DANAE

A dark matter experiment with RNDR DePFETs

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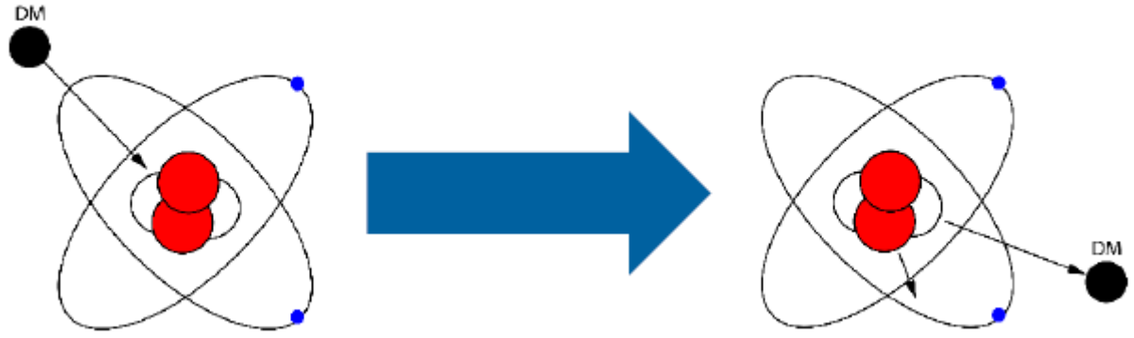
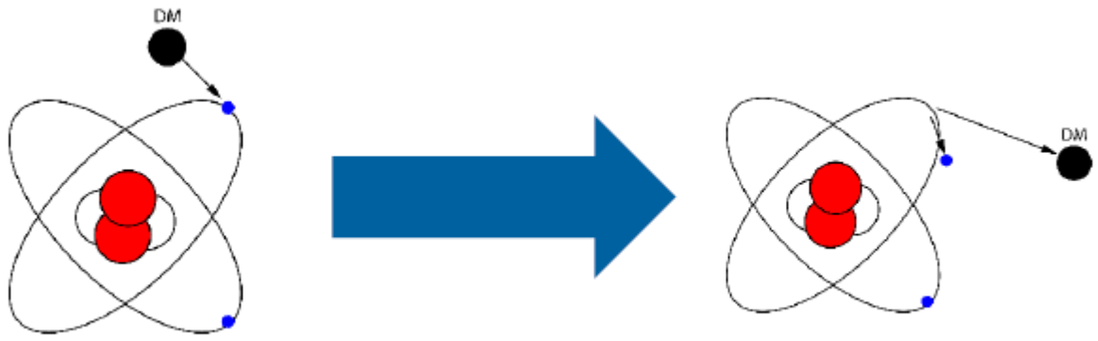


- Predicted particle mass for WIMP: 2 GeV/c^2 – 120 TeV/c^2
- Usual direct searches via nuclear recoils
- Threshold appr. 10 eV or 5 MeV/c^2

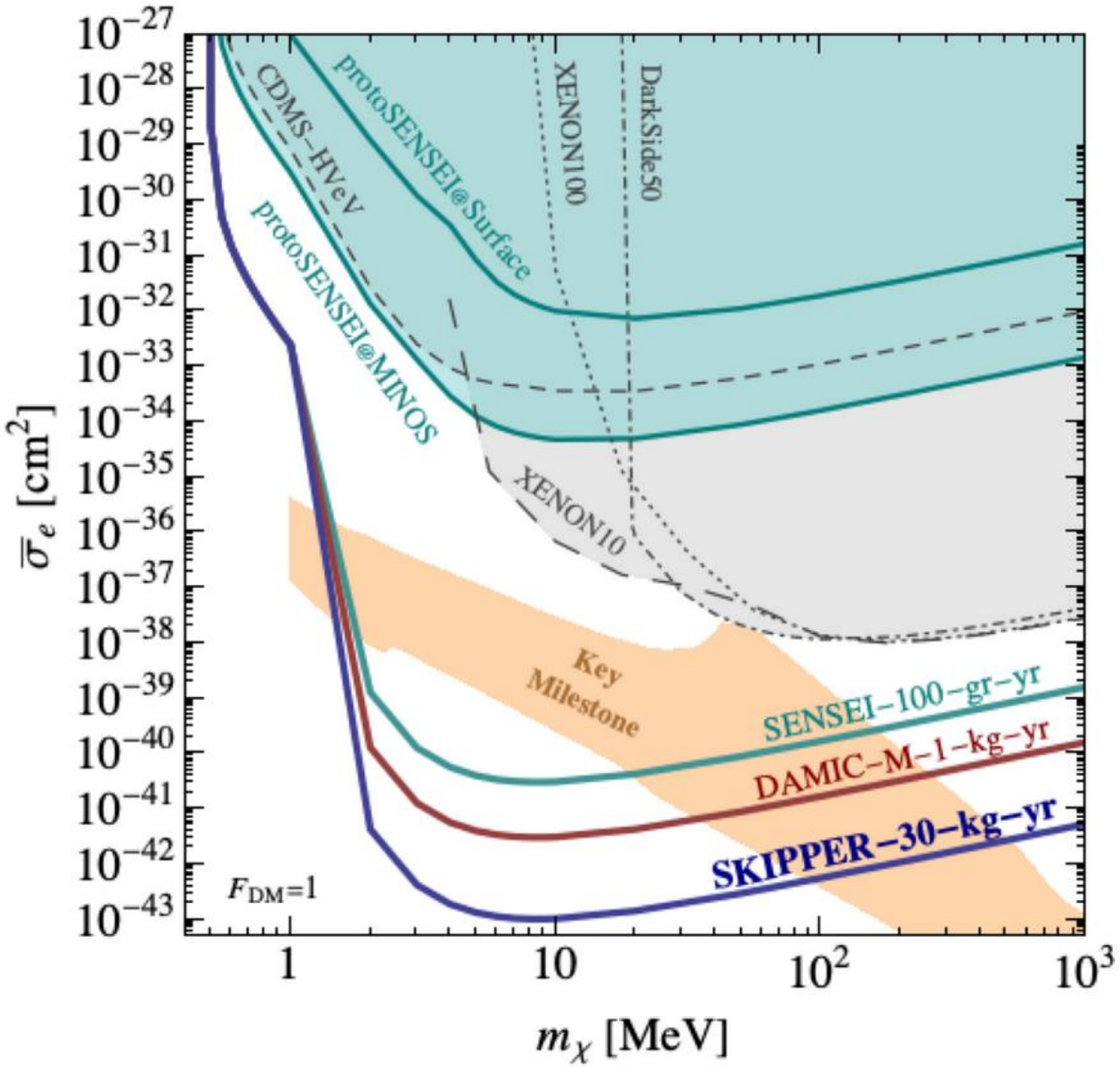
- Dark sector and light dark matter (e.g. SIMP, sterile neutrinos)
- Possible direct searches via electron scattering: keV/c^2 – GeV/c^2
- Threshold appr. 1 eV or 200 keV/c^2



-> Apply established silicon semiconductor technology for direct DM searches

- **Ongoing activities:**
  - DAMIC (40 g): no repetitive r/o (threshold appr. 40 eV)
  - SENSEI (some 100 g): starting 2021 skipper CCDs
  - DAMIC-M (in 1 kg range): starting 2023 with next generation skipper CCDs
  - Oscura (in 10 kg range): in development with skipper CCDs

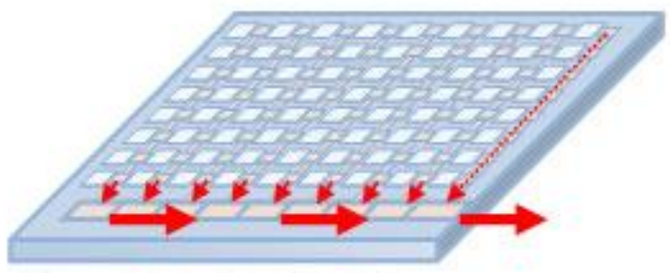
Vital field of research all applying CCD technology



