A Large-Area Cryogenic PhotoDetector, Applications, and a Light Dark Matter Search

Samuel Watkins
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Light Dark Matter Virtual Seminar

SUPER CDMS
Cryogenic Dark Matter Search

Berkeley
UNIVERSITY OF CALIFORNIA

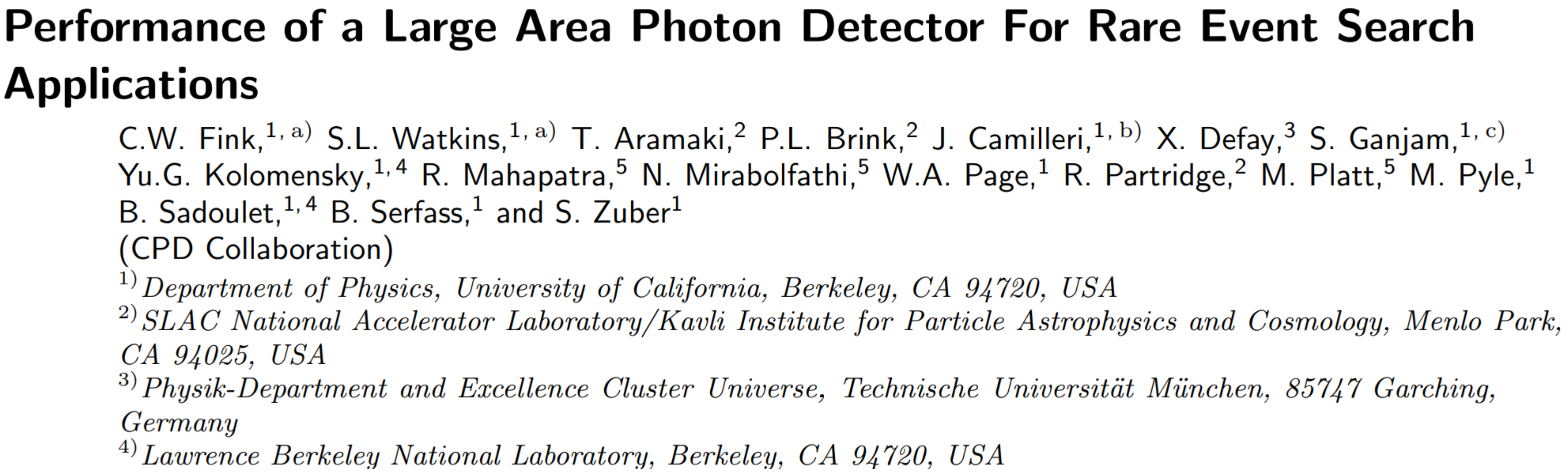
Outline

1. Performance of a Large Area Photon Detector for Rare Event Search Applications
   - arXiv:2009.14302, submitted to APL
   - CPD Collaboration paper on the Cryogenic PhotoDetector
   - Applications of the large-area photon detector to different rare event searches
   - Performance of the detector and comparison to other detectors

2. Light Dark Matter Search with a High-Resolution Athermal Phonon Detector Operated Above Ground
   - arXiv:2007.14289, submitted to PRL, in revisions
   - Combined effort between the SuperCDMS and CPD collaborations
   - Results from an above ground dark matter search

arXiv:2009.14302

Performance of a Large Area Photon Detector for Rare Event Search Applications



Performance of a Large Area Photon Detector For Rare Event Search Applications

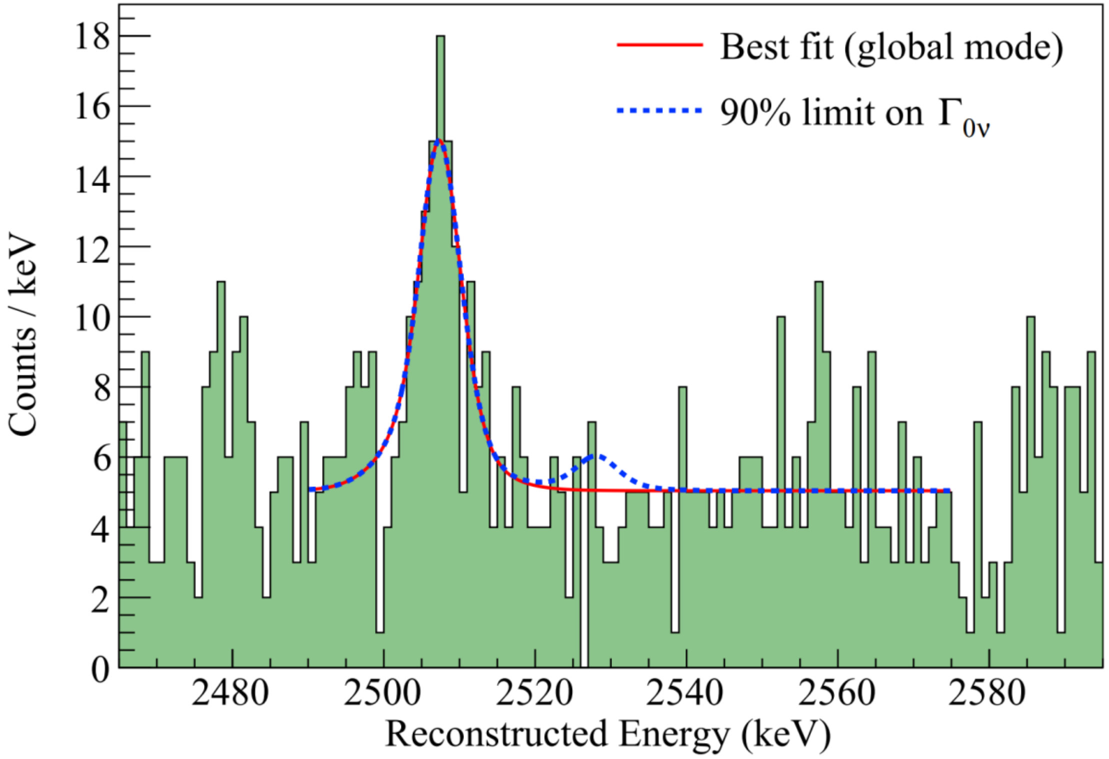
C.W. Fink,[1, a)] S.L. Watkins,[1, a)] T. Aramaki,[2] P.L. Brink,[2] J. Camilleri,[1, b)] X. Defay,[3] S. Ganjam,[1, c)] Yu.G. Kolomensky,[1, 4] R. Mahapatra,[5] N. Mirabolfathi,[5] W.A. Page,[1] R. Partridge,[2] M. Platt,[5] M. Pyle,[1] B. Sadoulet,[1, 4] B. Serfass,[1] and S. Zuber[1]
(CPD Collaboration)

1) *Department of Physics, University of California, Berkeley, CA 94720, USA*
2) *SLAC National Accelerator Laboratory/Kavli Institute for Particle Astrophysics and Cosmology, Menlo Park, CA 94025, USA*
3) *Physik-Department and Excellence Cluster Universe, Technische Universität München, 85747 Garching, Germany*
4) *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Designing a Large Area Photon Detector

arXiv:1912.10966

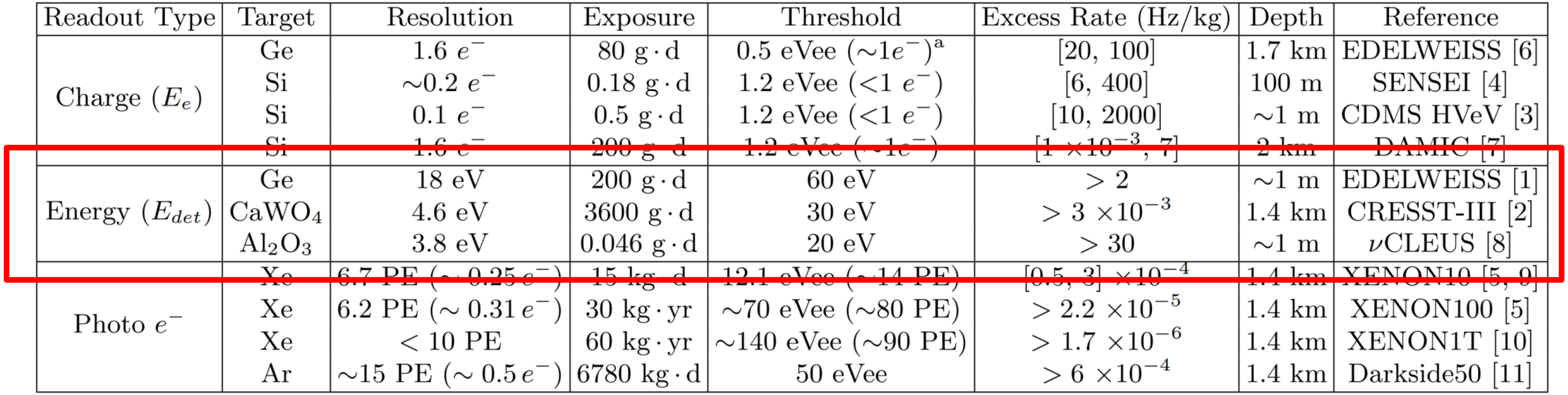
- Large area photon detectors have many applications
- Main application to neutrinoless double beta decay ($0\nu\beta\beta$) experiments
  - CUORE, CUPID, AMoRE
- Dominant source of background events are α decays from the surrounding environment
  - To reject this background, photon detectors with large surface areas and sub-$20\ \mathrm{eV}$ baseline energy resolutions are required
- Multiple ordinary double beta decay ($2\nu\beta\beta$) events are also a significant background
  - For the $^{100}\mathrm{Mo}$ isotope, timing resolutions down to $10\ \mu s$ are required



Latest CUORE result (2020): $\sim 90\%$ of the events in the ROI come from degraded α particles

Other Rare Event Search Applications

- Active photon veto for dark matter experiments
  - Many DM experiments (in the mass range of keV/c^2 to GeV/c^2) are dominated by unknown background signals in the energy range of $\mathcal{O}(1-100)\ \mathrm{eV}$
  - A sensitive large area detector could be useful for discriminating small energy depositions due to radiogenic surface backgrounds

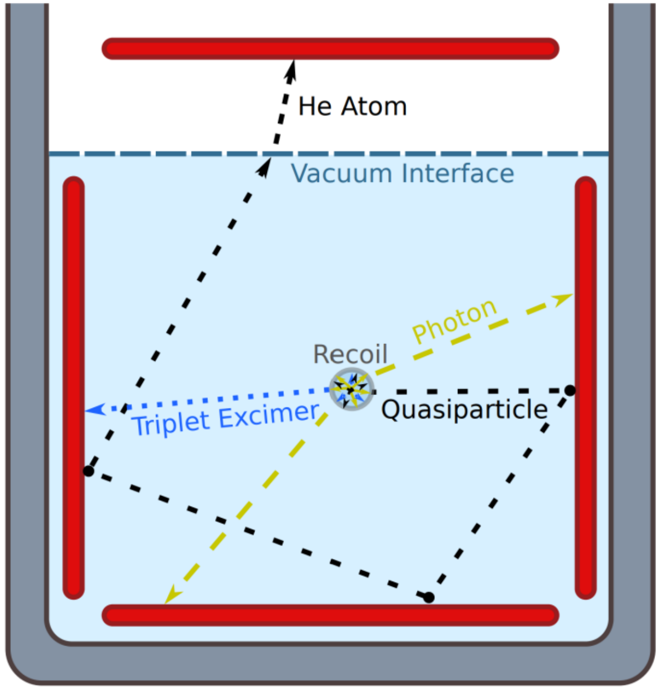


Readout Type	Target	Resolution	Exposure	Threshold	Excess Rate (Hz/kg)	Depth	Reference
Charge (E_e)	Ge	$1.6\ e^-$	$80\ \mathrm{g\cdot d}$	0.5 eVee ($\sim 1e^-$)$^{\mathrm{a}}$	[20, 100]	1.7 km	EDELWEISS [6]
	Si	$\sim 0.2\ e^-$	$0.18\ \mathrm{g\cdot d}$	1.2 eVee ($<1\ e^-$)	[6, 400]	100 m	SENSEI [4]
	Si	$0.1\ e^-$	$0.5\ \mathrm{g\cdot d}$	1.2 eVee ($<1\ e^-$)	[10, 2000]	~ 1 m	CDMS HVeV [3]
	Si	$1.6\ e^-$	$200\ \mathrm{g\cdot d}$	1.2 eVee ($\sim 1e^-$)	$[1 \times 10^{-3}, 7]$	2 km	DAMIC [7]
Energy (E_{det})	Ge	18 eV	$200\ \mathrm{g\cdot d}$	60 eV	> 2	~ 1 m	EDELWEISS [1]
	$\mathrm{CaWO_4}$	4.6 eV	$3600\ \mathrm{g\cdot d}$	30 eV	$> 3 \times 10^{-3}$	1.4 km	CRESST-III [2]
	$\mathrm{Al_2O_3}$	3.8 eV	$0.046\ \mathrm{g\cdot d}$	20 eV	> 30	~ 1 m	νCLEUS [8]
Photo e^-	Xe	6.7 PE ($\sim 0.25\,e^-$)	$15\ \mathrm{kg\cdot d}$	12.1 eVee (~ 14 PE)	$[0.5, 3] \times 10^{-4}$	1.4 km	XENON10 [5, 9]
	Xe	6.2 PE ($\sim 0.31\,e^-$)	$30\ \mathrm{kg\cdot yr}$	~ 70 eVee (~ 80 PE)	$> 2.2 \times 10^{-5}$	1.4 km	XENON100 [5]
	Xe	< 10 PE	$60\ \mathrm{kg\cdot yr}$	~ 140 eVee (~ 90 PE)	$> 1.7 \times 10^{-6}$	1.4 km	XENON1T [10]
	Ar	~ 15 PE ($\sim 0.5\,e^-$)	$6780\ \mathrm{kg\cdot d}$	50 eVee	$> 6 \times 10^{-4}$	1.4 km	Darkside50 [11]

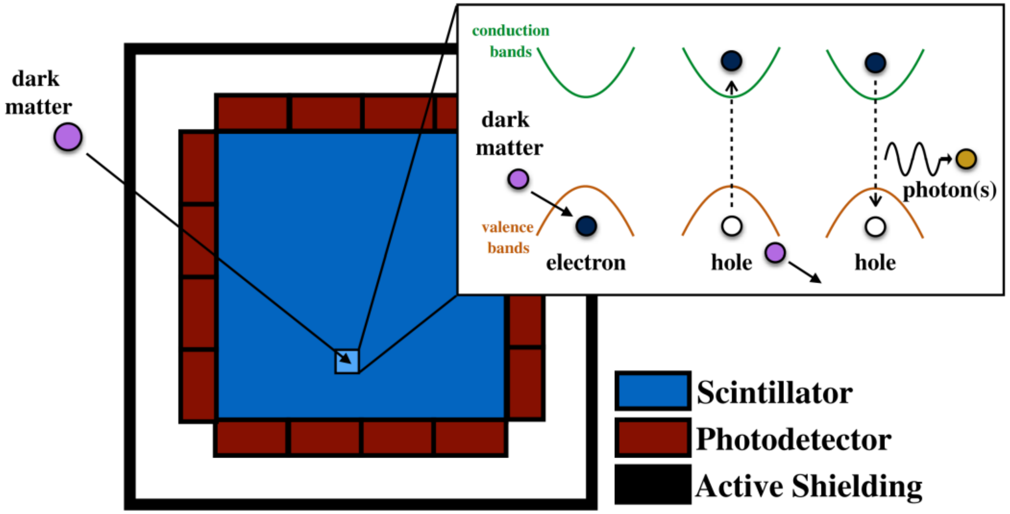
arXiv:2002.06937

More Rare Event Search Applications

- DM searches for inelastic recoils off scintillating crystals
  - DM scatters off electrons in a scintillating target and produces a signal of a few photons
- DM searches for interactions with superfluid He
  - Interactions with the He nuclei can give off photons and excimer molecules of energies at eV-scale



