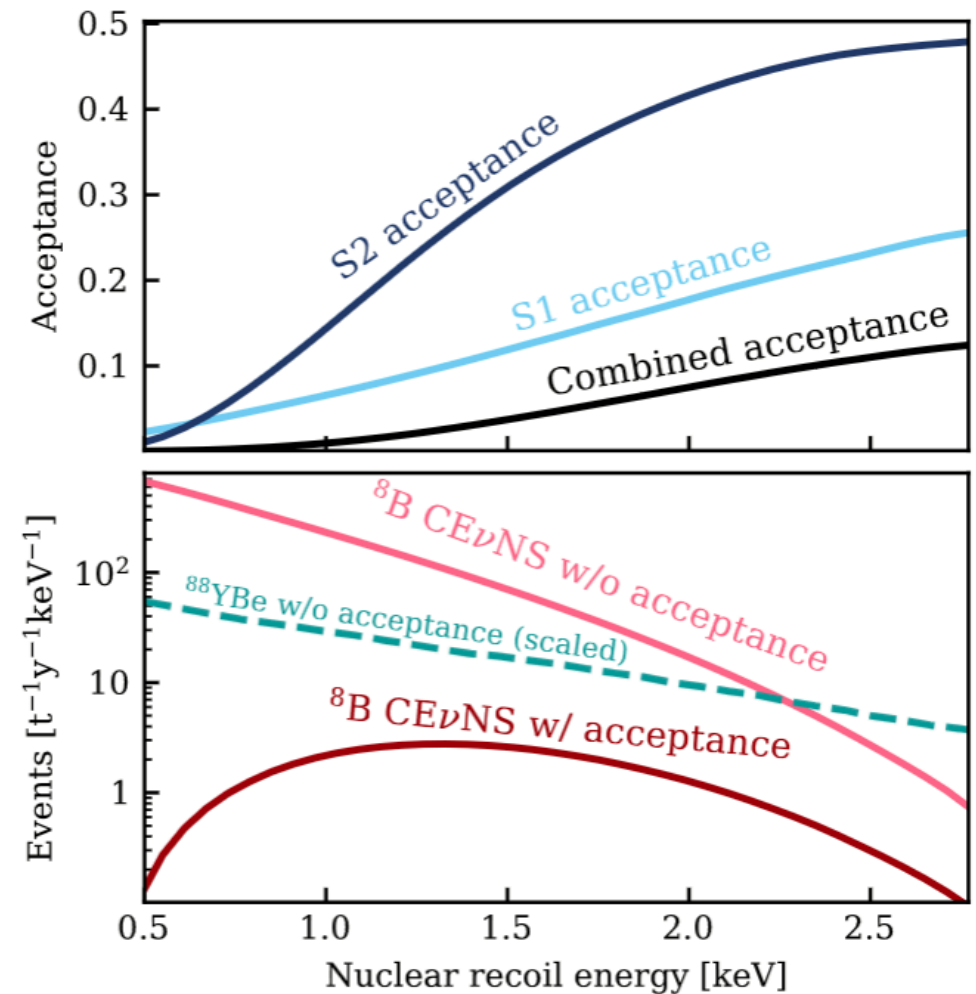


LOW-THRESHOLD SEARCHES

REACHING LOWER IN THRESHOLD

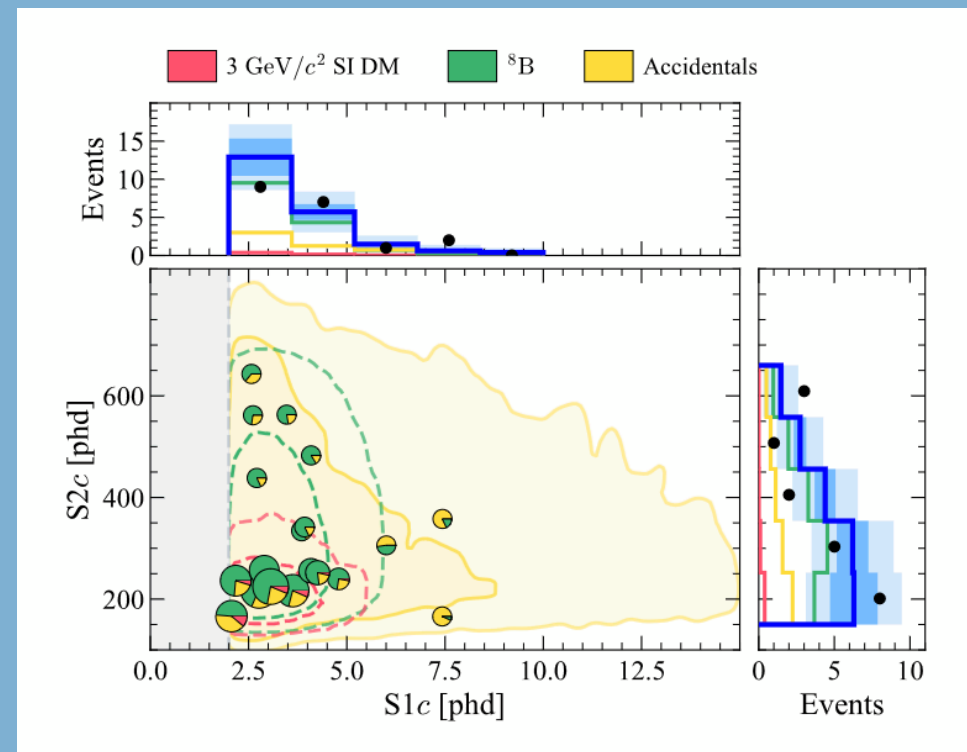
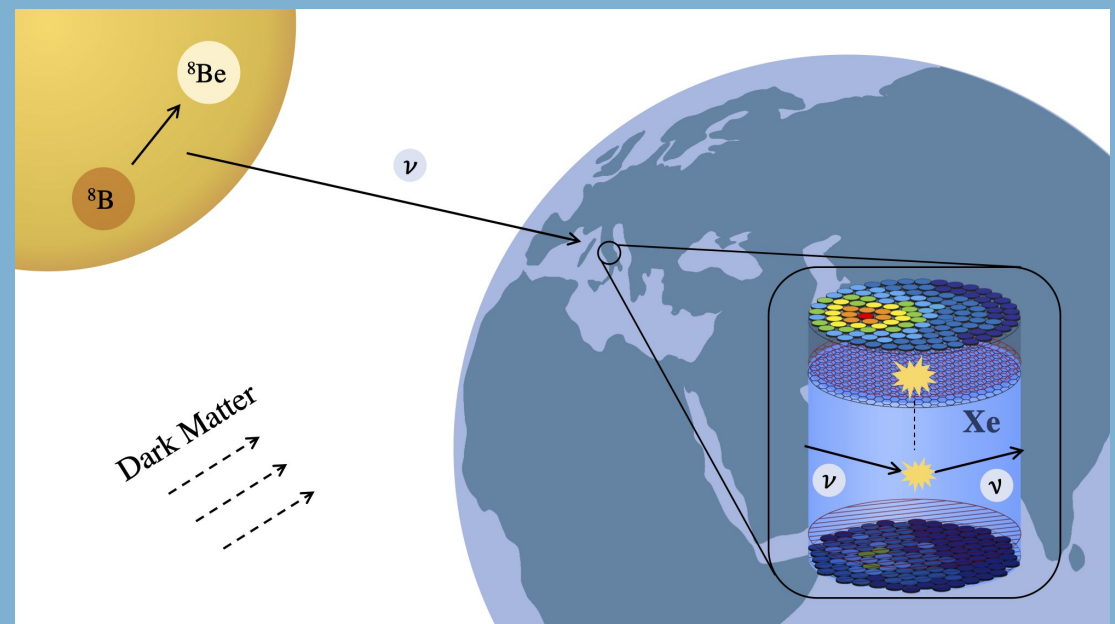
- liquid xenon TPCs are almost perfect— lowest background rate, enormous exposures
- One problem: to make a detectable recoil event you need around 3keV of energy
- The gains from being able to lower the threshold for xenon detectors can be massive, for example by
 - Searching for dark matter-electron scattering
 - Considering the Migdal Effect which predicts a small probability for a more visible event
 - Loosening cuts, even to the point of searching for only S2s



First Indication of Solar 8B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT
<https://arxiv.org/pdf/2408.02877>

DETECTING ^8B SOLAR NEUTRINOS

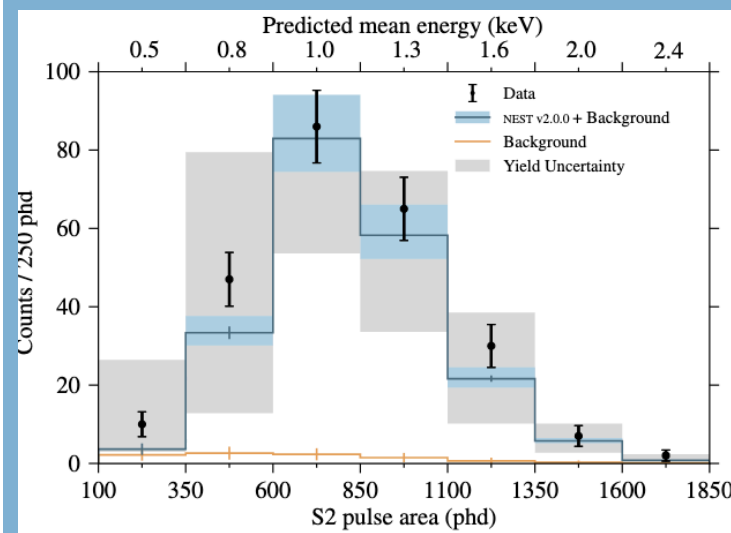
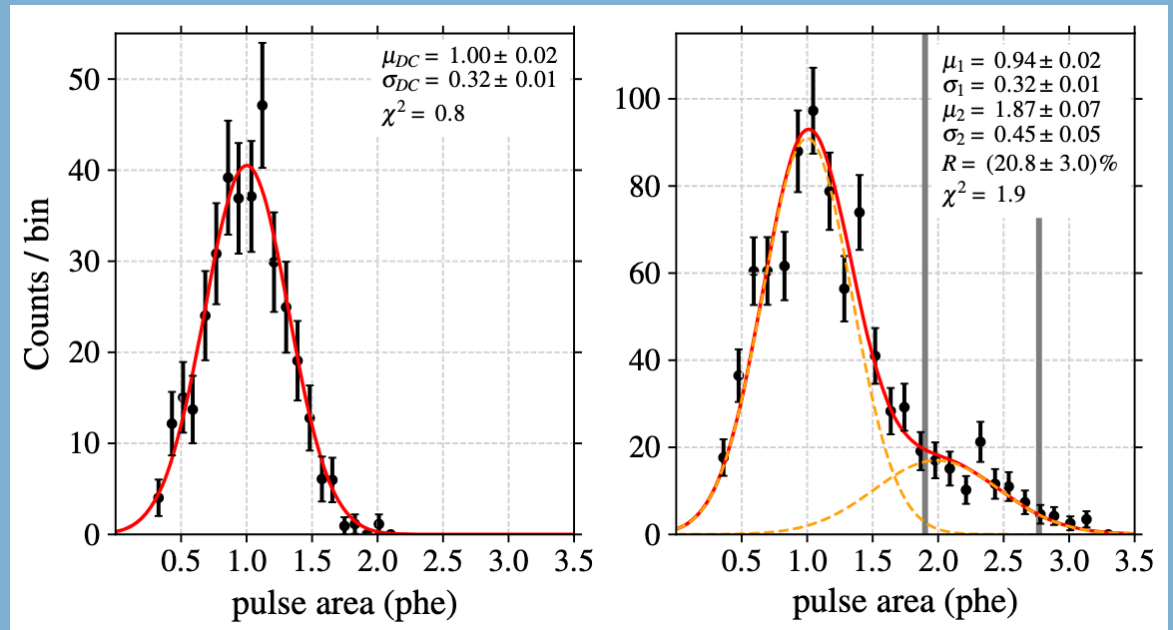
- LZ, PandaX and XENONnT have demonstrated analyses reaching lower in energy by using dedicated analyses
- To see the $\sim 2\text{keV}$ events, cuts must be relaxed
- XENONnT and PandaX used two-hit requirement for PMTs (PandaX also S2only)
- LZ loosened other cuts
 - And had more exposure :)
- These results are statistics-dominated, giving little precision
- But demonstrate and anchor the lower-energy performance of the detectors



DOUBLE PHOTOELECTRON EMISSION

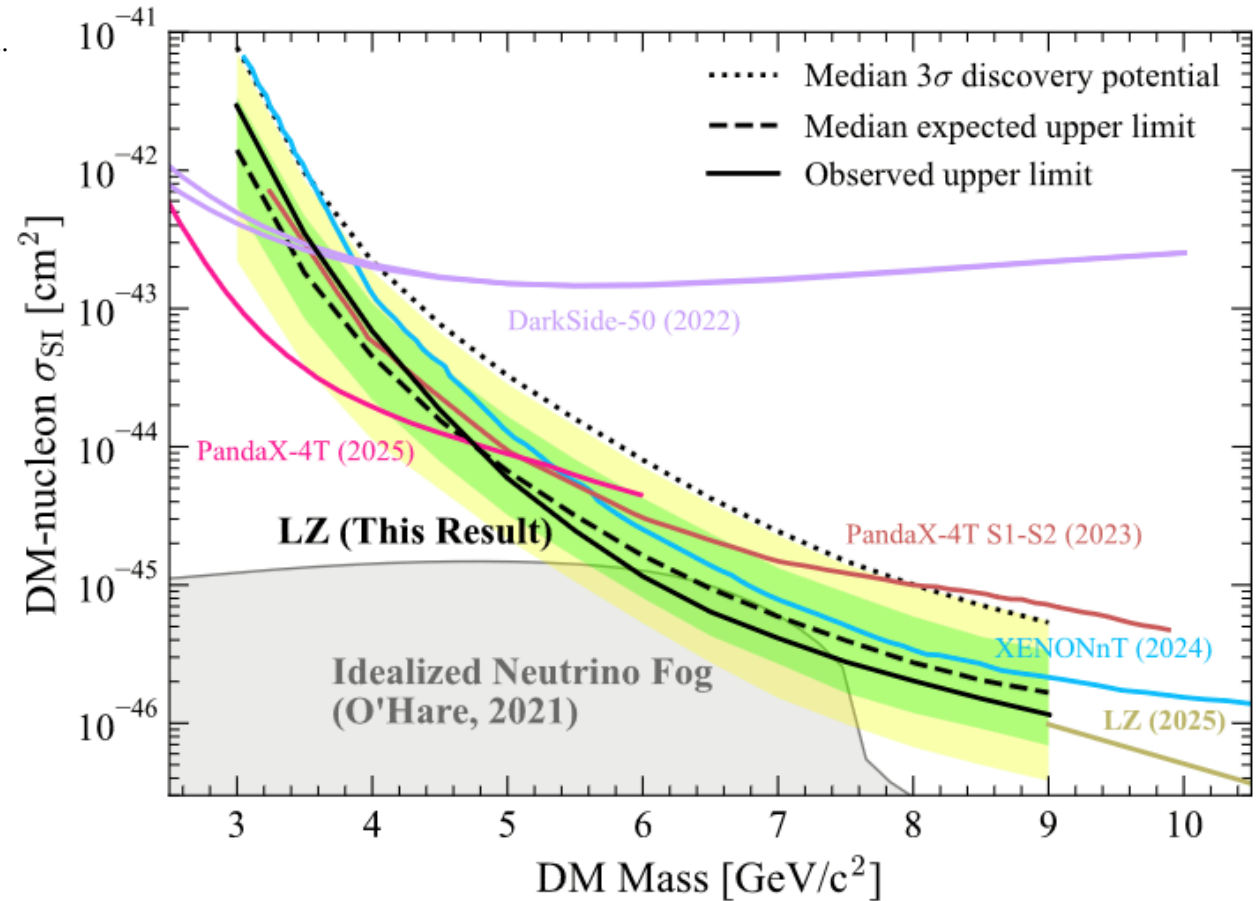
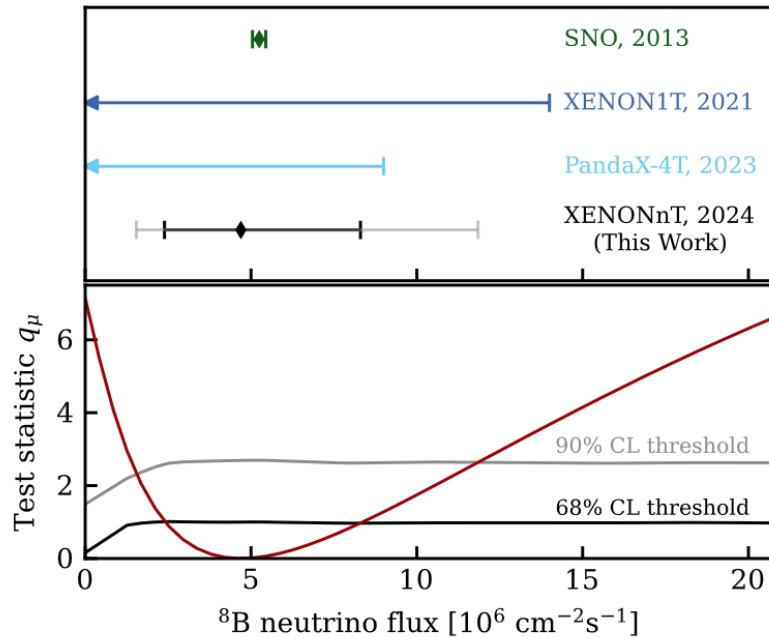
- A trick to preferentially select real S1 signals is that while PMT noise is approximately a Gaussian, a real VUV photon has a chance to emit two photoelectrons, giving a twice as large signal
- Lux analysis for low-energy events used this double photoelectron emission: a genuine scintillation photon has a probability of $\sim 17\%$ to liberate two photoelectrons hitting a PMT

D. S. Akerib et al. (LUX Collaboration). "Extending light WIMP searches to single scintillation photons in LUX". In: Phys. Rev. D 101.4 (2020), p. 042001. doi: 10.1103/PhysRevD.101.042001.



RESULTS

XENON result— bit less than 3 sigma made some people discuss wording..



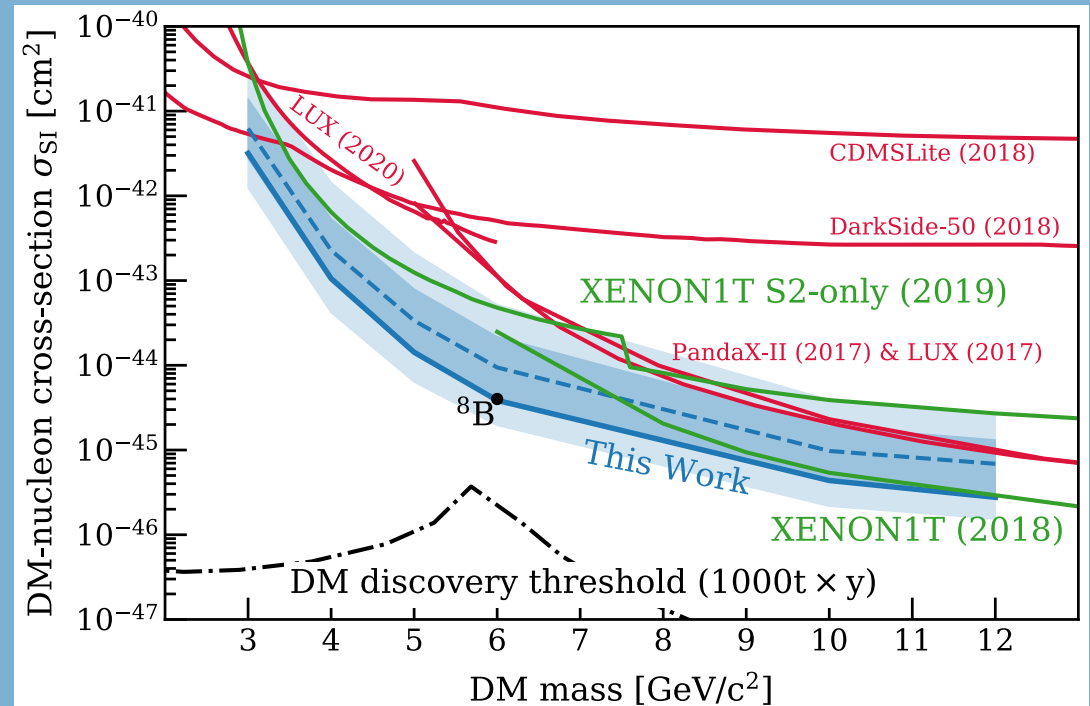
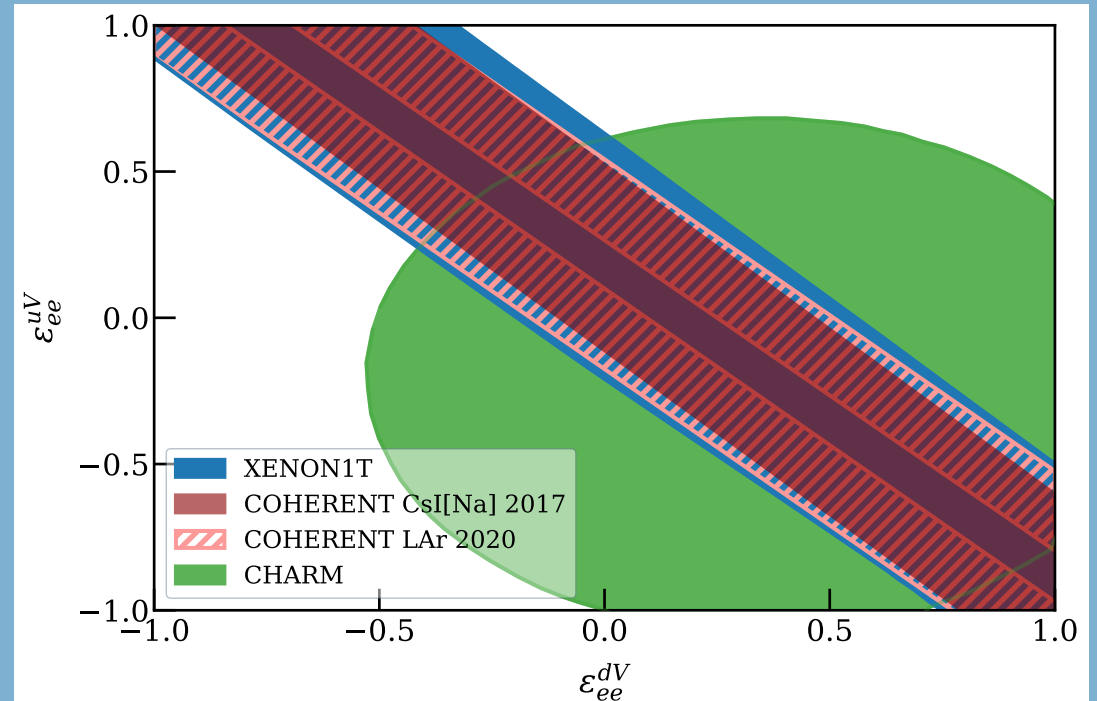
First Indication of Solar ^8B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT
<https://arxiv.org/pdf/2408.02877>

Searches for Light Dark Matter and Evidence of Coherent Elastic Neutrino-Nucleus Scattering of Solar Neutrinos with the LUX-ZEPLIN (LZ) Experiment
<https://arxiv.org/pdf/2512.08065v1>

NEW PHYSICS FROM ^8B

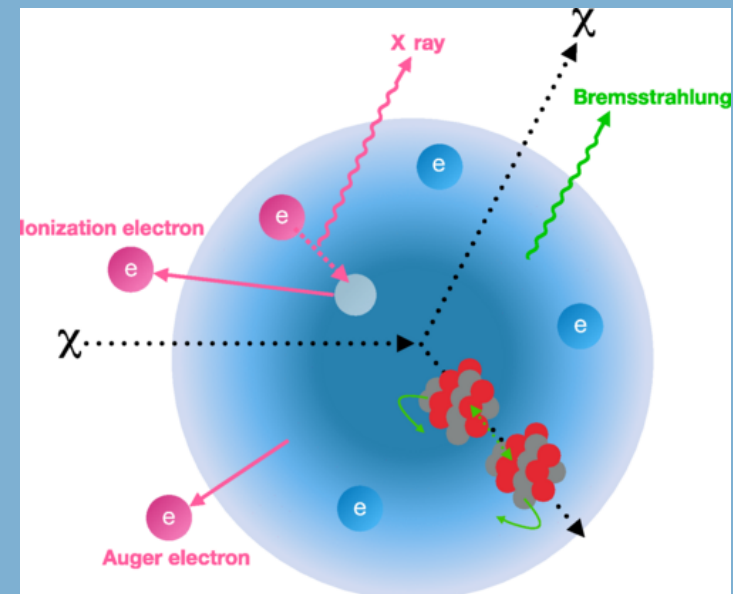
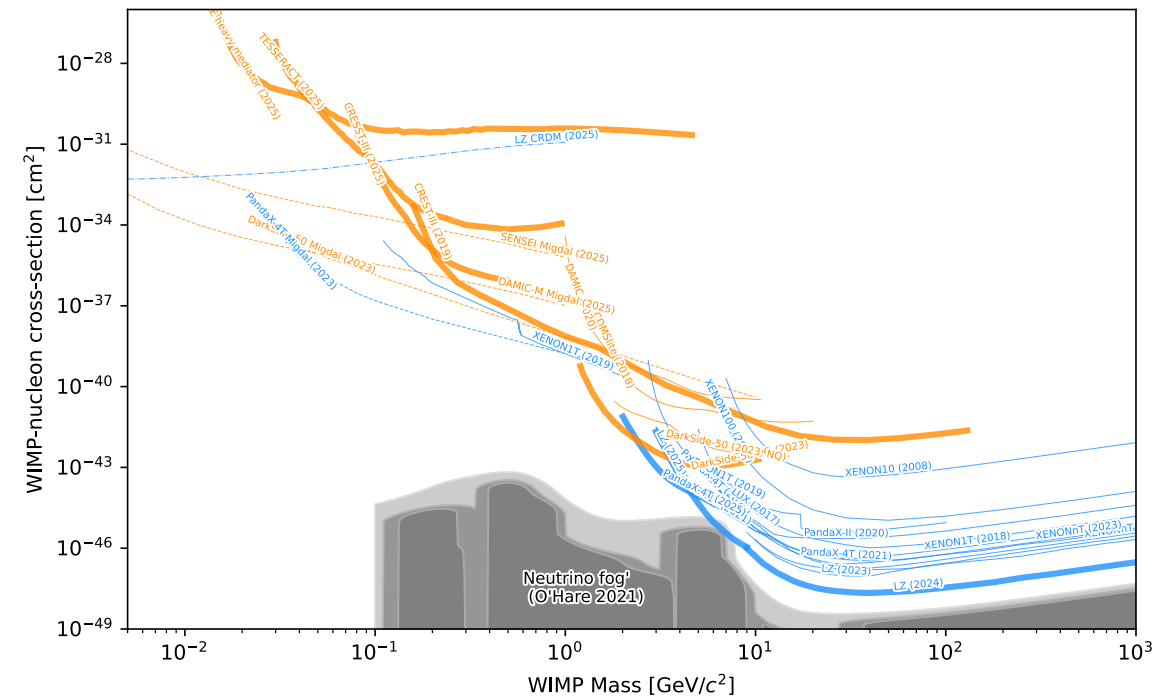
- The neutrino flux upper limit can be converted into constraints on possible vector neutrino-quark interactions
- By including all the external constraints on the signal rate are included; neutrino flux, charge and light yield, we may also constrain a WIMP signal between 6 and 12 GeV/c^2
- For the WIMP search, we use the interpolated light yield model rather than the constant, to better represent the best-fit and to accommodate the changing WIMP spectra
- The AC-background-only result, combined with an expectation of observing 2 neutrino events results in the upper limit being a downwards fluctuation with respect to the sensitivity

Search for Coherent Elastic Scattering of Solar ^8B Neutrinos in the XENON1T Dark Matter Experiment
<https://arxiv.org/abs/2012.02846>



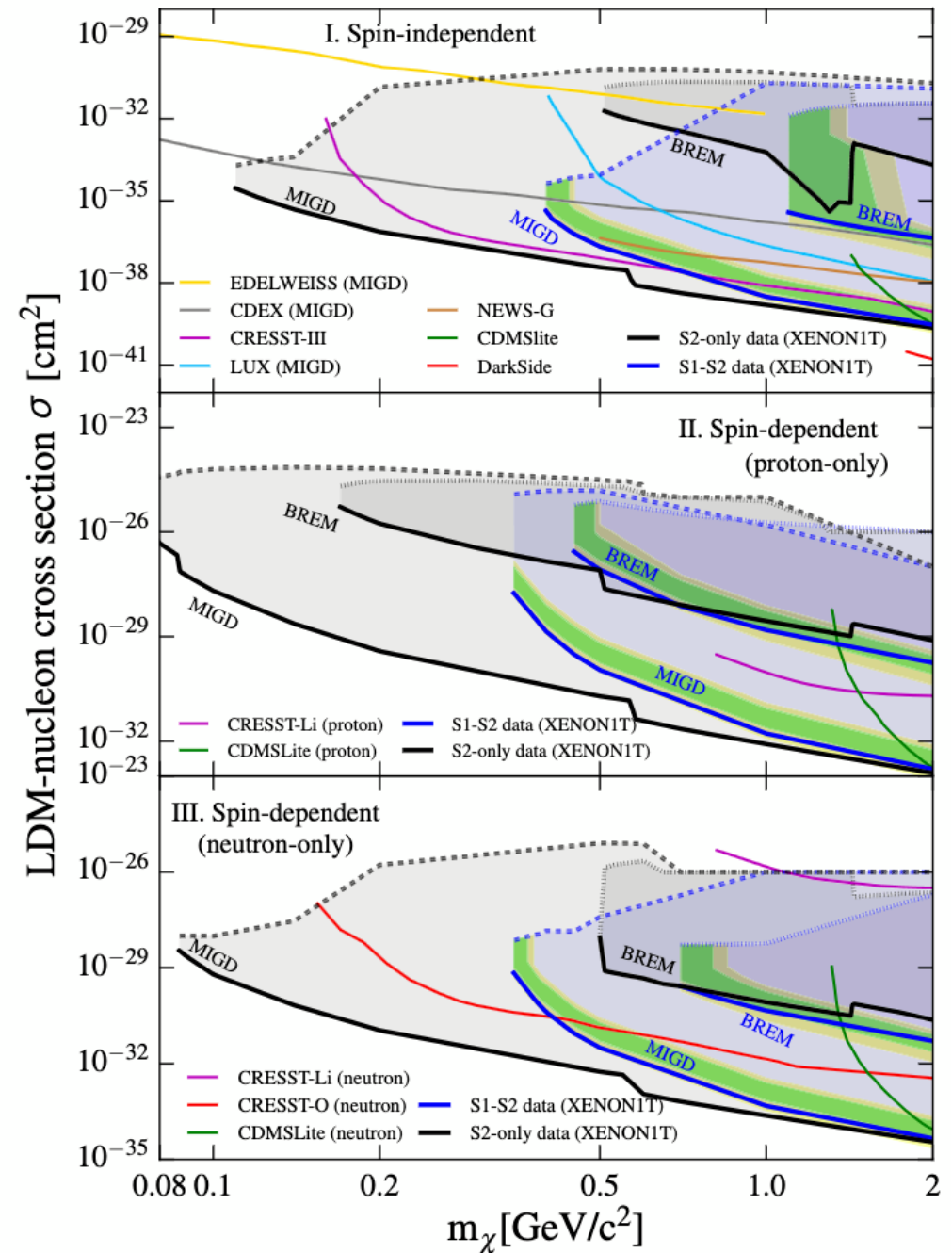
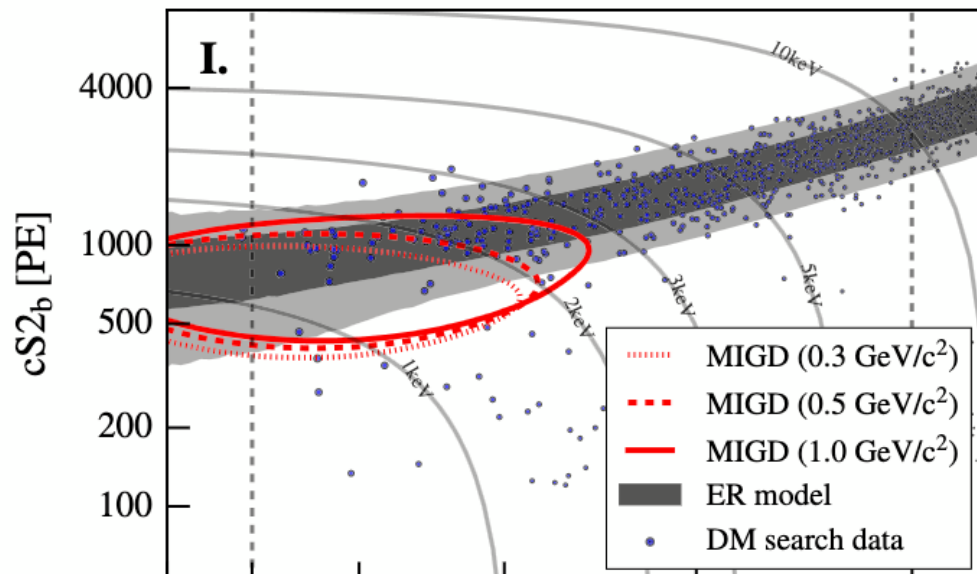
MIGDAL

- The threshold of IXe detectors is determined by the S1 coincidence requirement, but what about all the energy lost to heat?
- If dark matter-matter scattering lost less energy to heat, we could lower the threshold significantly
- The Migdal effect promises such an effect, predicting that in a nuclear recoil, the nucleus recoiling gets a momentum with respect to its electron cloud
- The polarized nucleus-electron cloud system is predicted to lead to bremsstrahlung and ionization — some (mainly outer shell) electrons are simply left behind



MIGDAL SEARCHES

- Even if the Migdal effect is predicted to be extremely rare— $p = 8 \times 10^{-6}$ for a $1\text{GeV}/c^2$ WIMP recoil, its effect is drastic for LXe detectors
- since it transforms a completely invisible recoil energy into a sometimes-visible one
 - $\epsilon \times$ instead of $0 \times$
- The Migdal effect primarily yields ionization electrons
- A signal with the Migdal effect lies almost in the ER band, and looks like a mixed NR+ER event



MIGDAL EVIDENCE

- This January, the MARVEL detector published evidence for the Migdal effect
- Using a gaseous time projection chamber, events are spread-out enough that the topology of a separate nuclear recoil and emitted electron can be resolved
- NRs leave a dense track, while the electron track has a lower density.
- Image classifier used to select NR- and ER-like tracks based on density and shape

