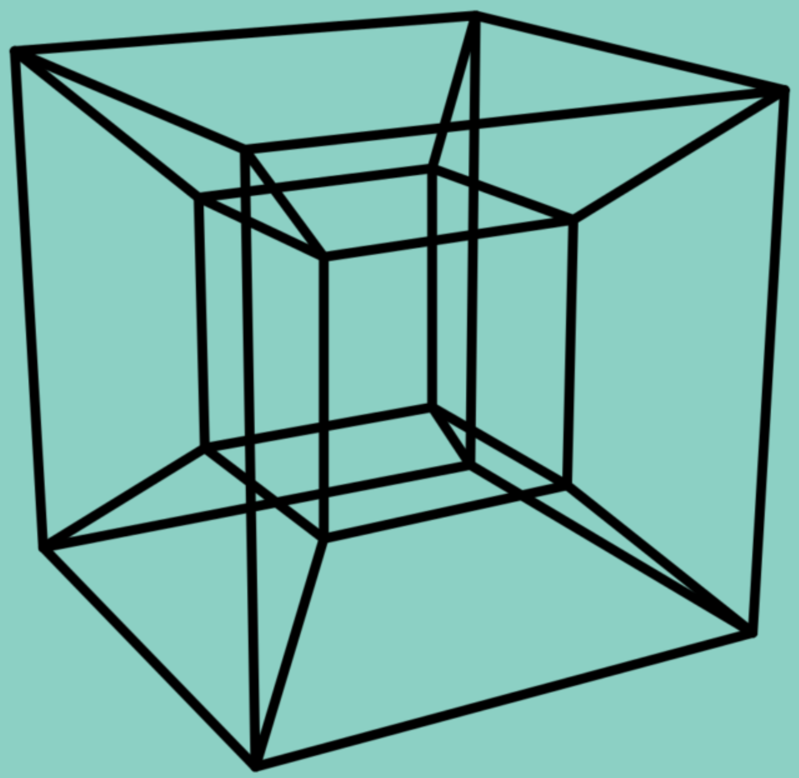
KNUT DUNDAS MORÅ | KNUT.MORAA@UZH.CH Astroparticle Symposium 2025

DARK MATTER SEARCHES WITH HELIUM TARGETS IN TESSERACT



TESSERACT: one collaboration, sub-eV resolution and several targets

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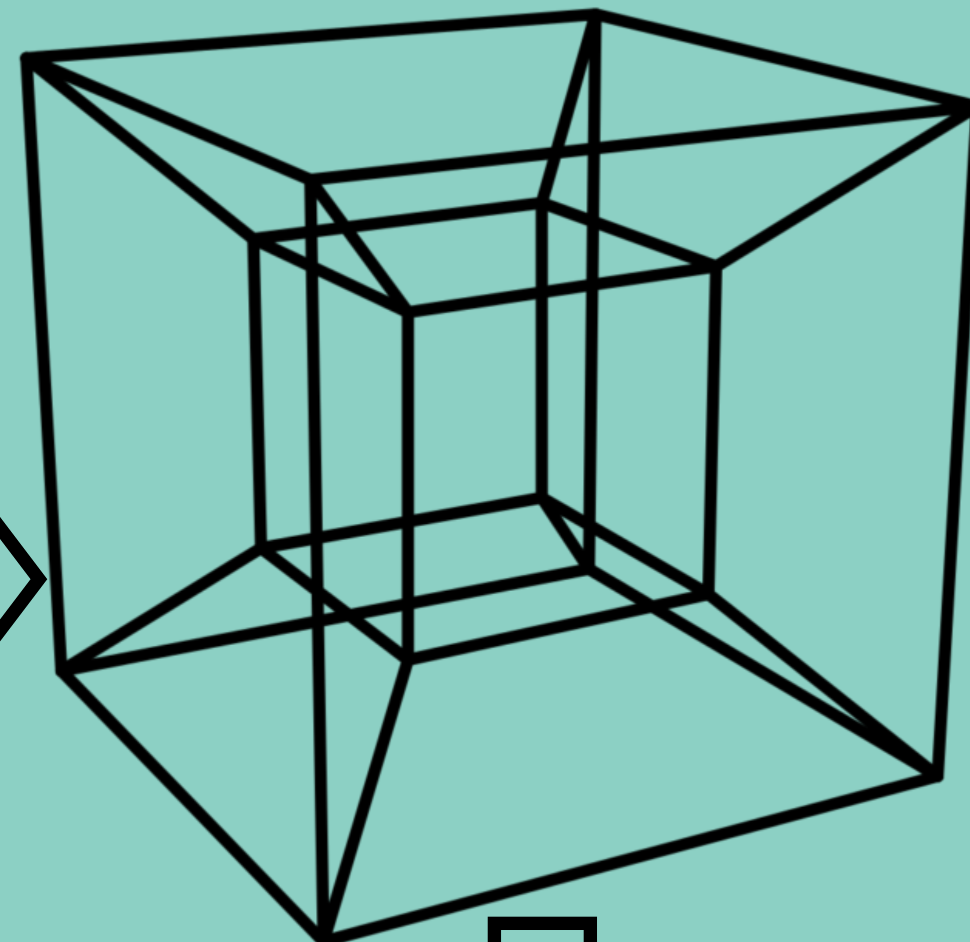
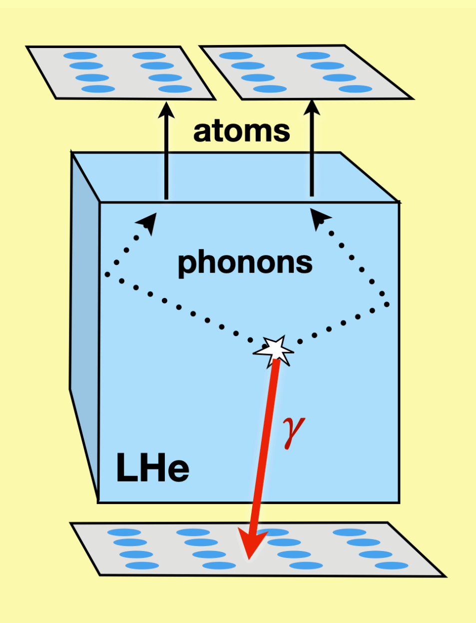
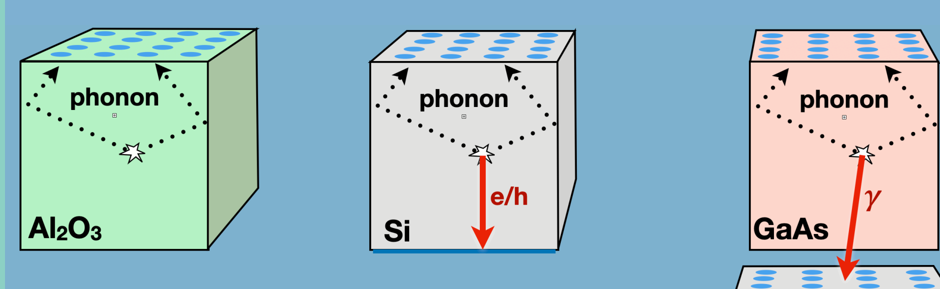


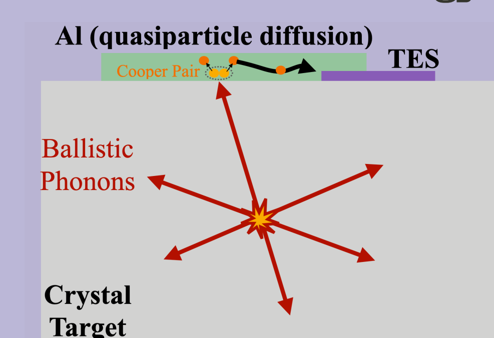
A superfluid ^{4}He target



Polar crystals instrumented with TESs – See Juliens talk Tuesday!



Shared Transition Edge Sensor (TES) technology



Diagrams by Scott Hertel

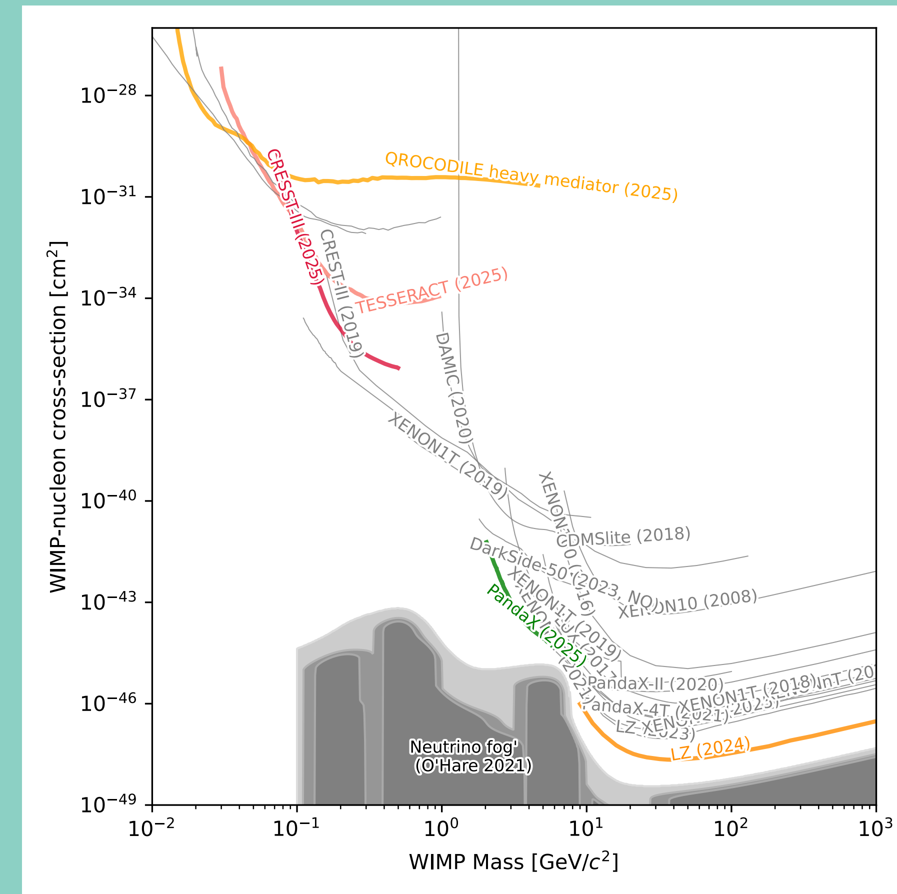
ABBREVIATIONS

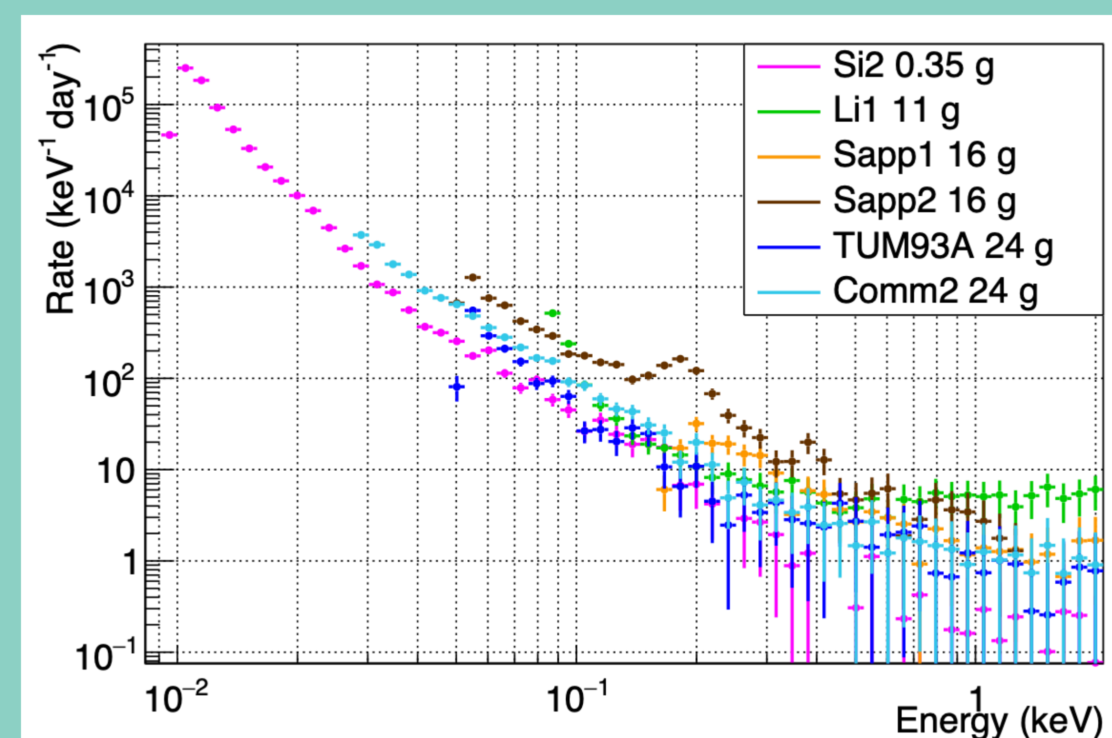
Transition
Edge
Sensors with
Sub-
Ev
Resolution
And
Cryogenic
Targets.

Transition
Edge
Sensors
(
H
elium
Roton
Apparatus for
Light
Dark matter
)

LOW-MASS DARK MATTER

- Below ~ 10 GeV/c^2, detecting DM is a fight against thresholds, with recoil energies in the eV scale and below
- As an upside, current constrains are ten orders of magnitude higher than they are in liquid xenon-land
    - If you scaled your target mass by number of DM particles, one tonne-year at 10^{-46} cm^2 equals three gram-days at 10^{-36} cm^2 (3000 including coherent enhancement)
- However, current detectors observe a signal-like background ("Low Energy Excess") that limits sensitivity progress
    - Appears as a phonon signal, and seems closely related to stresses/defects in the materials
- motivation for the TESSERACT multi-target approach!





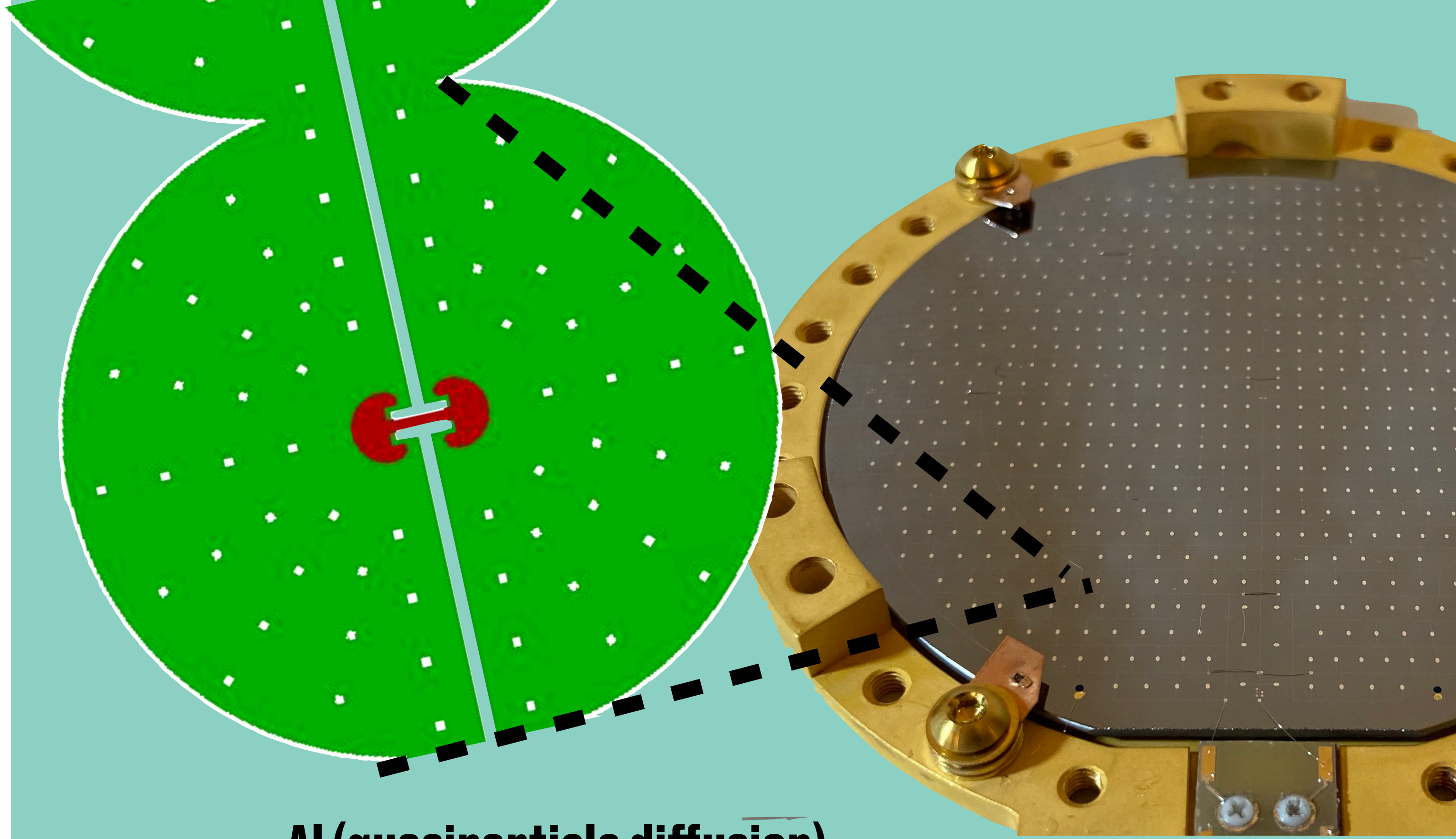
An overview of the CRESST collaboration's LEE studies: https://indico.cern.ch/event/1213348/contributions/5411385/attachments/2703269/4692370/EXCESS23_CRESST.pdf

