The SPICE and HeRALD experiments for sub-GeV dark matter direct detection

CIPANP 2022

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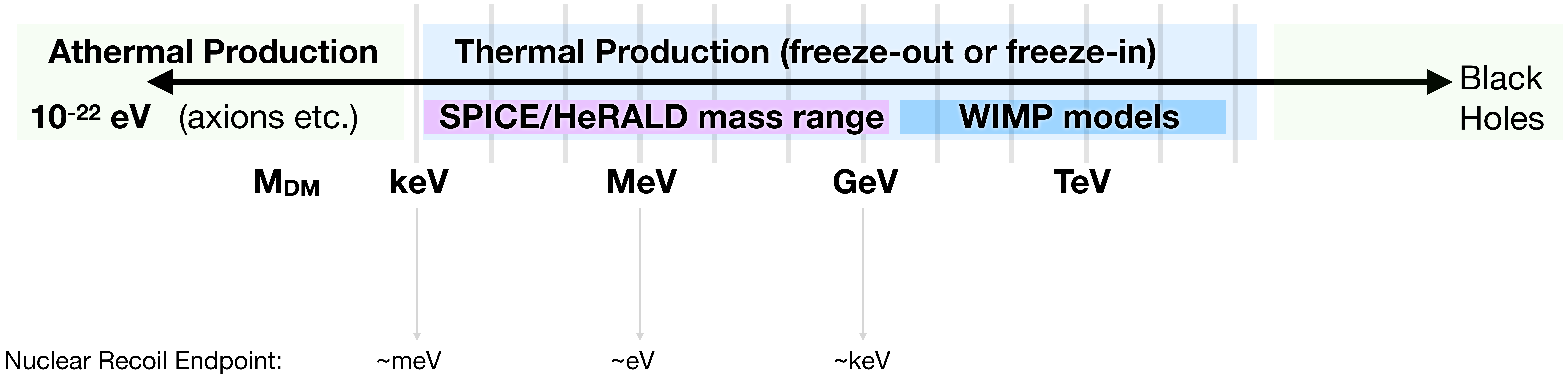
Dark Matter in the keV-MeV mass range

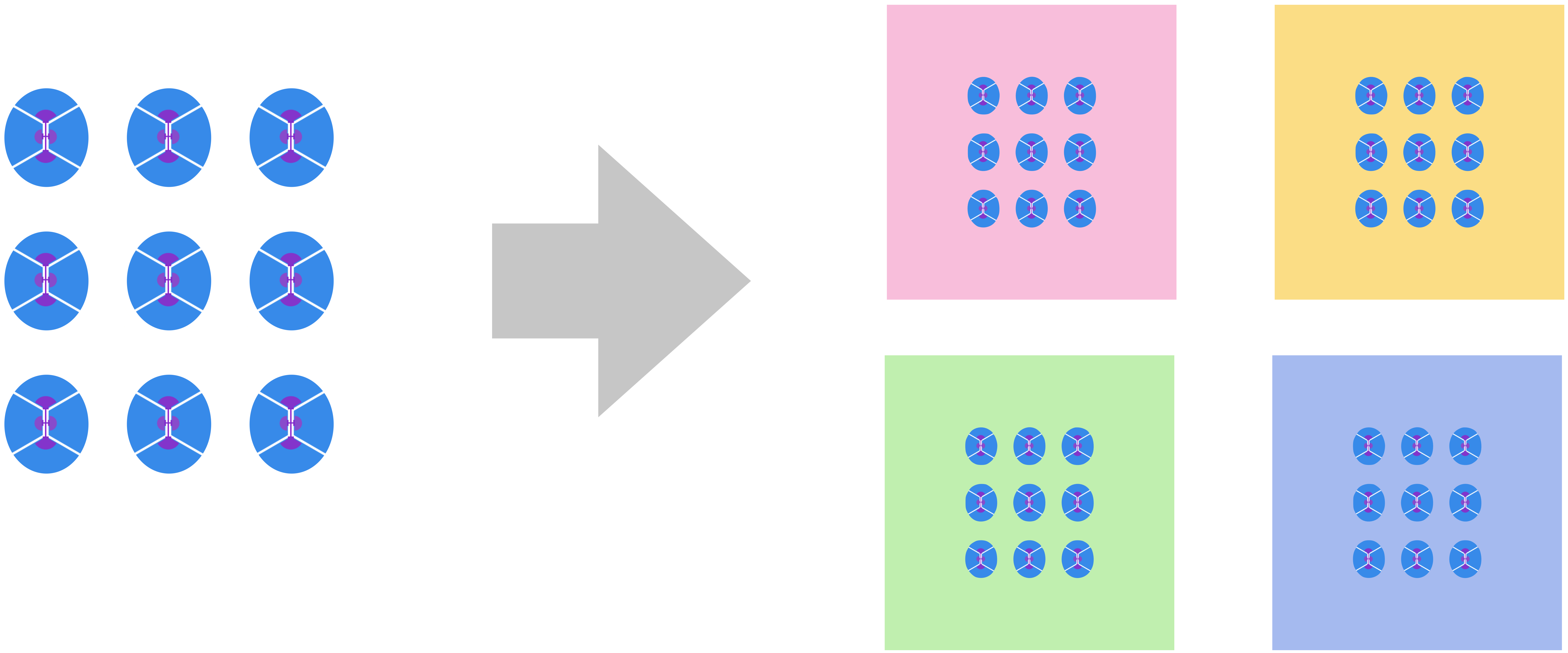
Consistent with simple thermal production after inflation (like other massive particles)
Typically require a new force mediator too, not just the DM particle.
Direct detection searches via electron scattering or nuclear scattering



Putting the most sensitive sensors on the most interesting targets

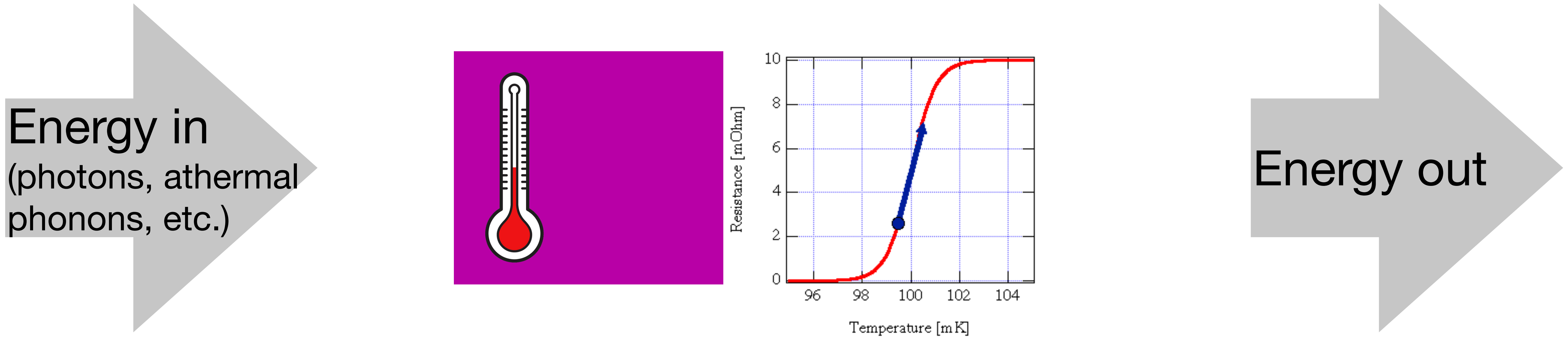
Step 1: Push Transition Edge Sensors to even lower threshold

Step 2: Apply those sensors to diverse target materials with diverse signals



Pushing Transition Edge Sensors to even lower threshold

TES's are not too complicated, and have been around for a long time…



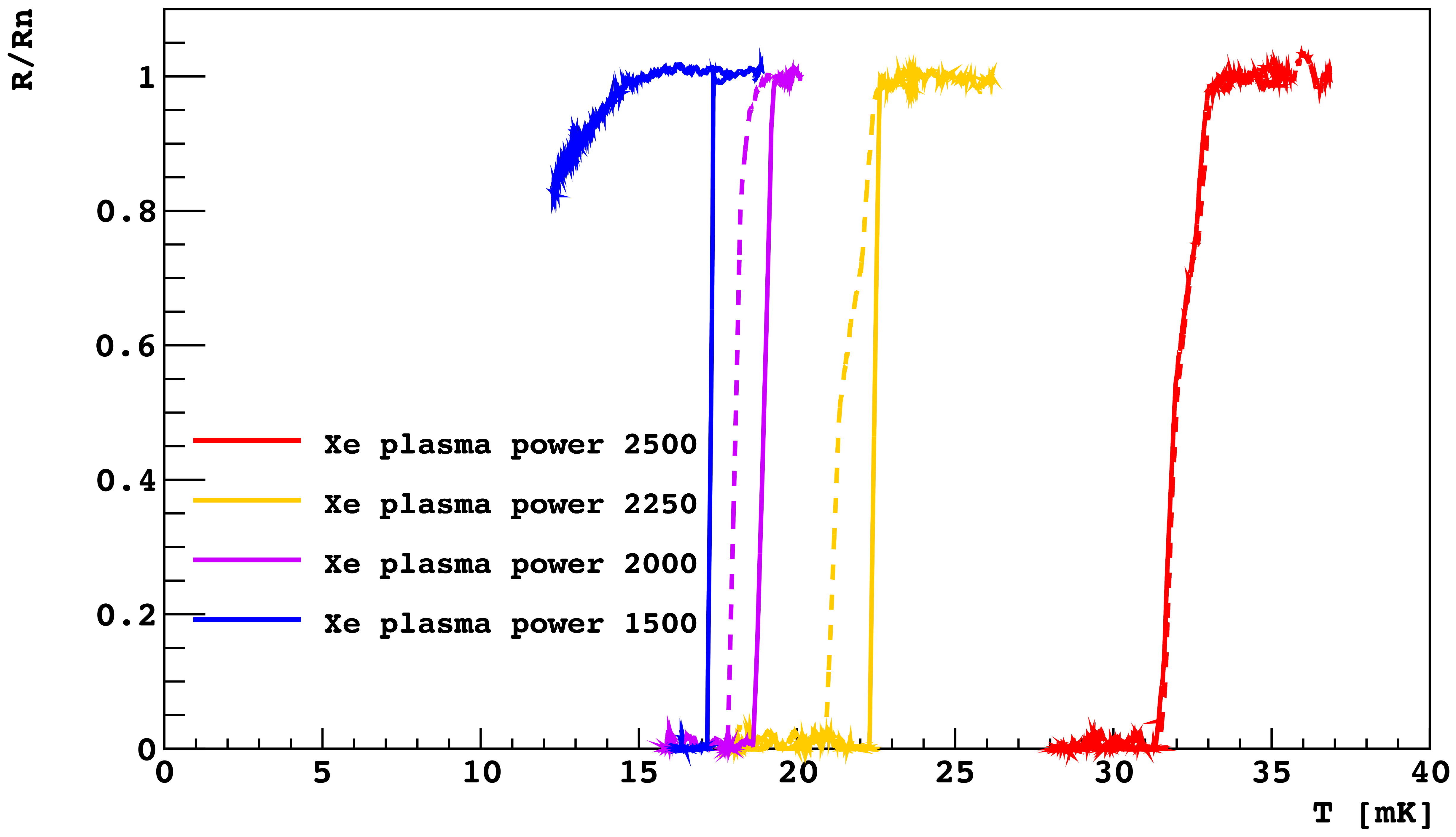
But dramatic improvement seems surprisingly accessible.

$$\sigma_{<E>} \propto \sqrt{VT^3}$$

1. Push the critical temperature as low as possible
2. Push the total TES volume as low as possible

Pushing Transition Edge Sensors to even lower threshold

1. Push the critical temperature as low as possible… done?



Collaborators at Texas A&M have now demonstrated the ability to tune Tc in the 15-20mK range.

Delicate tuning of the ratio of two phases of tungsten lattice structure.

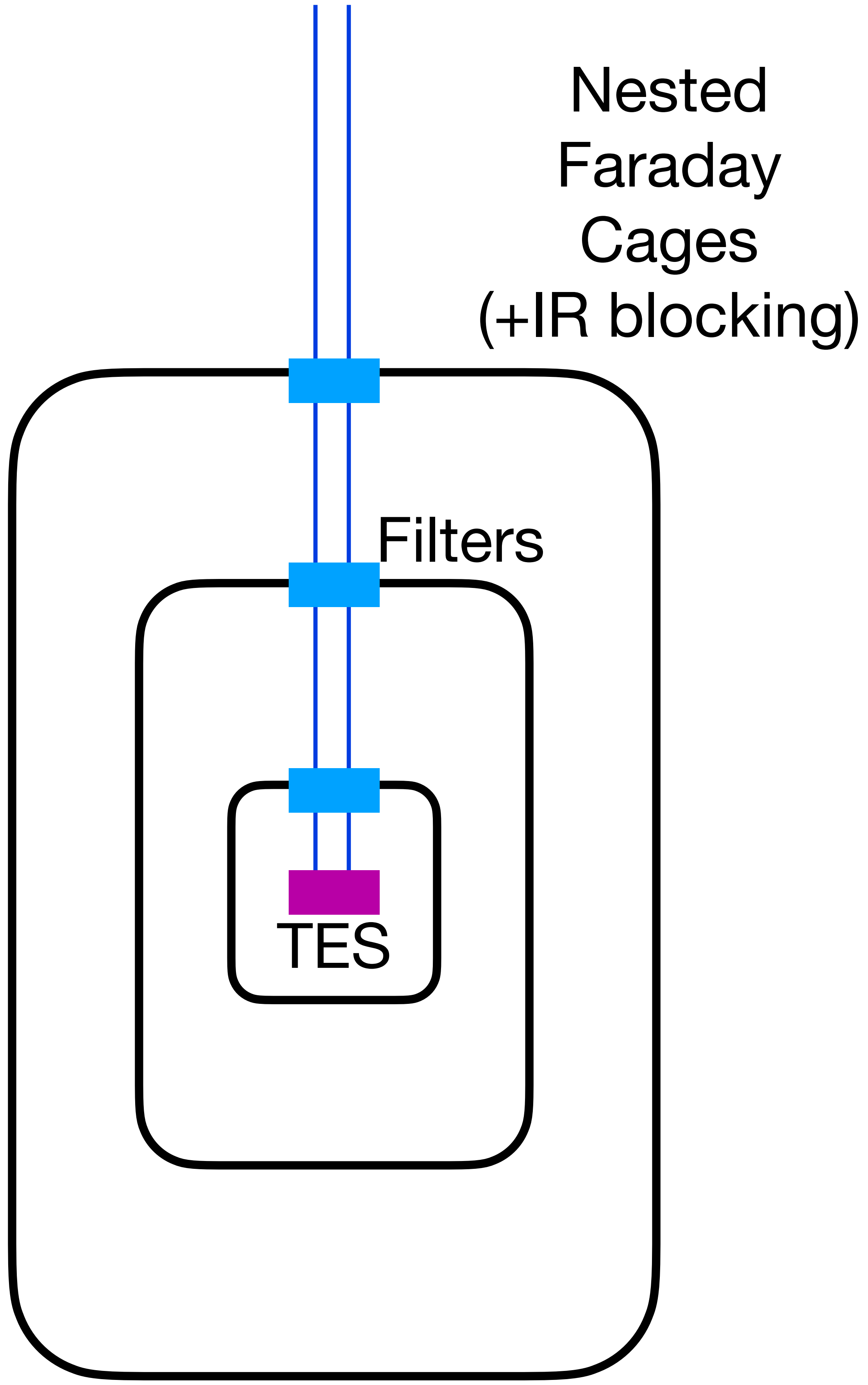
Pushing Transition Edge Sensors to even lower threshold

So… Tc is good, changing the volume is easy… are we ready for 1meV thresholds?

Next challenge: Parasitic heating

Once Tc and volume are low, it only takes femtoWatts or even attoWatts to drive the TES normal.

Extreme sensitivity to power is a double-edged sword!



Pushing Transition Edge Sensors to even lower threshold

Great, so now we're ready?

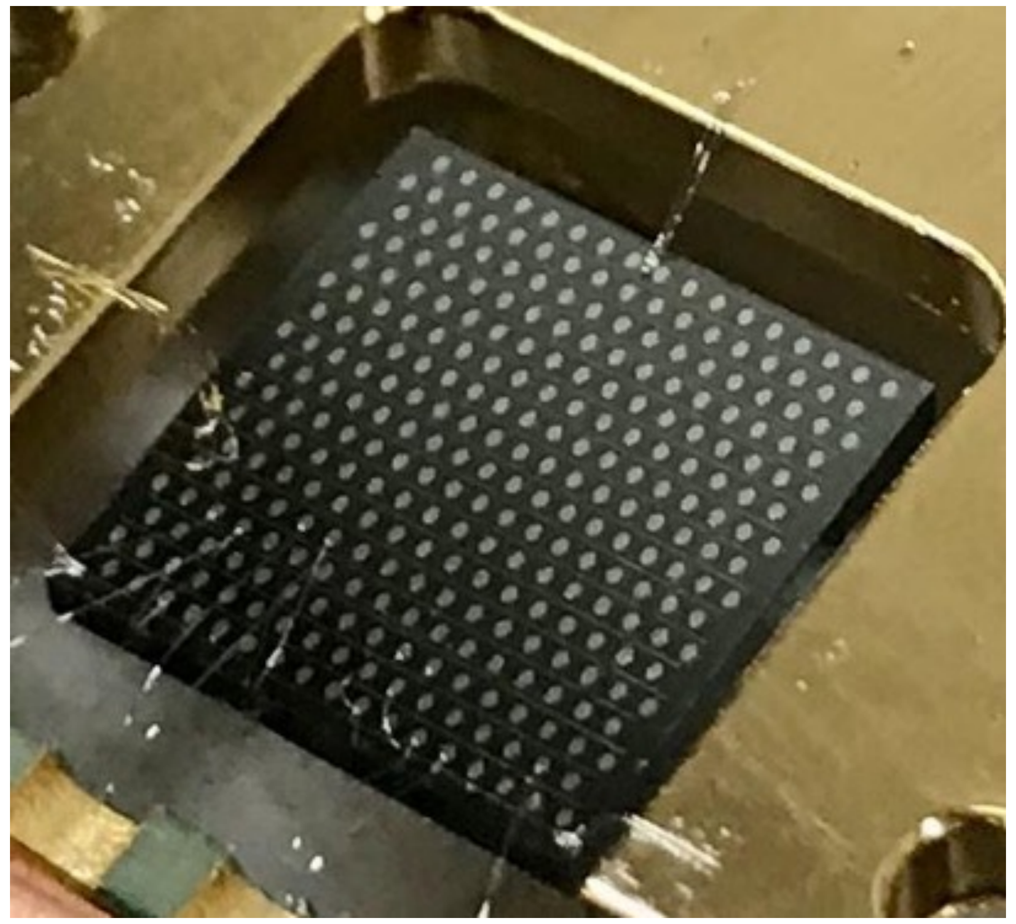
Next challenge: Spontaneous phonon emission

This is a challenge universal to low-threshold bolometer experiments, often called the "low-energy excess" or the "heat-only events".

