Progress & Challenges for Direct-Detection of Sub-GeV Dark Matter

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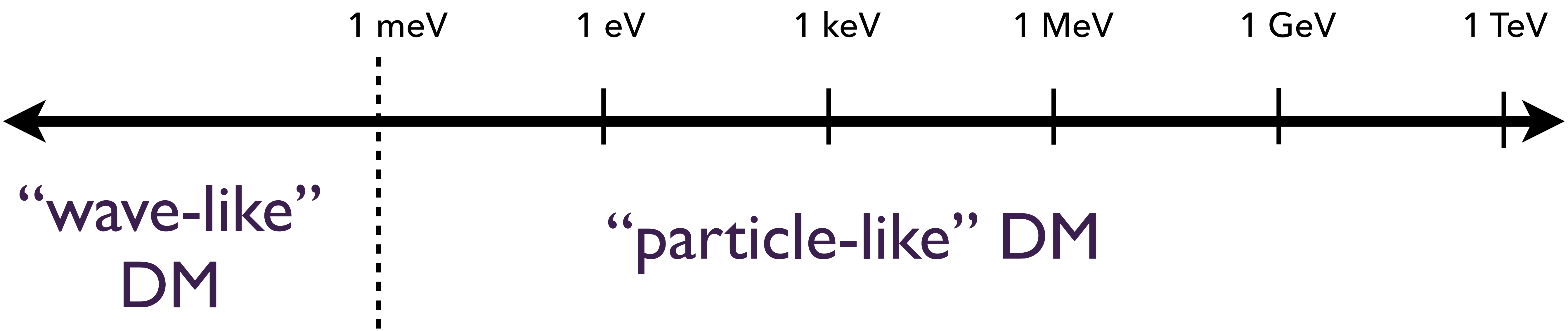
Stony Brook University

UCLA Dark Matter, March 29, 2023

Progress & Challenges for Direct-Detection of Sub-GeV Dark Matter

$\gg 100$ papers over past few years, so can only highlight a few results

Sub-GeV "particle-like" dark matter



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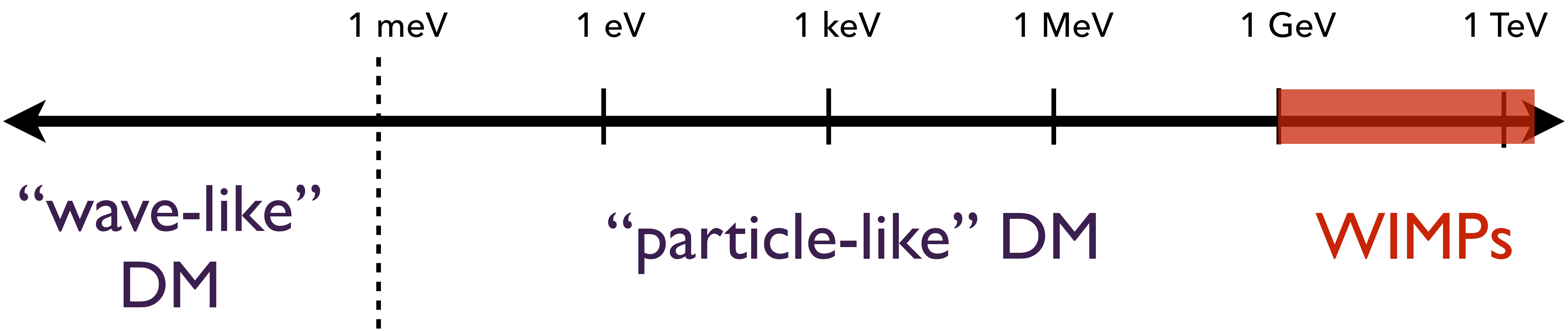

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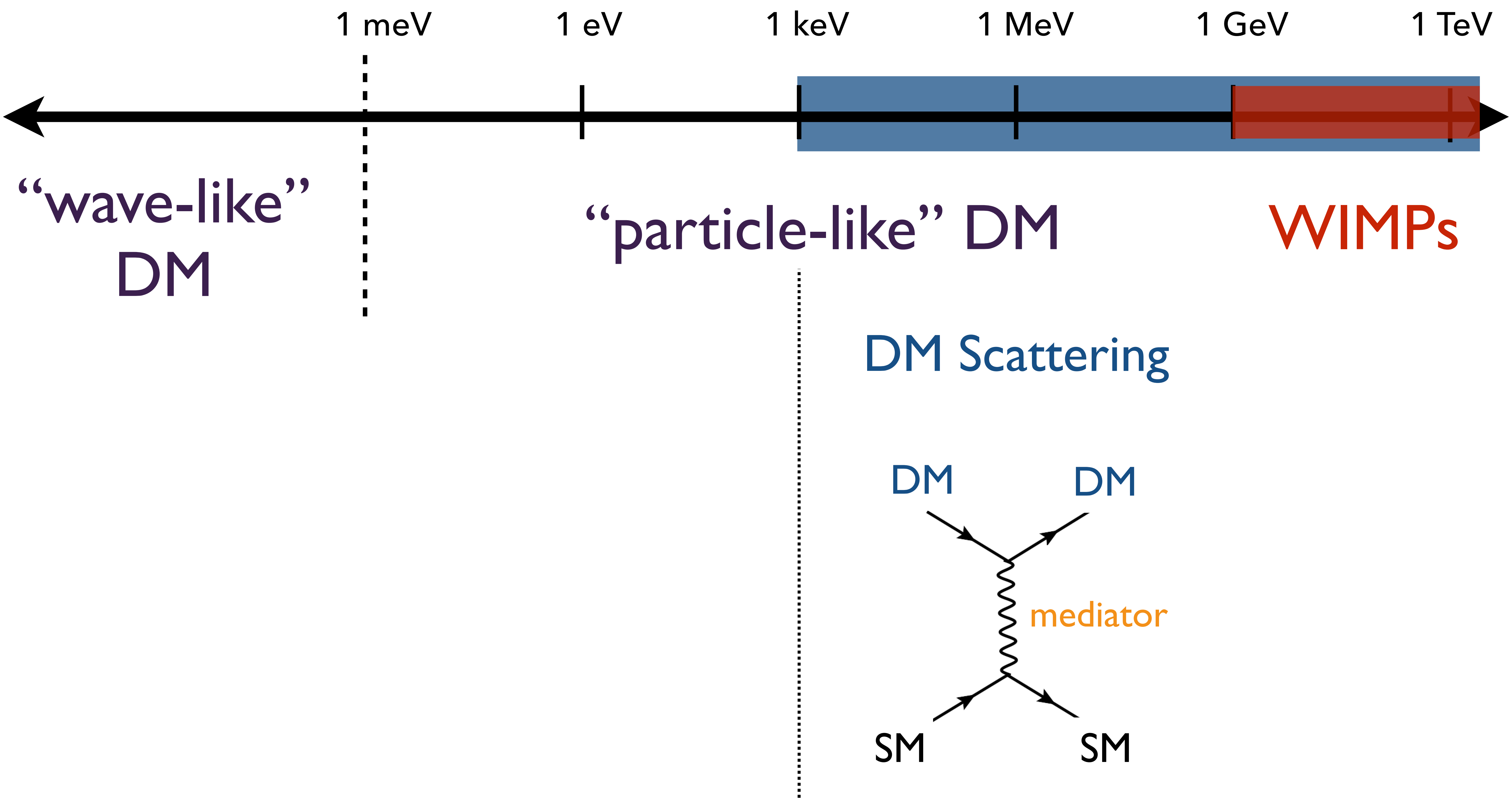

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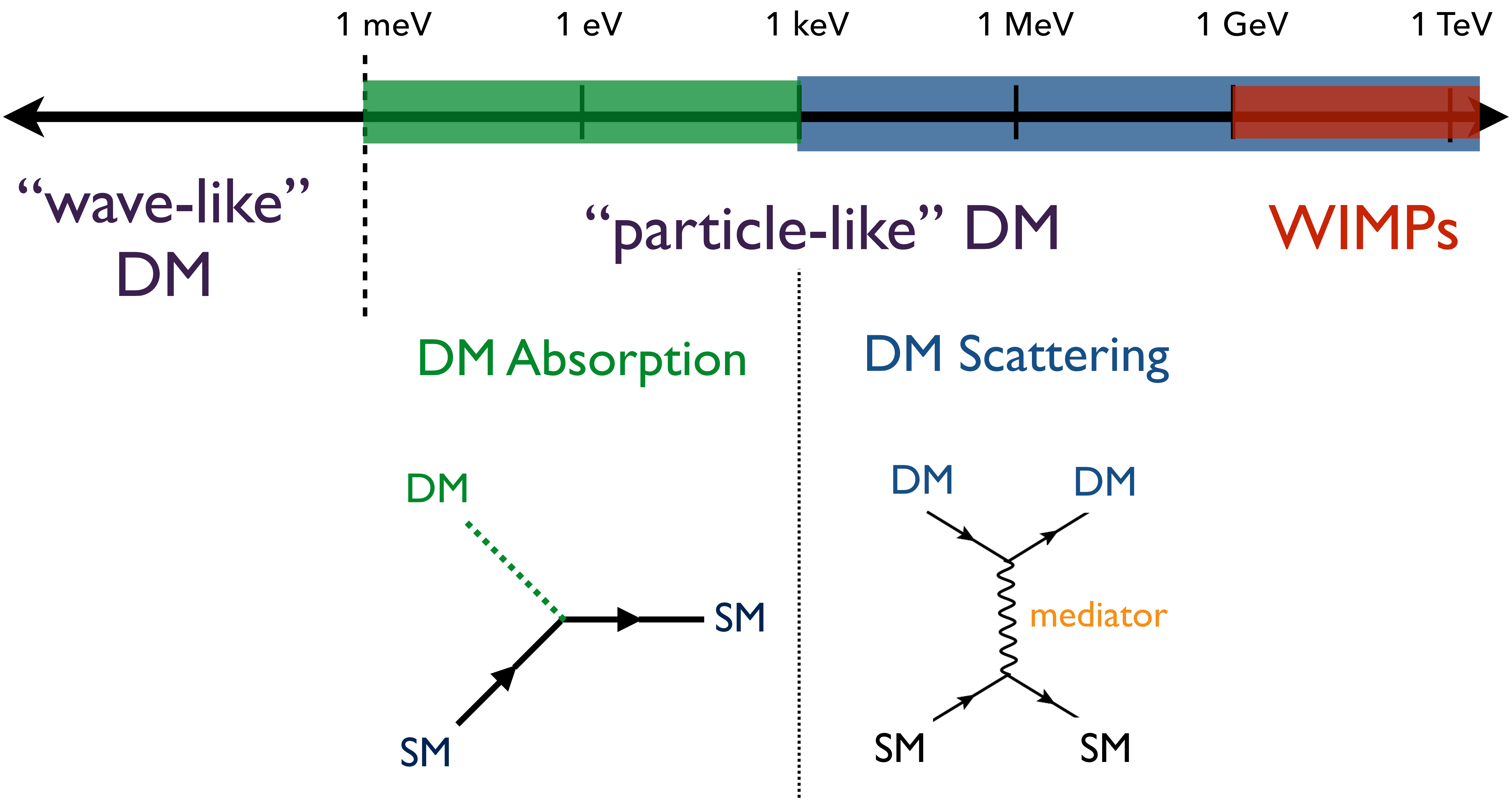
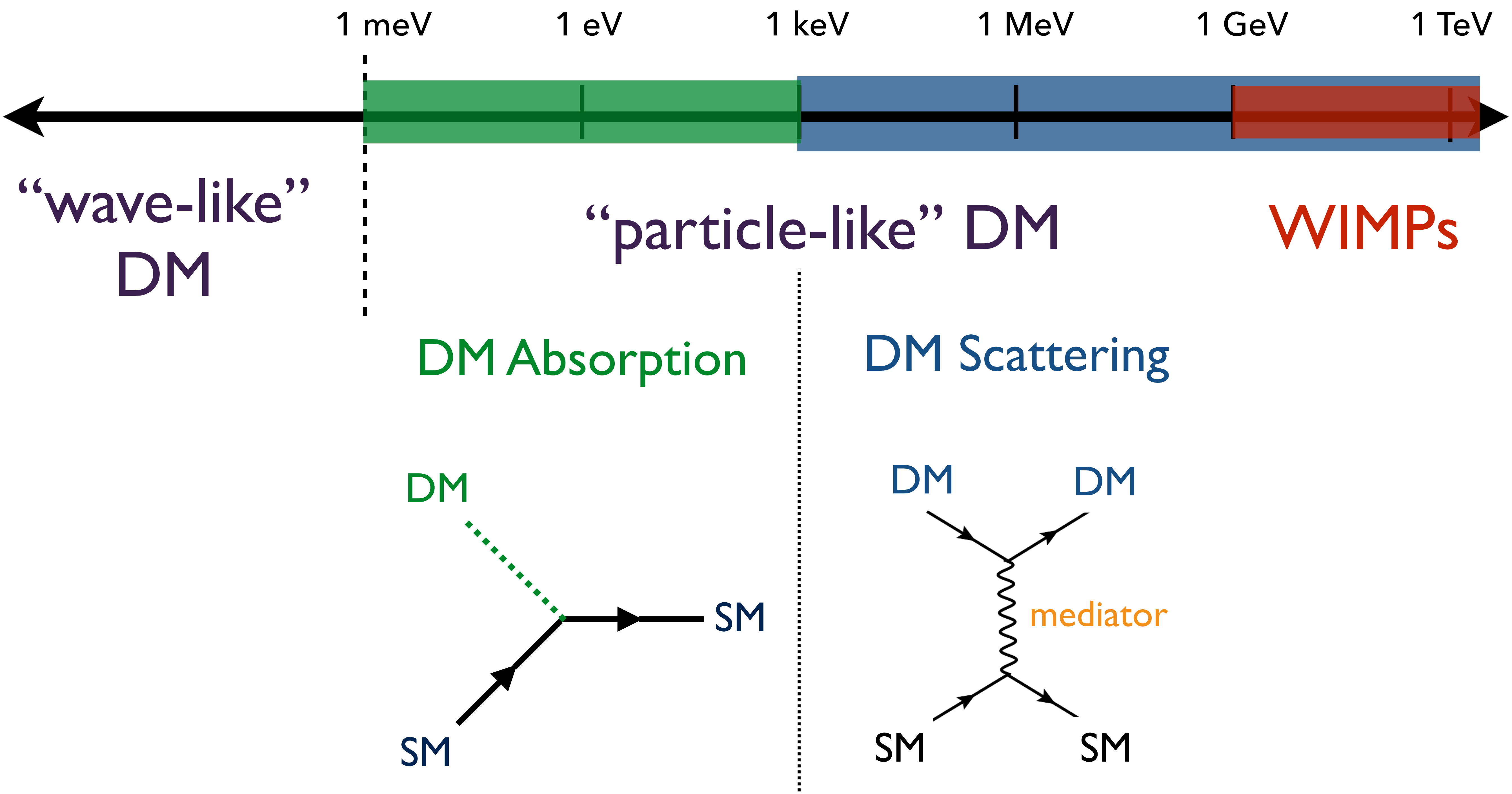


Sub-GeV "particle-like" dark matter

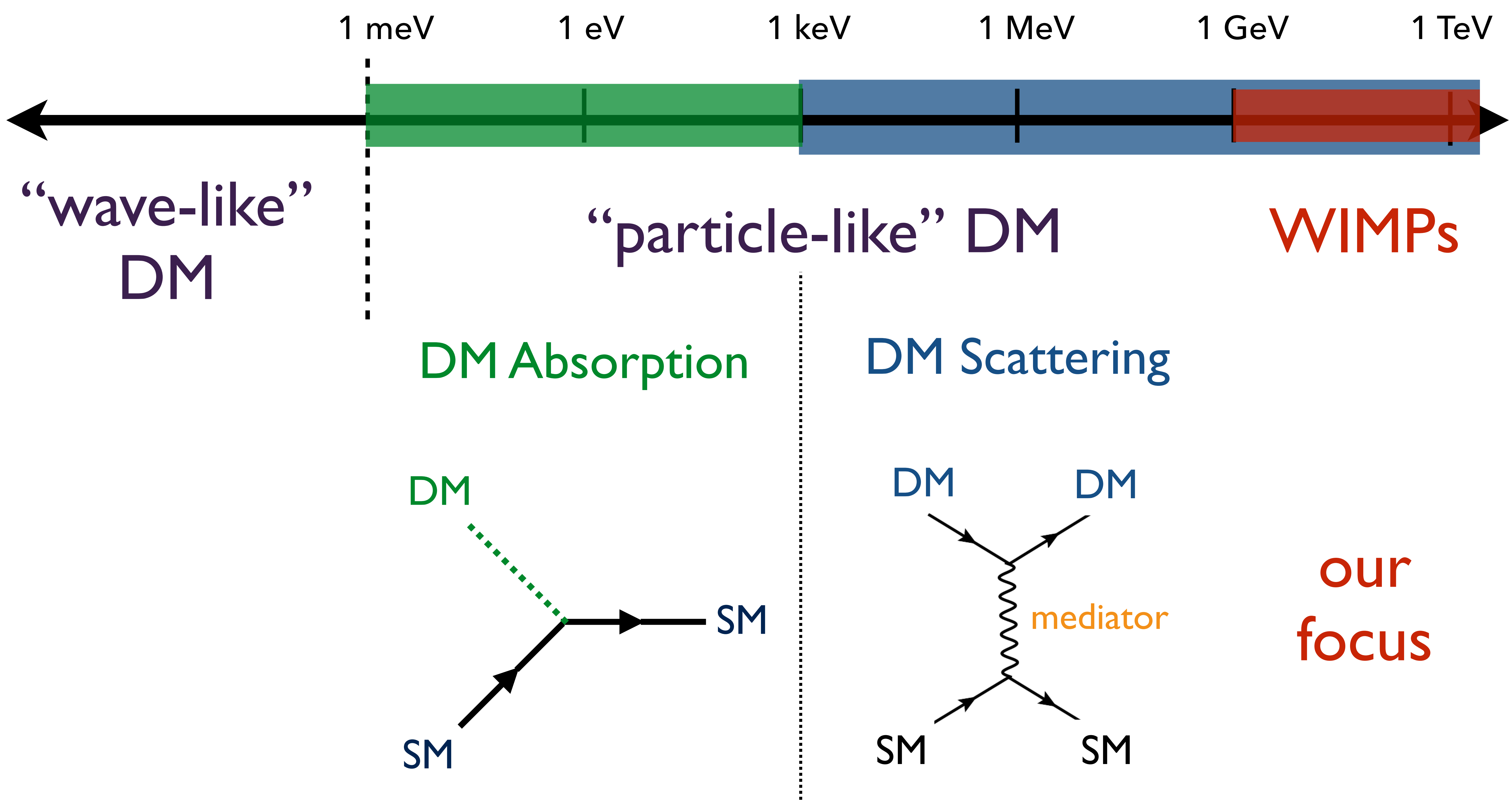


see backup slides for specific benchmark models

several DM production scenarios

(freeze-out, asymmetric, freeze-in, SIMP, ELDER, co-annihilation, …)

Sub-GeV "particle-like" dark matter



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several DM production scenarios

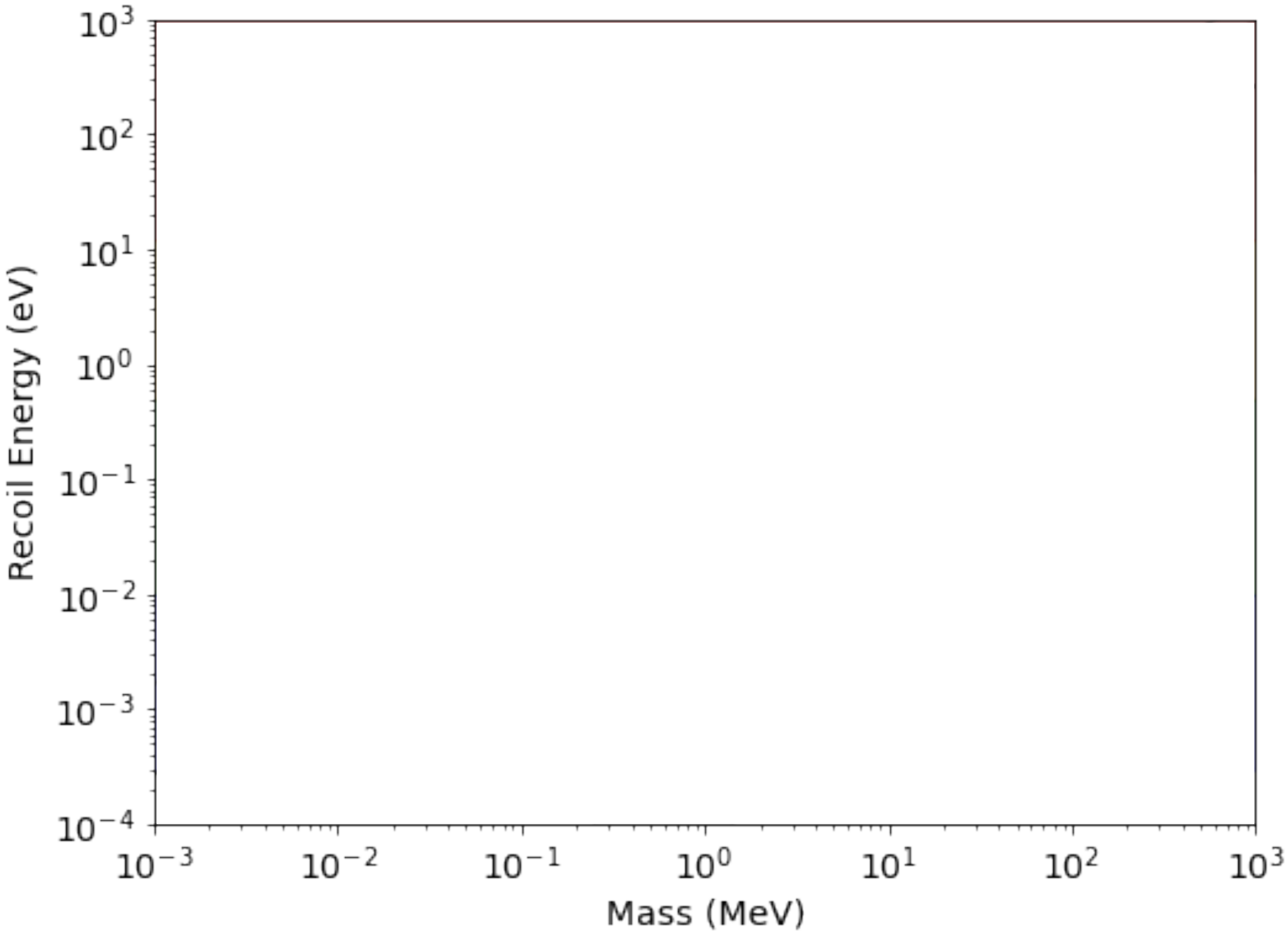
(freeze-out, asymmetric, freeze-in, SIMP, ELDER, co-annihilation, ...)

Significant progress in probing sub-GeV dark matter

- Several detection concepts, using variety of target materials

Many Detection Concepts, Target Materials, Technologies

Fig. adapted from 2203.08297



Many Detection Concepts, Target Materials, Technologies

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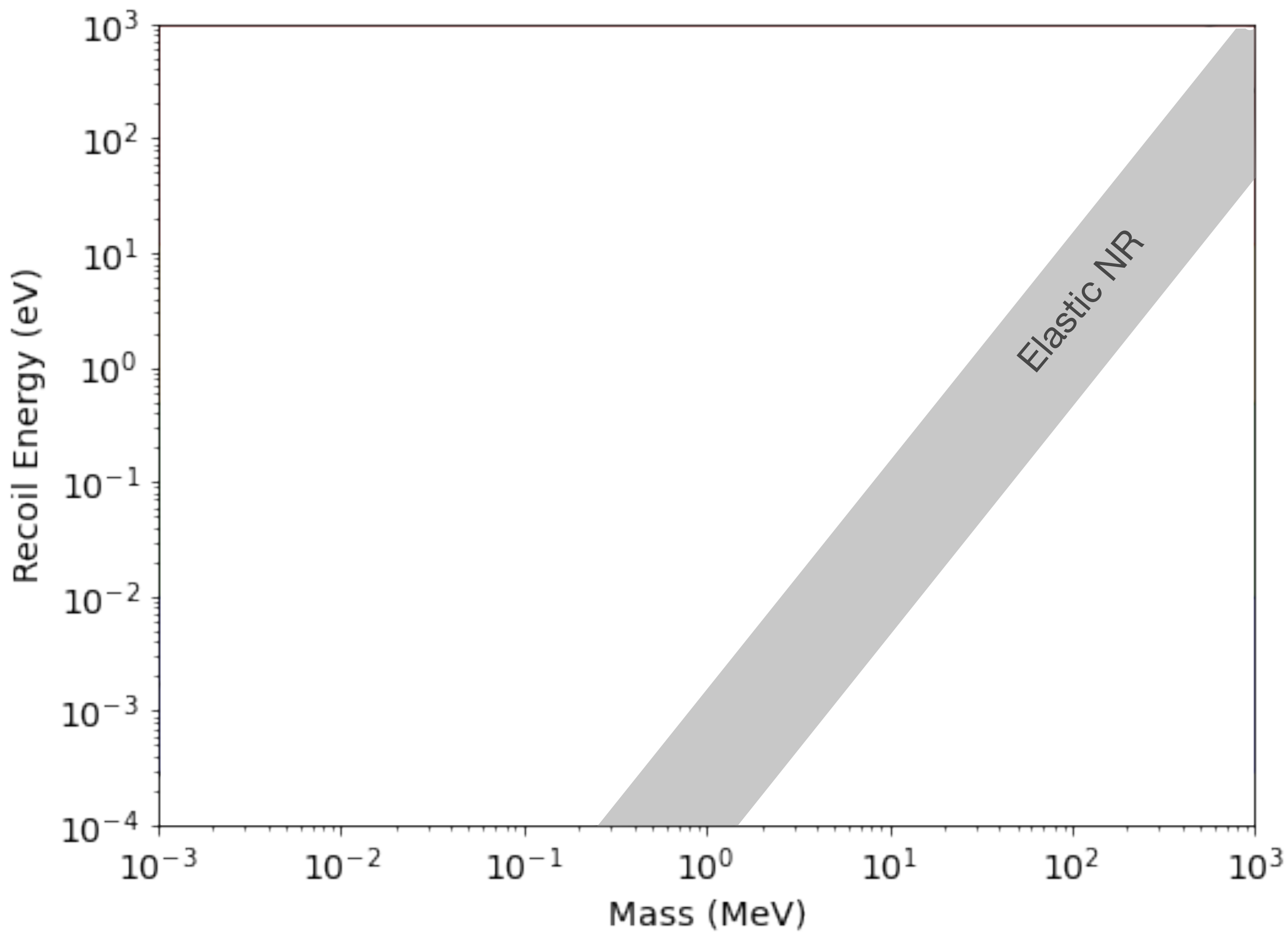
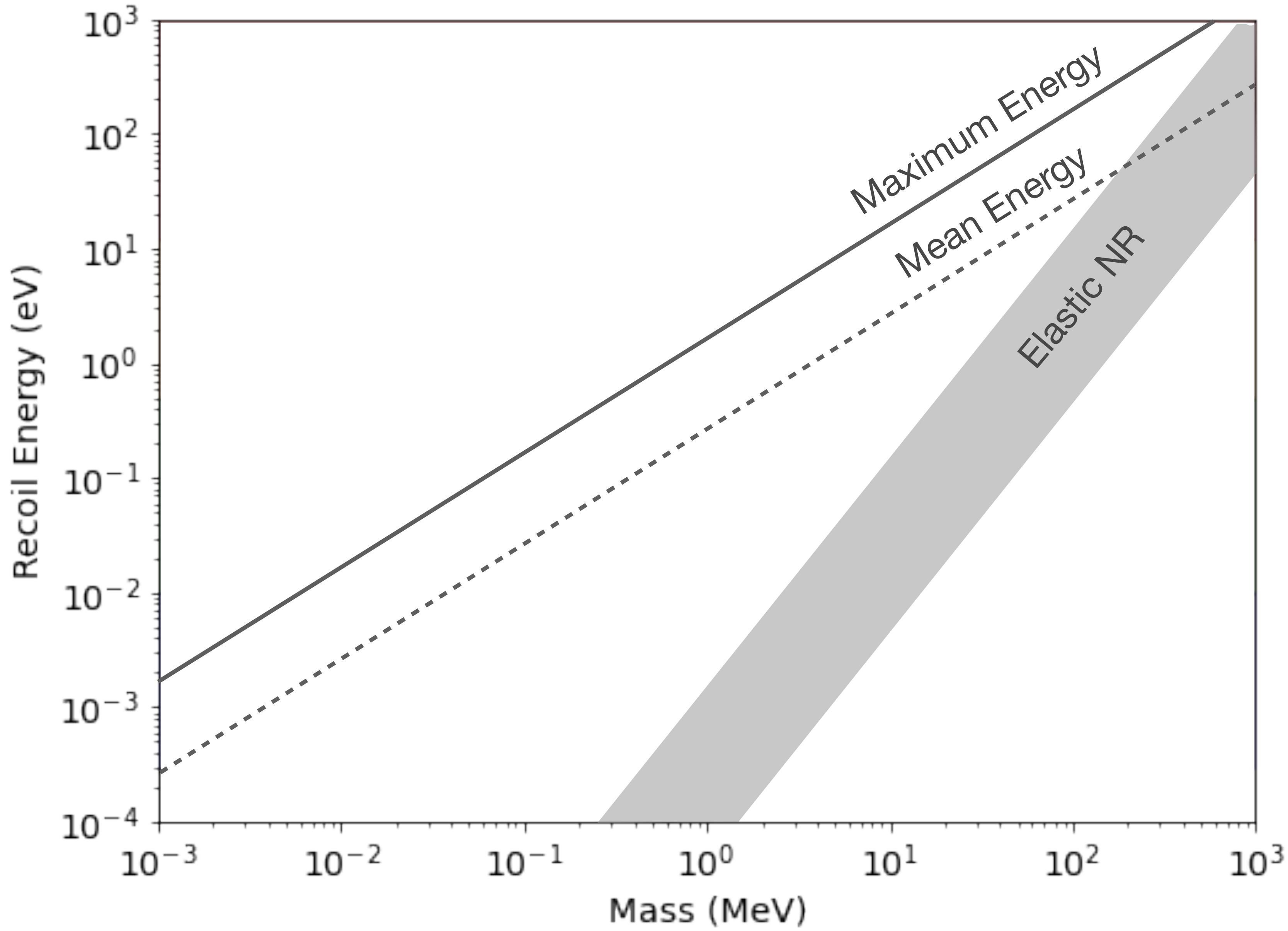


elastic DM-nucleus scattering:

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

Many Detection Concepts, Target Materials, Technologies

Fig. adapted from 2203.08297



DM kinetic energy

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

Many Detection Concepts, Target Materials, Technologies

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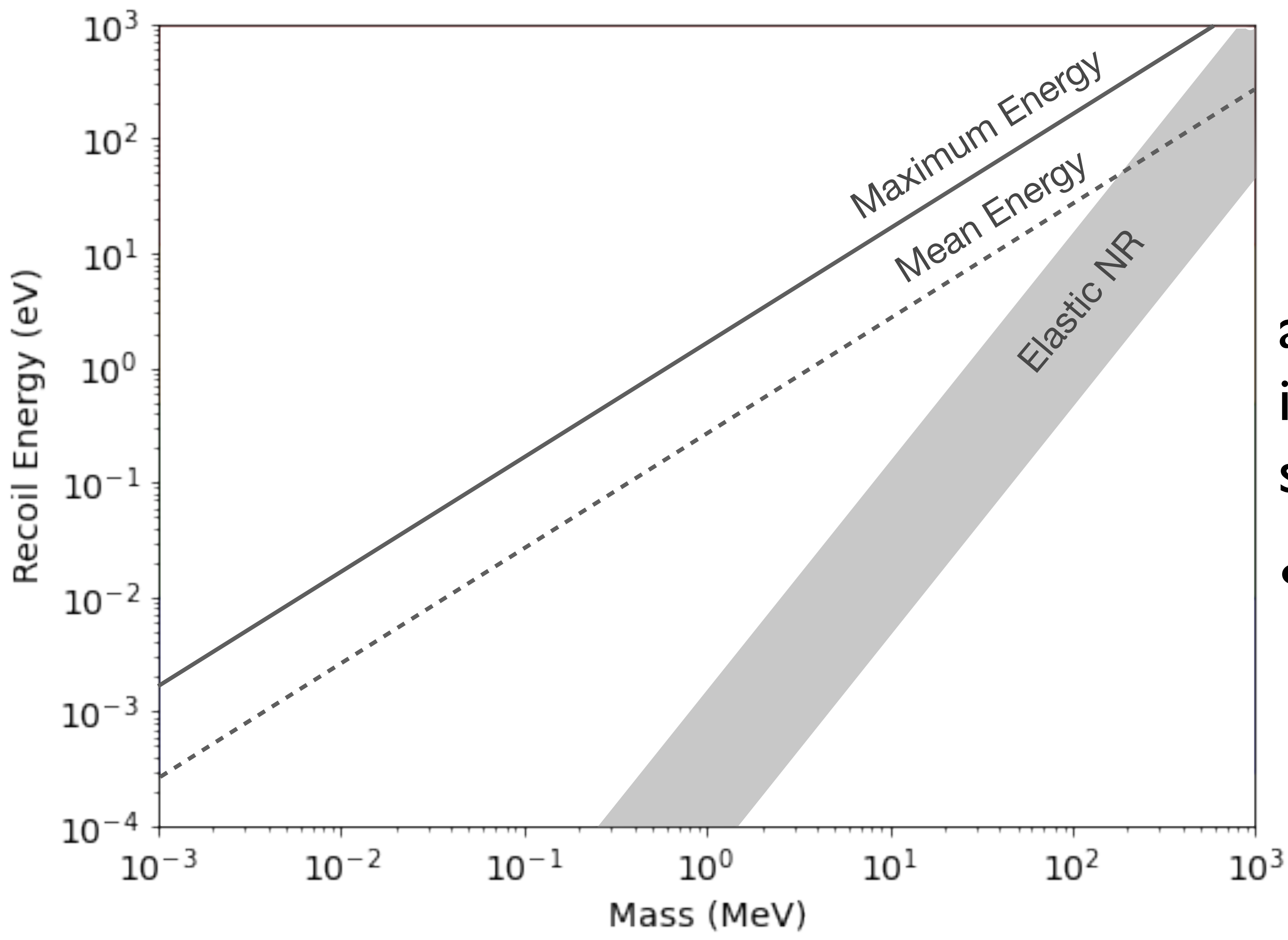
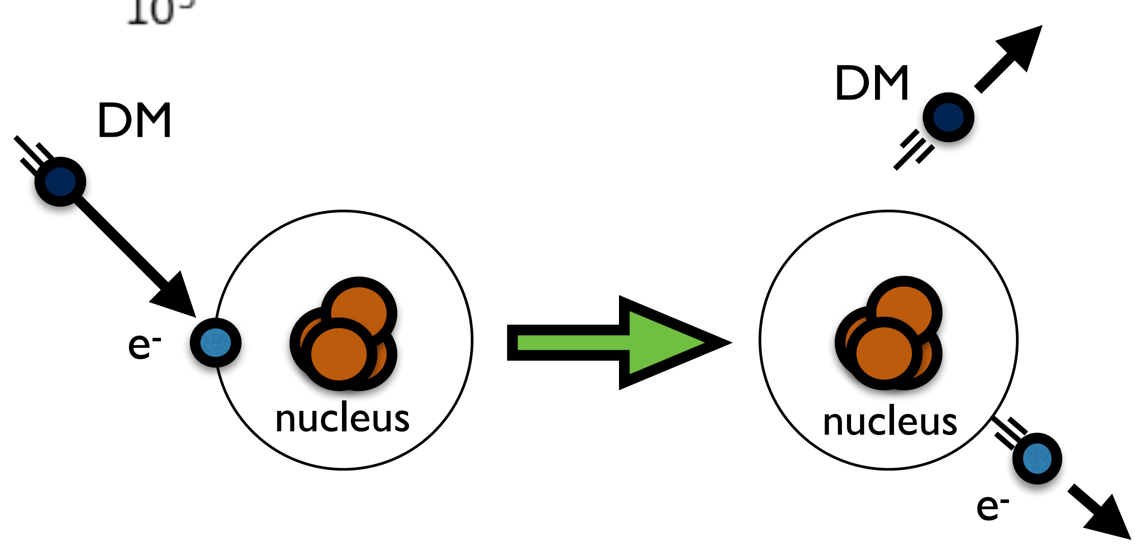


accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering



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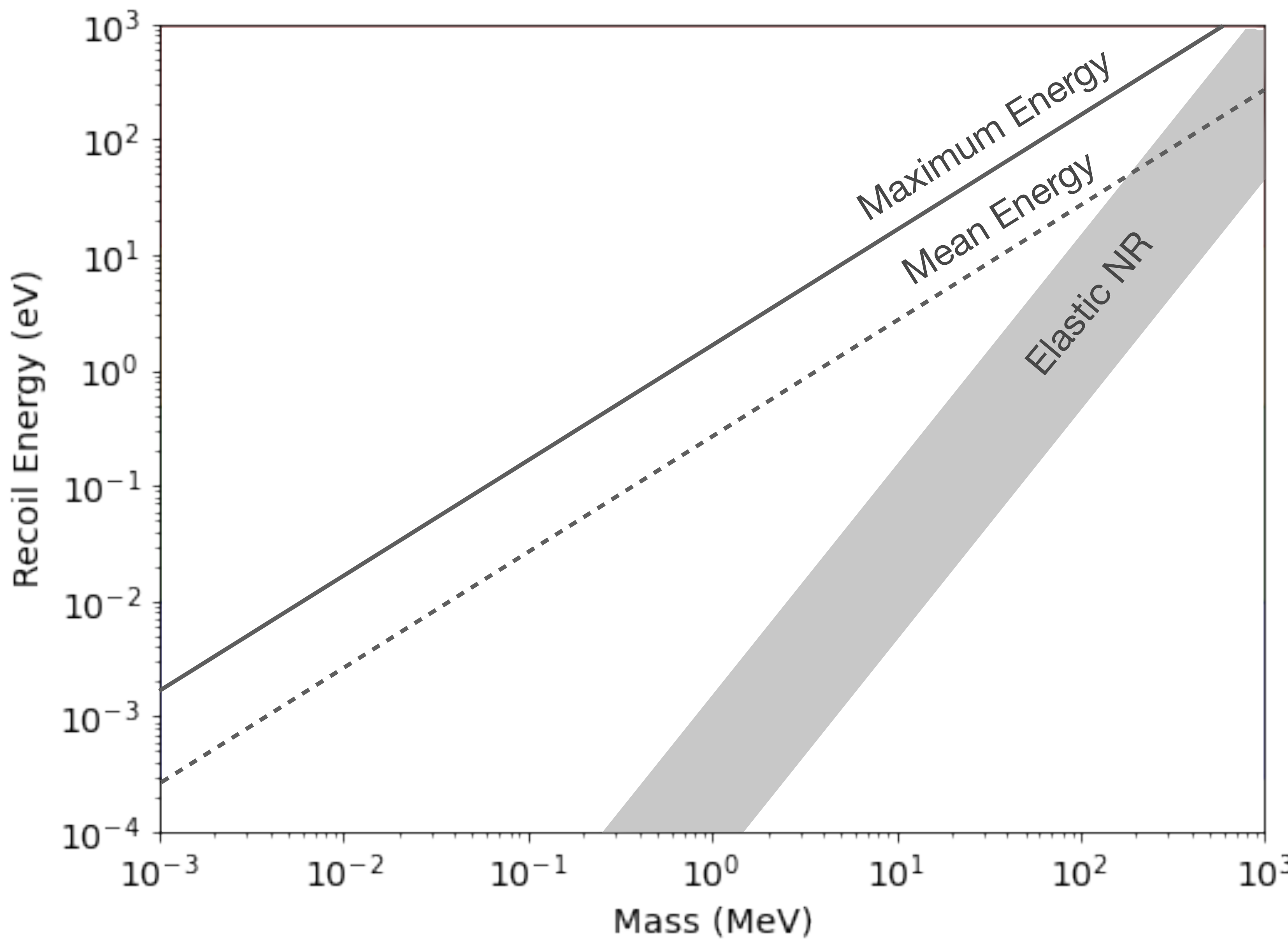

