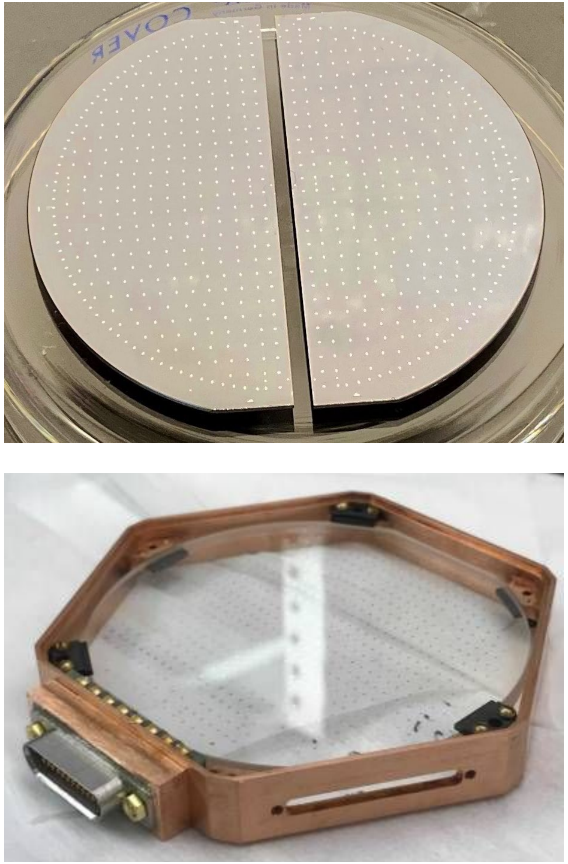


Progress Toward Low-Mass Dark Matter Detection with Superfluid He (HeRALD) and Polar Crystals (SPICE)

David Osterman, on behalf of the SPICE/HeRALD Collaboration
GUINEAPIG
July 13, 2023

SPICE | HeRALD

Outline

1. Intro to the collaboration and its goals
2. TES calorimetry and energy threshold
3. HeRALD description
4. SPICE description
5. Understanding and mitigating low energy backgrounds

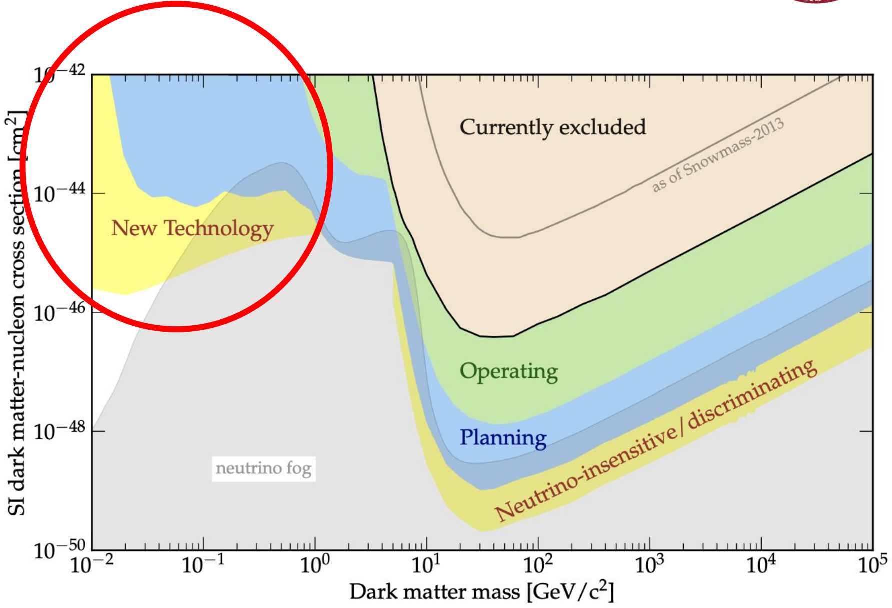
We are looking for light DM

Lower M_{DM} → higher n_{DM} → less need for high exposure

Traditional radiogenic backgrounds are less important → can build cheap experiments quickly

Different target materials probe different models

Can produce world-leading limits by operating gram-scale detectors with different target materials and days-long exposure



[1] Snowmass 2021 (arXiv:2209.07426)

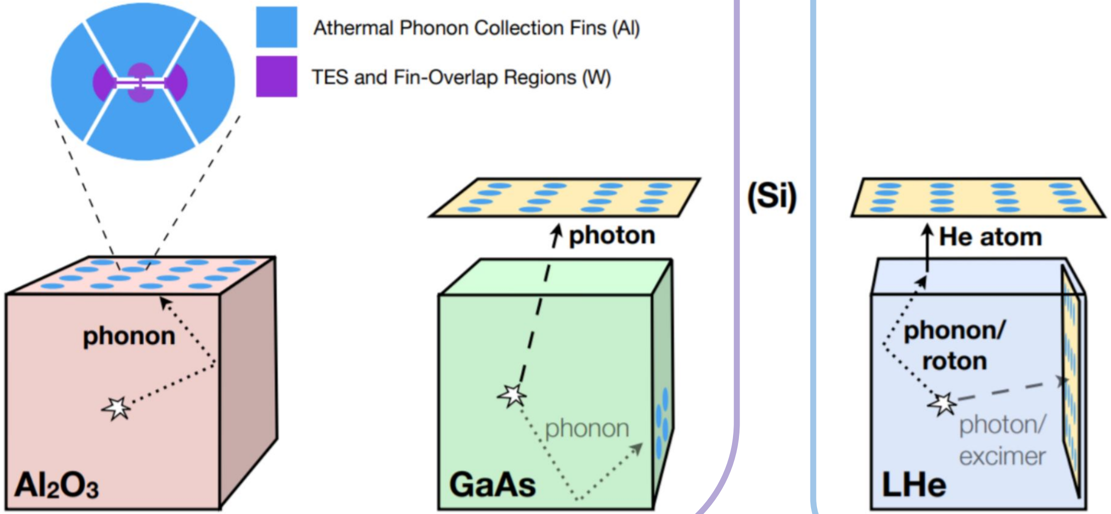
The SPICE/HeRALD collaboration

SPICE

polar crystal targets

HeRALD

superfluid
4He target



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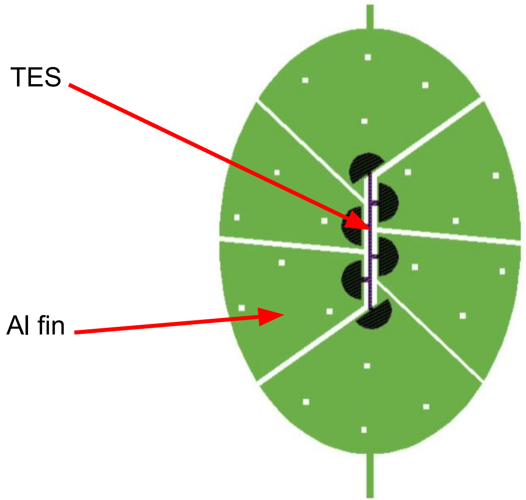
Two goals of both experiments

1. Good energy threshold

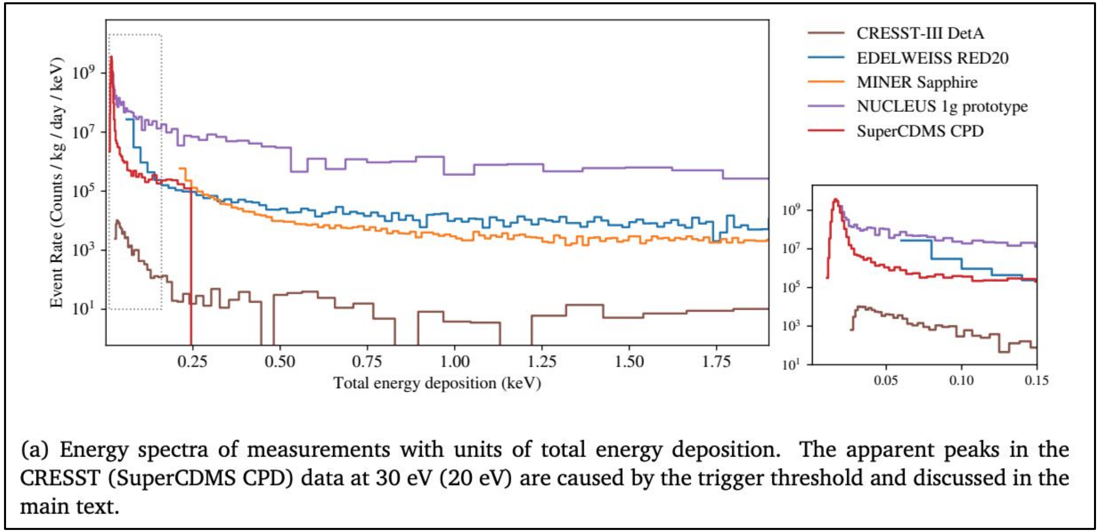
QET:
Quasiparticle-trap-assisted
Electrothermal-feedback
Transition-Edge-Sensor



Two goals of both experiments

1. Good energy threshold

2. Low backgrounds



(a) Energy spectra of measurements with units of total energy deposition. The apparent peaks in the CRESST (SuperCDMS CPD) data at 30 eV (20 eV) are caused by the trigger threshold and discussed in the main text.

[2] Adari, Prakruth, et al. "EXCESS workshop: Descriptions of rising low-energy spectra." *SciPost Physics Proceedings* 9 (2022): 001.

TES calorimetry and energy threshold

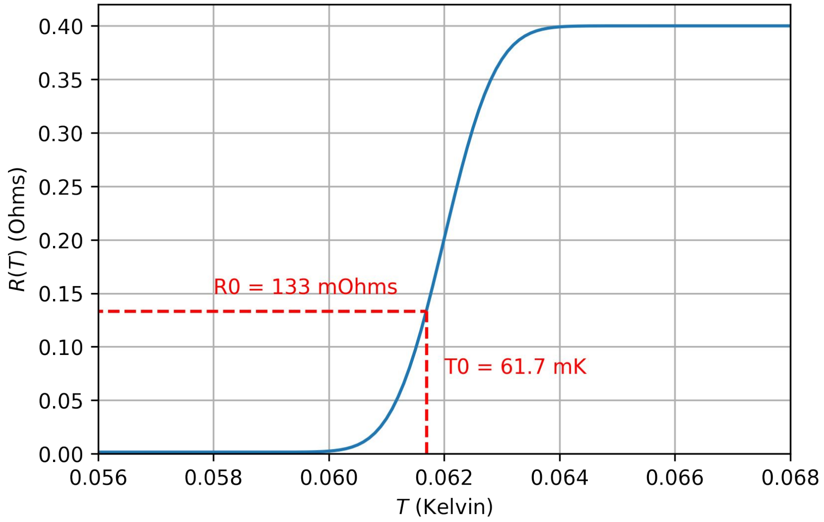
Transition Edge Sensors (TESs)

Superconducting metal (typically tungsten) biased at T_0 slightly less than the transition temperature s.t. $R_0 = R_N/3$

Small E deposit causes small T increase which causes sharp R increase

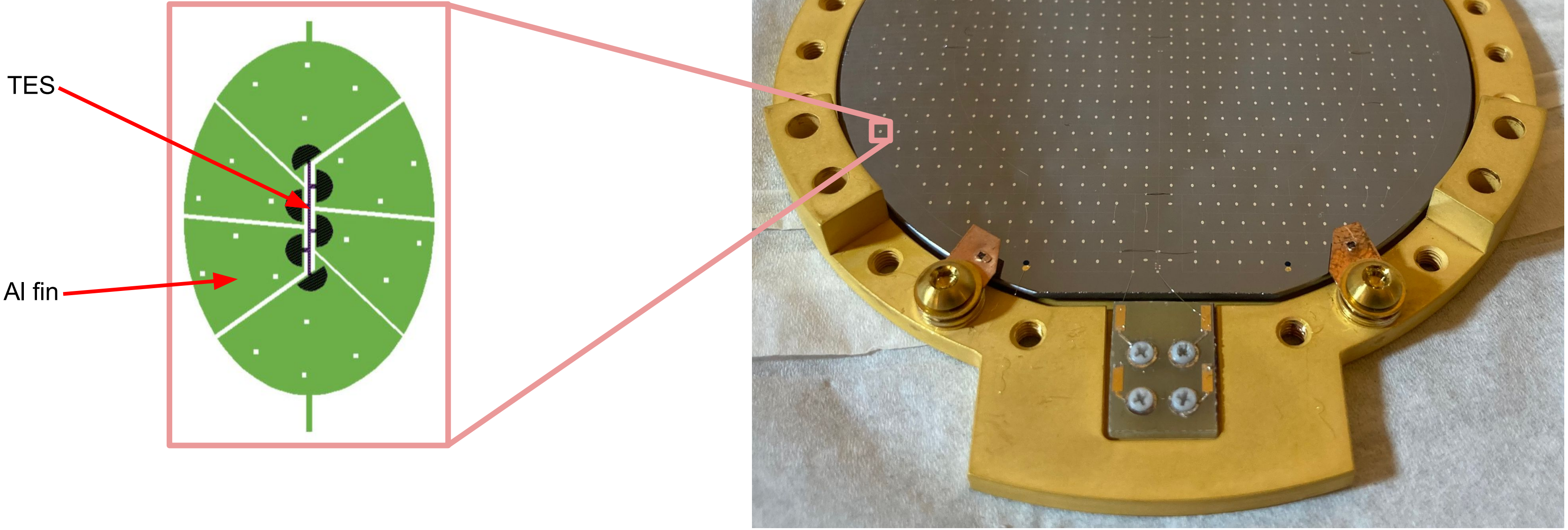
Electrothermal feedback makes the temperature stable

V-biased → Joule heating = V^2/R



Al fins funnel energy to the TES

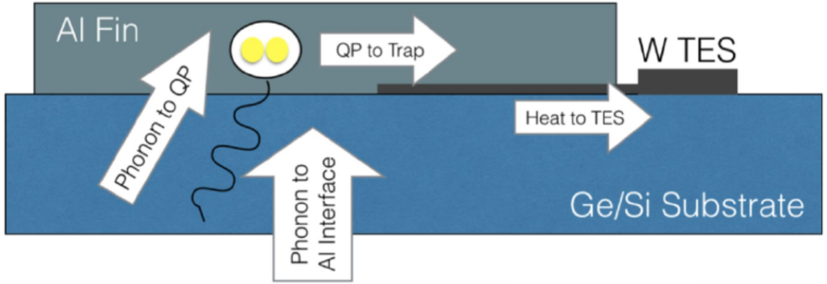
QET:
Quasiparticle-trap-assisted
Electrothermal-feedback
Transition-Edge-Sensor



Optimizing Al energy efficiency

Athermal phonons in the Si break Cooper pairs, forming quasiparticles (QPs)

QPs diffuse to the TES, which measures the change in R(T)



[3] Kurinsky, Noah. *The low-mass limit: Dark matter detectors with eV-scale energy resolution*. Stanford University, 2018.

