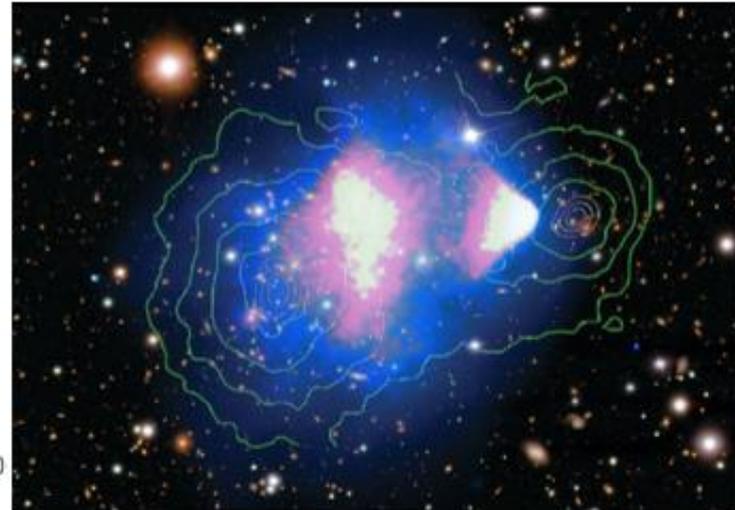
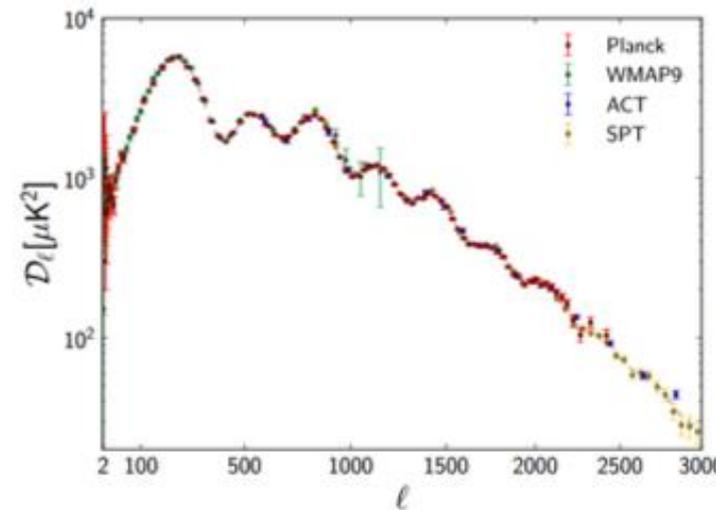
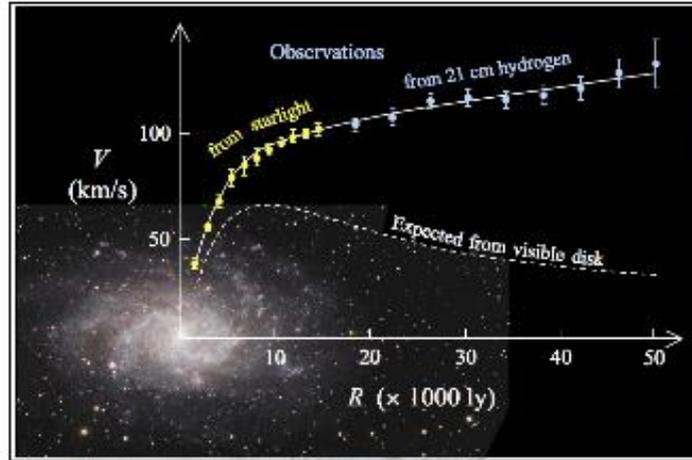
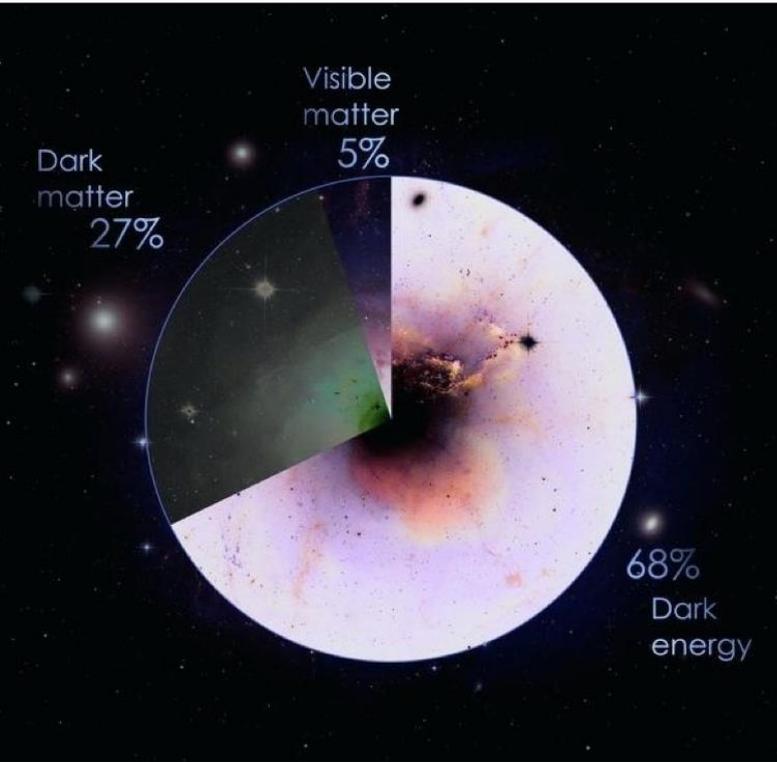


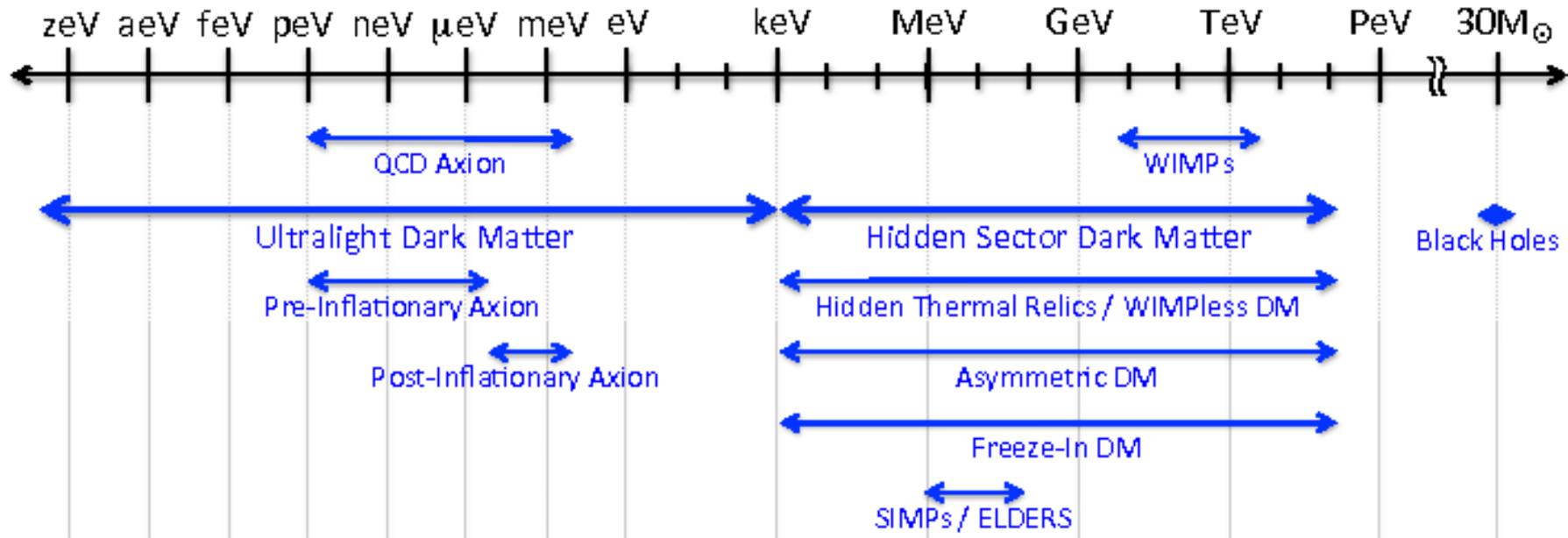
Skipper sensors: from world-leading Dark Sector limits in DAMIC-M to the future of low-noise imaging?

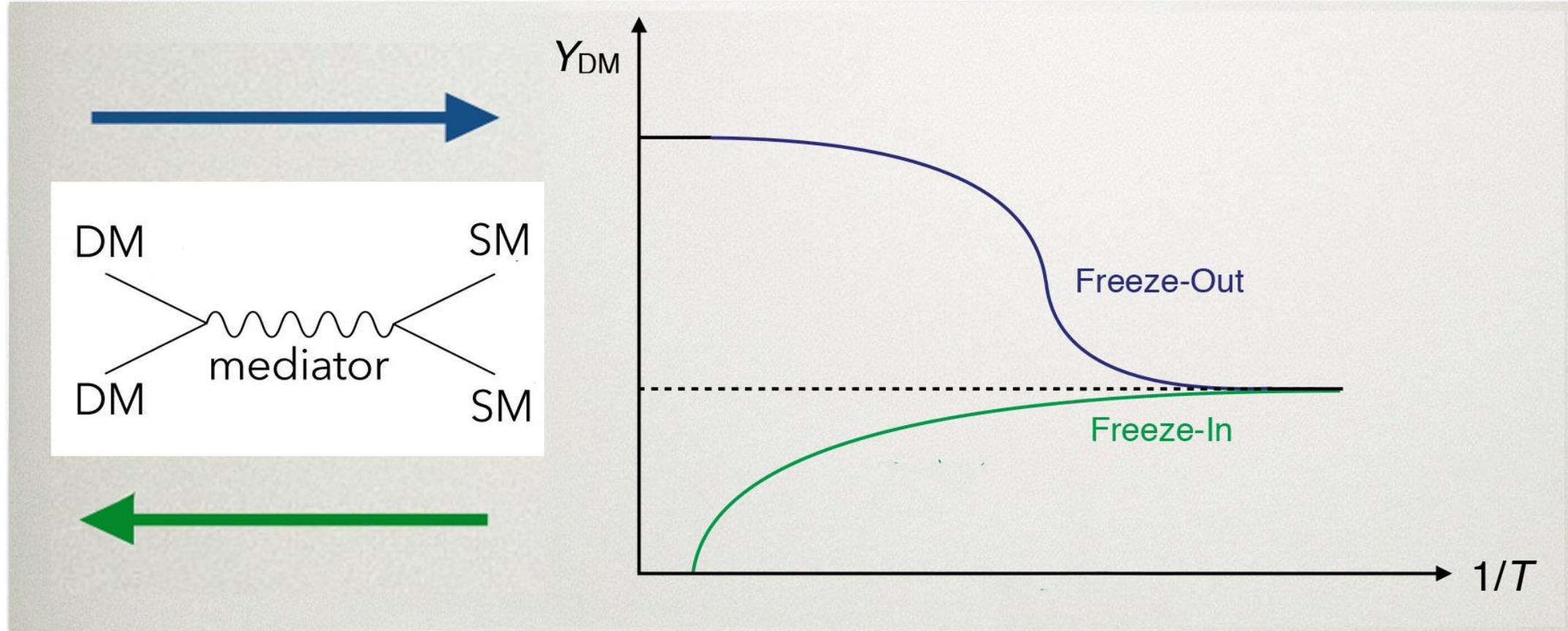
Xavier Bertou (IJCLab, IN2P3/CNRS), DAMIC-M experiment

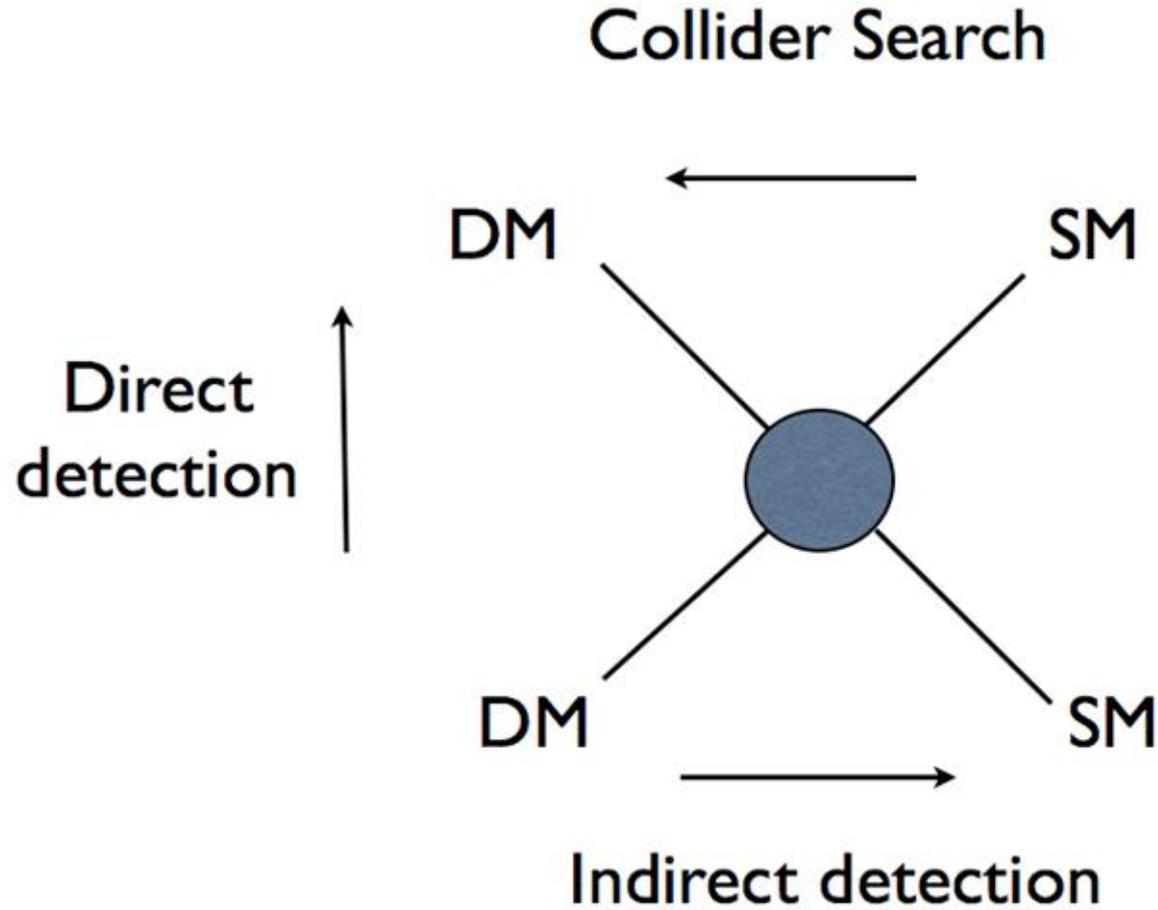
(1)

