Direct Detection of sub-GeV Dark Matter: A New Frontier

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Stony Brook University

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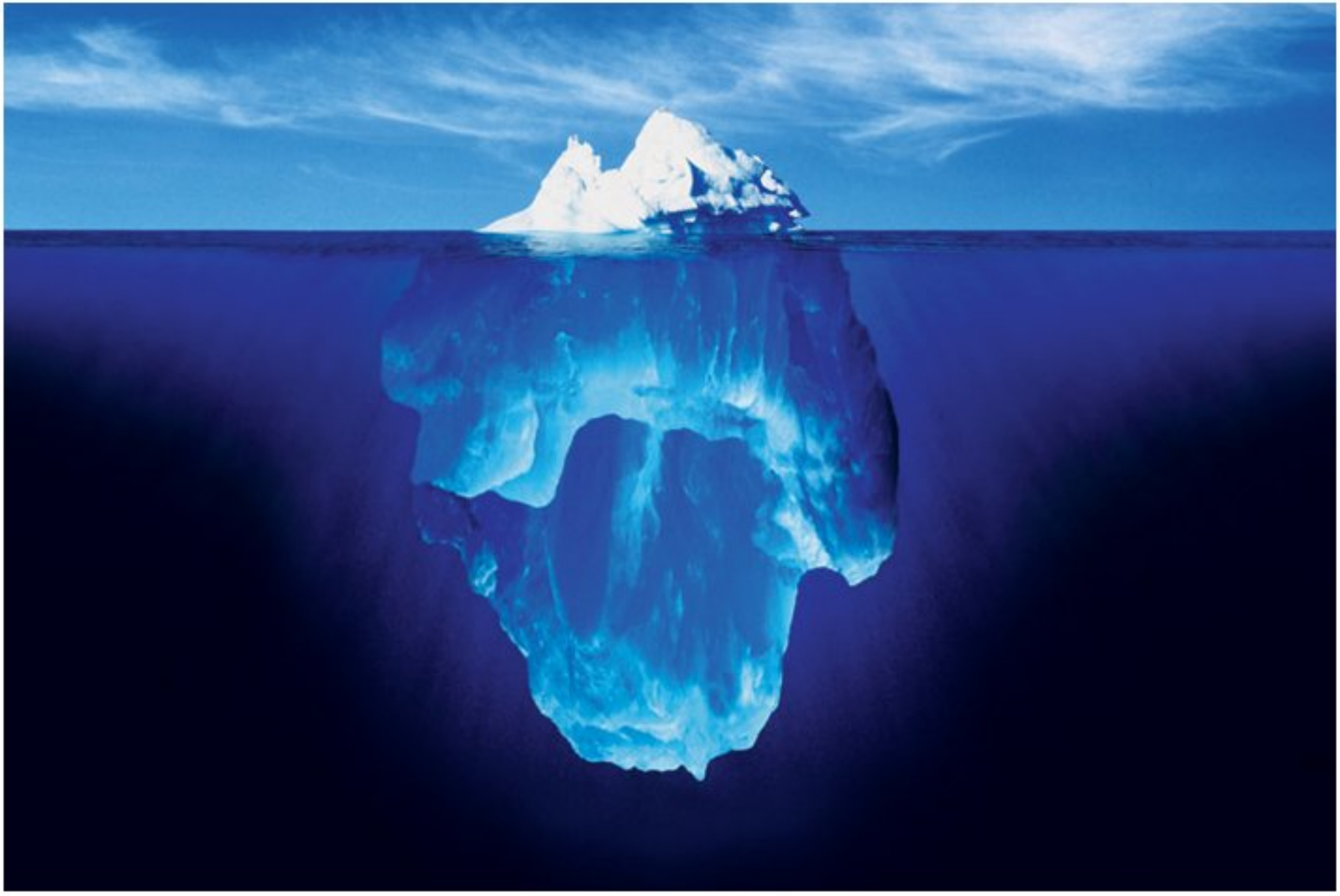
We don’t know the fundamental building blocks of ~85% of the Matter in the Universe



The matter we understand

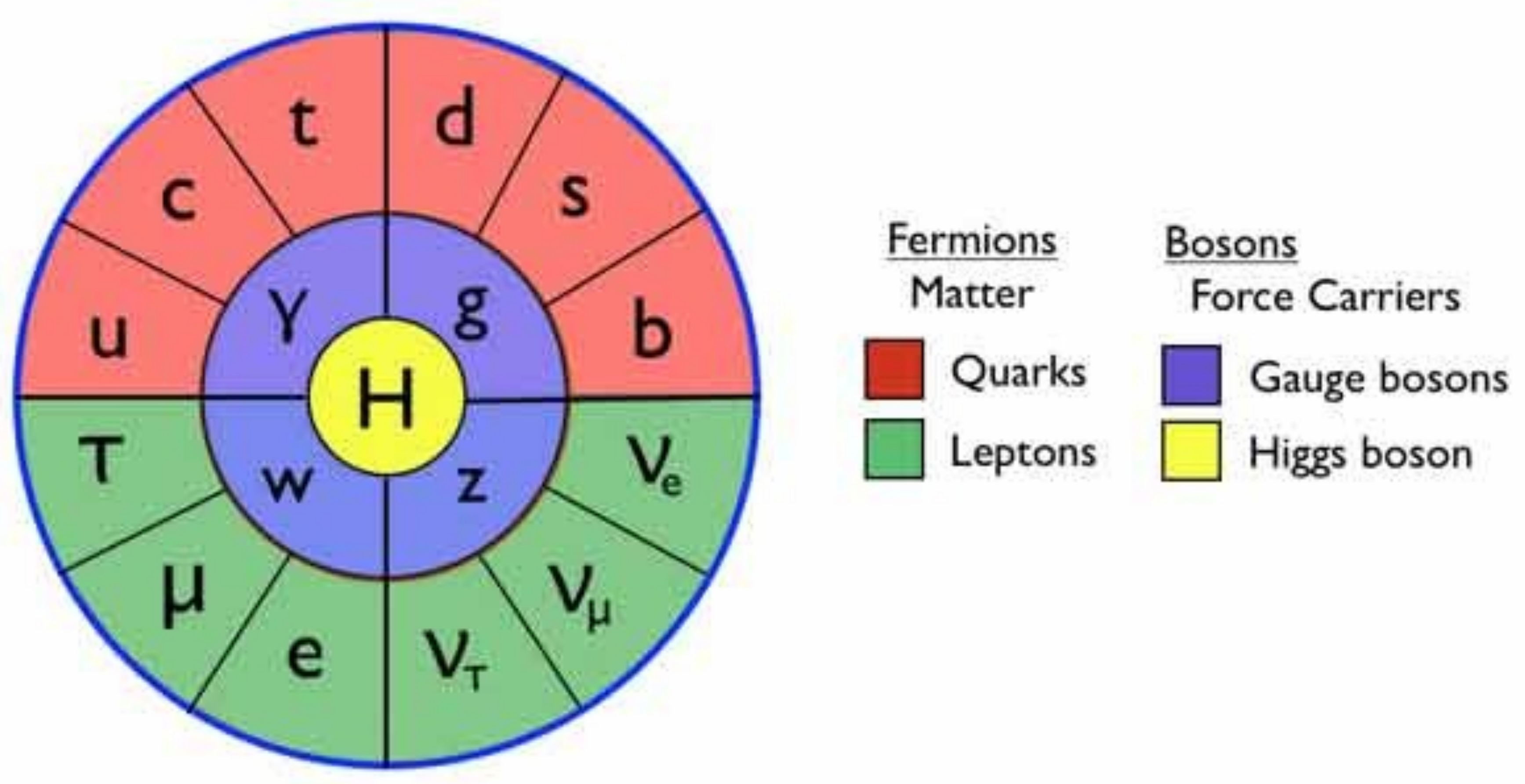


Fig. credit: W. Murch

described by the amazing

Standard Model of Particle Physics

The matter we don't understand: Dark Matter

well-established evidence for New Physics

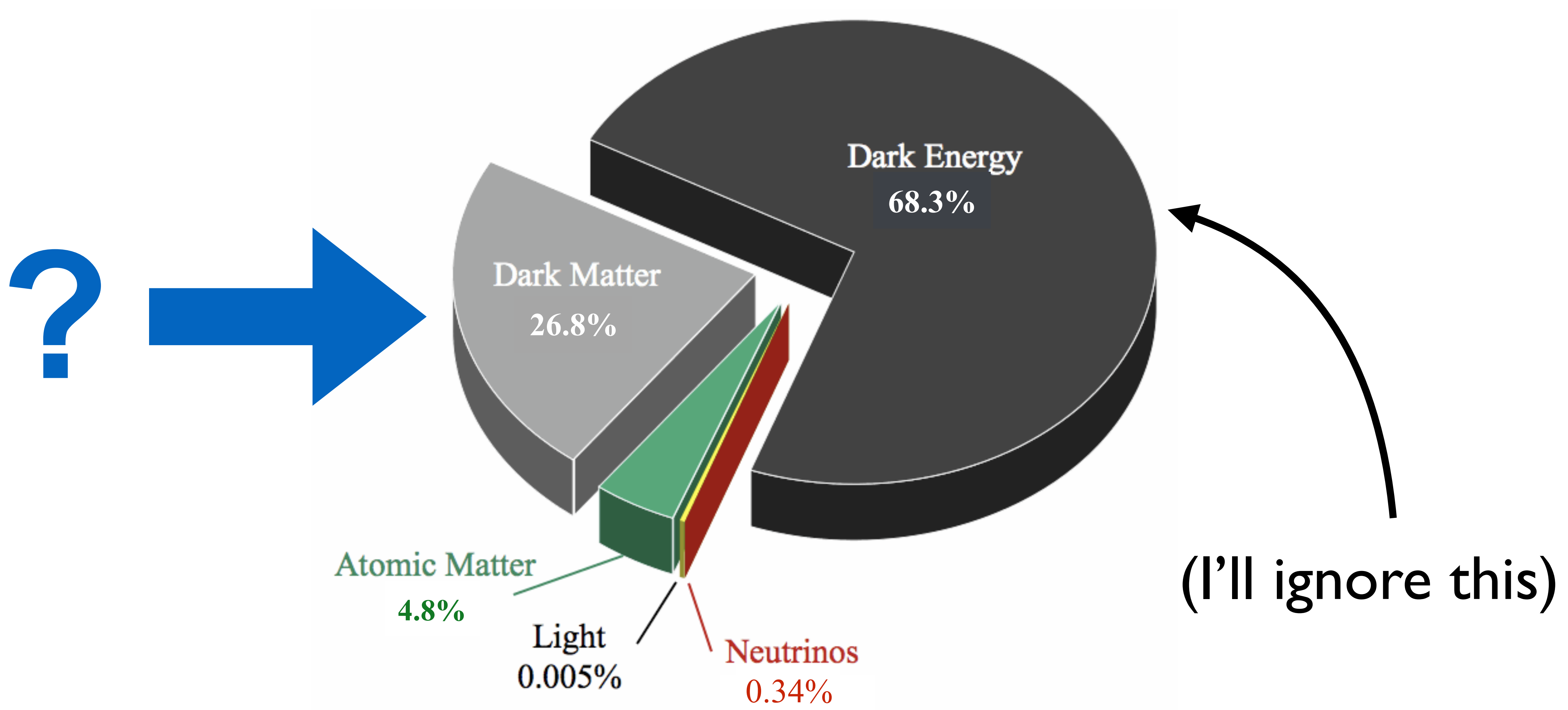
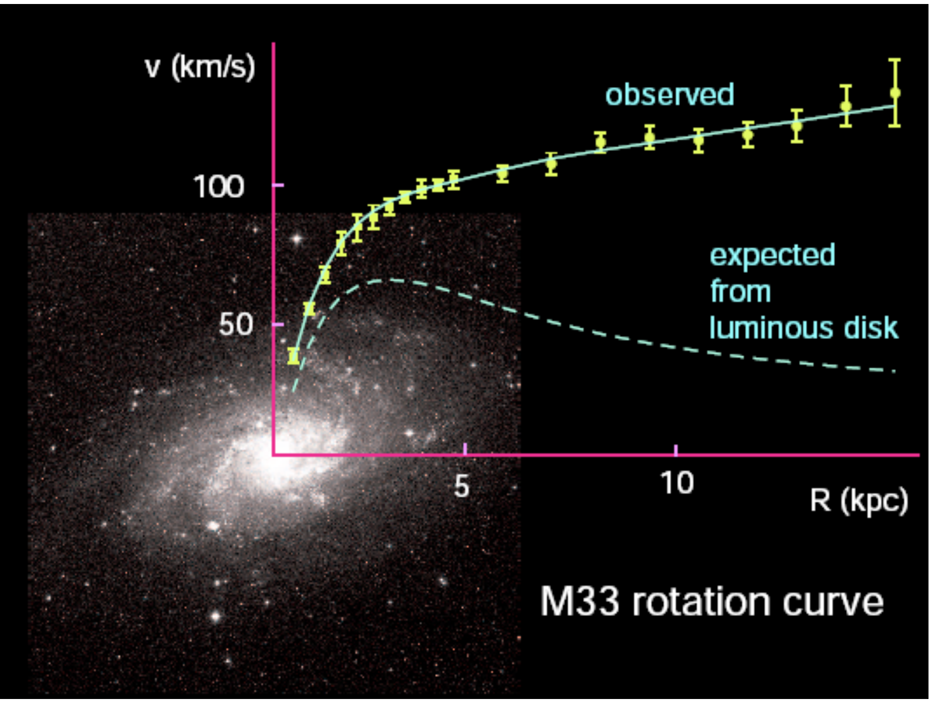
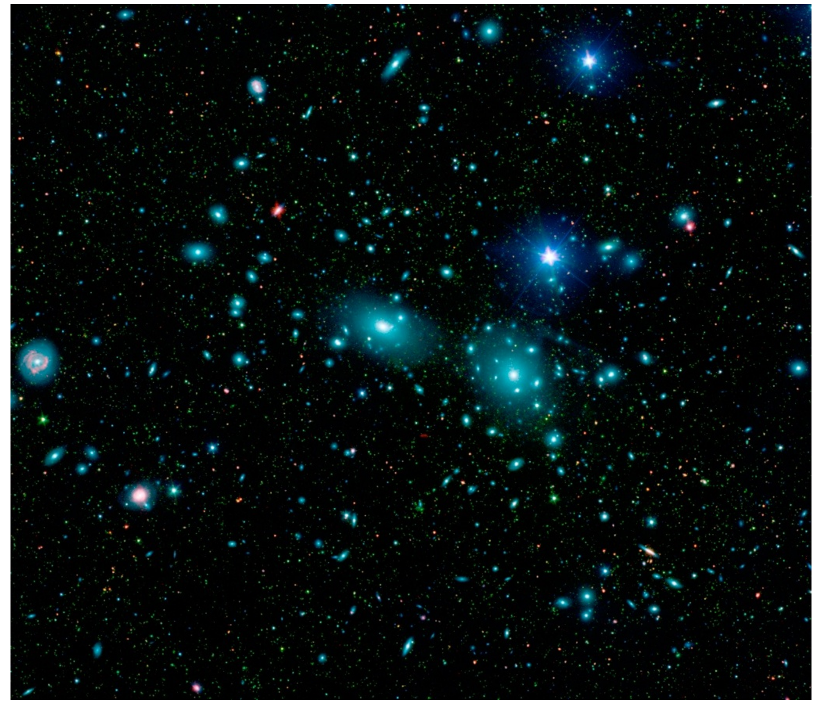
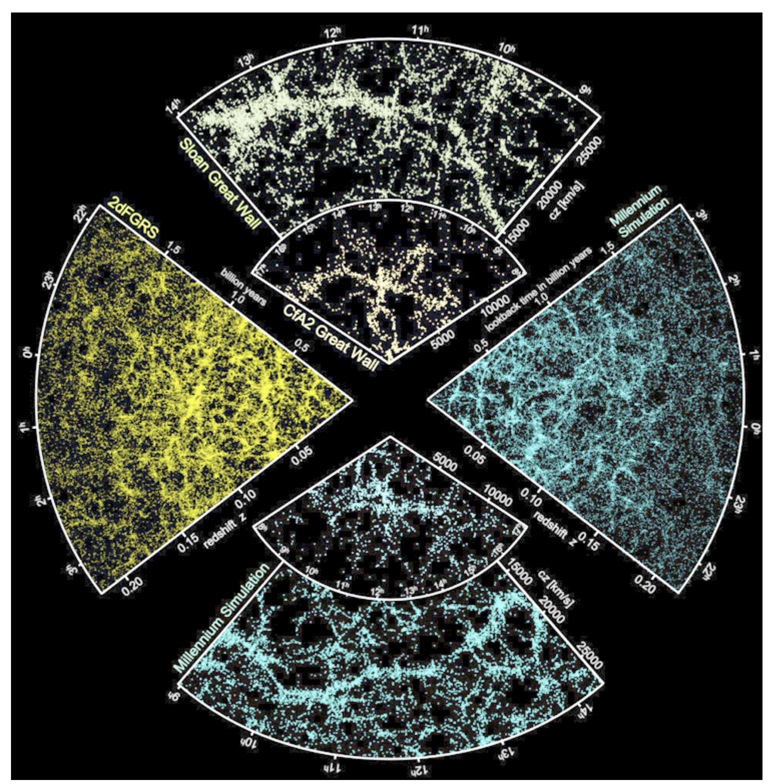


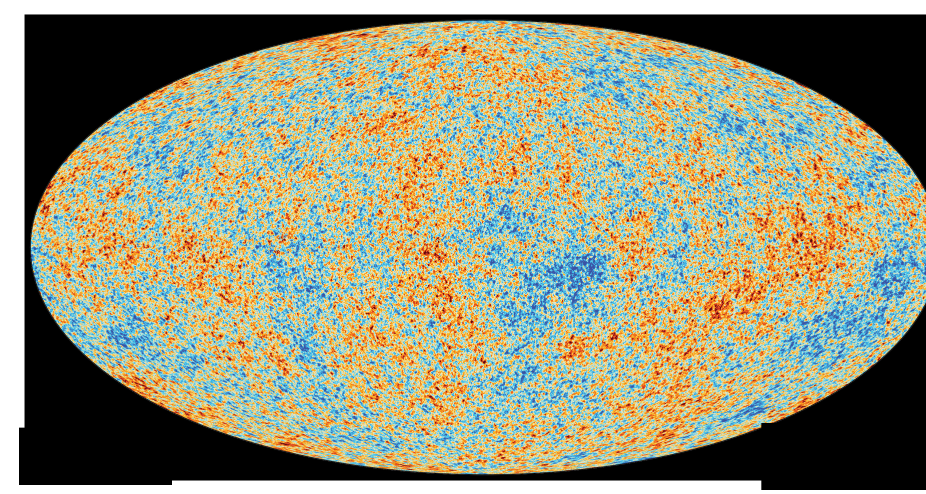
Fig. credit: adapted from people.virginia.edu/~dmw8f/astr5630/Topic01/t1_cos_combined.html

A lot of evidence, for example:









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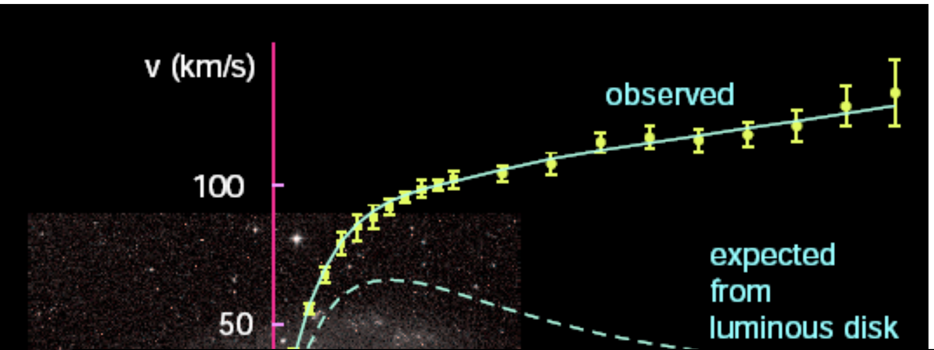
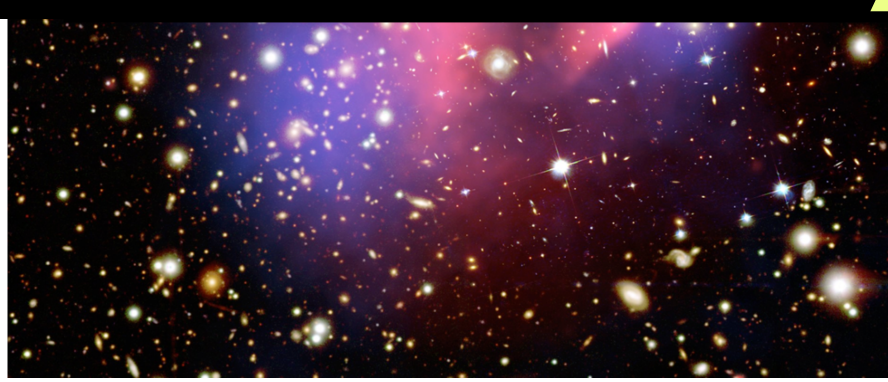
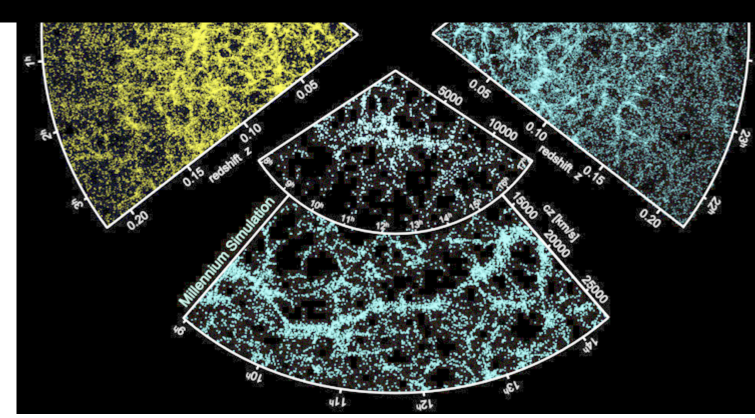
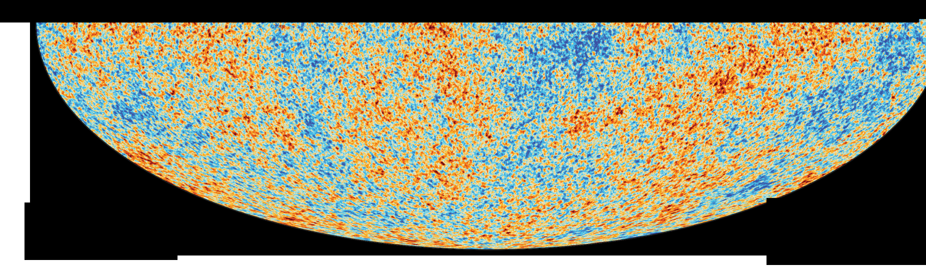


Postulating the existence of a new particle (“Dark Matter”) to describe these extensive data is very conservative…





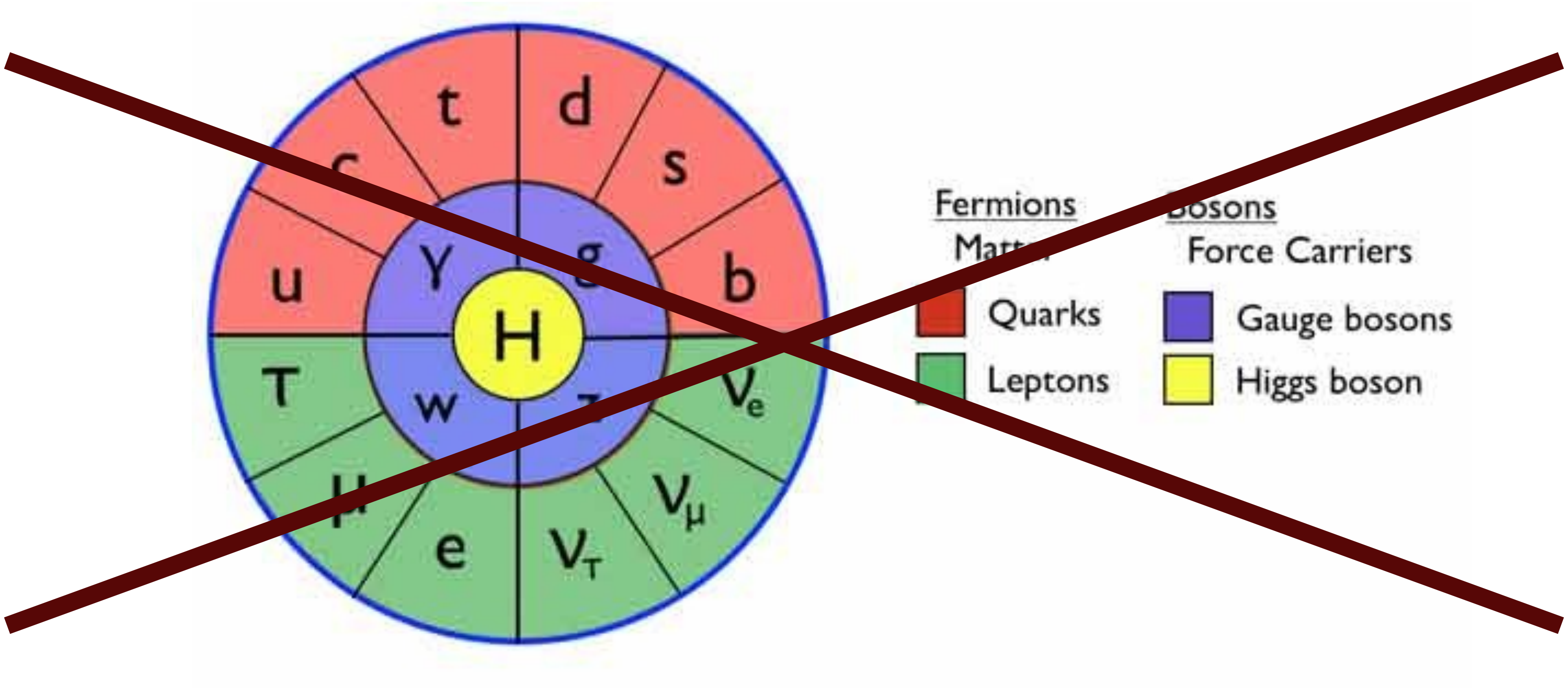


What is Dark Matter?

all evidence from gravitational interaction…

Uncovering its identity is one of the most important goals in particle physics today

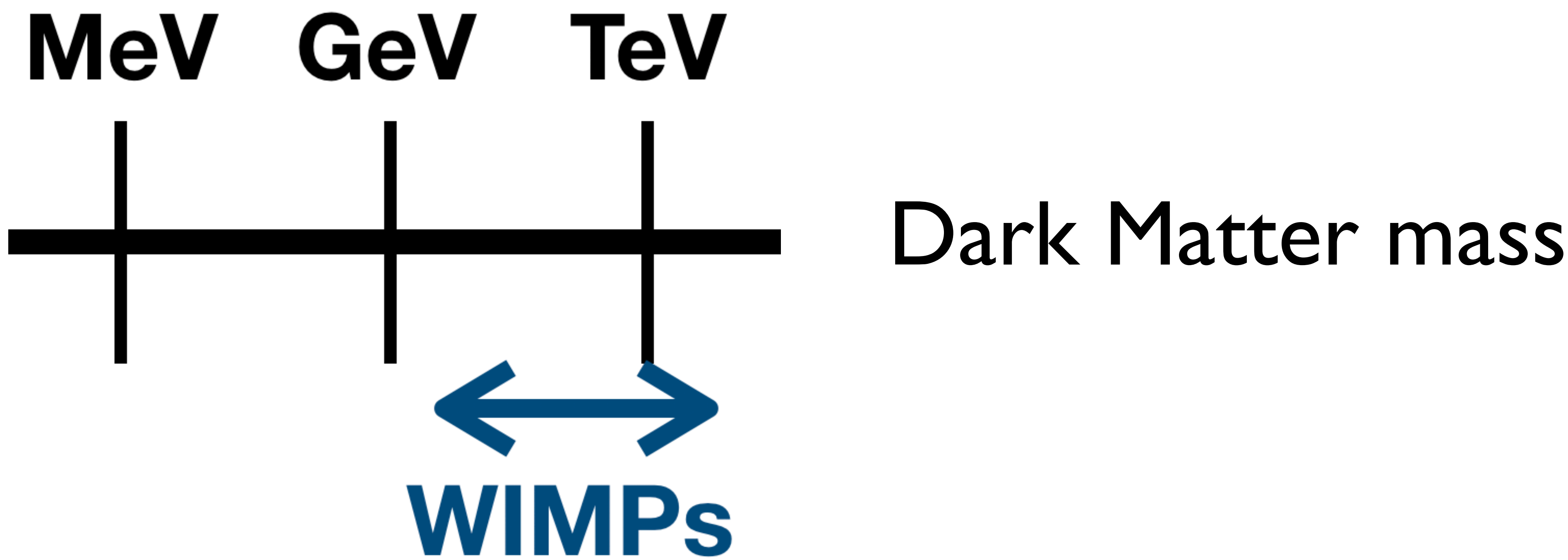
Mass? Spin? Interactions? Connections to Standard Model?
Part of a larger hidden sector?



Murch

None of the particles in Standard Model can be dark matter

WIMPs: favored candidate for many decades



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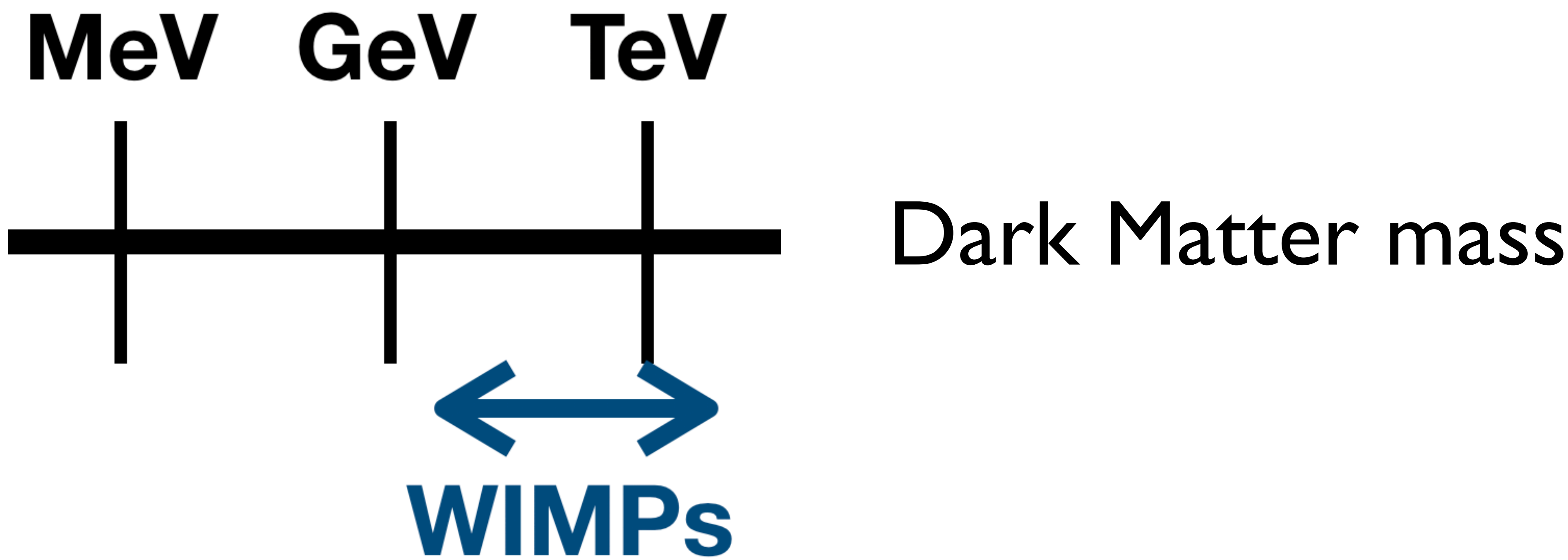
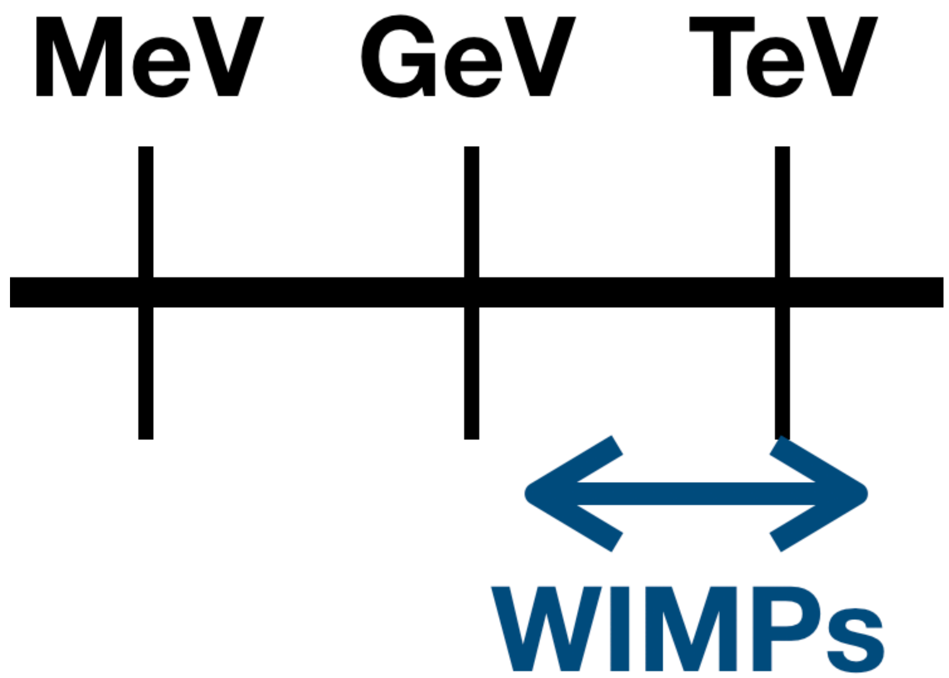


- Weakly Interactive Massive Particle (WIMPs)

WIMPs: favored candidate for many decades



Dark Matter mass

$$E = mc^2$$

Natural units:

$$E = m \quad c = 1$$

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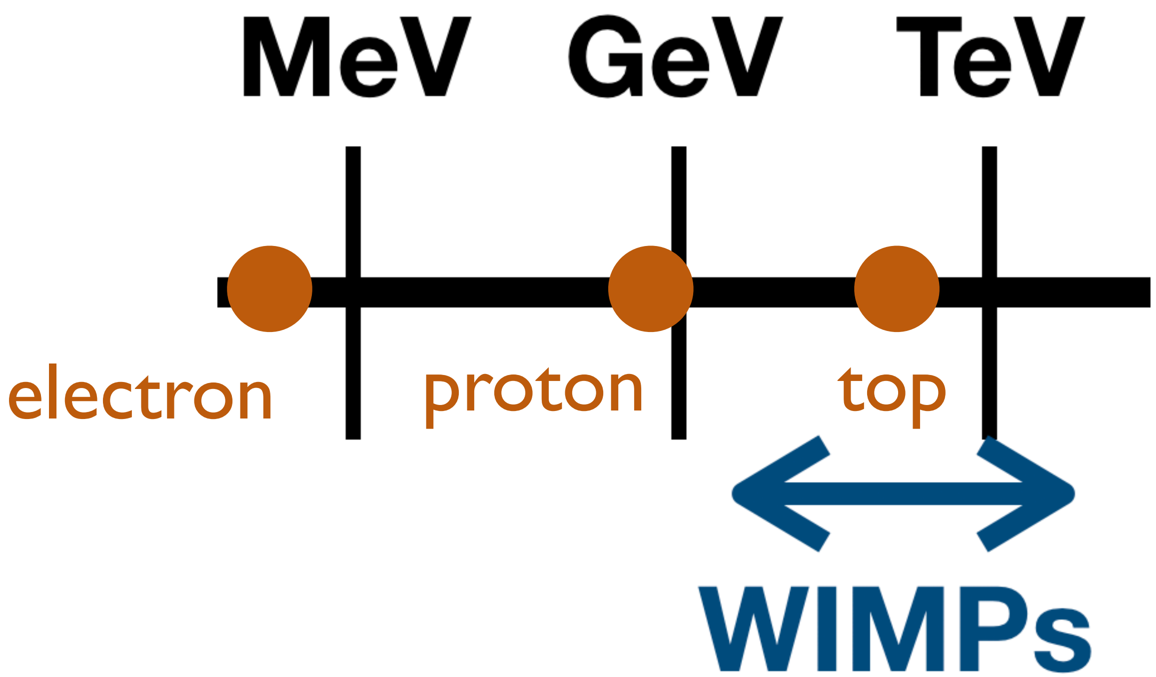

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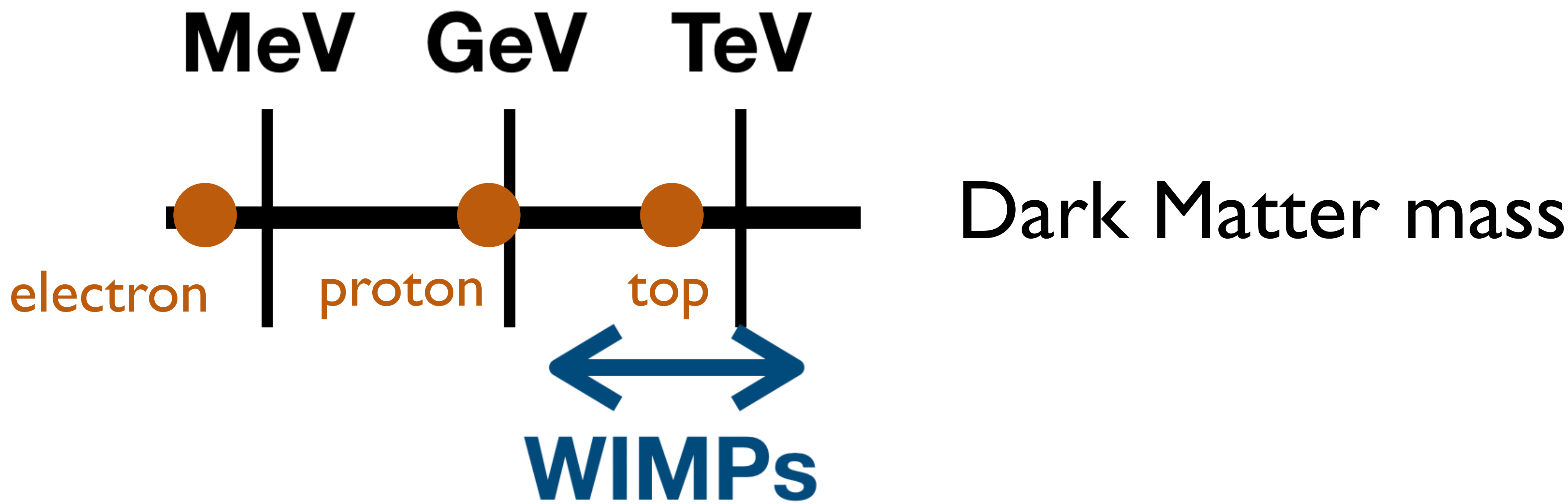
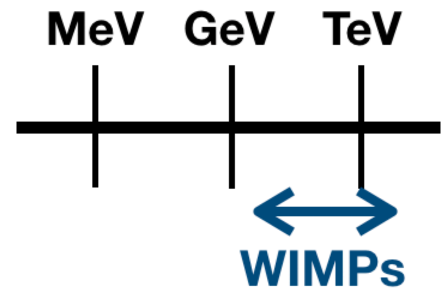
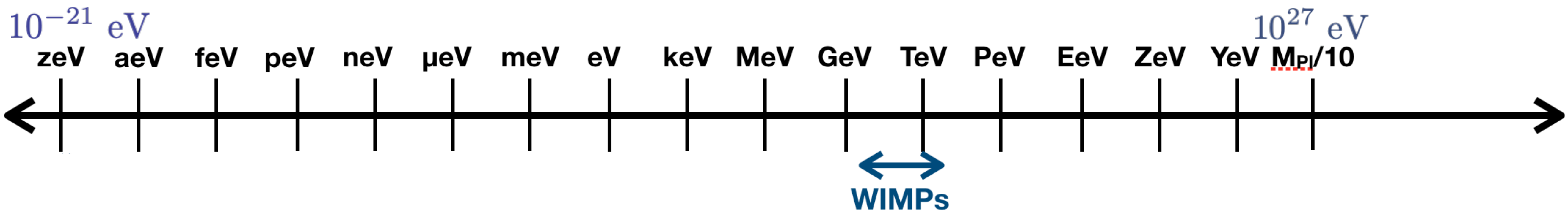


- Weakly Interactive Massive Particle (WIMPs)
- Interact through Weak force (W, Z bosons) or Higgs
- Motivated by several theoretical considerations
- Experimental searches for WIMPs are mature

Over past decade, theoretical efforts have shifted to other candidates, spanning a vast mass range…