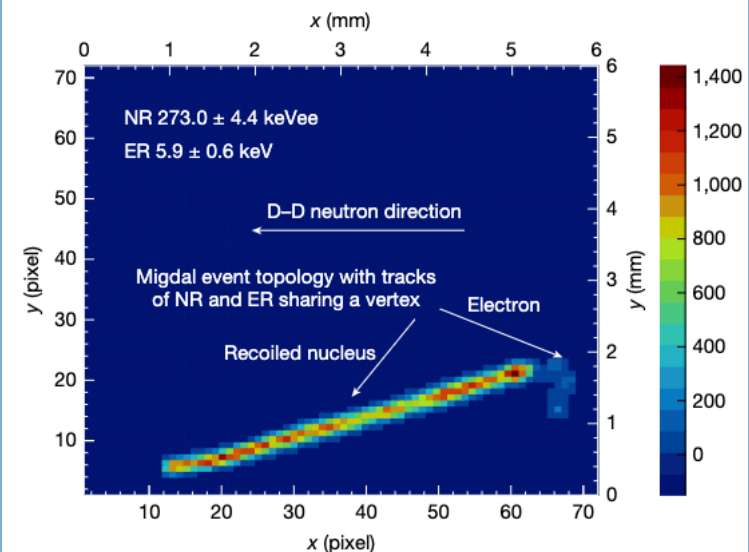
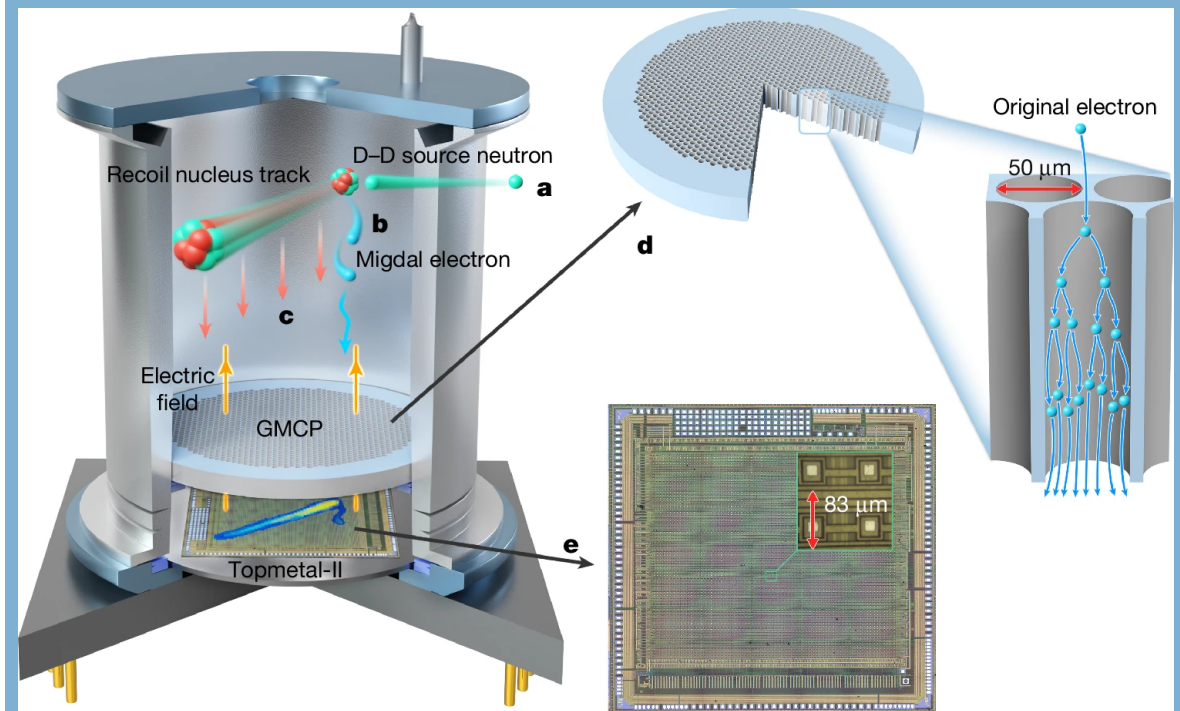
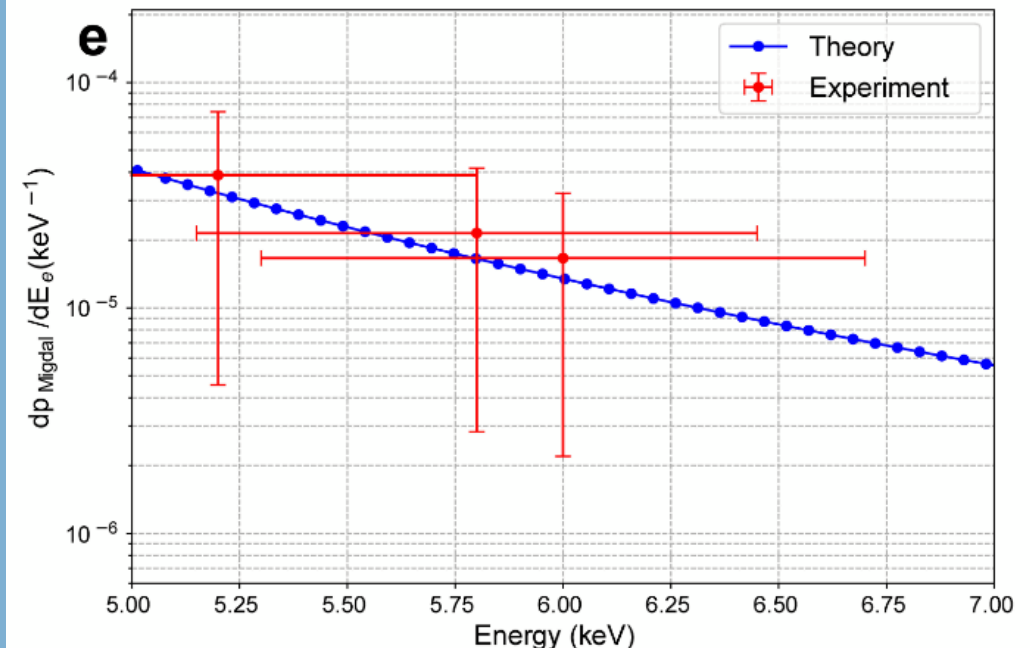
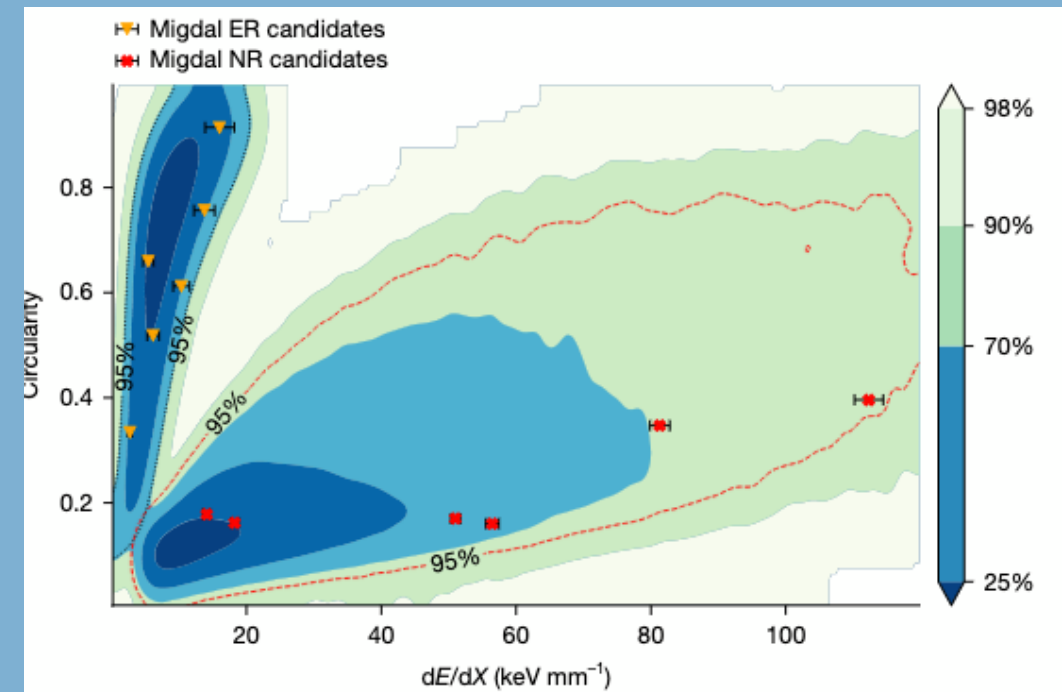


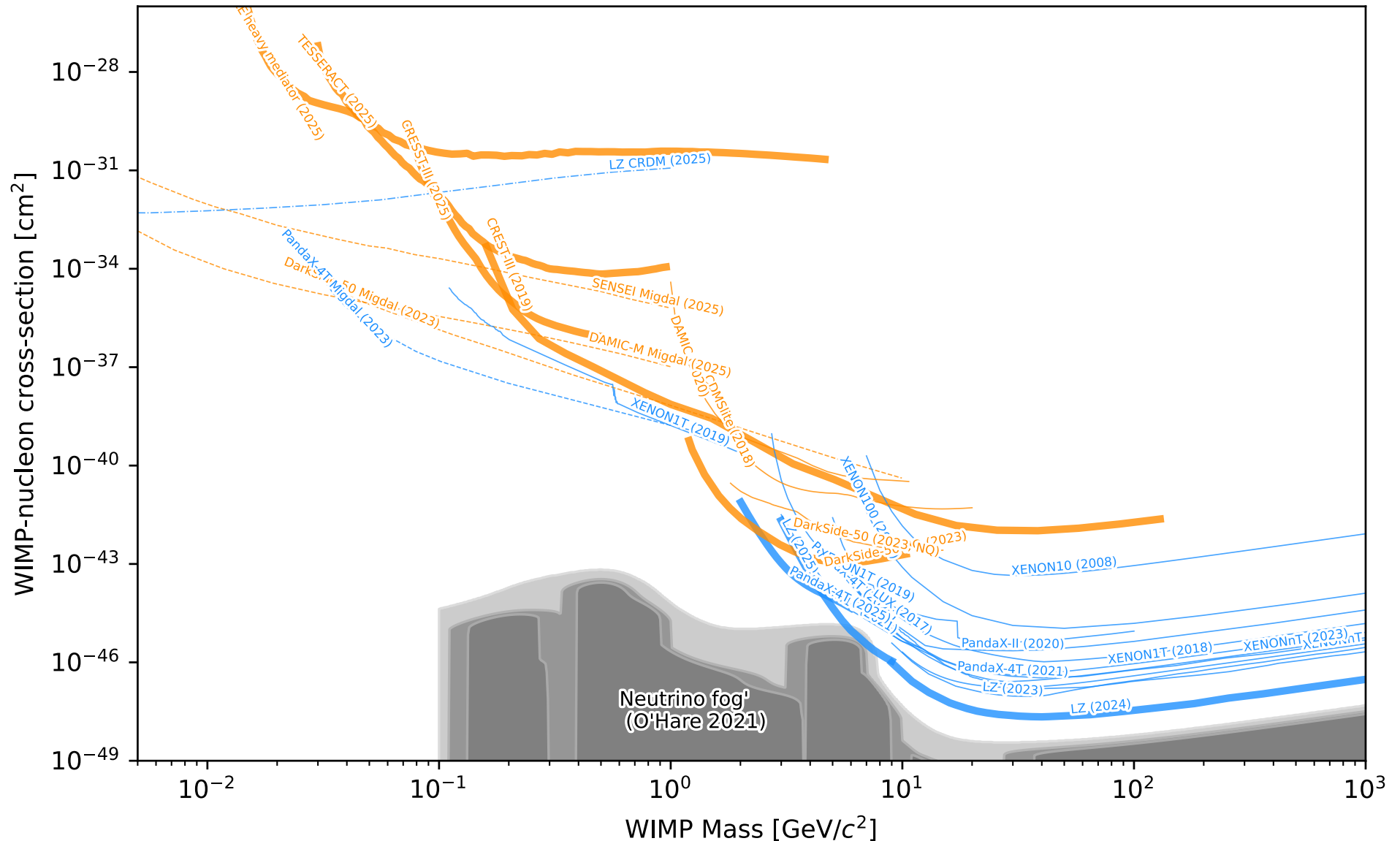
Fig. 2 | A Migdal event recorded in the experiment. The bright, long and straight track in the figure represents the NR track, whereas the faint track circled near the vertex of the recoil nucleus track represents the ER track. The horizontal arrow indicates the direction of the neutron beam.

MIGDAL EVIDENCE

- Calibrating Migdal in situ in lXe detectors would be extremely challenging— rare, and difficult to disentangle from ER backgrounds that are always present.
- Within large uncertainties, the MARVEL result agrees with the Migdal prediction
- However, this was a Helium + dimethyl ether target— can we extend this to xenon?
- Further, liquid recombination physics may be different
- So far, Migdal limits are still considered “separate”

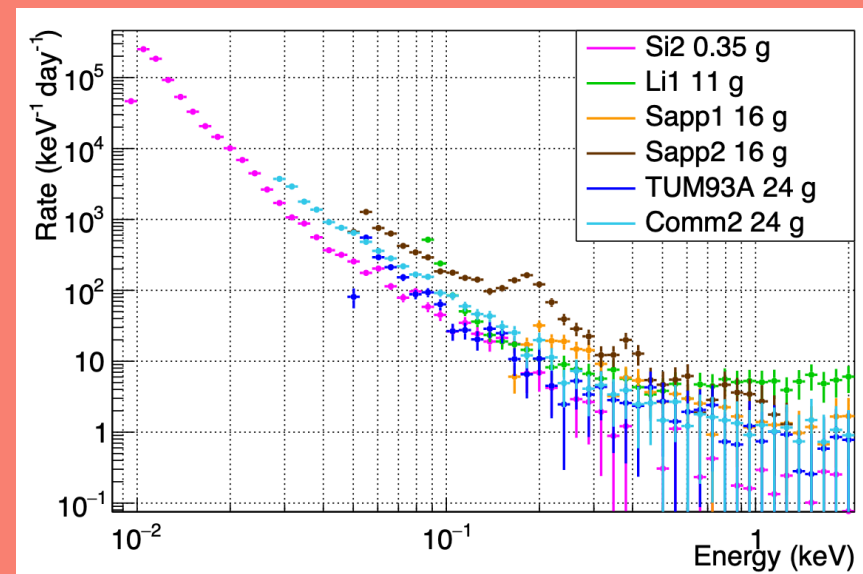
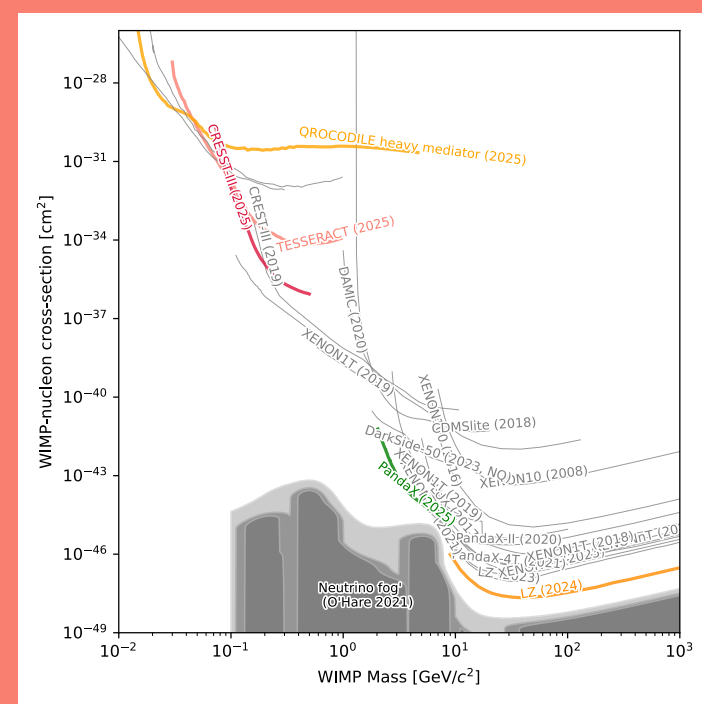


IF THE MIGDAL EFFECT IS REAL, ALL THE DASHED LINES AT LOW ENERGY WILL OVERTAKE DEDICATED EXPERIMENTS



LOW-MASS DARK MATTER

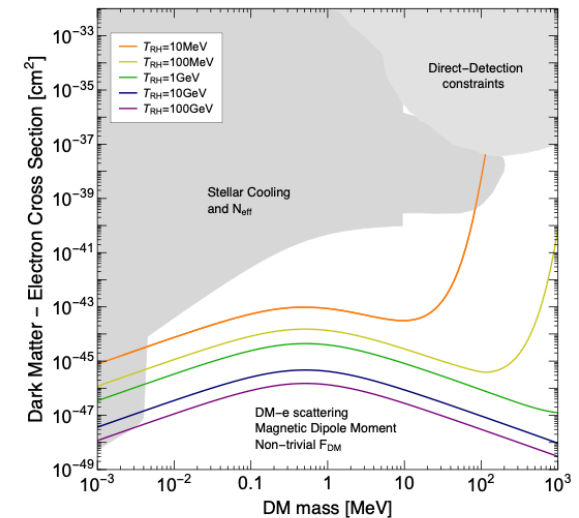
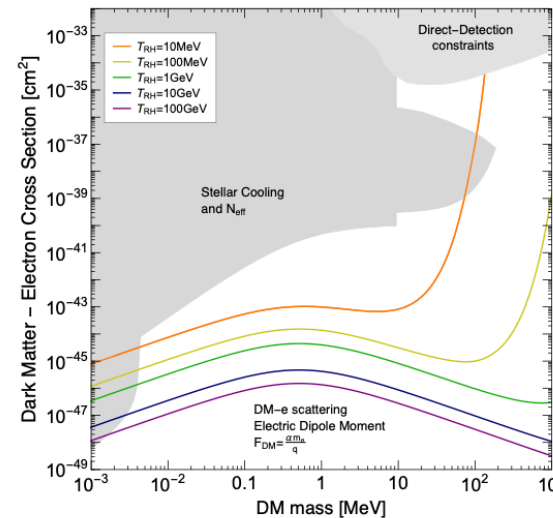
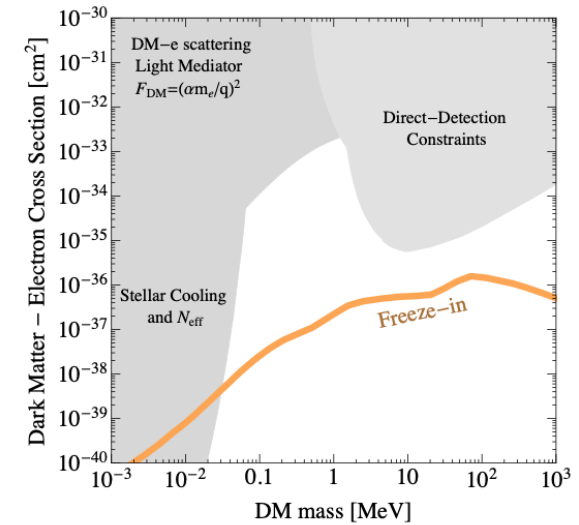
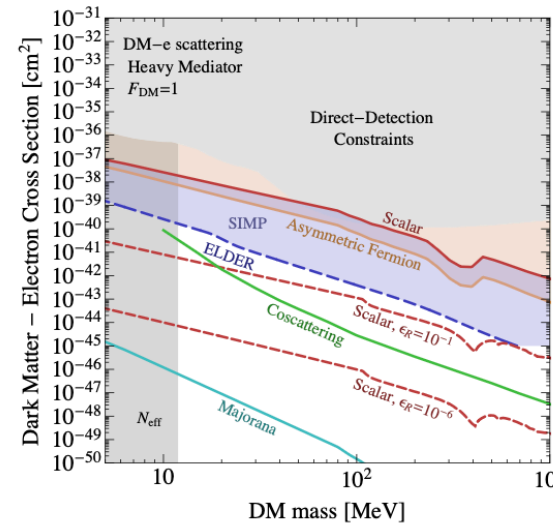
- Below $\sim 10 \text{ GeV}/c^2$, detecting DM is a fight against thresholds, with recoil energies in the eV scale and below
- As an upside, current constraints are ten orders of magnitude higher than they are in liquid xenon-land
- If you scaled your target mass by number of DM particles, one tonne-year 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/>

MANY VIABLE ALTERNATIVES TO WIMPS

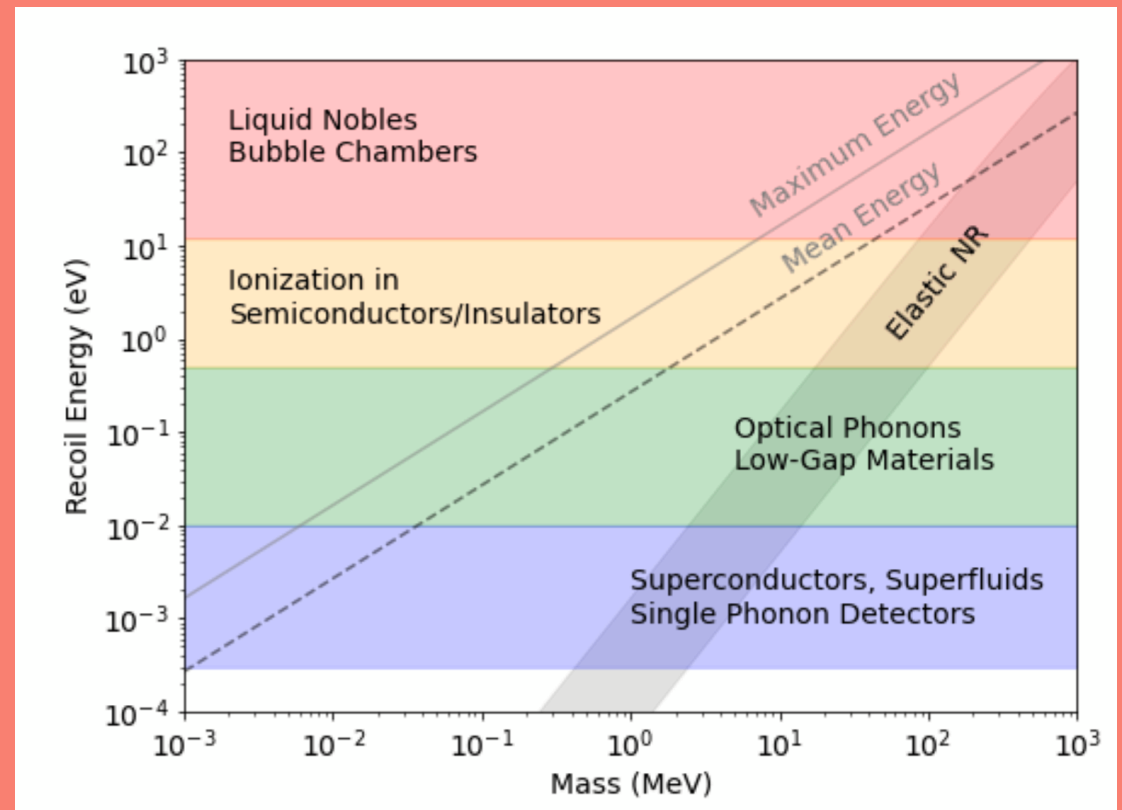
- For lower-mass dark matter, scattering with electrons also becomes relevant, and there is significant parameter space available to constrain in addition to the dark matter-nucleon one
- Note the astrophysical bounds at very low masses
- Mediator mass matters—unlike the weak interaction the transferred momentum might be comparable to the mediator mass
- Colored lines show models that give the right dark matter abundance



Snowmass2021 Cosmic Frontier:
The landscape of low-threshold dark matter direct detection in the next decade
2203.08297v2

HOW TO REACH LOW THRESHOLDS

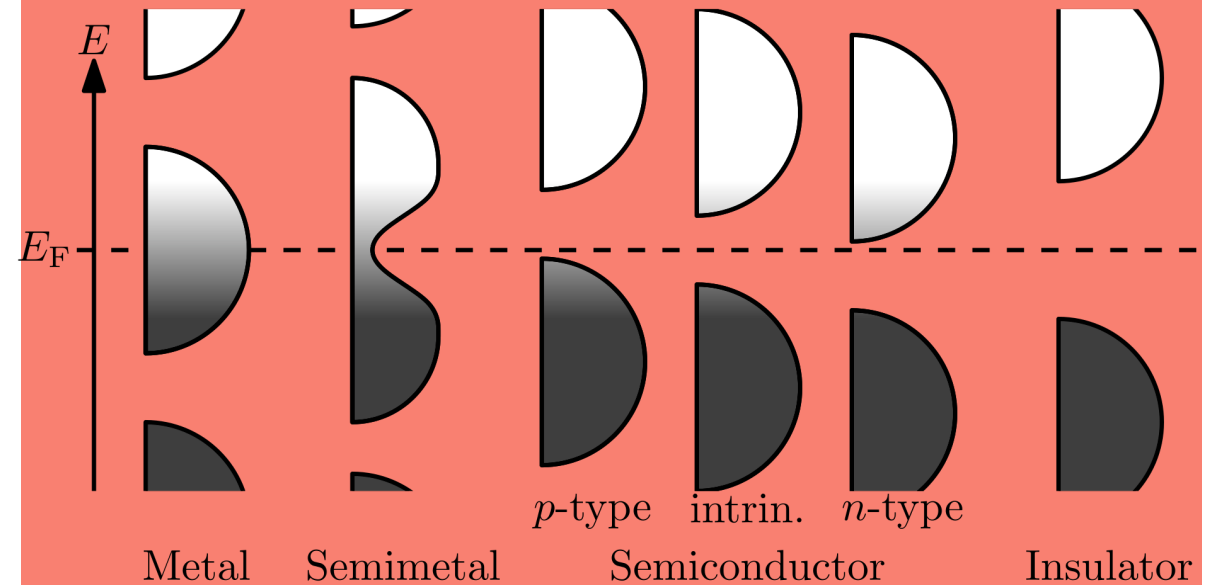
- To be sensitive to dark matter with masses below $\sim 1\text{GeV}/c^2$ requires detectors with thresholds around the eV scale or even below.
- What can our observable quanta be?
 - An eV is just on the infrared side of visible light, and around the ionization energy of many elements. (Low band-gap materials may reach lower)
 - Below ionization energies, atomic vibration—phonons or similar excited states are the relevant carriers.
- Cooling becomes a must below eV scales— otherwise you'll just see an enormous amount of IR energy



Snowmass2021 Cosmic Frontier:
The landscape of low-threshold dark matter direct detection in the next decade
2203.08297v2
Spectru, by
Vojtěch Hála and Gringer - Based on File:Inverse visible spectrum.svg, from wikimedia

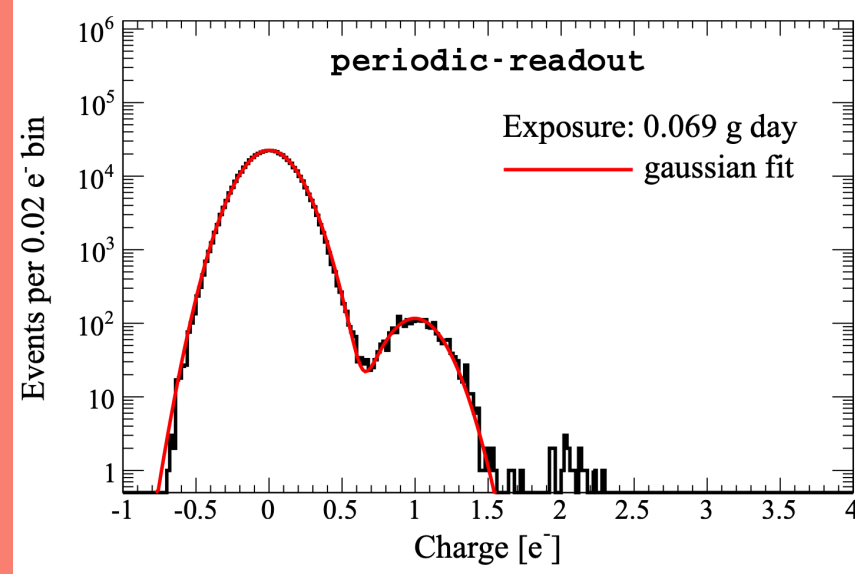
NON-CRYOGENIC DIRECT DETECTION

- Down to $\sim 1\text{eV}$ recoil energies, reading out ionisation-only can be done with solid-state charge detectors
- CCDs
- Semiconductor crystals
- These detectors have reached single-electron sensitivity: they could detect a dark matter event that only deposited enough energy to liberate one electron into the conduction band

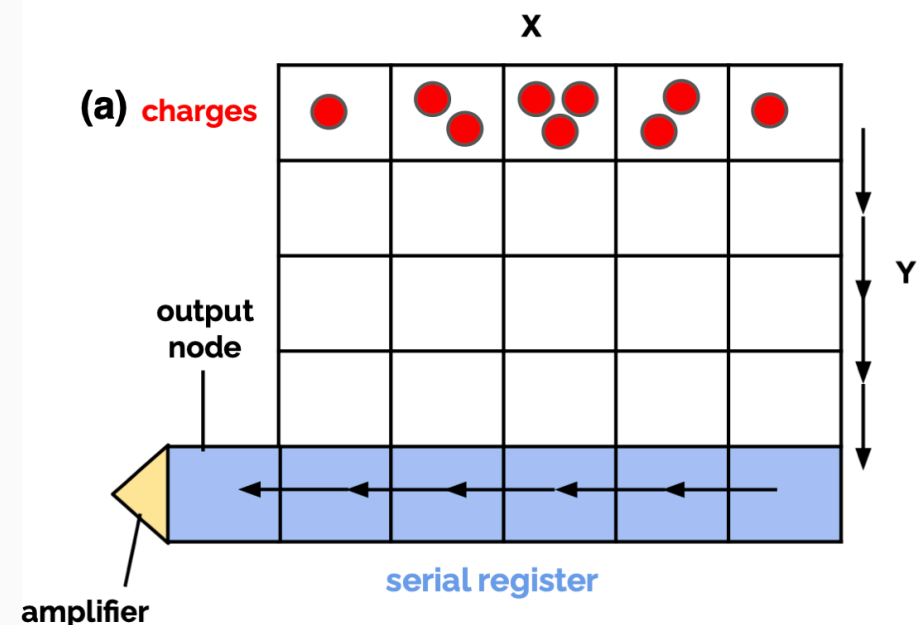


IONIZATION: CCDS

- DAMIC-M and SENSEI, using CCD sensors, have achieved energy thresholds of $\sim 50\text{eV}$
- Requires very low cosmogenic activation and Rn contamination— limit time aboveground
- Very low dark current achieved: $\sim 10^{-4}e^-/\text{pixel}/\text{day}$
- “Skipper” amplifiers read out the charge in a single pixel repeatedly, which gives single-electron resolution
- Scientific targets: DM-nucleon to $\sim 1\text{Gev}/c^2$ as well as DM- e^- scattering and full absorption (e.g. dark photon)



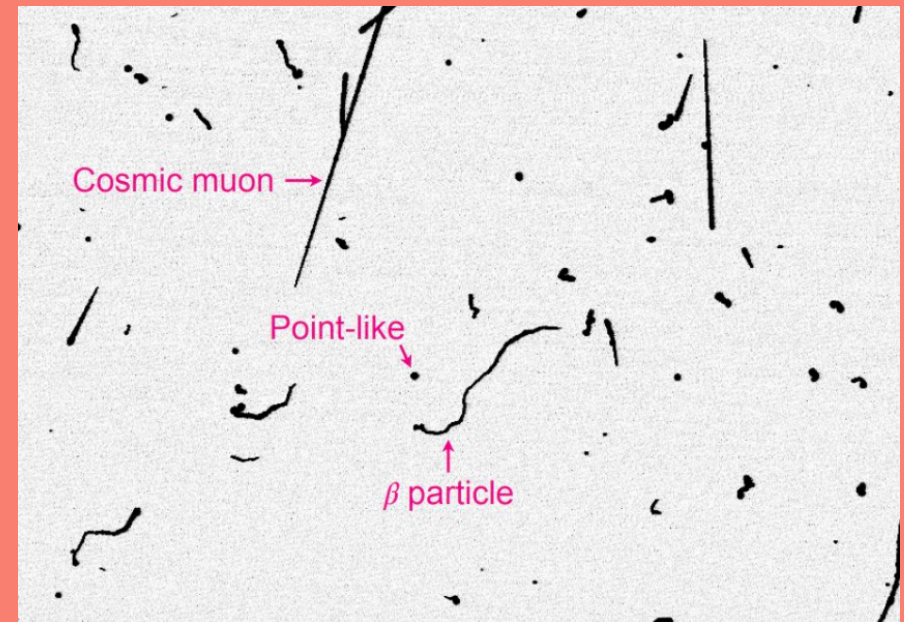
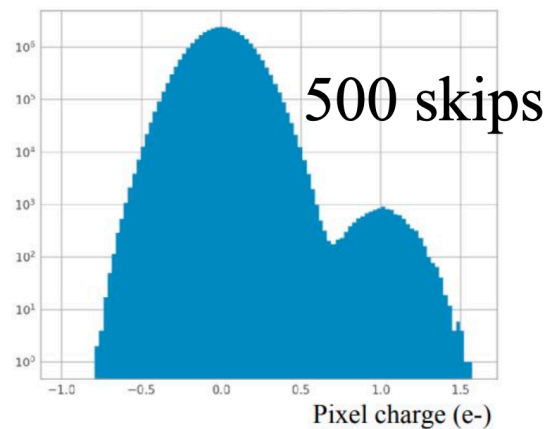
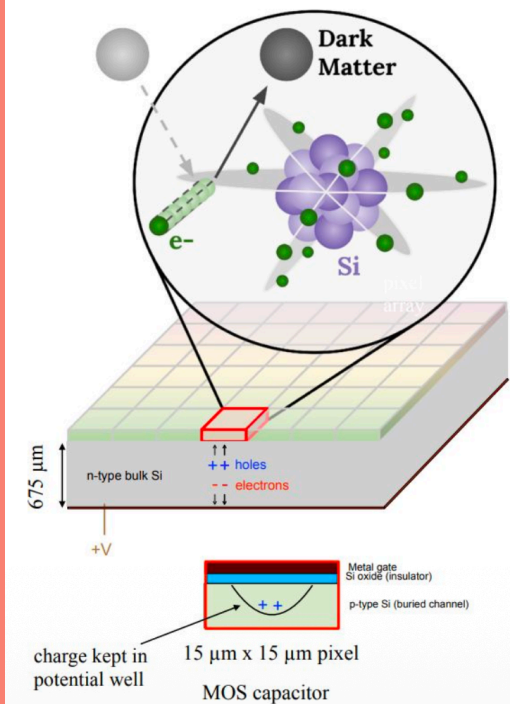
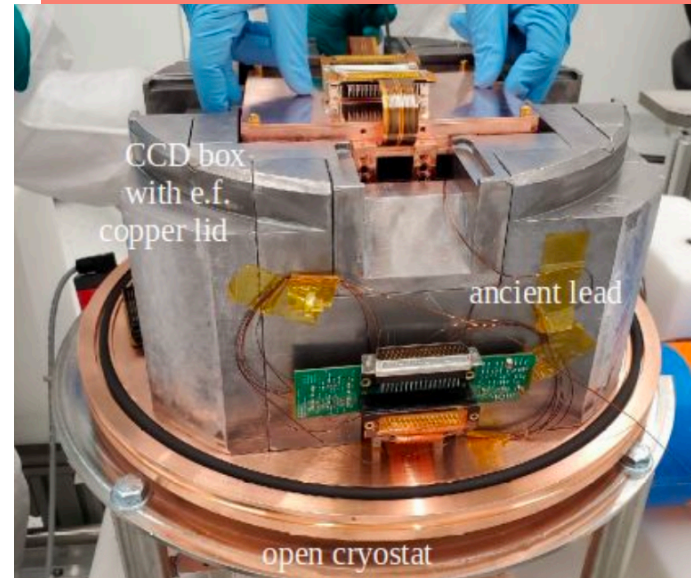
Orr Abramoff et al. SENSEI: Direct-Detection Constraints on Sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper-CCD. Phys. Rev. Lett., 122(16):161801, 2019. doi: 10.1103/PhysRevLett.122.161801.



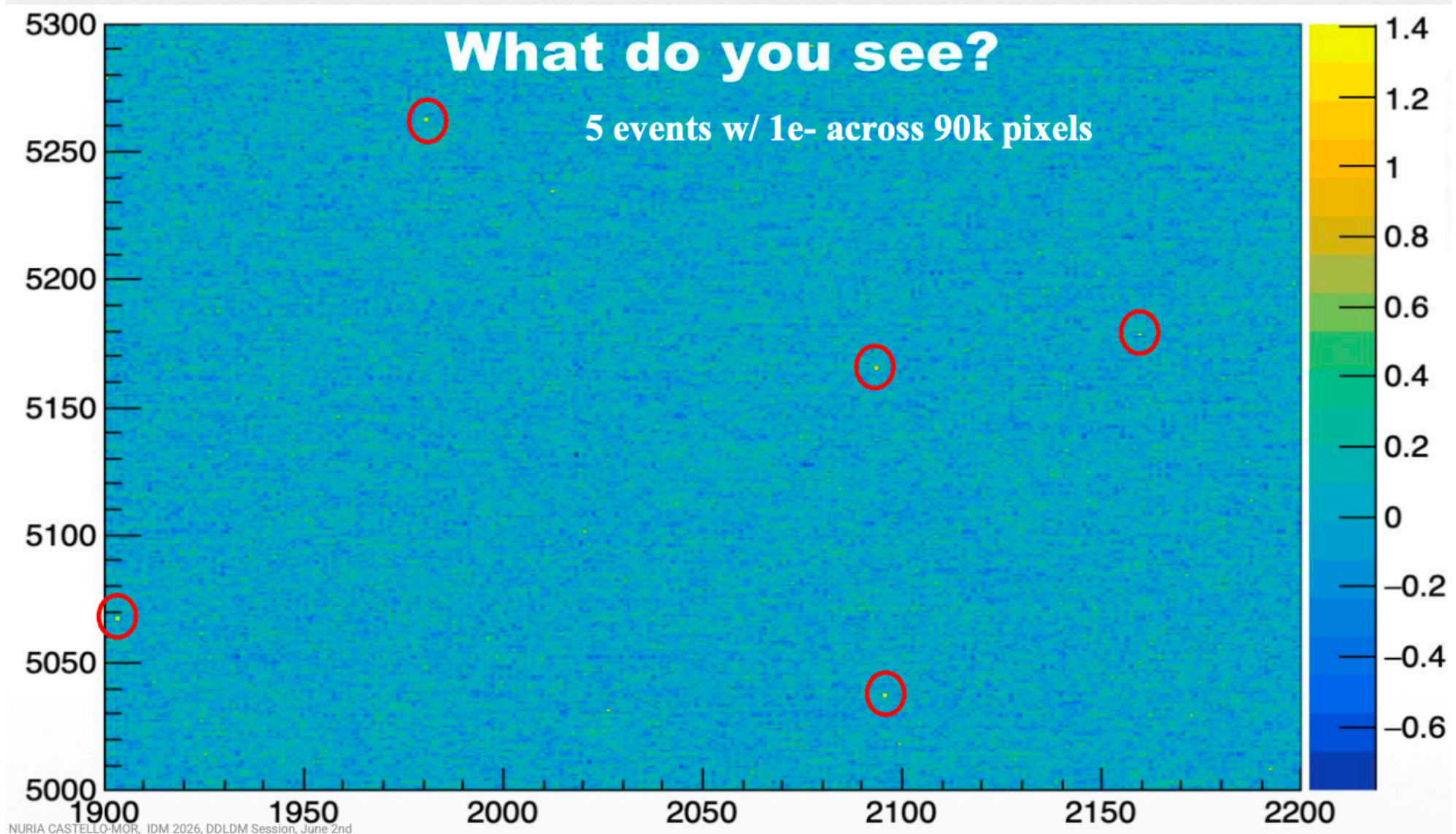
I. Arnquist et al. The DAMIC-M Experiment: Status and First Results. In 14th International Workshop on the Identification of Dark Matter 2022, 10 2022.

