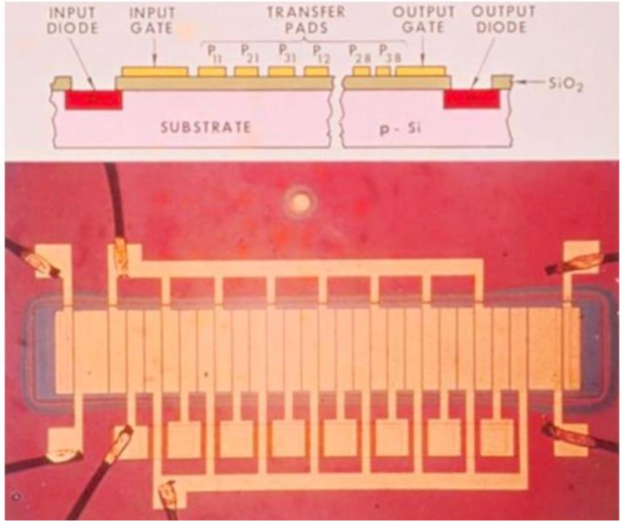
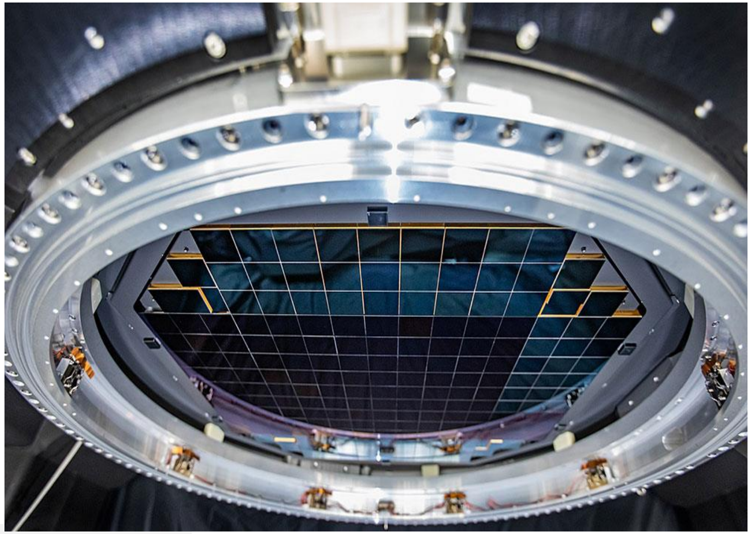
Skipper CMOS:
a single electron capacity fast camera

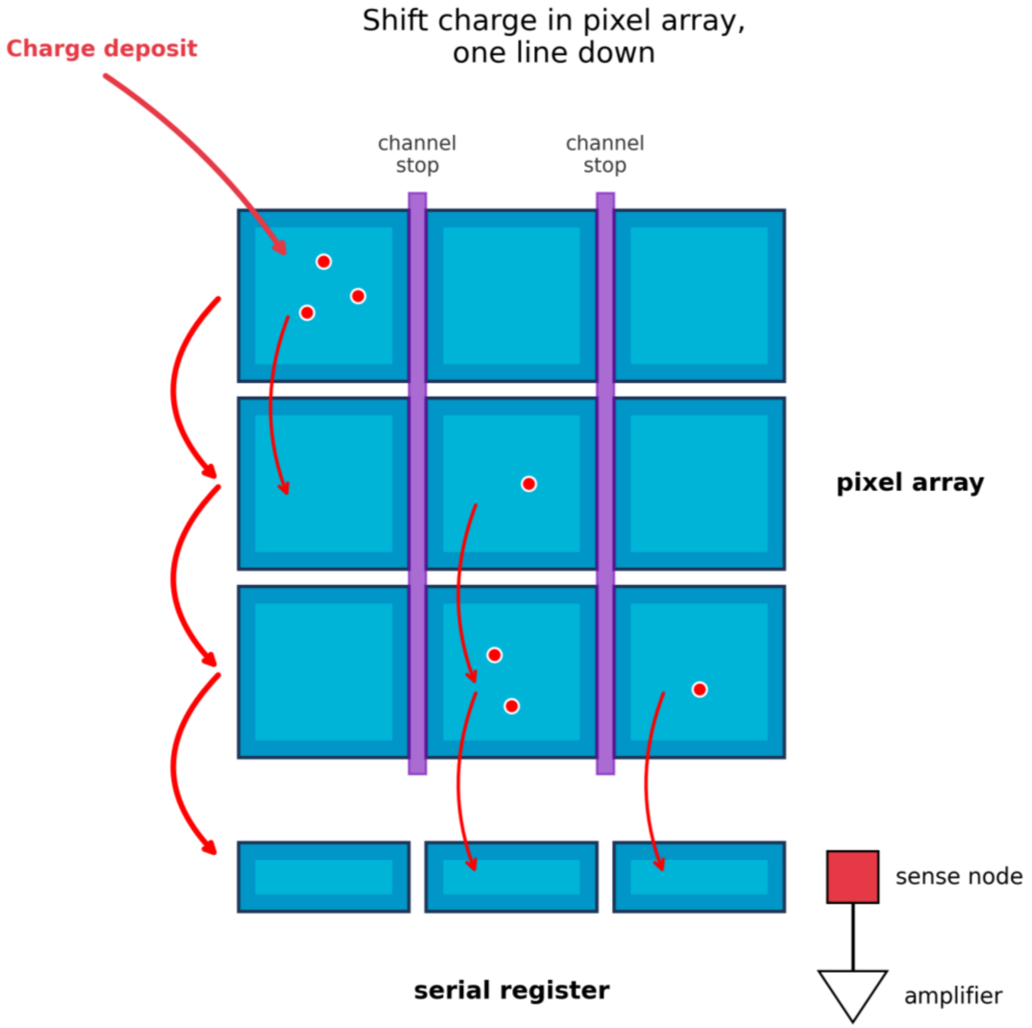
Jérôme Baudot, Xavier Bertou, Christian Bourgeois, Manuel Da Rocha Rolo, Davide Falchieri, Maciej Kachel, Lucio Pancheri, Angelo Rivetti

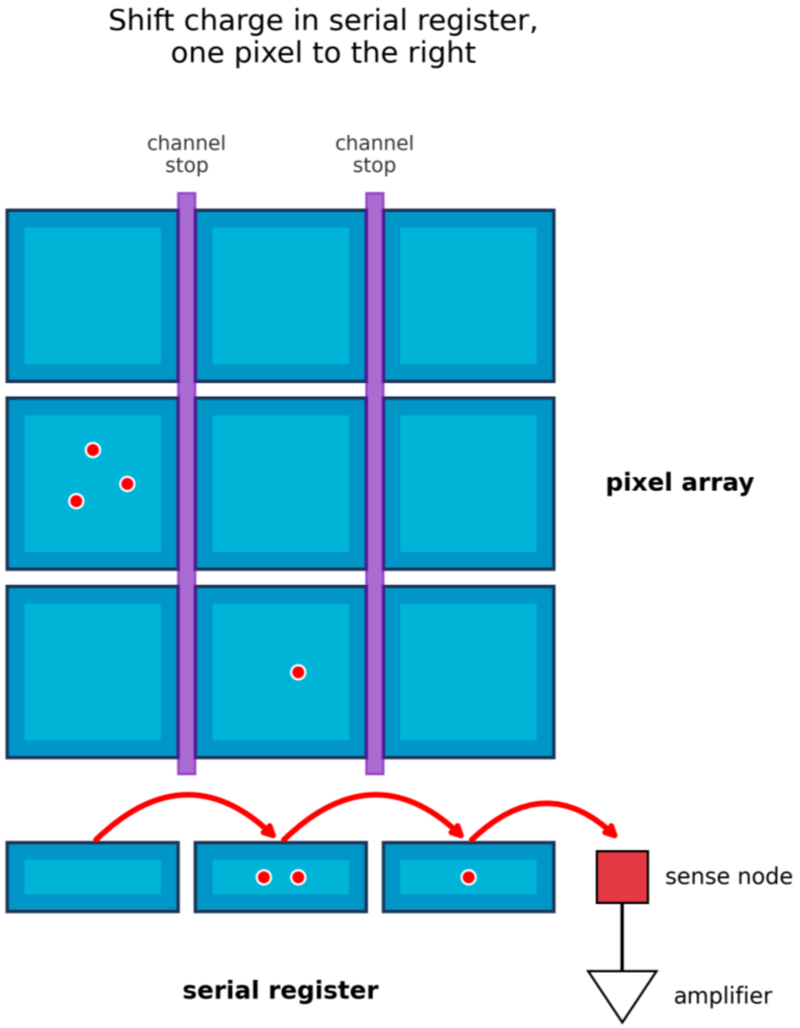
CCDs were invented in 1969 by Boyle and Smith (Bell Labs). The idea was to make a memory device, but it works better as an image sensor and was quickly used in consumer devices, with Kodak manufacturing the first digital camera in 1975.



