Direct Detection of sub-GeV Dark Matter

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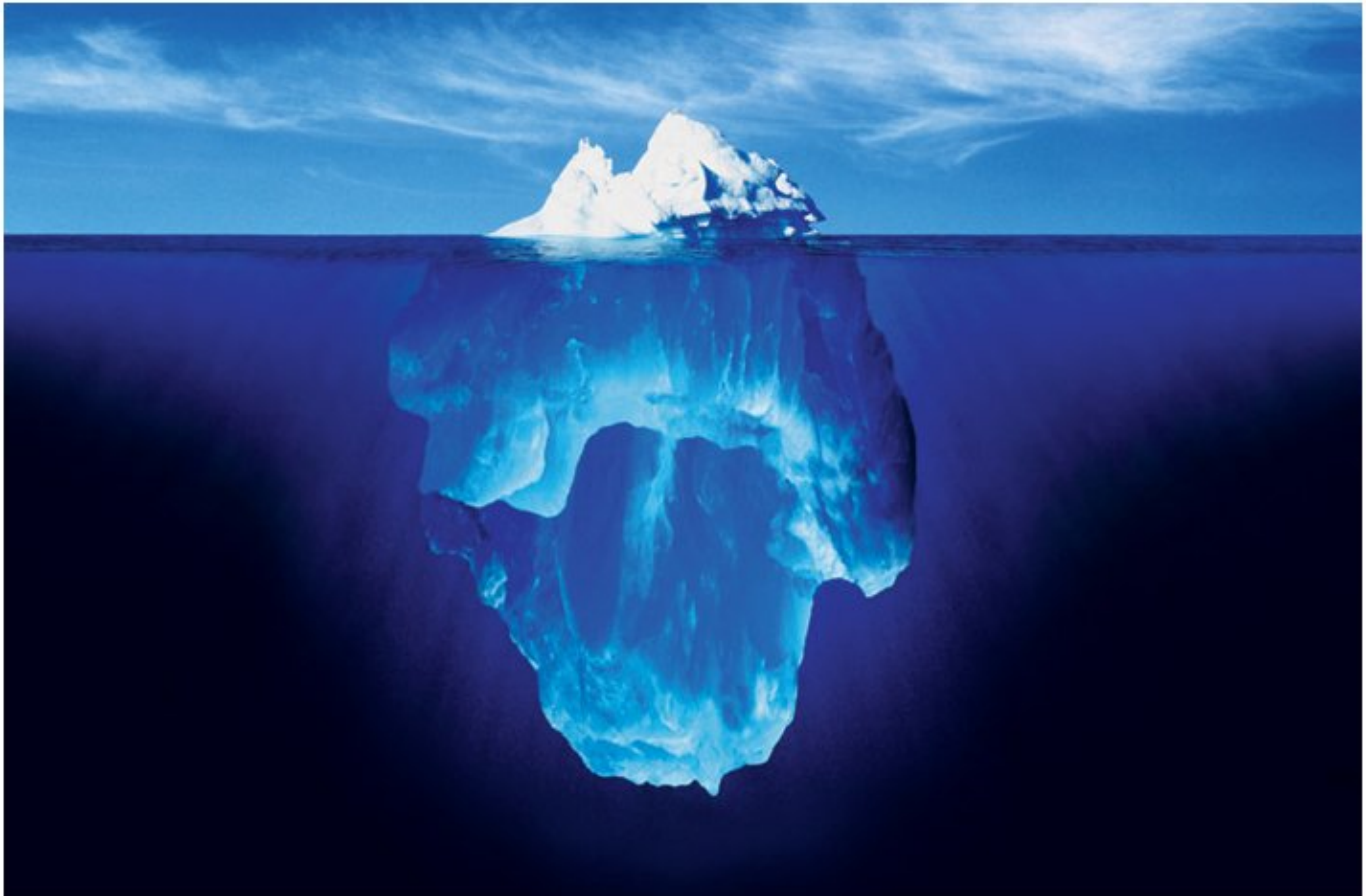
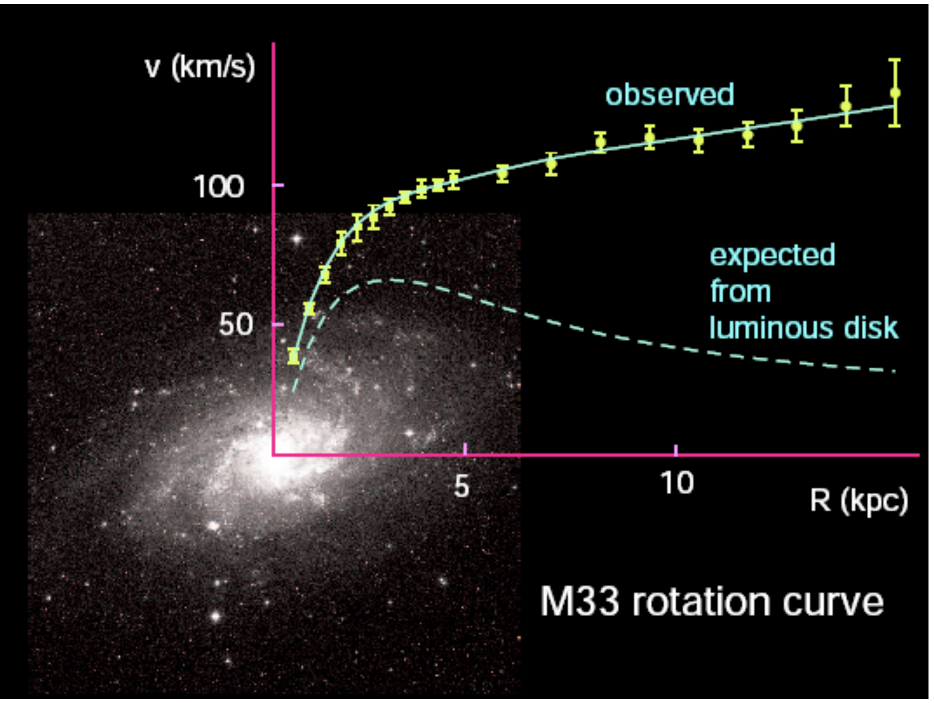
Stony Brook University

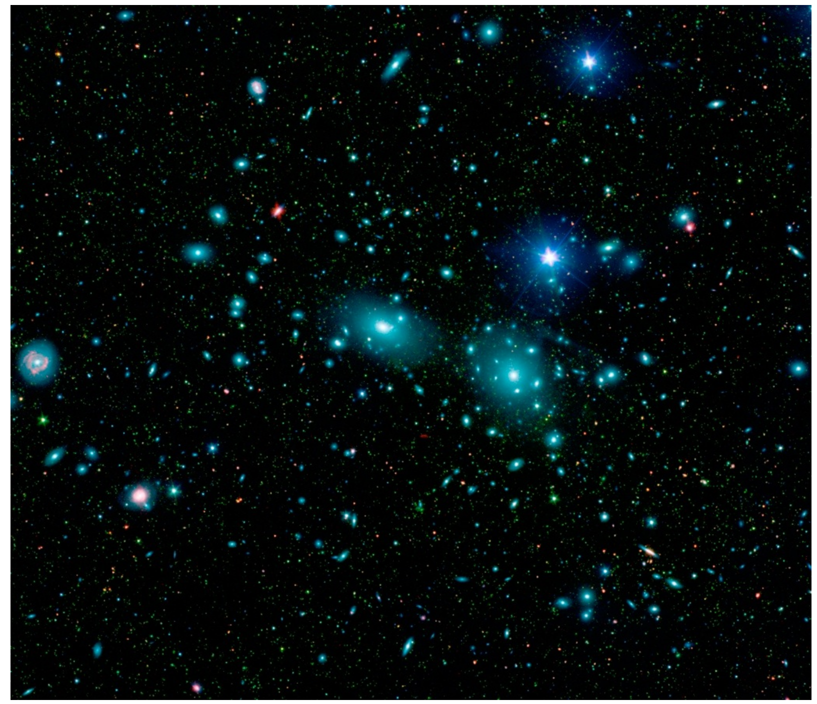
Colloquium, Institut de Fisica d'Altes Energies (IFAE), Dec 1, 2025

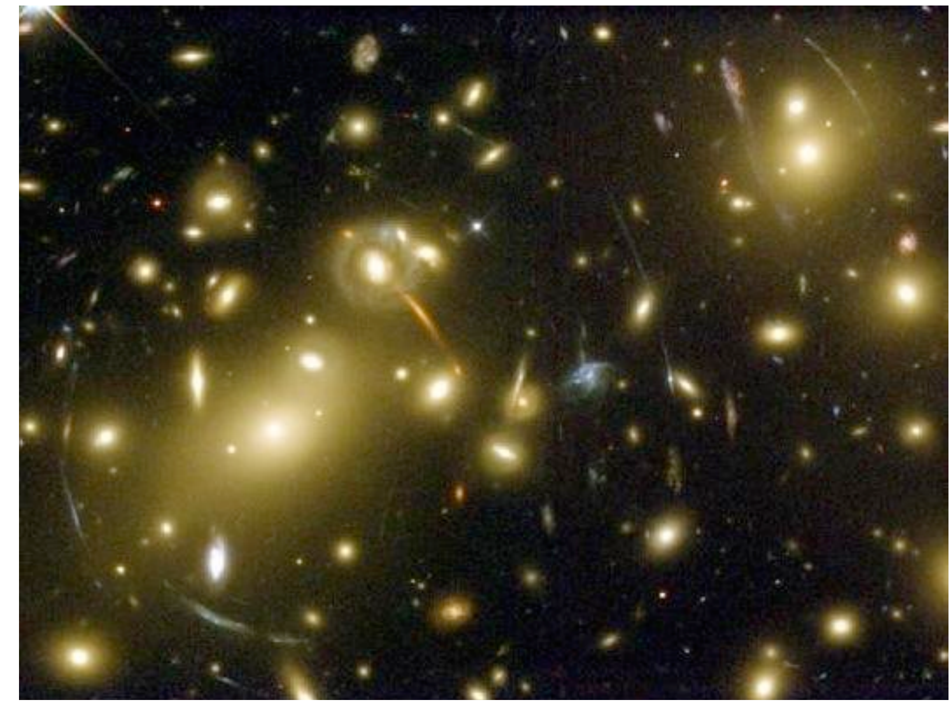
We don't know the fundamental building blocks of ~85% of the matter in the Universe

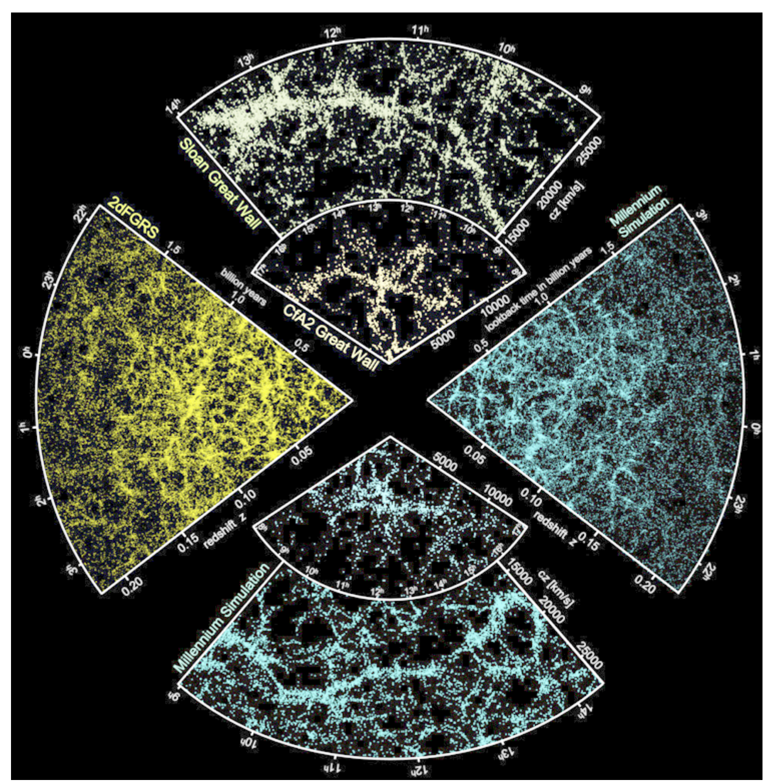


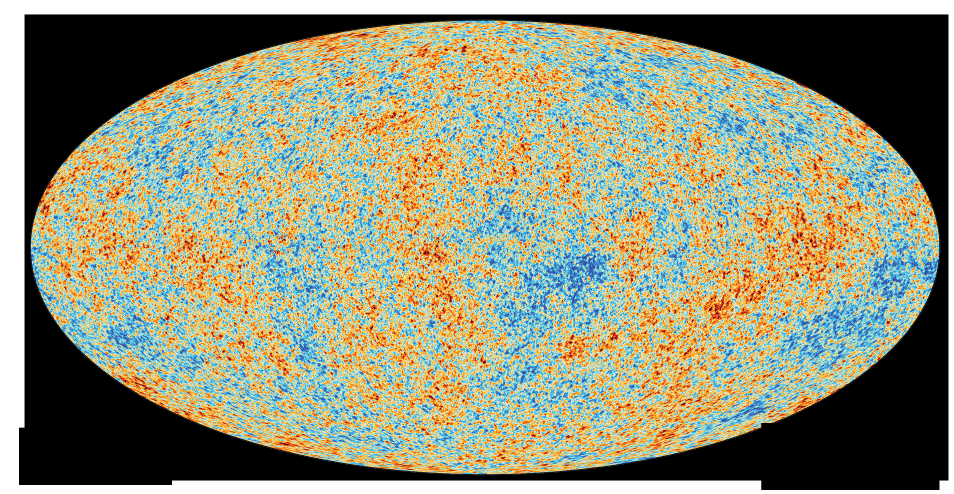
Extensive evidence for dark matter, e.g.











What is Dark Matter?

all evidence from gravitational interaction…

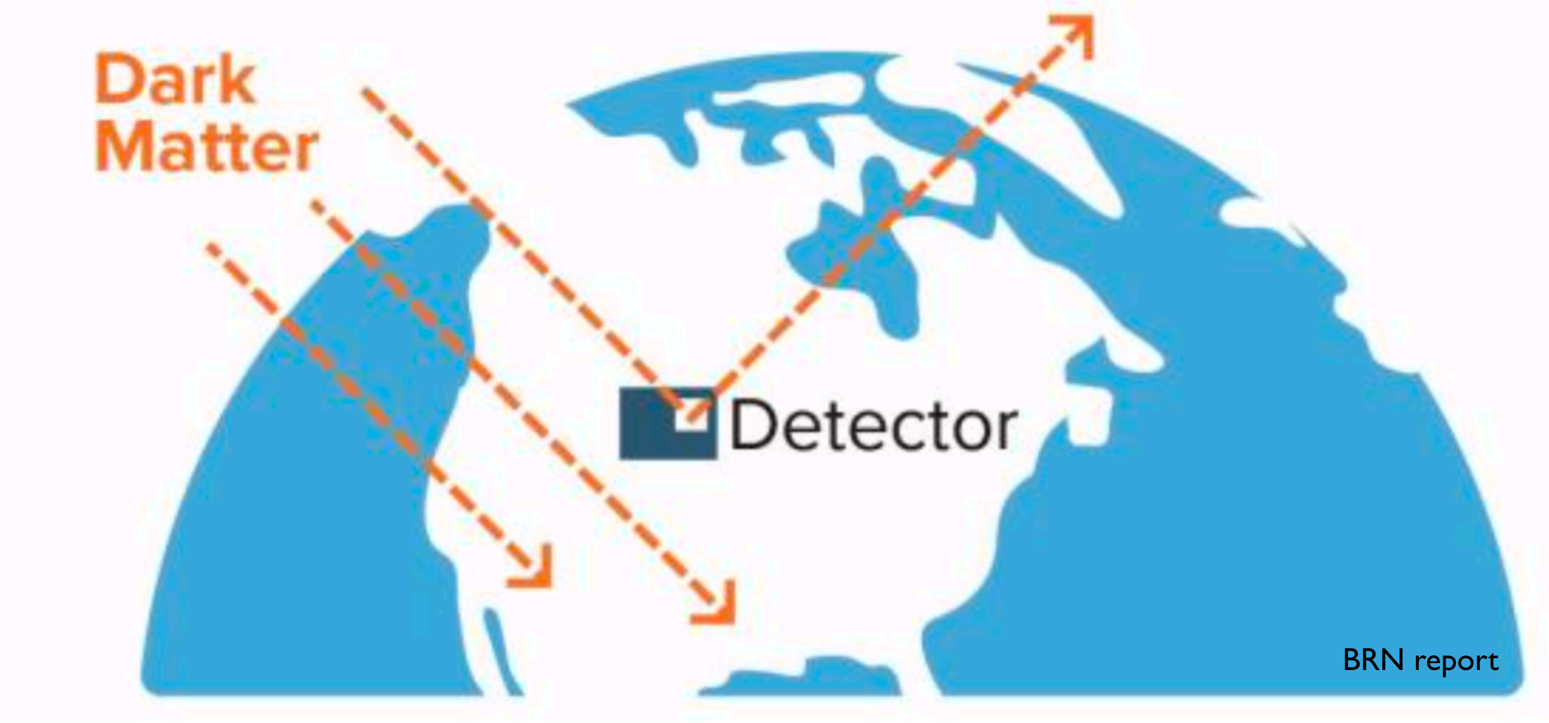
Uncovering its identity is one of the most important goals in particle physics today

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

“Direct Detection of Dark Matter”

A major component in our quest to identify DM

Goal: identify dark matter particles in our Milky-Way halo as they traverse Earth and interact in our detectors



requires an additional, <u>non-gravitational</u> interaction between dark matter and ordinary matter

Two important questions that guide experimental searches

How, and how strongly, does dark matter interact with ordinary matter?

E.g., does dark matter interact with:

- electrons?
- nuclei?
- photons?

What is the mass of dark matter?

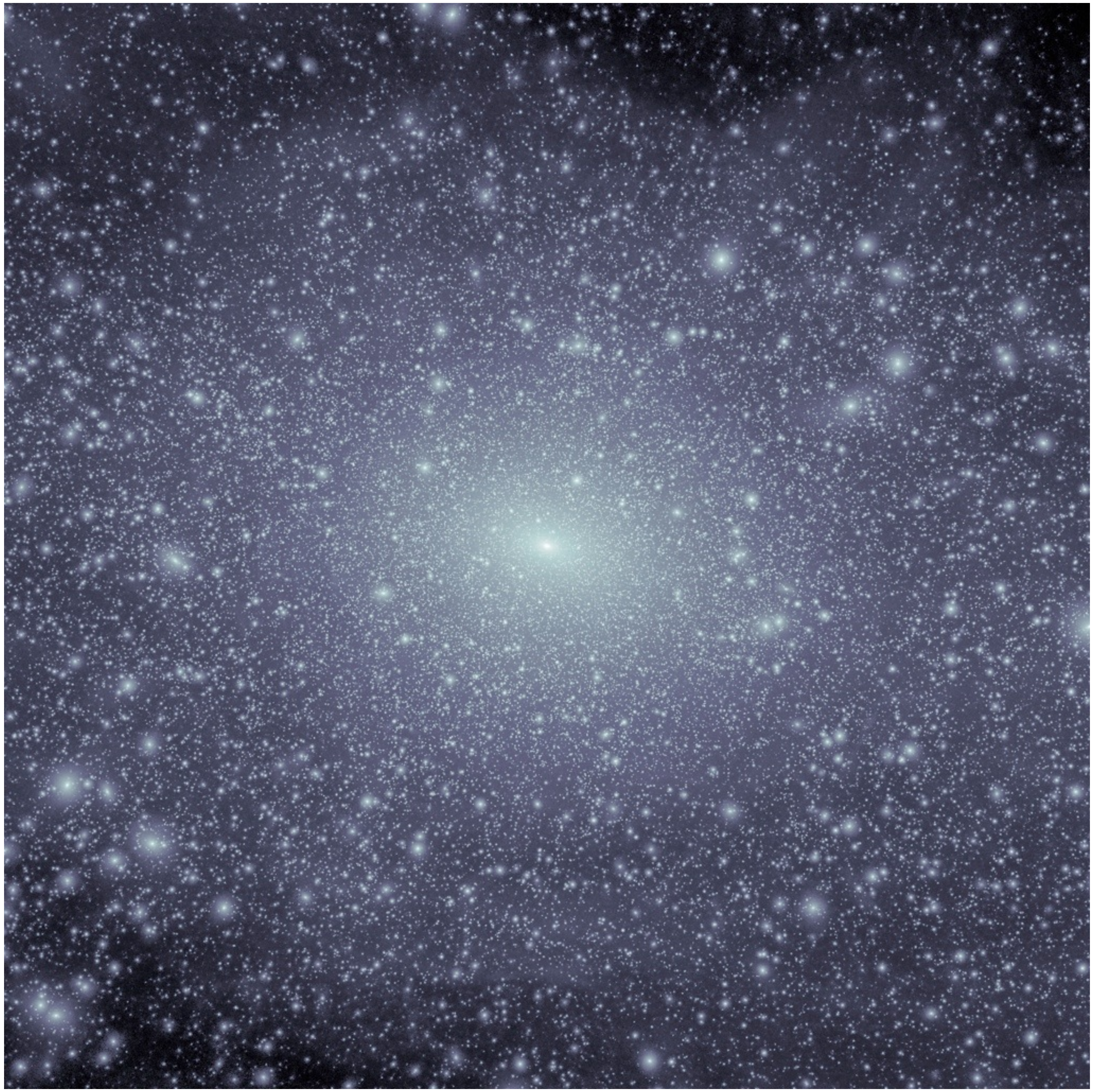
will discuss this more in next few slides

We do not know the answers, so a wide range of experiments are required

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

Via Lactea II simulation, Diemand et.al.

Dark Matter



MILKYWAY GALAXY

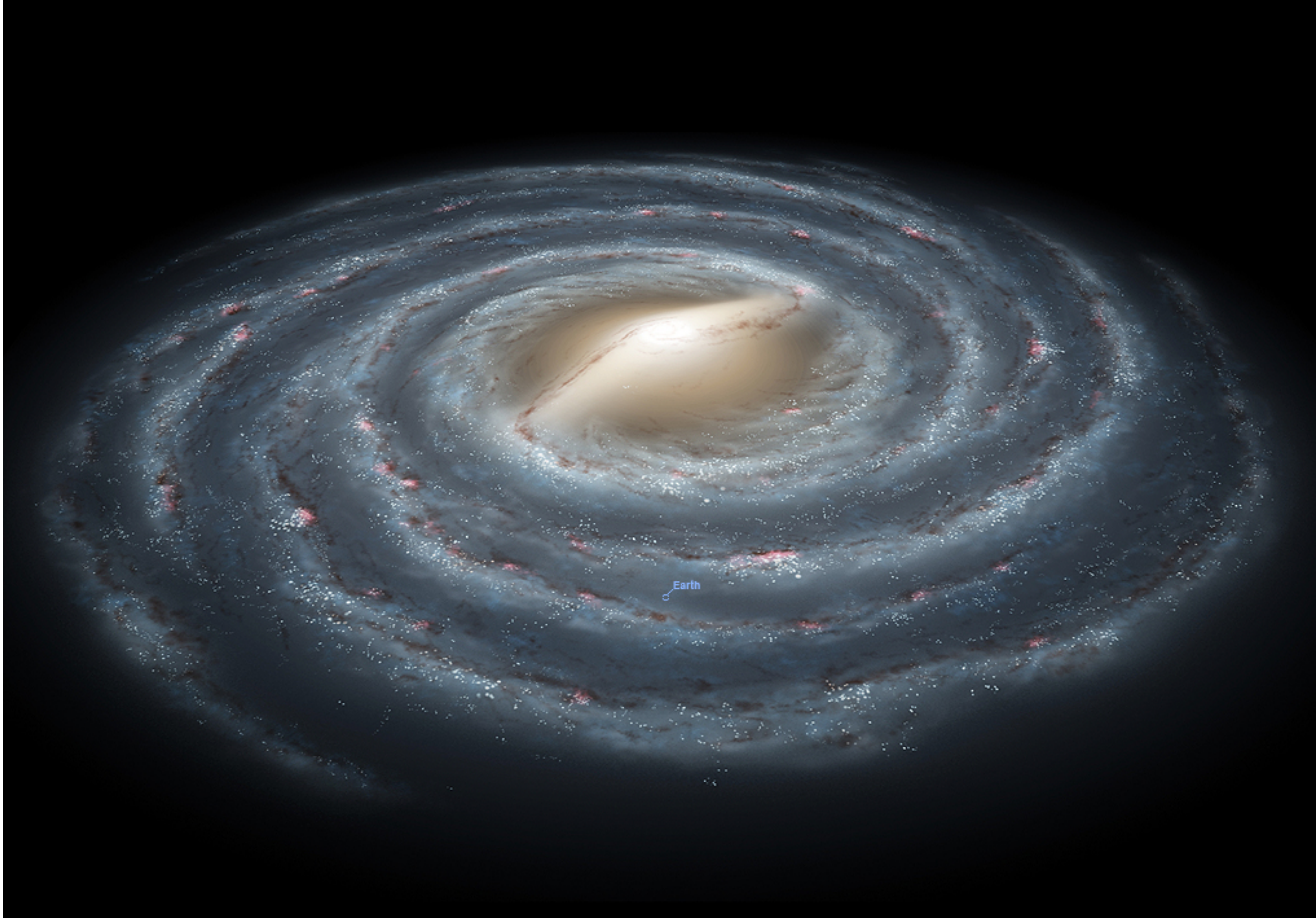


Image: R. Hurt, NASA

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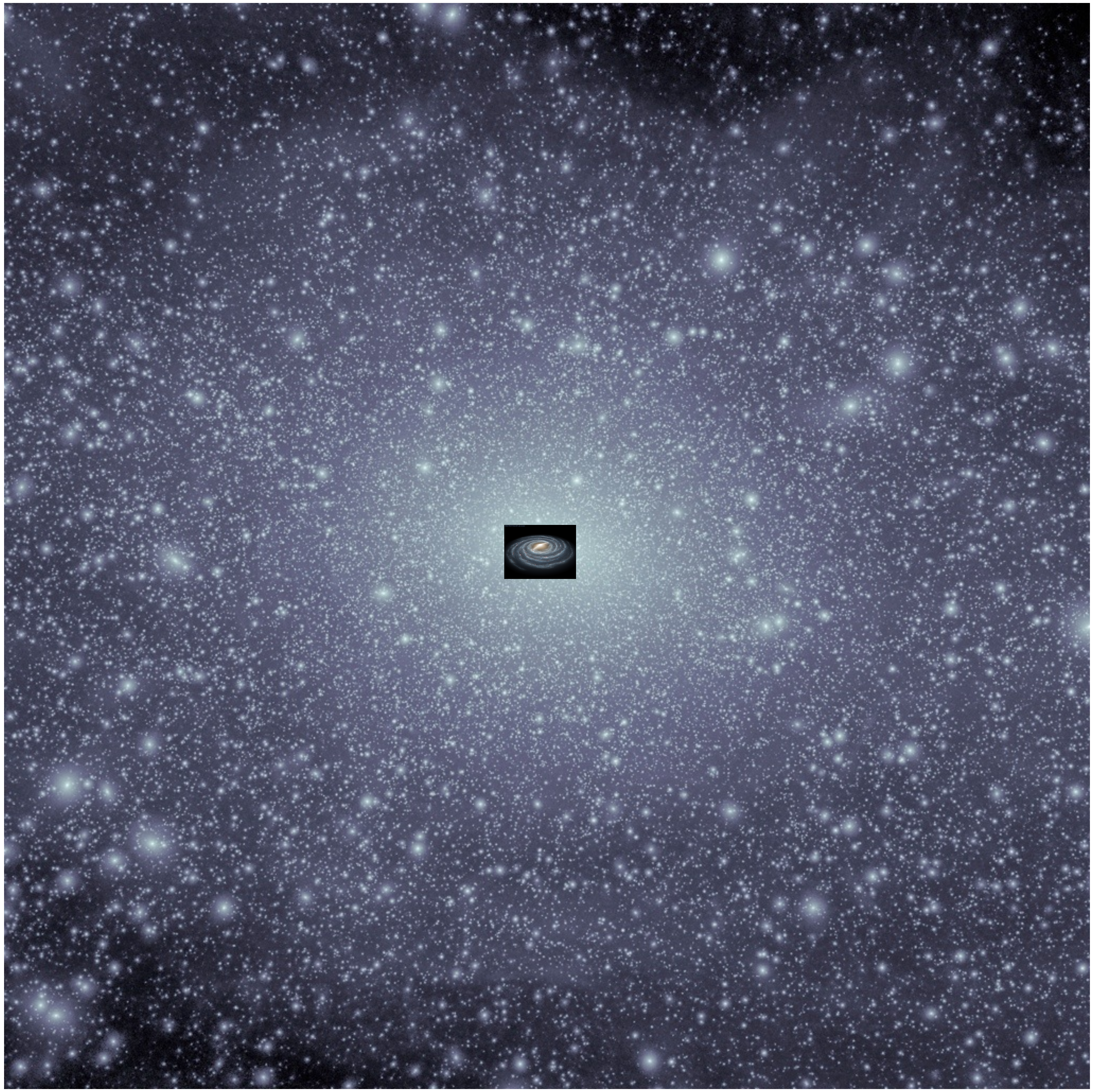

visible Milky Way galaxy is tiny compared to dark matter "halo"

How much dark matter is around us?

