Silicon devices with single charge resolution

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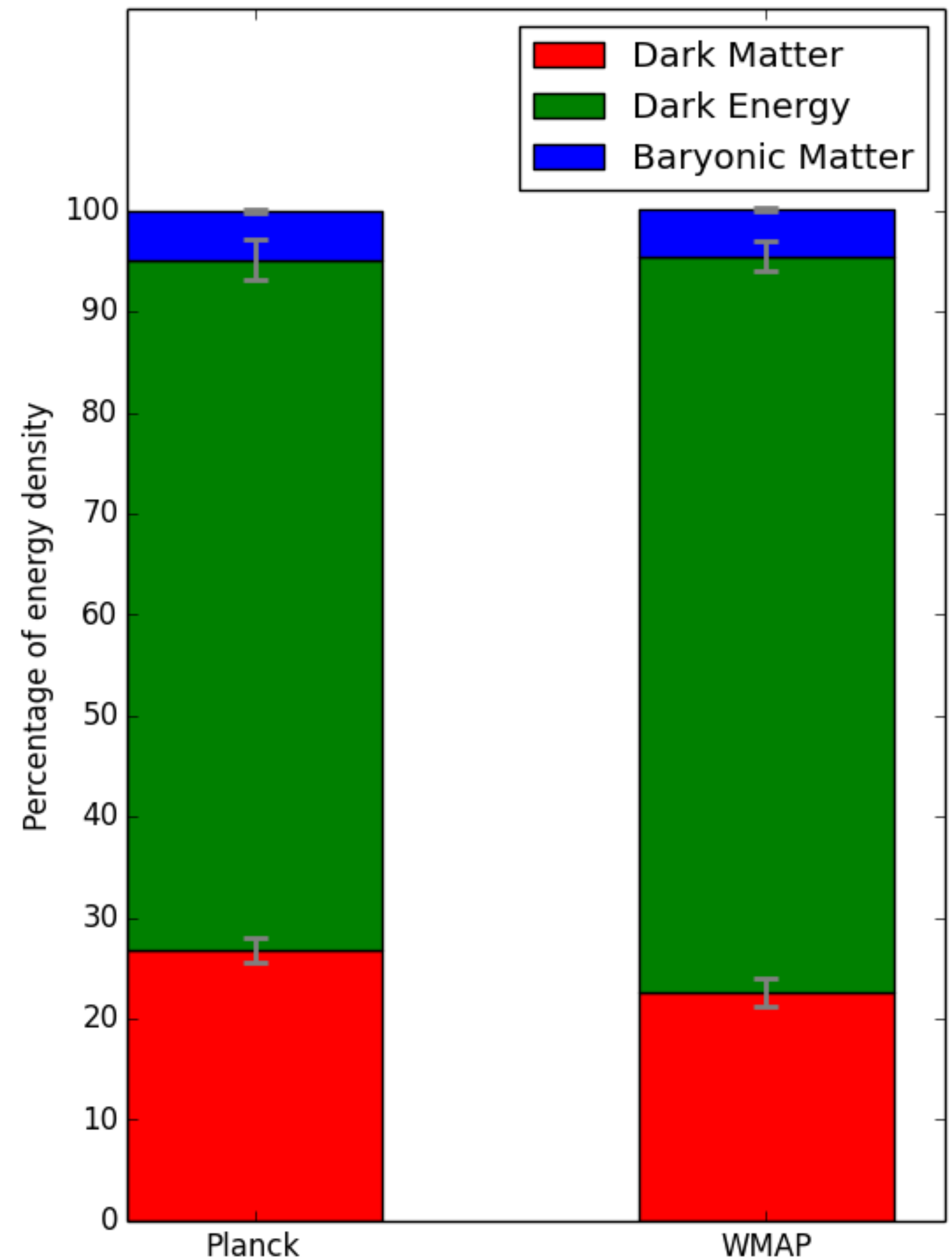
Survey of the universe

"Every textbook I have read in high school says that the universe is made of protons, electrons and a bunch of subatomic particles.

Well – they were wrong. The universe is made up of something we have no clue about."

-Michio Kaku



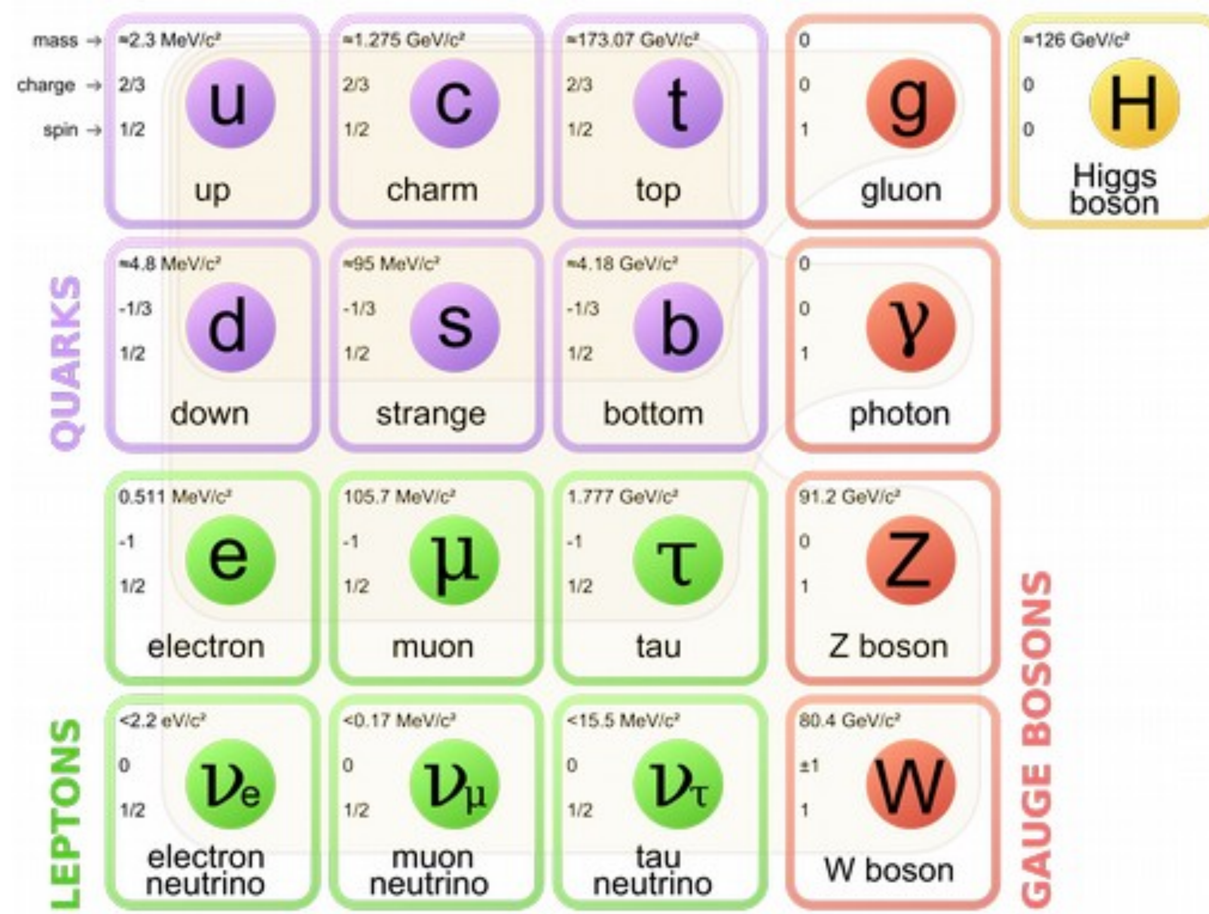
Possibilities

The most favored candidate for **dark matter** is a **particle** that

Can form **structures** ... and **halos**
(M. Roos, arXiv:1001.0316.)

Does not interact with light ... hence "**dark**"
(K. Sigurdson et al astro-ph/0406355)

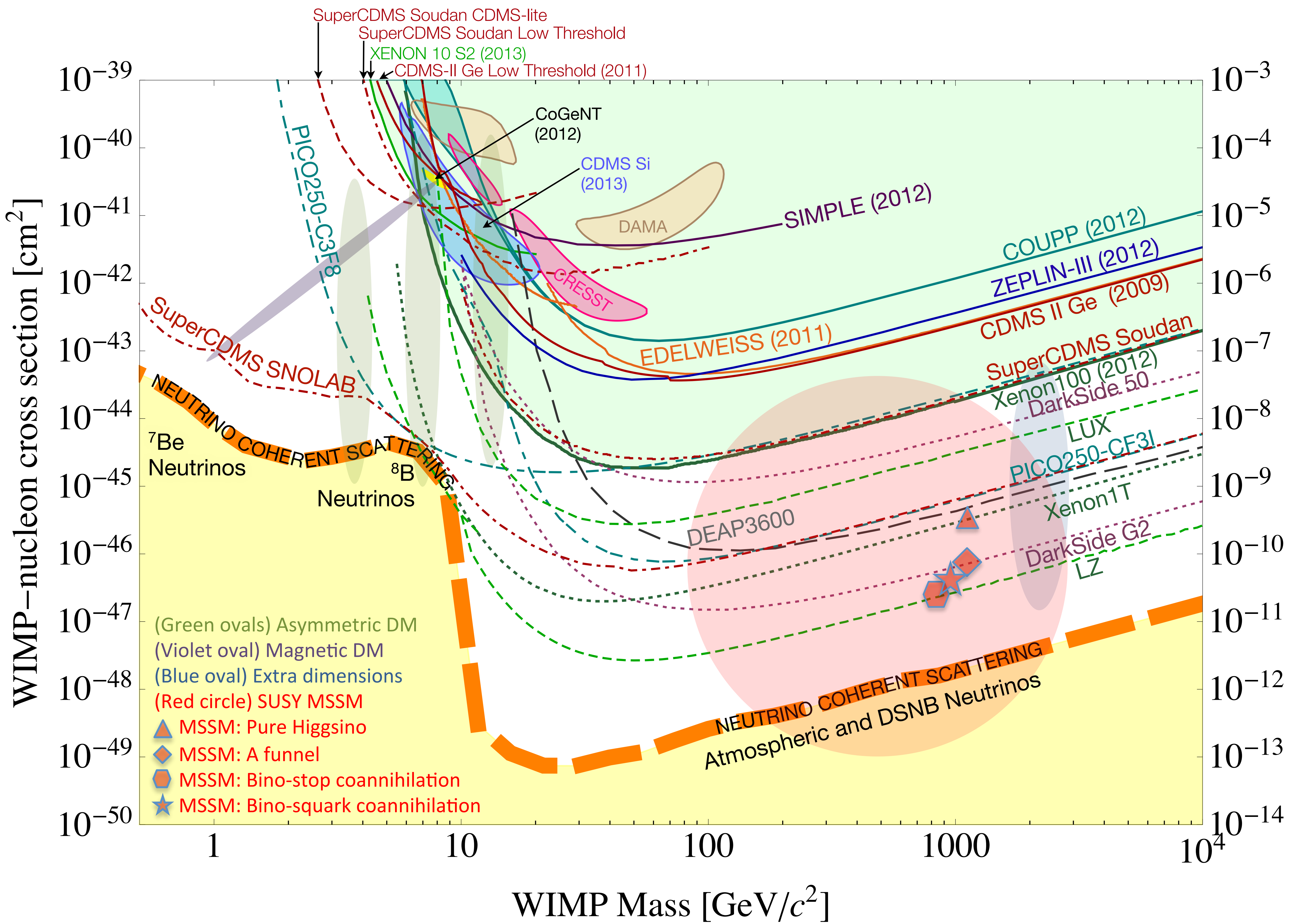
Is **massive** and "**cold**" or slow moving
(J. R. Primack, arXiv:0909.2247)



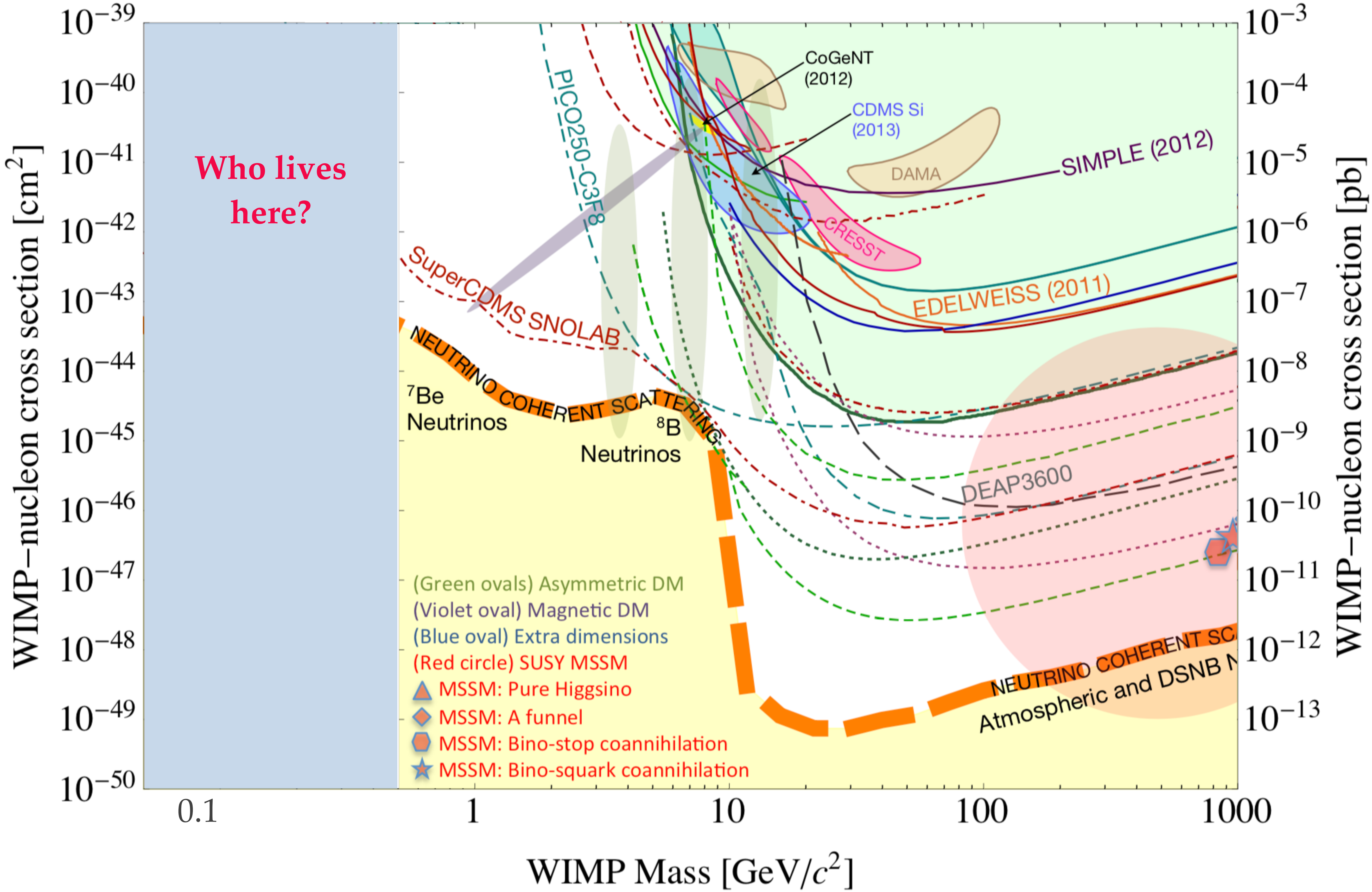
Non-Baryonic in nature
(K. Freese, B. Fields, and D. Graff, astro-ph/9904401.)

Is **neutral**
(S. D. McDermott et al arXiv:1011.2907)

Is **stable**
(S. De Lope Amigo et al arXiv:0812.4016)



SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
PICO250-C3F8
SuperCDMS SNOLAB
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
(Green ovals) Asymmetric DM
(Violet oval) Magnetic DM
(Blue oval) Extra dimensions
(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]



Who lives here?
WIMP−nucleon cross section [cm^2]
WIMP−nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
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10^{-3}
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10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0.1
1
10
100
1000
CoGeNT (2012)
CDMS Si (2013)
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NEUTRINO COHERENT SCATTERING
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(Green ovals) Asymmetric DM
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(Red circle) SUSY MSSM
MSSM: Pure Higgsino
MSSM: A funnel
MSSM: Bino-stop coannihilation
MSSM: Bino-squark coannihilation

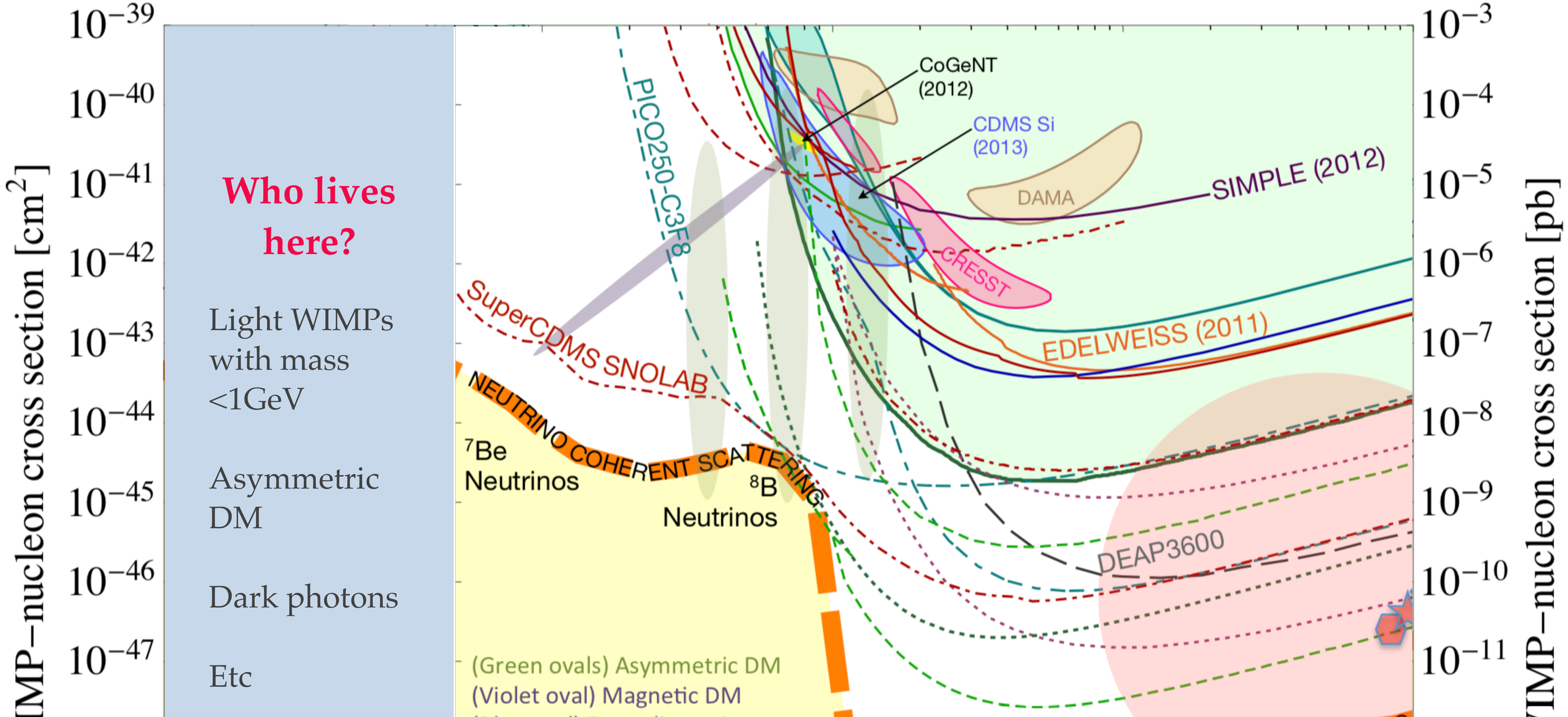
Who lives here?

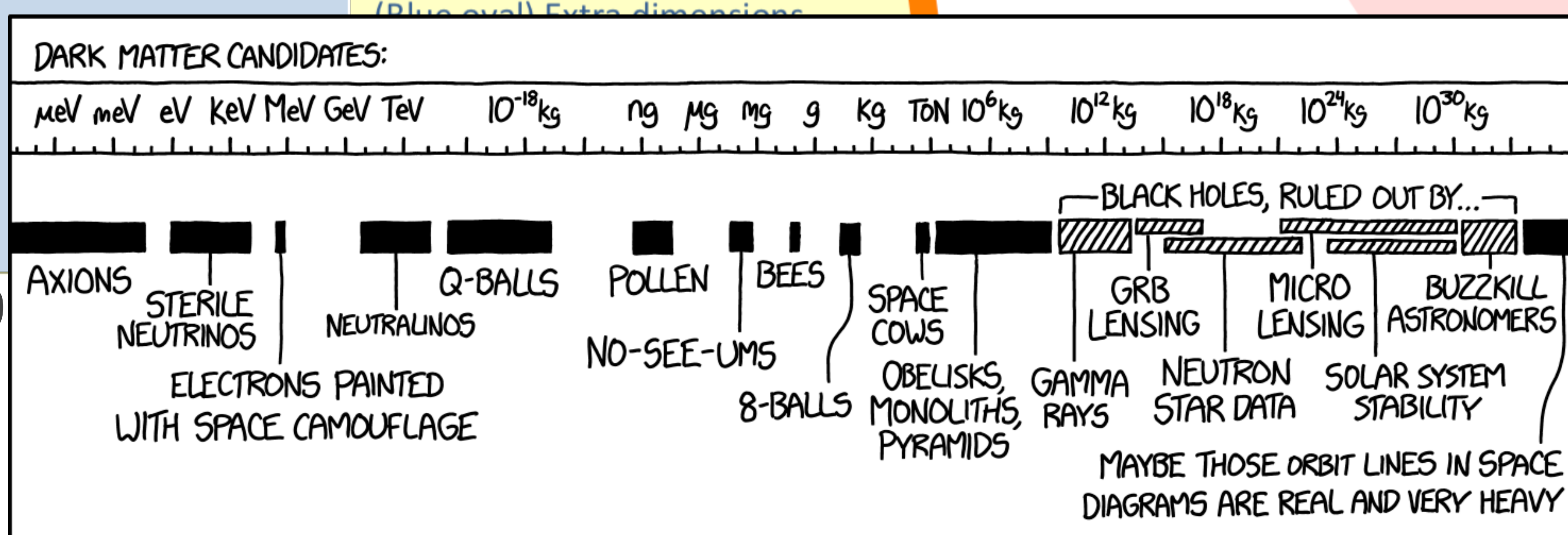
Light WIMPs with mass <1GeV

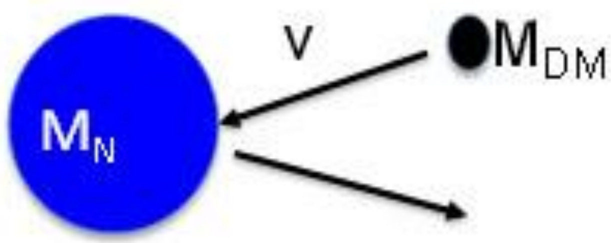
Asymmetric DM

Dark photons

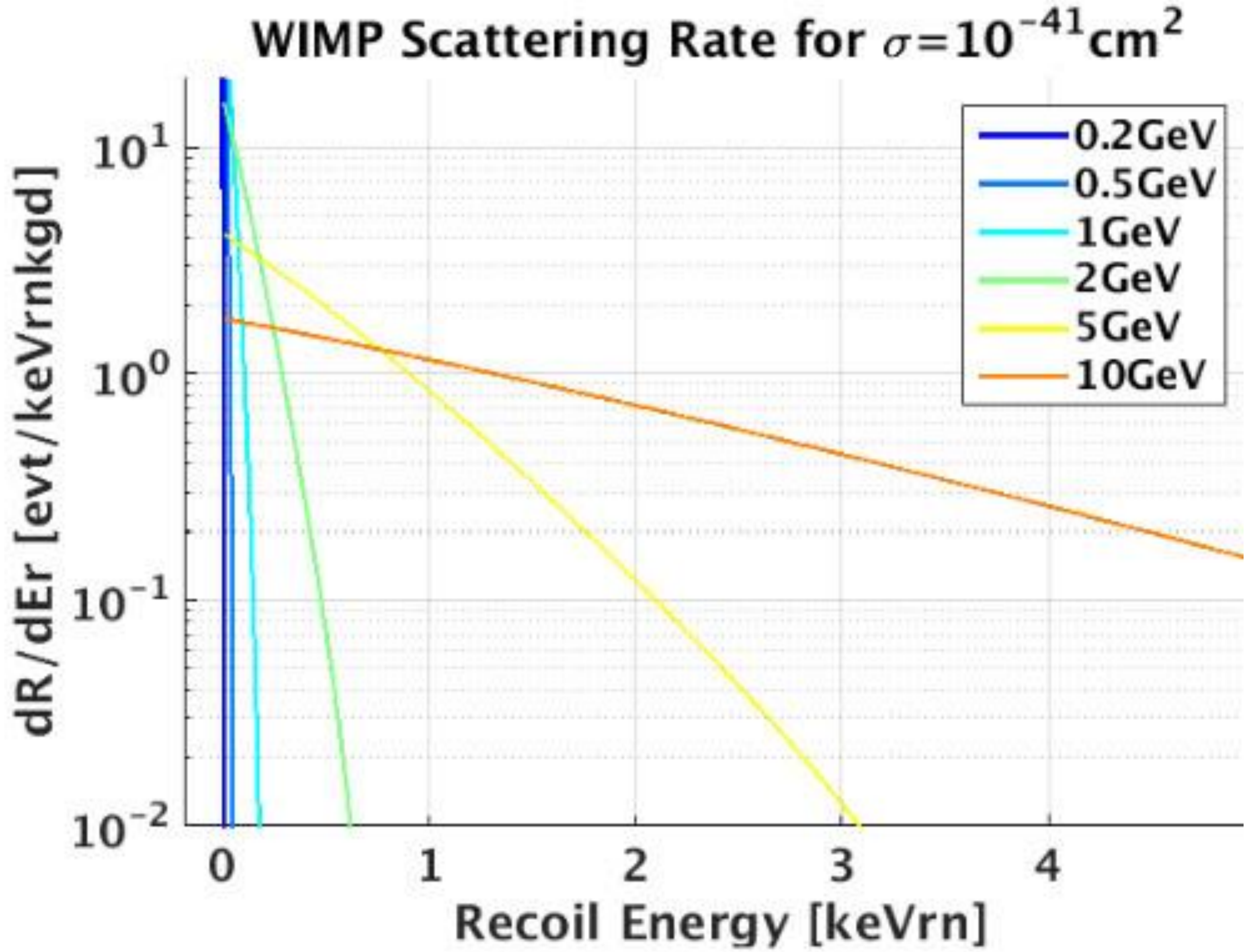
Etc







$$\Delta E = \frac{\Delta P^2}{2M_N} \sim \frac{2M_{DM}^2 v^2}{M_N}$$



Direct detection at low masses is a challenge

Conventional detectors have small or no sensitivity to low mass WIMPs.