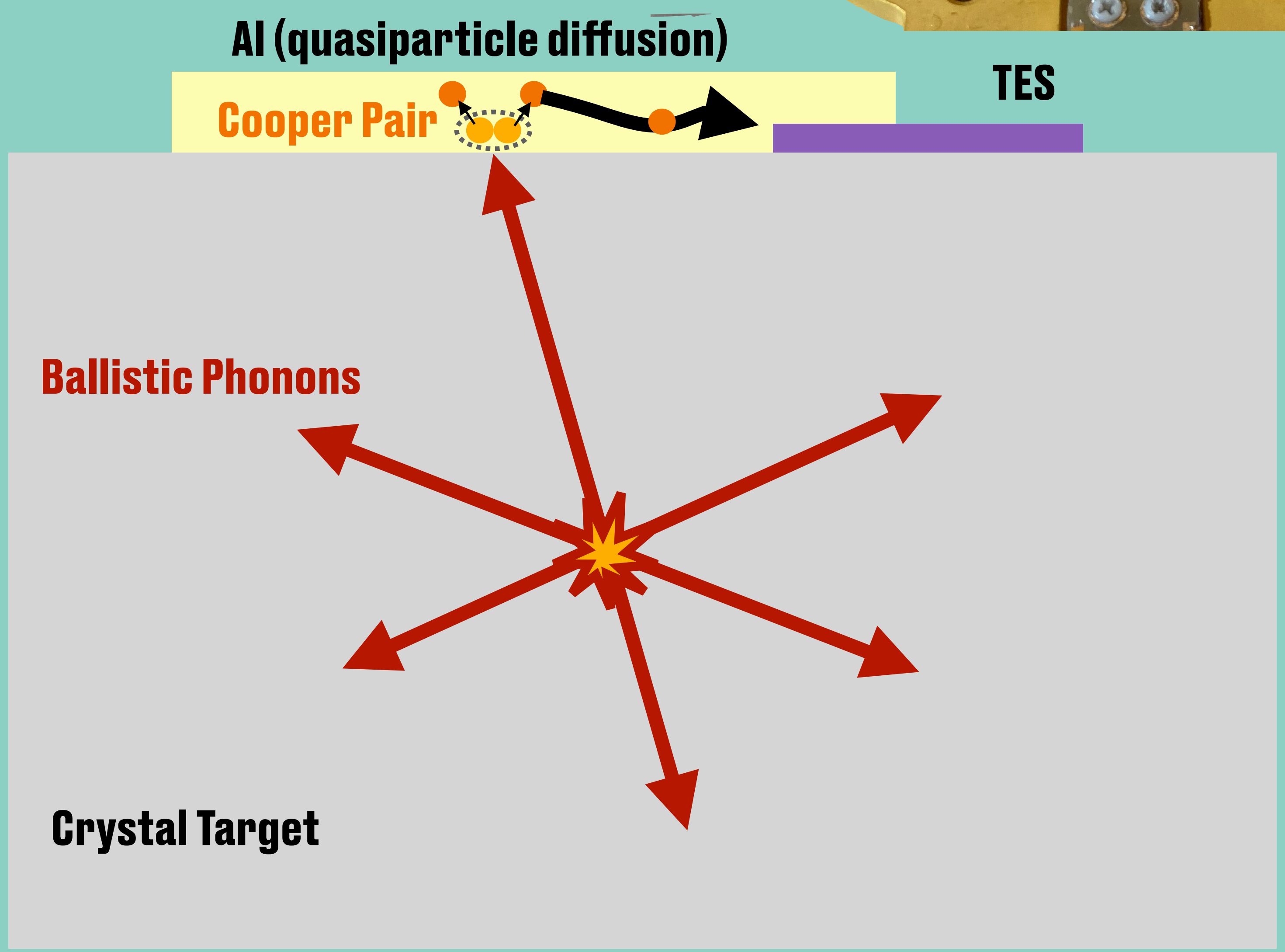
TRANSITION EDGE SENSORS

- Aluminium fins which collect phonons allow the TES itself to be as small as possible, improving energy resolution

- Phonon collection efficiency $\sim 50\,\%$

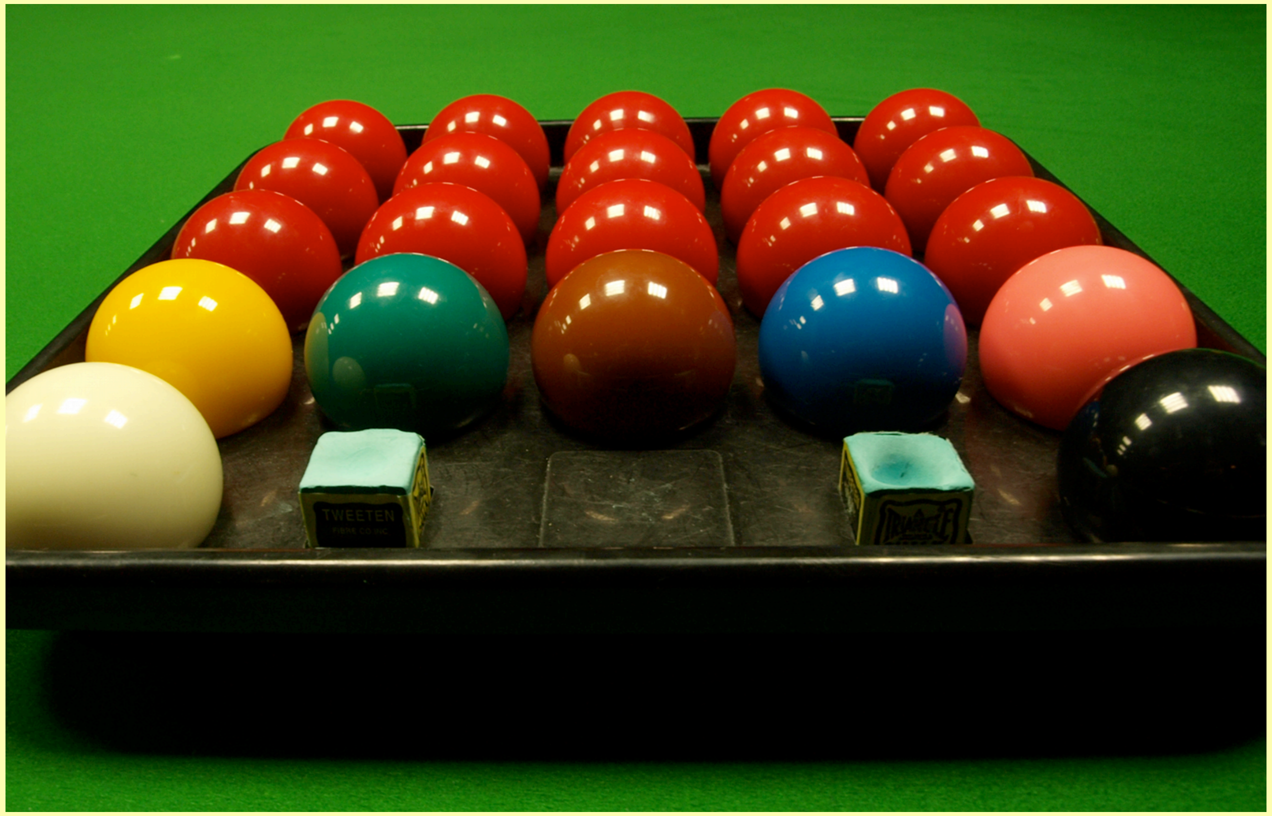
- TESSERACT TES transition temperatures go down to 15 mK, and aim for below-eV resolution and threshold of the TES





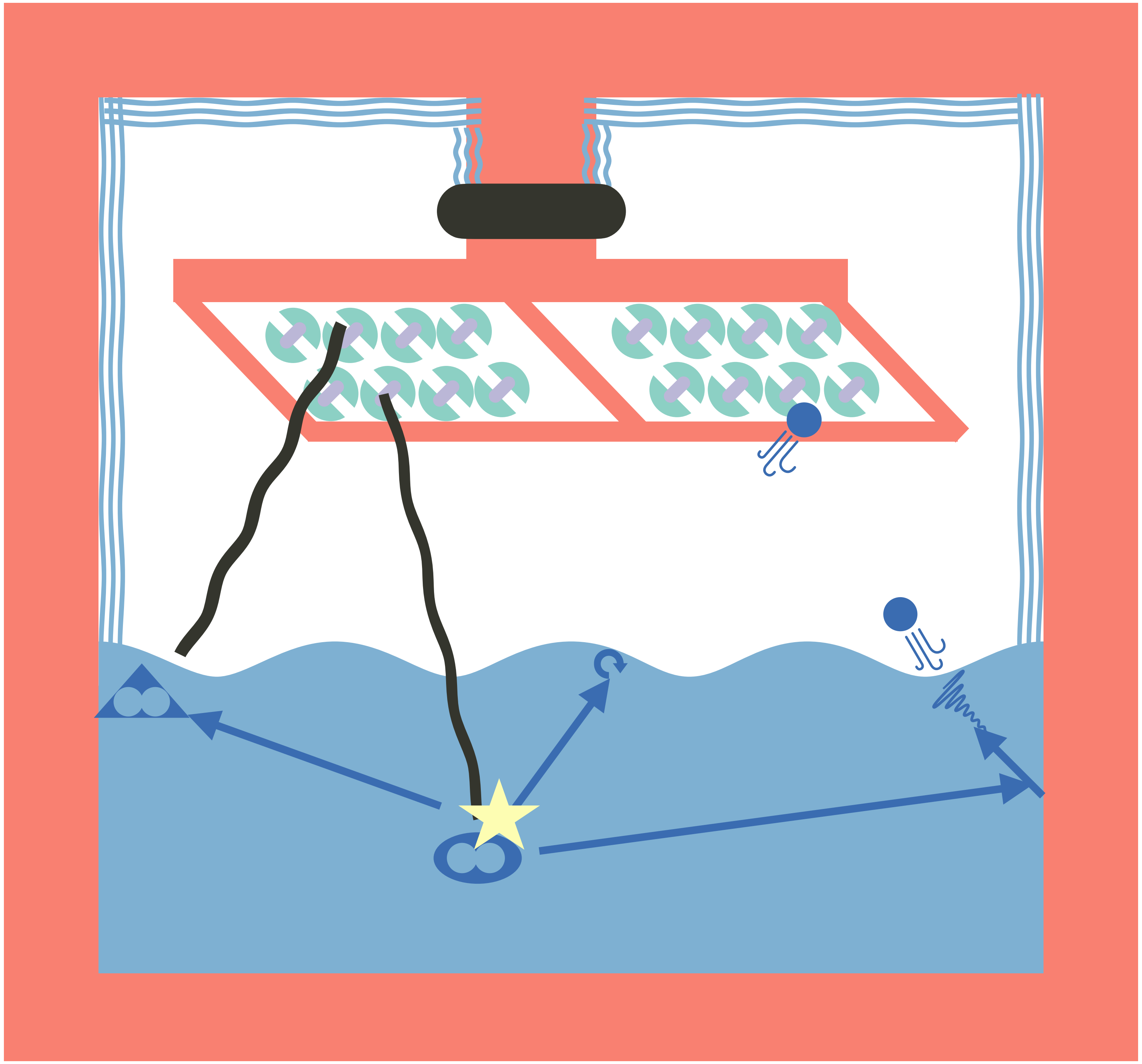
BENEFITS OF ^{4}HE

- TESSERACT aims to use several complimentary dark matter targets, all read out by transition edge sensors (TESs)
- Of these, superfluid helium offers no stress-related low-energy-excess (LEE) backgrounds
- Good match kinematically for ~ 1GeV$/c^2$ DM ($131/4 = 33$ times the maximum kinetic energy of Xe)
- As well as multiple signal quanta channels which allow signal/background discrimination
- Any non-He impurities will freeze out at the target temperatures, giving an extremely pure target

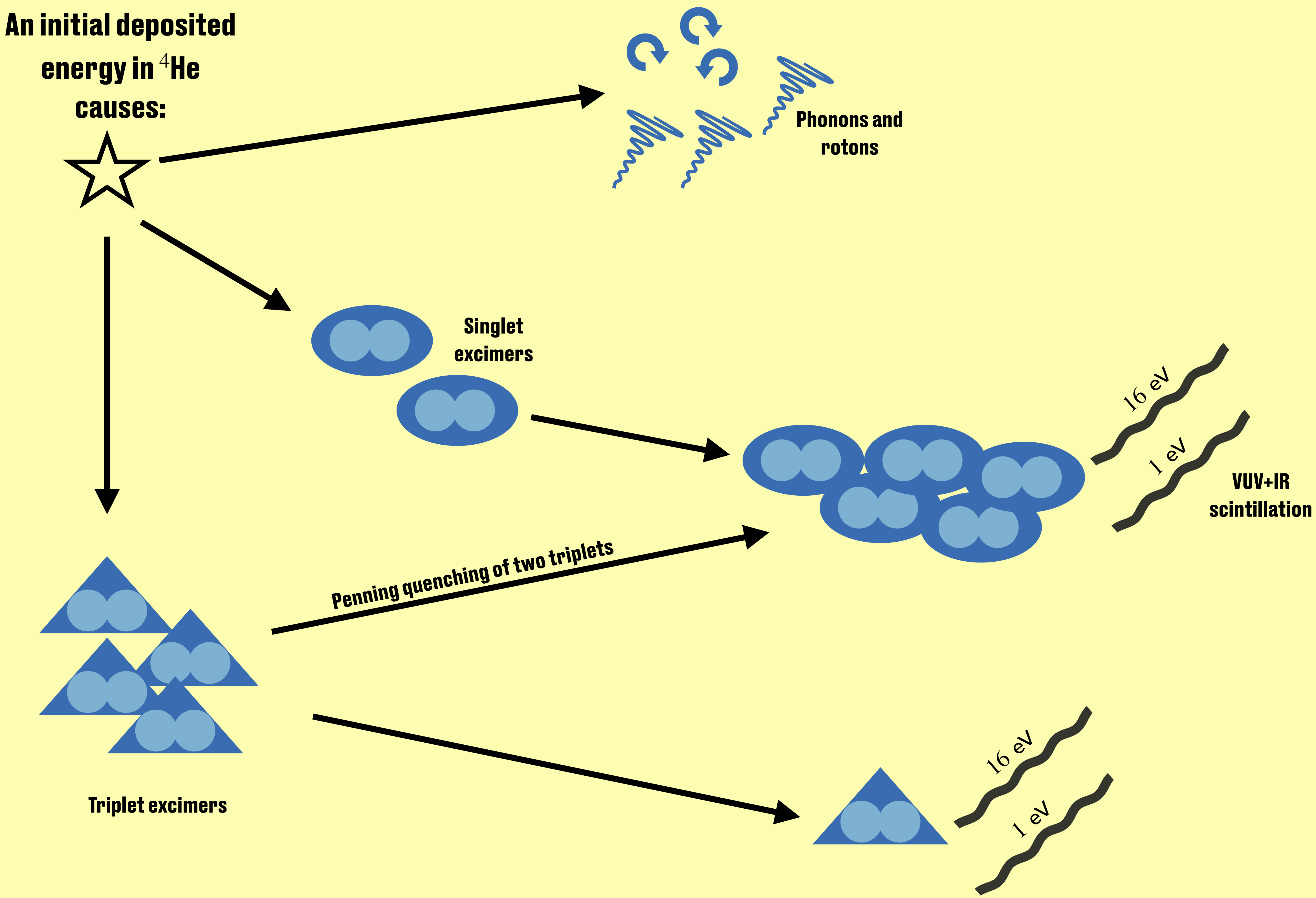


THE TESSERACT He CELL

- **Schematically, the He cell consists of a dry sensing platform instrumented with TESs above a target of superfluid He**
- **Interactions in the target create QPs (and, above 19.8 eV excitons)**
- **Combining the signal from the two processes gives signal-background discrimination capability**
- **coincidence between sensor segments allows discrimination against sensor backgrounds**

