Searching for DM with the SuperCDMS HVeV Detector

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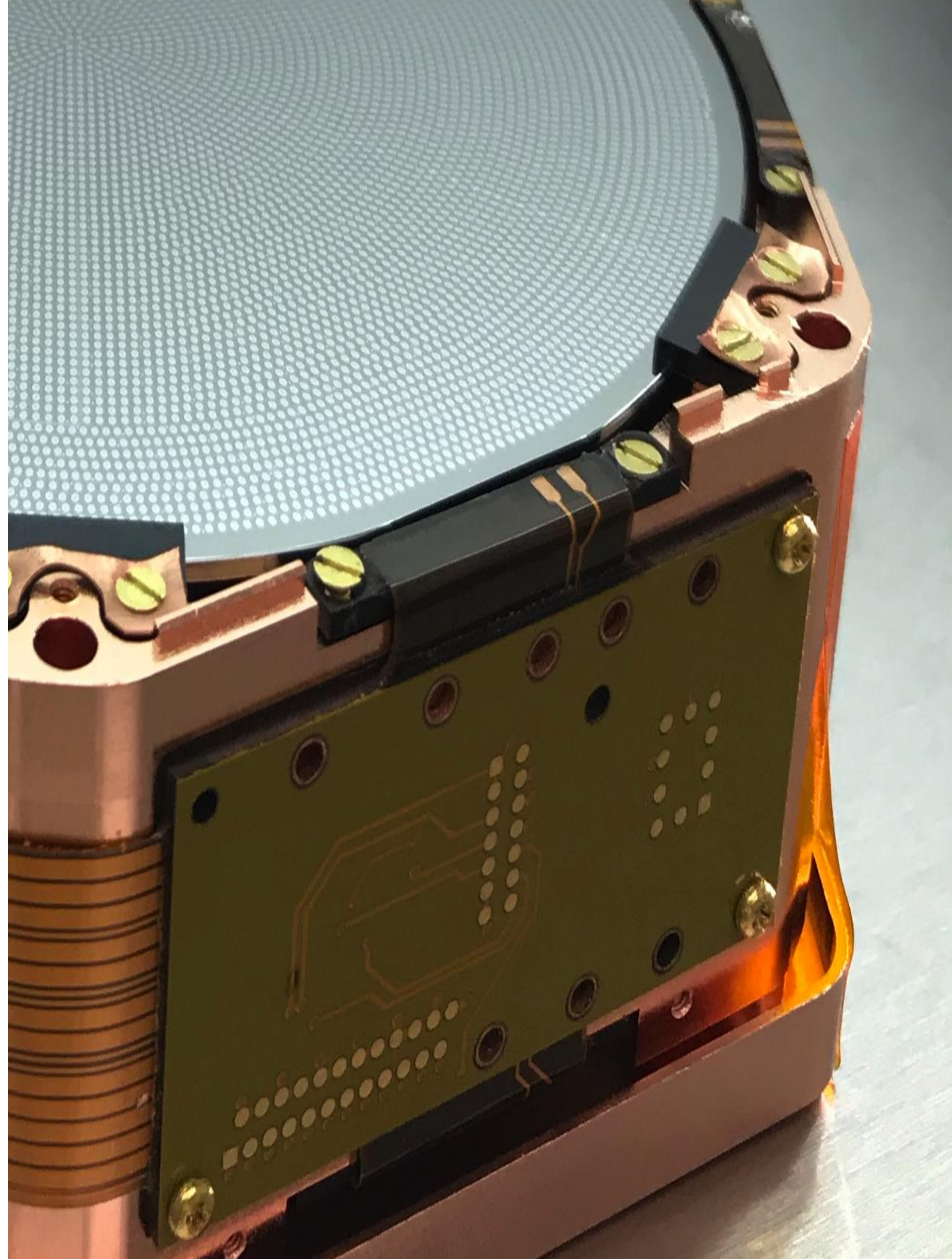
IEEE OEB LMAG

2021-04-28



California Inst. of Tech.	CNRS-LPN*	Durham University	FNAL	NISER	NIST*
Northwestern	PNNL	Queen's University	Santa Clara University	SLAC	South Dakota SM&T
SMU	SNOLAB	Stanford University	Texas A&M University	TRIUMF	U. British Columbia
	U. California, Berkeley	U. Colorado Denver	U. Evansville	U. Florida	
	U. Montréal	U. Minnesota	U. South Dakota	U. Toronto	

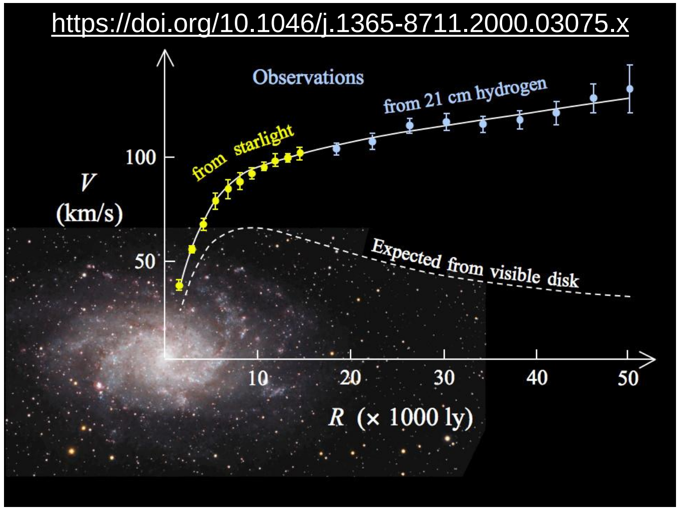
* Associate members

Outline

- ➢ Dark Matter
  1. Astronomical Observation
  2. WIMPs
  3. SuperCDMS
- ❑ Detector R&D Development
- ❑ DM Search

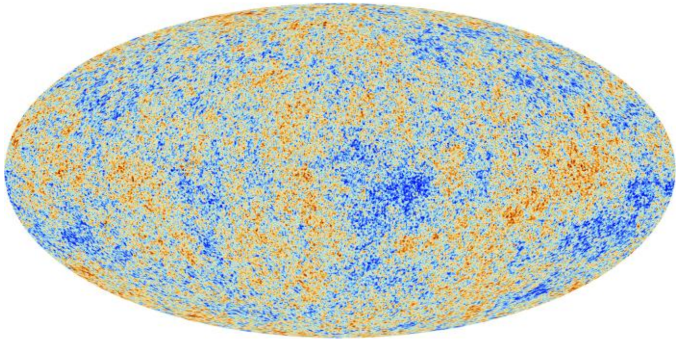
Beyond the Standard Model

M33 Galactic Rotation Curve

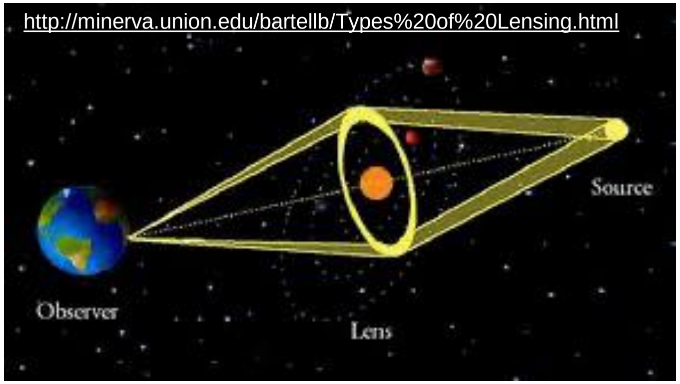


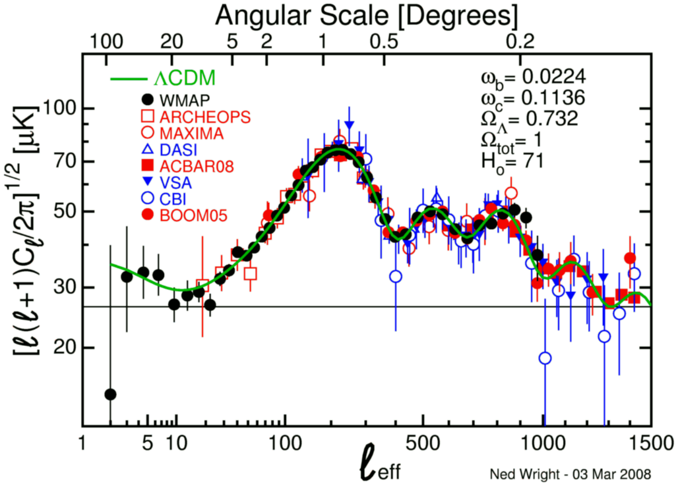
CMB Anisotropy

http://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB



Gravitational Lensing





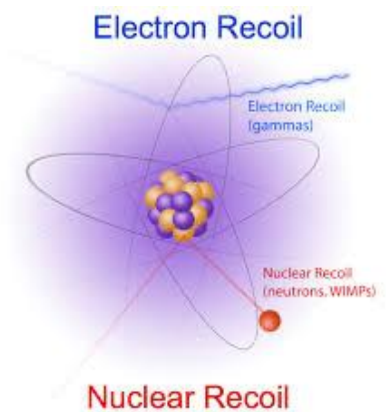
http://www.astro.ucla.edu/~wright/CMB-DT.html

Insufficient mass in the universe!

Weakly Interacting Massive Particles

Four Forces:

Electromagnetic, Weak, Strong, **Gravity**



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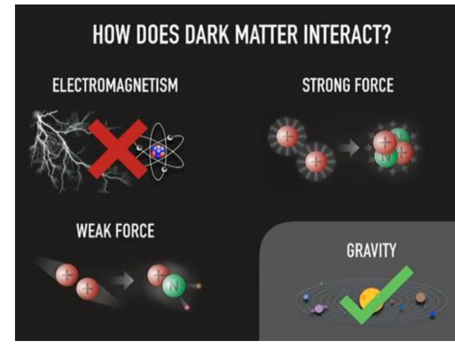


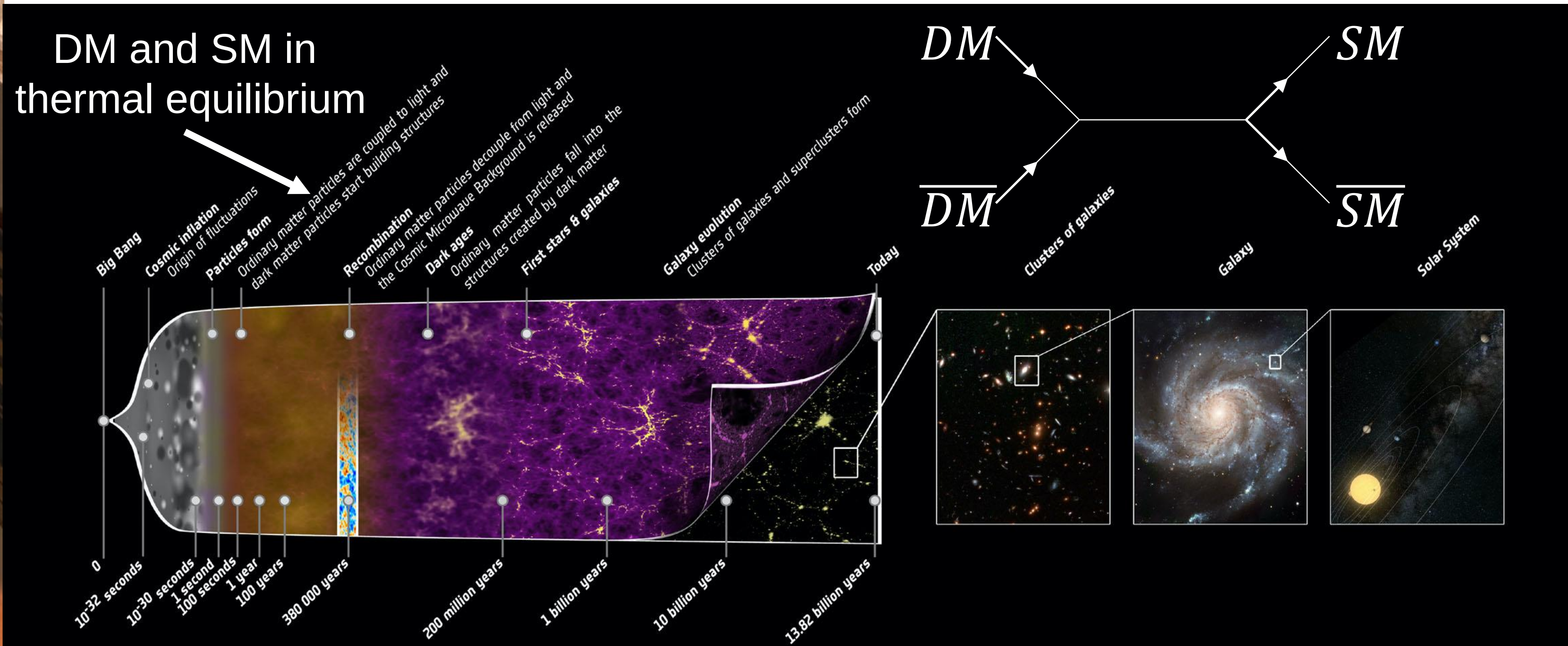
(PERIMETER INSTITUTE)
https://medium.com/starts-with-a-bang/the-wimp-miracle-hope-for-dark-matter-is-dead-9dc3f609dc0a

Super-Symmetry Theories:

Lightest supersymmetric particle (LSP)

Neutralino   Photino   Higgsino   Create a theory
Name your own DM particle

SUSY Motivation



https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA16876

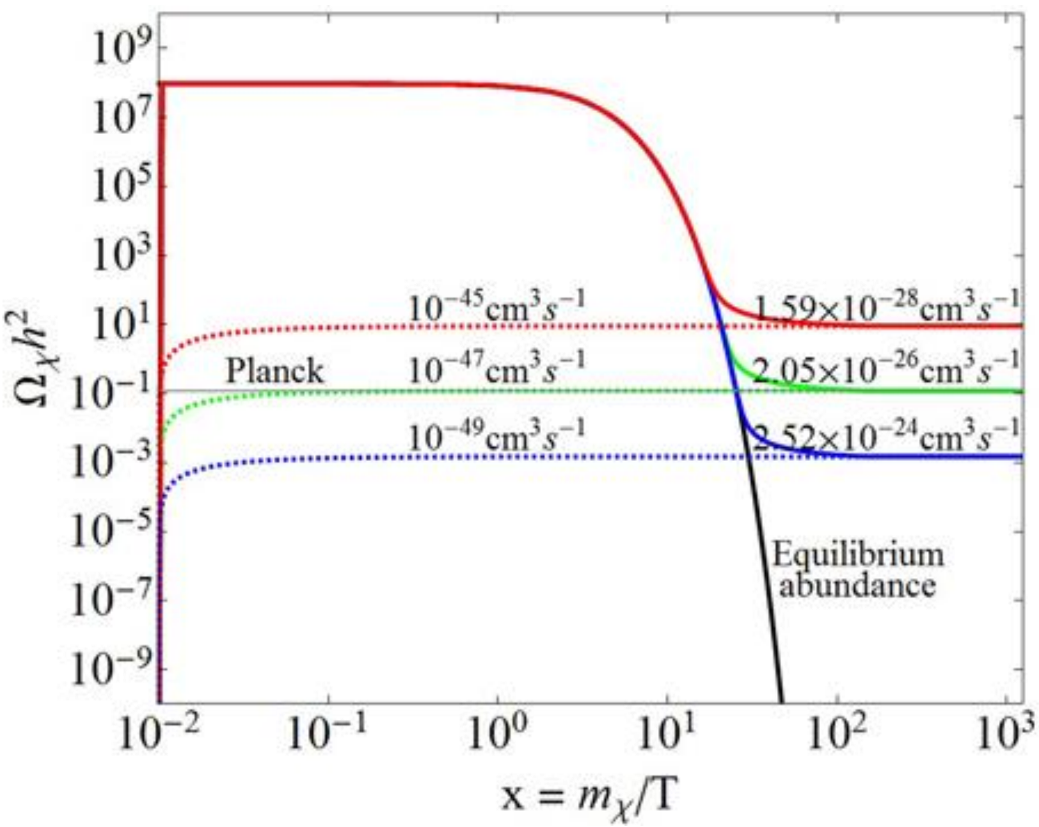
$$n_X = \frac{g}{2\pi^3}\int f(\boldsymbol{p},T)\,d^3\boldsymbol{p}$$

$n_X \propto T^3$ for $T \gg m_X$

$n_X \approx g\left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$ for $T \ll m_X$

“WIMP Miracle”

Front. Phys. (2014), https://doi.org/10.3389/fphy.2014.00026



DM annihilation rate into SM

$$\Gamma(T) = n_X(T)\langle\sigma_A v\rangle$$

@ Freeze-out, T_f

$$n_X(T_f) = \frac{1.66 g_*^{1/2} T_f^2}{m_{pl}\langle\sigma_A v\rangle}$$

$$\frac{n_X}{s}(T_f) = \frac{4.15}{g_*^{1/2} T_f m_{pl}\langle\sigma_A v\rangle}$$

$$\langle\sigma_A v\rangle = \frac{100}{g_*^{1/2} m_{pl}}\frac{s_0}{\rho_c\Omega_X h^2}$$

$$\langle\sigma_A v\rangle = 2.8\cdot 10^{-26} cm^3 s^{-1}\cdot\frac{0.11}{\Omega_X h^2}$$

Dark Matter Candidates

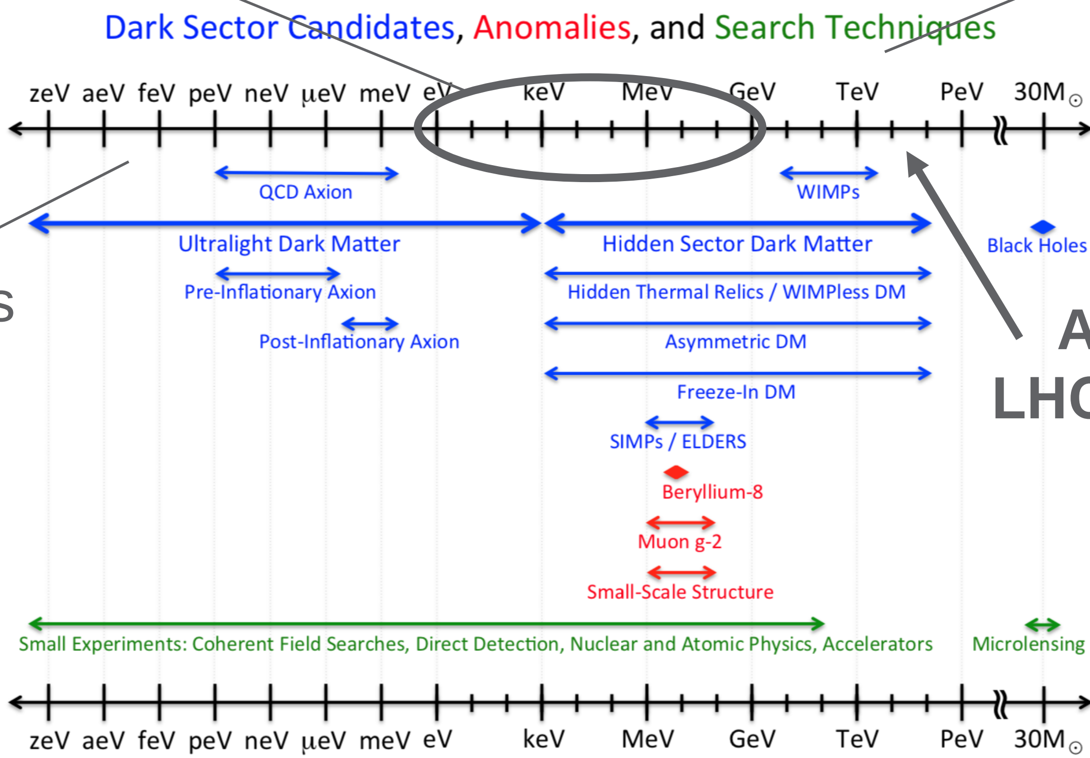
US Cosmic Visions: New Ideas in Dark Matter, ArXiv: 1707.04591

