Direct Detection of sub-GeV Dark Matter

Rouven Essig

Yang Institute for Theoretical Physics

Stony Brook University

The Future of Searches for Invisible Particles, Aachen, Dec 14-15, 2017

Collaborators

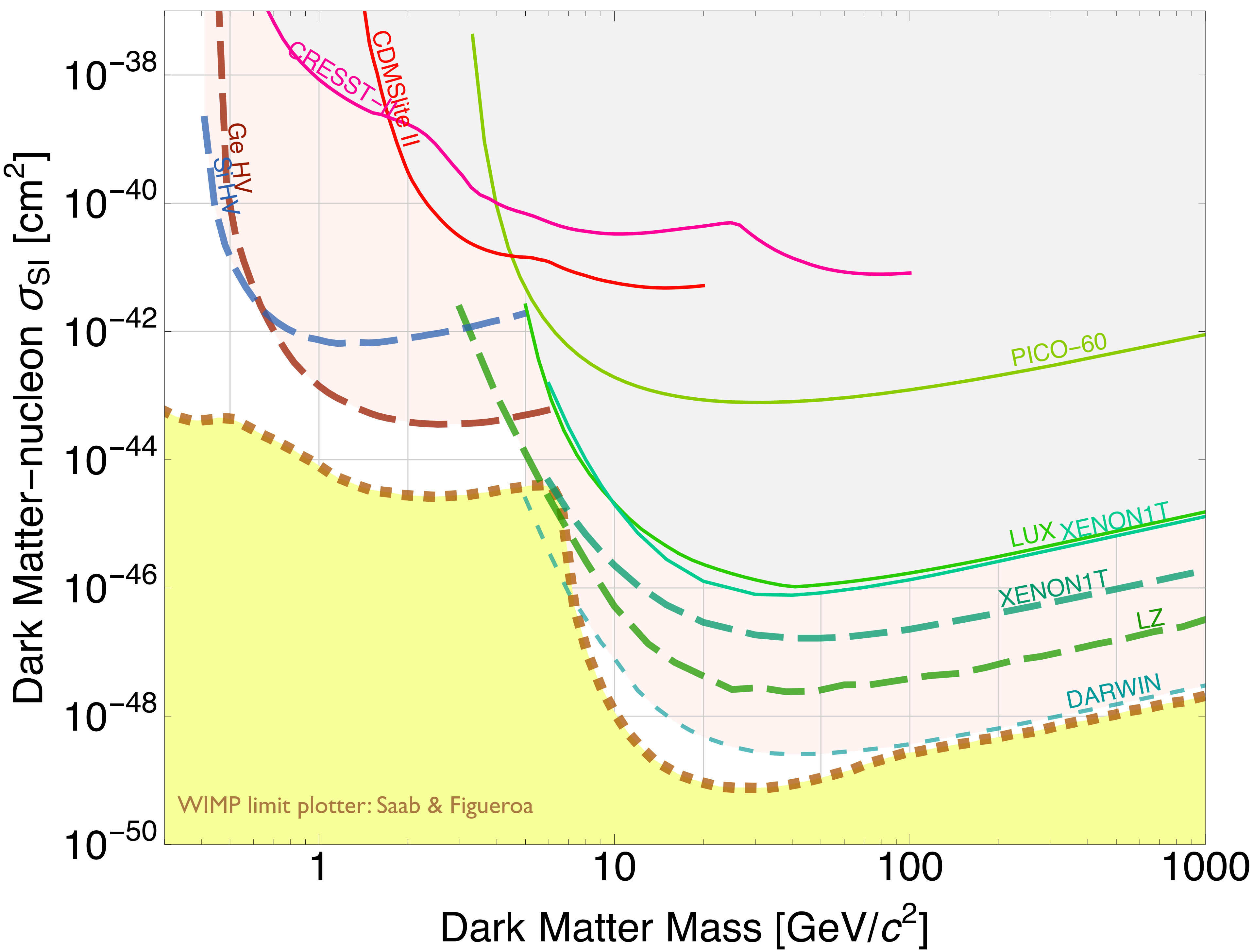
Theorists:

- Tomer Volansky, Jeremy Mardon
- Tien-Tien Yu, Marivi Fernandez-Serra
- Sam McDermott, Tobioka Kohsaku
- Jae Hyeok Chang, Andrea Massari, Mukul Sholapurkar, Adrian Soto, Yiming Zhong, Oren Slone, Itay Bloch

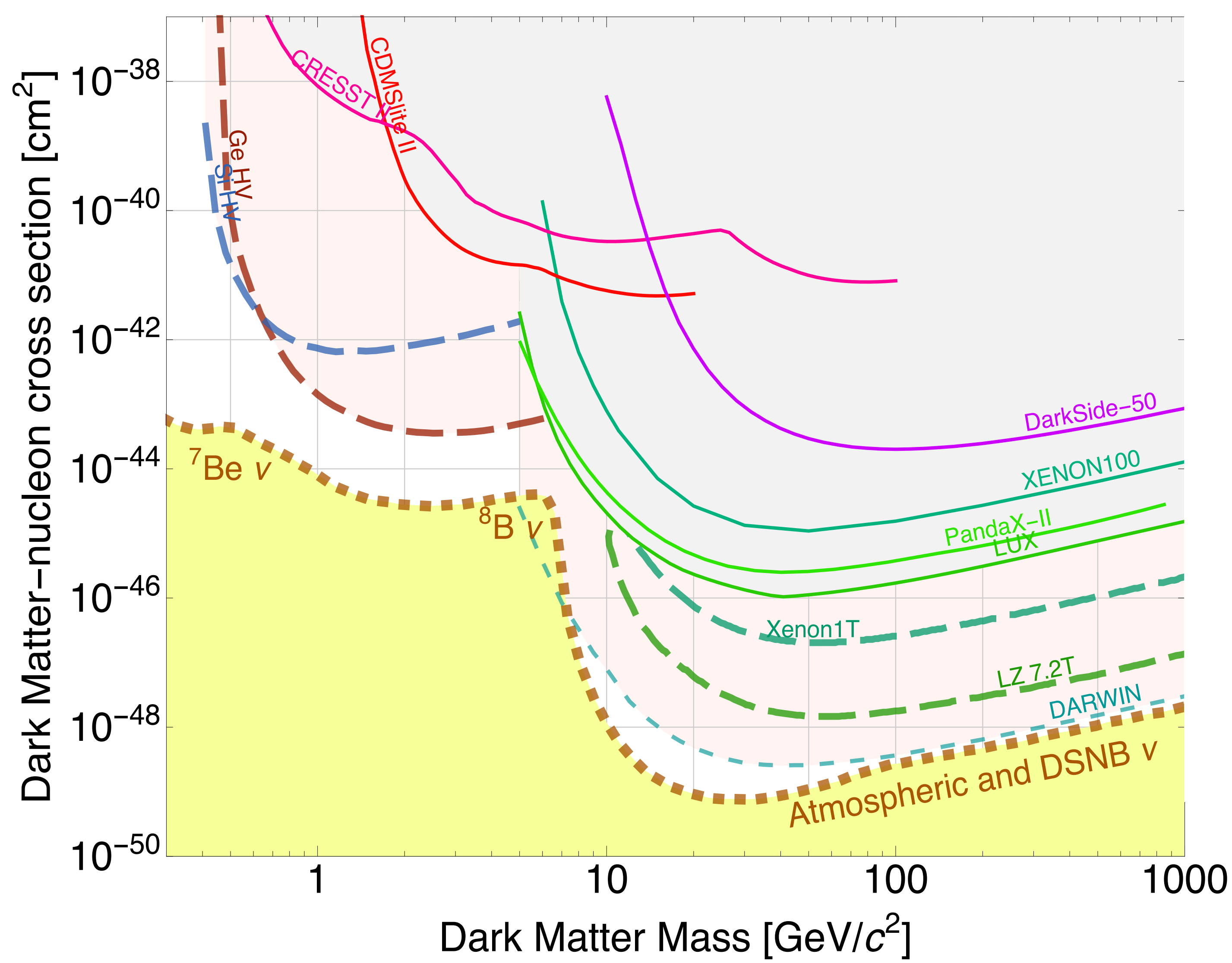
Experimentalists:

- **SENSEI:** J. Tiffenberg, J. Estrada, M. Sofo-Haro
- **UA'1:** A. Bernstein, R. Lang, K. Ni, P. Sorensen, J. Xu
- **GaAs scintillator:** S. Derenzo, M. Pyle

Direct-Detection Experiments usually search for nuclear recoils

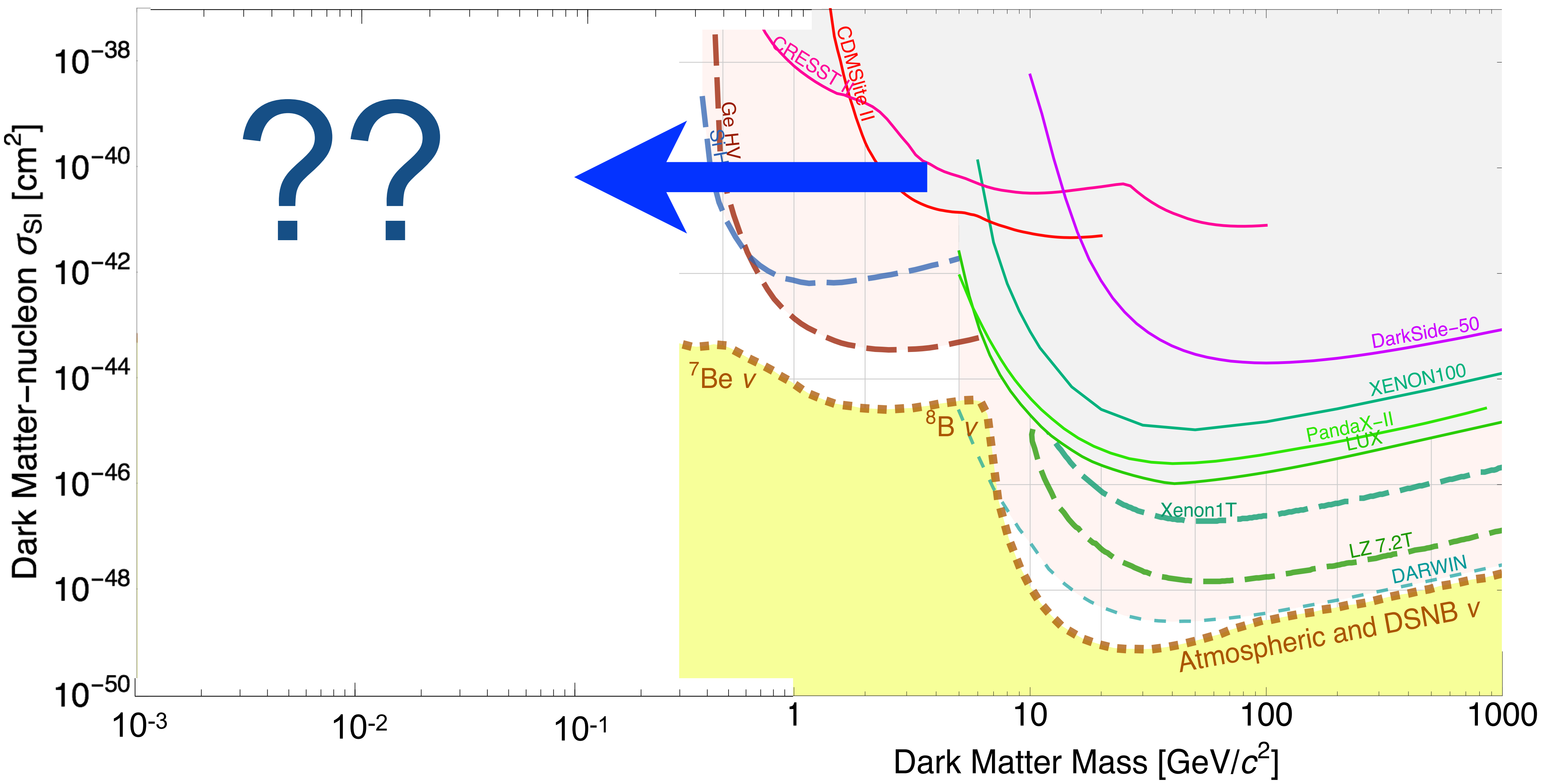


The WIMP program is active, important, and exciting!



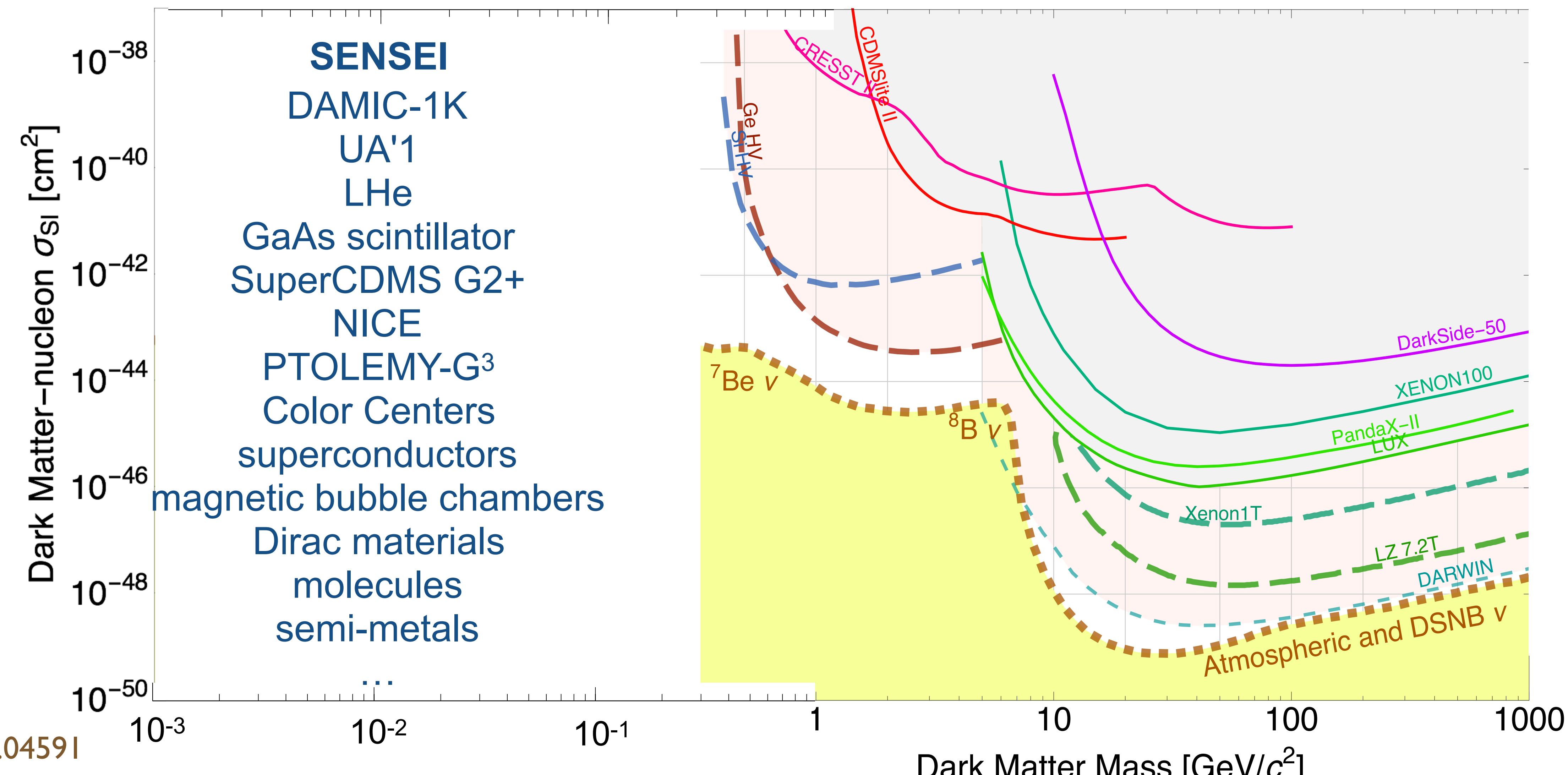
Dark Matter–nucleon cross section [cm^2]
Dark Matter Mass [GeV/c^2]
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
1
10
100
1000
CRESST
CDMSlite II
Ge HV
Si HV
DarkSide–50
XENON100
PandaX–II
LUX
Xenon1T
LZ 7.2T
DARWIN
^{7}Be ν
^{8}B ν
Atmospheric and DSNB ν

Can we probe < 1 GeV?



Take-away message: Yes!

- Constraints down to m_{DM}~5 MeV
- Significant improvements with **SENSEI** in 1–2 yrs
- + many other great ideas exist to probe new territory
- Probe simple & predictive benchmark models



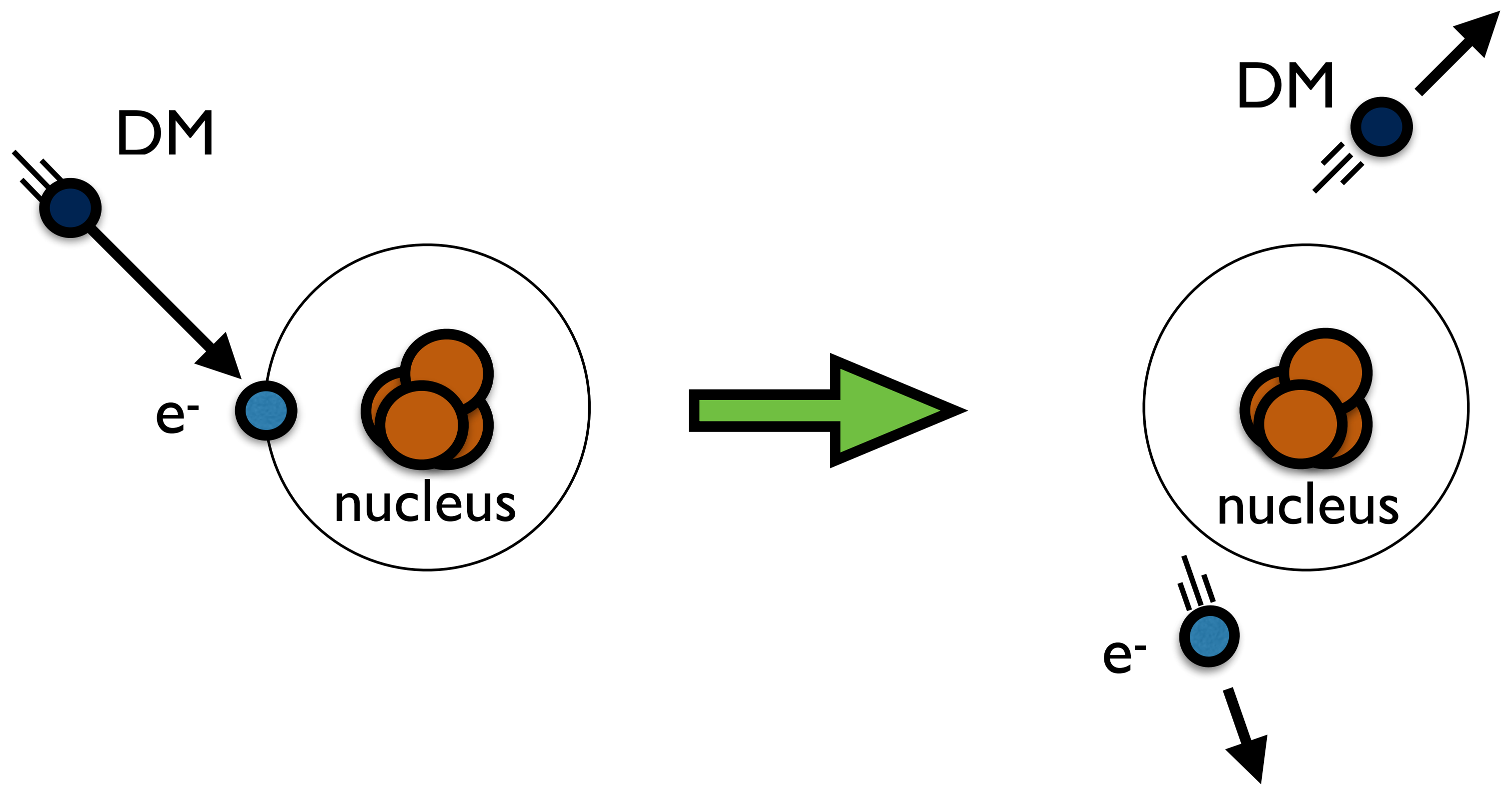
see 1707.04591 for a review

Outline

- Direct-detection concept
- SENSEI
- Prospects & Models (brief)

DM-electron scattering can probe $\ll$GeV

RE, Mardon, Volansky, 2011



Typically* produces a signal of one or a few electrons

*other signals also possible!

DM-electron scattering can probe $\ll$GeV

to overcome binding energy ΔE

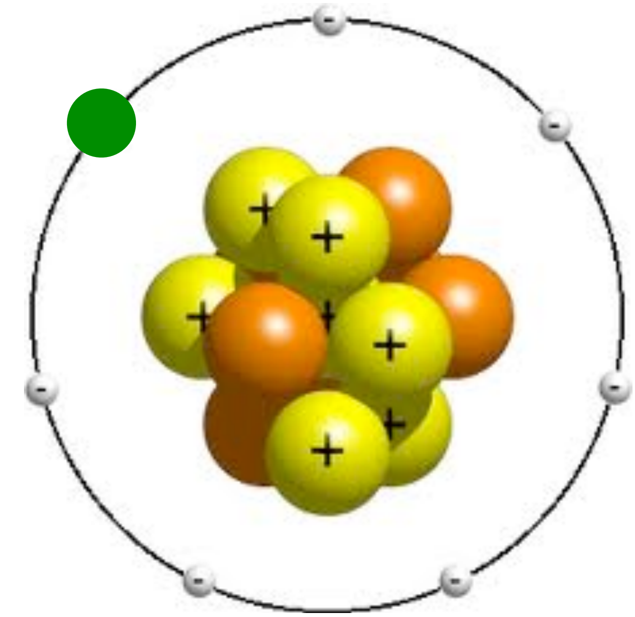
need $E_{\rm DM} \sim \frac{1}{2} m_{\rm DM}\, v_{\rm DM}^2 > \Delta E$

$$v_{\rm DM} \lesssim 600~{\rm km/s} \implies m_{\rm DM} \gtrsim 300~{\rm keV}~\left(\frac{\Delta E}{1~{\rm eV}}\right)$$

Note: typical recoil energy of e^- is a few eV

Target materials for electron recoils?

Type	Examples	mass threshold
Noble liquids	xenon	~3 MeV

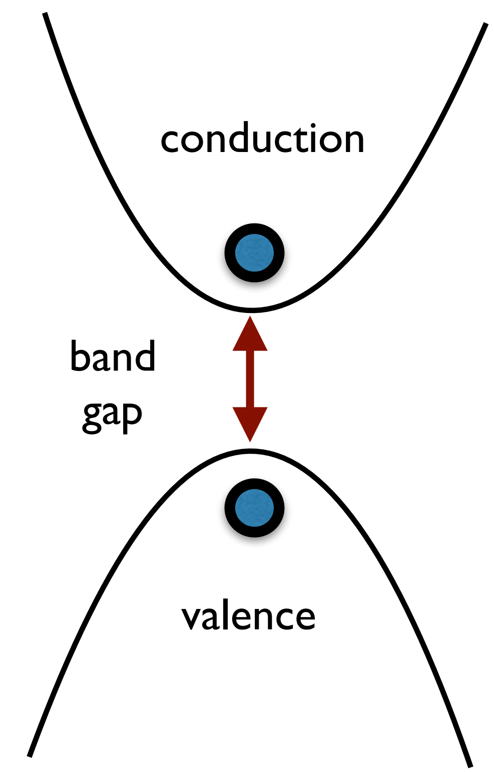


$$\Delta E \sim 10 \text{ eV}$$

RE, Mardon, Volansky
RE, Manalaysay, Mardon, Sorensen, Volansky
RE, Volansky, Yu
Bernstein, RE, Fernandez-Serra, Lang, Ni, Sorensen, Xu…

Target materials for electron recoils?

Type	Examples	mass threshold
Noble liquids	xenon	~3 MeV
Semiconductors	germanium, silicon	~300 keV



$$\Delta E \sim 1 \text{ eV}$$

RE, Mardon, Volansky
Graham, Kaplan, Rajendran, Walters
Lee, Lisanti, Mishra-Sharma, Safdi
RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

Target materials for electron recoils?

