Time resolution of SI detectors for direct LDM detection

IDM 2026, Zaragoza

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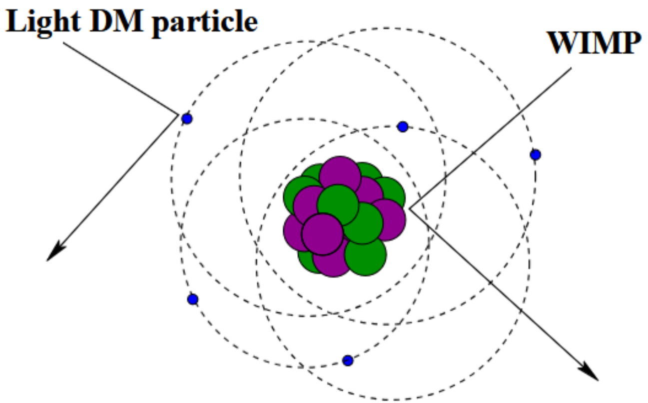
Direct Detection – Light Dark Matter

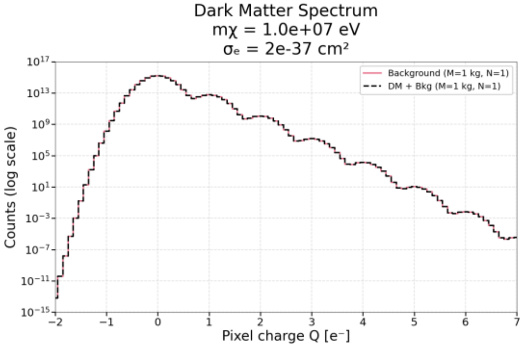
- Electron recoils in semiconductor targets
- Electrons treated as **bound** and **not at rest**
- Single-electron signal regime



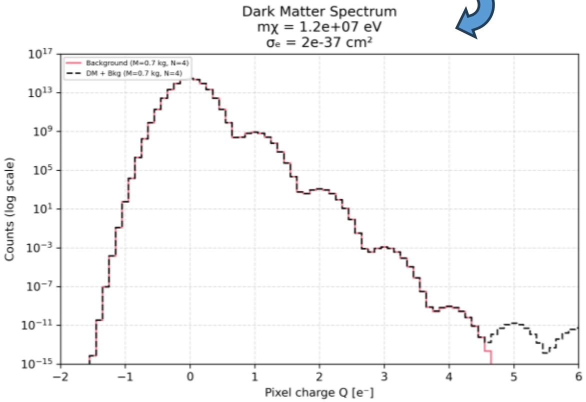
[Fernandez Moroni, TAUP 2023]

Why readout timing matters

- Single-electron sensitive detectors are background limited
- Background electrons accumulate during one frame
- Multiple background electrons appear as higher-electron events
- Signal/background separation becomes difficult



4x faster readout



Detector concepts

Skipper CCDs

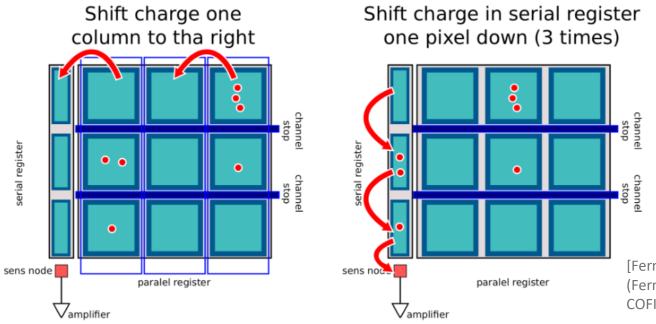
- Ultra-low background
- Long frame times

RNDR-DEPFETs (DANAE)

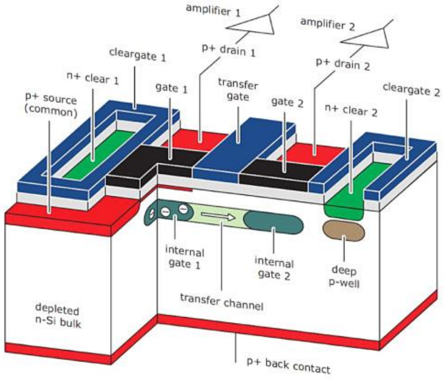
- Higher background
- Faster effective readout