MeV
GeV
TeV
WIMPs

The New Dark Matter Landscape



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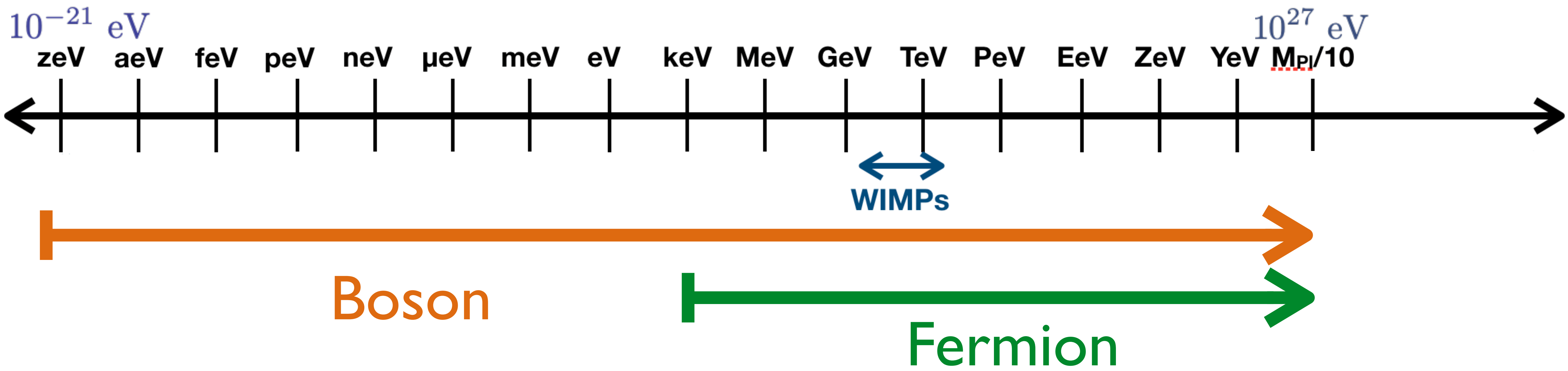
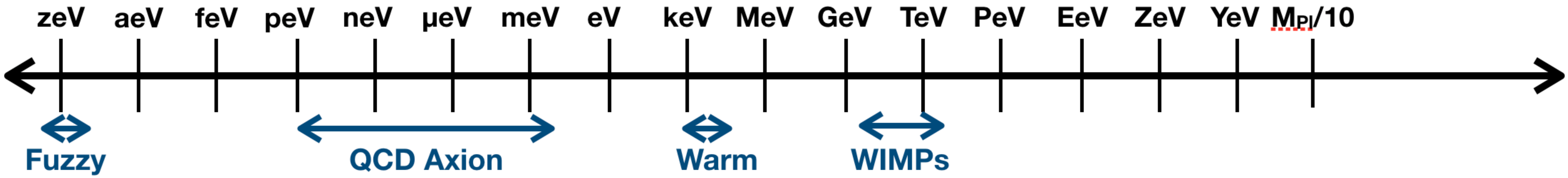


lower bound from existence of dwarf galaxies of size ~1 kpc

Bosons de Broglie wavelength: $\lambda \sim \frac{h}{p} \sim \frac{h}{mv} \sim 1\ \mathrm{kpc}$

Fermions not enough phase space from Pauli exclusion principle

The New Dark Matter Landscape



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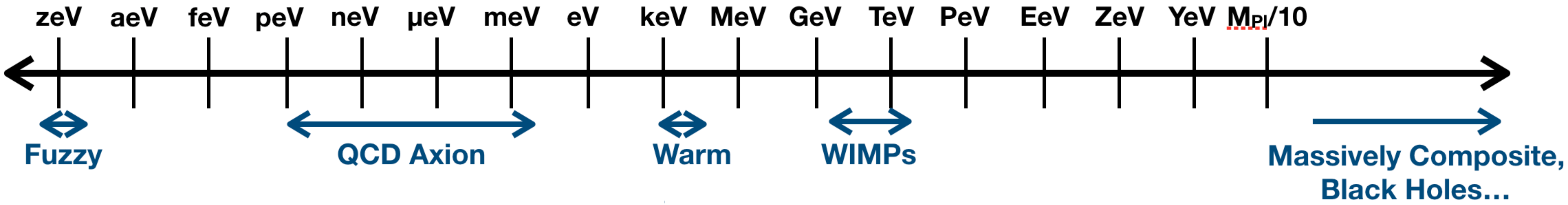

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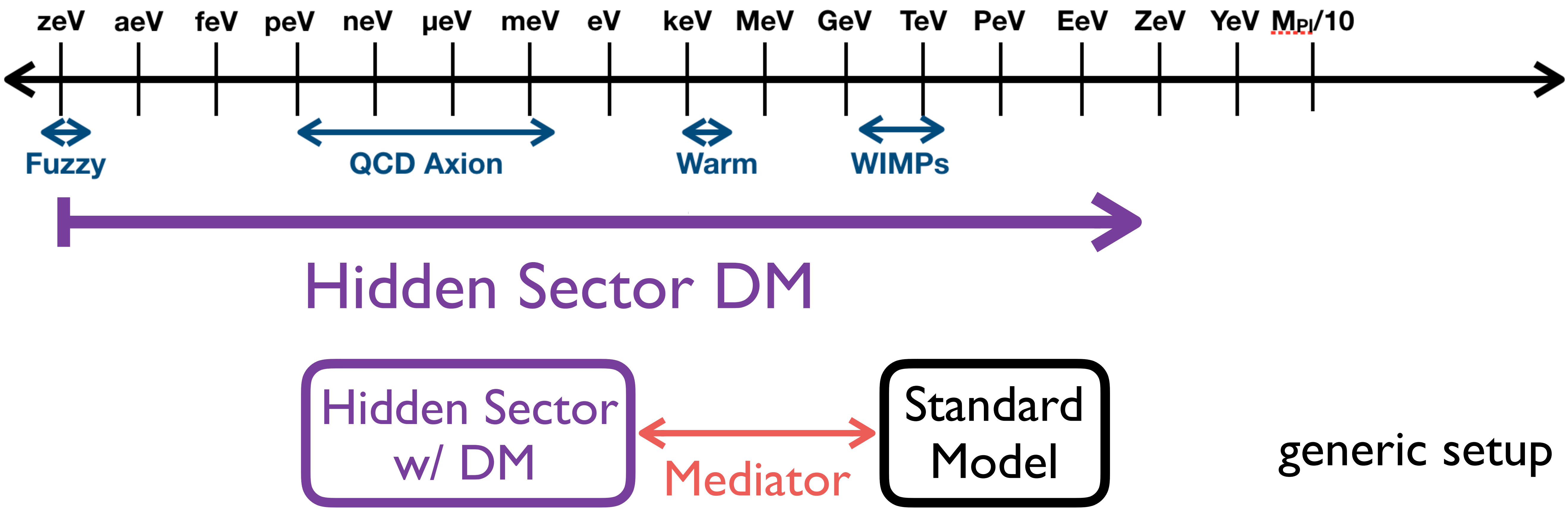
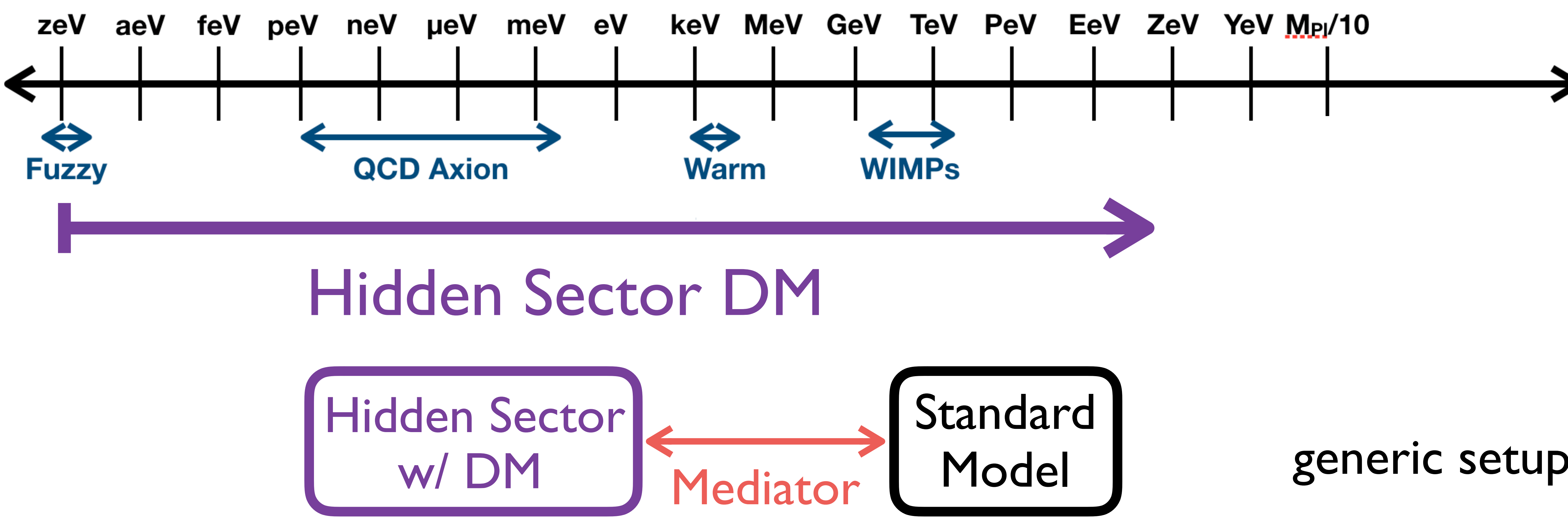


generic setup

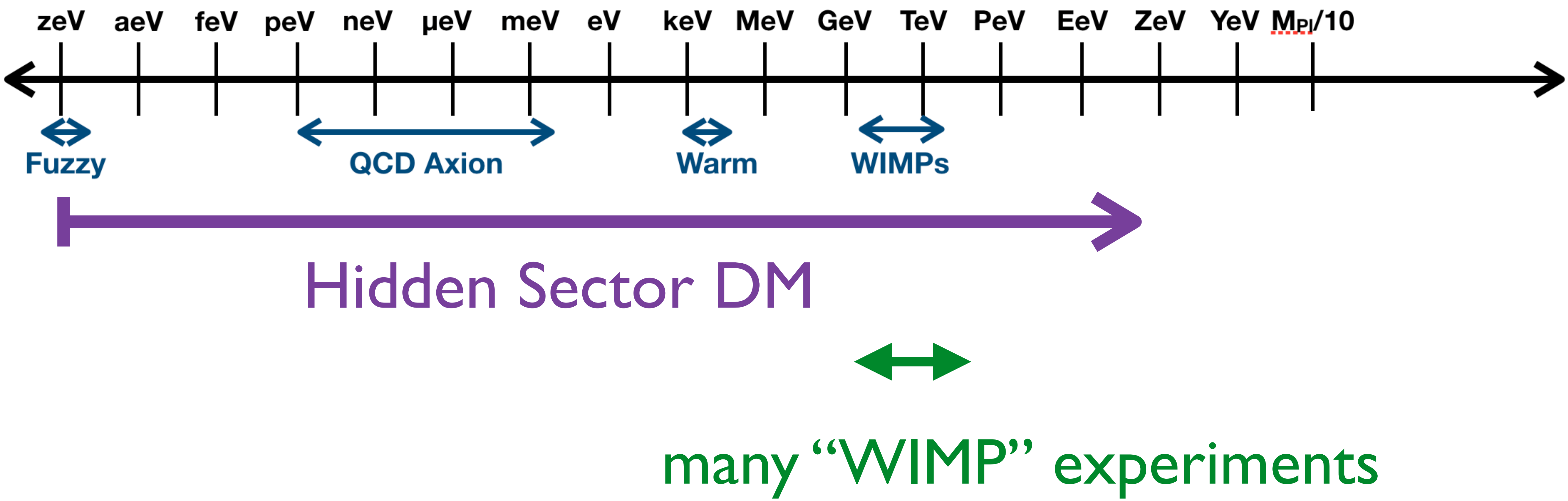
- Hidden sectors generic in top-down approaches
- Rich number of possibilities, but not "anything goes"
- Well-motivated models & DM production scenarios make sharp, testable predictions for astrophysical & terrestrial observables

The New Dark Matter Landscape



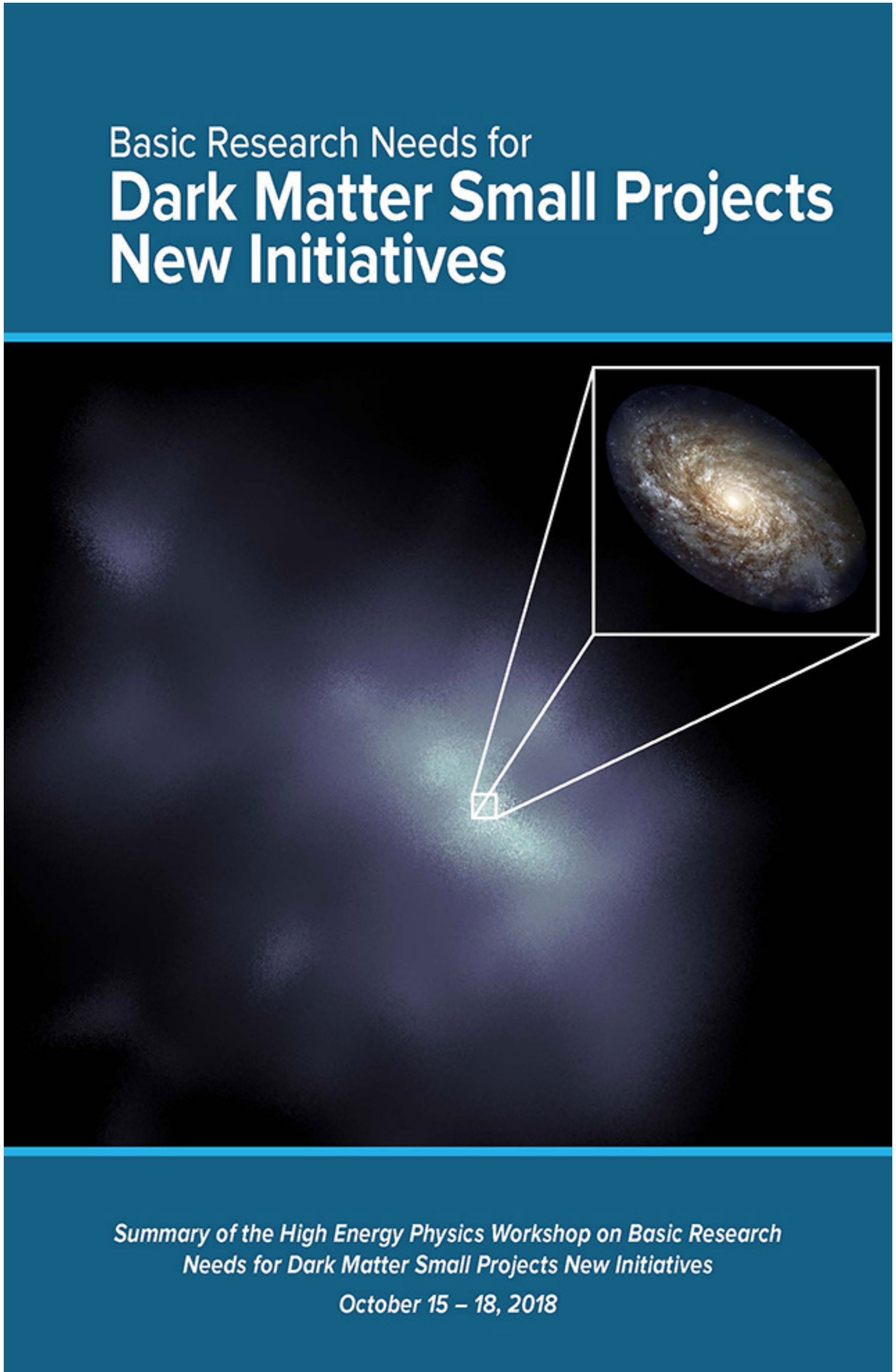
A broad search program is necessary to maximize our chances of identifying DM

The New Dark Matter Landscape



A vast mass range remains woefully under-explored

Several new ideas and experiments now allow us to explore much of it in coming decade



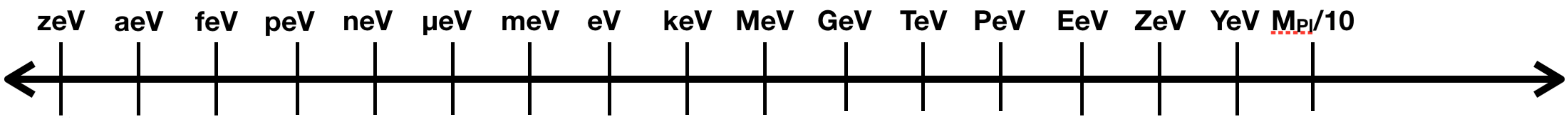
science.energy.gov/hep/community-resources/reports/

US Department of Energy report argues for a comprehensive experimental program:

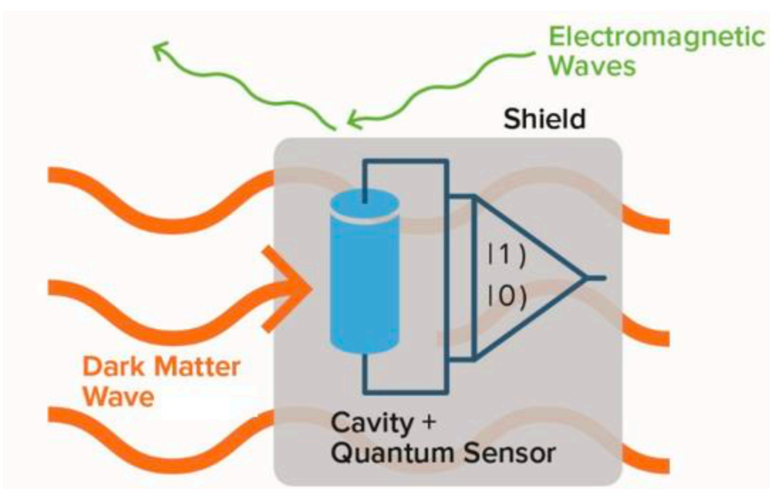
- coherent field searches
- accelerators
- direct detection

can explore DM with mass 30 orders of magnitude below proton

Experimental Strategies



Wavelike



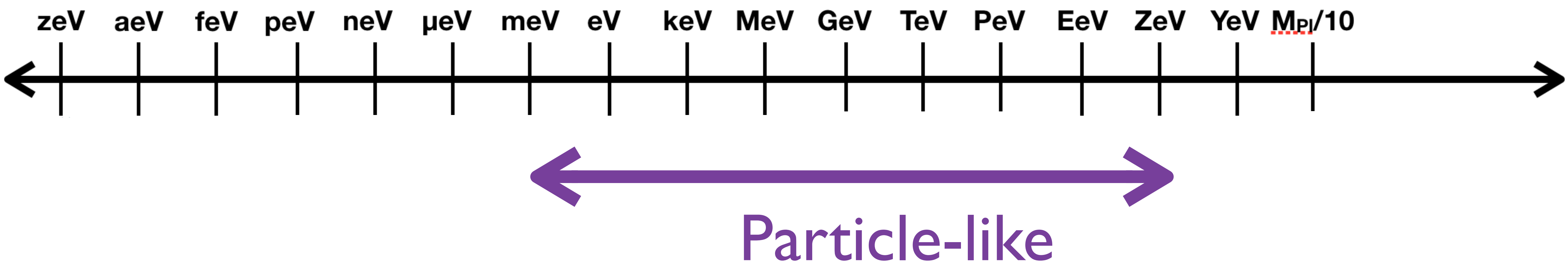
e.g. QCD axion, other pseudoscalars, scalars, vectors

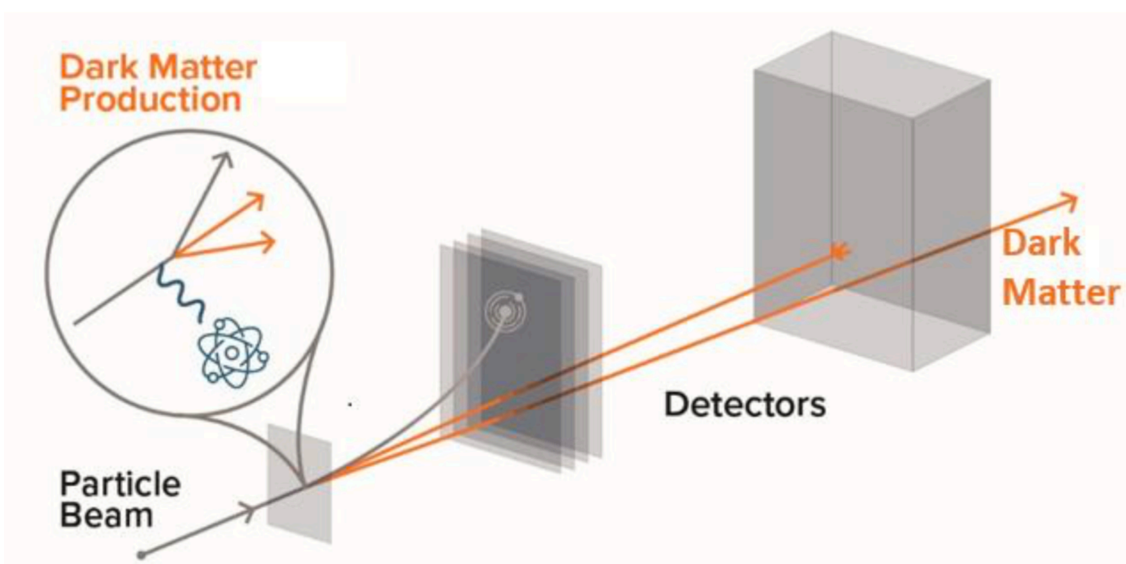
- high phase-space density
- detect coherent effect of entire field

ADMX, HAYSTAC, CASPEr, ABRACADABRA, DM-Radio, IAXO, ARIADNE…

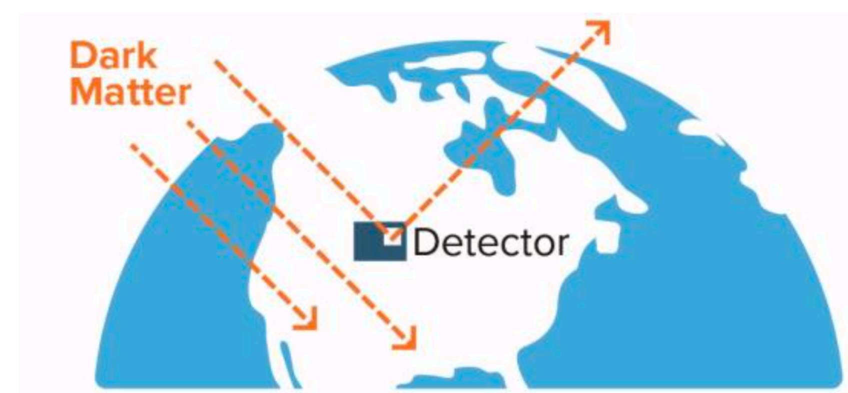
See DOE BRN report, or US Cosmic Visions White Paper

Experimental Strategies





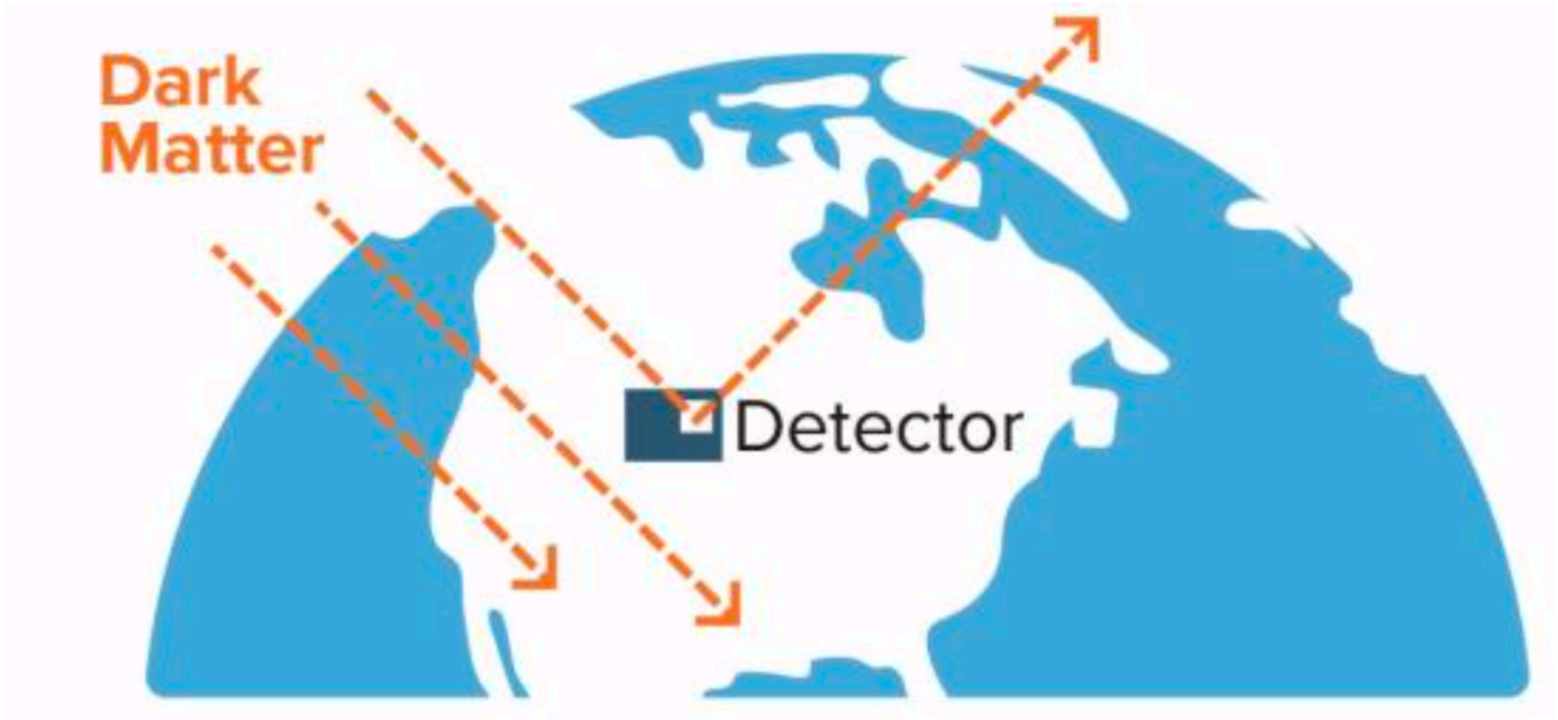
Accelerator Searches



Direct-Detection Searches

Figs from DOE BRN report

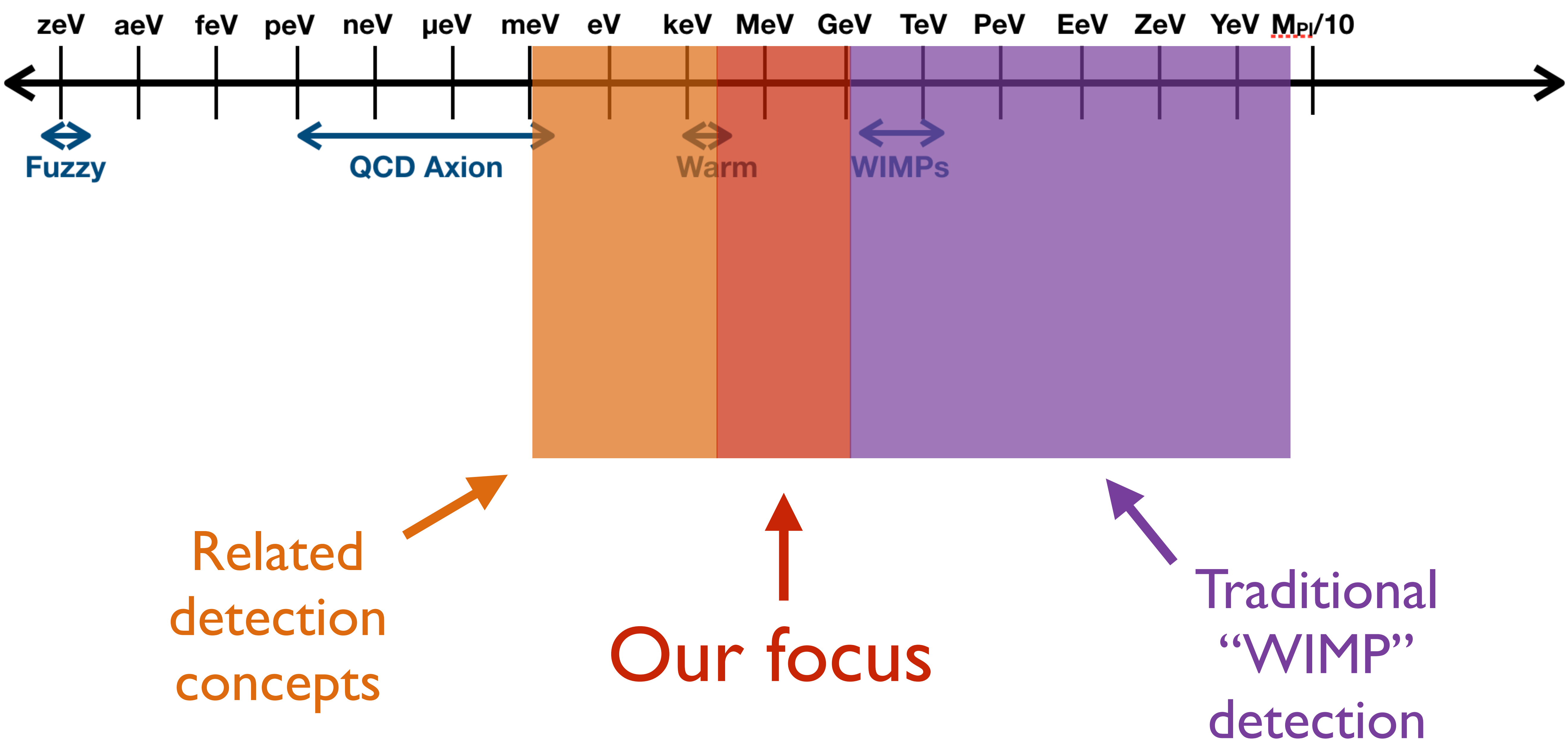
Direct Detection Searches



our focus for remainder of talk

Fig from DOE BRN report

Focus of remainder of talk



A new frontier with significant recent progress

Outline

- Direct-detection introduction

  The basics

- Detection concept for sub-GeV Dark Matter

  How to search for sub-GeV DM

- The SENSEI experiment

  The first dedicated experiment to probe for DM with masses between 500 keV to GeV

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- Direct-detection introduction
  The basics
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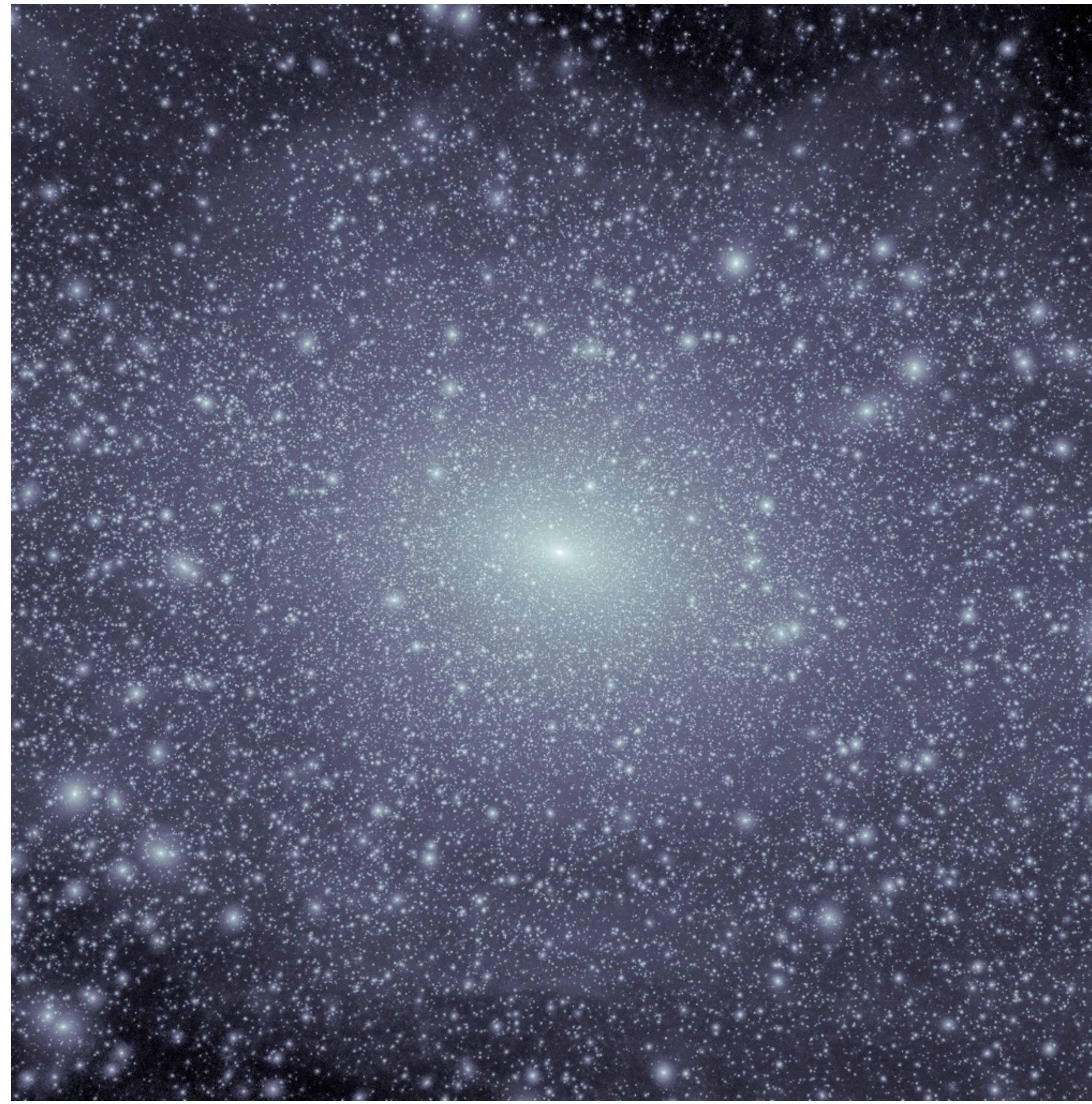
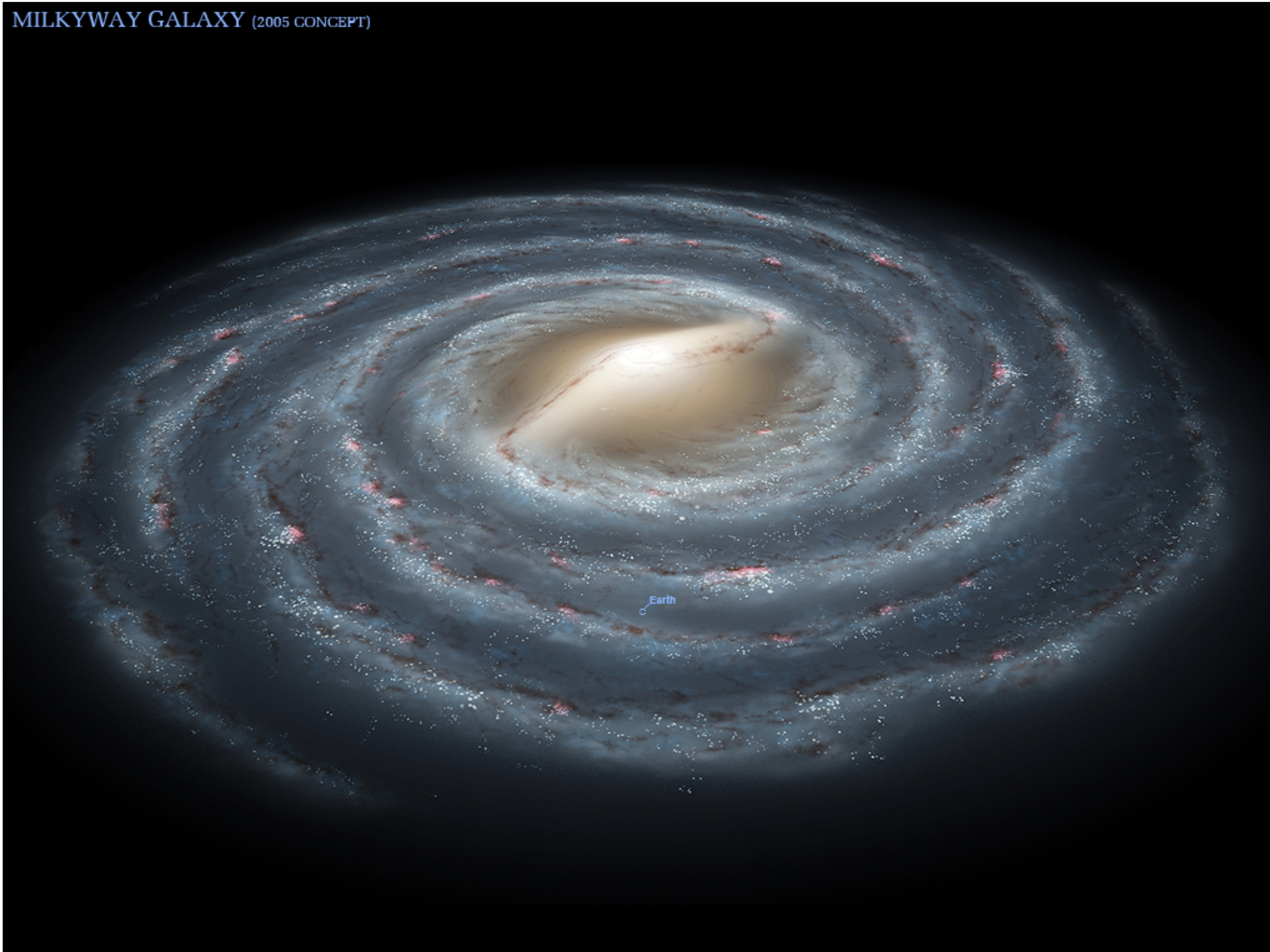
Our Solar System is inside a large Dark Matter "Halo"

Via Lactea II simulation, Diemand et.al.

Dark Matter

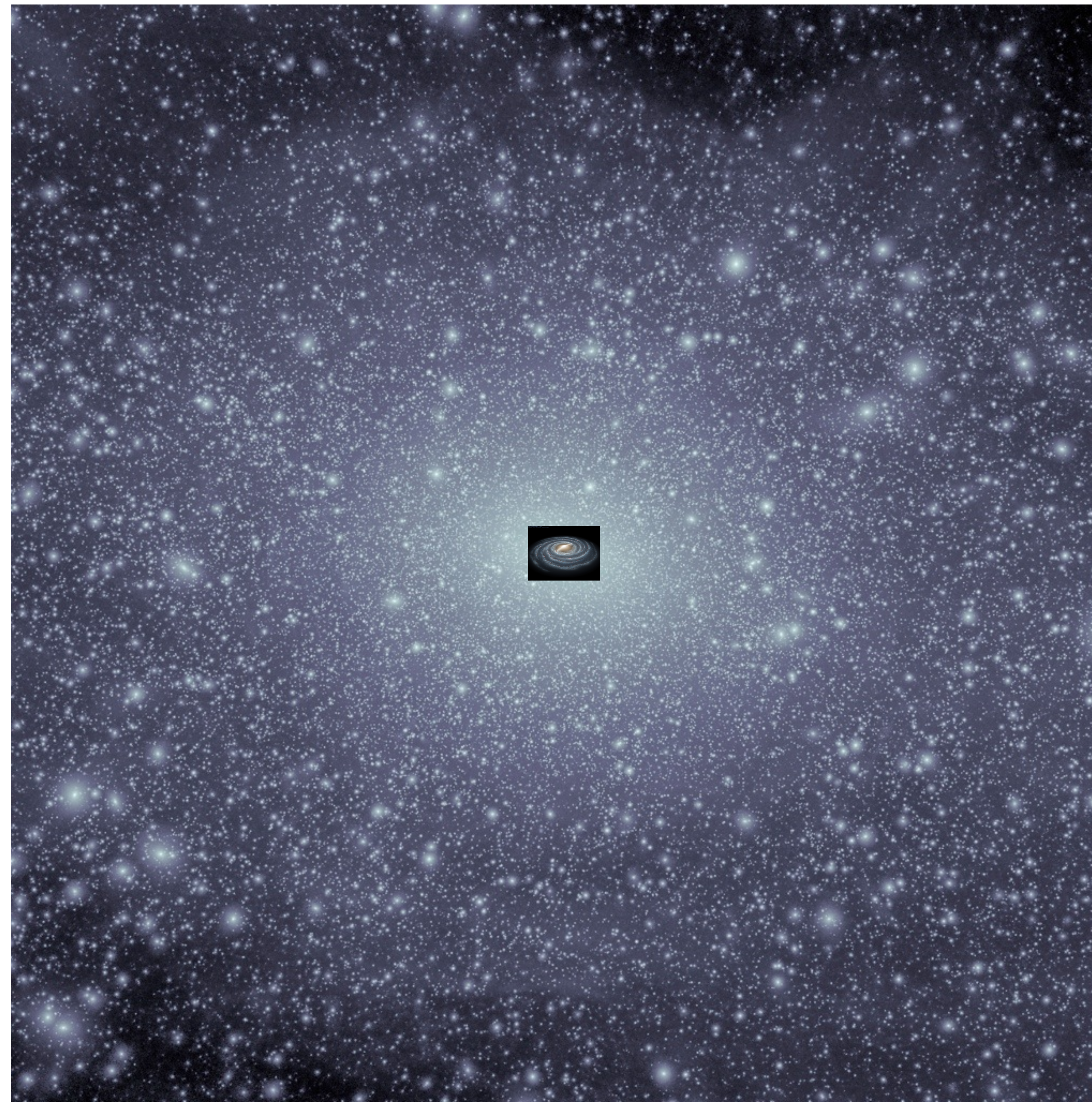



MILKYWAY GALAXY (2005 CONCEPT)
Earth

Our Solar System is inside a large Dark Matter "Halo"

Via Lactea II simulation, Diemand et.al.

Dark Matter



visible Milky Way galaxy
is tiny compared to
dark matter "halo"

The Dark Matter Around Us

local density: $\rho_{\rm DM} \simeq 0.4\,\frac{\rm GeV}{\rm cm^3}$

typical speed ~ 220 km/second (non-relativistic!)