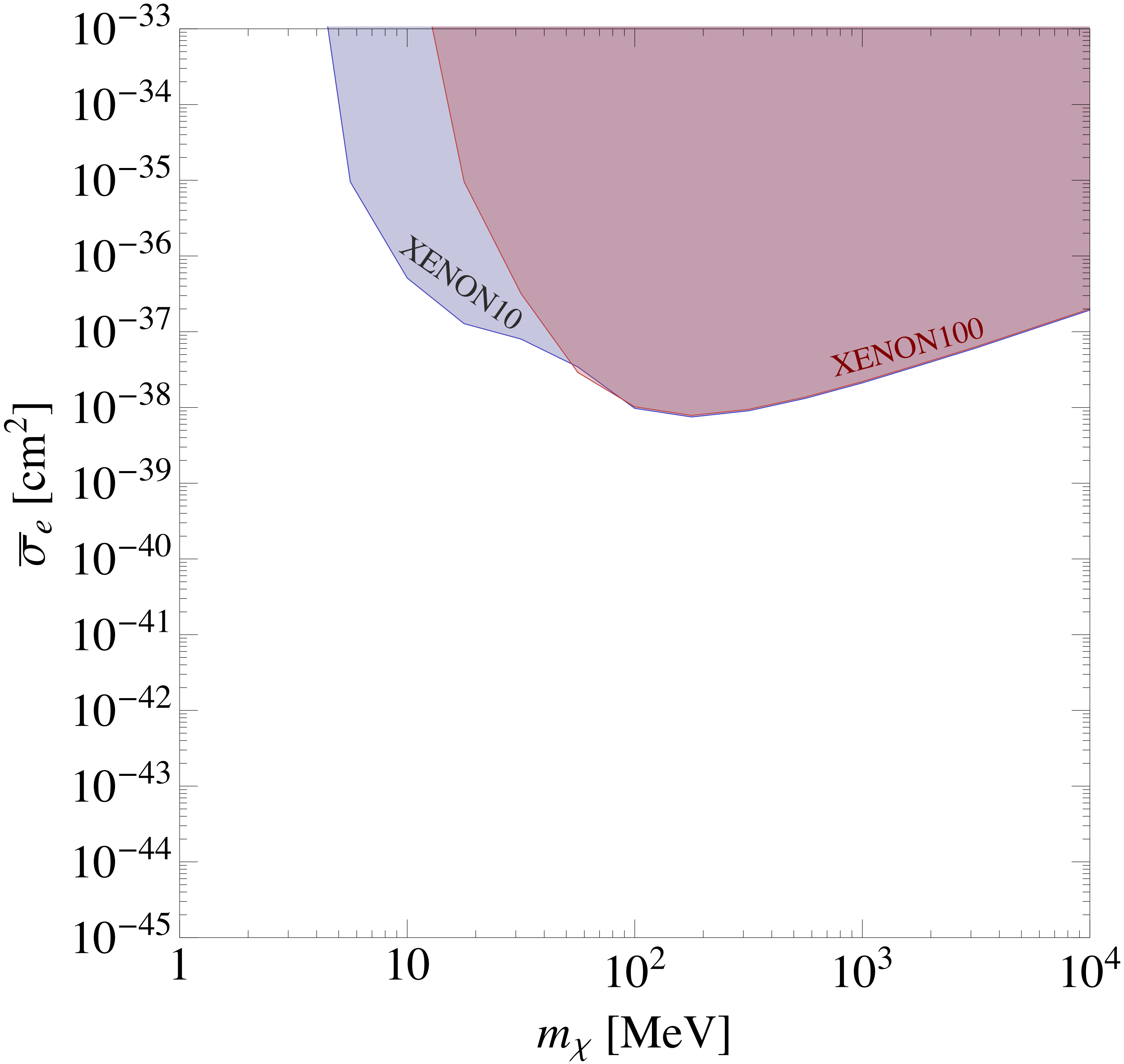
Type	Examples	mass threshold	Status
Noble liquids	xenon	~3 MeV	Done w/ XENON10+100 data; new proposal: UA′1 experiment
Semiconductors	germanium, silicon	~300 keV	funded experiment: SENSEI, m_{DM} ~ MeV
Many other ideas	GaAs, Graphene, He, superconductors…	various (> keV)	R&D ongoing/required

Constraints from XENON10/100 data

RE, Volansky, Yu 2017

updated from

RE, Manalaysay, Mardon, Sorensen, Volansky, 2012



- large detector-specific backgrounds currently limit sensitivity
- proposed experiment **UA′(1)** will seek to understand & mitigate these backgrounds & build a dedicated ~10 kg experiment

Bernstein, RE, Fernandez-Serra, Lang, Ni, Sorensen, Xu…

XENON10 data: 1104.3088
XENON100 data: 1605.06262

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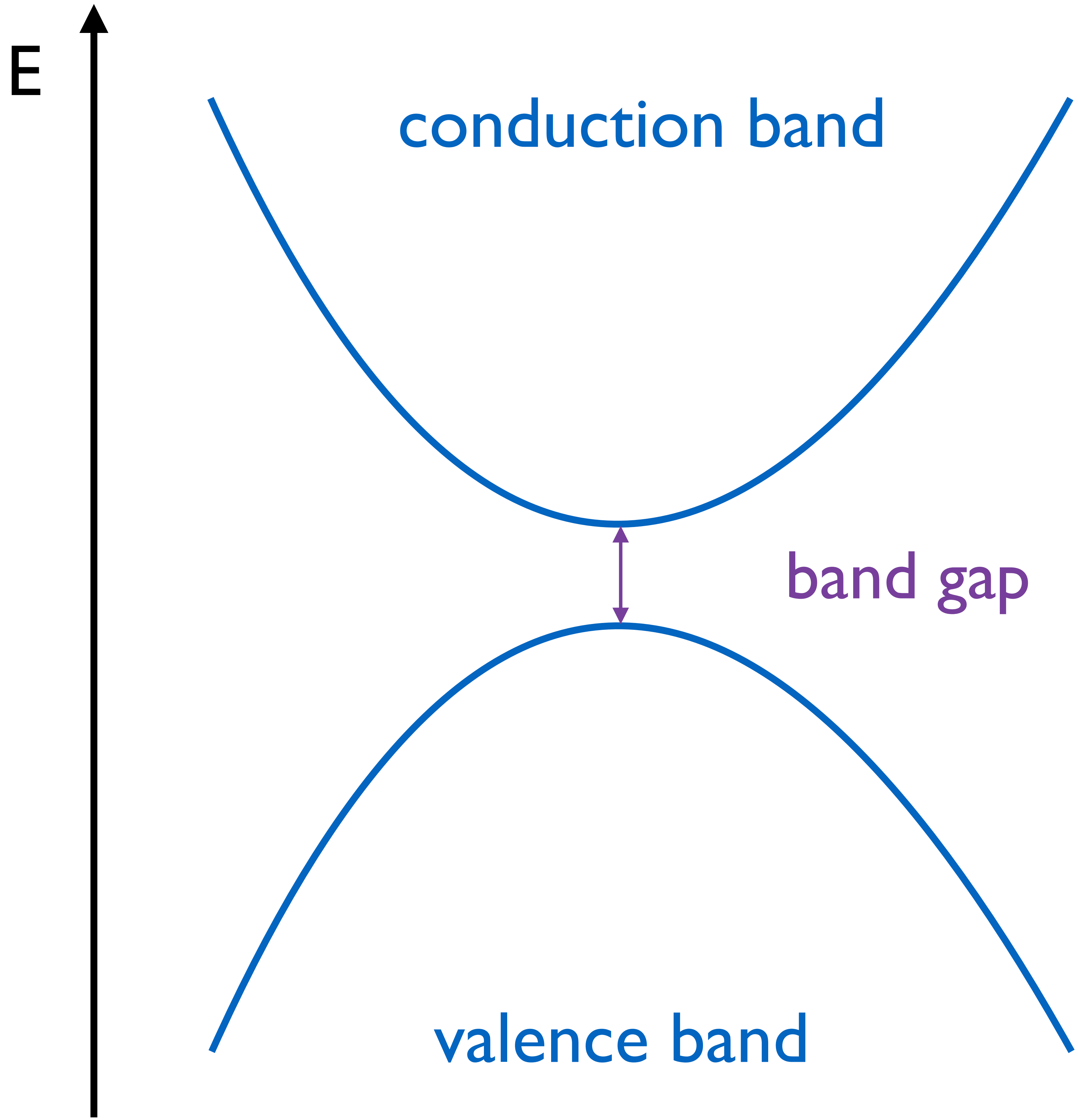
SENSEI's target material is silicon (a semiconductor)

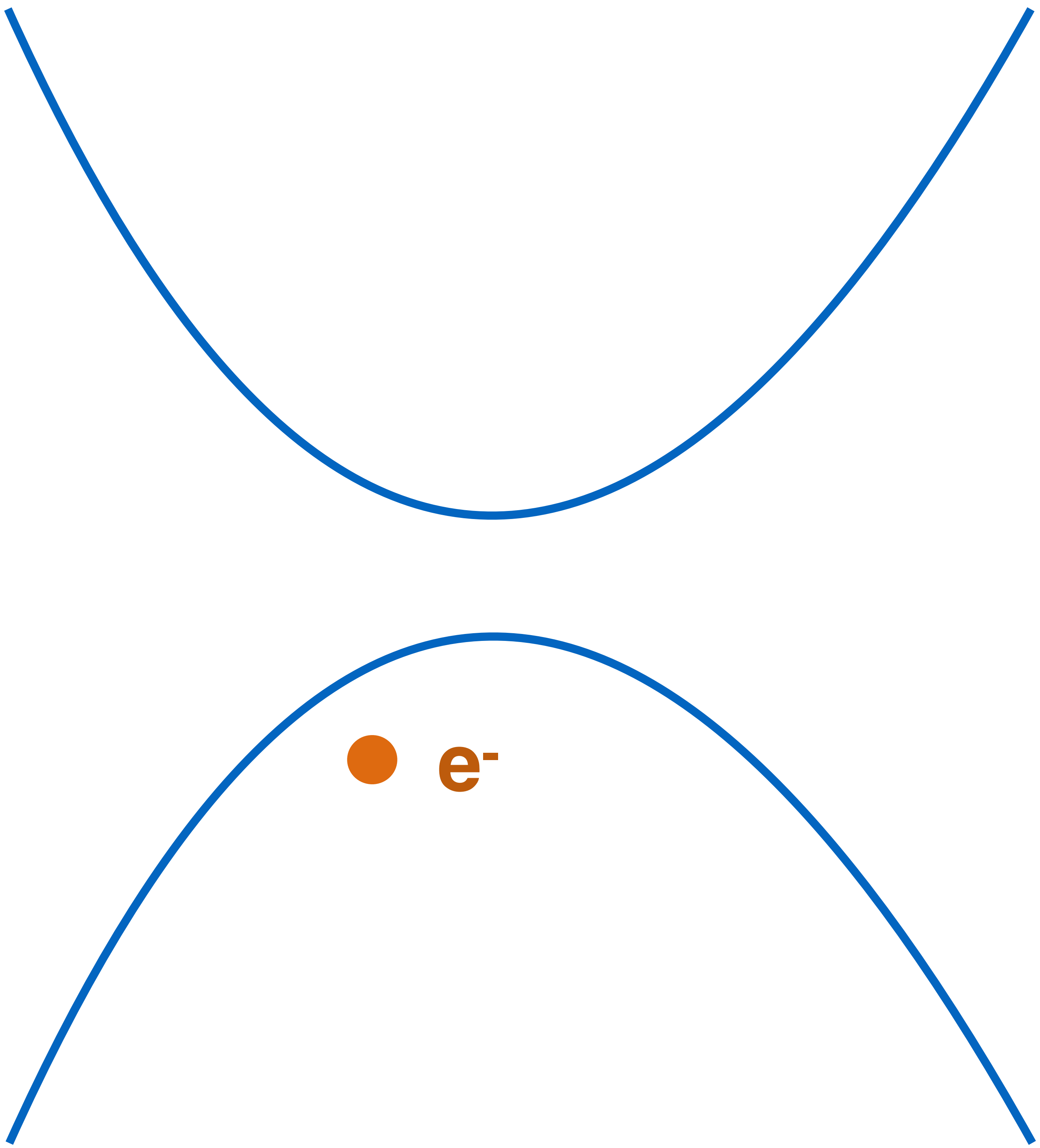
Semiconductors



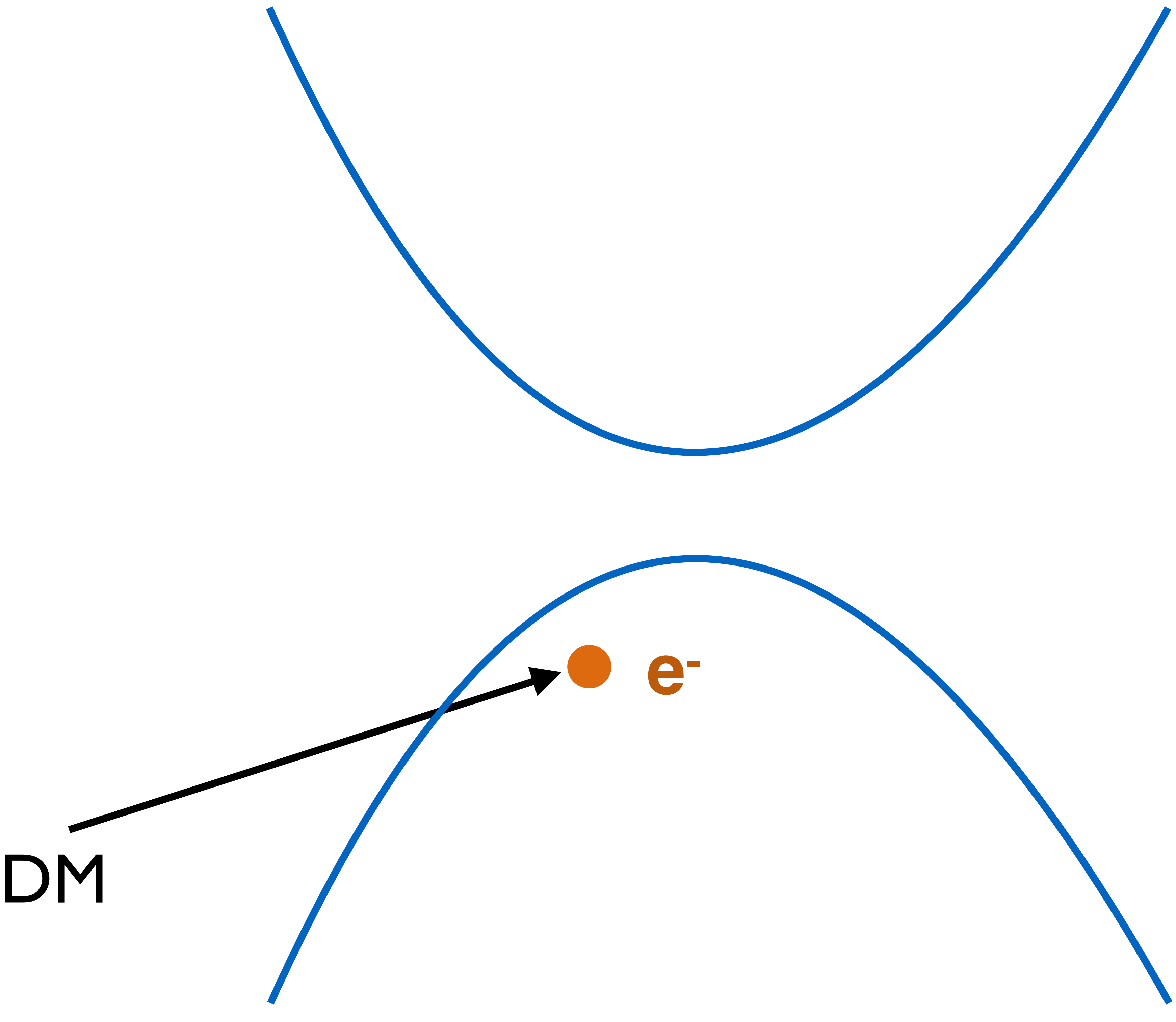
band gaps

Ge	0.67 eV
Si	1.1 eV

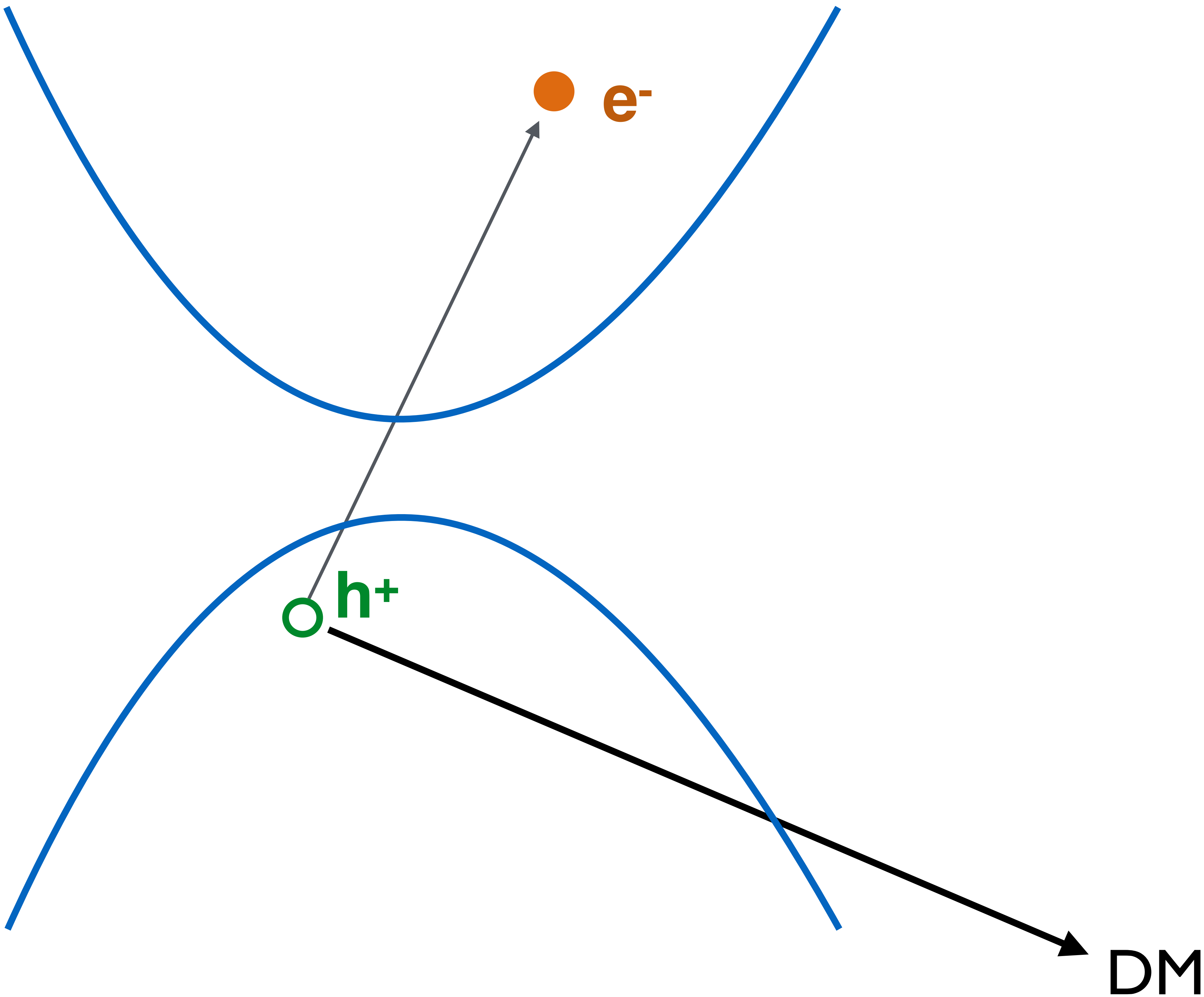
Semiconductors



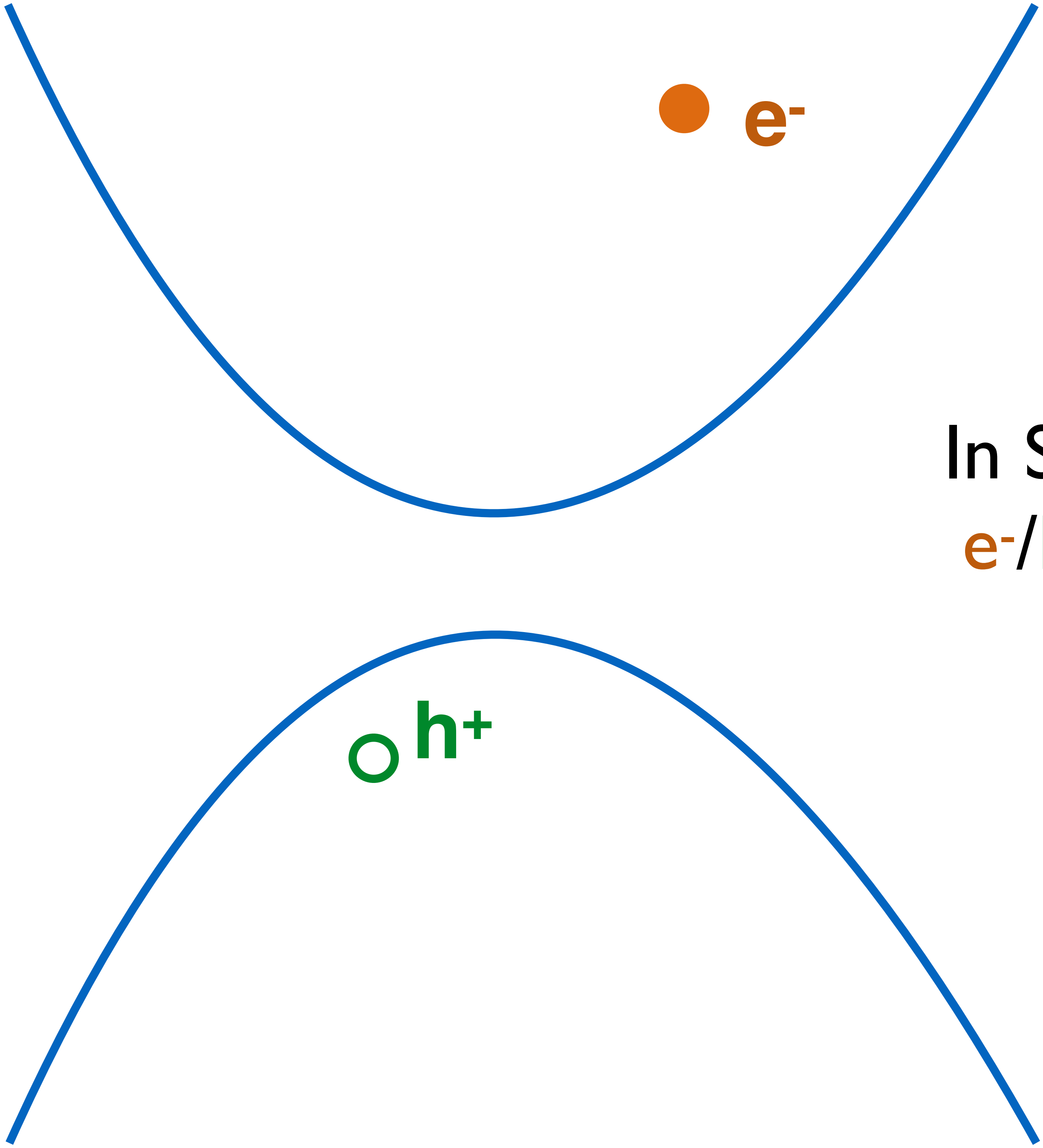
Semiconductors



Semiconductors

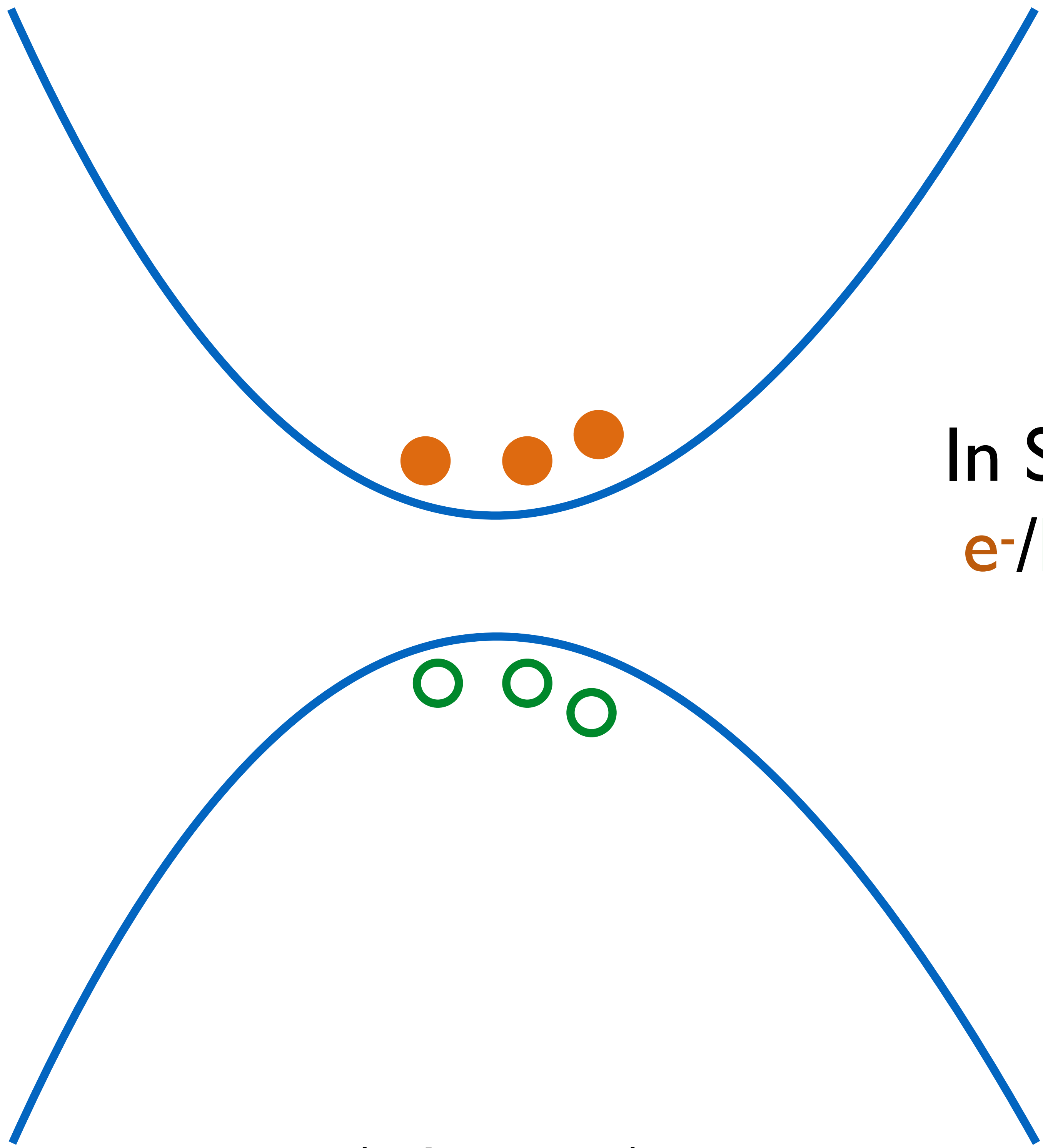


Semiconductors



In Si, create one additional e^-/h^+ pair for each 3.6 eV of recoil energy

Semiconductors

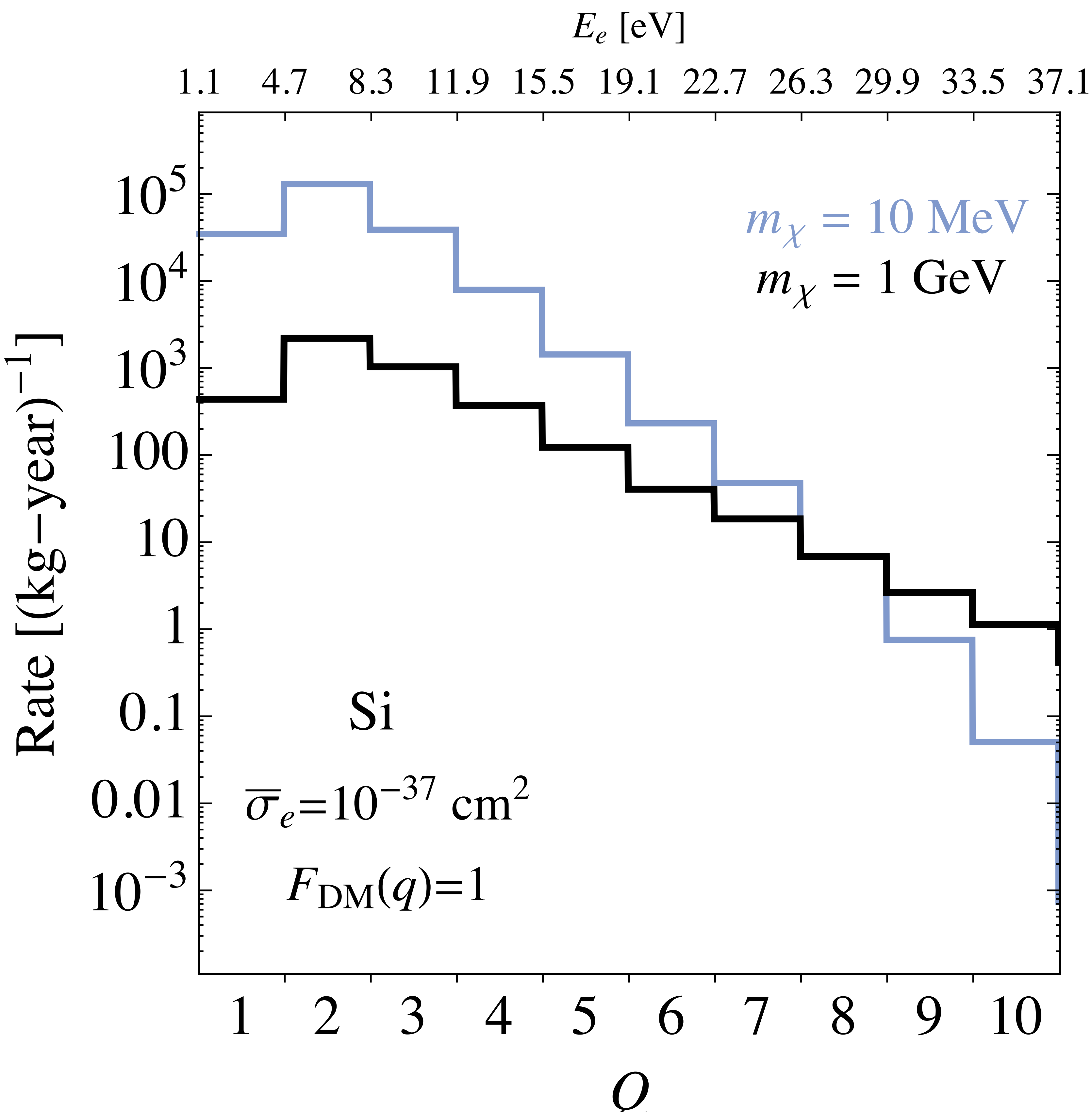


(schematic)