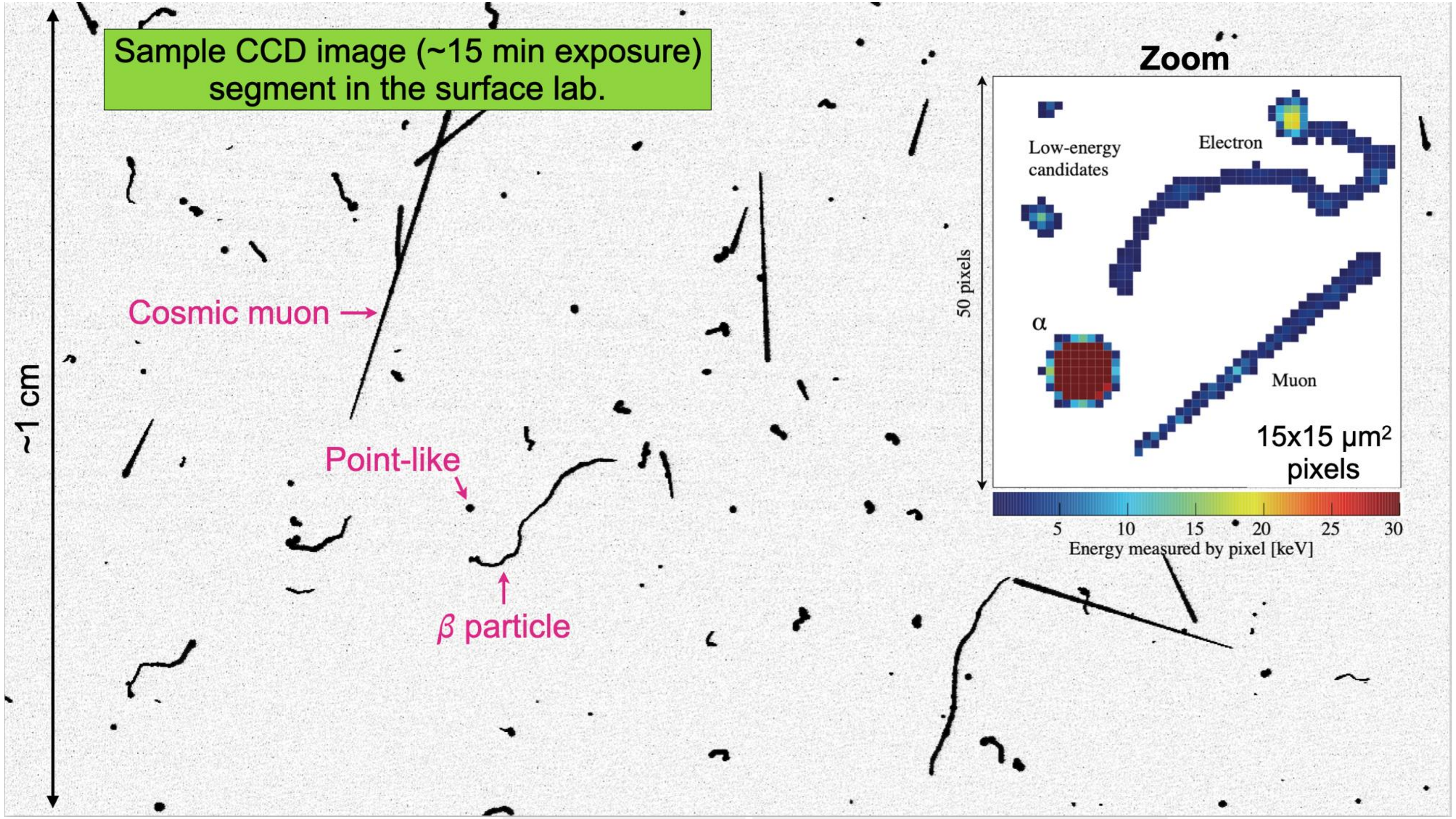


CCD pixel array reading principle

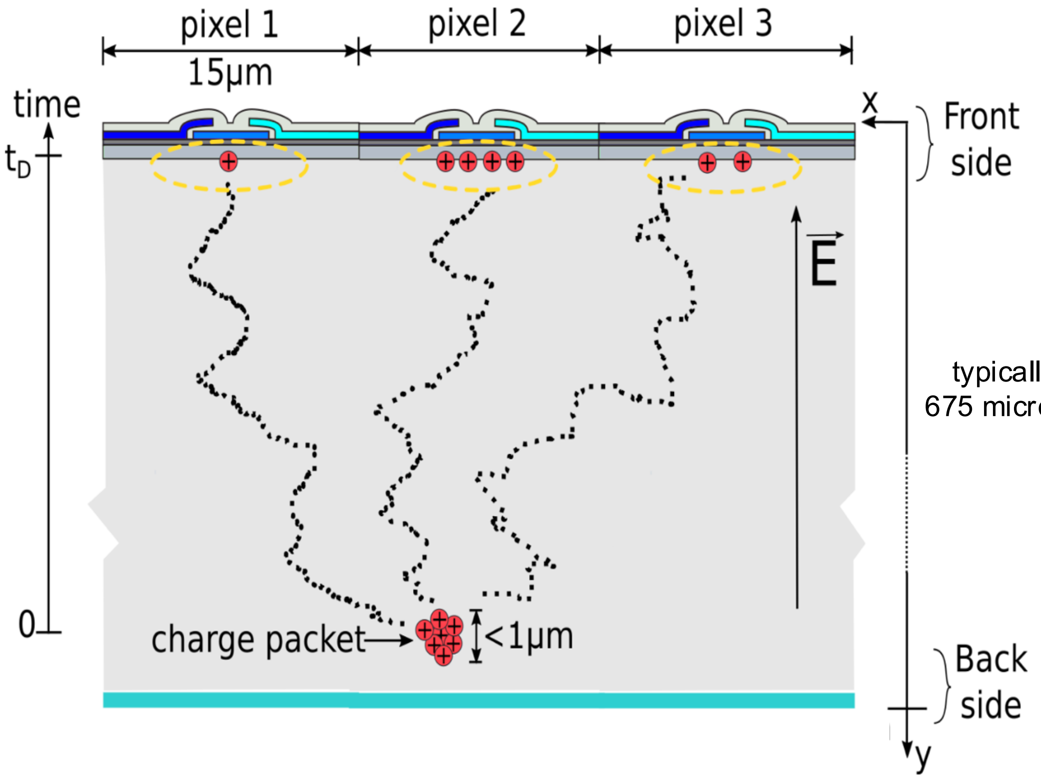




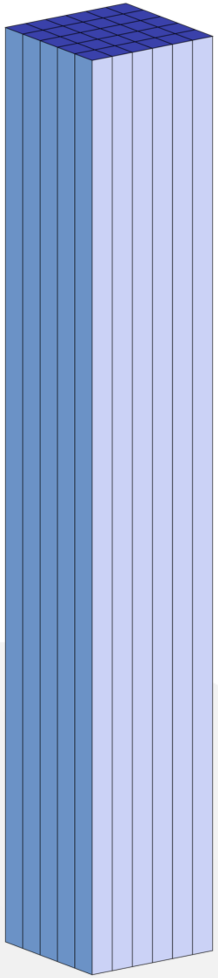
CCD as particle detector

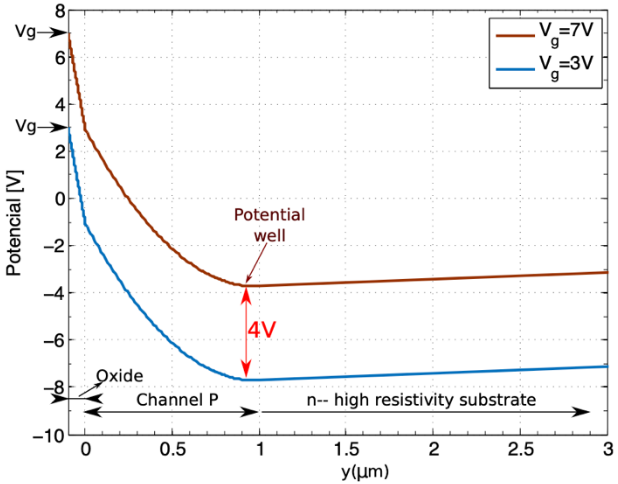


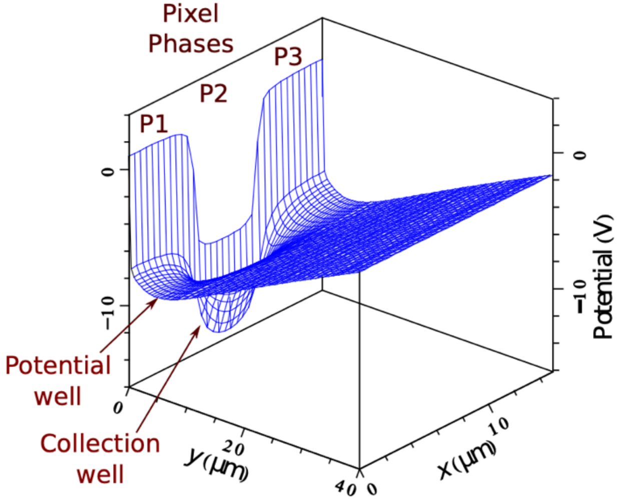
CCD as a dark matter detector



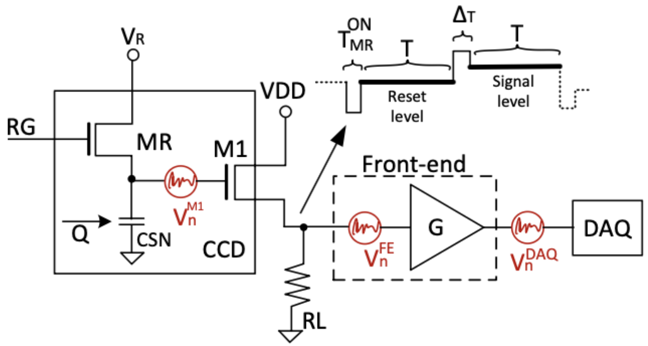
Pixel array
15um x 15um
x 675um

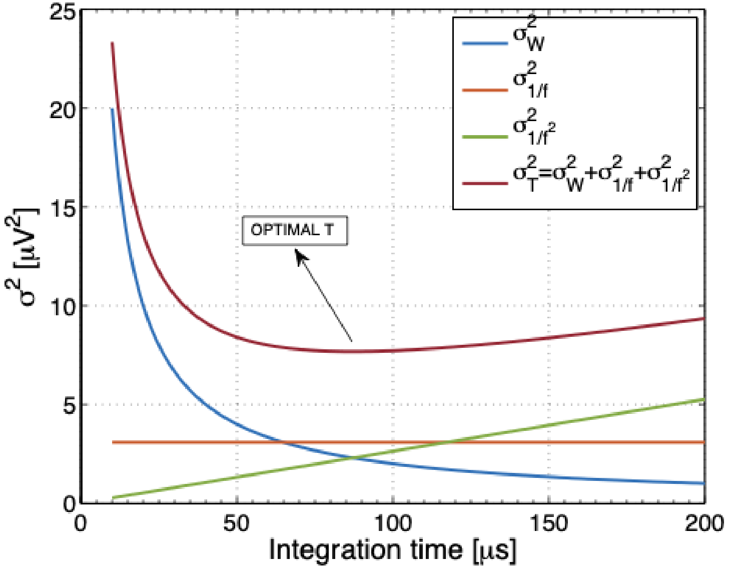


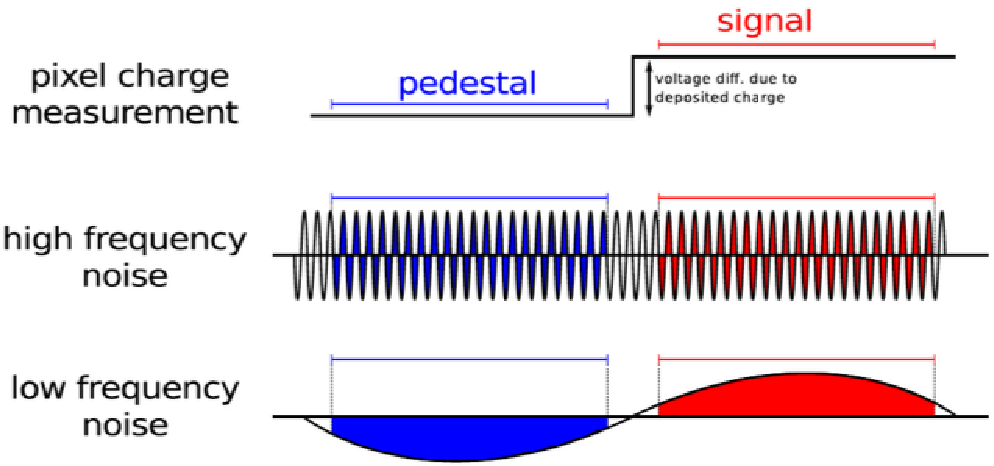




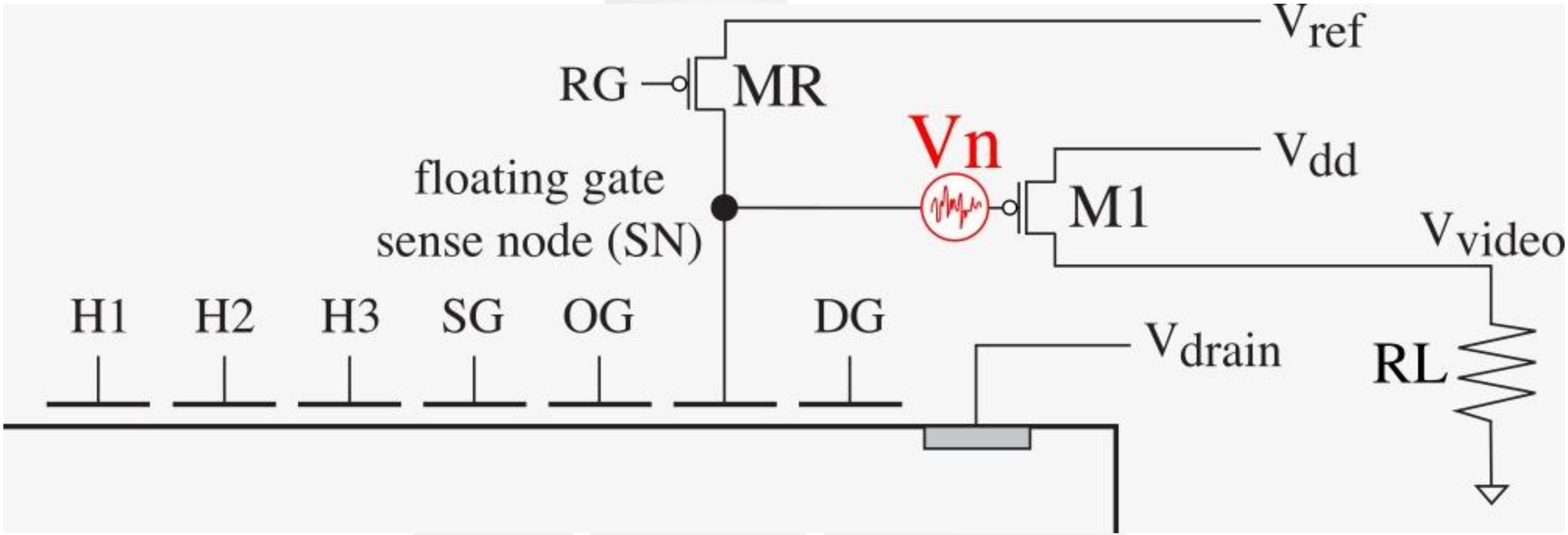
Correlated double sampling and low frequency noise

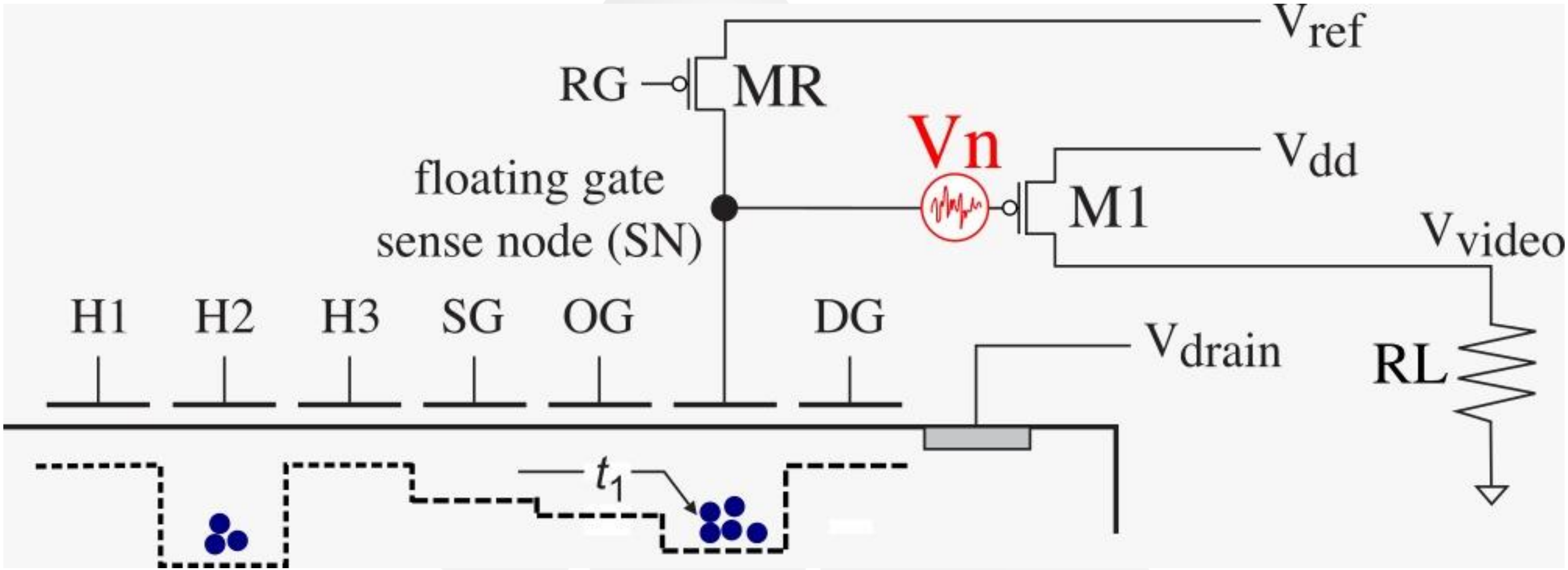


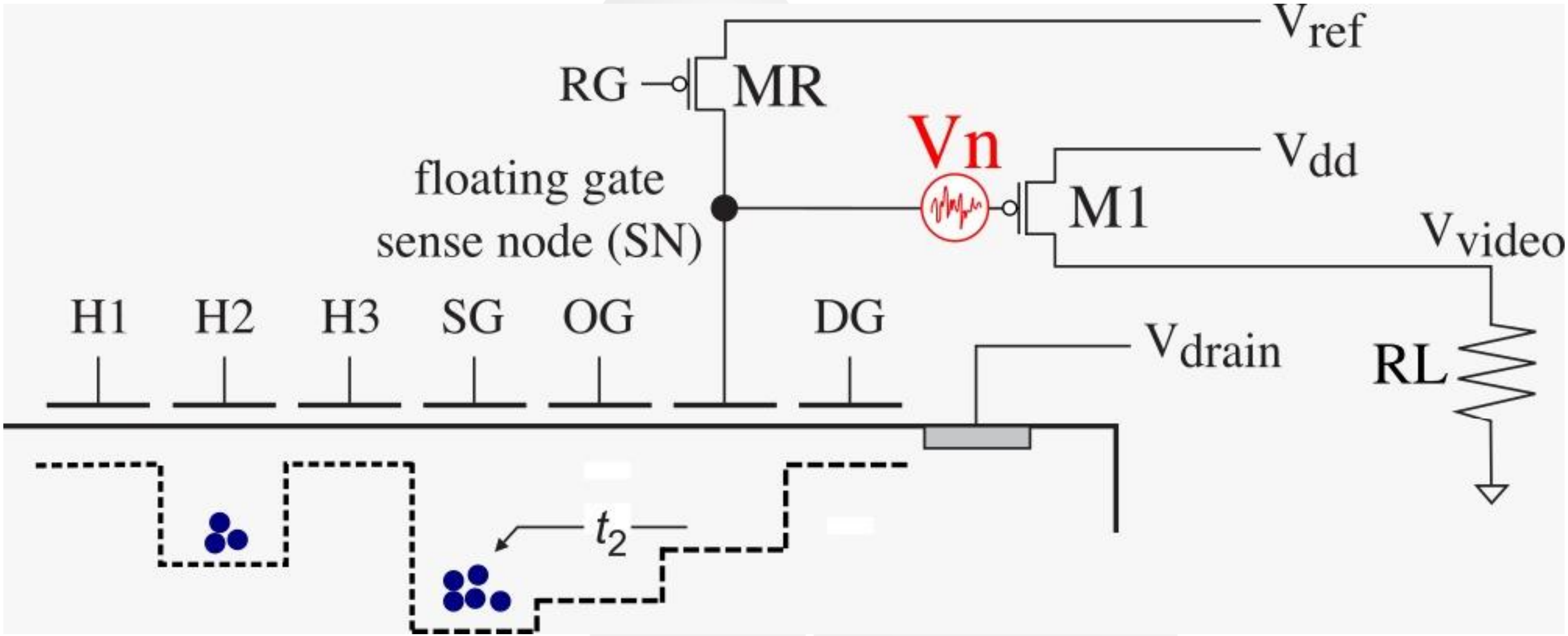




Nondestructive readout with the Skipper CCD




Vref
RG
MR
Vn
Vdd
floating gate
sense node (SN)
M1
Vvideo
H1
H2
H3
SG
OG
DG
Vdrain
RL
t1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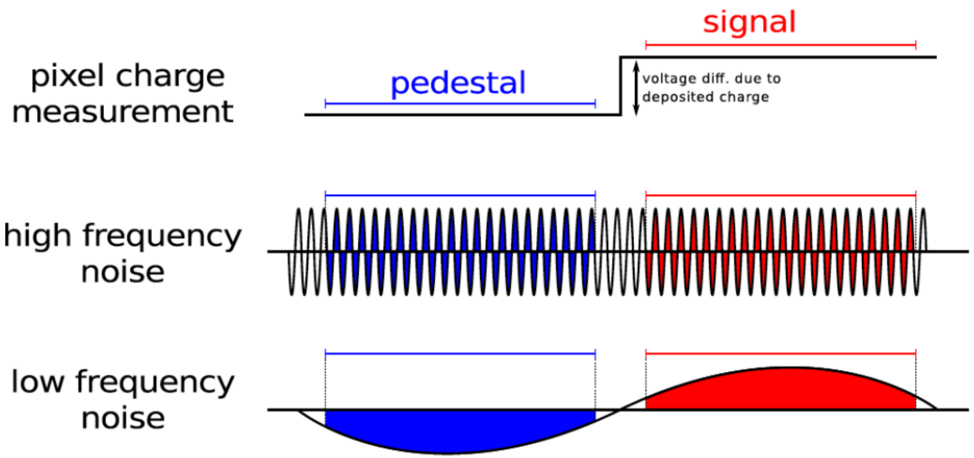
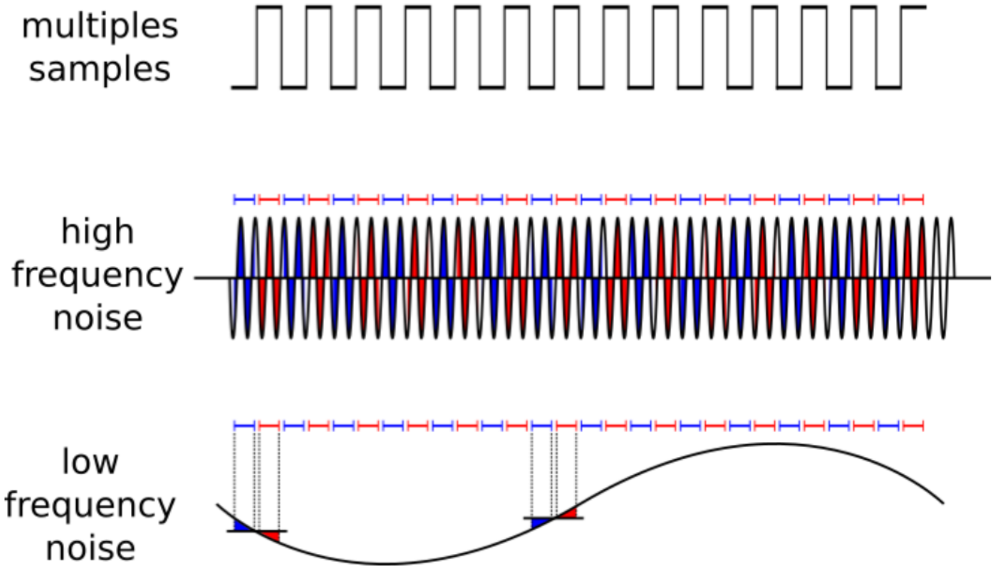
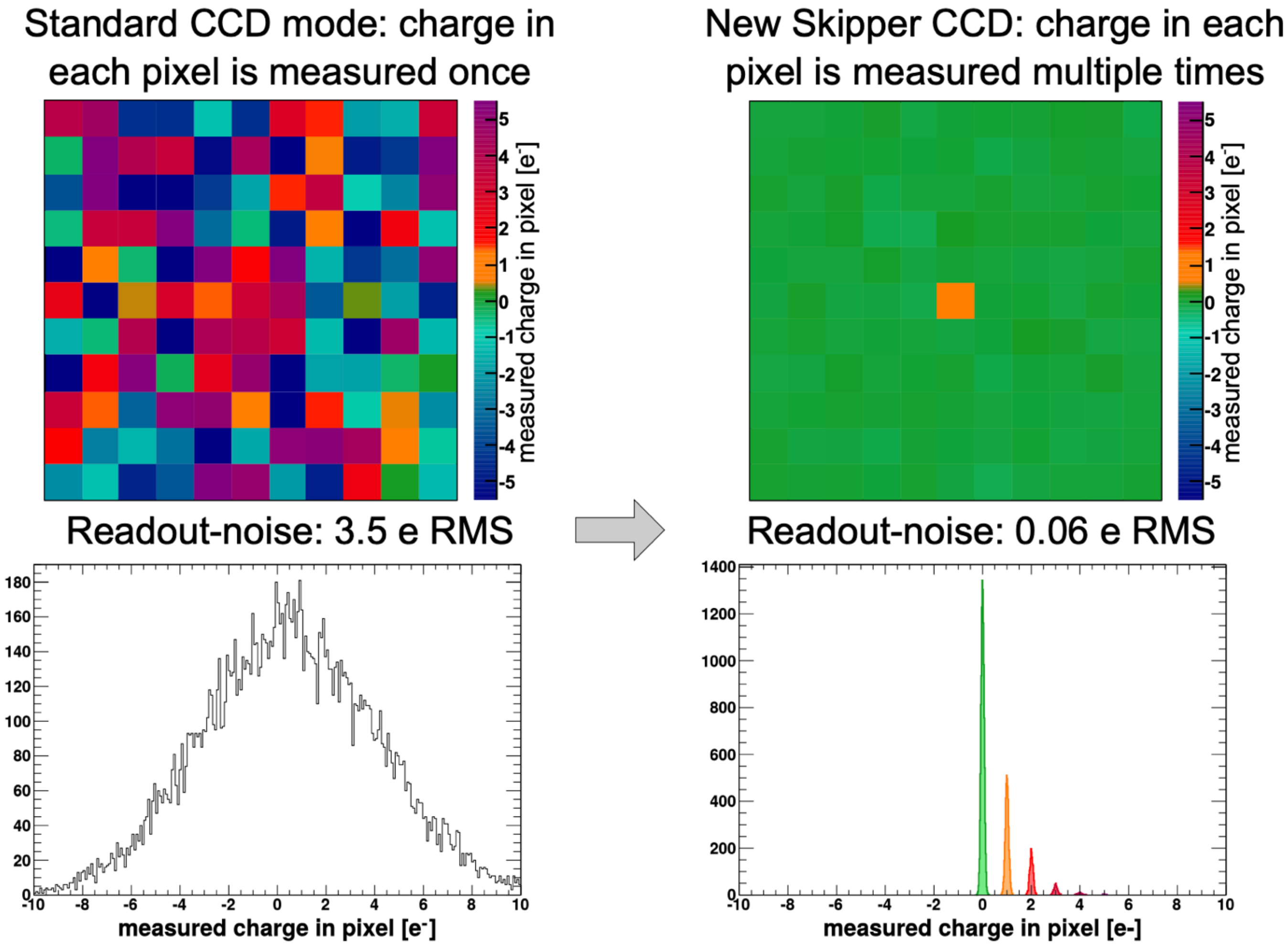




Noise goes in $1/\sqrt{N}$

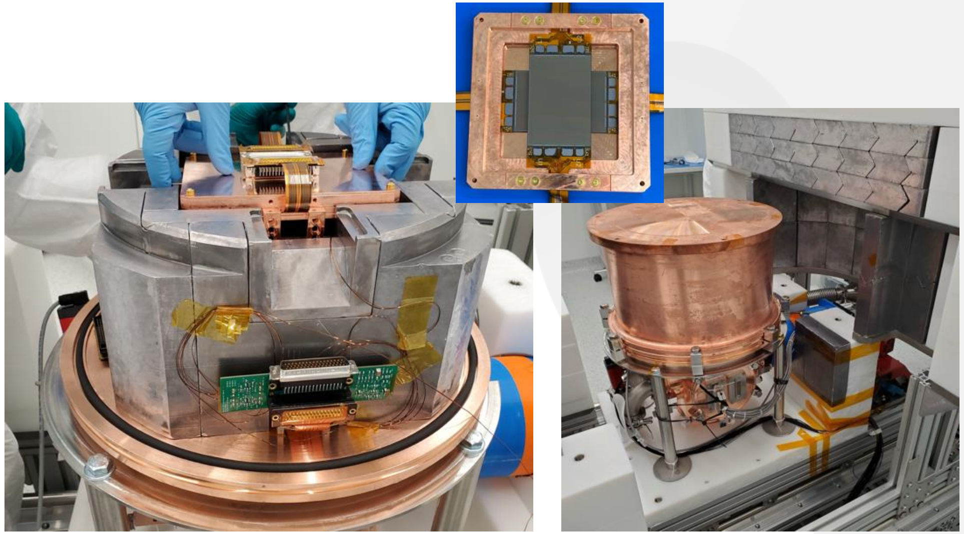
Single electron:
threshold is silicon
band gap (1.1 eV)

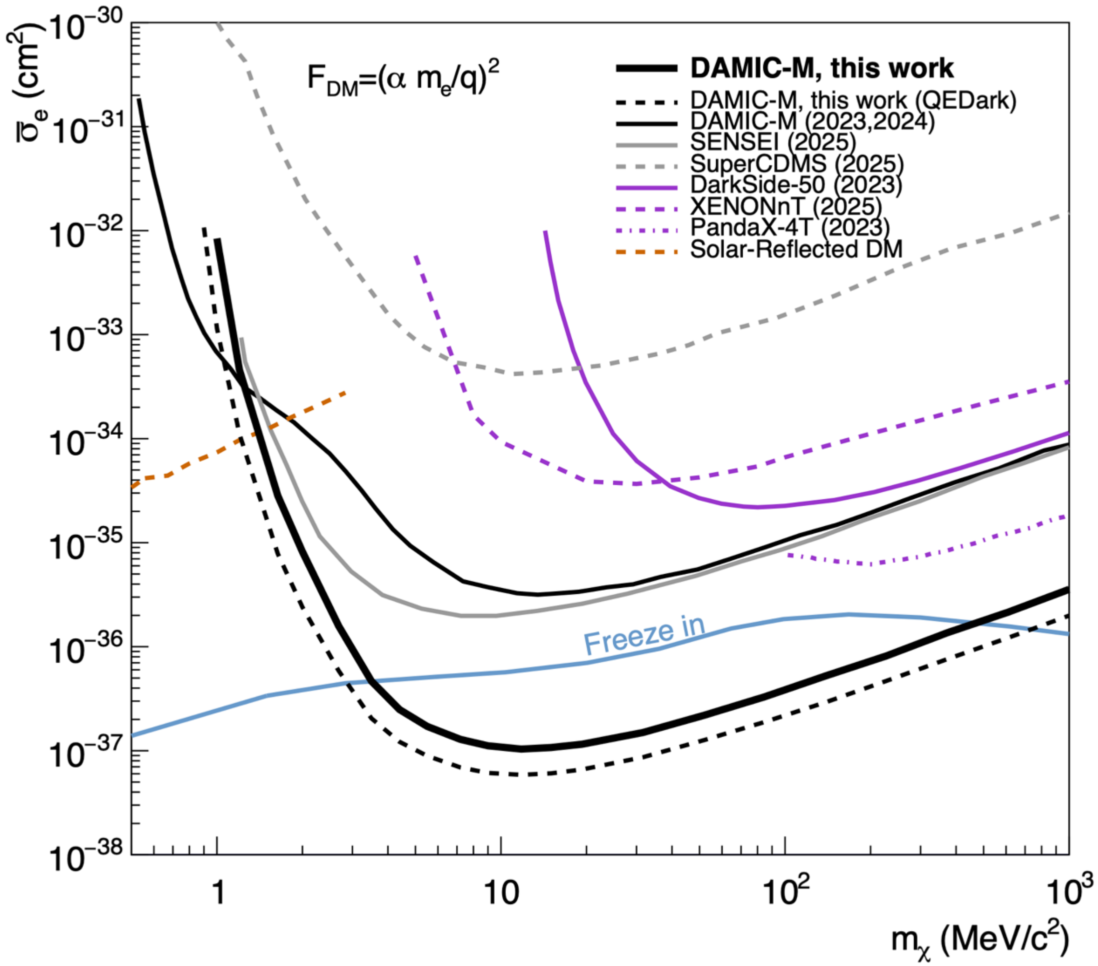
PRL 119, 131802 (2017)



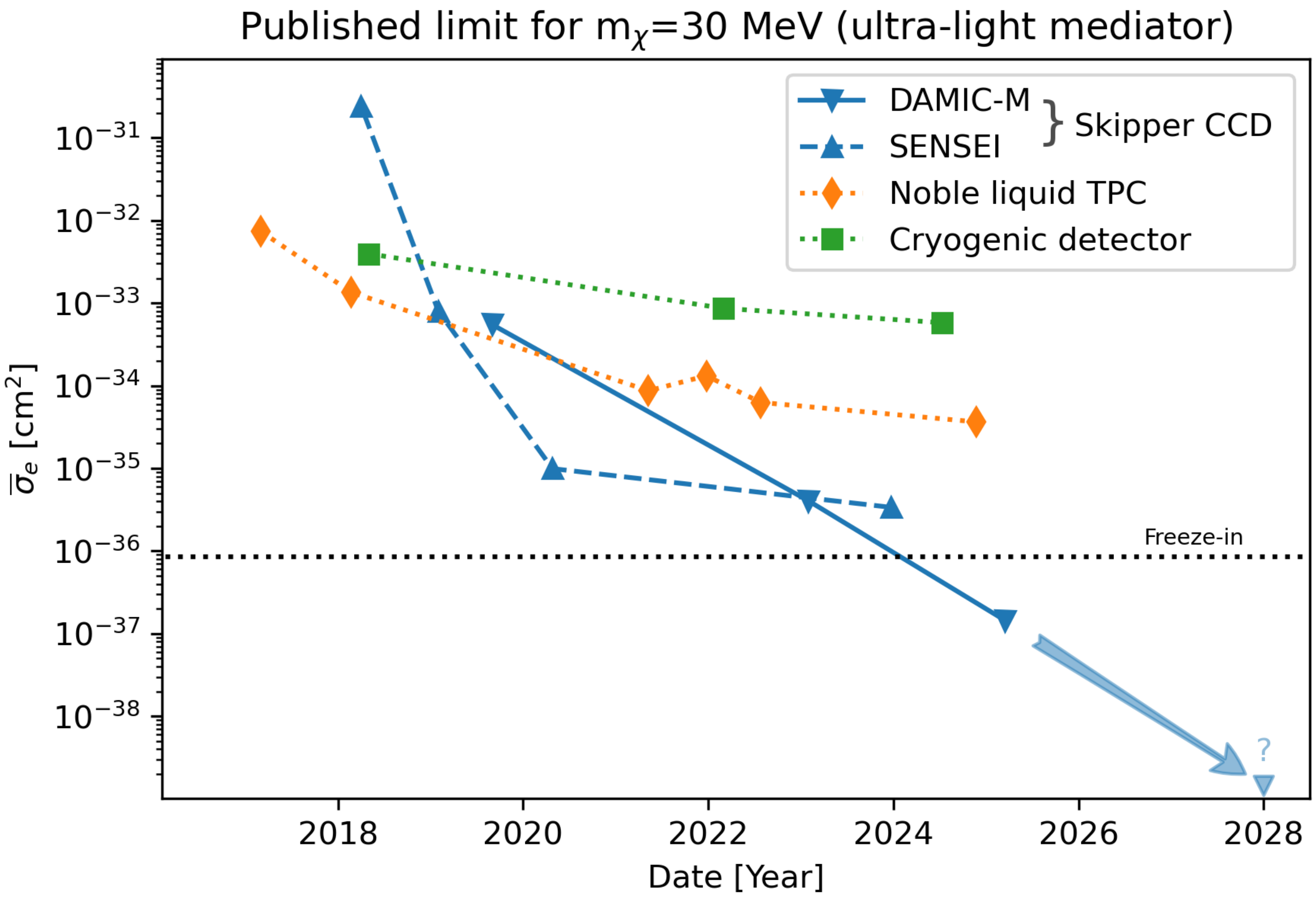
Probing Benchmark Models of Hidden-Sector Dark Matter with DAMIC-M

Phys. Rev. Lett. 135, 071002 (2025)





Skipper CCD vs other technologies



Note that the DAMIC-M results are form the prototype of the experiment (LBC)

Expect new results in 1-2 years

Skipper CCDs

- Skipper CCDs benefit from tens of years of CCD industry optimization
- Skipper CCDs can have arbitrary low readout noise (usually work at 0.2 e^- or less)
- DC can be extremely low, 5-200 e^-/g/day (less than 1e^- per pixel per year)
- Charge can be moved by cm over days without being lost

Skipper CCDs limitation

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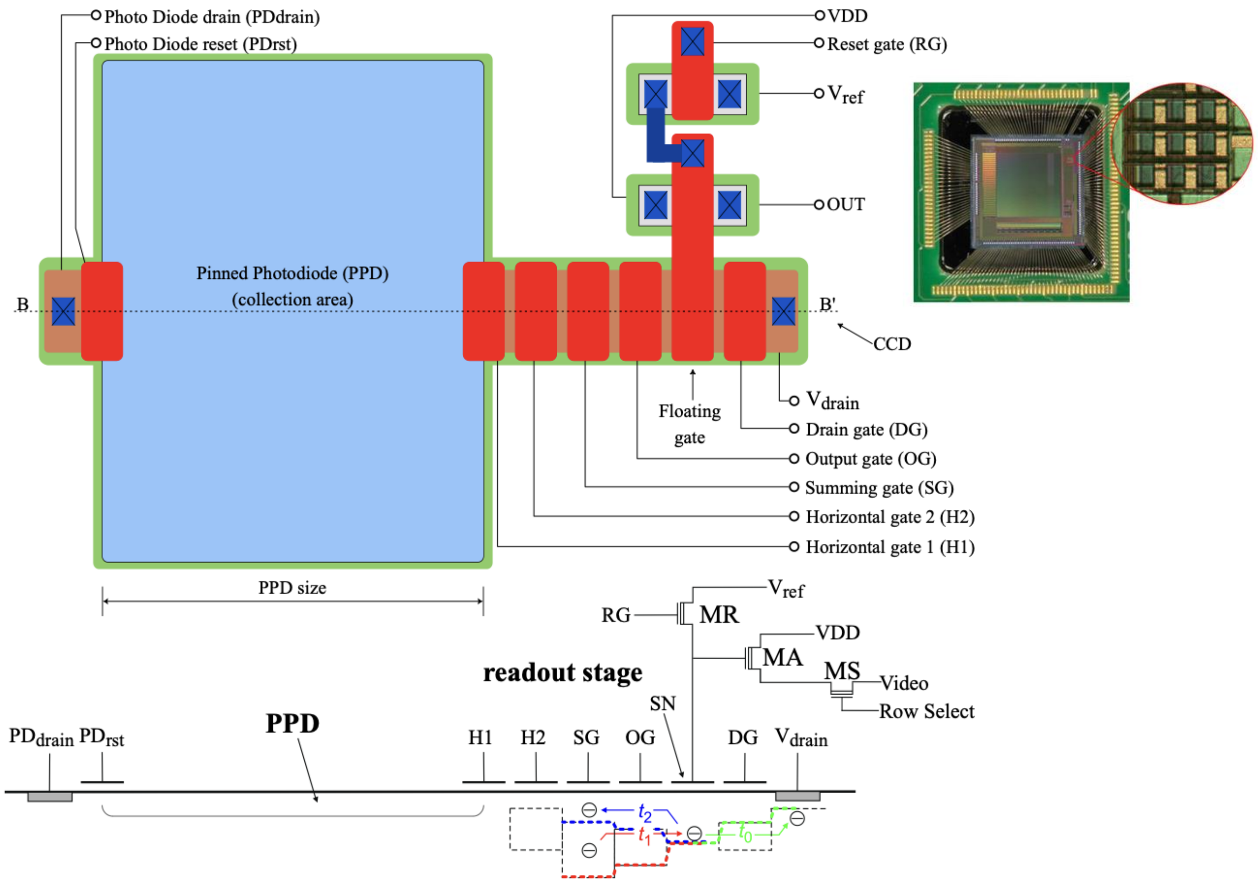
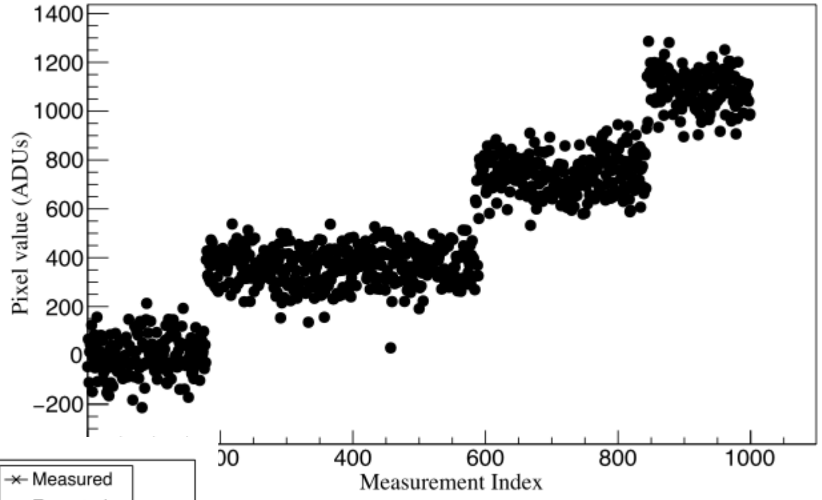
- Images take days to read out…
- No possible use outside of rare event searches

Skipper-in-CMOS: Non-Destructive Readout with Sub-Electron Noise Performance for Pixel Detectors

IEEE Transactions on Electron Devices, vol. 71, no. 11, pp. 6843-6849, Nov. 2024



Skipper in CMOS performance



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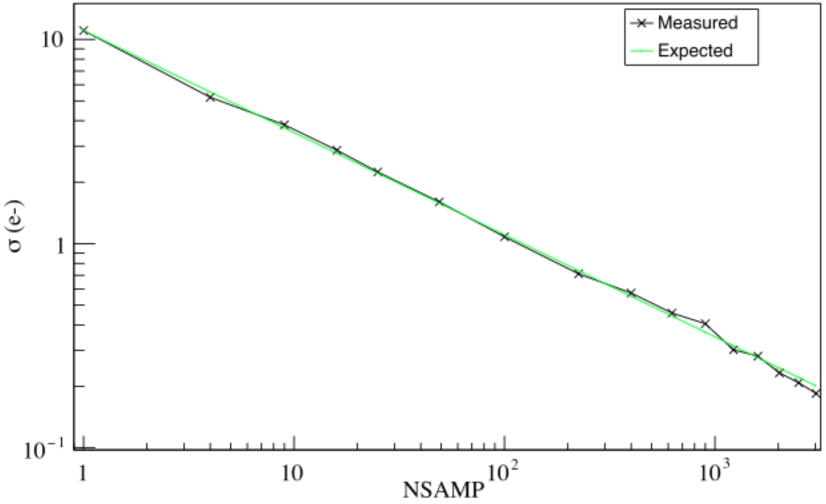
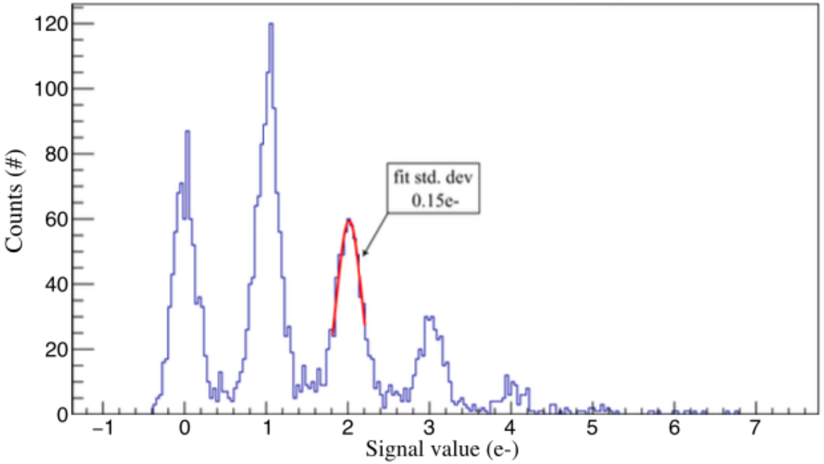
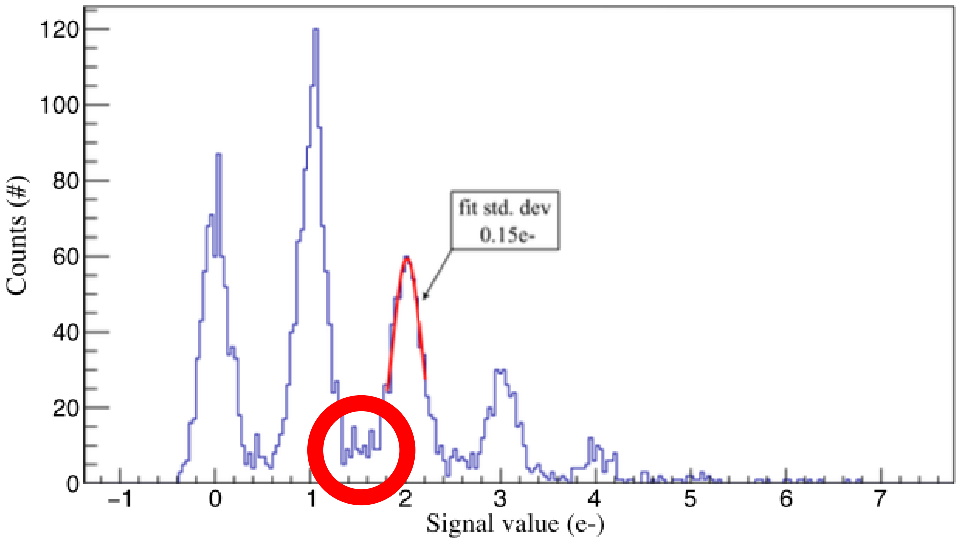
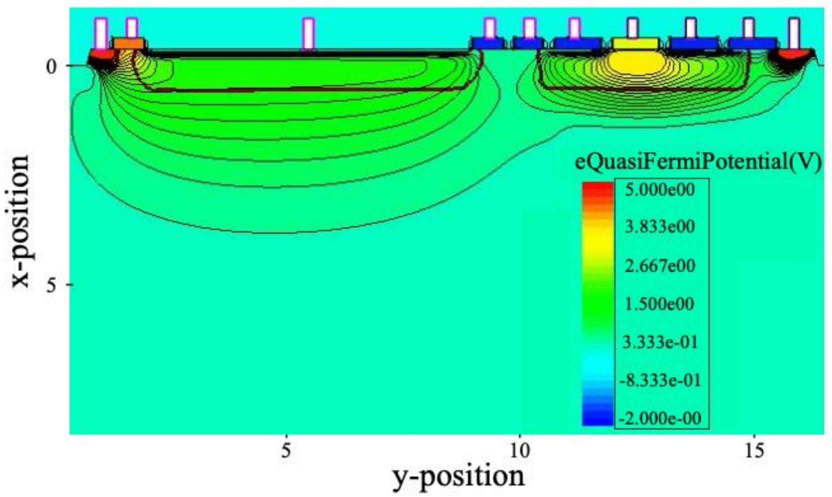


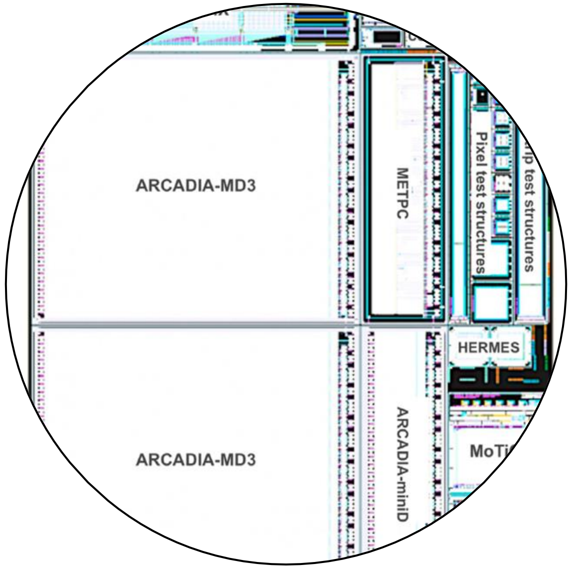


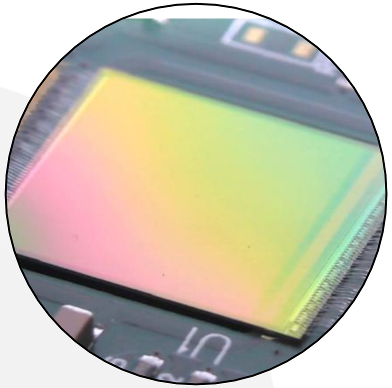
- Great performance for a prototype
- Main issues looking forward:
  - Thin sensor (few microns of collective area only)
  - High DC and fractional electron events