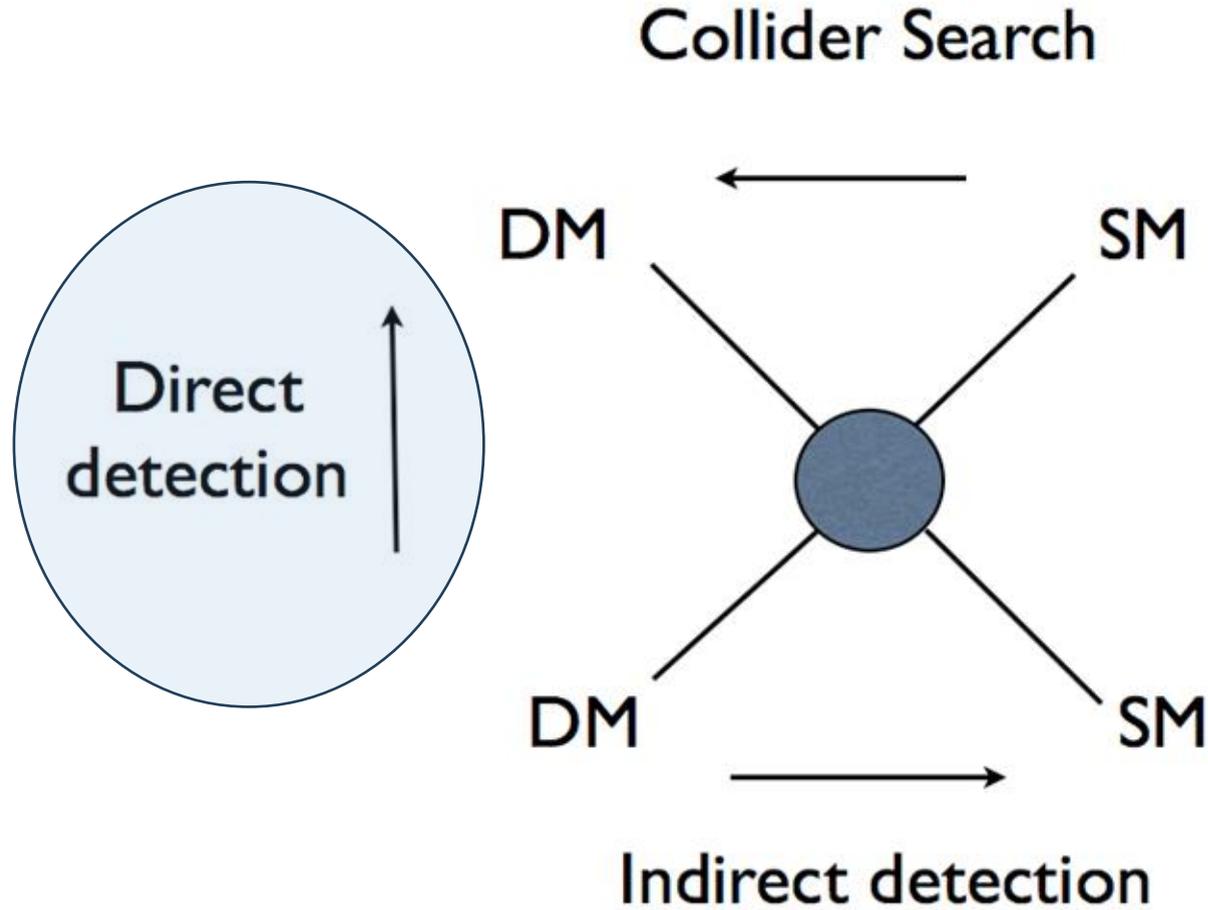
Dark Matter and low mass searches

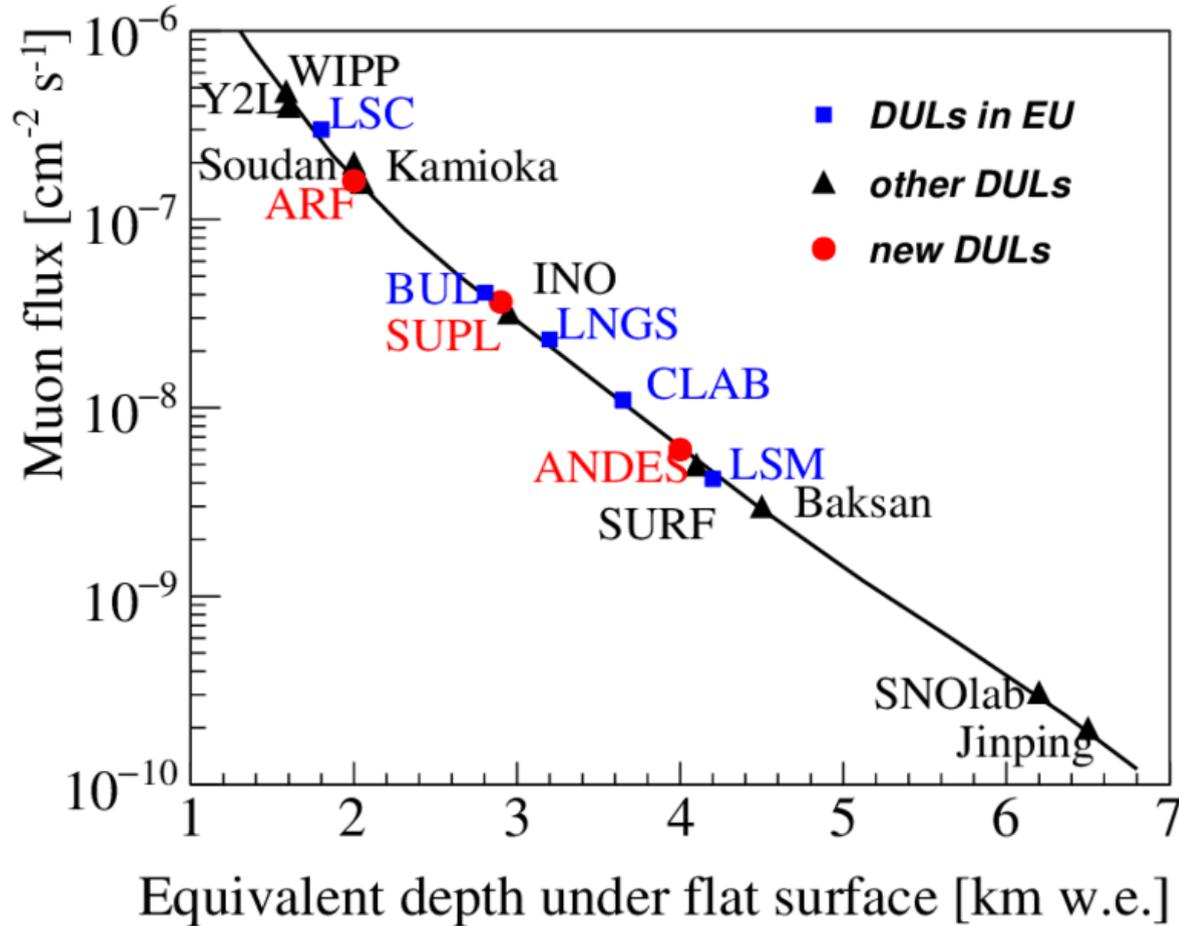


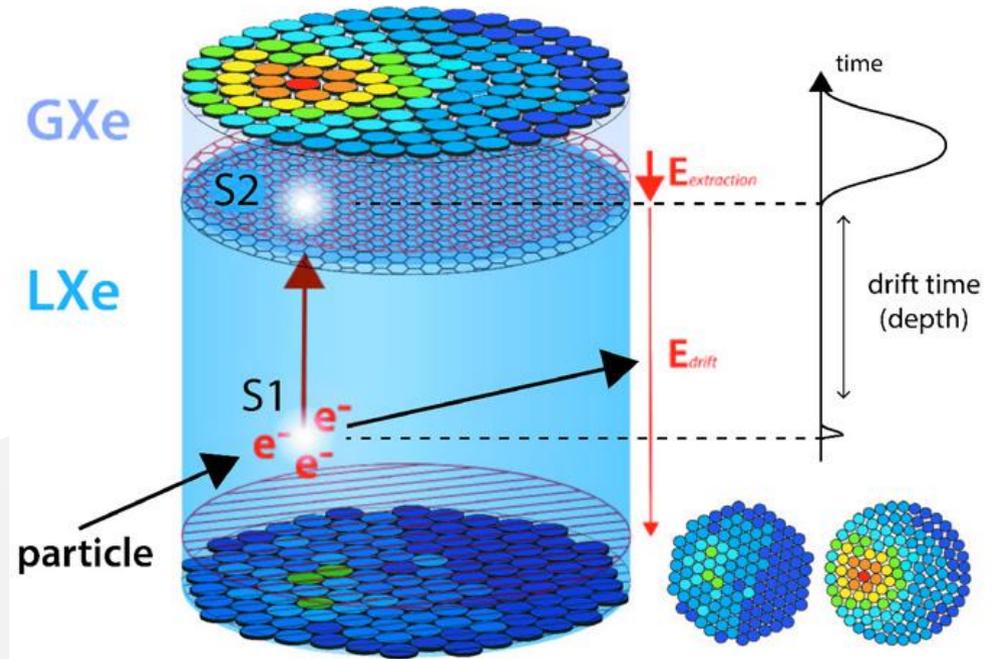


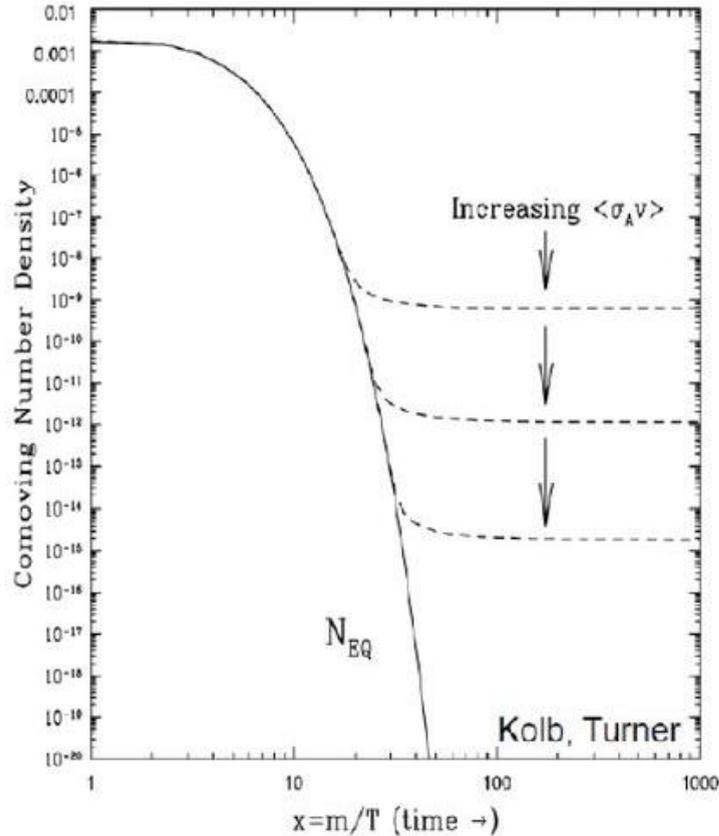








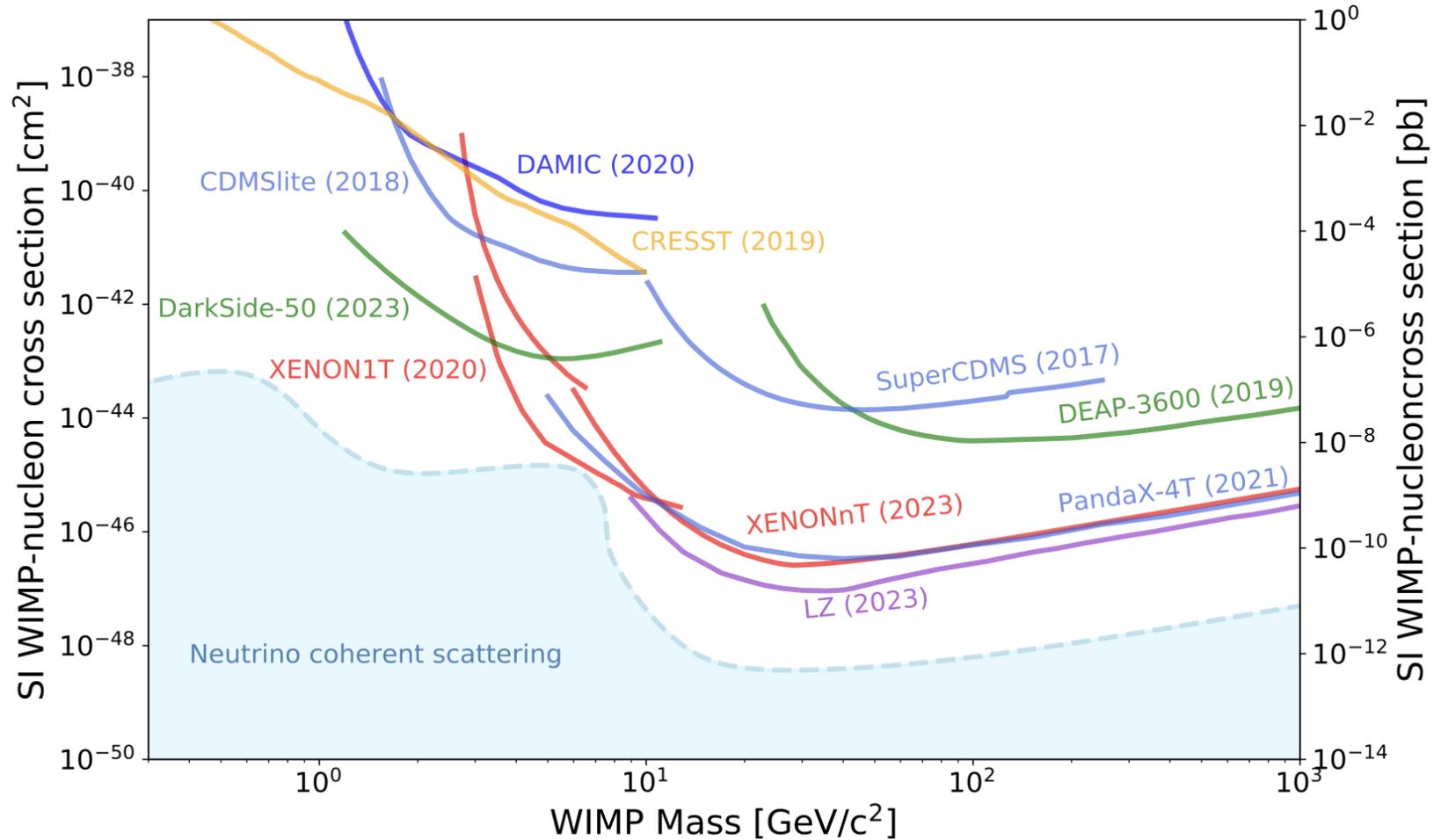


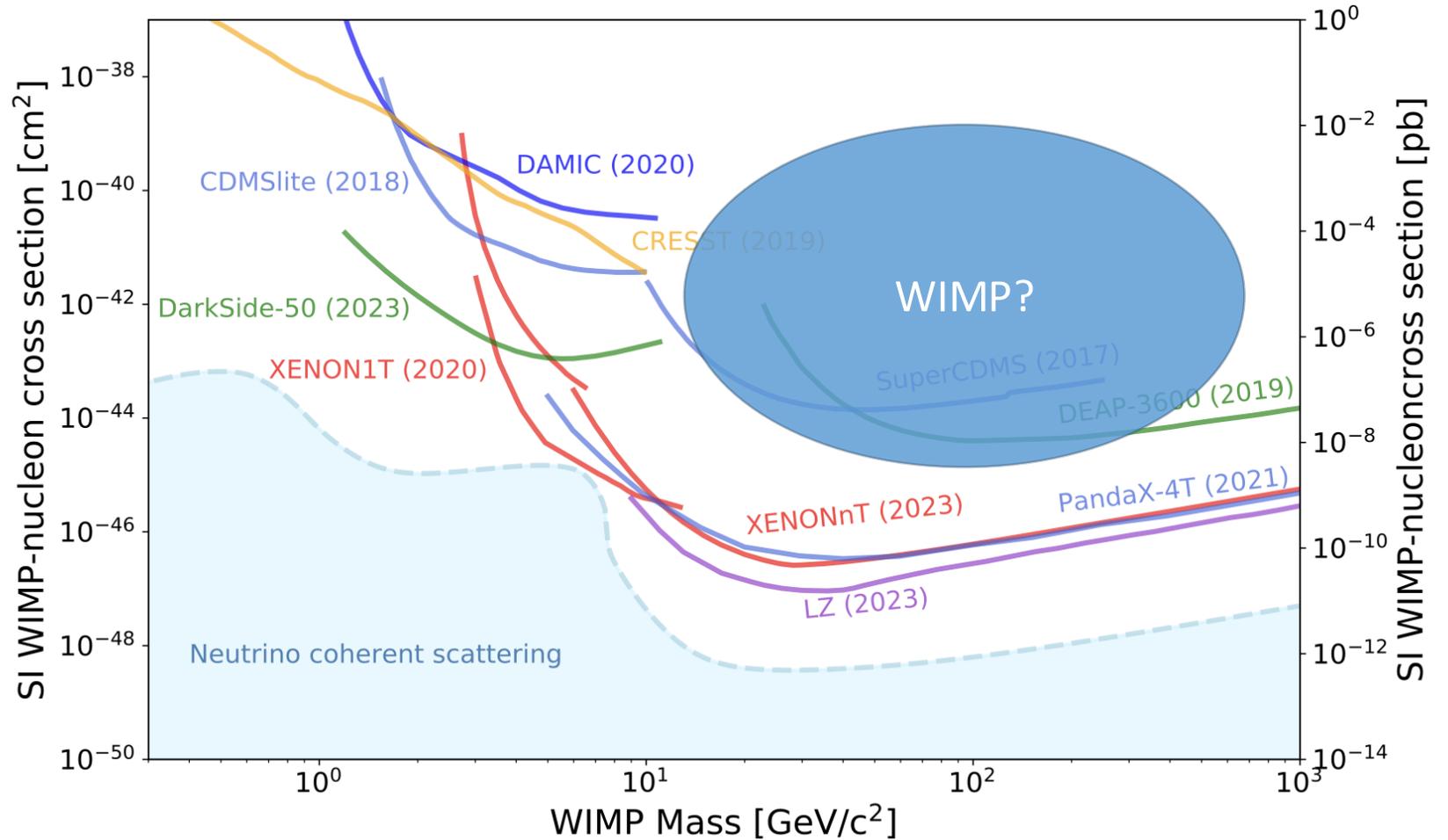


- LSP DM \in Weakly Interacting Massive Particle (WIMP)
- WIMPs are thermal equilibrium at hot temperature \rightarrow Pair annihilation \rightarrow Freeze out
- Relic density

$$\Omega \approx \frac{6 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_A v \rangle}$$
- $\langle \sigma_A v \rangle \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$

$$\Rightarrow \Omega \approx 20\% \text{ (WIMP miracle)}$$



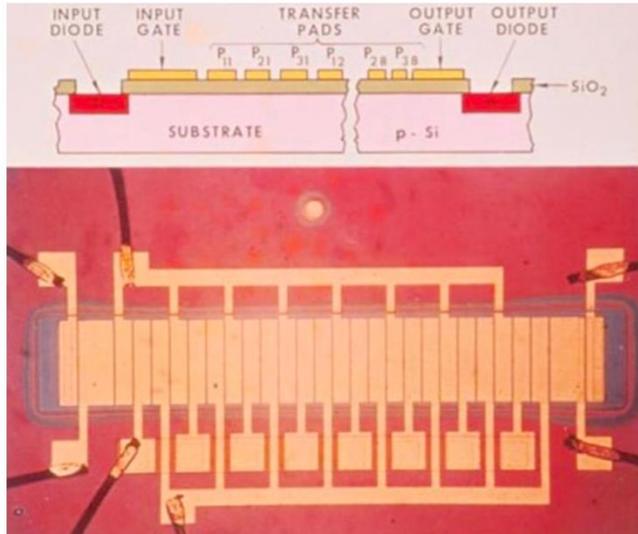


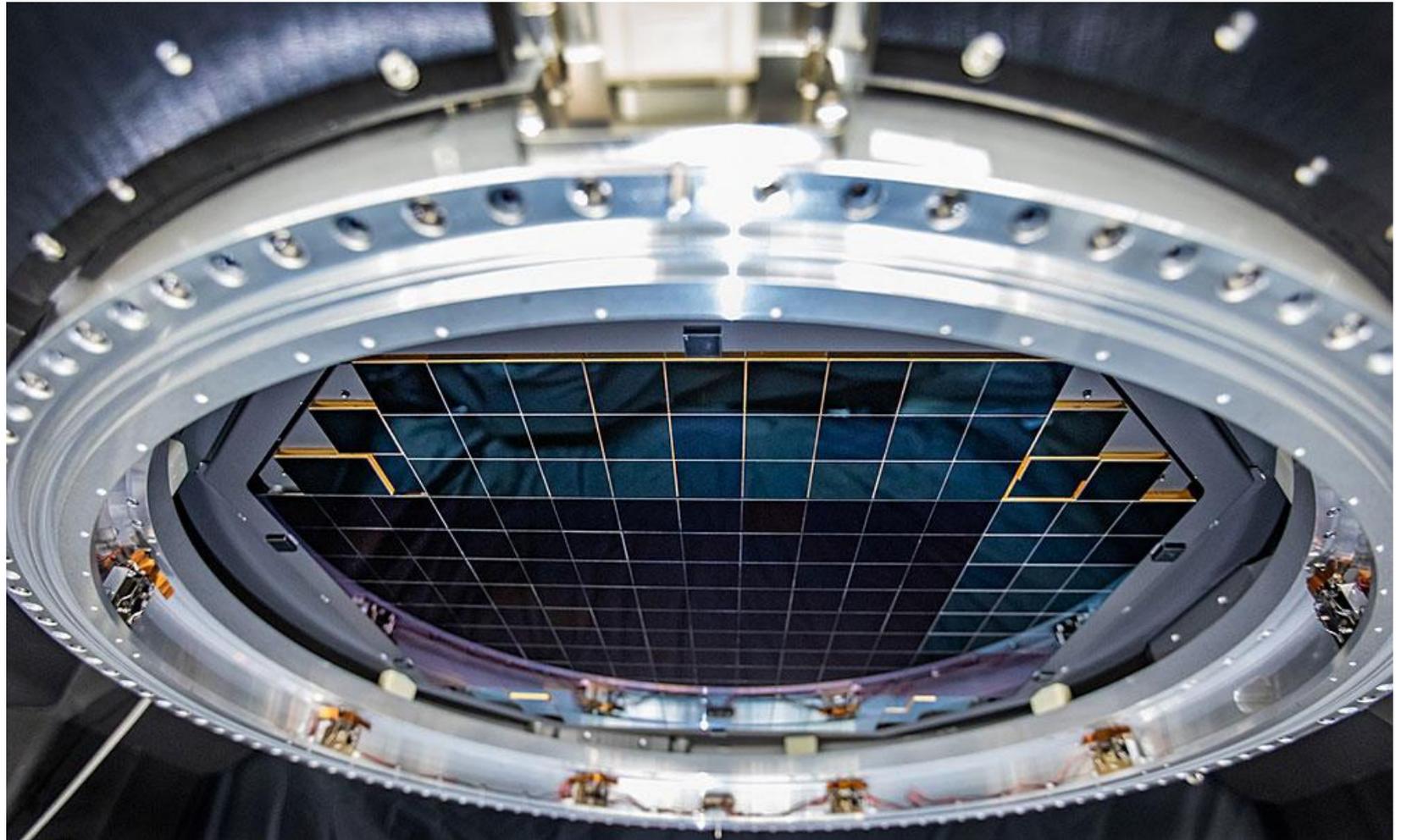
- Add a $U(1)$ symmetry
 - Minimal renormalizable portal to the Standard Model
 - Gauge invariance: kinetic mixing with SM $U(1)$
 - After EWSB, dark photon couples to electric charge
 - Light DM + light mediator opens the $< \text{GeV}$ scale
 - Nuclear recoils suppressed
 - Ideal to observe as electron recoil
 - Need to observe much smaller energy deposits

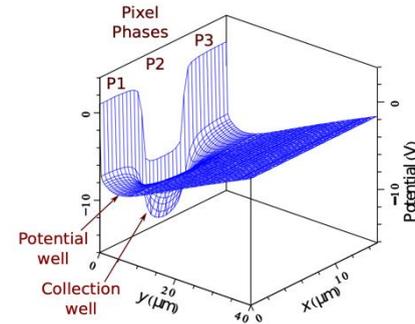
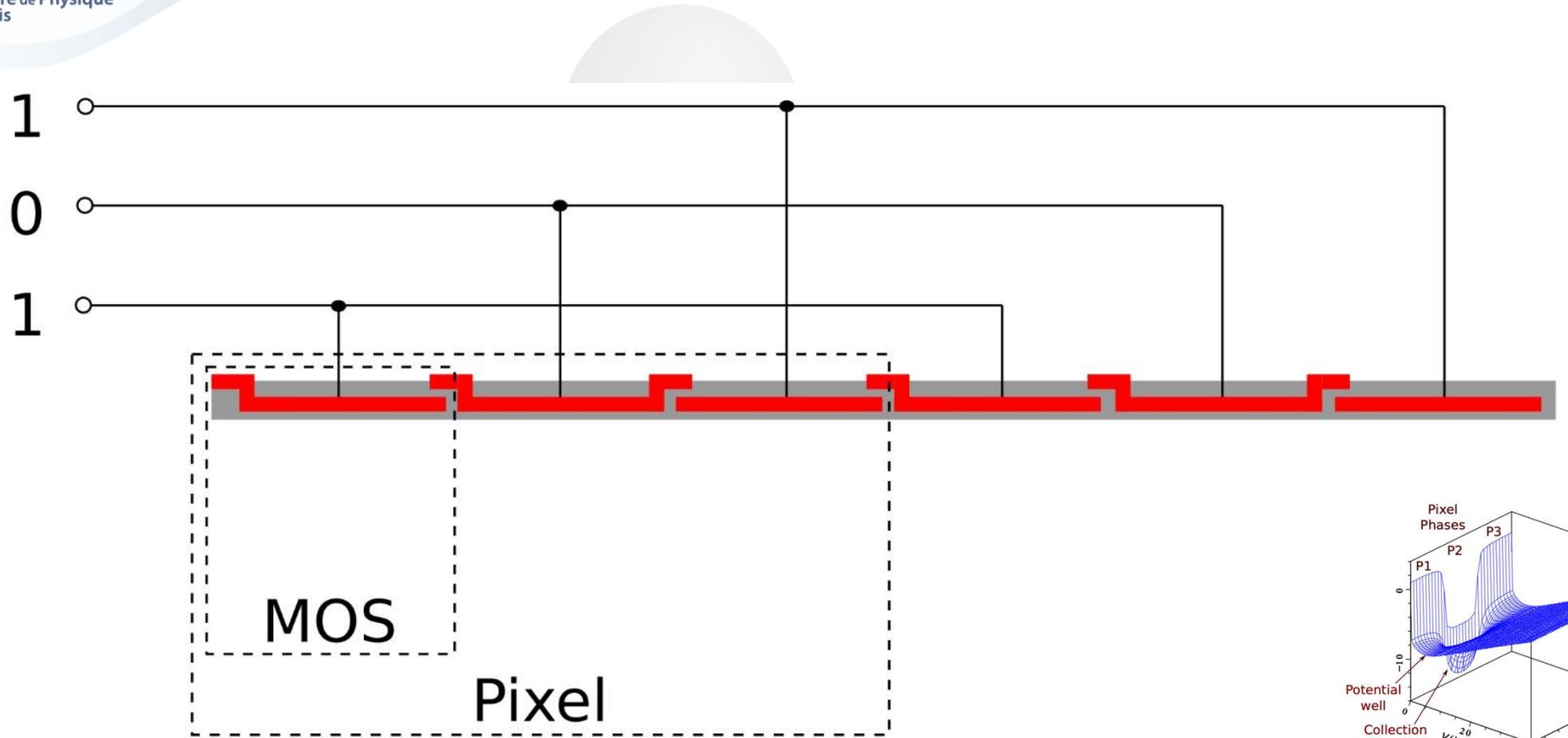
- **Nuclear recoil**
 - GeV to TeV Dark Matter particle
 - Coupling to nucleon
 - Deposited energies typically in the (tens) keV range
 - Can go down to 15-30 eV (Xenon, Argon)
- **Electron recoil**
 - MeV to GeV Dark Matter particle
 - Coupling to electron
 - Deposited energies in the eV range
 - Silicon band gap 1.2 eV

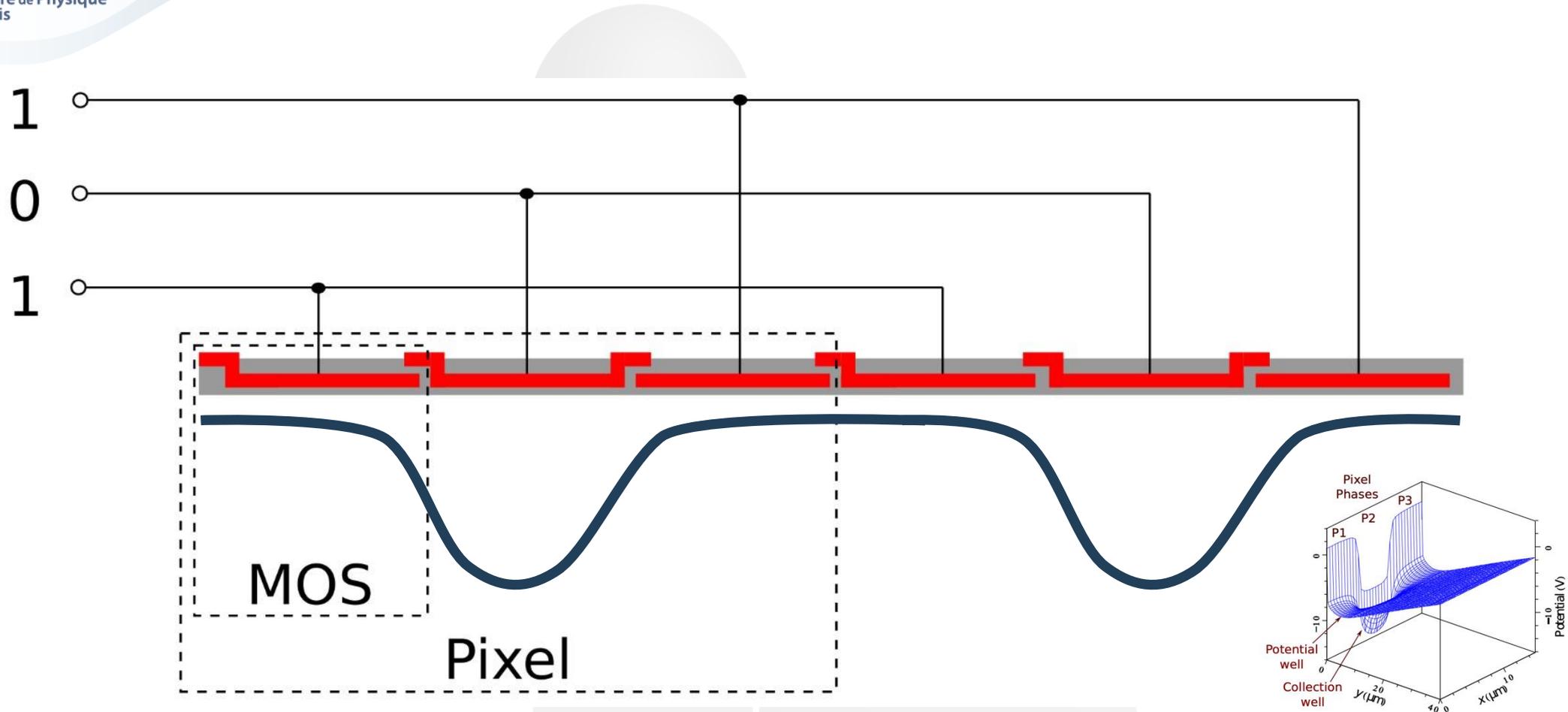
(2) CCD and Skipper CCD

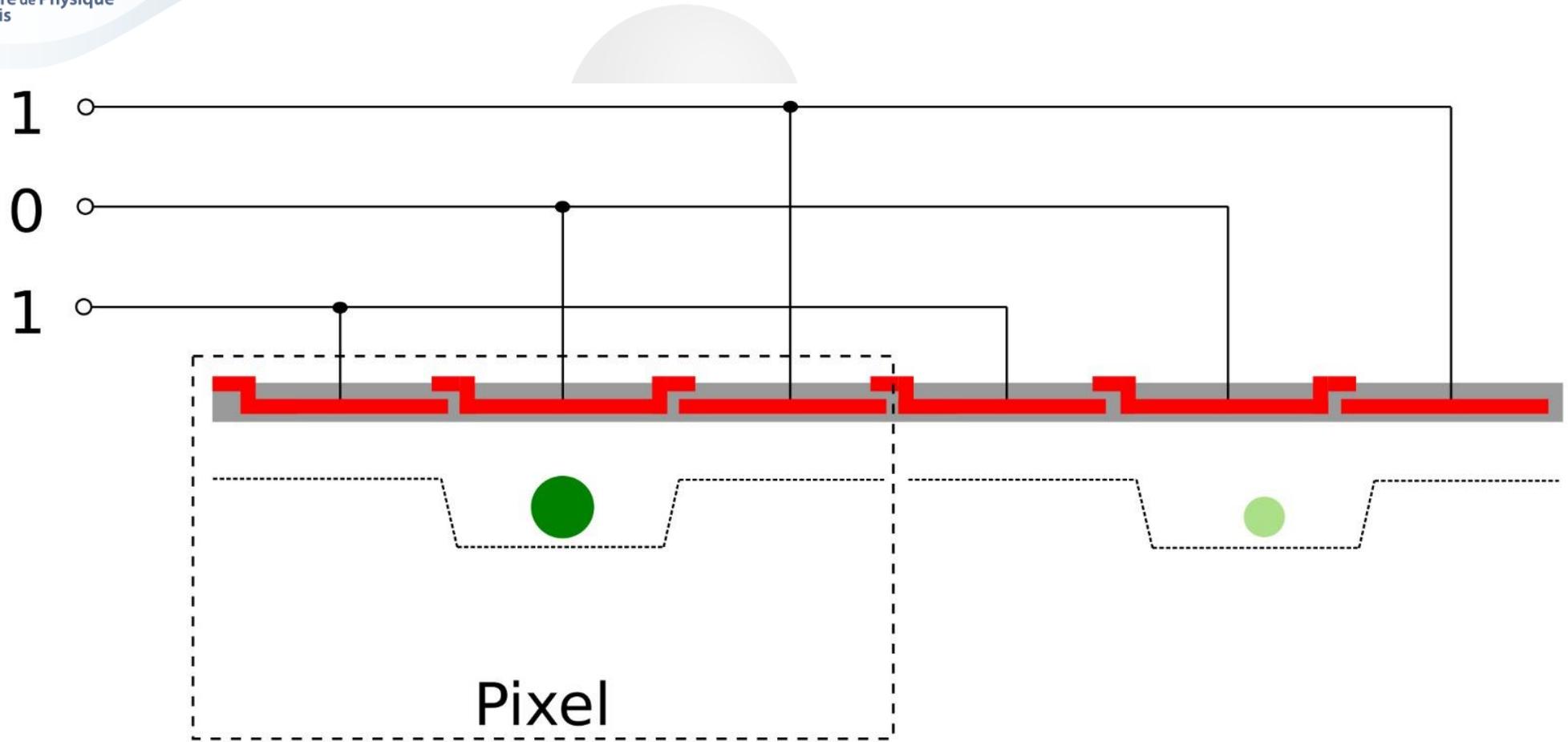
- CCD were invented in 1969 by Boyle and Smith (Bell Labs).
- The idea was to make a memory device, but it works better as an image sensor and was quickly used in consumer devices.
- In 1975, Kodak manufactured the first digital camera.