In Si, create one additional e^-/h^+ pair for each 3.6 eV of recoil energy

Rates increase dramatically for lower thresholds

RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu

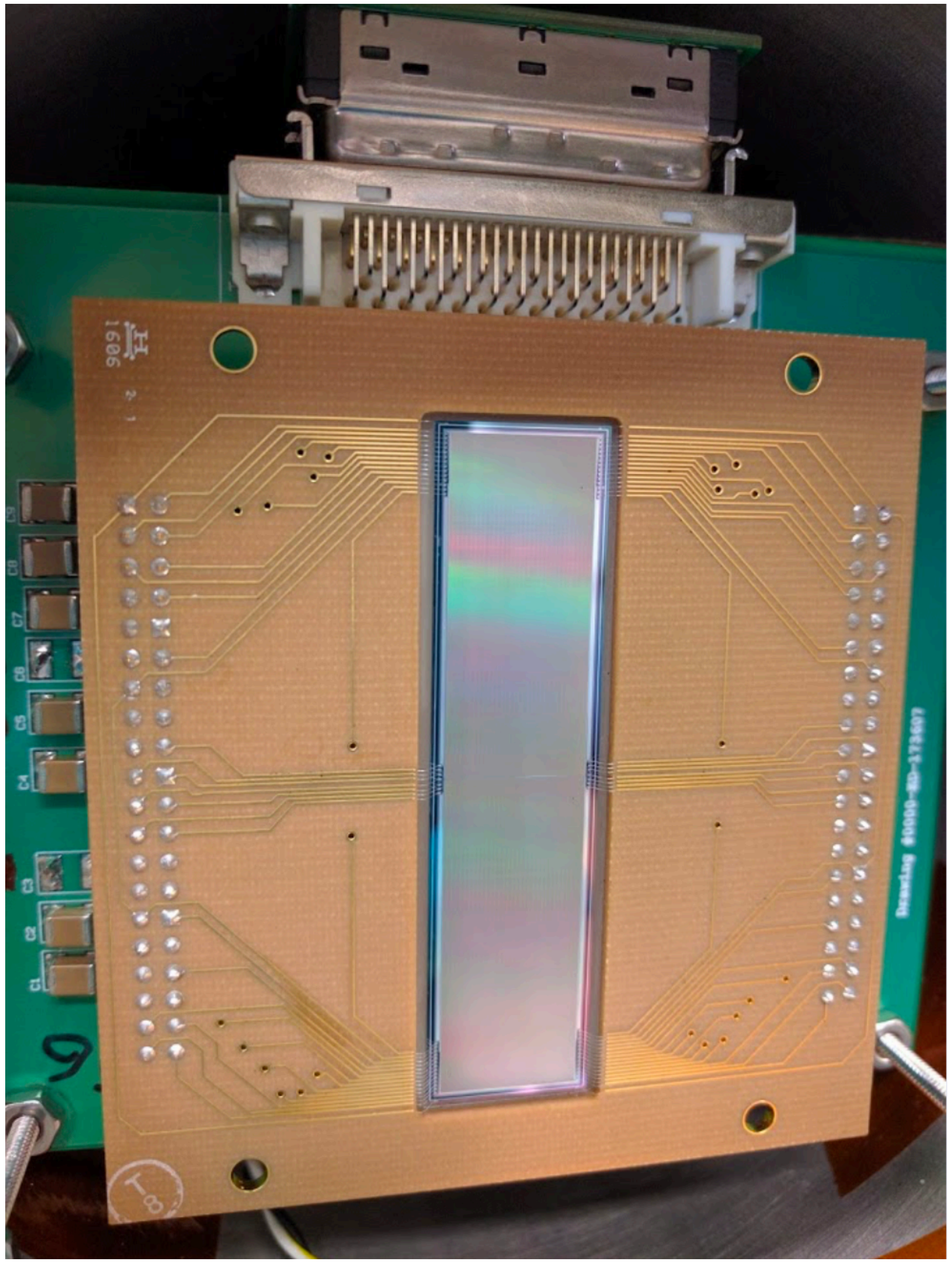


Best threshold before June 2017: ~ 11e$^-$ (40 eV)

A recent technological breakthrough enables much lower thresholds: SENSEI

http://ddldm.physics.sunysb.edu

SENSEI's target material are special silicon CCDs



~million pixels

"Skipper CCDs"

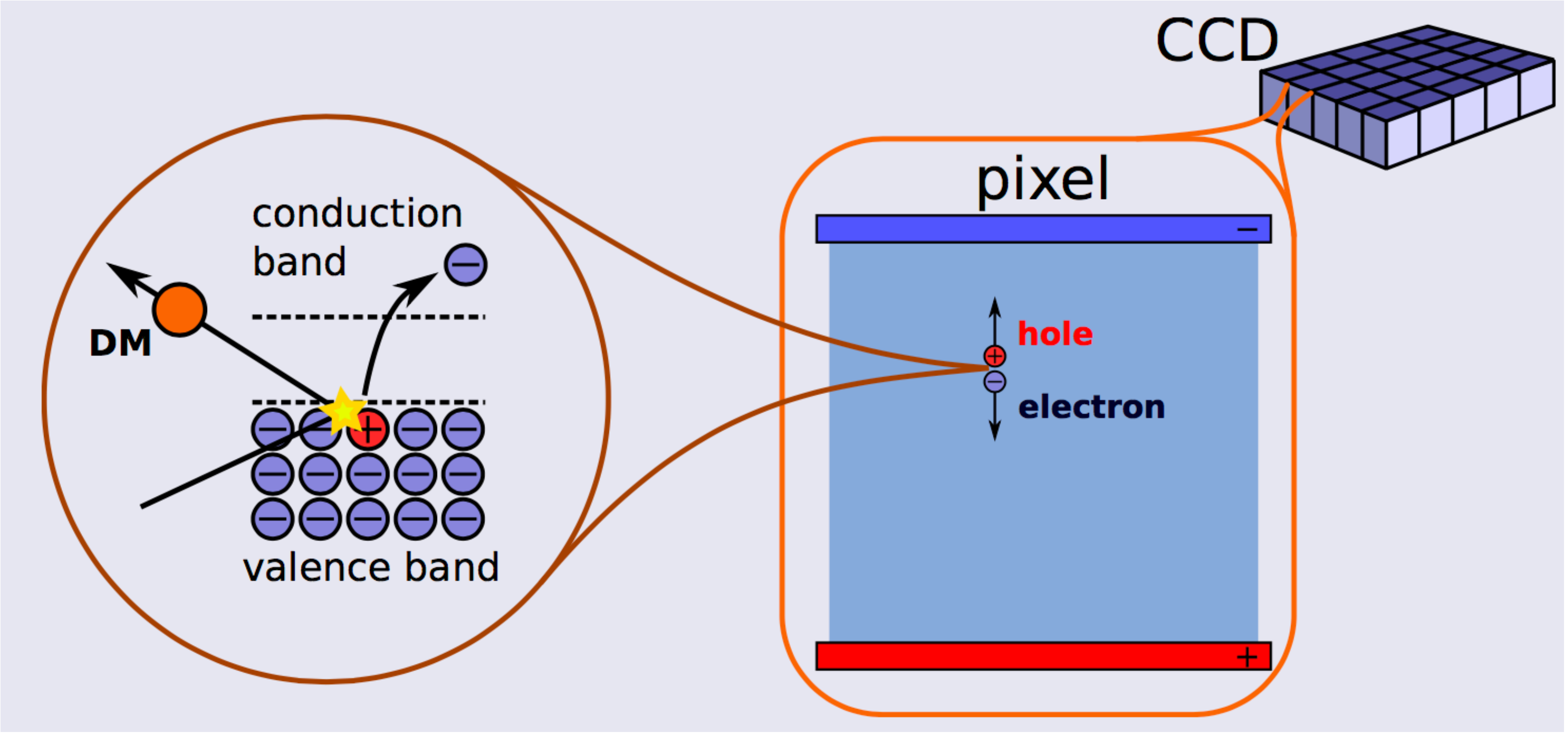
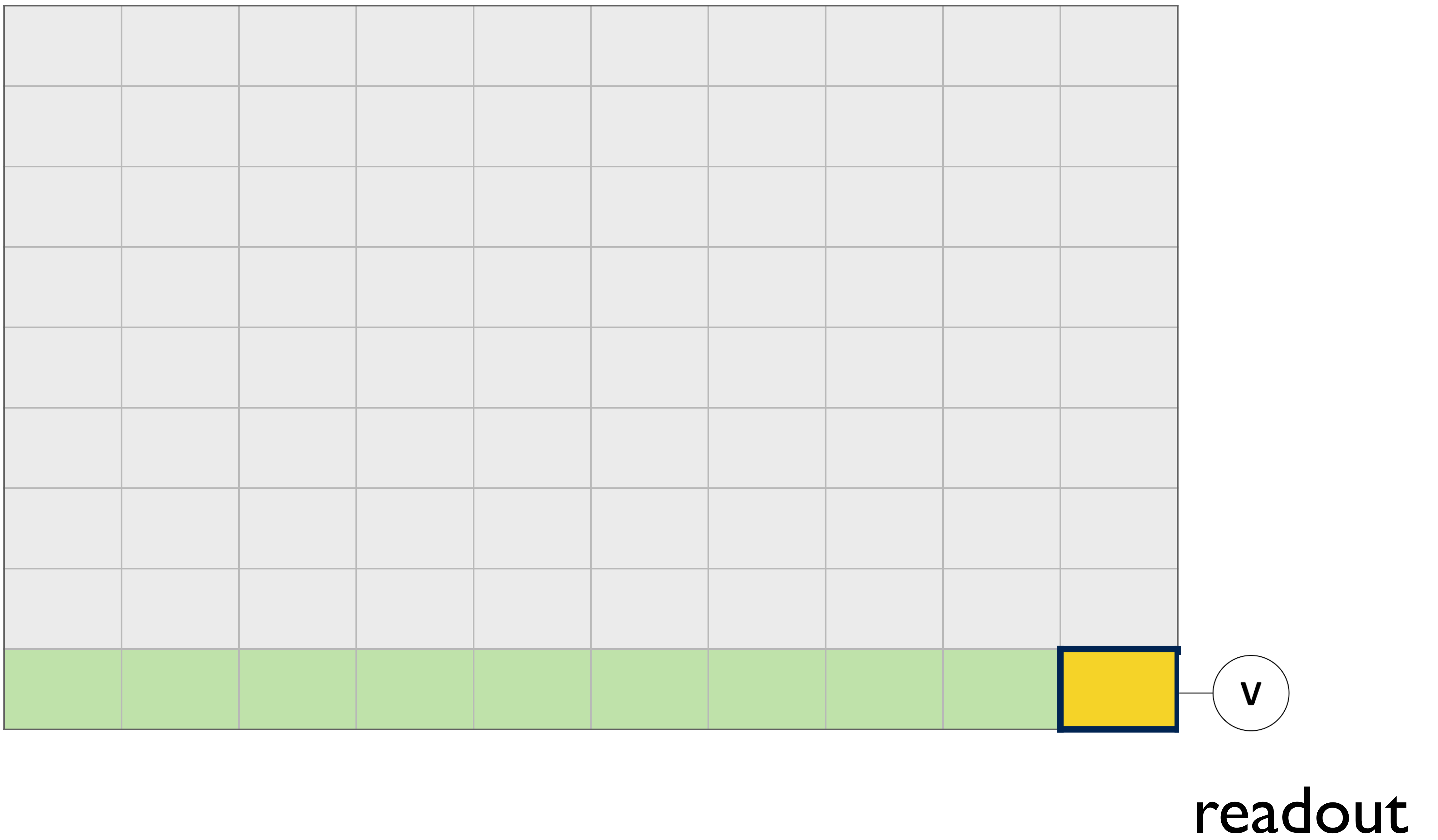
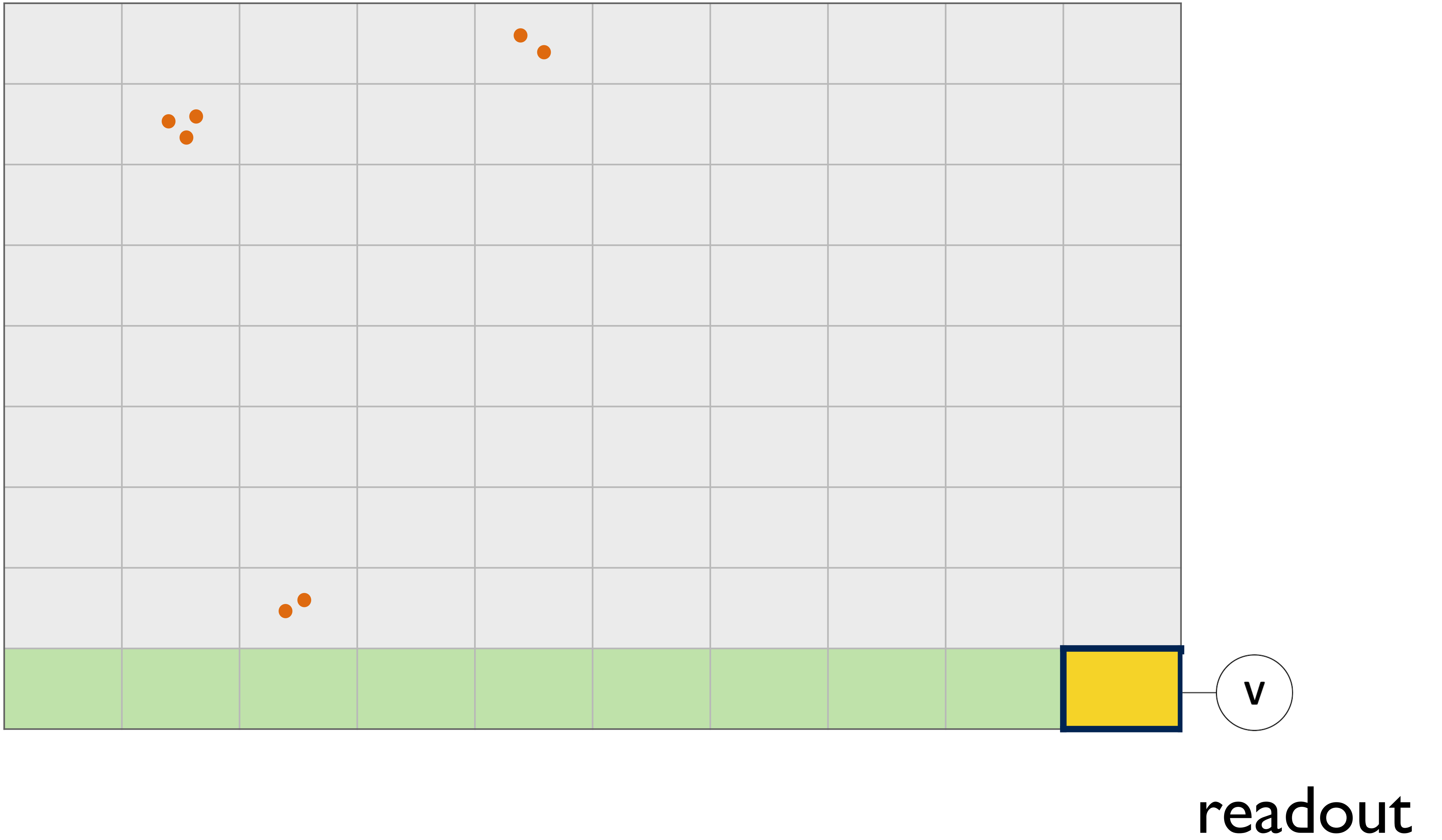


Figure credit: J. Tiffenberg

Moving & reading the charge (schematic)



Moving & reading the charge (schematic)



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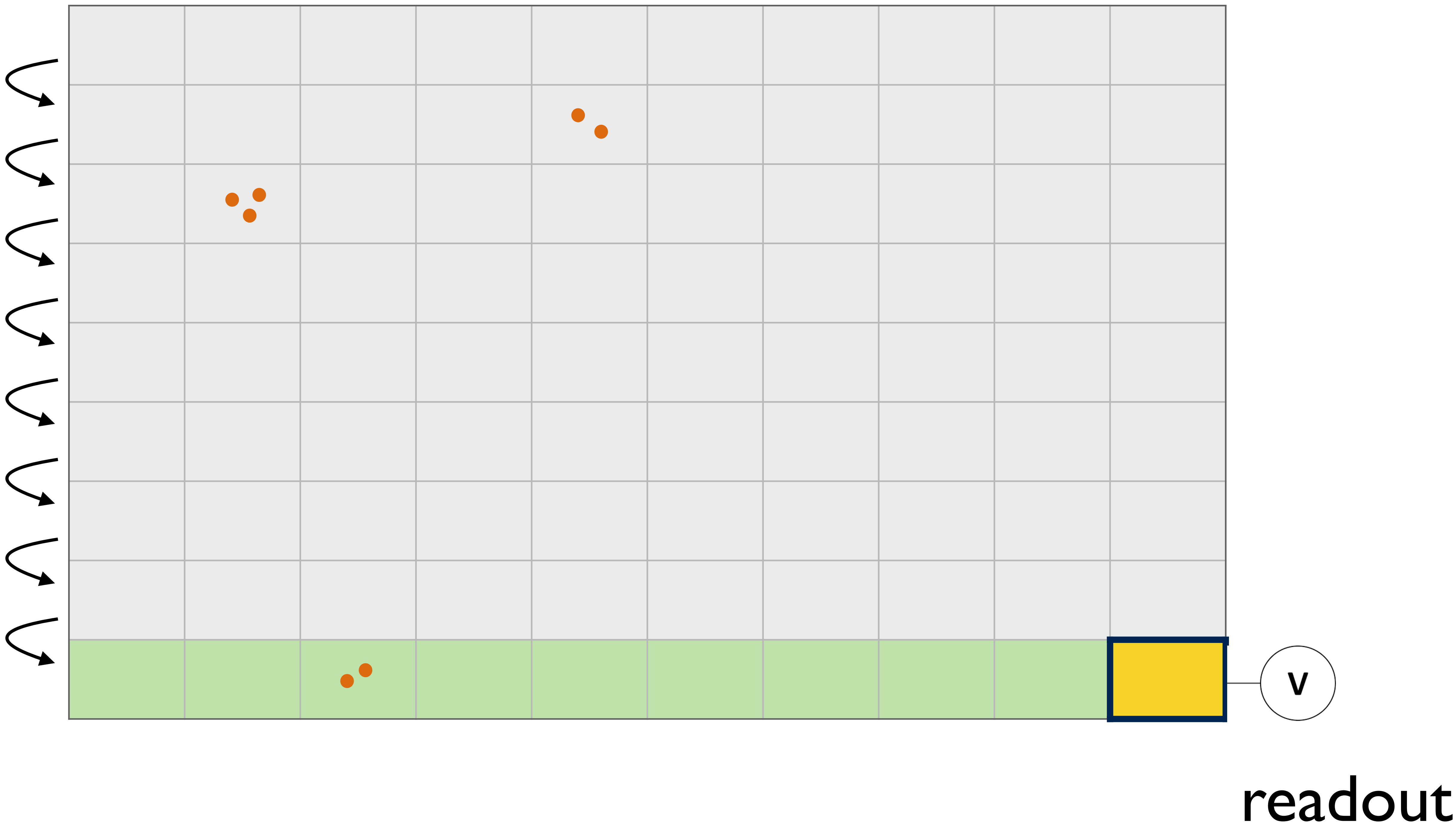
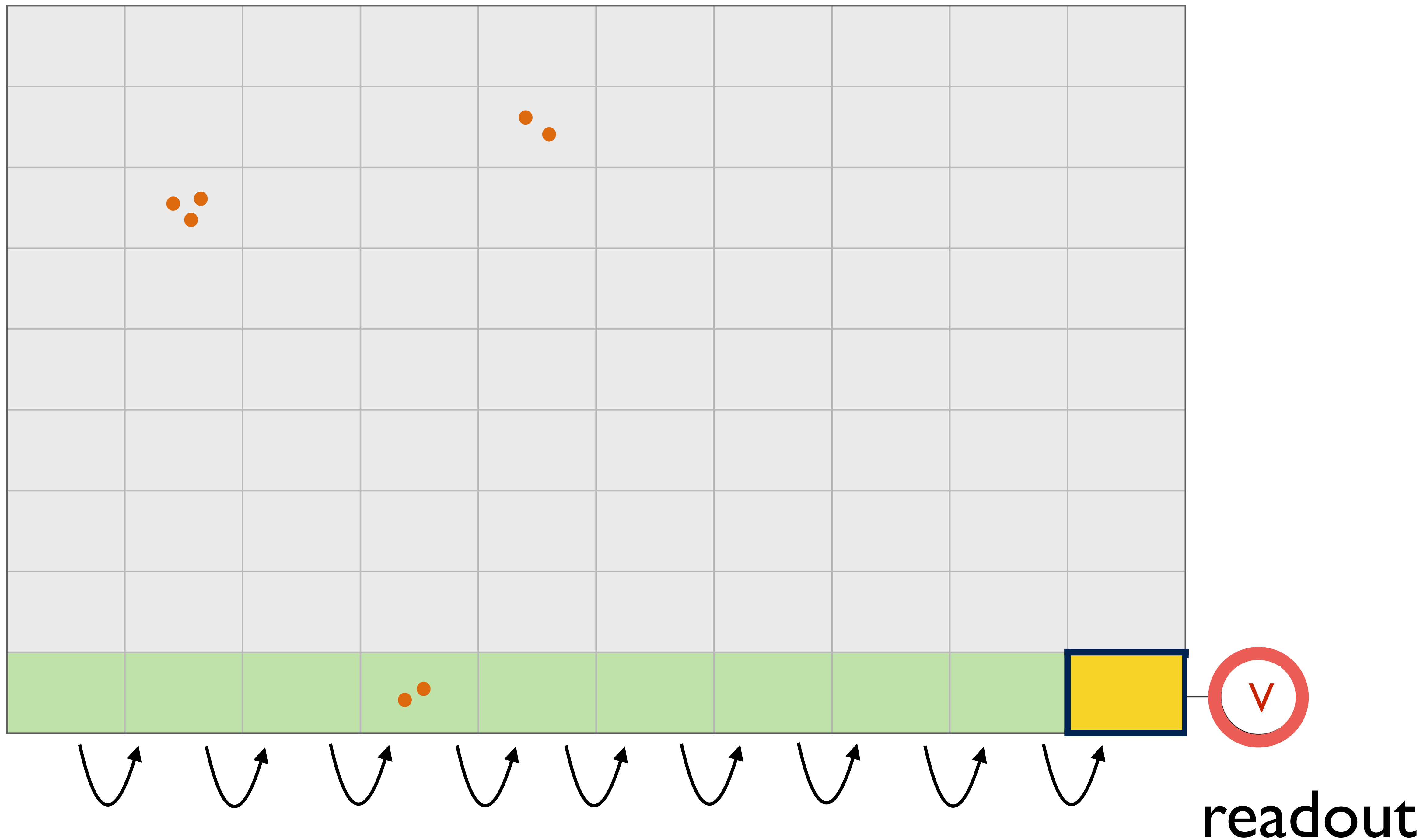