DAMIC-M

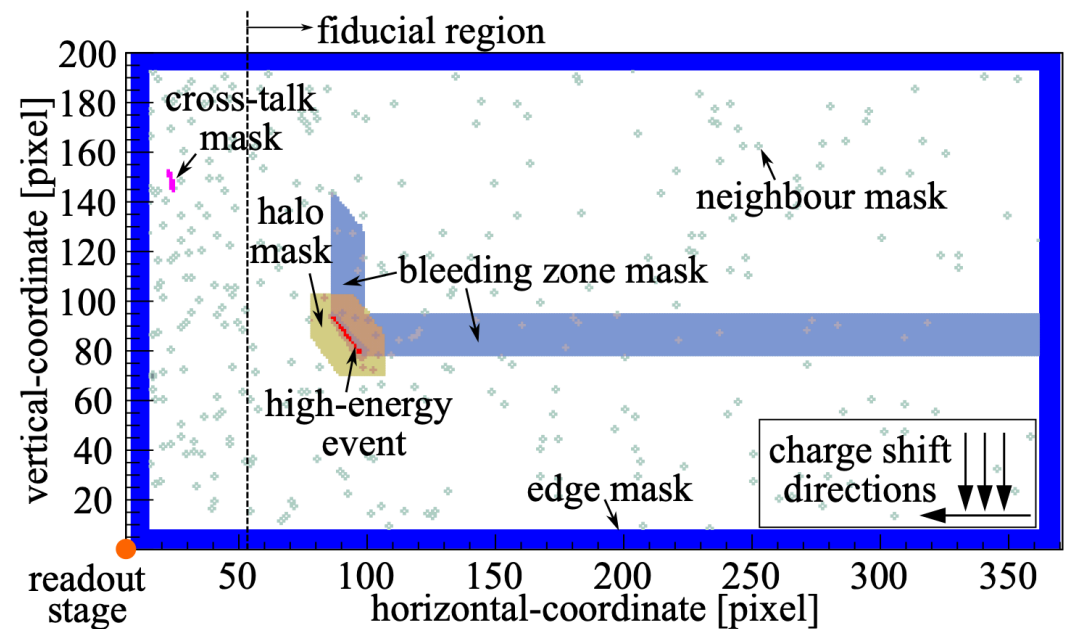
- DAMIC has operated a skipper CCD in the Modane underground lab
- Large exposure— 1.3 kilogram-days
- A year of running 26.4 g sensors
- 28 min/image
- 0.16 electron resolution
- noise: $1.3 \times 10^{-4} e^-/\text{pixel} - \text{day}$



Science Results from the DAMIC-M Low Background Chamber, Núria Castelló-Mor



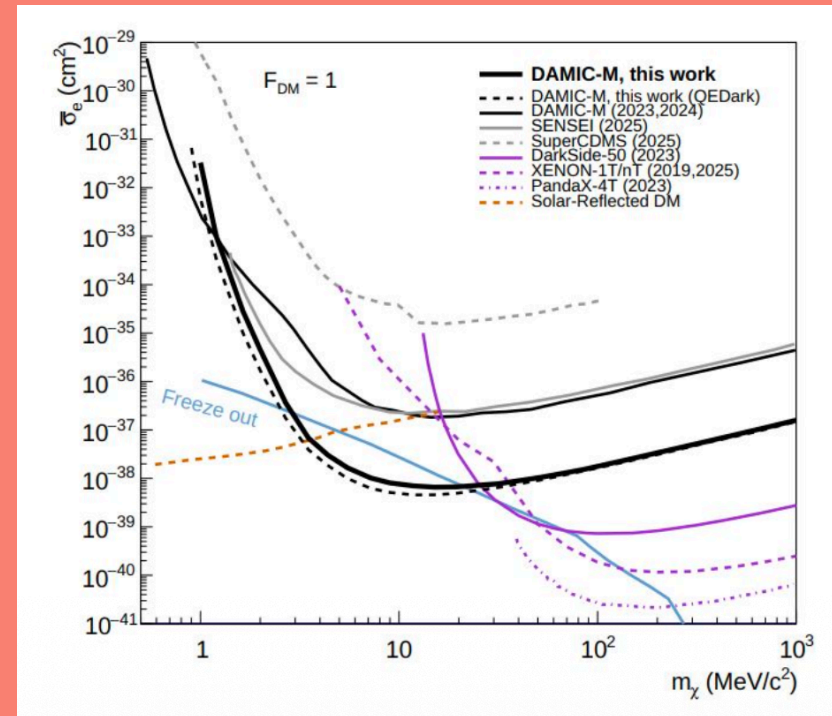
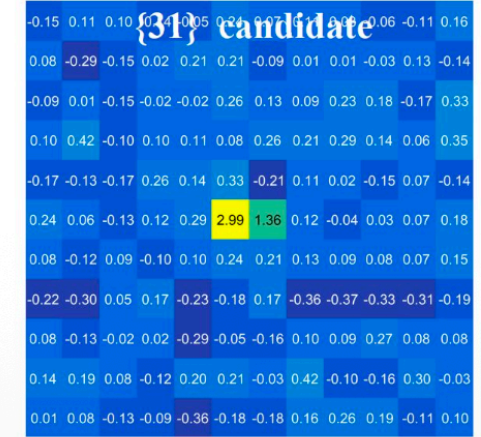
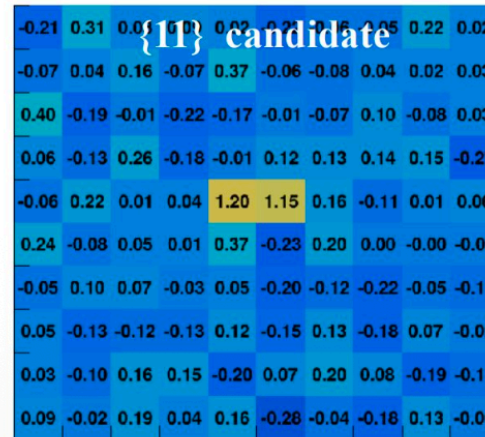
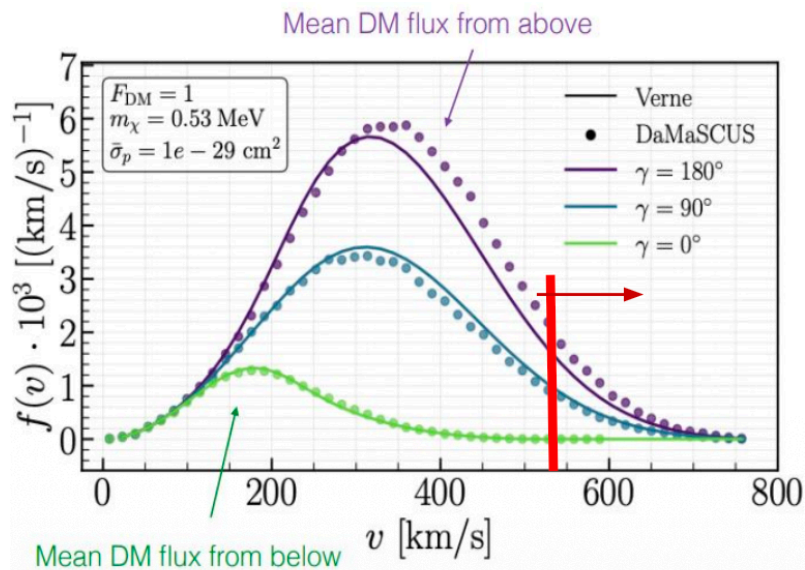
- Event candidates are classified based on the topology of the pixel hits
- Low-energy events will be a small blob, and a limited amount of depth information can be gained by the diffusion of the charge
- hits close to a high energy or near hot pixels are excluded



Orr Abramoff et al. SENSEI: Direct-Detection Constraints on Sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper-CCD. Phys. Rev. Lett., 122(16):161801, 2019. doi: 10.1103/PhysRevLett.122.161801.

DAMIC-M

- Event classified by topology and number of electrons in each bin—combinatorics and data-driven methods to estimate the rate of background events that make these patterns
- Data compatible with background
- Limits on DM-electron interaction
- but also on diurnal (daily) modulation and other models

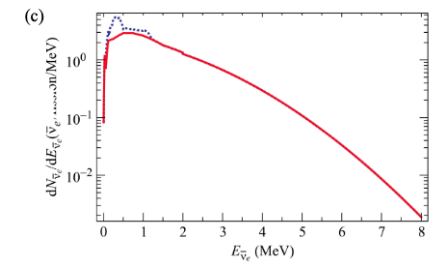
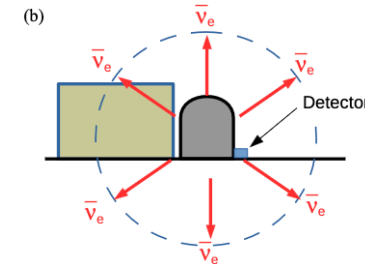
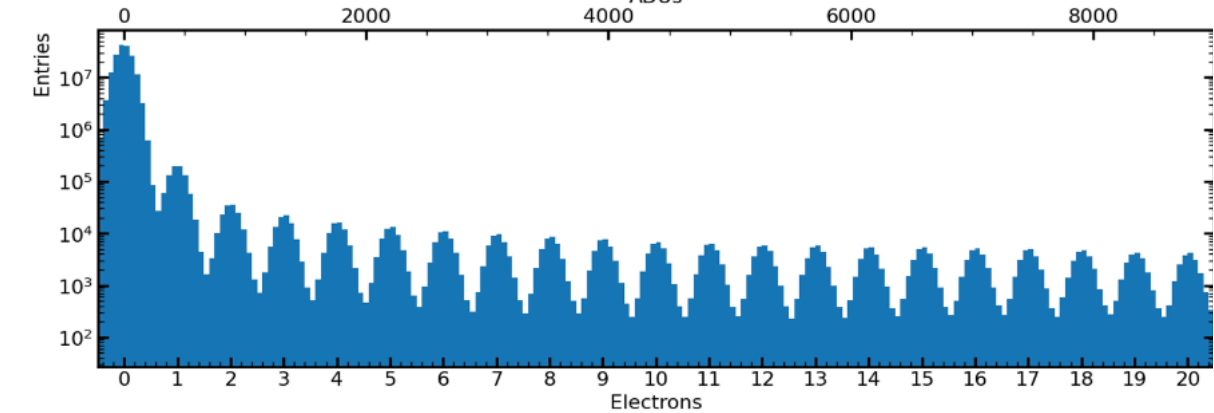
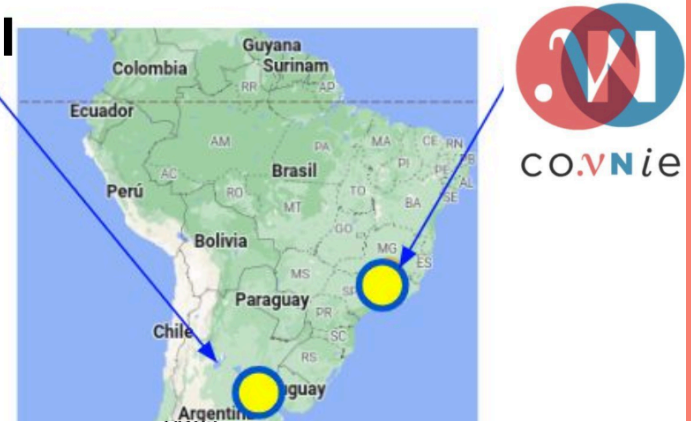


Science Results from the DAMIC-M Low Background Chamber, Núria Castelló-Mor

CONNIE

- Neutrinos are indistinguishable from dark matter, so neutrino detectors (for low-energy neutrinos) use many of the same concepts
- CONNIE uses CCDs near the Angra dos Reis nuclear reactor inside a radiation shield to attempt to discover coherent neutrino-nucleus interaction
- Background events may give different tracks, while signal event nuclear recoils are expected to hit a single pixel
- Some diffusion to neighboring pixels, but point-like
- With a 52g detector array, they expect around 0.8 signal events/day

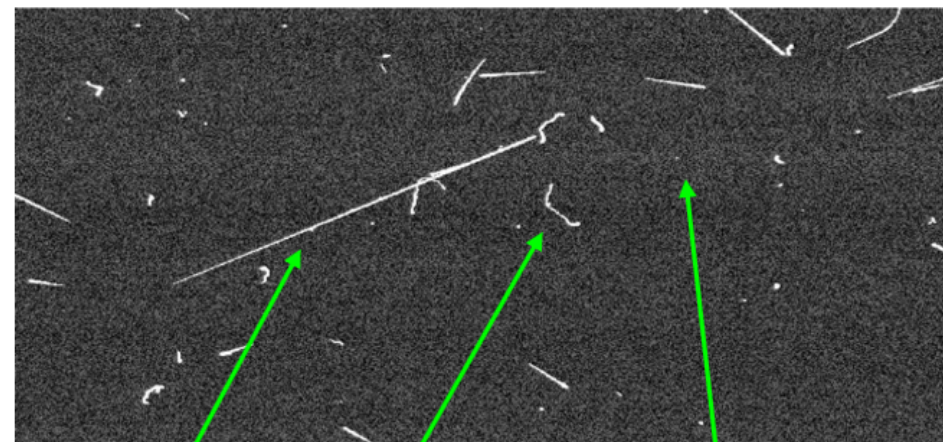
Atucha-II



The Connie experiment
<https://arxiv.org/pdf/1608.01565>
 Coherent scattering illustration by Robert Hamann
 Status and perspectives of
 the CONNIE experiment
 Irina Nasteva

CONNIE

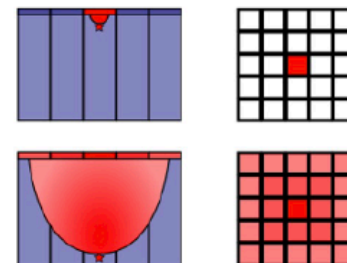
- Background rejection from topology depends on the depth of the event
- CONNIE uses a likelihood test to test the this-event-is-pointlike hypothesis!



muon

electron

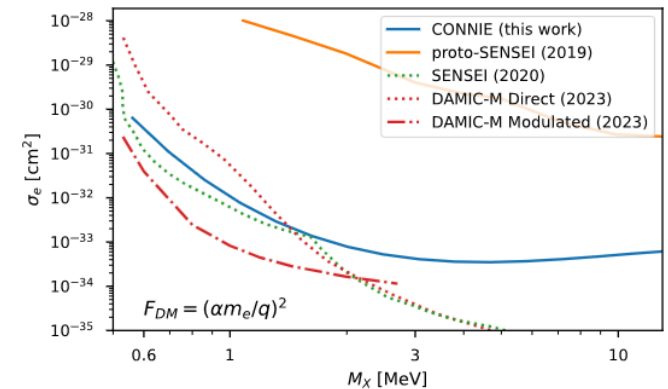
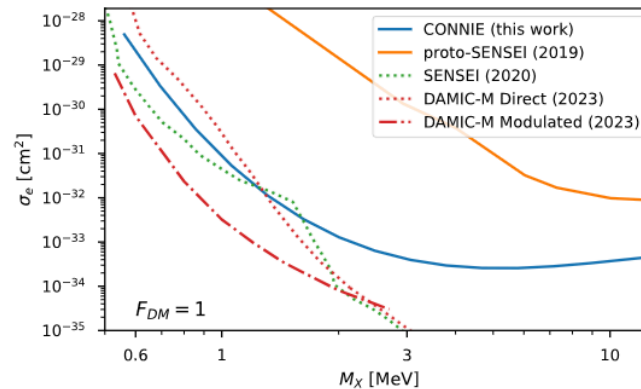
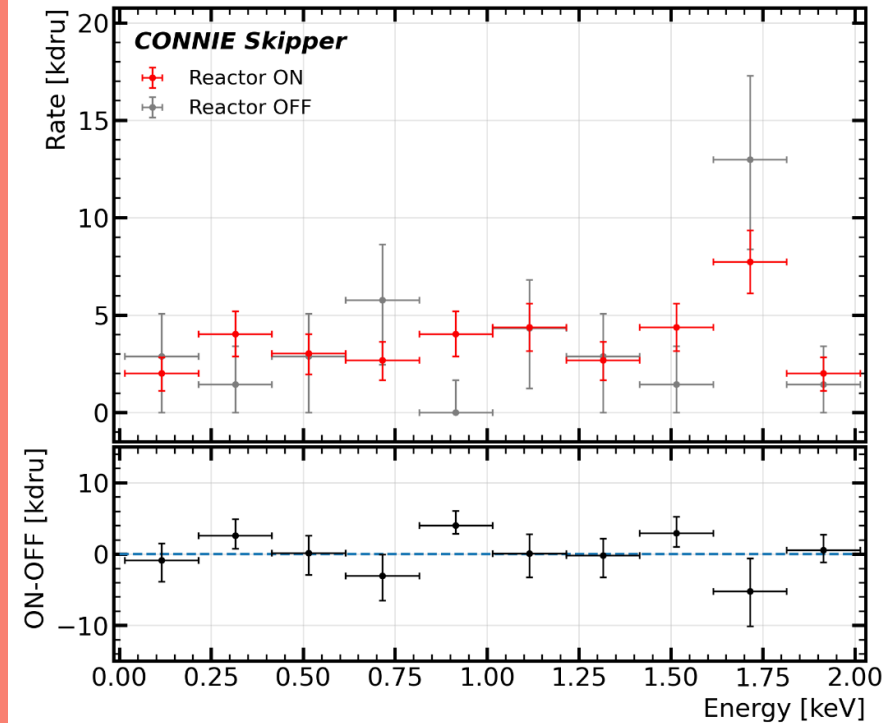
diffusion-limited hits
photons/neutrinos



The Connie experiment
<https://arxiv.org/pdf/1608.01565>
Coherent scattering illustration by Robert Hamann
Status and perspectives of
the CONNIE experiment
Irina Nasteva

CONNIE

- Results from CONNIE so far show no excess (need two orders of magnitude more sensitivity to reach the standard model prediction)
- Limits on DM-electron interactions even (dashed lines are underground detectors)

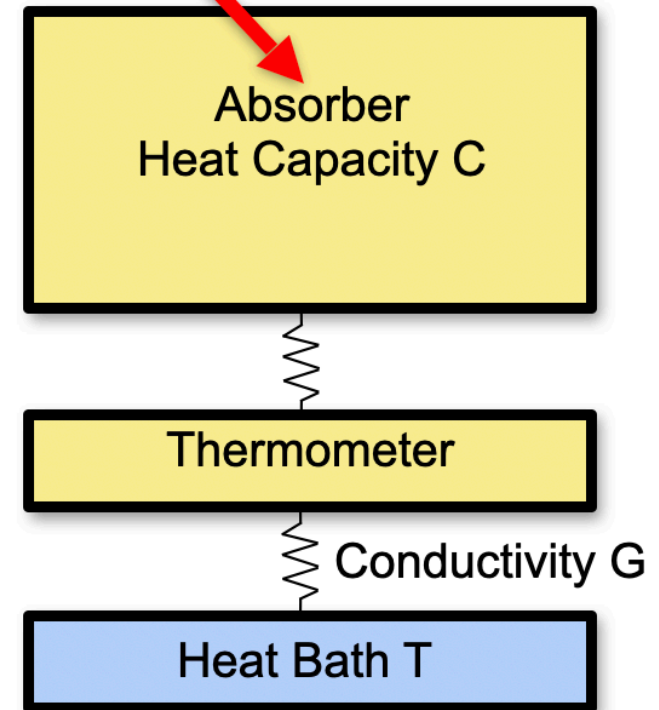


CRYOGENIC DETECTORS

- Absorber, heat capacity C , coupled to a thermometer, connected to a heat bath at temperature T
- Example numbers for detecting a relatively large energy deposition — a 1MeV beta in a 5×10^{-6} kg gold absorber:

$$\Delta T = \frac{E}{C}$$
$$\Delta T = \frac{10^6 \times 1.6 \times 10^{-19} \text{J}}{1.29 \times 10^{-4} \text{J/mgK} \times 5 \text{mg}} = 2.5 \times 10^{-10} \text{K}$$

Incoming Radiation



CRYOGENIC DETECTORS

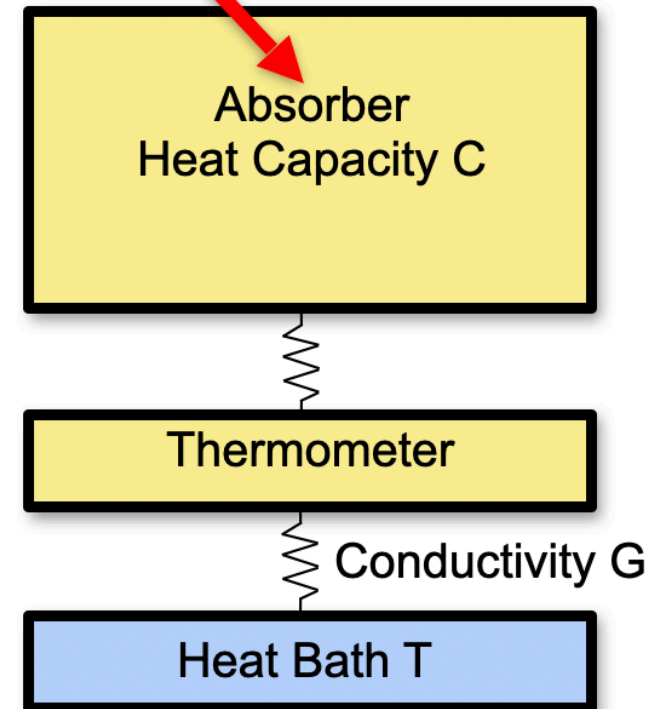
- The noise this temperature increase has to fight with are the natural Poisson fluctuations of the heat quanta (“phonons”)
- Making a simplified assumption that they all share the Boltzmann energy, we have that

$$\epsilon_p = k_B T \quad \text{ENERGY OF ONE PHONON}$$

$$N_p = \frac{E_{\text{thermal}}}{\epsilon_p} \quad \text{— NUMBER OF PHONONS}$$

$$N_p = \frac{mCT}{\epsilon_p}$$

Incoming Radiation



CRYOGENIC DETECTORS

$$N_p = \frac{E_{\text{thermal}}}{\epsilon_p}$$

$$\sigma_{E_T} = \sigma_{N_p} \epsilon_p = \sqrt{N_p} \epsilon_p = \sqrt{E_{\text{thermal}} \epsilon_p}$$

$$\sigma_{E_T} = \sqrt{C k_B T} \rightarrow \sigma_T = \sigma_{E_T} / C = \sqrt{\frac{k_B}{C}} T$$

- Considering only Poisson fluctuation in the number, we see that the temperature fluctuations $\propto T, \propto 1/\sqrt{C}$

$$\sigma_T = \sigma_{E_T} = \sqrt{\frac{1.38 \times 10^{-23} \text{J/K}}{1.29 \times 10^{-4} \text{J/mgK} \times 5 \text{mg}}} 300 \text{K} = 4.5 \times 10^{-8} \text{K}$$

- Two orders of magnitude above the $2 \times 10^{-10} \text{K}$ signal

CRYOGENIC DETECTORS

- What happens if we run this at 30mK instead of room temperature?
- Recall thermodynamics: the heat capacity changes as degrees of freedom are frozen out;

$$C = \gamma T + \beta T^3 + A/T^2$$

electrons

phonons

nuclear

- At this temperature, the heat capacity is 10^{-10}J/mg/K

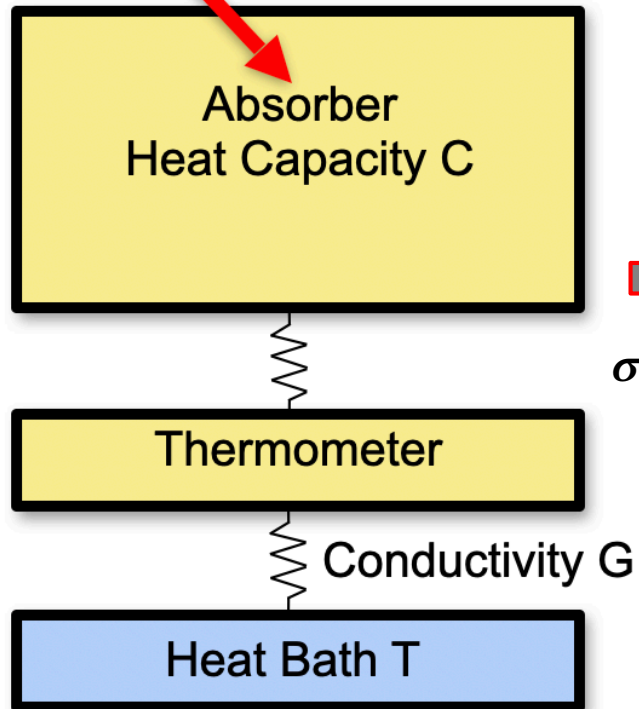
$$\Delta T = \frac{10^6 \times 1.6 \times 10^{-19}\text{J}}{10^{-10}\text{J/mgK} \times 5\text{mg}} = 3.2 \times 10^{-4}\text{K}$$

$$\sigma_T = \sigma_{E_T} = \sqrt{\frac{1.38 \times 10^{-23}\text{J/K}}{10^{-10}\text{J/mgK} \times 5\text{mg}}} 0.03\text{K} = 5 \times 10^{-9}\text{K}$$

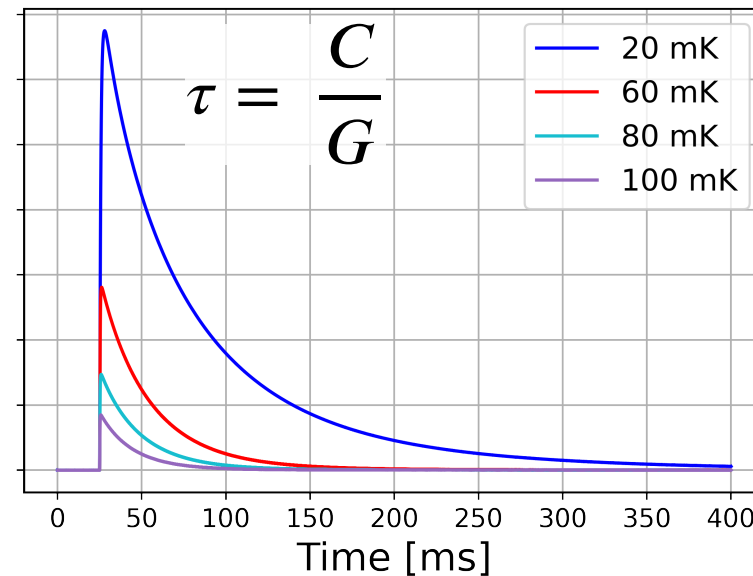
- A very respectable signal-to-noise of 10000!

CRYOGENIC DETECTORS

Incoming Radiation



$$\Delta T = \frac{E}{C}$$
$$\sigma E = \sqrt{Ck_B T^2}$$



- The absorber thermalises with some characteristic time constant before leaking the energy out via the thermal link to retain equilibrium

DILUTION REFRIGERATORS

- To reach milliKelvin temperatures, dilution refrigerators are the standard tool, using the enthalpy of mixing between ^4He and ^3He to reach the very lowest temperature.
- The two isotopes have different quantum properties— ^4He is a boson and forms a Bose-Einstein condensate with all particles at the ground state, while ^3He is a fermion
- Below 0.87K, the two isotopes cannot be arbitrarily mixed, and instead separates into a 100% ^3He -phase called the concentrated phase, and a mixed $^4\text{He} + ^3\text{He}$ -phase called the dilute phase with $\sim 6\%$ ^3He
- Heat is needed for a ^3He -atom to move from the concentrated phase to the dilute phase, so that by pumping ^3He into the mixing region and making it mix, and then extracting the hotter ^3He at a higher temperature stage before cooling it and sending it in again
- Modern “dry” fridges cool the ^3He with cryocoolers that can reach temperatures $\sim 2 - 3\text{K}$

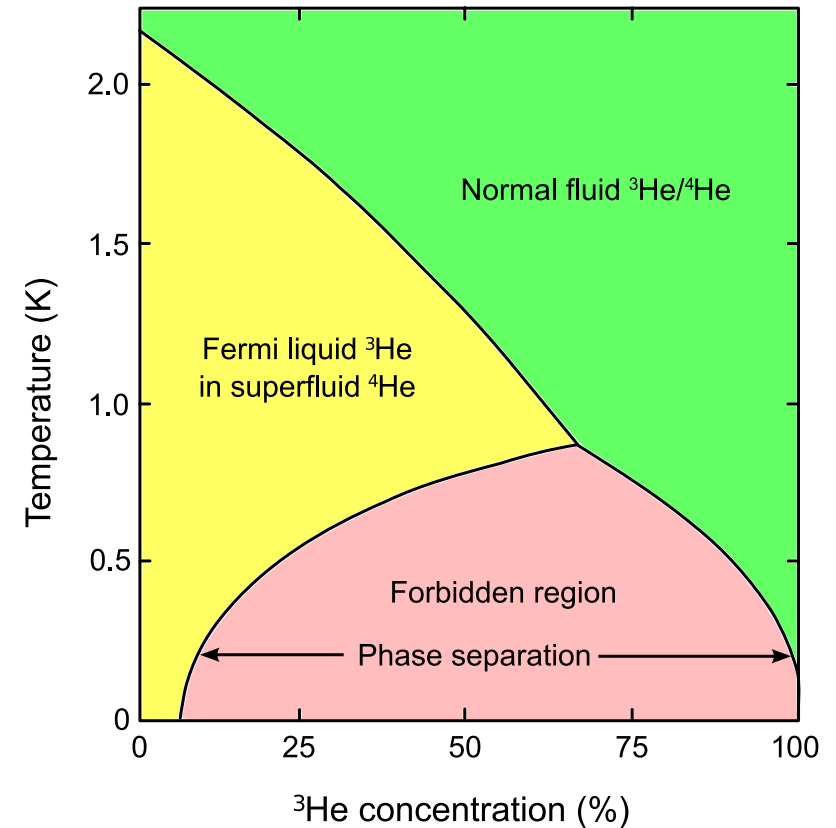
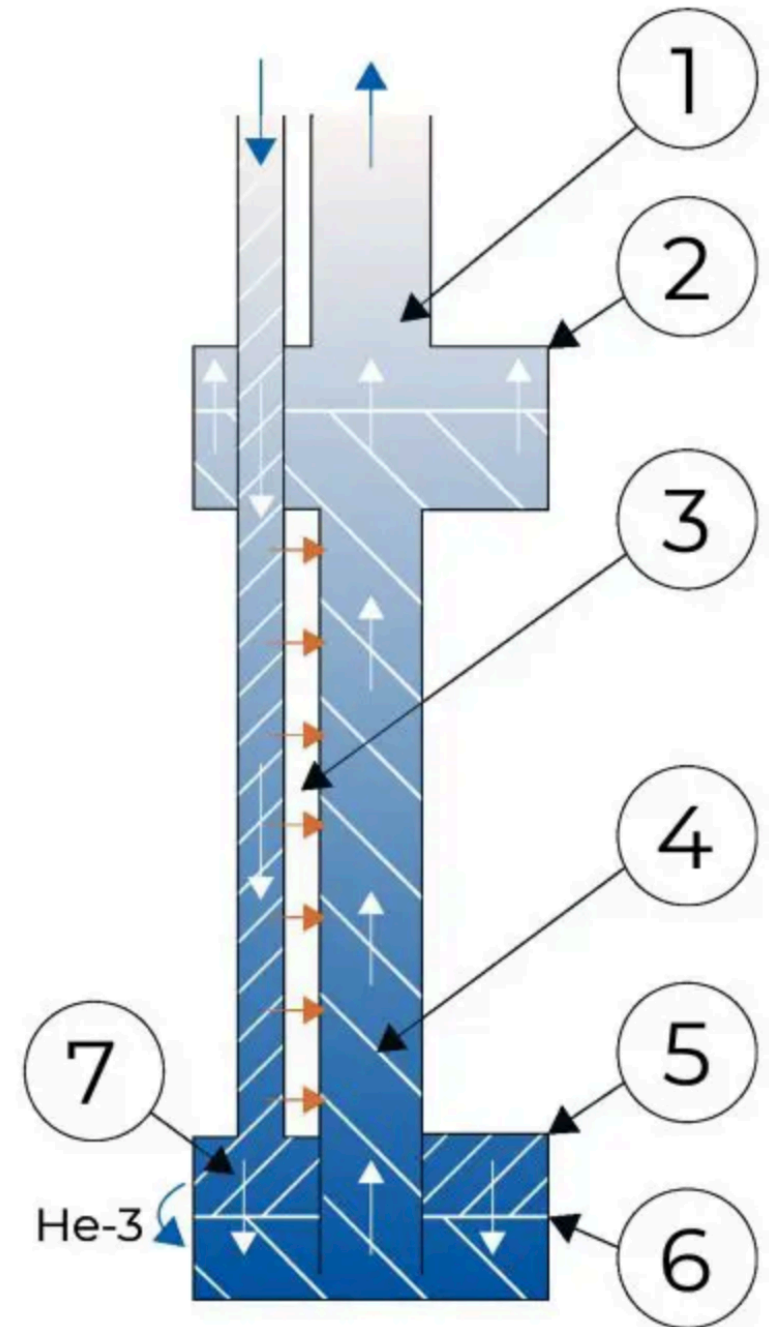


Diagram from wikipedia, credit: Mets501 and Bluefors <https://bluefors.com/stories/how-does-a-dilution-refrigerator-work/>

DILUTION REFRIGERATOR

1. ^3He -rich gas phase
2. Still, where ^3He is evaporated and sent to be cooled
3. heat exchangers— the outgoing dilute phase is heated up by the incoming concentrated phase, and the incoming concentrated phase is cooled down
4. Dilute phase being extracted from the mixing chamber
5. mixing chamber, thermally coupled to what we wish to cool
6. Phase separation between concentrated and dilute phase
7. incoming concentrated phase



DILUTION REFRIGERATORS

- In practice each stage of the dilution refrigerator is hung beneath each other to be isolated from each other, and in the vacuum vessel
- Stainless steel has low conductivity at mK temperatures, and give the insulating rods
- Experimental module hung underneath the lowest plate where mixing occurs
- Medium-scale infrastructure, costing ca. 1 mega-dollar, extensive use in quantum computing for example

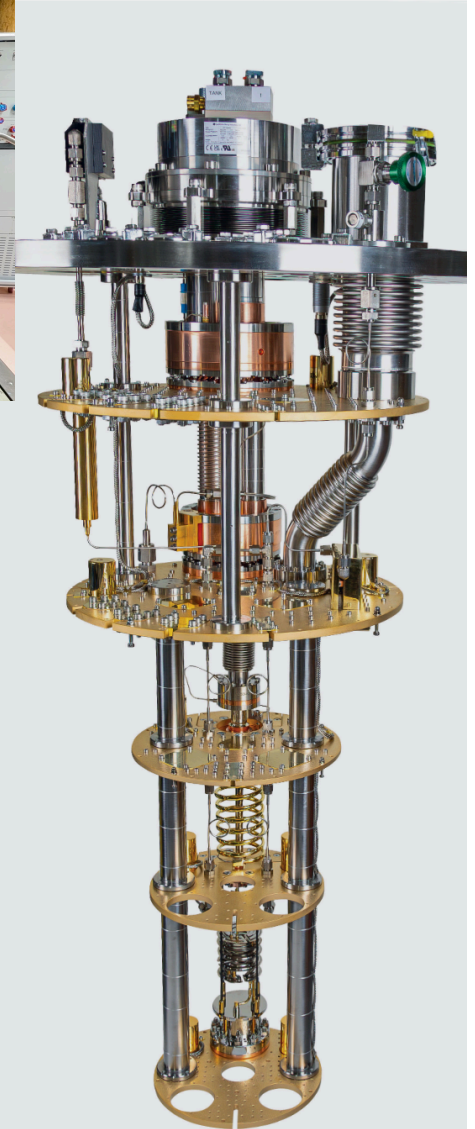


ProteoxS

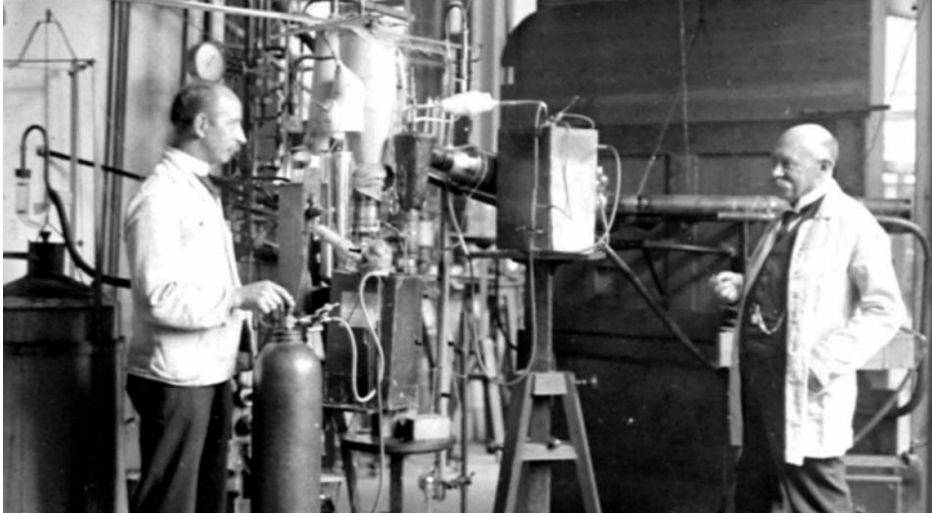
Delivering faster characterisation in a smaller size, with no compromise on performance

< 10 mK base temperature

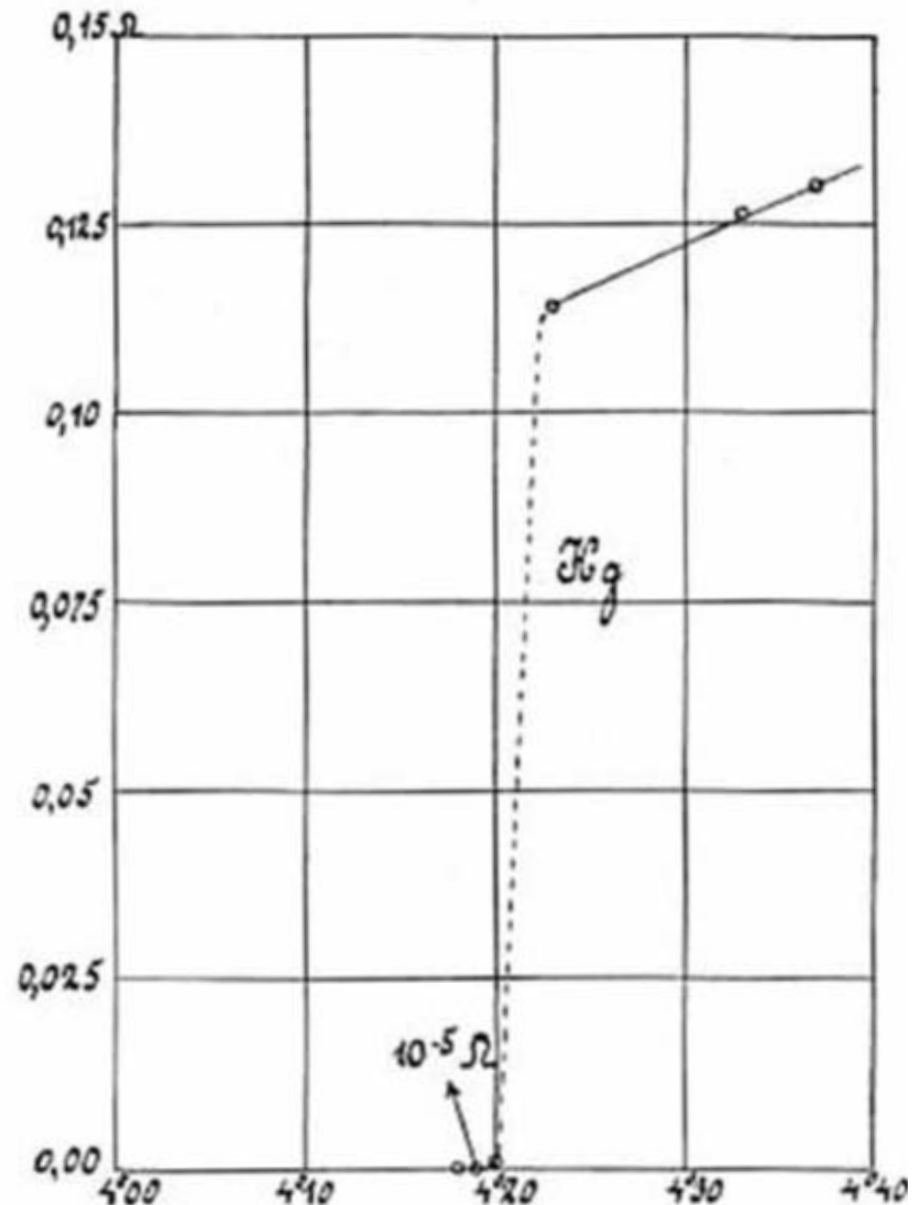
< 20 hours cool down



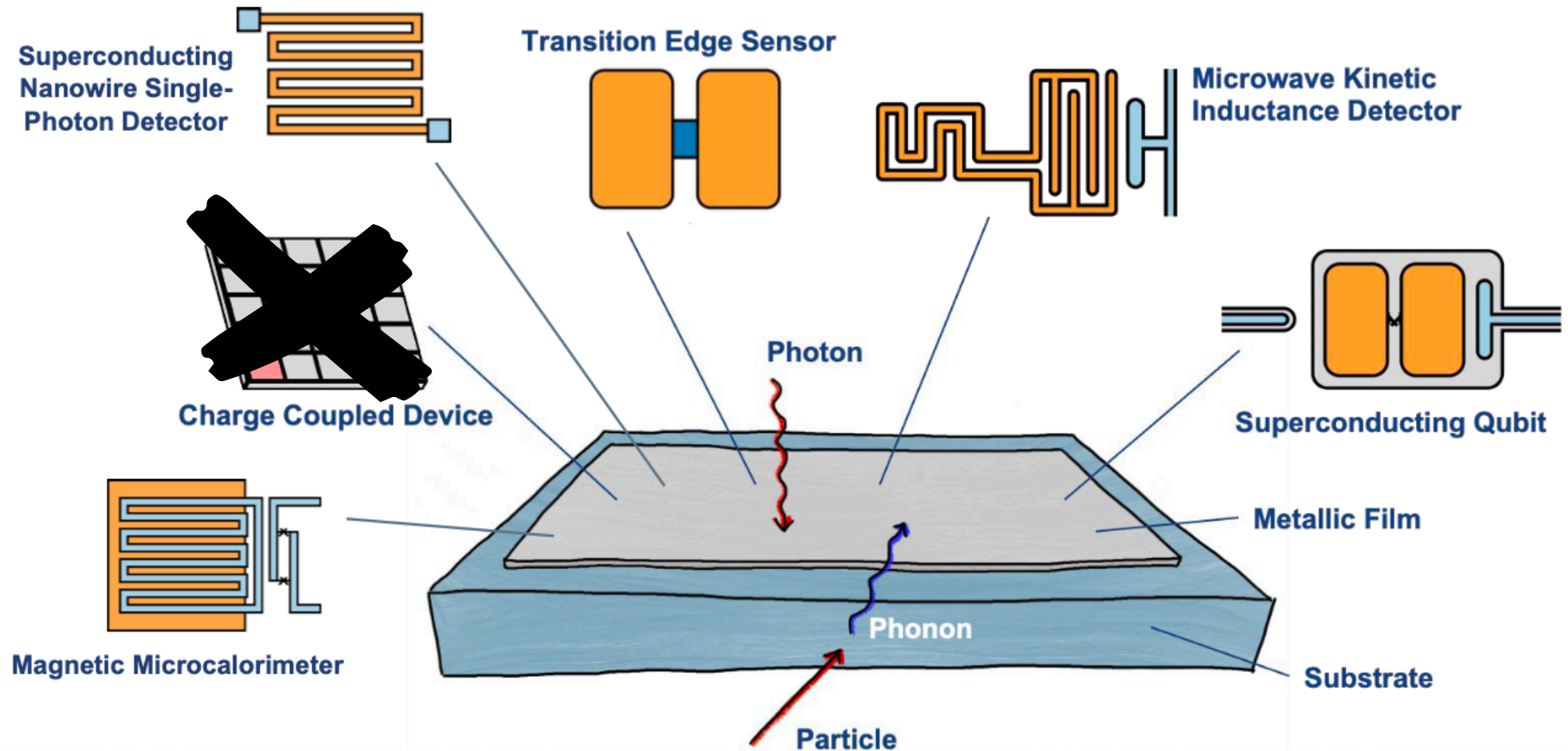
BONUS WITH LOW TEMPERATURE: SUPERCONDUCTIVITY!