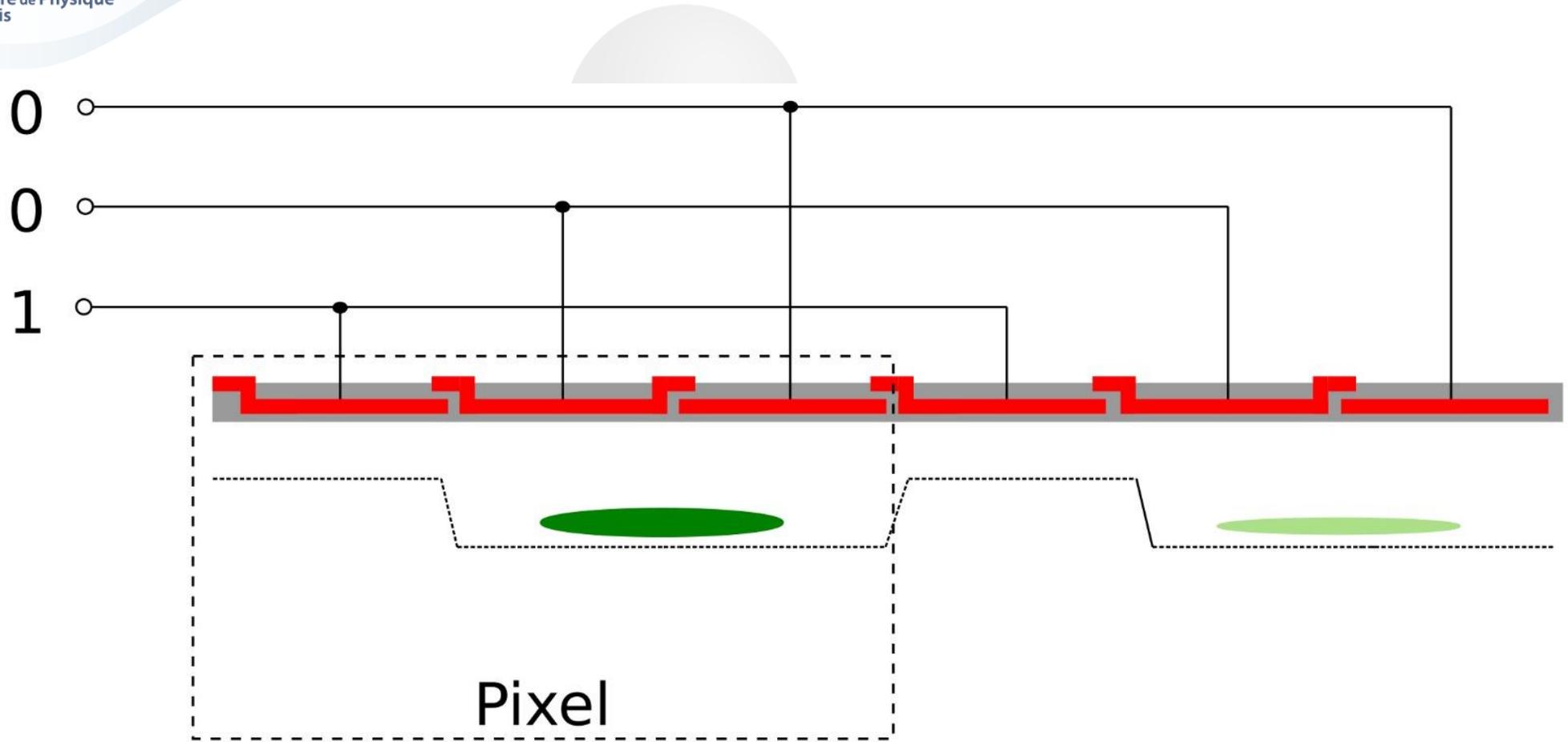


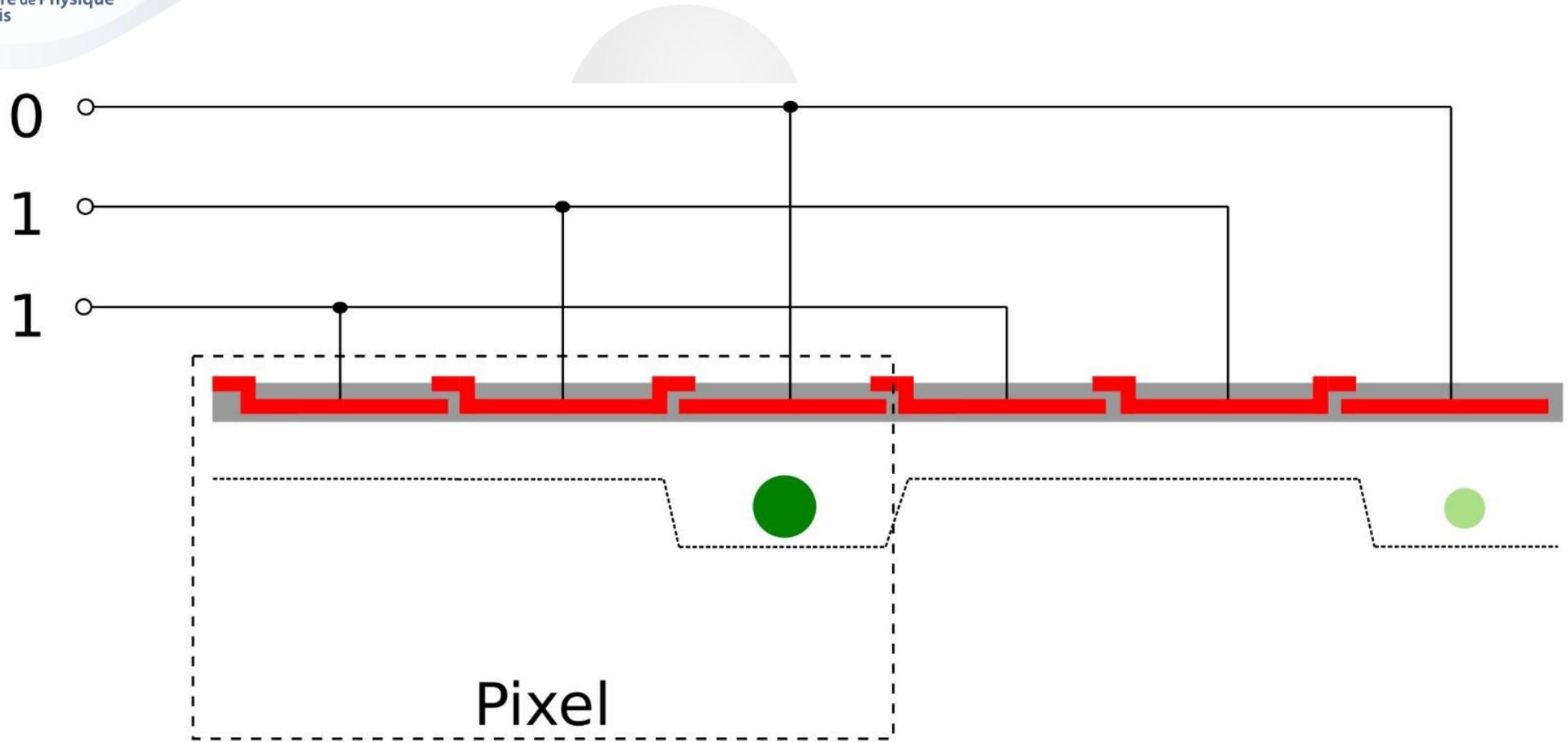


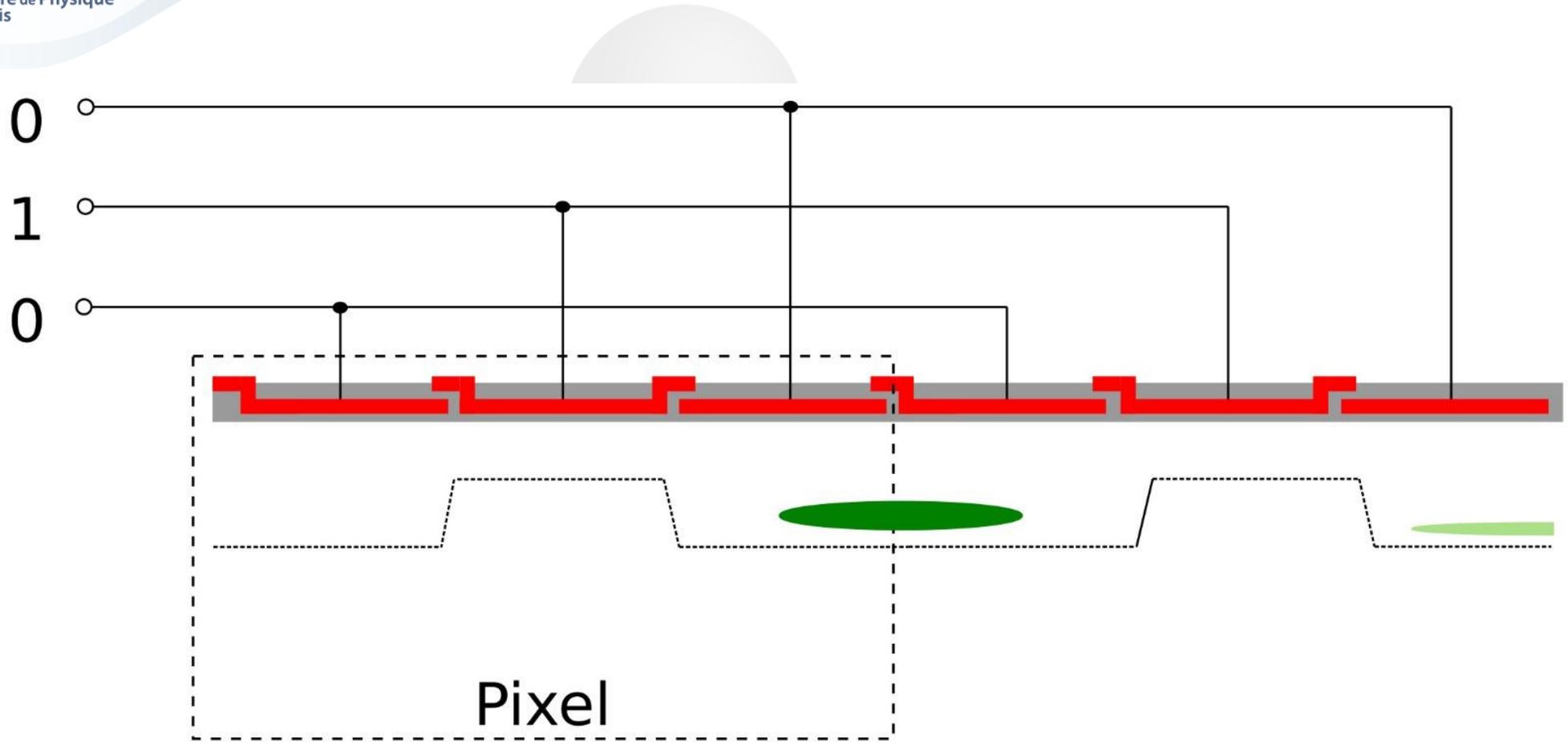


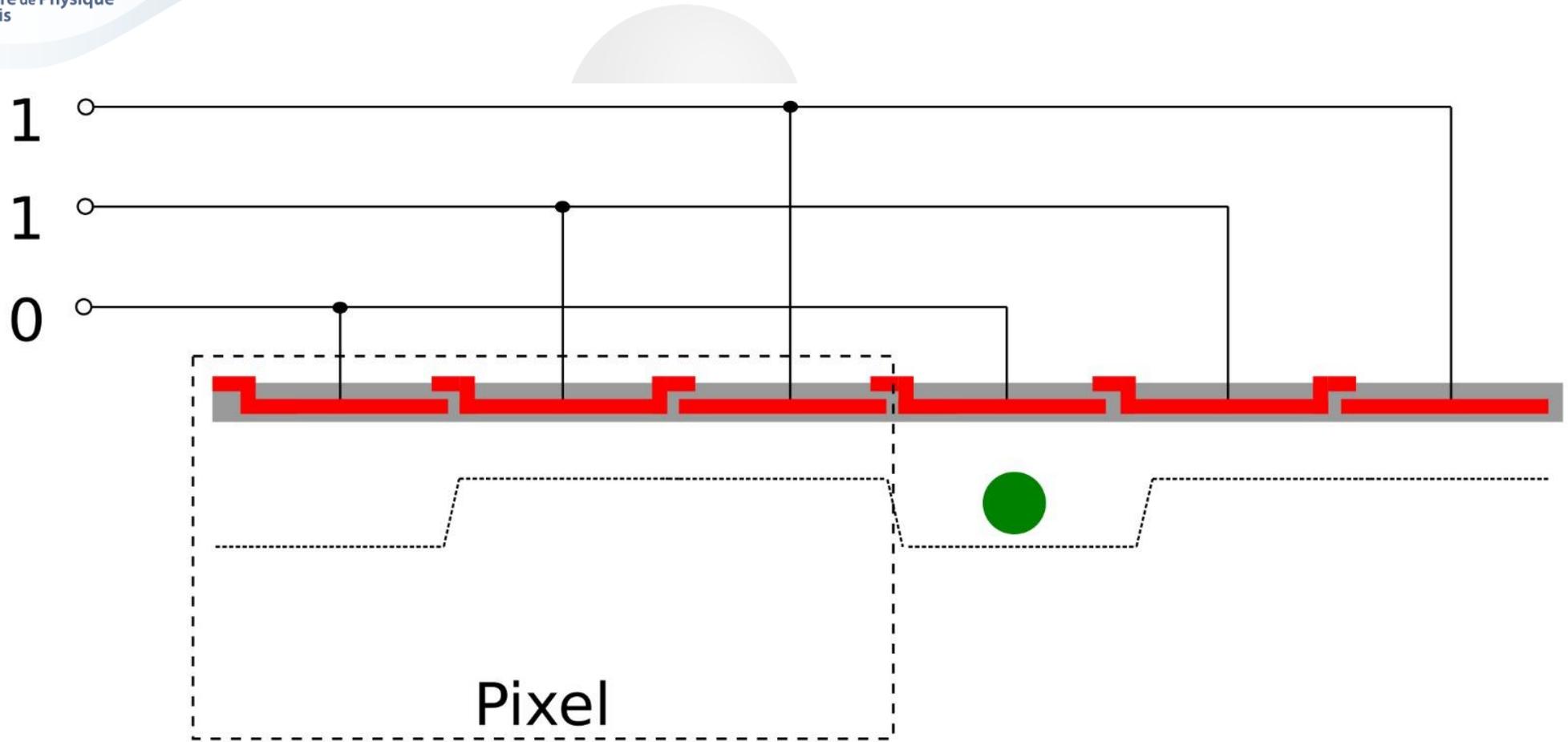


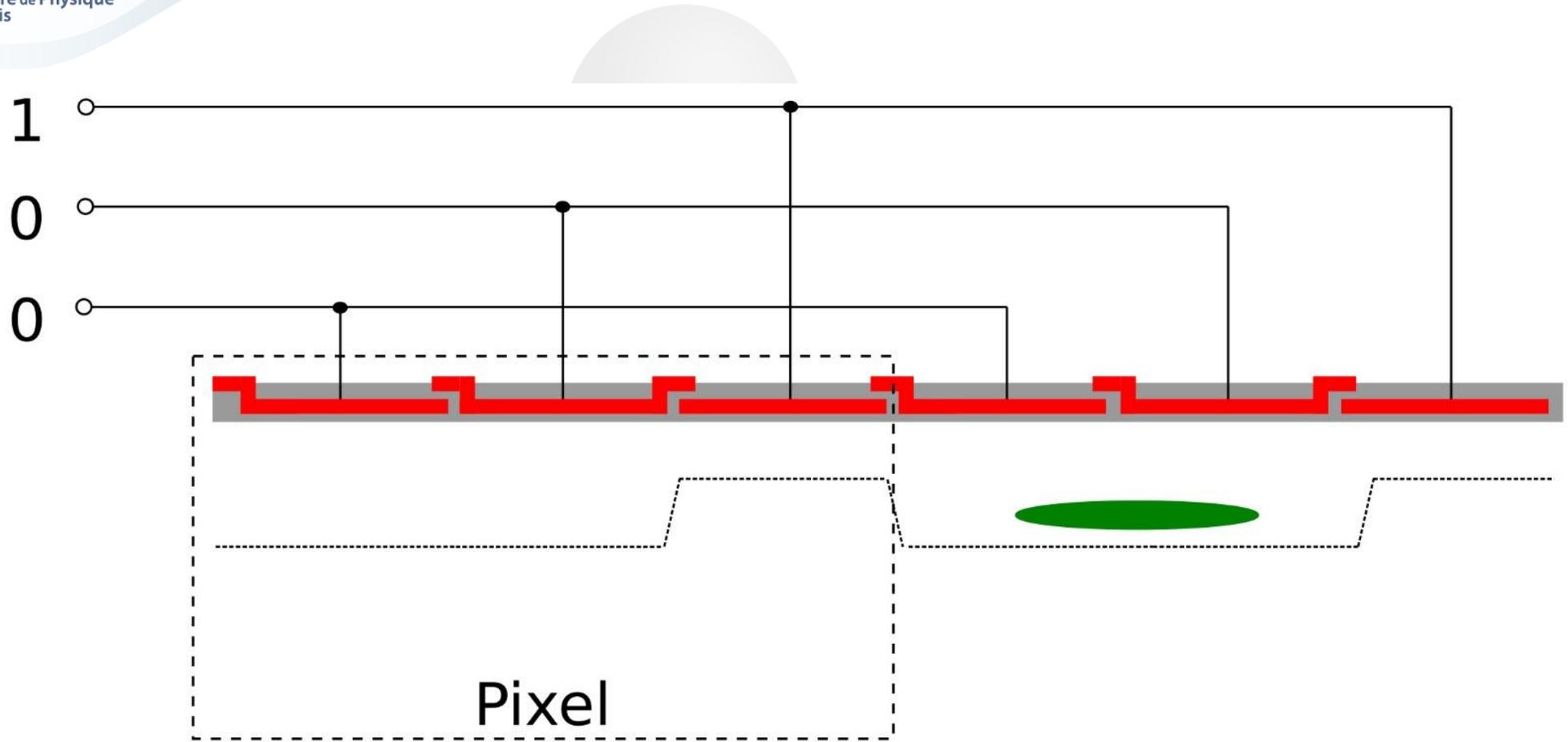


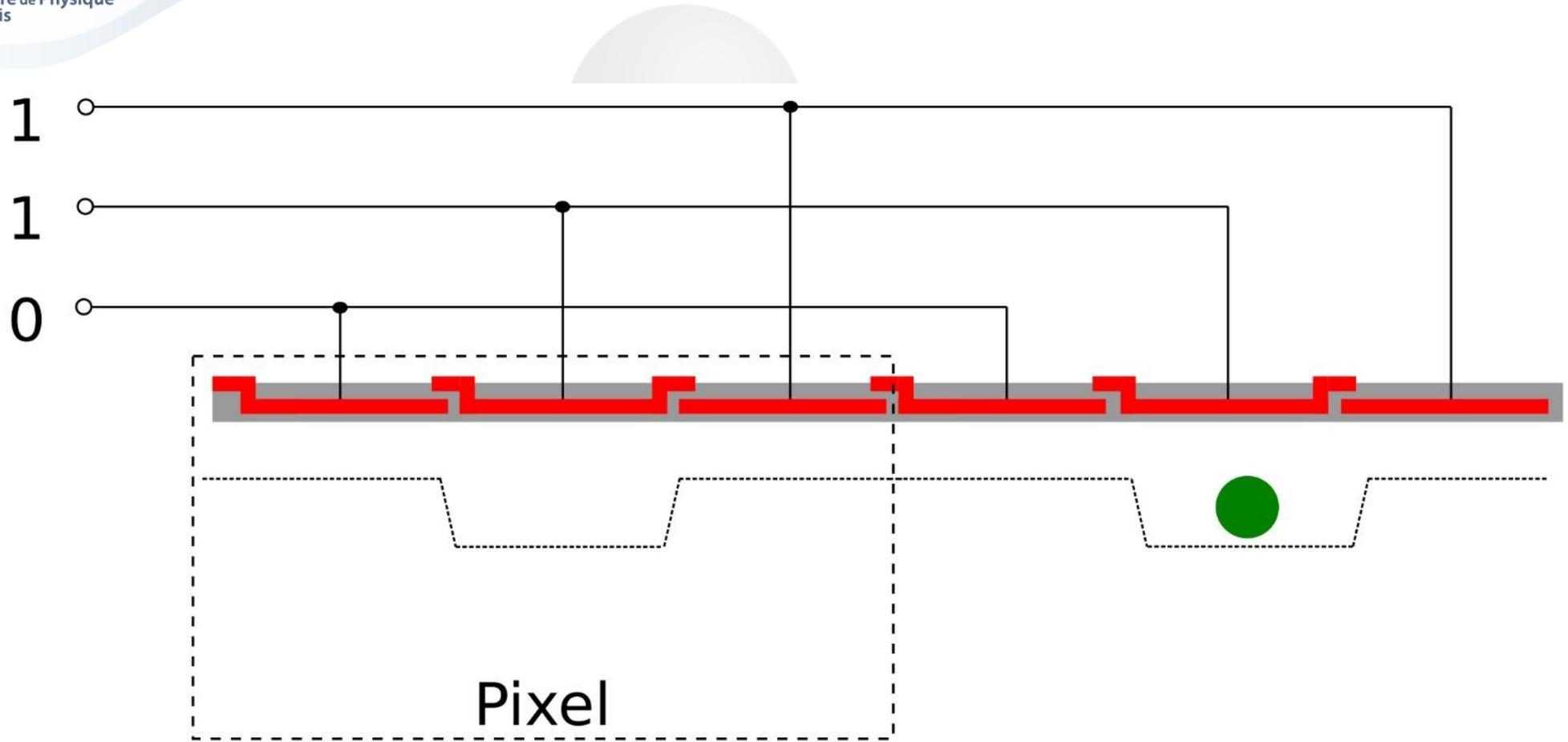




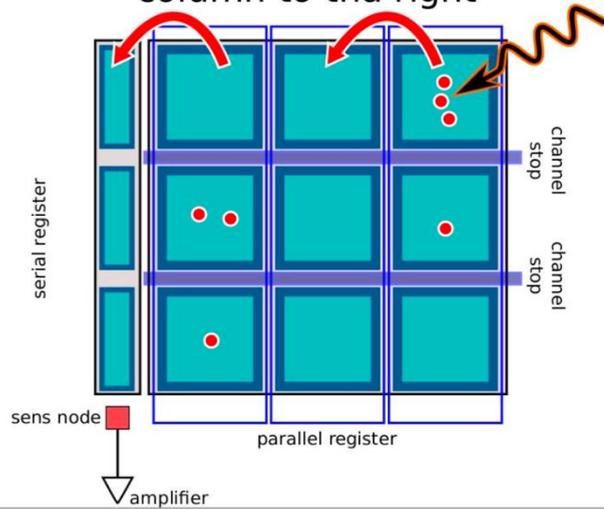




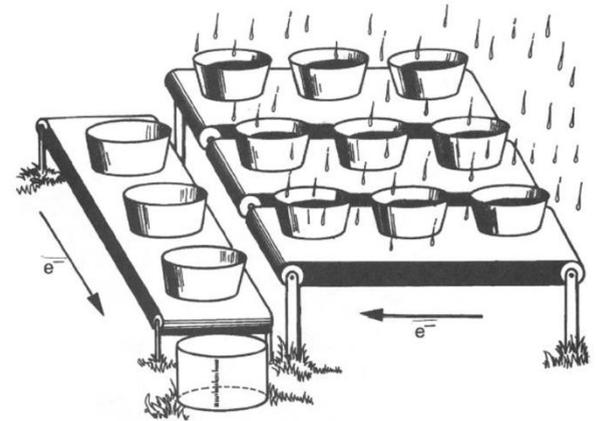
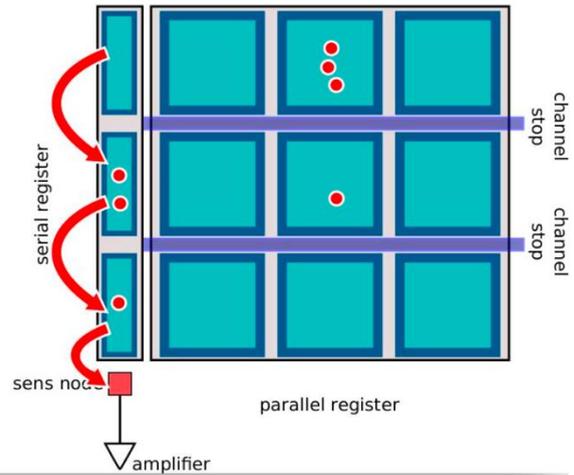


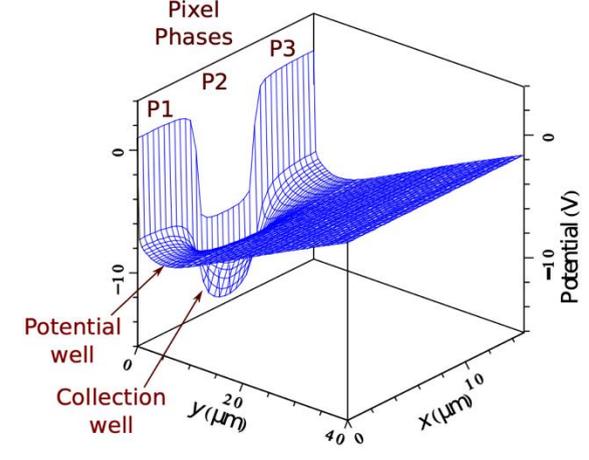
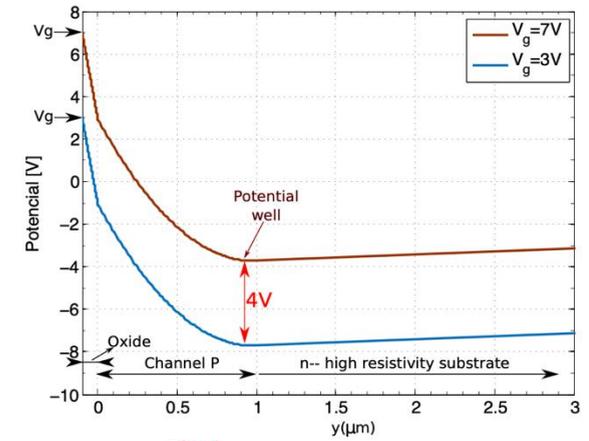
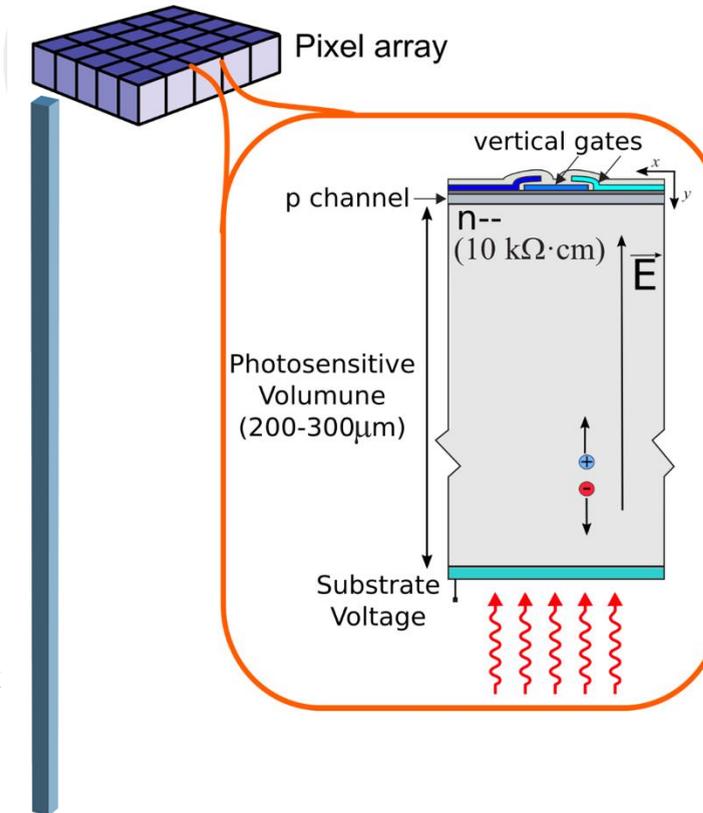
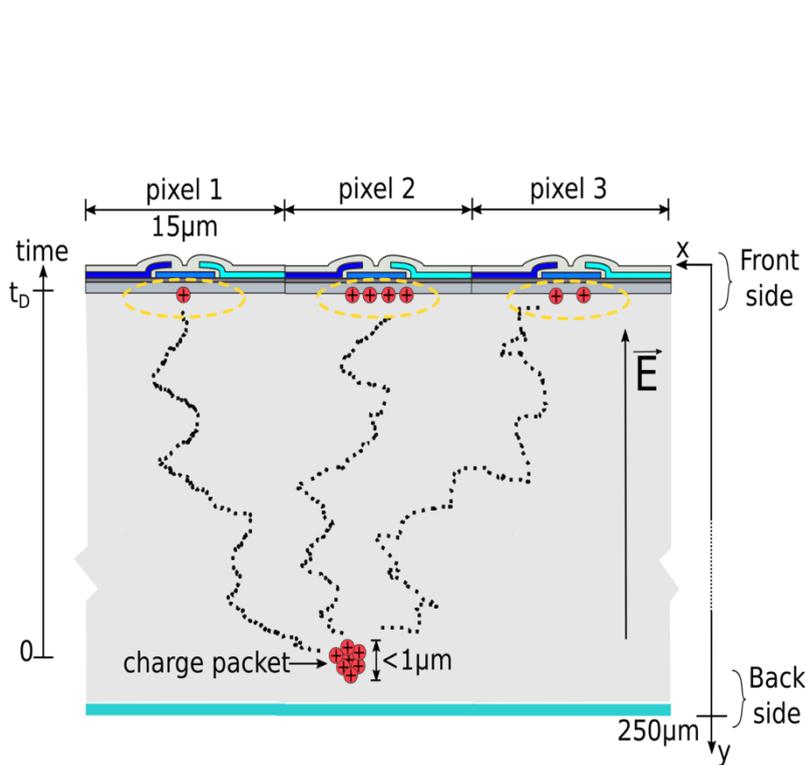