each liter contains a mass equivalent to ~400 protons

$\sim 2 \times 10^{-23}$ ounces

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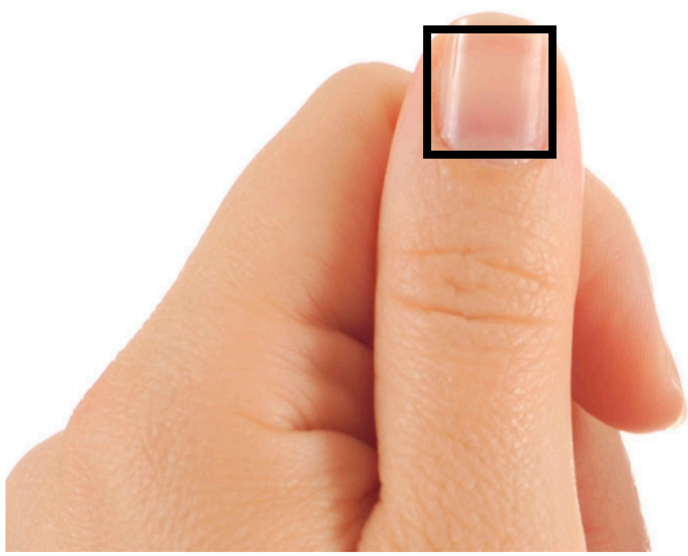
$$\text{Flux} \sim 7 \text{ million } \frac{\text{particles}}{\text{cm}^2 \text{ sec}}$$



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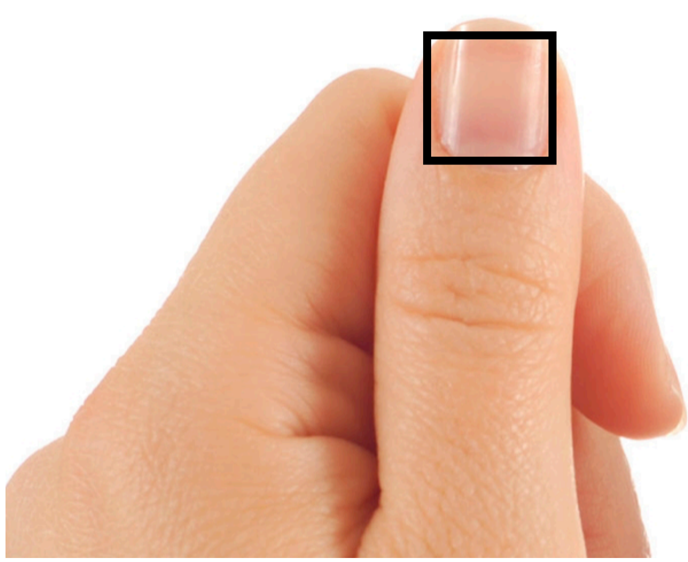
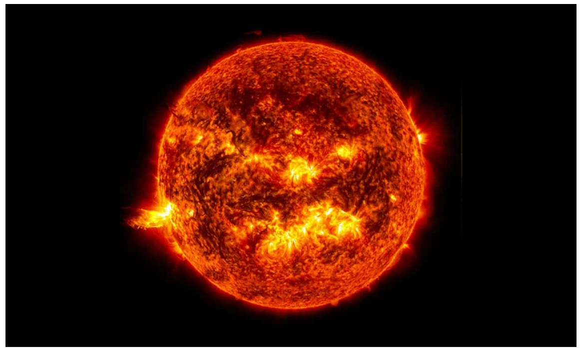


c.f. solar neutrinos: $\text{flux} \sim \frac{66 \text{ billion}}{\text{cm}^2 \text{ sec}}$



NASA/SDO

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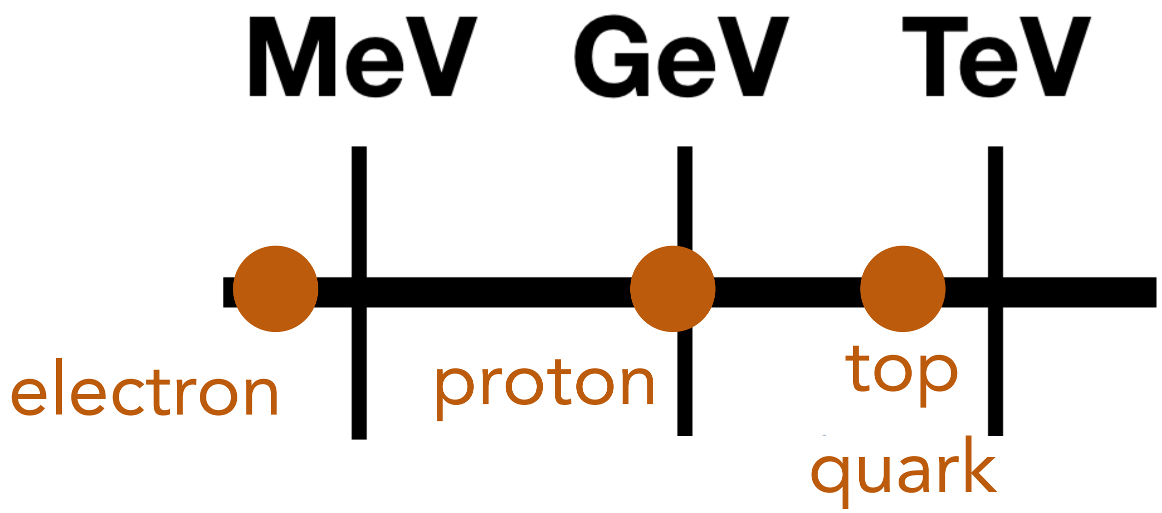
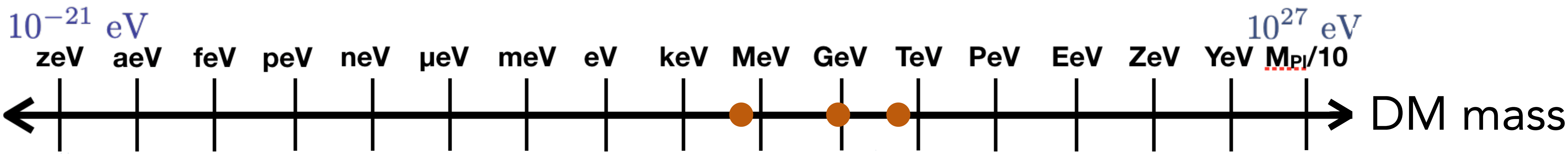
BUT: we do not know the DM mass!

Masses of some known particles

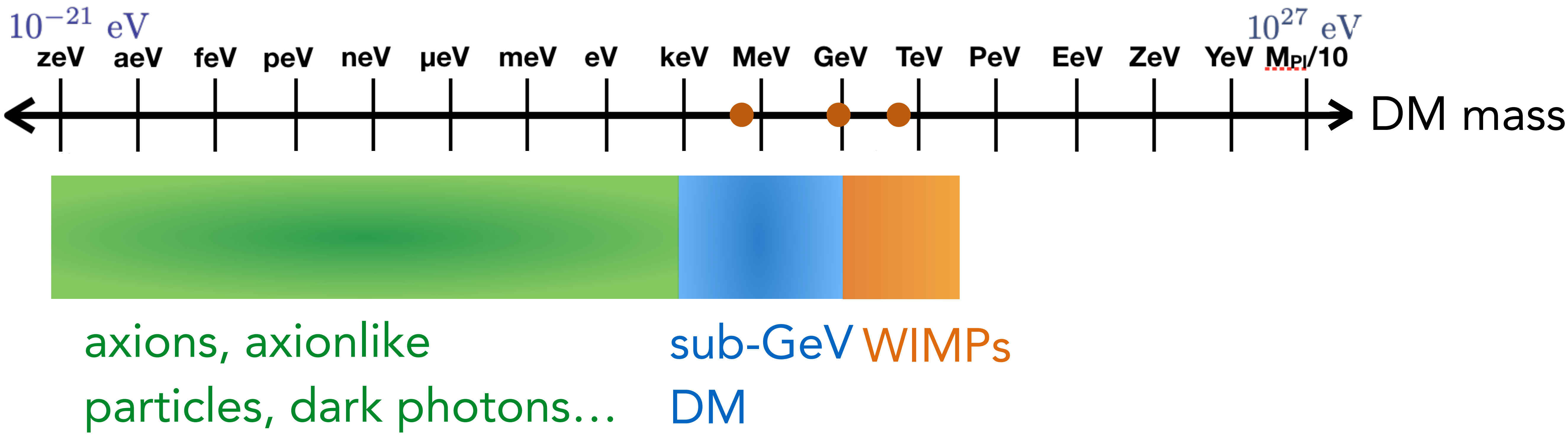


The Dark Matter Landscape



The range of possible DM masses is very large!

Some DM candidates



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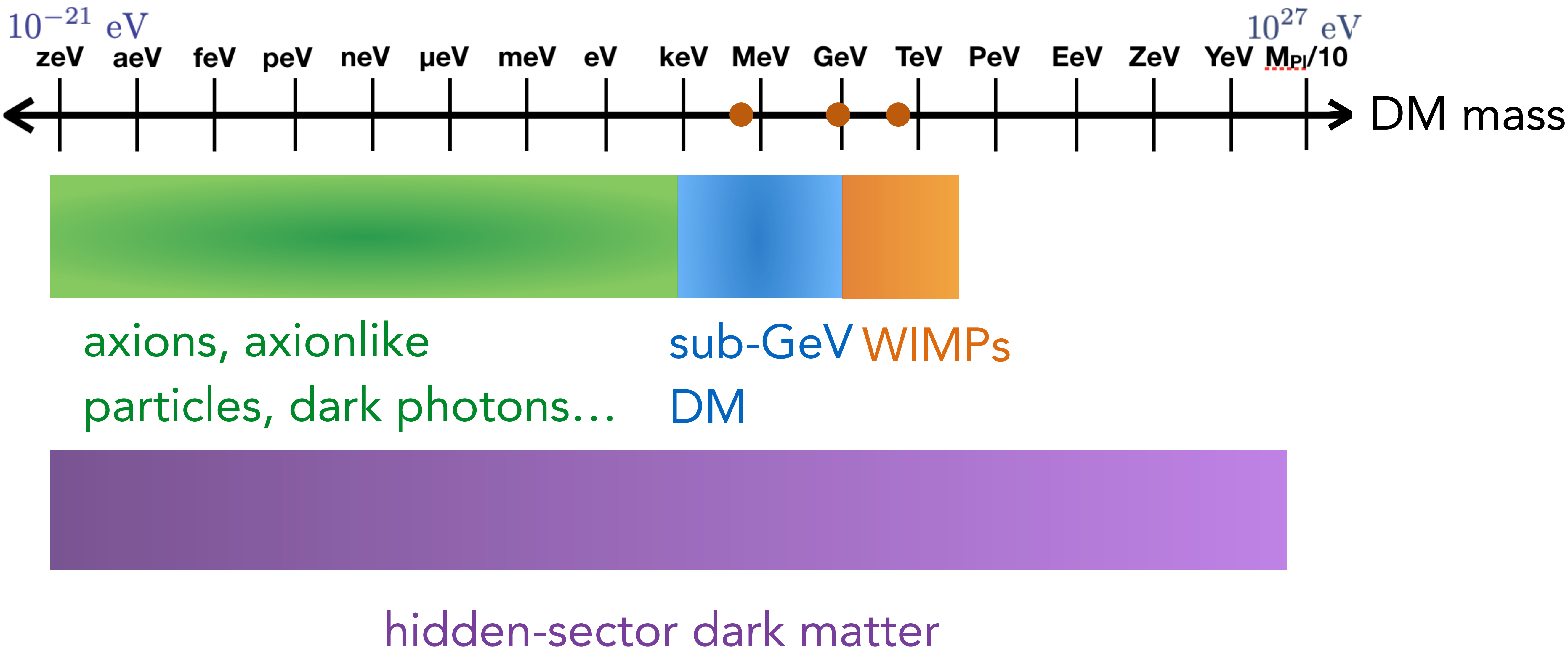
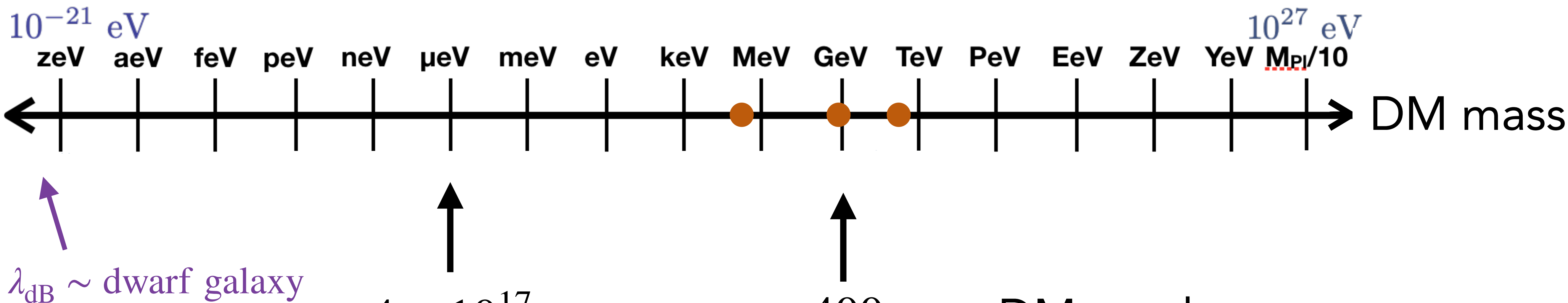


How does the DM mass affect laboratory searches?



$\sim \frac{4 \times 10^{17}}{\text{liter}}$ $\sim \frac{400}{\text{liter}}$ DM number density

smaller DM masses $\Longrightarrow$ higher number density

mean distance between DM particles becomes much smaller than their "de Broglie" wavelengths (the scale at which wave-like properties of particles are important)

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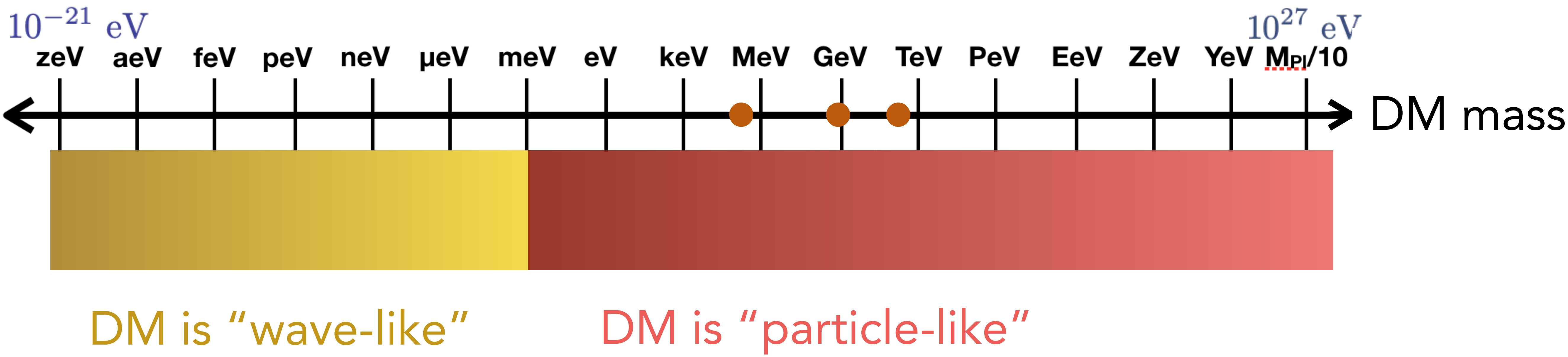
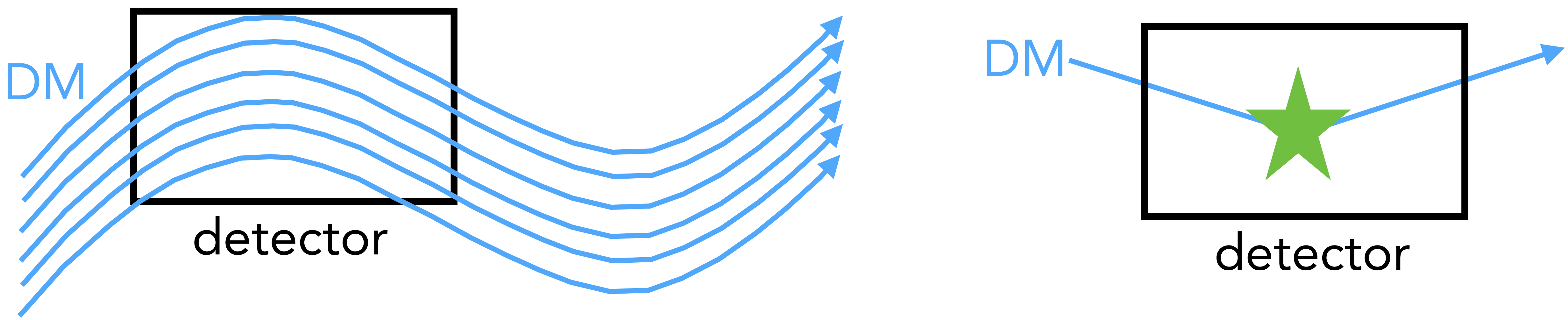
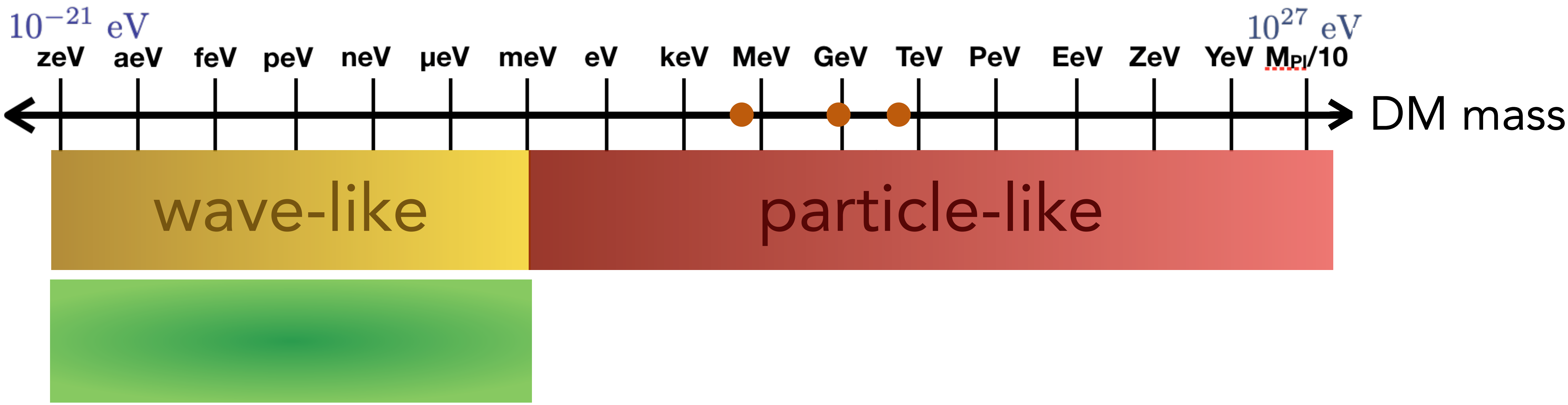




different masses require different search strategies

The Dark Matter Landscape

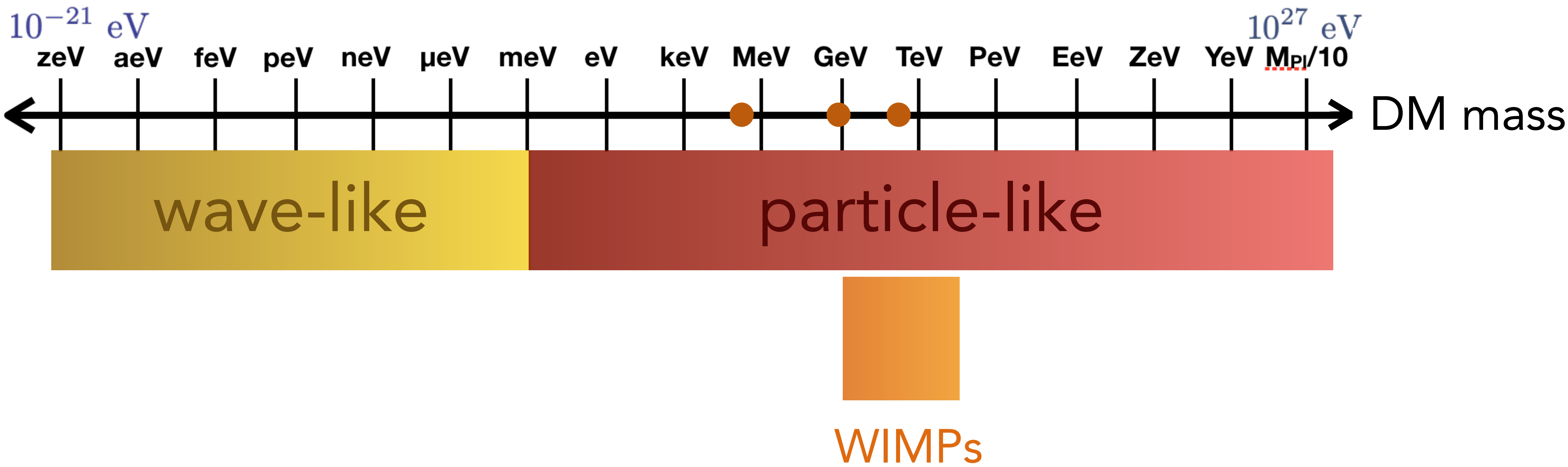


axions, axionlike particles, dark photons…

Recently, many small-scale experiments

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

The Dark Matter Landscape



Weakly Interacting Massive Particles

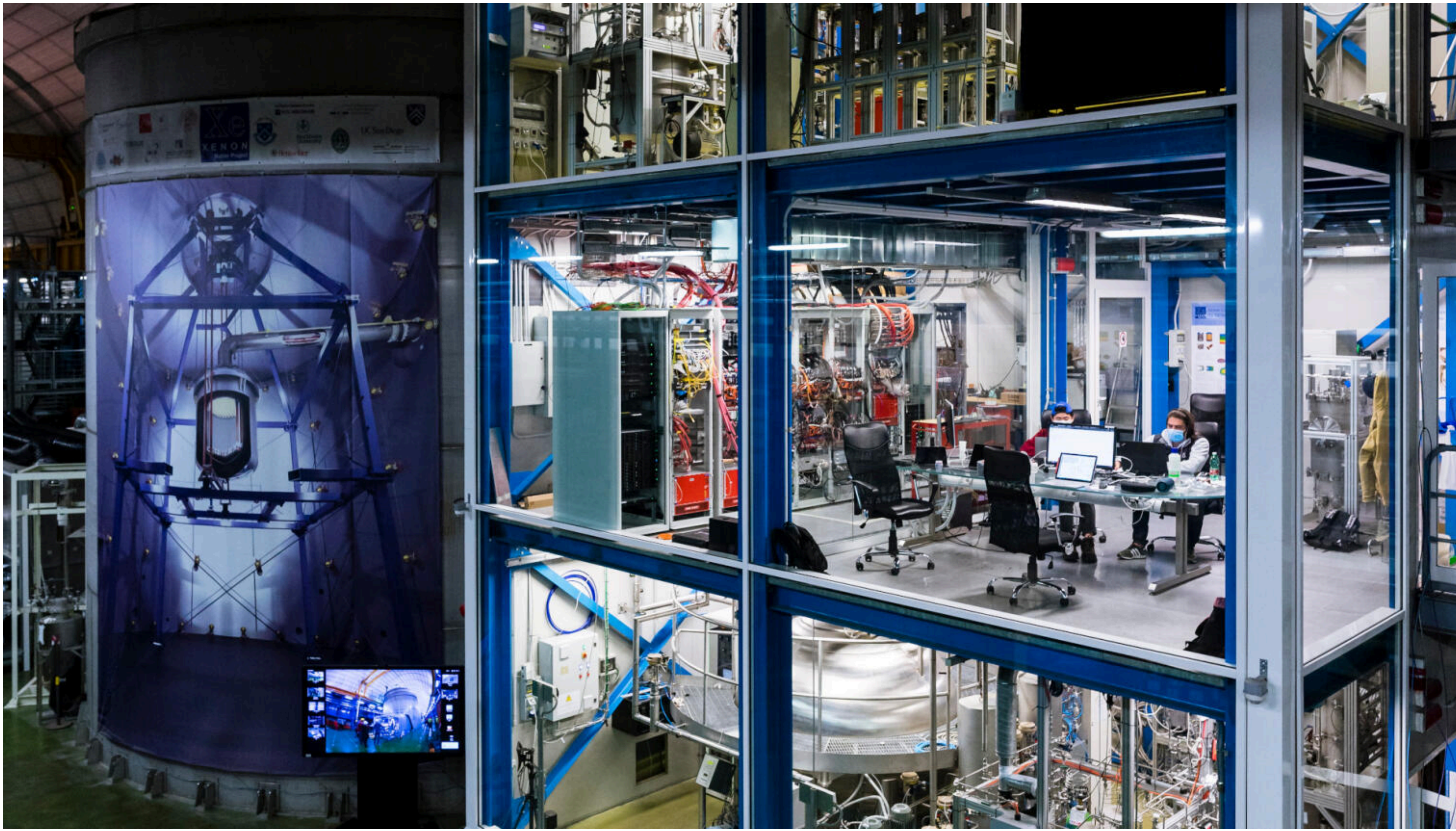
(motivated by "WIMP miracle" and theoretical questions about the Higgs boson)

until ~2015, the almost-sole focus of numerous experimental searches…

Experimental technology is mature

Examples: LZ, XENONnT, PANDA-X Experiments

XENONnT ~7 tonne liquid xenon



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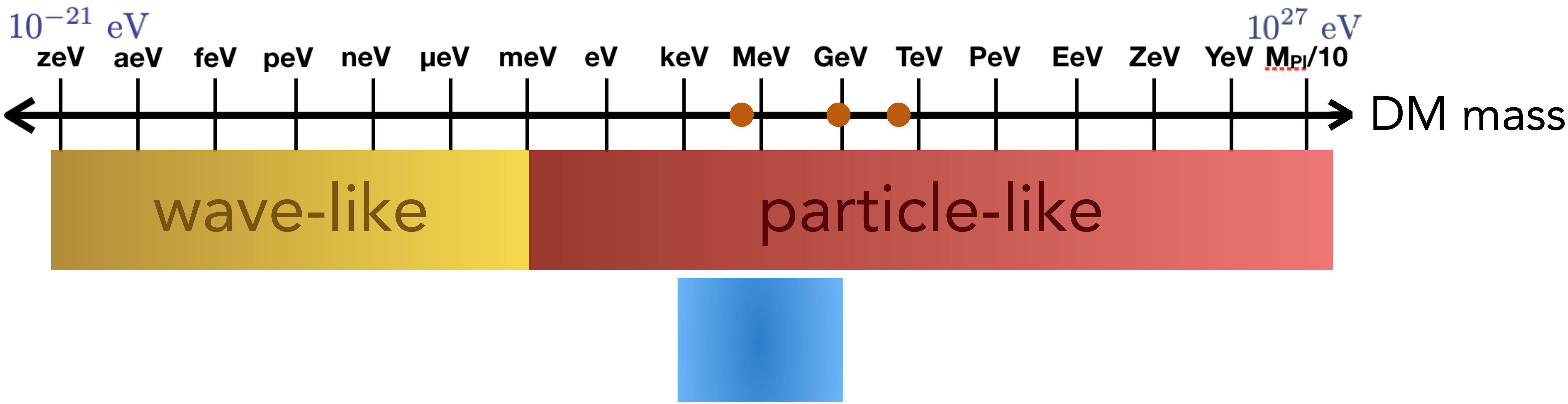


sub-GeV DM

several motivated candidates exist

Recently, many small-scale experiments

SENSEI, CDMS-HVeV, DAMIC-M, CRESST, EDELWEISS, XENON, DarkSide, EJ-301, …

Rest of talk will focus on this mass region

Outline

- Detection concepts for sub-GeV Dark Matter
- SENSEI & other Skipper-CCD experiments
- Probing sub-MeV DM & DM w/ large interactions

Outline

- Detection concepts for sub-GeV Dark Matter

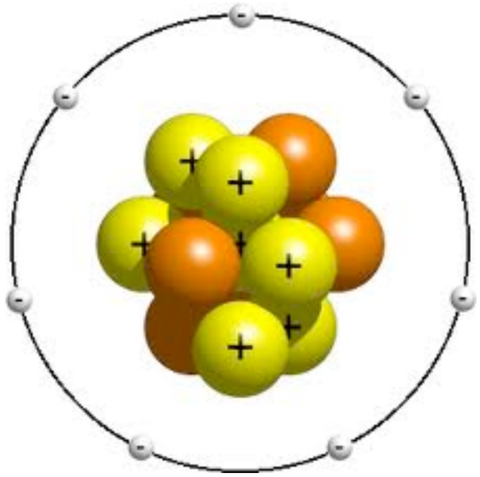
  How to search for sub-GeV DM

- SENSEI & other Skipper-CCD experiments

- Probing sub-MeV DM & DM w/ large interactions

Traditional “WIMP” Detection Concept

Put a detector with lots of
atoms deep underground

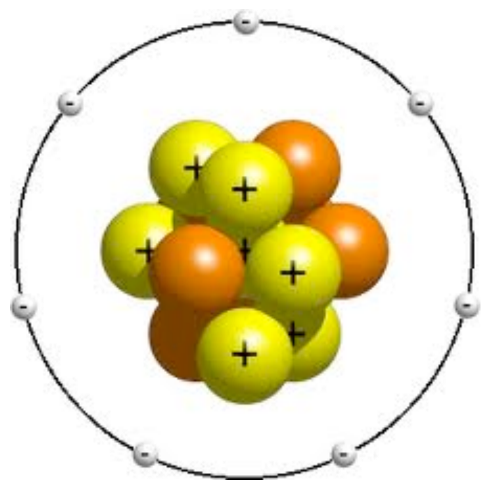


Atom

Traditional “WIMP” Detection Concept

Put a detector with lots of
atoms deep underground

and wait…



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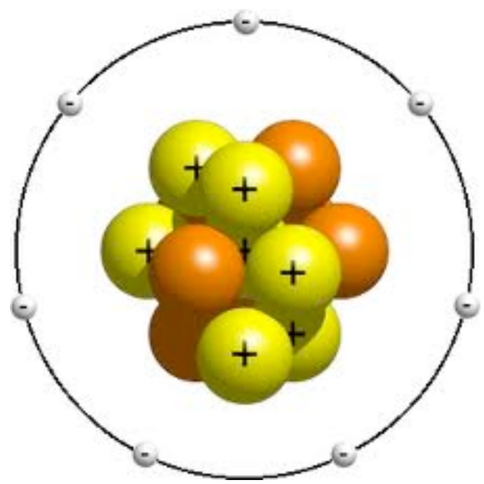

