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

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Stony Brook University

Symposium on Science at PAUL, January 16, 2024

About me

- Born and grew up in Johannesburg, South Africa
- undergraduate at Wits University 1998-2002
- went to USA for PhD & postdoc
- Faculty @ Stony Brook U. in New York since 2011
- Particle theorist, but work with many experimentalists (e.g., co-spokesperson of SENSEI)

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

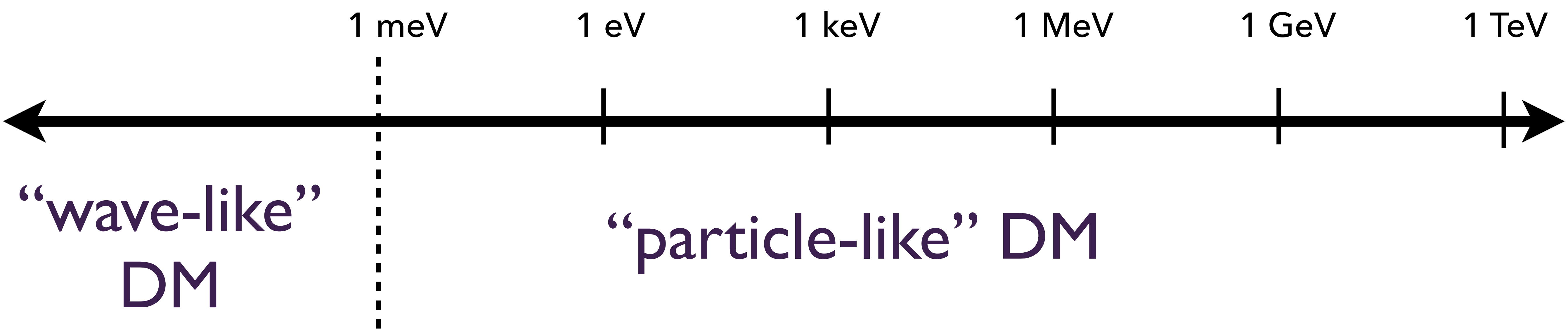
An opportunity for PAUL?

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

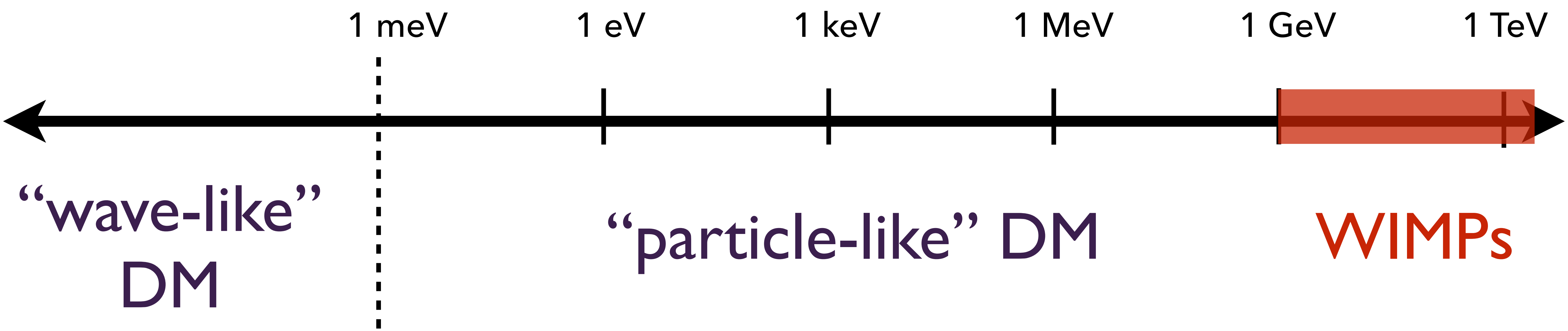
$\gg 100$ papers over past few years

will give brief, incomplete overview,
and focus on one example (SENSEI)

Sub-GeV "particle-like" dark matter



Sub-GeV "particle-like" dark matter



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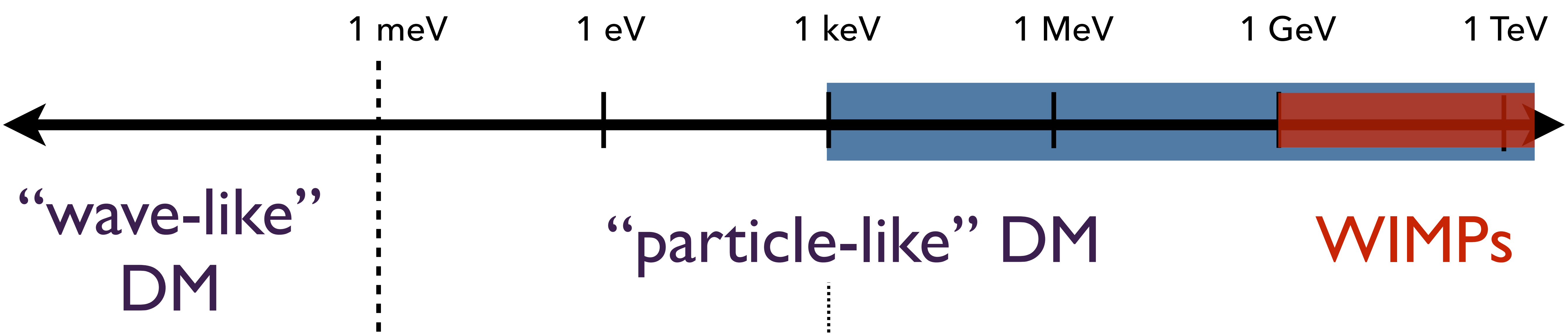
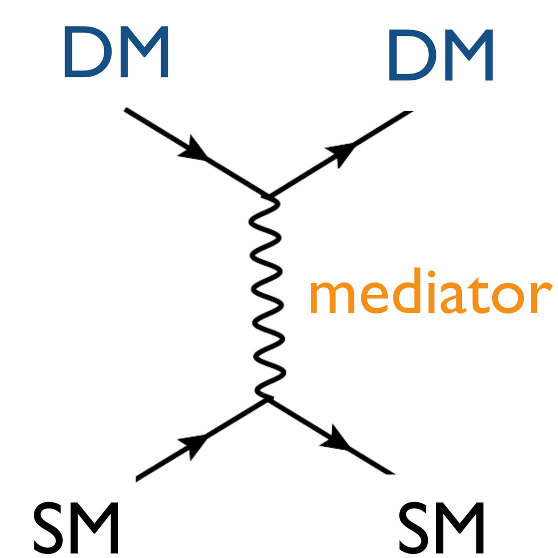
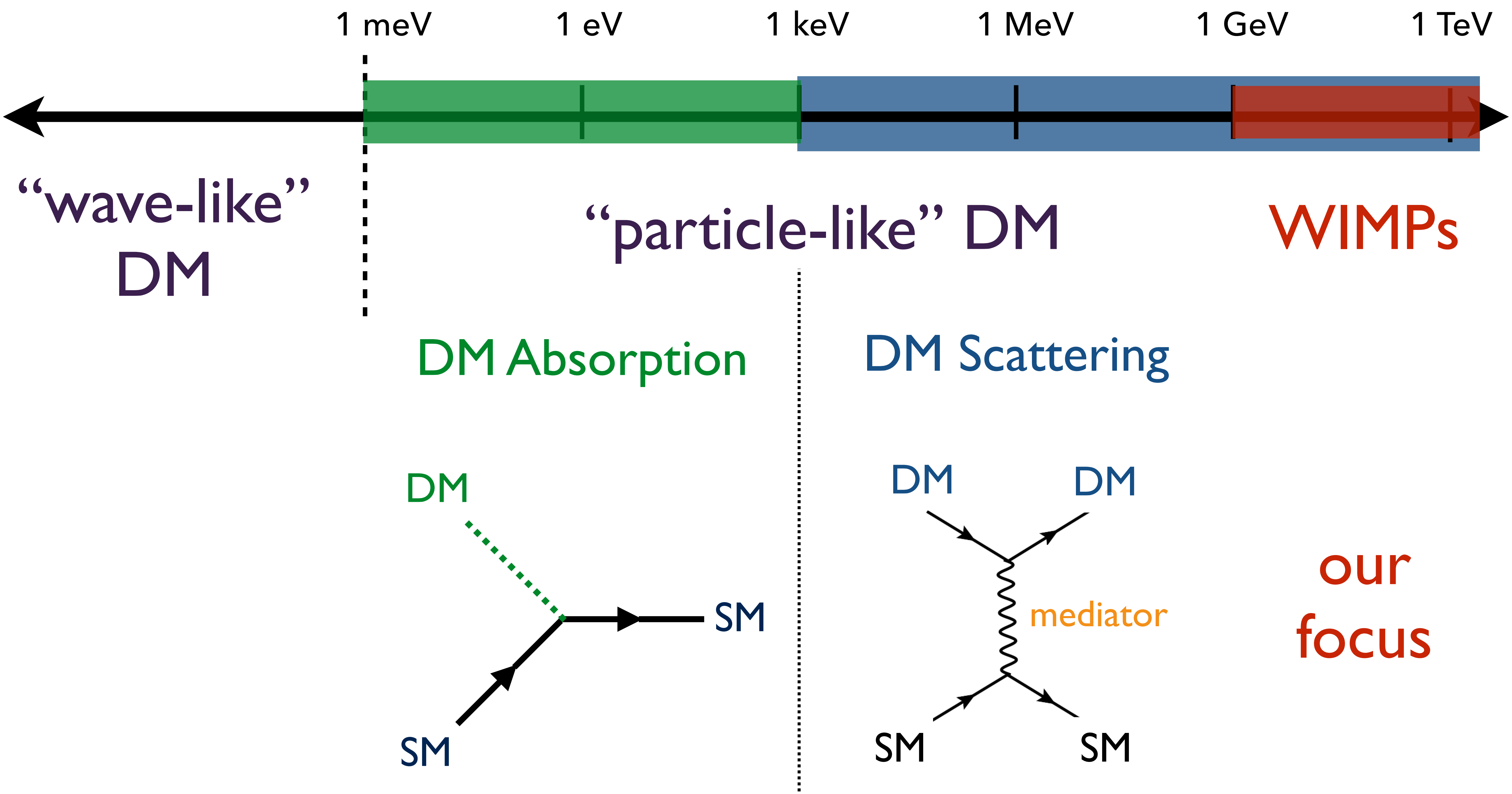


DM Scattering



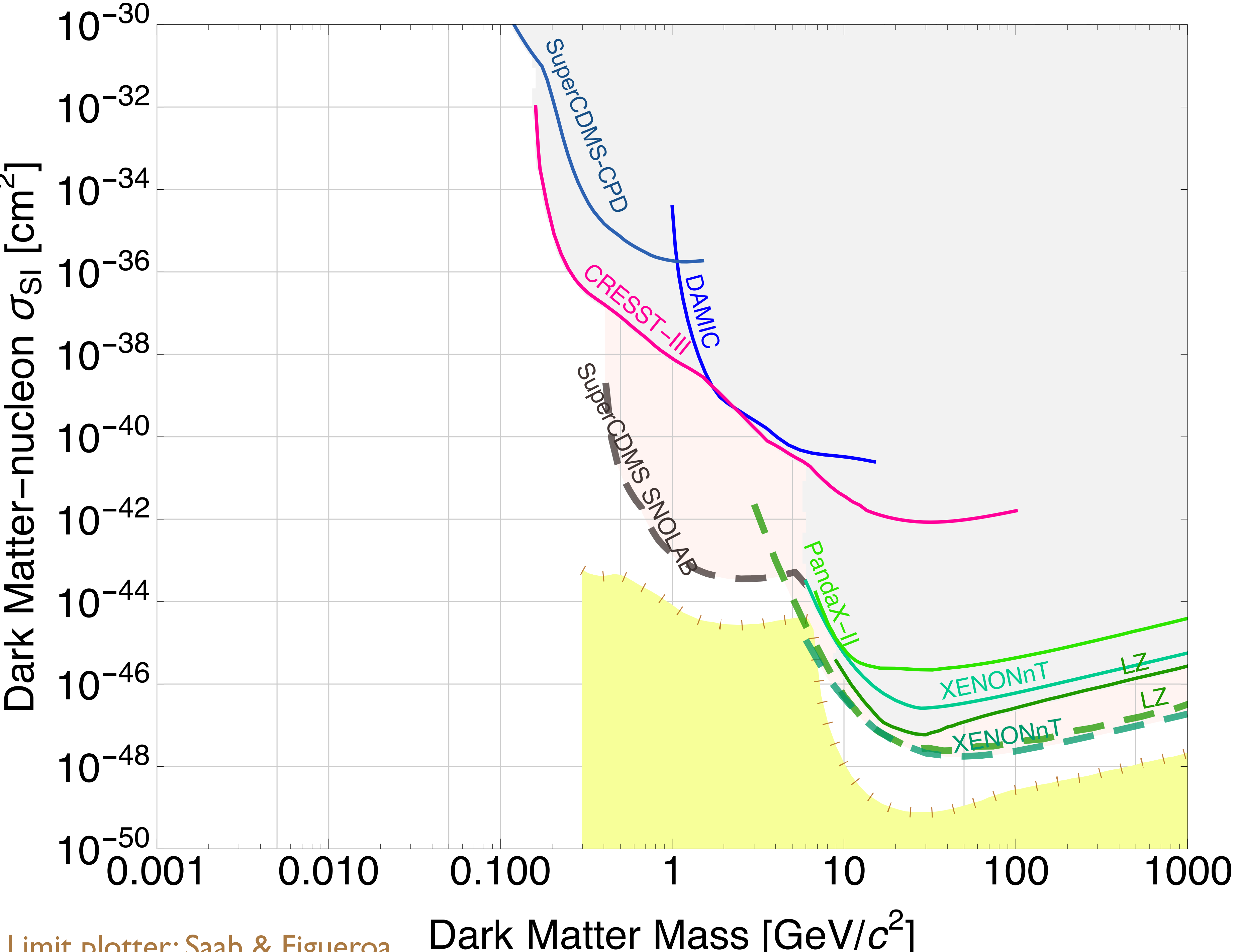
our focus

Sub-GeV "particle-like" dark matter



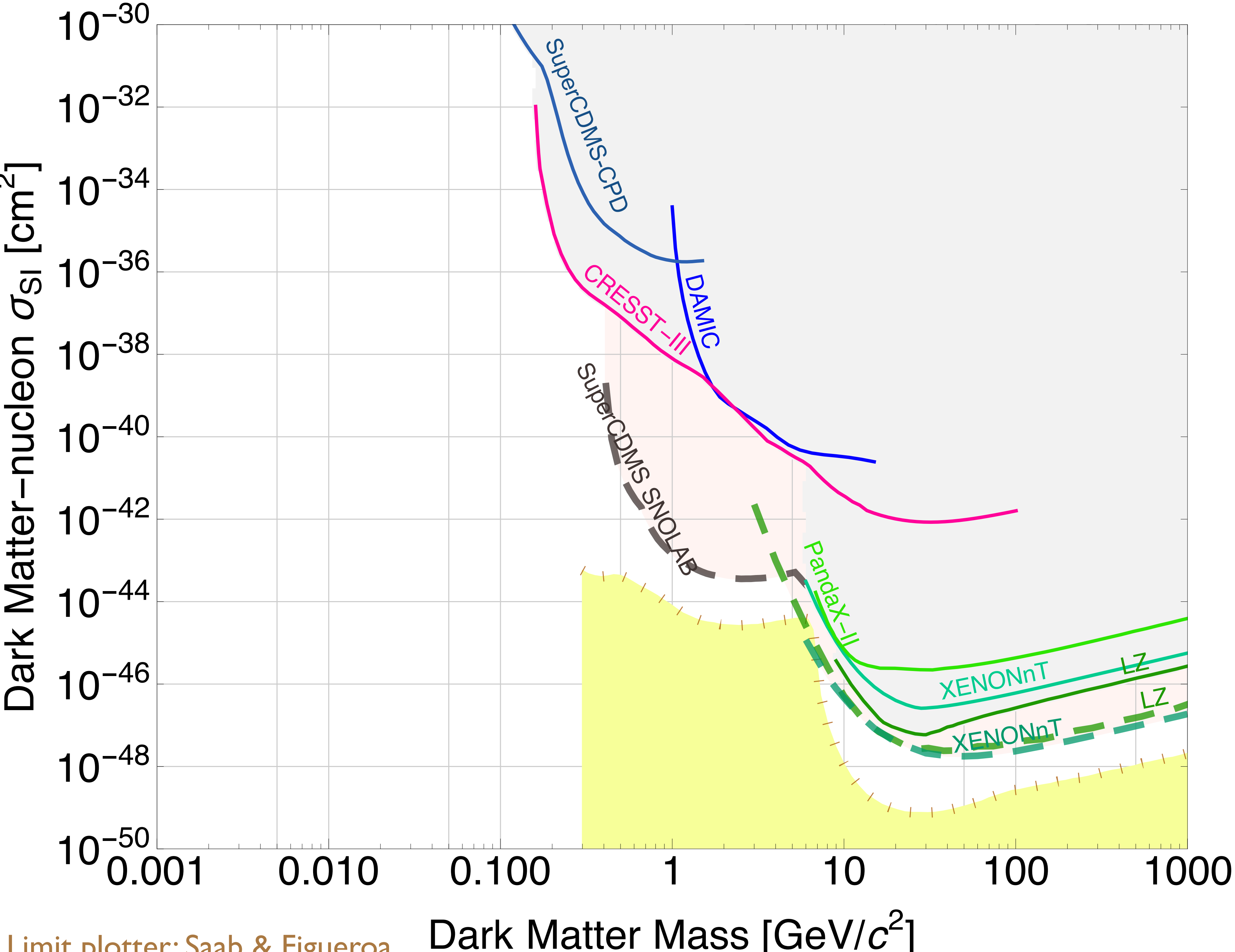
Some Current Constraints & Projections

- LZ, XENONnT, and PandaX w/ multi-ton detectors are dominating search for WIMPs



Limit plotter: Saab & Figueroa

What about DM w/ mass ≪ GeV ?



