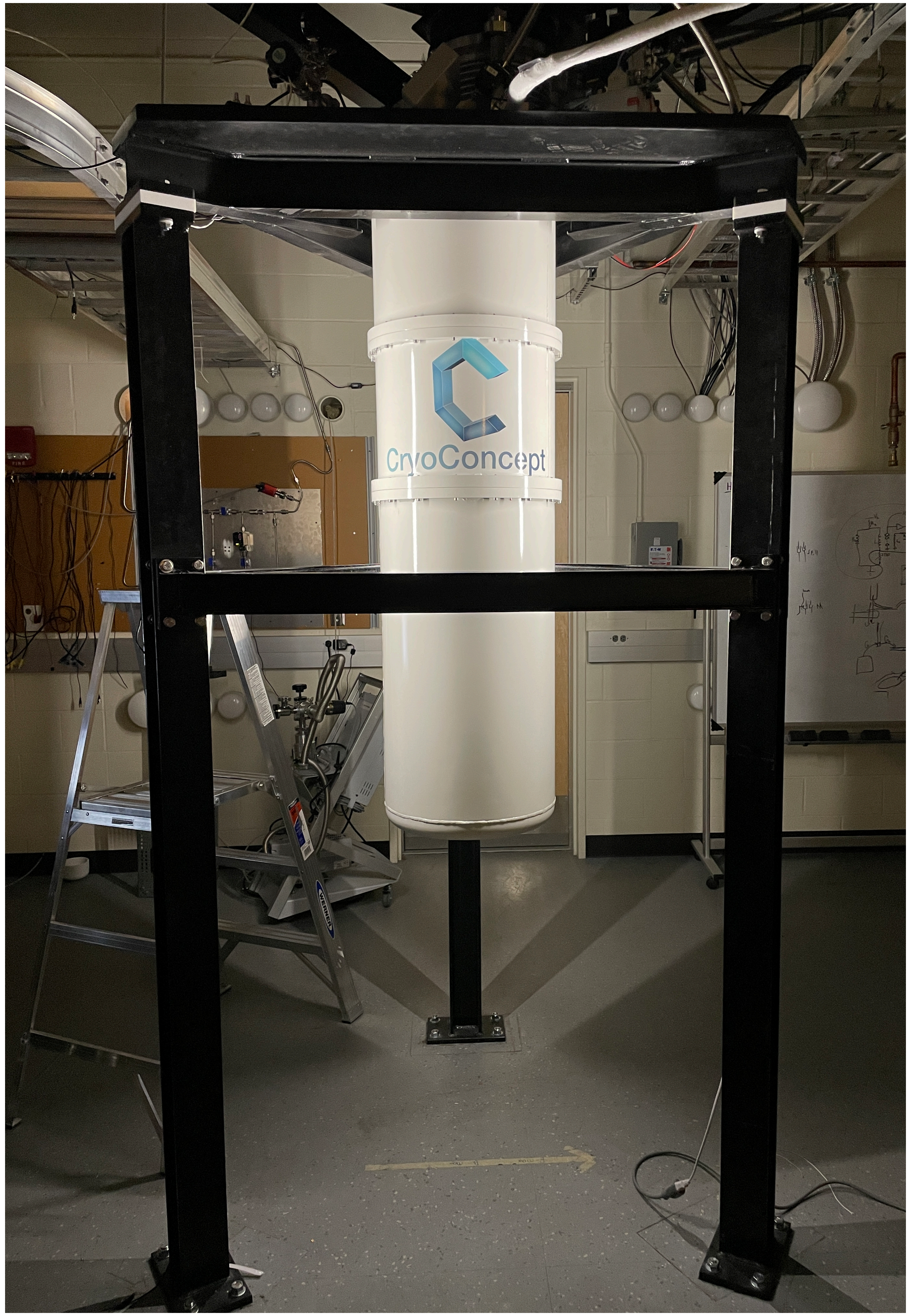


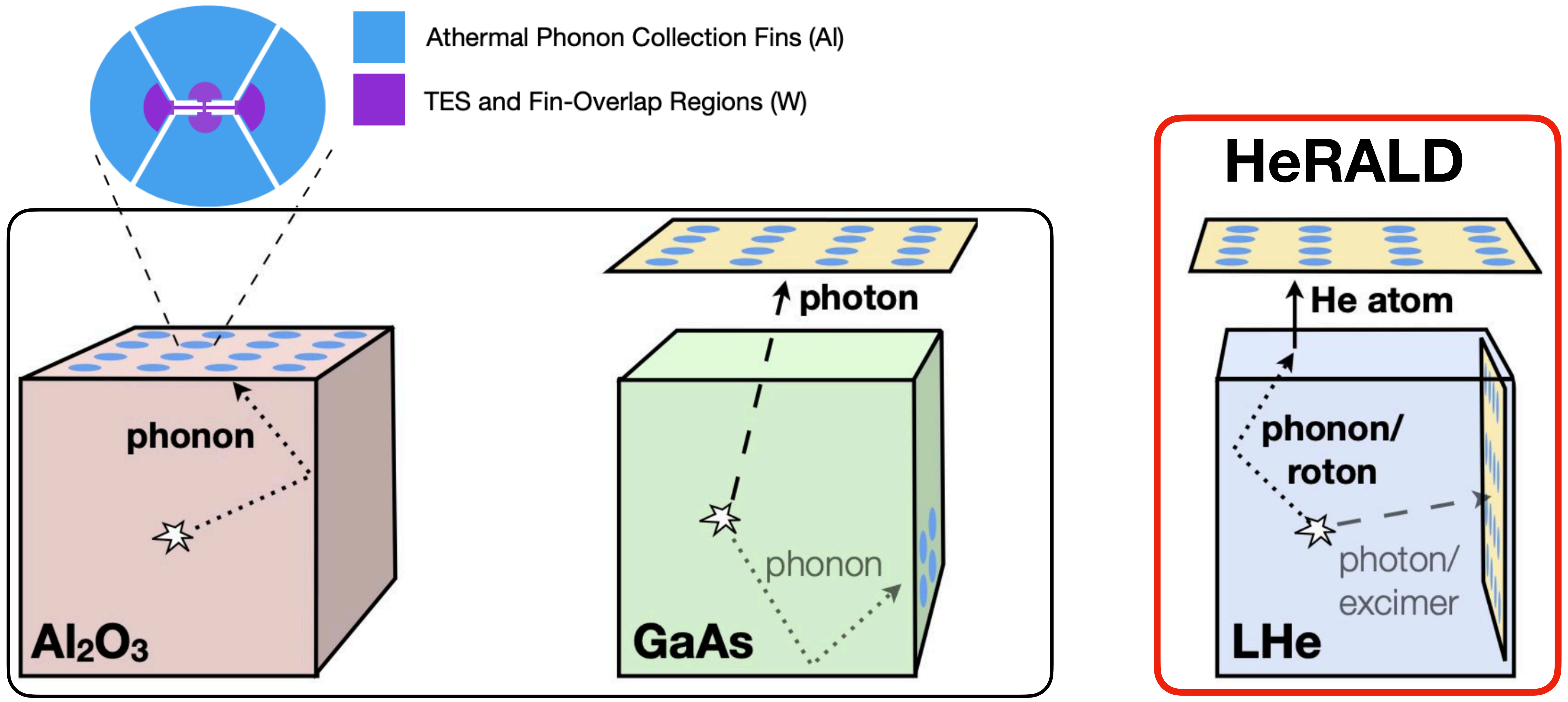
Progress towards HeRALD:

The **He**lium **R**oton **A**pparatus for **L**ight **D**ark **M**atter

Doug Pinckney, 30 November 2022
On Behalf of the SPICE/HeRALD Collaboration

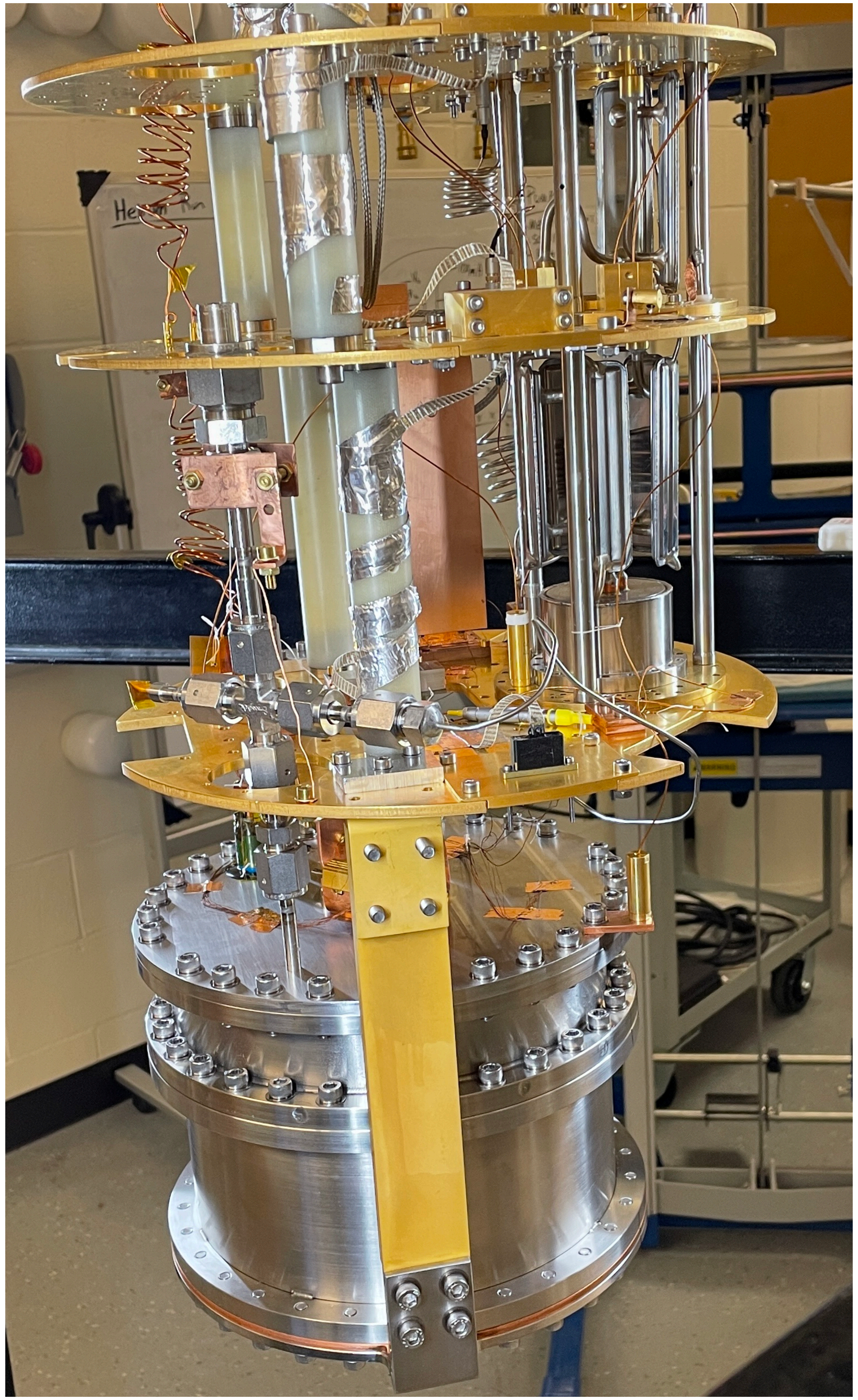
The SPICE/HeRALD Collaboration

- A particle physics experiment searching for "sub-GeV/c²" dark matter interacting with multiple target materials
    - United by shared Transition Edge Sensor (TES) sensor R&D
- Main design driver: lower detector threshold
- Snowmass Whitepaper Link



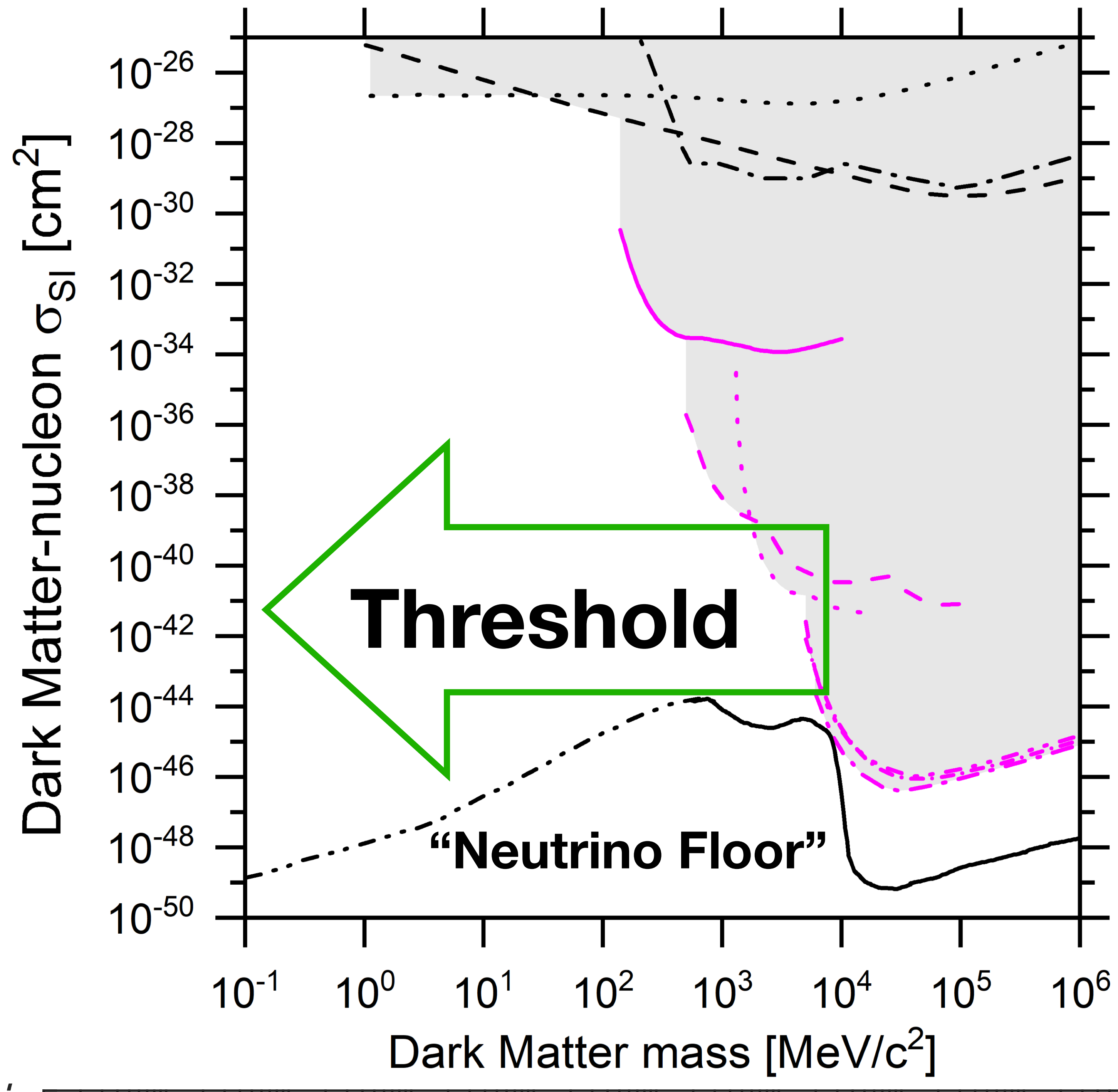
Overview

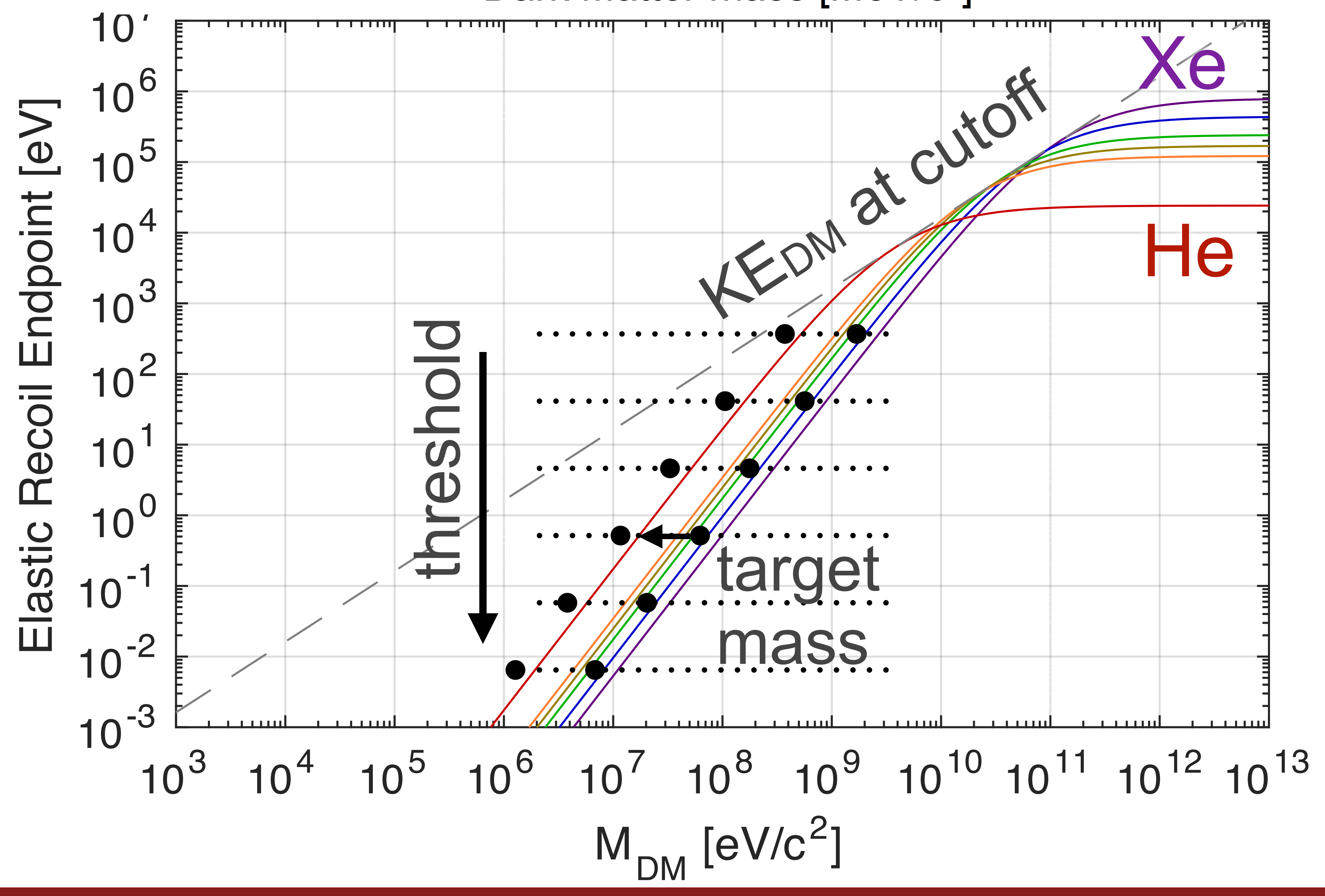
- Physics Motivation
- Detector Principle
- HeRALD V0.1: Design and Film Stopping
- First R&D from V0.1
- Future Plans



Sub-GeV Dark Matter

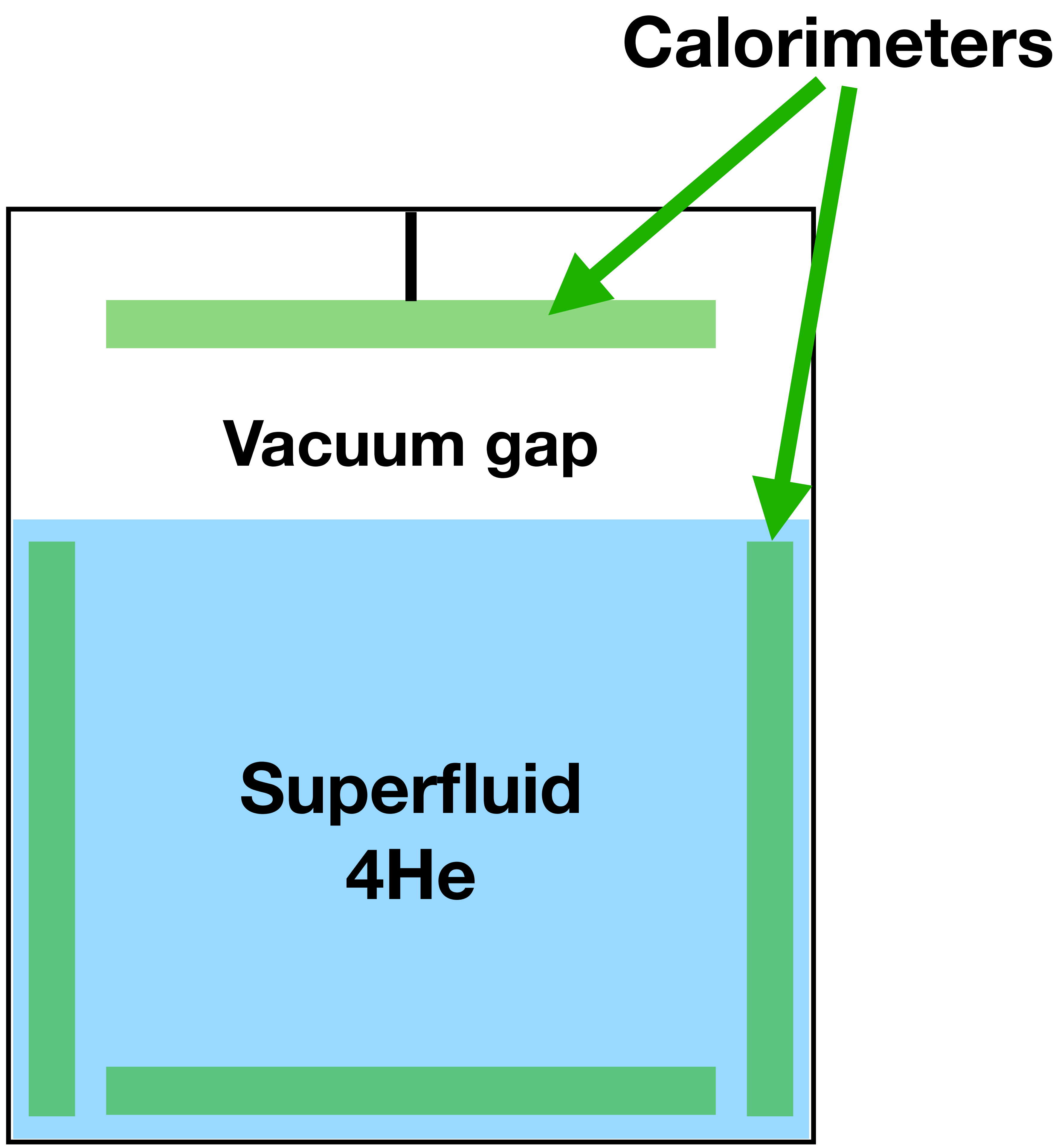
- Long history of searching for particle dark matter
    - No success as of yet, rapidly approaching neutrino “floor”
- Could dark matter be in the “sub-GeV” parameter space?
    - Requires lower detector thresholds to study
    - O(10 eV) threshold in an O(10 g) detector for 100 MeV DM



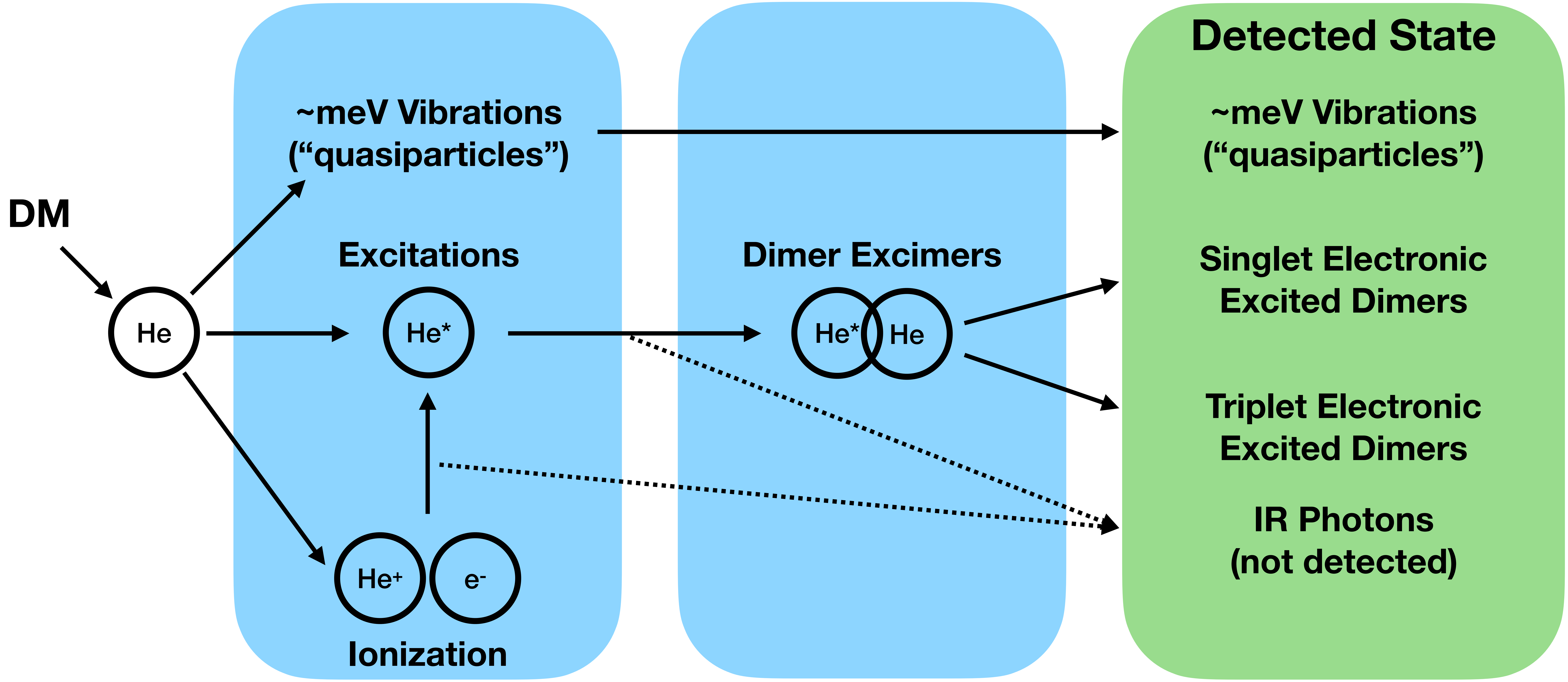


The HeRALD Detector

- Superfluid ^{4}He as a target material
  - Recoil energy can be fully reconstructed with TES calorimetry
  - Favorable recoil kinematics
  - Near zero bulk radiogenic backgrounds
  - No Compton backgrounds below 20 eV
- HERON R&D at Brown (Seidel, Maris), demonstrated key concepts
  - Searching for pp solar neutrinos. Suspended calorimeter only, ton scale, keV threshold



Excitations in ^4He

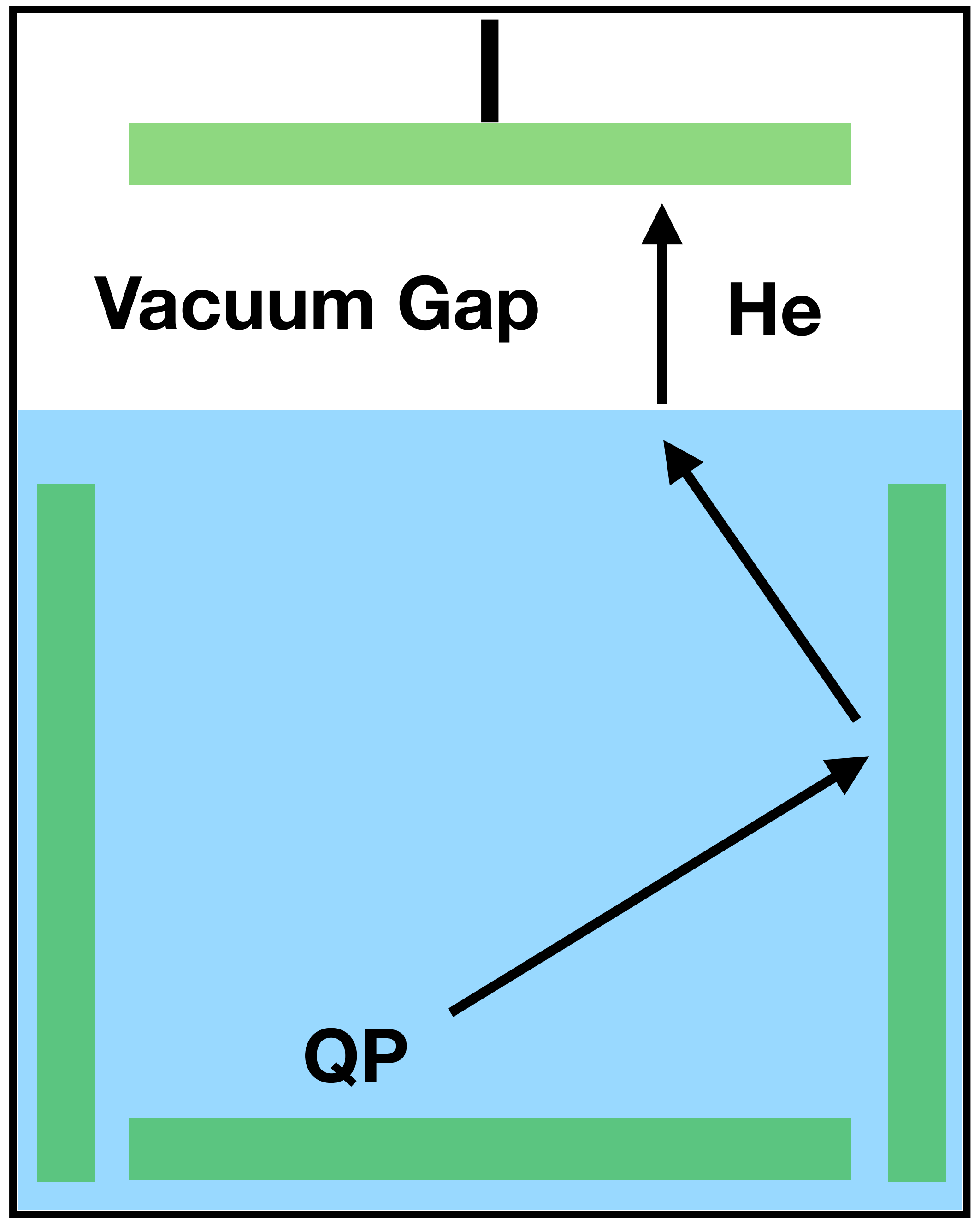


Excitations in ^{4}He

DM → He

O(ns)

Excitation	Detection Method
~meV Vibrations ("quasiparticles") (ballistic) →	Adsorption of quantum evaporated He atoms on upper calorimeter + adsorption gain, 50-400 us timescale
Singlet Electronic Excited Dimers (10 ns half-life)	
Triplet Electronic Excited Dimers (13 s half-life)	