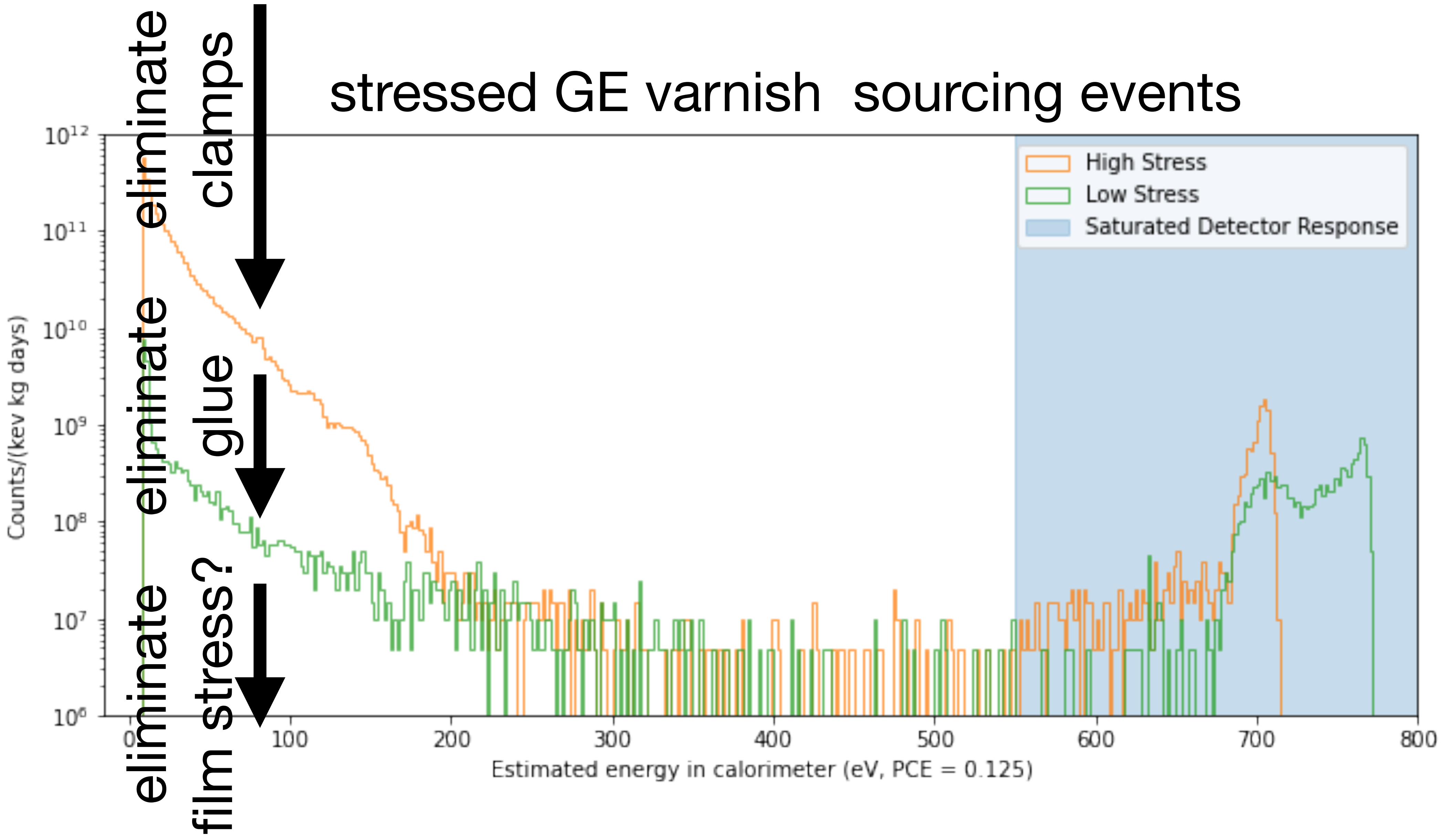
Type 1: At mechanical interfaces (clamps)

Type 2: Intrinsic to stressed materials (TES films, Al films, substrate, …)

sensor hanging by wire bonds



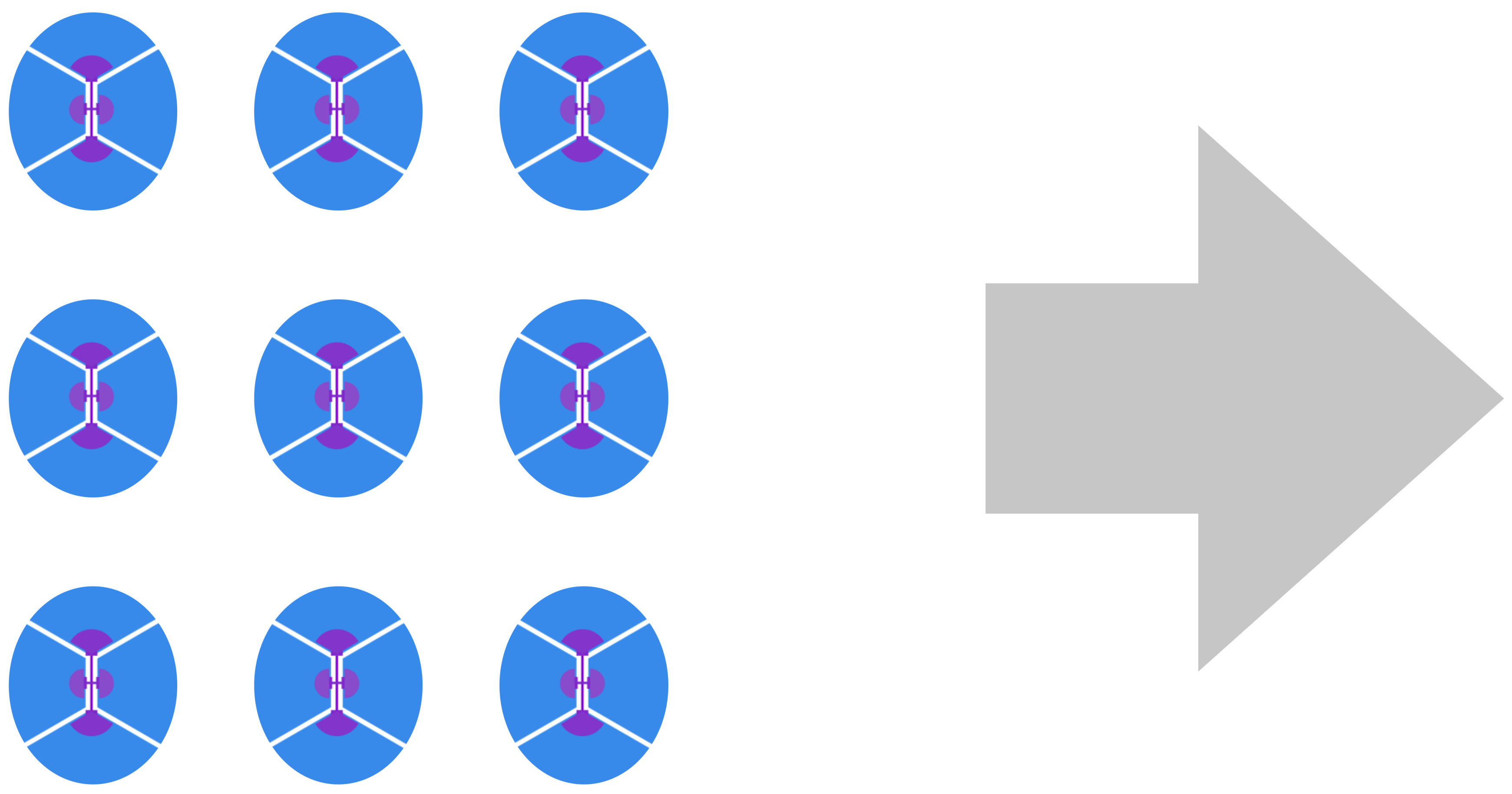
stressed GE varnish sourcing events



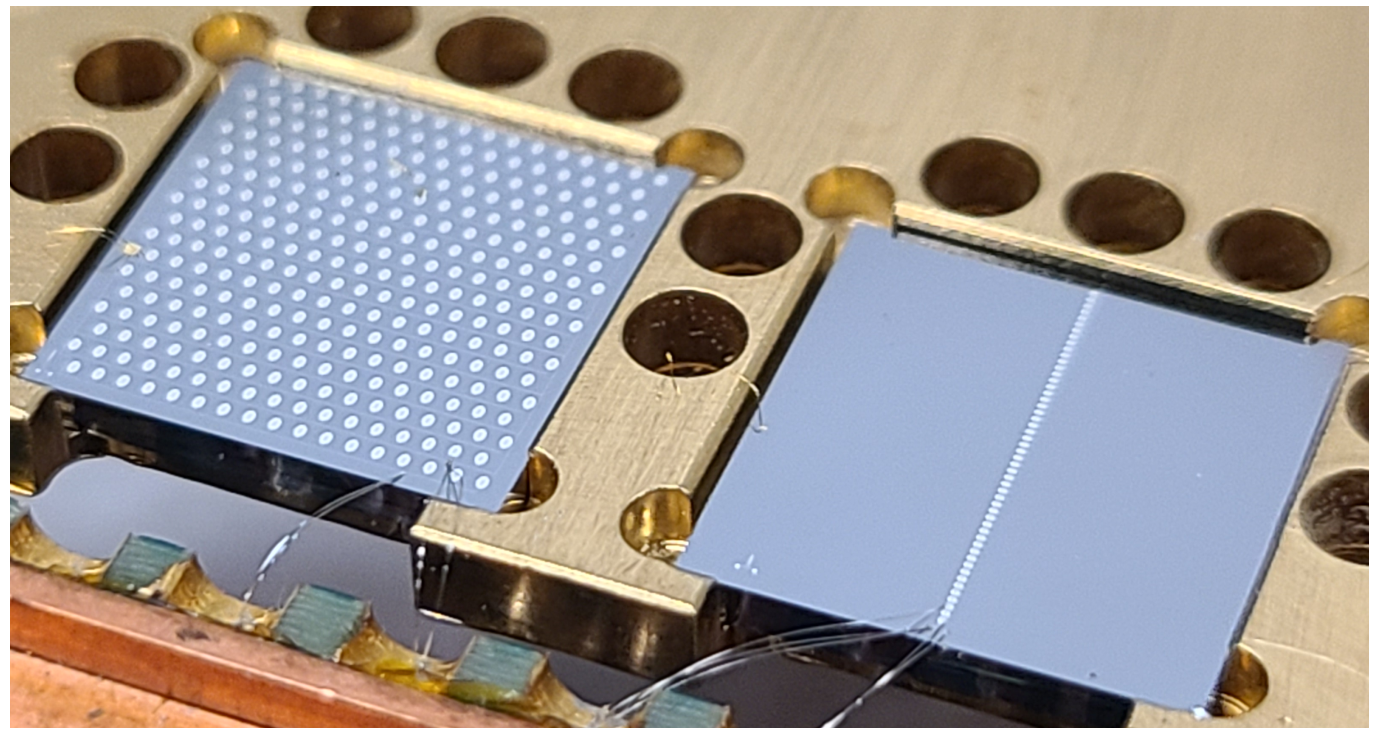
Current activities: Back to film R&D, goal of producing films with minimal stress.

Back to the big picture again

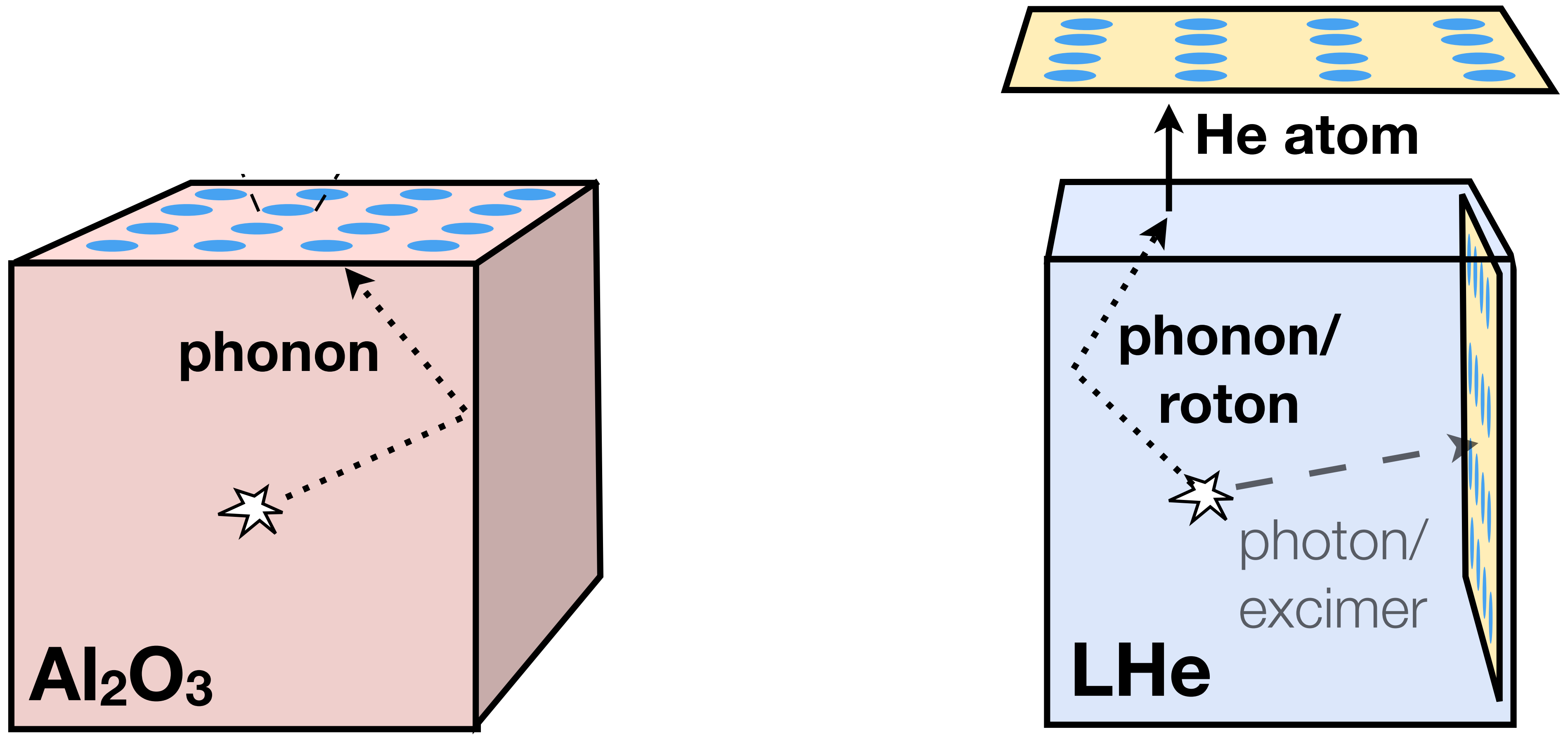
The main effort right now is reducing parasitic power and spontaneous phonon emission.