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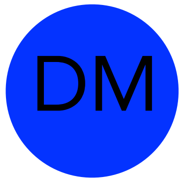

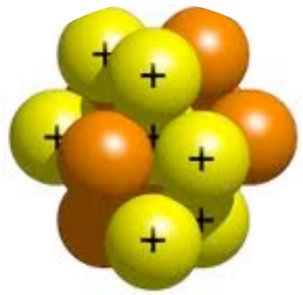

Recoiling
Nucleus

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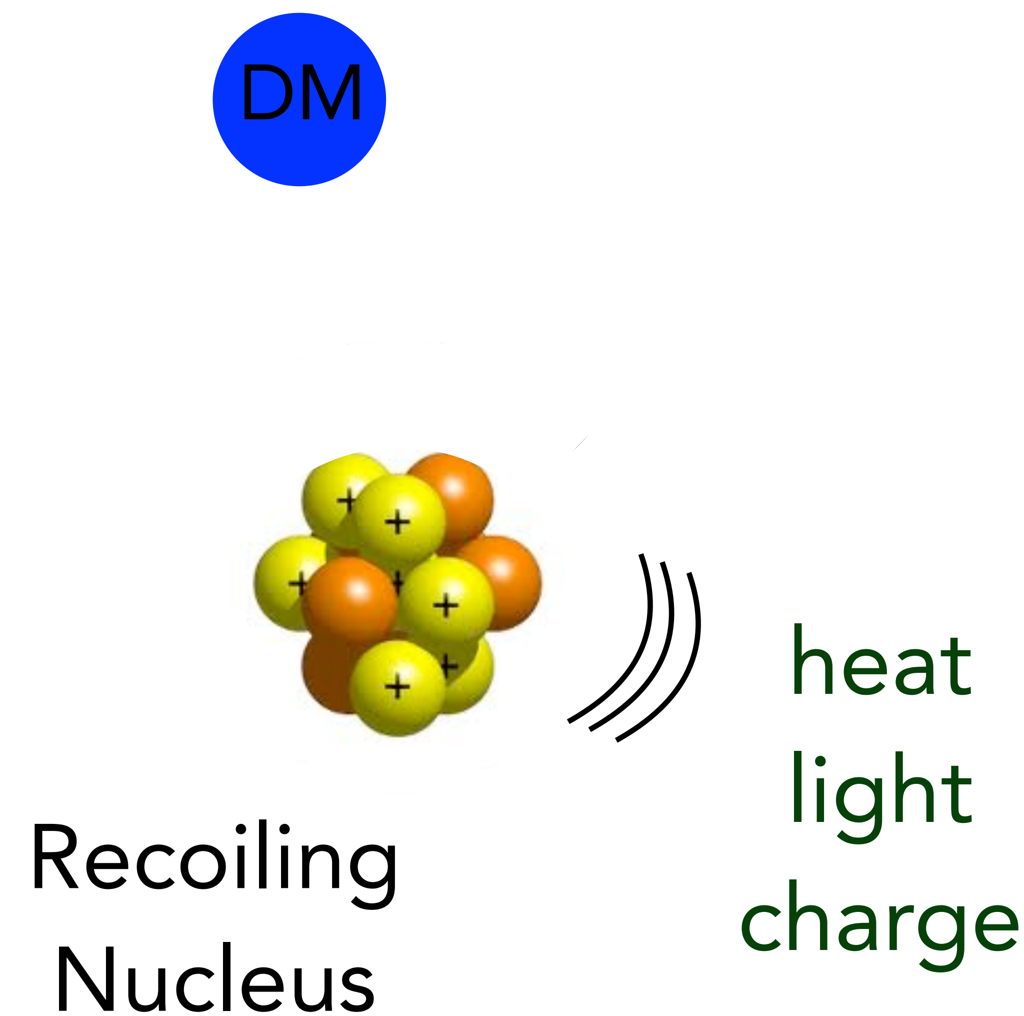
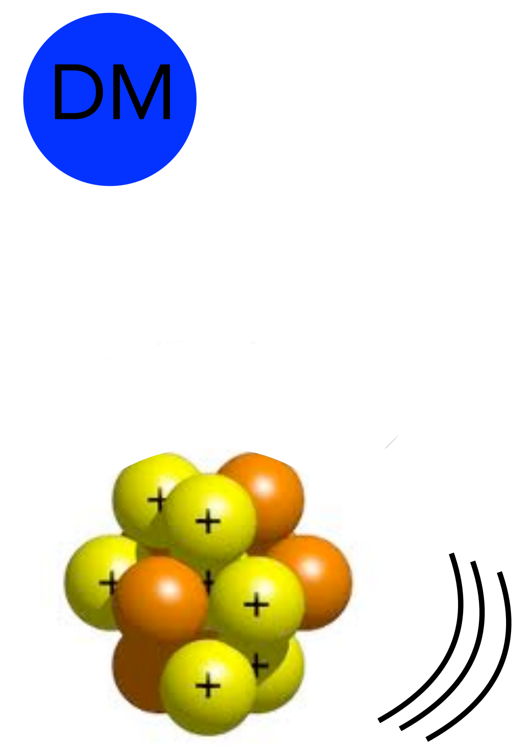


Traditional “WIMP” Detection Concept

Put a detector with lots of
atoms deep underground
and wait… until…

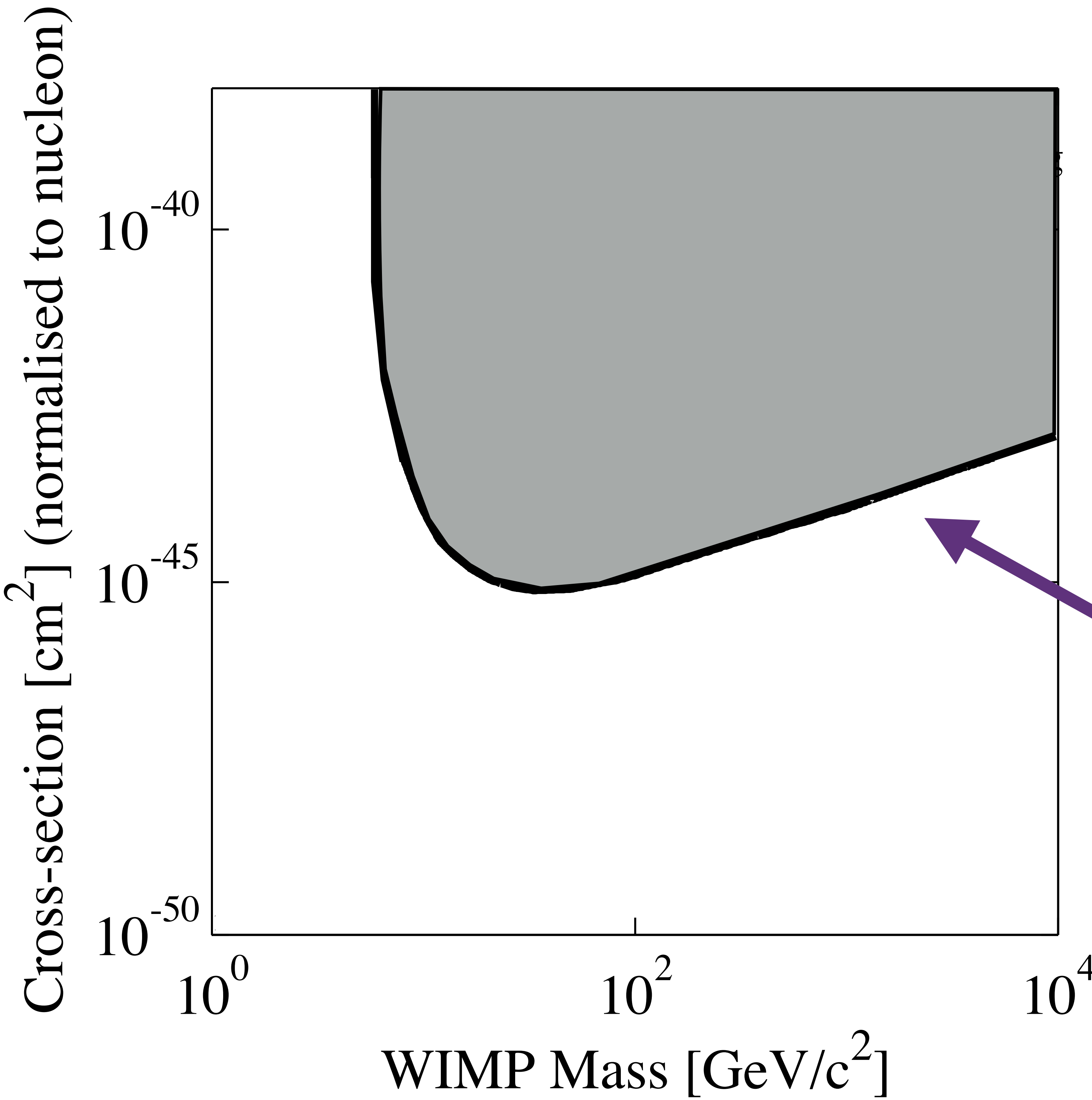
elastic DM-nucleus
scattering is like
billiard ball scattering



Recoiling
Nucleus

heat
light
charge

A typical direct detection exclusion curve

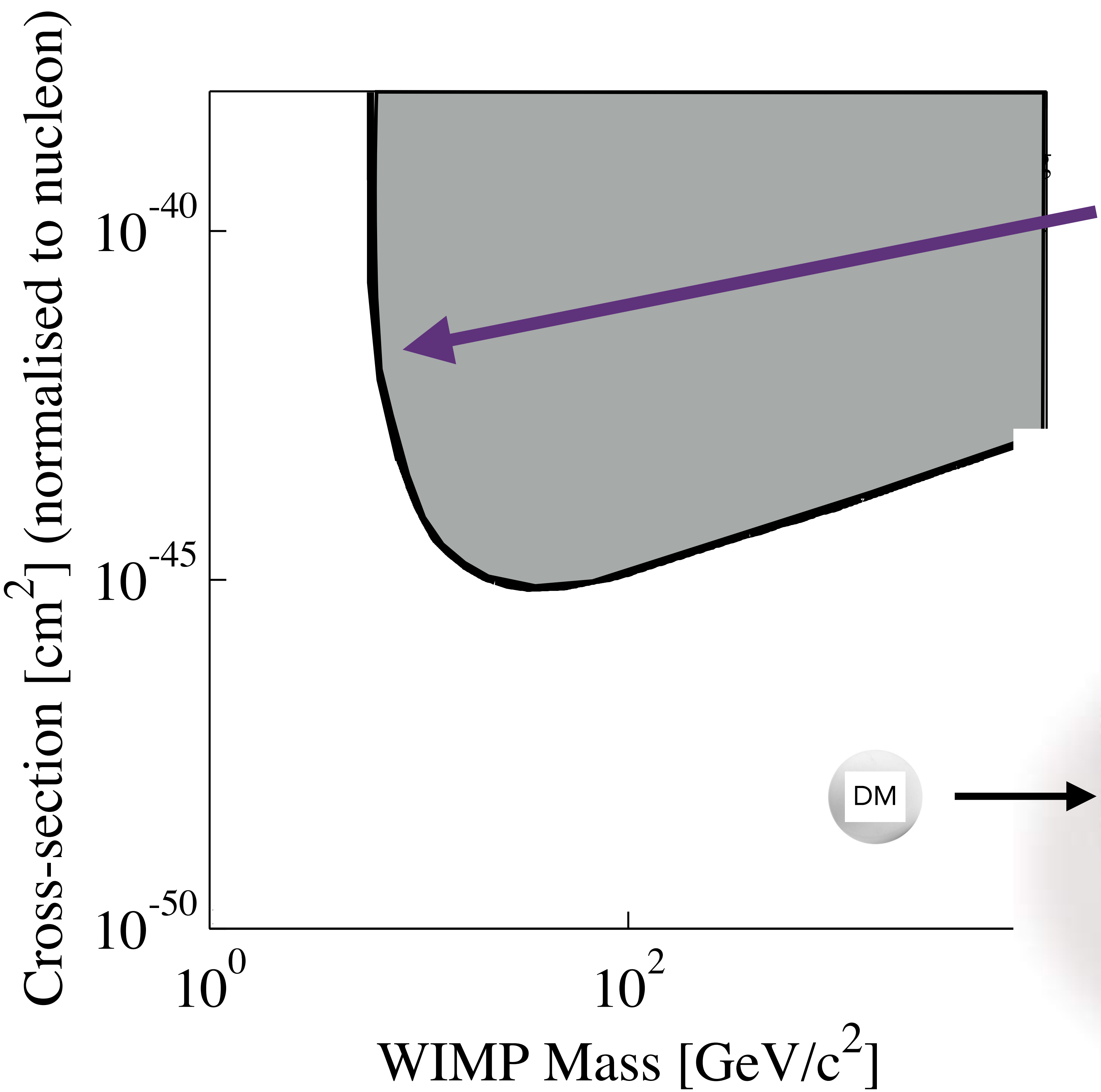


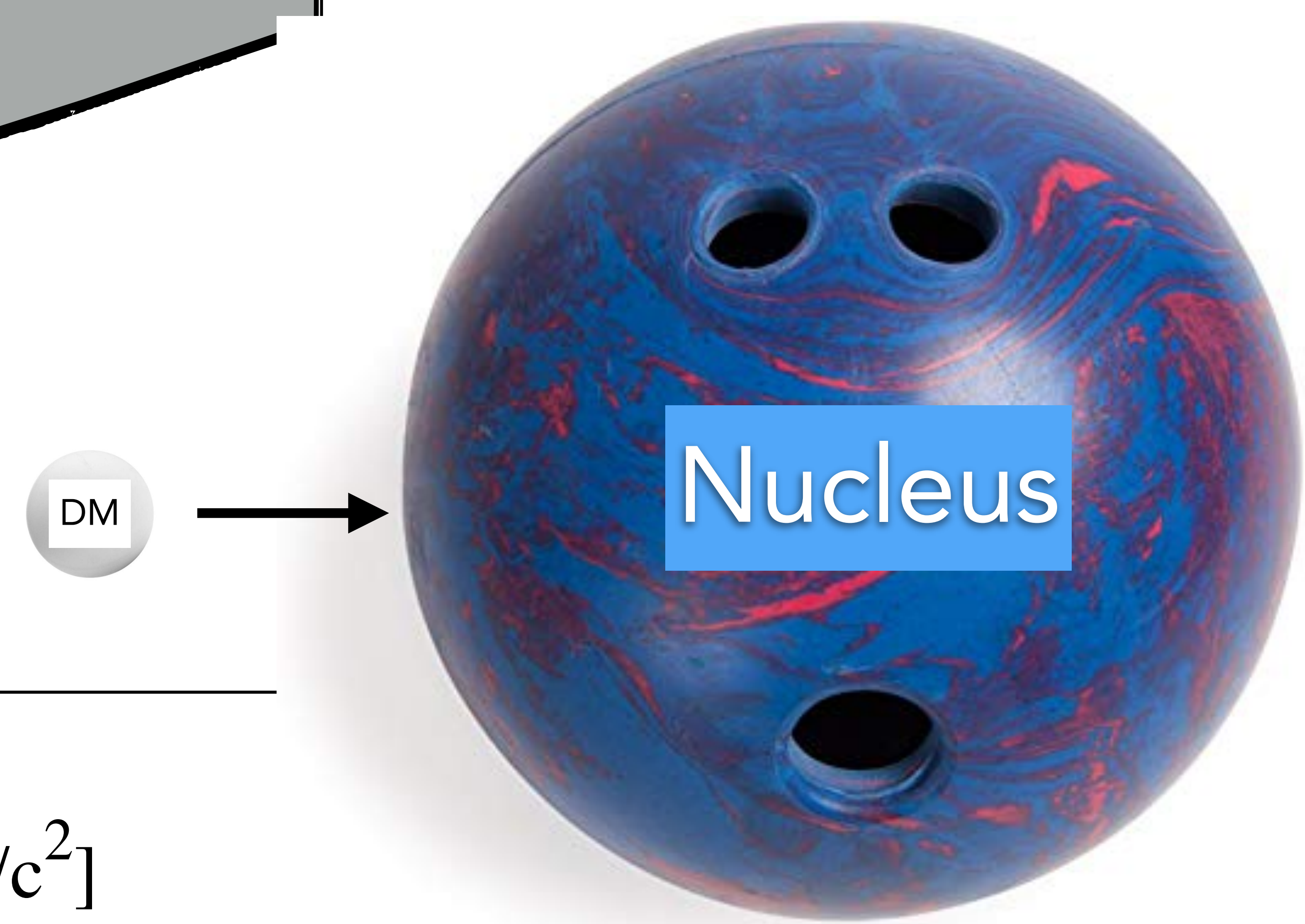
linear, since

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

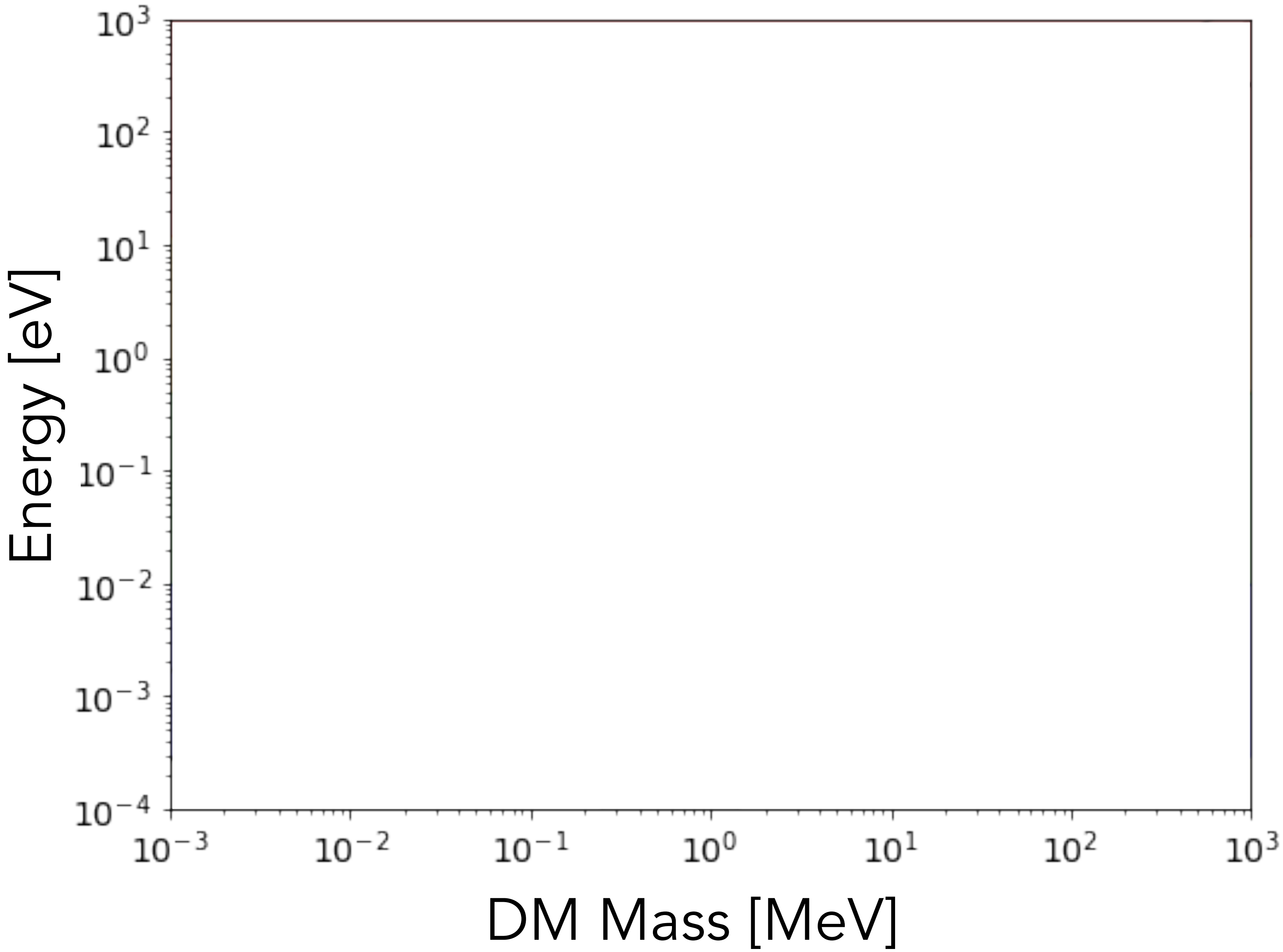
$$\propto \frac{0.4\ \text{GeV}/\text{cm}^3}{m}$$

A typical direct detection exclusion curve

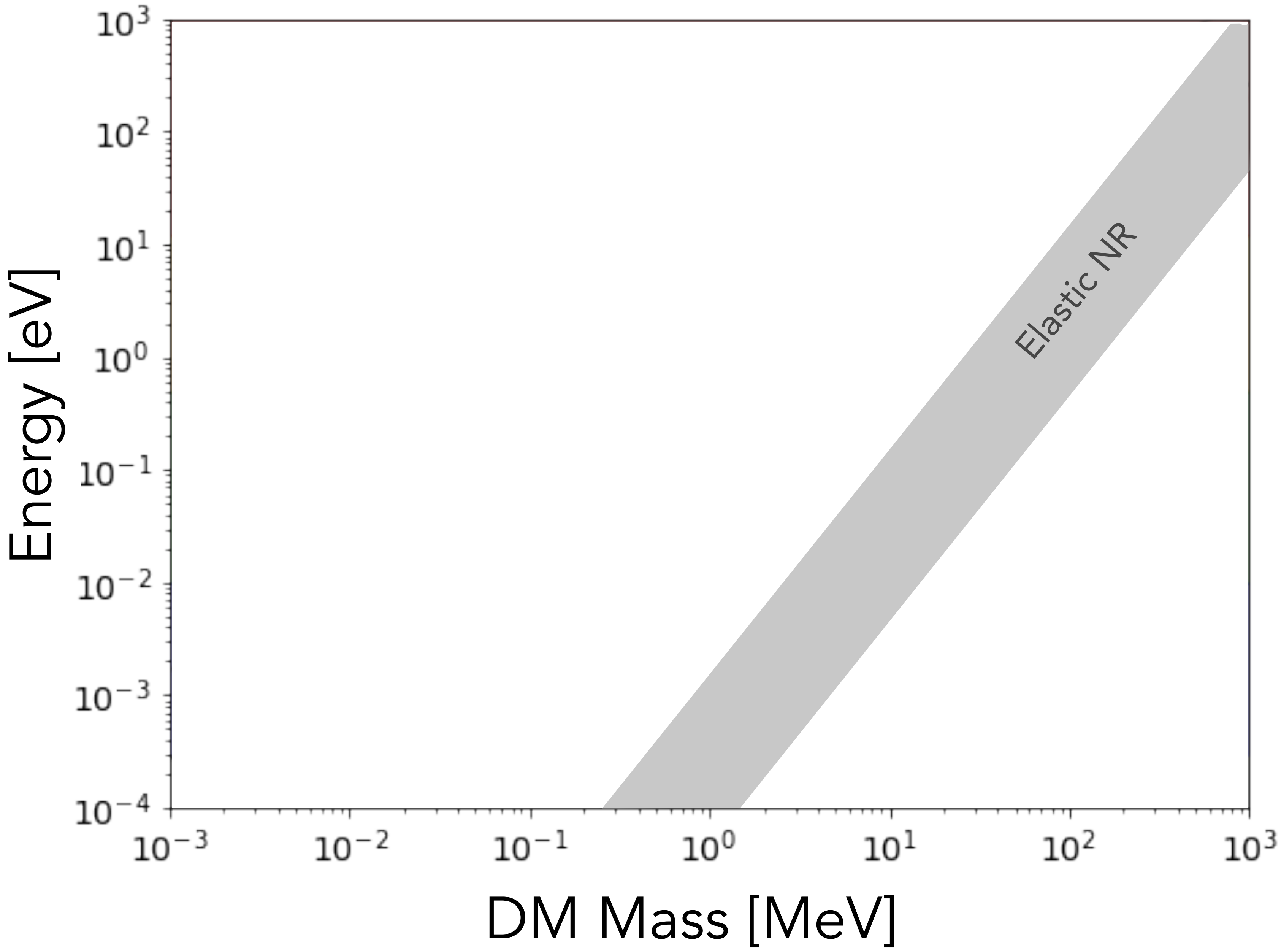




Kinematics of sub-GeV DM scattering



Elastic WIMP-nucleus scattering



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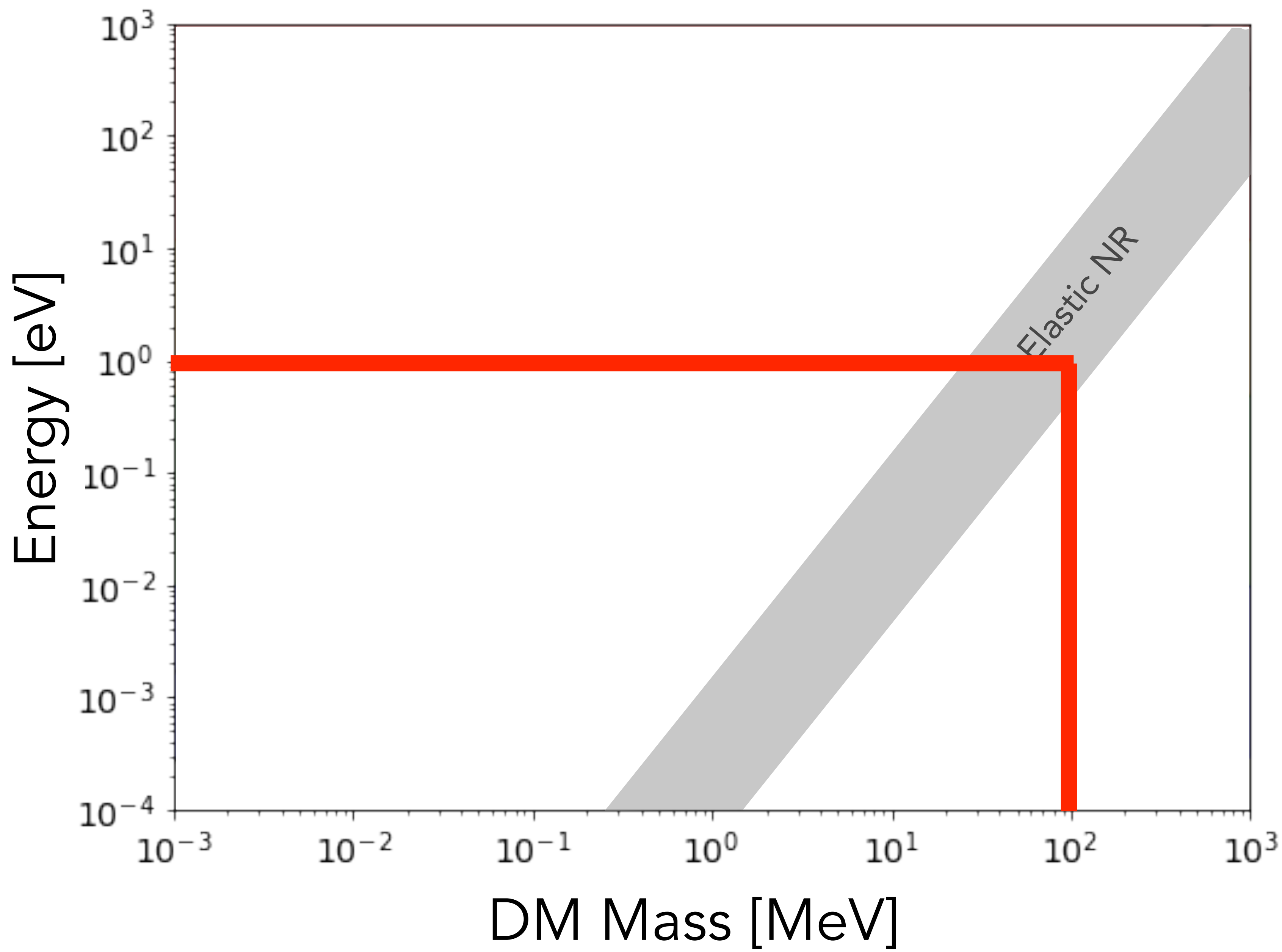
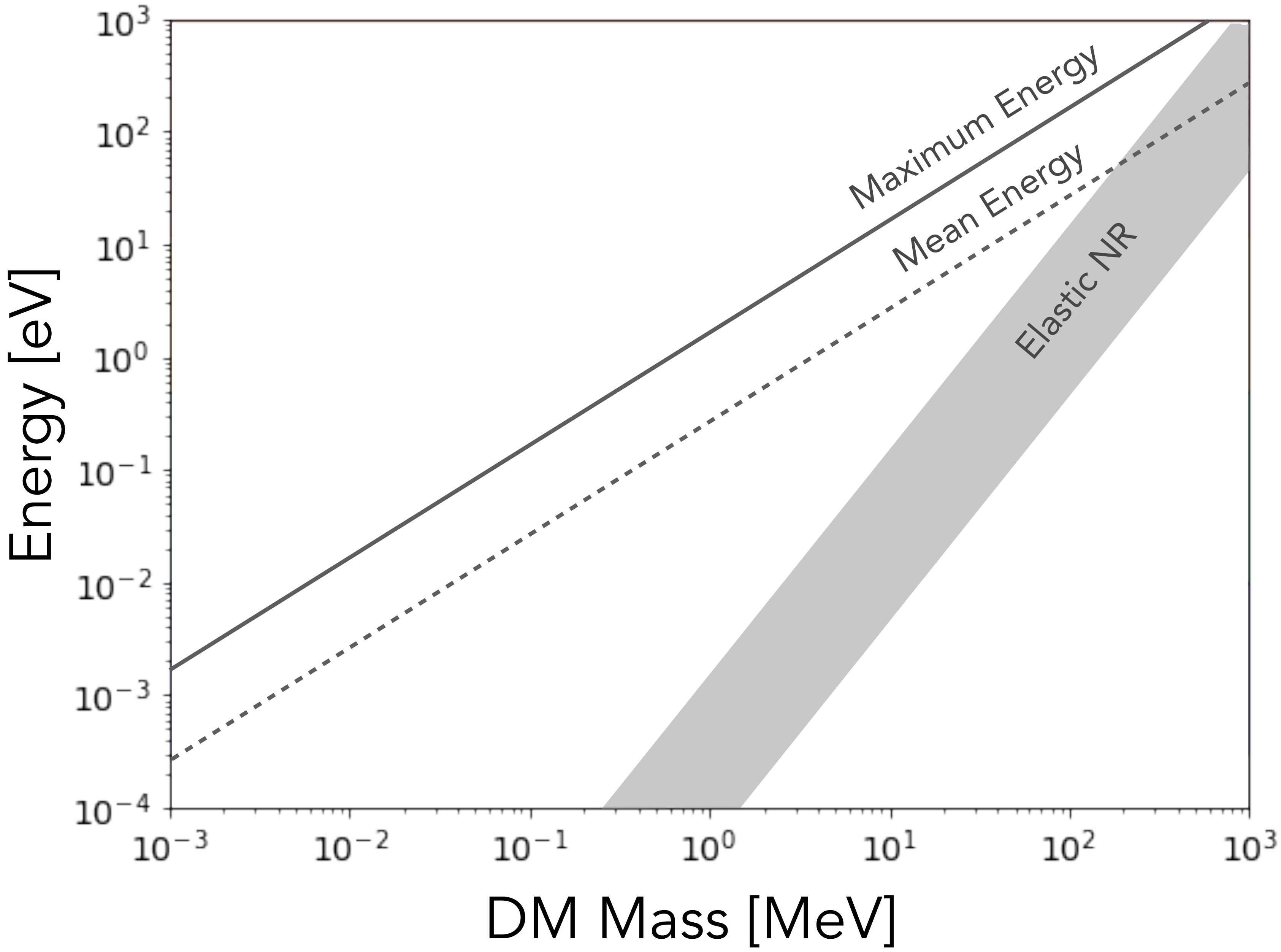


$$E_{\rm NR} = \frac{q^2}{2m_N} \sim 1\ {\rm eV} \left(\frac{m_{\rm DM}}{100\ {\rm MeV}}\right)^2 \left(\frac{28\ {\rm GeV}}{m_N}\right)$$

at low DM masses, very little energy transfer

Available DM kinetic energy is much larger!