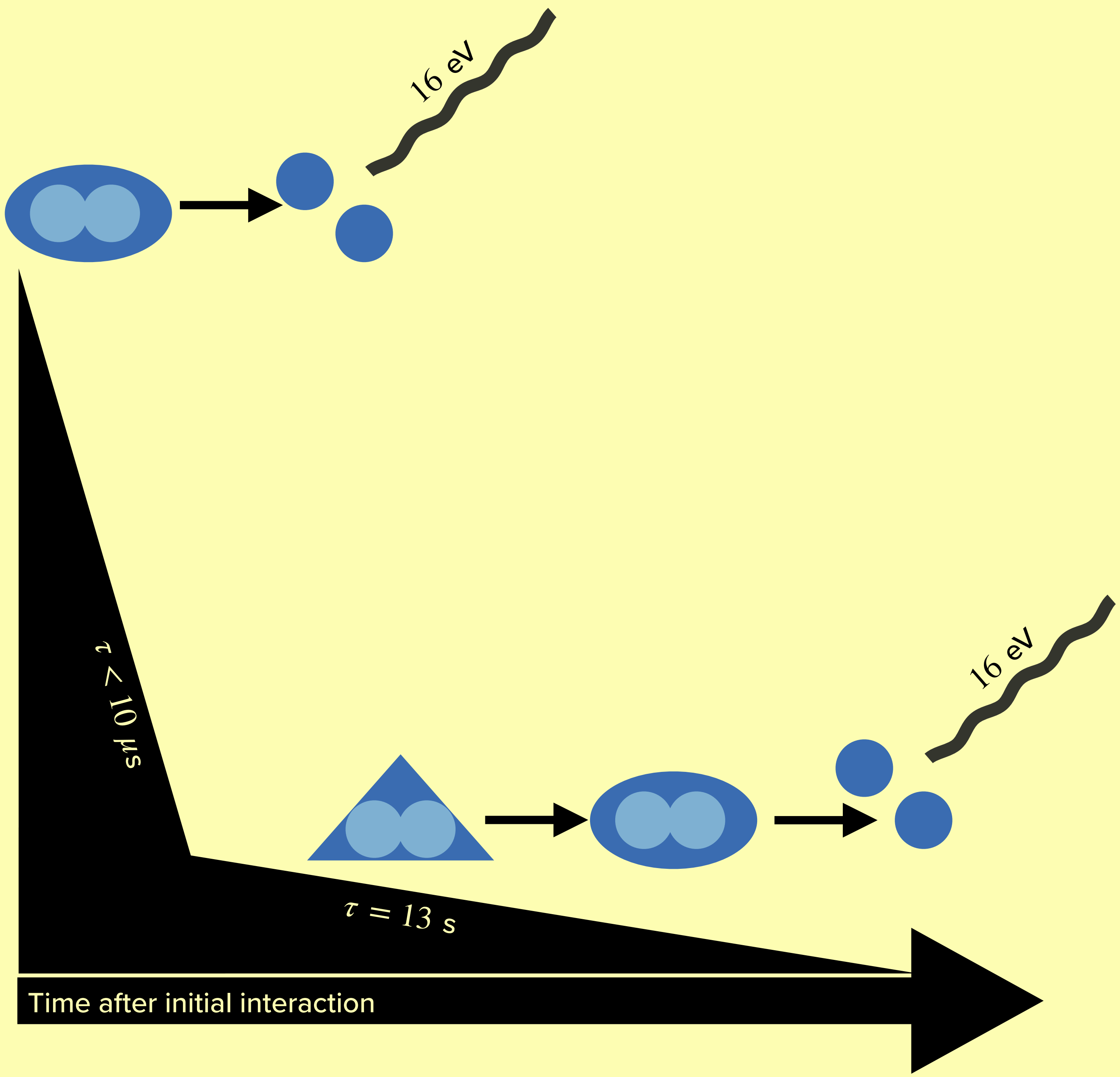


ENERGY PARTITION



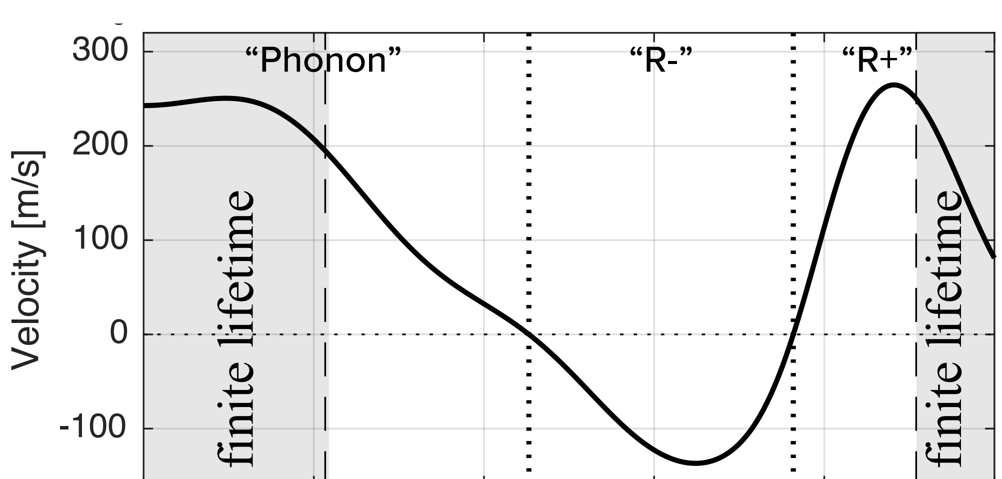
SCINTILLATION LIGHT

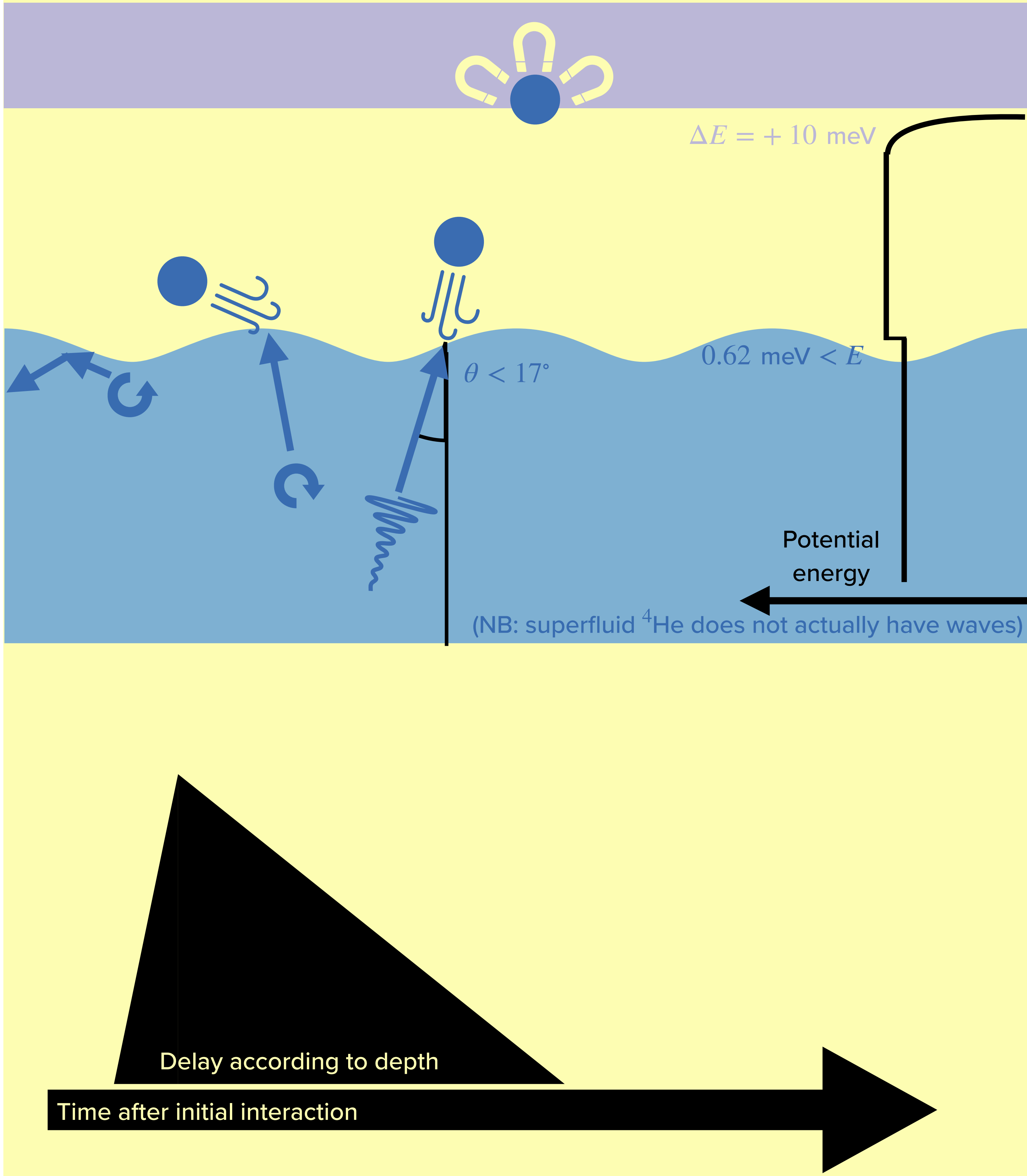
- Above the ^{4}He excitation energy of 19.8 eV, interactions can excite atoms into singlet and triplet dimers (or cause ionization that will recombine and create excitons)
    - This also eliminates Compton scatter backgrounds at the lowest energies, leaving coherent $\gamma-$scatters
- Singlet dimers rapidly de-excite and emit a fast scintillation signal, either in IR (1 eV) or vacuum UV (16 eV)
- triplet dimers are long-lived, and travel through the medium until they decay, or at a surface.



QUASIPARTICLE-INDUCED EVAPORATION

- Quasiparticle (QP) excitations of the superfluid include regular phonons as well as superfluid-distinctive modes called “rotons”.
- They move ballistically at ~ 100 m/s, giving an expected delay of $\sim 100\mu$s for each cm of depth
- When they reach a liquid surface, QPs with above 0.62 meV of energy can liberate single ^{4}He atoms which are emitted roughly isotropically.
  - Requires a low angle, approx $< 17^\circ$ from normal for efficient transfer
  - ^{4}He adsorbed at surfaces will release ~ 10 meV, giving a more than tenfold amplification of the QP signal energy
- The QP adsorption energy gain requires that the sensor is dry from He — need a way to prevent the superfluid to wet the sensor!





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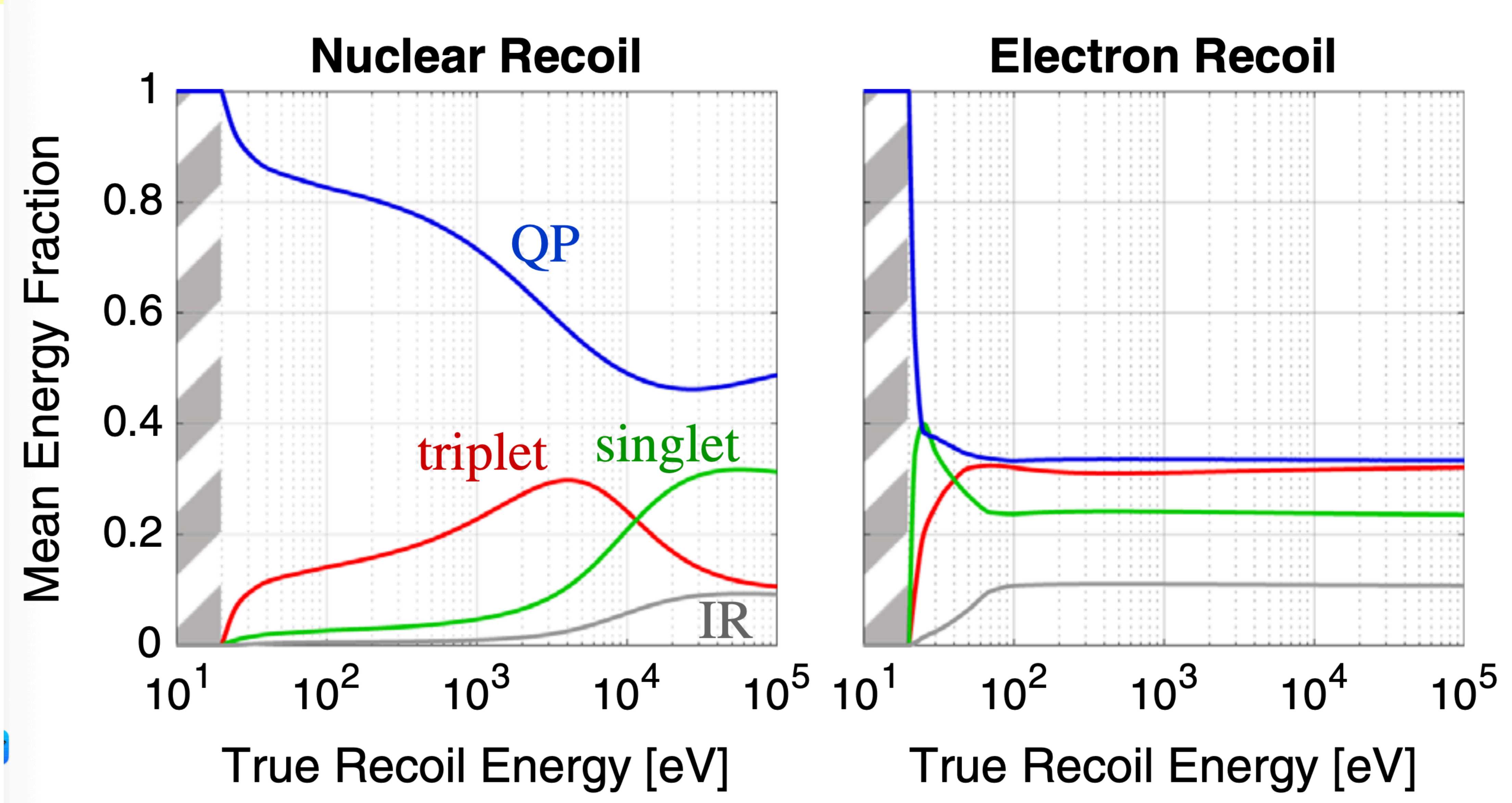
ENERGY PARTITION

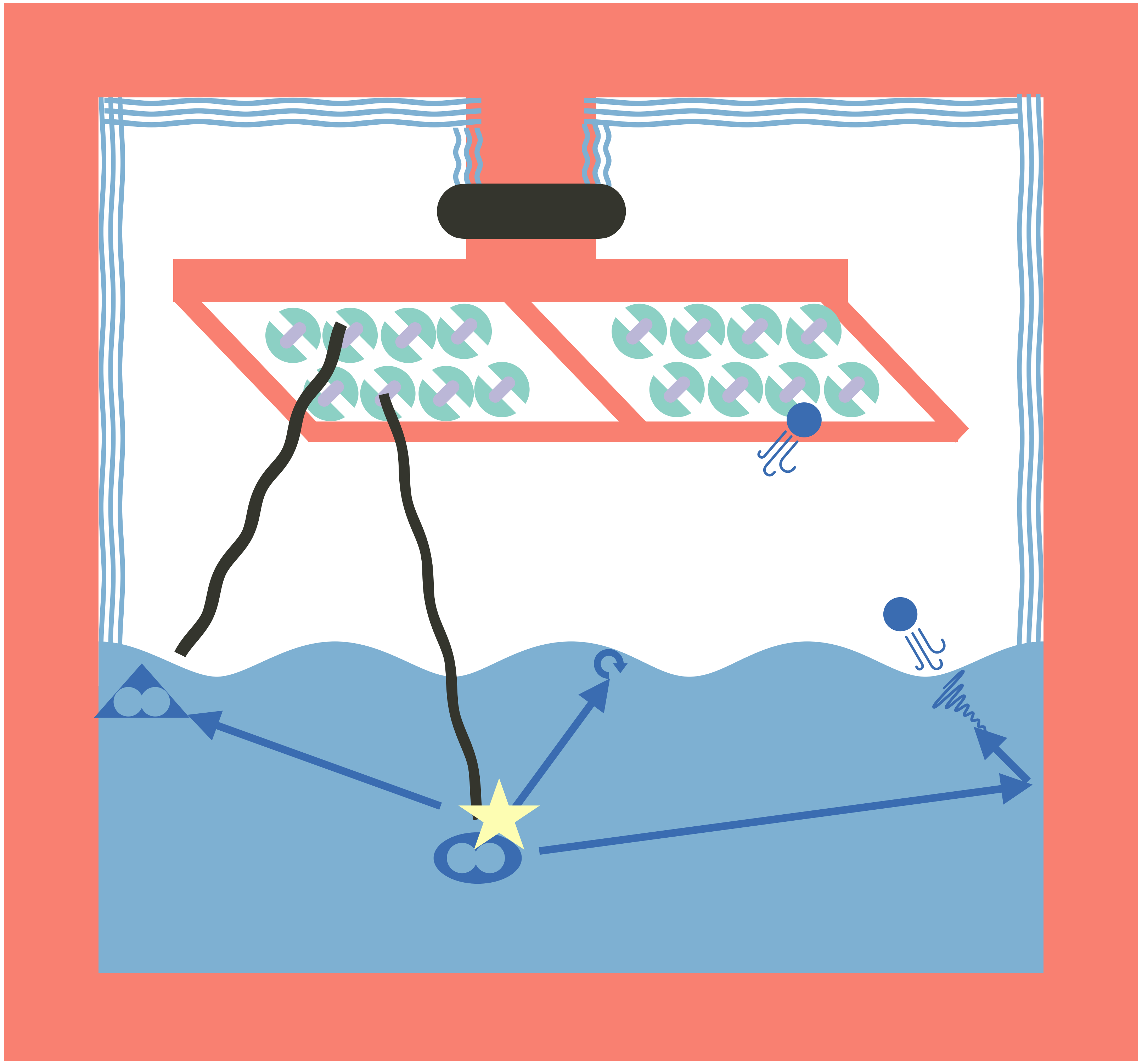


- **Below 19.8 eV, all energy goes into QP**
- **Above, nuclear and electronic recoils show very different QP:singlet:triplet ratios, with electronic recoils approximately sharing equally, while nuclear recoils are QP-heavy.**

S. A. Hertel, A. Biekert, J. Lin, V. Velan, and D. N. McKinsey, Direct detection of sub-GeV dark matter using a superfluid 4He target, Physical Review D 100, 092007 (2019).