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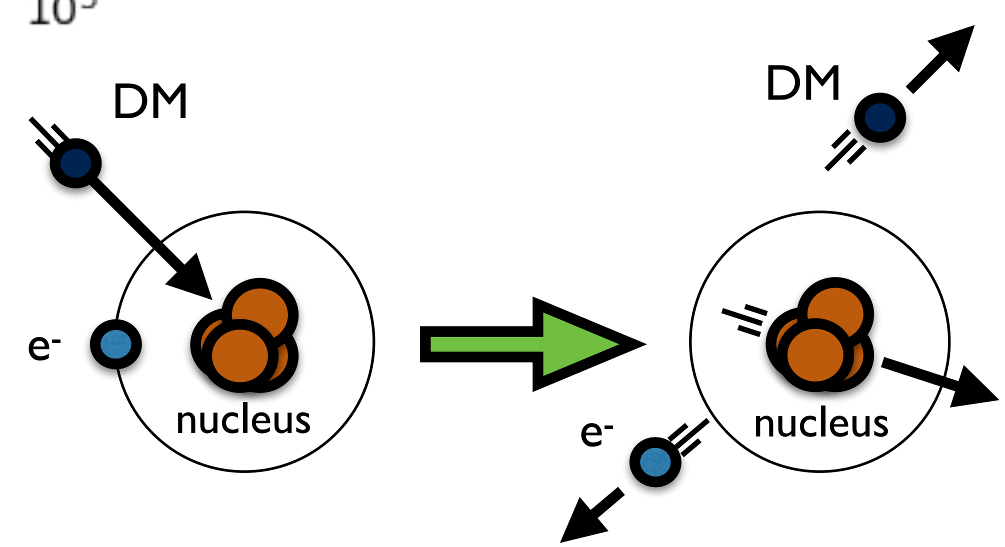
- DM-e scattering
- DM-N scattering w/ Migdal



Many Detection Concepts, Target Materials, Technologies

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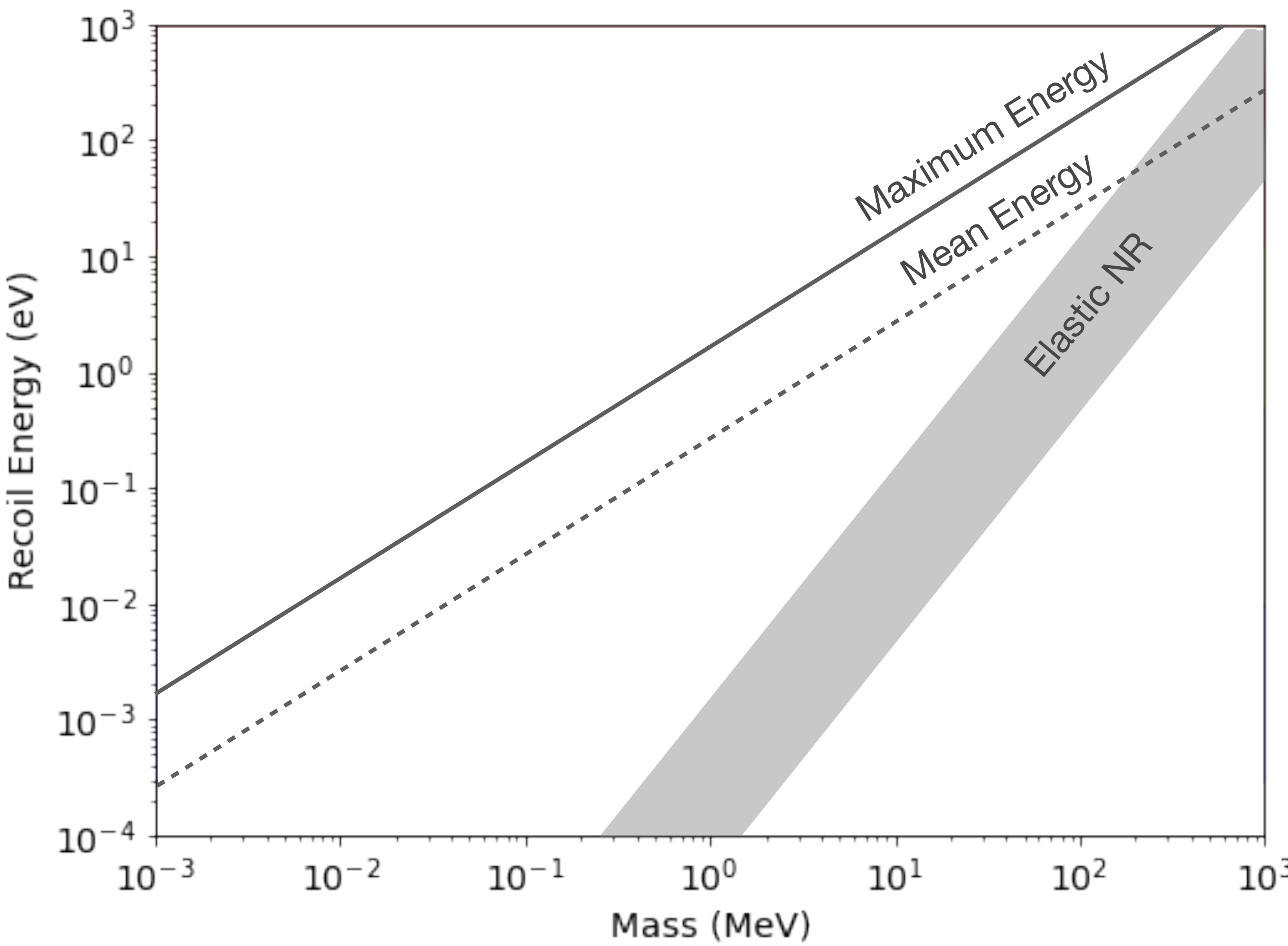

accessible through <u>inelastic</u> interactions (sometimes w/ suppressed rate), e.g.:

- DM-e scattering
- DM-N scattering w/ Migdal
- DM scattering w/ collective modes (e.g. phonons, magnons)

Many Detection Concepts, Target Materials, Technologies

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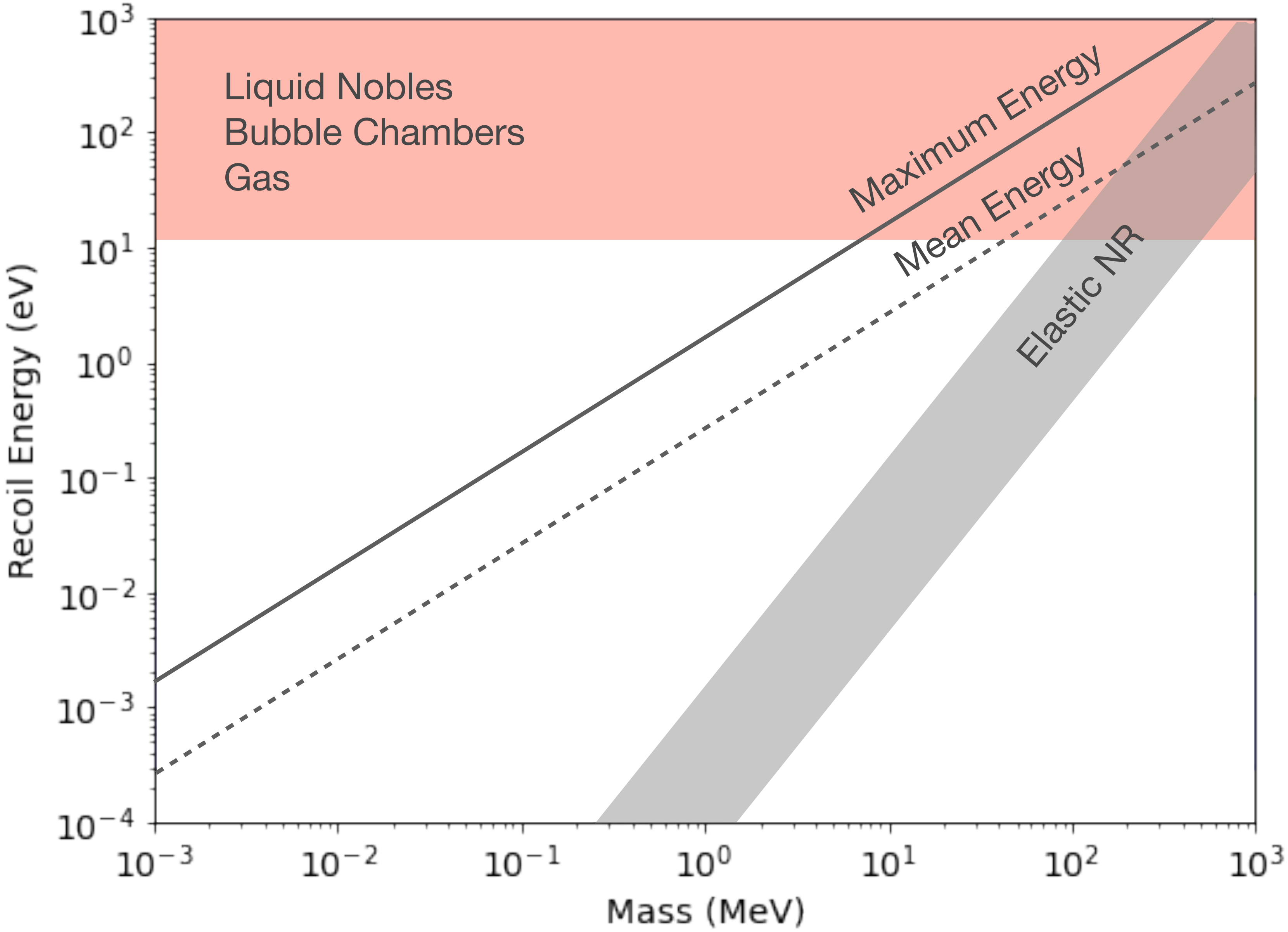

$\Delta E \sim 10$ eV

e.g. Xe, Ar, He

Many Detection Concepts, Target Materials, Technologies

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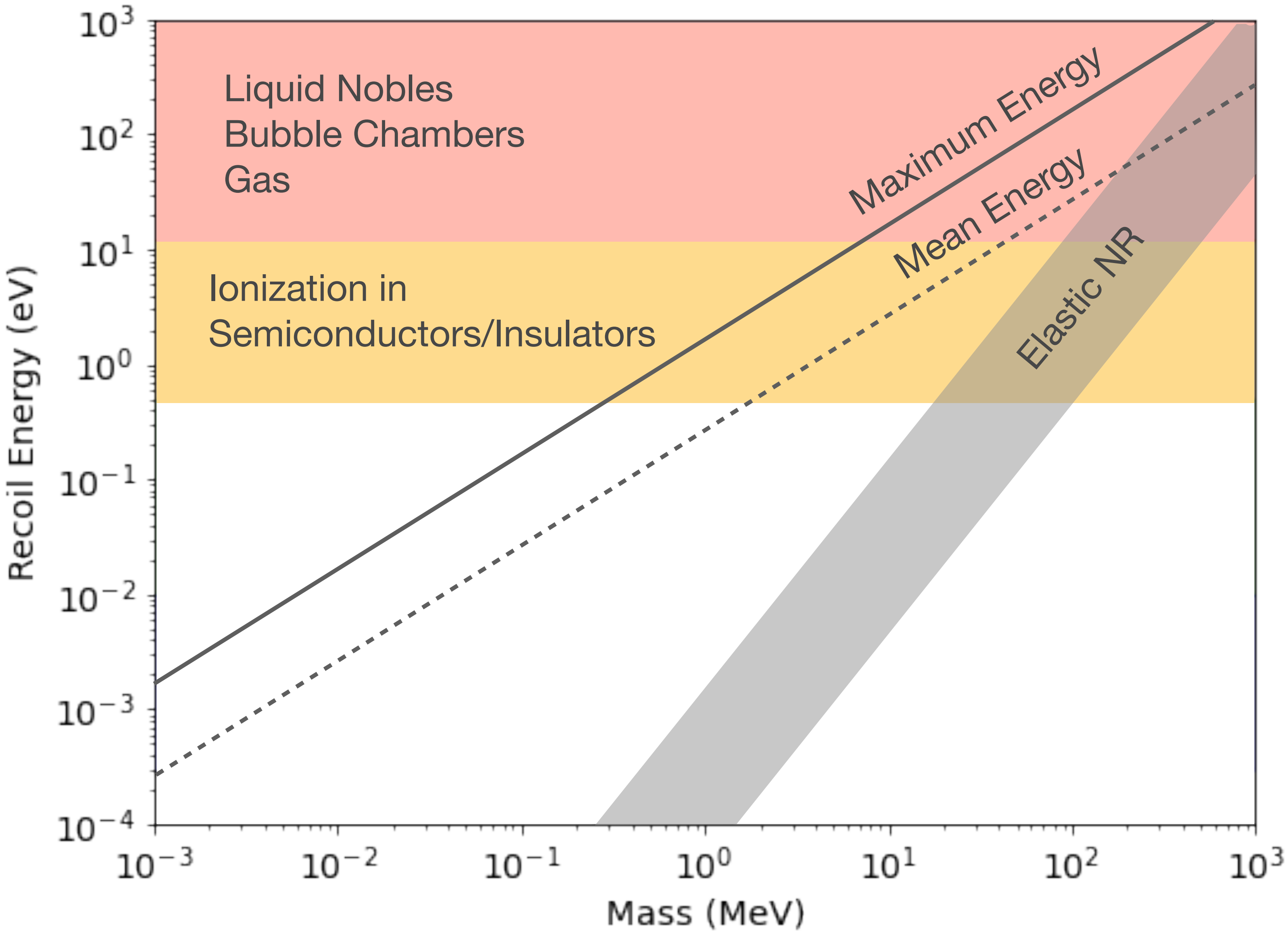

$\Delta E \sim 1$ eV

e.g. Si, Ge, GaAs, diamond, Quantum Dots, organic scintillators…

Many Detection Concepts, Target Materials, Technologies

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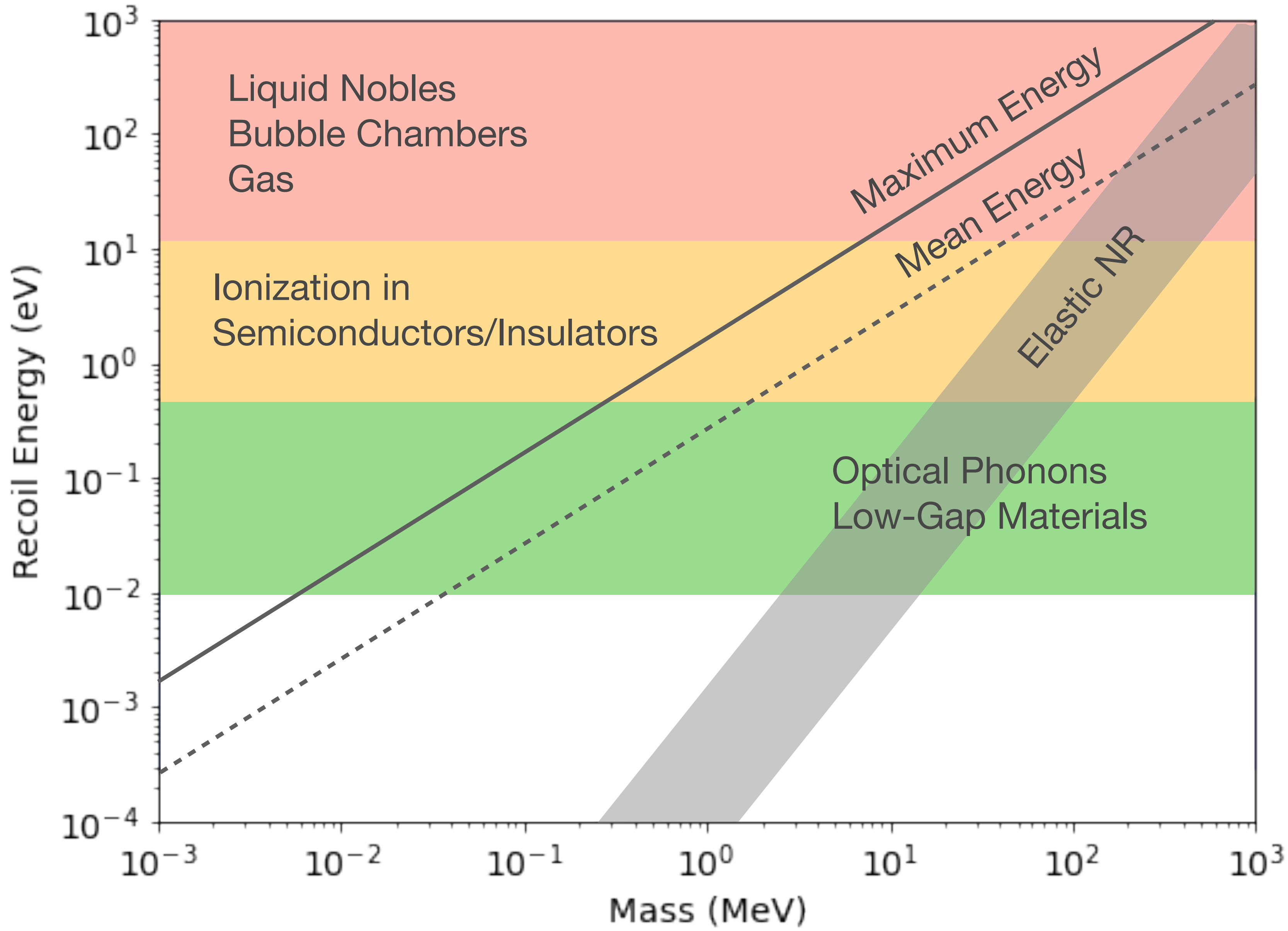

$\Delta E \sim 10 - 100$ meV
e.g. GaAs, sapphire, Dirac materials, doped s/c, …

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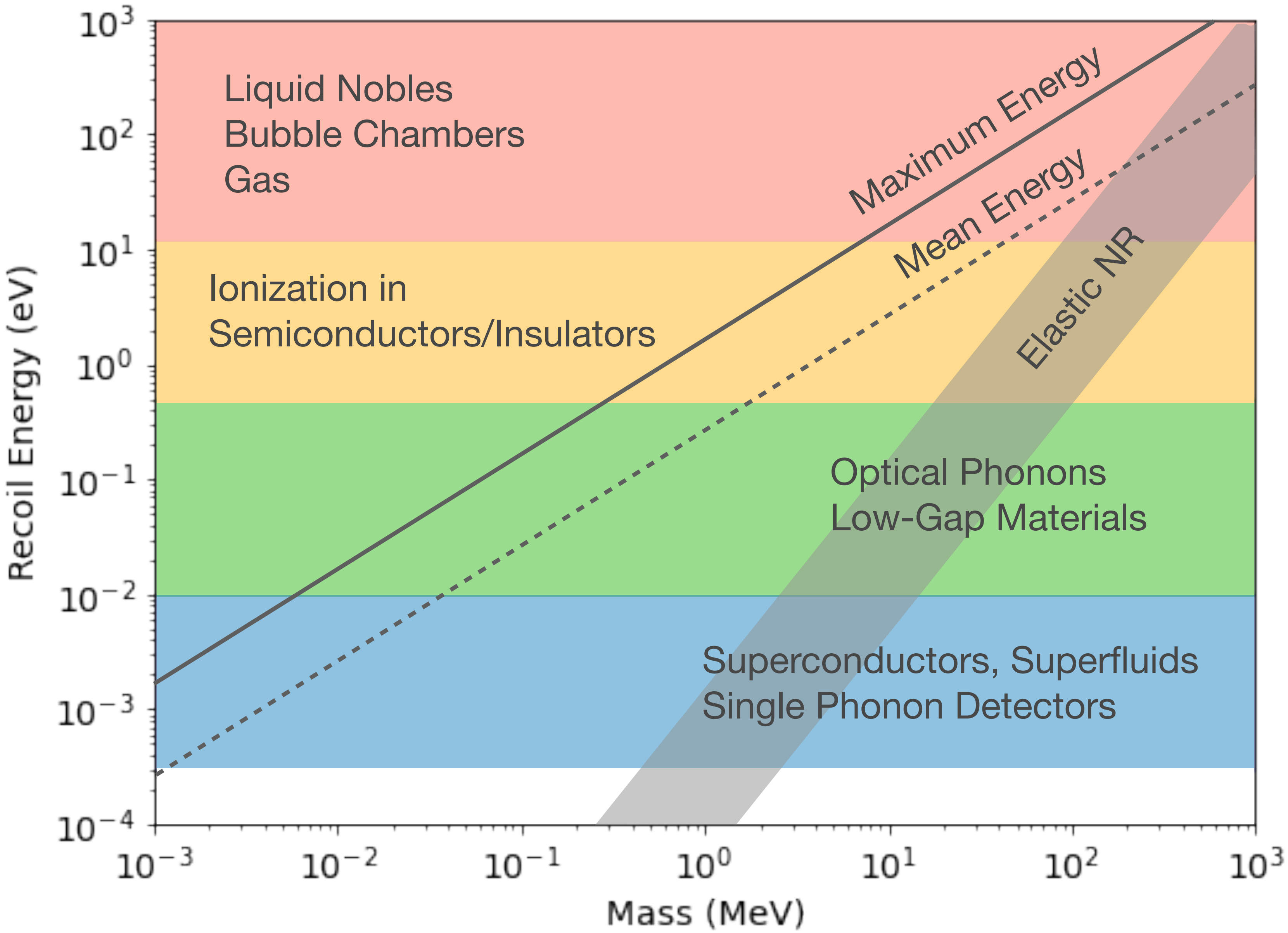

$\Delta E \sim 1$ meV

e.g. superfluids, superconductors

Many Detection Concepts, Target Materials, Technologies

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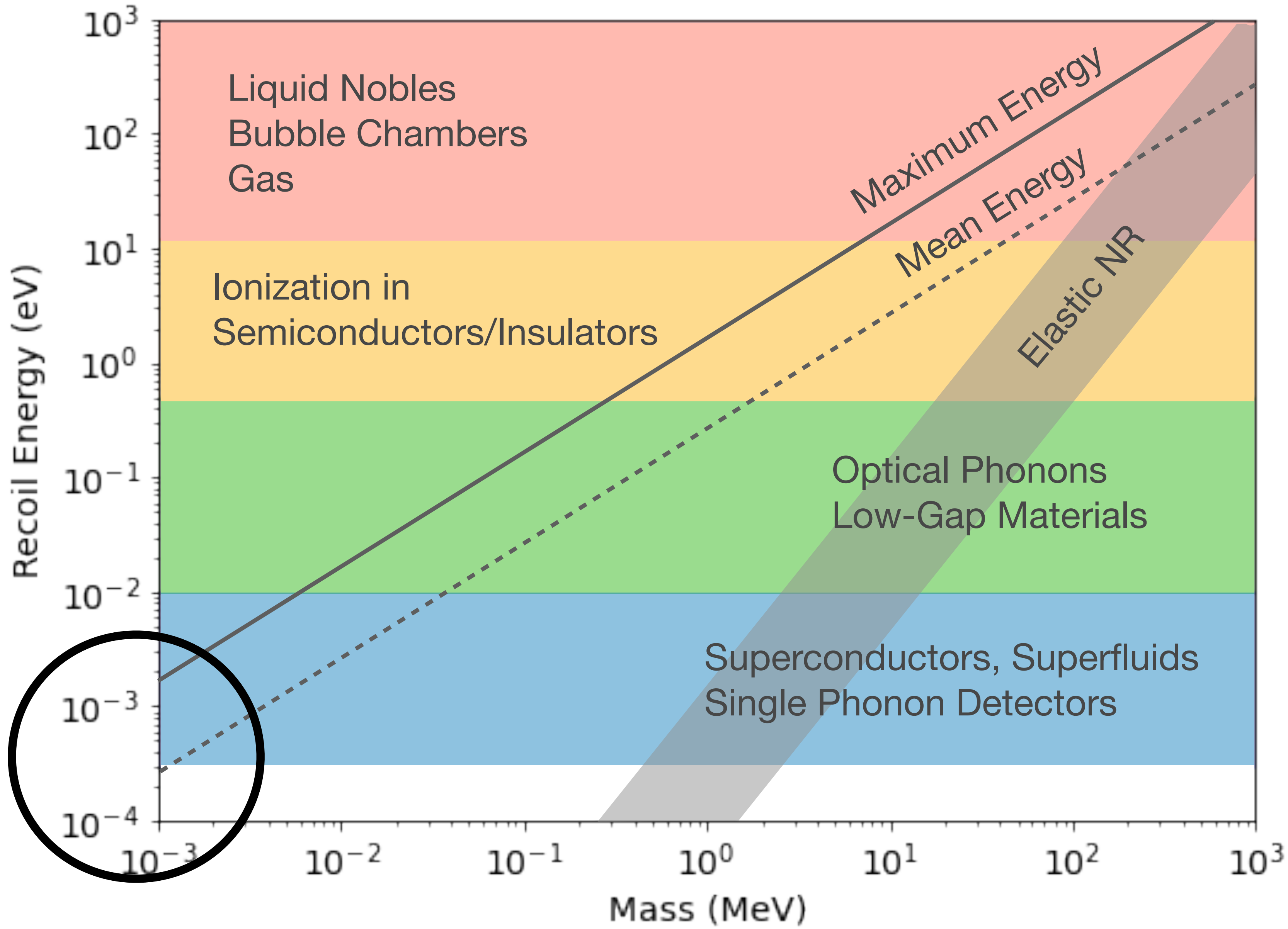
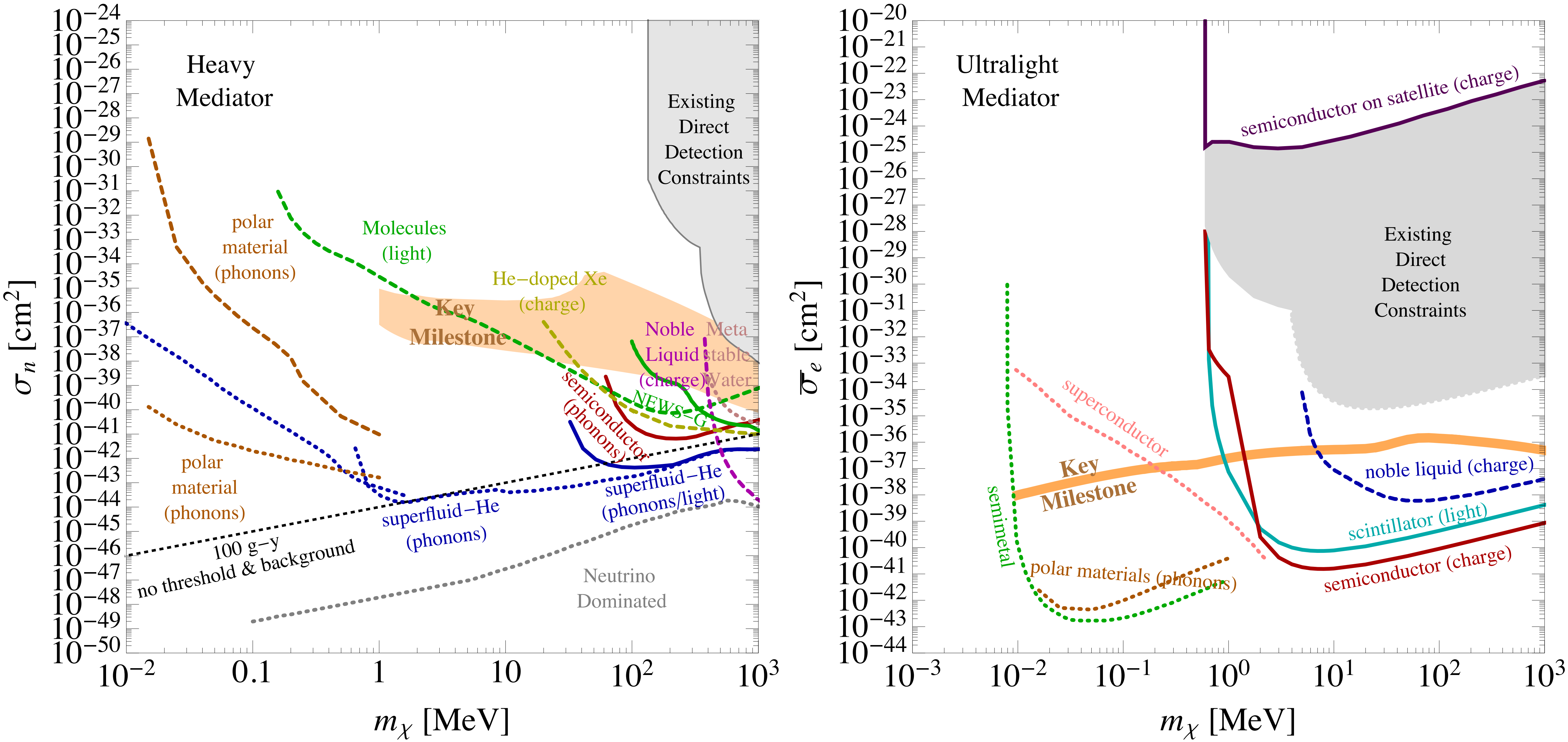


ultimate reach: keV masses w/ single phonon excitations or electron recoils from low-gap materials

Potential Sensitivities

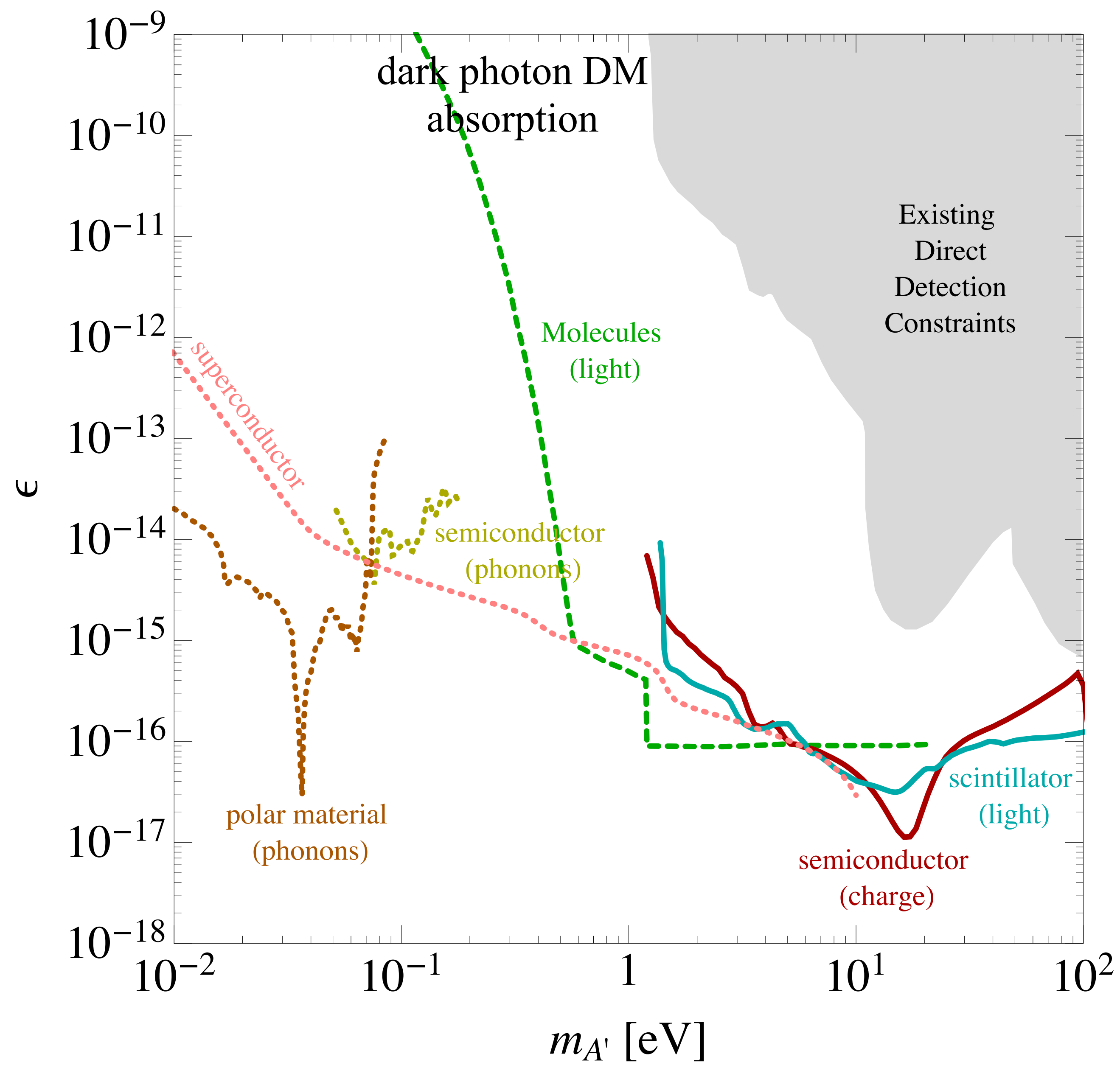
- DM scattering: $m_\chi \gtrsim \mathrm{keV}$



Figs from US DOE Basic Research Needs report 2018 (outdated)