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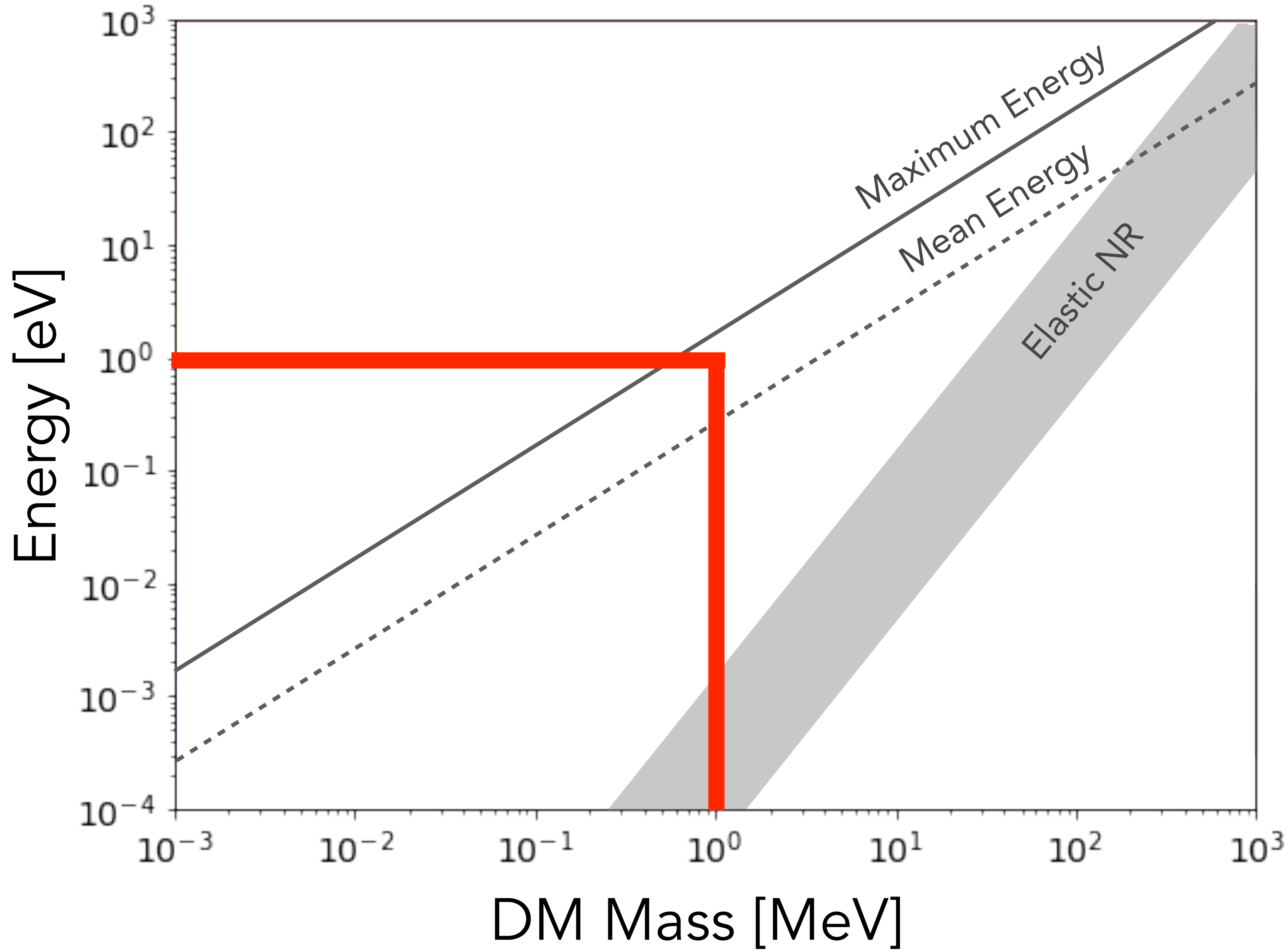

$$E_{\text{kin}} = \frac{1}{2} m_{\text{DM}} v_{\text{DM}}^2 \sim 1\ \text{eV} \left(\frac{m_{\text{DM}}}{1\ \text{MeV}} \right)$$

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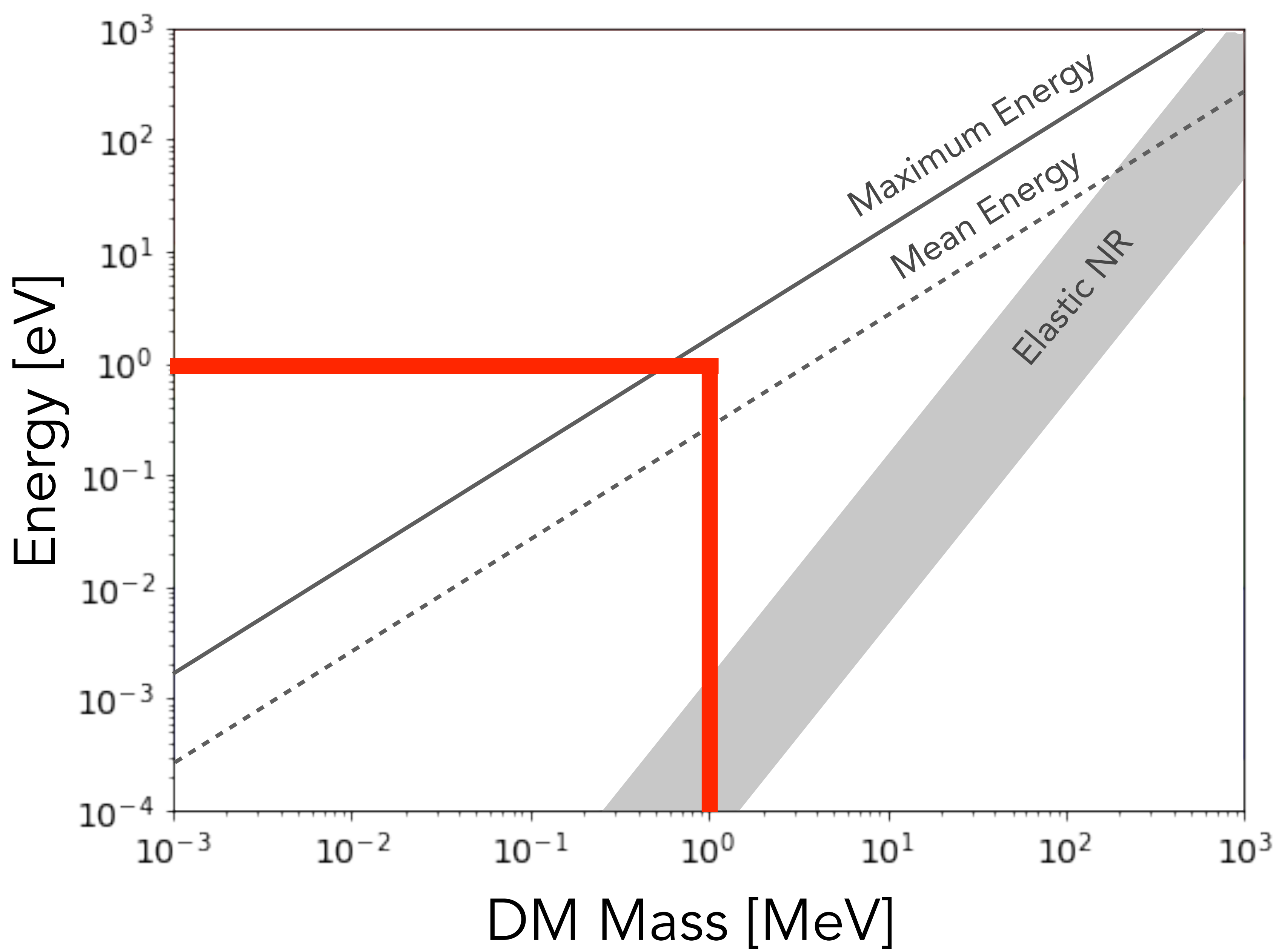

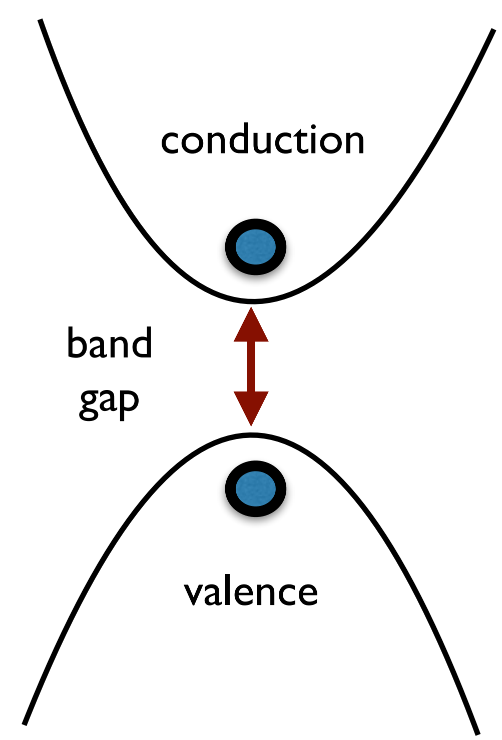

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e.g.,
silicon bandgap
is ~1 eV

Can transfer entire DM kinetic energy in inelastic scatters

- DM-e scattering

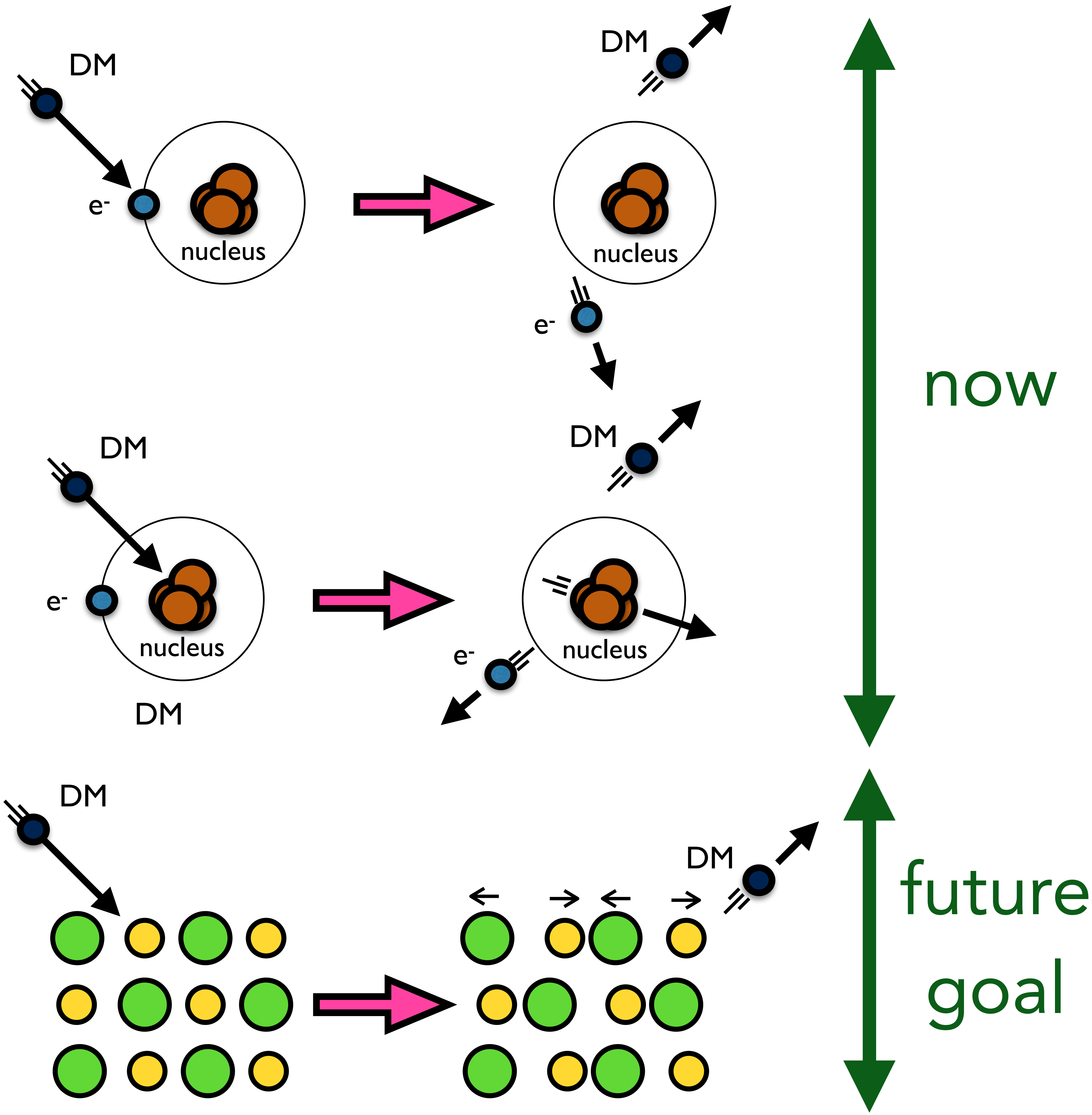
  RE, Mardon, Volansky

- DM-N scattering via Migdal effect

  Migdal; Vergados & Ejiri; Bernabei; Ibe, Nakano, Shoji, Suzuki

- DM scattering excites collective modes

  Knapen, Lin, Pyle, Zurek



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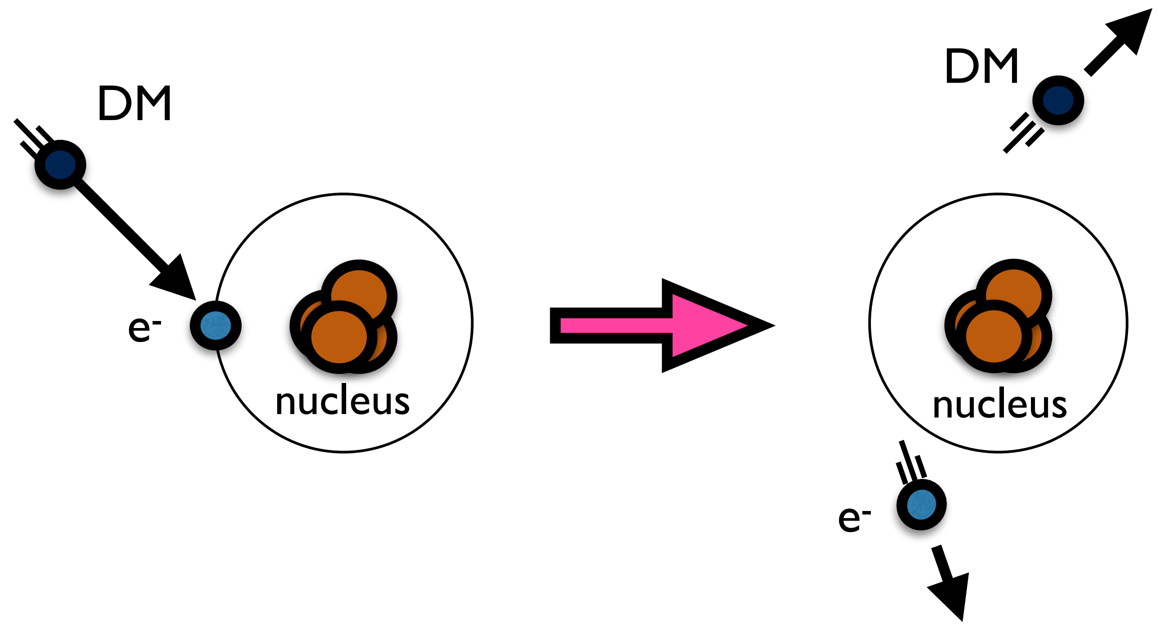
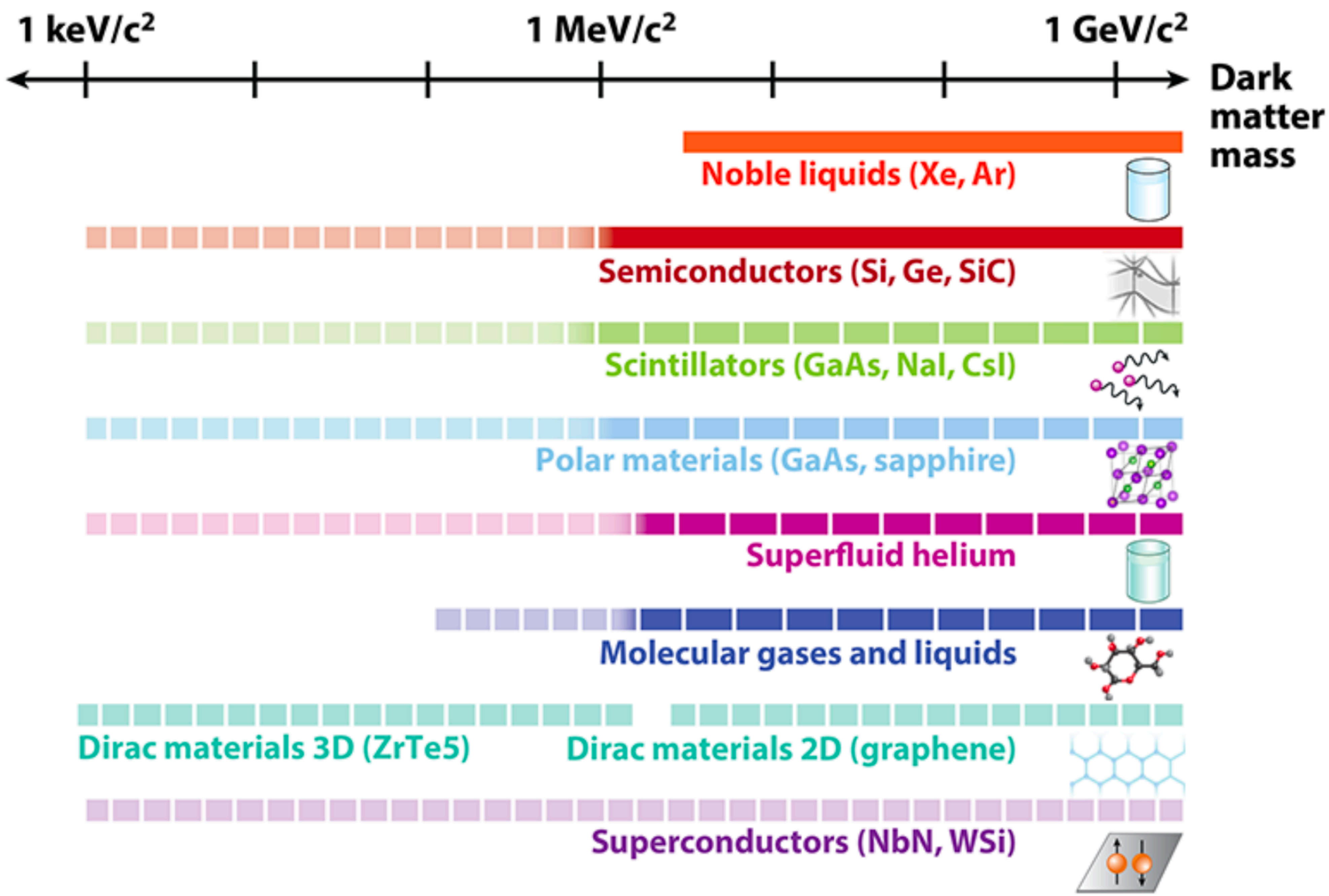


We'll focus on this

Various target materials w/ various excitation energies, e.g.



RE, "The low-mass dark matter frontier," Physics 13, 172, 2020

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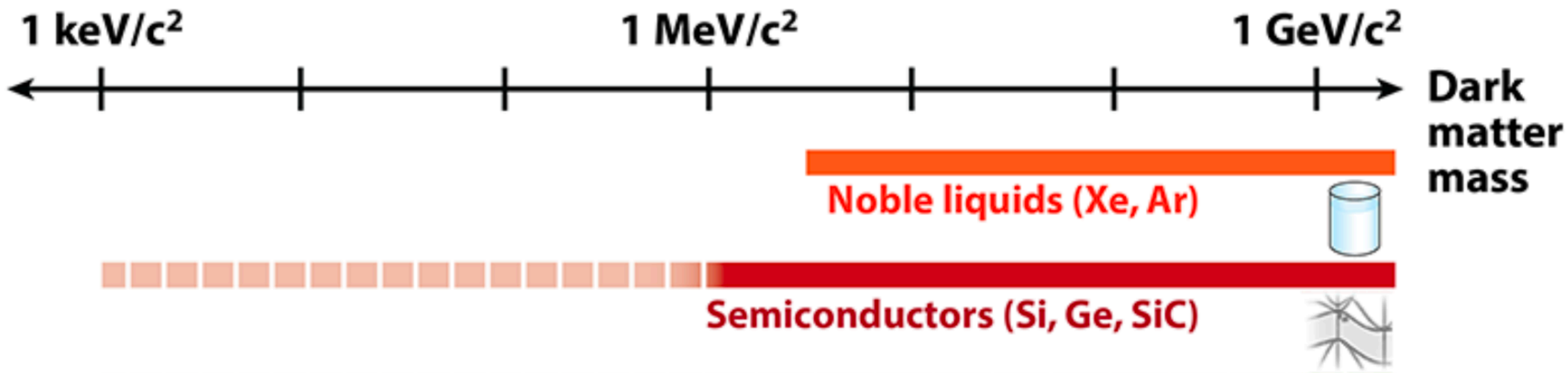
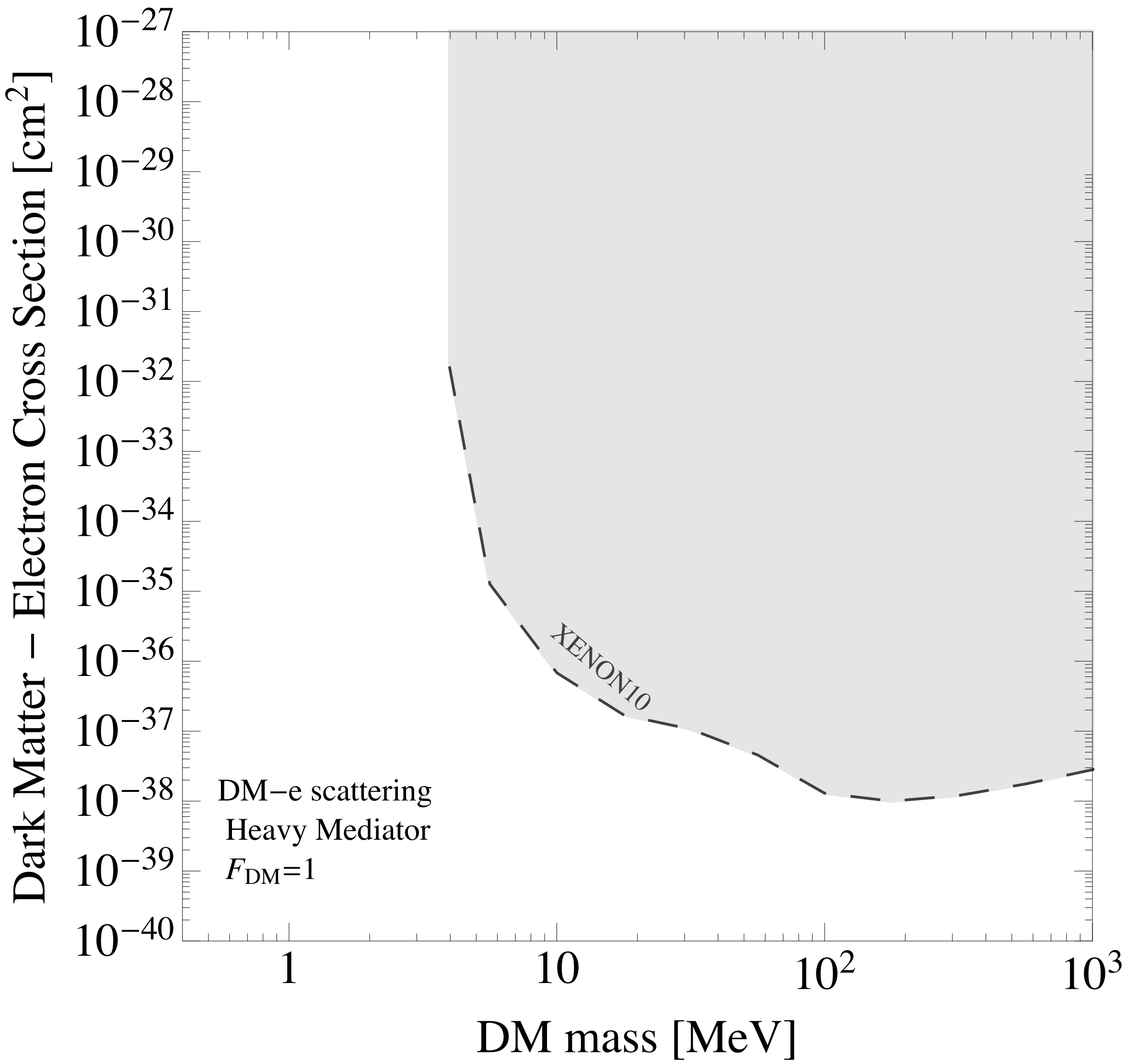


current searches mostly use these

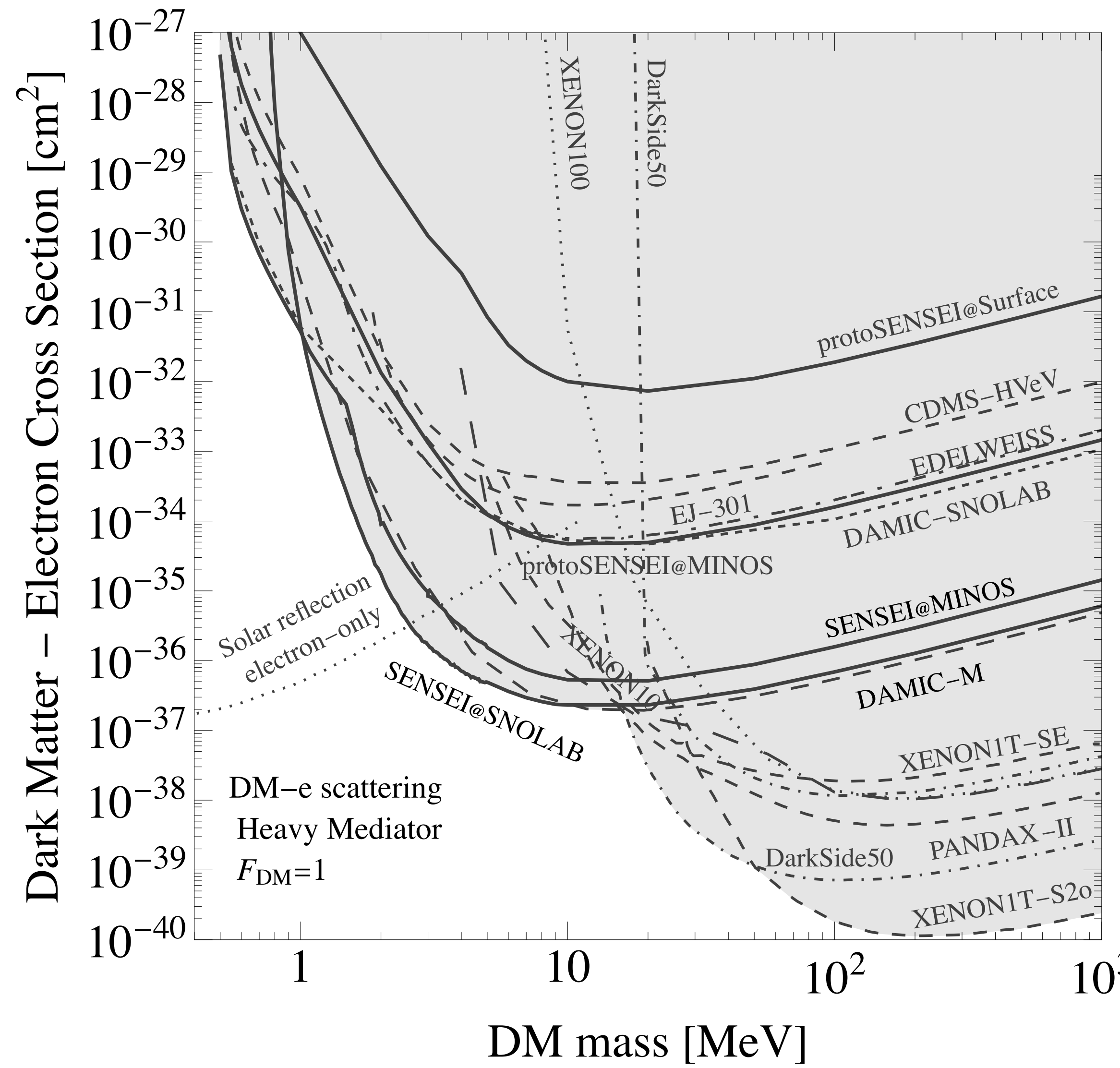
signal consists of one to a few electrons

