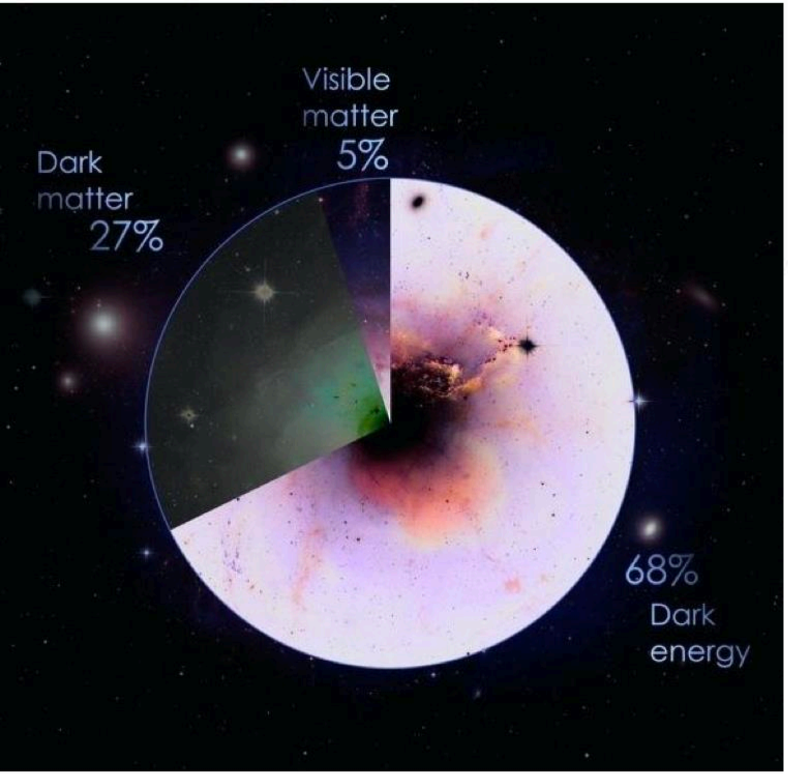
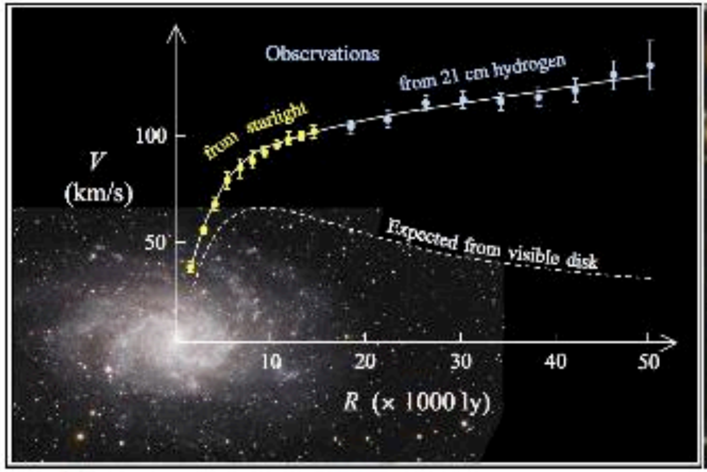
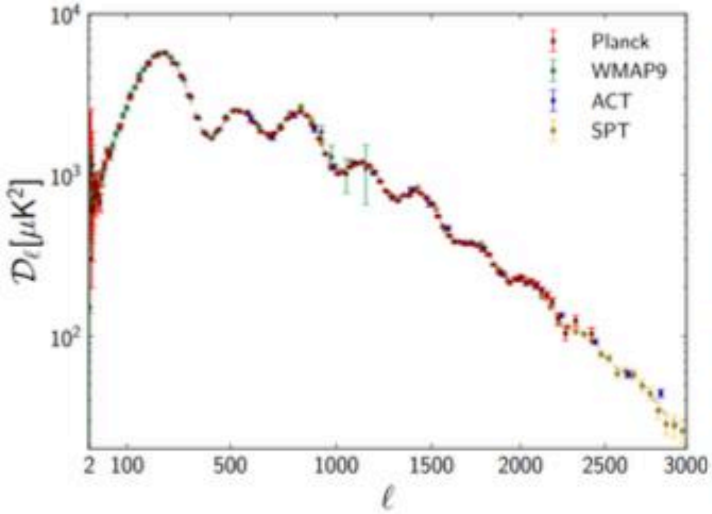
Probing the Dark Sector One Electron at a Time: Skipper CCDs and the DAMIC-M Experiment

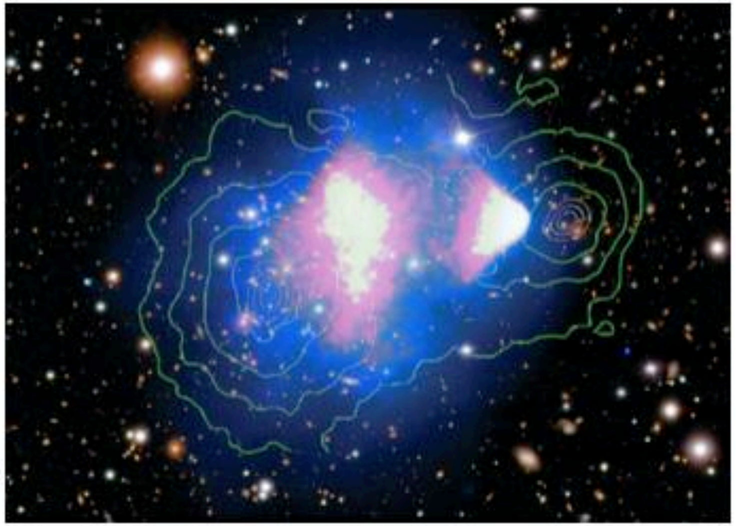
Xavier Bertou (IJCLab, IN2P3/CNRS), DAMIC-M experiment

(1)
Dark Matter and low mass searches

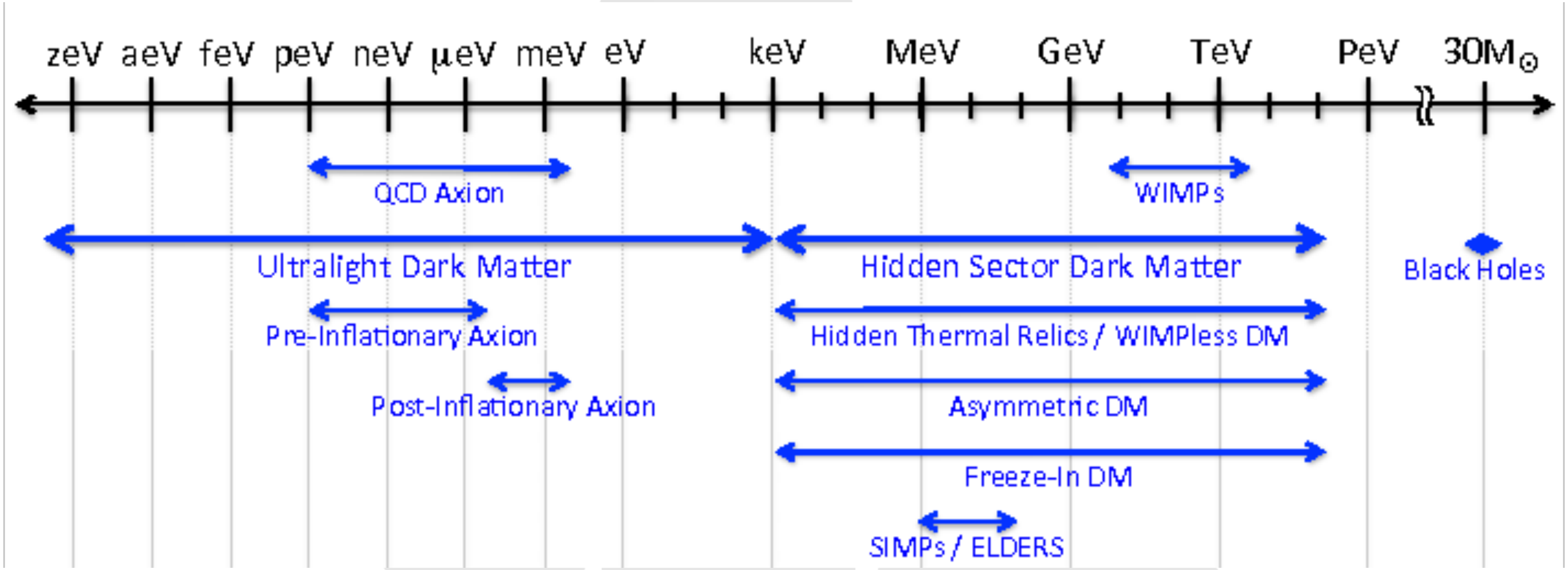

Visible
matter
5%
Dark
matter
27%
68%
Dark
energy


Observations
from 21 cm hydrogen
from starlight
V
(km/s)
100
50
Expected from visible disk
10
20
30
40
50
R (× 1000 ly)

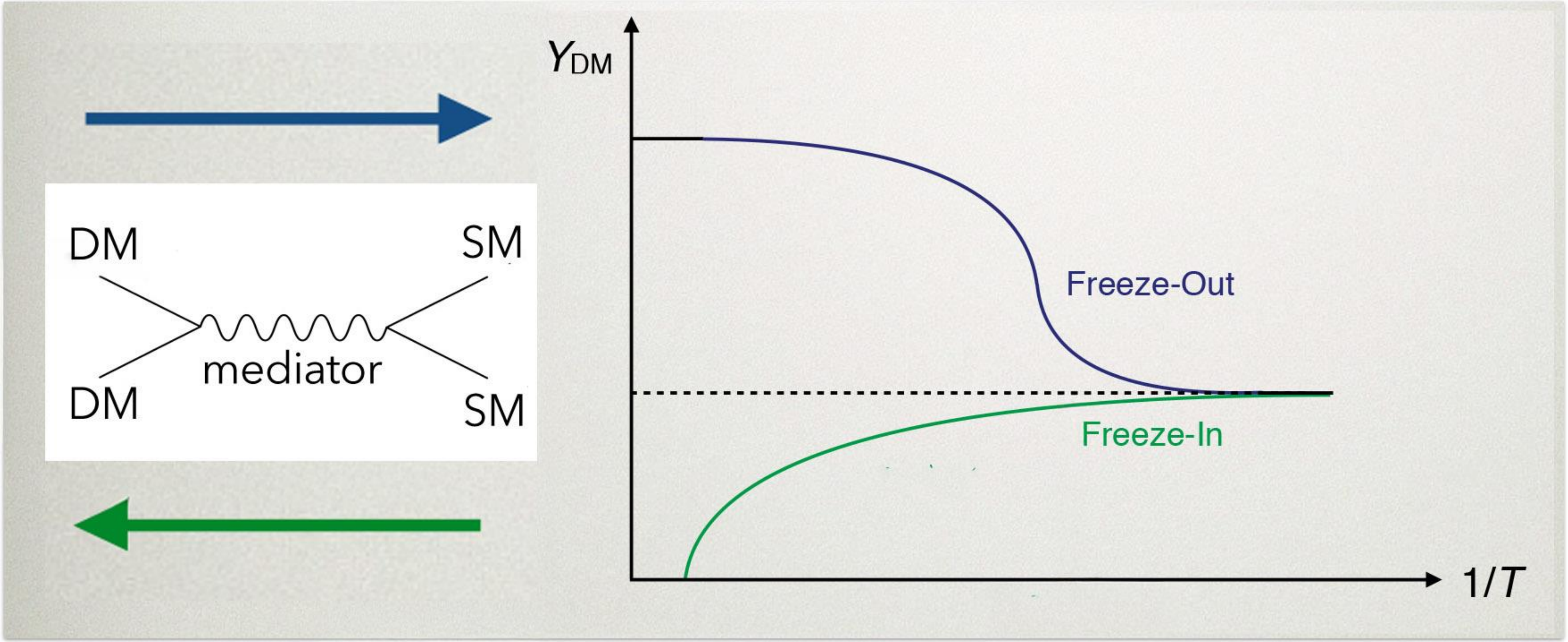

Planck
WMAP9
ACT
SPT
10^4
10^3
10^2
$\mathcal{D}_\ell [\mu K^2]$
2
100
500
1000
1500
2000
2500
3000
ℓ