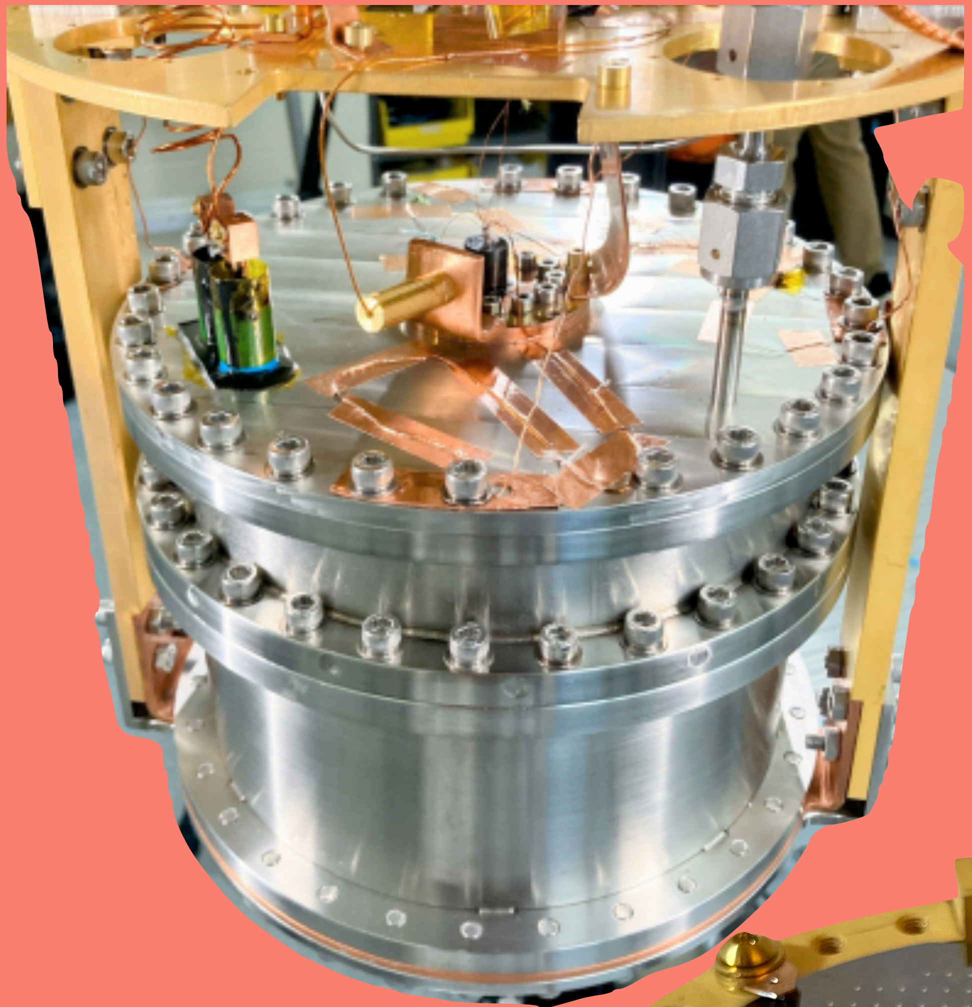
THE TESSERACT He CELL

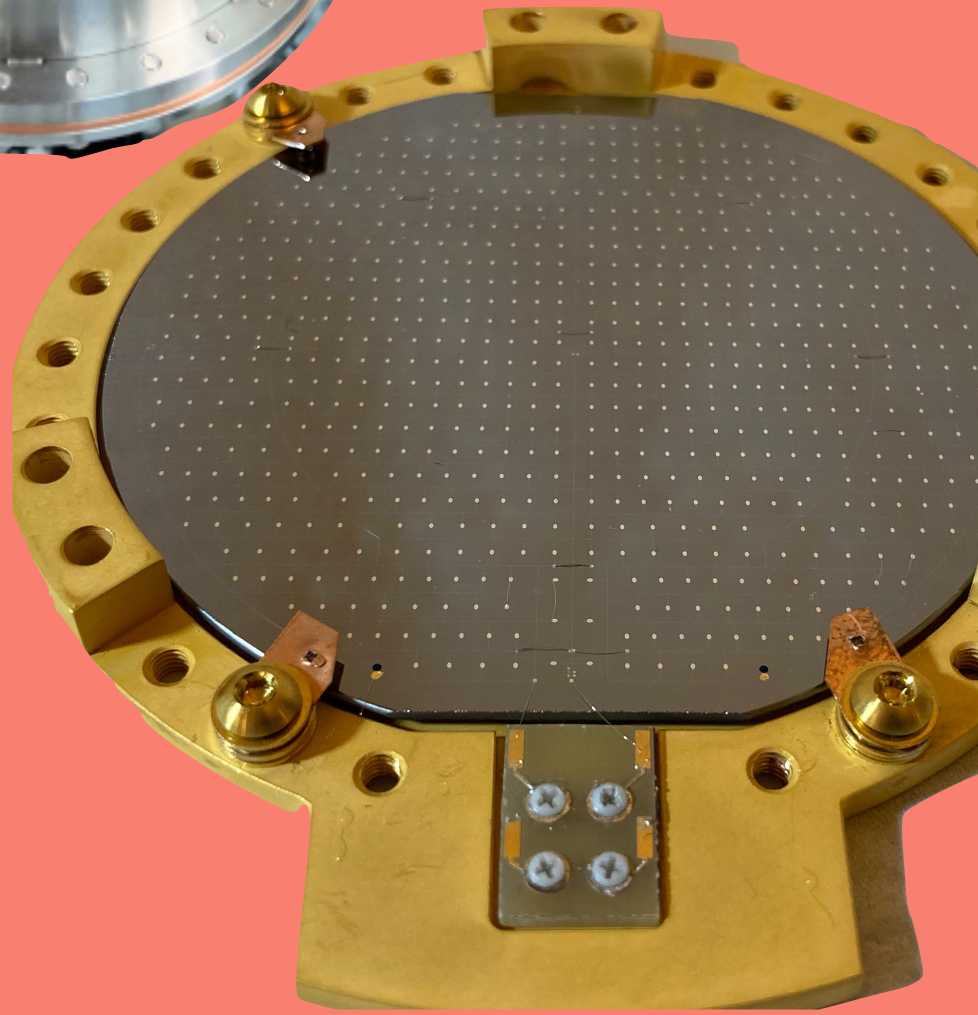
- **Interactions in the target create QPs (and, above 19.8 eV excitons)**
  - **Prompt dimer scintillation hits the sensors first,**
  - **Followed by a QP evaporation signal as they hit the surface and knock He atoms up**
  - **With a long tail of trimer scintillation following**



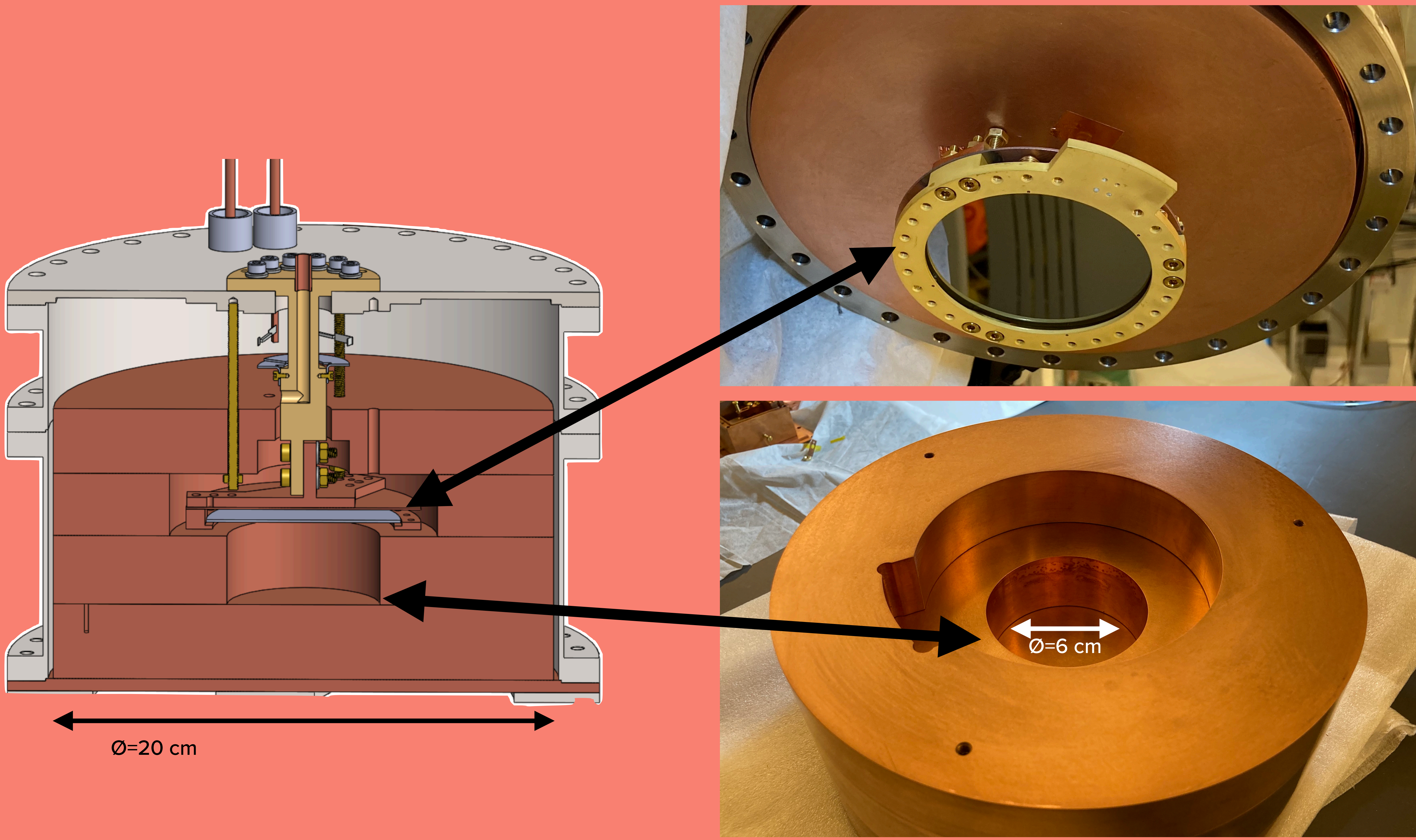
HeRALD V0.1

- A demonstration sensor using a two-channel design: a 3-inch 1mm thick Si wafer read out by a chain of hundreds of TESs in series
- Critical temperature: 51 mK
- ~ 10 g ^{4}He target, ^{3}He/^{4}He $< 5 \times 10^{-13}$
- Aims:
  - Demonstrate superfluid He target interactions with a single sensor
  - And demonstrate the capability to use a heat-free method of keeping the sensor platform free of superfluid helium



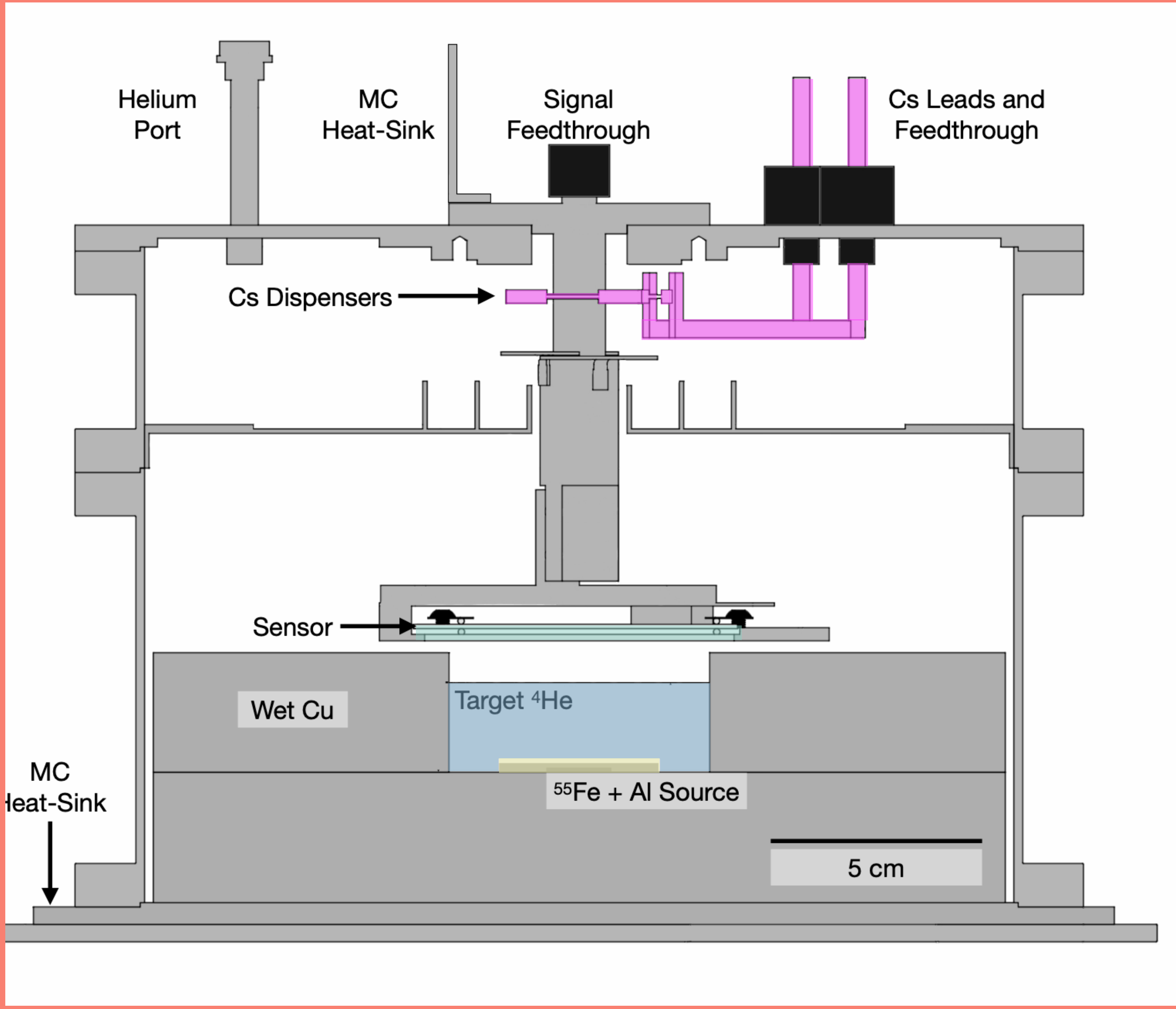


HeRALD V0.1



KEEPING THE SENSOR DRY

- He can be stopped from wetting surfaces with film burners
  - This would inject heat into the cell, diminishing the sensor threshold and also increase the heat capacity of the sensor
- A atomically sharp knife edge was evaluated, but it turned out less promising than
- Cesium and rubidium, peculiarly, are not wetted by superfluid He
- Cs oxidises easily and sometimes entertainingly
- The Cs barrier must be deposited in vacuum to prevent oxidation, and so it is injected in-situ as a vapor onto the sensor platform stem
- Baffles prevent the vapor hitting the target and sensor area.



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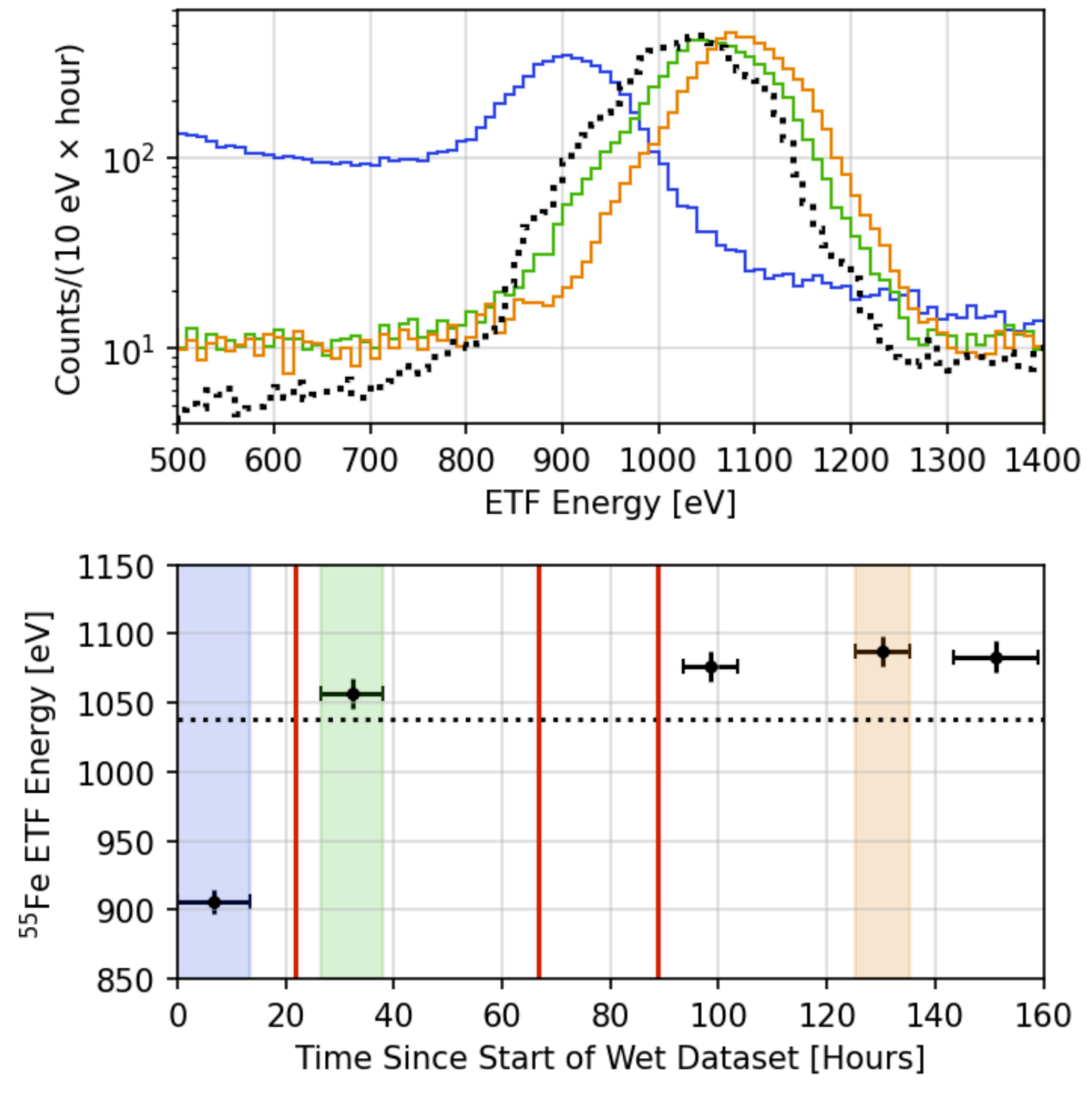
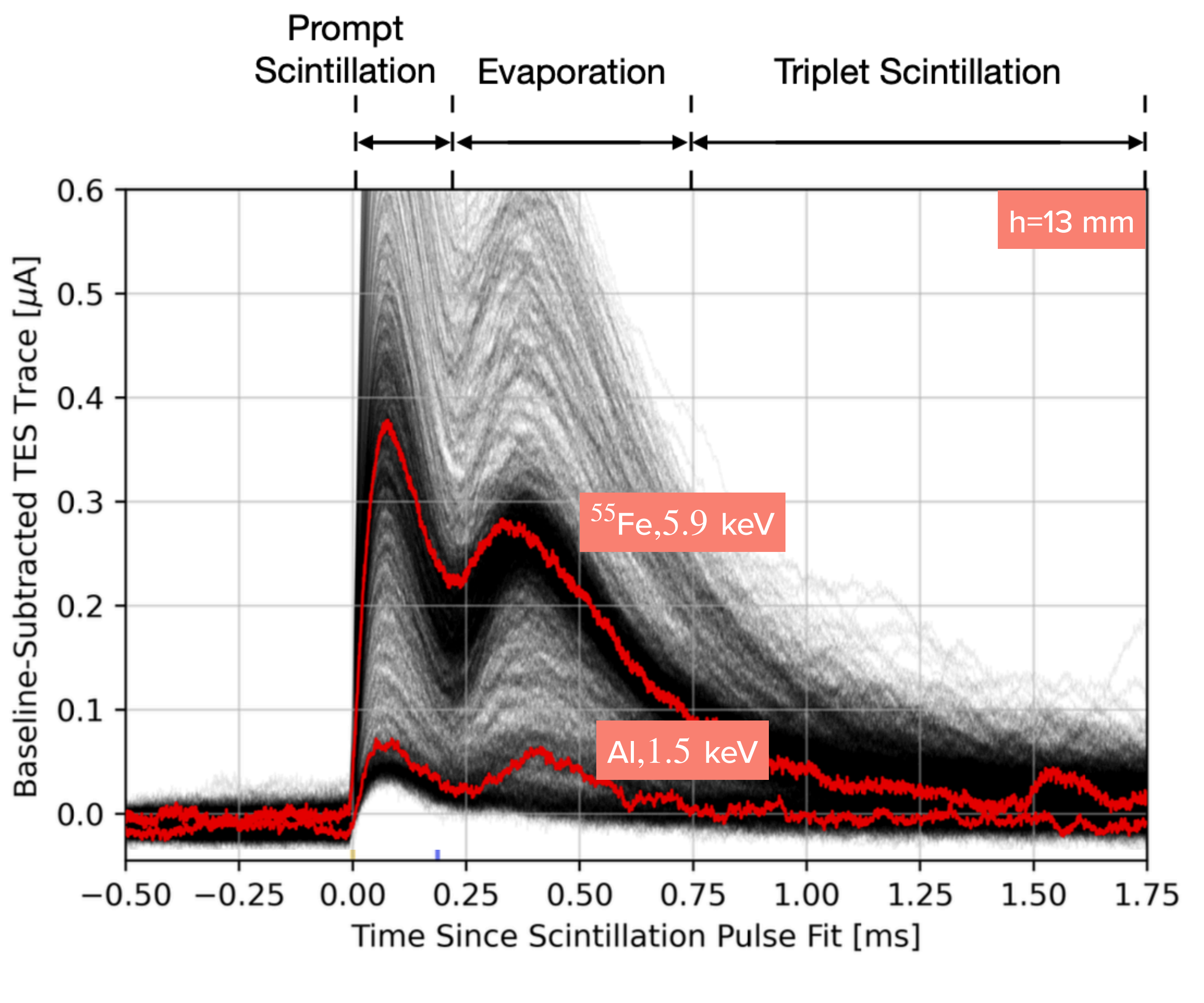
KEEPING THE SENSOR DRY