Potential Sensitivities

- DM scattering: $m_\chi \gtrsim$ keV
- DM absorption: $m_\chi \gtrsim$ meV



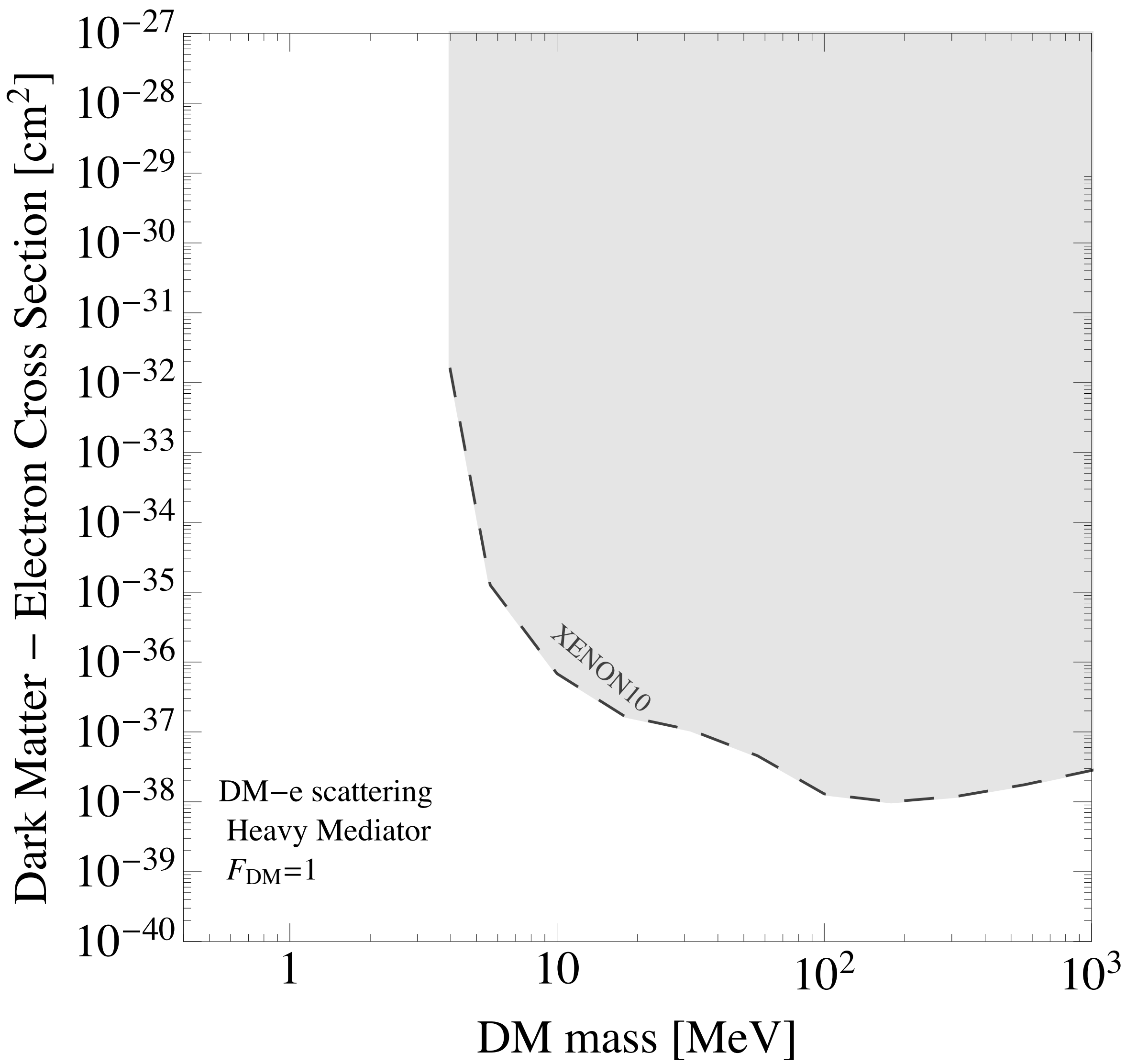
Figs from US DOE Basic Research Needs report 2018 (outdated)

Significant progress in probing sub-GeV dark matter

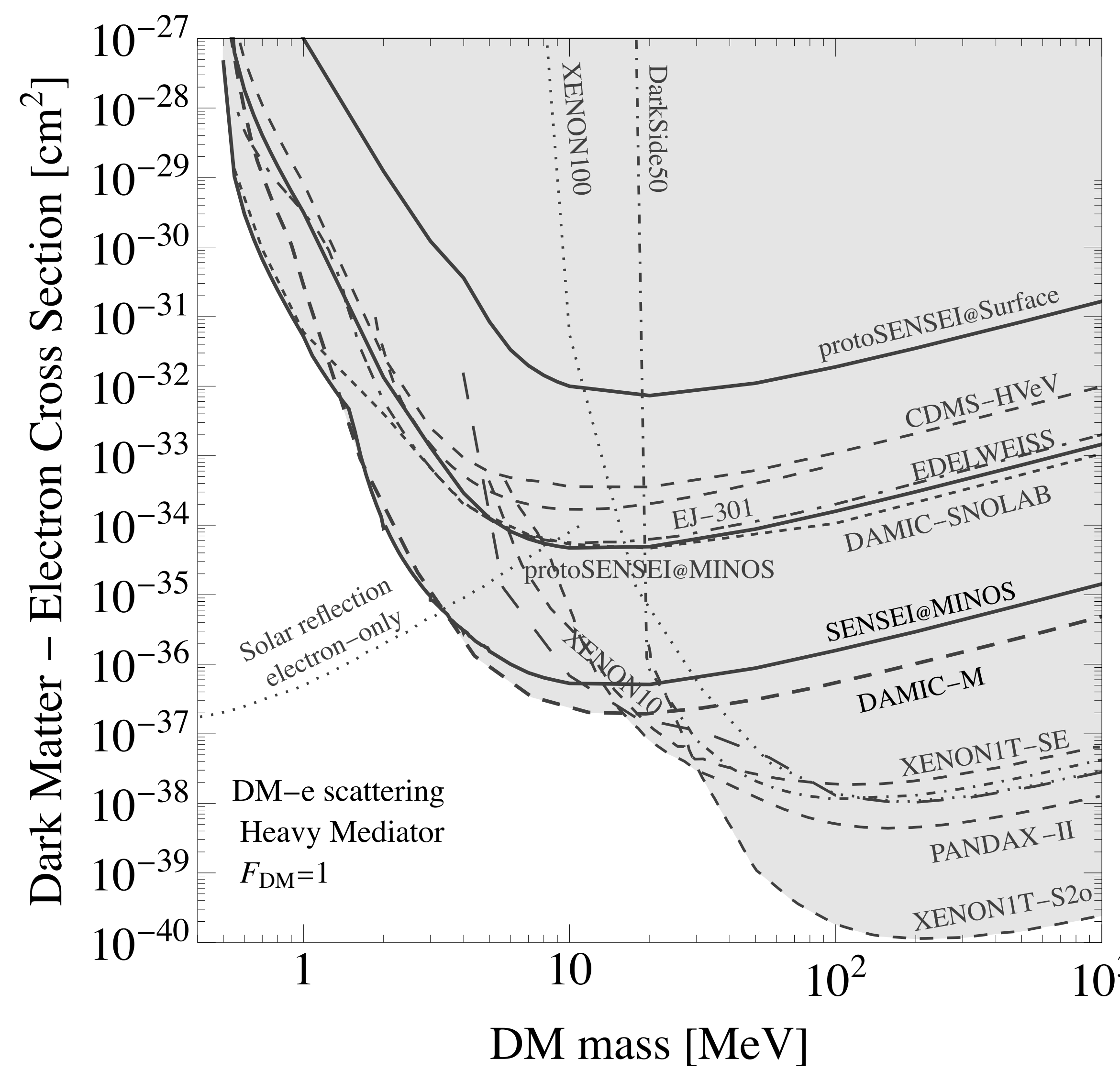
- Several detection concepts, using variety of target materials
- Multiple technologies/experiments can measure low-energy signals
    - e.g. two-phase TPCs, TES, Skipper-CCDs, …

Exciting experimental progress: DM-electron scattering

2012

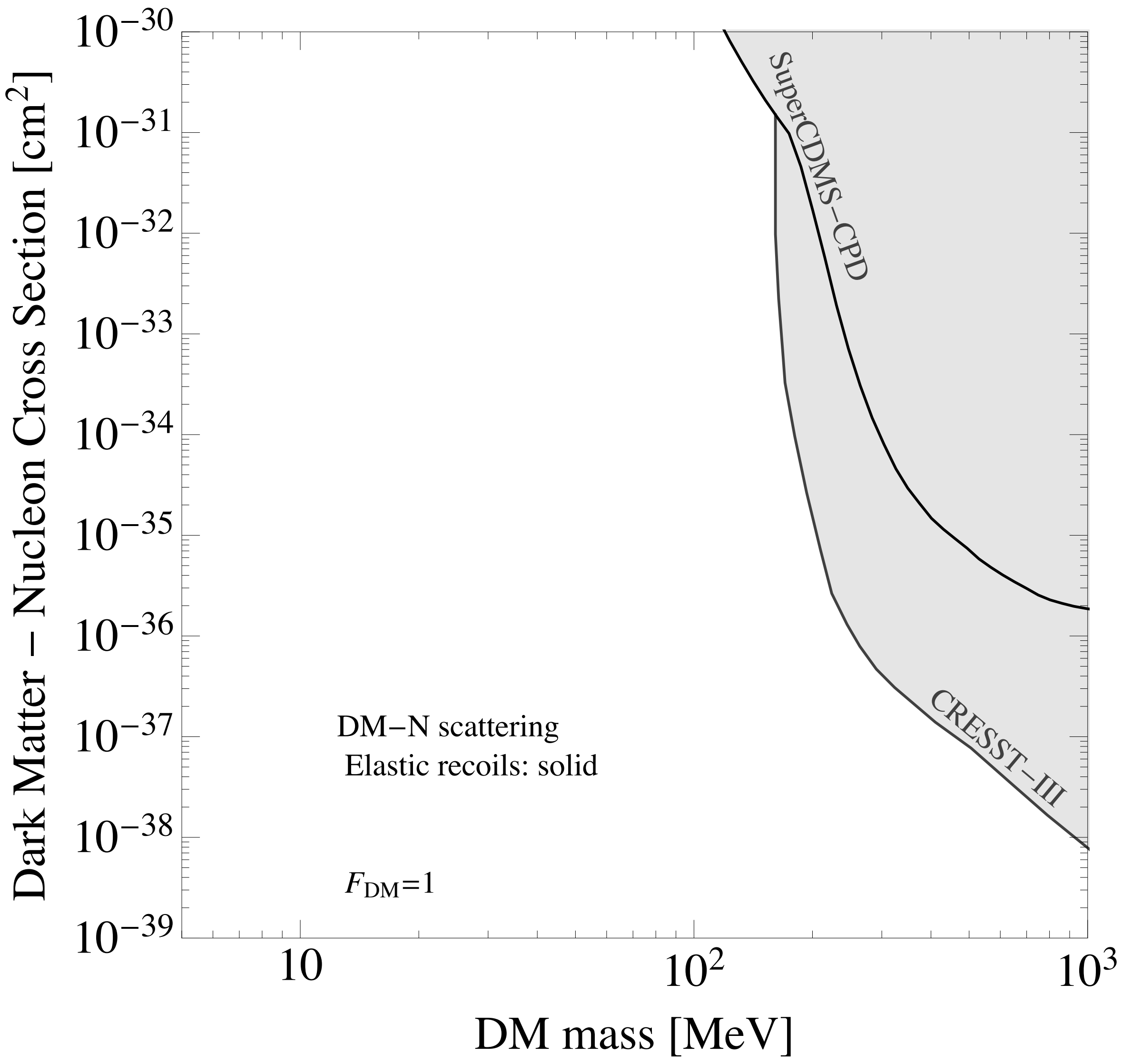


2023



Exciting experimental progress: DM-nucleus scattering

elastic DM-nucleus scattering



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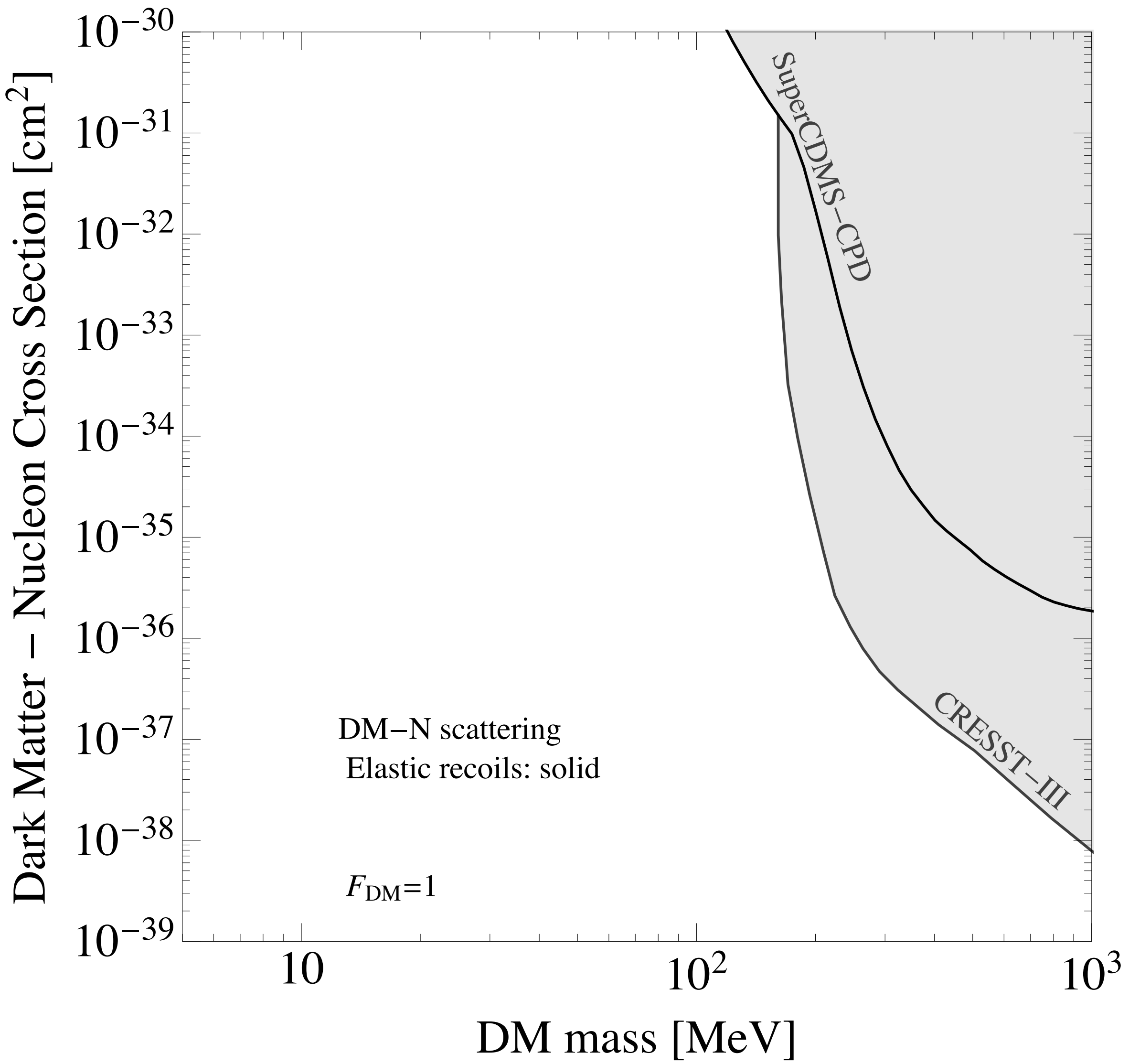
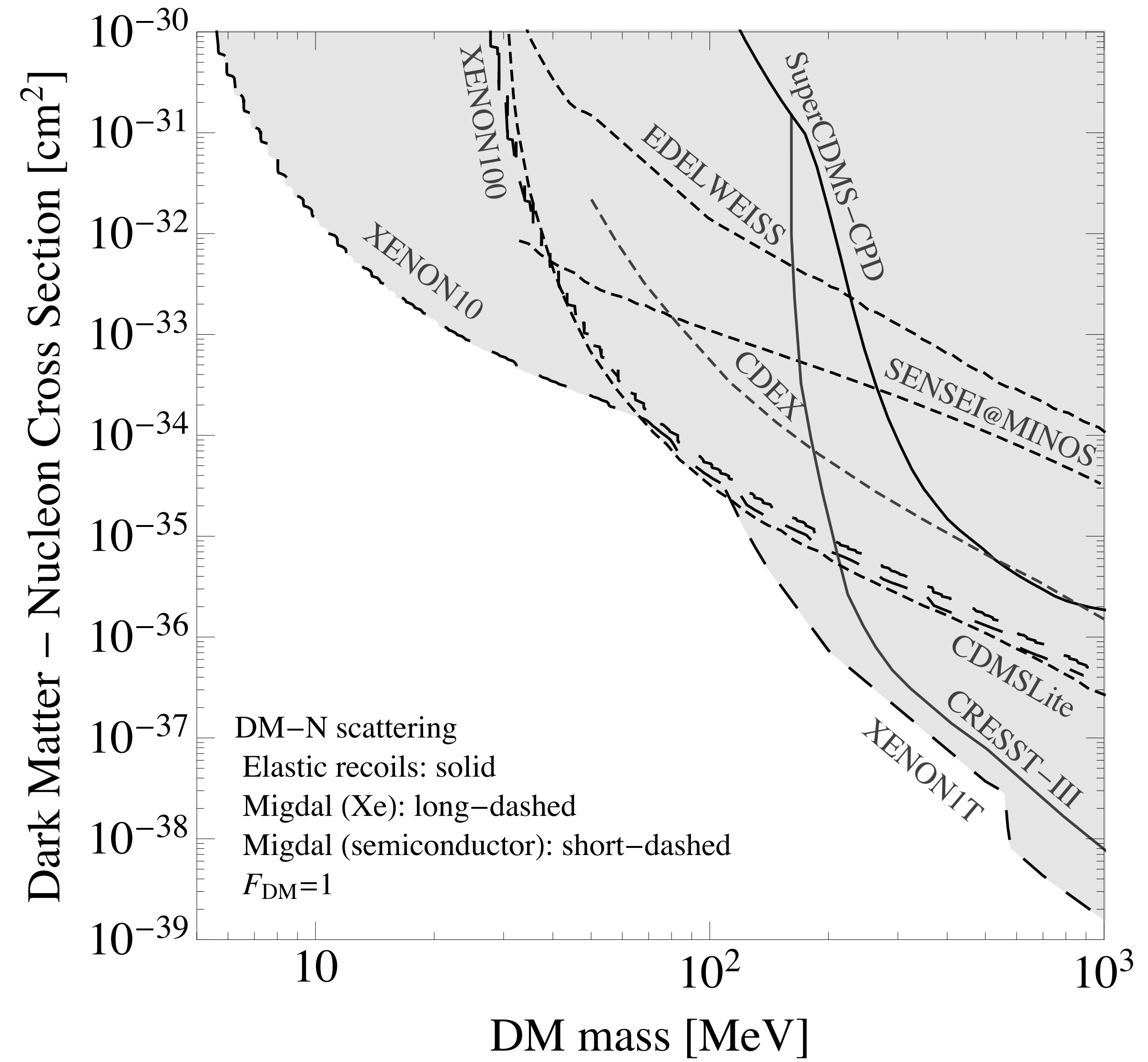
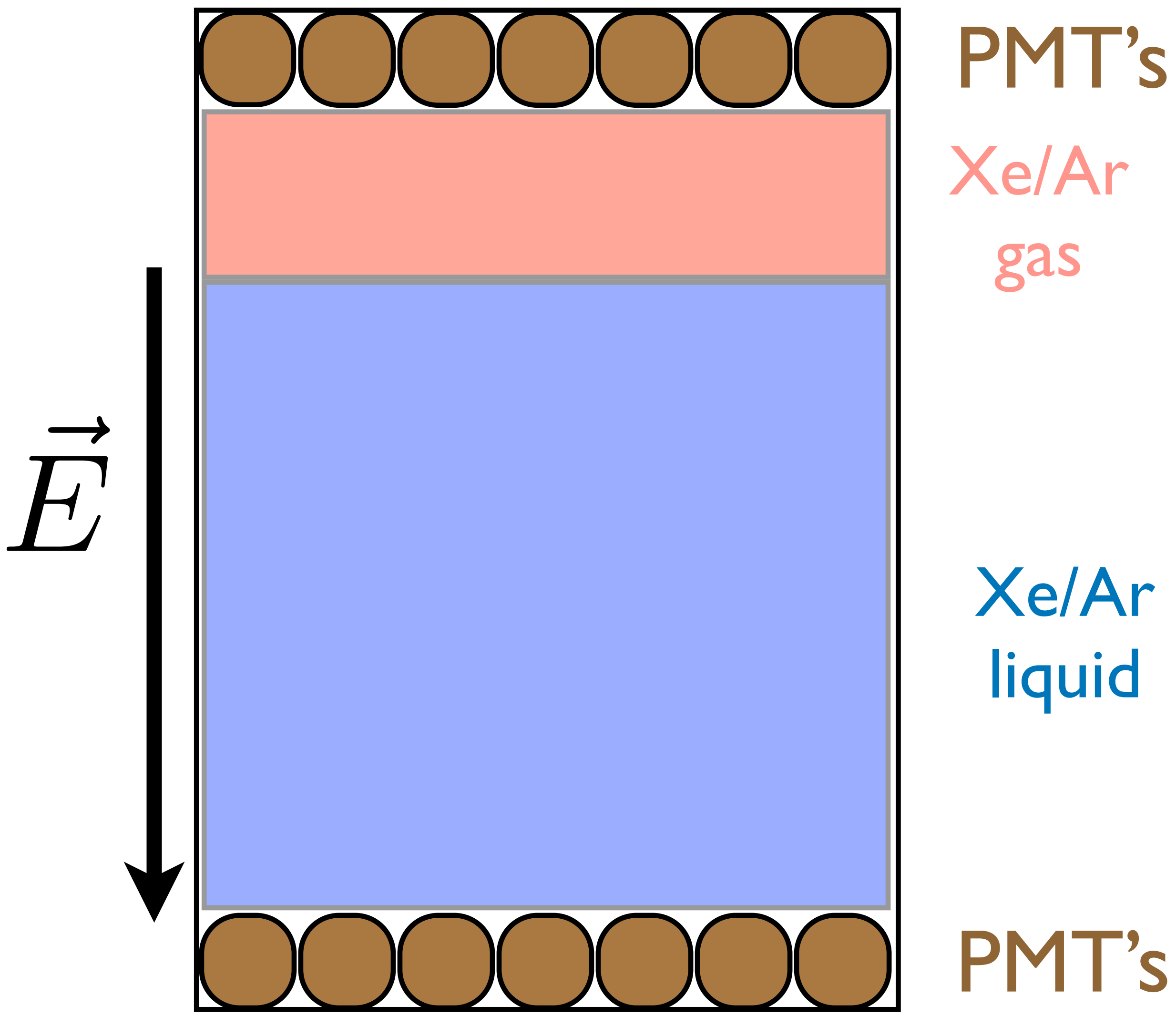


DM-nucleus scattering **w/ Migdal**



Two-phase TPCs (Xe, Ar)



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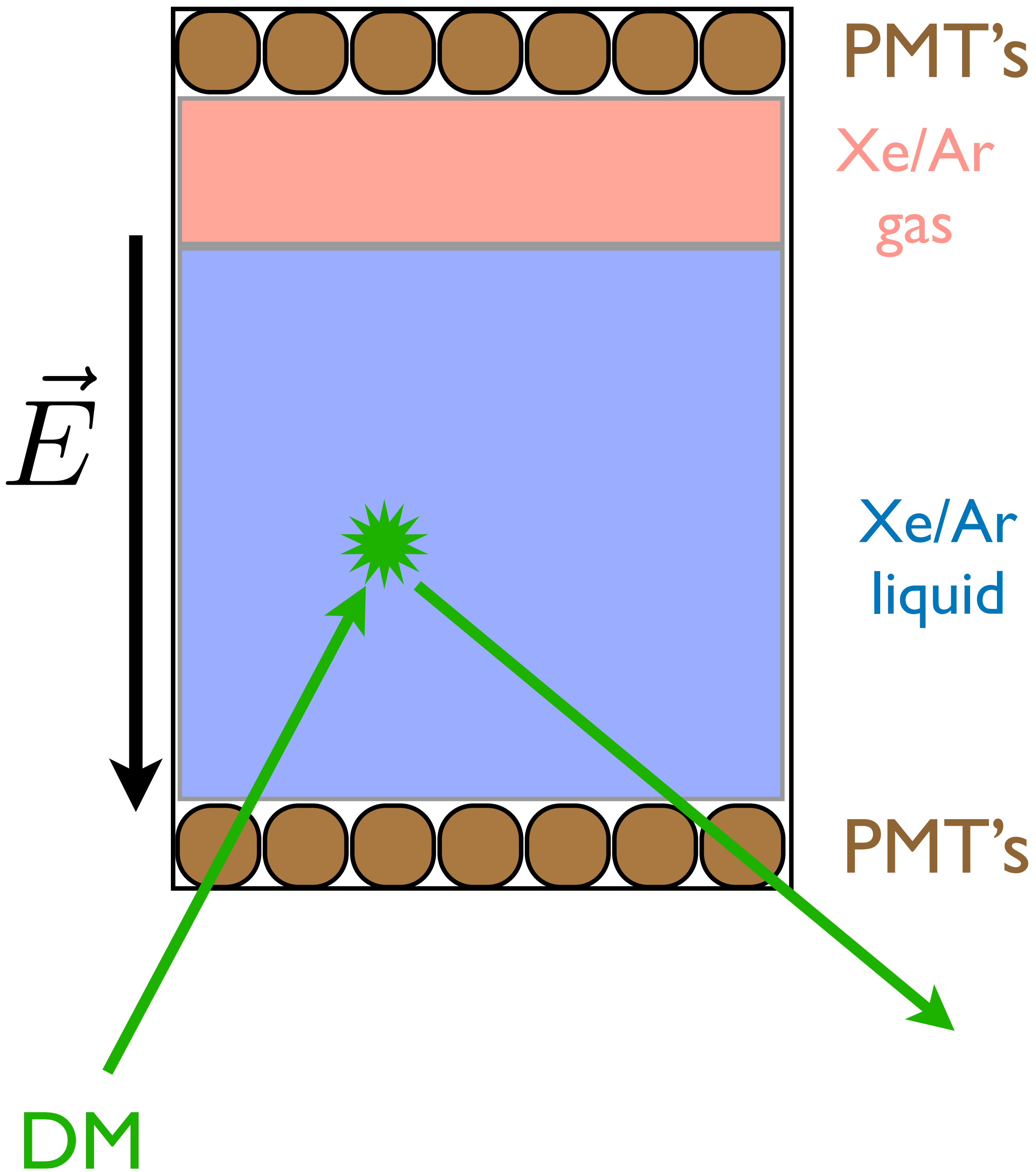

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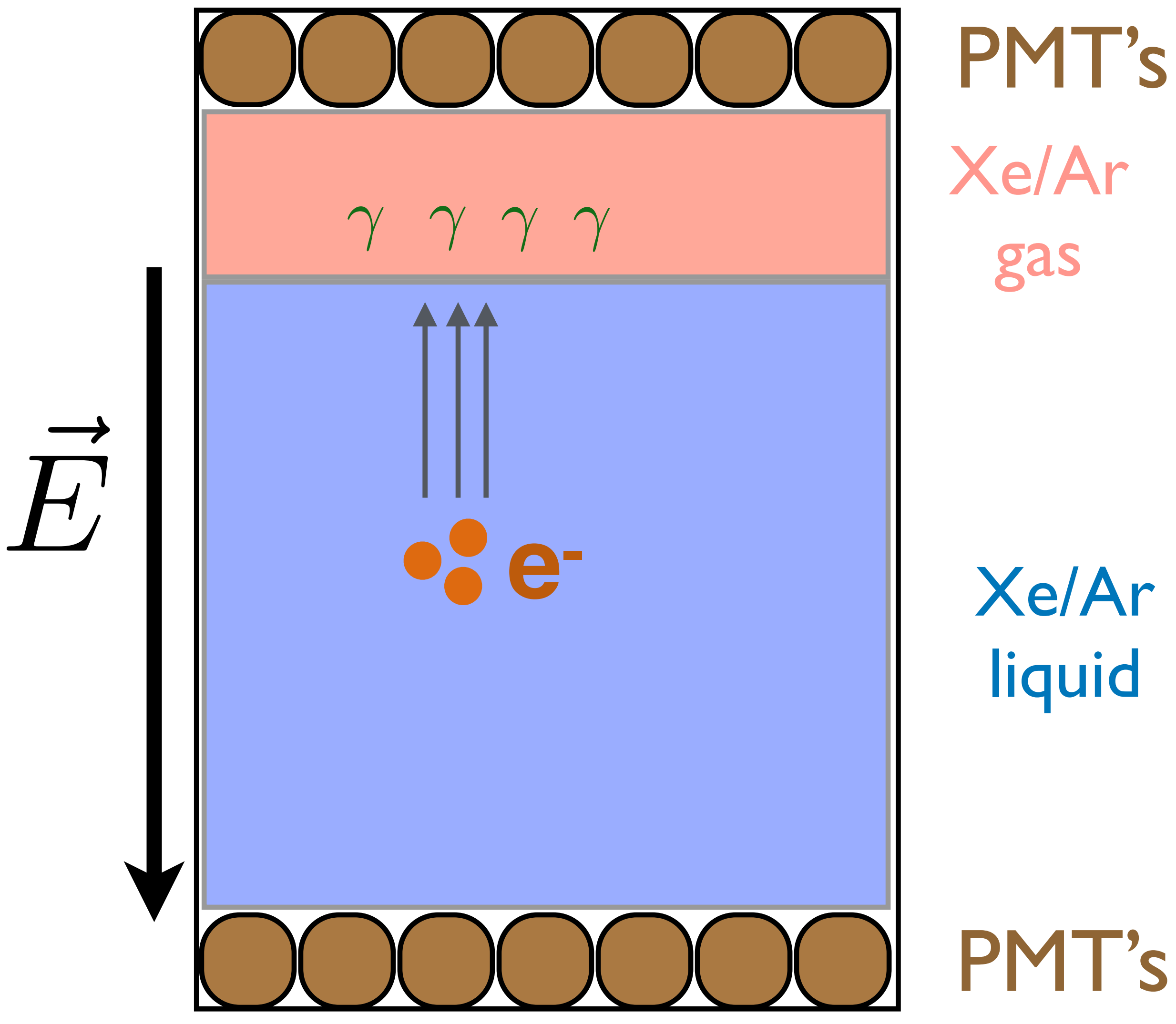
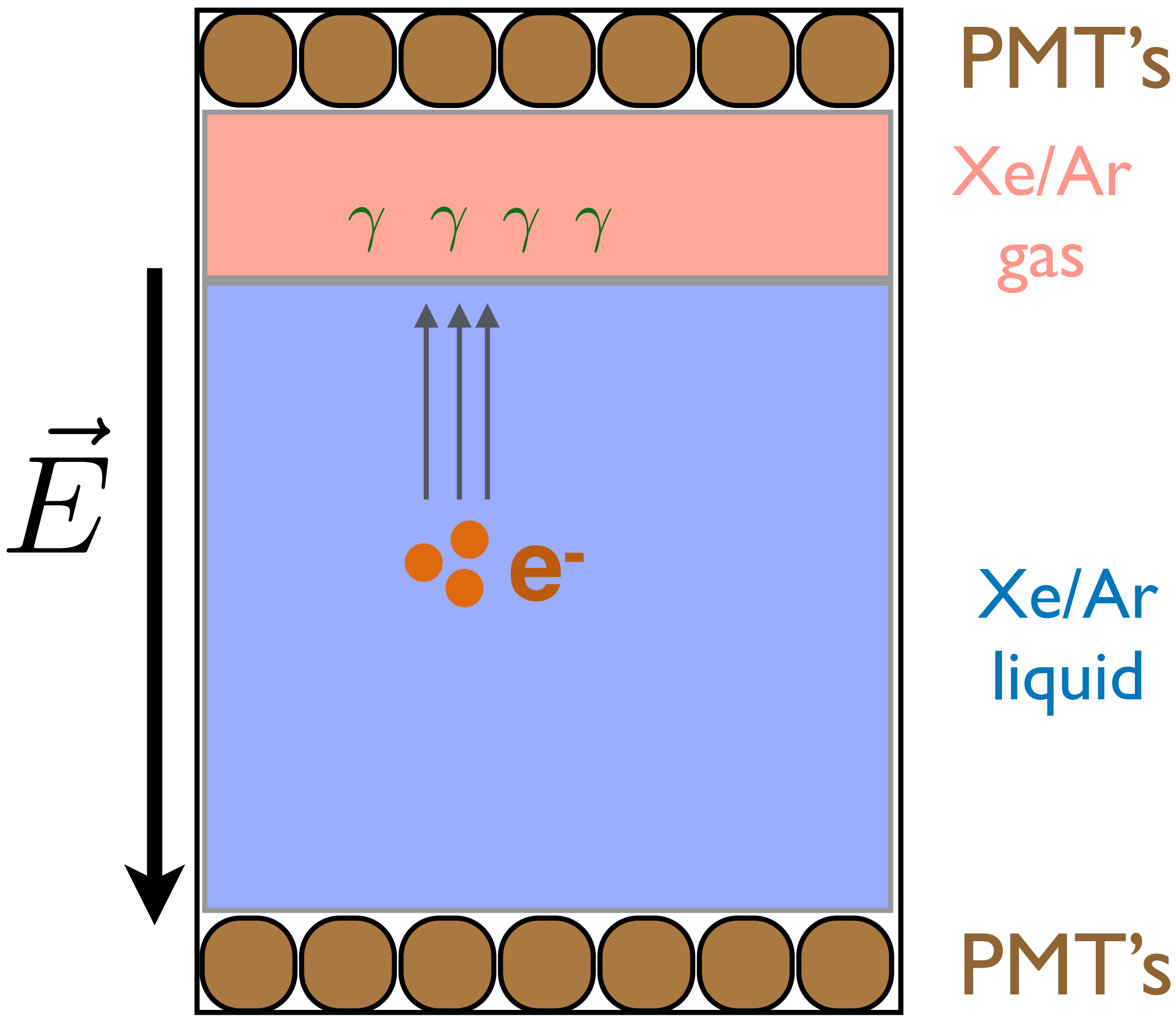


e- produce
scintillation light

e.g. XENON10/100/1T/nT, LZ, DarkSide, PandaX

talks/poster by E. Aprile, C. Galbiati, N. Zhou, S. Li

Two-phase TPCs (Xe, Ar)



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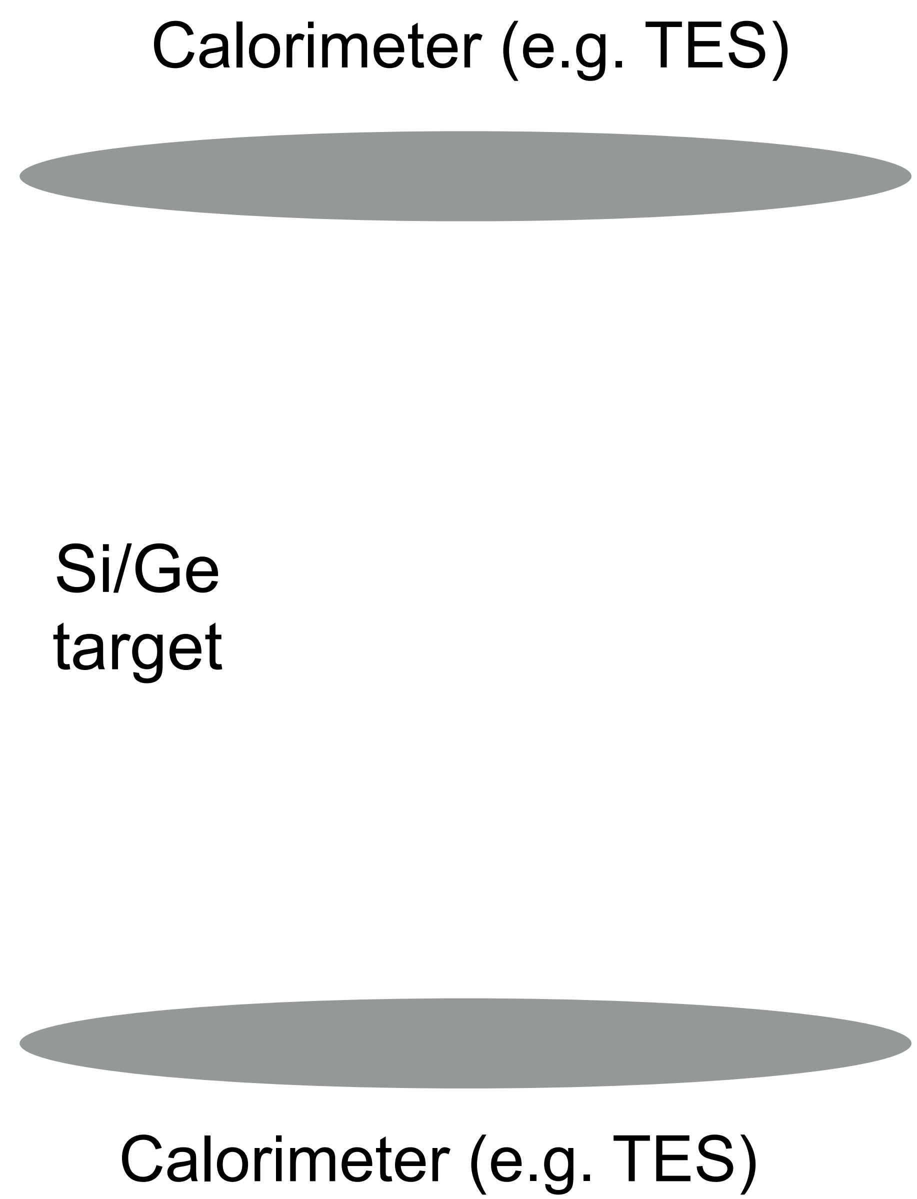
Phonon Sensors