Sensor R&D primarily on Si substrates



But in parallel, we are starting to apply the initial sensors to some initial target materials



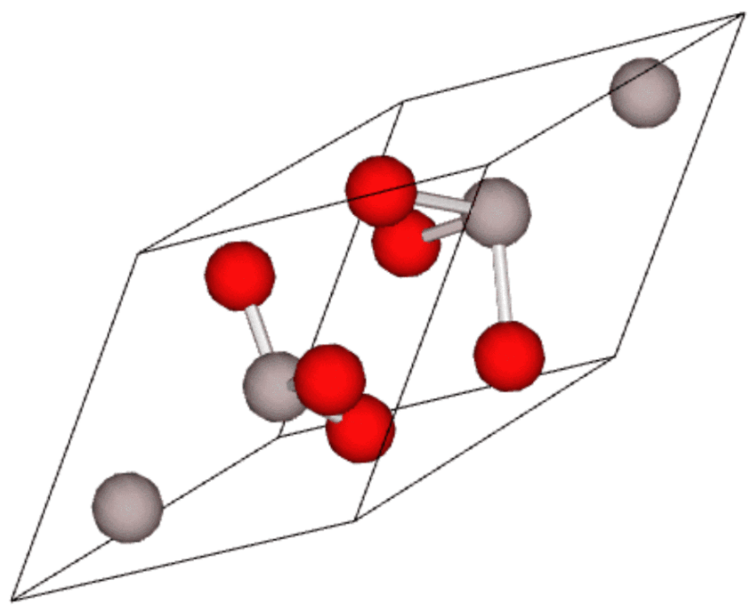
Sapphire, aka Al_2O_3 (part of SPICE)

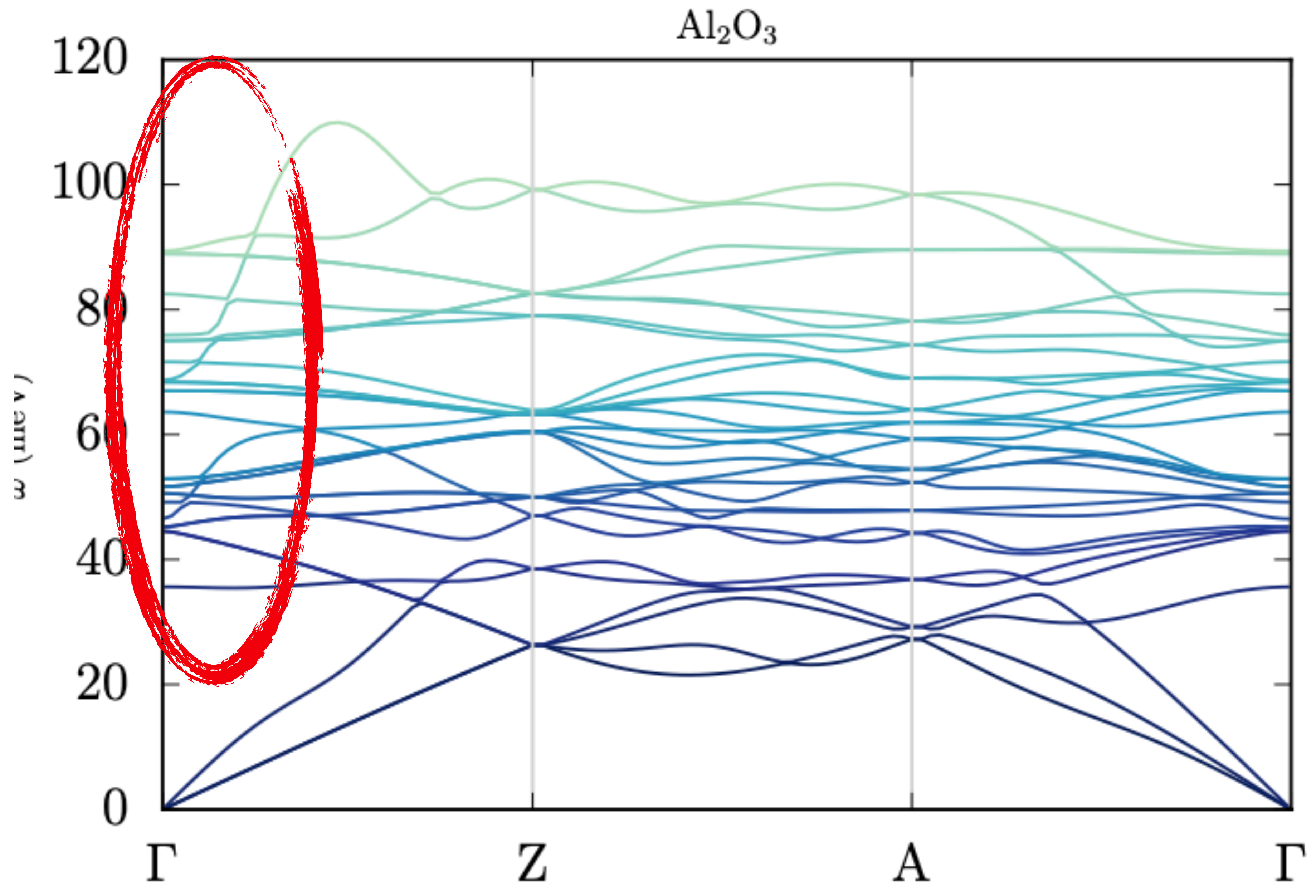
Key attributes:

1. Sapphire supports many optical phonon modes.
(phonons with a high energy:momentum ratio)

Instead thinking about ‘kicking an atom’ we now think about recoiling off the lattice, and ‘exciting a phonon’.

Optical phonons are kinematically well-matched to low-mass dark matter (similar effective mass)





2. Related: Sapphire is a polar crystal
(couples well to E&M-like inputs)

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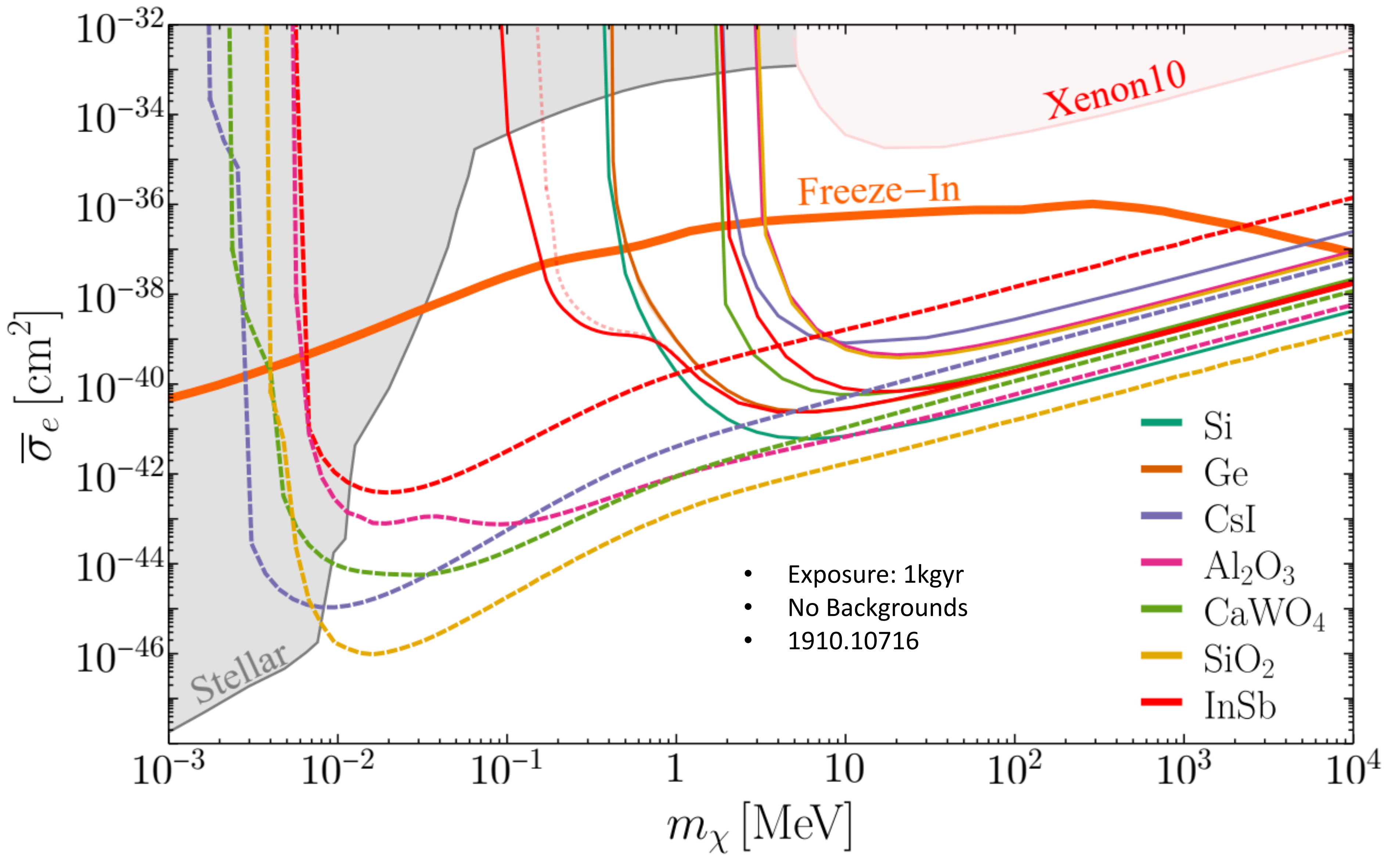
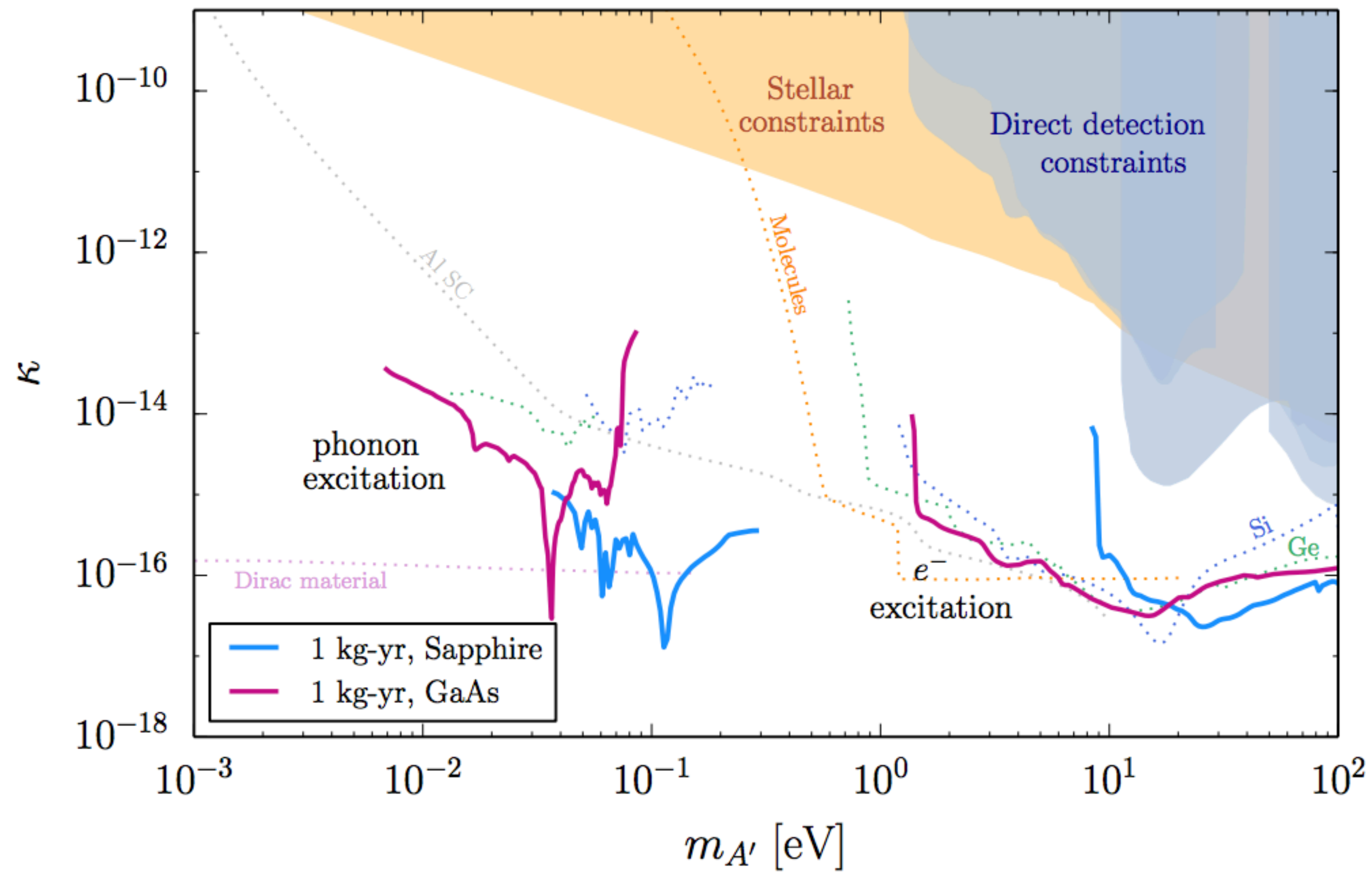
DM Scattering via Light Dark Photon



Dark Photon Dark Matter Absorption 1807.10291



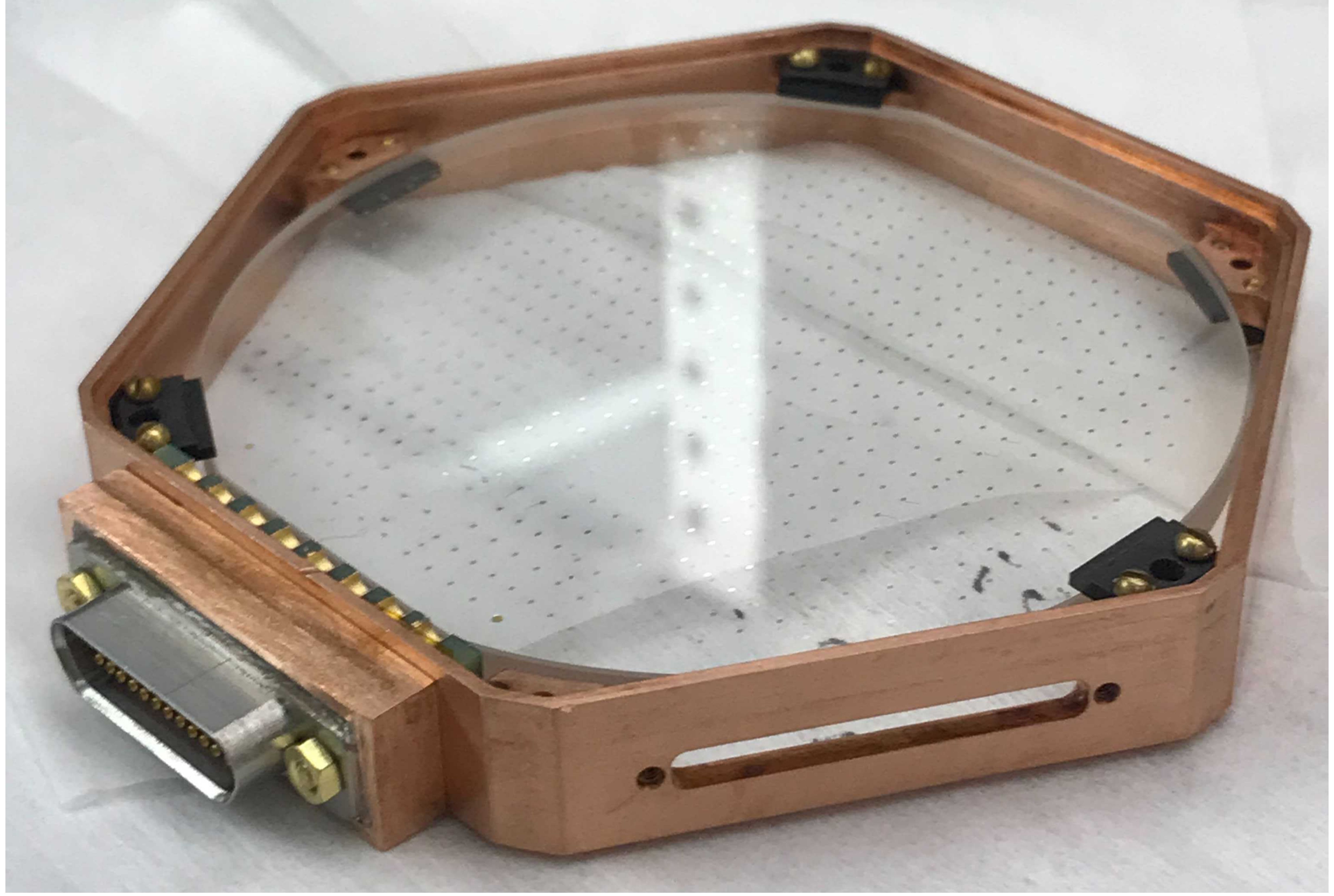
Sapphire, aka Al_2O_3 (part of SPICE)

Development:

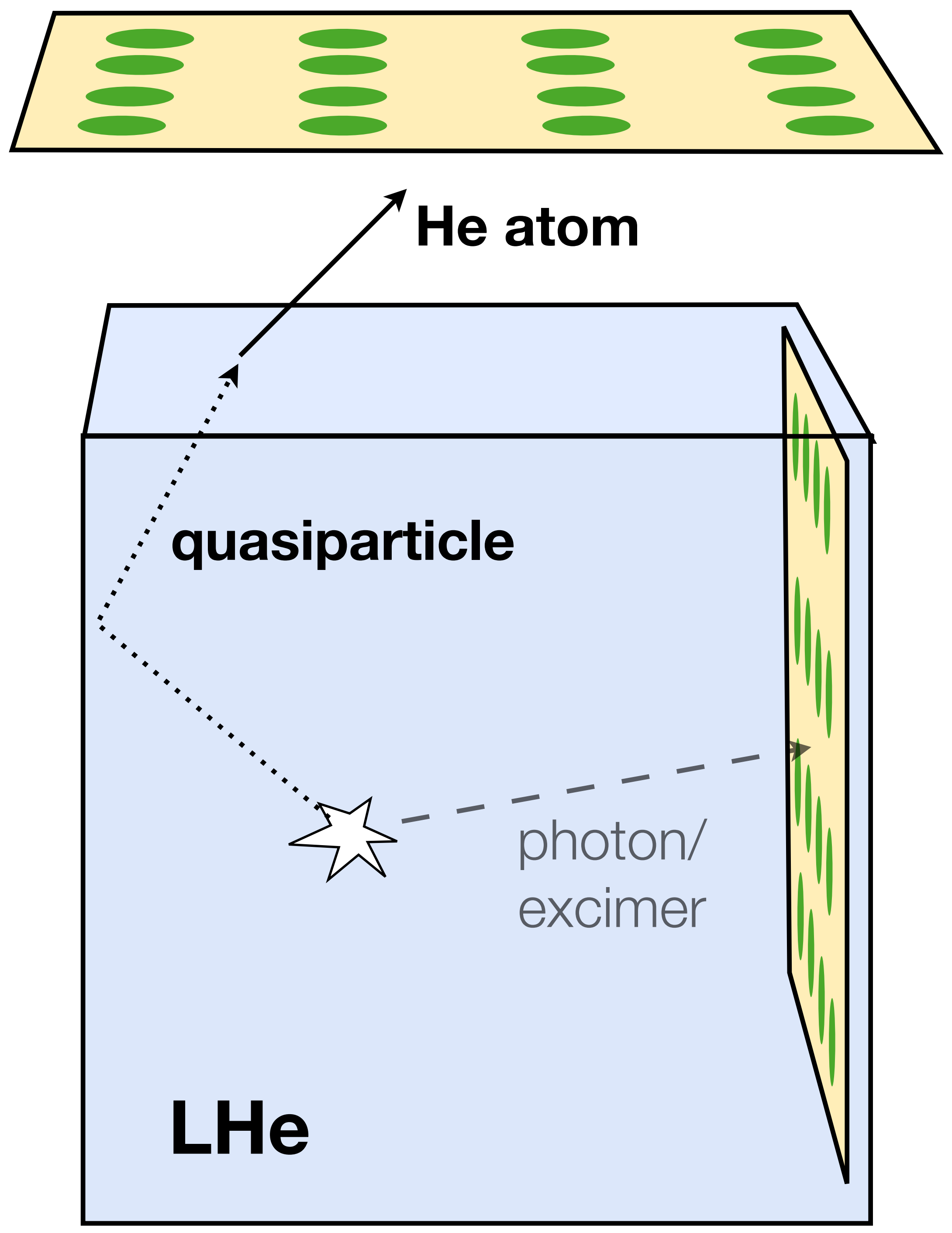
Design driver: Push threshold to single optical phonon scale, 10s of meV

TES fabrication on Sapphire now demonstrated!