- The HeRALD v0.1 cell demonstrated the Cs deposition
- ^{55}Fe source at the bottom covered by a thin Al layer gives a 5.9 keV gamma-ray and 1.5 keV fluorescence calibration lines
- First dataset after He fill showed a $14\,\%$ reduction in signal compared to the data taken before filling
    - Filling introduces some He gas alongside the superfluid, settling on the sensor
- Heating the sensor platform only with 2s heat pulses removes He, and achieves a higher signal amplitude than the no-He state that remains approximately stable with subsequent bakes



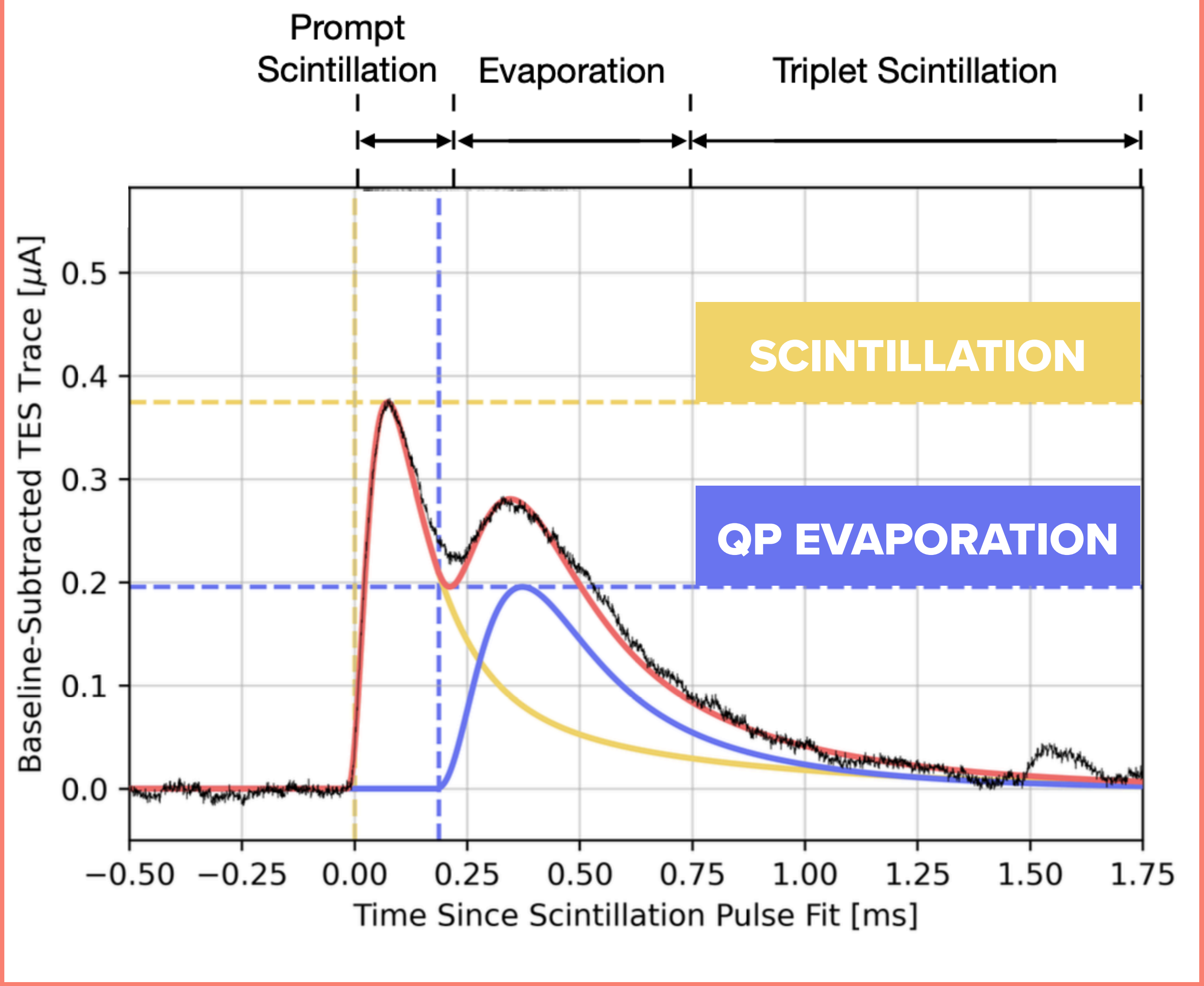
COLLECTED DATA

- **Data taken at several fill depths between 9 and 27.7 ± 2 mm**
- **10h data at each fill height**
- **taken as continuous data at 1.25 MHz, with offline reconstruction.**
- **Events are selected with anti-noise cuts to the pre-pulse region:**
  - **$< 1\,\%$ higher than the baseline average**
  - **Slope $< 2\sigma$ from the mean baseline slope**
  - **Events whose baseline standard deviation falls below the dataset mode plus the difference between the dataset mode and minimum**



DATA PROCESSING AND RECONSTRUCTION

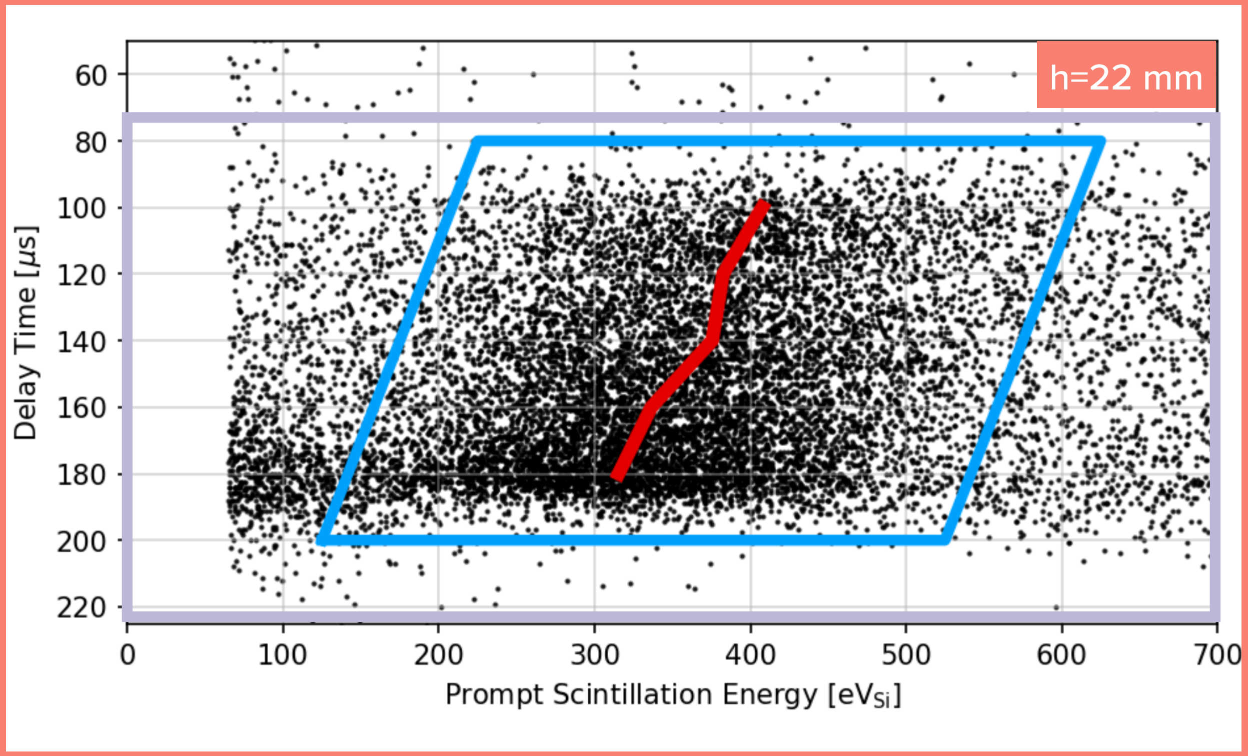
- The data is reconstructed using a two-step optimum filter algorithm,
  - First, a scintillation-only template is used to select reconstruction candidates
  - These candidates in a 5 ms window are reconstructed using a second optimum filter fit with a scintillation and QP evaporation signal template
- The noise power spectrum for the optimum filter is constructed from random sampling of the full data timeline
- The scintillation template are a combination of the rising shape from all scintillation signals, and the falling shape from γs that hit the Si absorber directly
- The average evaporation signal for h=22 mm is used as a template (<5% bias on the fitted amplitude)



EVENT SELECTION AND ENERGY CALIBRATION

- Loose scintillation-to-QP evaporation delay time cuts aim to select events in the He bulk
- χ^2 cuts select away events with a very poor template fit
- a ^{55}Fe selection is applied in energy+delay time to choose these events
- The detector energy scale is computed from pre-fill 1.5 keV Al fluorescence events directly hitting the Si wafer
  - Conversion between this and the energy reconstructed from the TES current alone, we find that the TES receives $26\,\%$ of the total energy on the Si
- The energy scale is adjusted by <6% with the position of the ^{55}Fe peak.

h [mm]	Minimum [μs]	Maximum [μs]
9	200	300
13	150	235
19	100	230
22	75	230
25	50	230
27.7	15	230



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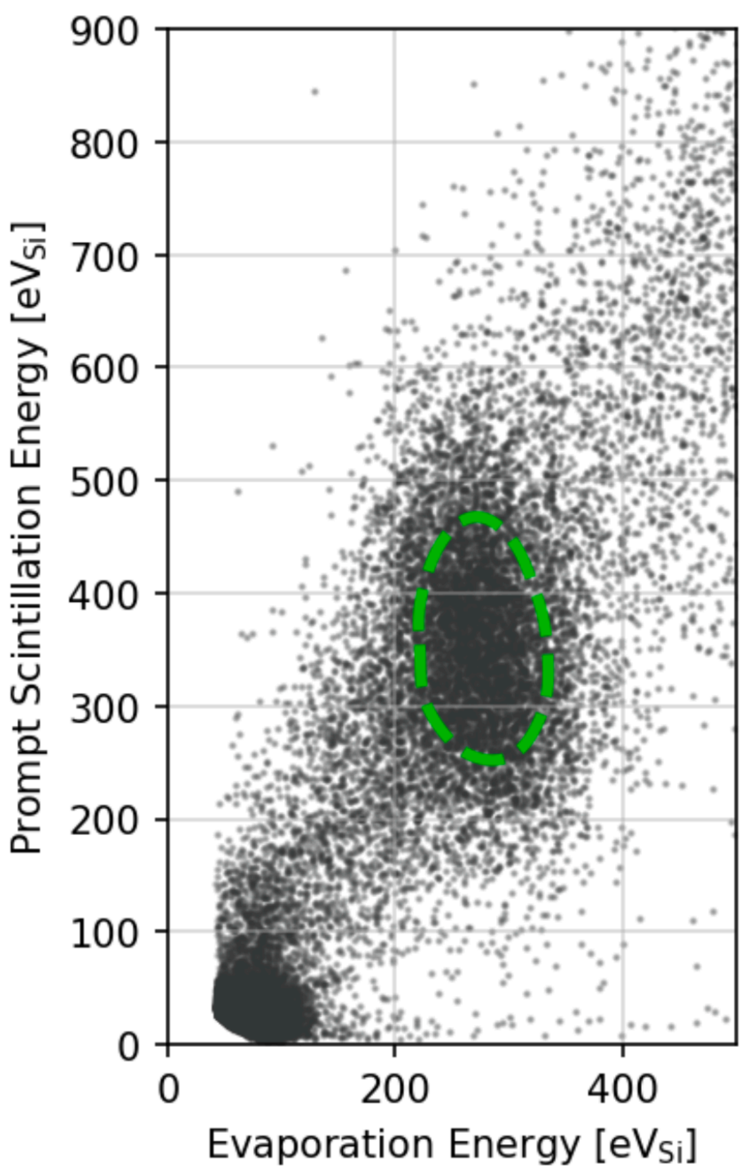
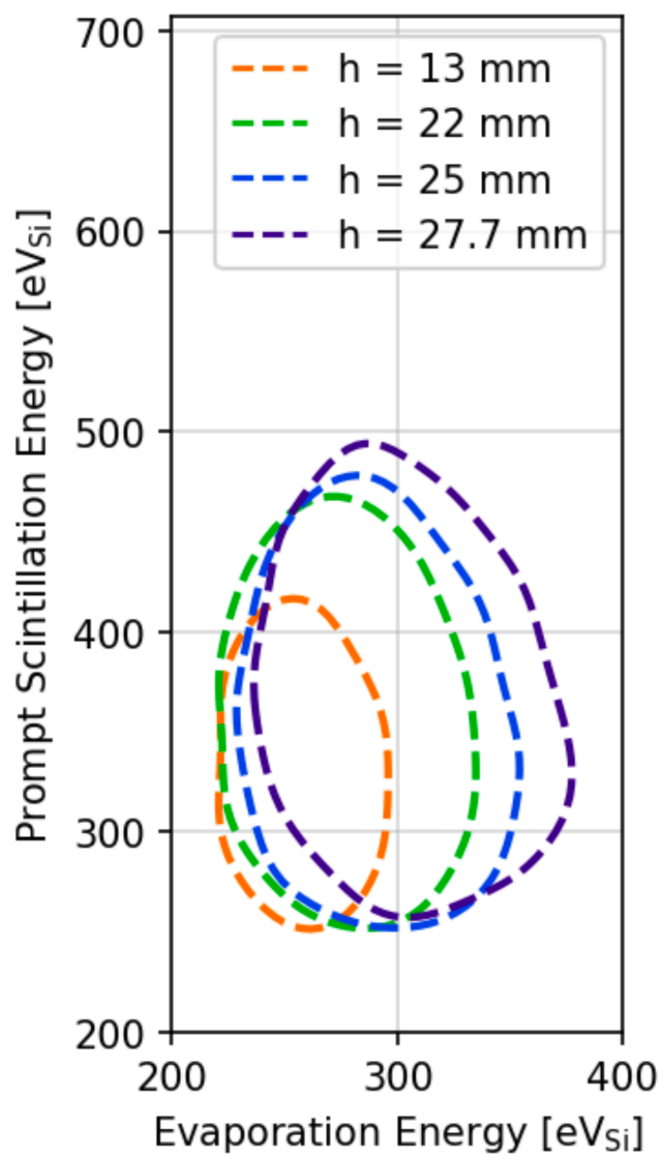
SIGNAL DISTRIBUTION