- "Higher background" + "faster readout" ⇒ "reduced occupancy“
- DANAE uses fast readout to compensate higher generation rates

Goal: approach Skipper-like occupancy conditions



[Fernandez Moroni & Estrada (Fermilab), COFI seminar, 2020]



Thermal background generation rate

λ_{dark}

- Physical thermal generation of charge carriers
- Dominant intrinsic detector background source
- Simulation input parameter:

$$\mathrm{e}^{-}\ \mathrm{pix}^{-1}\ \mathrm{day}^{-1}$$

- Converted to:

$$\mathrm{e}^{-}\ \mathrm{kg}^{-1}\ \mathrm{day}^{-1}$$

in most plot legends for detector comparison

Background model

- Poissonian background assumption
- Background electrons sampled independently per pixel and frame

Frame time and readout scaling

t_{frame}

- Effective accumulation duration per frame
- Longer frame times increase pile-up probability

N_{nodes}

- Phenomenological parallelization parameter
- Larger N_{nodes} →faster effective readout
- Reduces effective frame time
- Can be equated to # of amplifyers

$$N_{\text{nodes}} \uparrow \Rightarrow t_{\text{frame}} \downarrow$$

Relevant detector parameters:

- λ_{dark} defines the intrinsic background generation rate
- N_{nodes} modifies the effective frame time

- The resulting frame time is applied to the generation rate

- λ_{frame} becomes the central simulation parameter
- Used as the Poisson expectation value for background generation per pixel and frame

$$\lambda_{\text{frame}} = \lambda_{\text{dark}} \cdot t_{\text{frame}}$$

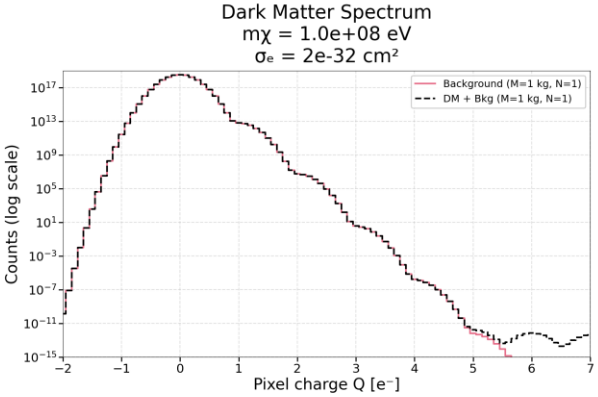
$$t_{\text{frame}} \propto \frac{1}{N_{\text{nodes}}}$$

$$\lambda_{\text{dark}} \uparrow \Rightarrow \lambda_{\text{frame}} \uparrow$$
$$t_{\text{frame}} \uparrow \Rightarrow \lambda_{\text{frame}} \uparrow$$

Trade-Off: Background rate and frame time

- **High** background generation rate
- **Short** effective frame time

$\lambda_{\text{dark}} \uparrow + t_{\text{frame}} \downarrow \Rightarrow \lambda_{\text{frame}}$ *comparable*

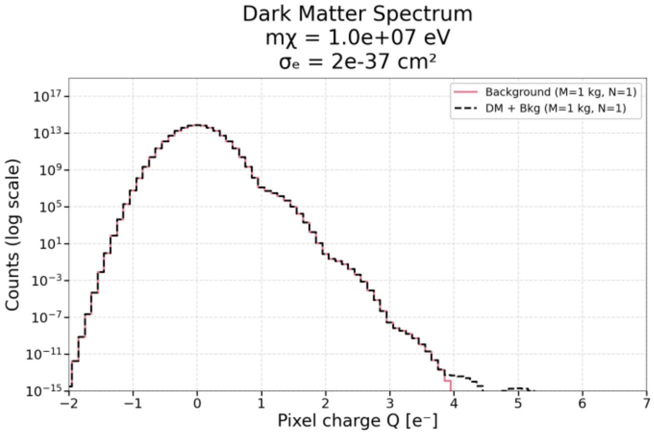


$m\chi = 1.0 \times 10^{8}$ eV

$\sigma_e = 2 \times 10^{-32}$ cm²

- **Low** background generation rate
- **Long** effective frame time

$\lambda_{\text{dark}} \downarrow + t_{\text{frame}} \uparrow \Rightarrow \lambda_{\text{frame}}$ *comparable*



