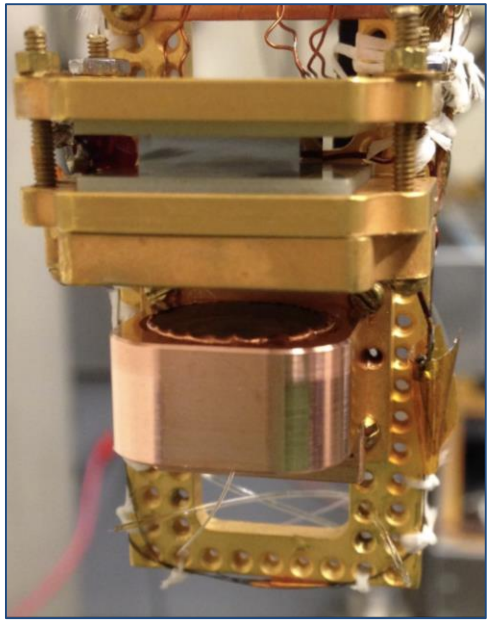
R&D for Light Mass Dark Matter Searches with SuperCDMS

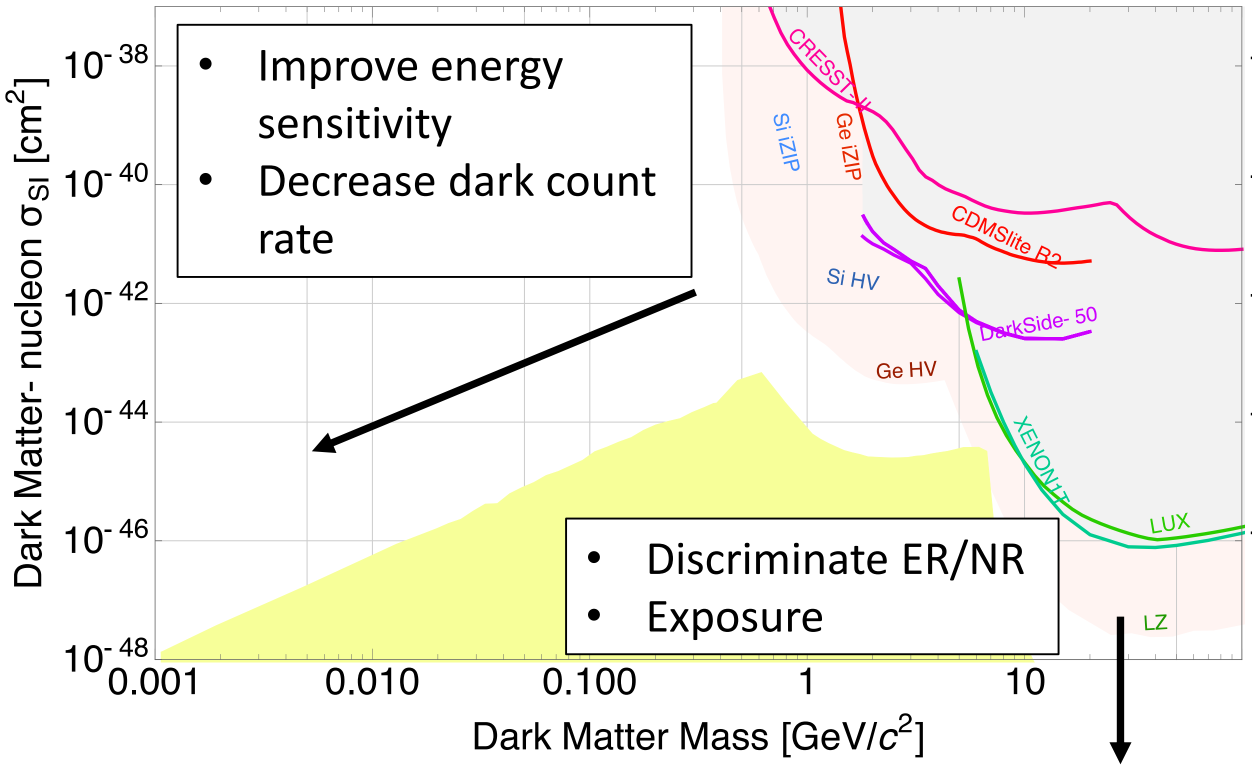
- Performance of a Large Area Photon Detector and Applications
- Single Charge Excitation via Phonon Amplification



Samuel Watkins, Noah Kurinsky

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



Improving Phonon Resolution

UC Berkeley

J. Camilleri, C. Fink, Y. Kolomensky, M. Pyle, B. Sadoulet, B. Serfass, S. Watkins

Texas A&M

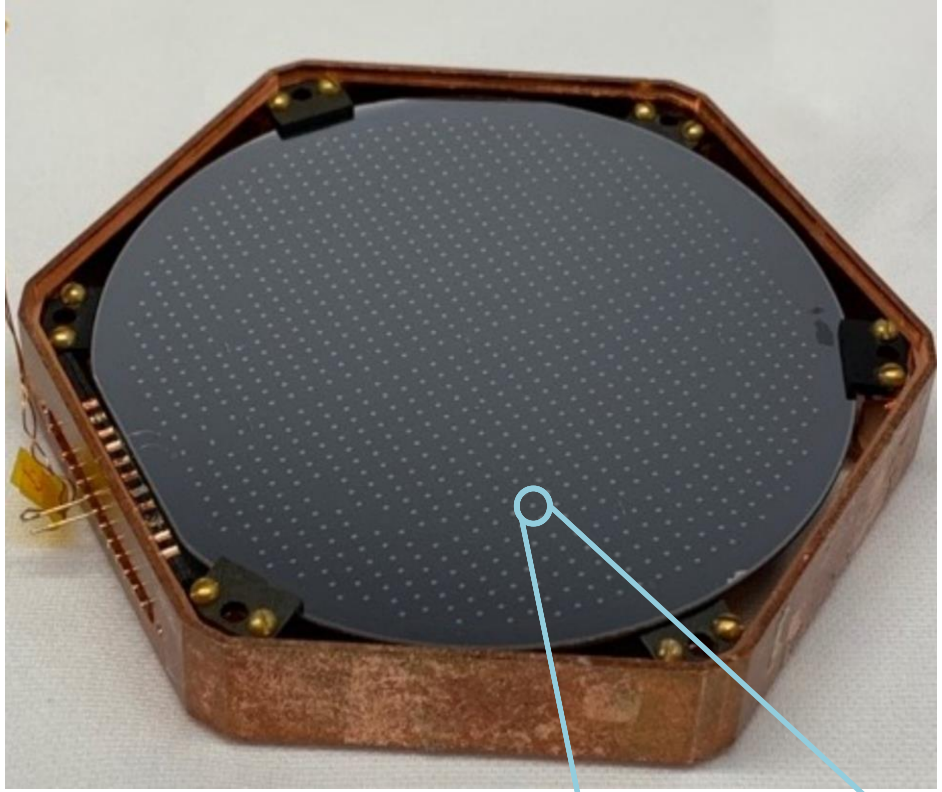
R. Harris, R. Mahapatra, N. Mirabolfathi, M. Platt

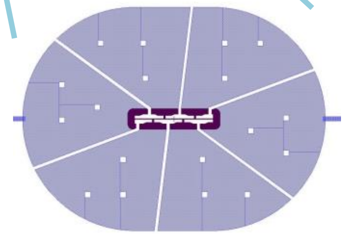
SLAC

T. Aramaki, P. Brink

Design of a Large Area Photon Detector

- The detector is a CDMS-style athermal phonon sensor
  - 1 mm thick silicon wafer, 45.6 cm^2 surface area
  - Mass of 10.6 grams
- The device has been optimized for photon detection
  - Distributed athermal sensor array read out by TESs
  - Single distributed channel gives a fast collection time of athermal phonons
  - This reduces efficiency penalties due to athermal phonon down conversion
  - $T_c = 41.5\ \mathrm{mK}$, lowering the expected energy resolution
- Designed originally for degraded alpha rejection in neutrinoless double beta decay and for an active photon veto for dark matter experiments