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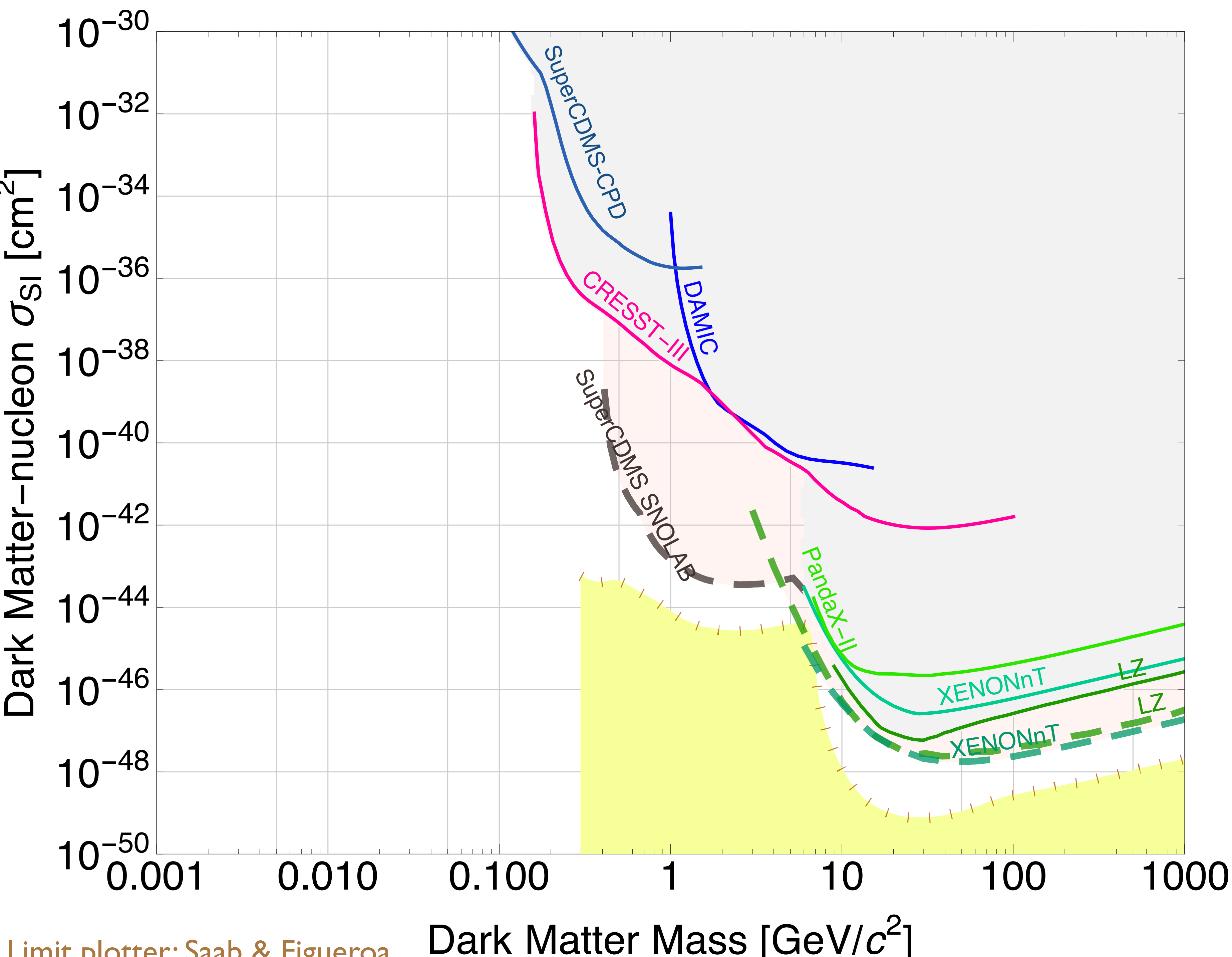
What about DM w/ mass ≪ GeV ?

- Constraints are weak, event rates are potentially large, and *small* experiments can search for DM



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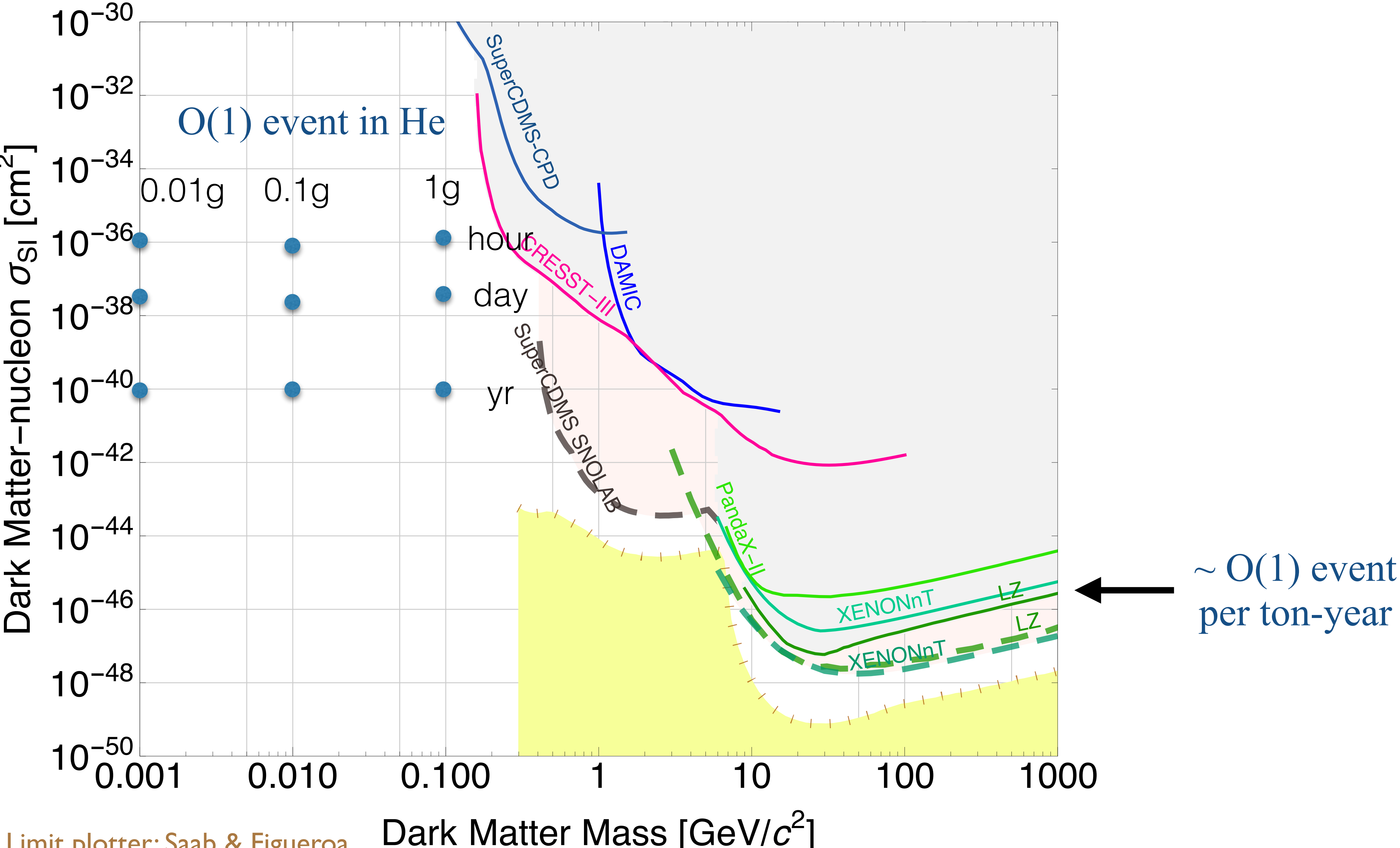
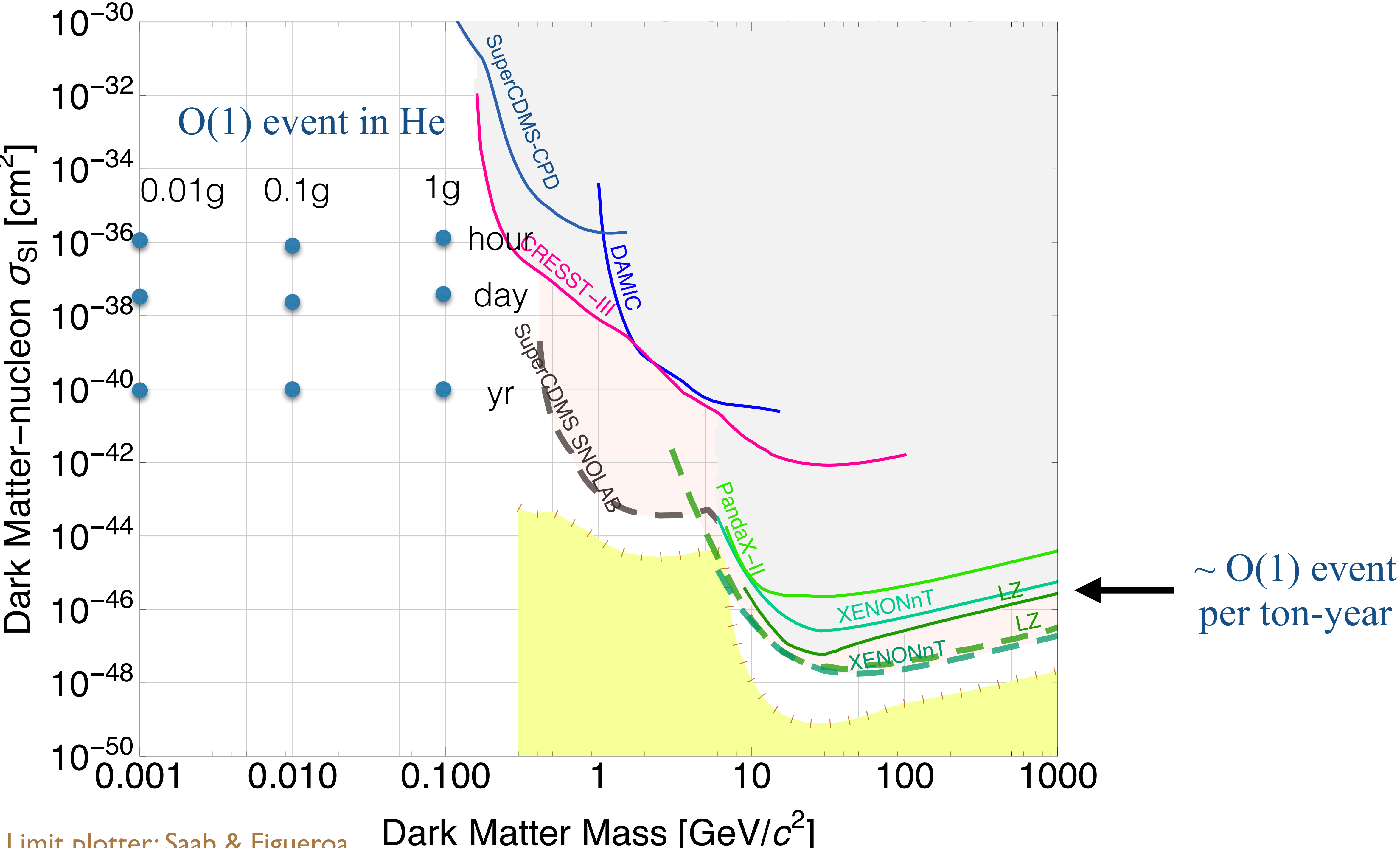


Limit plotter: Saab & Figueroa

What about DM w/ mass ≪ GeV ?

- Constraints are weak, event rates are potentially large, and *small* experiments can search for DM
- But need ultrasensitive detector & control over "new" backgrounds



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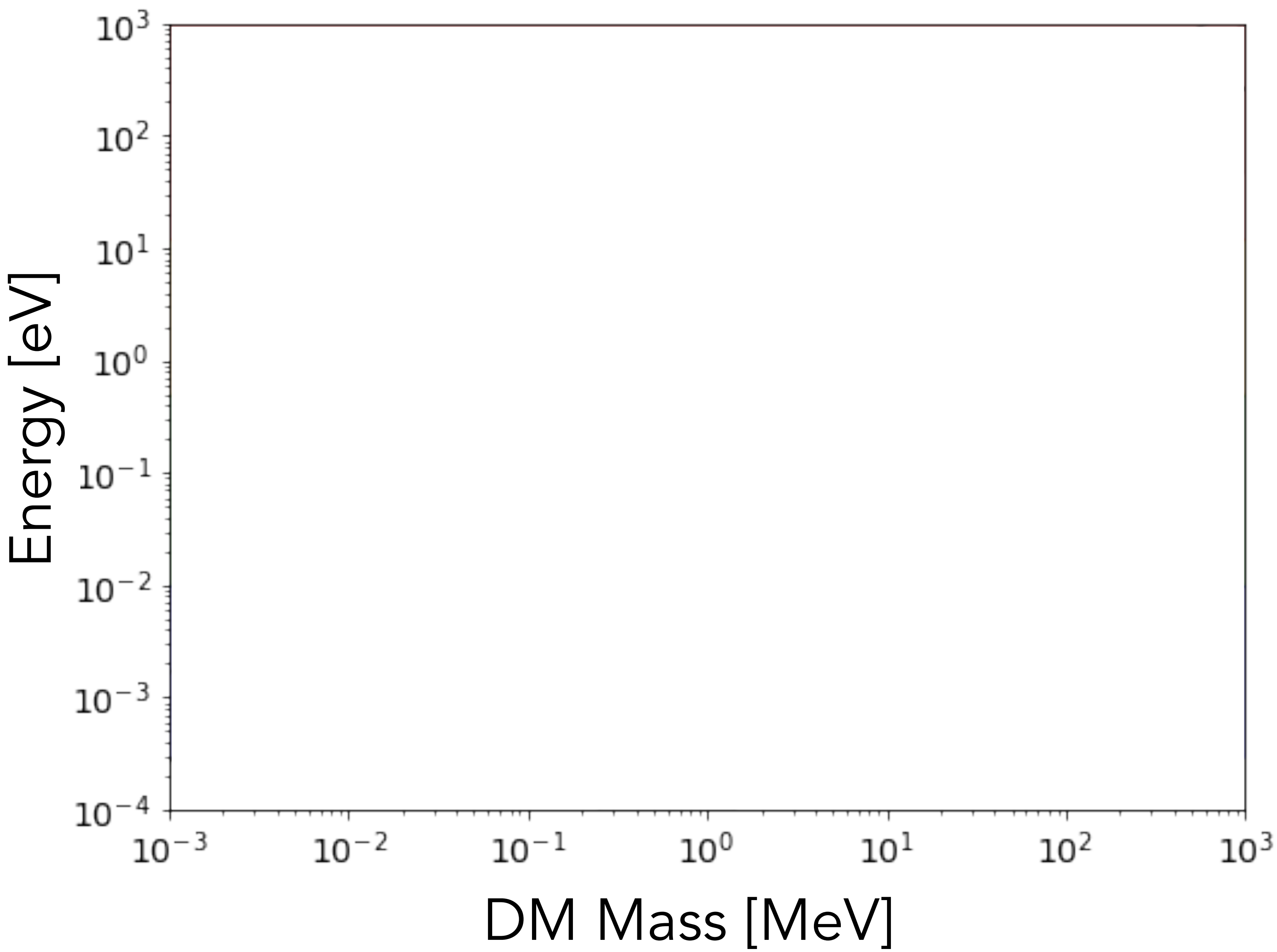
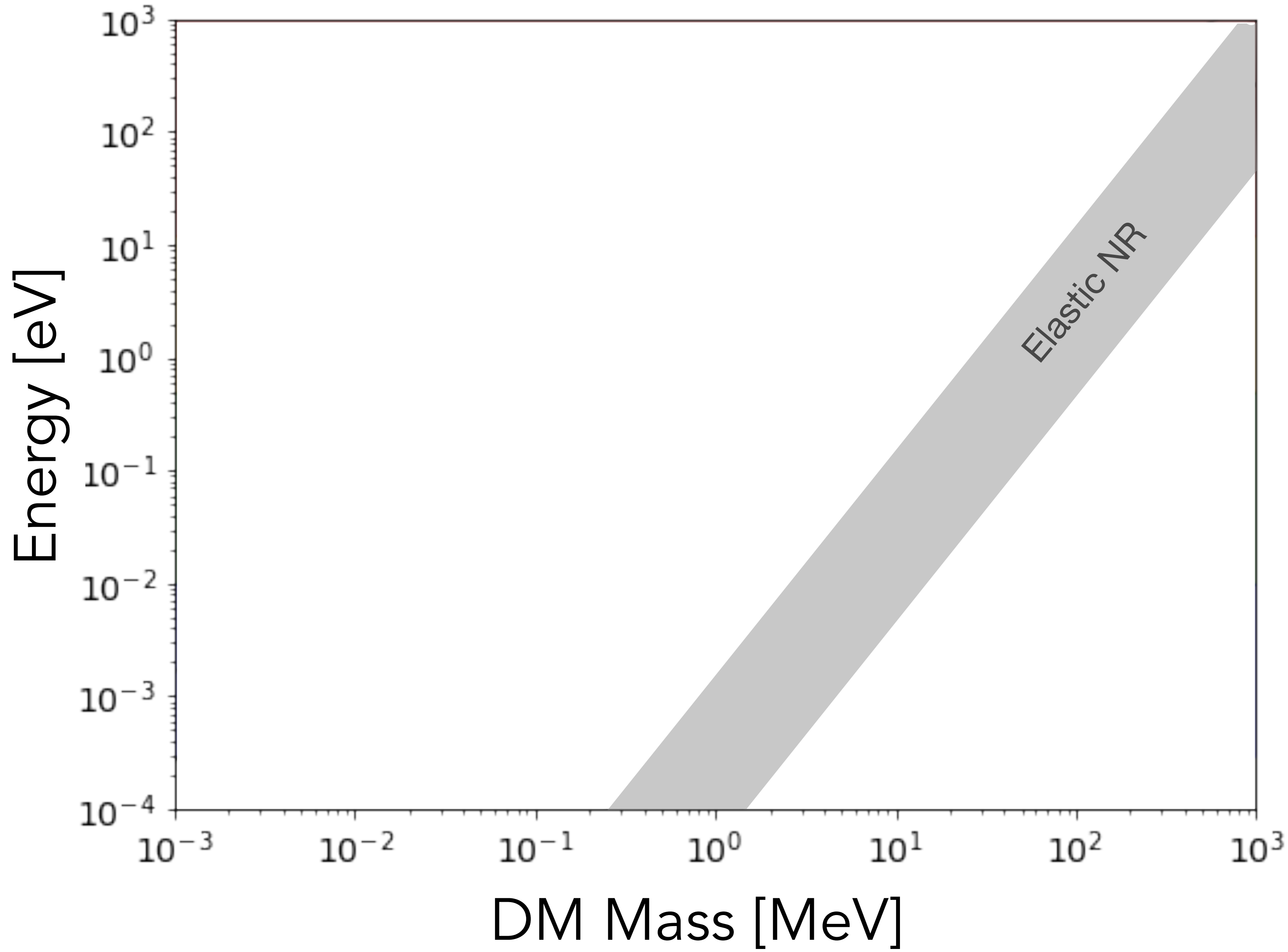
Kinematics of sub-GeV DM scattering