Low mass and Si based detectors

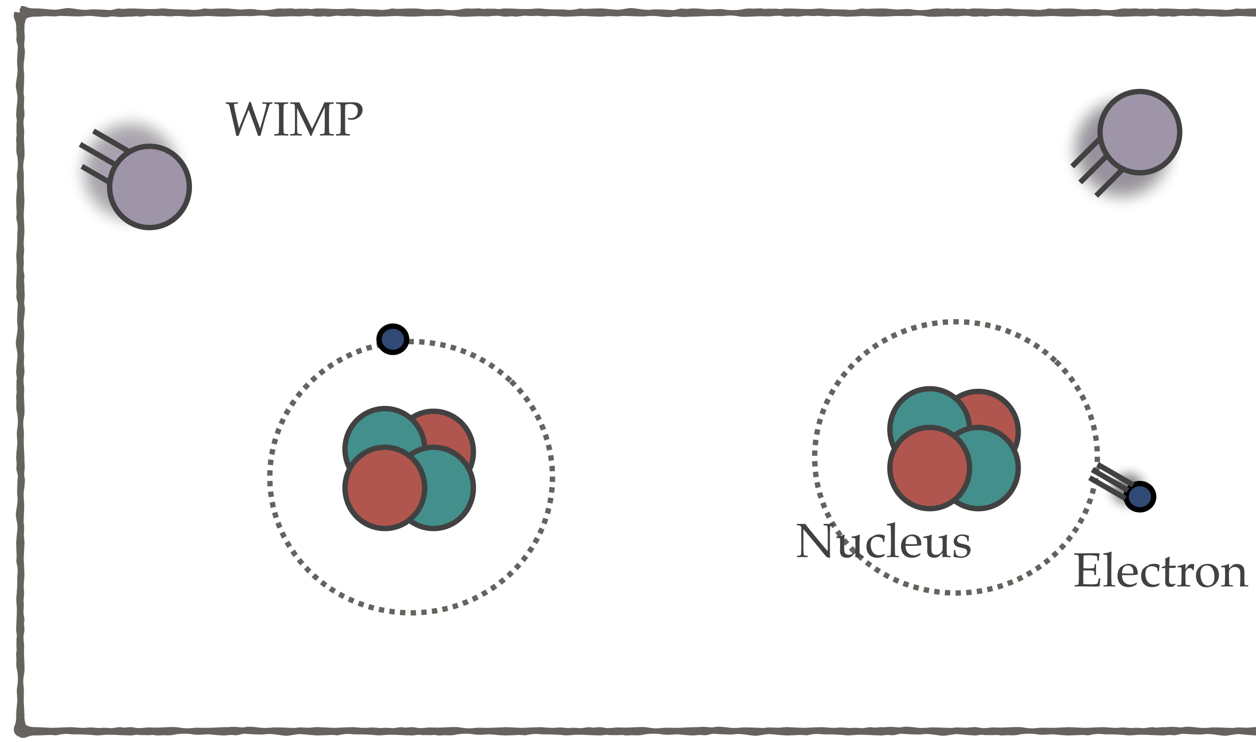
To detect low mass WIMPs, one needs either:

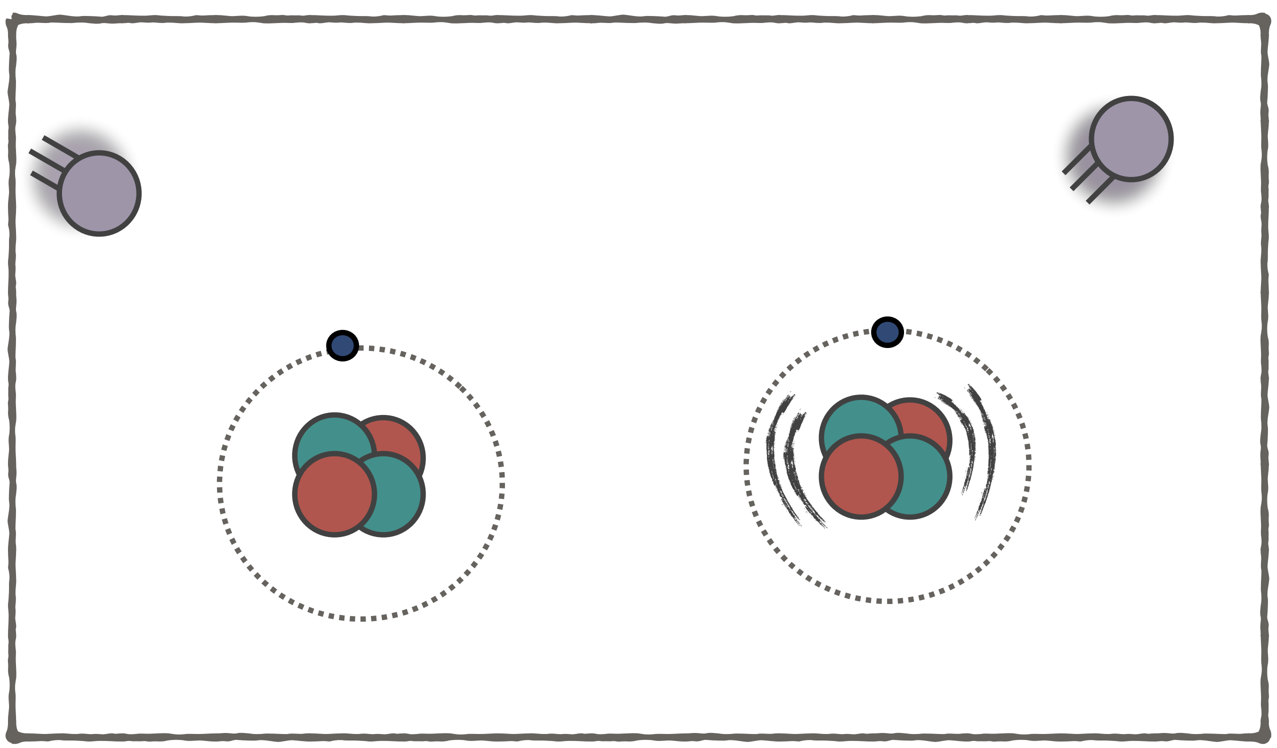
1. Low threshold or
2. Low mass targets

I will review:
Skipper CCDs (DAMIC-M)
DEPFETs (DANAE)
QETs (CDMSLite)

CCDs: two modes of interaction

WIMP-valence electron collision. The electron then recoils and deposits energy in the detector.





WIMP-nucleus elastic collision. The target nucleus recoils. We measure the energy of the recoiling nucleus. In DAMIC, the target is Si atoms.

Challenges of detection: Backgrounds

Radiogenic backgrounds are a challenge to any and all dark matter search experiments.

- **Detector materials – trace radioisotopes.**
- **Primordial U and Th** at 10^{-6} – 10^{-9} atoms/atom in any material.
- **Cosmic ray muons** and **spallation neutrons**.
- **Unstable isotopes produced** in the detector **by cosmic rays**.

Radiogenic background reduction to a fraction of a dru in DAMIC.

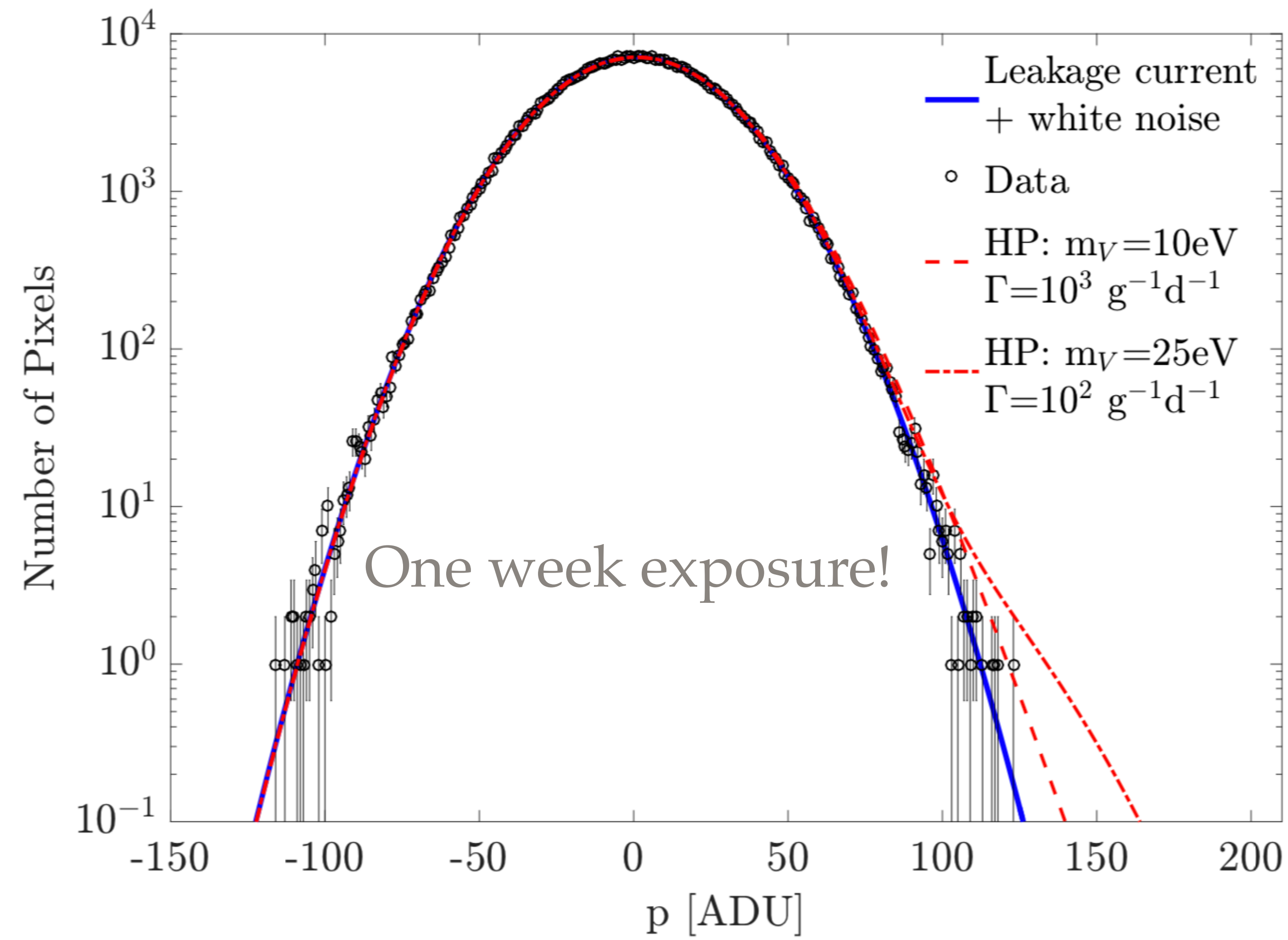
Challenges of detection: Leakage current

Silicon devices by their very nature are susceptible to **leakage currents**. Their sources could be:

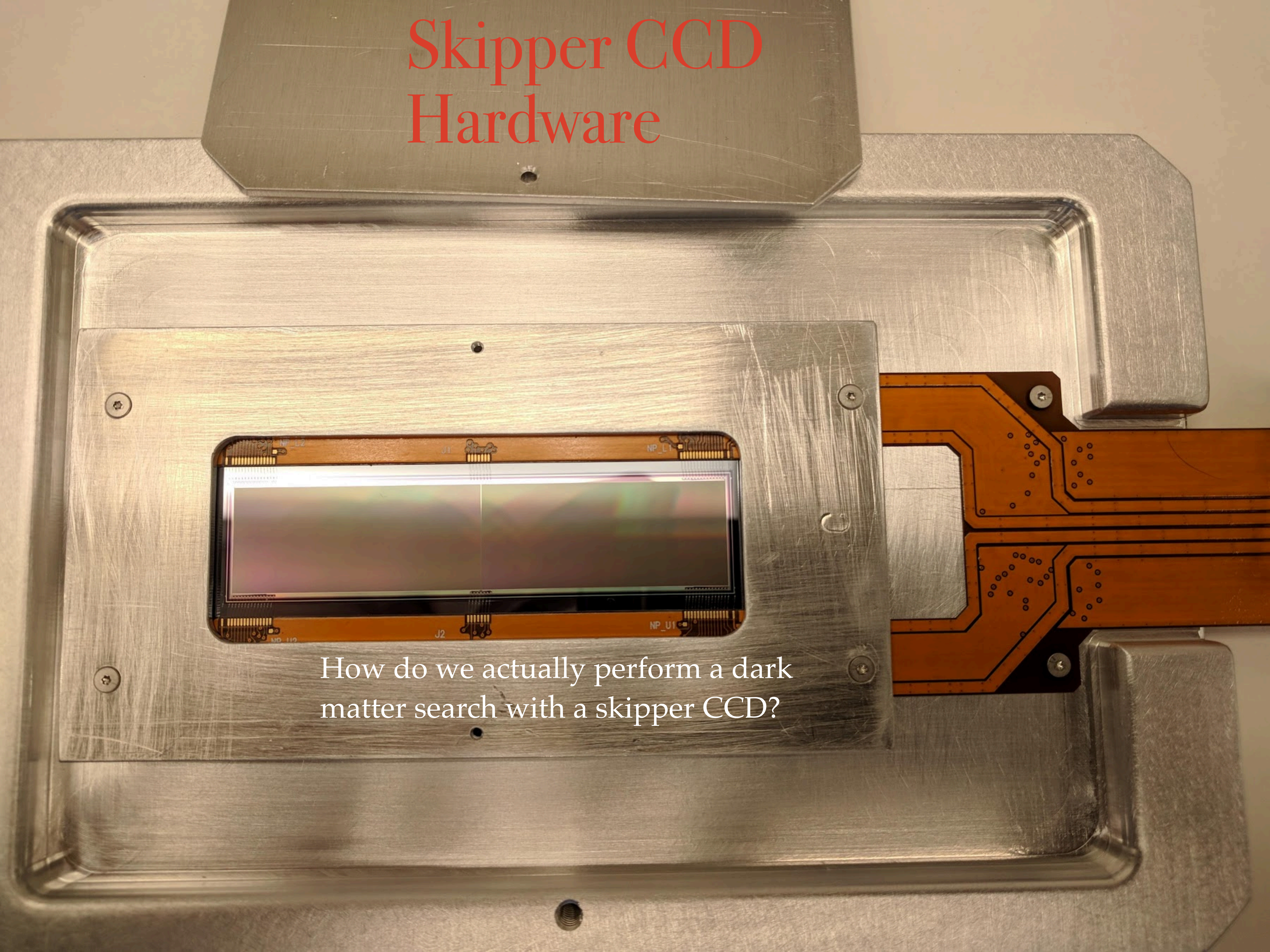
1. Dark current
2. Thermal noise
3. Light leakage / photon detection
4. Others

DAMIC CCDs have been shown to have a very small leakage current of **5x 10^{-22} A/cm^{2}.**

Readout noise is the dominant contribution.

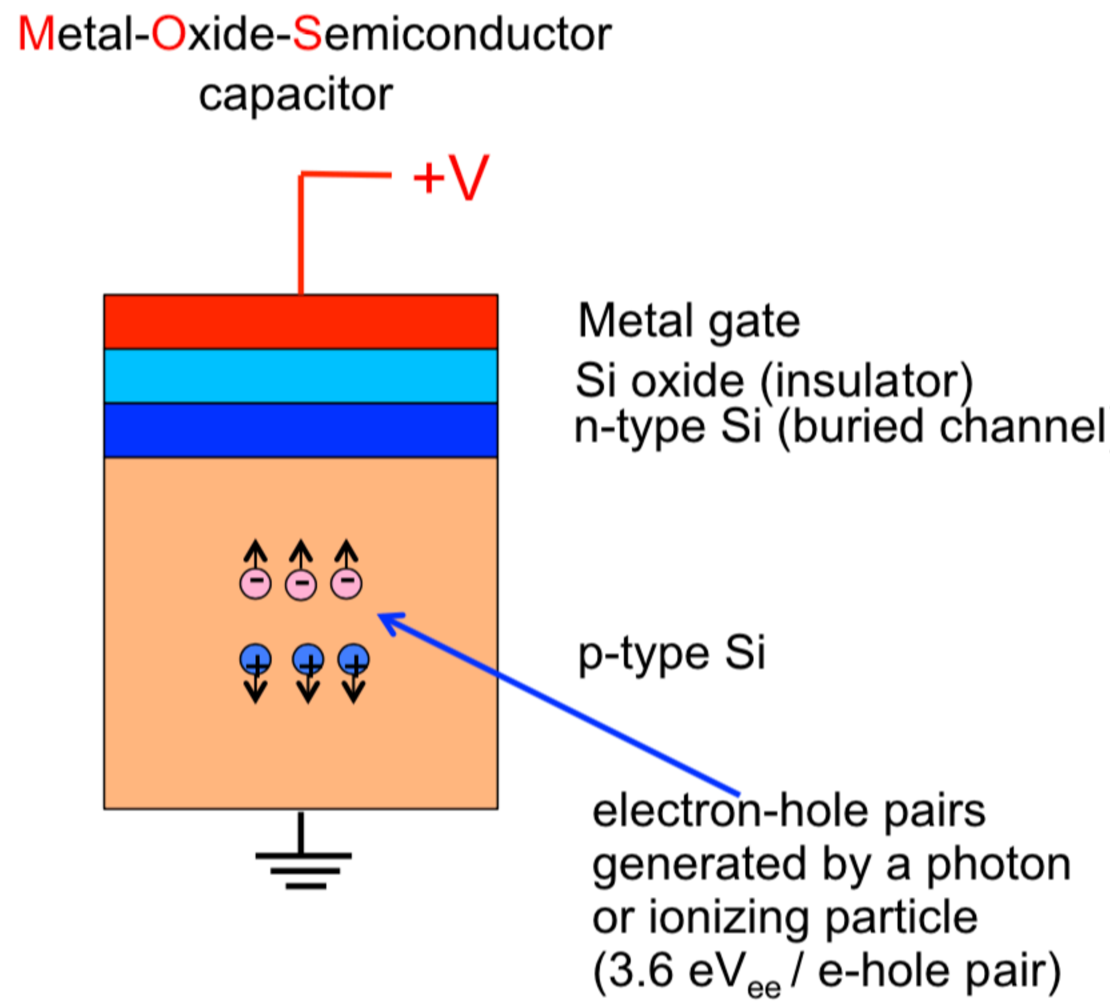


Skipper CCD Hardware

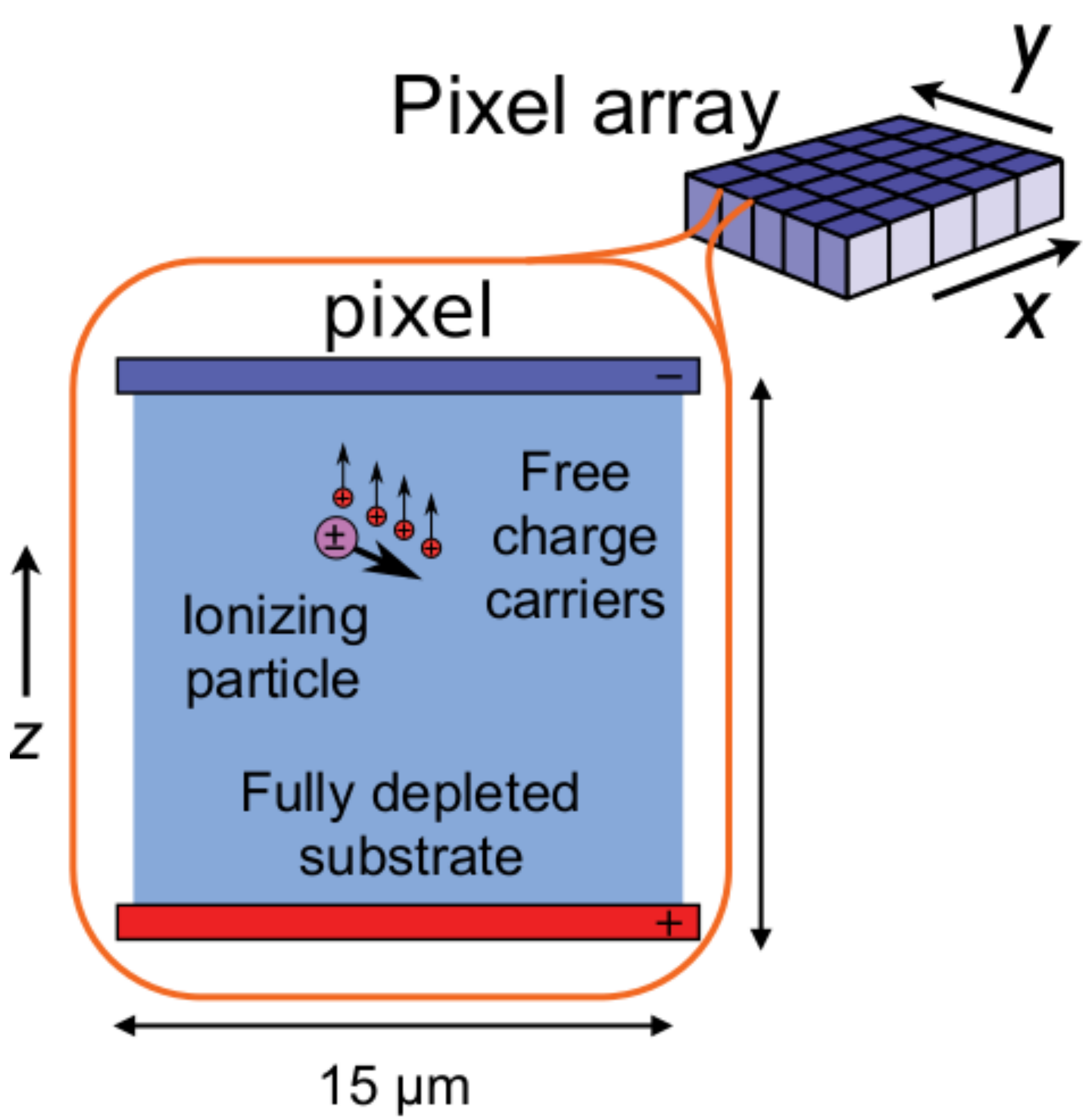


How do we actually perform a dark matter search with a skipper CCD?

CCD charge collection

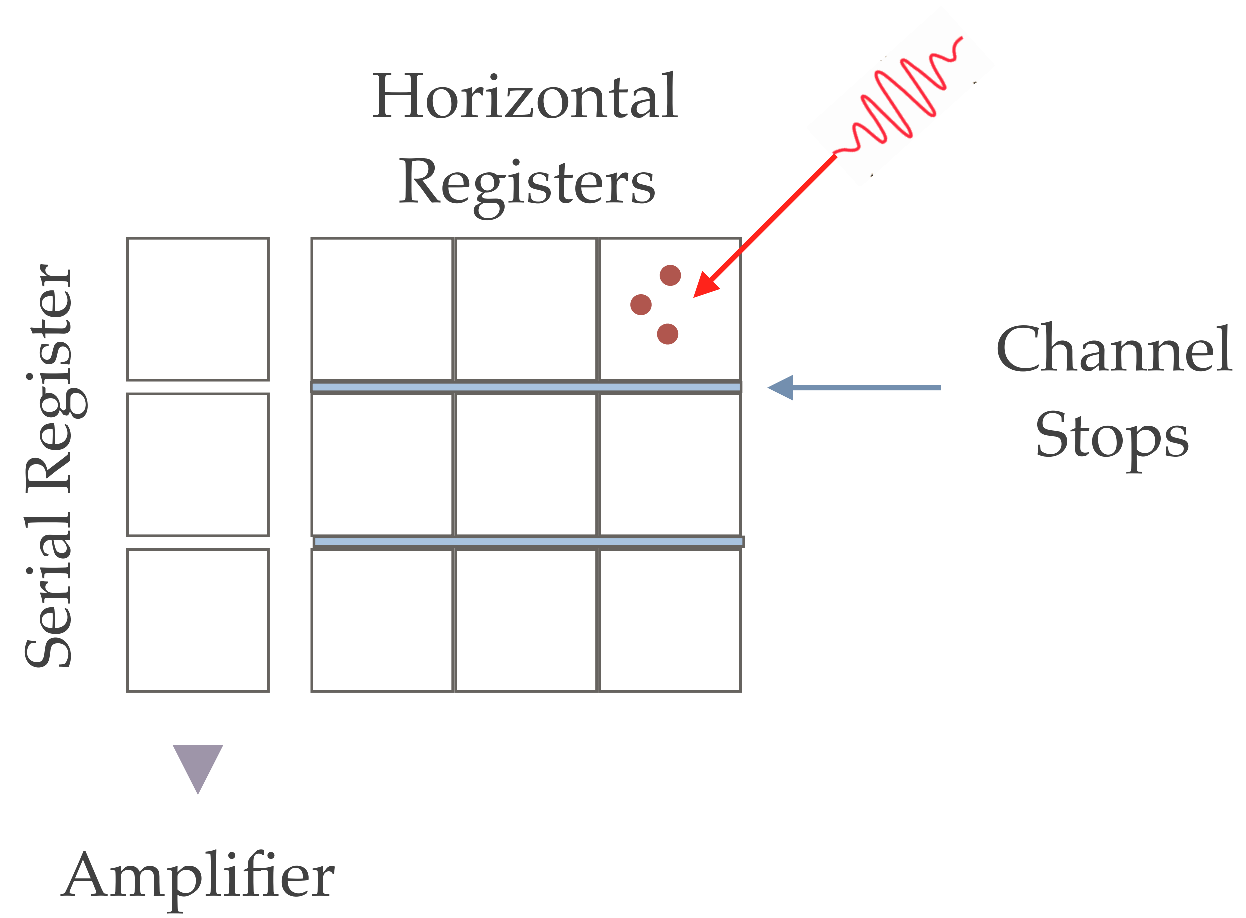


Credit: P. Privitera (UChicago/KICP)

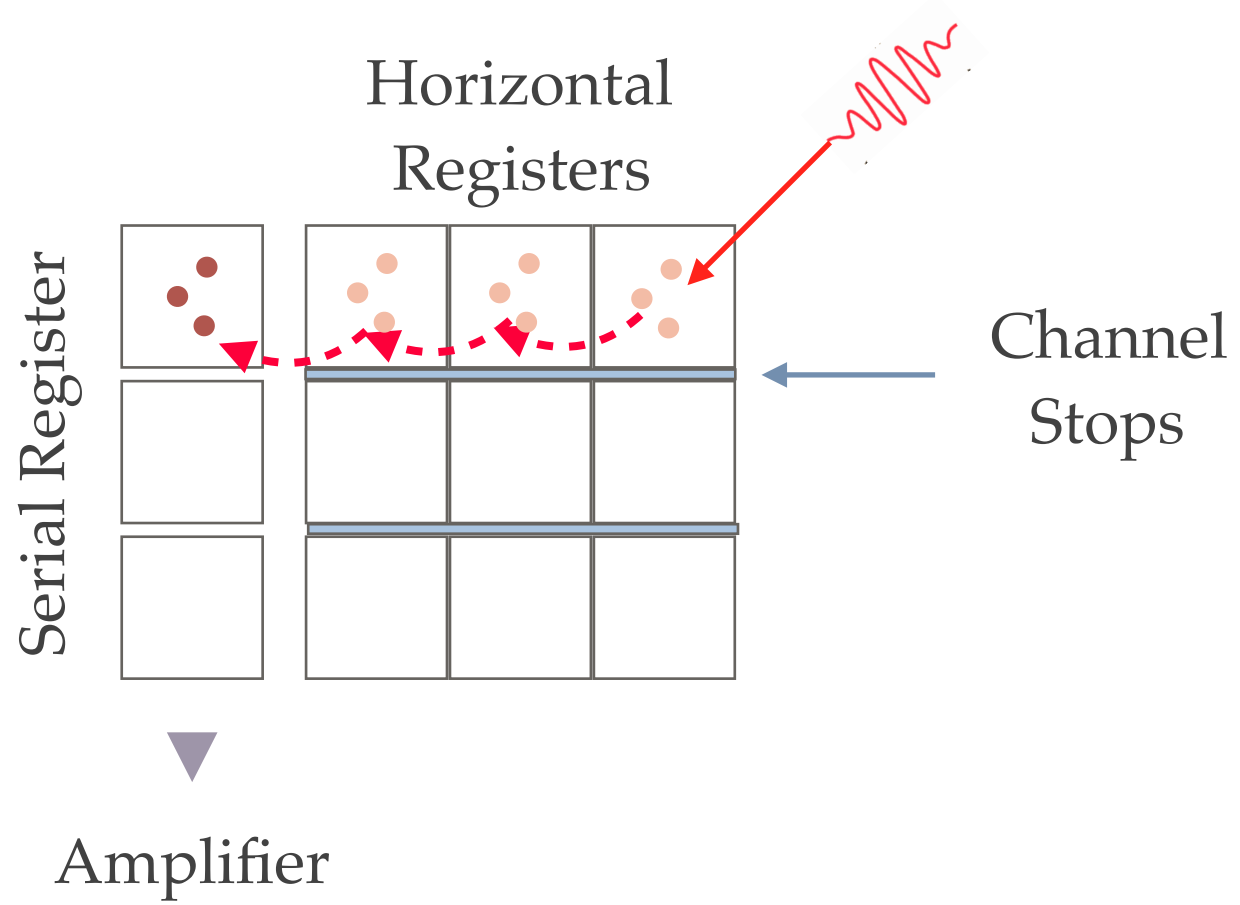


- A CCD is an **array of MOS capacitors**.
- During their exposure, **CCDs collect charges** from particle interactions. (3.6eV per electron-hole pair).
- The band gap is 1.2 eV.