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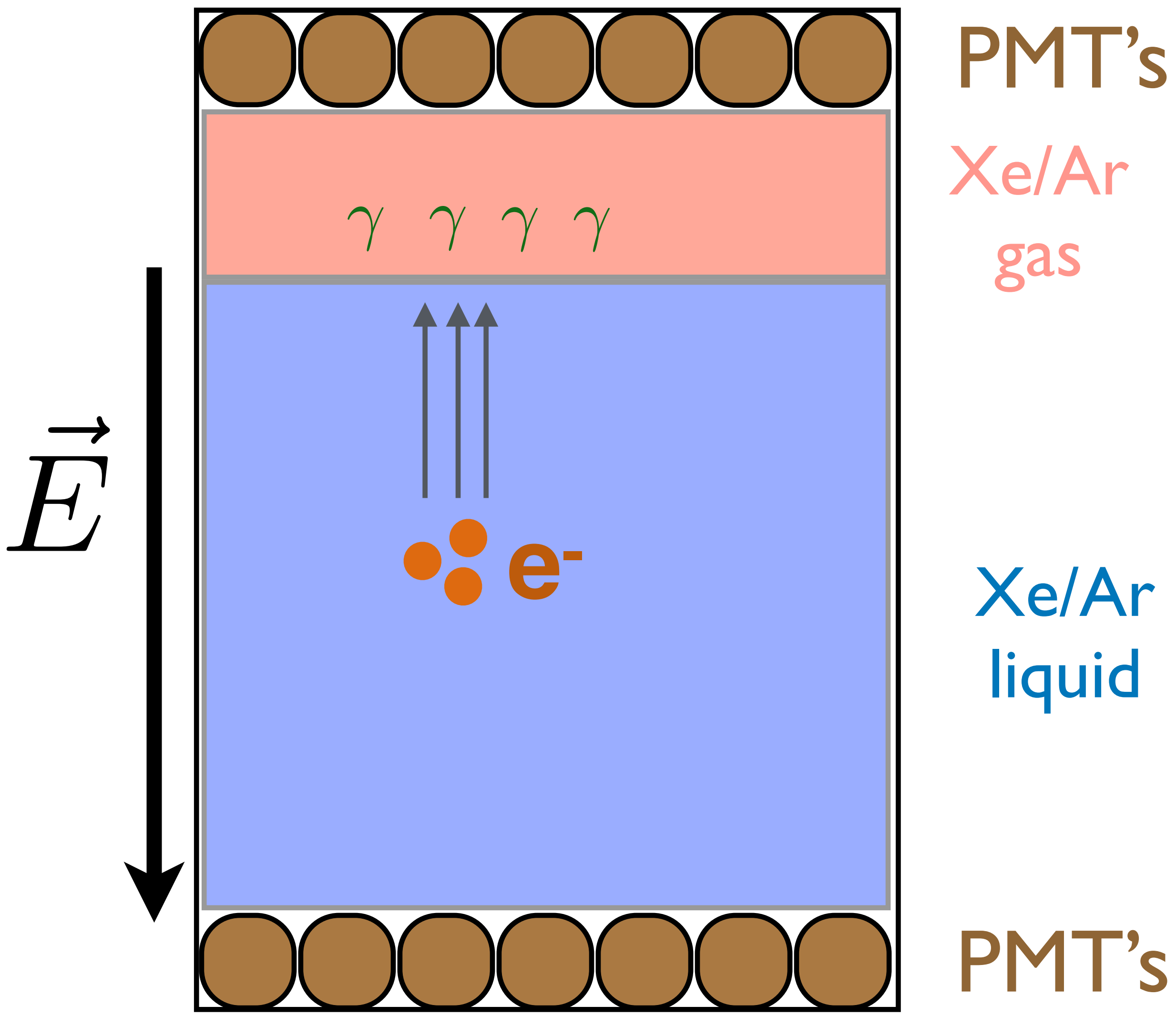

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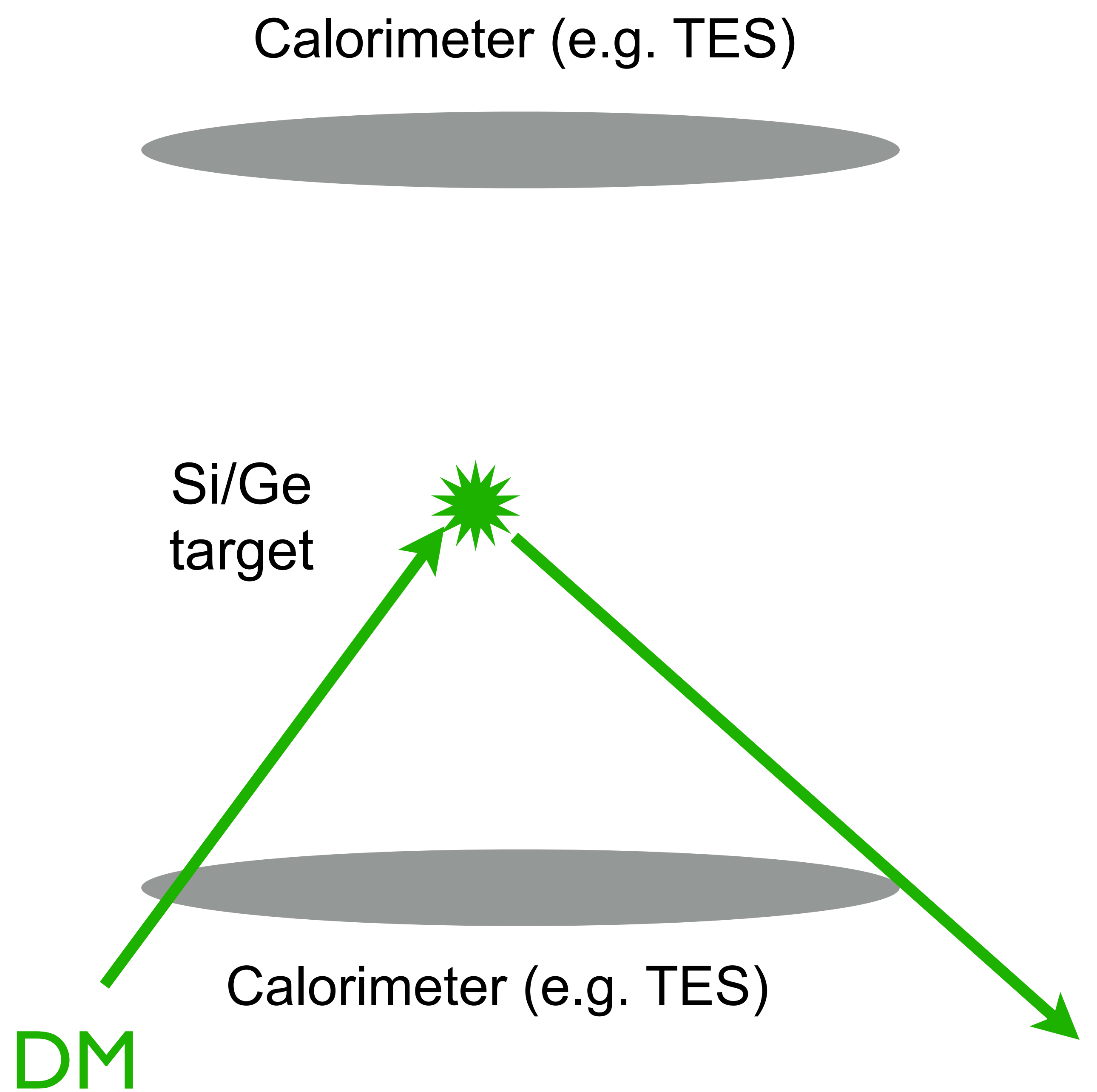

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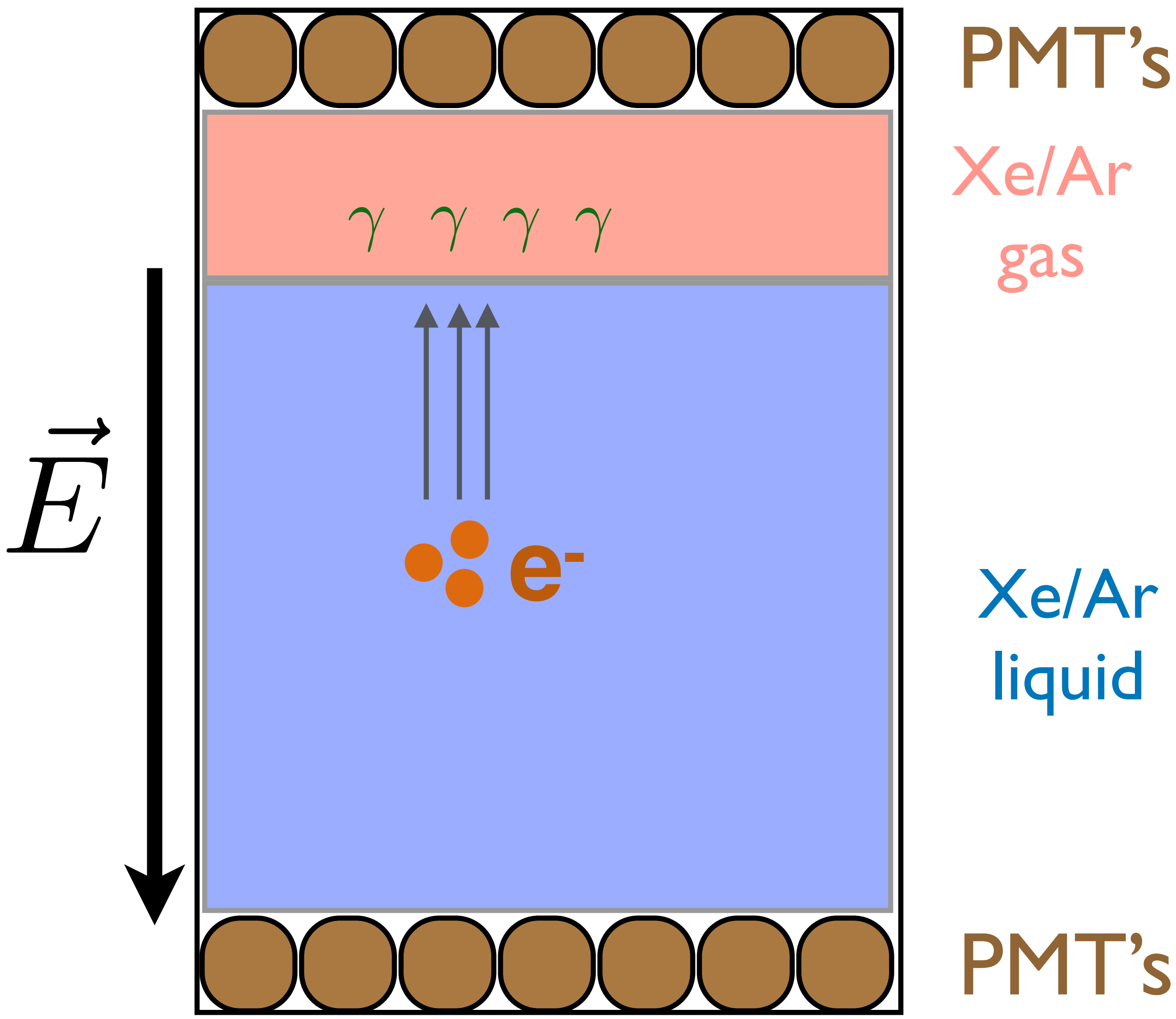

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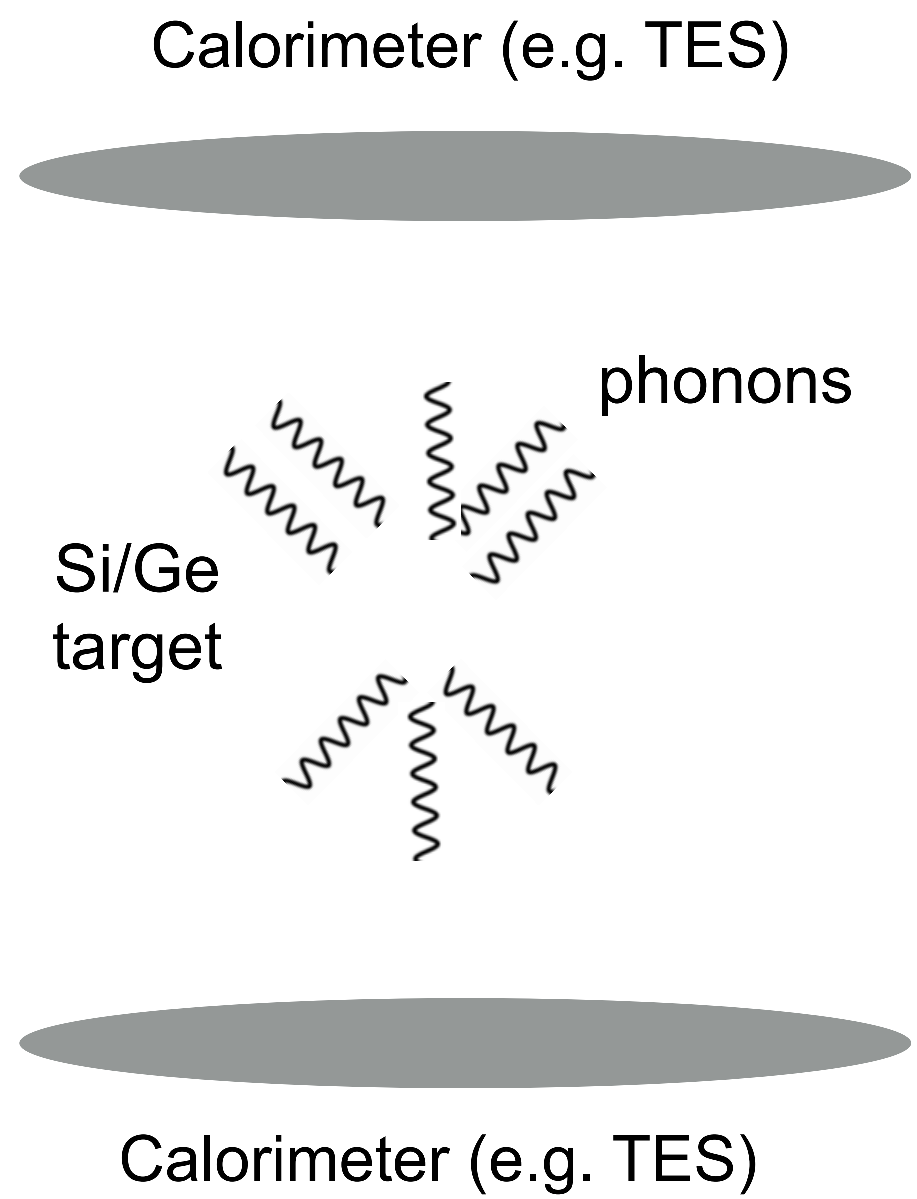
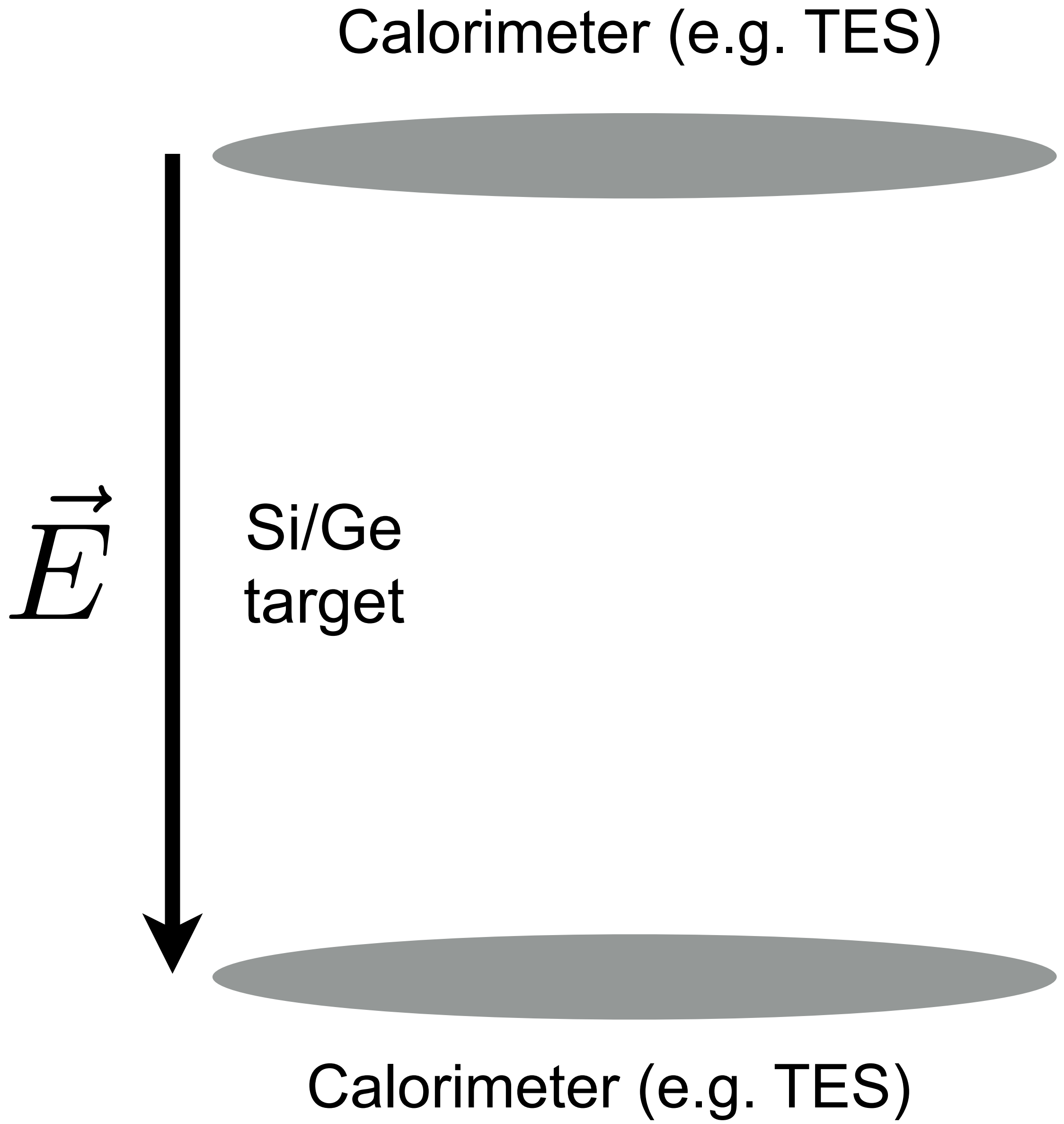


DM interaction produces heat/phonons

e.g. SuperCDMS, EDELWEISS, CRESST

talks by P. Cushman, J. Gascon, P. Gorla

Phonon Sensors



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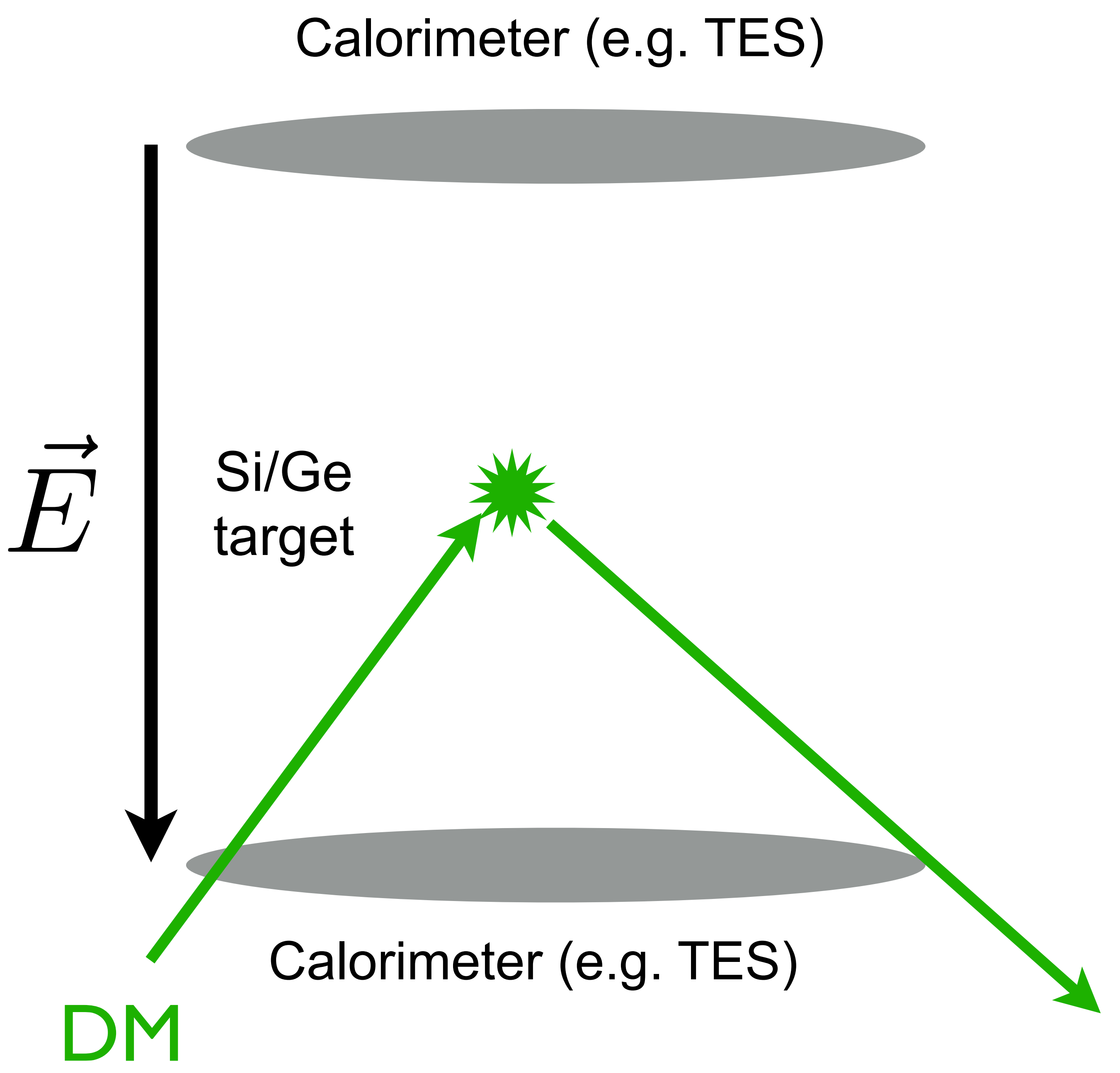

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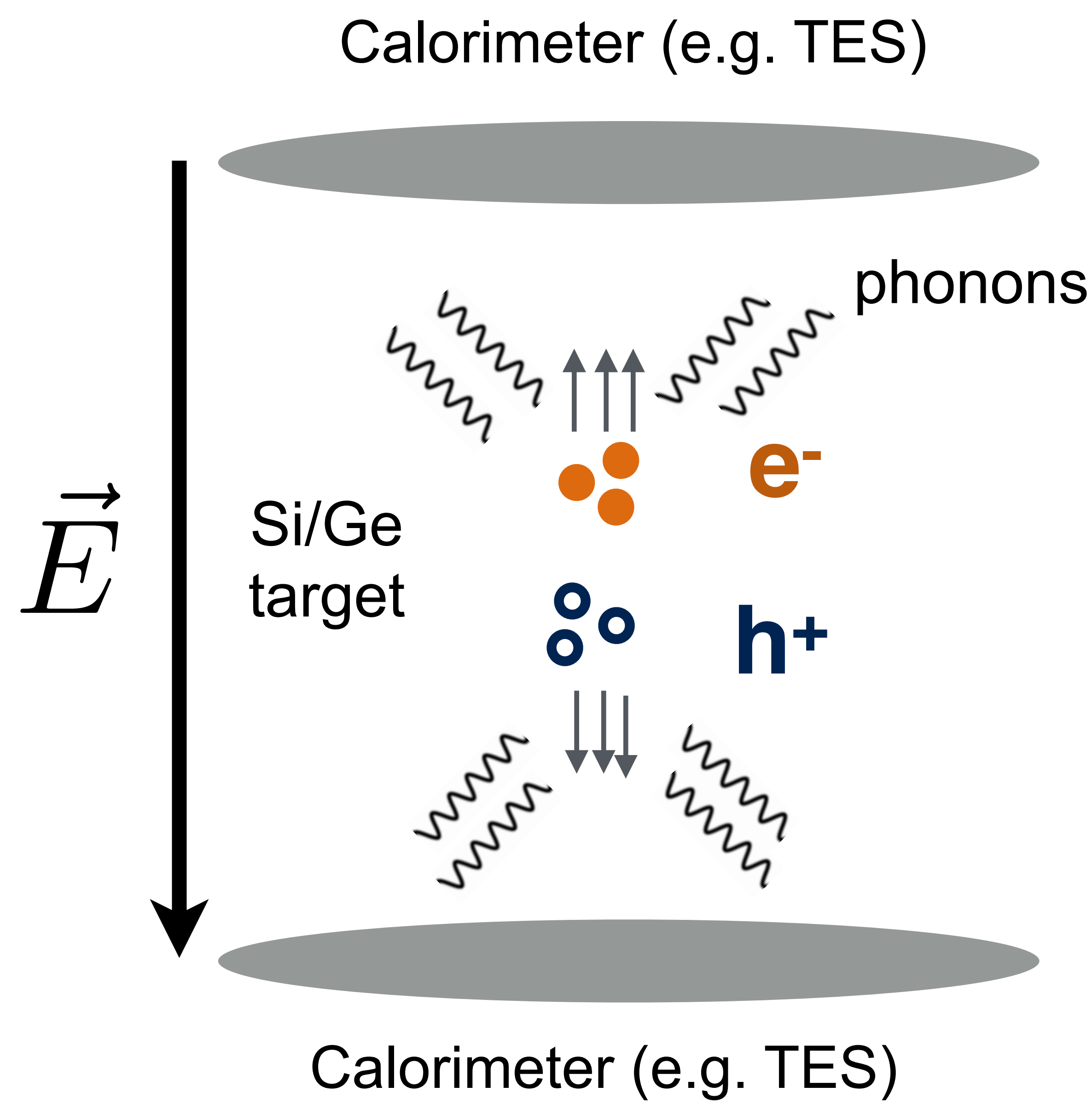


e^- & h^+ drift in E-field, emitting phonons

e.g. SuperCDMS, EDELWEISS

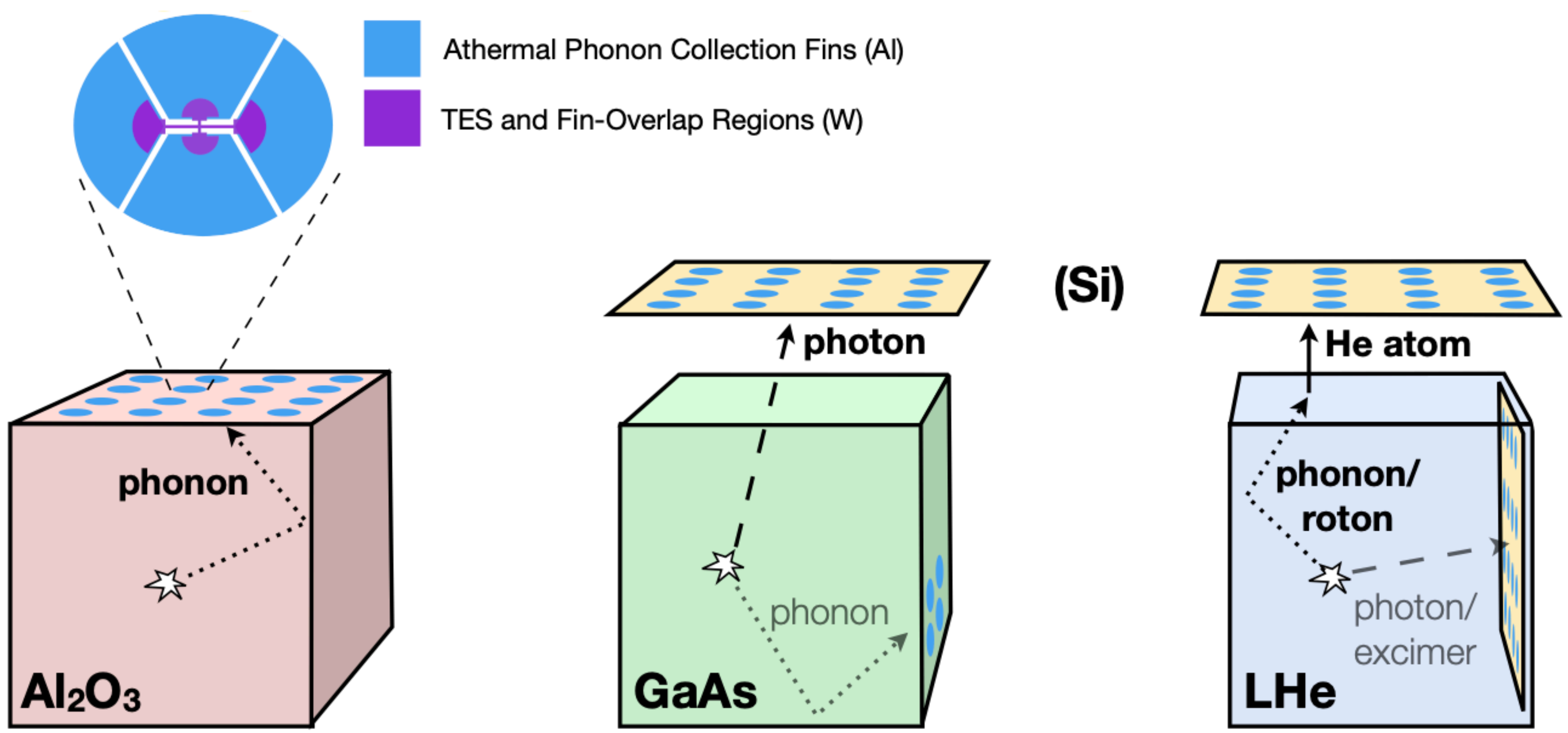
see talk by P. Cushman, J. Gascon

TESSERACT

R&D funded by DoE DMNI program

Transition Edge Sensors with Sub-EV Resolution And Cryogenic Targets

Goal: use multiple target materials + advances in TES sensor technology

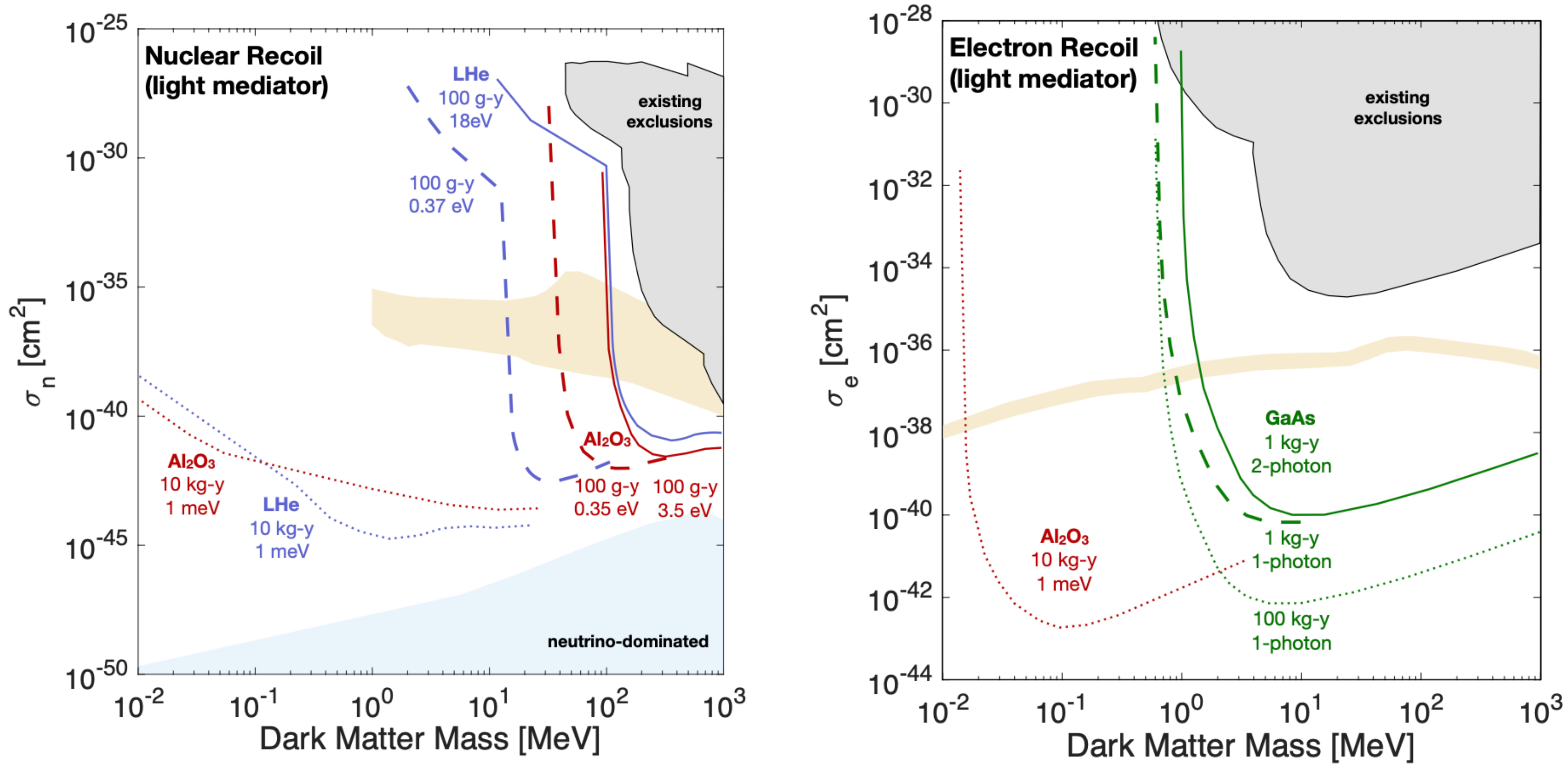


Liquid helium experiment (HeRALD)
GaAs and Sapphire-based experiments (SPICE)

see talks by Scott Hertel and Bjoern Penning

Figure from: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-IF1_IF8-120.pdf

TESSERACT

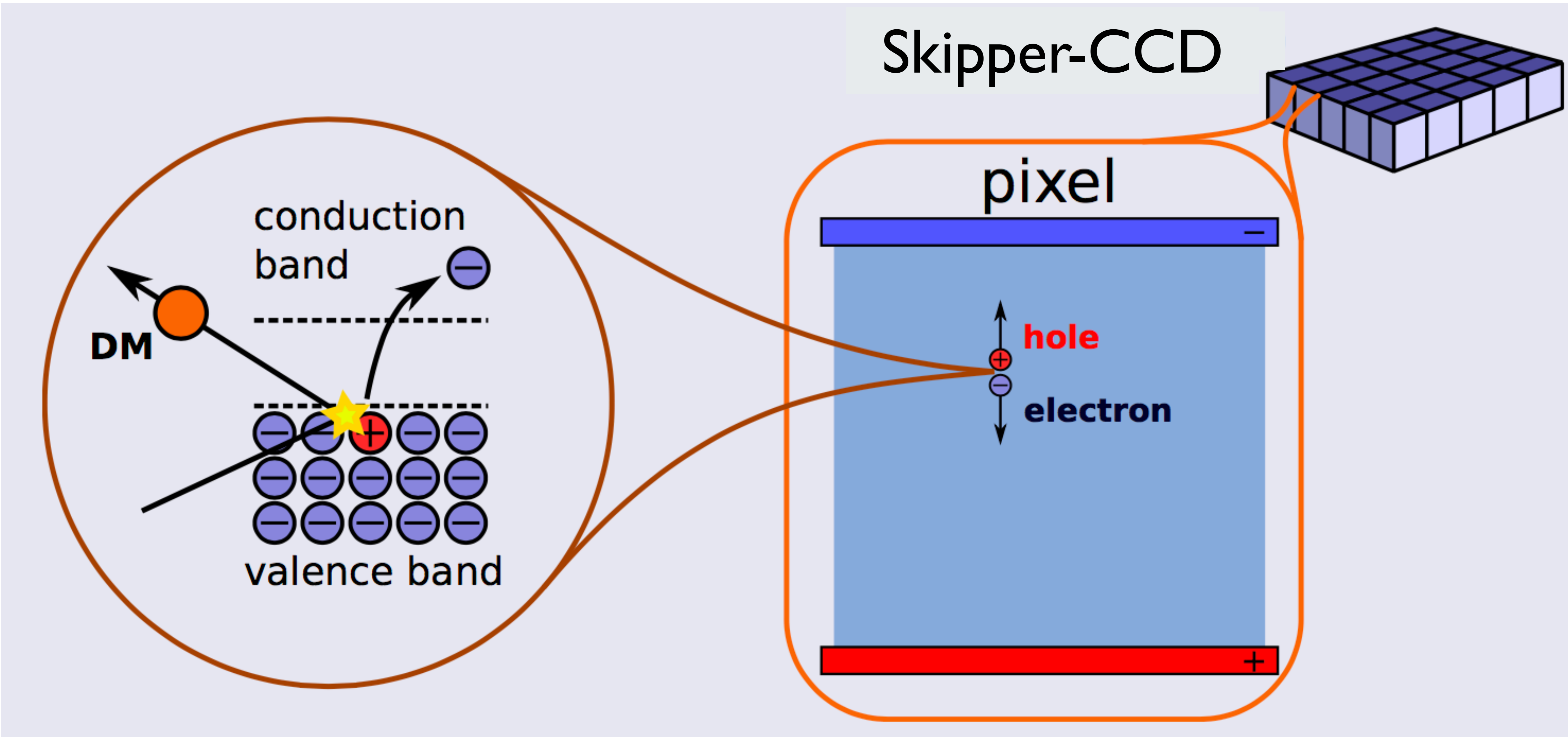


successful implementation of this program would probe orders of magnitude of DM parameter space

see talks by Scott Hertel and Bjoern Penning

Figure from: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-IF1_IF8-120.pdf