Tc too low for current parasitic power levels…
(no DM search data yet)



superfluid ^{4}He target: HeRALD



Evaporation Sensors

Primary channel
(sets threshold)

QP focus

Immersed Sensors

Secondary channels
(aid discrimination)

Excimer focus
(perhaps also low-energy QP)

Sensitivity to Low-mass Dark Matter

Comparatively low-mass nucleus (result: relatively high recoil energy endpoint)

Signal gain (threshold reduction) through quantum evaporation then adsorption

Suppression/Rejection of Backgrounds

Many gammas simply pass through (low-Z material)

Efficient electron recoil tagging above ~100eV (using scintillation/excimers)

No electron recoils below 20eV (He first excited state)

Complementarity with Crystal Target Materials

He quasiparticles long-lived and balistic at relatively high energies (~1meV)

Vacuum gap separates target and phonon sensor:
- QP must be highly-athermal to be sensed via evaporation
- suppression of sensor backgrounds via coincidence requirement

arXiv:1810.06283

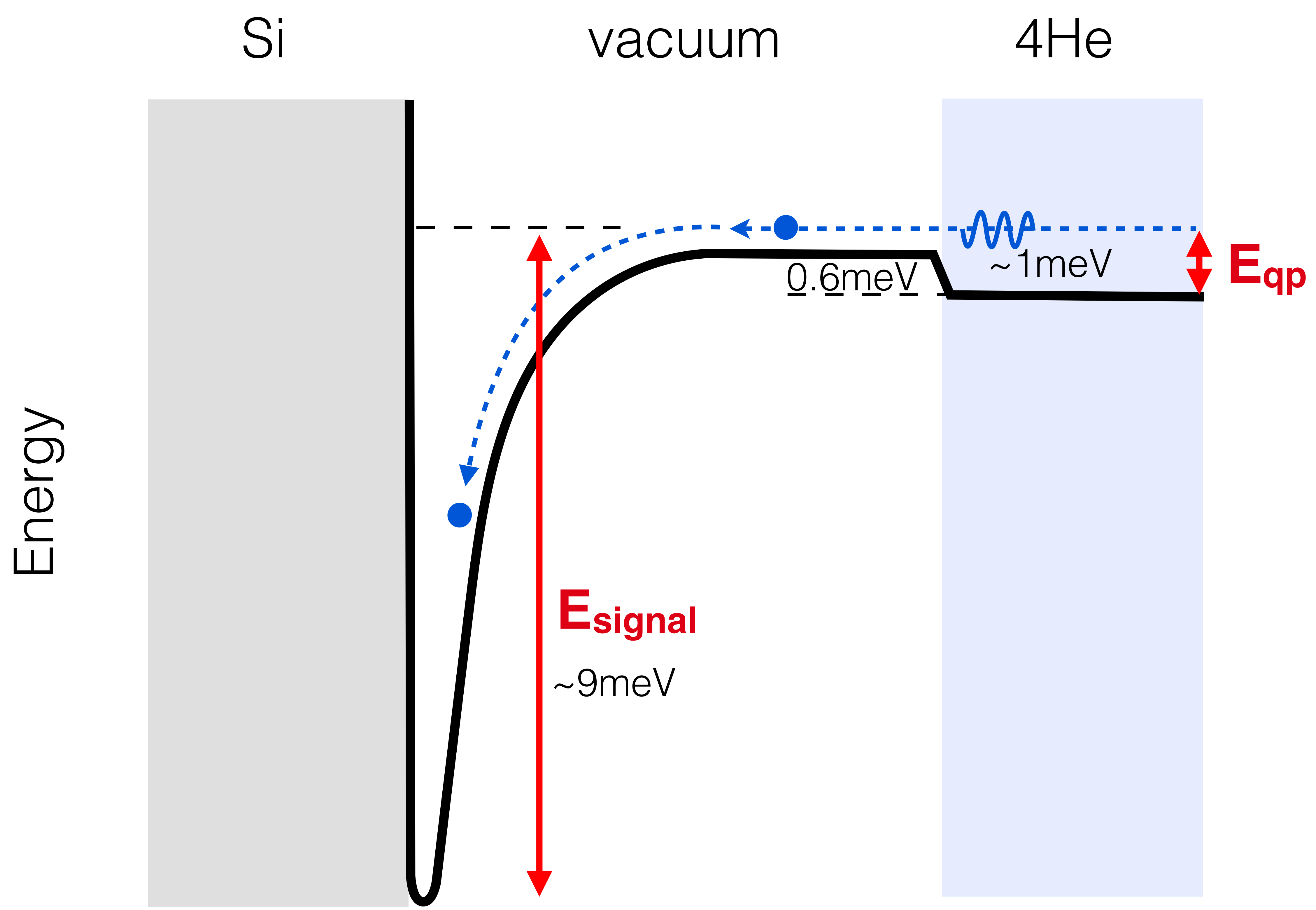
van der Waals gain

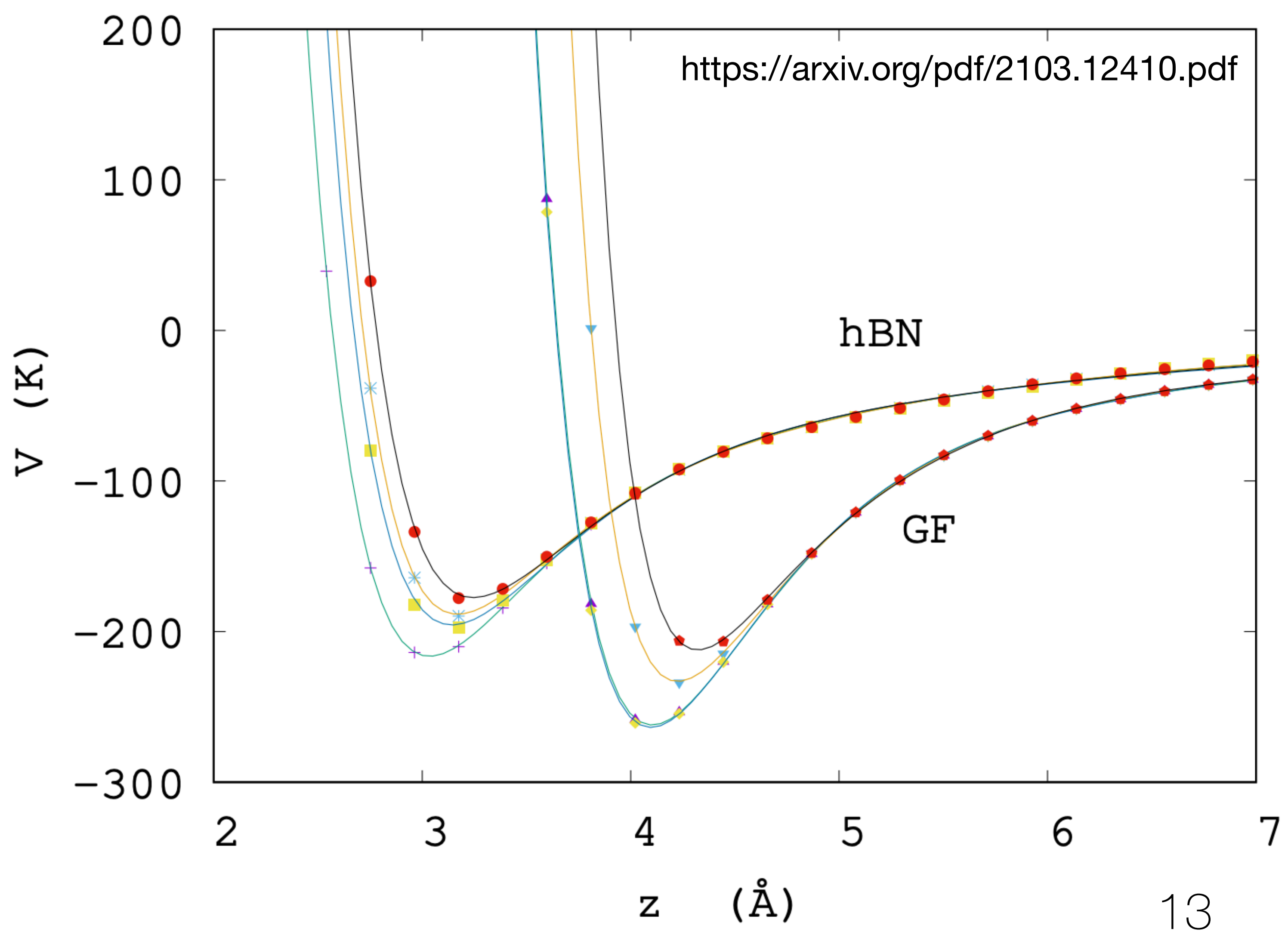
4He atom feels a ~9meV van der Waals potential at Si surface.

Simplistically:
1eV recoil energy in 4He becomes ~1000 rotons….
~1000 rotons becomes ~1000 evaporated atoms…
~1000 evaporated atoms becoms ~1000 x 9meV = 9eV

Question: *Can we further increase this ~9x “adsorption gain”?*

We can increase this van der Waals gain by using…..
polar crystal substrates! (perfect overlap with SPICE R&D)





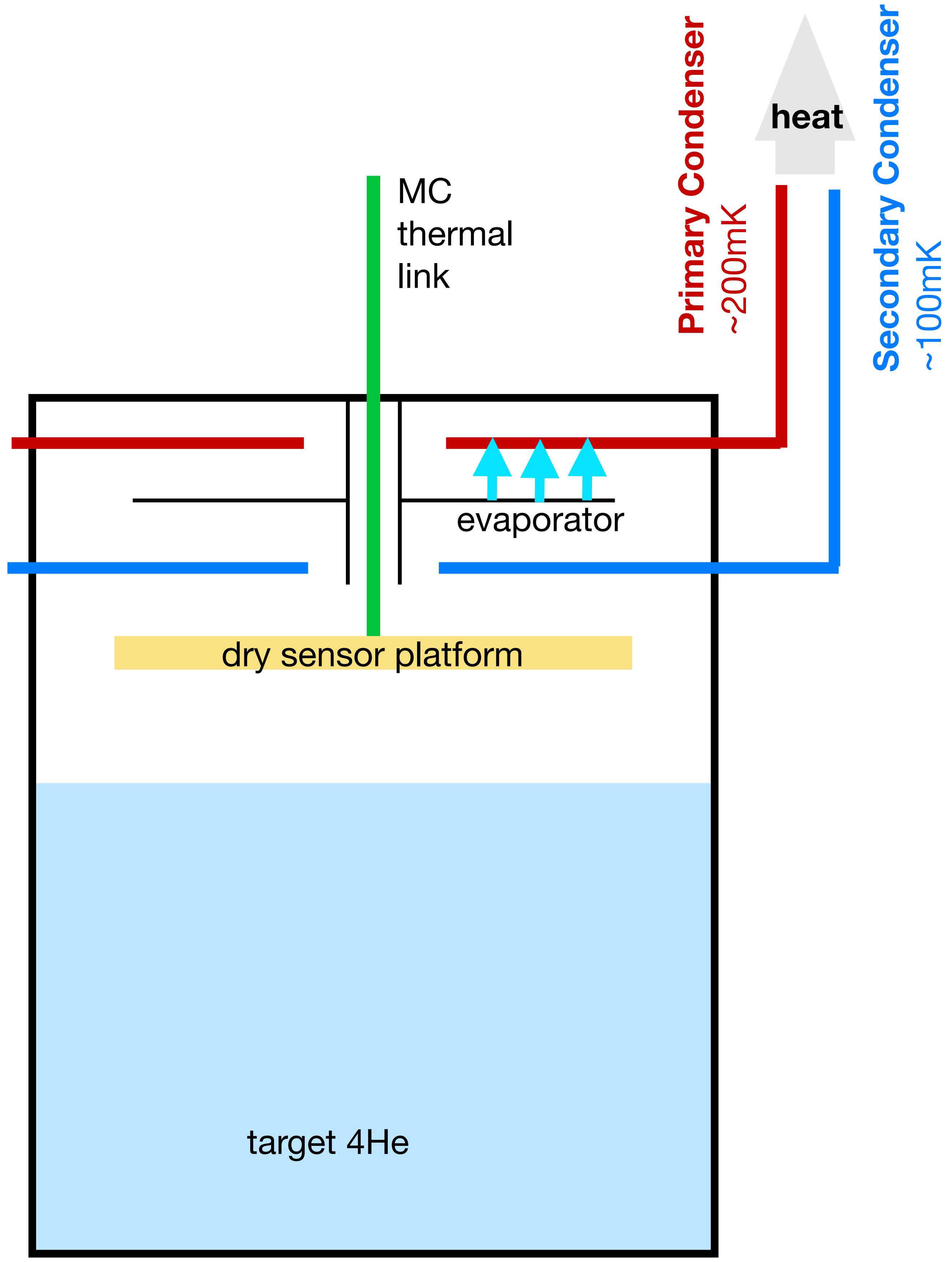
Film-Stopping

Film Burner

Well-demonstrated, by HERON R&D and others

Heat: *some* heatload on MC & sensor platform
(remember, calorimeter threshold: T^3)

Evaporation: *some* gas leakage (aka 'dark counts')



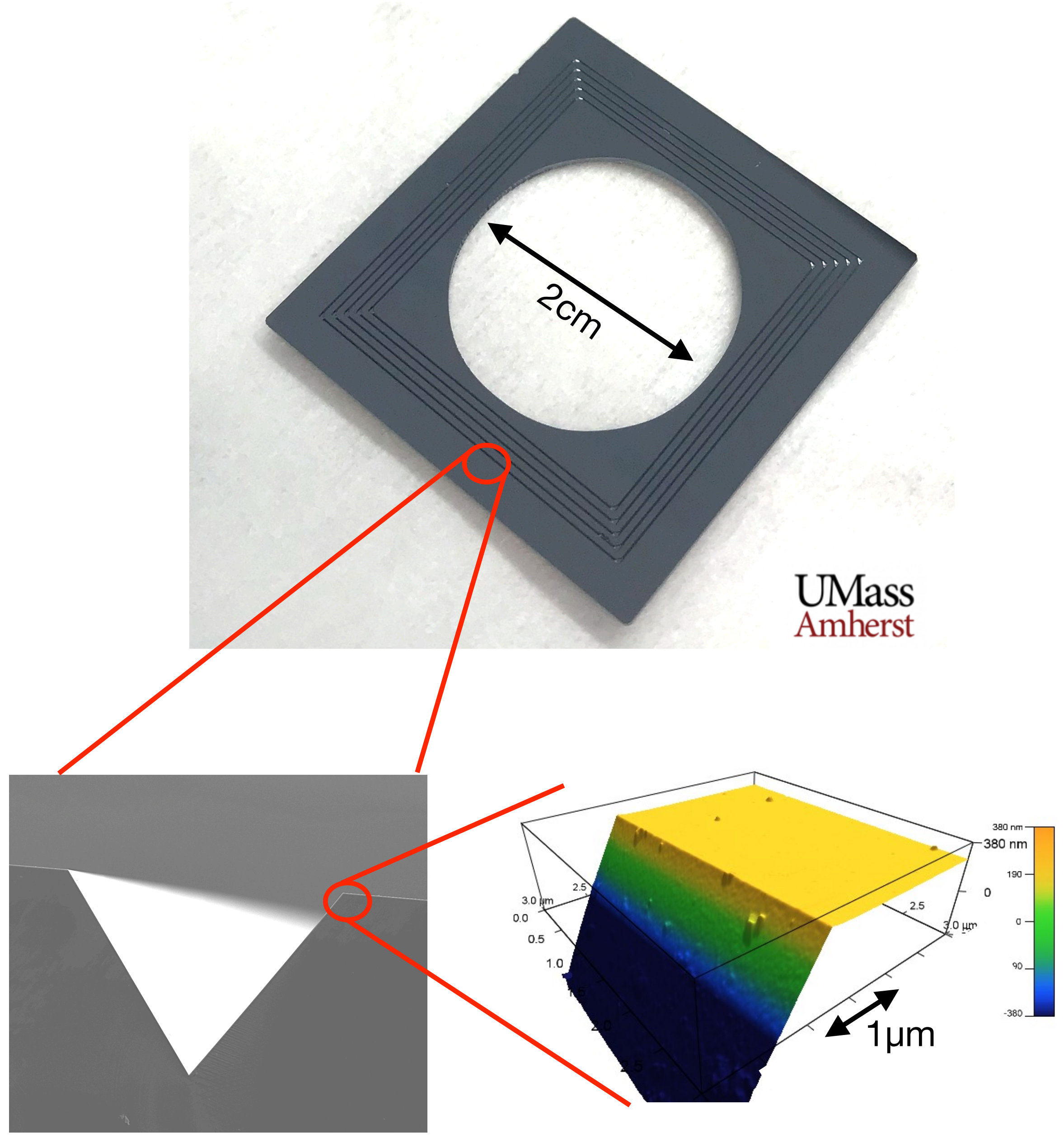
Goal: Dry sensor, all parts of cell at MC temperature, no evaporation/condensation.