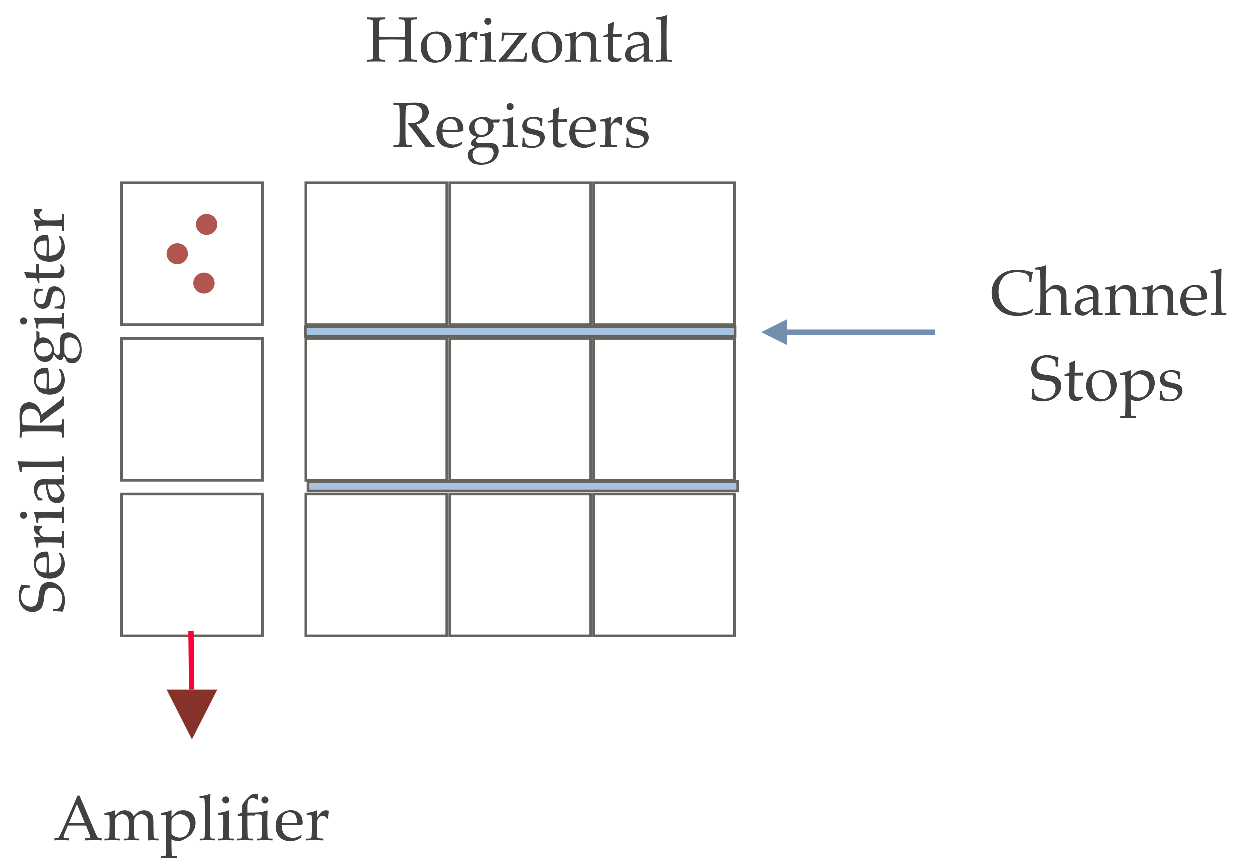
CCD: Moving charges



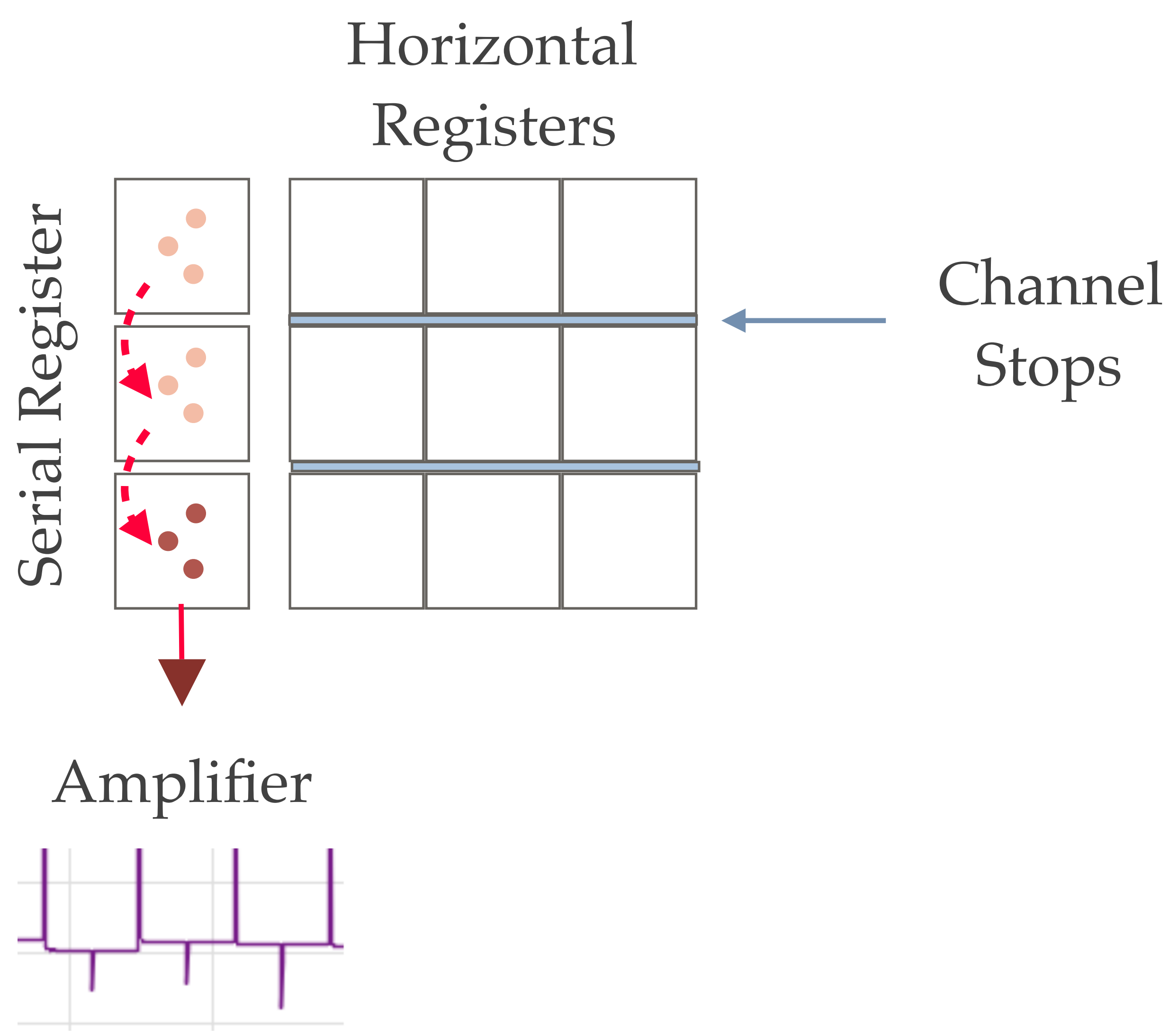
CCD: Moving charges



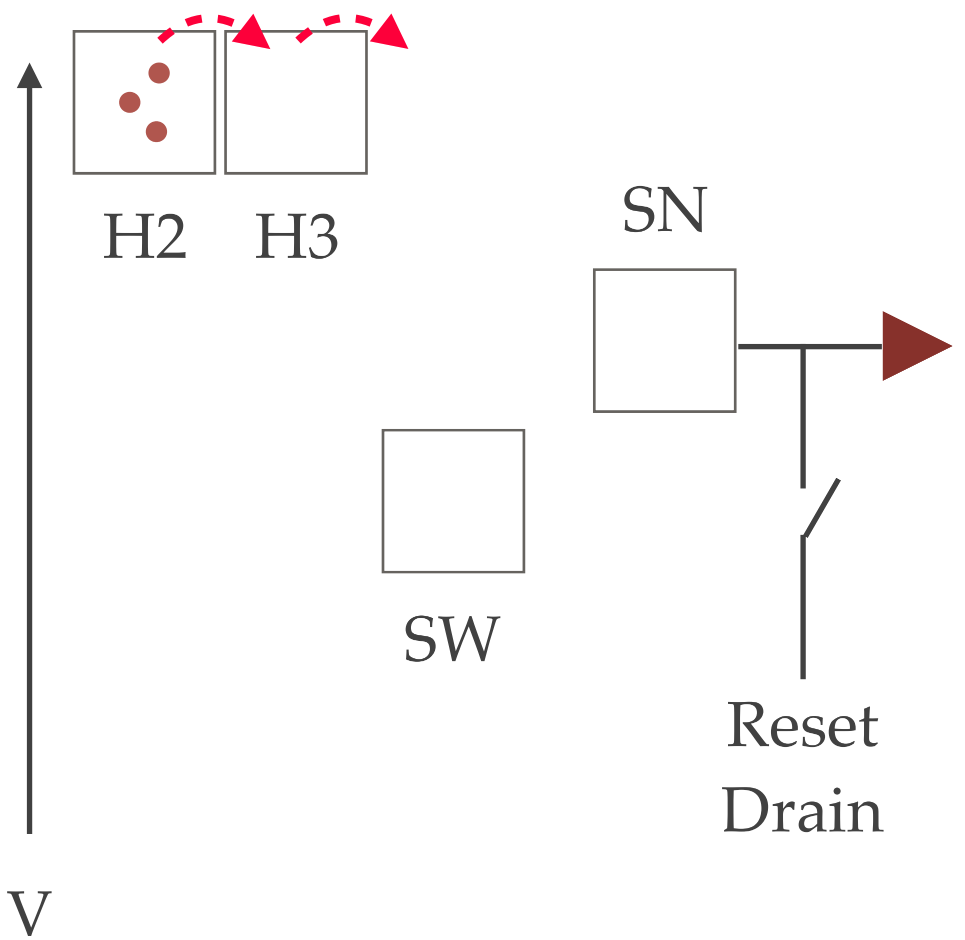
CCD: Moving charges

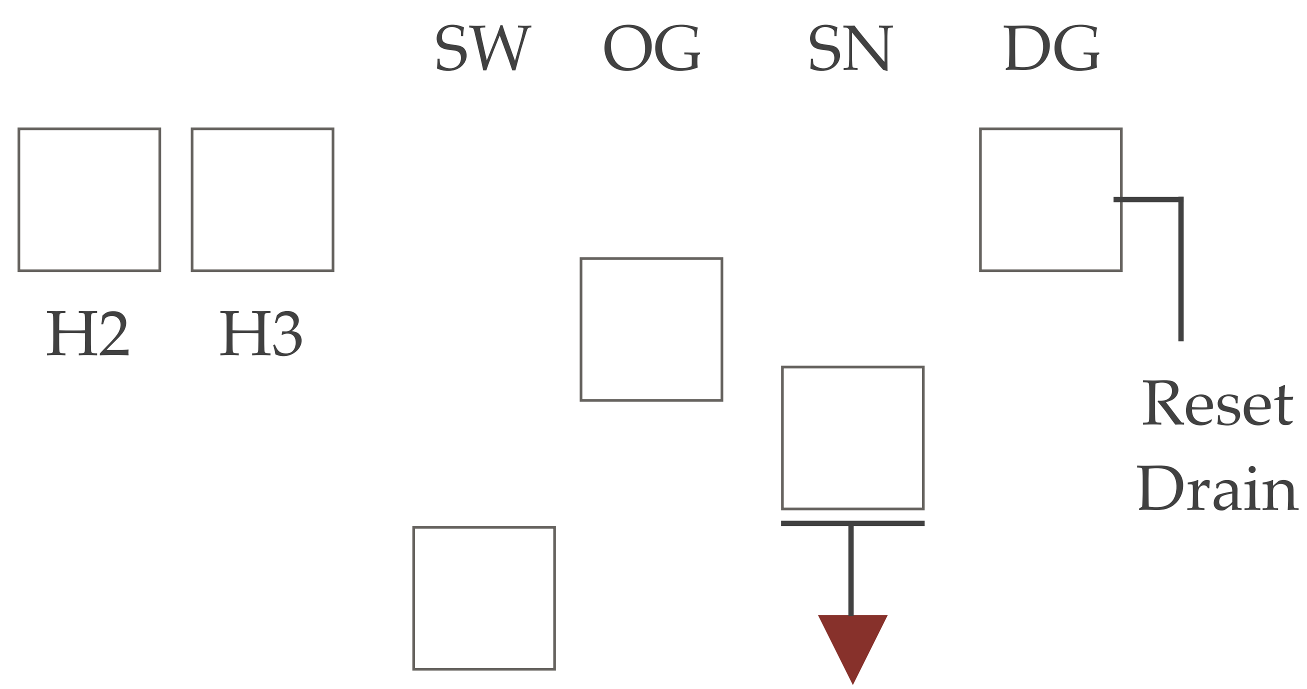


CCD: Moving charges



CCD: Measuring charges

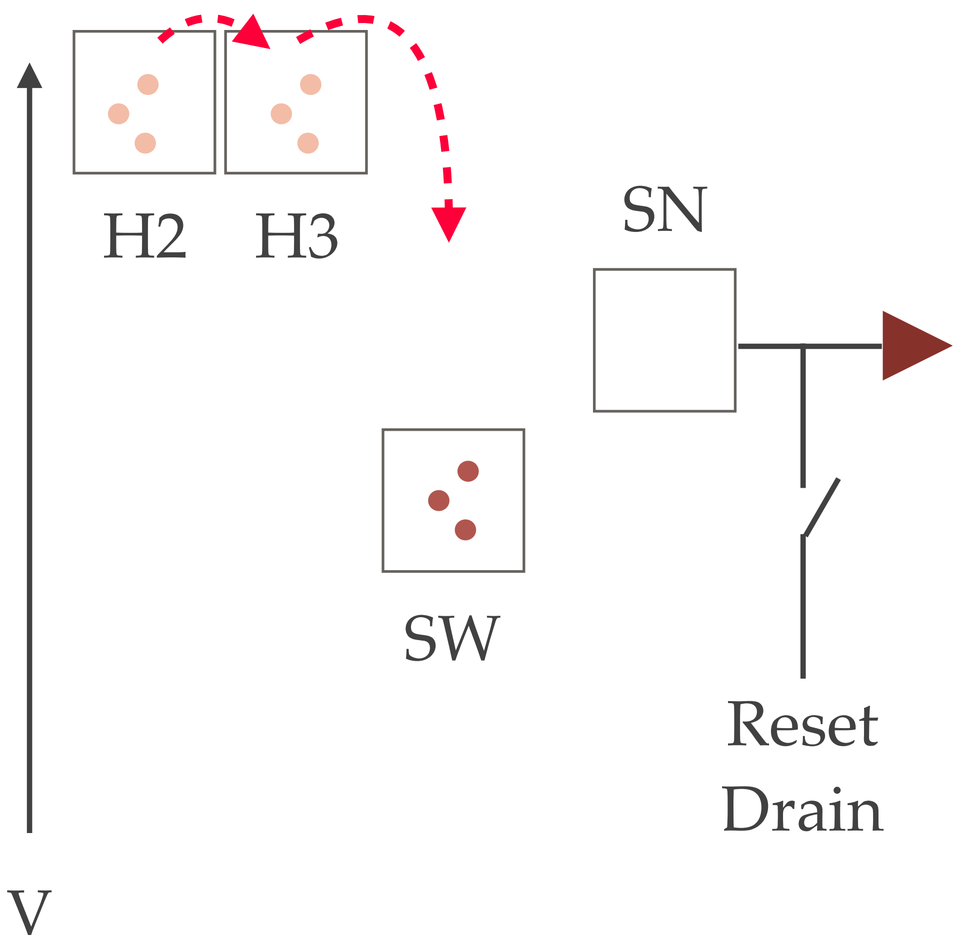


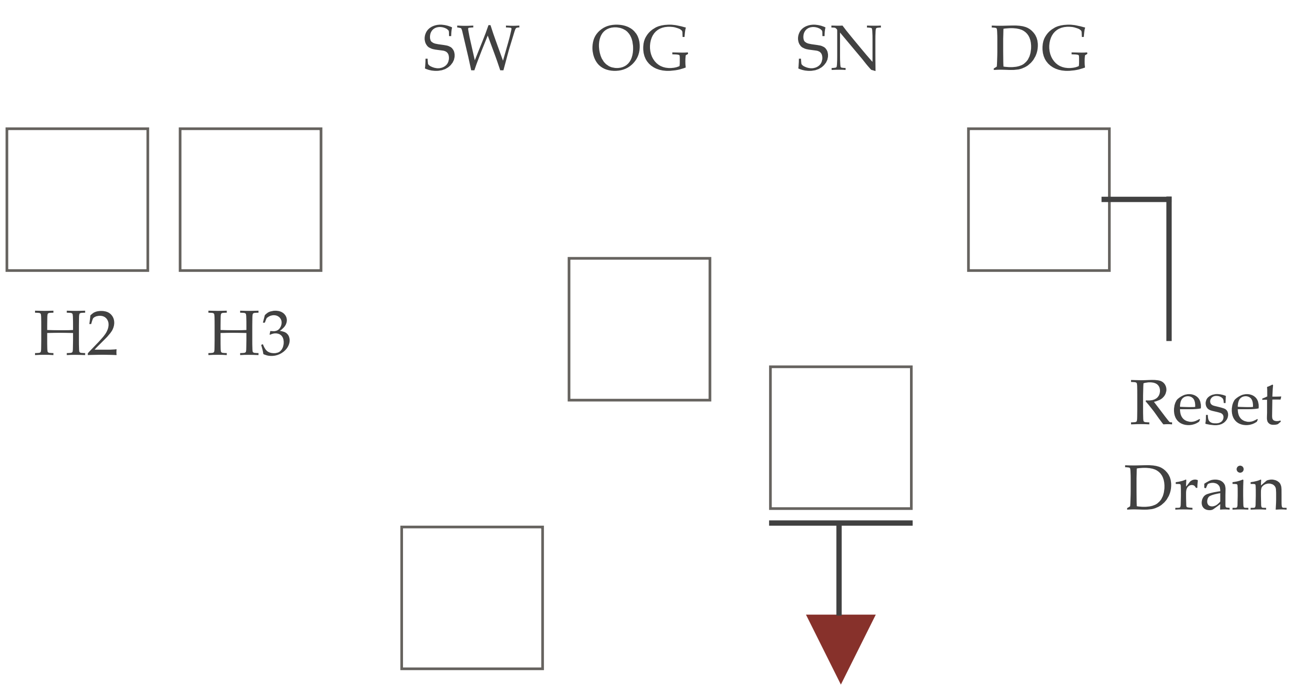


H: Horizontal register / serial register
SW: Summing well
SN: Sense node

OG: Output gate
DG: Drain gate

CCD: Measuring charges





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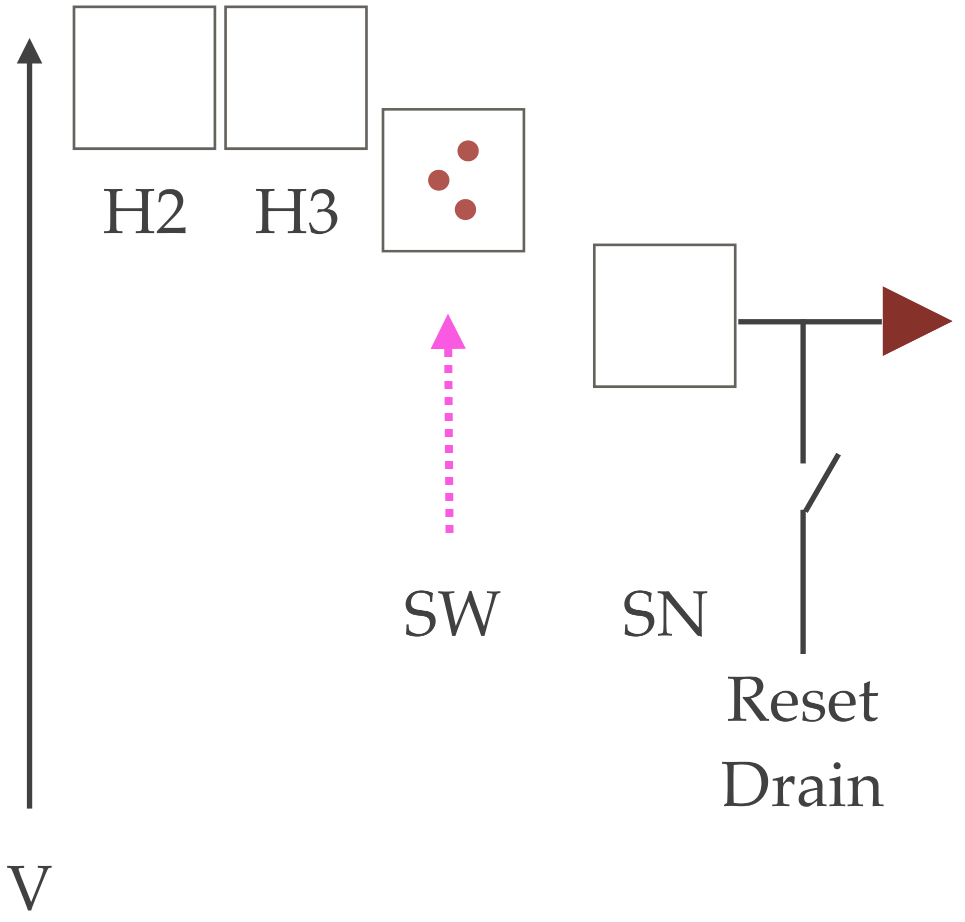
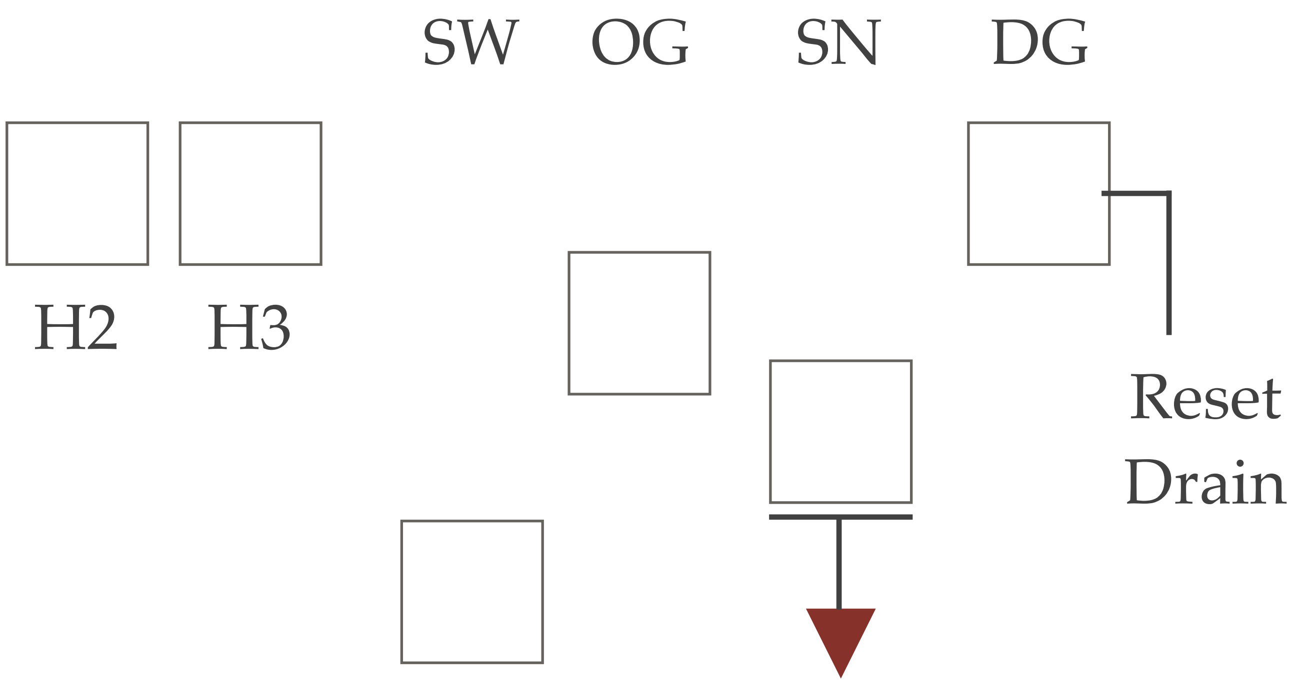
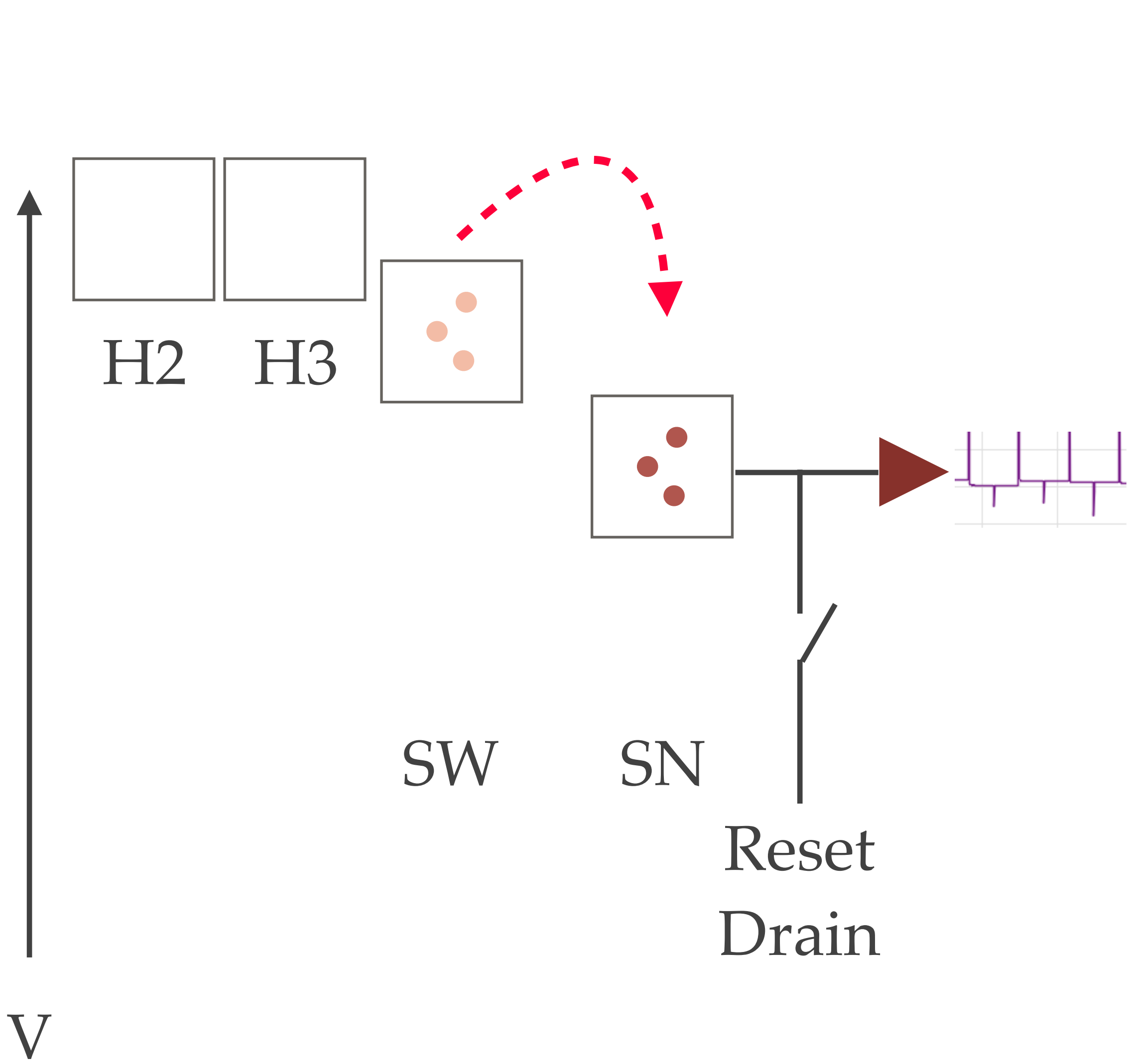
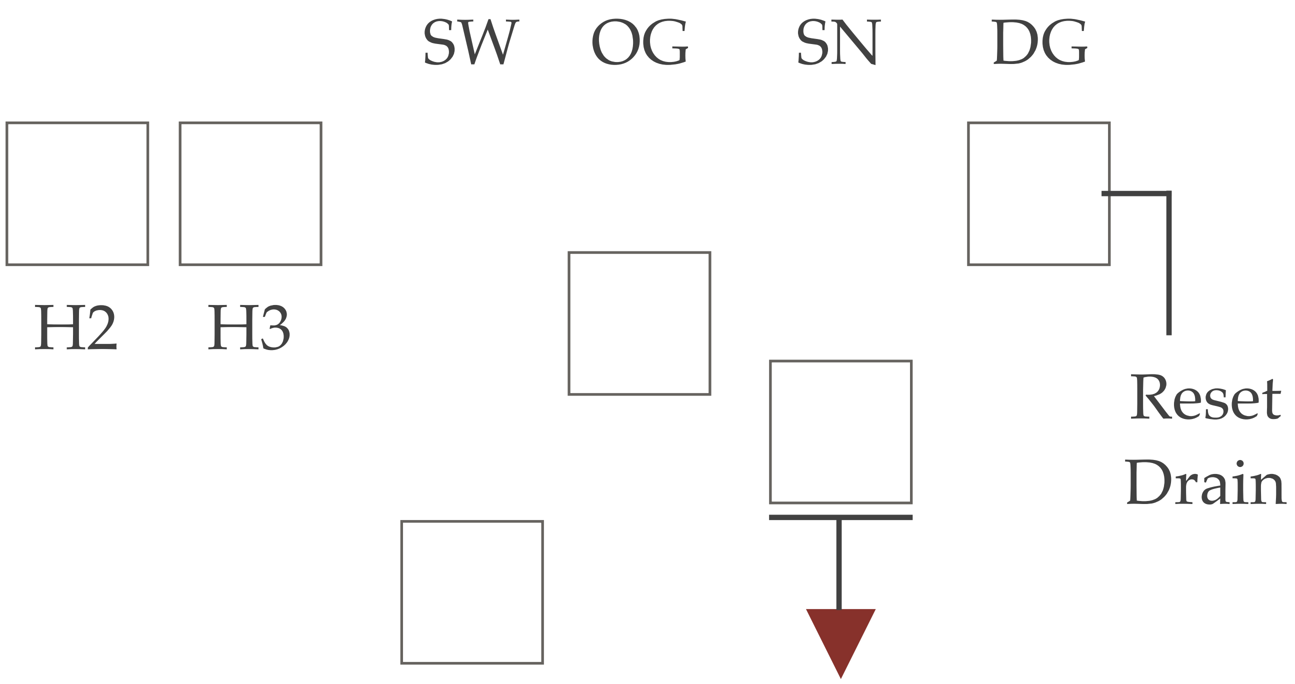