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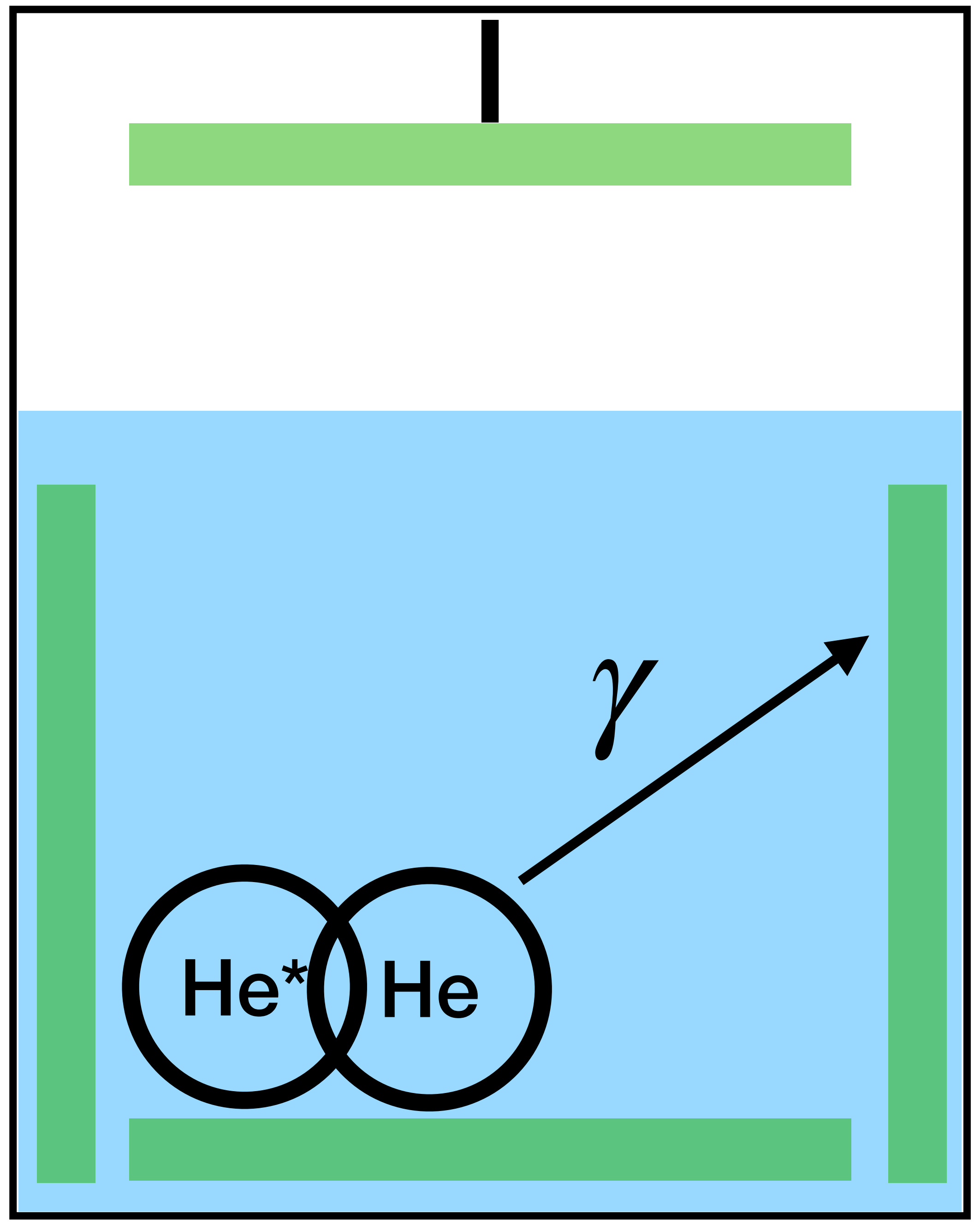
Triplet Electronic Excited Dimers (13 s half-life)	



Doug Pinckney hpinckney@umass.edu

Excitations in ^{4}He

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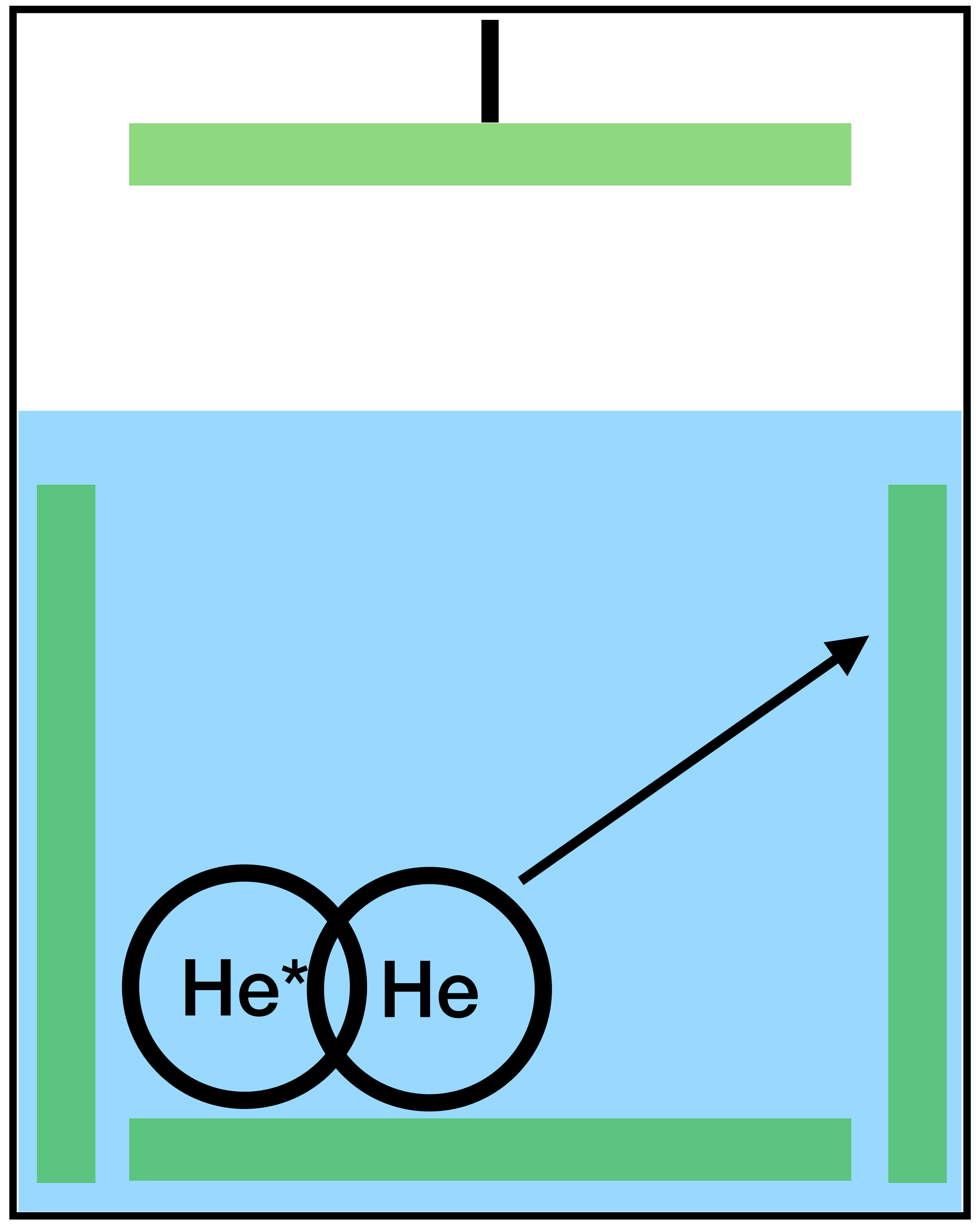
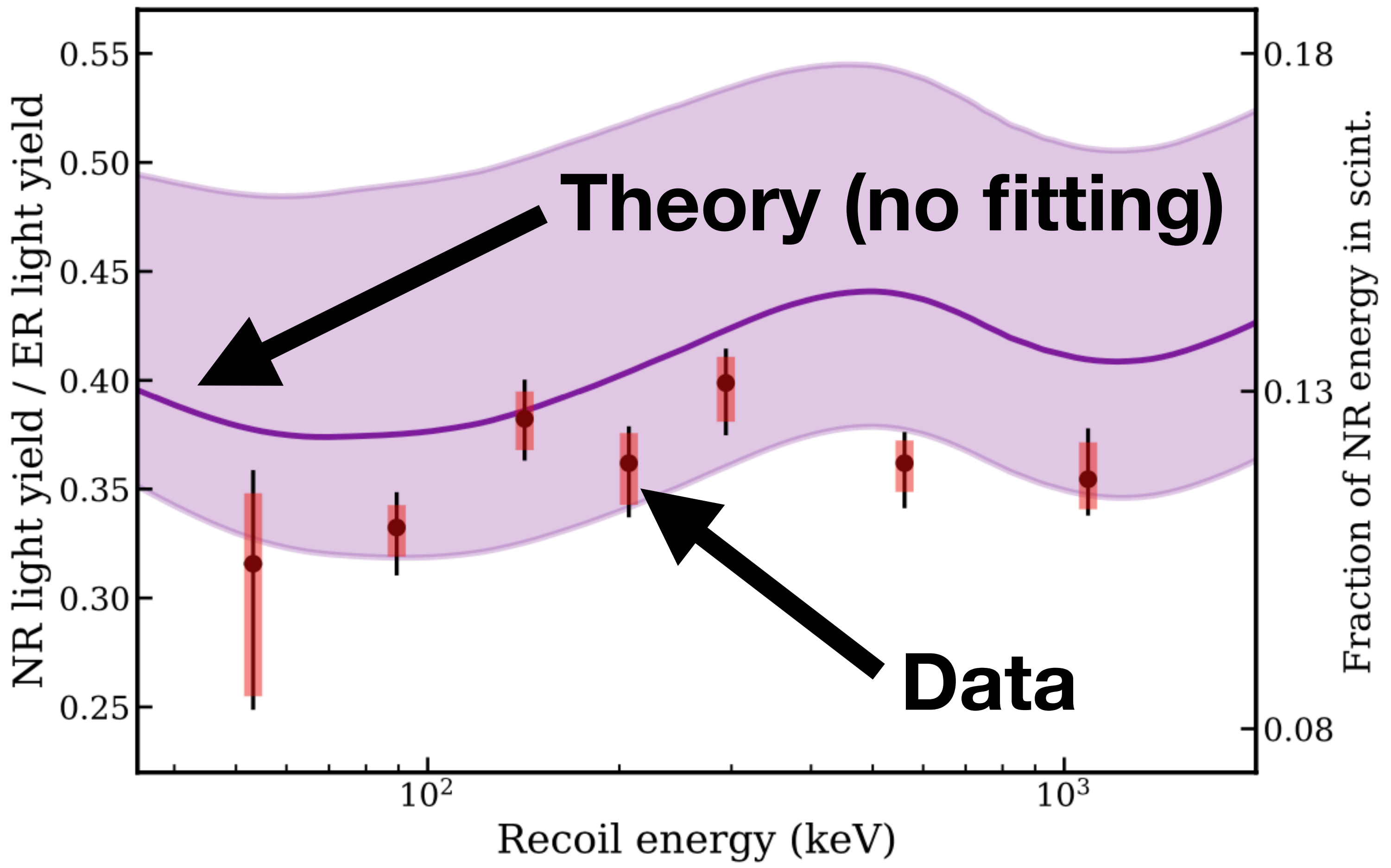
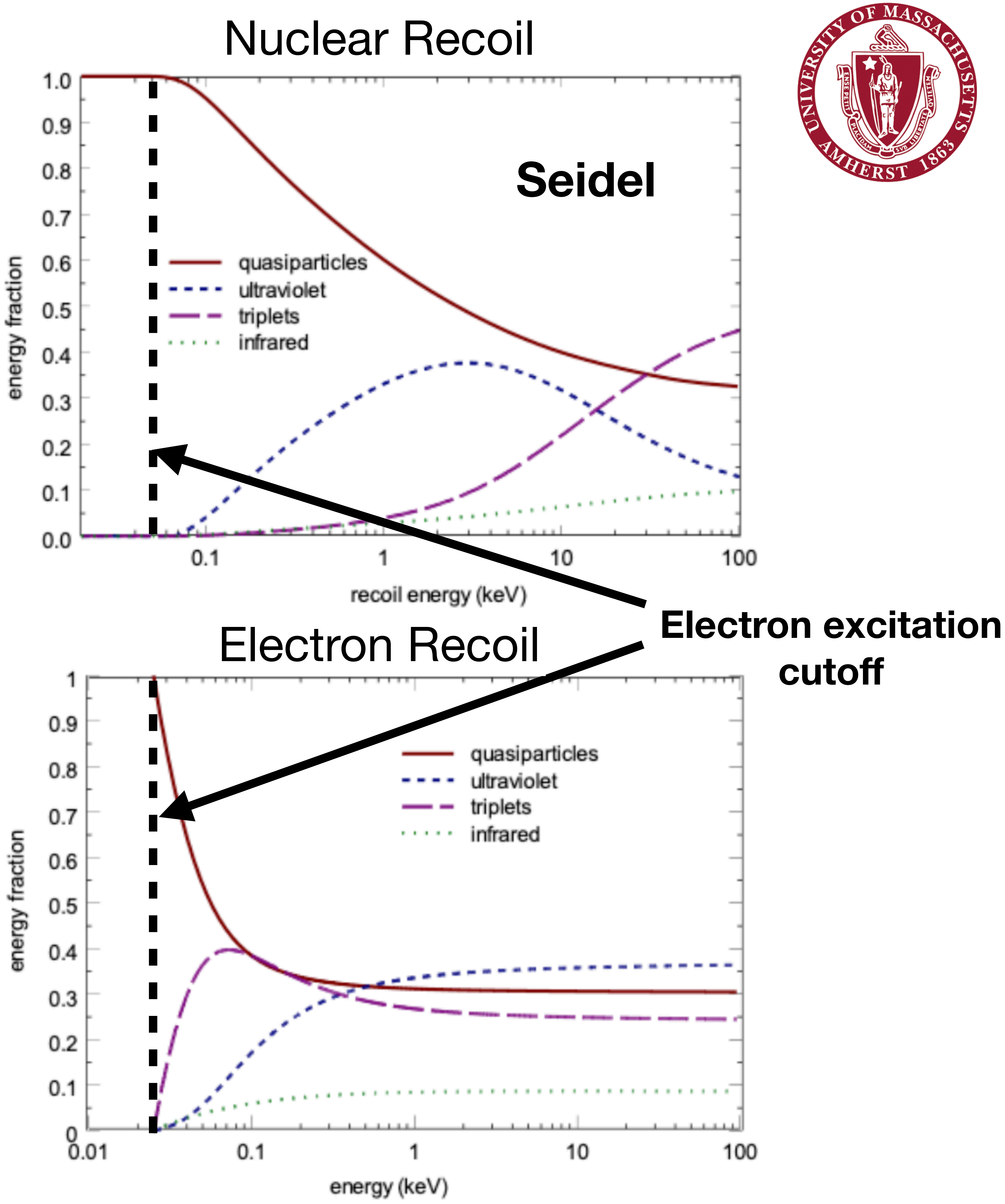
Singlet Electronic Excited Dimers (10 ns half-life)	UV (16 eV) photons absorbed in calorimeters
Triplet Electronic Excited Dimers (13 s half-life)	Ballistic, travel at O(1 m/s), deposit energy in immersed calorimeters



Energy Partitioning

- **Nuclear and electron recoils have different energy partitioning!**
- Estimated from measured excitation/ionization/elastic scattering cross sections
- Distinguishable with signal timing
- UCB group measuring this, Phys. Rev. D **105**, 092005

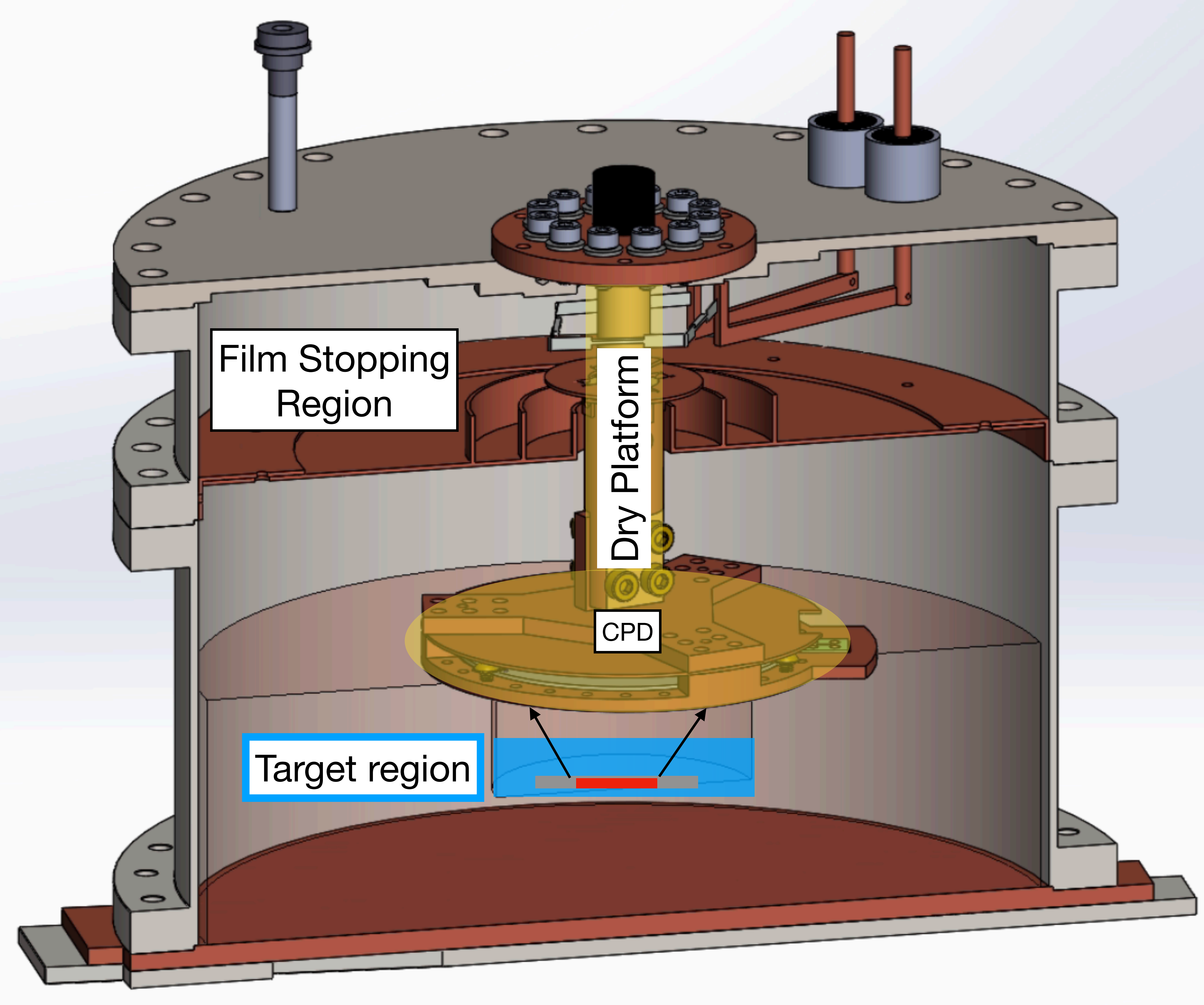




HeRALD V0.1: Design

- Goal: observe particle interactions with a superfluid film free, “athermal” TES

- Single suspended sensor, no immersed sensors



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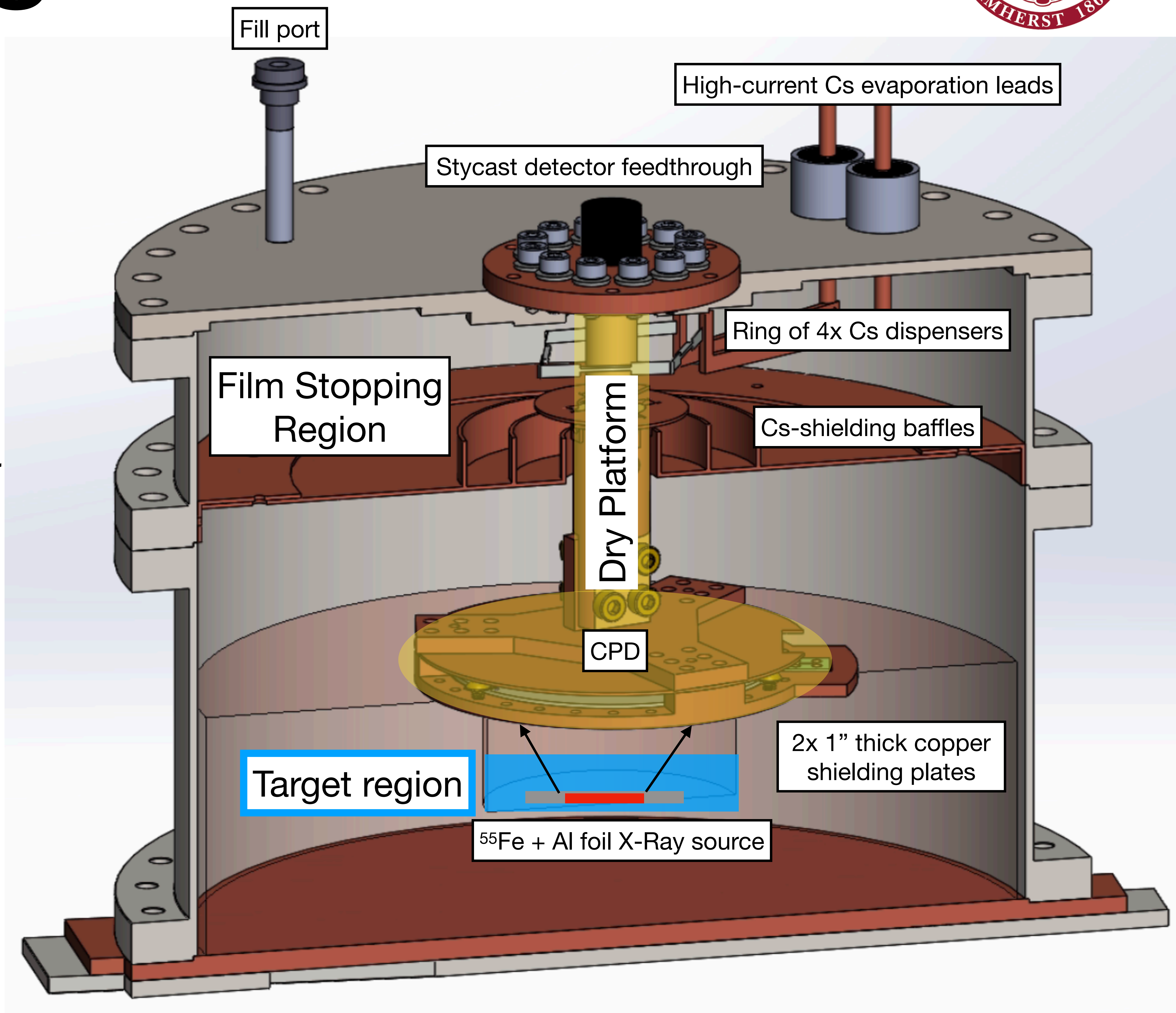
- Large stainless steel cell to accommodate future R&D projects
- Implementation of a Cs-based "film stopper"



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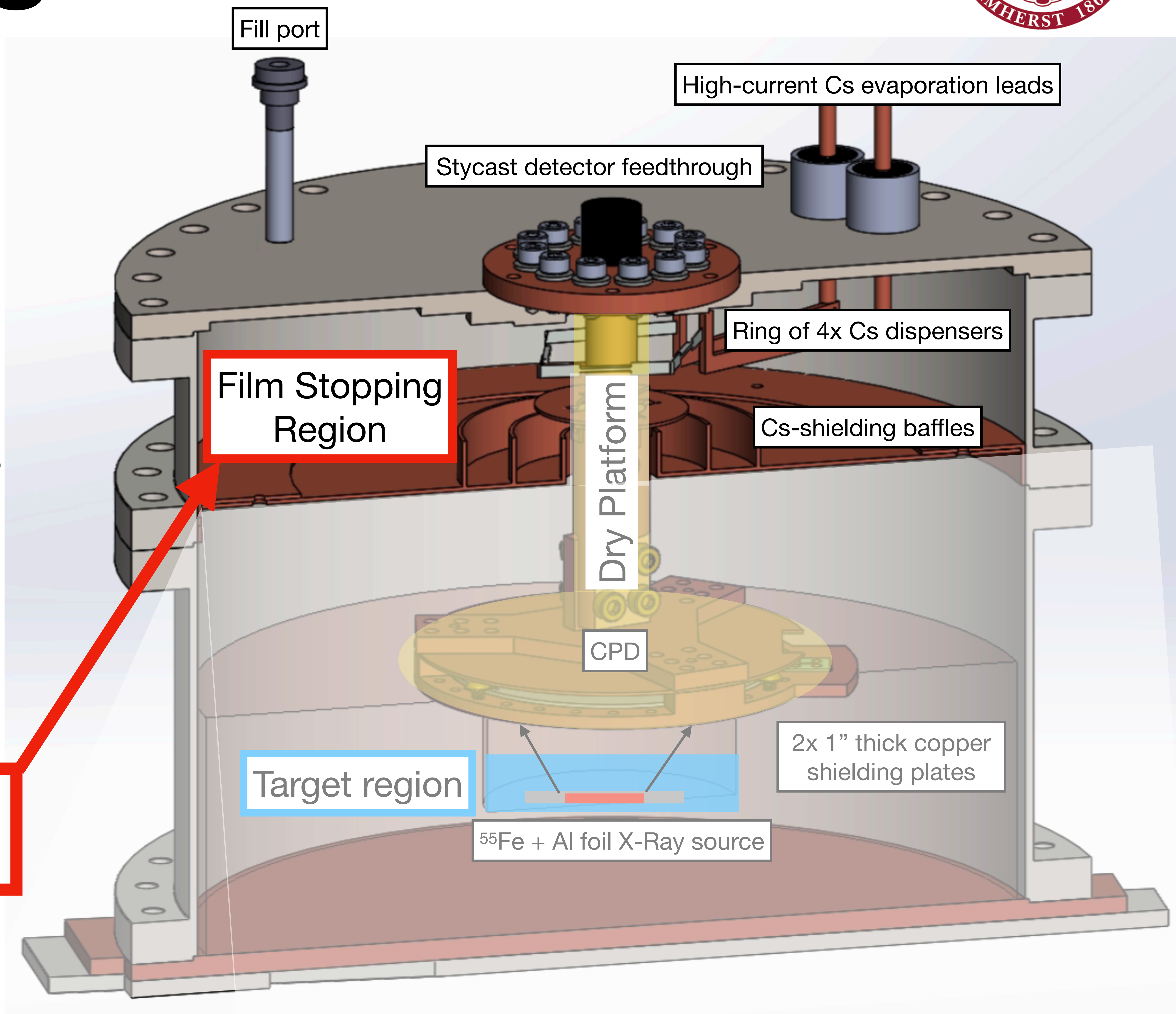
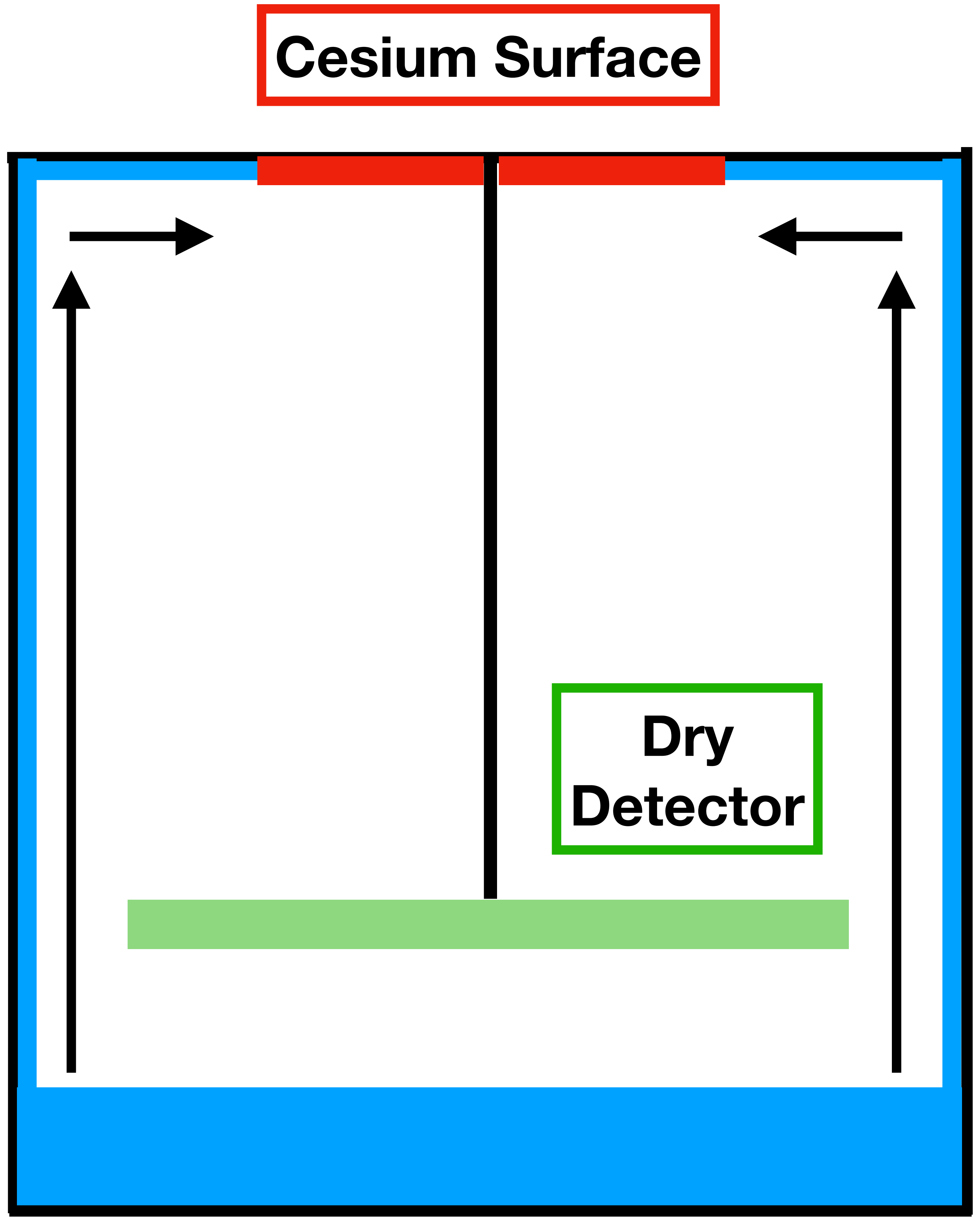