Knife Edge

Sharp corners can thin film to few-layer scales

Demonstrated at higher temperatures…
…but <100mK requires <10nm radius of curvature.

We have made ~7nm radius devices…
… but we're not overly optimistic it will work.



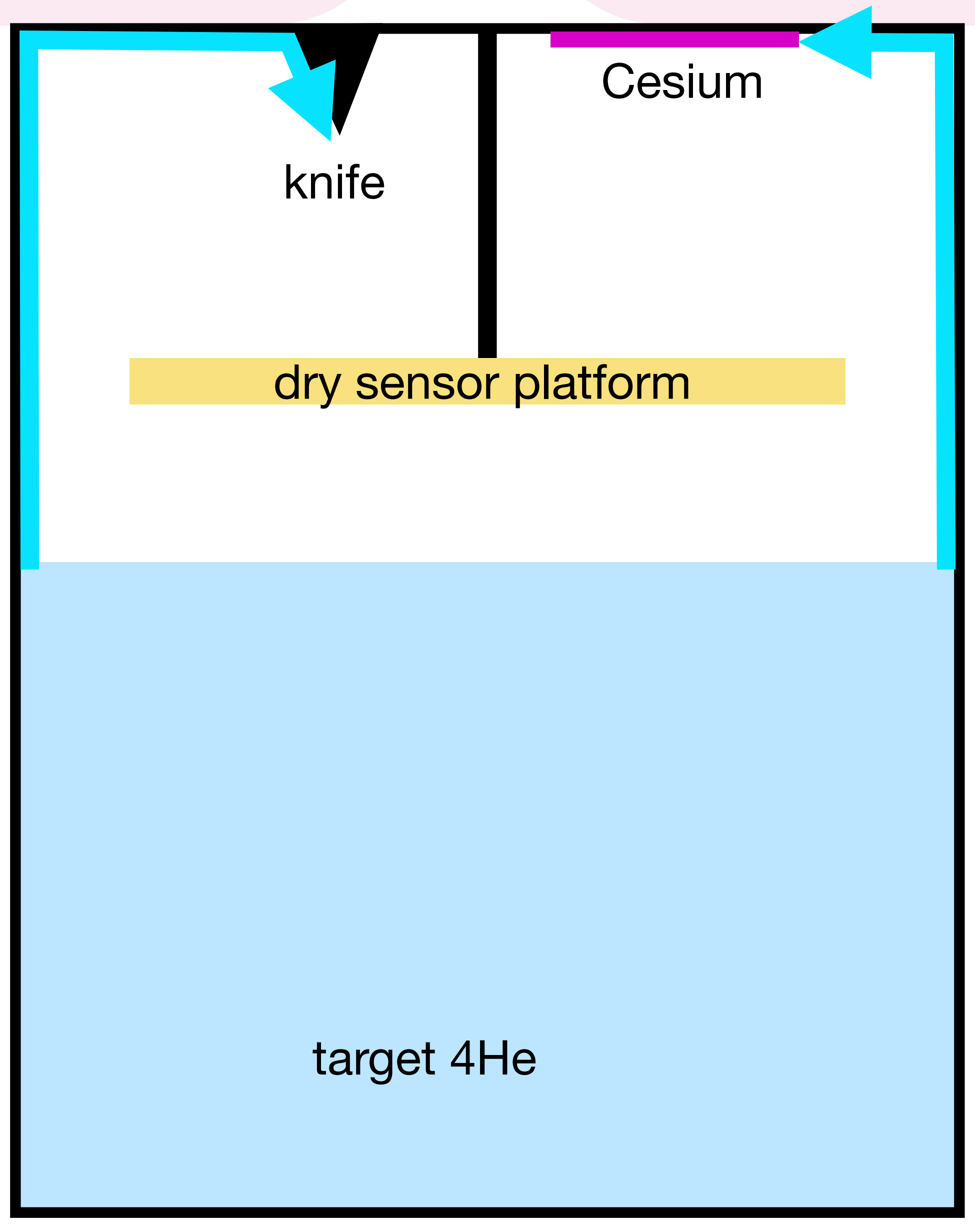
Cesium Film

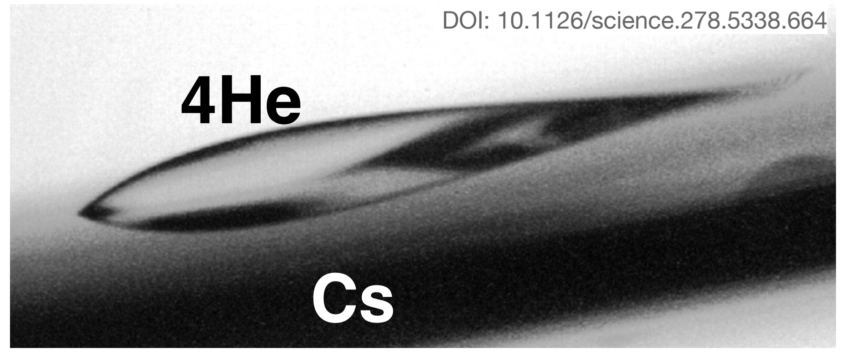
4He will not wet Cs

Commercial Cs dispensers well-demonstrated

Significant downsides: 1) complexity
2) Cs vapor pressure

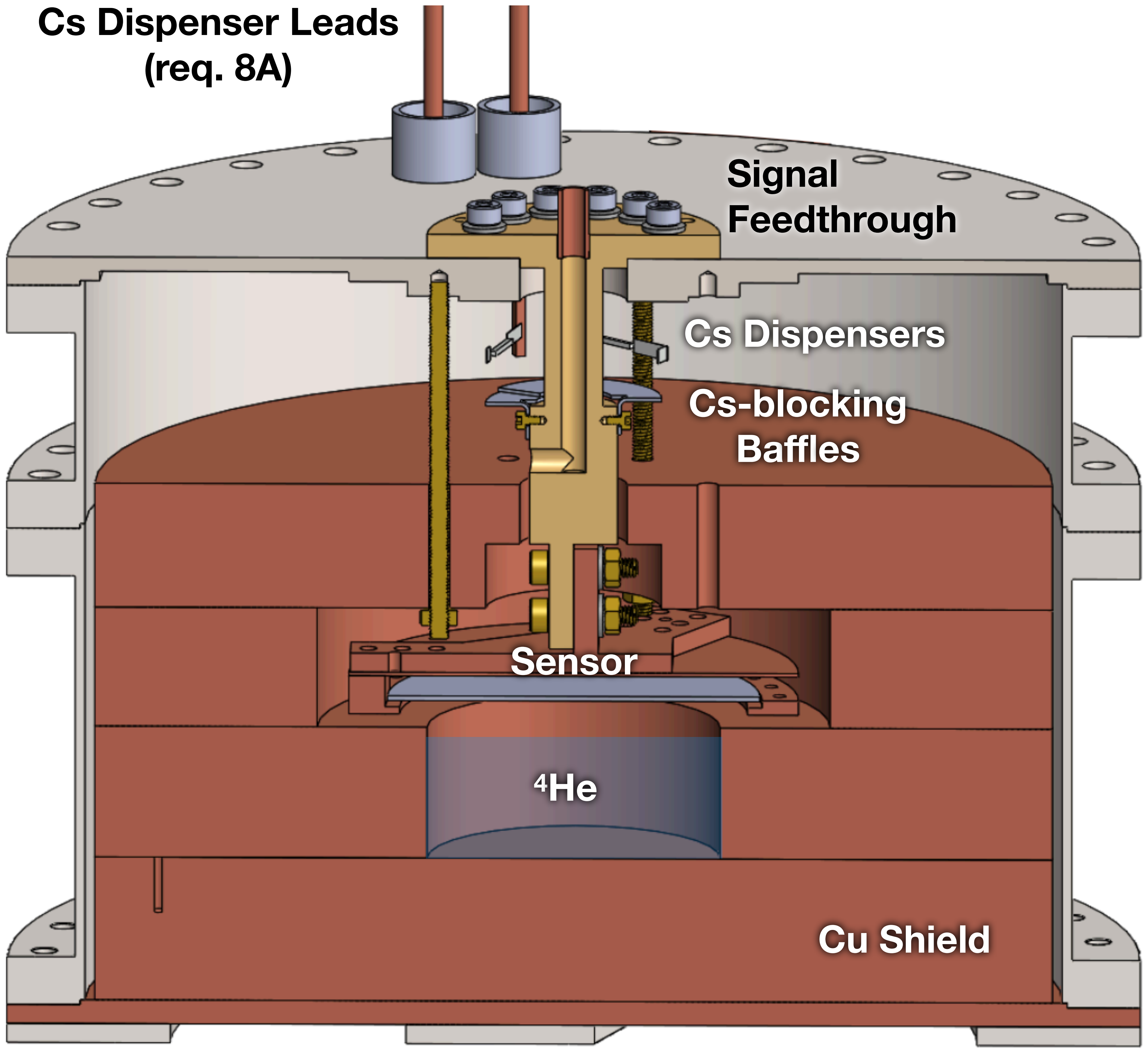
HeRALD baseline, despite practical downsides





Cs dispensers (SAES)

HeRALD R&D cell at UMass



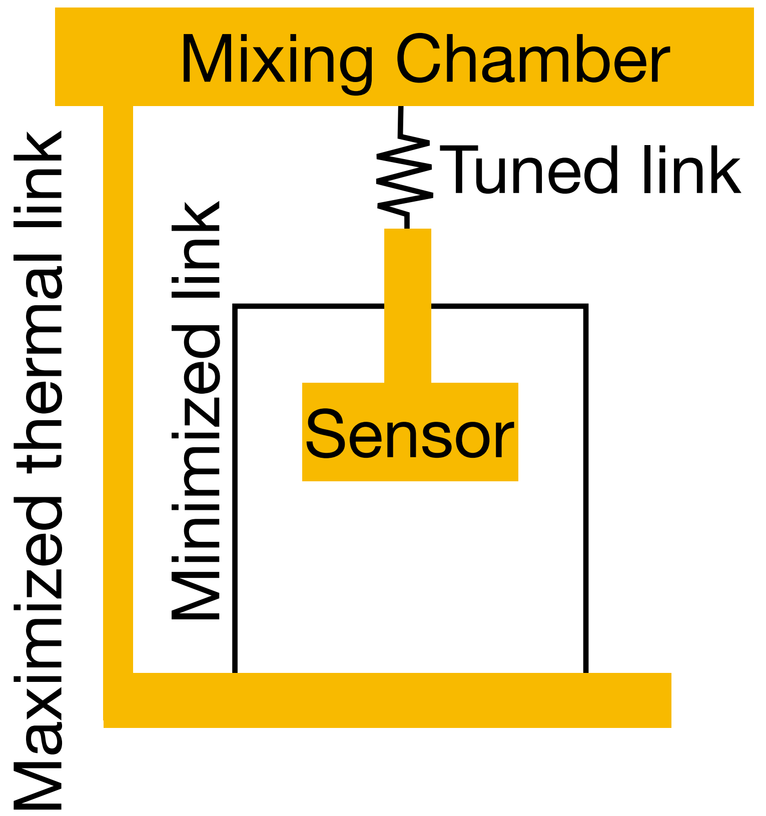
Primary driver: demonstrate Cs strategy for quantum evap. signals
Secondary driver: serve as a flexible testbed for subsequent work

Clean division between ‘dry’ sensor platform/pillar, and ‘wet’ target region, walls, etc.

Ring of Cs dispensers surrounding pillar, defines boundary

Thermal modeling important to design,
so that sensor can be baked dry (>10K),
keeing 4He low vapor-pressure (<100mK).

AND sensor needs to cool down again to <10mK

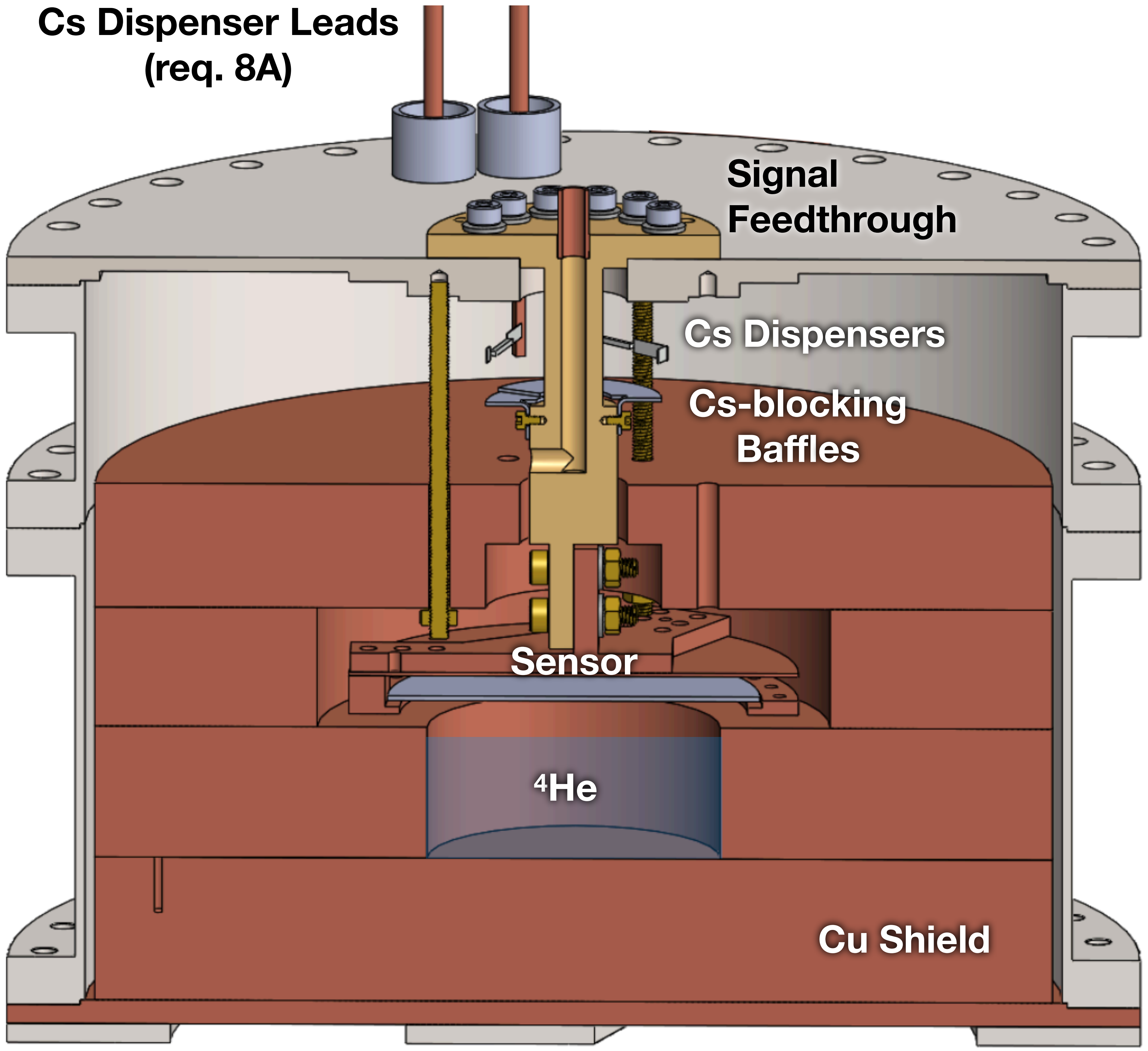


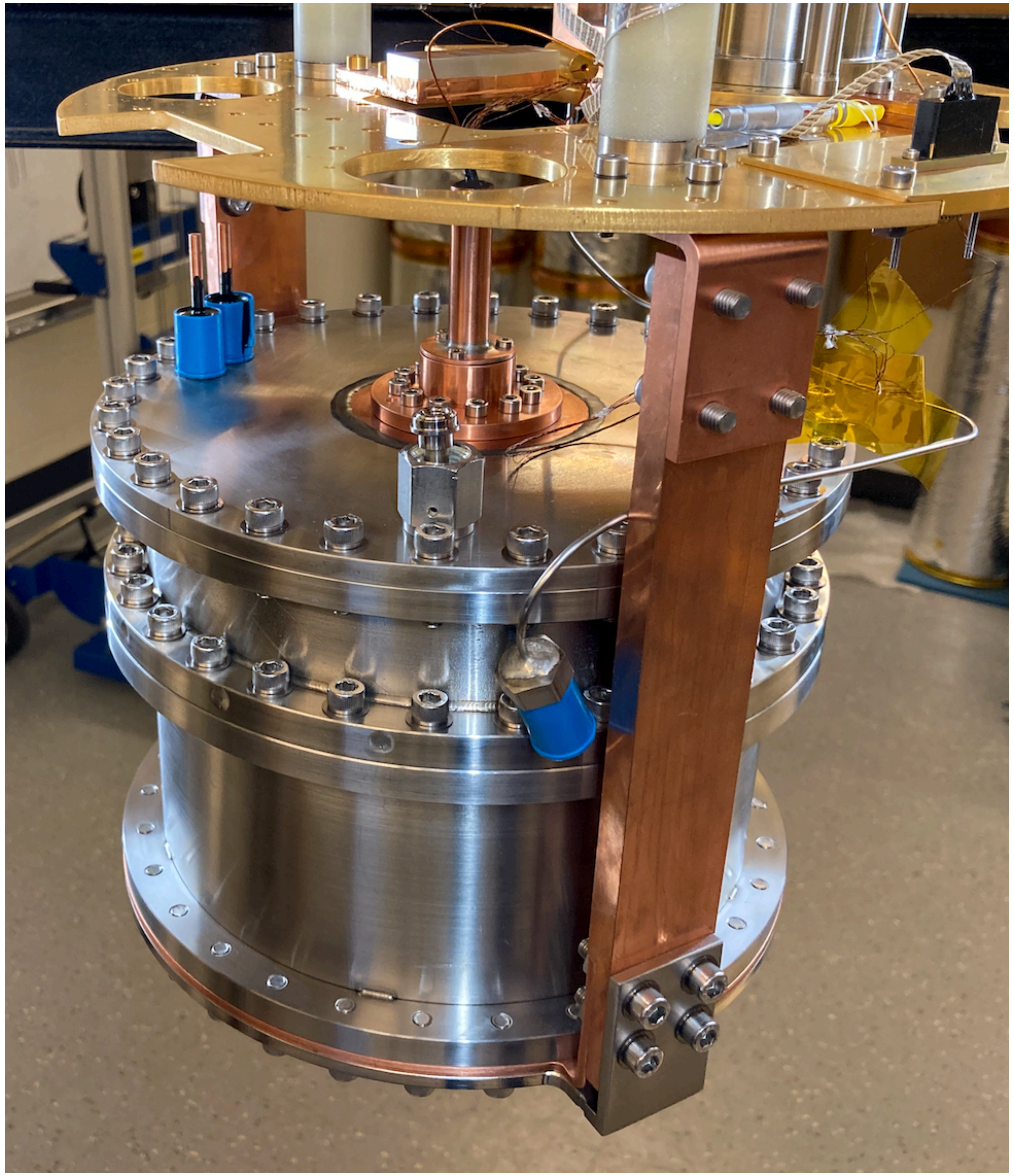
Large (20cm ⌀) stainless cell, plenty of space to work inside
(great for R&D, easy to change geometry)