Elastic WIMP-nucleus scattering



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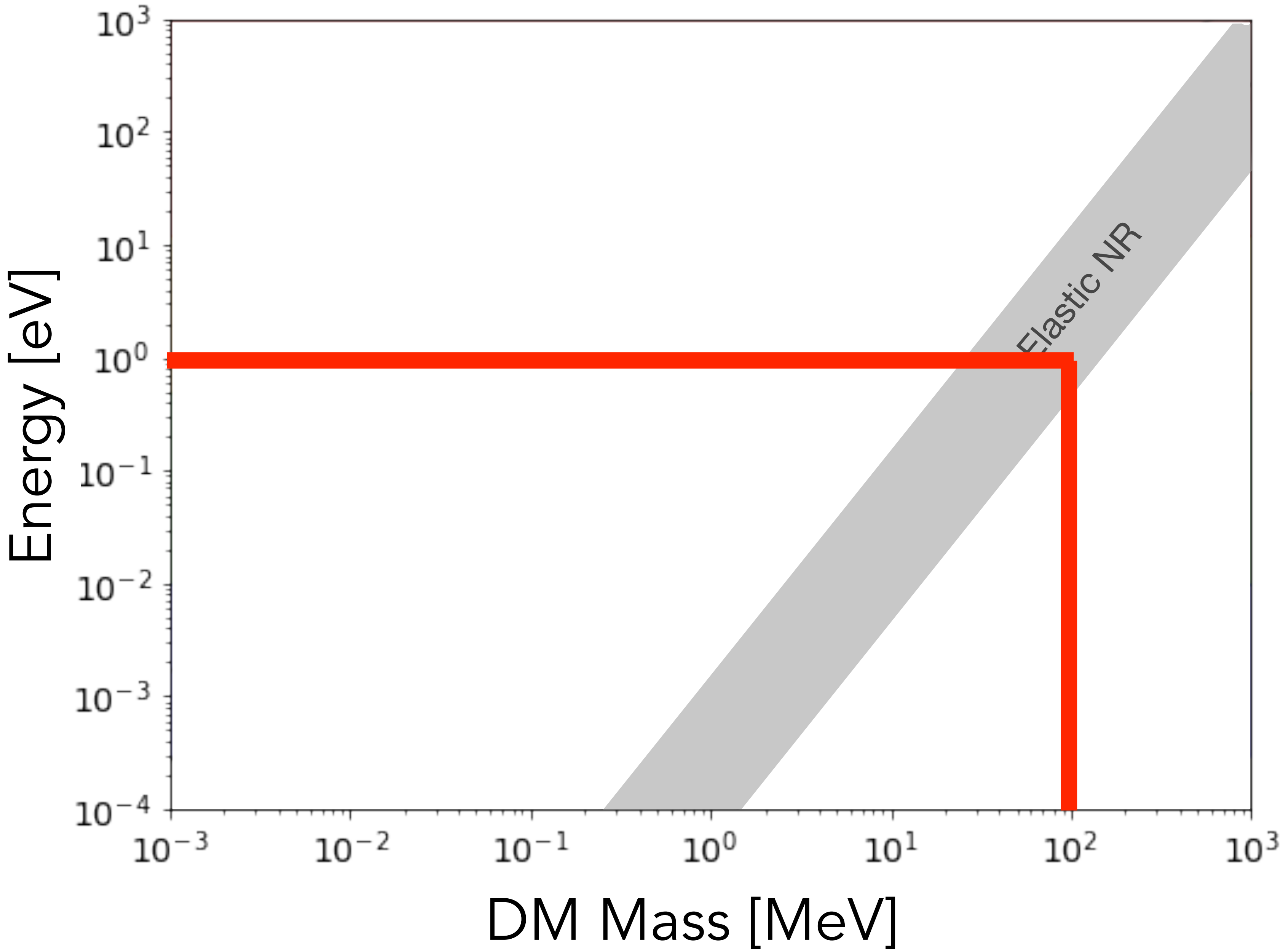
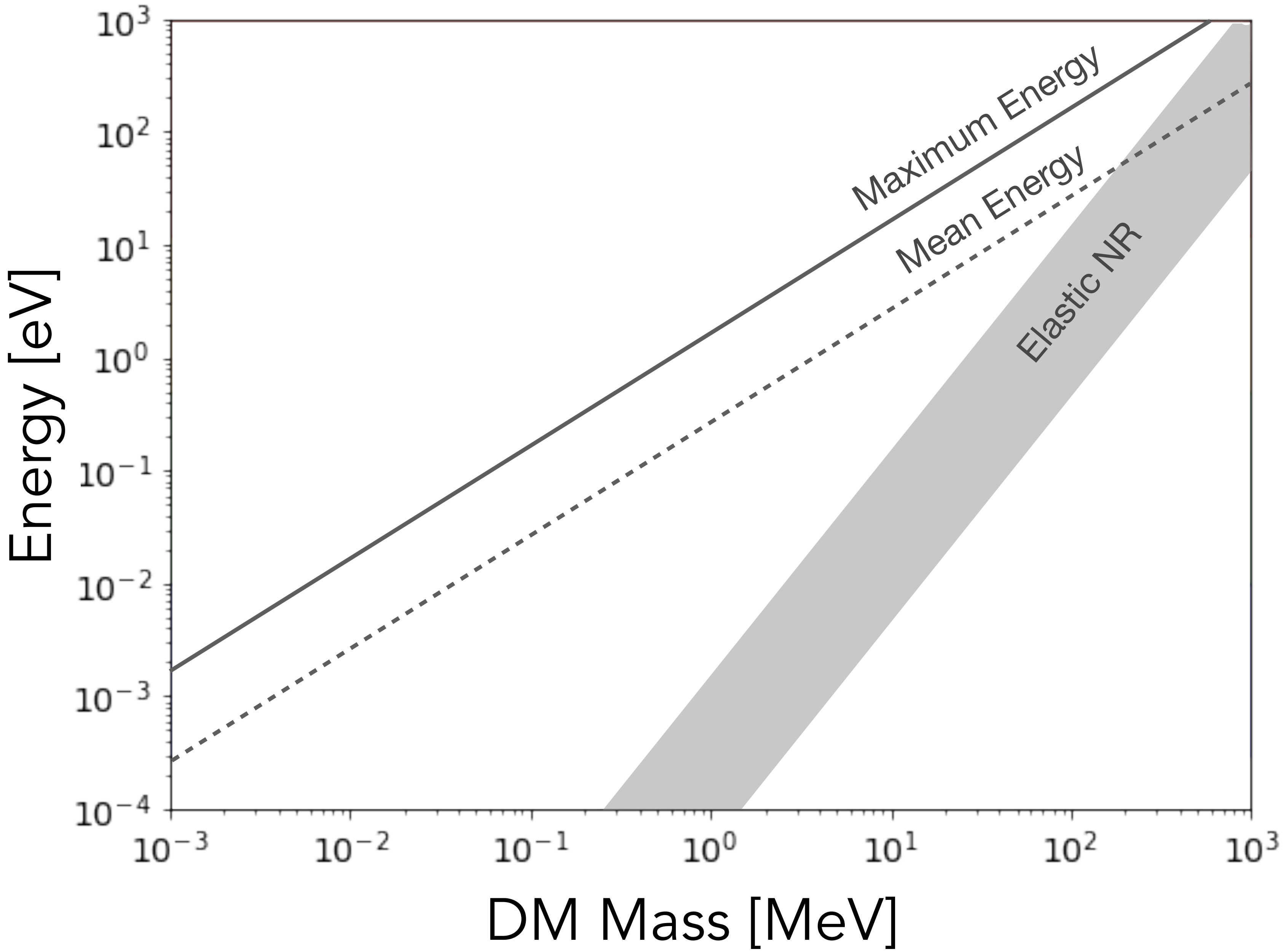


$$E_{\mathrm{NR}} = \frac{q^2}{2m_N} \sim 1\ \mathrm{eV} \left(\frac{m_{\mathrm{DM}}}{100\ \mathrm{MeV}}\right)^2 \left(\frac{28\ \mathrm{GeV}}{m_N}\right)$$

at low DM masses, very little energy transfer

Available DM kinetic energy is much larger!



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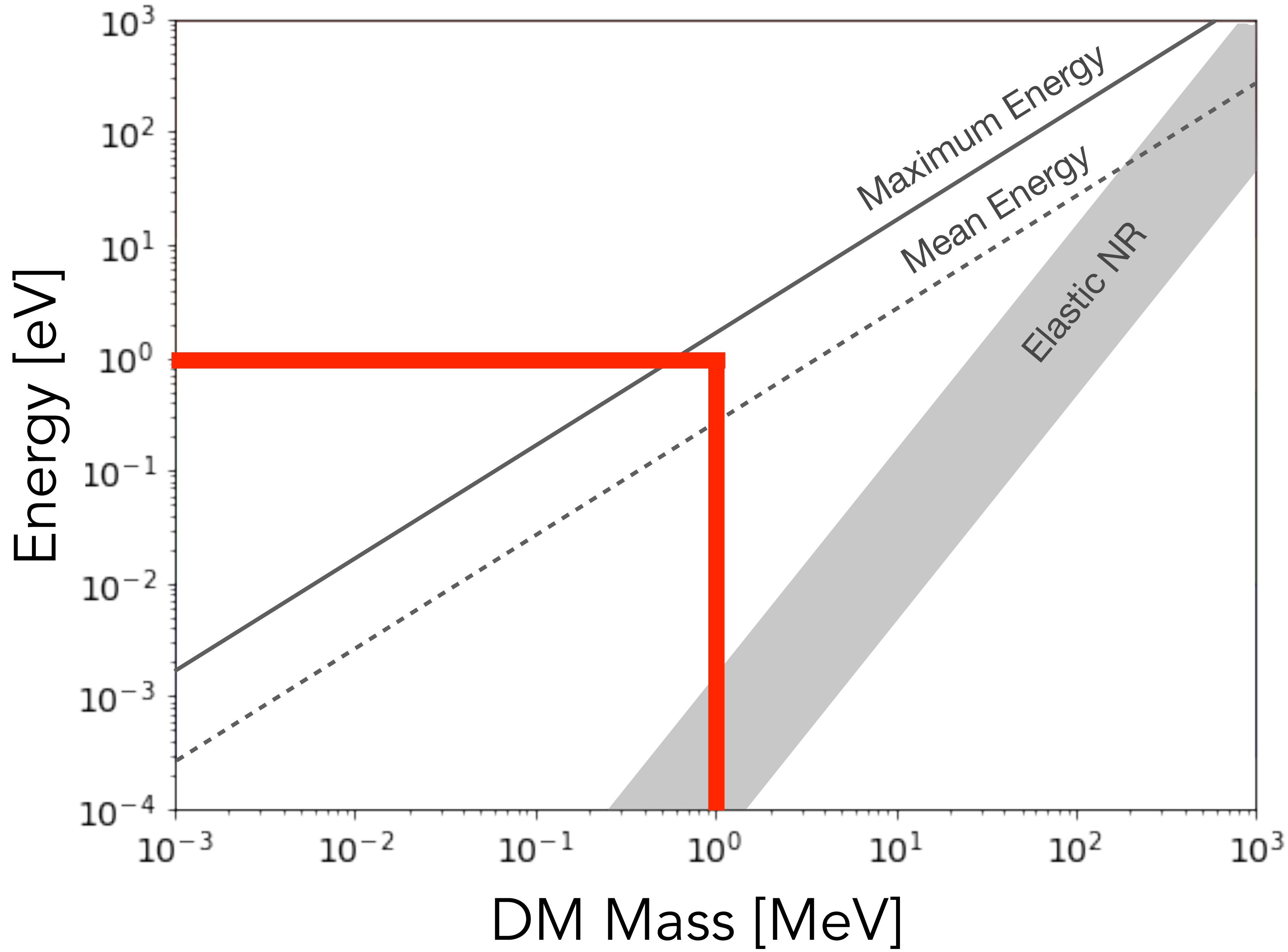
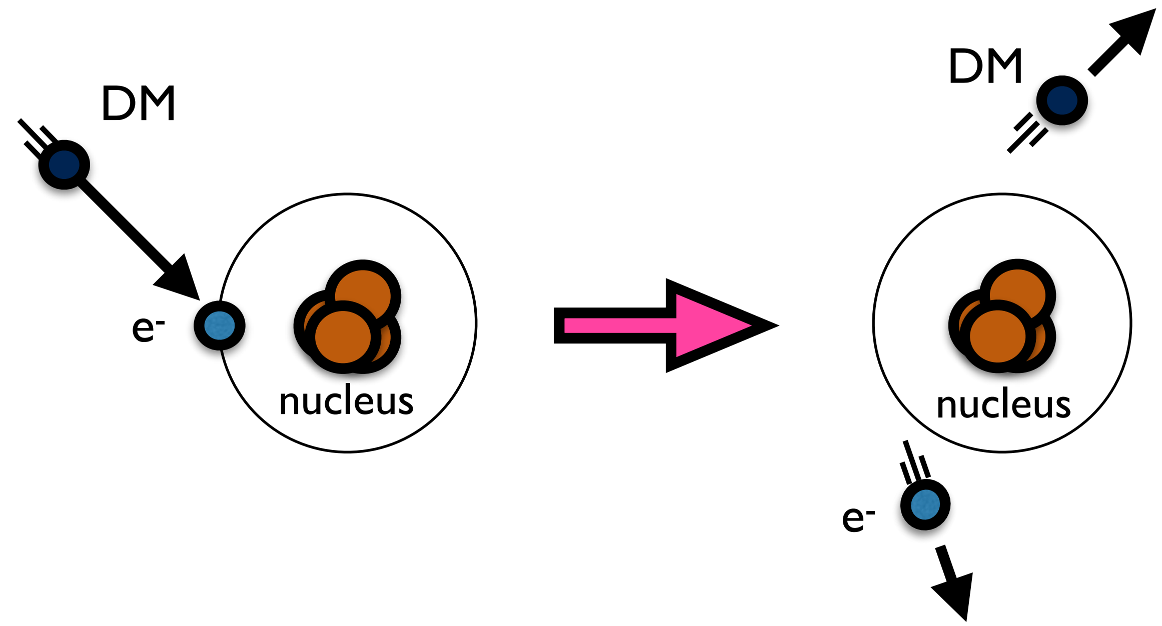


$$E_{\rm kin} = \frac{1}{2} m_{\rm DM} v_{\rm DM}^2 \sim 1~{\rm eV} \left(\frac{m_{\rm DM}}{1~{\rm MeV}} \right)$$

Can transfer entire DM kinetic energy in <u>inelastic</u> scatters

- DM-e scattering

RE, Mardon, Volansky



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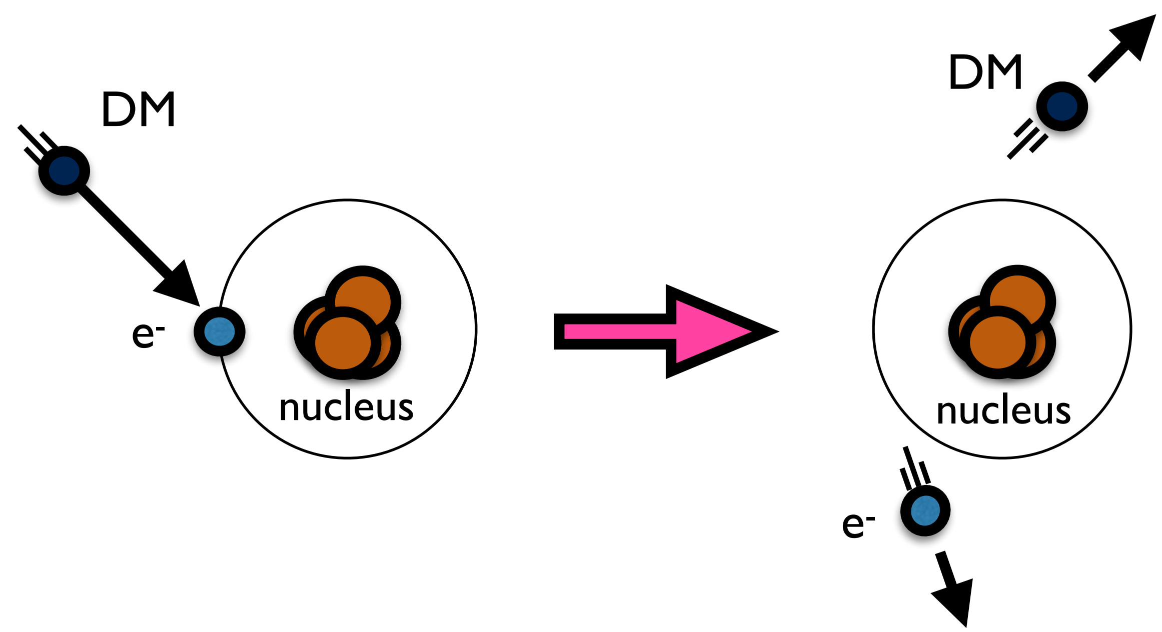
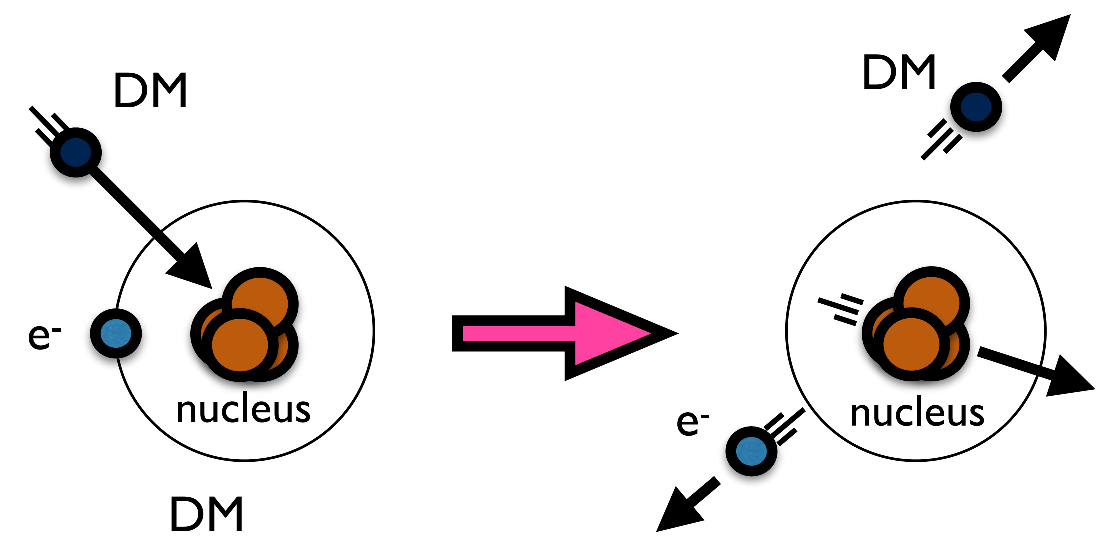