-> DePFETs offer a comparable performance with complementary features

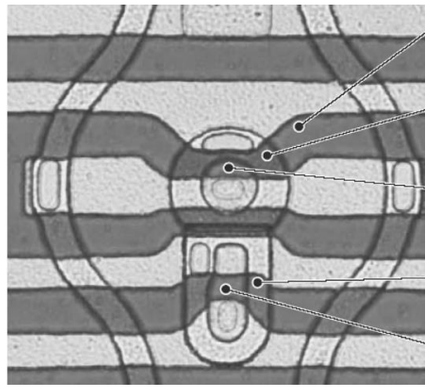
Skipper CCD:

- Spatial resolution via time projection (shift register)
  -> One r/o node for sensor or line
- Relatively slow (illumination)
- Simple pixel structure, long charge transfer needed
- Small pixel (15 x 15 μm^2)

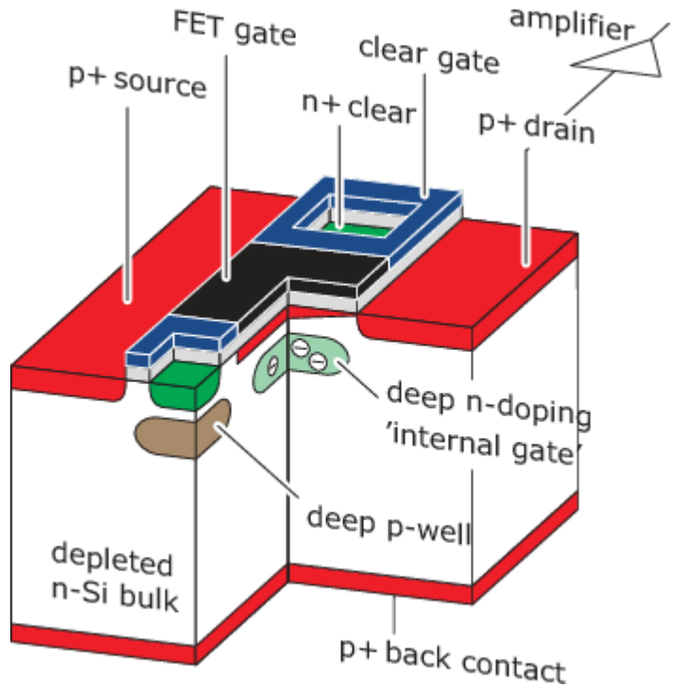


DePFET:

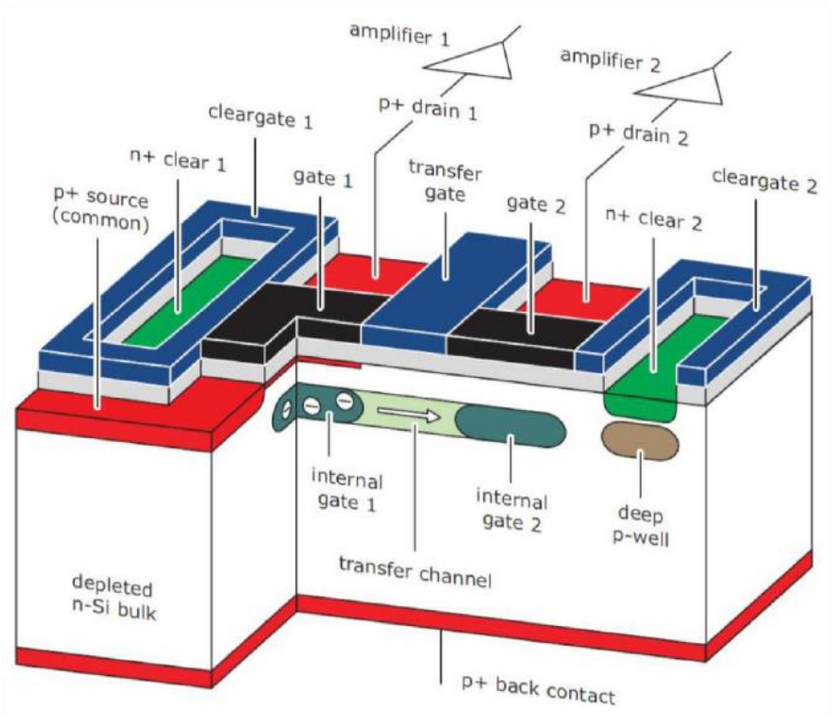
- Active pixel sensor, capable of full parallel operation
  -> One r/o node for each pixel
- Fast timing achievable
- Complex pixel structure, almost no charge transfer needed
- Medium pixel size (75 x 75 μm^2) smaller pixel feasible

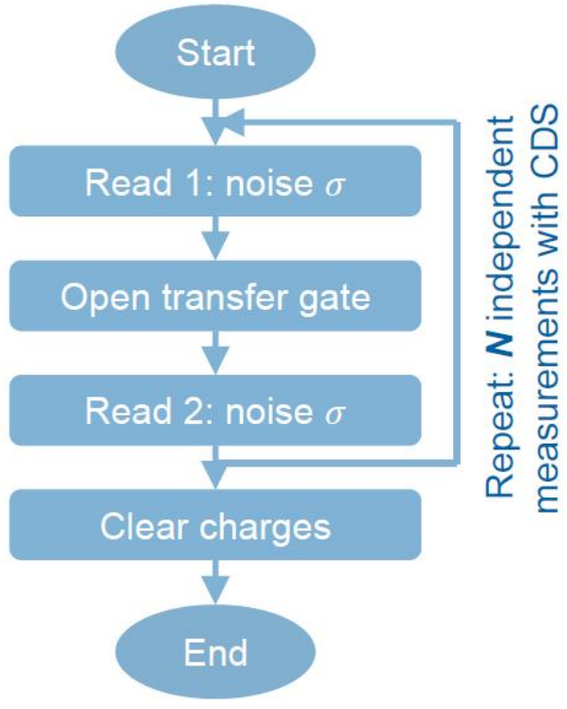


- **DePFET**
  - e^- collected in the internal gate
  - Gate on -> establish current between SRC and DR proportional to nr. of e^- -> signal
  - Sample signal with e^- – clear e^- by cleargate and clear on – sample signal without e^- (Correlated double sampling)
  - Appr. 2 e^- ENC per one r/o at 3 µs

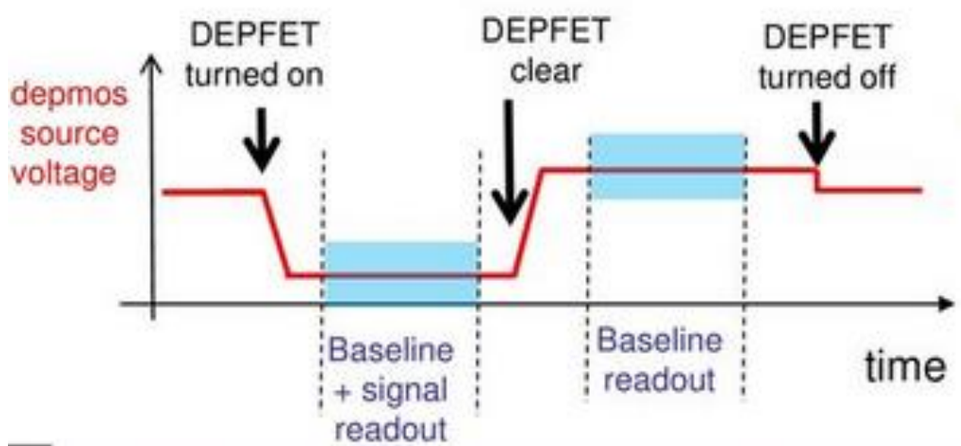


- **RNDR - DePFET**
  - Couple two DePFET pixels
  - Instead of clearing e^-, shift to additional internal gate through transfer gate
  - Perform repetitive r/o
  - Noise scales with $1/\sqrt{N}$