High resolution detectors

Noble liquids

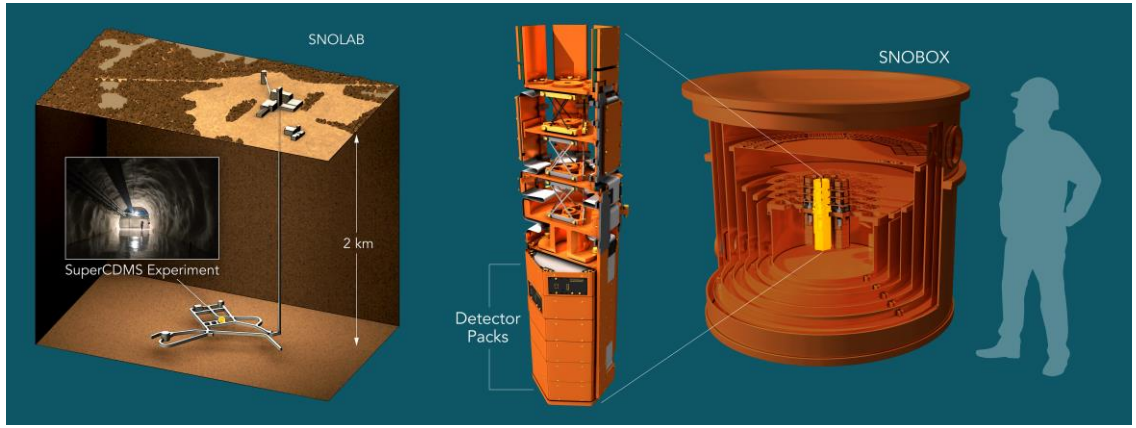
High Q Resonators

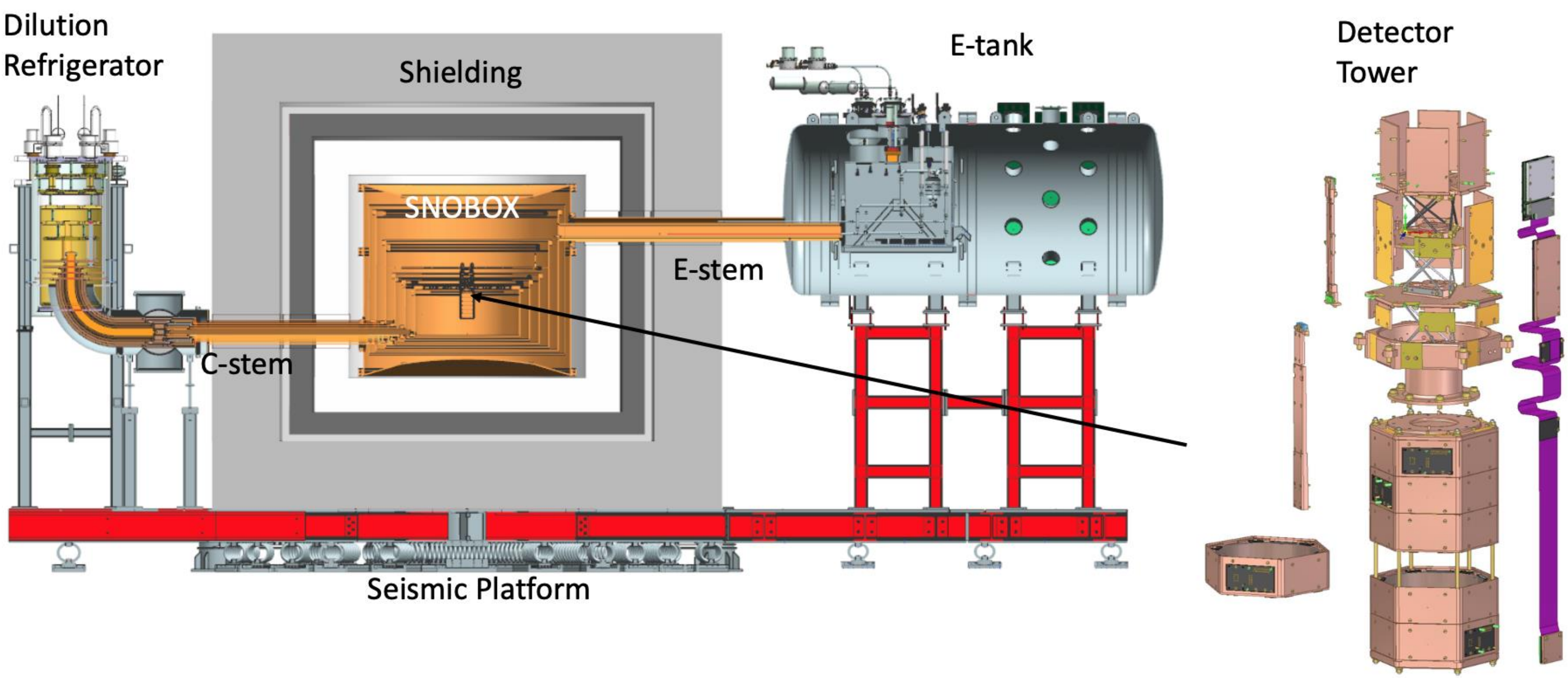
Accelerators: LHC “creates” DM



SuperCDMS primary goal is 300 MeV to 6 GeV mass range

SNOLAB SuperCDMS





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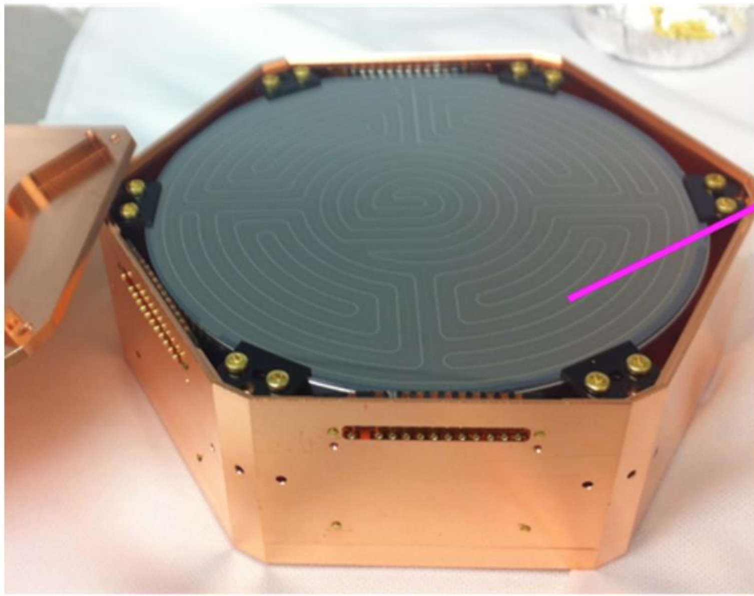
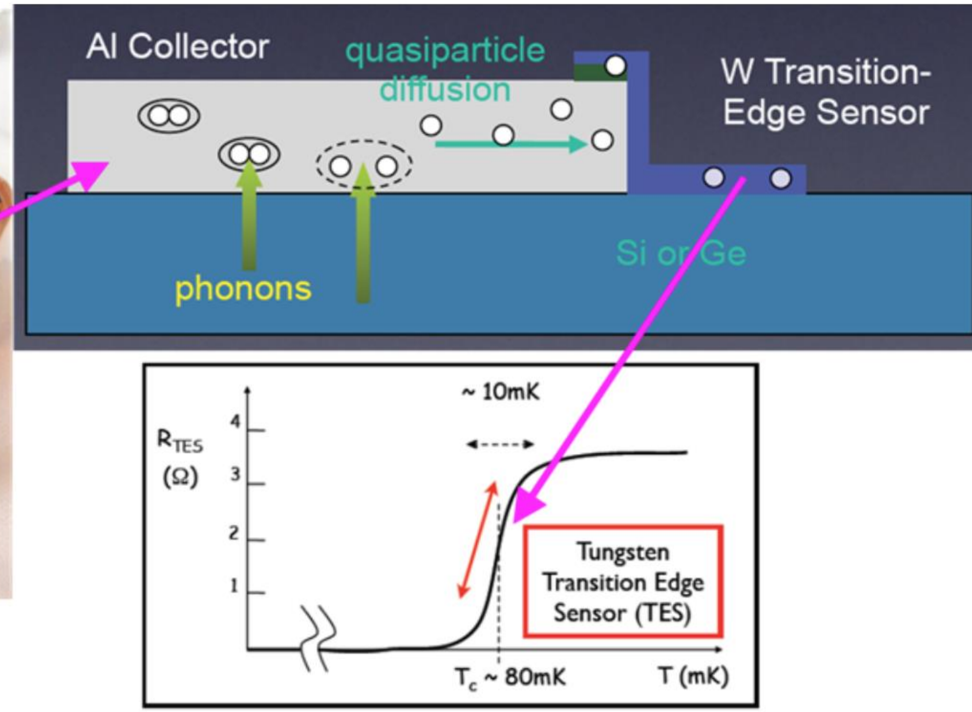
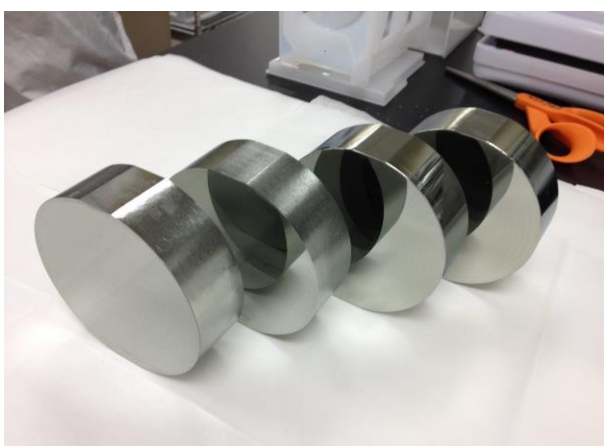
Quasiparticle-assisted Electrothermal-feedback Transition Edge Sensors (QETs)







High Voltage (HV):

- Phonon signal
- Large Bias Voltage
- Neganov-Trofimov-Luke Effect

interleaved Z-dependent Ionization and Phonon (iZIP):

- Phonon signal
- Charge signal
- Small Bias Voltage

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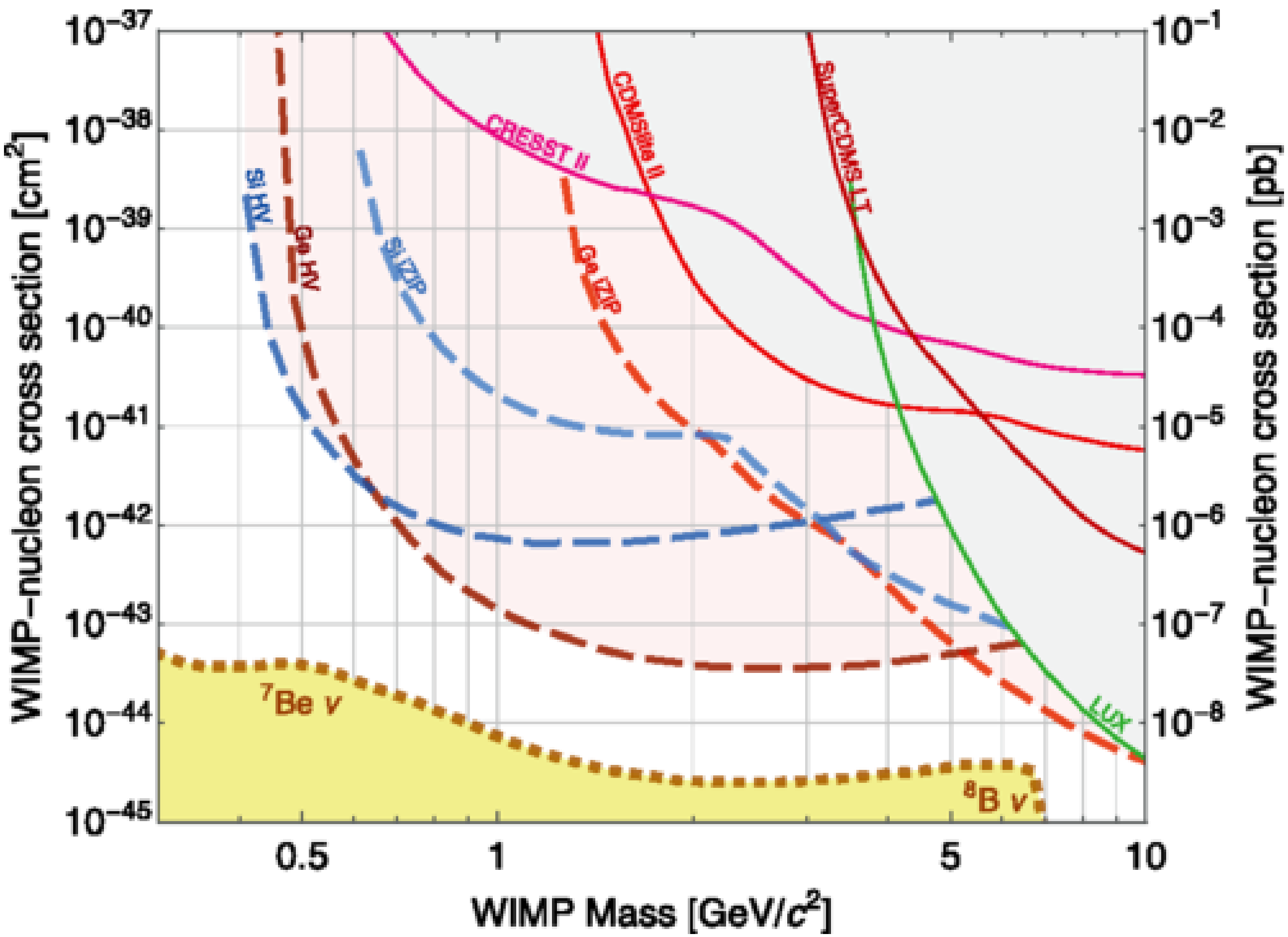
Projected Sensitivity

Phys. Rev. D **95**, 082002, https://doi.org/10.1103/PhysRevD.95.082002



Improved sensitivity to lower masses and cross-sections

Outline

✓Dark Matter

➢Detector R&D Developments

1. High resolution phonon detectors
2. Dilution refrigerator laser upgrade
3. SuperCDMS HVeV response
4. Detector Modeling

❑DM Search

Transition Edge Sensor

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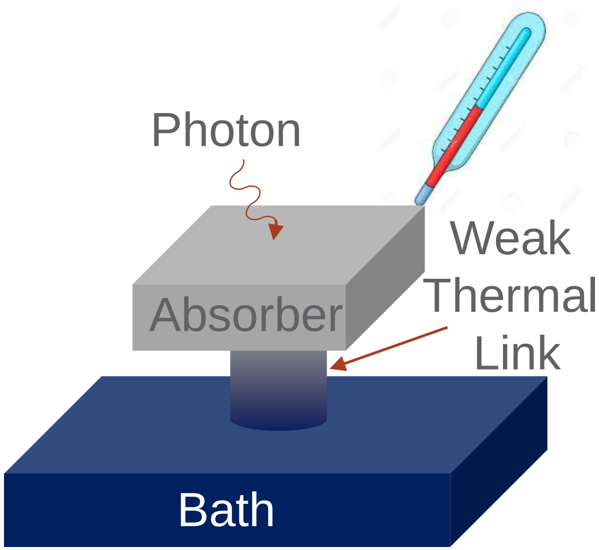
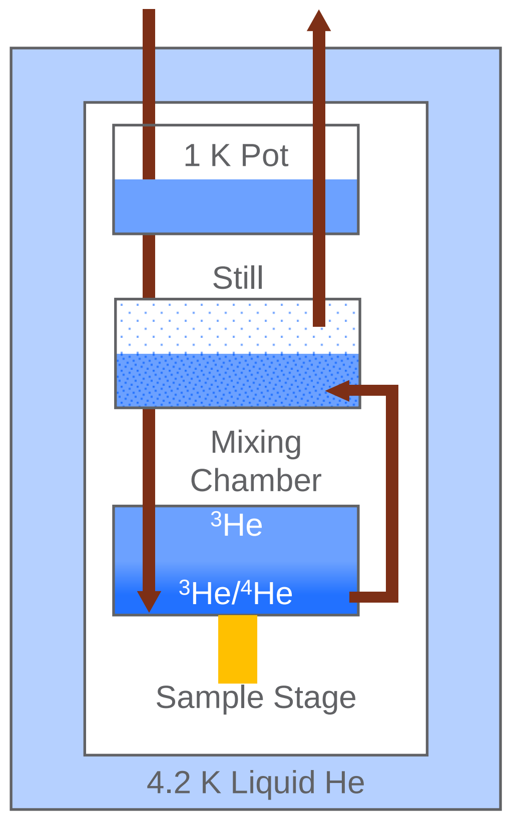
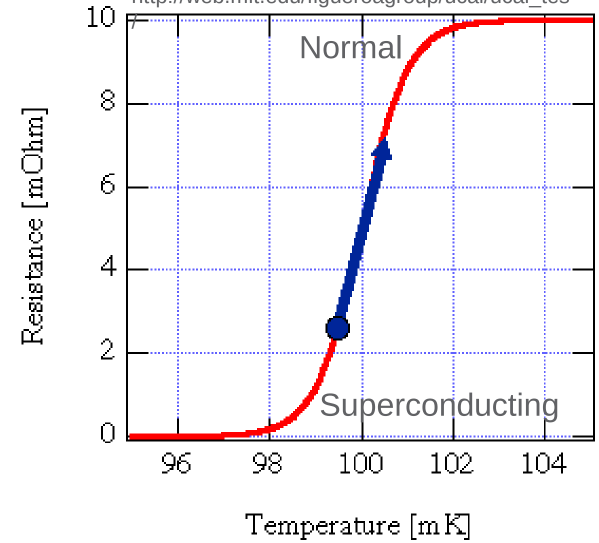
Microcalorimeters

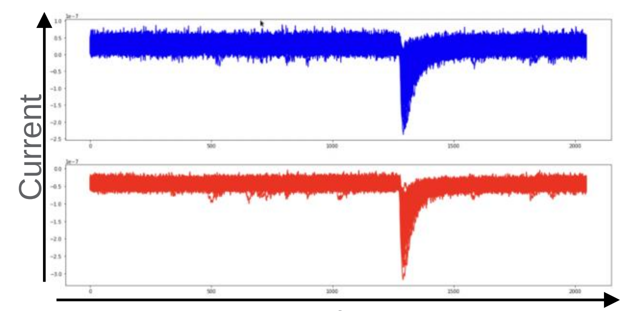


Dilution Refrigerator



Response



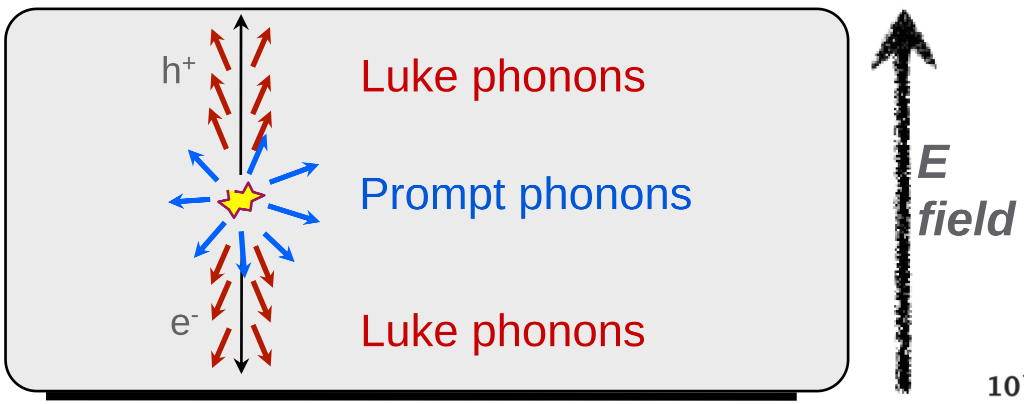


High resolution detectors with tunable bandwidth

SuperCDMS HV Detectors

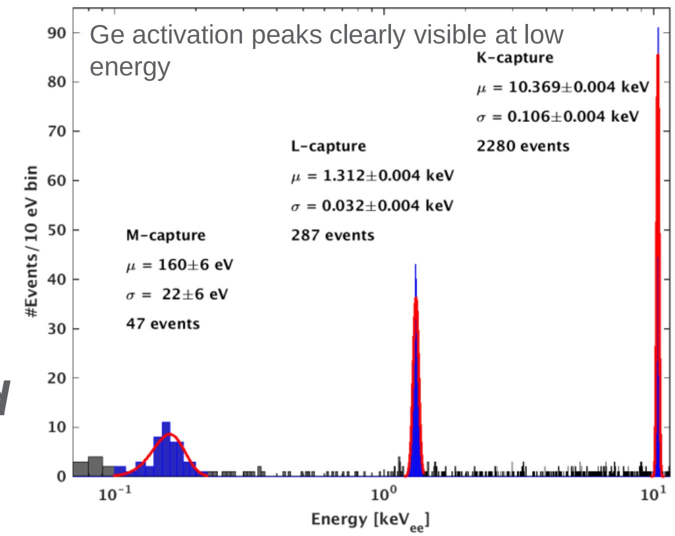
Phys. Rev. Lett. **116**, 071301, https://doi.org/10.1103/PhysRevLett.116.071301

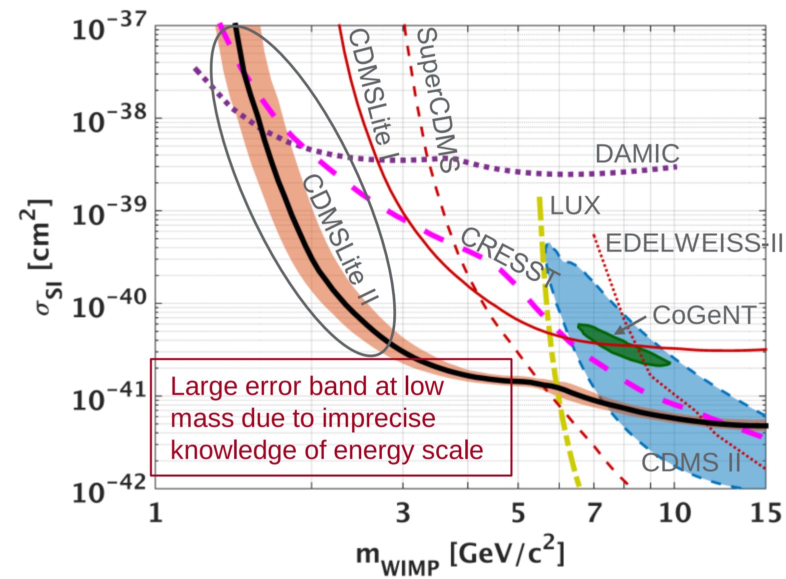
Neganov-Trofimov-Luke Effect



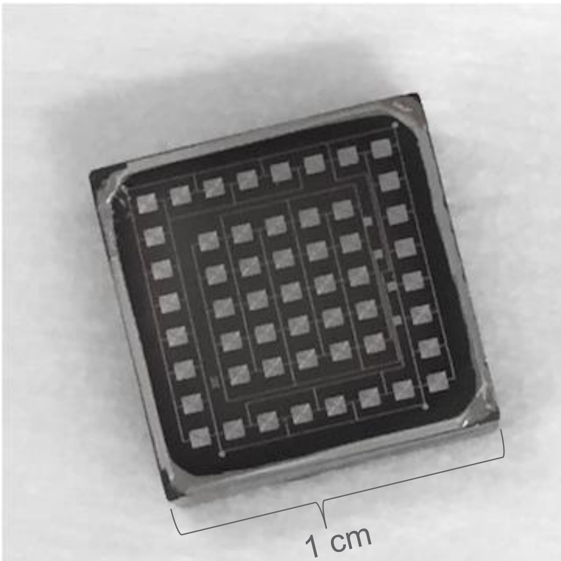
Phonon energy = $E_{recoil} + E_{Luke}$

Need to improve detector resolution!