SENSEI/DAMIC-M/Oscura: Detection concept



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

Skipper-CCD operation (SENSEI)

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

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

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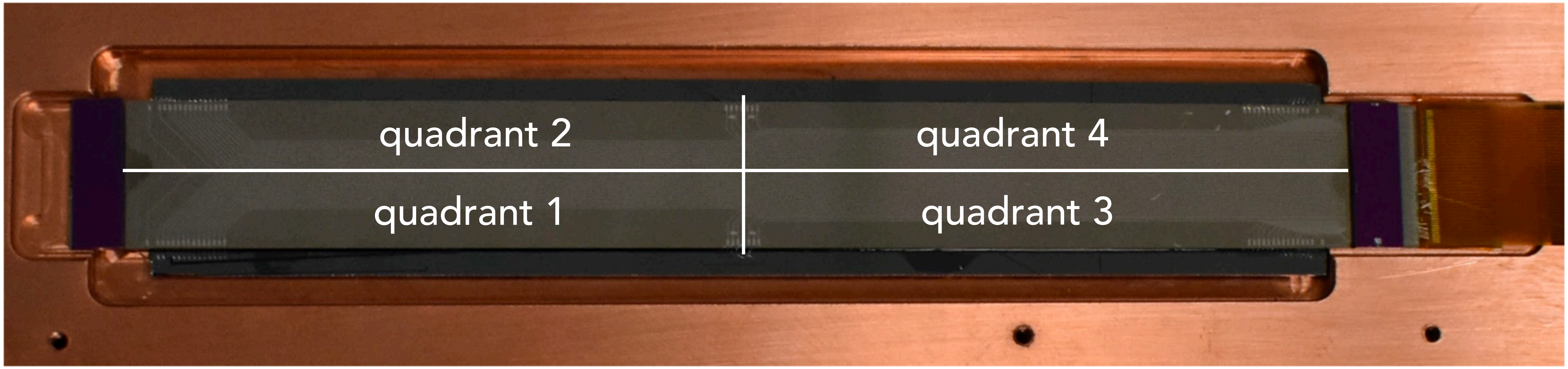

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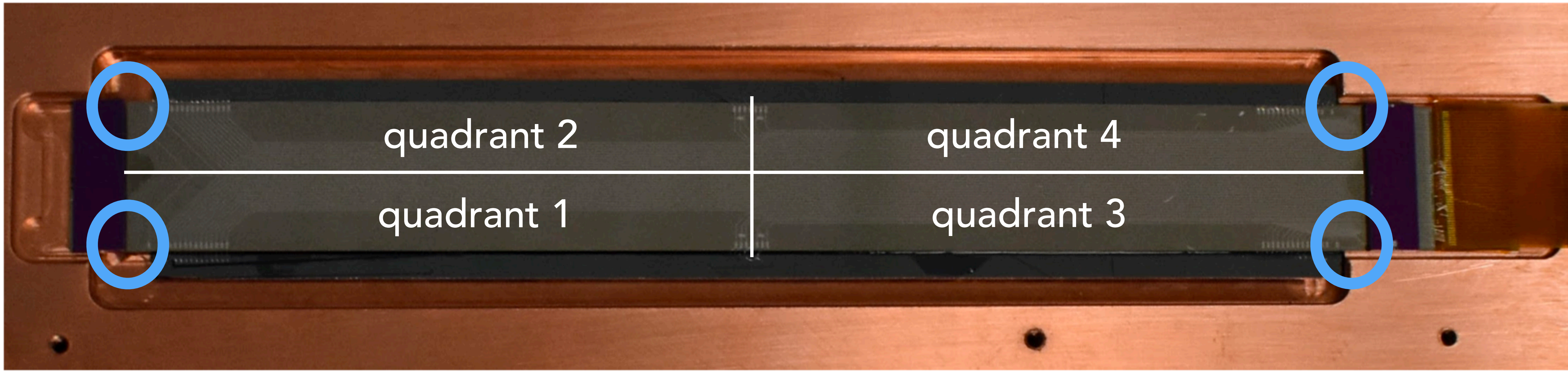

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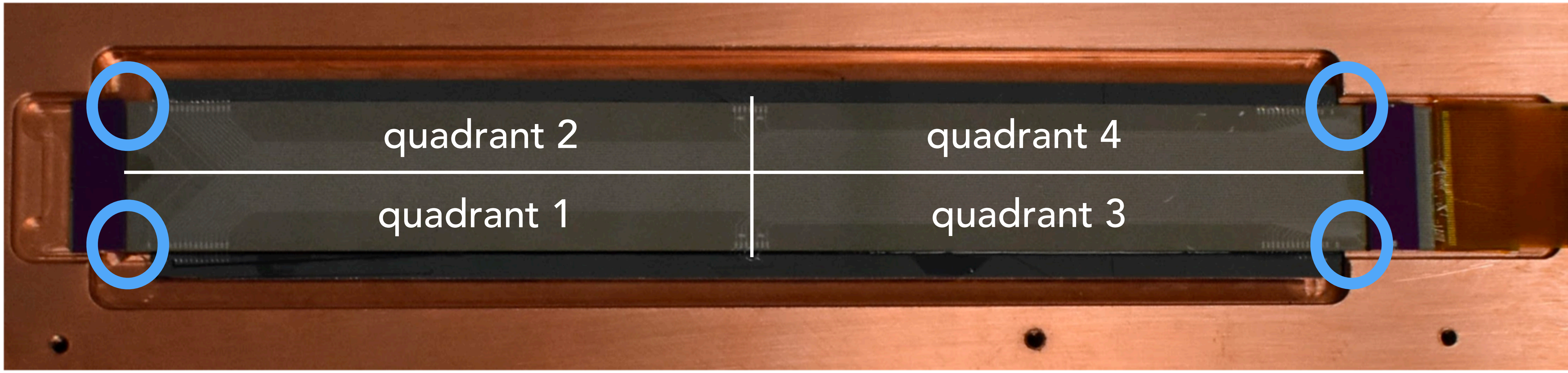

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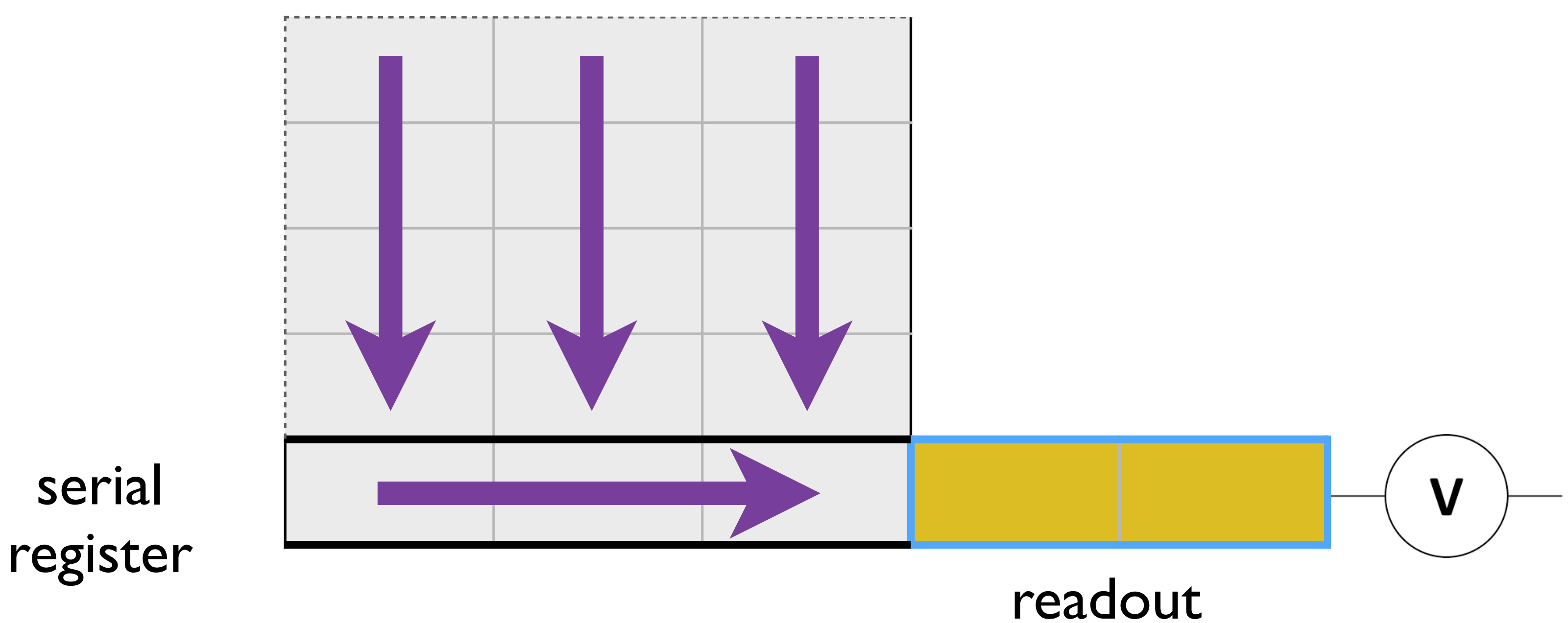

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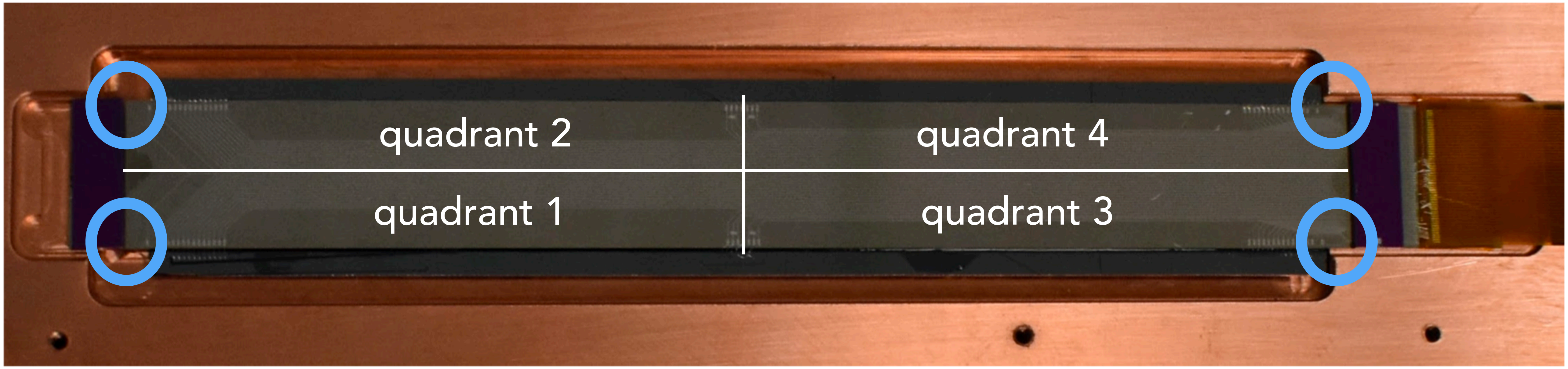

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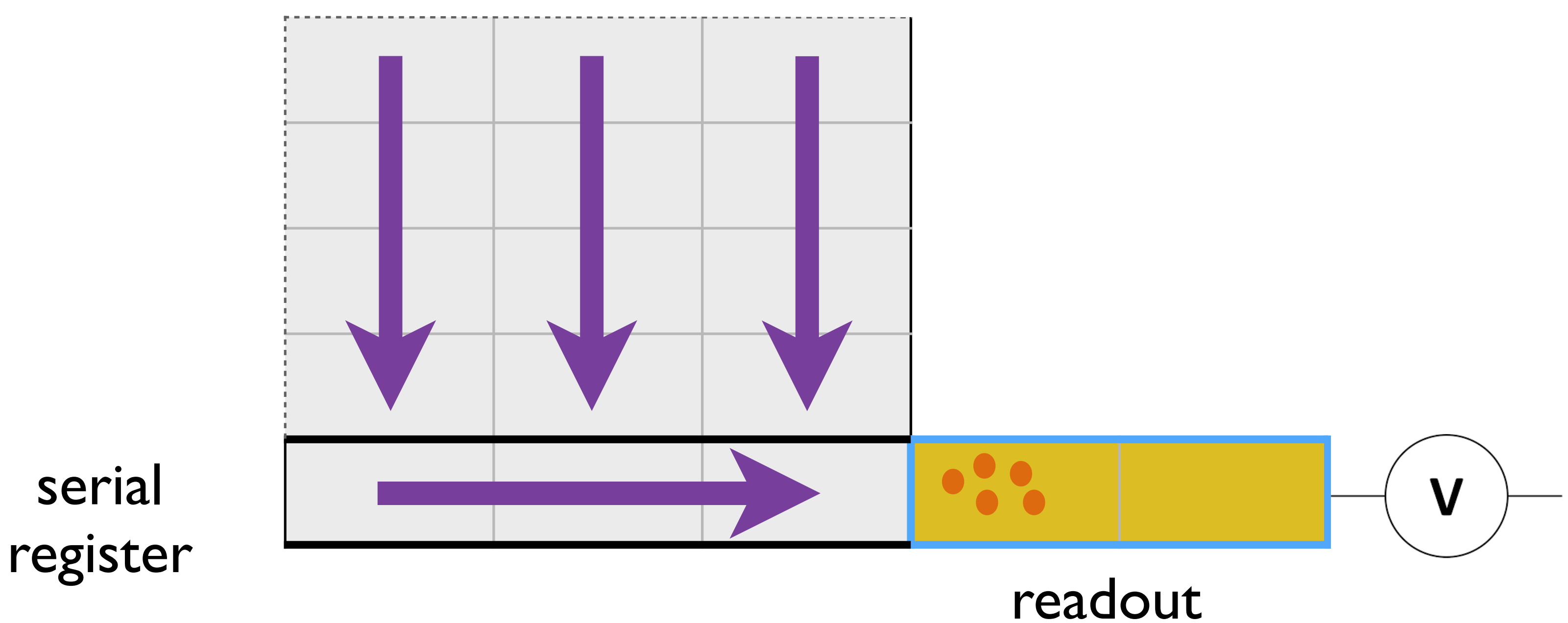

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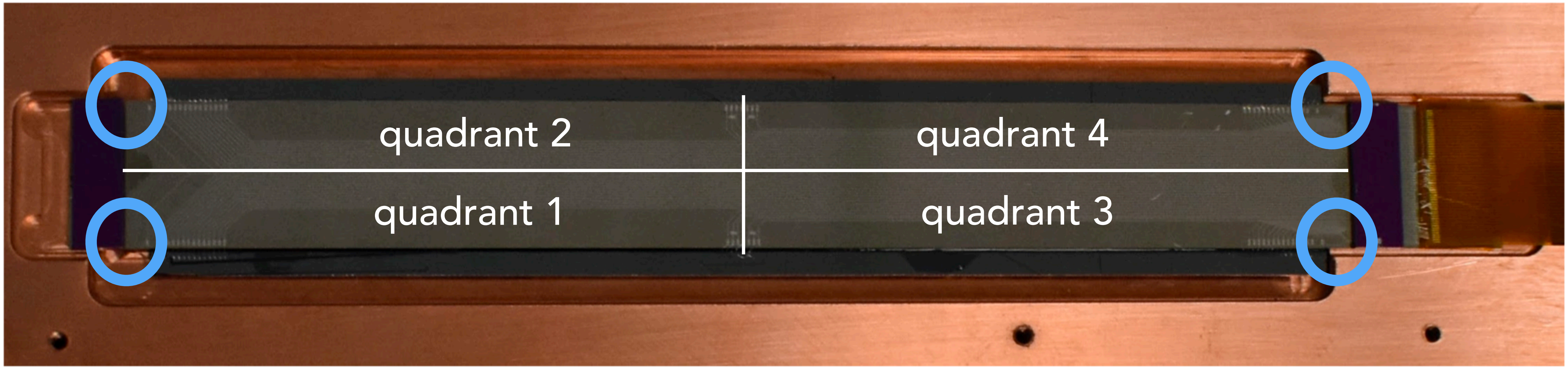

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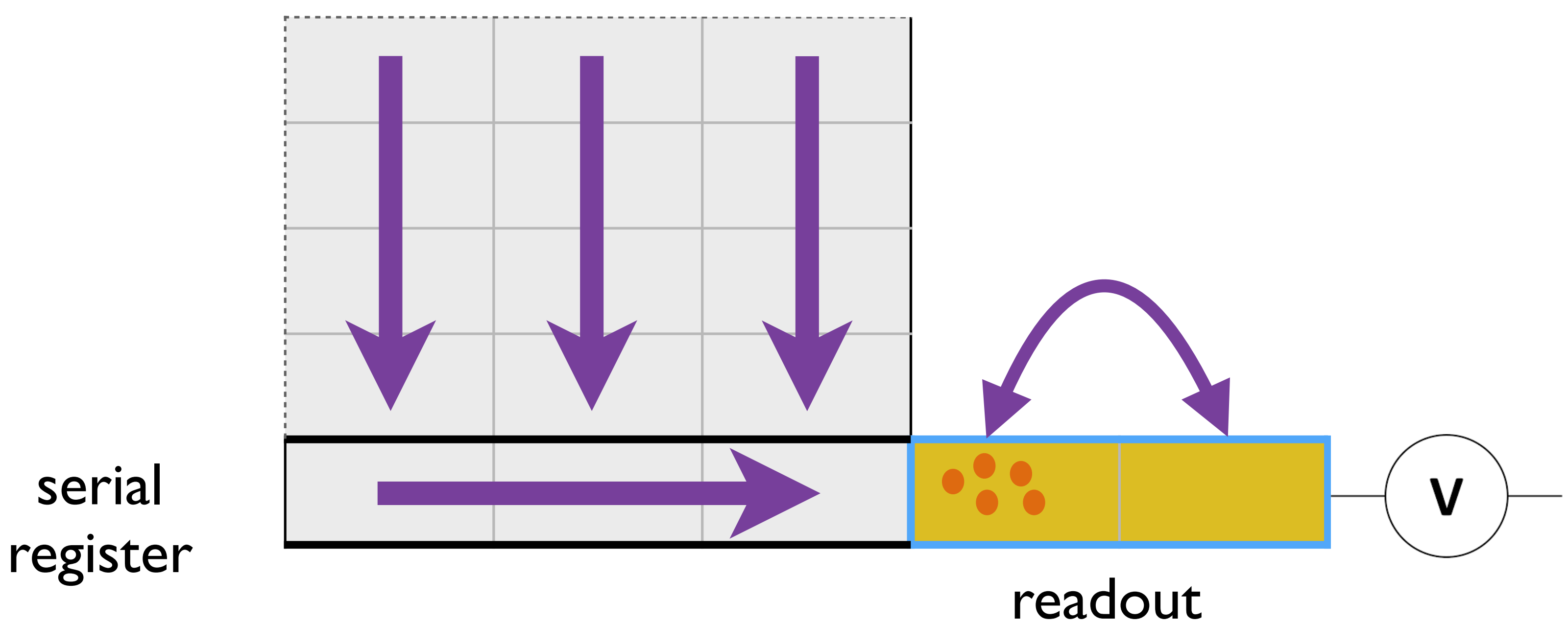

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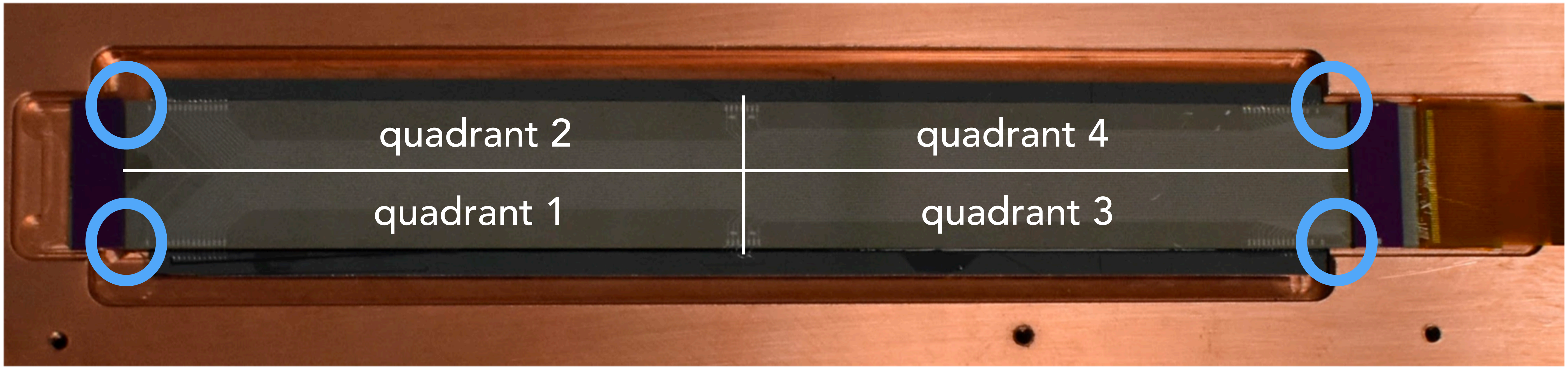

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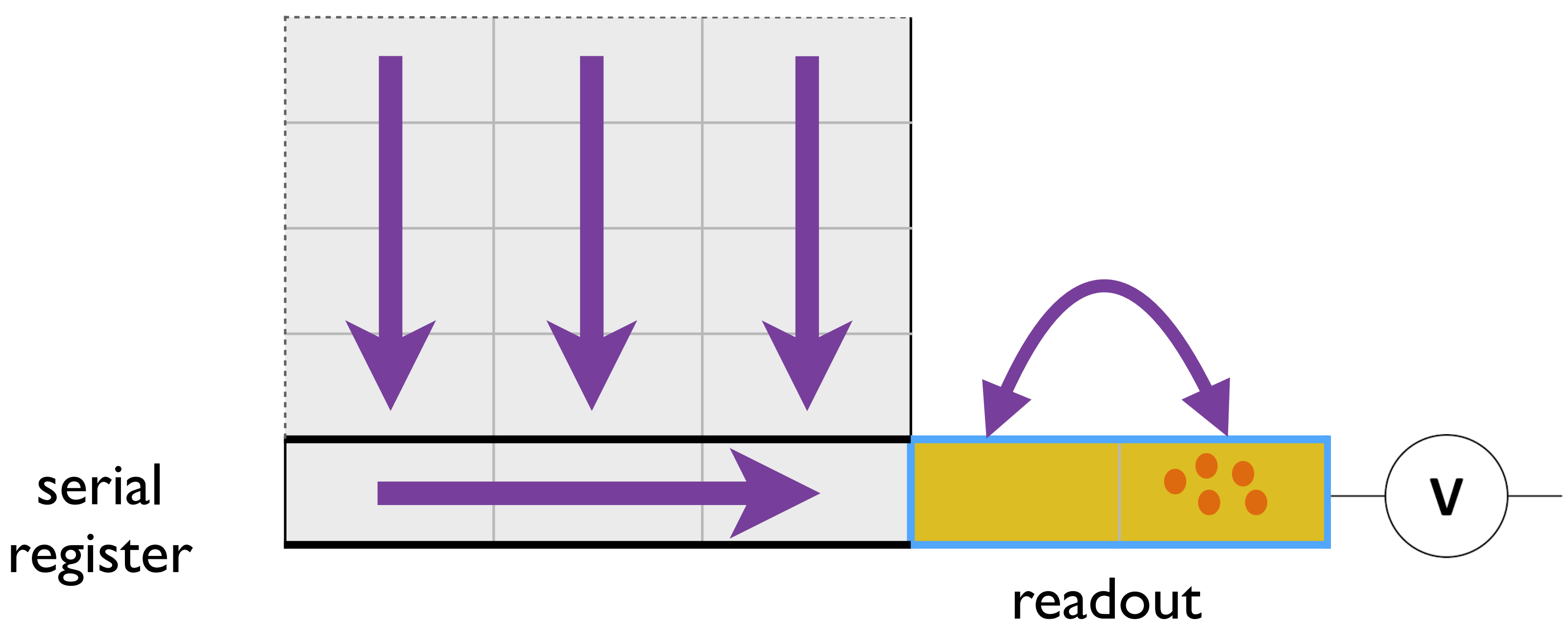

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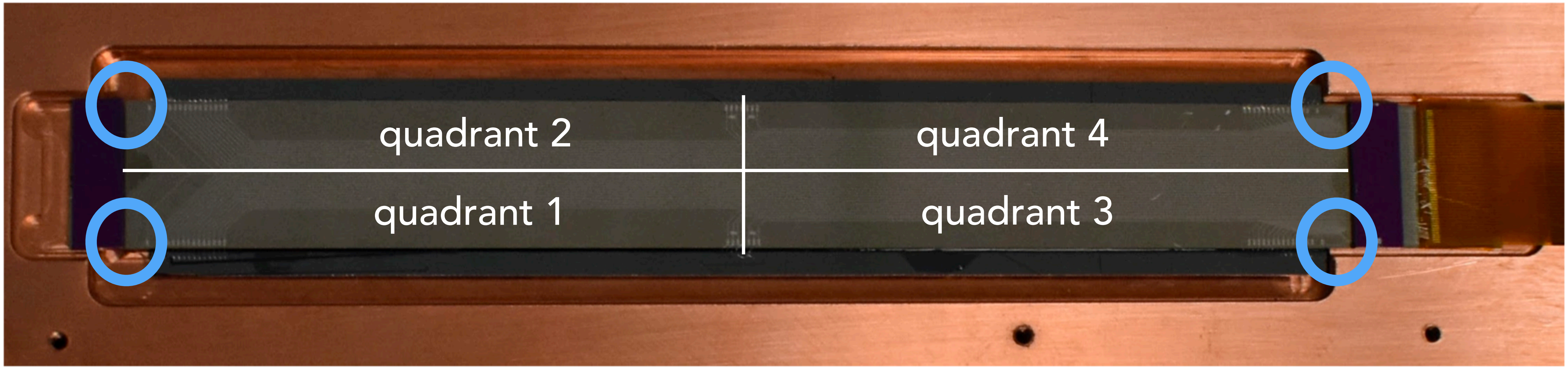

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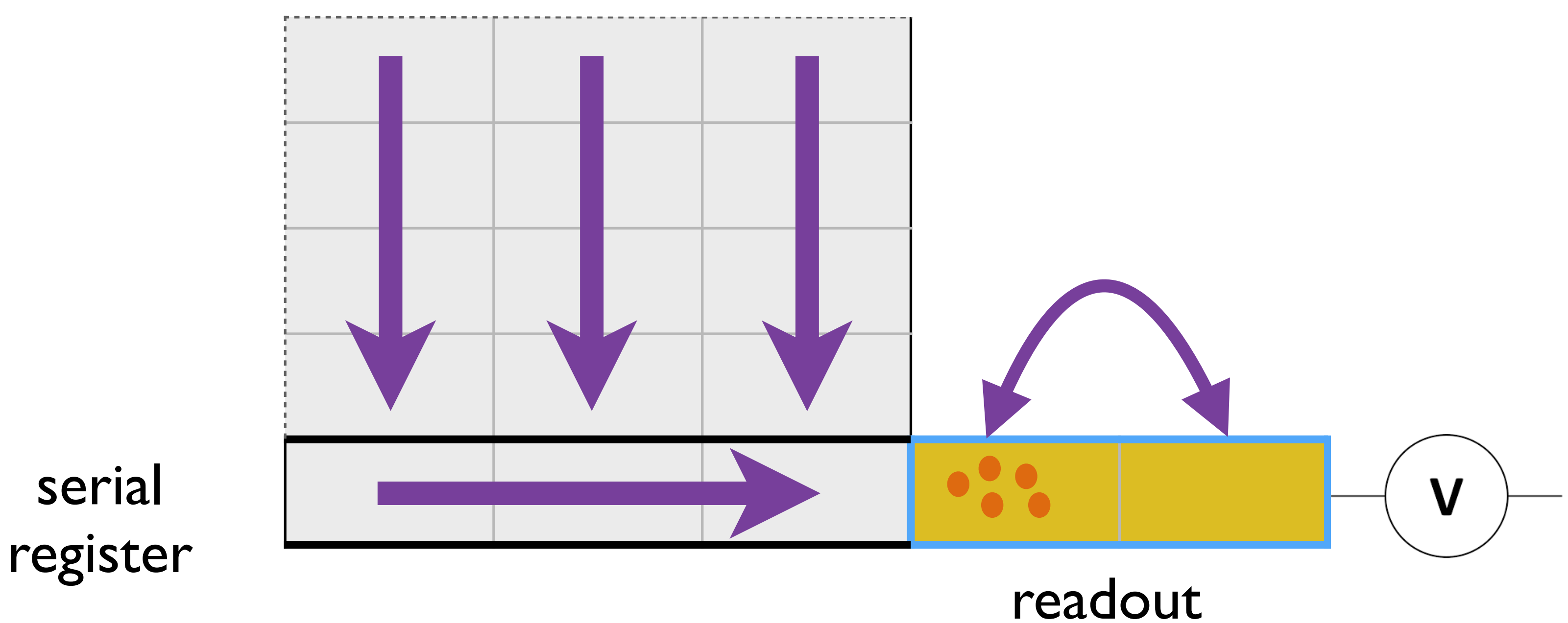

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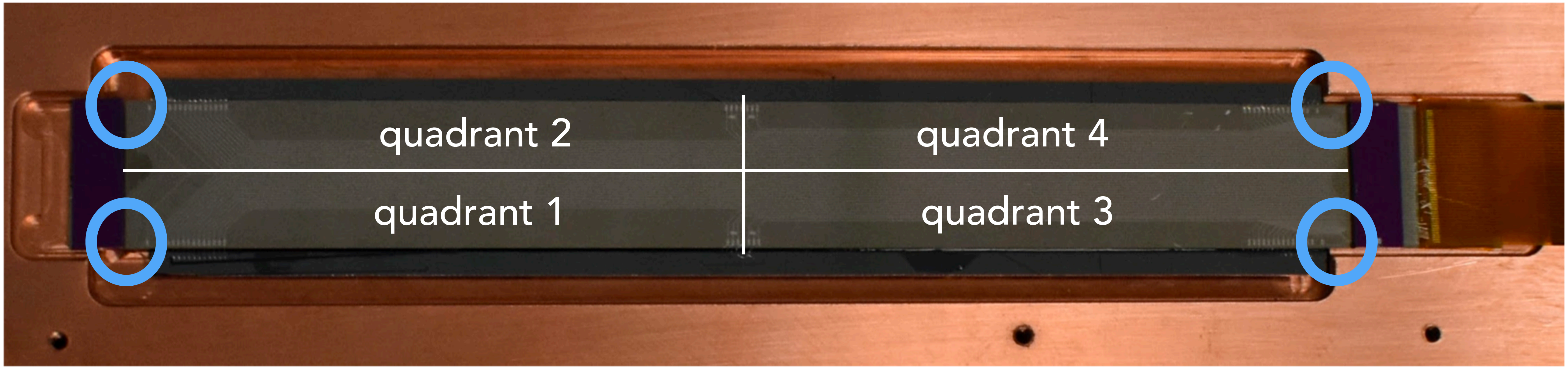

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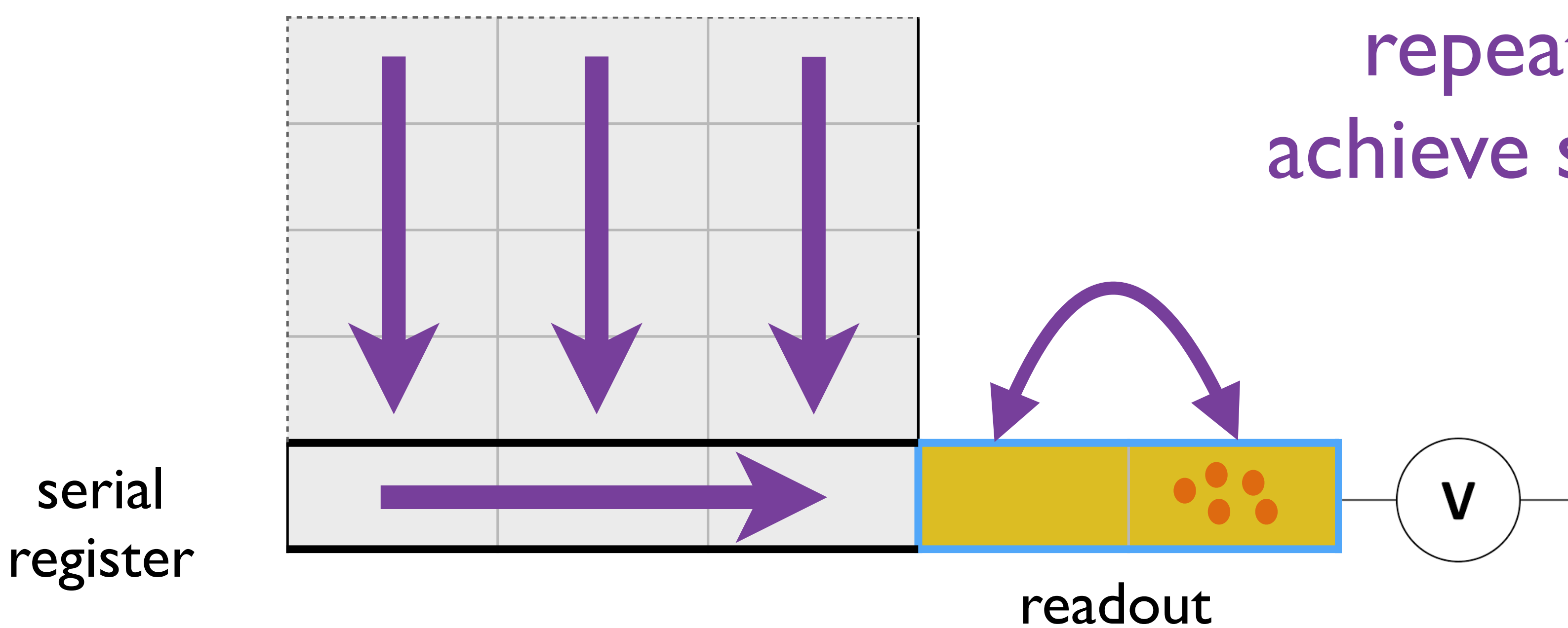

repeatedly measure charge to achieve sub-electron readout noise

Tiffenberg et.al. 2017

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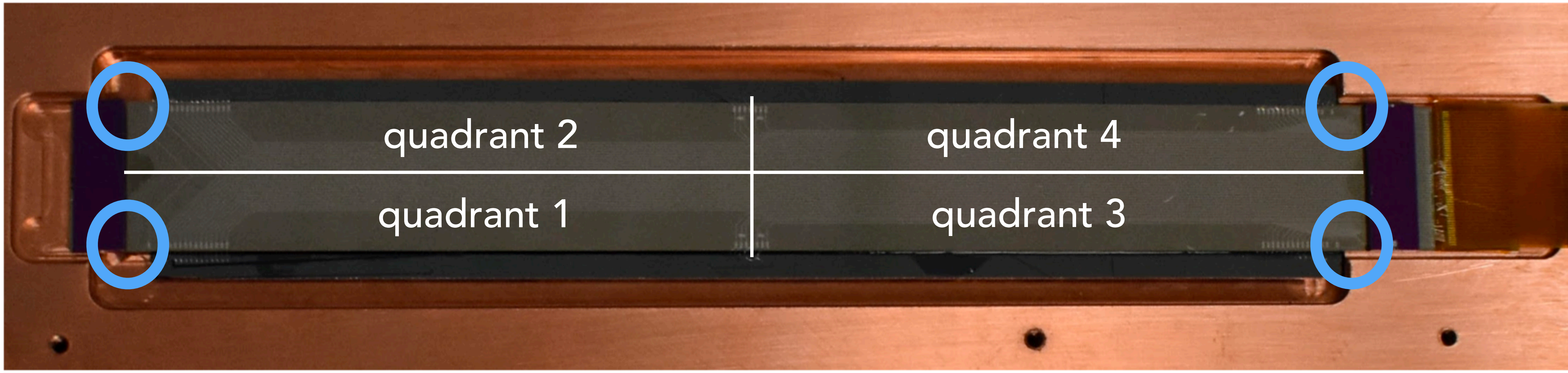
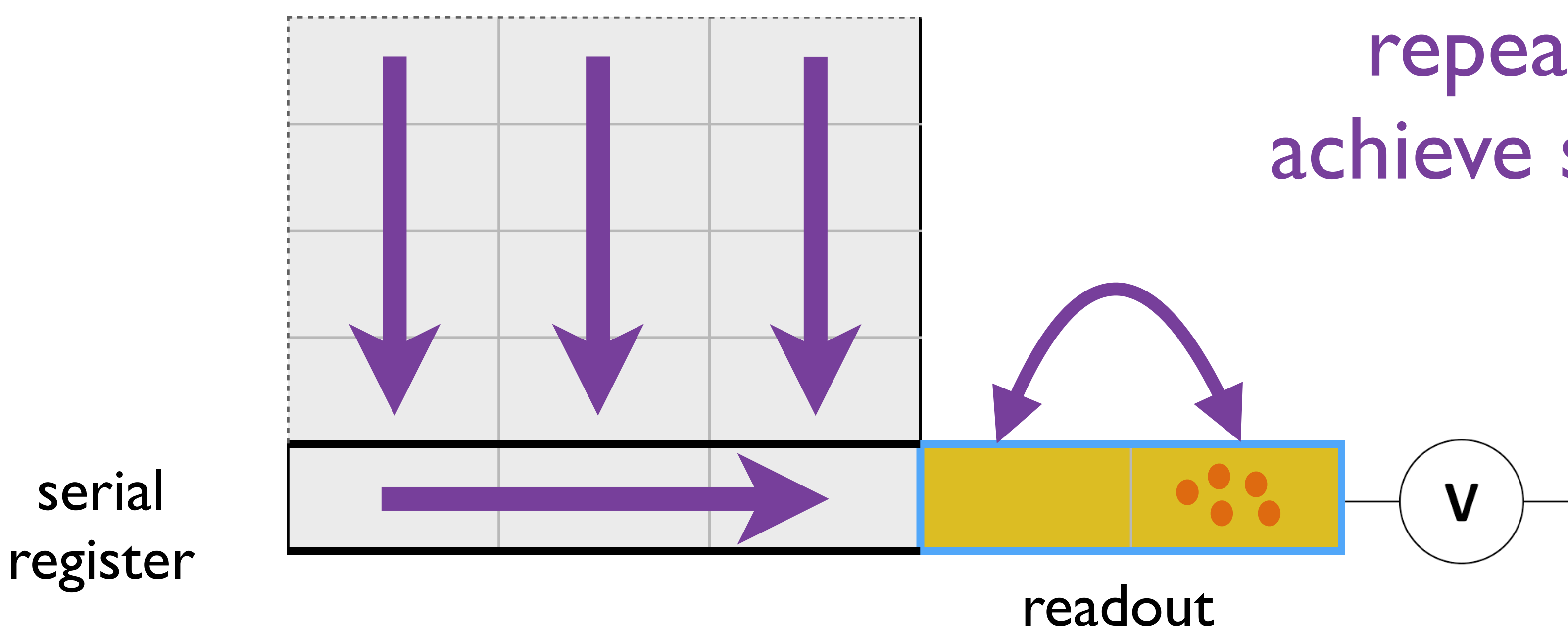