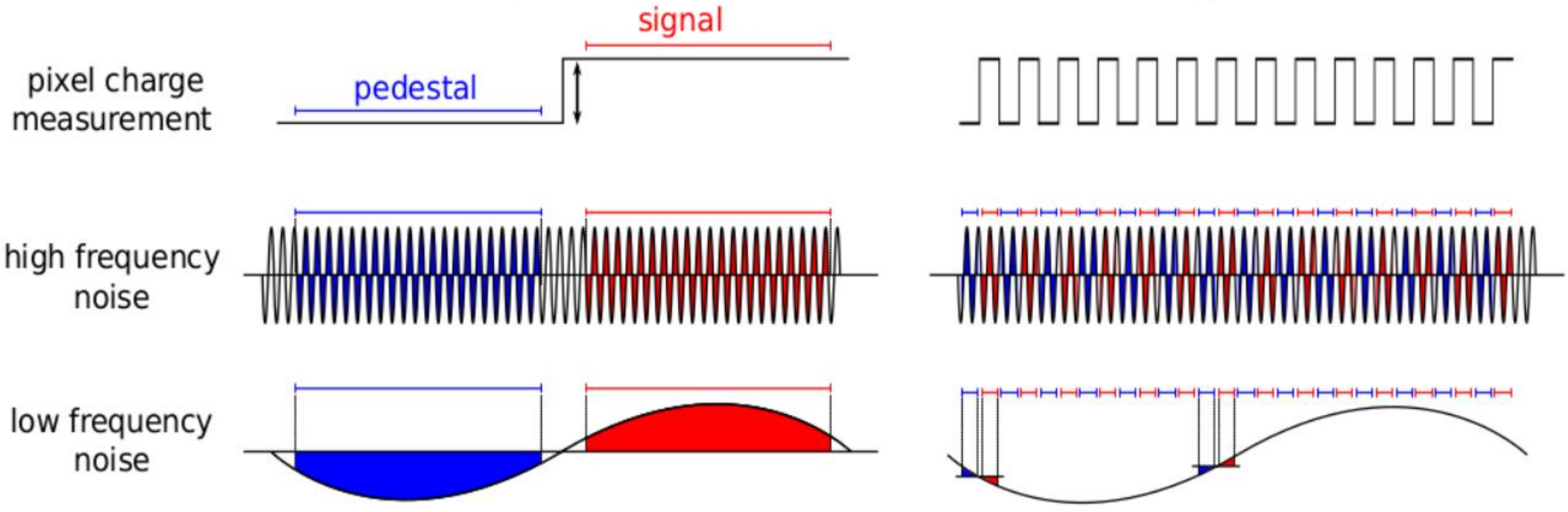




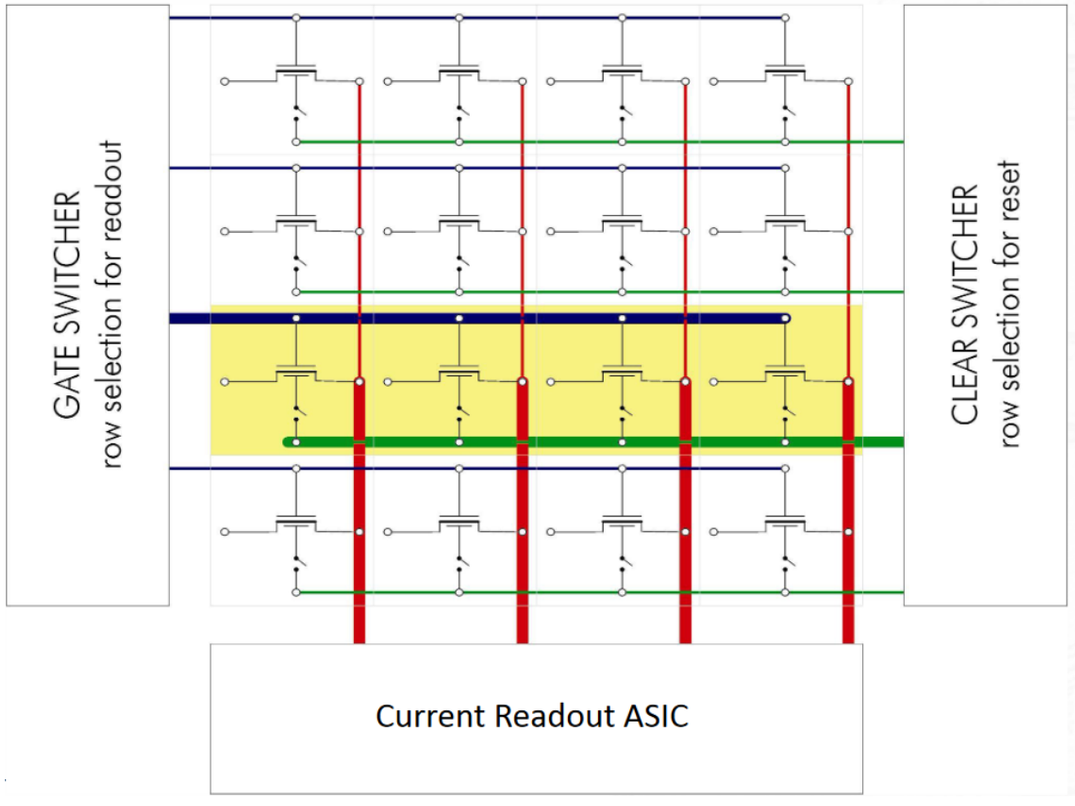
- White or high frequency noise is reduced in the same way by
  - Long signal integration (CDS)
  - Repetitive readout