- Helium was liquified by Heike K. Onnes in 1908
- 1911— some metals, such as mercury, has a sharp loss of resistance as temperature got lower



ALMOST ALL LOW-ENERGY PHONON/PHOTON DETECTORS USES SUPERCONDUCTIVITY



EXAMPLE: SNSPDS

- With a little meander of superconductive wire, you can apply a current through that will flow without resistance.
- Current below, but not far below the superconductive breakdown voltage
- A deposited energy in the wire will heat it up locally, and possibly turn a bit of the wire normal.
- Resistance then enlarges the hotspot, current drops, which you detect as an event (binary 1-0 only!)
- The drop in current lets the wire cool down, and the detector resents

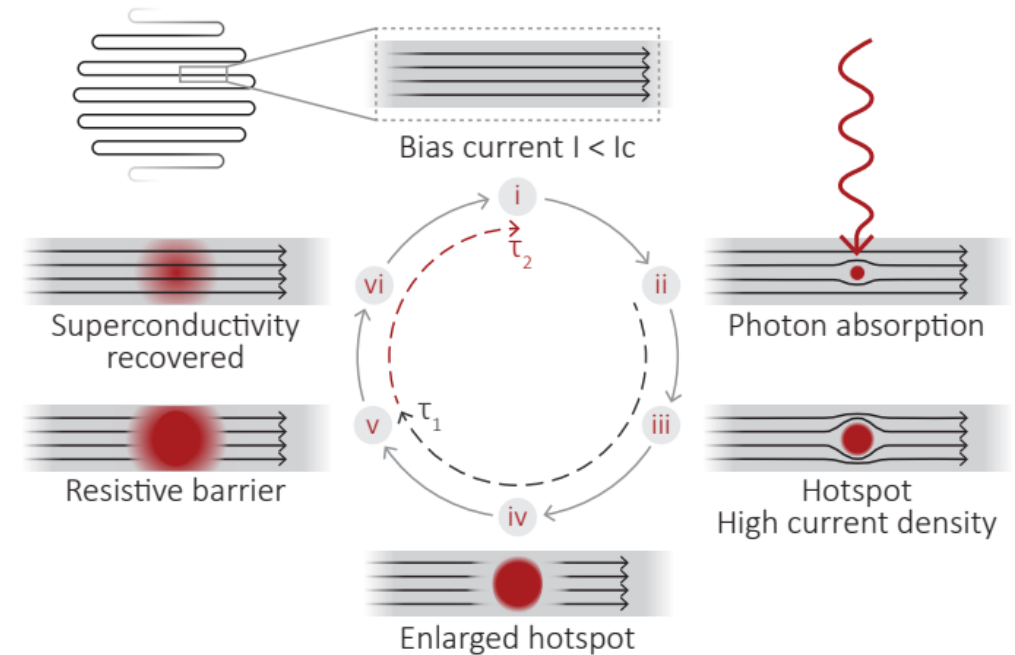
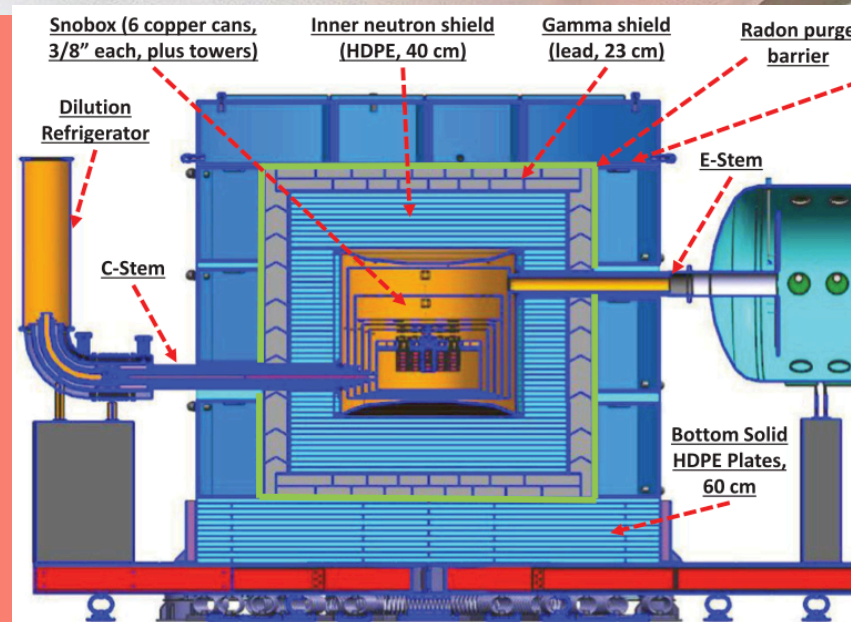
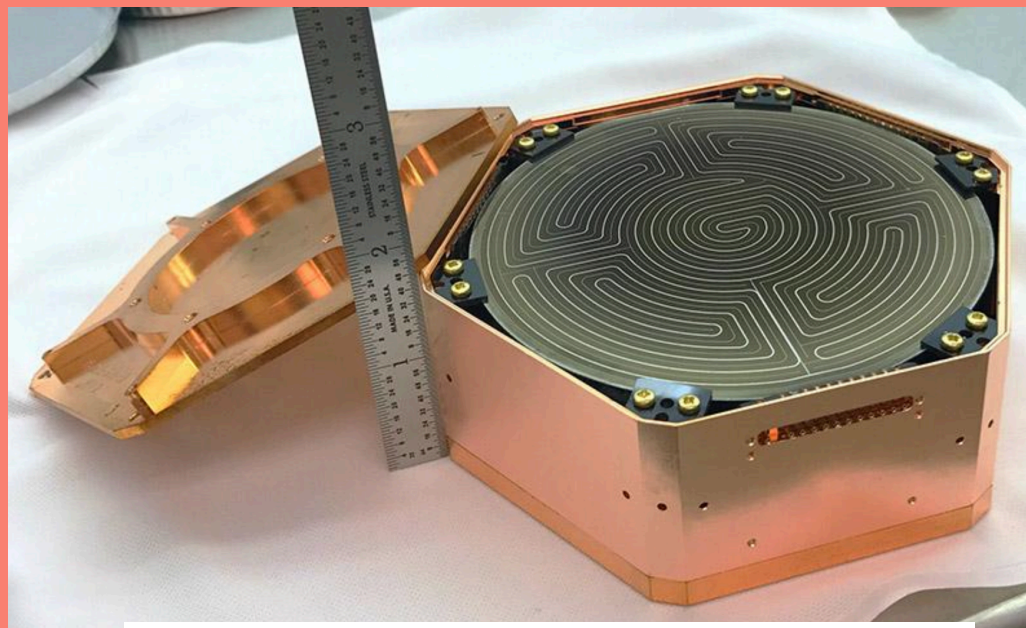


Figure adapted from: Natarajan et al. *Supercond. Sci. Technol.* 25, 063001 (2012).

CRYSTALS: CDMS

- SuperCDMS SNOLAB is the latest of a series of CDMS direct detection experiments
- Previously at the Soudan laboratory, but SNOLAB gives almost 3 times the overburden, and a factor 250 reduction in neutrons from muons.
- made up of solid-state detector modules of germanium (1.4kg) or silicon (0.6kg) crystals, held at 15 – 30mK
- Observables are heat (as phonons) and charge
- Phonons are read out with transition edge sensors (TES), sensitive to $\Delta T \sim 10\text{mK}$

Detector image courtesy of SuperCDMS
<https://supercdms.slac.stanford.edu/>



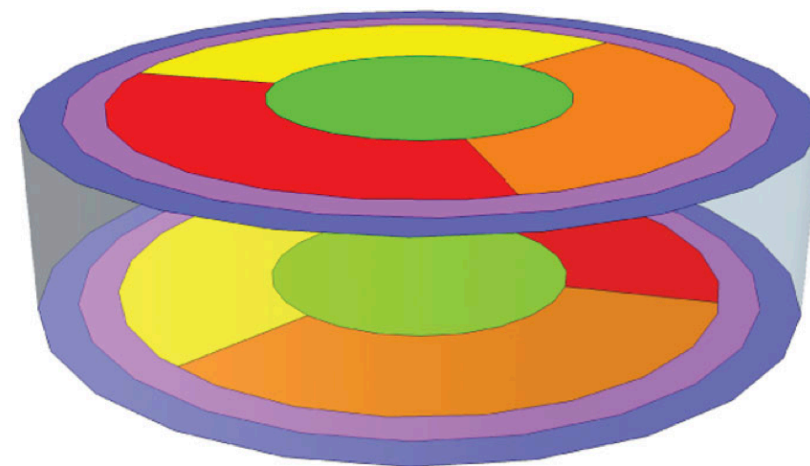
R. Agnese et al. Projected Sensitivity of the SuperCDMS SNOLAB experiment. Phys. Rev. D, 95(8):082002, 2017. doi: 10.1103/PhysRevD.95.082002.

CRYSTALS: CDMS

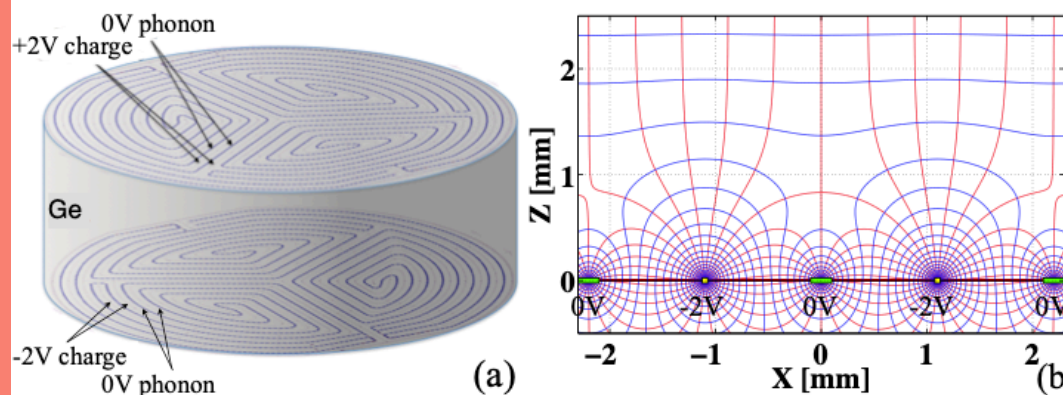
- SuperCDMS uses two run modes:
- The CDMSlite mode uses a high amplification voltage to lower the energy threshold
- Under a higher drift field, the charge carriers drifted through the detector emit additional phonons, which are then read out
- Downside: lower ER/NR discrimination capability
- The interleaved mode (iZIP) reads out charge as well as phonons
- Rejects ER events based on charge/phonon ratio
- Surface backgrounds are also reduced with a positive bias on the ionisation channels, funnelling the charges

R. Agnese et al. Projected Sensitivity of the SuperCDMS SNOLAB experiment. Phys. Rev. D, 95(8):082002, 2017. doi: 10.1103/PhysRevD.95.082002.

HV:



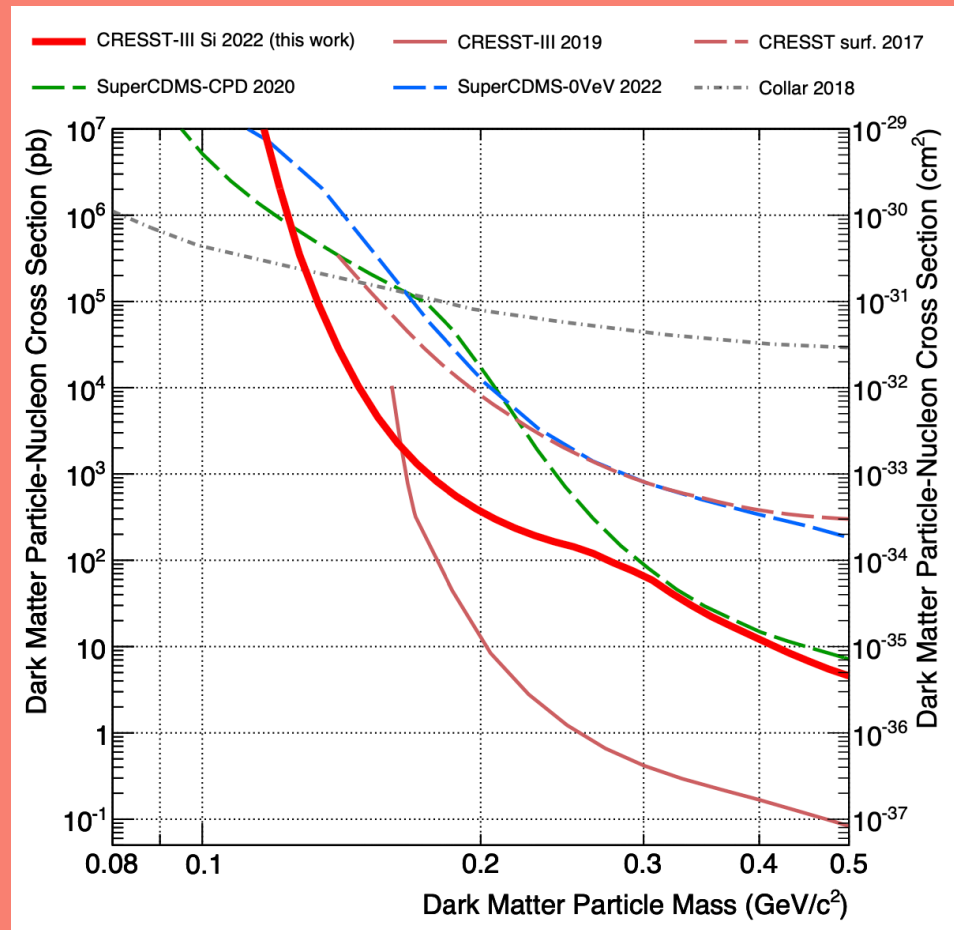
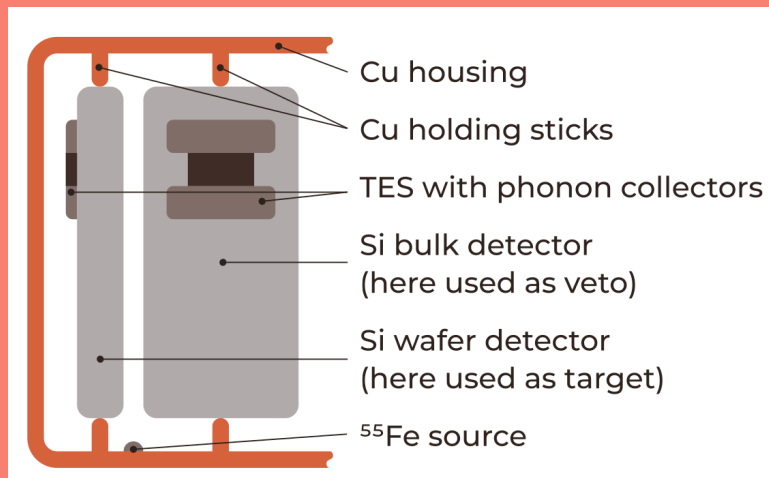
Phonon channel segmentation shown with color



R. Agnese et al. Demonstration of Surface Electron Rejection with Interleaved Germanium Detectors for Dark Matter Searches. Appl. Phys. Lett., 103:164105, 2013. doi: 10.1063/1.4826093.

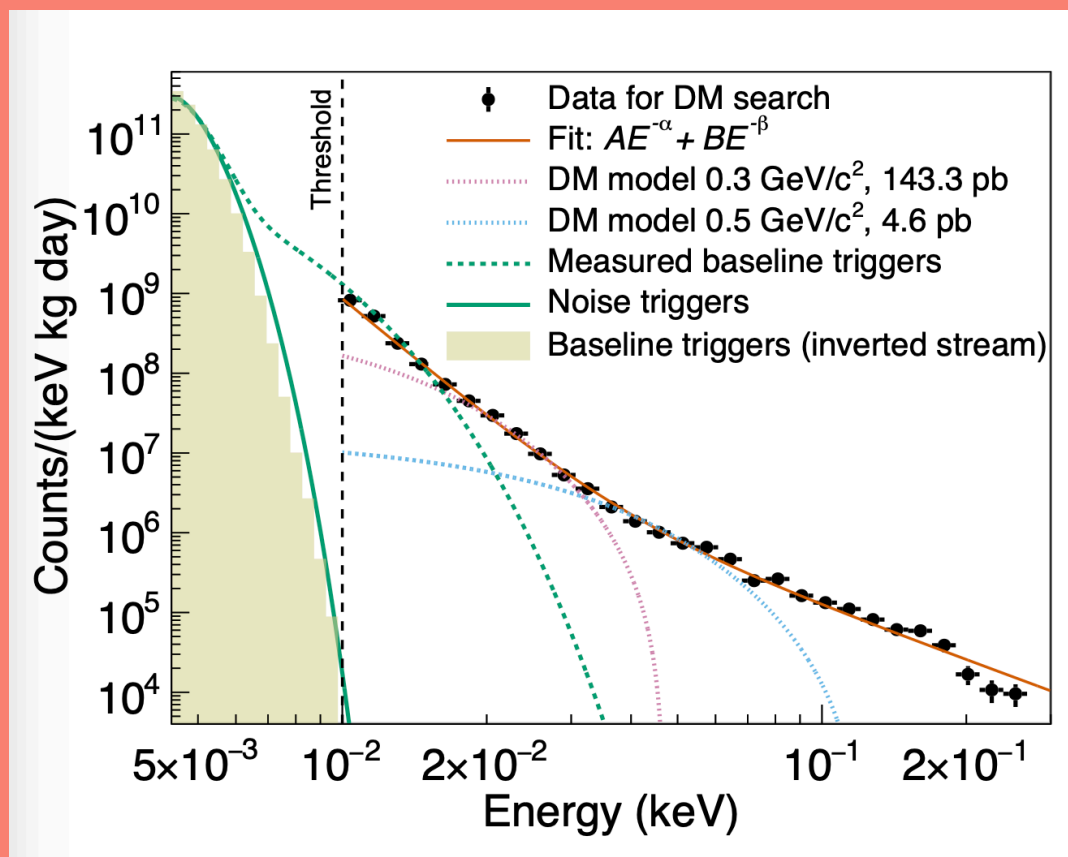
CRYSTALS: CRESST-III

- A range of crystal targets; CaWO_4 , Al_2O_3 , LiAlO_2 , Si held at 10 mK, and operating as calorimeters read out by a transition-edge sensor
- Observables: phonons and (for scintillators) scintillation light, which provides ER/NR discrimination
- Choosing a specific low-noise crystal, CRESST-III was able to put limits down to $0.115 \text{ GeV}/c^2$ with an energy threshold of 10 eV



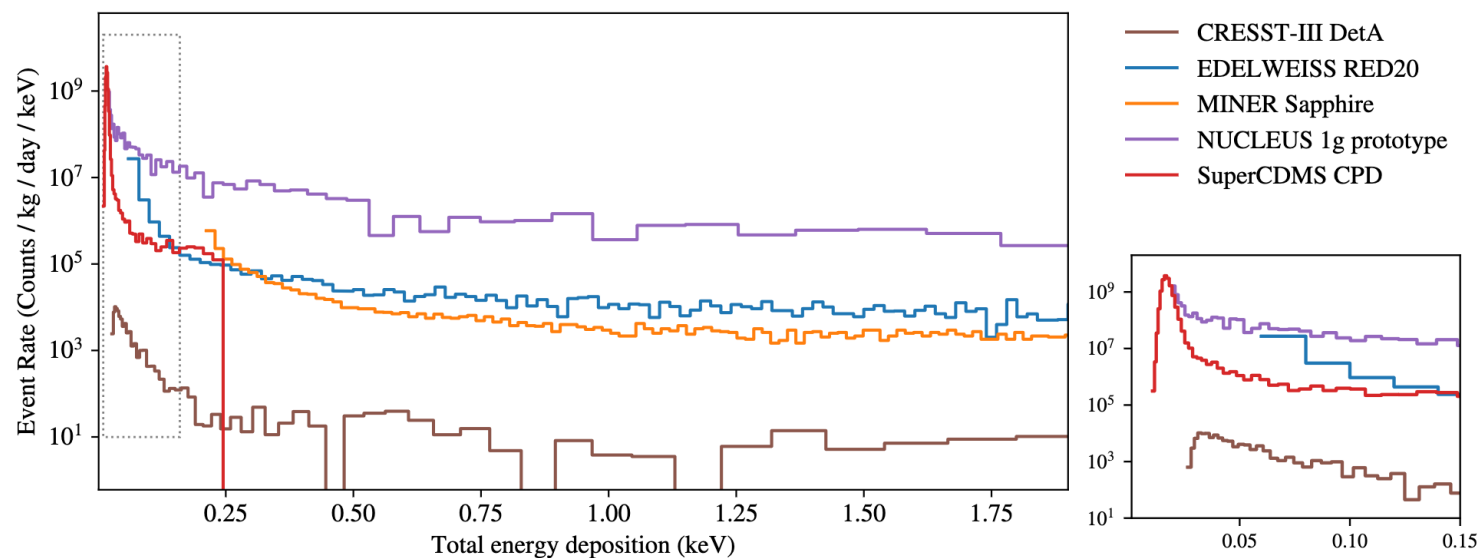
LOW-ENERGY EXCESS

- One reason for the extensive R&D applied to the low-energy region is the sheer difficulty of detecting low-energy interactions
- However, this has now been eclipsed by a much more challenging one: the low-energy excess, which is observed by all low-energy detectors as a rising rate of events going towards the lowest energies
- However, this excess depends on both detectors (or even individual sensors) and varies between time periods, with large changes when you heat up and cool down again
- Not dark matter!
- But an extremely challenging background

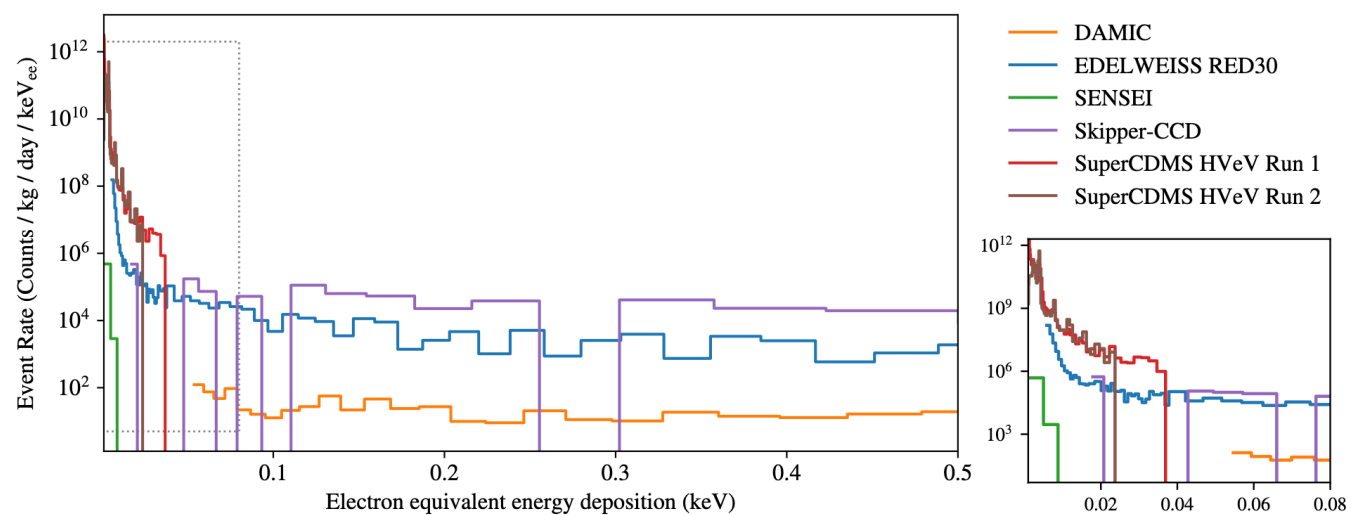


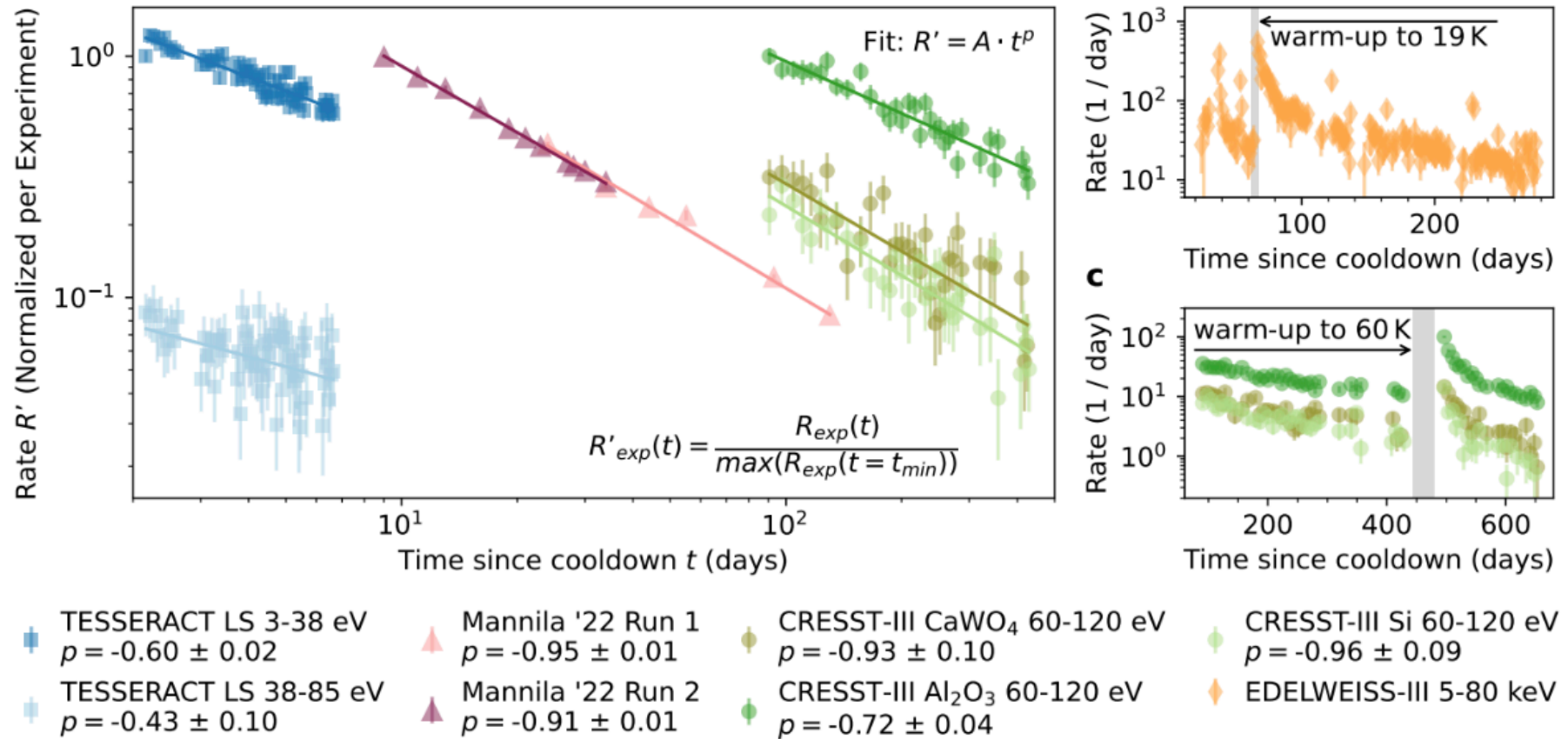
Abdelhameed, A. H. et al. (CRESST). First results from the CRESST-III low-mass dark matter program. Phys. Rev. D, 100(10):102002, 2019. doi: 10.1103/PhysRevD.100.102002.

G. Angloher et al. Results on sub-GeV Dark Matter from a 10 eV Threshold CRESST-III Silicon Detector. 12 2022.



● The EXCESS workshop series have tried to collect the experimental results to most easily compare and share lessons

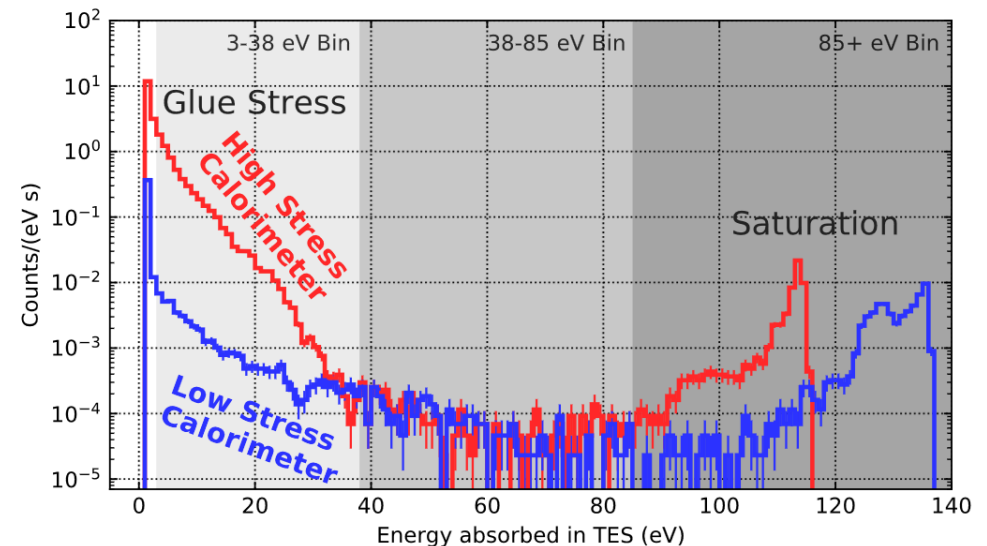
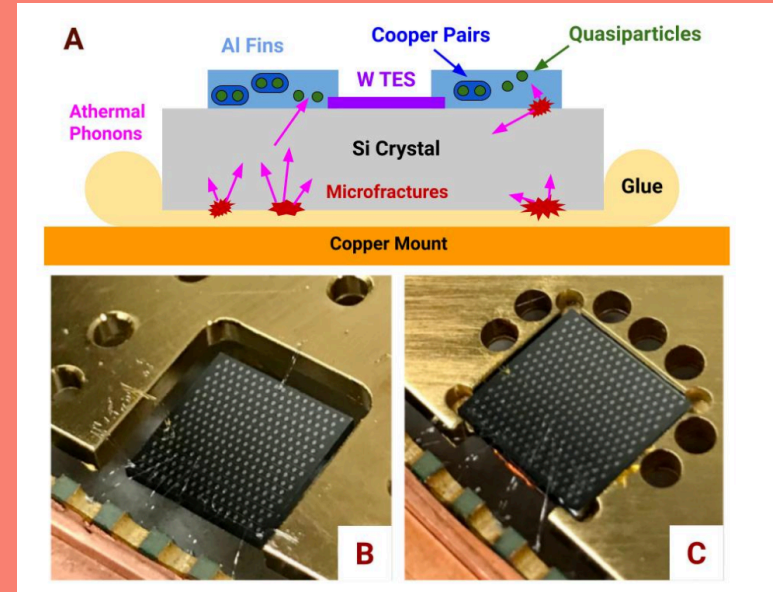




- Significant dependence on thermal cycling, and decays with time

LEE IS ASSOCIATED WITH STRESS

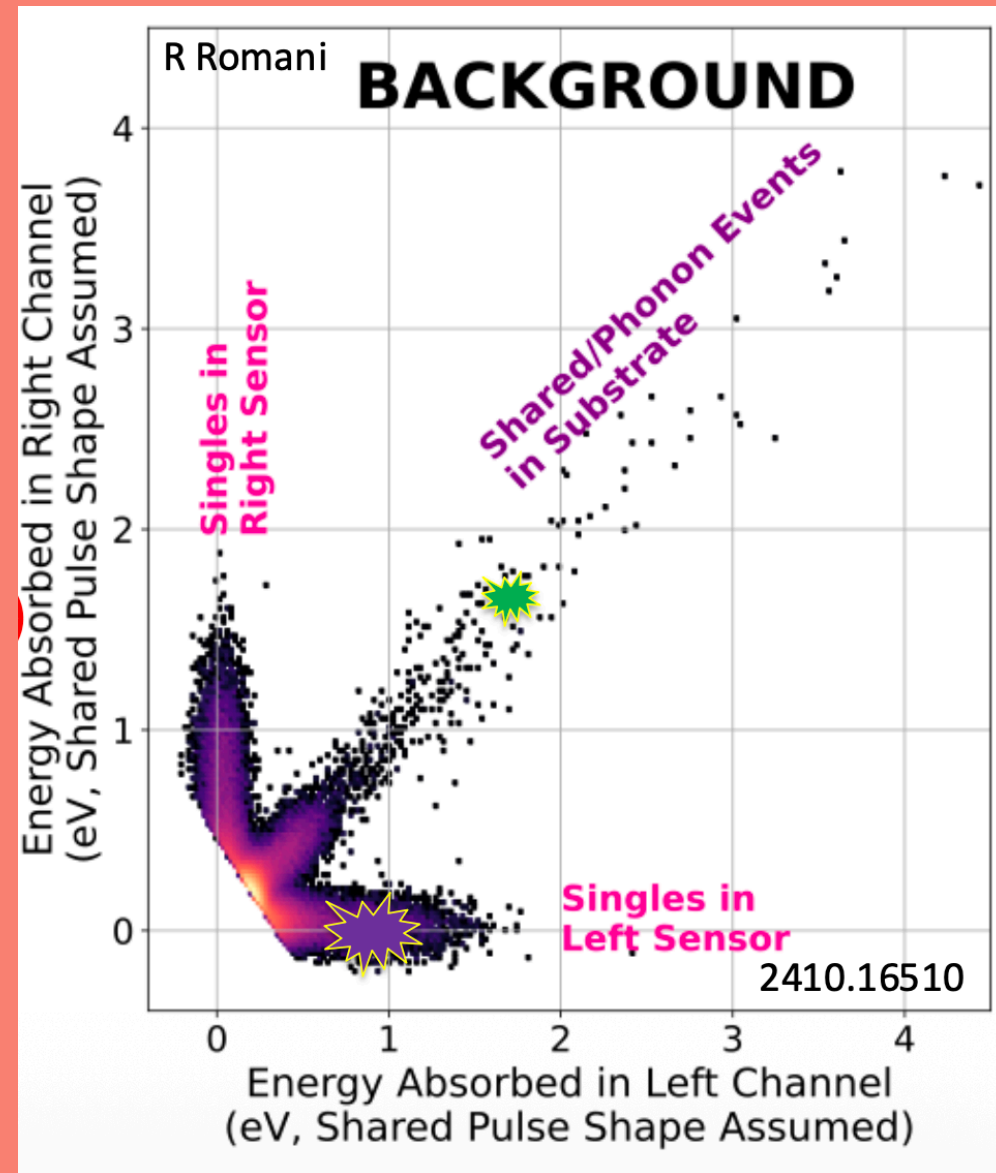
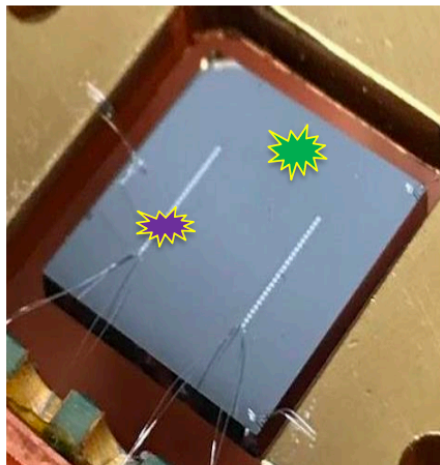
- Setups with more stress—glued components, strong clamping etc. display more LEE
- In the glue sample, used varnish as a glue
- Suspending the crystal by wires, or just resting (no clamping) apply less stress on the system.