Exciting experimental progress in past decade: e.g., DM-electron scattering

2012



~now



RE, Manalaysay, Mardon, Sorensen, Volansky

many collaborations!

several ultrasensitive detectors can now measure the produced charge (2-phase TPCs, Skipper-CCDs, TES,…)

Outline

- Detection concepts for sub-GeV Dark Matter
- SENSEI & other Skipper-CCD experiments
- Probing sub-MeV DM & DM w/ large interactions

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- Detection concepts for sub-GeV Dark Matter

- SENSEI & other Skipper-CCD experiments

  SENSEI is the first dedicated experiment to probe DM with masses as low as 1 MeV

- Probing sub-MeV DM & DM w/ large interactions

Sub-Electron Noise Skipper-CCD Experimental Instrument

+ DAMIC-M & Oscura

The SENSEI Collaboration

Fermilab

Ana Botti
Gustavo Cancelo
Fernando Chierchie
Michael Crisler
Alex Drilca-Wagner
Juan Estrada
Guillermo Fernandez
Nathan Saffold
Miguel Sofo-Haro
Leandro Stefanazzi
Kelly Stifter
Javier Tiffenberg*
Sho Uemura

Berkeley Lab

Steve Holland

Tel Aviv University / אוניברסיטת תל אביב

Liron Barak
Yonathan Ben Gal
Miguel Daal
Erez Etzion
Yonathan Kehat
Yaron Korn
Aviv Orly
Tomer Volansky*

The University of California, Berkeley

Itay Bloch

Stony Brook University

Prakruth Adari
Rouven Essig*
Aman Singal
Yikai Wu

University of Oregon

Ansh Desai
Tien-Tien Yu

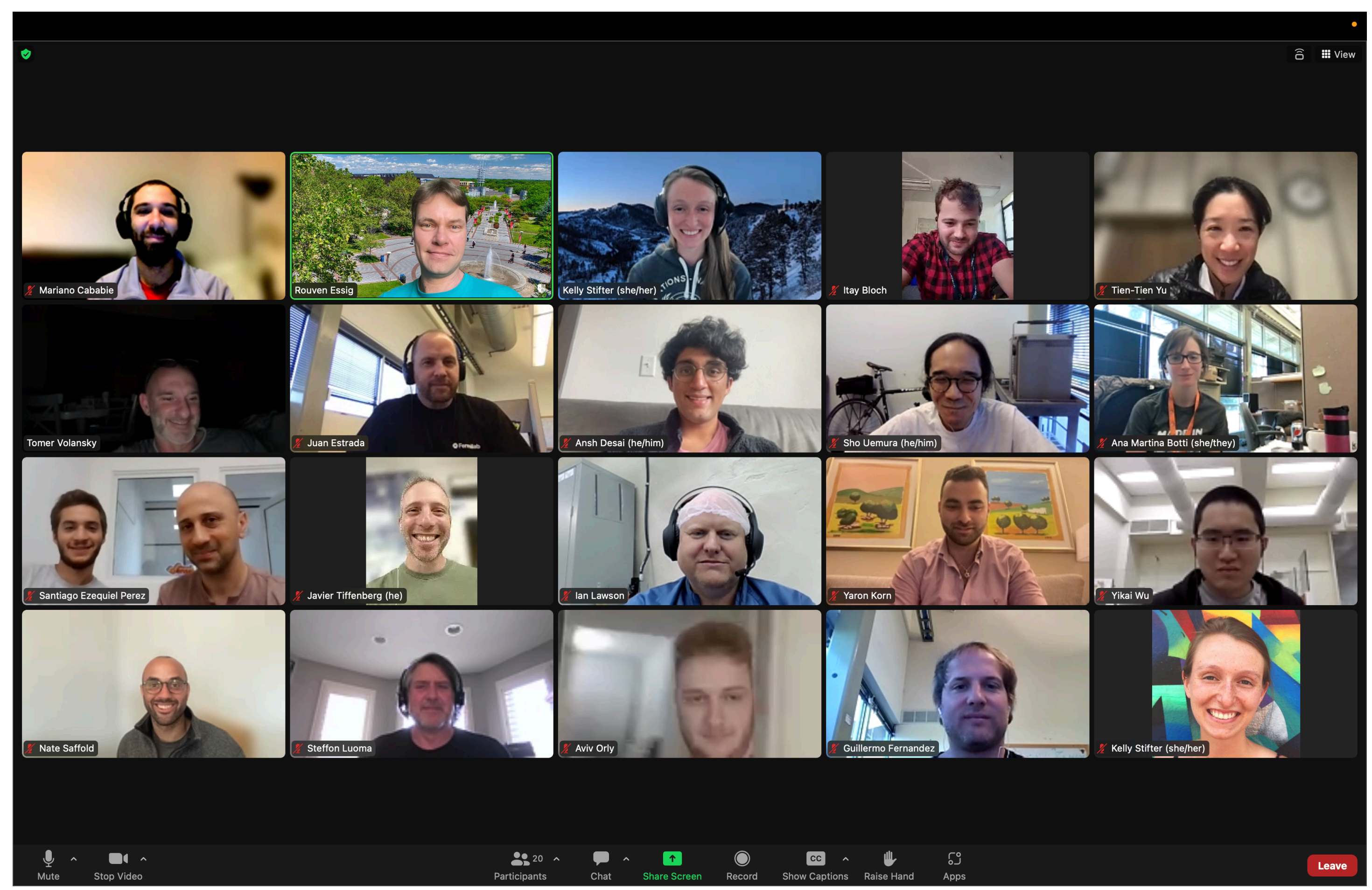
universidad de buenos aires - exactas, departamento de Física Juan José Giambiagi

Mariano Cababie
Santiago Perez
Dario Rodrigues

SNOLAB

Ian Lawson
Steffon Luoma

HEISING-SIMONS FOUNDATION



*spokespersons

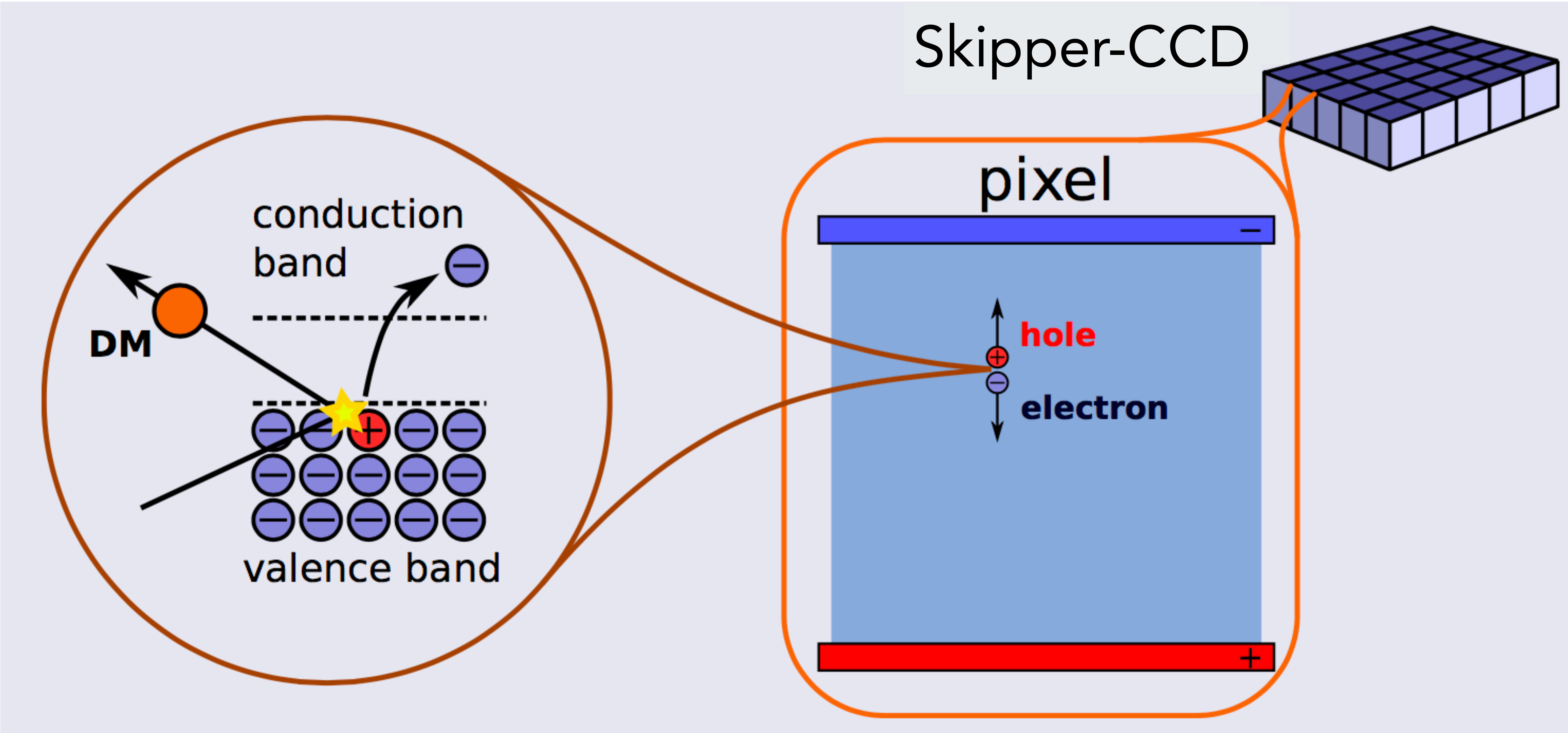
SENSEI's target material are special silicon CCDs

"Skipper CCDs"

designed at LBNL, fabricated at Teledyne DALSA Semiconductor

- ~5.4 million pixels, each pixel: $15\ \mu m \times 15\ \mu m \times 675\ \mu m$
- total size ~ 1.6 cm $\times$ 9.4 cm, ~2 gram

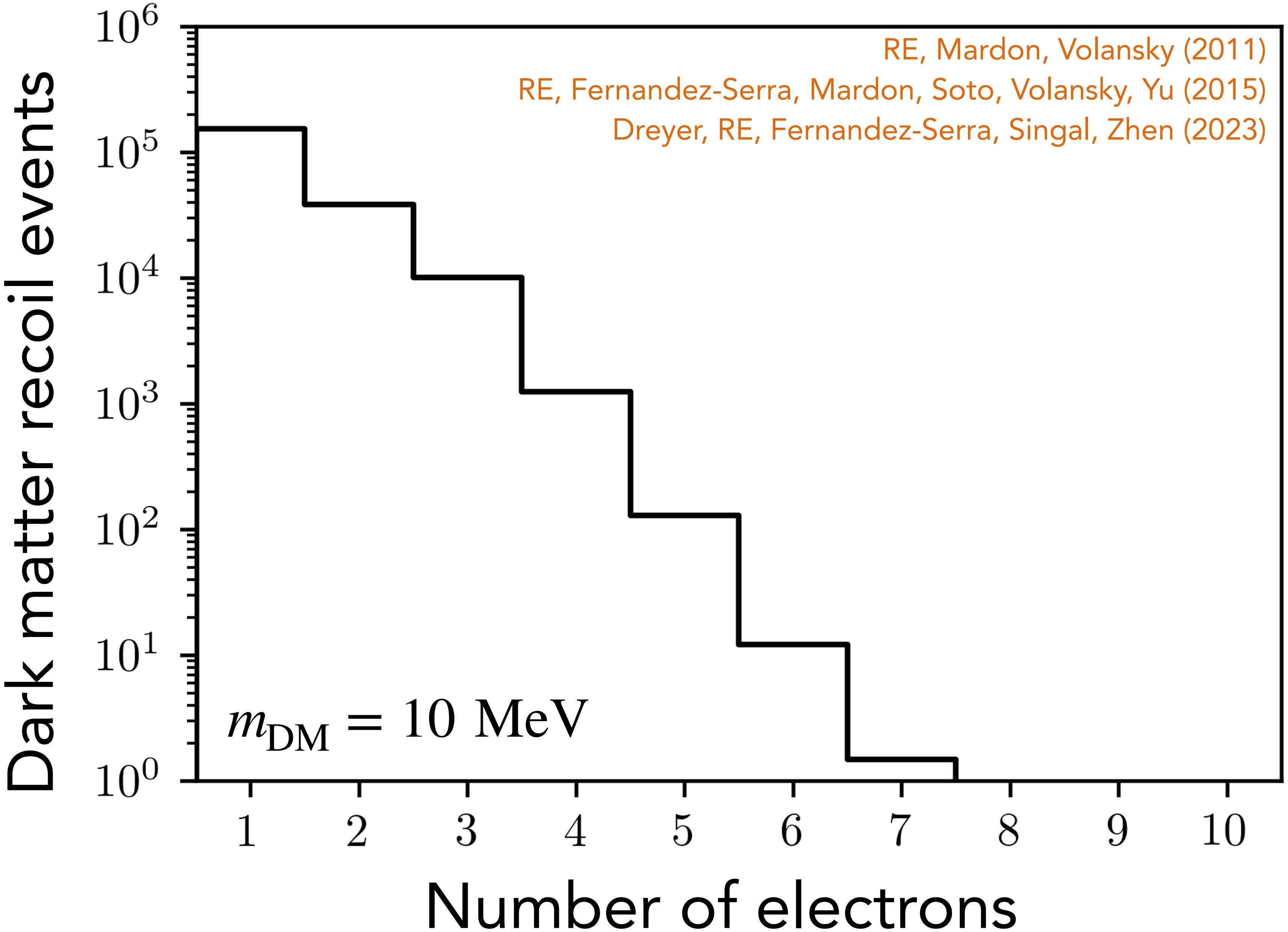
Detection concept



DM would create <u>one</u> or a <u>few</u> electrons in a pixel

(Event rate depends on interaction strength)

Spectrum of electrons produced by DM-e scattering



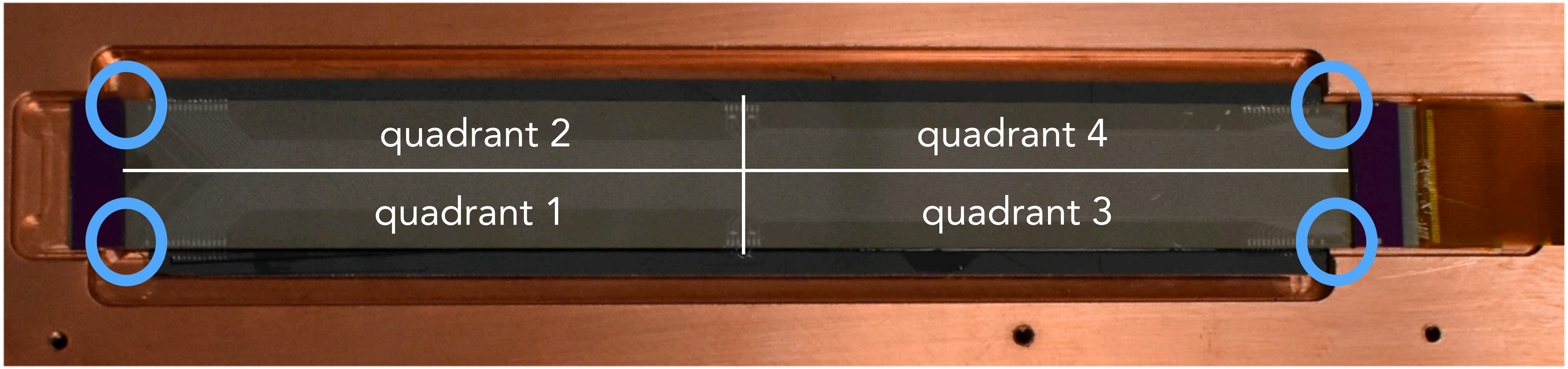
- Before June 2017, best detectors only sensitive to $\gtrsim 10\ e^-$
- Skipper-CCDs are sensitive to $\geq 1\ e^-$!

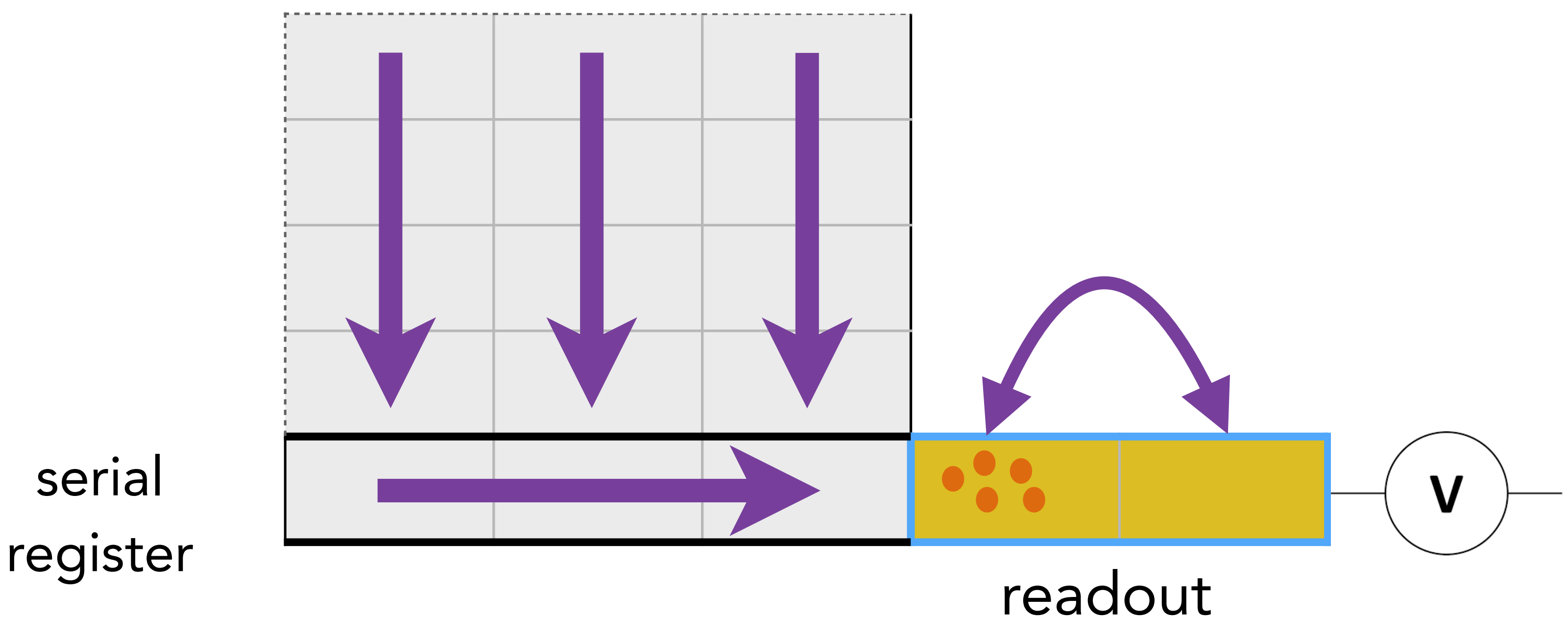
technologies from SuperCDMS, EDELWEISS, & TESSERACT have achieved comparable sensitivities

Theory calculations done in collaboration with condensed matter theorists

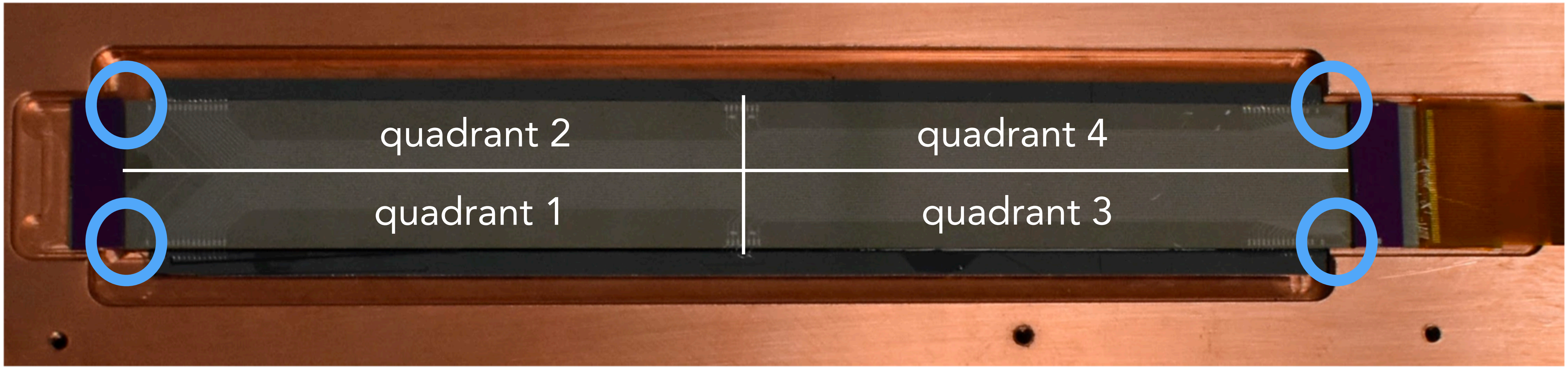
see also e.g. Griffin, Inzani, Trickle, Zhang, Zurek; Trickle; Knapen, Kozaczuk, Lin; Hochberg, Kahn, Kurinsky, Lehmann, Yu; Catena, Emken, Matas, Spaldin, Urdshals; Peterson, Watkins, Lane, Zhu