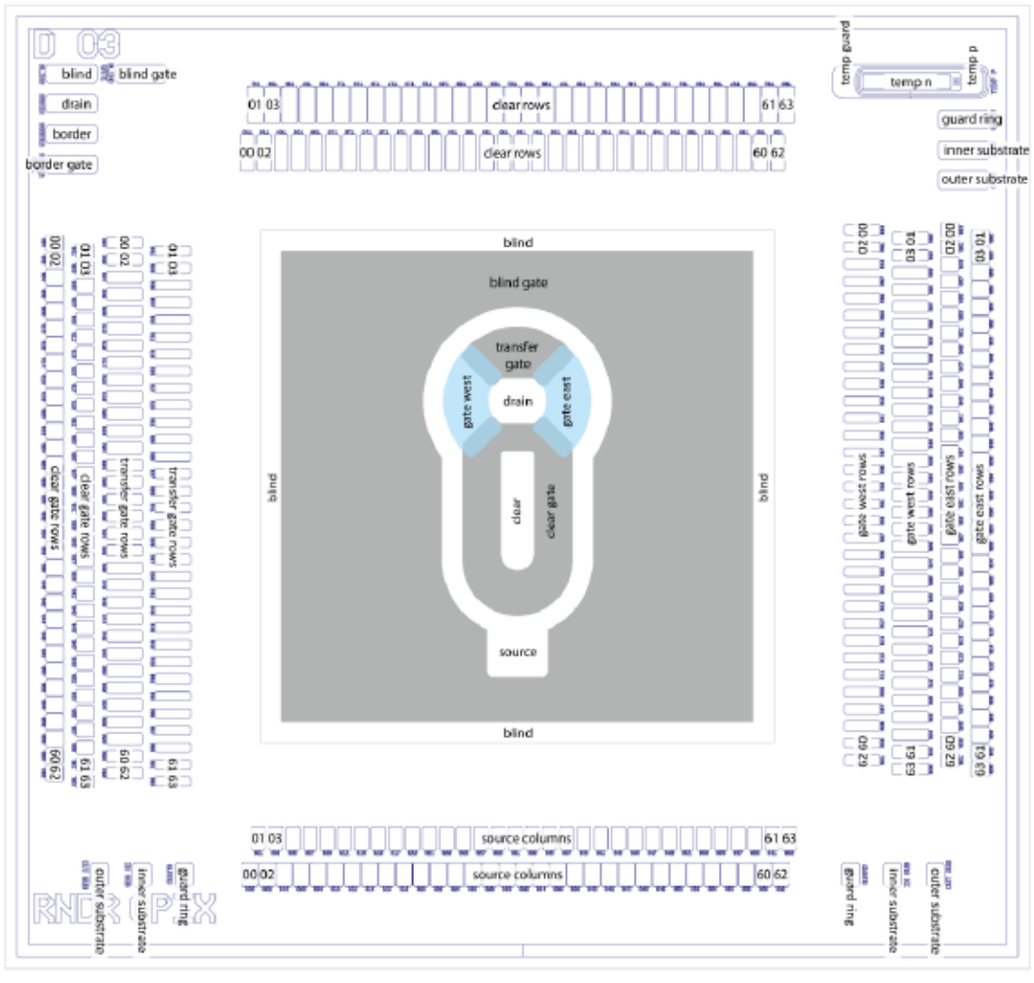


- 1/f or low frequency noise requires independent samples of the same signal to be reduced -> RNDR



- A DePFET pixel is the unit cell of a sensor matrix
  - Rows: Ext. gates, transfer gate, clear gate and clear
  - Columns: Connected to r/o nodes (Drains)
  - Rolling shutter: Pixels of one row are r/o in parallel others are turned off





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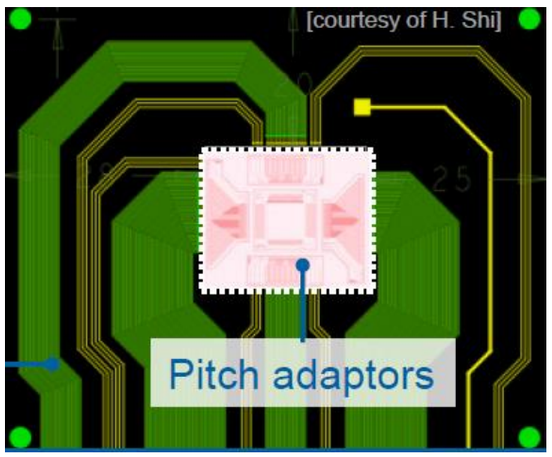
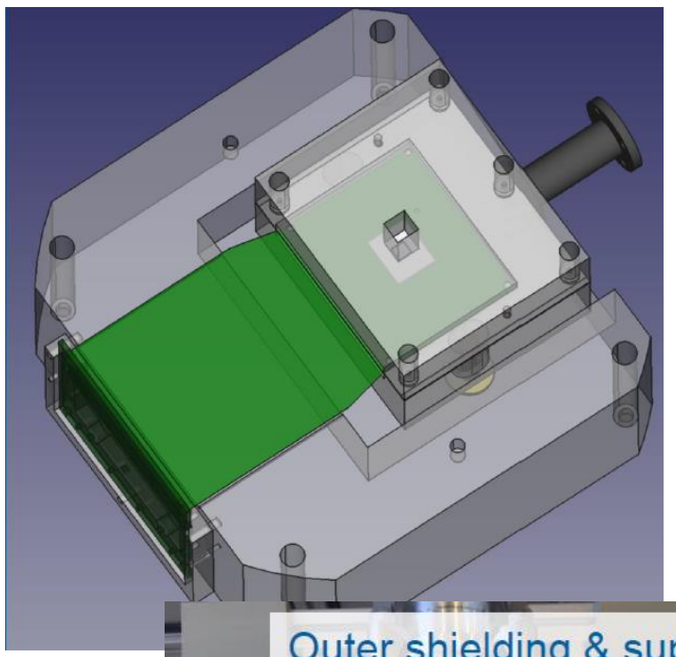
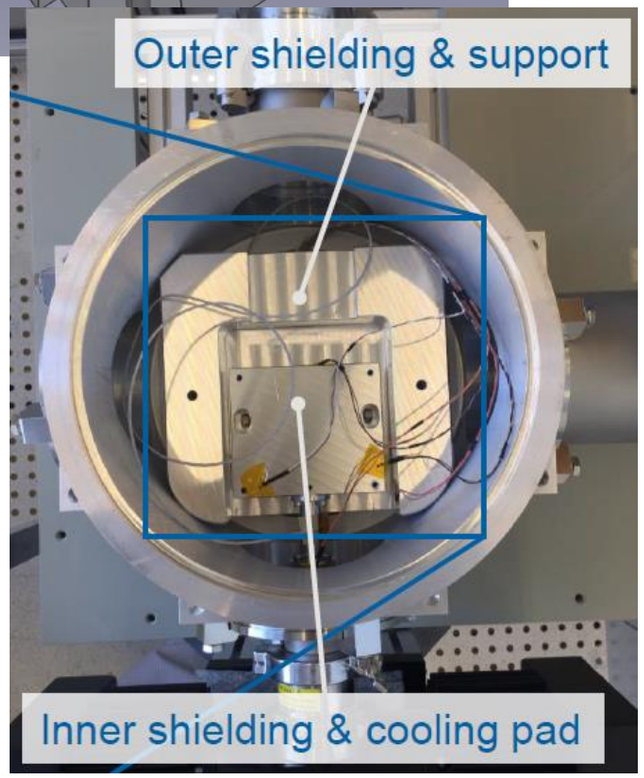
DANAE setup:

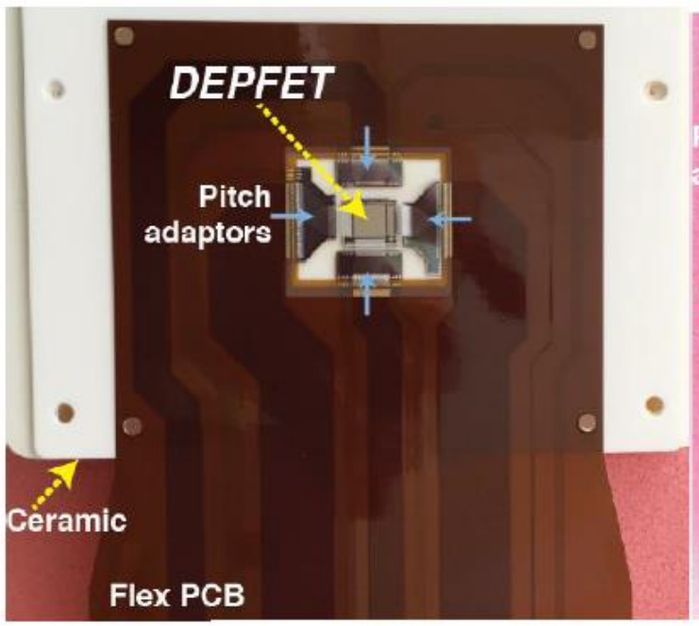
- First operation of an RNDR – DePFET matrix
- 64 x 64 pixels a 75 x 75 x 450 μm^3, 24 mg
- Operation in vacuum appr. 10^{-6} mbar
- Stirling cryostat to reach sensor temperatures appr. -160° C