For DM mass of 1 GeV:

- Each liter of space would have ~400 particles

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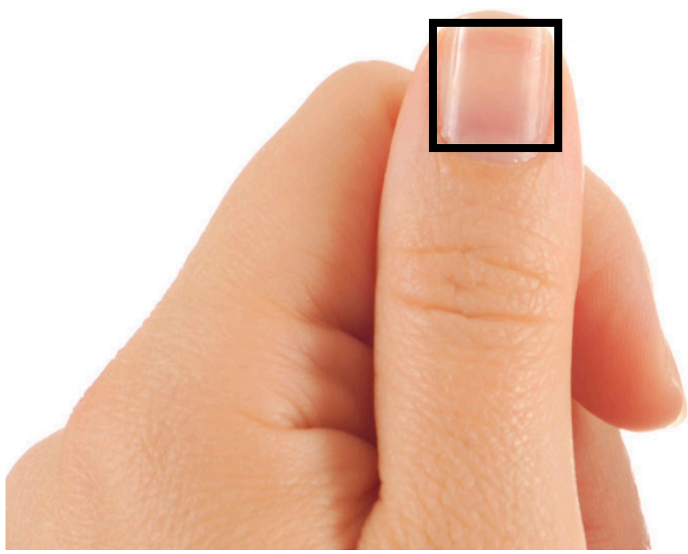

For DM mass of 1 GeV:

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- $\text{Flux} \sim 10 \text{ million } \frac{\text{particles}}{\text{cm}^2 \text{ sec}}$

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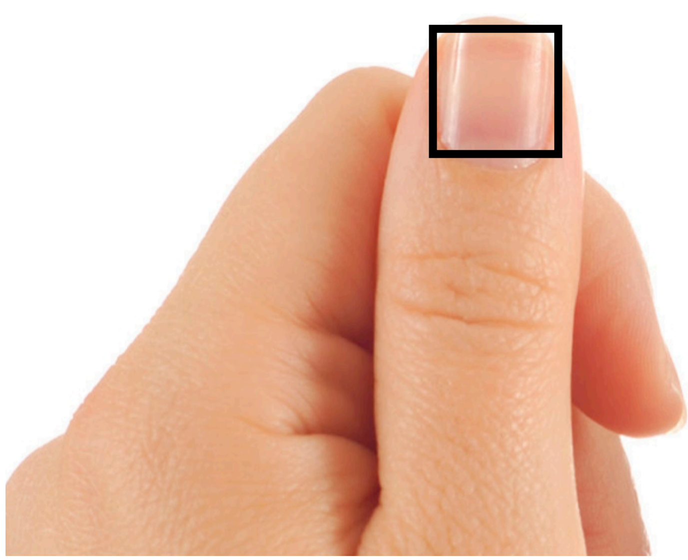

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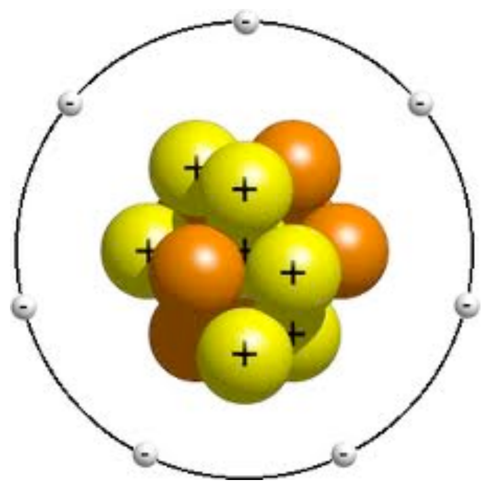
- $\mathrm{Flux} \sim 10 \text{ million } \frac{\text{particles}}{\mathrm{cm}^2 \text{ sec}}$

c.f. solar neutrinos: $\text{flux} \sim \frac{60 \text{ billion}}{\mathrm{cm}^2 \text{ sec}}$

Traditional "WIMP" Detection Concept

Put a detector with lots of atoms deep underground

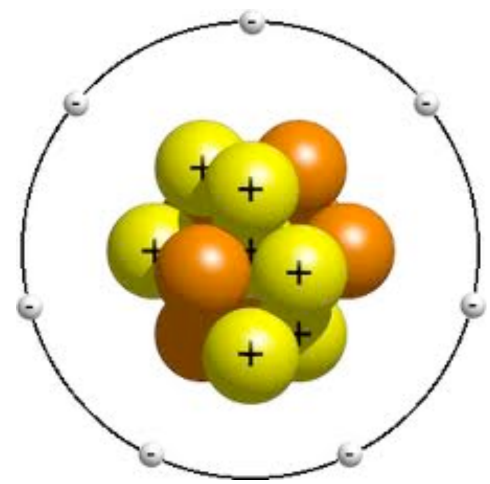


Atom

Traditional “WIMP” Detection Concept

Put a detector with lots of atoms deep underground

and wait...



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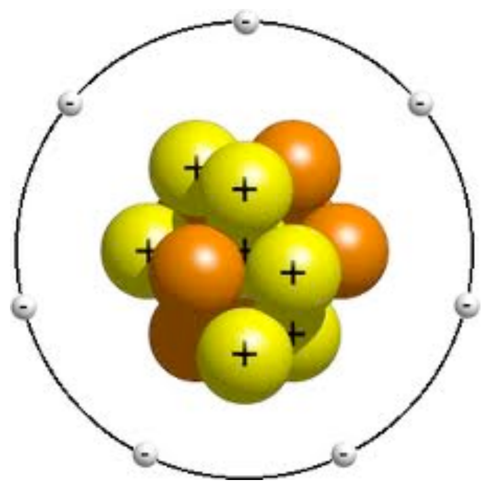

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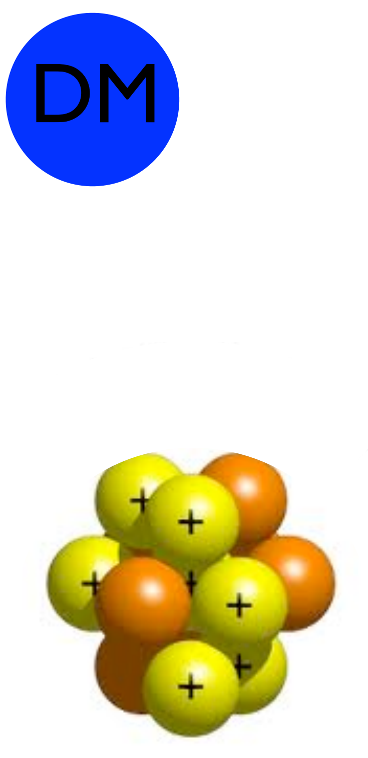

Recoiling Nucleus

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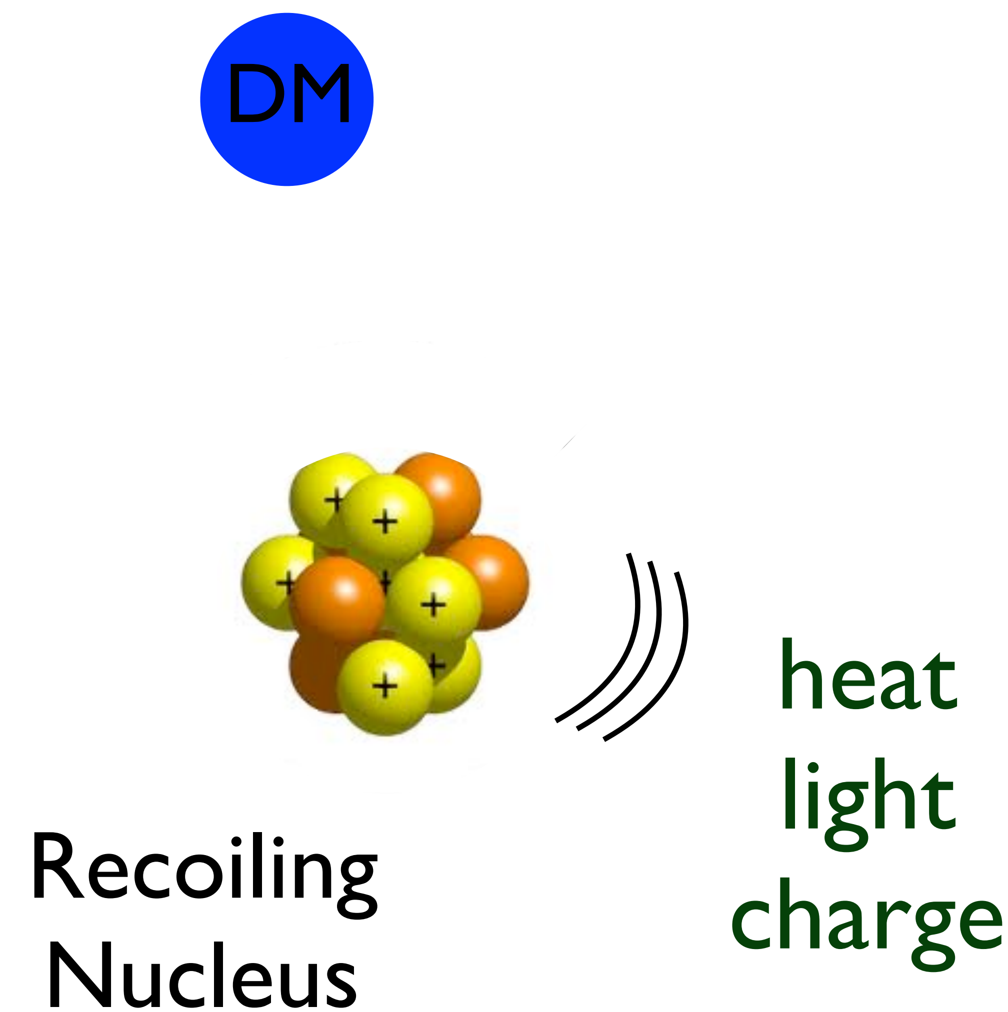

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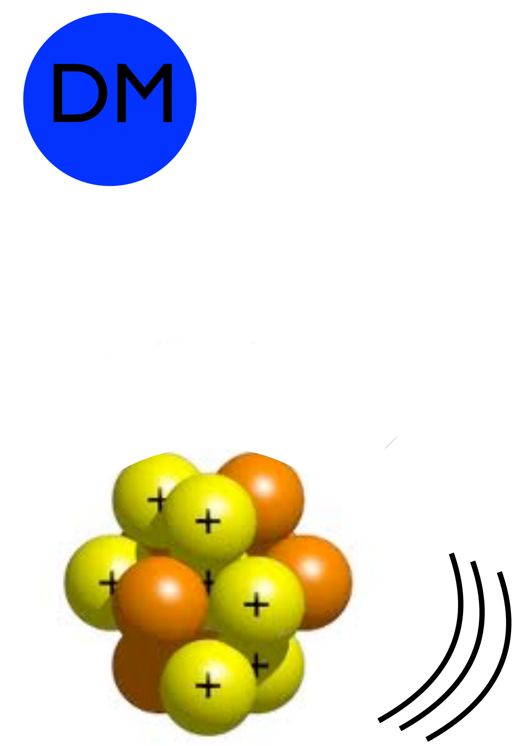
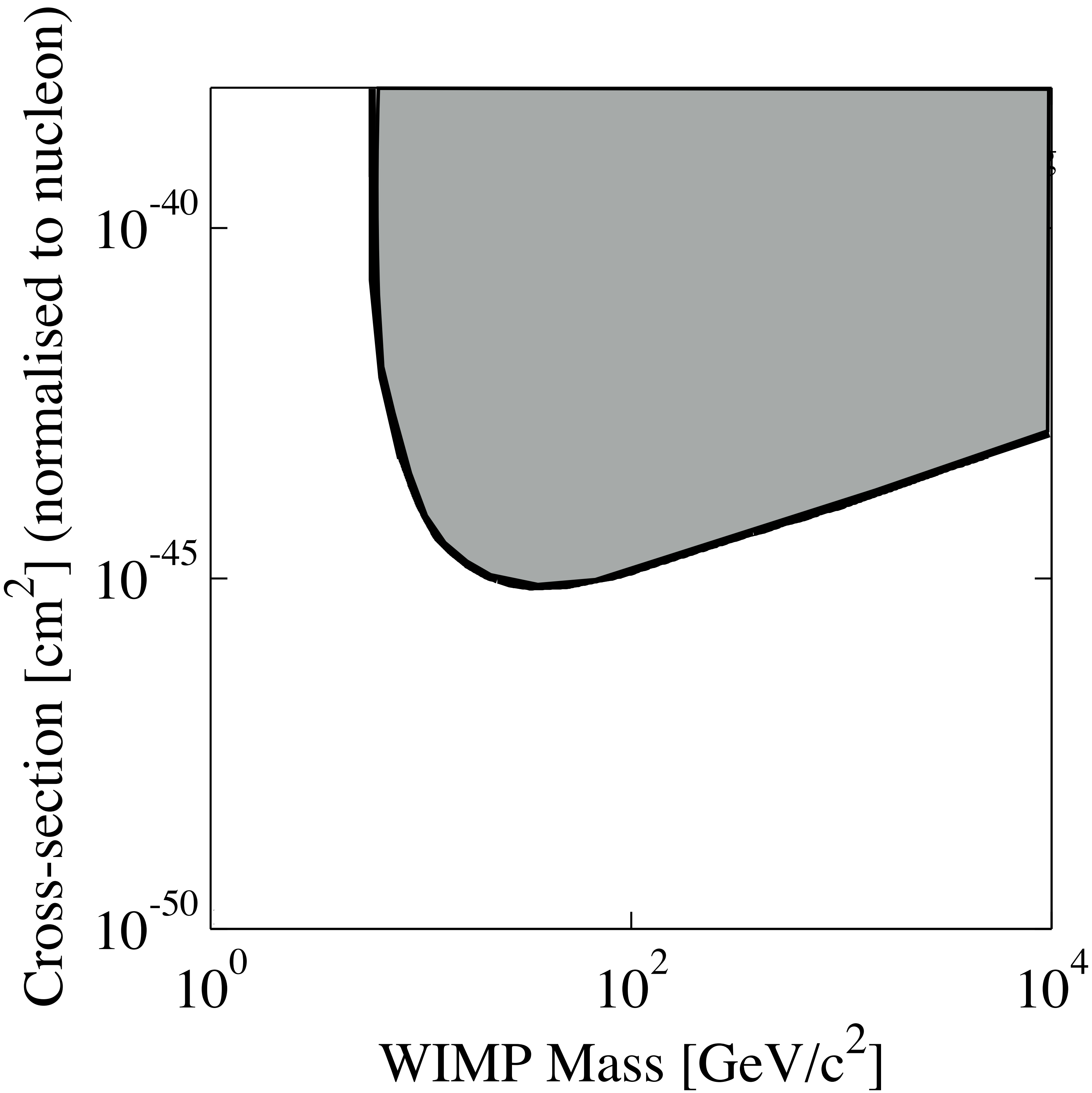
kinematics is
like billiard
ball scattering



Recoiling
Nucleus

heat
light
charge

A typical direct detection exclusion curve



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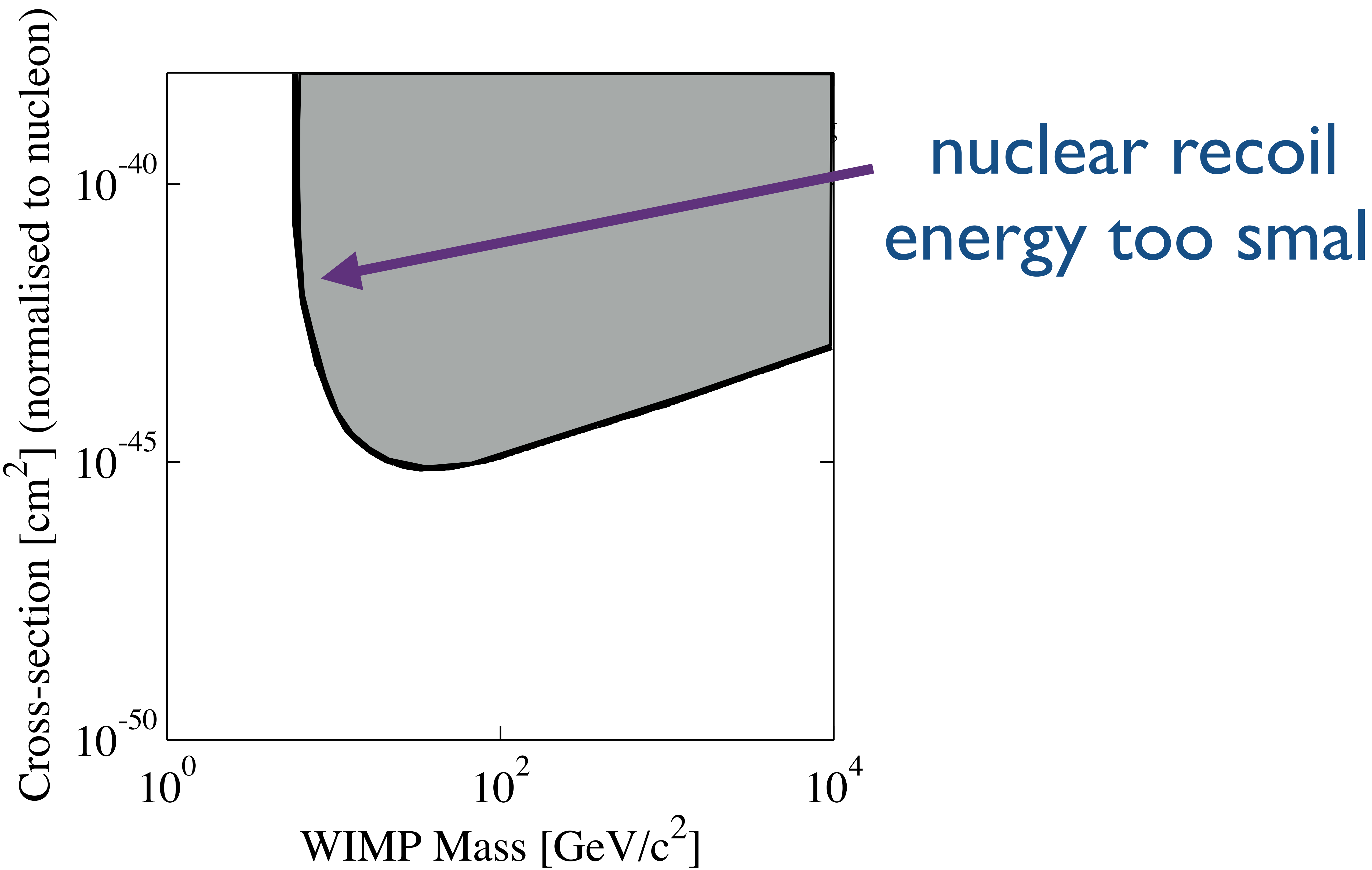

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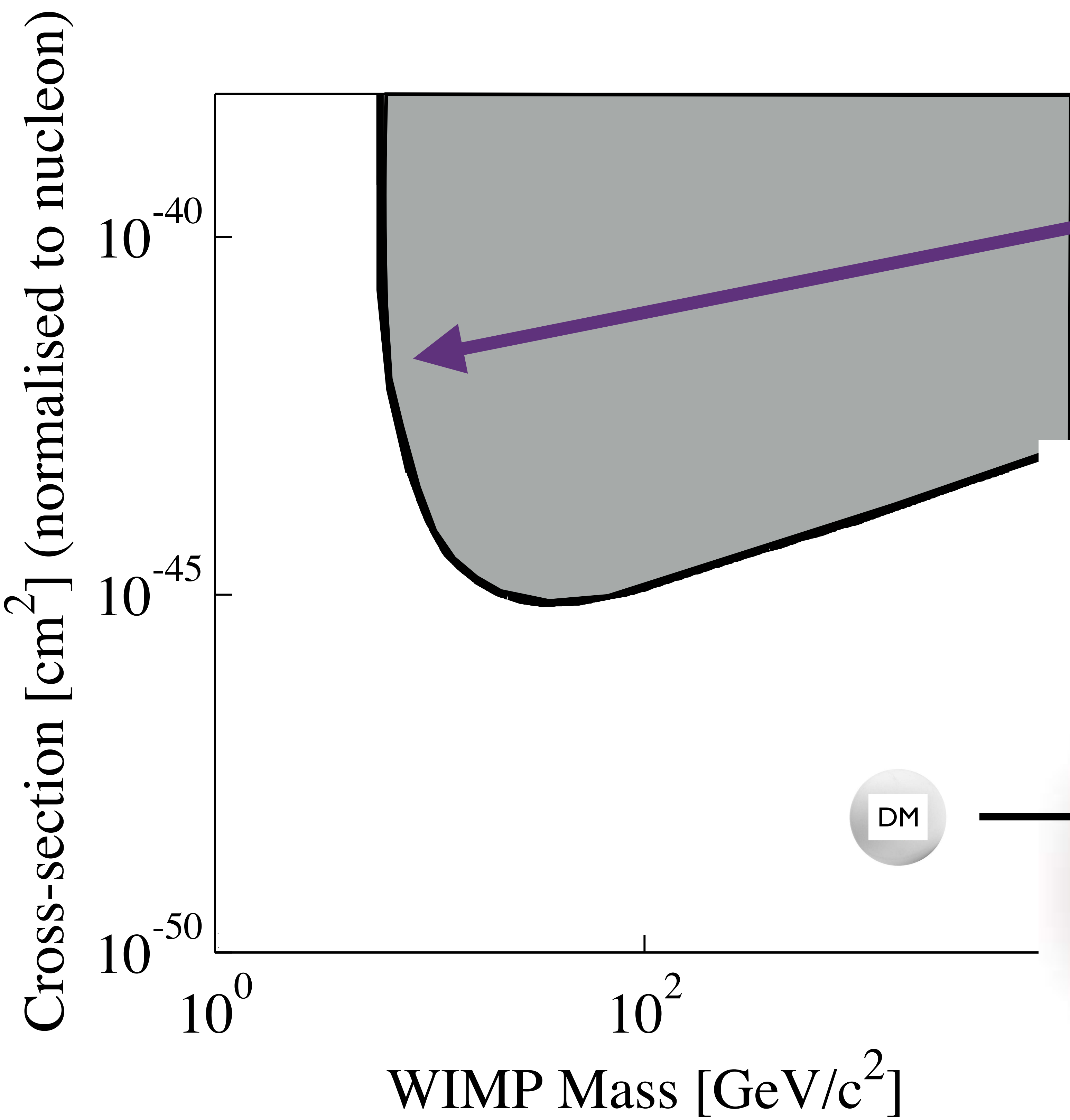
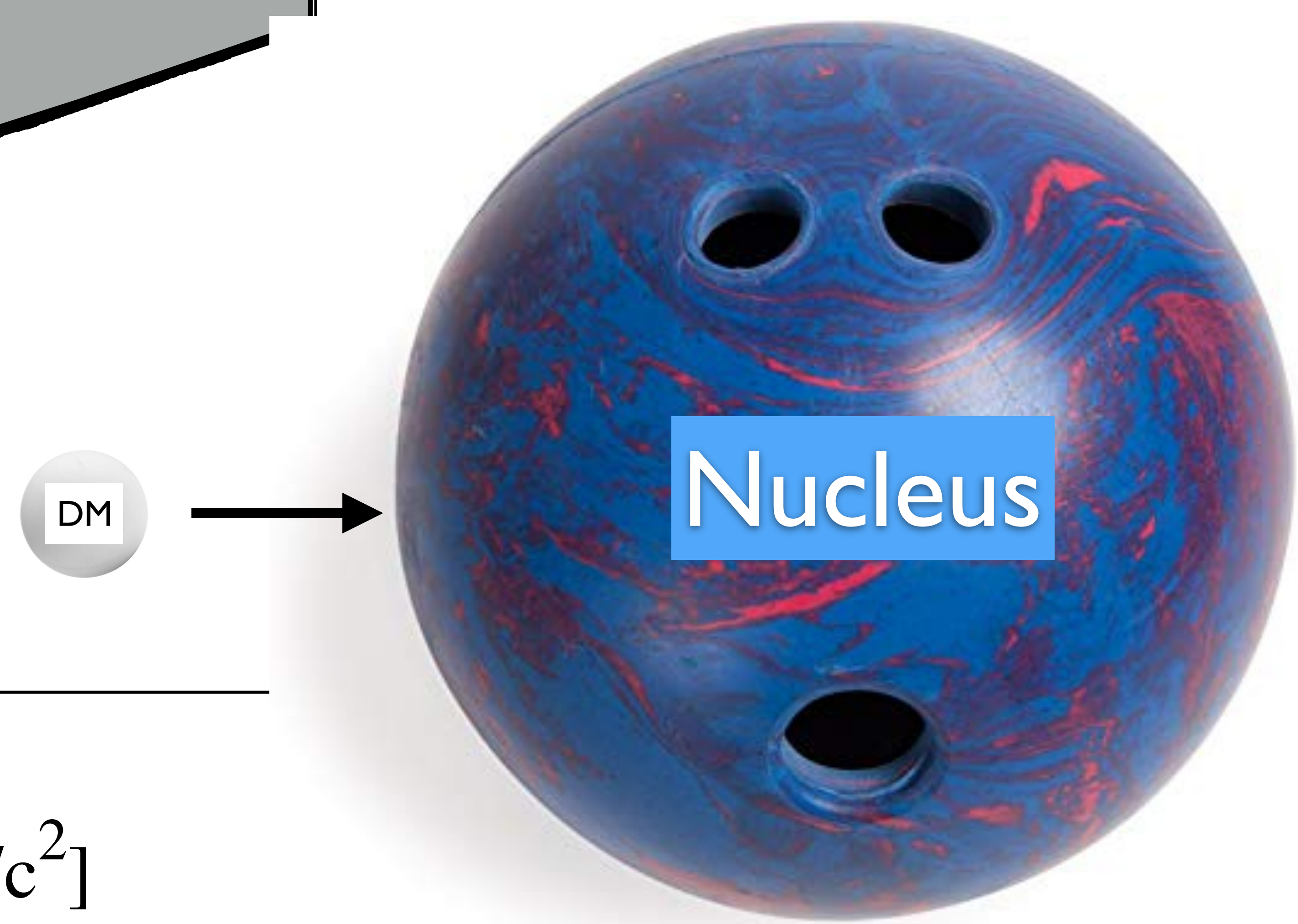


nuclear recoil energy too small



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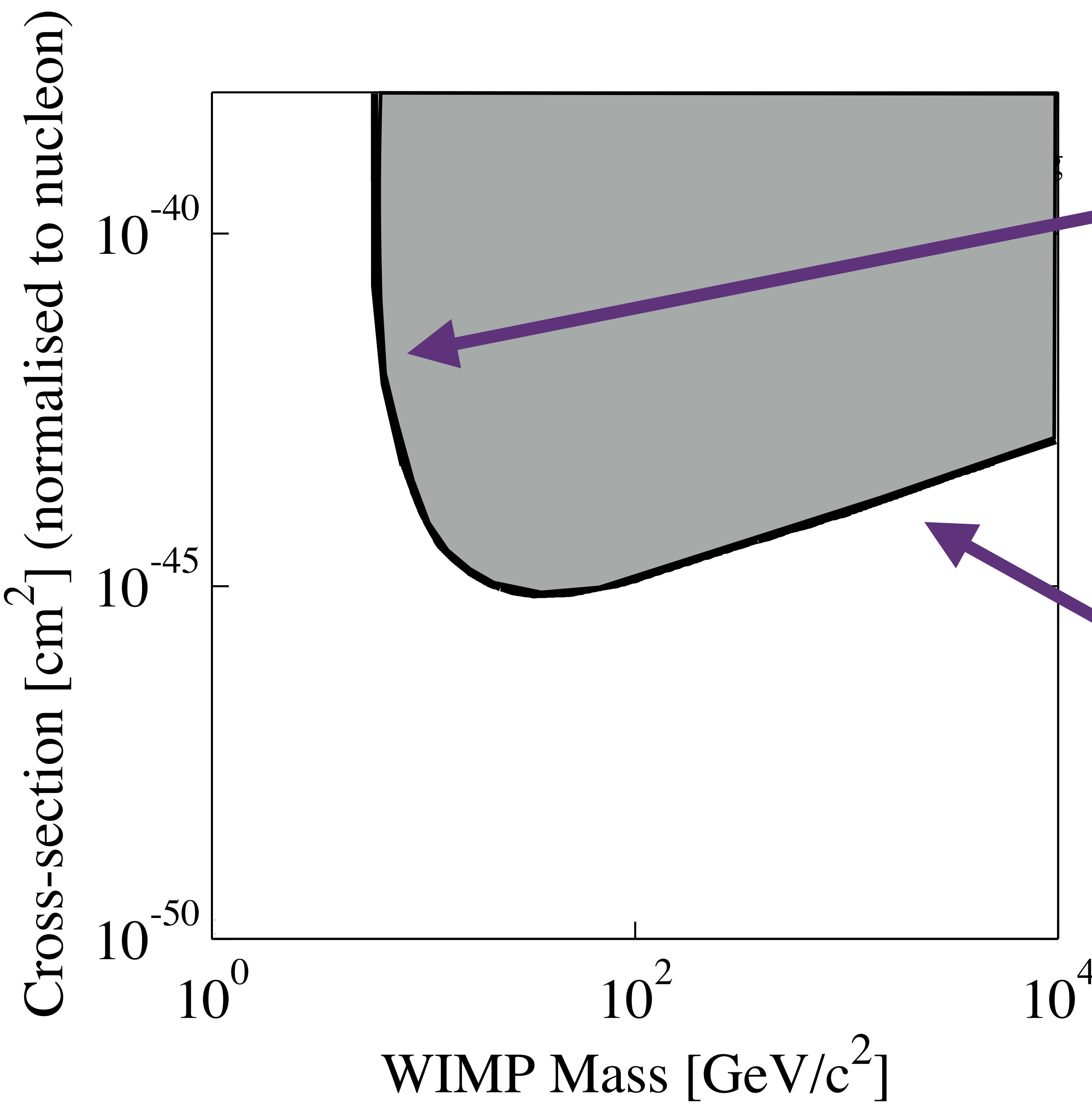


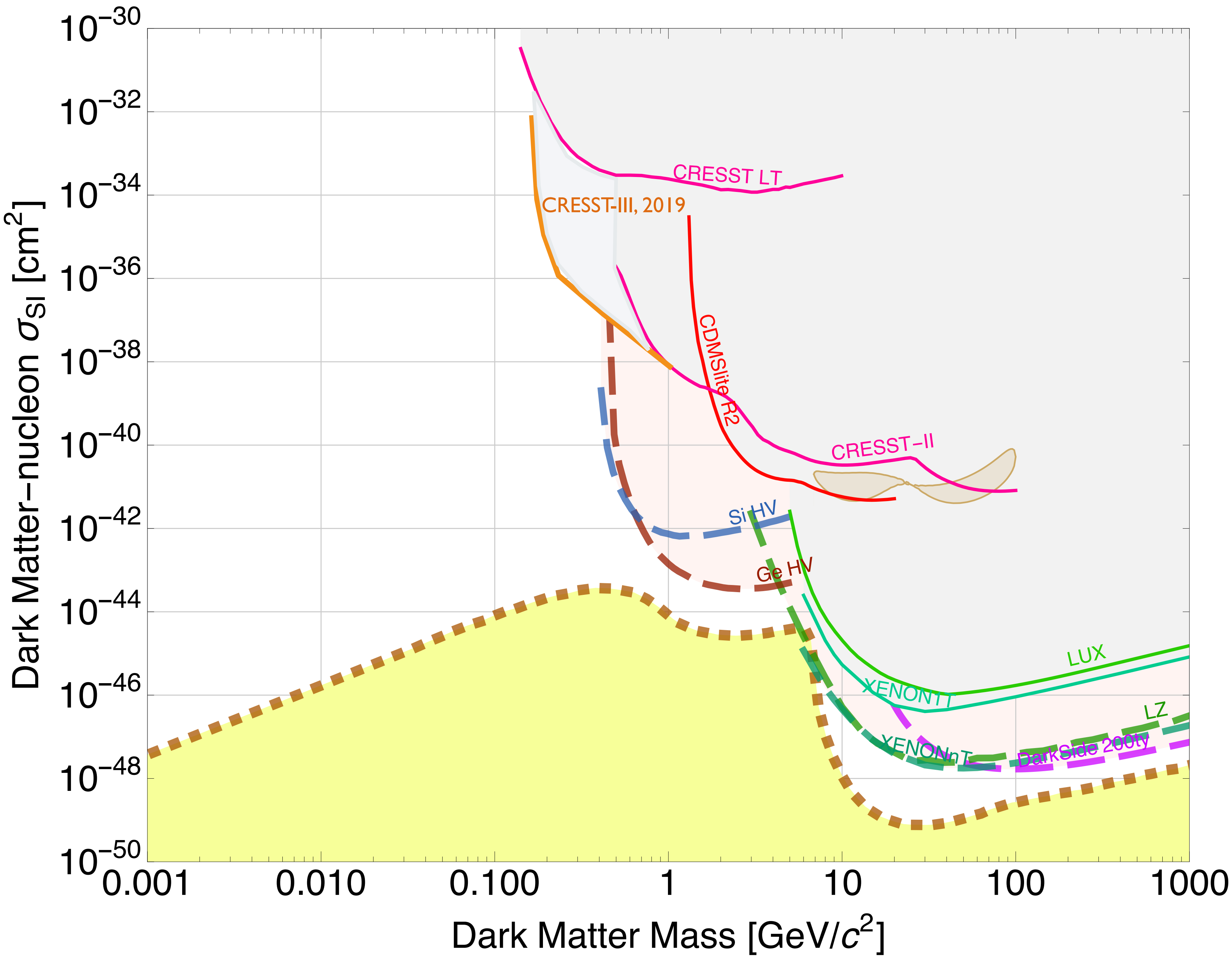
nuclear recoil energy too small

linear, since

$$\text{Rate} \propto n \propto \frac{\rho}{m}$$

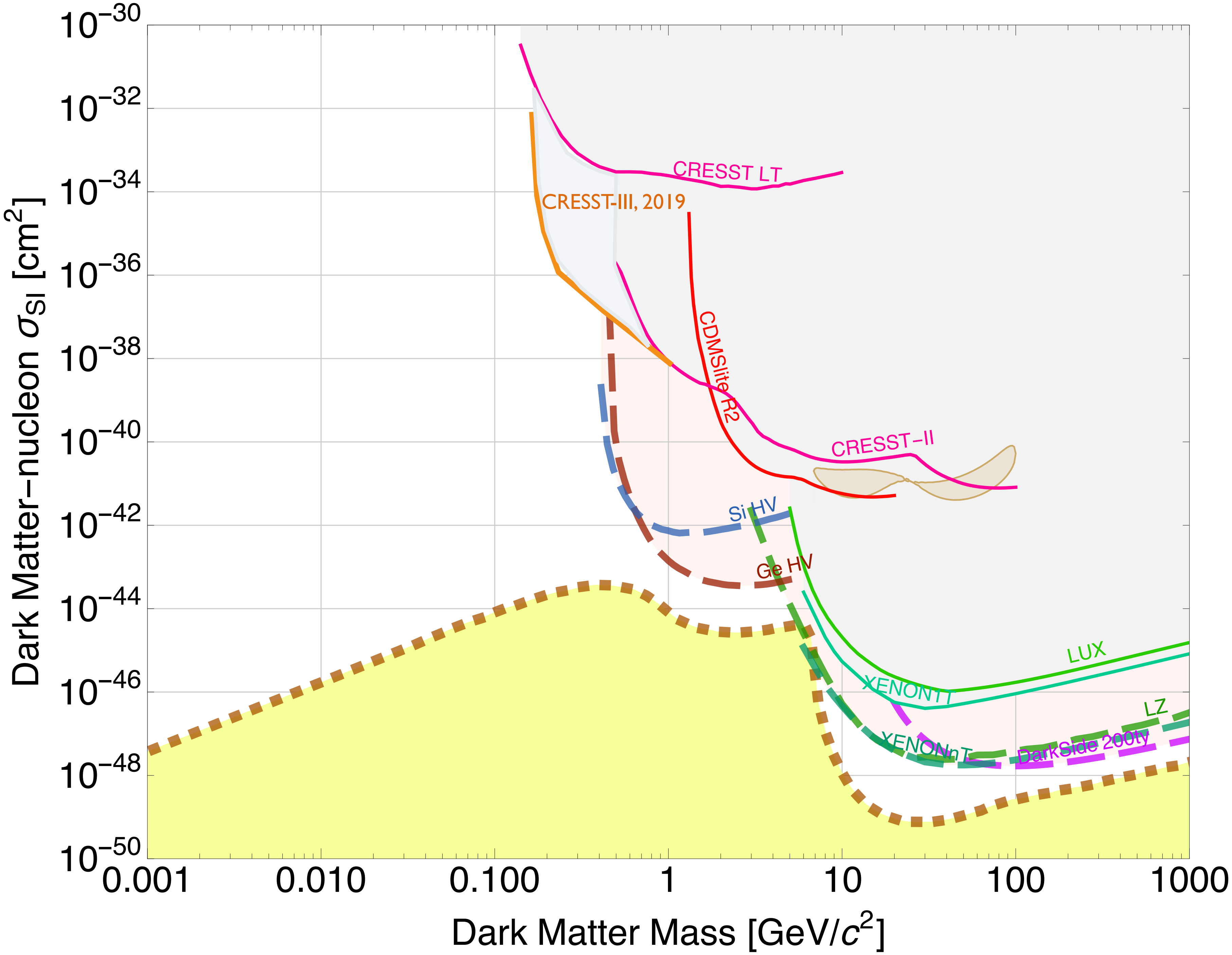
$$\propto \frac{0.4\ \text{GeV}/\text{cm}^3}{m}$$

Current Constraints & Projections



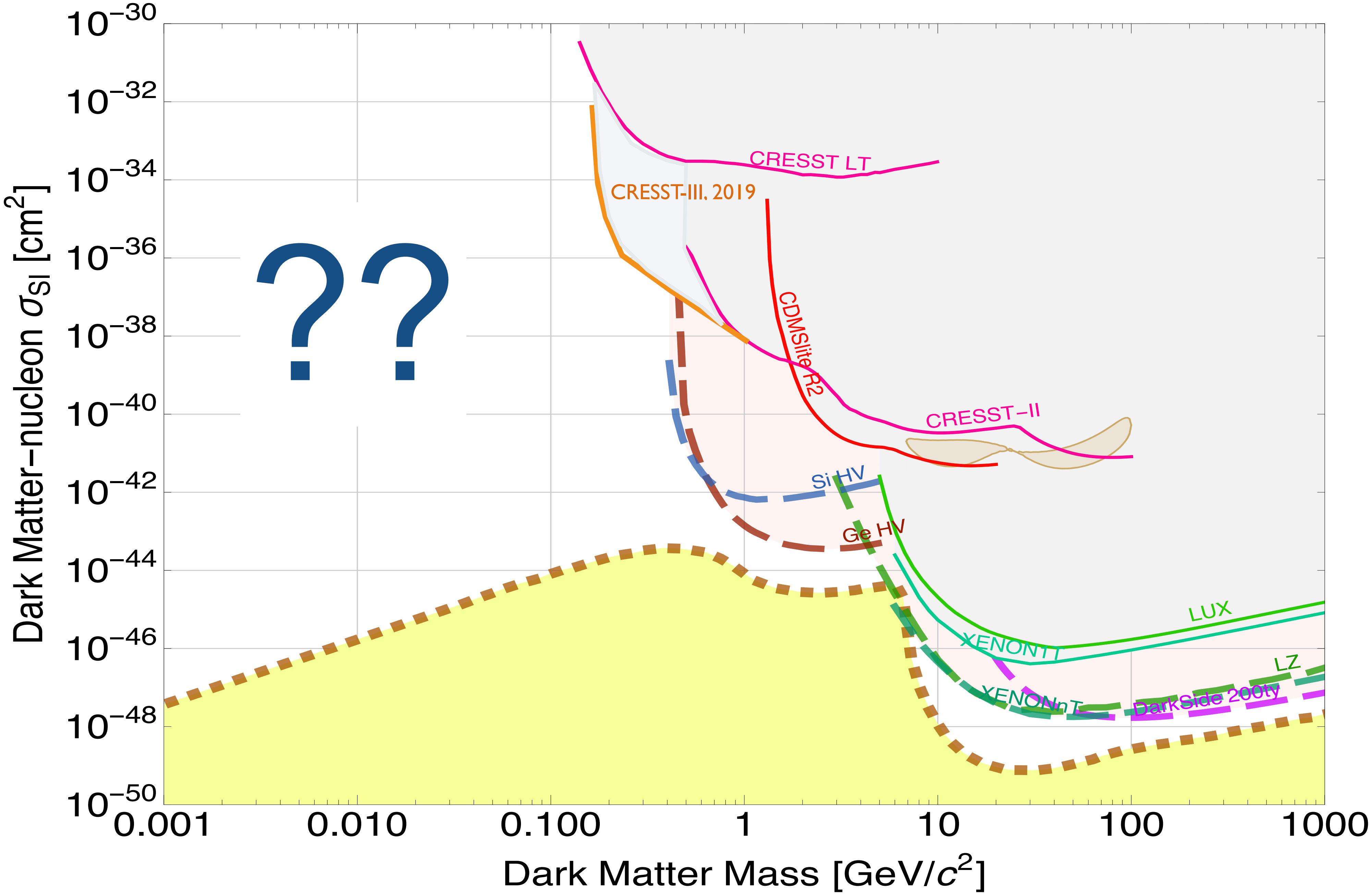
Limit plotter: Saab & Figueroa

Current Constraints & Projections



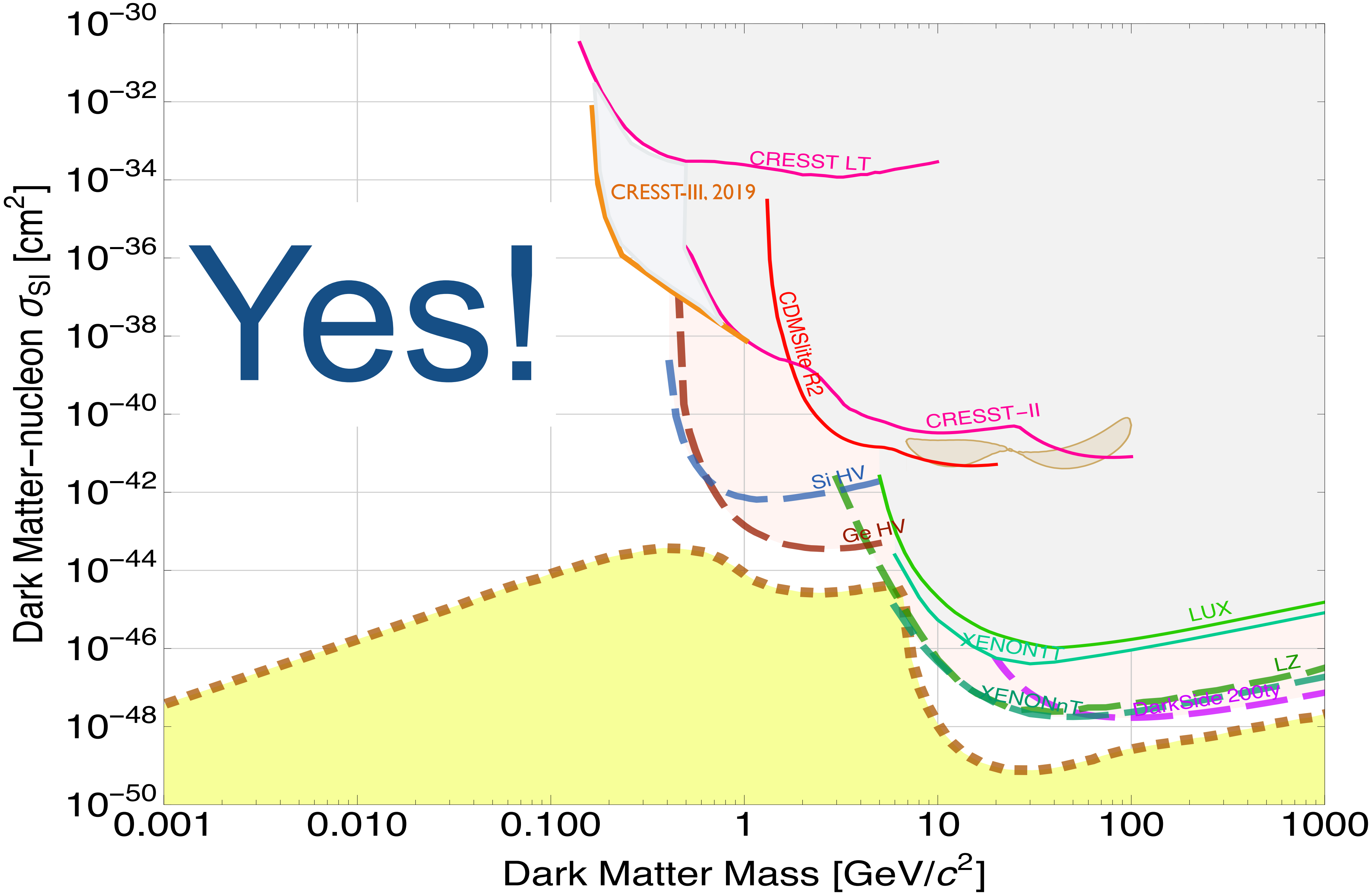
The WIMP program is active, important, and exciting!