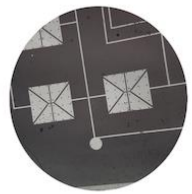




SuperCDMS HVeV Detector R&D

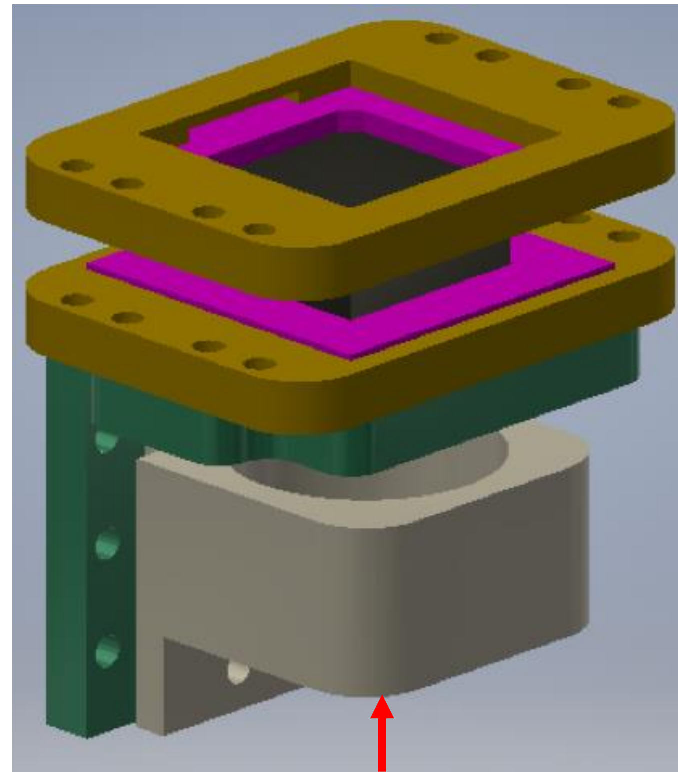


Top



Bottom

Quasiparticle-trap-assisted
Electro-thermal-feedback
Transition-edge sensor
(QET)

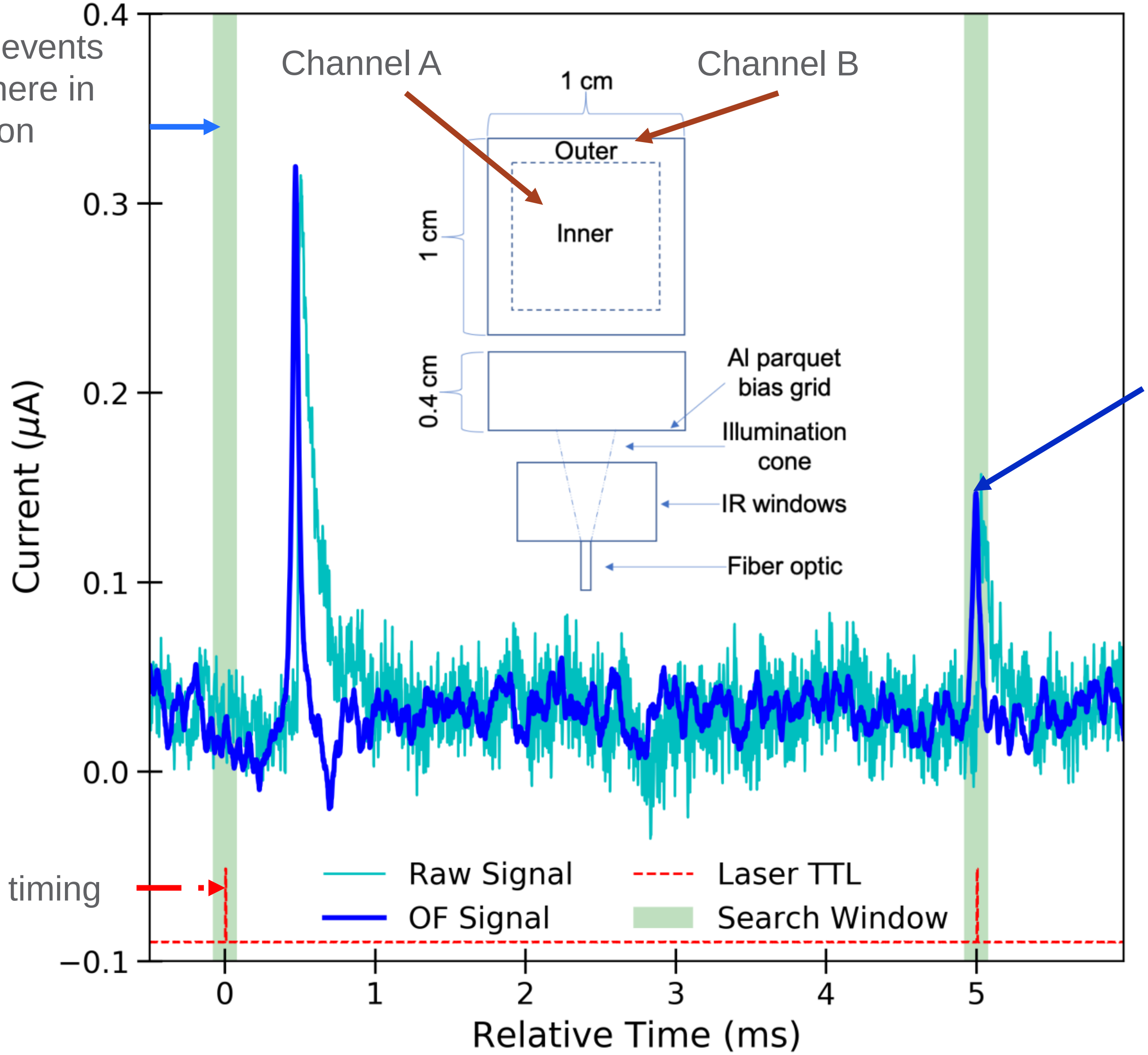


Pulsed monochromatic 650 nm (~1.9 eV) laser

Two channel QET with NTL amplification capabilities

Optimal Filtering Processing Pulse Parameters

Zero photon events occur anywhere in this region



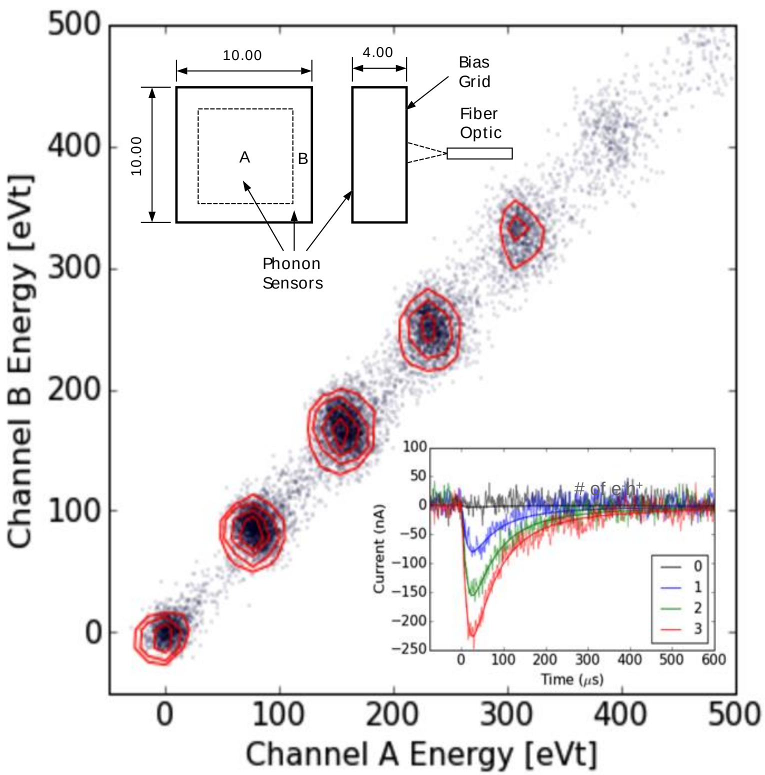
TTL timing

Max OF(t_i) = amp
t_i = pulse timing

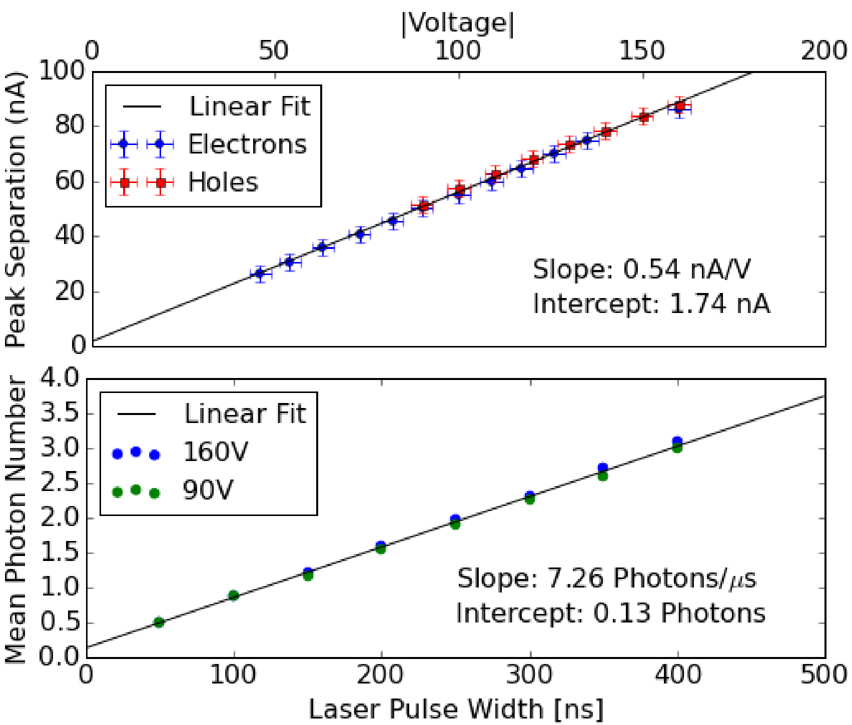
HVeV Laser Response

Appl. Phys. Lett. **112**, 043501 (2018); https://doi.org/10.1063/1.5010699

Integer e^-h^+ Pairs @ 160V Bias



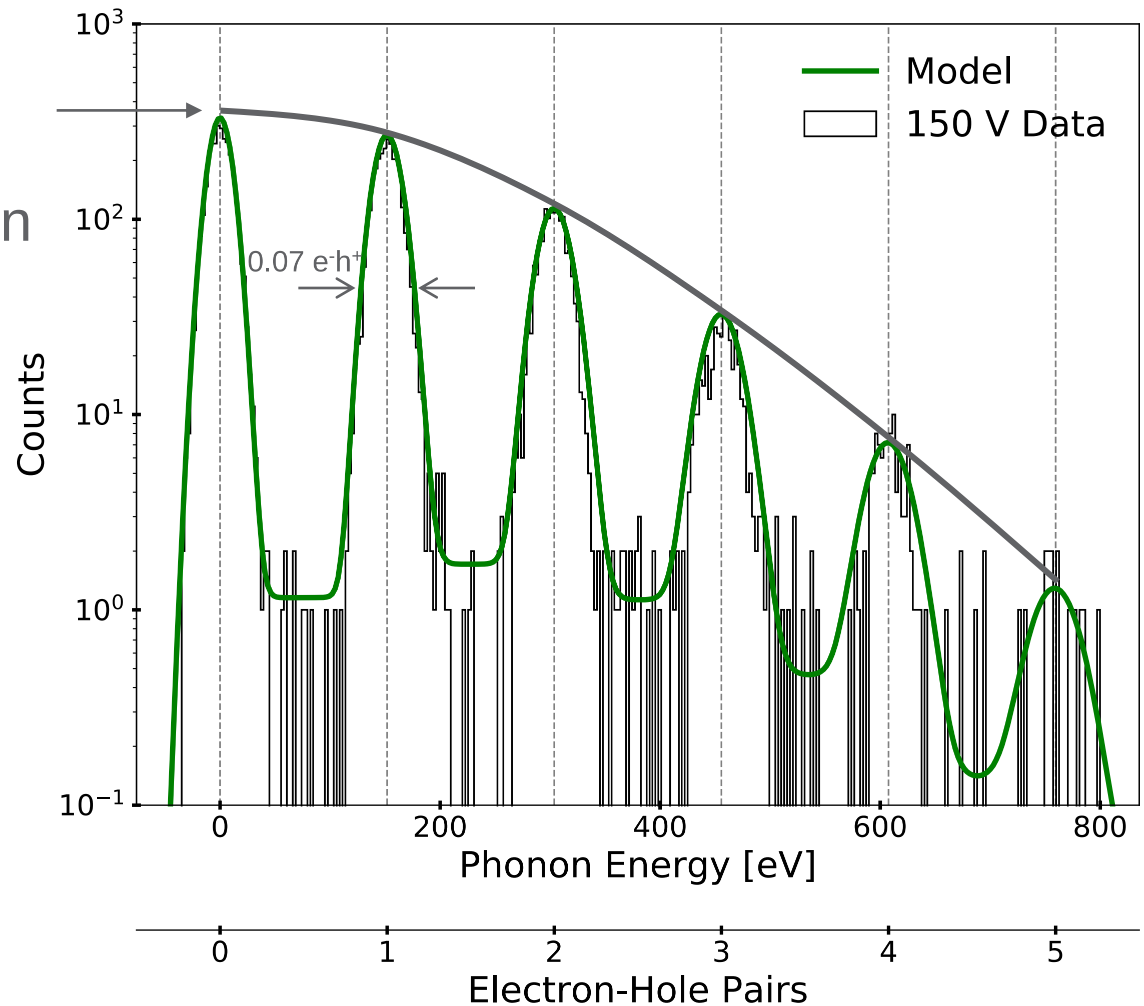
Gain Linearity



First observation of e^-h^+ pairs in Si crystal with a phonon sensor

HVeV Detector Calibration

Poisson
Envelope
Distribution

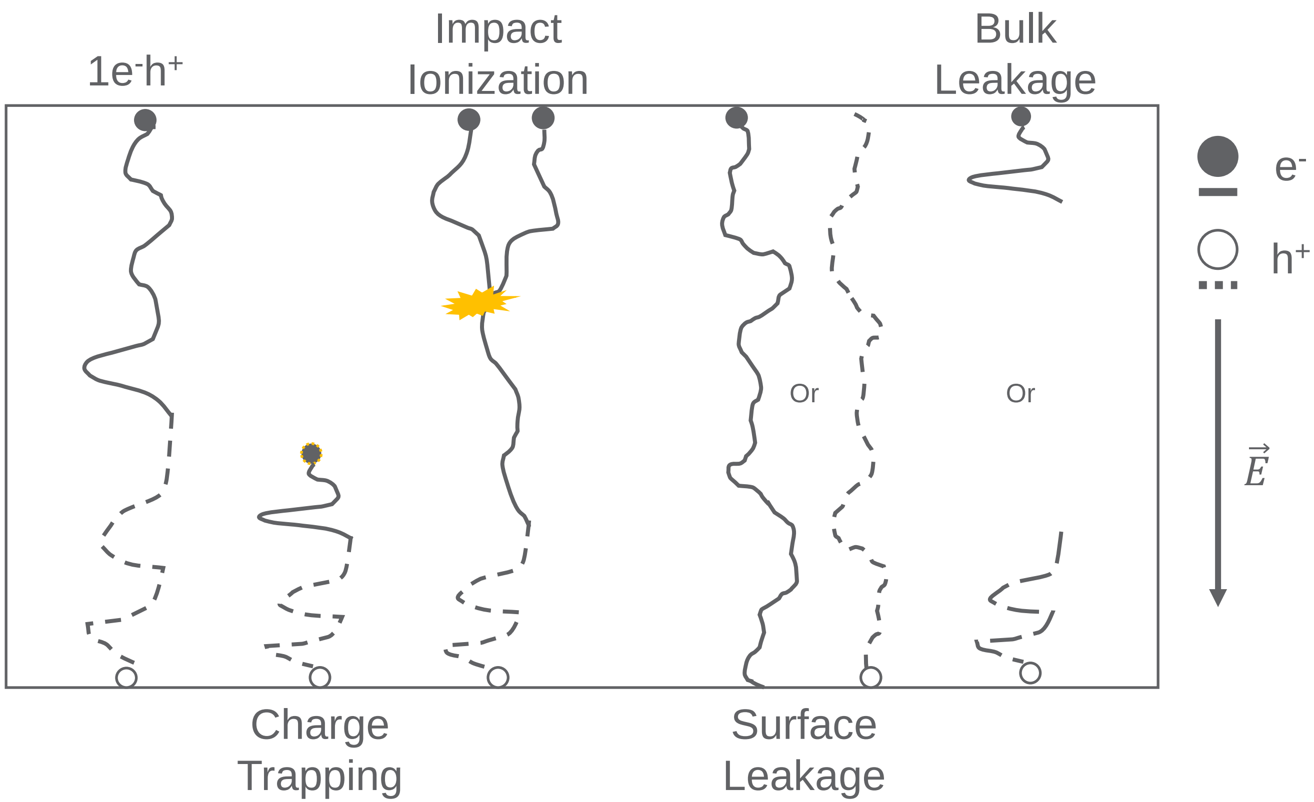


Calibration laser shows new features between peaks!

Physical Model

Impact Ionization and Charge Trapping

J. of Low Temp. **199**, 598–605(2020), https://doi.org/10.1007/s10909-020-02349-x



Single e⁻h⁺ pair PDF:

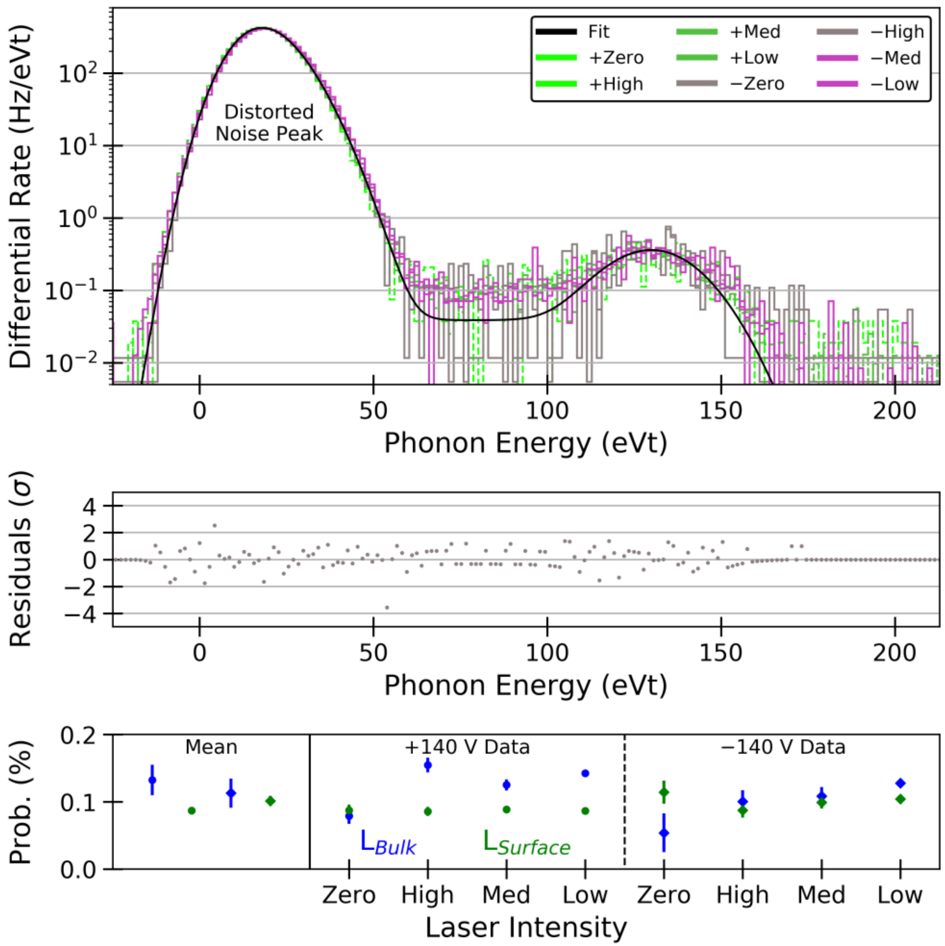
$$ {}^{(1)}h(x) = A_1\delta(x-1) + A_{-}\Theta(x-0)\Theta(1-x) + A_{+}\,\Theta(x-1)\Theta(2-x) $$

mth e⁻h⁺ pair PDF:

$$ {}^{(m)}h(x) = \int_{-\infty}^{\infty} {}^{(1)}h(x')\,{}^{(m-1)}h(x-x')\,dx' $$

Where A_- is the charge trapping probability, A_+ is the impact ionization probability, $A_1 = (1 - A_- - A_+)$, and $\Theta(x)$ is the Heaviside function.

Detector Leakage Background



The normalized background spectra (top), one residual at -140 V high intensity (middle) and fitted bulk & surface leakage probabilities (bottom) for all 8 configurations.