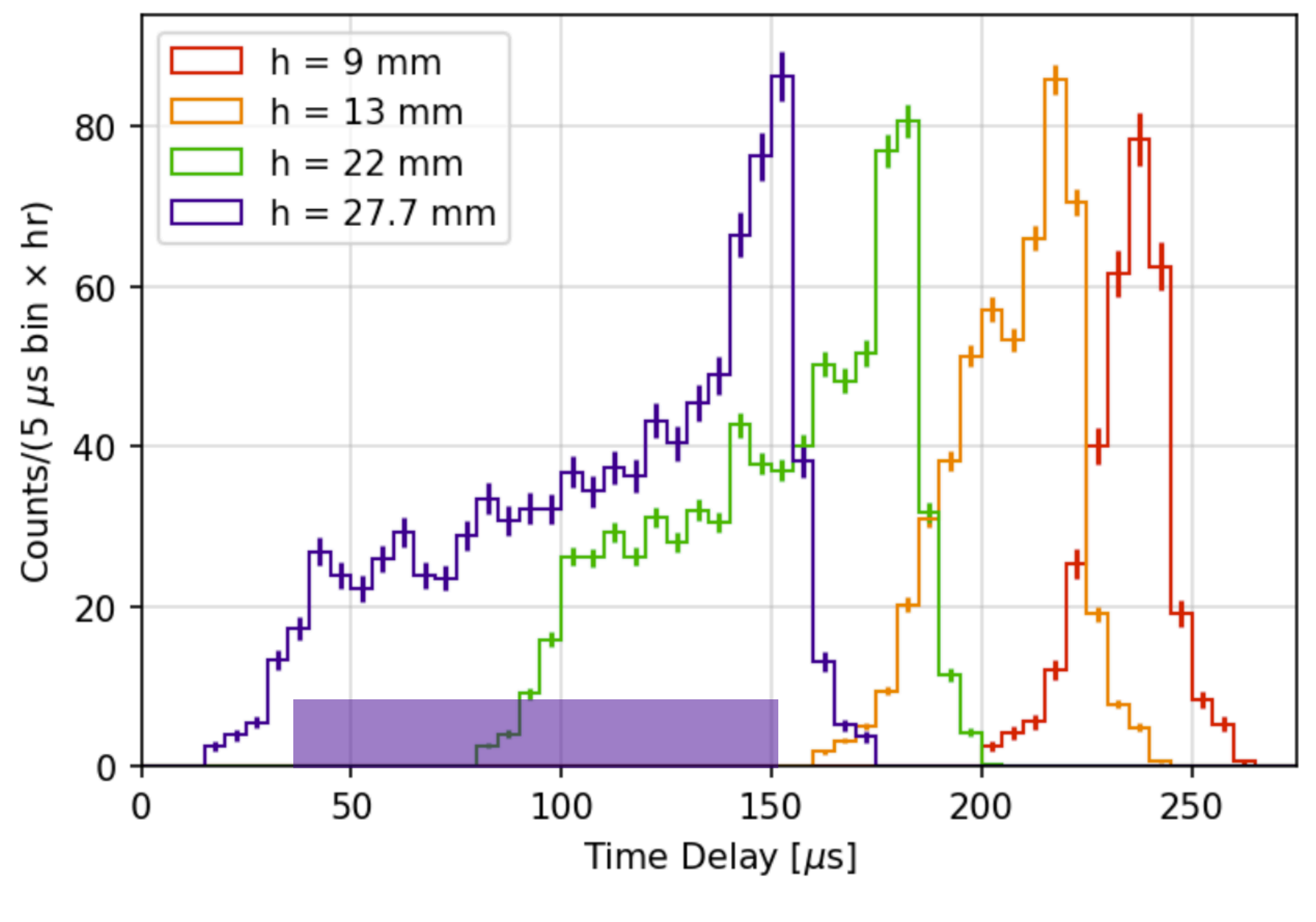
- The reconstructed scintillation and QP signals of the ^{55}Fe shows the expected roughly equal division of scintillation and evaporation signals
- The scintillation energy is also consistent with the solid angle of the Si wafer from the fill.
- Relatively higher variation in the scintillation channel— fewer quanta! Some 20-ish for the ^{55}Fe and around 5 for the Al fluorescence signal barely seen, while the evaporation signal may be in the thousands
- The He response model predicts 1975 eV energy going to QPs in the bulk, giving a 'gain factor' of 0.15 ± 0.01 for HeRALD 0.1
  - The evaporated energy, unamplified is much lower, around 30 eV, highlighting the benefit of adsorption amplification

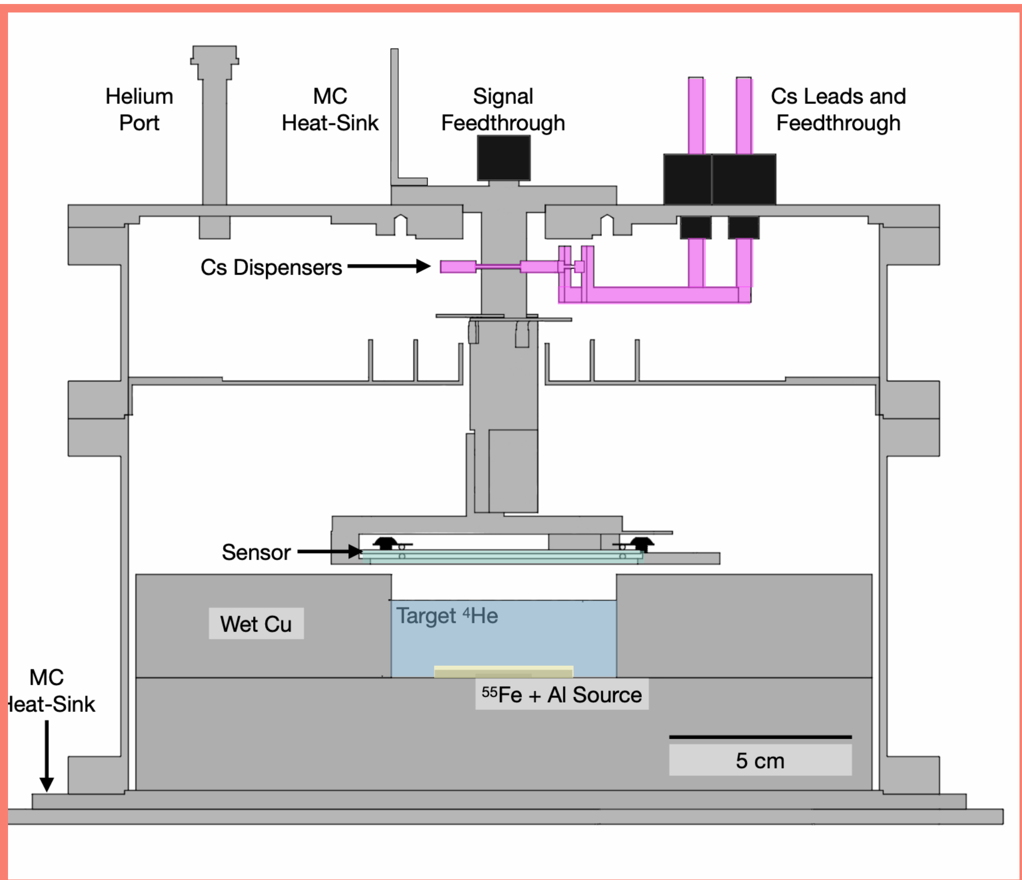


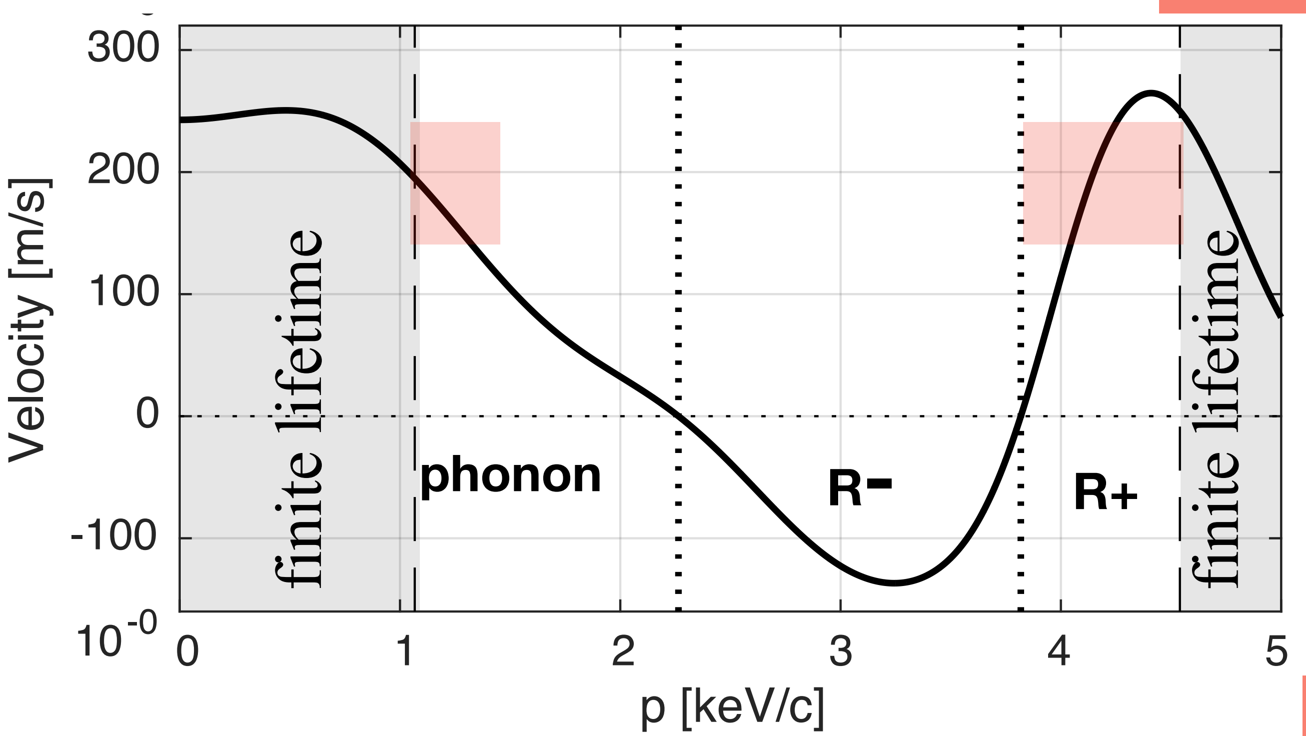


DEPTH DEPENDENCE

- As the detector fills, more of the QP-evaporation path is made by the faster QP
- Peak at longest drift time—short-range auger electrons causing a more localised signal?
- From the h=27.7 mm, the QP drift speed can be roughly estimated as
$27.7\ \mathbf{mm}/(150\ \mu s - 40\ \mu s)$
$\sim 250\mathbf{m/s},$

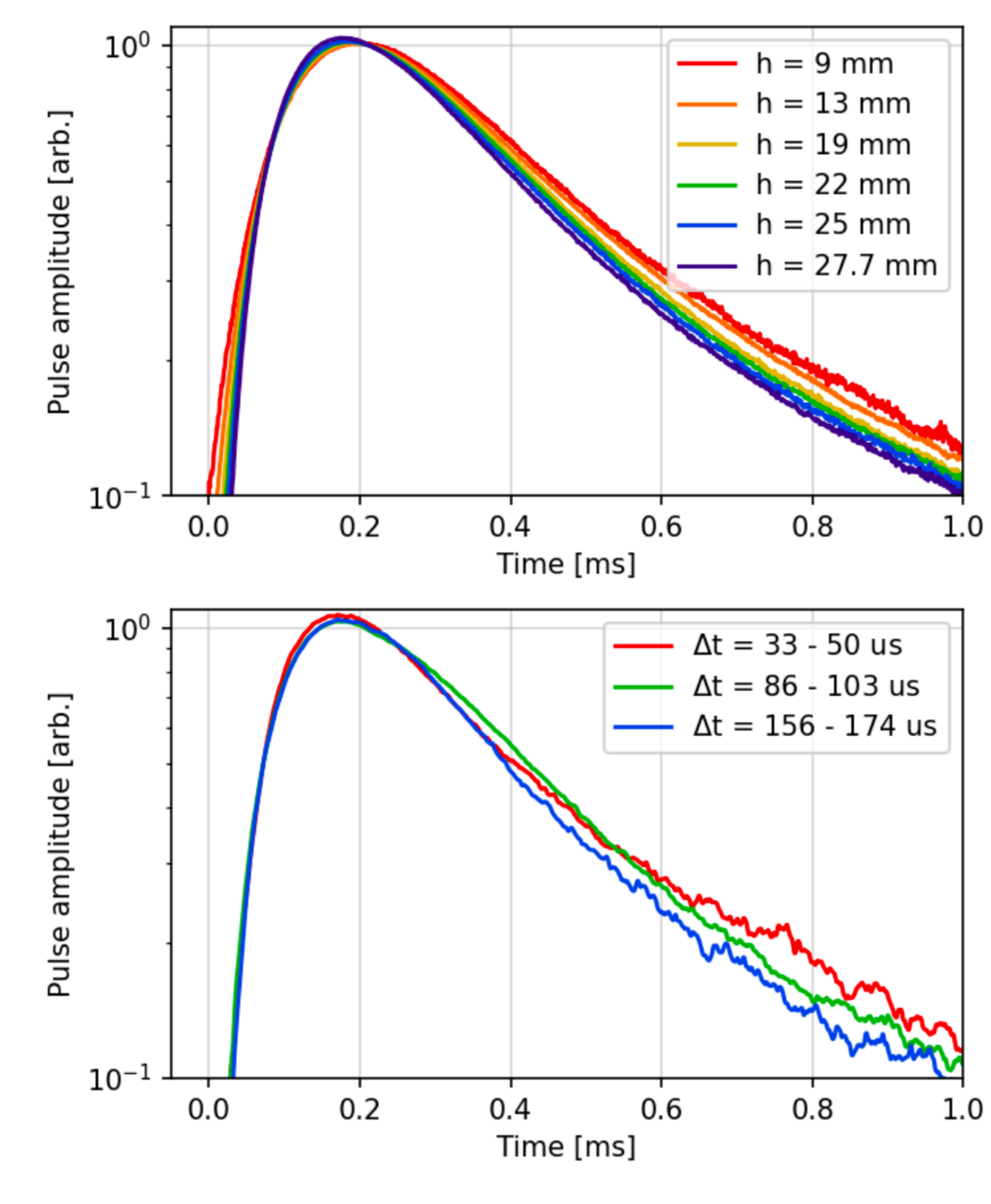




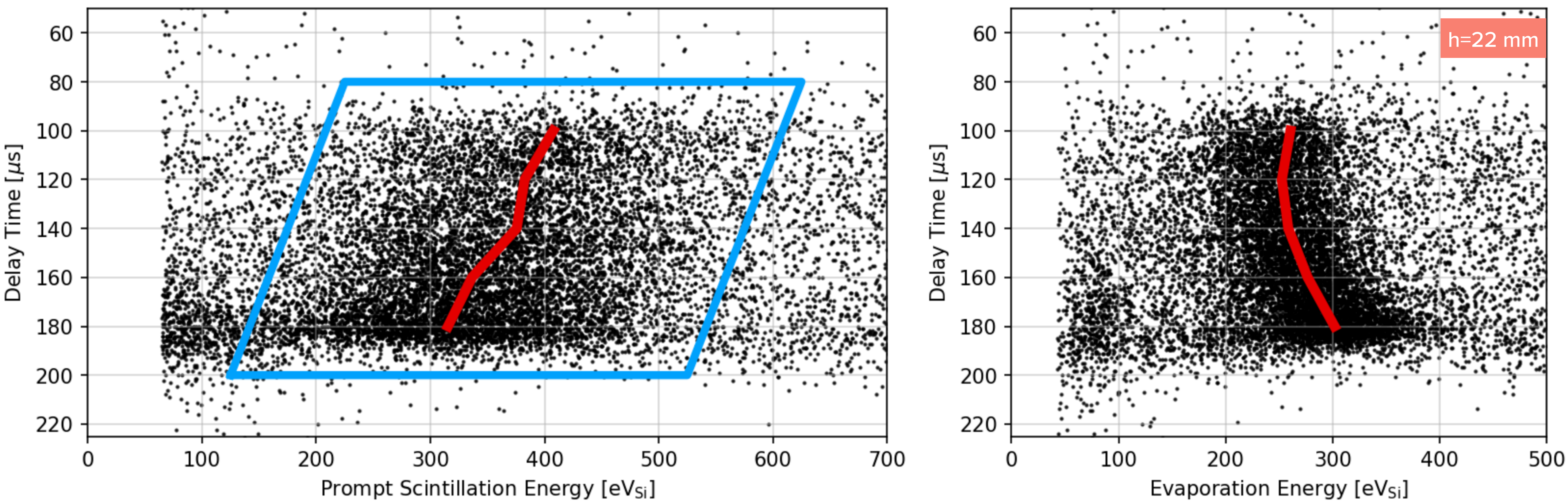


SHAPE OF EVAPORATION SIGNAL

- Evaporation pulse shapes were kept fixed in the reconstruction, but show small variations with depth, both in the mean between fills and in the shape at different depths
- Lower fills have broader shapes, as the QPs move roughly twice as fast as the atoms they kick out, plus more variation in the paths to the sensor
- At the same fill but different depths, the tail is a bit fatter for events happening high up in the bulk
  - Could be some QPs first travelling down and then being reflected? The time is roughly right, with 0.4 ms being the round-trip time for a QP with $v \sim 200$m/s and $d = 50$ mm

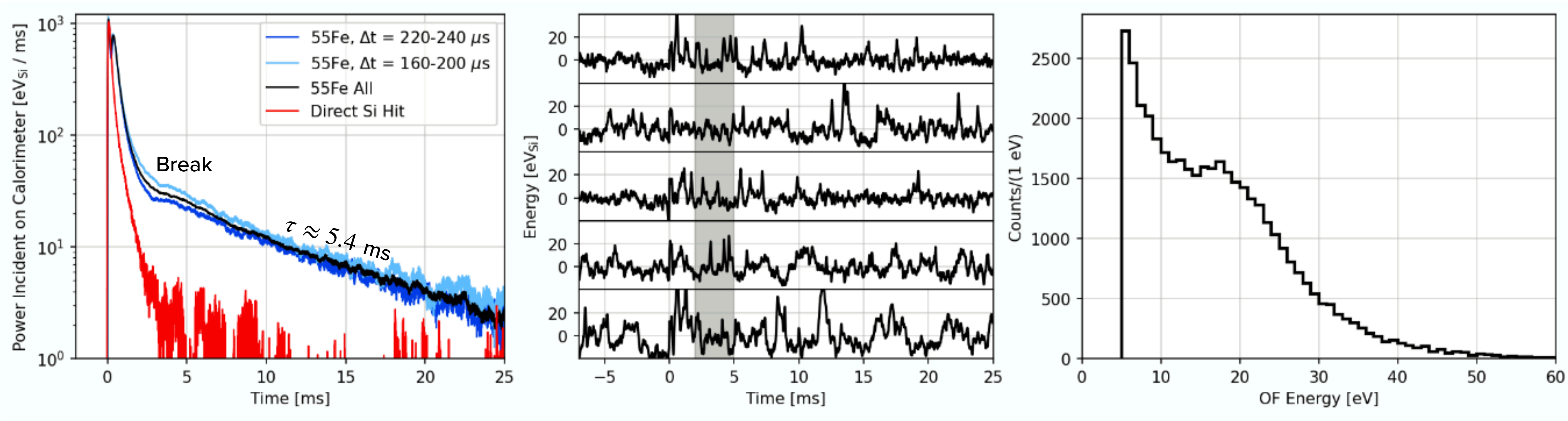


DEPTH DEPENDENCE OF AMPLITUDE



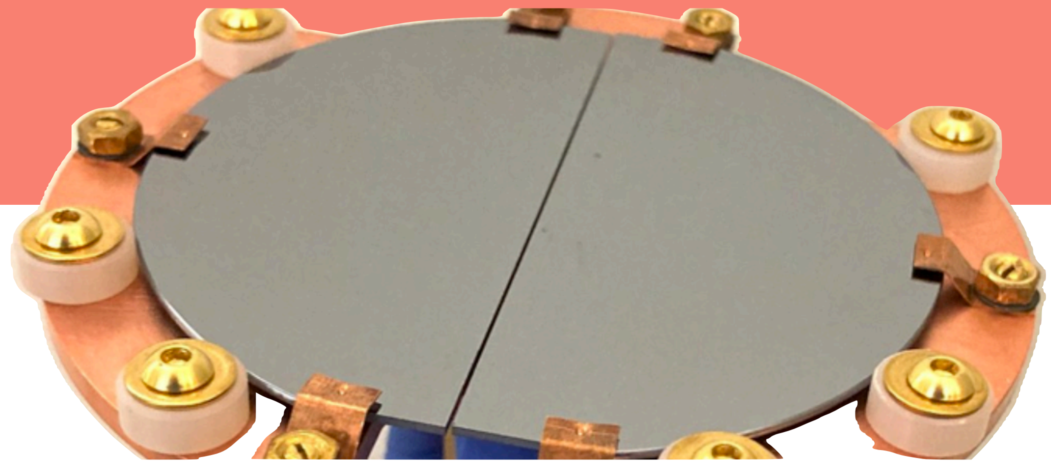
- **Higher rate near bottom, where we also can see the shorter-ranged 1.5 keV Al fluorescence events**
- **Scintillation light decreases with depth,**
- **While the QP evaporation signal increases— the expectation from the 17° requirement is a constant, so this could also be explained by QPs reflecting and then getting another try towards the surface**
- **Scale consistent with a reflection probability ~ 0.3**