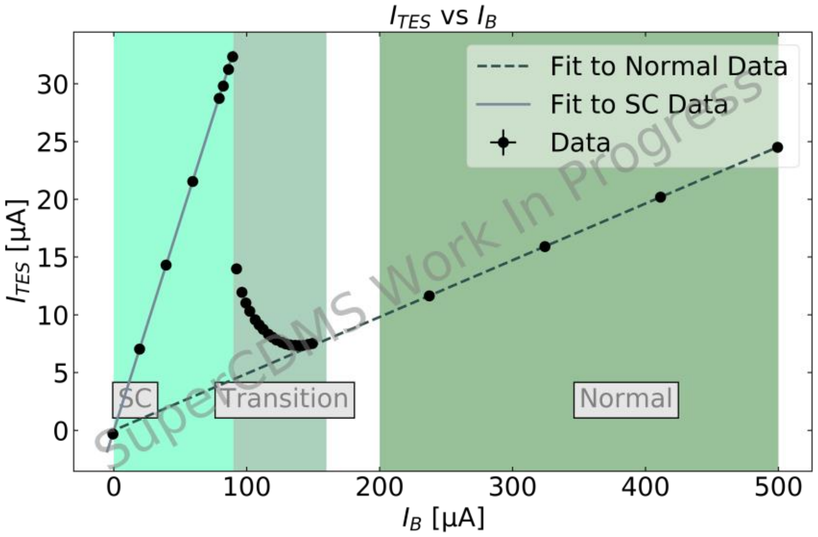


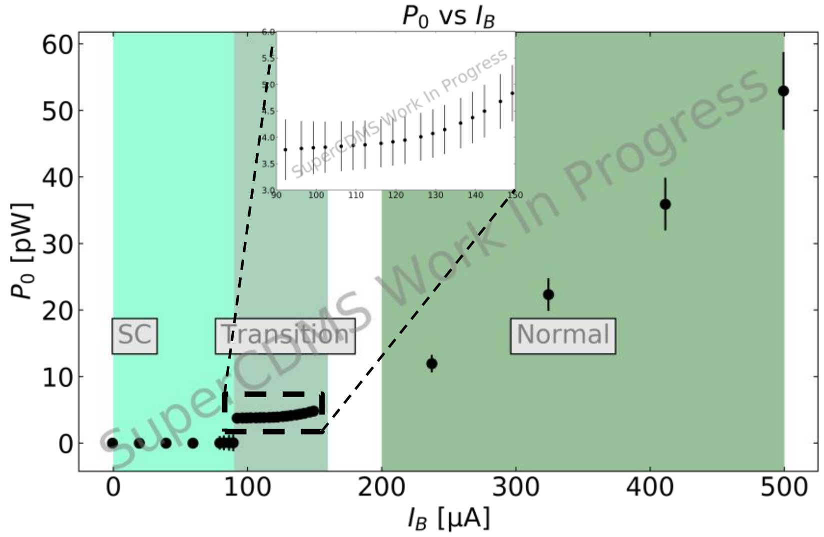
Characterizing the Detector

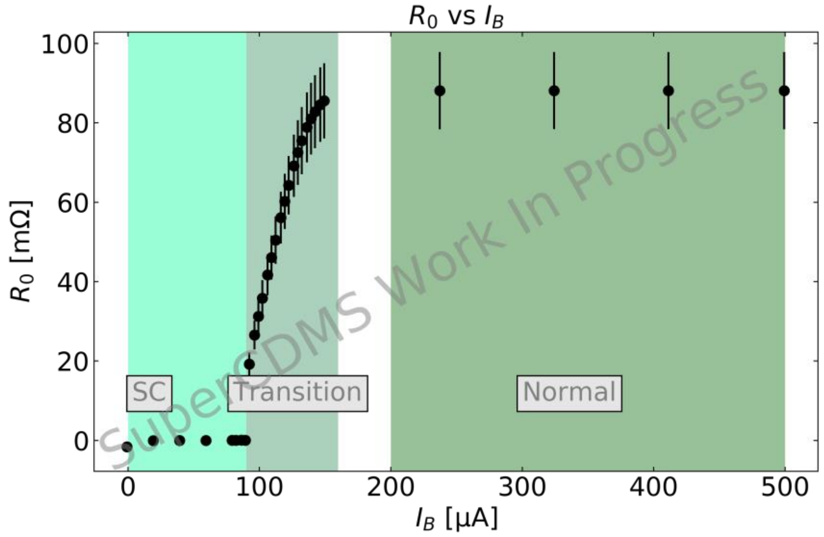
- In order to characterize the detector, we took an IV curve and $\partial I/\partial V$ data, allowing us to:
  - Determine the normal resistance, $R_N = 88.1 \pm 10.2\ \mathrm{m\Omega}$
  - Determine the parasitic resistance, $R_p = 8.7 \pm 0.9\ \ \mathrm{m\Omega}$
  - Calculate the bias power in transition, $\boldsymbol{P_0 = 3.8 \pm 0.5\ \mathrm{pW}}$
  - The TES resistance and current through TES as a function of bias current

limited by 10% R_{sh} systematic error, where $R_{\mathrm{sh}} = 5\ \mathrm{m\Omega}$

- With a fit to the complex impedance, we have enough information to fully characterize our detector