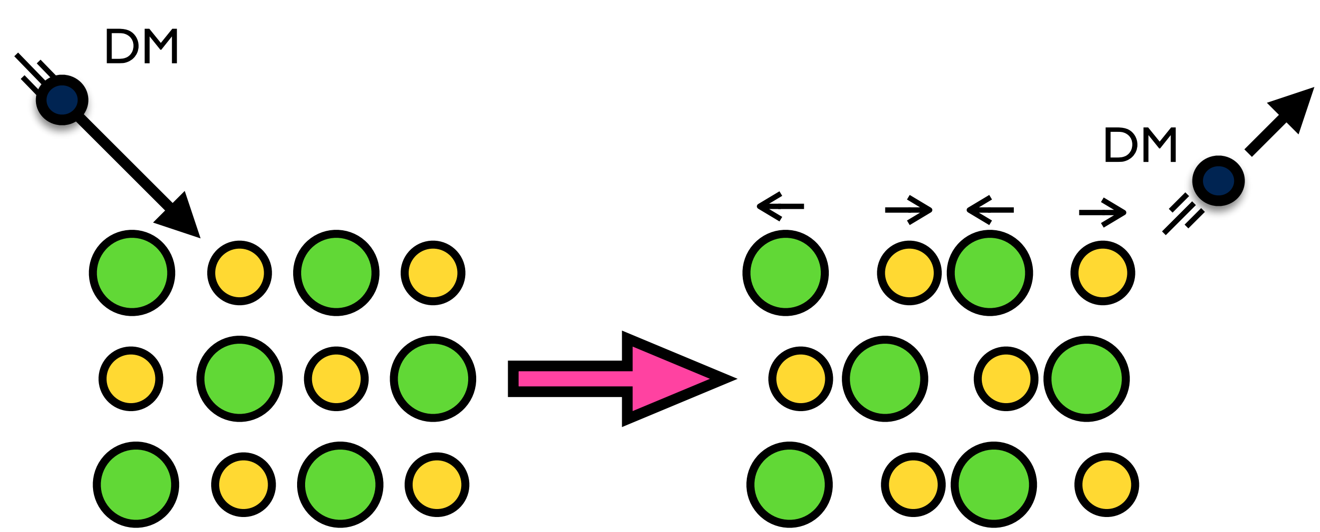
- DM-N scattering via Migdal effect

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

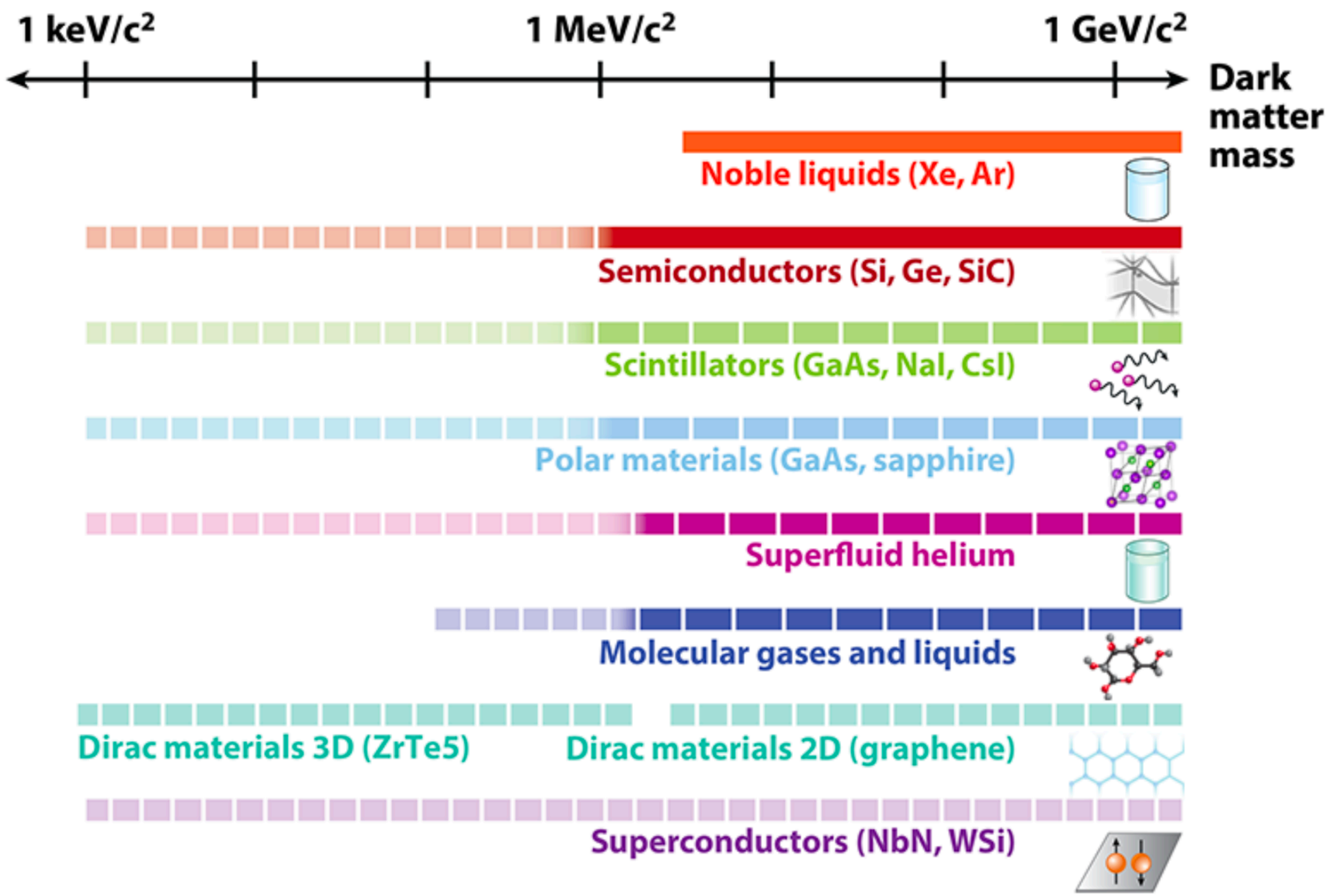


- DM scattering w/ collective modes (e.g. optical phonons)

  Knapen, Lin, Pyle, Zurek

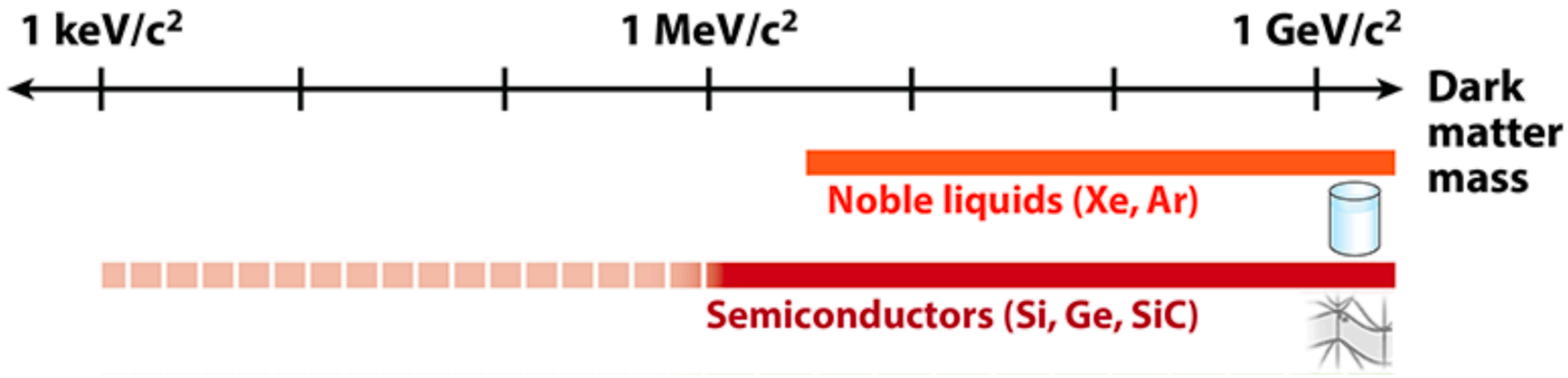


Various target materials w/ various excitation energies, e.g.



R. Essig, "The low-mass dark matter frontier," Physics 13, 172, 2020

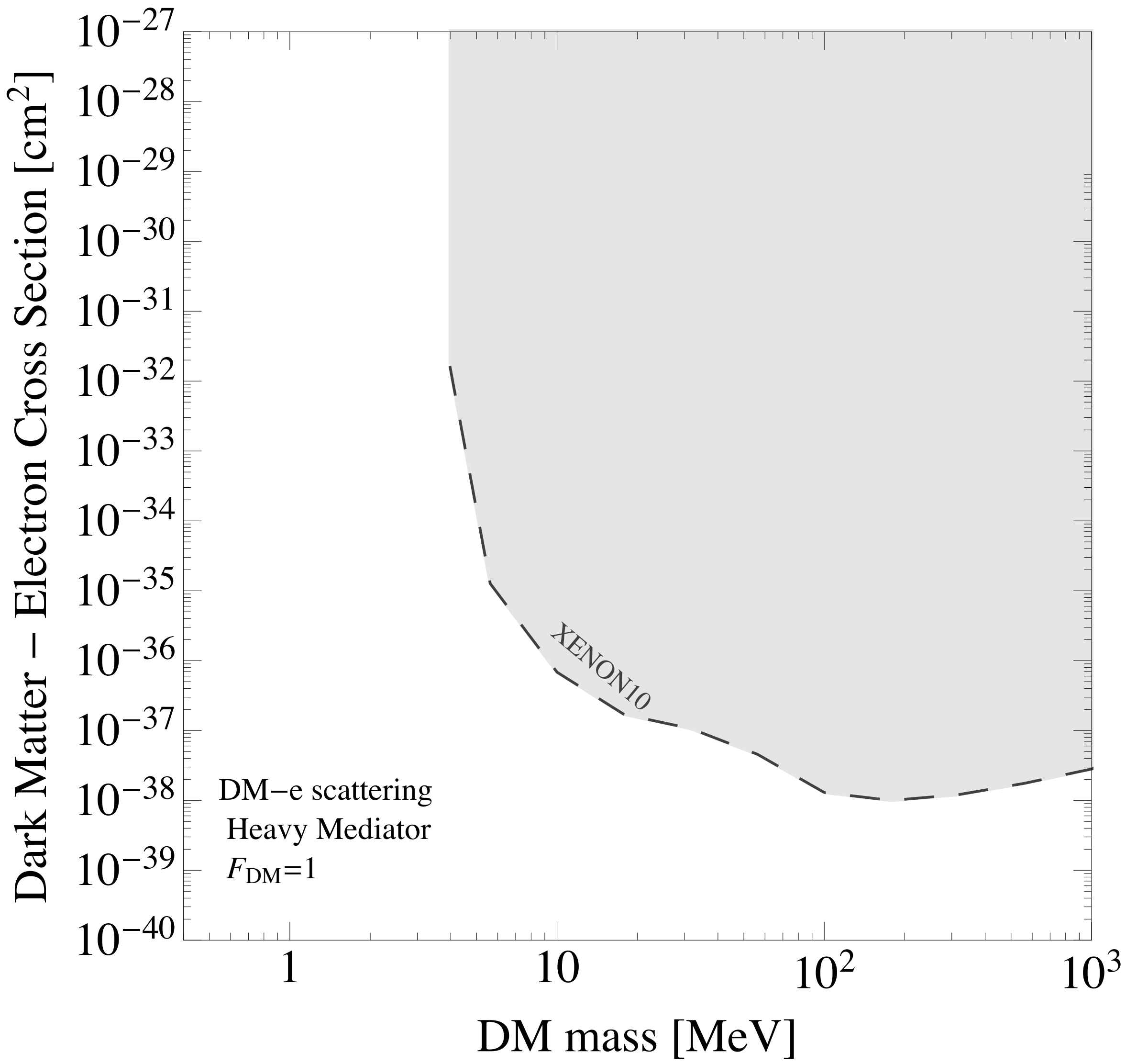
Various target materials w/ various excitation energies, e.g.



signal consists of one to a few electrons

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

2012



RE, Manalaysay, Mardon, Sorensen, Volansky

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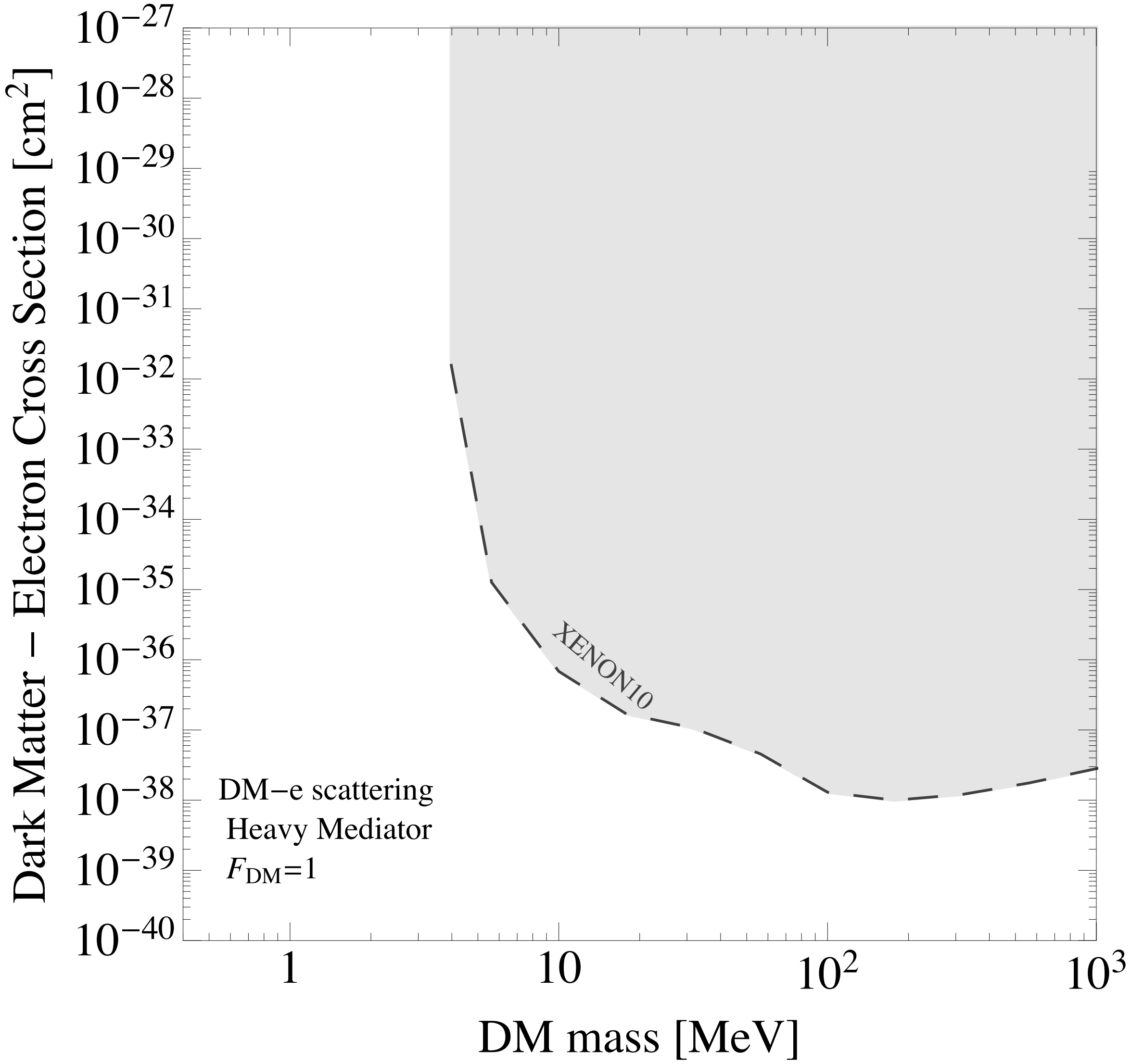
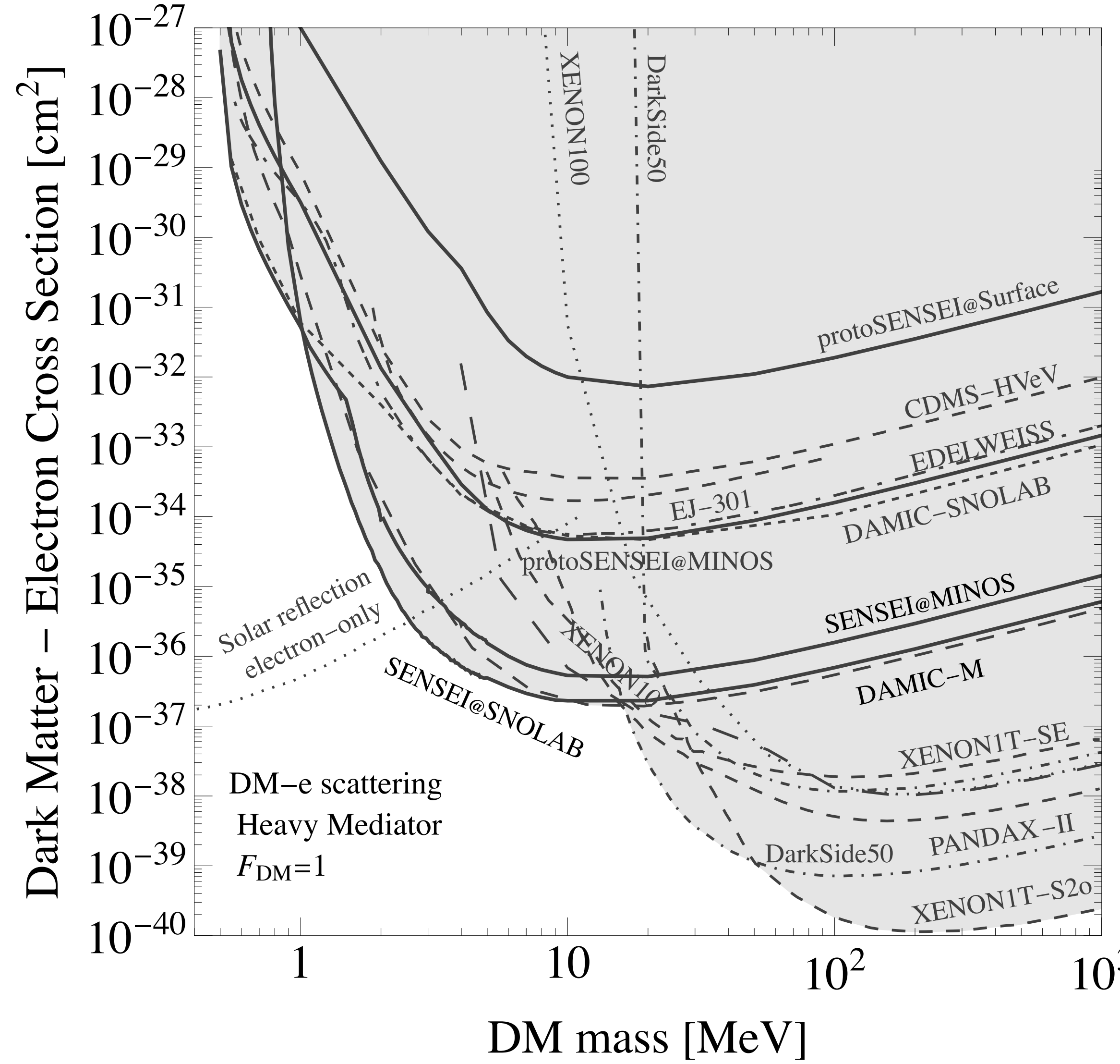


