AUGUST 1, 2019 – **PHYSTAT DM**

BELINA VON KROSIGK (BELINA.VON.KROSIGK@DESY.DE)

BACKGROUND AND DETECTOR RESPONSE MODELING IN SINGLE ELECTRON-HOLE PAIR SENSITIVE CRYSTAL DETECTORS

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Emmy Noether-Programm
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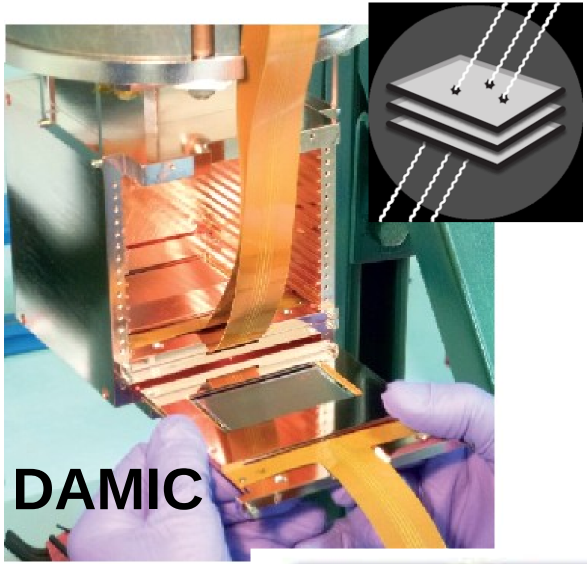
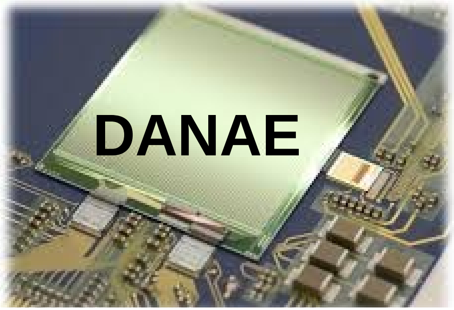
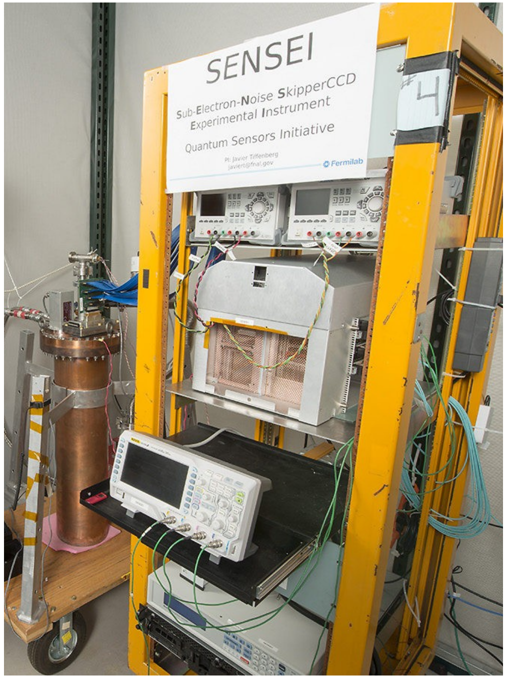
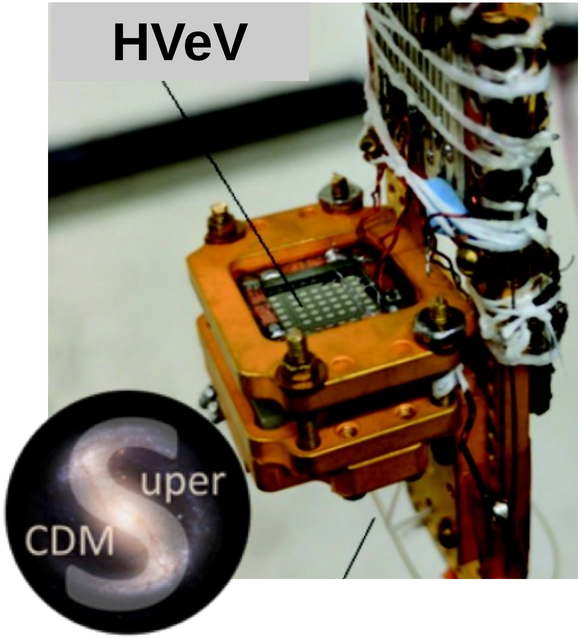
CURRENT EXPERIMENTS AND DEVICES...





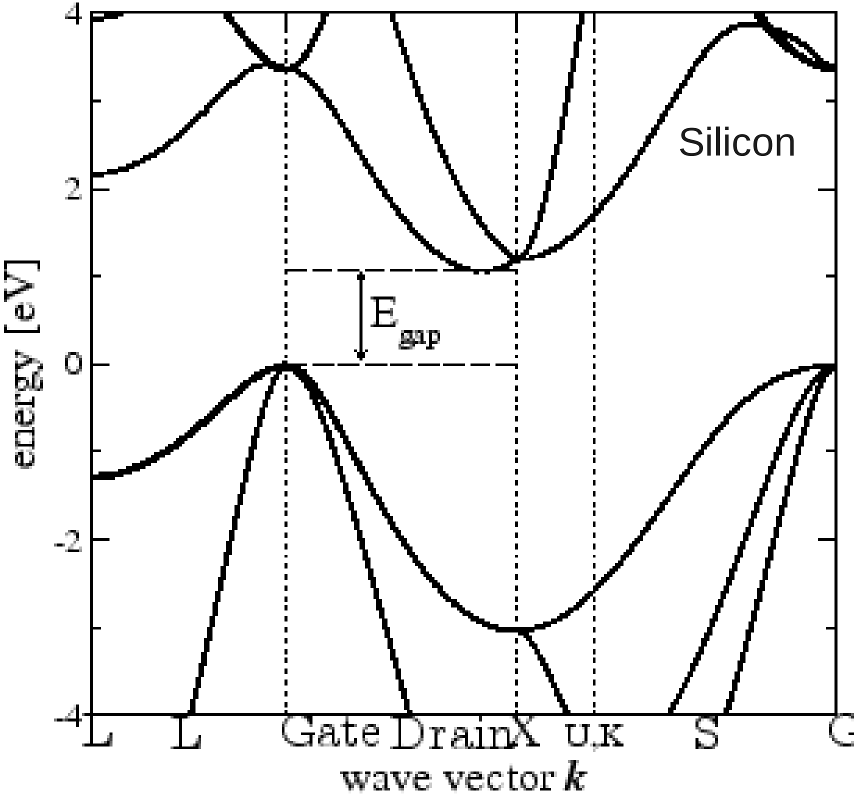




… focusing on DM searches.

SINGLE e/h PAIR SENSITIVITY (QUANTIZATION)

ENERGY SCALE



- E_{gap} ≈ 1.2 eV.
  - Indirect gap requires phonon assistance.
  - Temperature dependent.
- ε_{Si} ≈ 3.6 eV.
  - Average energy to produce e/h pair.
  - Temperature dependent.
- Sensitive to energy deposits of O(eV) (electron scattering) to O(10eV) (nuclear scattering).

ENERGY SCALE...

… in the realm of solid states physics.

Solid state physics	Particle physics
$E < 30$ eV	$E >$ keV
Multi-body system	Free particles
Allowed energies/momenta given by dispersion relation	$E = p^2/2m$
Particles may have effective masses	Particle masses well defined

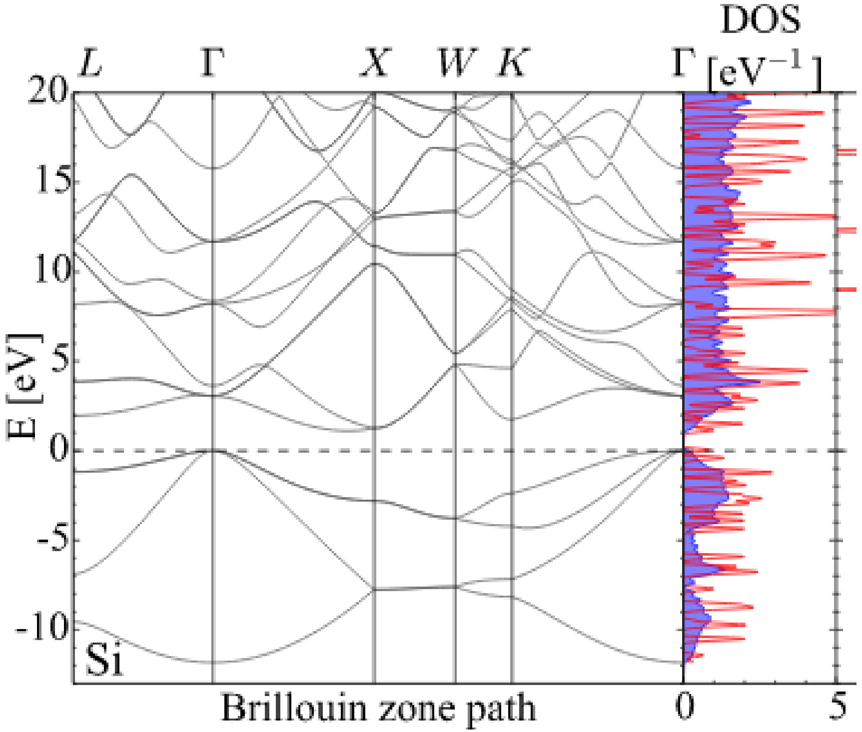
Table: A. E. Robinson

CHALLENGES

- Detector response
  - Details of the band structure become increasingly important.
  - PDF to get *n* e/h pairs given an energy deposition E_{dep} required, $P(n_{eh}|E_{dep})$.
    - Fano statistics.
    - In case of nuclear recoil: quenching (ionization yield < 1).
  - Crystal impurities can lead to partial energy deposits => events between quantization peaks.
- Backgrounds
  - Spectral information about radioactive decays at eV scale required.
    - Relevance is exposure dependent.
  - IR and optical photons are significant background at lowest energies.
  - Dark/leakage current is significant to dominant background at lowest energies.