Large amount of Cu within cell (~27kg !), based on four 1” plates.
- ‘filler’ material to define the 4He target region
- nearly 4pi gamma shield (we see ~0.7 Bq in the 10g of Si, pretty good)

Currently using single-channel TES array on 3-inch wafer.
4He target region: 6cm ⌀

photos, show and tell…





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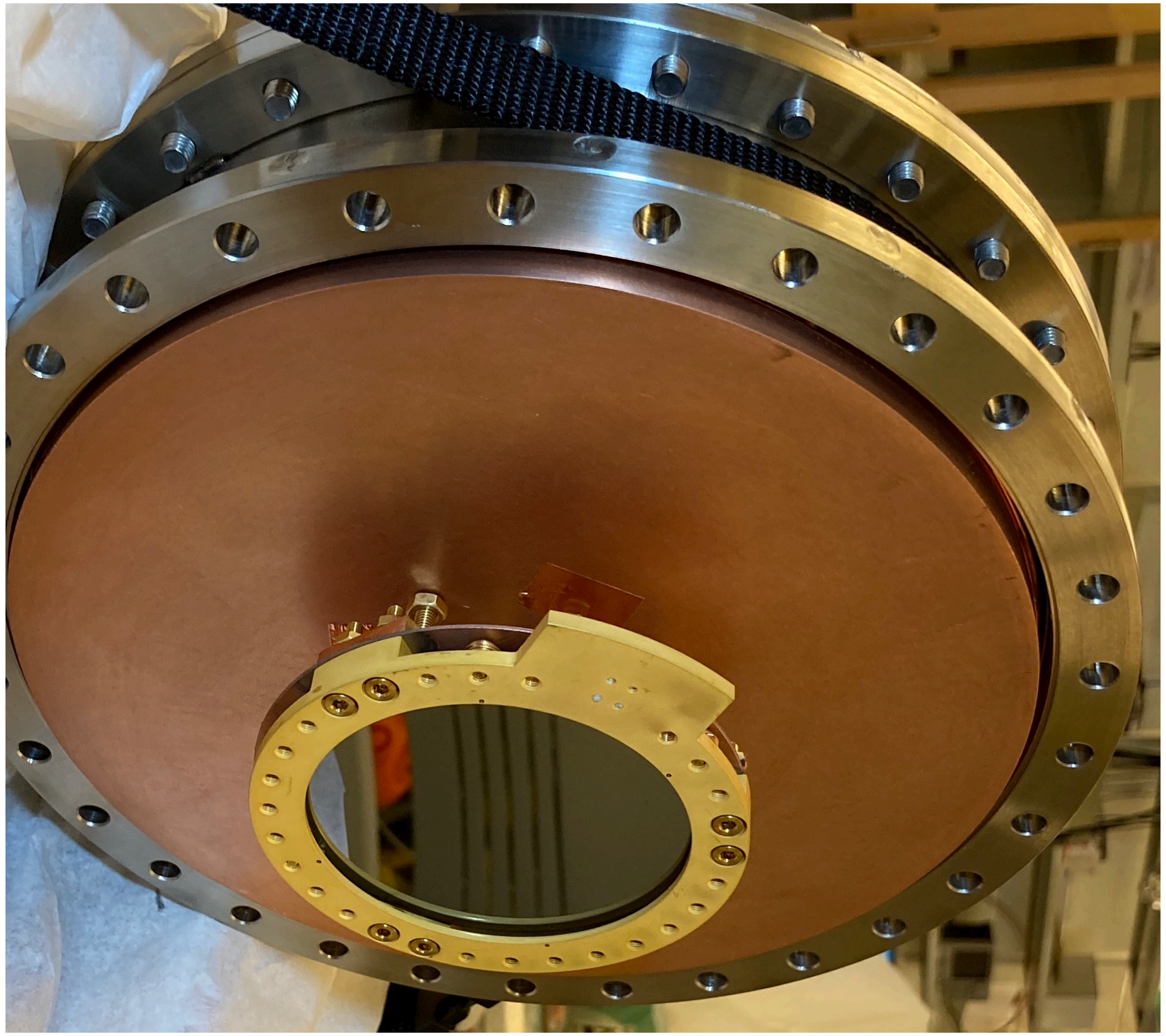
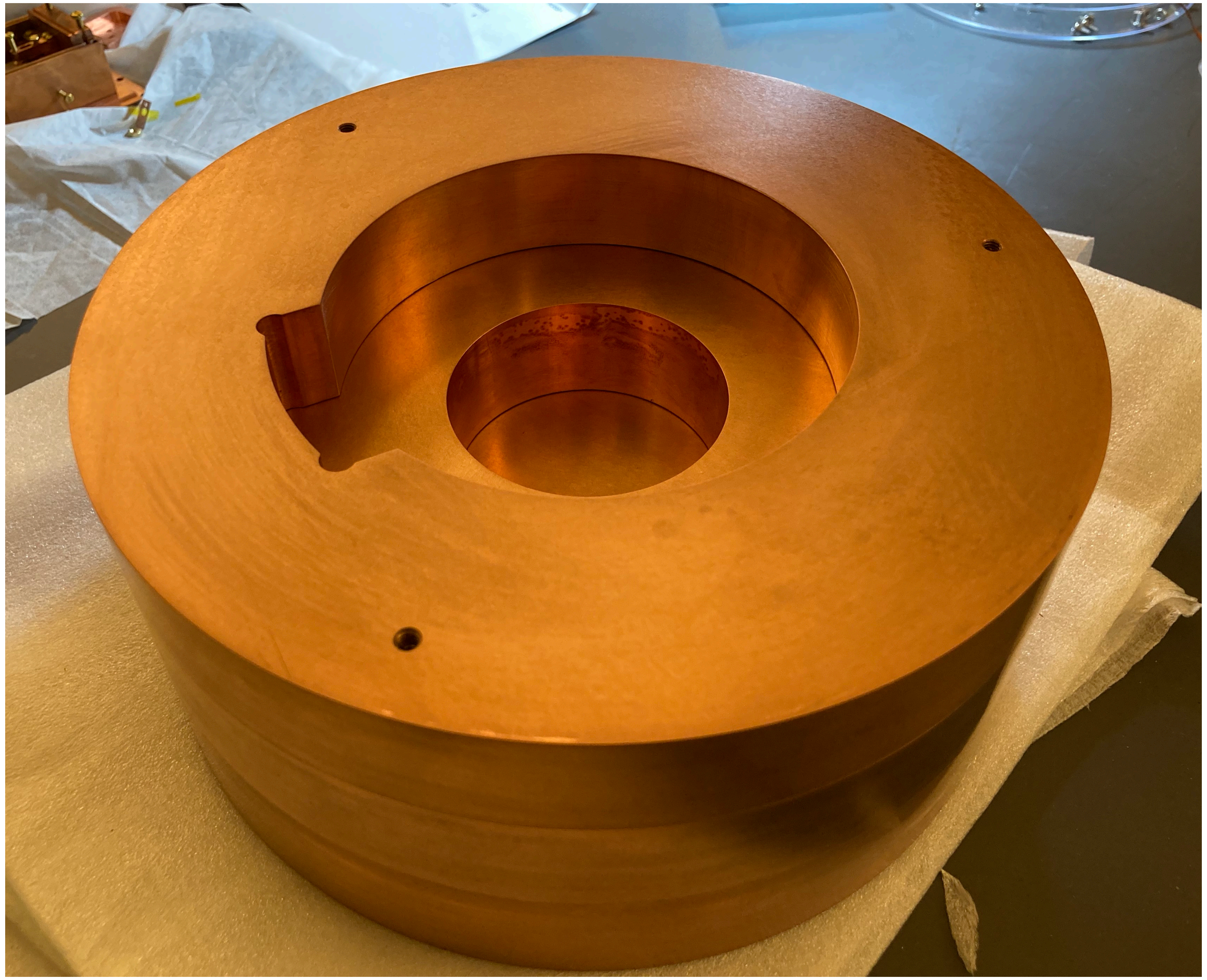
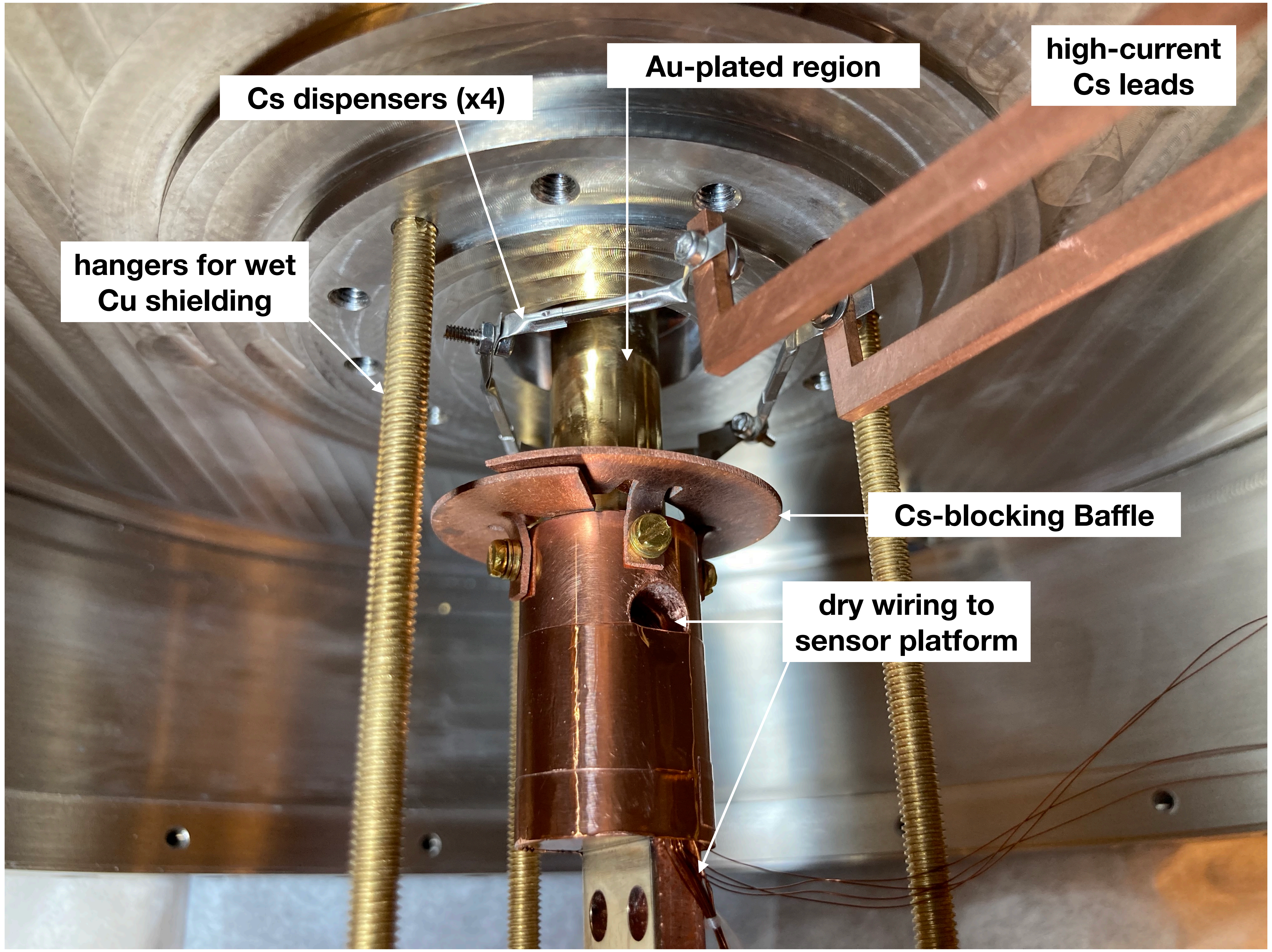
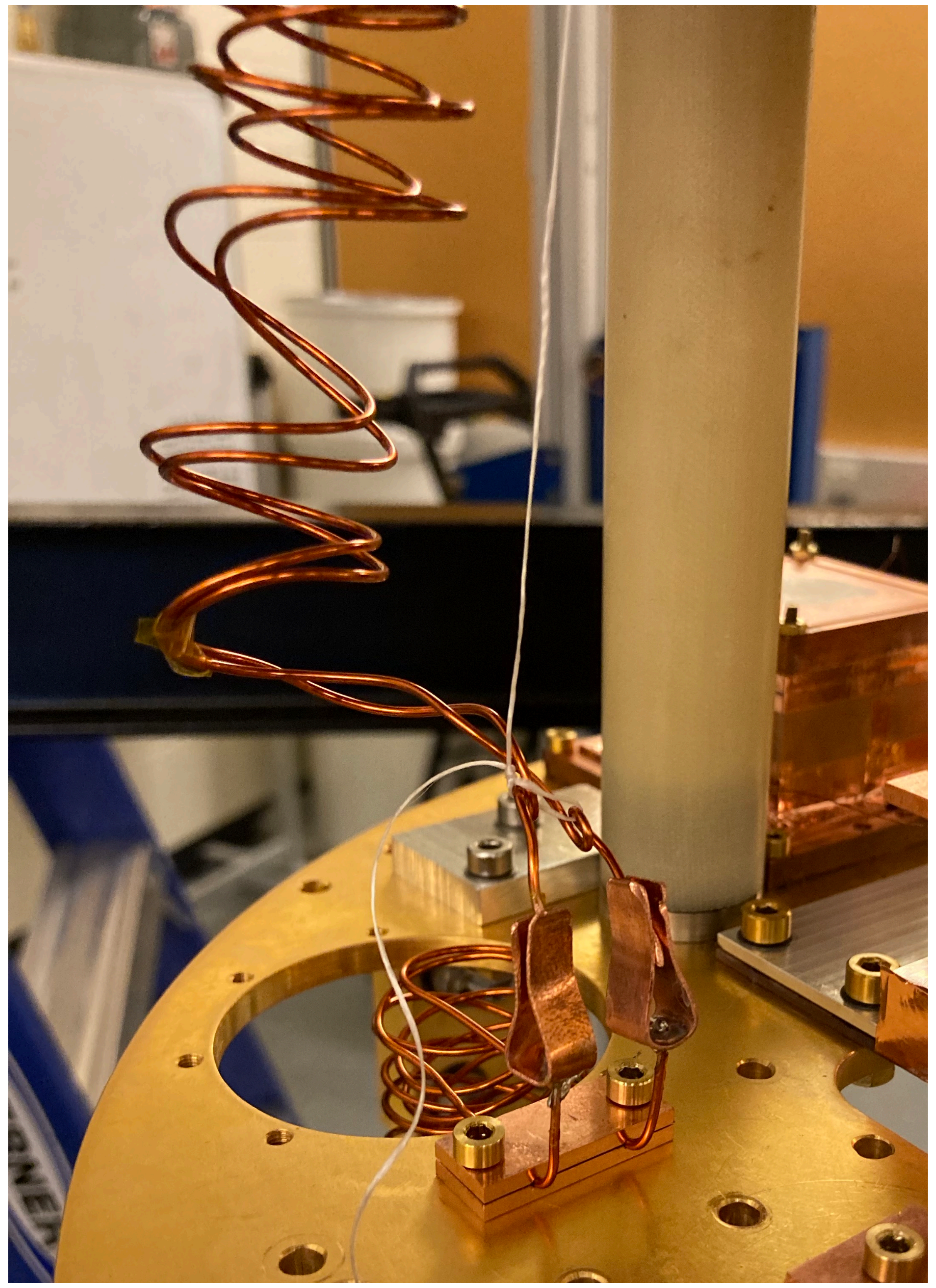