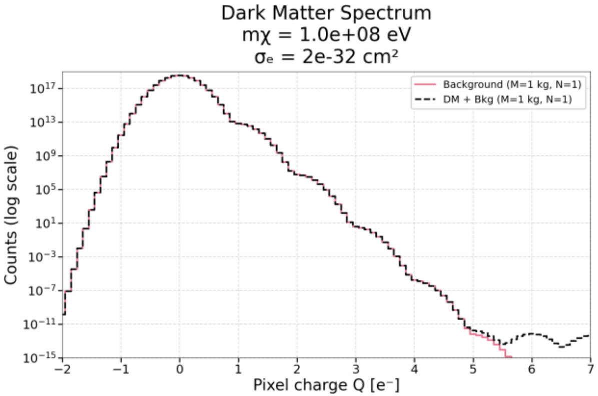
$m\chi = 1.0 \times 10^{8}$ eV

$\sigma_e = 2 \times 10^{-37}$ cm²

Trade-Off: Background rate and frame time

- **High** background generation rate
- **Short** effective frame time

$\lambda_{\text{dark}} \uparrow + t_{\text{frame}} \downarrow \Rightarrow \lambda_{\text{frame}}$ *comparable*



- **Low** background generation rate
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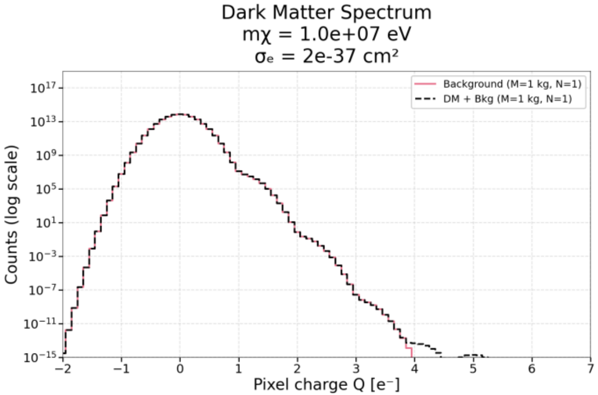


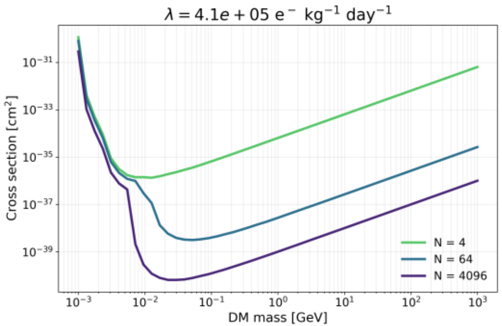
Faster readout can compensate for higher background generation rates