Robin Anthony-Petersen et al. A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning. 8 2022.

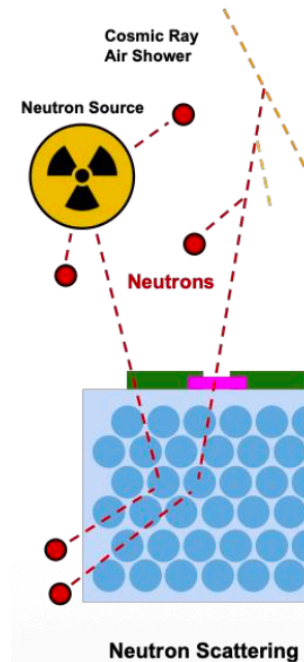
LEE IS HAPPENS BOTH IN THE TES AND THE BULK

- Running with two TES sensors, a large population of single-TES hits point to e.g. stress between the films making up the TES
- Plus a population of shared events associated with the substructure
- Work ongoing— scale with surface, volume of the substrate?
- Indication: thickness/volume

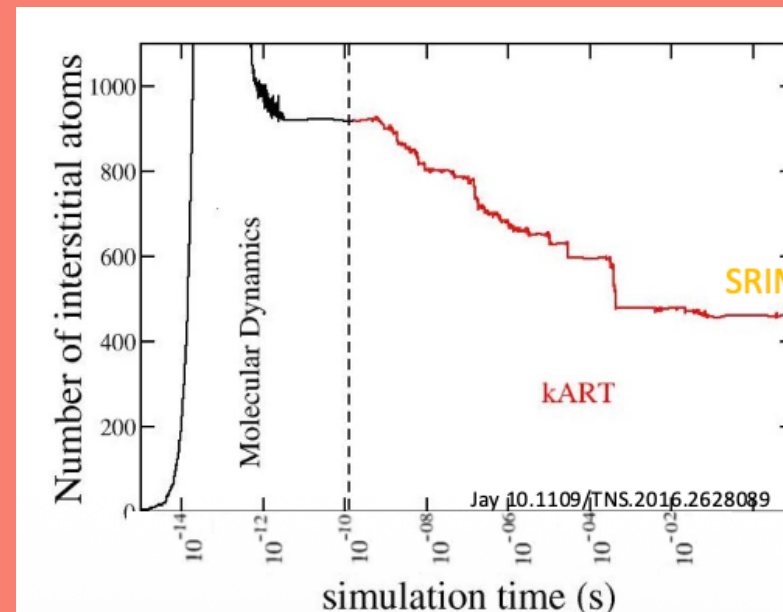


POSSIBILITY: CRYSTAL DEFECTS FROM COSMIC RAYS

- This is currently investigated by among other TESSERACT
- Difficult calculations required to compute the decay of defects
- The experiment tried doing an irradiation A/B test
 - See excess in irradiated device
 - but not quite the right spectral shape,
 - and not a high enough rate



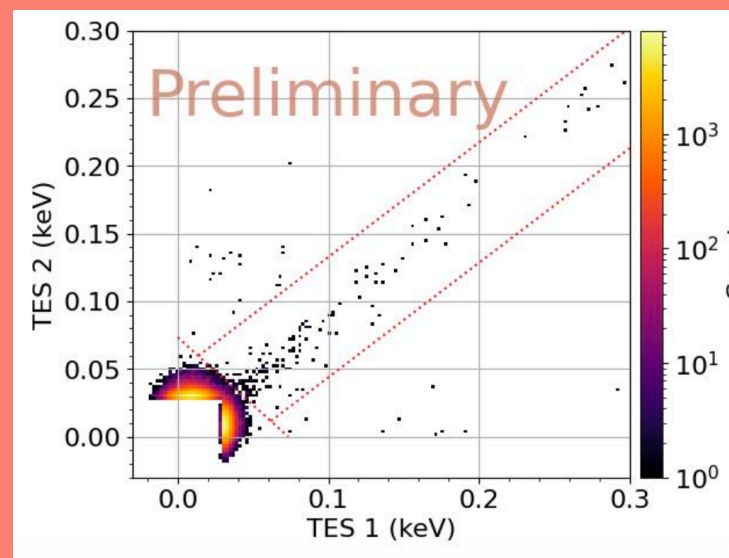
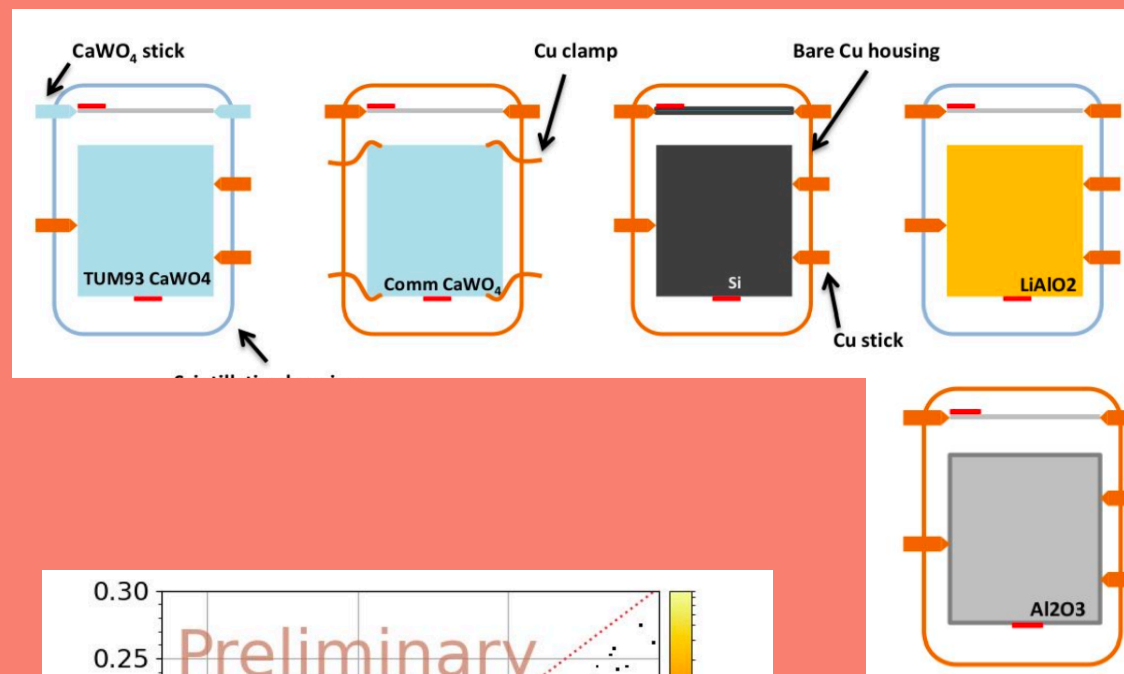
Matt Pyle
Probing the Sources of Low Energy Excess:
Defects from Fast Neutrons and Environmental
Vibrations



CRESST LEE INVESTIGATION

- CRESST has performed several modifications to their detector to investigate the excess:
 - Different material
 - changing the mass
 - changing the crystal holder
 - Scintillating materials
 - different geometries
- Two decay constants— 10 days and 250 days
- Many backgrounds are single-sensor, but an appreciable rate also in double.

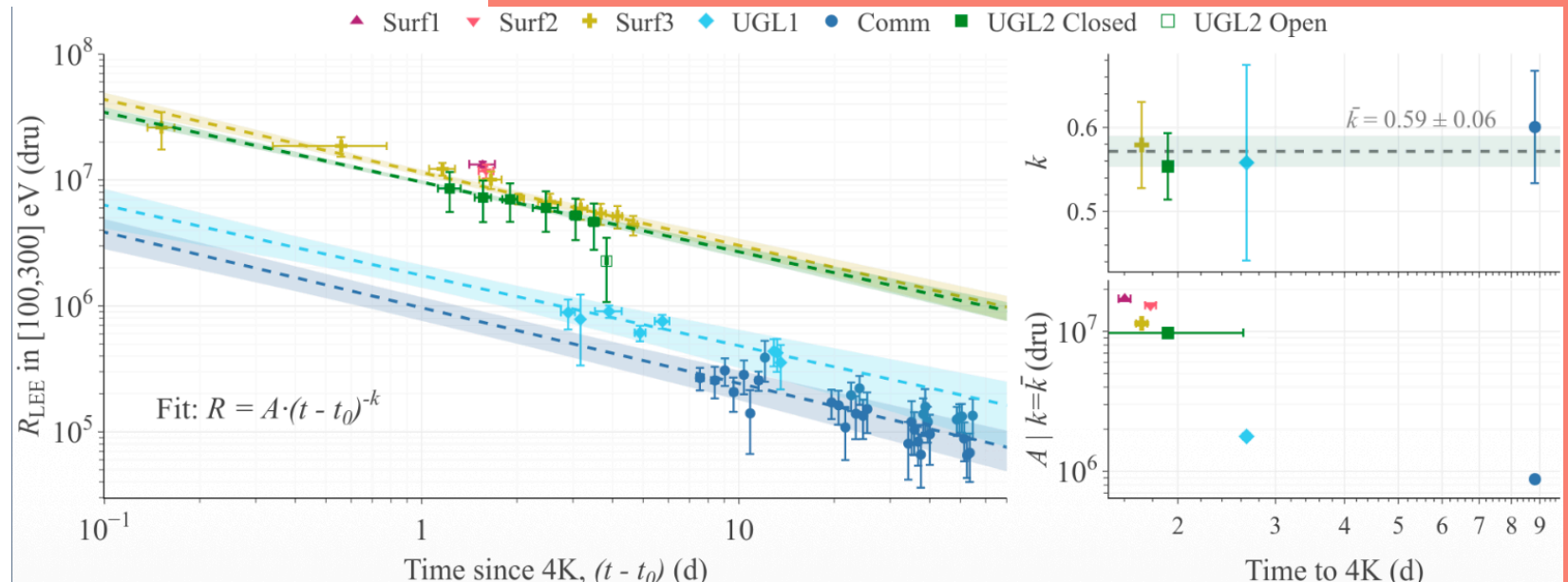
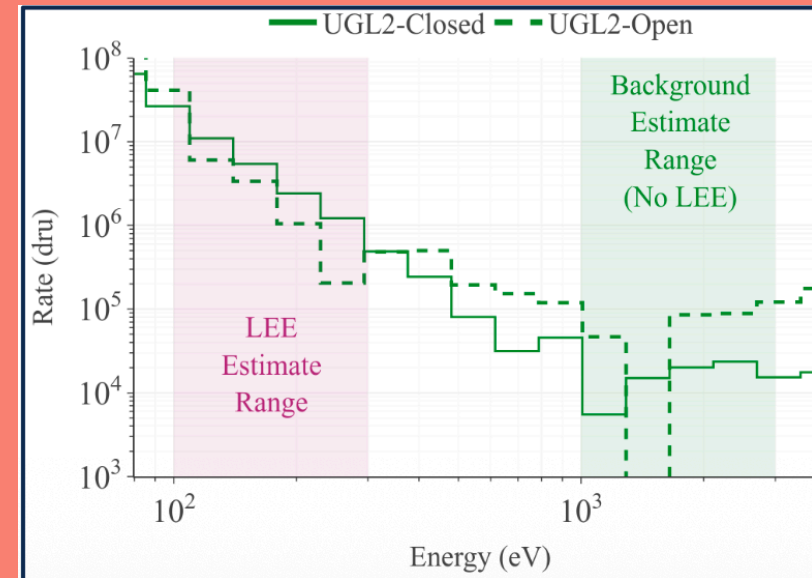
The low-energy excess in the detector modules of CRESST III, Anna Bertolini, EXCESS 2026



NUCLEUS LEE INVESTIGATION

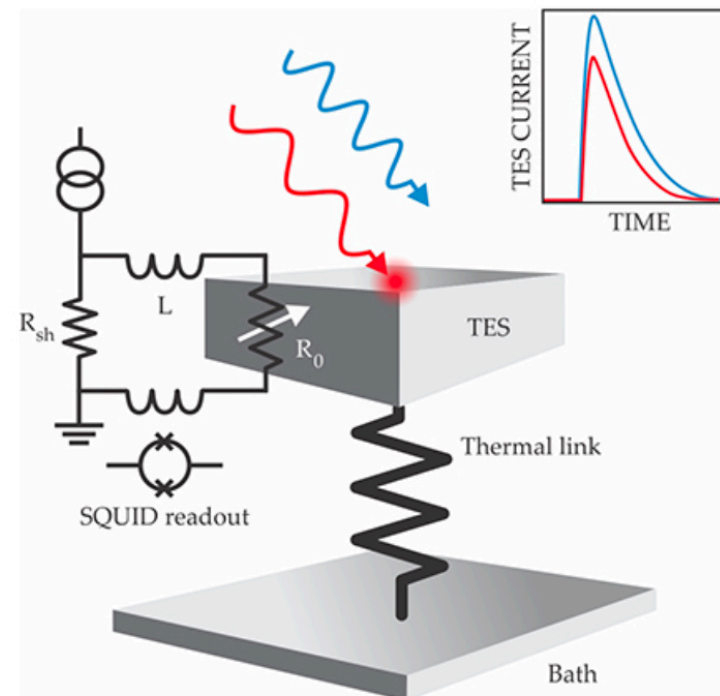
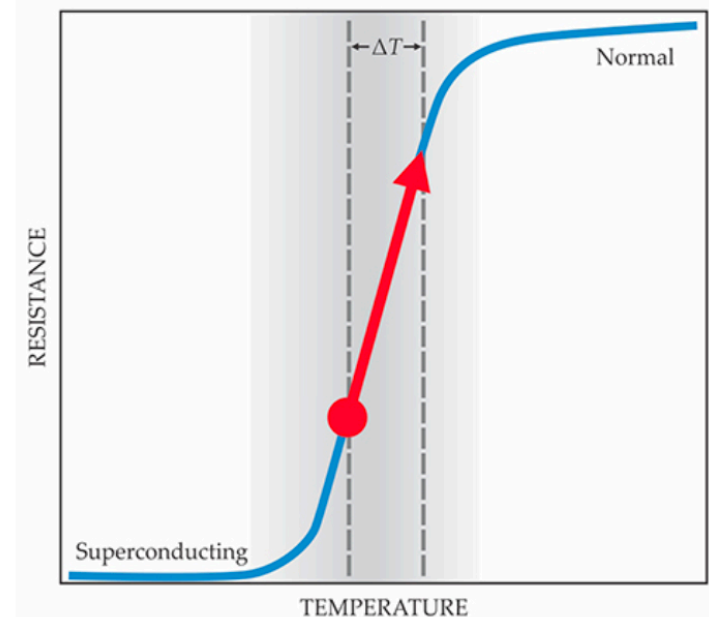
- No difference between shield open/closed or muon veto tagging — suggesting it's not an external radiation source
- Similar decay constant for different runs, but different rate
- Dependence on cooldown history?

New LEE findings from NUCLEUS, Georgio de Castello, EXCESS 2026



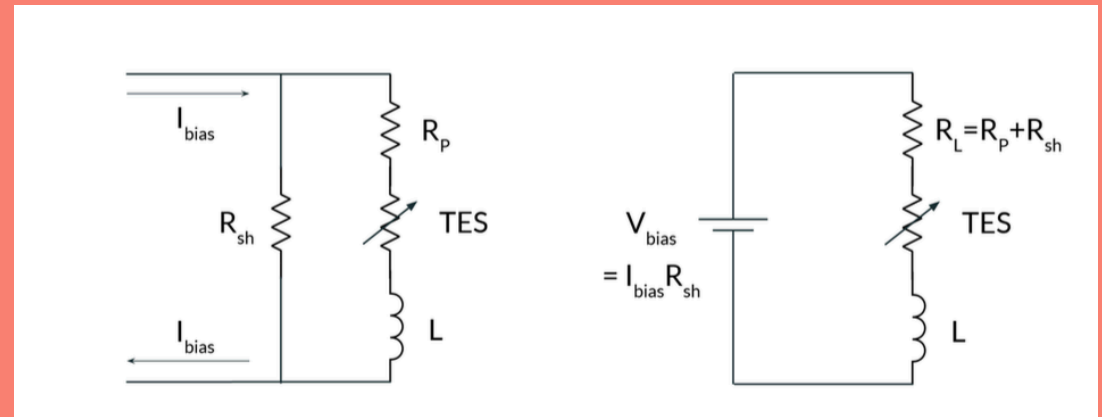
TES CONCEPT

- The concept of a transition edge sensor is simple: hold a superconducting sensor within the transition region, and detect the large change in resistance when it heats up.
- The challenge is to
 - Read out this sensor, and
 - reset the detector after heating made it normal-resisting.
- Solution: negative electrothermal feedback, allowing the device to re-set



TES CONCEPT

- **Constant current:** $P = I^2 R$, so if R increases, current increases.
- **Constant voltage:** $P = V^2 / R$, so decreasing power $\rightarrow$ negative electrothermal feedback
- Practically done by a current bias through a shunt resistor
- The inductance of the circuit is coupled to a Superconducting QUantum Interference Device (SQUID) which you can think of as just a readout device for our purposes
- Two governing equations; Kirchoffs law for the electric case, and the thermal interaction between the device, the bath and a possible energy contribution



TES EQUATIONS

$$L \frac{dI}{dt} = V_{bias} - IR_L - IR(T, I) + \delta V$$

Inductance

Voltage bias

Parasitic resistance

TES resistance

voltage impulse

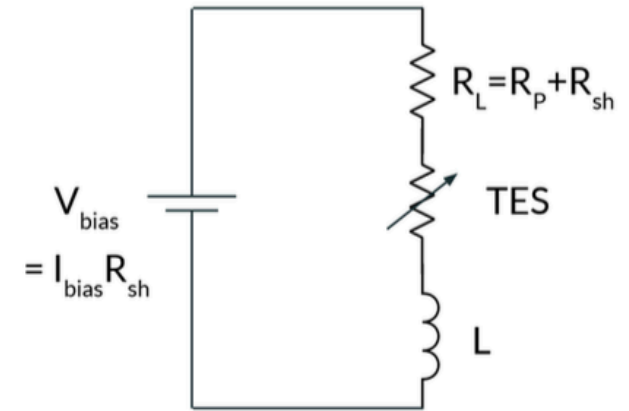
$$C \frac{dT}{dt} = P_J - P_{bath} + \delta P$$

Heat capacity

Joule Heating

Heat loss to bath

Heat impulse



TES EQUATIONS

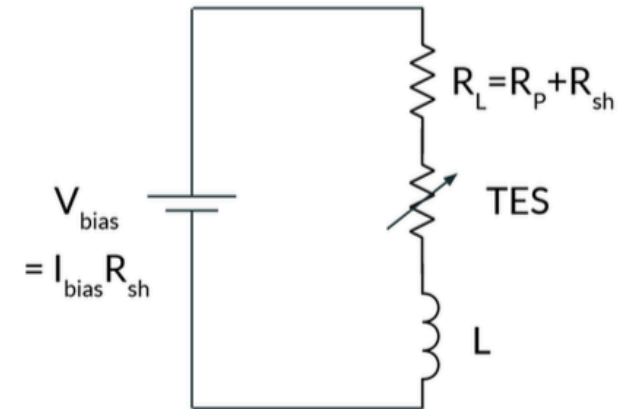
$$\alpha = \frac{\partial R}{\partial T} = \frac{R_0}{R_0} \frac{\partial R}{\partial T}$$

Change in resistance with temperature—

$$\beta = \frac{\partial R}{\partial I} = \frac{I_0}{R_0} \frac{\partial R}{\partial I}$$

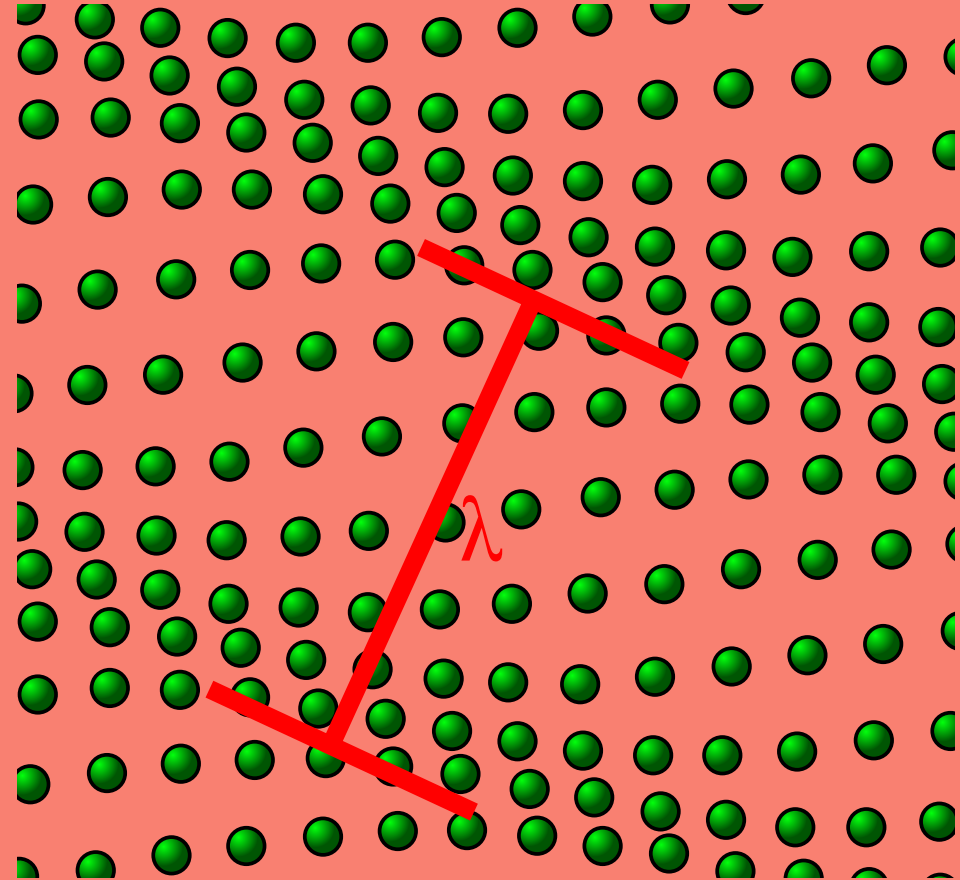
And with current

- Calibration will characterise the TES system, and we'd use these for reconstruction



PHONON

- Phonons are “quanta of vibration” — if you have any sort of crystal, the particles, being Quantum, will, at the lowest level behave like it, and only certain vibrational modes will exist.
- Phonons can behave as bosonic particles, scattering, being absorbed etc.



Wikimedia, by [FlorianMarquardt](#)

ATHERMAL PHONON SENSORS

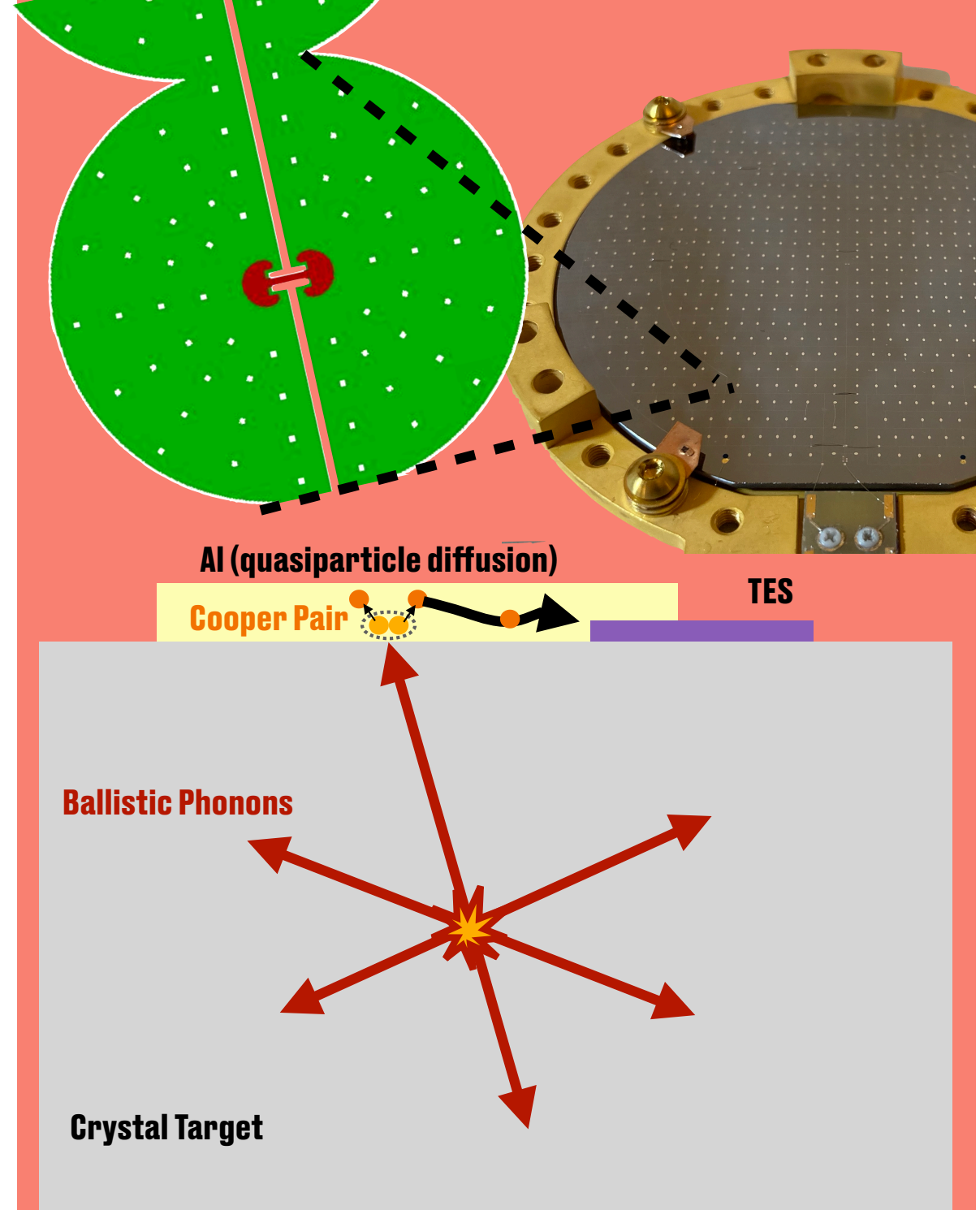
- Since the detector resolution improves with smaller heat capacity (volume) of the TES, we wish for this to be as small as possible
- However, then we don't have a target for our dark matter!
- Traditional solution: make a big absorber material, and use the TES to measure the temperature of this block of matter.
- However, that spreads the heat energy out thin, and worsens our energy resolution
- Another problem: details of thermal conductivity means that the TES will not be in thermal equilibrium with a big absorber

$$\sigma^2 \propto V_{TES} T_c^3 / \alpha$$

$$\sigma^2 \propto C_{abs} T_0^2$$

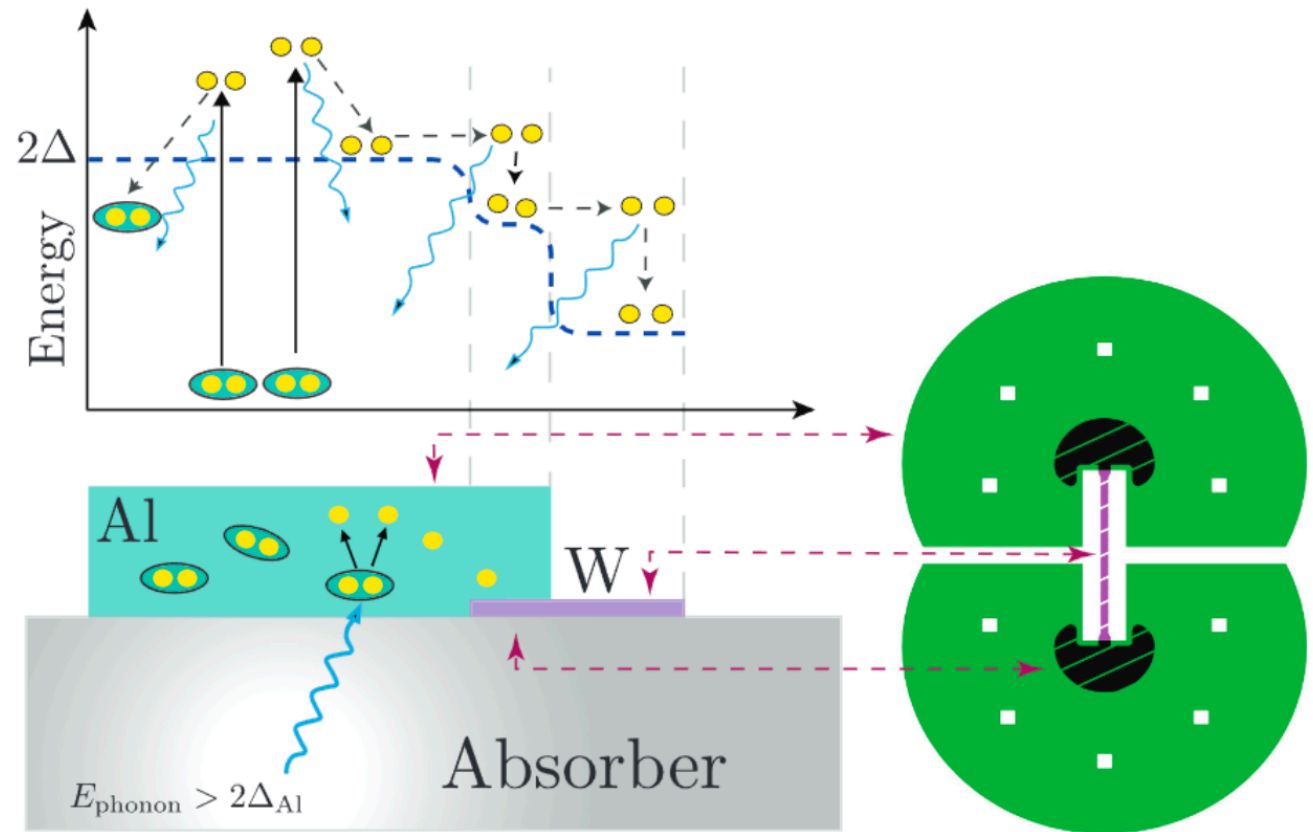
ATHERMAL PHONON SENSING

- The solution is to detect not thermal energy directly, but athermal phonons— vibrations ringing in the material before it has had the chance to equilibrate
- We trap the phonons in a Quasiparticle-trap-assisted-electrothermal-feedback-TES: QET: built up by
 - a block of absorber material,
 - on the surface, a superconducting collection fin of aluminium, giving the device a large surface area,
 - connected to a tungsten TES



ATHERMAL PHONON SENSING

- Phonons can break cooper pairs into quasiparticles that then travel through the fins, creating lower-energy excited states
- The tungsten has a lower T_c , which makes it concentrate these excited states, where they thermalise, concentrating the energy in the much smaller TES
- Despite that all these processes are lossy, the net effect is an enhanced sensitivity



Far and Wide: Searches for Particle Dark Matter with the LZ and TESSERACT Experiments
Michael Williams, PhD thesis

ABBREVIATIONS

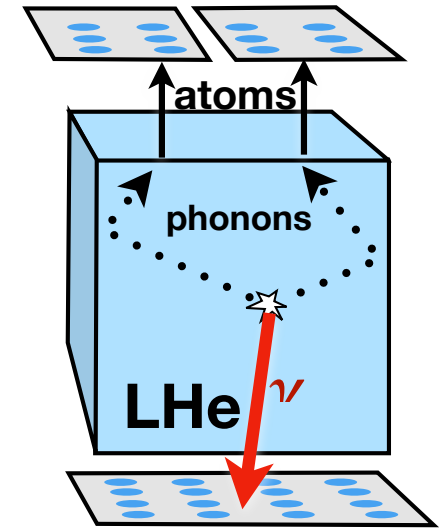
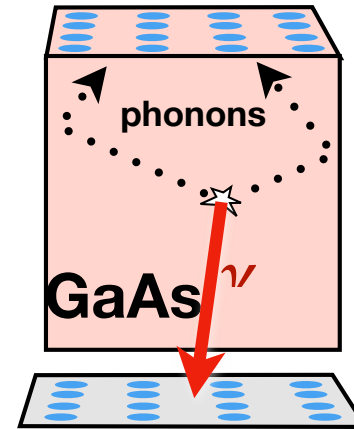
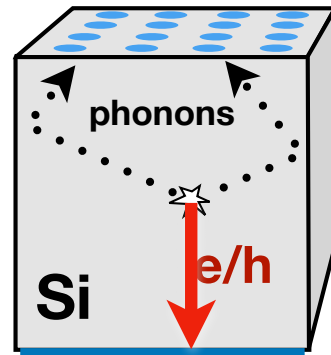
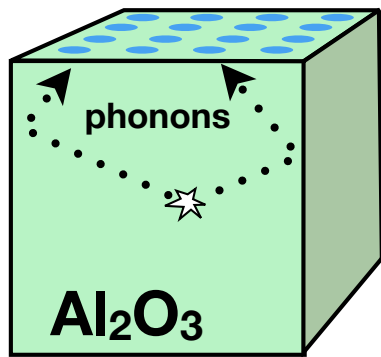
**Transition
Edge
Sensors with
Sub-
Eν
Resolution
And
Cryogenic
Targets.**

**Transition
Edge
Sensors**

**H
elium
Roton
Apparatus for
Light
Dark matter**

- I'll mostly be presenting the TESSERACT sensors here as emblems of the larger field :)

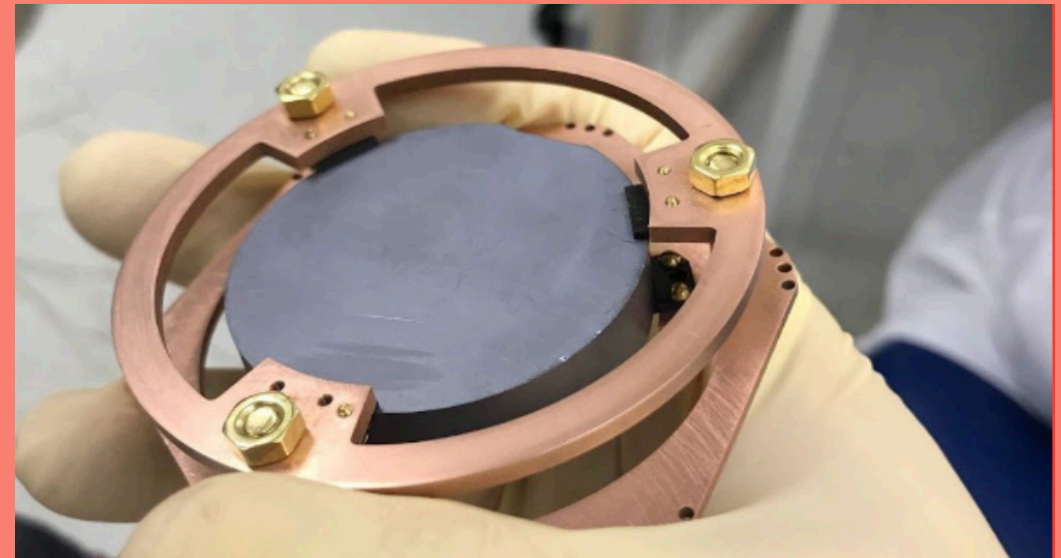
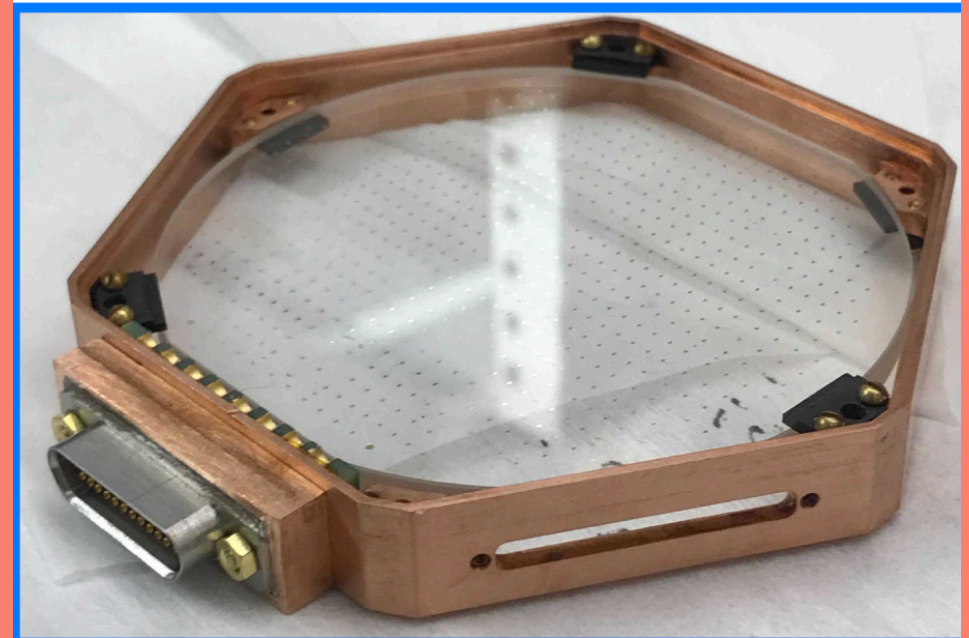
SEVERAL SENSORS!