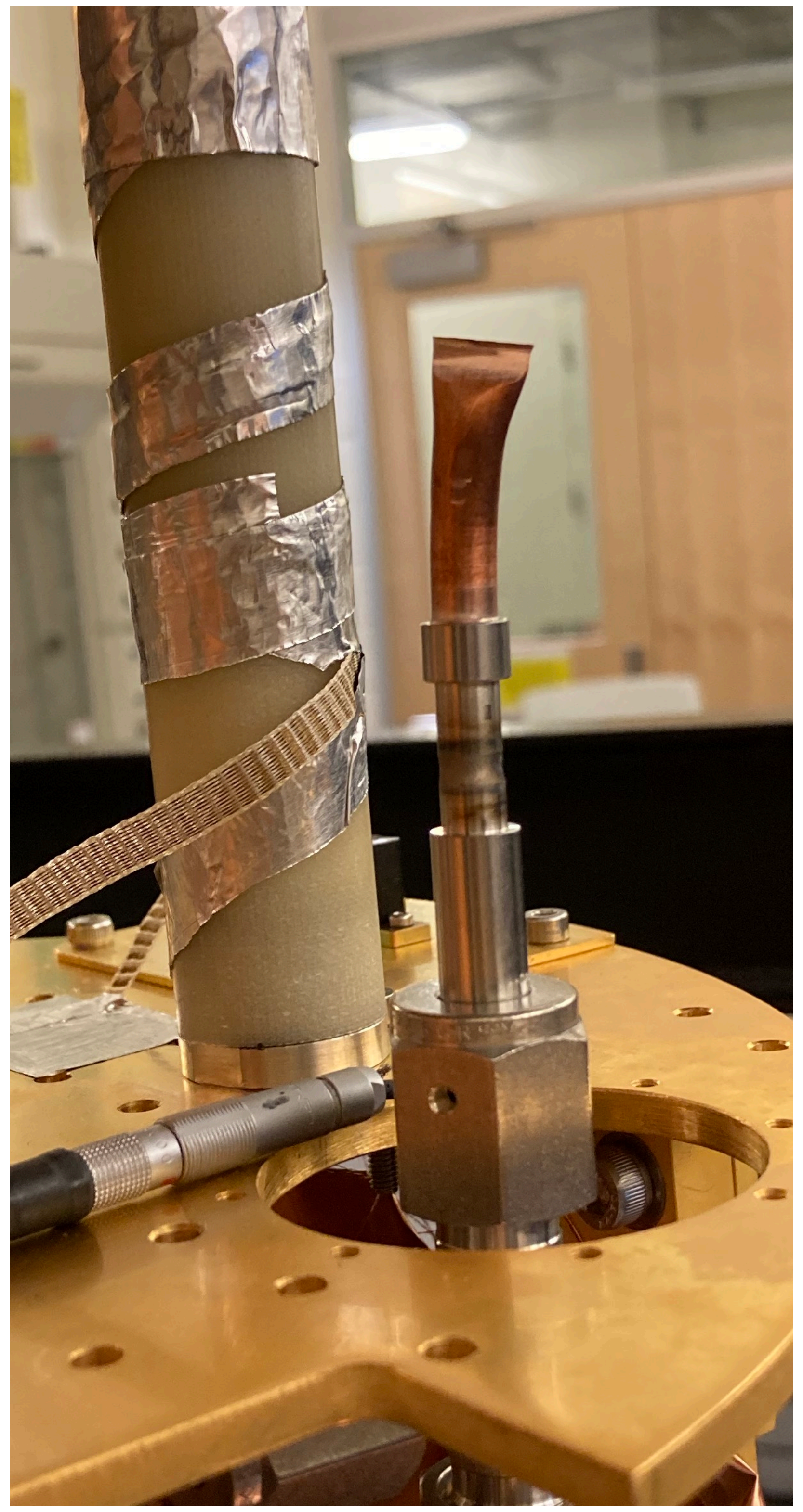
photos, show and tell...



pull-away Cs leads



pinch-off pump-out port



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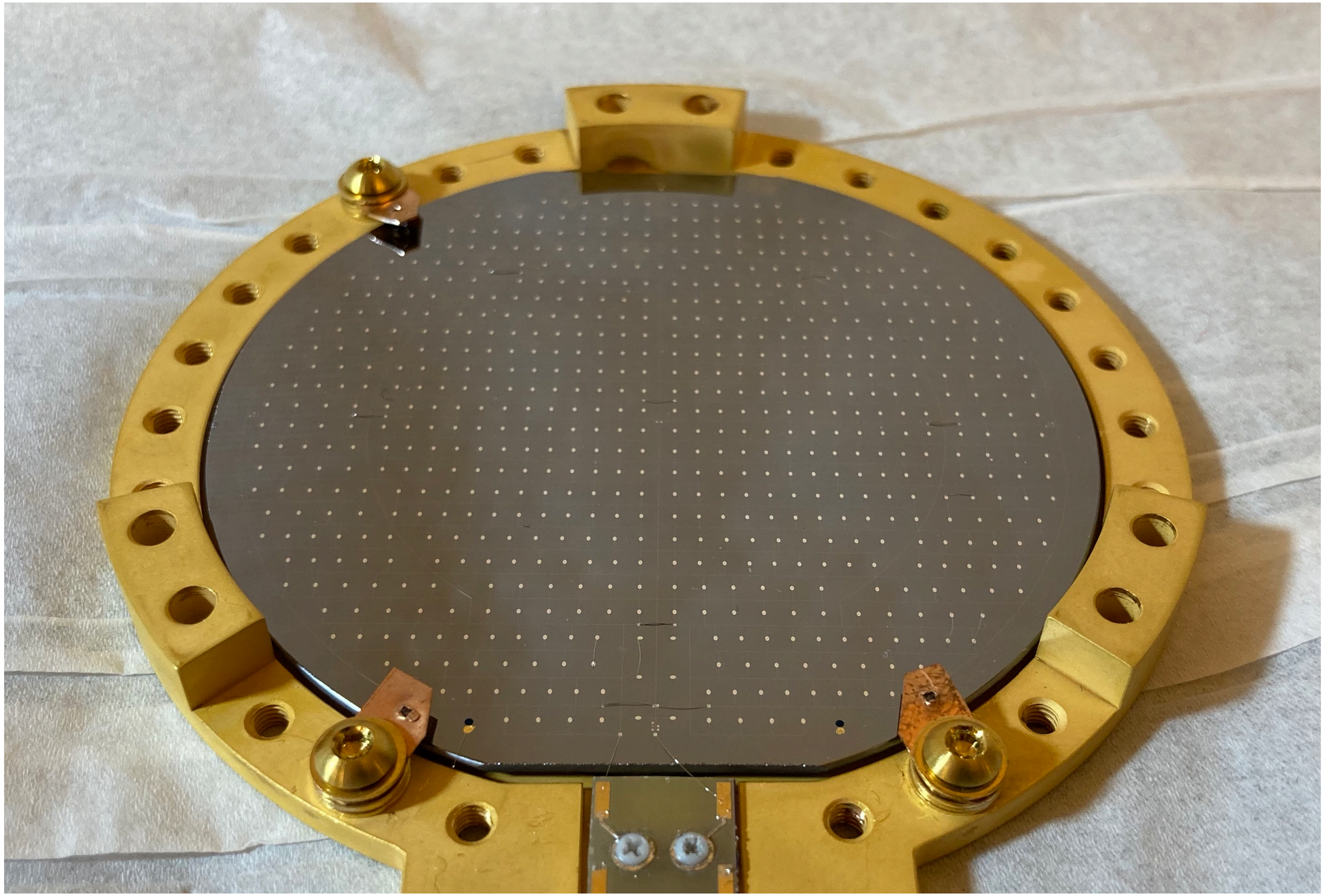
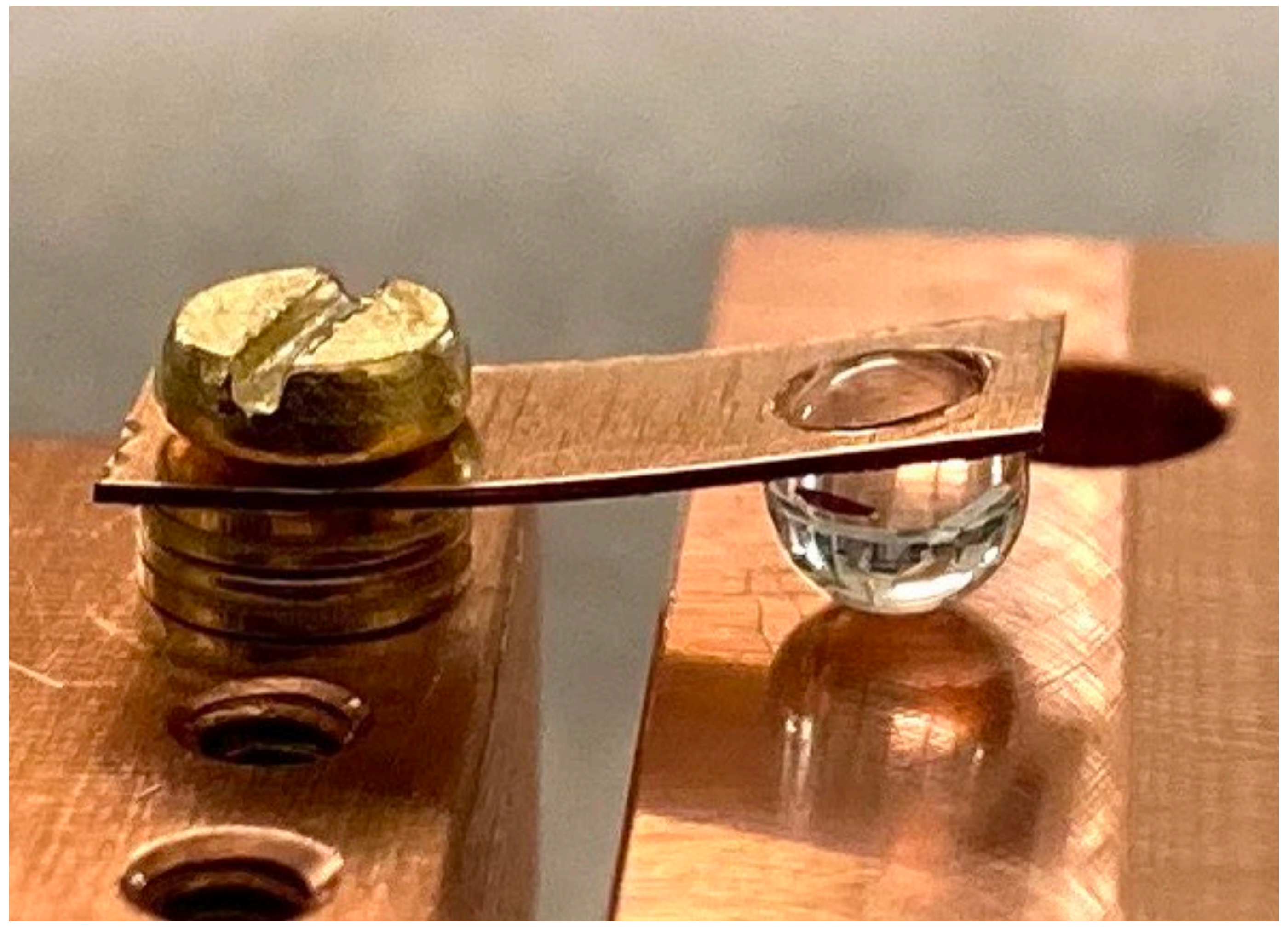
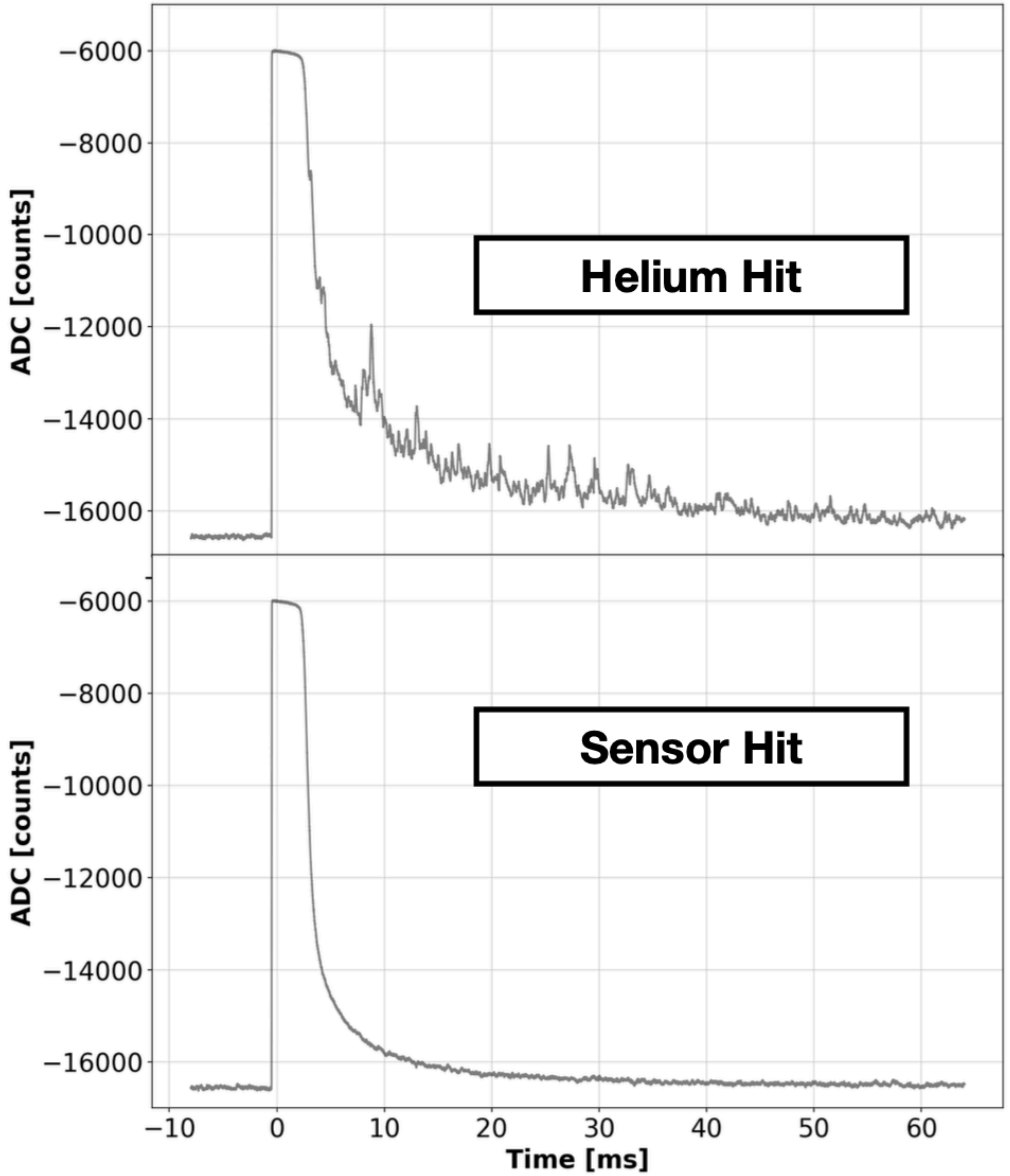




First looks at the data… (very very preliminary)

We see two clearly distinct categories of large (saturating) events.

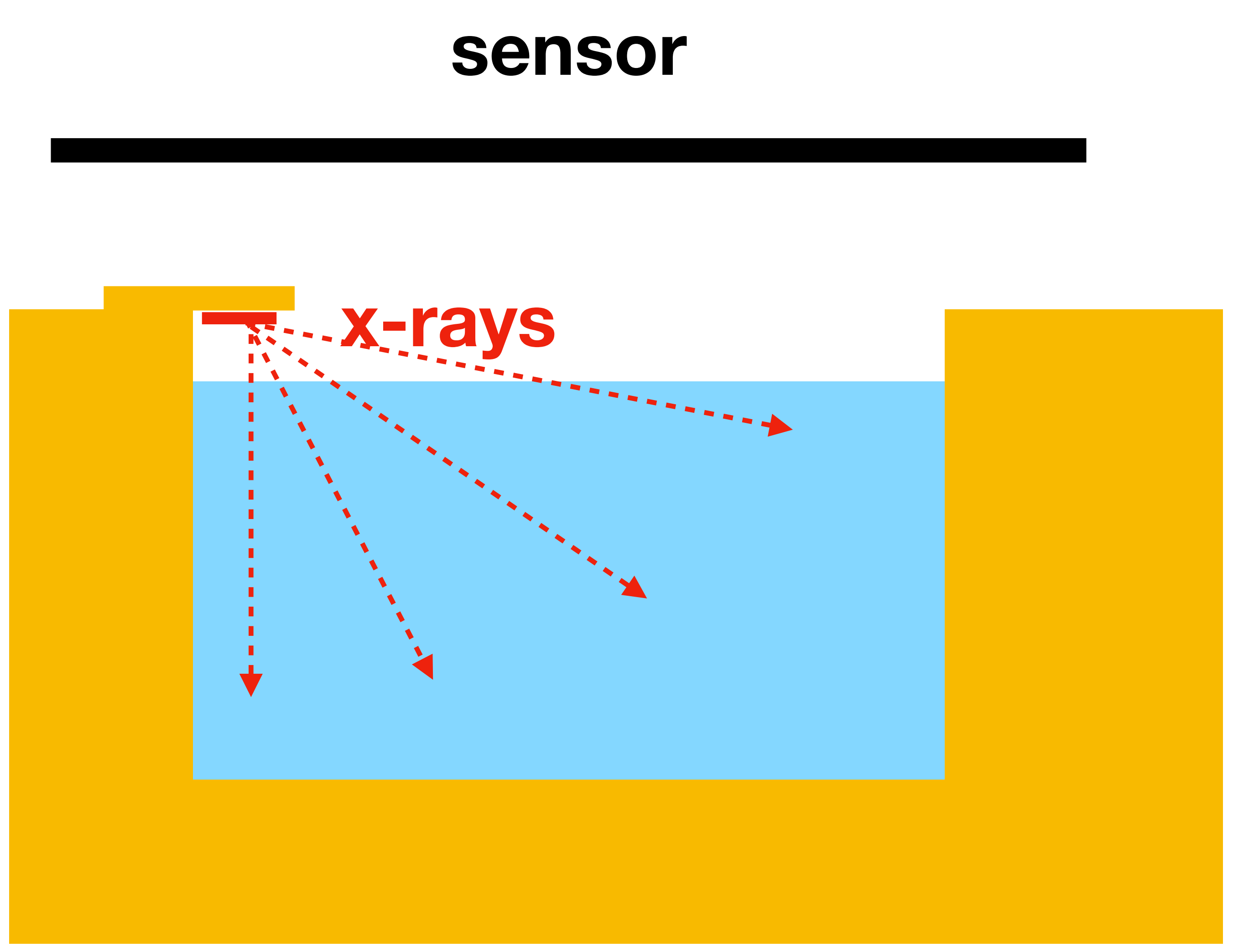
The population we call 'helium hits' are likely showing the decays of the long-lived triplet excimer population.