DETECTOR RESPONSE

BOUND ELECTRONS

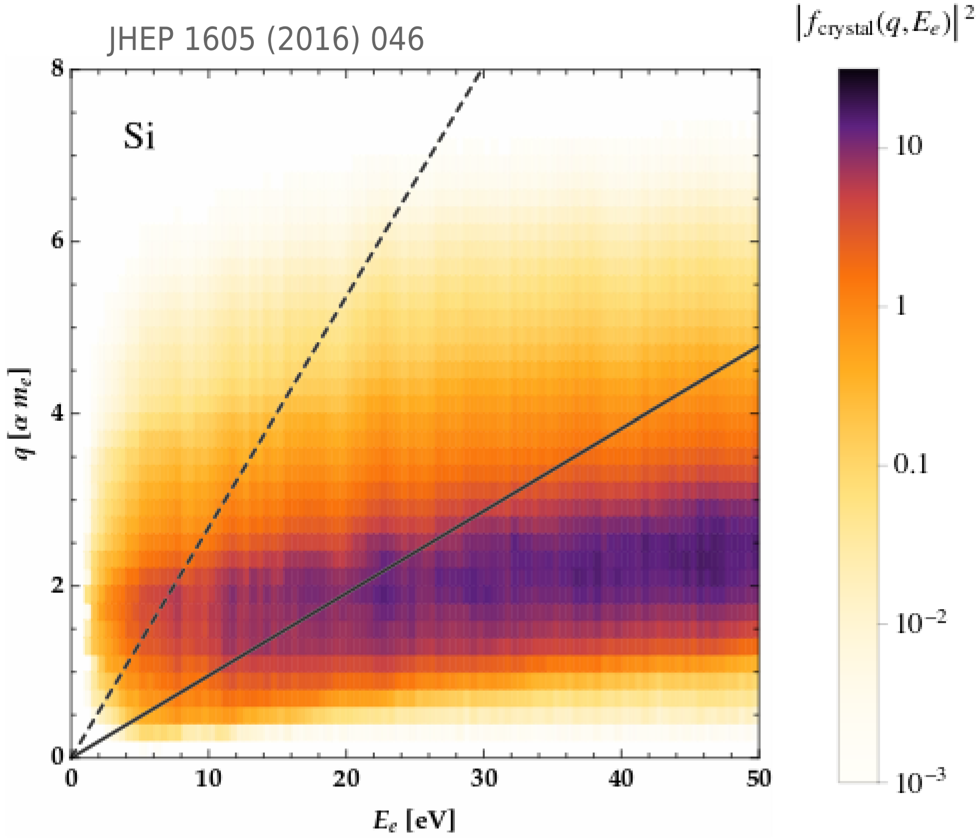


JHEP 1605 (2016) 046

- Indefinite momentum.
  - Very large momenta possible.
- Crystal lattice is complex multi-body system.
  - Valence electrons delocalized with complicated structure of energy levels.
- Scattering rates highly sensitive to energy-level structure and momentum distribution.

CRYSTAL FORM FACTOR

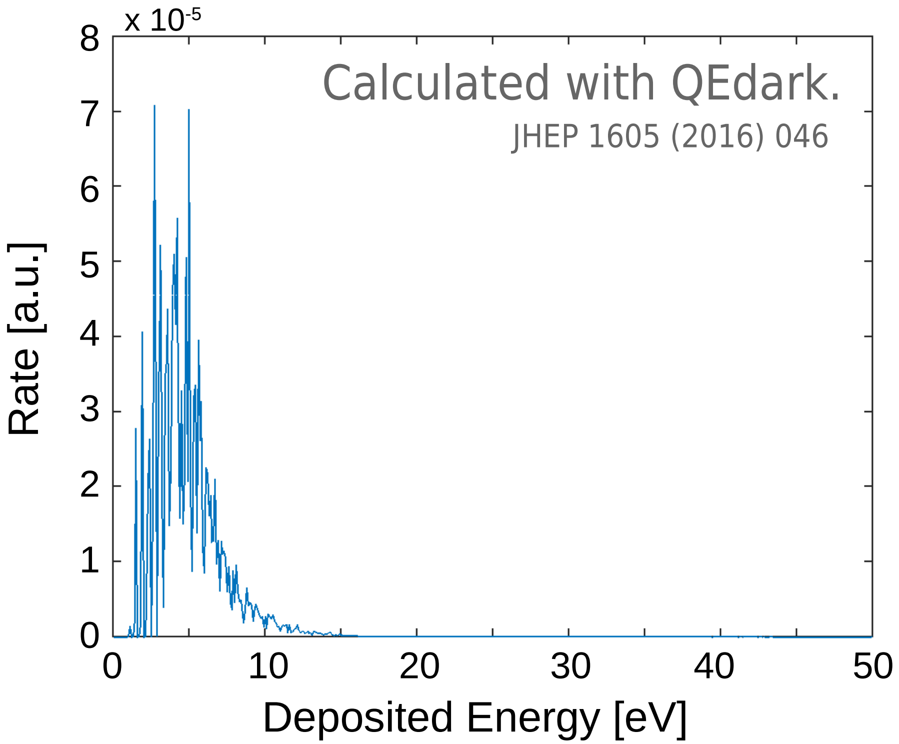
JHEP 1605 (2016) 046



- Encodes all relevant electron binding effects.
  - q: Momentum transfer.
  - E_e: Energy transferred to the electron.
- Numerical approximation up to 52^{nd} conduction band.
  - Covering energy transitions up to ~57 eV.
  - Enough for DM-e^- scattering processes.
  - Not necessarily enough for other processes.

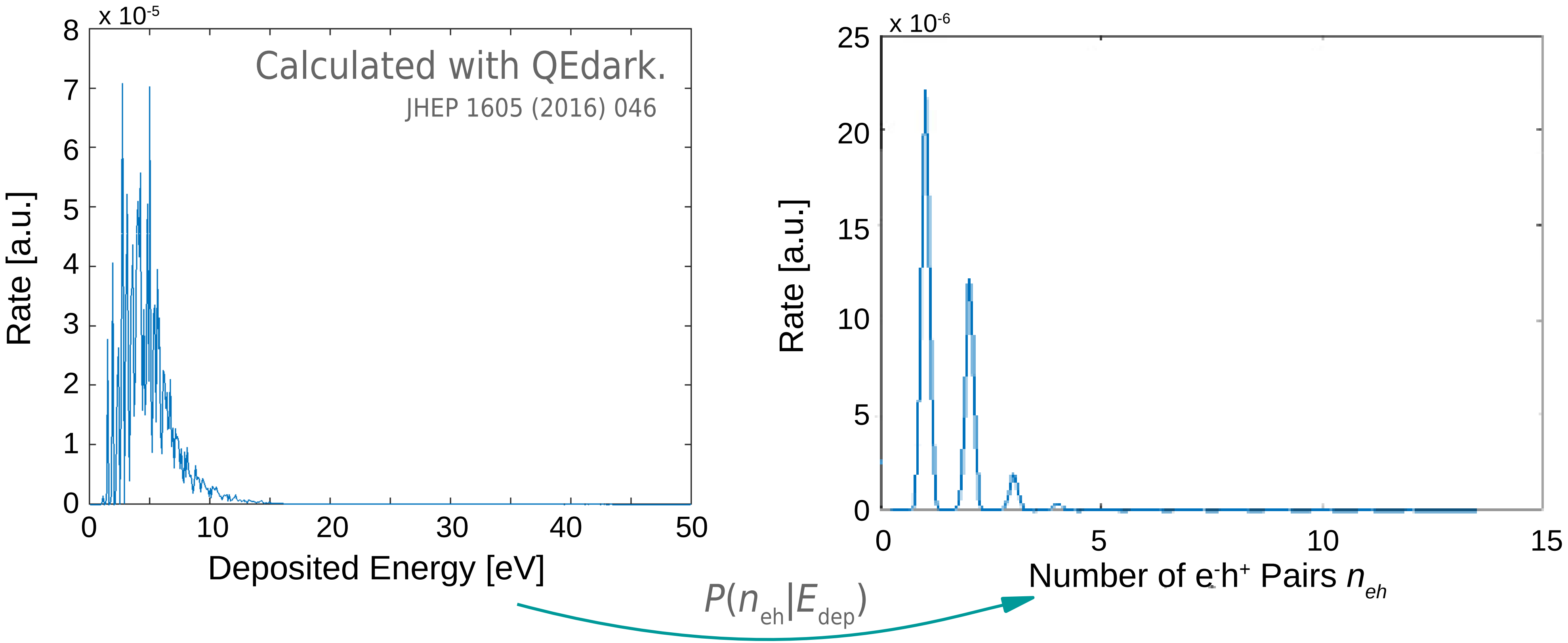
ELECTRON RECOIL SIGNAL MODEL, AN EXAMPLE

500 MeV DM scattering off electron ($F_{DM} = 1$).



FROM CONTINUOUS TO QUANTIZED SPECTRUM

500 MeV DM scattering off electron (F_{DM} = 1).



IONIZATION PDF $P(n_{\text{eh}}|E_{\text{dep}})$

- Most simple model ignores Fano term:

$$n_{\text{eh}} = 1 + \lfloor (E_e - E_{\text{gap}})/\varepsilon \rfloor$$

- Still simple, but with Fano term (see this link for more details):

$$\langle n_{\text{eh}}(E_e)\rangle = \begin{cases} 0 & E_e < \epsilon_{gap} \\ 1 & \epsilon_{gap} < E_e < \epsilon_{\text{eh}} \\ E_e/\epsilon_{\text{eh}} & \epsilon_{\text{eh}} < E_e \end{cases}$$

Delta functions (first two cases)

Discrete distributions generated with Fano factor F (third case)

$$F = \frac{\sigma^2}{\langle n_{\text{eh}}\rangle}$$

- Ideally calculate more accurately or measure.