Conventional wisdom:
no sensitivity to DM w/ mass $\ll$ GeV

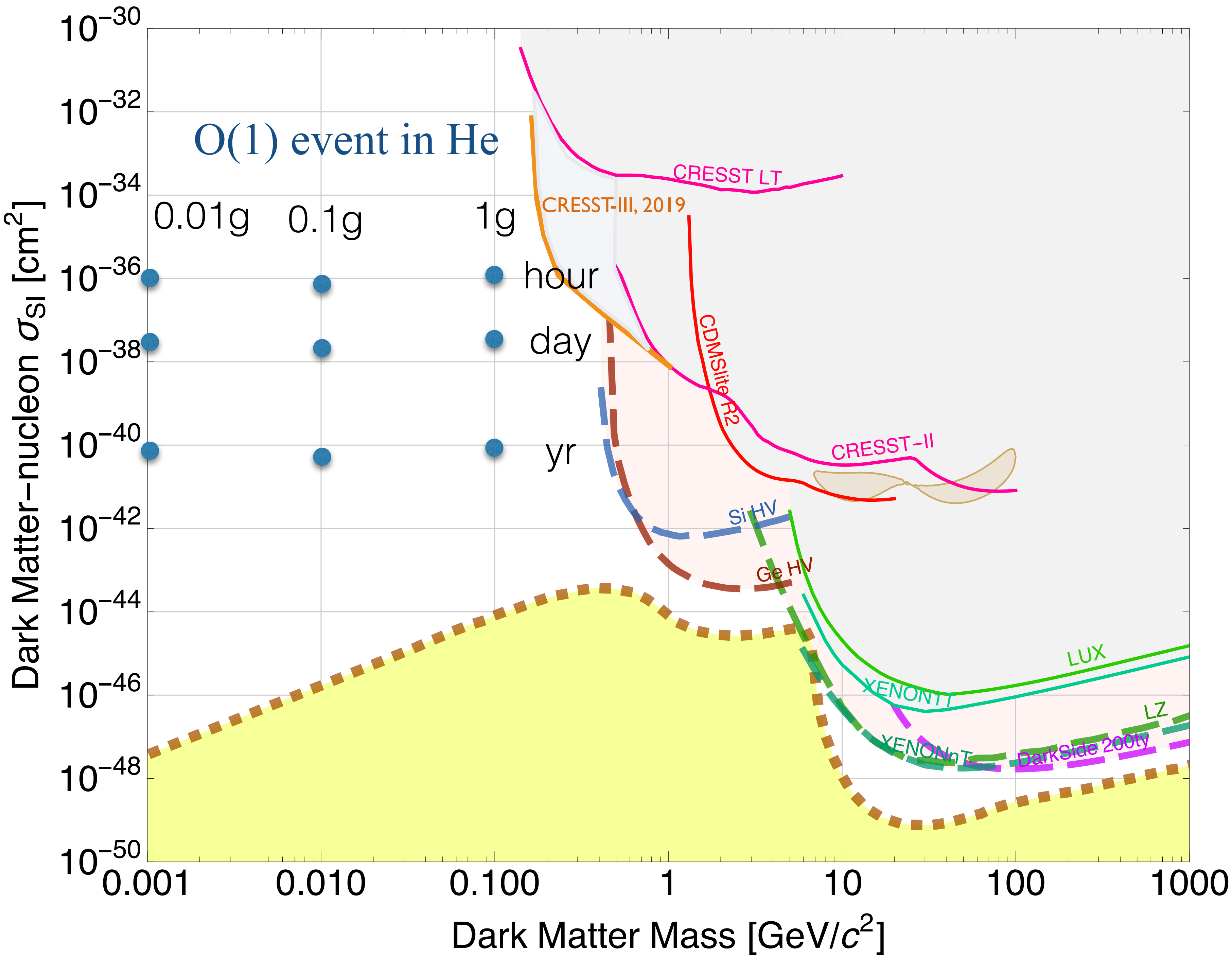


Take-away message:

- Direct-detection constraints now exist down to m_{DM}~500 keV
- Significant improvements expected this year (SENSEI…)



Why <u>small</u> experiments can (in principle) probe orders of magnitude of new sub-GeV DM parameter space



- event rates are large
- but first challenge is to have sensitivity to low energies!
- second challenge is to control backgrounds to enable a <u>discovery</u>

Limit plotter: Saab & Figueroa

Outline

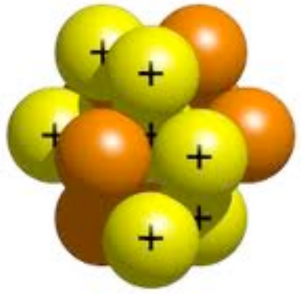
- Direct-detection introduction
- Detection concept for sub-GeV Dark Matter

  How to search for sub-GeV DM
- The SENSEI experiment

Cannot use elastic nuclear recoils for detection

Light DM $\lesssim 1~\mathrm{GeV}$

inefficient momentum and energy transfer



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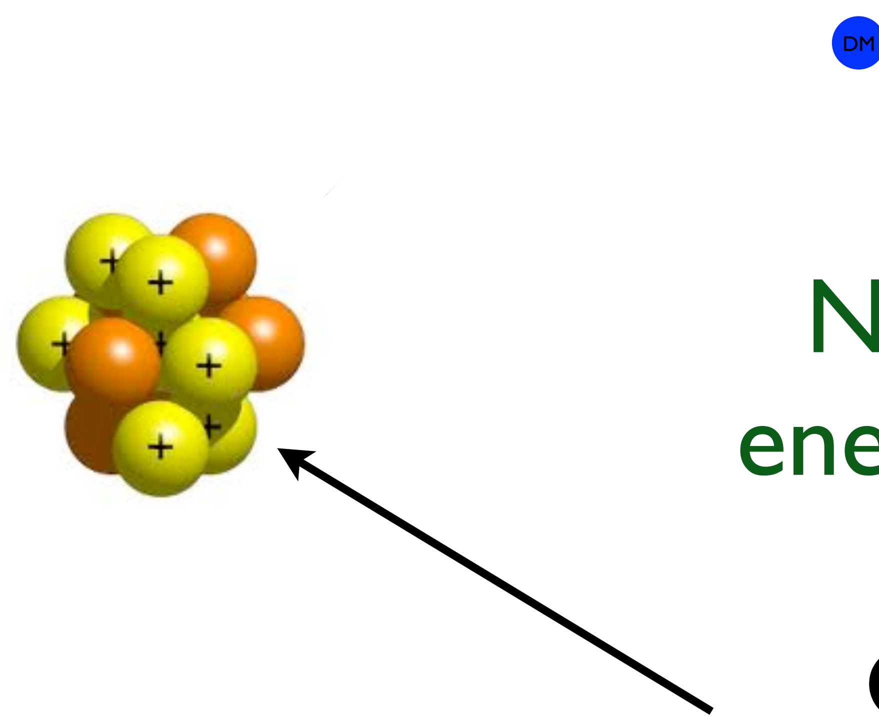


Not enough energy transfer

Can’t see recoiling nucleus

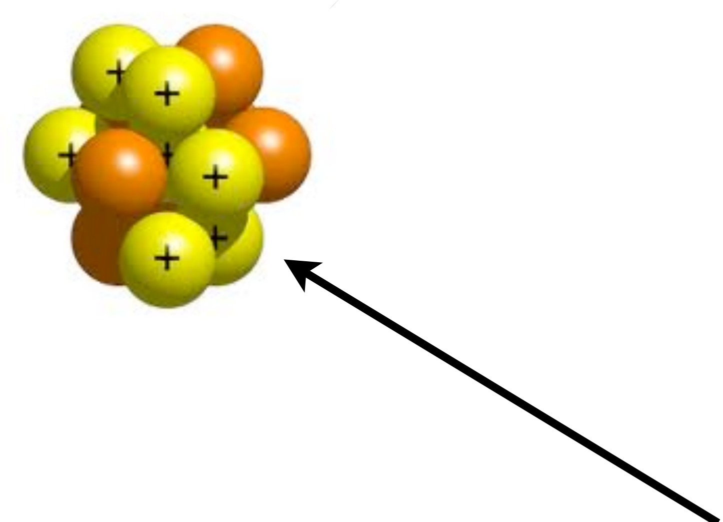
Cannot use elastic nuclear recoils for detection

Light DM $\lesssim 1\ \mathrm{GeV}$

inefficient momentum and energy transfer

DM

But "inelastic" processes allow for much more energy transfer!
(several ideas exist)

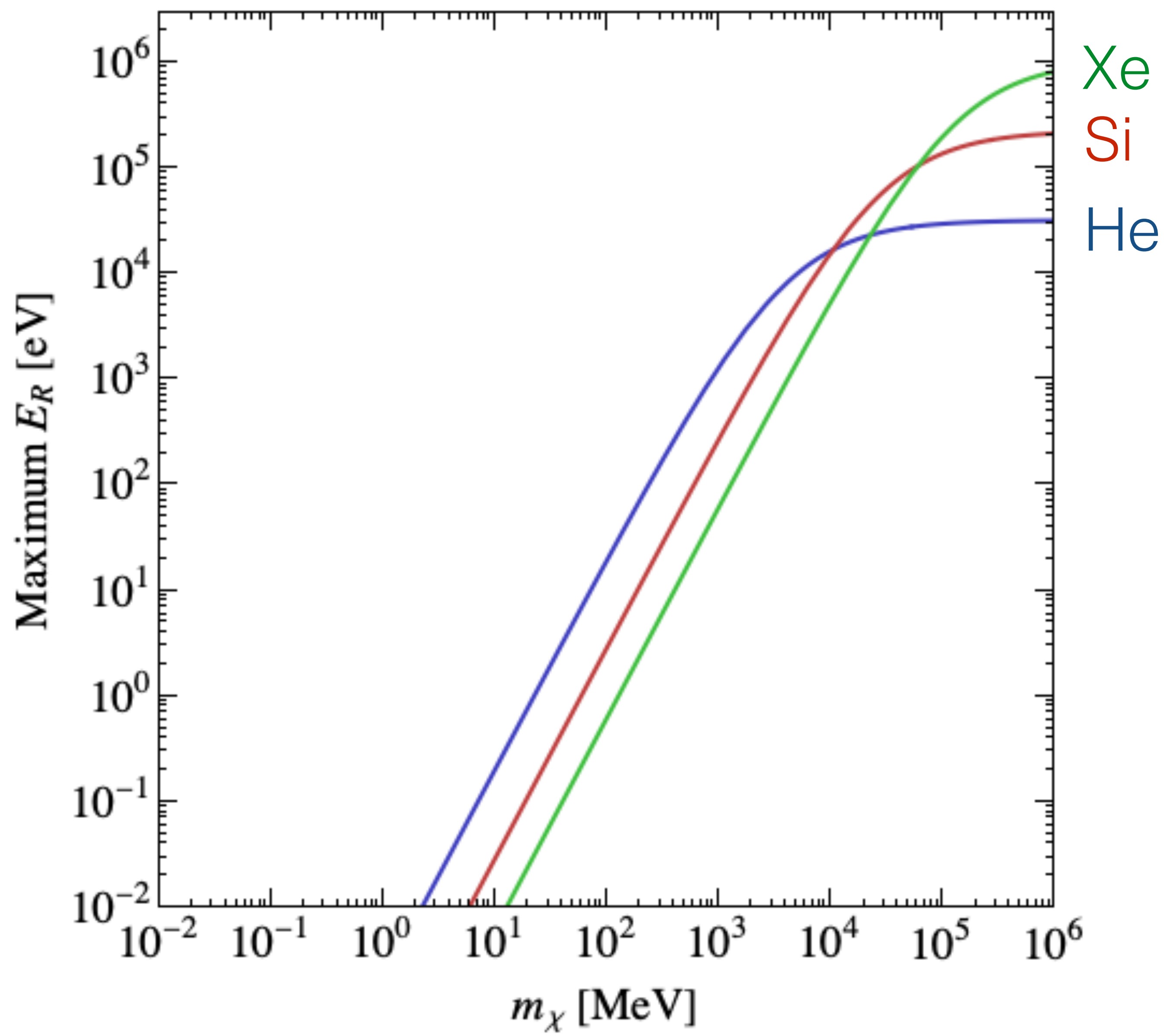


Not enough energy transfer

Can't see recoiling nucleus

Nuclear recoil energy vs DM kinetic energy

$$E_{\rm NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \simeq \frac{2m_\chi^2 v_\chi^2}{m_N}$$



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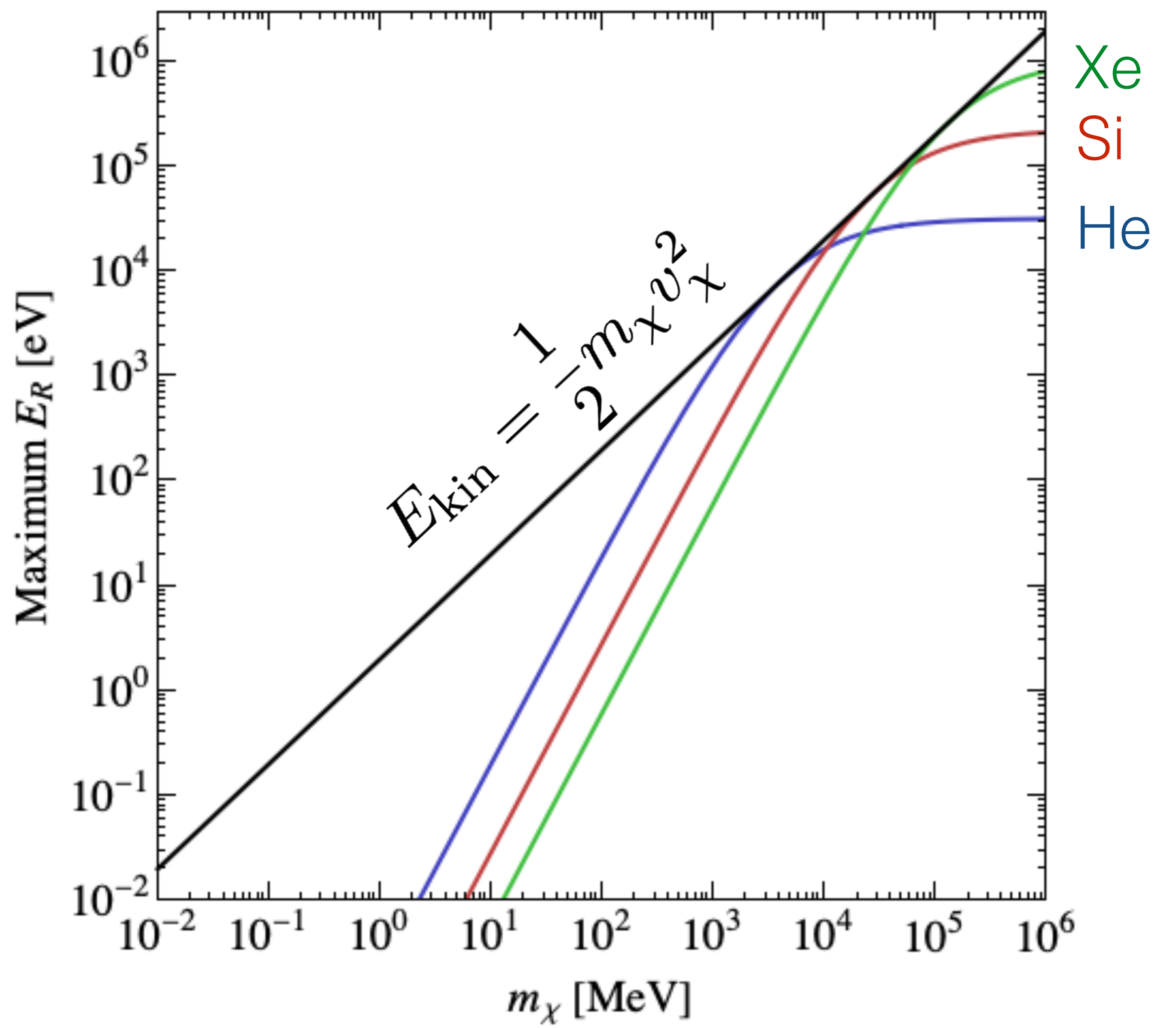
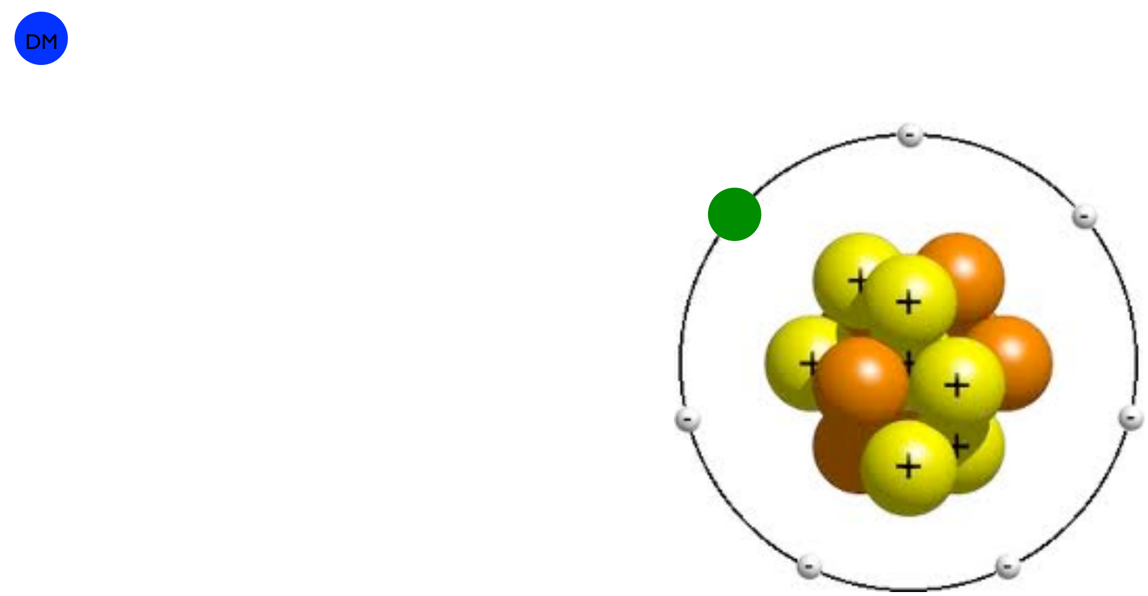


DM-electron scattering can probe ≪ GeV!

RE, Mardon, Volansky, 2011



Atom

DM-electron scattering can probe ≪ GeV!

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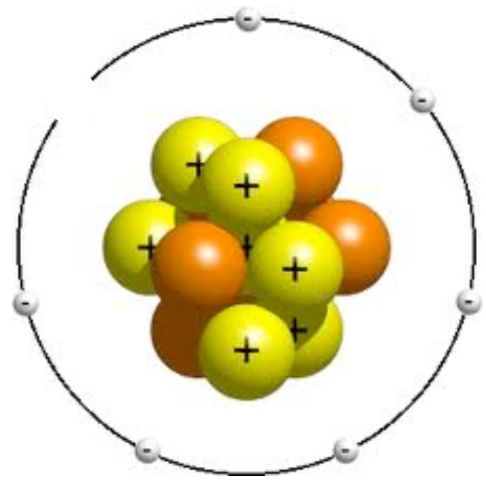


Atom

Typically produces a signal of only one to a few electrons

DM-electron scattering kinematics

electron

$m_e \sim 0.5\ \text{MeV}$

DM

$$v_e \sim \alpha \simeq \frac{1}{137}$$

$$v_{\text{DM}} \sim \frac{1}{1000}$$

Bound electron moves much faster than the DM

Can in principle transfer entire DM kinetic energy to electron!

Mass threshold?

to overcome binding energy ΔE

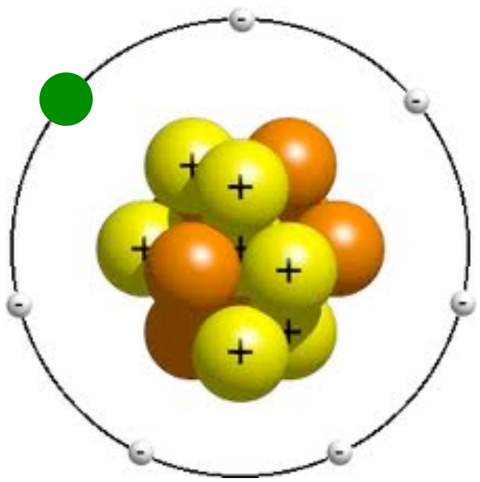
need $E_{\rm DM} \sim \frac{1}{2} m_{\rm DM}\, v_{\rm DM}^2 > \Delta E$

$$\Longrightarrow m_{\rm DM} > \frac{\Delta E}{\frac{1}{2} v_{\rm DM}^2}$$

$$v_{\rm DM} \lesssim 600 \text{ km/s} \Longrightarrow m_{\rm DM} \gtrsim \frac{1 \text{ eV}}{\frac{1}{2}(2 \times 10^{-3})^2} \times \left(\frac{\Delta E}{1 \text{ eV}}\right)$$

$$\Longrightarrow m_{\rm DM} \gtrsim 500 \text{ keV} \times \left(\frac{\Delta E}{1 \text{ eV}}\right)$$

Target materials for electron recoils?



noble liquids

$$\Delta E \sim 10 \text{ eV}$$
$$m_{\rm DM} \sim 5 \text{ MeV}$$

RE, Mardon, Volansky; RE, Manalaysay, Mardon, Sorensen, Volansky; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; Derenzo, RE, Massari, Soto, Yu; RE, Volansky, Yu; RE, Sholarpurkar, Yu; Emken, RE, Kouvaris, Sholarpurkar; Derenzo, Bourret, Hanrahan, Bizarri; Graham, Kaplan, Rajendran, Walters; Lee, Lisanti, Mishra-Sharma, Safdi; DarkSide-50; XENON1t; …

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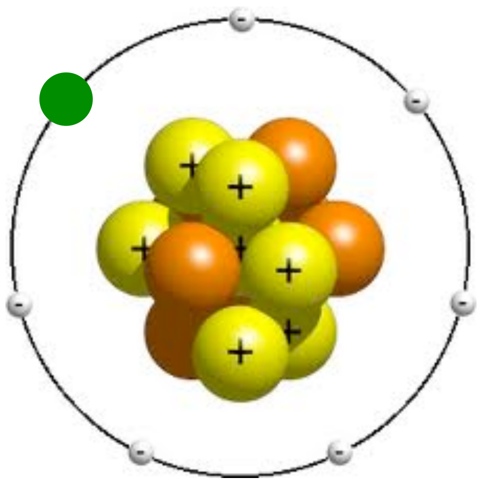

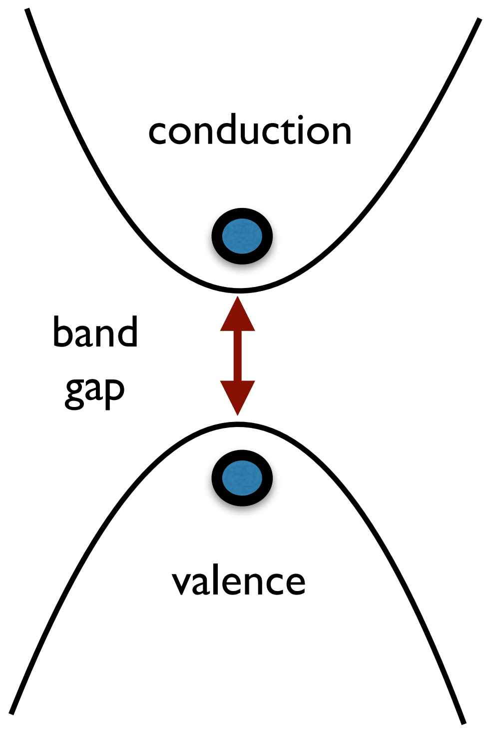

noble liquids

$\Delta E \sim 10$ eV

$m_{\rm DM} \sim 5$ MeV

semiconductors
scintillators

$\Delta E \sim 1$ eV

$m_{\rm DM} \sim 500$ keV

RE, Mardon, Volansky; RE, Manalaysay, Mardon, Sorensen, Volansky; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; Derenzo, RE, Massari, Soto, Yu; RE, Volansky, Yu; RE, Sholarpurkar, Yu; Emken, RE, Kouvaris, Sholarpurkar; Derenzo, Bourret, Hanrahan, Bizarri; Graham, Kaplan, Rajendran, Walters; Lee, Lisanti, Mishra-Sharma, Safdi; DarkSide-50; XENON1t; …

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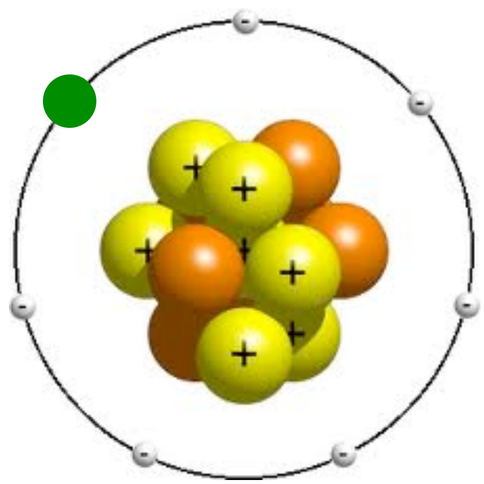
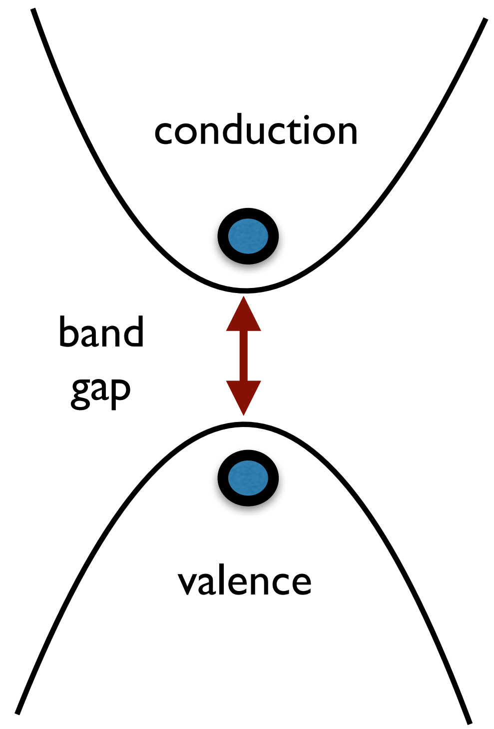
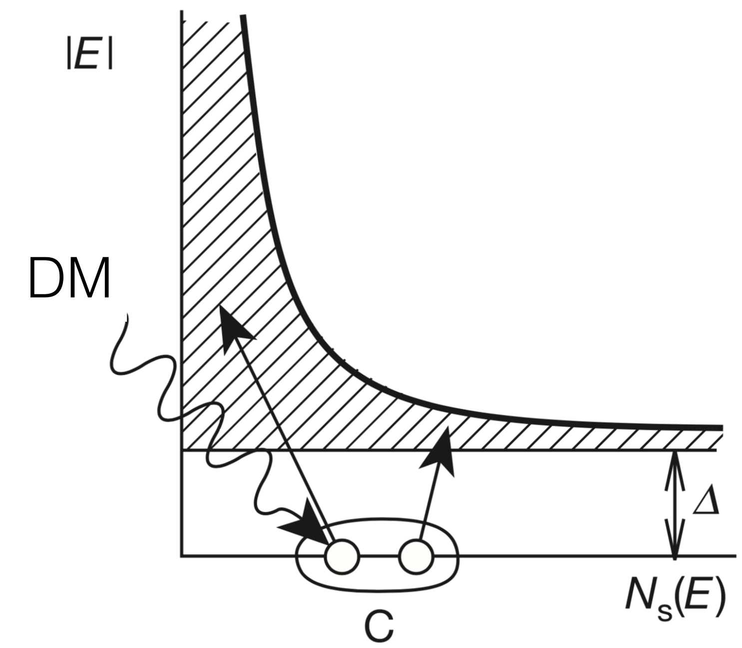
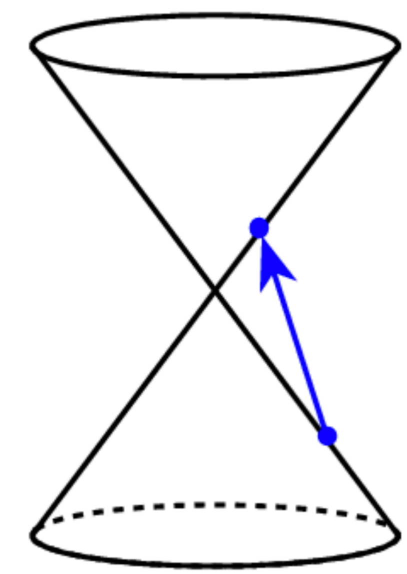






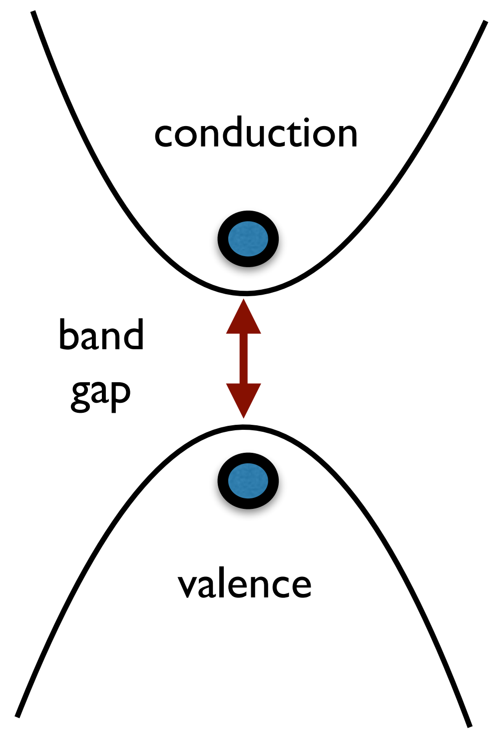


noble liquids	semiconductors scintillators	superconductors	Dirac materials
$\Delta E \sim 10$ eV	$\Delta E \sim 1$ eV	$\Delta E \sim$ few meV	
$m_{\rm DM} \sim 5$ MeV	$m_{\rm DM} \sim 500$ keV	$m_{\rm DM} \sim$ keV	

RE, Mardon, Volansky; RE, Manalaysay, Mardon, Sorensen, Volansky; RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu; Derenzo, RE, Massari, Soto, Yu; RE, Volansky, Yu; RE, Sholarpurkar, Yu; Emken, RE, Kouvaris, Sholarpurkar; Derenzo, Bourret, Hanrahan, Bizarri; Graham, Kaplan, Rajendran, Walters; Lee, Lisanti, Mishra-Sharma, Safdi; DarkSide-50; XENON1t; …

Hochberg, Kahn, Lisanti, Tully, Zurek; Hochberg, Zhao, Zurek; Hochberg, Pyle, Zhao, Zurek; Hochberg, Lin, Zurek; Hochberg, Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin, Liu, Weber, Neaton; Knapen, Lin, Pyle, Zurek; Griffin, Knapen, Lin, Zurek; …

Target materials for electron recoils?



semiconductors

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

$$m_{\text{DM}} \sim 500 \text{ keV}$$

We'll discuss this

Outline

- Direct-detection introduction
- Detection concept for sub-GeV Dark Matter
- The SENSEI experiment

  The first dedicated experiment to probe for DM with masses between 500 keV to GeV

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- Detection concept for sub-GeV Dark Matter
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  The first dedicated experiment to probe for DM with masses between 500 keV to GeV

Sub-Electron Noise Skipper-CCD Experimental Instrument

The SENSEI Collaboration

Fermilab:

- F. Chierchie, M. Crisler, A. Drlica-Wagner, J. Estrada, G. Fernandez, M. Sofo-Haro, J. Tiffenberg*

Stony Brook:

- N. Bachhawat, L. Chaplinsky, R. Essig*, D. Gift, Dawa, S. Munagavalasa, A. Singal

Tel-Aviv:

- O. Abramoff, L. Barack, I. Bloch, E. Etzion, A. Orly J. Taenzer, S. Uemura, T. Volansky*

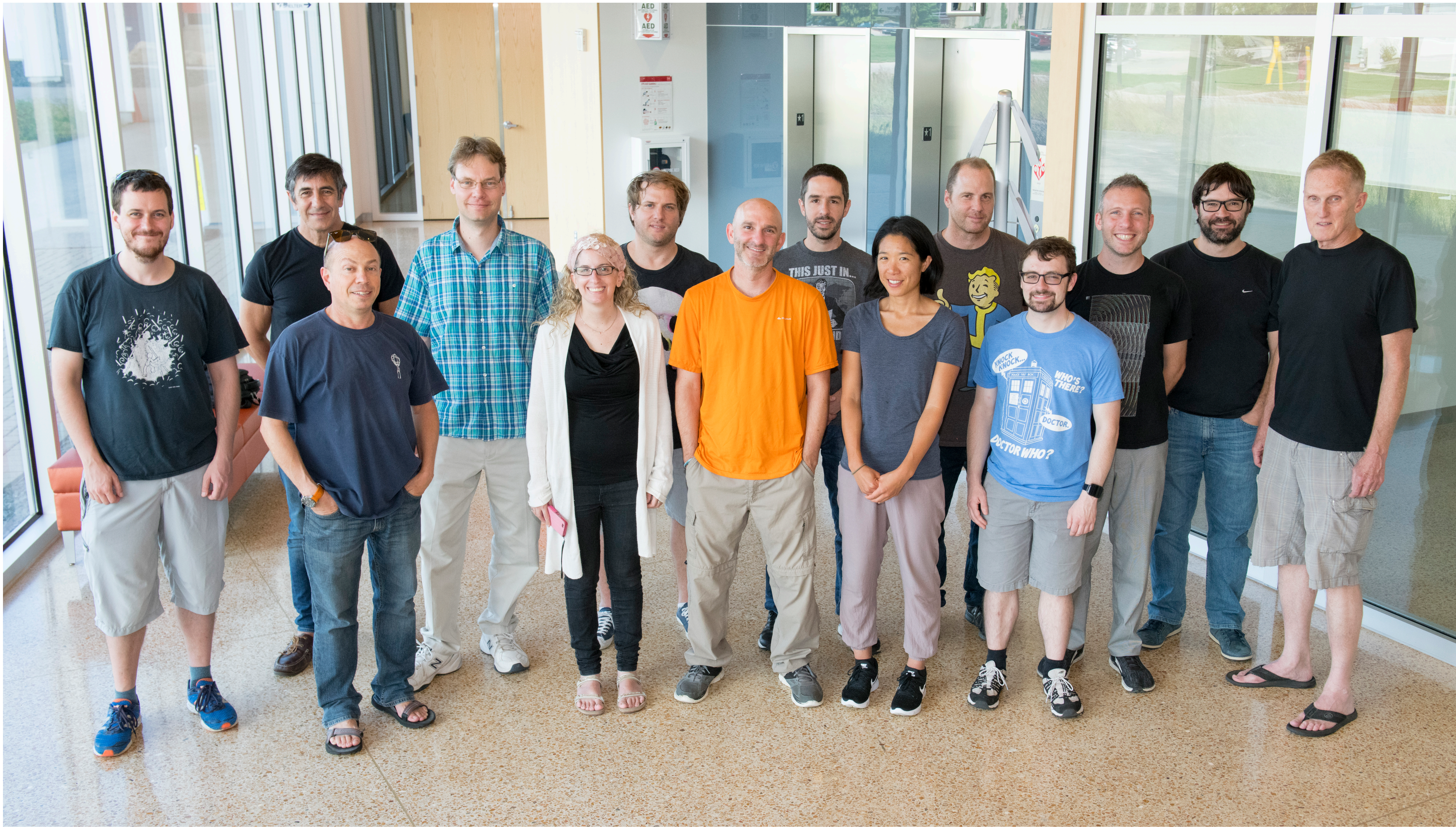
U. Oregon:

- T.-T. Yu

Fully funded by Heising-Simons Foundation & Fermilab

*spokespersons

The SENSEI Collaboration



(not everyone present)

SENSEI's target material are special silicon CCDs

A typical CCD

"Charge-Coupled Device"