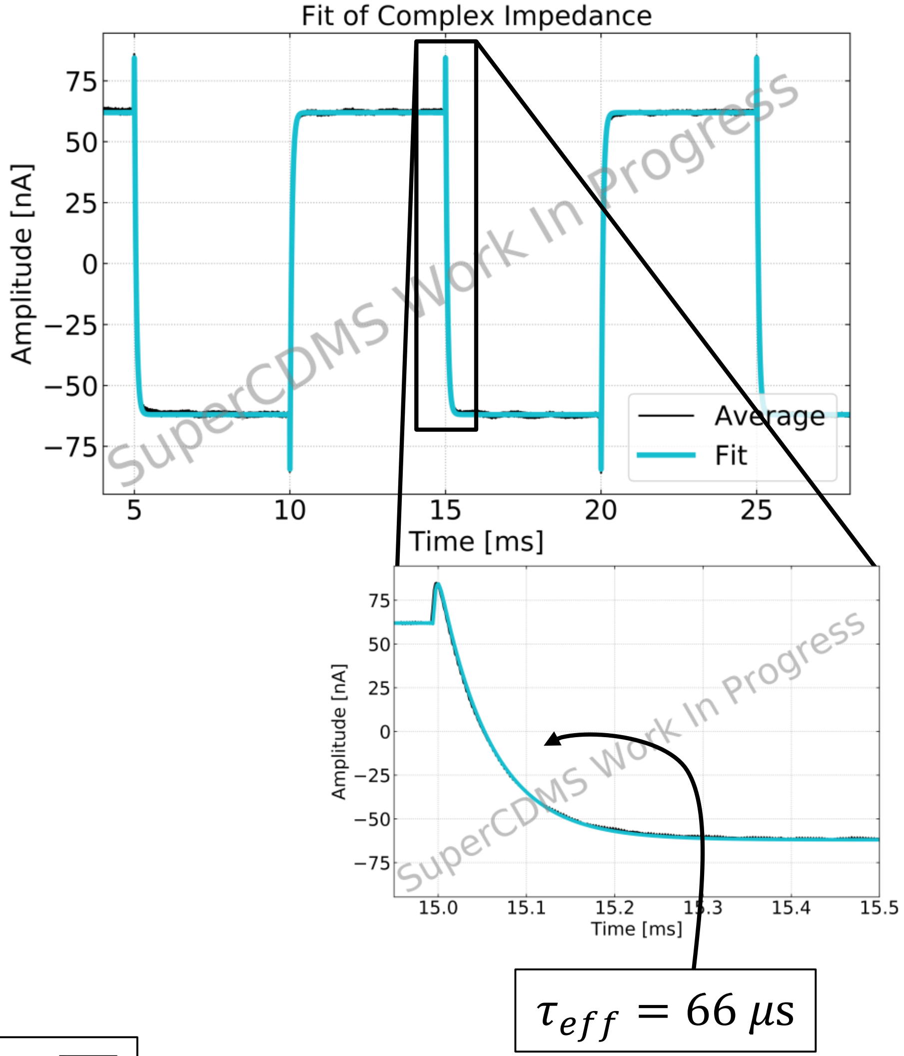


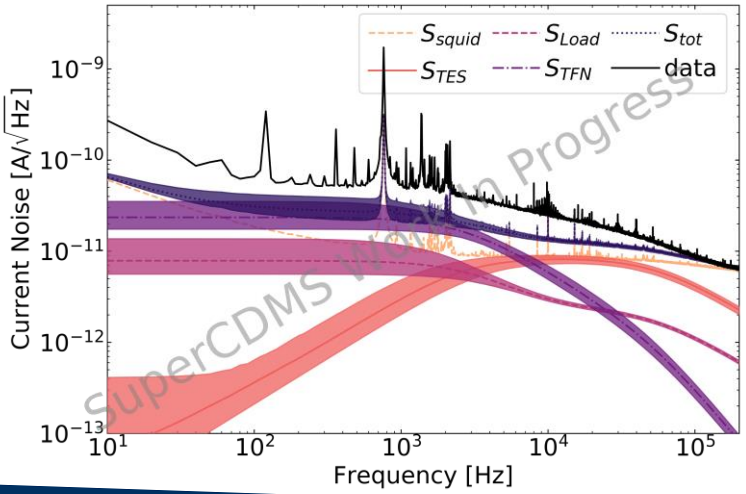


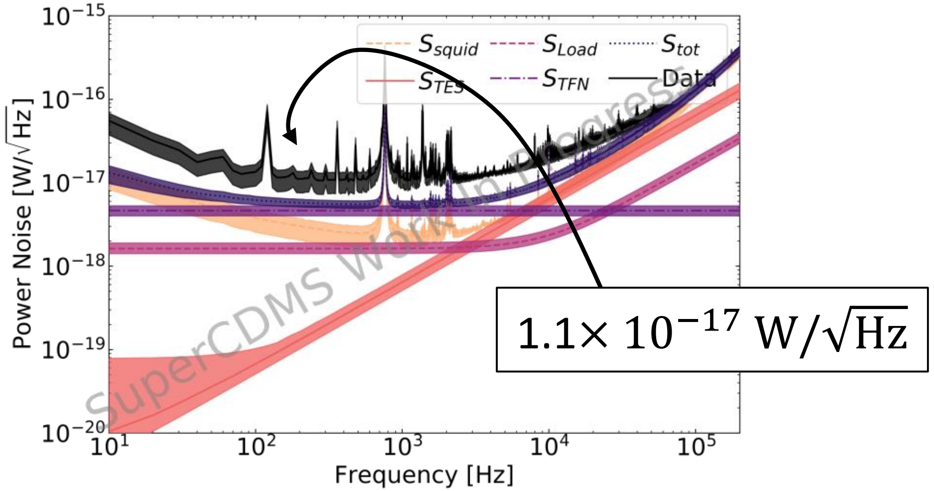


Modeling the Noise

- At each bias point, we took:
  - Noise data for calculation of PSDs
  - Data with a square wave down the TES bias line for fitting the complex admittance using standard TES modeling
- This data allows us to model the system to determine the bias point with the best energy resolution
- At the optimal bias point:
  - The fall time of the TES is fast with $\tau_{eff} = 66\ \mu s$
  - Our NEP is $1.1 \times 10^{-17}\ \mathrm{W}/\sqrt{\mathrm{Hz}}$
  - We are within a factor of 2 of the theoretical performance

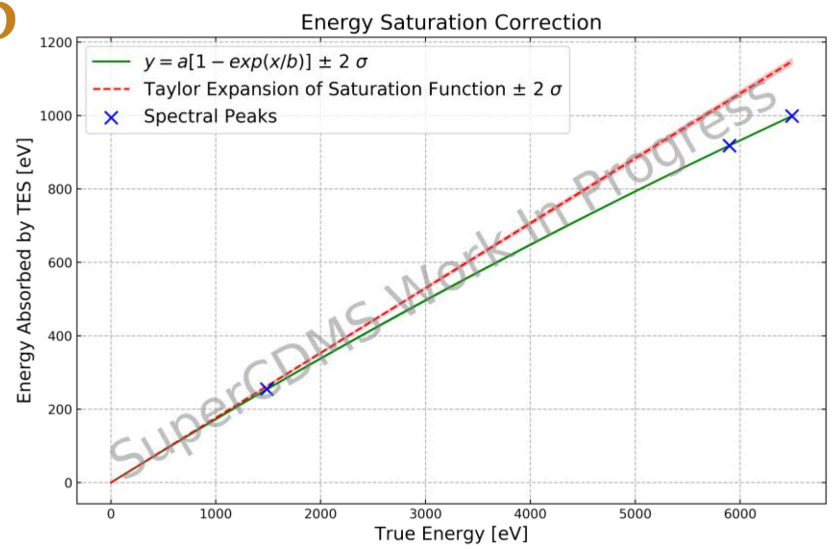


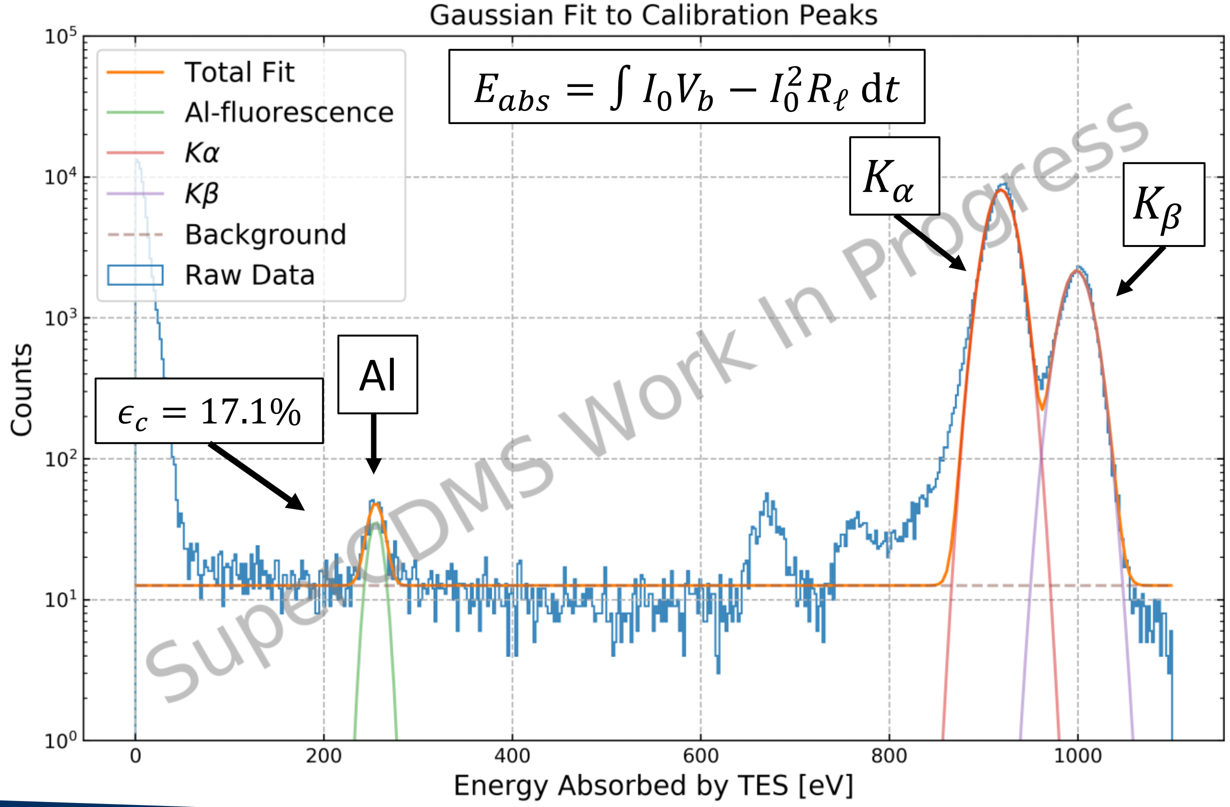




Spectrum and Calibration using Fe-55

- We have a collimated Fe-55 calibration source
  - K-α and K-β peaks are visible (5.9 keV and 6.5 keV)
  - Used aluminum foil for attenuation, resulting in a collimated aluminum fluorescence line at 1.5 keV





- The spectrum is calibrated using the energy absorbed by the TES to reduce the effect of saturation
  - Al line implies a phonon collection efficiency of 17.1%, close to the expected 20%

- We use the functional form $y = a(1 - e^{-x/b})$ to model the saturation and use a linear fit to the Al line to take into account calibration systematics

- We then use the same saturation model to calibrate the Optimum Filter amplitude to units of energy via the energy absorbed

Detector Performance

- From the good randoms after cuts, the energy resolution is now directly calculable
- We find that this detector has an energy resolution of $\boldsymbol{\sigma_E = 3.9 \pm 0.1(\text{stat.}) \pm 0.18(\text{sys.})\ \text{eV}}$
  - This detector is a world-leading device for detecting photons given its size!