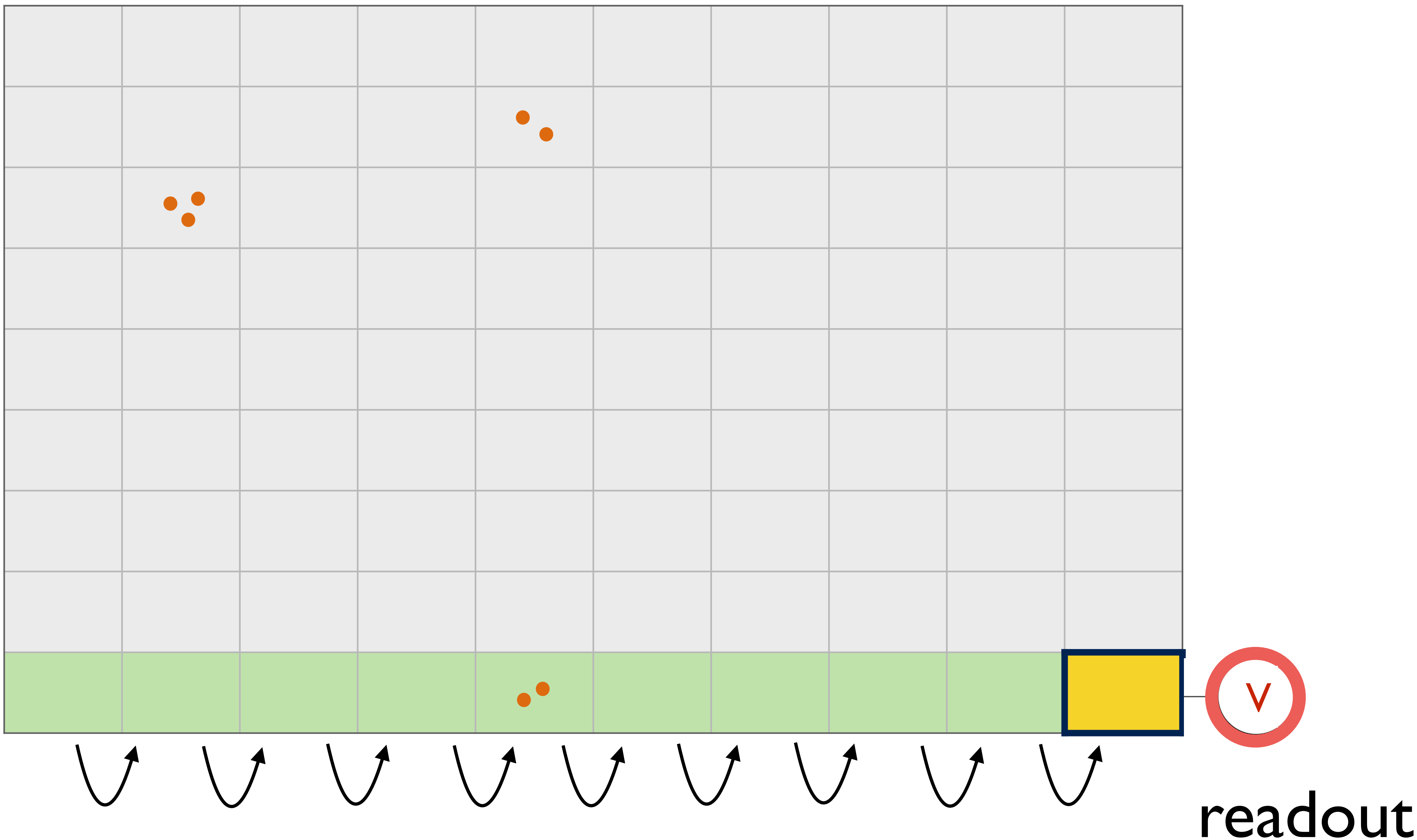
- shift each pixel charge down by one row

Moving & reading the charge (schematic)



- then shift pixel charge in bottom row to the right step-by-step and measure charge in each pixel

Moving & reading the charge (schematic)



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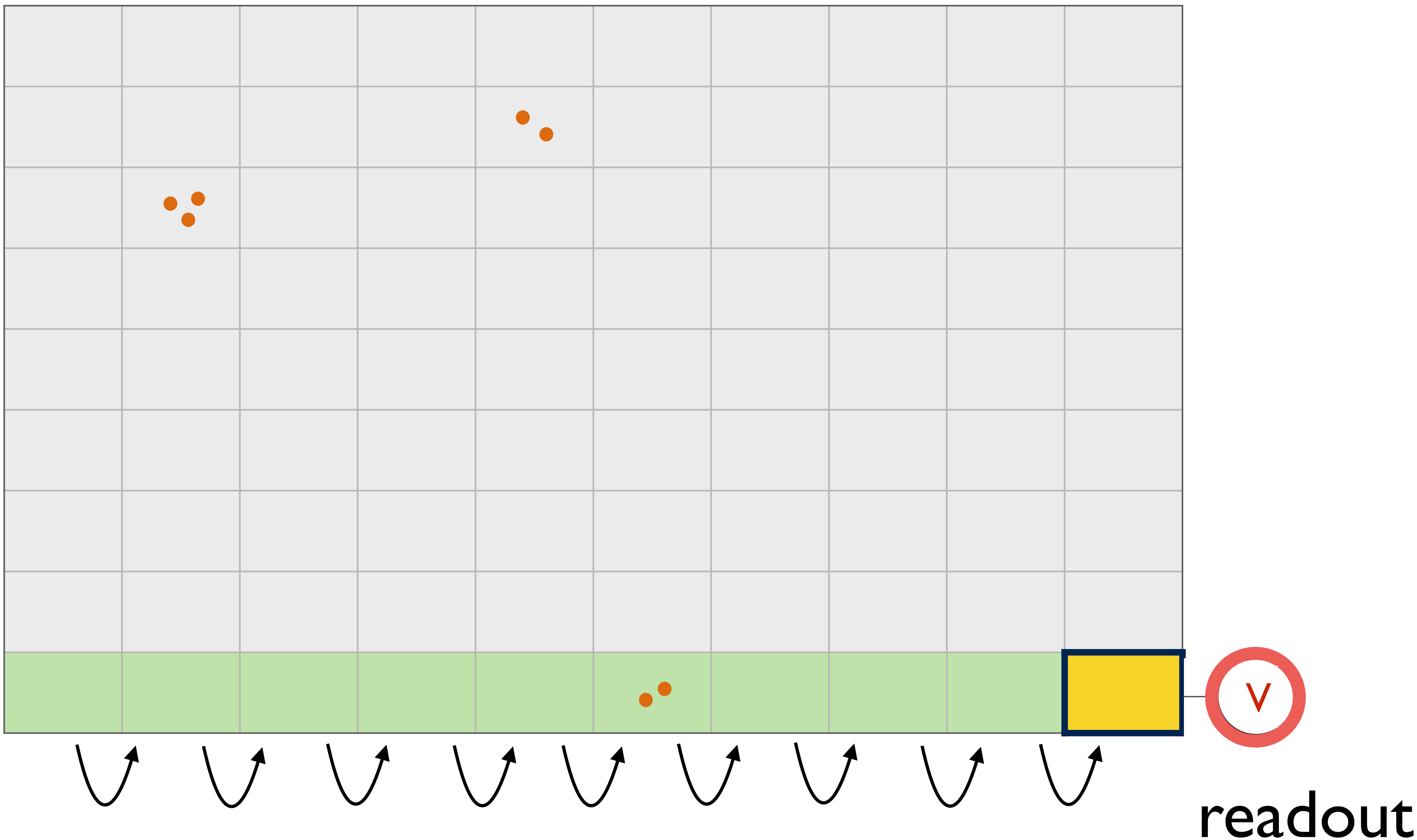

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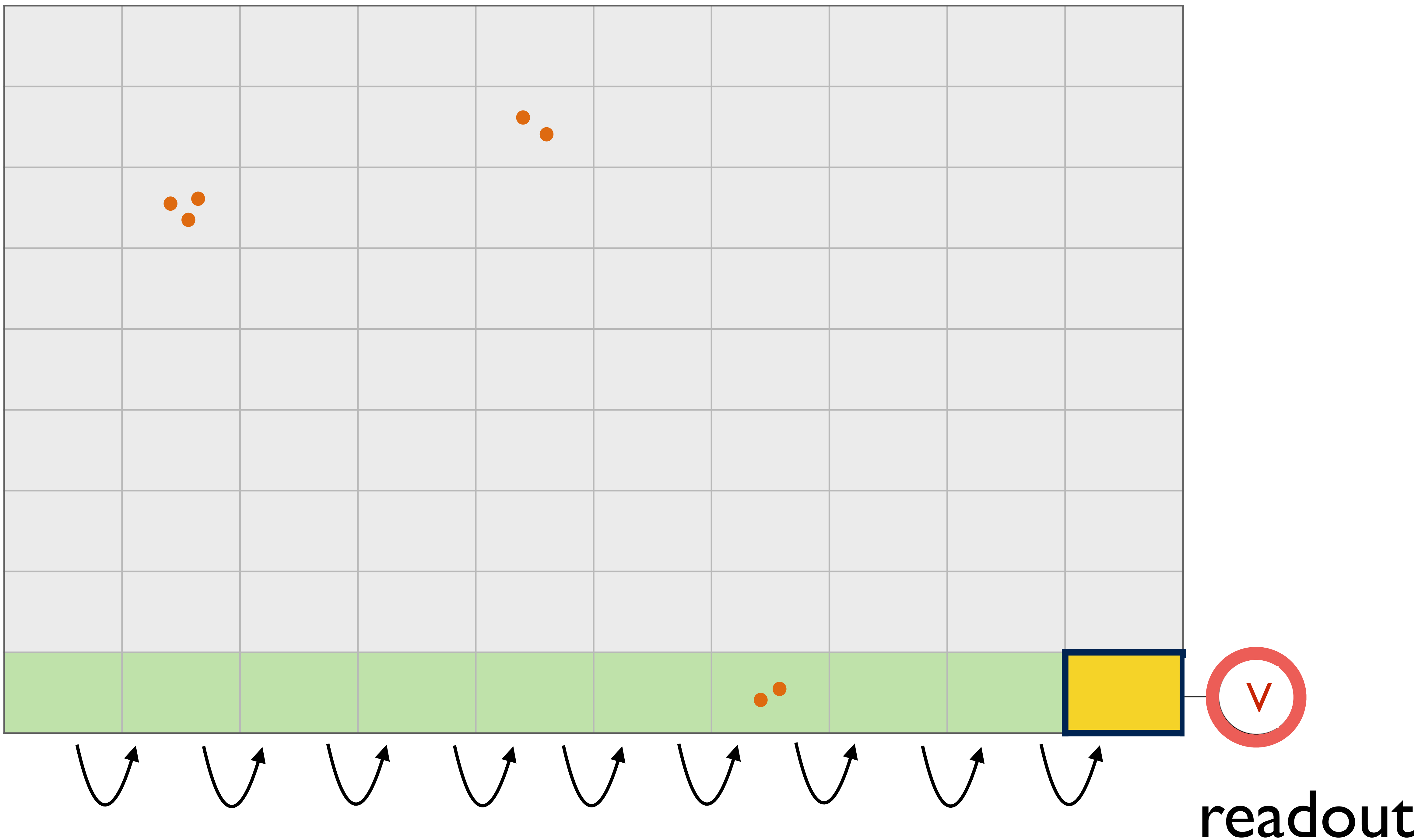

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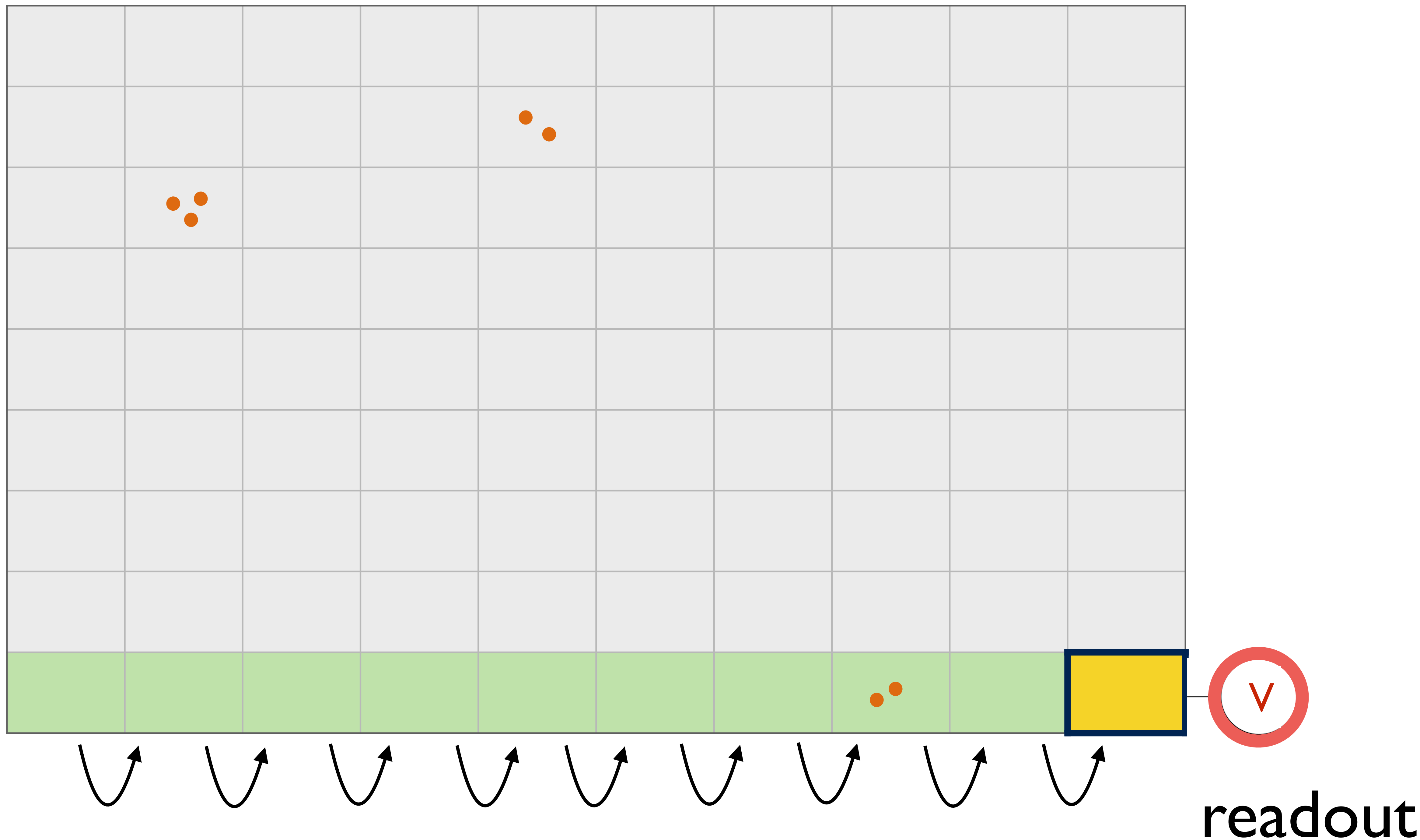

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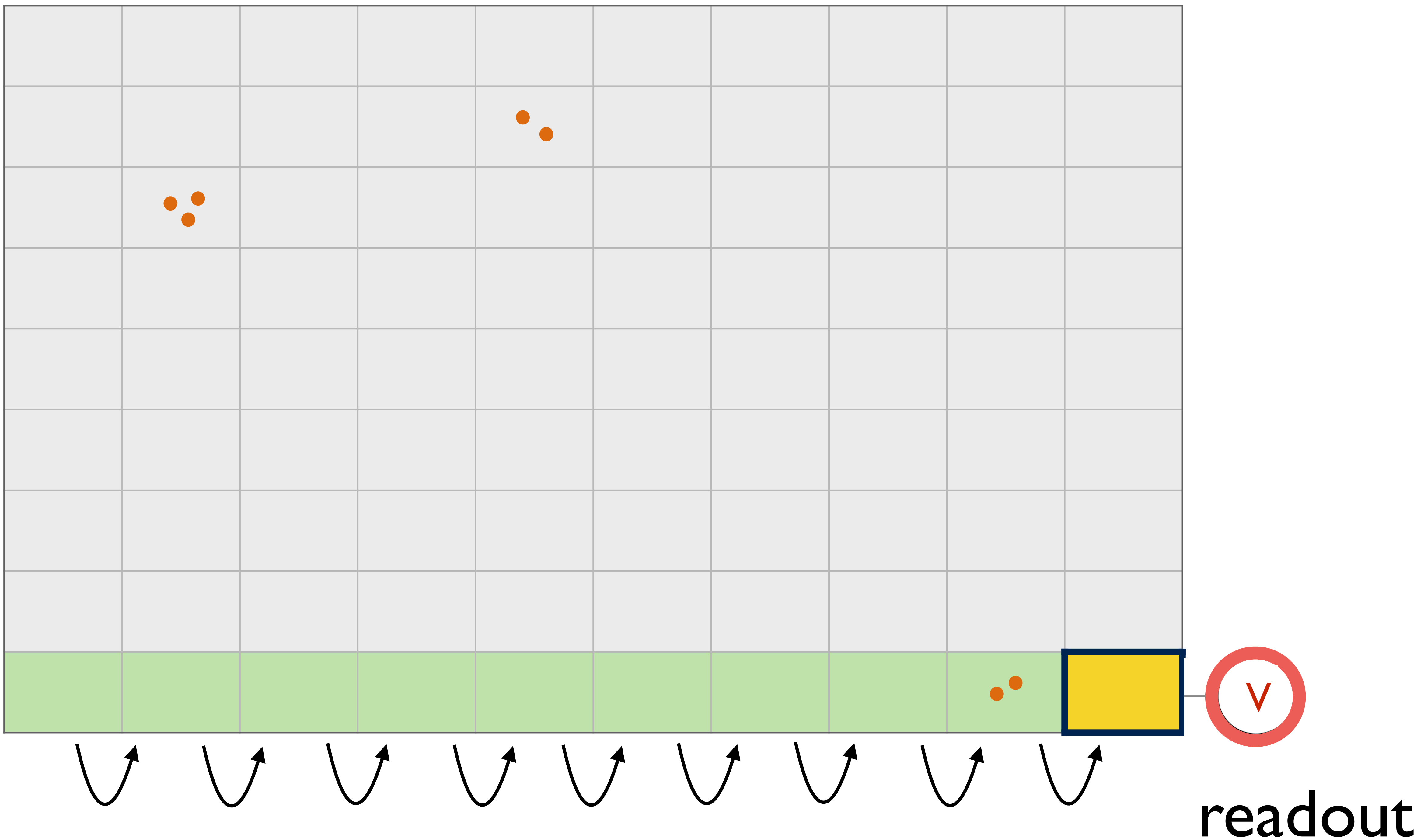

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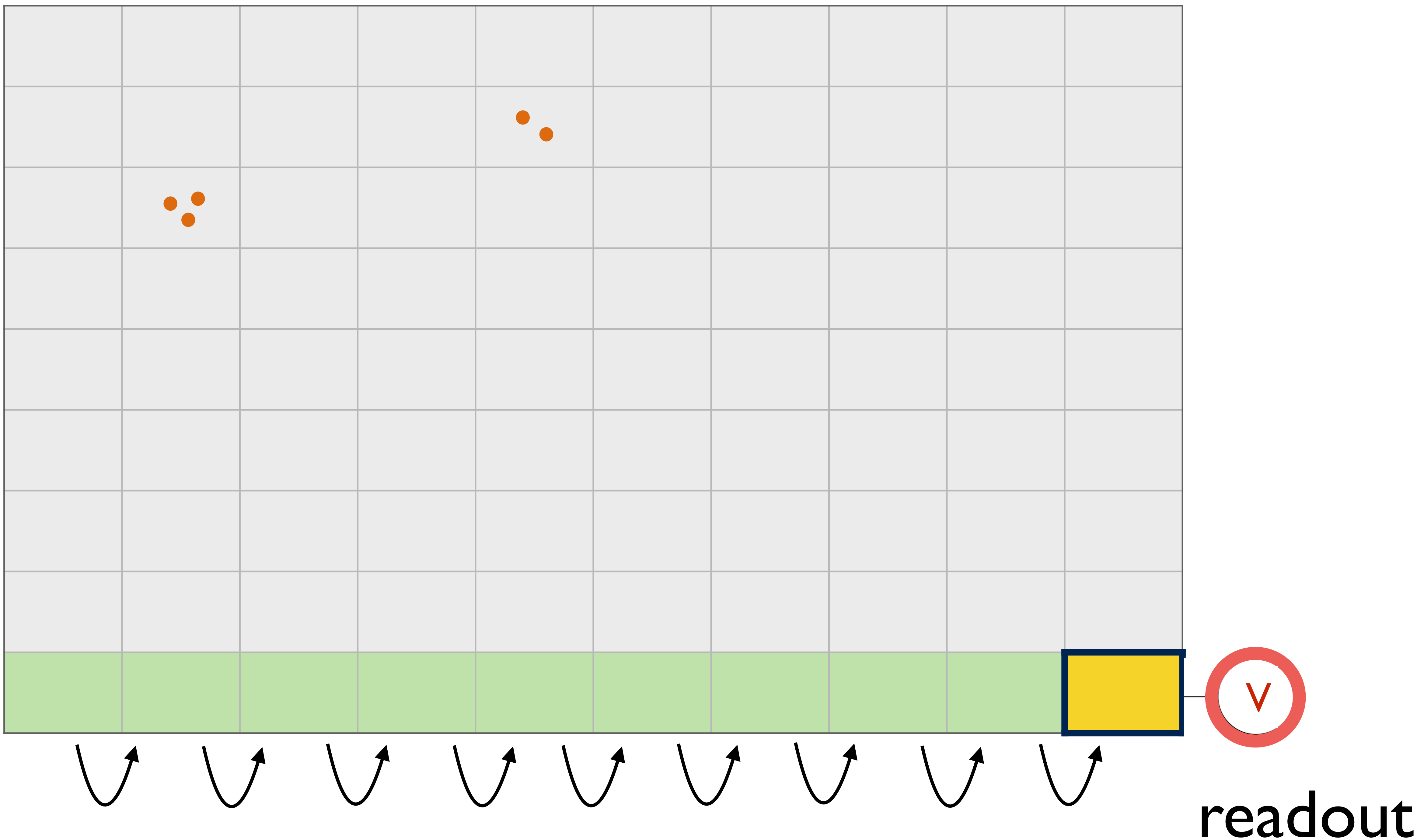

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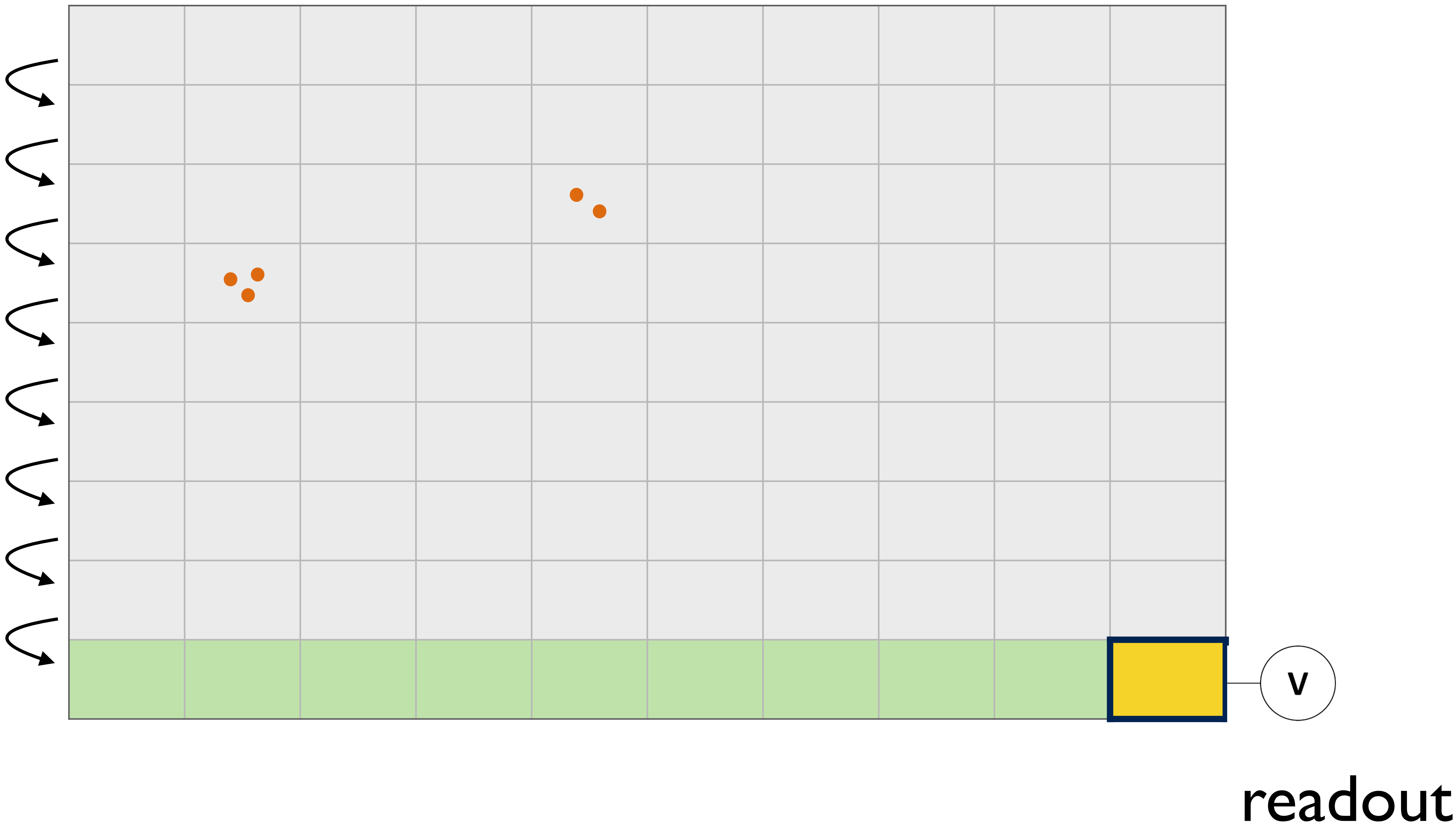
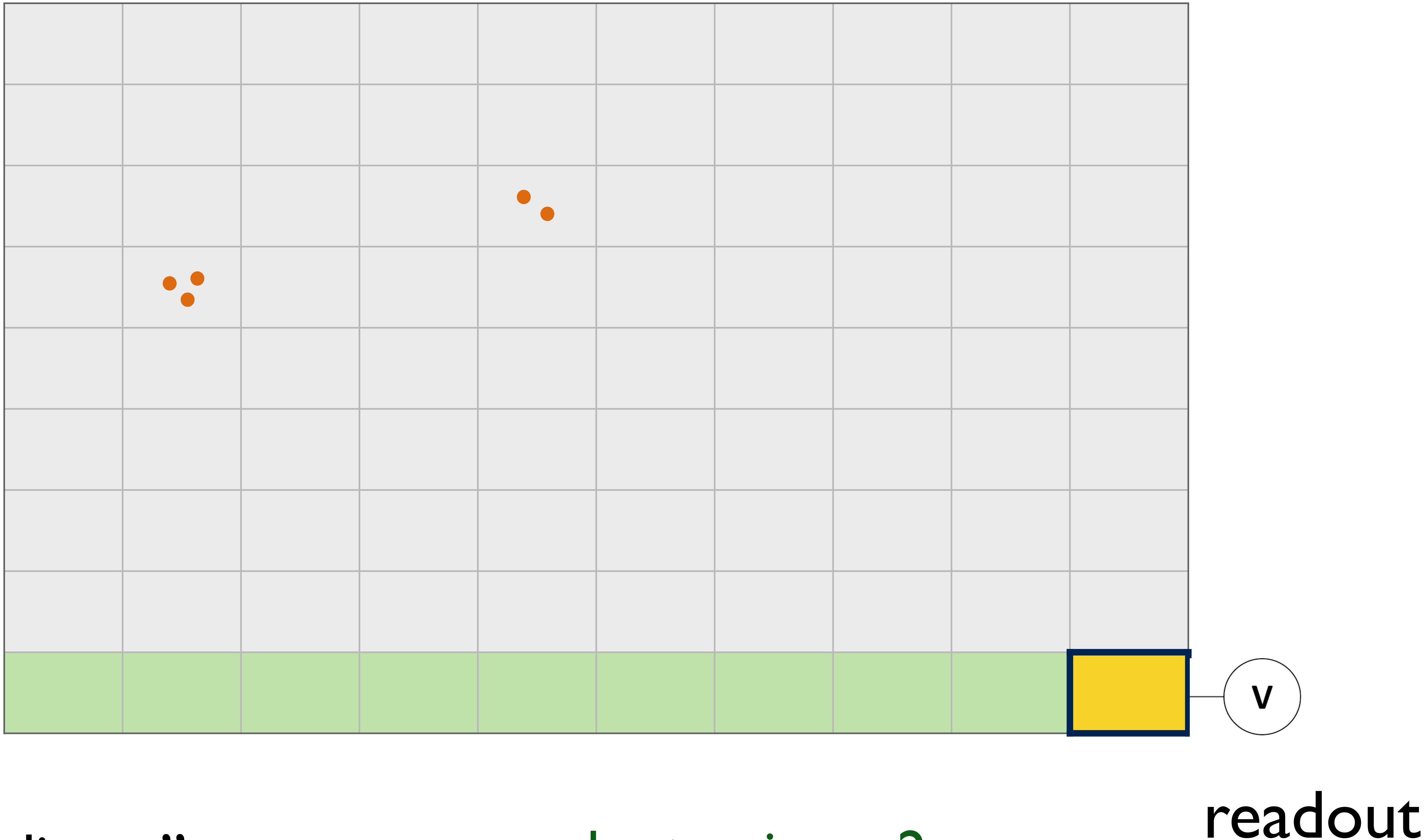