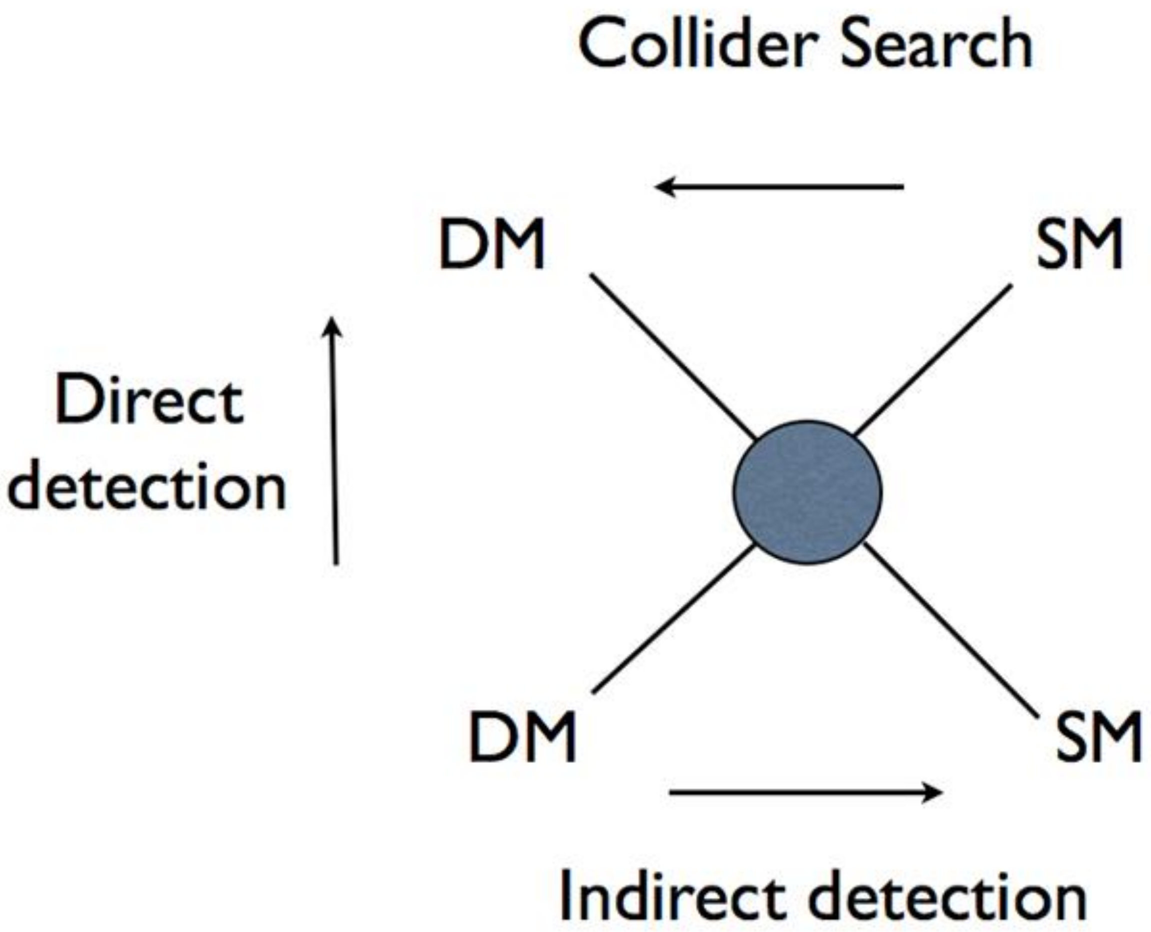


Mass range

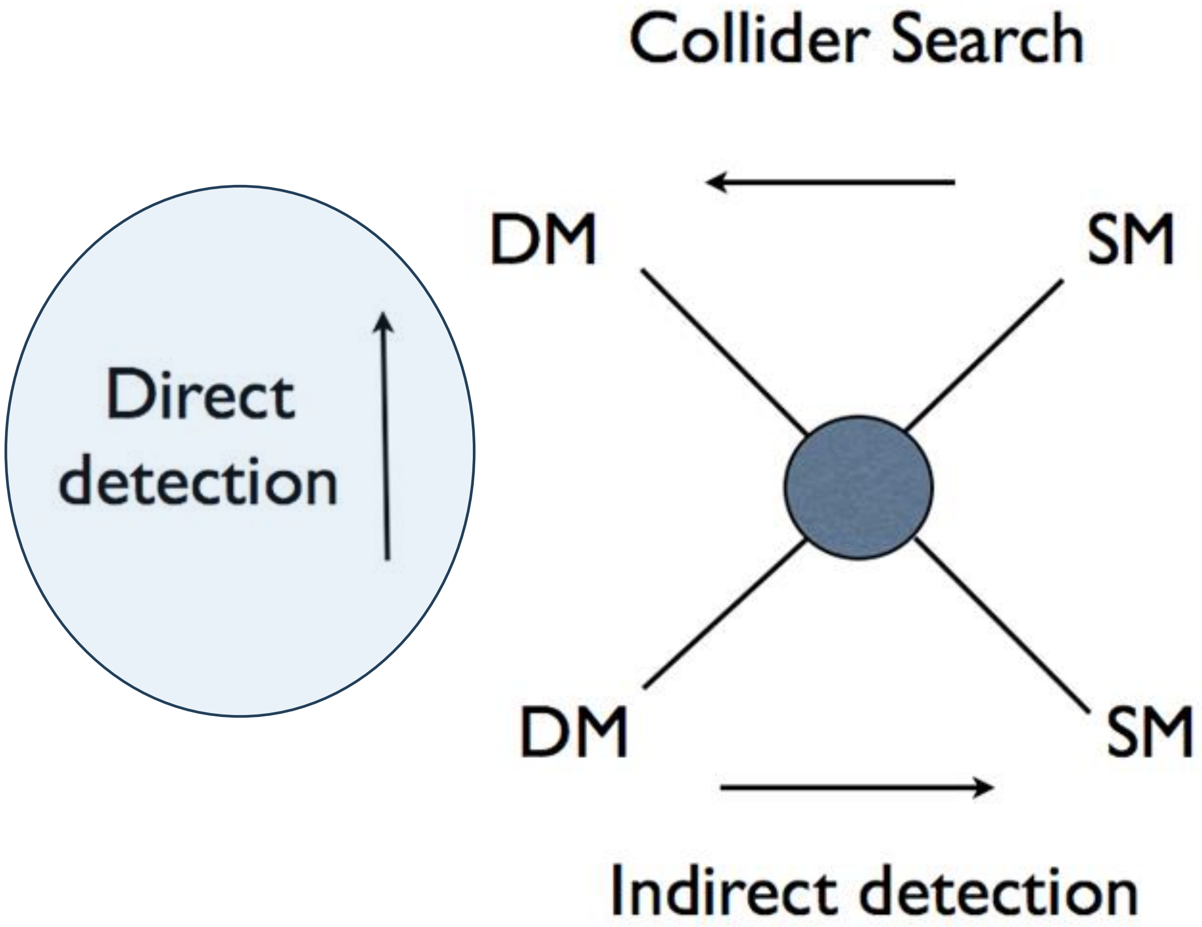

zeV aeV feV peV neV µeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS

How to create Dark Matter – Freeze-in/out

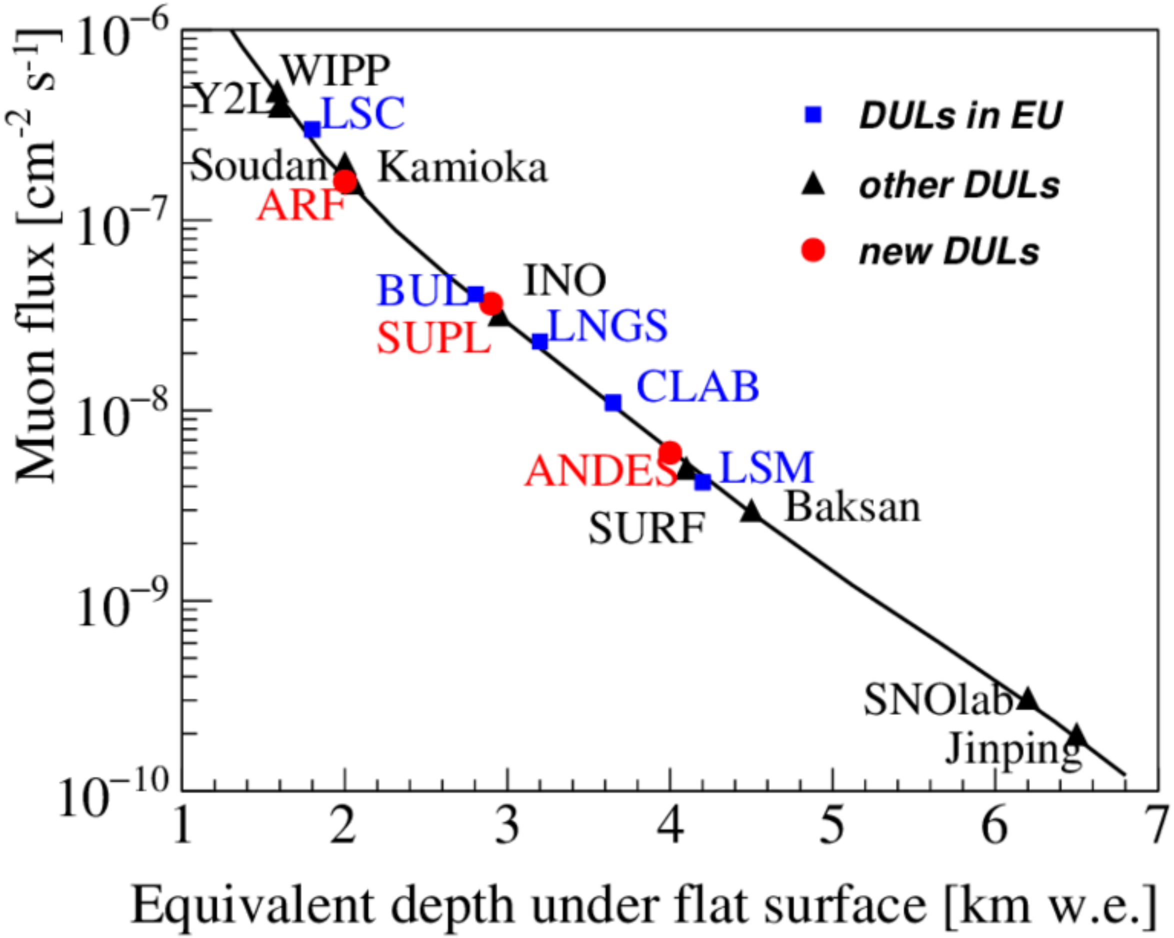



Collider Search
DM
SM
Direct detection
DM
SM
Indirect detection

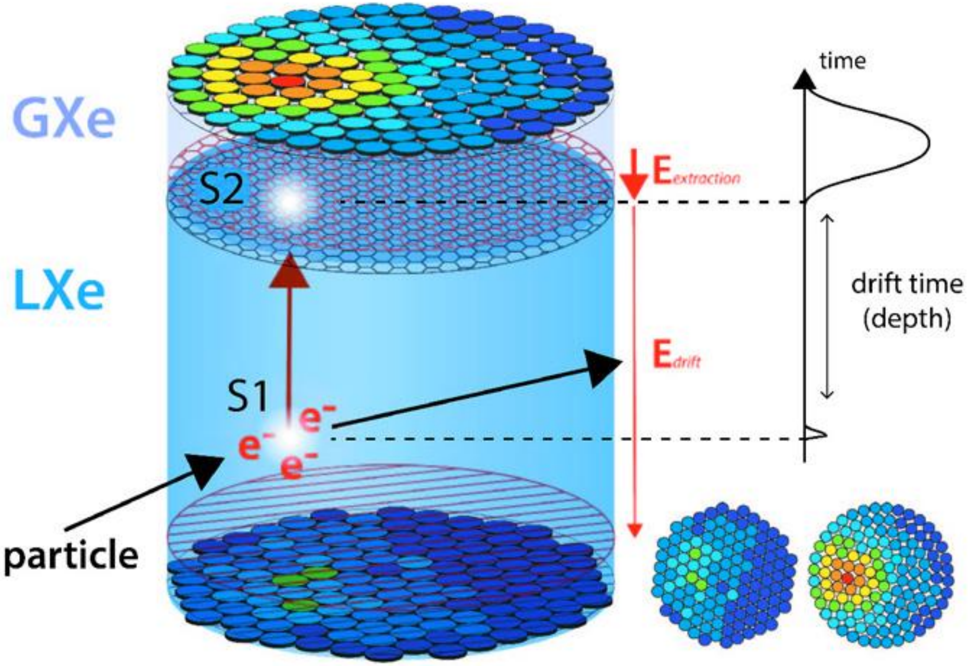
How to search for Dark Matter



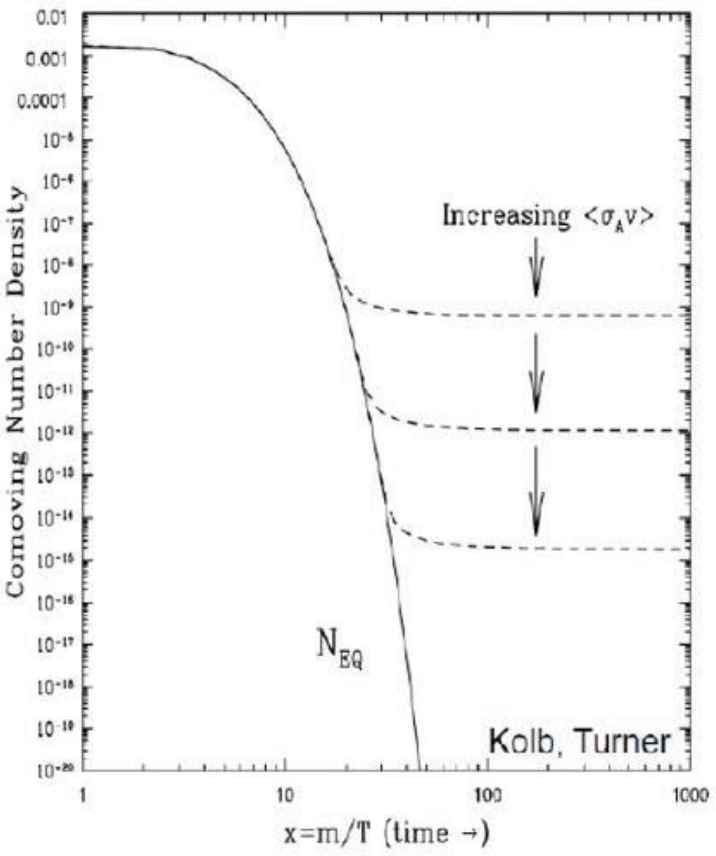
Background: cosmic rays



Build a detector and observe nuclear recoils

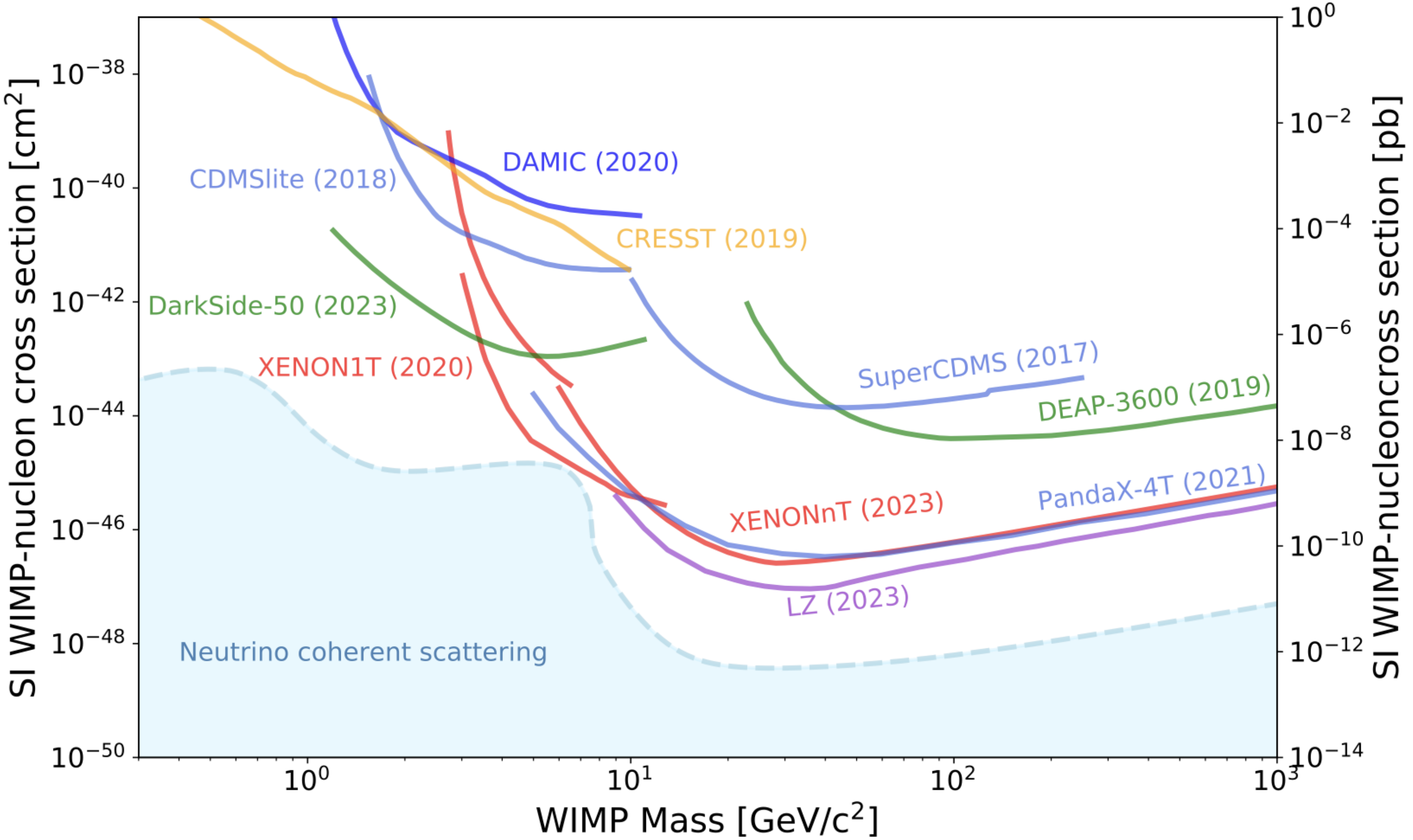


WIMP Miracle

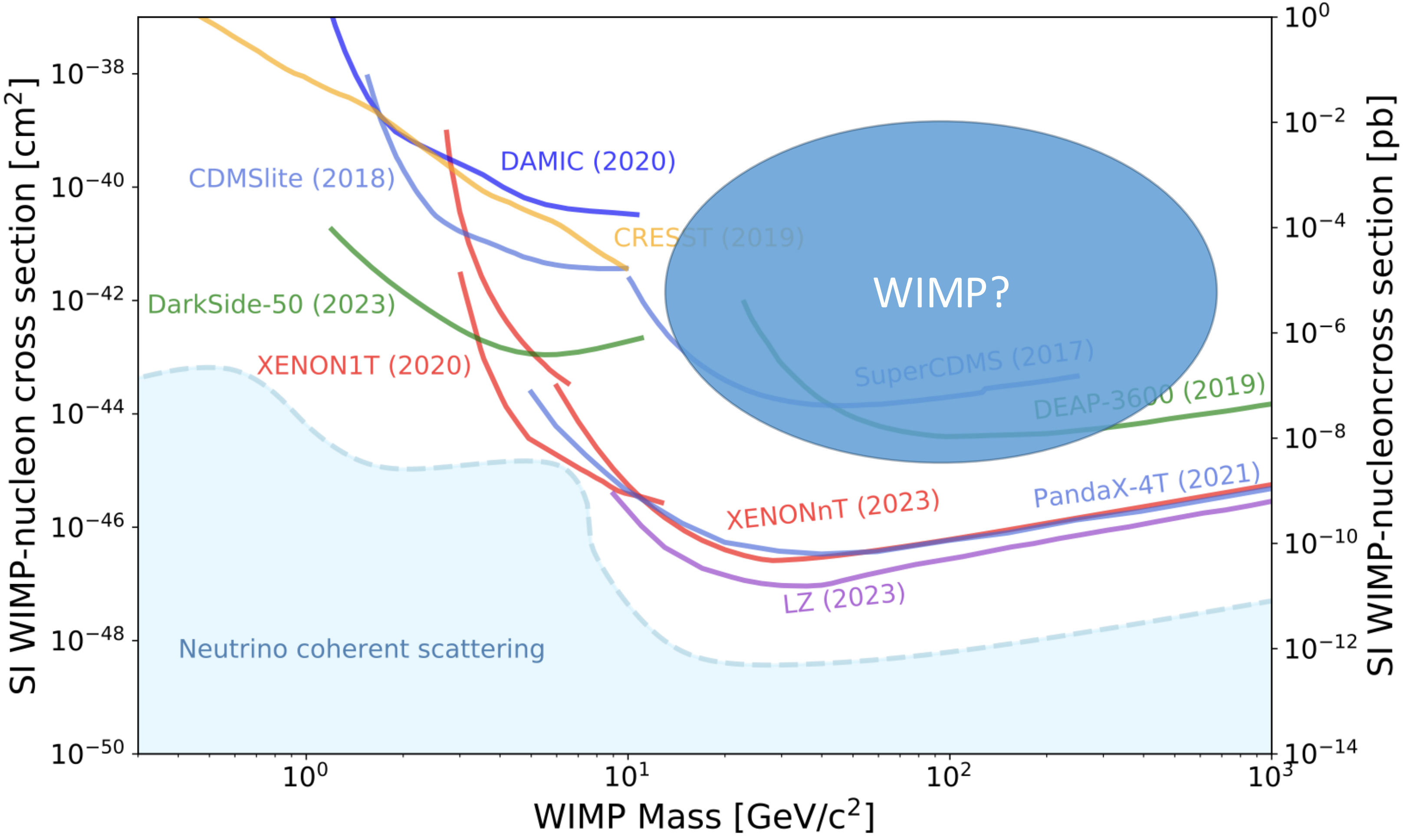


- LSP DM $\in$ Weakly Interacting Massive Particle (WIMP)
- WIMPs are thermal equilibrium at hot temperature $\rightarrow$ Pair annihilation $\rightarrow$ Freeze out
- Relic density
  $$\Omega \approx \frac{6 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma_A v \rangle}$$
- $\langle \sigma_A v \rangle \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$
  $\Rightarrow \Omega \approx 20\%$ (WIMP miracle)

(Not so) Current limits to the WIMP



(Not so) Current limits to the WIMP



Dark Sector: the simplest expansion of SM

- 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 <GeV scale
    - Nuclear recoils suppressed
    - Ideal to observe as electron recoil
    - Need to observe much smaller energy deposits

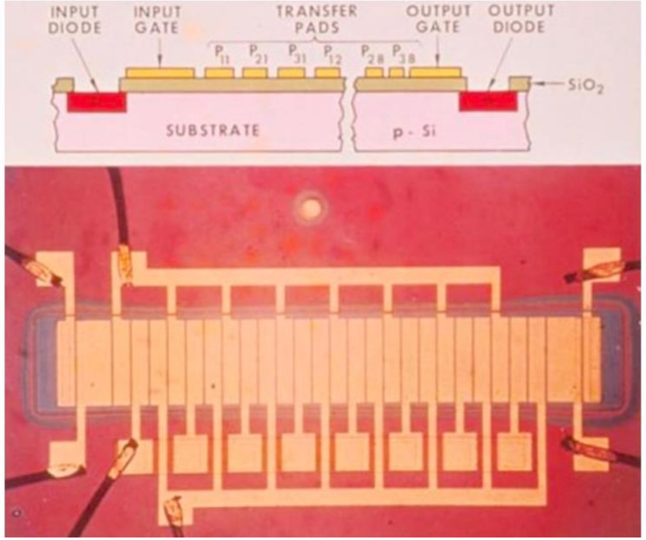
Energy scales

- 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

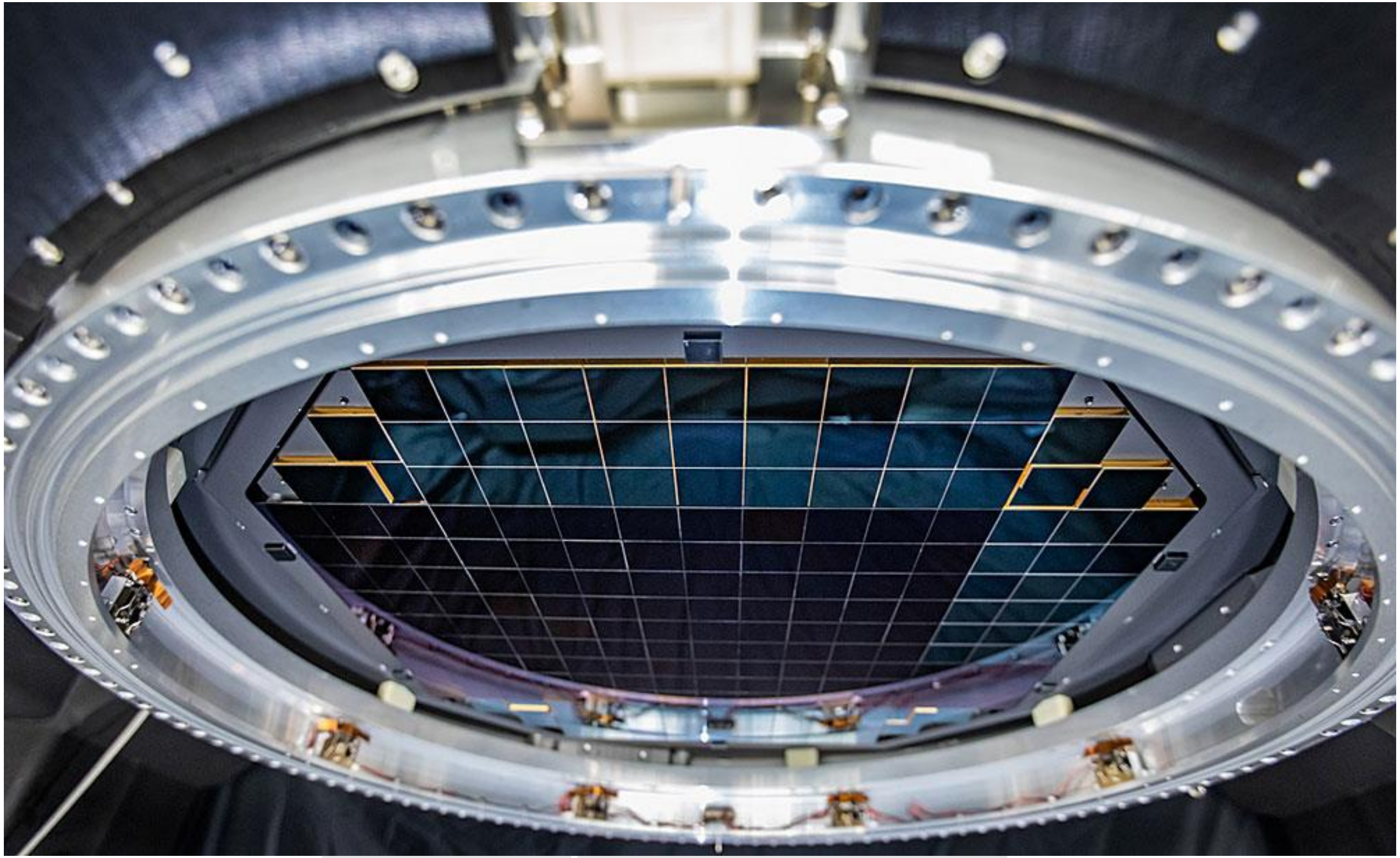
(2)
CCD and Skipper CCD

The non-skipper CCD (the CCD)

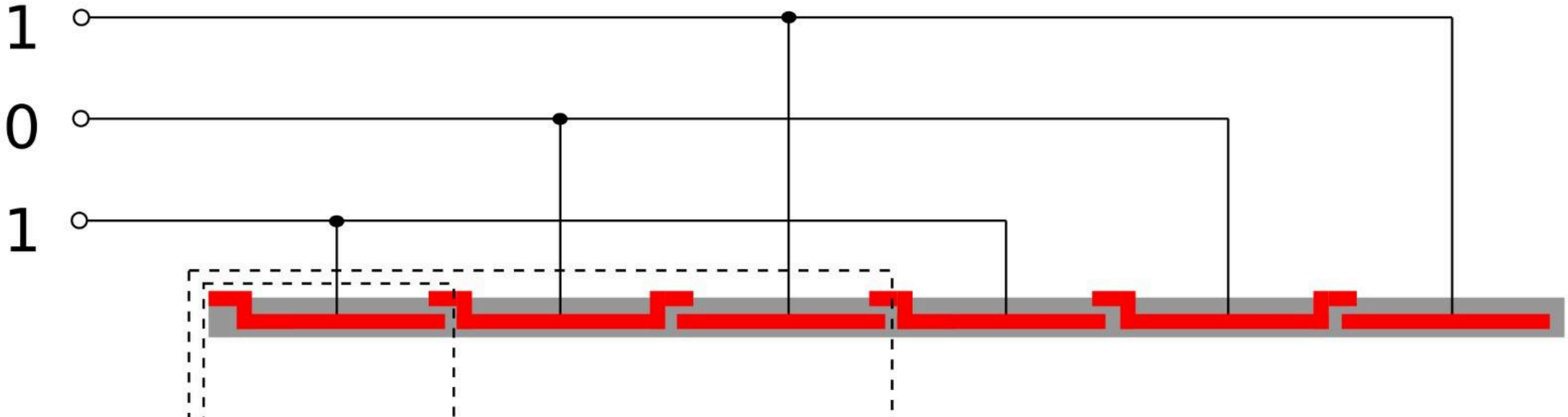
- CCD were invented in 1969 by Boyle and Smith (Bell Labs).
- The idea was to make a memory device, but it works better as an image sensor and was quickly used in consumer devices.
- In 1975, Kodak manufactured the first digital camera.

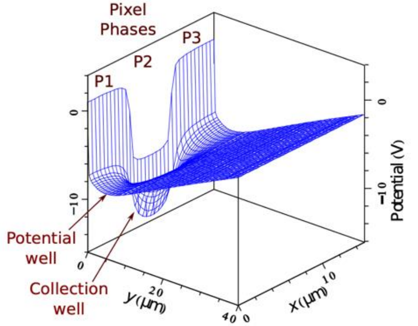


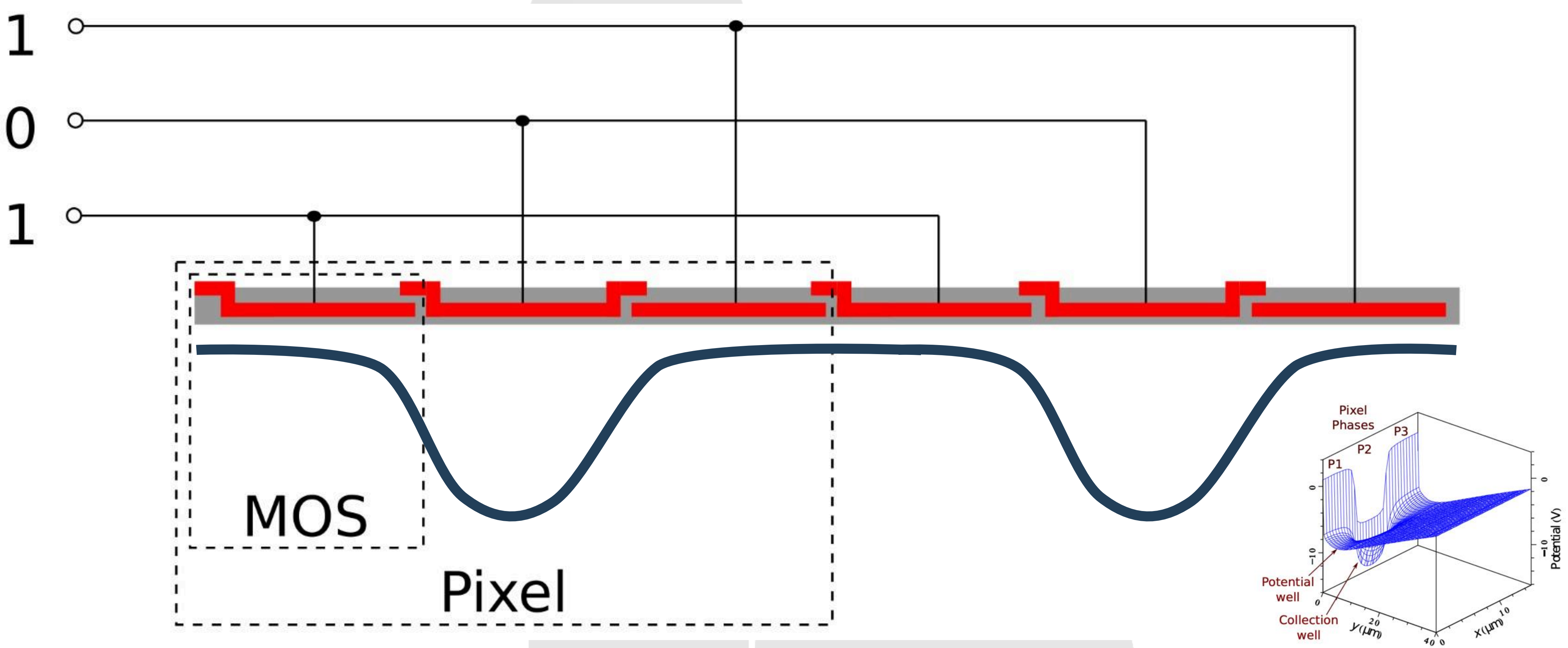
CCD in astronomy



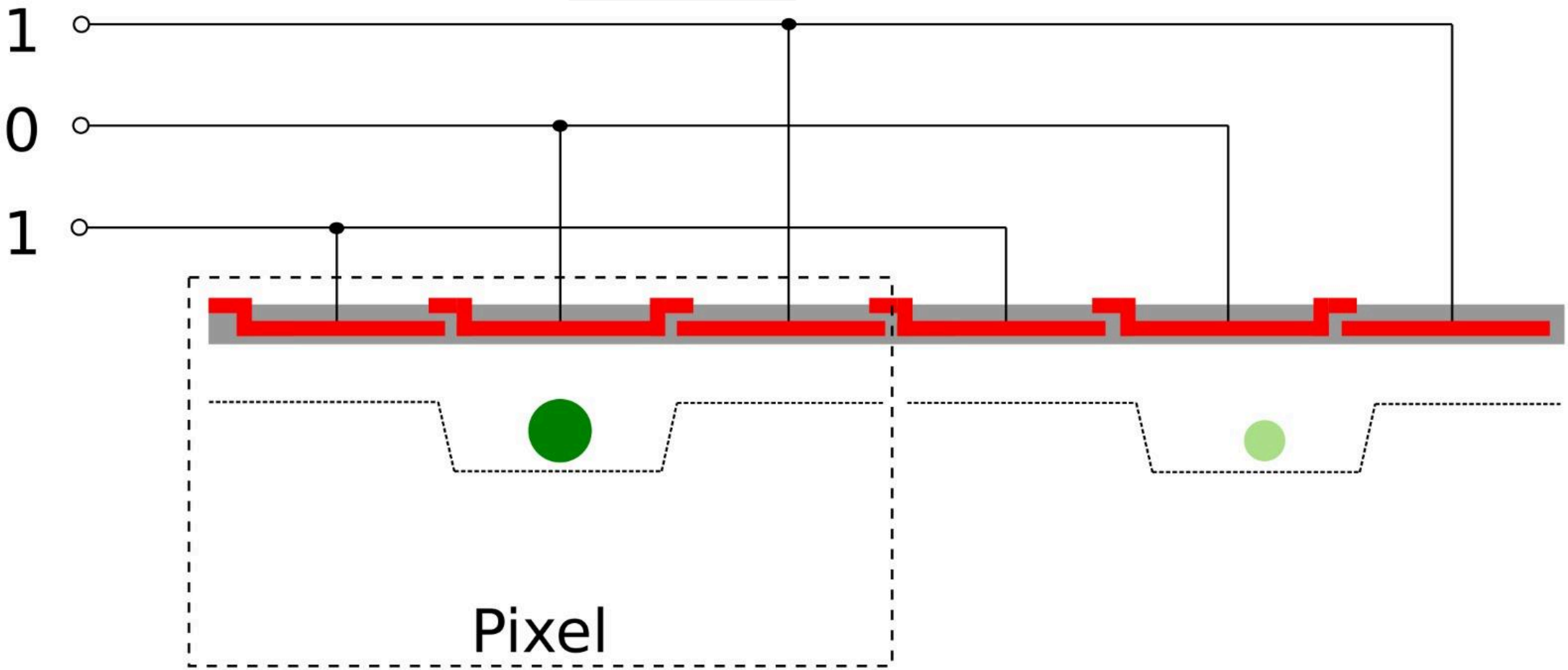
CCD principle



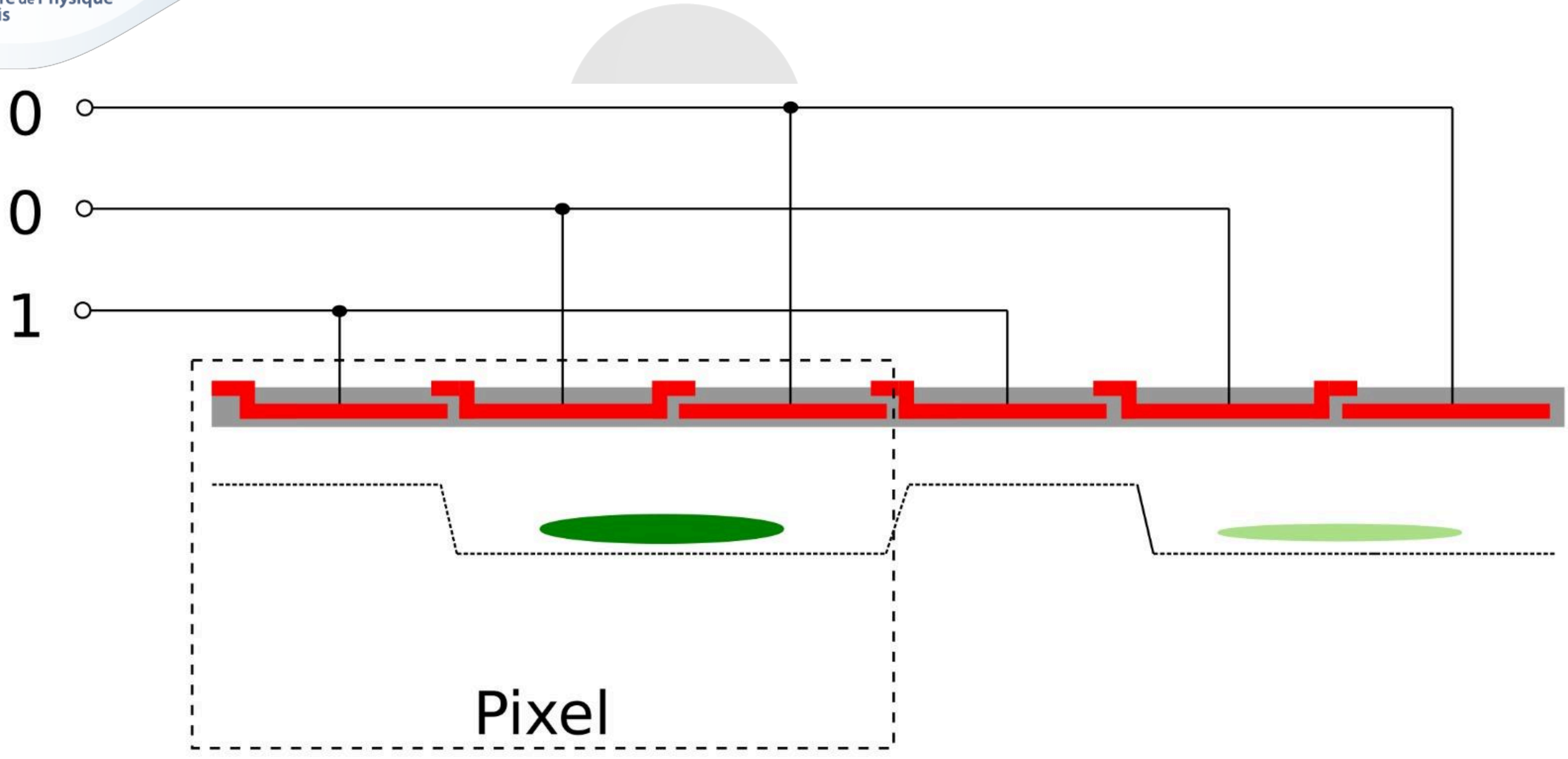



1
0
1
MOS
Pixel
Pixel
Phases
P1
P2
P3
Potential
well
Collection
well
y(µm)
x(µm)
Potential (V)