~ 2 cm $\times$ 10 cm, 5.4 Mpix



repeatedly measure charge to achieve sub-electron readout noise

Tiffenberg et.al. 2017

designed at LBNL and fabricated at Teledyne DALSA Semiconductor

Skipper-CCD Detectors: Status and Plans

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Skipper-CCD Detectors: Status and Plans

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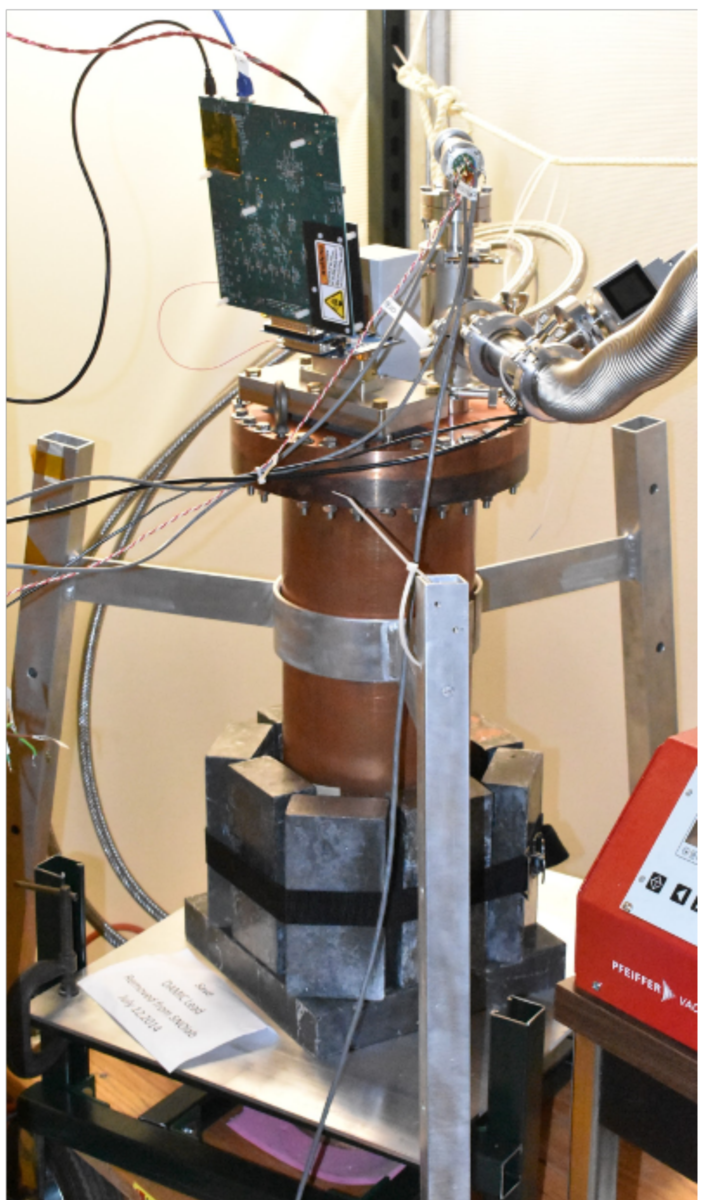
  - Detectors operating at Fermilab & SNOLAB



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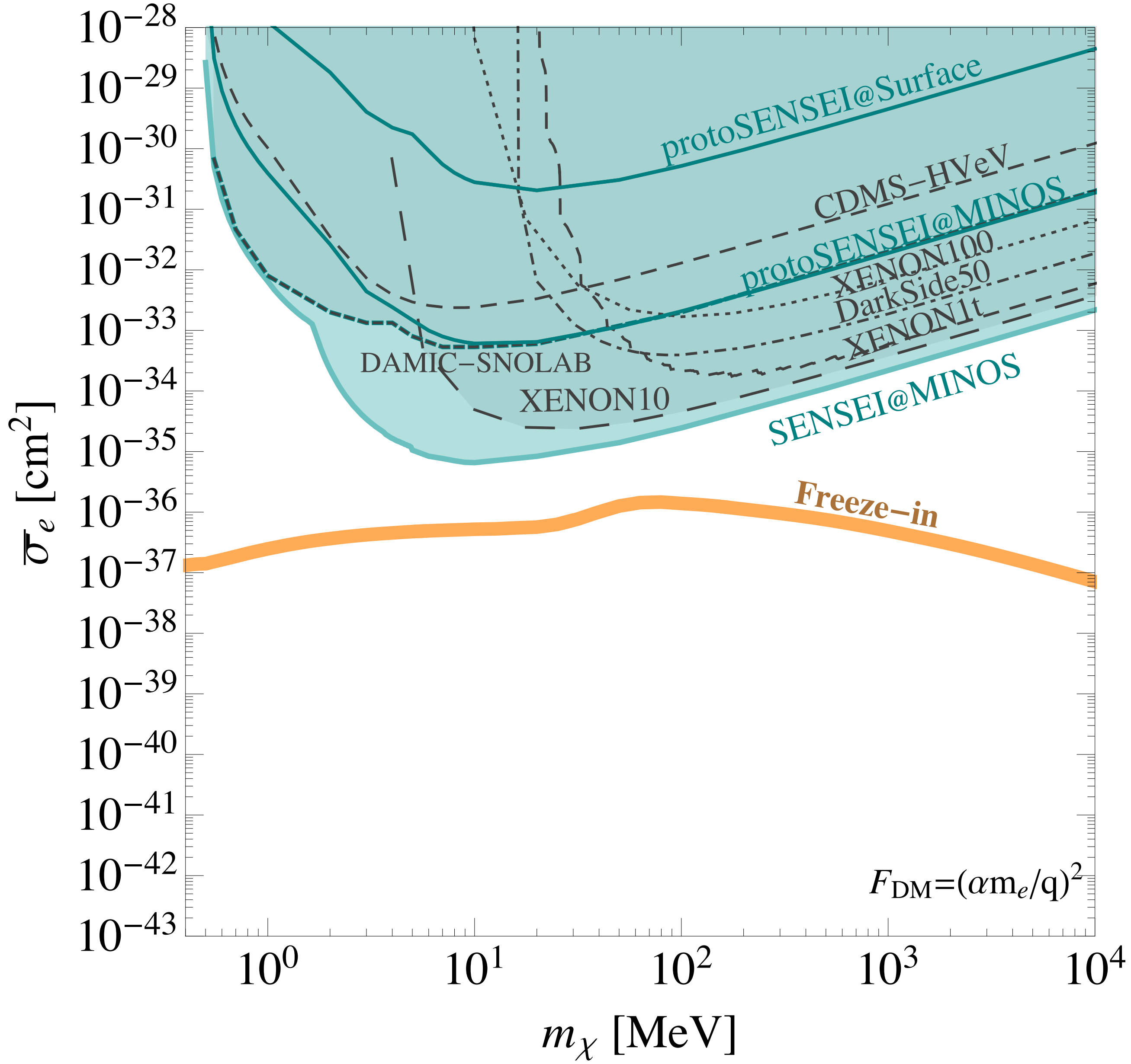

1804.00088, PRL
1901.10478, PRL
2004.11378, PRL

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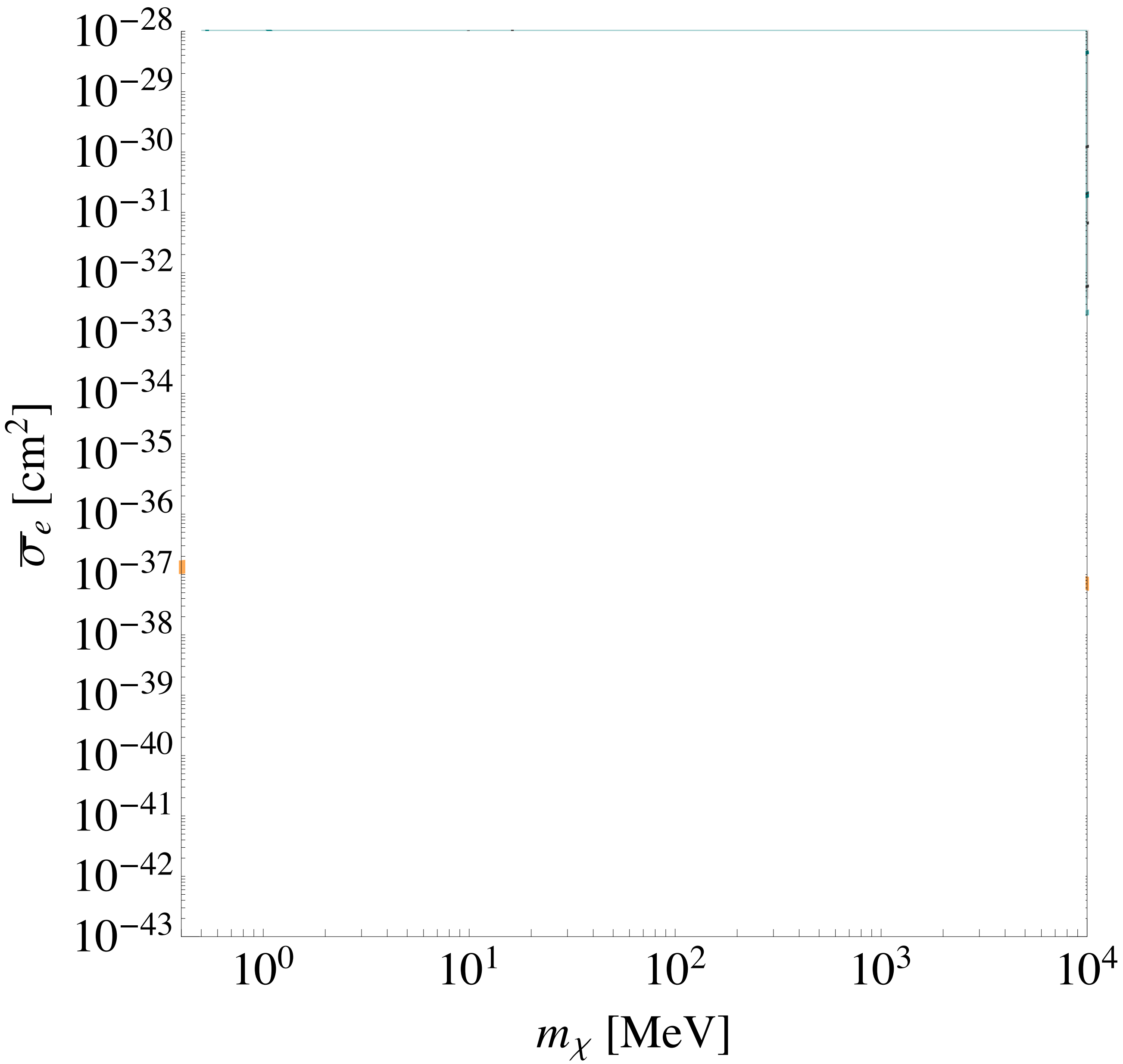

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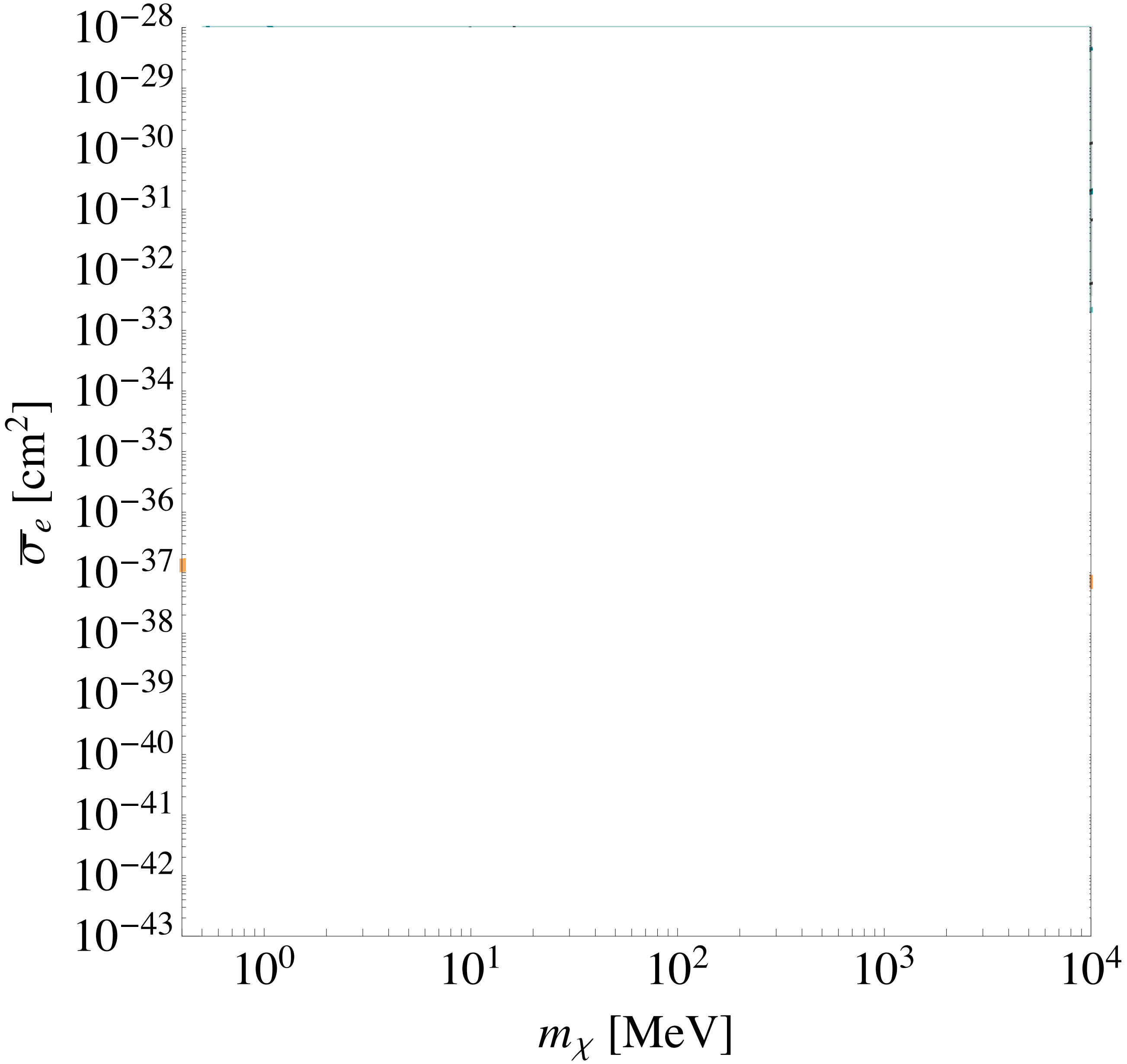

see Kelly Stifter's talk on Friday!

Skipper-CCD Detectors: Status and Plans

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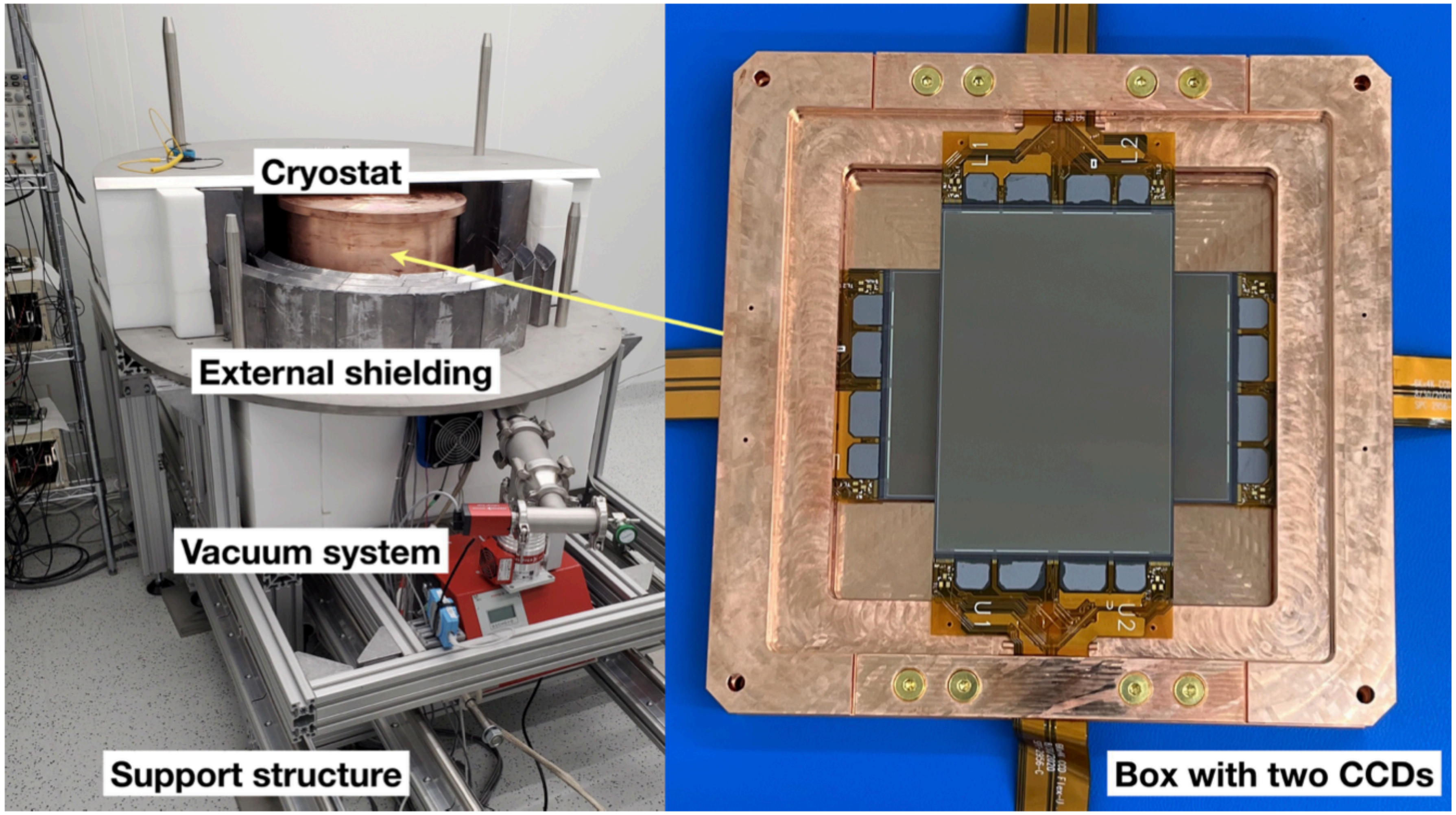
Skipper-CCD Detectors: Status and Plans

- DAMIC-M (see talk by J.-P. Zopounidis):
  - First results w/ ~18 g detector at Modane (2302.02372)



2302.02372

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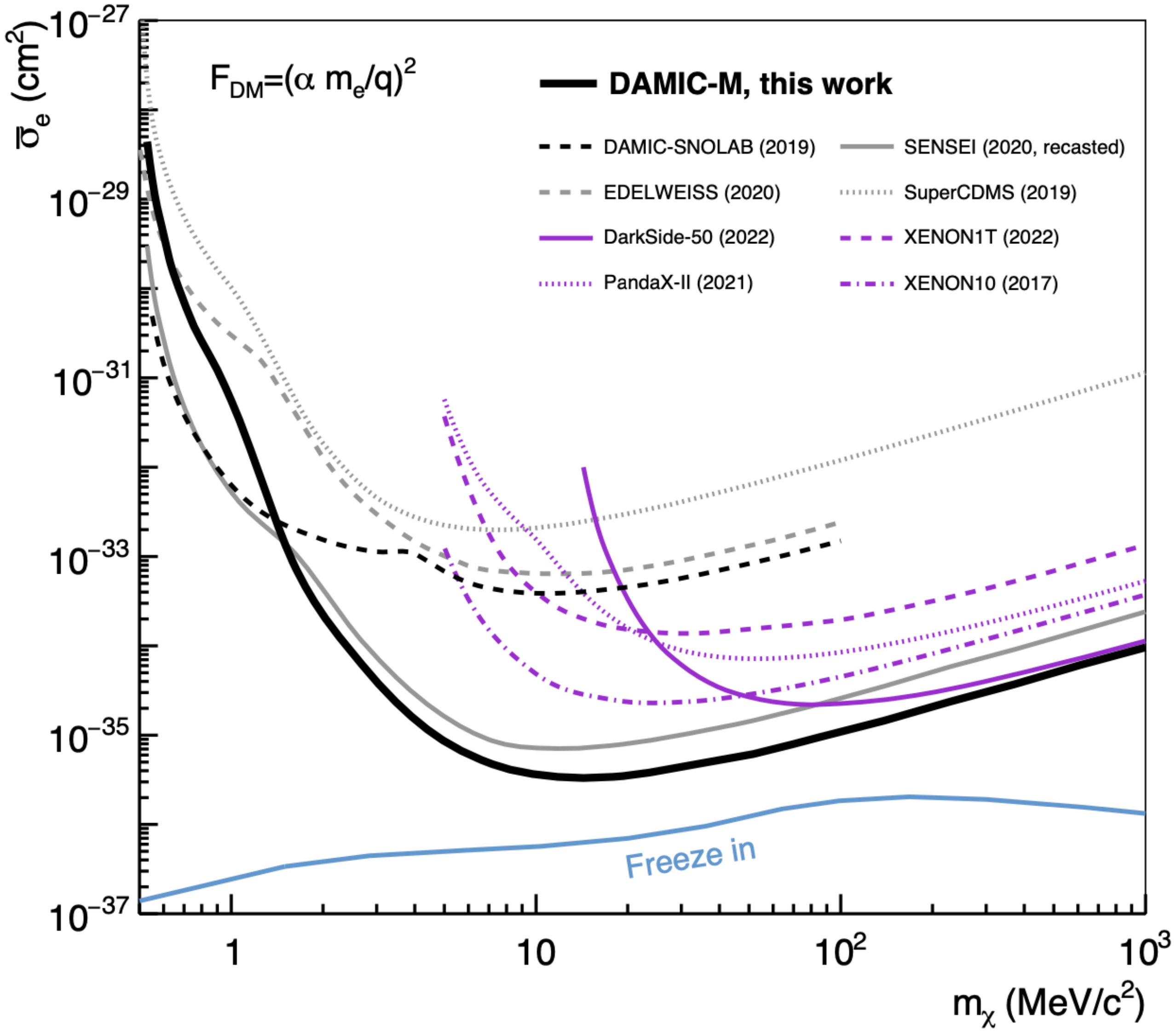

2302.02372

Skipper-CCD Detectors: Status and Plans

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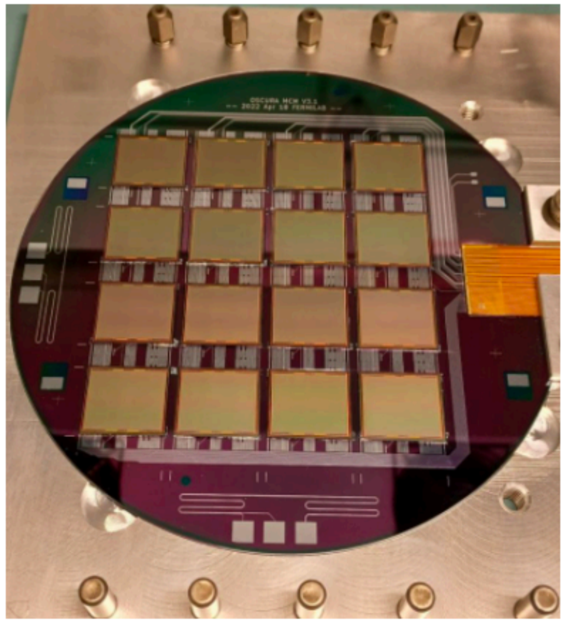
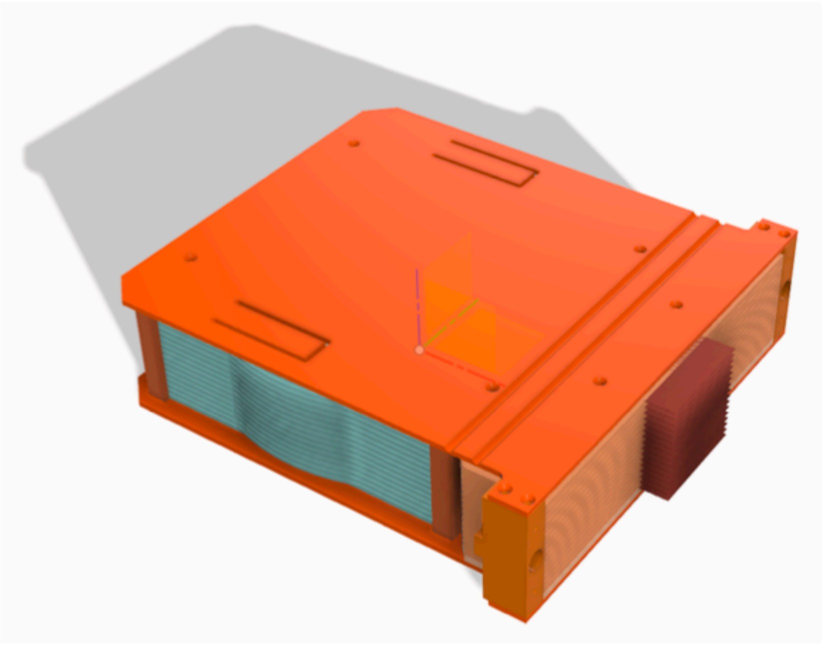
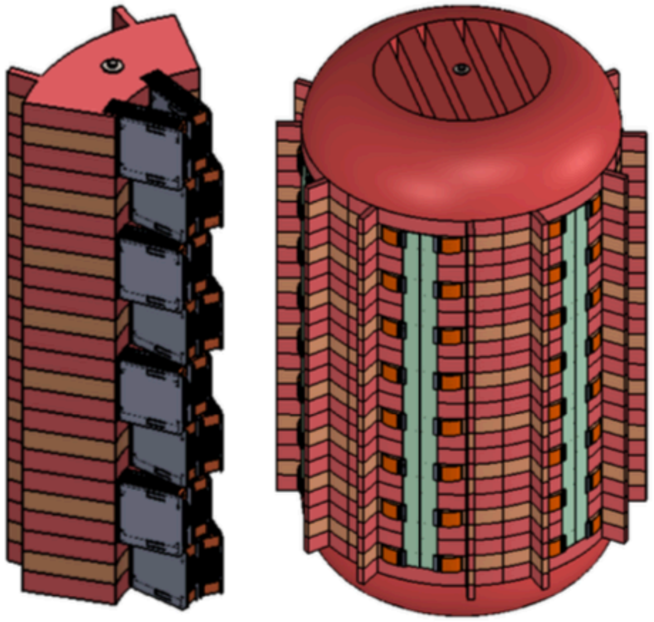
- Oscura (see talk by Brenda Cervantes):
  - R&D funded by DoE DMNI program
  - Goal: ~ 10 kg detector

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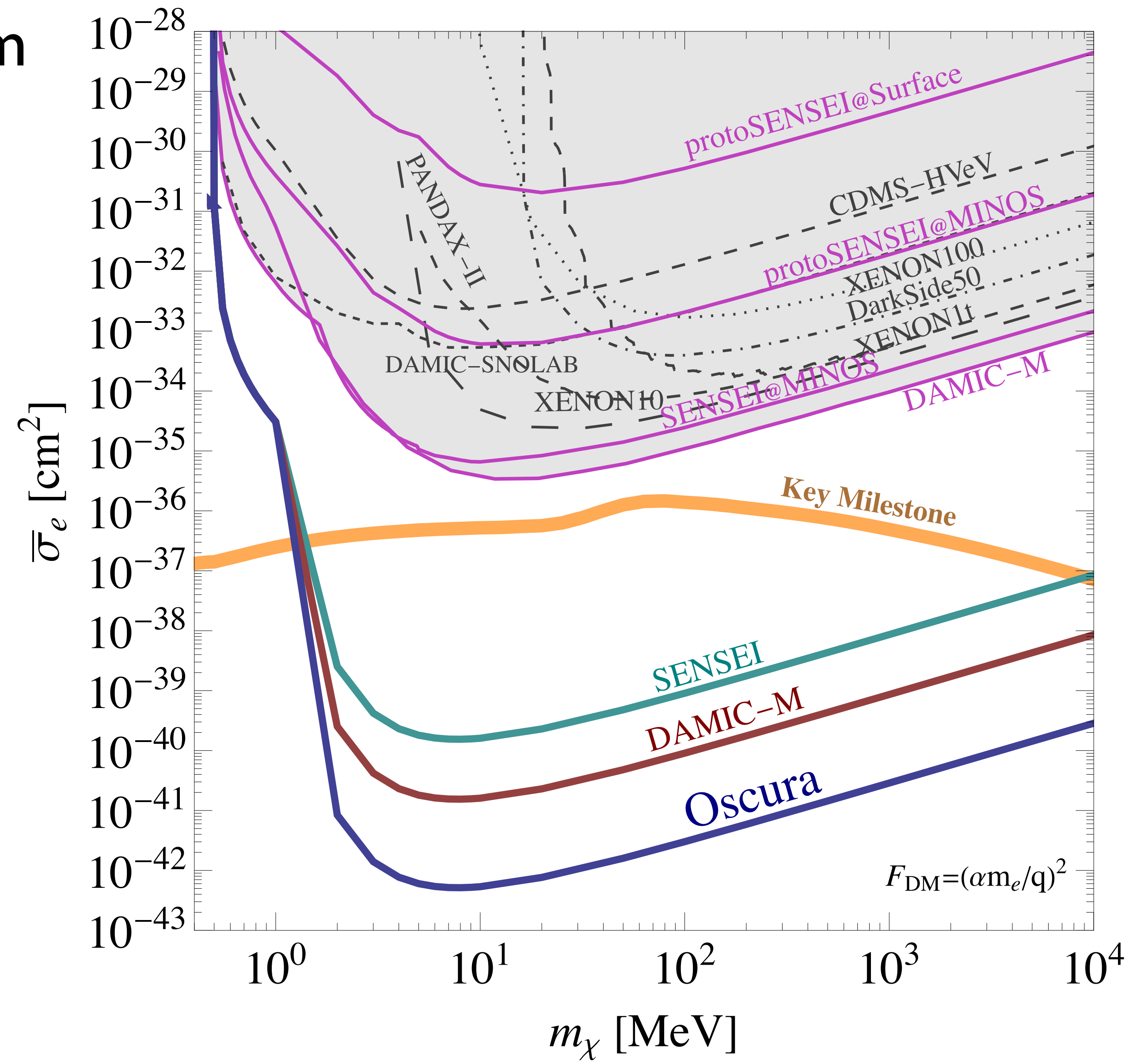

successful implementation of this program would probe orders of magnitude of DM parameter space

Many other technologies/detectors discussed at UCLA DM!

- SNSPDs — talk by Matt Shaw
- Qubits — poster by Ryan Linehan + talk by Osmond Wen
- MKIDs — poster by Dylan Temples
- Quantum Charge Parity Detectors — poster by Karthik Ramanathan
- Narrow-gap Semiconductors (SPLENDOR) — poster by Samuel Watkins
- Supercooled water (Snowball chamber) — talk by Matthew Szydagis
- HydroX — talk by Scott Haselschwardt
- + stuff I forgot to mention (sorry!)