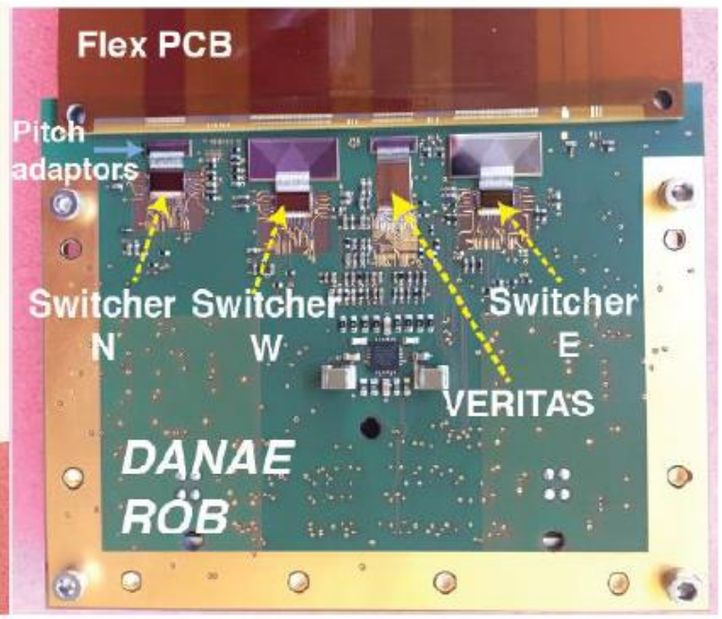






[courtesy of H. Shi]

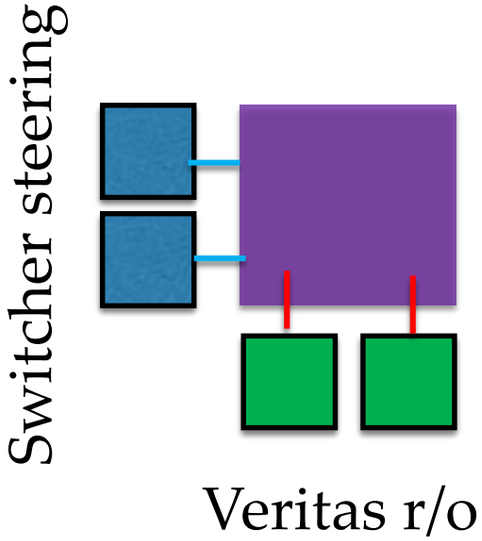




How to scale the sensitive mass?

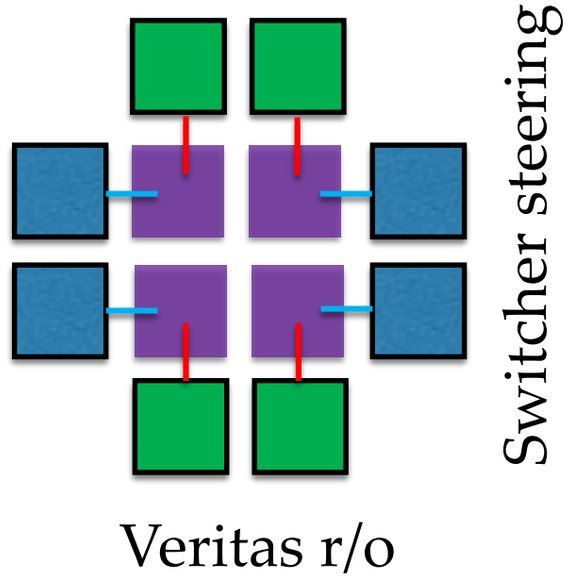
Employ a few large sensors

+ Reduce complexity (nr. of ASICs of experiment $2\sqrt{n}$, n ~ 64x64 pixel)
- Strict requirements on fabrication



Employ many small sensors

- Requires the operation of many ASICs ($2n$, n ~ 64x64 pixel)
+ Flexible fabrication



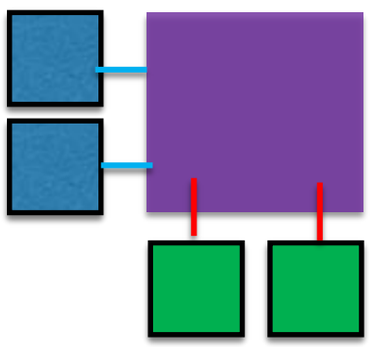
How to scale the sensitive mass?

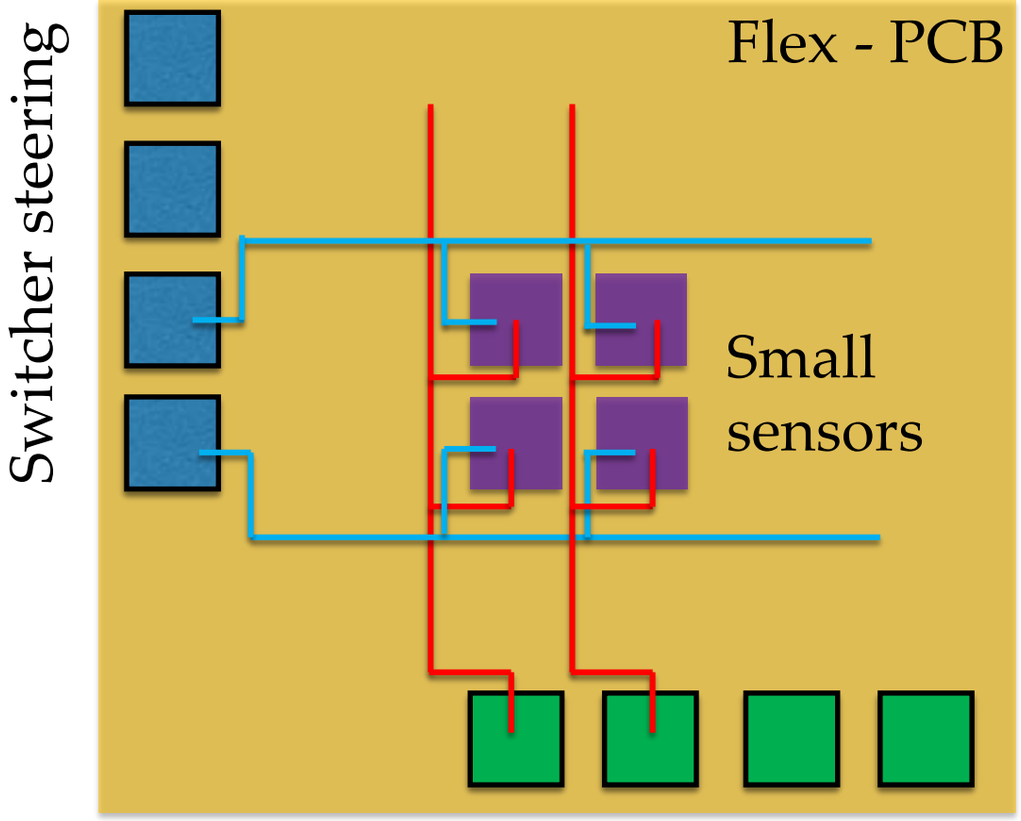
-> active DePFET pixel concept with flex – PCB offers option of "patched" detector

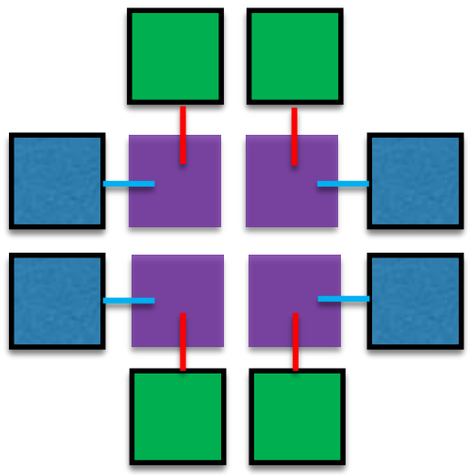
+ reduce number of ASICs

+ ease fabrication

- Non continuous area (DM applications for bkg. rejection)