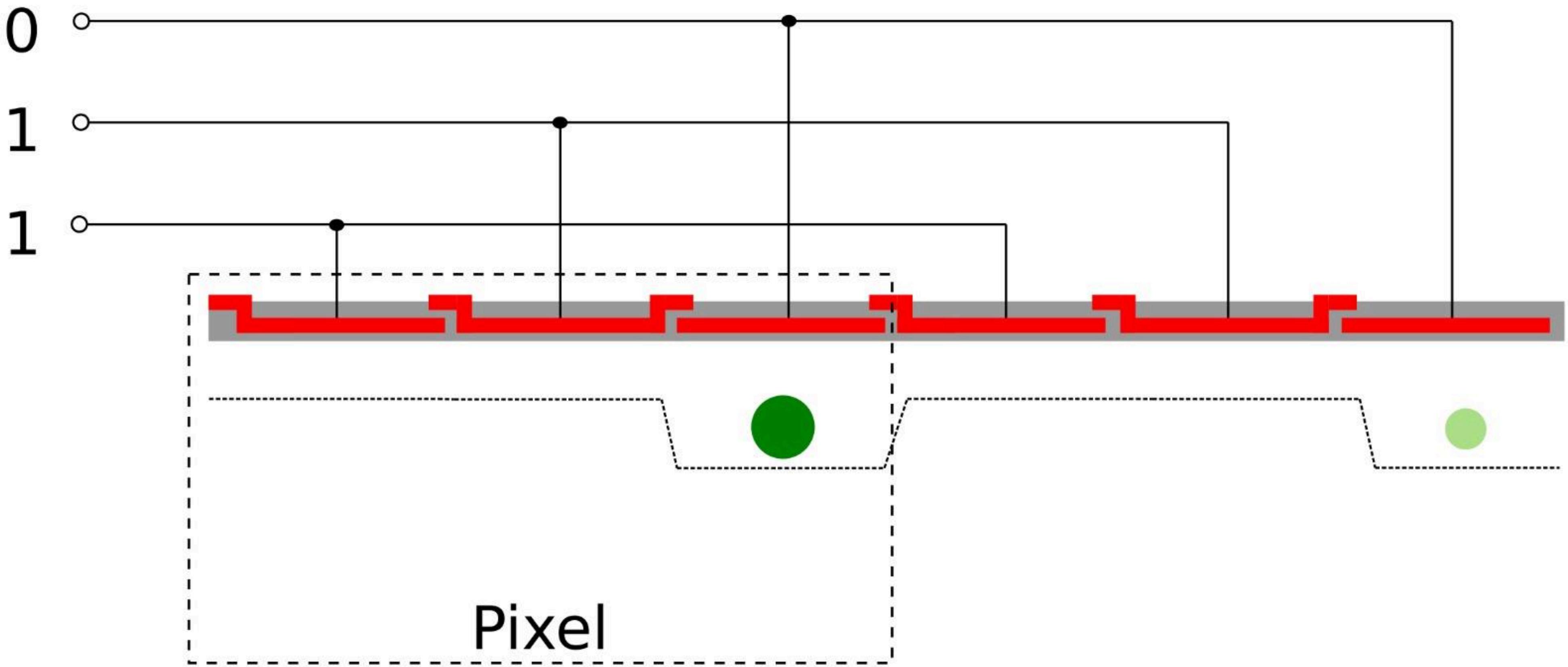
CCD principle



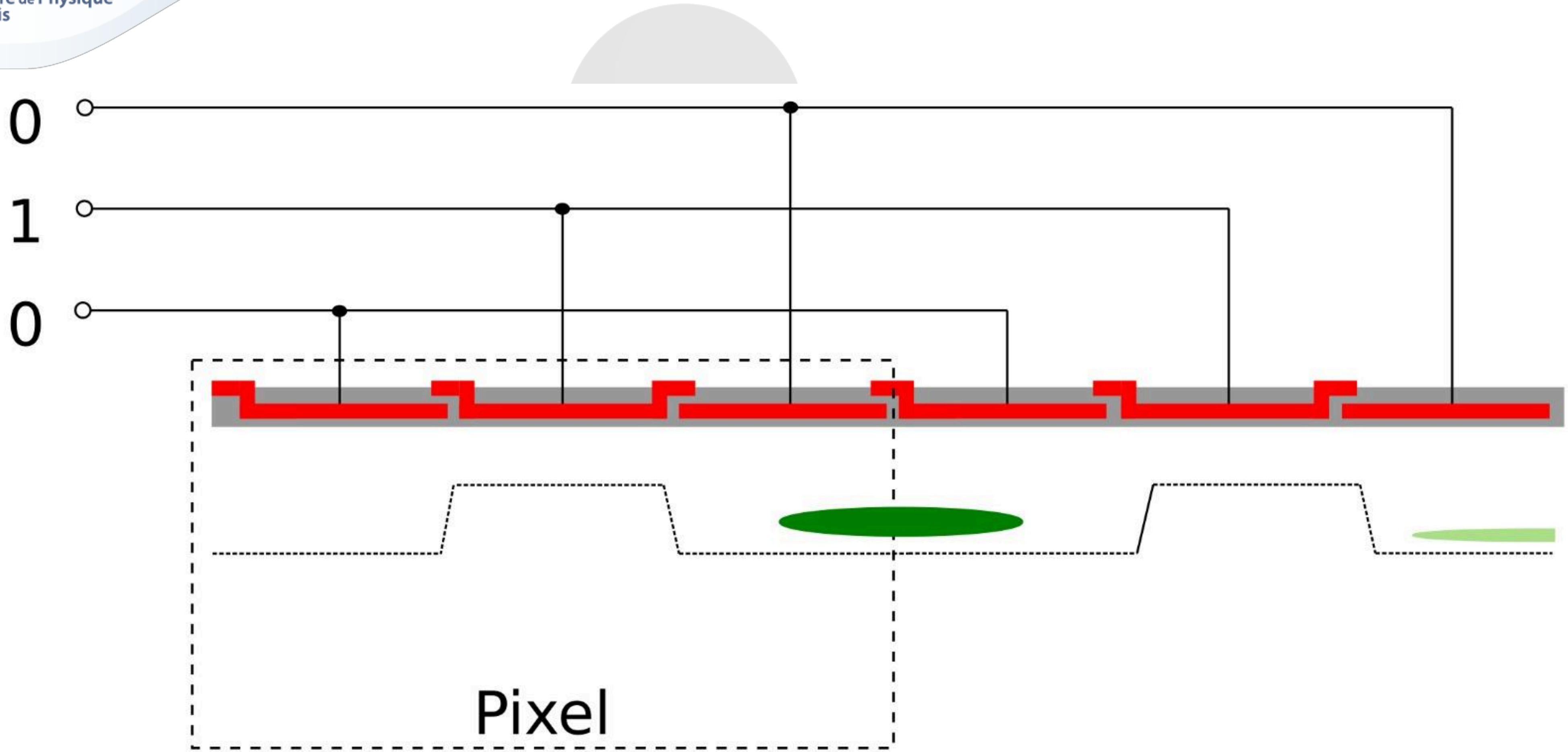
CCD principle



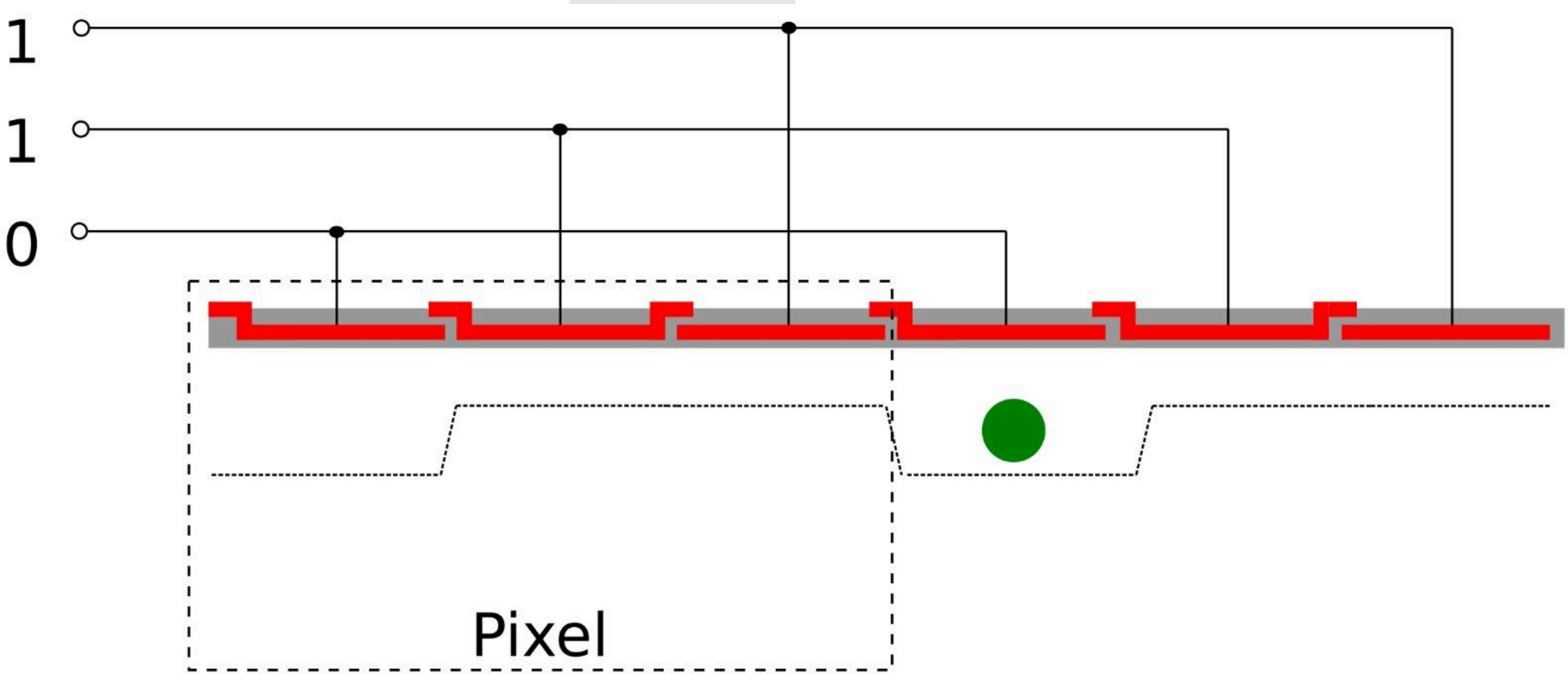
CCD principle



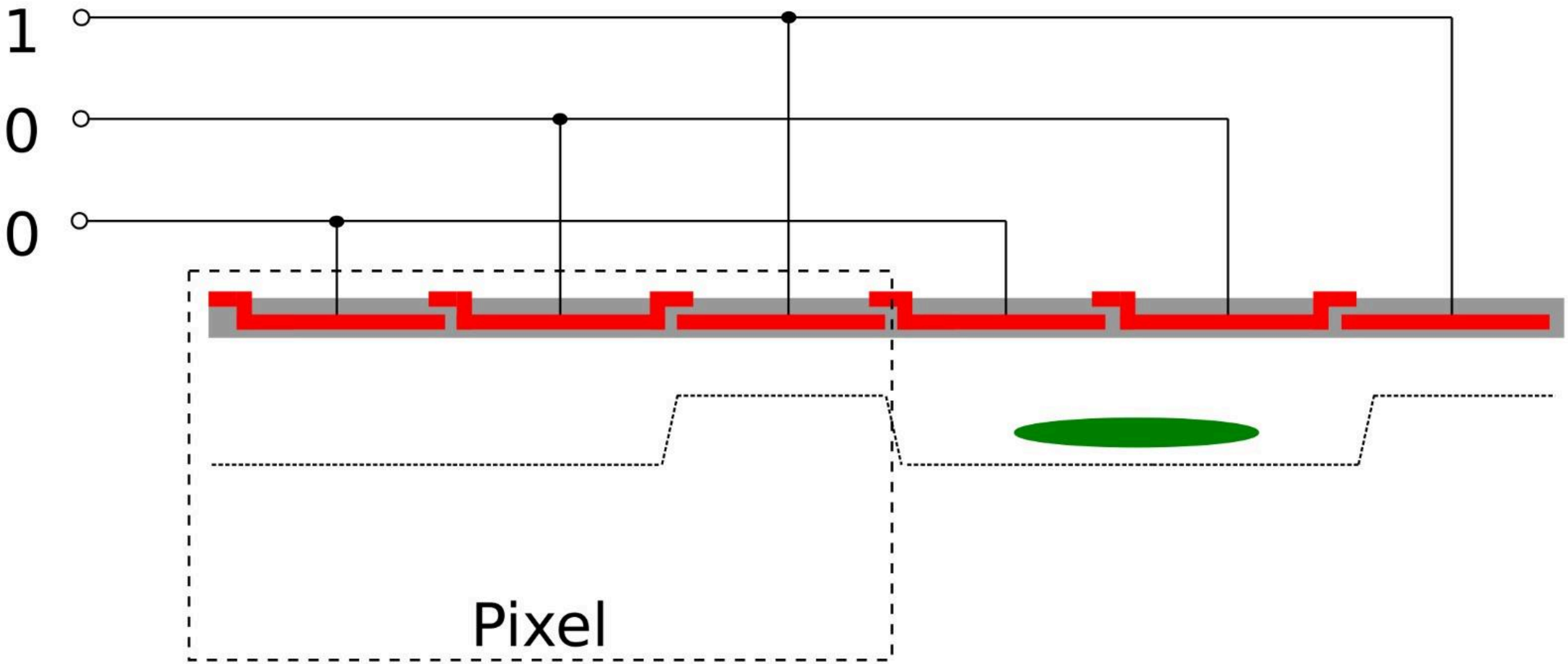
CCD principle



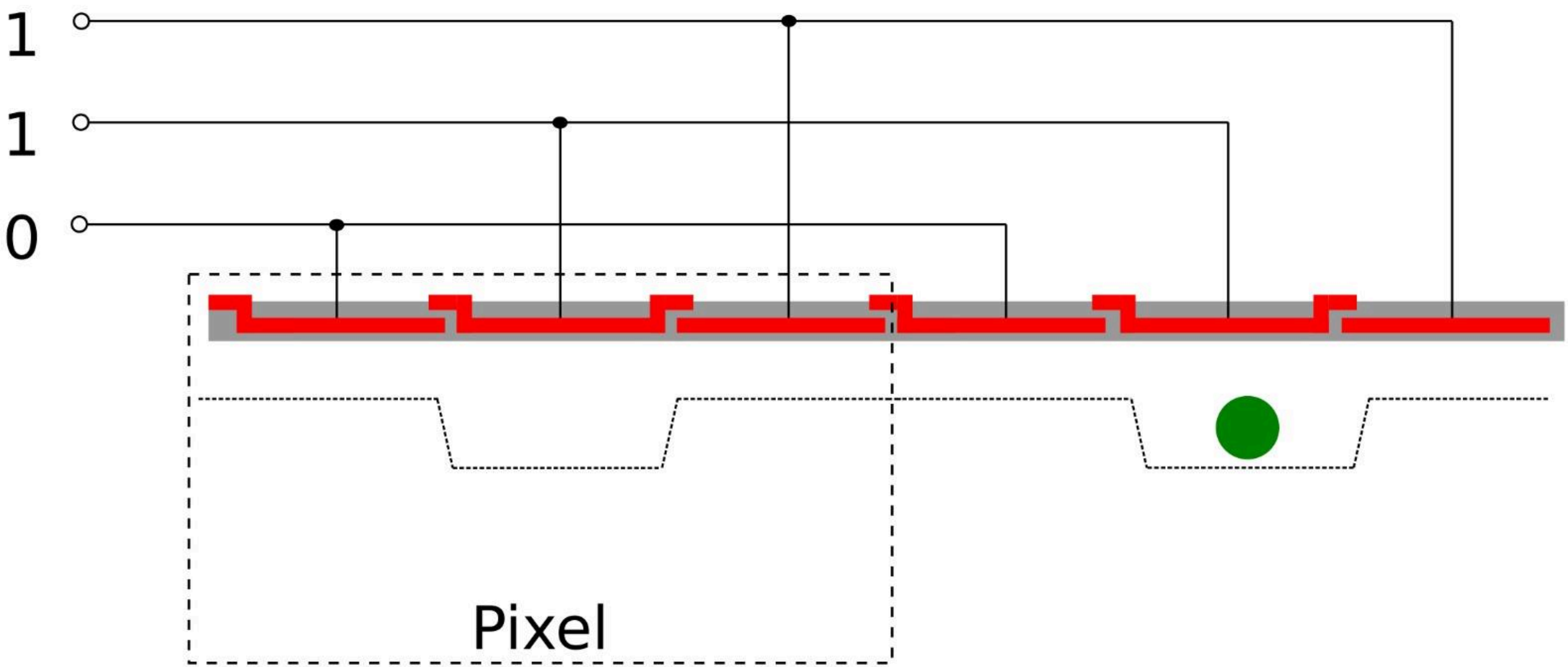
CCD principle



CCD principle



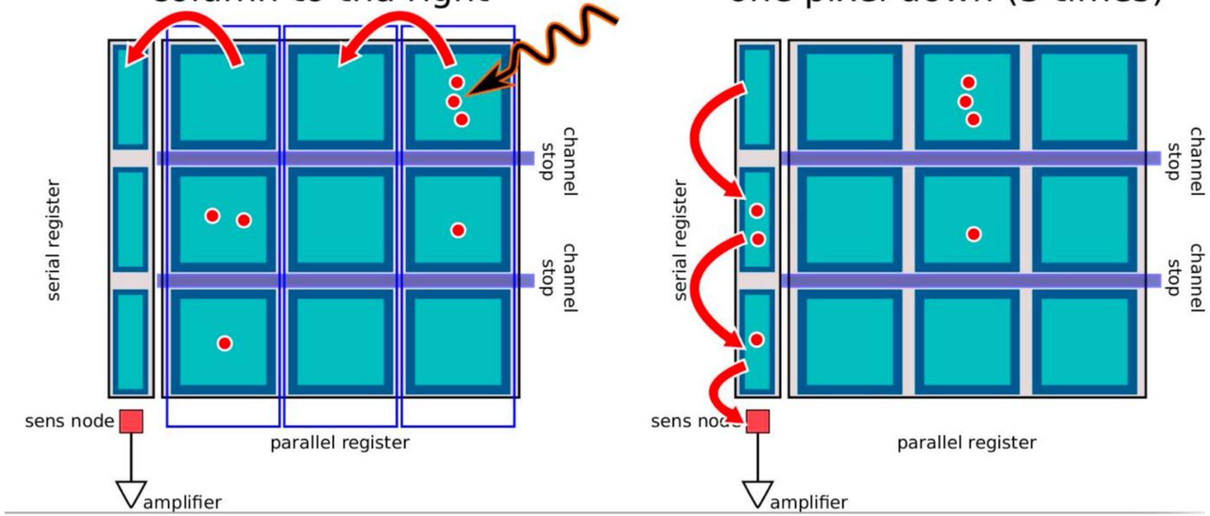
CCD principle

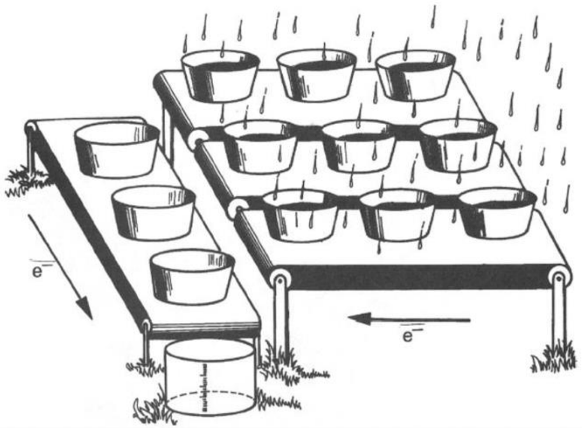


CCD principle

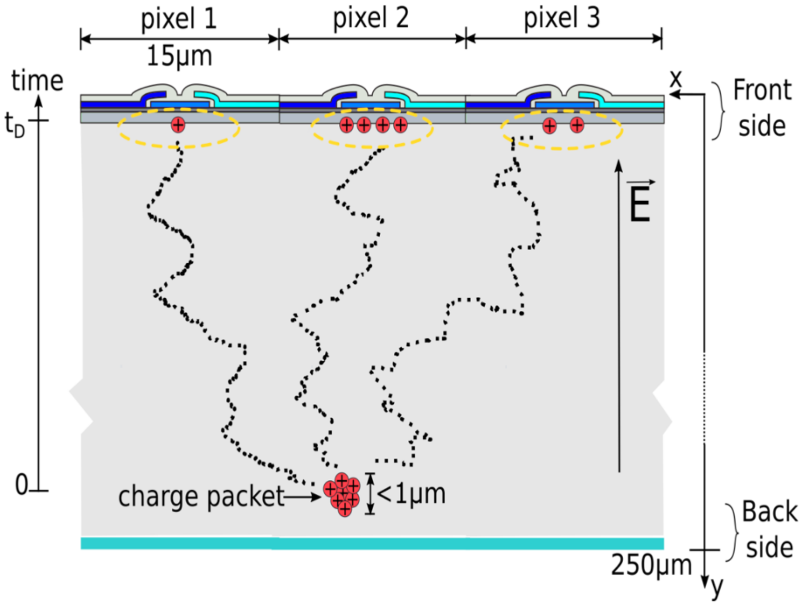
Shift charge one column to tha right

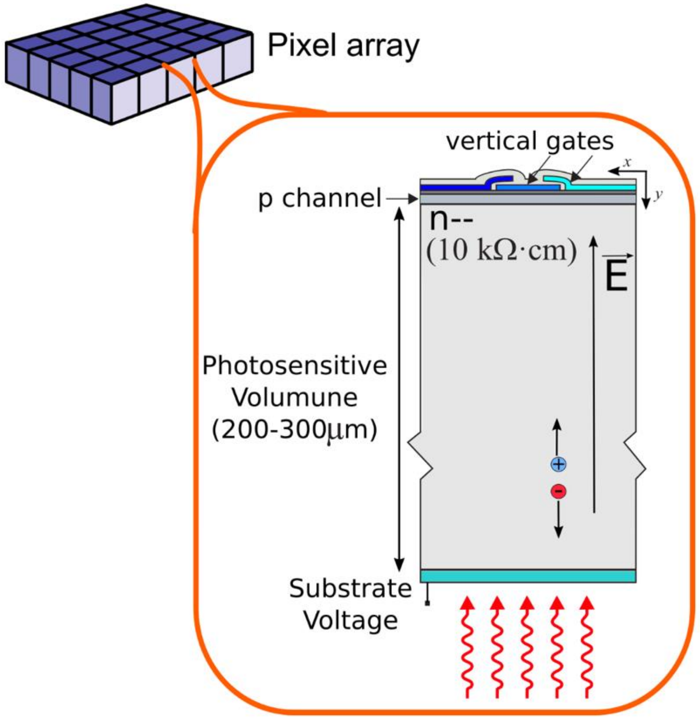
Shift charge in serial register one pixel down (3 times)