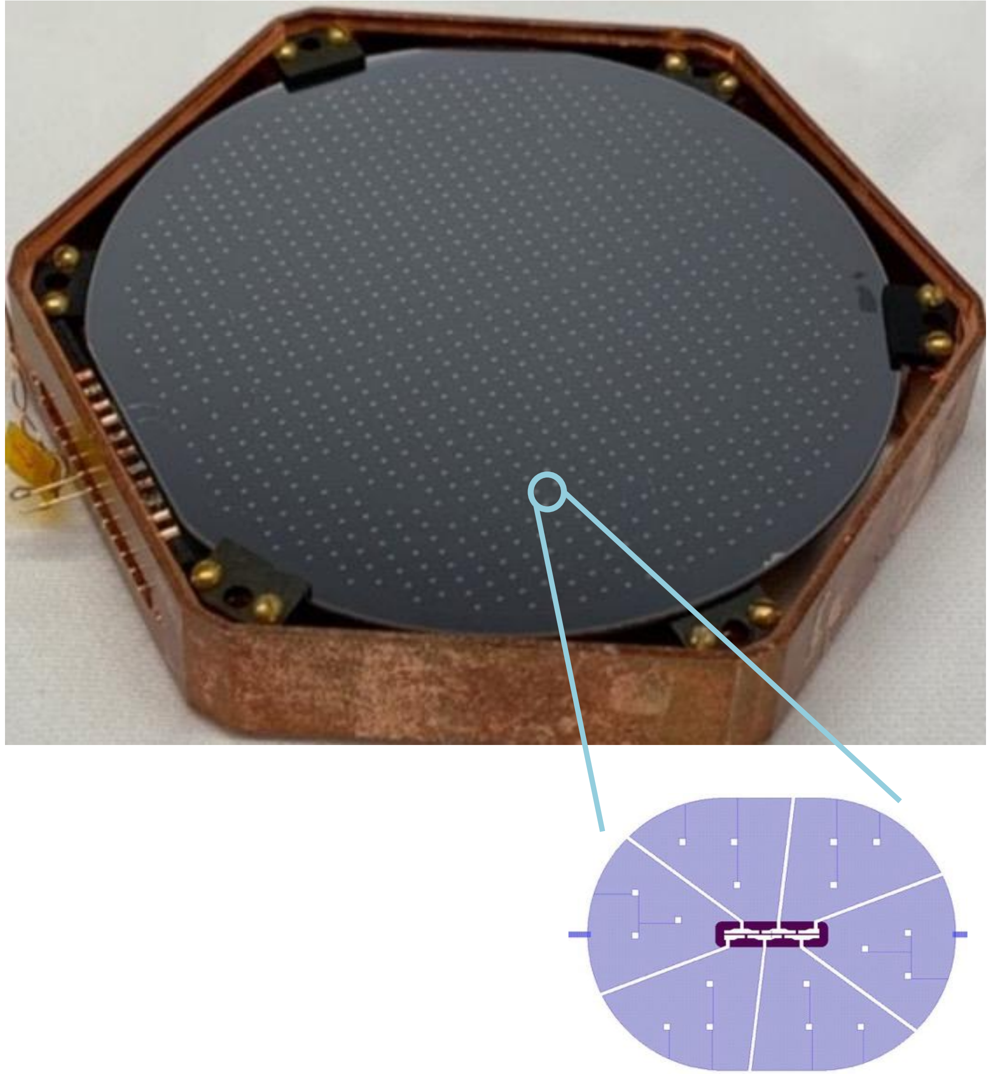
arXiv:1810.06283



DOI:10.1103.PhysRevD.96.016026

Cryogenic PhotoDetector (CPD)

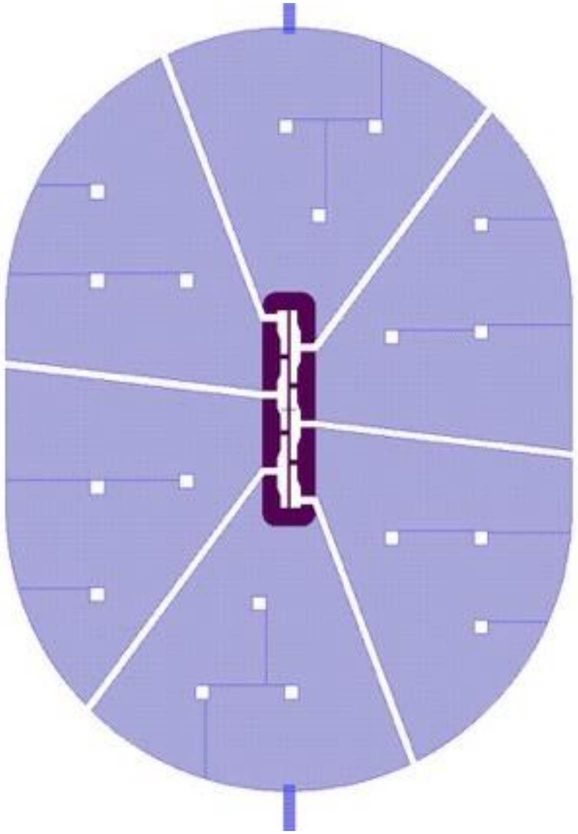
- The detector is a CDMS-style athermal phonon sensor
- Si wafer
  - 45.6 cm^2 surface area
  - 1-mm-thick
  - Mass of 10.6 grams
- One side of wafer is instrumented with a single distributed channel of QETs
- Opposite side is noninstrumented and unpolished
- Held by six cirlex clamps
- The device has been optimized as a large area photon detector

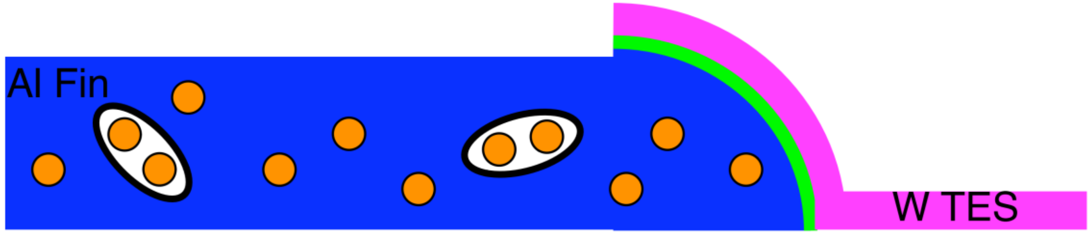


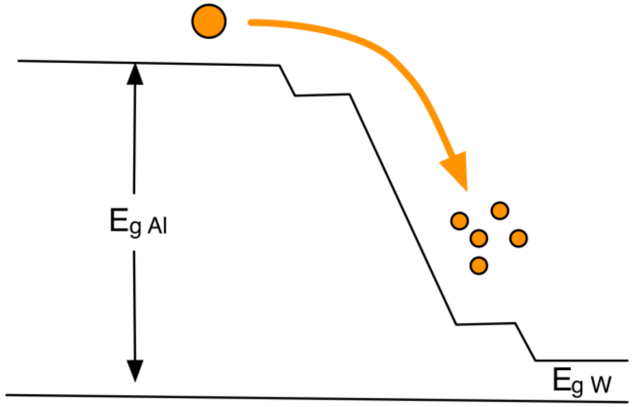
QET Design

- The detector mask has been optimized for photon detection
  - Distributed athermal sensor array read out by QETs
  - Single distributed channel gives a fast collection time of athermal phonons
  - This reduces efficiency penalties due to athermal phonon down conversion

Specification	Value
TES Length [μm]	140
TES Thickness [nm]	40
TES Width [μm]	3.5
Number of Al Fins	6
Al Fin Length [μm]	200
Al Fin Thickness [nm]	600
Al-W Overlap [μm]	10
Number of QETs	1031
Active Surface Area [%]	1.9
Passive Surface Area [%]	0.2



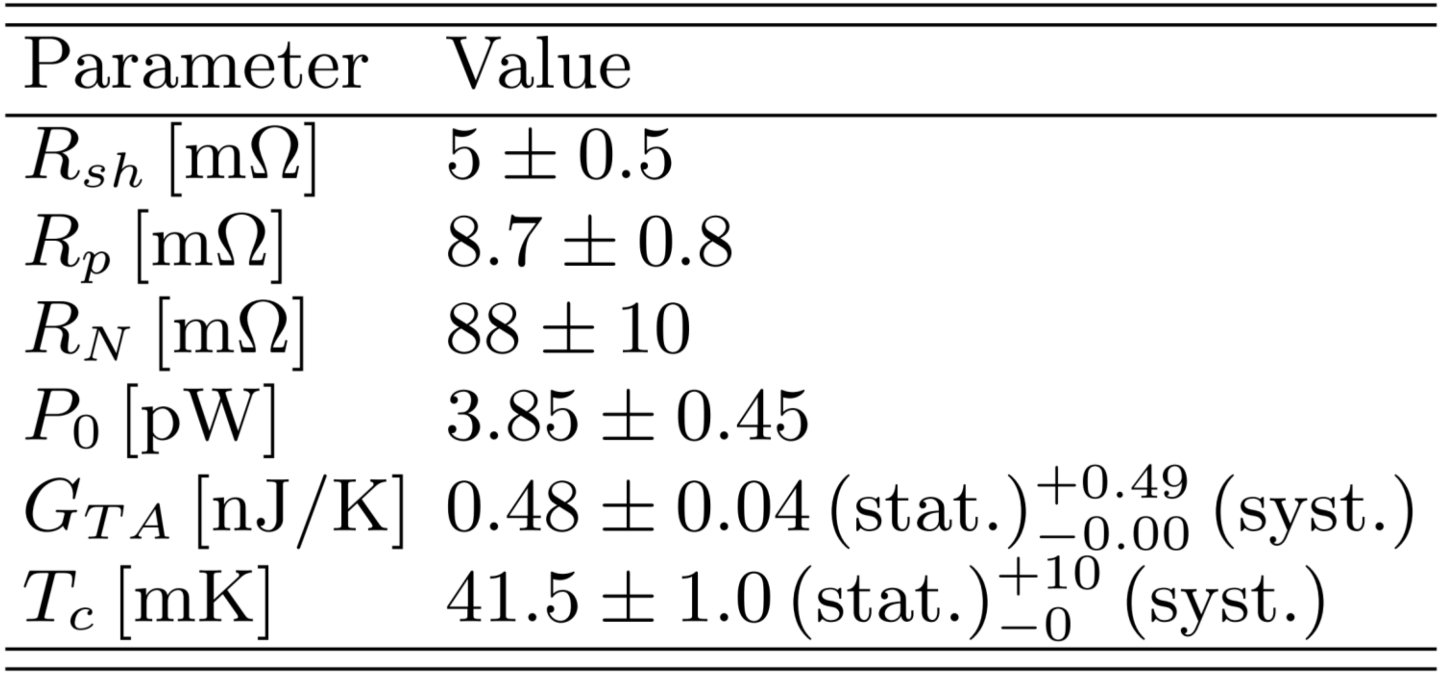




DOI:10.2172/1127926

Detector Characteristics

- Detector characterization via IV curve and $\partial I/\partial V$ data
  - Simple to determine the DC characteristics of the device from IV

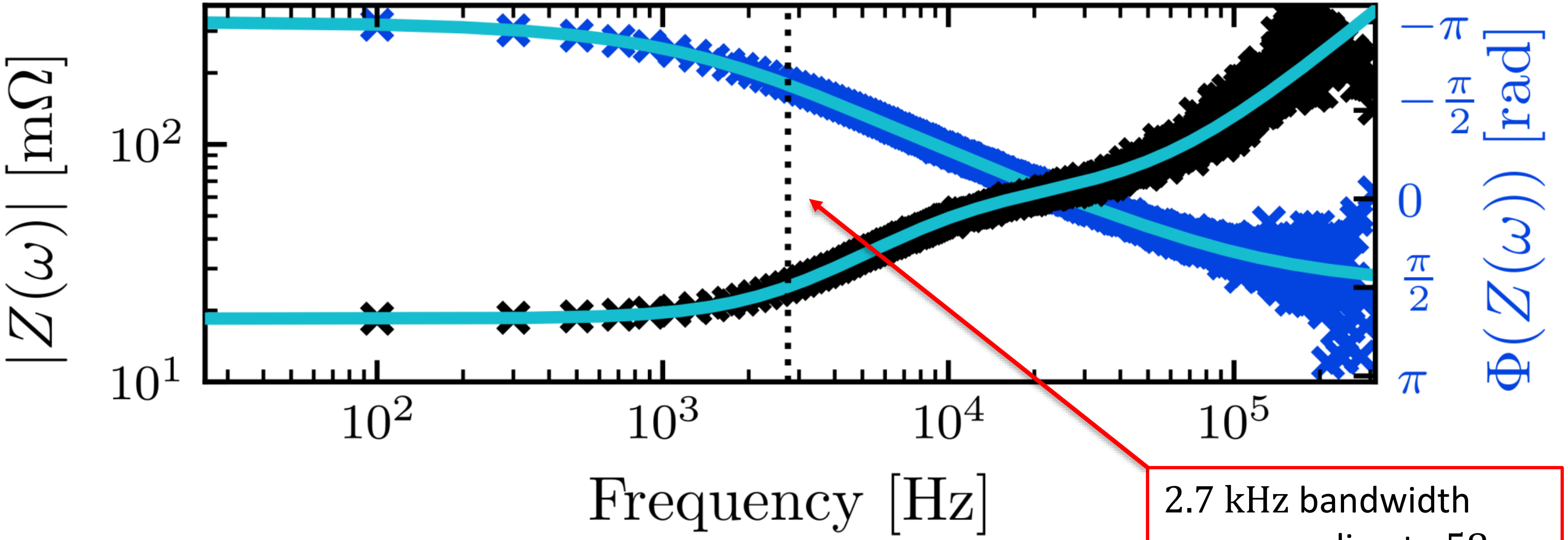


Parameter	Value
R_{sh} [mΩ]	5 ± 0.5
R_p [mΩ]	8.7 ± 0.8
R_N [mΩ]	88 ± 10
P_0 [pW]	3.85 ± 0.45
G_{TA} [nJ/K]	$0.48 \pm 0.04\,(\mathrm{stat.})^{+0.49}_{-0.00}\,(\mathrm{syst.})$
T_c [mK]	$41.5 \pm 1.0\,(\mathrm{stat.})^{+10}_{-0}\,(\mathrm{syst.})$

Note: Systematic errors are upper bounds on these values, from analysis of excess noise

Detector Characteristics

- From the $\partial I/\partial V$ data, we can measure the complex impedance
  - Using the usual single-body small signal approximation, we calculate a sensor fall time of $58\ \mu s$
  - There is also a secondary fall time of $370\ \mu s$, though its effect is negligible