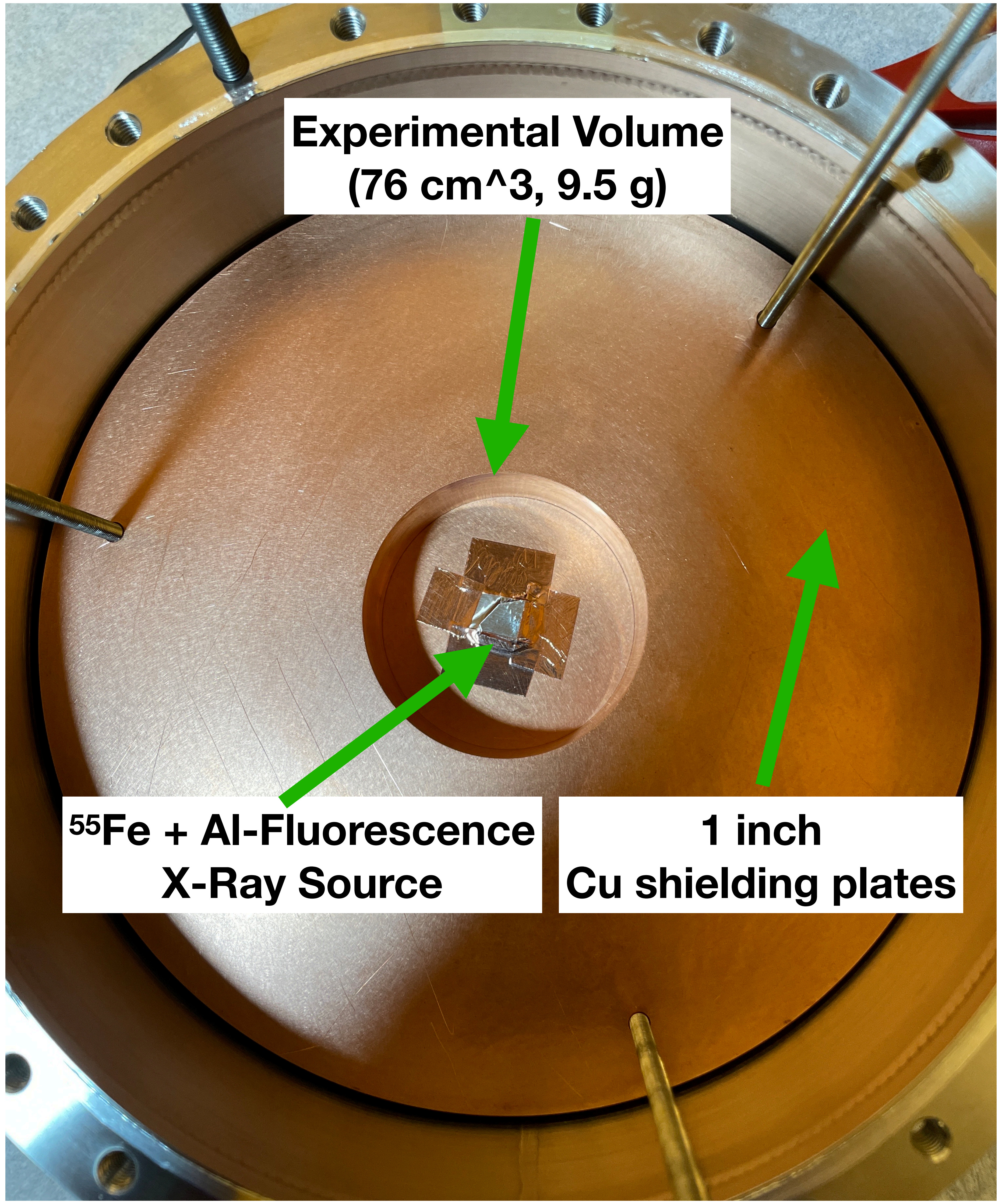
Film Stopping

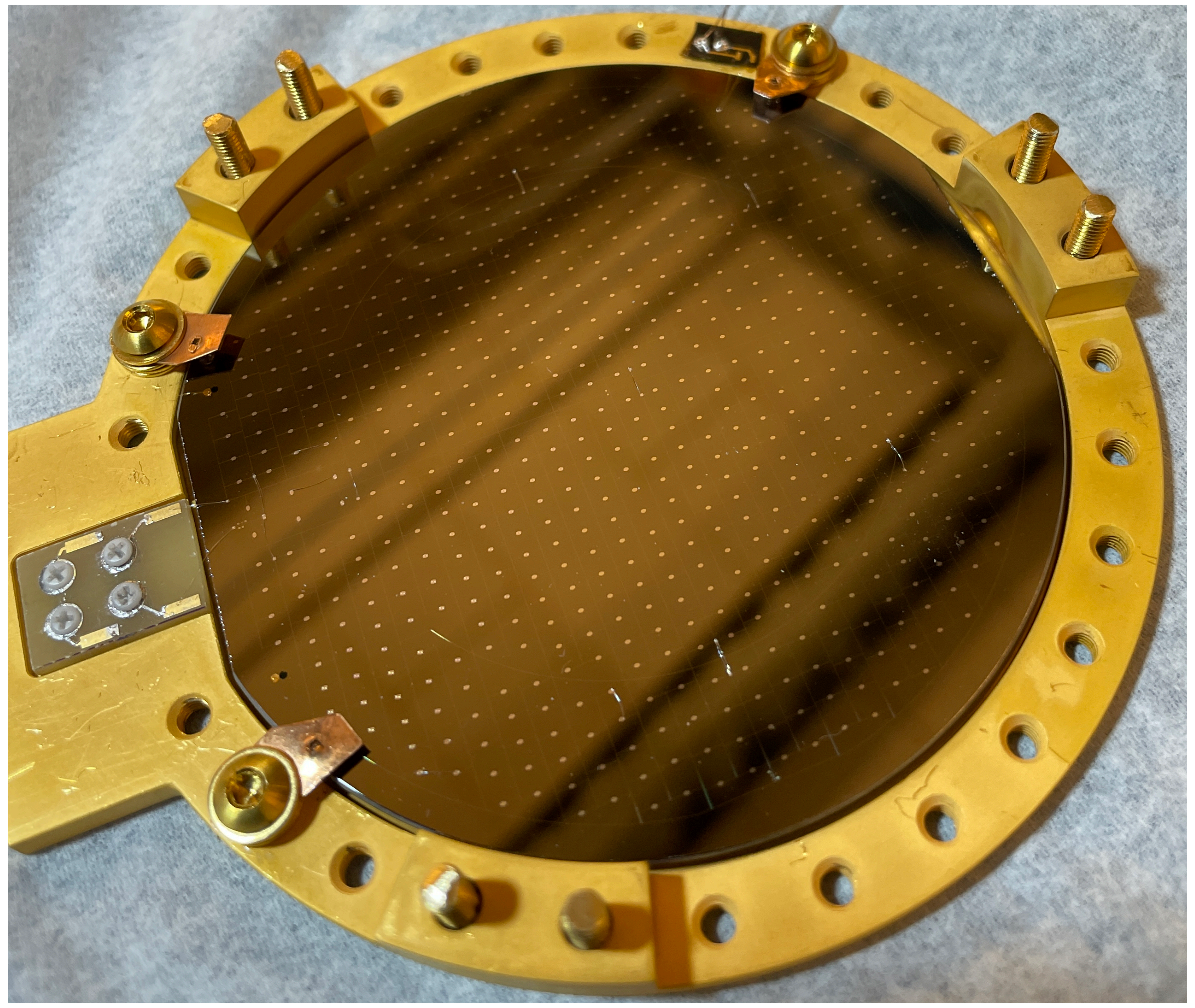
- **<u>Problem:</u>** Superfluid ^{4}He covers all surfaces of a closed container. Do not want this on calorimeter!
  - Preserve adsorption gain
  - Empirically: superfluid on calorimeter degrades performance
- **<u>Solution:</u>** Superfluid ^{4}He does not wet Cs, deposit a ring of Cs between helium target and calorimeter

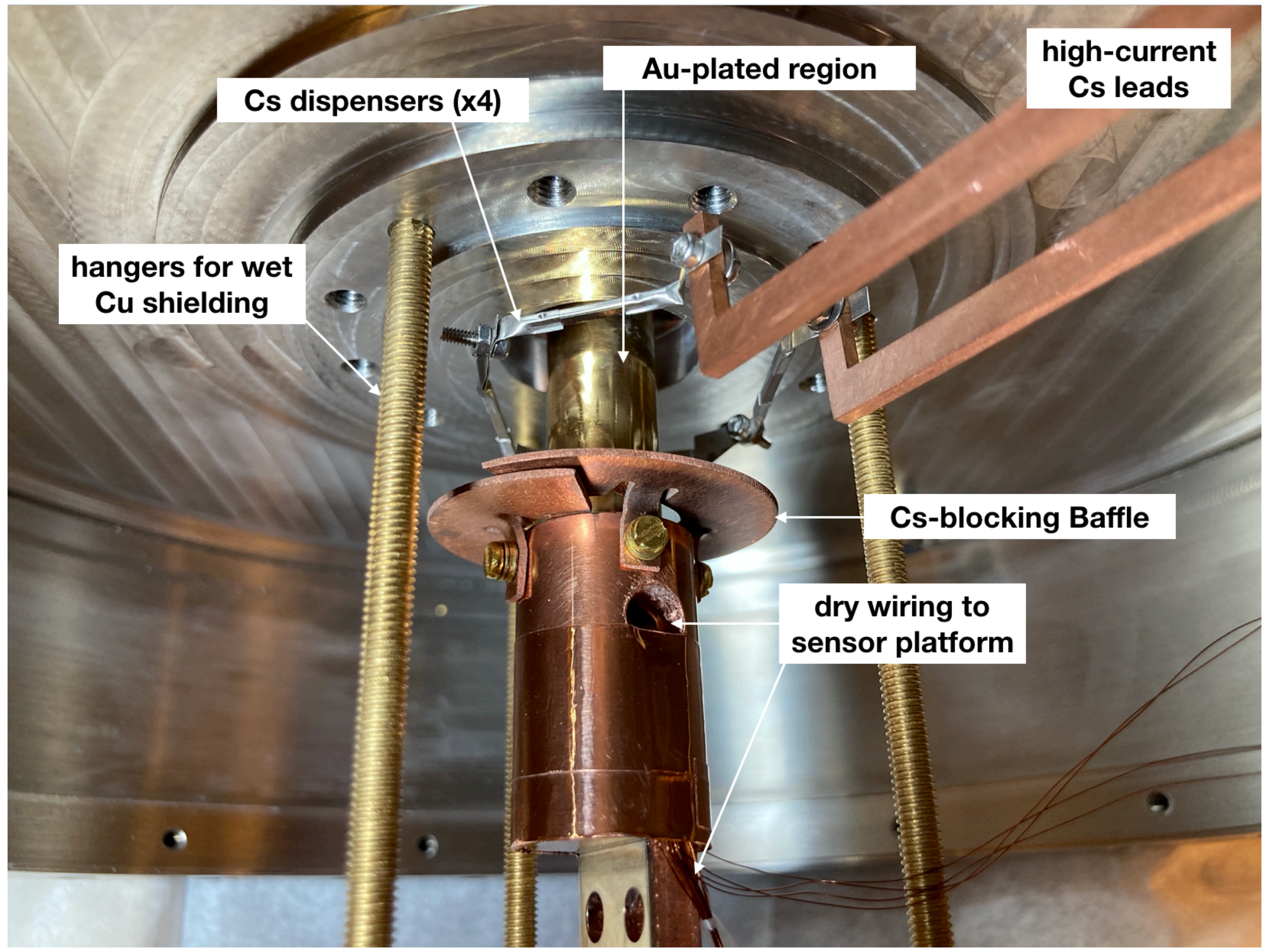
  Ketola, Wang, Hallock PRL 68, 201 (1992)

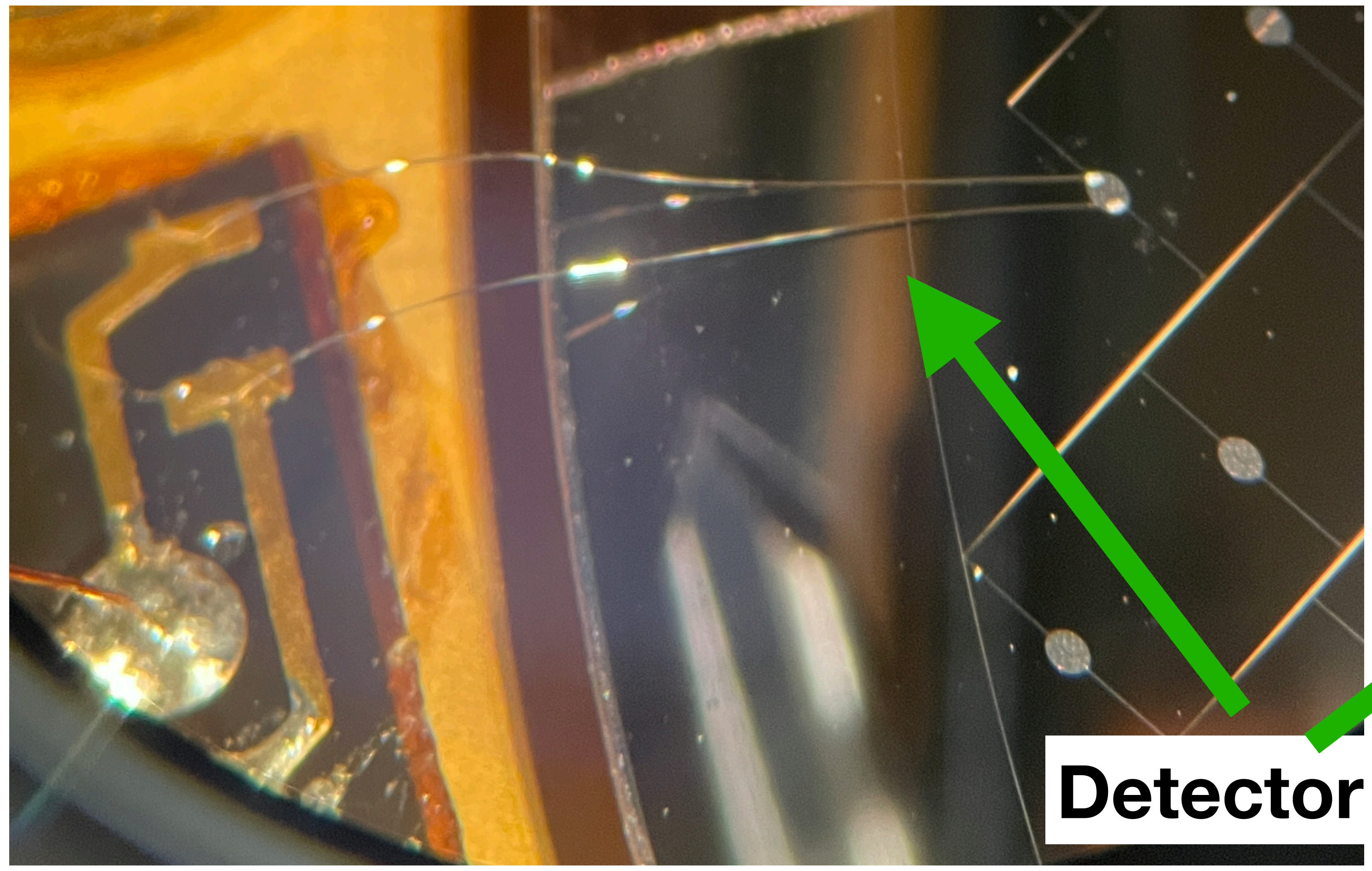


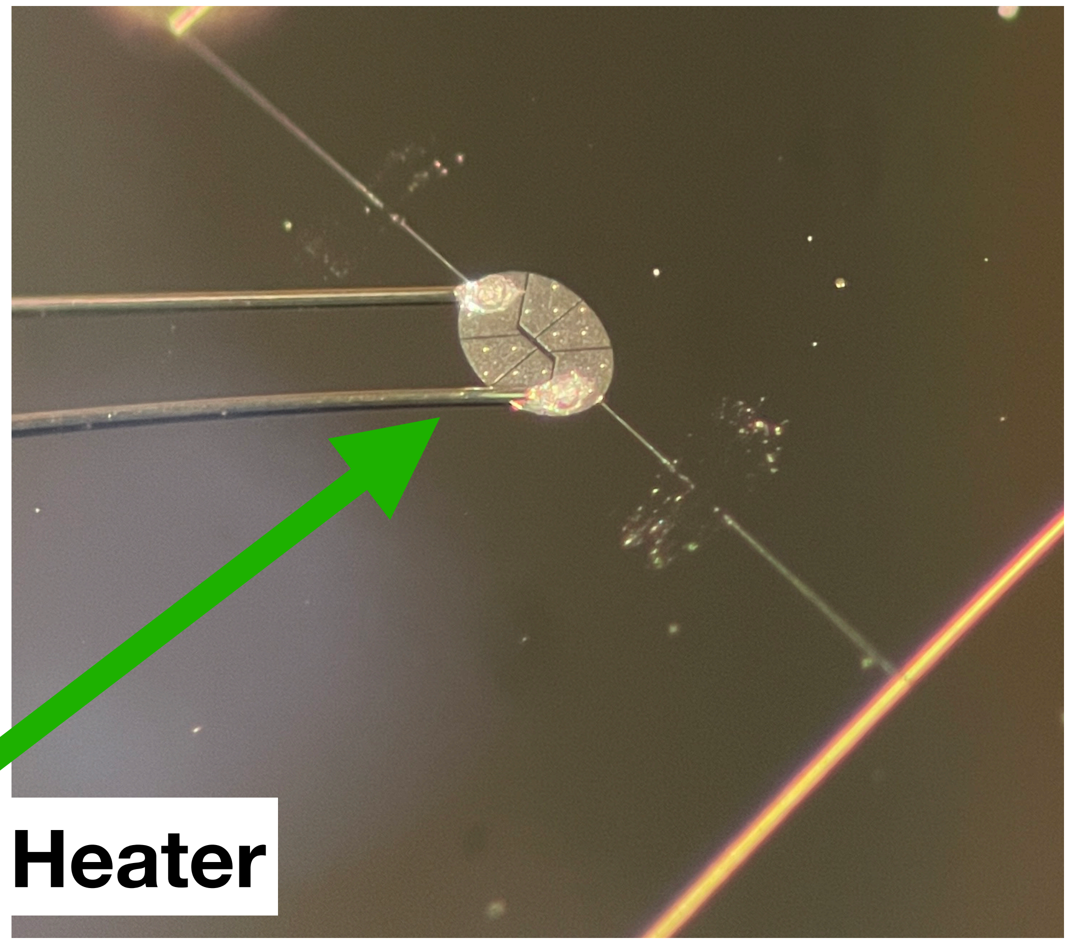
HeRALD V0.1: Photo Tour 1



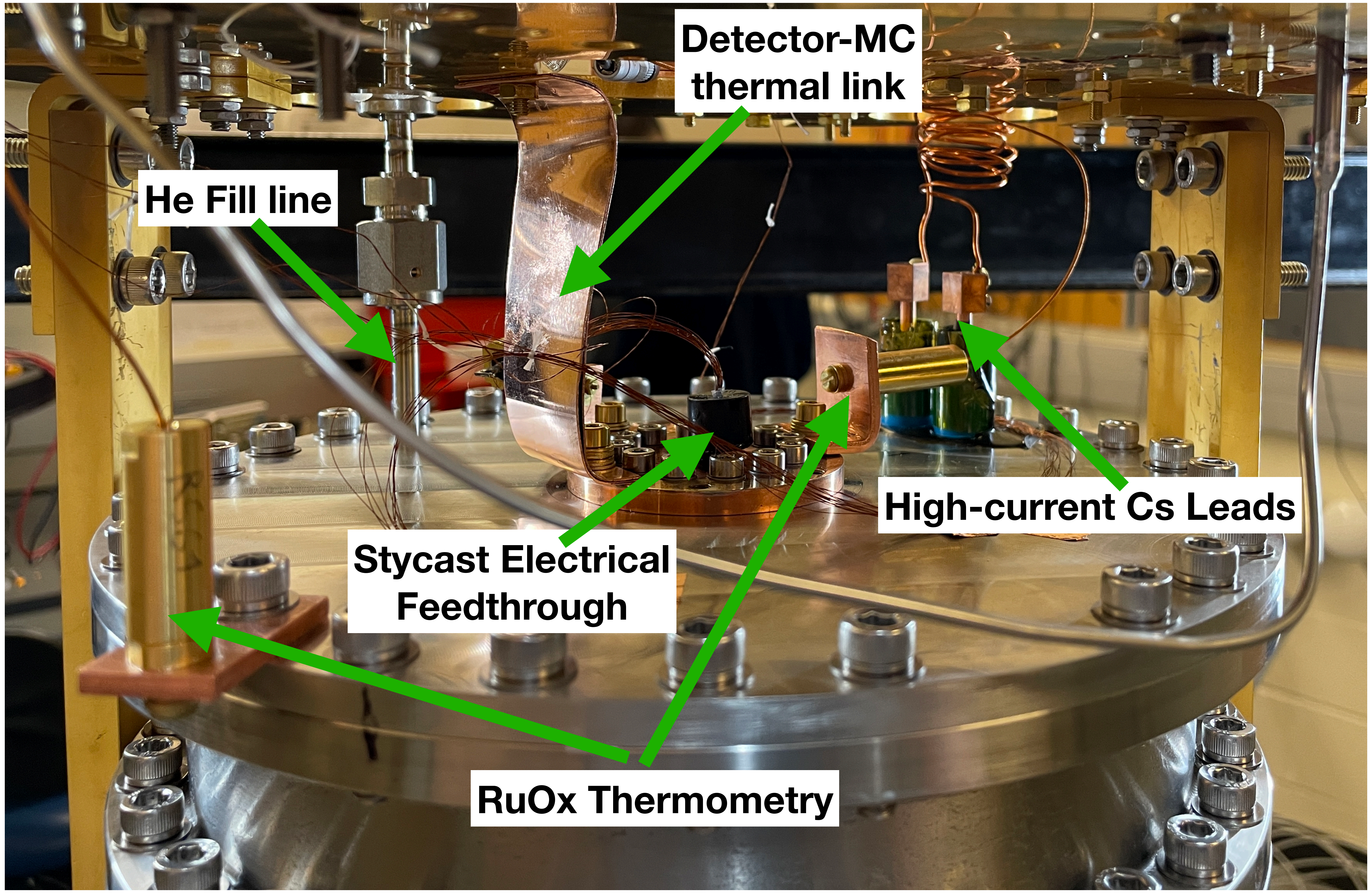




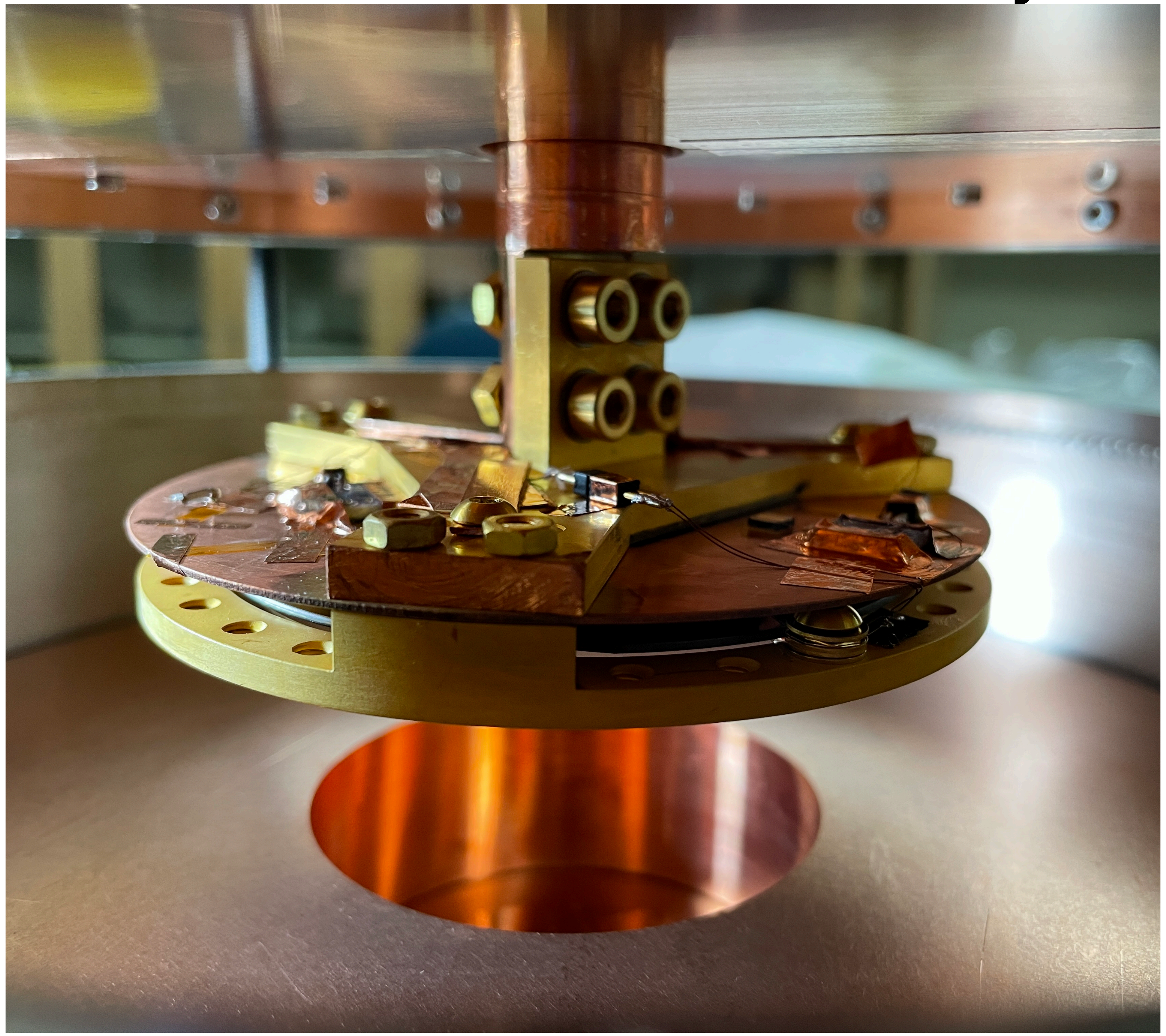




HeRALD V0.1: Photo Tour 2



Detector, mid-assembly



First R&D Results

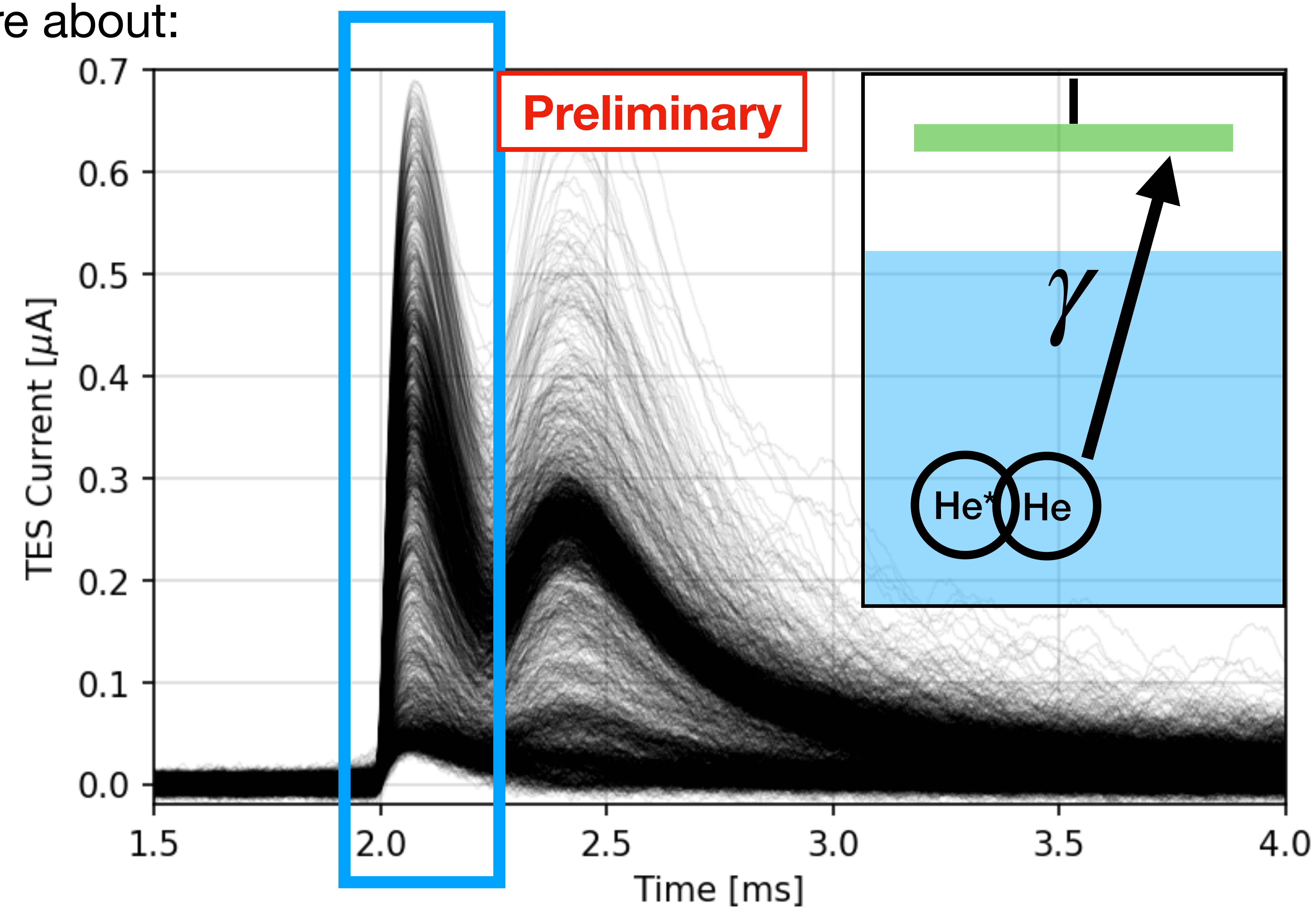
Results from HeRALD V0.1

- Prompt Scintillation
- Quantum Evaporation
- Triplets
- Misc.