IONIZATION PDF $P(n_{eh}|E_{dep})$

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→ Delta functions (first two cases)

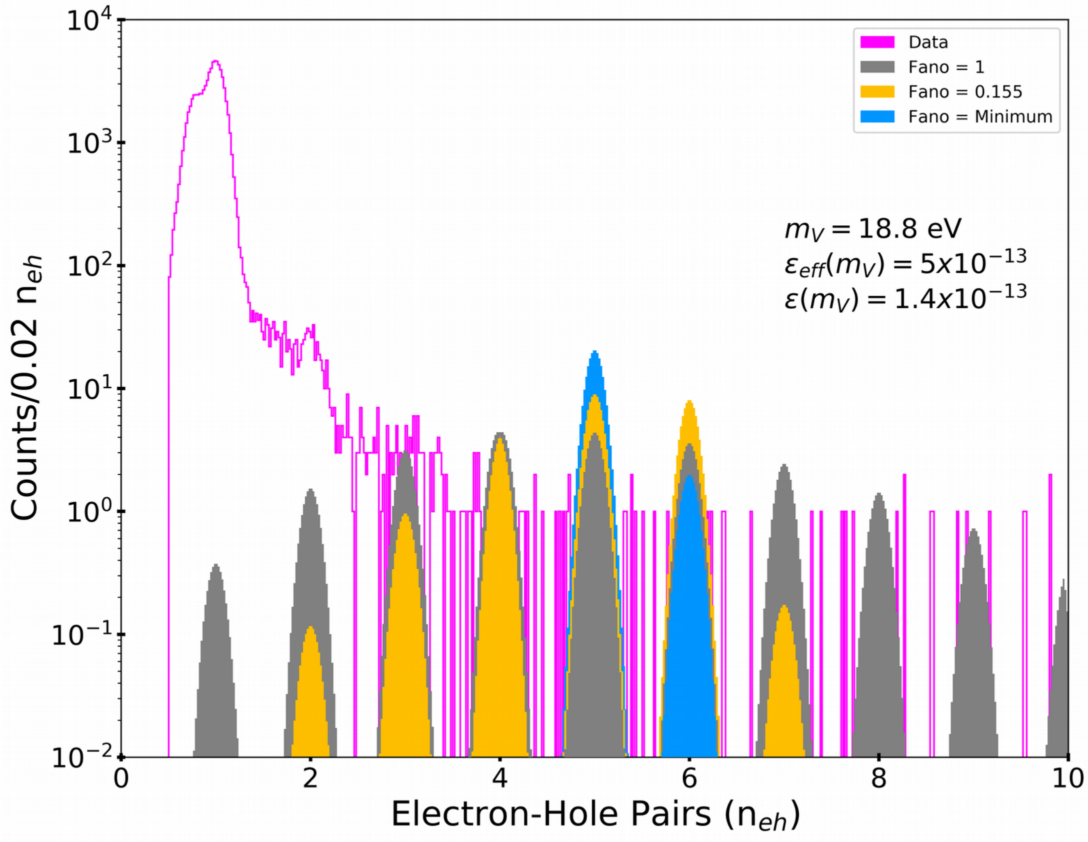
→ Discrete distributions generated with Fano factor F (third case)

$$F = \frac{\sigma^2}{\langle n_{eh} \rangle}$$

Efforts ongoing!

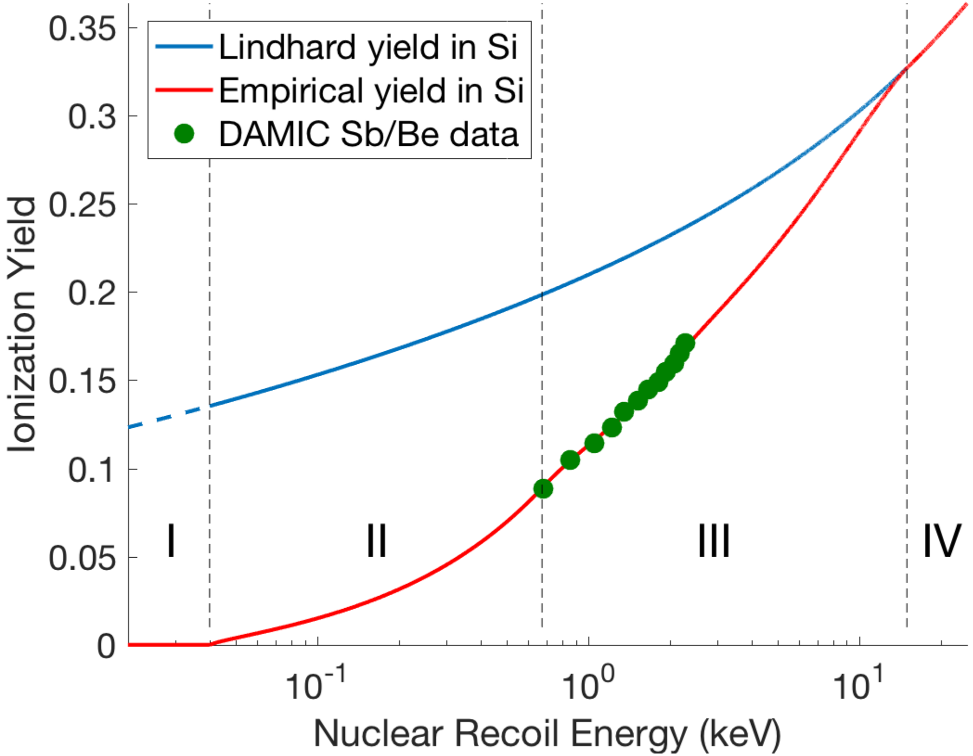
- Ideally calculate more accurately or measure.

IONIZATION PDF $P(n_{eh}|E_{dep})$



RESPONSE TO NUCLEAR RECOILS

Phys. Rev. D 95, 082002 (2017),
Phys. Rev. D 94, 082007 (2016)



- Semi-empirical Lindhard theory
  - Not in agreement with low energy data.
  - No data available below ~ 0.7 keV nuclear recoil energy (≙ 60 eV electron equivalent energy).
- Fano noise in ionization signal for low energy nuclear recoils unknown in silicon.

CRYSTAL IMPURITIES

- Detector response or background?
- Occurrence and significance depends on detector design.

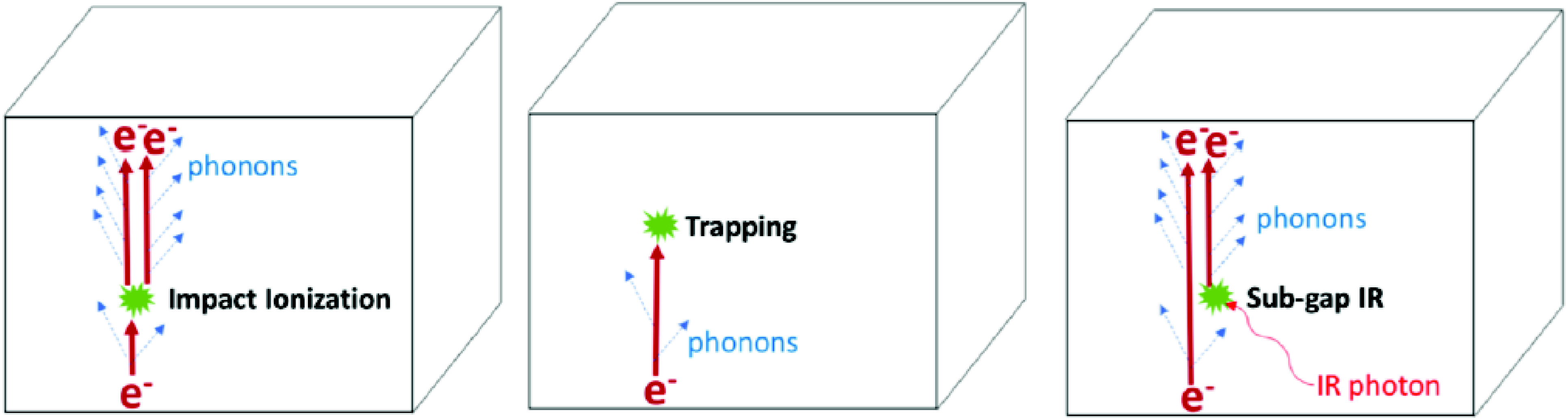
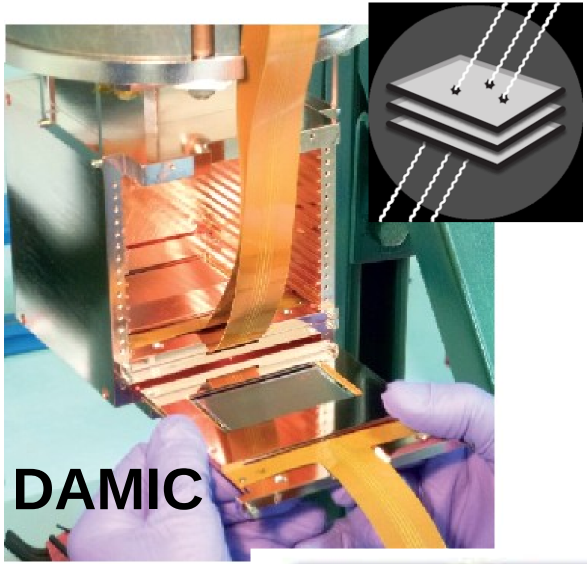
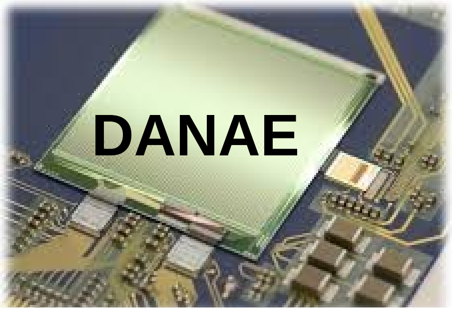