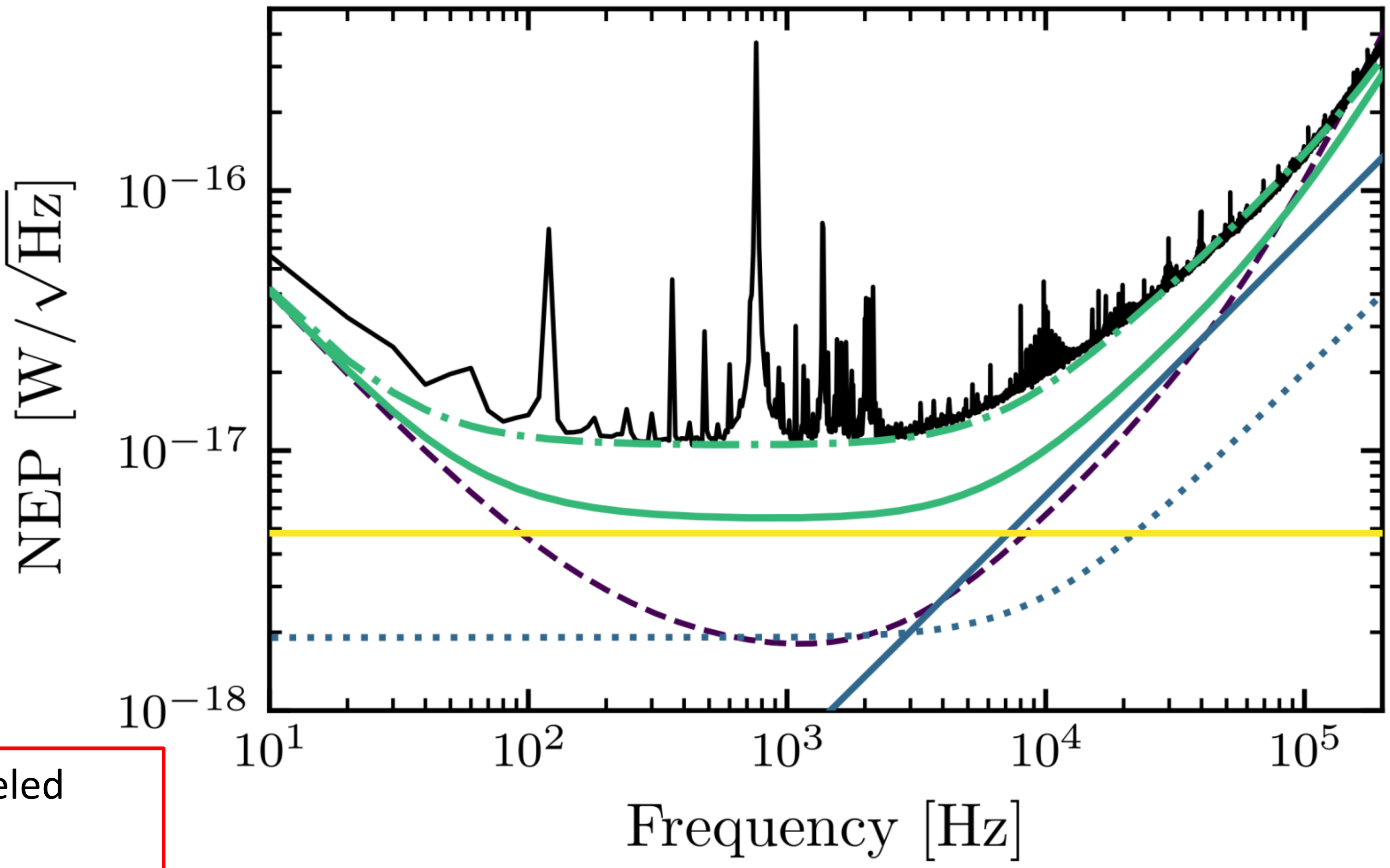


2.7 kHz bandwidth corresponding to $58\ \mu s$

Noise Modeling

- Using the small signal approximation, the noise equivalent power (NEP) can be calculated
  - Use the $\partial I/\partial V$ and IV curve data to calculate the current-to-power transfer function ($\partial I/\partial P$)
  - Convert the measured current-referred power spectral density to the NEP

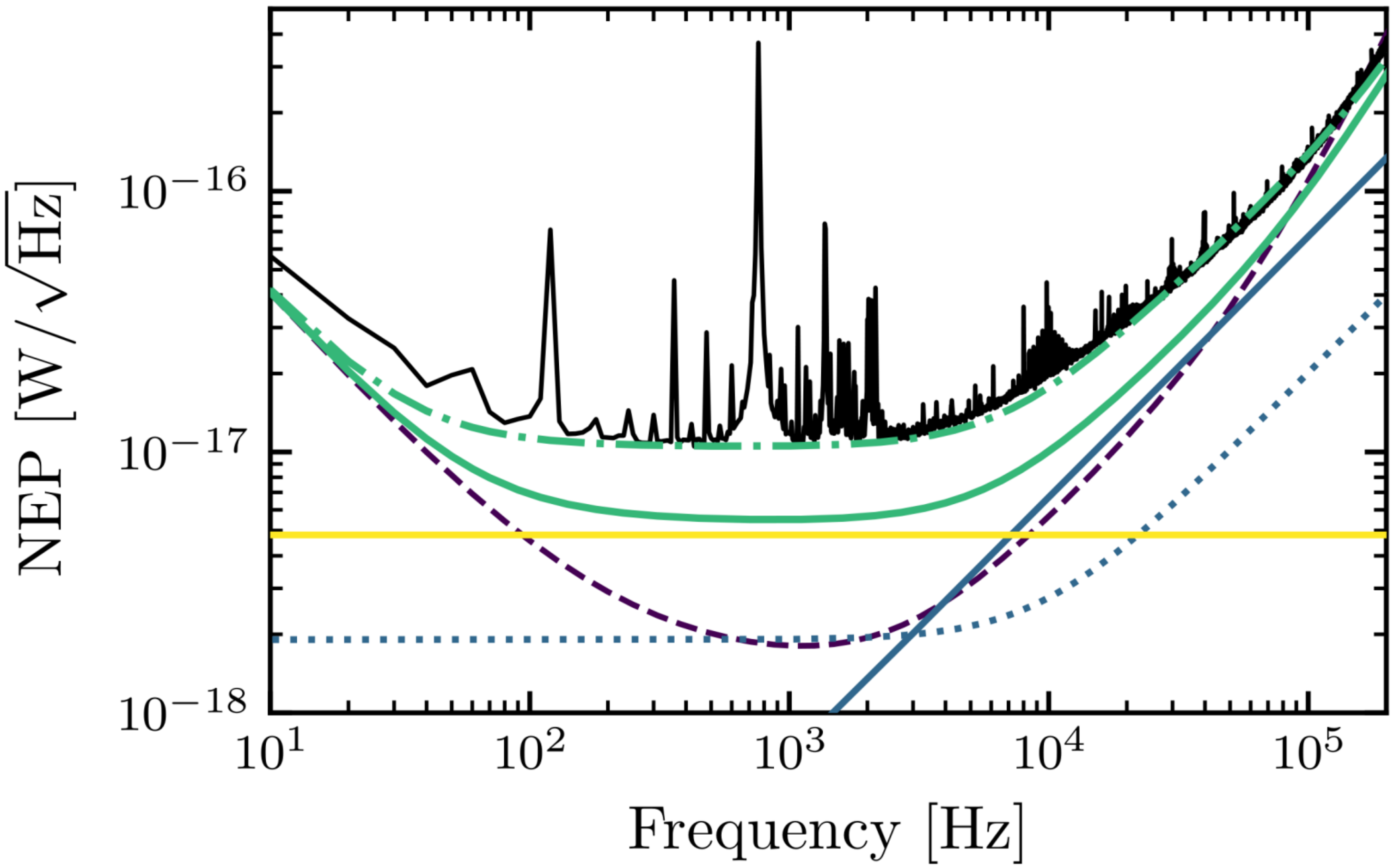
$$S_P(\omega) = \frac{S_I(\omega)}{|\partial I/\partial P(\omega)|^2}$$



- Solid green line is the total modeled noise spectrum
- Alternating dashed and dotted line is an estimate of the modeled + excess noise

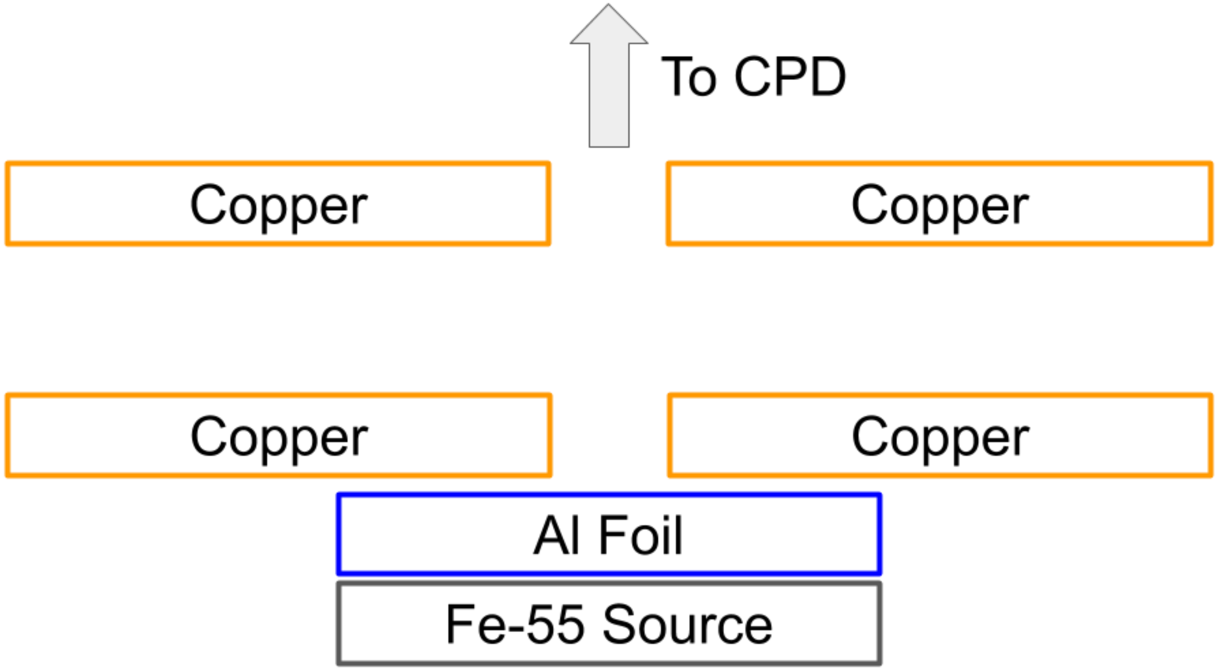
Excess Noise

- There is excess noise both in and above the sensor bandwidth
- In-band excess noise
  - Bias-independent by a factor of ~2
  - Consistent with:
    - A white noise spectrum in power of $8 \times 10^{-18}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$ (e.g. a light leak)
    - A parasitic DC power in the bias circuit of $6\ \mathrm{pW}$
- Above band excess noise
  - Bias-dependent
  - Can be modeled as excess TES Johnson noise (i.e. the M factor)
  - Values of M up to 1.8 can account for this excess



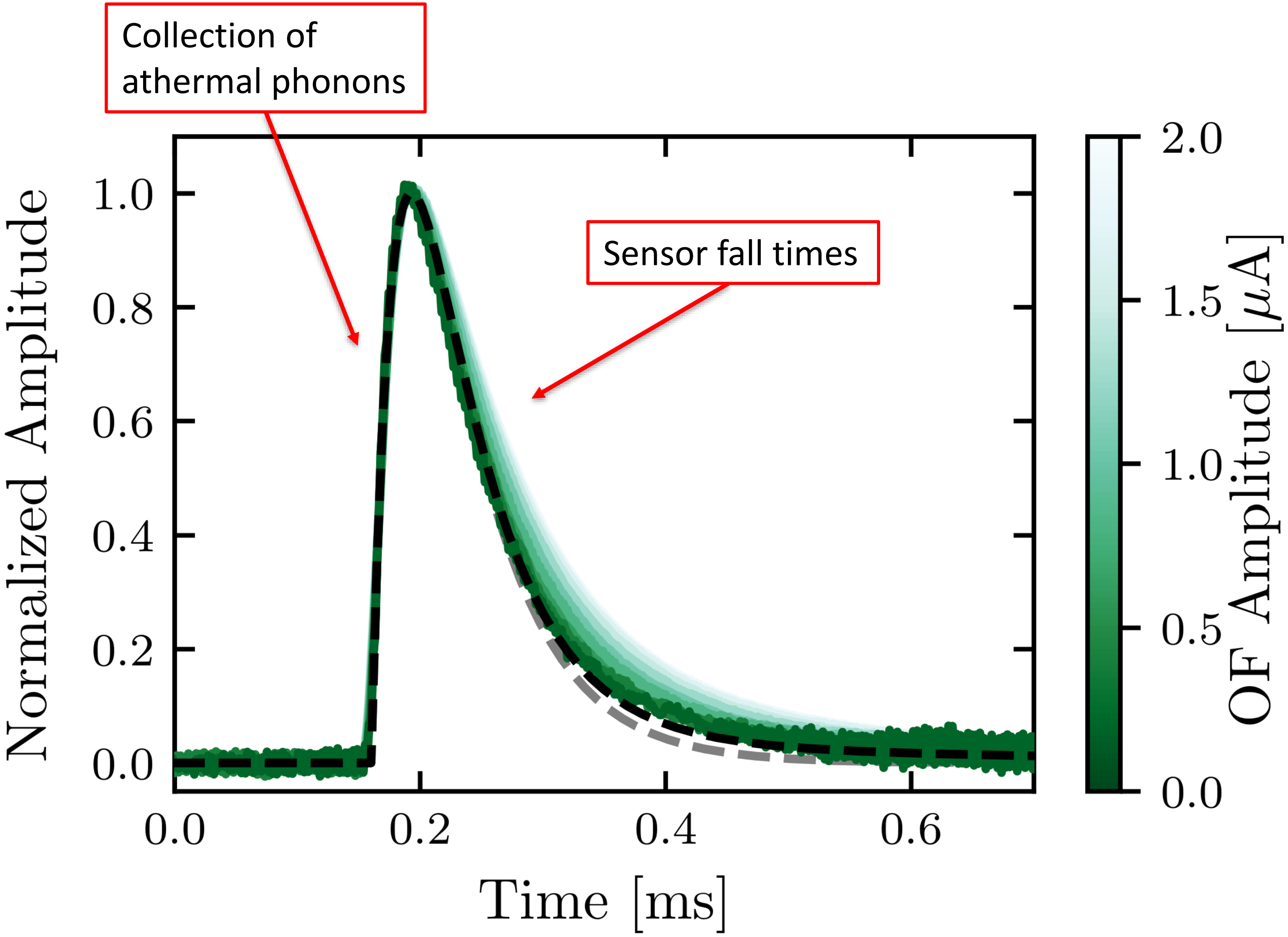
Calibration Peaks

- Fe-55 source is used to provide a calibration
  - Provides $5.9\ \mathrm{keV}$ (K_α) and $6.5\ \mathrm{keV}$ (K_β) X-ray peaks
- Two layers of copper with holes collimate the photons
- A thin layer of aluminum was placed over the Fe-55 source
  - Attenuates the rate of the Fe-55 photons
  - Provides an additional calibration line at $1.5\ \mathrm{keV}$ from the Al fluorescence