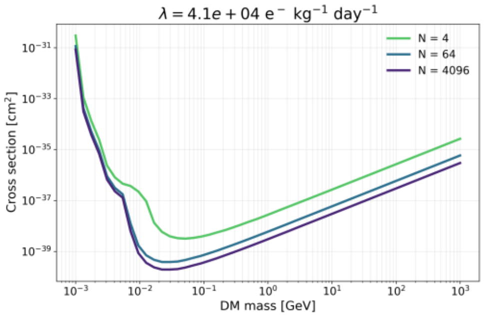
Results – Scaling with generation rate

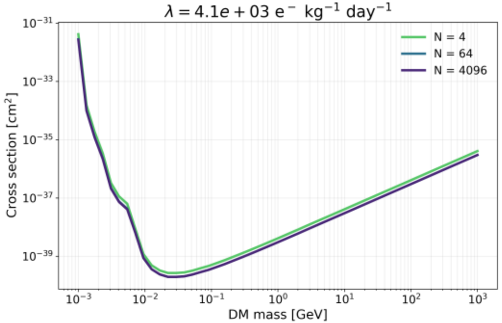
$\lambda_{\text{dark}} = 10$ e-/pix/day

$\lambda_{\text{dark}} = 1$ e-/pix/day

$\lambda_{\text{dark}} = 0.1$ e-/pix/day



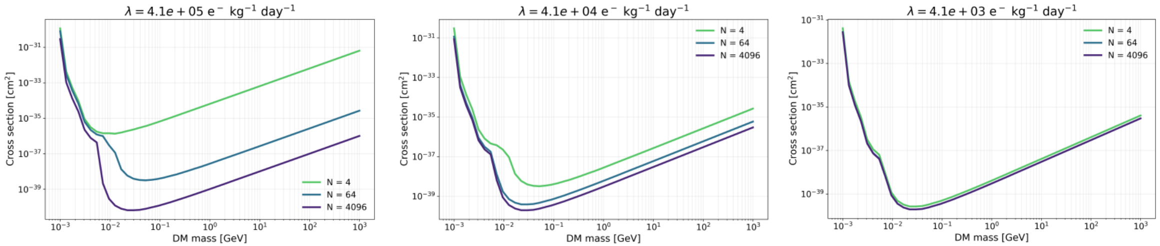




Faster readout

Lower generation rate

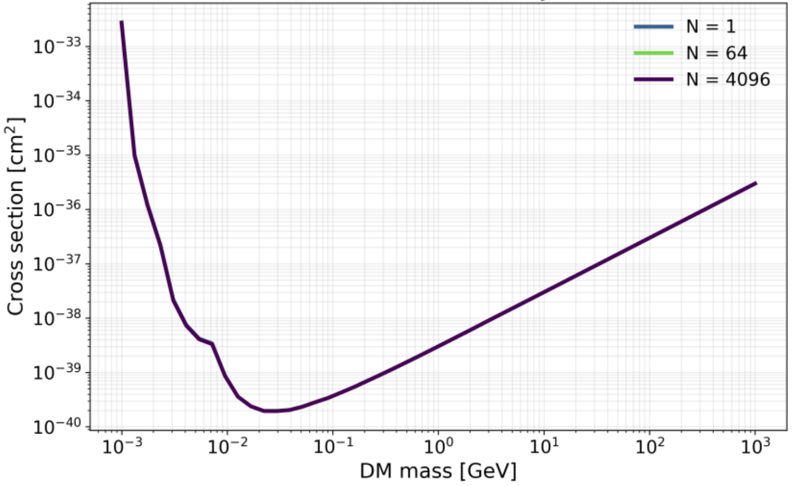
Results – Scaling with generation rate



Lower generation rate

Faster readout

$\lambda_{\text{dark}} = \text{1e-3 e-/pix/day}$



Saturation at low generation rates
→ Faster readout does not improve sensitivity

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Can readout speed compensate detector mass?

Table 16: Comparison of readout parallelization in the long- and short-frame-time regimes.

Long frame time 20 h → 17 s		Short frame time 60 s → 0.94 s	
Configuration	σ [cm^2]	Configuration	σ [cm^2]
0.002 kg / 4 nodes	7.1×10^{-35}	0.002 kg / 4 nodes	1.15×10^{-38}
0.002 kg / 4096 nodes	1.5×10^{-38}	0.002 kg / 4096 nodes	4.32×10^{-38}
10 kg / 4 nodes	1.4×10^{-38}	10 kg / 4 nodes	2.30×10^{-42}
10 kg / 4096 nodes	2.9×10^{-42}	10 kg / 4096 nodes	8.64×10^{-42}

$\lambda_{\text{dark}} = 10$ e-/pix/day

Readout parallelization does **not** provide a viable path for compensating increased detector mass under DANAE-like operating conditions; such compensation is only observed for substantially longer readout times.

Where are the limits?