	Sensor	Area (cm^2)	σ_E [eV]	$\frac{\sigma_E}{\sqrt{\mathrm{Area}}}\ \left[\frac{\mathrm{eV}}{\mathrm{cm}}\right]$
CRESST 2 LD Rothe et al JLTP 193,1160 (2018)	W TES	12.5	4-7	1.1-2.0
LMO-3 LD E. Armengaud et al, Eur. Phys. J. C (2017) 77 :785	NTD	5	7.7	3.4
CALDER 1801.08403	Al/Ti/Al MKID	4	26	13
This Detector	**W TES**	**45.6**	**3.9**	**0.58**

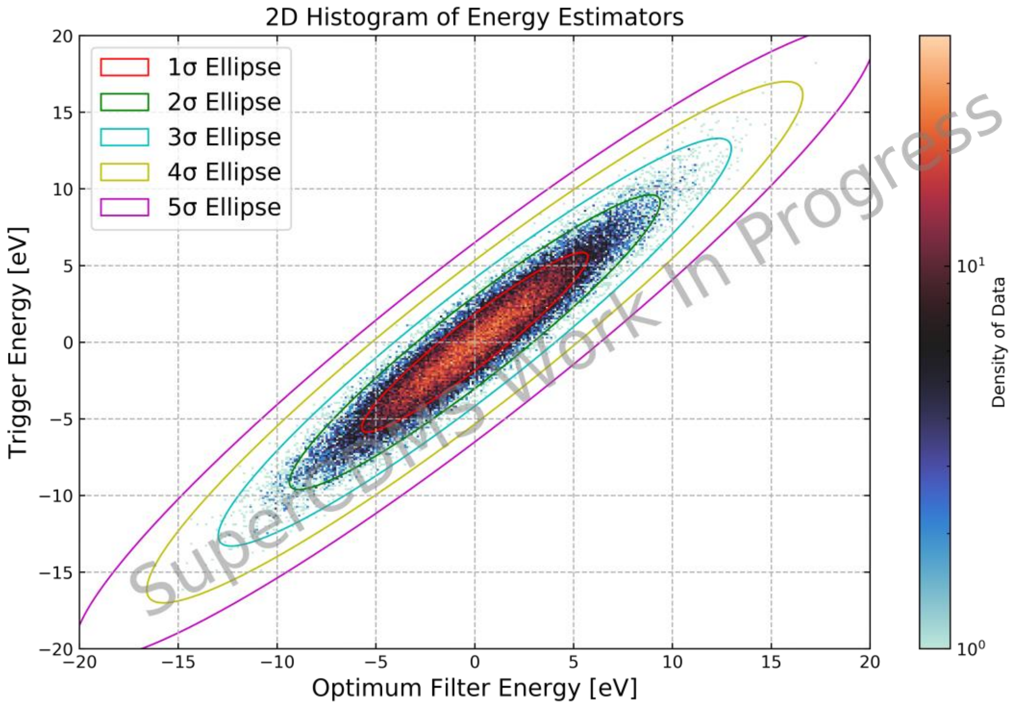
Applications to a Dark Matter Search

- Though not optimized for a dark matter search, the 3.9 eV energy resolution of this device implies a meaningful low threshold search
- In collaboration with SuperCDMS, we ran the detector at a SLAC surface facility for 22 hours
  - We expect to be background limited

Different Energy Estimators

For any event with true energy E_0, we have two strongly correlated energy estimators:

1. The amplitude from the SuperCDMS prototype DAQ's digital FPGA triggering algorithm, E_T
   - This is a continuous triggering algorithm using an Optimum Filter on downsampled data
2. The offline OF amplitude, E', our reconstructed energy for all events
   - This is a refined energy estimator, which should have the best energy resolution



- The correlations between these two energy estimators need to be understood and taken into account for our signal and efficiency modeling

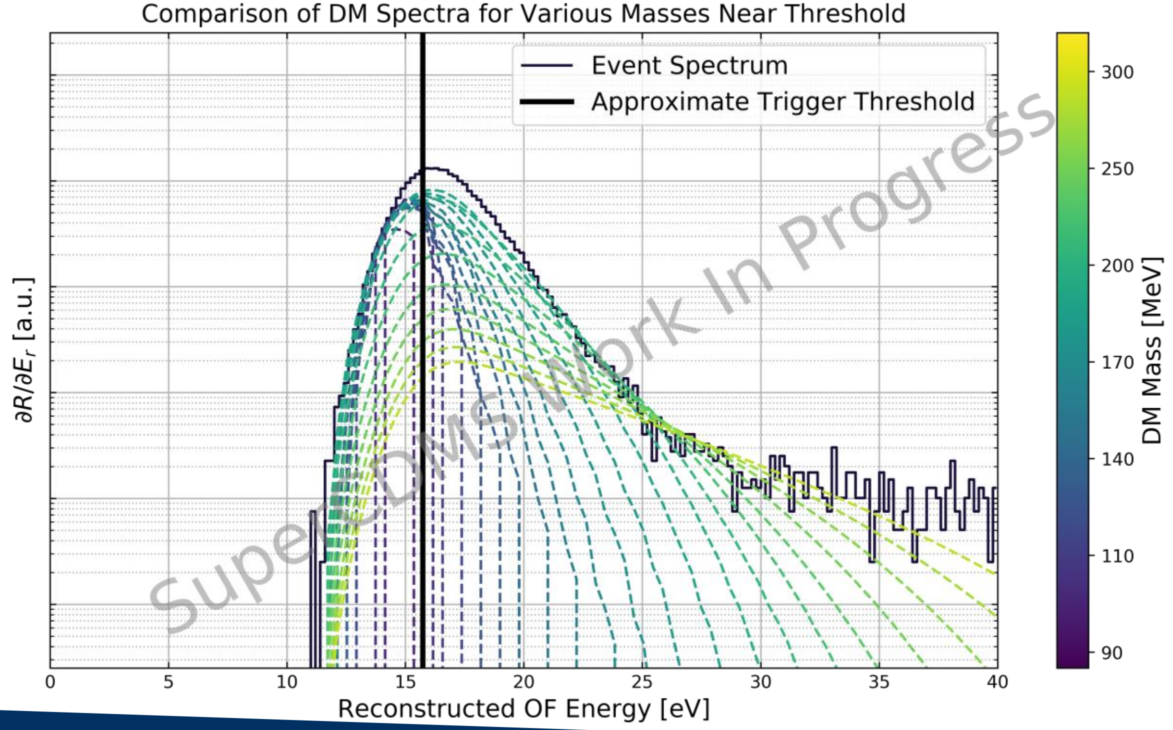
Modeling the $\partial R/\partial E_R$

- How can we take into account the correlation?
  - Convolve the true differential rate model with the 2D Gaussian relating the two energy estimators

$$\frac{\partial R}{\partial E'}(E') = \int_{0^+}^{\infty}\int_{\delta}^{\infty} \mathcal{N}(E', E_T|\Sigma, E_0)\frac{\partial R}{\partial E_0}(E_0)\epsilon(E', E_T)\mathrm{d}E_T\mathrm{d}E_0$$

Σ is the covariance of the two energy estimators
δ is the trigger threshold
$\epsilon(E', E_T)$ denotes efficiencies

- To the right, we see the effect of the smearing on differential rates corresponding to various dark matter masses
  - Sensitivity to dark matter of masses in the range of 90-200 MeV requires energy sensitivity on the order of 10 eV
  - This shows the importance of low energy thresholds for DM searches in this mass region



Interesting Results Coming

- The results of the dark matter analysis are forthcoming
  - We are working through some final systematic checks
  - Expect results on arXiV in the near-future

- The potential of this device is clear for future science results
  - SuperCDMS plans to run the device underground at CUTE in Winter 2020
  - The noise environment should be improved
  - The background rate should be much lower
  - Depending on the above two points, a future search could extend the reach of the previous above-ground search significantly

- The sensitivity of this device lends itself well to other experiments for use as background rejection
  - The **3.9 eV** resolution is a world-leading number for a device of this size ($45.6\ \mathrm{cm}^2$ area)

Cryogenic Underground TEst facility

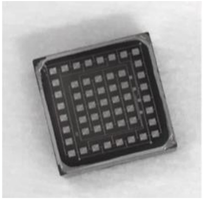
Measuring single electron-hole excitations using phonon amplification

Fermilab
N. Kurinsky,
Northwestern University
H. Douglas Pinckney, E. Figueroa-Feliciano, Z. Hong, B. Nebolsky, R. Ren
Santa Clara University
B.A. Young
SLAC
P.L. Brink, R. Partridge, A. Tomada, J.J. Yen

Stanford University
B. Cabrera, R.A. Moffatt, F. Ponce, R.K. Romani, S. Yellin
Texas A&M
R. Mahapatra, N. Mirabolfathi, M. Platt
UC Berkeley
S. Ganjam, M. Pyle
University of Montreal
L. Wills