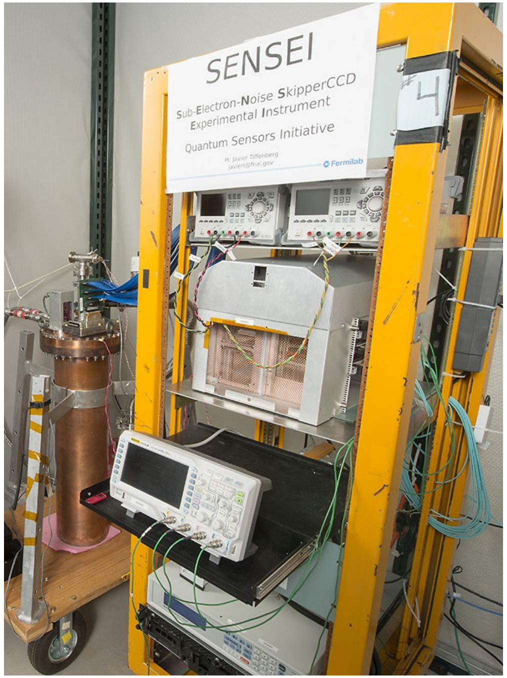
Figure: R. K. Romani

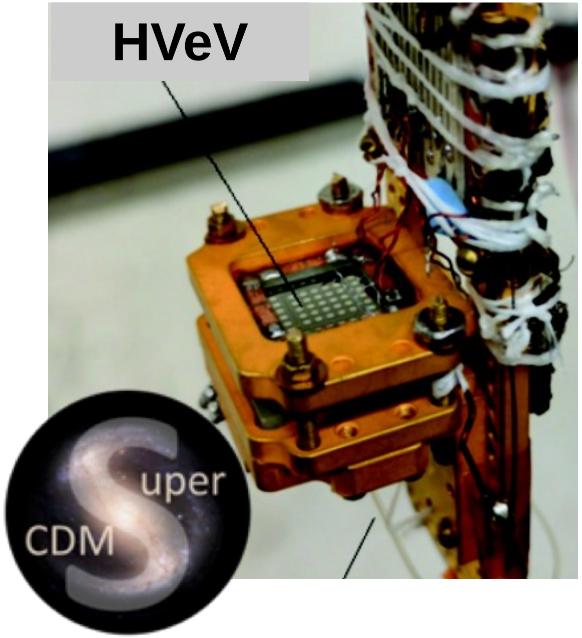
DOMINANT BACKGROUNDS (AFTER ANALYSIS CUTS)

CURRENT EXPERIMENTS AND DEVICES...



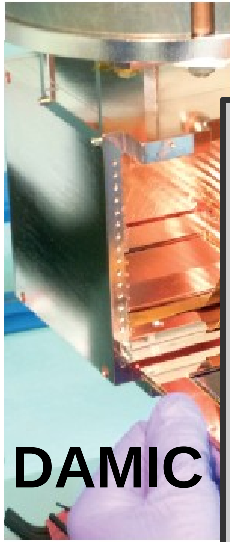


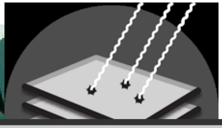


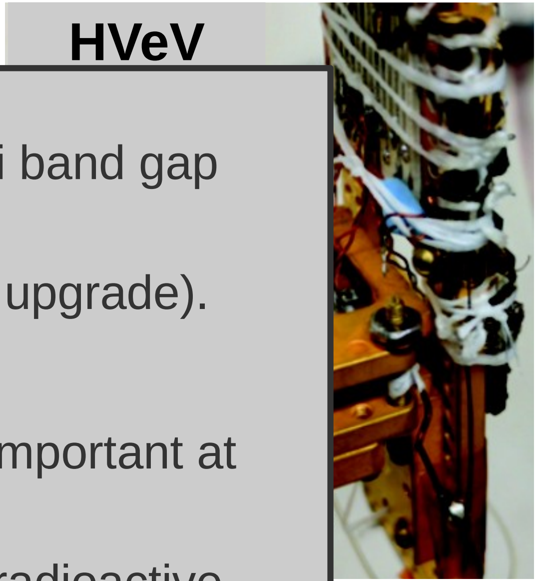


… focusing on DM searches.

CURRENT EXPERIMENTS AND DEVICES...

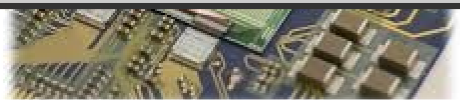






- All capable of reaching ~1-3 eV energy threshold (Si band gap at ~1.2 eV).
- All capable of reaching resolution of < $1e^-$ (now or in upgrade).

- All subject to dark counts, a “background” that isn’t important at higher thresholds.
- At small exposures typical backgrounds (neutrinos, radioactive decays, …) not the dominating background source.

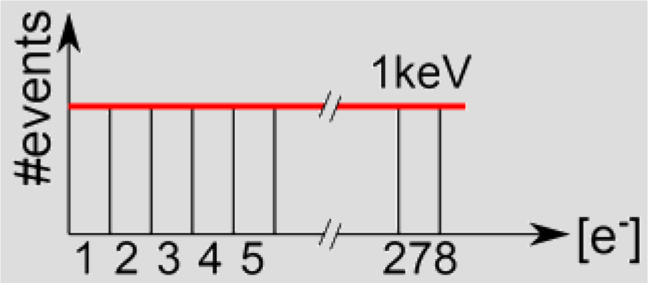


… focusing on DM searches.

EXEMPLARY PARTICLE BACKGROUND ESTIMATE

- Assuming exposure of 100 g years = 36.5 kg days.
- Assuming DAMIC background:
  - 5 DRU (events/kg/day/keV) in the 0-1 keV range.

    → N_{bkg} = **36.5** kg days x **5** DRU = **182.5** events.
  - Dominated by external gammas → **flat Compton spectrum.**

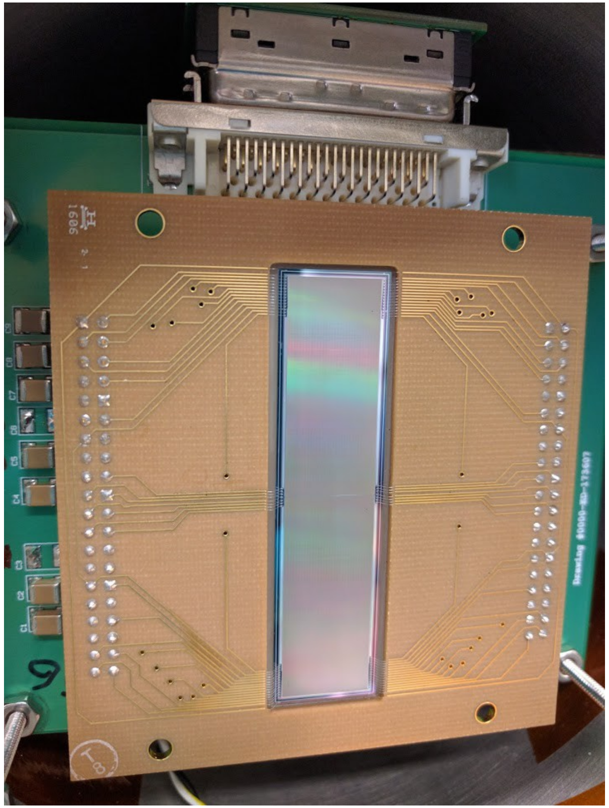


- 182.5 events over 1000 eV / ε_{Si} = 278 electron bins (ε_{Si} = 3.6 eV).

  → **Expect 0.65 bkd events per electron bin.**

DARK COUNTS / DARK CURRENT

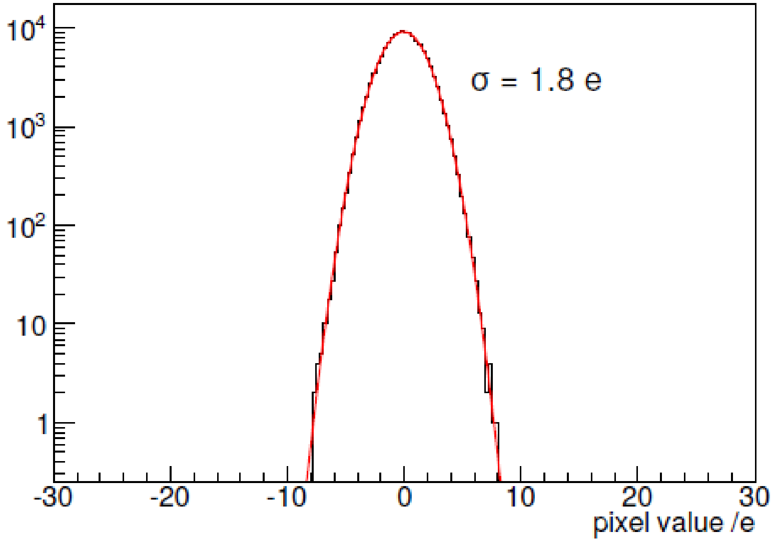
SENSEI



- Skipper-CCD prototype designed at LBL MSL.
- 200 & 250 μm thick, 15 × 15 μm^2 pixel size.
- Two form factors 4k x 1k (0.5 g) & 1.2k x 0.7k pixels.
- Parasitic run, optic coating and Si resistivity ~10 kΩ.
- 4 amplifiers per CCD, three different RO stage designs.