- Readout optimisation remains **effective** as long as background **generation rates exceed** current **Skipper CCD levels**
- **Higher generation rates** can be partially **compensated** by faster readout
- At Skipper-like regimes (**~10−3–10−5e−pix−1day−1**), readout improvements provide **no additional benefit**
- **Further sensitivity gains** are then driven primarily by **reducing the generation rate** itself

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Outlook

Simplified model – possible improvements

- Simplified RNDR and charge-conversion treatment
- No charge transport or pixel-defect modeling
- **Only thermal background** currently included

- Readout optimisation likely becomes even more important in realistic high-background regimes

Backup Slides

Supplementary: Reference Data

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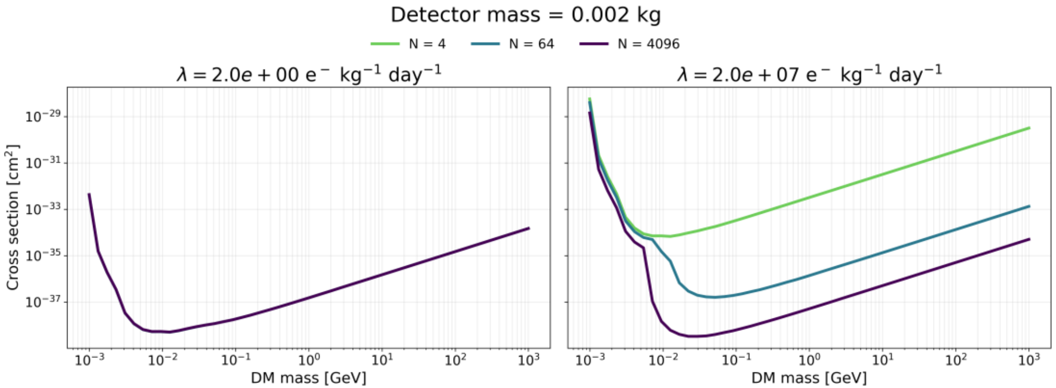
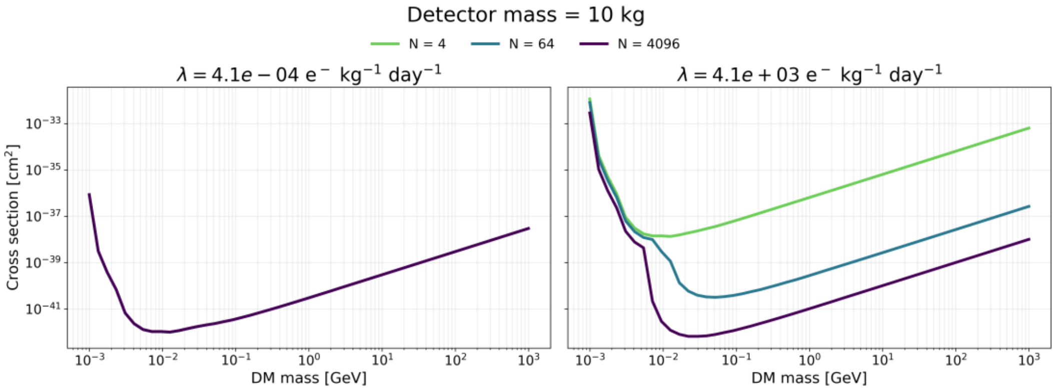
Table 6.1.1: Comparison of key detector and operating parameters for SENSEI, DAMIC-M, OSCURA, and DANAE.