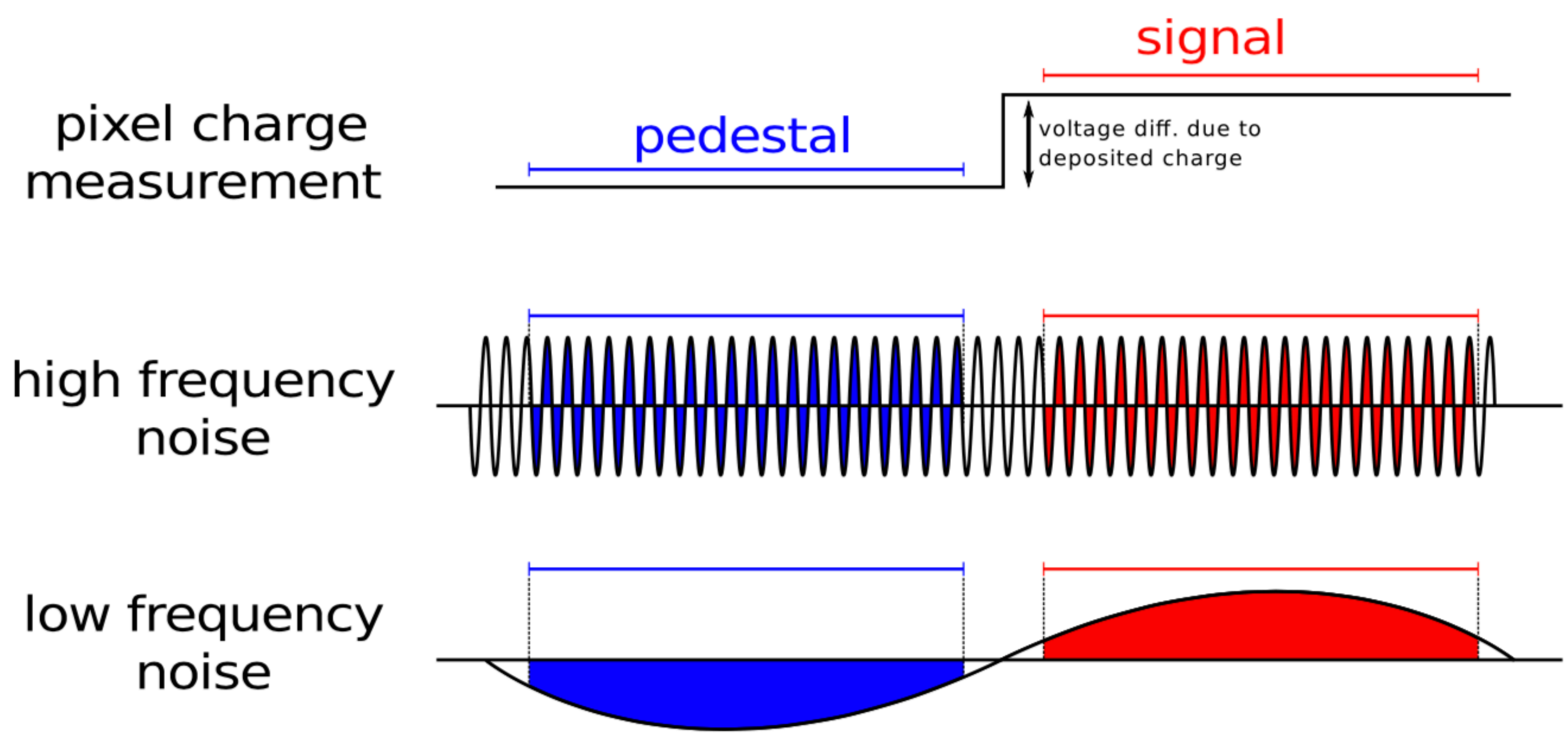


CCD: Measuring charges





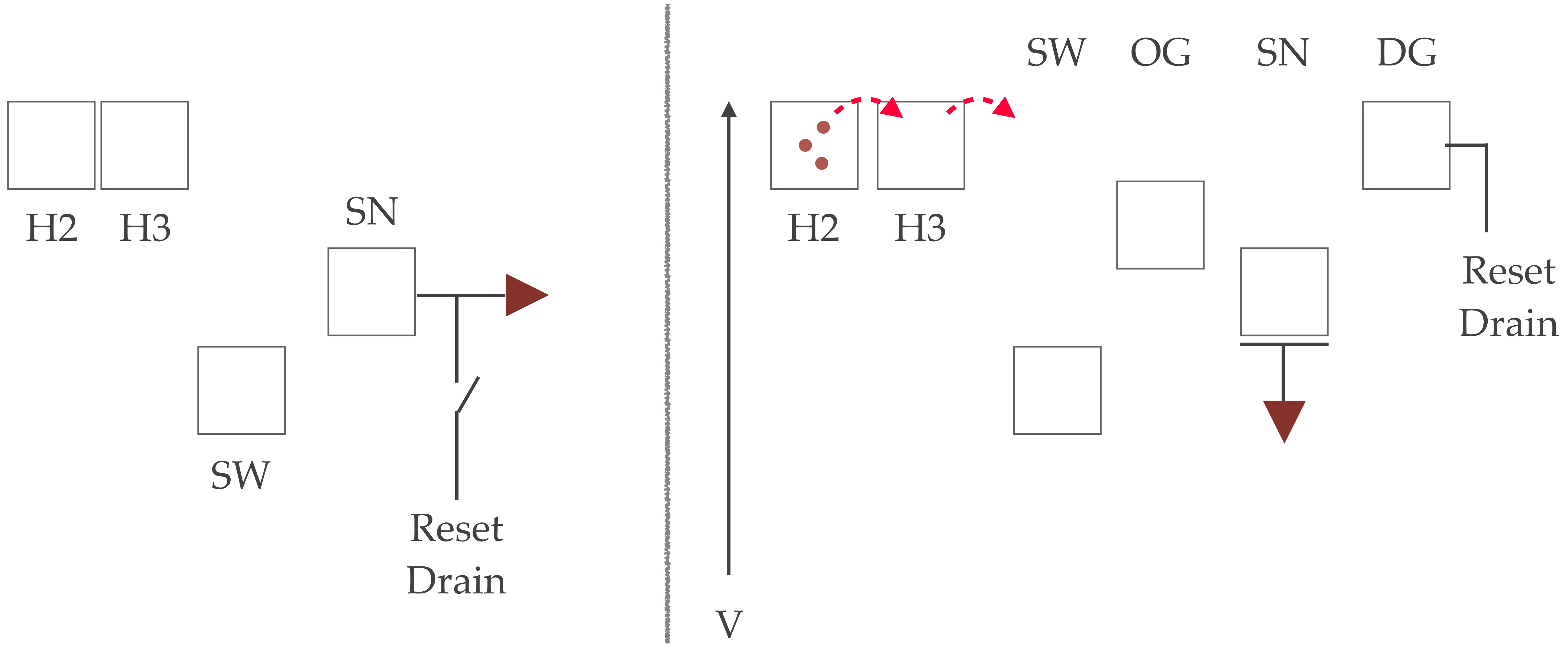
Noise in measurement



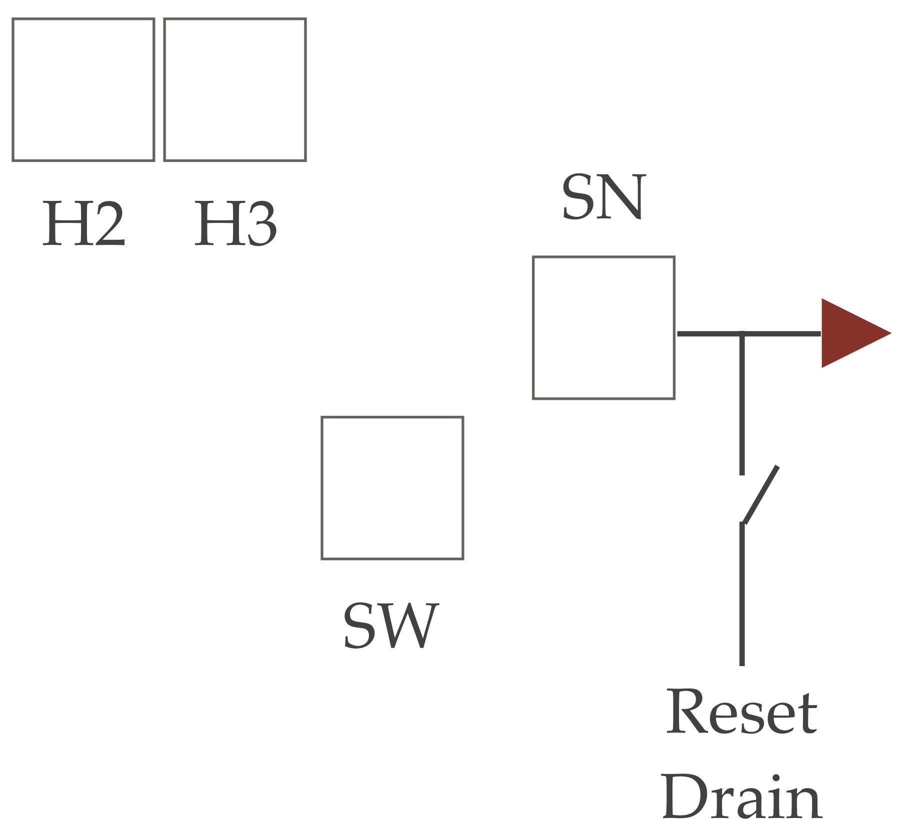
Credit: J Tiffenberg (FNAL)

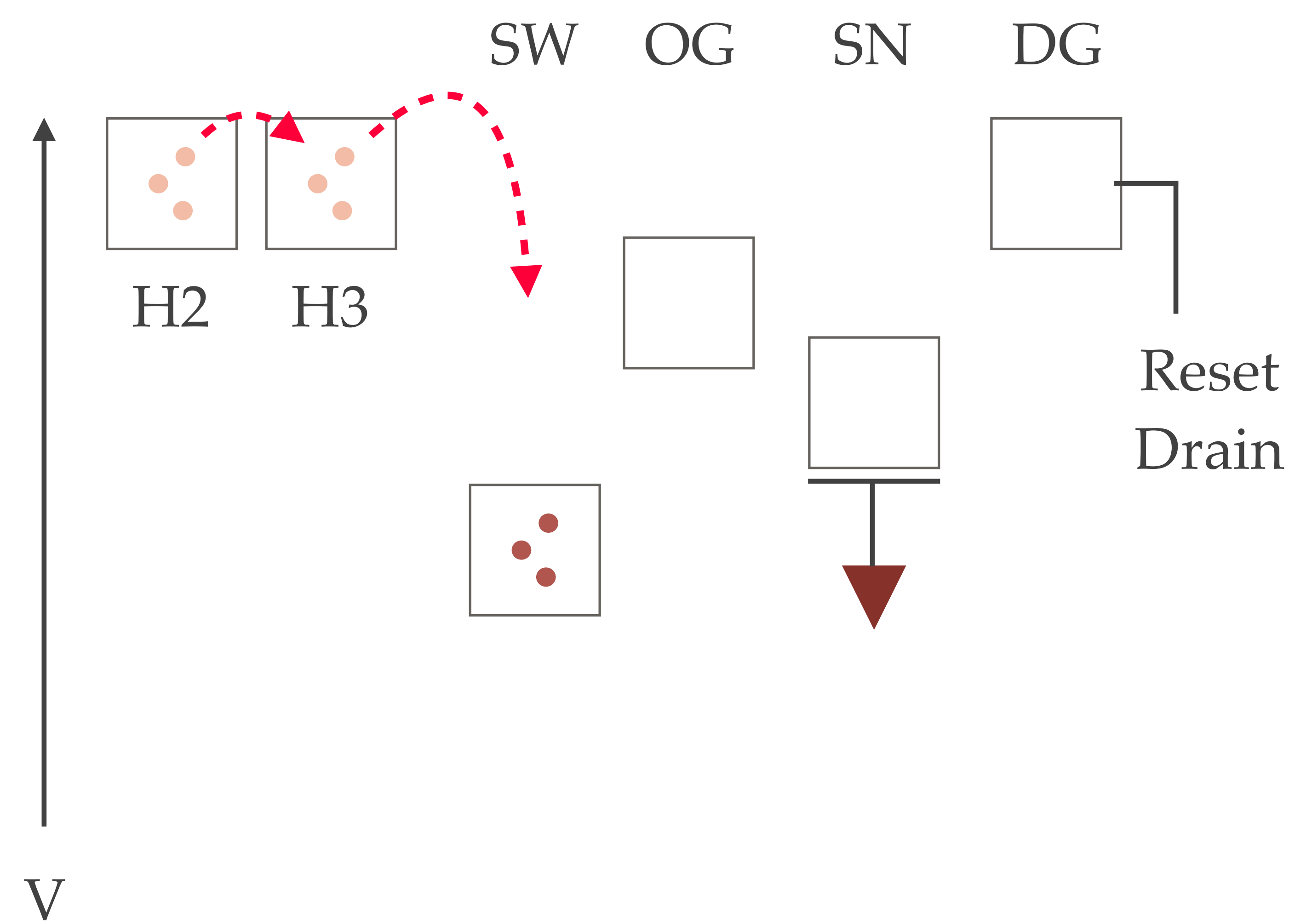
- Correlated double sampling (CDS) eliminates HF noise
- LF noise is still a problem.