Significant progress in probing sub-GeV dark matter

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    - multiple codes (QEDark, DarkELF, EXCEED-DM, QCDark)

Improved Calculation of DM-e Scattering Rates

relate rates to dielectric function, include screening, include effects from core electrons

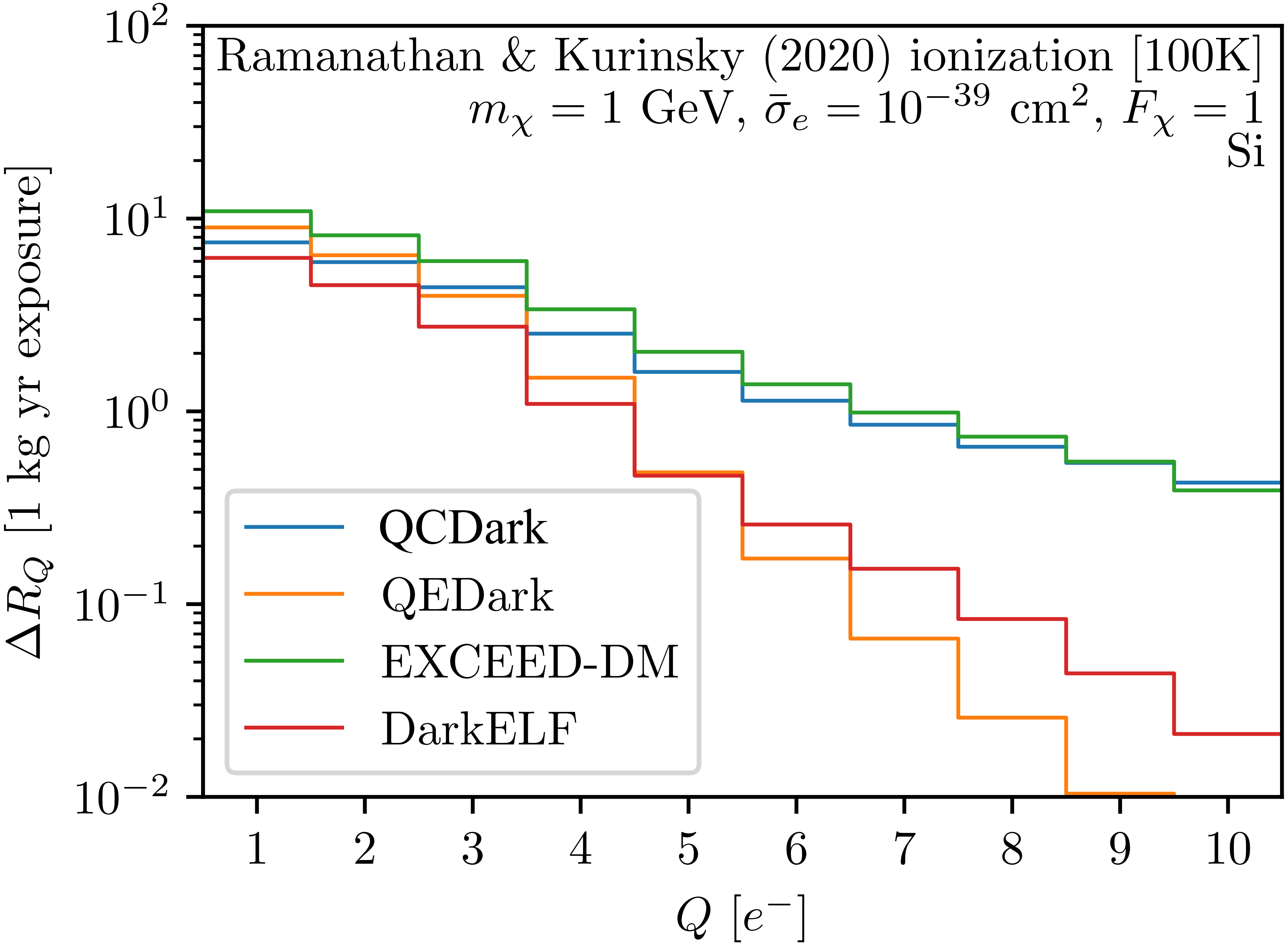
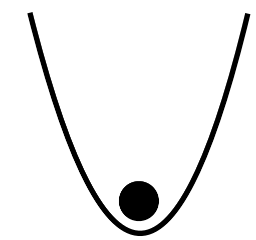


Figure from:
Dreyer, RE, Fernandez-Serra, Singal, Zhen (to appear)

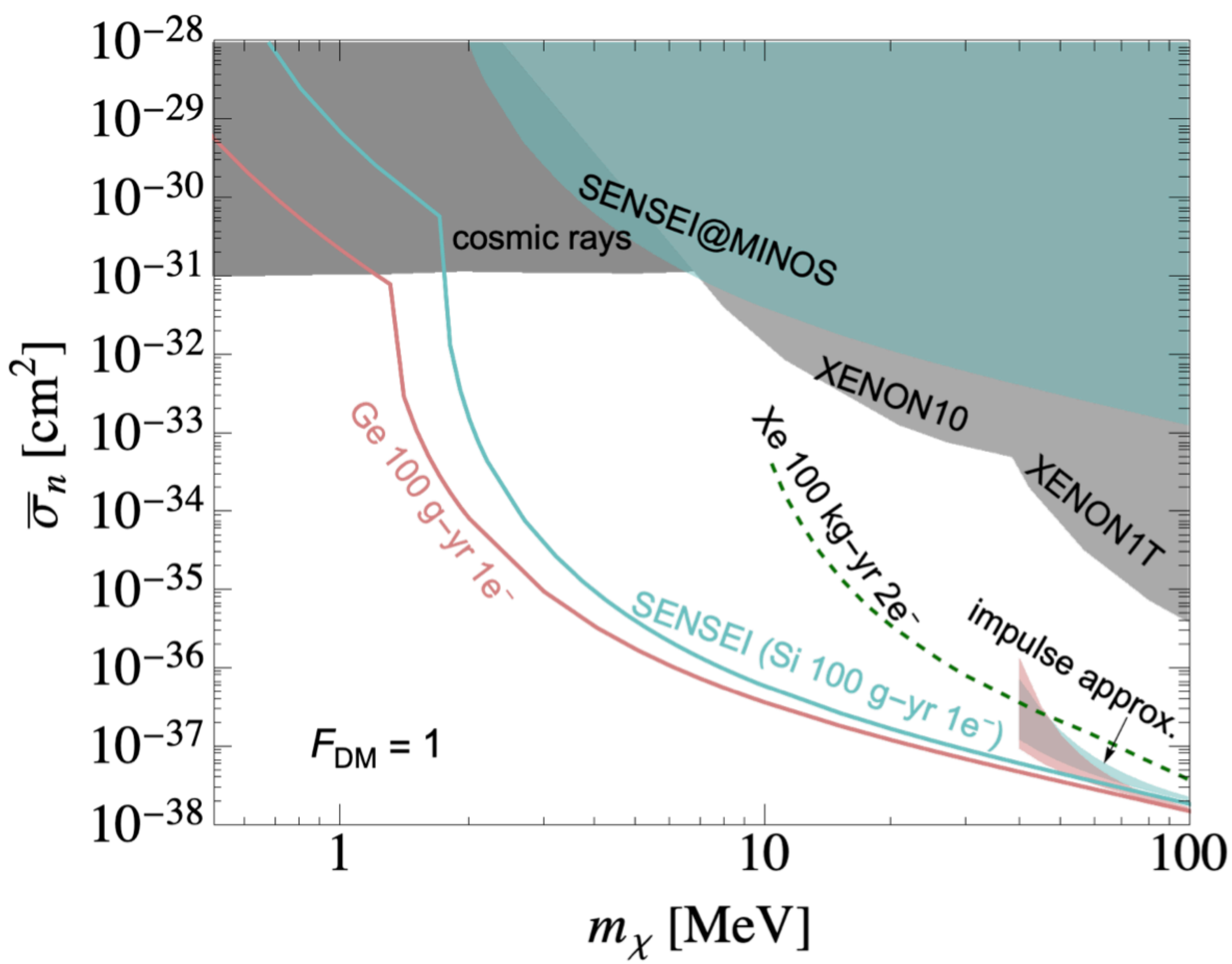
QCDark: Dreyer, RE, Fernandez-Serra, Singal, Zhen (to appear)
QEDark: RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu (1509.01598)
EXCEED-DM: Griffin, Inzani, Trickle, Zhang, Zurek (2105.05253); Trickle (2210.14917)
DarkELF: Knapen, Kozaczuk, Lin (2101.08275, 2104.12786); see also Hochberg, Kahn, Kurinsky, Lehmann, Yu (2101.08263)

Improved Calculation of Migdal Rates



Example: semiconductors

- response of nucleus differs from free nucleus (e.g., can generate phonons)
- use an EFT to reliably calculate Migdal for DM masses < 100 MeV



Berghaus, Esposito, RE, Sholapurkar (2210.06490)

see also
Knapen, Kozaczuk, Lin (2011.09496);
Liang, Zhang, Zheng, Zhang (1912.13484);
Liang, Mo, Zheng, Zhang (2011.13352, 2205.03395)

for recent updates to Migdal rates in other materials, see e.g. Liu, Wu, Chi, Chen (2007.10965)
Cox, Dolan, McCabe, Quiney (2208.12222)

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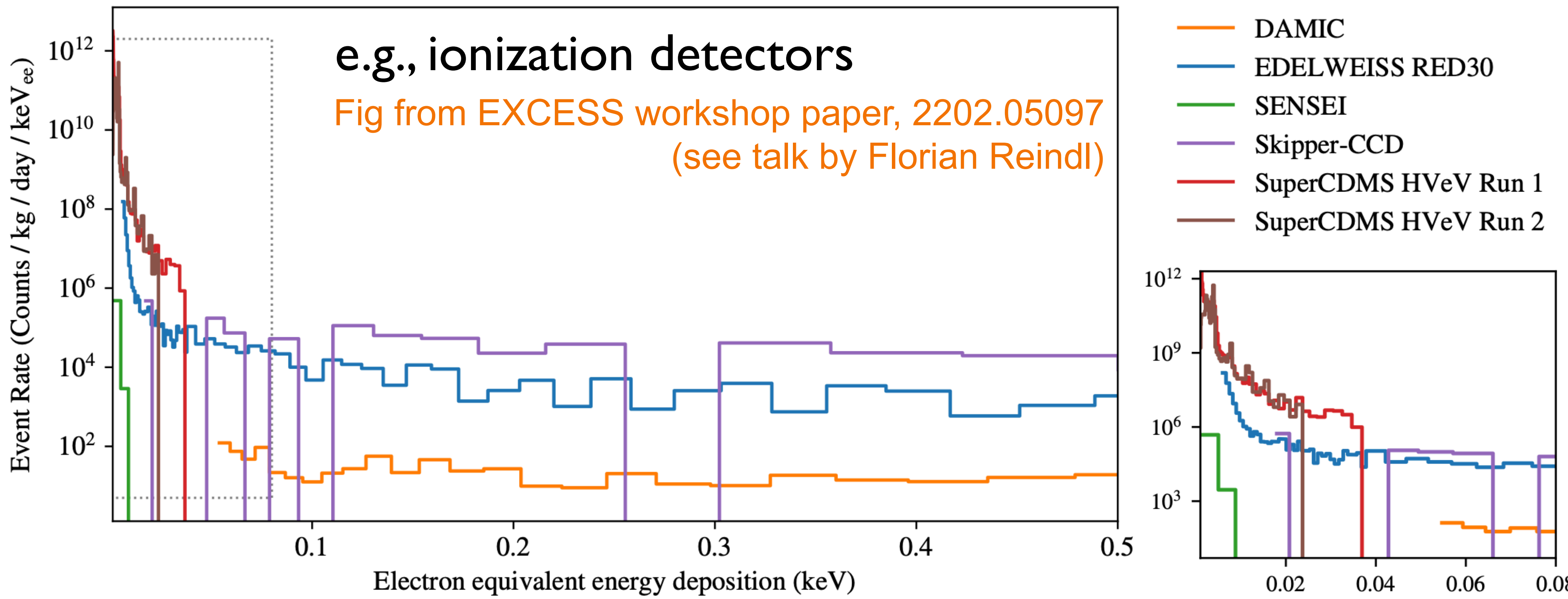
All sub-GeV DM experiments see “excess” low-energy events



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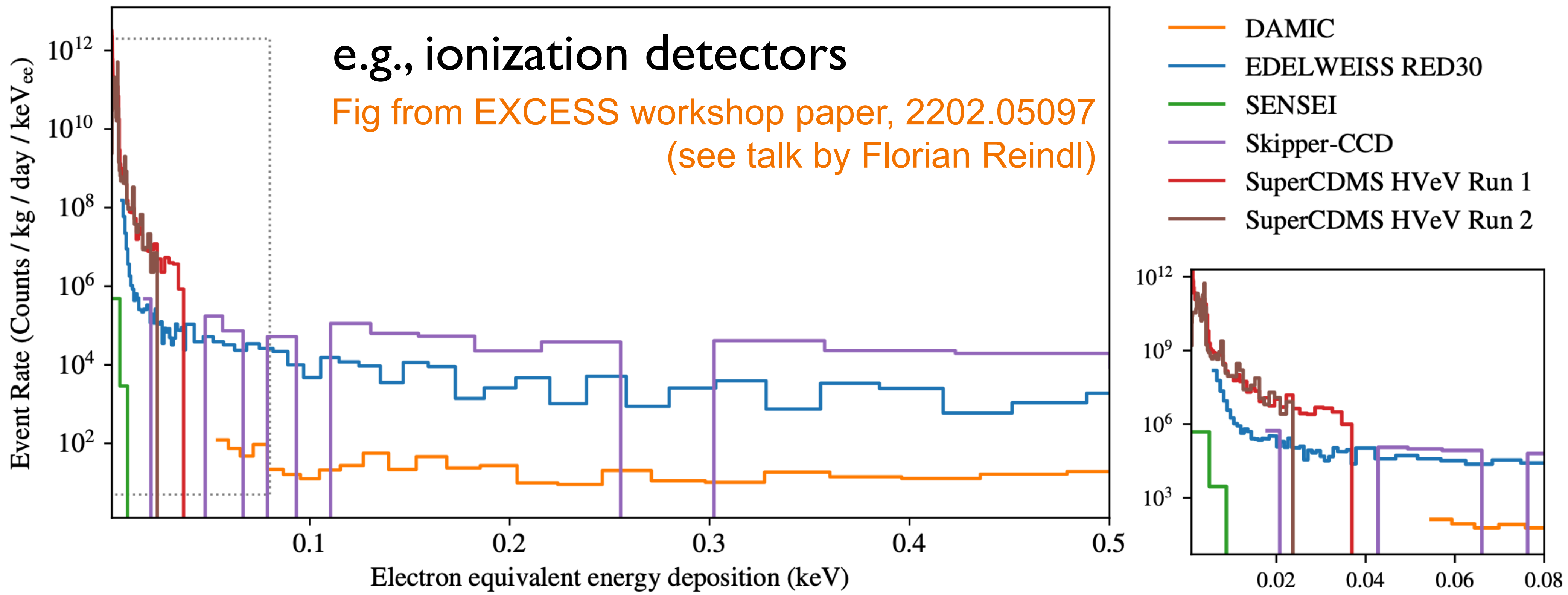

Excesses have multiple, novel, subtle, only-partially-understood origins, e.g.

- SuperCDMS-CPD/EDELWEISS/CRESST: stress-induced phonon bursts?

  e.g. 2207.09375; 2208.02790;

- SuperCDMS HVeV: Cherenkov; luminescence

  Du, Egana-Ugrinovic, RE, Sholapurkar (2011.13939); SuperCDMS (2204.08038)

- SENSEI: Cherenkov, radiative recombination of e^-/h^+ pairs, + others?

  Du, Egana-Ugrinovic, RE, Sholapurkar (2011.13939)

Very active research direction!

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  - e.g., Migdal effect, Compton spectrum

Migdal effect has never been observed in laboratory, but is being used to set some of the strongest bounds on sub-GeV DM-nucleus interactions…

Migdal calibration w/ neutrons in silicon and xenon

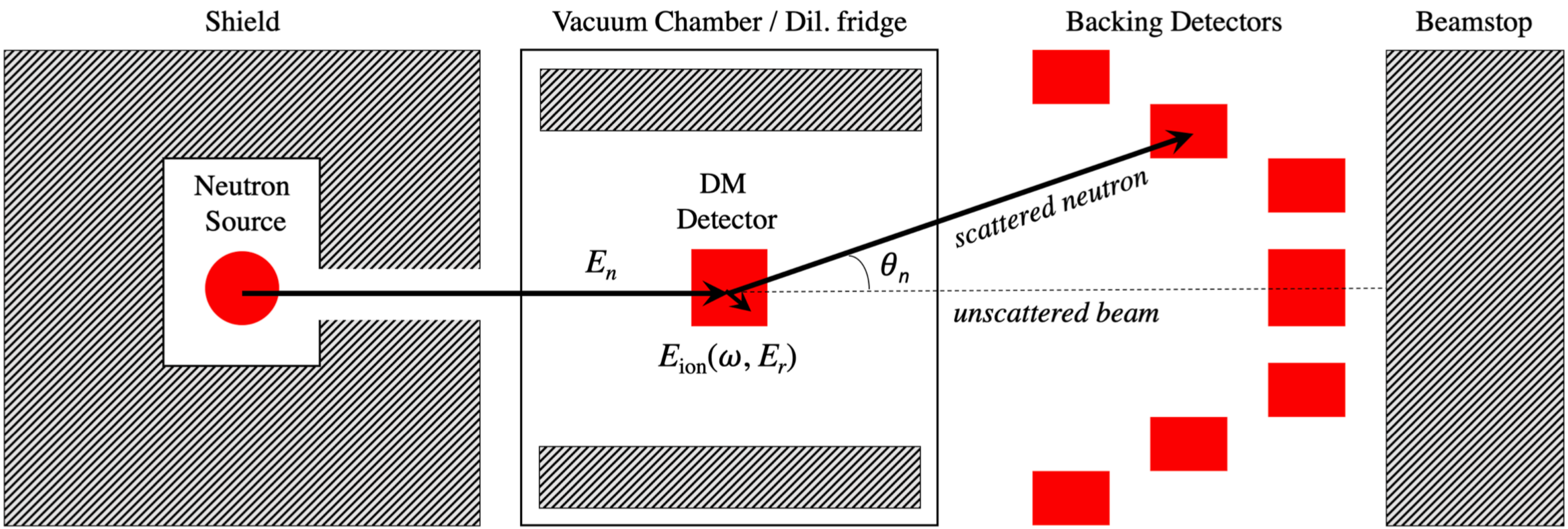
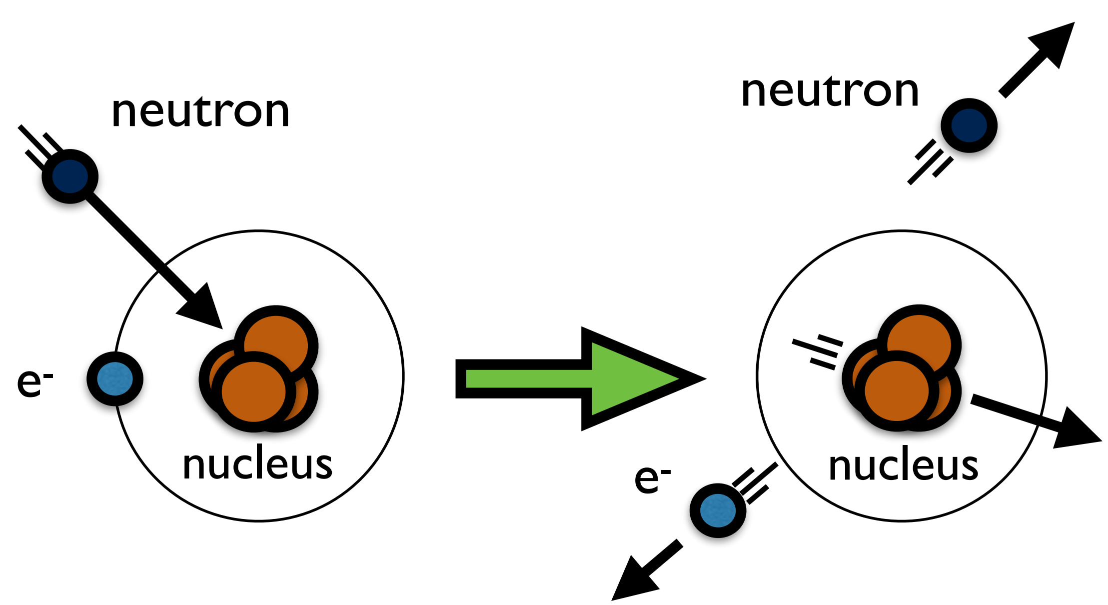
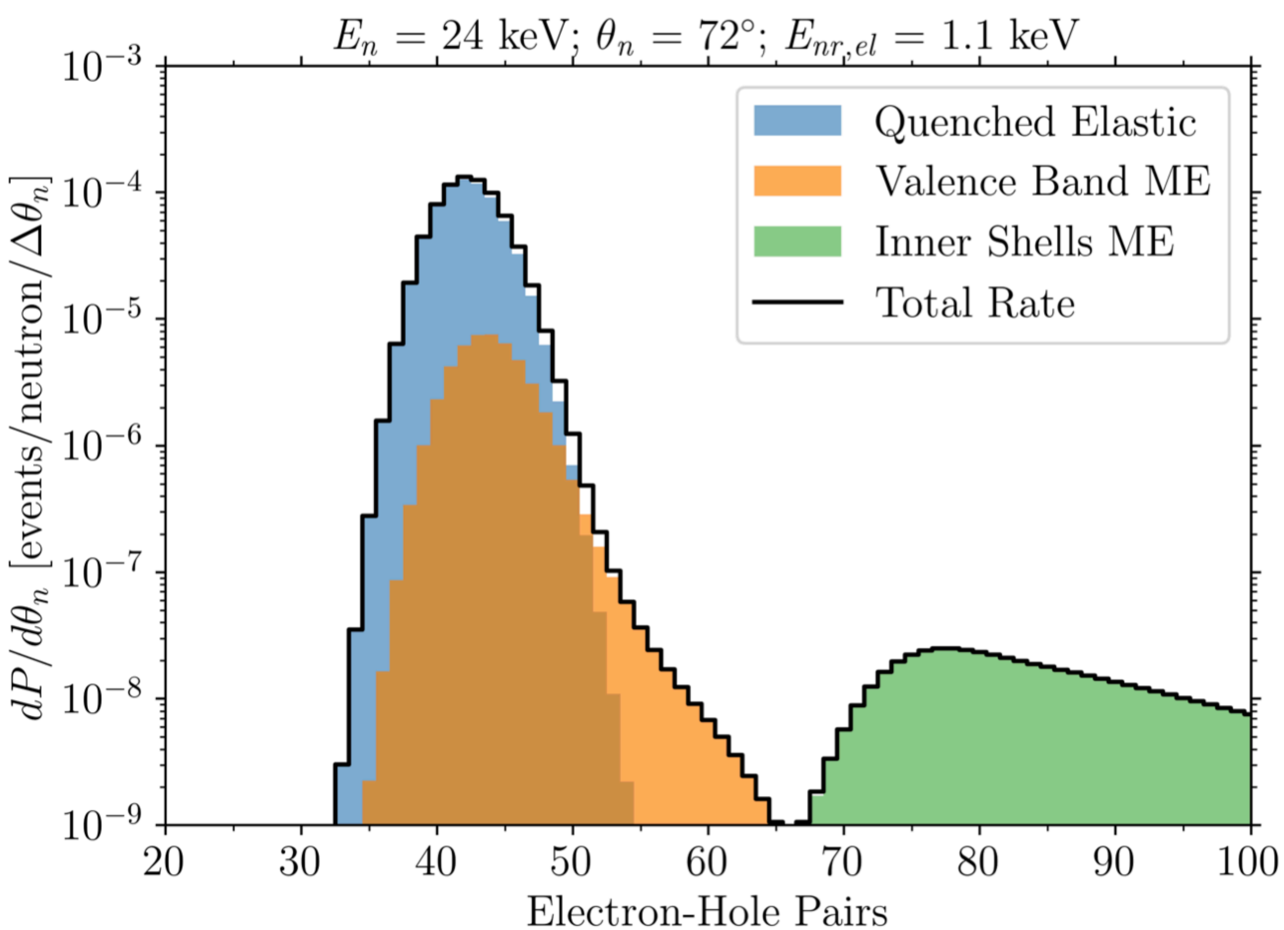


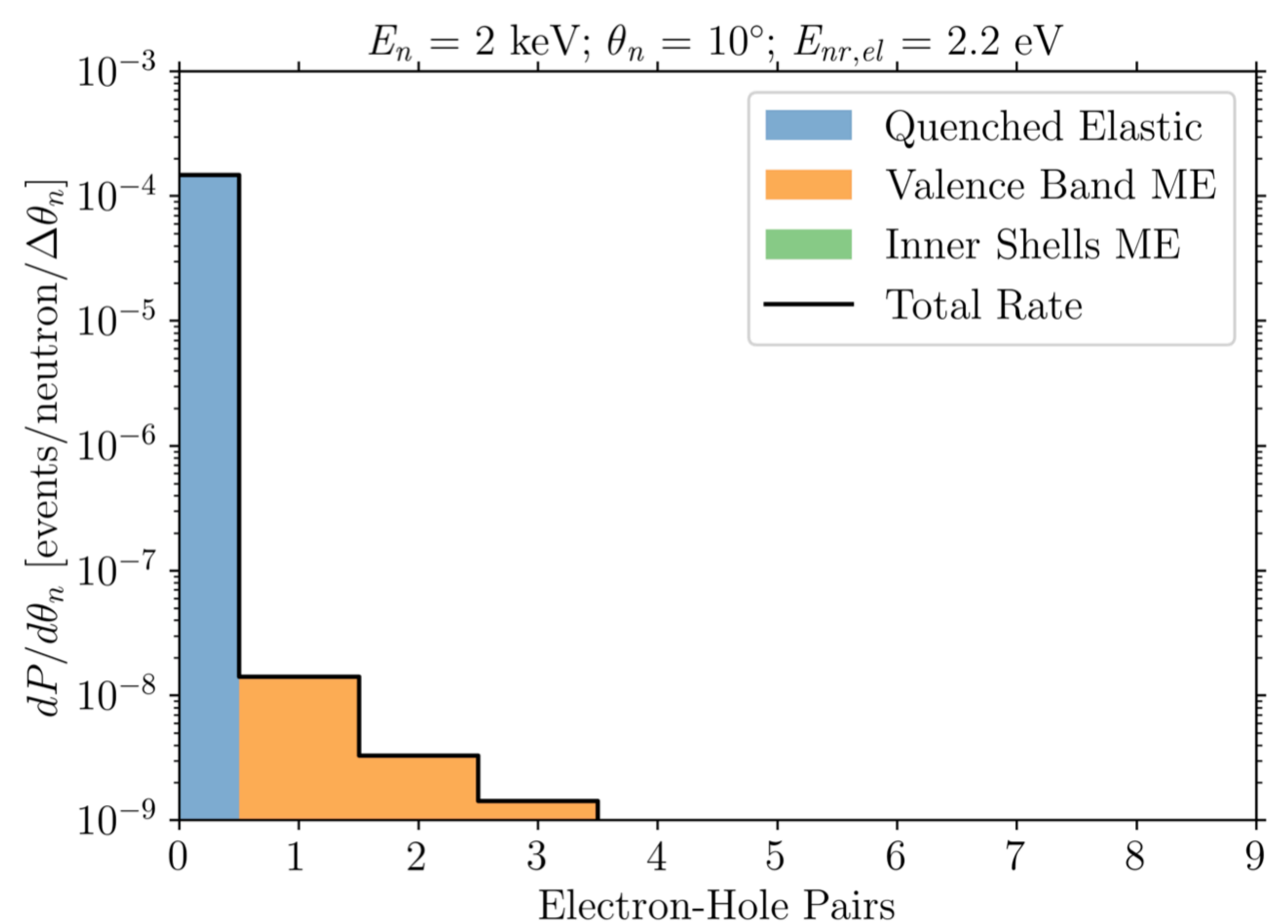
Fig from: Adams, Baxter, Day RE, Kahn, 2210.04917



Detecting Migdal Effect in Si

Adams, Baxter, Day RE, Kahn, 2210.04917





Challenge: Migdal signal is much smaller than signal from neutron elastic scattering

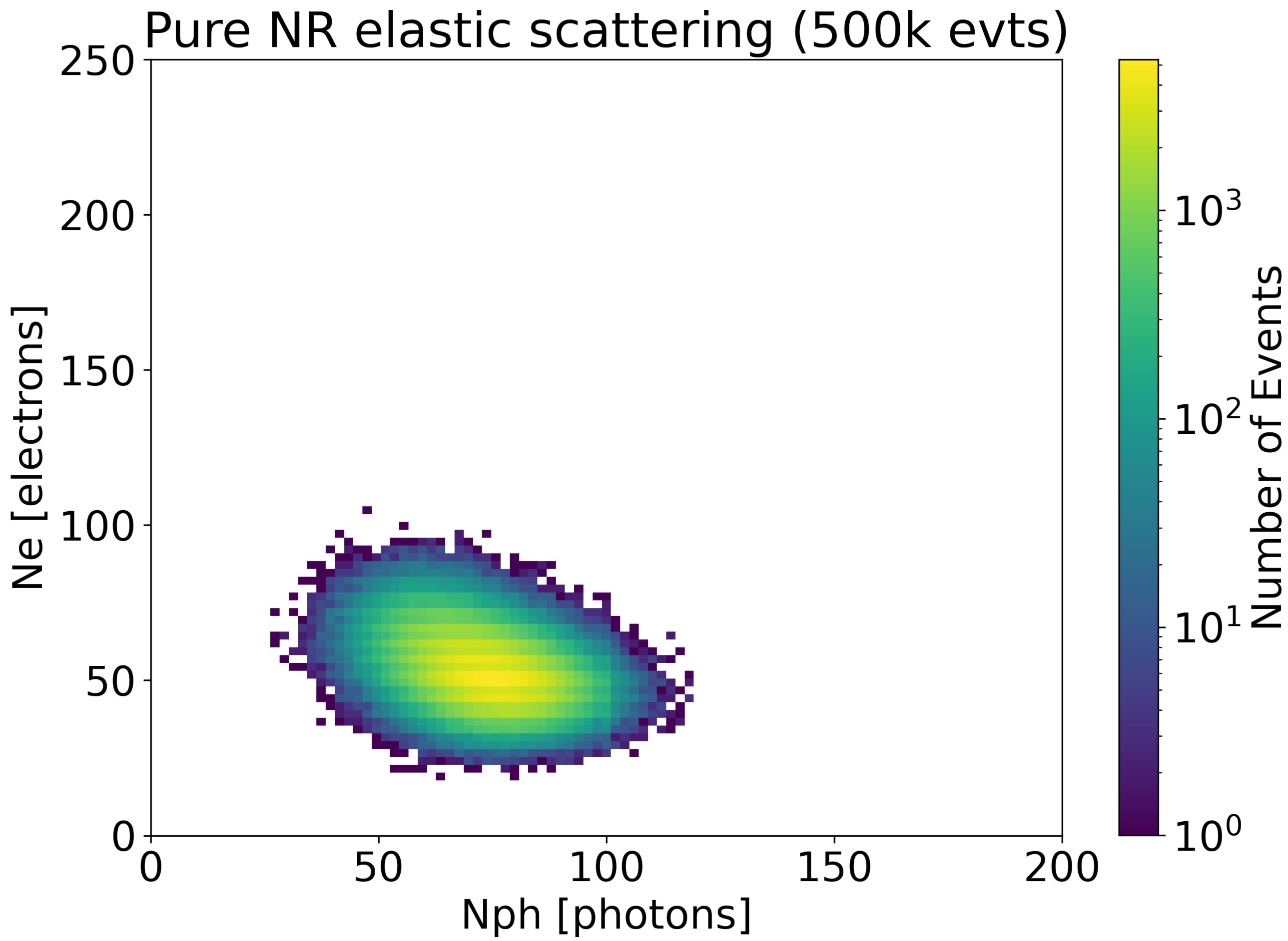
However, Migdal event produces more ionization!

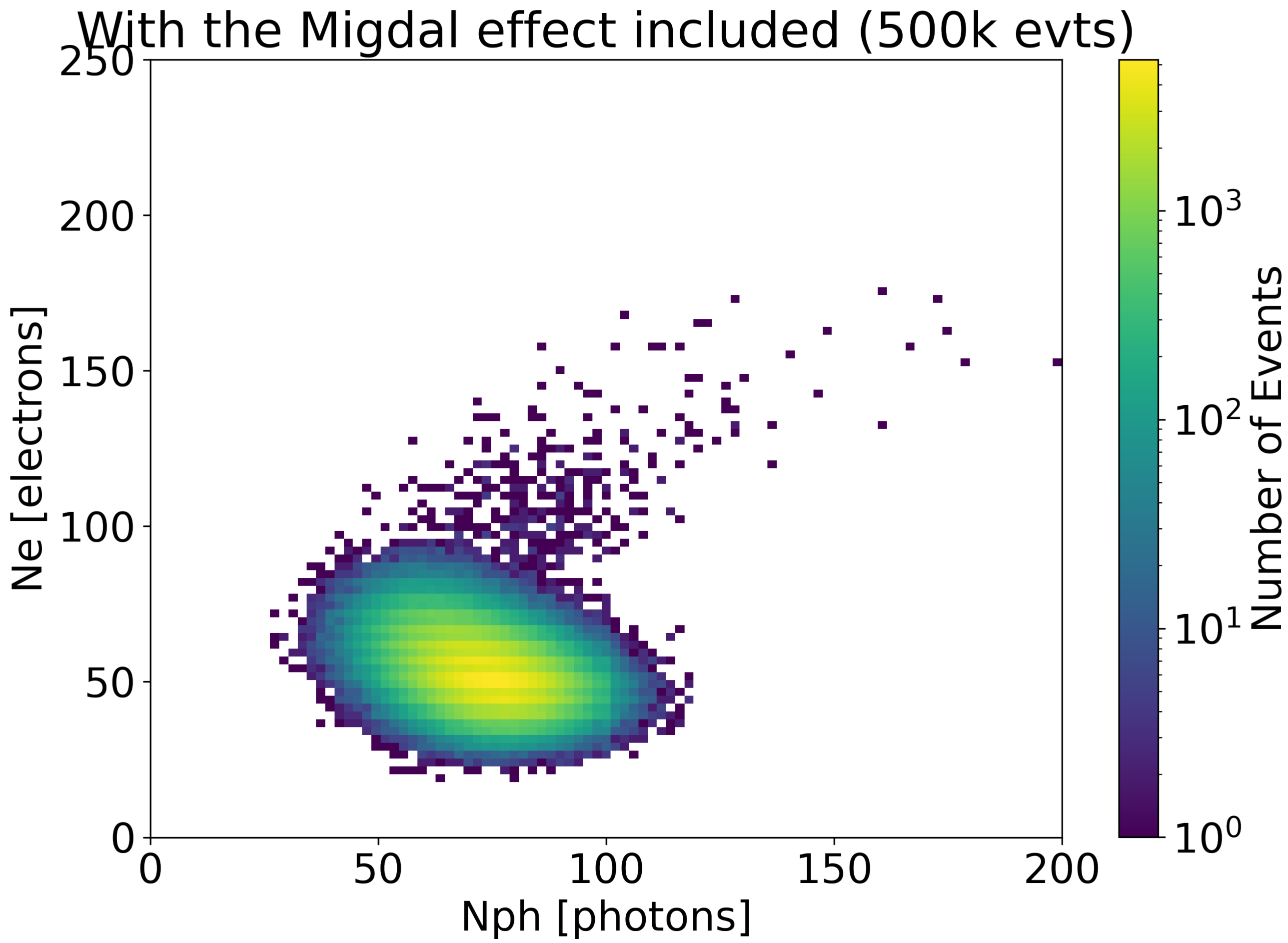
see poster by Dan Baxter

Detecting Migdal Effect in liquid Xe

Xu, Adams, Lenardo, Pershing, Mannino, Bernard, Kingston, Mizrachi, Lin, RE, Mozin, Kerr, Bernstein, Tripathi to appear

Simulation of signal for $E_n = 14$ MeV, $17°$





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We have taken data at LLNL and analyzed it!