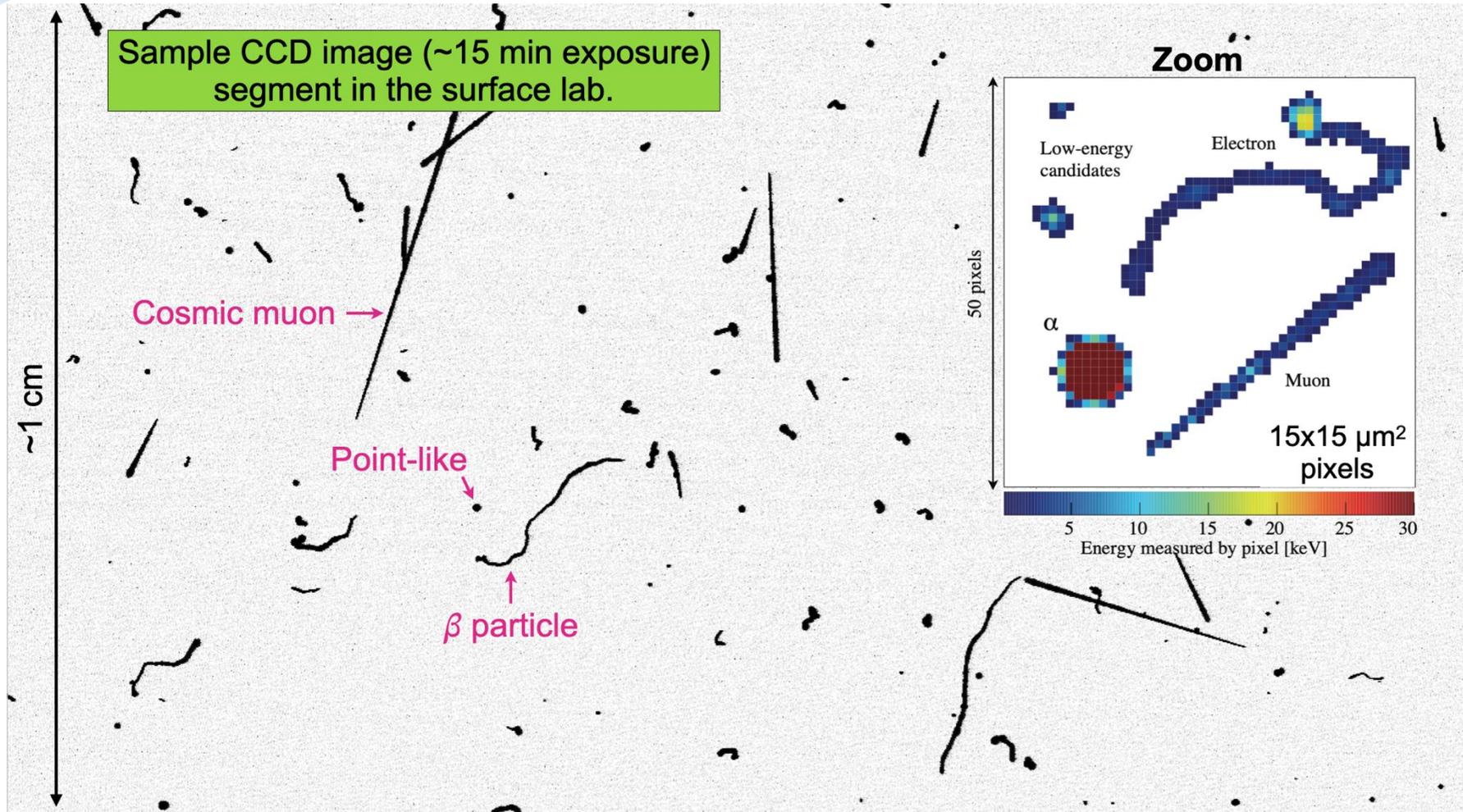
Shift charge one column to the right

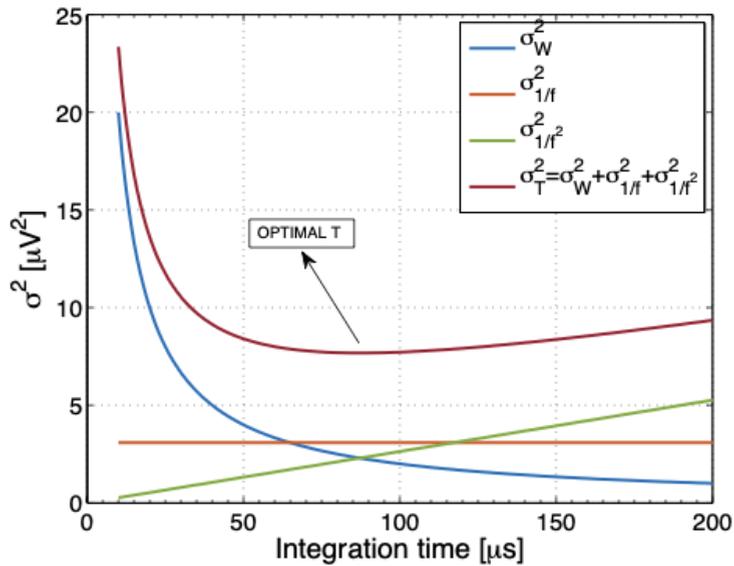
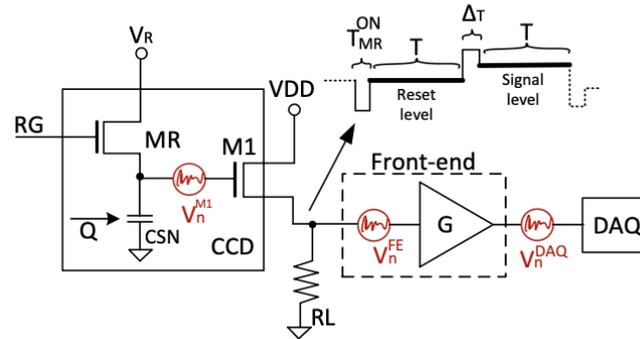


Shift charge in serial register one pixel down (3 times)

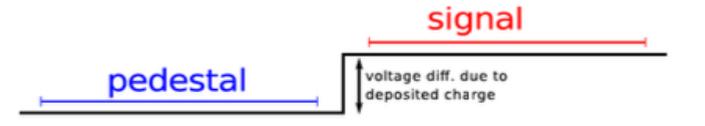




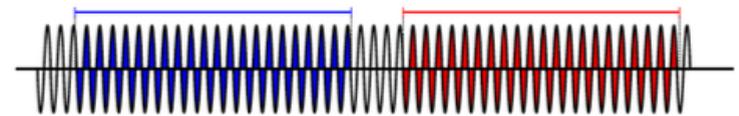




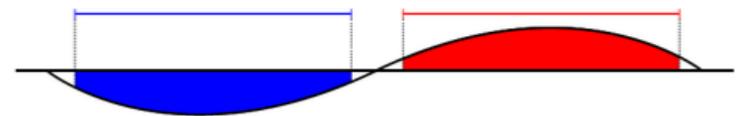
pixel charge measurement

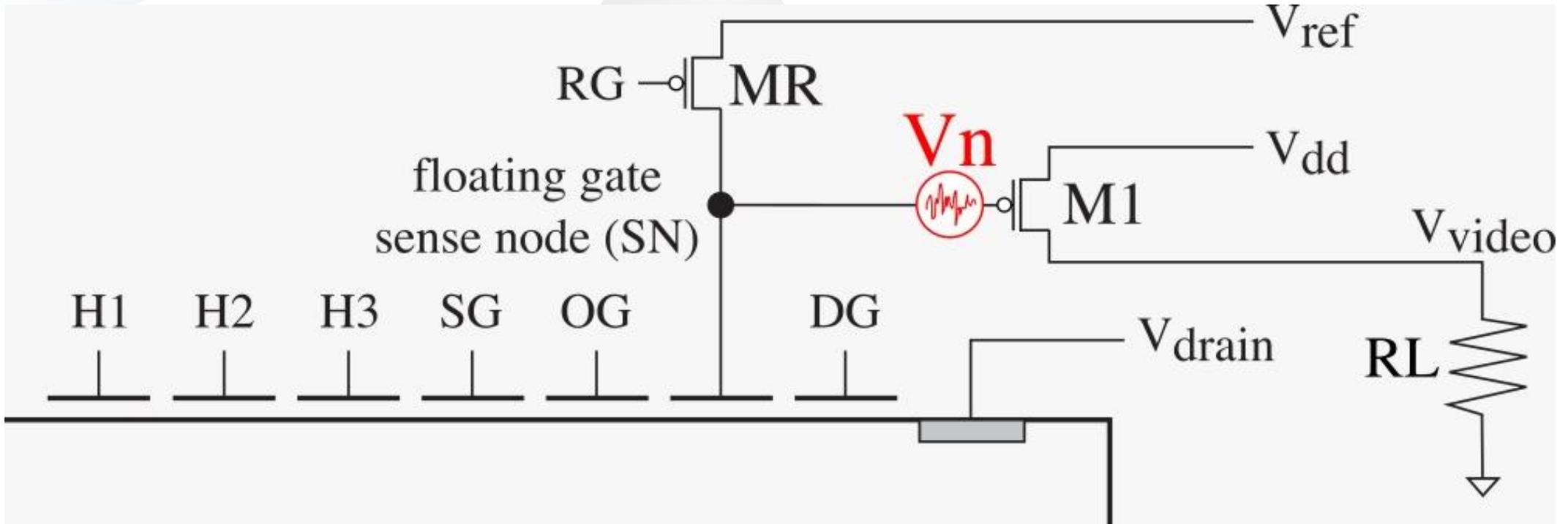


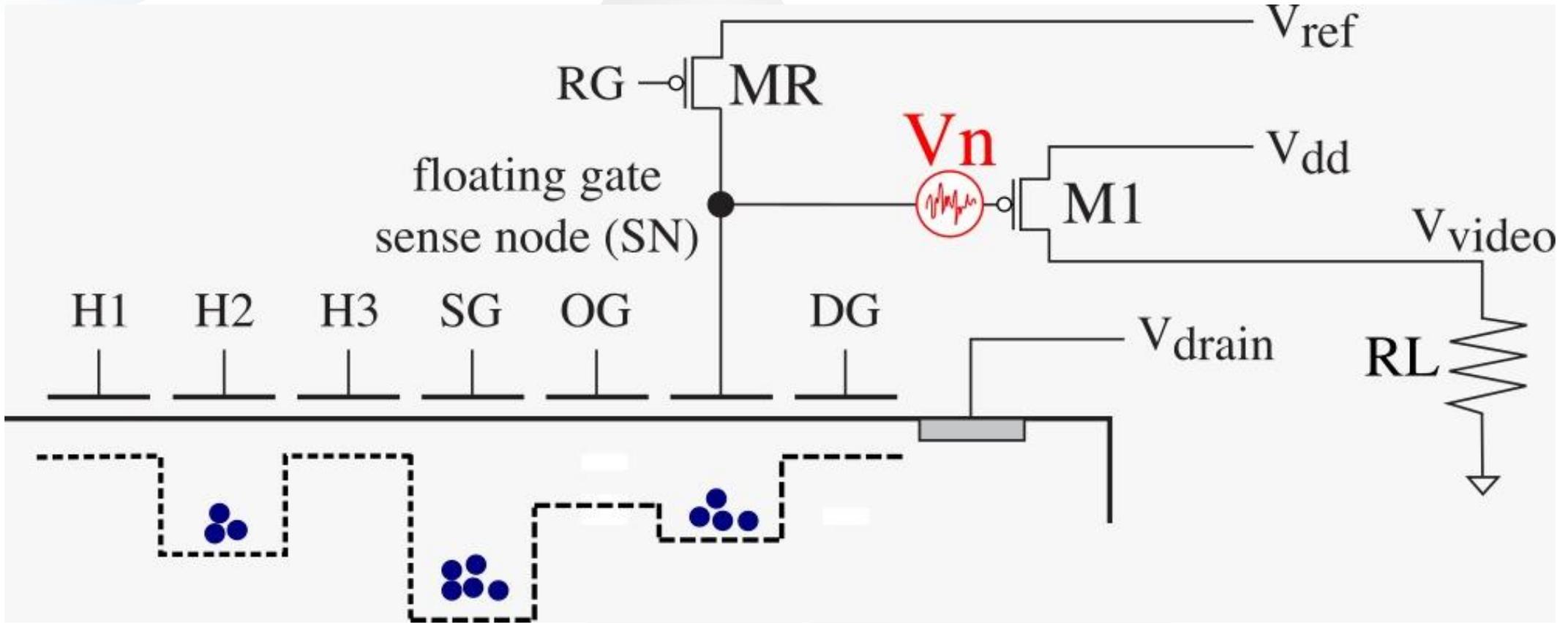
high frequency noise

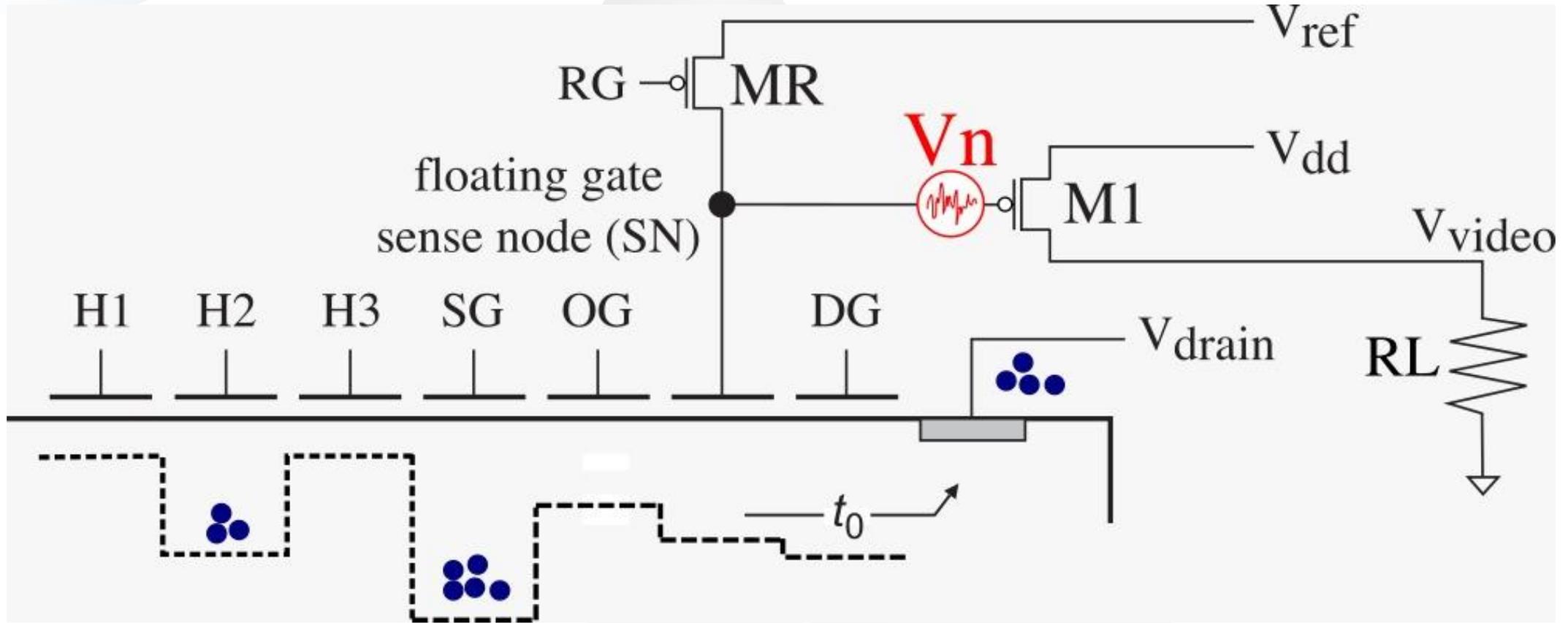


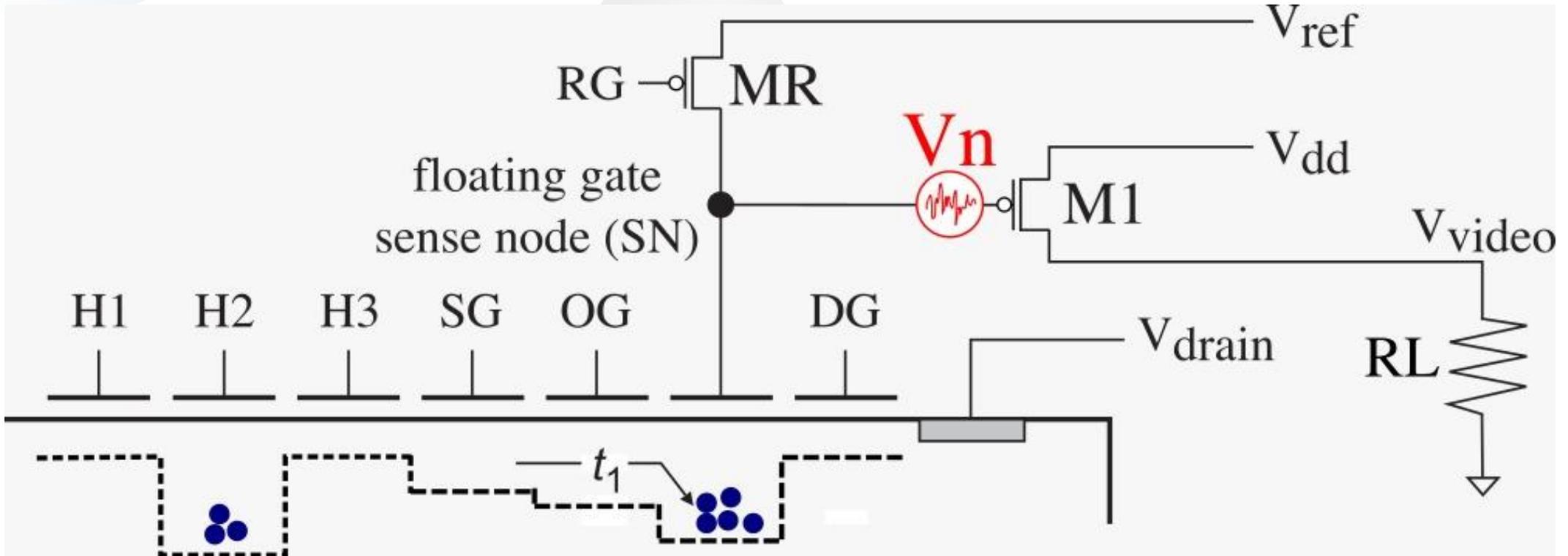
low frequency noise

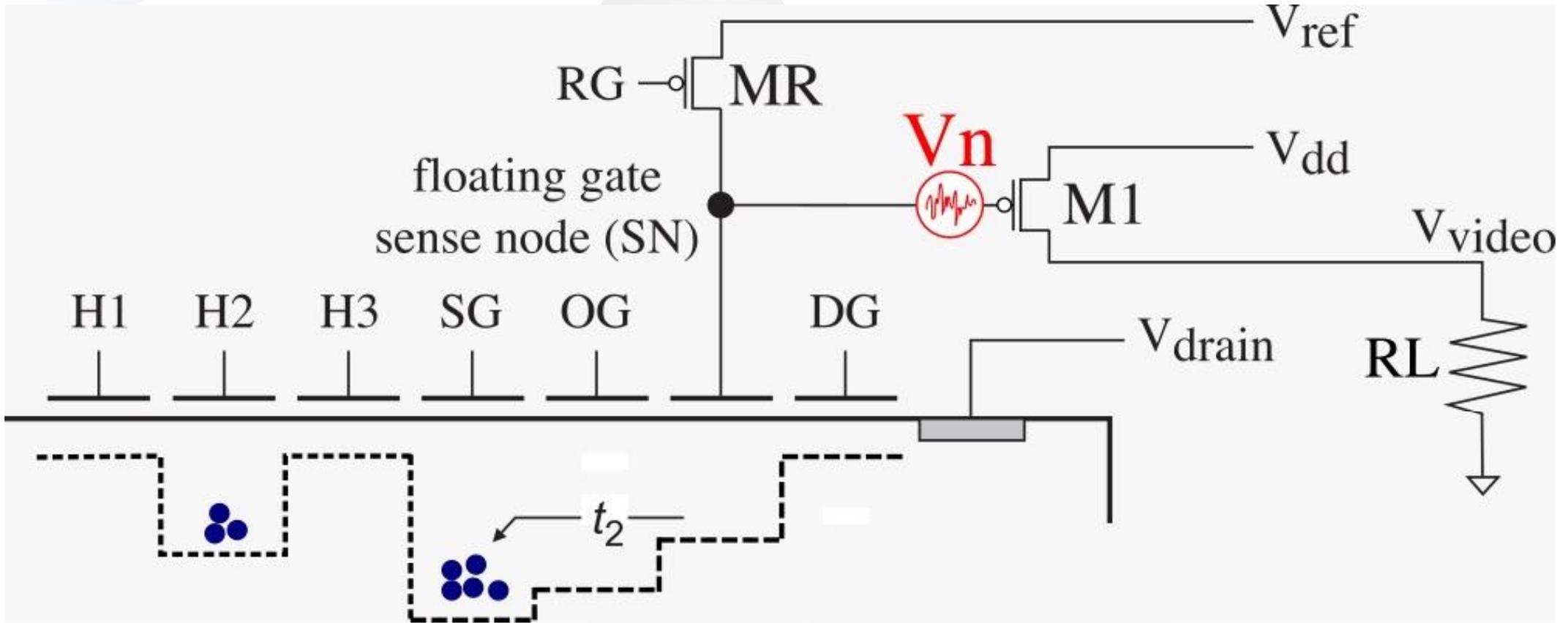


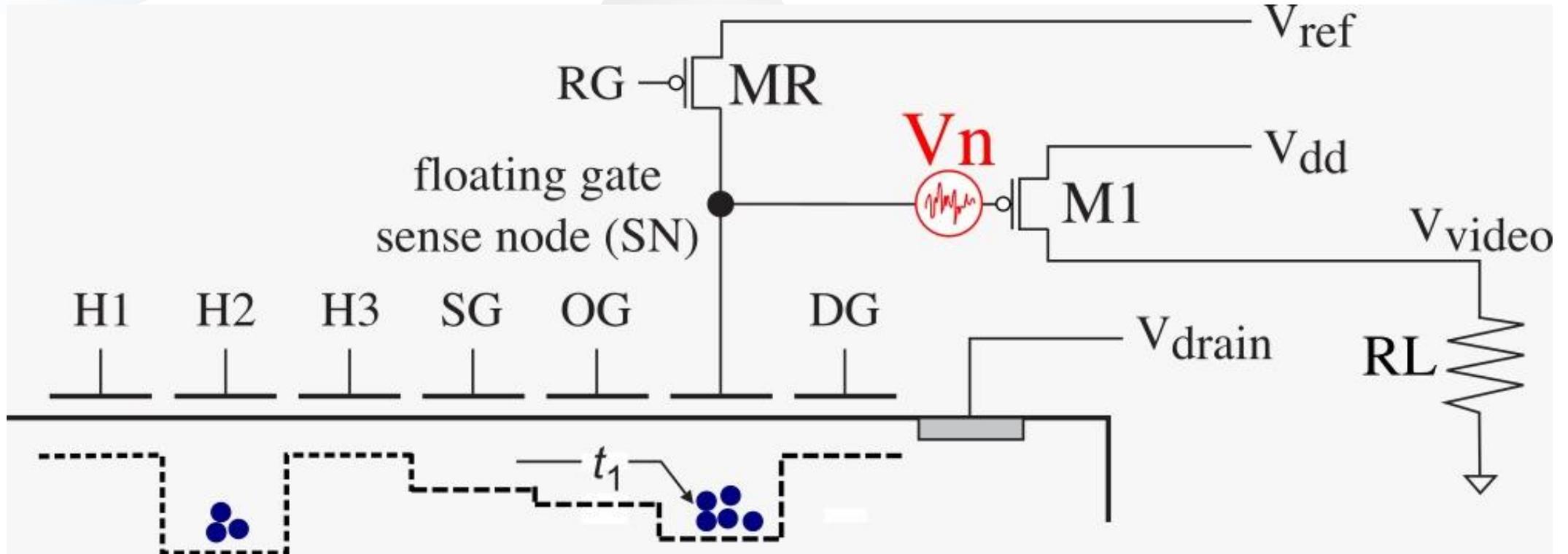


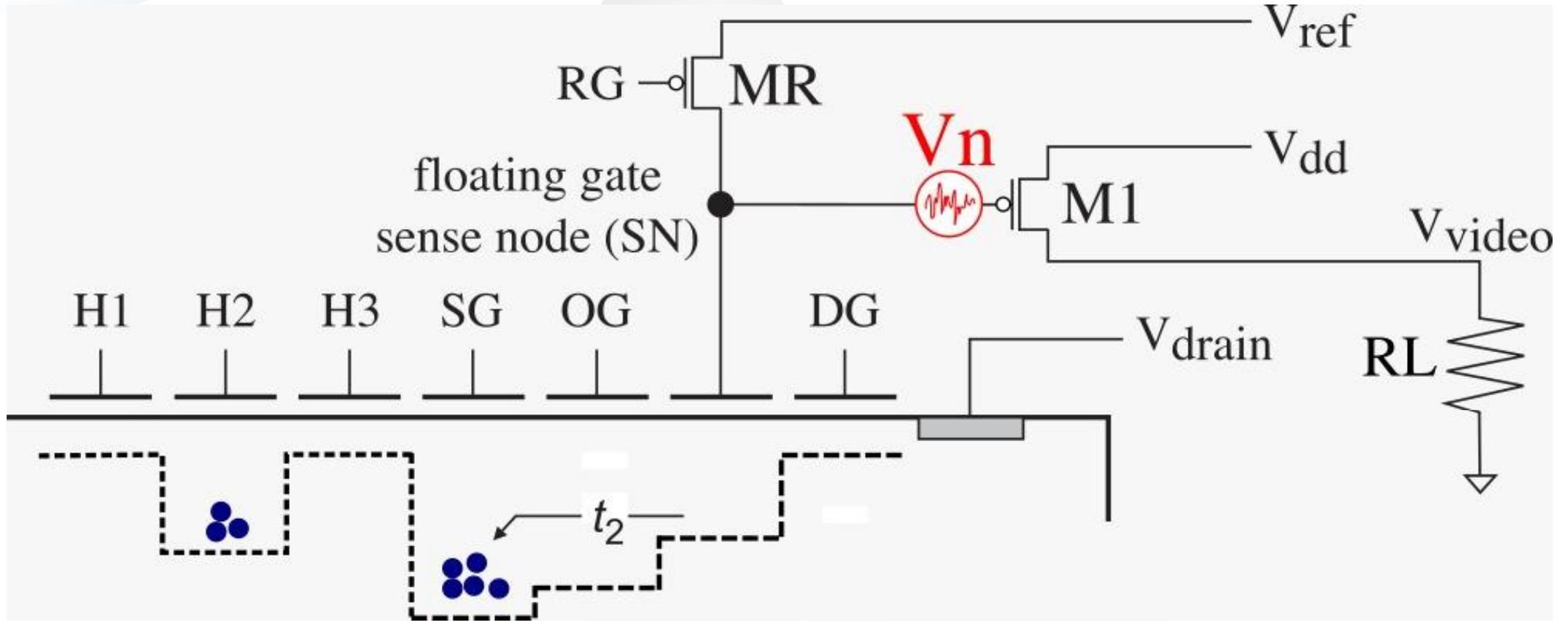


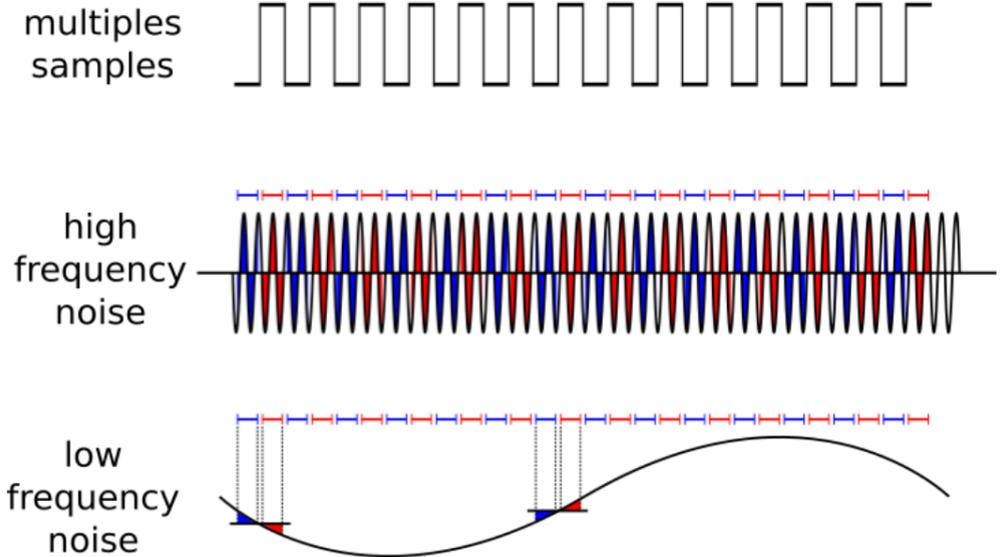
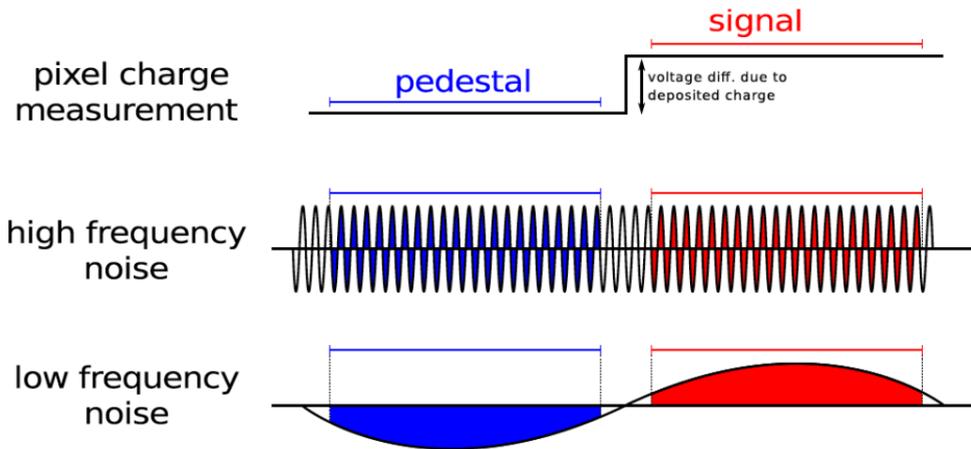












Noise goes in $1/\sqrt{N}$

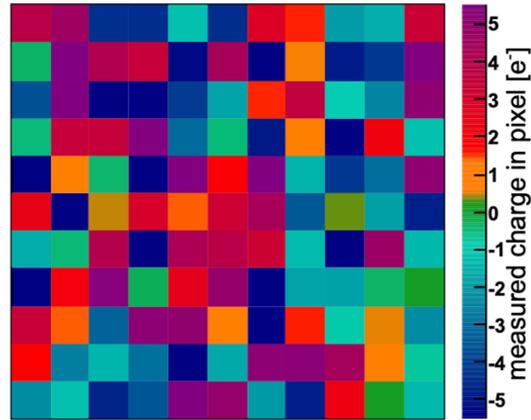
Single electron:

 threshold is silicon

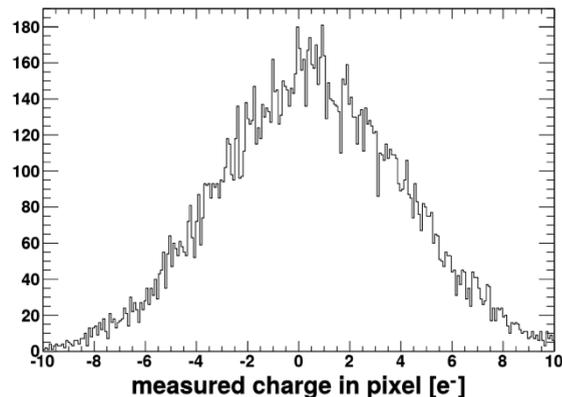
 band gap (1.1 eV)

PRL 119, 131802 (2017)

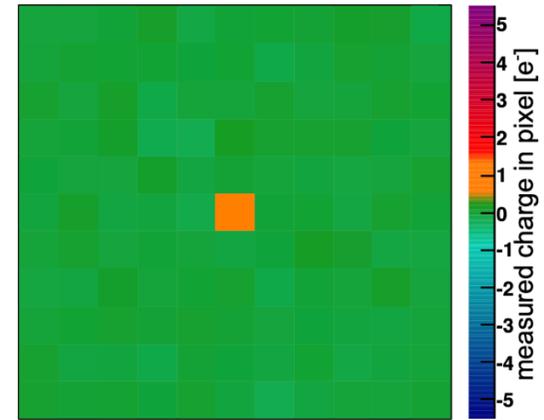
Standard CCD mode: charge in each pixel is measured once



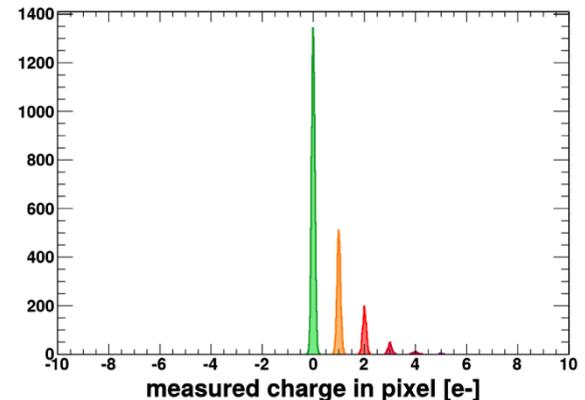
Readout-noise: 3.5 e RMS



New Skipper CCD: charge in each pixel is measured multiple times



Readout-noise: 0.06 e RMS



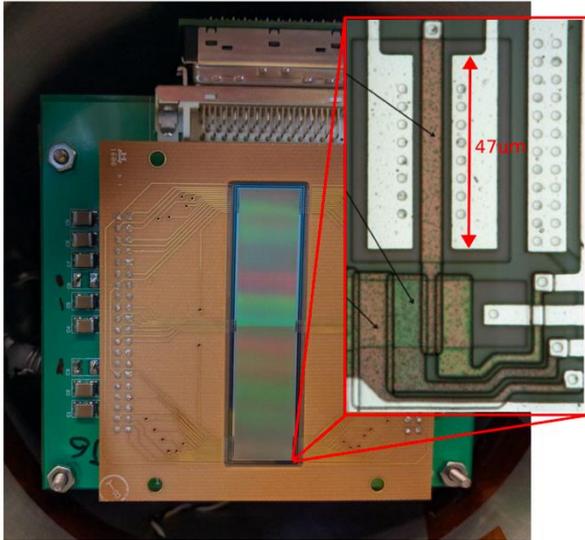
What can a Skipper CCD do?

It can move a charge of $1 e^-$ across 10cm over 24h and measure it perfectly

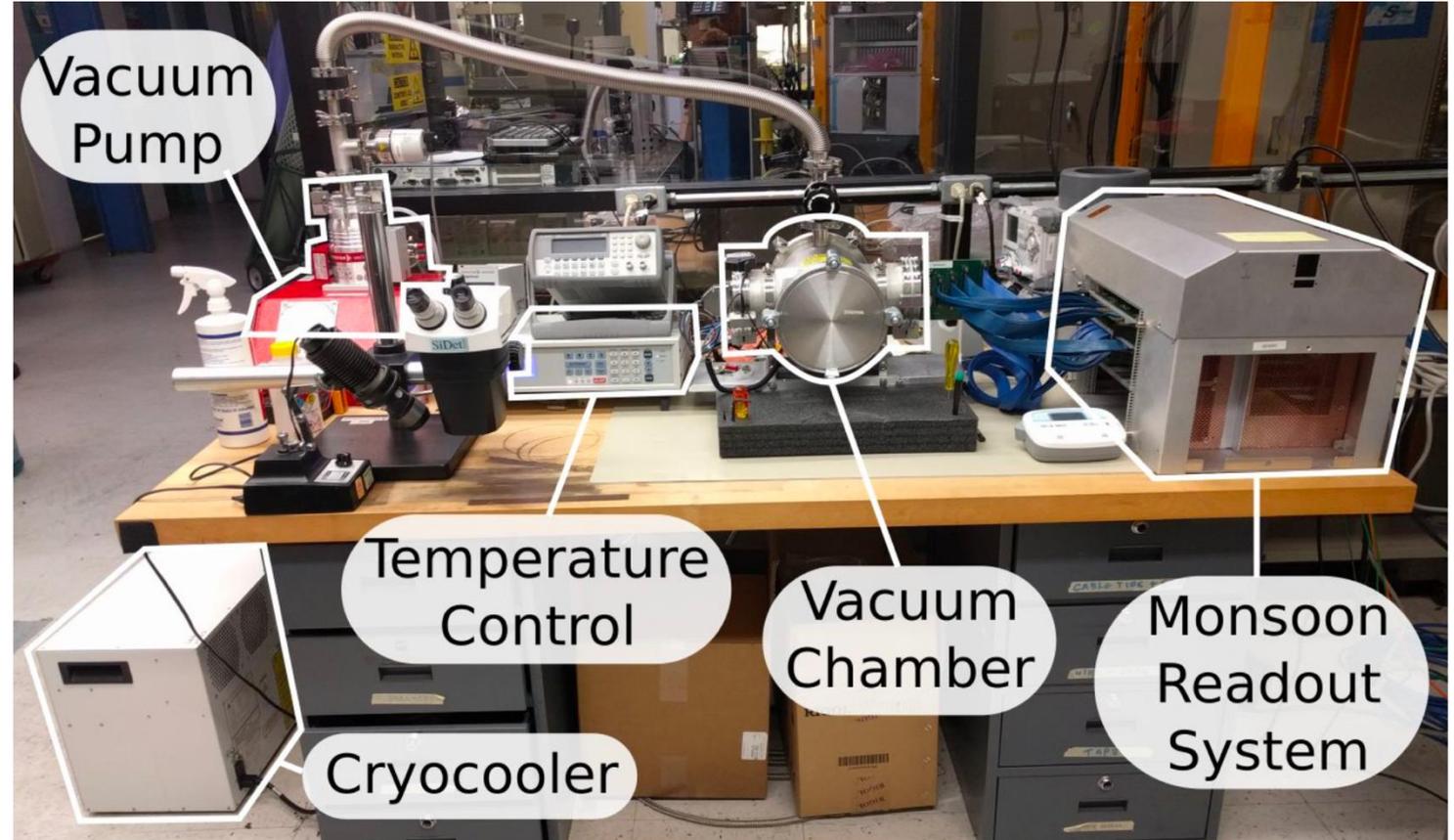
(and operate with a DC of $\sim 5 e^- / g / \text{day}$)

(3)

The Skipper CCD and Dark Matter

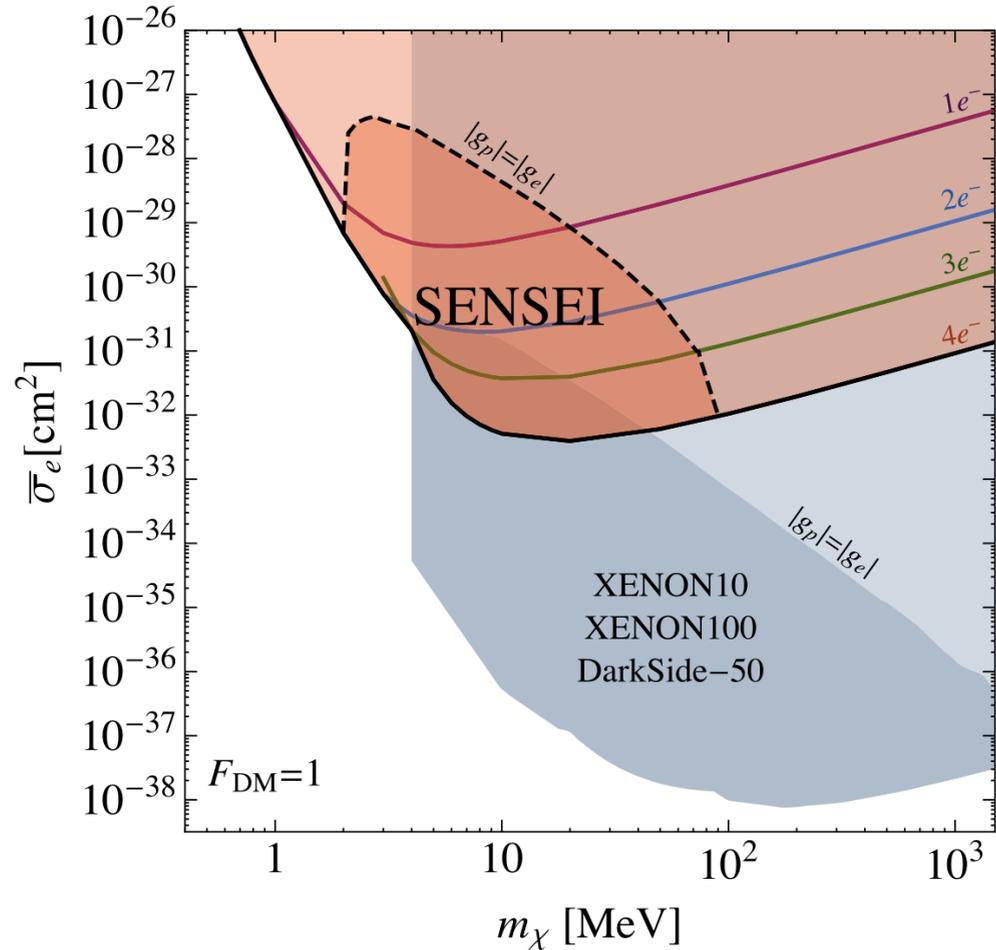


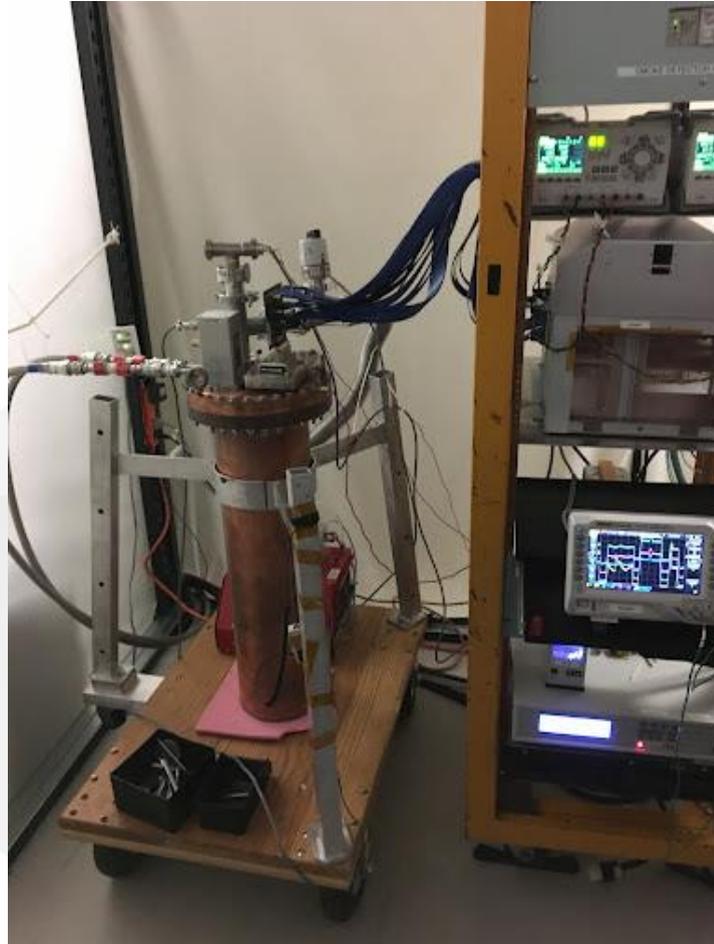
250 µm depth
0.1g



SENSEI: First Direct-Detection Constraints on sub-GeV Dark Matter from a Surface Run

Phys. Rev. Lett. 121, 061803 (2018)





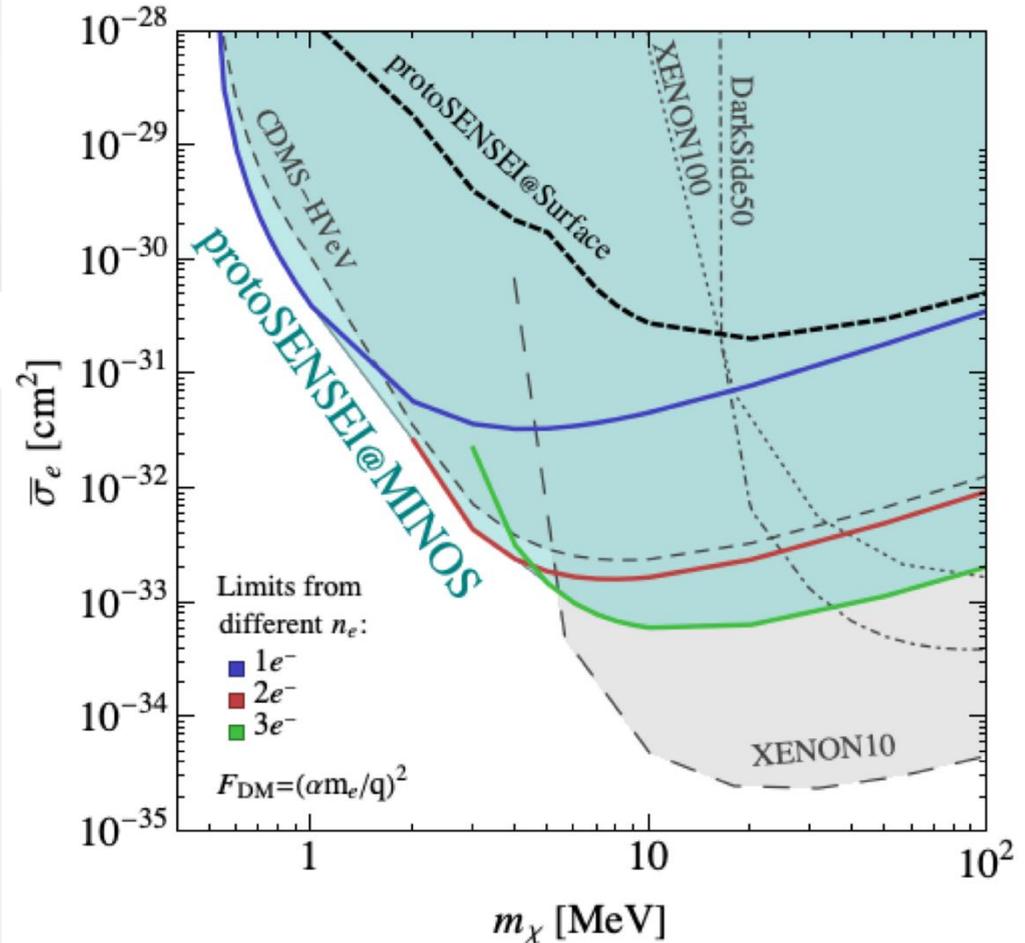
SENSEI: Direct-Detection

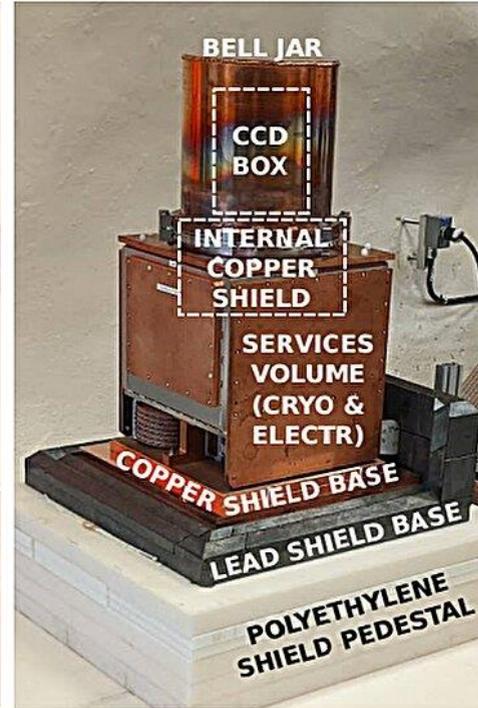
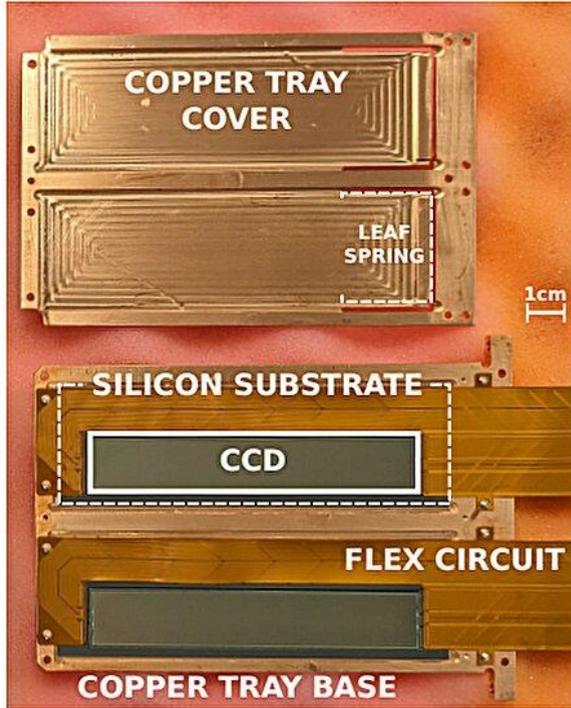
 Constraints on Sub-GeV Dark

 Matter from a Shallow Underground

 Run Using a Prototype Skipper-CCD

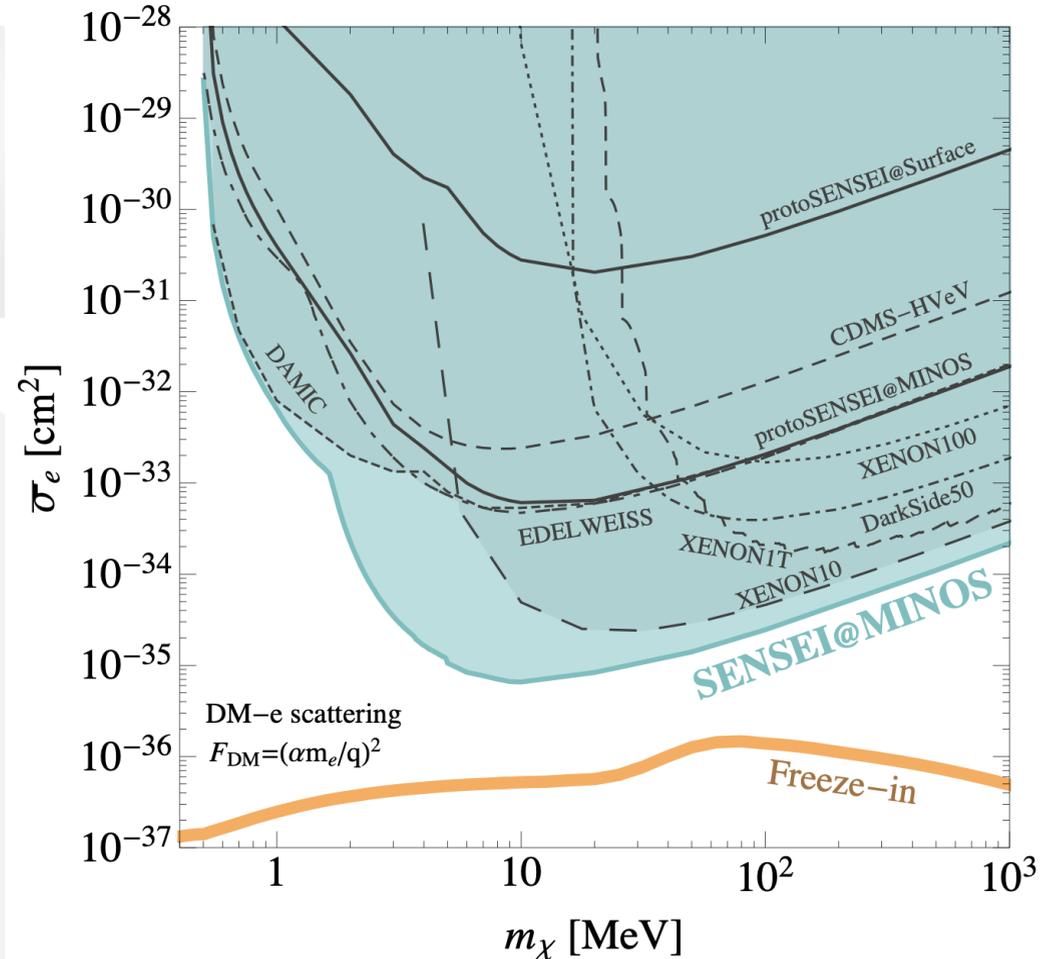
Phys. Rev. Lett. 122, 161801 (2019)





SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD

Phys. Rev. Lett. 125, 171802 (2020)



(4) DAMIC-M



Comisi n Nacional
 de Energ a At mica

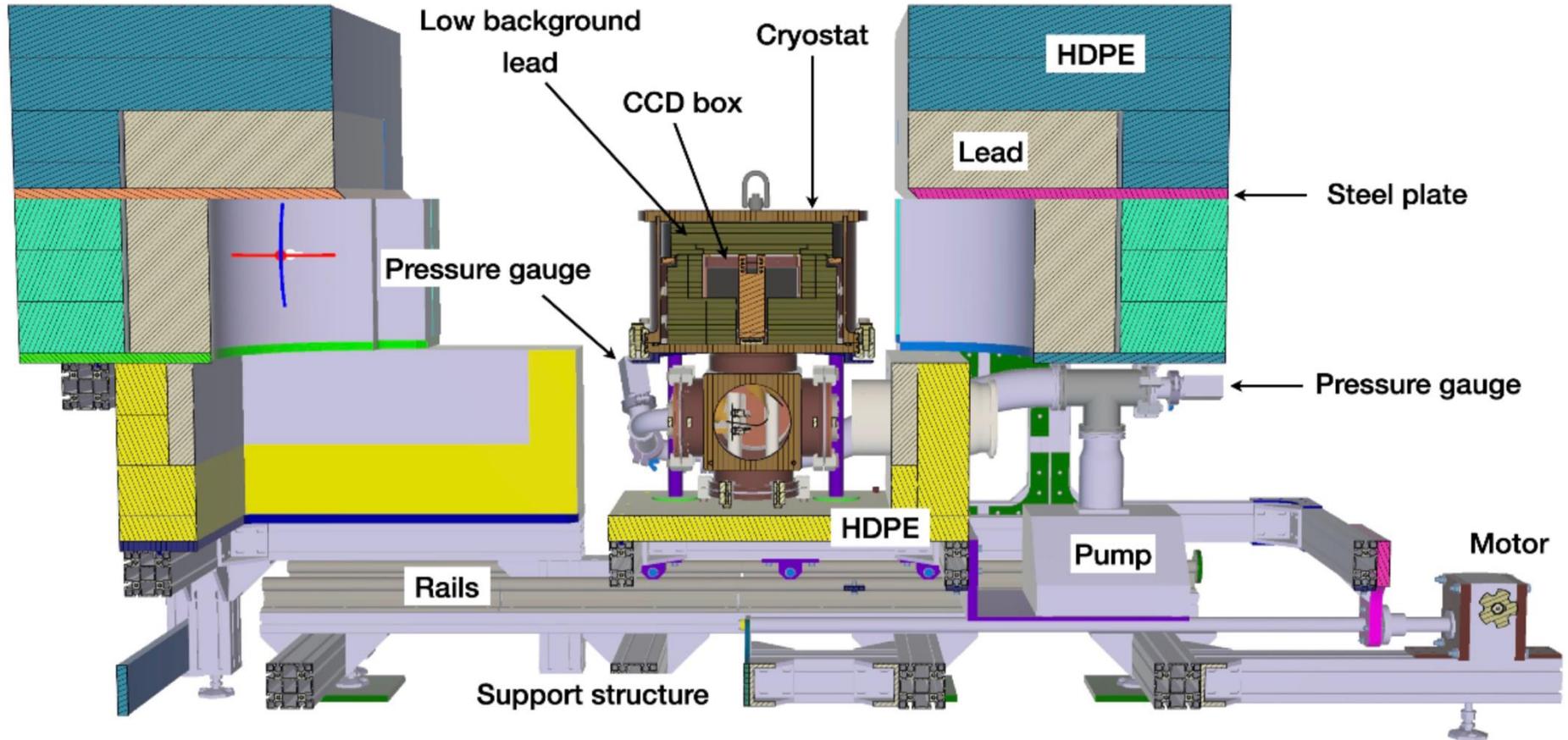


Instituto de F sica de Cantabria

First step

LBC
Low
Background
Chamber





CCD controllers and power supplies

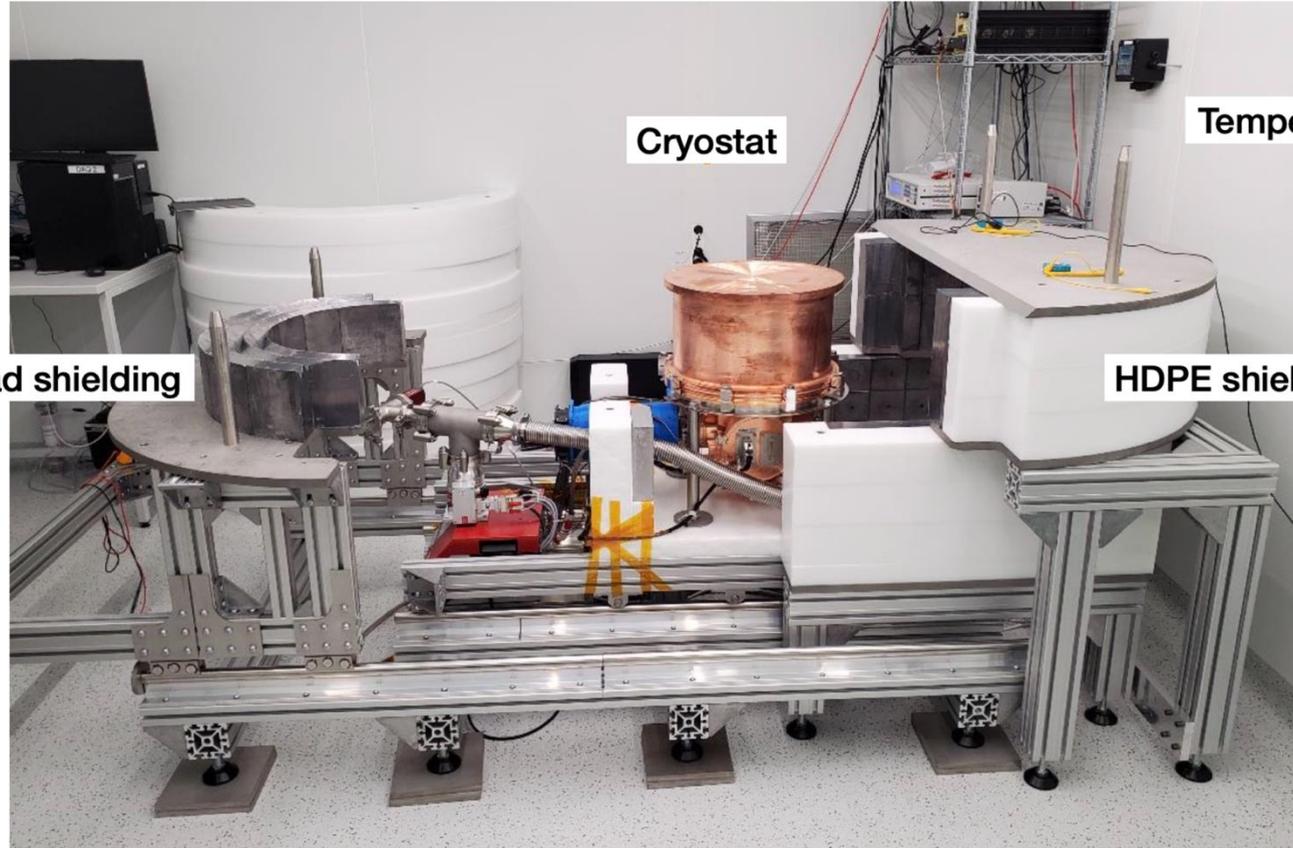
DAQ and slow
control PCs

External lead shielding

Cryostat

Temperature controller

HDPE shielding

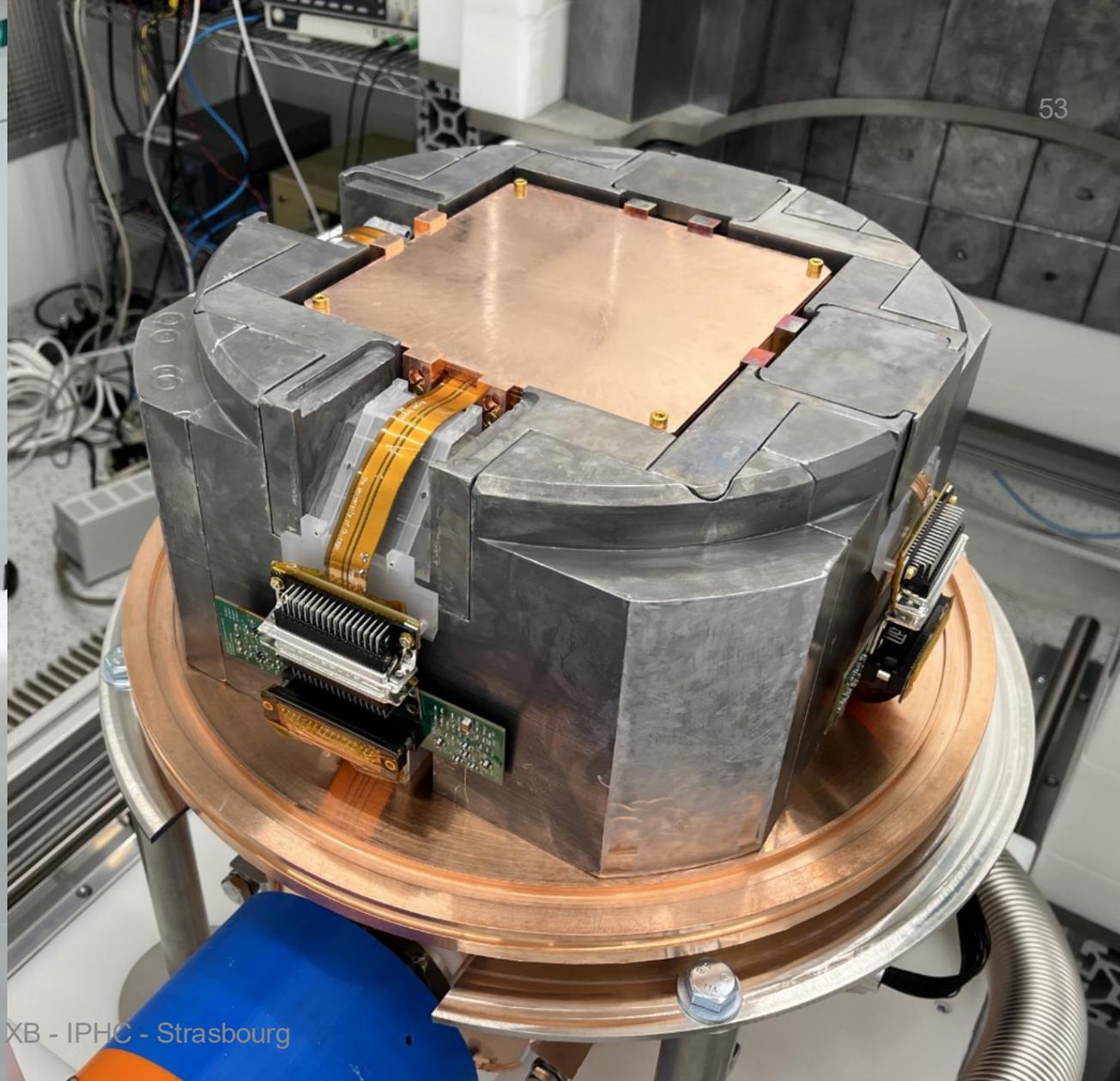


Support structure

Vacuum pump and pressure gauges

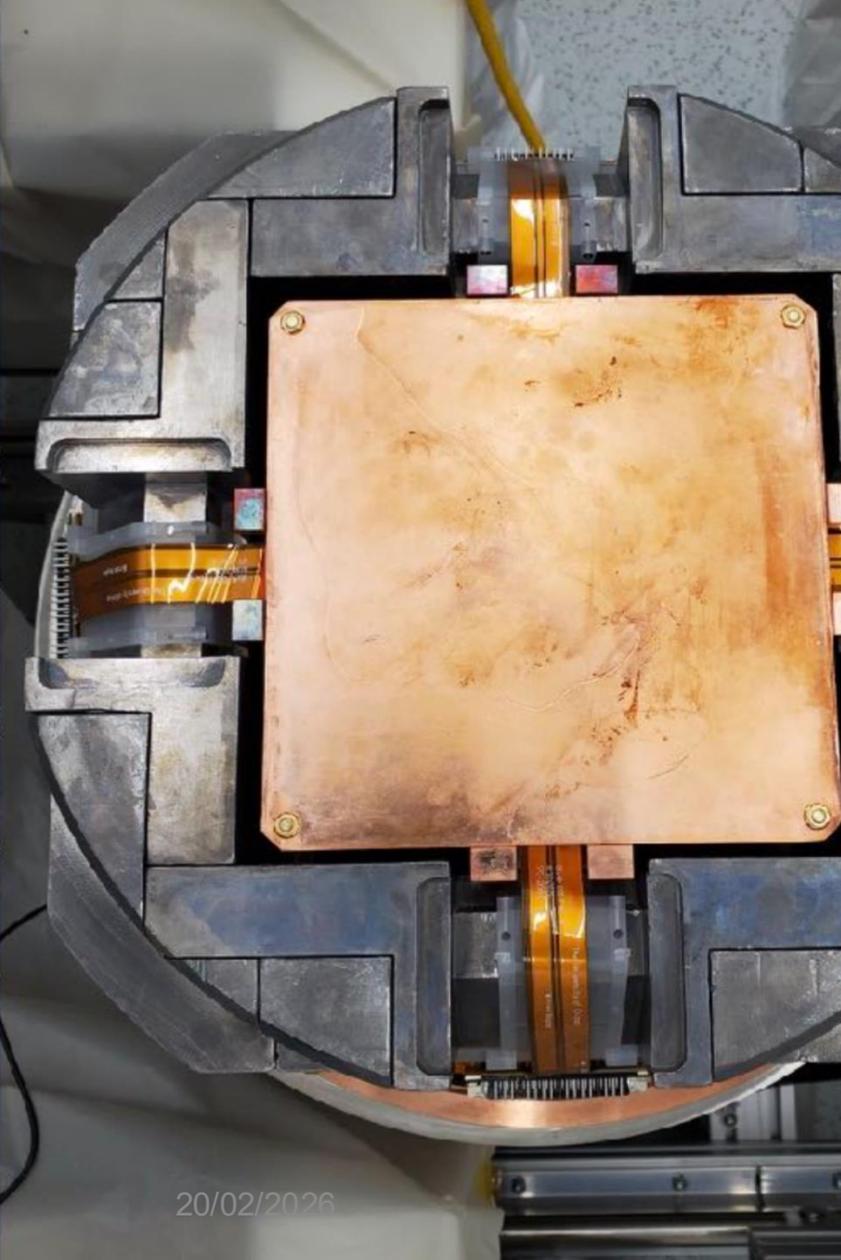


20/02/2026

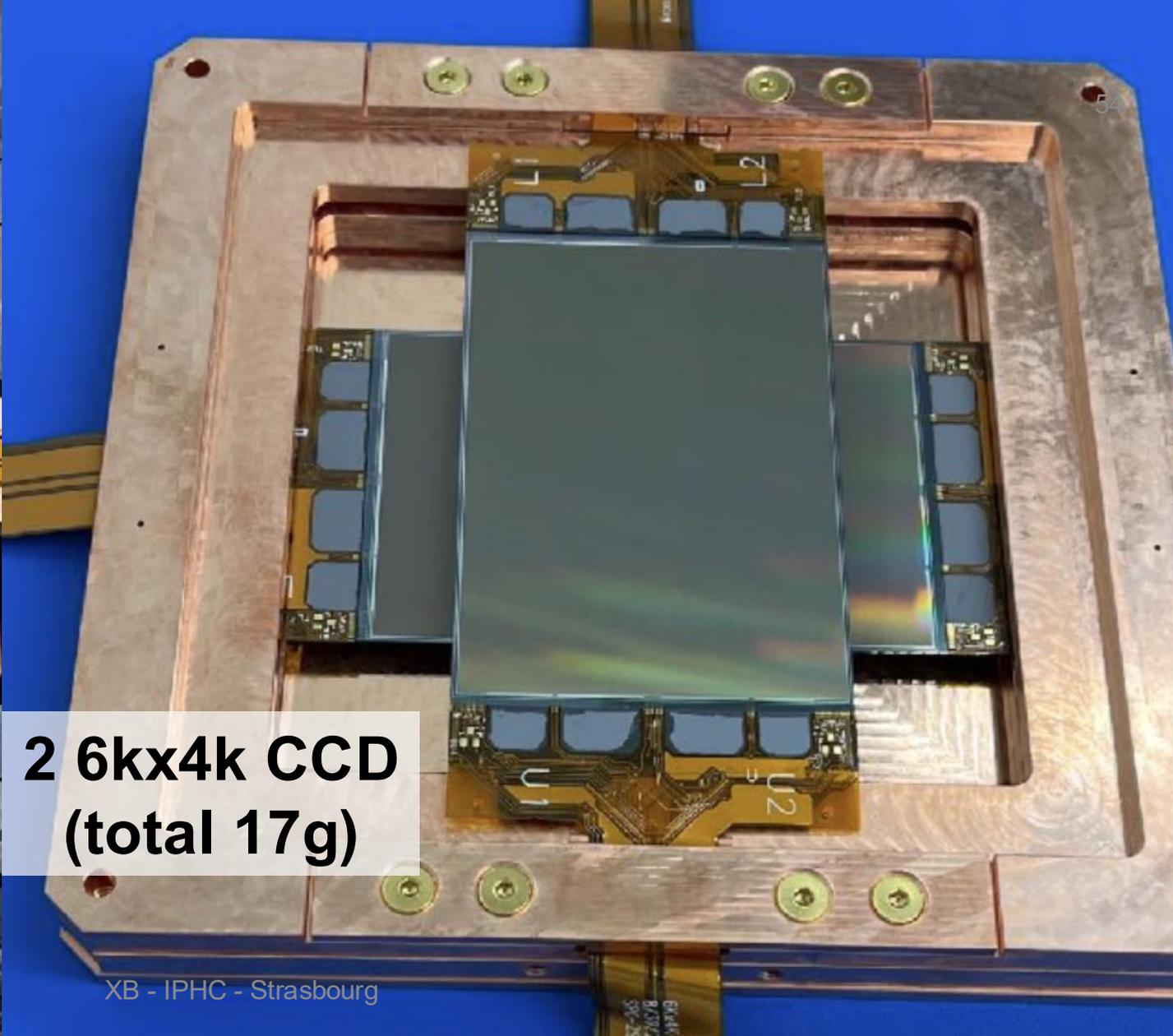


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XB - IPHC - Strasbourg



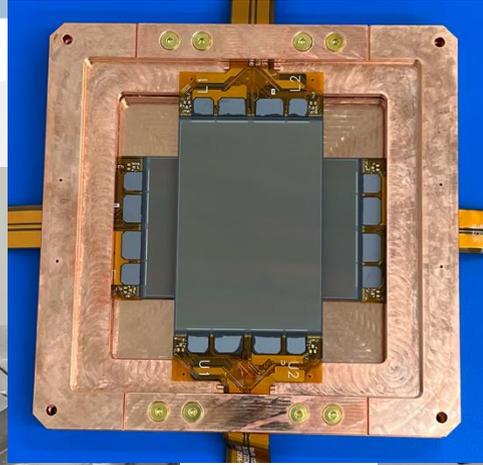
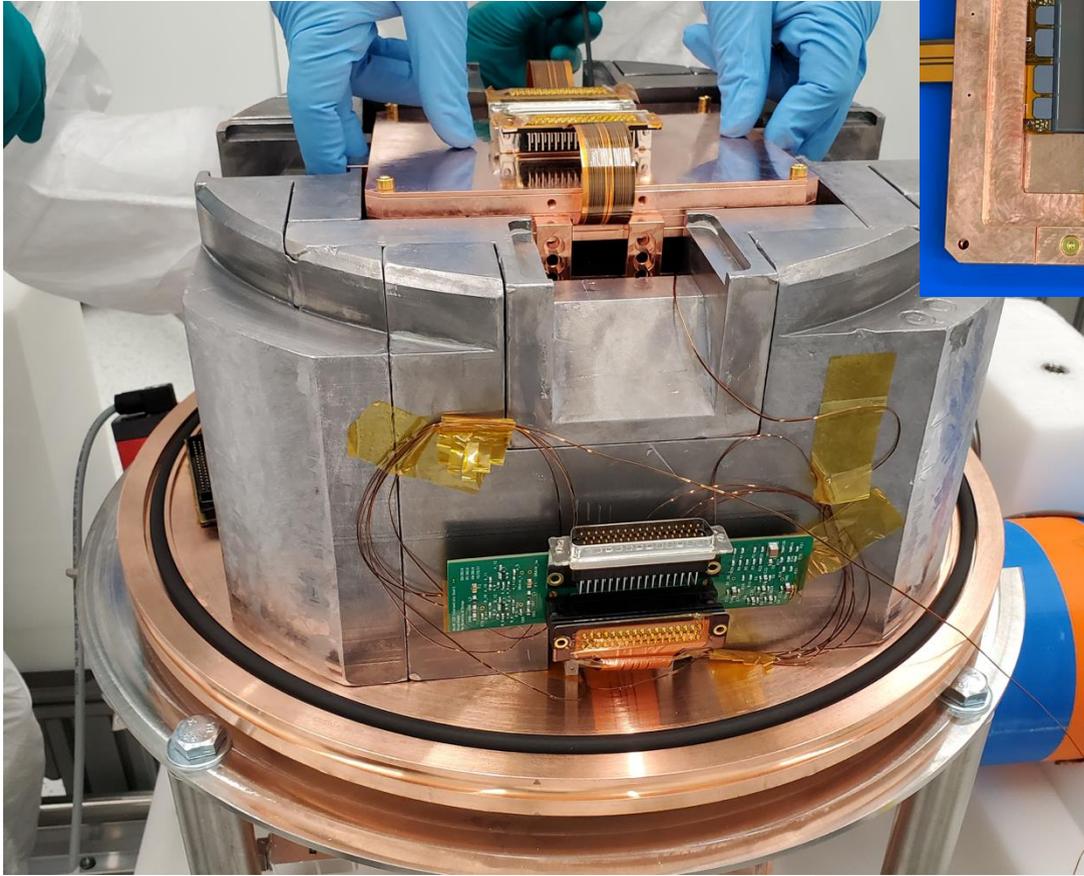
20/02/2026



54

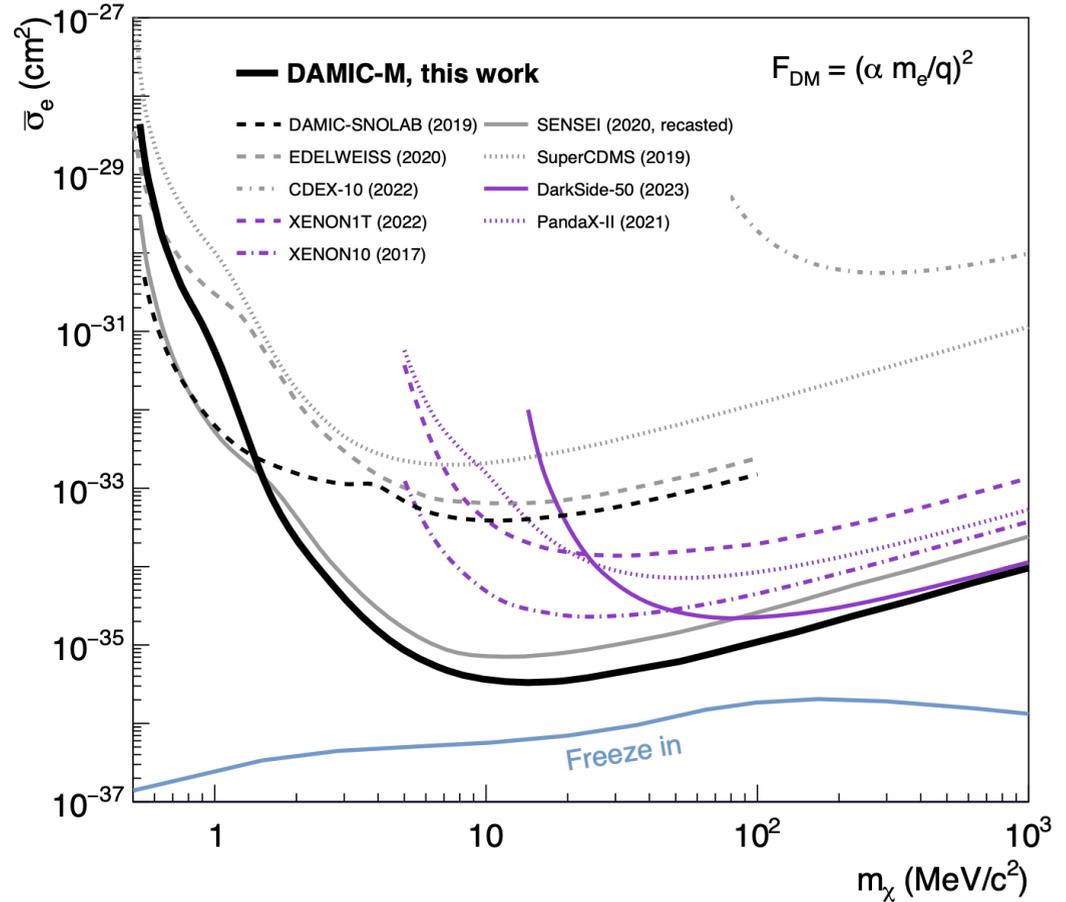
**2 6kx4k CCD
(total 17g)**

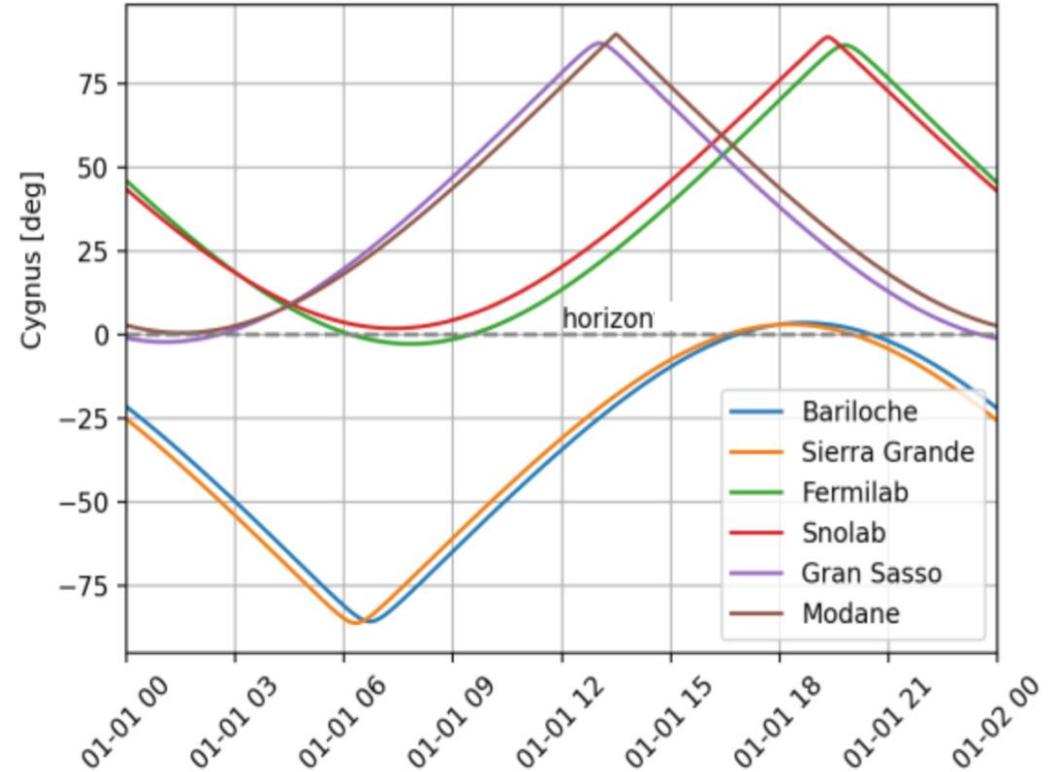
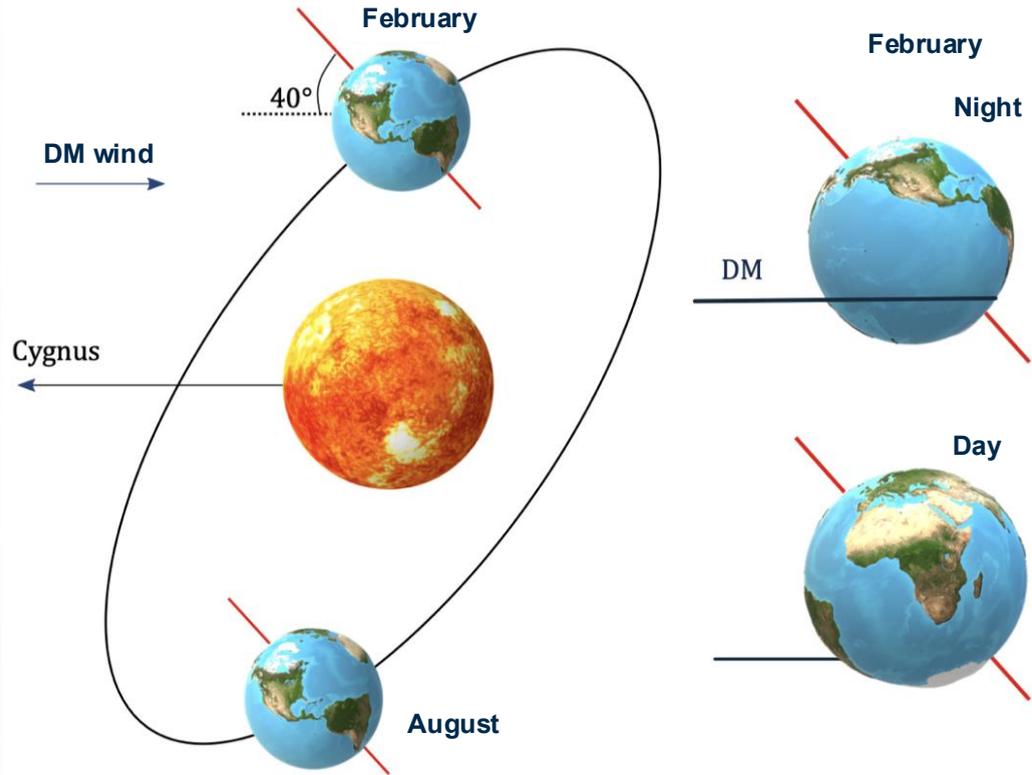
XB - IPHC - Strasbourg

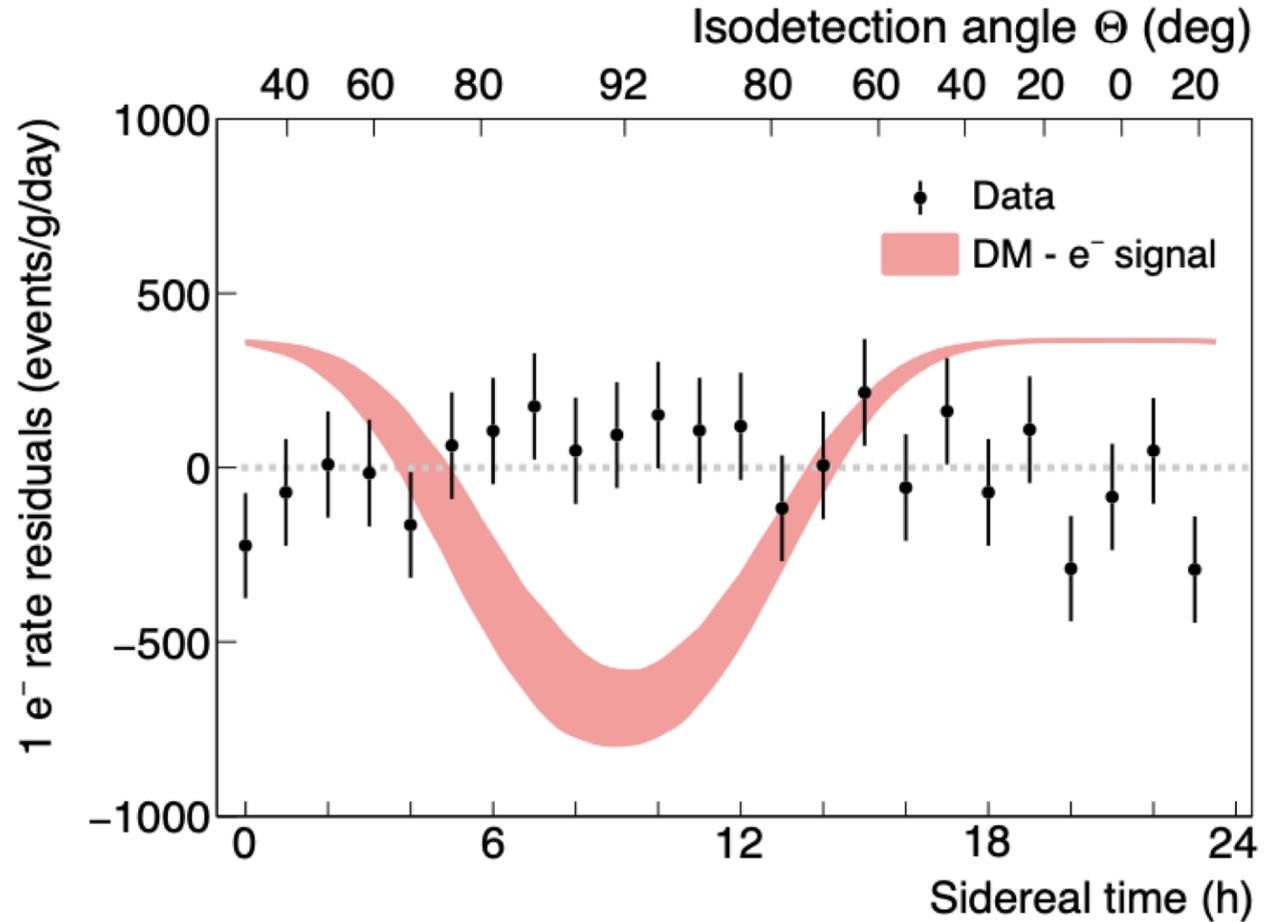


First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons

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

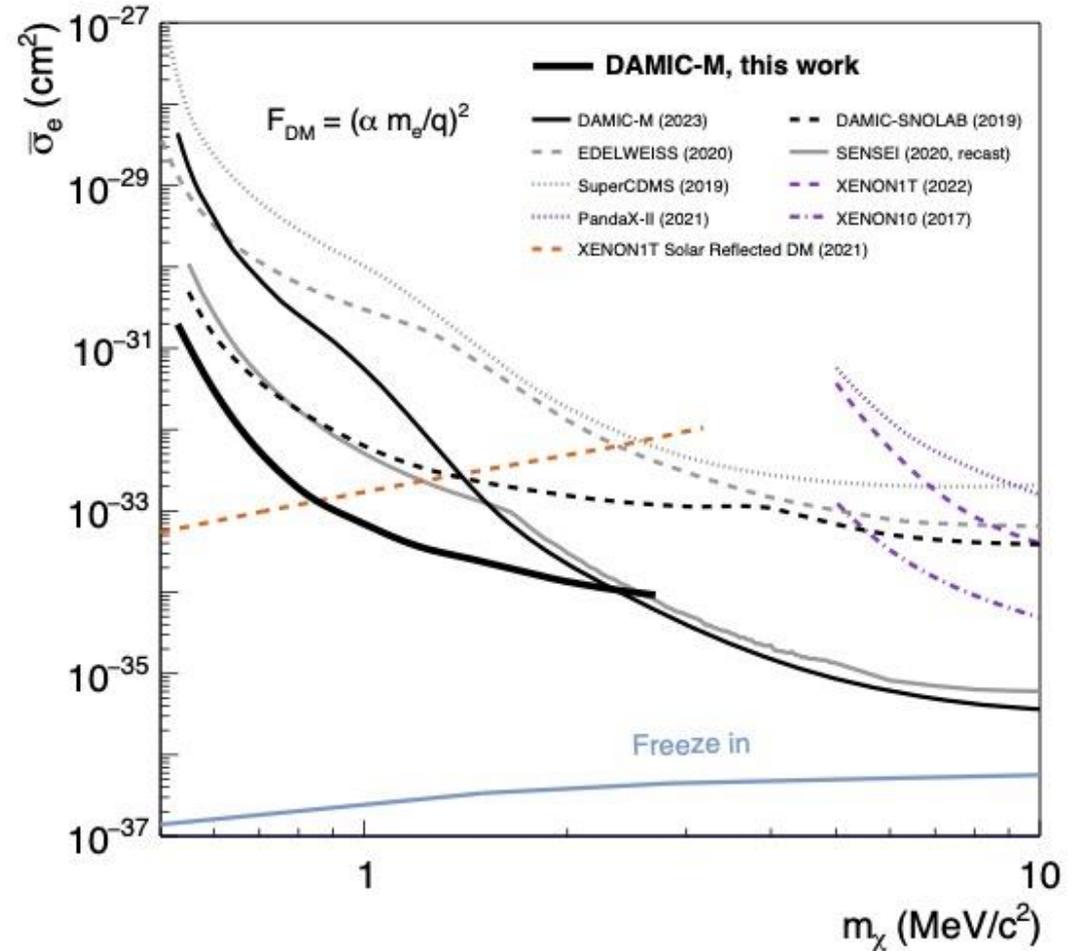


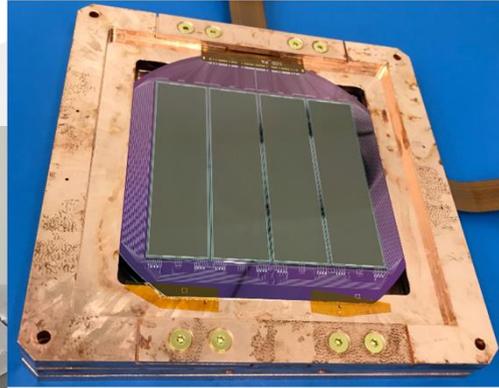
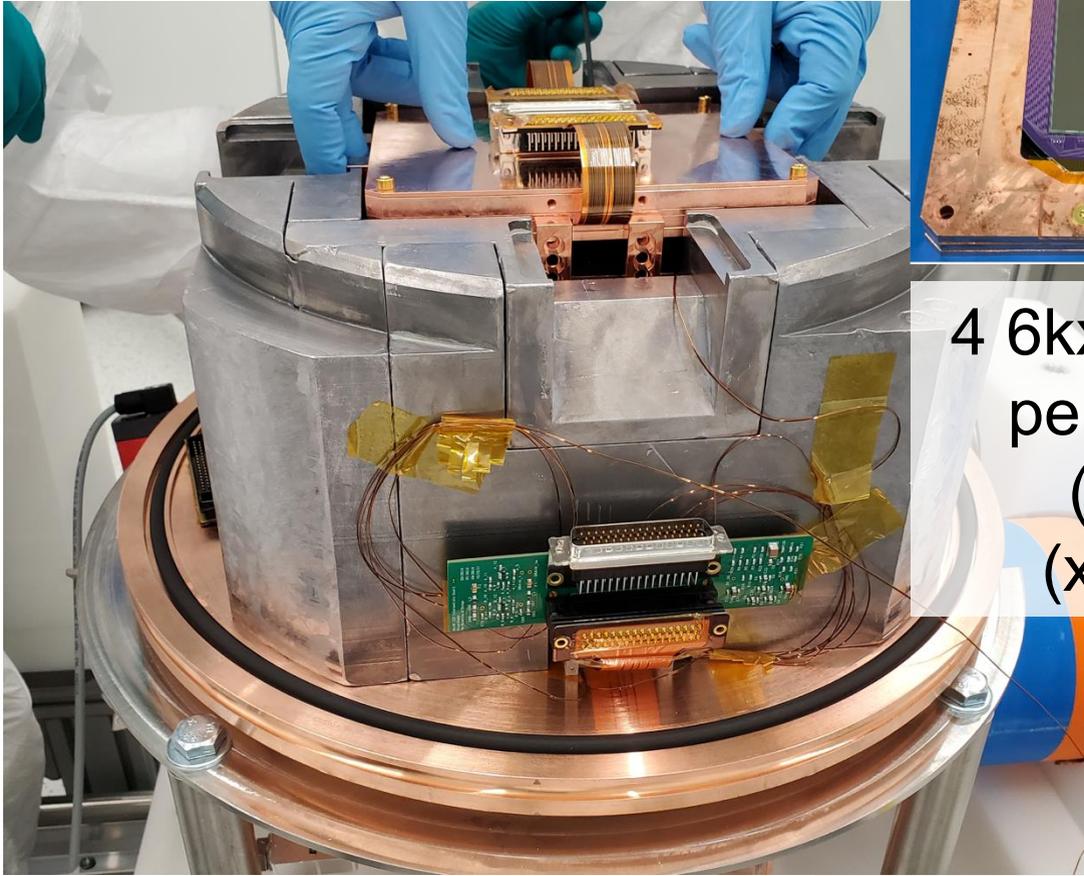




Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M

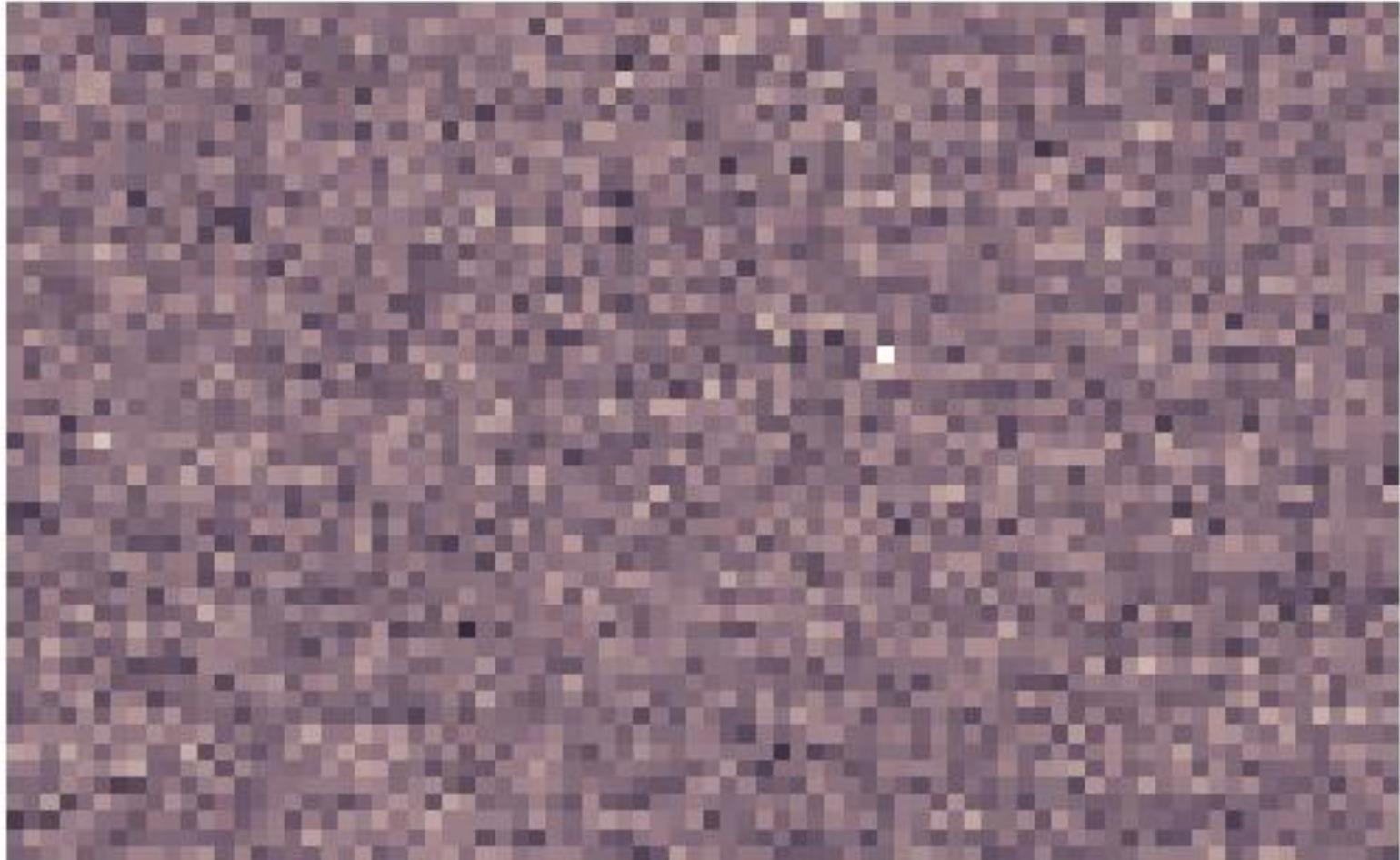
Phys. Rev. Lett. 132, 101006 (2024)

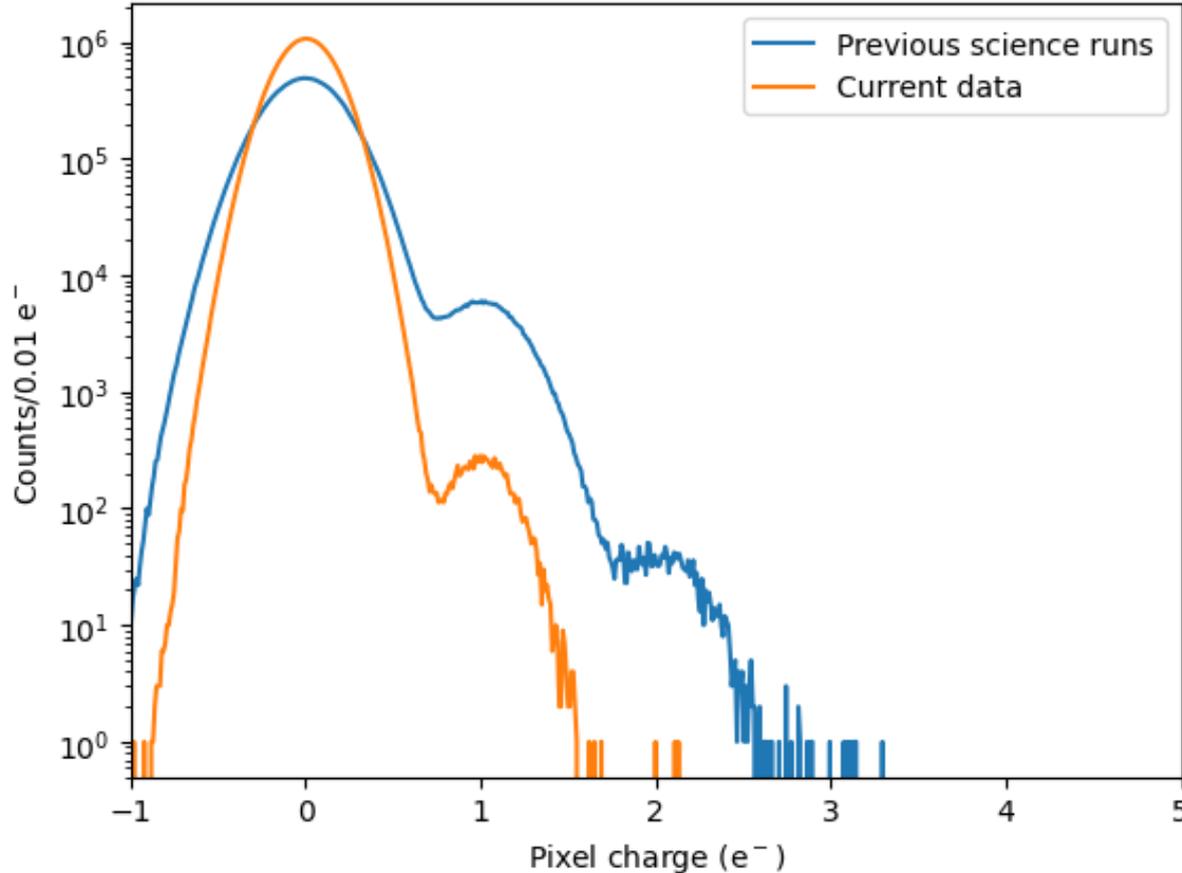




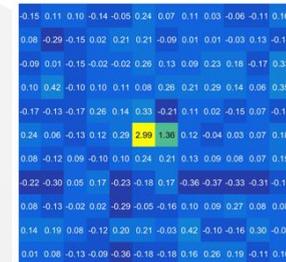
4 6kx1.5k CCD
per module
(13.4g)
(x2=27g)





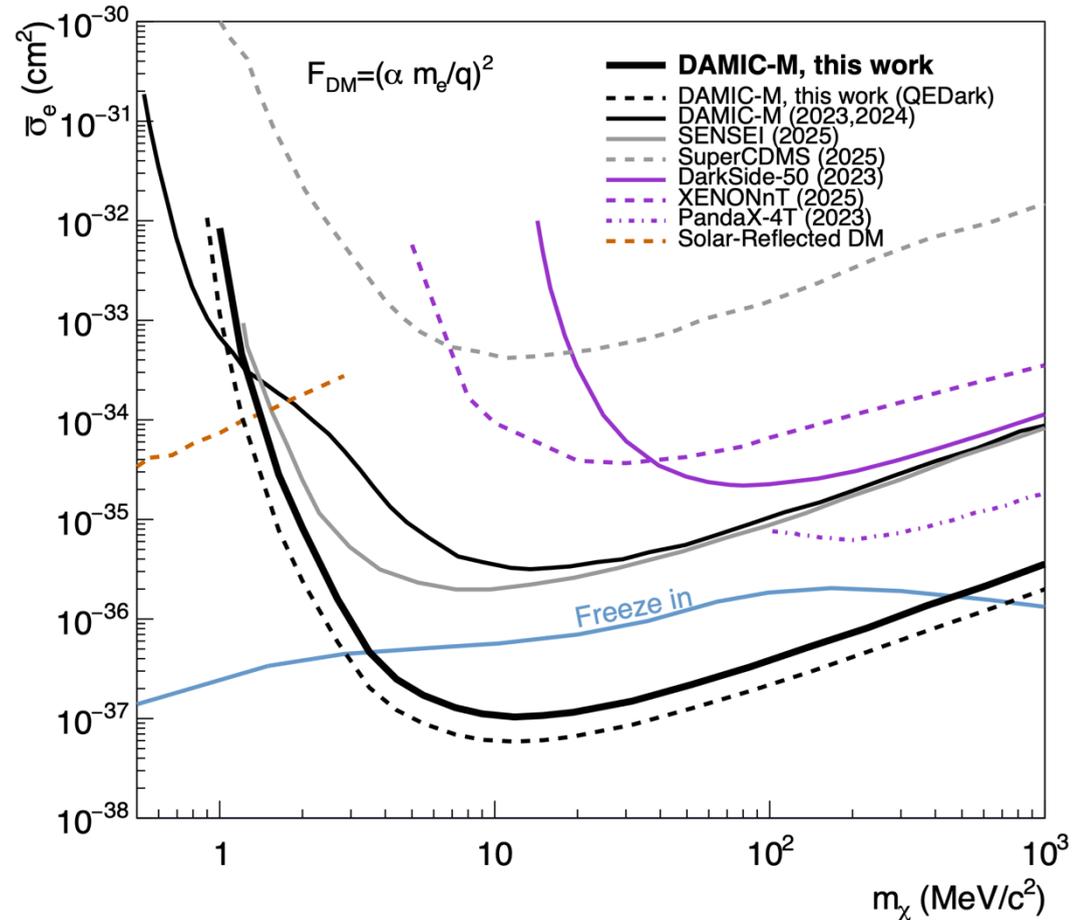


	Pattern p		
	$\{11\}$	$\{21\}$	$\{111\}$
D_p	144	0	0
B_p^{rc}	141.4	0.111	0.042
B_p^{rad}	0.039	0.039	0.016
	$\{31\}$	$\{22\}$	$\{211\}$
D_p	1	0	0
B_p^{rc}	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.052	0.011	0.035



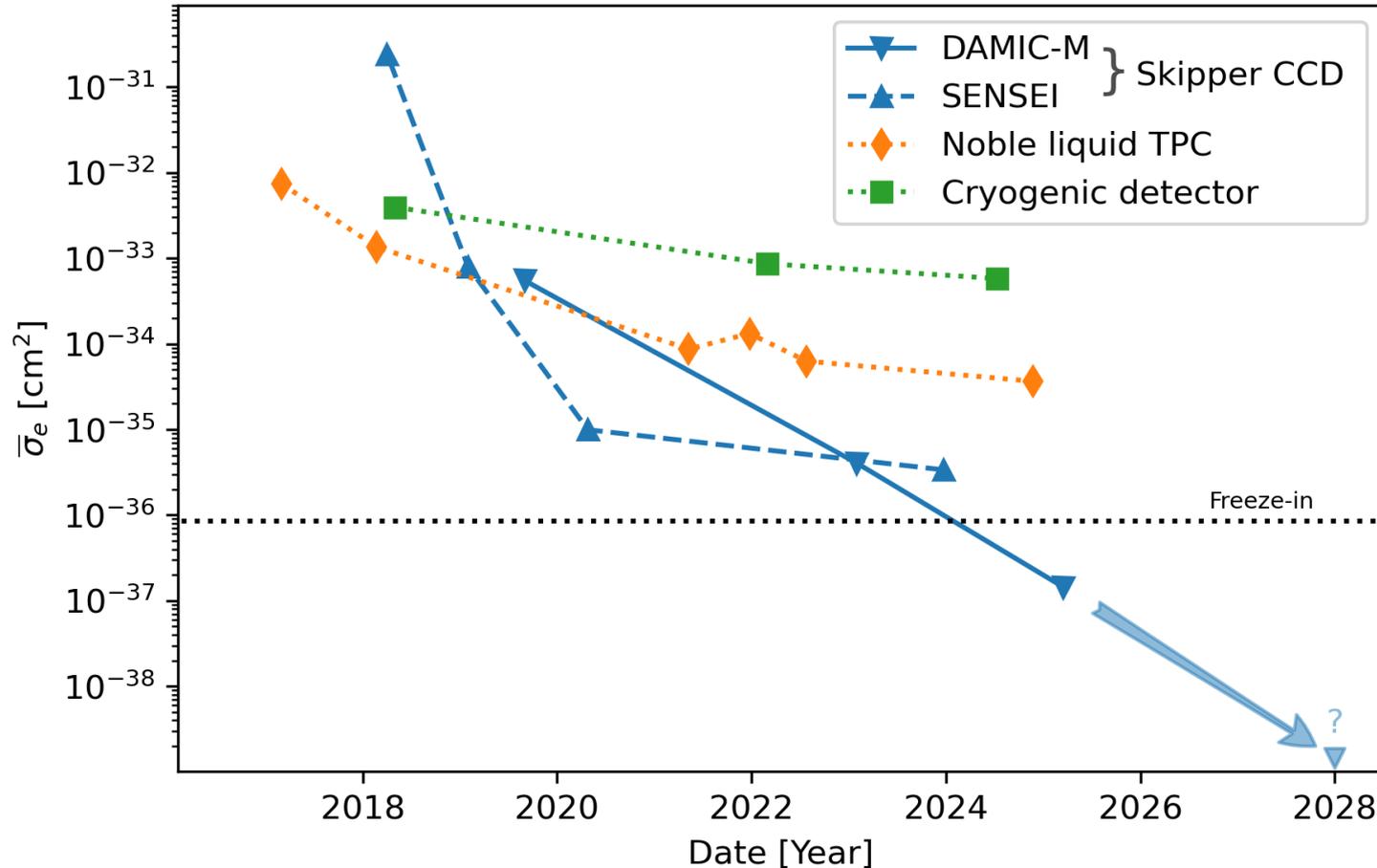
Probing Benchmark Models of Hidden-Sector Dark Matter with DAMIC-M

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



1. Tiffenberg et al, Single-electron and single-photon sensitivity with a silicon Skipper CCD, Phys. Rev. Lett. 119, 131802 (2017)
2. The SENSEI Collaboration, SENSEI: First Direct-Detection Constraints on sub-GeV Dark Matter from a Surface Run, Phys. Rev. Lett. 121, 061803 (2018)
3. The SENSEI Collaboration, SENSEI: Direct-Detection Constraints on Sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper-CCD, Phys. Rev. Lett. 122, 161801 (2019)
4. The SENSEI Collaboration, SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD, Phys. Rev. Lett. 125, 171802 (2020)
5. The DAMIC-M Collaboration, First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons, Phys. Rev. Lett. 130, 171003 (2023)
6. The DAMIC-M Collaboration, Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M, Phys. Rev. Lett. 132, 101006 (2024)
7. The DAMIC-M Collaboration, Probing Benchmark Models of Hidden-Sector Dark Matter with DAMIC-M, arXiv:2503.14617, Phys. Rev. Lett. 135, 071002 (2025)

Published limit for $m_\chi=30$ MeV (ultra-light mediator)

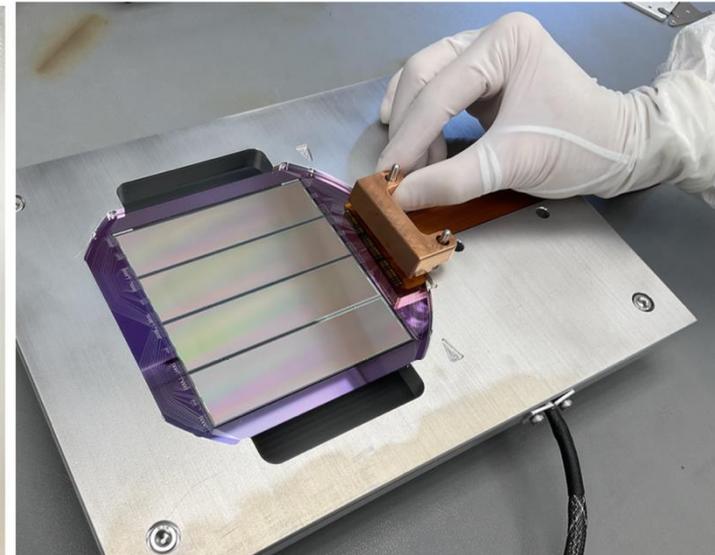
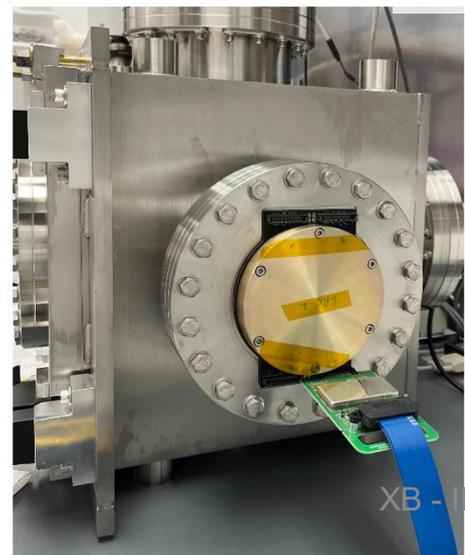


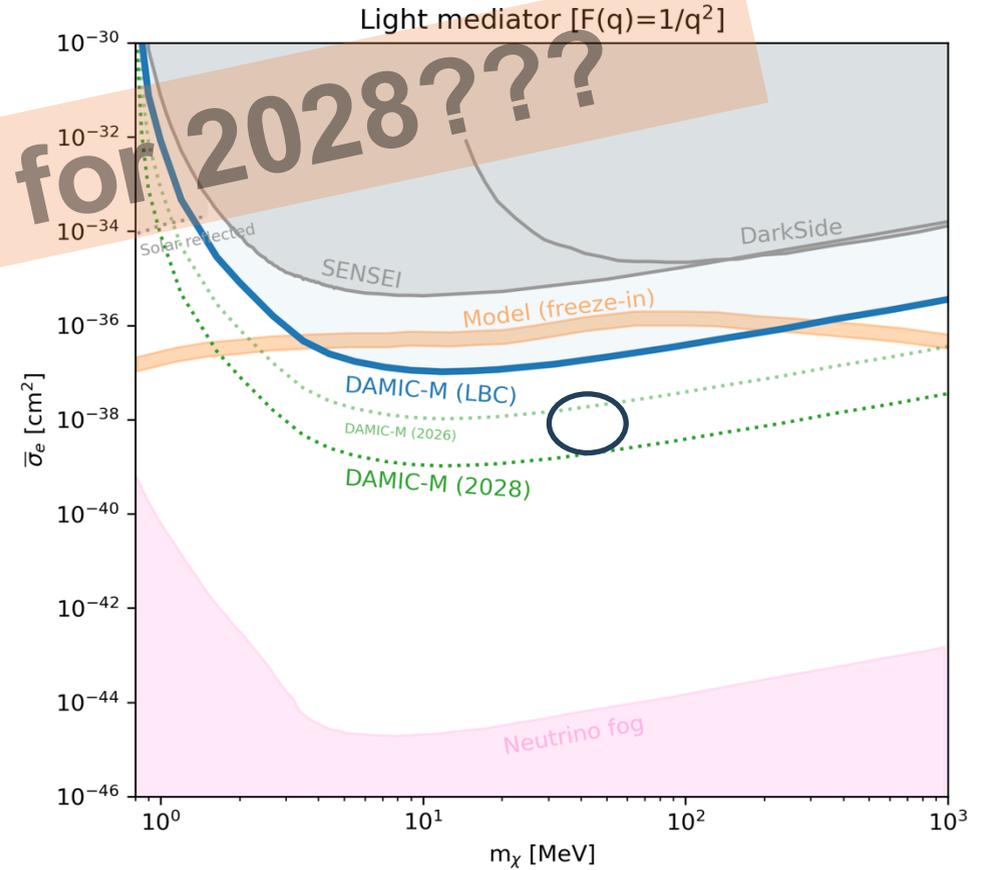
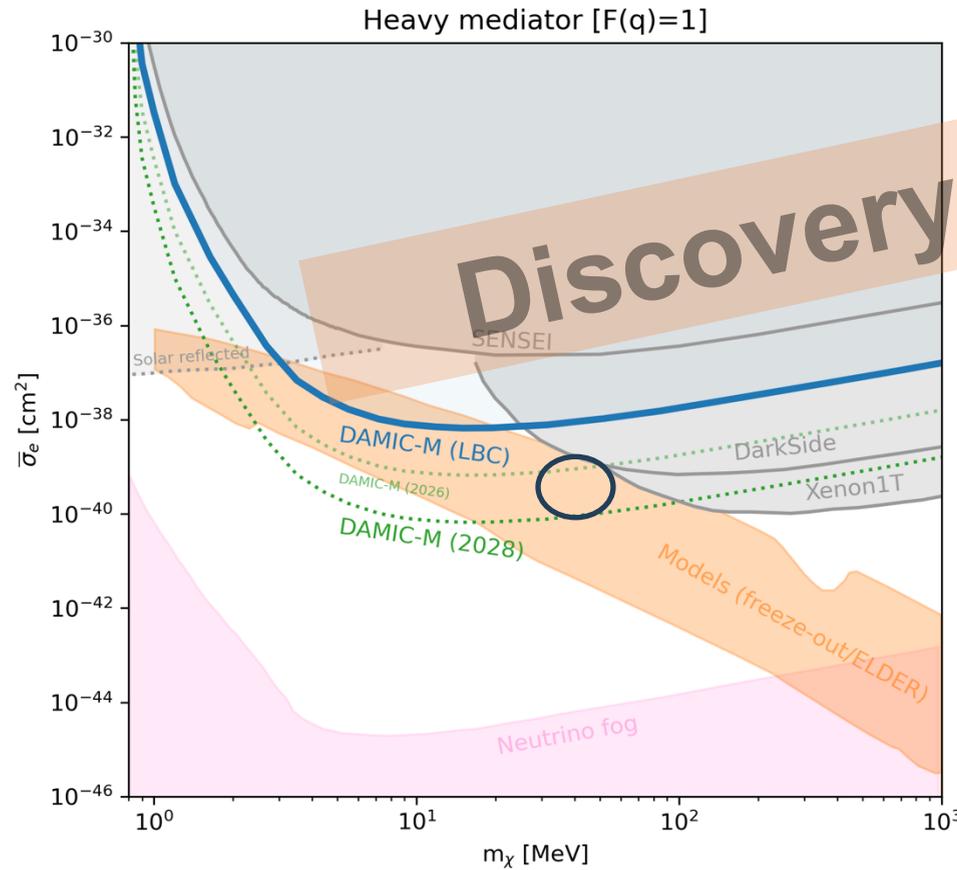
Note that the DAMIC-M results are from the prototype of the experiment (LBC)

Expect new results in 1-2 years



26 modules ready (350g)







(5)
What Next?

What can a Skipper CCD do?

It can move a charge of $1 e^-$ across 10cm over 24h and measure it perfectly

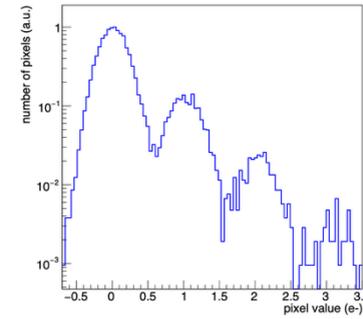
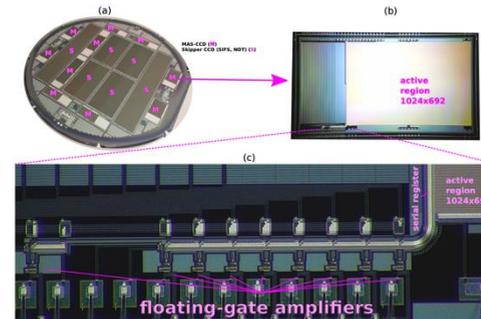
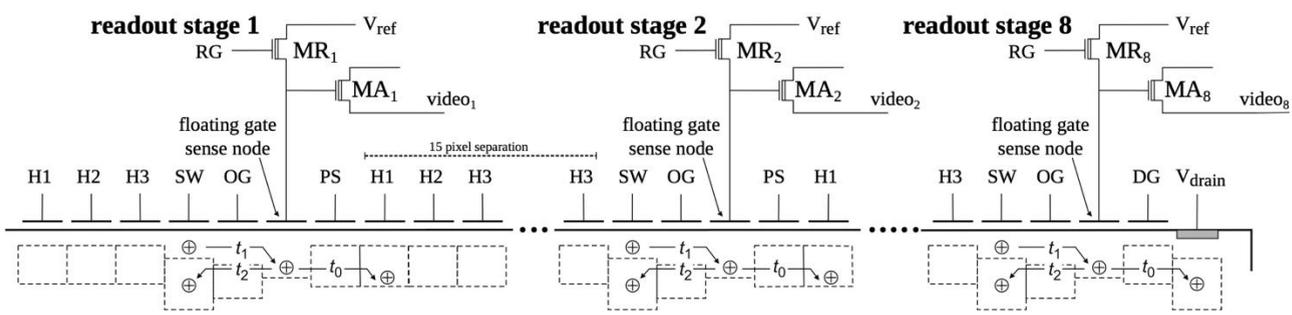
(and operate with a DC of $\sim 5 e^- / g / \text{day}$)

What can a Skipper CCD do?

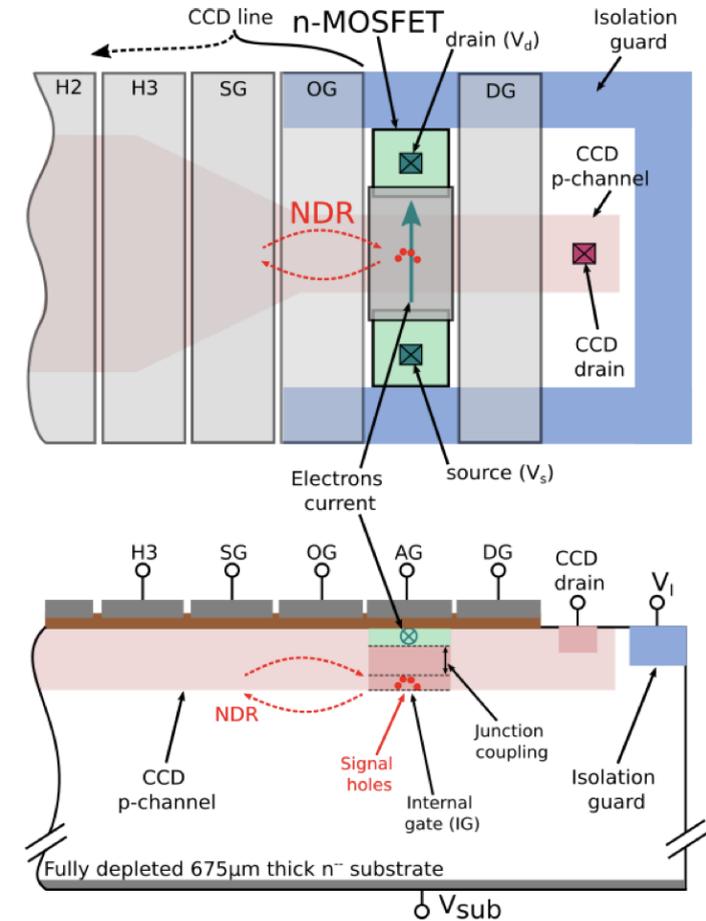
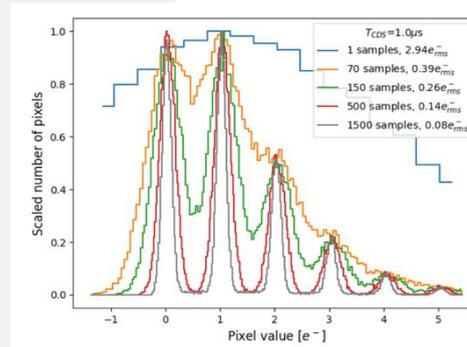
It can move a charge of $1 e^-$ across 10cm **over 24h** and measure it perfectly

(and operate with a DC of $\sim 5 e^- / g / \text{day}$)

- Fast Single-Quantum Measurement with a Multi-Amplifier Sensing Charge-Coupled Device
 - IEEE T-ED, 71, 6 (2024)
- Multi-Amplifier Sensing Charge-coupled Devices for Next Generation Spectroscopy
 - PASP, Volume 136, Issue 9, 095002, 2024

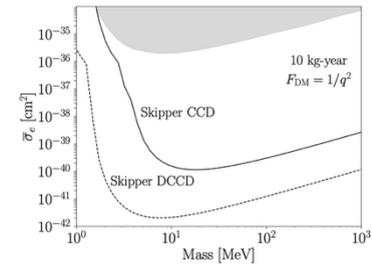
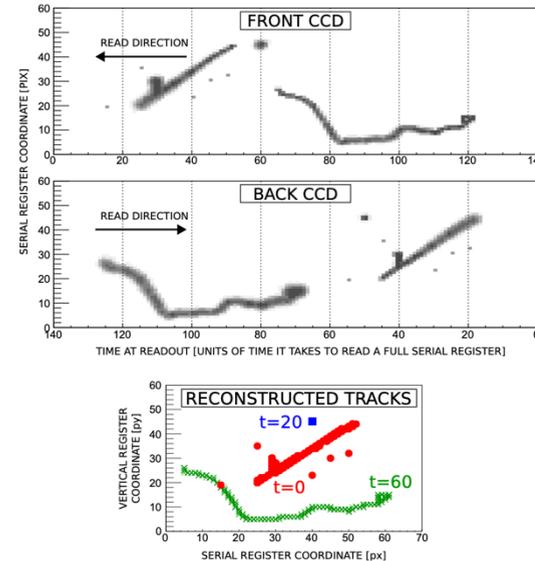
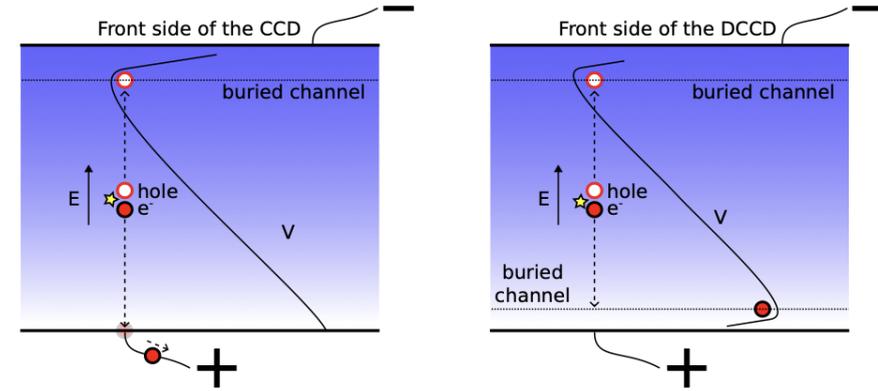
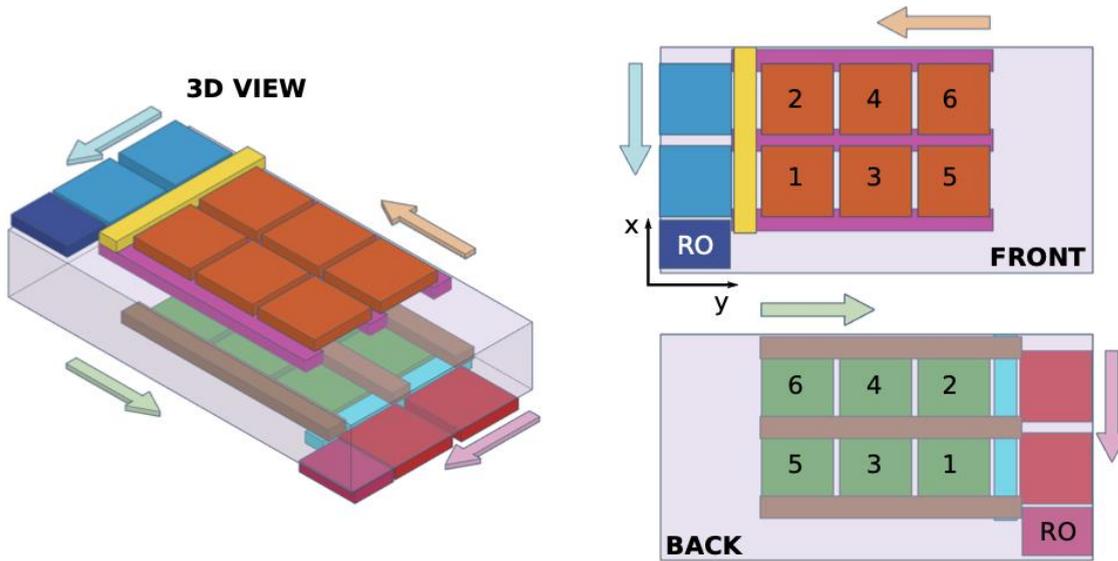


- SiSeRO: FGA – MOSFET
- Achieving Single-Electron Sensitivity at Enhanced Speed in Fully-Depleted CCDs with Double-Gate MOSFETs
 - Phys. Rev. Lett. 133, 121003 (2024)
- Achieves 0.15 e- RMS in 0.9ms (1.1kpix/s), 10-20 times faster than skipper CCD

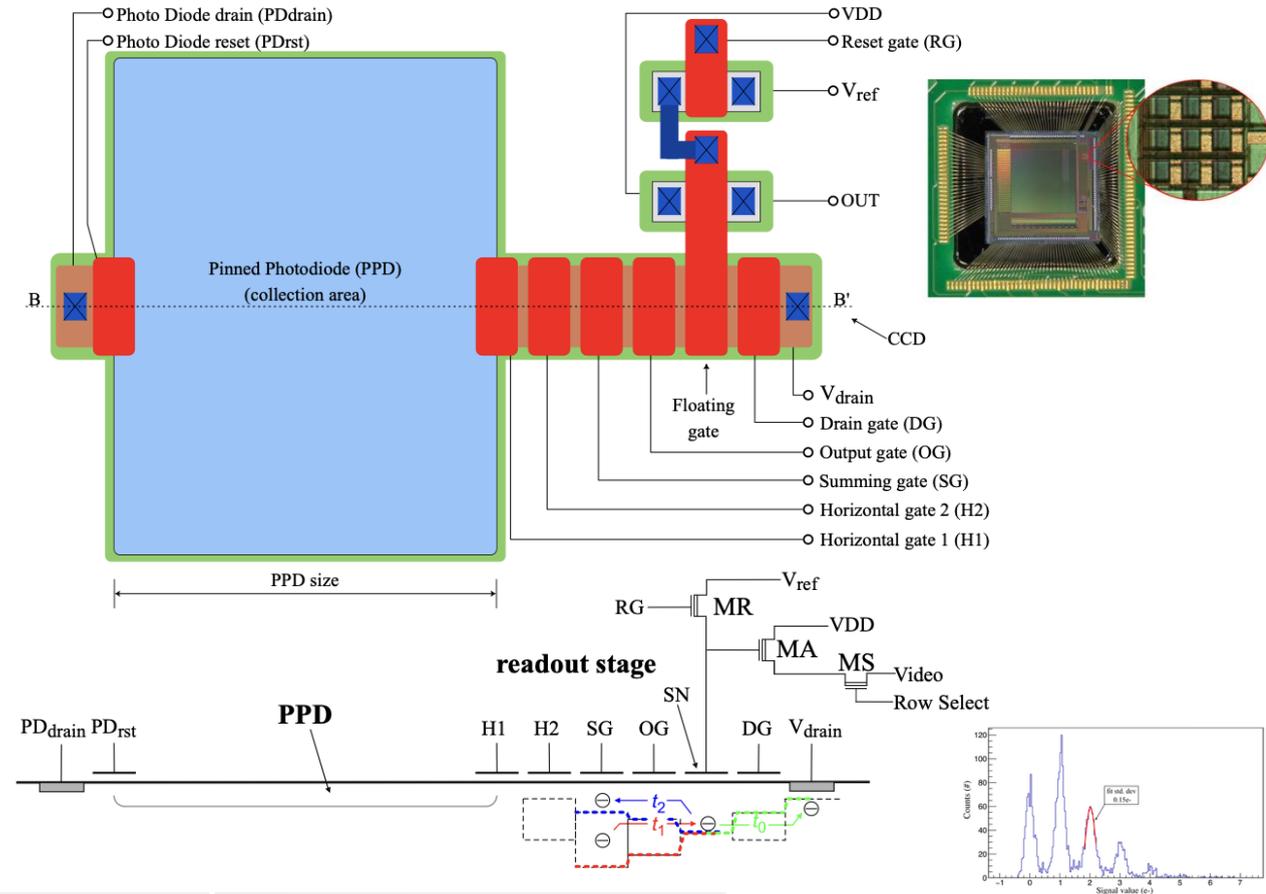


• Dual-sided Charge-Coupled Devices

- arXiv:2307.13723

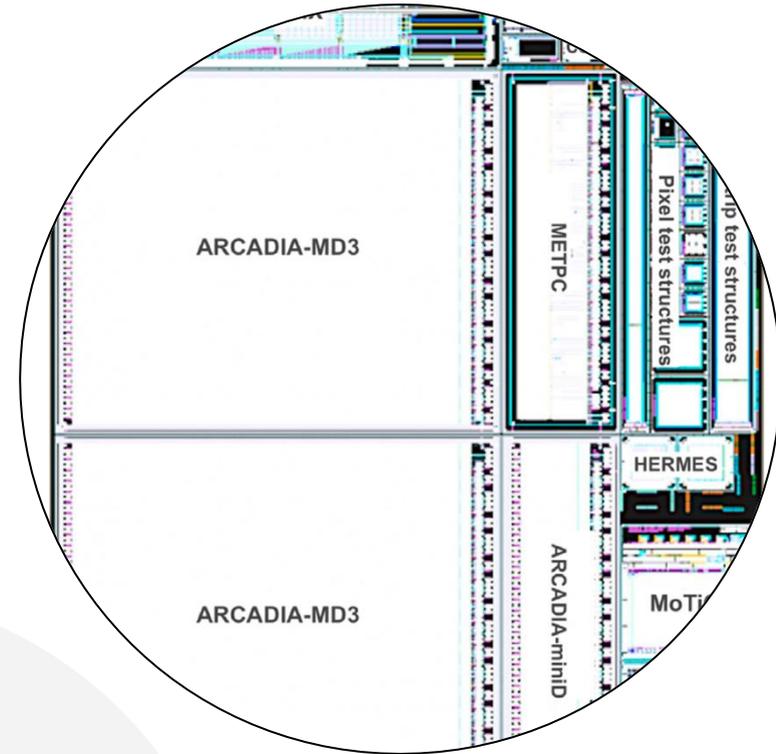
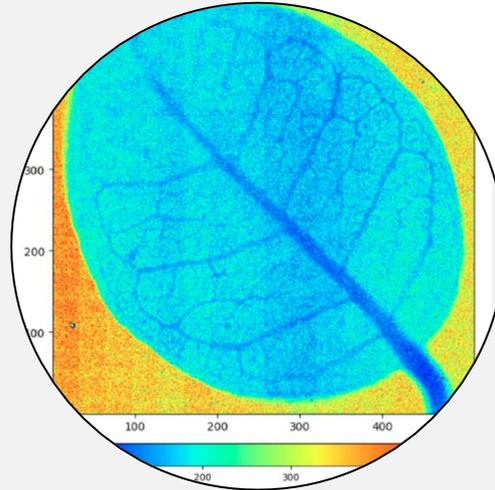
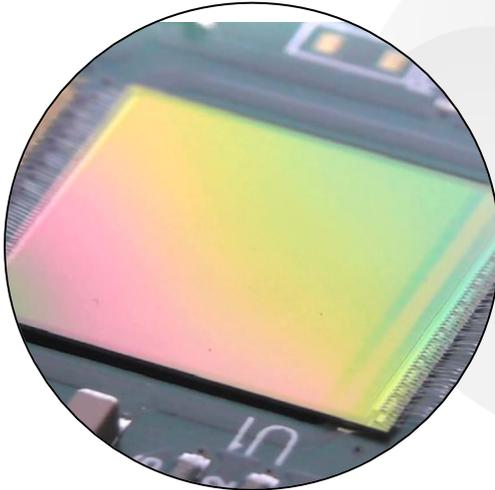


- CMOS Skipper
- Skipper-in-CMOS: Non-Destructive Readout with Sub-Electron Noise Performance for Pixel Detectors
 - IEEE Transactions on Electron Devices, vol. 71, no. 11, pp. 6843-6849, Nov. 2024



- All Skipper CCD detector developments have occurred in Berkeley and Fermilab
- Skipper CCD read-out and operation know-how is present in Europe. Detector design and production is the issue
- Key people are supporting collaborative technology transfer from the US to Europe, with the aim of building equivalent capability in Europe
- Need to identify foundry for prototyping at reasonable cost

- 110nm CMOS technology @ Lfoundry
- Thick, fully depleted, high resistivity
- Platform available for development



- Skipper CCDs are unique detectors with single electron detection capability and sub-electron reading noise
- They provide world-leading sensitivity, outperforming other technologies by orders of magnitude in sensitivity
- The LBC prototype of DAMIC-M has explored the expected freeze-in (and freeze-out) parameter space and excluded it
- DAMIC-M will improve by 1-2 orders of magnitude the LBC limits

- Used in other experiments: CONNIE (coherent neutrino scattering), Dark Beats/Moskita (mCP search), DARKNESS (X-ray nano satellite)
- Considered for future ones: OSCURA (10kg scale), DESI, few photons interferometry, exo-Earth searches (HWO)...
- New developments under way for skipper CCDs (MAS-CCD, SiSeRO-CCD, dual face skippers, CMOS-Skipper...)