Weighted Bulk Leakage:

0.132 ± 0.023% @ +140 V

0.113 ± 0.022% @ −140 V

Weighted Surface Leakage:

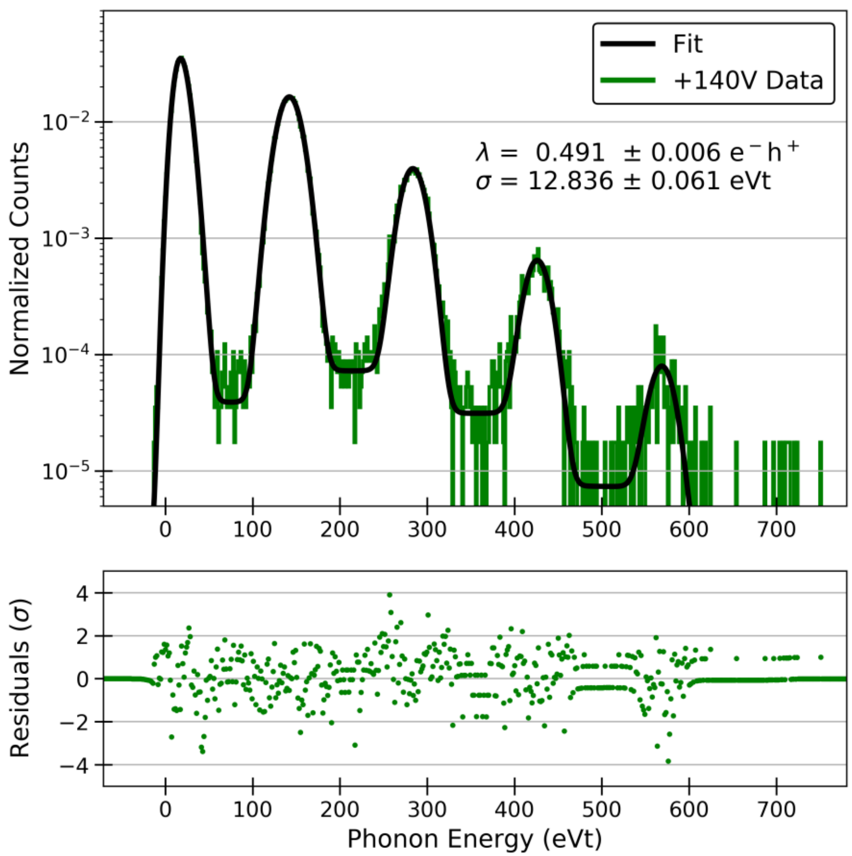
0.087 ± 0.001% @ +140 V

0.101 ± 0.007% @ −140 V

Impact Ionization and Charge Trapping

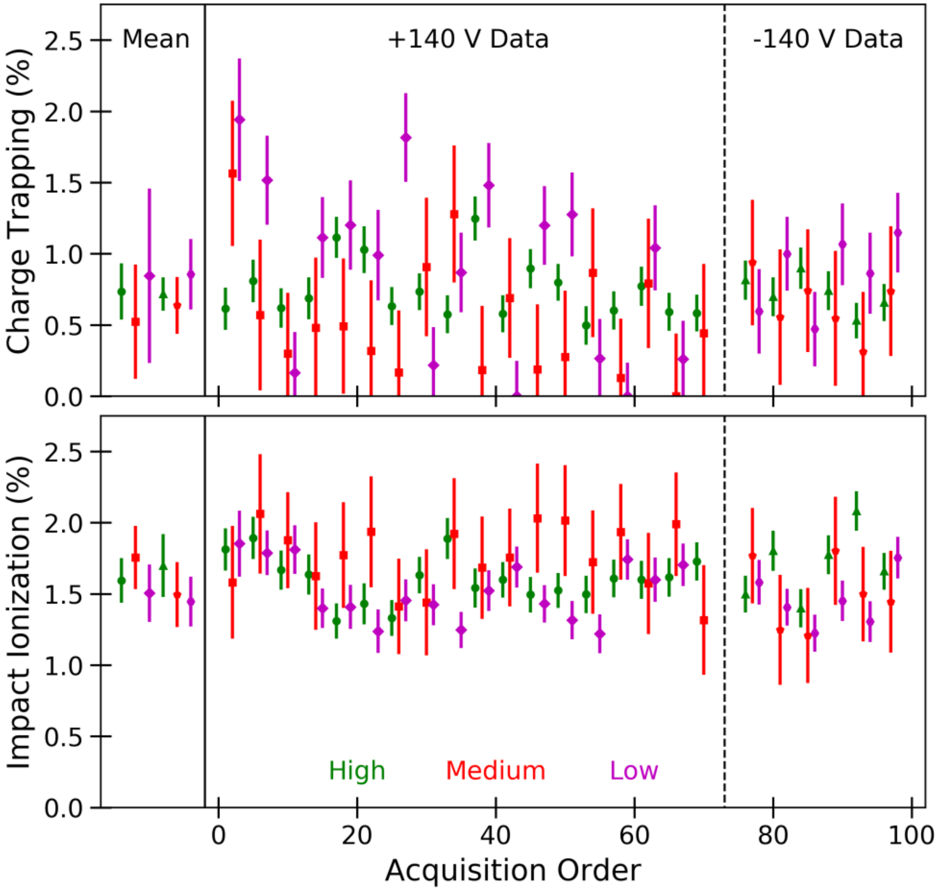
Phys. Rev. D **101**, 031101(R), https://doi.org/10.1103/PhysRevD.101.031101

$$M(x) = \kappa P_0(\lambda) \cdot B(x) + \sum_{m=1}^{m_{max}} P_m(\lambda) \left({}^{(m)}h \circledast G(\sigma) \right)(x)$$



(Top) Spectrum of laser-induced events (green) after cuts (~4 minutes), with analytical fit (black line) that includes charge leakage, impact ionization and charge trapping. (Bottom) Residuals normalized by the bin counting statistics. Bins with zero counts were artificially set to zero.

Charge Trapping & Impact Ionization



Weighted Charge Trapping Probability:
0.713 ± 0.093%
Mean free path: 56 cm

Weighted Impact Ionization Probability:
1.576 ± 0.110%
Mean free path: 25 cm

Outline

✓Dark Matter

✓Detector R&D Developments

➢DM Search

1. Run 1: Stanford University
2. Run 2: Northwestern University
3. Analysis and DM Exclusion

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Stanford University Run 1

Phys. Rev. Lett. **121**, 051301, https://doi.org/PhysRevLett.121.051301

Si Crystal w/ Phonon sensor

G10 holder

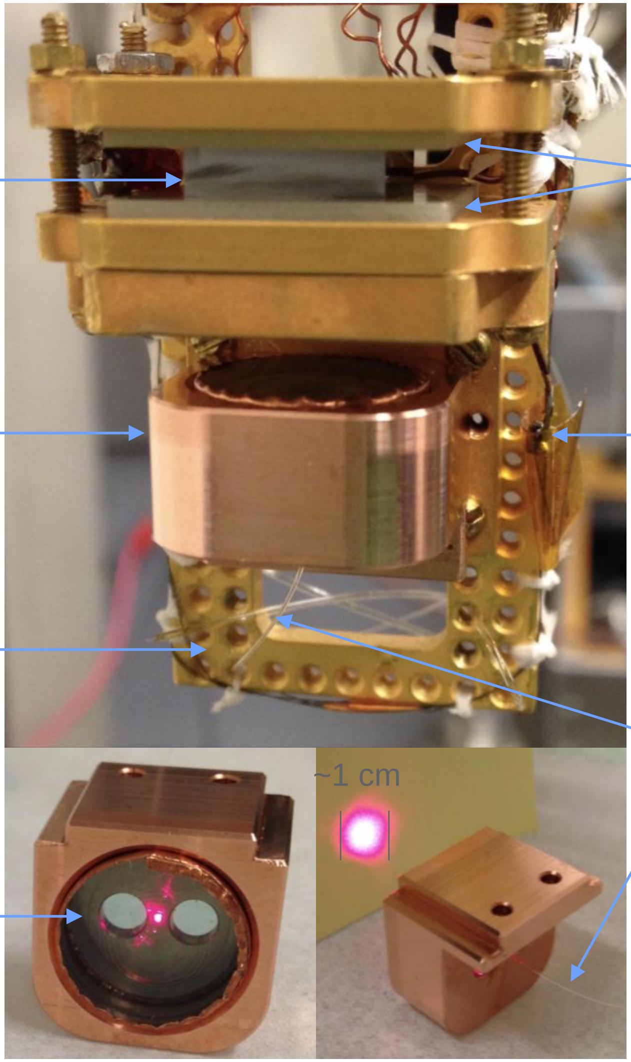
Cu holder

HV bias line

Dilution refrigerator sample stage (30 mK)

Fiber Optic

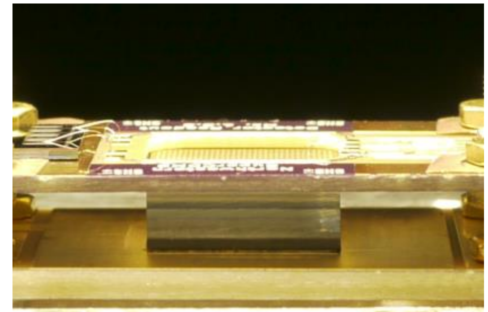
KG-3 IR filters

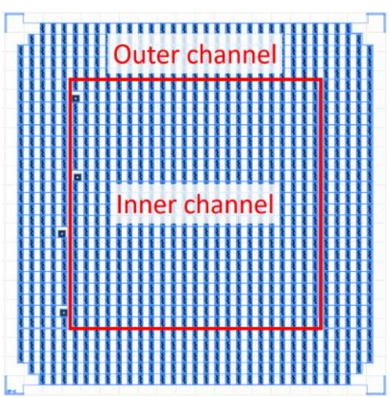


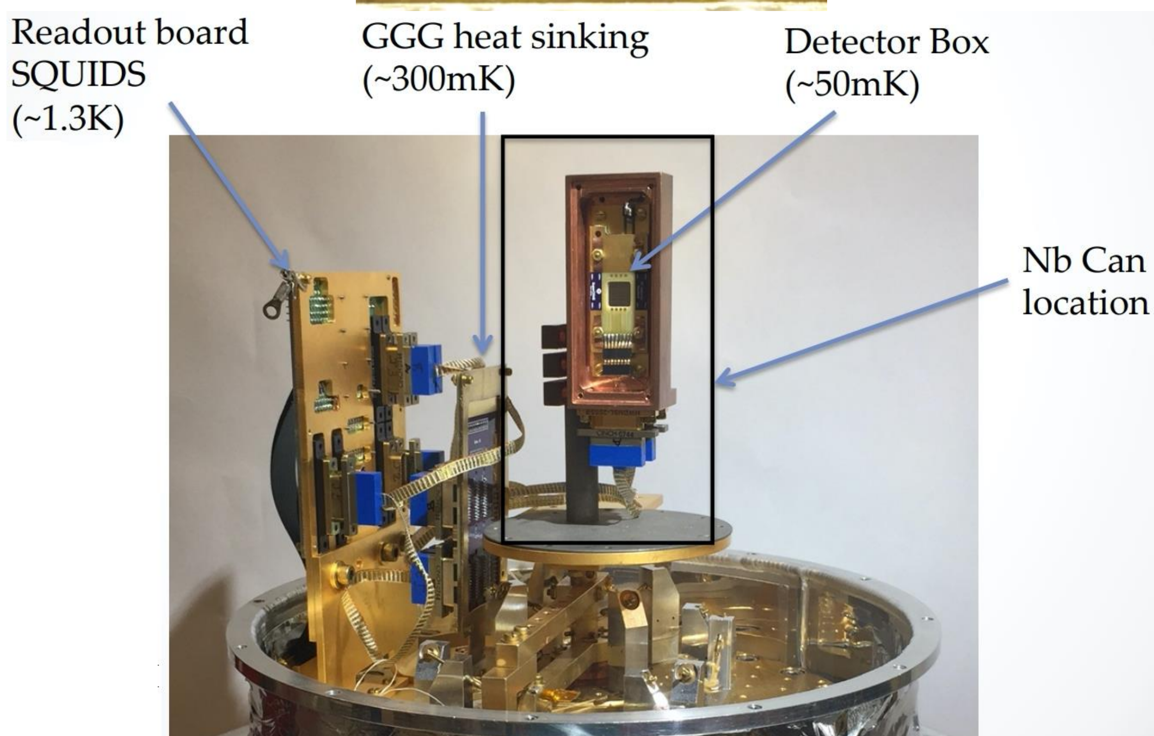
NTL Amplification and monochromatic source

Northwestern University Run 2

Phys. Rev. D **102**, 091101(R), https://doi.org/10.1103/PhysRevD.102.091101

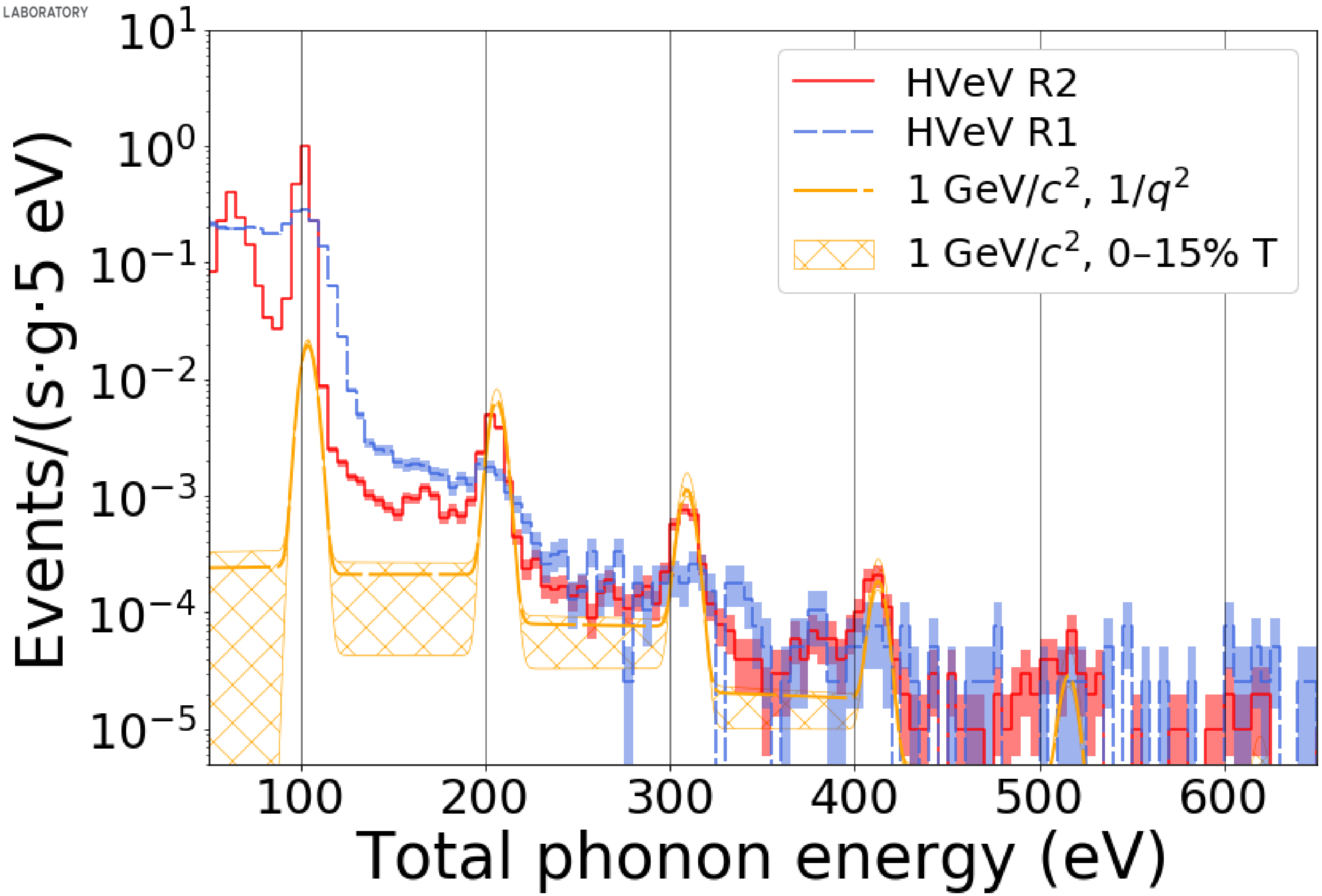






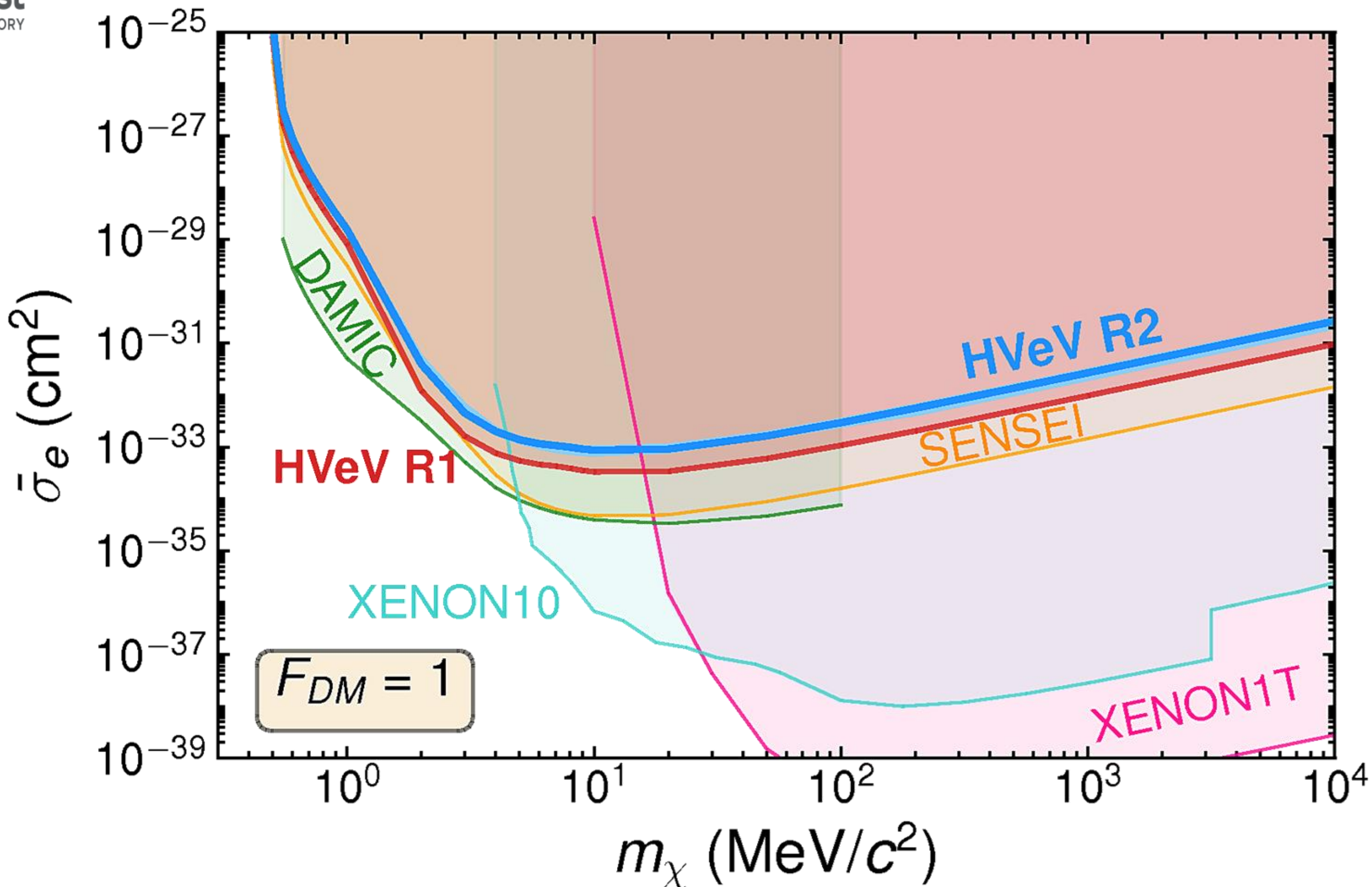
LED illumination from QET side

DM Search Run 2



DM search spectrum are similar in the two runs.