Pulse Shape

- Characteristic time constants
  - $20\ \mu s$ rise time
  - $58\ \mu s$ dominant fall time
  - Secondary $370\ \mu s$ fall time
  - Long lived ~ 3 ms exponential tail
- Last two were found to be negligible for the DM search
  - Less than 2% effects
  - Results were independent of inclusion in the analysis

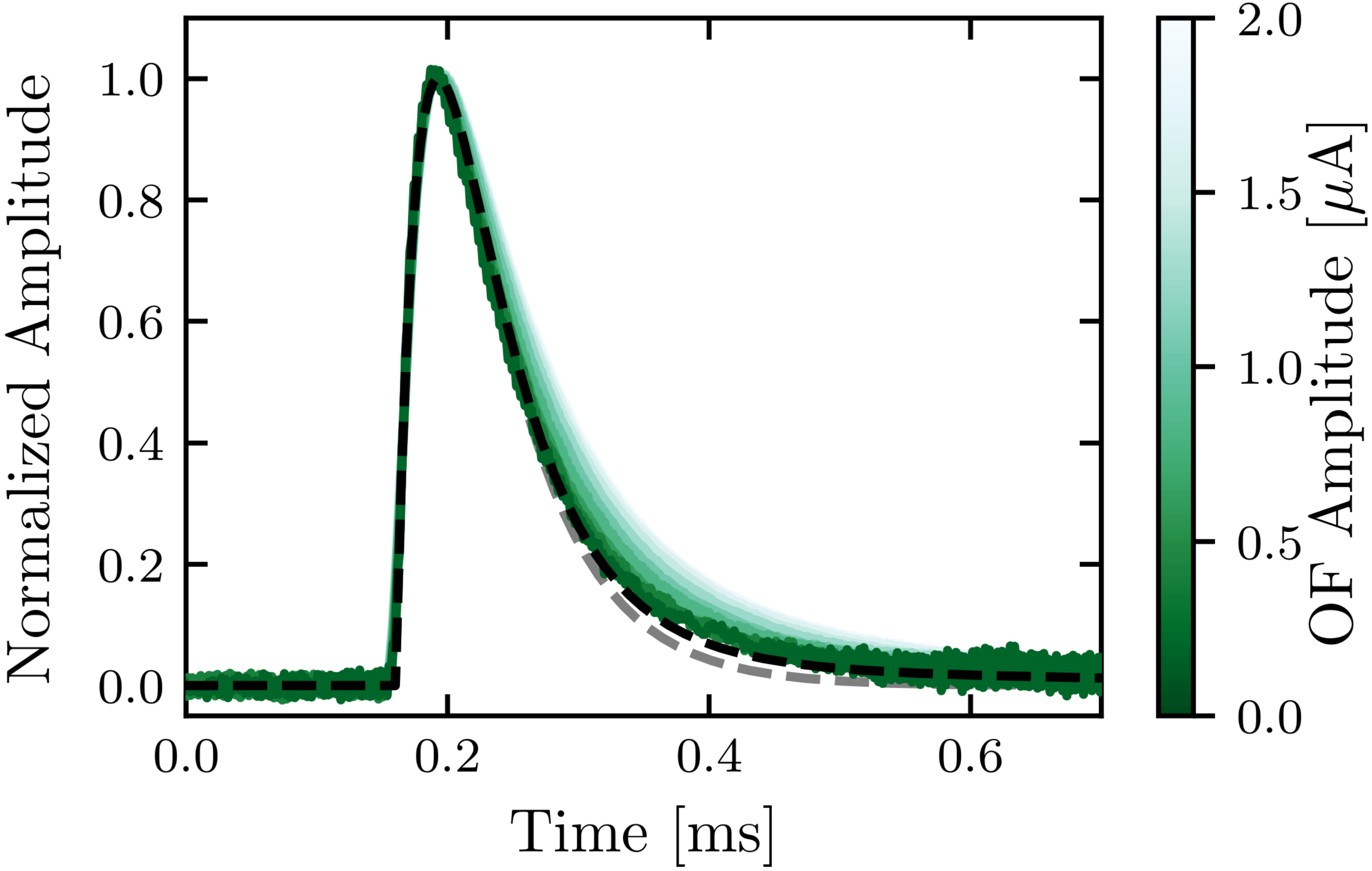


Collection of athermal phonons

Sensor fall times

Local Saturation Effects

- For events with large energies, we see a lengthened dominant fall time
- These are high-energy, single-particle events
  - Local events push nearby QETs into the normal regime, slowing down the response of the total single-channel device
- For scintillation events, the photons would be isotropic
  - Energy would be spread out across the entire detector channel, avoiding these saturation effects



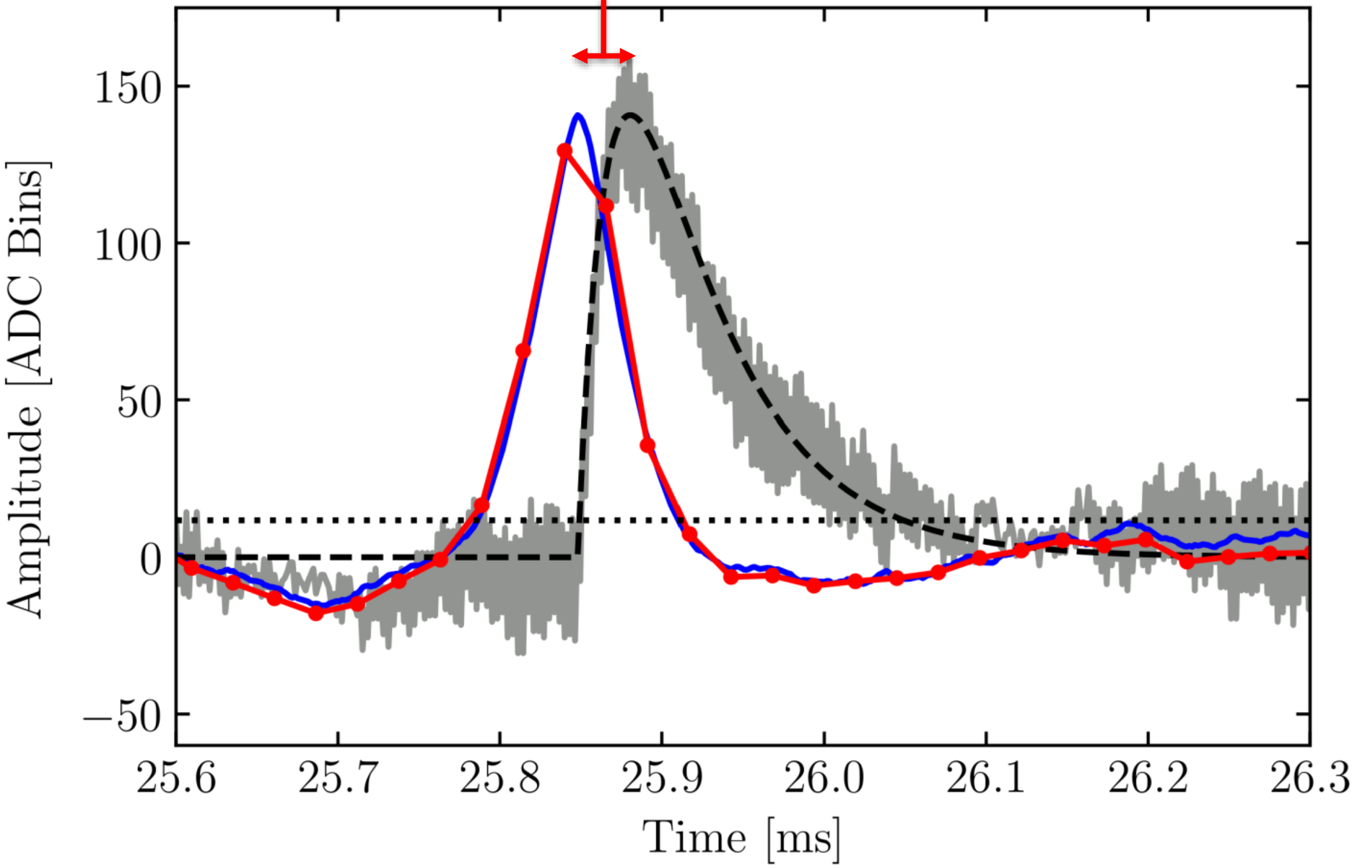
Energy Estimators

For any event with true energy E_0, we have three different energy estimators:

1. Amplitude E_T from the SuperCDMS prototype DAQ's digital FPGA triggering algorithm
    - A continuous triggering algorithm on a downsampled trace
2. Offline Optimal Filter (OF) amplitude E' provides the reconstructed energy for all events
    - Search in the neighborhood of the trigger time to find the best estimate
3. Energy removed by electrothermal feedback E_{ETF}
    - An integral energy estimator, which is less susceptible to saturation effects

$$E_{\mathrm{ETF}} = \int_0^T \left[(V_b - 2I_0R_\ell)\Delta I(t) - \Delta I(t)^2 R_\ell\right] \mathrm{d}t$$

The "shift" is an artifact of the filters



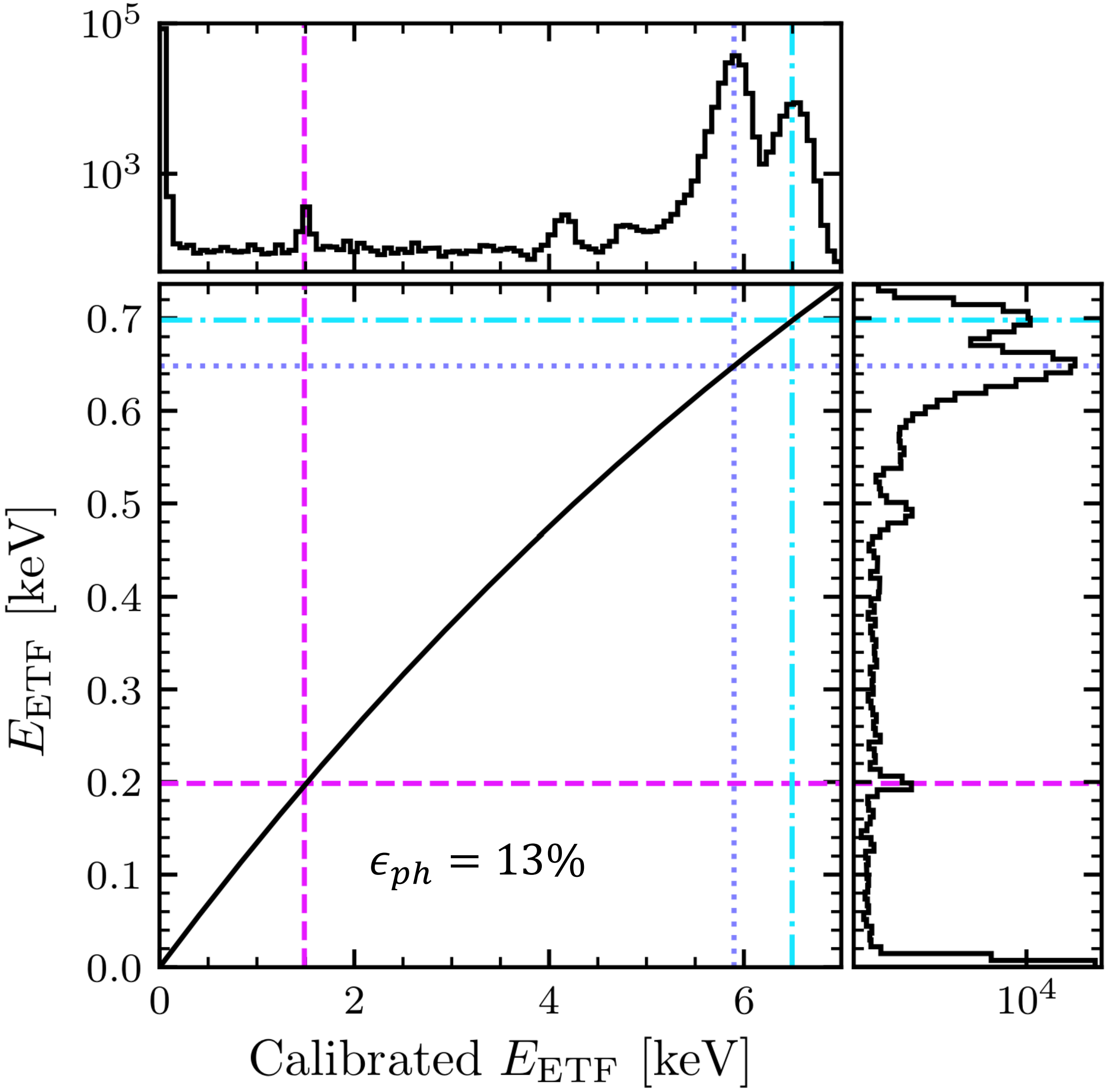
Total trace is 52 ms long

Energy Calibration (Technical Paper)

- Using an exponential saturation model, we calibrate E_{ETF} to the true energy scale

$$E_{\mathrm{ETF}} = a\left(1 - \exp\left(-\frac{E_{\mathrm{true}}}{b}\right)\right)$$

- At low energies (below about 300 eV), the saturation effects are negligible
- To calibrate the reconstructed energy E', we use a linear model at these low energies between it and the calibrated E_{ETF}
- The empirical formula has a systematic error associated with it
  - Estimated as calibrating E_{ETF} linearly to the Al line