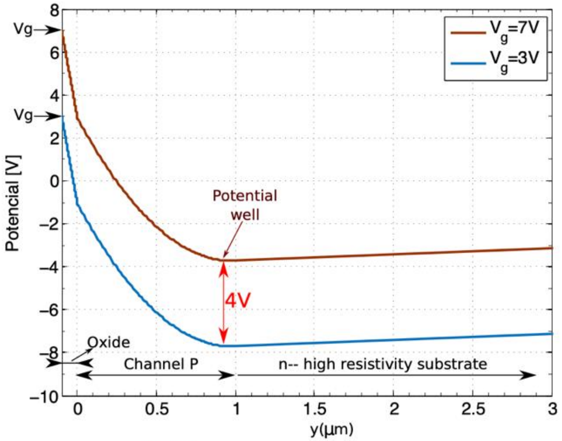


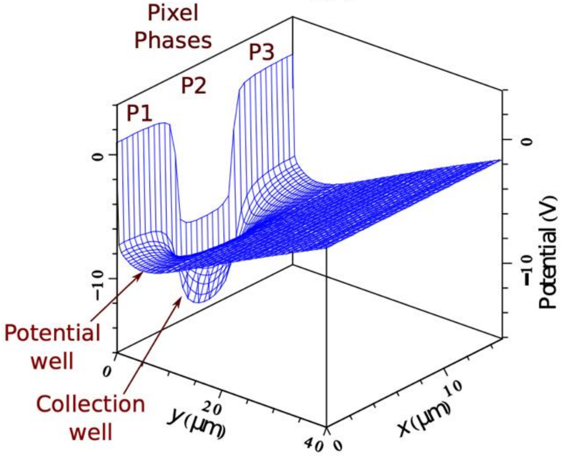


CCD as a particle detector

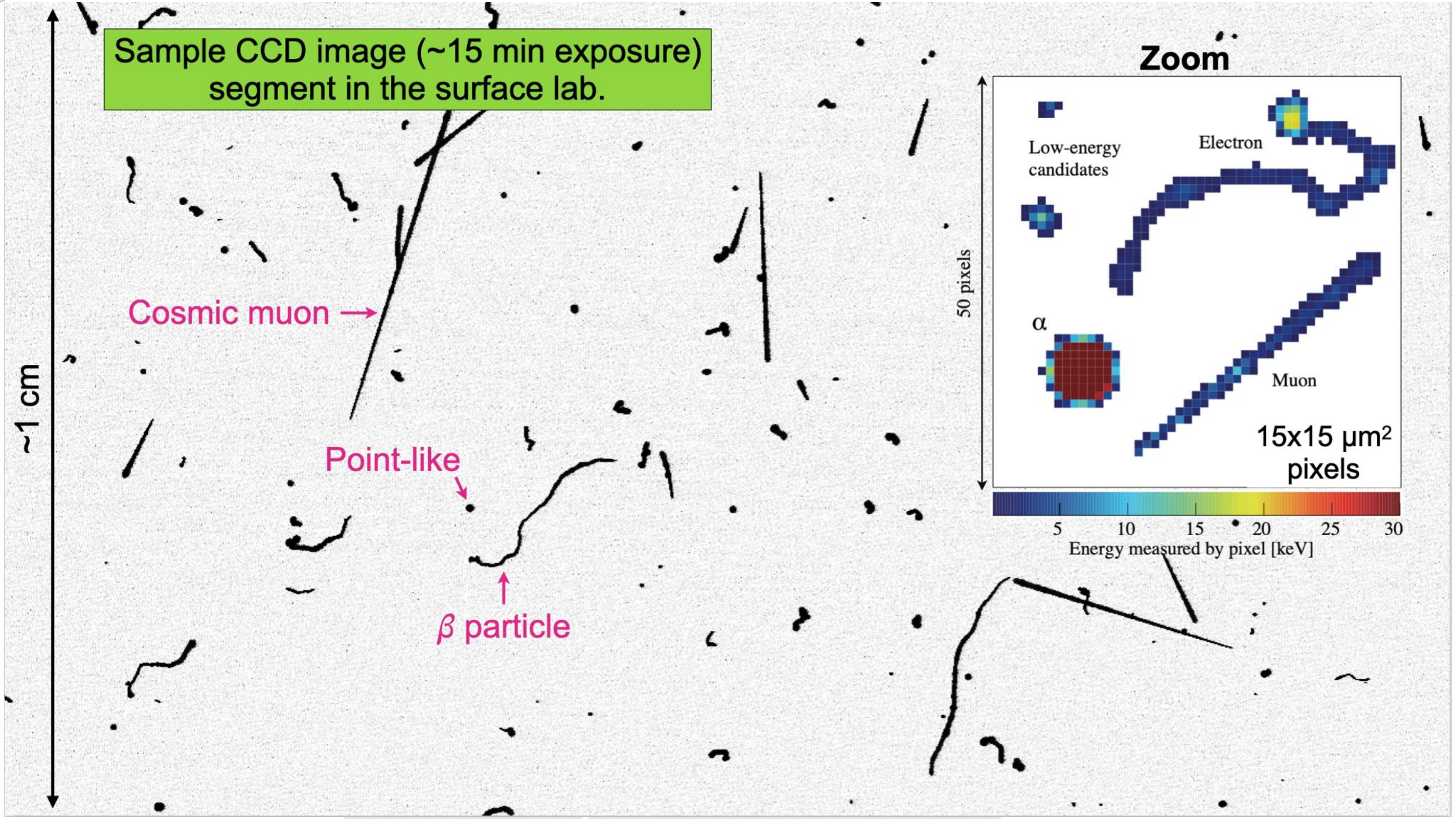






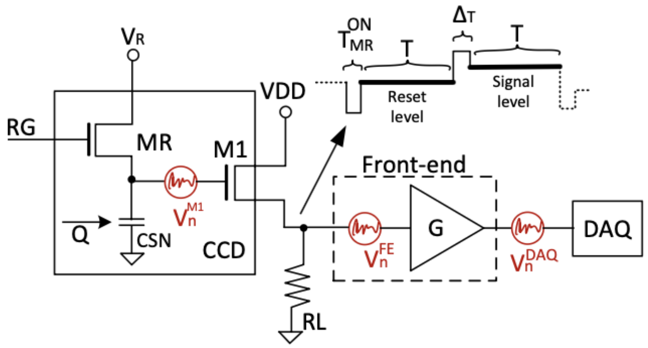


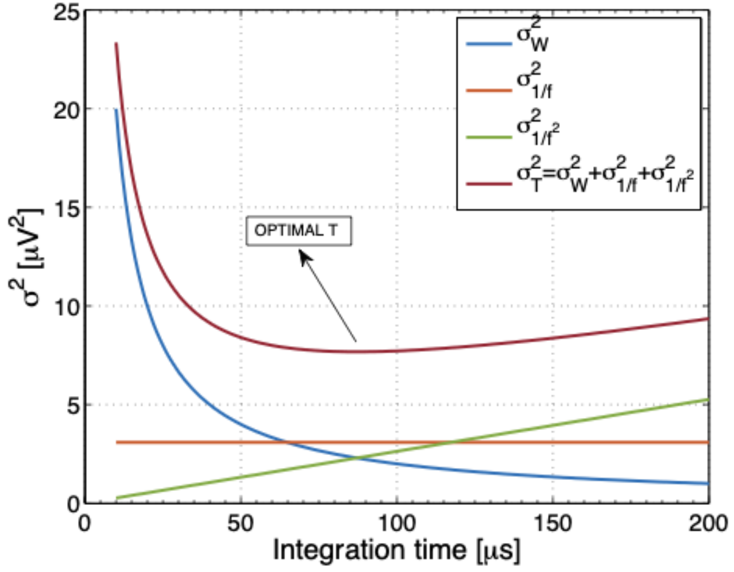
CCD image

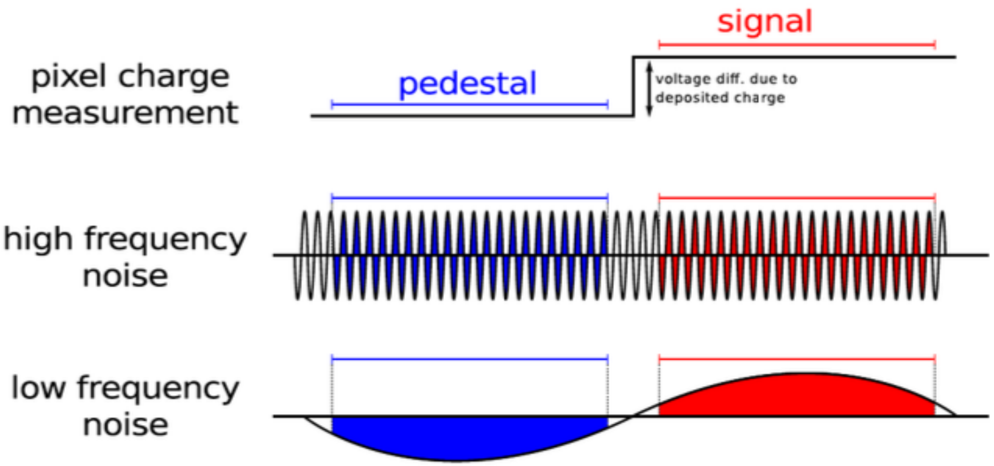


~1 cm
Sample CCD image (~15 min exposure)
segment in the surface lab.
Cosmic muon →
Point-like
β particle
Zoom
50 pixels
Low-energy
candidates
Electron
α
Muon
15x15 μm² pixels
5 10 15 20 25 30
Energy measured by pixel [keV]

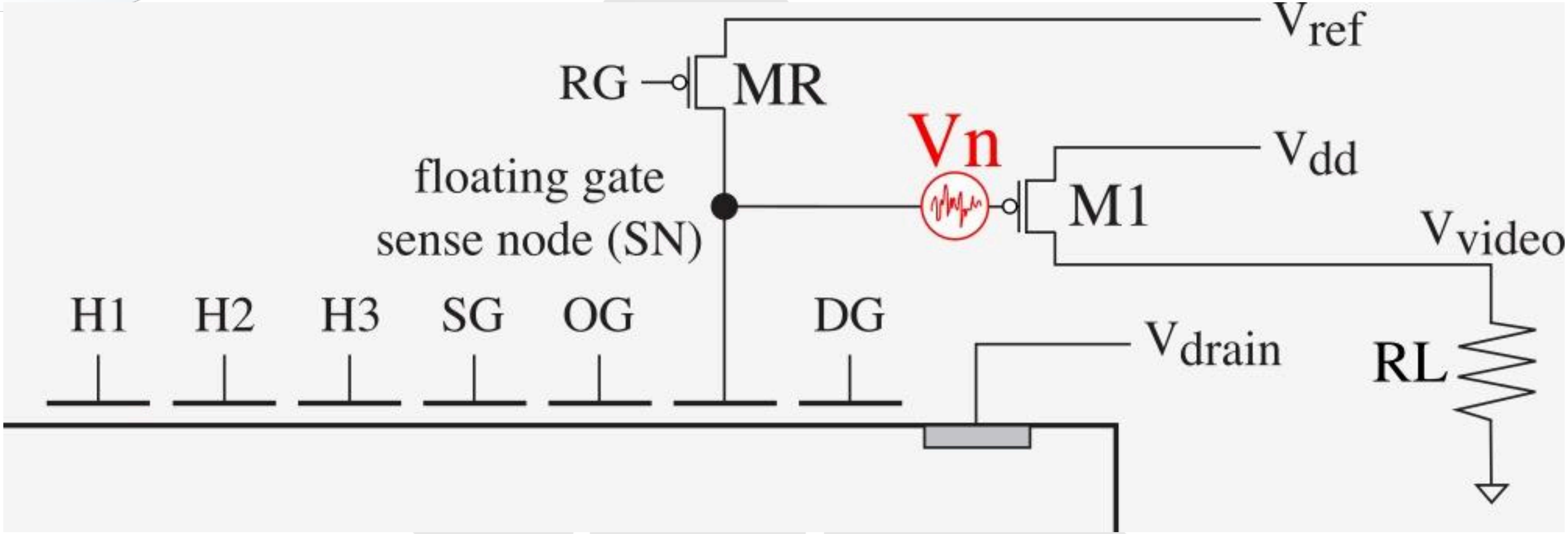
CCD problem: low frequency noise

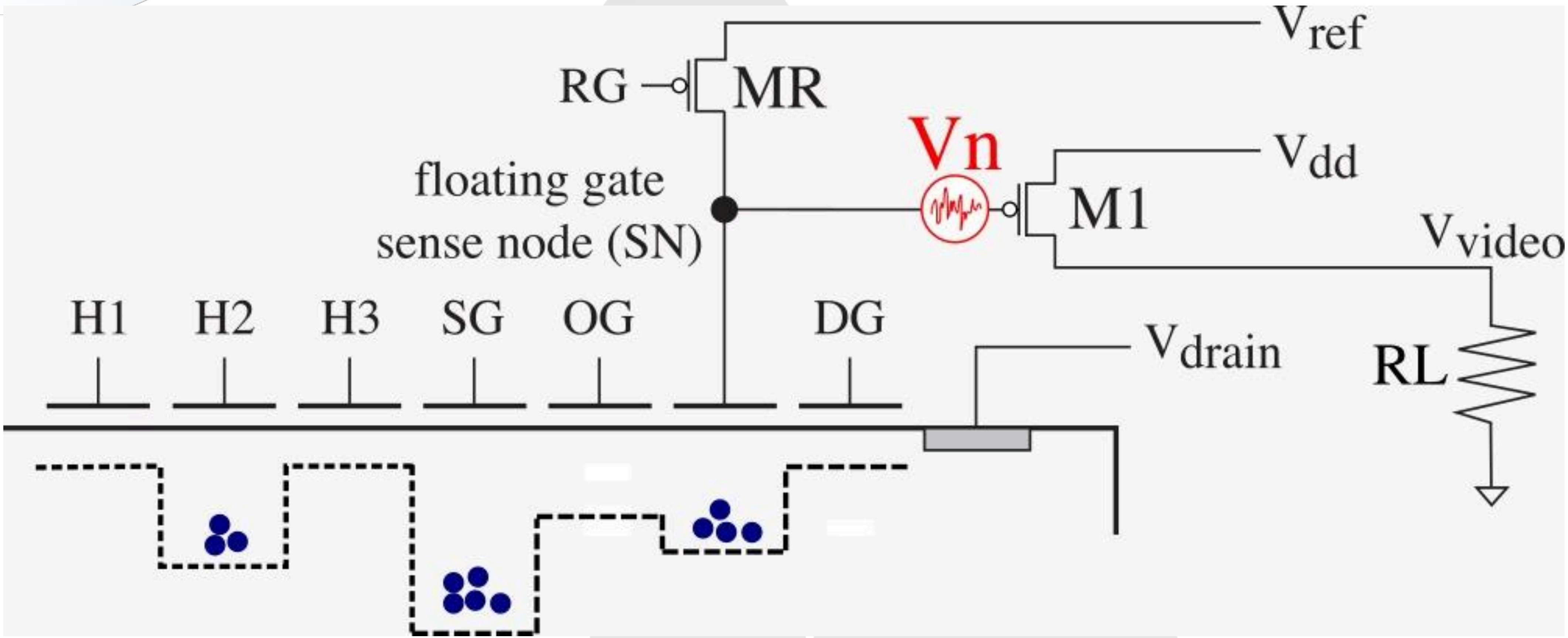


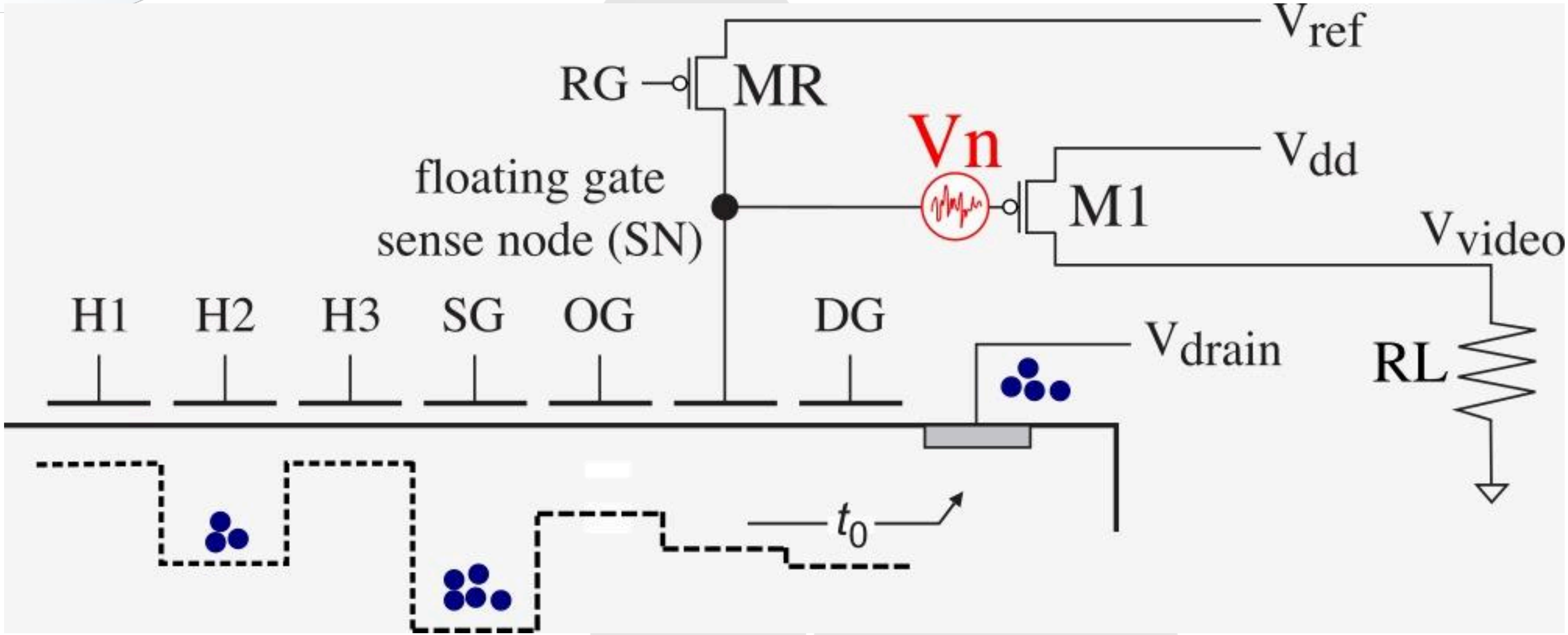




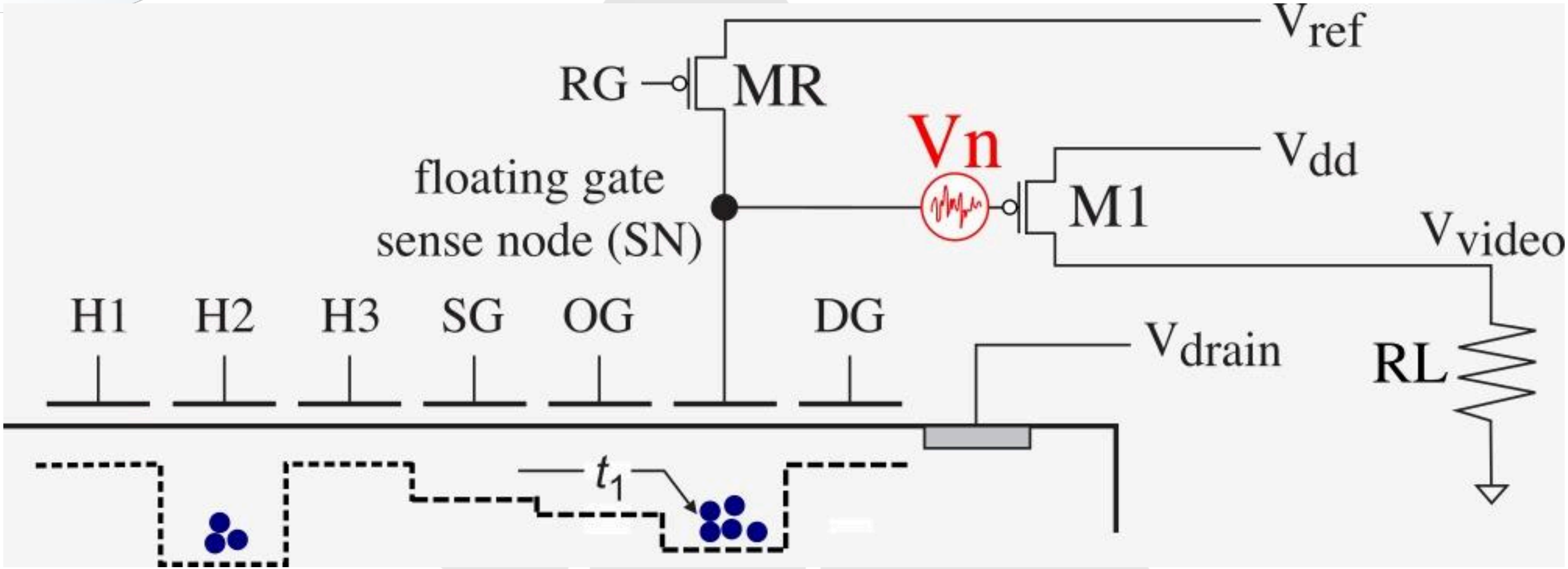
Introducing the Skipper CCD



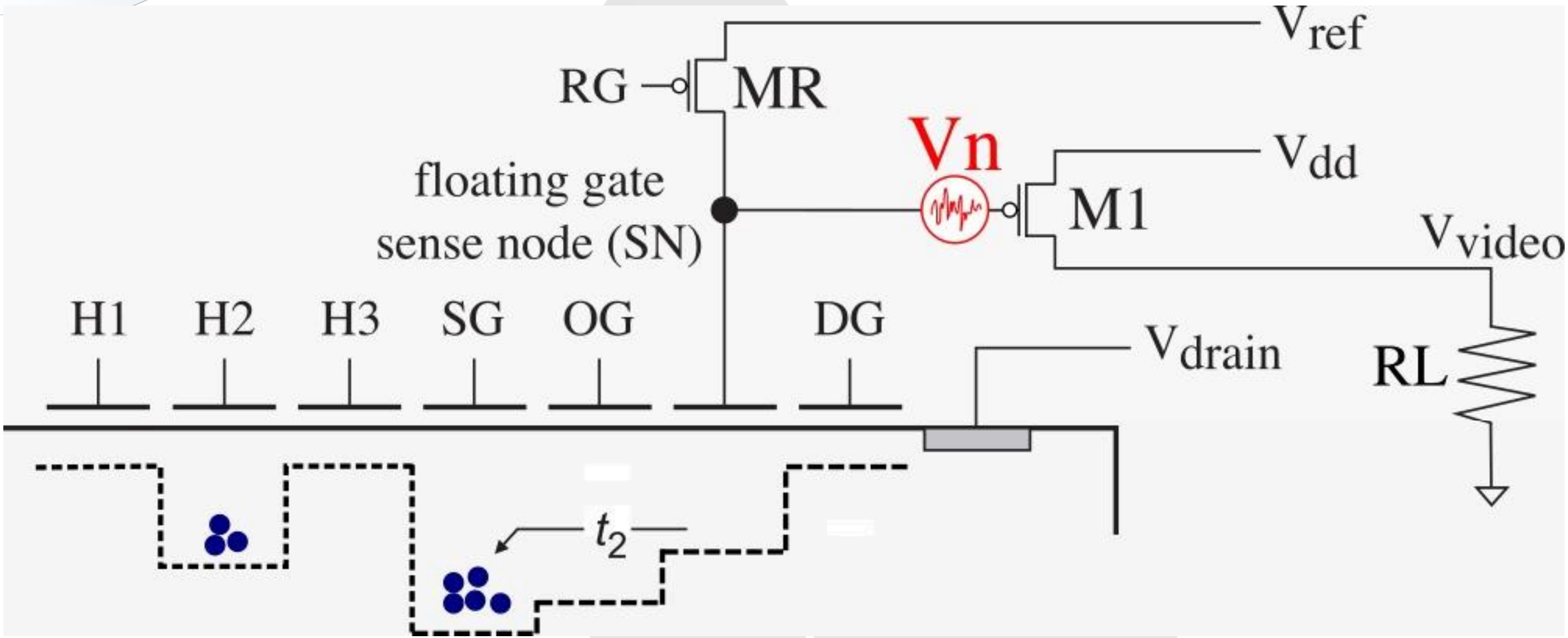

Vref
RG
MR
Vn
Vdd
floating gate
sense node (SN)
M1
Vvideo
H1
H2
H3
SG
OG
DG
Vdrain
RL


Vref
RG
MR
Vn
Vdd
floating gate
sense node (SN)
M1
Vvideo
H1
H2
H3
SG
OG
DG
Vdrain
RL
t0