Skipper CCD: Measuring charges

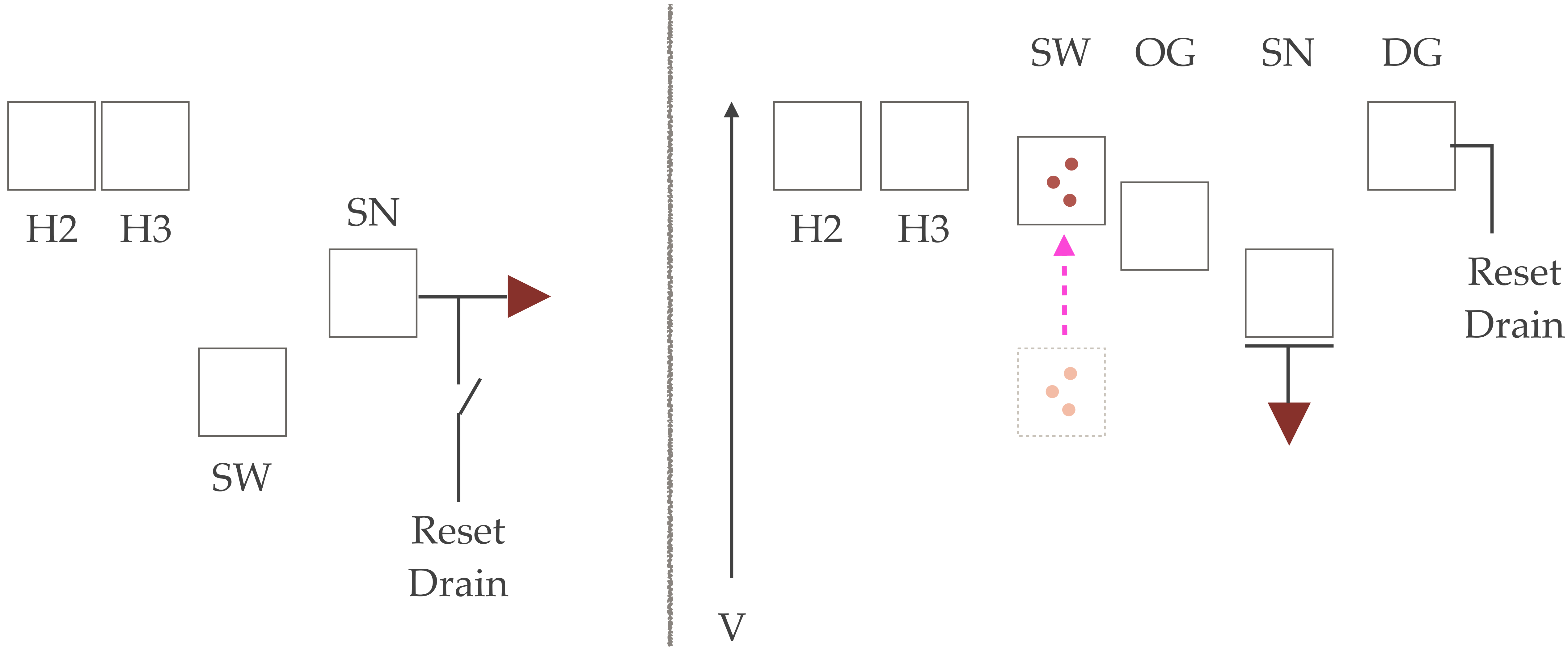


Skipper CCD: Measuring charges

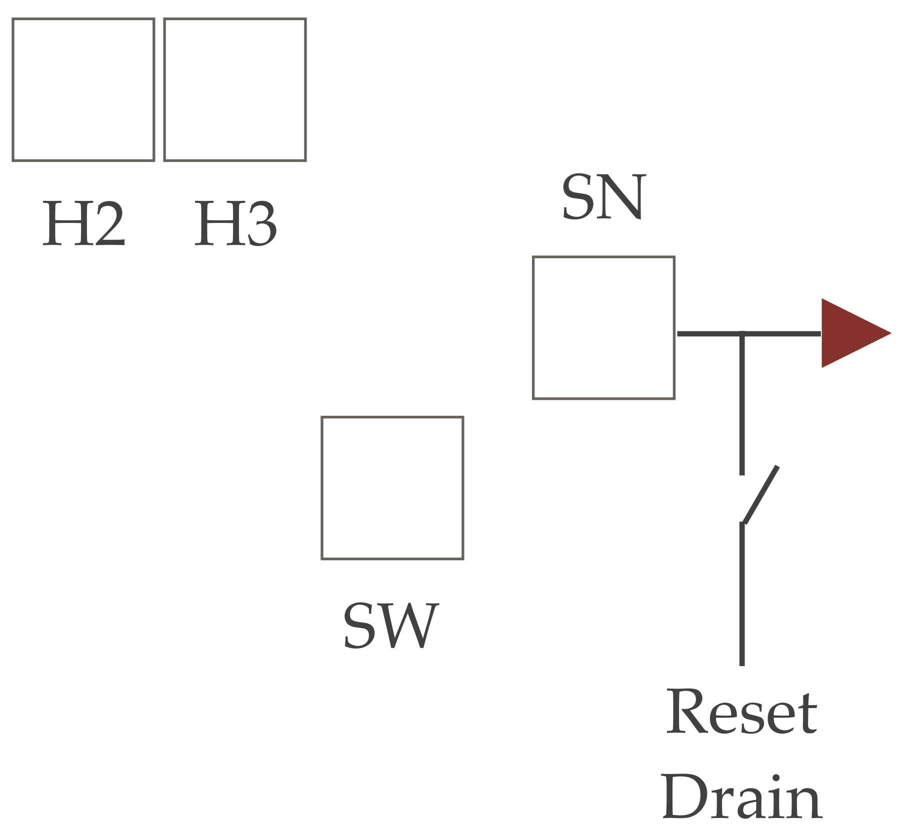


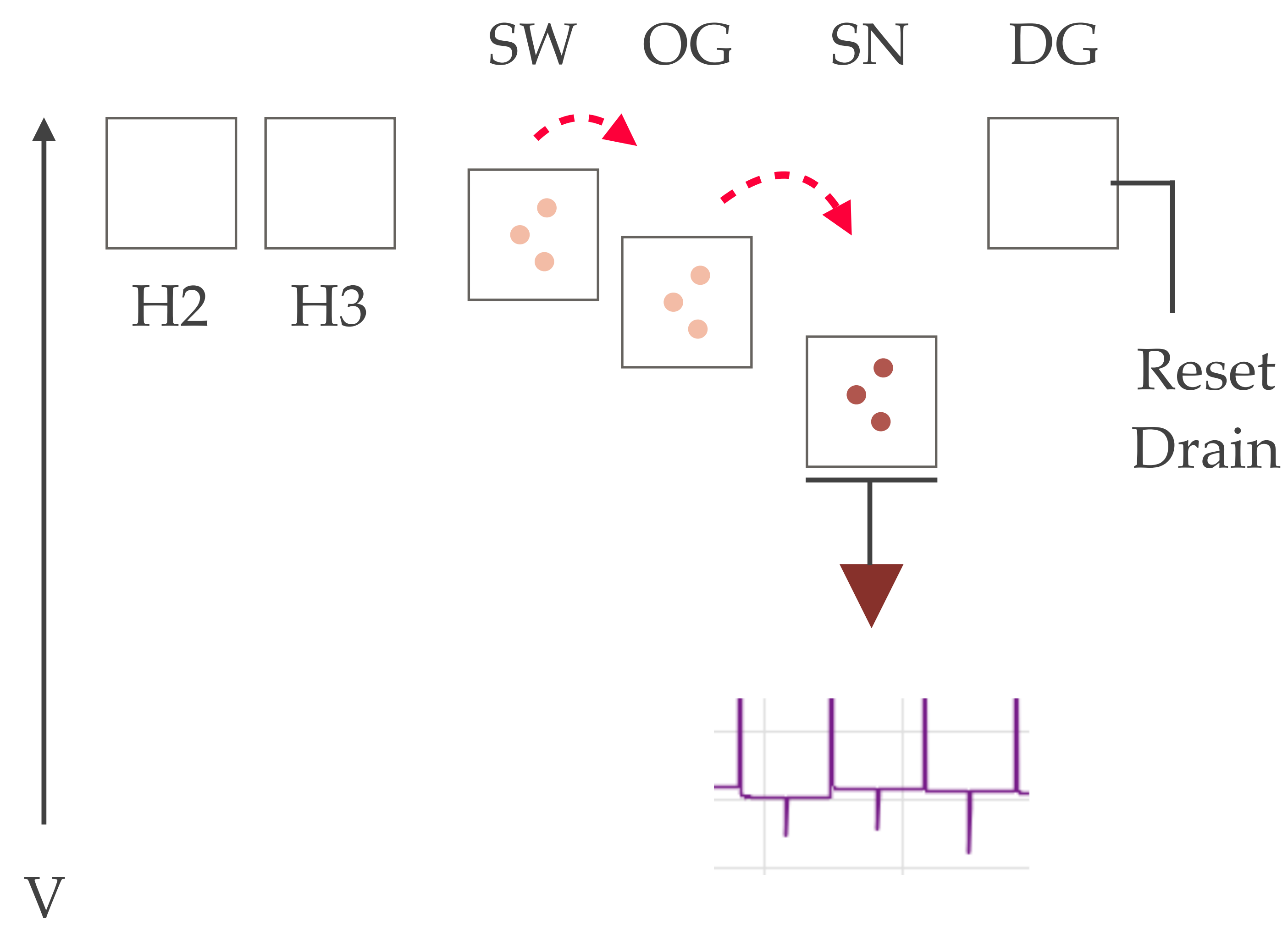


Skipper CCD: Measuring charges

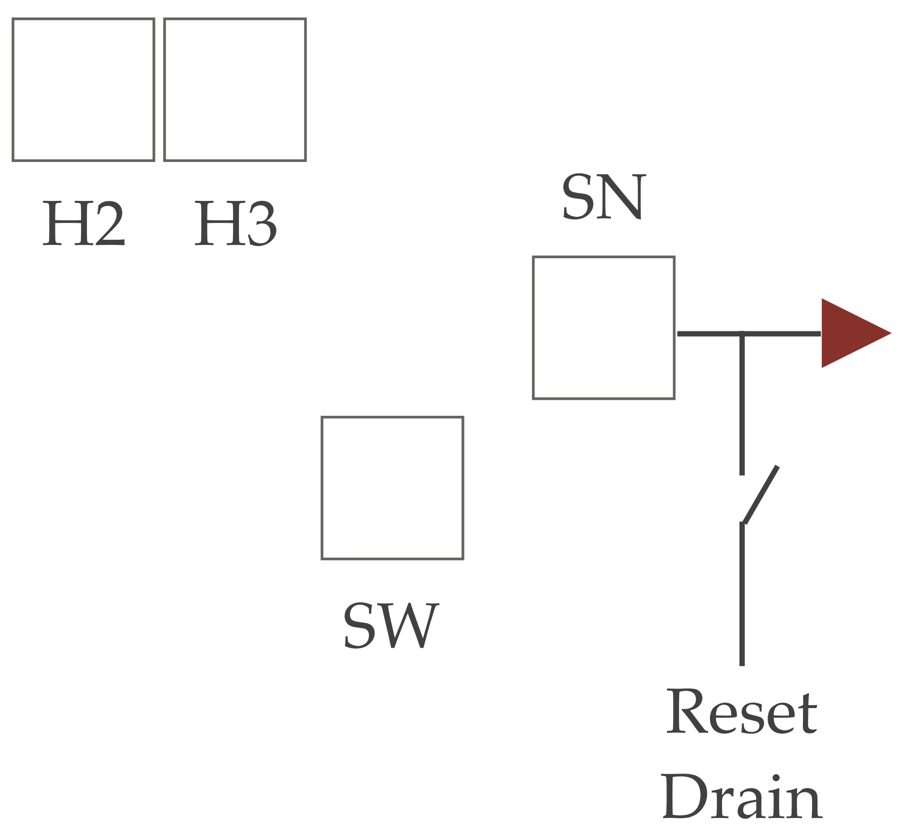


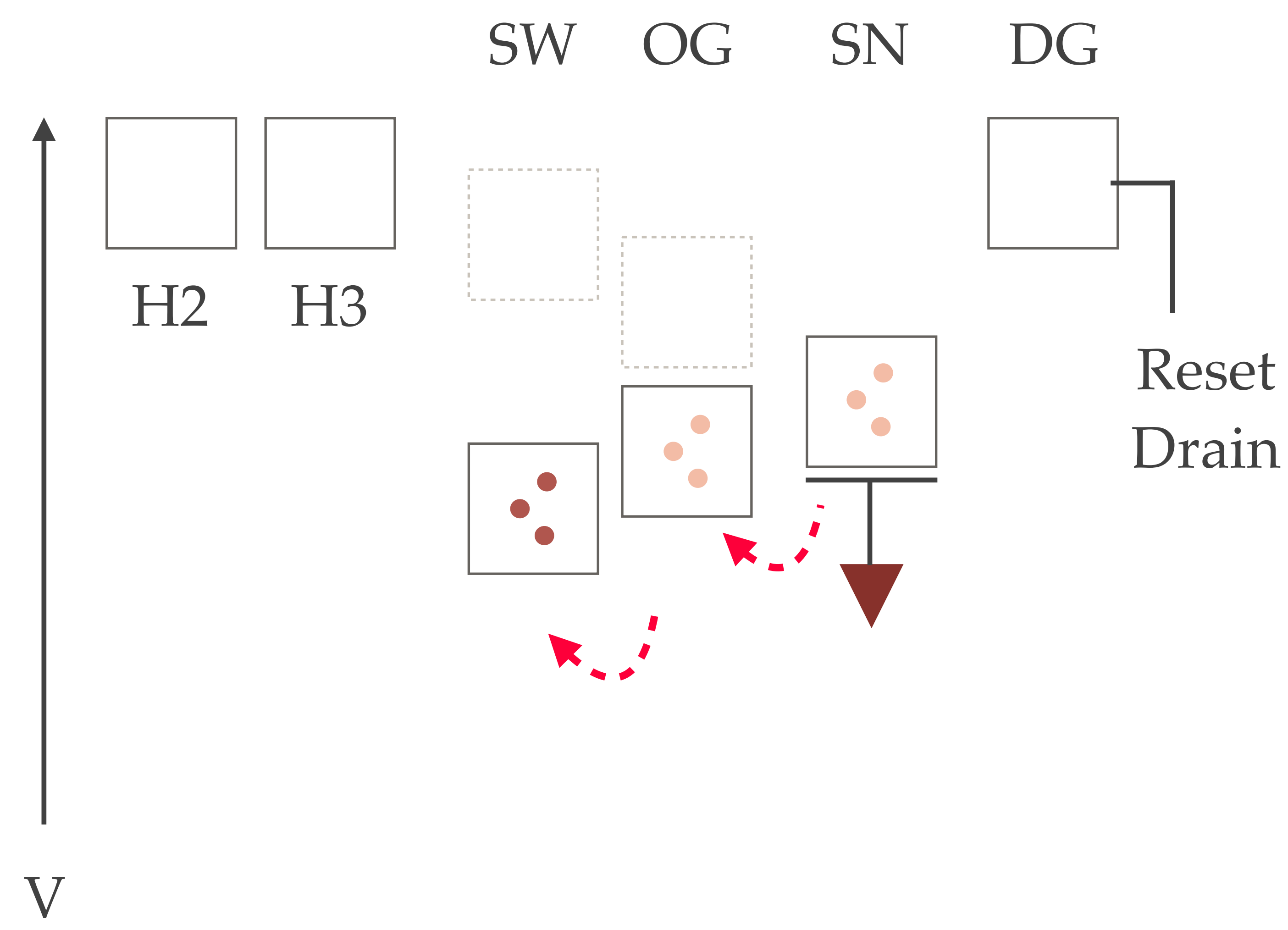
Skipper CCD: Measuring charges



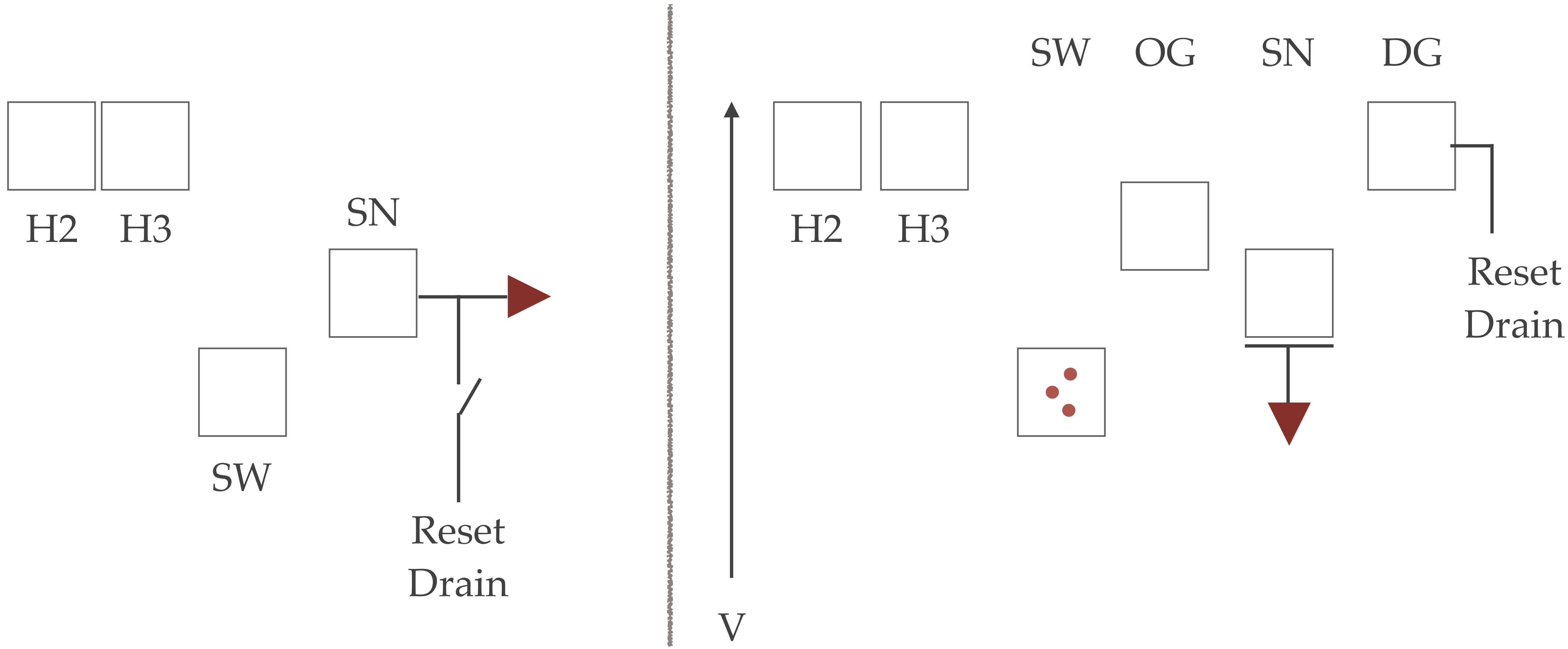


Skipper CCD:
Measuring charges

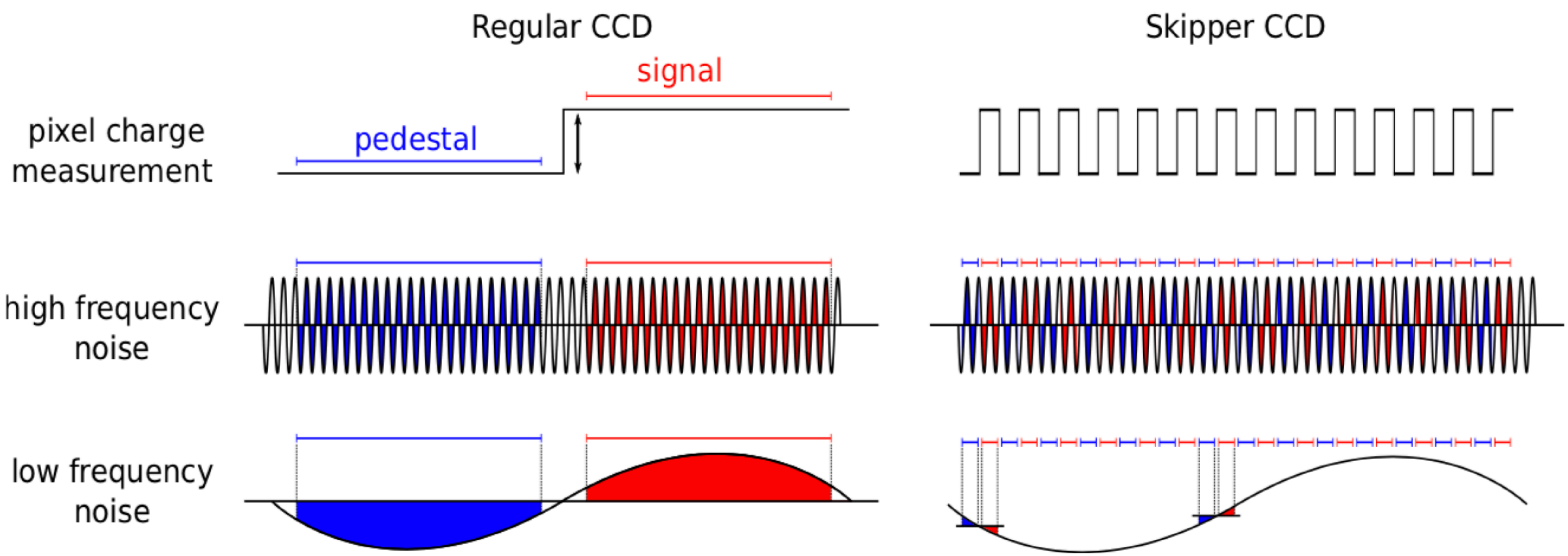




Skipper CCD: Measuring charges



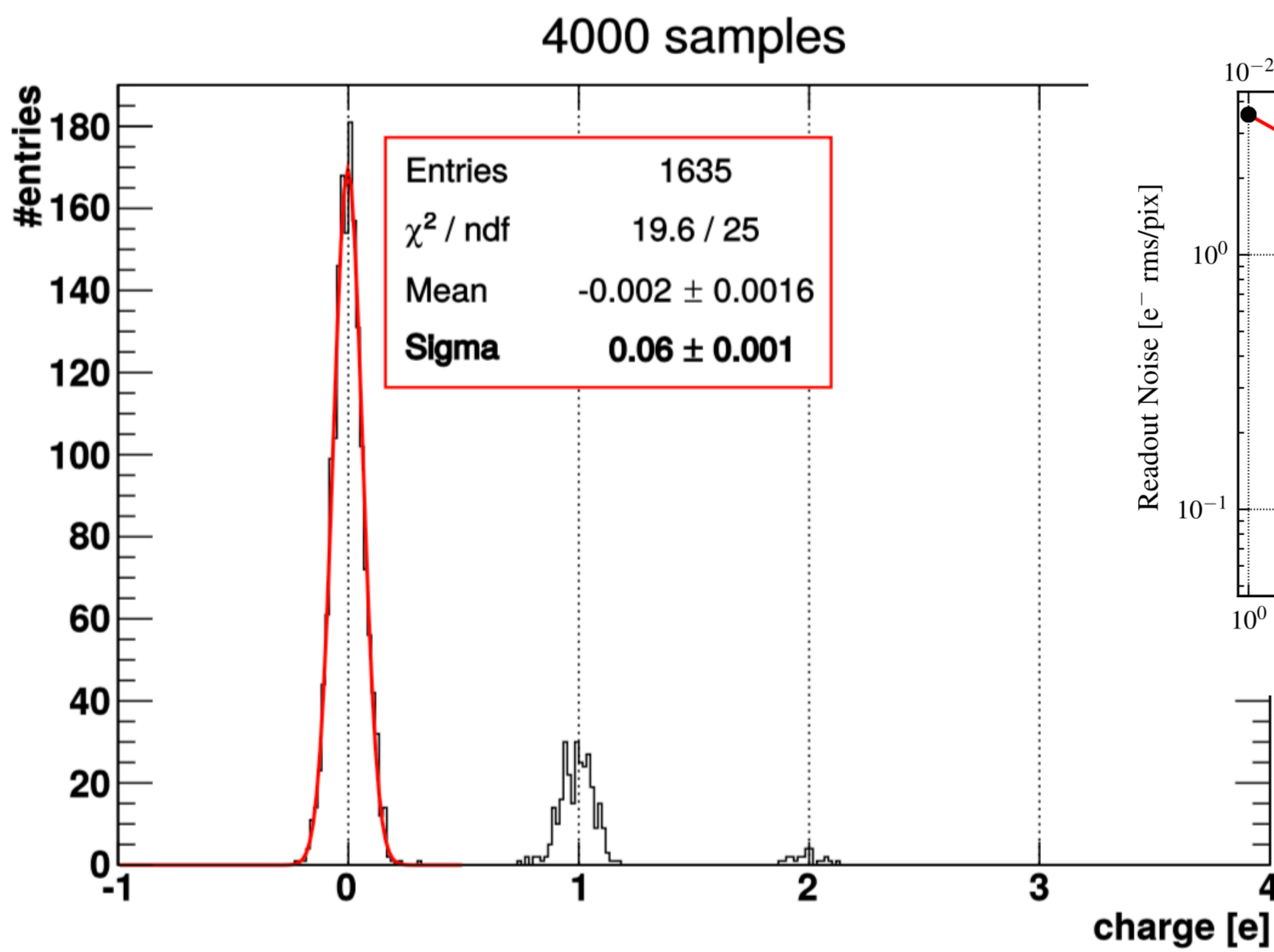
Skipper CCD vs a regular CCD

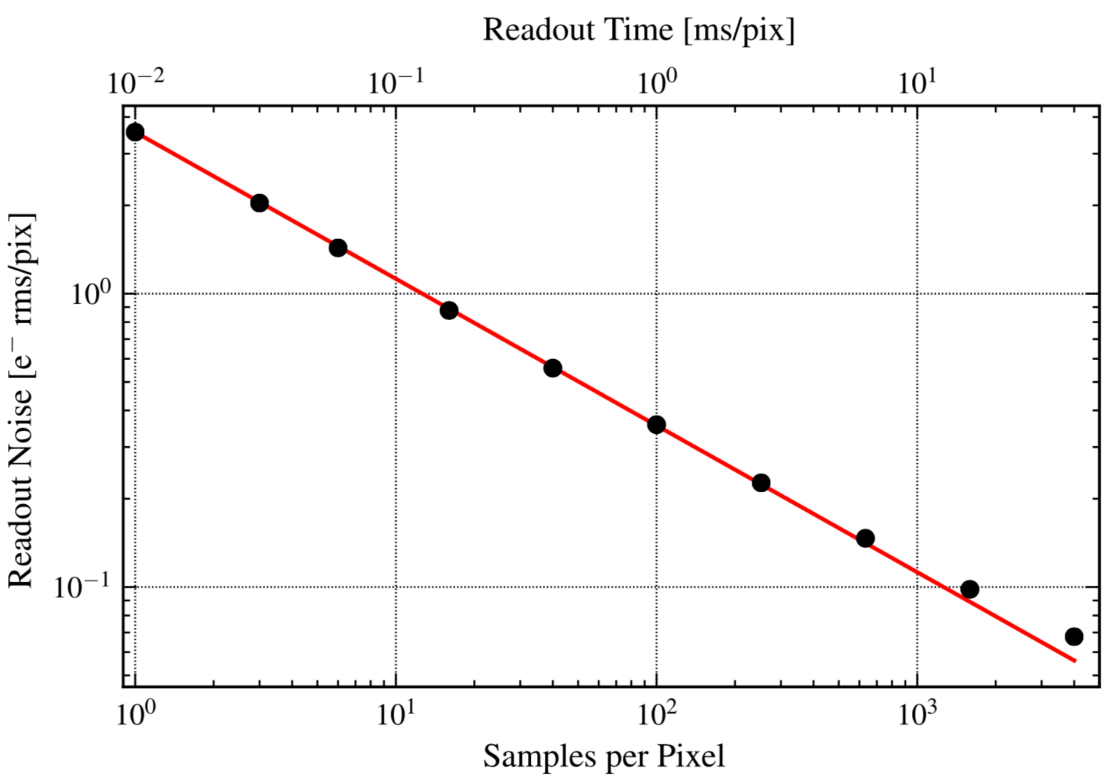


Credit: J Tiffenberg (FNAL)

- A skipper CCD allows multiple non-destructive charge measurement.

Skipper CCD resolution



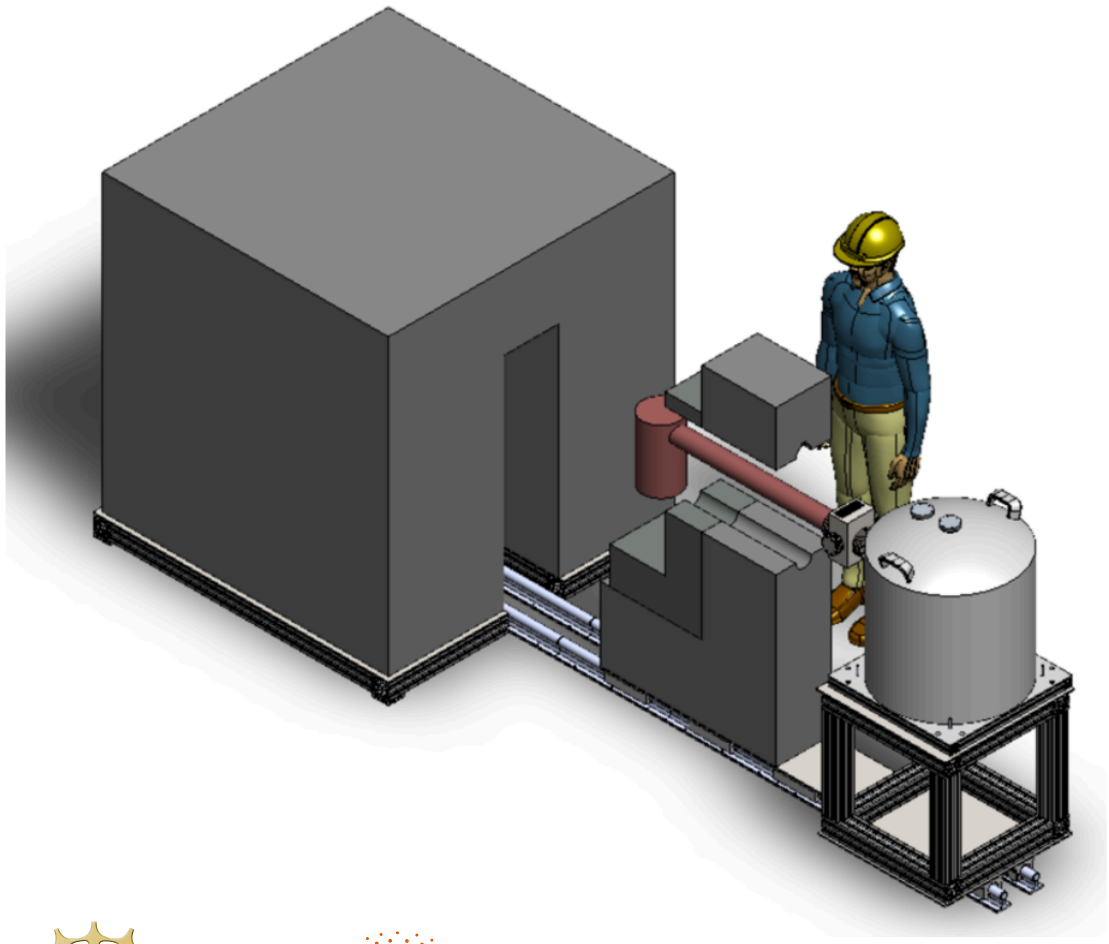


- J. Tiffenberg has demonstrated that a resolution of 0.06 e- may be achieved on an LBNL CCD.

Dark matter with skipper CCDs

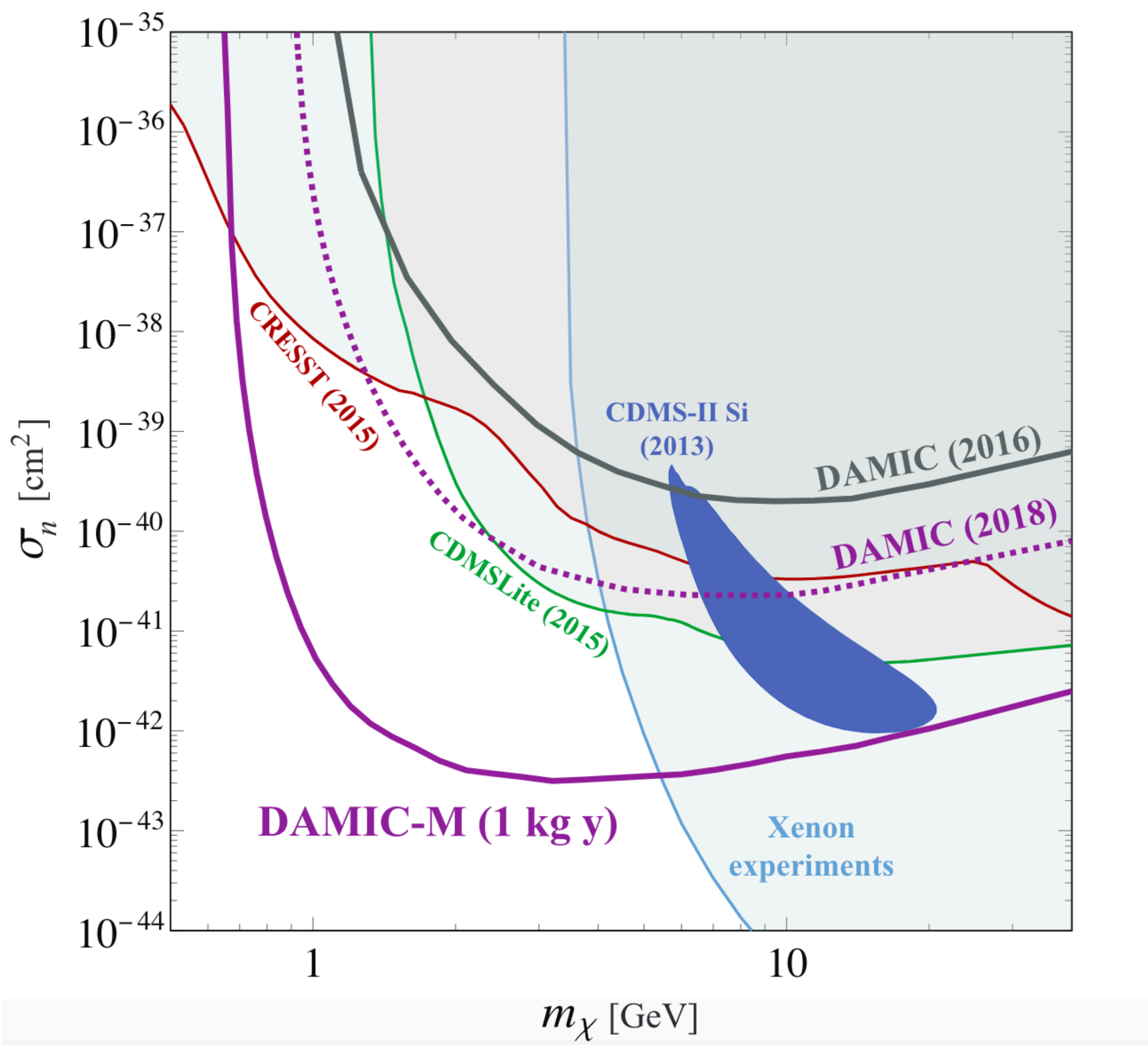
- The **DAMIC-M** experiment is being constructed at **LSM (Laboratoire Souterrain de Modane)**

- DAMIC-M will use **50 skipper CCDs**.
- The total active mass will be **1 kg**.
- The **most massive CCDs** ever built 6k by 6k pixels, mass of 20g.
- Background reduction to a **fraction of a dru**.
- **Exceptionally low leakage current** of 10^{-3} e^{-}/pixel/day
- **1800 MPix and scalable!**