RE, Manalaysay, Mardon, Sorensen, Volansky

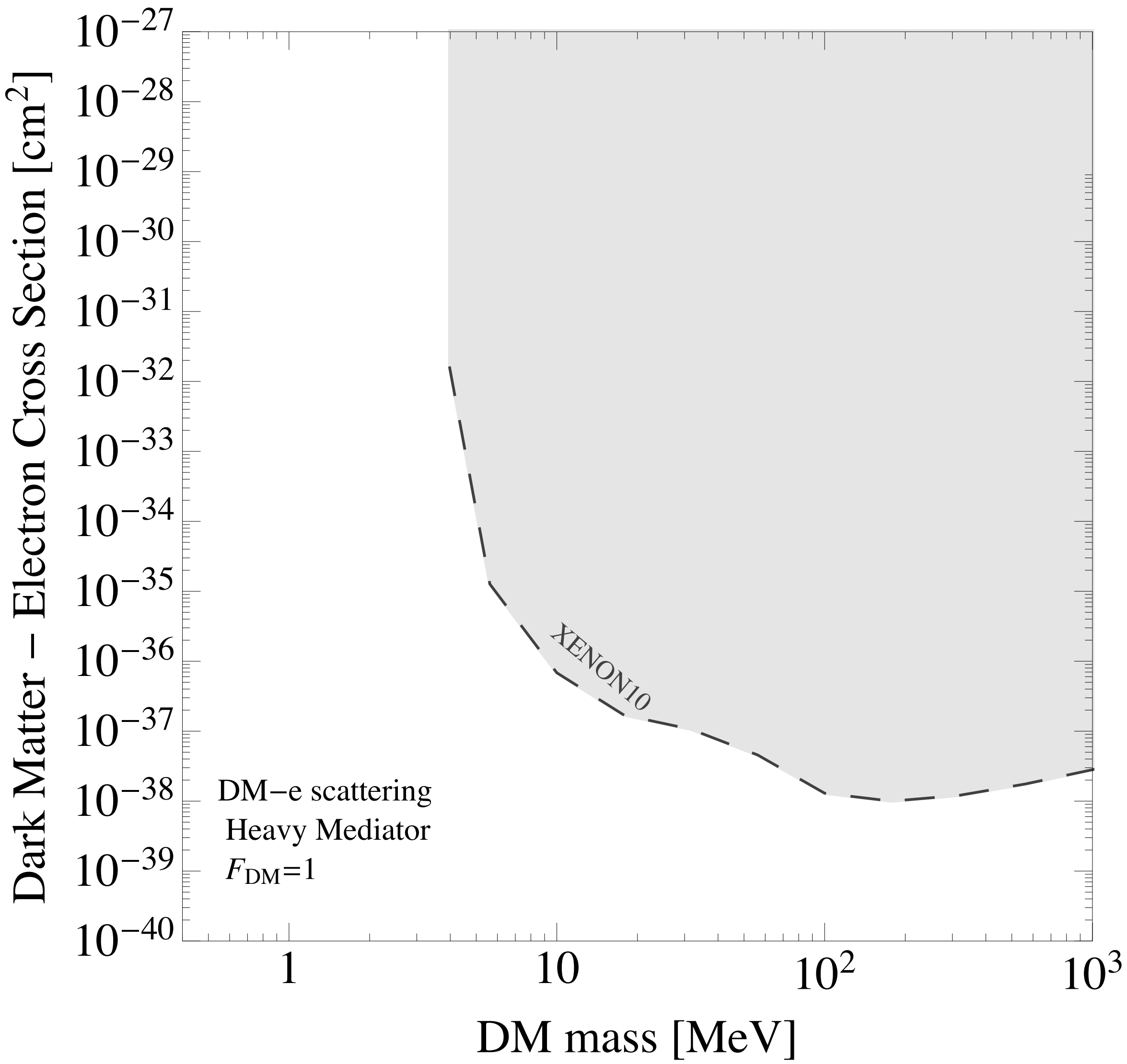
2024



many collaborations!

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

2012



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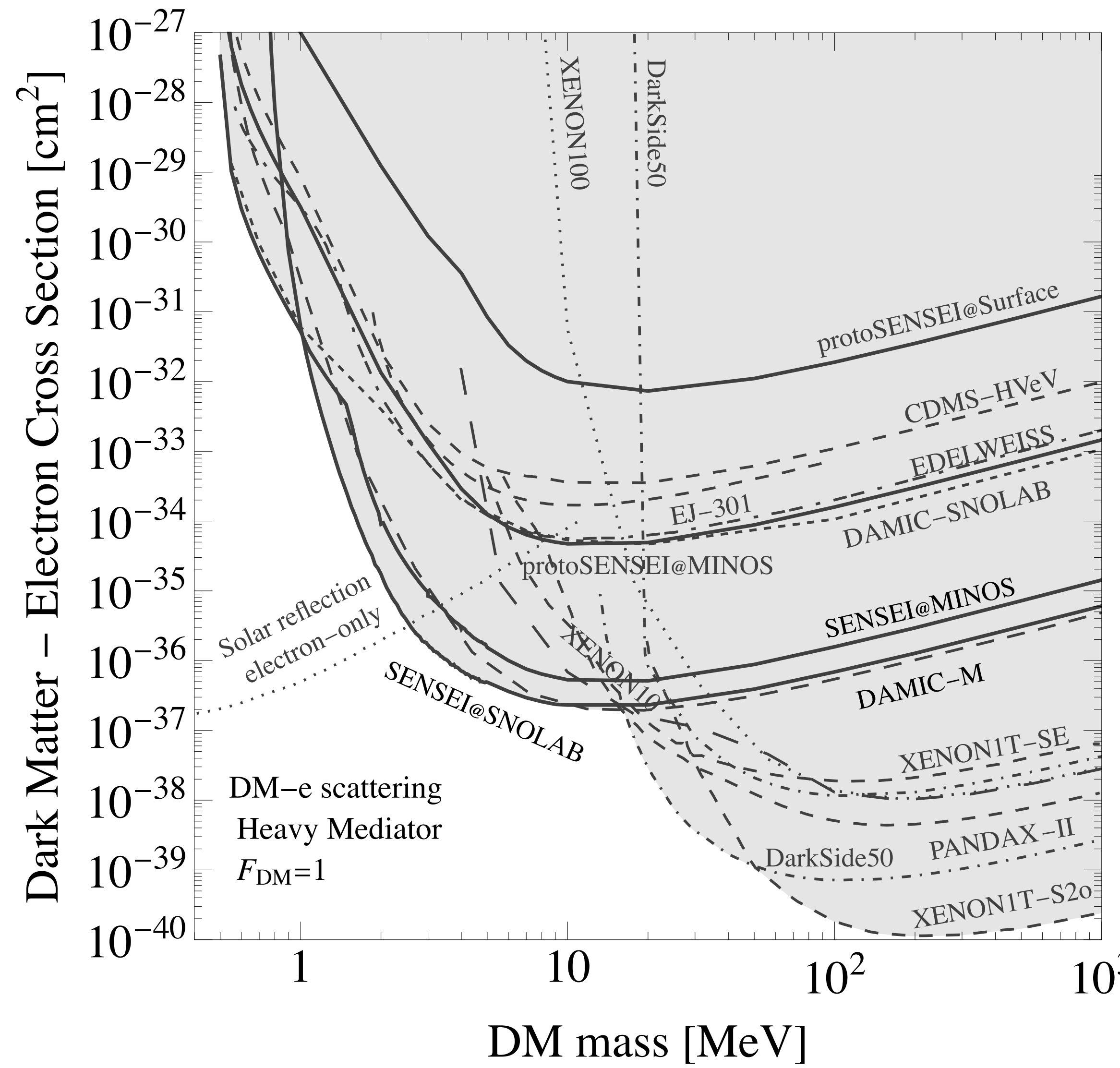
2024



many collaborations!

<u>several</u> ultrasensitive detectors can measure the produced charge (2-phase TPCs, Skipper-CCDs, TES,…)

Discuss one example:

SENSEI

silicon Skipper-CCDs
(bandgap ~ 1 eV)

can probe ~MeV DM

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

+ Timon Emken
+ Silvia Scorza
+ Hailin Xu

Stony Brook University

Prakruth Adari
Rouven Essig*
Aman Singal
Yikai Wu

UNIVERSITY OF OREGON

Ansh Desai
Tien-Tien Yu

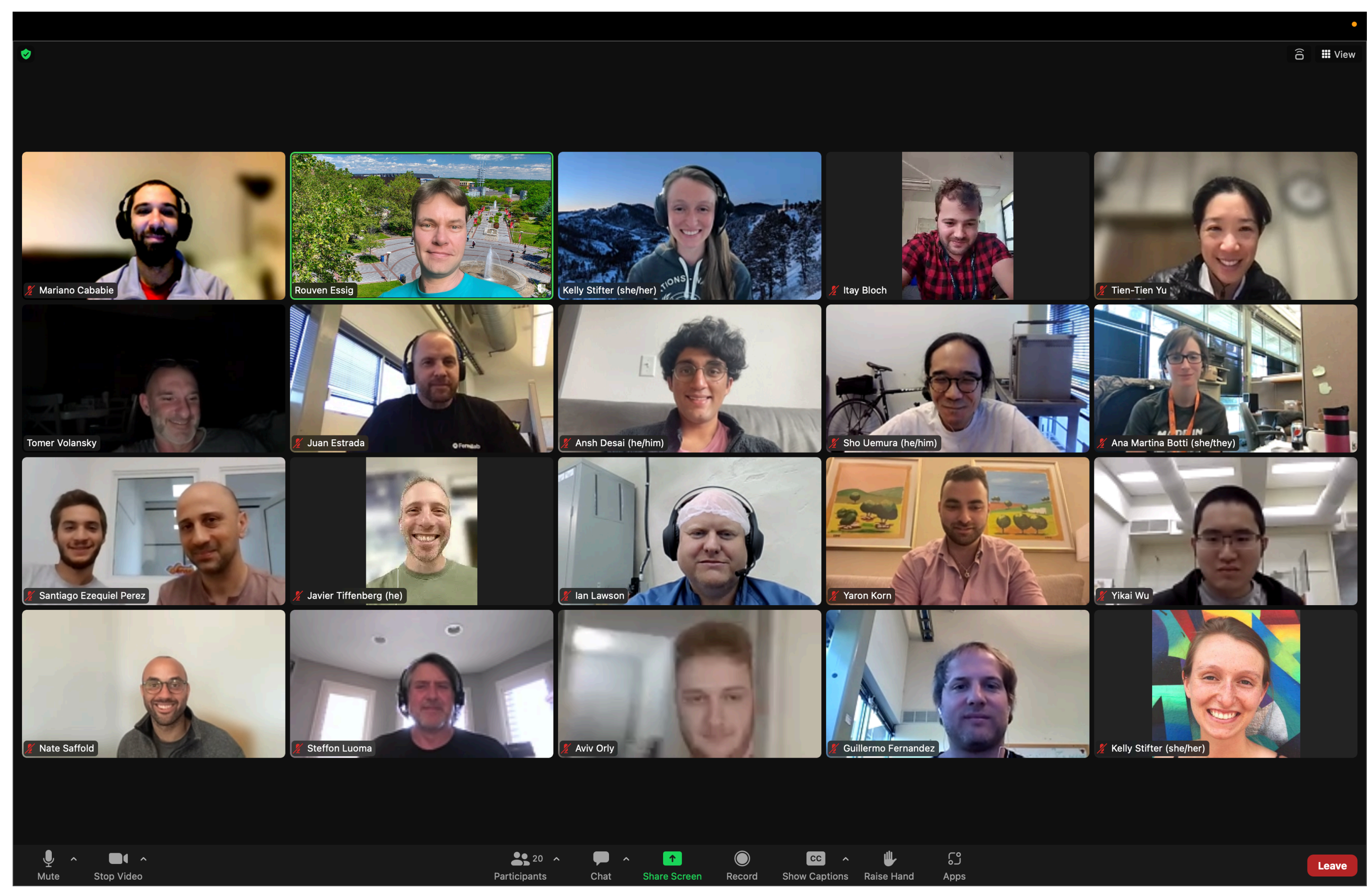
universidad de buenos aires - exactas, departamento de física Juan José Giambiagi

Mariano Cababie
Santiago Perez
Dario Rodrigues

SNOLAB

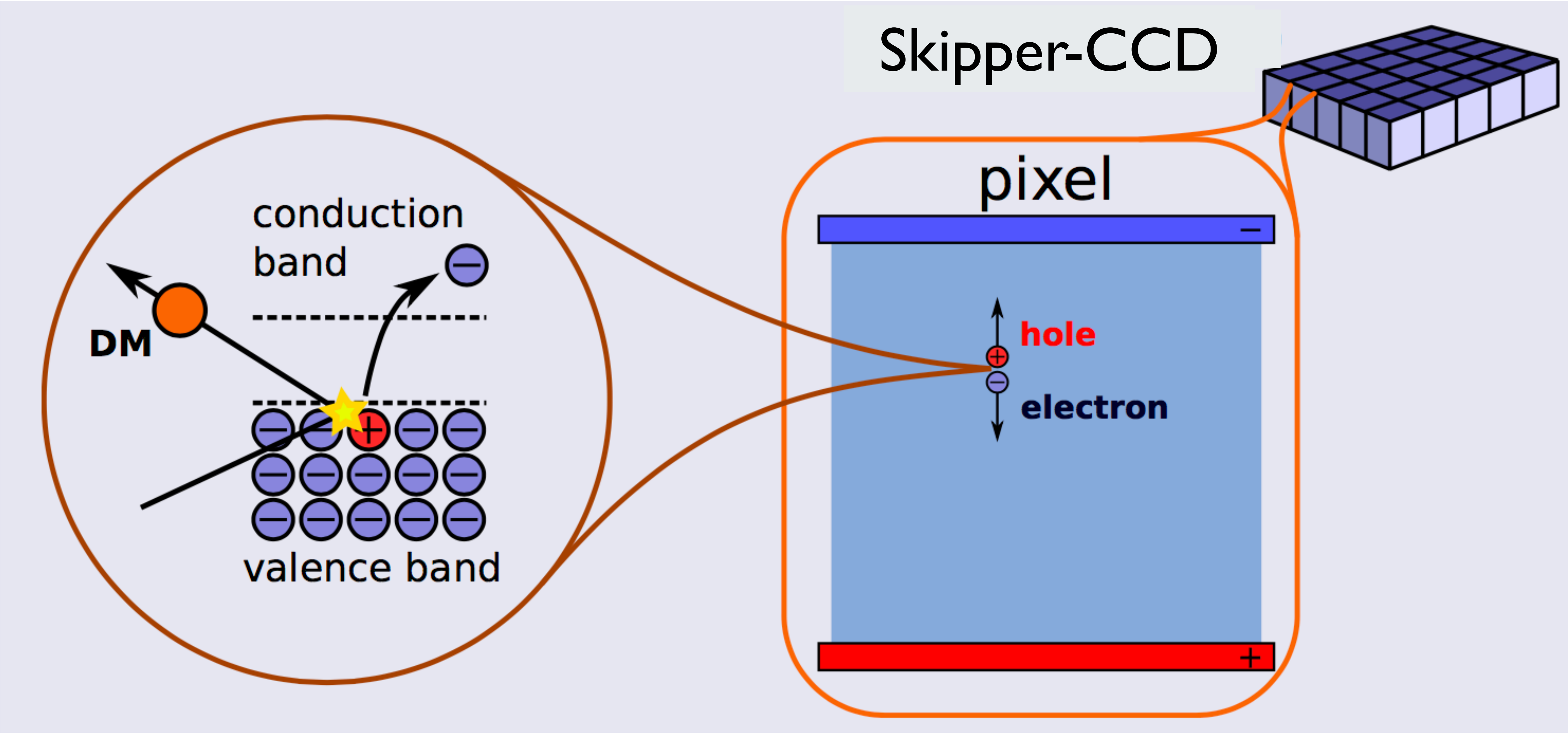
Ian Lawson
Steffon Luoma

HEISING-SIMONS FOUNDATION



*spokespersons

SENSEI detection concept



DM would create one or a few electron-hole pairs in a pixel

Skipper-CCD operation (SENSEI)