First Helium Results: Pulse Shapes

- For events in the helium, there are four main components to the pulses that we care about:

1. Prompt amplitude (scintillation)
2. Delayed amplitude (evaporation)
3. Delay time (location)
4. "After pulsing" (triplets)



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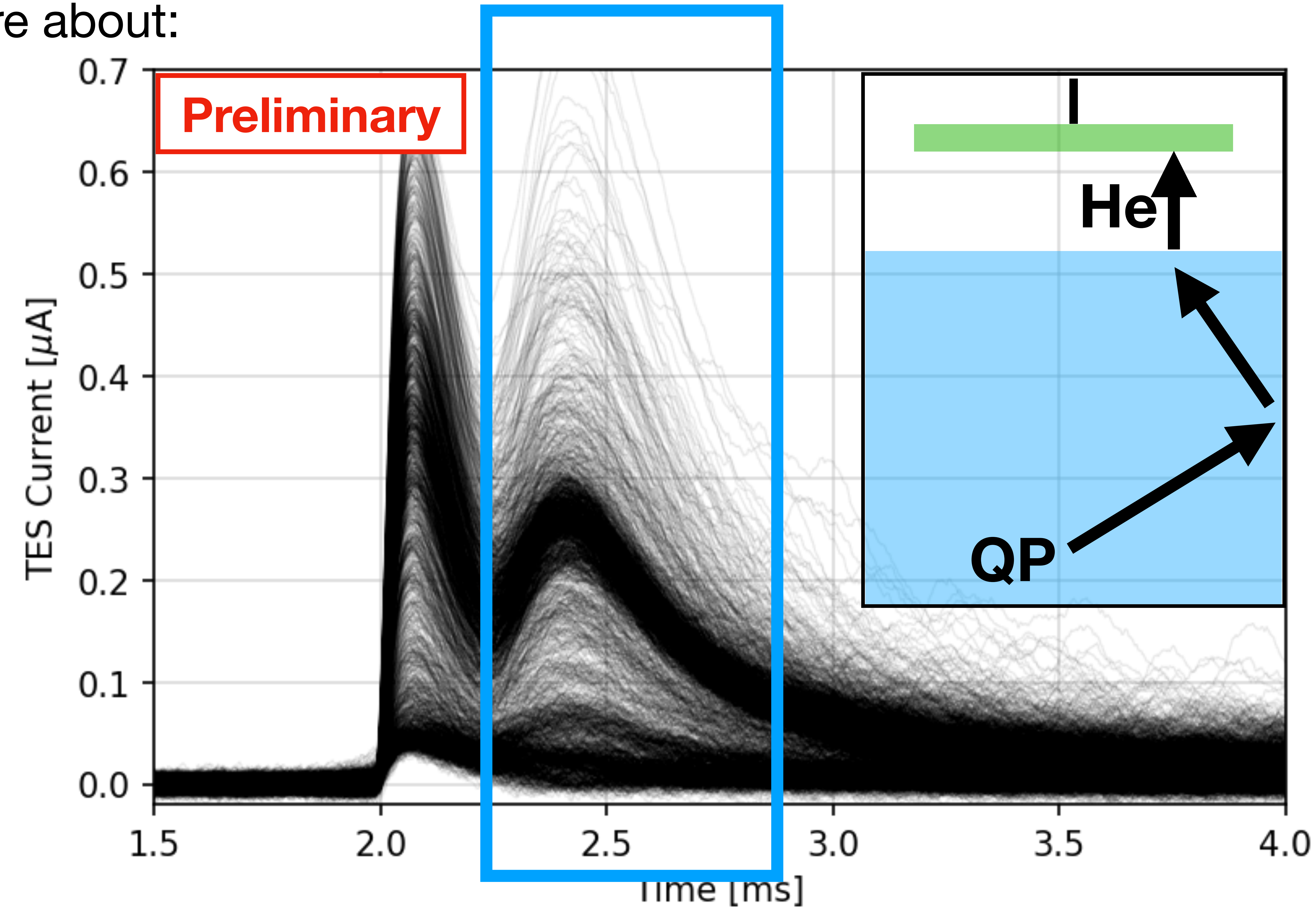

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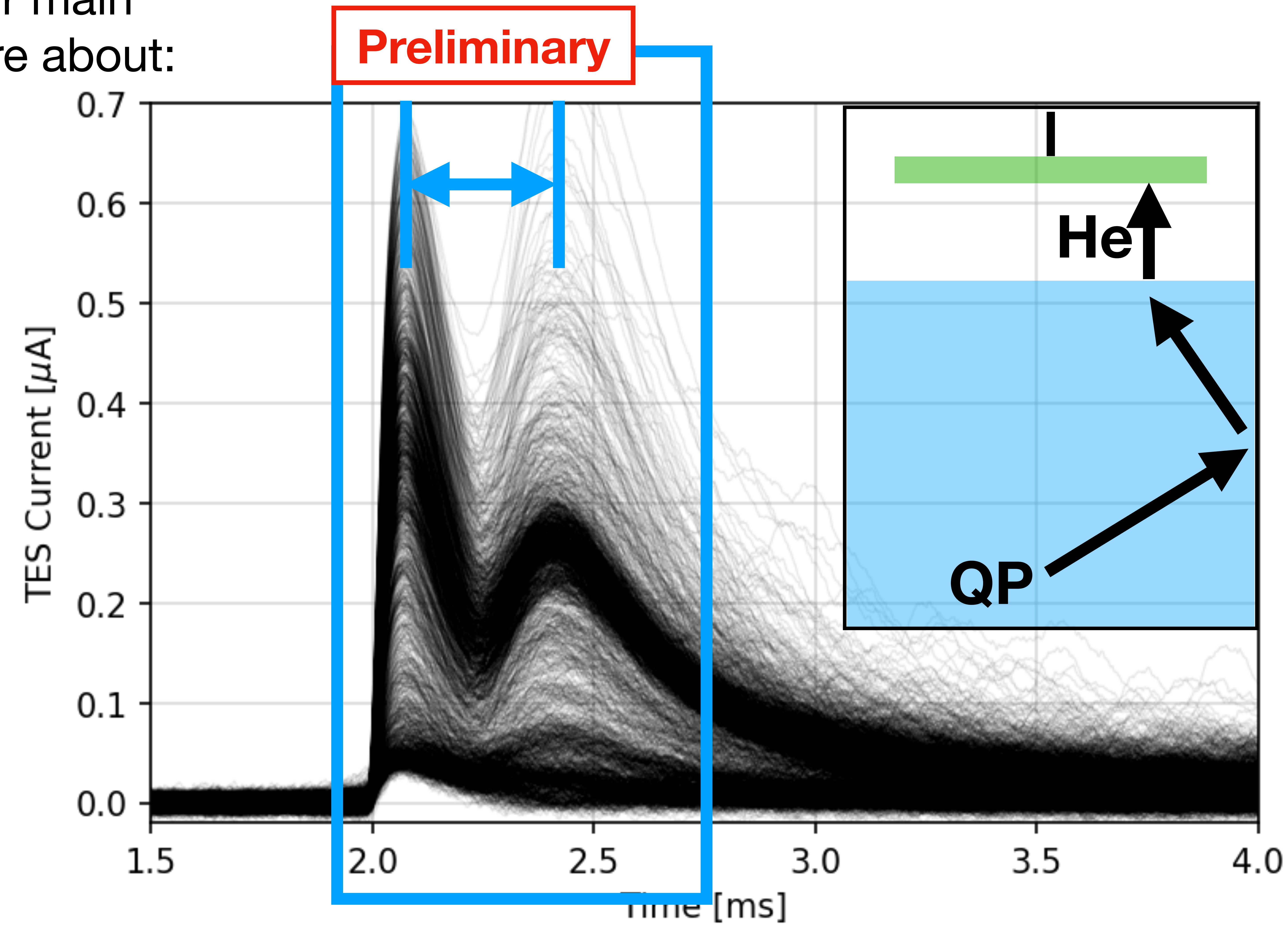

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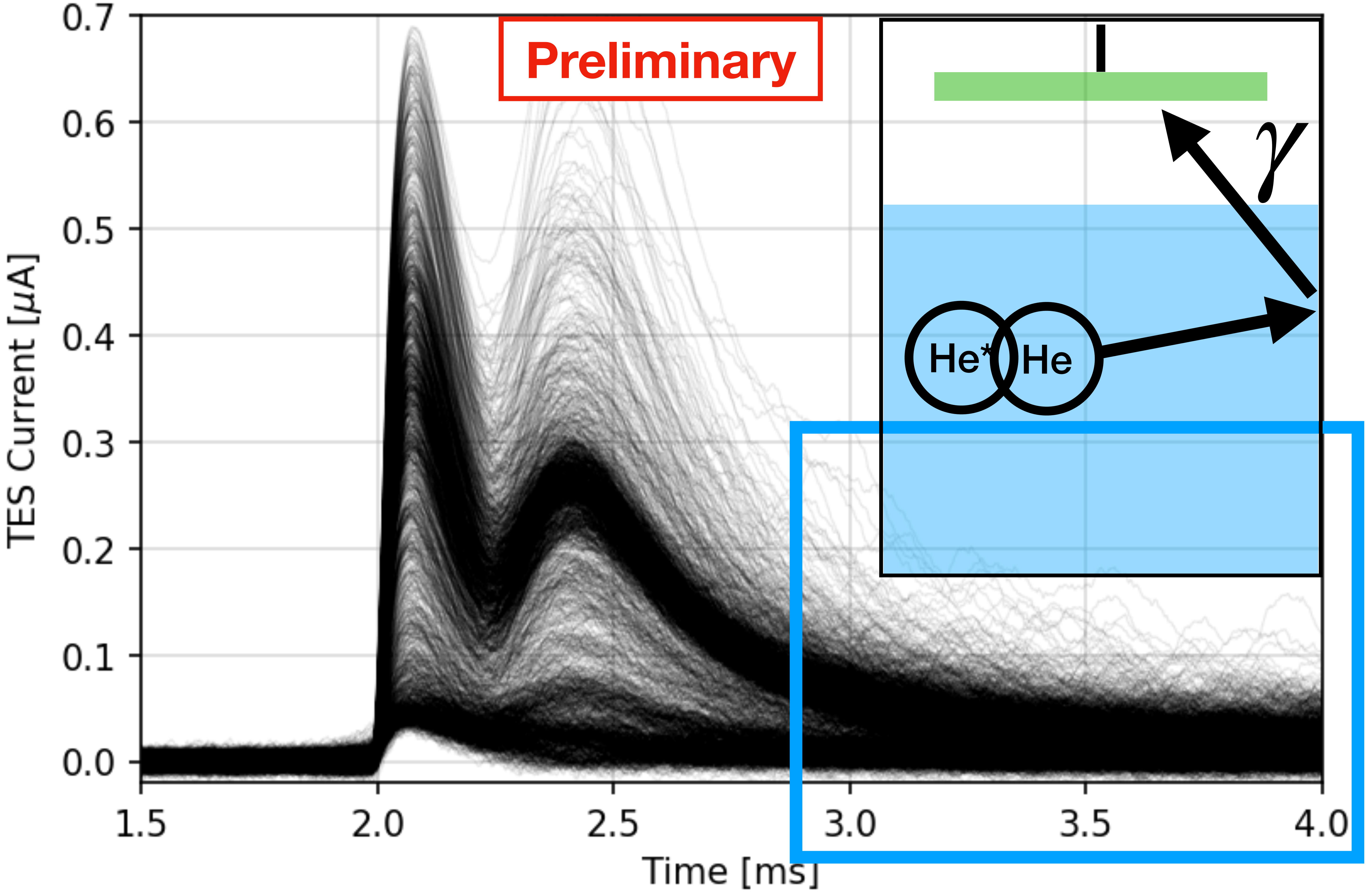
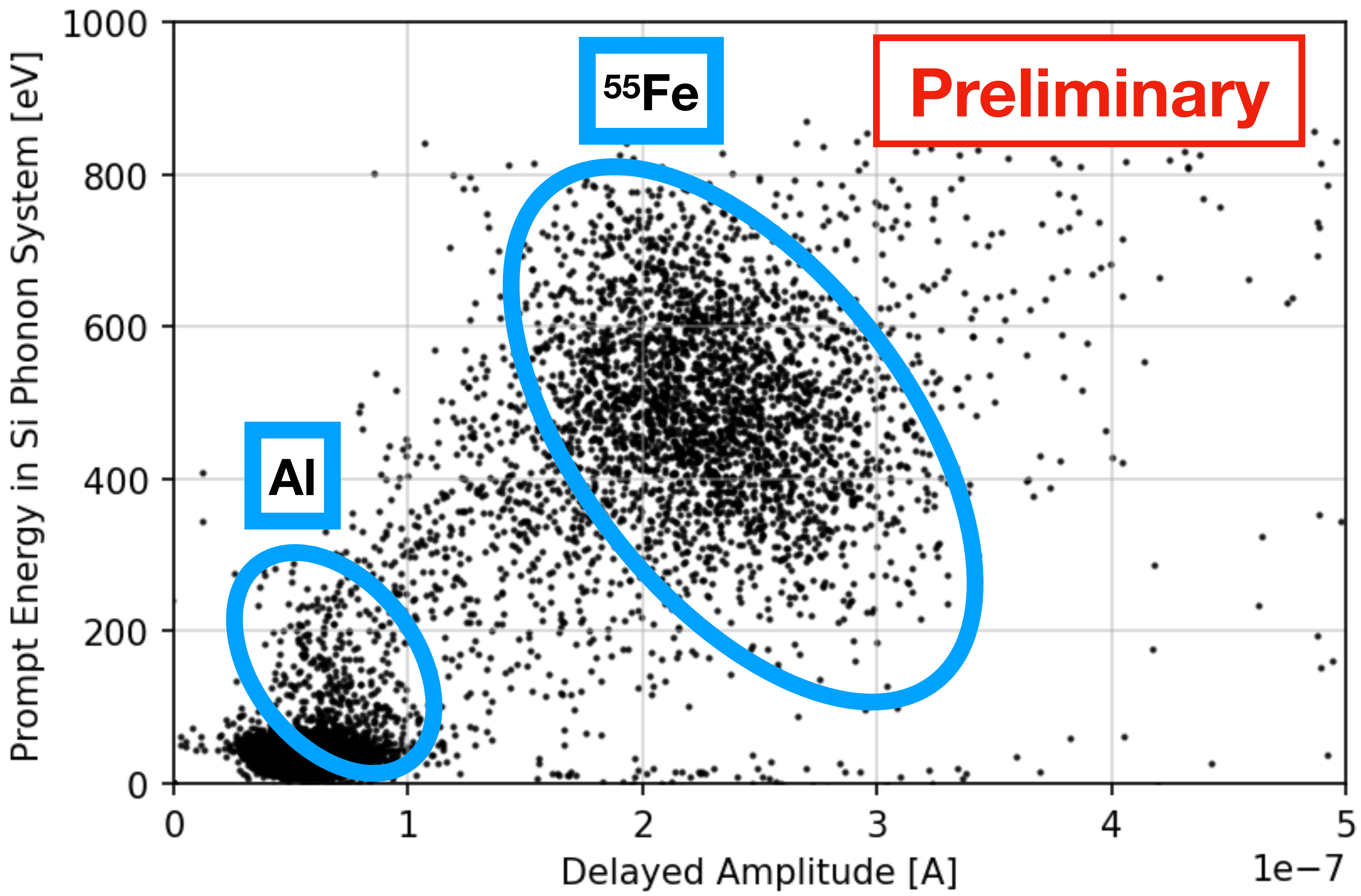


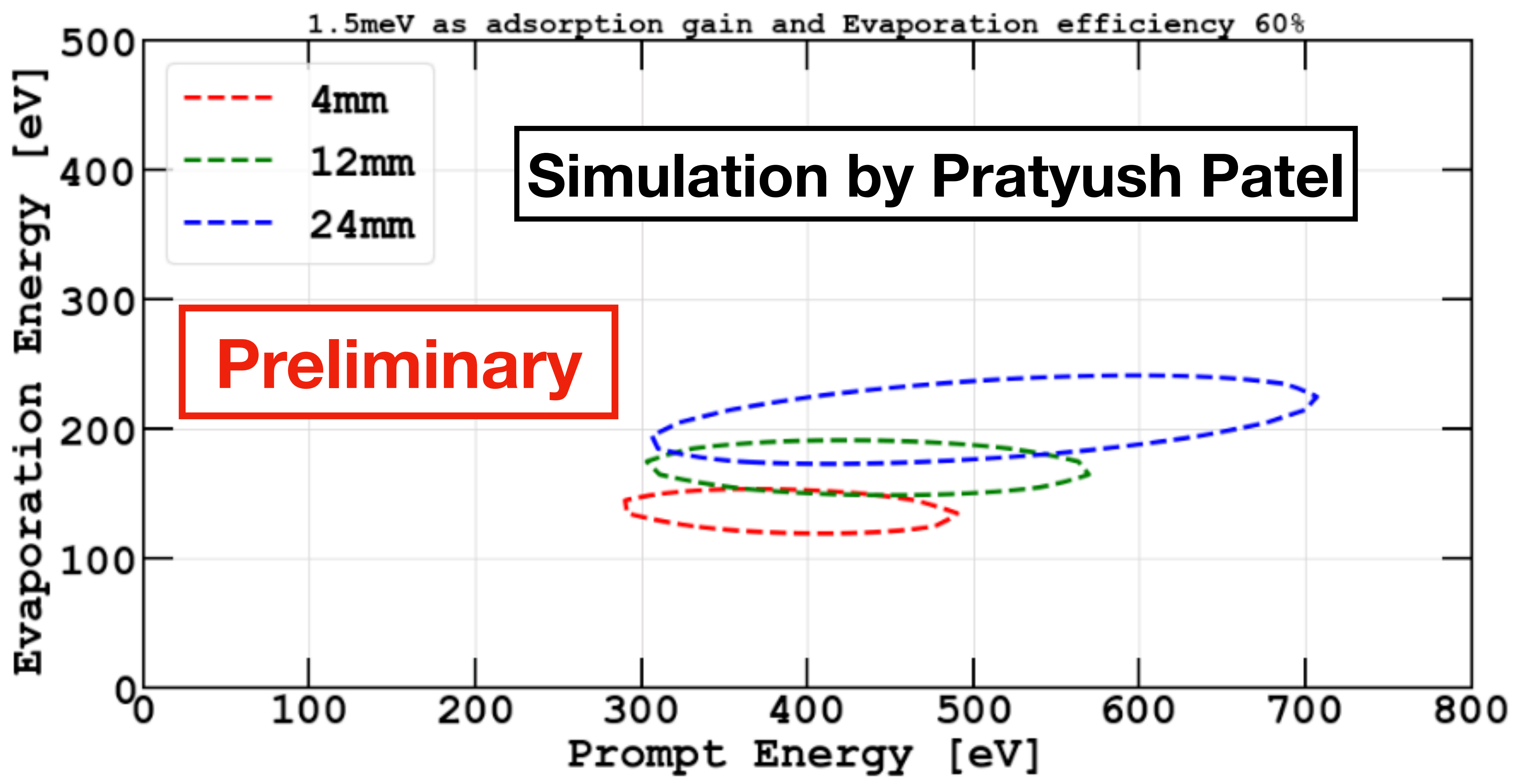
Prompt Scintillation: Amplitudes

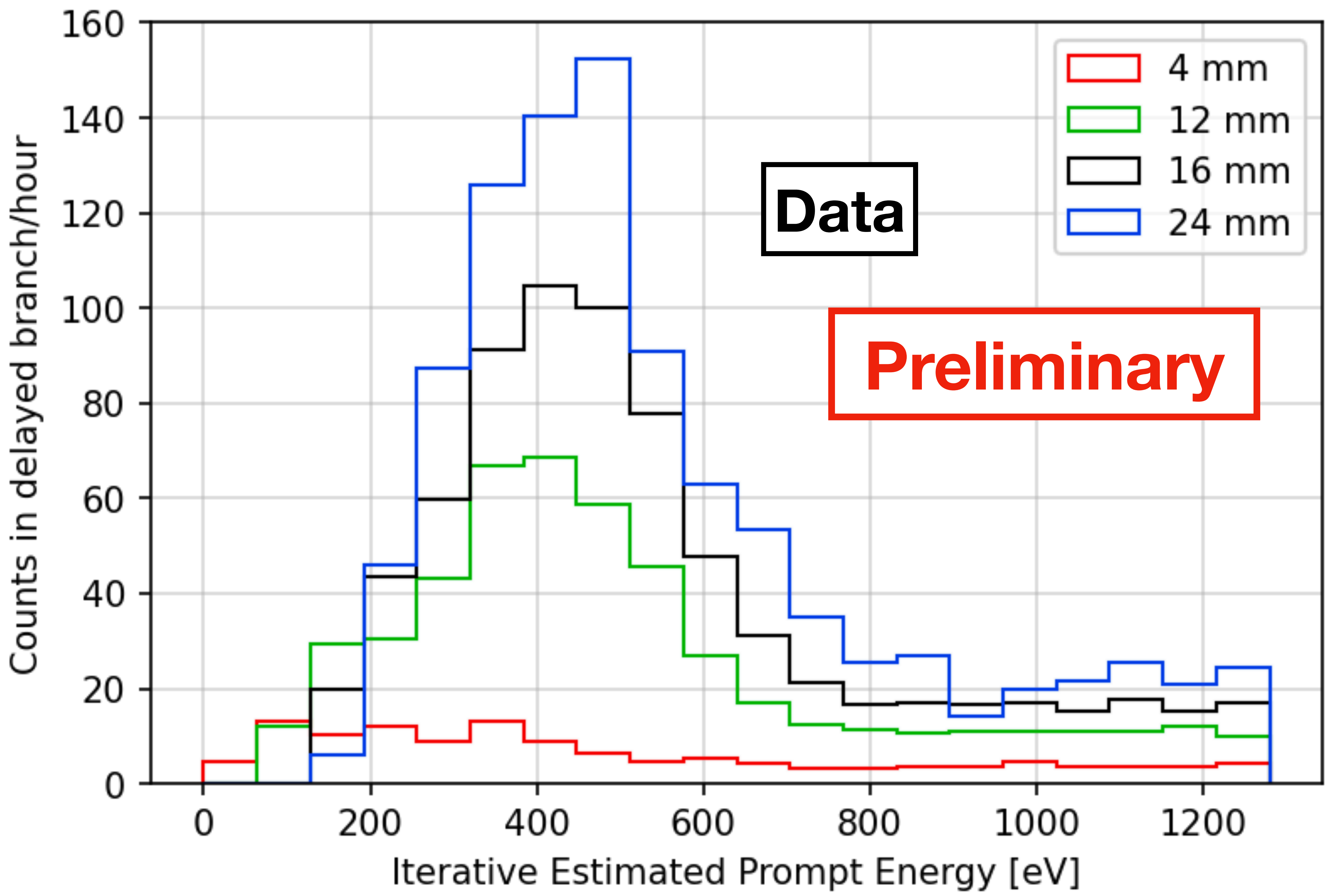
- ^{55}Fe X-rays (5.9 keV):
  - Scintillation signal (both amplitude and fluctuations!) well-match naive expectation using expected yields and solid angles
  - 'Naive expectation' there assumes no 16eV reflection. Also assumes no IR reflection and perfect IR absorption in Si (worth considering more).
- Al fluorescence X-rays (1.5 keV)
  - Peak extends above noise blob. Expect significant fraction of few-photon events (5 photons on average)



Prompt Scintillation vs Fill Height

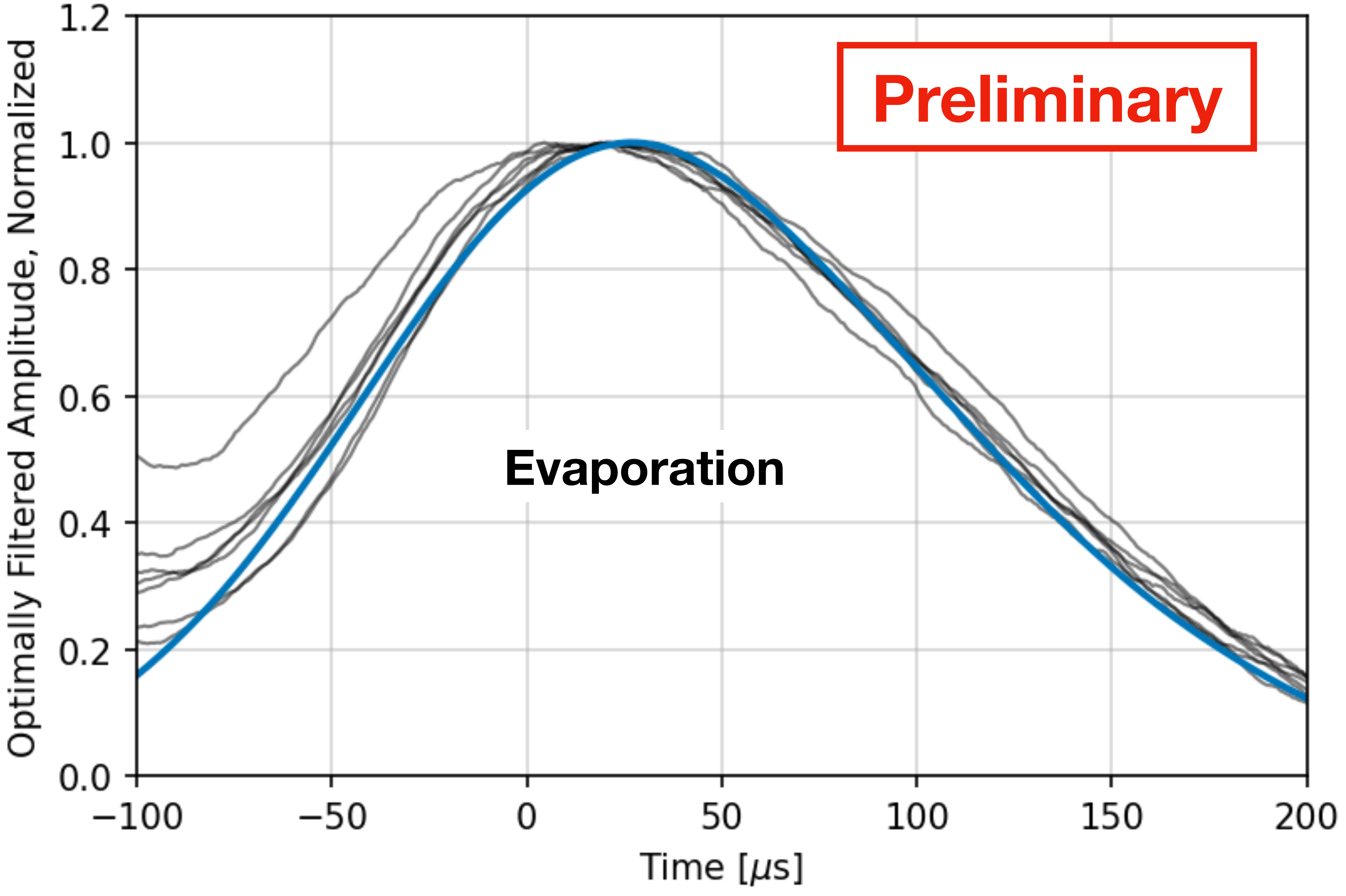
- ^{55}Fe X-rays (5.9 keV):
  - Prompt scintillation gains higher energy "tail" as more fill heights become accessible
  - Rate increases with fill height (^{55}Fe path length in helium is greater than helium volume)

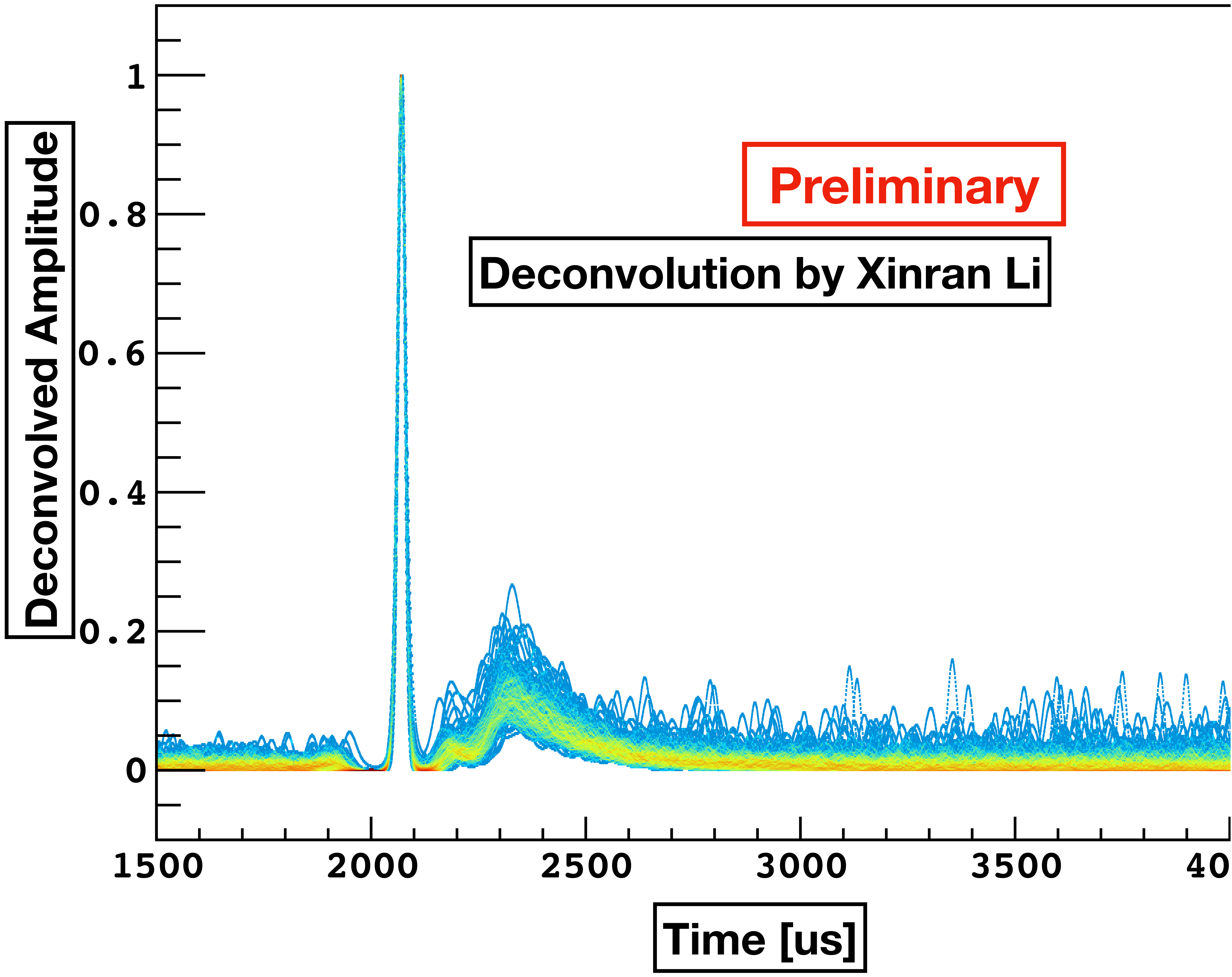




Evaporation: Shape

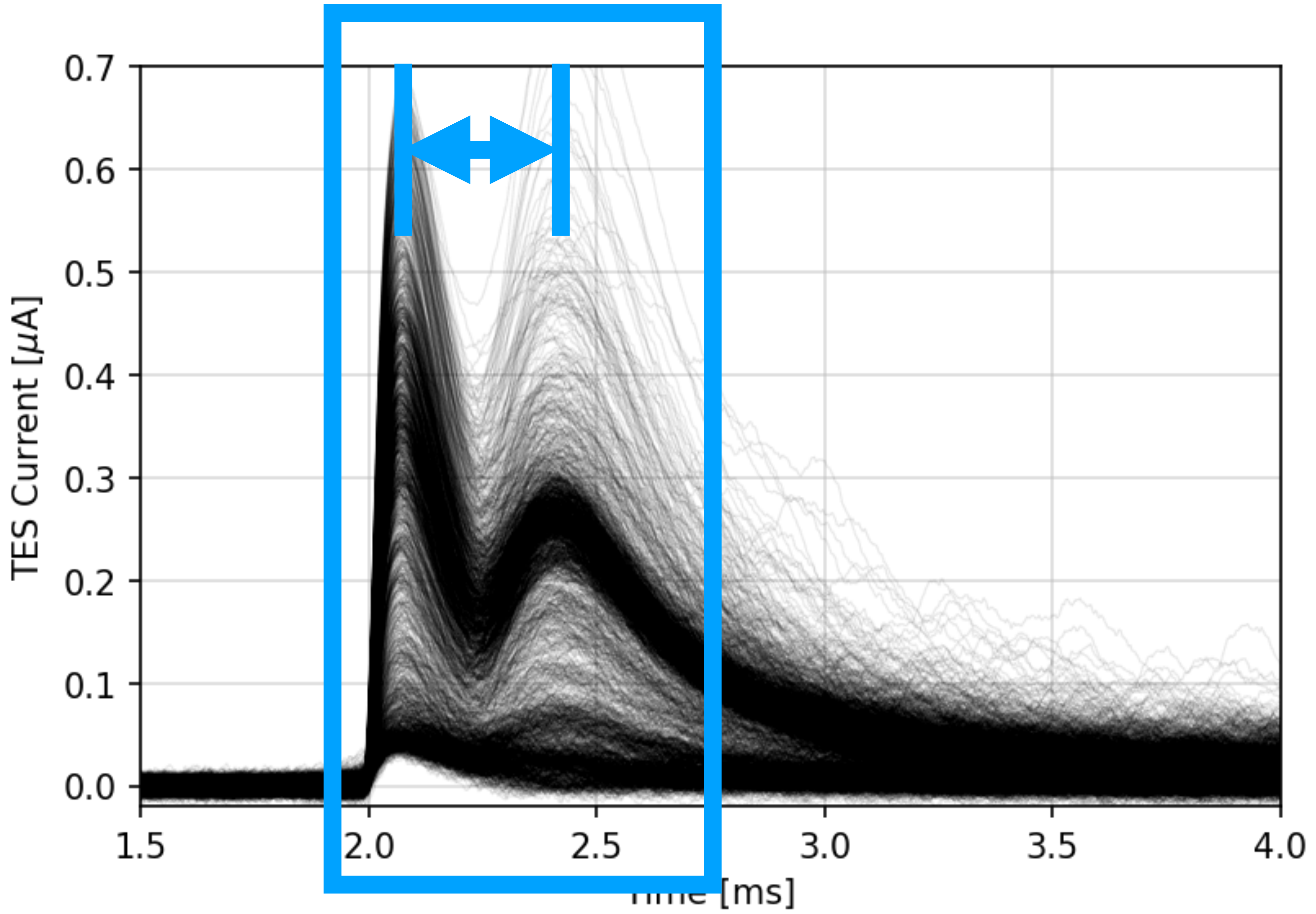
- Evaporation pulses have a finite width
    - Longer than the delta-function response
- Significant variation in pulse shapes