- repeat

Moving & reading the charge (schematic)



“ordinary” scientific CCDs:

rms readout noise ~ 2e$^-$

$\Longrightarrow$ “high” threshold ~ 10e$^-$

Skipper CCD

- allows multiple sampling of the same pixel without corrupting the charge packet:

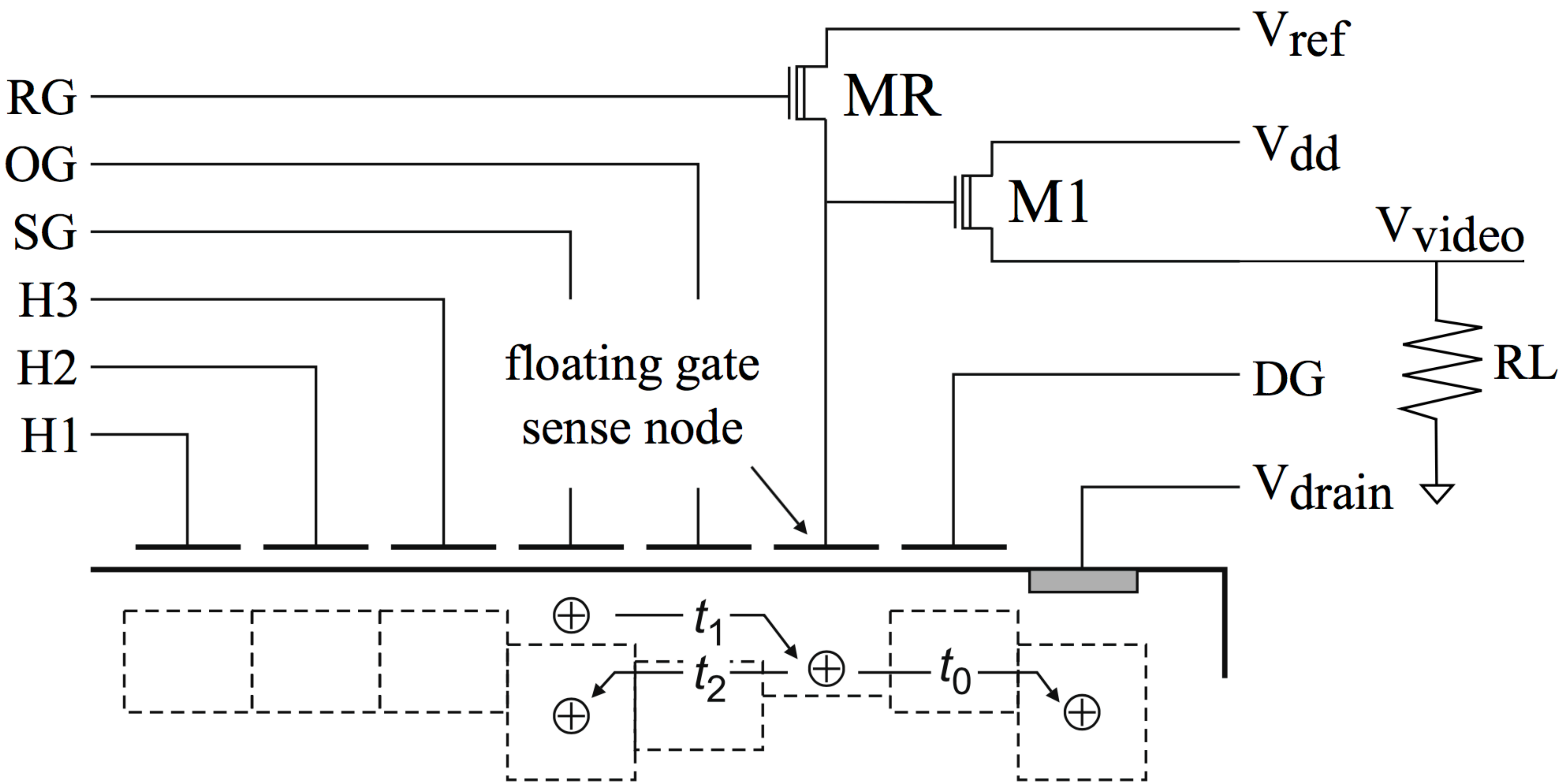
$$\text{pixel value} = \frac{1}{N}\sum_{i}^{N}(\text{pixel sample})_i$$

- developed in collaboration with LBNL MicroSystems Lab
- successfully demonstrated in a Fermilab LDRD project (2016)

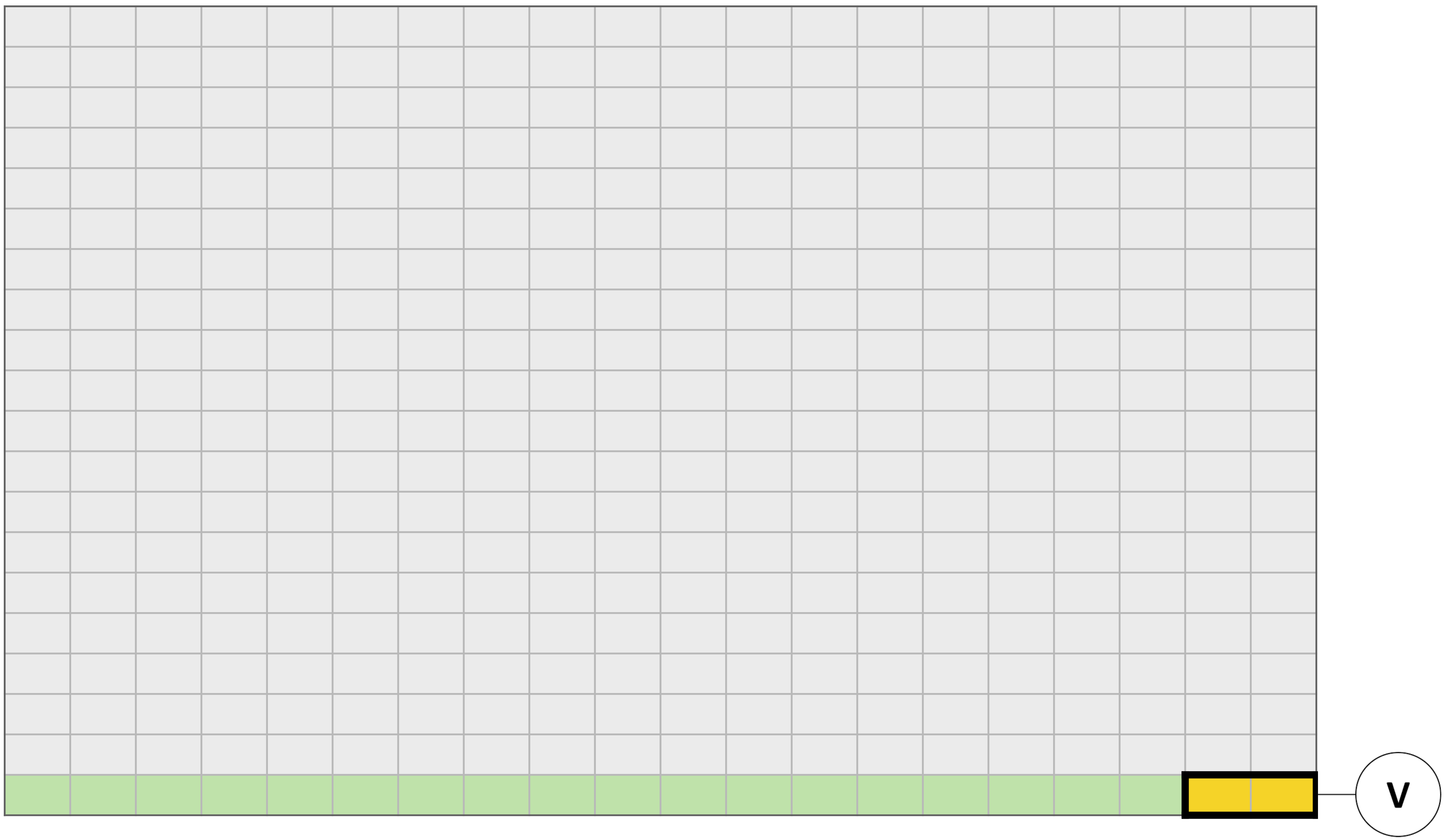
Tiffenberg (PI), Bebek, Guardincerri, Sofo-Haro, Holland, RE, Mardon, Volansky, Yu

Achieved rms noise ~ 0.06 e^- $\Longrightarrow$ Dramatic reduction in threshold!