- A program to share well-characterised and developed TES sensors (0.3 eV) with several sensors:
 - Sapphire
 - Silicon
 - GaAs
 - Superfluid helium

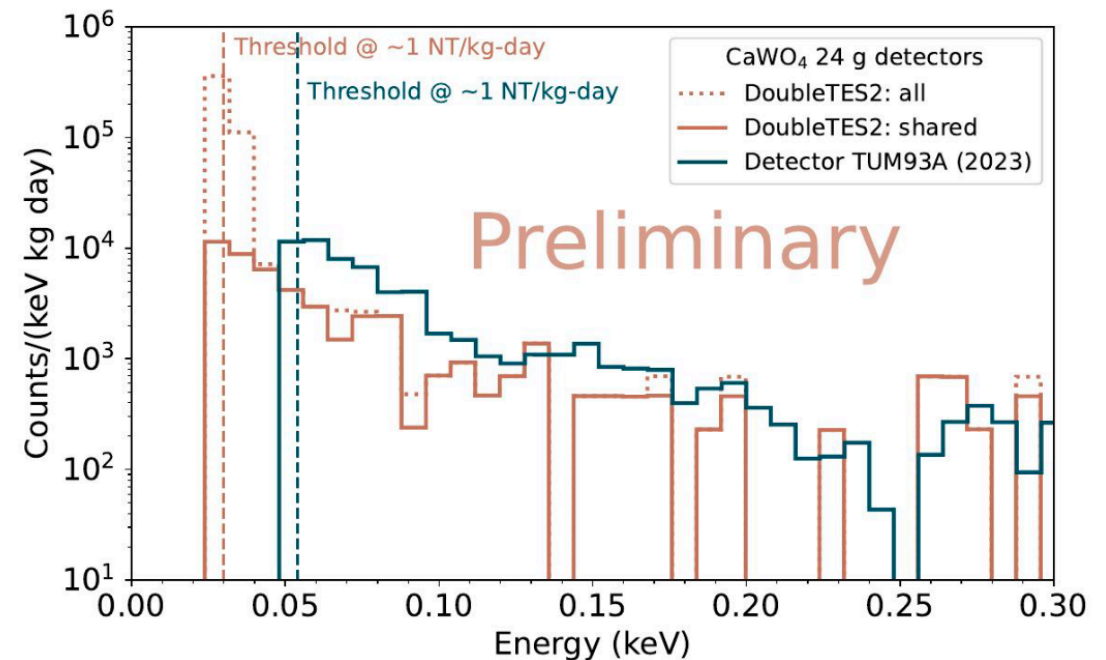
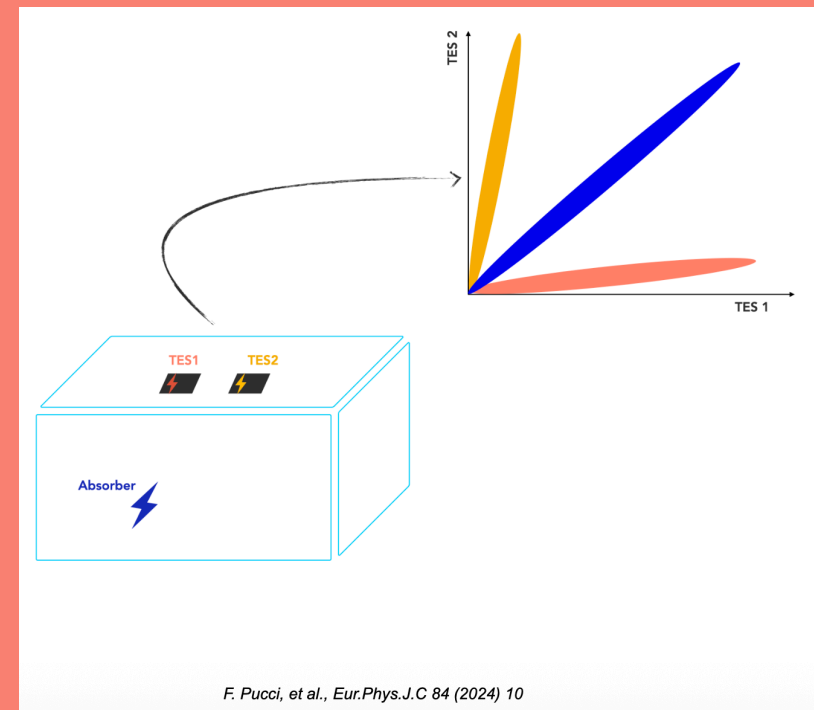
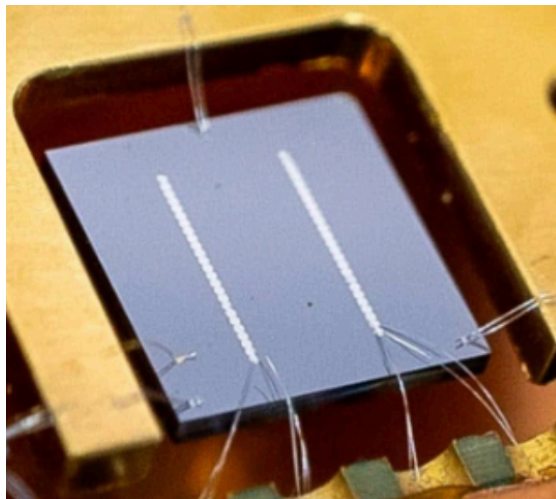
SAPPHIRE AND GAAS SENSOR

- Sapphire has a dense structure of allowed phonon modes allowing matching to low-mass dark matter
 - $\sim 0.1\text{eV}$
- Also couples to electrical dipoles to be sensitive to dark photons
- GaAs is polar, also allowing coupling to low-mass dark matter
- Also scintillation light— can operate phonon/photon coincidence to better characterise backgrounds



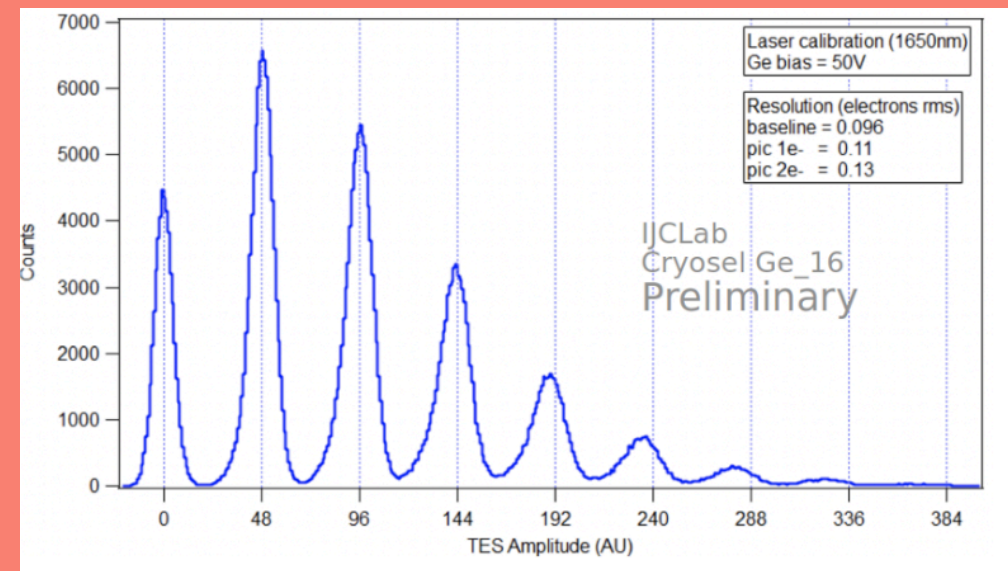
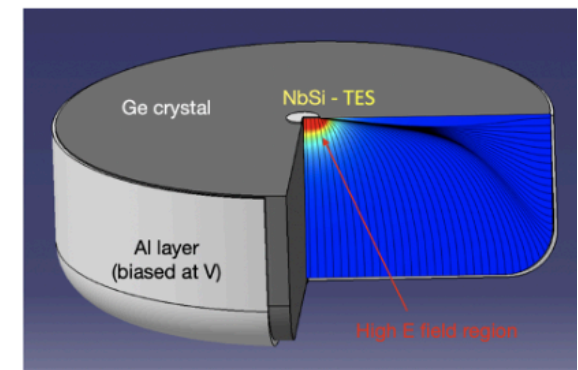
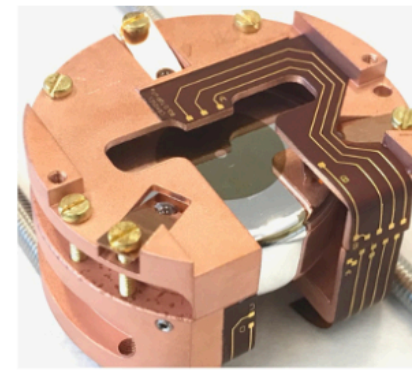
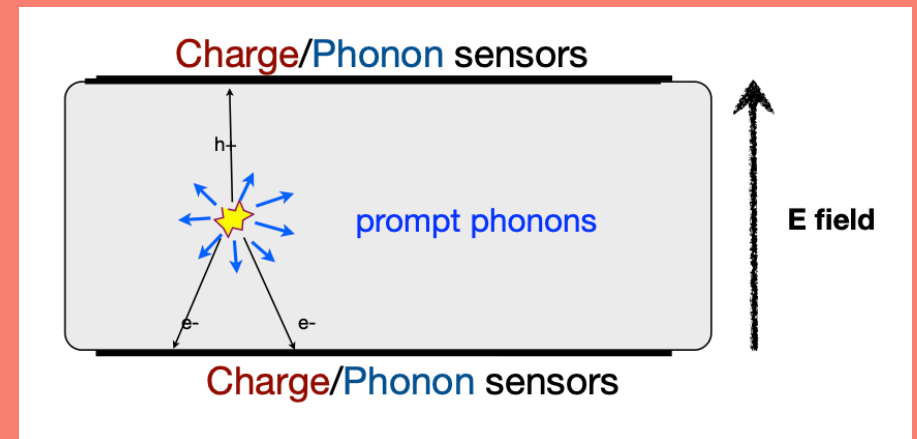
SAPPHIRE AND GAAS SENSOR

- In order to reduce the effect of backgrounds, these TESs operated in coincidence can reduce a significant amount of the background by reducing the TES-related noise



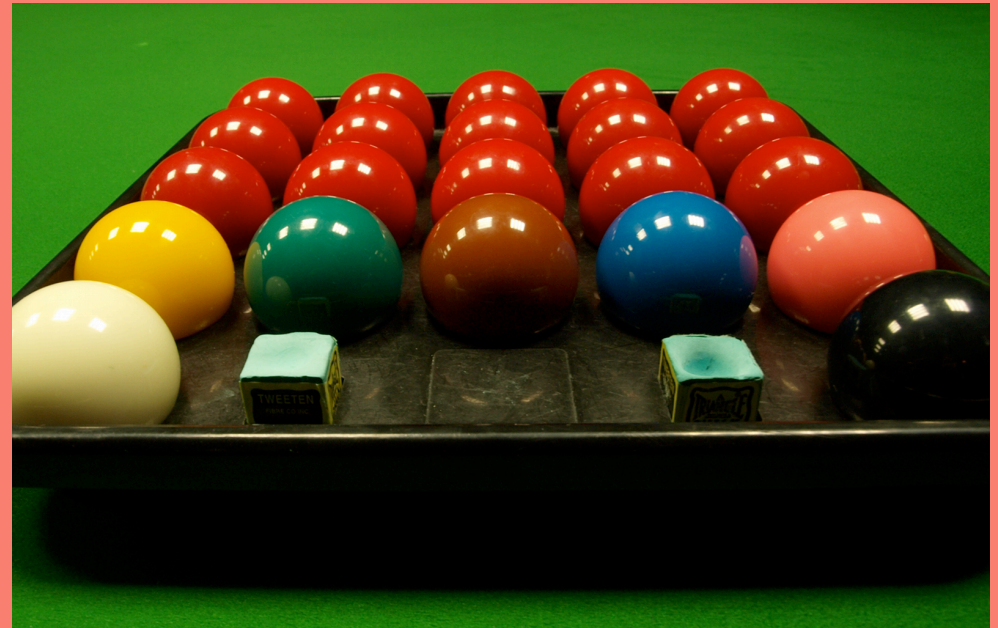
GERMANIUM SENSORS

- With a semiconductor crystal, you can detect both ionization and phonons
- Depending on the applied field, you can turn the electrons into further phonons via the Neganov-Luke effect
- Sensitivity to single-electrons



BENEFITS OF ⁴HE

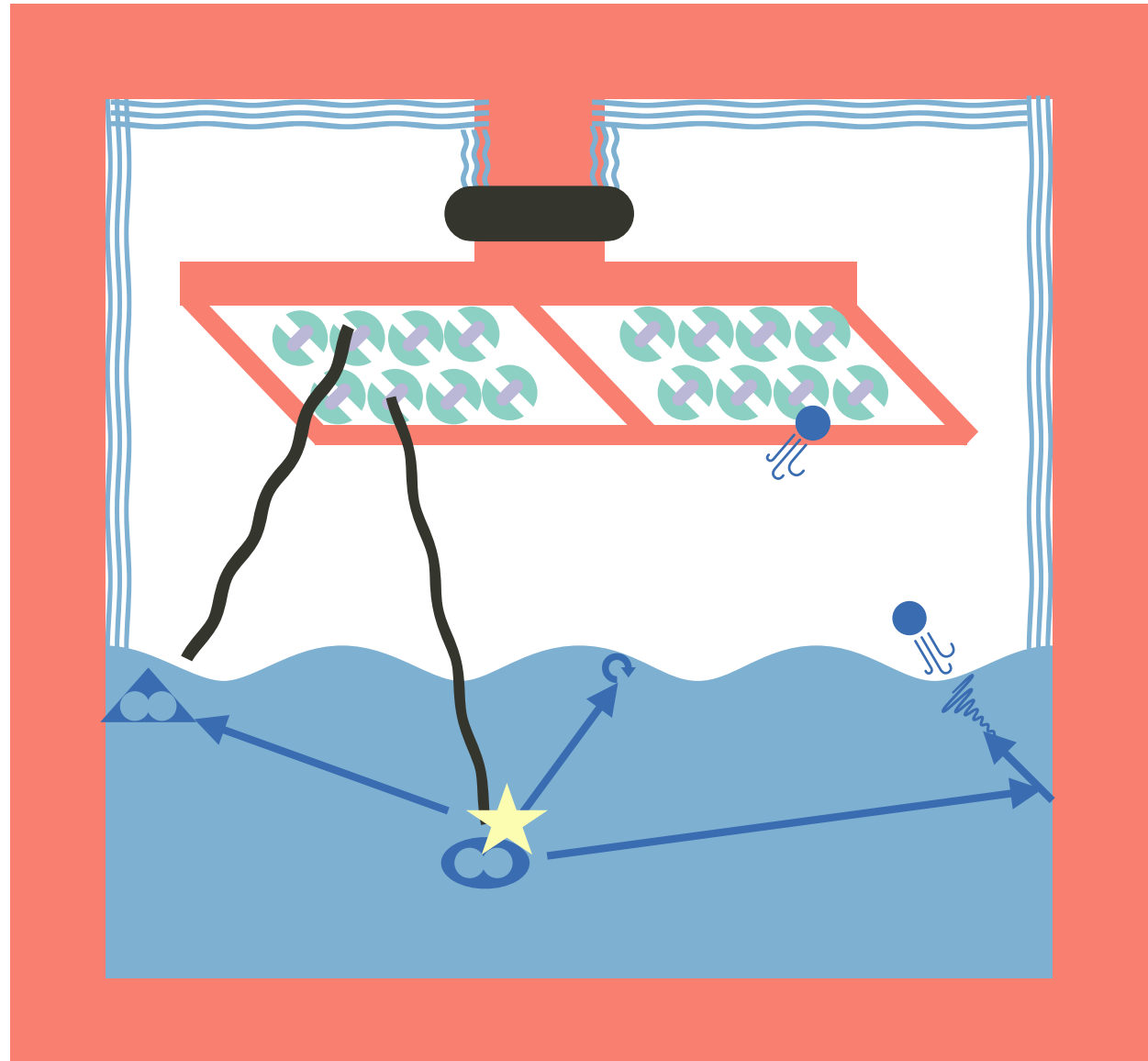
- **TESSERACT** aims to use several complimentary dark matter targets, all read out by transition edge sensors (TESs)
- Of these, superfluid helium offers no stress-related low-energy-excess (LEE) backgrounds
- Good match kinematically for $\sim 1\text{GeV}/c^2$ DM ($131/4 = 33$ times the maximum kinetic 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



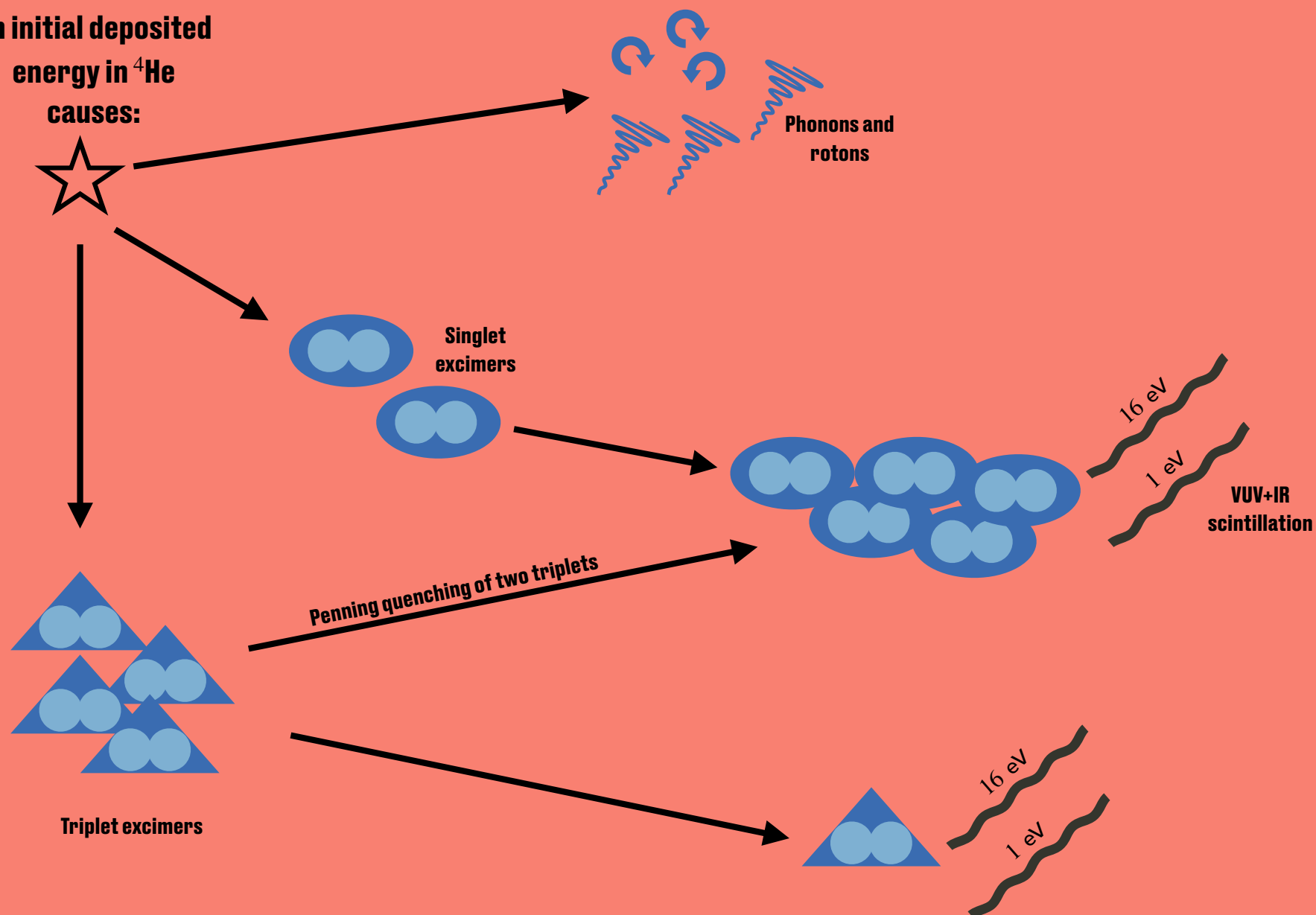
By barfisch - Own work, CC BY-SA 3.0, <https://commons.wikimedia.org/w/index.php?curid=17391023>

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

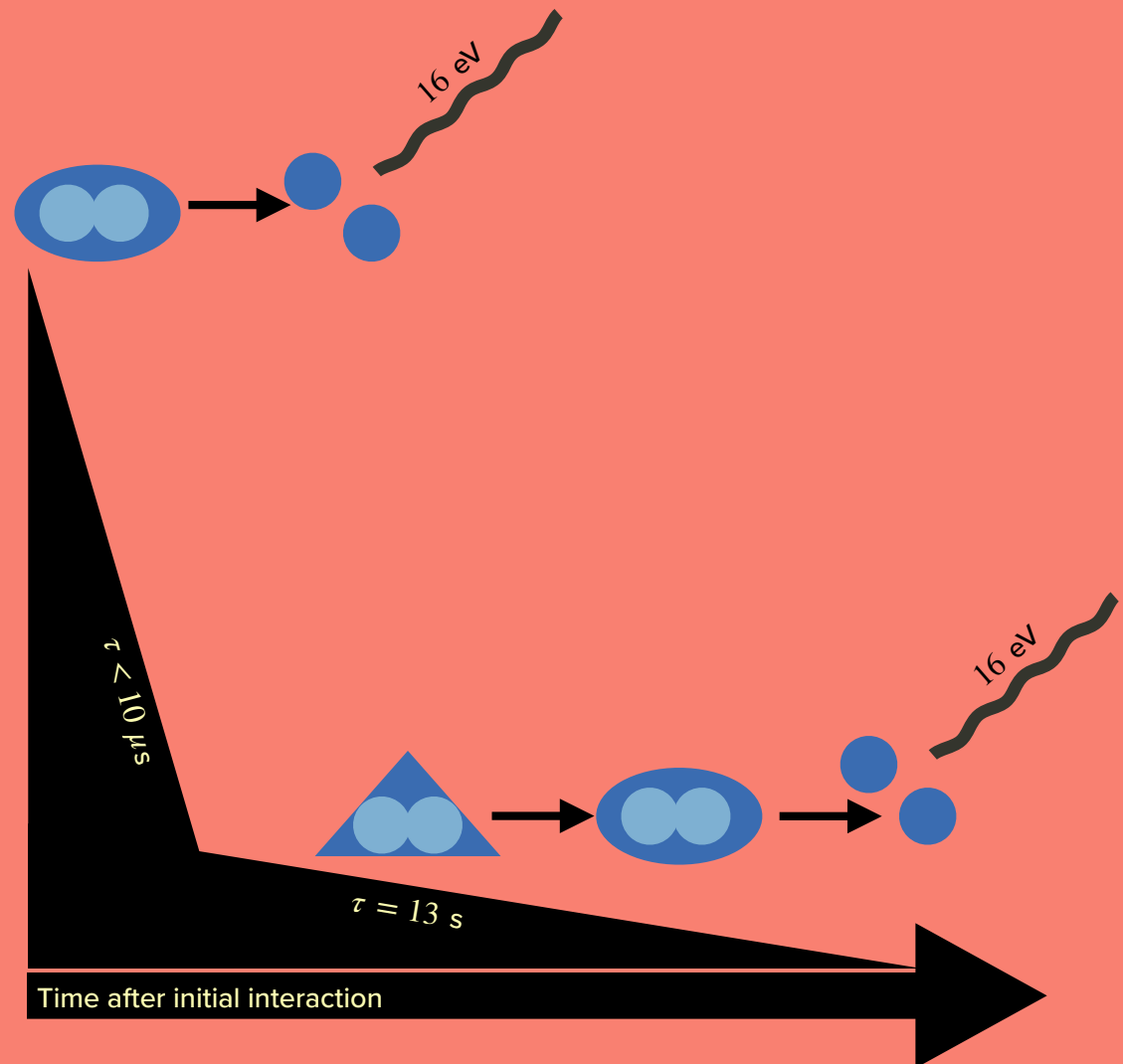


An initial deposited
energy in ^4He
causes:



SCINTILLATION LIGHT

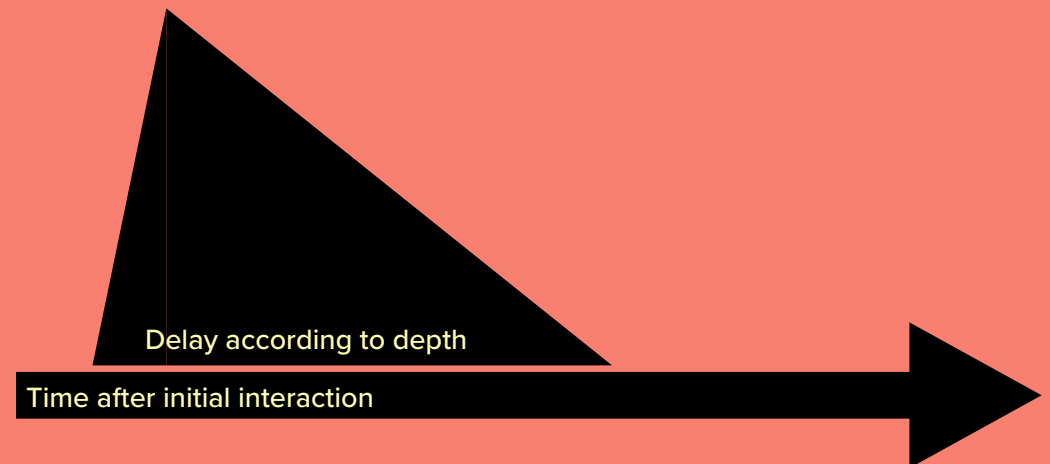
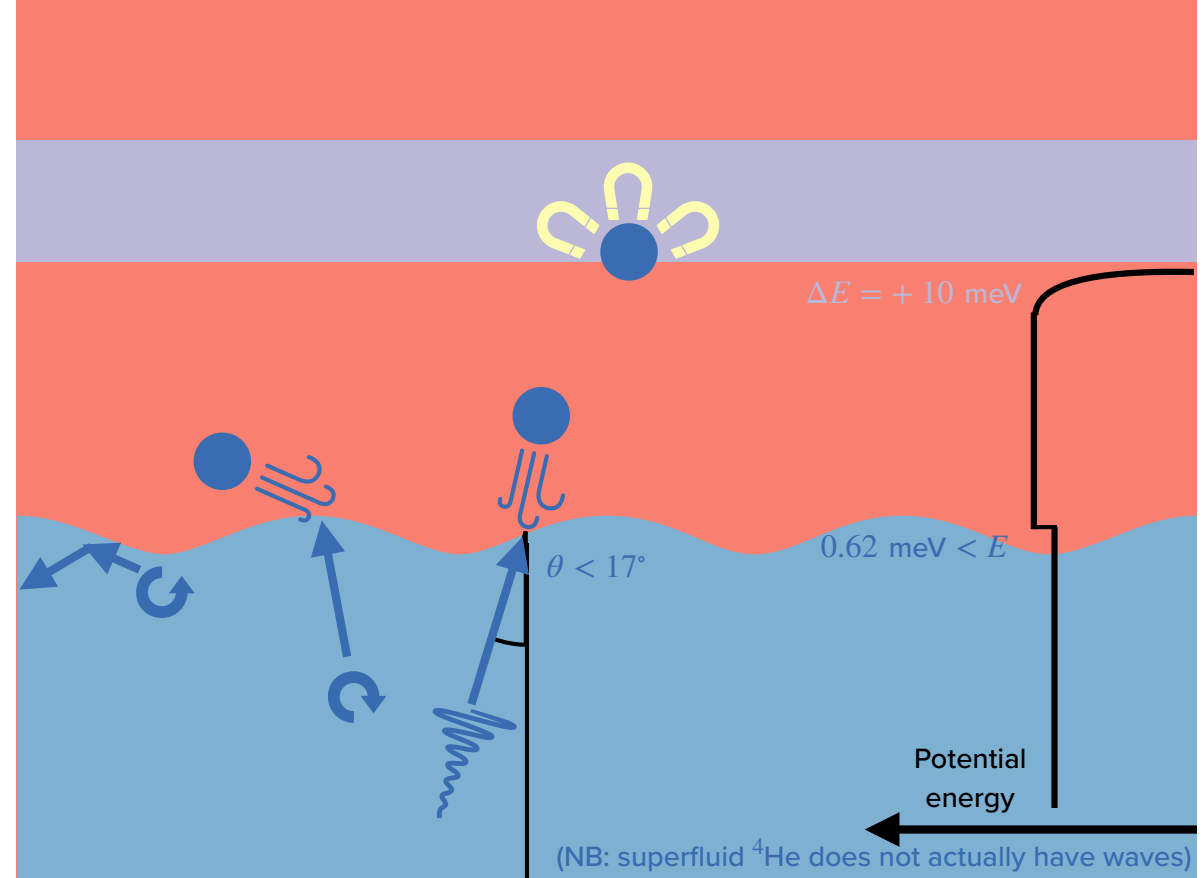
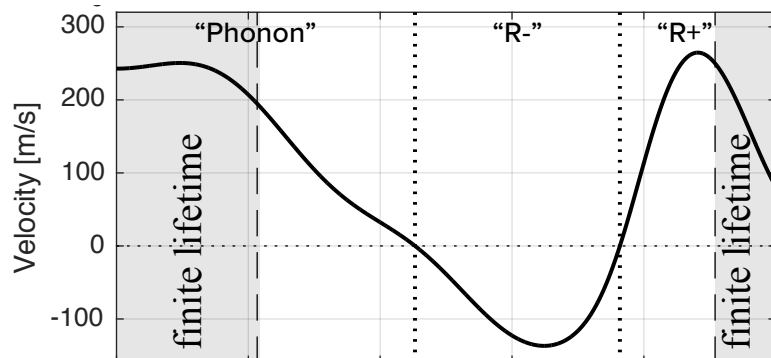
- Above the ^4He excitation energy of 19.8 eV, interactions can excite atoms into singlet and triplet dimers (or cause ionization that will recombine and create excitons)
- This also eliminates Compton scatter backgrounds at the lowest energies, leaving coherent γ -scatters
- Singlet dimers rapidly de-excite 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.



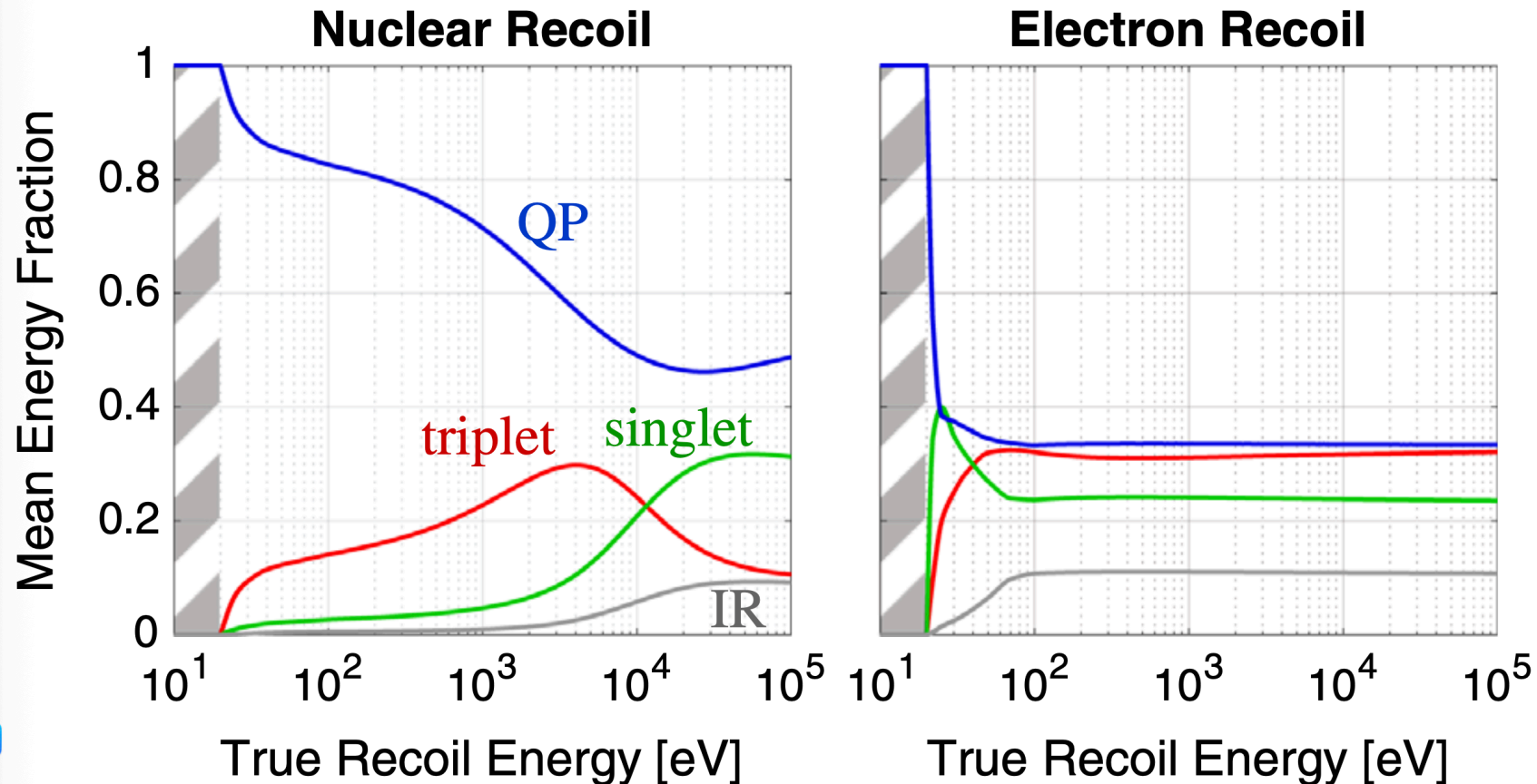
QUASIPARTICLE-INDUCED EVAPORATION

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 $\sim 100\mu\text{s}$ for each cm of depth
- When they reach a liquid surface, QPs with above 0.62 meV of energy can liberate single ^4He atoms which are emitted roughly isotropically.
- Requires a low angle, approx $< 17^\circ$ from normal for efficient transfer
- ^4He adsorbed at surfaces will release ~ 10 meV, giving a more than tenfold amplification of the QP signal energy



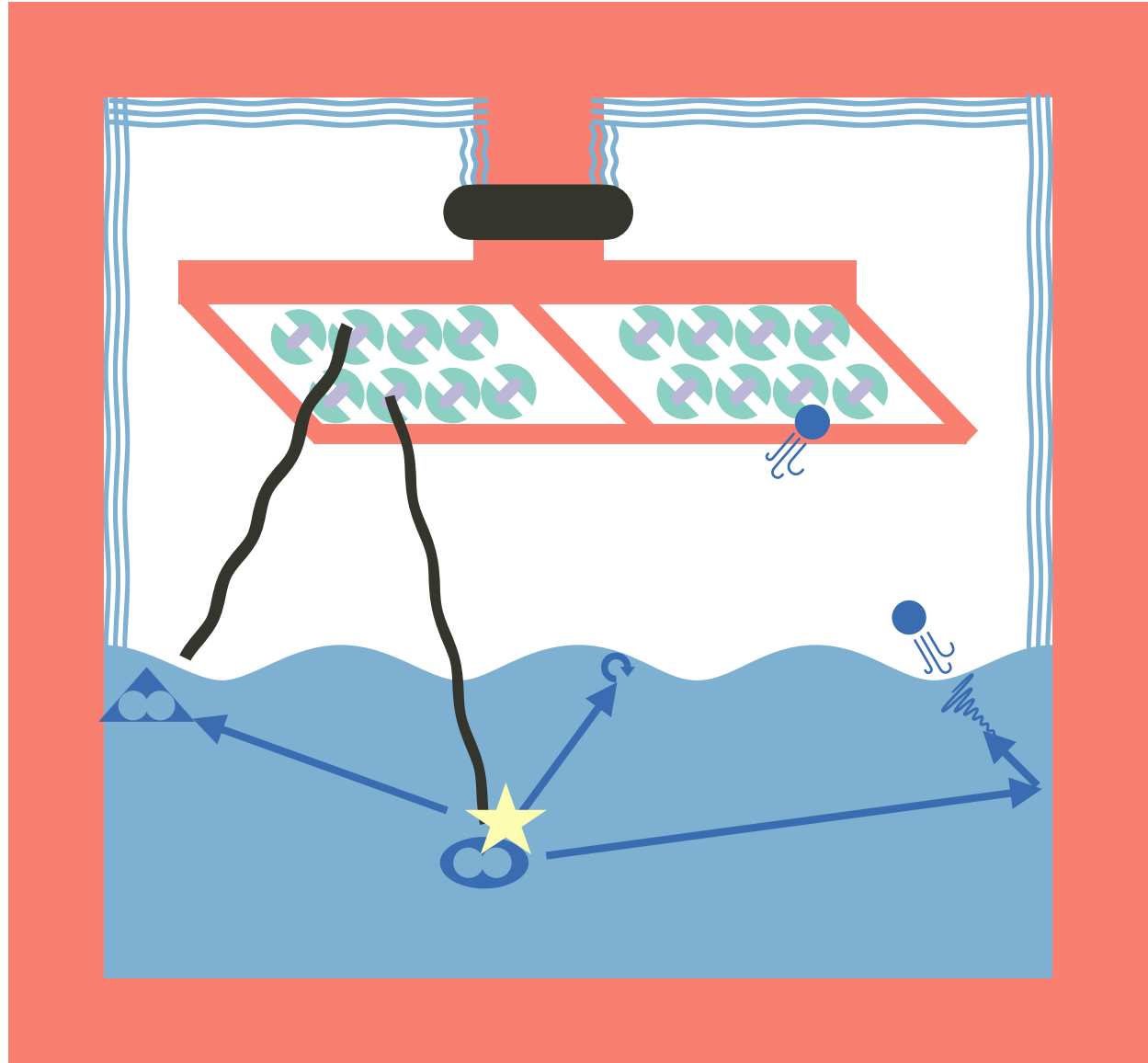
ENERGY PARTITION



- 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.