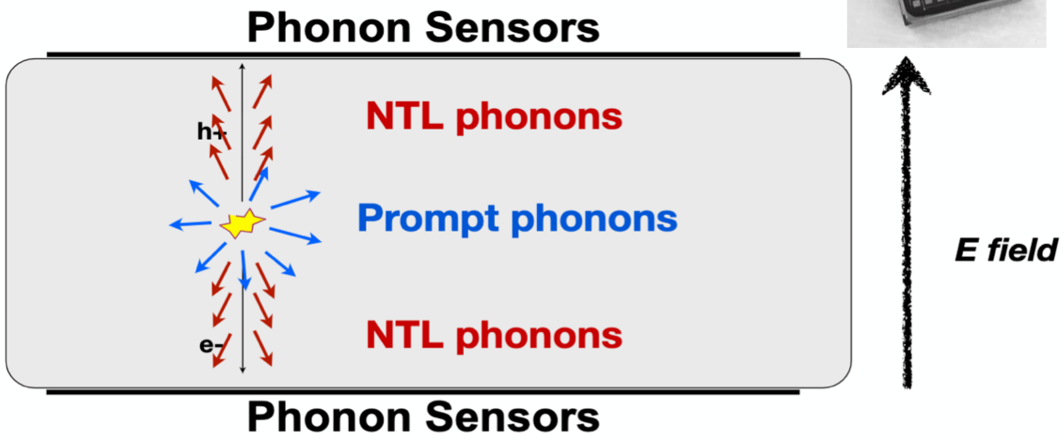
In collaboration with SuperCDMS

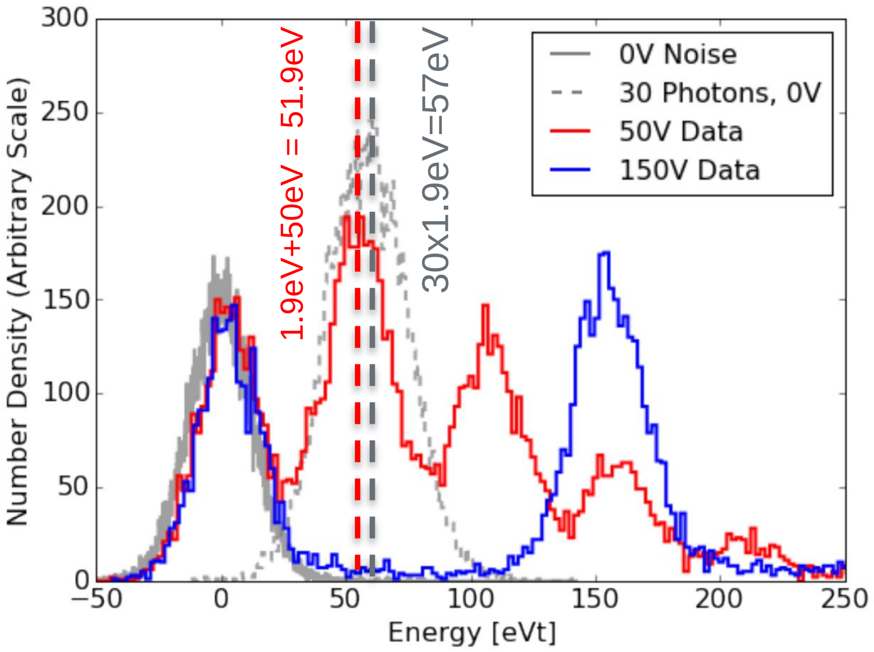
Charge Detection via Neganov-Tiramov-Luke (NTL) Amplification



- Phonons are produced when charges are drifted in an electric field; makes sense by energy conservation alone

$$E_{phonon} = E_{recoil} + V * n_{eh}$$
$$= E_{recoil}\left[1 + V * \left(\frac{y(E_{recoil})}{\varepsilon_{eh}}\right)\right]$$



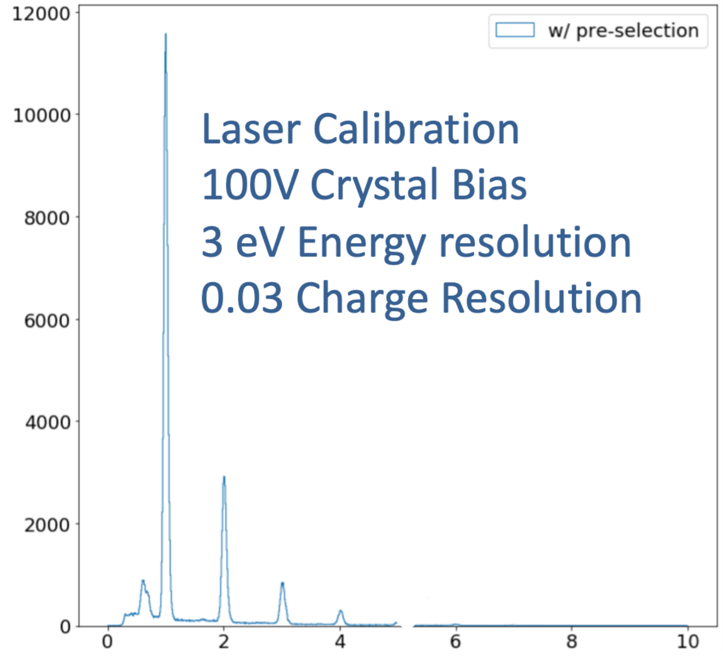


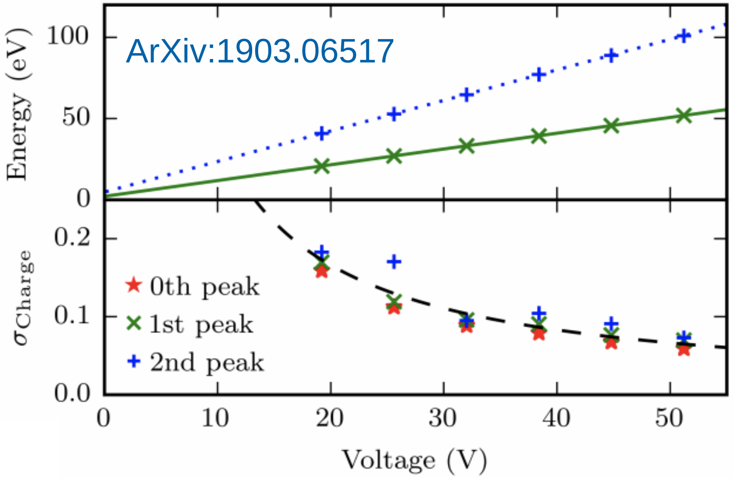
Romani et. al. 2017 (https://arxiv.org/abs/1710.09335)

- Resolution measured using fiber-coupled optical laser with 1.9 eV photons incident on detector face.
- Nearly all energy eventually ends up in phonon system and is measured
  - Phonons from electronic relaxation
  - Phonons from nuclear scattering
  - Recombination phonons produced when charge carriers drop back below the band-gap
  - NTL phonons produced during charge drift

Recent Progress: Phonon Resolution

- Two prototype detectors achieved 3 eV phonon resolution
  - 1mm thick contact free design (top)
  - 4mm thick contact electrode design (bottom)
- Contact electrode design capable of up to 220V bias before breakdown
- 0.03 electron-hole pair resolution achieved in contact design
- DM search with 4mm thick (1g) detector in progress, results expected by September 2019