First looks at the data… (very very preliminary)

How will quantum evaporation appear in our setup?

We include an 55Fe source shining down into the target (x-rays, ~6 keV)



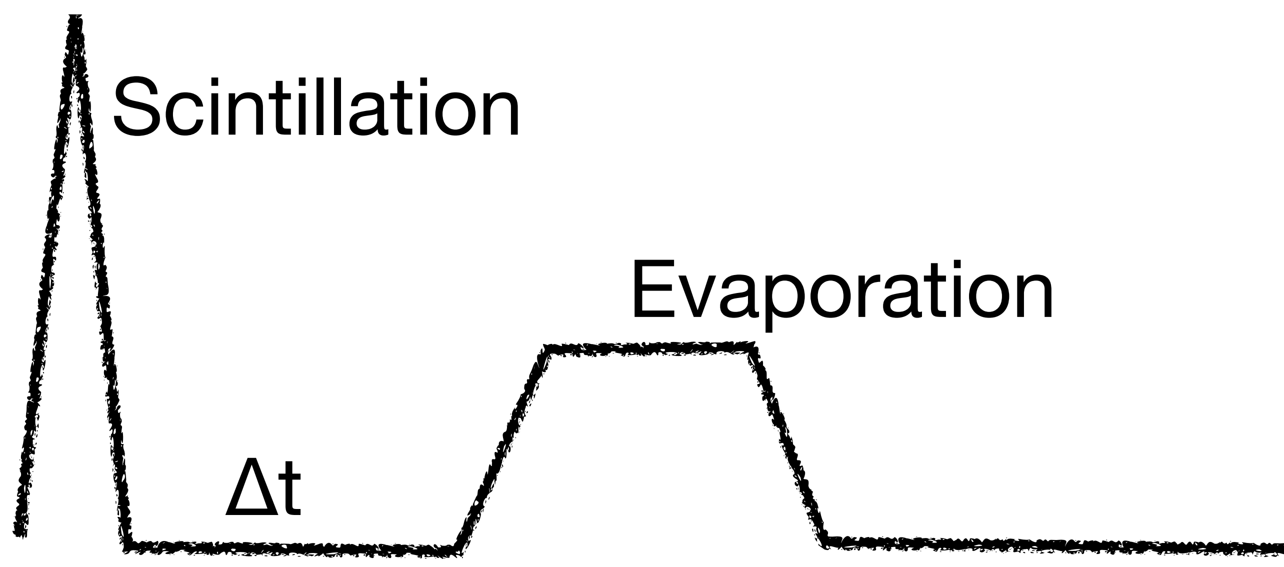
We expect to see two pulses:

1. **prompt scintillation**

   ~2keV of photons before solid angle…
   (roughly 1keV at top and 0.5keV at bottom)

2. **Evaporation delayed by Δt = depth/vel.**

   ~2cm target thickness, ~200m/s R+ velocity…
   … expect Δt scale of order 100μs timing



First looks at the data… (very very preliminary)

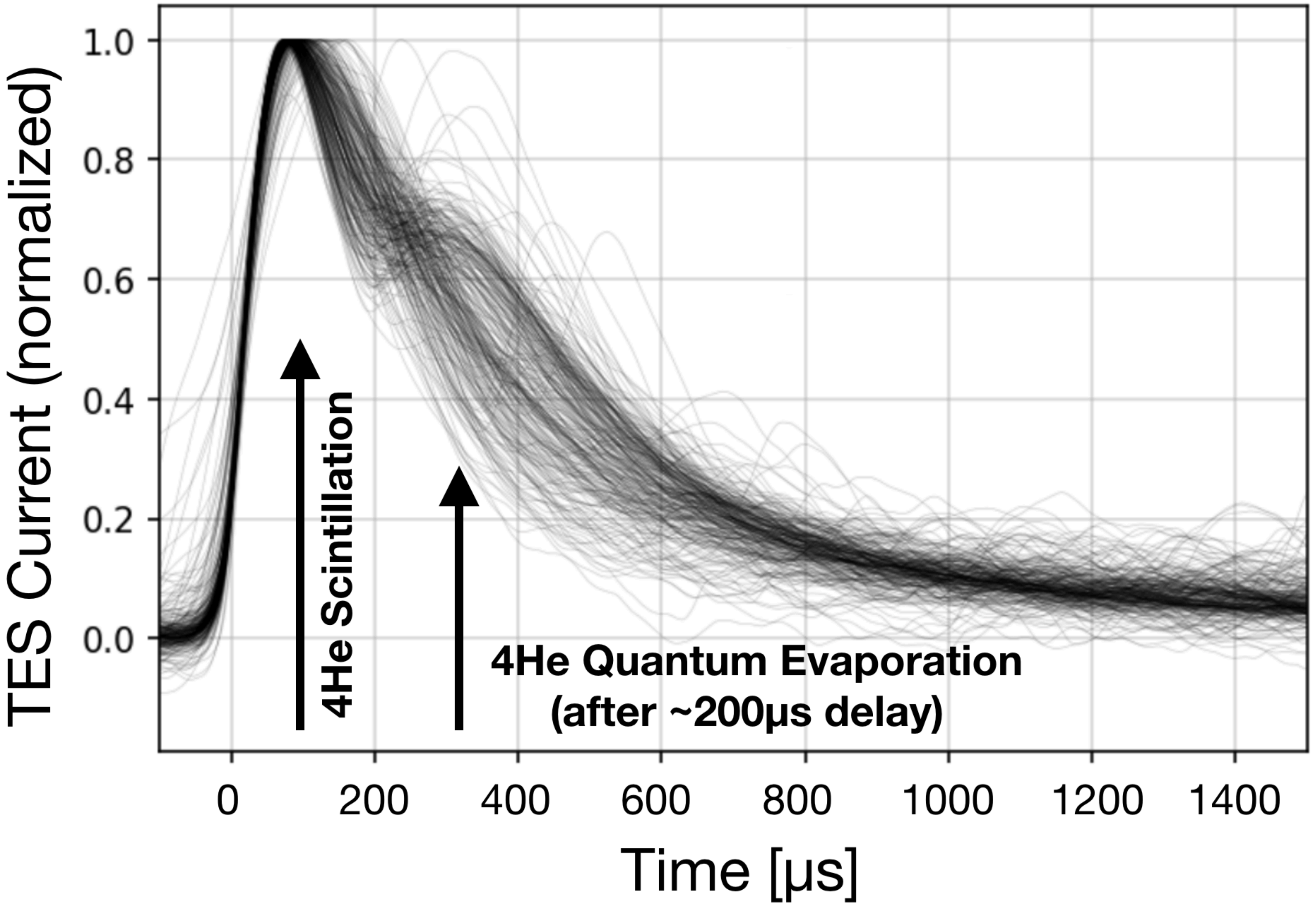
Observations not far from expectation!

-Clear population of double-pulses at the energies we expect for 55Fe

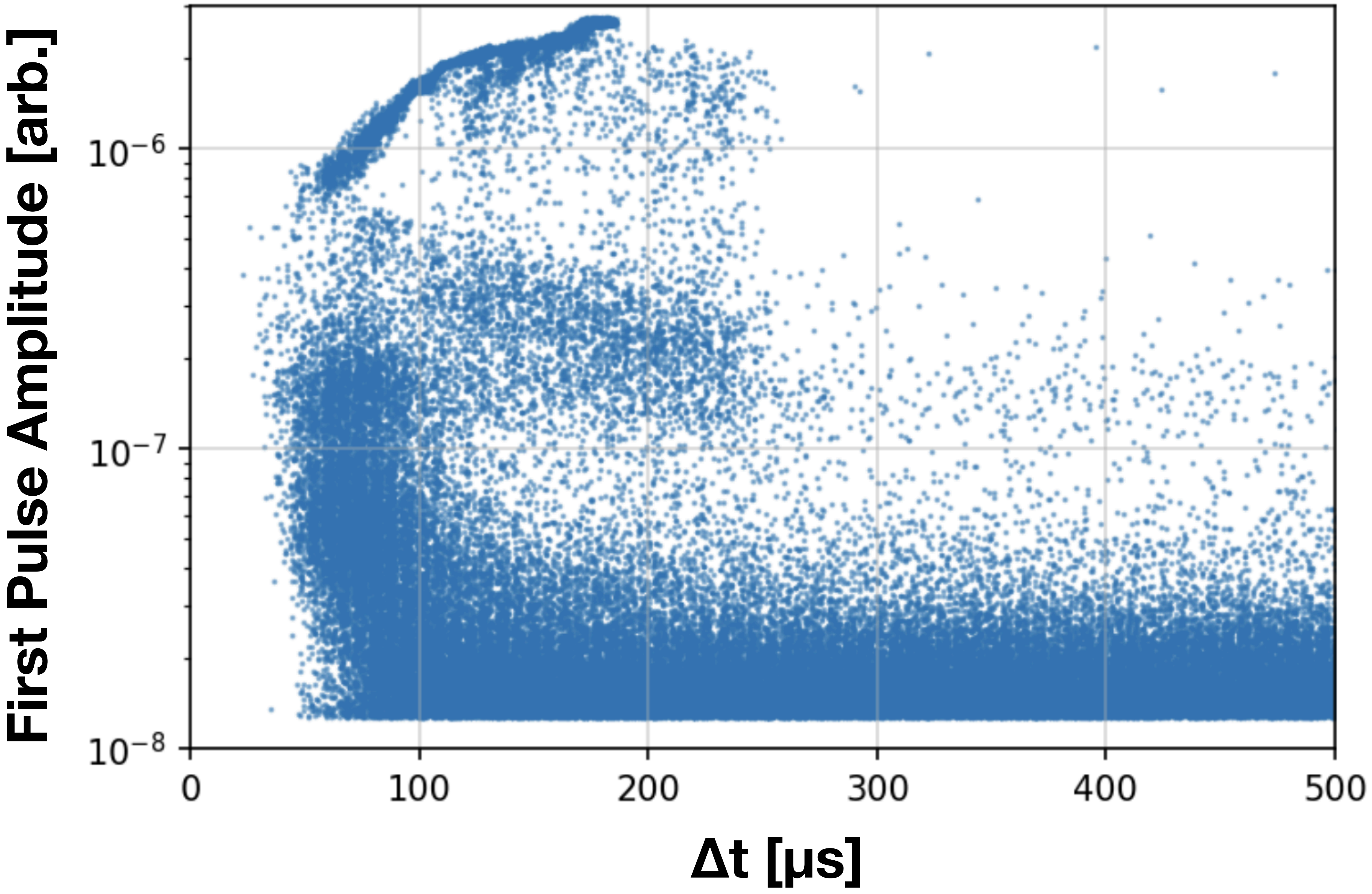
-Broad distribution in Δt out to a 'cliff' of ~240μs
(seen in both the 55Fe population and our gamma backgrounds)

-Anti-correlation seen as expected from solid angle (prompt smaller when Δt bigger)

A collection of similar-sized pulses

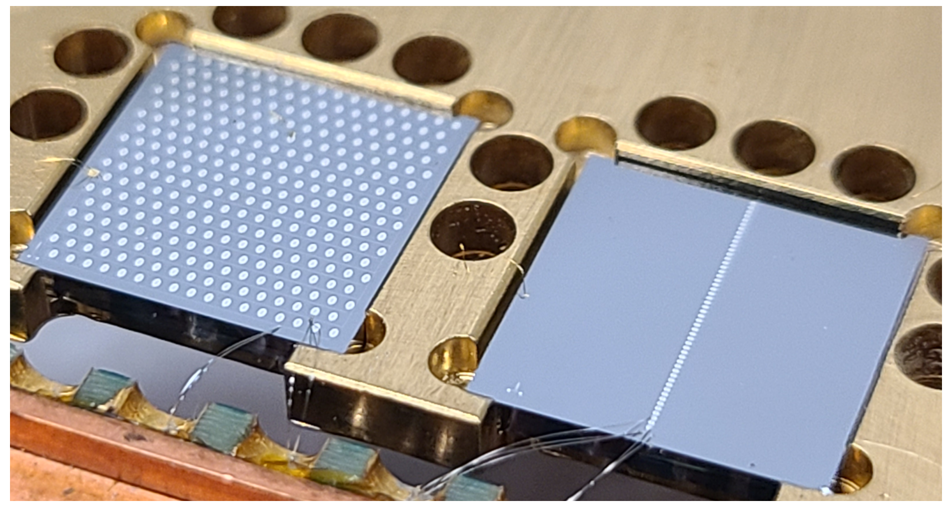


Fitting a two-pulse model to each trigger

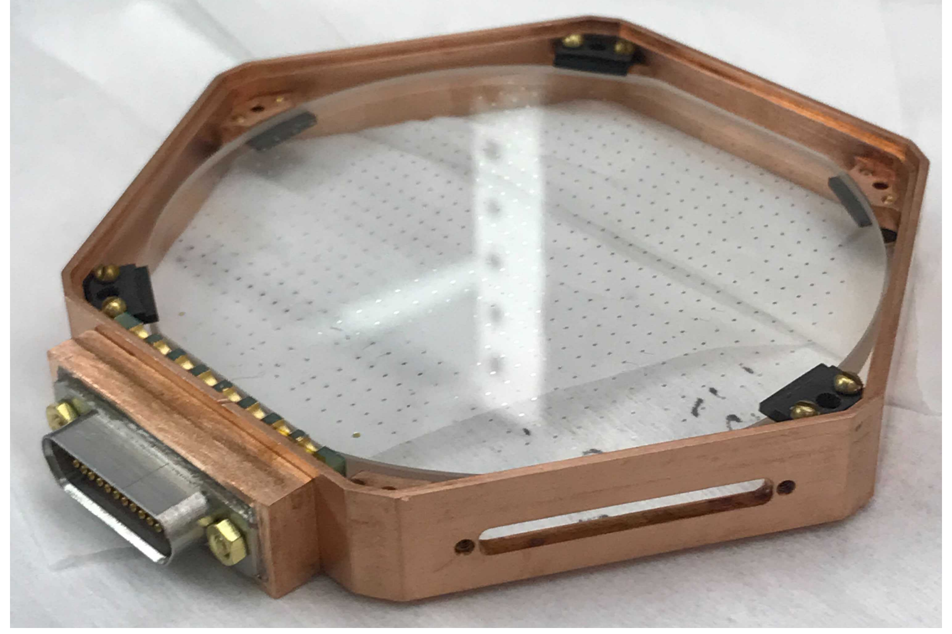


Summary

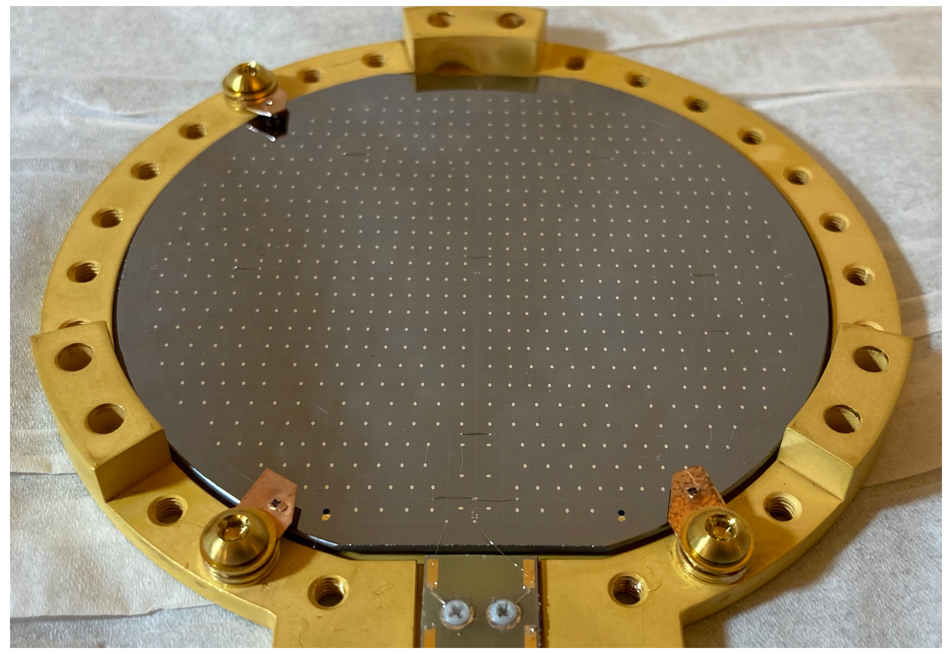
Lots of work going on, lots of exciting progress on all fronts!



- TESs now have the goal Tc, goal power sensitivity
- Next step: remove sources of parasitic power and phonons



- Sapphire is a compelling DM target material
- Single optical phonon sensitivity appears within reach



- Superfluid 4He is also a compelling DM target material
- Now studying and optimizing evaporation signals