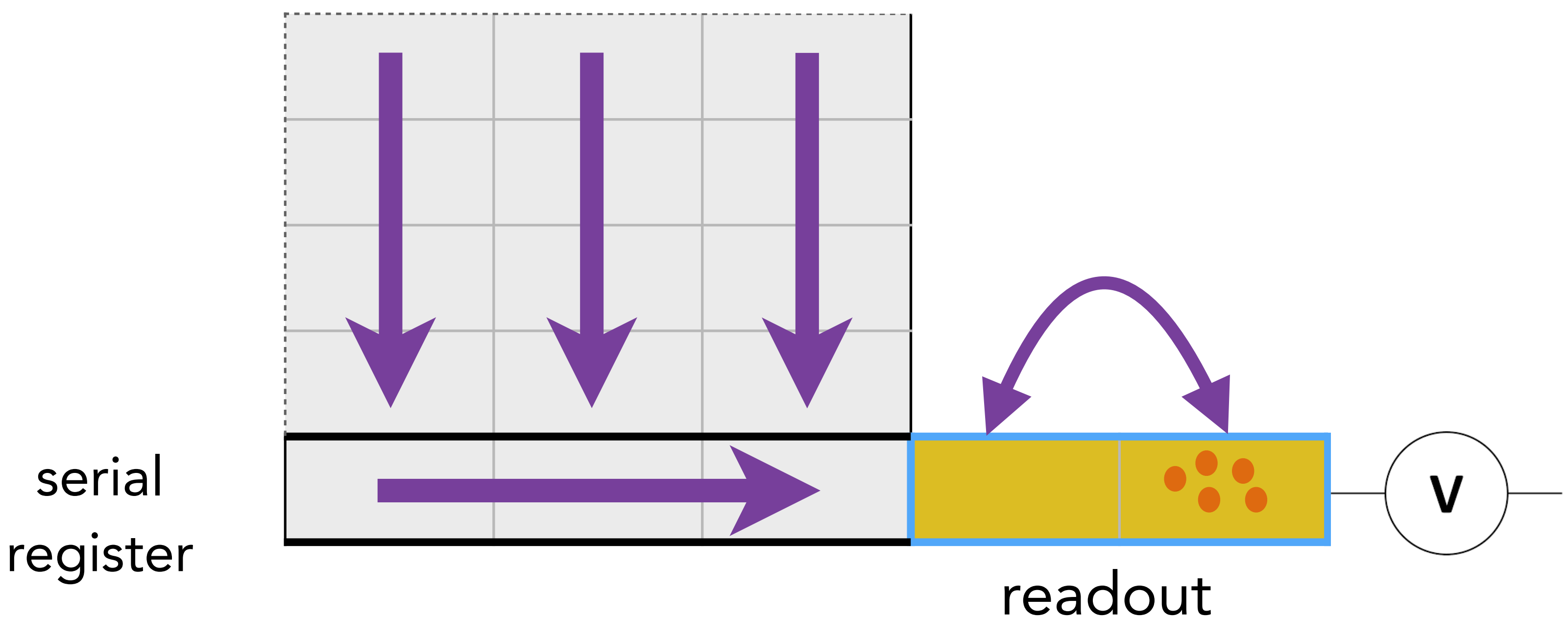
Skipper-CCD operation



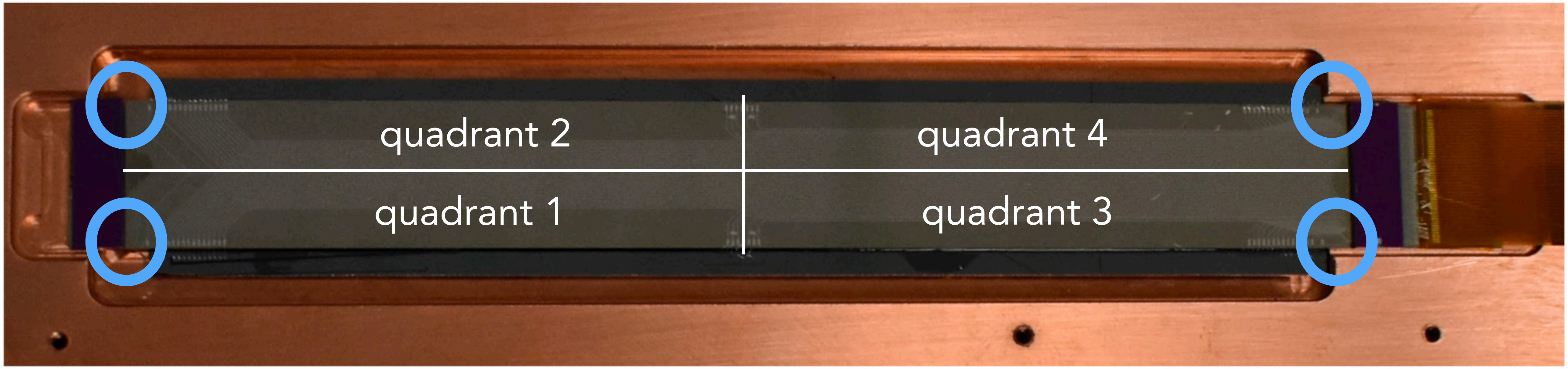


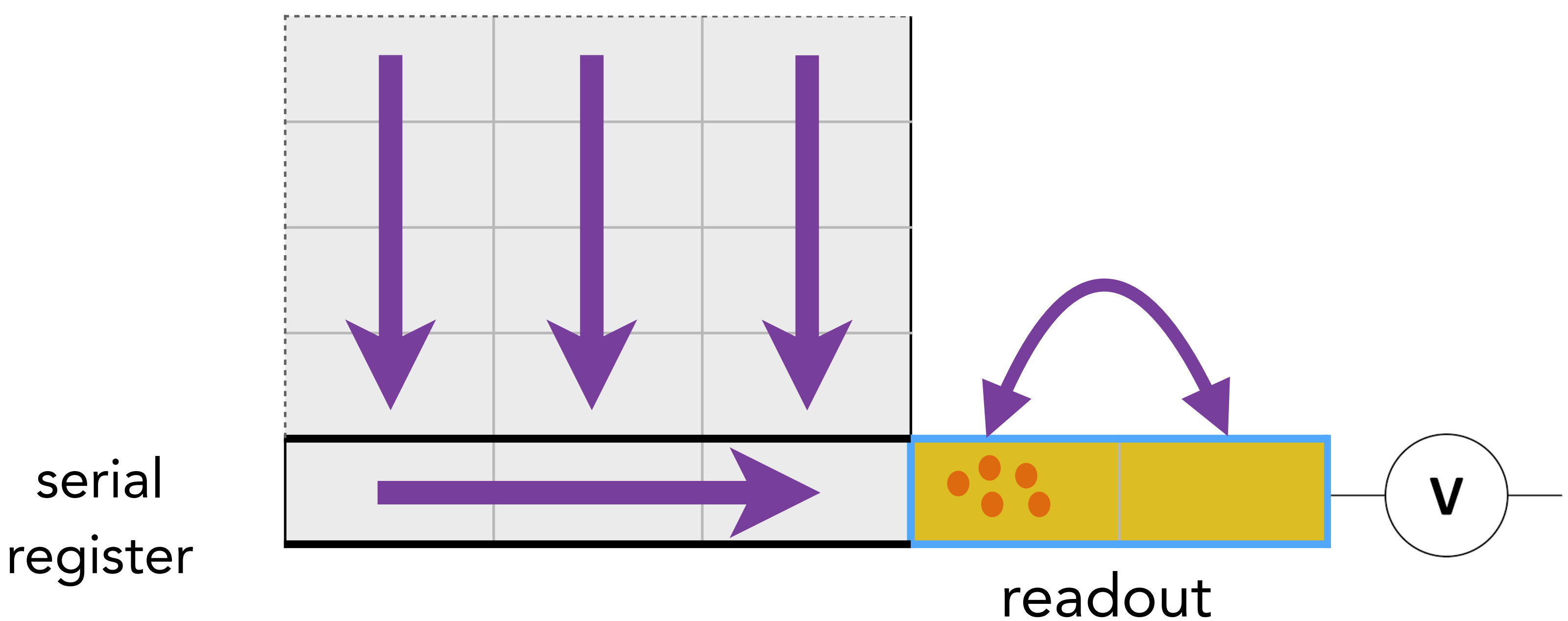
Skipper-CCD operation



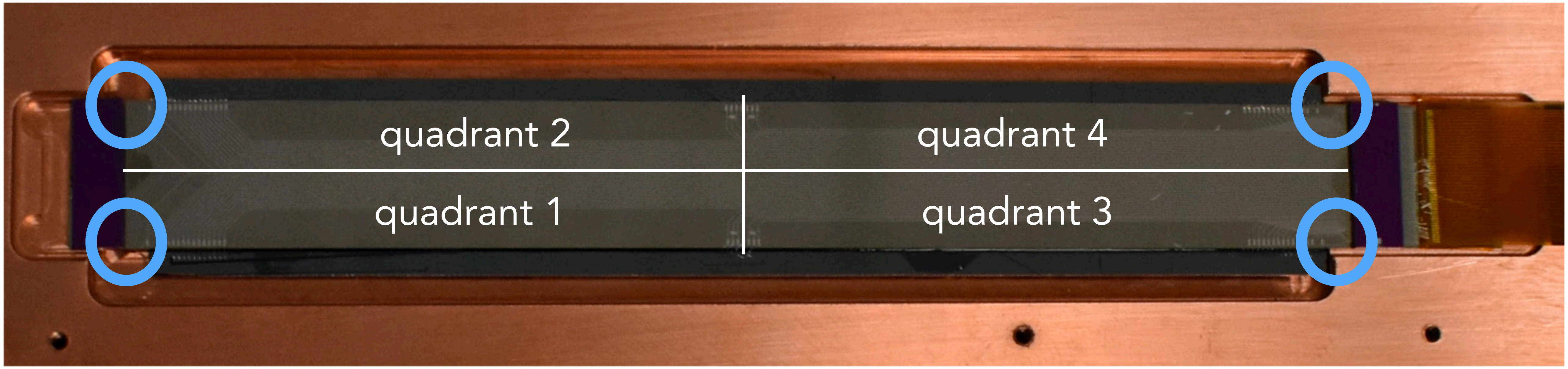


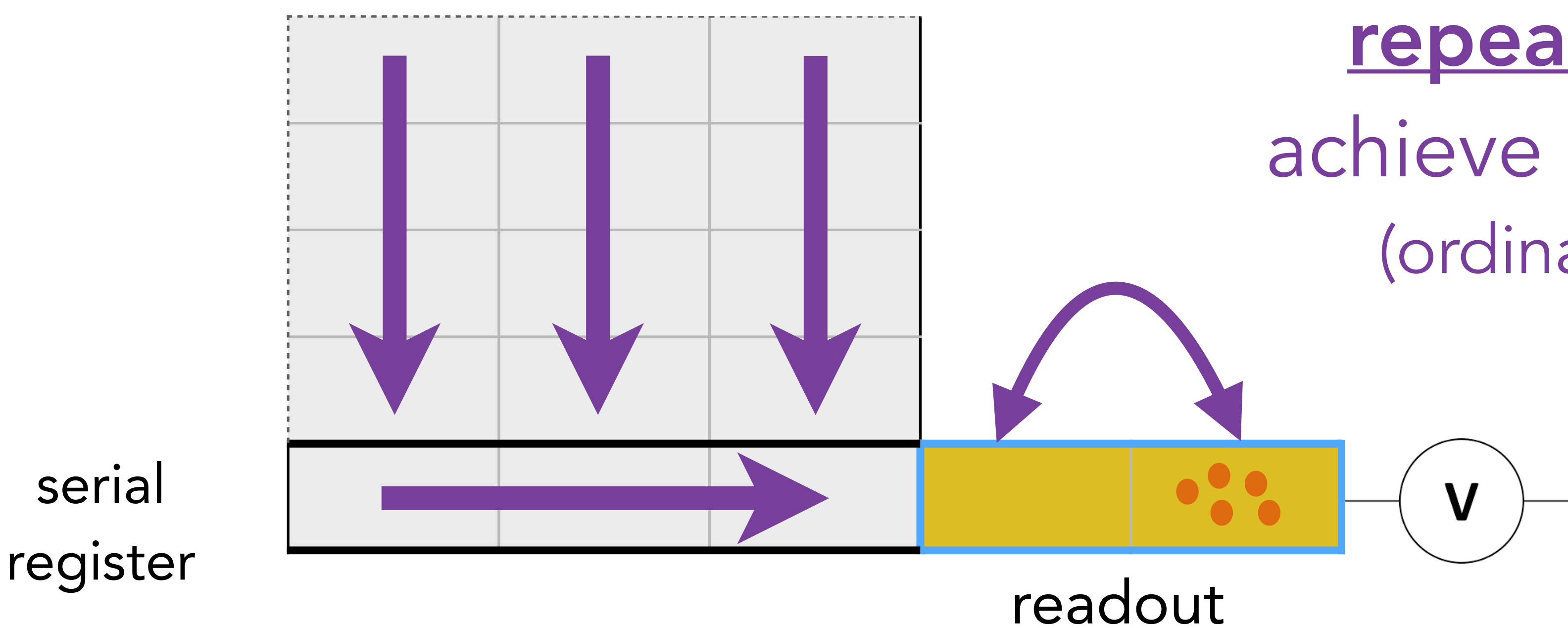
Skipper-CCD operation





Skipper-CCD operation

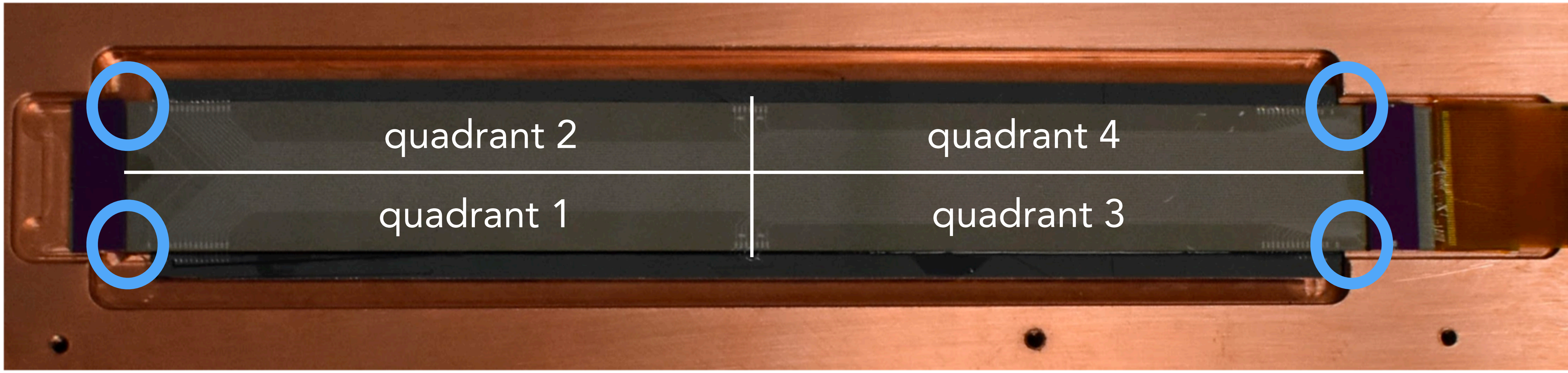


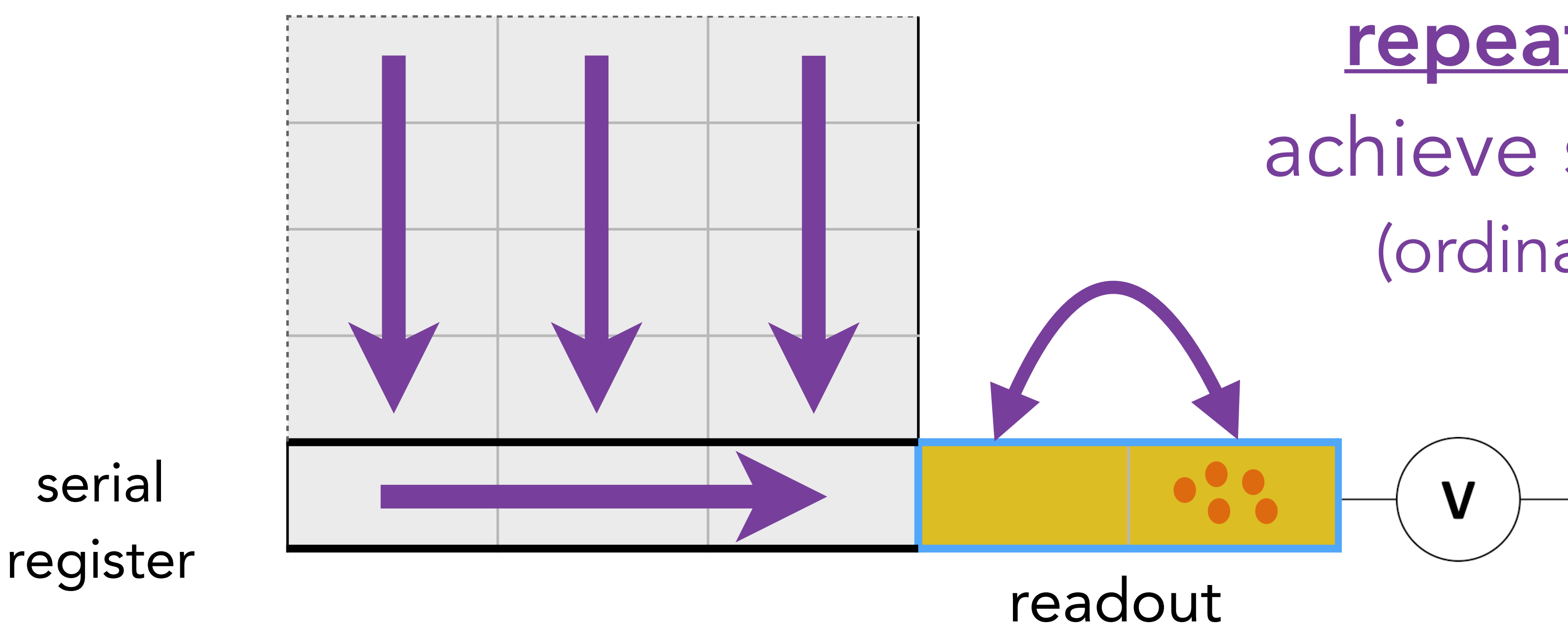


repeatedly measure charge to achieve sub-electron readout noise
(ordinary CCD measures only **once**)

Tiffenberg et.al. 2017

Skipper-CCD operation





repeatedly measure charge to achieve sub-electron readout noise
(ordinary CCD measures only **once**)

Tiffenberg et.al. 2017

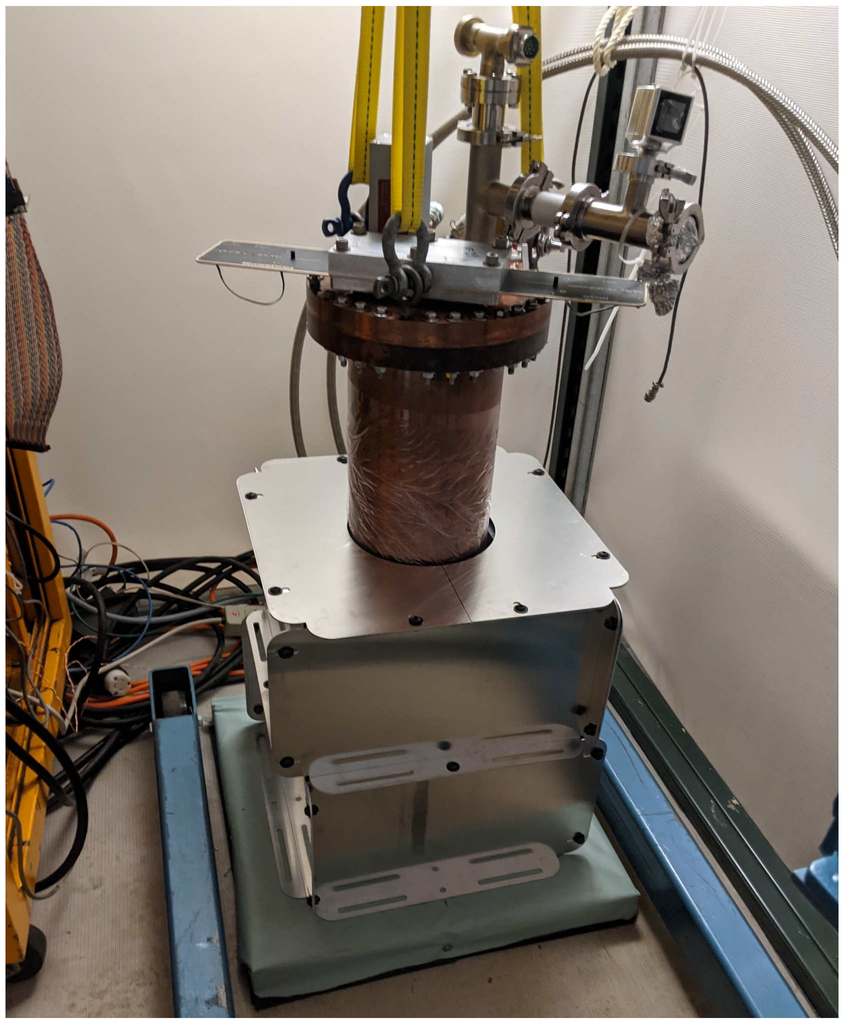
can **precisely** measure charge in each pixel, enabling a super-sensitive search for DM

“SENSEI”

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

SENSEI has two DM detectors operating, which have produced numerous world-leading DM results

@Fermilab (near Chicago)



~100 m underground

(near MINOS detector)

@SNOLAB, Canada

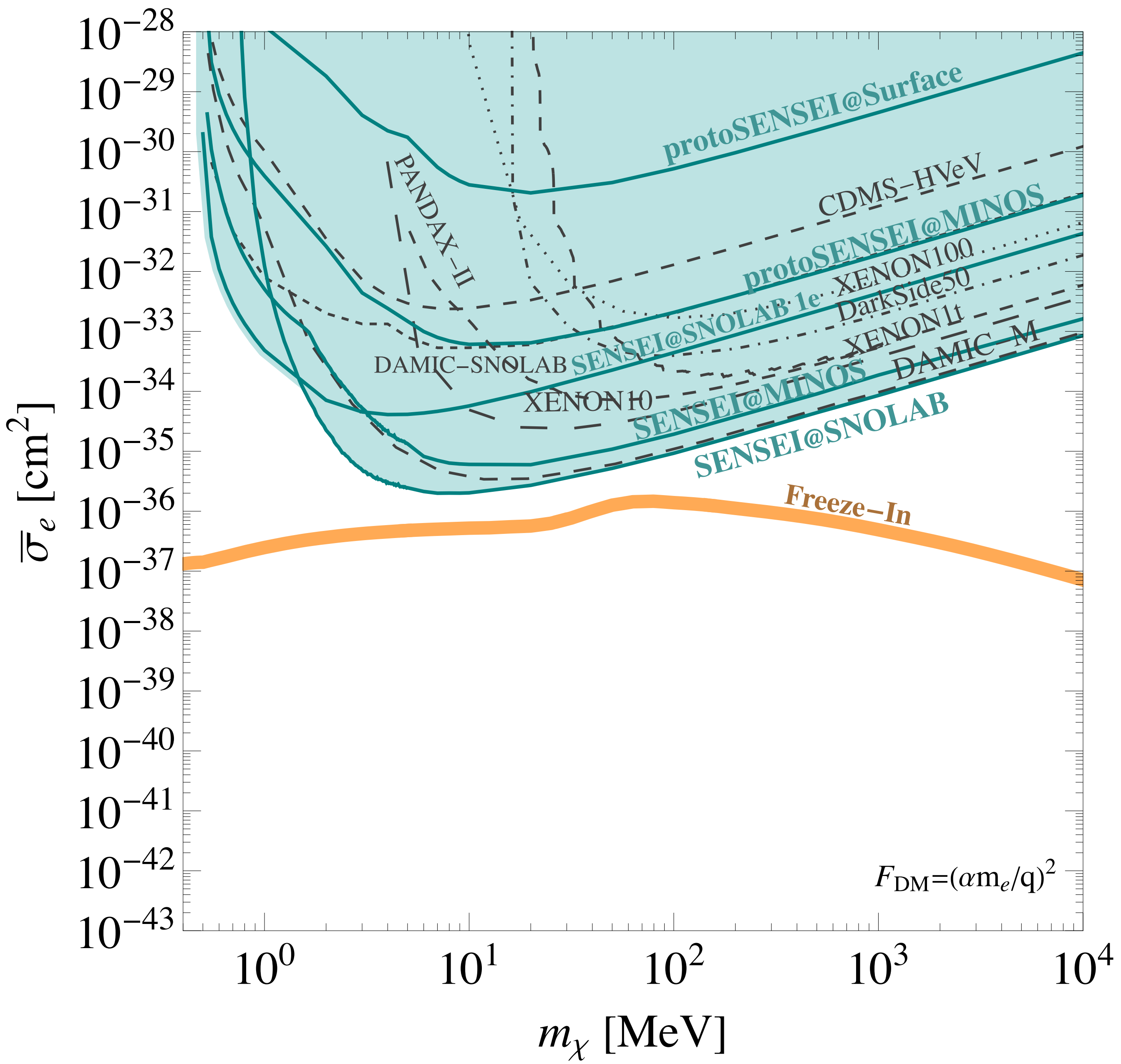
~2,000 m underground

SENSEI Milestones

2017	2018-2019	2020	2021-2023	2024-2026
• Demonstrate Skipper-CCD	0.1g (prototype) • surface • MINOS	• 2g at MINOS • discovered novel backgrounds	• 1e background • mCP search • 12g at SNOLAB	• 1e record • modulation • charge traps • 40g at SNOLAB (ongoing)
1706.00028, PRL	1804.00088, PRL 1901.10478, PRL	2004.11378, PRL Du, RE, Egaña-Ugrinovic, Sholapurkar (2011.13939, PRX)	2106.08347, PRA 2305.04964, PRL 2312.13342, PRL	2410.18716, PRL 2510.20889, PRL (sub.) 2510.23336, PRA (sub.)

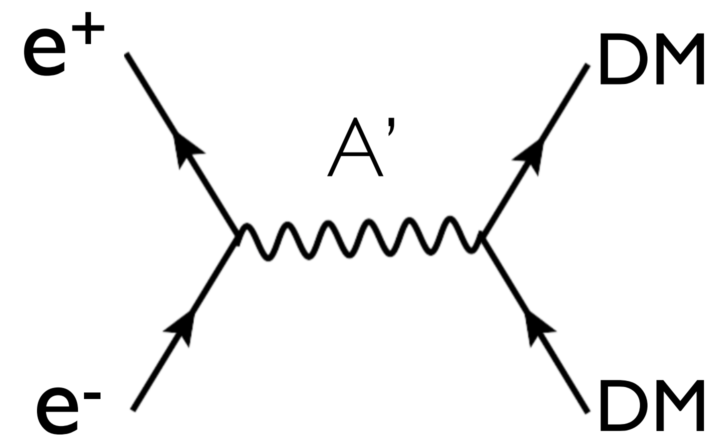
Building up from 0.1 g to 40 g (now) and beyond, w/ each step providing world-leading sensitivity to dark matter

Example of SENSEI Results



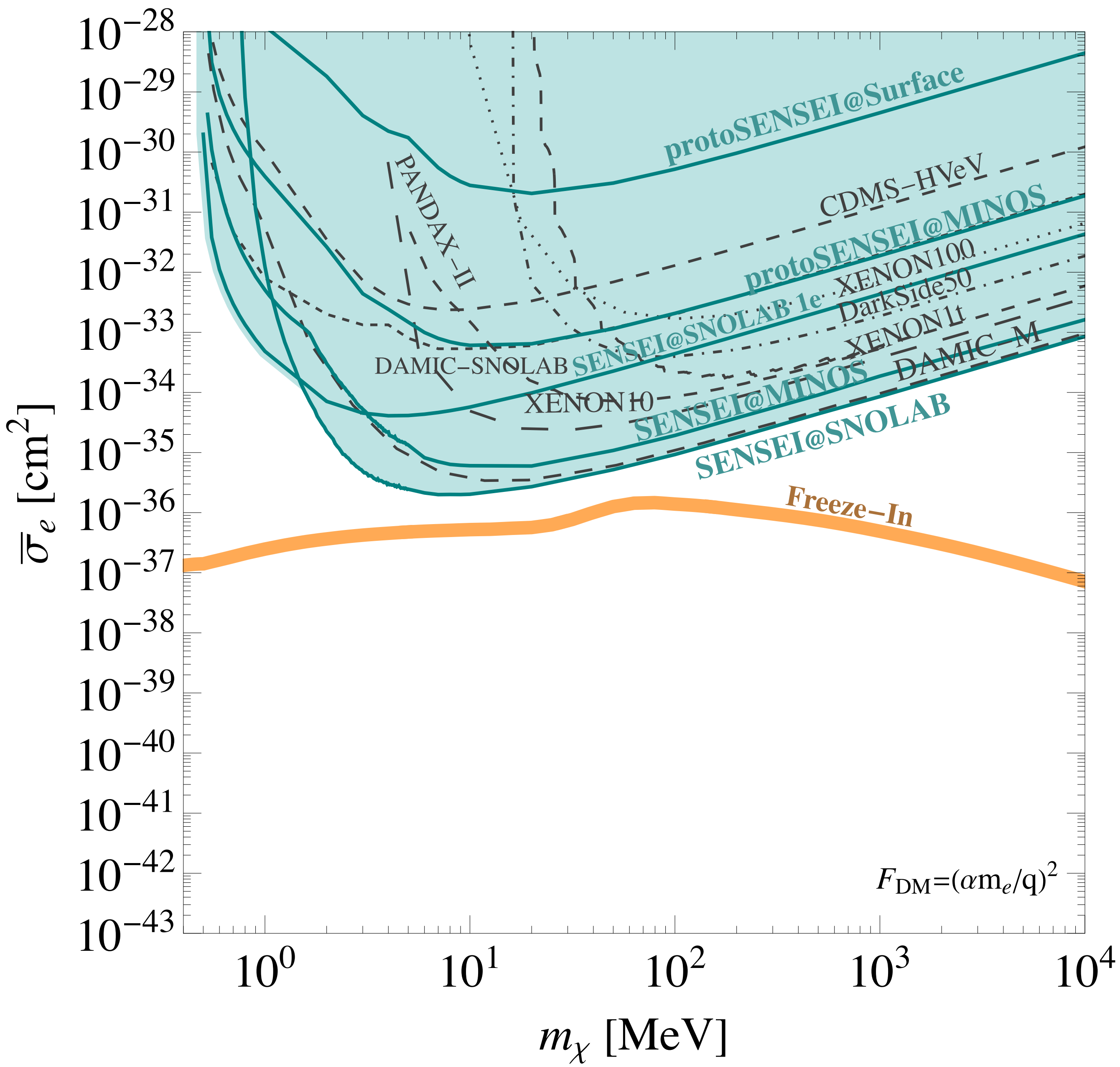
- orange line: "freeze-in DM"

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



other models in backup

Example of SENSEI Results

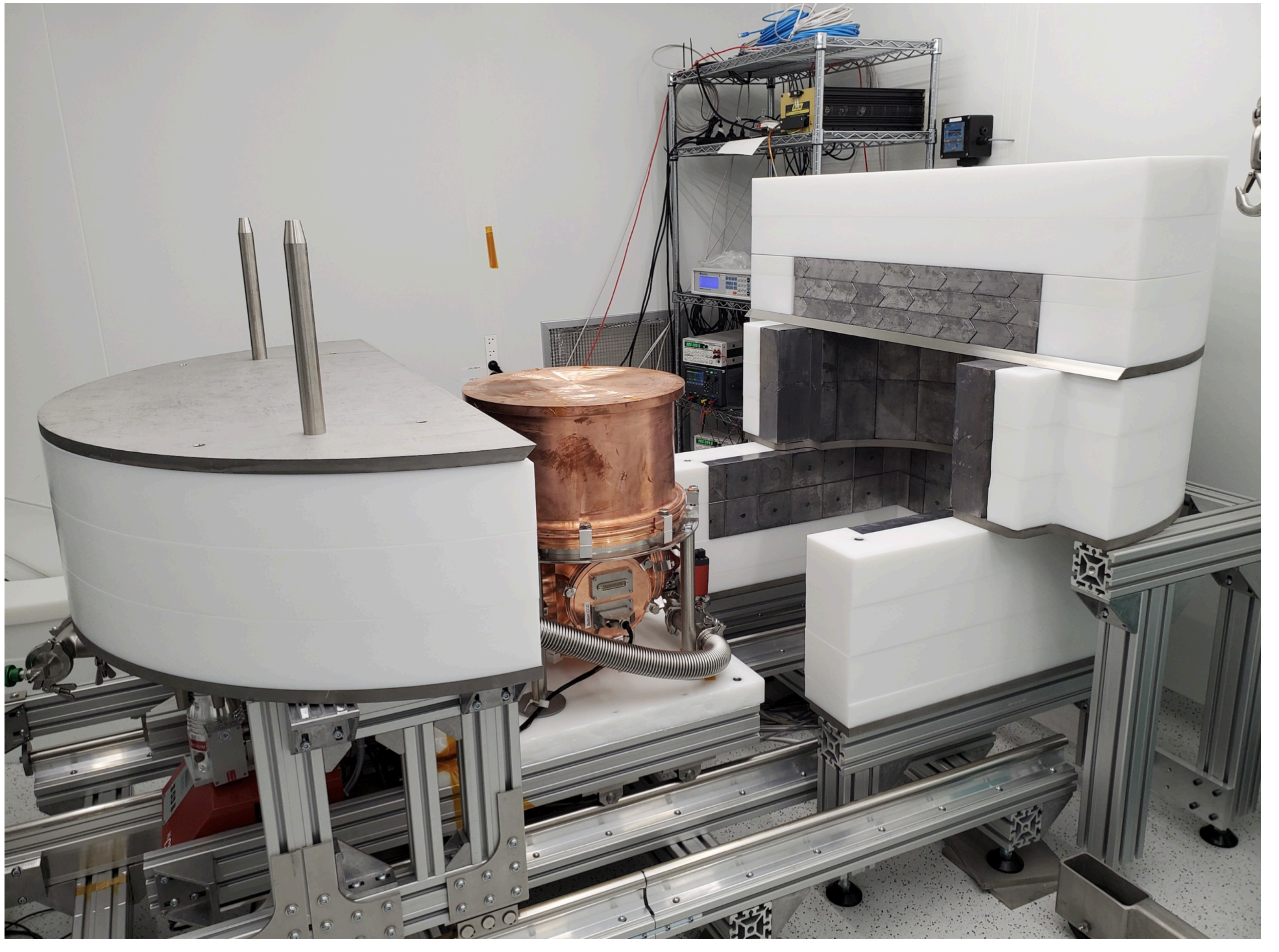


- orange line: "freeze-in DM"