Experiment	SENSEI Surface [28]	SENSEI MINOS [29]	SENSEI SNOLAB 2020 [29]	SENSEI SNOLAB 2025 [30]	DAMIC-M [26, 31]	OSCURA Proto. [32]	OSCURA Goal [33]	DANAE [34]
Detector technology	Skipper CCD	Skipper CCD	Skipper CCD	Skipper CCD	Skipper CCD	Skipper CCD	Skipper CCD	RNDR-DEPFET
Detector mass	0.071 g	1.93 g	2.23 g	2.19 g	$\sim$ 18 g	prototype sensors	10 kg	10.7 mg
Exposure / operation mode	73.6 min	20 h	20 h	0–20 h exposures	39.97 g day	variable exposures	30 kg yr planned	0.1–4.0 s exposure sweep
Total pixels	9.0×10^5	5.4×10^6	6.3×10^6	6.3×10^6	5.1×10^7	1.35×10^6	2.8×10^{10}	4096
Actually used pixels	677 664	full detector	not explicitly stated	hardware-binned superpixels	640 × 110 ROI	full prototype sensor	planned full detector	3690
Pixel dimensions	15 × 15 × 200 μm^3	15 × 15 × 675 μm^3	15 × 15 × 675 μm^3	15 × 15 × 665 μm^3	15 × 15 × 670 μm^3	15 × 15 × 725 μm^3	15 × 15 × 700 μm^3	50 × 50 × 450 μm^3
Readout repetitions	—	300	300	300	650	324	—	800
Readout / frame time	73.6 min	20 h	20 h	16 min/image	5.13 min/image	exposure dependent	$\sim$ 2 h/image	1.22 s/frame
Readout noise	sub-electron	0.14 e^- RMS	0.14 e^- RMS	0.14 e^- RMS	$\sim$ 0.2 e^- RMS	$\sim$ 0.2 e^- RMS	$2e^-$ threshold target	$\sim$ 0.31 e^- RMS
λ_{dark} [e^-/pix/day]	1.14	3.7×10^{-3}	2.4×10^{-4}	$(1.39 \pm 0.11) \times 10^{-5}$	5.6×10^{-2}	$(1.8 \pm 0.3) \times 10^{-3}$	10^{-6}	18
Lowest reported single-e^- rate	1.14	3.7×10^{-3}	1.59×10^{-4}	$(1.39 \pm 0.11) \times 10^{-5}$	—	$(1.8 \pm 0.3) \times 10^{-3}$	10^{-6} target	—
λ_{dark} [e^-/pix/readout]	5.8×10^{-2}	3.08×10^{-3}	2×10^{-4}	exposure dependent	2×10^{-4}	exposure dependent	8.3×10^{-8}	2.5×10^{-4}
λ_{dark} [e^-/kg/day]	1.1×10^{10}	1.05×10^7	6.8×10^5	39.8 ± 3.1	1.58×10^8	$\sim 5 \times 10^7$	2.8×10^3	7.0×10^9

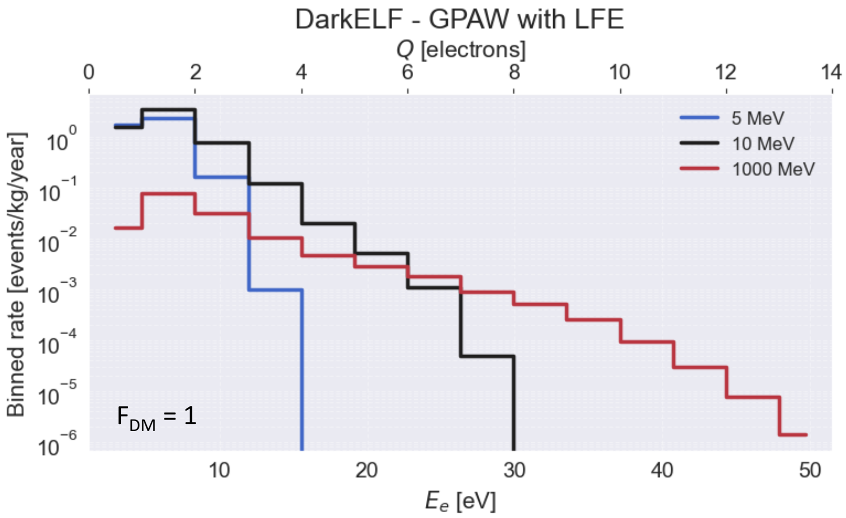
Note: For skipper-CCD detectors, the quoted readout or exposure time corresponds to the effective integration time of one complete detector image, since pixels are measured sequentially. For DANAE, the quoted frame time corresponds to the full detector cycle including repetitive RNDR measurements of all rows, while the row readout time refers only to the active readout duration of a single row within that cycle. Values of λ_{dark} [e^-/pix/readout] were derived from the corresponding image or frame durations where possible. The OSCURA prototype values correspond to dedicated underground characterization measurements of newly fabricated prototype skipper-CCD sensors operated at MINOS, whereas the OSCURA goal values represent projected full-scale experiment targets rather than experimentally measured detector performance. The listed single-electron rates correspond to experimentally measured exposure-dependent event rates where available. The SENSEI SNOLAB 2025 value represents the currently lowest experimentally reported single-electron background rate achieved in a silicon detector with single-electron sensitivity.

Results – mass scaling





- Mass scaling simply shifts the curves in the y axis



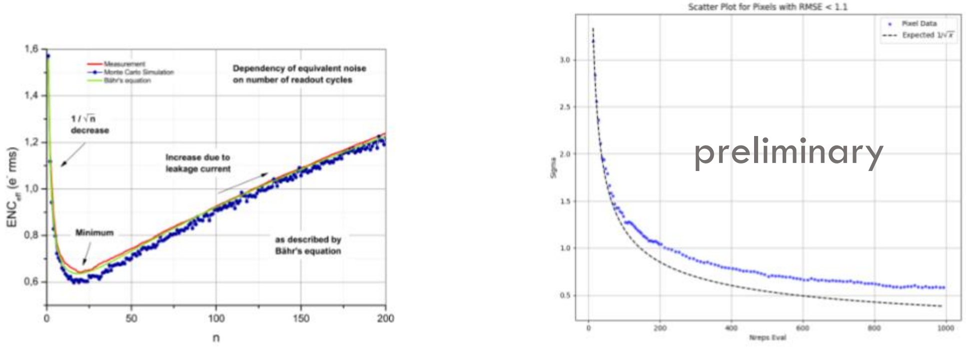
- Signal was generated with the DarkELF Python package by [insert]
- eV to Q conversion woes doen via

$$E_Q = \begin{cases} 0, & Q = 0, \\ E_{\text{gap}} + (Q-1)\,\varepsilon_0, & Q \geq 1, \end{cases}$$

- For all subsequent analyses and results a Heavy Mediator (FDM = 1) is assumed, however the possibility for others is technically provided

RNDR regime

$$\sigma_{\text{readout}} \propto \frac{1}{\sqrt{N_{\text{RNDR}}}}$$



(a) Ideal $1/\sqrt{n}$ scaling and Bähr-model prediction [17].

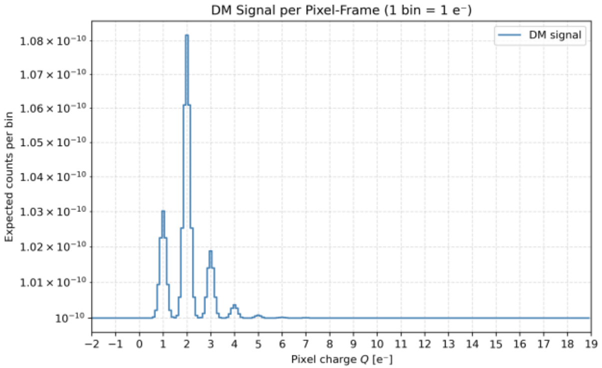
(b) Measured RNDR noise curve for a representative clean pixel.

Figure 4.2.2: Comparison of RNDR noise evolution. (a) Ideal statistical scaling and the Bähr-model prediction [17]. (b) Preliminary RNDR noise behaviour observed in the DANAE detector (clean pixel, RMSE < 1.1).

Simulation method – Spectrum generation

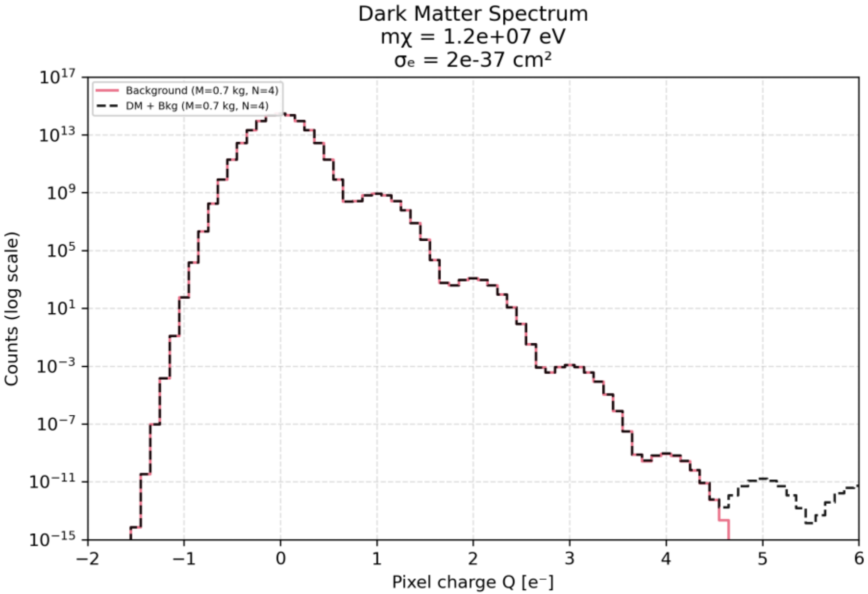
Full Spectrum – overlap of DM-signal and background