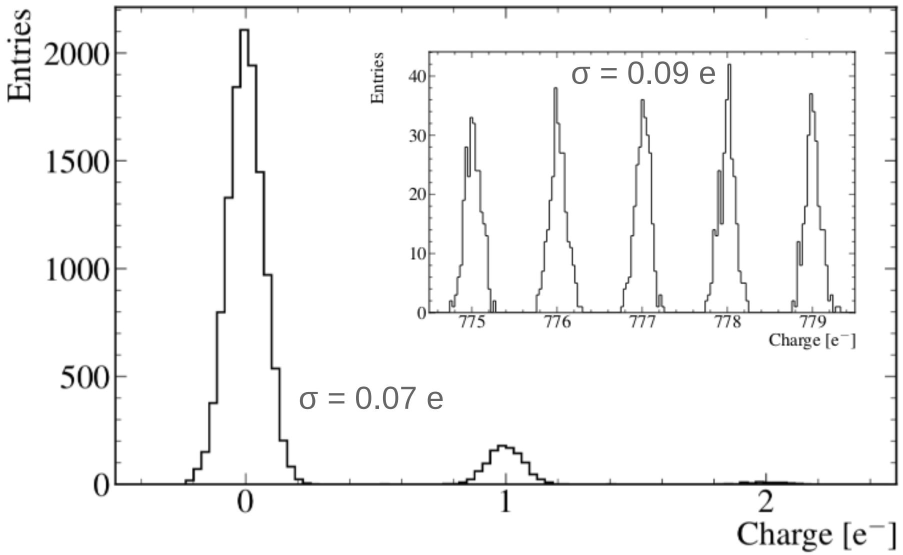
SENSEI

Readout noise, regular scientific CCD.



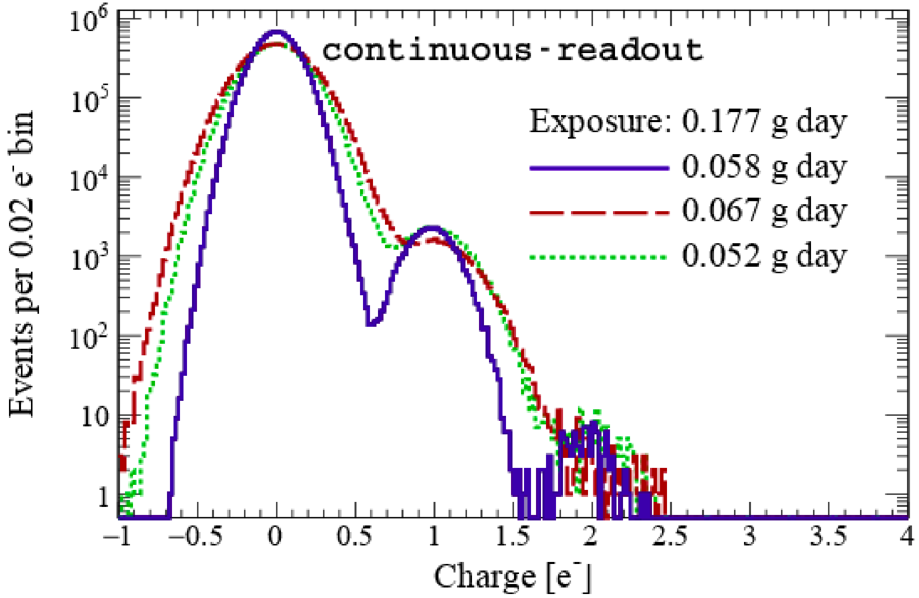
Sub-electron noise with skipper readout.

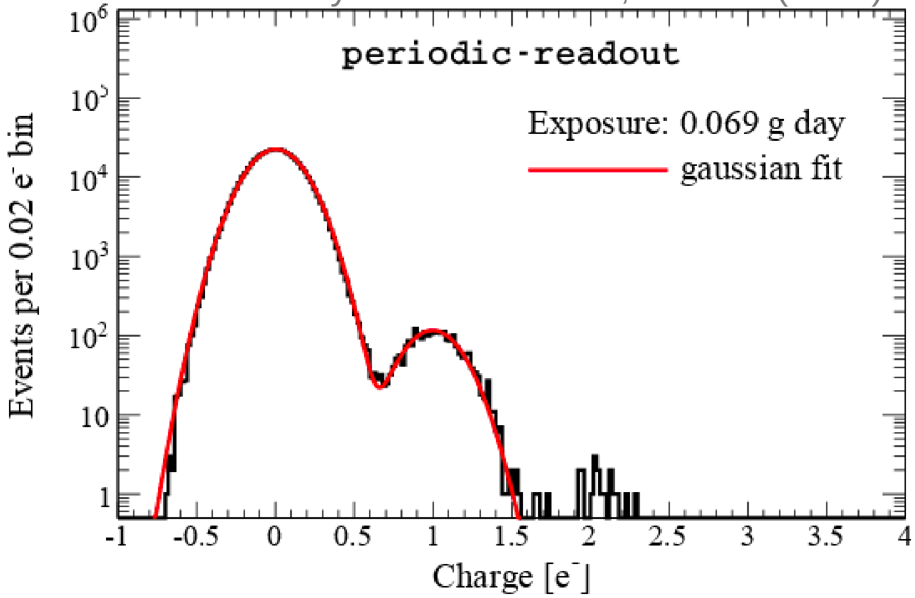
J. Tiffenberg *et al*, Phys. Rev. Lett. **119**, 131802 (2017) [arXiv:1706.00028]



SENSEI

Phys. Rev. Lett. 122, 161801 (2019)

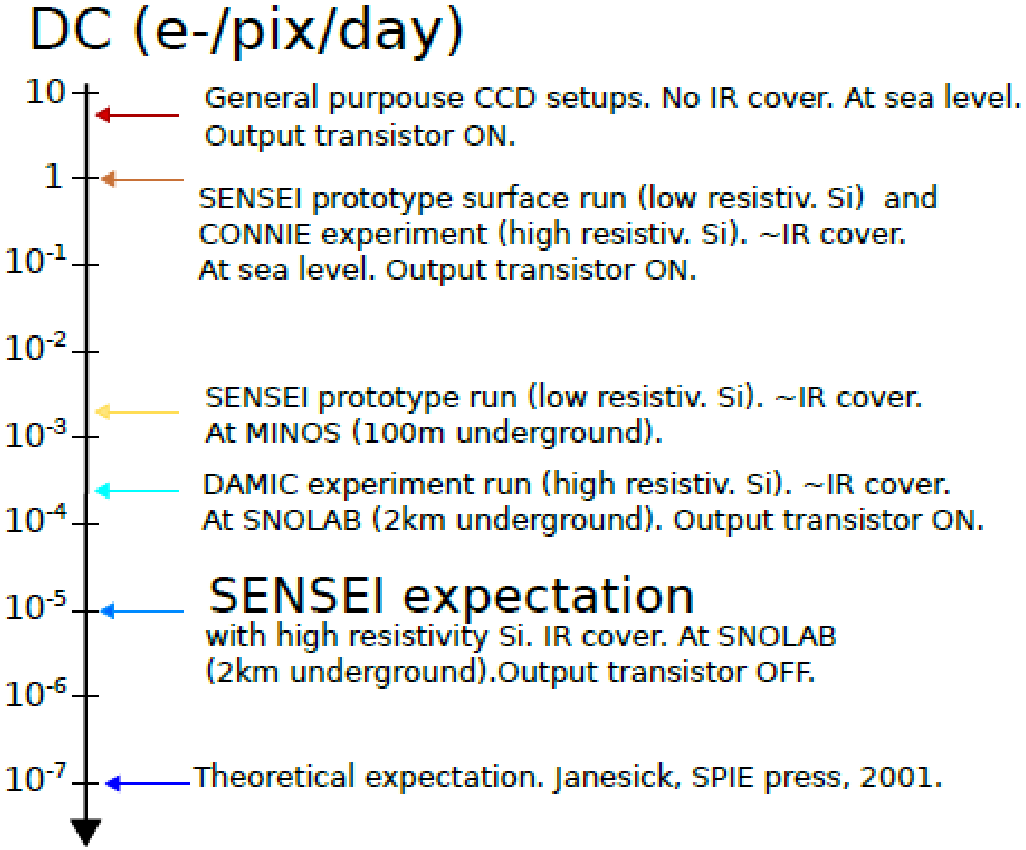




Dark Current $[e^- pix^{-1} day^{-1}]$	$\geq 1e^-$ [pix]	$\geq 2e^-$ [pix]	$\geq 3e^-$ [pix]
10^{-5}	1×10^{6}	3×10^{-1}	7×10^{-8}