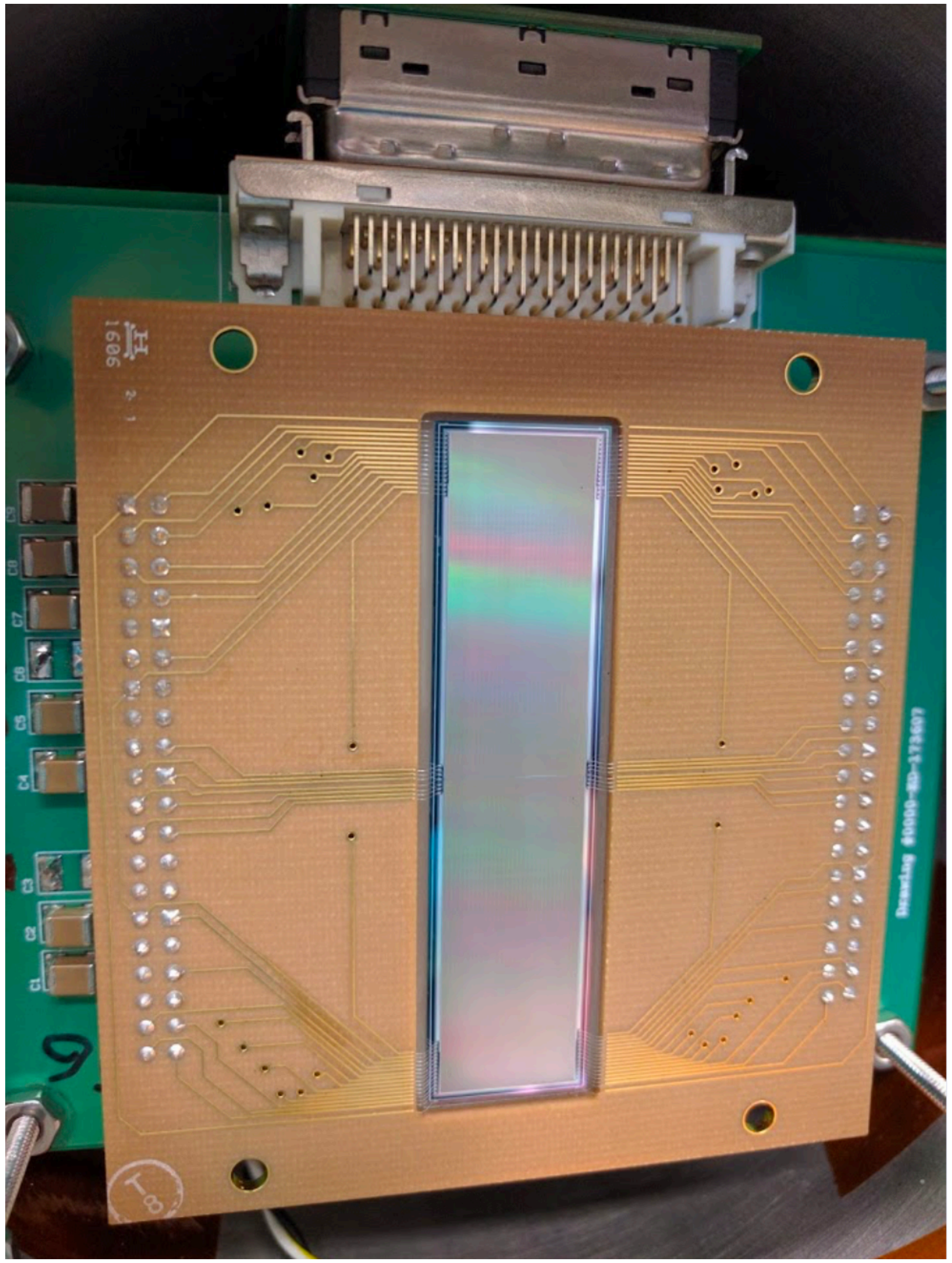
Light incident on CCD will get converted to electrons

thehonestanalytics.com

Can get beautiful images…

Horsehead and Flame Nebulae in Orion. Figure credit: Warren Keller

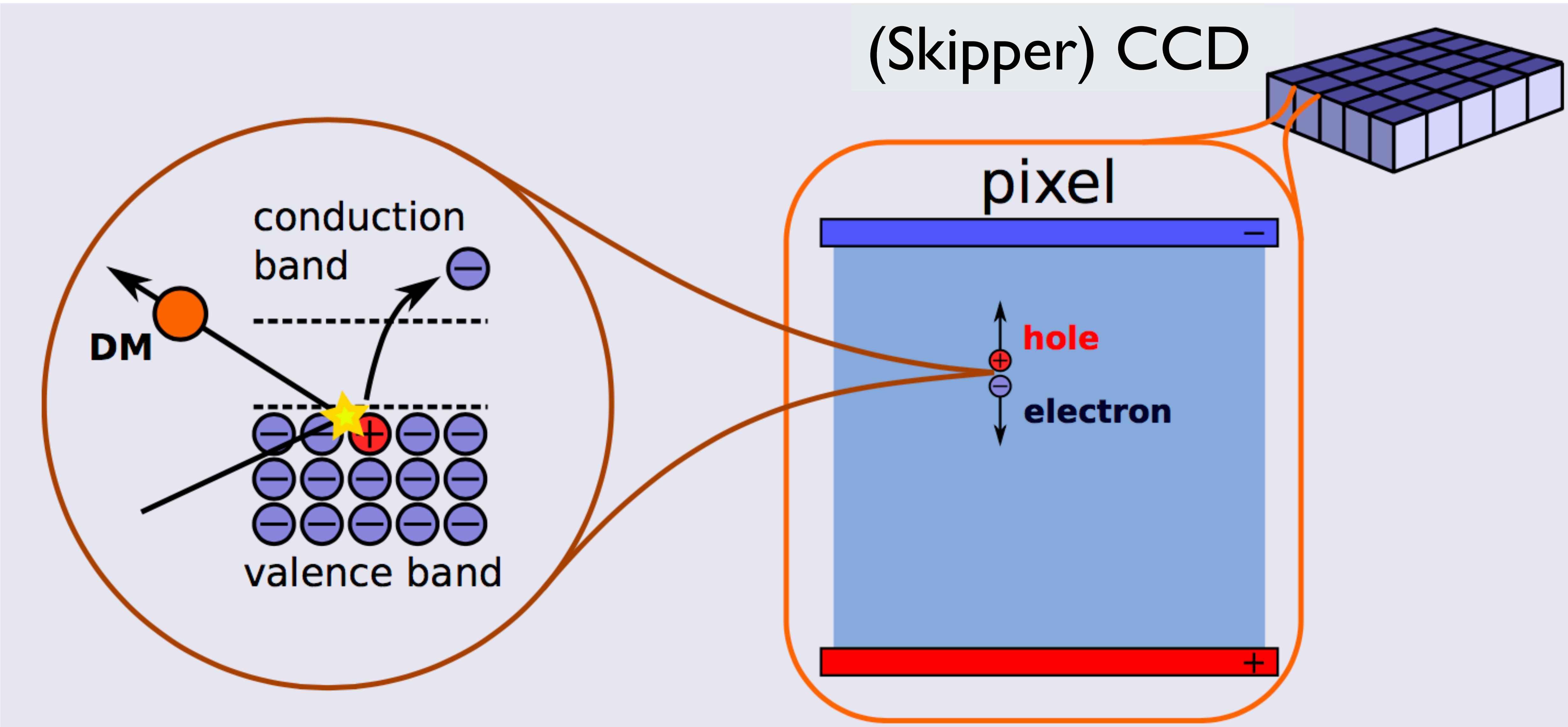
SENSEI's target material are special silicon CCDs



~1 million pixels

"Skipper CCDs"

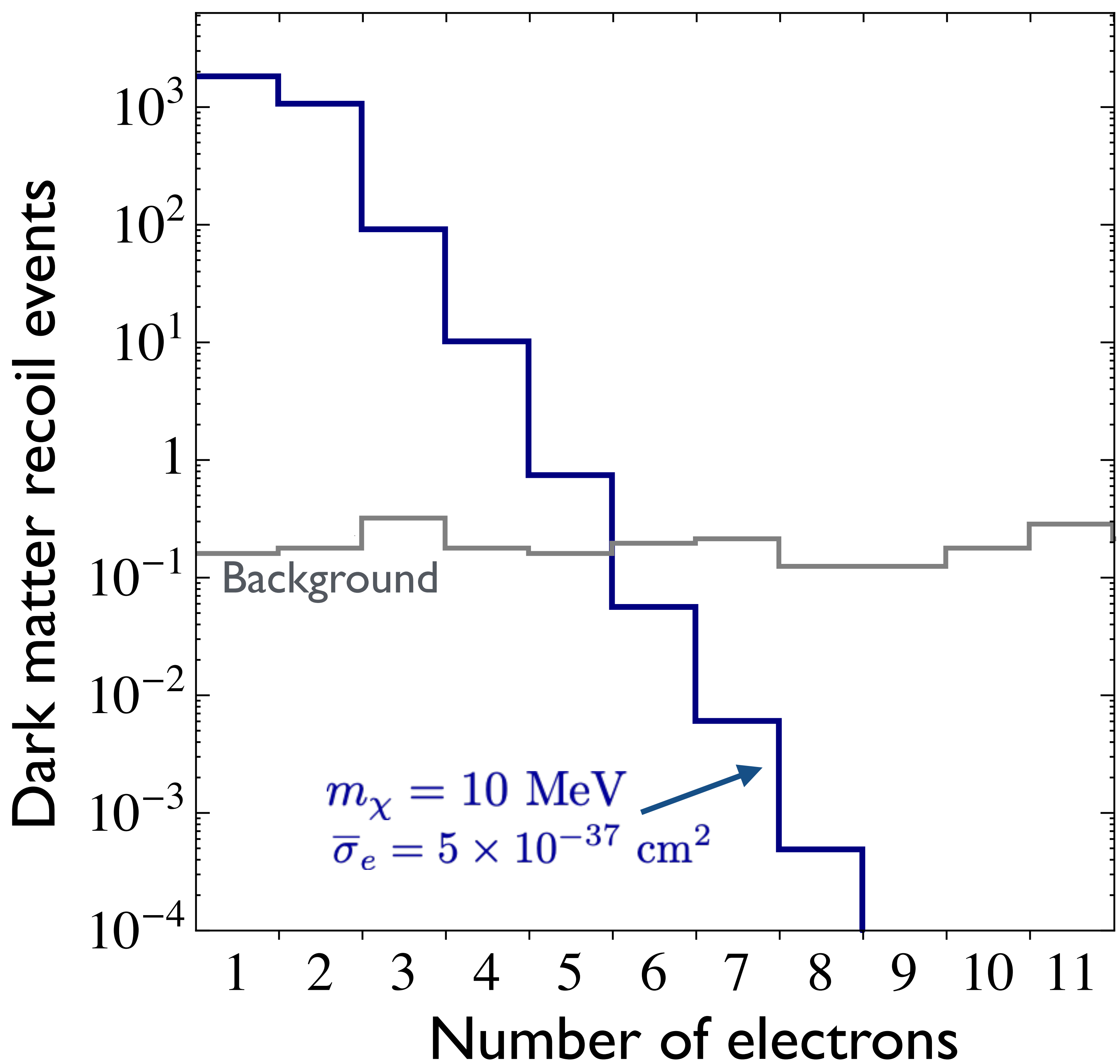
Detection idea



DM would create one or a few electrons in a pixel

(Event rate depends on interaction strength)

Spectrum of electrons produced by dark matter

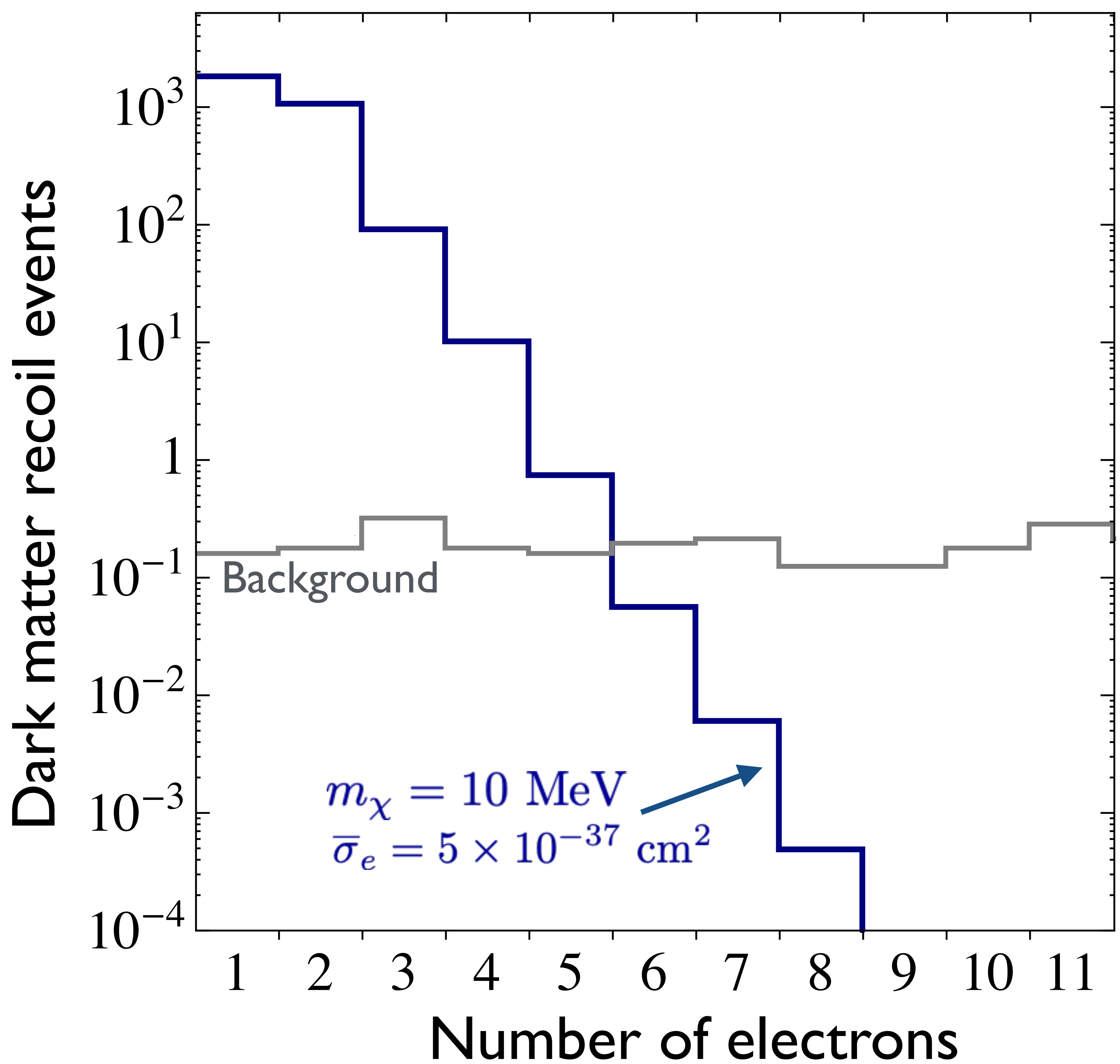


Calculating these rates is challenging!

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

http://ddldm.physics.sunysb.edu

Spectrum of electrons produced by dark matter



Before June 2017, best detectors only sensitive to $\gtrsim$10 electrons

http://ddldm.physics.sunysb.edu

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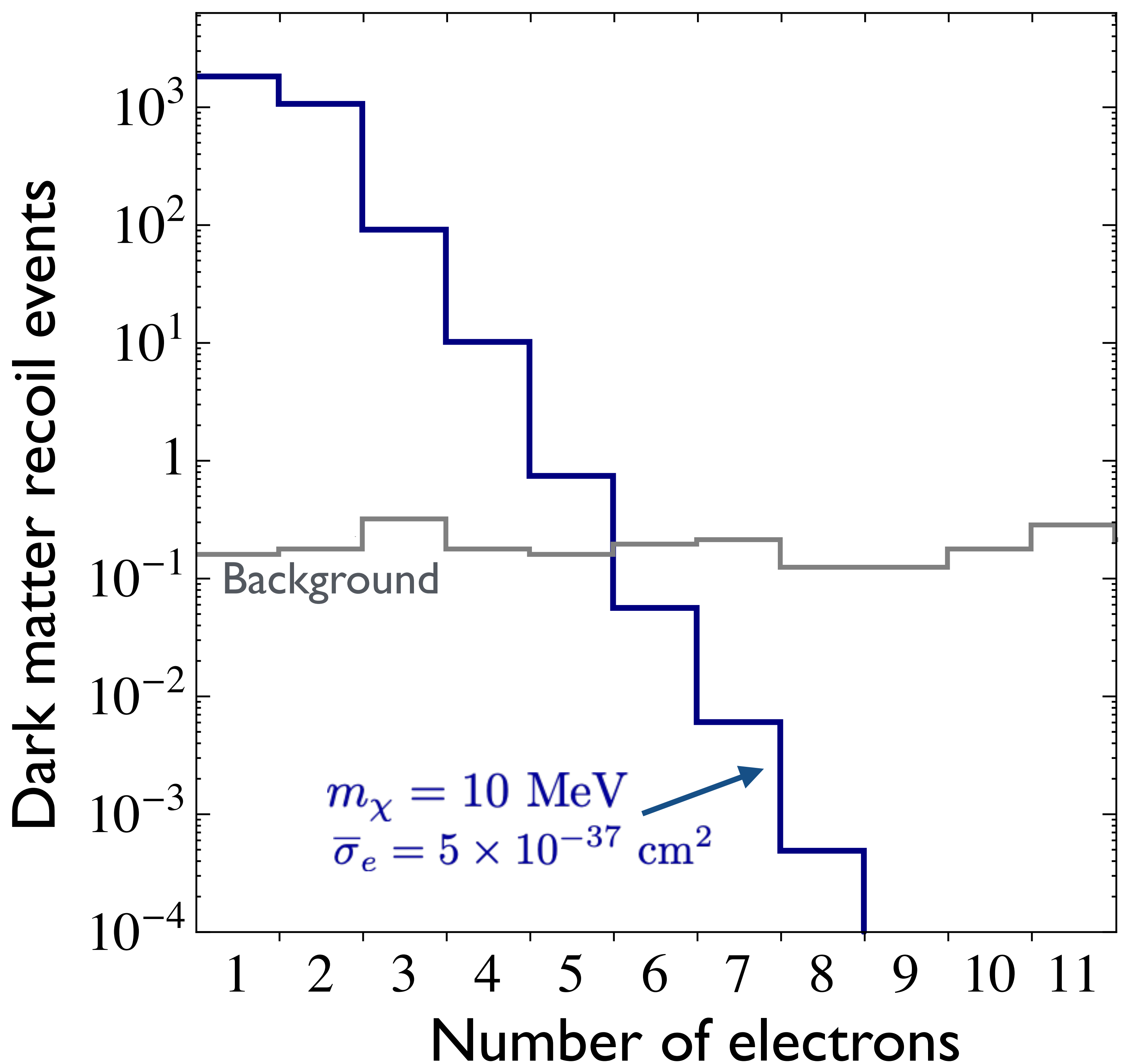

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But SENSEI's Skipper-CCDs are sensitive even to single electrons!

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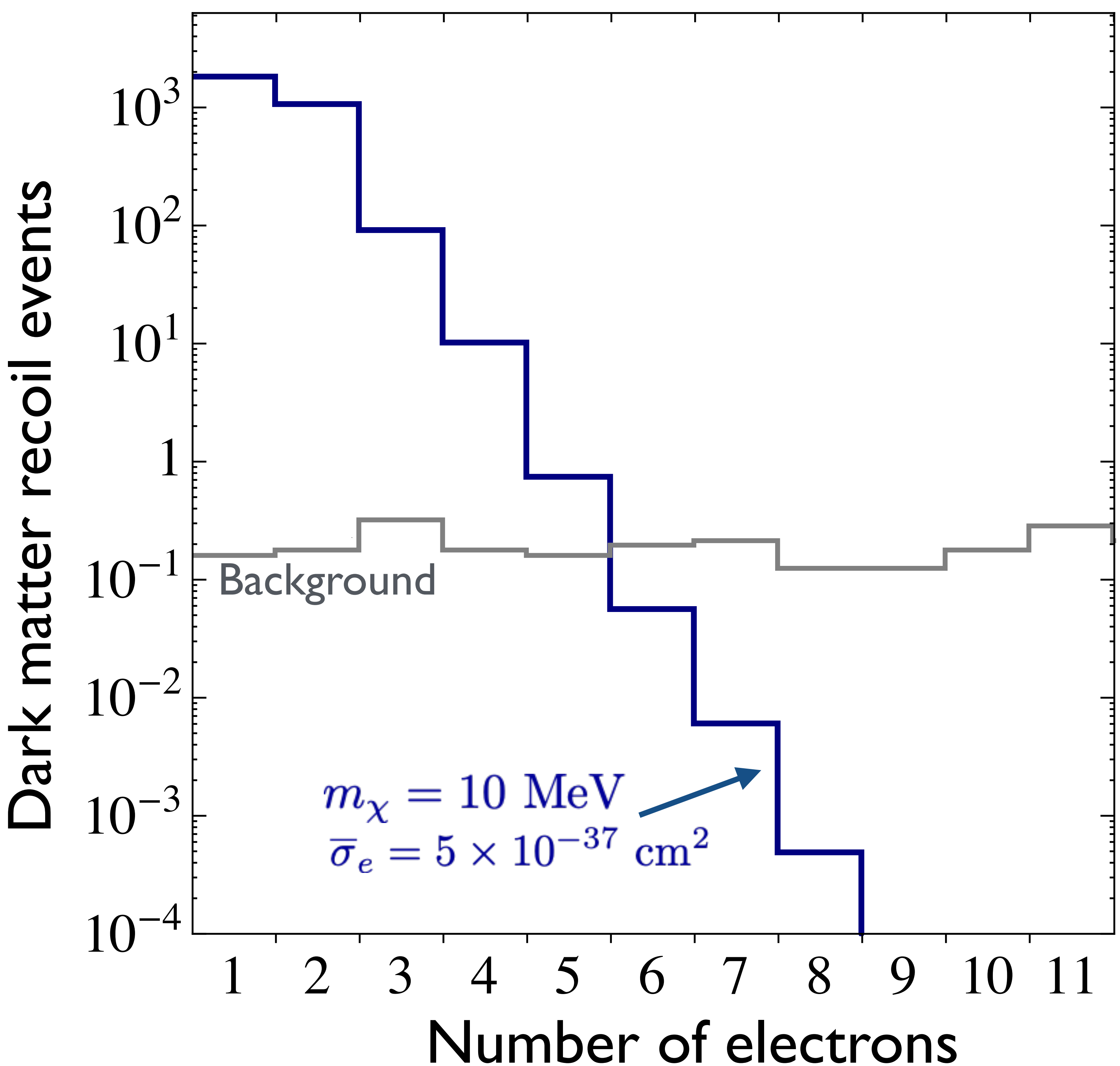


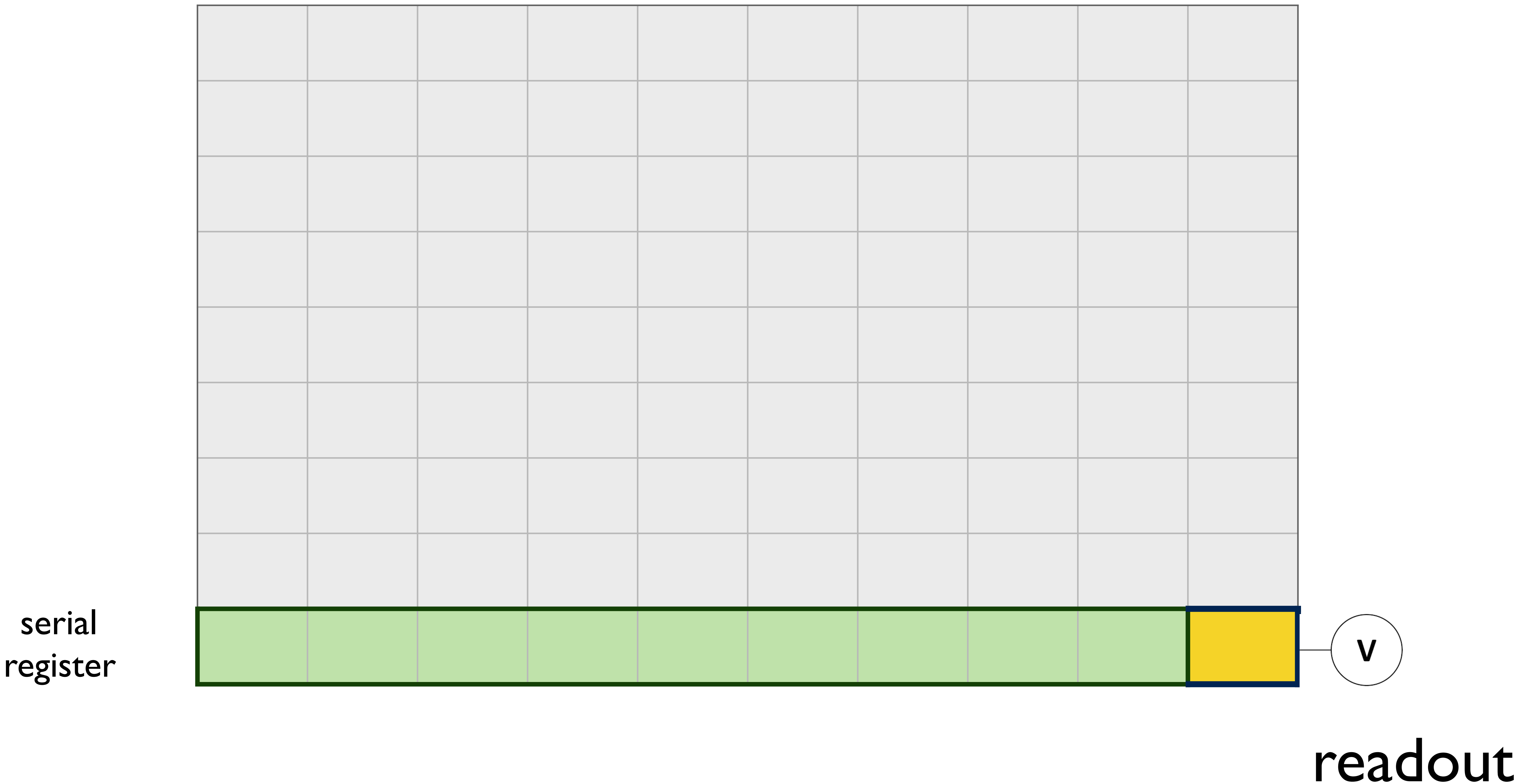
Before June 2017, best detectors only sensitive to $\gtrsim$10 electrons

But SENSEI's Skipper-CCDs are sensitive even to single electrons!

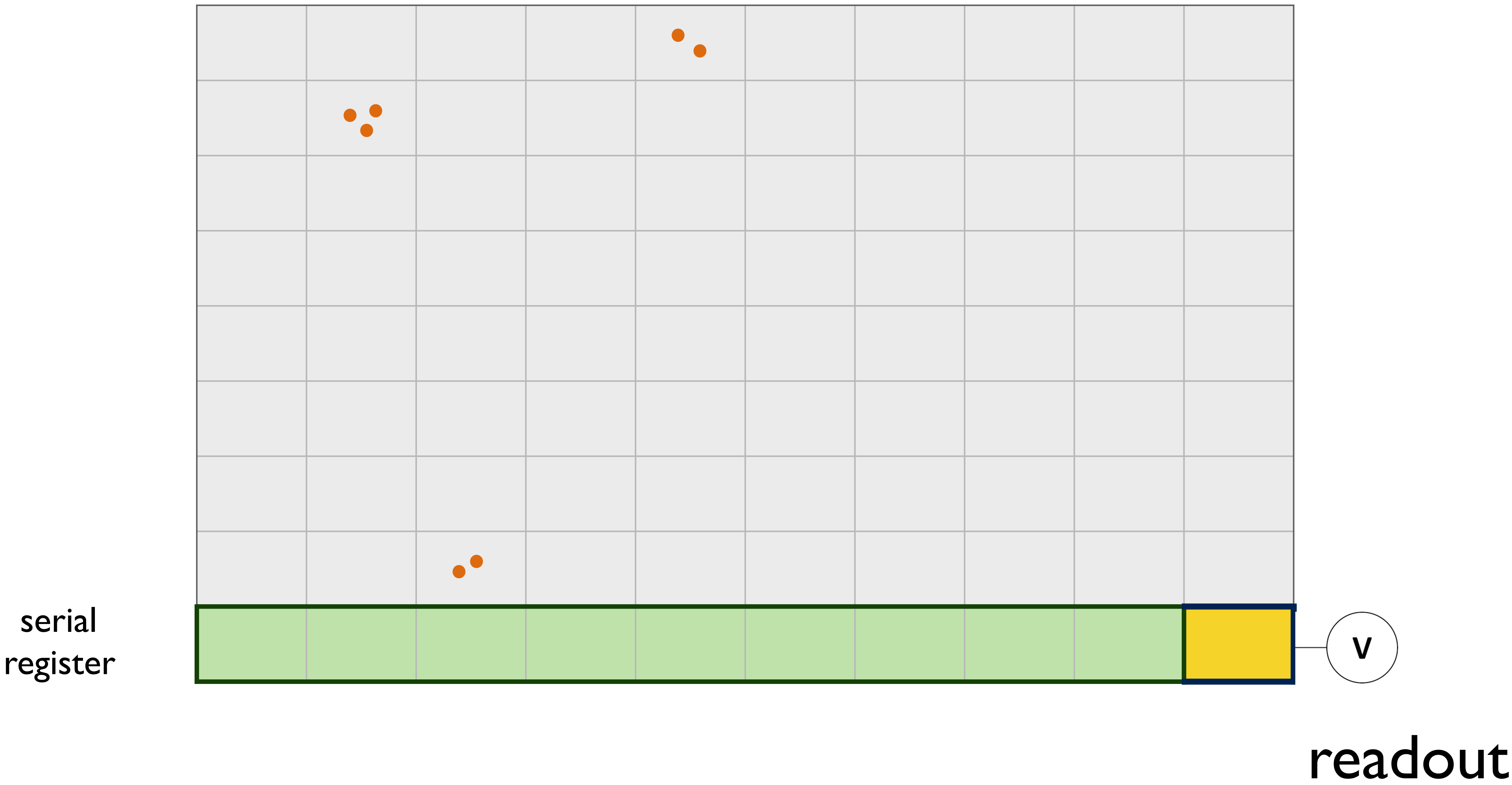
SuperCDMS (TES) & DANAE (DEPFETs) have also demonstrated sensitivity to single electrons!

http://ddldm.physics.sunysb.edu

Moving & reading the charge (schematic)



Moving & reading the charge (schematic)



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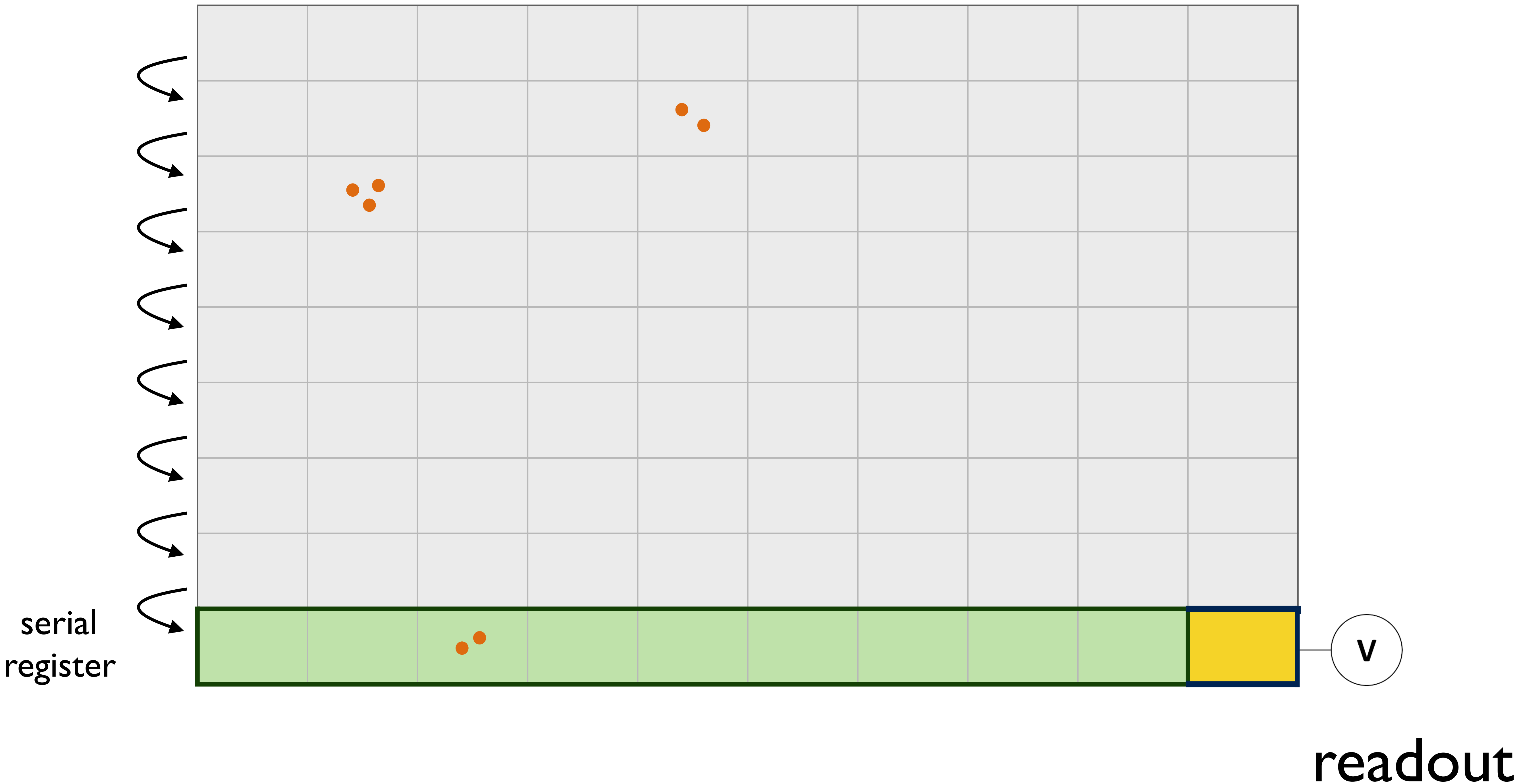
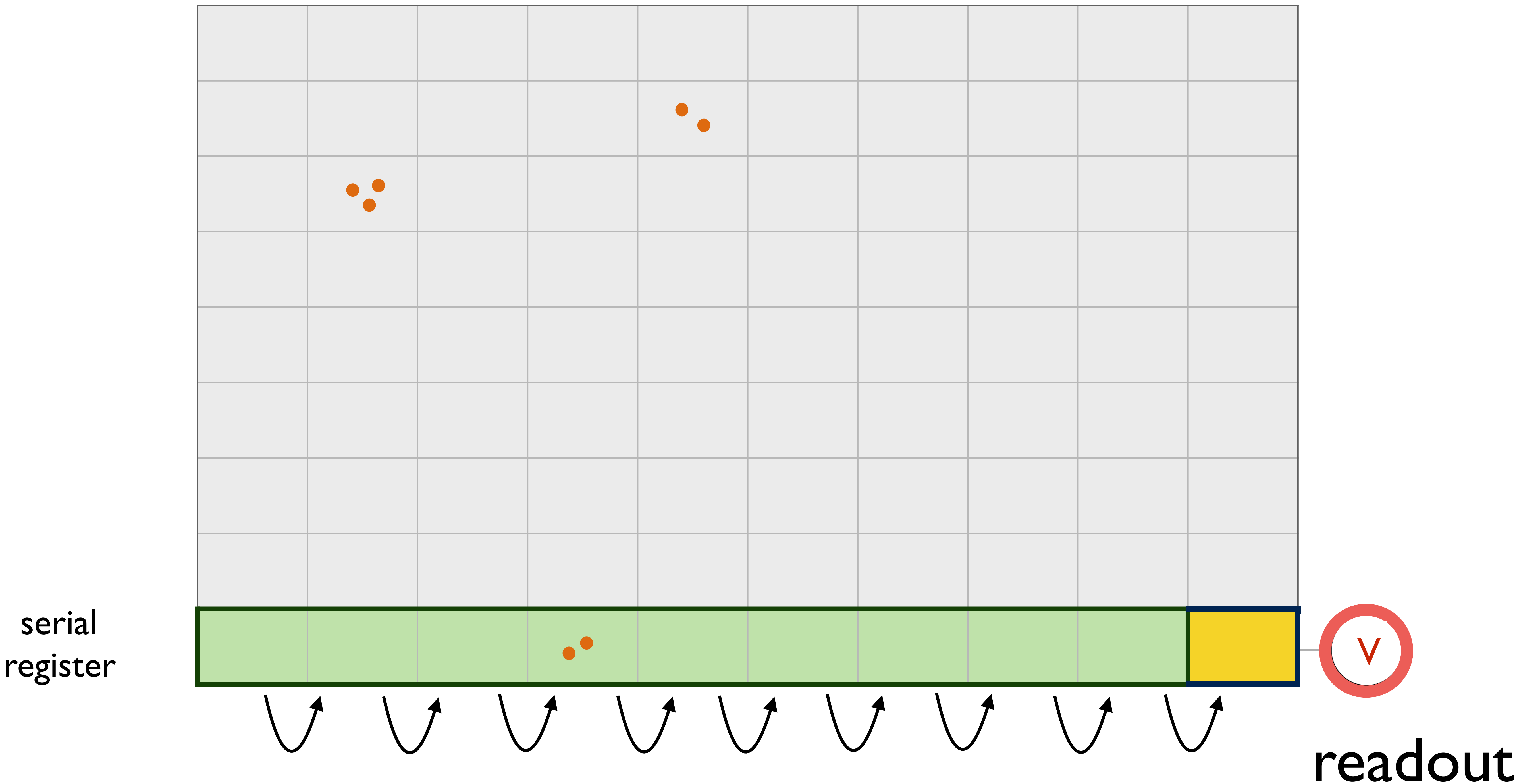


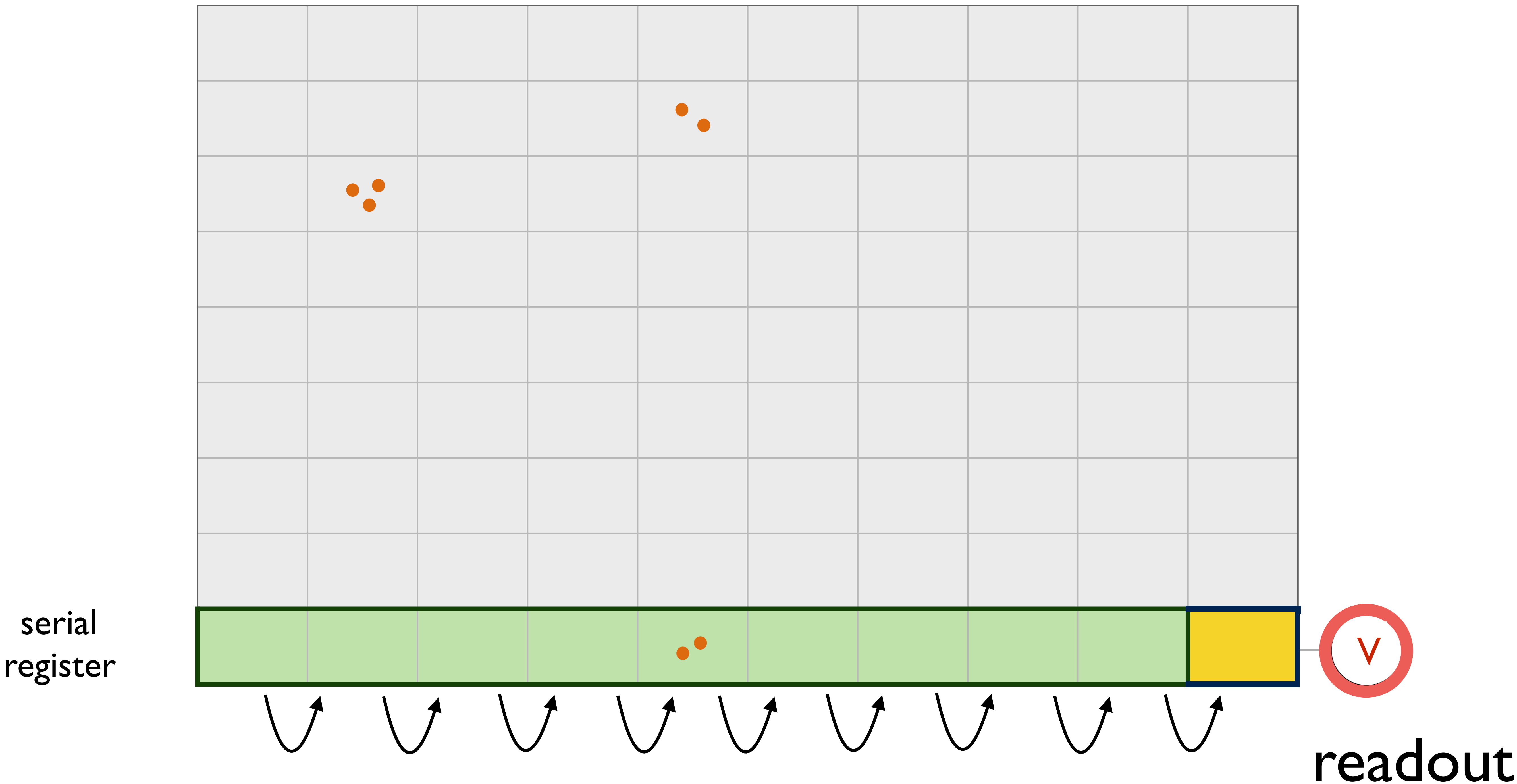
- shift each pixel charge down by one row

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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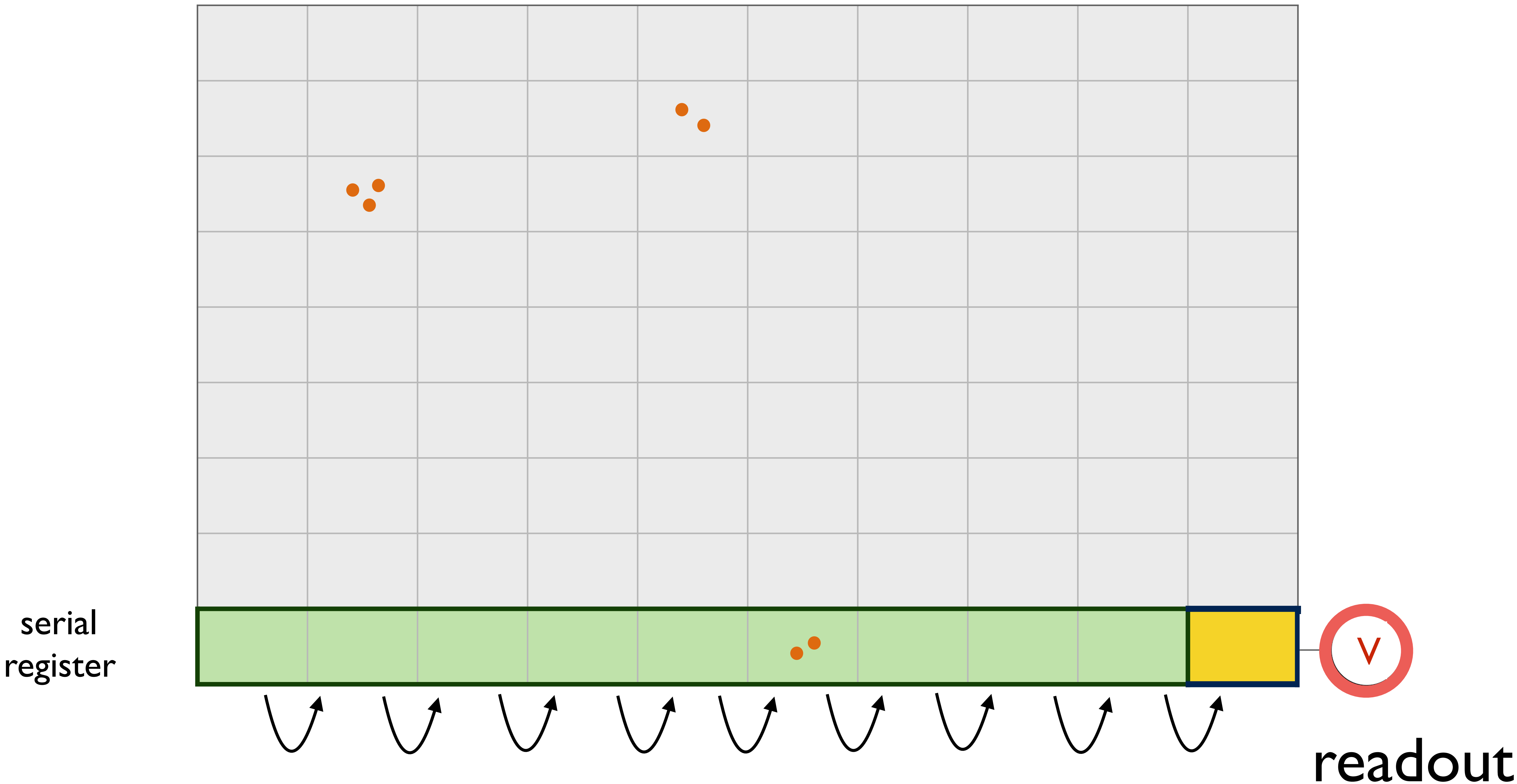