~ 2 cm $\times$ 10 cm, 5.4 Mpix

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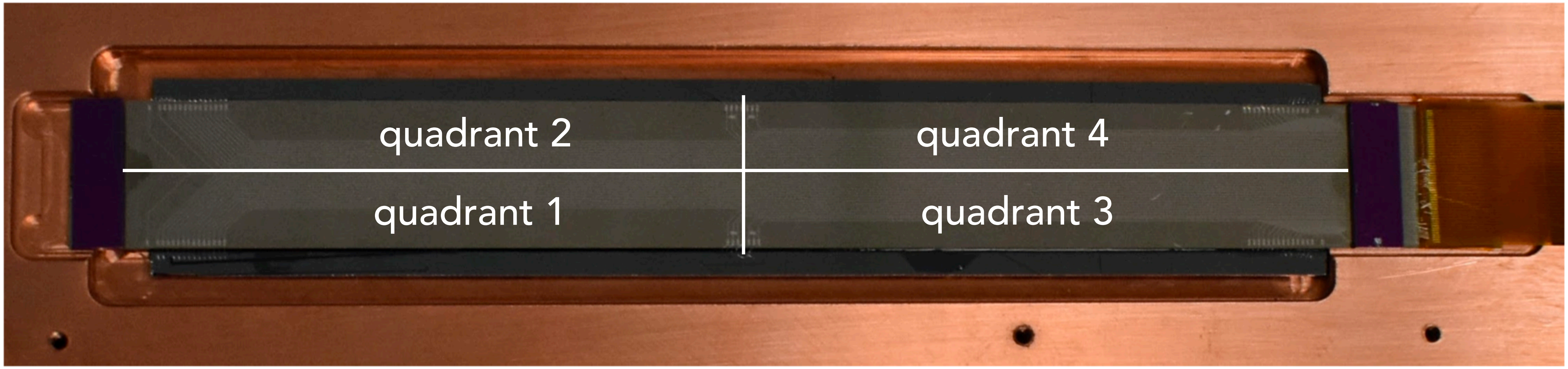

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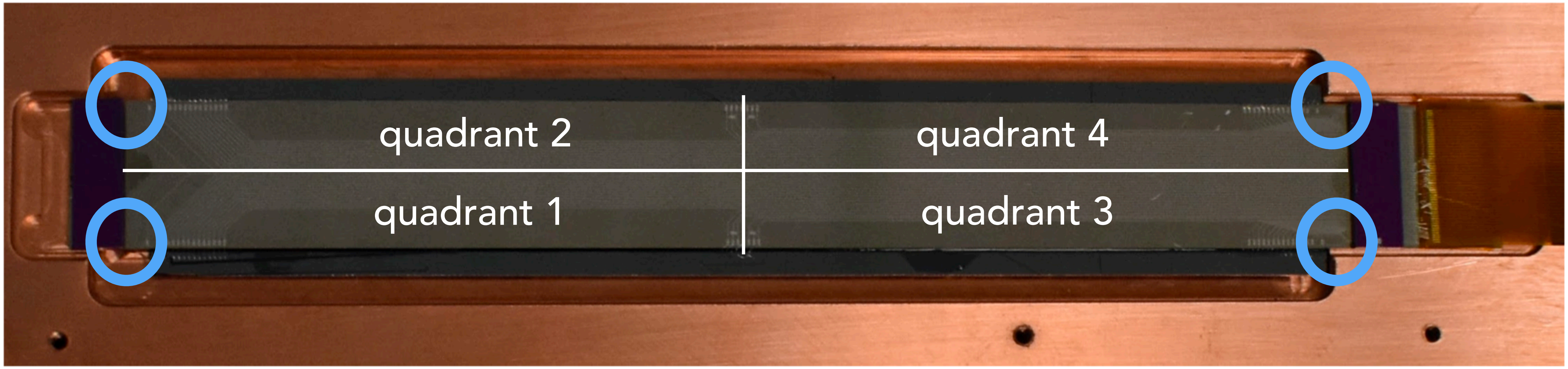

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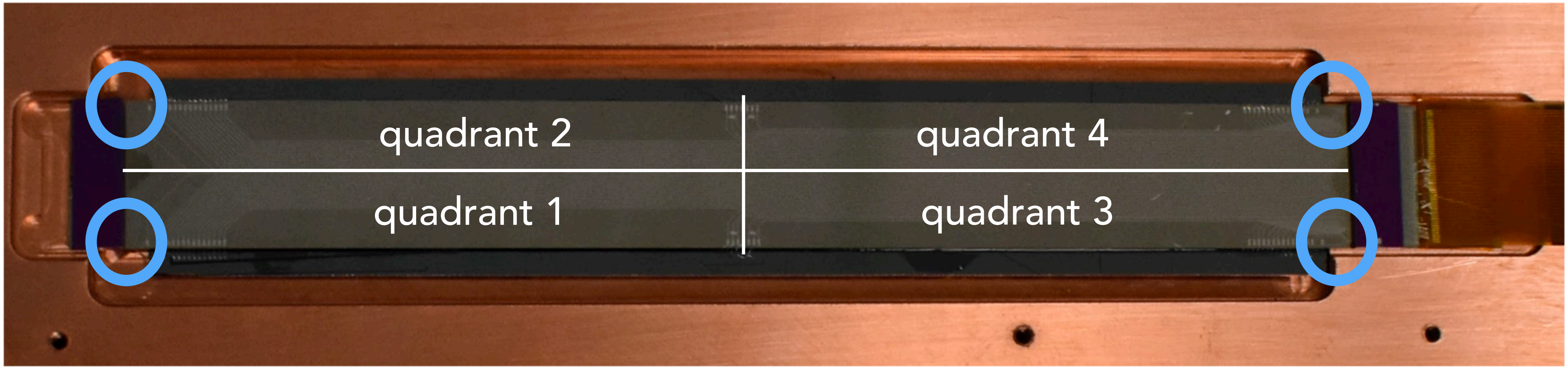

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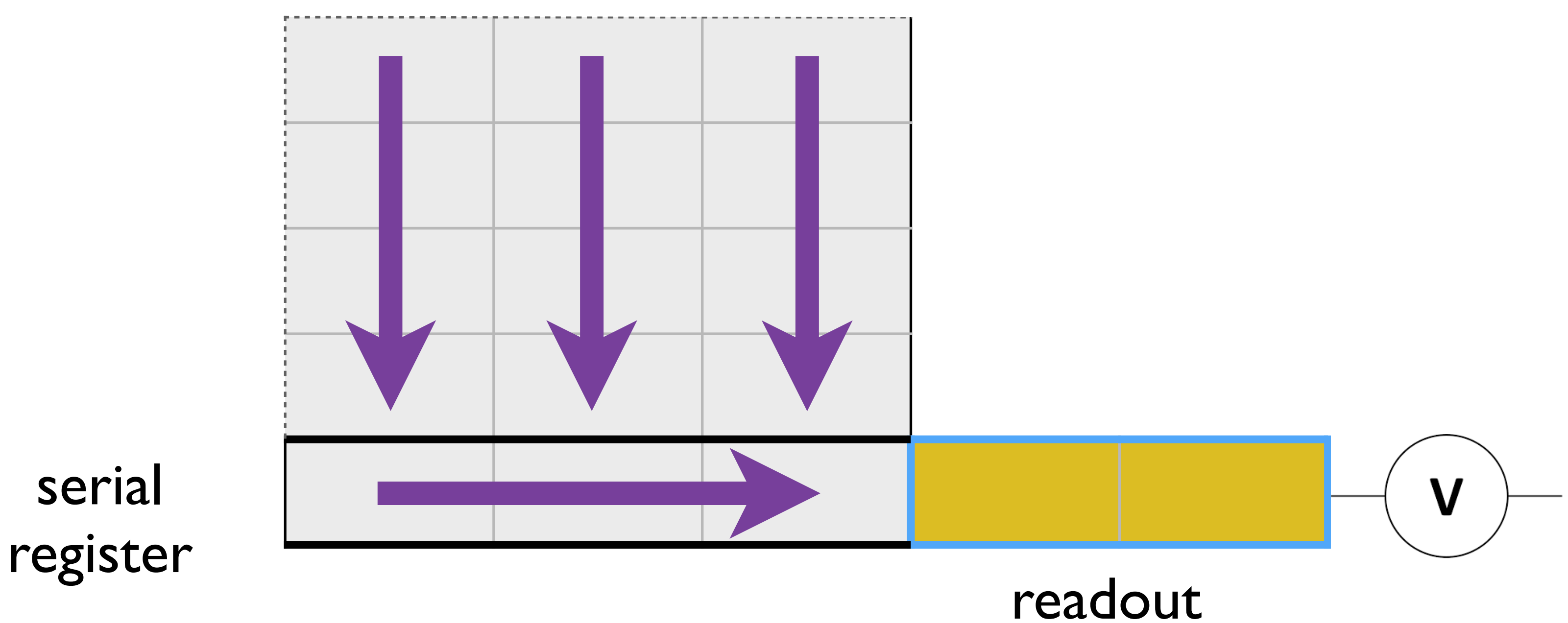

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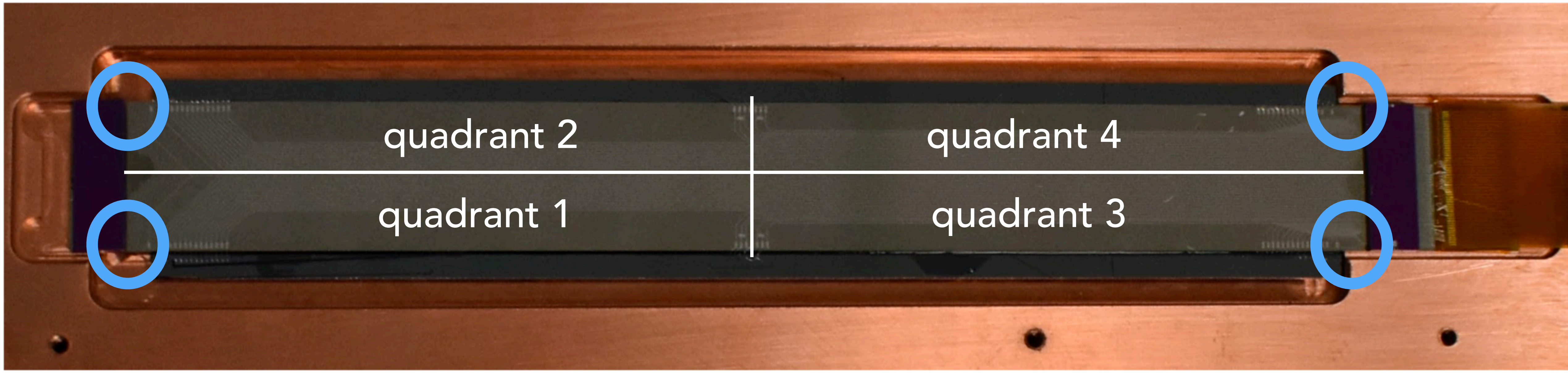

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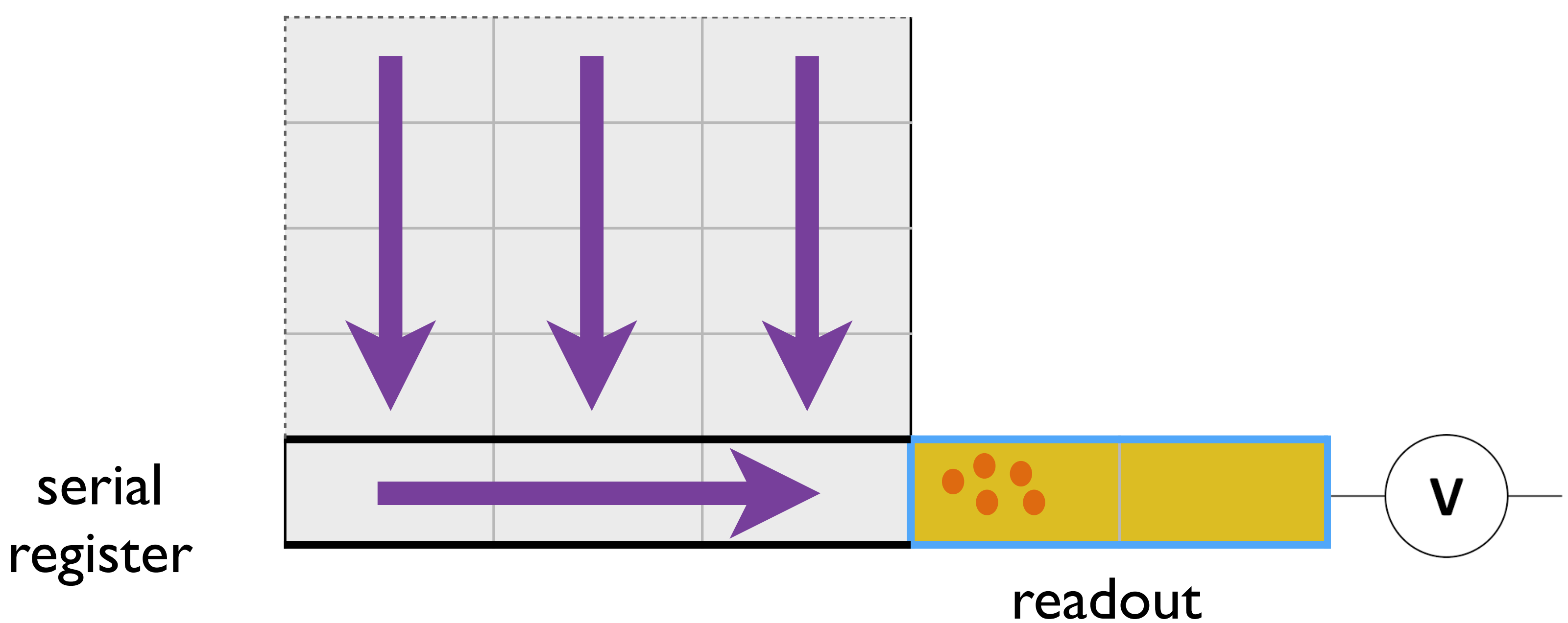

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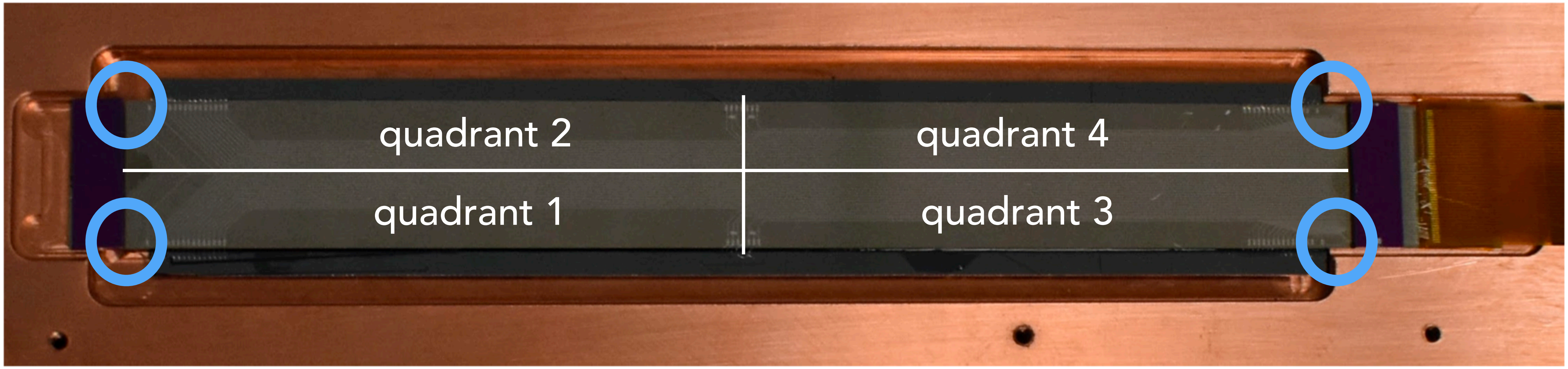