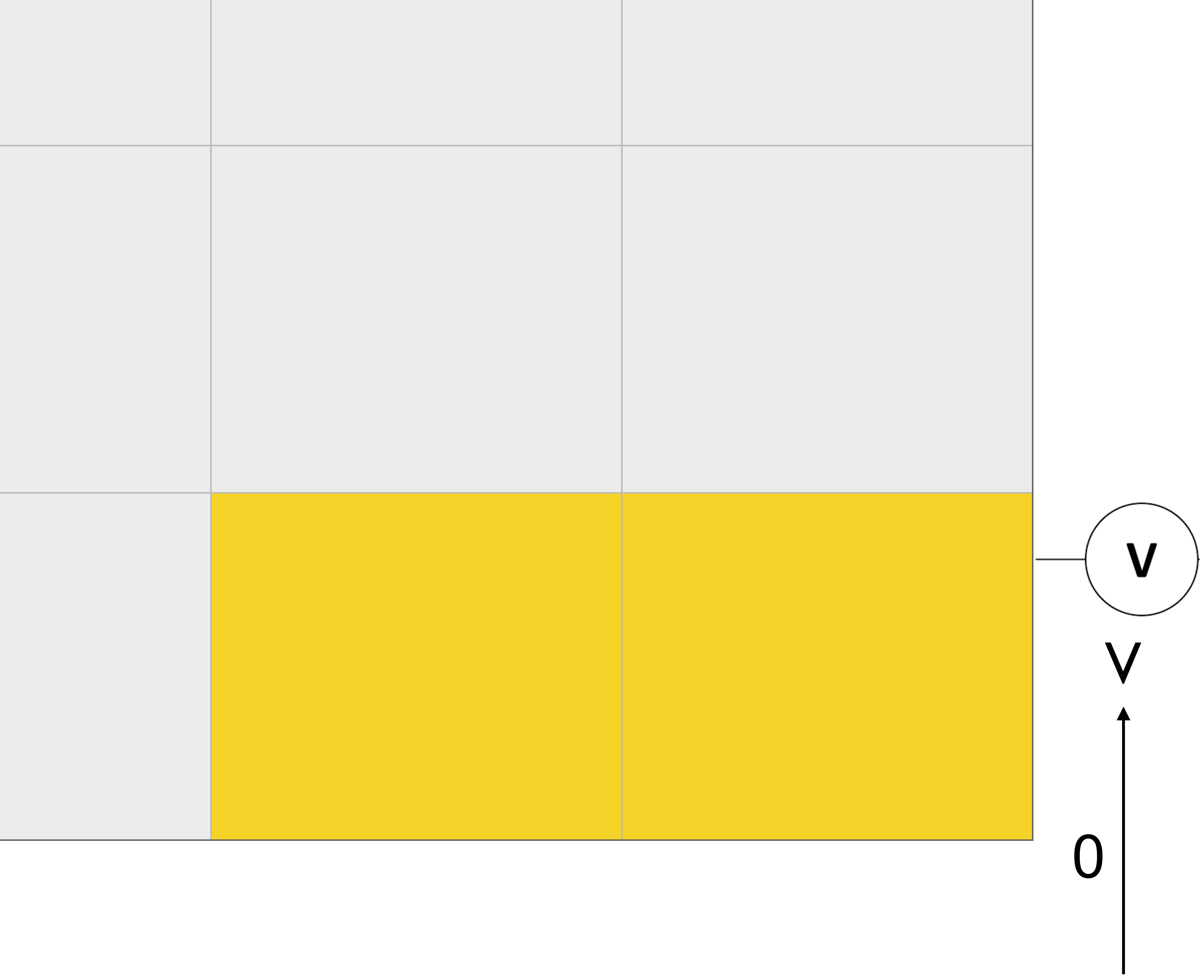
Improved CCD output stage

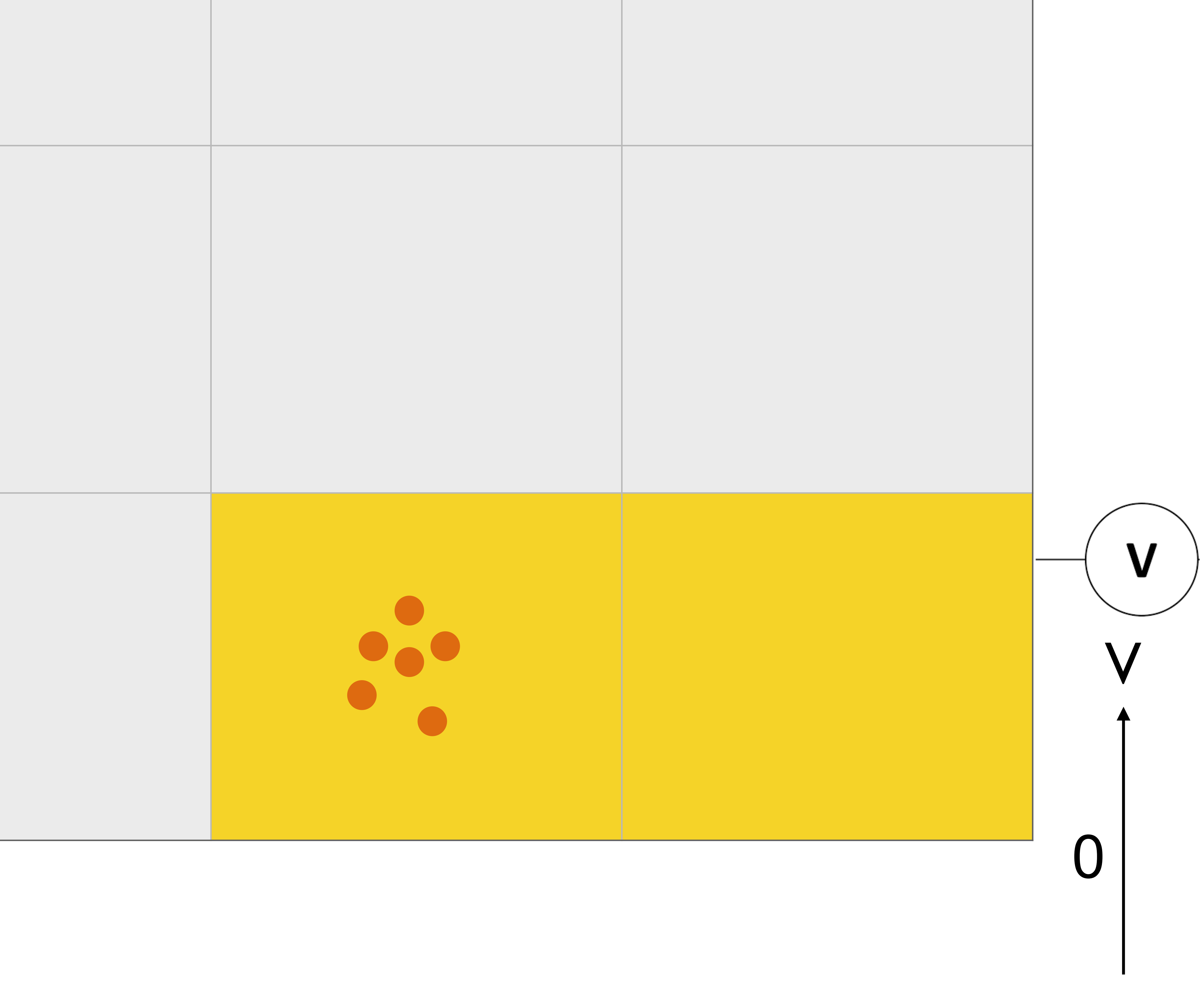


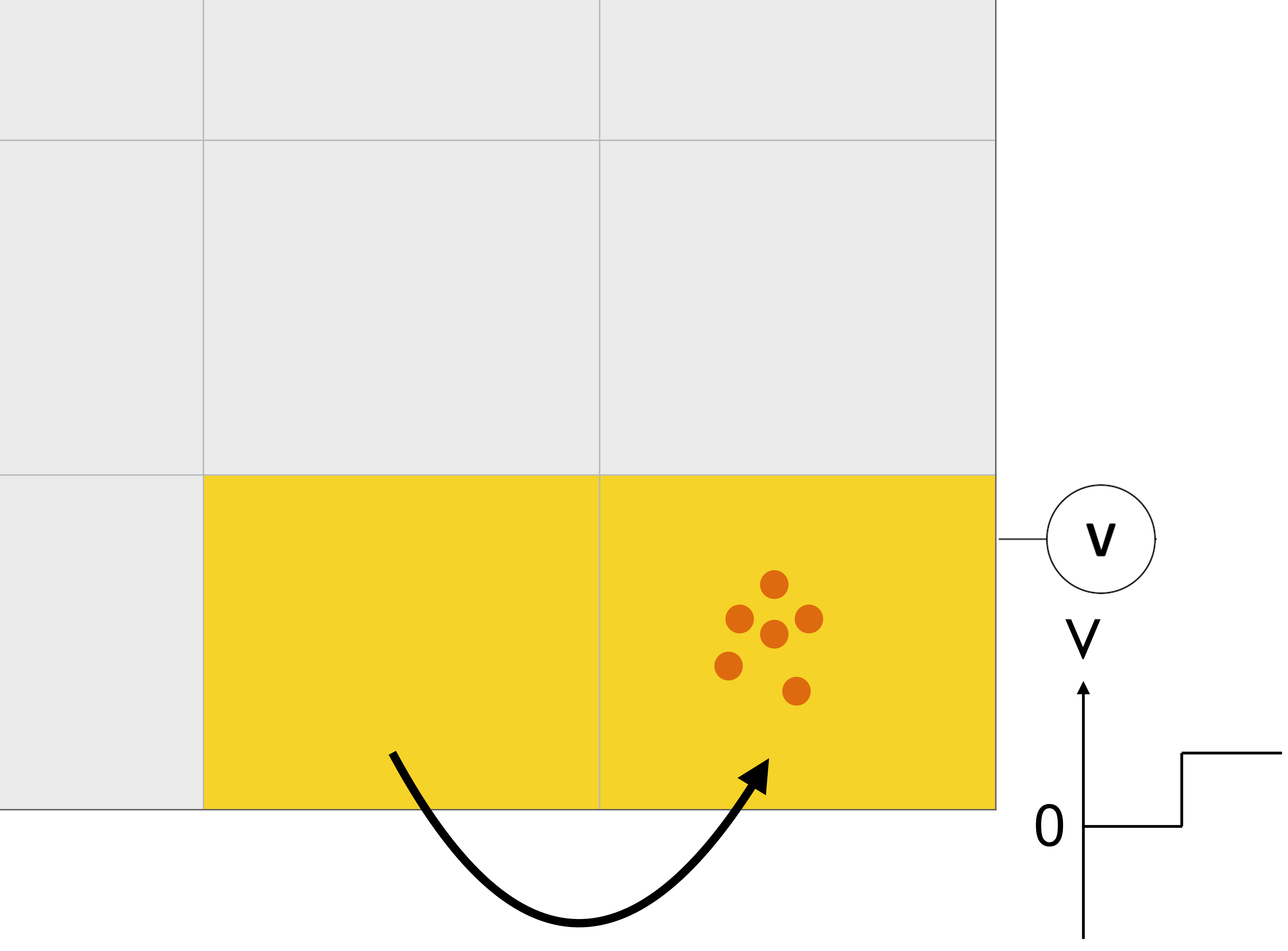
more schematically…

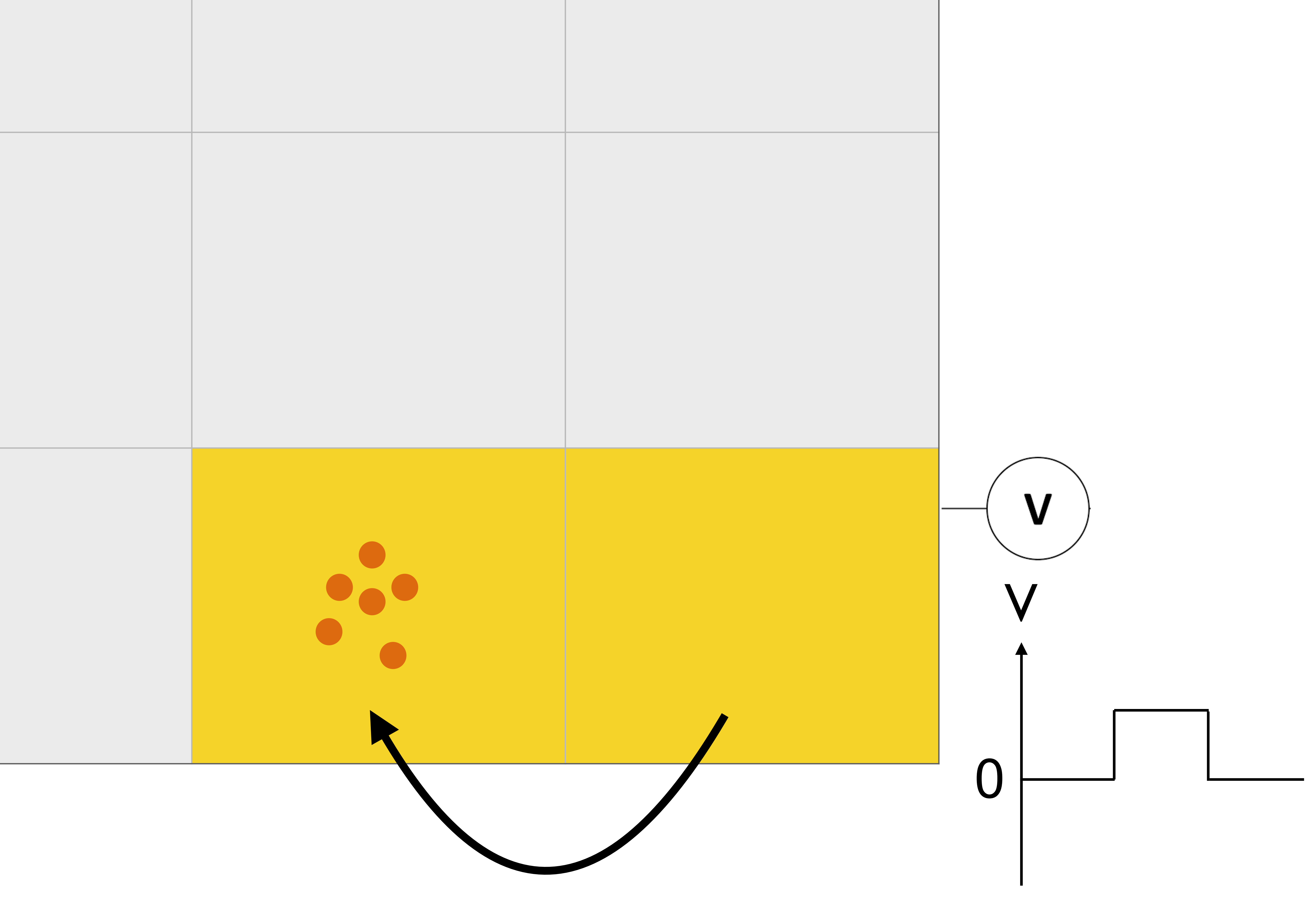


modified
readout stage


V
V
0

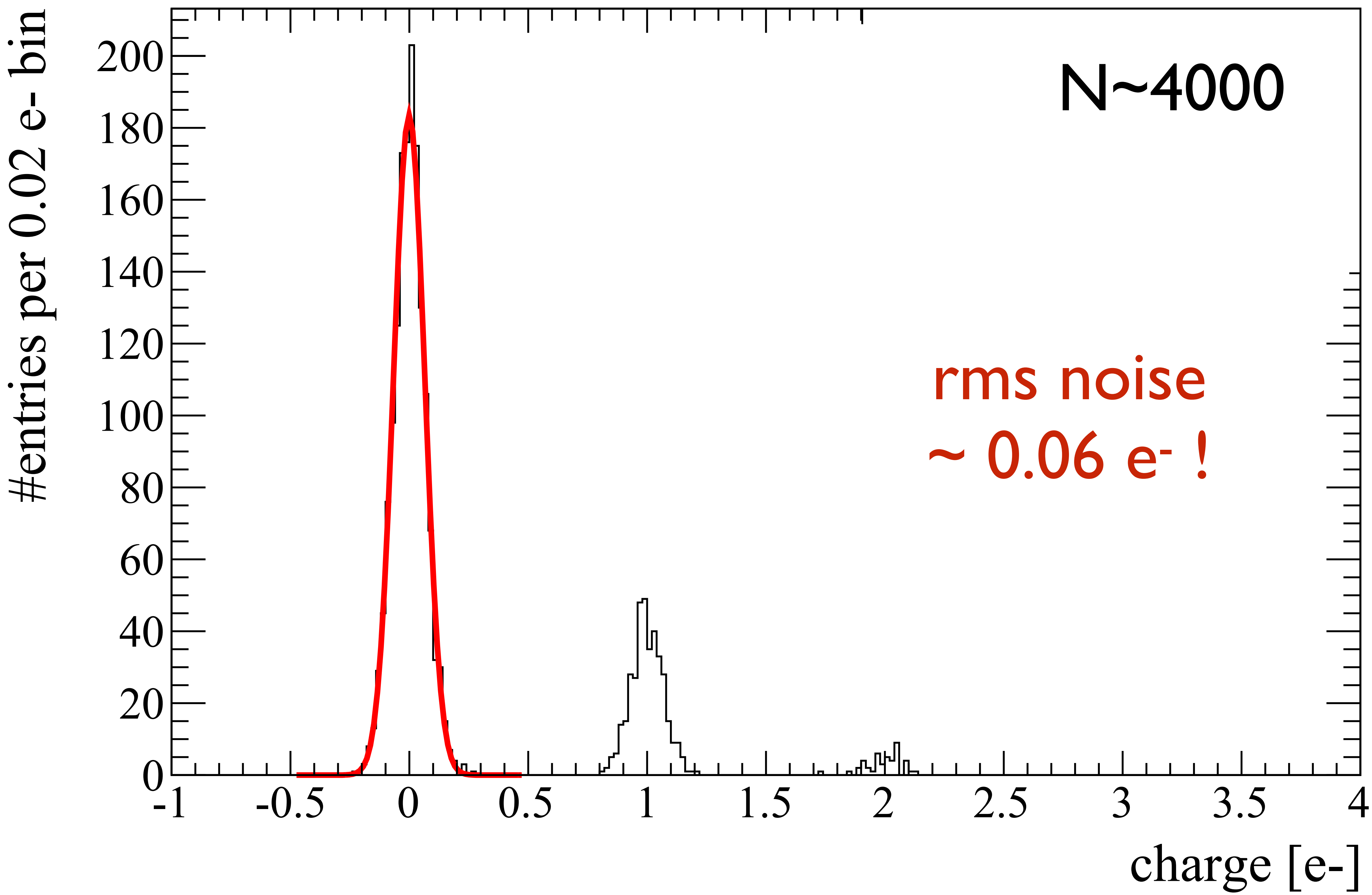

V
V
0


V
V
0



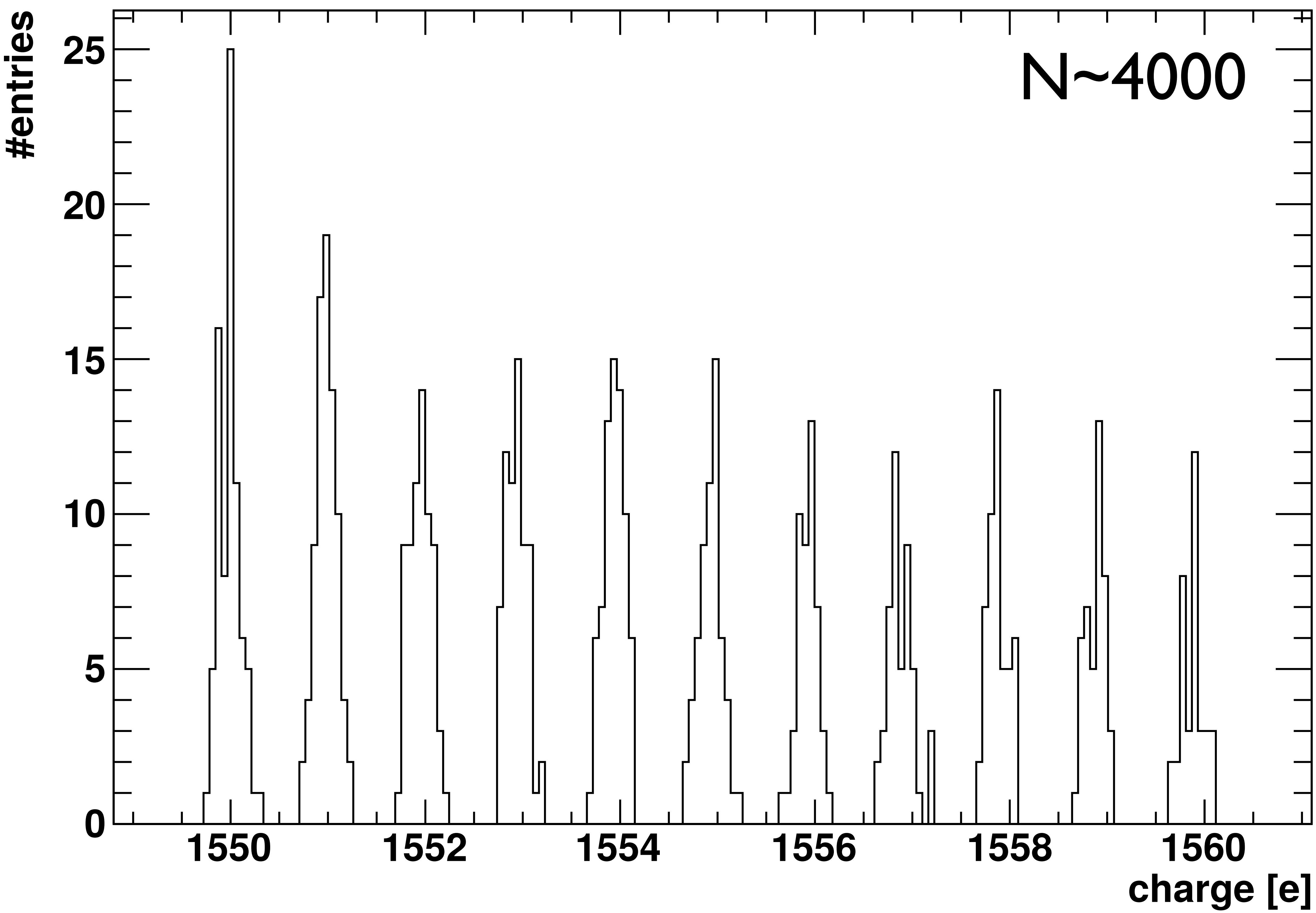
repeat N times

Counting Electrons



Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, PRL)

Counting Electrons



Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, PRL)

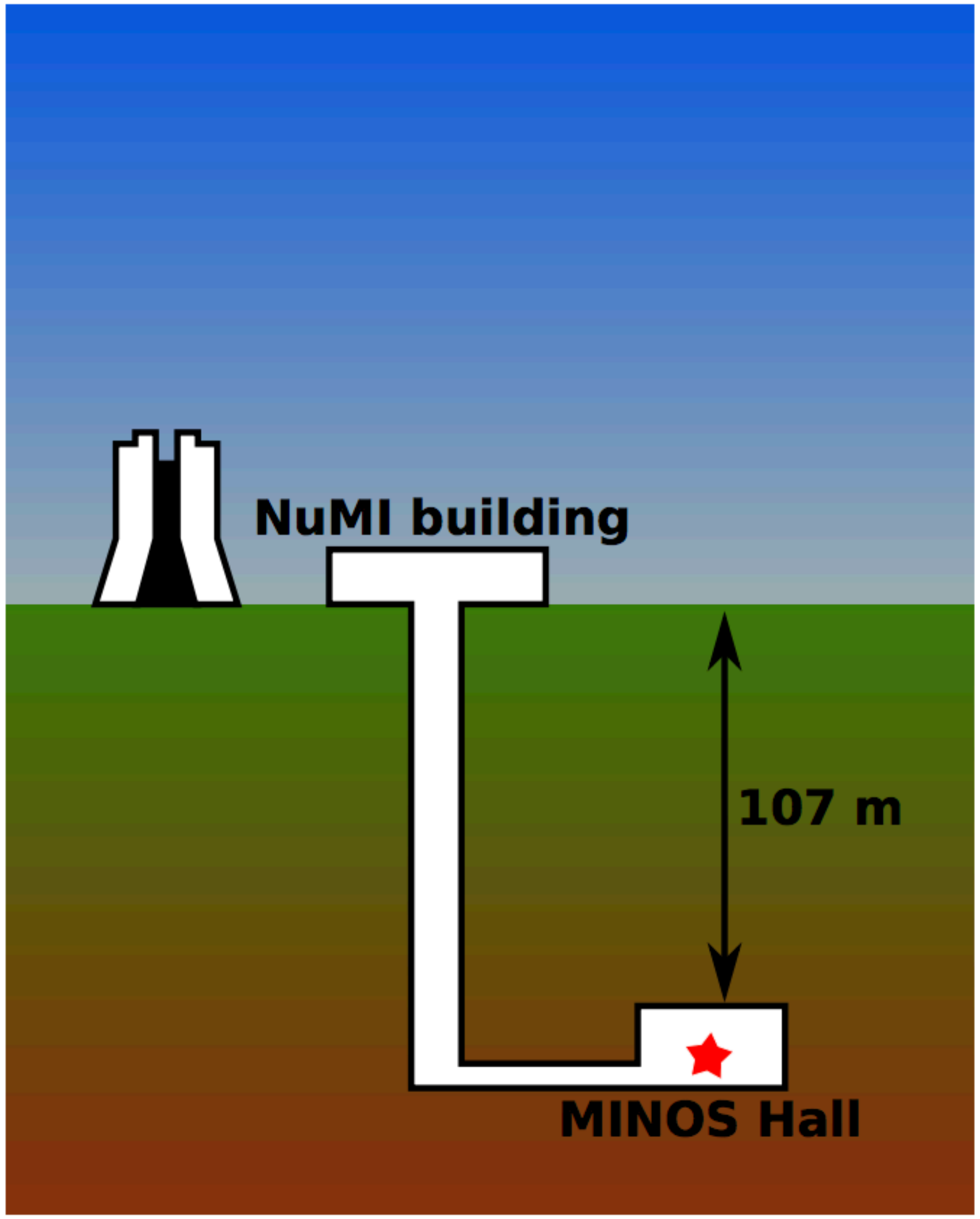
The SENSEI Collaboration

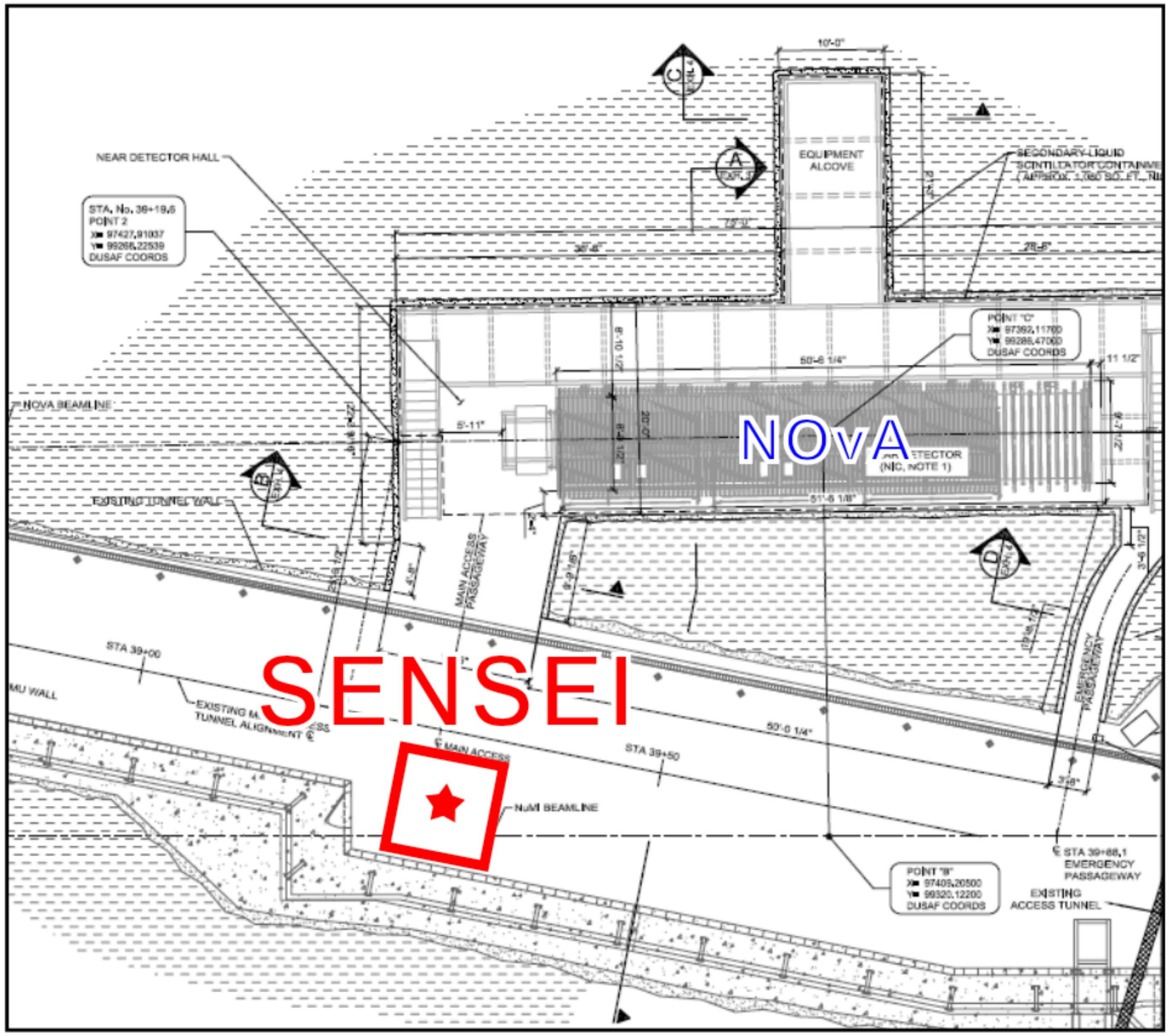
RE, Estrada, Sofo-Haro, Tiffenberg, Volansky, Yu (+ more to come)

Goal: search for ultralight & hidden-sector DM using 100 grams of Skipper CCDs

- Sub-Electron-Noise Skipper-CCD Experimental Instrument
- <0.1 gram prototype* is already underground in MINOS hall… we're taking data to understand backgrounds and to begin optimizing analysis procedure

*produced parasitically while producing CCDs used for astronomical applications, consisting of lower-resistivity and lower-quality silicon than we want for a "real" DM experiment, thinned, with a reflective coating (possibly radioactive)


NuMI building
107 m
MINOS Hall


NOvA
SENSEI
NEAR DETECTOR HALL
EQUIPMENT ALCOVE
NuMI BEAMLINE


RACK PROTECTION


Fermilab
SMOKE DETECTOR WILL TRIP 110V AC
RACK PROTECTION

The SENSEI Collaboration

RE, Estrada, Sofo-Haro, Tiffenberg, Volansky, Yu (+ more to come)

- Experiment is funded
- Supported by Fermilab & a ~$1-million grant from Heising-Simons Foundation for a 100 gram experiment [RE, Tiffenberg]
- Timescale to start taking data (first at MINOS, then deeper):
  - 1 year for ~10 grams
  - 2 years for ~100 grams

SENSEI: backgrounds?

- ☑ readout noise: irrelevant

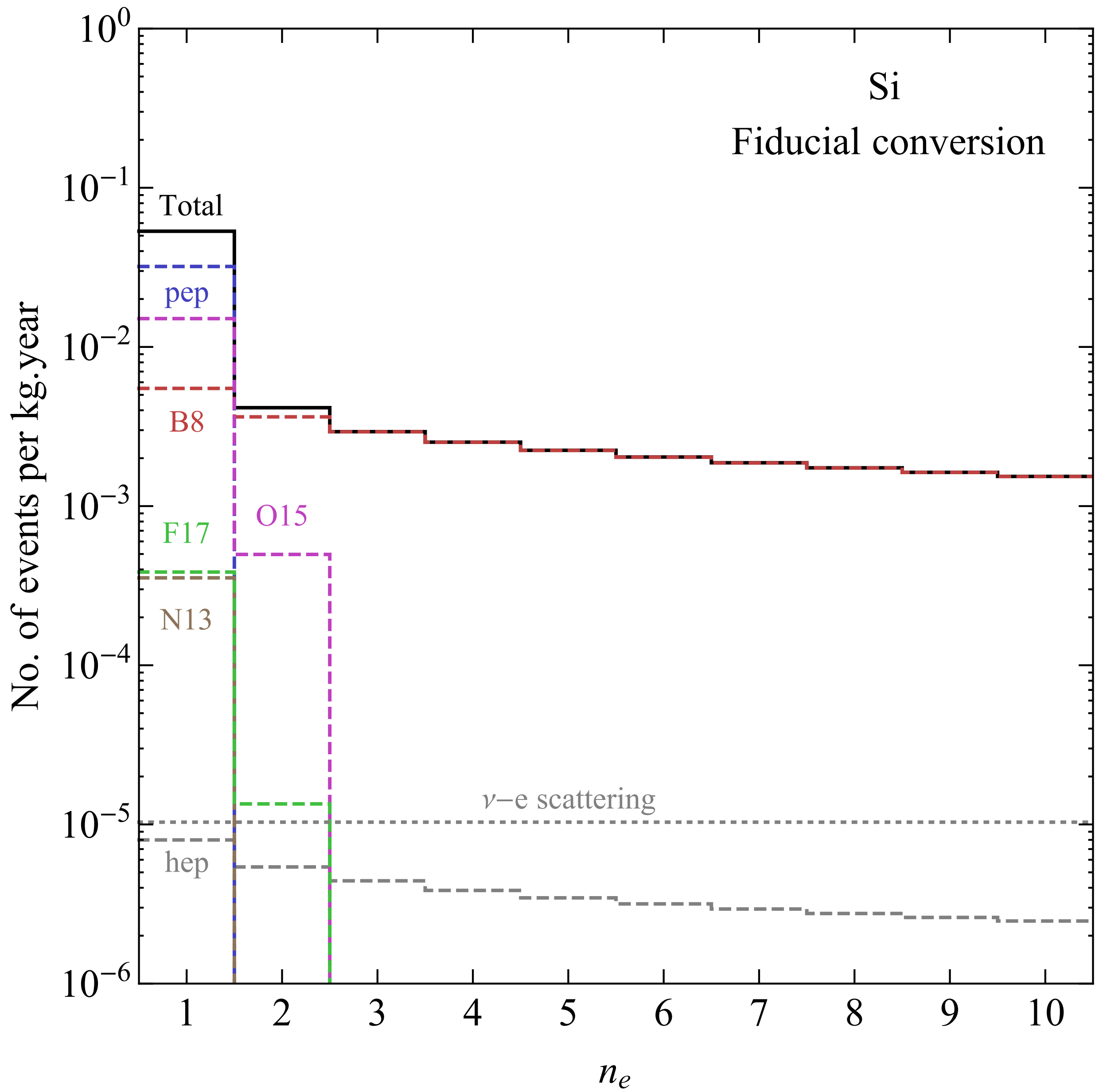
SENSEI: backgrounds?

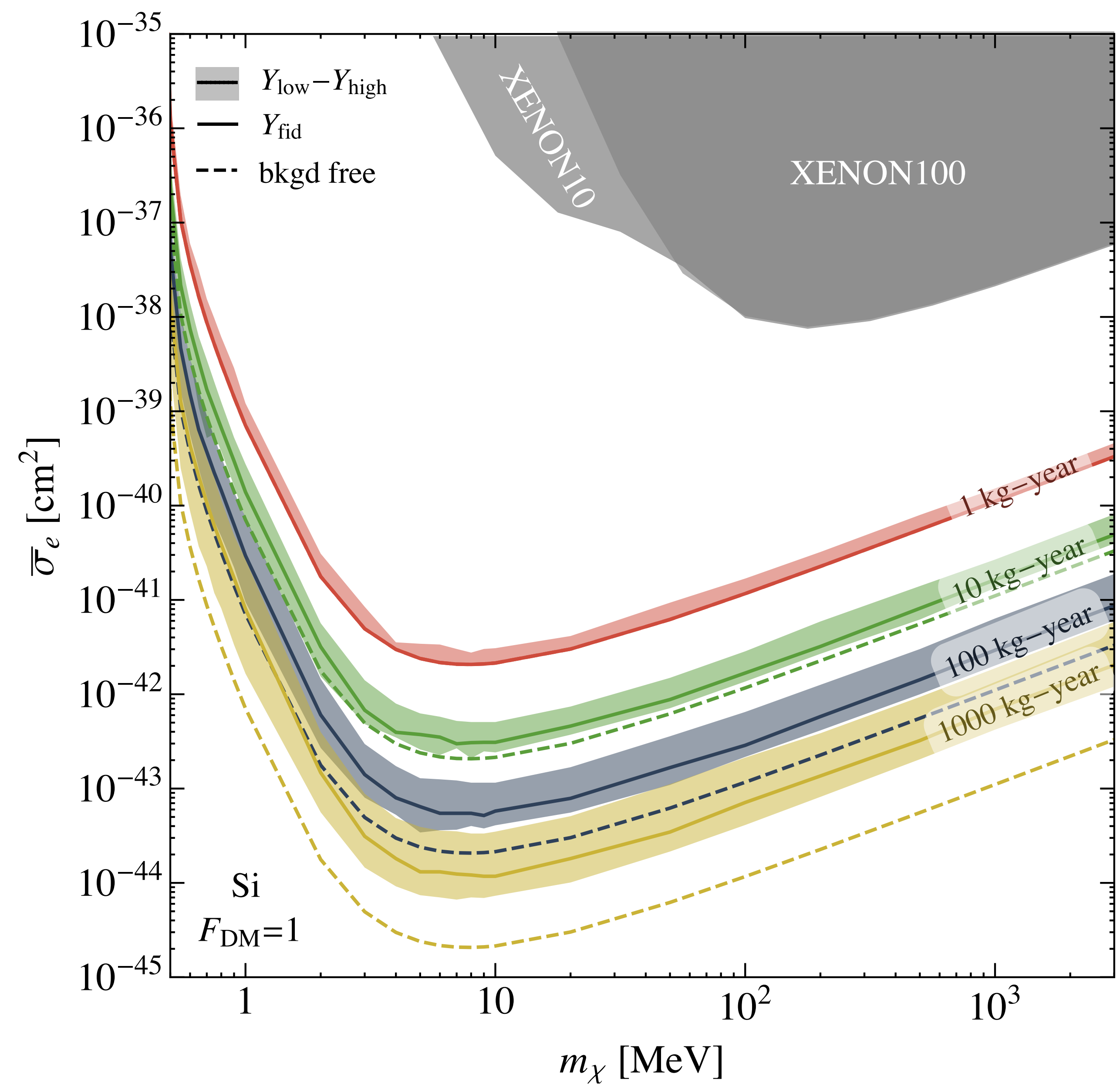
- ☑ readout noise: irrelevant
- ☑ Solar neutrinos: irrelevant

RE, Sholapurkar, Yu (to appear)

Solar neutrino background

RE, Sholapurkar, Yu (to appear)





only relevant for exposures $\gtrsim 1\ \text{kg} - \text{year}$

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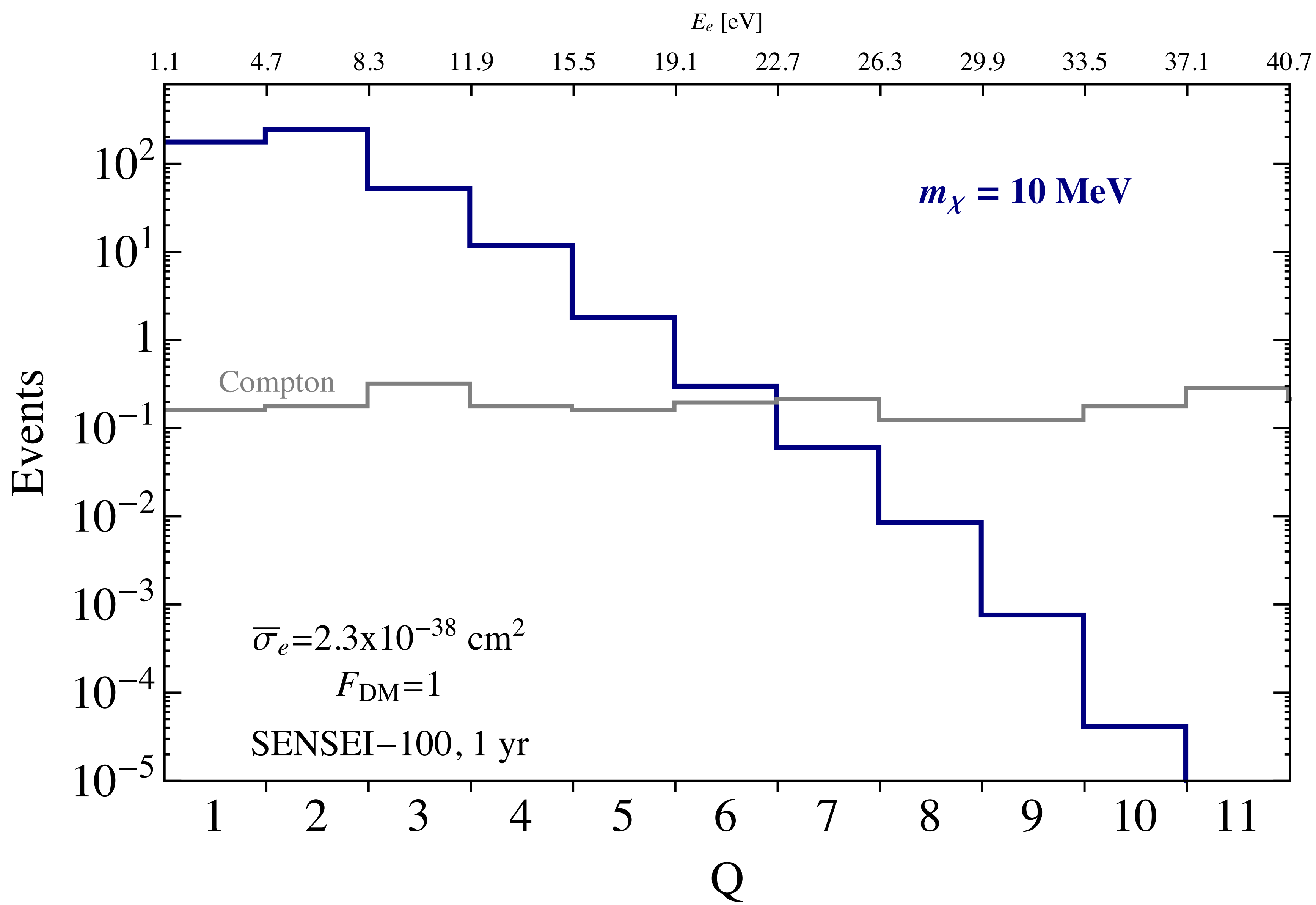

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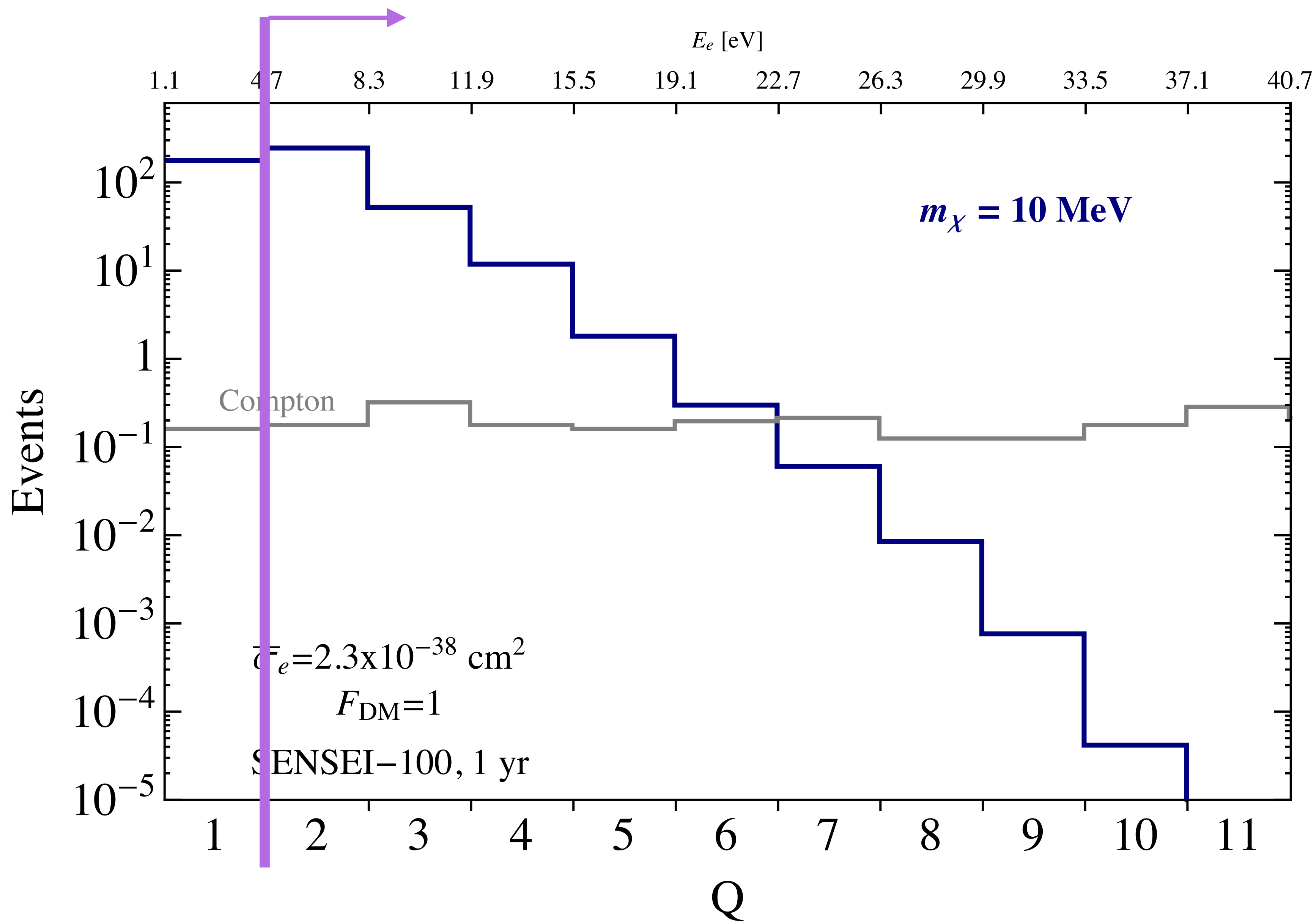
- (☑) Dark current $\Longrightarrow$ theoretically expected threshold is 2e⁻



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4k x 4k = 16 million pix CCD, readout time ~1 hour

	Number of DC events (100 g y)	
Q_{th}	$\mathbf{DC = 1 \times 10^{-3}}$ **e pix^{-1}day^{-1}**	$\mathbf{DC = 10^{-7}}$ **e pix^{-1}day^{-1}**
1	1×10^{8}	1×10^{4}
2	2×10^{4}	2×10^{-5}
3	3×10^{-2}	3×10^{-14}

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(measured upper limit) (theoretical expectation)

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- ☑ Radiogenic backgrounds: <1 event
- (☑) Dark current $\Longrightarrow$ theoretically expected threshold is $2e^-$
- ✤ Surprise backgrounds? Hopefully not!