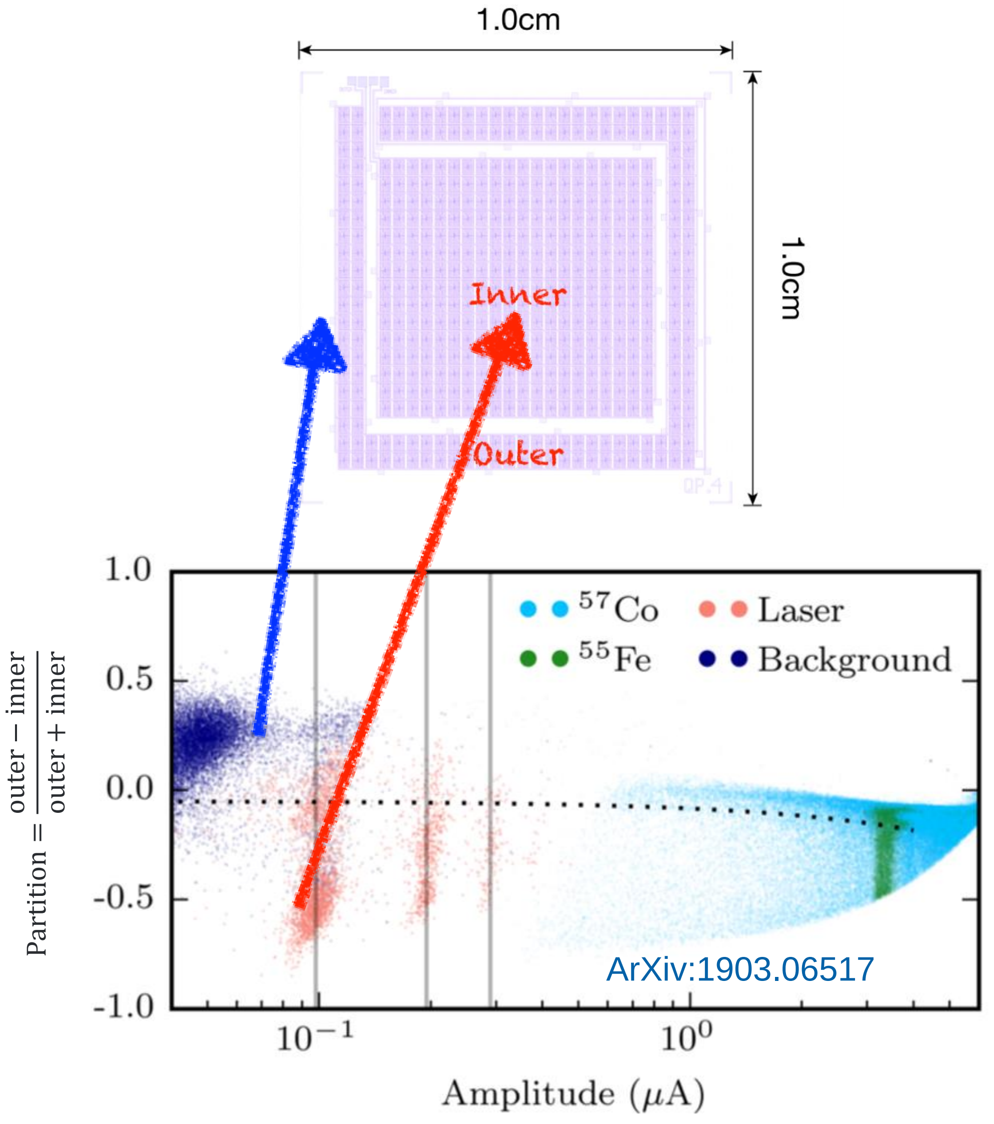




Recent Progress: Edge-Dominated Leakage

- New prototypes demonstrate position dependence in the non-quantized data hinted at during HVeV Run 1
- Two-channel design allows for rejection of high radius events
- Nearly contact-free biasing scheme isolates contact along the crystal edge
  - Prevents charge tunneling through most of the high-voltage face
- Non-quantized leakage is dominant at high radius
  - 95% of non-quantized events removed by 50% radial cut efficiency
  - 80% of quantized events removed by the same cut

See Poster by N. Kurinsky
“SuperCDMS HV Detector R&D” (1-56)
for more details



Near-Term ERDM Scattering Reach

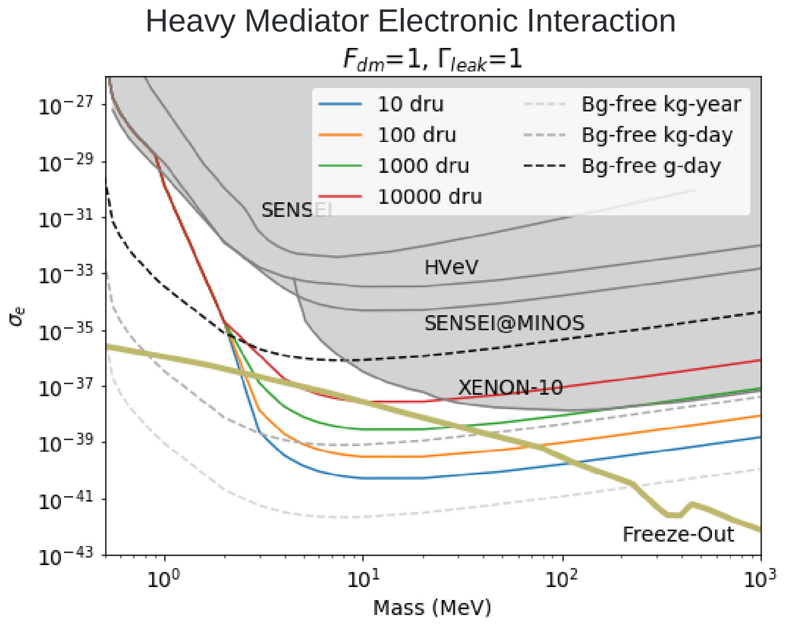
- New SENSEI@MINOS limits comparable to HVeV surface run
  - HVeV at our underground R&D experimental site NEXUS is similarly very promising

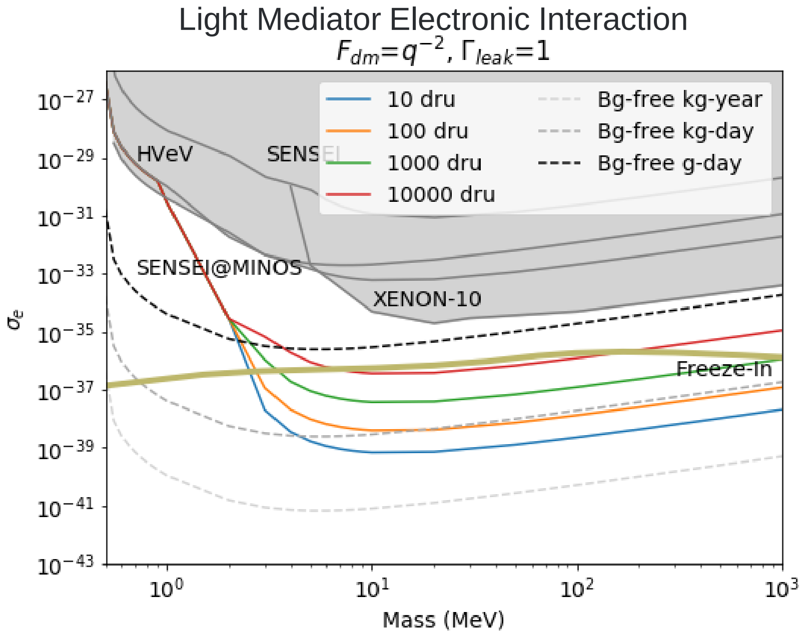
See Poster by Z. Hong
“Overview of SuperCDMS Experiment”
(1-85) for more details

- With improvements in leakage current that we expect to achieve at NEXUS (~100 dru), relic density can be probed with ~100g payload
  - gram-month begins to probe relic density at current levels

- Leakage current improvement improves reach across mass range
  - 100x improvement significantly improves overall exposure reach
  - Various ways to improve surface leakage, work already ongoing to experiment with new insulating layers

See Poster by N. Kurinsky
“SuperCDMS HV Detector R&D” (1-56)
for more details





Summary

- Lots of work in improving sensitivity for light mass dark matter detection
  - Improving phonon resolution for better sensitivity to DM-nucleon interactions
  - Decreasing charge leakage for better sensitivity to DM-electron interactions
- In both these respects, SuperCDMS expects meaningful results from DM searches in the near future
  - Finishing up a DM search analysis with our 3.9 eV photon detector
  - Continuing R&D on reducing leakage

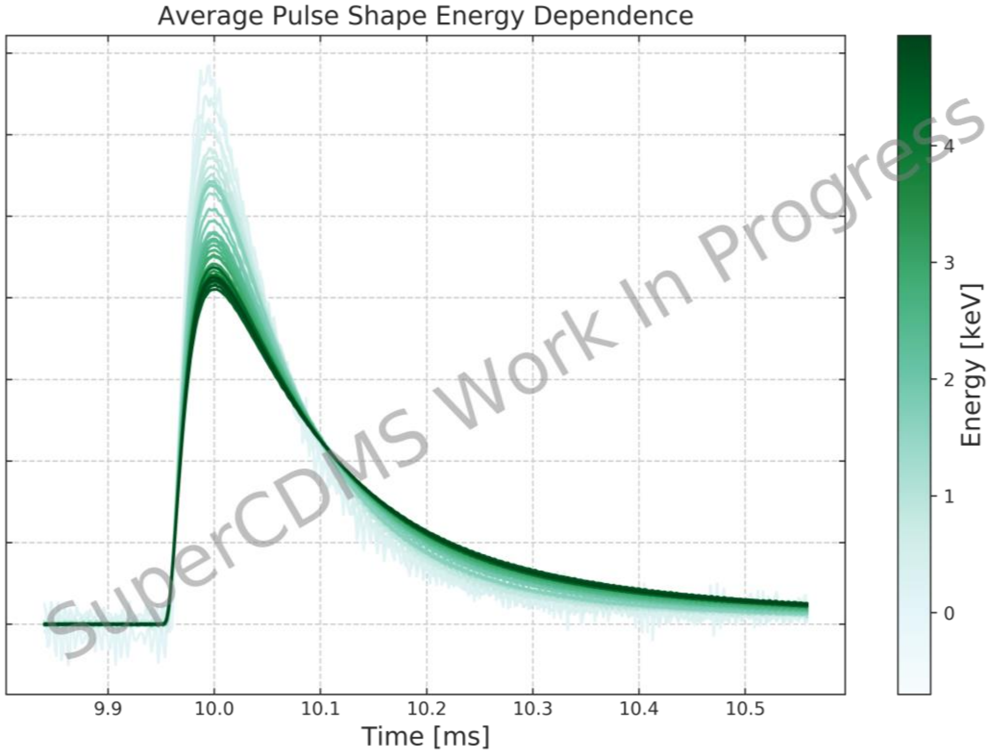
Backup Slides

Local Saturation of Single Site Events

- In this detector, we have local saturation for single site events, which can be seen from the pulse fall time monotonically increasing in length as energy increases
  - Rise time is determined by the phonon collection time, $\tau_c = 20\ \mu s$
  - Fall time at low energy is determined by TES fall time, $\tau_{eff} = 66\ \mu s$