Expected Baseline Energy Resolution

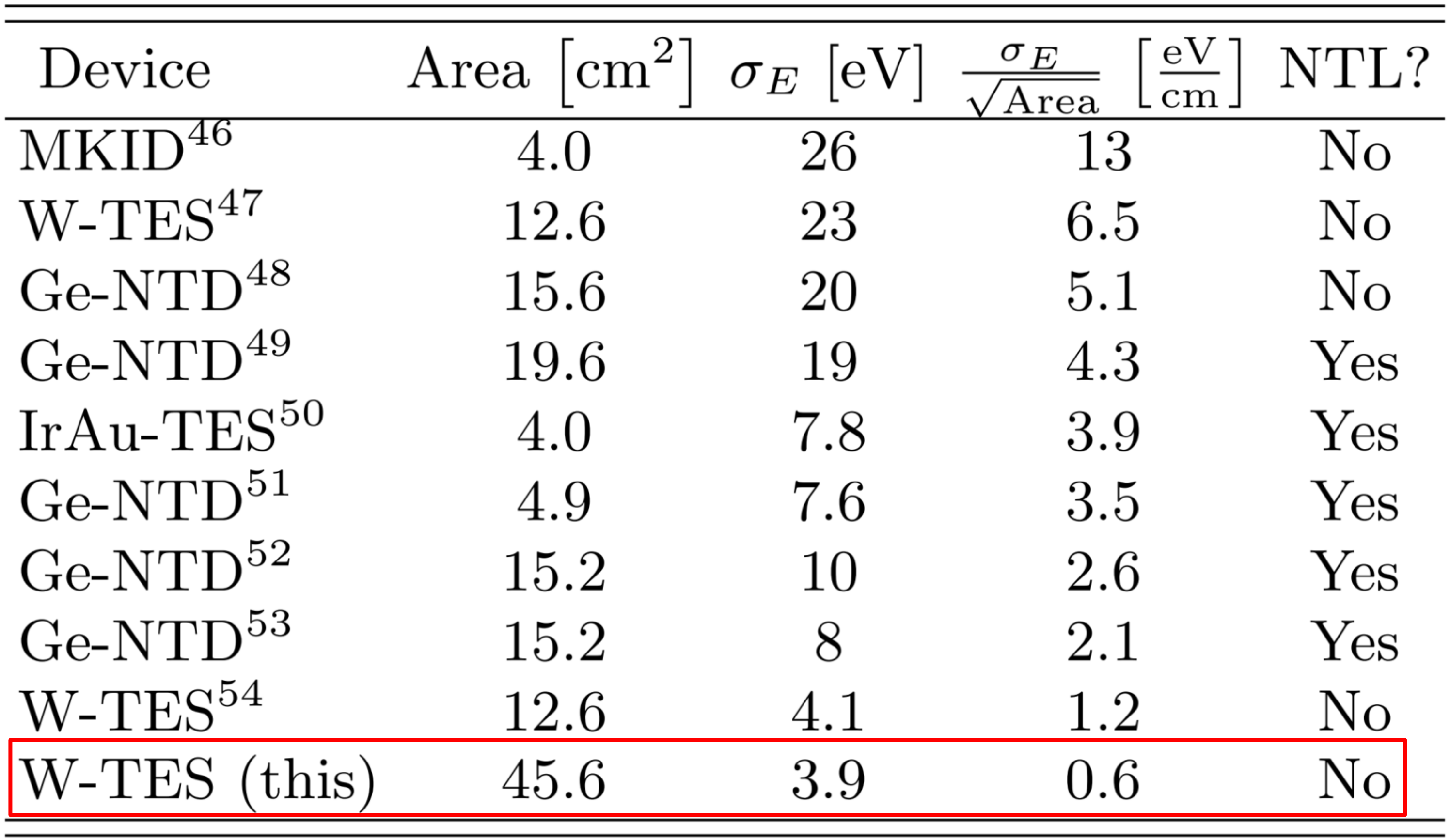
- We can estimate the baseline energy resolution using:
  - The observed power-referred noise spectrum, $S_P(\omega)$
  - The power-referred phonon-pulse shape, $p(\omega) = \frac{1}{1+j\omega\tau_{ph}}, \tau_{ph} = 20\ \mu s$
  - The phonon collection efficiency, $\epsilon = 13\%$

$$\sigma_E^2 = \left[\varepsilon^2 \int_0^\infty \frac{d\omega}{2\pi} \frac{4|p(\omega)|^2}{S_P(\omega)}\right]^{-1}$$

- This gives an expected baseline energy resolution of 3.9 ± 0.4 eV

Baseline Energy Resolution

- From the randomly triggered events, we can measure the baseline energy resolution
- As these events were consistent with a normal distribution, we simply take the RMS of the distribution
- This gives an energy resolution of $\sigma_E = 3.86 \pm 0.04(\text{stat.})^{+0.23}_{-0.00}(\text{syst.})\ \text{eV}$
- World-leading for a detector of its size and without Neganov-Trofimov-Luke (NTL) amplification



Device	Area $[\text{cm}^2]$	σ_E [eV]	$\frac{\sigma_E}{\sqrt{\text{Area}}}$ $\left[\frac{\text{eV}}{\text{cm}}\right]$	NTL?
MKID[46]	4.0	26	13	No
W-TES[47]	12.6	23	6.5	No
Ge-NTD[48]	15.6	20	5.1	No
Ge-NTD[49]	19.6	19	4.3	Yes
IrAu-TES[50]	4.0	7.8	3.9	Yes
Ge-NTD[51]	4.9	7.6	3.5	Yes
Ge-NTD[52]	15.2	10	2.6	Yes
Ge-NTD[53]	15.2	8	2.1	Yes
W-TES[54]	12.6	4.1	1.2	No
W-TES (this)	45.6	3.9	0.6	No

Expected Timing Resolution

- For $0\nu\beta\beta$ experiments, pileup of $2\nu\beta\beta$ events is a significant background
- The expected timing resolution can be estimated using the OF formalism

$$\sigma_{t_0}^2 = \left[A^2 \int_{-\infty}^{\infty} df \, \omega^2 \frac{|s(f)|^2}{J(f)} \right]^{-1}$$

A: OF amplitude
$s(f)$: pulse template
$J(f)$: power spectral density

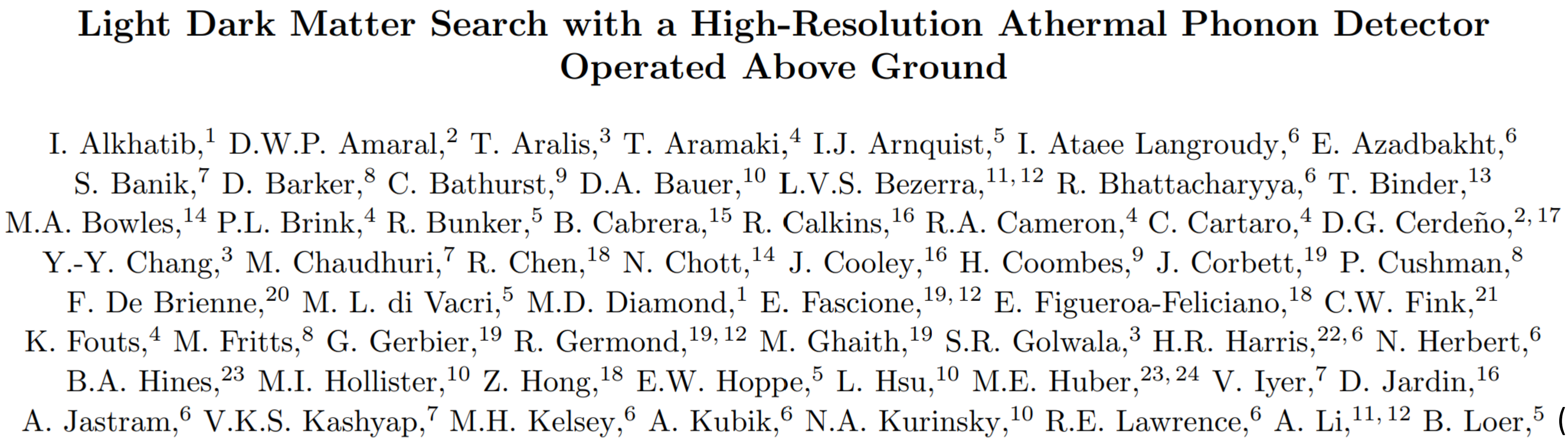
- Provides an estimate of the minimum resolving time for two pileup events
- For a $5\sigma_E$ event, the timing resolution is $\boxed{\sigma_{t_0} = 2.3\ \mu s}$

Well-Optimized for $0\nu\beta\beta$ Applications

- The baseline resolution of the CPD surpasses the requirements of the CUPID experiment to make negligible the α background
  - $3.86\ \mathrm{eV}$ is a factor of five less than the sub-$20\ \mathrm{eV}$ goal
- The timing resolution is expected to make multiple $2\nu\beta\beta$ events a negligible background
  - The expected timing resolution is $\sigma_{t_0} = 2.3\ \mu s$ for a $5\sigma_E$ event
  - Most experiments require less than $\sim 1\ \mathrm{ms}$
  - For the CUPID and CUPID-1T experiments, this requirement is about $300\ \mu s$ and $10\ \mu s$, respectively
- The detector does not require NTL amplification
  - Relying on this phenomenon has often resulted in excess dark counts

arXiv:2007.14289

Light Dark Matter Search with a High-Resolution Athermal Phonon Detector Operated Above Ground

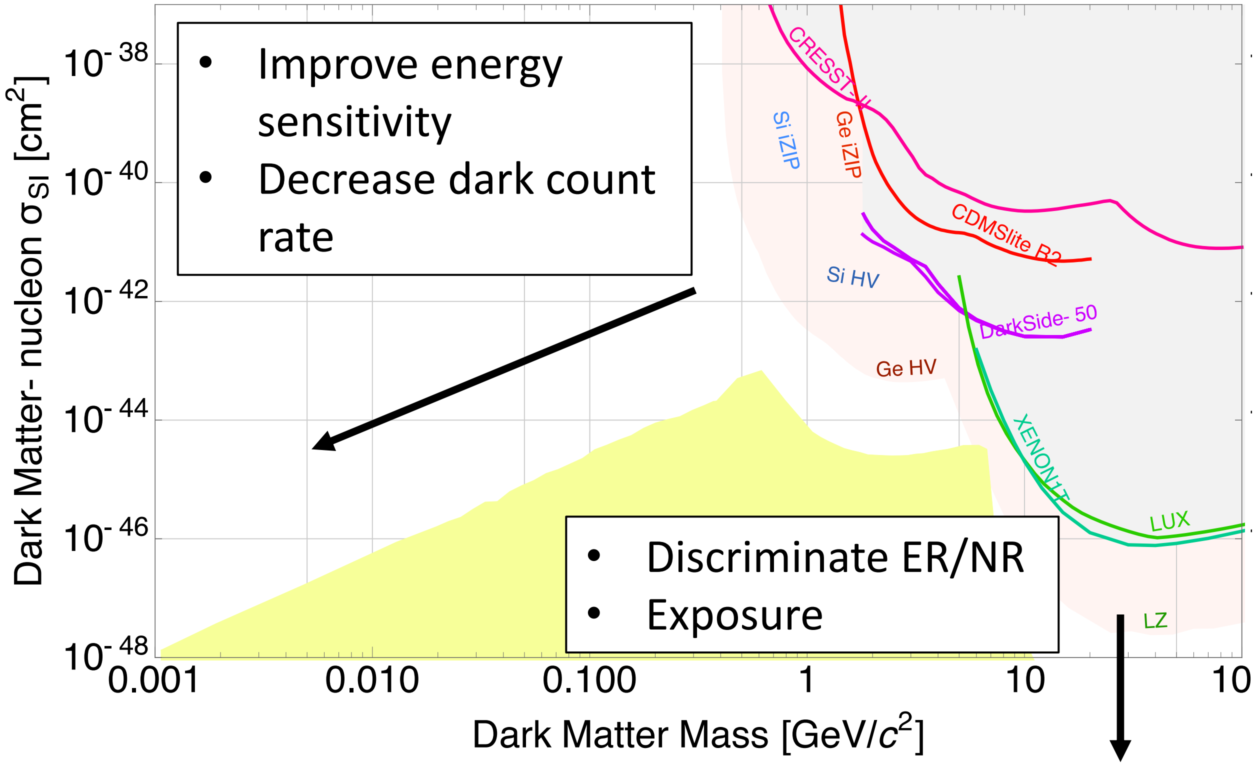


Light Dark Matter Search with a High-Resolution Athermal Phonon Detector Operated Above Ground

I. Alkhatib,[1] D.W.P. Amaral,[2] T. Aralis,[3] T. Aramaki,[4] I.J. Arnquist,[5] I. Ataee Langroudy,[6] E. Azadbakht,[6]
S. Banik,[7] D. Barker,[8] C. Bathurst,[9] D.A. Bauer,[10] L.V.S. Bezerra,[11,12] R. Bhattacharyya,[6] T. Binder,[13]
M.A. Bowles,[14] P.L. Brink,[4] R. Bunker,[5] B. Cabrera,[15] R. Calkins,[16] R.A. Cameron,[4] C. Cartaro,[4] D.G. Cerdeño,[2,17]
Y.-Y. Chang,[3] M. Chaudhuri,[7] R. Chen,[18] N. Chott,[14] J. Cooley,[16] H. Coombes,[9] J. Corbett,[19] P. Cushman,[8]
F. De Brienne,[20] M. L. di Vacri,[5] M.D. Diamond,[1] E. Fascione,[19,12] E. Figueroa-Feliciano,[18] C.W. Fink,[21]
K. Fouts,[4] M. Fritts,[8] G. Gerbier,[19] R. Germond,[19,12] M. Ghaith,[19] S.R. Golwala,[3] H.R. Harris,[22,6] N. Herbert,[6]
B.A. Hines,[23] M.I. Hollister,[10] Z. Hong,[18] E.W. Hoppe,[5] L. Hsu,[10] M.E. Huber,[23,24] V. Iyer,[7] D. Jardin,[16]
A. Jastram,[6] V.K.S. Kashyap,[7] M.H. Kelsey,[6] A. Kubik,[6] N.A. Kurinsky,[10] R.E. Lawrence,[6] A. Li,[11,12] B. Loer,[5] (*et. al.*)

Light Mass Dark Matter Direct Detection

- At high mass, improved sensitivity is achieved via increased exposure and improving electron recoil/nuclear recoil discrimination
- At low mass, improved sensitivity is achieved by lowering energy thresholds
  - Can be done with small detectors
- For DM-nucleon interactions, lower thresholds can be achieved by improving phonon resolution
- For DM-electronic interactions, single ionization excitation has been achieved
  - We must lower the dark count rate



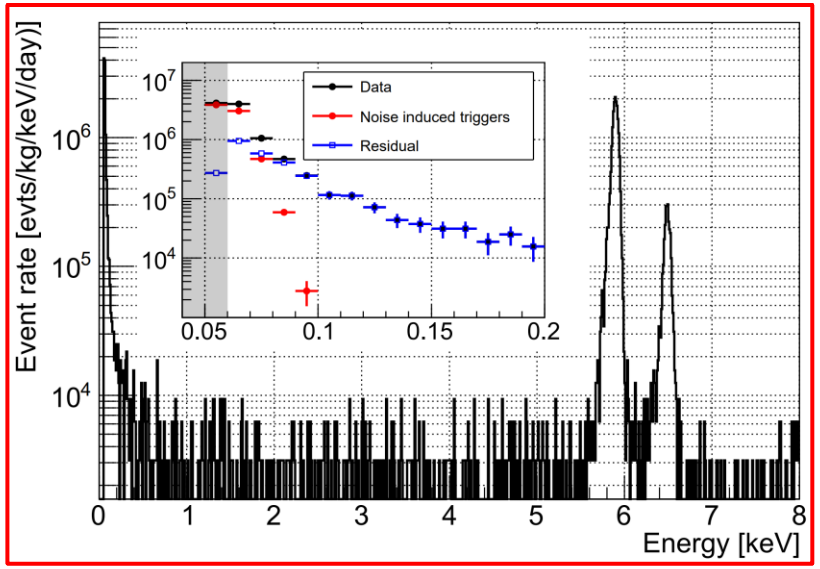
- Improve energy sensitivity
- Decrease dark count rate