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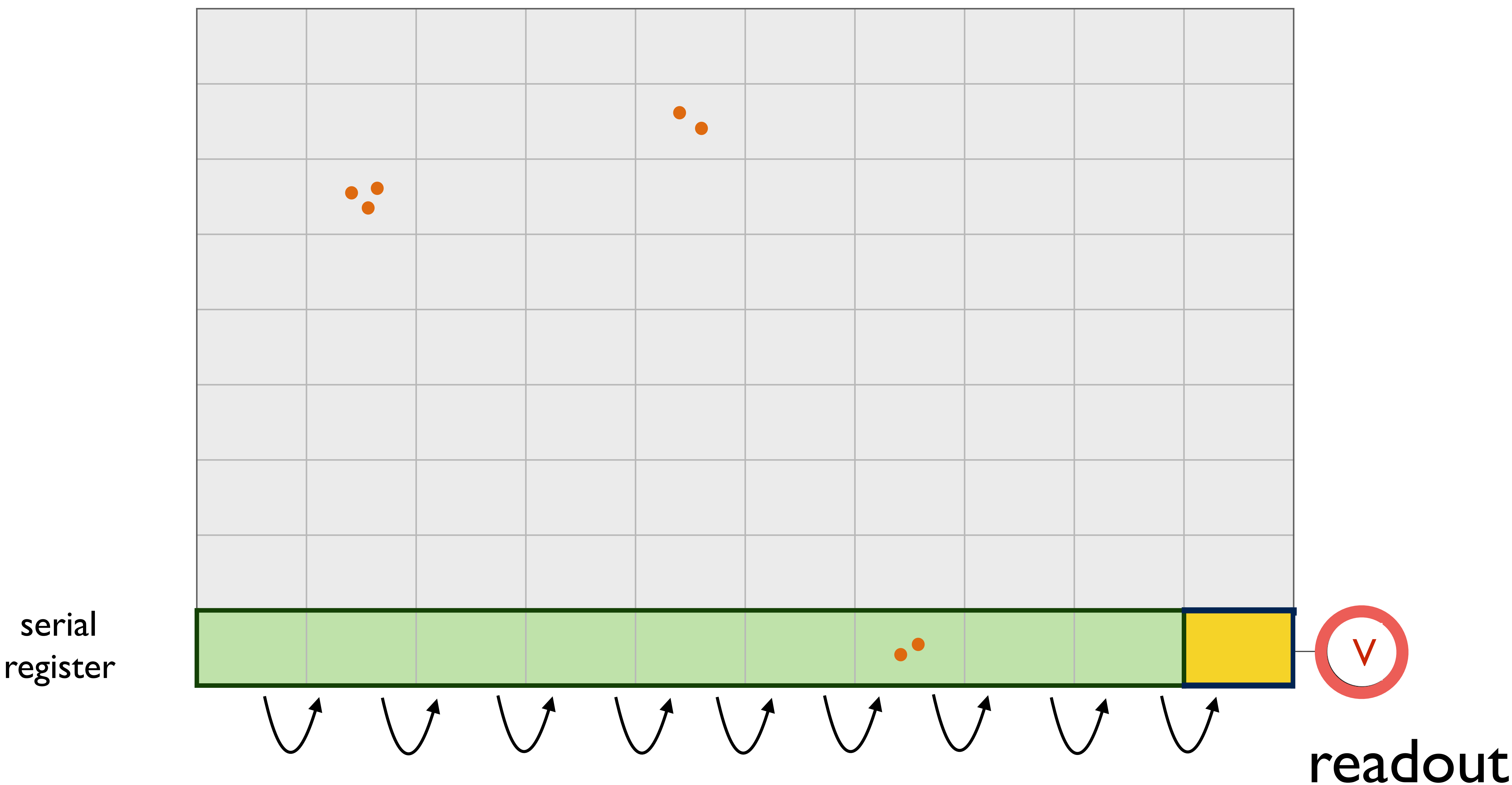

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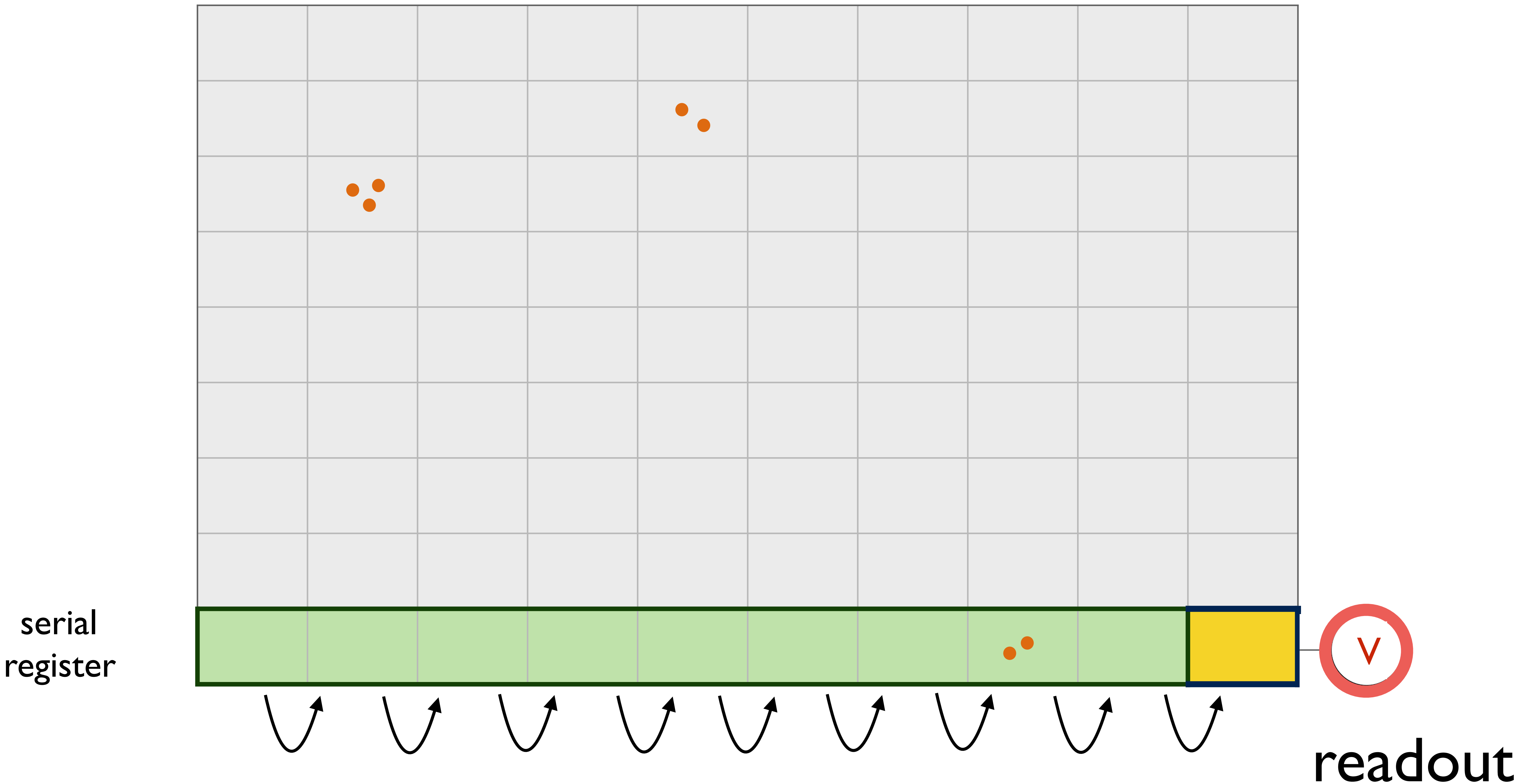

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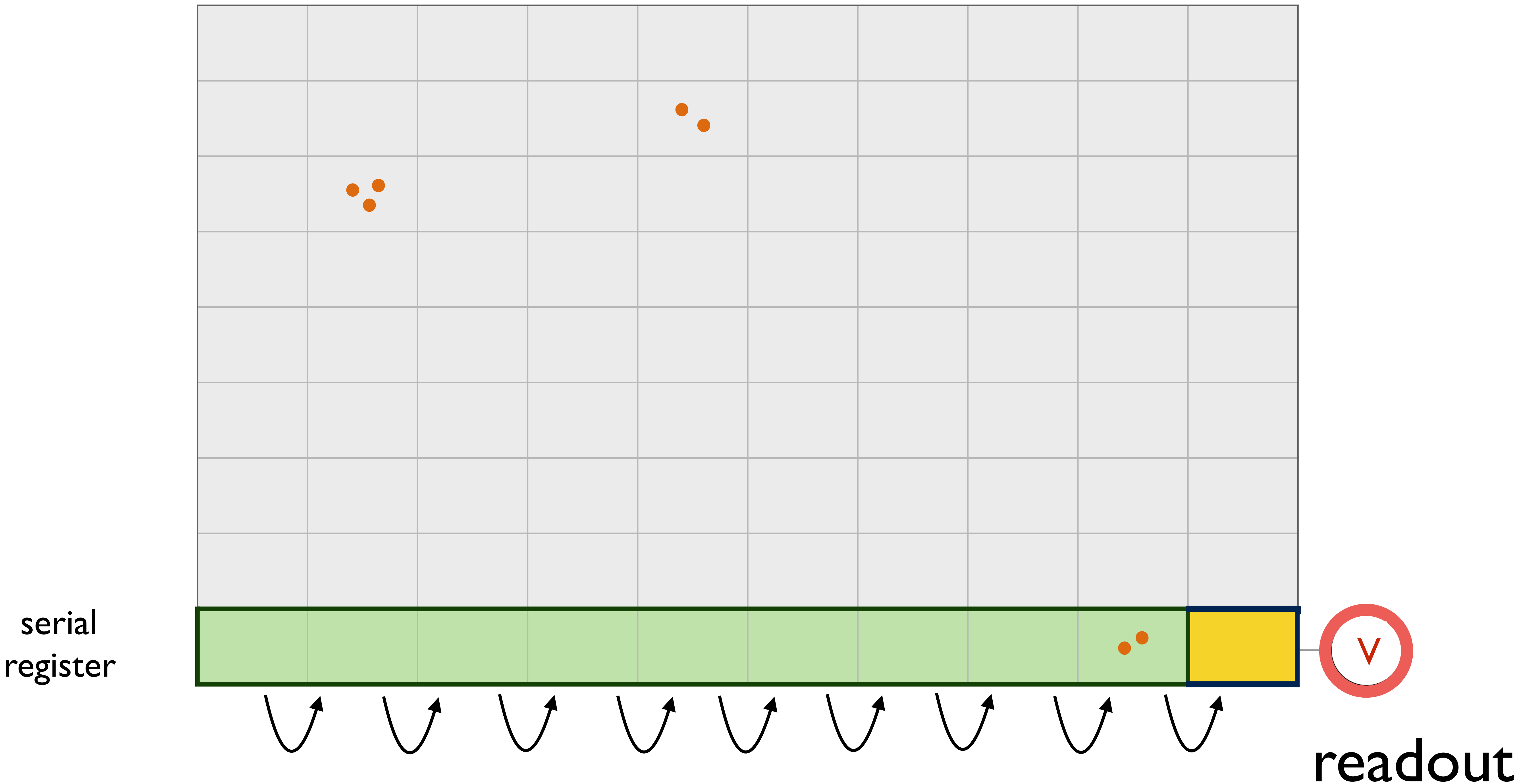

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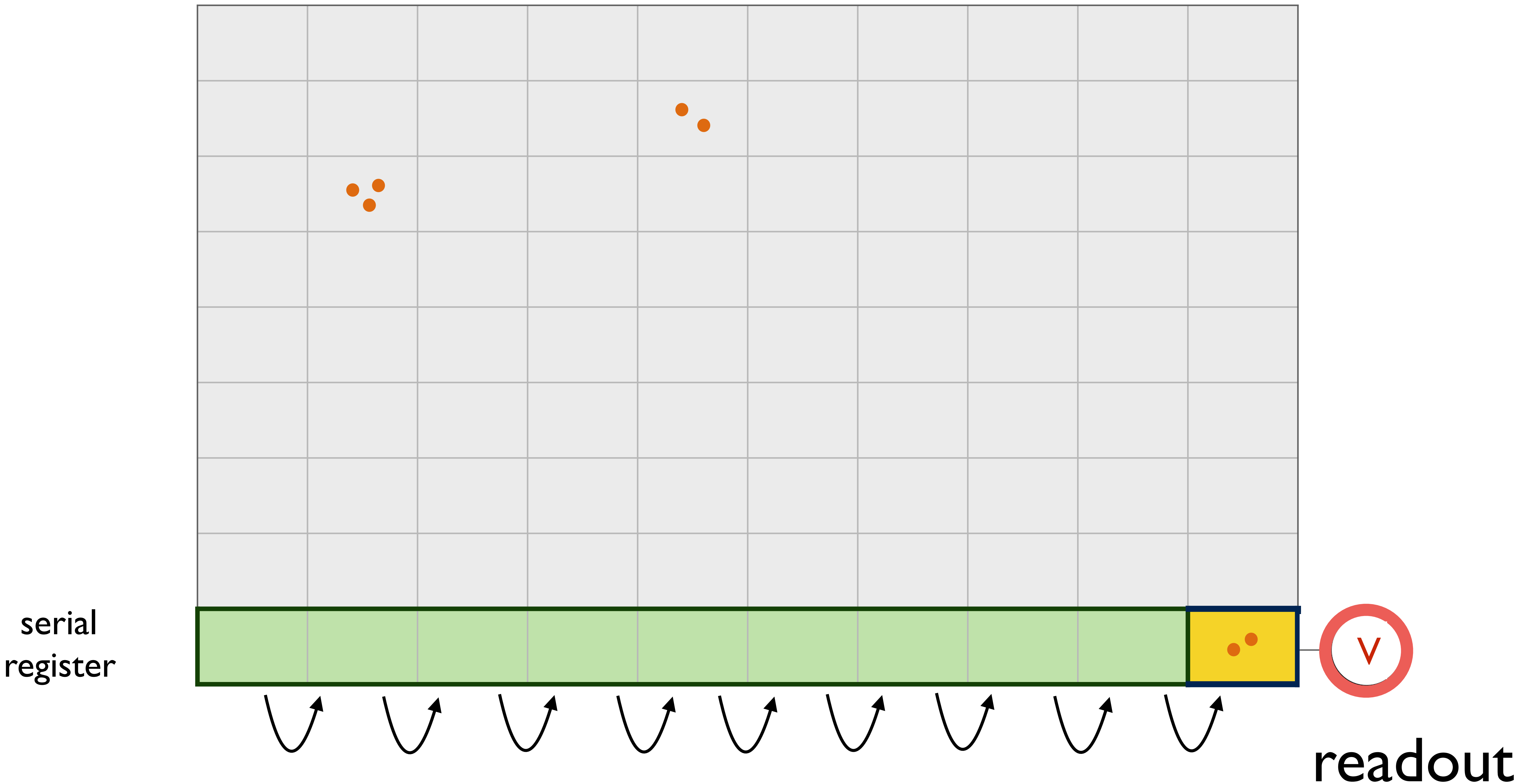
Moving & reading the charge (schematic)



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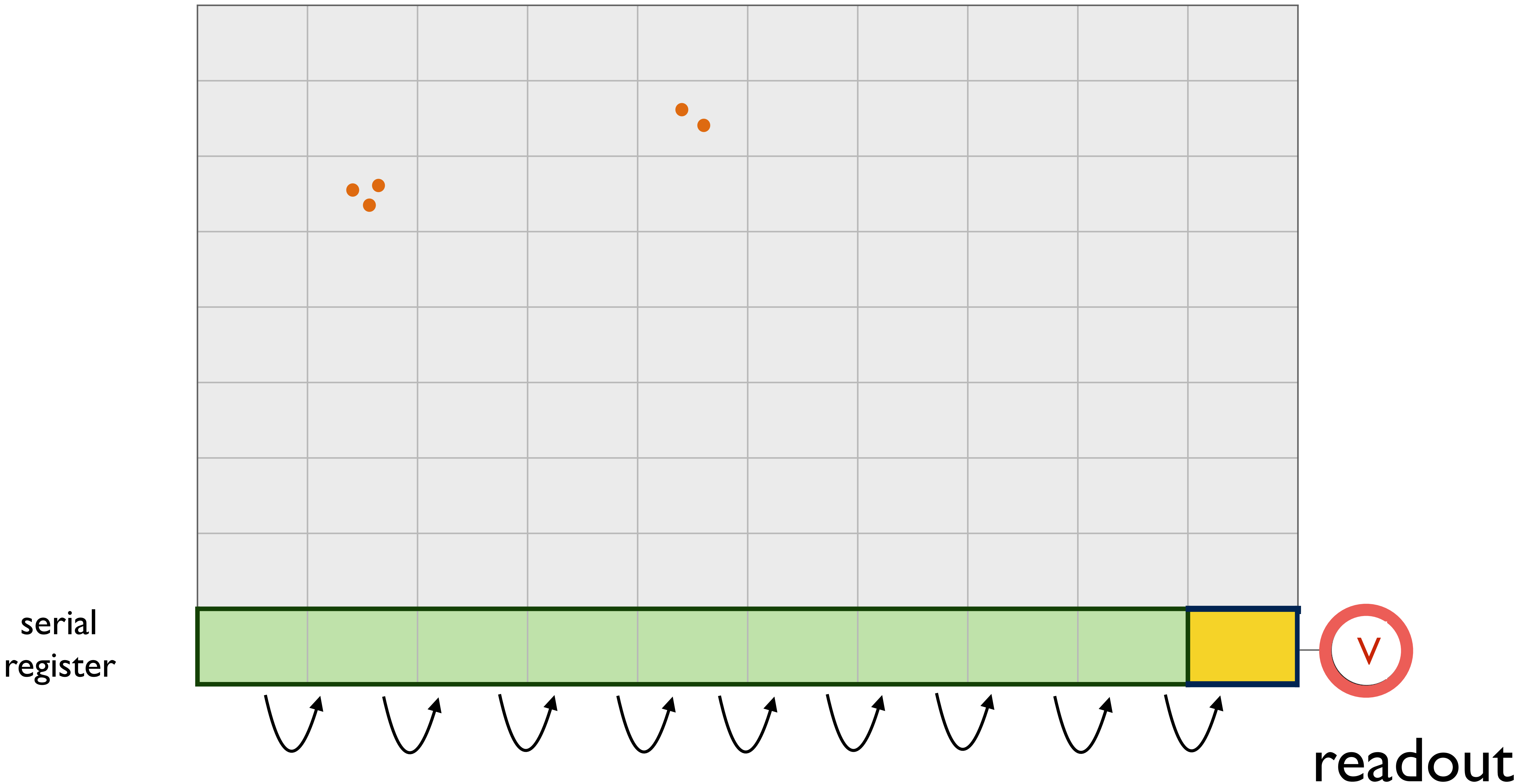

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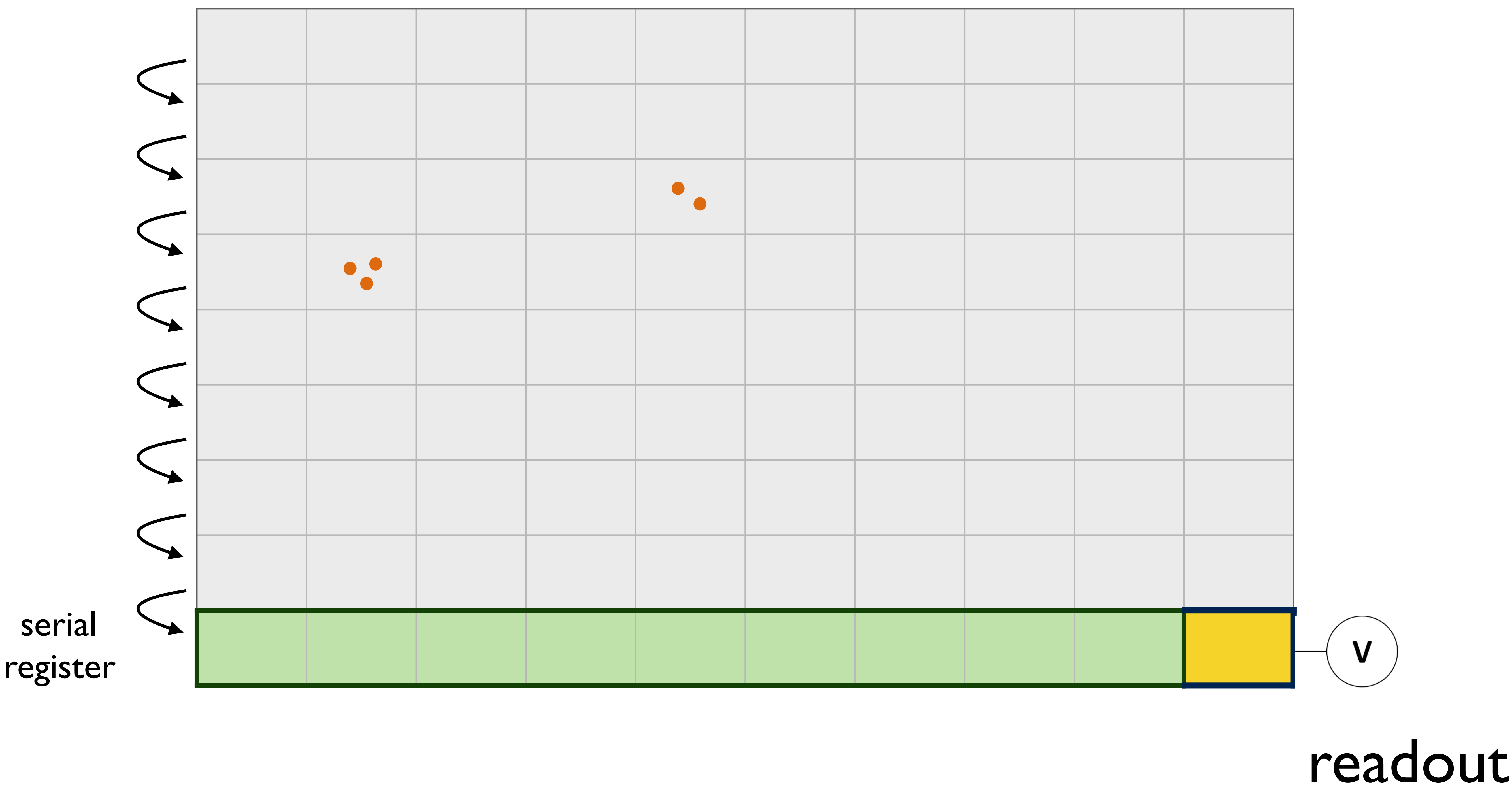
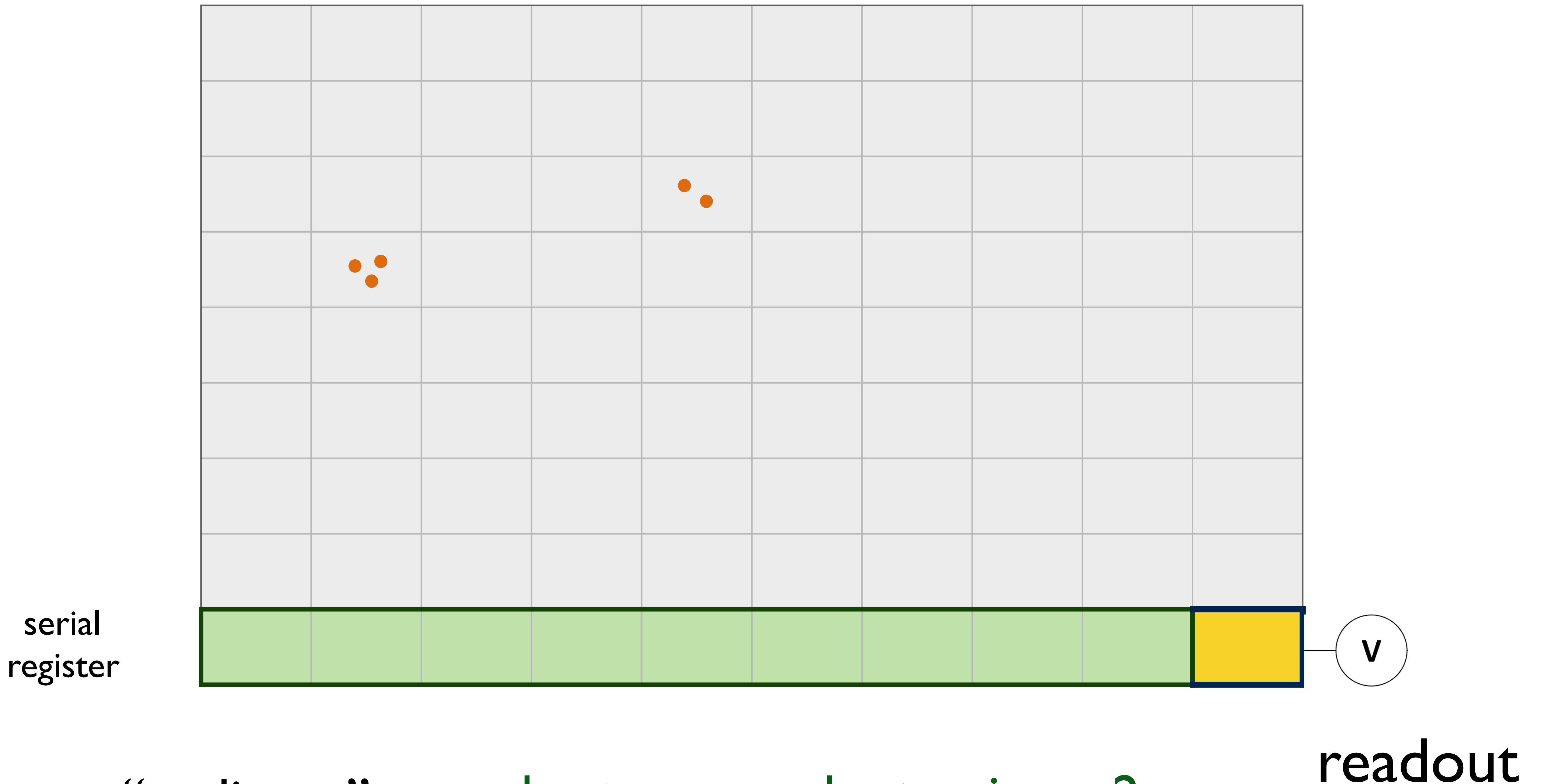
Moving & reading the charge (schematic)



- repeat

Moving & reading the charge (schematic)



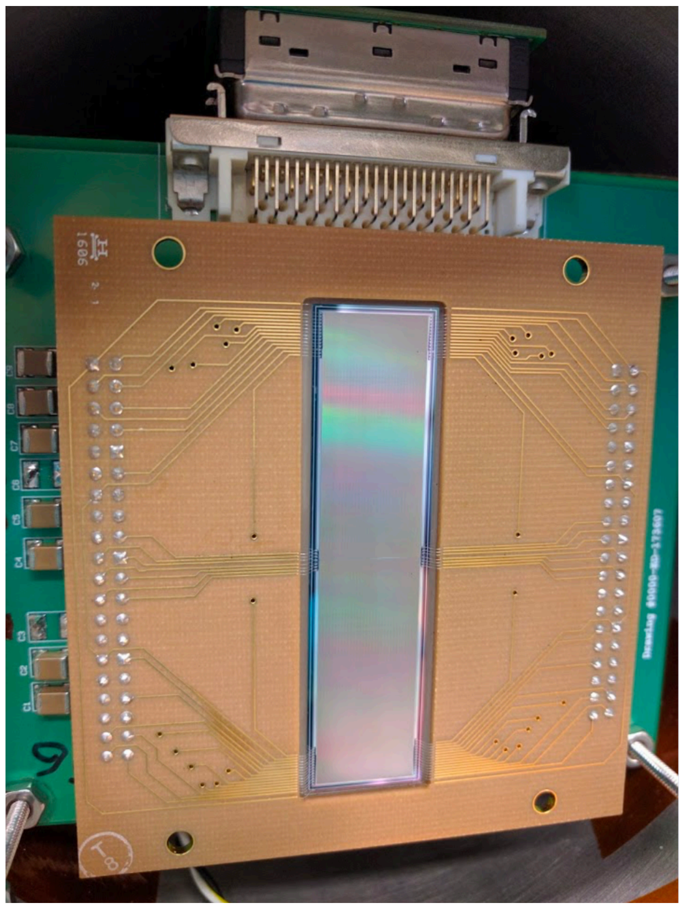
"ordinary" scientific CCDs:

best rms readout noise ~ $2e^-$

$\Longrightarrow$ "high" threshold ~ $10e^-$

Skipper-CCD operation (schematic)

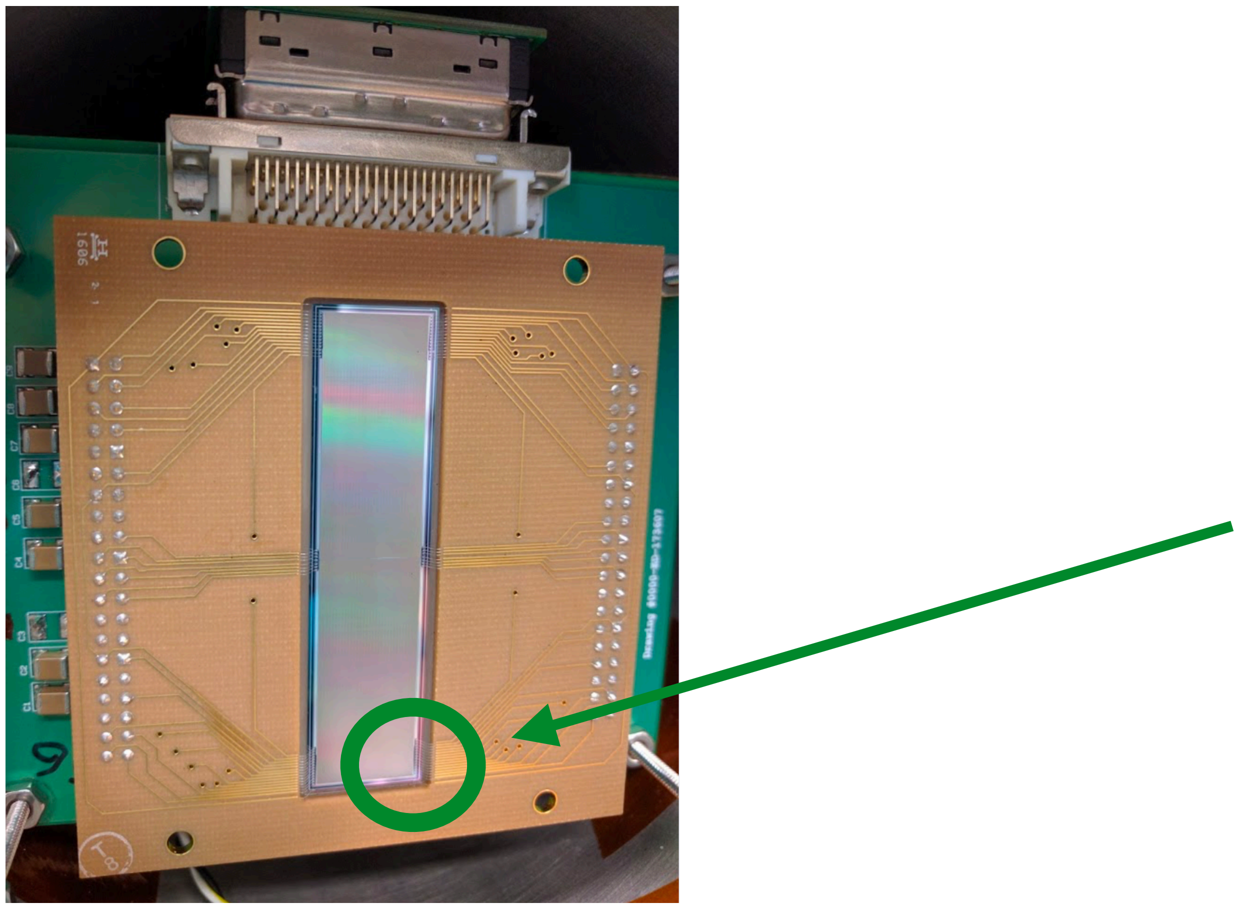
silicon Skipper-CCD



~million pixels

Skipper-CCD operation (schematic)

silicon Skipper-CCD



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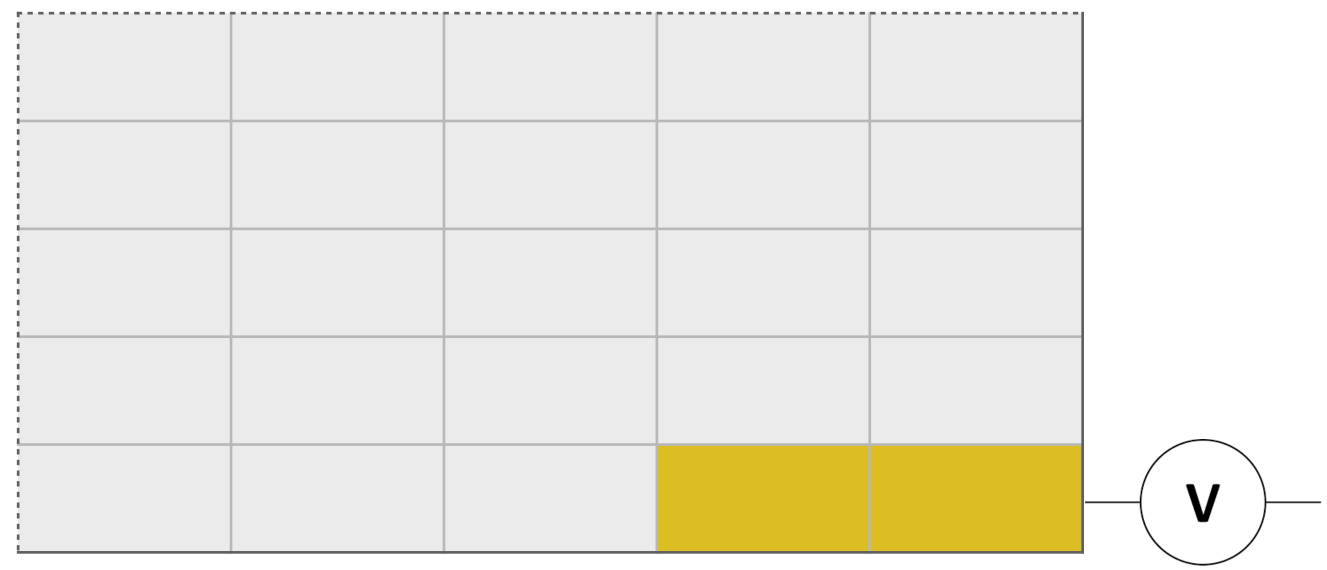

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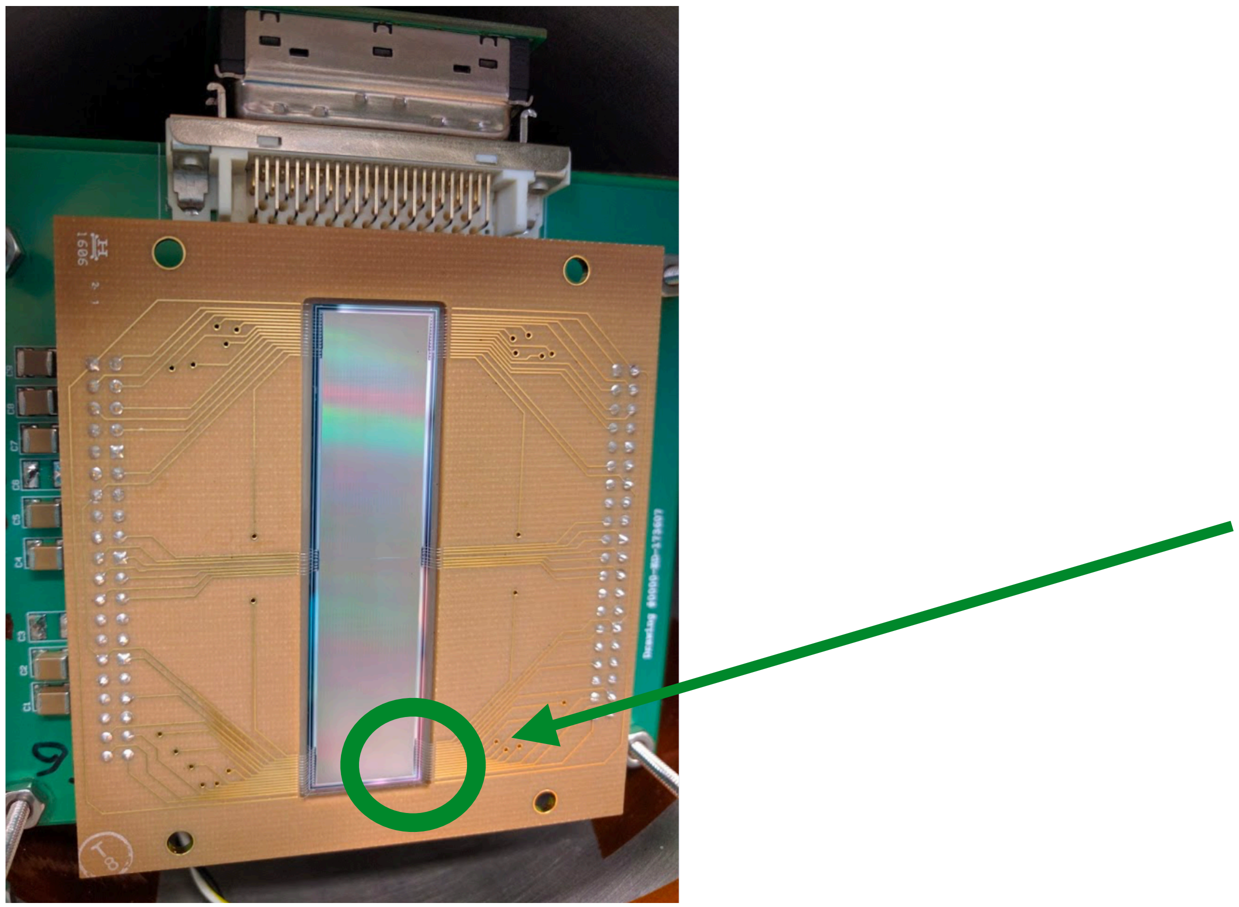

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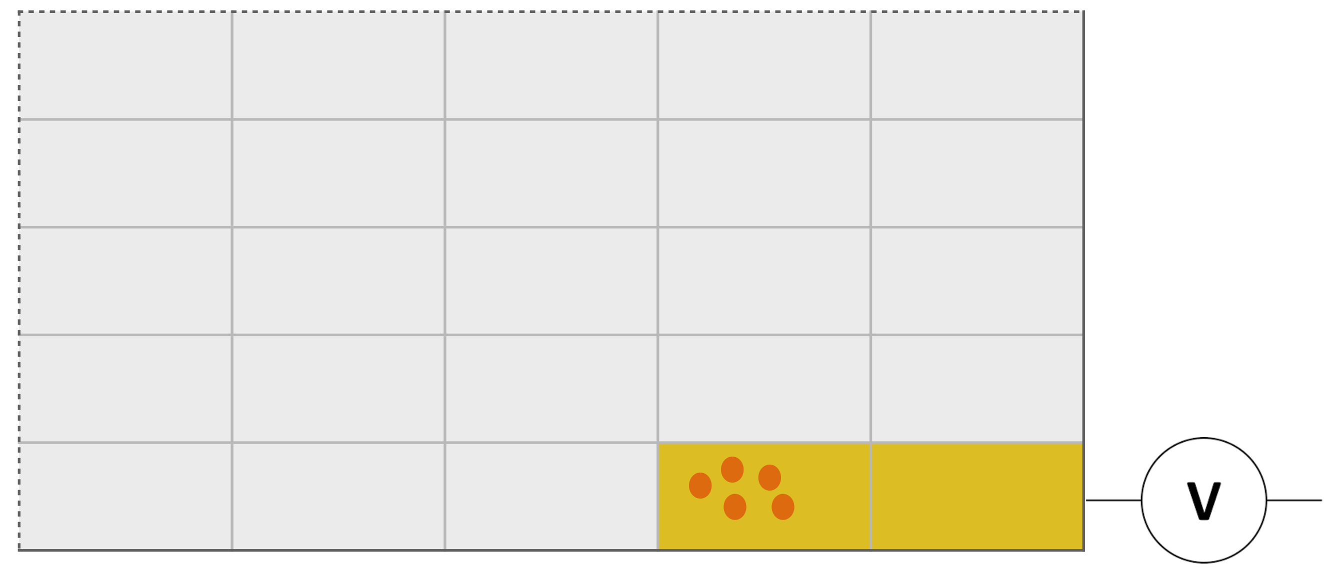