Use these values as an analytic template for the Optimum Filter

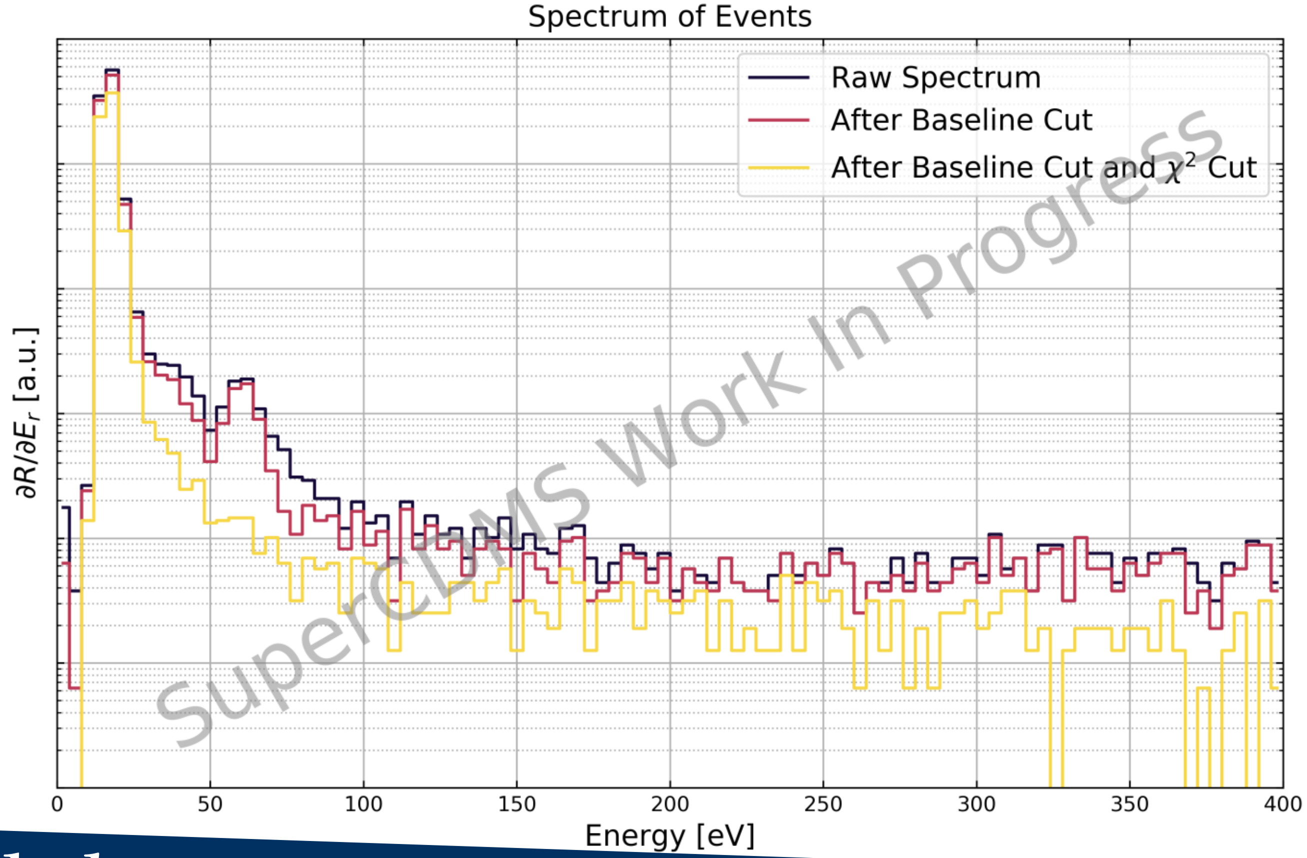
Pulses normalized to have the same integral

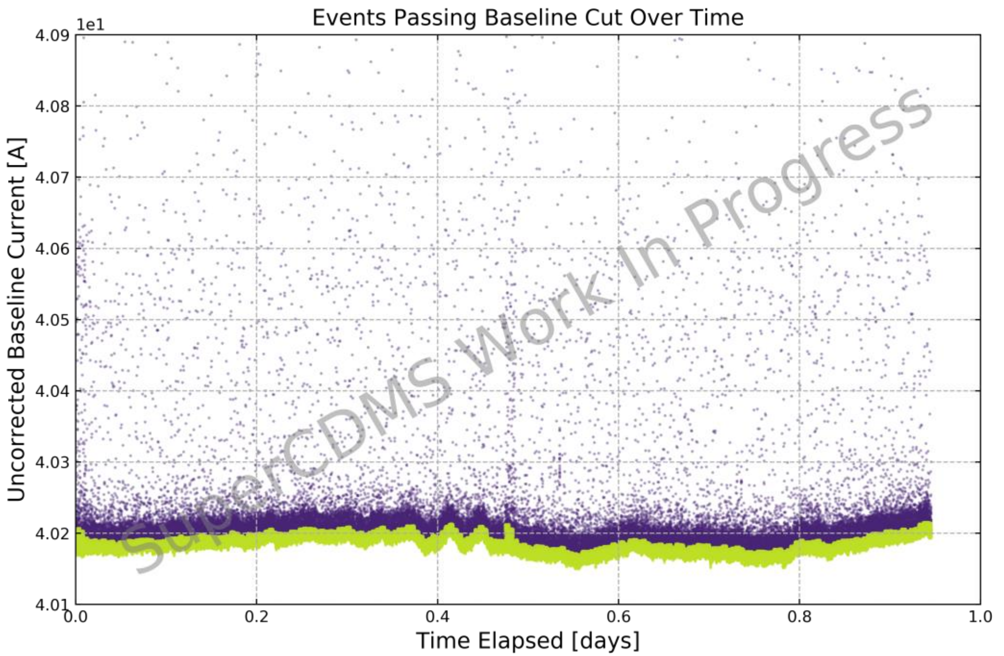


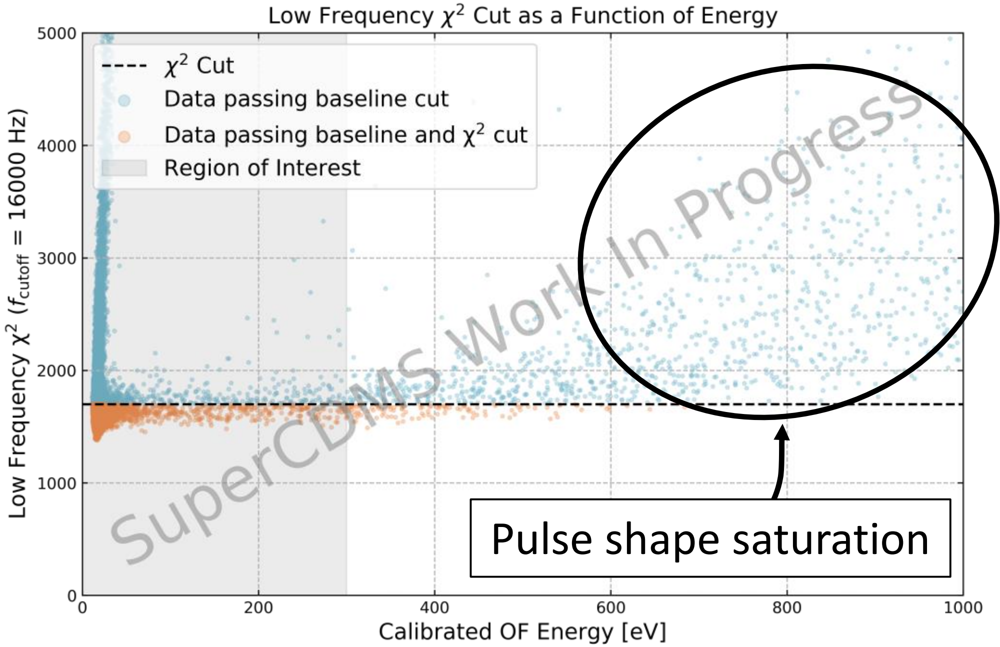
In the case of scintillation, events would be spread out uniformly across the detector, such that we would not see local saturation effects

Simple Event Selection

- The DC baseline is relatively constant over time
- The χ^2 cut passage should be constant in our signal band (below 300 eV), as there is no local saturation in this range