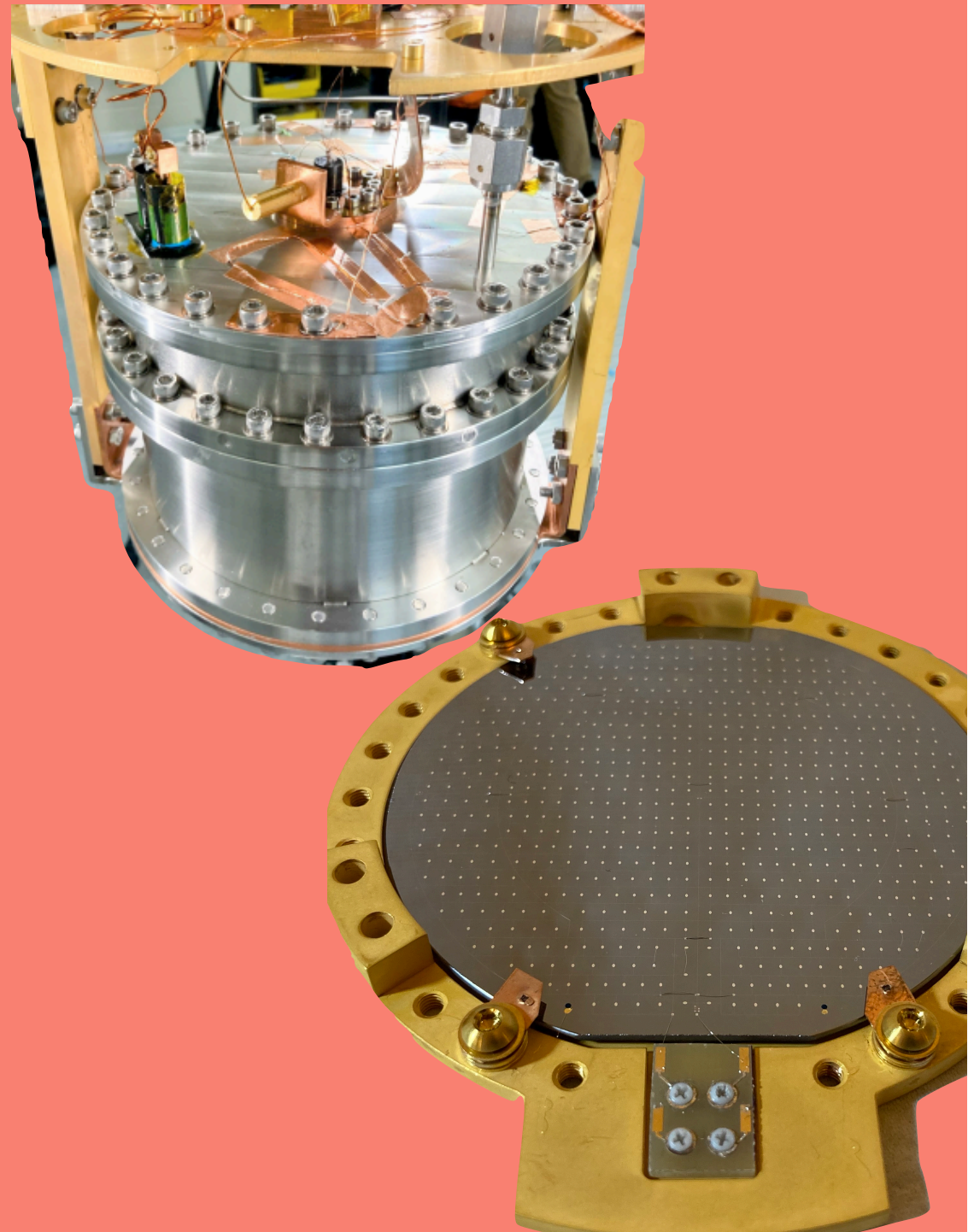
THE TESSERACT He CELL

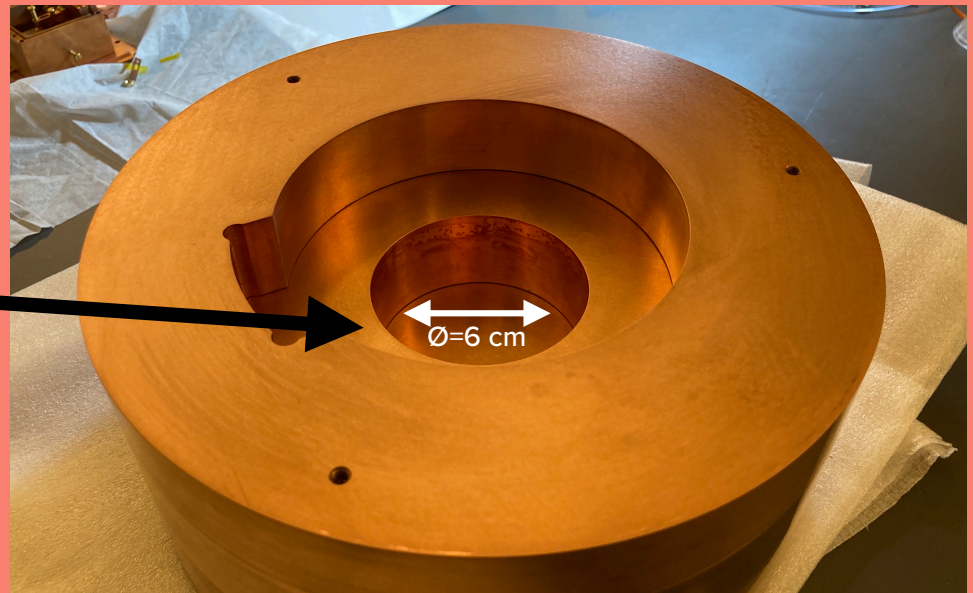
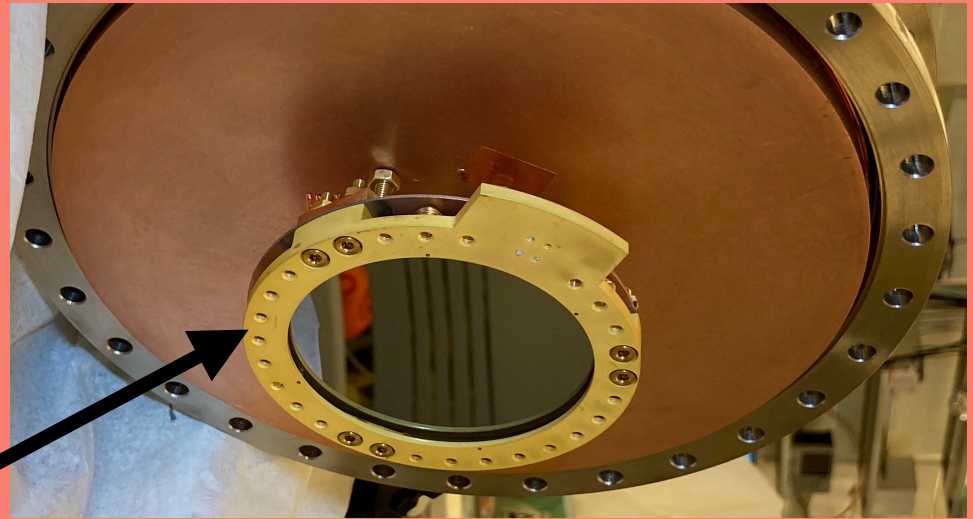
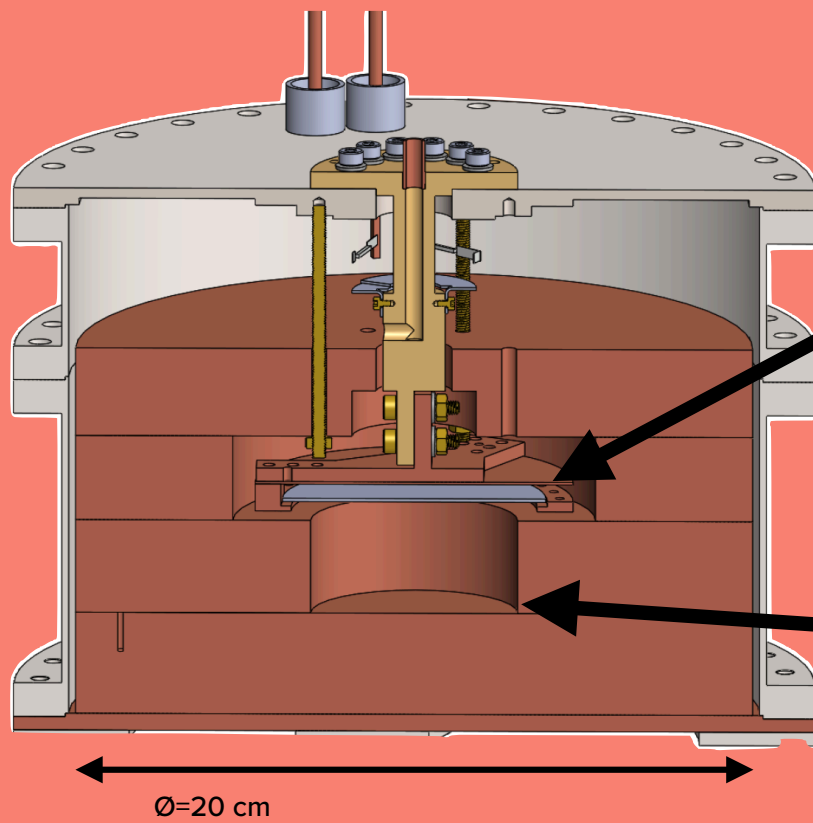
- Interactions in the target create QPs (and, above 19.8 eV excitons)
- Prompt dimer scintillation hits the sensors first,
- Followed by a QP evaporation signal as they hit the surface and knock He atoms up
- With a long tail of trimer scintillation following



HeRALD V0.1

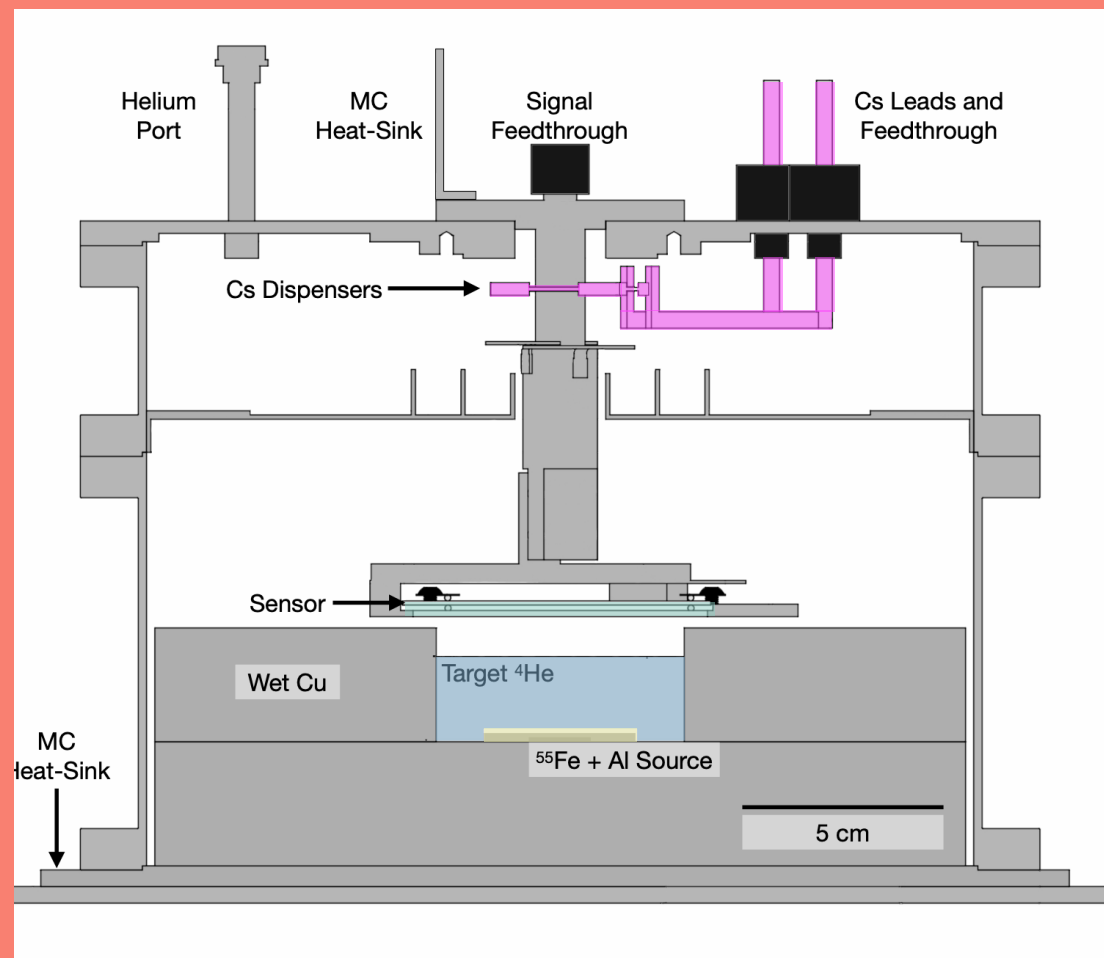
- A demonstration sensor using a two-channel design: a 3-inch 1mm thick Si wafer read out by a chain of hundreds of TESs in series
- Critical temperature: 51 mK
- $\sim 10 \text{ g } ^4\text{He}$ target,
 $^3\text{He}/^4\text{He} < 5 \times 10^{-13}$
- Aims:
 - Demonstrate superfluid He target interactions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





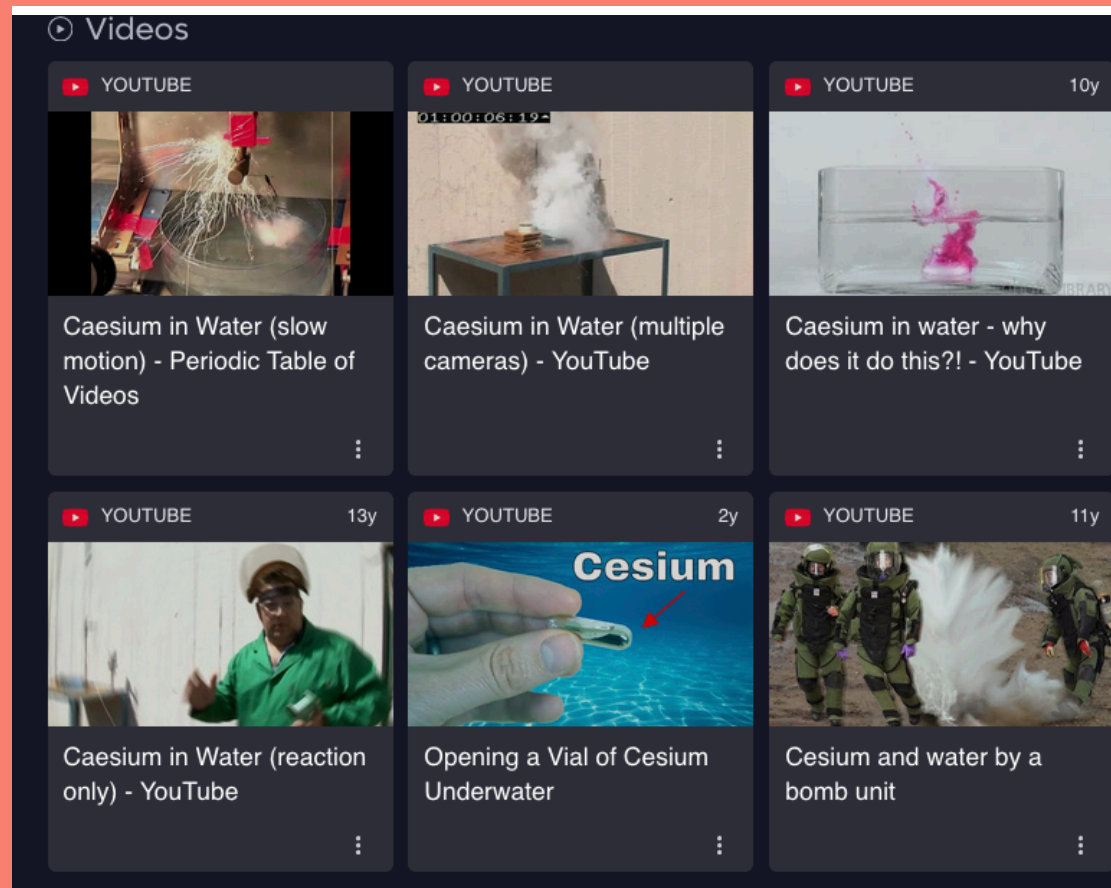
KEEPING THE SENSOR DRY

- 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.



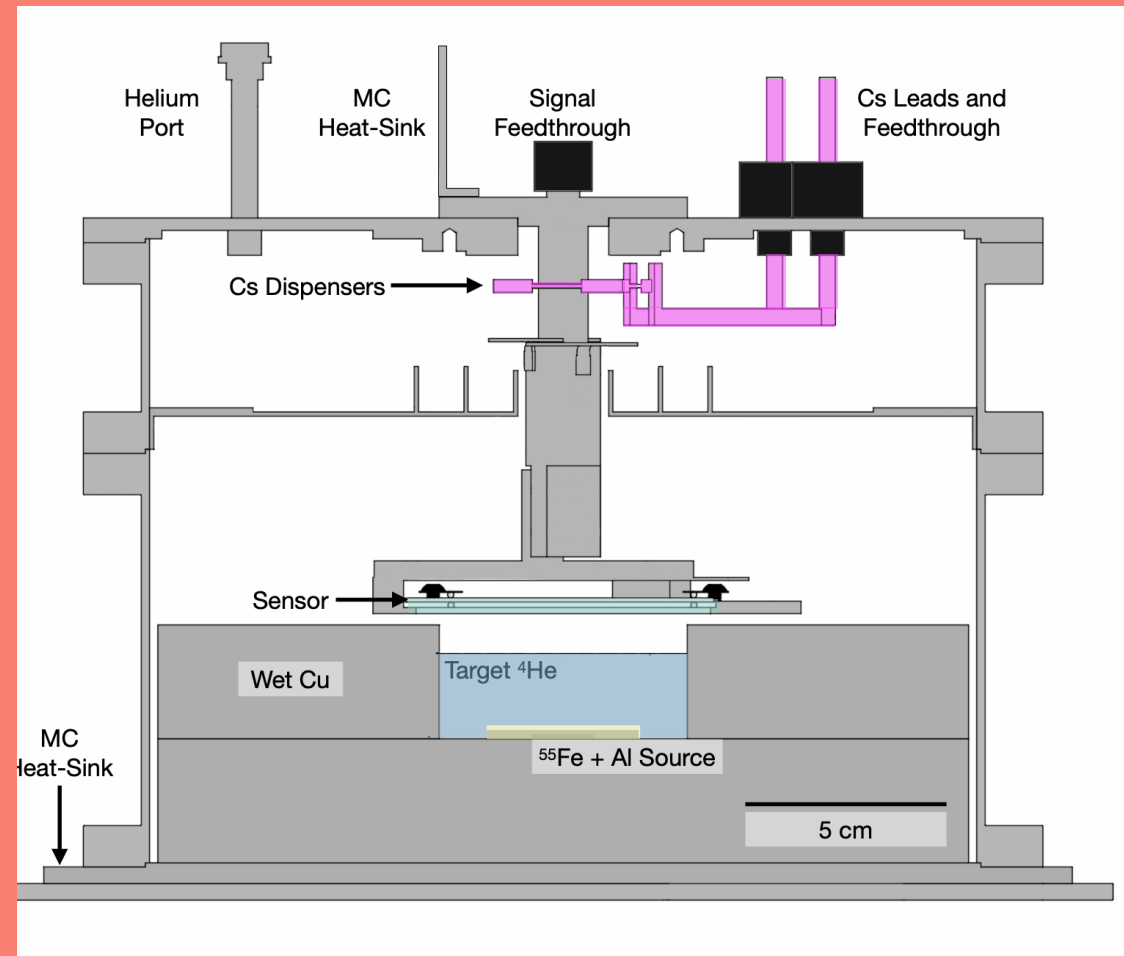
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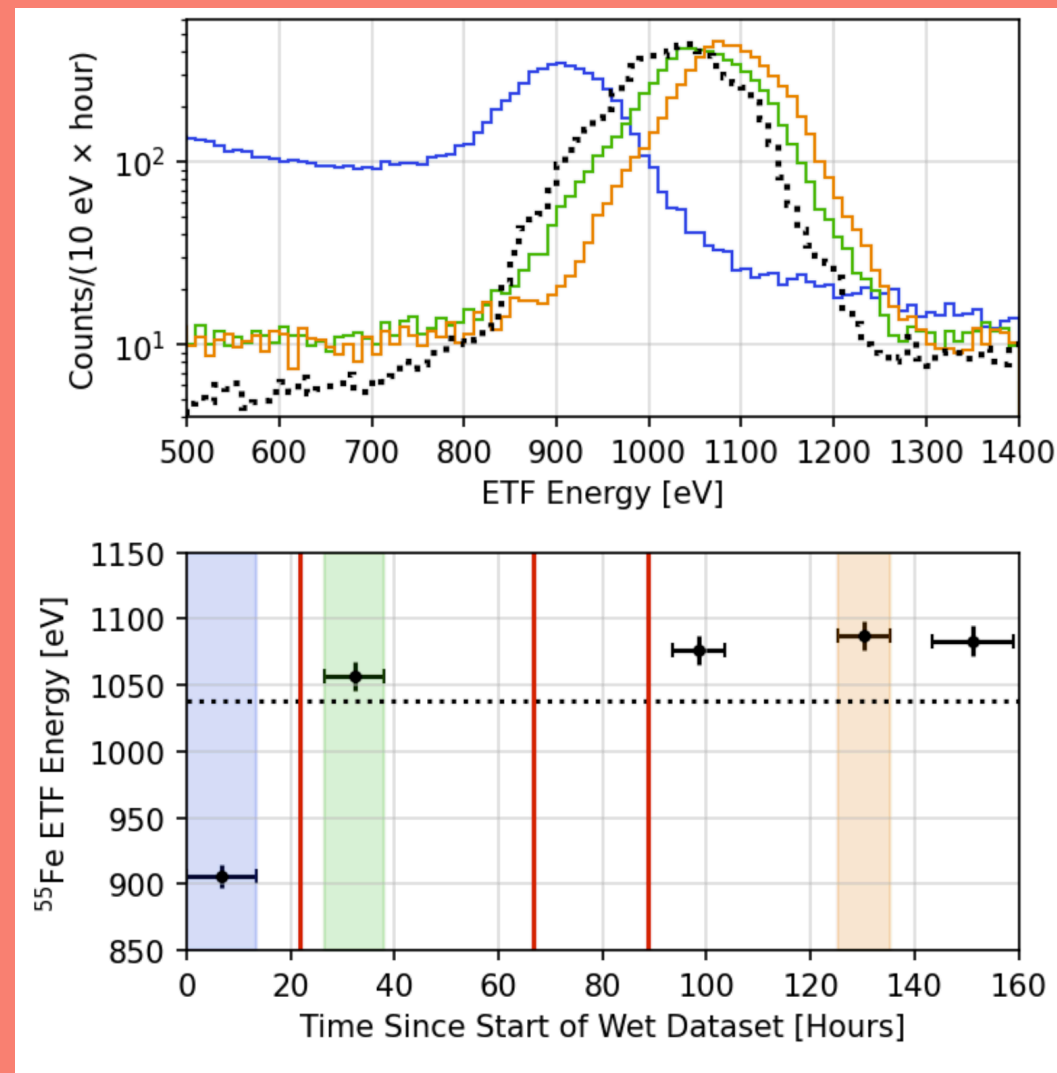
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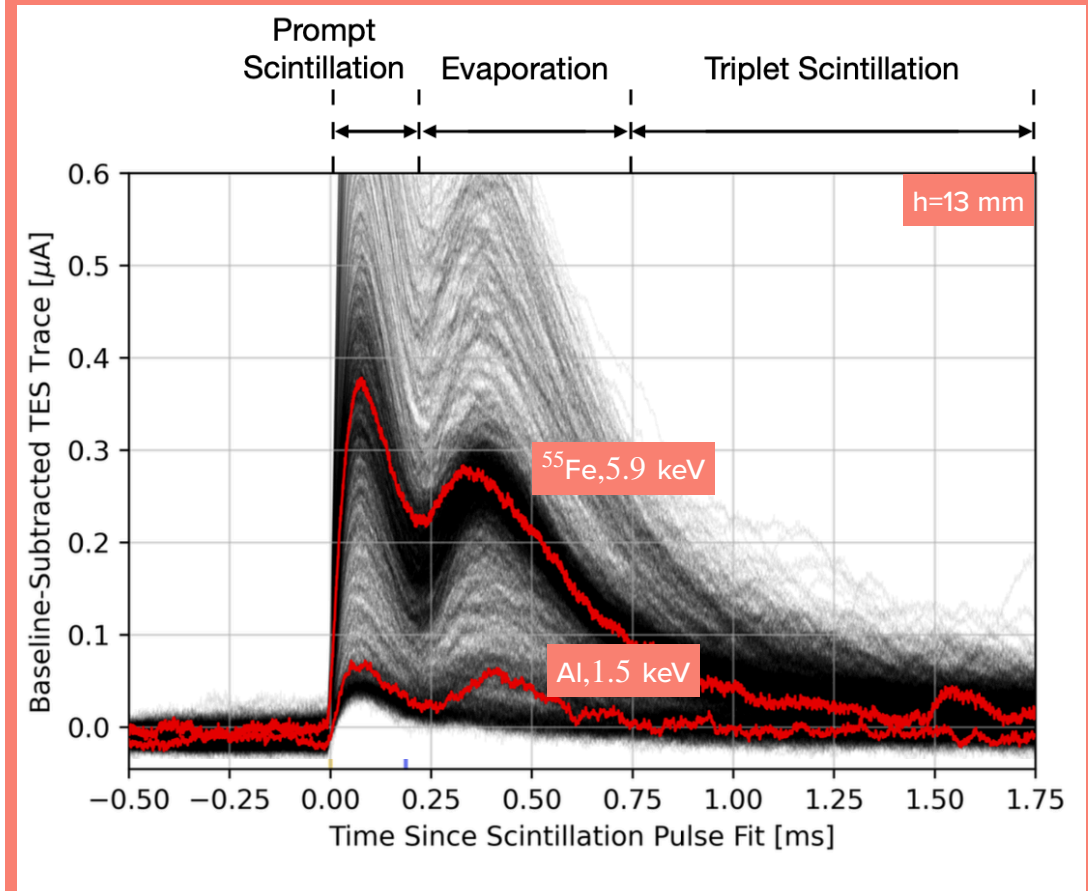
KEEPING THE SENSOR DRY

- 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



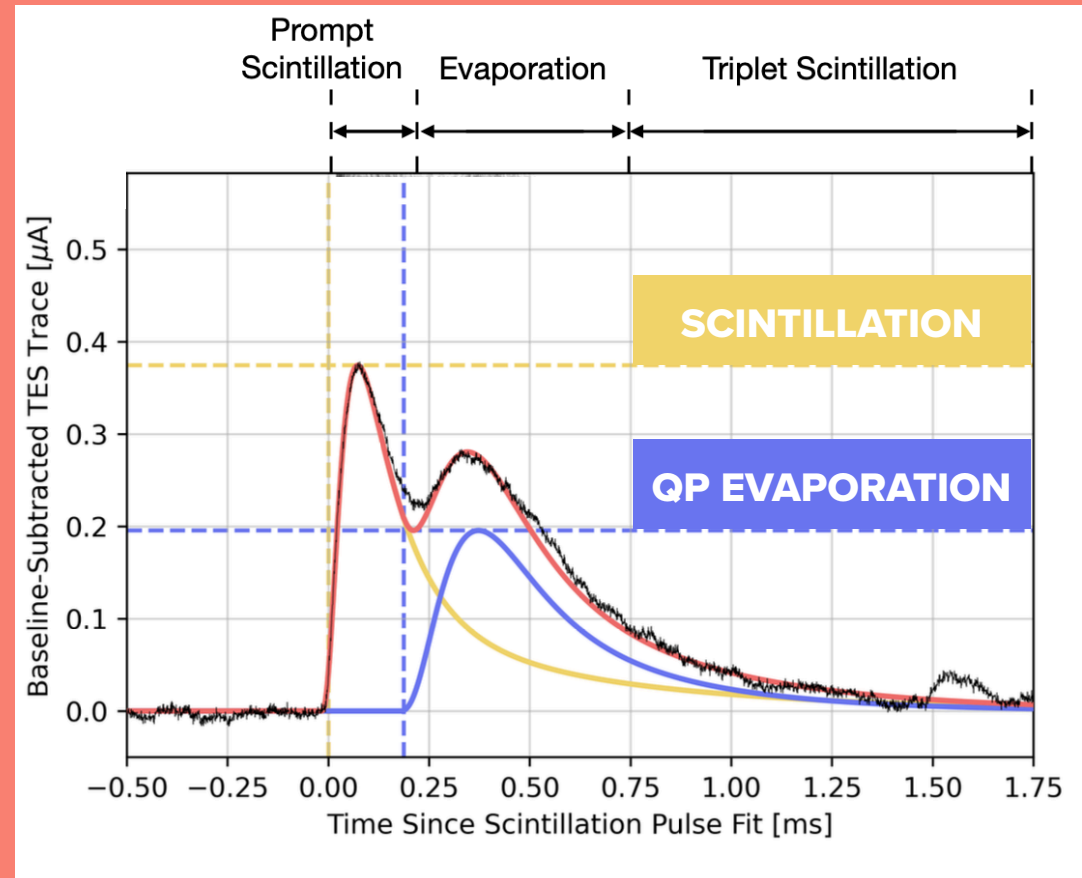
COLLECTED DATA

- 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

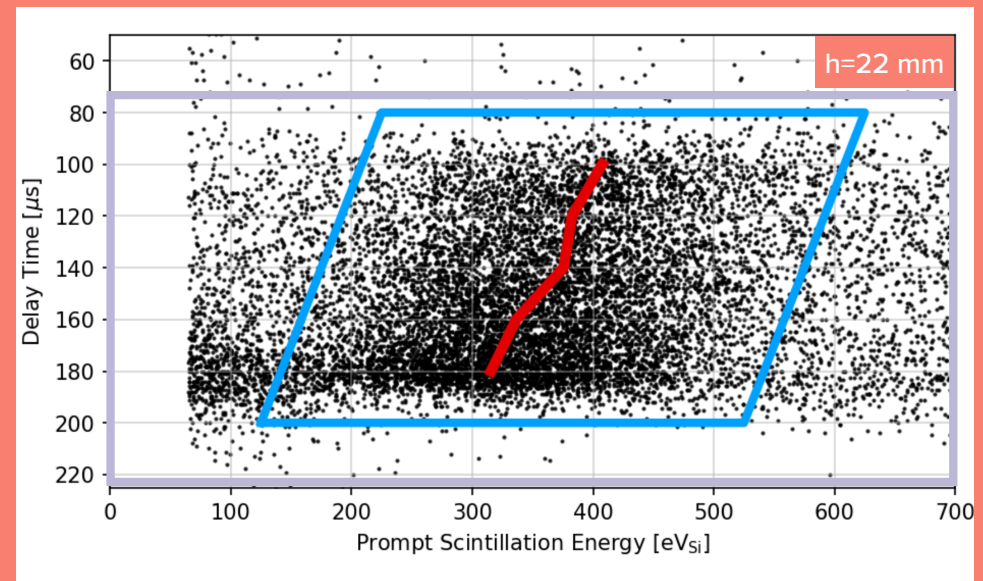
- The data is reconstructed using a two-step optimum filter algorithm,
 - First, a scintillation-only template is used to select reconstruction candidates
 - These candidates in a 5 ms window are reconstructed using a second optimum filter fit with a scintillation and QP evaporation signal template
- 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 γ s 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

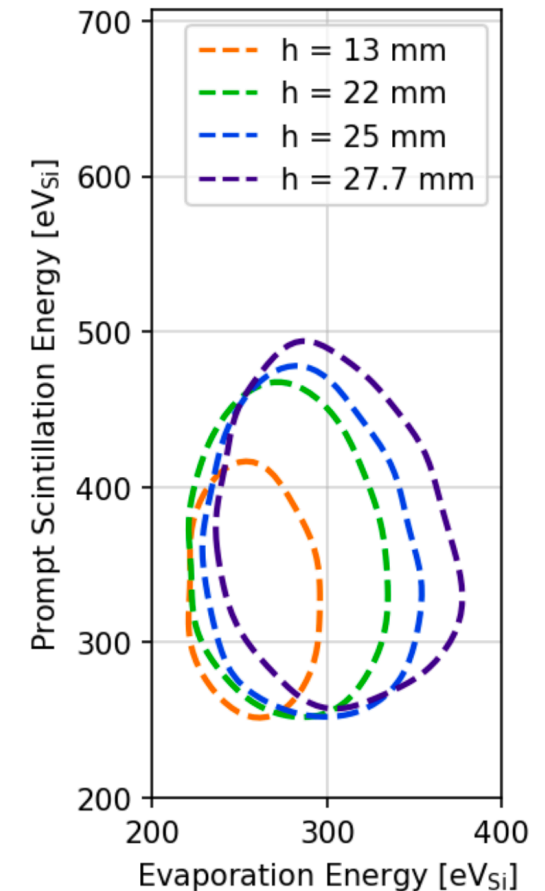
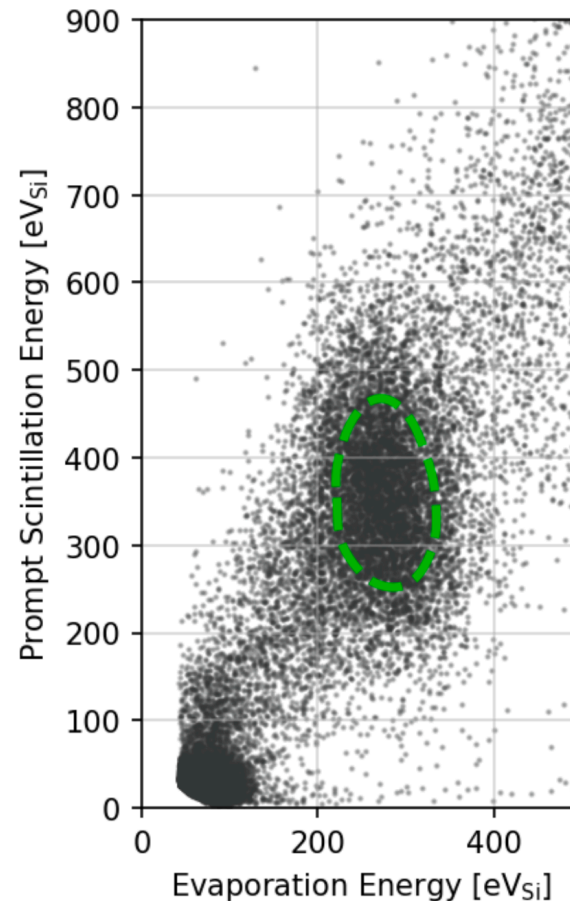
- Loose scintillation-to-QP evaporation delay time cuts aim to select events in the He bulk
- χ^2 cuts select away events with a very poor template fit
- a ^{55}Fe selection is applied in energy+delay time to choose these events
- The detector energy scale is computed from pre-fill 1.5 keV Al fluorescence 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