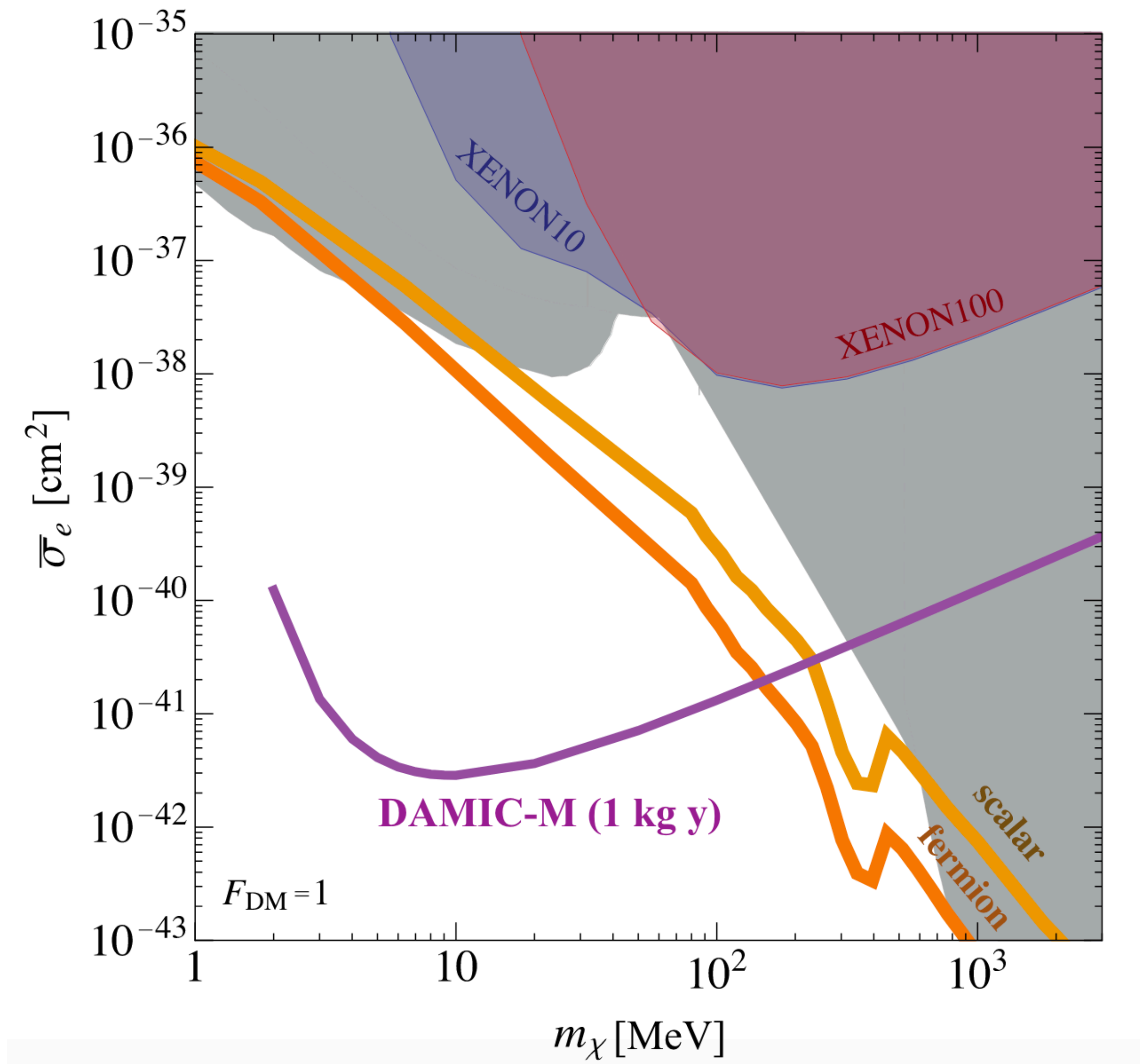


European Research Council
Established by the European Commission

Dark matter search projections

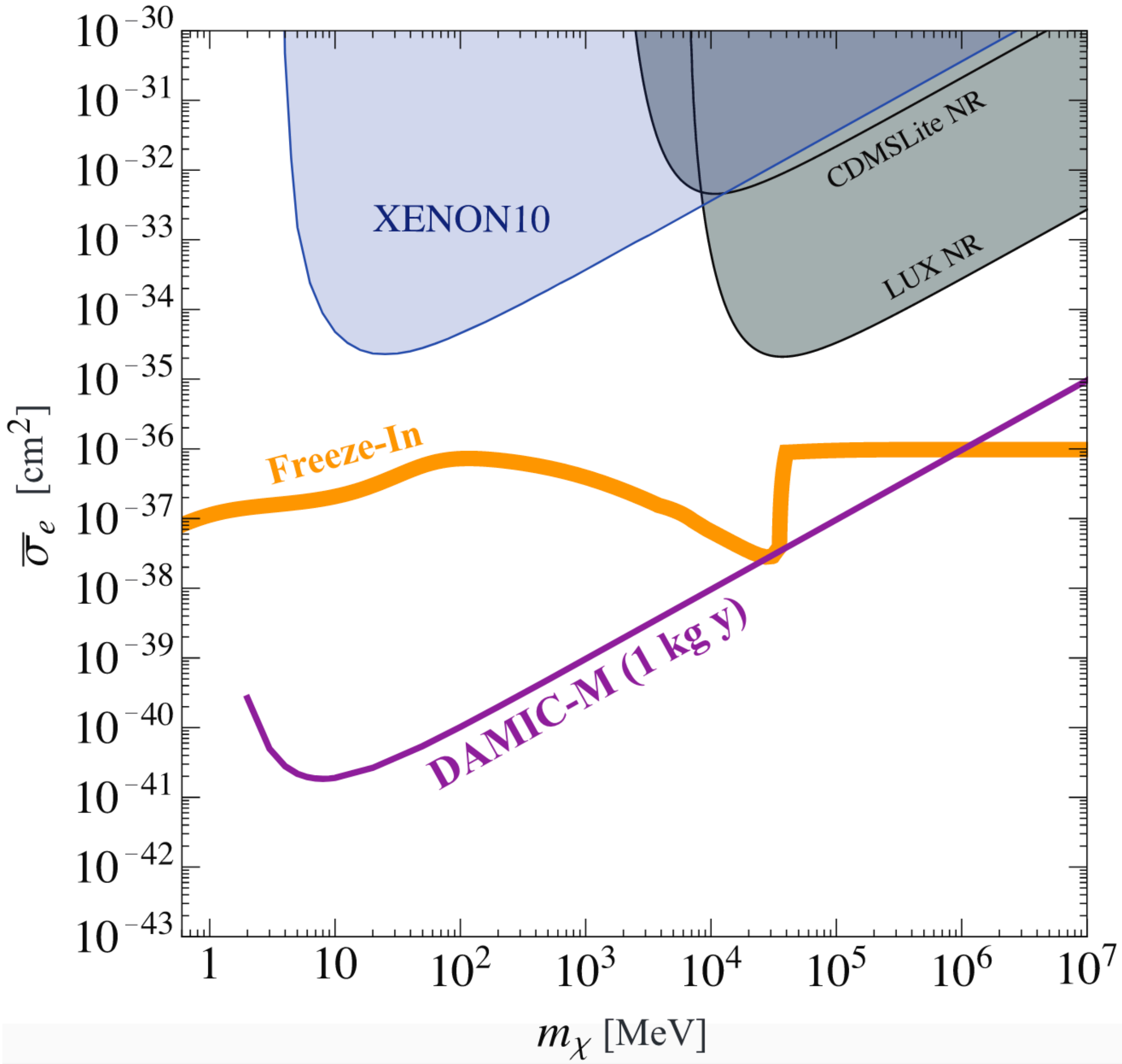


WIMP dark matter

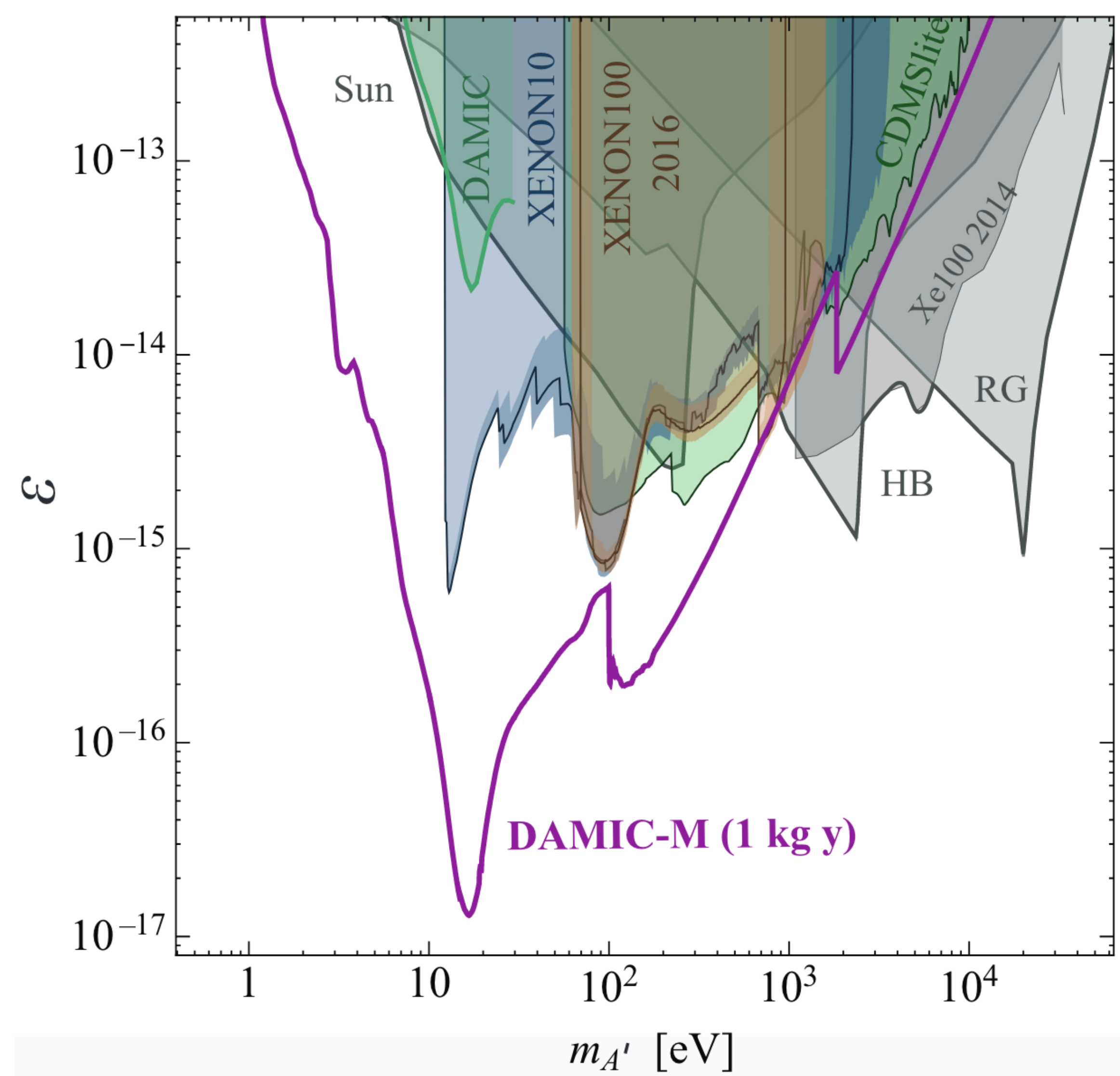


Dark photon - heavy mediator

Dark matter search projections



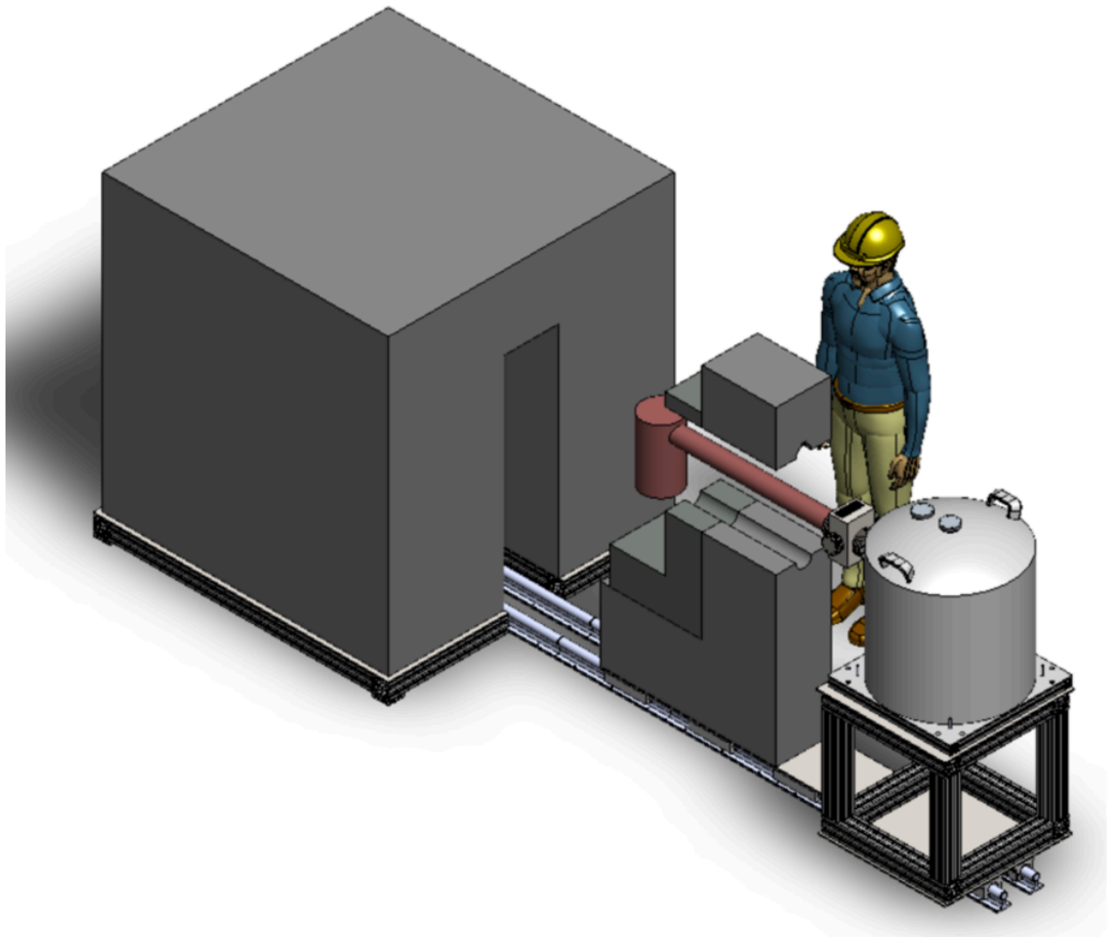
Dark photon - light mediator



Hidden photon as dark matter

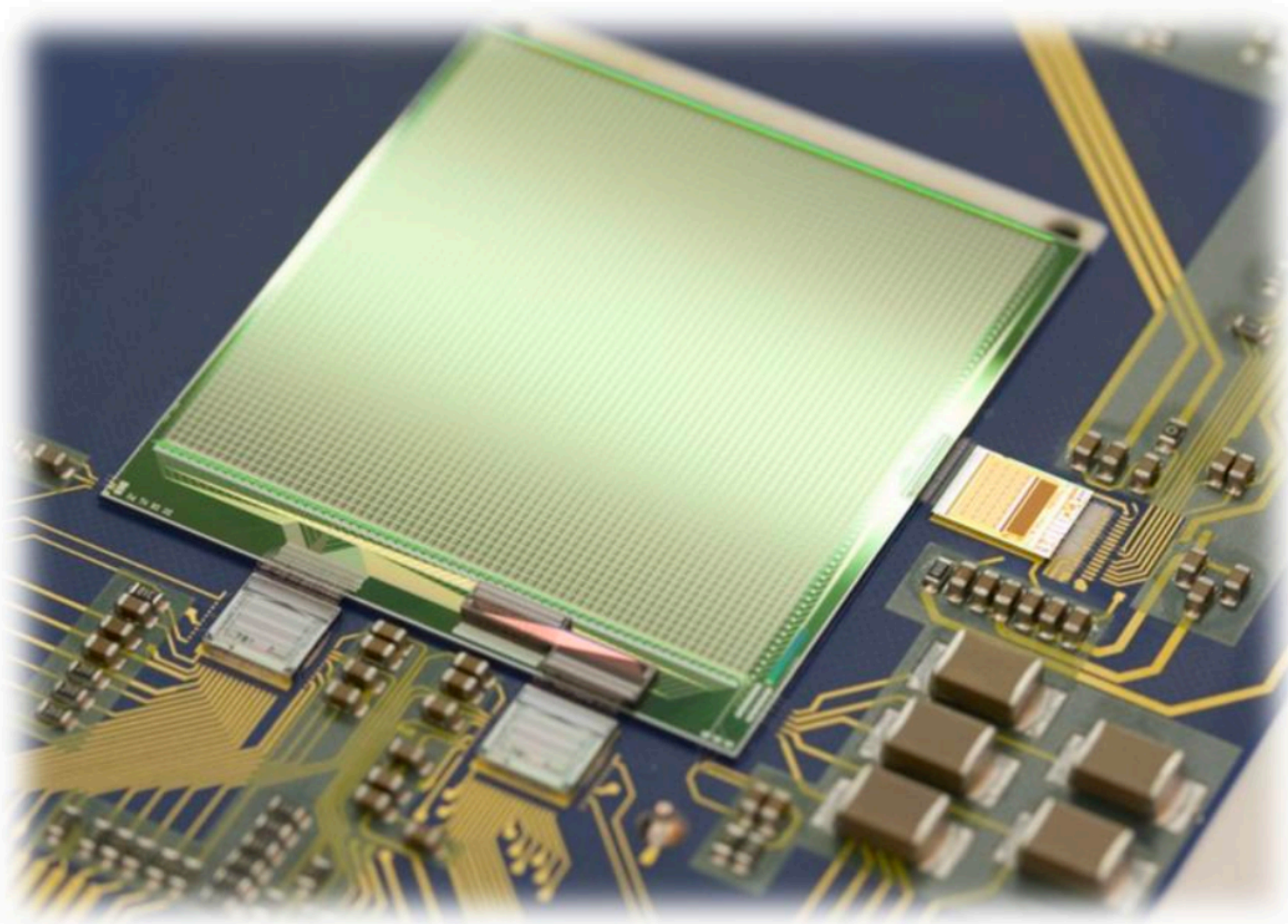
Skipper CCD summary

- Skipper CCDs can **reach** the theoretical limit of **ionization** sensors **down to the Si band gap**.
- Skipper CCDs can **measure single electron - hole pair** with a resolution of 0.06 eV.
- The DAMIC experiment has demonstrated that CCDs can be constructed with **very low leakage current.**
- DAMIC-M (under construction) will use **50 skipper CCDs** to search for dark matter.



DEPFET

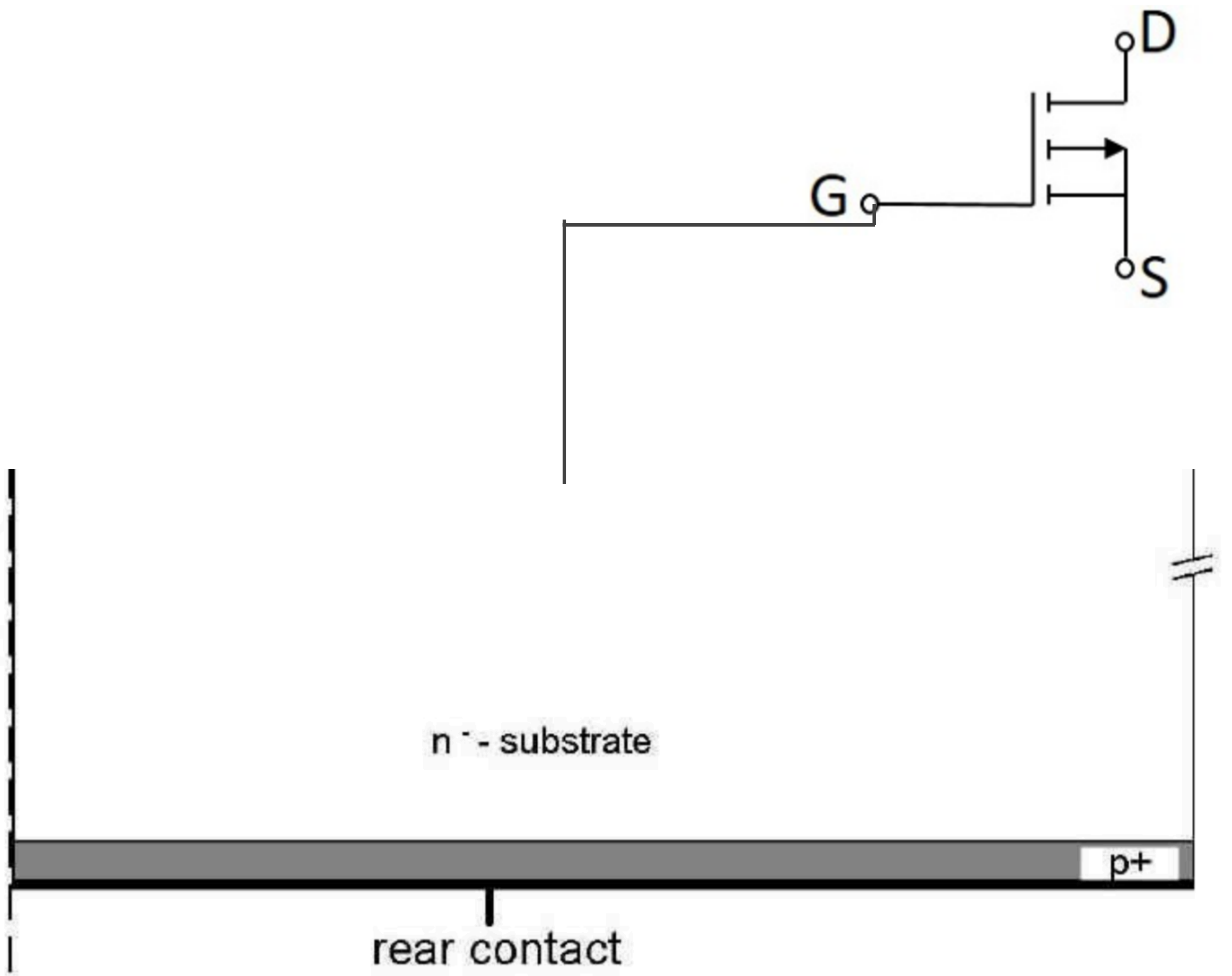
- Depleted field effect transistors (DEPFETs) are **Si based devices** that provide the detection and amplification of particles jointly



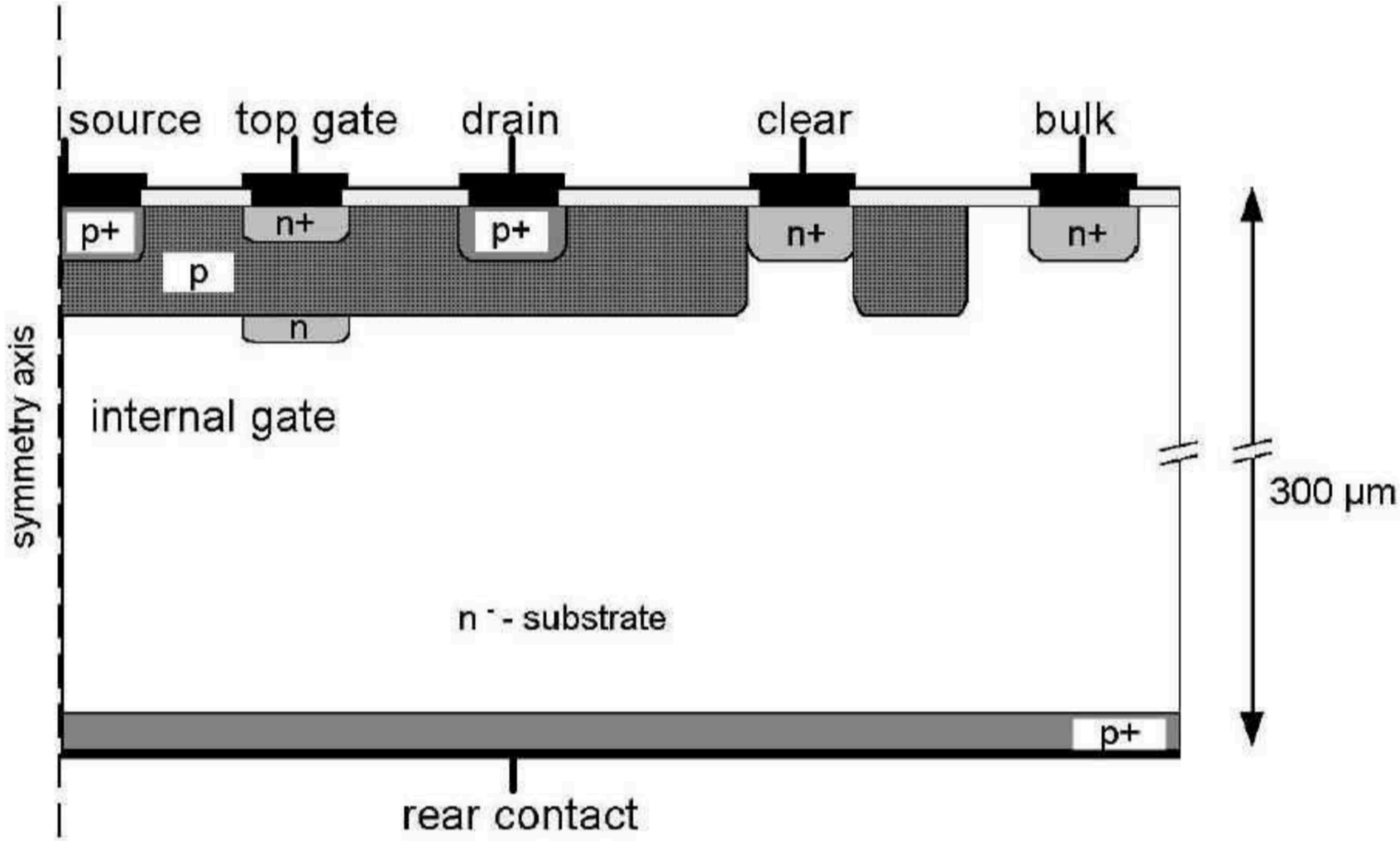
From a CCD to DEPFET

Detection and amplification

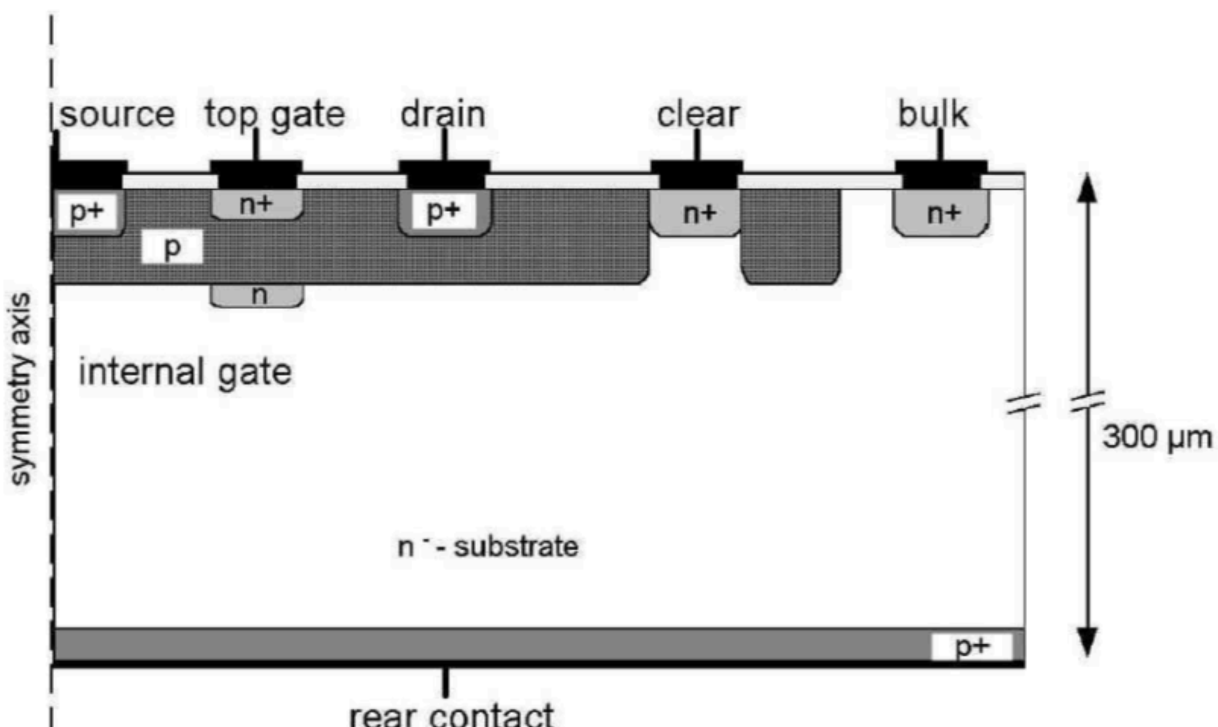
Si device to collect charges from particle interactions



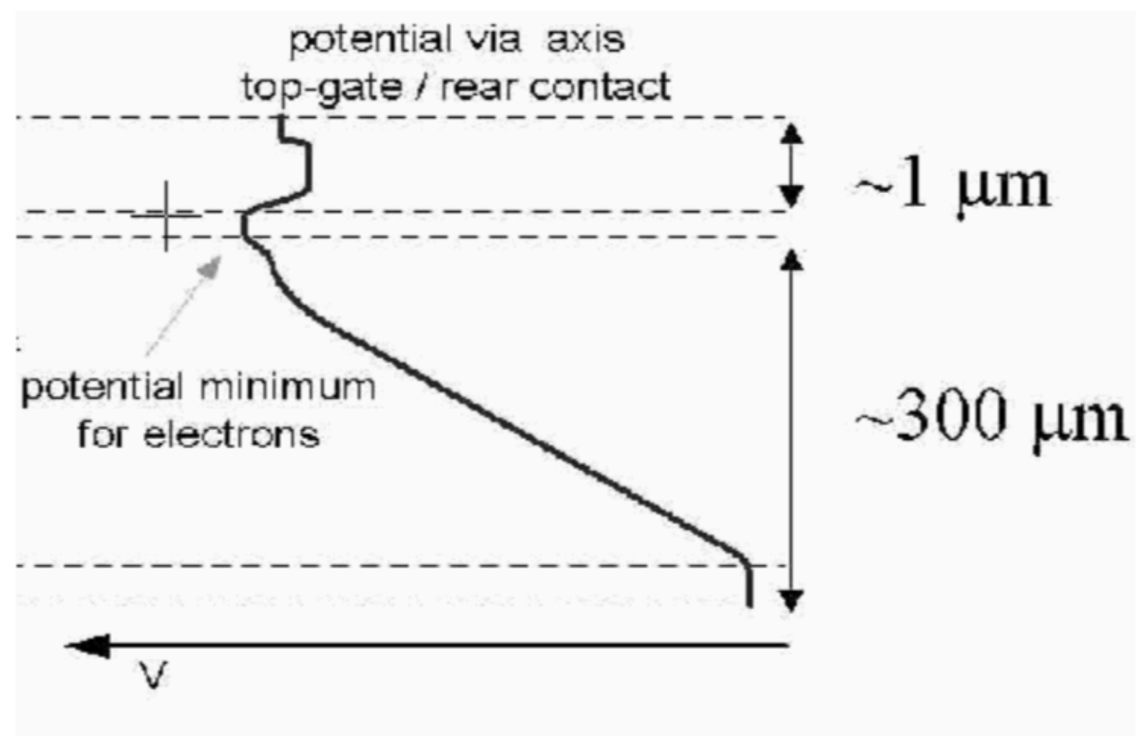
DEPFET


source
top gate
drain
clear
bulk
p+
n+
p+
n+
n+
p
n
symmetry axis
internal gate
300 µm
n - - substrate
p+
rear contact

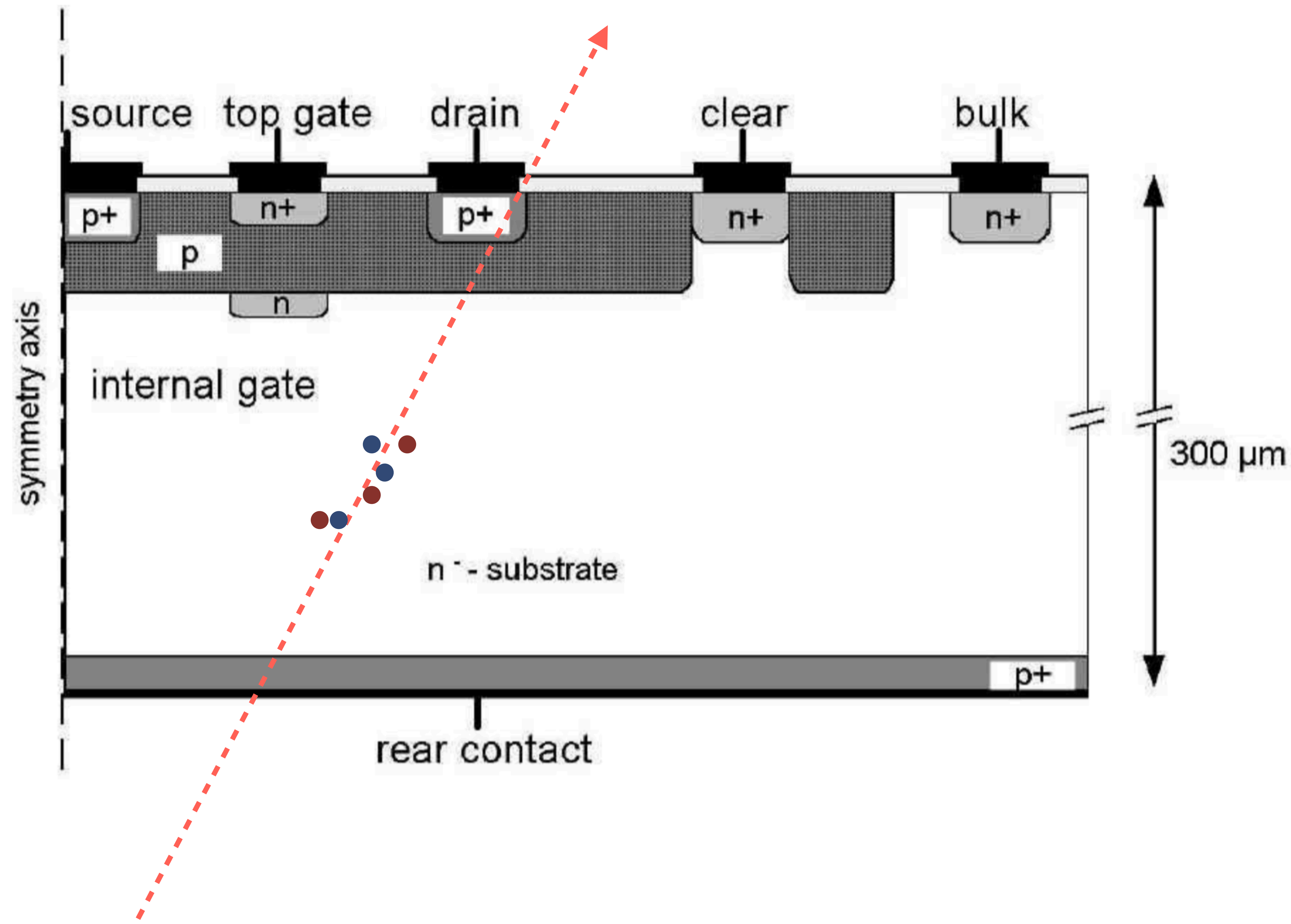
DEPFET



Negative
Voltage



DEPFET


source
top gate
drain
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n ⁻- substrate
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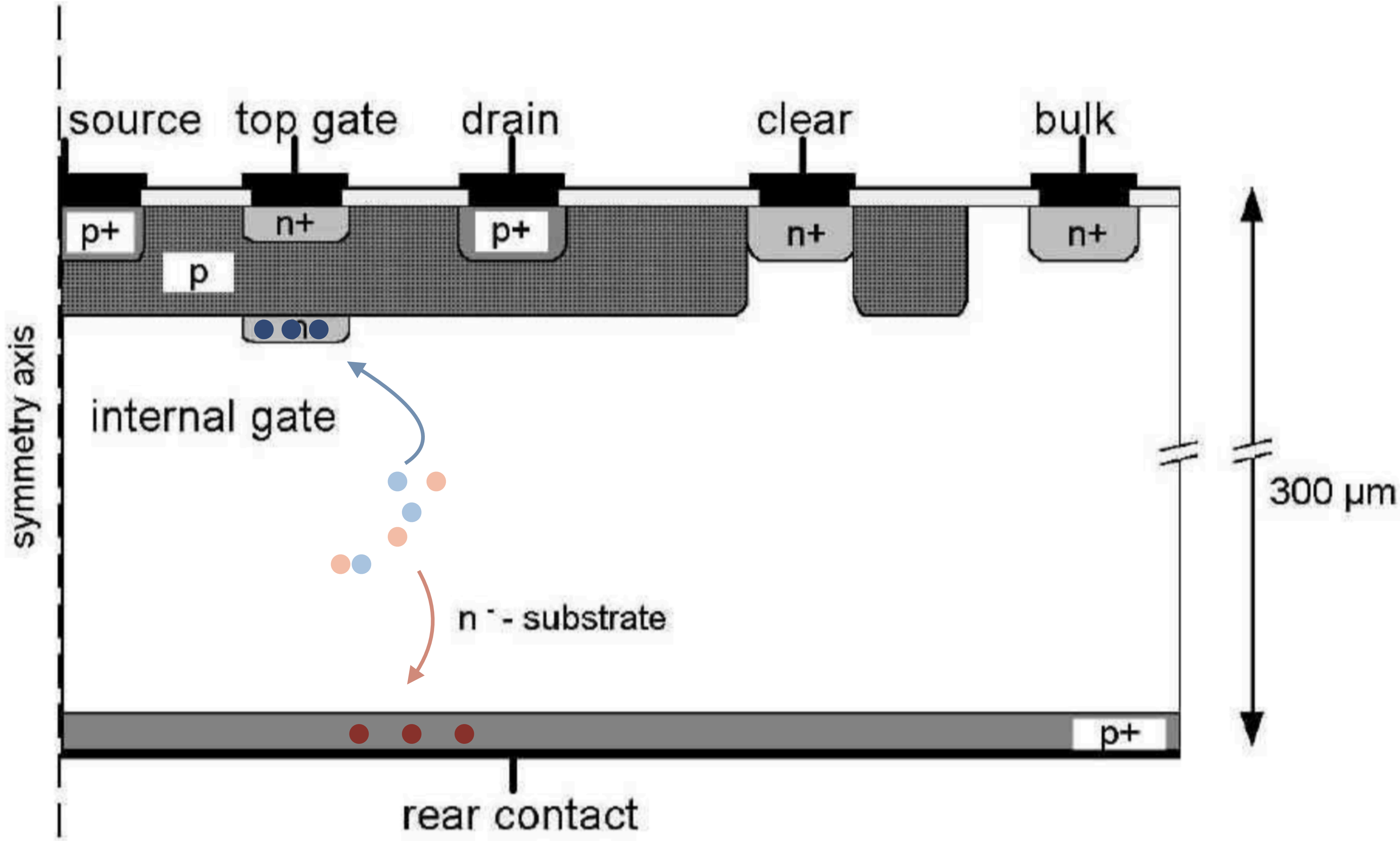
rear contact