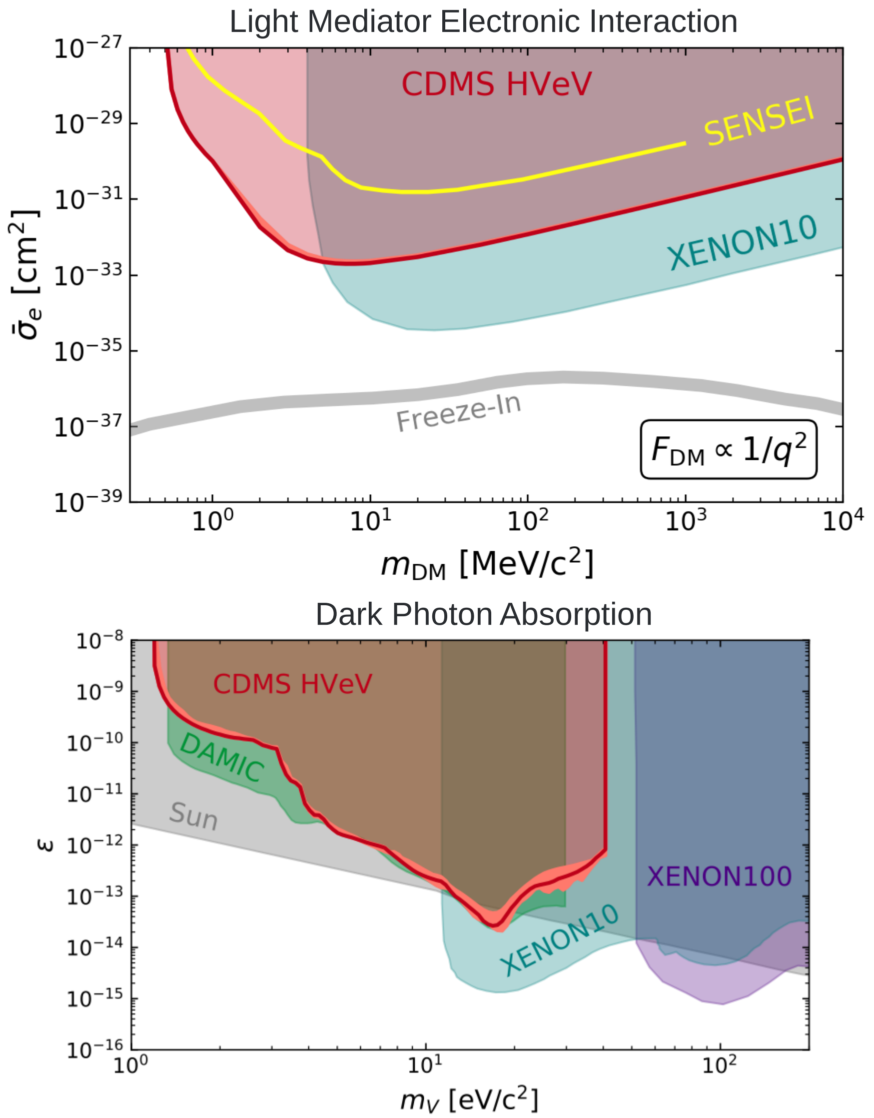




Limits on Sub-GeV Dark Matter

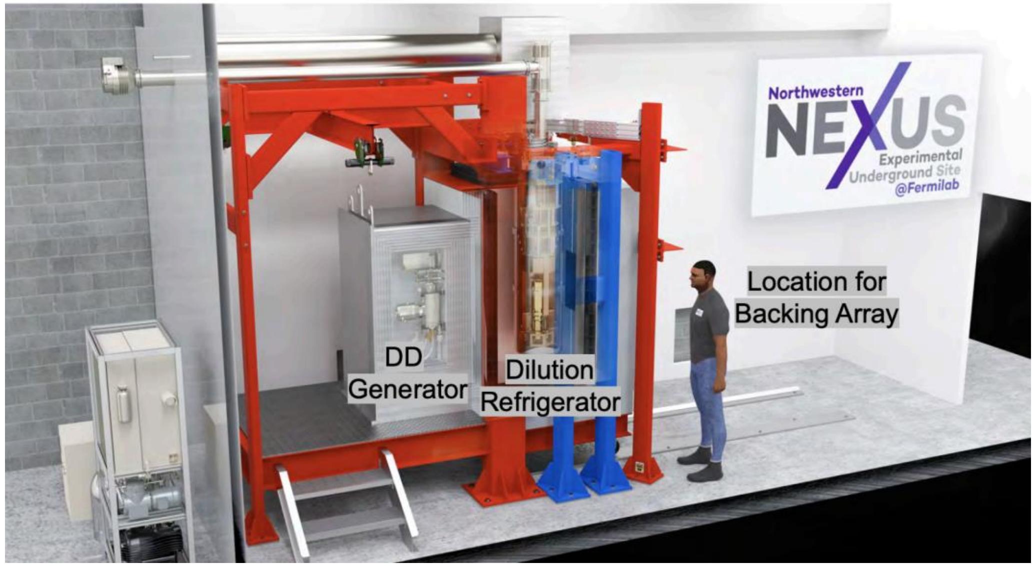
SuperCDMS Collaboration 2018 (https://arxiv.org/abs/1804.00088)

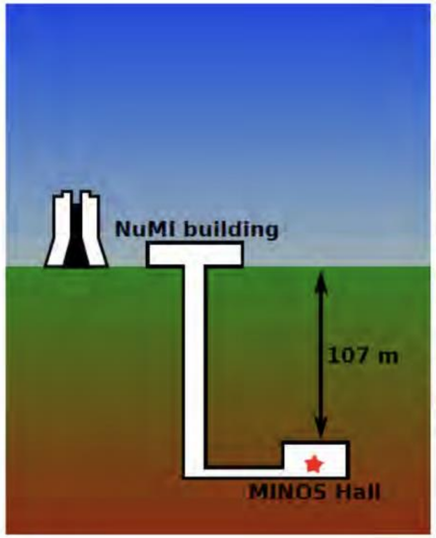
- Momentum dependent limits achieve smallest cross-section at low energy
  - Lowering energy threshold allows us to probe the same cross-section with $\sim 1/10000$ of the mass of Xenon10 at $4\ \mathrm{MeV}$
  - Our prototype detector has world-leading limits for $\sim 0.5\text{-}5\ \mathrm{MeV}$
- Better pileup rejection and resolution allow us to probe the same dark-photon parameter space as DAMIC with $1/60$ of the exposure
  - both searches are background limited
- This was the opening shot in the next generation of light dark matter searches

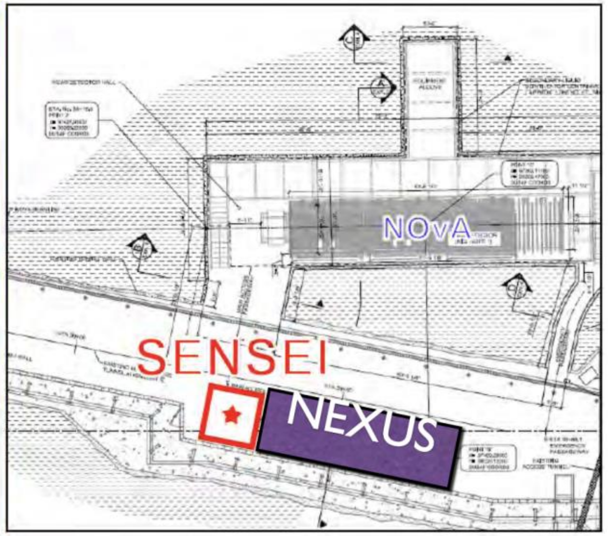


NEXUS: Underground Experimental Site for R&D

See Poster by Z. Hong
“Overview of SuperCDMS Experiment”
(1-85) for more details







NEXUS Si/Ge Experimental Timeline

- Now (Prototype Run): 1 gram
  - 1 gram, 4 eV resolution (20 eV threshold)
  - 0.05 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 4 keV in energy
  - DM search with 1 gram-week
- Late Summer 2019: 10 grams,
  - 2-4 ~4g detectors
  - 4 eV resolution (20 eV threshold),
  - 0.05 electron-hole pair resolution (<1 e-h threshold)
  - 4 eV to 40 keV in energy
  - DM search with 1 gram-month

Leakage R&D

- Fall 2019-Winter 2020: 30-100 grams,
  - 4 eV resolution (20 eV threshold)
  - 0.01 electron-hole pair resolution
  - 4 eV to 40 keV in energy
  - DM search with 1-10 gram-year (~kg day)
- Late 2020 - Early 2021: 10 kg payload
  - <20 eV threshold
  - Up to 60 keV in energy
  - 0.01 electron-hole pair resolution
  - DM search/***neutrino physics*** with 1 kg-year of exposure

Larger Crystals or Multiplexing