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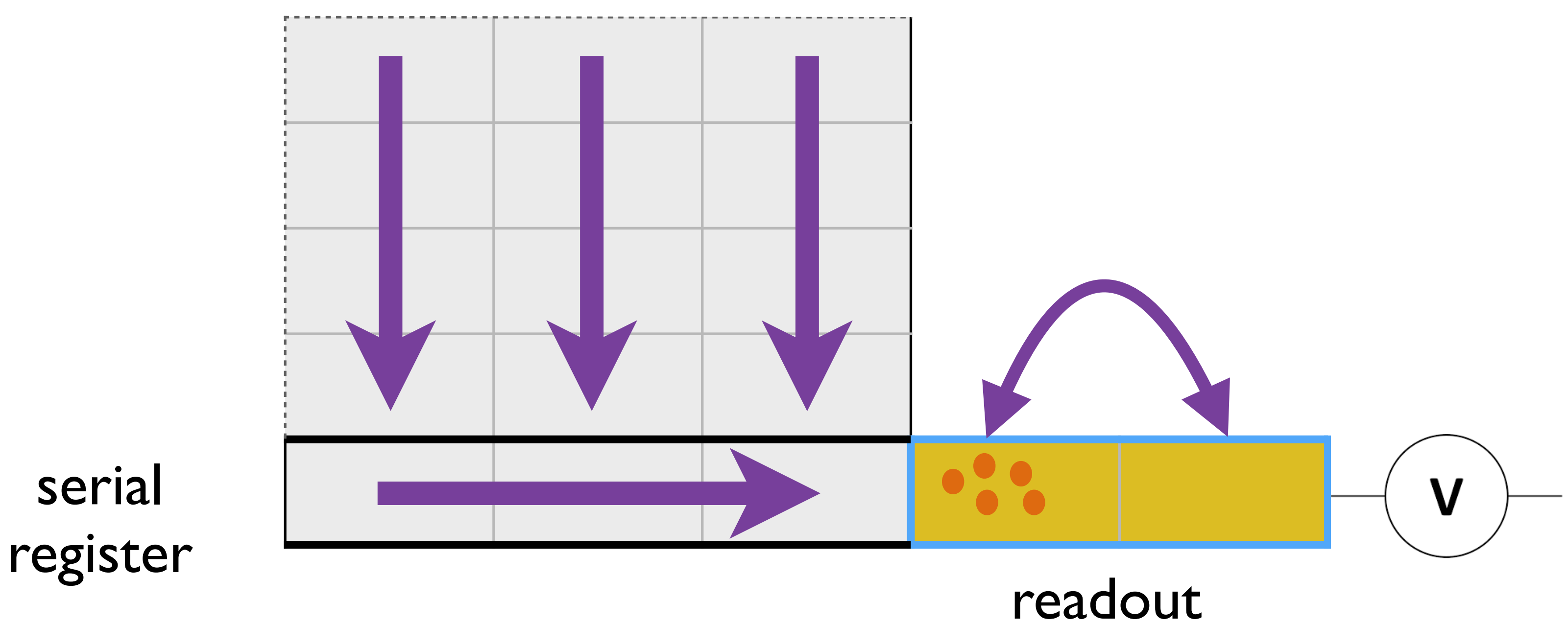

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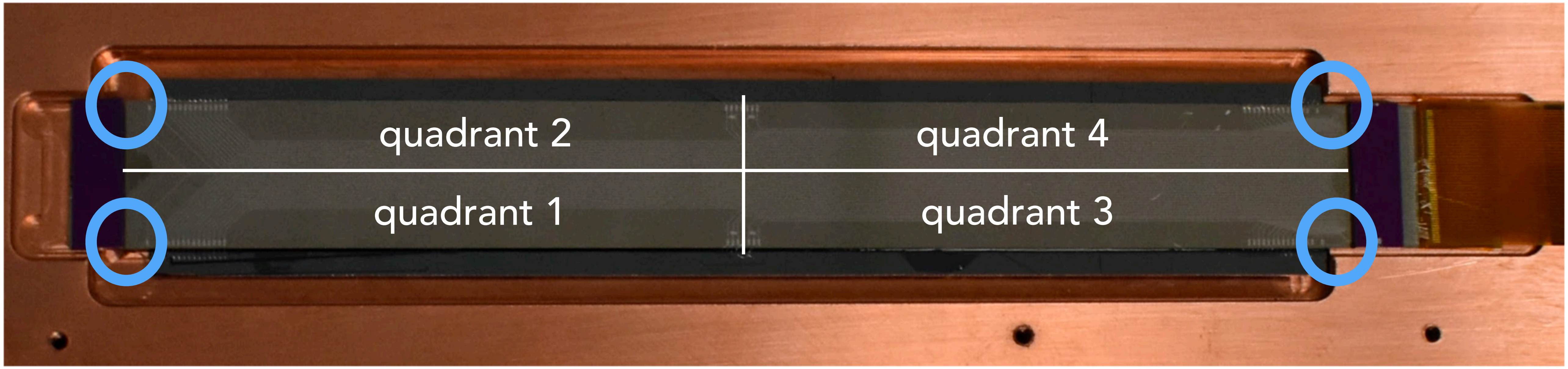
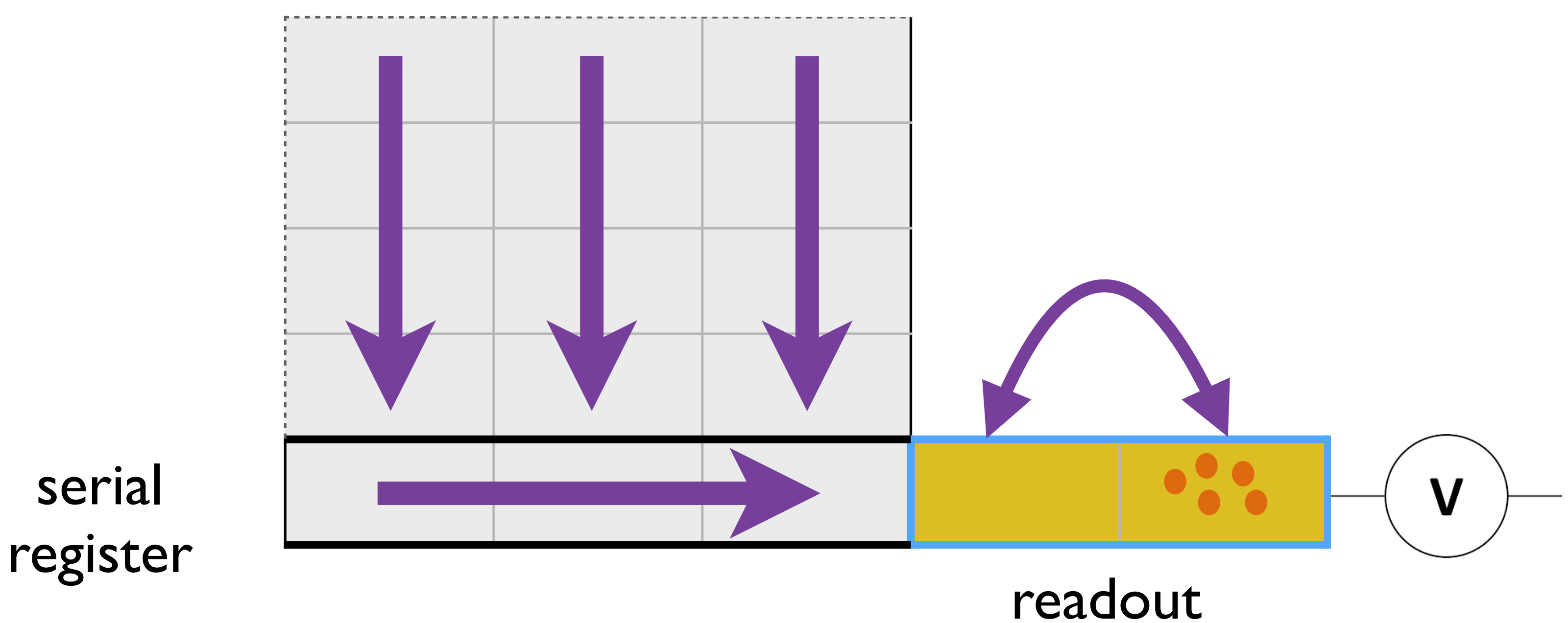


$\sim 2\ \text{cm} \times 10\ \text{cm},\ 5.4\ \text{Mpix}$



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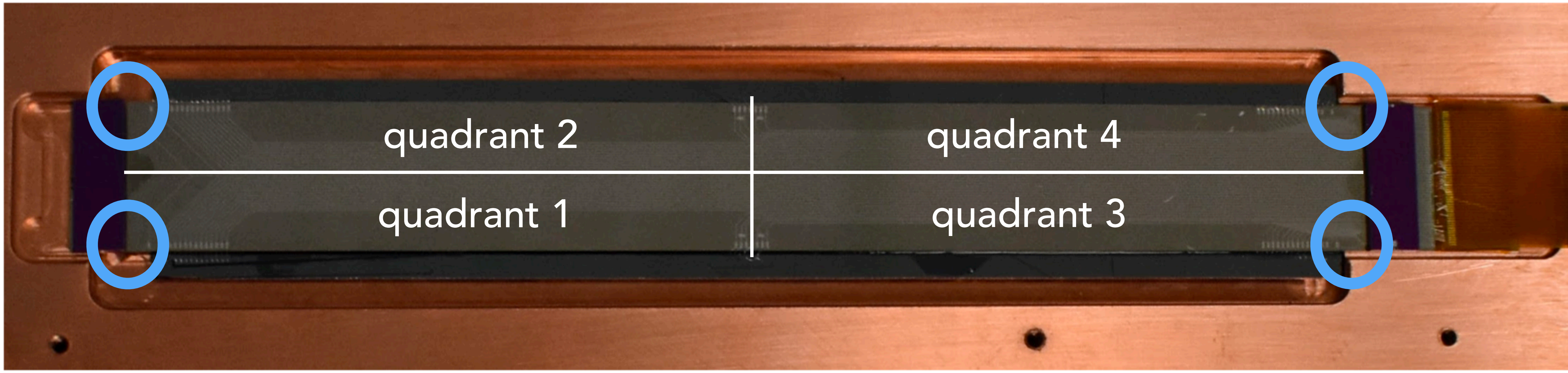

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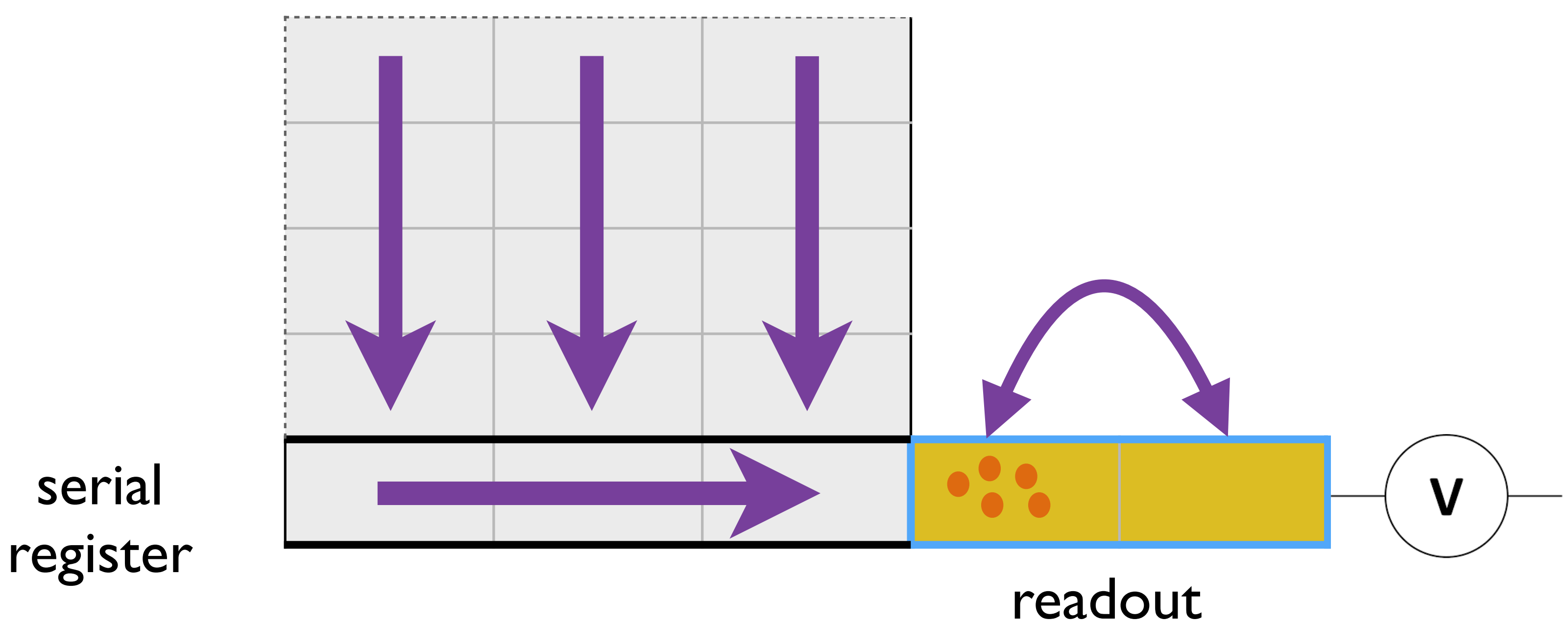

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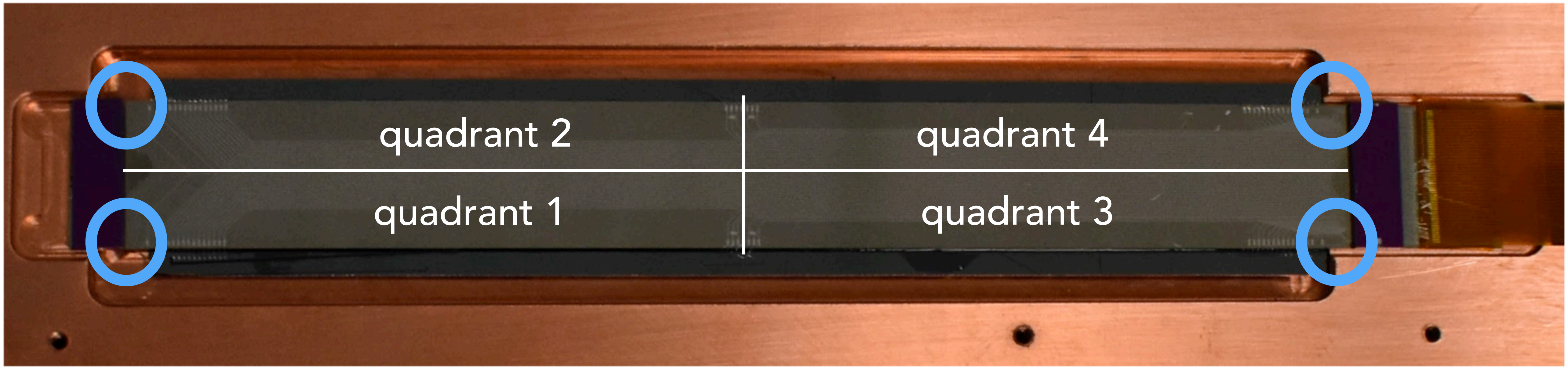

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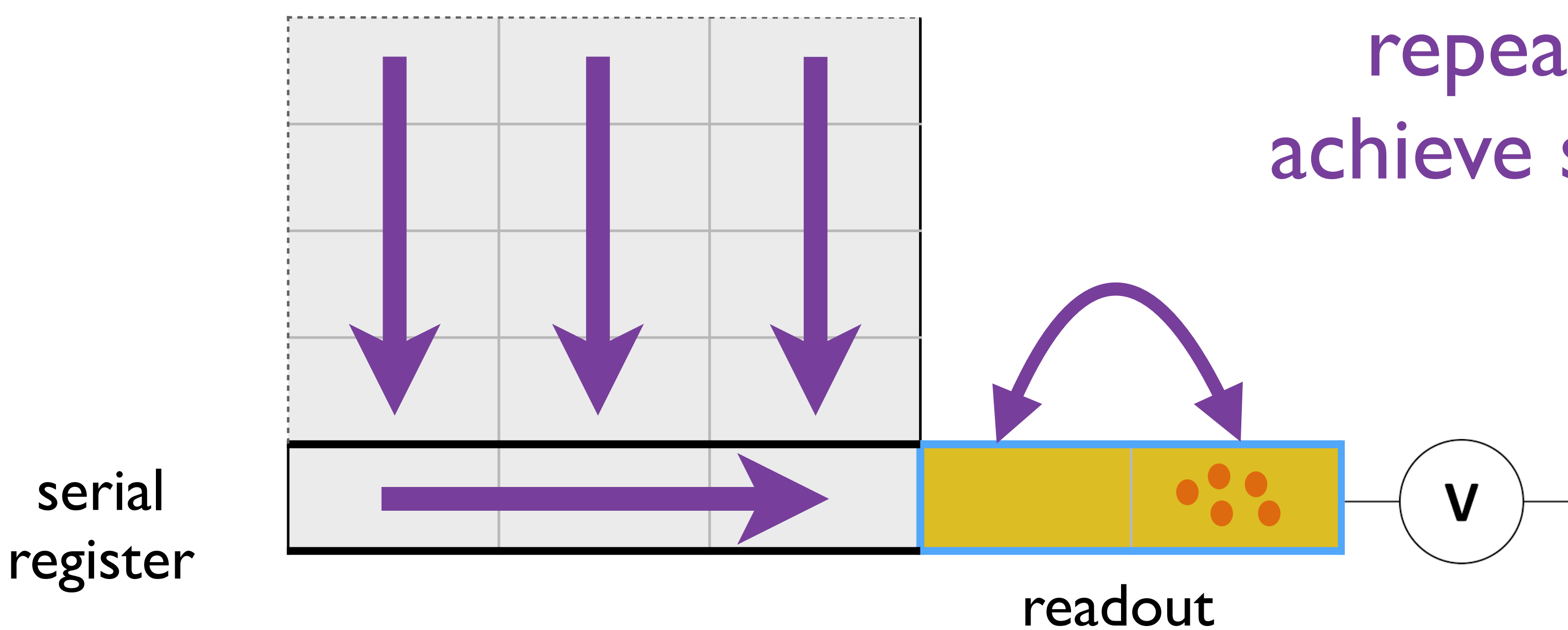

repeatedly measure charge to achieve sub-electron readout noise

Tiffenberg et.al. 2017

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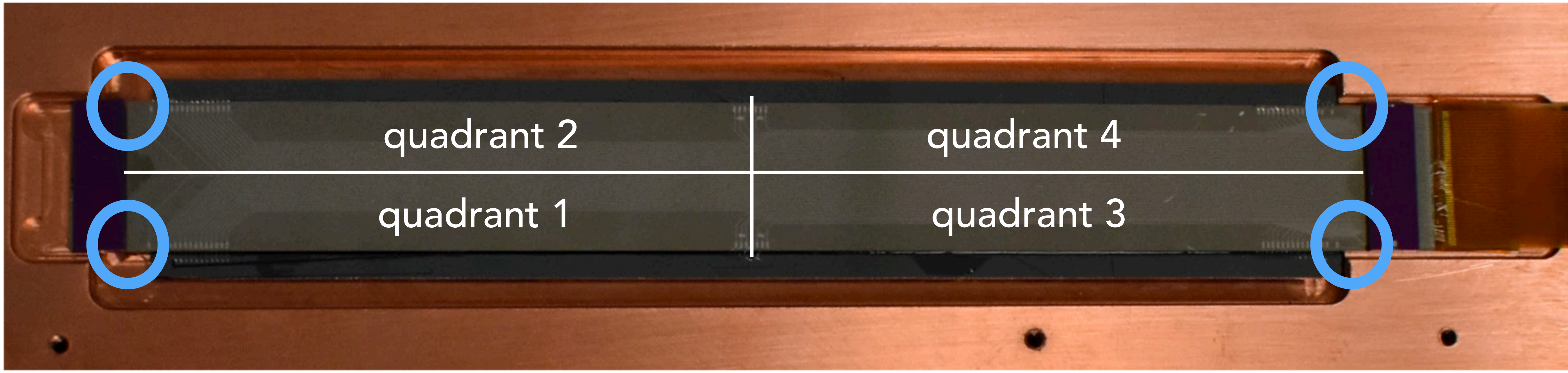