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

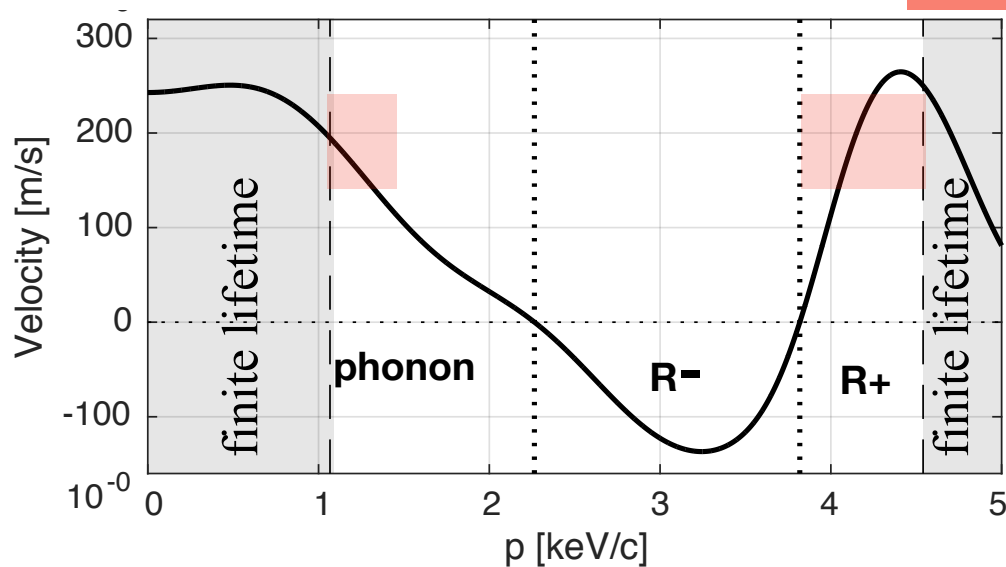
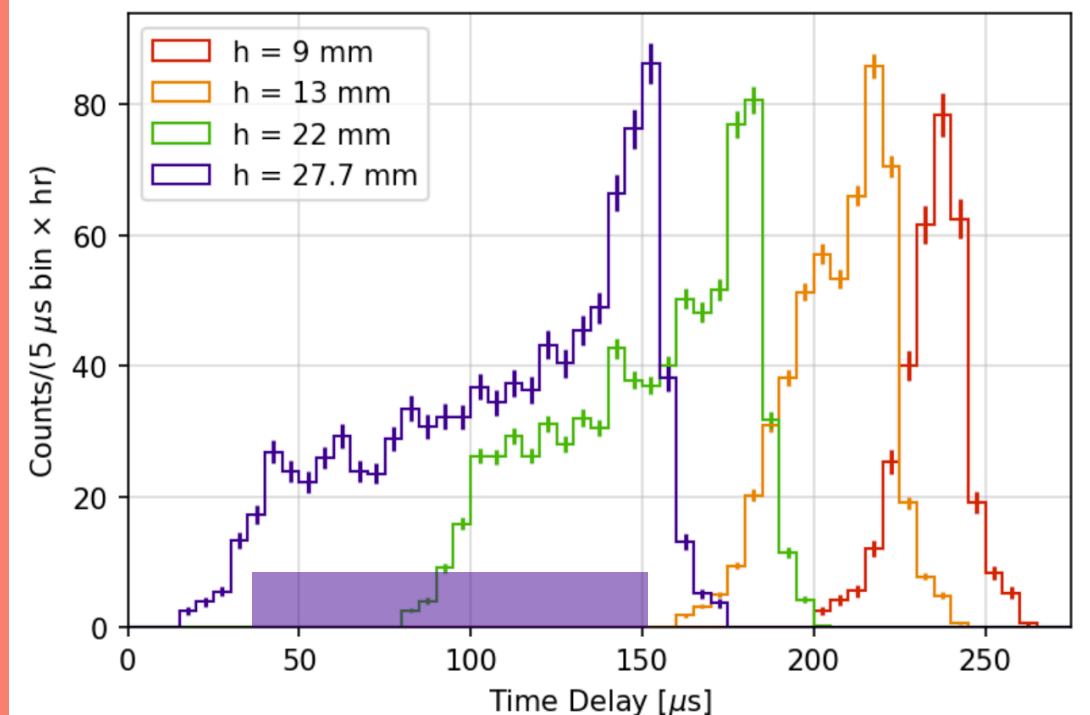


DEPTH DEPENDENCE

- 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

$$\frac{27.7 \text{ mm}}{(150 \mu\text{s} - 40 \mu\text{s})}$$

$$\sim 250 \text{ m/s},$$

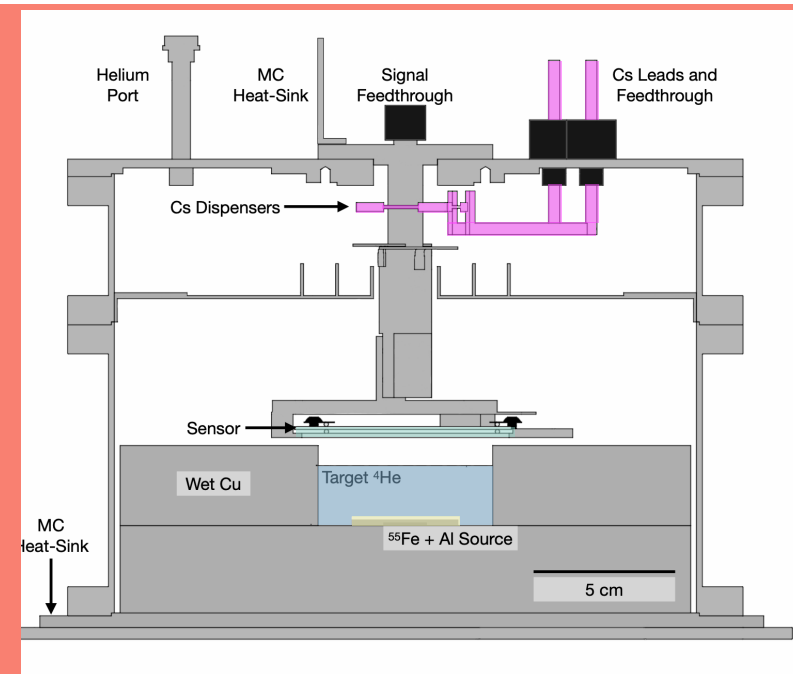
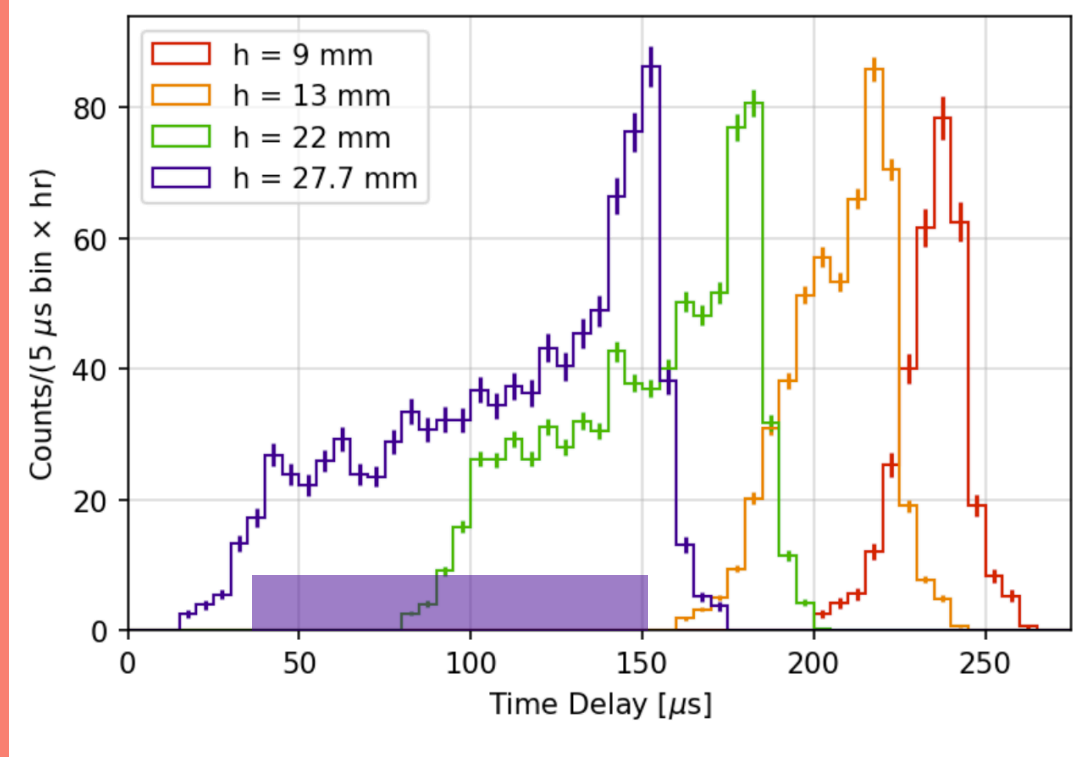
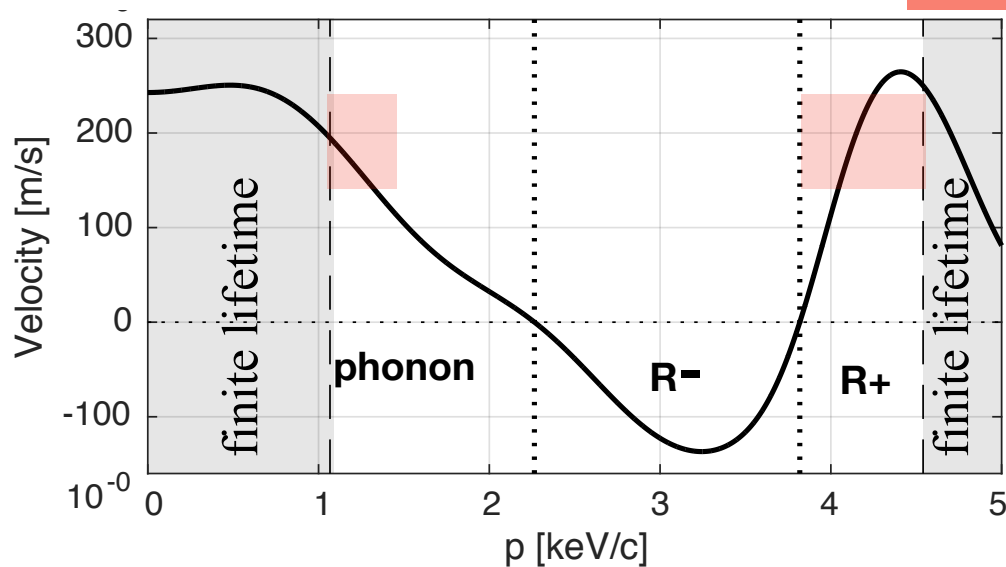


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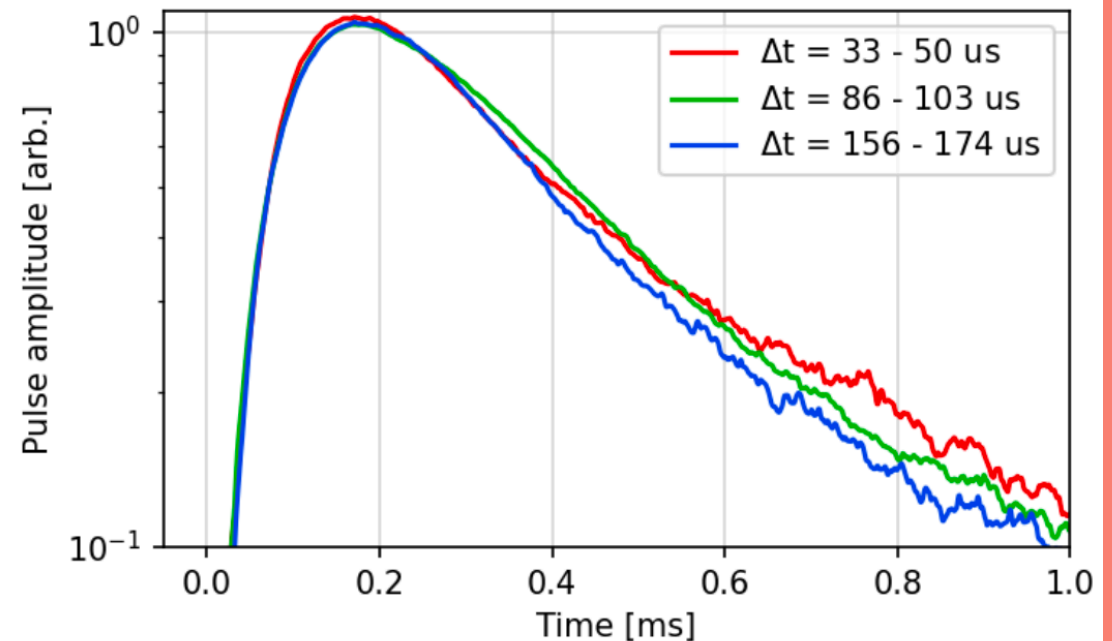
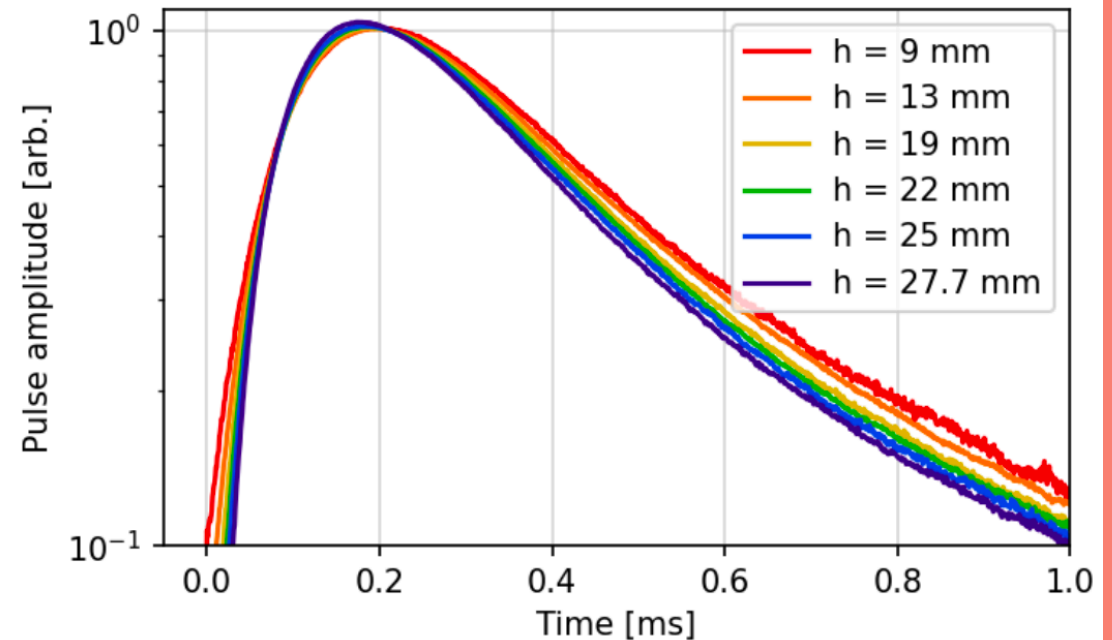
$$27.7 \text{ mm} / (150 \mu\text{s} - 40 \mu\text{s})$$

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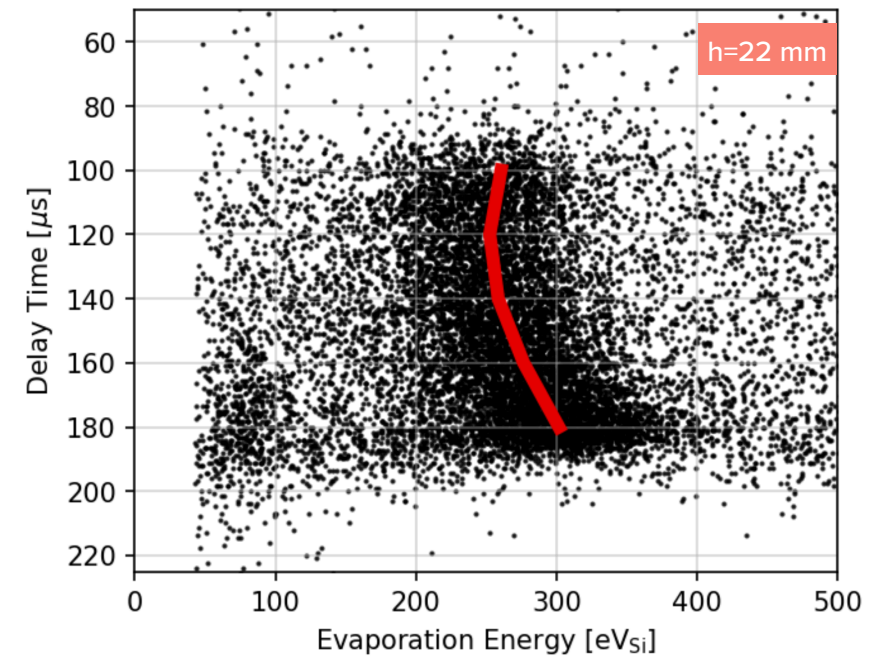
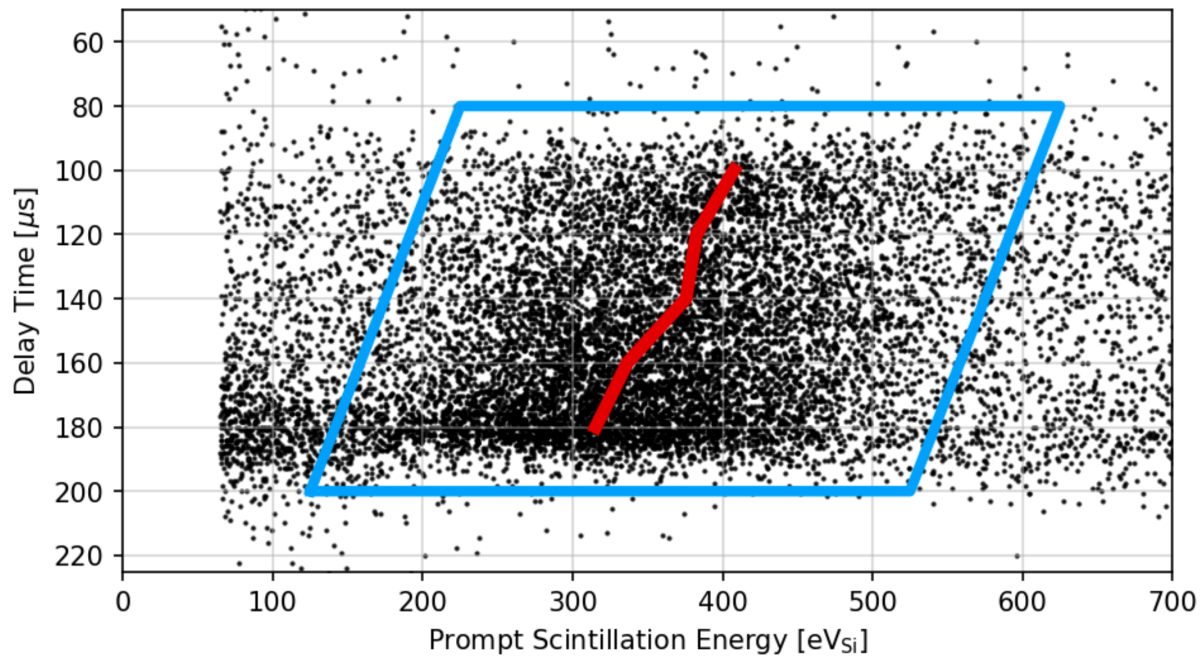


SHAPE OF EVAPORATION SIGNAL

- 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 $v \sim 200 \text{ m/s}$ and $d = 50 \text{ mm}$

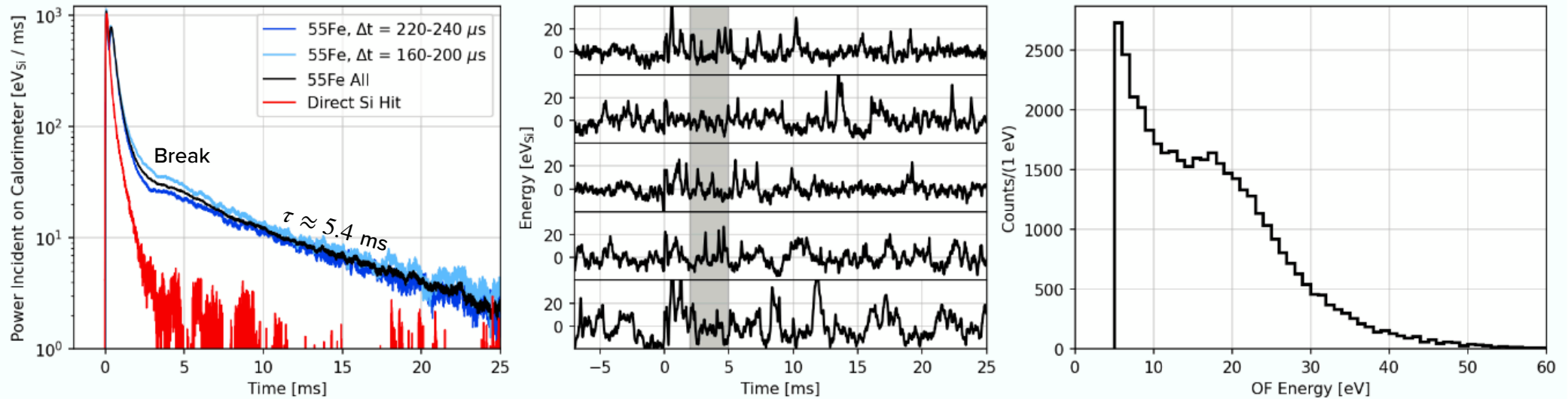


DEPTH DEPENDENCE OF AMPLITUDE



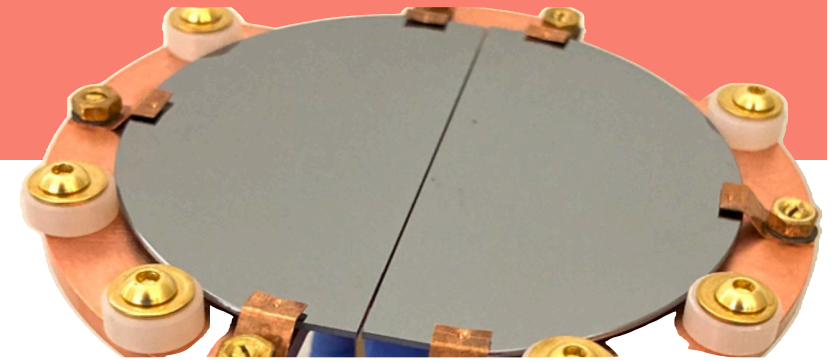
- Higher rate near bottom, where we also can see the shorter-ranged 1.5 keV Al fluorescence events
- Scintillation light decreases with depth,
- While the QP evaporation signal increases— the expectation from the 17° requirement is a constant, so this could also be explained by QPs reflecting and then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

DELAYED TRIPLET SIGNAL

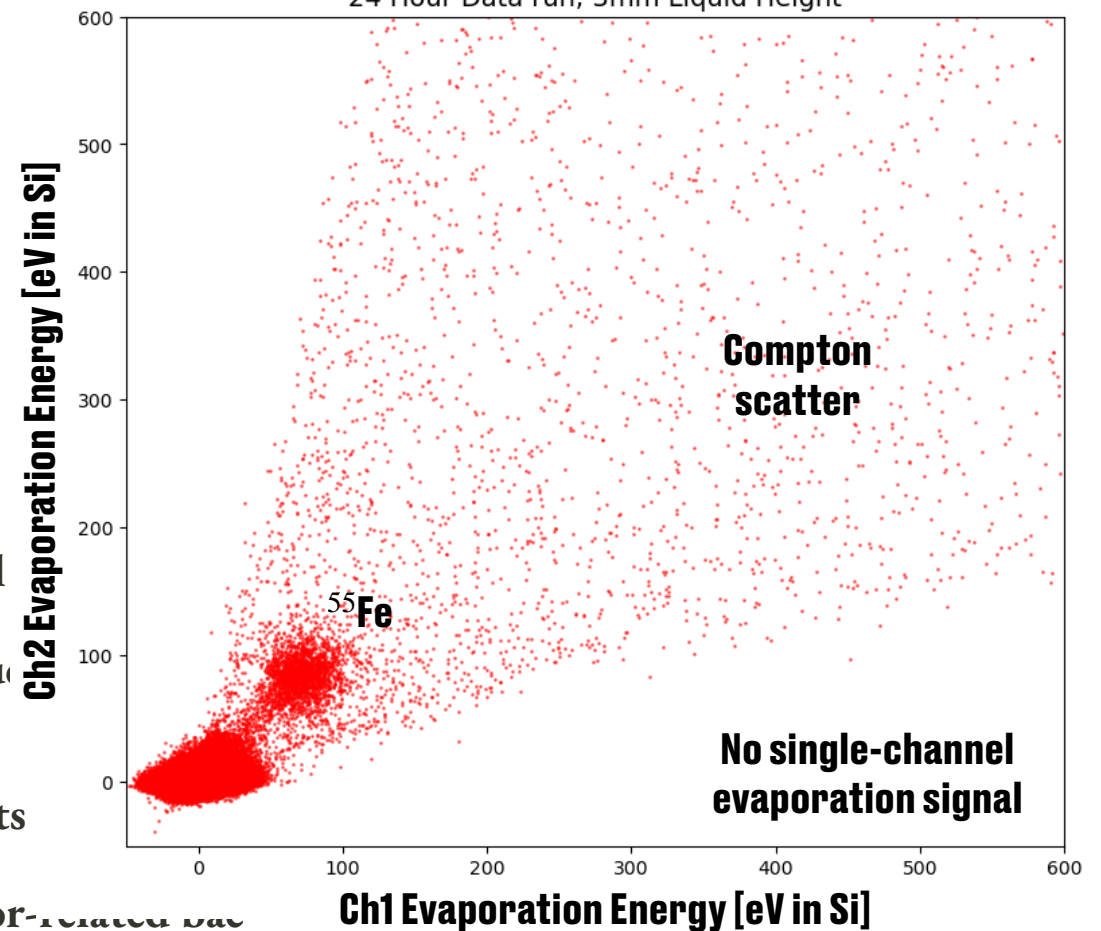


- The delayed triplet pulses are much longer-lived, moving with some m/s velocity until they hit a metal surface and de-excite, or interact with another triplet.
- The average waveform, shown to the left, show a break around 4 ms, the time expected to reach the surrounding metal surfaces
- The longer 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

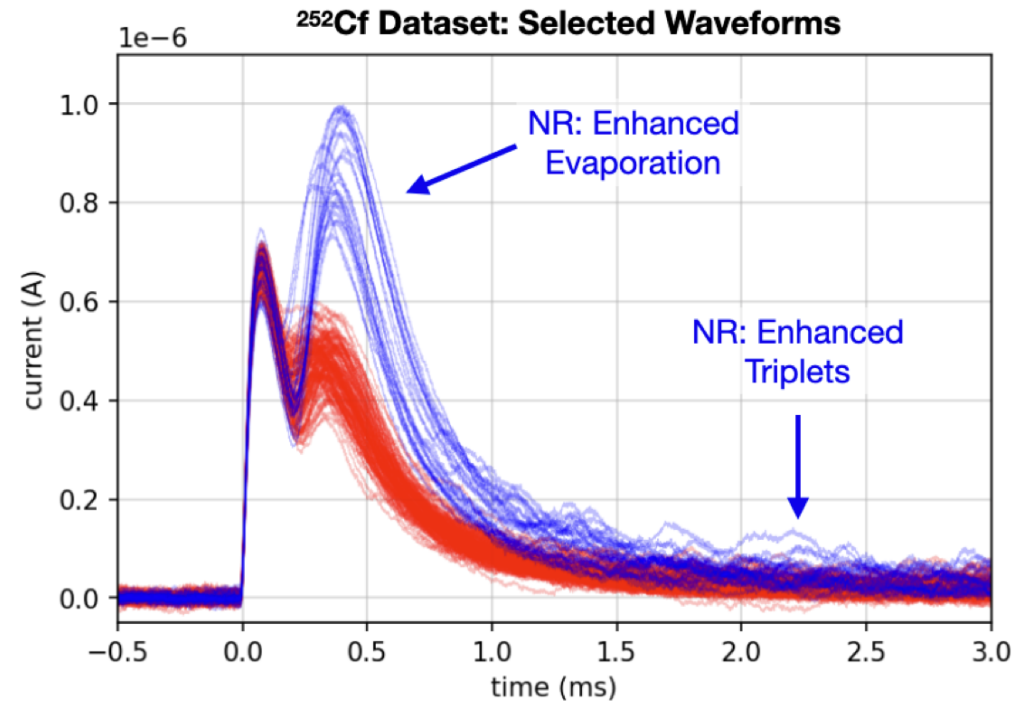
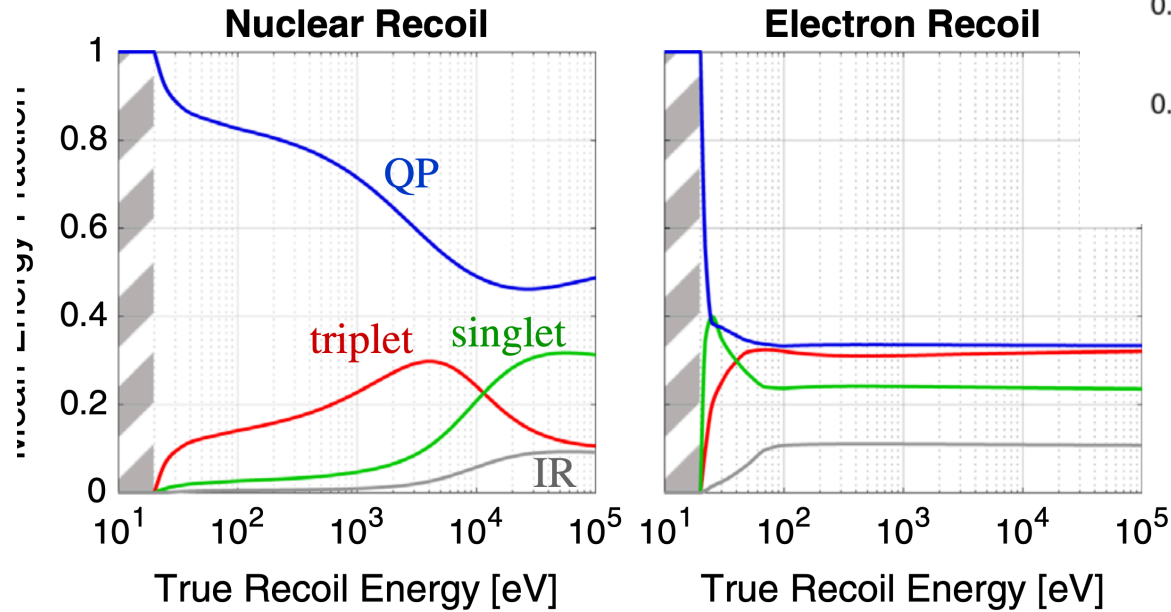


HeRALD v0.1 Split Evaporation Energy Partitioning
24 Hour Data run; 3mm Liquid Height



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

ENERGY PARTITION

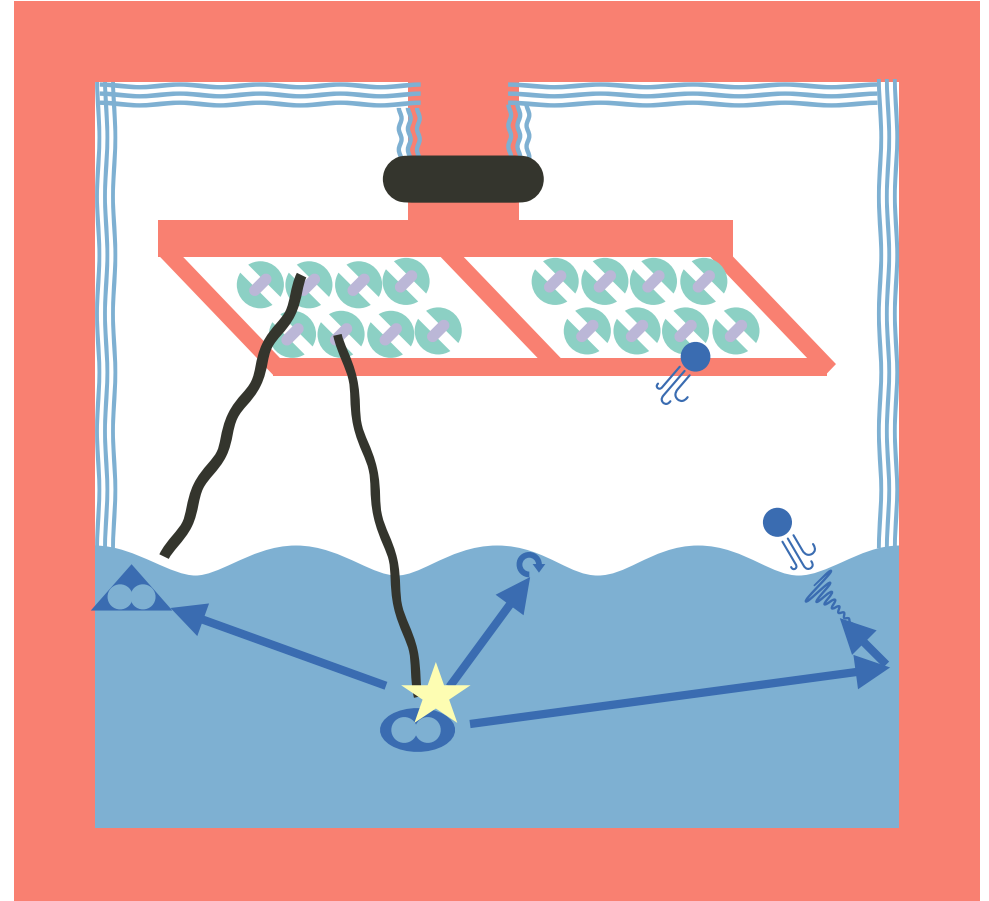


at QP:singlet:triplet ratios, with electronic recoils are QP-heavy.

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).

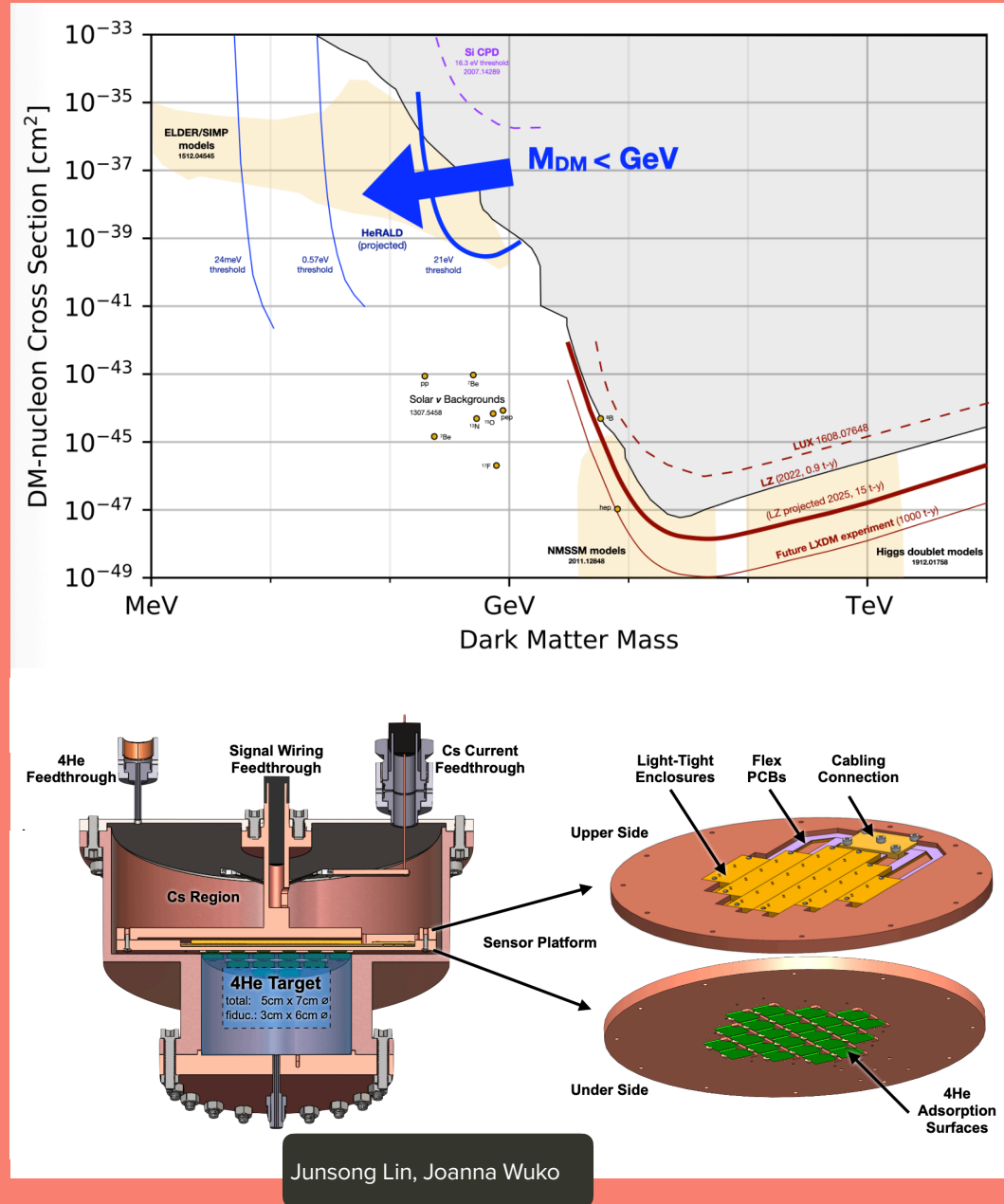
TESSERACT V0.1 LESSONS

- 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 $0.2 \text{ GeV}/c^2$
- 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 < 1 eV
- 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 ~ 30 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

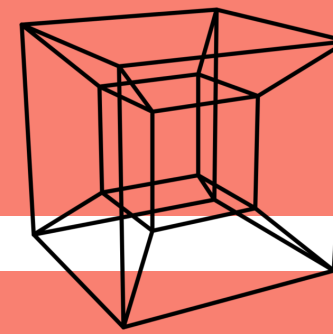


NEXT STEPS: DARK MATTER SEARCHES?



- 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

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](https://arxiv.org/abs/2307.11877)
or on tesseract.lbl.gov



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