Electron Recoil DM Search

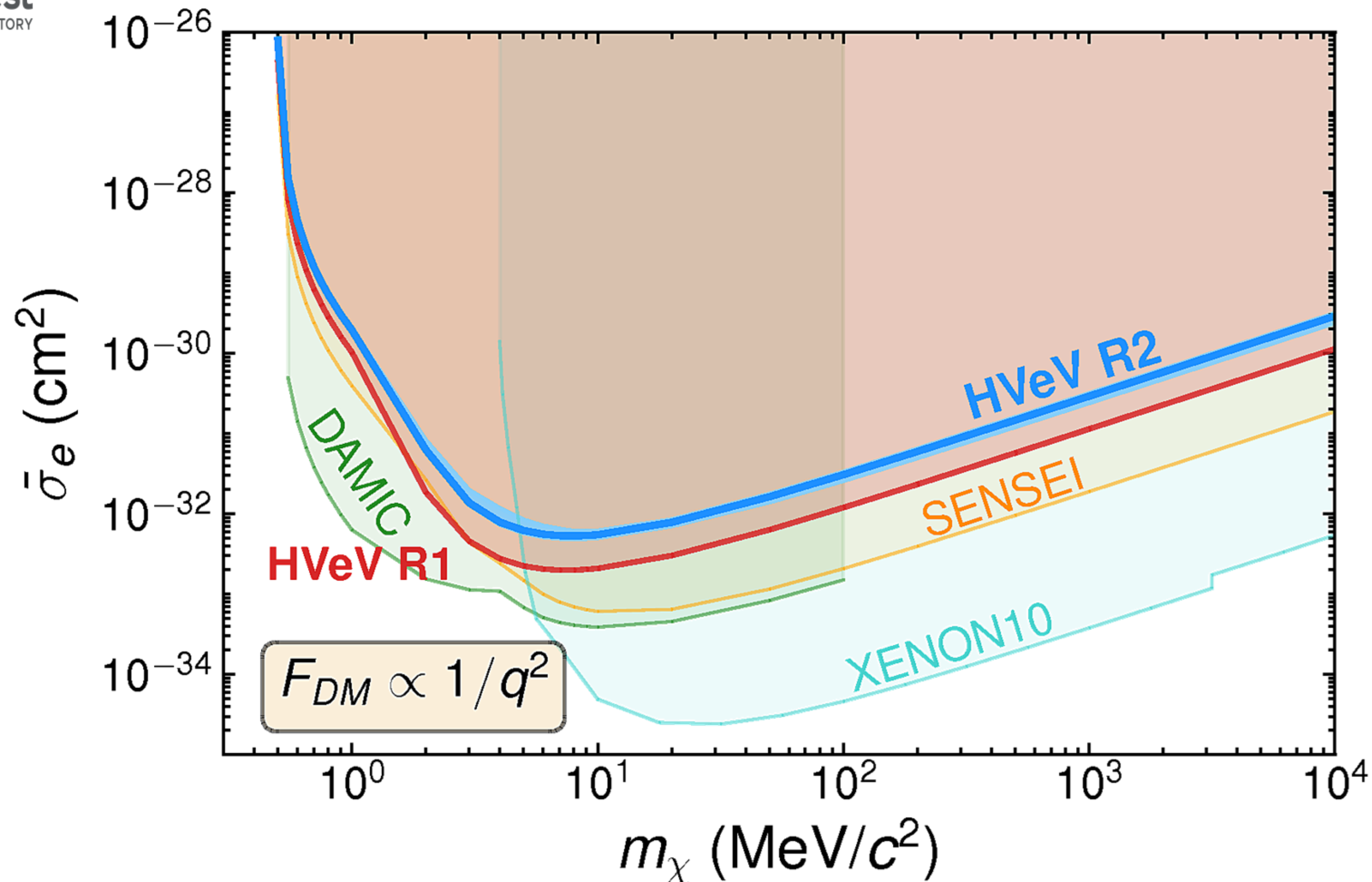


$$\frac{dR}{d(\ln(E_R))} = V_{Det}\frac{\rho_{DM}}{m_X}\frac{\rho_{Si}}{2m_{Si}}\bar{\sigma}_e\alpha\frac{m_e^2}{\mu_X^2}I_{Crystal}$$

Eqn. from http://www.doi.org/10.1007/JHEP05(2016)046

Improved heavy mediator ERDM limits to 0.5 MeV

Electron Recoil DM Search



$$\frac{dR}{d(\ln(E_R))} = V_{Det}\frac{\rho_{DM}}{m_X}\frac{\rho_{Si}}{2m_{Si}}\bar{\sigma}_e\alpha\frac{m_e^2}{\mu_X^2}I_{Crystal}$$

Eqn. from http://www.doi.org/10.1007/JHEP05(2016)046

Improved heavy mediator ERDM limits to 0.5 MeV

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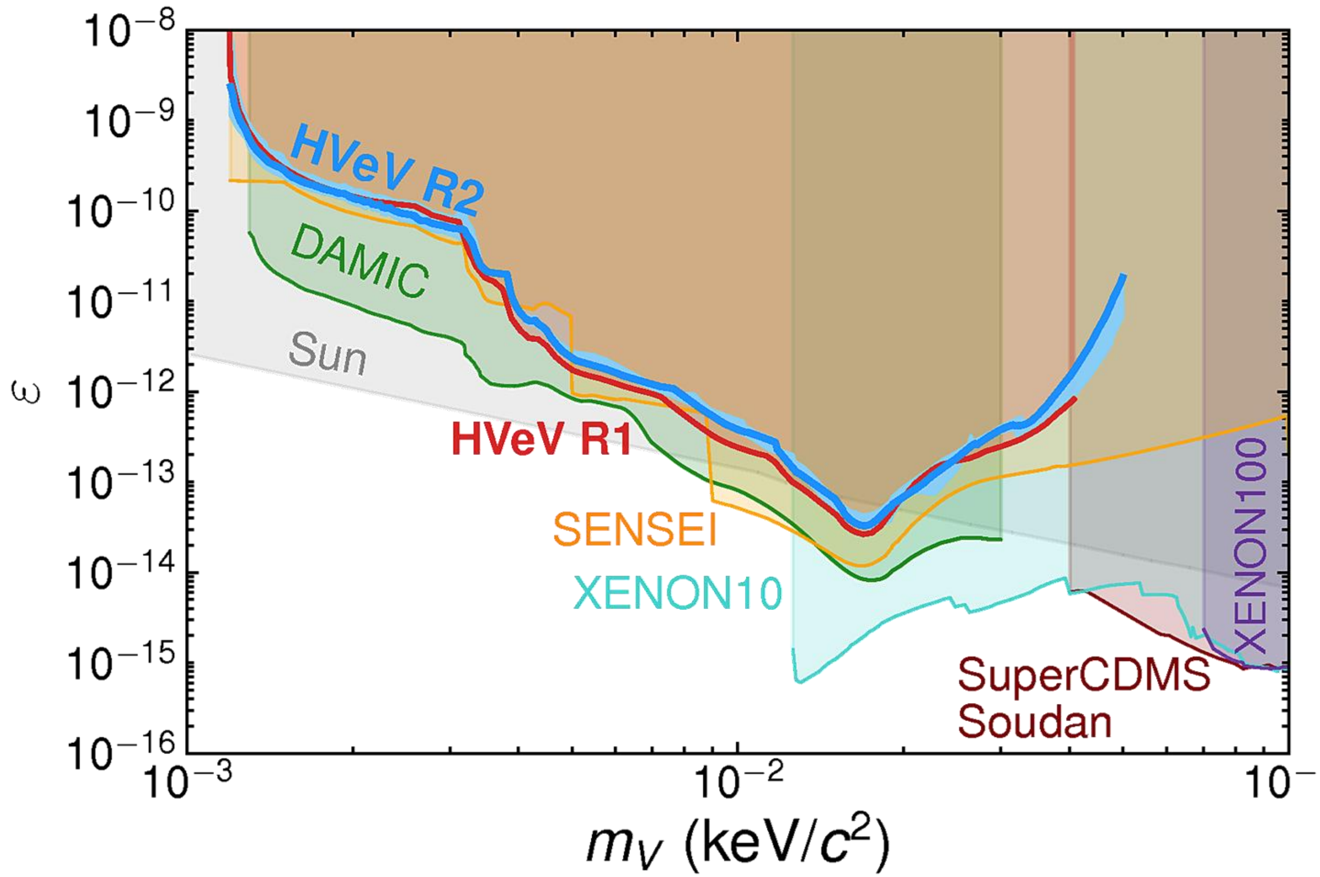
Dark Photon DM Search



$$R = V_{Det}\frac{\rho_{DM}}{m_V}\varepsilon_{eff}^2(m_V,\sigma)\sigma_1(m_V)$$

Eqn. from http://www.doi.org/10.1103/PhysRevD.95.023013

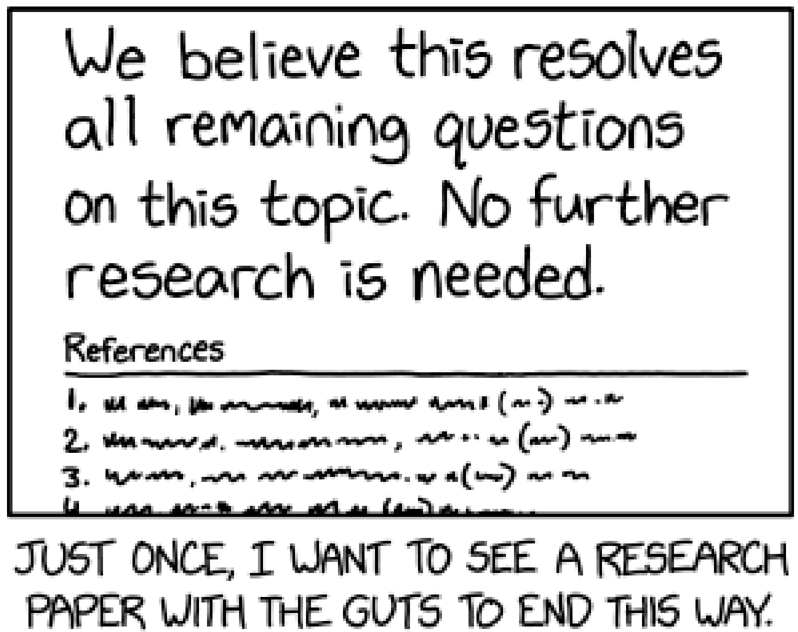
Dark photon limit is consistent with other measurements

Conclusion

- Single $e^{-}h^{+}$ pair resolution with NTL gain
- Achieved comparable sensitivity to that reported by DAMIC for Dark Photons
- Improved constraints on inelastic ERDM for both heavy and light mediators down to 0.5 MeV
- Developed technique to measuring IICT
- Model is integrated into new DM search

Questions…

https://xkcd.com/2268/



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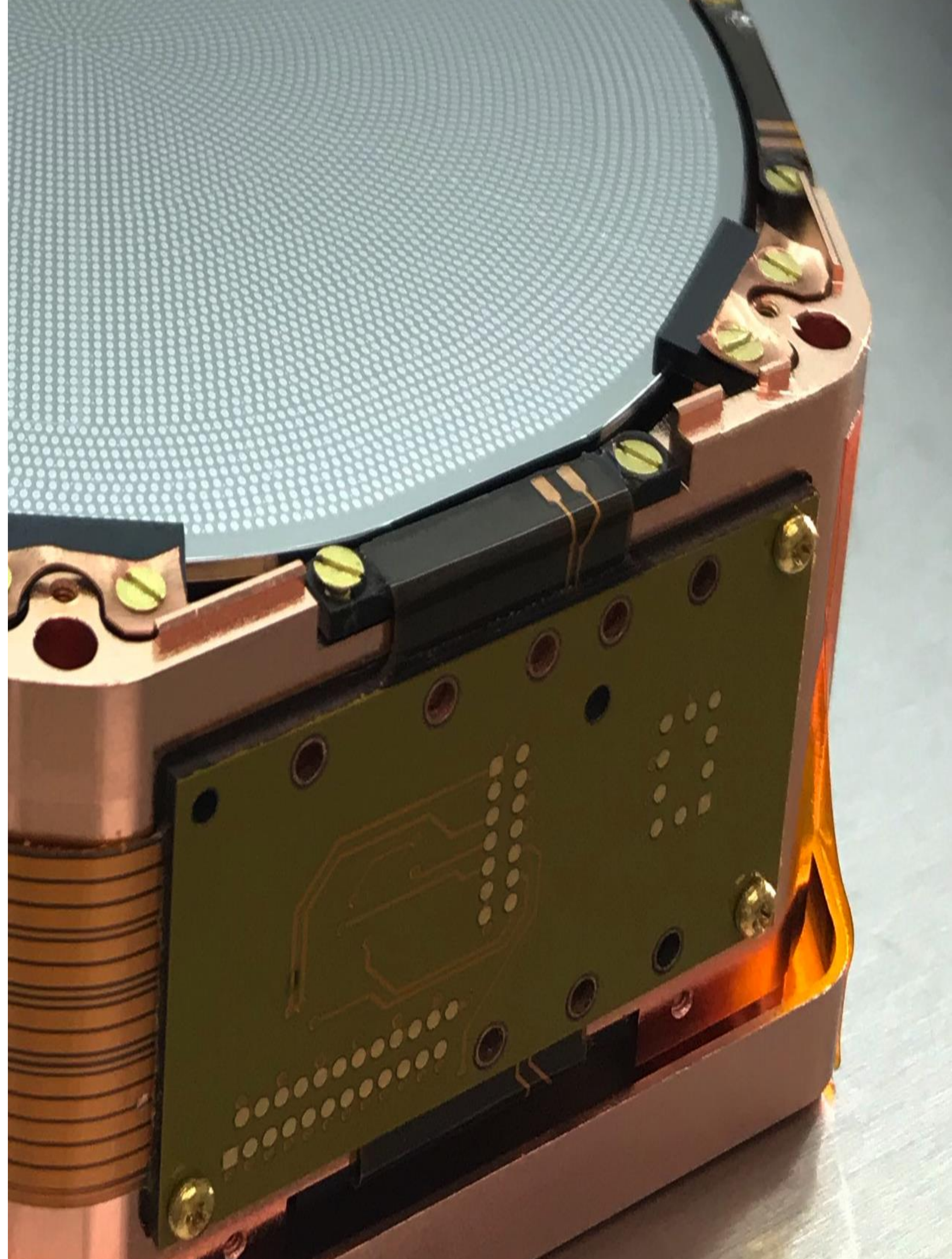
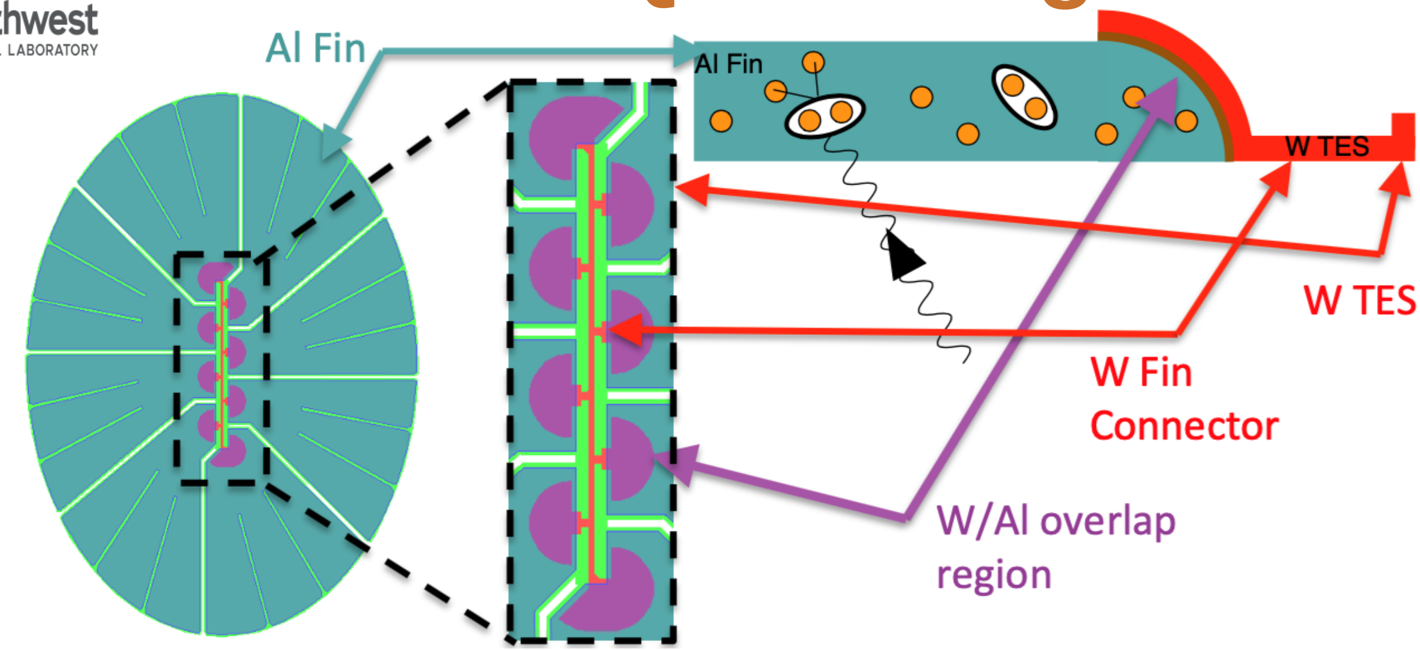
Backup Slides



Questions…

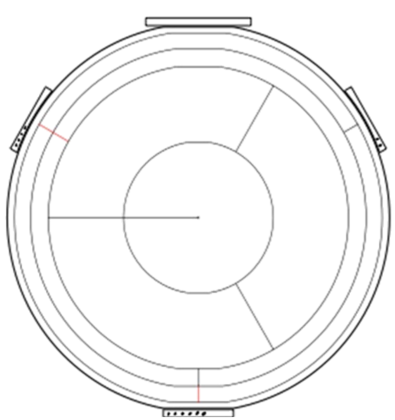
https://loadingartist.com/comic/out-of-sight/

QET Design



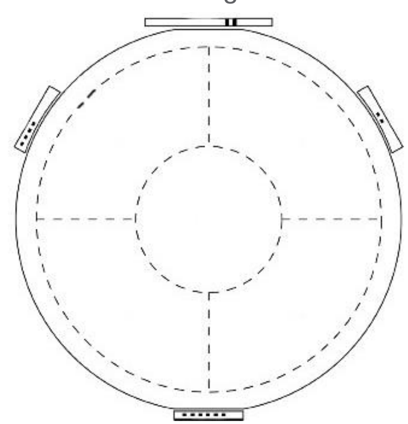
High Voltage (HV):

- Phonon signal
- Large Bias Voltage
- Neganov-Trofimov-Luke Effect



interleaved Z-dependent Ionization and Phonon (iZIP):

- Phonon signal
- Charge signal
- Small Bias Voltage



Outline

✓Dark Matter

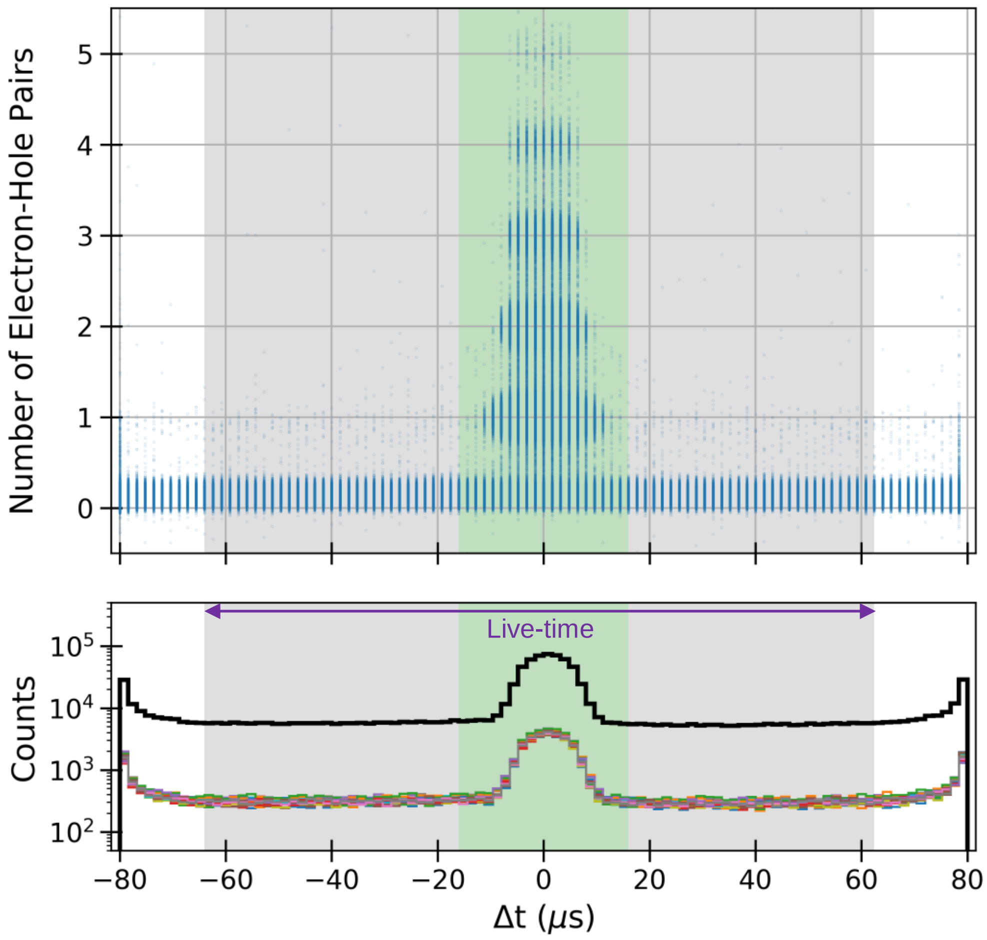
✓Detector R&D Developments

✓DM Search

➢Improved Detector Modeling

1. Charge trapping and impact ionization model
2. Data Quality
3. Background analysis
4. Charge trapping and impact ionization analysis

Background Selection

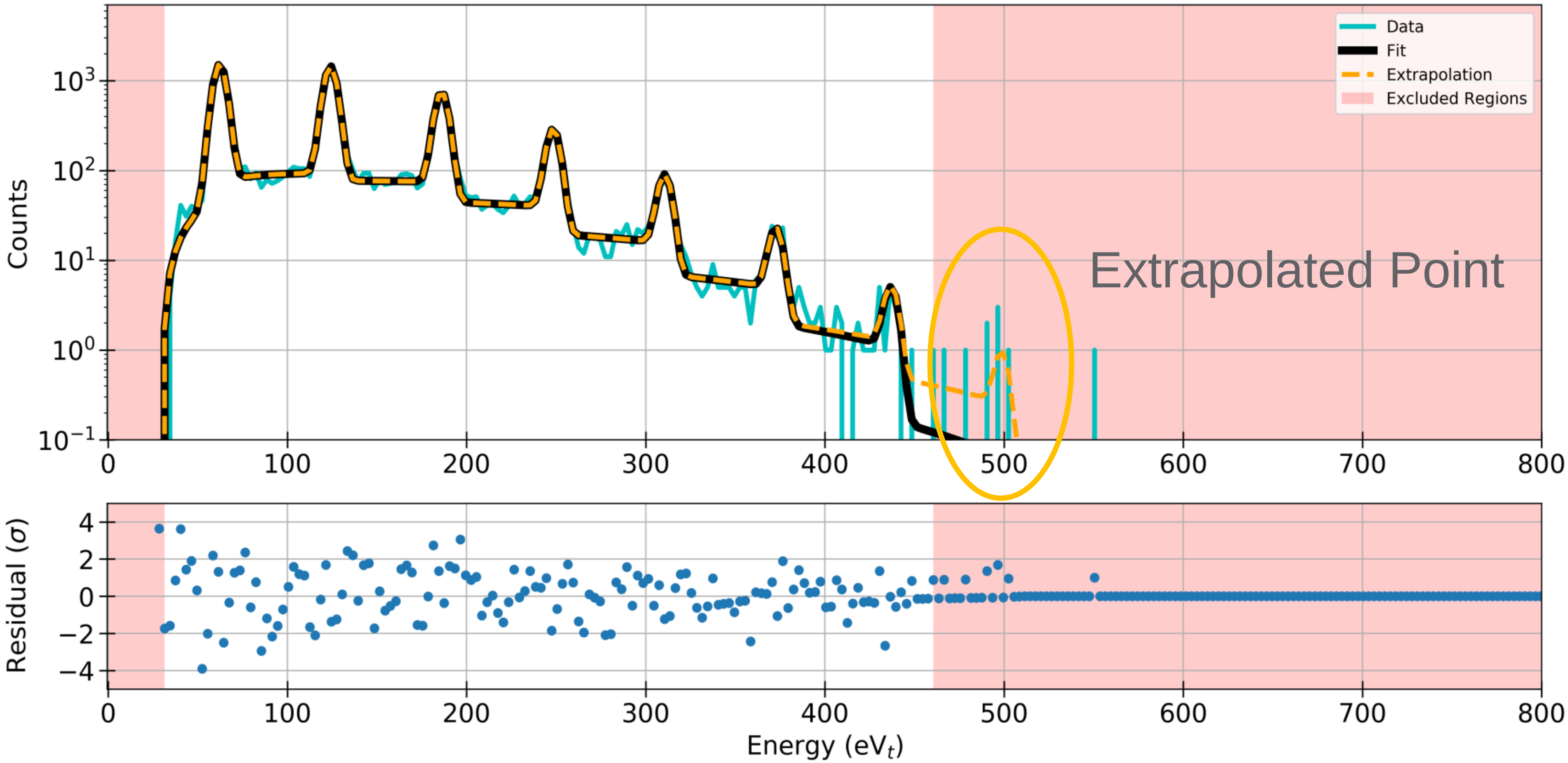


Energy (top) and counts (bottom) of events as a function of the pulse OF arrival time relative to laser TTL