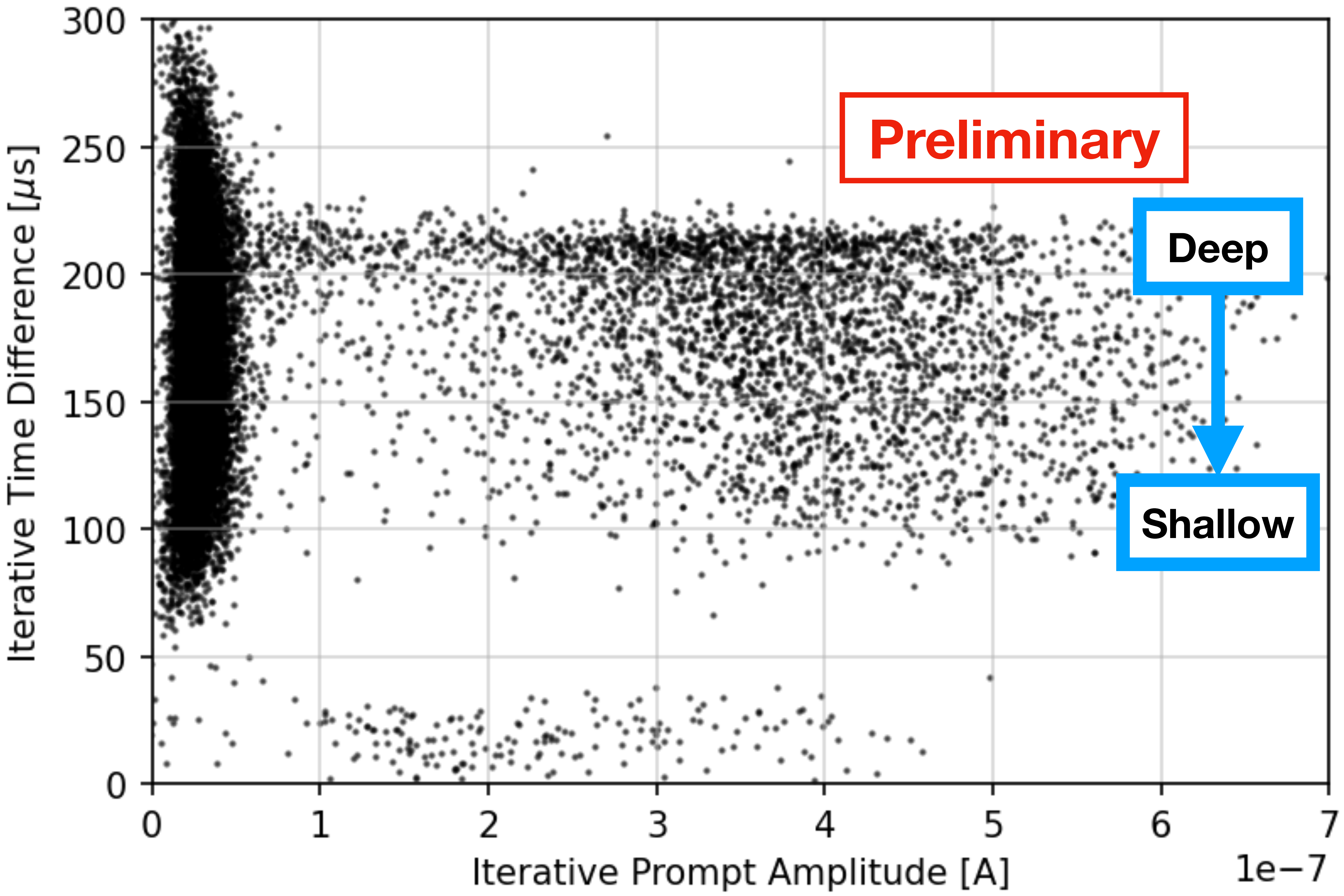




Evaporation: Timing

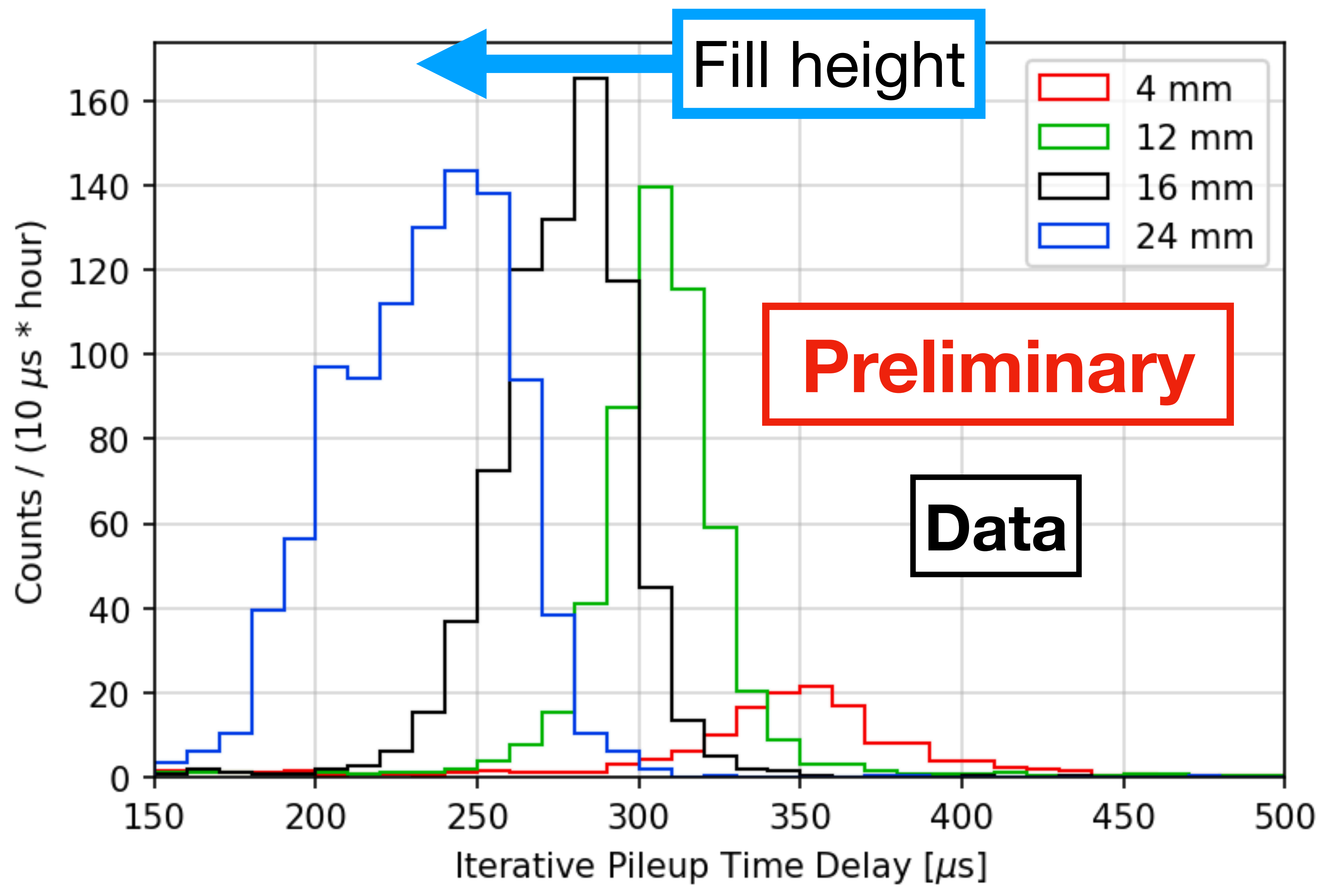
- Evaporation delay time seems to encode depth in the detector
- Shallower events have larger collection efficiency (detector subtends more solid angle)

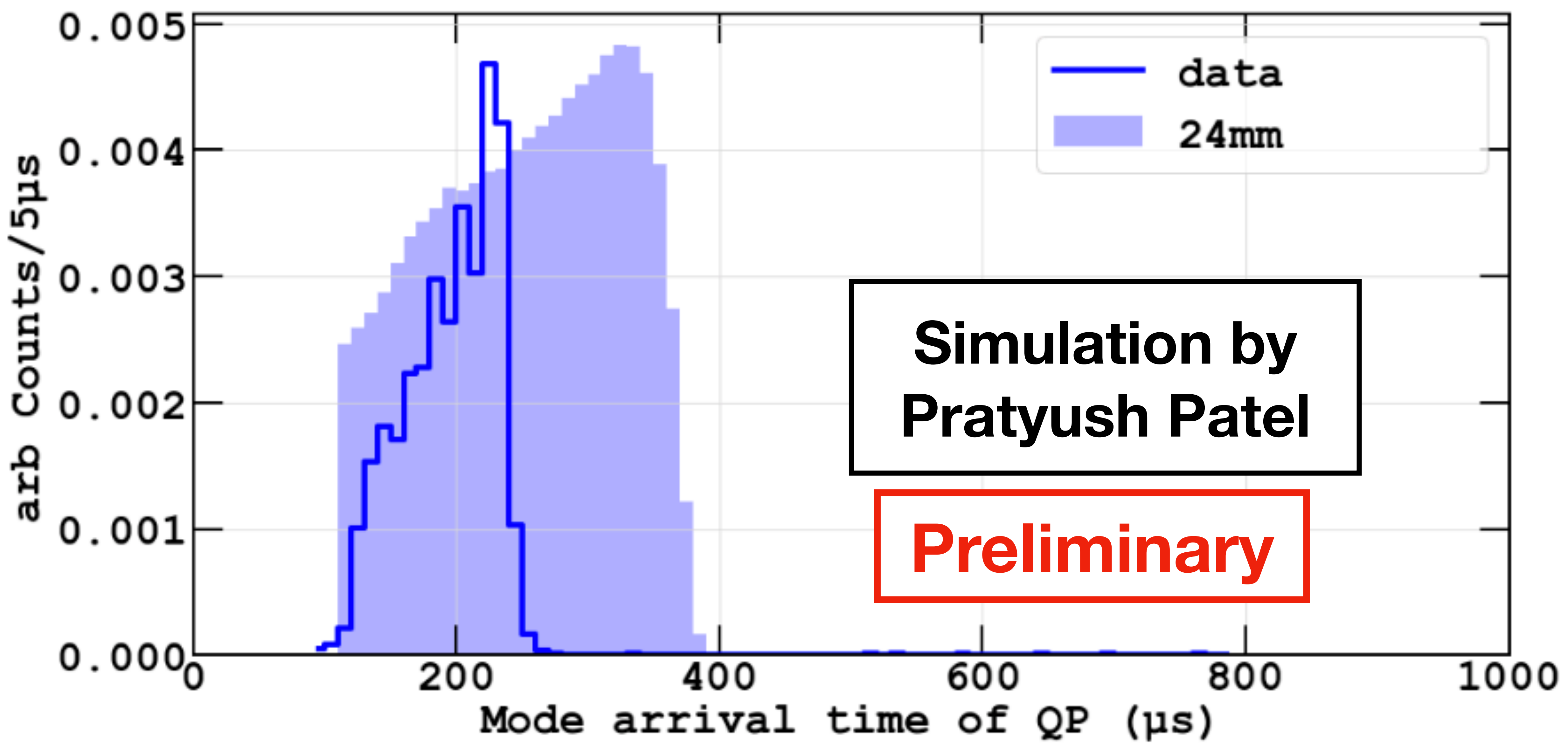




Evaporation: Timing

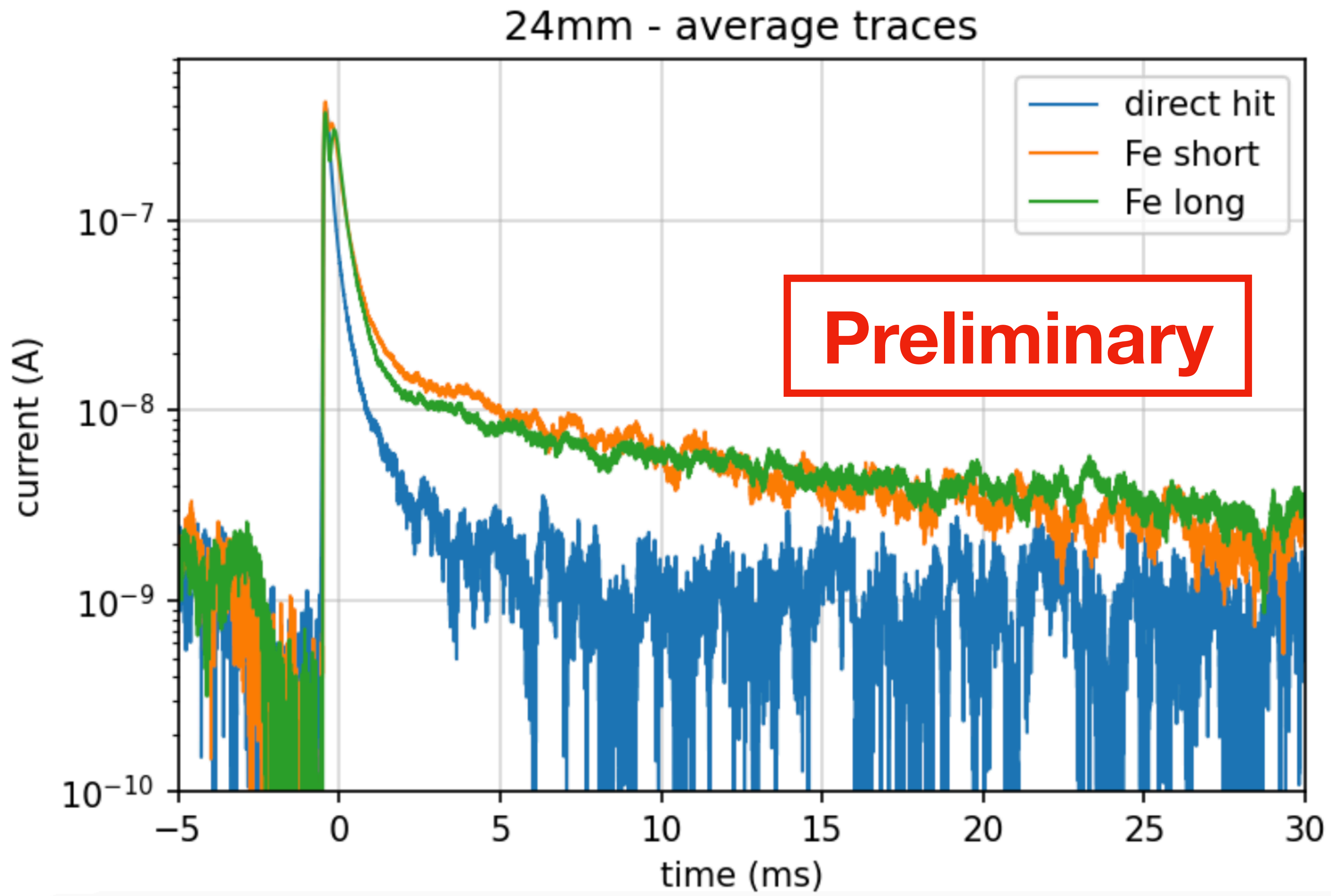
- At the order-of-magnitude level, timing-vs-fill height makes sense
    - Delay time shrinks when helium level is increased
        - Energy travels faster as a quasiparticle in the helium than as an atom
    - At deeper fill levels there is a greater spread in delay times
        - QP transit time becomes comparable to atom-in-vacuum transit time
- Details of timing (arrival distributions) still being understood

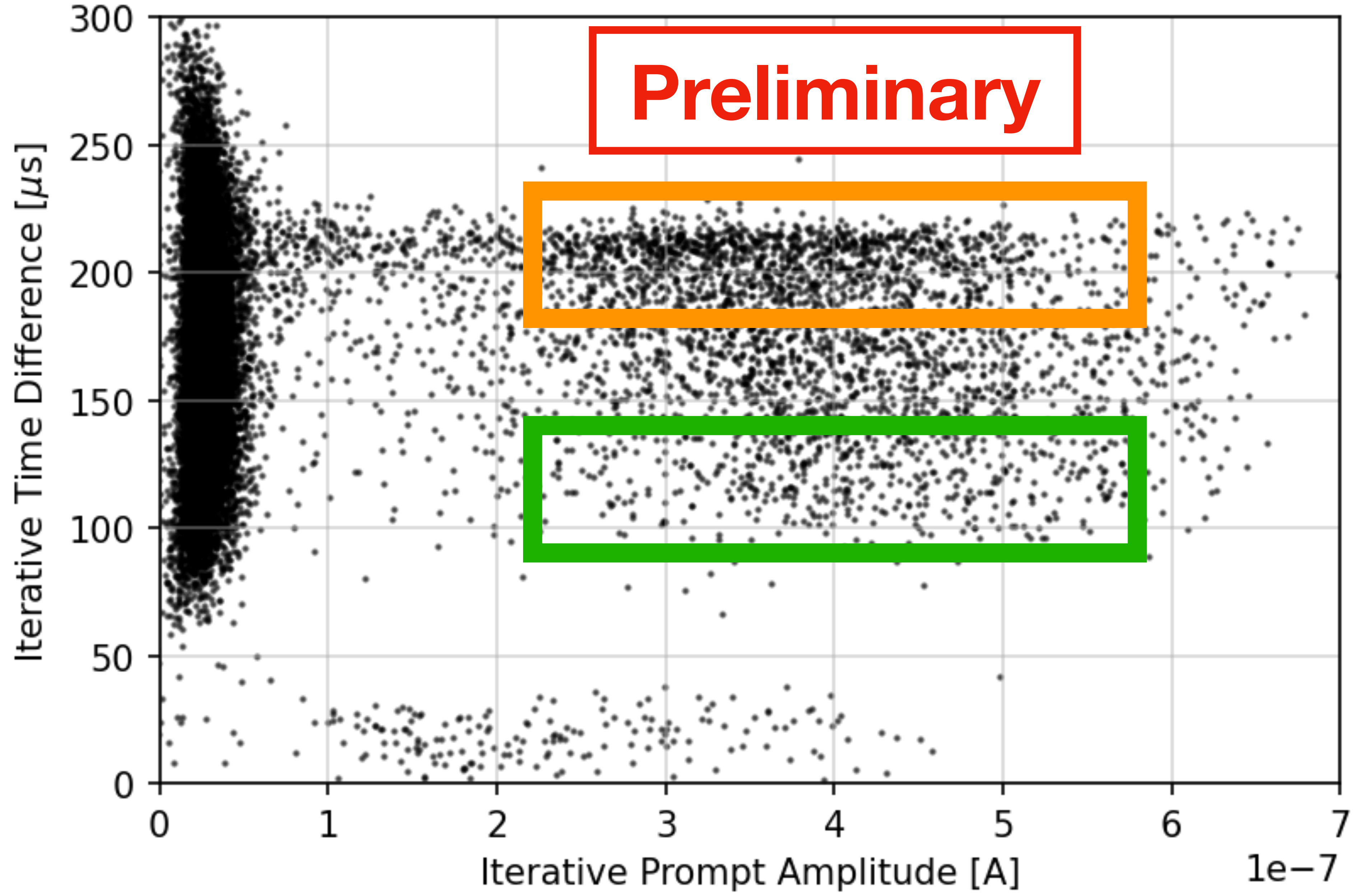




Triplets: Amplitude

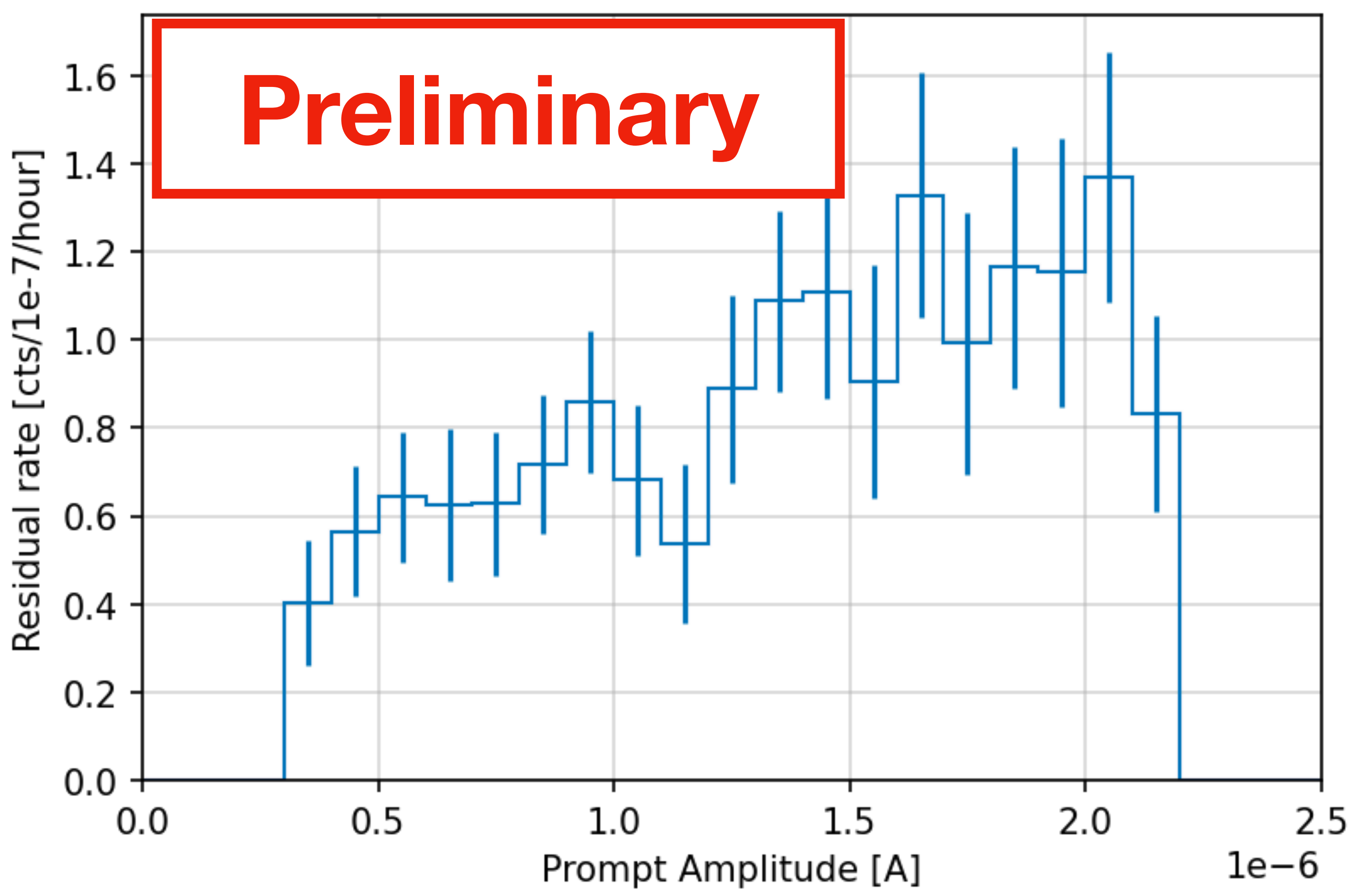
- Work done by David Osterman
- Appearance of a ~5 ms decay constant in averages of ^{55}Fe pulses
- "triplet timing" depends on scintillation - evaporation time delay! (height in detector)
- Some hints at correlations in timing?

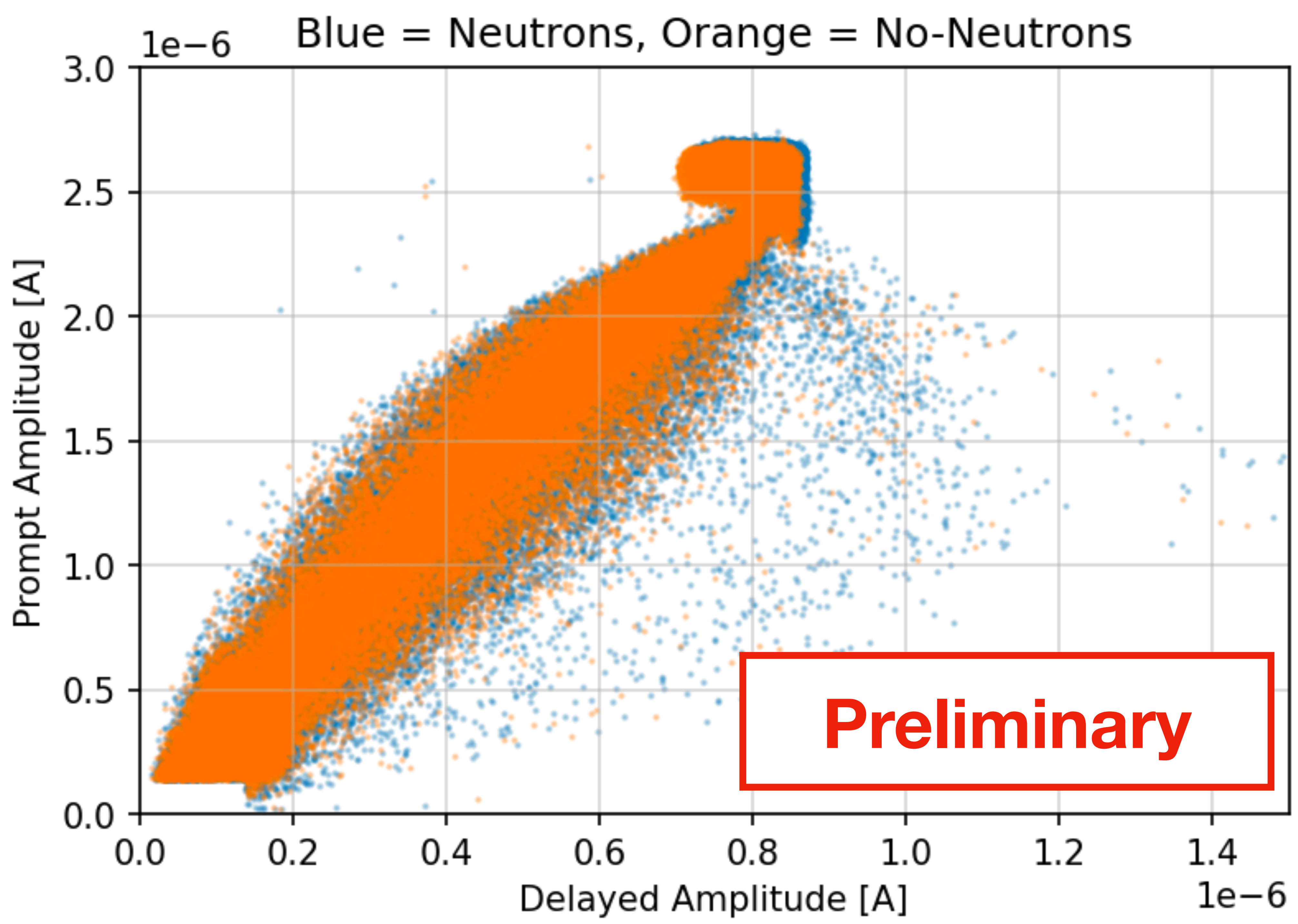




ER/NR Response

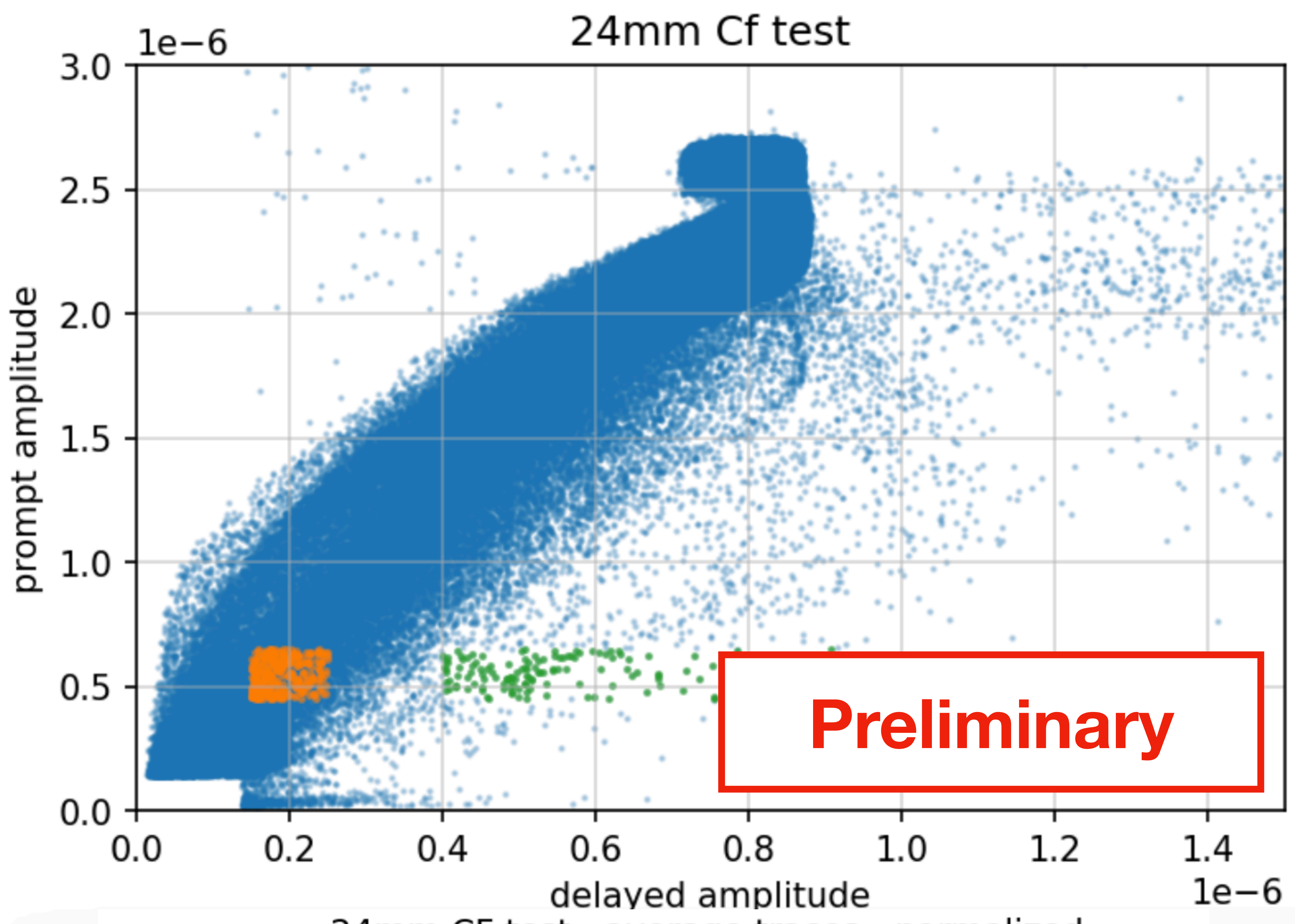
- From signal channel yield models, expect the ability to distinguish between ER and NR events
- Data with and without ^{252}Cf source
- Event population appears at higher delayed amplitude. Expected for NR events