- Discriminate ER/NR
- Exposure

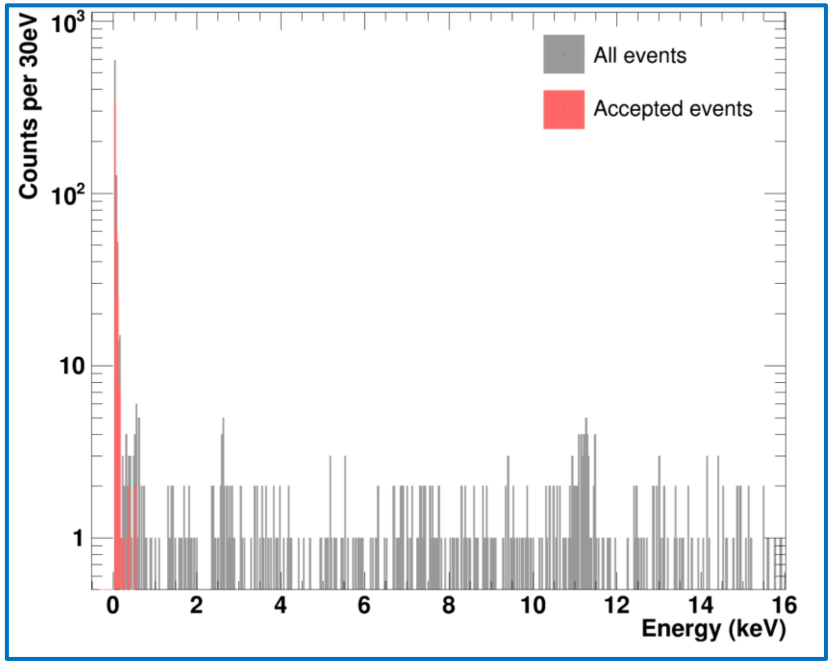
Low Threshold Searches

- Recent low threshold searches
  - EDELWEISS: 60 eV threshold, 18 eV resolution
  - CRESST-III: 30 eV threshold, 4.6 eV resolution
  - CRESST Above Ground: 20 eV threshold, 3.8 eV resolution
- Though not optimized for a DM search, the resolution of the CPD implies a meaningful DM search
  - Pursued in collaboration with SuperCDMS
  - Depending on the observed background at low energies, the result should be competitive

arXiv:1901.03588



arXiv:1904.00498



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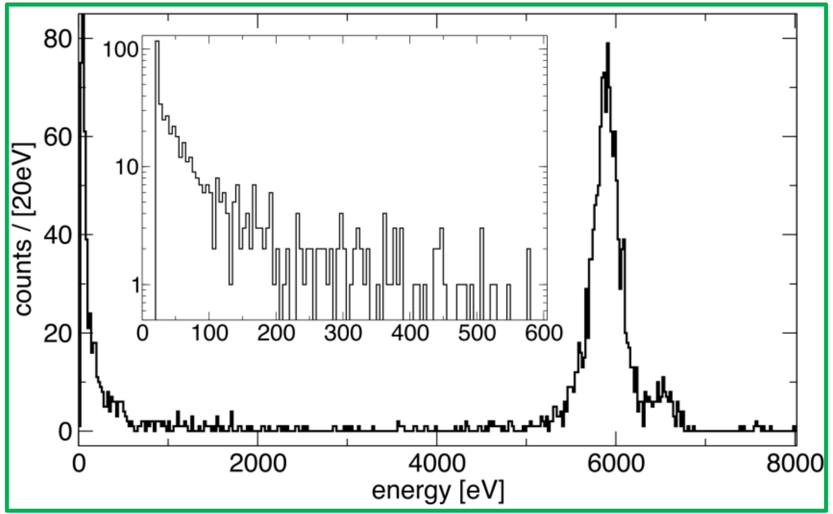
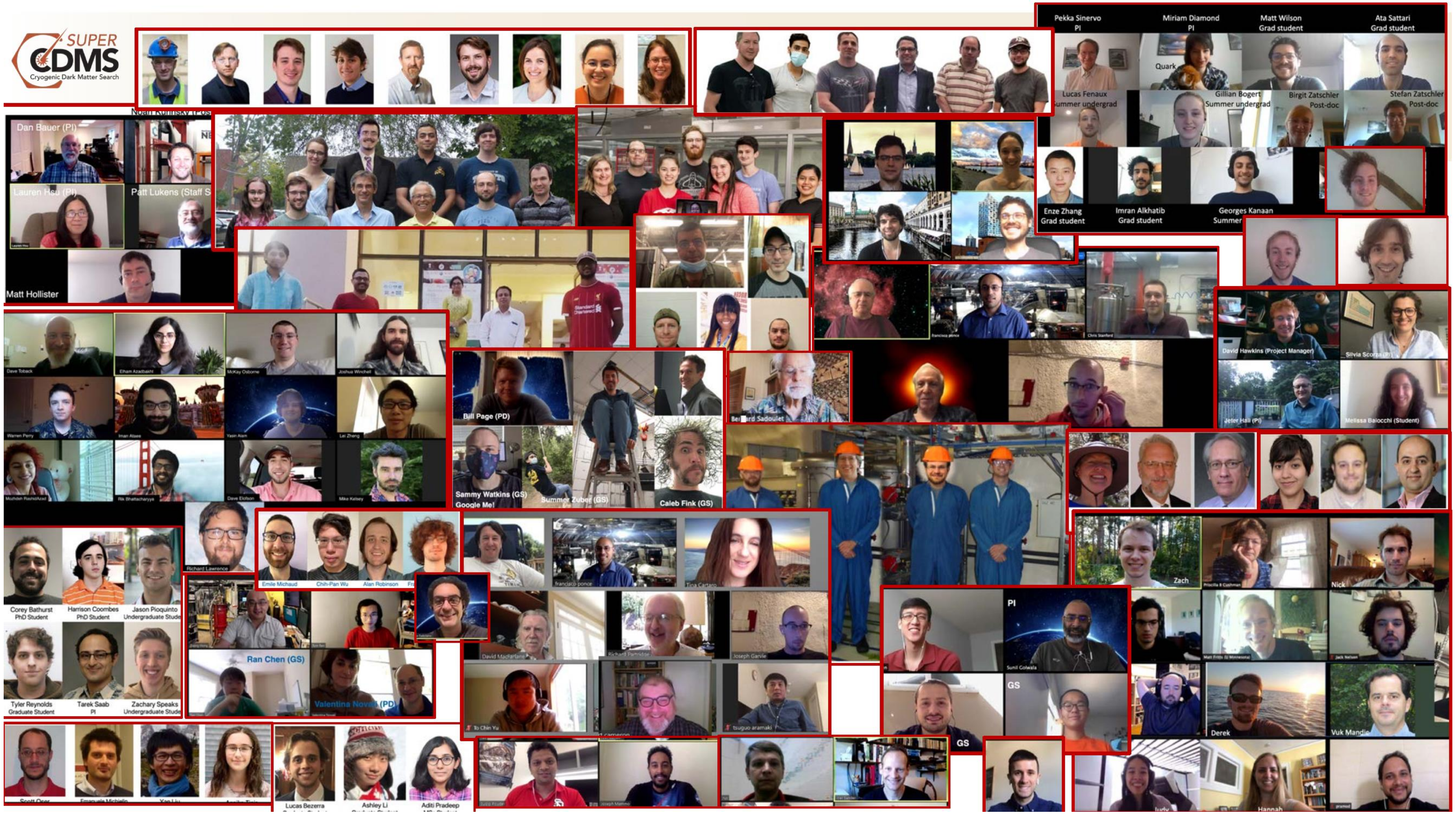


SuperCDMS Collaboration



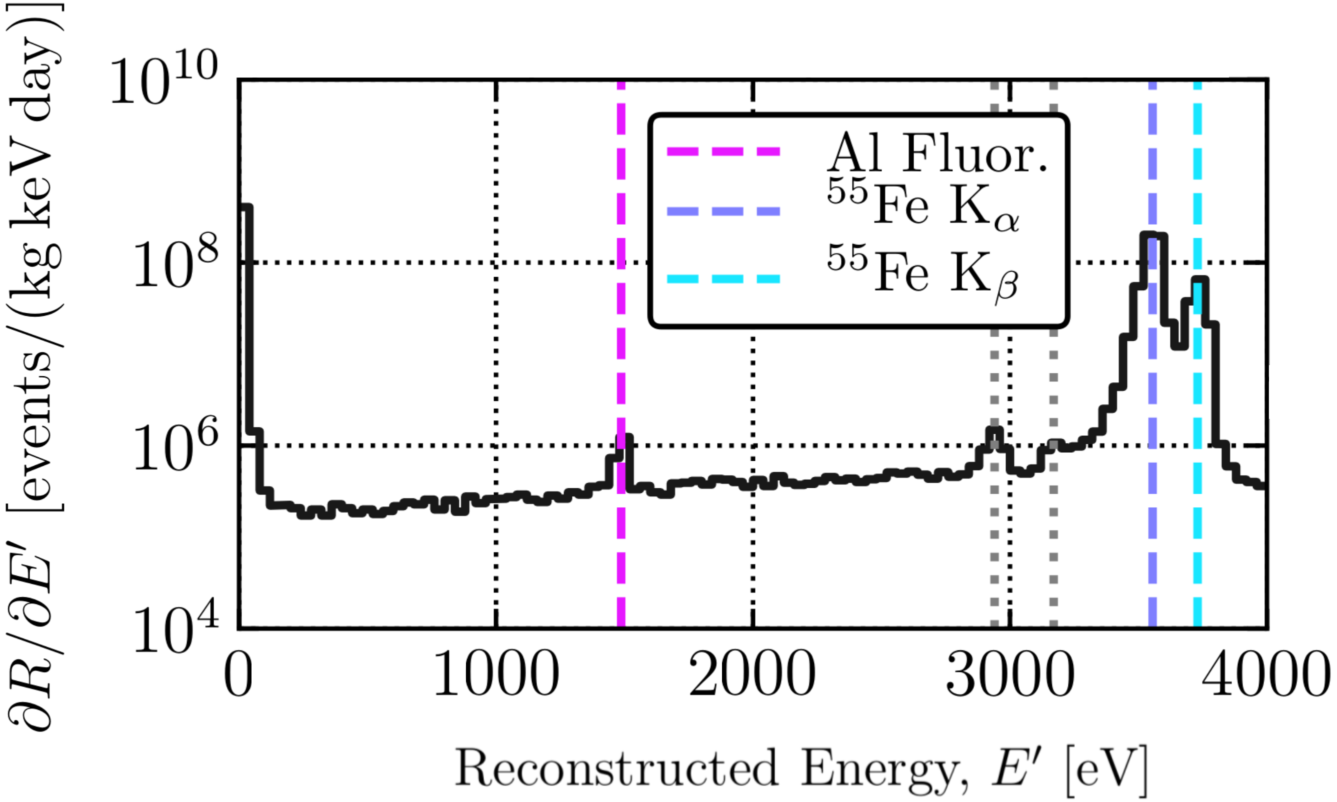
Above Ground Dark Matter Search

- At the SLAC National Accelerator Laboratory, a DM Search was carried out
    - Elevation of $\sim 100\text{ m}$
    - Exposure of $9.9\text{ gram-days (22 hours)}$
    - Minimal shielding
    - Threshold set at 4.2σ
- At the surface, we should be background limited

SLAC NATIONAL ACCELERATOR LABORATORY

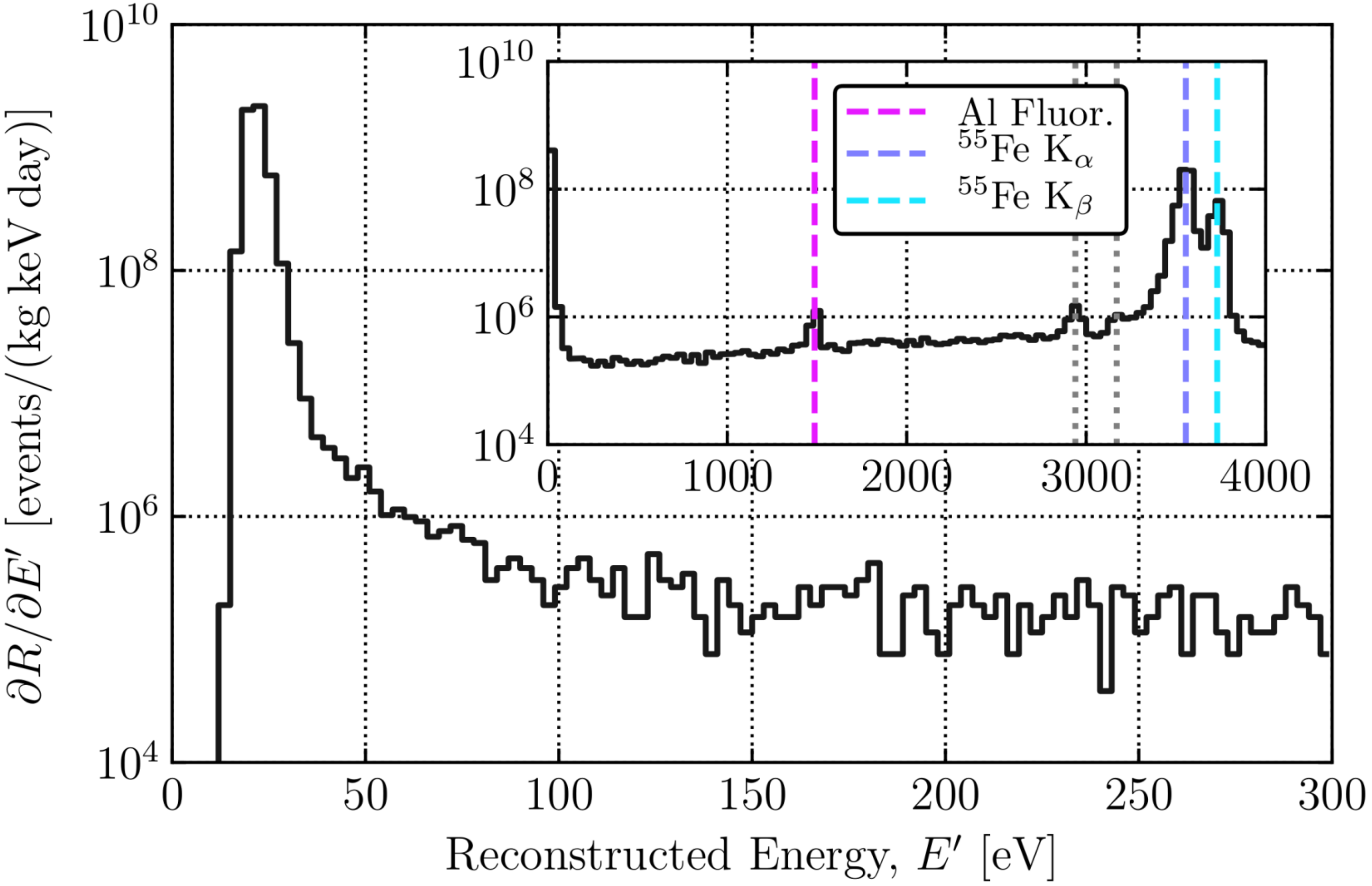
DM Search Calibration

- Note the 3.9 eV number is at odds with the 4.9 eV number in the DM paper
- The DM search paper uses a much more conservative calibration
  - We simply calibrate the OF amplitude to the known energy of the Al line
- This kept the calibration conservative
  - Overestimating event energies leads to a higher threshold and increases the event rate of our spectrum
- The main reason being that the technical calibration had been developed by the CPD Collaboration only earlier this year
  - We may update the DM paper with the new calibration



Event Spectrum

- Region of interest is below 300 eV
- Reconstructed energy is the offline OF amplitude E' calibrated linearly to the Al line
- We see a flat background of $\sim 2 \times 10^5$ DRU down to about 150 eV
  - Mainly Compton scattering of the gamma-ray background
- Below this, the event rate increases, implying we have a background of unknown origin