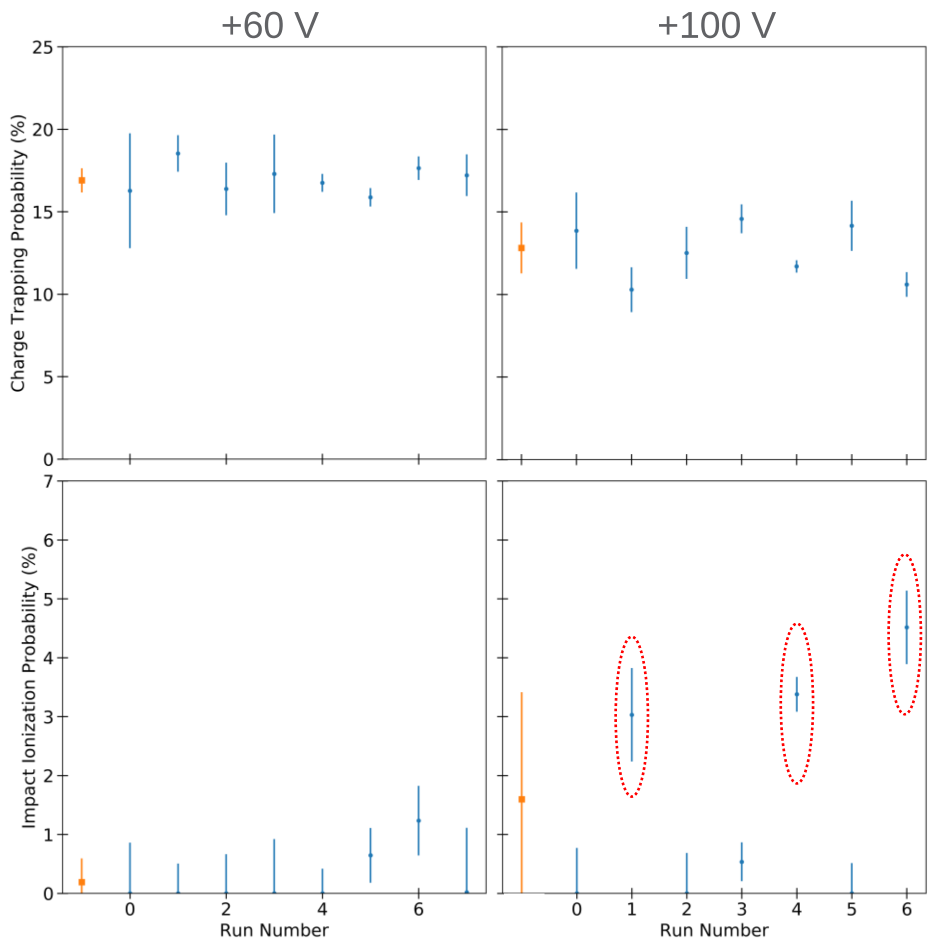
Background can be selected based on timing

Run 2 Analysis

$$M_{eff}(x) = erf\left(\frac{x - x_{eff}}{\sqrt{2\sigma_{eff}^2}}\right)\sum_{m=1}^{m_{max}} P_m(\lambda)\left({}^{(m)}h \circledast G(\sigma)\right)(x)$$



Charge Trapping & Impact Ionization



Weighted Charge Trapping Probability:
16.9 ± 0.7% @ 60 V
13.7 ± 0.7% @ 100 V
Mean free path: 29 cm & 24 cm

Weighted Impact Ionization Probability:
0.2 ± 0.4% @ 60 V
0.1 ± 0.2% @ 100 V

Underfits in the 100 V spectra data are excluded from final weighted averages

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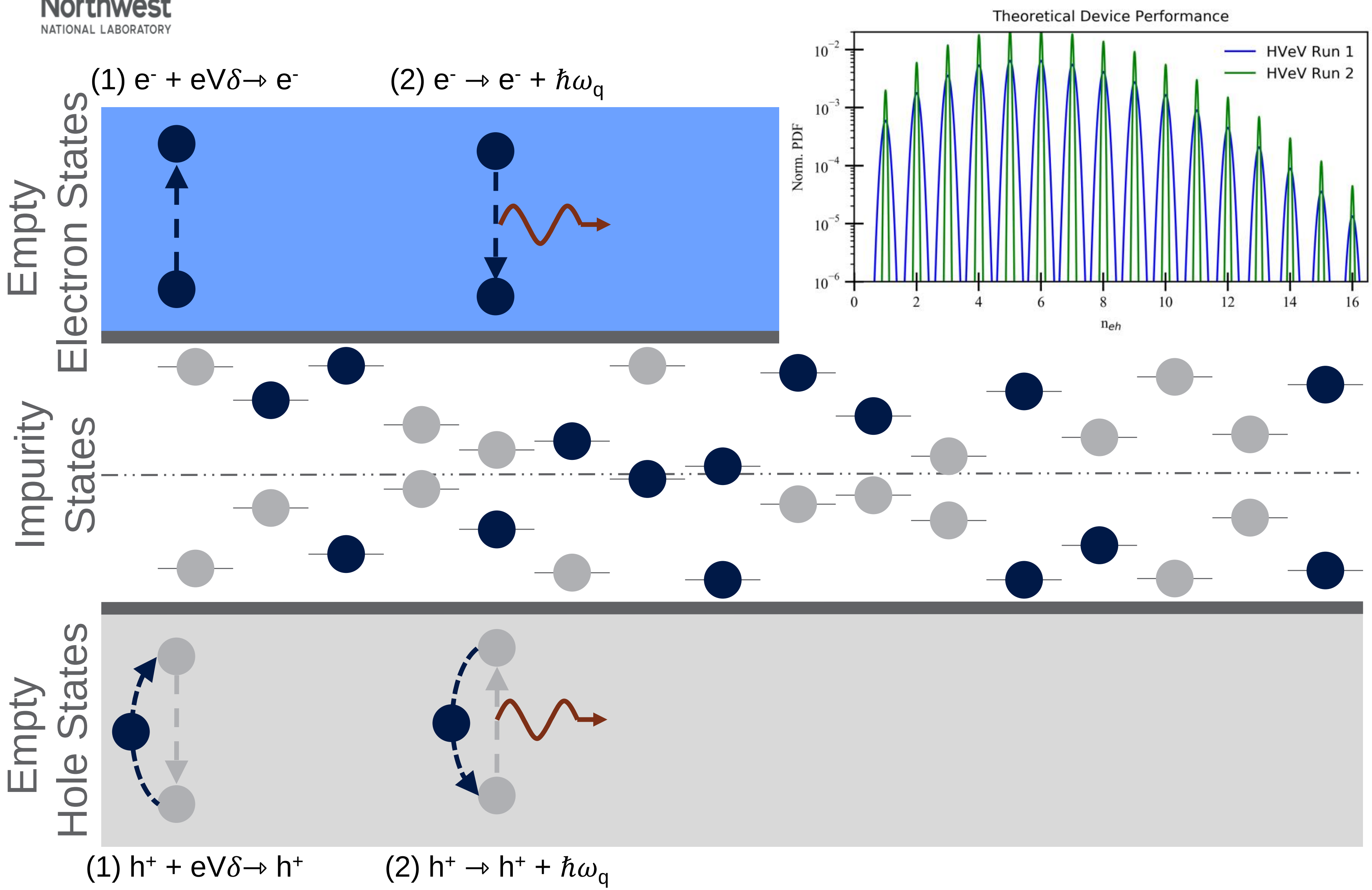
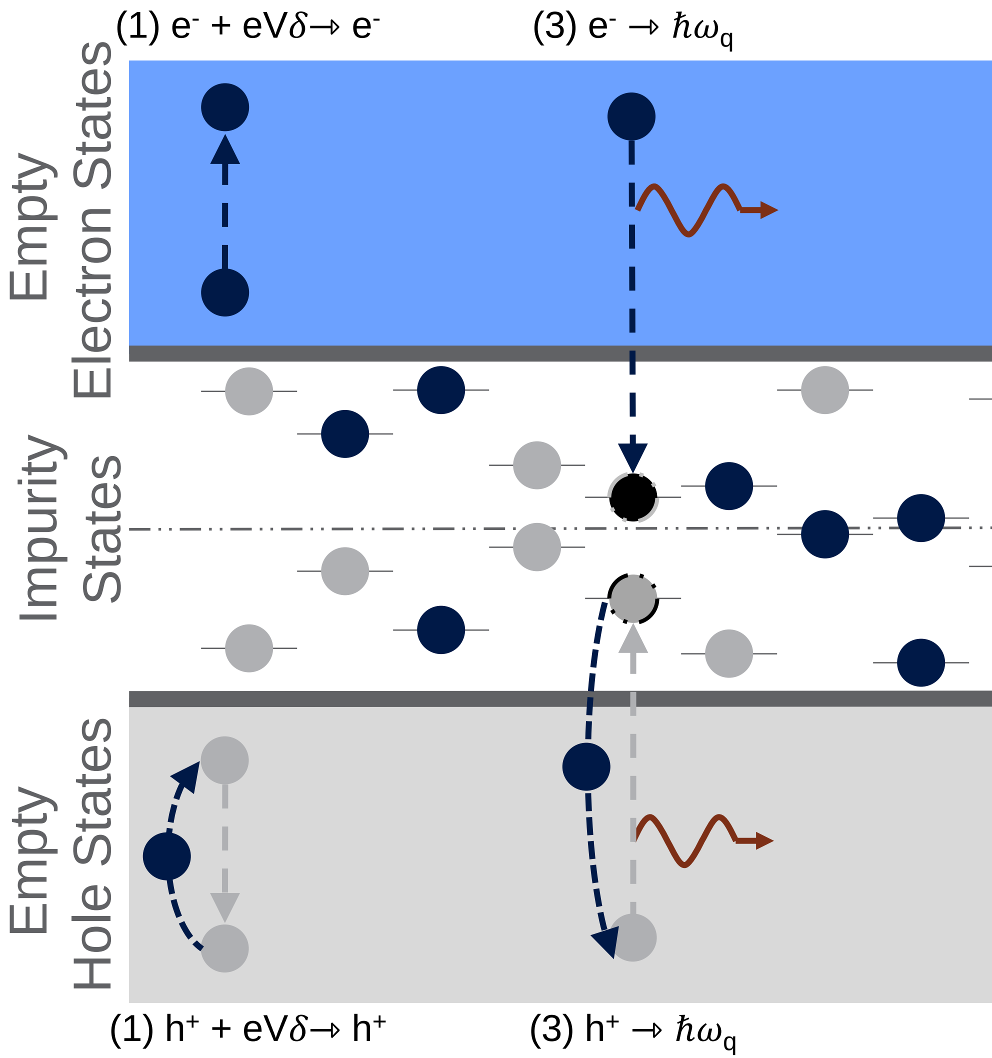
Conclusion

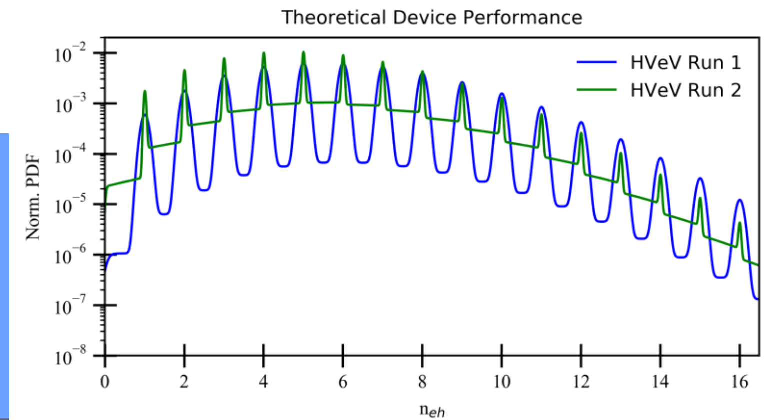
- Single $e^{-}h^{+}$ pair resolution with NTL gain
- Achieved comparable sensitivity to that reported by DAMIC for Dark Photons
- Improved constraints on inelastic ERDM for both heavy and light mediators down to 0.5 MeV
- Demonstrate time domain OF for semi-continuous mode acquisitions
- Developed technique to measuring IICT
- Observed no dependence on crystal polarity
- Observed dependence on crystal bias voltage
- Model is integrated into new DM search

NTL Amplification



Charge Trapping





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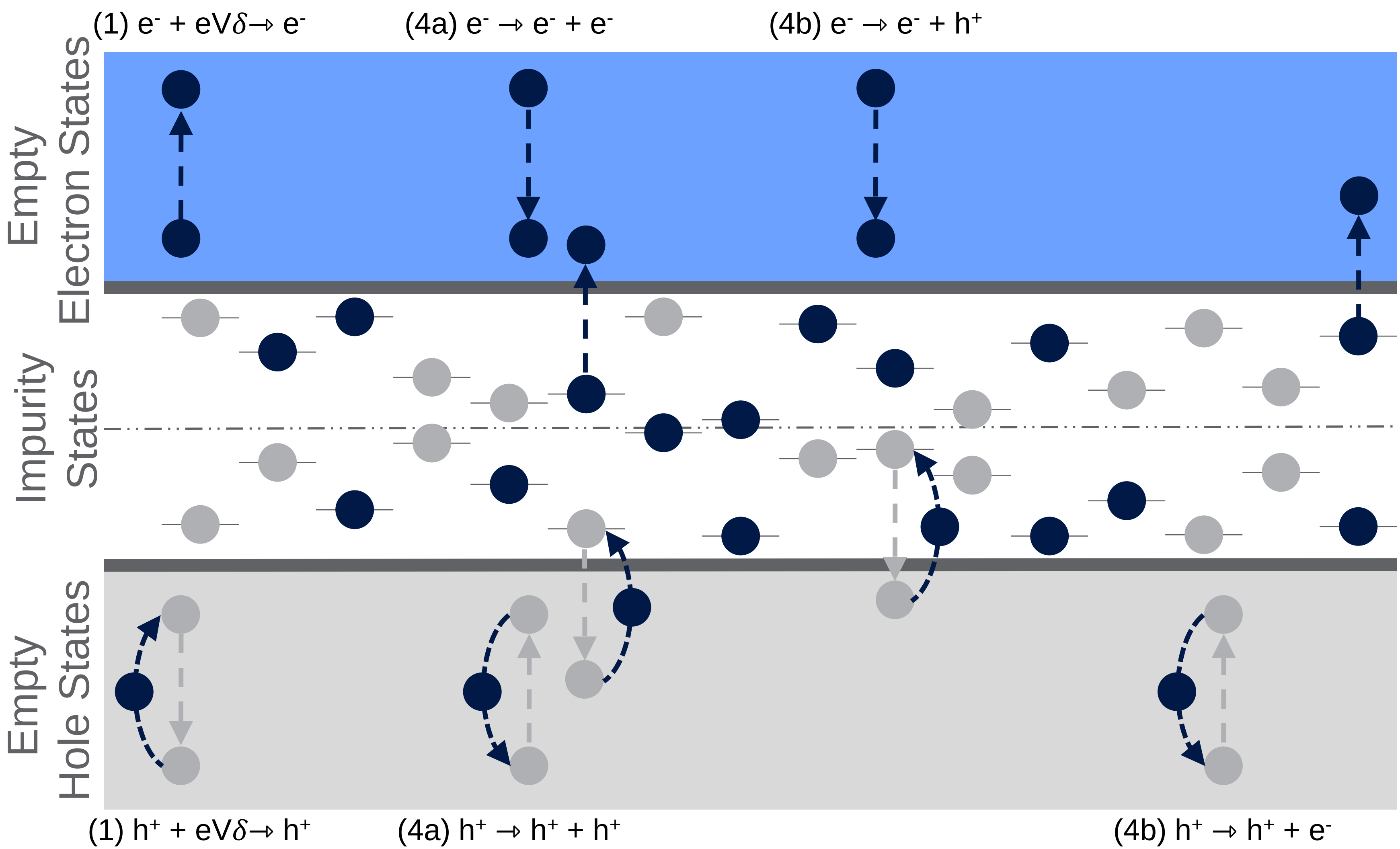
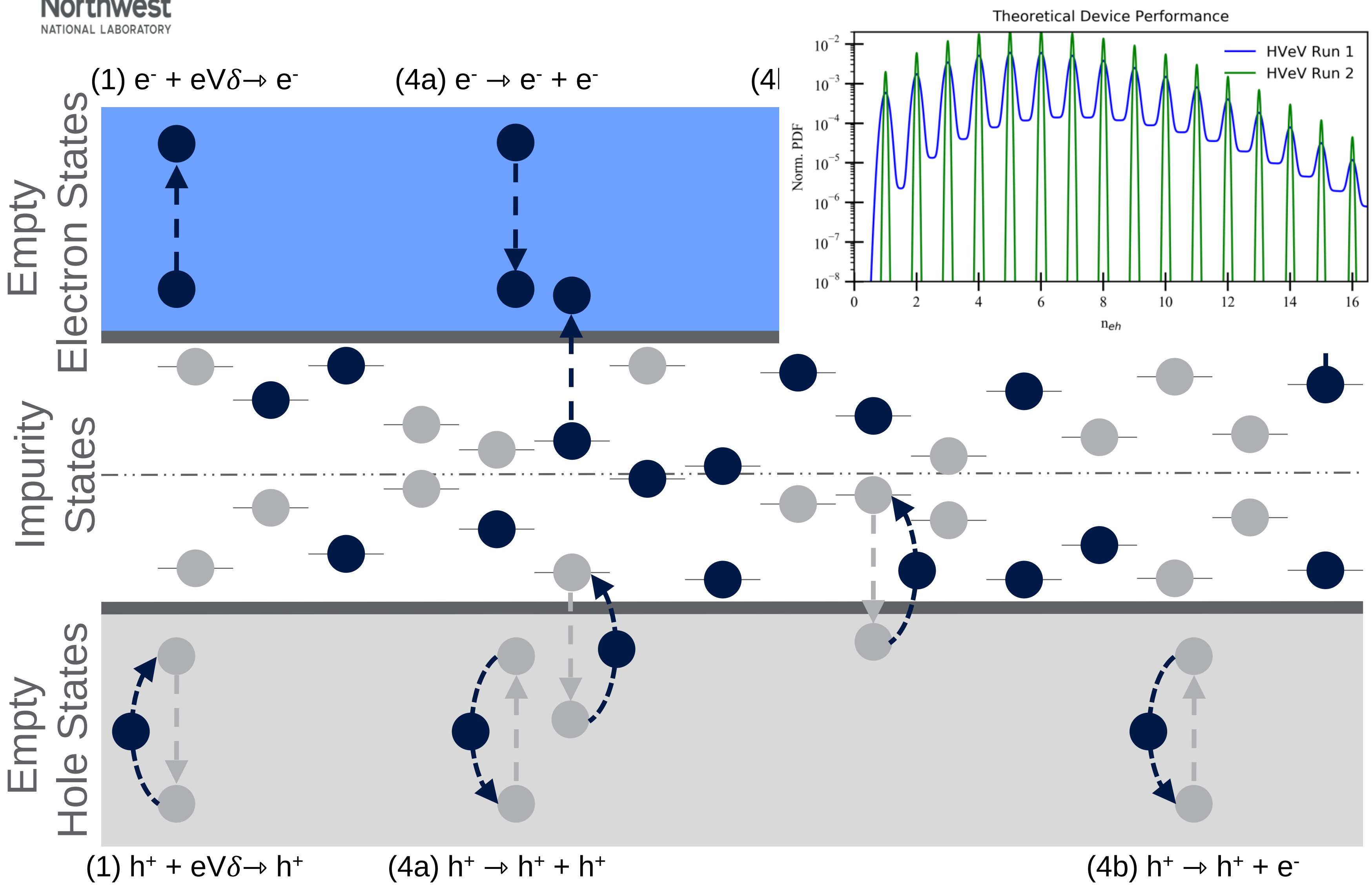
Impact Ionization