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

- Detector upgraded, new science run ongoing

The next step: DAMIC-M

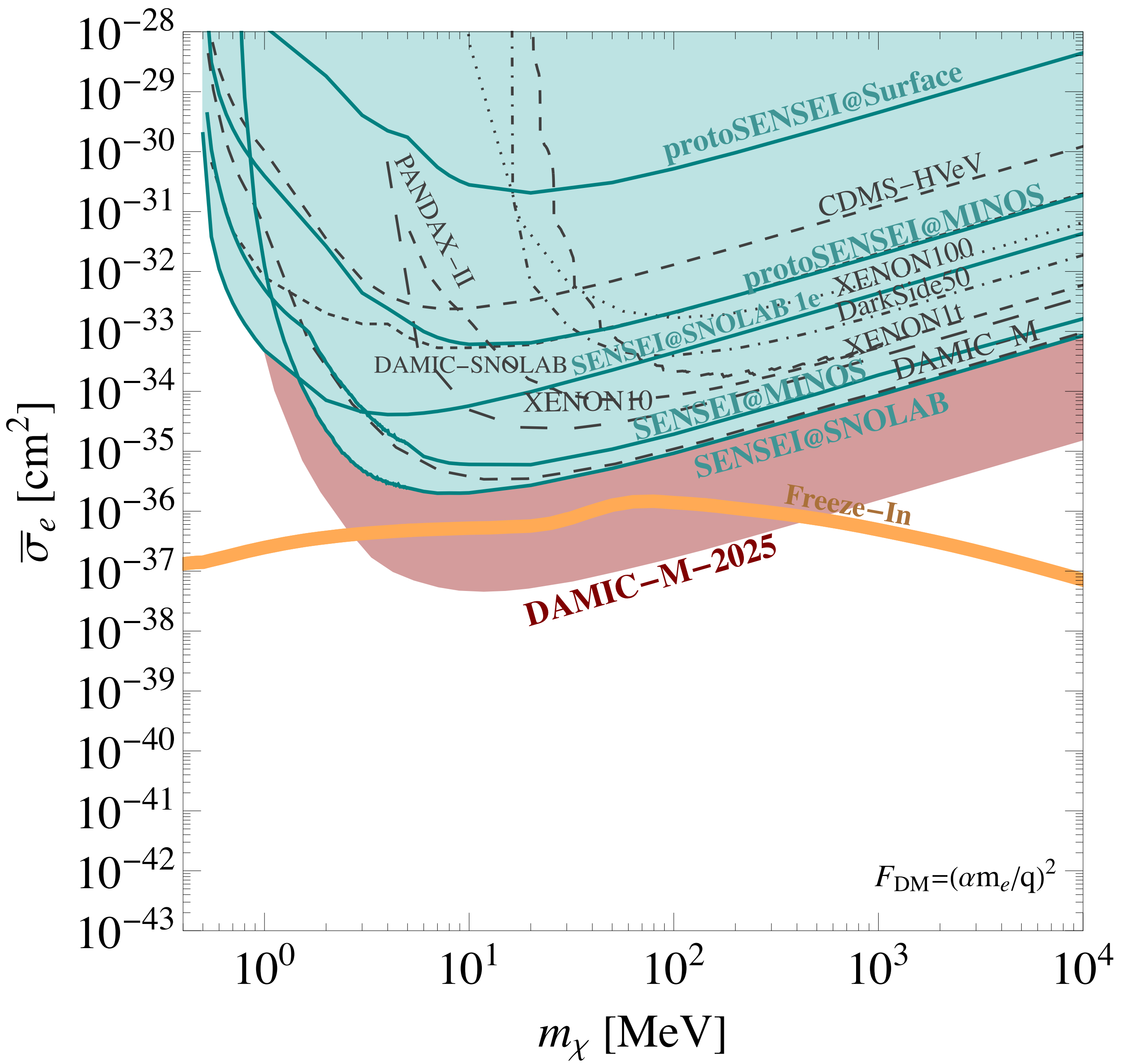


from:
2407.17872

- @Modane (~1,700 m underground)
- DM results in 2023 and 2025

2302.02372
2503.14617

Example of DAMIC-M results



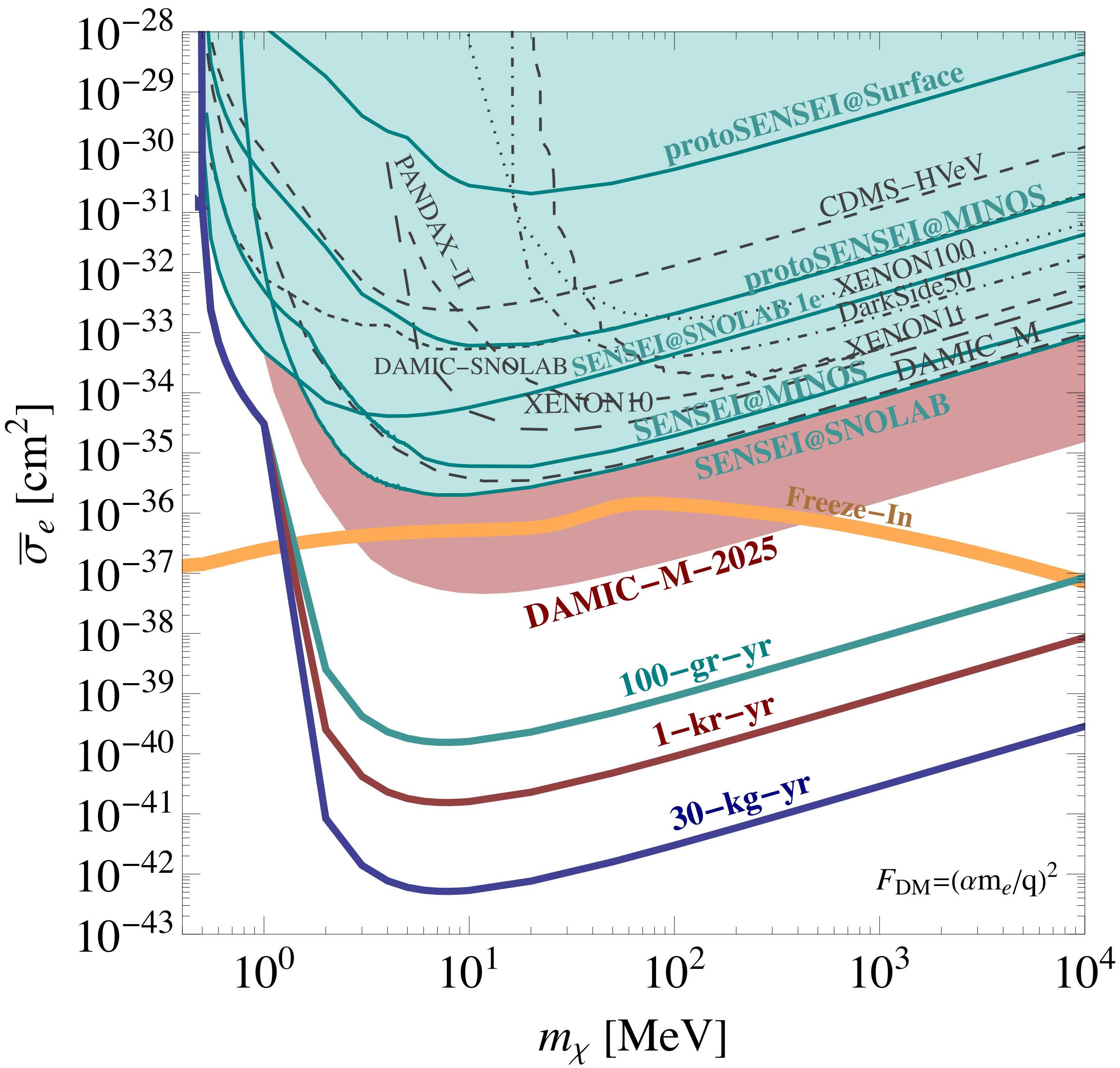
- 26.4 g; exposure ~1.3 kg-day

2503.14617

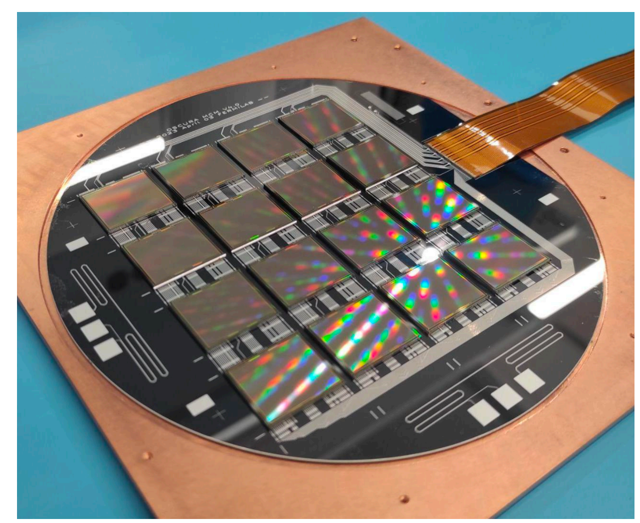
- probing theory benchmarks

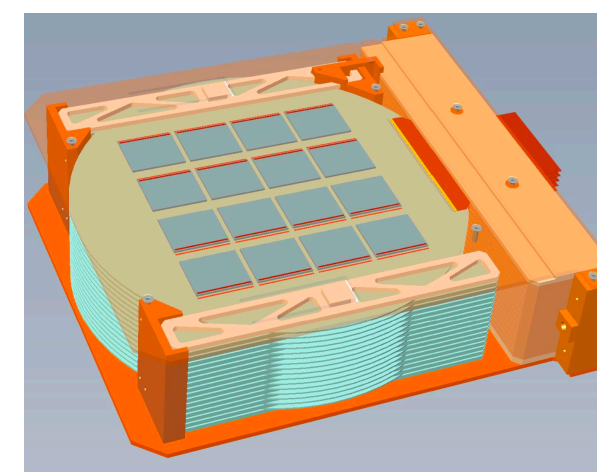
- next step: increase mass to ~700 g

Exciting Skipper-CCD Program ahead



- SENSEI: ~40 gram (SNOLAB)
- DAMIC-M: ~700 g (Modane)
- Oscura: ~10 kg (R&D funded)



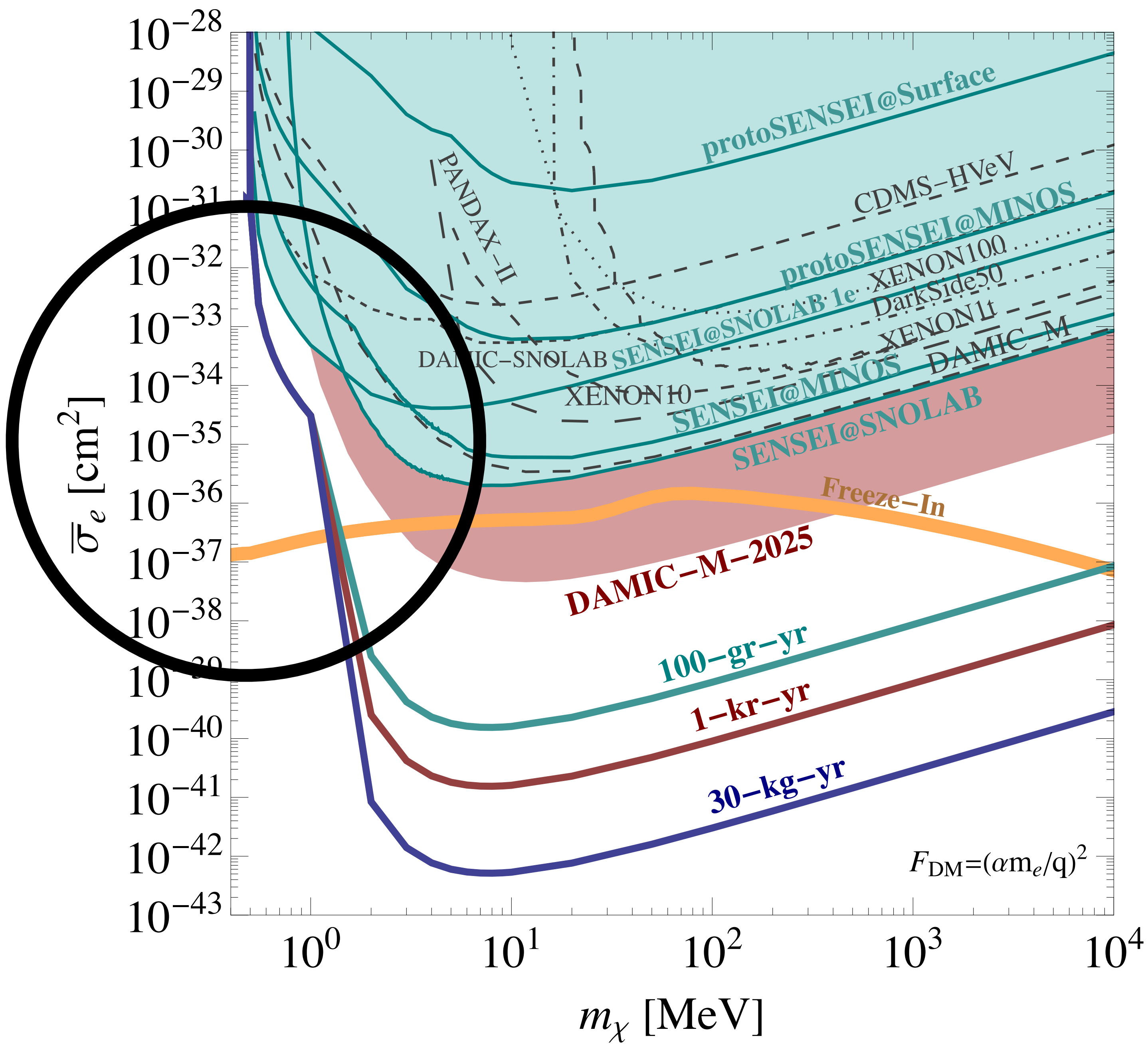


Main challenge: controlling low-energy backgrounds

Outline

- Detection concepts for sub-GeV Dark Matter
- SENSEI & other Skipper-CCD experiments
- → Probing sub-MeV DM & DM w/ large interactions

What about probing sub-MeV DM?



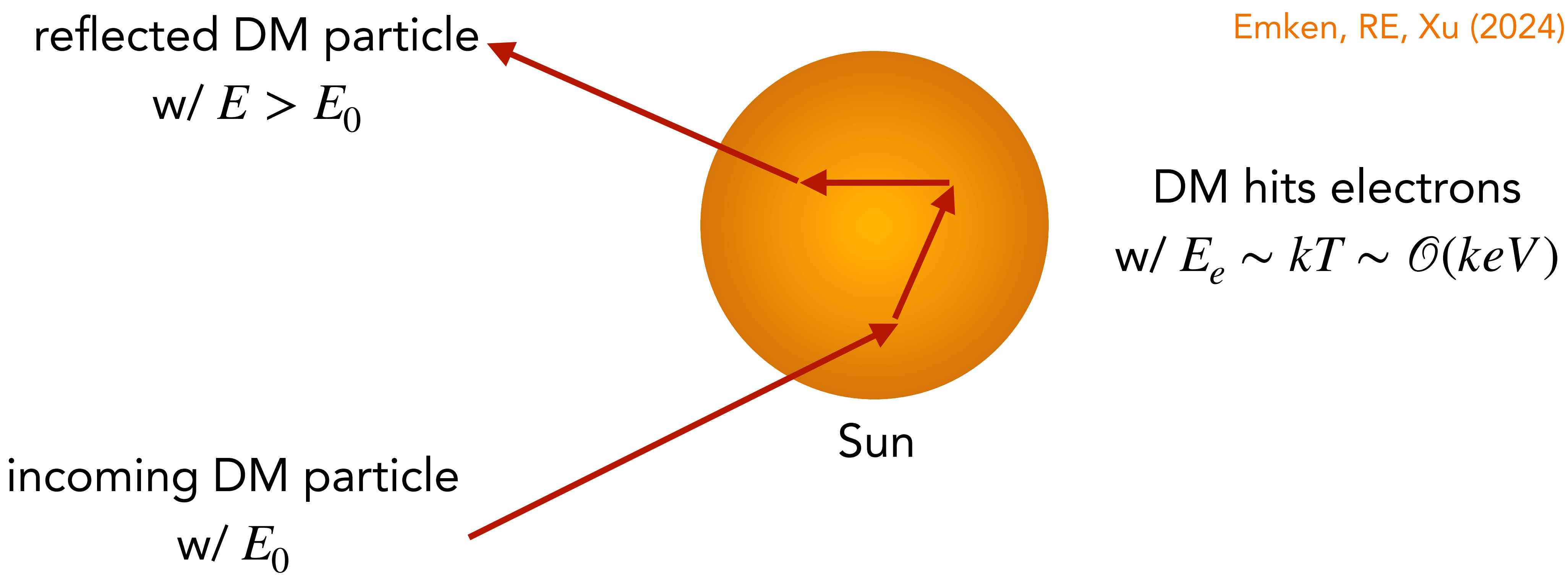
Several ideas requiring R&D exist, but can also use silicon and noble-liquid detectors

e.g., Superconductors: Hochberg, Zhao, Zurek (1504.07237); Hochberg, Pyle, Zhao, Zurek (1512.04533);
Dirac materials: Hochberg (1708.08929);
Superfluid Helium: Knapen, Lin, Zurek, (1611.06228);
Optical phonons in polar materials: Knapen, Lin, Pyle, Zurek (1712.06598);
Doped semiconductors: Du, Egaña-Ugrinovic, RE, Sholapurkar (2212.04504)

Dark Matter can scatter and accelerate in Sun

before DM scatters in detector, it can scatter in the Sun

An, Pospelov, Pradler, Ritz (2018)
Emken, Kouvaris, Nielsen (2018)
Emken (2021)
An, Nie, Pospelov, Pradler (2021)
Emken, RE, Xu (2024)



boosts sub-MeV DM particles to **large velocities**, allowing them to be detected in, e.g., a silicon or xenon detector

"Solar-reflected DM" Flux

$m_\chi = 100$ keV

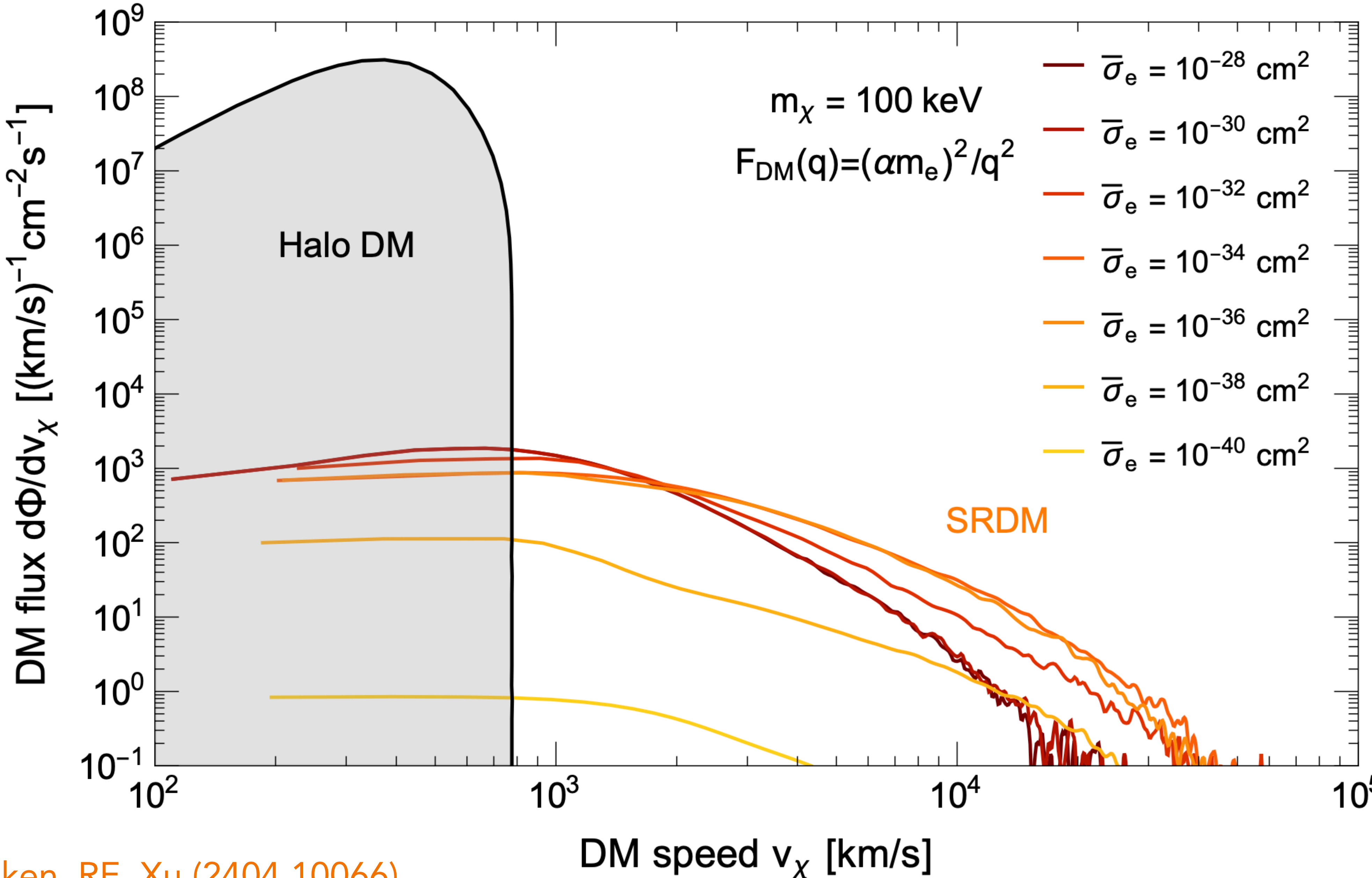


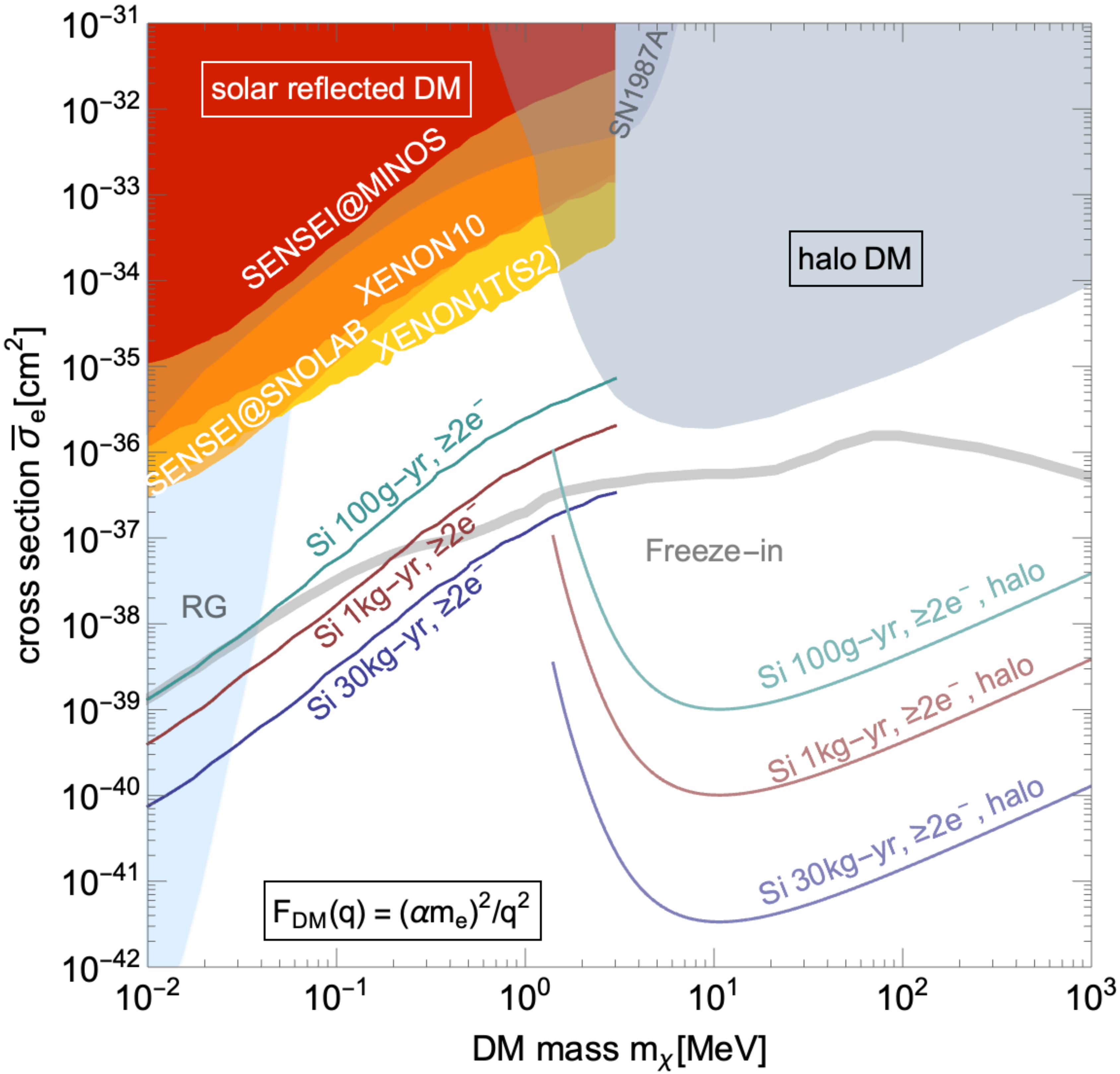
Fig: Emken, RE, Xu (2404.10066)

get high-velocity component

Constraints & Projections on Solar-reflected DM

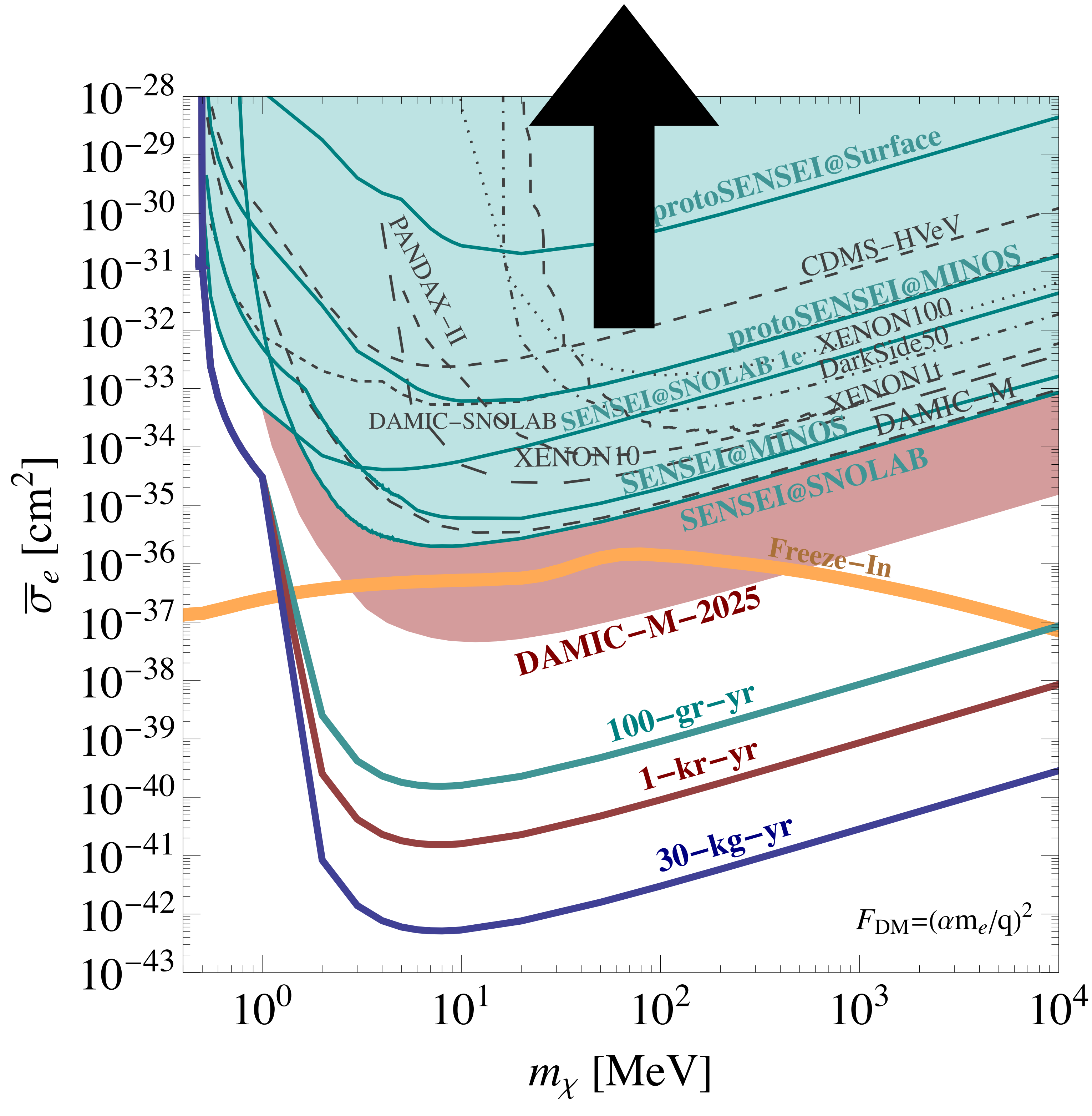
Emken, RE, Hailin Xu (2404.10066)

An, Nie, Pospelov, Pradler (2108.10332)



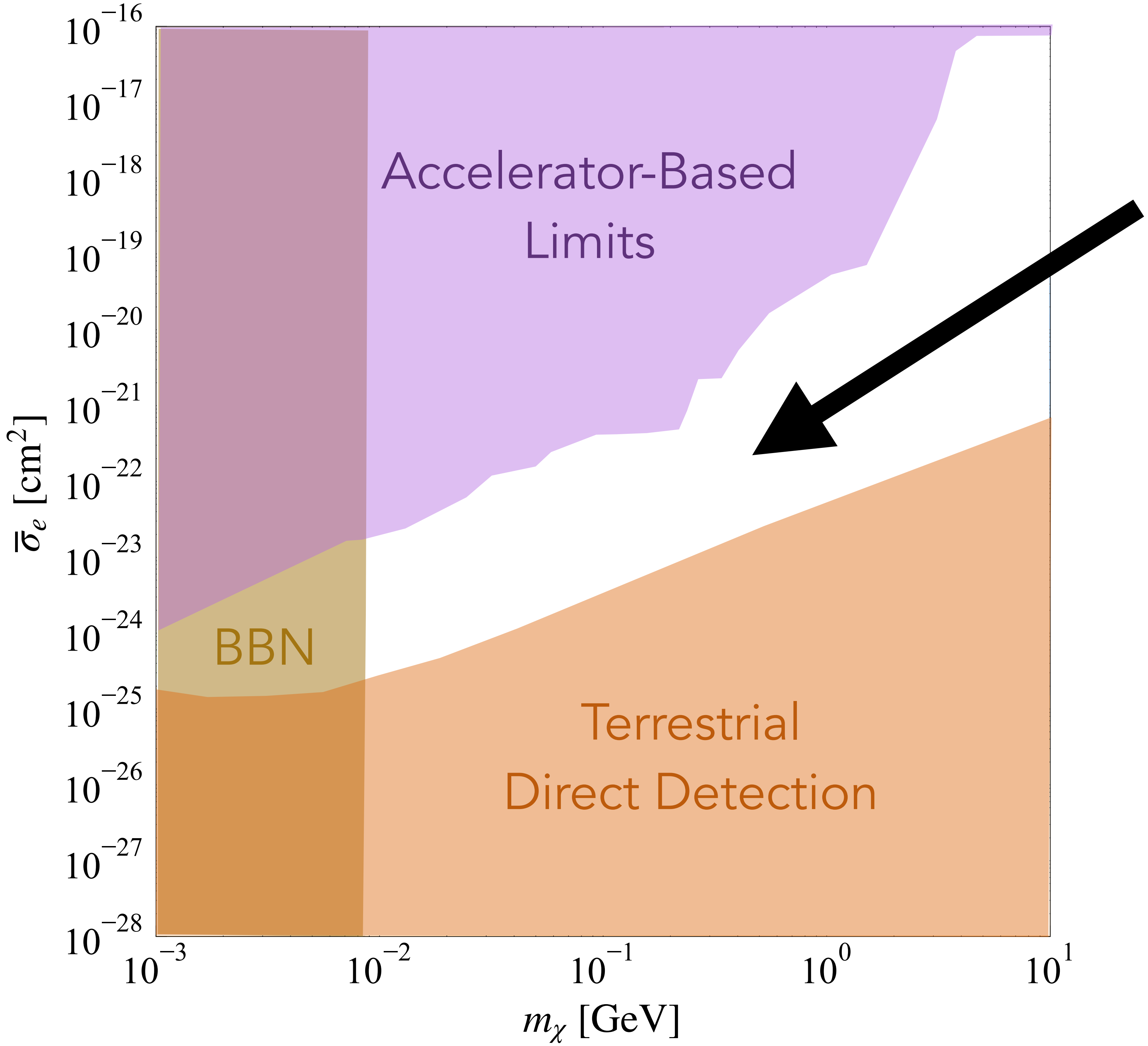
Si detector
(e.g. Oscura)
can in principle
probe entire
“freeze-in target”

What about DM w/ very large interactions?