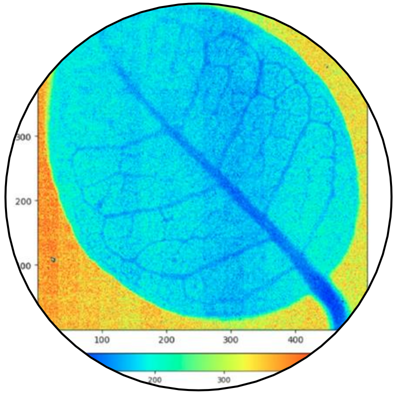




- 110nm CMOS technology @ Lfoundry
- Thick, fully depleted, high resistivity
- 250 microns demonstrated, 500 to 700 microns currently under test
- Platform available for development

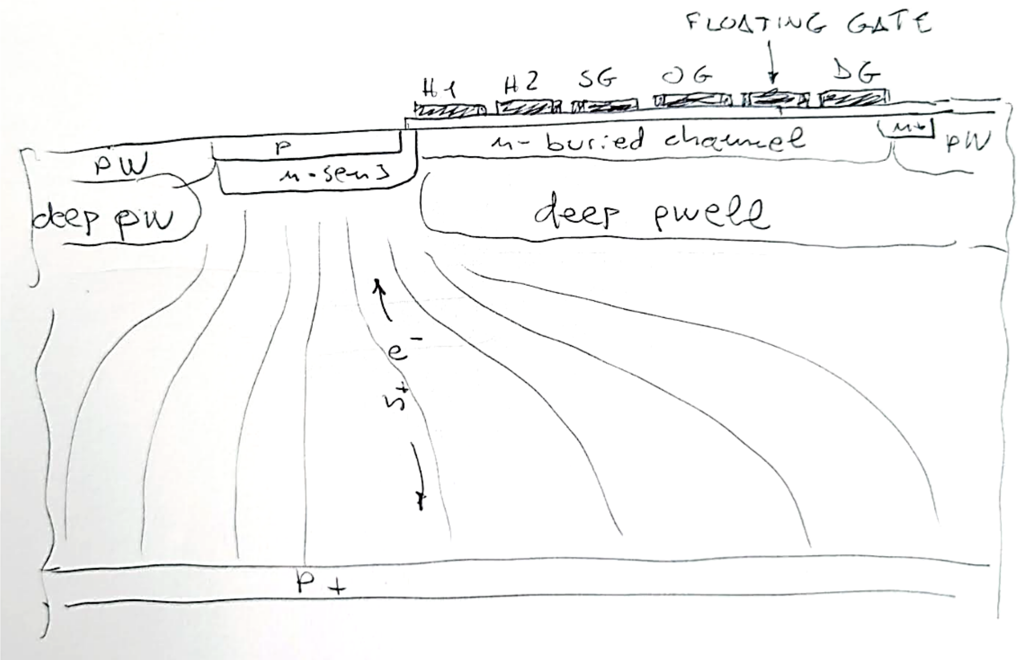






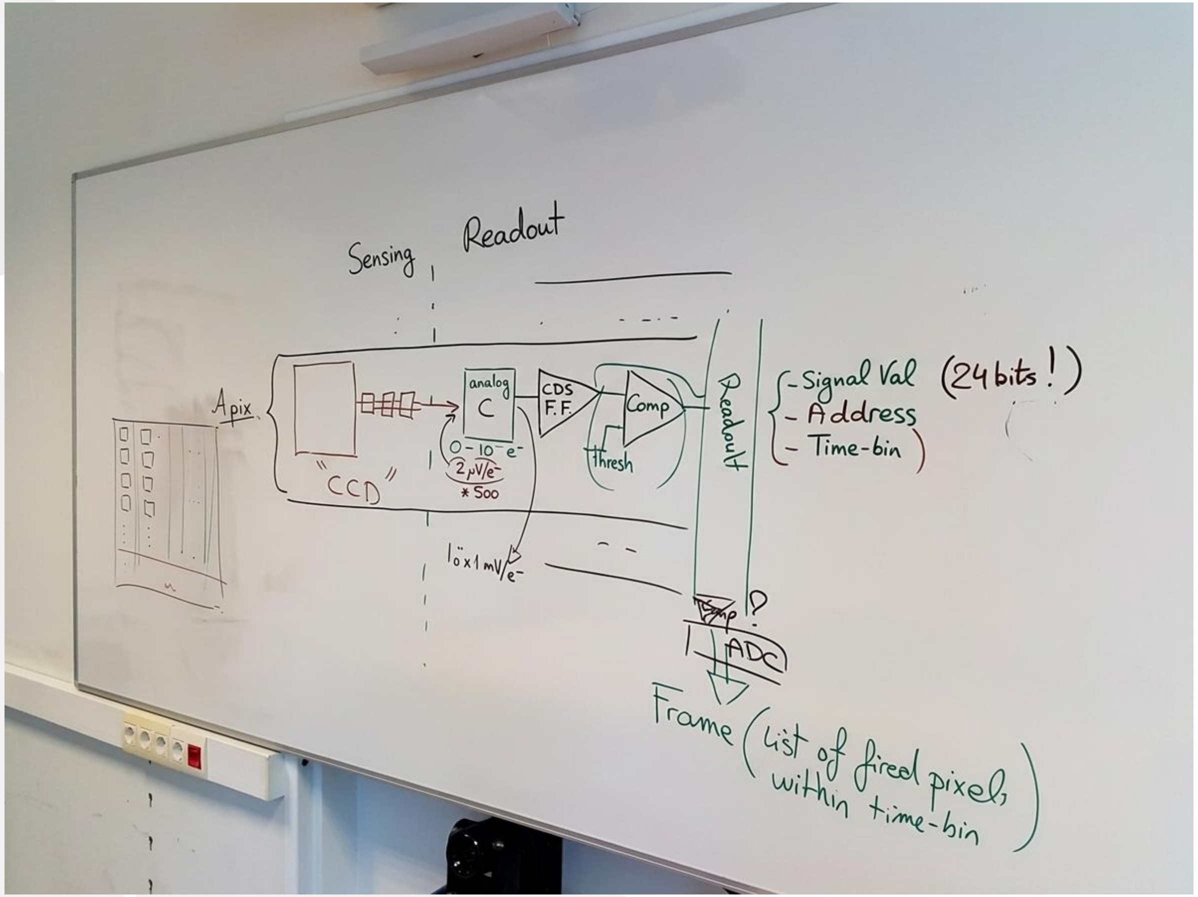
ARCADIA@INFN status

- Collaboration established
  - Zoom meetings end 2025
  - Discussion during IN2P3-INFN detector meeting at LPNHE in November 2025
  - First meeting in Torino in February 2026
  - Kick-off meeting in Trento last week
- Foreseen schedule:
  - Basic simulations of the pixel structure in the ARCADIA process
  - Discussion with Lfoundry about the fabrication
  - Multiple pixel structure designs, externally driven
  - Pixel structure integration in March 2027 ARCADIA production run



Hybridization readout

- Move CMOS readout glowing to a second chip and shield it with a metal layer
- Activity discussed at meetings in IPHC:
  - First meeting in February 2026
  - Kick-off meeting 2 weeks ago
  - First ideas drafted
  - Pixel level CDS and triggering
  - Some thoughts on dynamic range
  - Readout may depend on CMOS usage
  - Clear for Dark Matter searches, less clear in other environments



PARIS-CMOS

Platform for **A**dvanced **R**eadout and **I**maging with **S**kipper CMOS

Plateforme **A**vancée de **R**éception d'**I**mages **S**kipper CMOS

- To be installed at IJCLab
- In collaboration with different institutes (IN2P3 - IJCLab, IPHC; INFN - Torino, Trento, Bologna and others)…
- Soon to be expanded to LPNHE and UoC (Chicago, Paris Campus)
- Supported at both kick-off meetings at IPHC and Trento
- Financing from UPS, DIM-ORIGINES, CNRS
- Will test the first runs of production

PARIS-CMOS

Conclusions

- Skipper CCDs are one-of-a-kind imagers with extremely low Dark Current and perfect resolution achieved by multiple nondestructive readouts of each pixel charge
- Readout can take hours or days
- CMOS parallelization can improve readout speed by factors of millions
- These sensors could then be used outside the niche of Dark Matter searches for applications in low light imaging (quantum optics, soft X-ray/EUV camera, biology microscopy, exoplanet searches…)
- A Skipper-in-CMOS was successfully achieved by colleagues in the US, achieving sub-electron resolution in a thin sensor, with some partial charge readout issues
- Thick fully depleted CMOS sensors such as the ARCADIA platform could provide an alternative for Skipper CCDs while keeping the necessary large mass per sensor for Dark Matter searches
- Hybridization of readout should improve DC and partial charge readout of current CMOS skipper sensors and be optimized for specific usage of the sensor
- We expect to demonstrate the functioning of these sensors with this PARIS-CMOS project