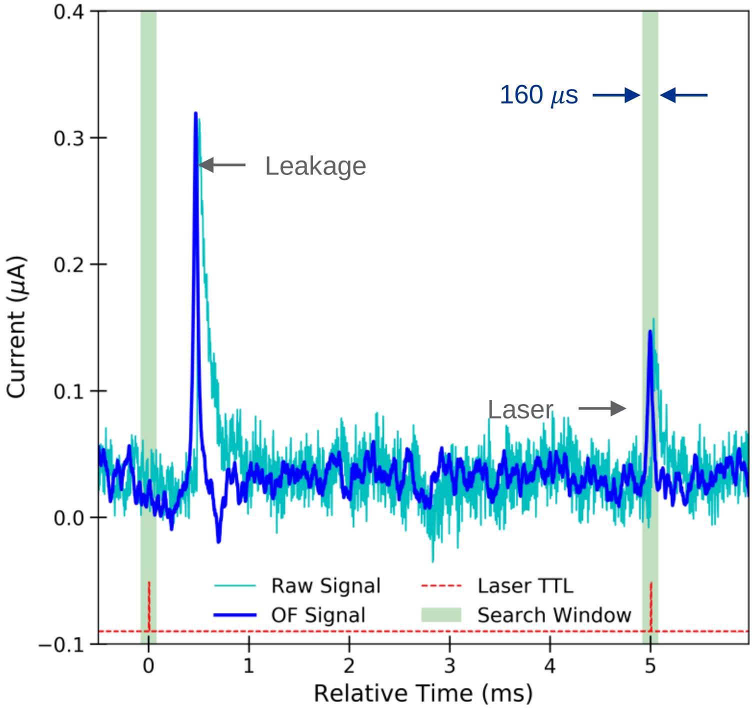


Impact Ionization



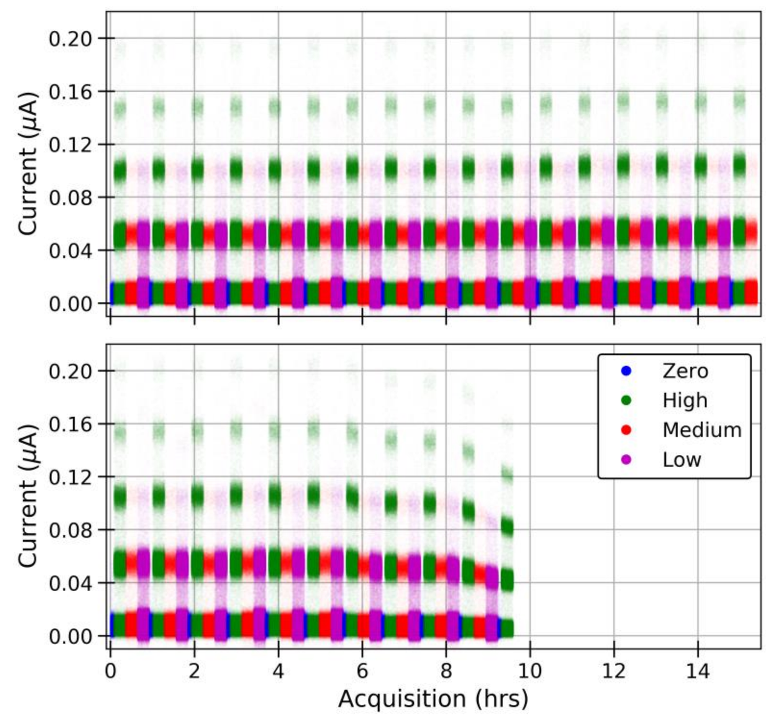
Semi-Continuous Acquisition

Tagged Laser Events



Time-shifting optimal filter (OF) amplitude as a function of time (blue curve).

Detector Stability

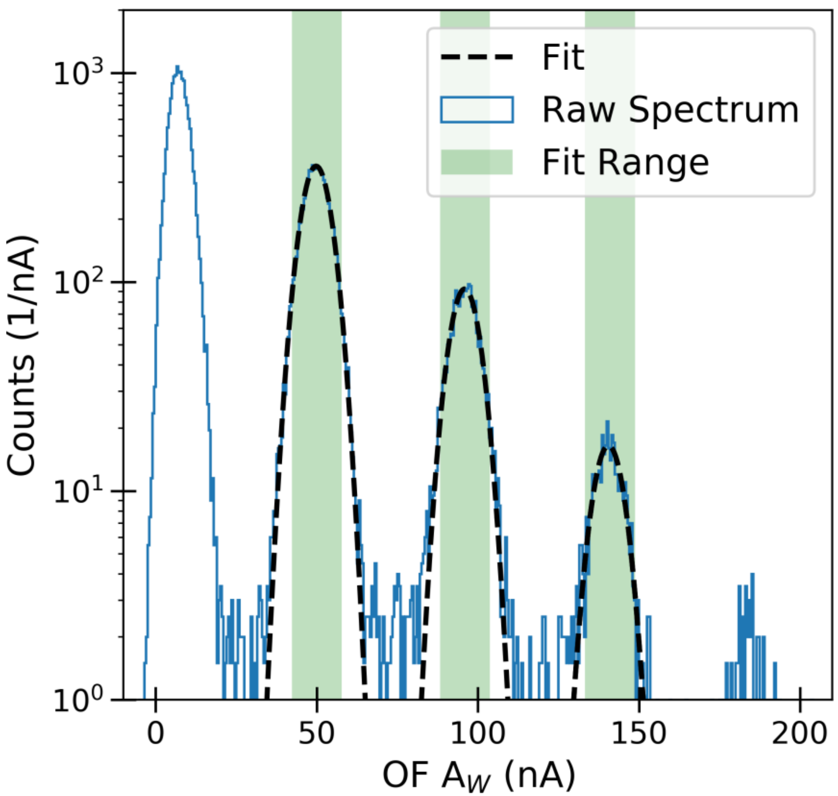


Detector responsivity over 27(18) hours of real-time acquisition with a +(-)140 V bias and four intensities for 8 configurations.

Eight configurations used in study and DR was nominally stable throughout

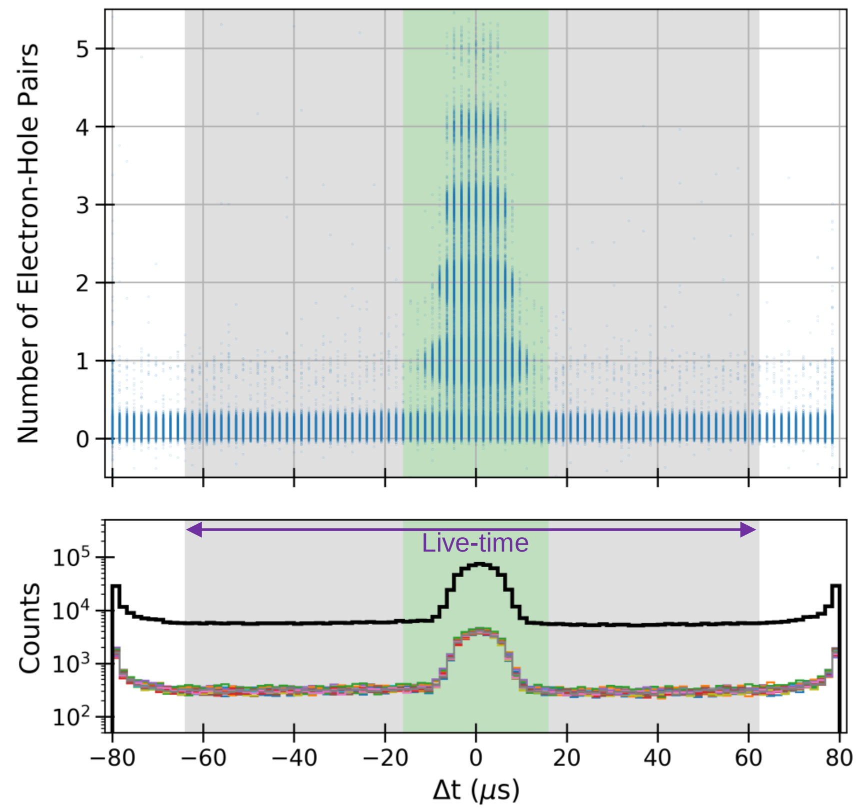
Calibration & Background

Peak Fitting



Calibration was performed using the centroids of a Gaussian fit to the 1, 2, & 3 n_{eh} peaks.

Relative Arrival Time

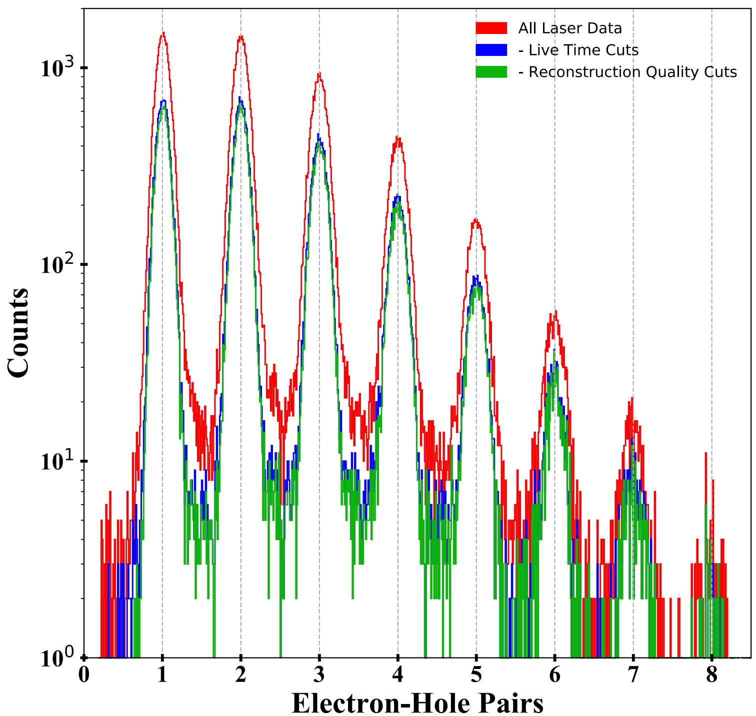


Energy (top) and counts (bottom) of events as a function of the OF estimated relative arrival time.

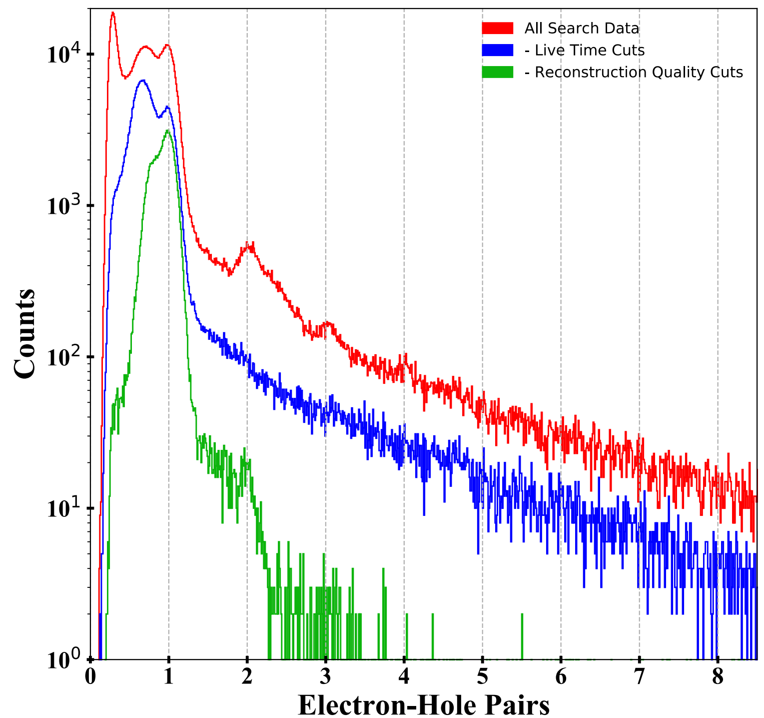
Background can be selected based on timing

Data Selection Run 1

Calibration Laser Data



DM Search Data



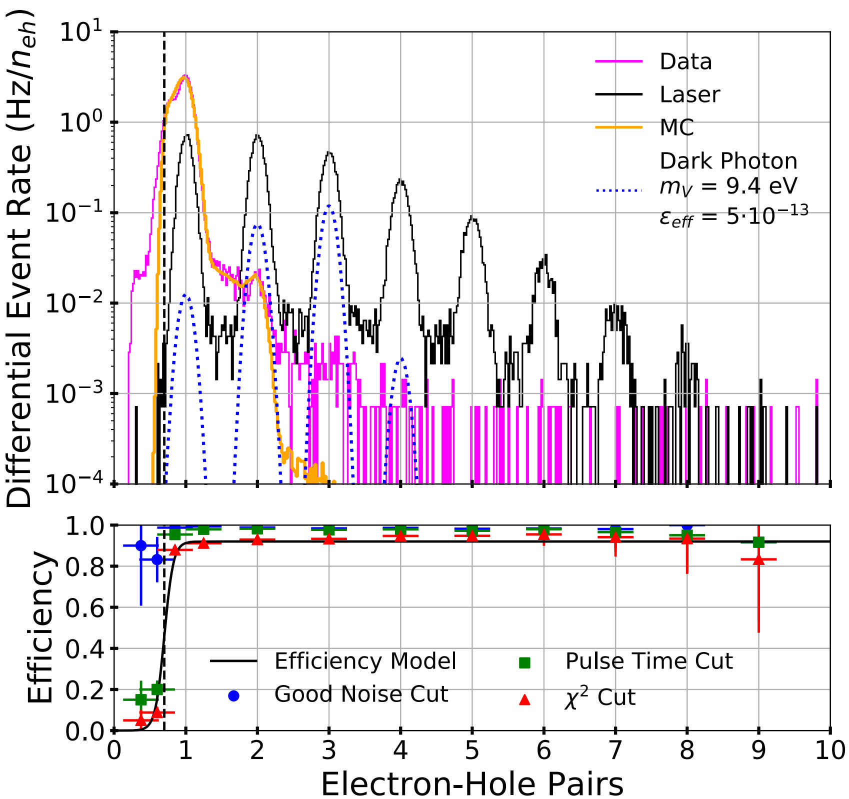
Periods of high low-frequency background, high surface leakage, and poor system stability were removed as part of the live time cuts. Events with excessive noise in the pre-trigger, start times far from the trigger window or bad time domain chi-square were rejected as part of the reconstruction quality cuts.

Science exposure of 0.49 gram-days

DM Search Data Run 1

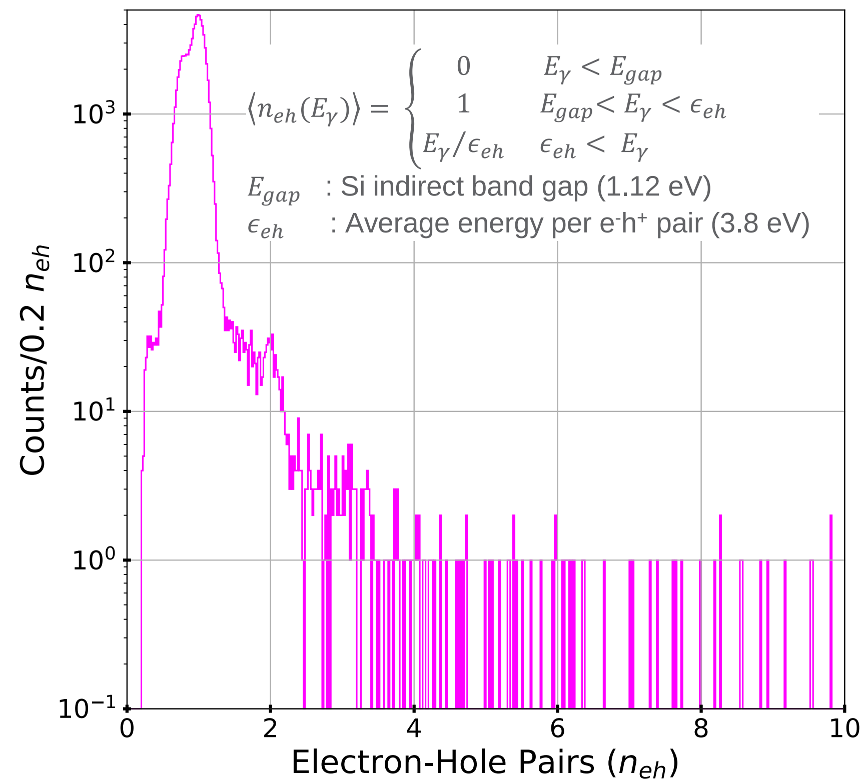
Phys. Rev. Lett. **121**, 051301 (2018); https://doi.org/10.1103/PhysRevLett.121.051301

Models and Cut Efficiency



Laser spectrum is used to calculate the reconstruction quality cut efficiency

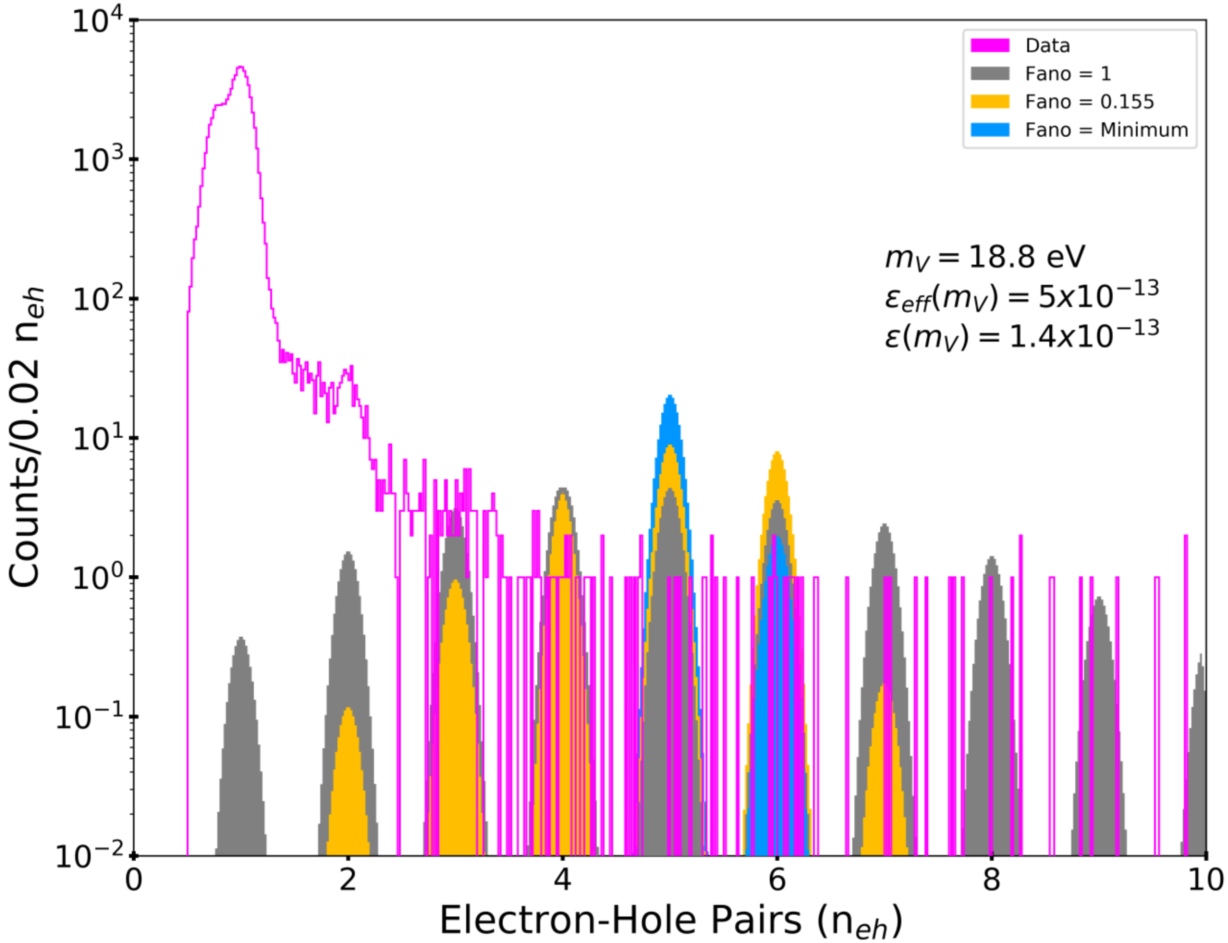
Optimal Interval



Optimal interval method is applied to sections of data within 2σ of quantized laser peaks.