A subcomponent of DM could have very large interactions

(e.g., DM that has an effective millicharge)



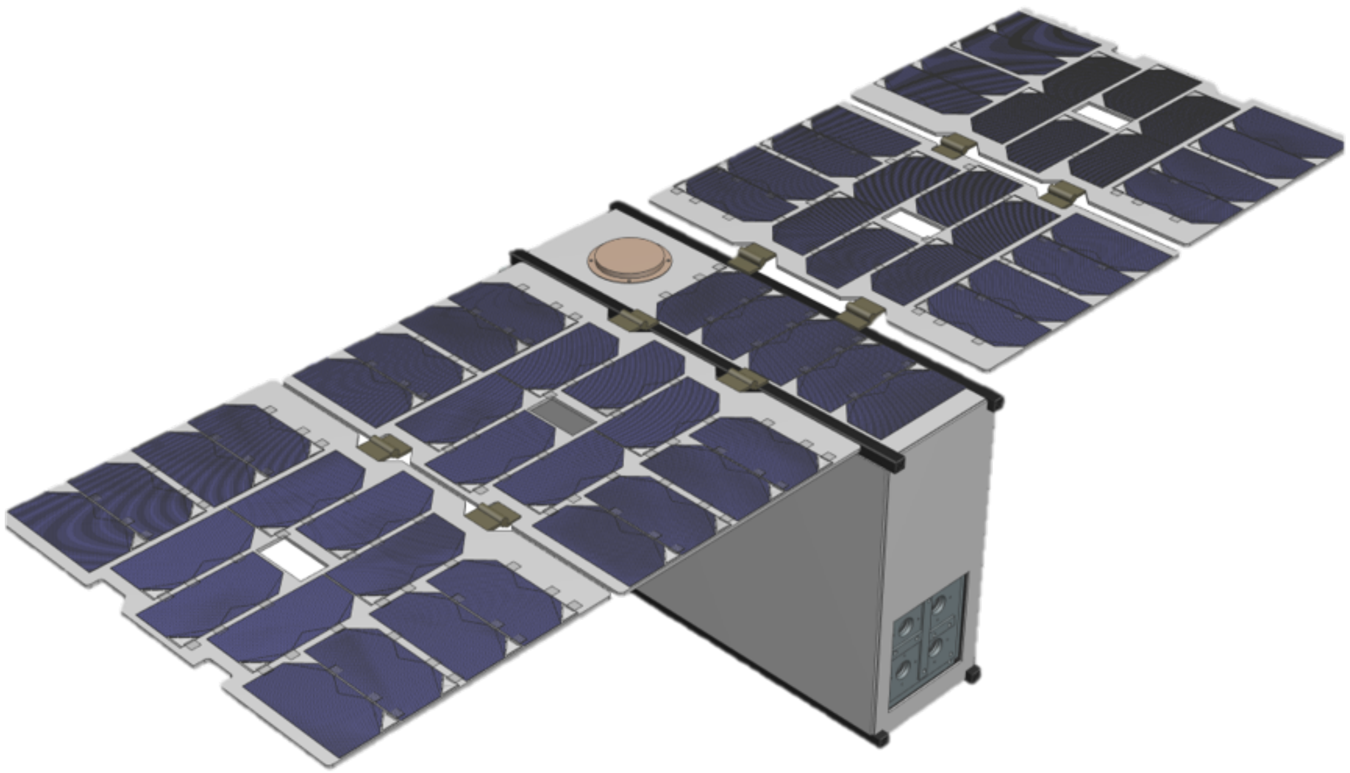
DM cannot penetrate atmosphere to reach detector…

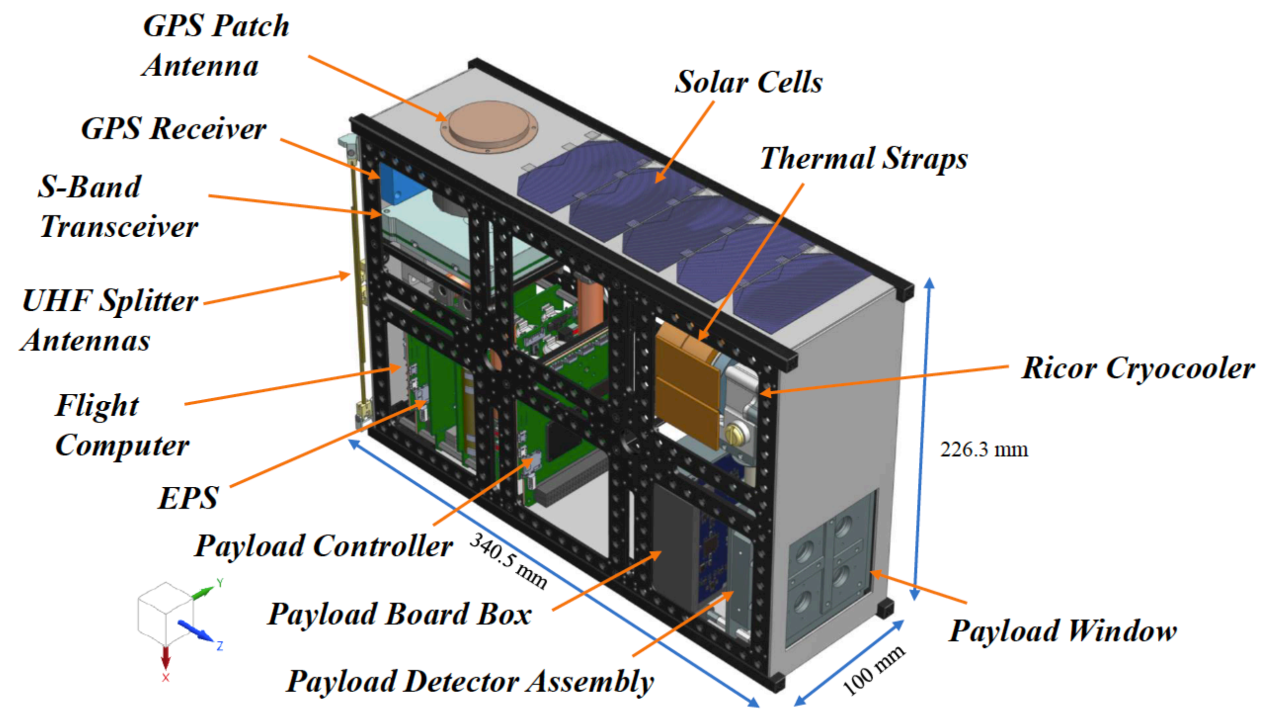
no bounds from usual direct detection!

Probe this region w/ detectors on a balloon or satellite

(schematic)

The DarkNESS mission





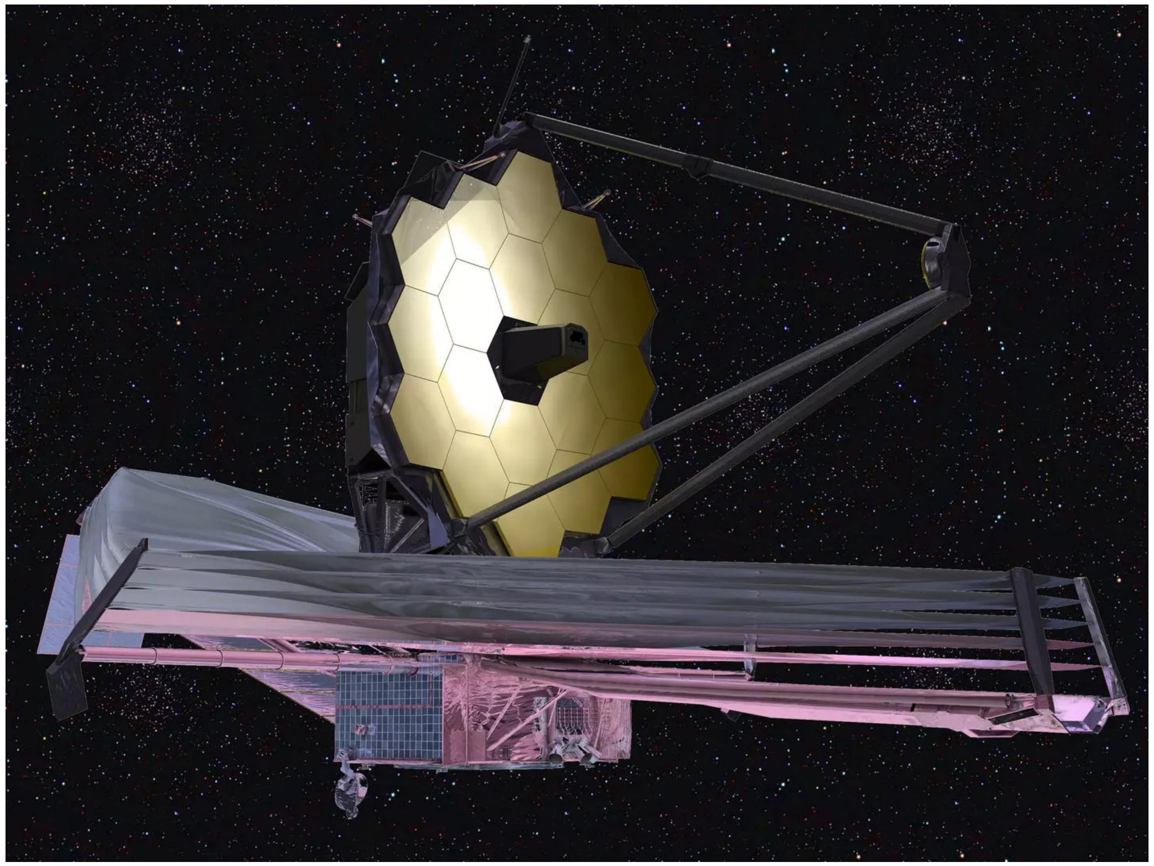
- Four 1.3 Mpix **Skipper-CCDs** on a CubeSat
- Goals: probe strongly interacting DM & decaying DM, demonstrate Skipper-CCD operation in space
- expected launch in 2026
- ~2 years in orbit

e.g., 2505.16981

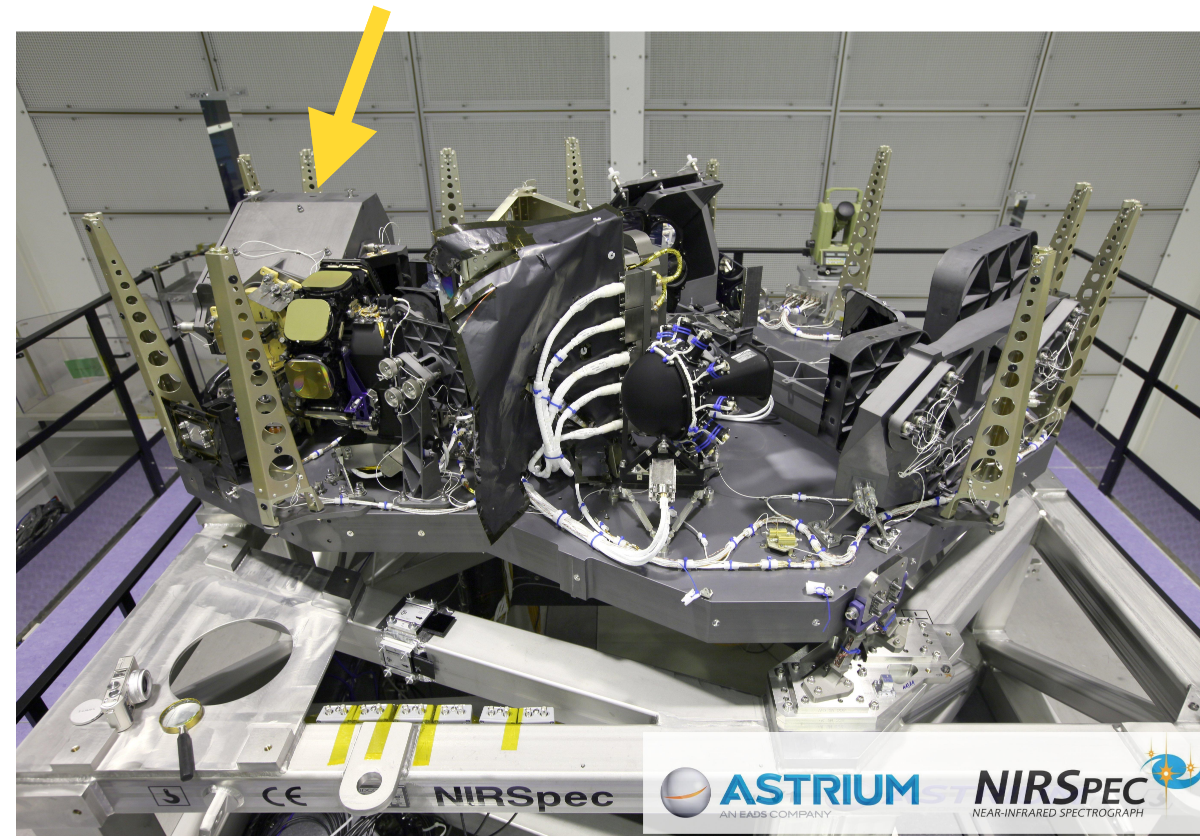
What about using existing detectors in space?

Use JWST NIRSpec detectors!

Du, RE, Rauscher, Xu (2412.13131, PRL)



Detectors are in here



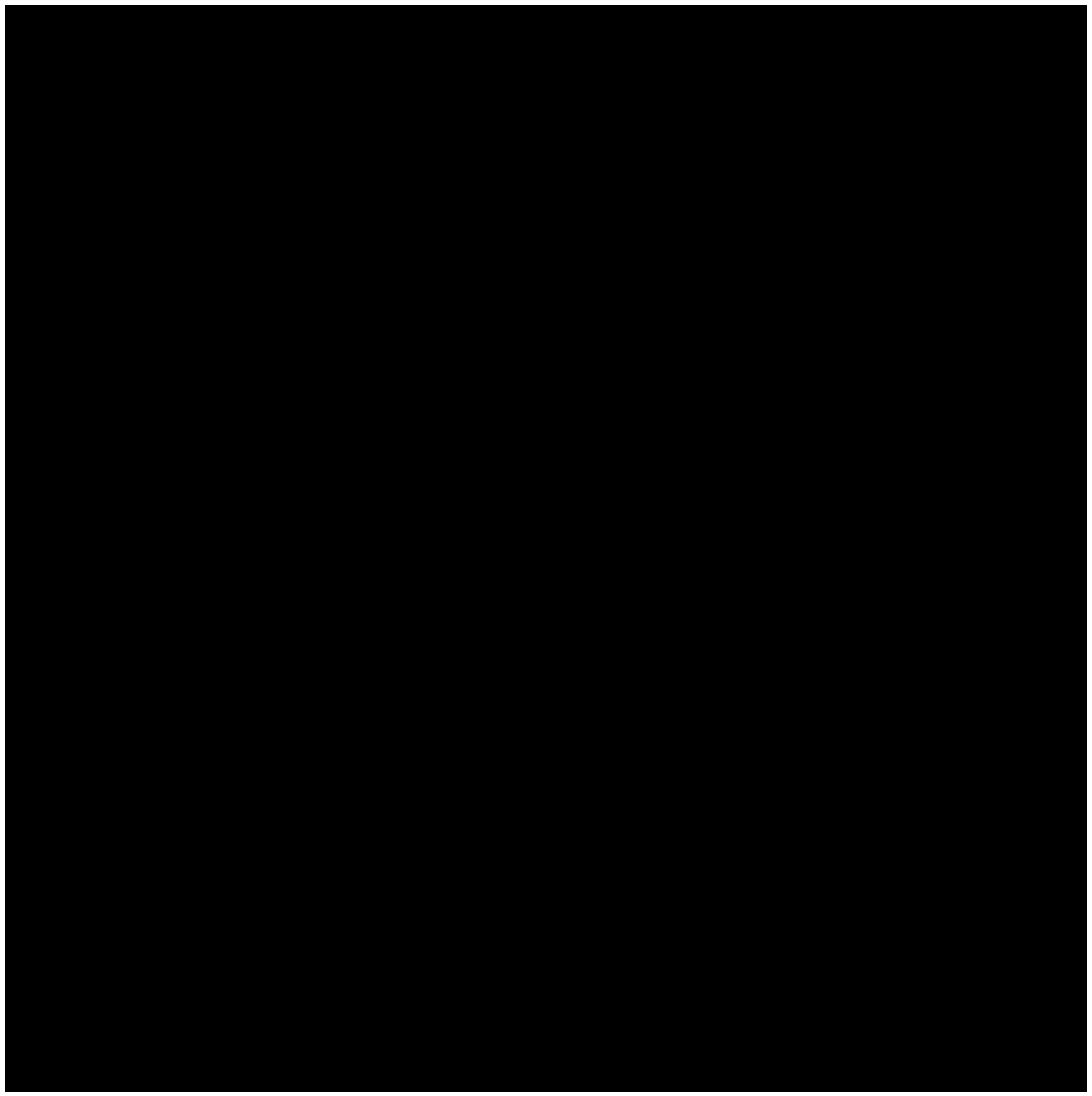
- positioned at L2; little shielding
- Two detectors, each ~4.2 million pixels, 0.05 g
- $E_{\rm gap} = 0.23$ eV
- use "dark" images (w/ closed shutter) to probe DM-e^- scattering

What do JWST’s “dark images” look like?

They obviously don’t look like this!

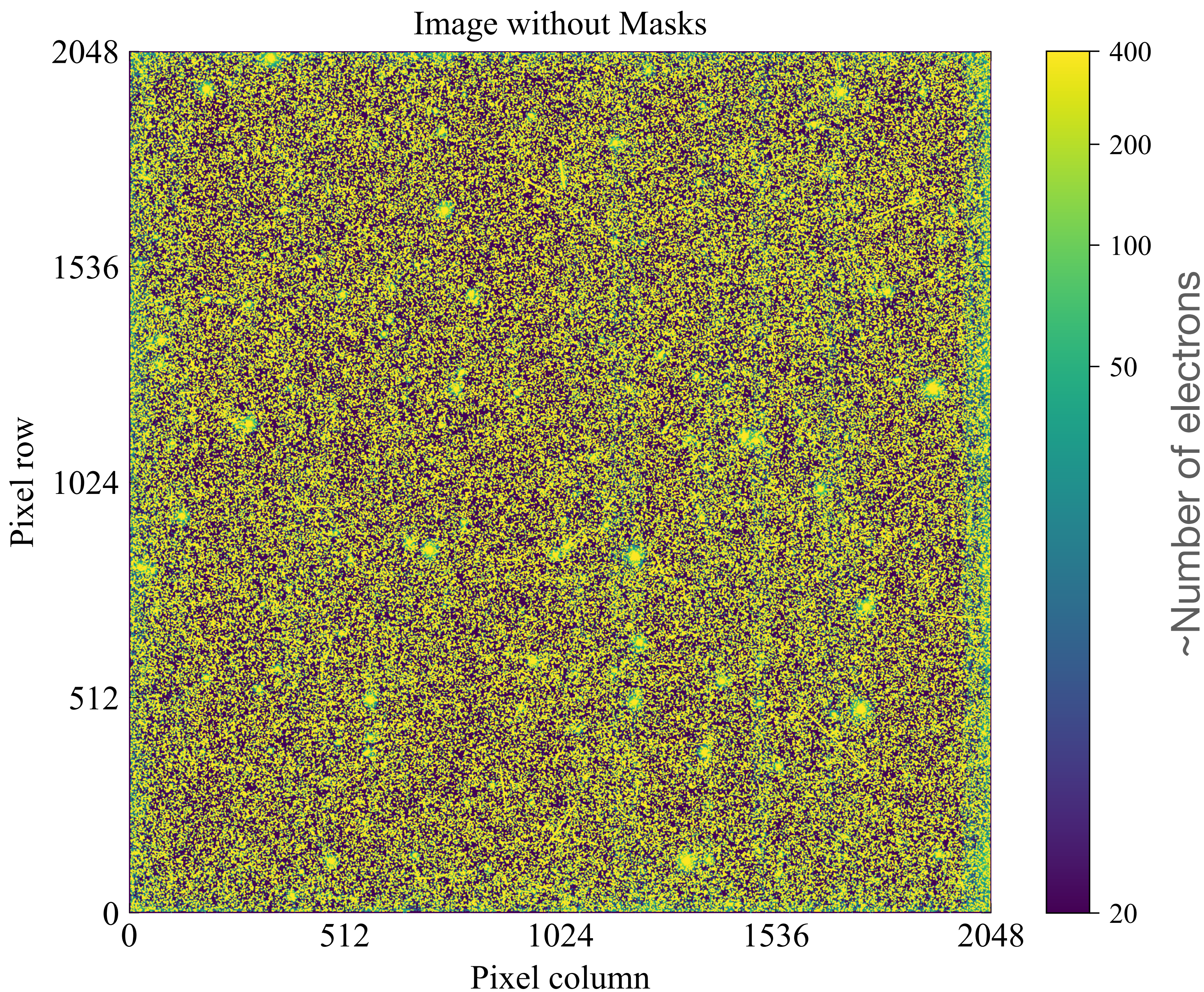
What do JWST's "dark images" look like?

You might think they look like this:



What do JWST's "dark images" look like?

But they actually look like this!



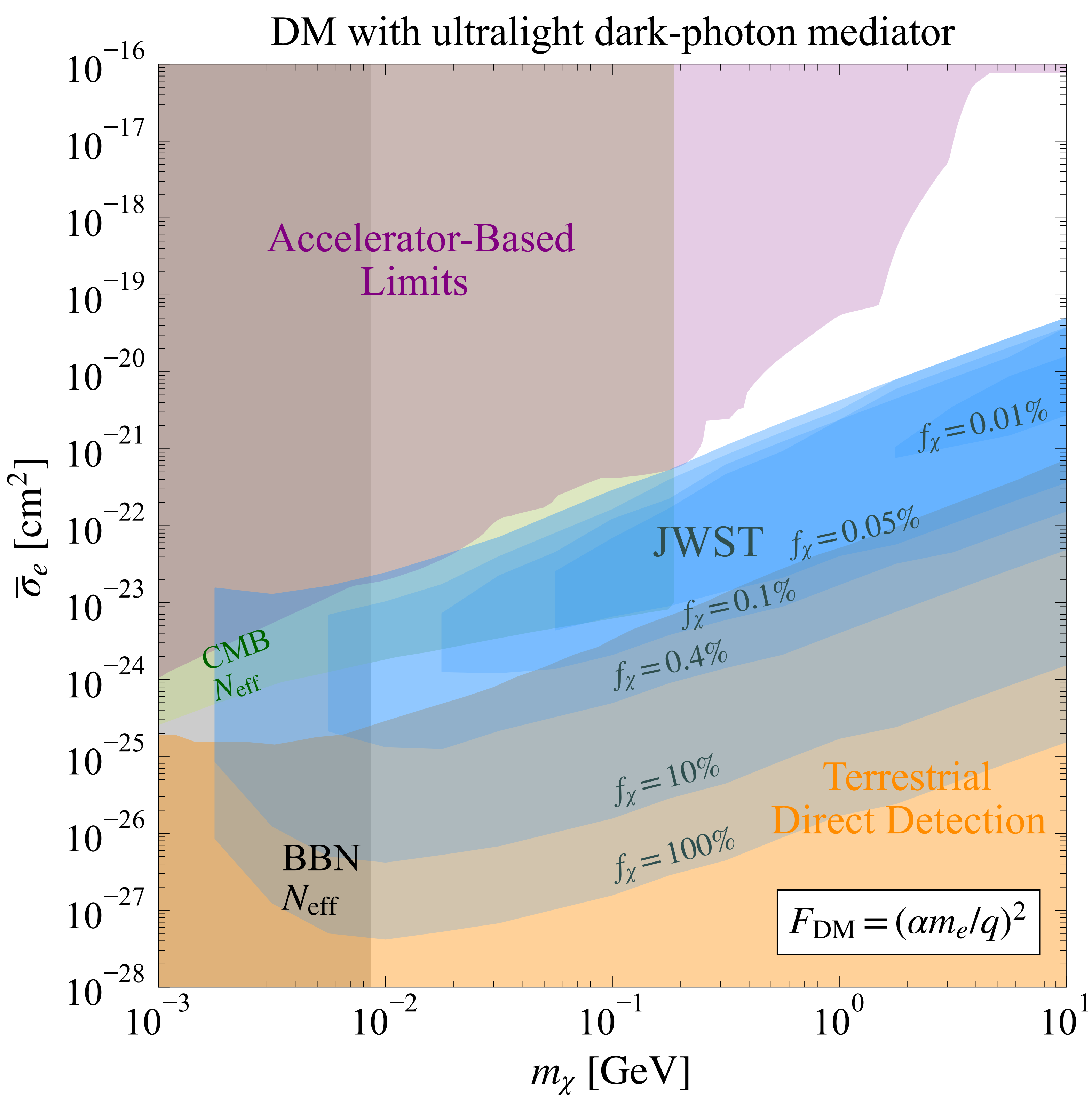
Du, RE, Rauscher, Xu (2412.13131, PRL)

- ~1 hour exposure
- many cosmic-rays, Cherenkov, dark current etc.

To search for DM:

- mask high-energy pixels
- Remaining background is well-fit by dark current, inconsistent w/ DM

Constraints on DM w/ large interactions



bound depends on DM abundance f_χ

Du, RE, Rauscher, Xu (2412.13131, PRL)

Summary

- Goal: uncover the identity of dark matter!
- A wide range of materials and ultrasensitive detectors are used to probe DM across a vast range of masses & various interactions
- This research spans many fields in physics, including particle physics, astrophysics, cosmology, condensed matter physics, AMO, detector & device physics, and quantum sensing