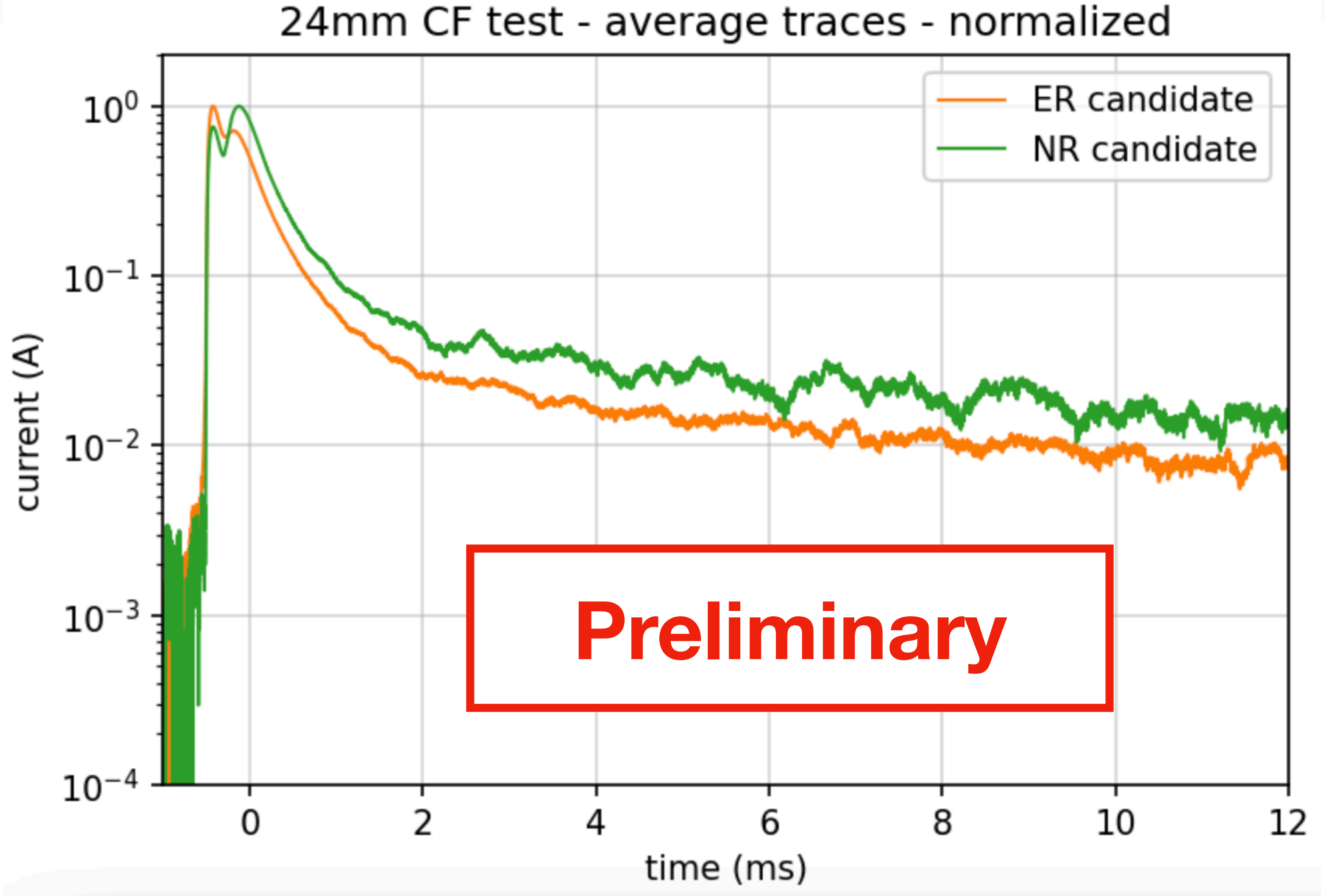




ER/NR Response

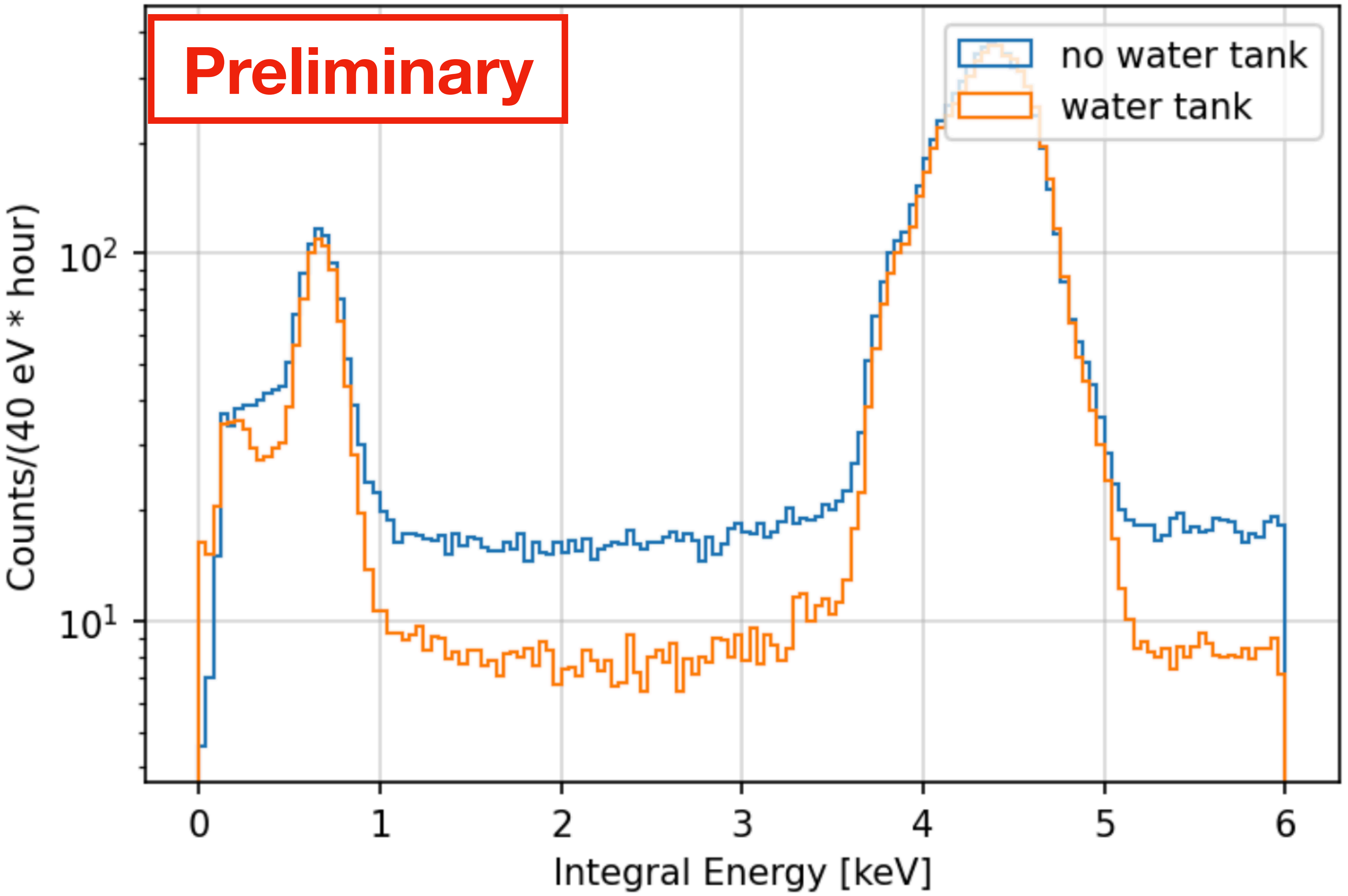
- From signal channel yield models, expect the ability to distinguish between ER and NR events
- Data with and without ^{252}Cf source
- Event population appears at higher delayed amplitude. Expected for NR events
- Perhaps some evidence for increased triplet yield in “NR-like” events

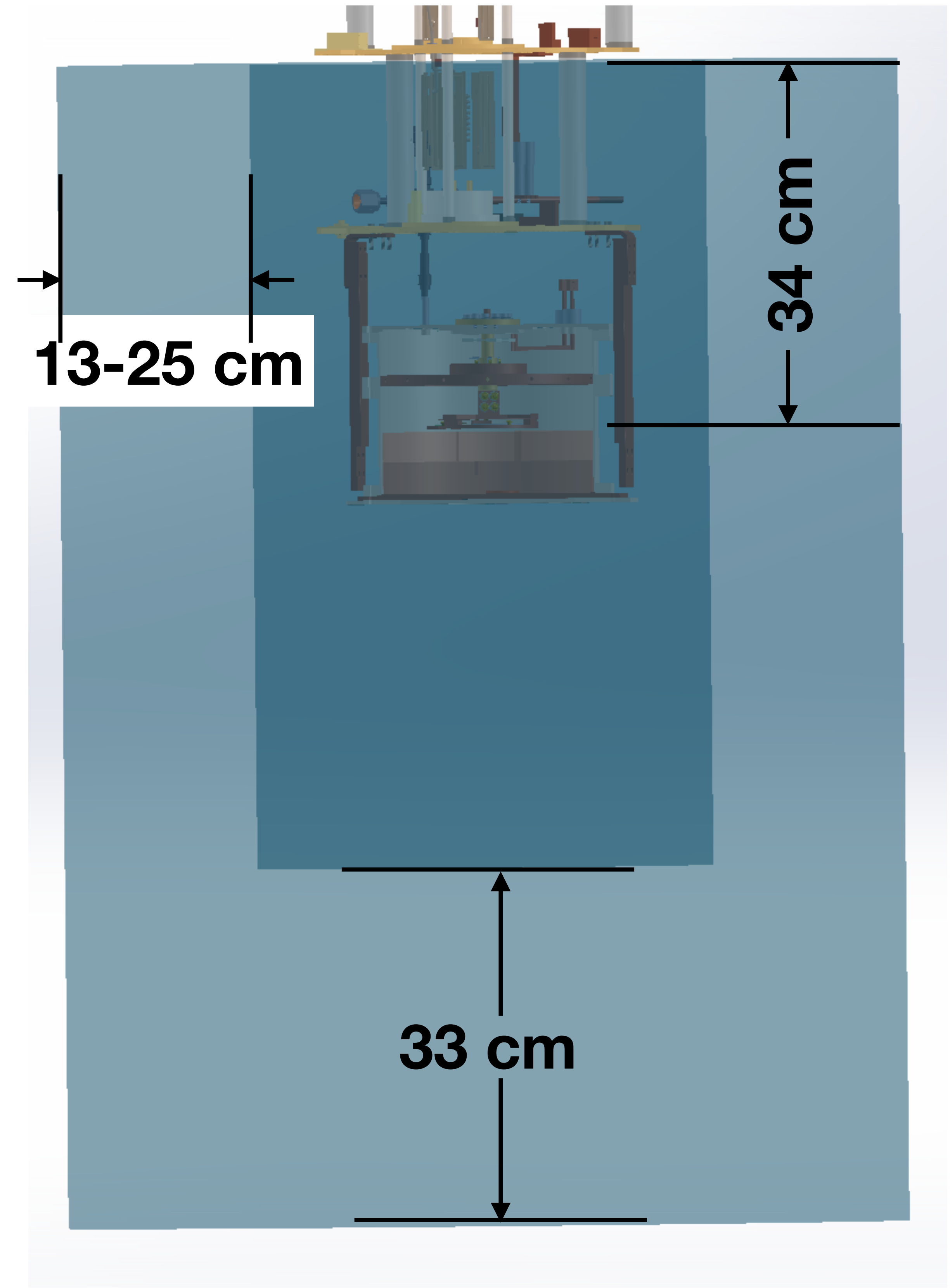




Water Shield

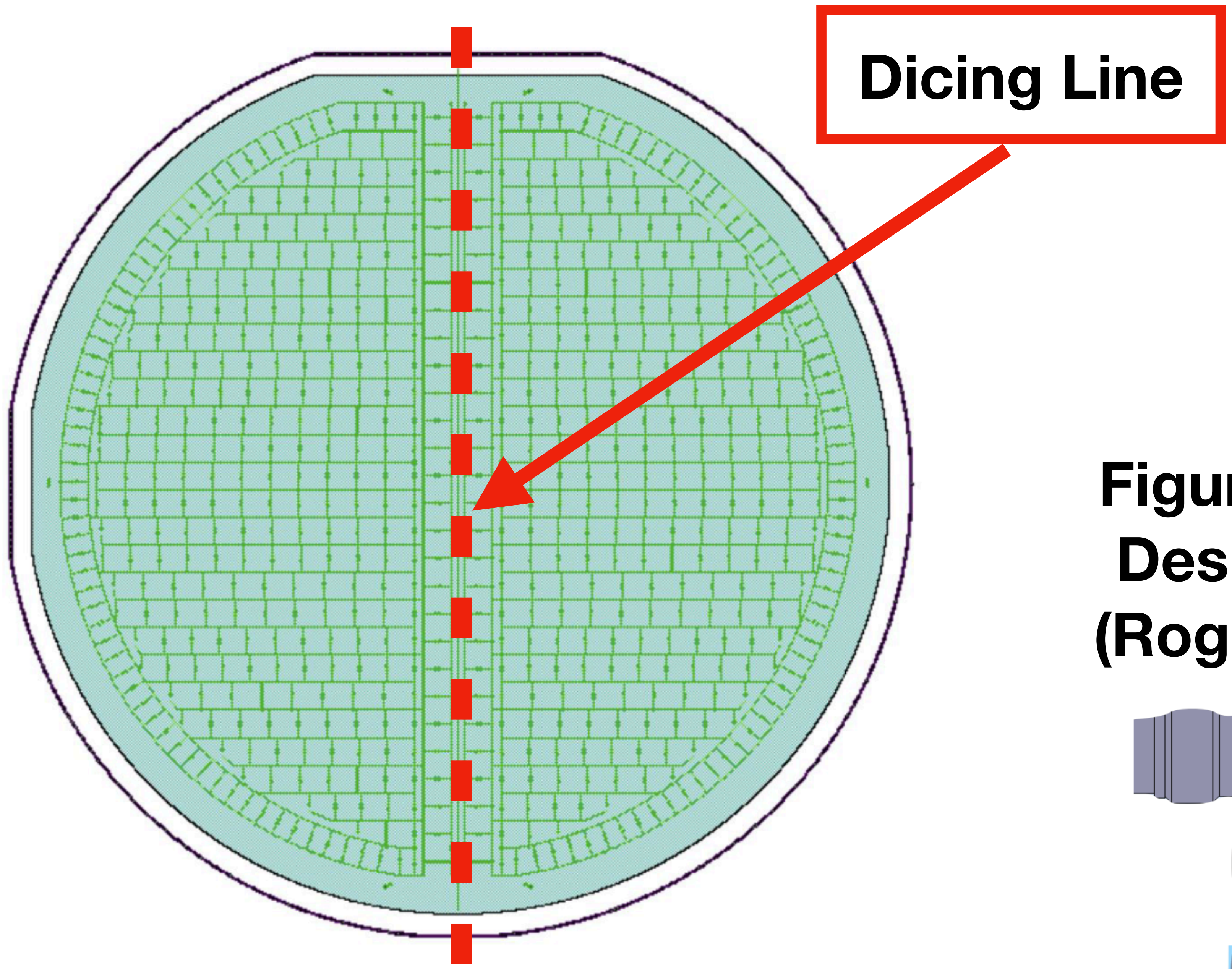
- Added a water shield to attenuate ambient gammas
- Seems to have worked! ~factor of 2 reduction in gamma background, improved resolution





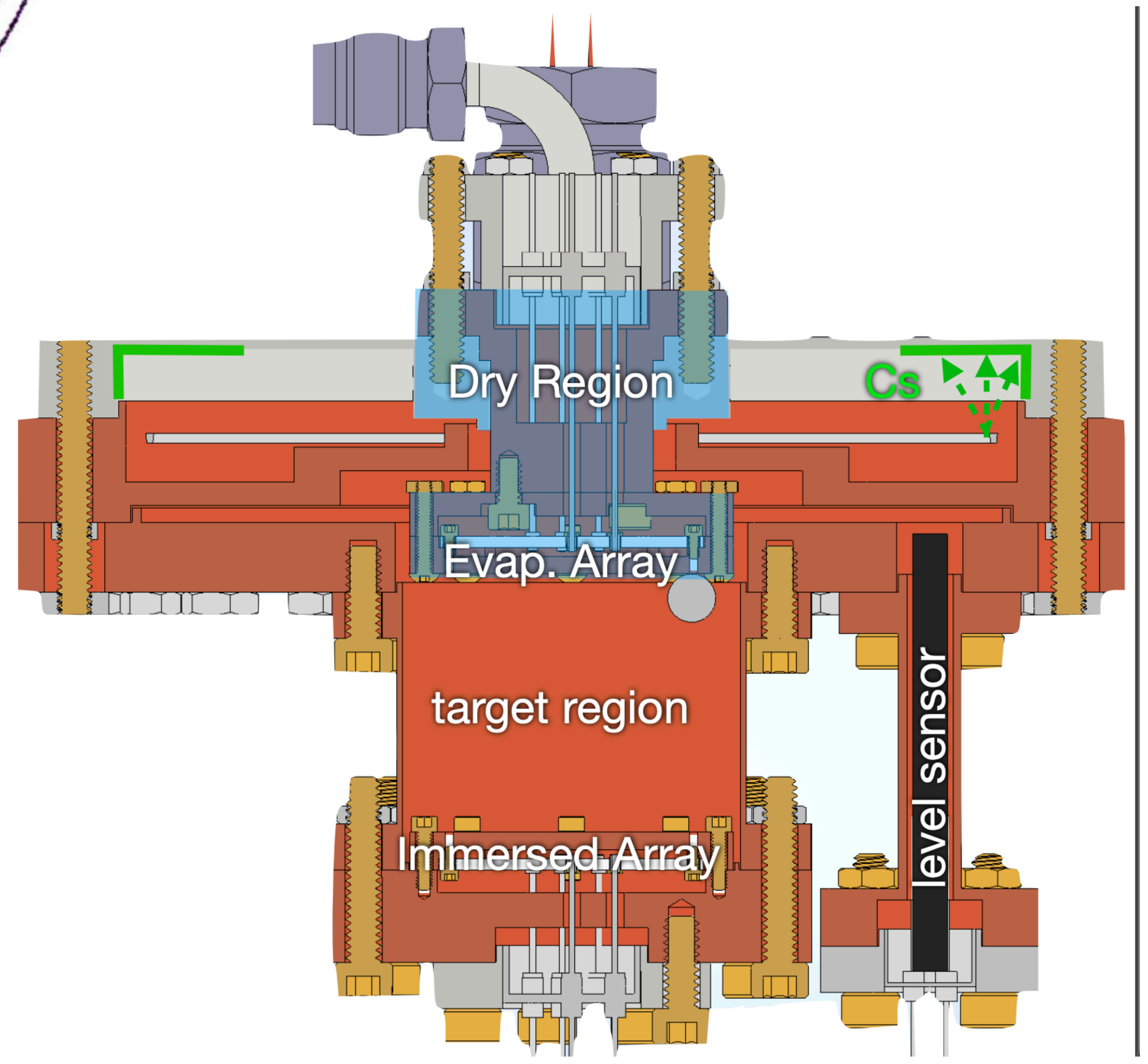
Near Term Measurements

- Quantify efficiencies of signal channels, with particular emphasis on evaporation
- Improve distinction between ER and NR events
- Search for low energy peak from singlet excitations
- Attempt an above-ground DM search
    - Current threshold ~250 eV_{nr} from evaporation channel, ~380 MeV DM mass
- Upgrade to a "split detector" design to veto sensor anti-coincidence
- Improved design under construction at UCB



Design Credit: David Osterman

Figure from Scott Hertel Design by UC Berkeley (Roger Romani + others)



Conclusions

- HeRALD V0.1 is operating with a Cs-based film stopper below 10 mK
- An improved design is under construction at UCB/LBNL
- Stay tuned!

Other SPICE/HeRALD Talks at CPAD:

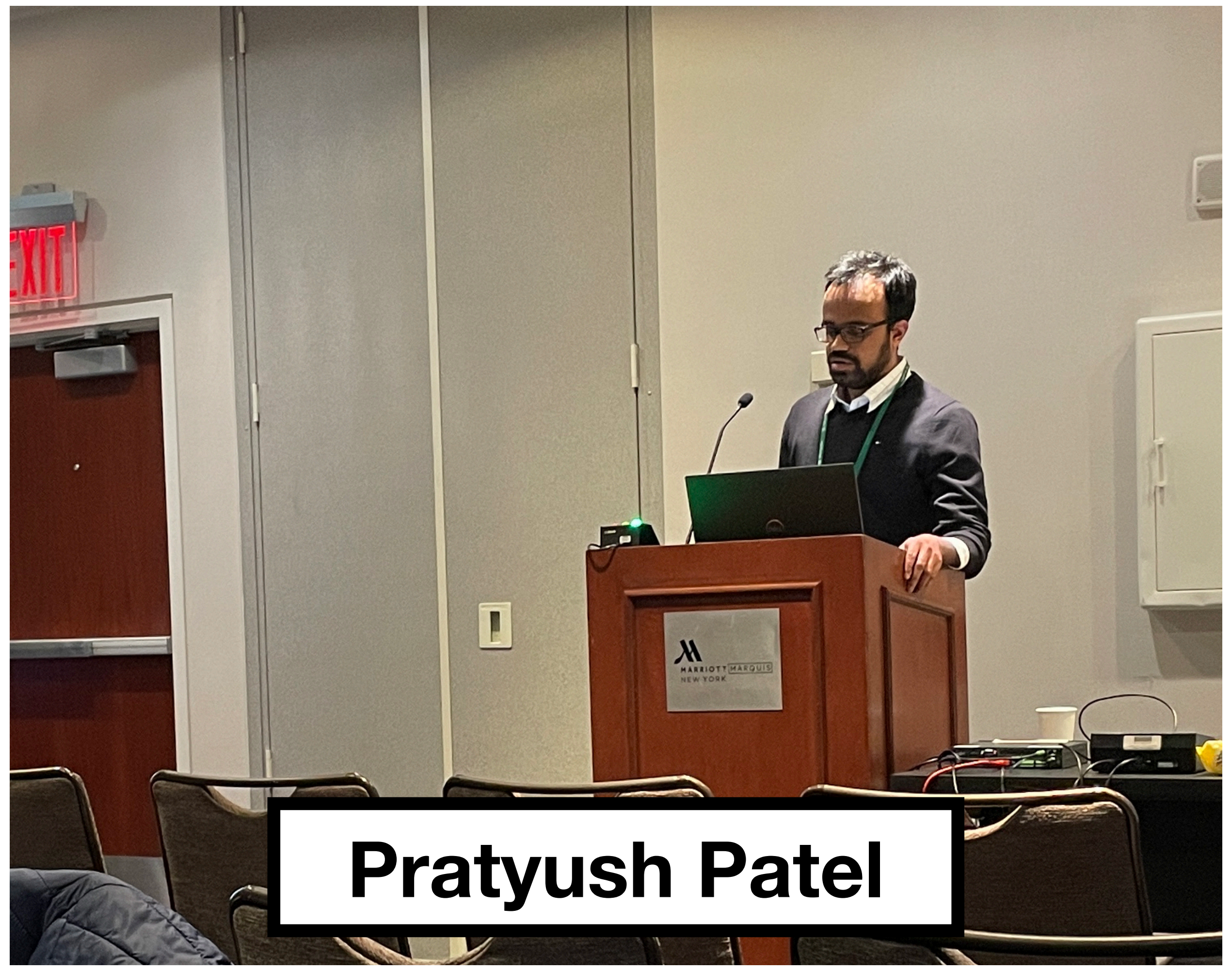
- **Roger Romani - Wednesday at 13:35, WG4**
- **Pratyush Patel - Thursday at 9:50, WG8**
- **Xinran Li - Thursday at 10:35, WG4**
- **David Osterman - Thursday at 10:55, WG4**

+Charlie Veihmeyer, Kylie Gannon, Gus Yacteen

David Osterman


PI: Scott Hertel


Luke Chaplinsky

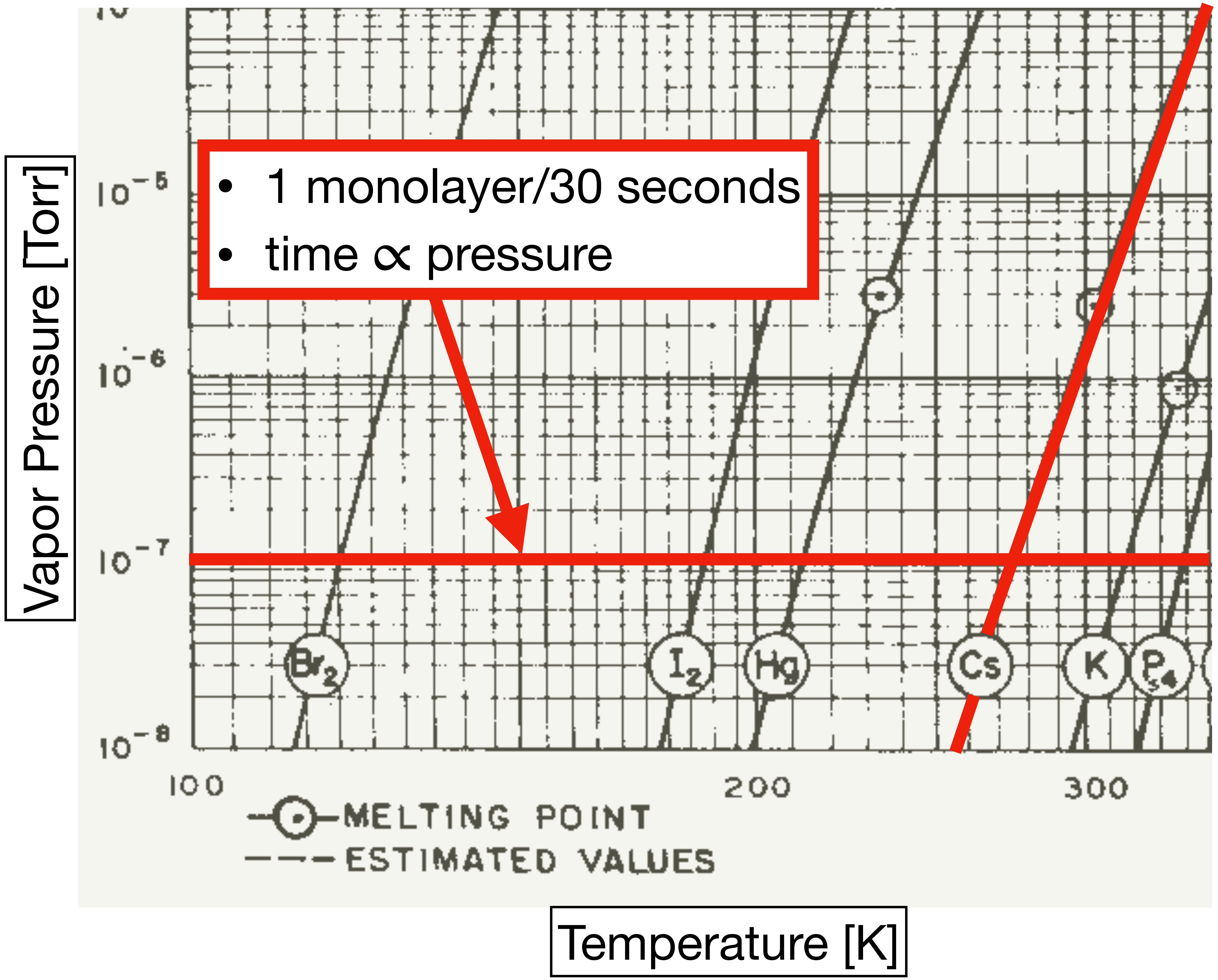


Pratyush Patel

Extras

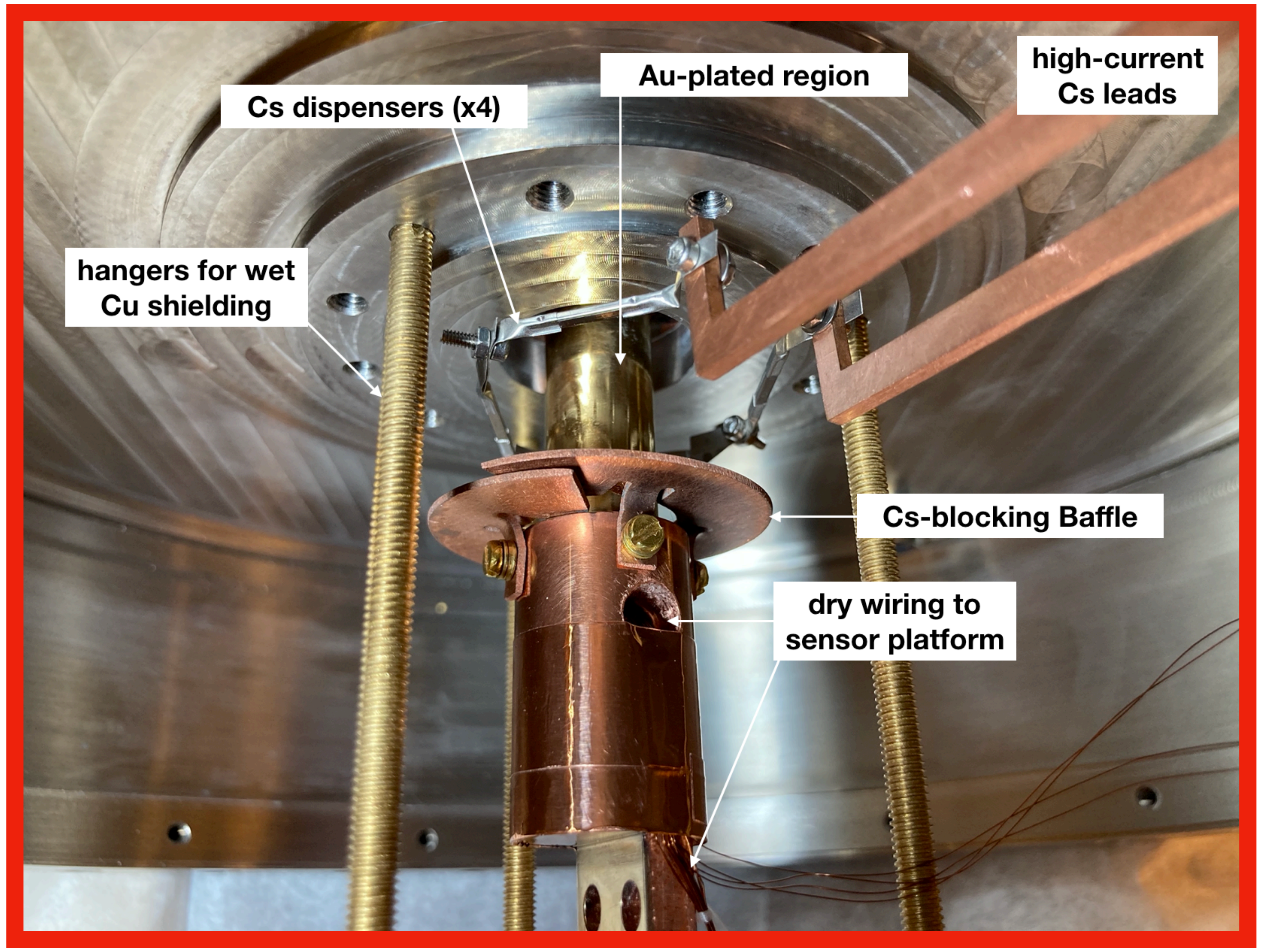
Film Stopping: Cs Challenges

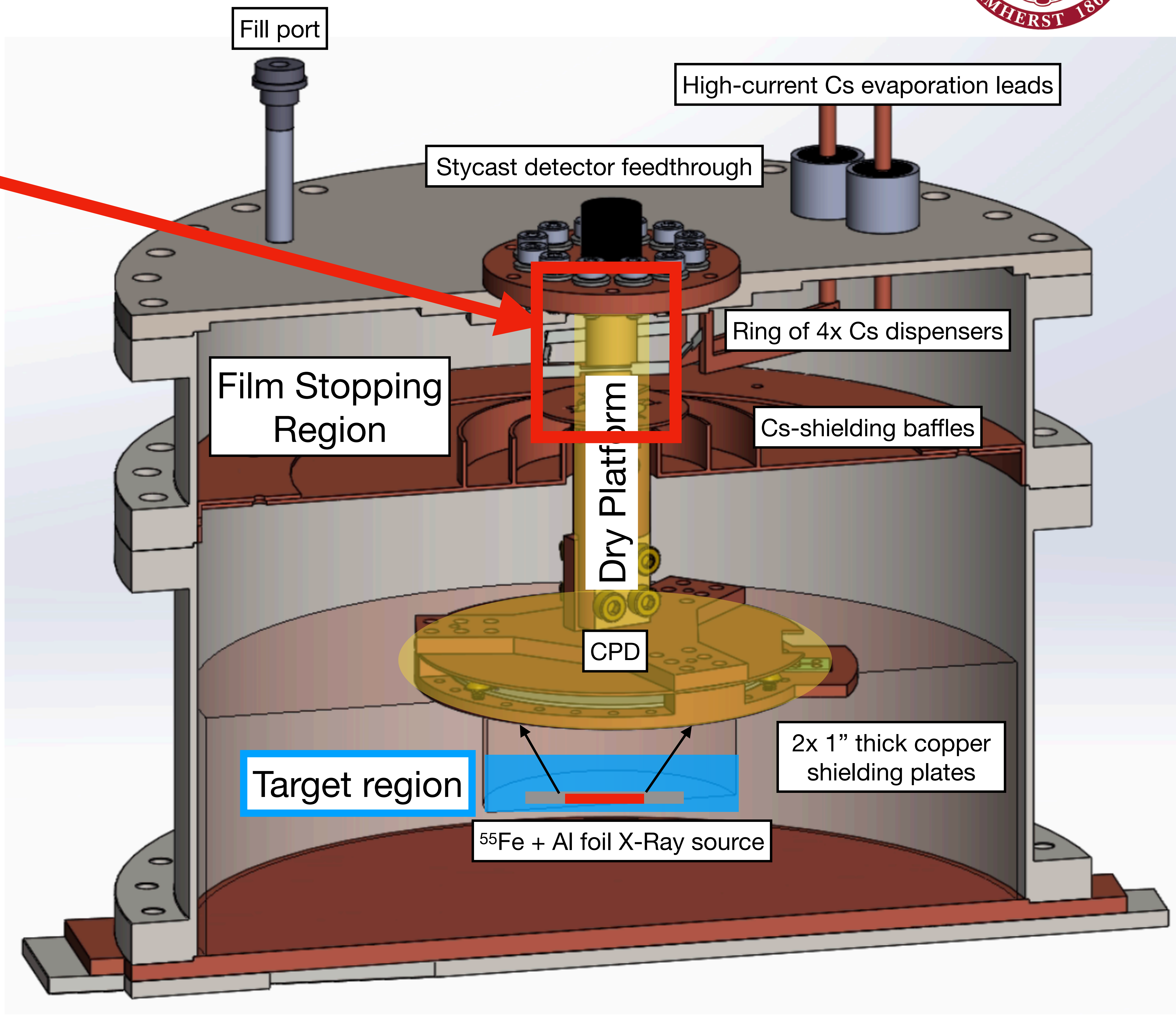
1. Cs is highly reactive with air
    - Evaporate it in-situ
2. Cs has a high vapor pressure
    - 1 monolayer/hour around 220 K
    - Perform the evaporation cold
3. Cs requires temperatures of ~800 C to evaporate
    - Current leads must supply 7.5 A of current