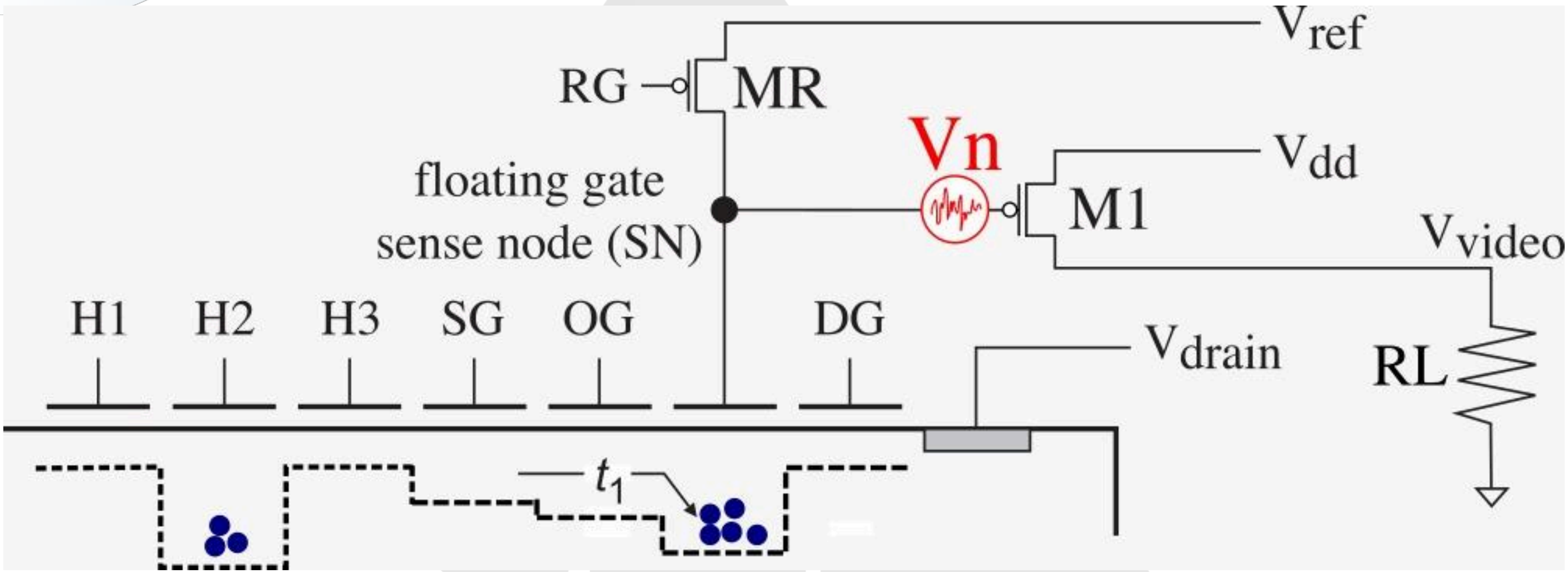
Introducing the Skipper CCD



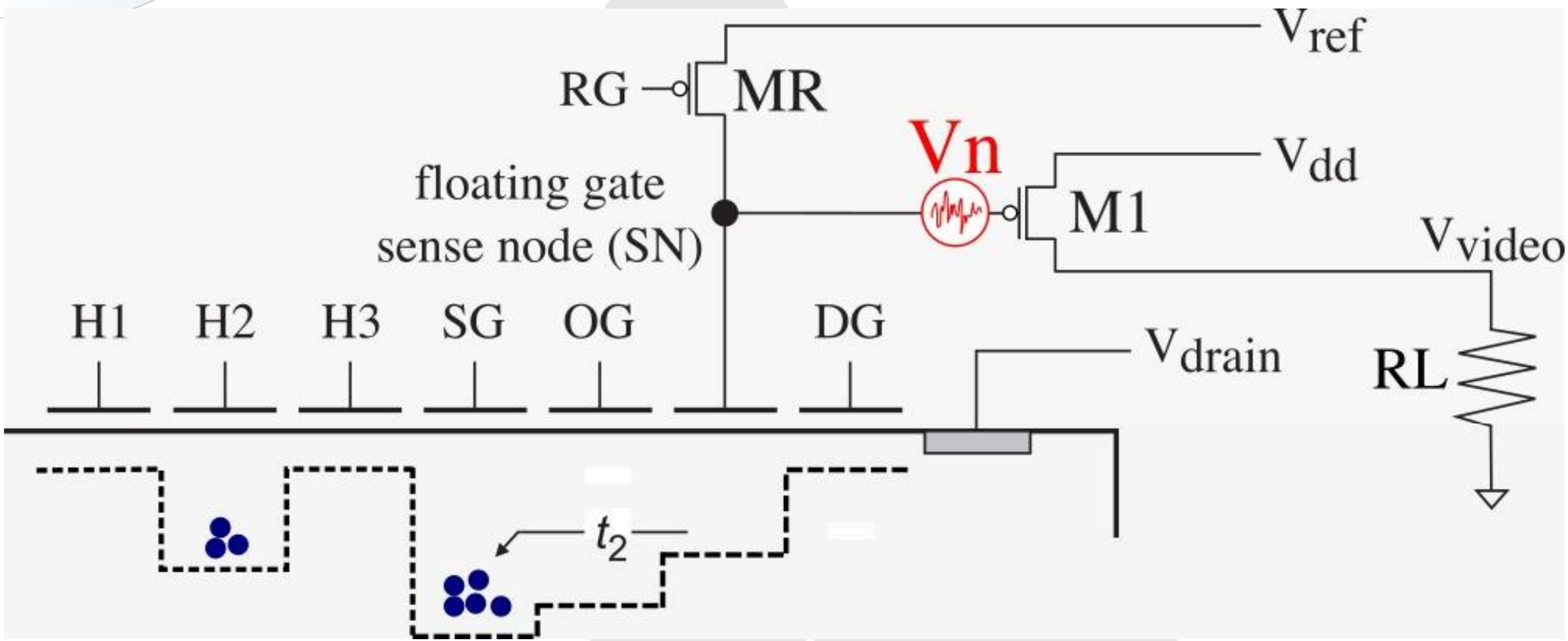
Introducing the Skipper CCD



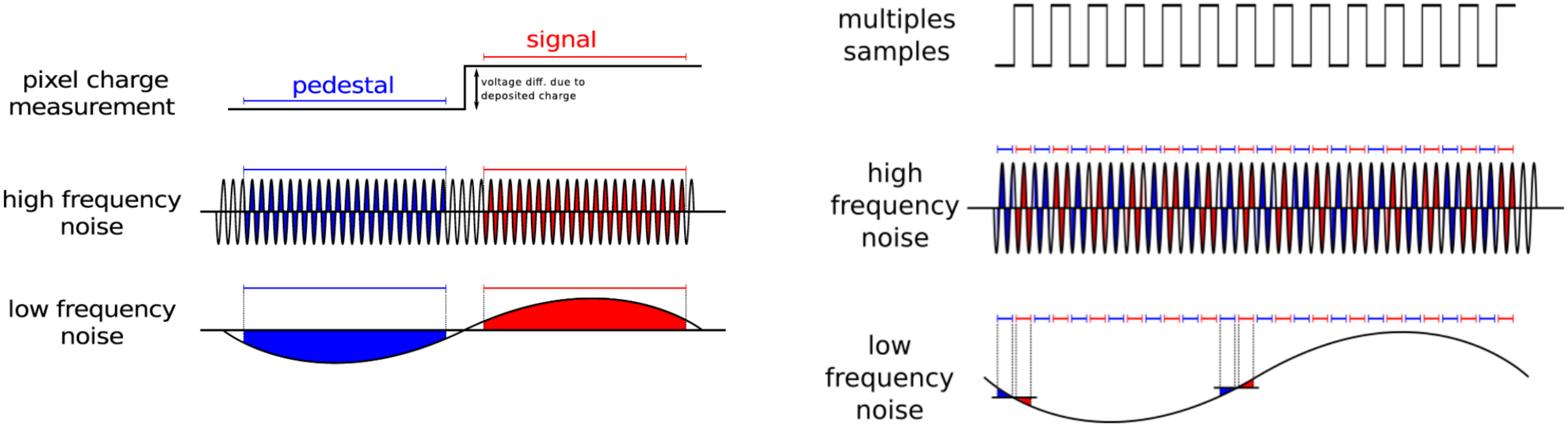
Introducing the Skipper CCD



Introducing the Skipper CCD



Introducing the Skipper CCD

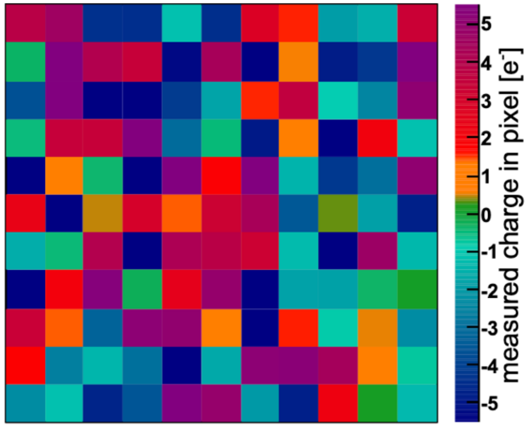


Noise goes in $1/\sqrt{N}$

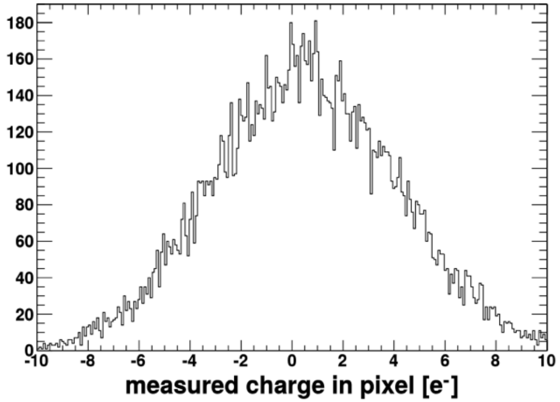
Single electron:
threshold is silicon
band gap (1.1 eV)

PRL 119, 131802 (2017)

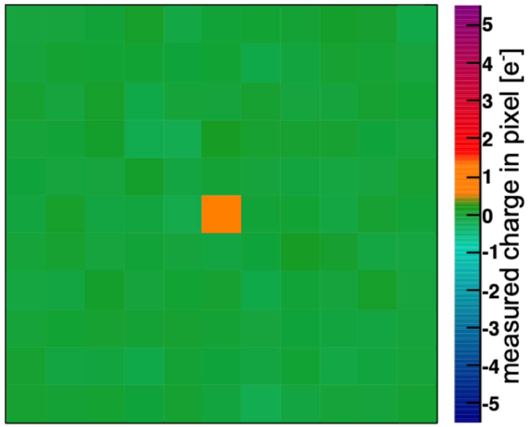
Standard CCD mode: charge in each pixel is measured once



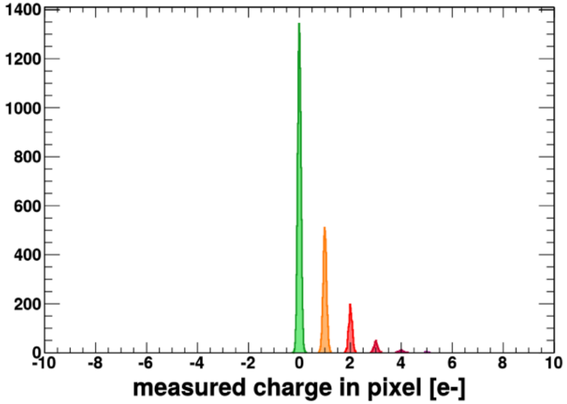
Readout-noise: 3.5 e RMS



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



Readout-noise: 0.06 e RMS



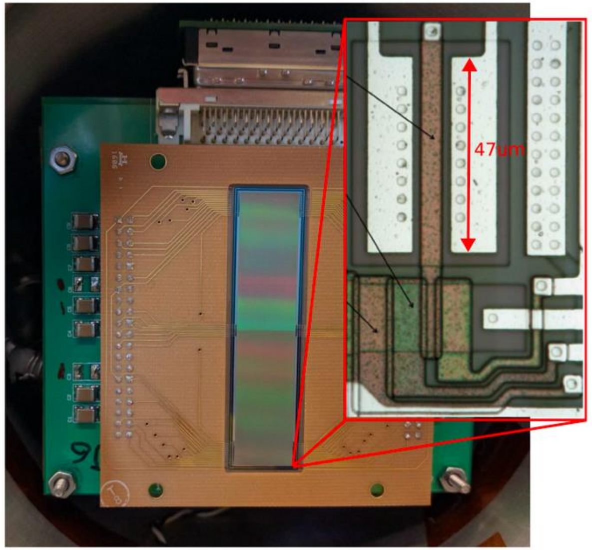
What can a Skipper CCD do?

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

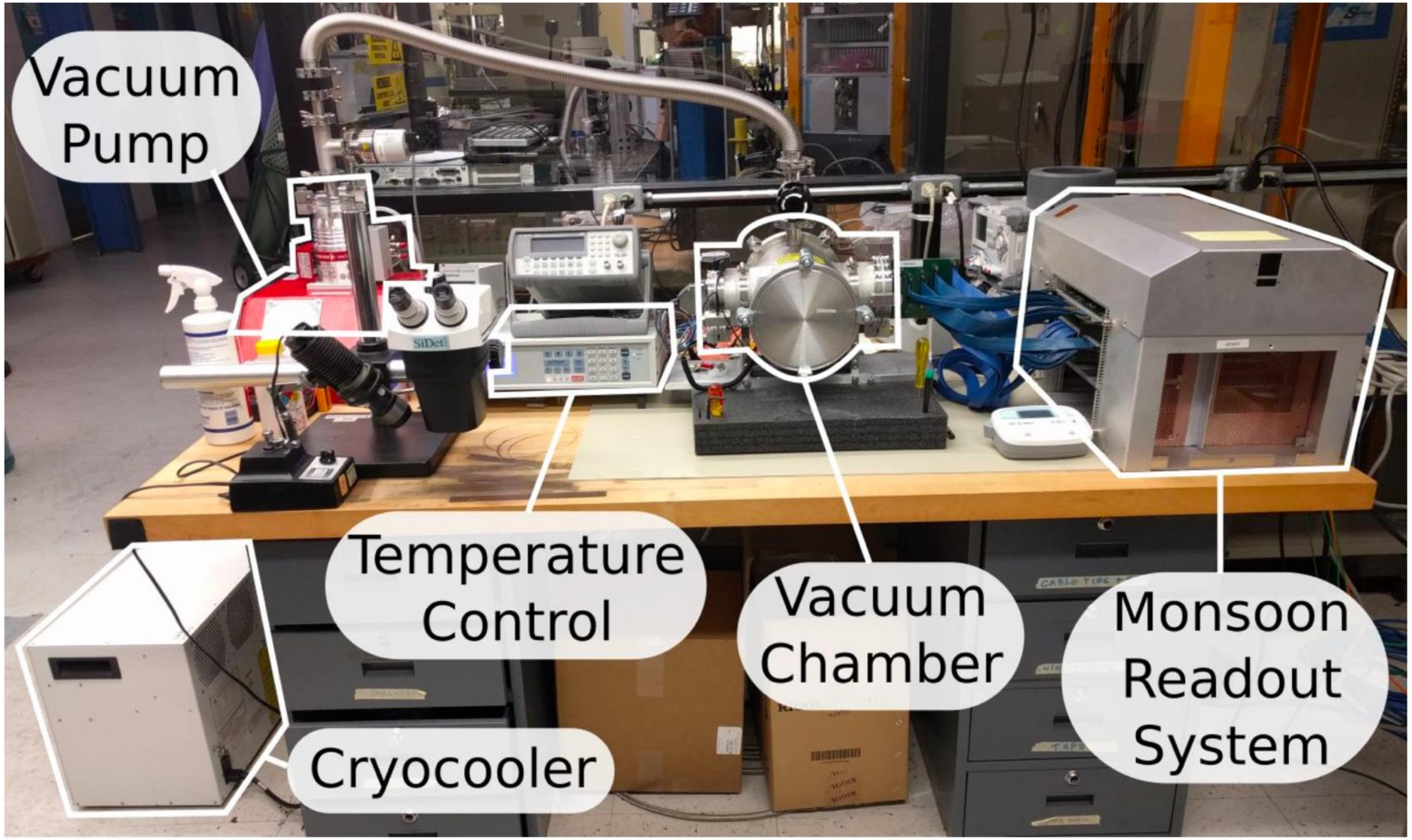
(and operate with a DC of less than 200 e^- / g / day, i.e. 1 e^- / pix / 30 years)

(3)
The Skipper CCD and Dark Matter

First Skipper CCD readout system

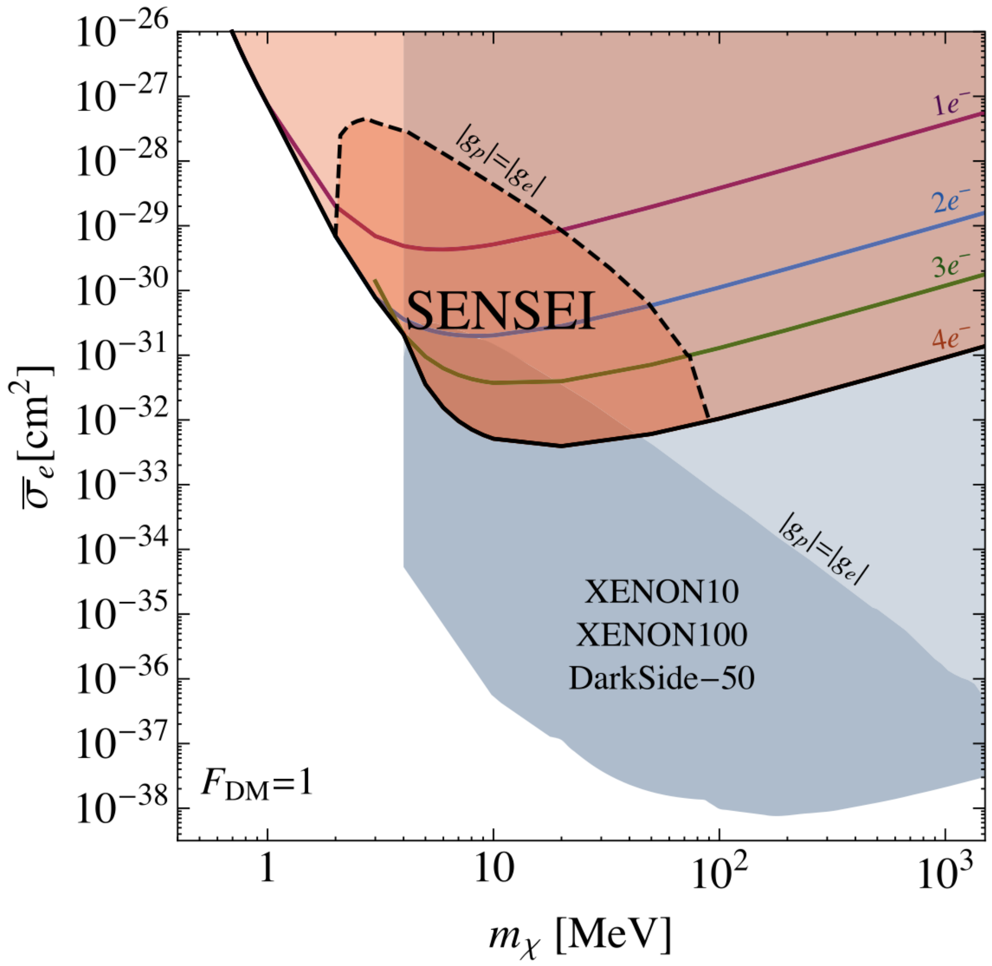


250 um depth
0.1g

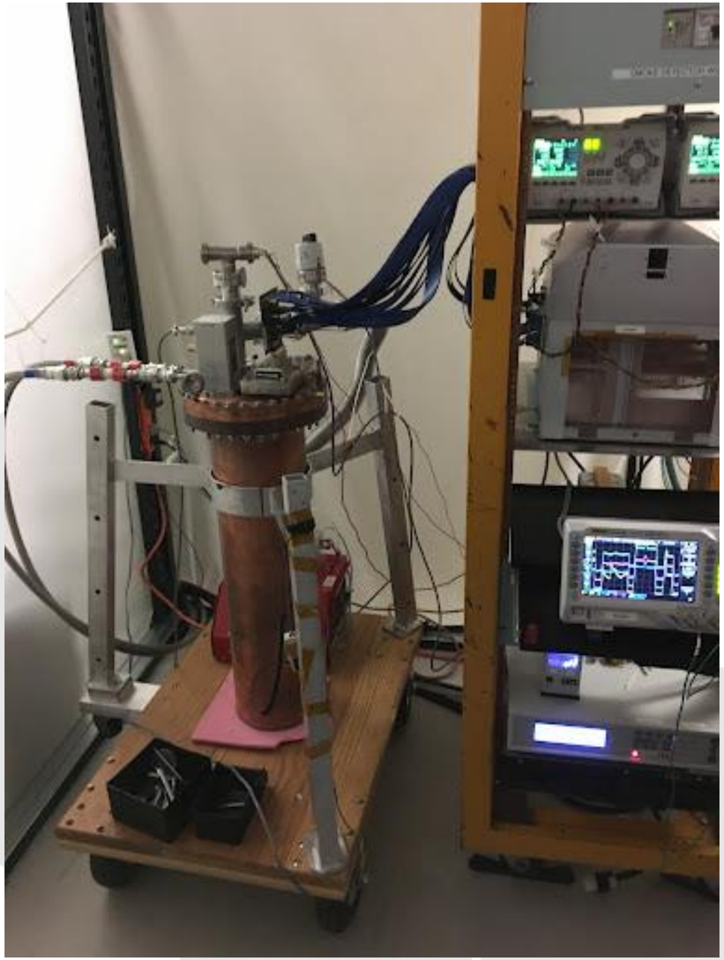


SENSEI: First Direct-Detection Constraints on sub-GeV Dark Matter from a Surface Run

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

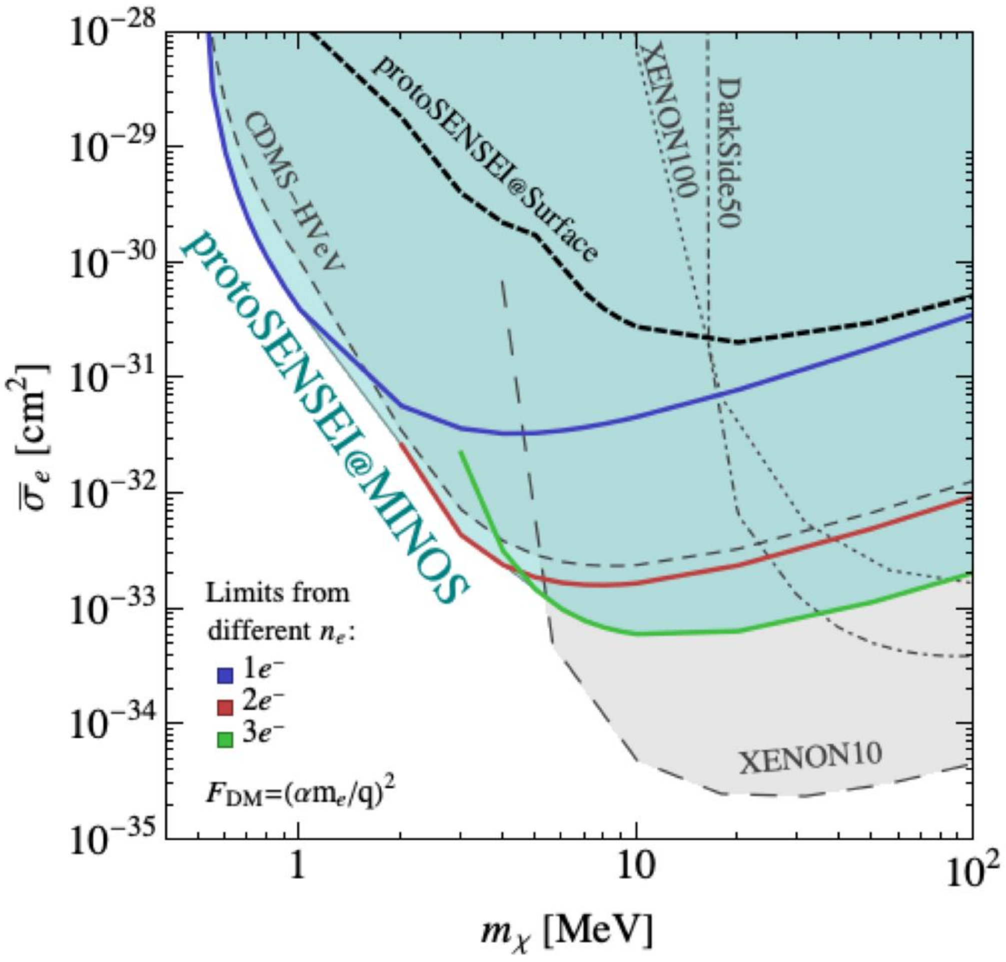


Better experimental setup at shallow site

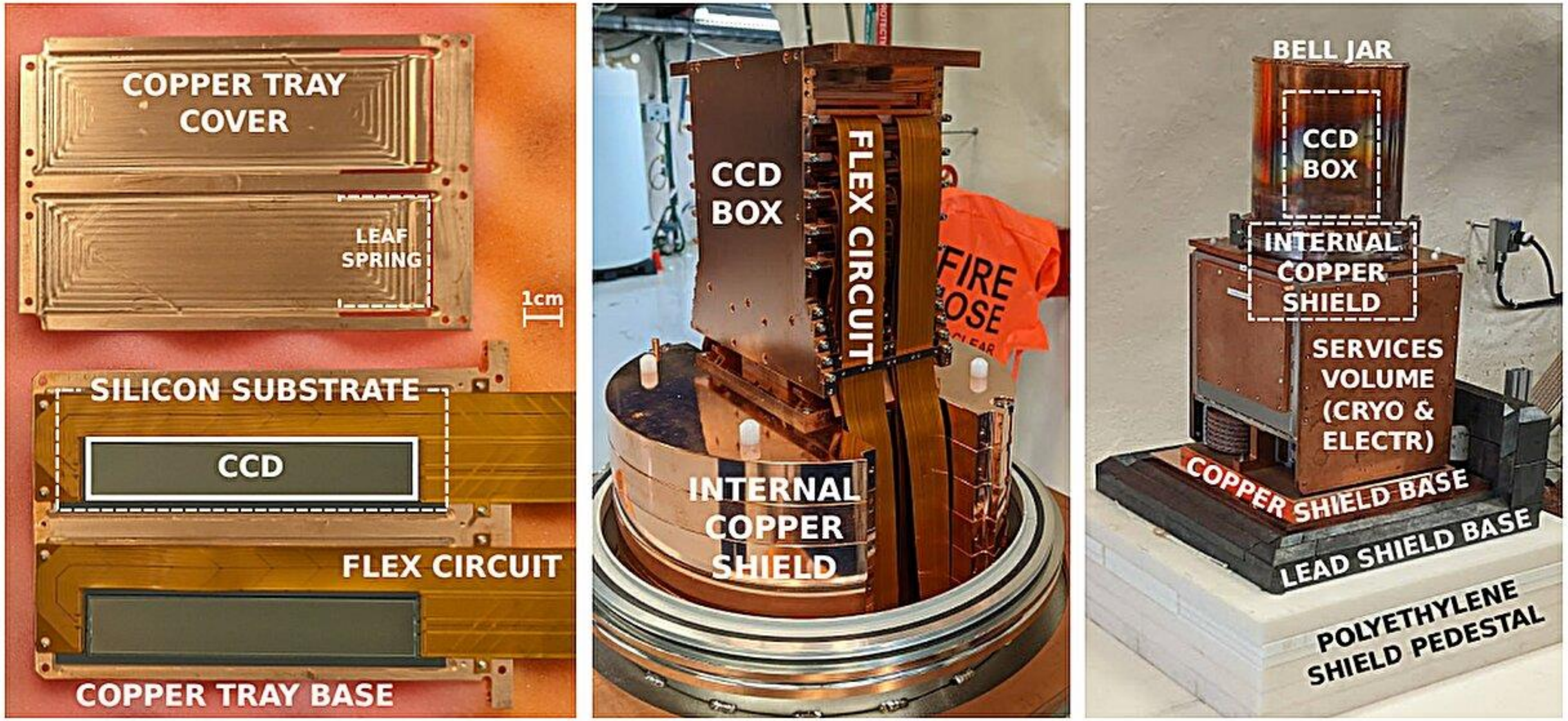


SENSEI: Direct-Detection Constraints on Sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper-CCD