DELAYED TRIPLET SIGNAL

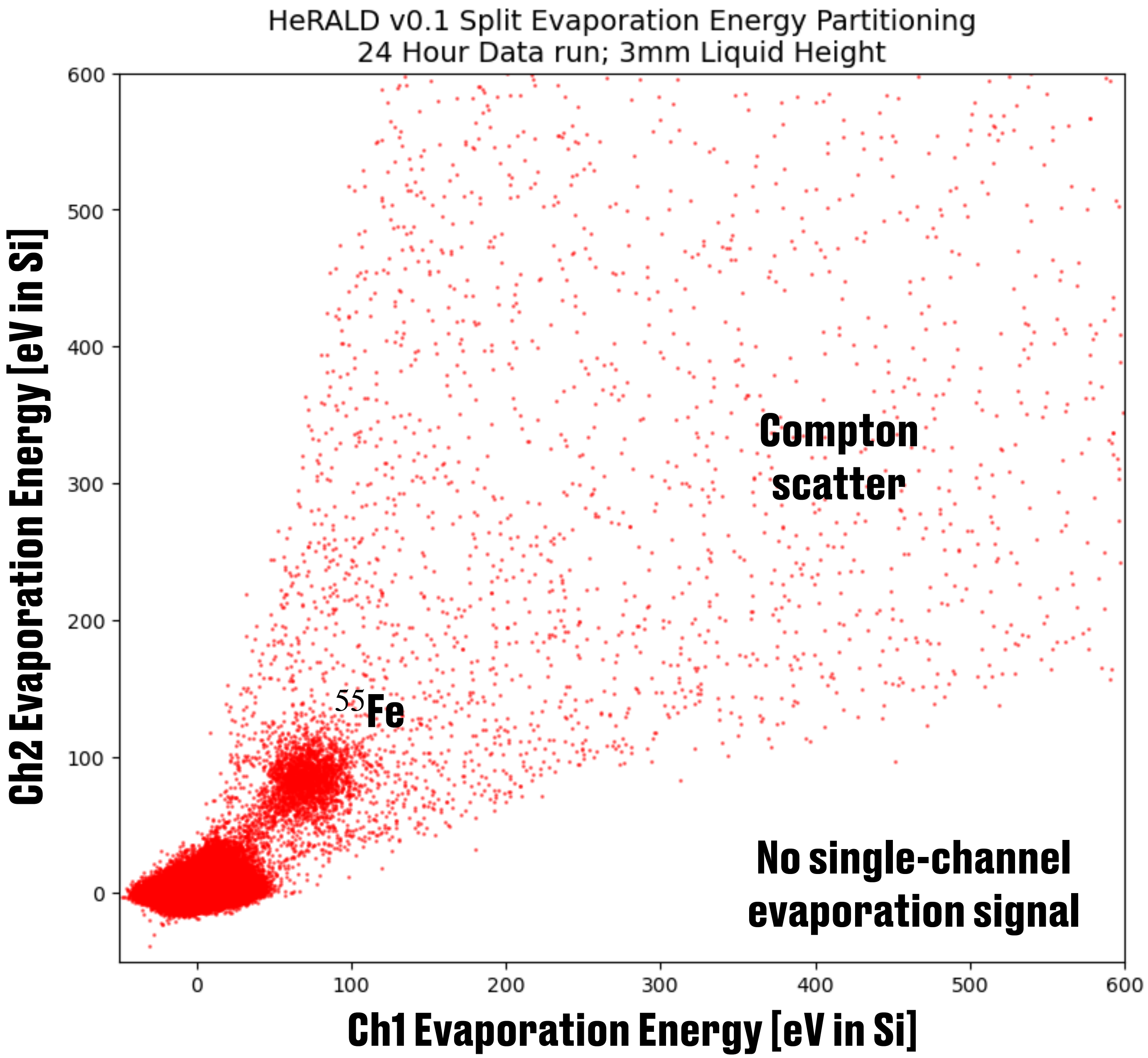


- The delayed triplet pulses are much longer-lived, moving with some m/s velocity until they hit a metal surface and de-excite, or interact with another triplet.
- The average waveform, shown to the left, show a break around 4 ms, the time expected to reach the surrounding metal surfaces
- The longer tail, possibly due to triplets stuck on the surface, is still decaying quicker than the 13s lifetime. Integrated area is around 200 eV, again consistent with approximately equal split in signal components.
- The middle plot shows the residual (minus baseline, scintillation and QP evaporation), reconstructed with a scintillation-only template.
- Subsequent runs show better resolution, and the triplet signal is well defined in energy, providing an in-situ calibration

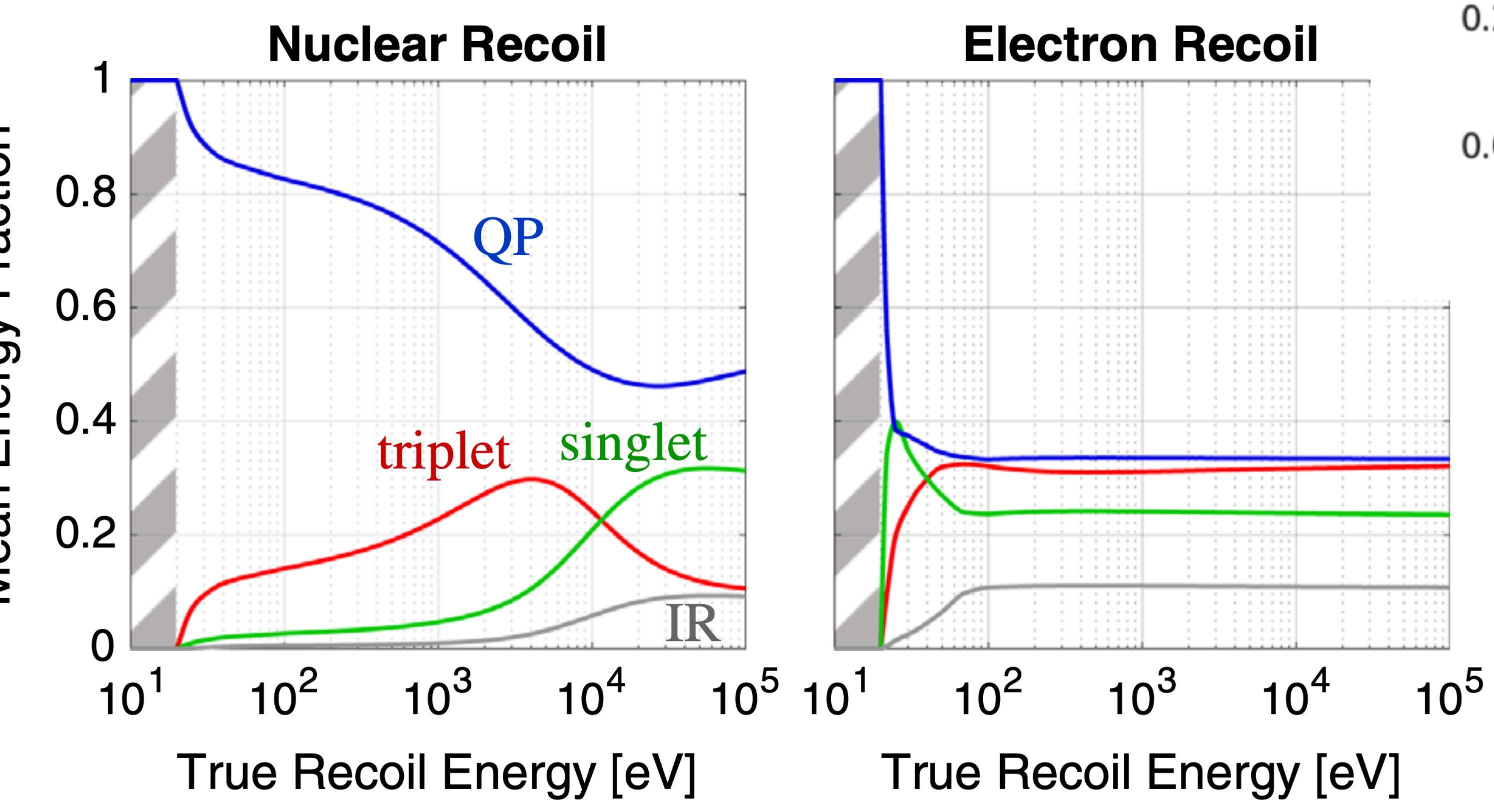
EVAPORATION CHANNEL COINCIDENCE

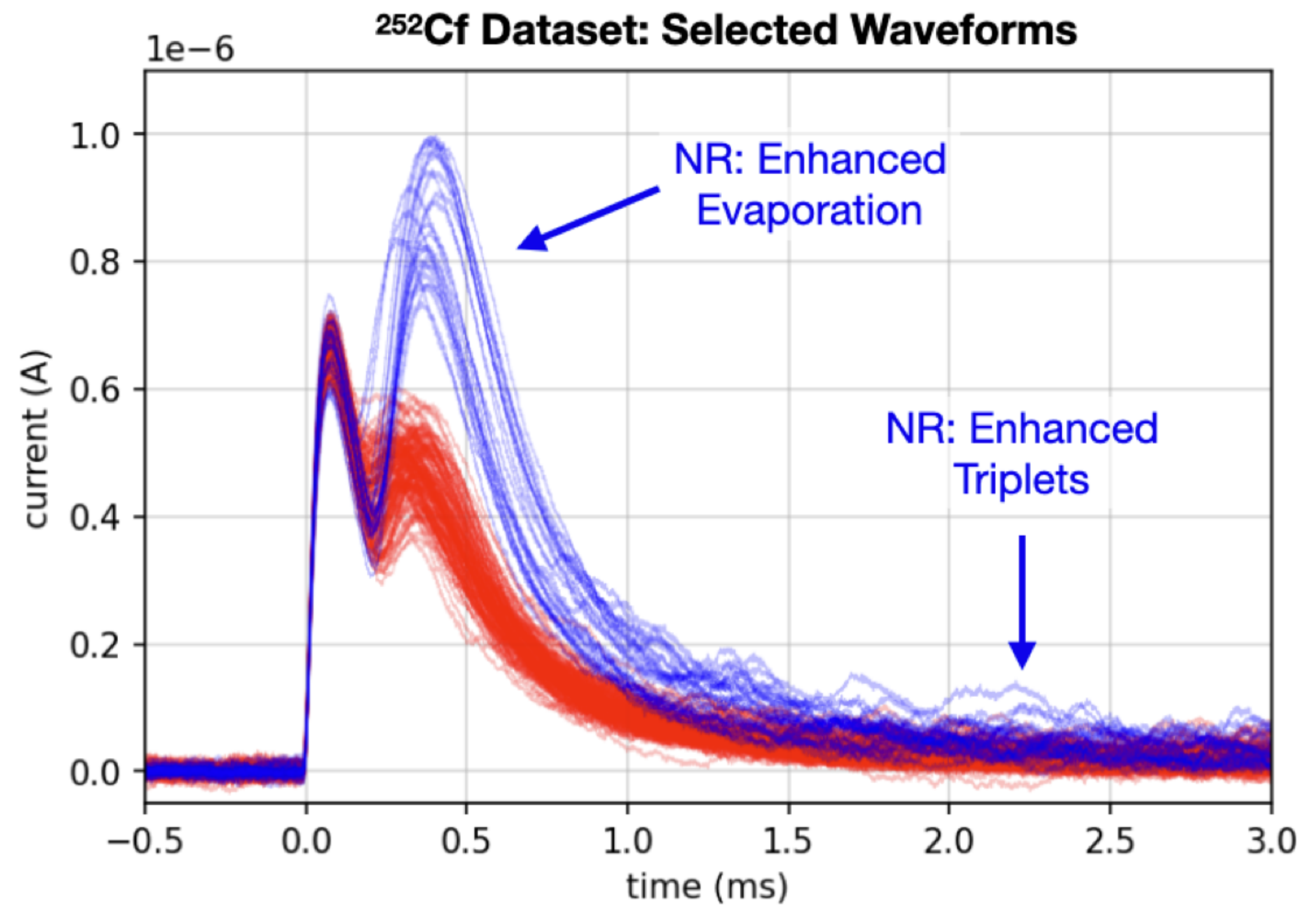


- Further development and R&D: two channel sensor
- Splitting the Si sensor in two allows us to study coincidences — when there is a QP evaporation signal, it is always in both channels
- Pre-fill data shows up as single detector events
- This is a powerful discriminant against sensor-related backgrounds!



ENERGY PARTITION

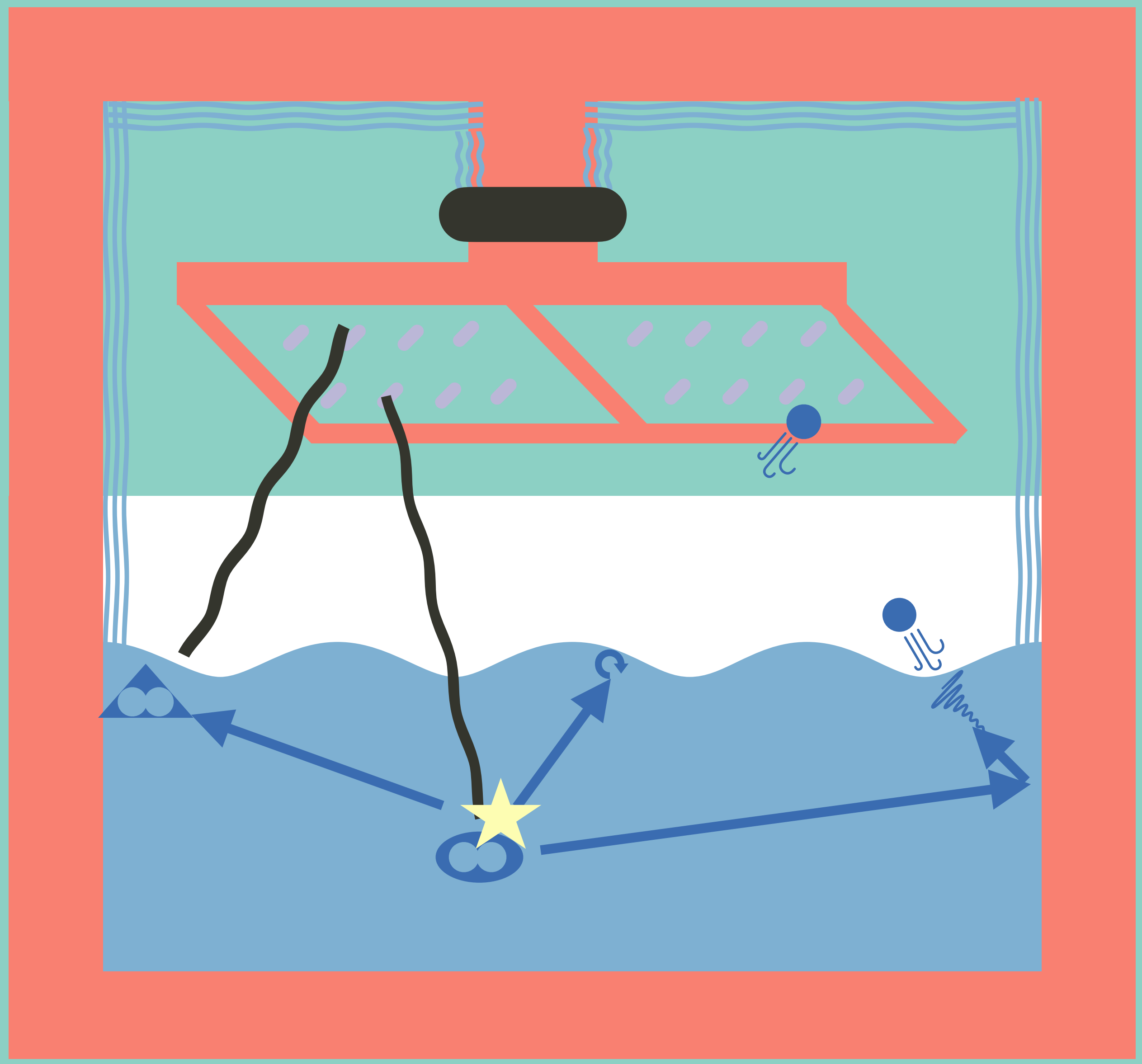




S. A. Hertel, A. Biekert, J. Lin, V. Velan, and D. N. McKinsey, Direct detection of sub-GeV dark matter using a superfluid 4He target, Physical Review D 100, 092007 (2019).