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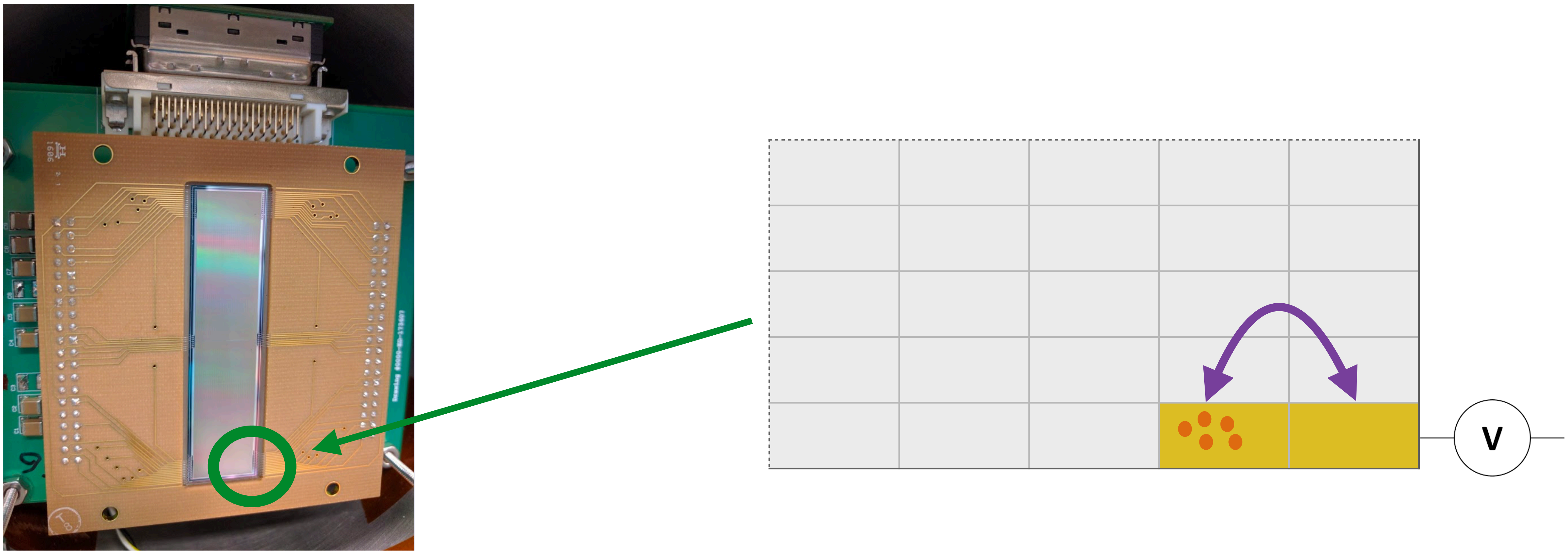
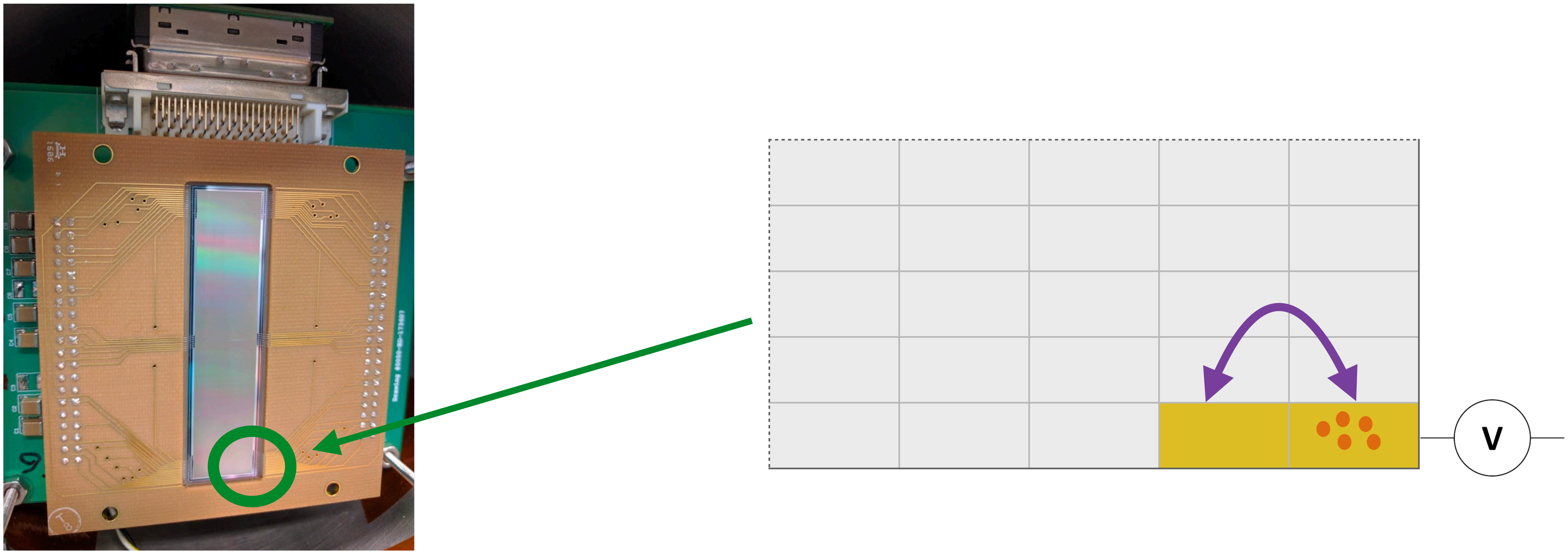


~million pixels

repeatedly measure charge to
achieve sub-electron readout noise

Skipper-CCD operation (schematic)

silicon Skipper-CCD



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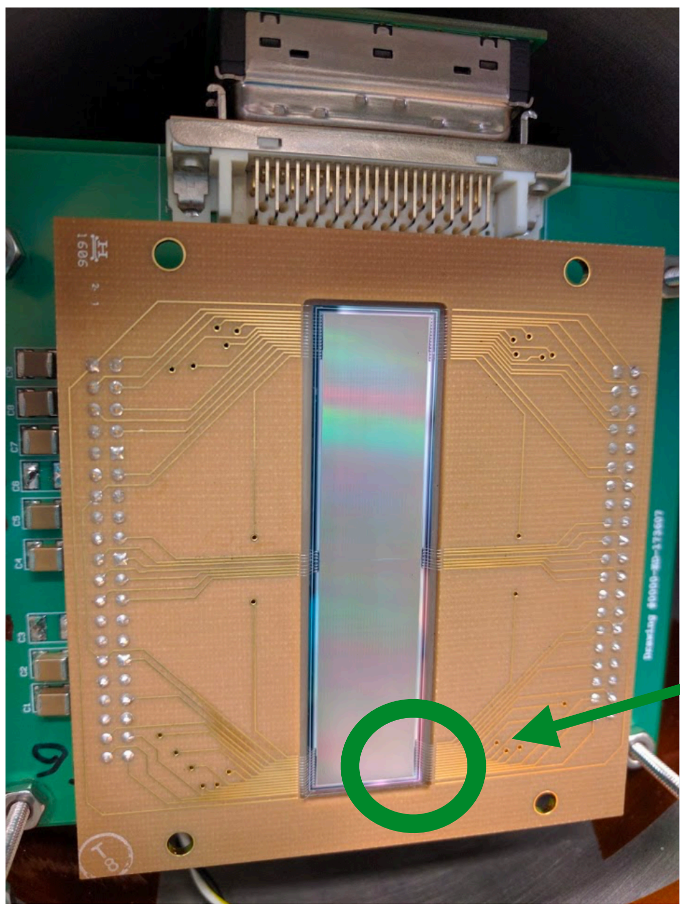
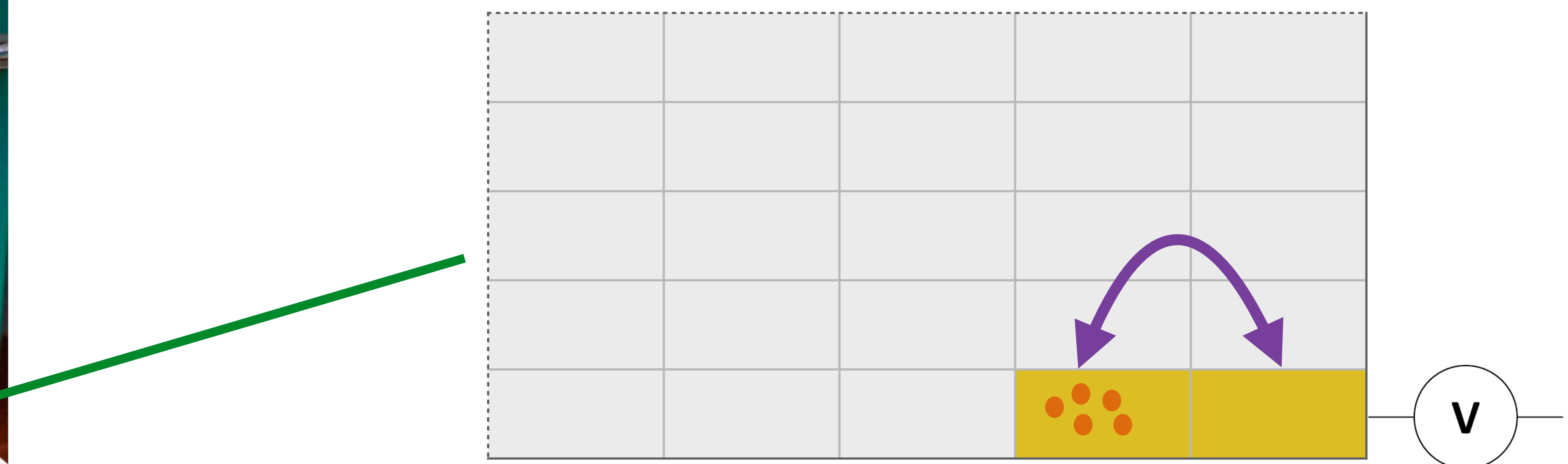
Skipper-CCD operation (schematic)

silicon Skipper-CCD



~million pixels



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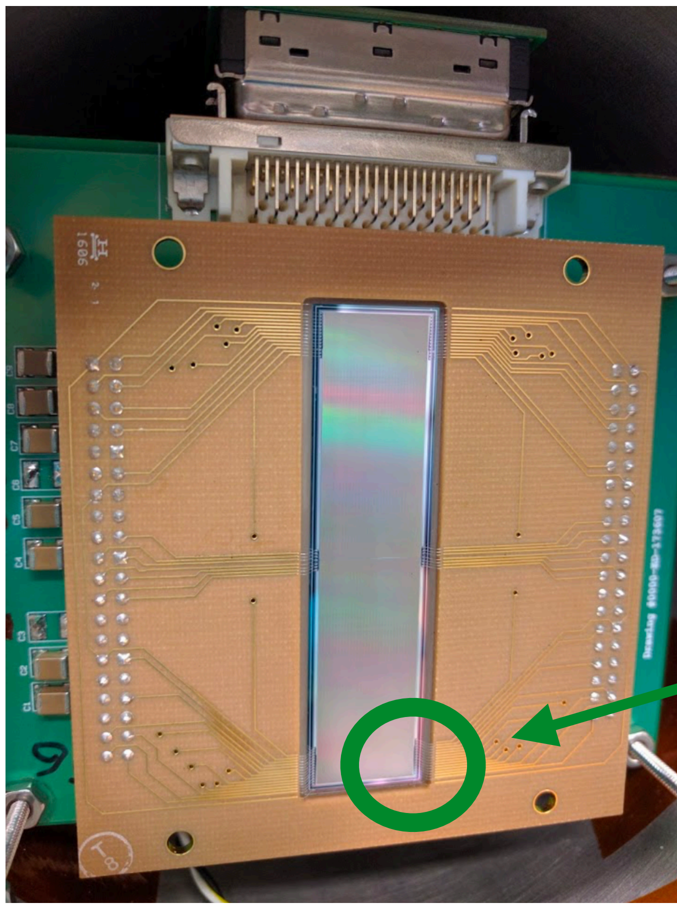
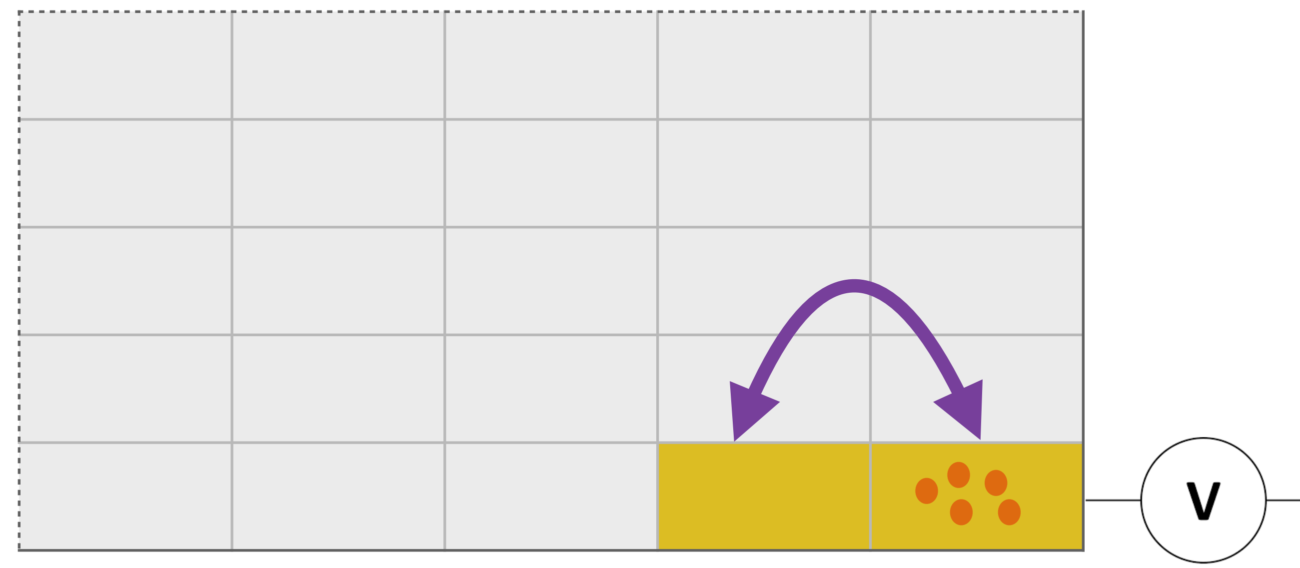
Skipper-CCD operation (schematic)

silicon Skipper-CCD



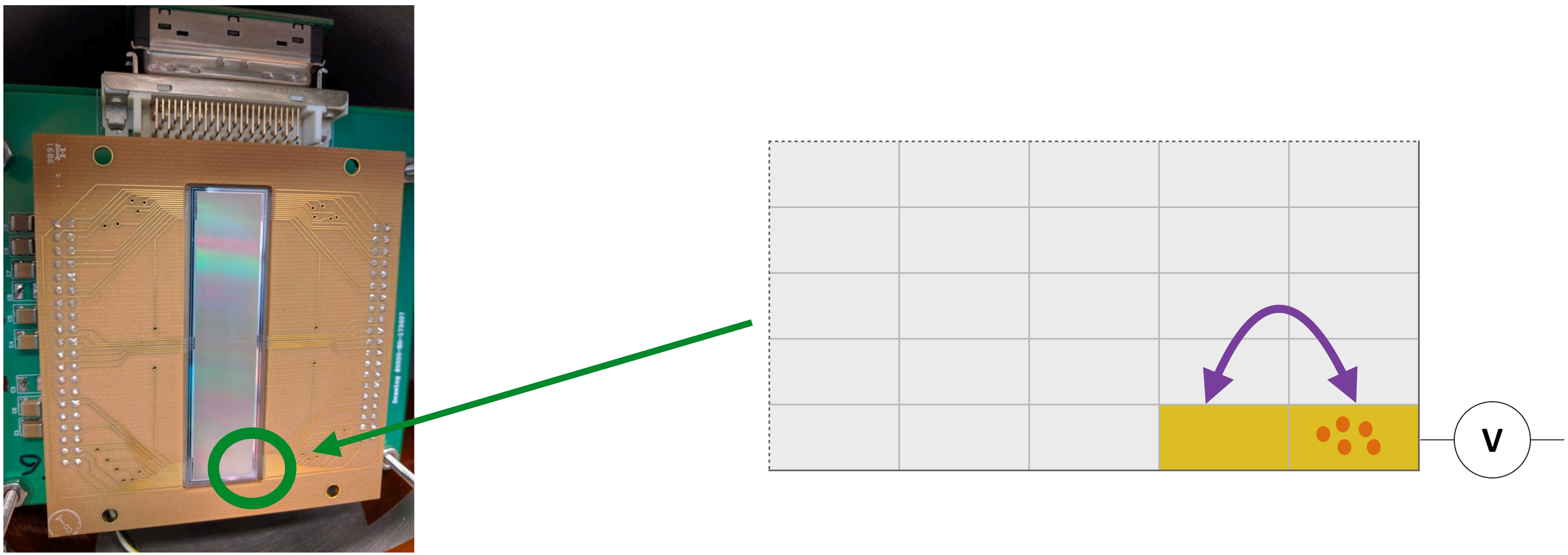
~million pixels



repeatedly measure charge to achieve sub-electron readout noise

Skipper-CCD operation (schematic)

silicon Skipper-CCD



~million pixels

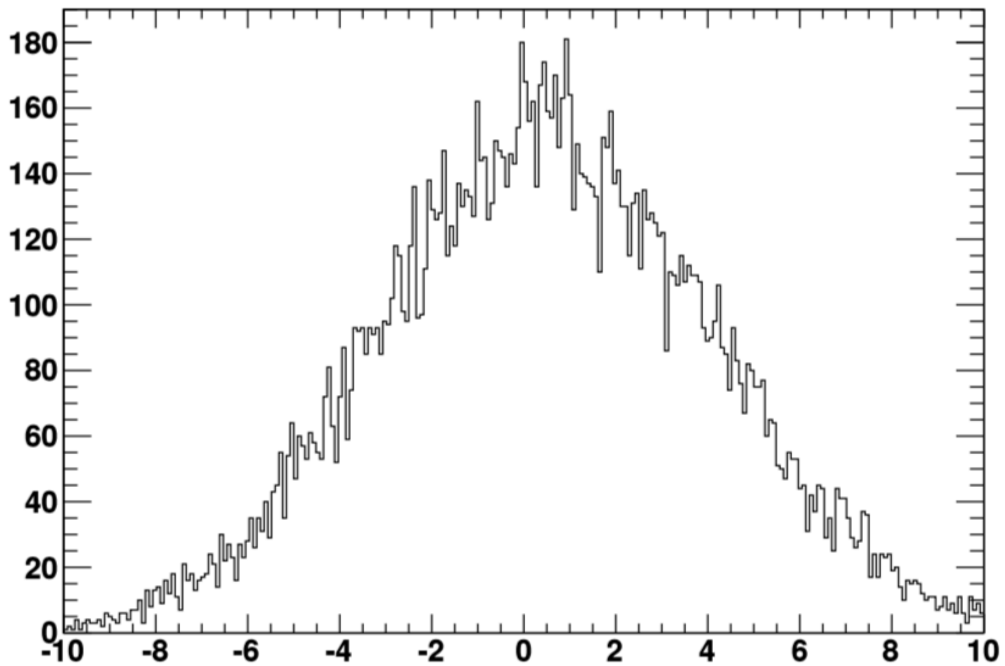
repeatedly measure charge to achieve sub-electron readout noise

developed in collaboration between FNAL & LBNL MicroSystems Lab

Can count individual electrons, w/ ~zero noise

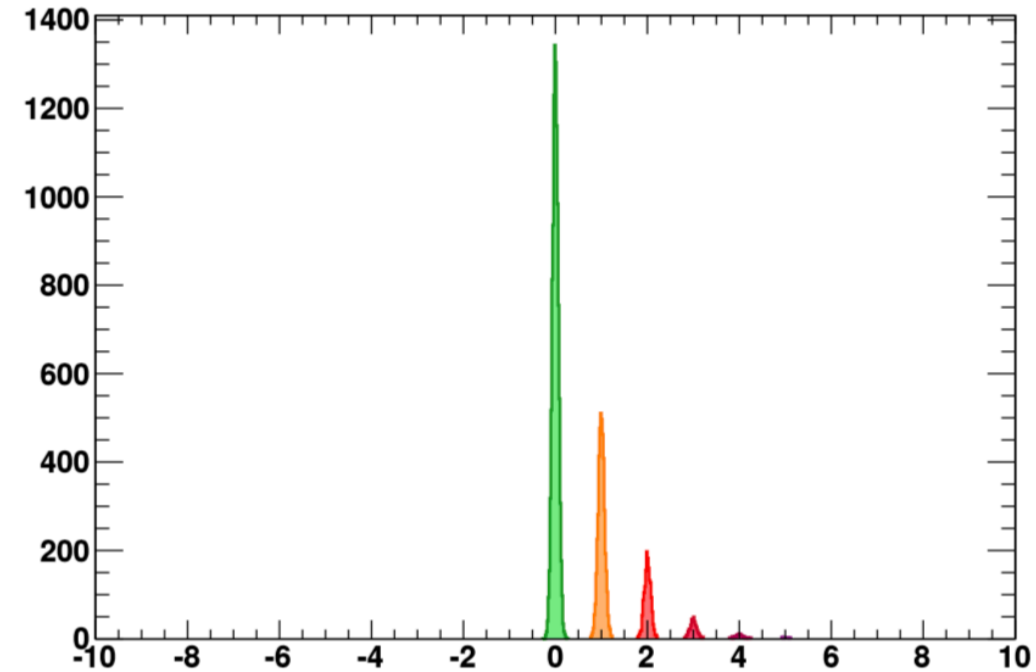
Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, PRL)

Si: traditional CCD



electron-hole pairs

Si: Skipper-CCD



electron-hole pairs

rms noise ~3 e^-
(single measurement)

rms noise ~0.06 e^- !
(4000 repeated measurements)

successfully demonstrated by SENSEI in a Fermilab LDRD project

enables a super-sensitive search for DM

“SENSEI”

“Sub-Electron-Noise Skipper-CCD Experimental Instrument”

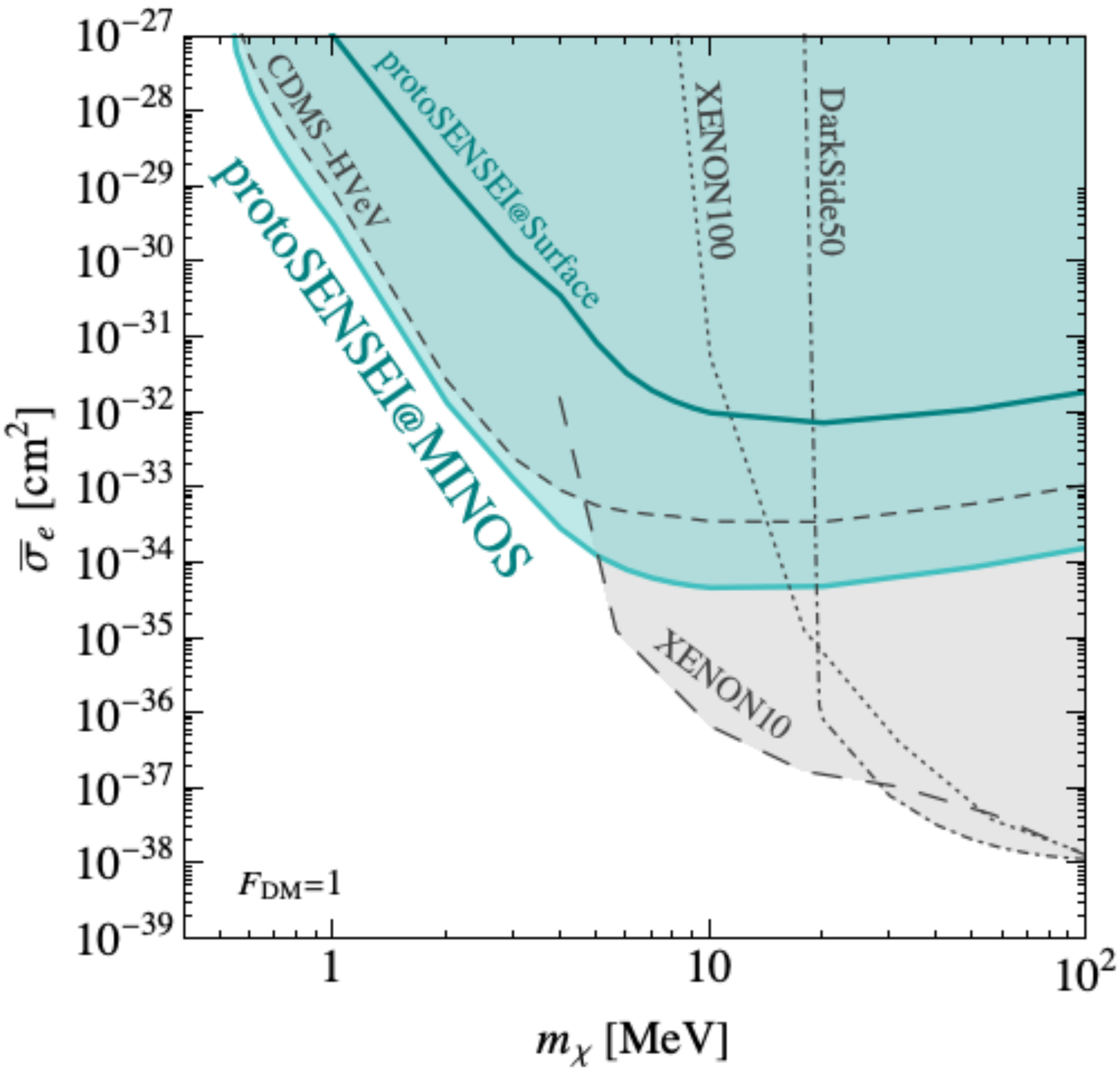
First SENSEI DM results using a prototype Skipper CCD

- One ~0.094 gram prototype Skipper-CCD was packaged and tested for a DM search in 2017 and also took data in 2018

detector is tiny!

SENSEI DM constraints from prototype at FNAL

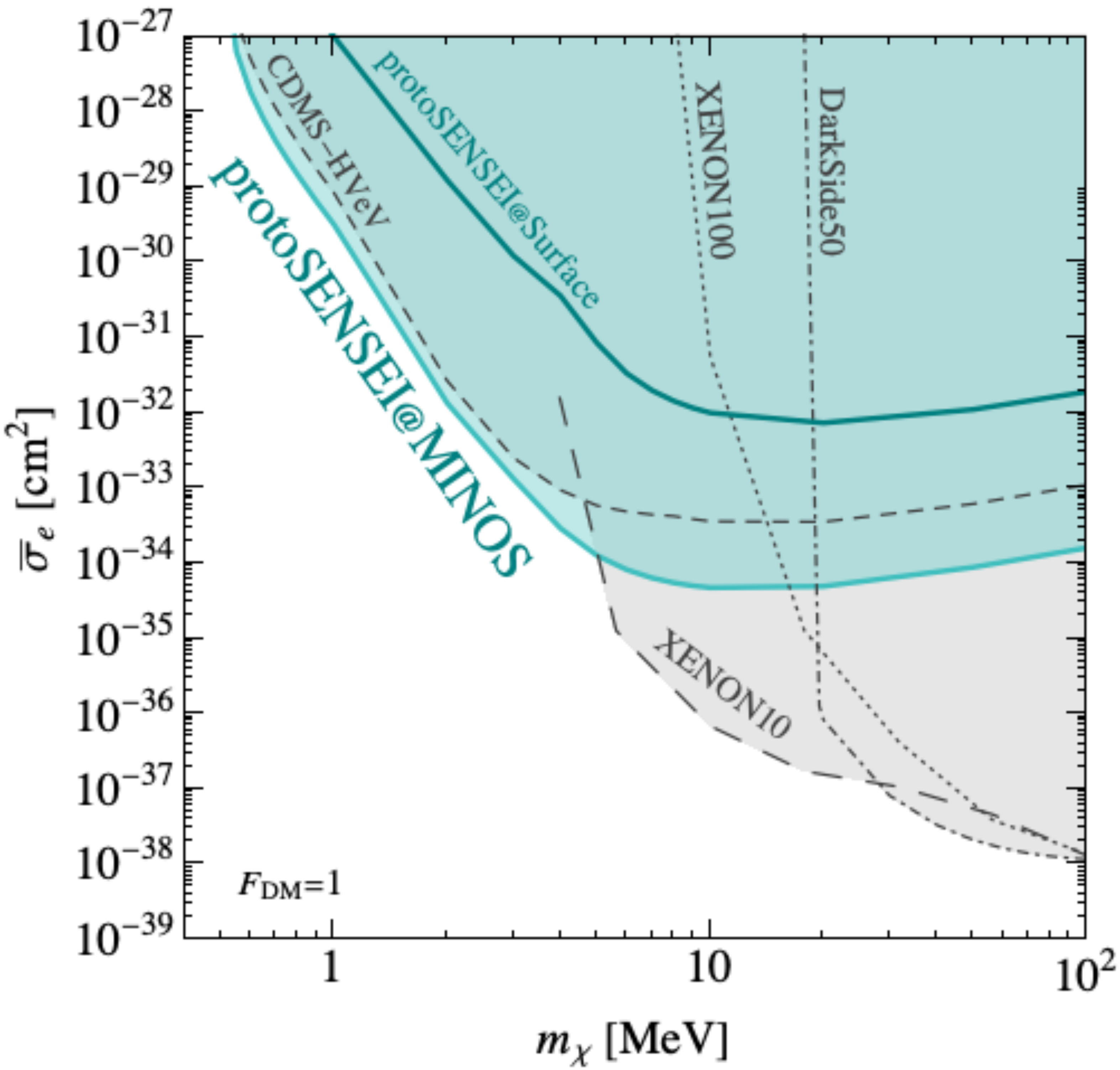
SENSEI Collaboration,
1804.00088 & 1901.10478, PRL



- tiny exposures:
  surface: ~0.02 gram-days
  MINOS: ~0.246 gram-days

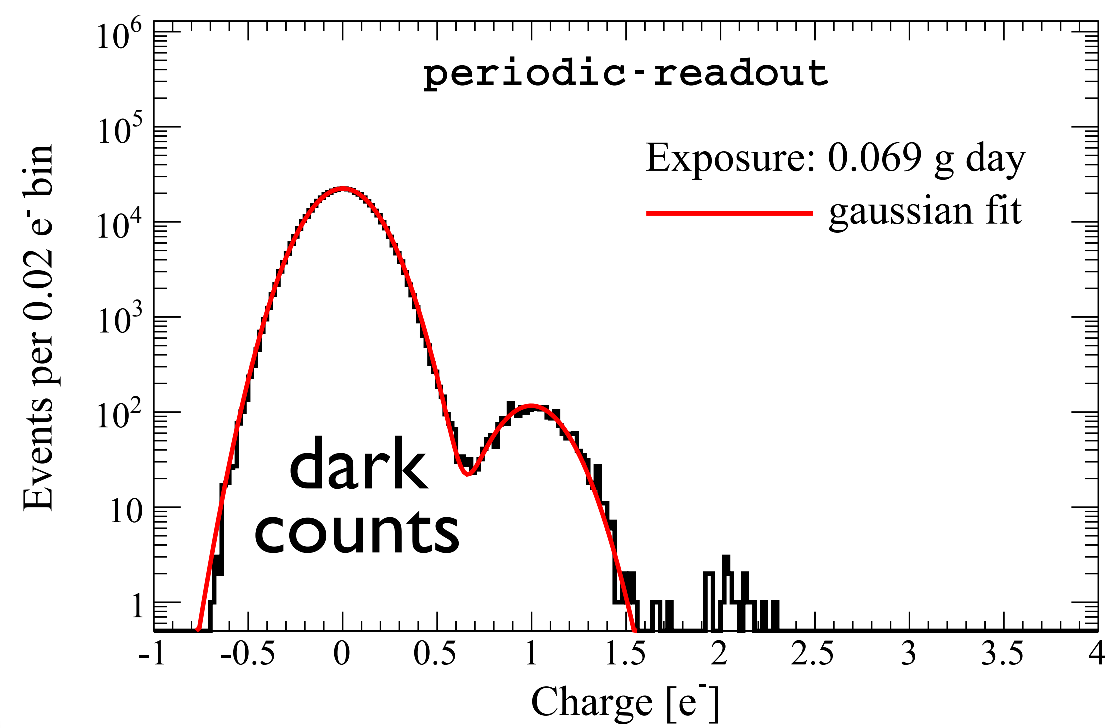
SENSEI DM constraints from prototype at FNAL

SENSEI Collaboration,
1804.00088 & 1901.10478, PRL



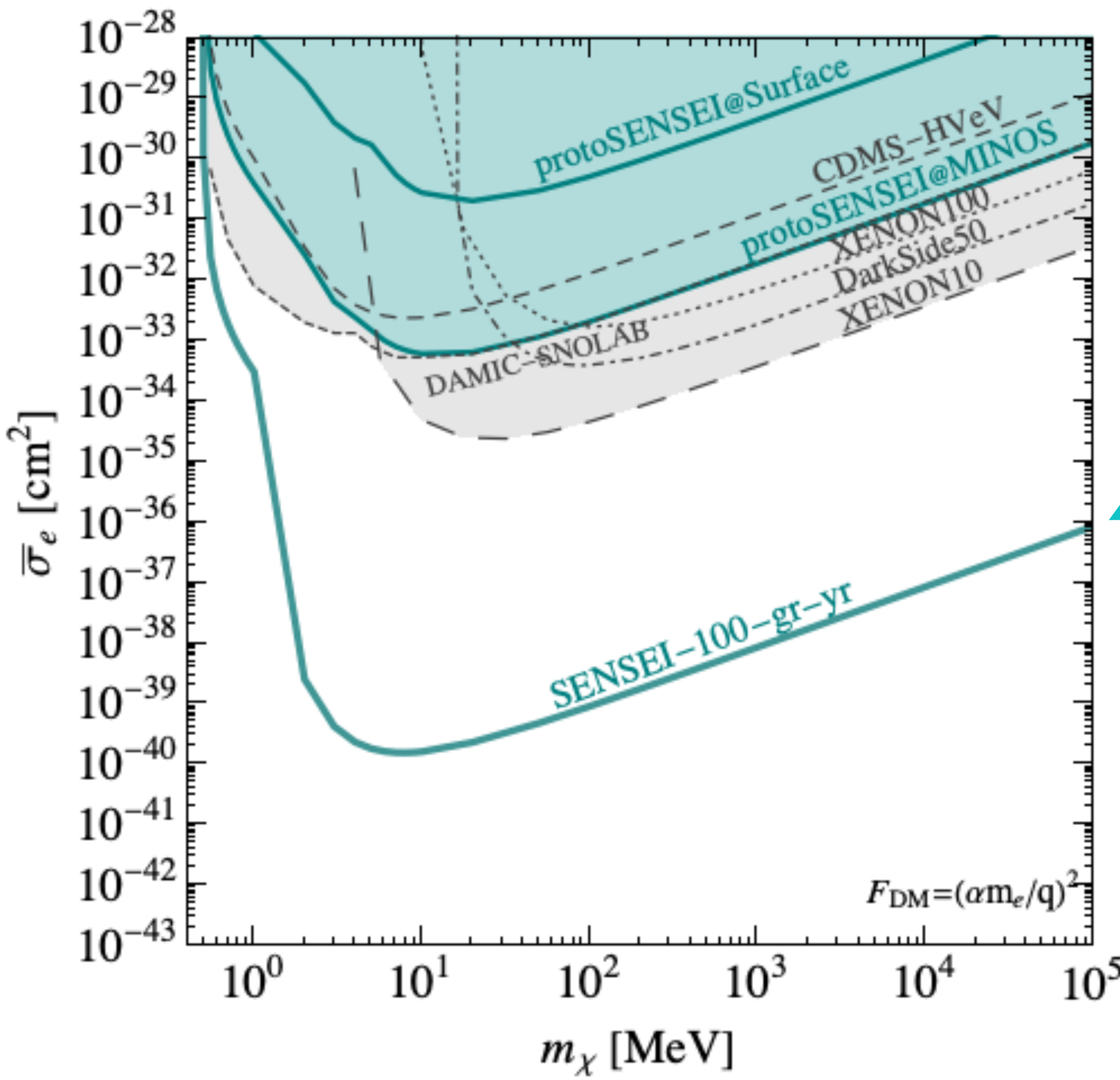
- tiny exposures:
  surface: ~0.02 gram-days
  MINOS: ~0.246 gram-days

currently limited by exposure (not backgrounds) for $n_e>2$



expect even better performance from science-grade sensors

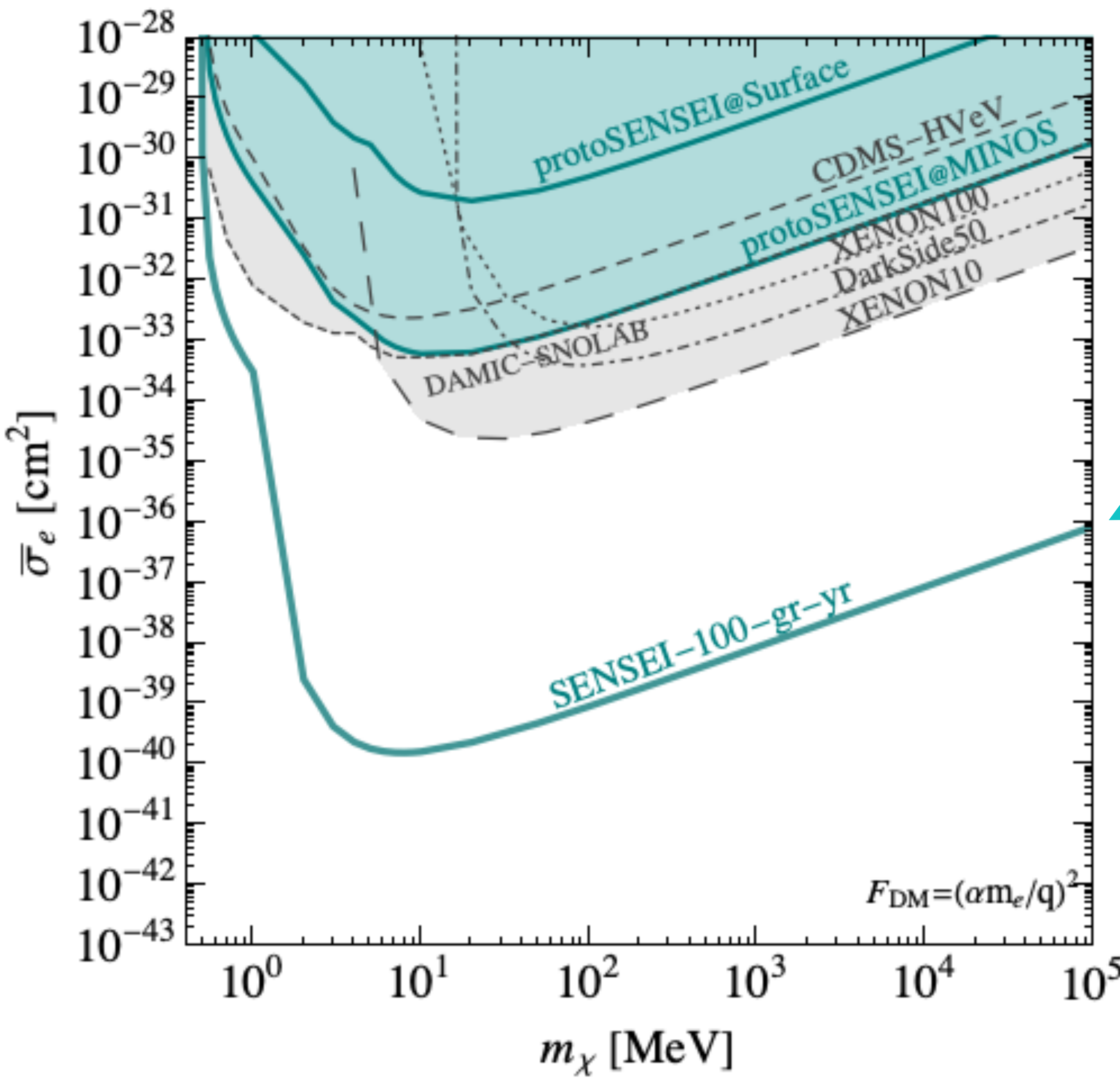
SENSEI projection for 100 g of science-grade Skipper-CCDs



SENSEI: 100 g @ SNOLAB
(funded, 2020)

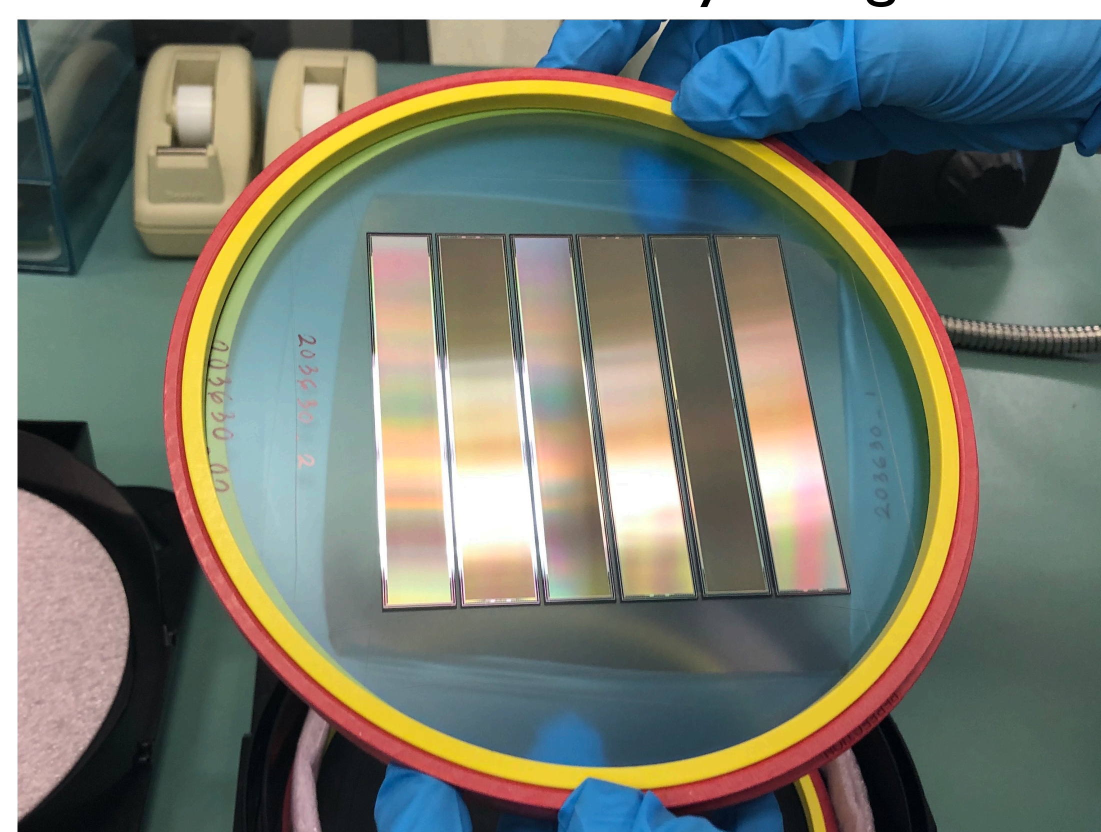
100 gram detector would probe new parameter space after taking only ~1 hour of data!