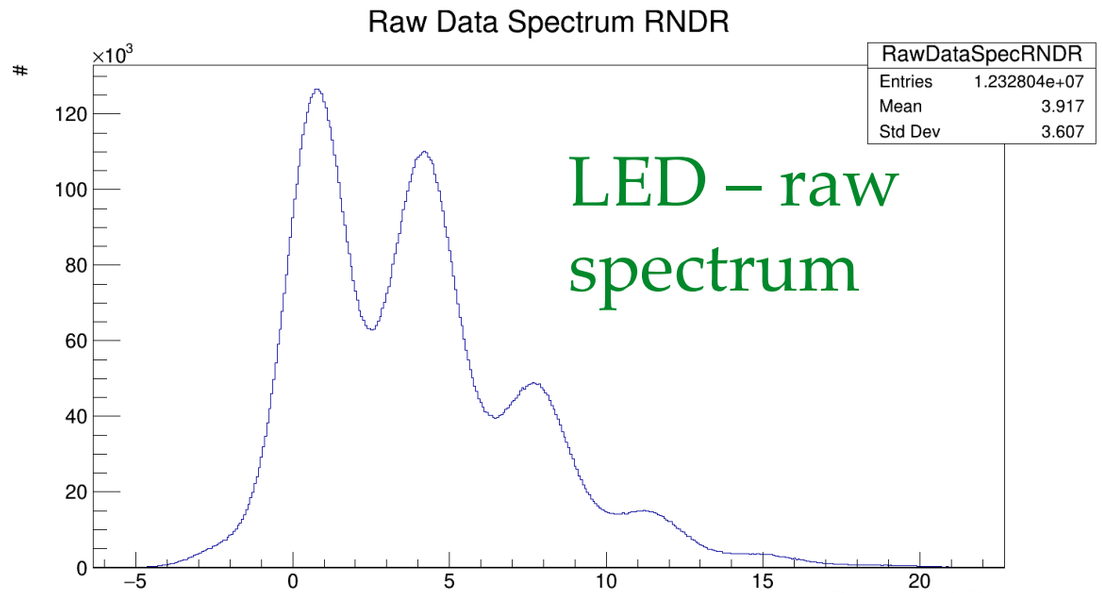


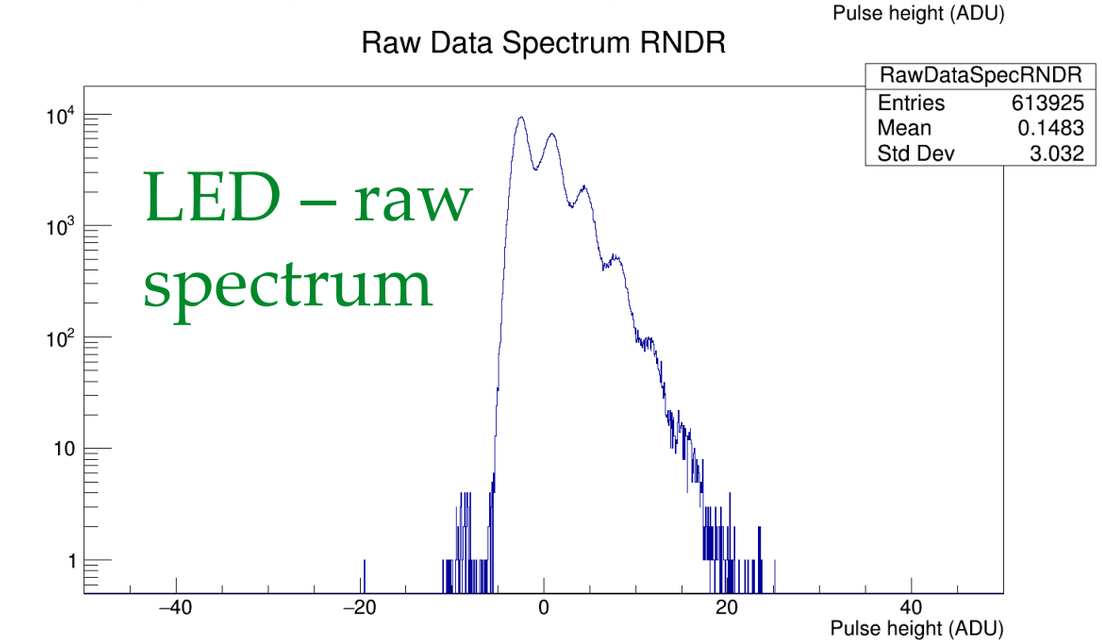




Matrix Results - general

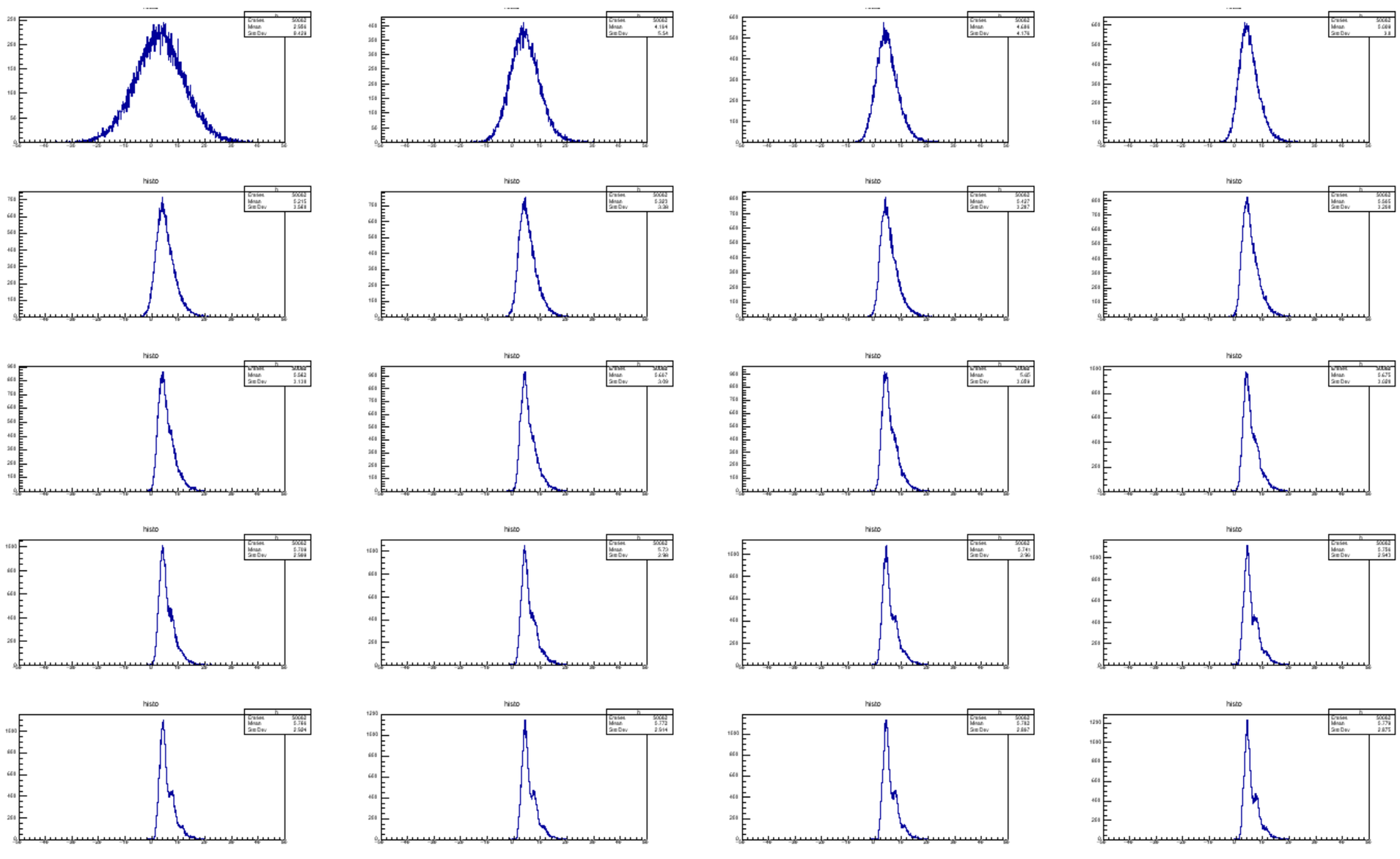
- Data analysis had to be adapted
- Measurements of LED “source”, operated in “single photon” mode
- 200 repetitions a appr. 18 µs (per sng r/o) signals merged by average for each pixel
- Raw spectrum: uncalibrated averaged values of each pixel





Merging signals

10 Rep

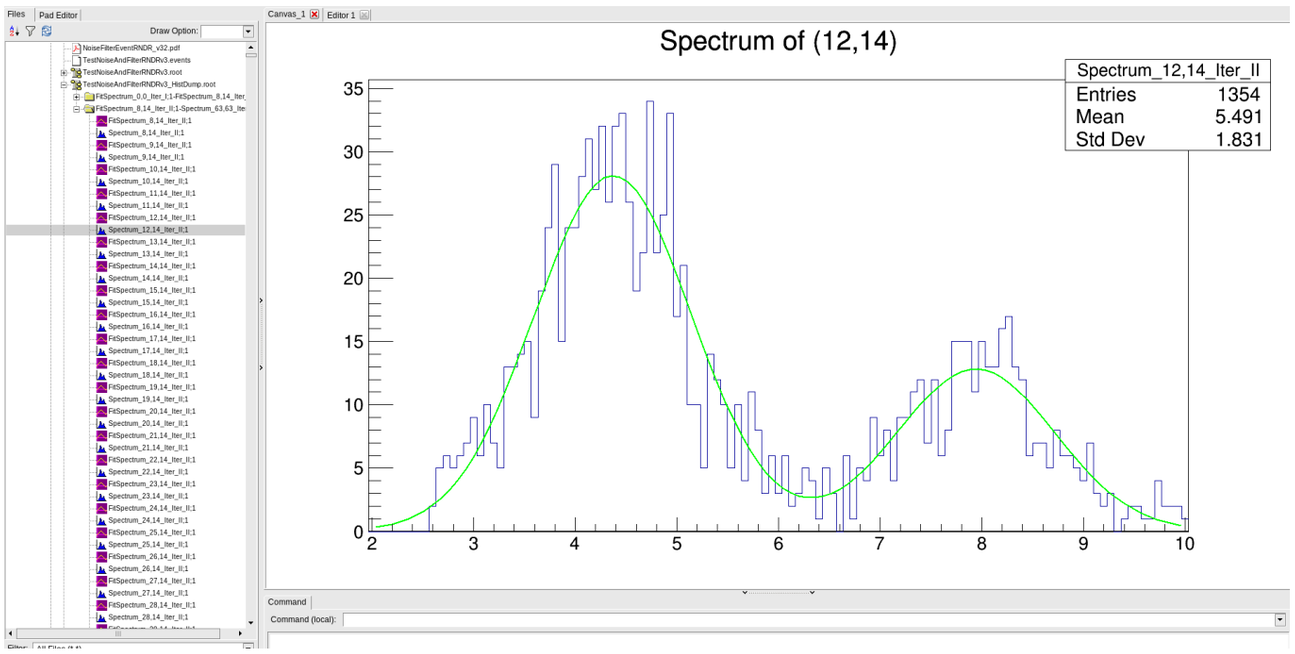


40 Rep

170 Rep

200 Rep

Calibration

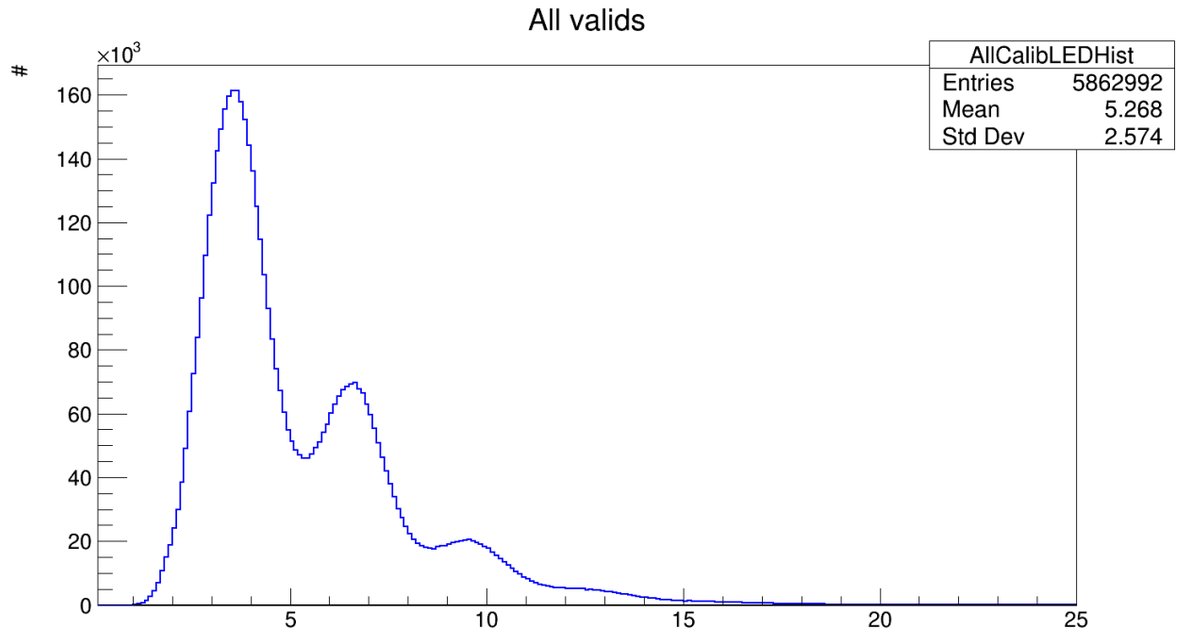


- After event filtering (noise cut) single pixel spectra are stored and fitted to identify signal peaks

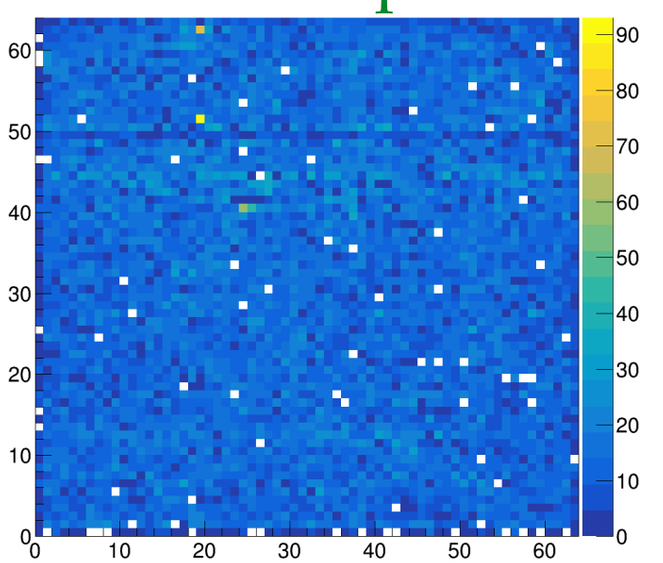
- Different performance of pixels -> challenging for fitting algorithm (multiple Gauss + bkg.)