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

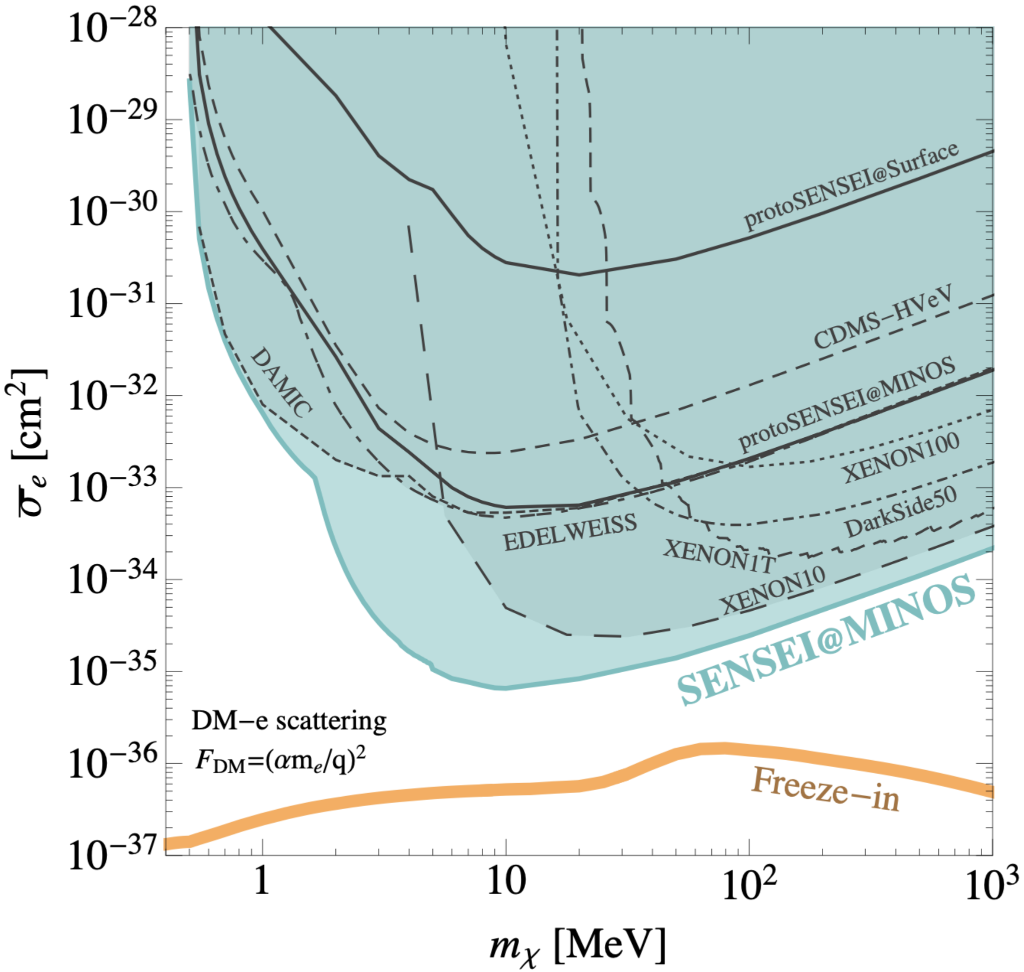


Improving detector, then going deeper and more quiet



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

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



(4)
DAMIC-M

The DAMIC-M collaboration

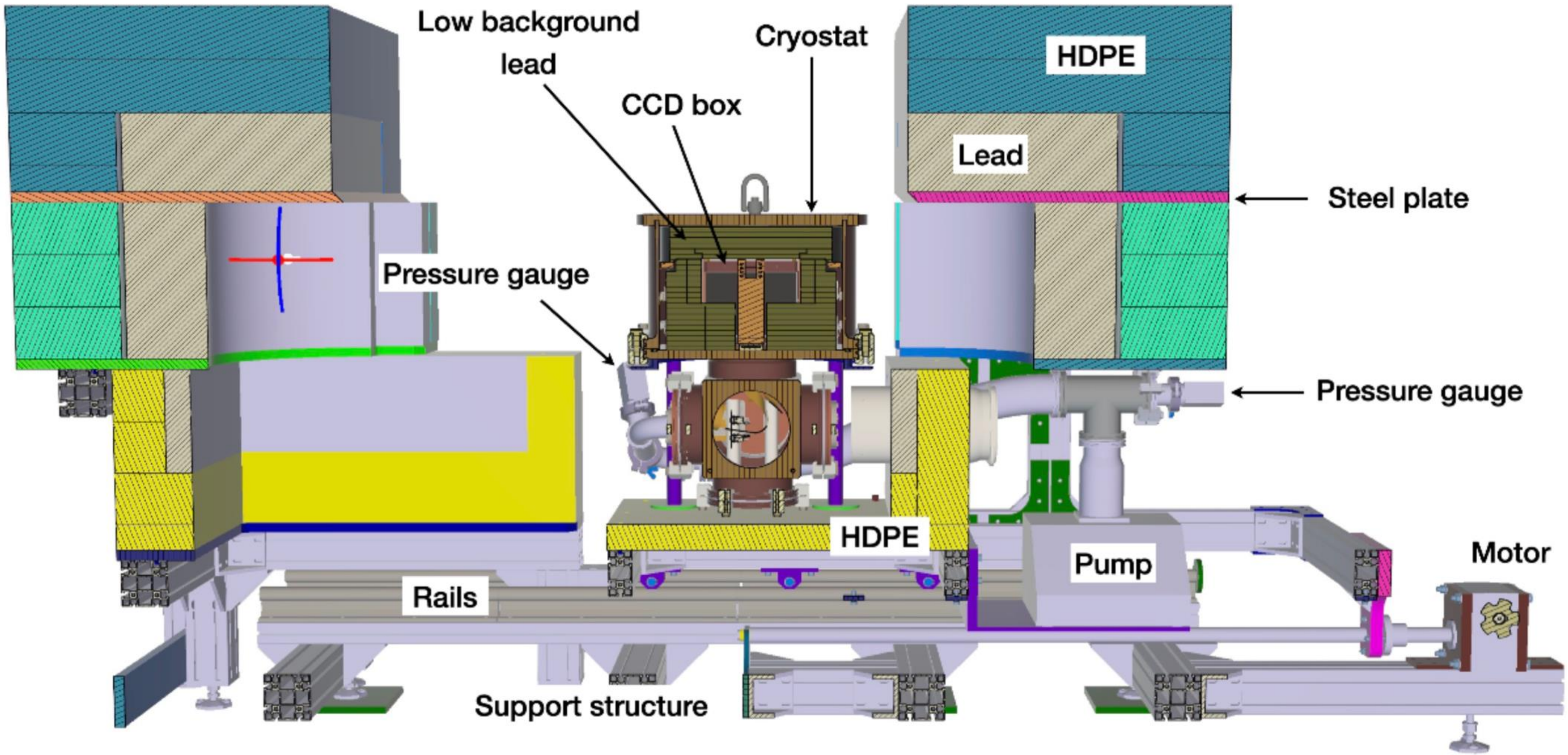
European Research Council
Established by the European Commission

Working on a next generation detector

First step

LBC
Low
Background
Chamber

Model



Low background
lead
Cryostat
CCD box
HDPE
Lead
Steel plate
Pressure gauge
Pressure gauge
HDPE
Pump
Motor
Rails
Support structure

Reality

CCD controllers and power supplies

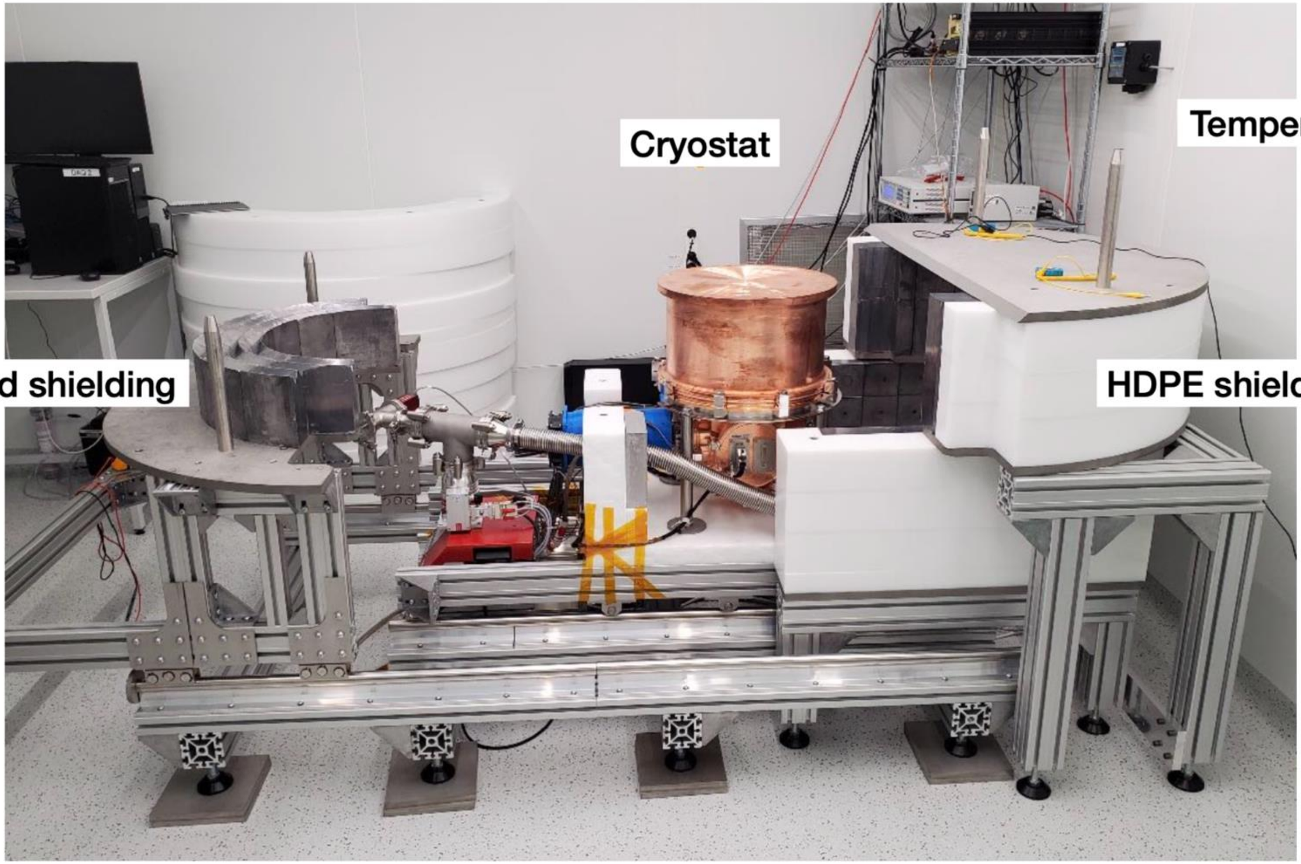
DAQ and slow control PCs

Cryostat

Temperature controller

External lead shielding

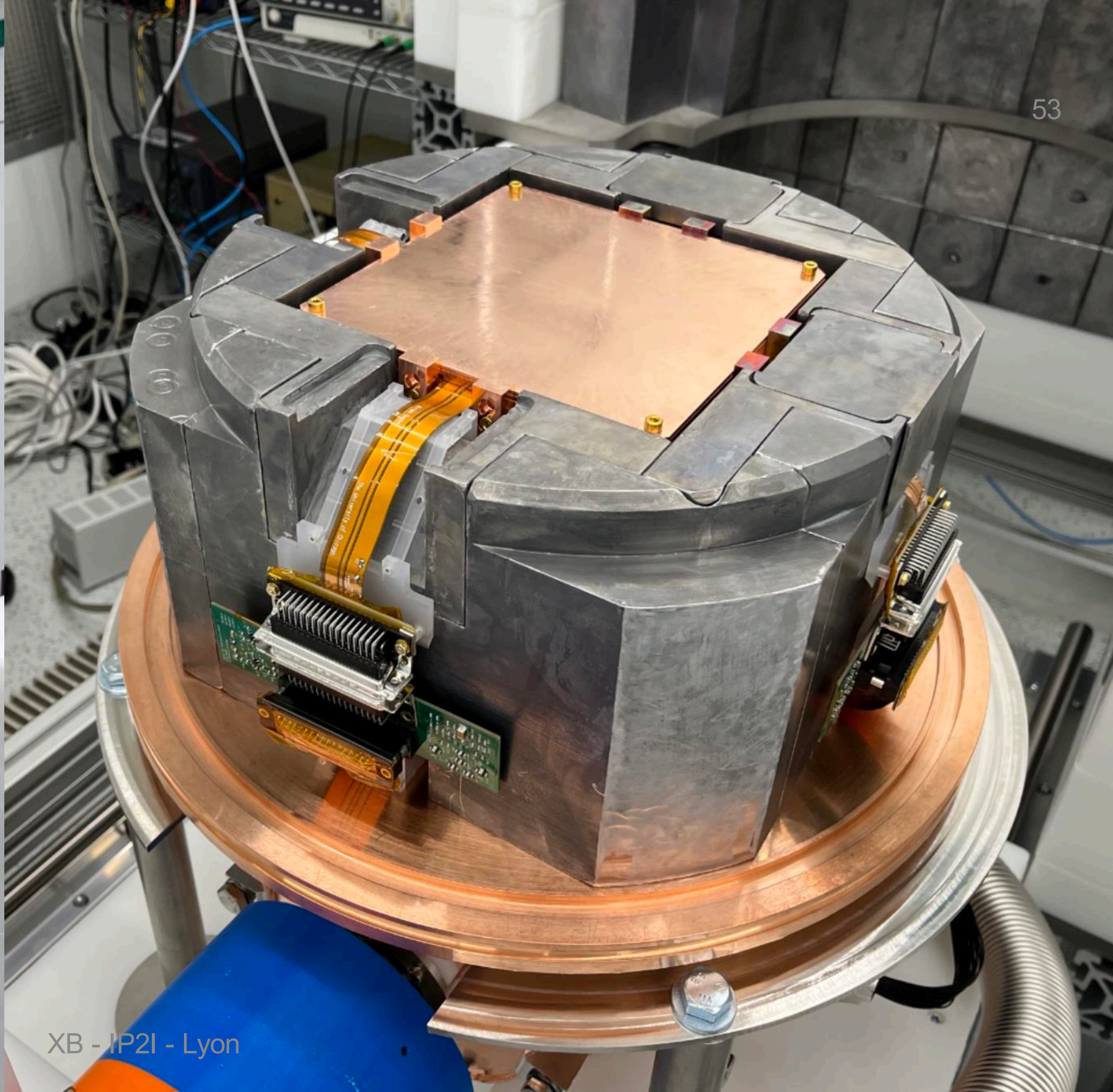
HDPE shielding

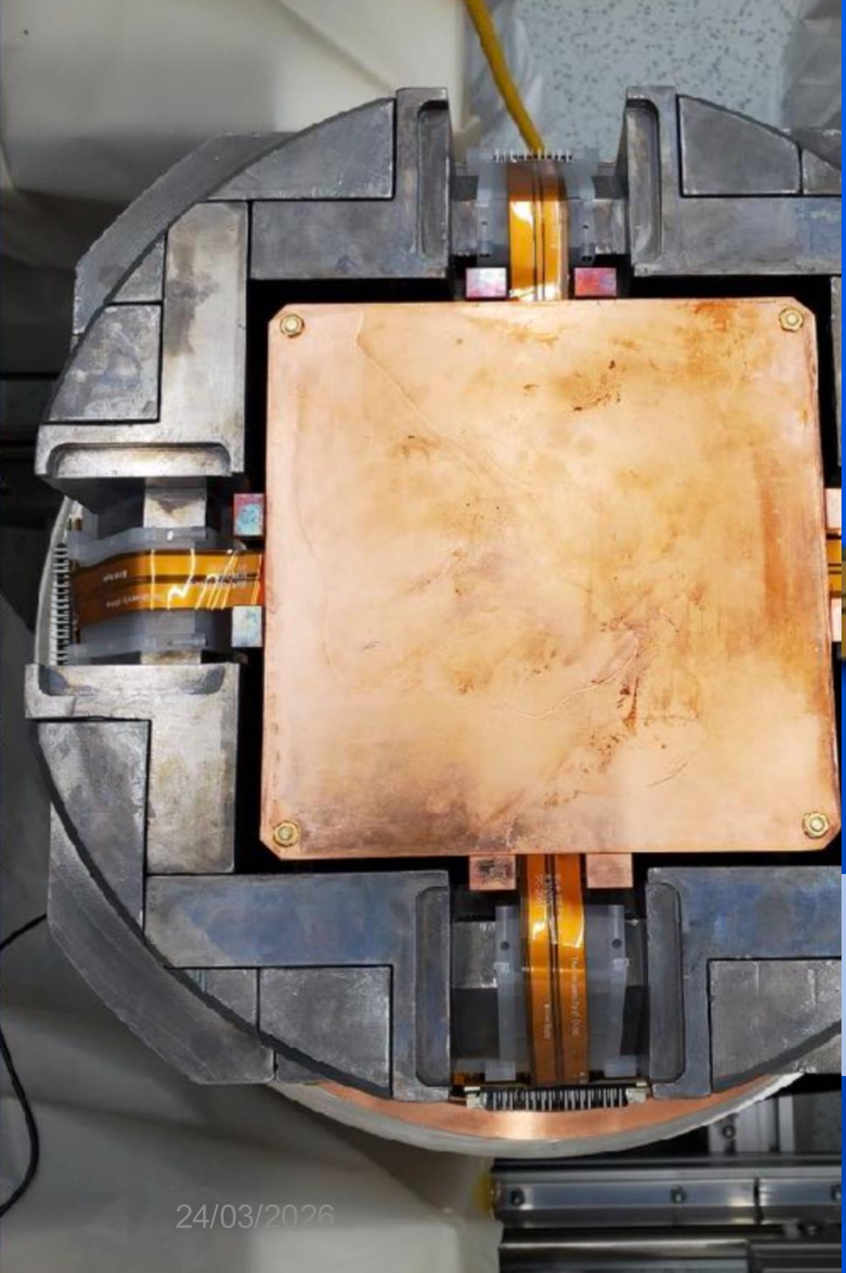


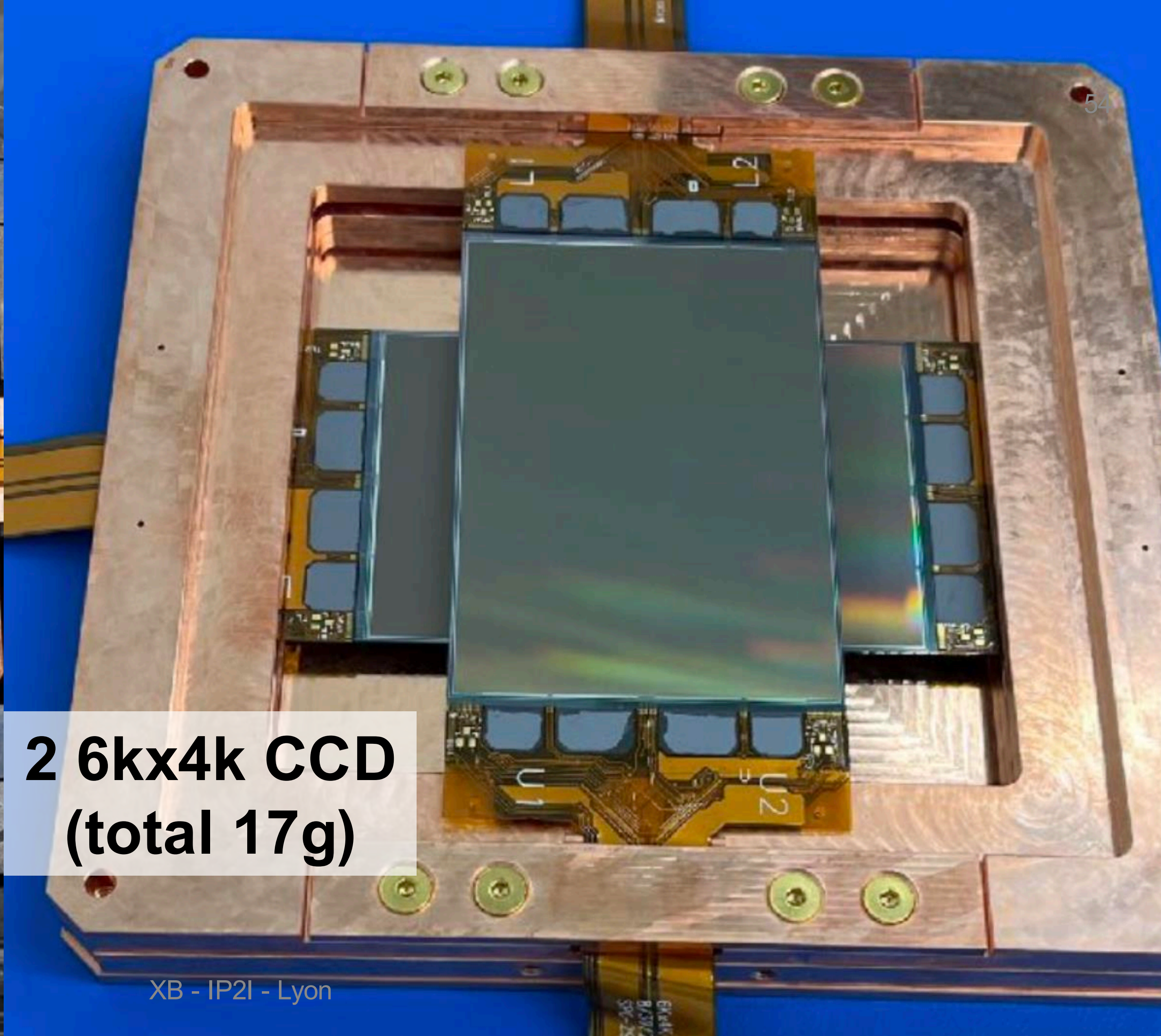
Support structure

Vacuum pump and pressure gauges


Temperature

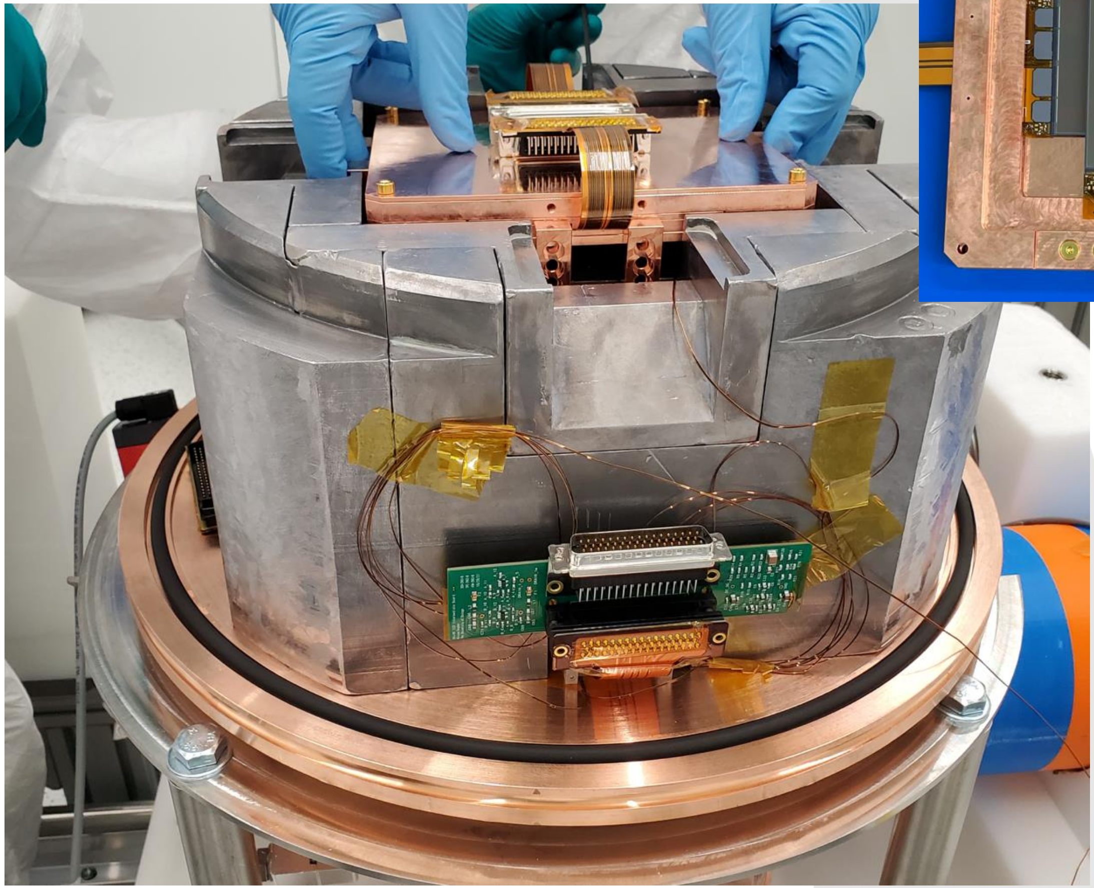


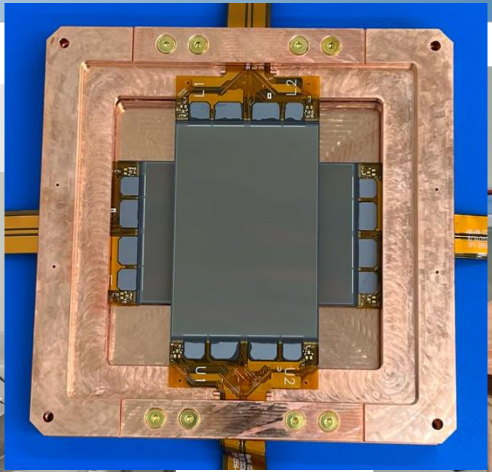




2 6kx4k CCD
(total 17g)