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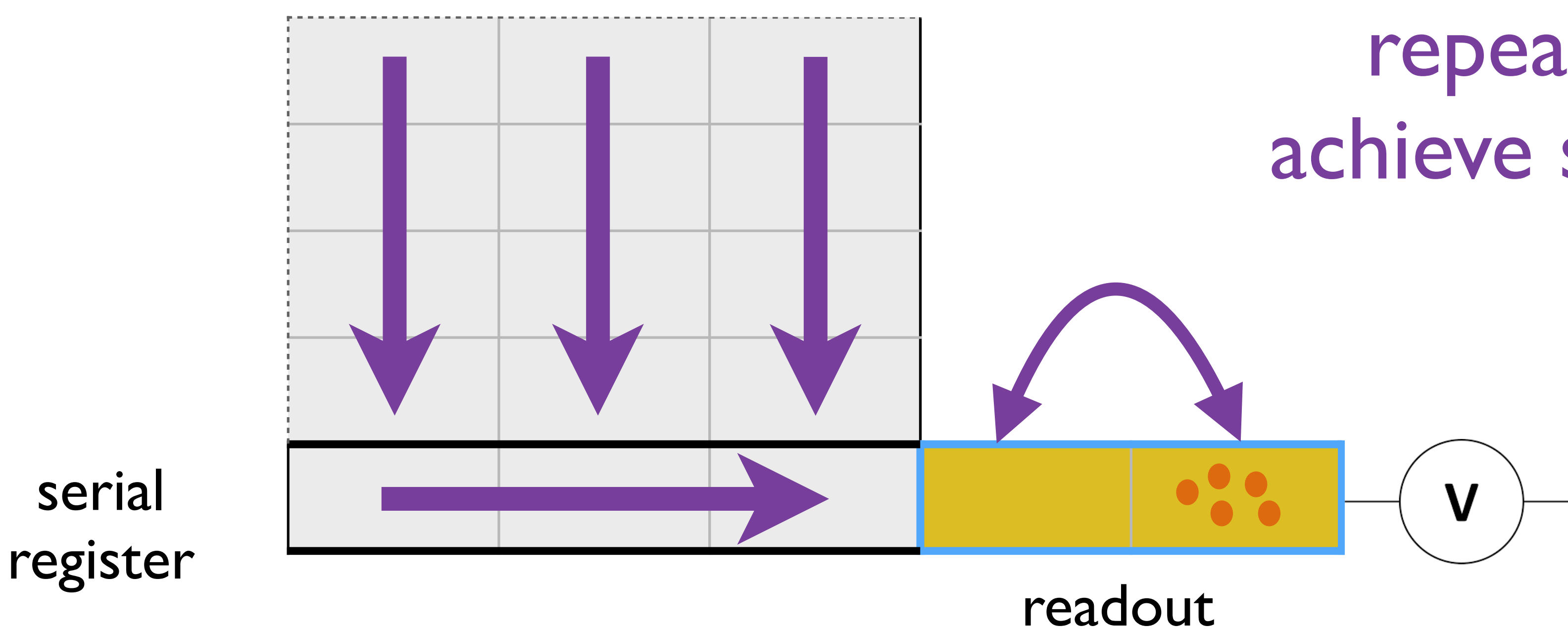


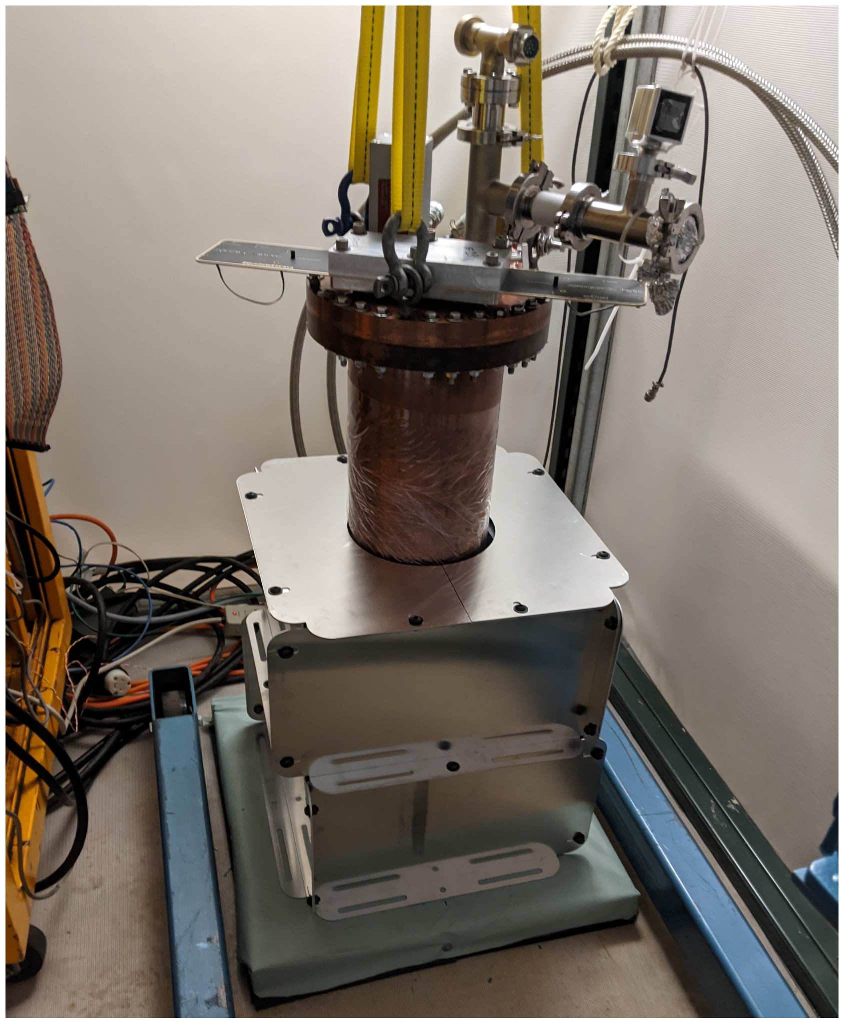
repeatedly measure charge to achieve sub-electron readout noise

Tiffenberg et.al. 2017

designed at LBNL and fabricated at Teledyne DALSA Semiconductor

SENSEI has two DM detectors operating

@Fermilab (near Chicago)



@SNOLAB, Canada

- ~100 m underground
- some lead shielding

- ~2,000 m underground (no muons)
- better shielding

Dark Matter Results from SENSEI

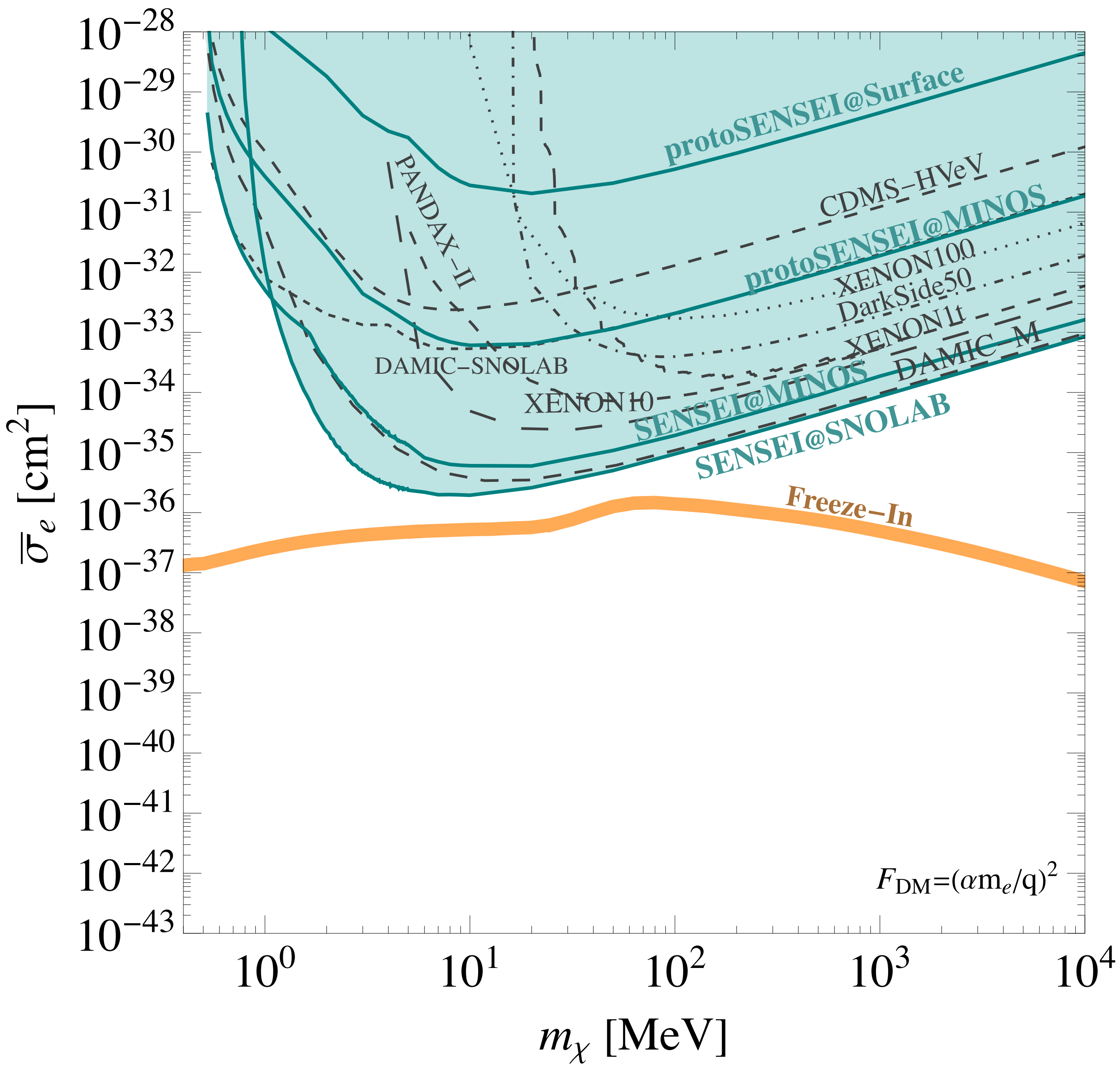
SENSEI@Fermilab: three science runs

- 1 prototype Skipper-CCD (0.0947 gram)
  - 2018: surface — 1804.00088, PRL
  - 2019: ~100m underground — 1901.10478, PRL, Editor's suggestion
- 1 science-grade Skipper-CCD (1.925 gram)
  - 2020: ~100m underground — 2004.11378, PRL, Editor's suggestion

SENSEI@SNOLAB: one science run

- 6 science-grade Skipper-CCDs (~12 gram)
  - 2023: ~2,000m underground — 2312.13342, submitted to PRL

Example of Results

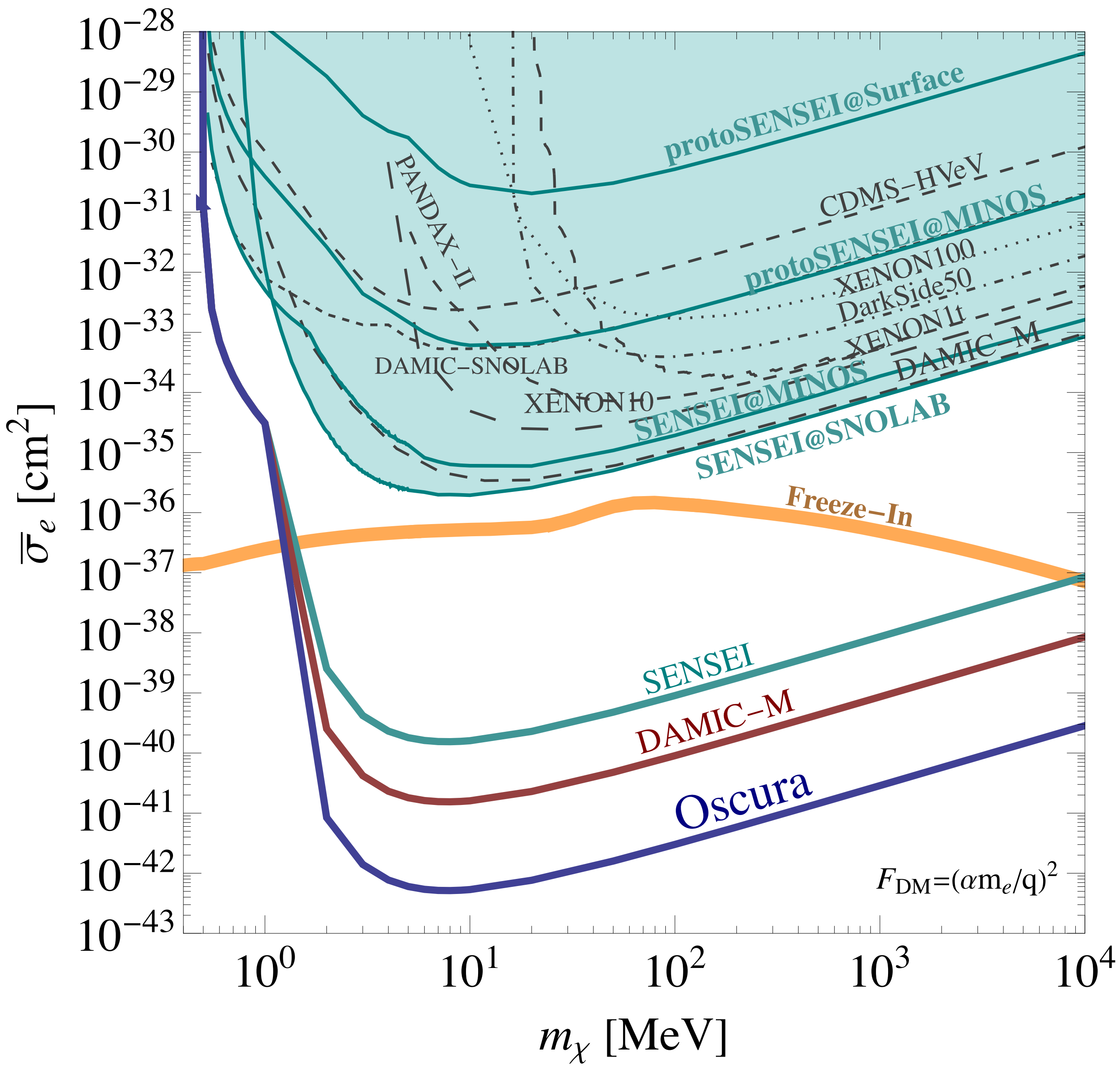


- Leading constraints for several dark matter models
- orange line: "freeze-in DM"

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

- Detector upgraded, next science run ongoing

Exciting Skipper-CCD program ahead



- SENSEI: ~100 gram (SNOLAB)
- DAMIC-M: ~1 kg (Modane, ~2024)
- Oscura: 10 kg (R&D funded, ~2026)

Summary: an opportunity for PAUL?

- Direct detection of dark matter is a vibrant field
- PAUL will not compete with "big" (ton-scale) experiments searching for WIMPs (XENONnT, LZ, PandaX, DarkSide…)
- BUT: small "inexpensive" experiments with ultrasensitive detectors and small collaborations (~10-30 scientists) can search for "sub-GeV" dark matter and produce world-leading science (discussed one example: SENSEI)
- Excellent training ground for students; exposure to the many aspects needed to create a successful experiment; any one person can have a big impact
- Fast-moving, dynamic field
- How best to attract interested groups?

Thank you

Some references providing summaries & overviews

- RE, Mardon, Volansky, “Direct Detection of Sub-GeV Dark Matter,” Phys. Rev., D85, p. 076007, 2012, arXiv: 1108.5383
- M. Battaglieri et al., “US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report,” arXiv: 1707.04591
- Report of the Workshop “Basic Research Needs for Dark Matter Small Projects New Initiatives” is available online at: https://science.osti.gov/-/media/hep/pdf/Reports/Dark_Matter_New_Initiatives_rpt.pdf
- R. Essig, “The low-mass dark matter frontier,” Physics 13, 172, 2020
- Y. Kahn and T. Lin, “Searches for light dark matter using condensed matter systems,” arXiv:2108.03239
- R. Essig et al., “Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade,” in Snowmass 2021, arXiv: 2203.08297

Many challenges remain, and much remains to be done…

e.g.

- Understand (novel) low-energy backgrounds
- Increase detector sensitivity & target mass
- Understand/calibrate detector response to dark matter

More SENSEI results

2312.13342