Matrix Results - general

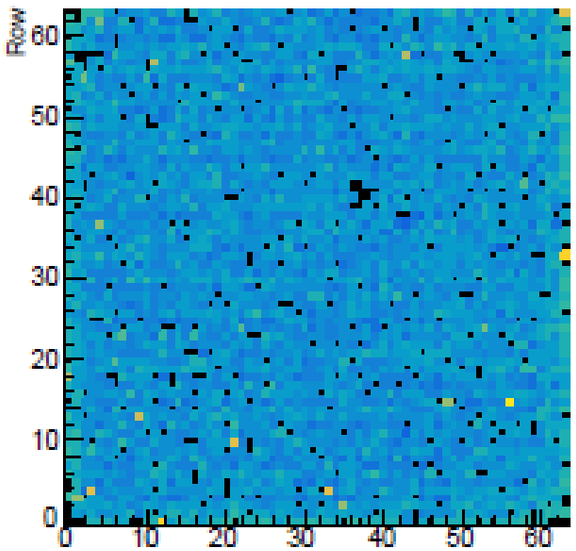
- Calibrated spectrum (at eV)
- Calibrated noise after 200 repetitions at about 0.15 e$^-$ENC
- Homogenous performance on sensor

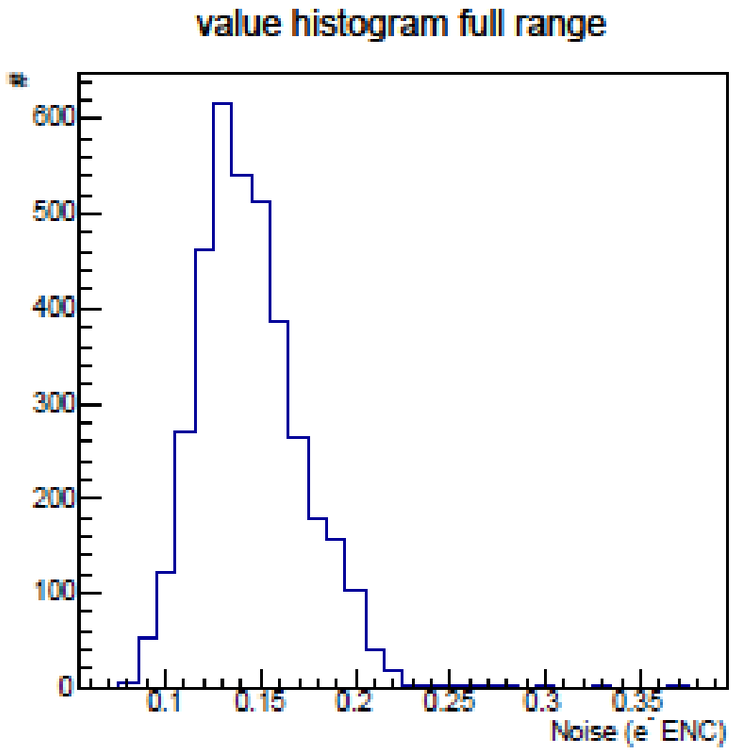


"Hitmap"



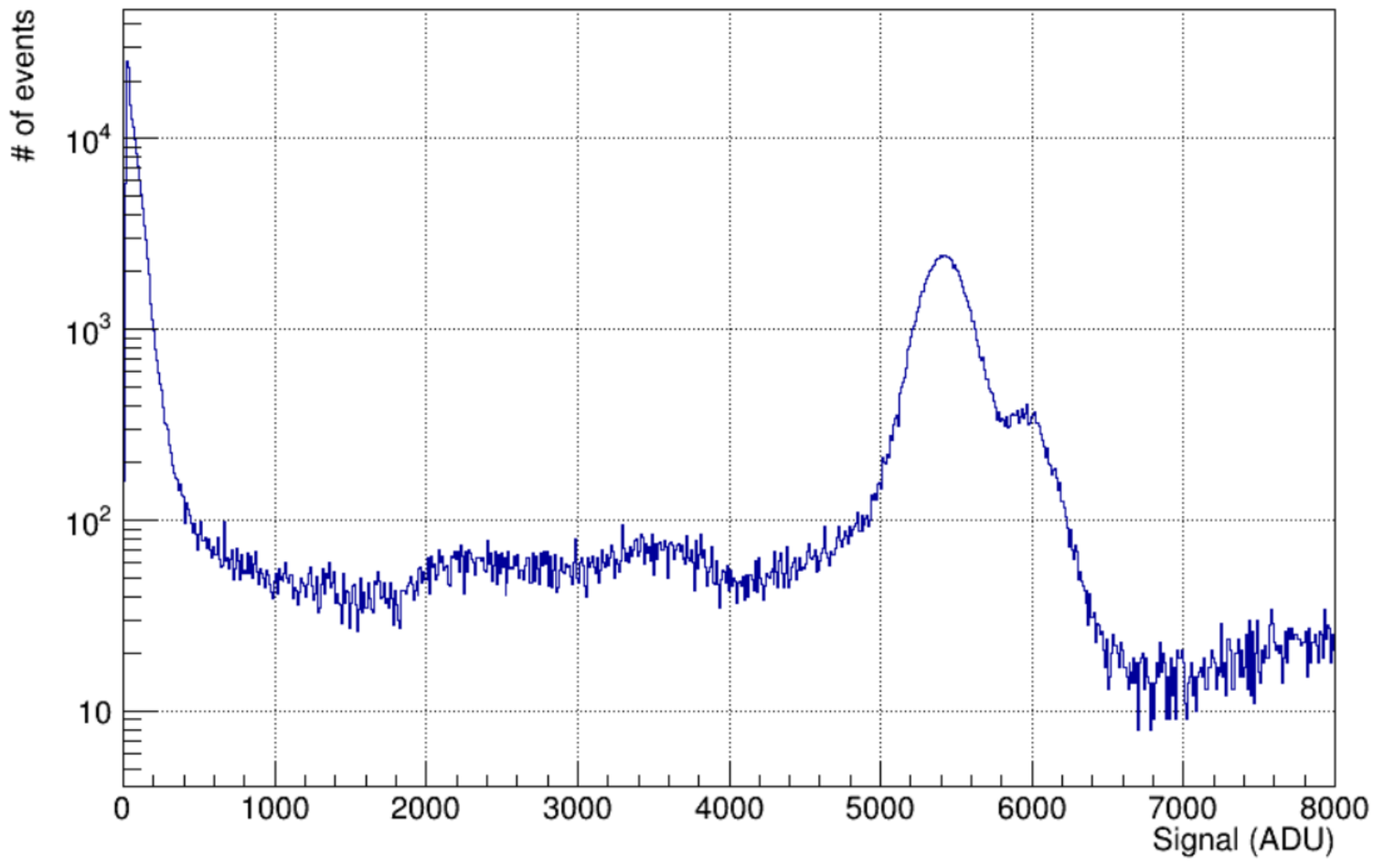
"Noisemap"



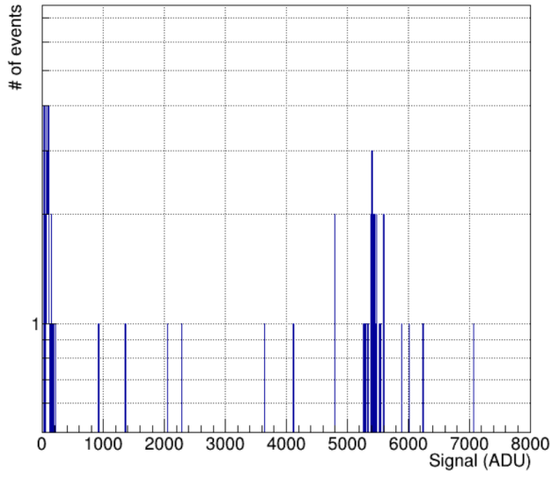


^{55}Fe – Source (preliminary)

- Recombined spectrum before calibration
- Not sufficient signals per pixel for calibration
- Plateau due to interframe splits



Pixel (25/25)



Current generation:
"Absolute" dimension: $e^-/m^2/sek$
"Relevant" dimension: $e^-/pix/ro$

- Exposure dependent "bulk leakage current": 0.006 $e^-/pix/ro$ (comparable to skipper CCDs) ✔
- Additional current due to spurious charge carrier generation, which scales with the number of clocking a voltage (edge of signal) ✘

Conclusion
- RNDR-DePFET matrix sensors work well w.r.t. sub-electron noise and homogeneity
- Extended calibration with ^{55}Fe source ongoing
- Modelling of optimized operation, considering the spurious charge carrier generation
- Data collection for background studies scheduled