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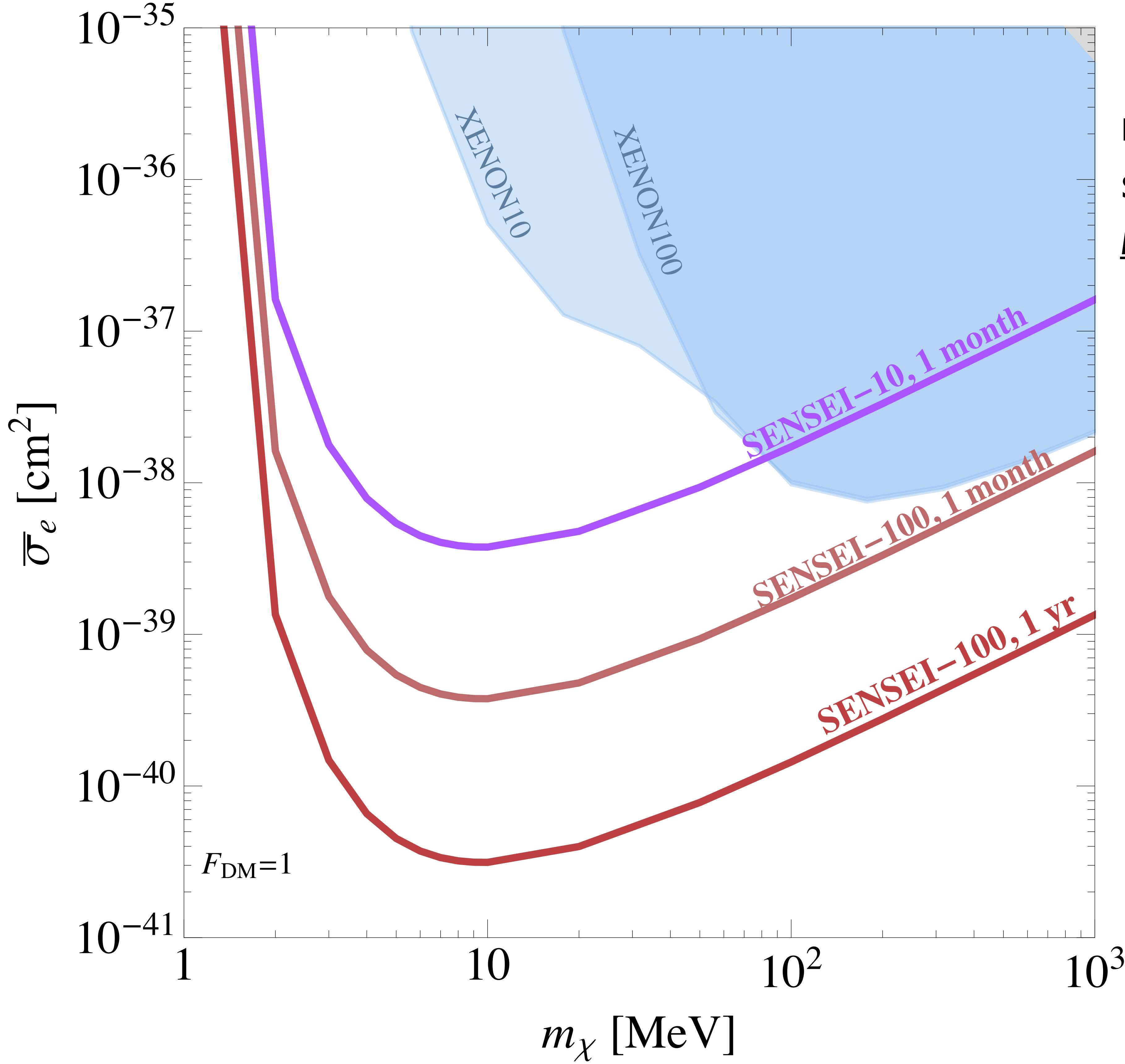
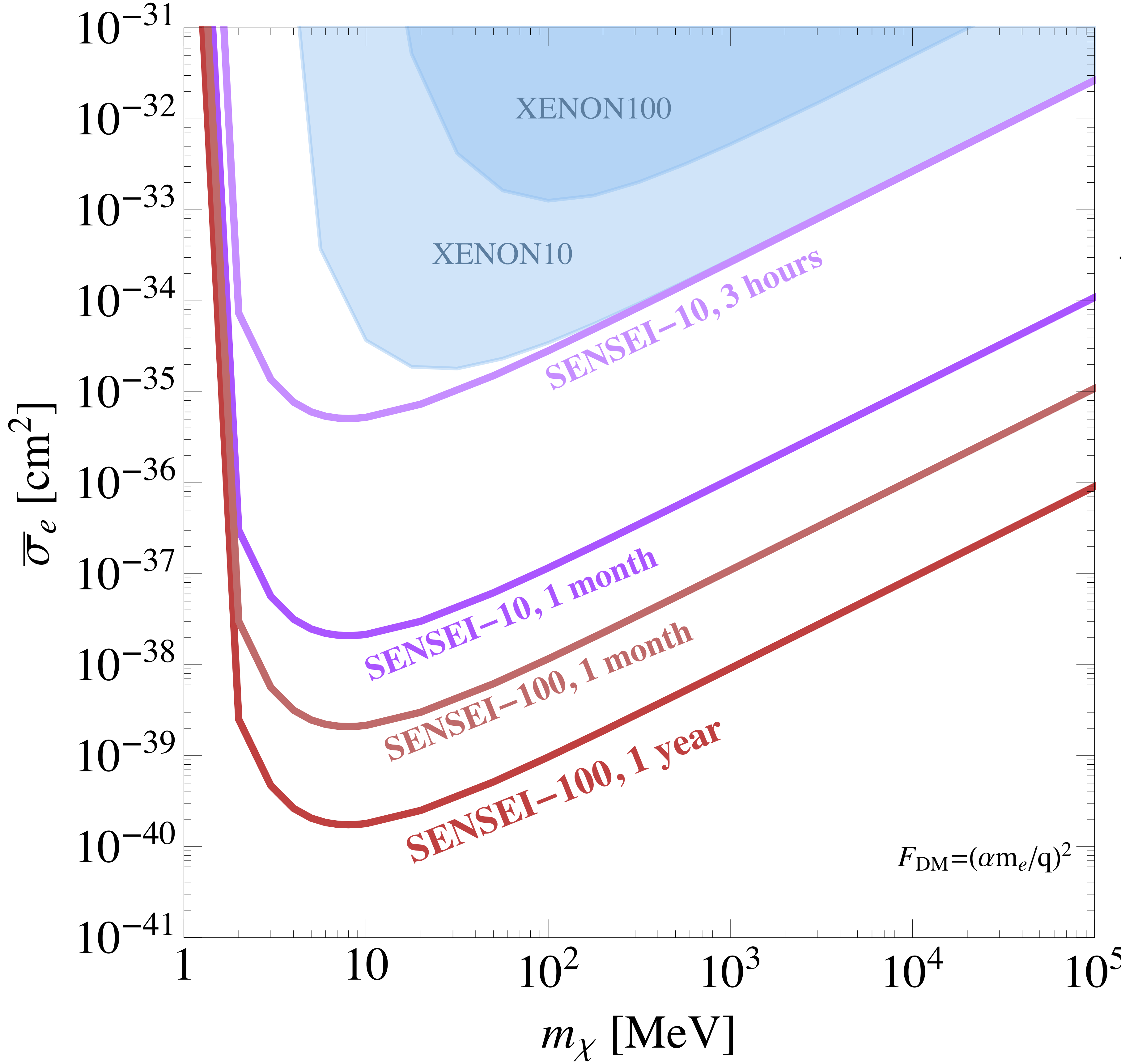
SENSEI projections



$m_{mediator}$ >> keV, scattering is momentum-*<u>independent</u>*

SENSEI projections

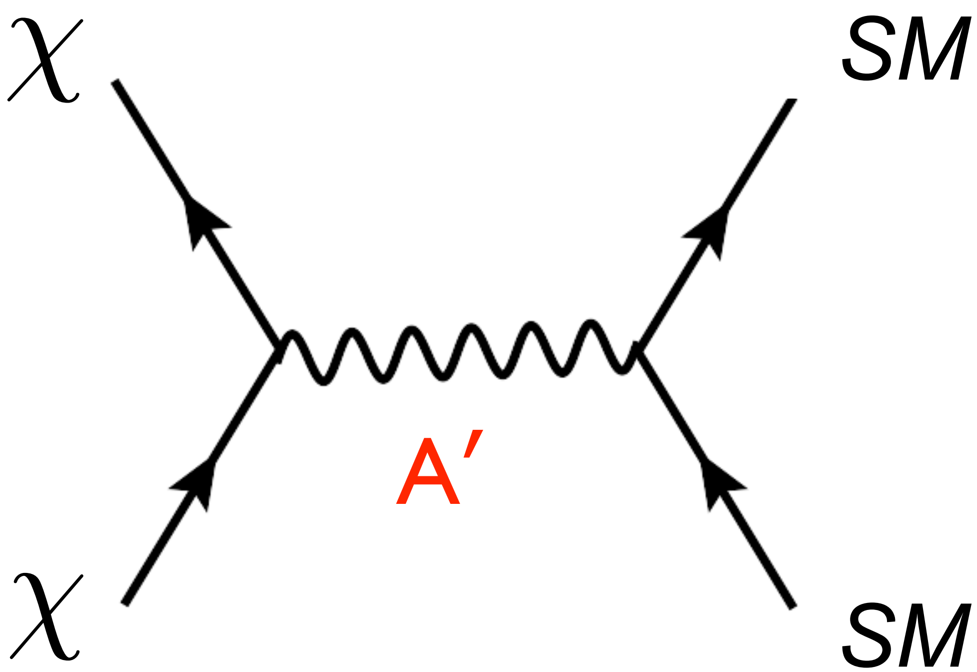


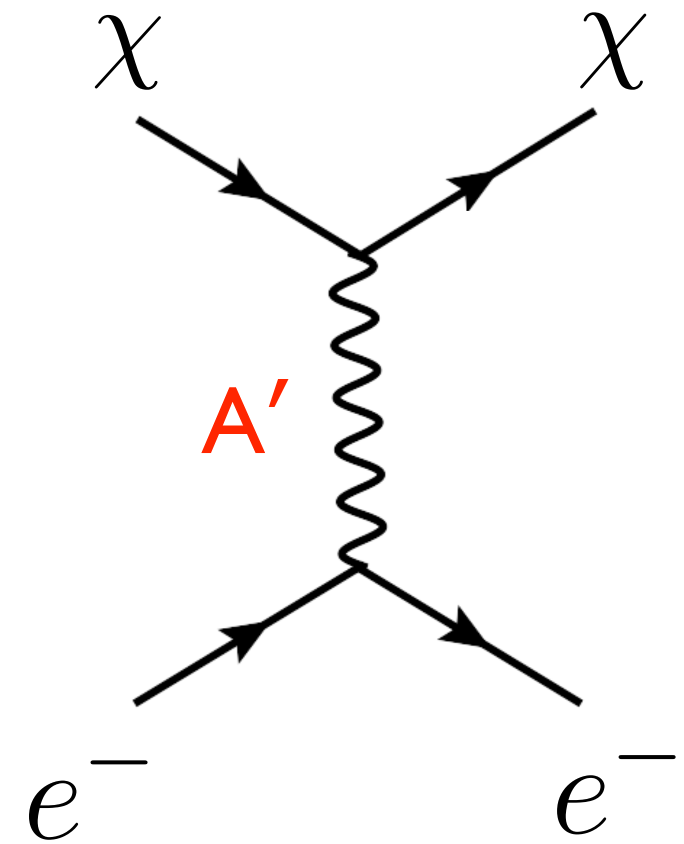
$m_{mediator}$ << keV, scattering is momentum-*dependent*

$$\bar{\sigma}_e \propto \frac{1}{q^4}$$

10-grams would improve on XENON10 in ~3 hrs!

There are several predictive benchmarks!





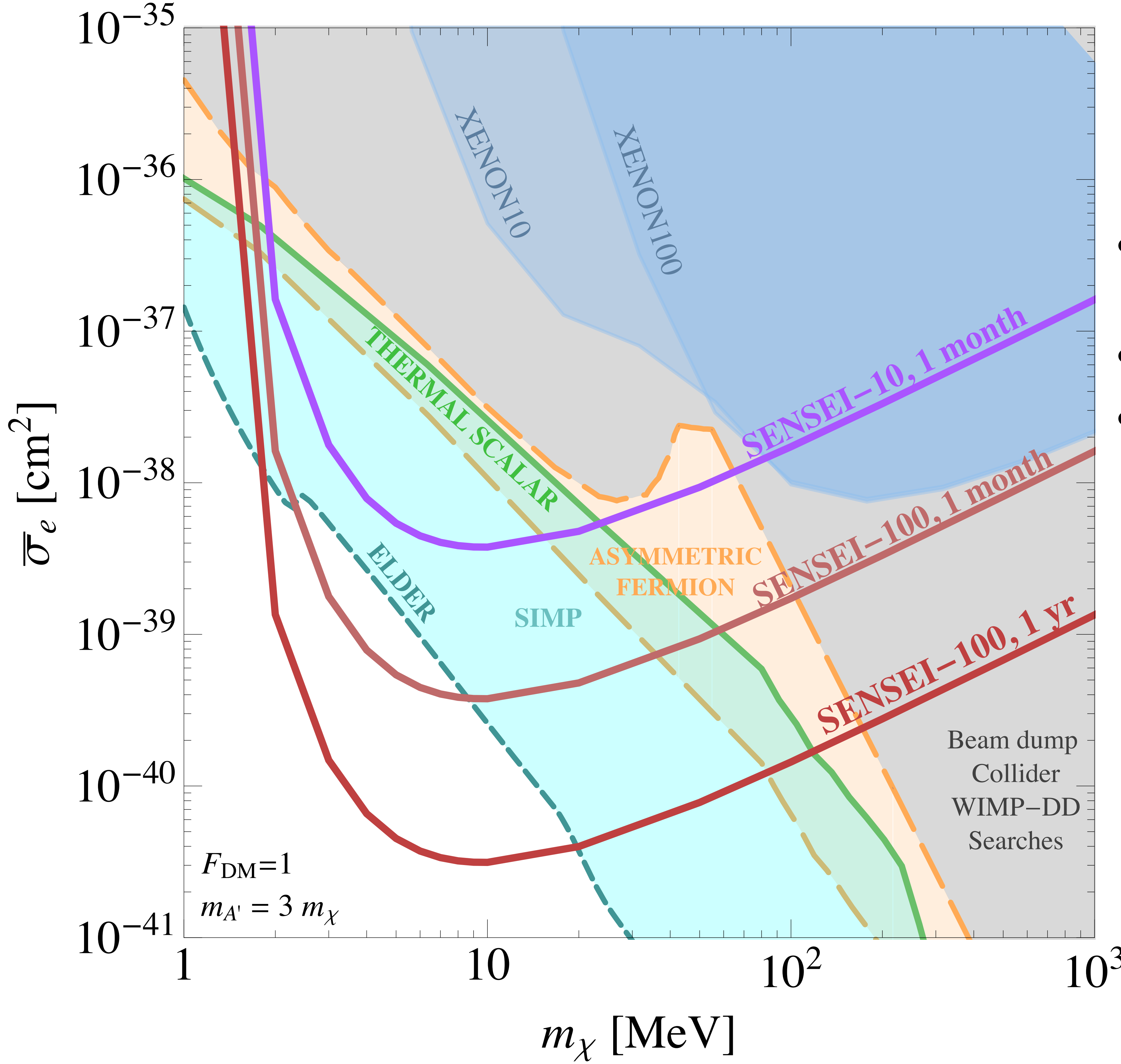
obtain relic abundance via freeze-out, or freeze-in, or a $\chi\bar{\chi}$ asymmetry etc.

$\Longrightarrow$ fixes model parameters

fixes direct-detection rates!

see e.g. Boehm & Fayet (2003); Borodatchenkova, Choudhury, Drees (2005); Izaguirre, Krnjaic, Schuster, Toro (2015); RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (2015)

SENSEI sensitivity to DM + “heavy” A′ mediator



Constraints:

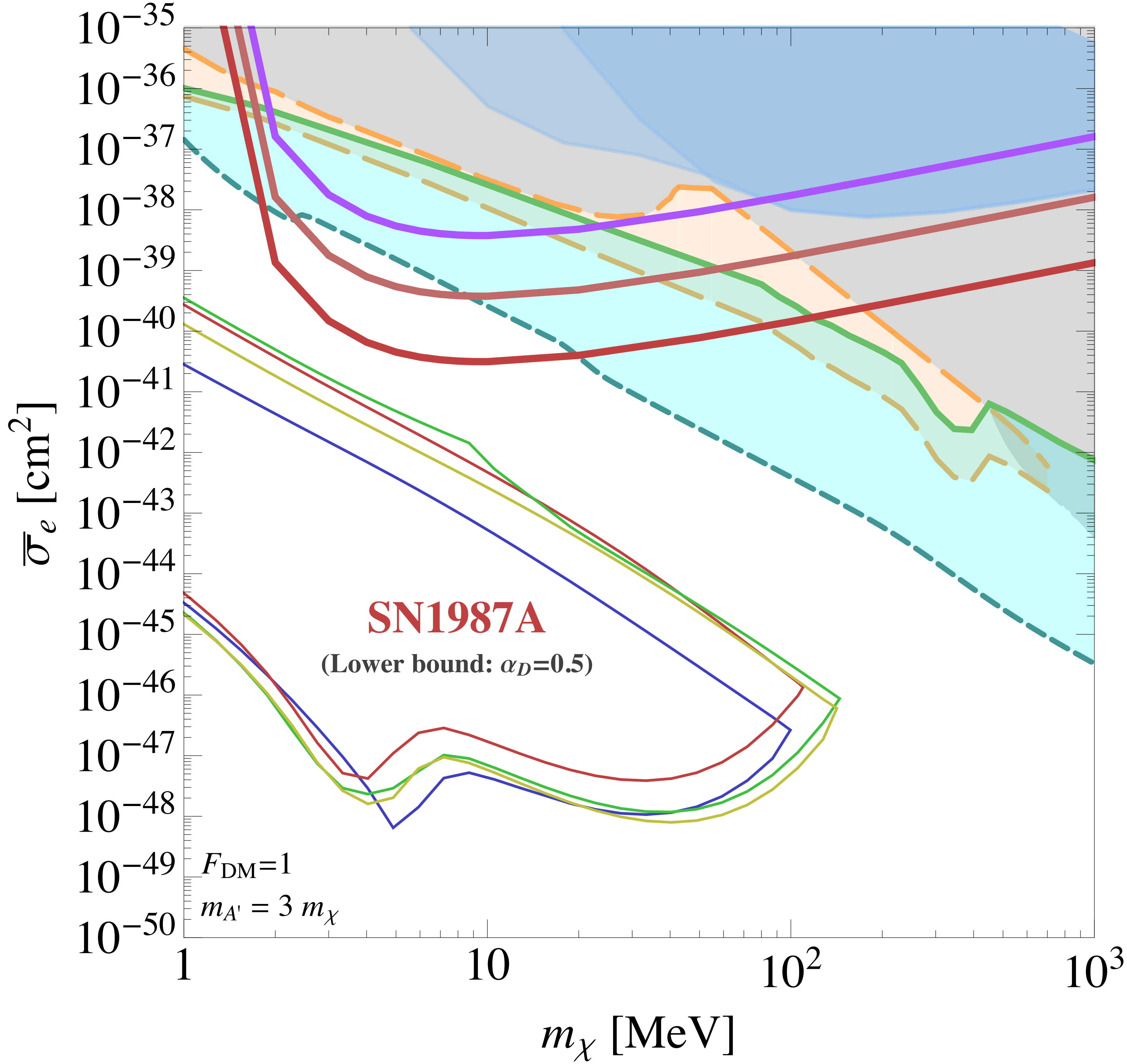
- beam dumps
  (LSND, E137, MiniBooNE)
- WIMP NR searches
- Babar

Models:

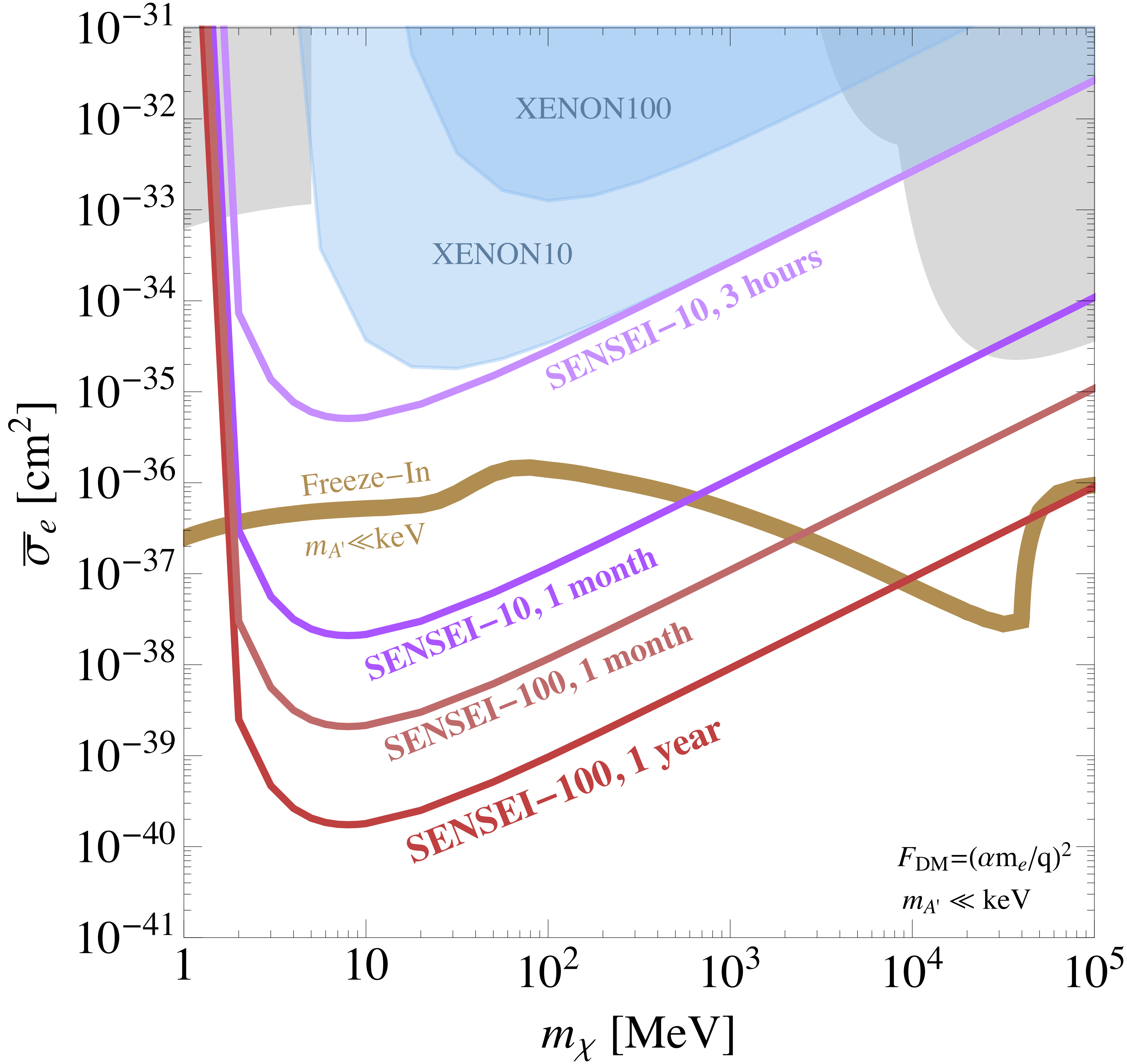
- thermal scalar
- asymmetric fermion
- SIMP
- ELDER