Data Quality Cuts: Baseline Cut

- For the data quality cuts, we purposefully kept it simple and energy-independent
- Baseline is defined as the average output in the prepulse section of each event
  - i.e. the first $25.6\ \mathrm{ms}$ of each trace
- Remove events that lie on excessively sloping baselines (e.g. thermal tails from large energy depositions)
  - Bin baselines in $400\ \mathrm{s}$ long bins
  - Remove from each bin 10% of events that have the highest baseline
  - Energy-independent method

Nominal muon flux at surface:
$\sim 1\ \mathrm{muon/cm^2}$/min

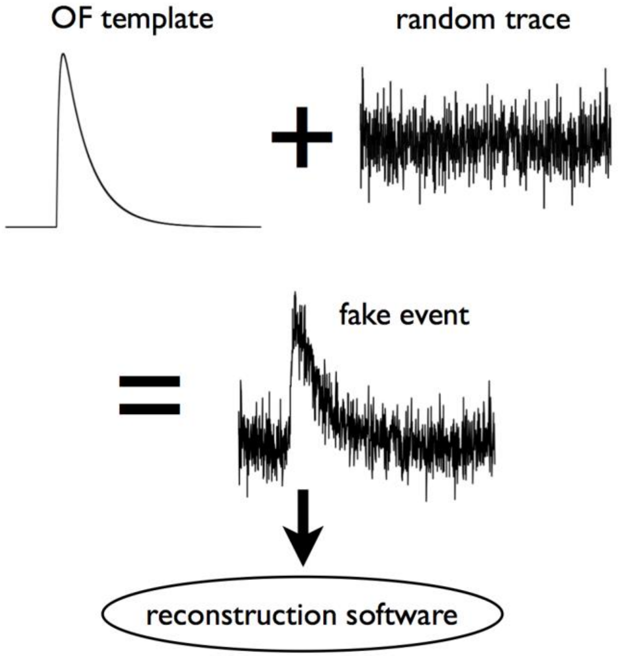
Data Quality Cuts: Chi-Square Cut

- Low frequency chi-square cut for a general goodness-of-fit cut
  - Truncate integral at $f_{\text{cutoff}} = 16\ \text{kHz}$ to remove superfluous degrees of freedom
  - Removes events that do not match our expected signal well
  - Could be glitches, pileup events, vibrationally-induced events, etc.
- Used a pulse simulation to measure the chi-square cut efficiency
  - Cannot use the science data, as it is polluted with non-DM signal-like events
  - Instead inject noise from the in-run randoms to the pulse template, scaling the latter over the energies in the ROI
  - Find that the chi-square cut efficiency is 98.5%
- We kept this cut very loose, as reasonable variation of the cut values had no significant impact on experimental sensitivity
  - Energy-independent, as pulse-shape variation in ROI is minimal

$\tau_r = 20\ \mu s \rightarrow 8.0\ \text{kHz}$

$\tau_f = 58\ \mu s \rightarrow 2.7\ \text{kHz}$

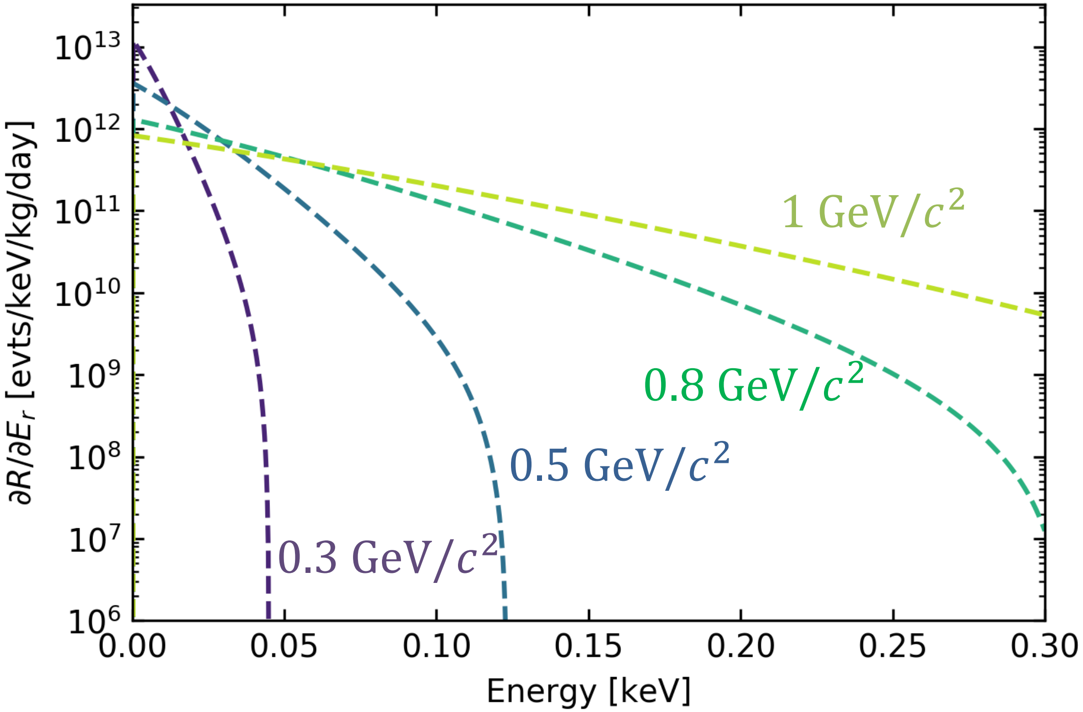
$$\chi^2_{LF} = \int_{-f_{\text{cutoff}}}^{f_{\text{cutoff}}} df \frac{|\tilde{v}(f) - \hat{A}\tilde{s}(f)|^2}{J(f)}$$



Dark Matter Signal Model

- For the signal model, we use standard astrophysical parameters for the DM velocity distribution
  - Velocity of the Sun about the galactic center of $v_0 = 220\ \mathrm{km/s}$
  - Mean orbital velocity of the Earth of $v_E = 232\ \mathrm{km/s}$
  - Galactic escape velocity of $v_{\mathrm{esc}} = 544\ \mathrm{km/s}$
  - Local DM density of $0.3\ \mathrm{GeV/cm^3}$

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{\rho_\chi}{m_\chi} \int_{v_{\min}}^{\infty} v f(\mathbf{v}) \frac{\mathrm{d}\sigma_{\chi N}}{\mathrm{d}E_R}\, \mathrm{d}^3\mathbf{v}$$



Differential Event Rate Model

- We trigger on one energy estimator E_T, but use E' for our reconstructed energy
  - These are both OF amplitudes, so they are highly correlated
- How can we take into account the correlation?
  - Convolve the true differential rate model with the joint probability density function relating the energy estimators to the true energy
  - Include the various cuts

$$\frac{\partial R}{\partial E'}(E') = \int_0^\infty dE_T \int_0^\infty dE_0 \, \Theta(E_T - \delta) \\ \times \varepsilon(E', E_T, E_0) P(E', E_T | E_0) \frac{\partial R}{\partial E_0}(E_0)$$

- We need an estimate of the PDF

Measuring the PDF

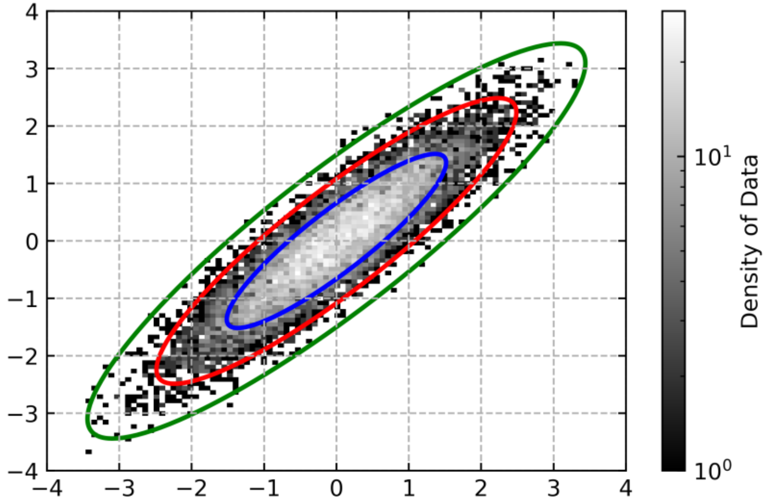
- The OF looks for the largest amplitude in a specified window
- When the signal-to-noise ratio is low, there is a bias towards positive fluctuations
  - In our case, there is a nonnegligible effect of the latching near threshold
  - We cannot simply use the Gaussian approximation of the PDF
- Using the randomly triggered events, we simulate data at various energies
  - Data is simulated throughout the ROI
  - A software simulation of the FPGA triggering algorithm allows us to directly compare the energy estimators to the true energy
  - At each energy simulated, we can directly measure the PDF, allowing us to calculate the expected differential rate spectrum

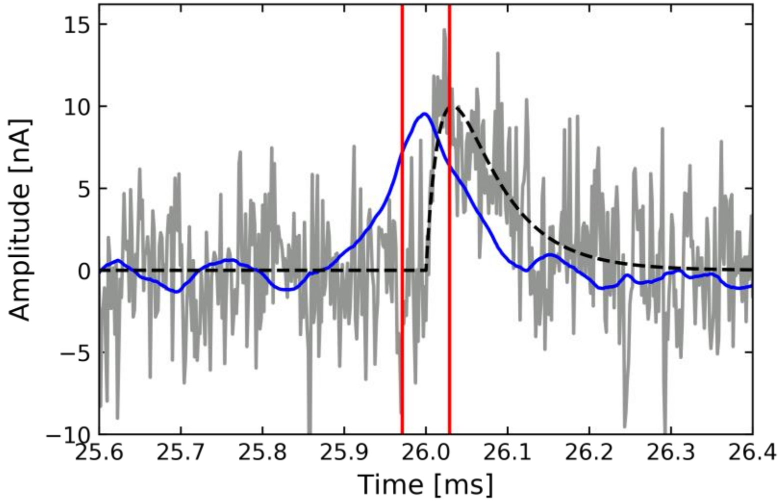
Conservative Cuts to Simulated Data

Two cuts added to simulated data:

1. 99.7% confidence ellipse cut
   - Remove simulated events with energy estimator values outside of the ellipse
   - Ellipse defined by covariance matrix of energy estimators at zero energy
   - Ensures we do not have sensitivity to events with zero energy
2. FPGA trigger time cut
   - Removes events whose trigger time was not within half of a pulse fall time of the true event time
   - Ensures the simulated event was detected by the simulated FPGA algorithm

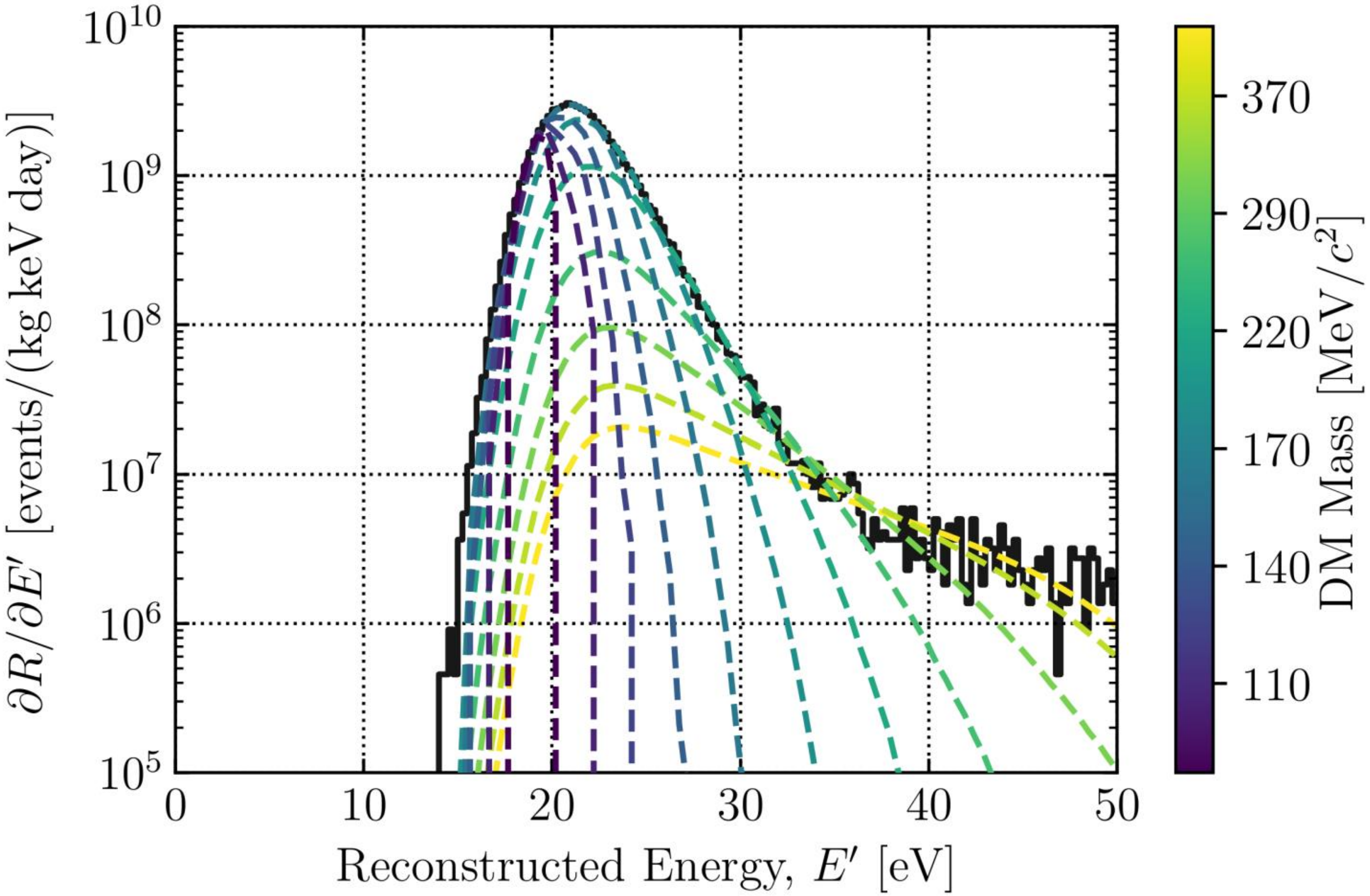
Each of these cuts reduces our signal efficiency and ensures our modelling is conservative