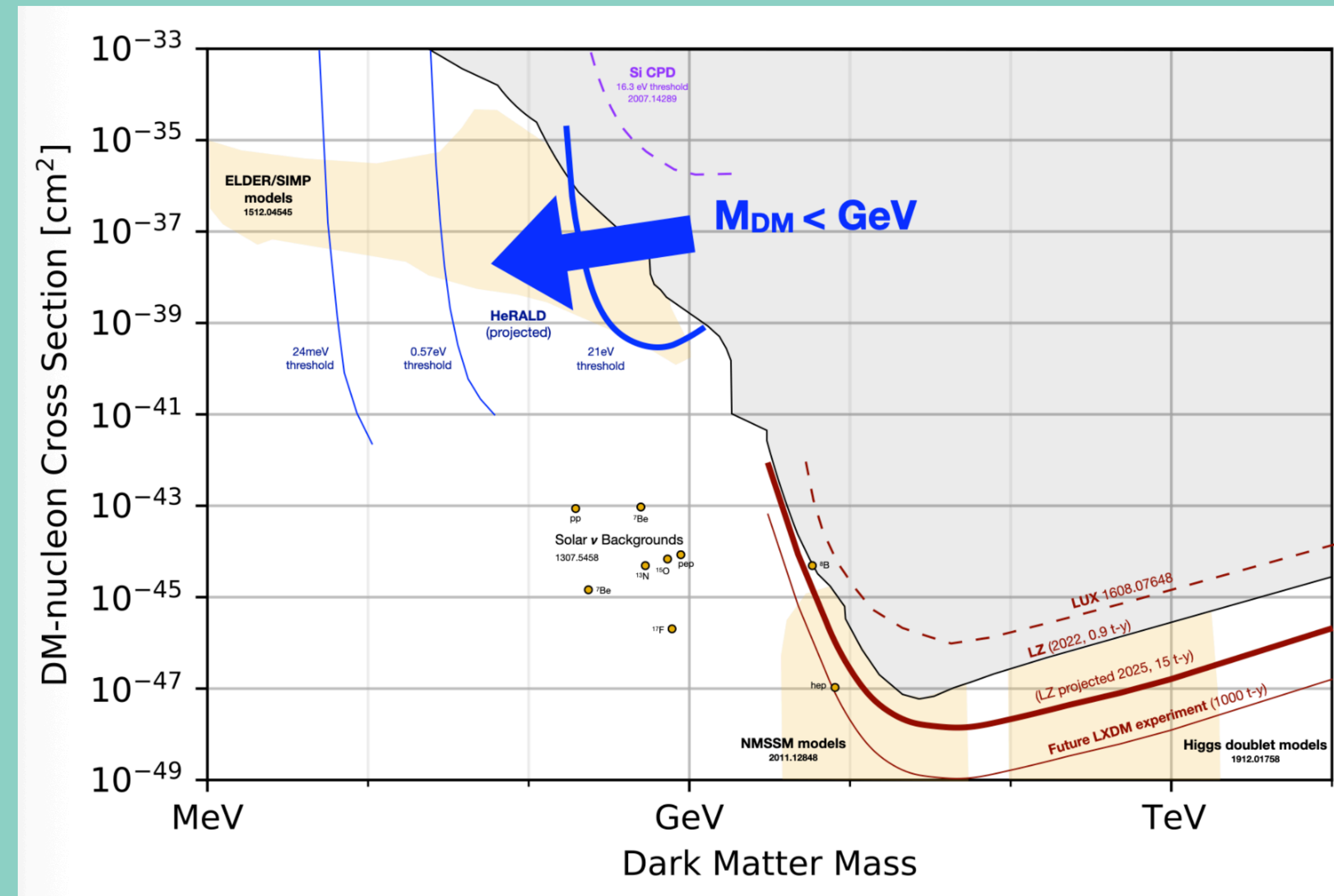
TESSERACT V0.1 LESSONS

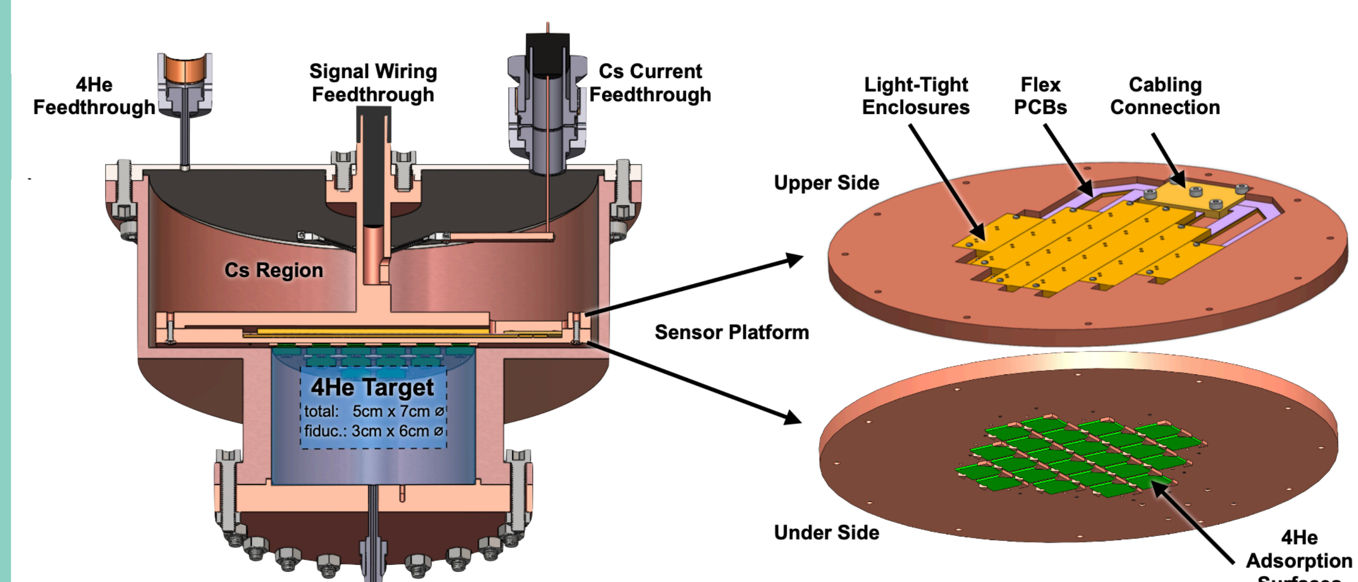
- **Demonstrated QP evaporation gain of 0.15 ± 0.01**
- **An implied nuclear recoil threshold of ~ 145 eV from the optimal filter 5σ threshold combined with the QP evaporation gain**
- **The lighter He targets compensates for the lower-than unity gain, giving a similar mass threshold for HeRALD as for a Si detector, around 0.2 GeV/c^2**
- **Triplets decay away faster than 13 s, reducing the concern of a constant dark count**



TOWARDS TESSERACT He 1.0!

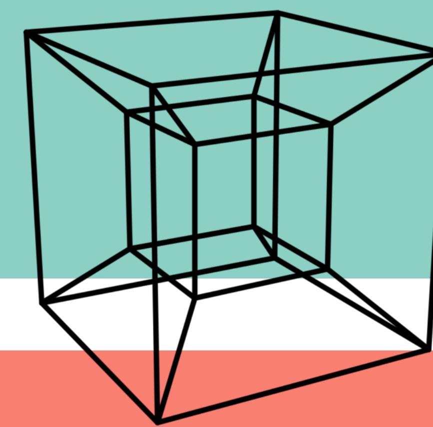
- With a heat-free He blocking solution, the next generation He detectors can go down in critical temperature to ~ 20 mK, with thresholds < 1eV
- New sensor pad materials can enhance the QP evaporation gain
- Improved surface reflectivity would yield a significant signal enhancement
- A factor two improvement in both combined with the lower energy thresholds would allow TESSERACT to probe dark matter masses down to $\sim 30\ \mathrm{MeV/c^2}$
- Higher sensor segmentation will enable better signal/background discrimination and make position reconstruction accessible
- Runs without sources to characterise noise and/or discover dark matter





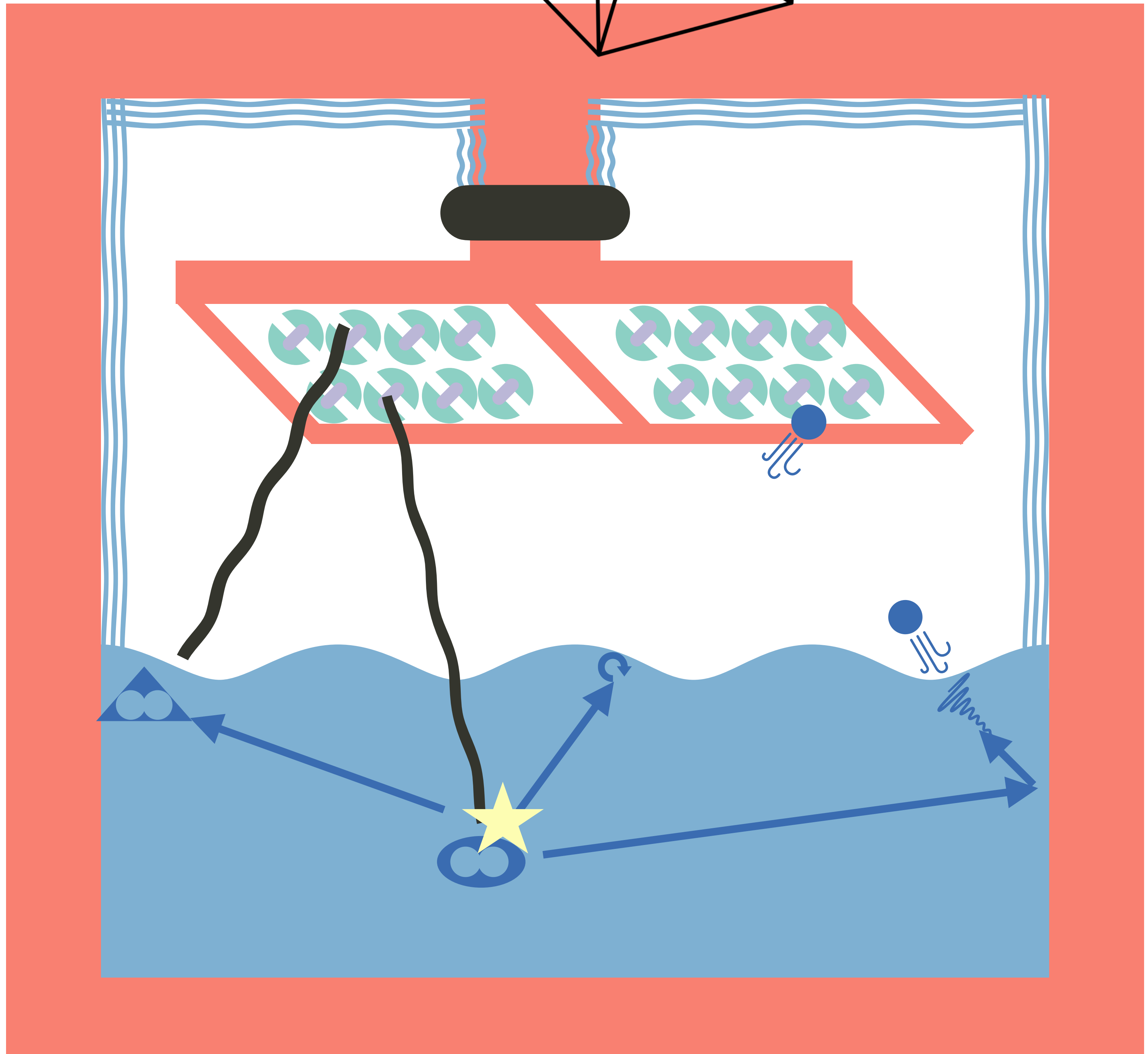
Junsong Lin, Joanna Wuko

NEXT STEPS: DARK MATTER SEARCHES?



I debated with myself if there should be a ! or a ? here

- **The detector concept for superfluid He has been successfully demonstrated!**
- **Following a major conceptual design report review for the DOE, TESSERACT is a DOE “project”**
- **Targeting underground installation @ Modane in 2028, alongside surface science runs**
- **Underground science runs at LSM scheduled for 2029**



LSM

Read more:
R. Anthony-Petersen et al, “First Demonstration of the HeRALD Superfluid Helium Detector Concept” Phys.Rev.D 110 (2024) 7, 072006 e-Print:2307.11877
or on tesseract.lbl.gov

Thanks to: Schweizerischer Nationalfonds

TESSERACT: one collaboration, sub-eV resolution and several targets

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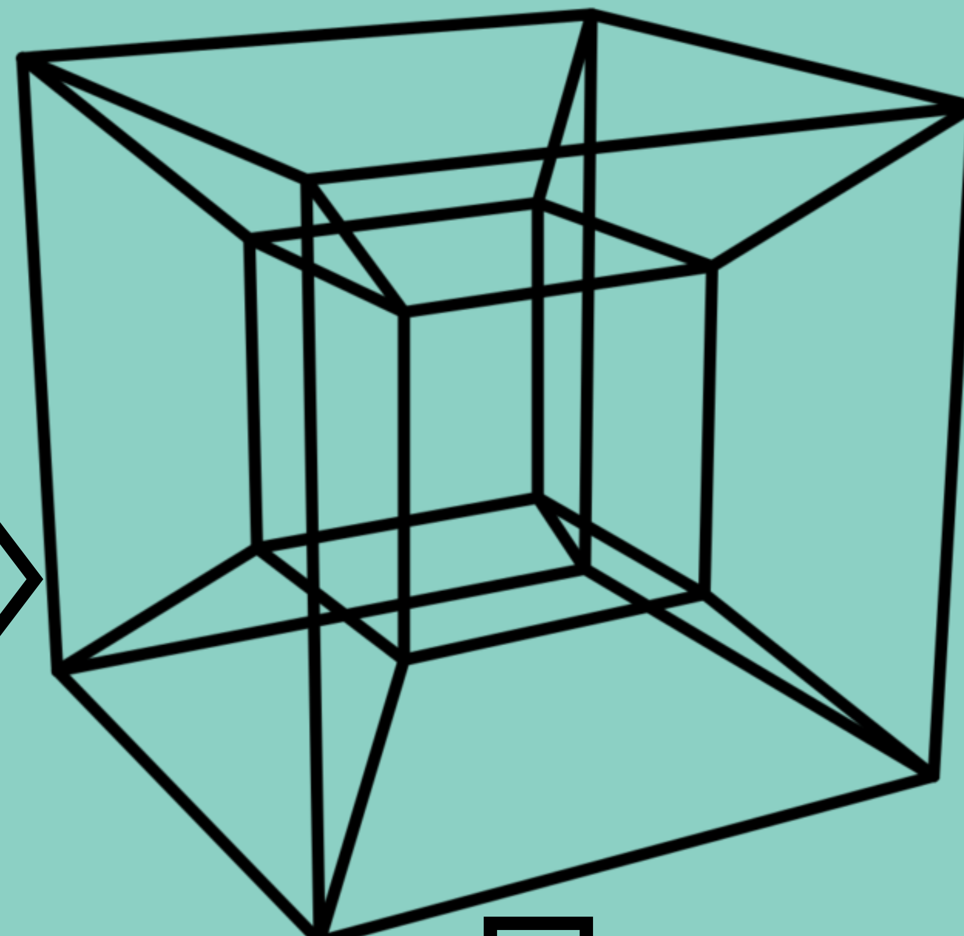
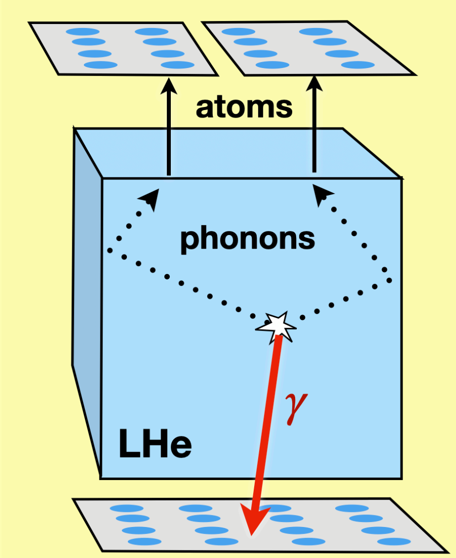
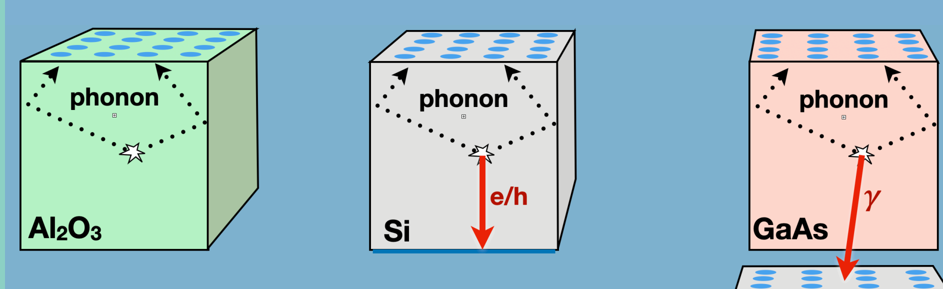


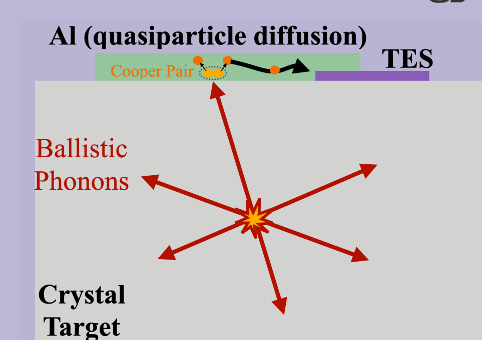
HeRALD: a superfluid ^{4}He target



SPICE: polar crystals instrumented with TESs— See Juliens talk Tuesday!



Shared Transition Edge Sensor (TES) technology



Diagrams by Scott Hertel