New supernova SN1987A cooling bounds

Chang, RE, McDermott
(to appear)



SENSEI sensitivity to DM + "ultralight" A′ mediator



Constraints:

- WIMP NR searches
- BBN, SN1987A

Model:

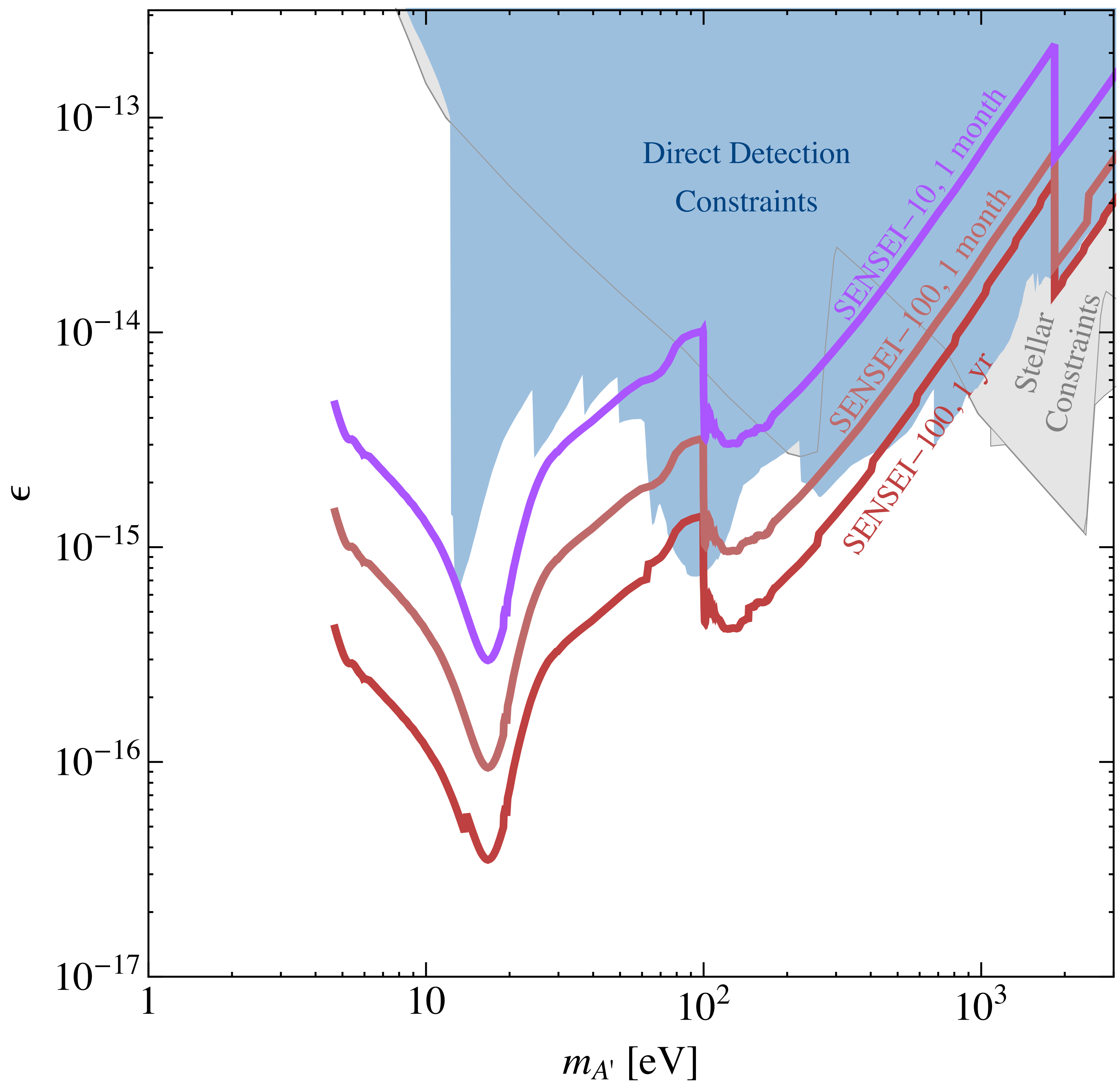
- freeze-in DM

RE, Mardon, Volansky

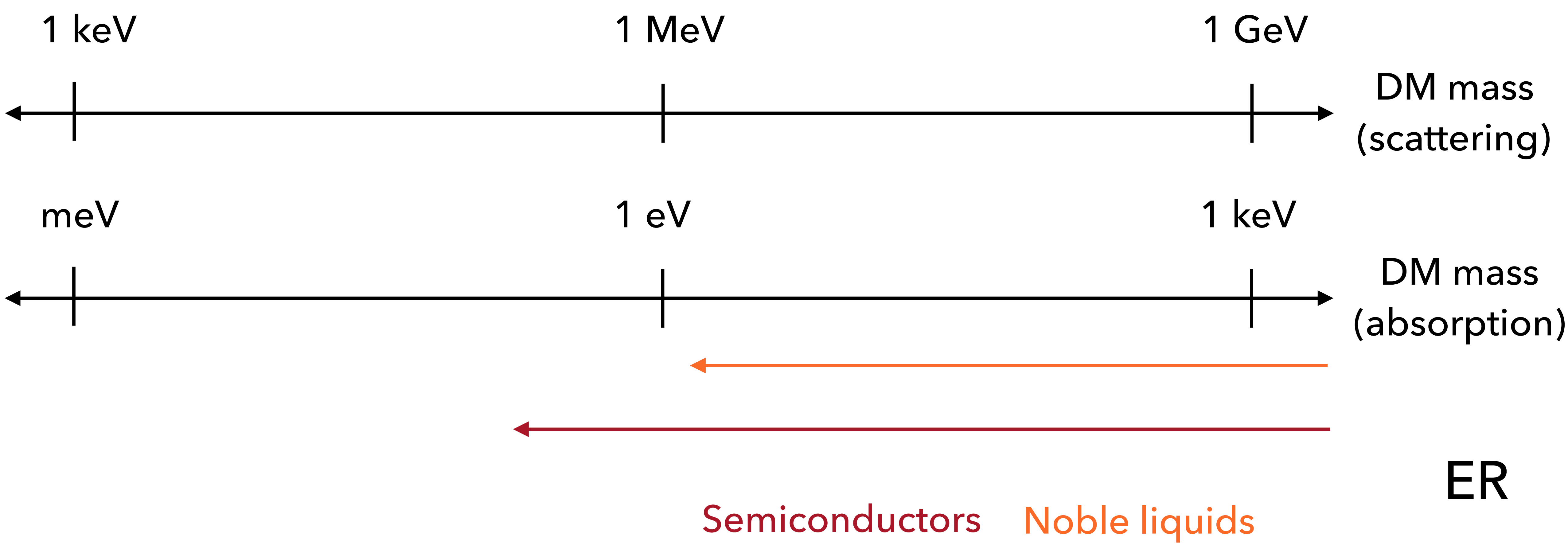
SENSEI sensitivity to absorption of dark-photon DM

Bloch, RE, Tobioka, Volansky, Yu

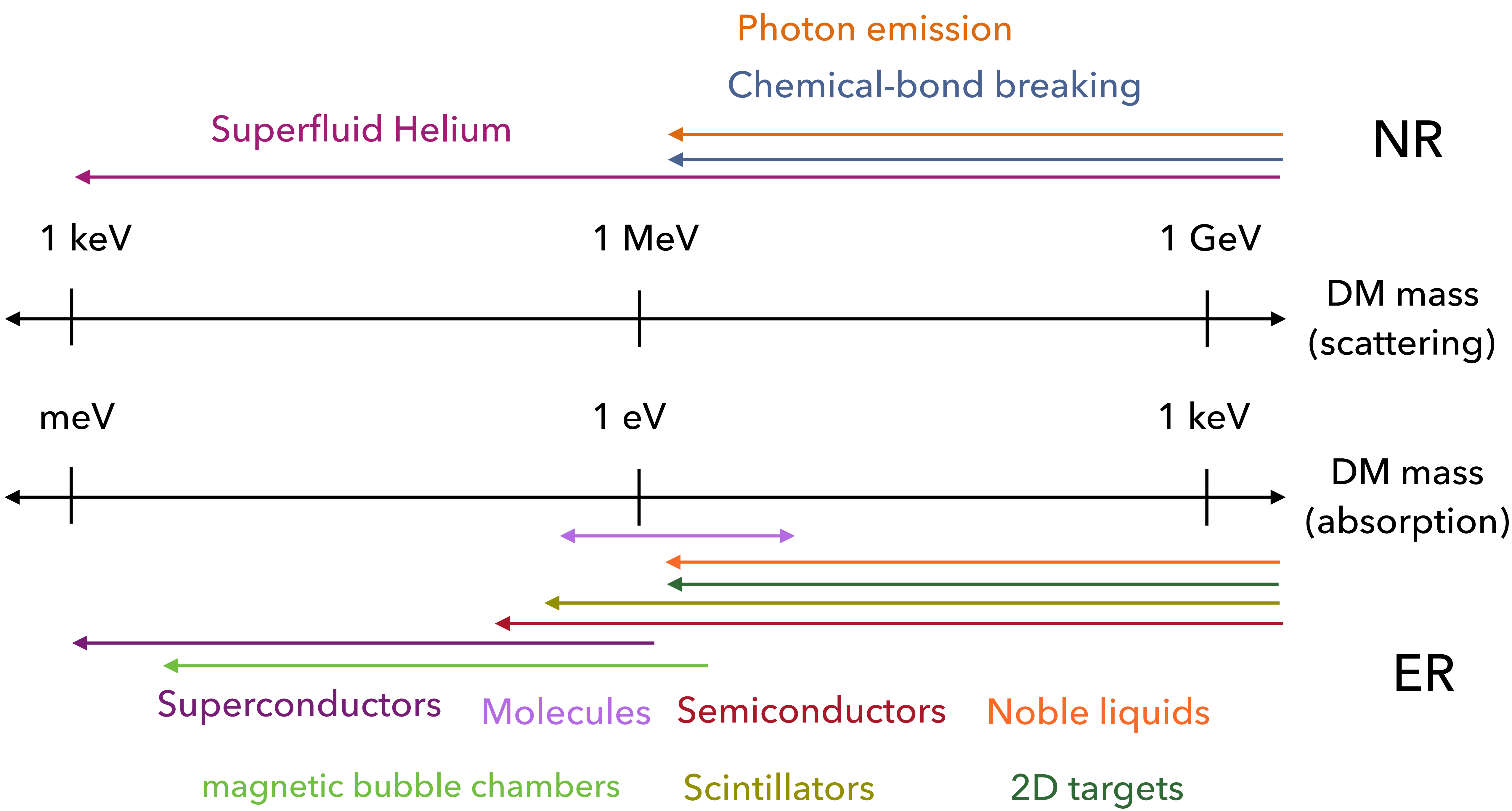
see also Hochberg, Lin, Zurek



Recent explosion of new direct-detection ideas



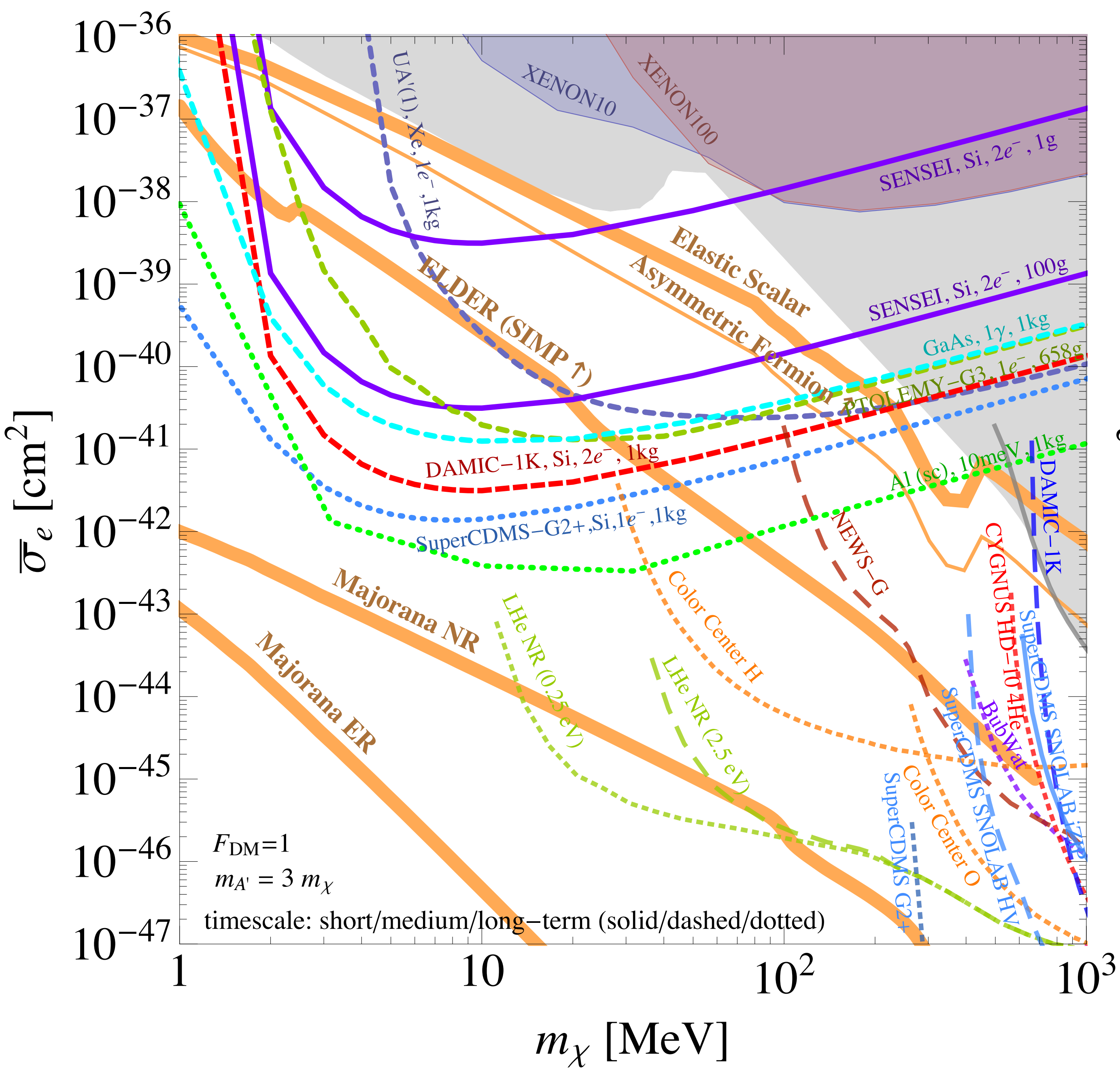
Recent explosion of new direct-detection ideas

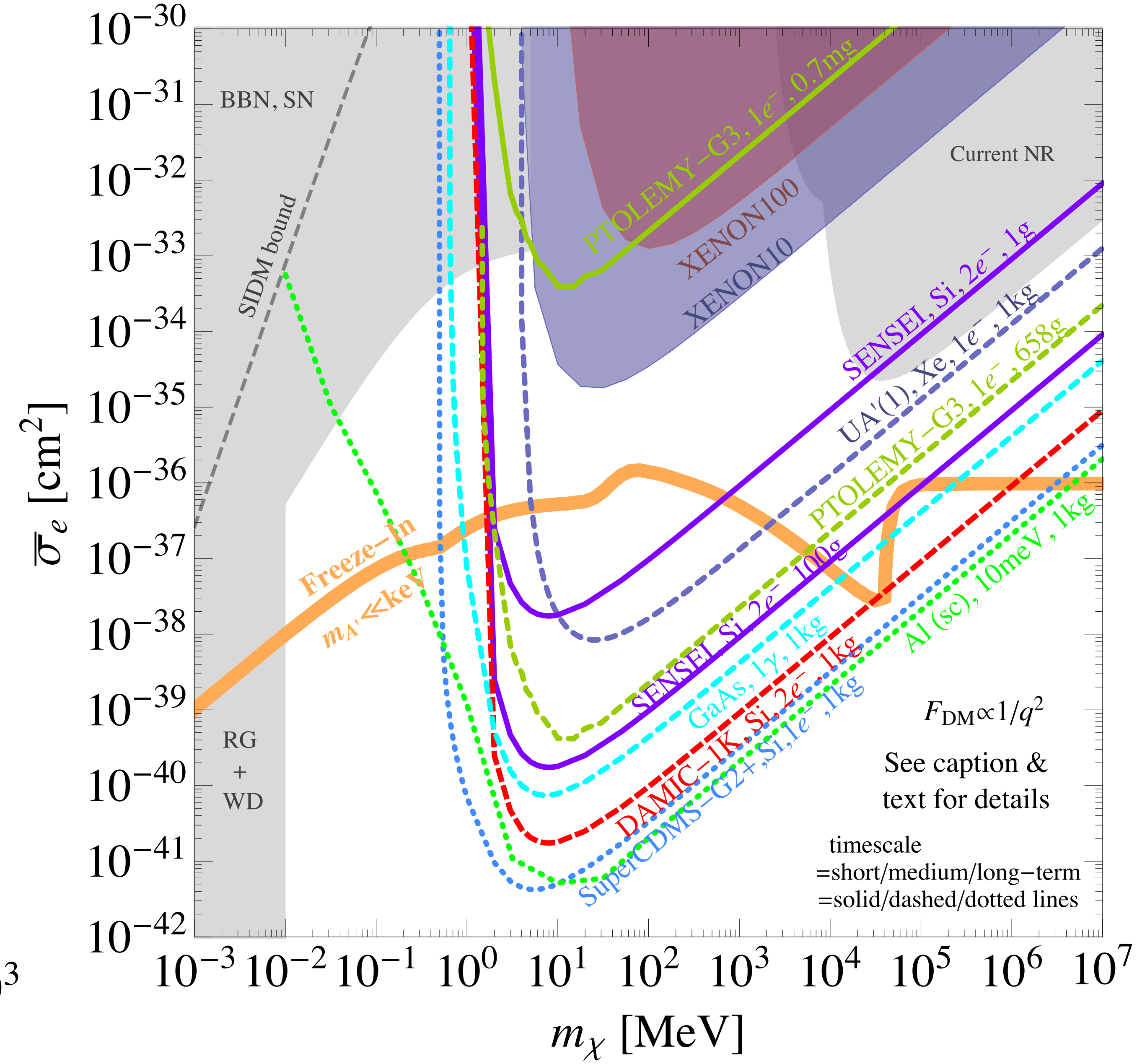


see US Cosmic Visions white paper, 1707.04591

Recent explosion of new direct-detection ideas

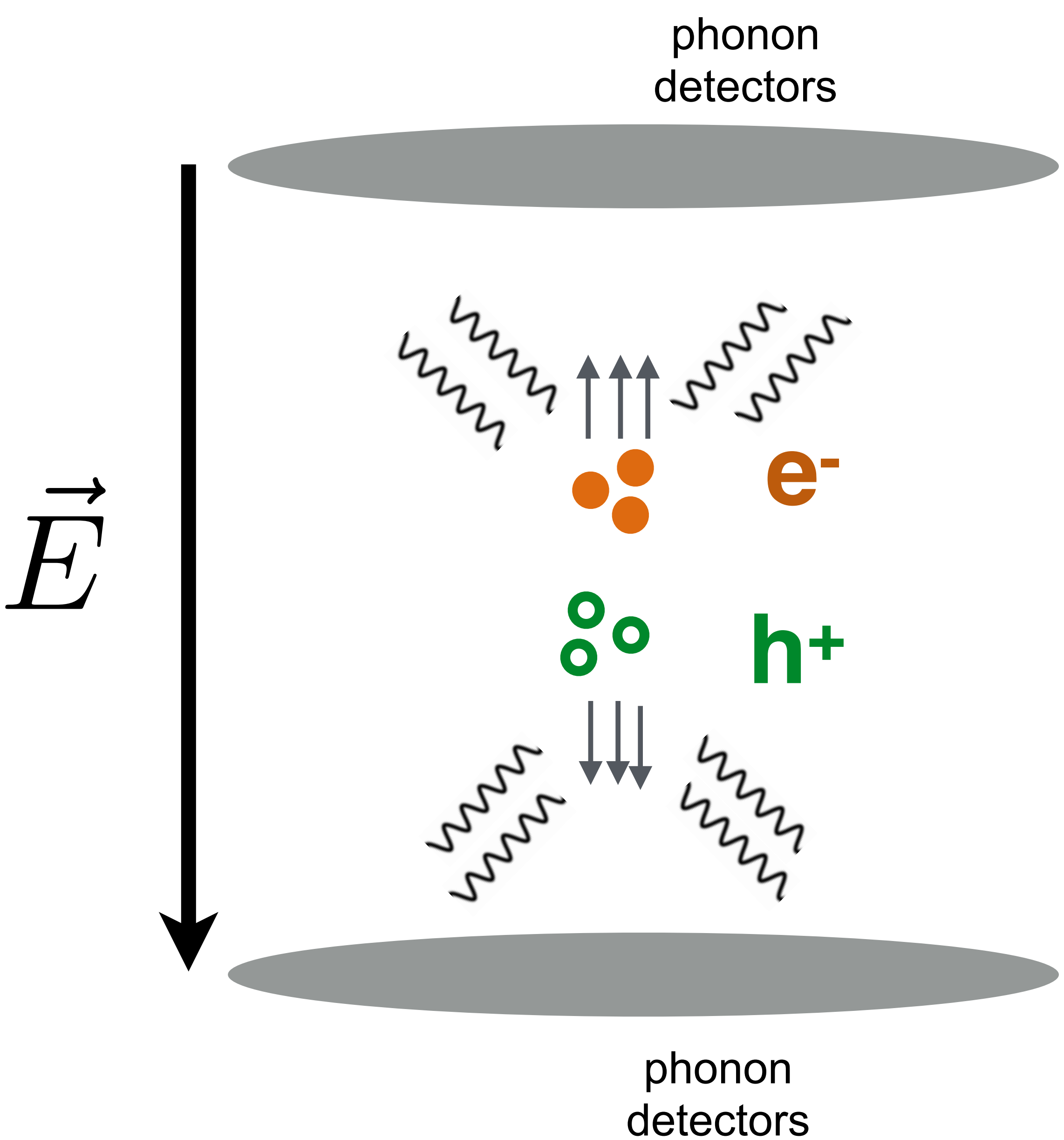
from CV white paper, 1707.04591

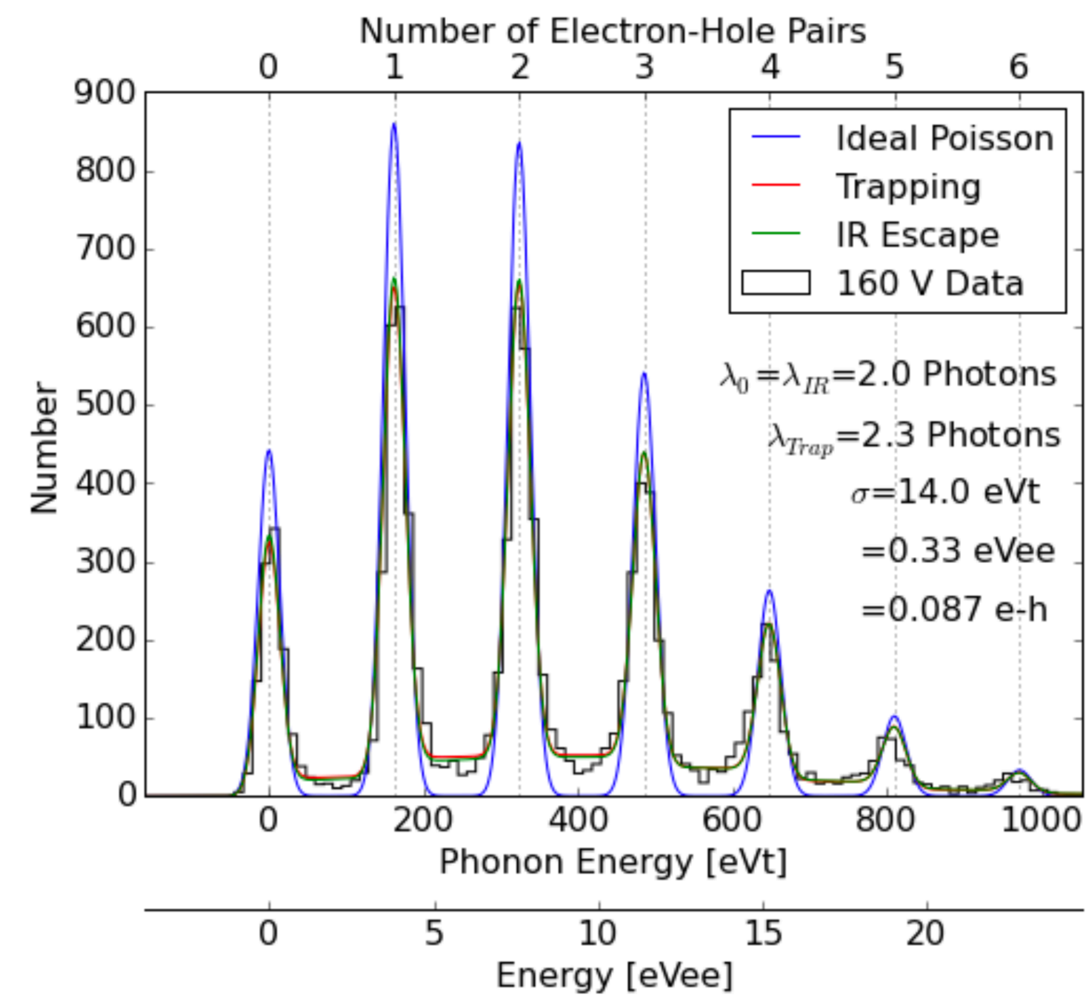




SENSEI is currently leading the pack, but a lot of exciting R&D is ongoing!

Another recent breakthrough in detecting single electrons





1710.09335, Romani et.al.

e^- & h^+ drift in E-field, emitting phonons

(SuperCDMS)

Summary

- Direct detection down to MeV masses is now possible
- Xenon experiments have demonstrated sensitivity

  significant improvements if backgrounds can be mitigated: UA′(1)
- SENSEI will probe large new regions of uncharted territory in next ~2–3 years
- We don't know what DM is, but many ideas exist that allow for a broad program consisting of many small-scale experiments to search beyond WIMPs. This is necessary to maximize our chances of identifying DM.