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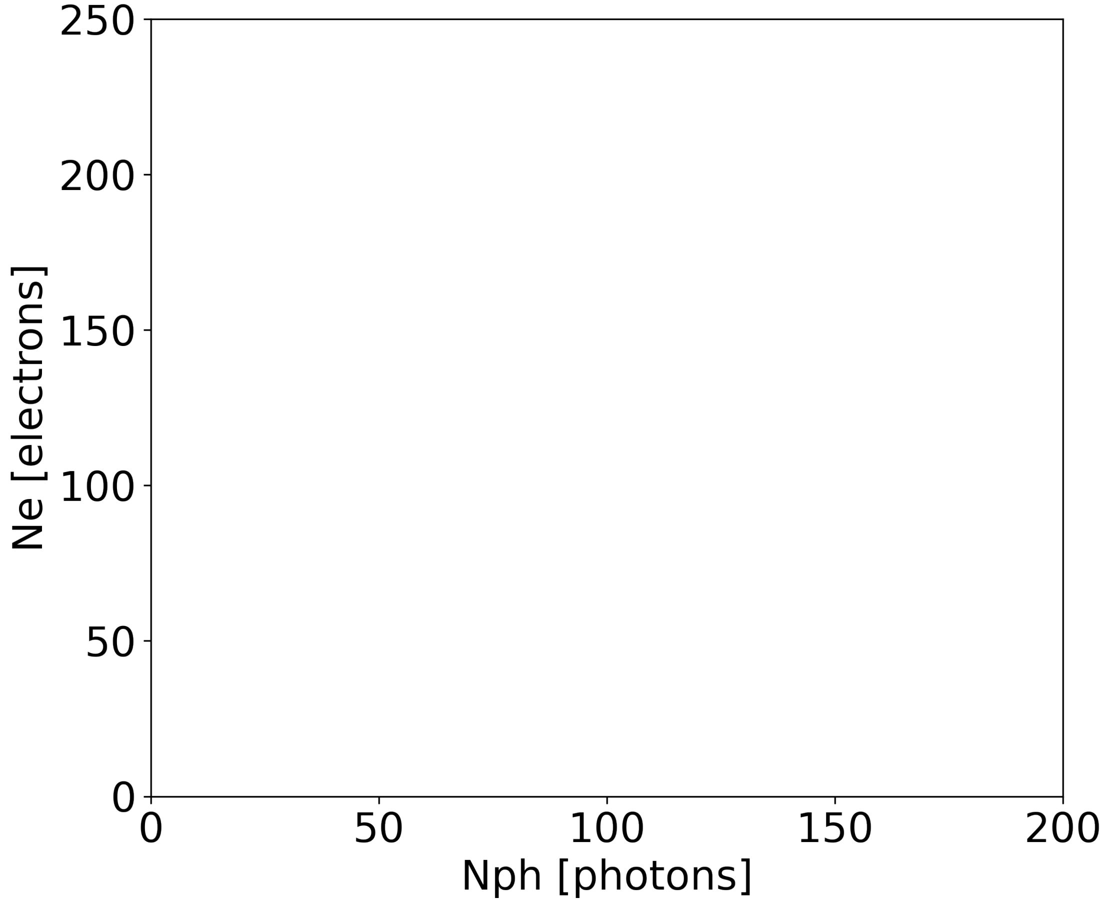

see talk on Friday
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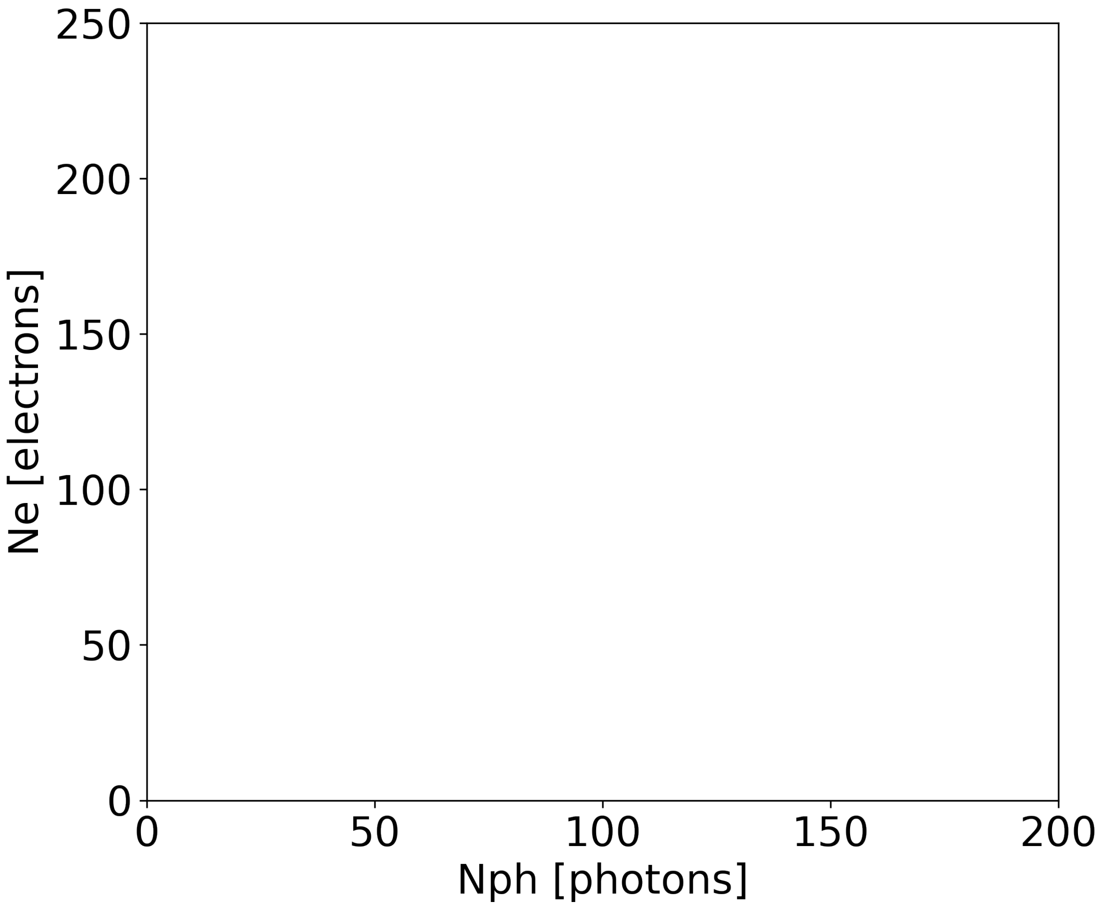

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+ talk on Migdal search in LZ by Jeanne Bang

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- Calibrating DM signals and low-energy backgrounds
  - e.g., Migdal effect, Compton spectrum
- Improved understanding of new signals for DM
  - e.g., solar reflection, diurnal modulation, millicharged DM

Searching for Accelerated Component of Dark Matter

take advantage of "accelerated" DM component
to probe sub-MeV DM w/ existing detectors

- cosmic-ray boosted DM — Bringmann, Pospelov (2019); Cappiello, Beacom (2019)
- solar-reflected DM — An, Pospelov, Pradler, Ritz (2018); Emken, Kouvaris, Nielsen (2018); An, Nie, Pospelov, Pradler (2021)

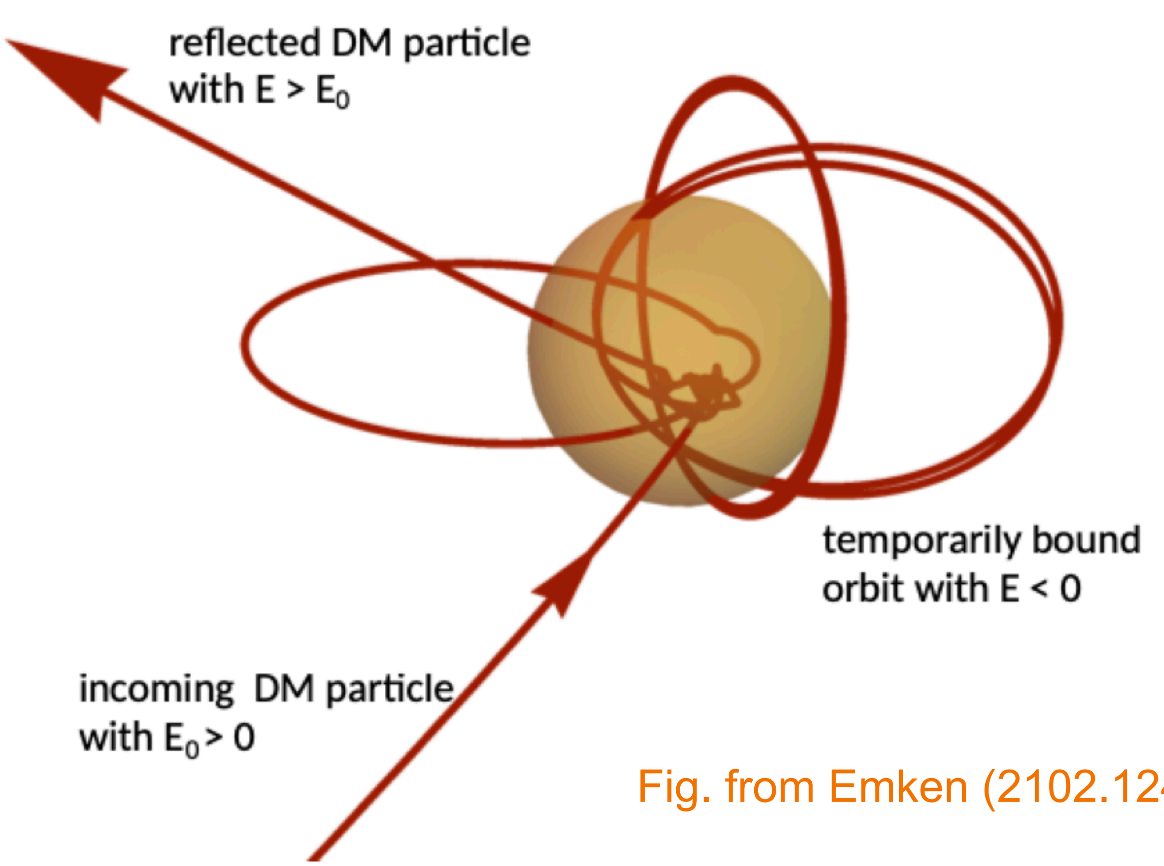


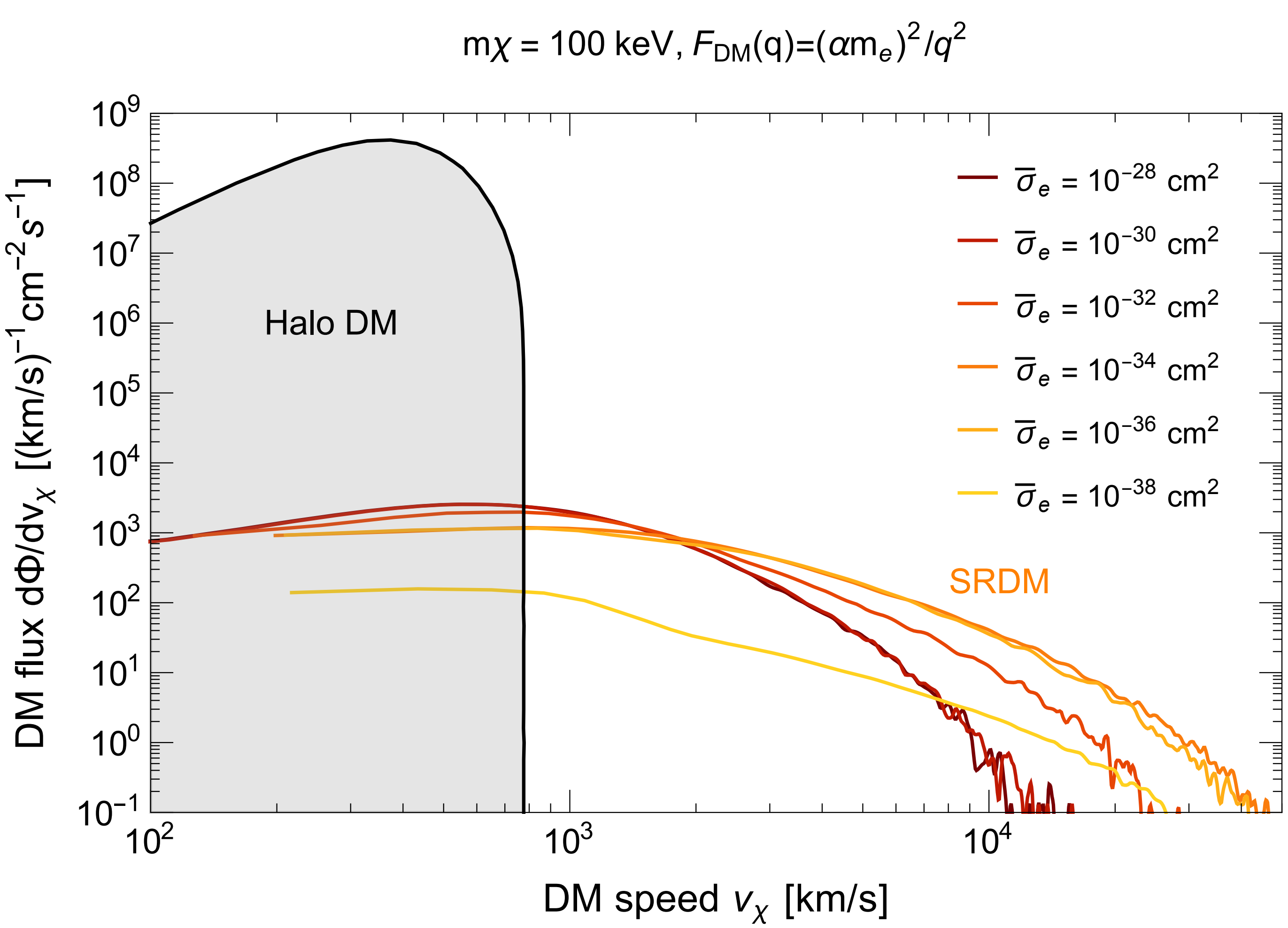
Fig. from Emken (2102.12483)

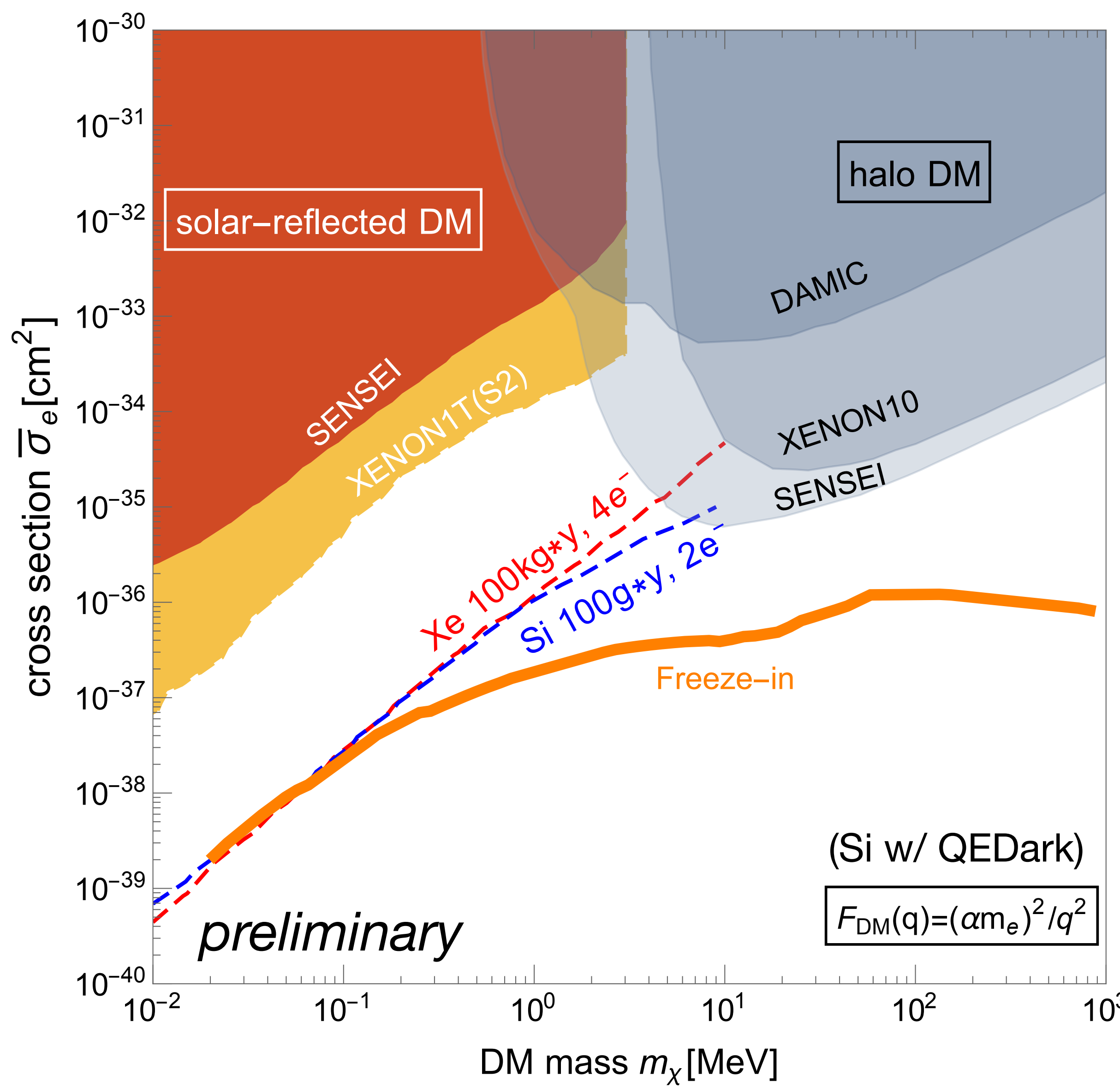
Solar reflected Dark Matter w/ Light Mediators

Emken, RE, Hailin Xu (to appear)

see also An, Nie, Pospelov, Pradler (2021)

updated bounds/projections (w/ in-medium effects + new simulations) show excellent reach for e.g. Si/Xe detectors for sub-MeV DM!





Summary

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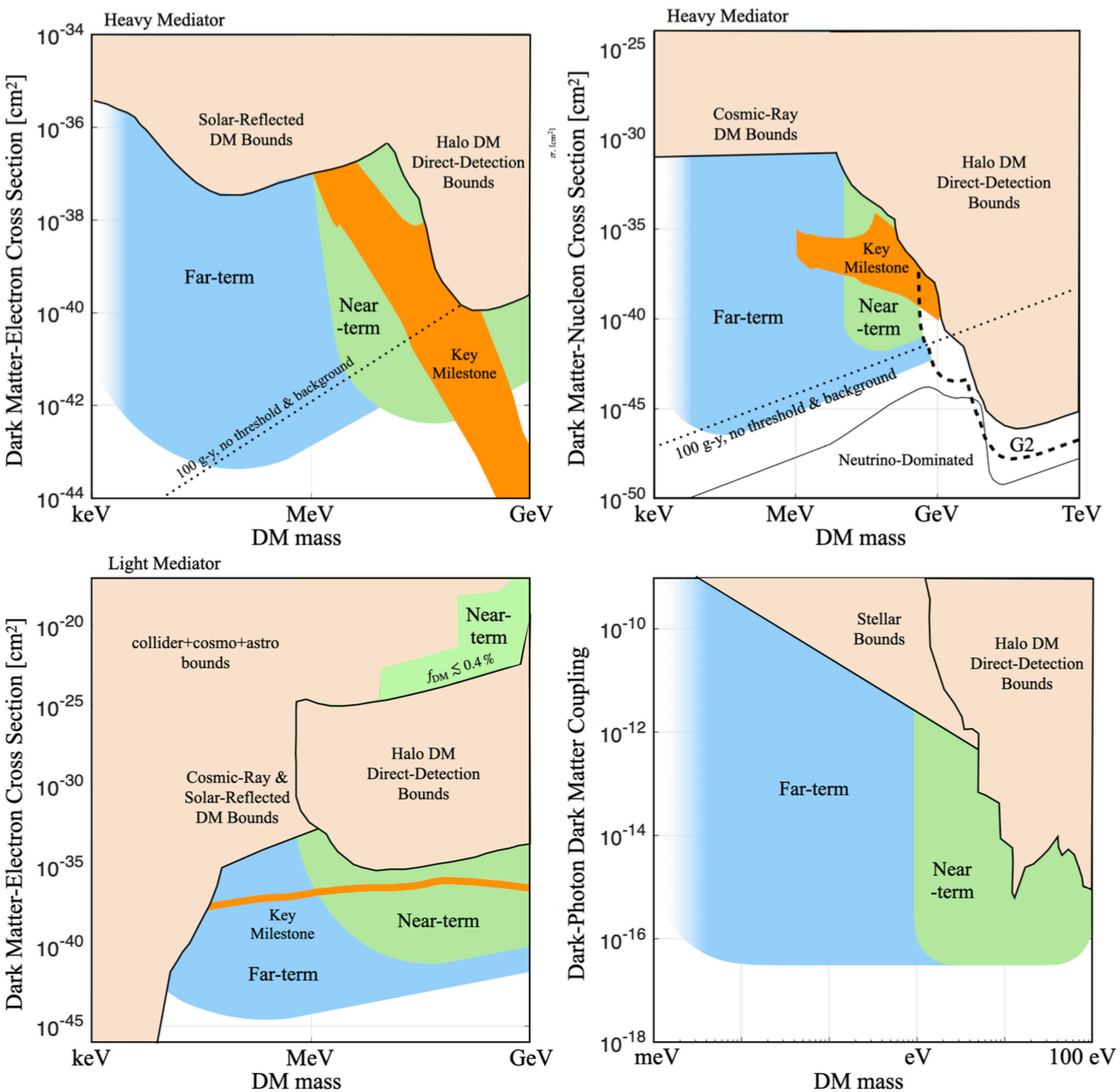
a lot of progress, but many fun challenges remain…

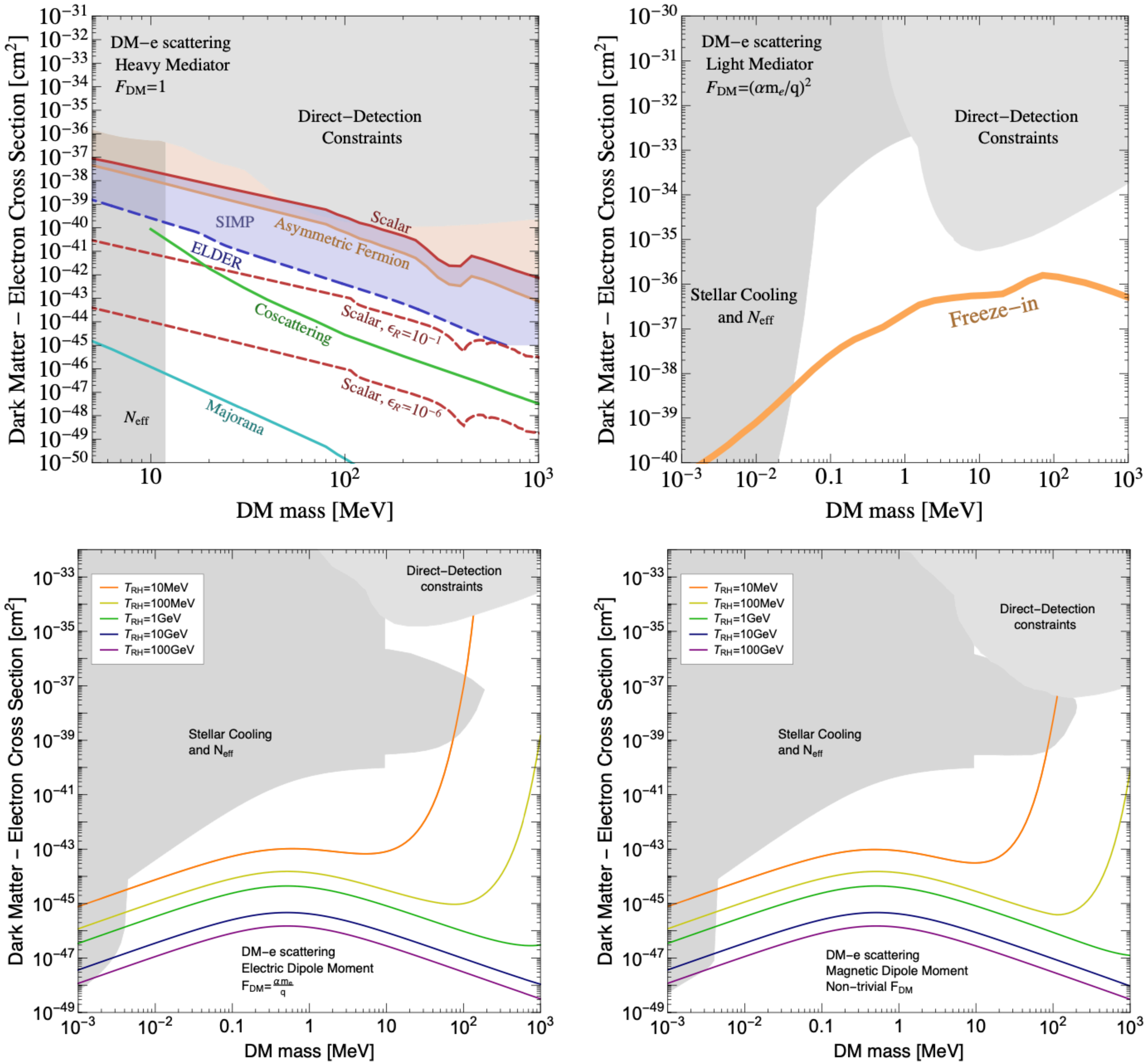
If we overcome challenges, can probe orders of magnitude of DM parameter space!



see Snowmass review:
RE, Giovanetti, Kurinsky, McKinsey, Ramanathan, Stifter, Yu (2203.08297)

Backup

Some specific benchmark targets

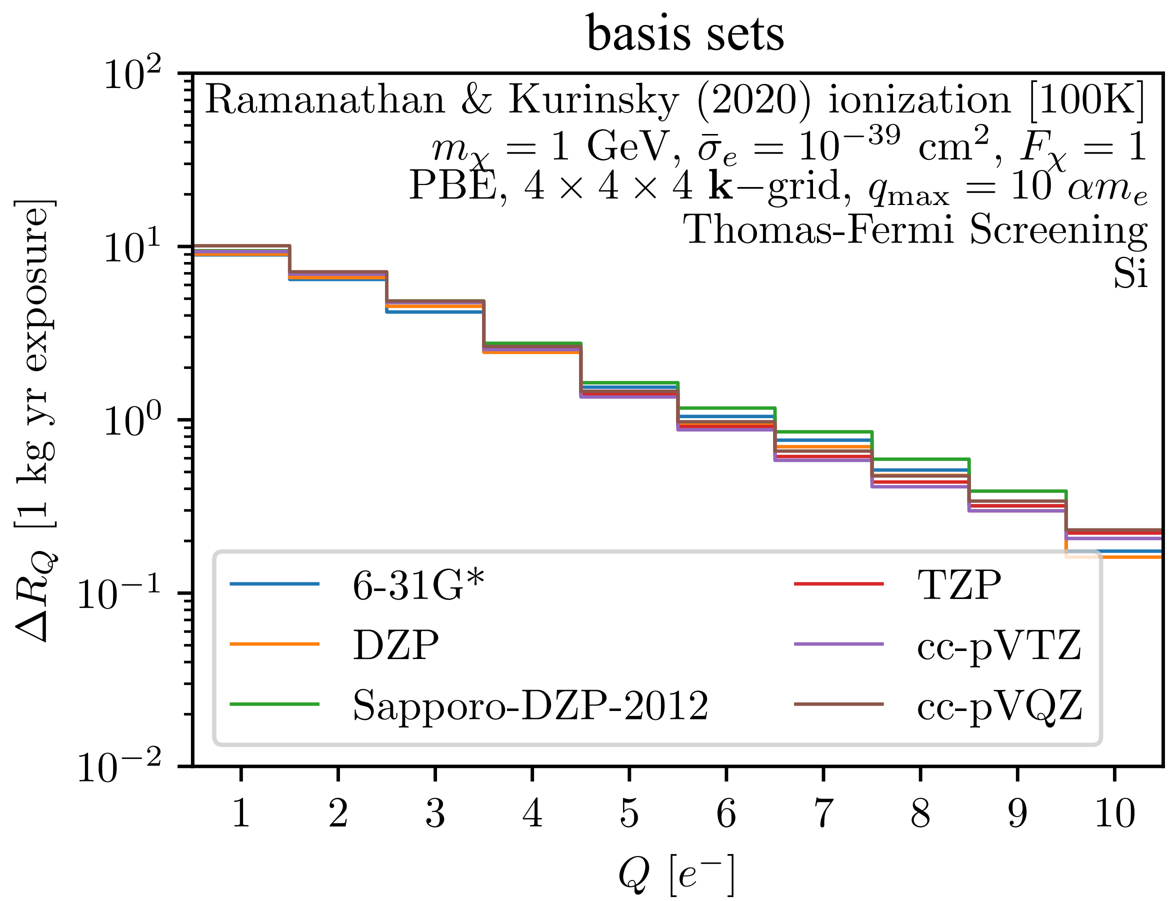


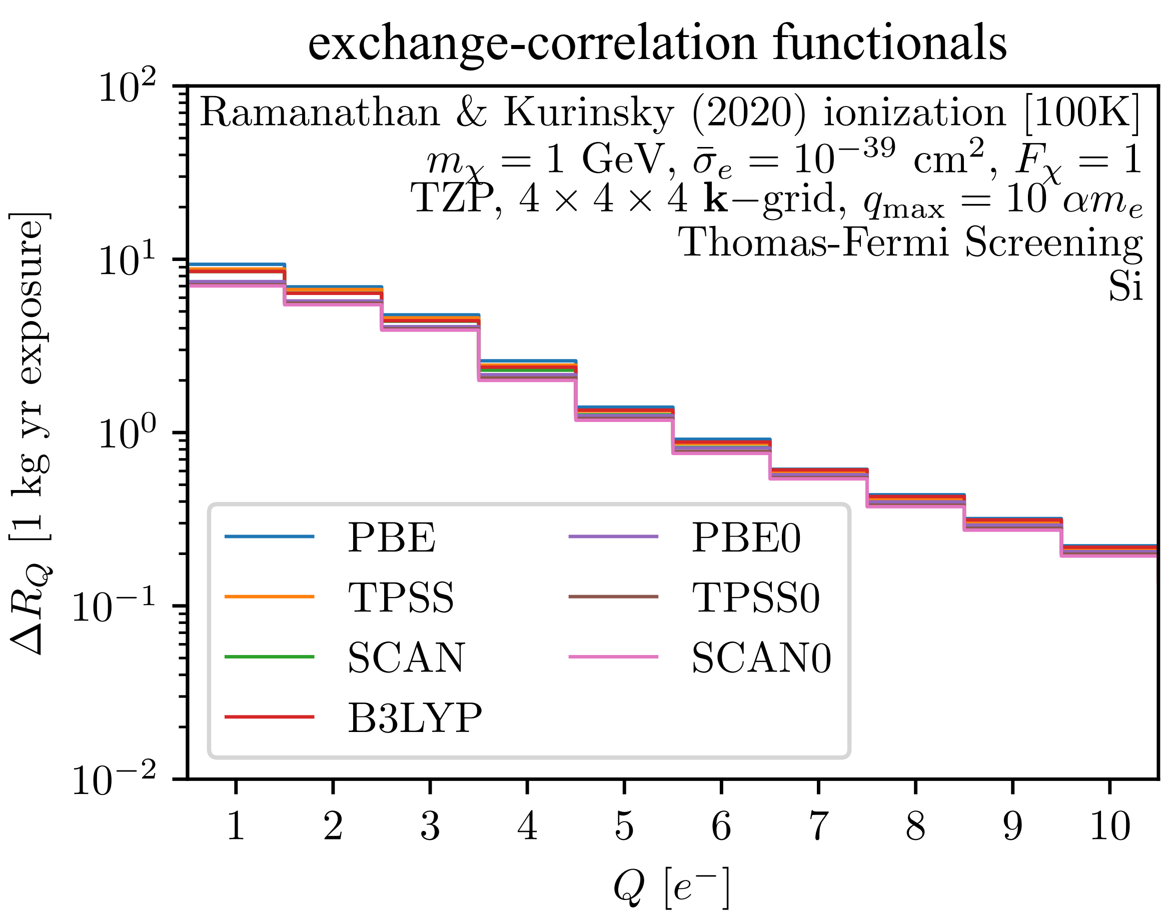
For references, see Snowmass review: RE, Giovanetti, Kurinsky, McKinsey, Ramanathan, Stifter, Yu (2203.08297)

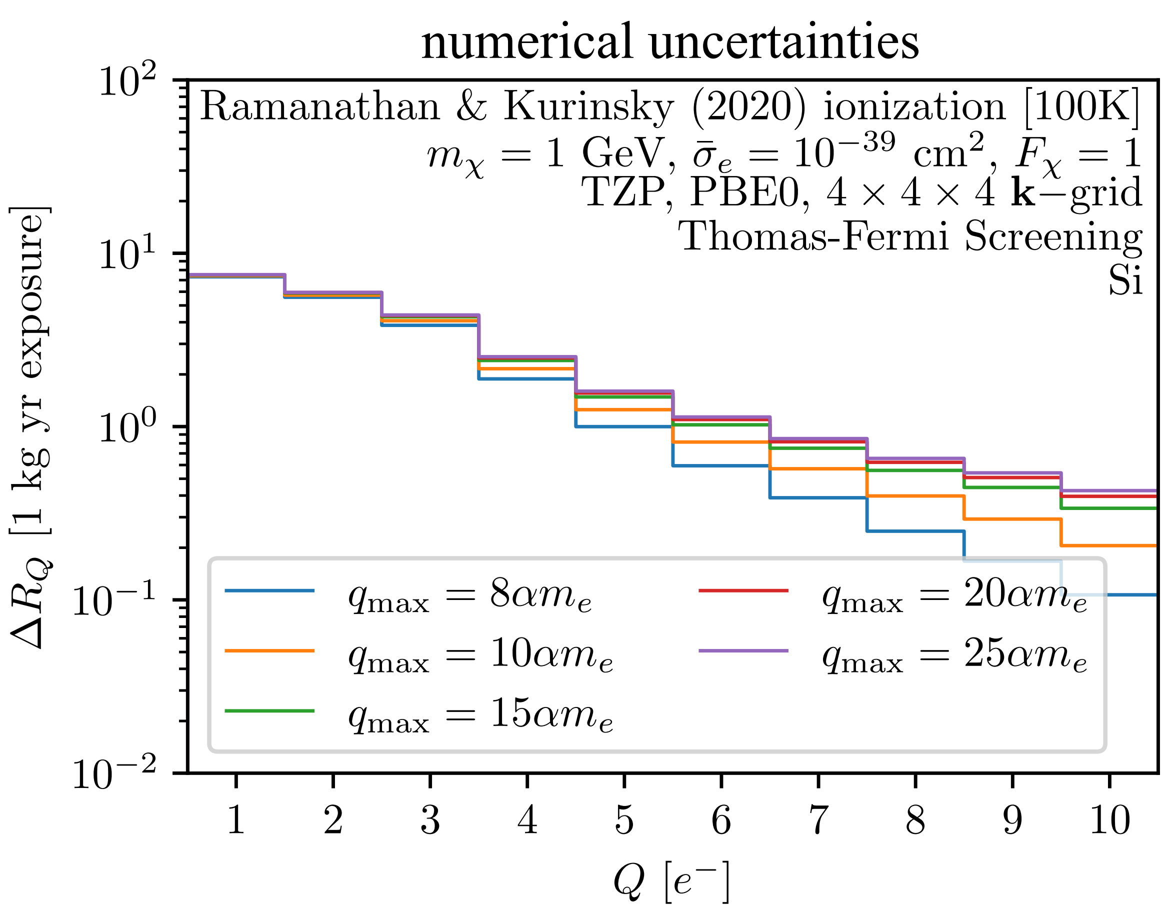
Detailed Evaluation of Systematic Uncertainties

theory uncertainties are not zero,
but are under control

Figures from:
Dreyer, RE, Fernandez-Serra, Singal, Zhen
(to appear)







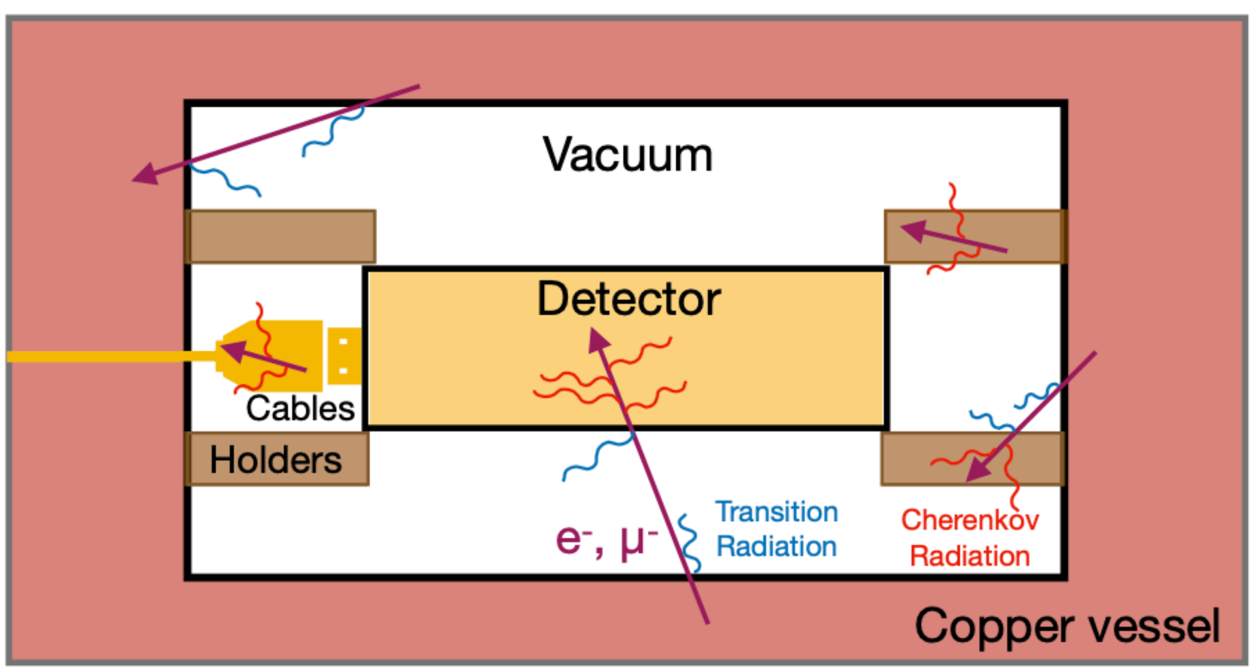
Sources of low-energy events

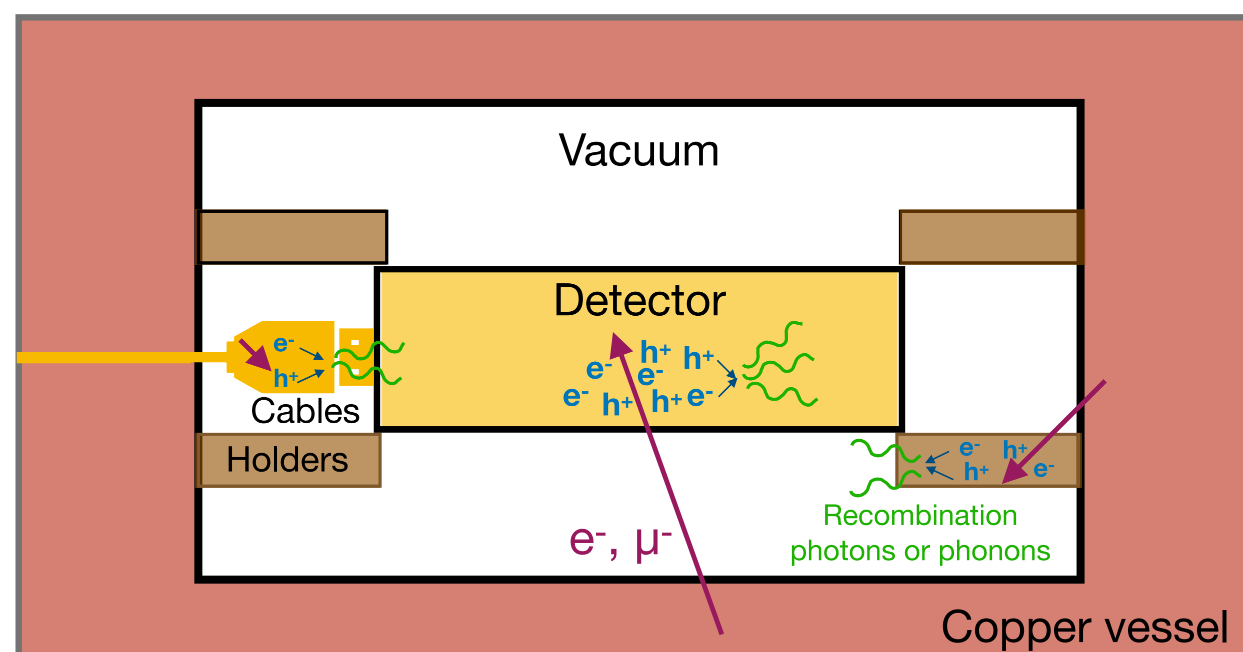
Peizhi Du, