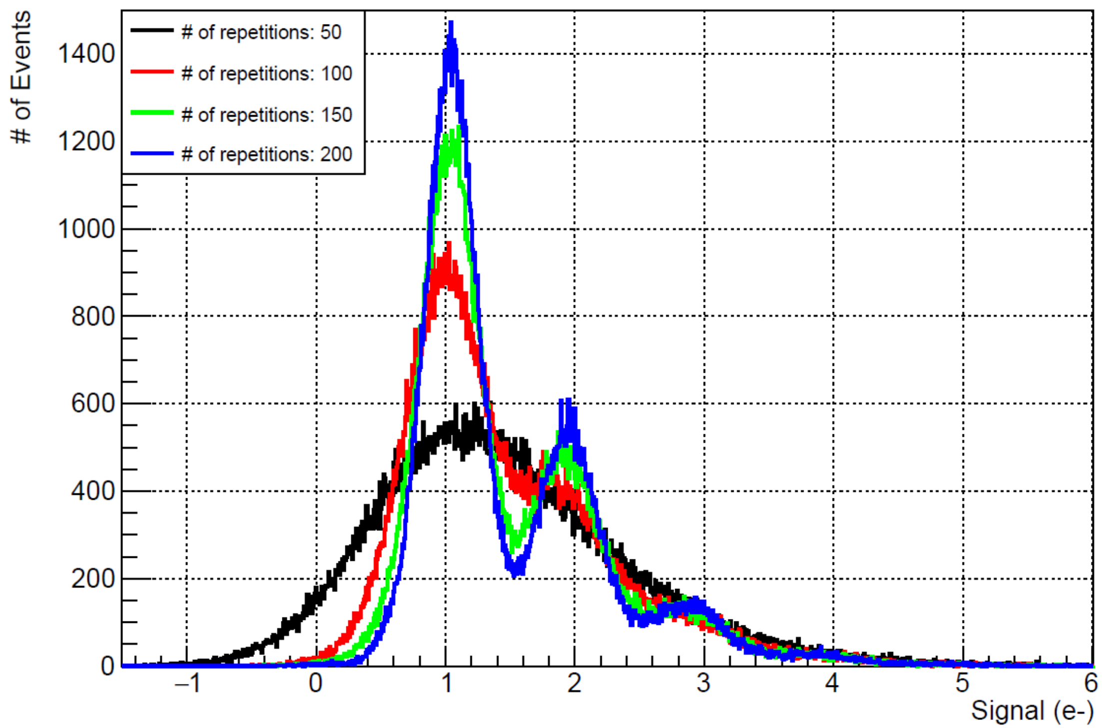


DANAE

A direct search for light dark matter with RNDR-DEPFET detectors

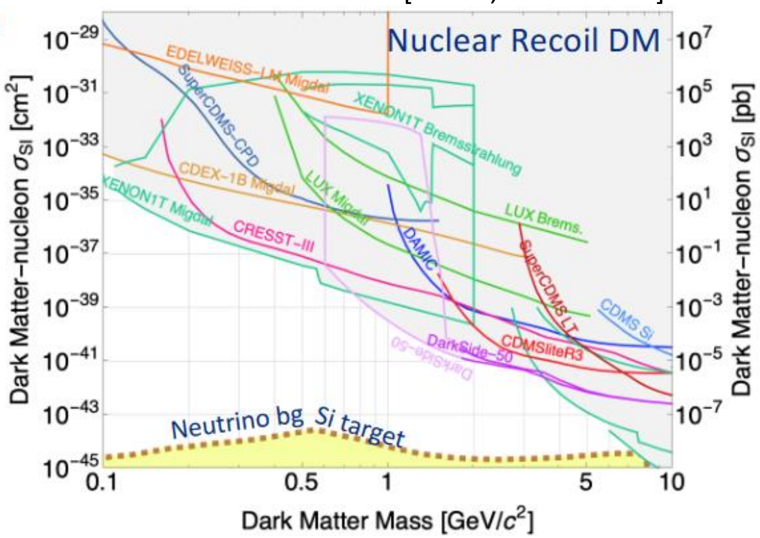
HEPHY/FHWN

I. Introduction: Light dark matter

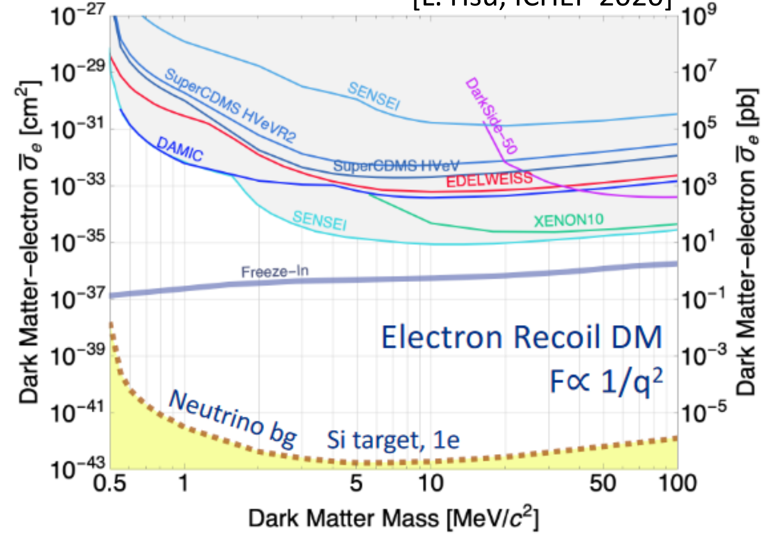
Classical approach
- Motivated by SUSY, Lee-Weinberg bound
- Particle mass: above 1 GeV/c^2
- Main event signature: nuclear recoils
- Experiments: large scale, no discoveries

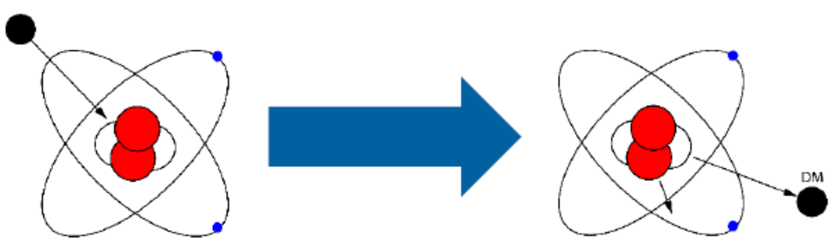
Light dark matter approach
- Motivated by dark sector, ELDER, SIMP
- Particle mass: above 100 keV/c^2
- Main event signature: electron recoils
- Moderate sensitive mass needed

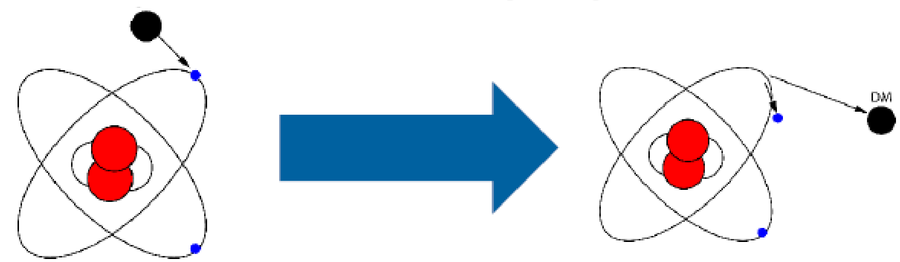
[L. Hsu, ICHEP 2020]



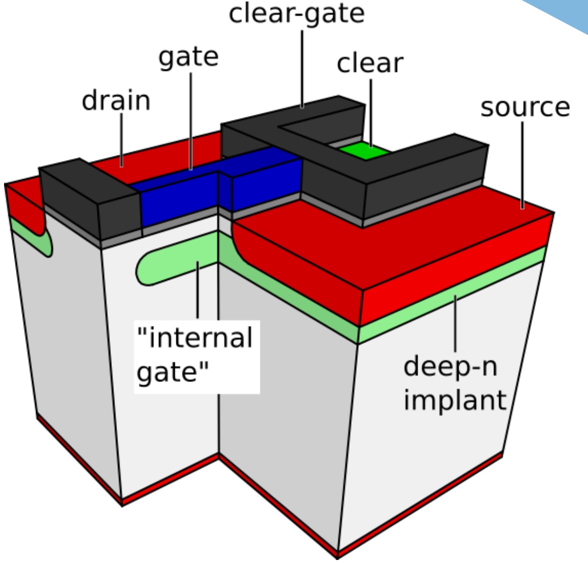
[L. Hsu, ICHEP 2020]





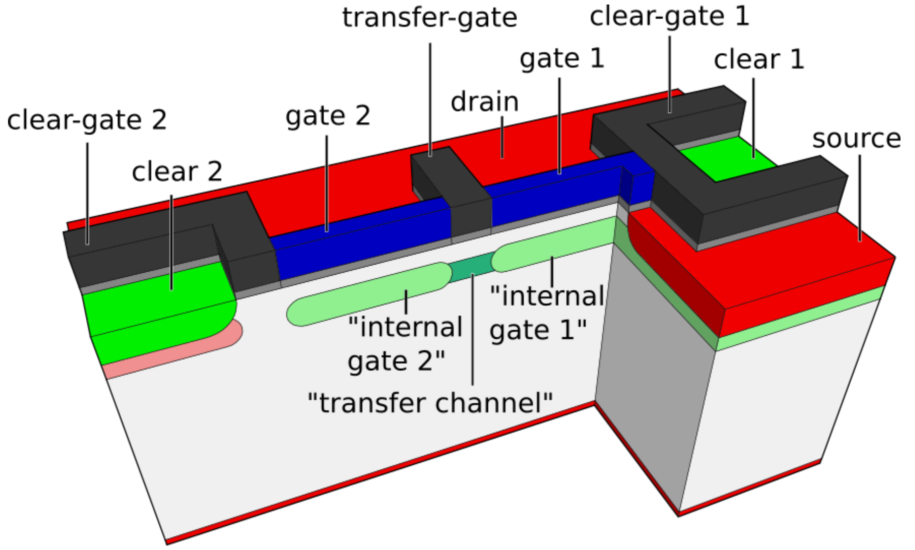


II. DANAE: RNDR-DEPFETs



DEPFET detectors

- Technology established in astrophysics (Bepi-Columbo, ATHENA) and particle physics (Belle)
- DEPFET principle:
  - Side wards fully depleted bulk
  - e^- are collected in internal gate
  - conductivity of transistor channel is proportional to number of e^-
  - e^- are removed by the clear contact



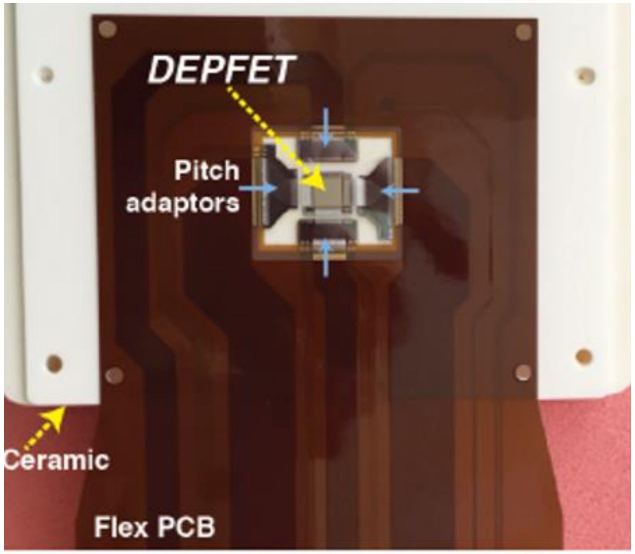
RNDR-DEPFET detectors

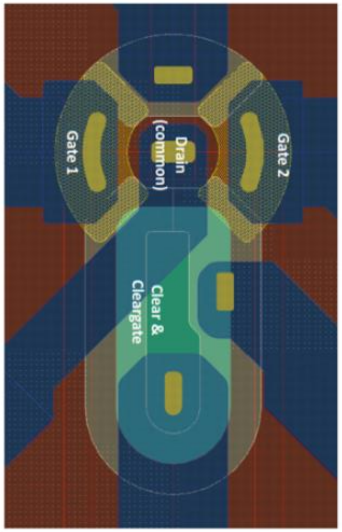
- Instead of removing the e^-, they are shifted to a second internal gate
- Repetitive independent (n) readout cycles of same signal
- Reduction of noise by $1/\sqrt{n}$

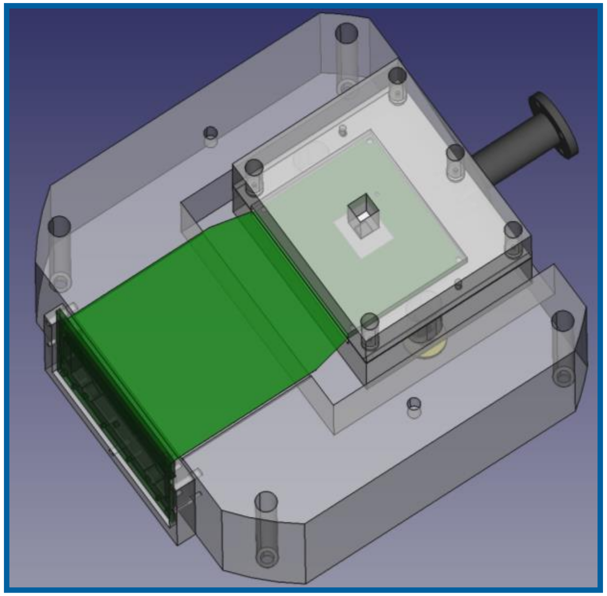
II. DANAE: RNDR-DEPFETs

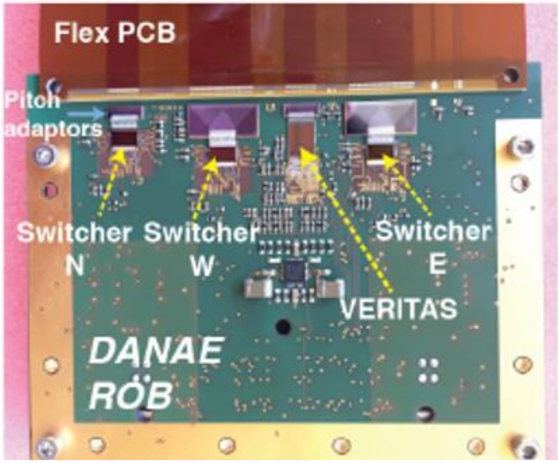
DANAE Module

- 64x64 RNDR-DEPFET pixels a 50x50 µm^2
- Sensor glued on carrier ceramic and wire bonded to flexible PCB
- Sensor mounted in inner and outer Al shielding block with separated front end electronic





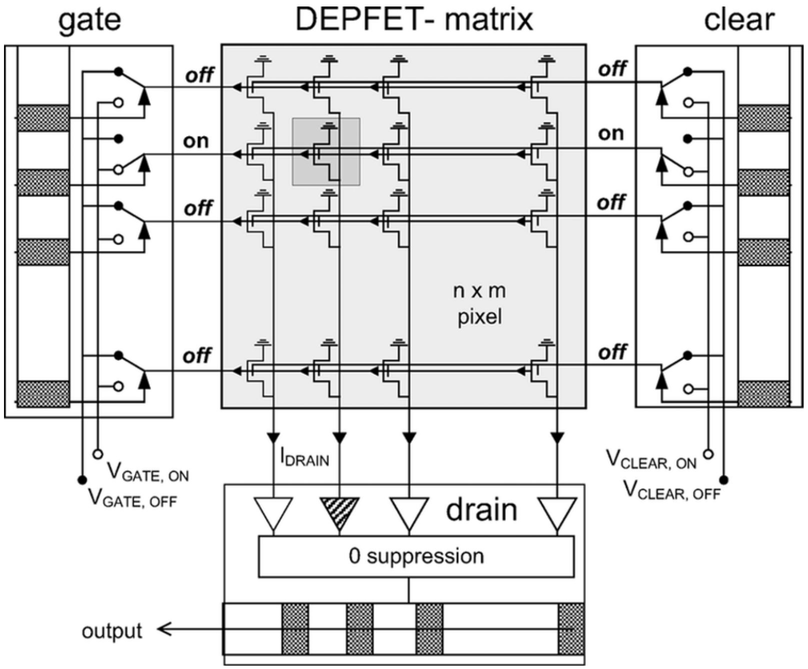


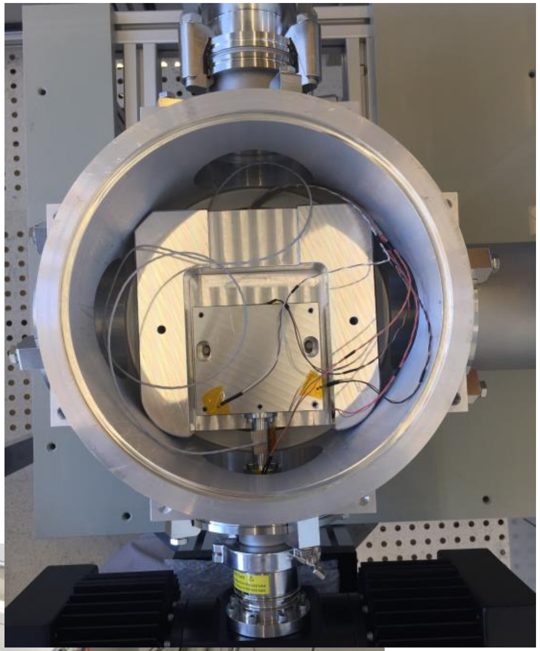


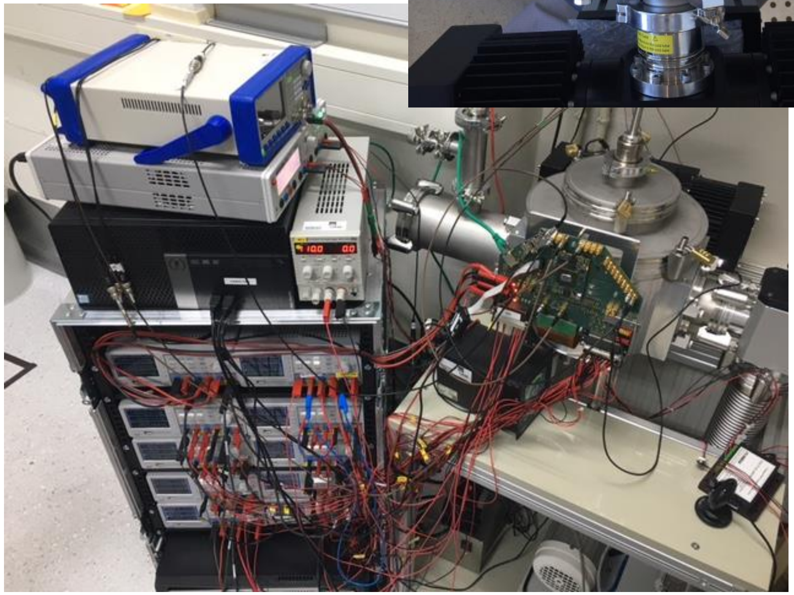
II. DANAE: RNDR-DEPFETs

DANAE Setup

- Inner block connected to Stirling cooler, placed in vacuum chamber
- Both blocks are hosted in a vacuum chamber and operated by a power tower and DAQ PC
- Rolling shutter operation and acquisition of each repetition for averaging in post processing



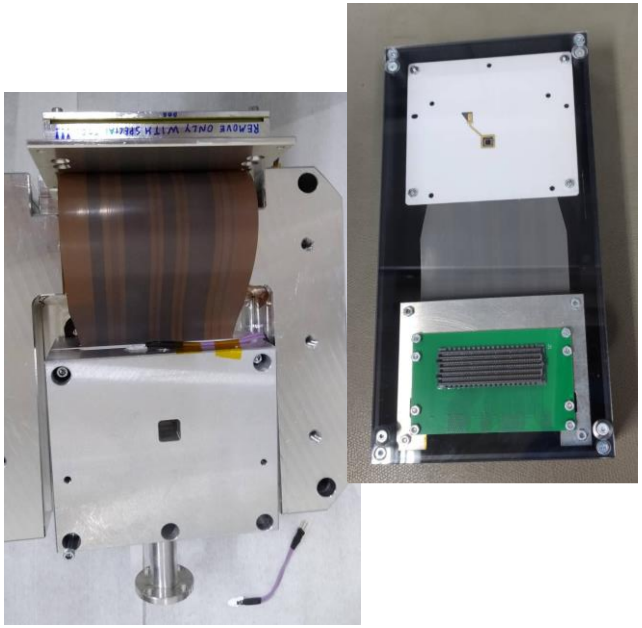




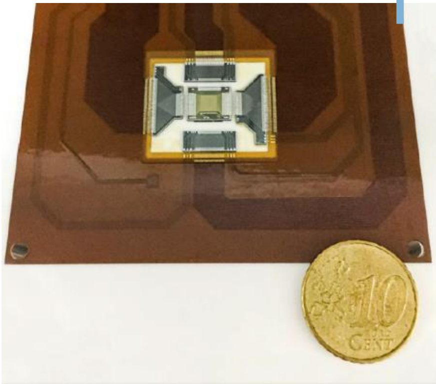
II. DANAE: RNDR-DEPFETs

DANAE Modules Updates

- To operate different sensors with similar FEE, a FMC plug was introduced in between the readout board and sensor
- To provide debug options for commissioning of new modules, a break out board can be inserted in between the sensor and the readout board

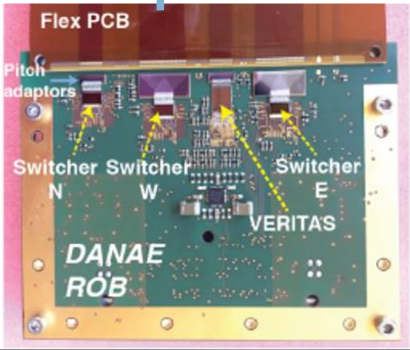


Sensor



V0: Flexible PCB
V1: With FMC Plug and debug readout Board

FEE board



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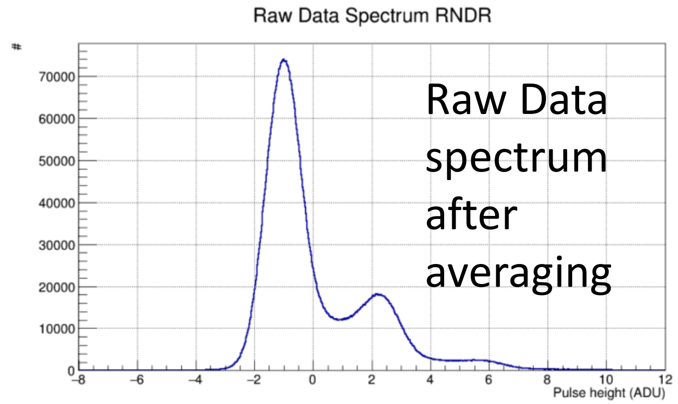
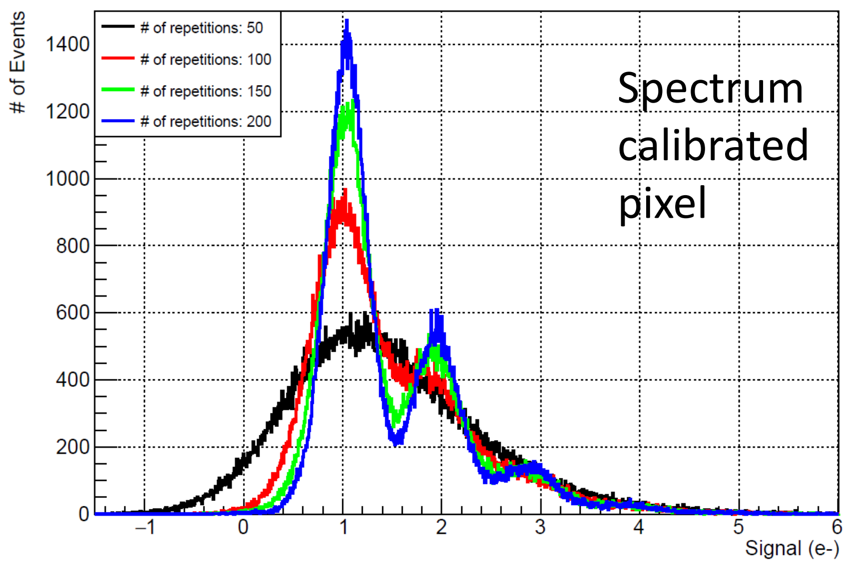
Results

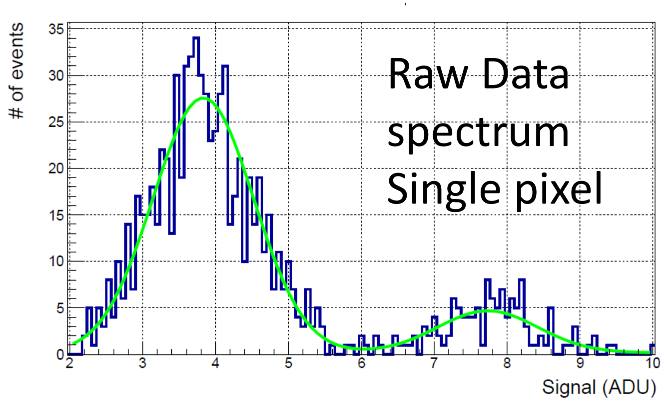
III. DANAE: Performance – LED

Calibrated spectra of LED

- Calibration with LED operated with faint signals to generate single electron spectra
- Noise reduction: Follows expected trend is reduced to about 0.15 e^-ENC
- Analysis software: Python custom development software: APANTIAS (A Python ANalysis Tool for In-depth sensor Array Statistics) https://github.com/shakamaran/apantias/







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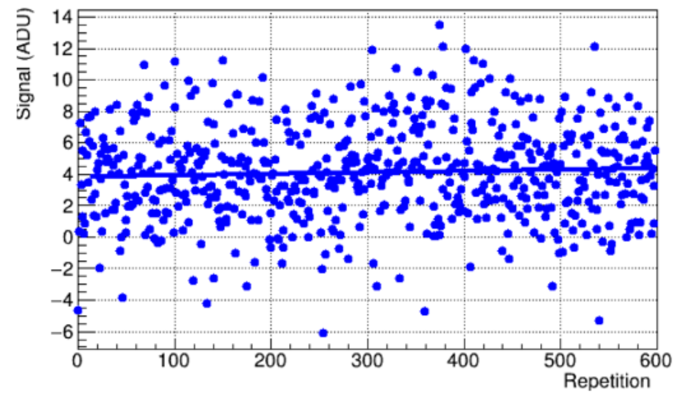
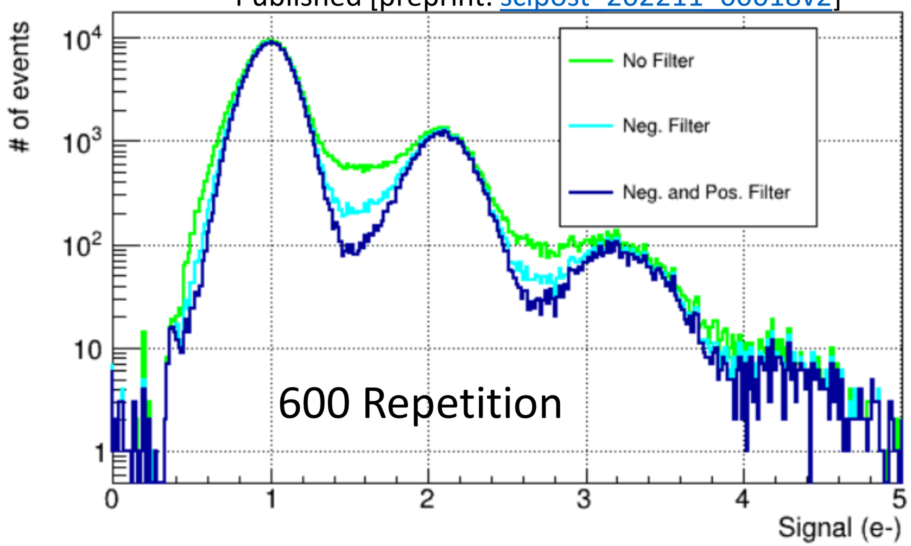
III. DANAE: Performance – LED

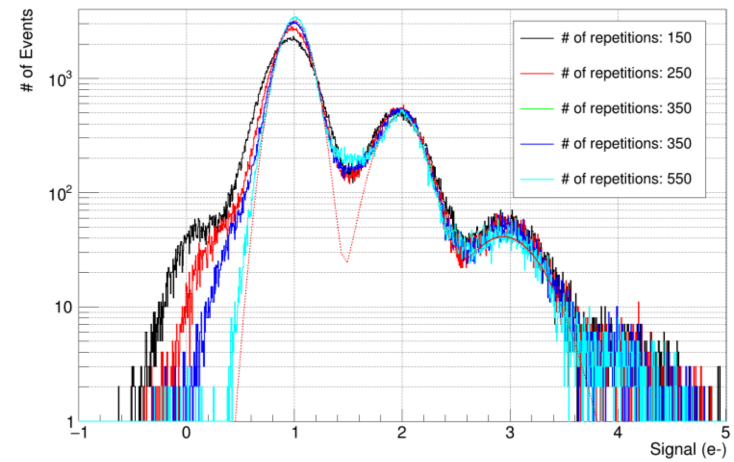
Calibrated spectra of LED

- Spectra for different number of averaged repetitions (up to 600)
- Performance affected from generated or lost electrons during readout
- Inspection of single events (slope of signal vs. number of repetition) enables to identify and filter affected events



Published [preprint: scipost_202211_00018v2]

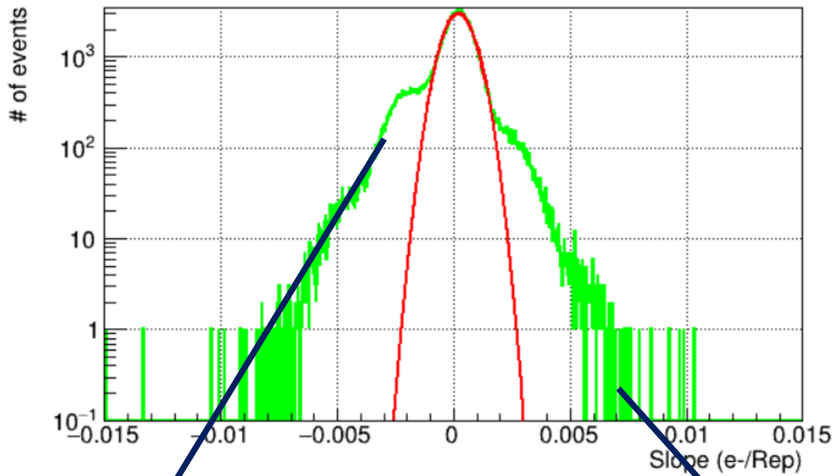




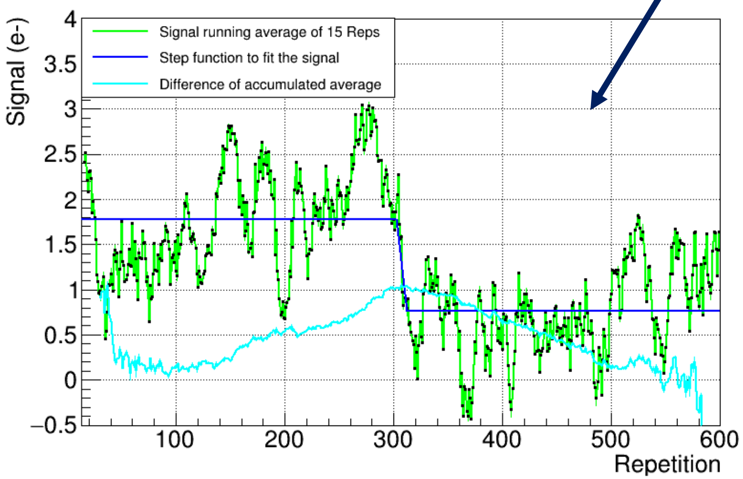
III. DANAE: Performance – LED

What to learn from slopes?

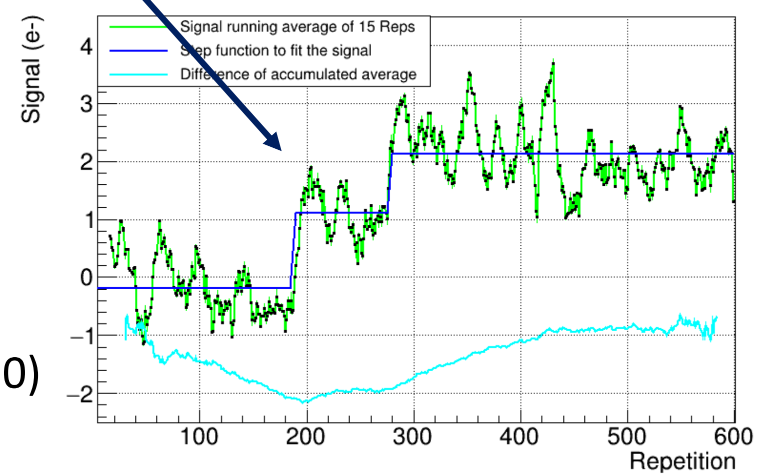
- Sufficient large number of repetitions -> distribution with pos. and neg. shoulders evolves
- Deviation from gauss shape -> identify events
- First shoulder one electrons second two, etc.



- slope **below** 3 sigma (loss)
- slope **above** 5 sigma (generation)



- Running average of readings (10)

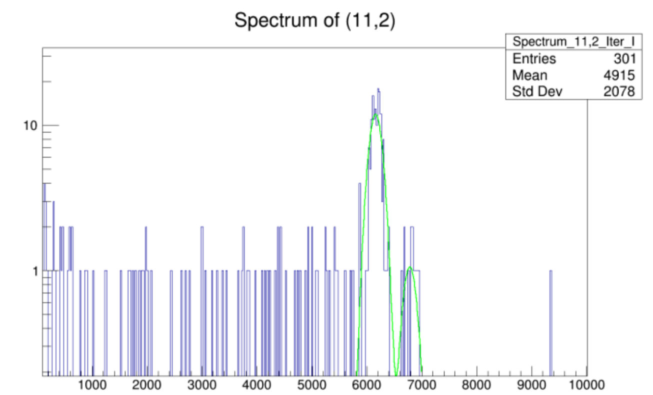


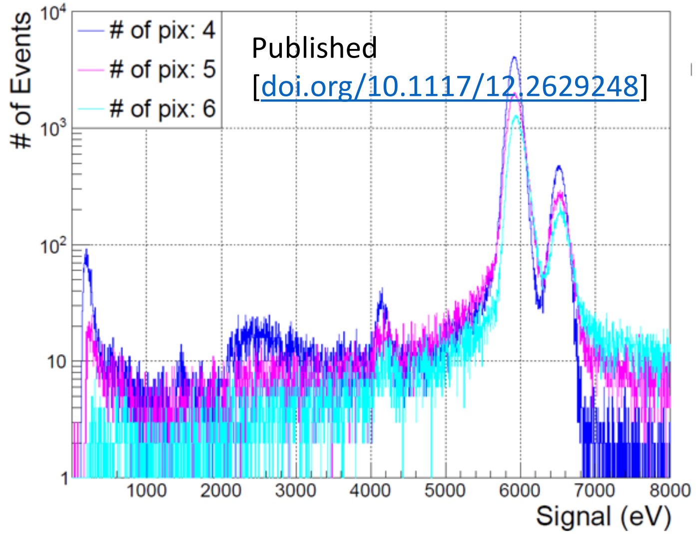
III. DANAE: Performance – ^{55}Fe

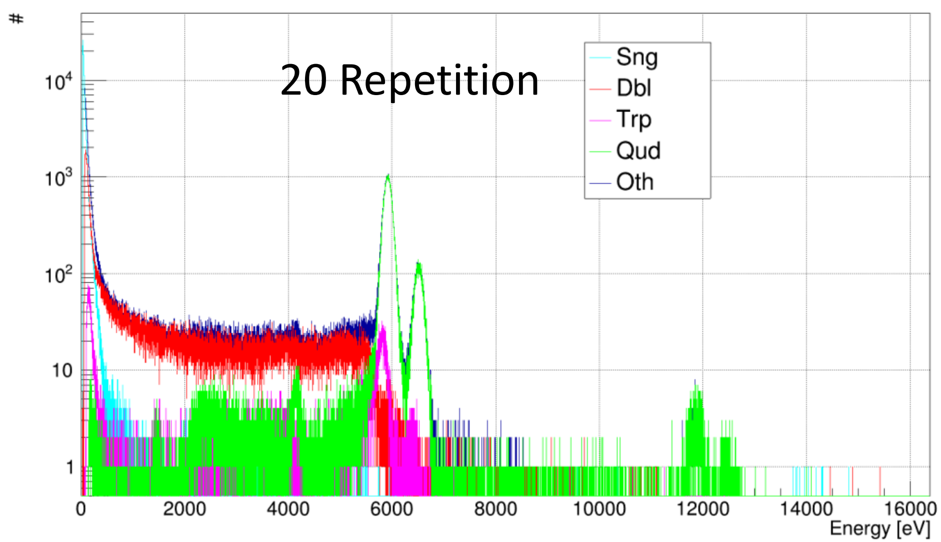
Detector performance with ^{55}Fe

- ^{55}Fe spectrum recorded with
  - Calibration on 6 keV lines
- Effects to be considered:
  - Small pixels and thick bulk material ➔ large charge cloud (> four pixels)
  - Specific (slow) r/o in combination with large charge cloud ➔ interframe splits (broken patterns)

➔ Background rejection and identification of keV X-rays possible



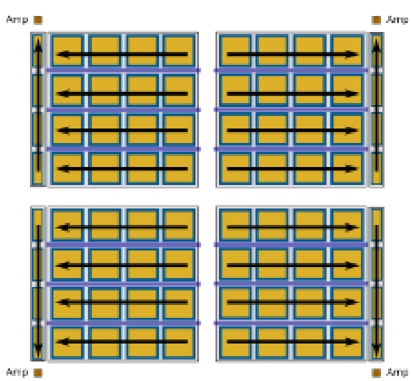


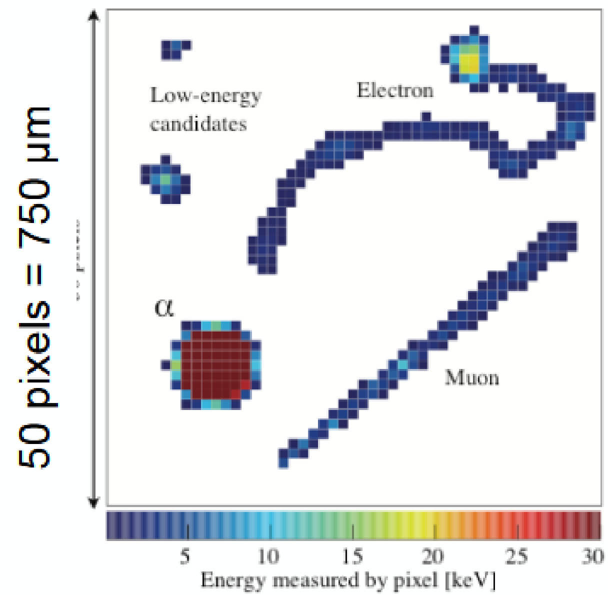


III. DANAE: Comparison Skipper-CCD

Skipper CCD for LDM searches

- In the last yeas skipper-CCD established for direct detection experiments of LDM
- Small pixel structures for bkg. particle identification and reduced generation rate per pixel
- Lateral charge transfer to readout node result in frame rates of several hours





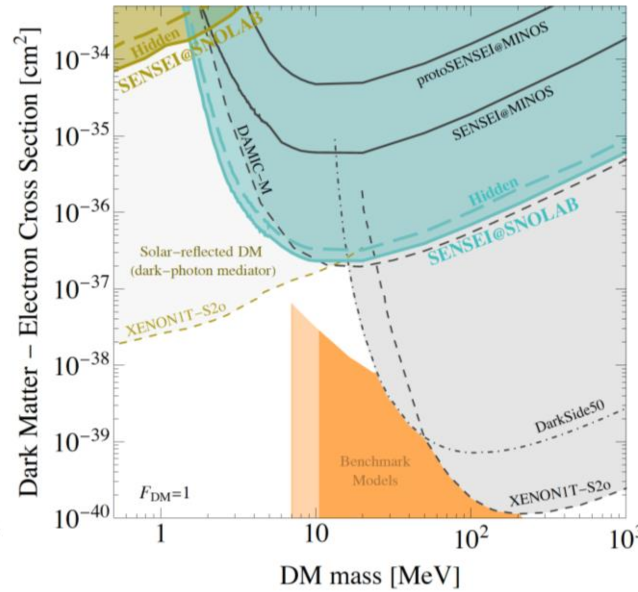
III. DANAE: Comparison Skipper-CCD

Skipper CCD results

- Select events with $2e^-$ and $3e^-$
- Use single electron events to estimate $2e^-$ and $3e^-$ event rate
- Use cluster layout to remove obvious background sources (noise, bad pixels, clusters,…)
- Exposure of 20h followed by 8h readout time (1.5 Mpixels)
- Slow readout impacts pile-up events and prevents external veto
- Calculate limit using detailed electron scattering predictions and $2e^-$ and $3e^-$ events

cut flow table

	Expo.		Events, $2e^-$			Events, $3e^-$	
Mask	[g-day]	Eff.	horz	vert	diag	2p	3p
-	534.89	-	60121	25993	31572	10759	41240
Noise	436.53	0.817	9109	10623	9584	5636	9176
Crosstalk	435.68	0.998	9031	10226	9525	5248	8996
Edge	379.41	0.871	7250	8486	7314	4392	7432
Bad col.	217.88	0.574	5357	4008	5512	2808	5696
Bad pix.	217.86	1.000	5347	4000	5503	2804	5691
Full-well	213.08	0.978	981	435	759	181	511
Serial reg.	213.05	1.000	789	335	557	139	333
Bleed	208.96	0.982	740	275	446	136	312
Halo	194.43	0.931	687	239	397	128	286
Low-E	100.72	0.522	188	13	32	3	7
Shape	100.72	1.000	10	13	32	3	1



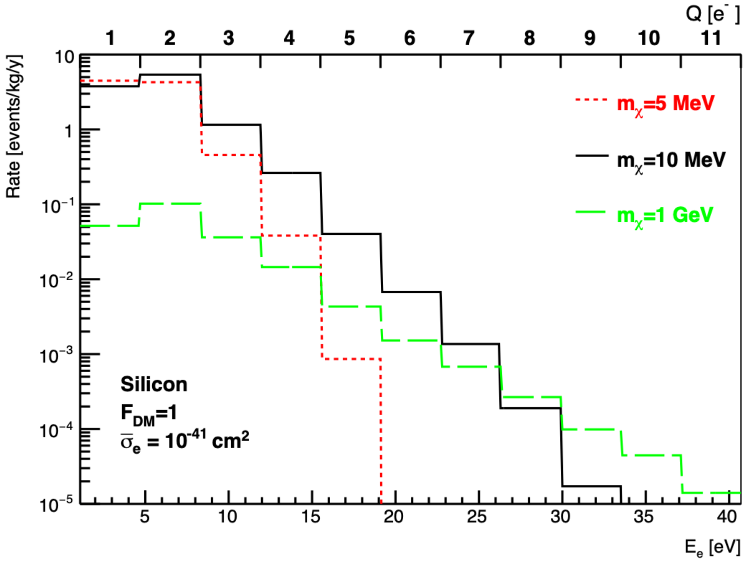
arxiv 2312.13342

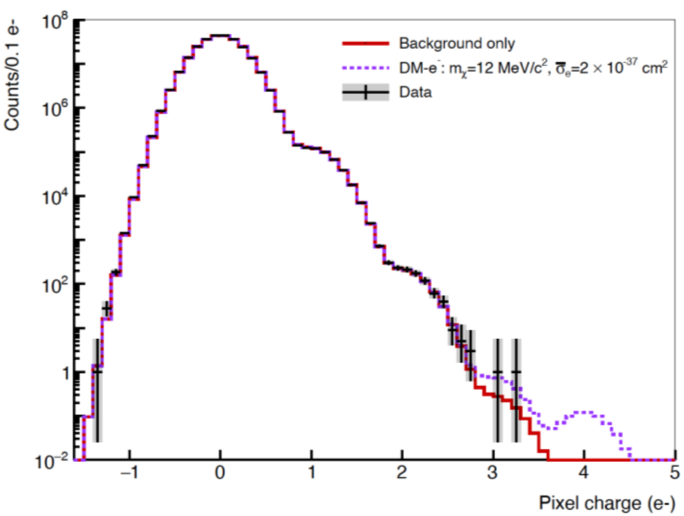
III. DANAE: Comparison Skipper-CCD

Simulation of expected signals

- Expected event rate of events with one, two, three or more electrons depends on mass of DM candidate
- Simulation with open source software packages (DarkCode, DarkELF,...) to generate recoil spectrum
- Expected background spectrum modelled with combination of Gaussian (noise) and Poisson (leakage current) distribution
- Comparison of expected DM spectrum with background spectrum

➔ Fast sampling rate reduce multiple electron peaks of thermal signal (pile up)





Phys. Rev. Lett. 130, 171003 (2023)

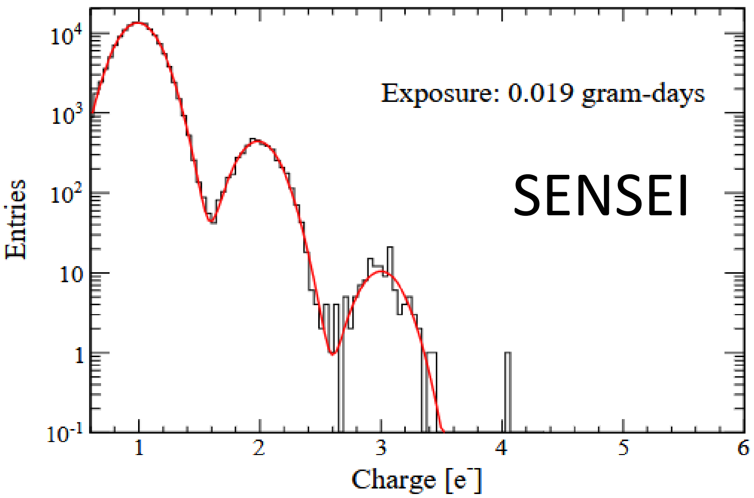
III. DANAE: Comparison Skipper-CCD

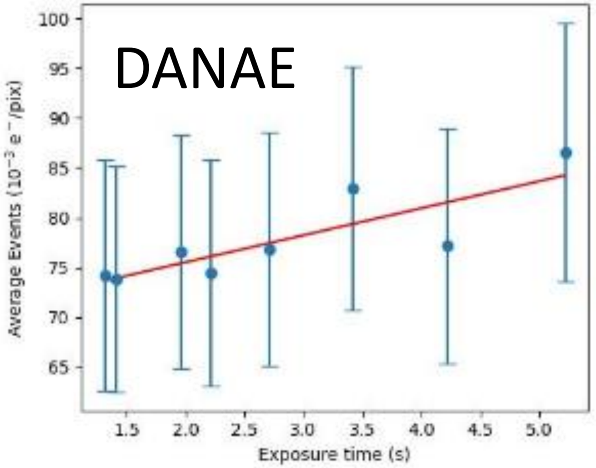
Operation in a surface run lab

- SENSEI skipper-CCD sensor (624×362 pixels, $15 \times 15 \times 200\ \mu m^3$)
- 1.14 e^-/pixel/day readout (12.6 e^-/g/sec) with a readout time of 74 min results in 0.058 e^-/pixel/readout
- DANAE RNDR-DEPFET sensor (64×64 pixels, $50 \times 50 \times 450\ \mu m^3$)
- Preliminary results for upper limit is 70 e^-/pixel/day (31 e^-/g/sec) with a readout time of 1.6 sec results in 0.001 e^-/pixel/readout

- BUT: Exposure independent generation rate at DANAE dominates electron generation and is under investigation

https://arxiv.org/pdf/1804.00088



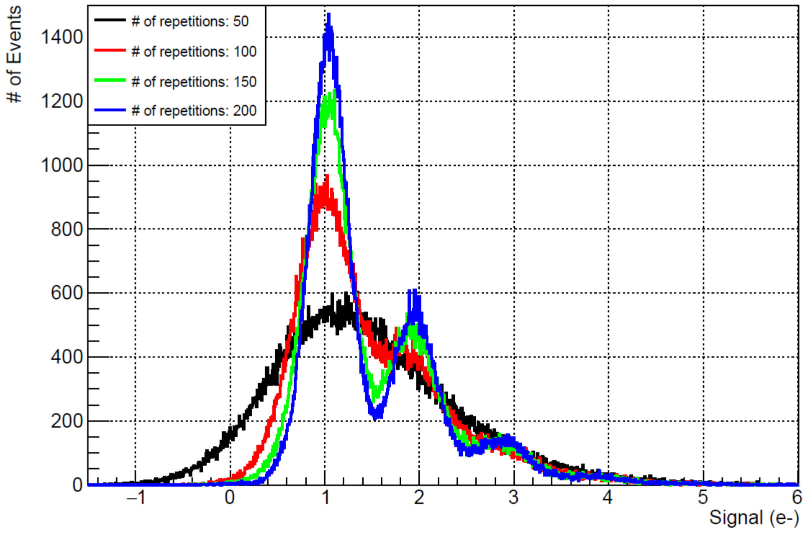


Conclusion and Outlook

- Investigation of exposure independent charge carrier generation ongoing

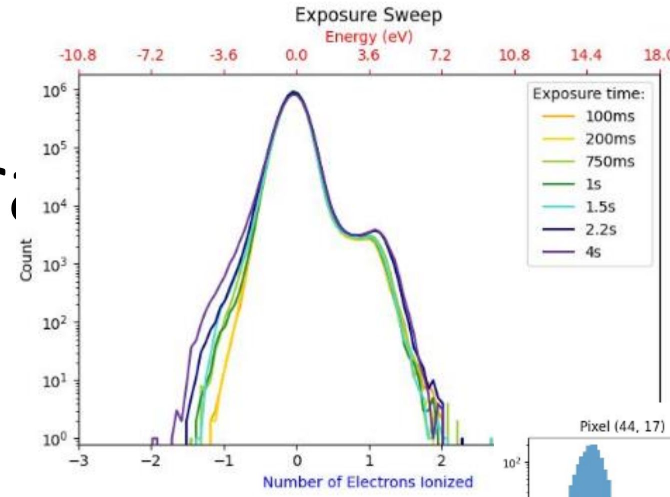
- Preparation of surface run and analysis ongoing

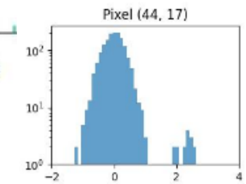
- Modelling of expected DM signal and quantification of sensitivity increase of fast sensors ongoing



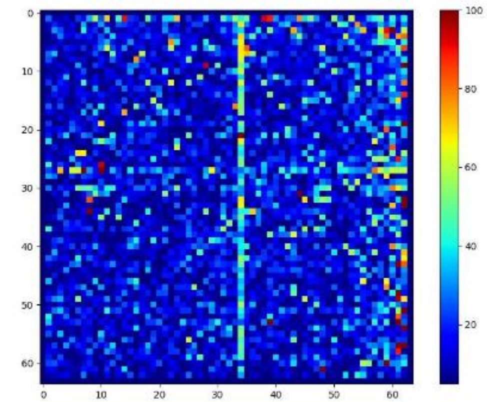
Thank you for the attention

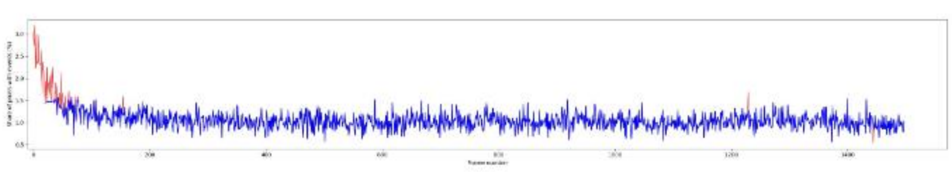
Backup: DANAE Gener

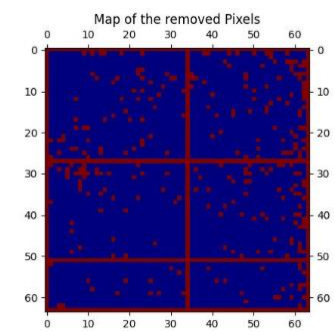




- Readout per frame: 1.2 sec
- Additional exposure of 100 ms to 4 sec
- Raw data spectrum -> single electron events only (gain calibration ongoing)
- Event map for a total exposure of 2.22 sec and pixel masking of appr. 12%
- Events per frame -> Frame masking to take saturation into account







Backup: Skipper CCD Status and plans

10 kg Skipper CCDs with a total exposure of **30 kg·y** (24k sensors)

Background:

- reduce the dark current rate by two orders of magnitude **~10^{-6} e^{-}/pix/day**
- reduction of external and internal background rate by several orders to **0.01 events/kg/day/keV**

readout speed to **166 pix/sec** (2h for 24k sensors with 28 Gpixel)