Table:
G. Fernandez Moroni

SENSEI IN COMPARISON WITH OTHER CCD SETUPS



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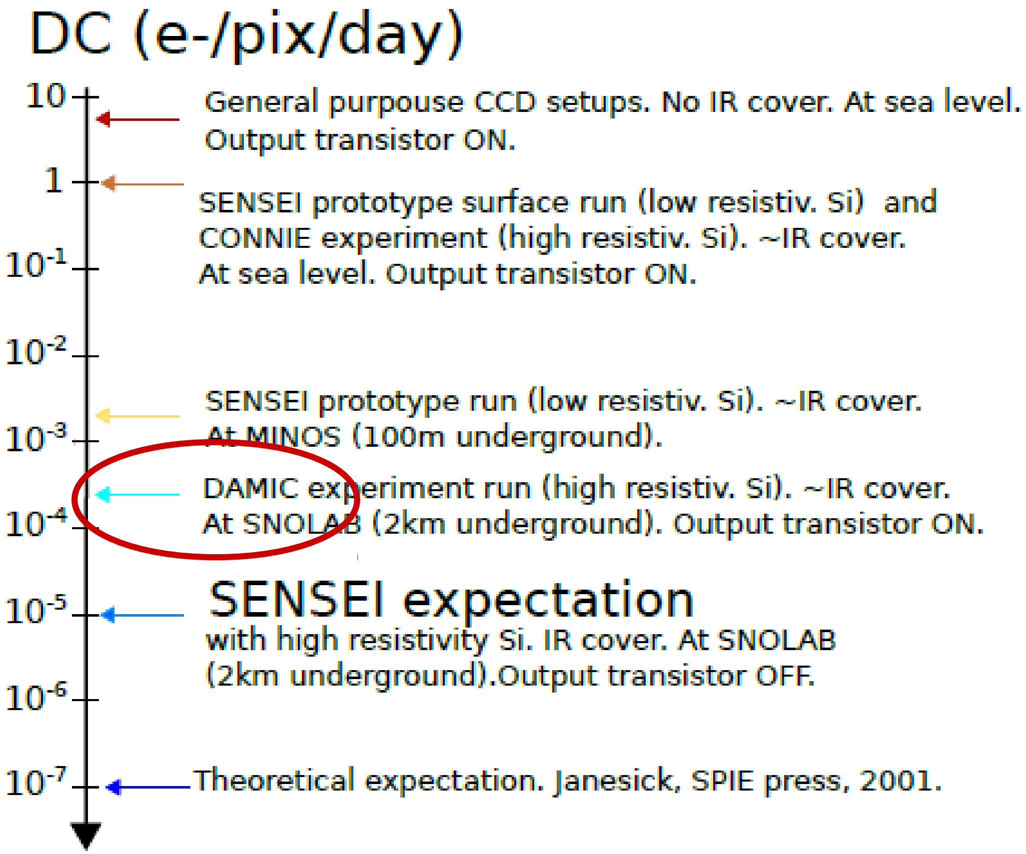
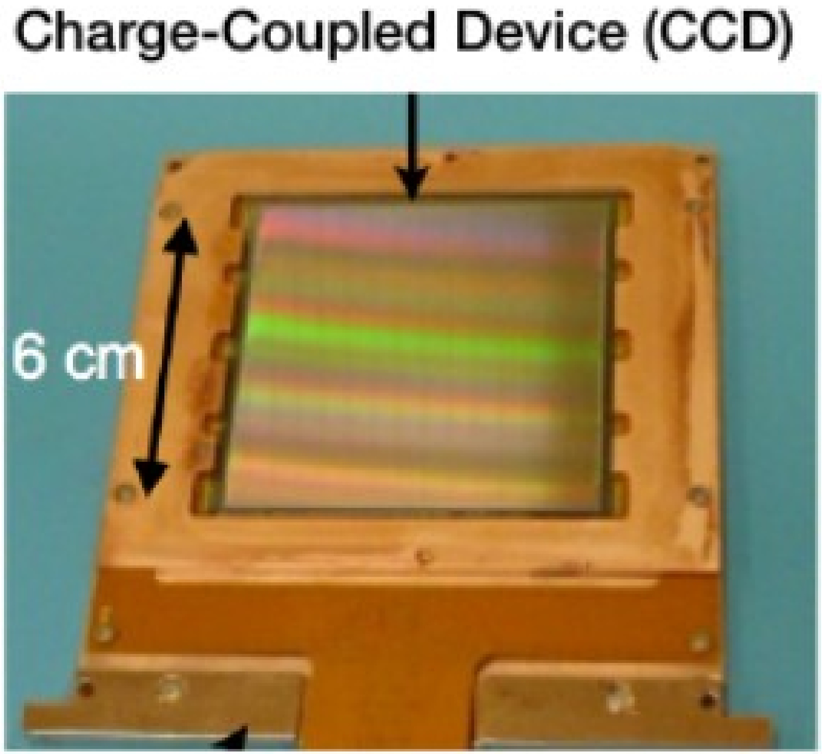


DAMIC-SNOLAB

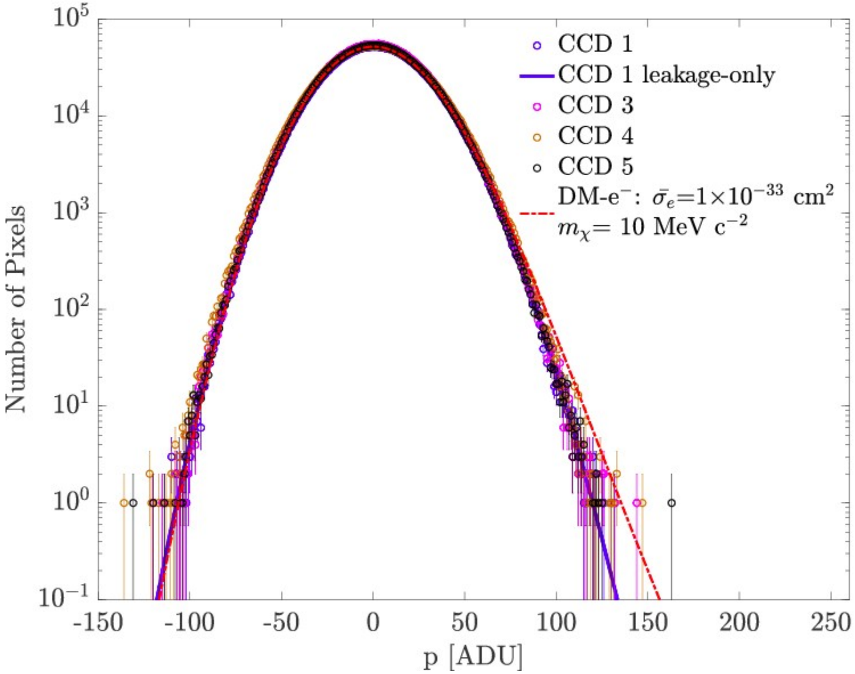


- 7 fully depleted CCDs.
- Each 675 μm thick, 15 × 15 μm^2 pixel size.
- Each 4k x 4k pixels (6.0 g).
- $\sigma \approx 2\ e^-$ => not yet single e/h pair sensitive.
  - DAMIC-M will use skipper readout => $\sigma < 1\ e^-$.
- But lowest dark current to date:

9×10^{-4} e/pix/day or $2\text{-}6 \times 10^{-22}$ A cm^{-2}.

DAMIC-SNOLAB

arXiv:1907.12628

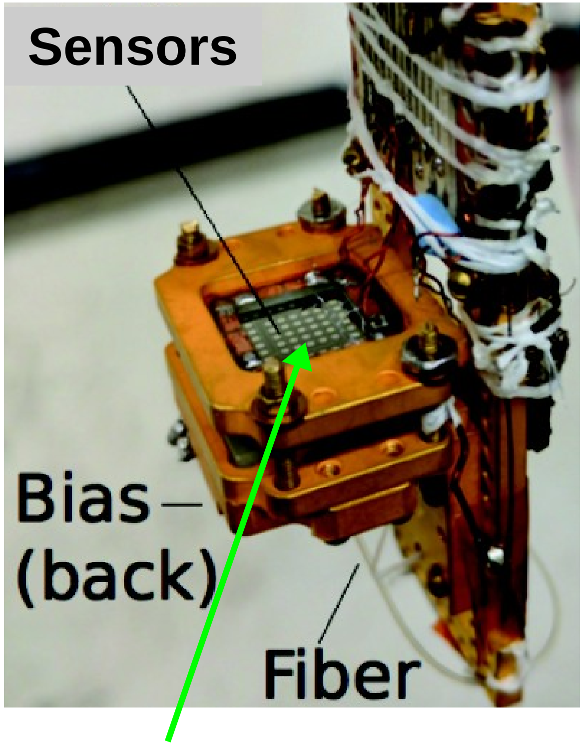


- 7 fully depleted CCDs.
- Each 675 µm thick, 15 × 15 µm^2 pixel size.
- Each 4k x 4k pixels (6.0 g).
- σ ≈ 2 e$^-$ => not yet single e/h pair sensitive.
  - DAMIC-M will use skipper readout => σ < 1 e$^-$.
- But lowest dark current to date:

$9\text{x}10^{-4}$ e/pix/day or 2-6×10^{-22} A cm^{-2}.

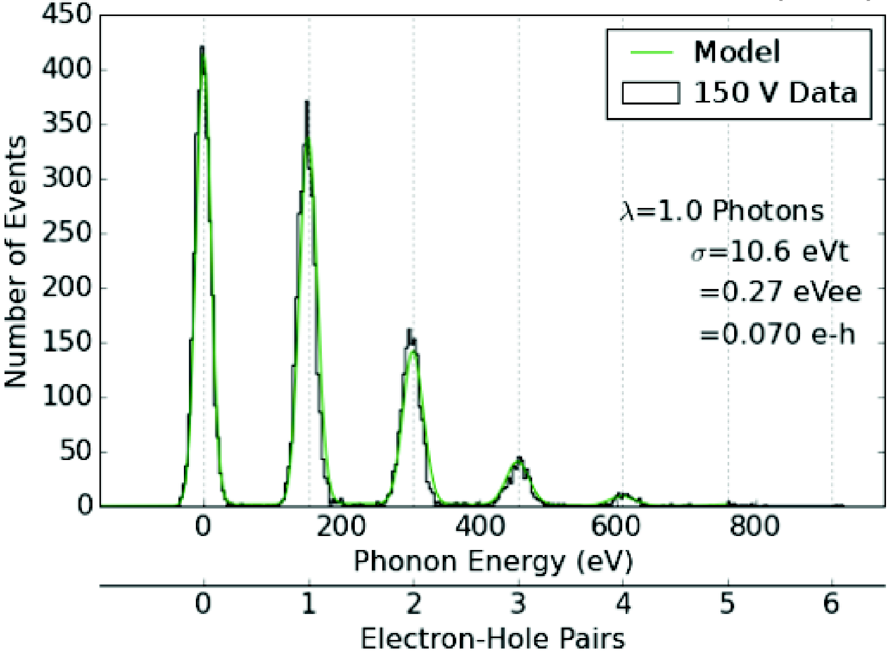
SuperCDMS HVeV PROTOTYPE R&D DETECTOR

Appl.Phys.Lett. 112 (2018) 043501



Si crystal (1 cm^2 x 4 mm, 0.93 g)

Laser Data PRL 121, 051301 (2018)



- Sensitivity to single e-h+ pairs in Si crystal with phonon sensors.

CRYSTAL IMPURITIES

- Detector response or background?
- Occurrence and significance depends on detector design.