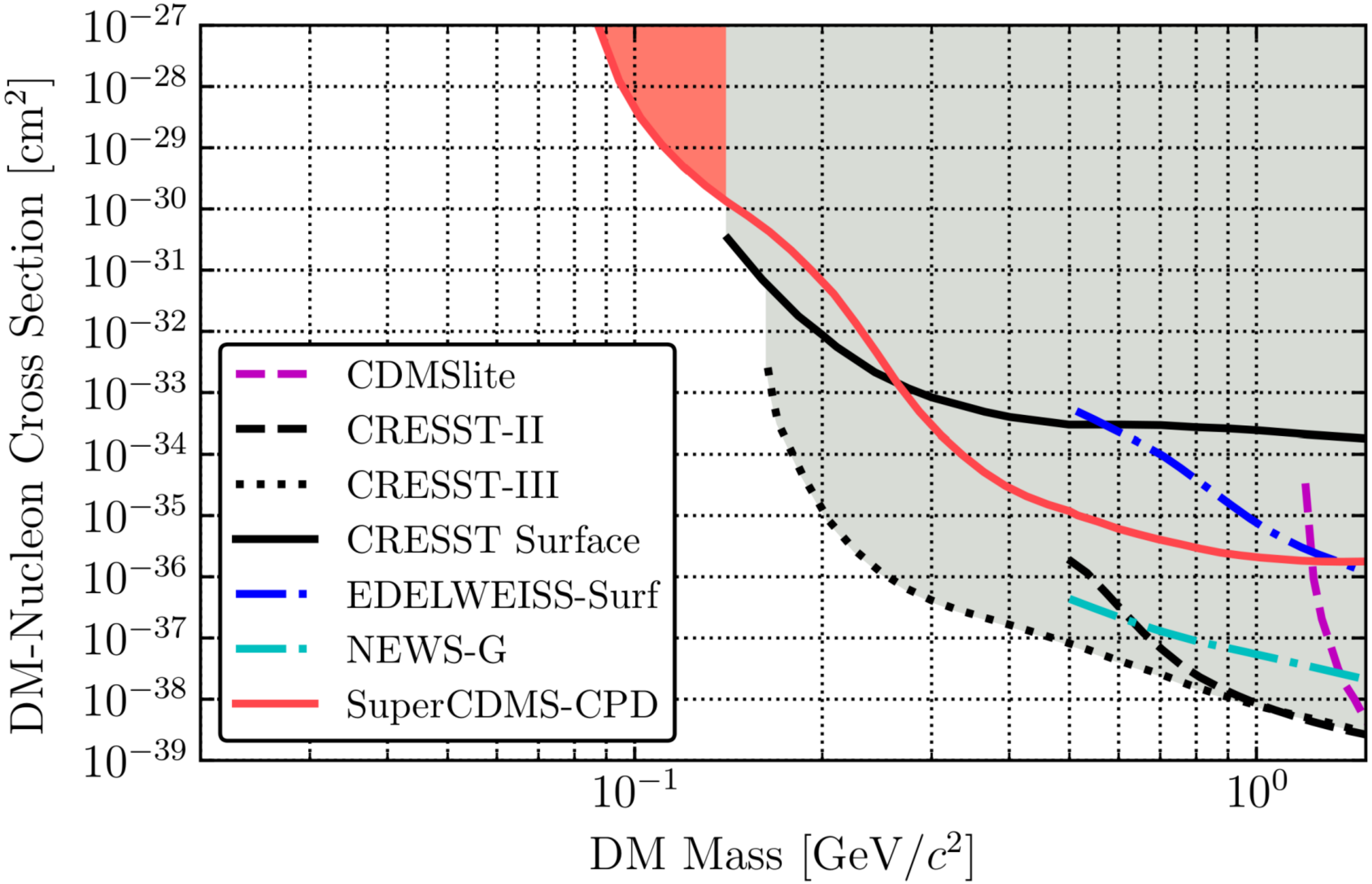
Differential Rate Spectra

- The effect of smearing at threshold is shown in the figure to the right
- Each dashed line corresponds to a different dark matter mass
  - Sensitivity to DM masses below $200\ \mathrm{MeV}/c^2$ requires energy sensitivity below $20\ \mathrm{eV}$
  - This shows the importance of low energy thresholds for DM searches in this mass region
- Using the Optimum Interval method, we can use this signal model to set a 90% confidence limit



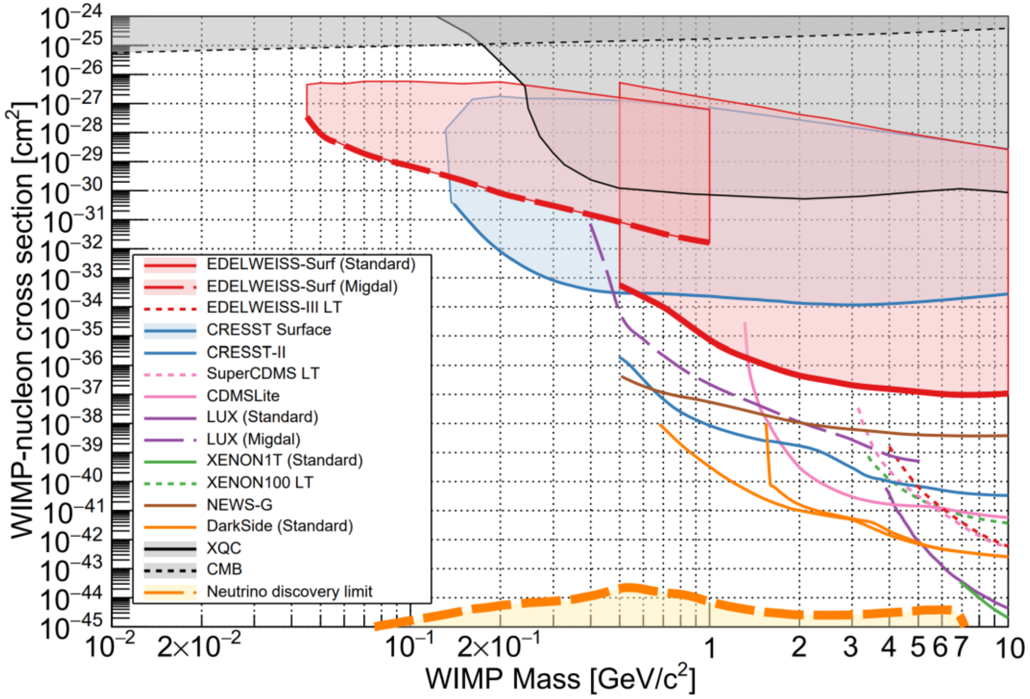
Results

- World-leading sensitivity to nuclear-recoiling DM from $140\ \mathrm{MeV}/c^2$ to $87\ \mathrm{MeV}/c$^2
- World-leading sensitivity to nuclear-recoiling DM for an above-ground experiment from $1.35\ \mathrm{GeV}/c^2$ to $250\ \mathrm{MeV}/c^2$
- Athermal phonon sensors with eV-scale resolution have great potential for future DM searches

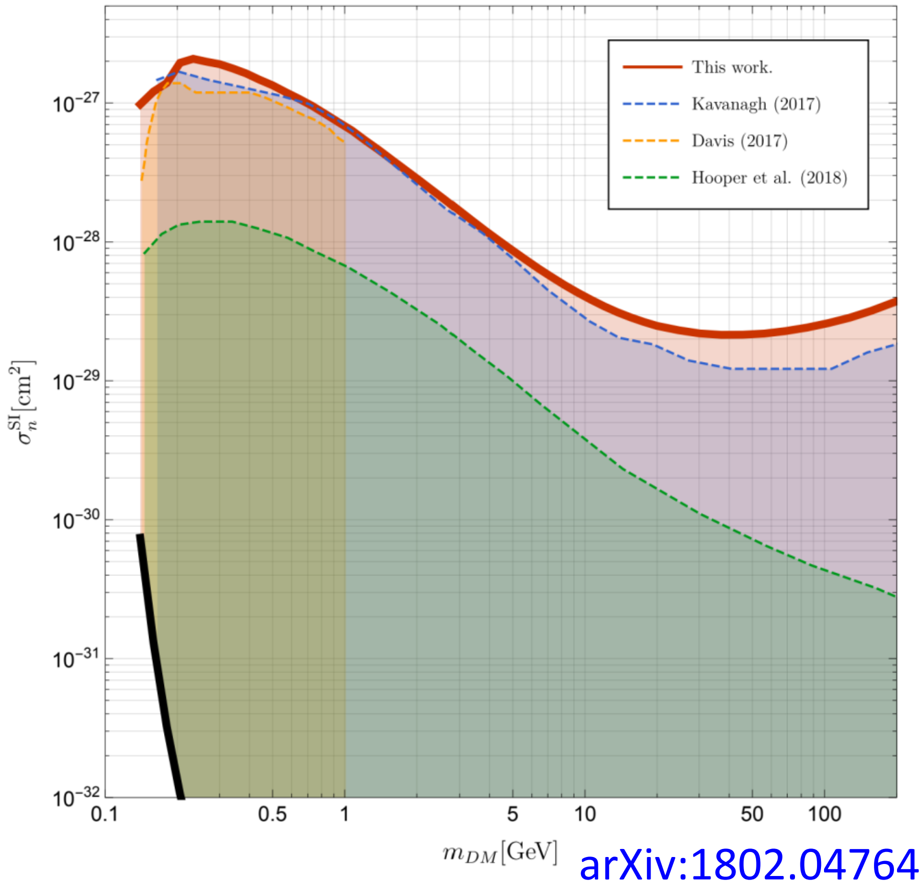


Strongly Interacting DM

- For strongly interacting dark matter, a limit was not calculated
  - Overburden was similar to that in both the EDELWEISS and CRESST above ground searches
  - We expect to have sensitivity to strongly interacting DM up to cross sections of $10^{-27}\ \mathrm{cm}^2$



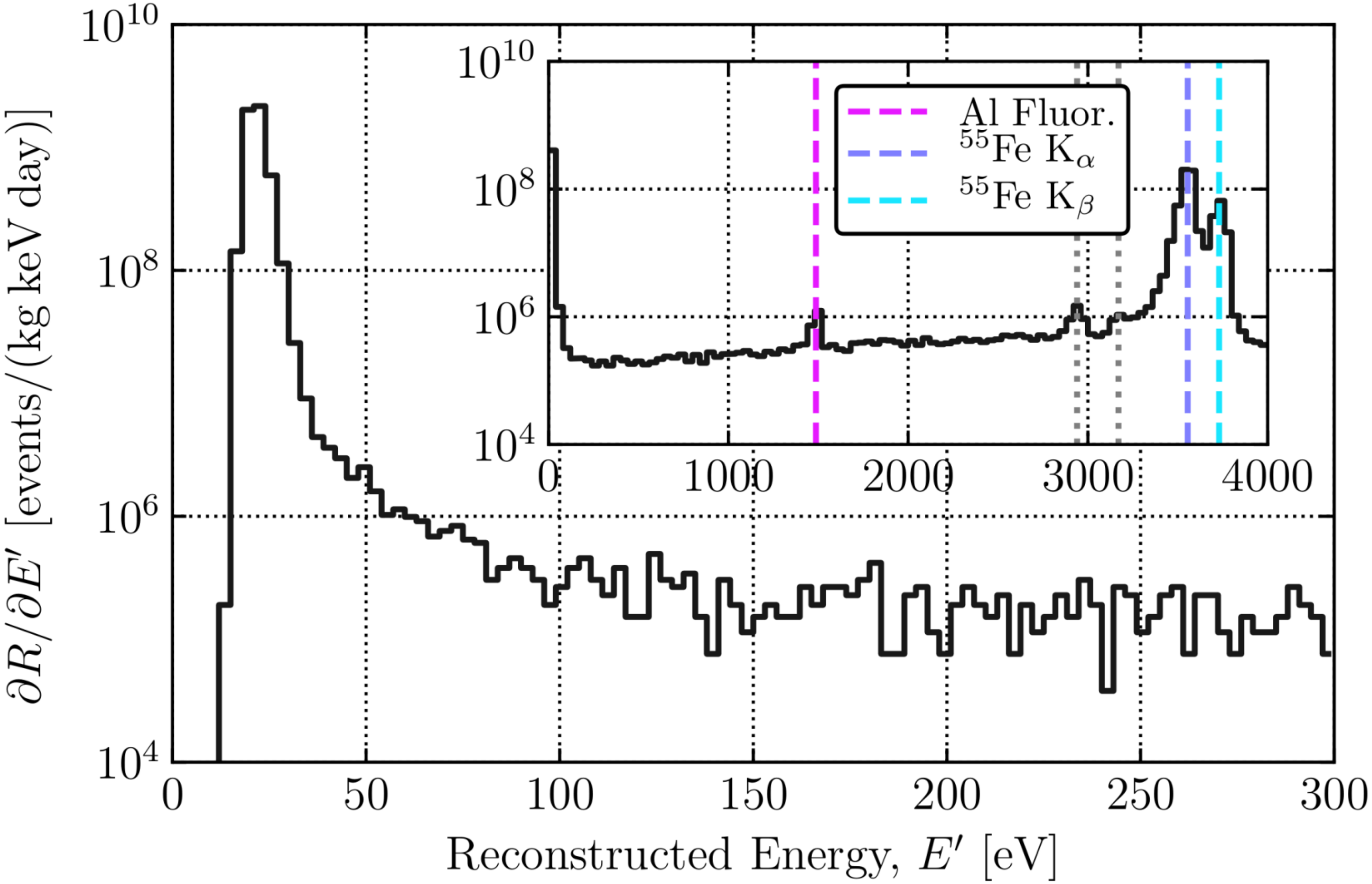
arXiv:1901.03588



arXiv:1802.04764

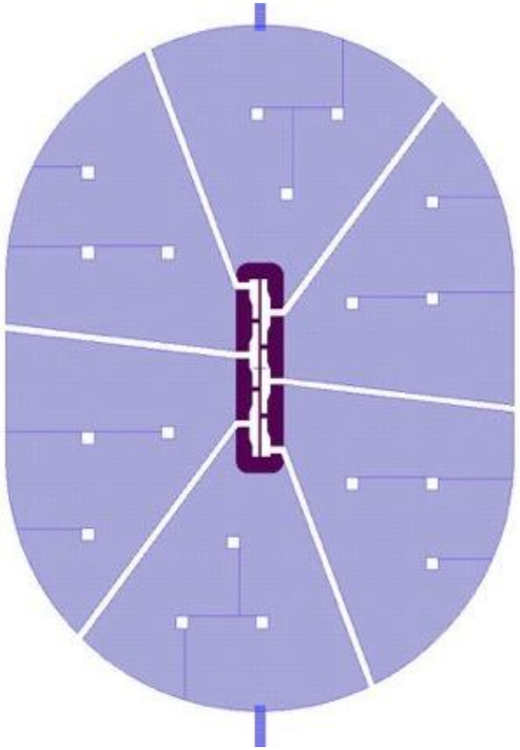
Excess Background

- Excesses below ~150 eV
- Excess exponential background below 100 eV
- Below ~30 eV, the background appears to be higher than expected from noise triggers
- Origins of backgrounds are unclear
  - Possibly crystal cracking
  - We did attempt to use detectors sandwiched around CPD for a possible veto, but no improvement
- Actively investigating this background
  - Plan to run the CPD underground



Future CPD Outlook

- Actively designing the next-generation of the CPD
  - Further optimizations of Al-W overlap and the total Al coverage
  - Expectation is up to a factor of 2 improvement in energy resolution through adjustments to these characteristics
  - Should be an even better photon detector for rare event search applications
  - Potential for a lower threshold DM search with this new device



Future Above Ground Experiments

- The large surface area relative to the small volume means that CPD isn't optimized for a DM search
- If we decrease the number of QETs (decreasing the instrumented area) and increase the volume, the baseline energy resolution should be improved
- With devices of order $1\ \mathrm{cm}^3$, we can expect roughly an order of magnitude improvement in baseline energy resolution through these geometric considerations alone
- Plans to fabricate devices with these design principles in mind, for which even lower threshold above ground searches should be achievable

Thank You!

SUPER CDMS

Cryogenic Dark Matter Search