Film Stopping: Implementation

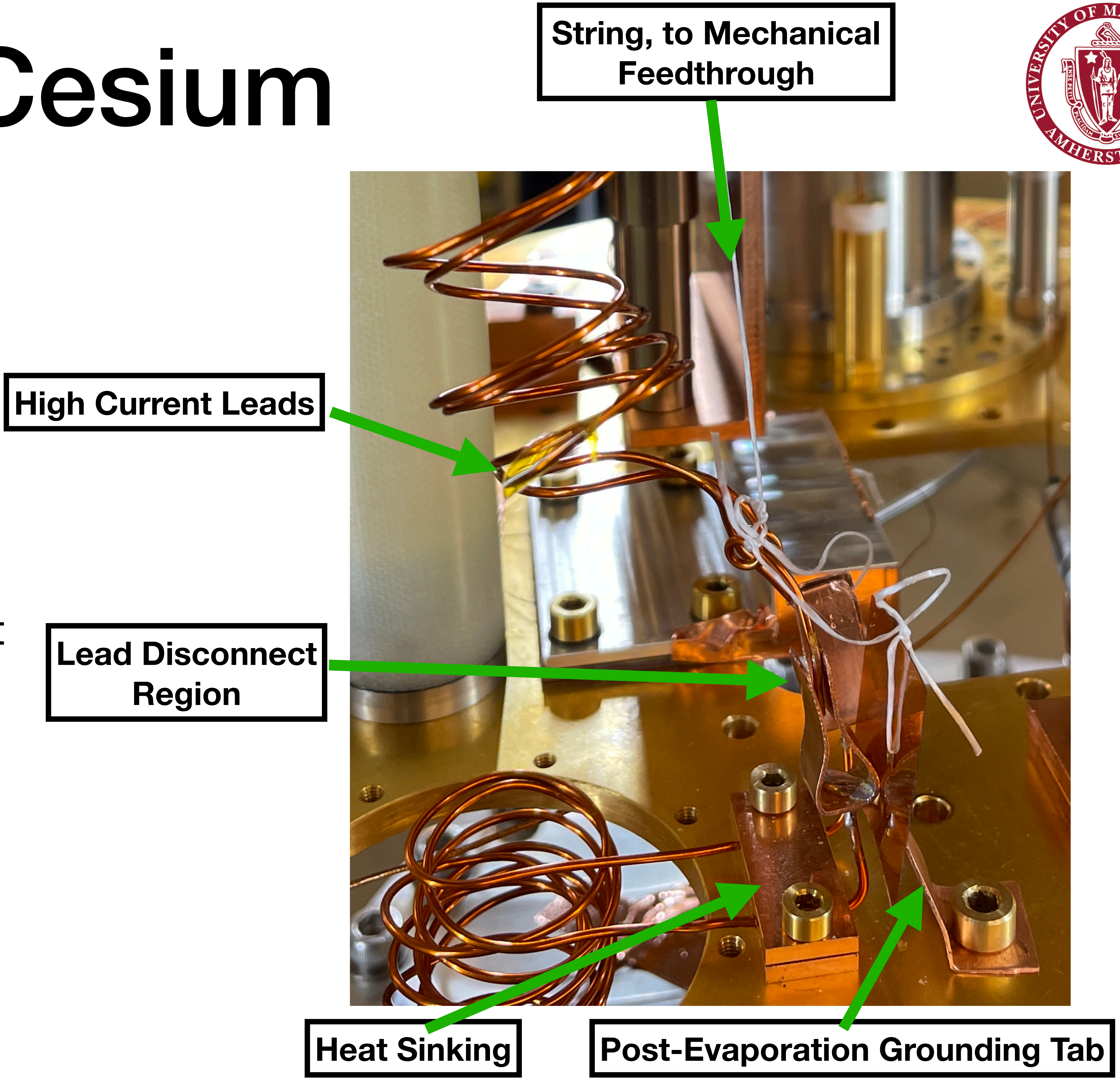
- To solve these challenges, deposit in situ between 4 K and 60 K on Au-plated Cu substrate
    - Ramp to 7.5 A current, 0.1 A/min. Soak at 7.5 A for 20 minutes





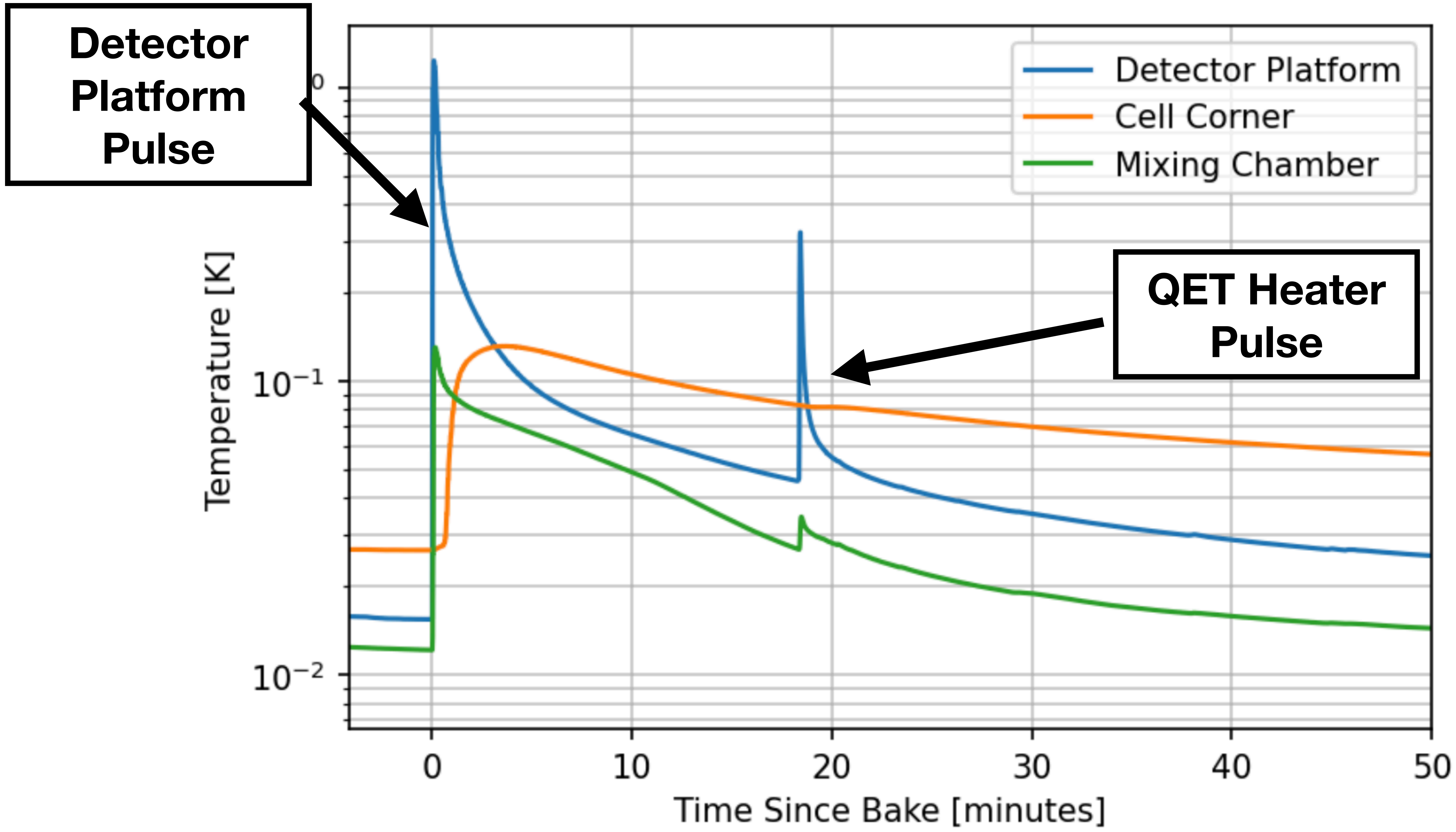
Film Stopping: Cesium

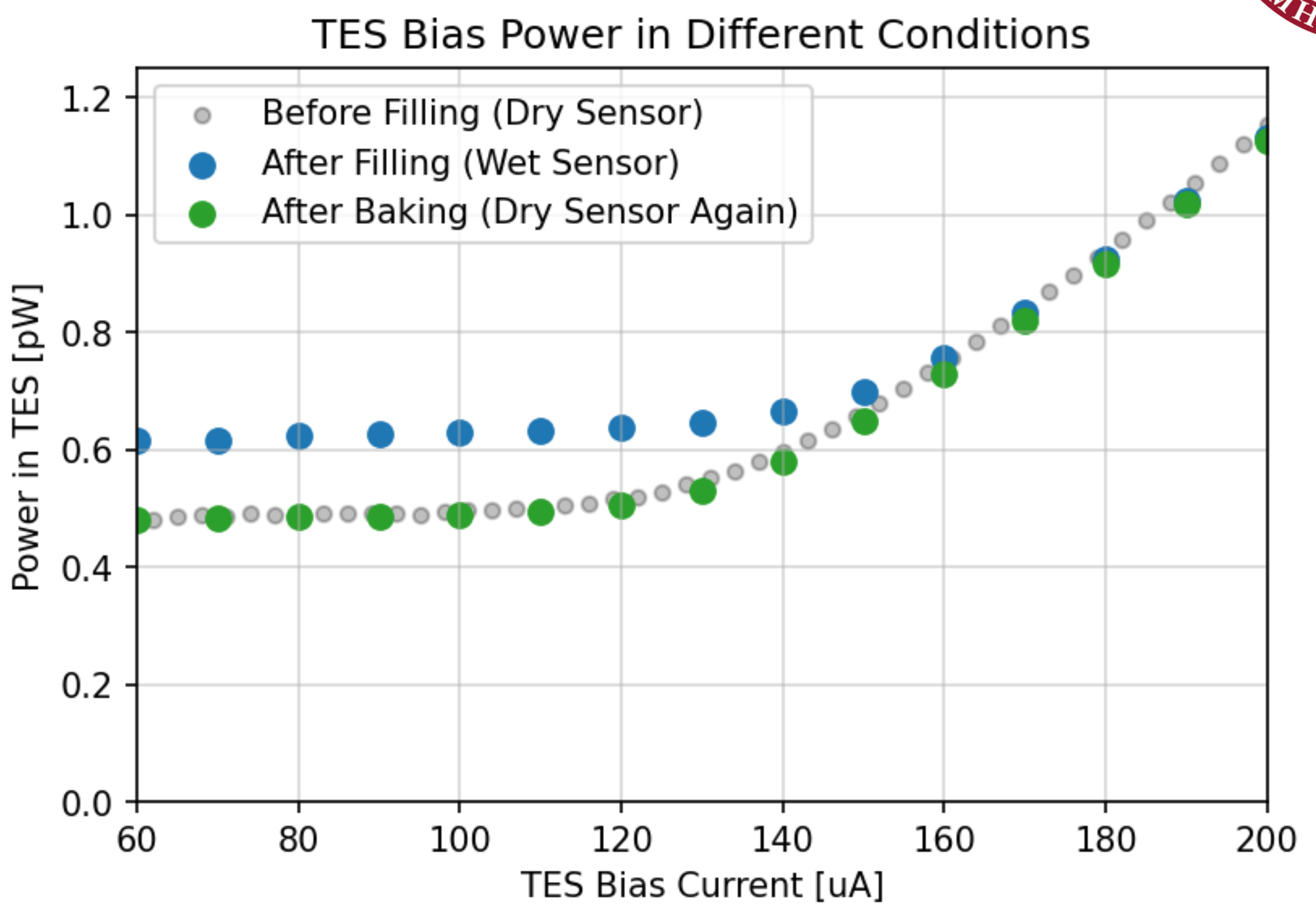
- To solve these challenges, deposit in situ between 4 K and 60 K on Au-plated Cu substrate
    - Ramp to 7.5 A current, 0.1 A/min. Soak at 7.5 A for 20 minutes
- Linear motion feedthrough disconnects the high current leads at MC and Still stages
- CO_2 purge on warm up

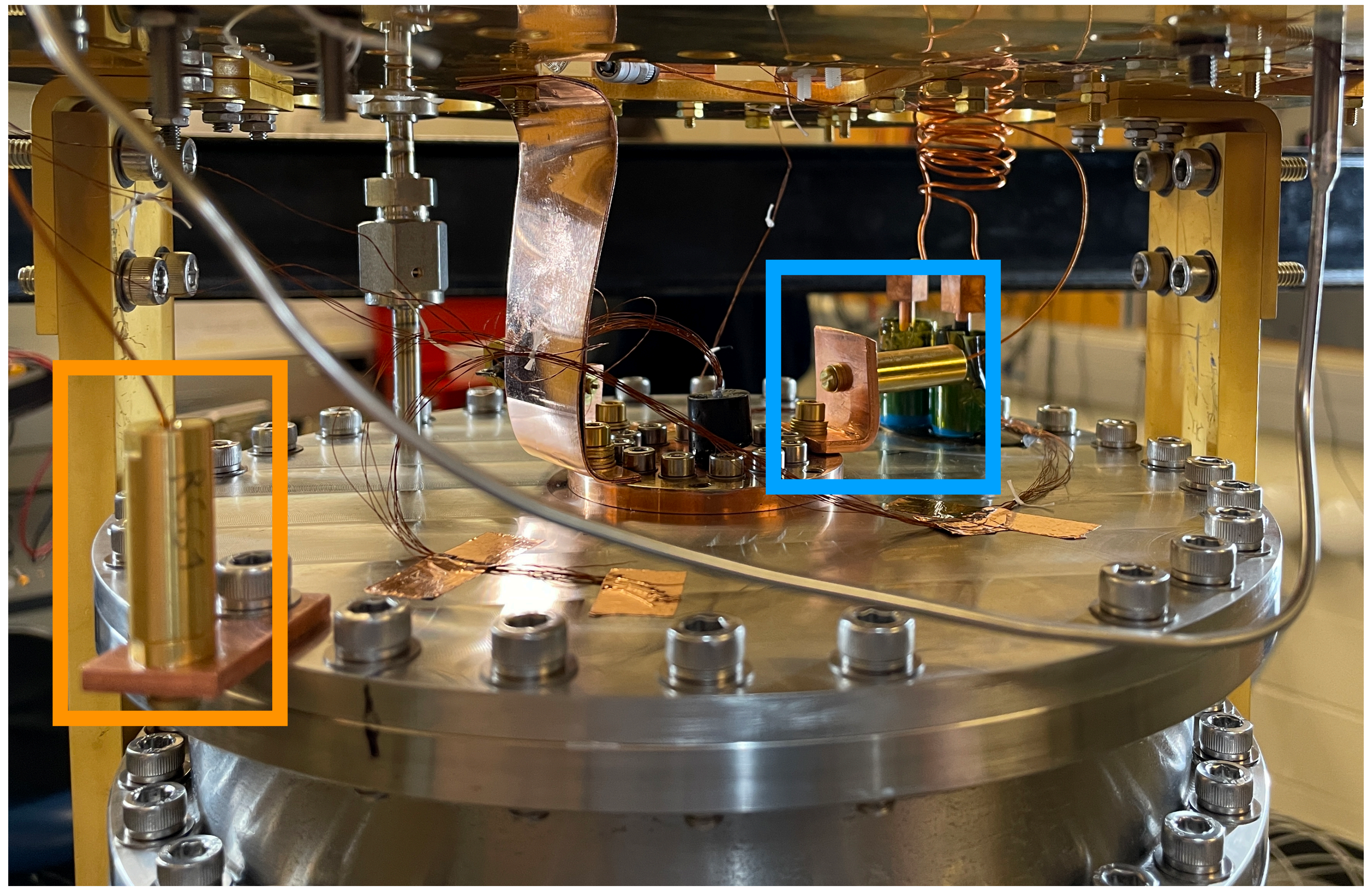


Baking the Calorimeter

- Detector platform reached “5 mK” (below RuOx range)
- Bias power indicates helium removal

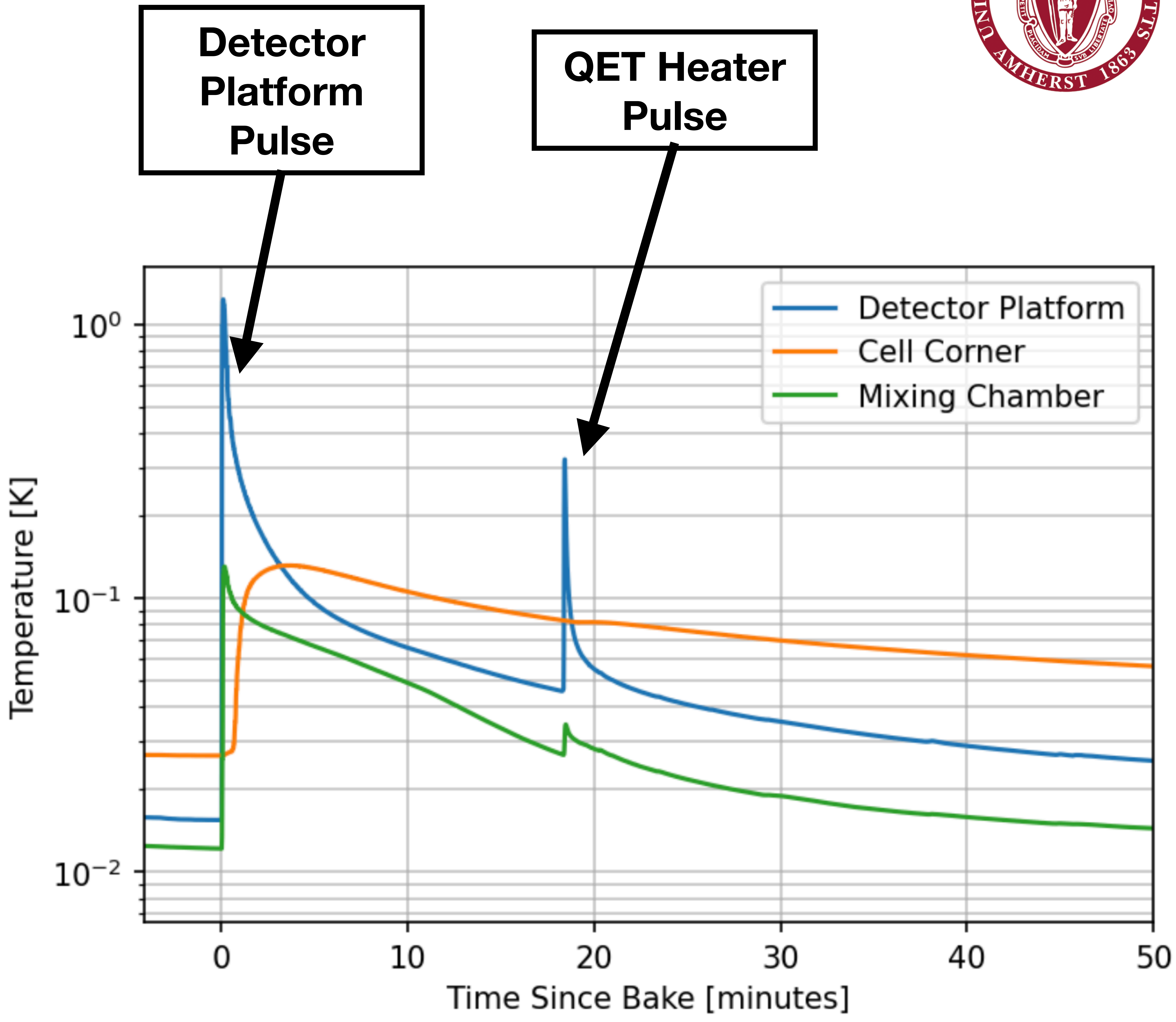






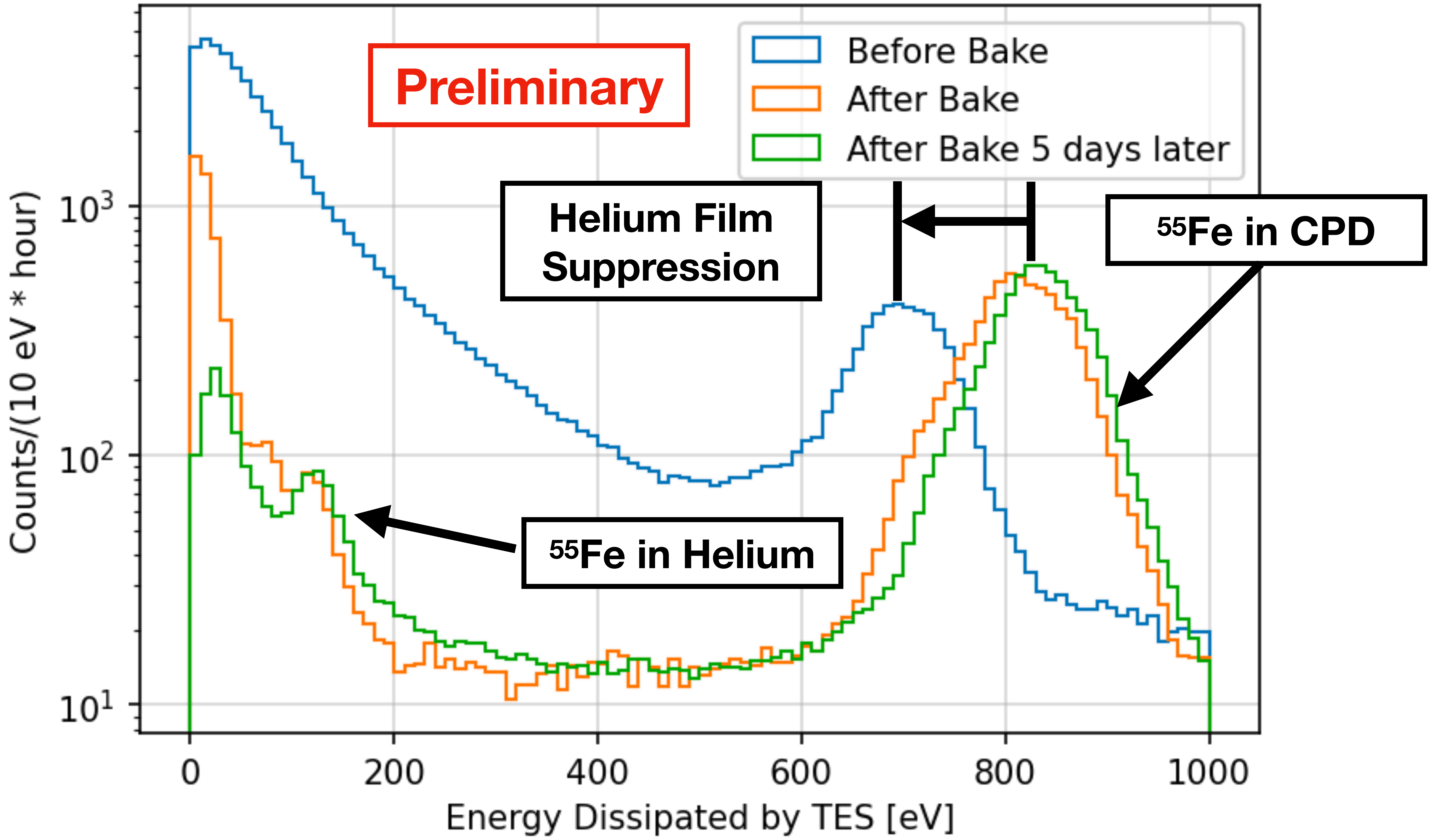
Detector Baking

- Goal to get “dry” surfaces above ~350 mK, while keeping “wet” surfaces below 225 mK
    - Need to prevent “wet” surfaces from re-evaporating helium onto the detector
- Current run:
    - Detector reaches 1.2 K, hottest “wet” surface reaches 130 mK
    - Engineered thermal links to achieve this goal



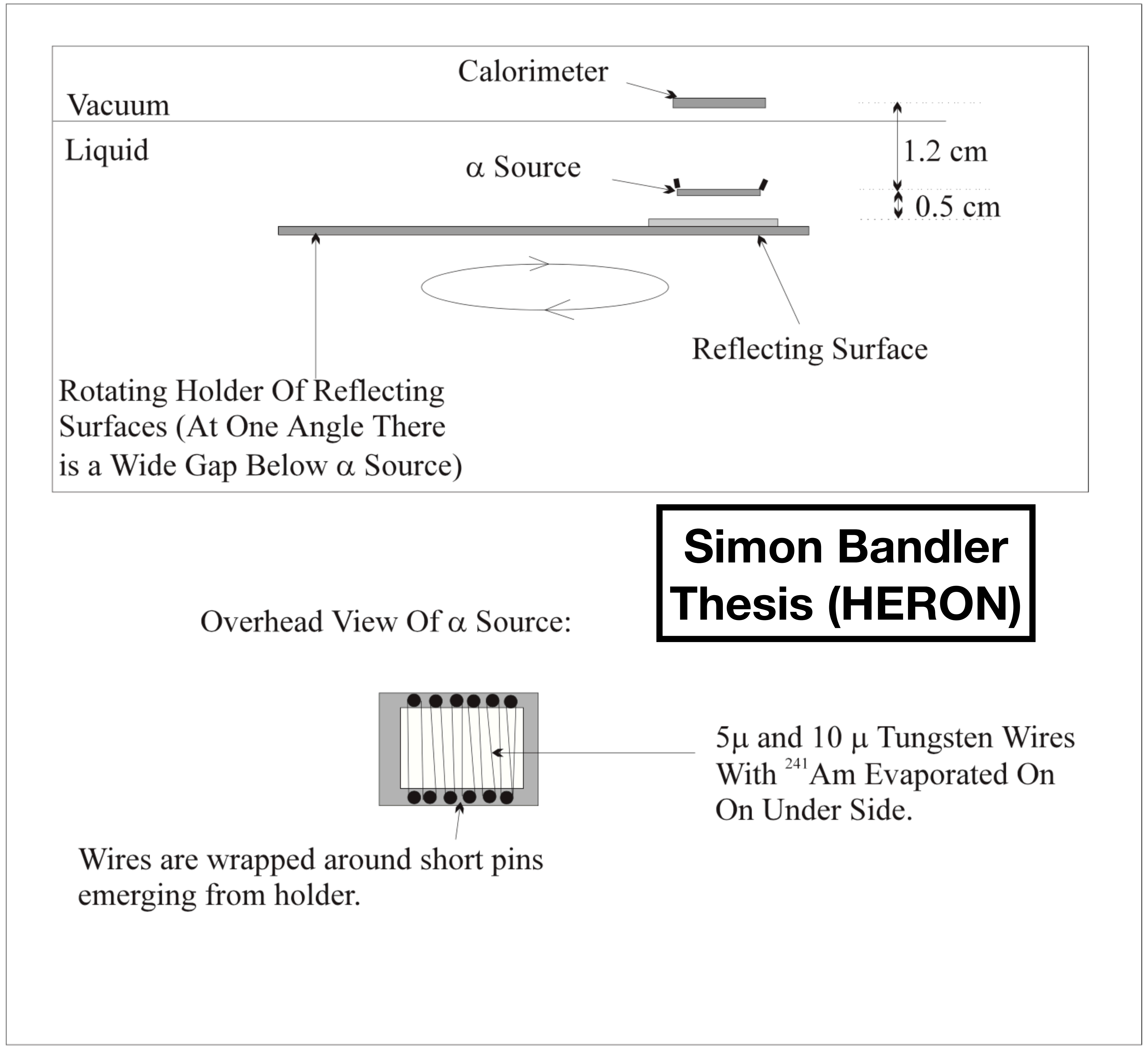
Baking the Calorimeter

- Detector platform reached “5 mK” (below RuOx range)
- Bias power indicates helium removal
- Shift in ^{55}Fe peak after baking



Future Measurements

- Study how vibrational quasiparticles reflect from various surfaces
    - Some of this work was done by HERON. Do this work with an expanded materials set (Cs coatings, stainless steel, wavelength shifter, others?)



Simon Bandler Thesis (HERON)

Fig 6.3. Schematic of experiment to investigate the reflection coefficient of rotons from various materials.