DEPFET



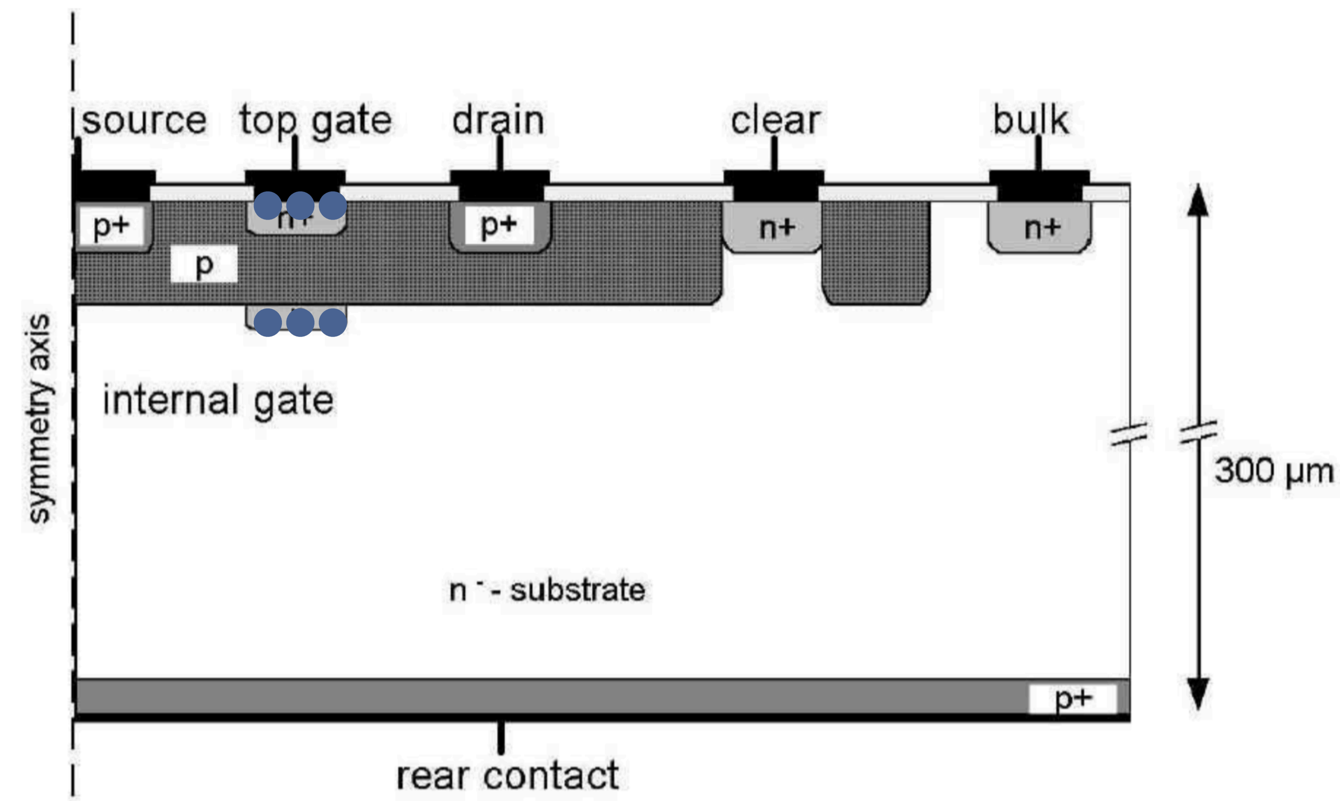
source
top gate
drain
clear
bulk
p+
n+
p+
n+
n+
p
internal gate
symmetry axis
n - substrate
300 µm
p+
rear contact

DEPFET

Voltage at the top gate **controls** the **resistance** of the source-drain circuit.

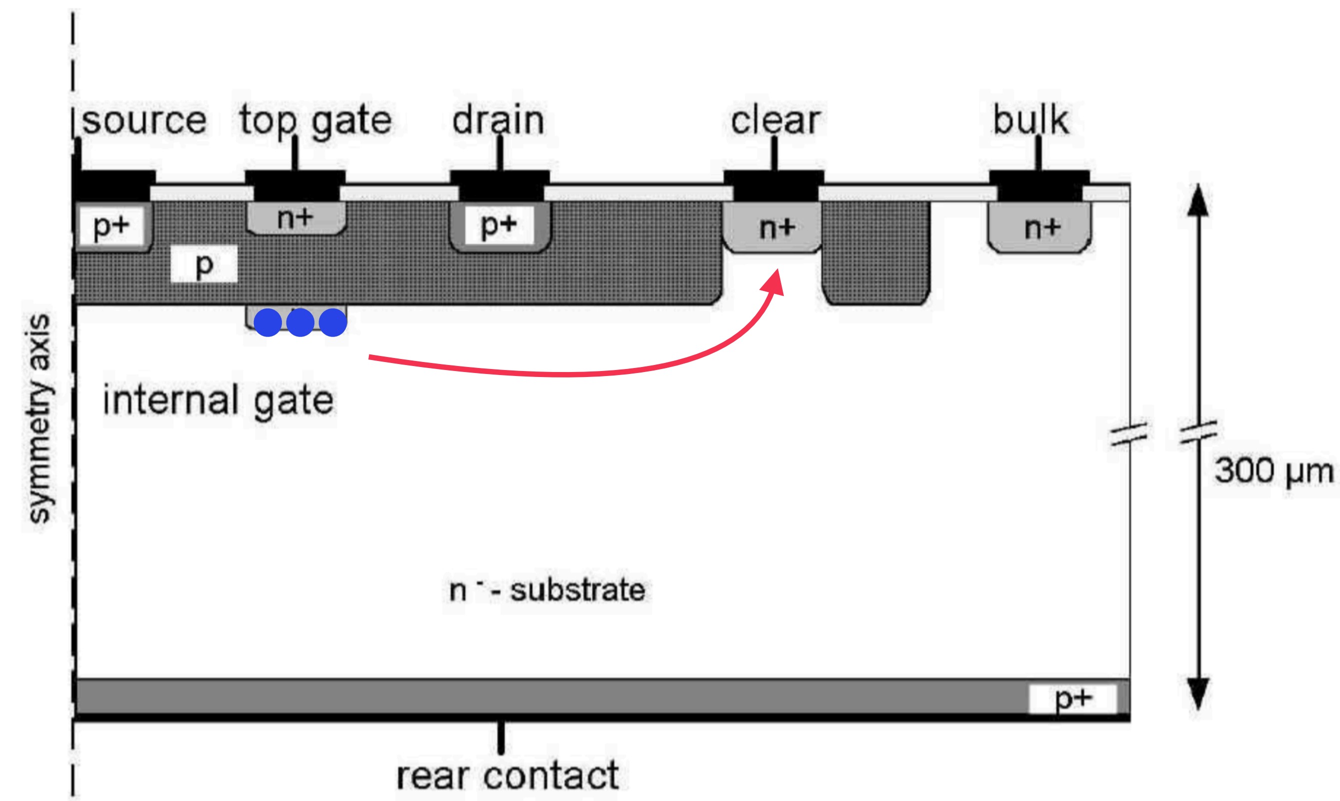
Charges on the internal gate **induces image charges** on the top gate thereby **modulating the resistance** of the source-drain circuit.

A **measurement** of the source-drain resistance is a measurement of the **charges collected**.



DEPFET

Charges are then cleared by applying an electric field with the clear gate.

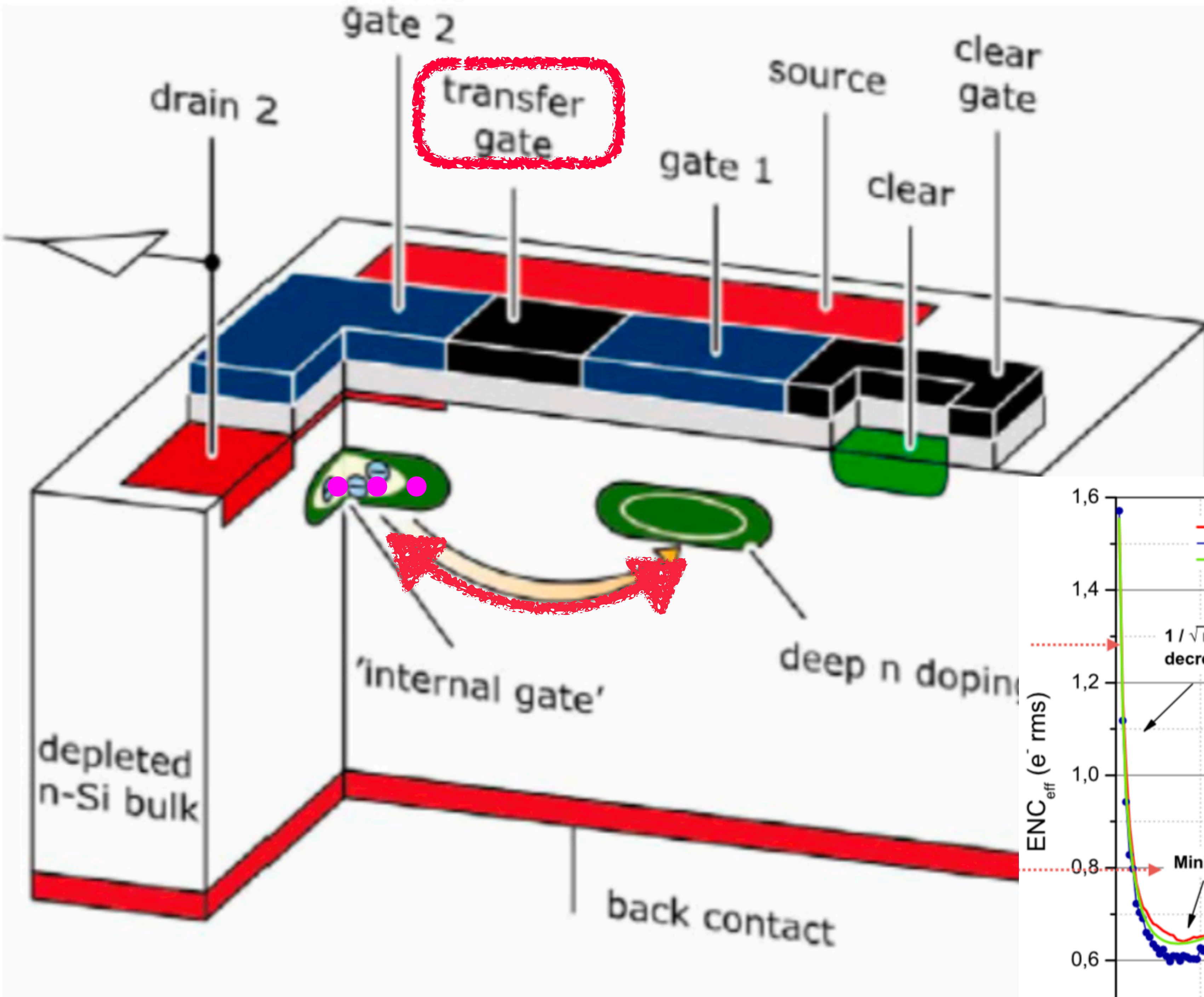


Repeated measurements

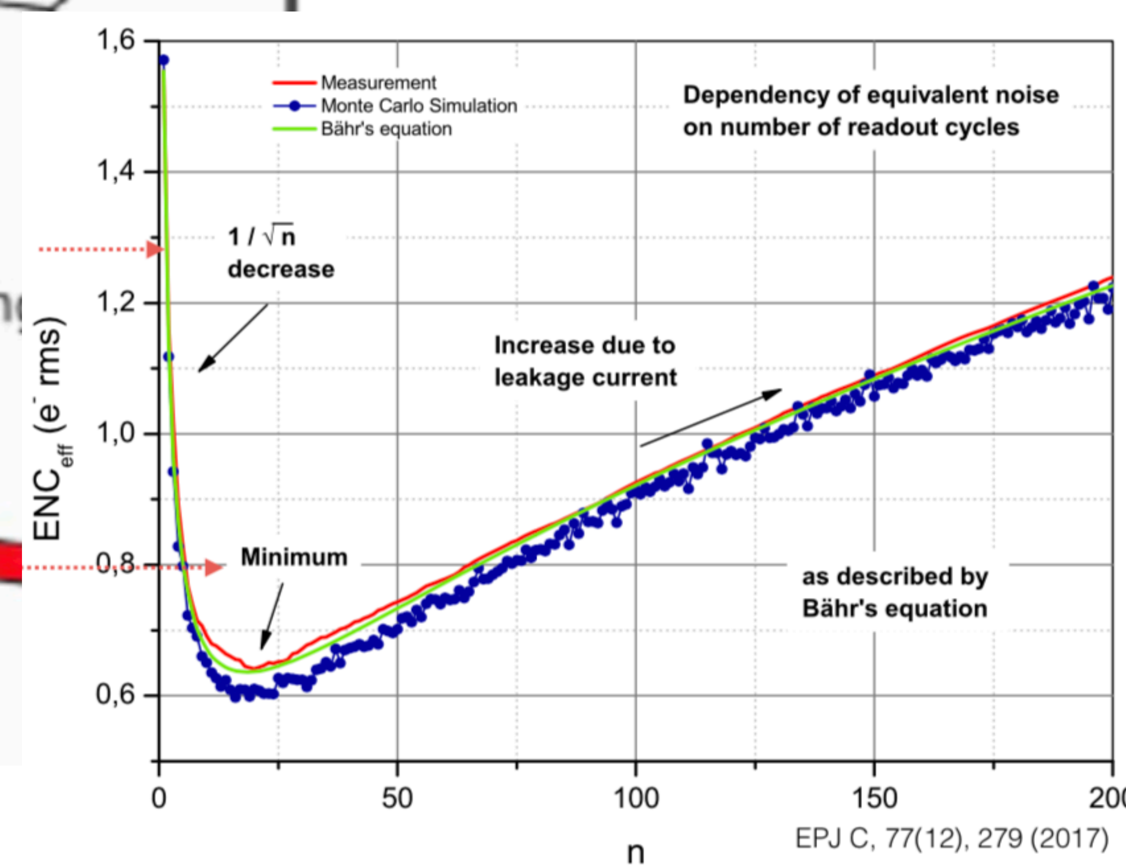
How does one overcome the 1/f noise with DEPFETs and perform multiple charge measurements?

Simple, build 2 of them side by side!

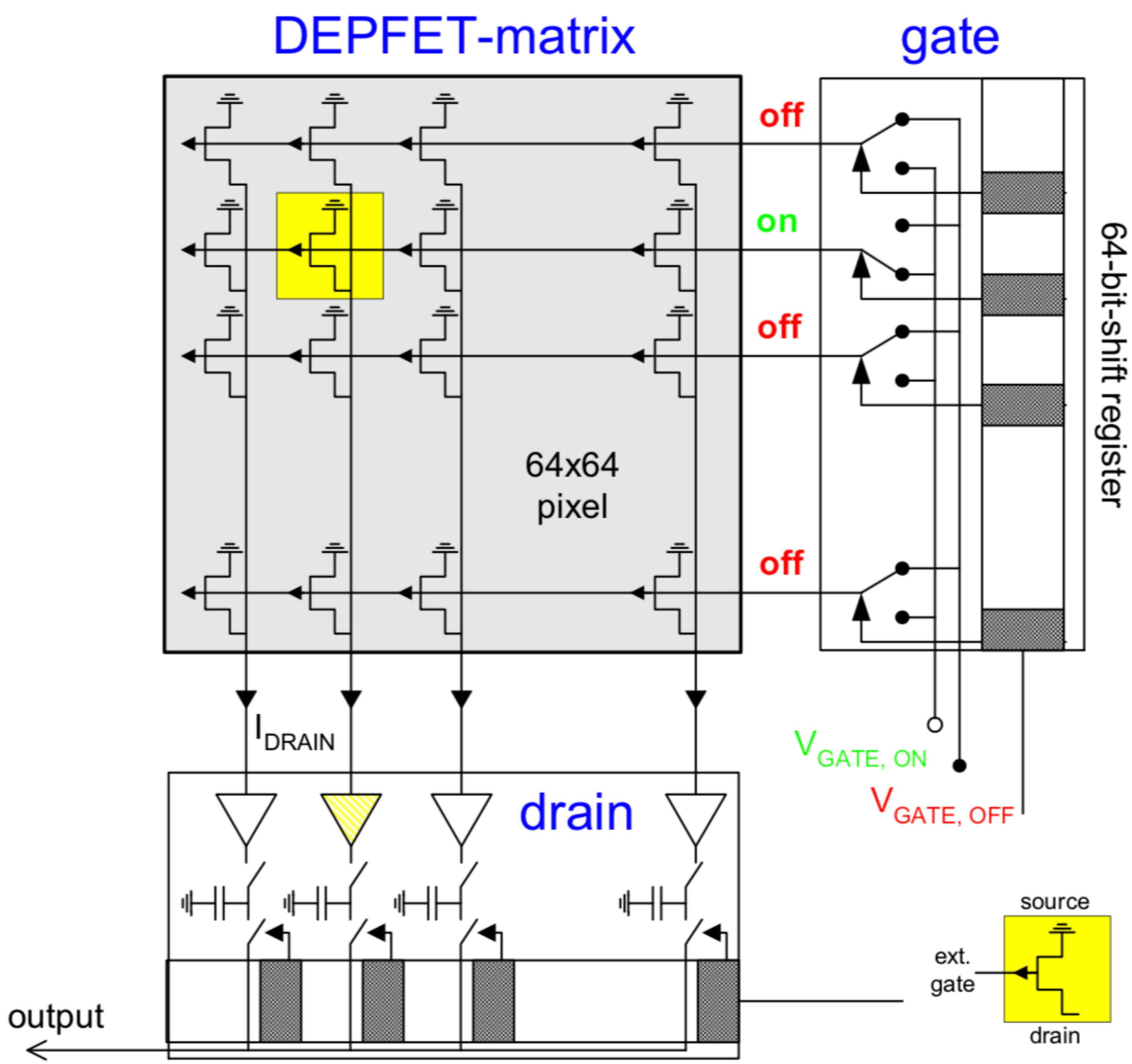
RNDR-DEPFET



EPJ C, 77(12), 279 (2017)



RNDR-DEPFET



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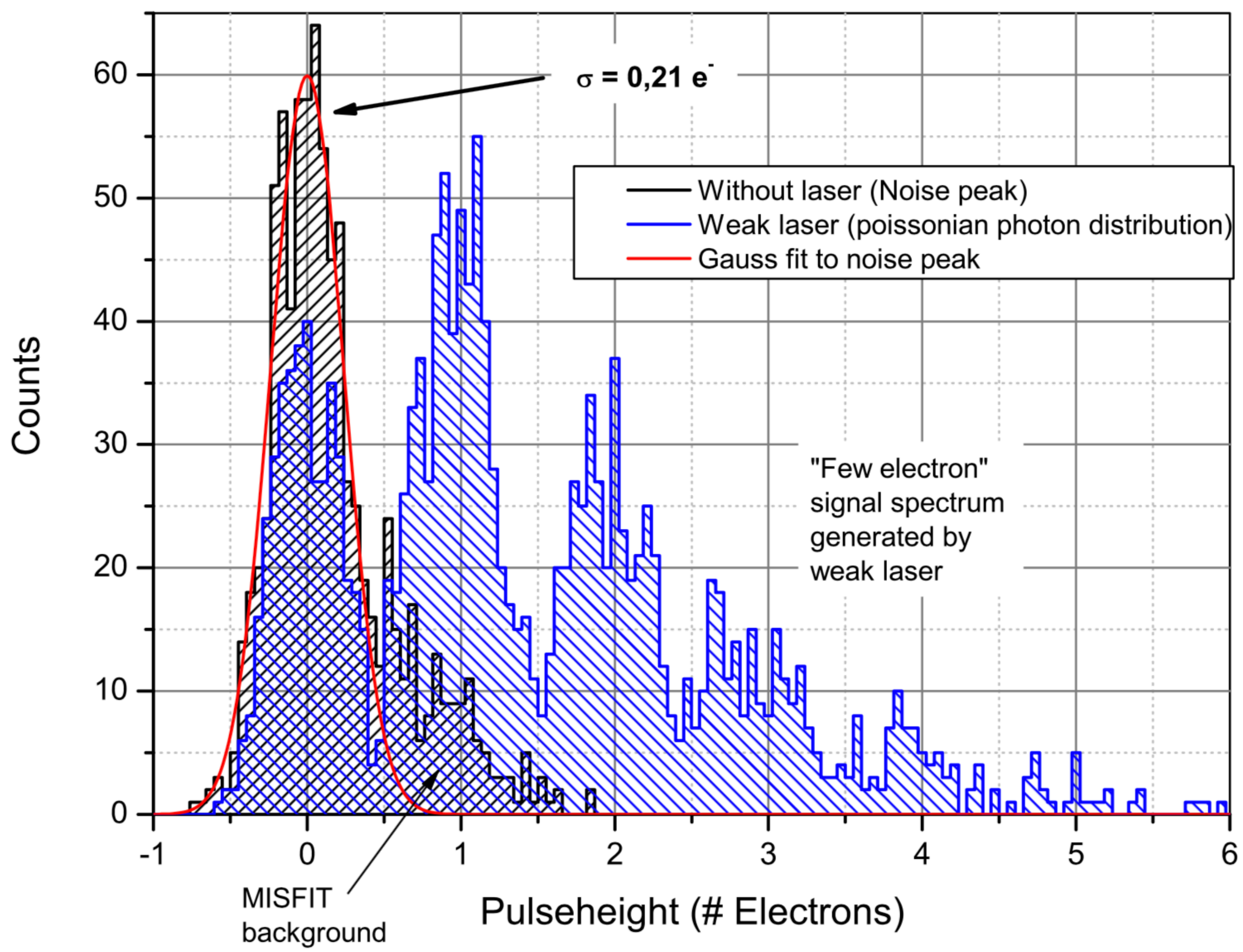
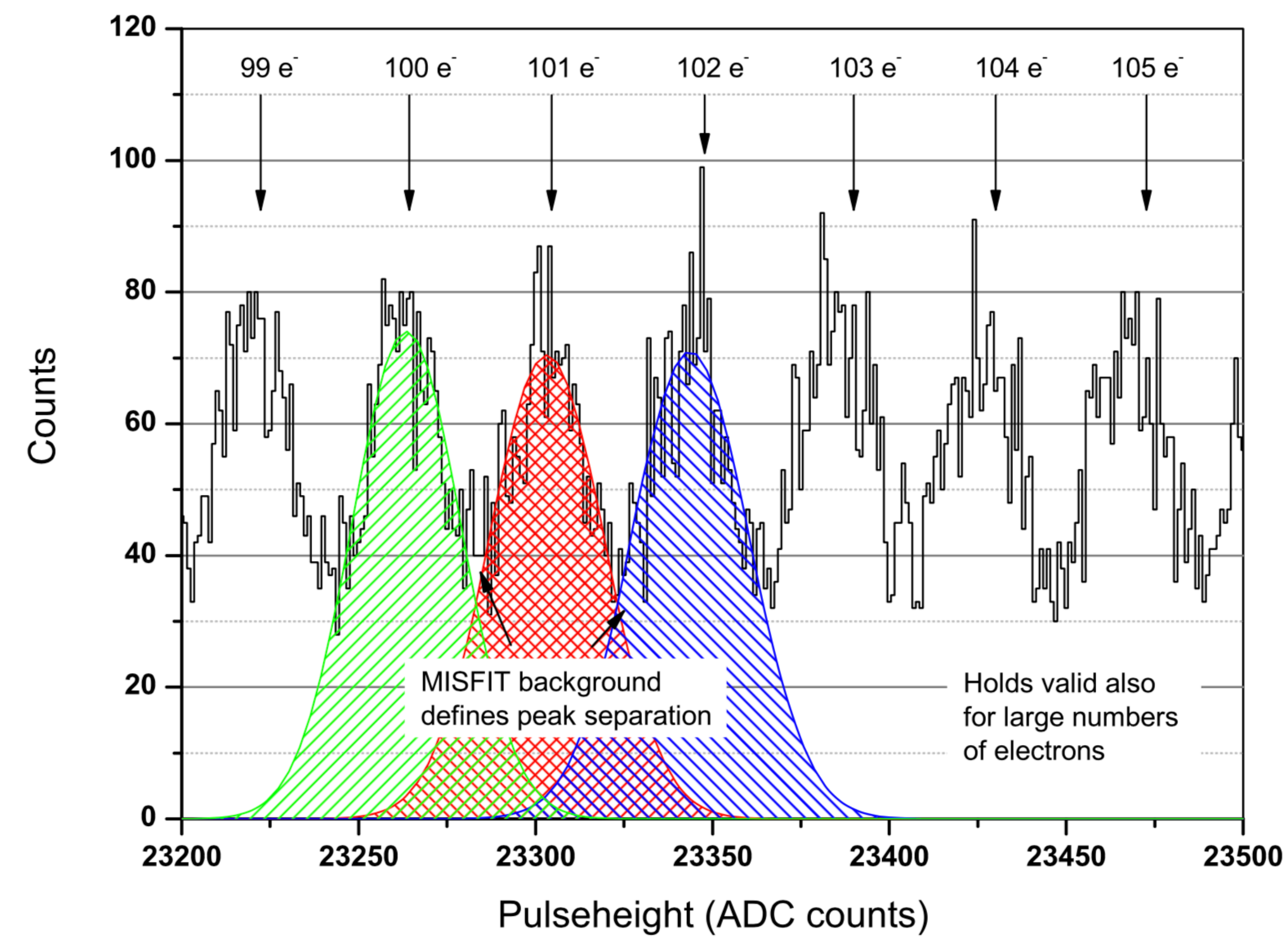
Many such **gates** can be put on **one silicon** and a whole **row can be read at once.**

Inactive pixels not being read consume very **little to no power** but remain active for particle detection.