Optimizing Al energy efficiency

Athermal phonons in the Si break Cooper pairs, forming quasiparticles (QPs)

QPs diffuse to the TES, which measures the change in R(T)

QPs cannot diffuse backward from lower energy to higher energy

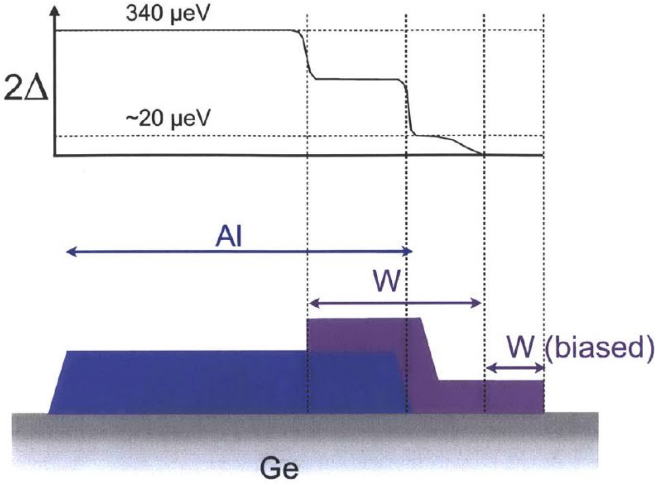


Figure 6-3: A depiction of the physical structures of the quasiparticle gap (bottom) and their resulting quasiparticle energies (top). Quasiparticles in the aluminum film gradually diffuse to regions of lower gap energy (right) and become trapped.

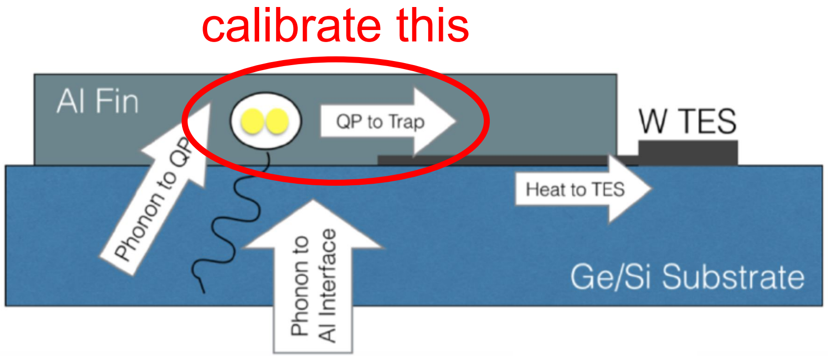
[4] Hertel, Scott A. "Advancing the search for dark matter: from CDMS II to SuperCDMS." *Ph. D. Thesis* (2012).ç

Optimizing Al energy efficiency

QP diffusion is critical, but there is a tradeoff: higher Al surface coverage means

- Higher efficiency of capturing athermal phonons from the substrate
- QPs need to diffuse longer distances, and are more likely to be trapped on imperfections in the Al, decreasing the overall energy efficiency

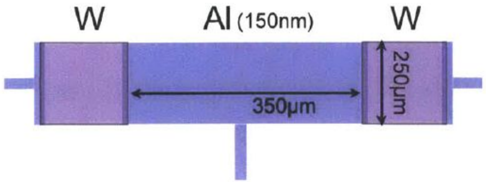
Need to optimize the Al fin length according to the characteristic QP diffusion length (ℓ_d) in Al

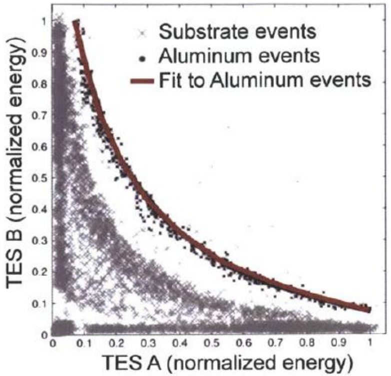


“Banana” experiments to measure QP diffusion

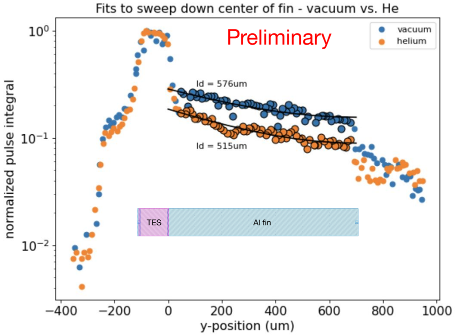
1997 CDMS banana experiment (Xray)
150nm thick Al fins
Measured ℓ_d = 180um
→This is why our Al fins are 150um long

[4] Hertel, Scott A. "Advancing the search for dark matter: from CDMS II to SuperCDMS." *Ph. D. Thesis* (2012).





2023 HeRALD banana experiment (laser)
150nm thick Al fins fabbed at ANL
Preliminary measurements of ℓ_d ~ 500um
→Longer Al fins?
→Improvement in active Al coverage?



This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists, Office of Science Graduate Student Research (SCGSR) program. The SCGSR program is administered by the Oak Ridge Institute for Science and Education for the DOE under contract number DE-SC0014664.

Optimizing TES energy resolution

Energy resolution scales strongly with T_c and TES volume

Current state-of-the-art T_c for tungsten TES is 40mK

T_c = 15mK W TES has been demonstrated → 19x improvement in resolution?

Can also decrease the TES volume for further improvement

$$\sigma_E \mathrel{\tilde{\propto}} T_c^3 \sqrt{\frac{V_{TES} V_{crystal}}{l_{fin}}}$$

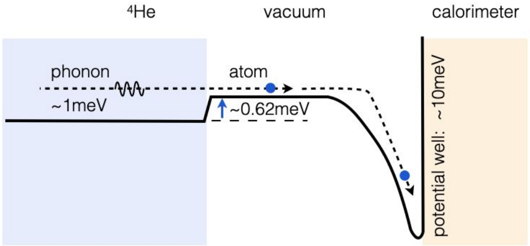
The HeRALD Experiment

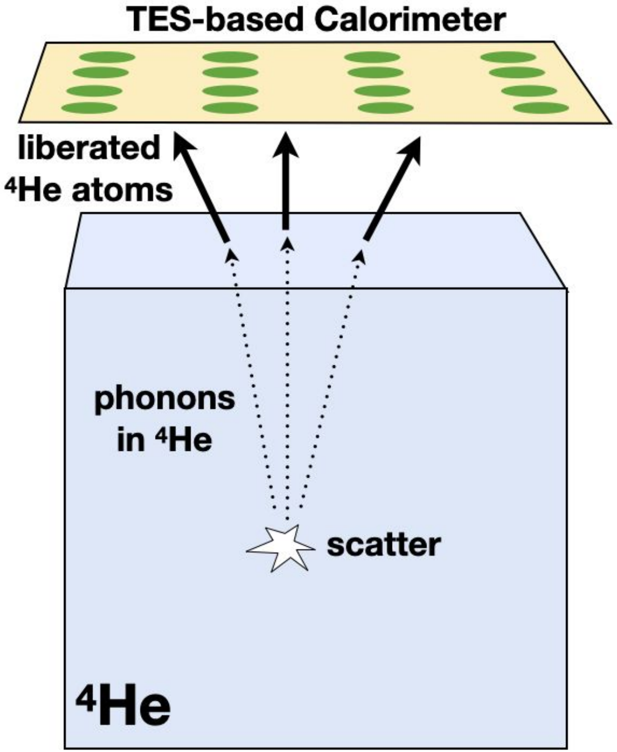
Advantages of superfluid 4He

Low mass makes 4He sensitive to energy deposits down to ~1 meV

$$T_{\mathrm{NR}} \le \frac{2m_\chi^2 m_N v_\chi^2}{(m_\chi + m_N)^2}$$

0.62 meV to quantum evaporate He atom, 10meV absorption → x10 gain





Advantages of superfluid He

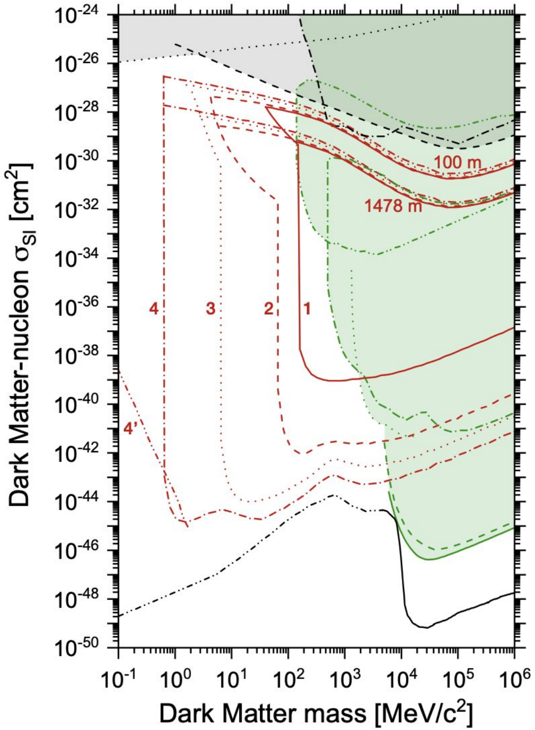
1: 1 kg-day, 40eV threshold

2: 1 kg-yr, 10eV threshold

3: 10 kg-yr, 100meV threshold

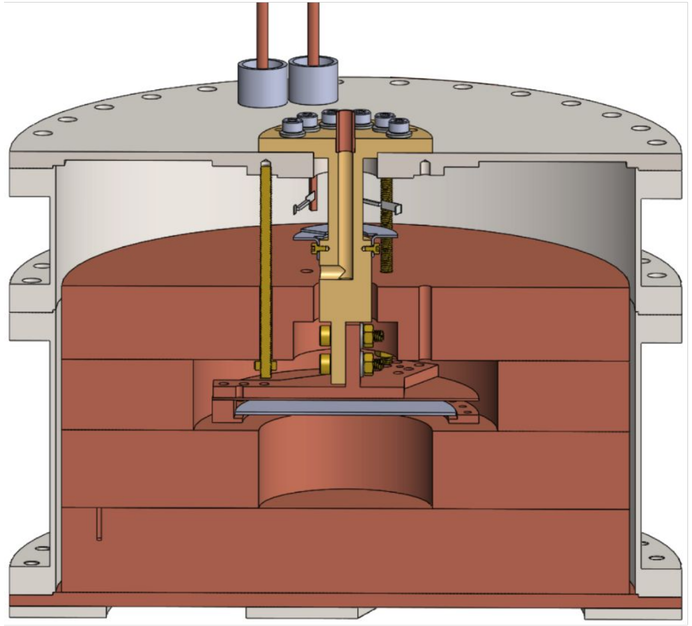
4: 100 kg-yr, 1meV threshold

4’: 100 kg-yr, 1meV threshold, off-shell phonon processes

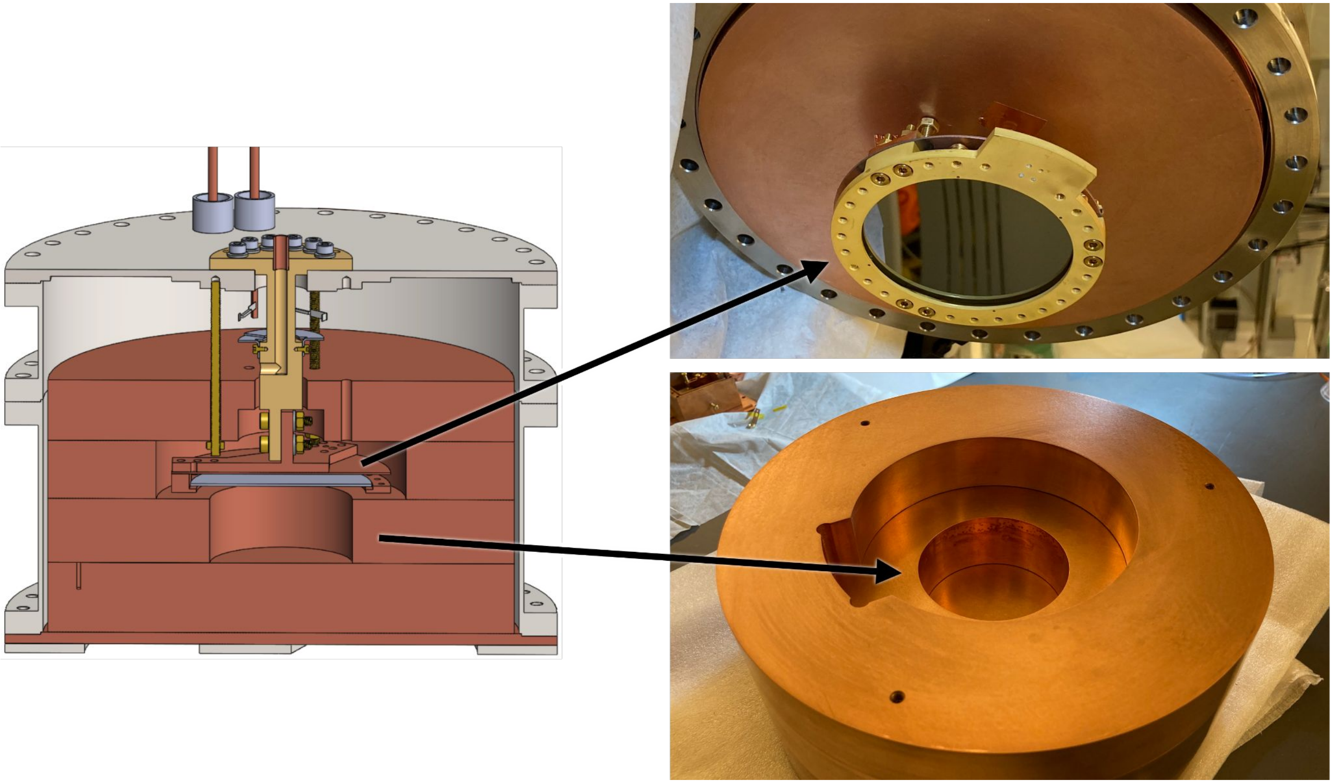


[5] Hertel, Scott A., et al. "Direct detection of sub-GeV dark matter using a superfluid He 4 target." *Physical Review D* 100.9 (2019): 092007.

HeRALD v0.1



HeRALD v0.1

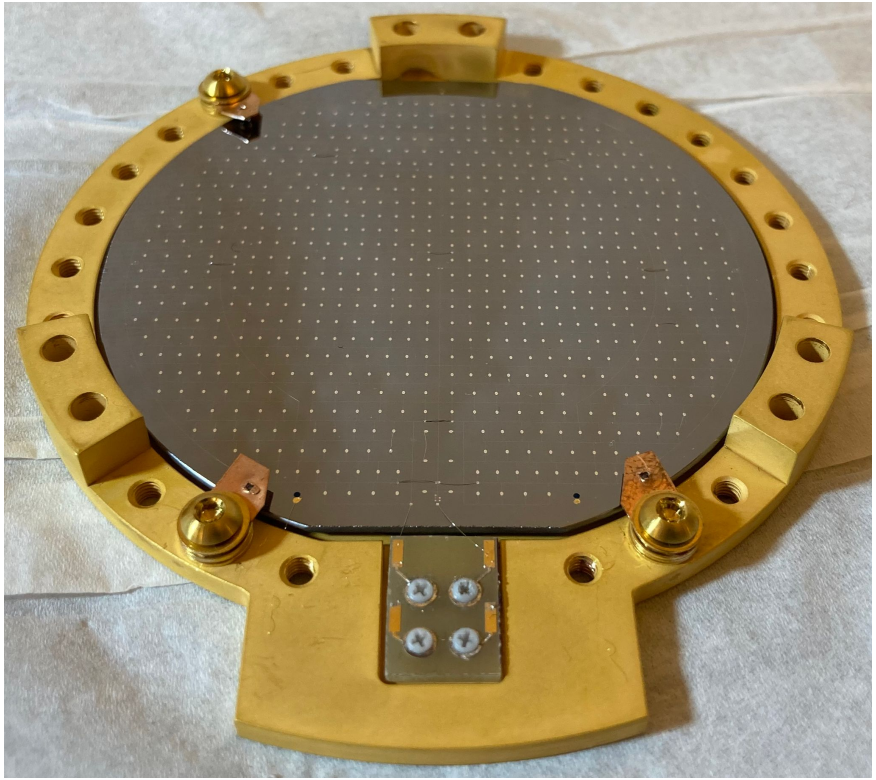


The cryogenic photodetector (CPD)

The sensor (CPDv2) is a 3” diameter, 1mm thick, 10g Si wafer

~700 tungsten Transition Edge Sensors (TESs) with $T_c = 51\text{mK}$

~2.3eV resolution (σ) for energy in Si



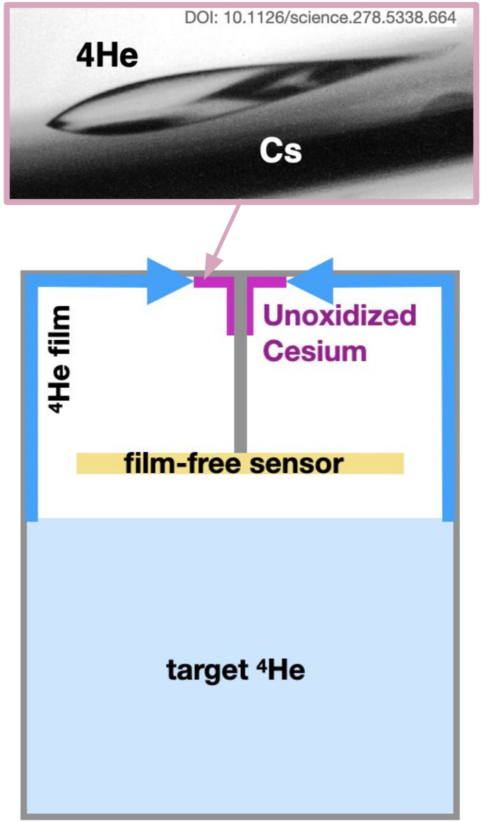
HeRALD v0.1

Target He volume with single sensor suspended above

Cesium stops superfluid He from creeping onto the sensor

High current (>7A) dispensers deposit Cs onto sensor post

Baffles separate Cs region from sensor region


DOI: 10.1126/science.278.5338.664

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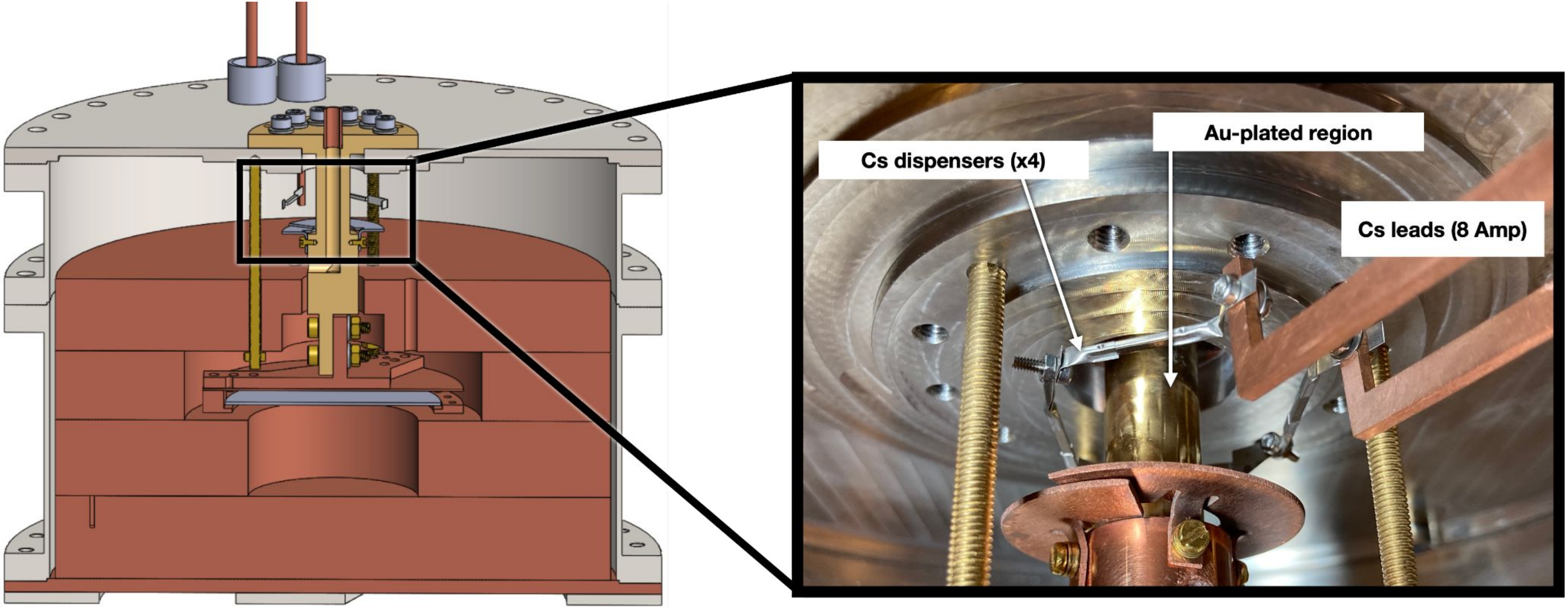
HeRALD v0.1



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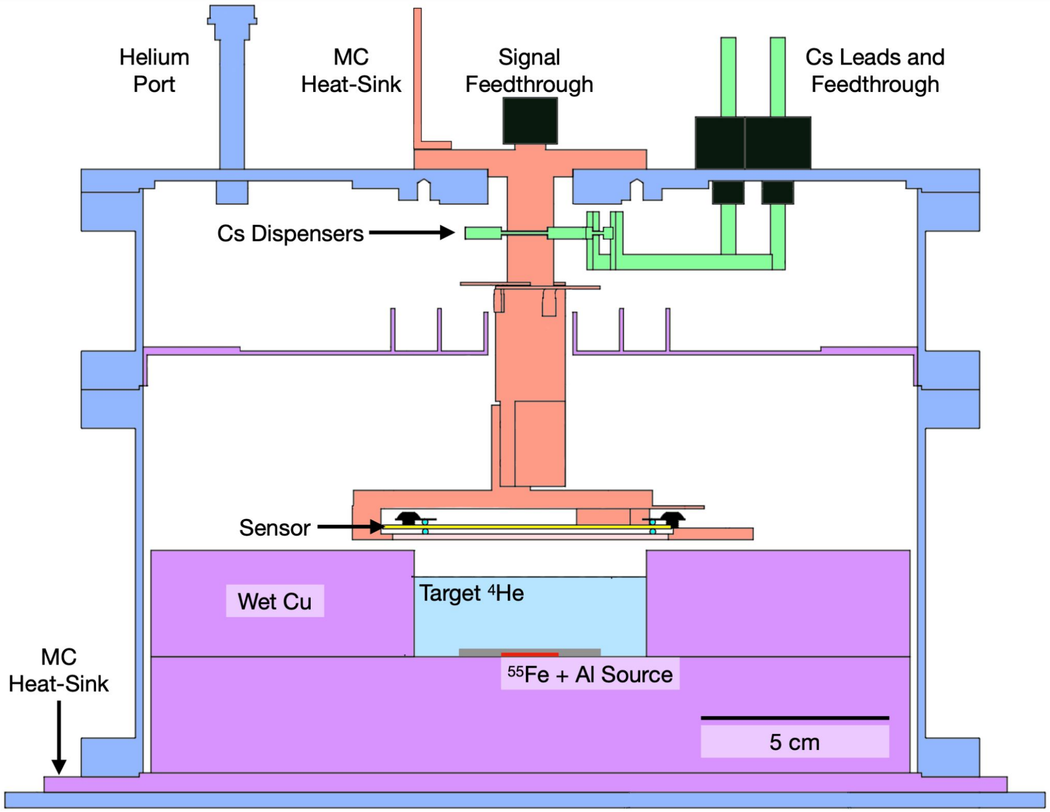
HeRALD v0.1

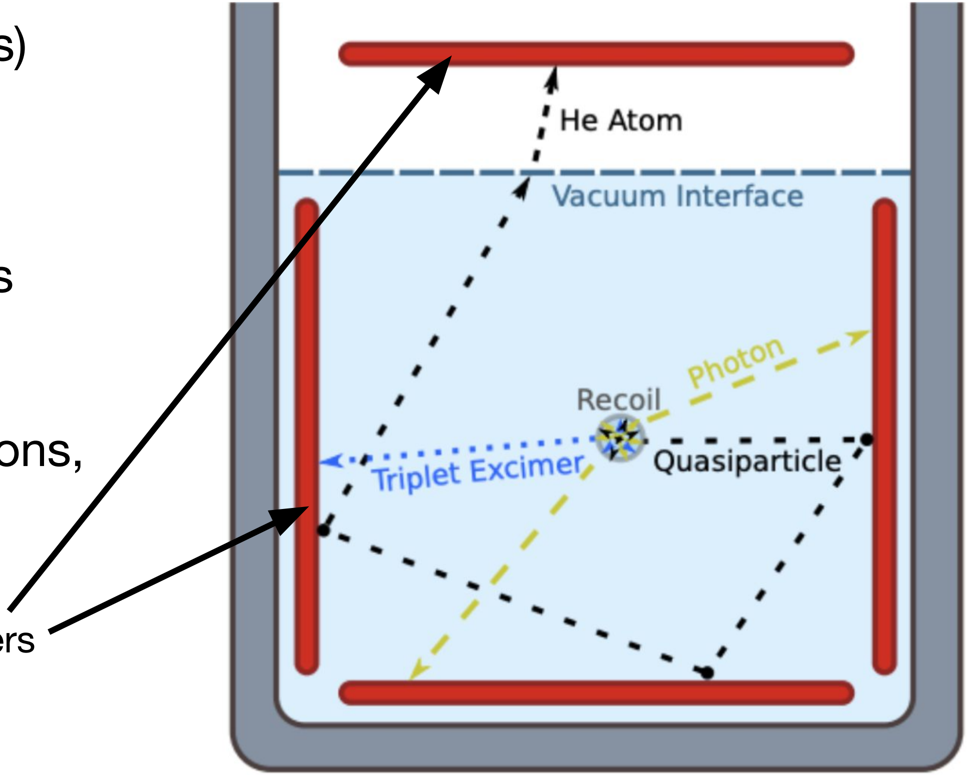

Helium Port
MC Heat-Sink
Signal Feedthrough
Cs Leads and Feedthrough
Cs Dispensers
Sensor
Wet Cu
Target ^{4}He
^{55}Fe + Al Source
MC Heat-Sink
5 cm

Three signal channels

16eV photons - from quickly (10ns) decaying He_2* singlet excimers

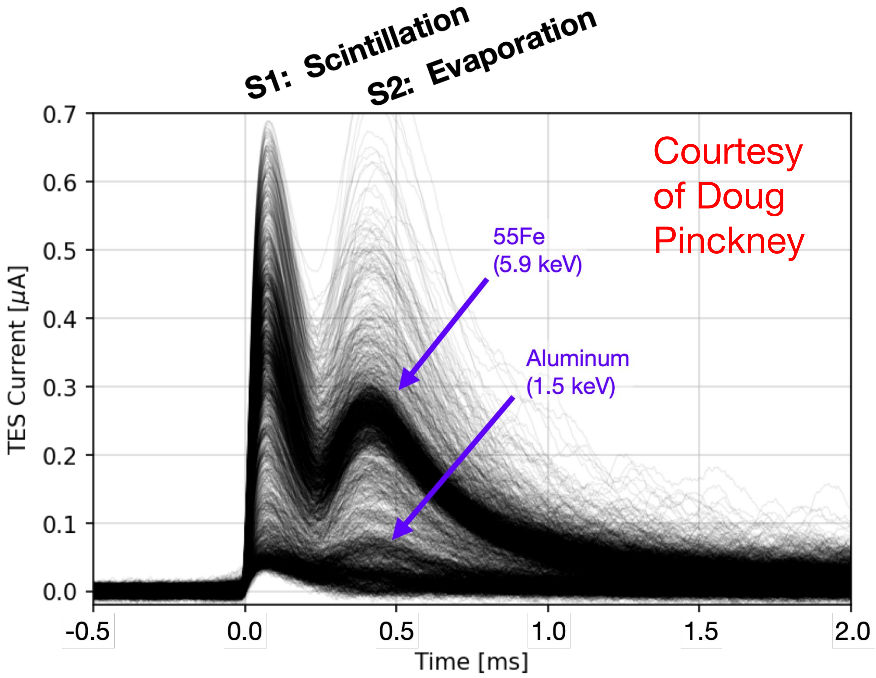
He_2* triplet excimers - propagate ballistically at 1m/s; long-lived (13s halflife) → quench on walls

Quasiparticles - phonons and rotons, the excitations of superfluid He



calorimeters

Initial HeRALD R&D data

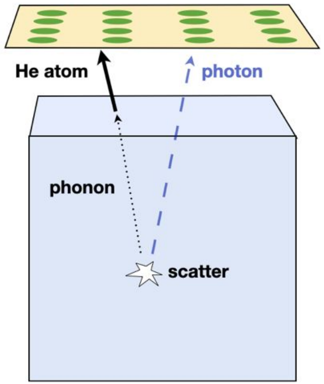


Courtesy of Doug Pinckney

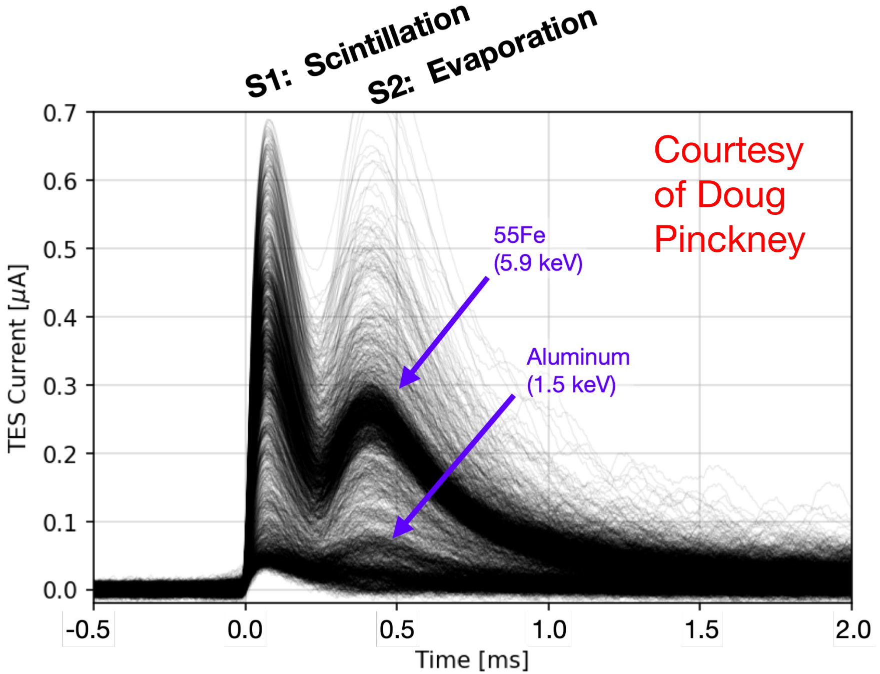
S1: singlet scintillation photons
S2: He evaporation some Δt later

He thickness $\mathcal{O}$(1cm)
v_{phonon} $\mathcal{O}$(100m/s)

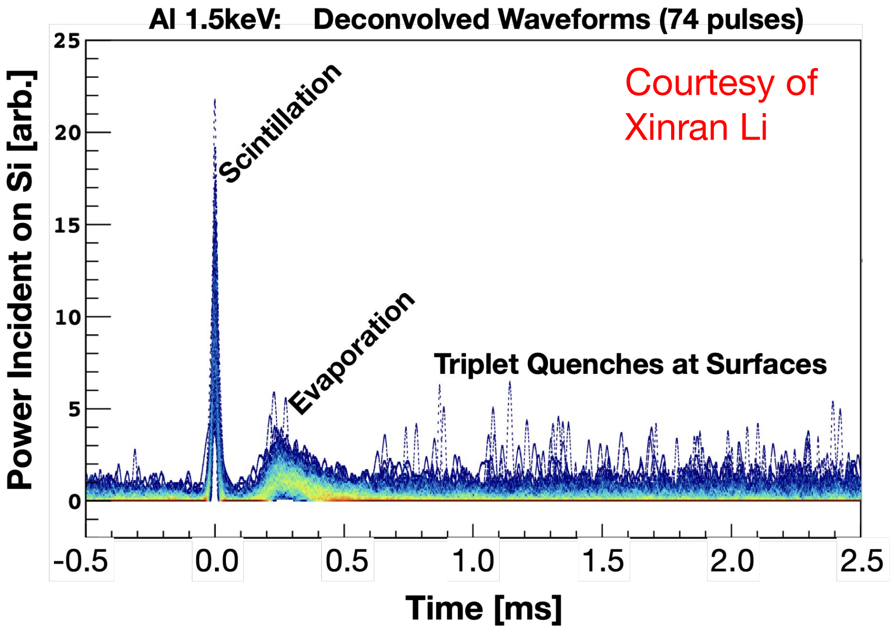
→ **Δt $\mathcal{O}$(100us)**



Initial HeRALD R&D data



Courtesy of Doug Pinckney



Courtesy of Xinran Li

Initial HeRALD R&D data

Two clear populations from calibration Xray energies:

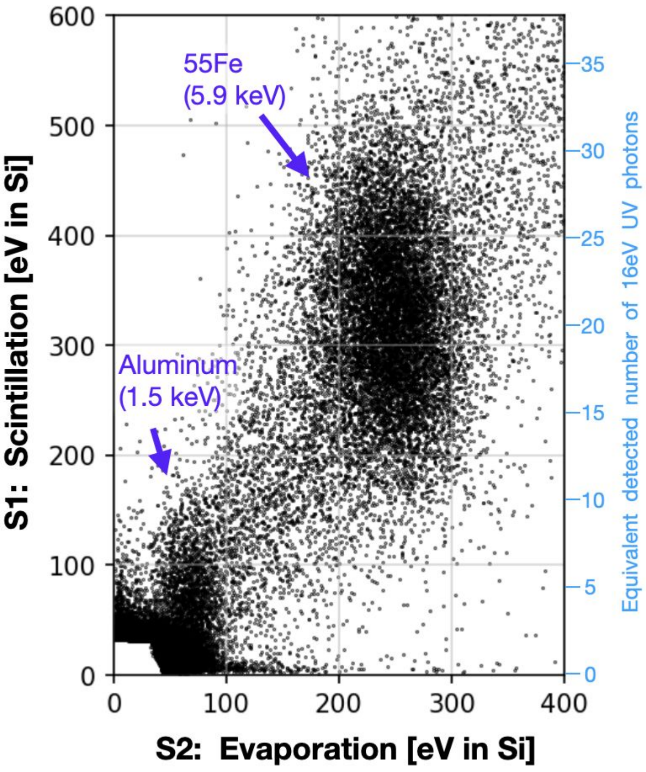
- 5.9keV (55Fe)
- 1.5keV (Al fluorescence)

Scintillation:

- Matches expectation from light yield and solid angle

Evaporation:

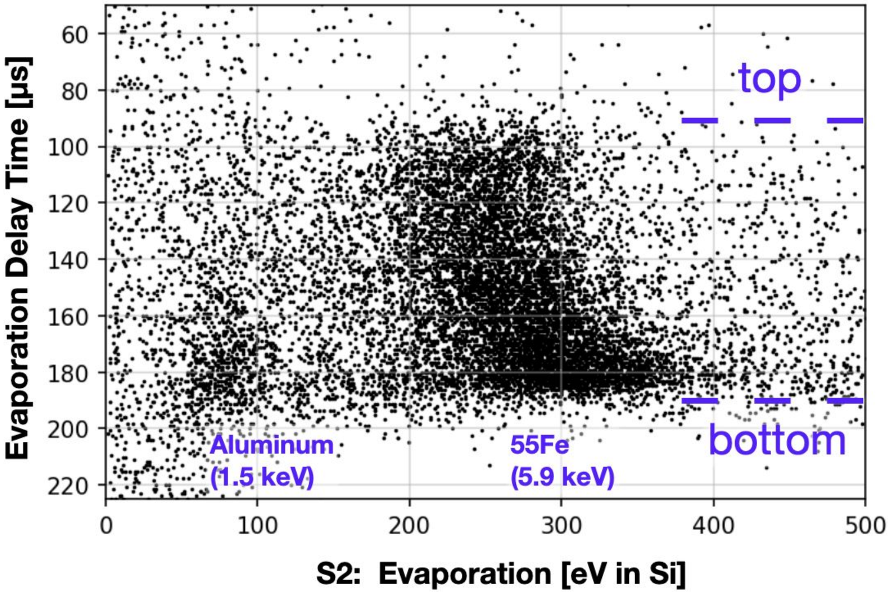
- Roughly matches expectation, but lots more to study!



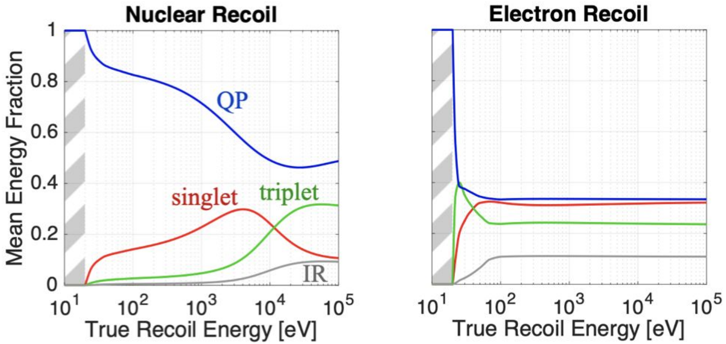
Initial HeRALD R&D data

Δt delay before evaporation signal is depth-dependent

As expected:
- 55Fe depth spread is ~uniform
- Al is only near the bottom



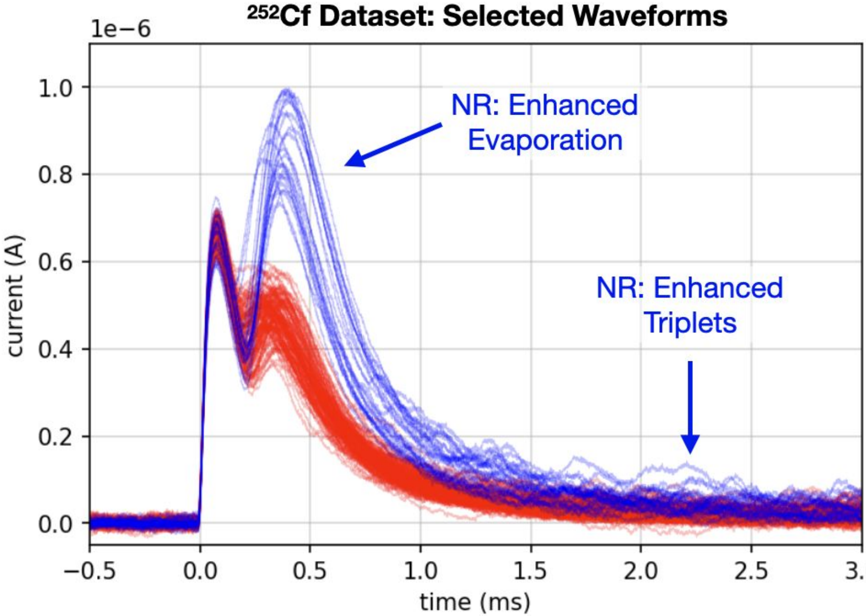
Initial HeRALD R&D data



Intended signal region <20eV (only QPs), but we can still look at ER/NR above 20eV

Preliminary 252Cf observations:

- Higher evaporation:scintillation ratio
- Larger triplet fraction



NR: Enhanced Evaporation

NR: Enhanced Triplets

Initial HeRALD R&D paper by HD Pinckney should be on arXiv next week!

The SPICE Experiment

SPICE targets and their motivations

Sapphire (Al_2O_3)

- Polar crystal → optical phonons (very low effective mass)
- Oxygen nuclei are light → good kinematic matching to light DM

SiO_2

- Polar crystal
- Great dark photon coupling

GaAs

- Polar crystal
- Scintillation and phonon signals → NR/ER discrimination down to very low energies

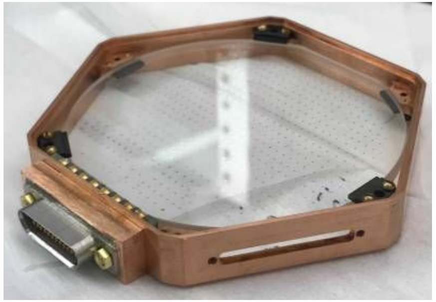
arXiv: 1910.10716 Griffin et. al. 2021

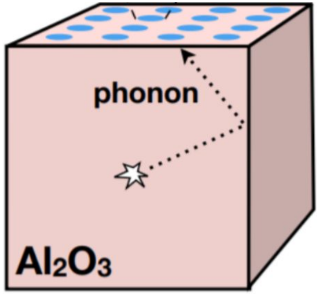
Sapphire (Al_2O_3) target

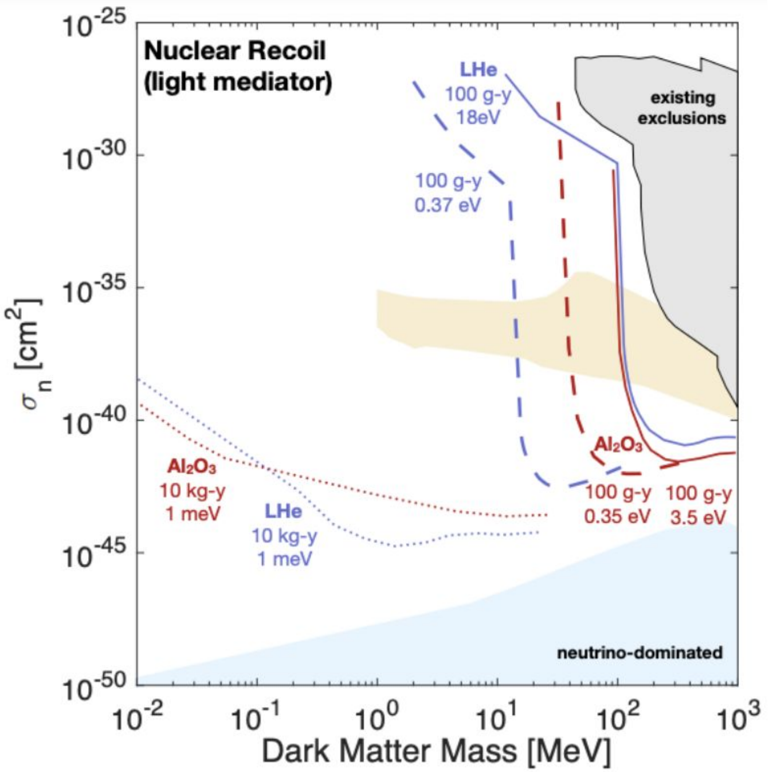
Low mass oxygen nuclei good NR scattering targets

Polar unit cell → optical phonons down to ~100meV

Prototype detector (below) demonstrates we can make devices out of this material



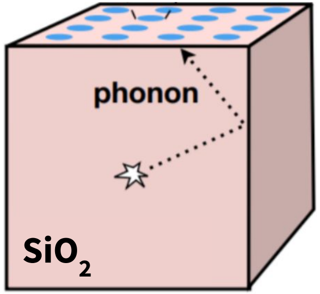


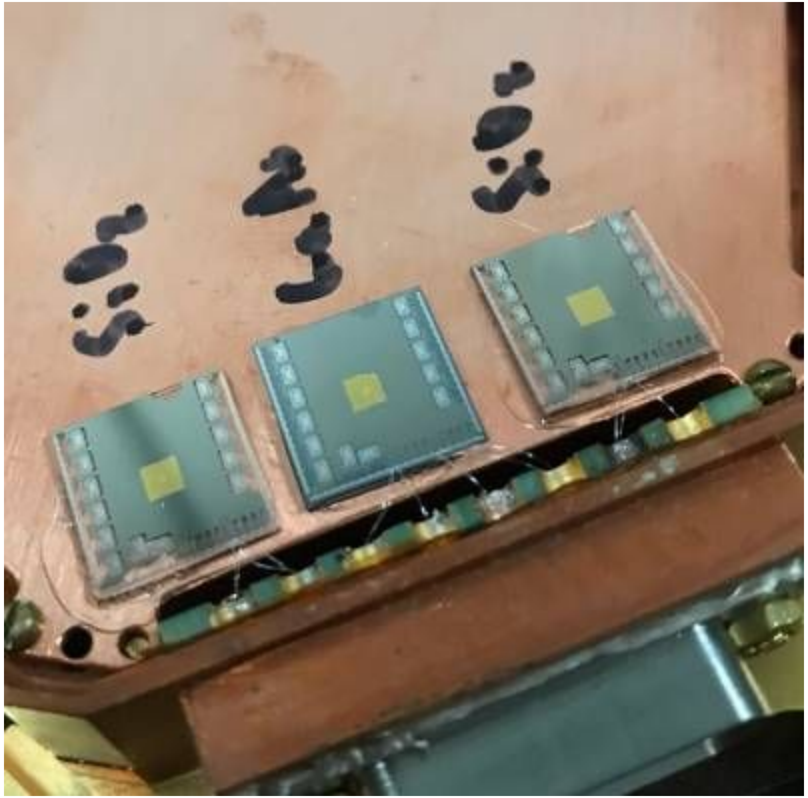


SiO_2 target

Great coupling to dark photons, high quality factor (see arXiv: 1910.10716)

TESs on SiO_2 substrates (right) work!

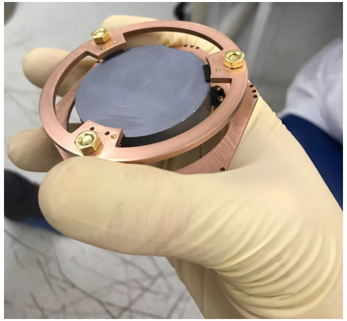


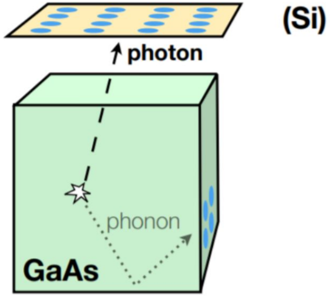


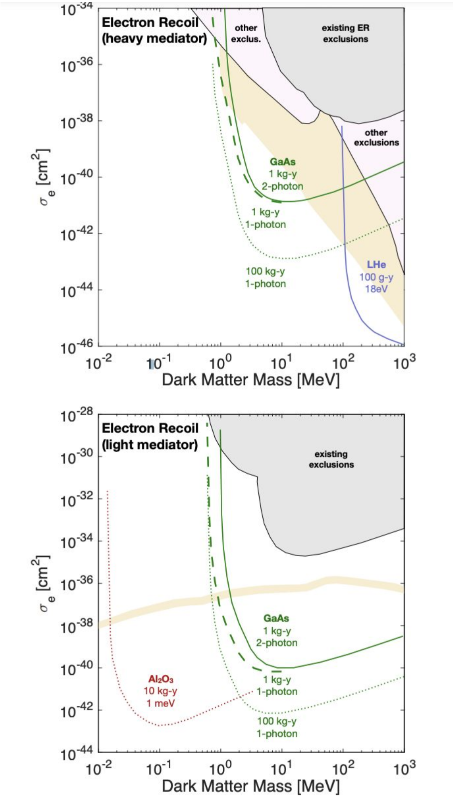
GaAs target

Scintillation and phonon signal → ER/NR discrimination down to eV-scale signals

GaAs scintillation has been observed (from device below)



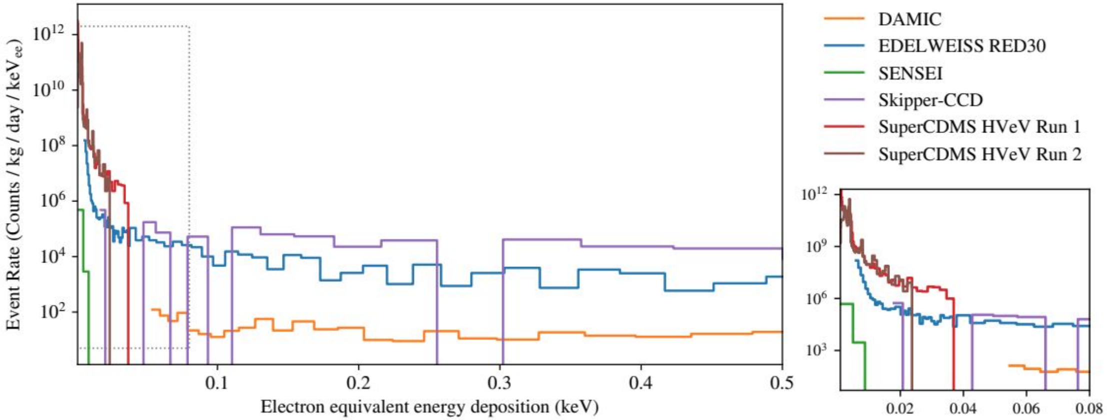




Understanding and mitigating low-energy backgrounds

The low-energy excess

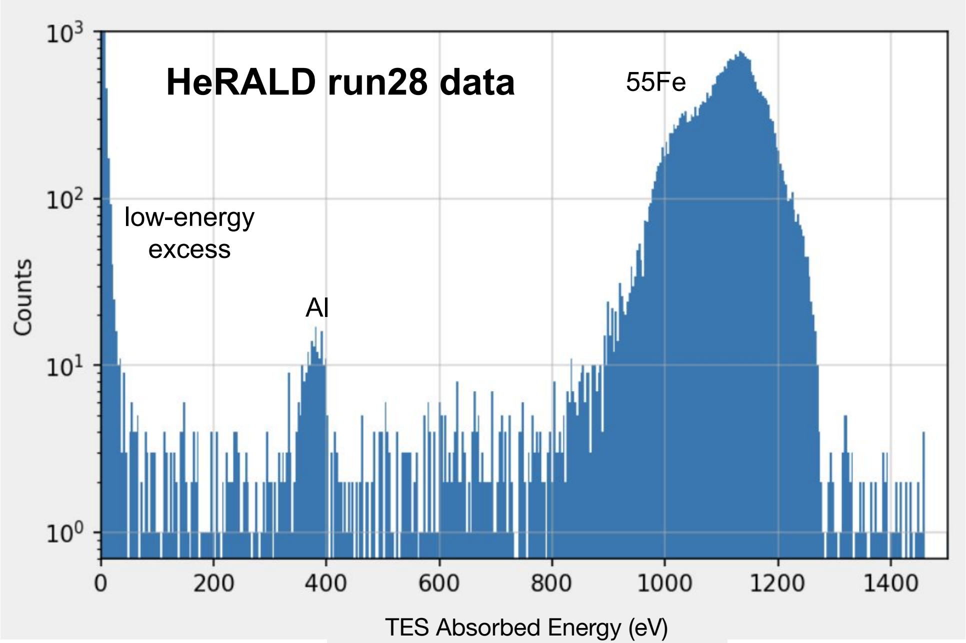
The primary background in all phonon-based experiments at eV scales



(b) Energy spectra of measurements with units of electron equivalent energy deposition. Note that this energy scale can only be approximated for SuperCDMS HVeV data (see Sec. 2.1.5).

The low-energy excess

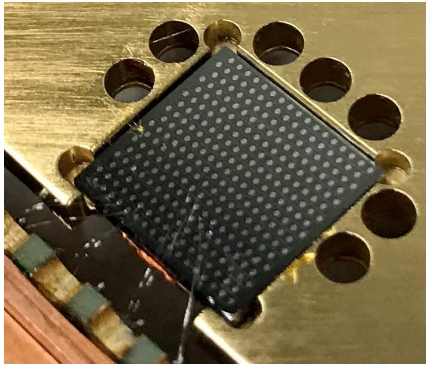
The primary background in all phonon-based experiments at eV scales



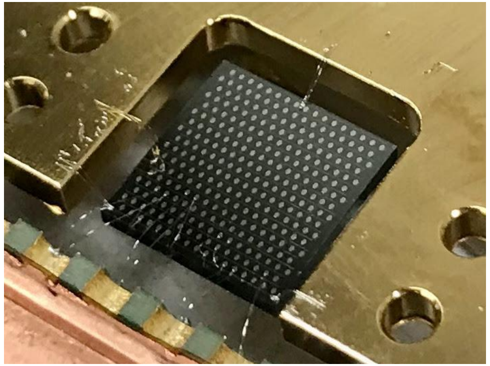
SPICE stress studies: purposefully creating stress events

Two identical TES-based athermal phonon detectors - 1cm^2 by 1mm thick silicon substrate

One **glued** down to Cu substrate (high stress), one **suspended** from wire bonds (low stress)

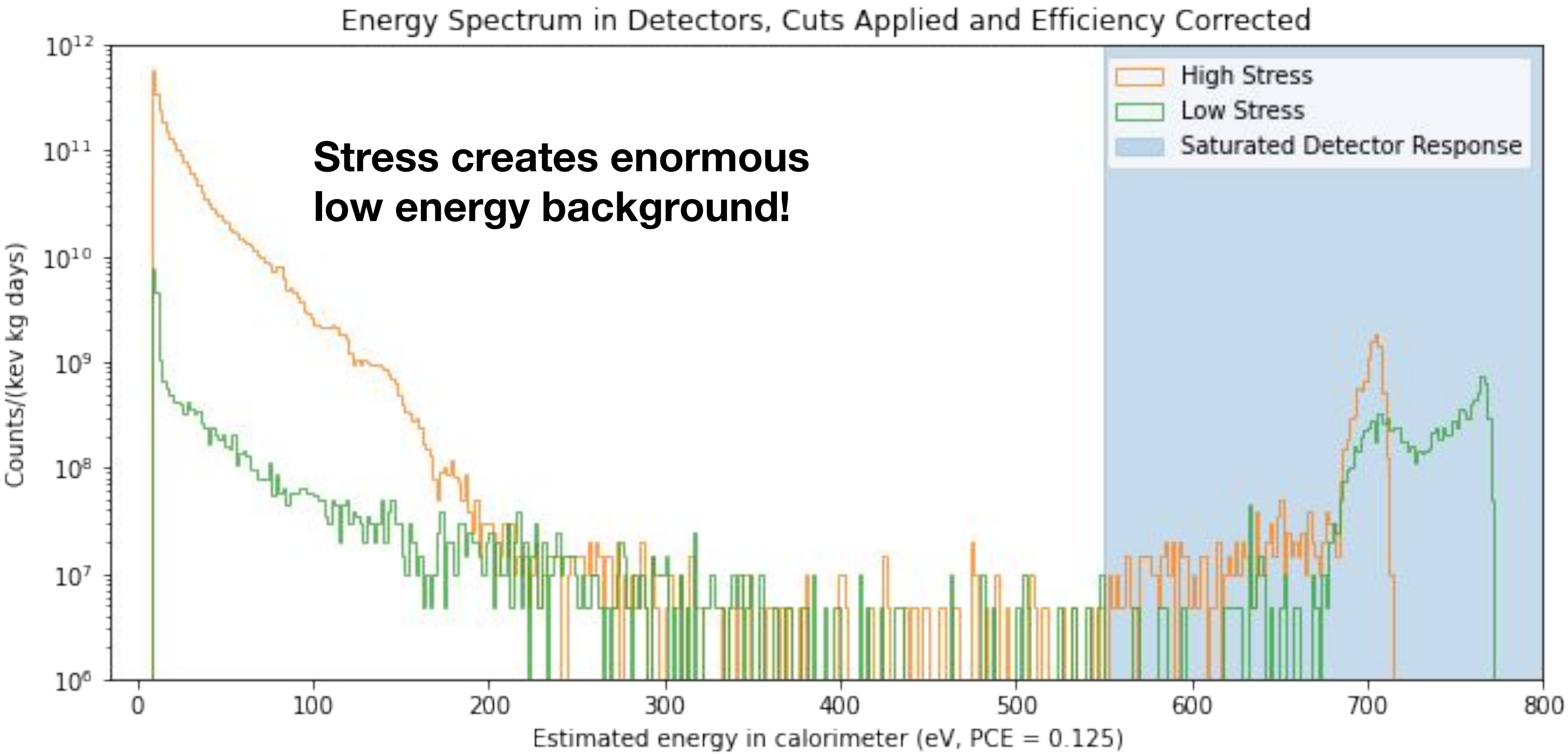


High stress



Low stress

SPICE stress studies: purposefully creating stress events



Stress creates enormous low energy background!

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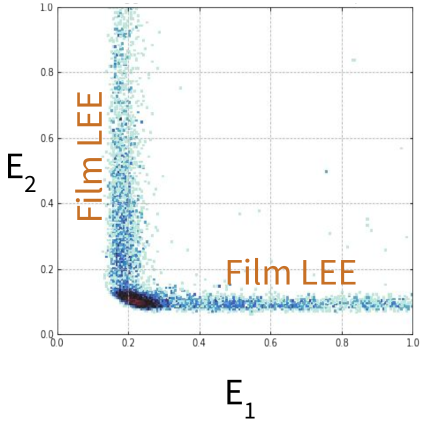
SPICE stress studies: What could be causing stress events?

Tungsten film stress? (upper right)

-Plot is from chip with two TESs and the rest of the surface covered with Al to remove substrate phonons

-From stress-induced microfractures in W?

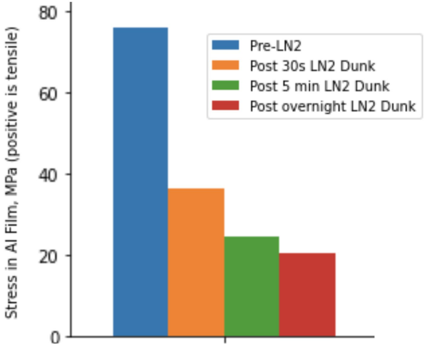
-Can be mitigated by moving to other TES materials: IrPt, AlMn, etc.



Al film stress? (lower right)

-Strong evidence for Al deformation over time at low temperatures

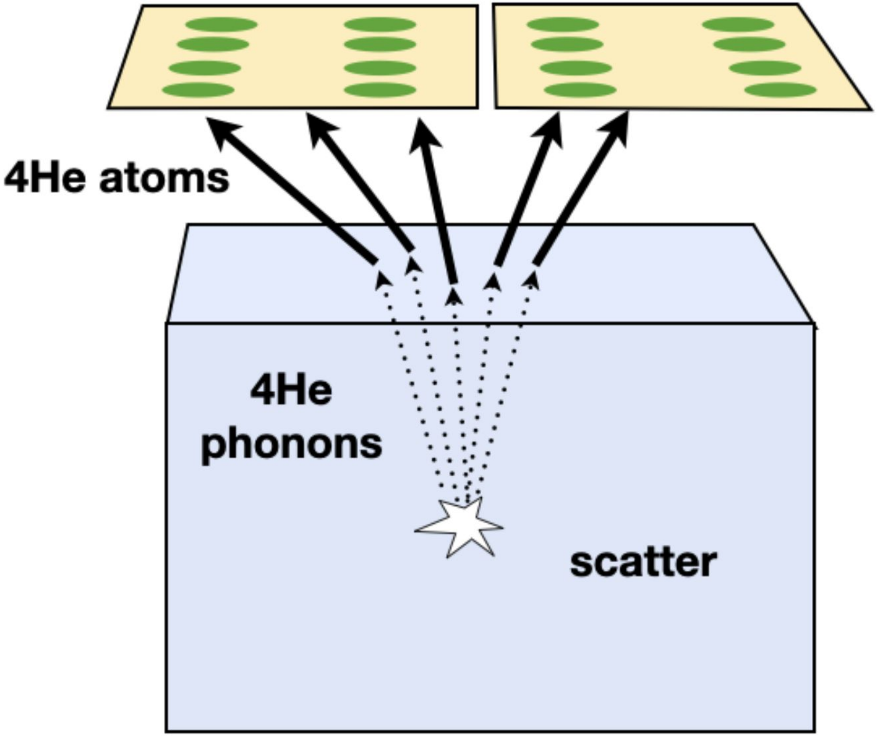
-Point of plot: cooling Al caused the release of some stress



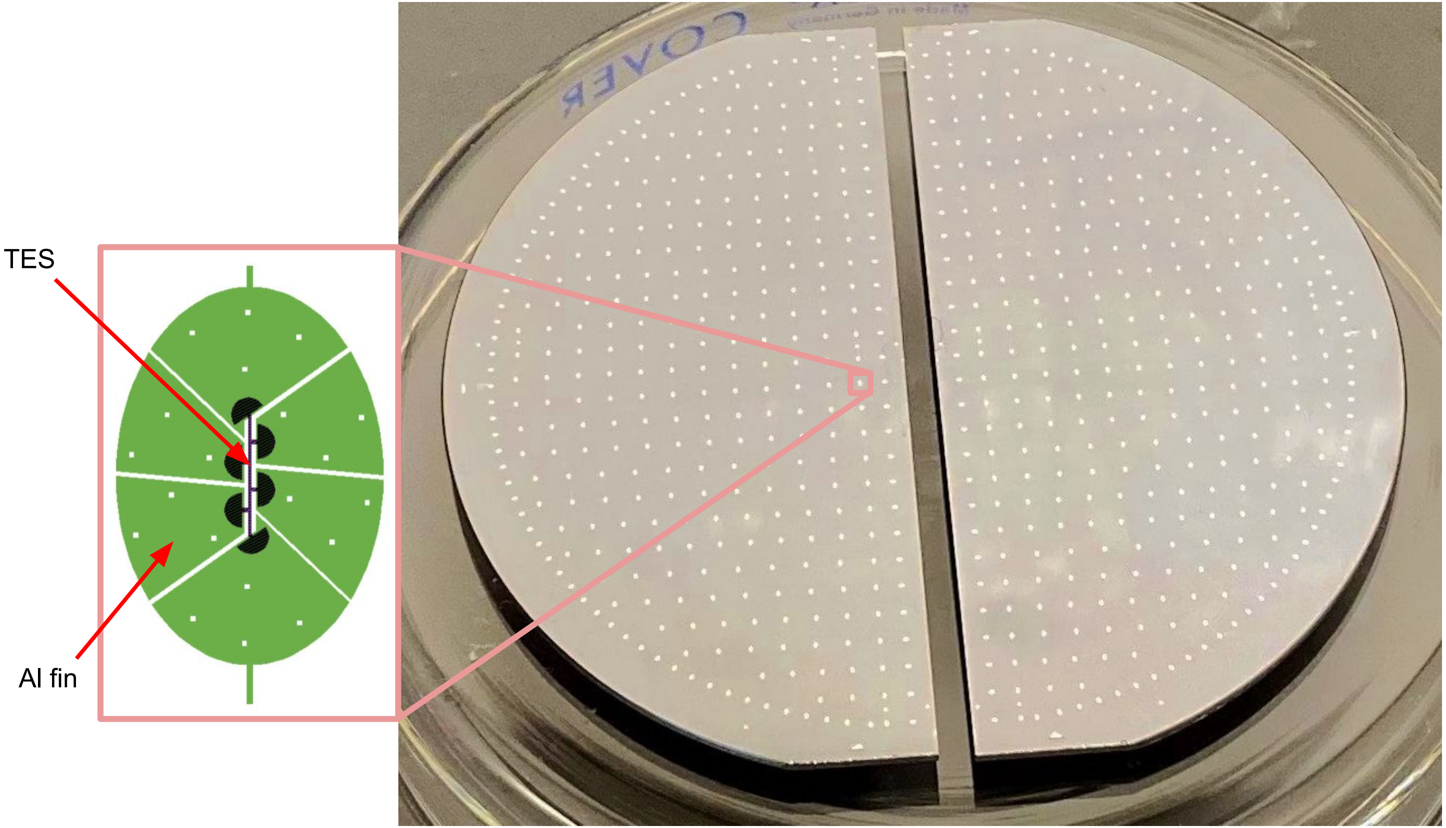
HeRALD LEE mitigation effort: coincidence discrimination

Goal: use two detector channels (separate wafers) to eliminate this excess by coincidence

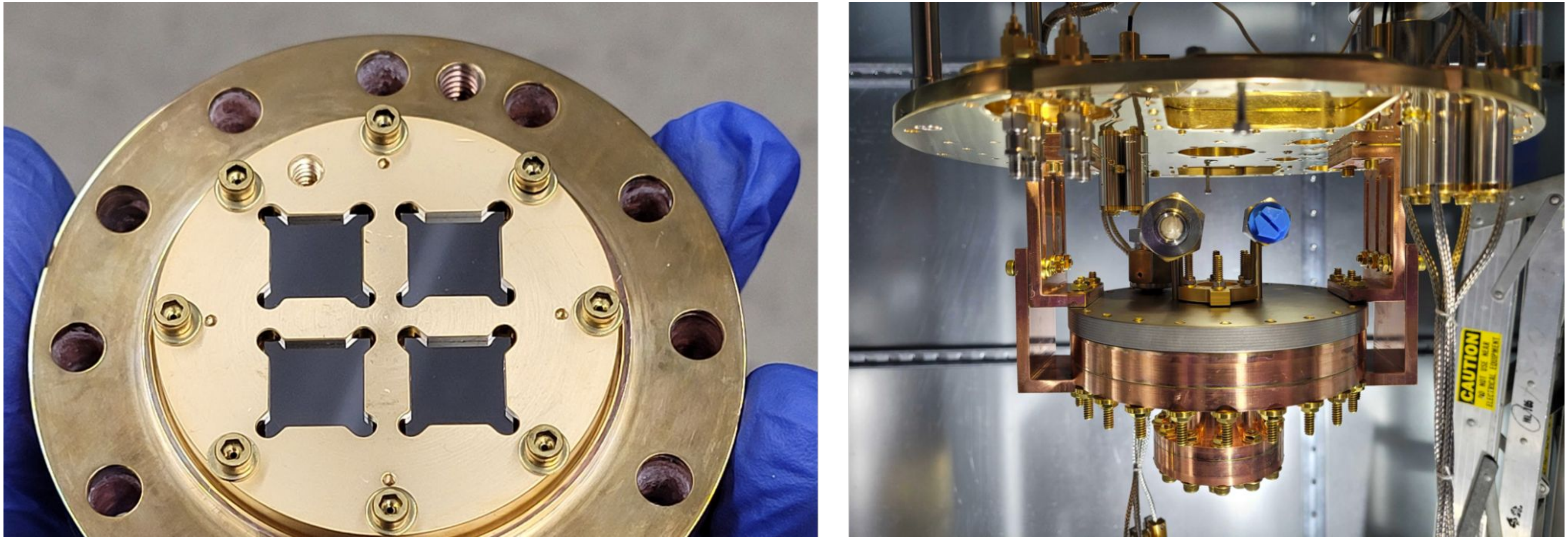
- -An event in the He will be visible in both channels
- -A spontaneous phonon event in a photodetector will show up only in that one channel



HeRALD v0.1 - 2-channel runs happening soon!



HeRALD v0.2 - 4-channels!



Summary

HeRALD:

- Demonstrated superfluid He film stopping with Cs, and measured scintillation, evaporation, and triplet events in superfluid 4He target (on arXiv next week!)
- Measured improved QP diffusion in Al fins (paper in production)
- Next: Discriminate LEE stress events with coincidence

SPICE

- Demonstrated sapphire, GaAs, and SiO_2 target materials
- Measured LEE-type events from stress
- Next: Eliminate LEE stress events with different TES materials

Extra slides

Recent dark matter exclusions for direct detection

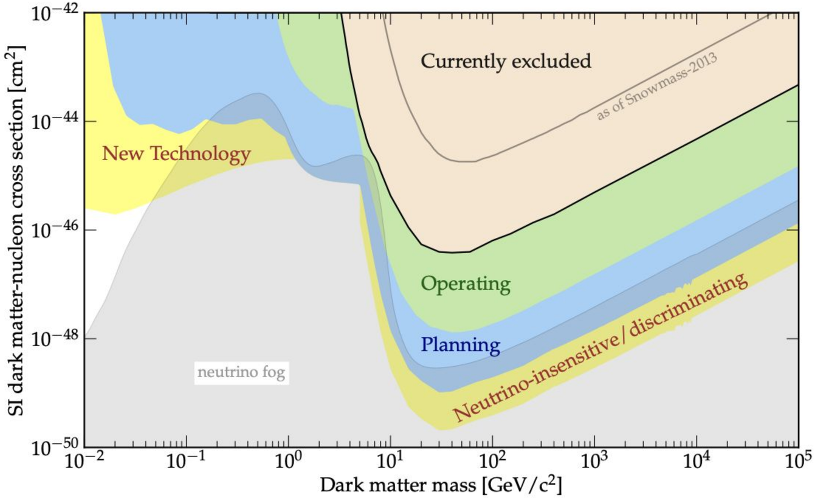
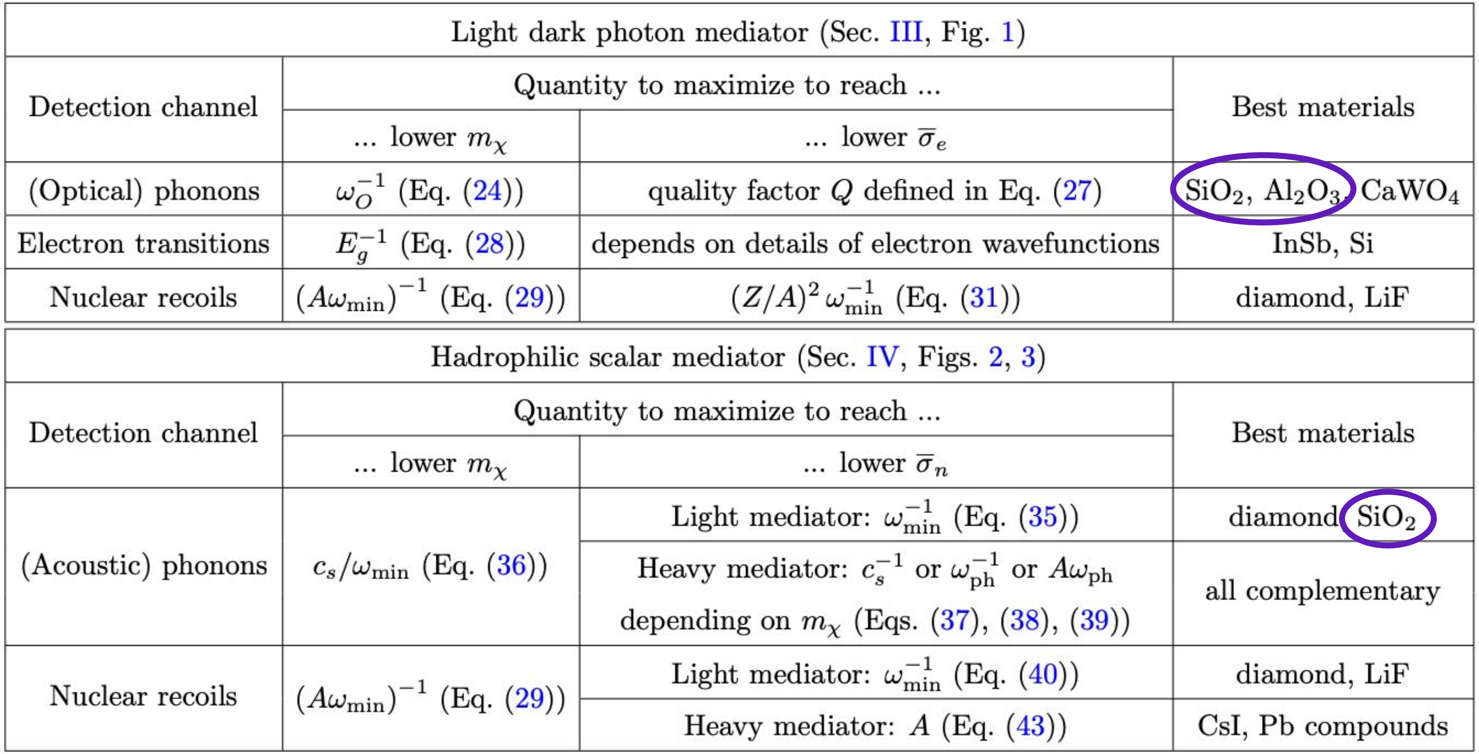


Figure 7: Combined Spin-independent dark-matter nucleon scattering cross section space. Currently 90% c.l. constraints are shown in shaded beige [240–255] (data points taken from [239]) while the reach of currently operating experiments are shown in green (LZ, XENONnT, PandaX-4T, SuperCDMS SNOLAB, SBC). The limits from 2013 are shown as a gray line [256]. Future experiments are shown in blue (SuperCDMS, DarkSide-LowMass, SBC, 1000 ton-year liquid xenon, ARGO) and yellow (Snowball and Planned× 5). The neutrino fog for a xenon target is presented in gray as described in Sec. 4.3.2. Plot reproduced from Ref. [2].

[4] Jodi Cooley, Tongyan Lin, W Hugh Lippincott, Tracy R Slatyer, Tien-Tien Yu, Daniel S Akerib, Tsuguo Aramaki, Daniel Baxter, Torsten Bringmann, Ray Bunker, et al. Report of the topical group on particle dark matter for snowmass 2021.arXiv preprint arXiv:2209.07426, 2022.

Different models and materials



Light dark photon mediator (Sec. III, Fig. 1)			
Detection channel	Quantity to maximize to reach ...		Best materials
	... lower m_χ	... lower $\overline{\sigma}_e$	
(Optical) phonons	ω_O^{-1} (Eq. (24))	quality factor Q defined in Eq. (27)	SiO_2, Al_2O_3, $CaWO_4$
Electron transitions	E_g^{-1} (Eq. (28))	depends on details of electron wavefunctions	InSb, Si
Nuclear recoils	$(A\omega_{\mathrm{min}})^{-1}$ (Eq. (29))	$(Z/A)^2\,\omega_{\mathrm{min}}^{-1}$ (Eq. (31))	diamond, LiF

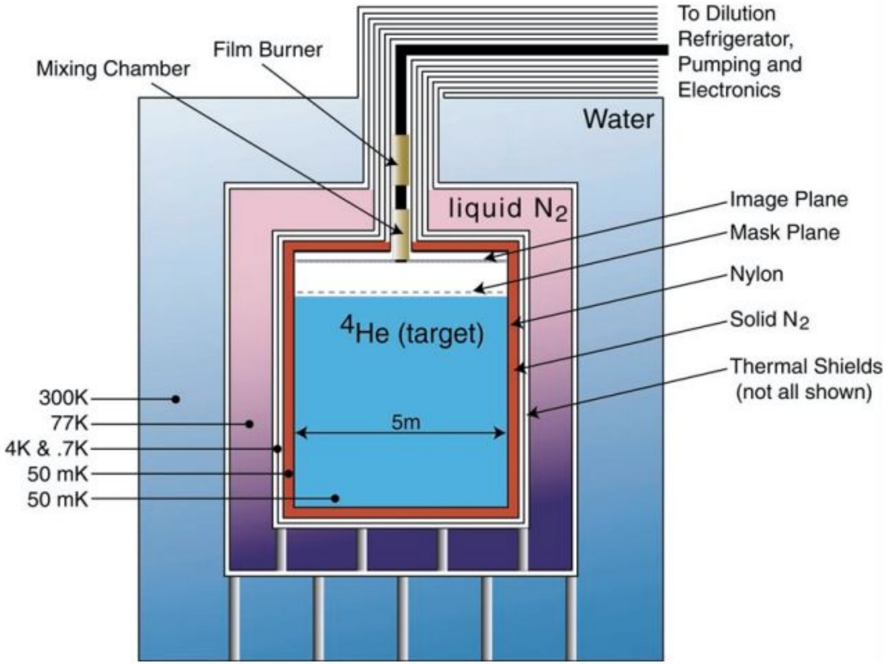
Hadrophilic scalar mediator (Sec. IV, Figs. 2, 3)			
Detection channel	Quantity to maximize to reach ...		Best materials
	... lower m_χ	... lower $\overline{\sigma}_n$	
(Acoustic) phonons	$c_s/\omega_{\mathrm{min}}$ (Eq. (36))	Light mediator: $\omega_{\mathrm{min}}^{-1}$ (Eq. (35))	diamond, SiO_2
		Heavy mediator: c_s^{-1} or $\omega_{\mathrm{ph}}^{-1}$ or $A\omega_{\mathrm{ph}}$ depending on m_χ (Eqs. (37), (38), (39))	all complementary
Nuclear recoils	$(A\omega_{\mathrm{min}})^{-1}$ (Eq. (29))	Light mediator: $\omega_{\mathrm{min}}^{-1}$ (Eq. (40))	diamond, LiF
		Heavy mediator: A (Eq. (43))	CsI, Pb compounds

arXiv: 1910.10716 Griffin et. al. 2021

The inspiration for HeRALD

Inspiration comes from HERON (right), a detector that used superfluid He as a target to detect neutrinos, a very light particle

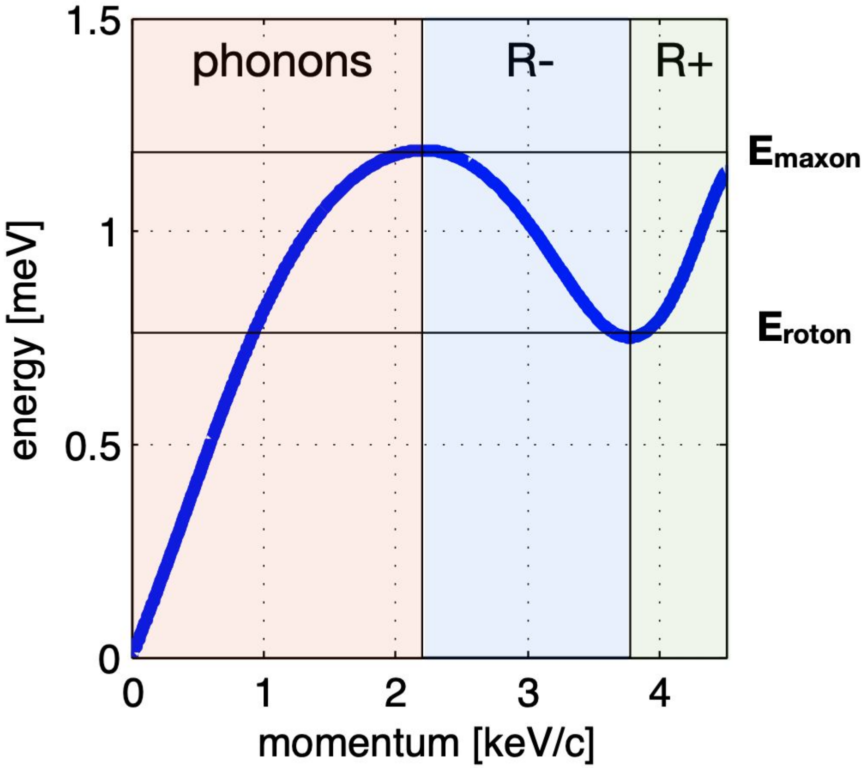
HeRALD uses the same principle: a light target (He atoms) to detect a light particle (light dark matter)



[5] J.S. Adams. The heron project. Low Energy Solar Neutrino Detection, 2001.

Quantum evaporation from phonons/rotons

Phonons and rotons are the excitations of superfluid He

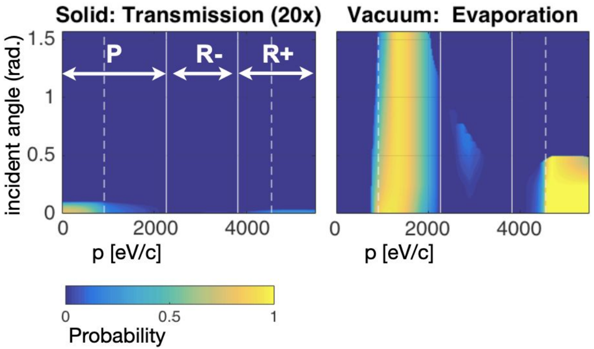


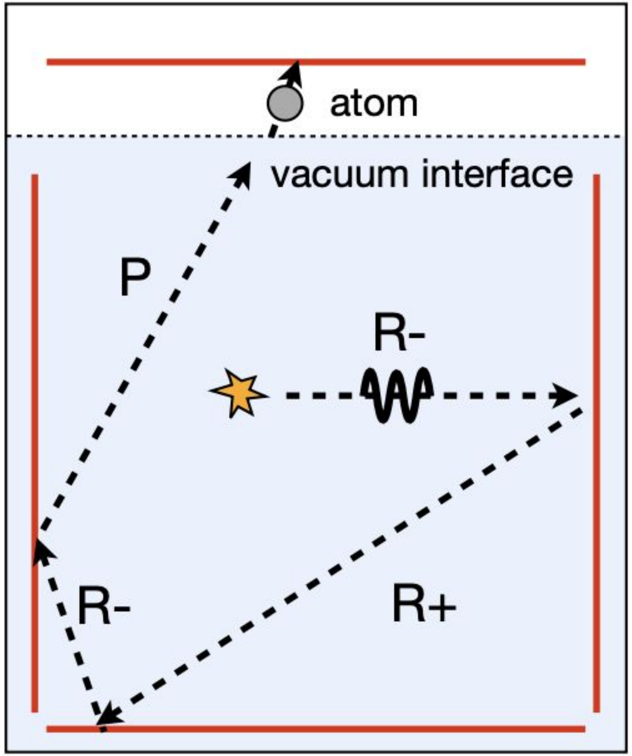
Quantum evaporation from phonons/rotons

Phonons and rotons are the excitations of superfluid He

Kapitza resistance causes reflection at solid interfaces

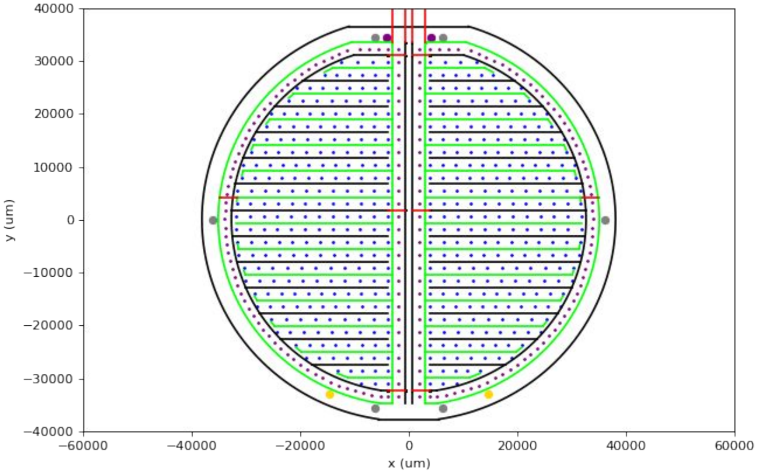
He atom quantum evaporation at superfluid surface within a certain incident angle





CPDv3 features

- 🟩 - channel 1
- ⬛ - channel 2; wafer edge
- 🟥 - electrical wire bonds
- 🔵 - QETs in horizontal rows
- 🟣 - QETs around CPD half edges
- 🟡 - gold thermalization bond pads
- ⚪ - hanging bond pads
- 🟣 - heater QETs


map of features

CPDv3 specs vs CPDv2

	CPDv2 (wal-e)	CPDv3 (split)
Al lead (on each QET) width	?? (something >4um)	6um
N_{QET}	673	678 (339 per half)
$R_{N,eff}$ (all TESs in parallel)	200mΩ	397mΩ (for each half)
Active surface coverage	0.68%	0.67%
Passive surface coverage	0.18%	0.17%

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CPDv3 features

678 QETs (339 per half) - same QET specs as CPDv2

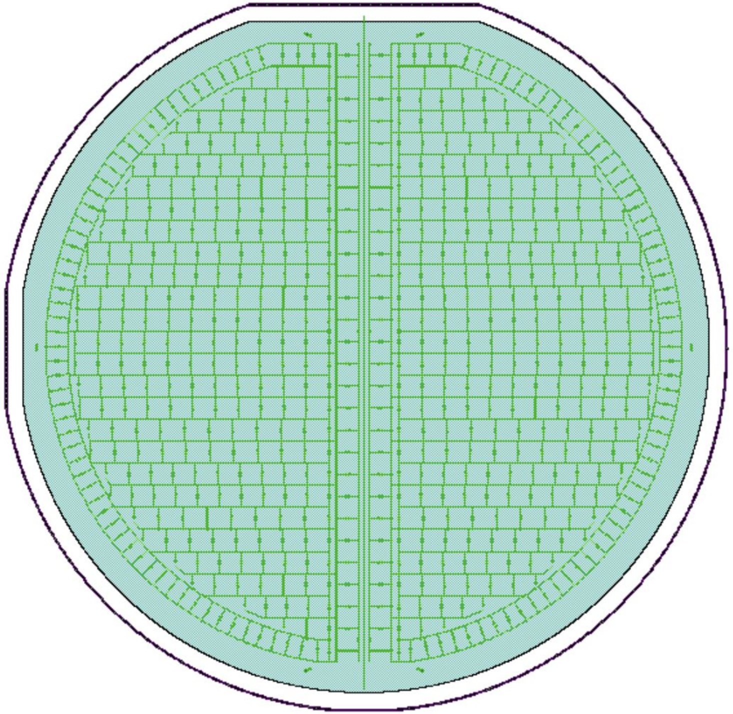
1 gold bond pad per half - for thermalization

1 “heater QET” per half - for heating and also as a second signal channel if necessary

3 hanging bond pads per half - if we wish to hang the CPD with 2 mil Al wire bonds

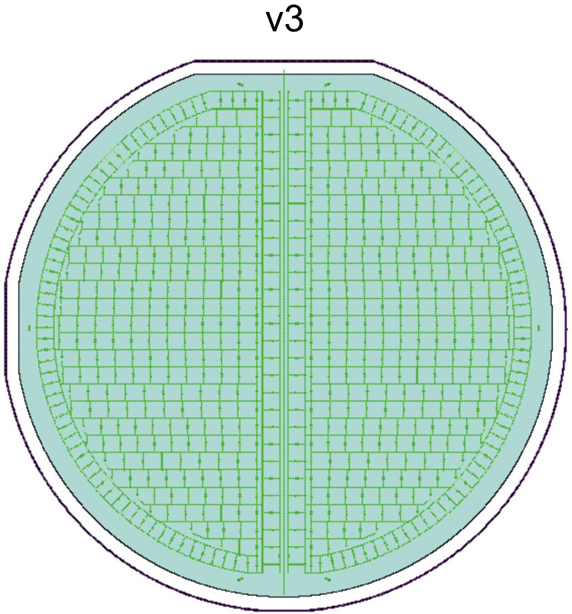
76.2mm diameter 1mm thick wafer with 22mm flat edge at top and 11mm flat edge at bottom

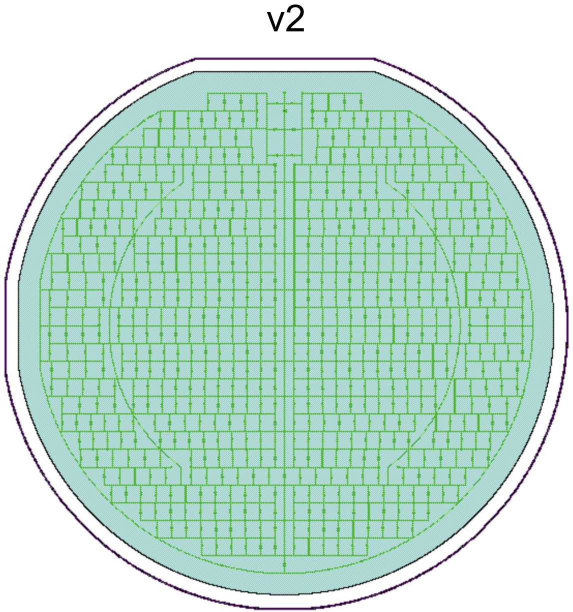
Note: Substrate in right image is turquoise. The black outline outside the substrate is a guiding feature on the Al and W masks to help with alignment. This guiding feature will appear in the respective colors of the individual mask design layers.



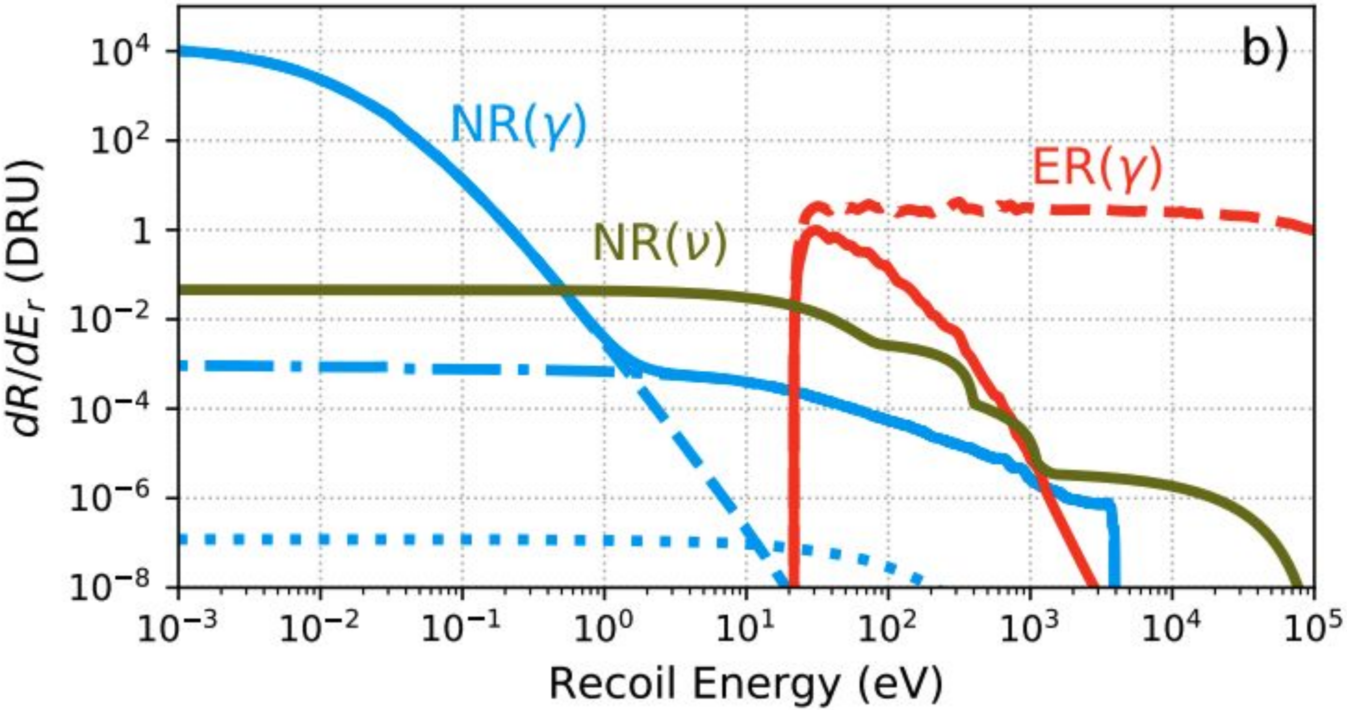
David Osterman dosterman@umass.edu

CPDv3 vs CPDv2





Background rates for exclusion curves



[12] Hertel, Scott A., et al. "Direct detection of sub-GeV dark matter using a superfluid He 4 target." *Physical Review D* 100.9 (2019): 092007.