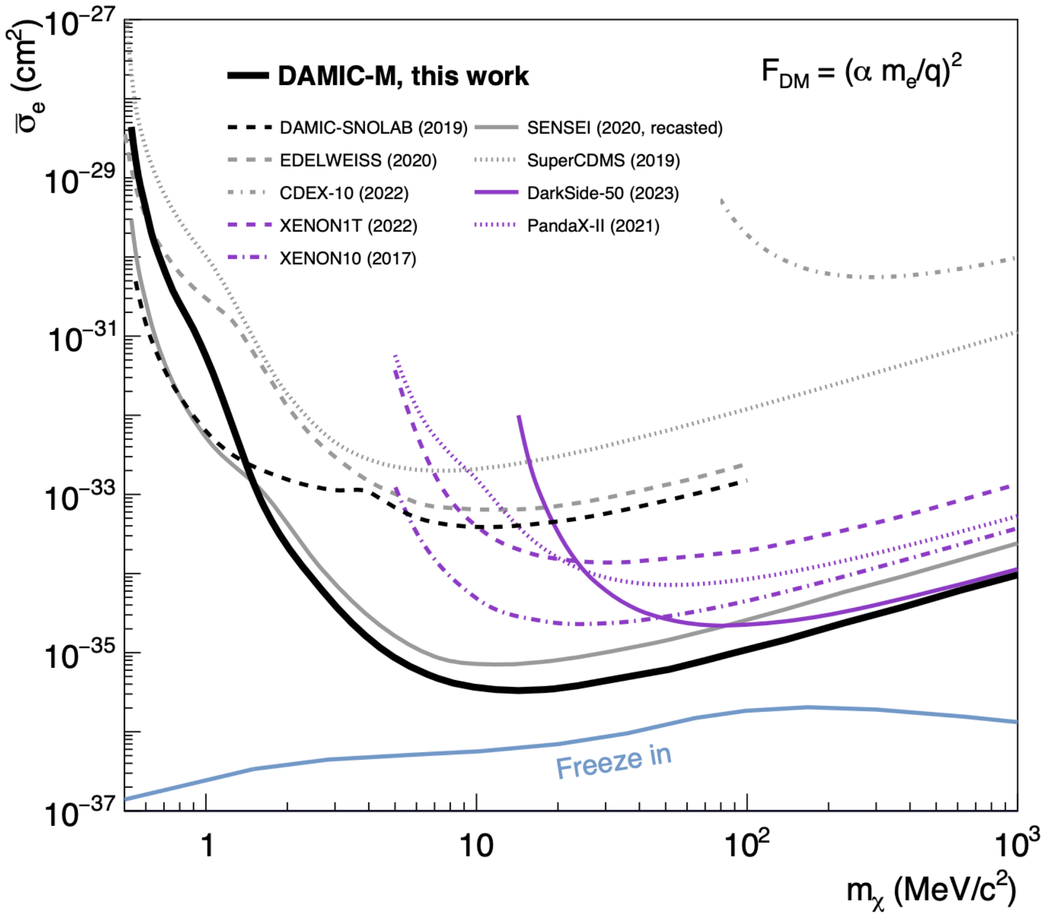
Next generation experiment: DAMIC-M (LBC)



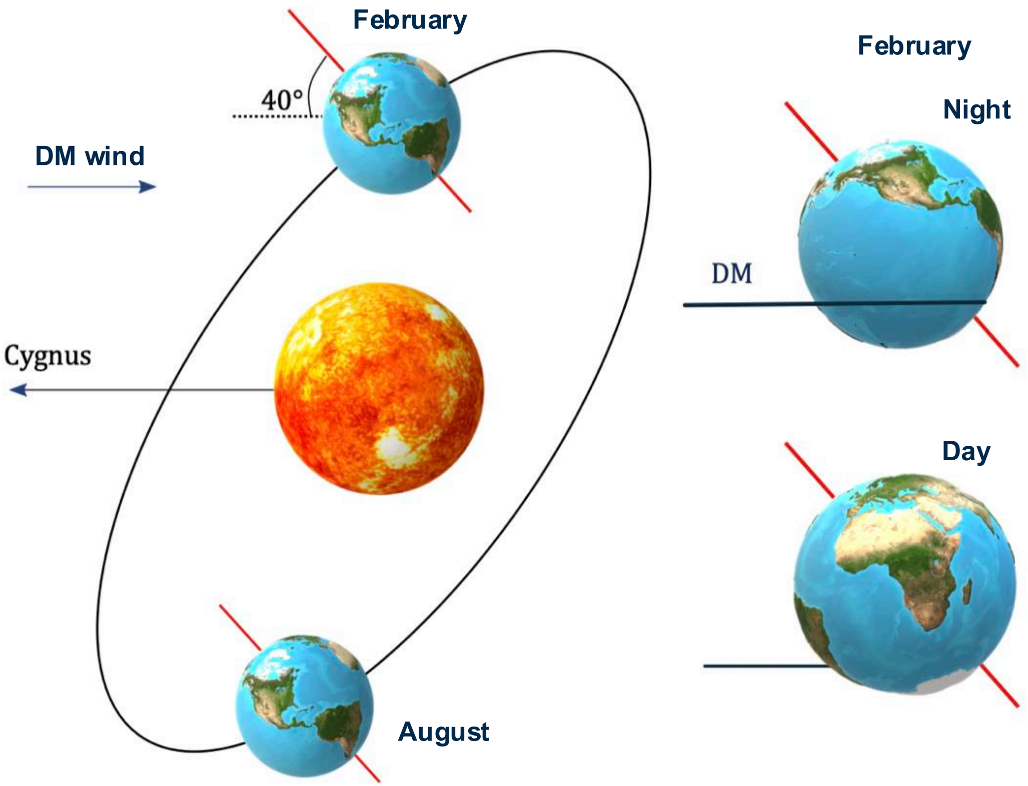


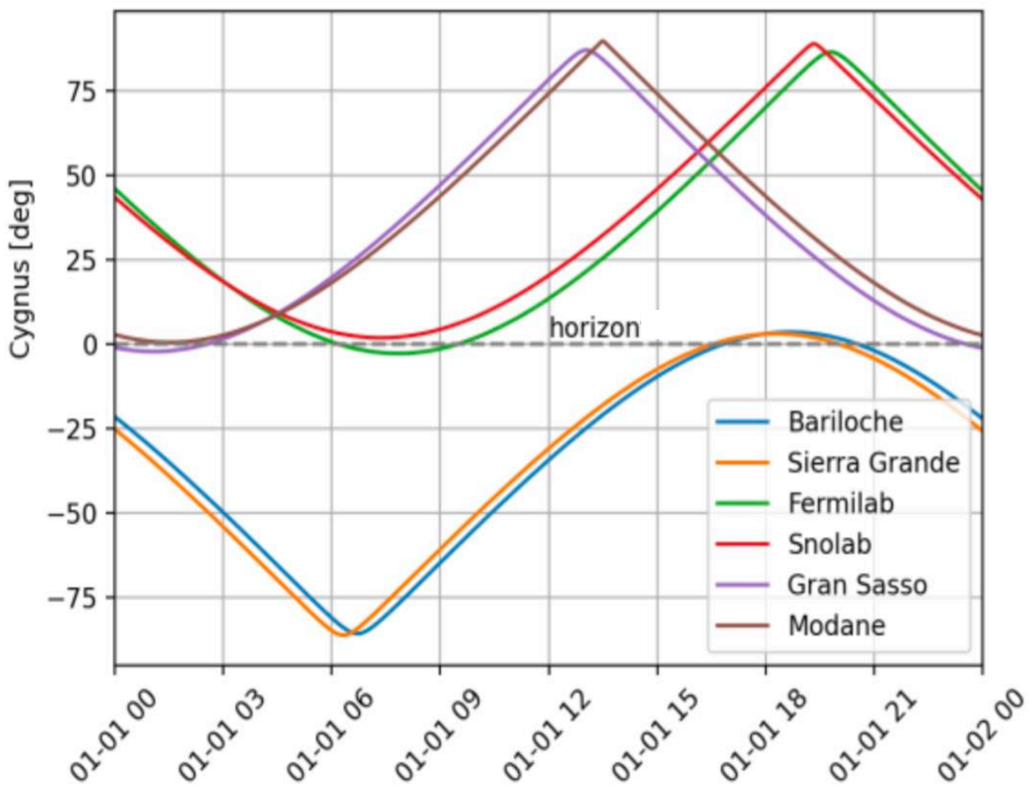
First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons

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

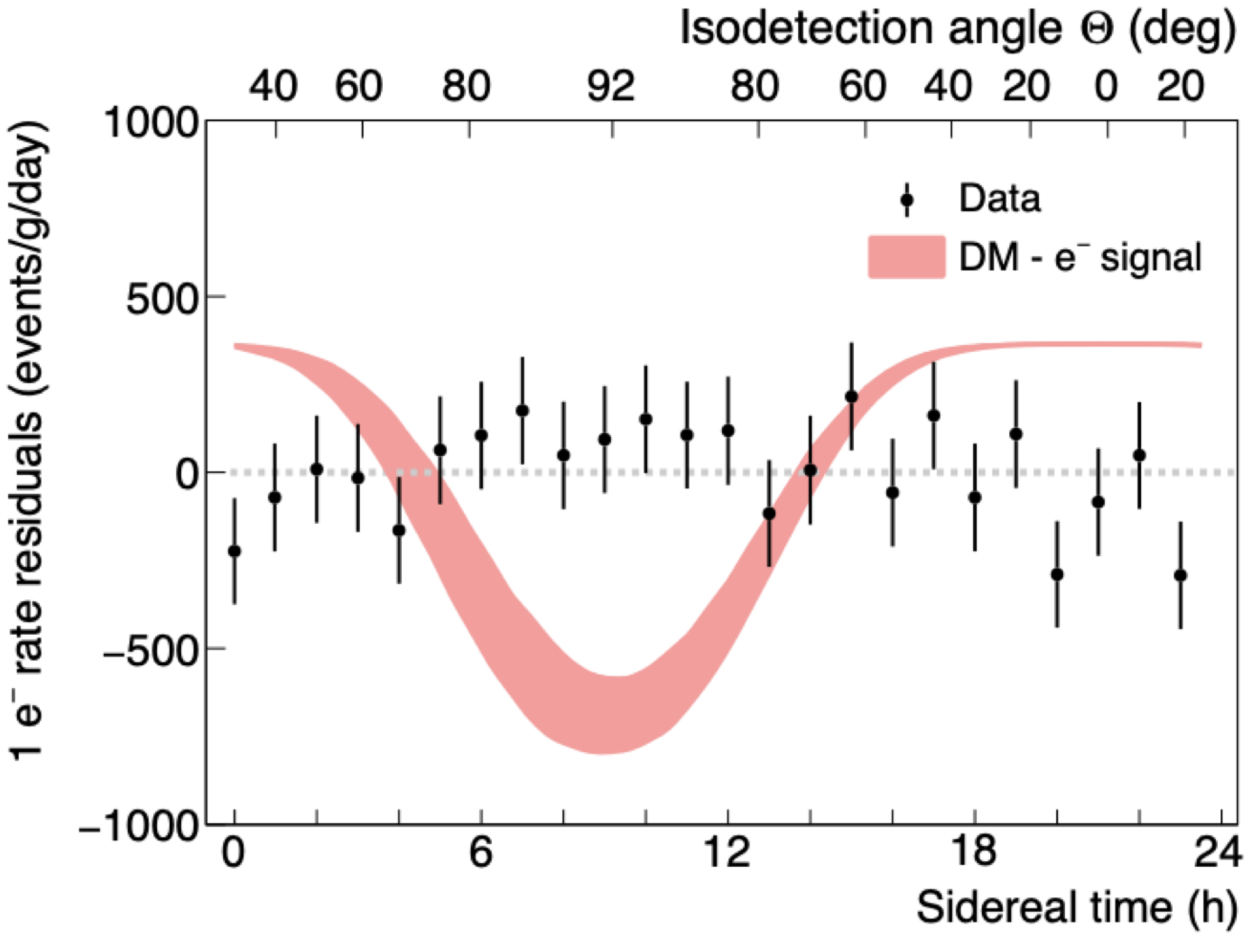


Daily modulation of Dark Matter



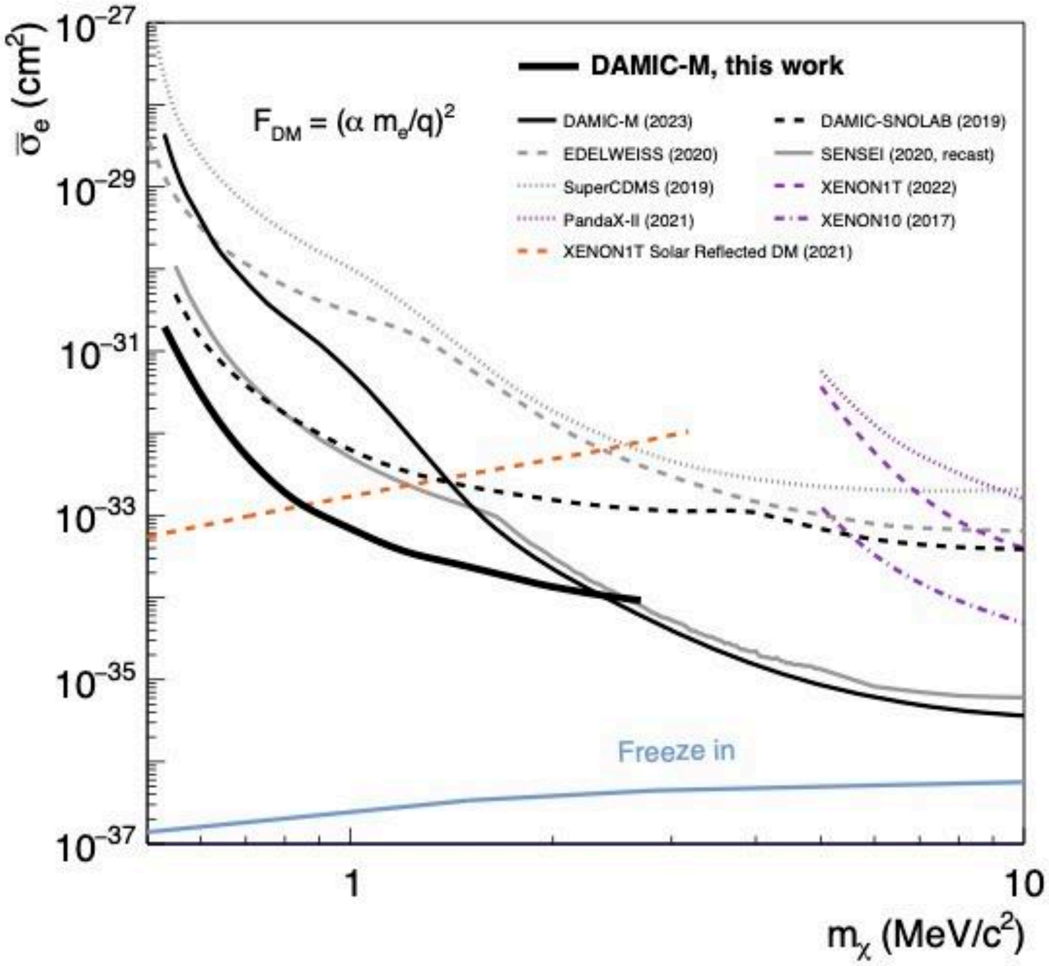


Modulation non observation

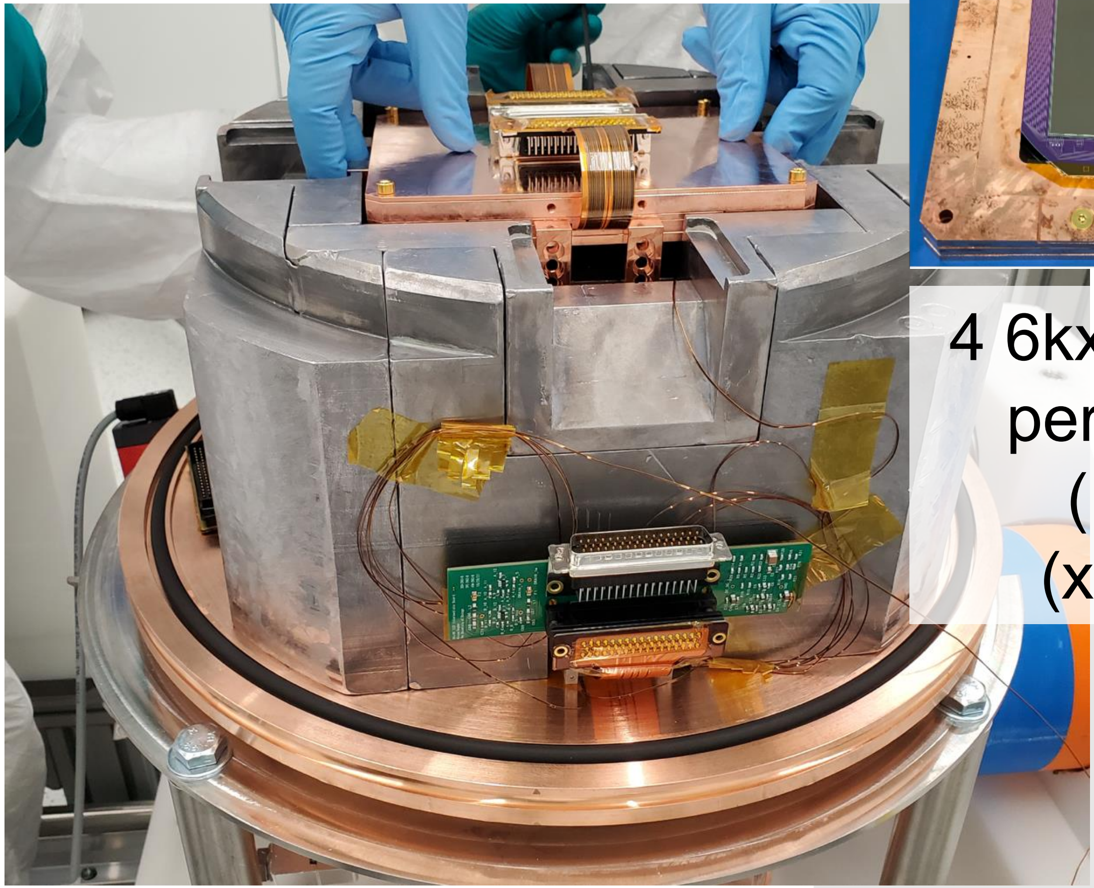


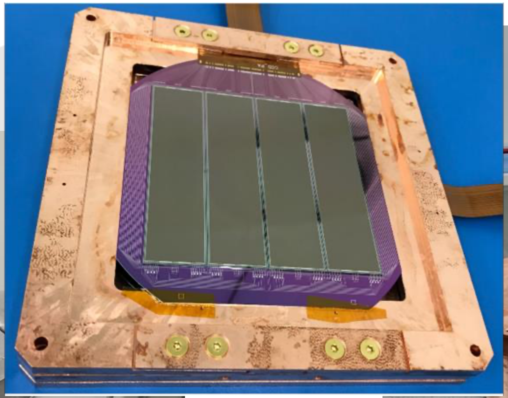
Search for Daily Modulation of MeV Dark Matter Signals with DAMIC-M

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



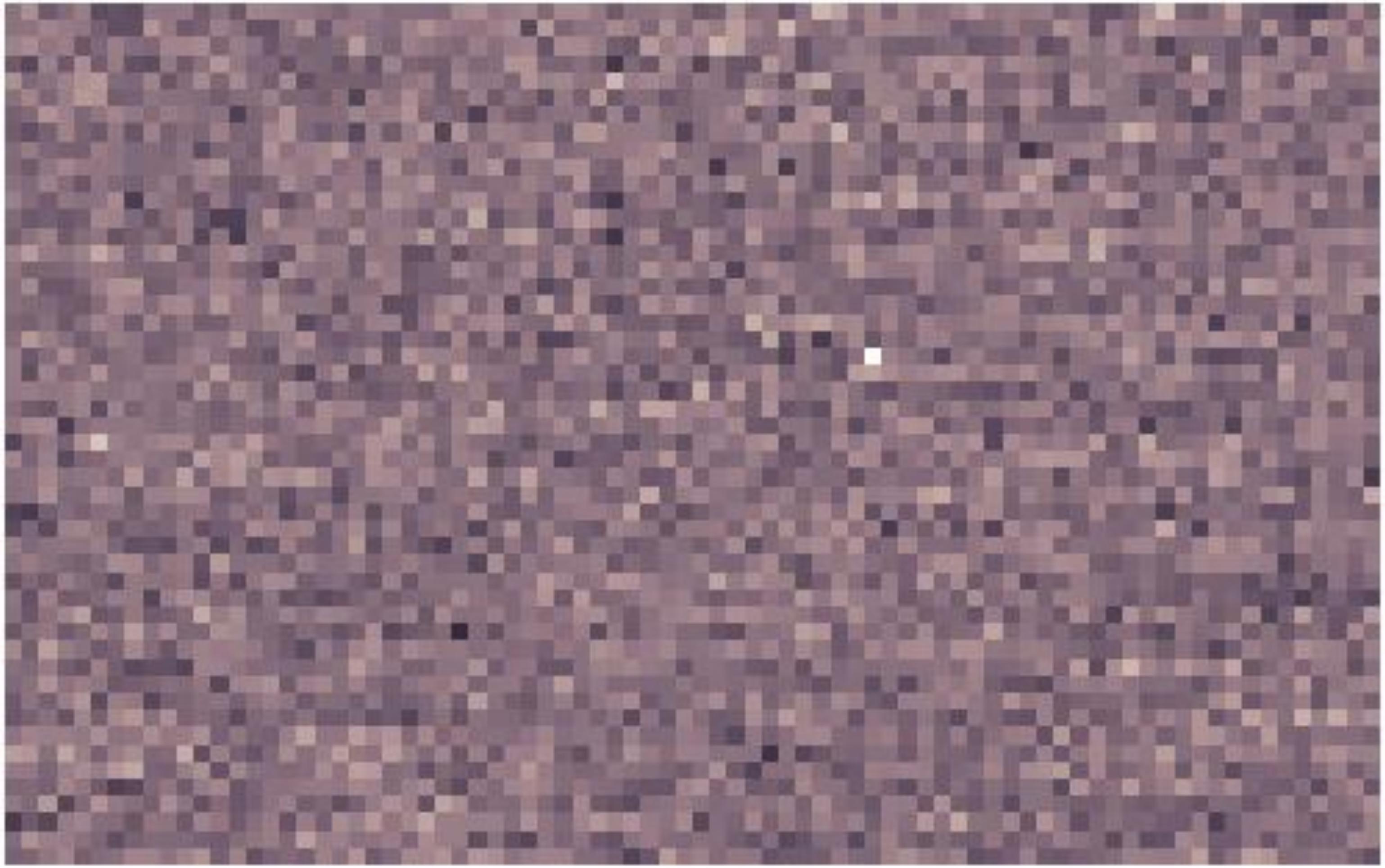
Improved detectors and setup at LBC



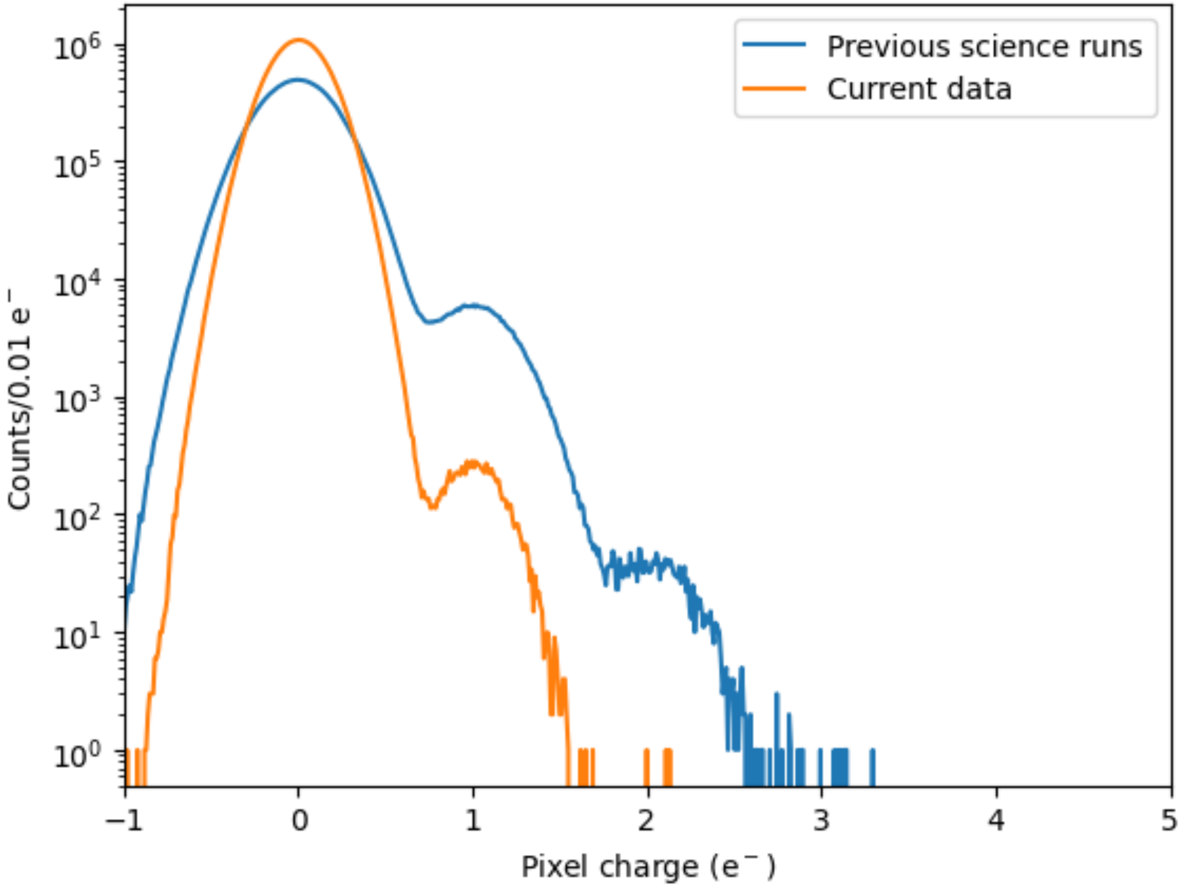


4 6kx1.5k CCD per module (13.4g) (x2=27g)

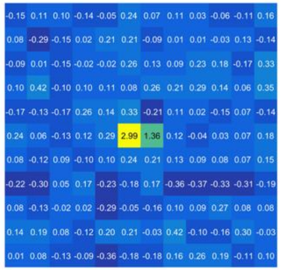
Typical current DAMIC-M portion of an image



Improved DC, looking for patterns

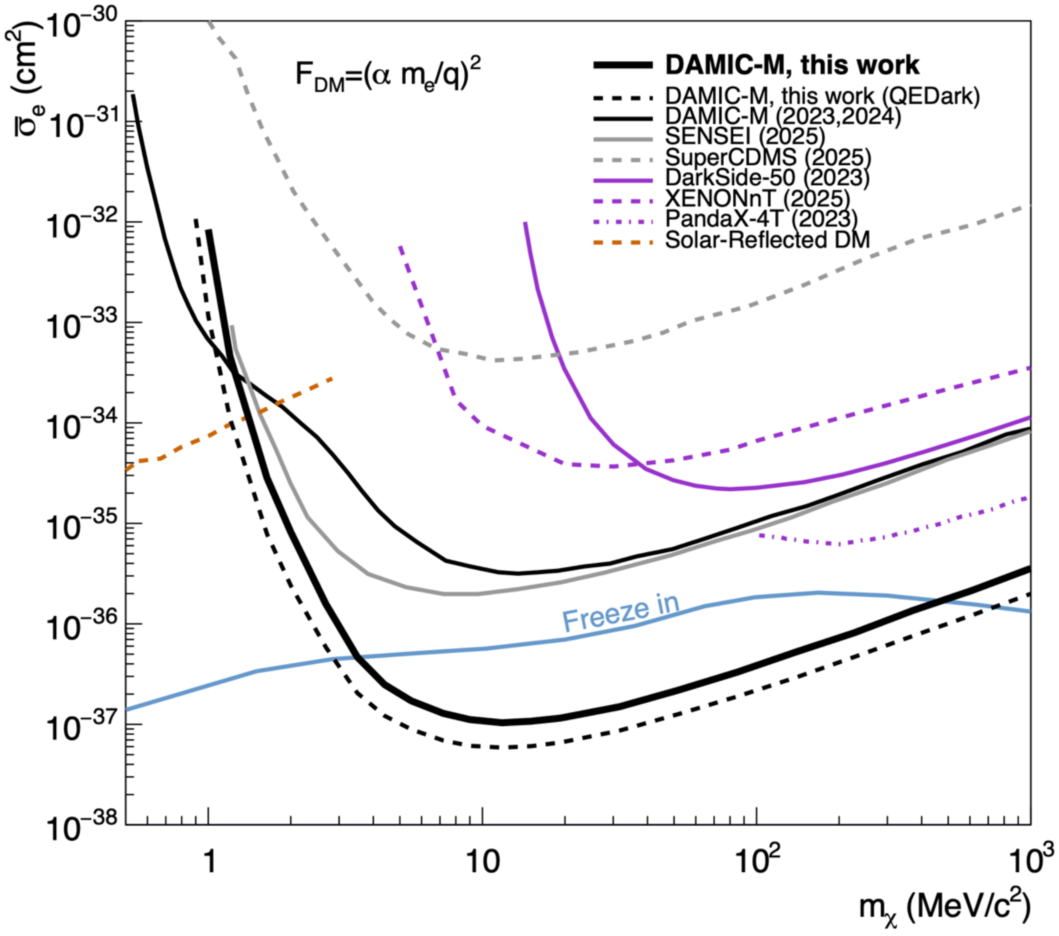


	Pattern p		
	{11}	{21}	{111}
D_p	144	0	0
B_p^{rc}	141.4	0.111	0.042
B_p^{rad}	0.039	0.039	0.016
	{31}	{22}	{211}
D_p	1	0	0
B_p^{rc}	0.019	$2.5 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$
B_p^{rad}	0.052	0.011	0.035



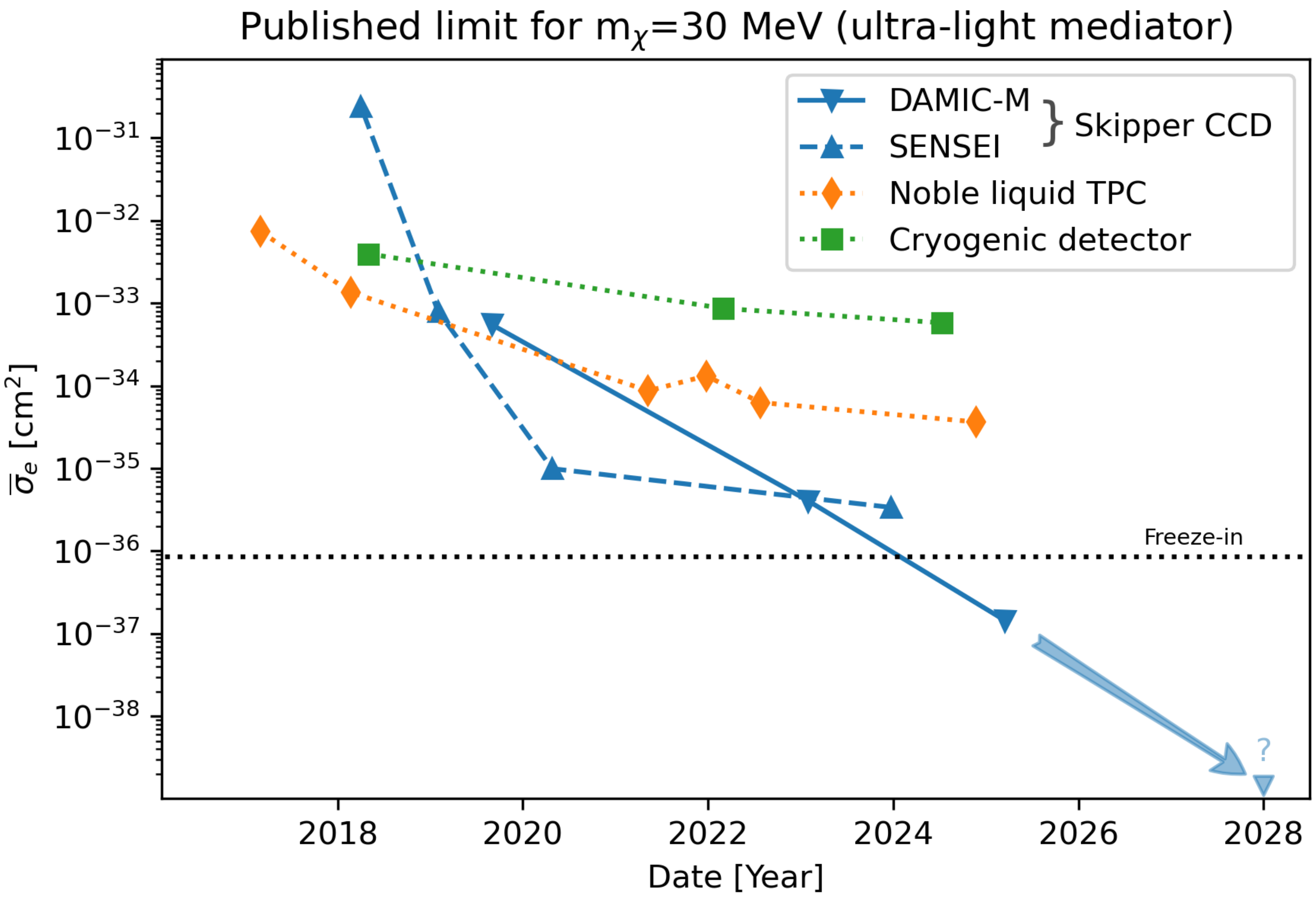
Probing Benchmark Models of Hidden-Sector Dark Matter with DAMIC-M

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)

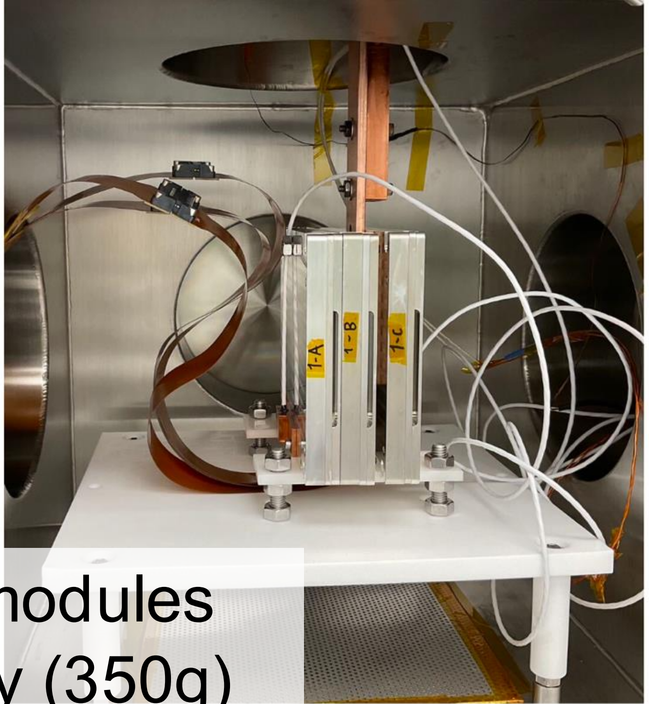
Skipper CCD vs other technologies



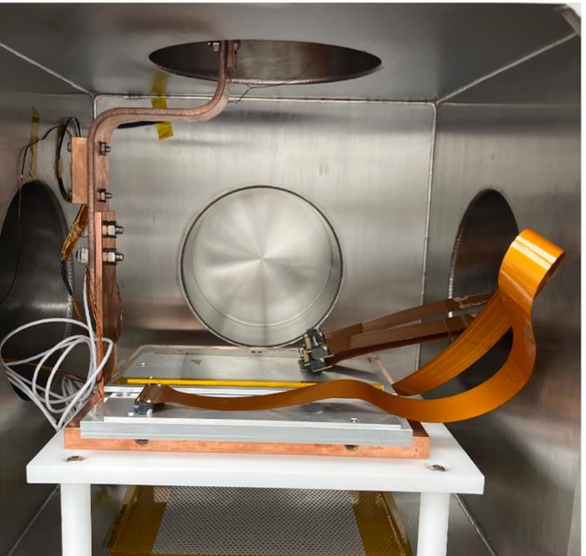
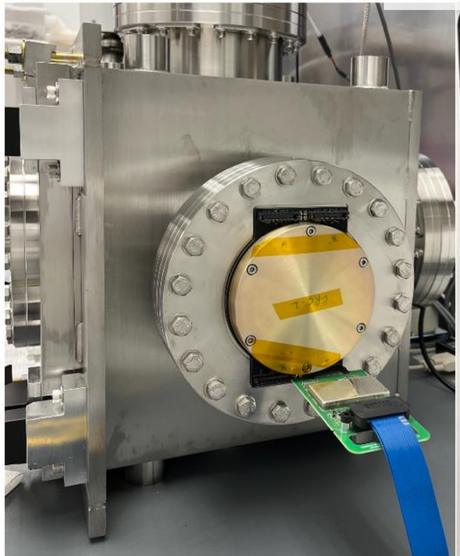
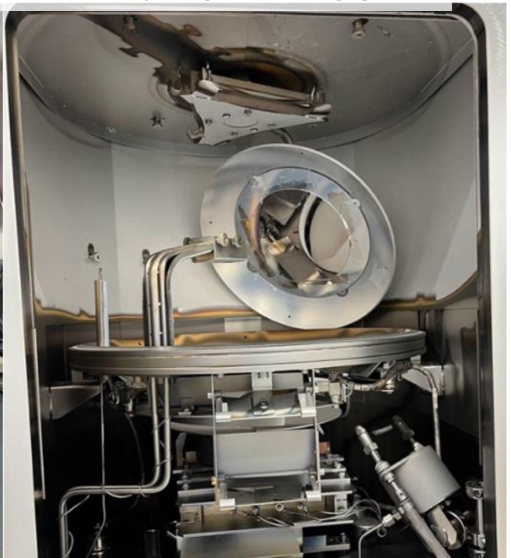
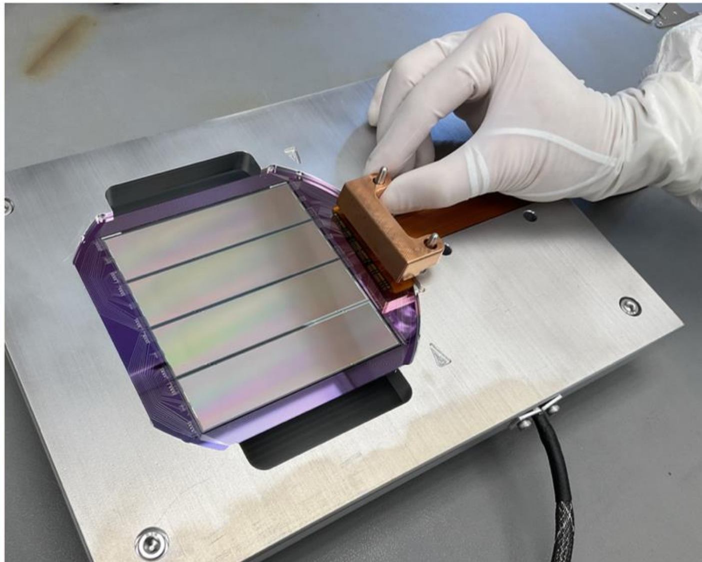
Note that the DAMIC-M results are form the prototype of the experiment (LBC)

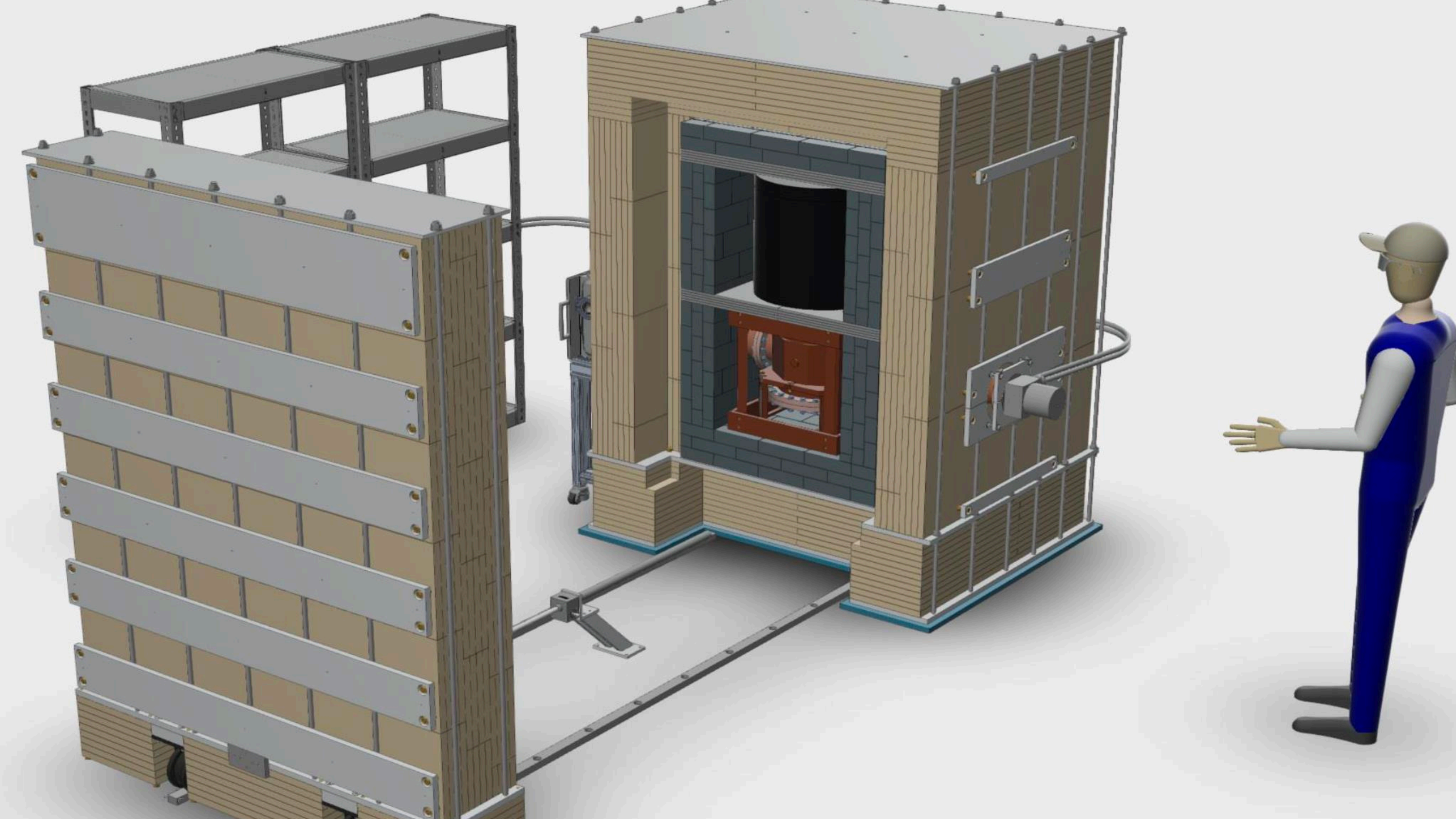
Expect new results in 1-2 years





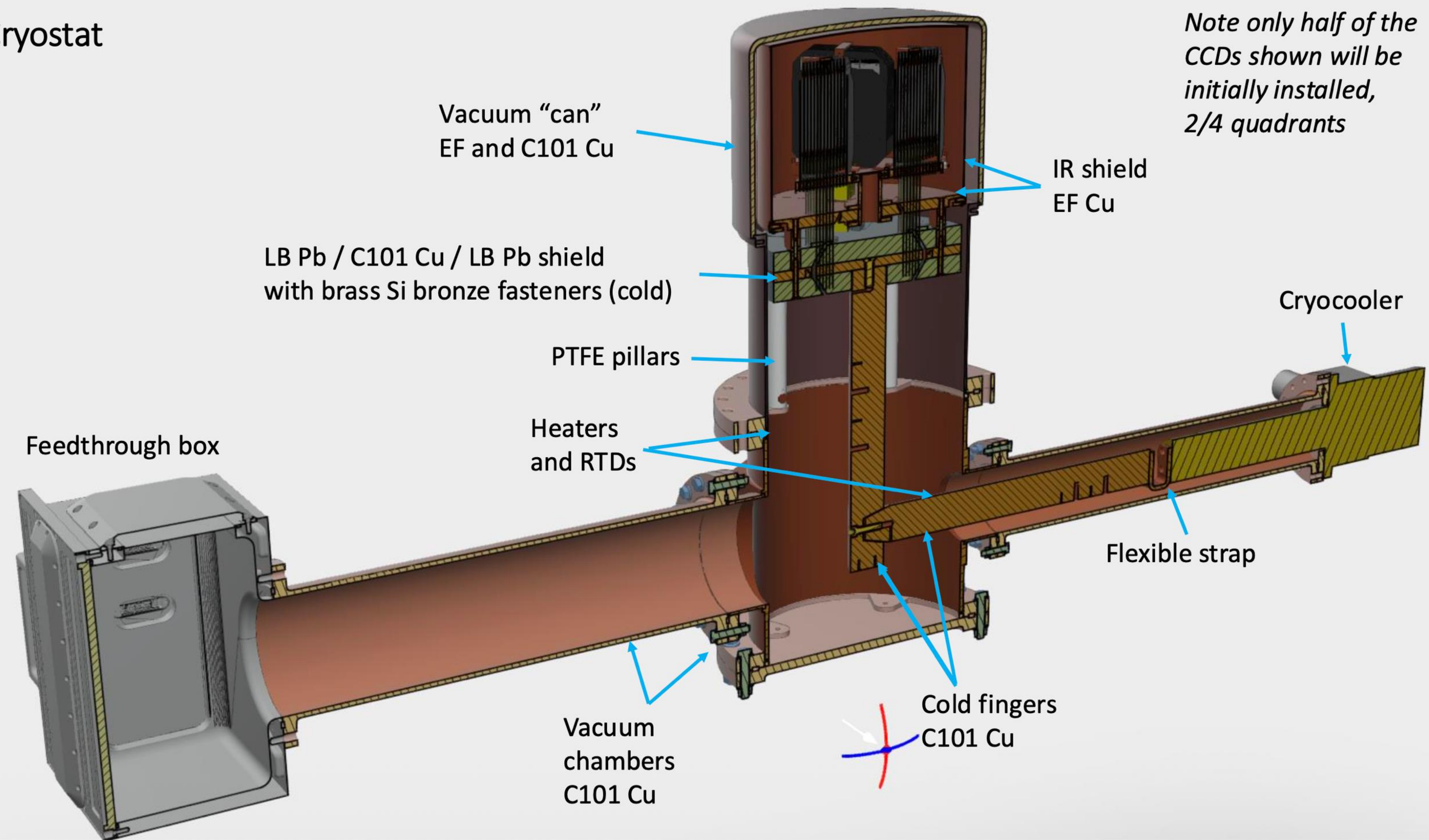
26 modules ready (350g)



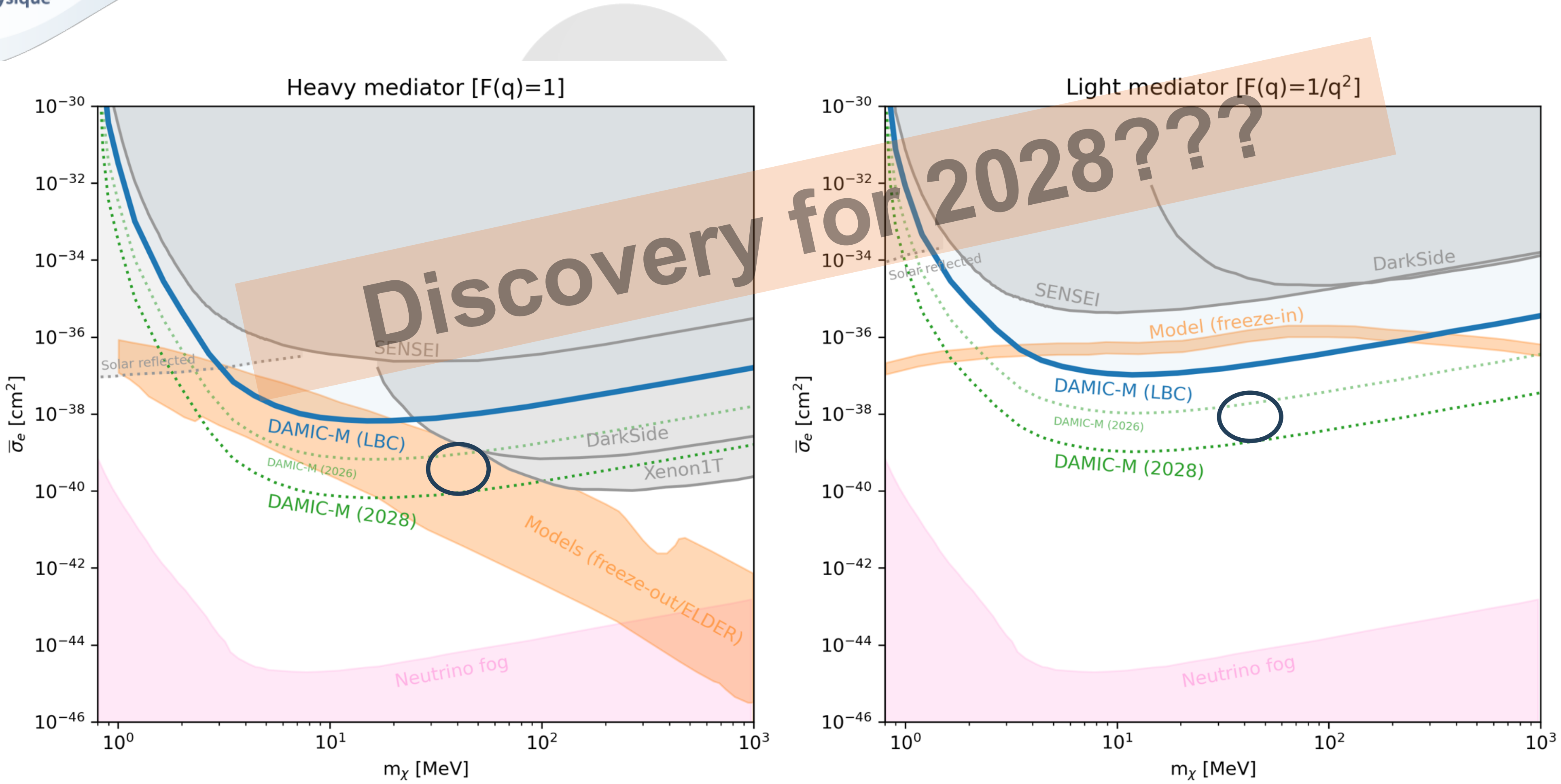
Cryostat

Note only half of the CCDs shown will be initially installed, 2/4 quadrants



From plans to reality…

Turning on in September 2026 and…



Conclusions and perspectives

- 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 explore 1-2 orders of magnitude below the current LBC limits

Skipper CCDs are:

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

Thank you!

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