Single electron sensitivity





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Plots taken from DANAE experiment using DEPFETs for dark mater detection

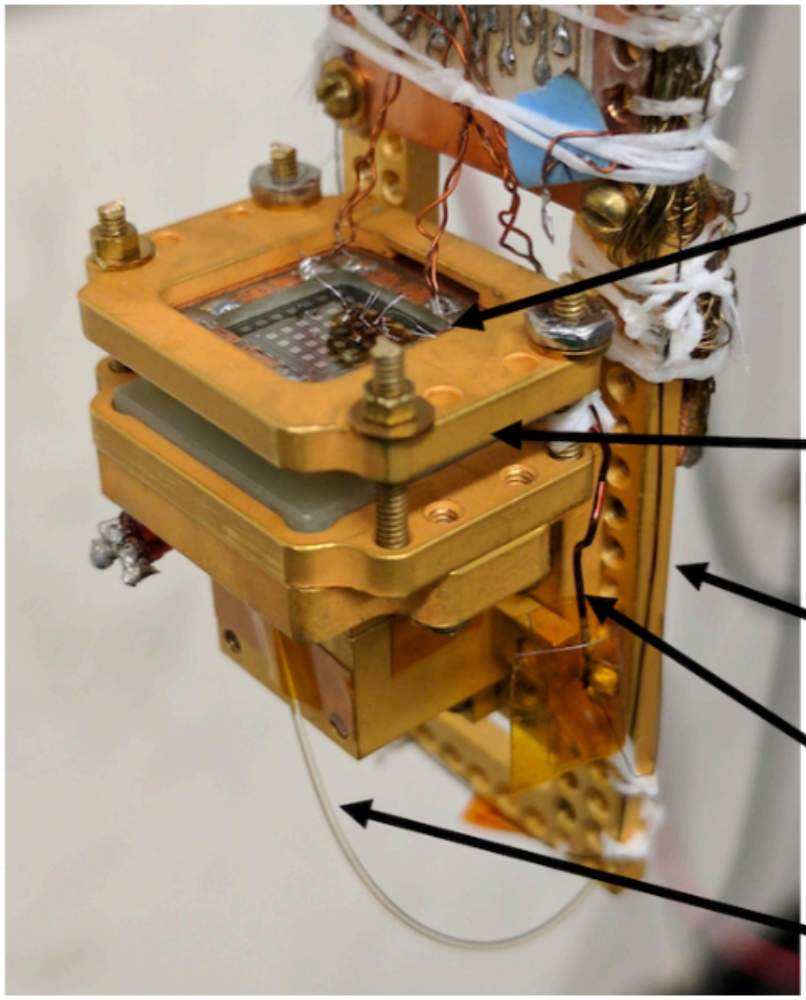
DEPFETs vs Skipper CCDs

Type	Pixel format	Operating Temperature	Dark current	Readout time	Readout noise
Skipper CCD	15 x 15 x 200 (SENSEI) 15x15x675 (DAMIC-M)	140 K	< 1e-/pix/day (SENSEI) < 10^{-3} e^-/pix/day (DAMIC)	10 us/pix	0.068 e^- RMS (LBNL CCDs)
DEPFET	75x75x450	200 K	<1 e- /pix/day	4 us/64 pix	0.2 e- rms/pix

DEPFET Summary

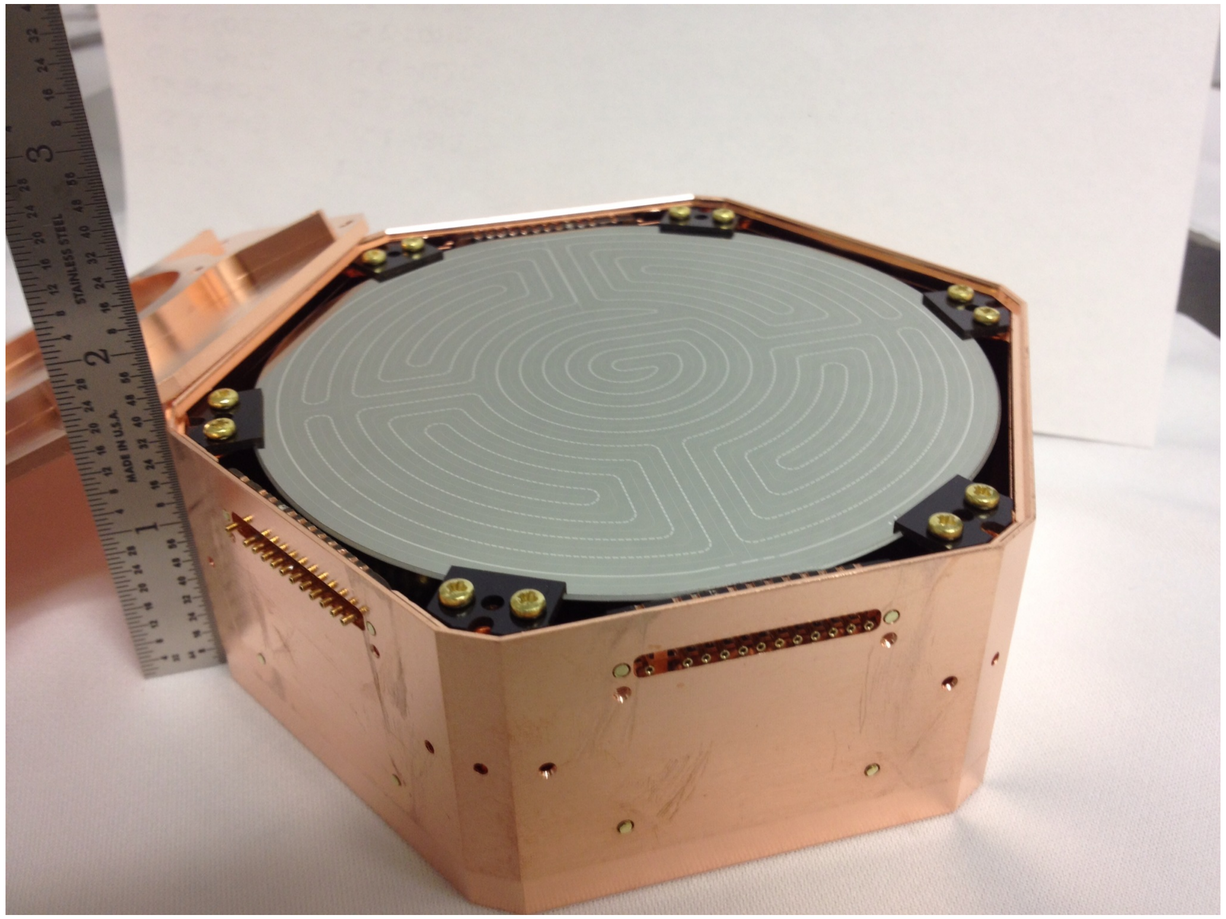
- DEPFETs and Skipper CCDs are similar devices with different implementations of the readout stage.
- DEPFETs also have the potential to detect single electron-hole pairs. The resolution is 0.2 e- RMS/pk.

QETs

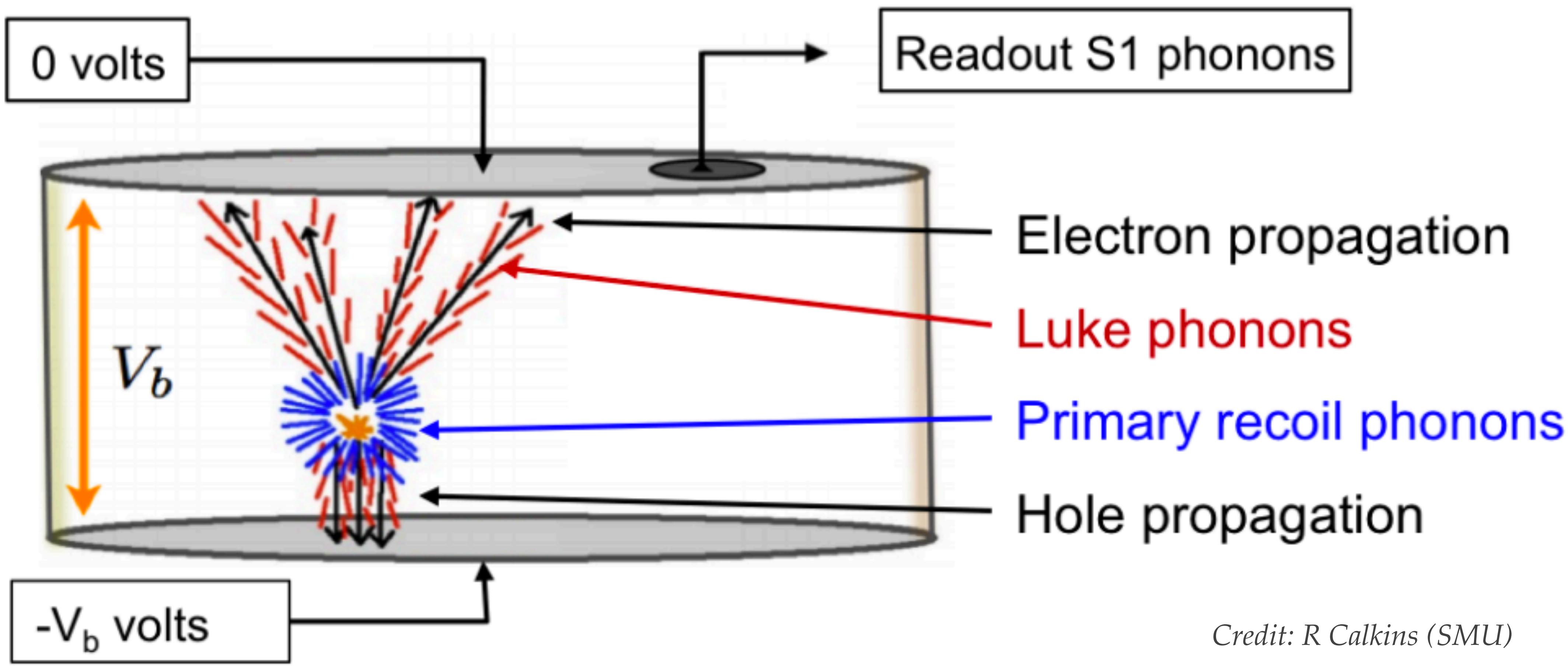

Si crystal/
phonon sensors
Crystal holder
Dilution refrigerator
sample stage (30 mK)
Bias voltage line
Fiber optic

SuperCDMS

- Superconducting devices.
- Si and Ge hockey puck style detectors at 50 mK.
- Electrodes to detect charges and transition edge sensors to detect phonons.



SuperCDMS HV



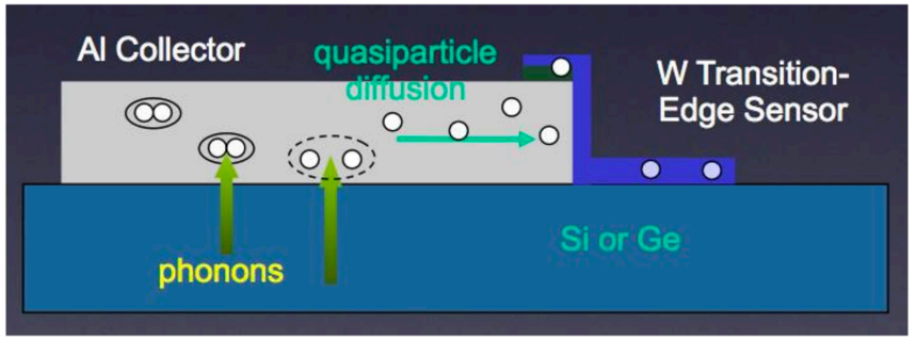
Credit: R Calkins (SMU)

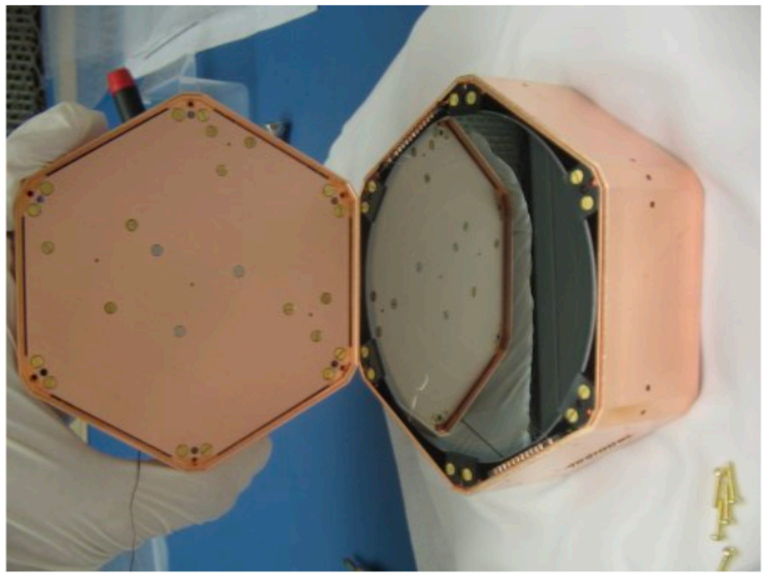
- Recoil produces e-h pairs.
- The electrons drift to the top and holes drift to the bottom.
- Drifting charges gain energy from the E field and radiate this energy as phonons. Larger field = more amplification. This is the Neganov-Luke effect.

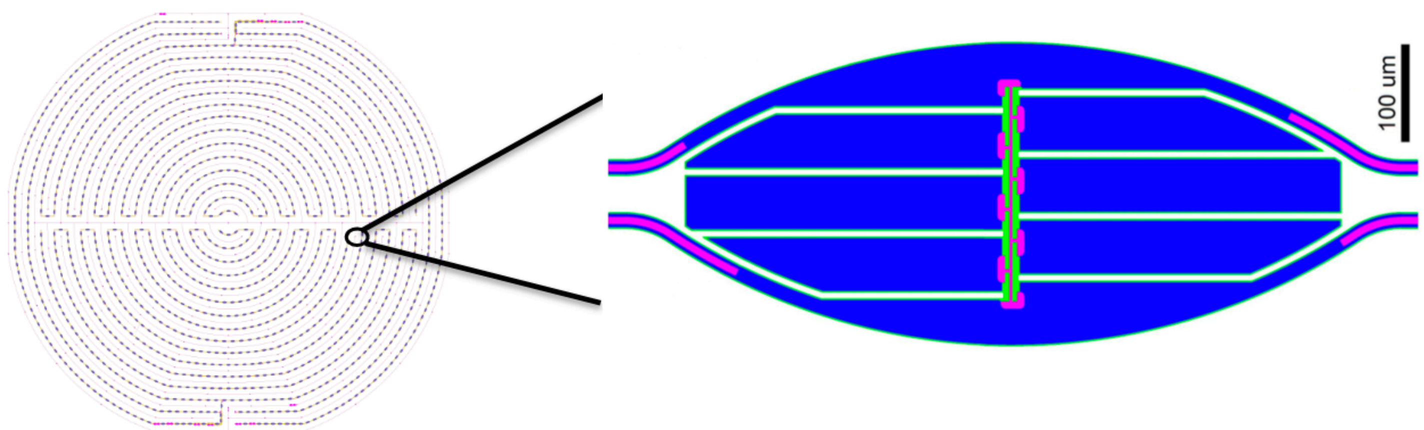
SuperCDMS HV prototype

- A high electric field (140V instead of the normal 4V) is used to amplify the phonon signal.
- The threshold is between 0.2 and 0.5 e-h pairs.

QETs





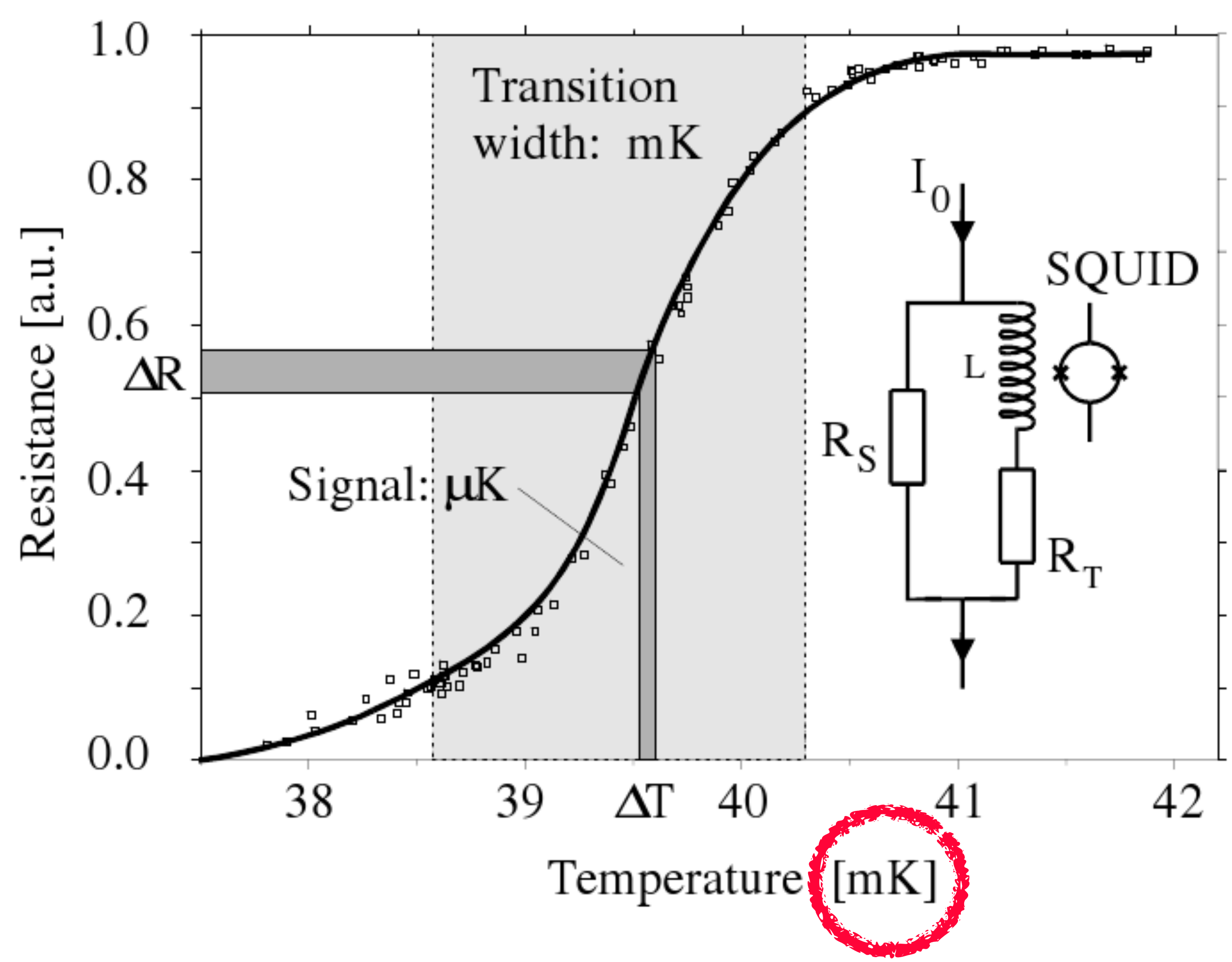


arXiv: 1310.8327

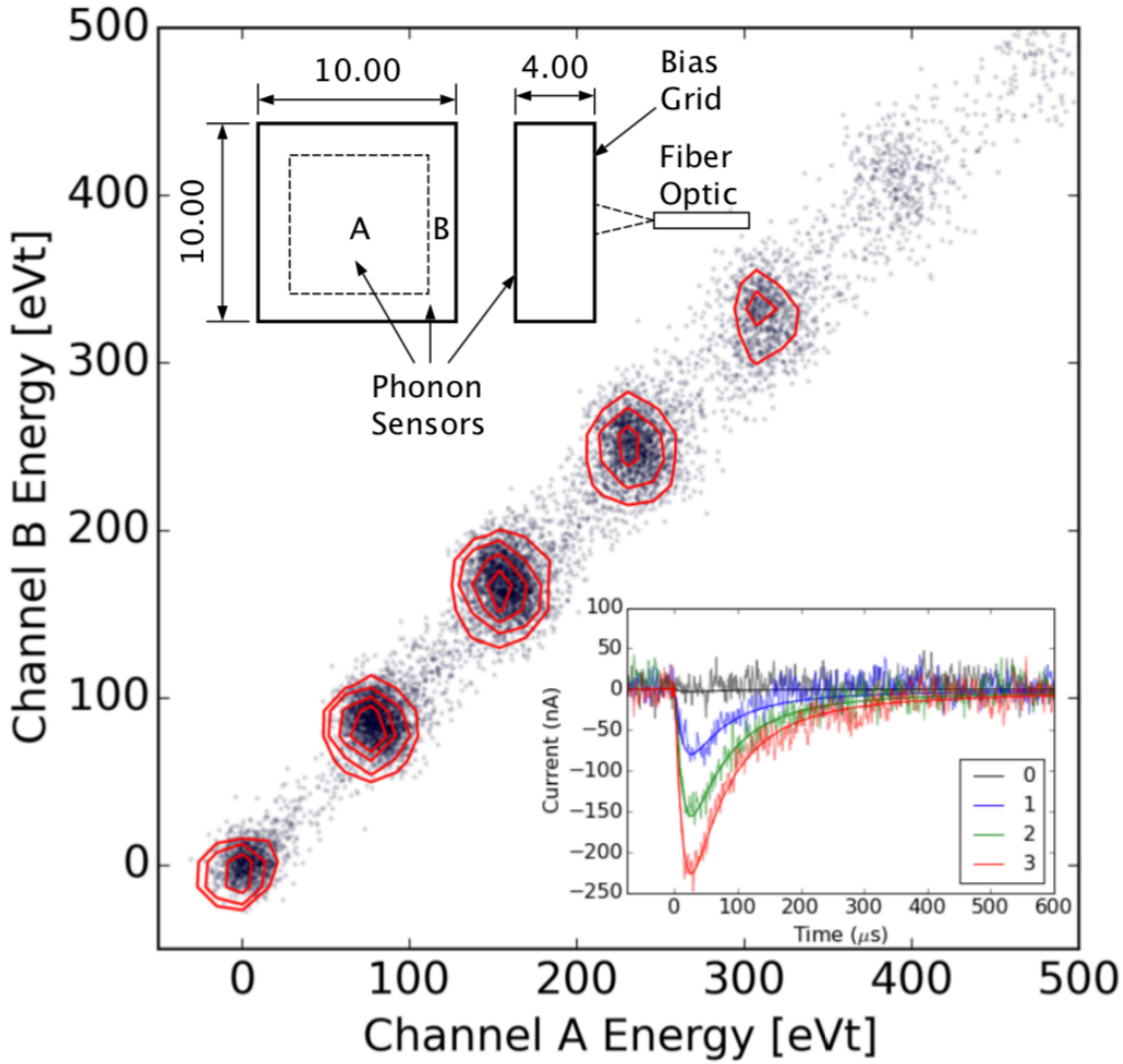
- **Superconducting aluminum fins**, full of Cooper pairs.
- Phonons break a Cooper pairs forming "quasiparticles".
- Band gap is smaller in Tungsten (W) than Al, so quasiparticles move to the W, lose energy and cant get back out.
- Phonon energy now concentrated in the W transition edge sensor.
- This is the "Quasiparticle assisted Electrothermal Feedback detector" or QET.

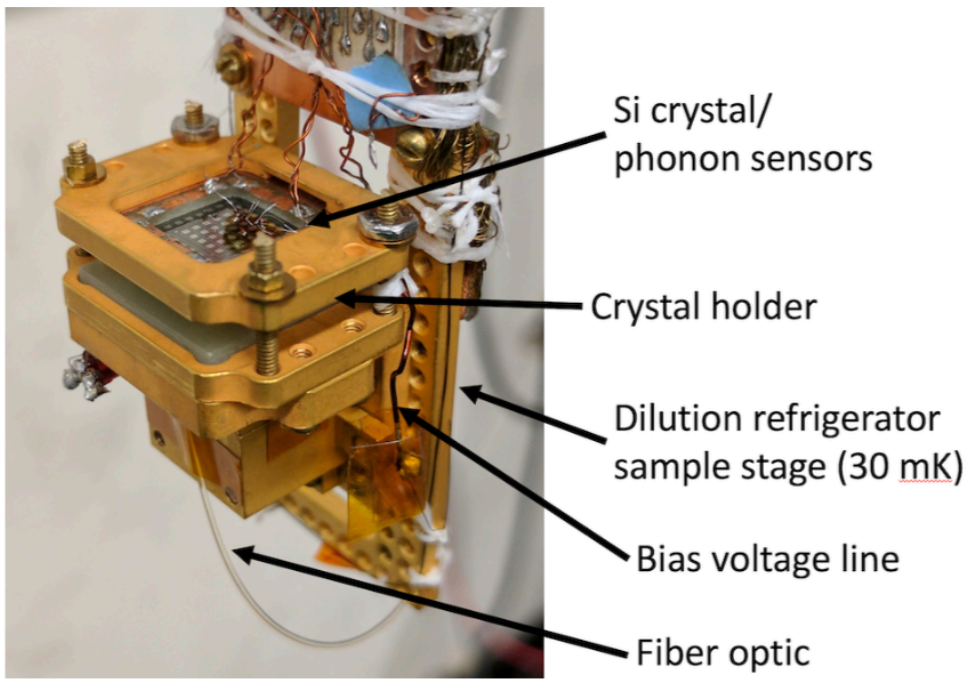
TES Sensors

- The W transition edge sensor (TES) is a superconductor near its critical temperature (Tc).
- The resistance of a superconductor goes up sharply past Tc.
- This change is measured using a SQUID.



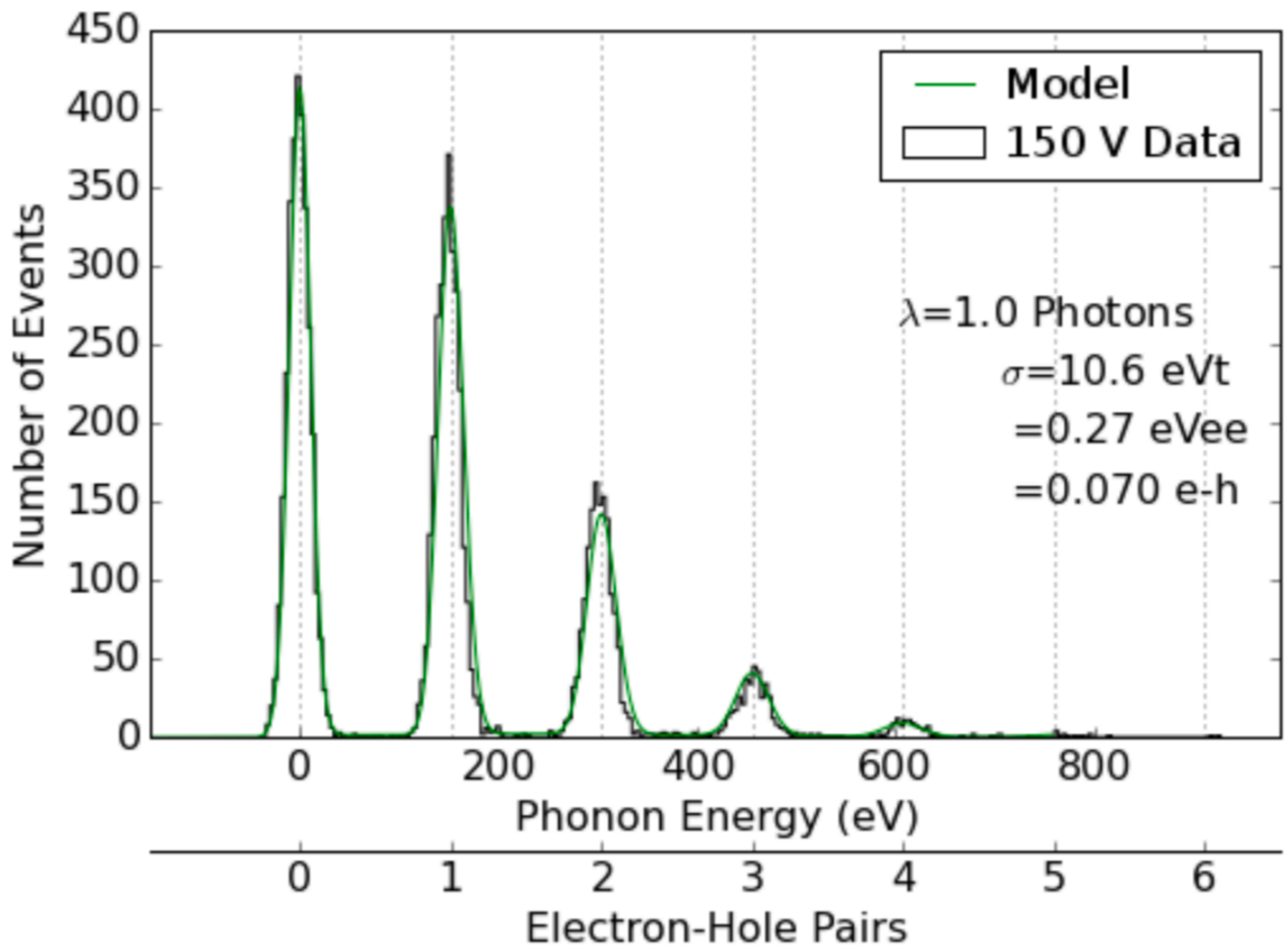
CDMS HV Prototype





Romani et al.
arXiv: 1710.09335

Seeing single charges



Laser calibration data of QETs showing
a resolution of 0.07 electron hole pairs

Romani et al.
arXiv: 1710.09335

QETs Summary

- Electron-hole pair movement in Si produces Neganov-Luke phonons.
- Measurement of phonons via TES sensors assisted by quasiparticle traps.
- Single charge measurement demonstrated with 0.07 e- resolution

DEPFETs vs Skipper CCDs vs QETs

Type	Pixel format	Operating Temperature	Dark current	Readout time	Readout noise
Skipper CCD	15um x 15um x 200um (SENSEI) 15um x 15um x675 um (DAMIC-M)	140 K	< 1e-/pix/day (SENSEI) < 10^{-3} e^-/pix/day	10 us/pix	0.068 e^- RMS (LBNL CCDs)
DEPFET	75x75x450	200 K	<1 e- /pix/day	4 us/64 pix	0.2 e- rms/pix
QET	1cm x 1cm x 4 mm (single crystal)	30-35 mK	10 e-h pairs/sec*	10 us	0.09 e-

Note: Energy resolution of Skipper CCDs and DEPFET are not limited by wafer size. QET's phonon signal resolution degrades with increasing size

**See M. Pyle's slides from the talk on Monday 1:30PM*

Summary

- Skipper CCDs and DEPFETs are semiconductor devices that **achieve** their **sensitivity** by **measuring charges repeatedly** many times over.
- DAMIC has **demonstrated** that CCDs can be constructed with a **very low dark curren**t.
- QETs achieve their sensitivity by measuring **Neganov Luke phonons** with **transition edge sensors** assisted by quasiparticle traps.
- All three technologies are being used presently for low mass dark matter searches.