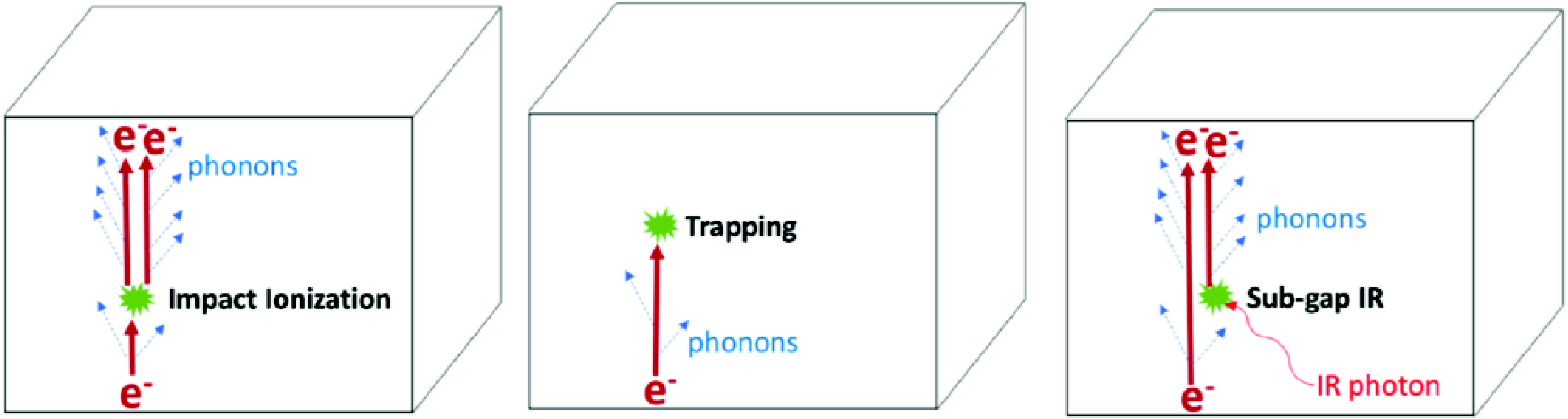
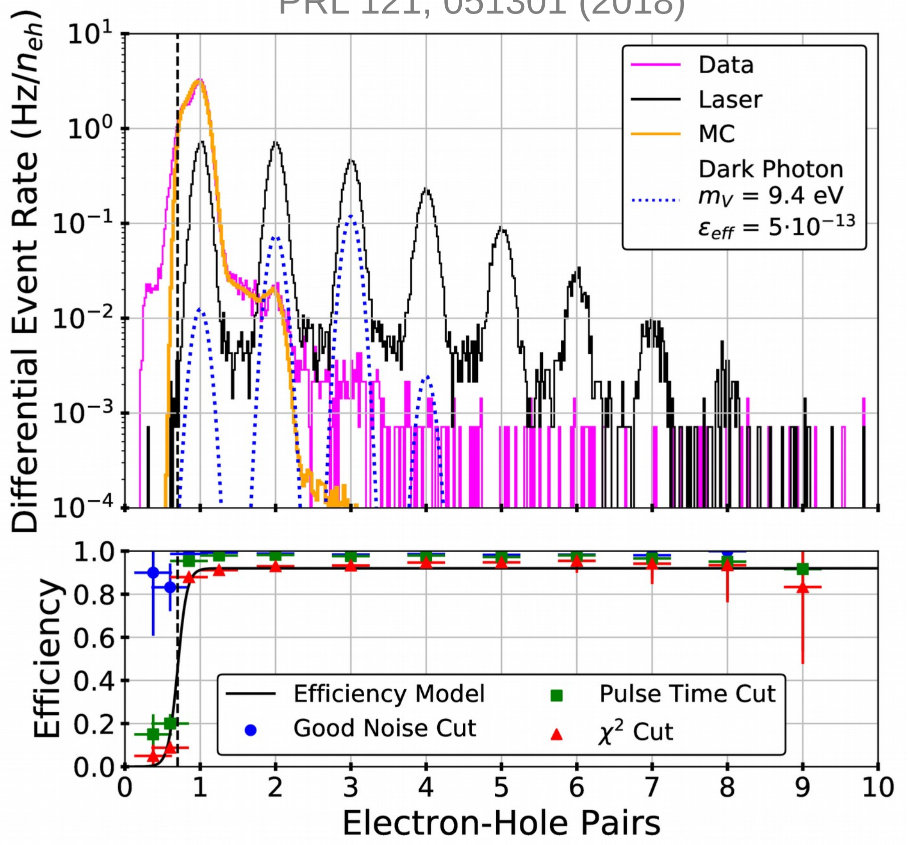


Figure: R. K. Romani

SuperCDMS HVeV PROTOTYPE R&D DETECTOR

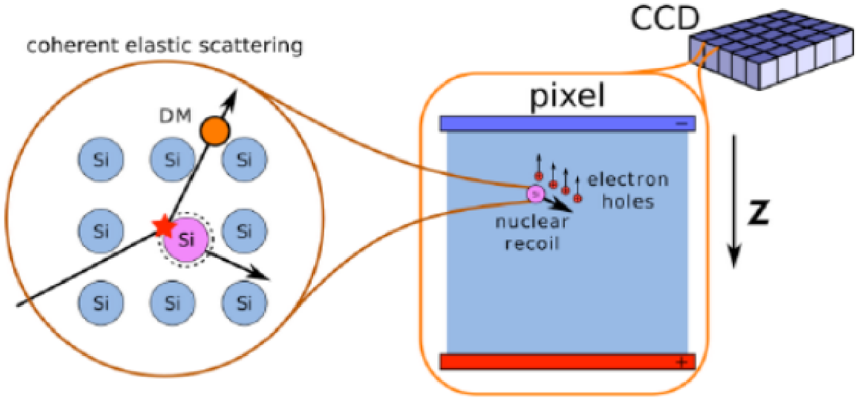
PRL 121, 051301 (2018)



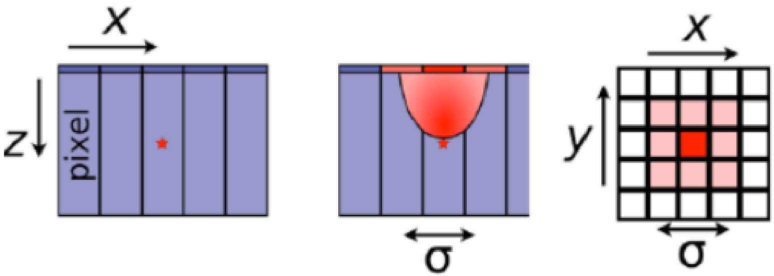
- Background consistent with IR leakage at low energies.
- High-energy tail was not anticipated,
  - Could be due to coherent scattering component or instrumental background.
- Dark current of ~10^{-18}A cm^{-2}
- Used Optimum Interval method for limit setting accepting full background hit in peak regions.
  - Notable improvement possible already with same data set.

ADDITIONAL INFORMATION

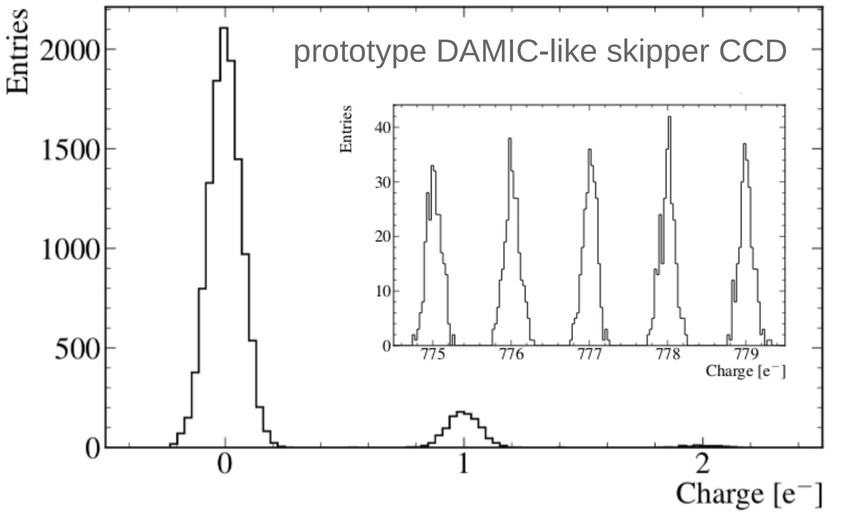
DAMIC-M (DAMIC at MODANE)



3.7 eV to create e-h pair



J. Tiffenberg *et al*, Phys. Rev. Lett. **119**, 131802 (2017) [arXiv:1706.00028]



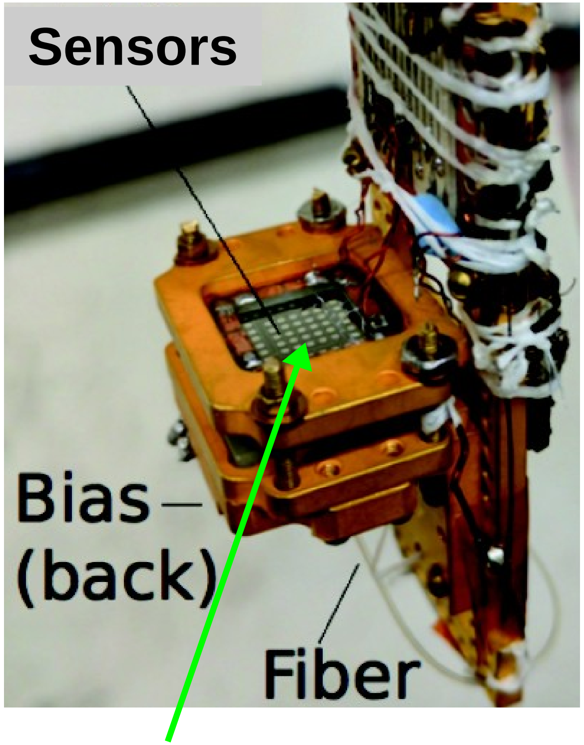
- DAMIC-M CCD: 6k x 6k pixels over 9x9 cm^2 with 1 mm thickness (20 g of mass).

  => 3x more massive than SNOLAB CCDs.

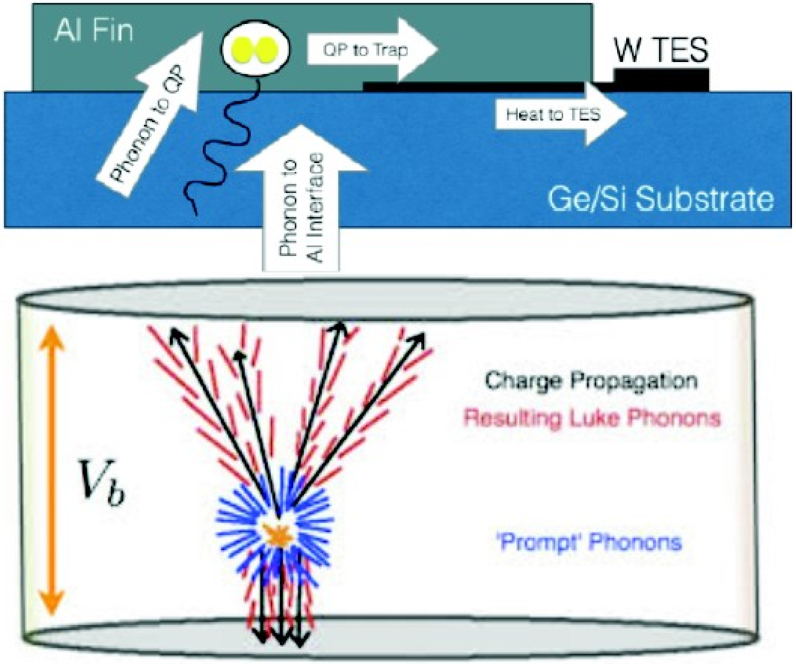
- Integration of “skipper” readout scheme.

SuperCDMS HVeV
PROTOTYPE R&D DETECTOR

R.K. Romani et al., Appl.Phys.Lett. 112 (2018) 043501

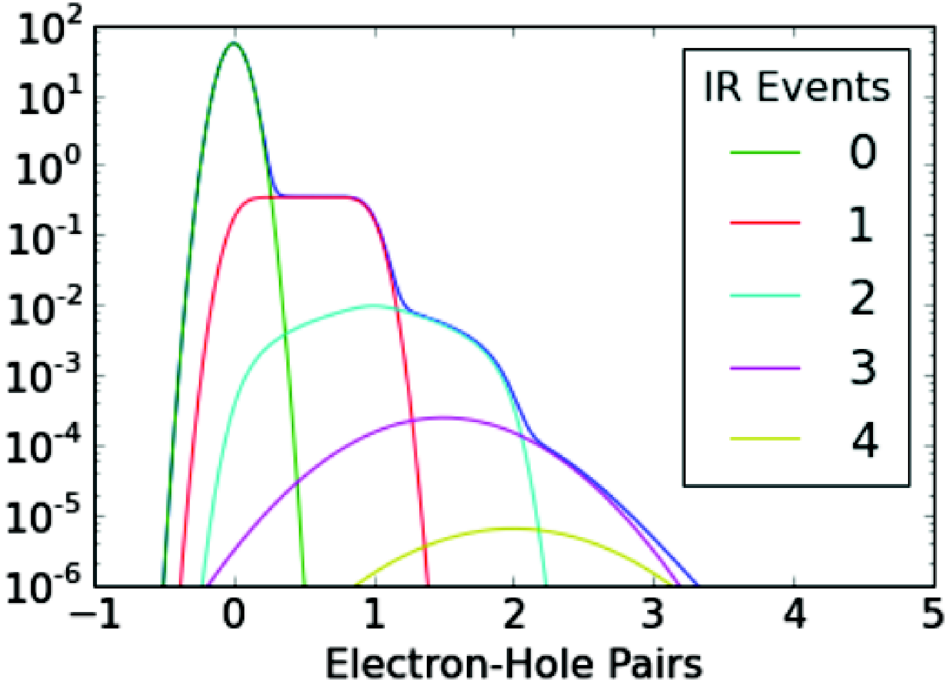


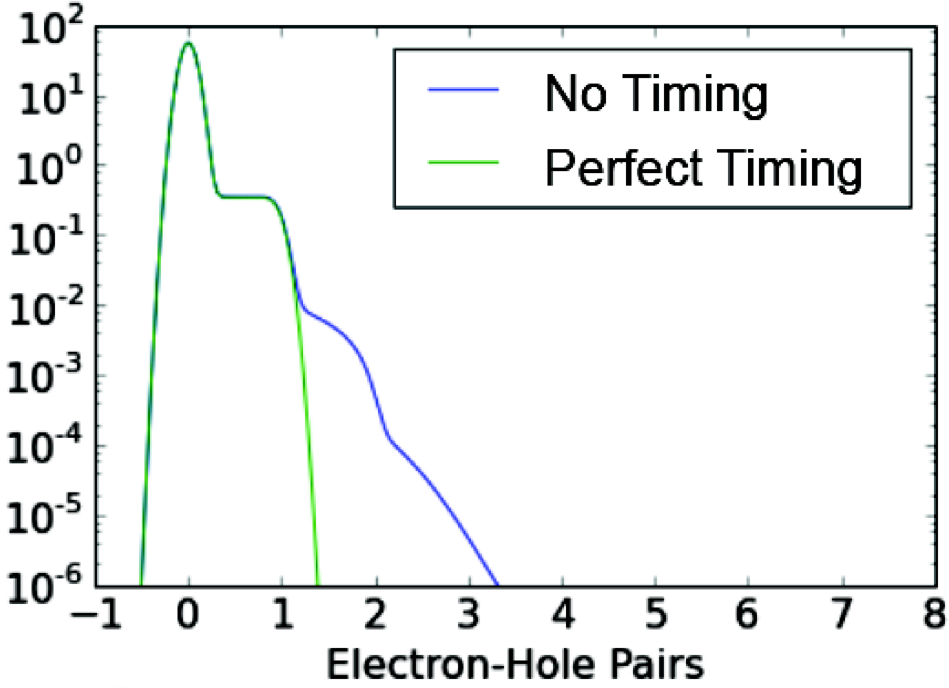
Si crystal (1cm^2 x 4mm, 0.93 g)



- Sensitivity to single e-h+ pairs in Si crystal with phonon sensors.

SuperCDMS HVeV
NON-QUANTIZED BACKGROUNDS: IR

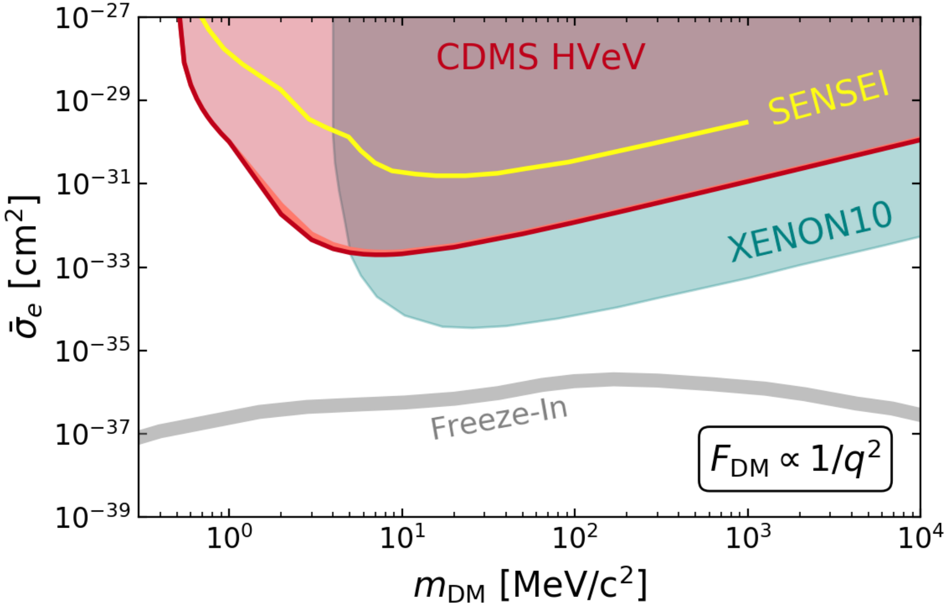


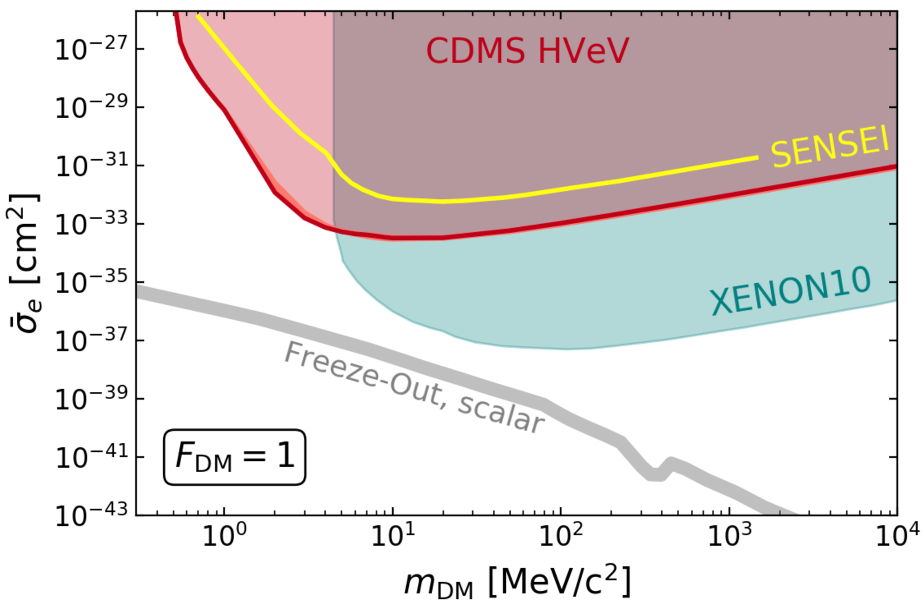


$$\Gamma \propto n_{imp} E_{imp}^3 e^{-\frac{E_{imp}}{k_b T}}$$

SURFACE LIMITS WITH SILICON DEVICES

PRL 121, 051301 (2018)





- Salmon band in HVeV limit due to varying the Fano term.