SENSEI projection for 100 g of science-grade Skipper-CCDs

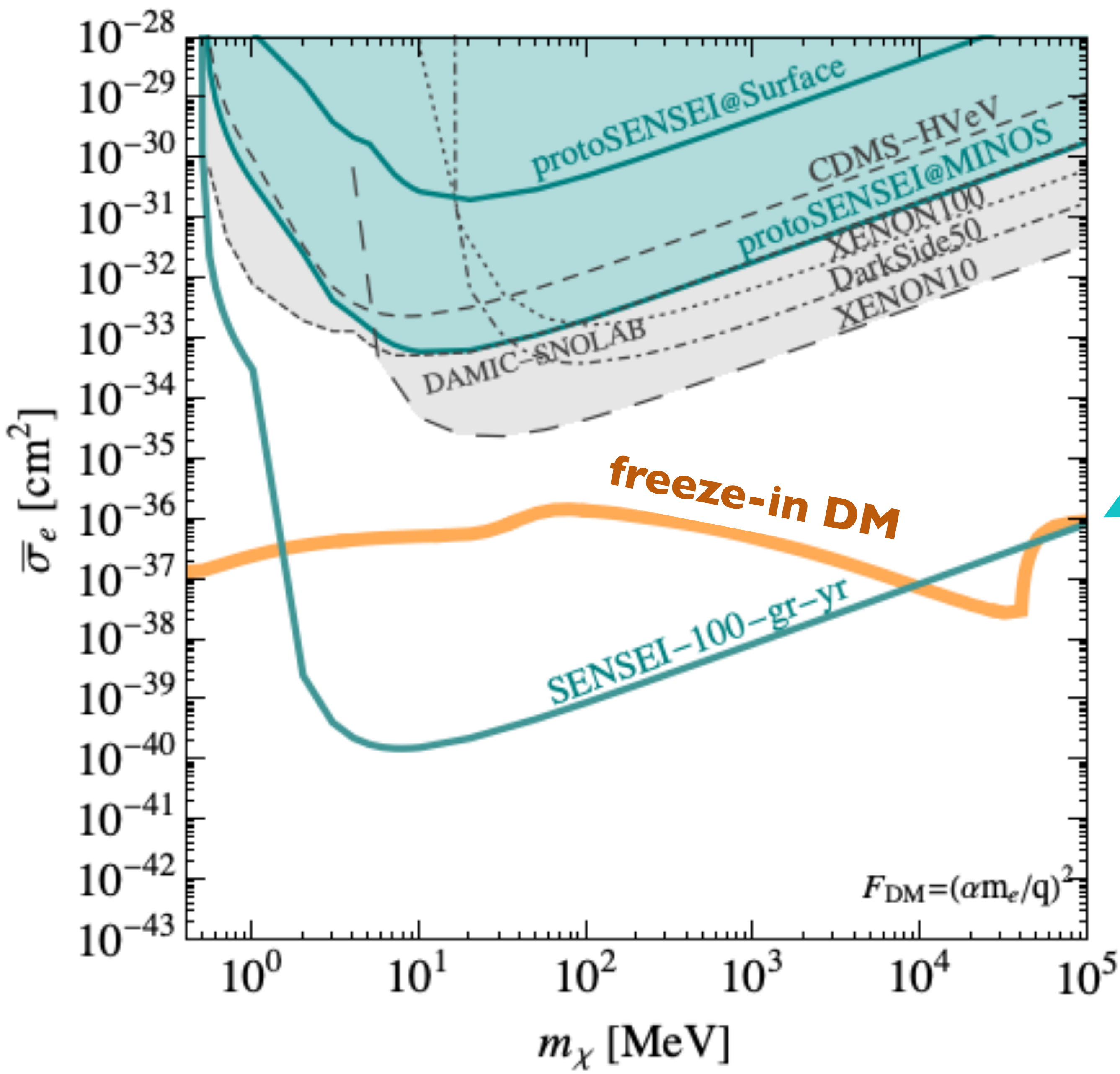


SENSEI: 100 g @ SNOLAB
(funded, 2020)

new sensors are already being tested



SENSEI projection for 100 g of science-grade Skipper-CCDs

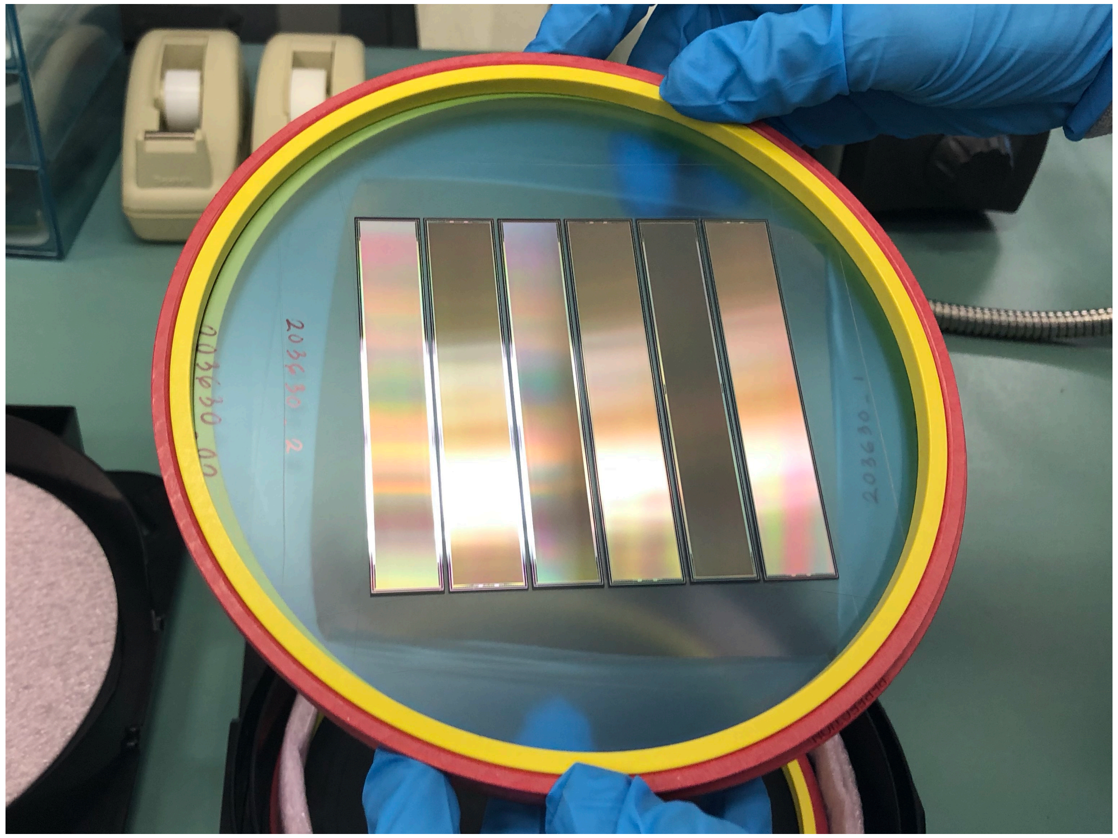


- orange: "freeze-in DM"

RE, Mardon, Volansky 2011
Chu, Hambye, Tytgat, 2011
RE, Fernandez-Serra, Soto, Mardon, Volansky, Yu 2015
Dvorkin, Lin, Schutz 2019

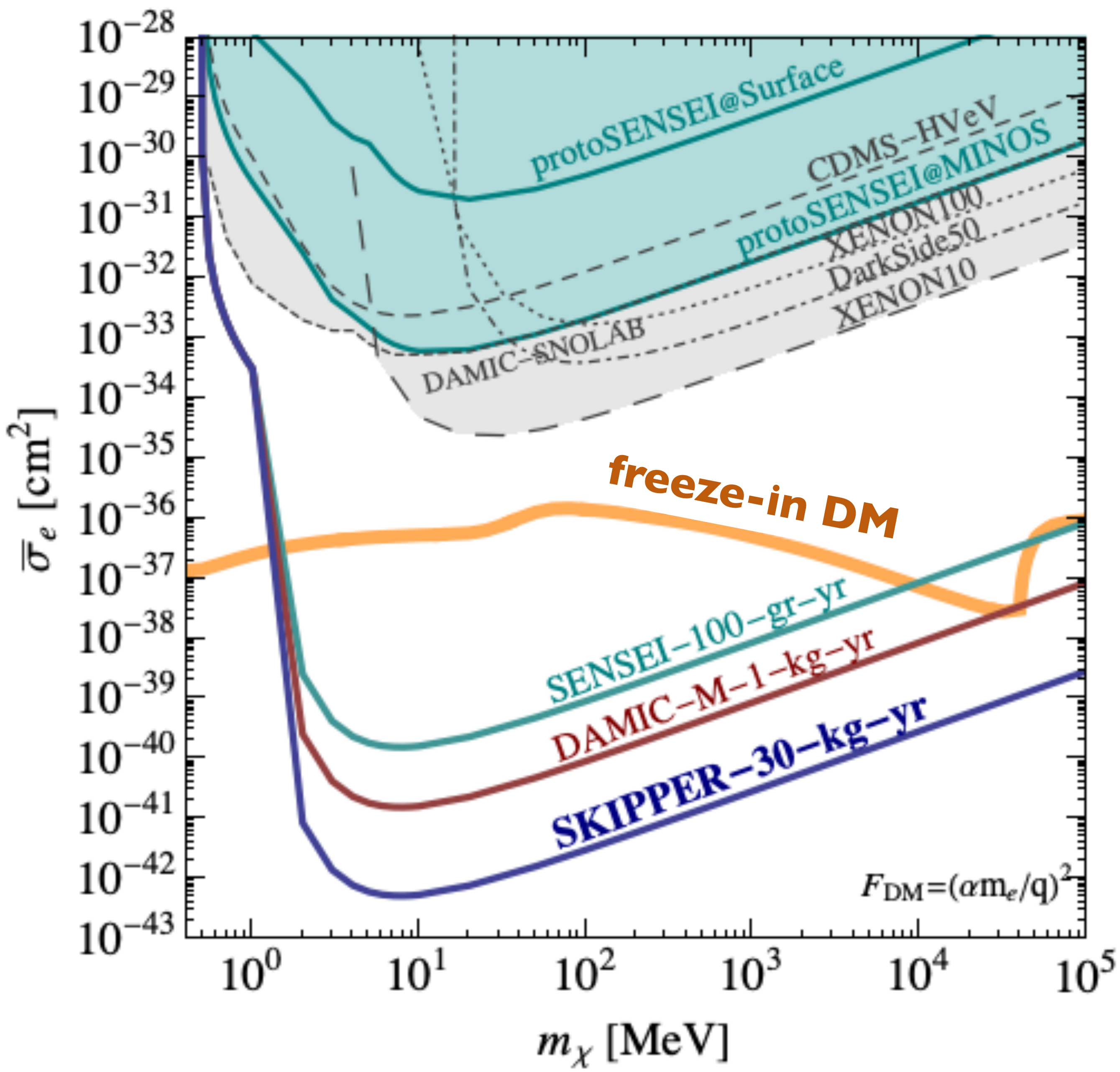
SENSEI: 100 g @ SNOLAB
(funded, 2020)

new sensors are already being tested



[see backup slides for other models like SIMP, ELDER, freeze-out, asymmetric]

SENSEI & other planned Skipper-CCD detectors



SENSEI: 100 g @ SNOLAB
(funded, 2020)

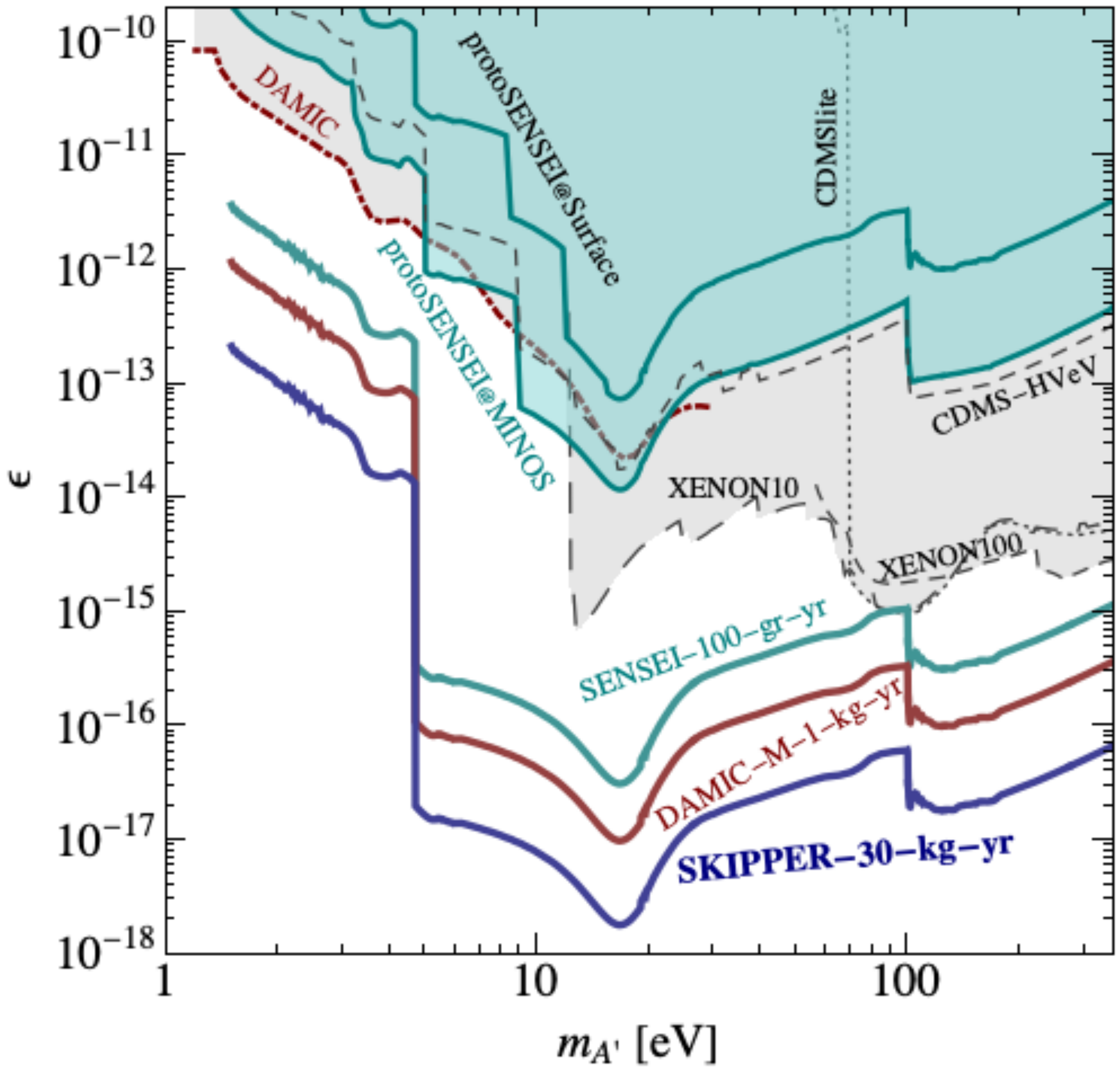
DAMIC-M: 1 kg @ Modane
(funded, 2023)

OSCURA: 10 kg
(R&D recently funded by DoE)

PI/Co-PIs: Estrada, Chavarria, RE, Loer, Privitera
+M. Crisler, M. Fernandez-Serra, R. Saldanha, J. Tiffenberg…

Absorption of dark photon DM

based on calculations by
Bloch, RE, Tobioka, Volansky, Yu



SENSEI: 100 g @ SNOLAB

DAMIC-M: 1 kg gram @ Modane

OSCURA: 10 kg

Backgrounds?

Background	SENSEI (0.1 kg-yr)
Solar neutrinos	Irrelevant
Radiogenic Backgrounds	< 1 event with some effort
Dark Current	Main uncertainty

RE, Sholapurkar, Yu

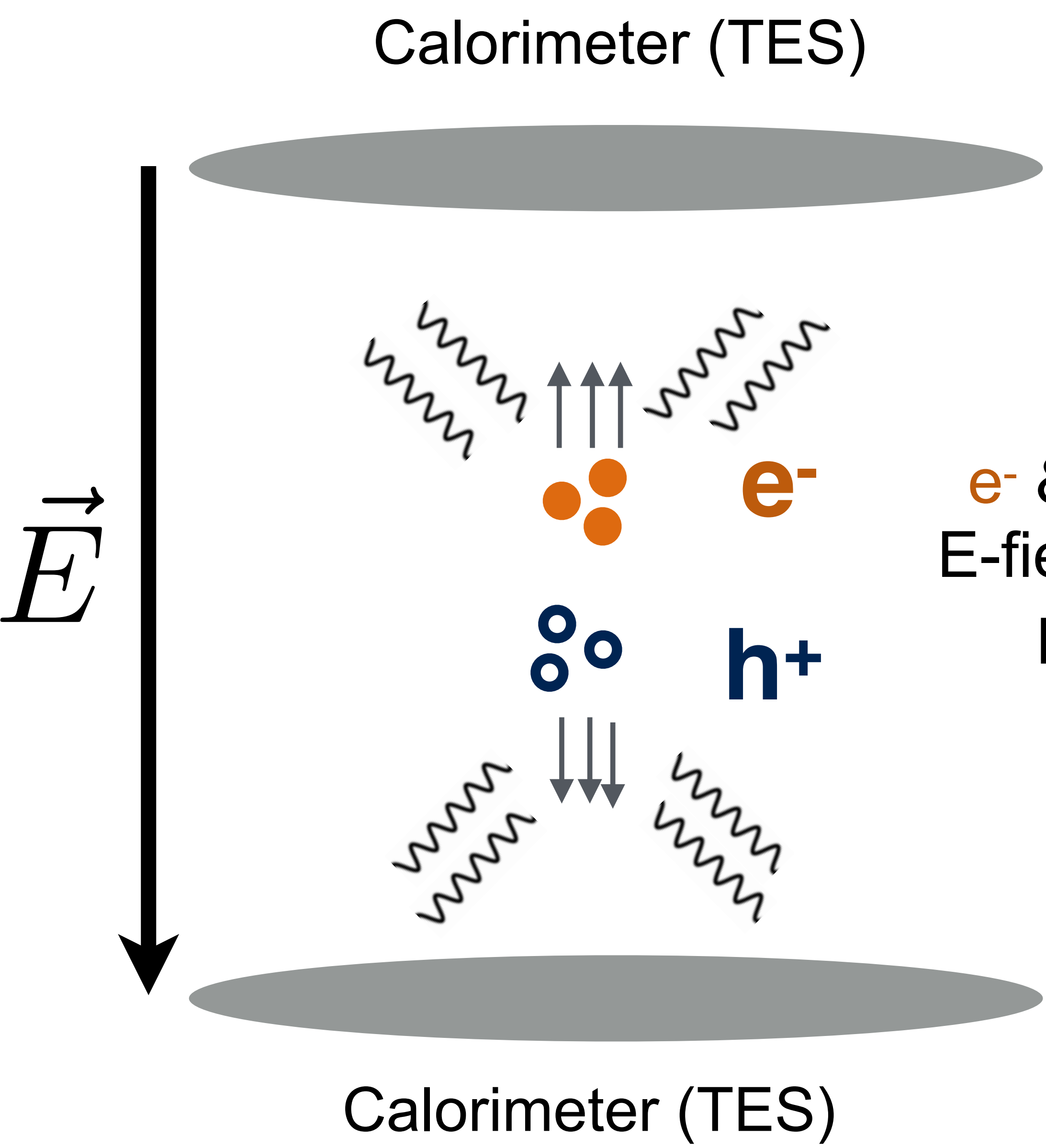
Size of dark current (from e.g. thermal fluctuations) is main uncertainty; will limit discovery threshold to at least $2e^-$

Backgrounds?

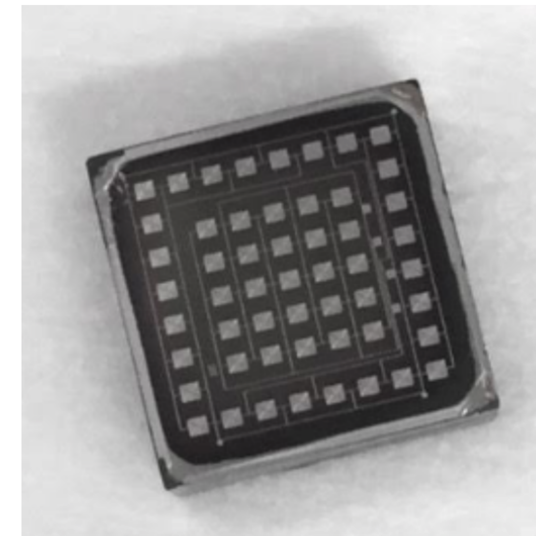
Background	SENSEI (0.1 kg-yr)	DAMIC-M (1 kg-yr)	OSCURA (30 kg-yr)
Solar neutrinos	Irrelevant	Irrelevant	O(few events)
Radiogenic Backgrounds	< 1 event with some effort	< 1 event with a lot of effort	< 1 event with significant effort
Dark Current	Main uncertainty	Main uncertainty	Main uncertainty

Size of dark current (from e.g. thermal fluctuations) is main uncertainty; will limit discovery threshold to at least $2e^-$

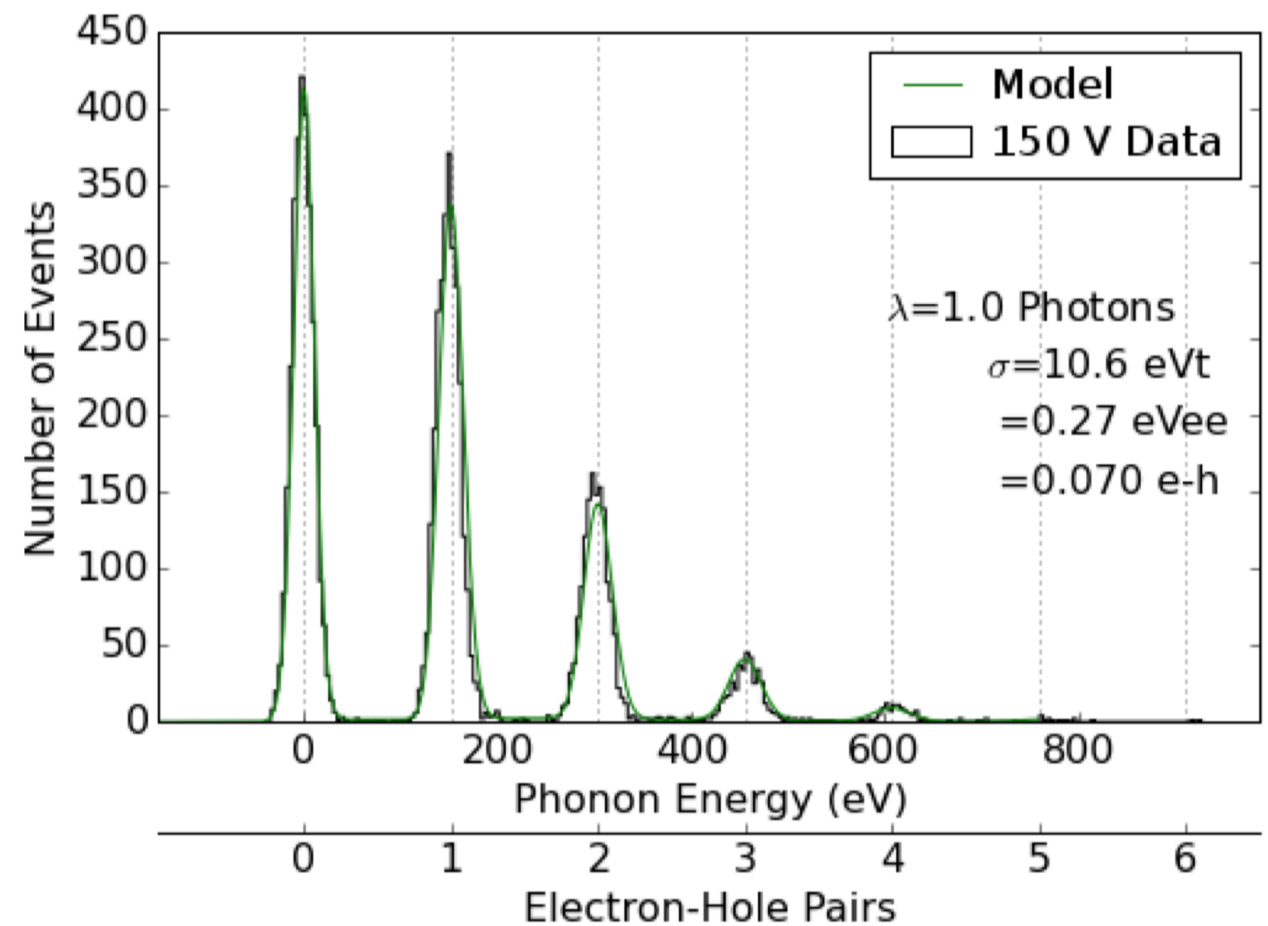
SuperCDMS “High Voltage” charge amplification w/ TES readout



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



10x10x4 mm

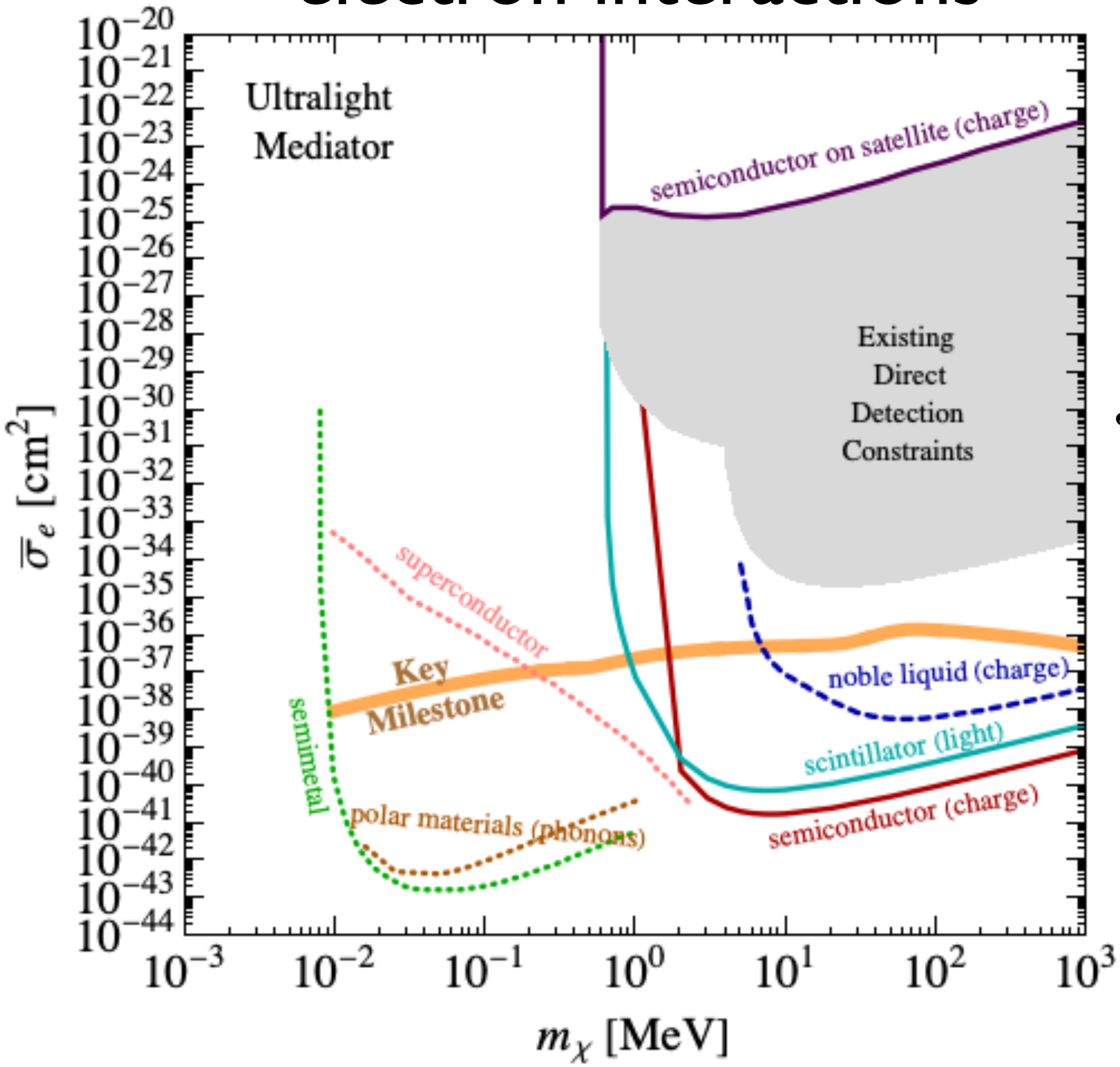


Romani et.al. 2017, SuperCDMS 2018

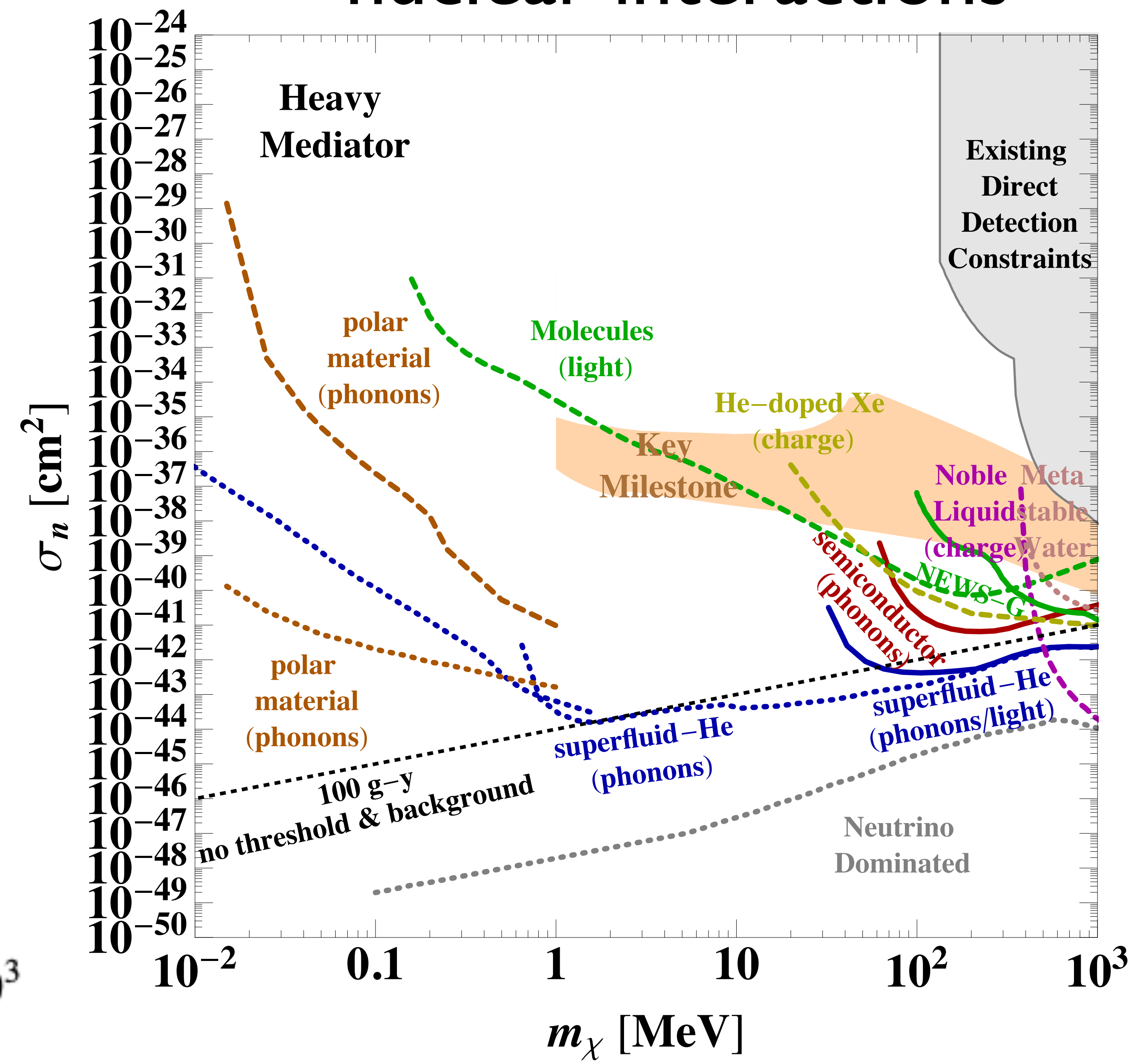
Recent explosion of new direct-detection ideas

from US DoE Basic Research Needs report

electron interactions



nuclear interactions



SENSEI is making great progress, but other experiments (SuperCDMS!) and R&D efforts are progressing very fast!

The LBECA Collaboration

"Low Background Electron Counting Apparatus"

LBNL:

- P. Sorensen

LLNL:

- A. Bernstein, S. Pereverzev, J. Xu

Purdue

- F. M. Clark, A. Kopec, R. Lang

Stony Brook:

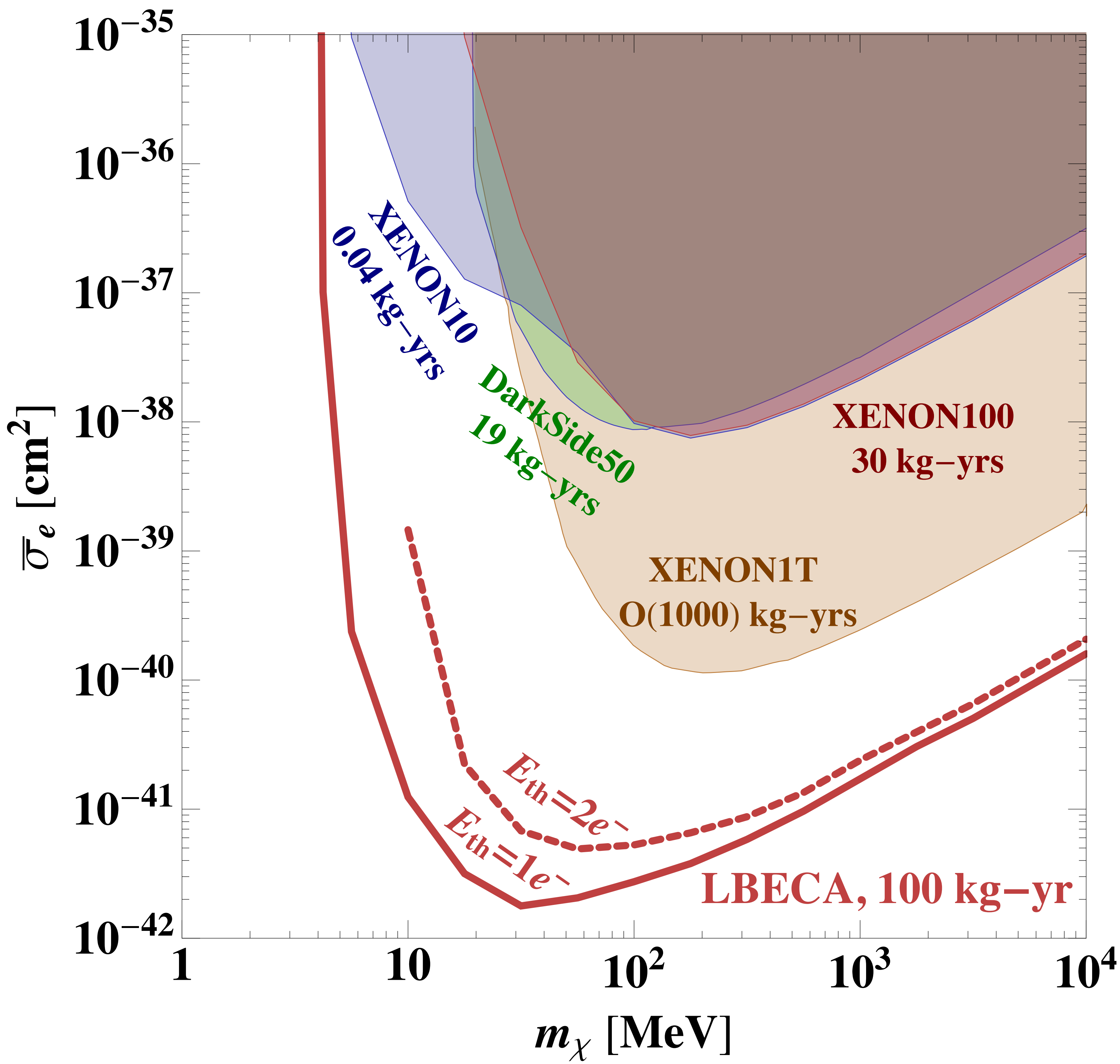
- R. Essig, M. Fernandez-Serra, C. Zhen

UC San Diego:

- K. Ni, J. Long, J. Ye

R&D partially funded by US DoE

LBECA Goal



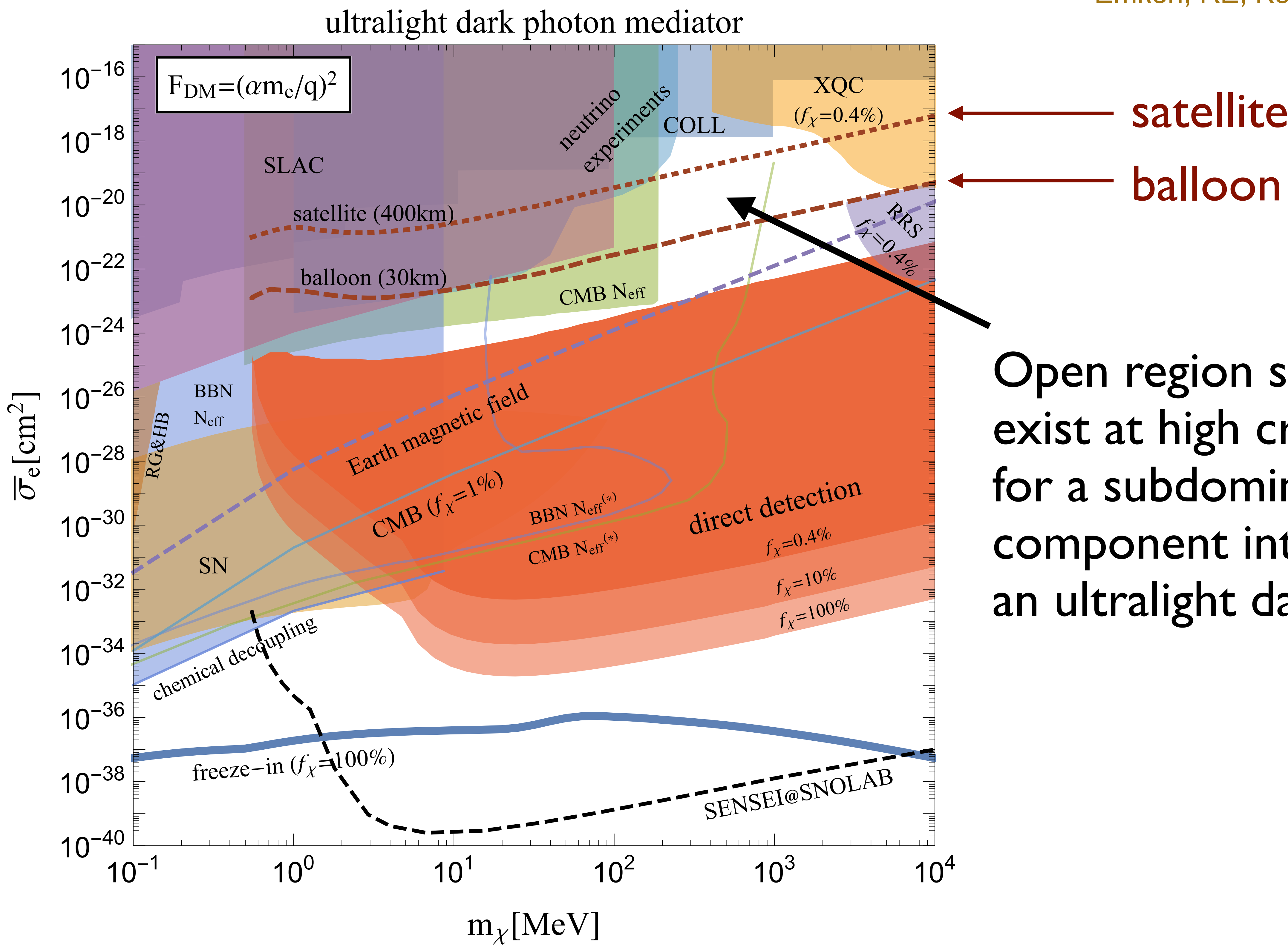
100 kg liquid xenon detector w/ reduced backgrounds

(previous noble-liquid detectors have been background limited)

R&D ongoing

A Skipper-CCD on a satellite/balloon can probe strongly interacting DM

Emken, RE, Kouvaris, Sholarpurkar



Open region seems to exist at high cross sections for a subdominant DM component interacting w/ an ultralight dark photon

Summary

- Goal: uncover the identity of dark matter!
- A much wider class of DM models, spanning a vast mass range, are now actively being considered compared to ~10 years ago
- Direct detection of sub-GeV DM is now possible, with several ideas and proposals
- SENSEI has first results and will probe vast new regions of uncharted territory in next ~1–2 years

Thank you!