Limit search region to expected DM signal regions

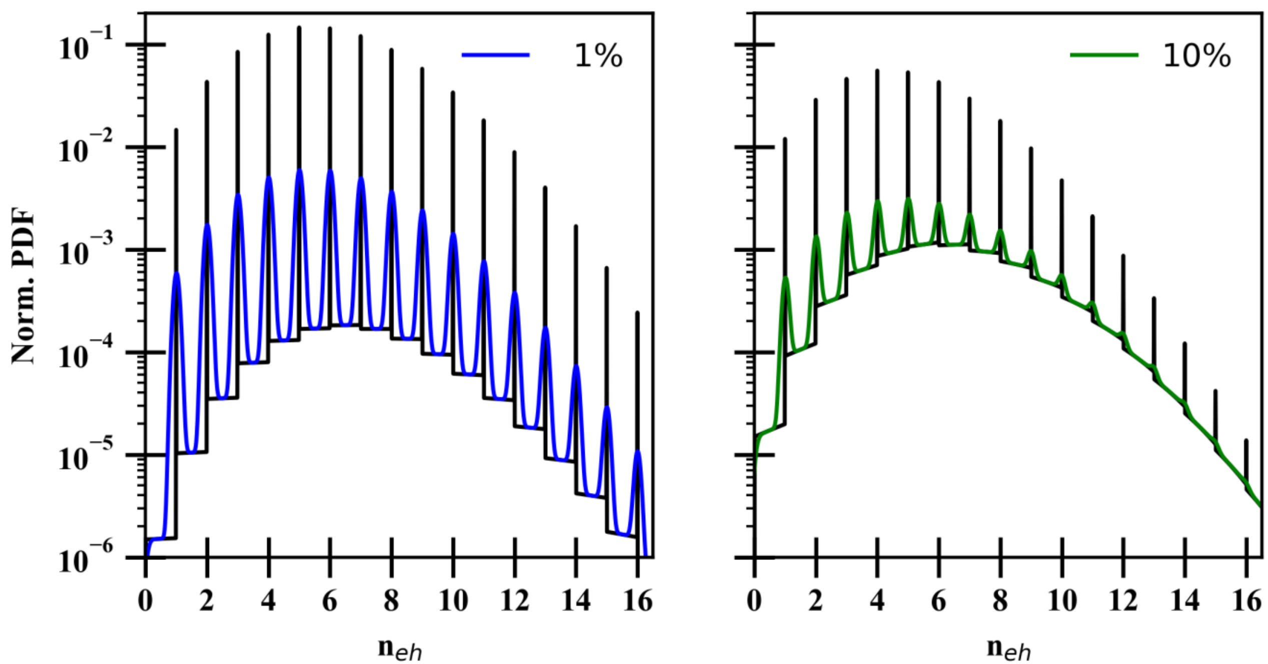
DM Search Data Run 1



Example of modeling a Dark Photon no IICT is considered

Detector Laser Response

w/ Charge Trapping and Impact Ionization

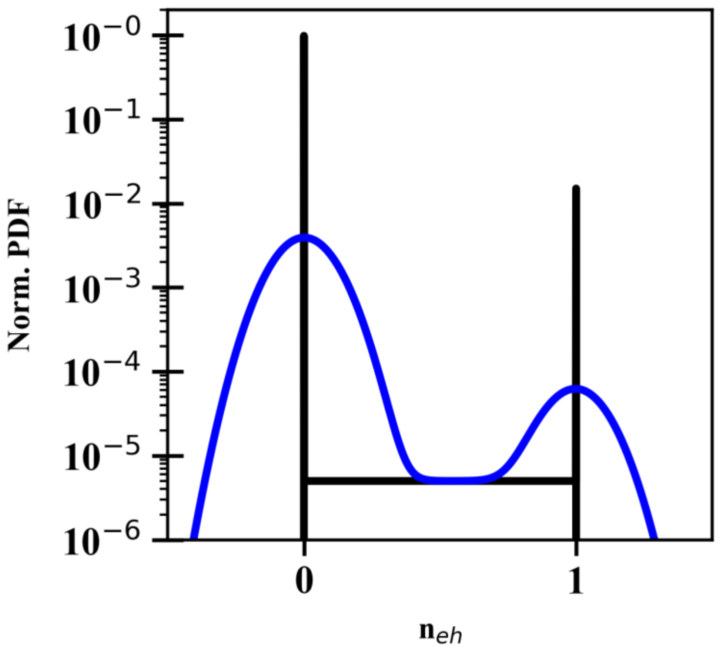


$$M'(x) = \sum_{m=1}^{m_{max}} P_m(\lambda)\left({}^{(m)}h \circledast G(\sigma)\right)(x)$$

Where $P_m(\lambda)$ is the Poisson distribution, $\lambda = 6$ is the average number of photons per pulse, m is the number of photons, G(σ) is the Gaussian distribution, and $\sigma = 0.1\ e^-h^+$ is the detector resolution.

Leakage Background

$$R(x) = R_{Surf}\delta(x - c_1) + \frac{R_{Bulk}}{(c_1 - c_0)}\Theta(x - c_0)\Theta(c_1 - x)$$



$$\underline{B(x)}$$

$$= \frac{NL_0}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-c_0)^2}{2\sigma^2}} \left(\frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{x - c_0}{\sqrt{2\sigma^2}}\right)\right)\right)^{N-1}$$

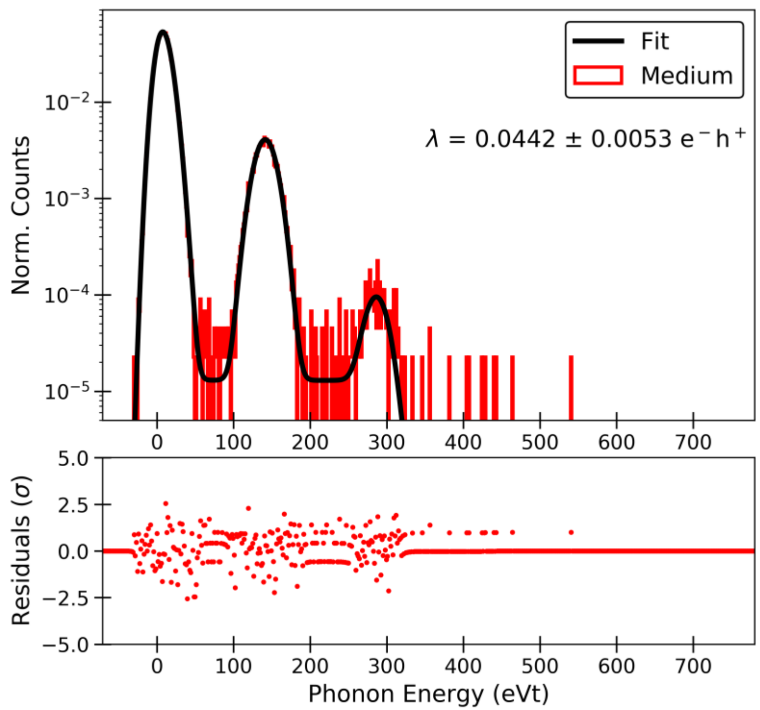
$$+ \frac{L_{Surf}}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-c_1)^2}{2\sigma^2}}$$

$$+ \frac{L_{Bulk}}{(c_1 - c_0)}\left(\mathrm{erf}\left(\frac{x - c_0}{\sqrt{2\sigma^2}}\right) - \mathrm{erf}\left(\frac{x - c_1}{\sqrt{2\sigma^2}}\right)\right)$$

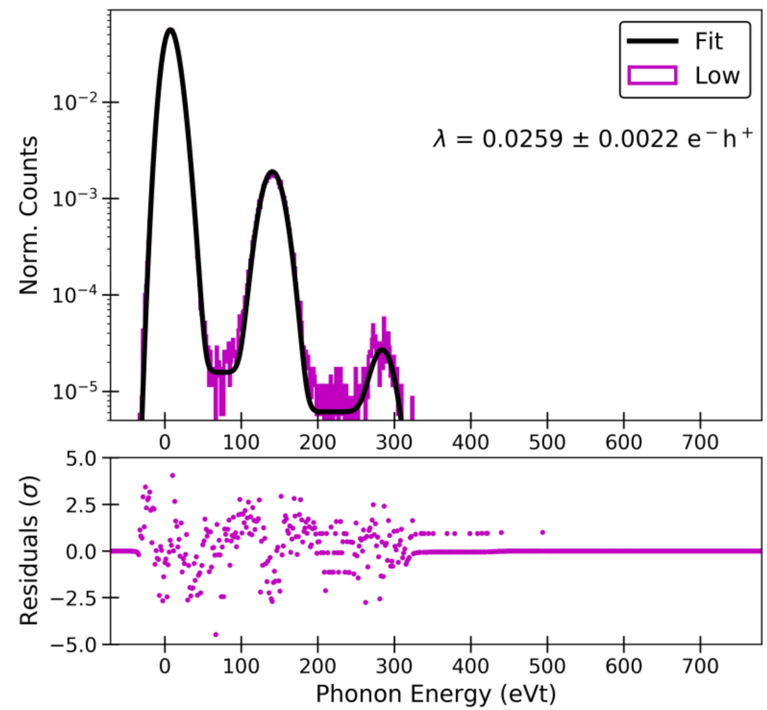
The acquisition is triggered on the laser TTL and analysis is carried out with a time-shifting OF

Sample Fits

Medium Laser



Low Laser



Impact ionization and charge trapping fit (black curves) for a single acquisition cycle at +140 V crystal bias with medium (red), and low (purple) intensity laser. The curves have been normalized by dividing by the total counts in the spectrum. (Bottom row) Residual counts normalized by the individual bin standard deviations. Bins with zero counts were artificially set to zero.

Multi-Photon Response

Biometrika, **19**, 225–239 & 240–244 (1927);https://doi.org/10.1093/biomet/19.3-4.225,
& https://doi.org/10.1093/biomet/19.3-4.240

m^{th} $e^{-}h^{+}$ pair PDF with impact ionization and trapping :

$$^{m}h(x) = \int_{-\infty}^{\infty} {}^{1}h(x')\,^{m-1}h(x-x')dx'$$

$$= A_1^m \delta(x-m) + mA_1^{m-1}A_{-}\Theta(x-m+1)\Theta(m-x) + mA_1^{m-1}A_{+}\Theta(x-m)\Theta(m+1-x)$$

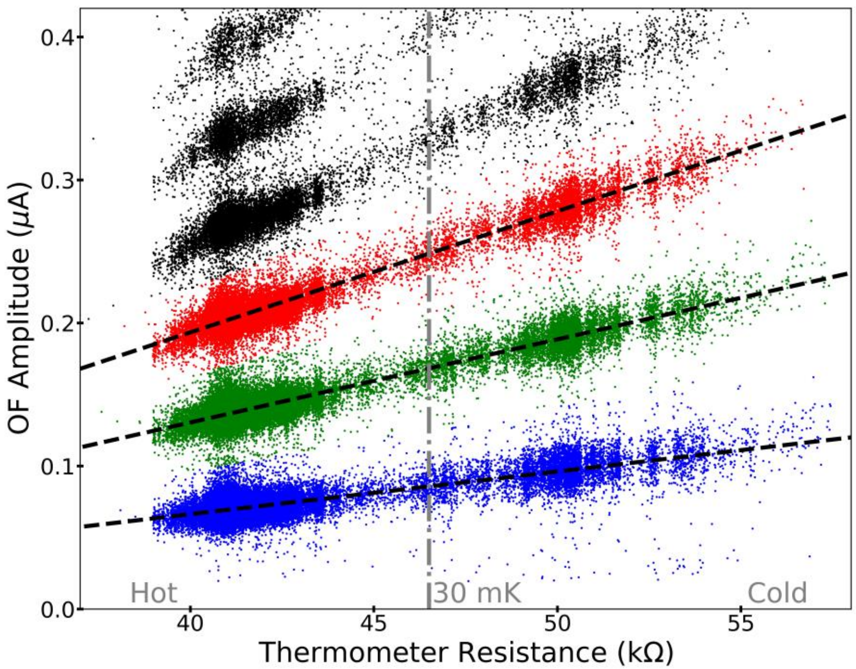
$$+ \sum_{i=0}^{m-2}\sum_{j=0}^{m-i}\sum_{n=1}^{m-i} A_{mijn}(n+m-j-x)^{m-i-j}\Theta(n+m-j-x)\,\Theta(x-m+j)$$

Where

$$A_{mijn} = \frac{A_1^i A_{-}^j A_{+}^{m-i-j} m!}{i!\,j!\,(m-i-j)!}\frac{(-1)^{m-i-n}(m-i)!}{n!\,(m-i-n)!}\frac{1}{(m-i-1)!}$$

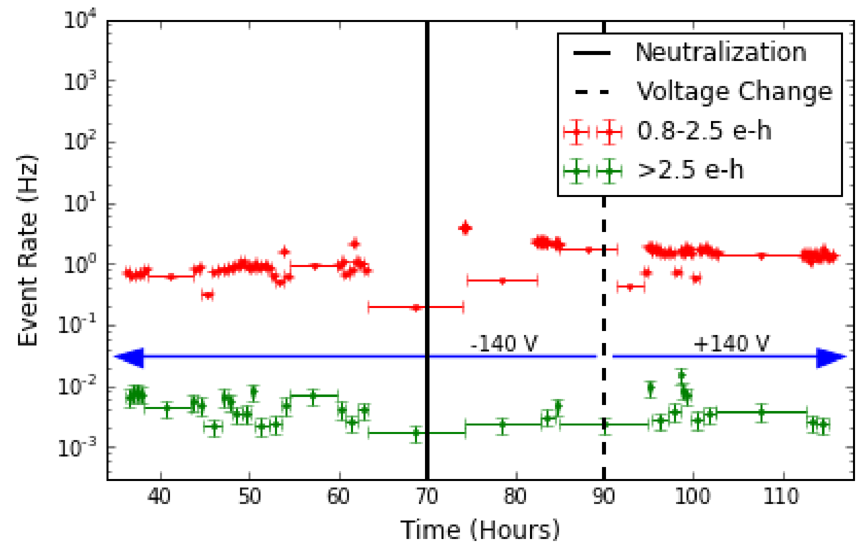
System Stability

Temperature Calibration



Reconstructed amplitude scales linearly with resistance from a RuOx thermometer used to measure the DR temperature.

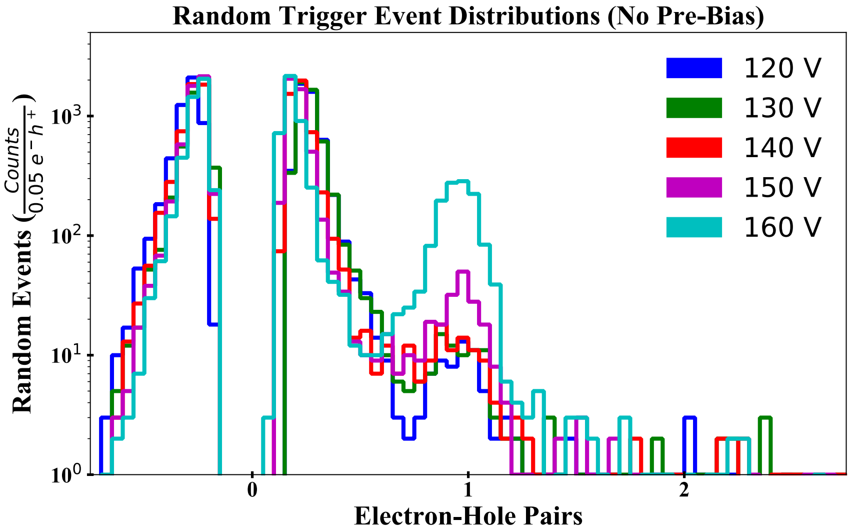
Leakage Rates for DM Search

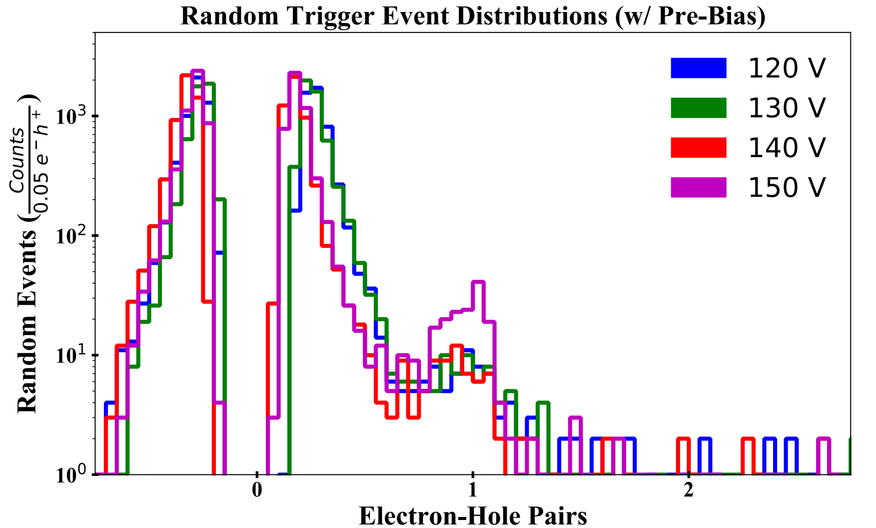


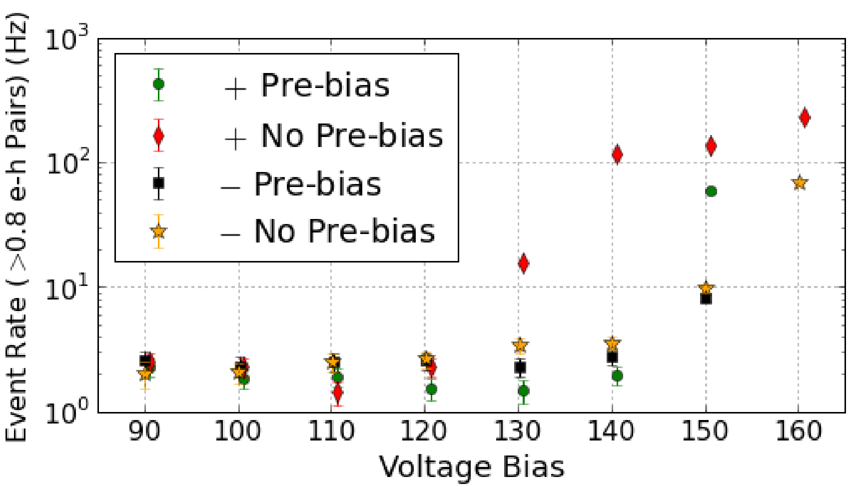
Detector neutralization performed at 70 hours due to increased levels of surface leakage. An increase in the bulk leakage rate was observed afterwards.

Temperature varied and bulk leakage rate was constant

Limitations on NTL Gain





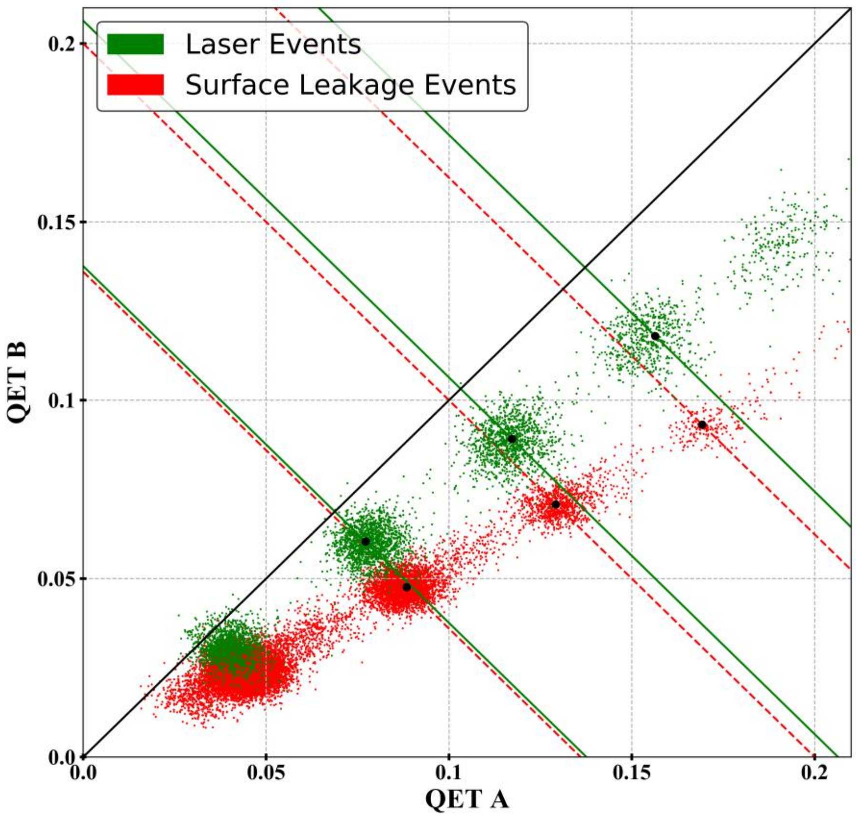


- Bi-modal distribution caused by time shifting optimal filter
- Bulk leakage events have a flat distribution between 0-1 e^-h^+ pairs
- Surface leakage events have quantized energy
- Full break down at 180 V

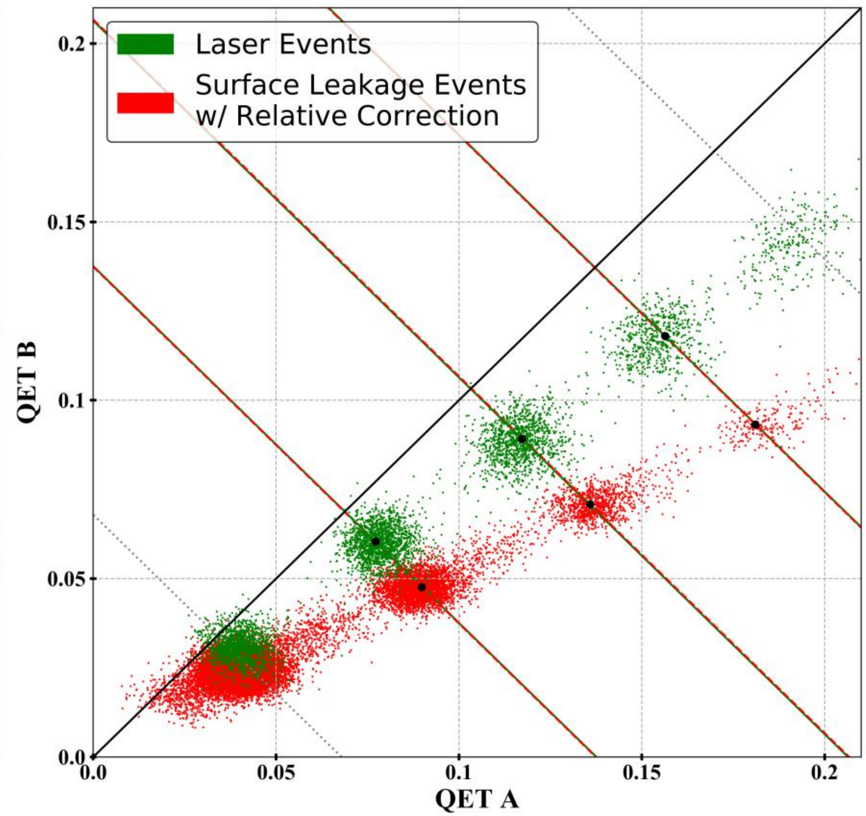
Minimize surface leakage by using ±140 V

Relative Detector Calibration

Unmatched



Matched



QET A appears to have losses requiring a 13% correction to get surface events to land on lines of equal energy with the laser