Future Measurements

- Study how vibrational quasiparticles reflect from various surfaces
  - Some of this work was done by HERON. Do this work with an expanded materials set (Cs coatings, stainless steel, wavelength shifter, others?)
- Study how triplets interact with the superfluid-vacuum interface

Triplet de-excitation on metalic surfaces

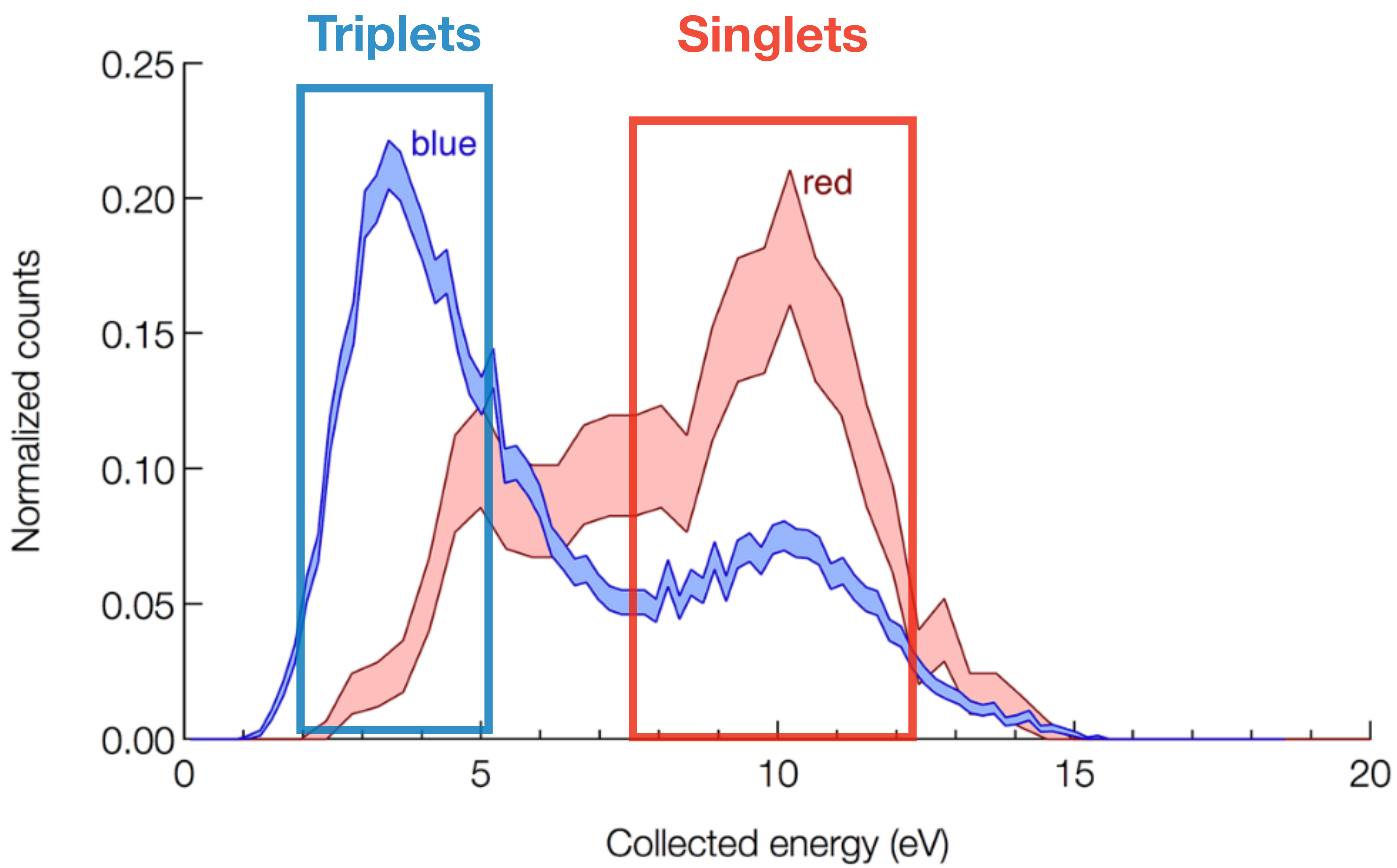


Fig. 4 *Red curve* Detected emission spectrum of singlet He_2^* decays (683 counts). *Blue curve* Total spectrum of all detected events (13 256 counts). *Shaded area between lines* indicates error, calculated as ± the square-root of the counts in each bin (Color figure online)

Carter et al. J Low Temp Phys (2017) 186:183–196

Future Measurements

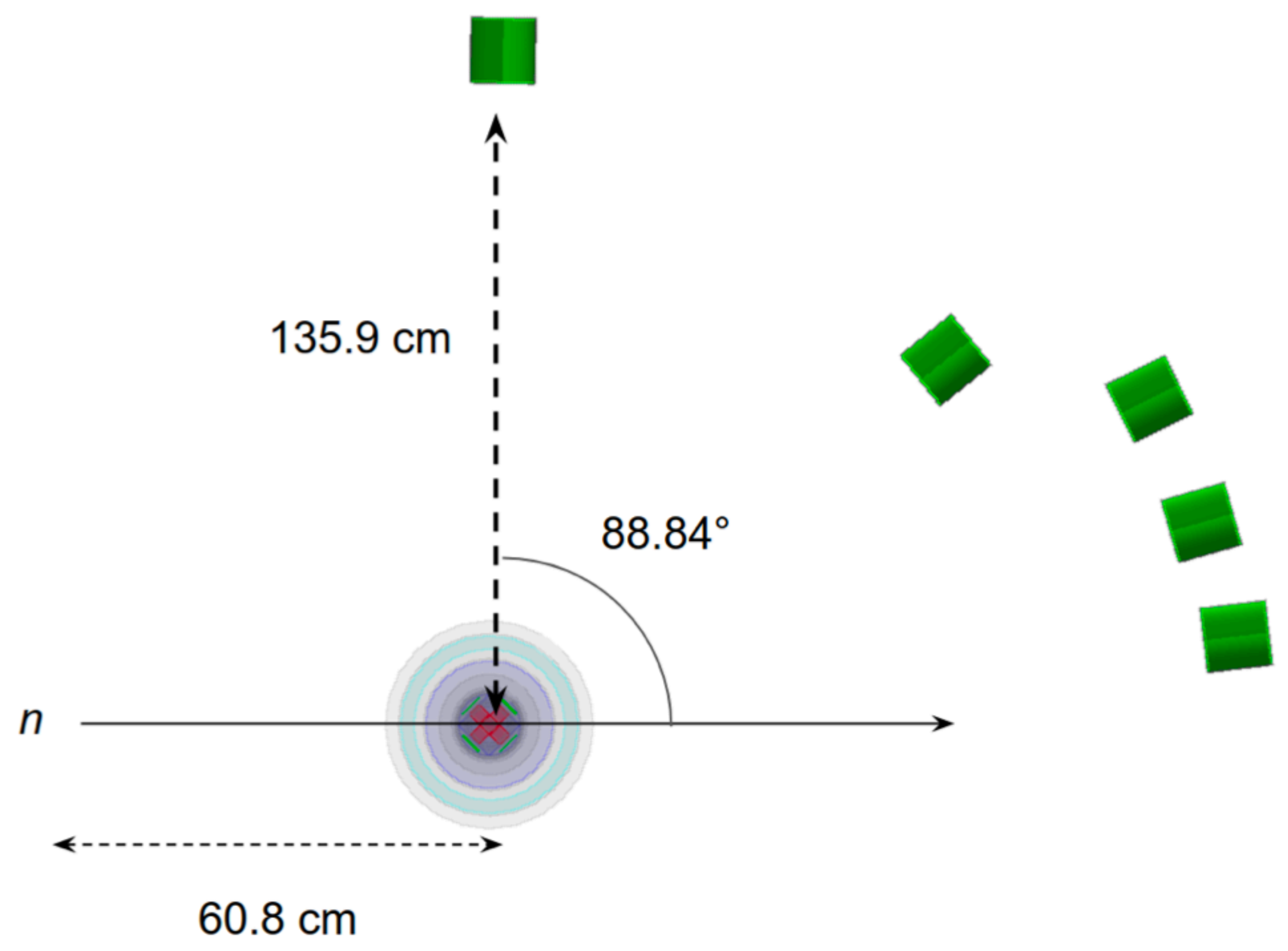
- Study how vibrational quasiparticles reflect from various surfaces
    - Some of this work was done by HERON. Do this work with an expanded materials set (Cs coatings, stainless steel, wavelength shifter, others?)
- Study how triplets interact with the superfluid-vacuum interface
- Enhance adhesion gain with high van der waals materials

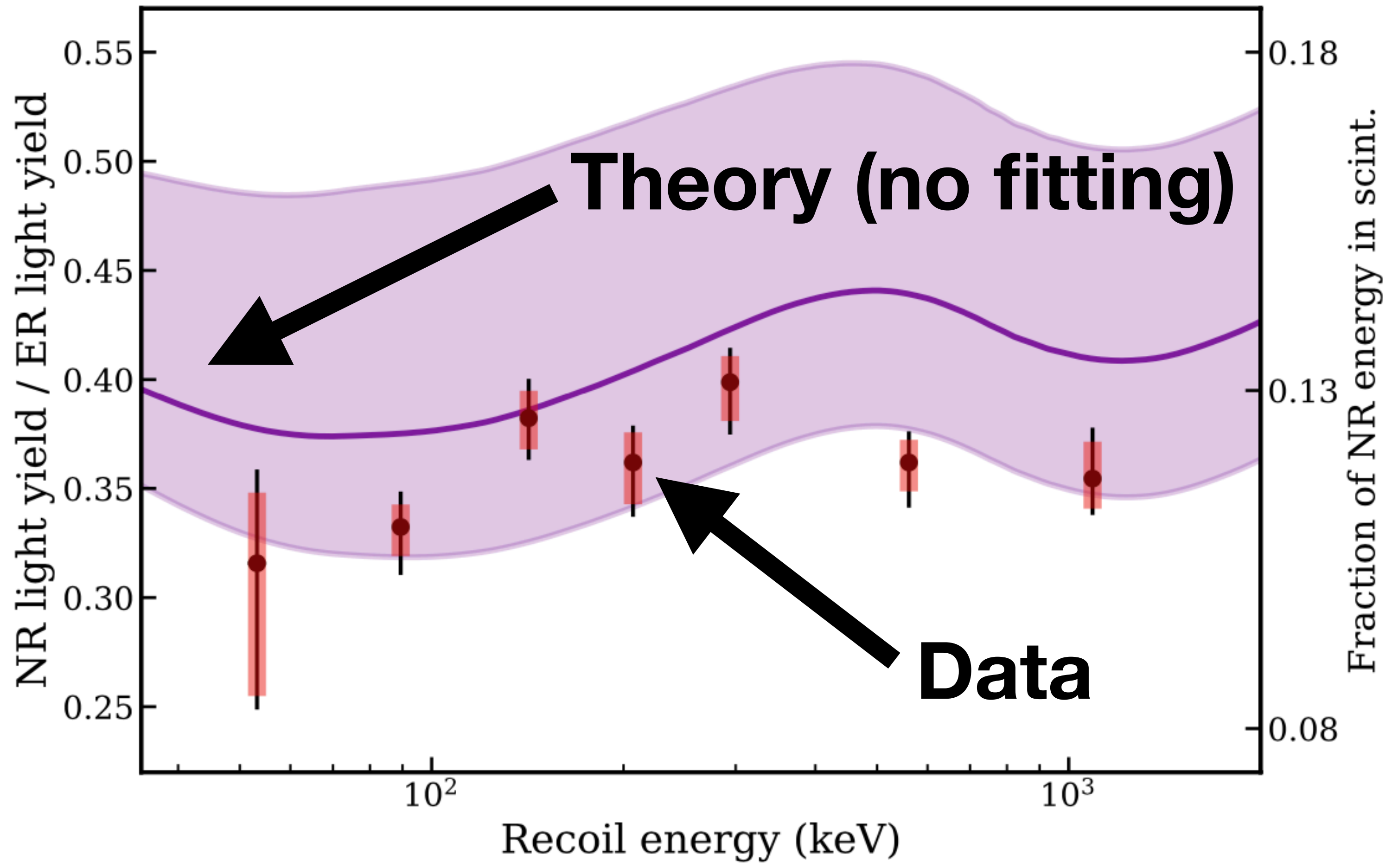
Material	He-Material VdW Potential [meV]
Silicon [1]	7
Graphene [1]	12
Fluoro-graphene [2]	32

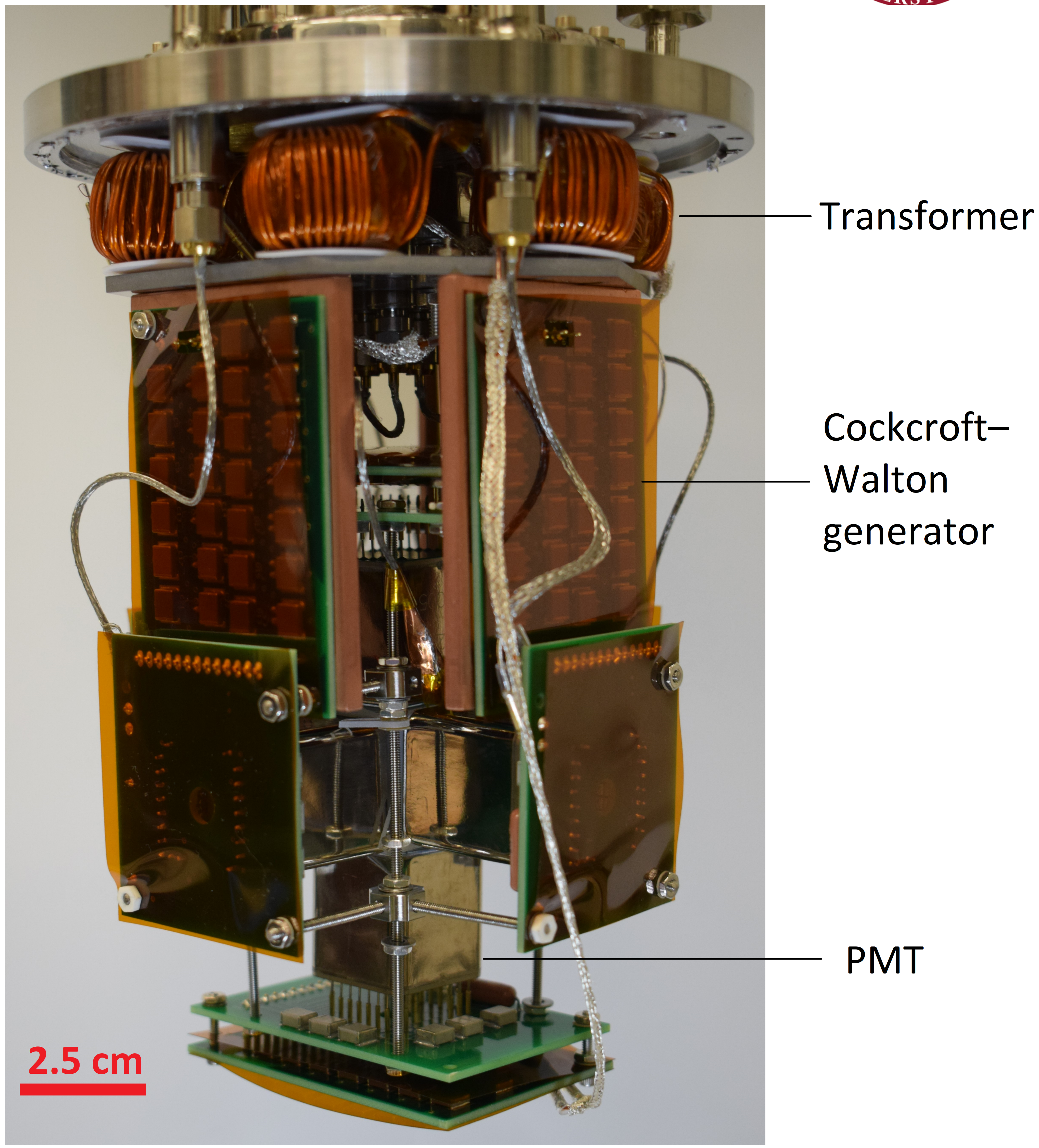
1. Reatto et al. Novel Substrates for helium adsorption: Graphene and Graphene-Fluoride
2. Vidali et al. Potentials of Physical Adsorption

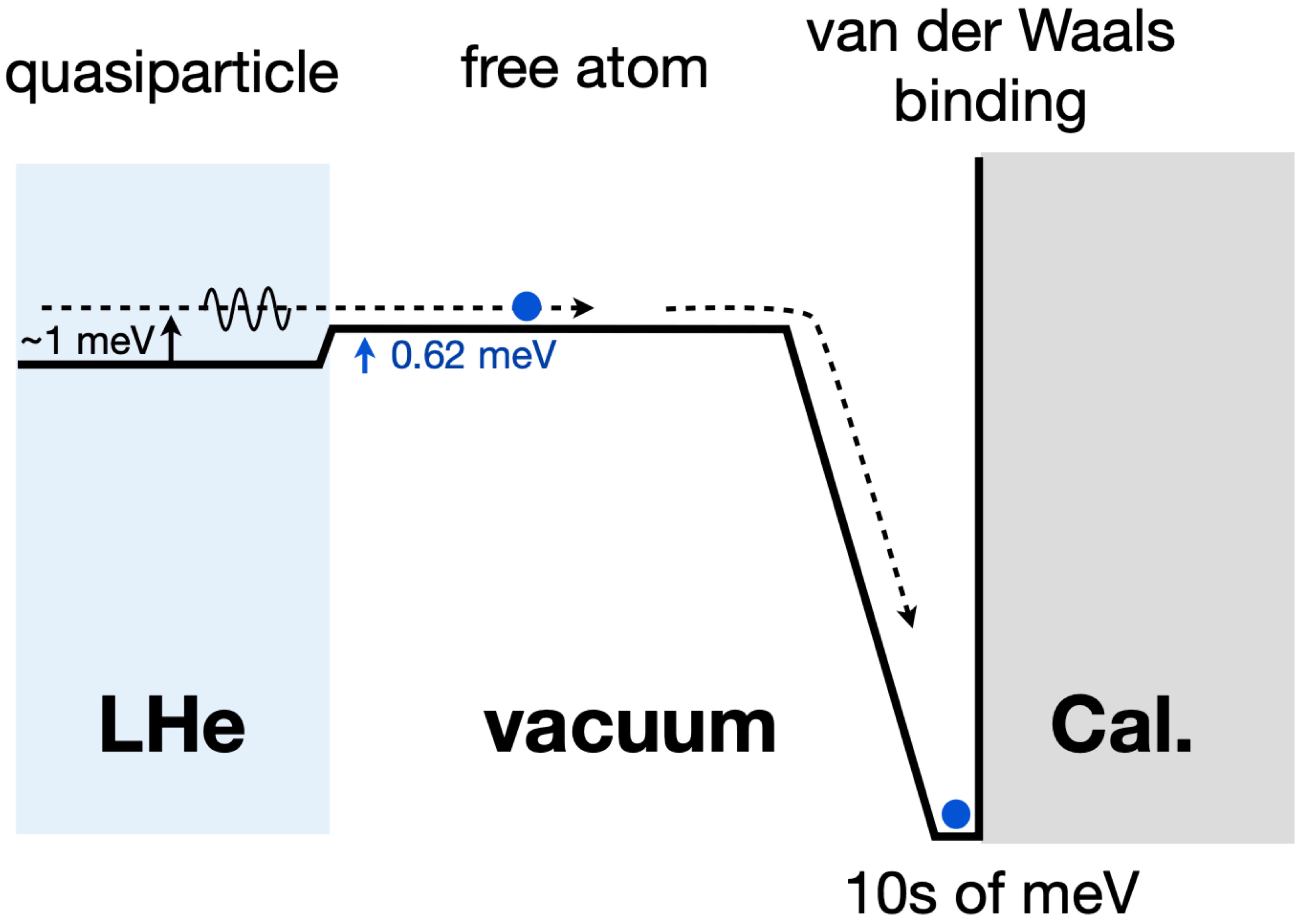
Scintillation Yield of 4He at UCB

- Performed down to ~100 keV so far, with plans to push this lower
- Data above 100 keV agrees well with theoretical predictions
- Using a UMass-designed backing detector for lower energy measurements



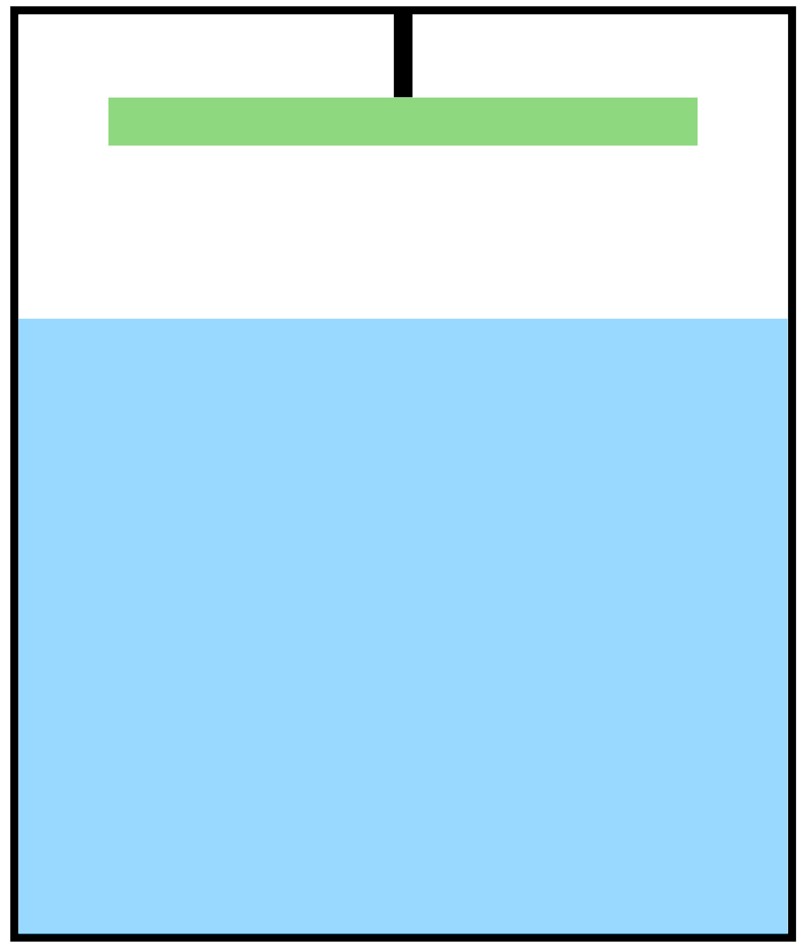


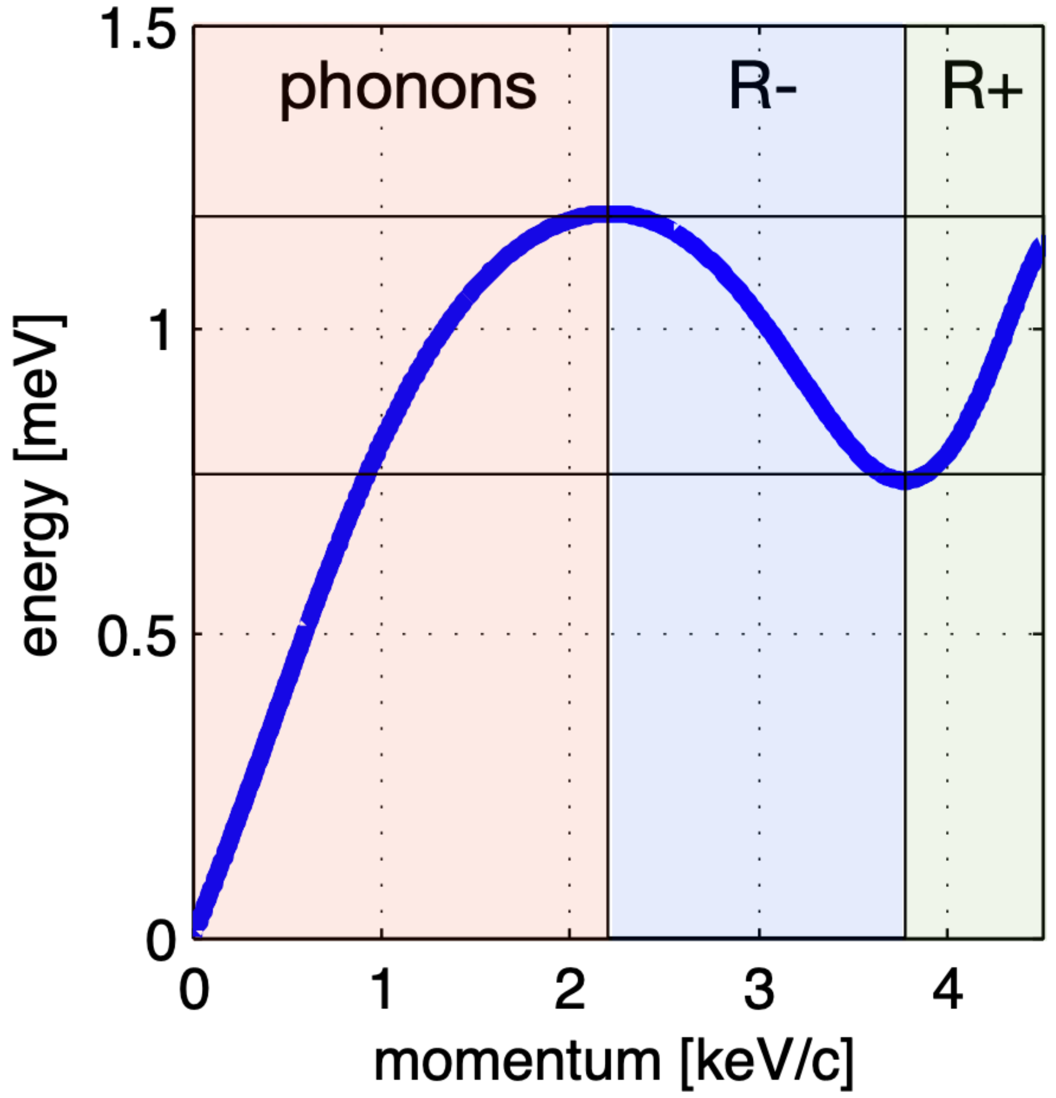



quasiparticle
free atom
van der Waals binding
~1 meV
0.62 meV
LHe
vacuum
Cal.
10s of meV

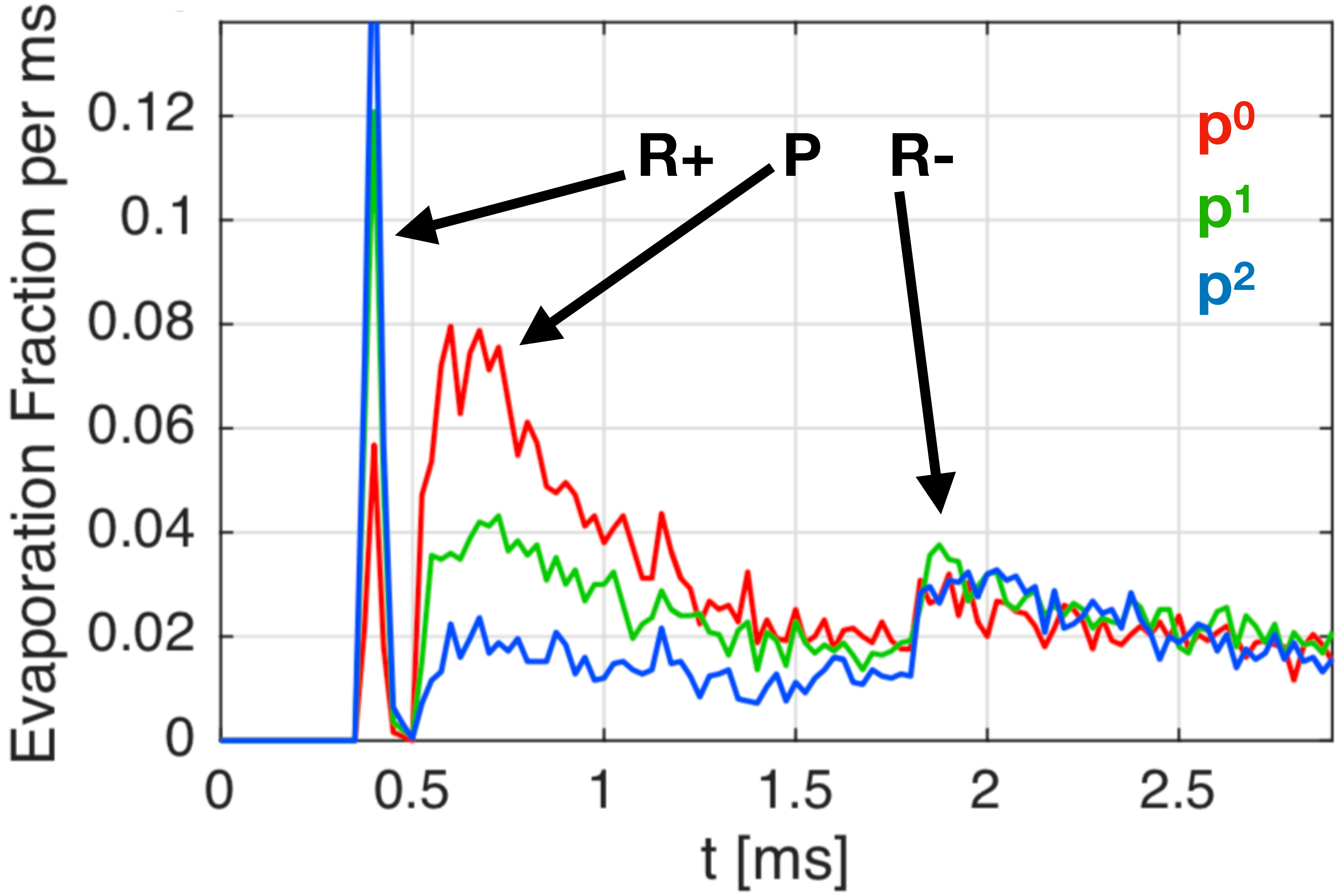
Another Example Waveform

- 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



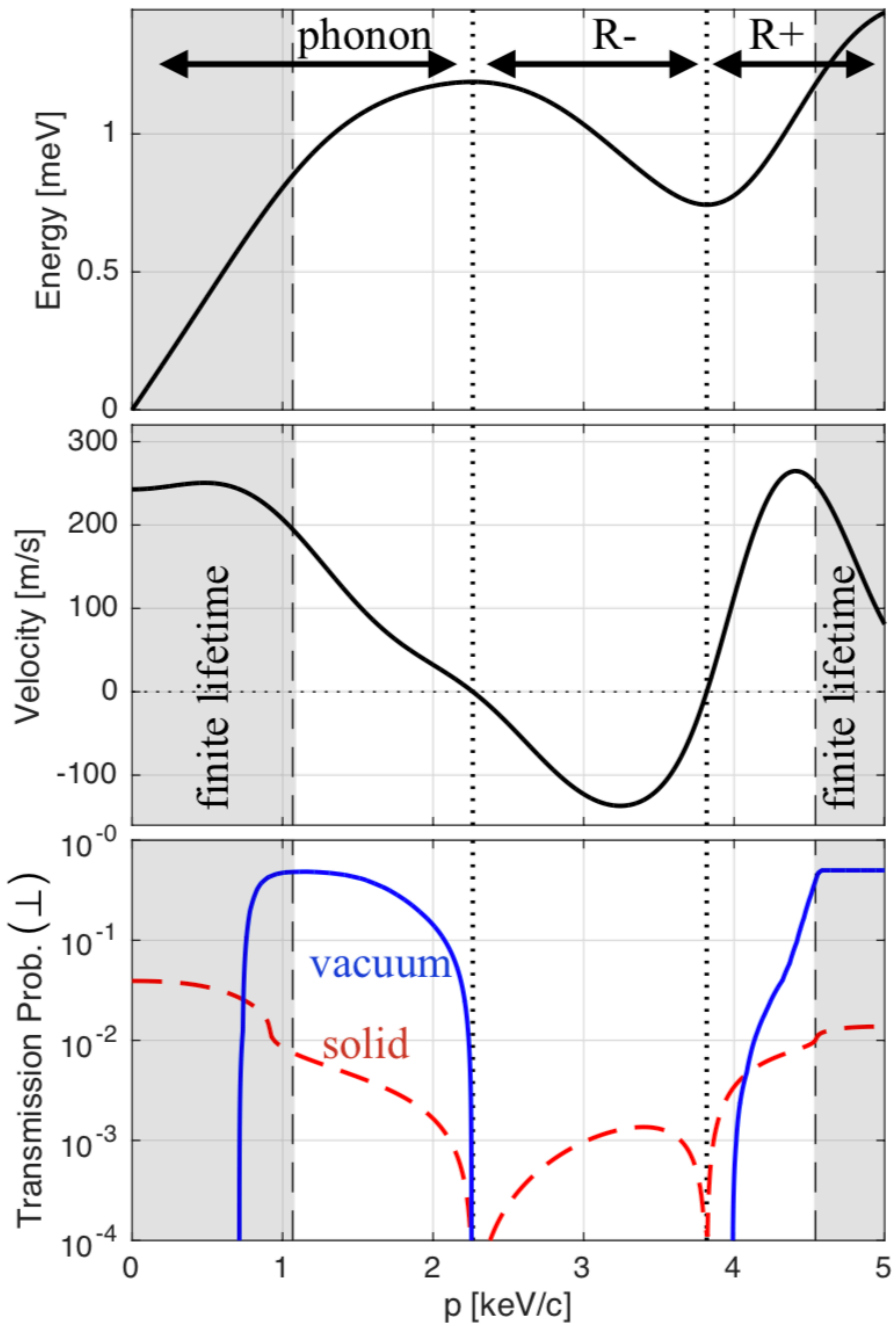


FIG. 3. Several fundamental characteristics of superfluid ^{4}He quasiparticles are here illustrated. TOP: the dispersion relation. MIDDLE: the group velocity. BOTTOM: transmission probabilities at normal incidence in two cases, incident on a ^{4}He-solid interface with solid phonon outgoing state (red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