Simulated signal (DarkELF)



Thermal background regime

$$B(p \mid \{\lambda_i\}, \sigma_{\text{res}}) = \sum_{i=1}^{N_{\text{pix}}} \sum_{n_q=0}^{\infty} \text{Pois}(n_q \mid \lambda_i)\,\mathcal{N}(p - n_q; \sigma_{\text{res}}),$$

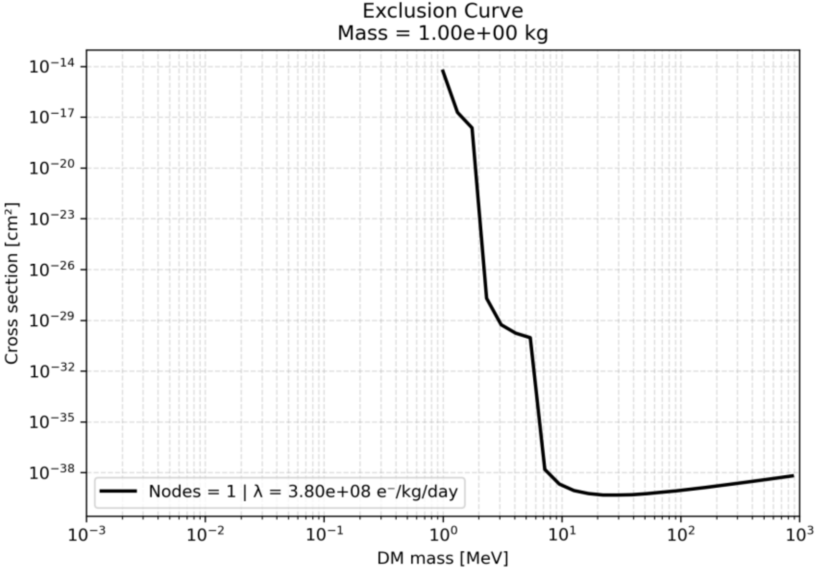


Simulation method – Exclusion area

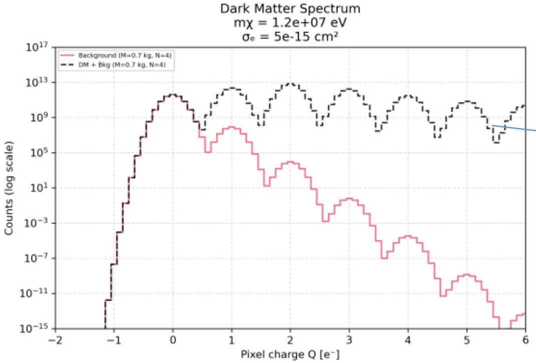
- For all exclusion areas exposure time was set to 365days
- kg/year scaling was achieved by varying detector mass

- Parameter space sampled logarithmically in:
  – dark matter mass
  – interaction cross section

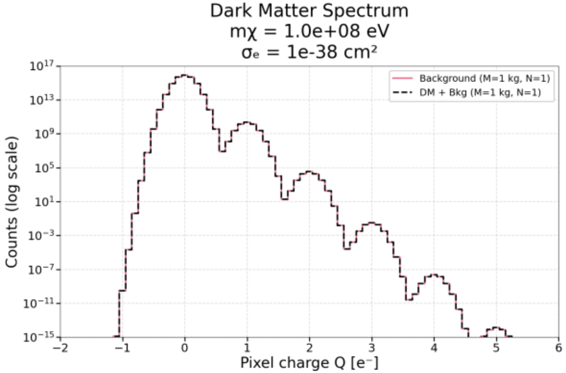
- 50 sampling points per axis
- Exclusion curves extracted from the resulting discrete parameter grid



Simulation Method – Exclusion Area



excluded



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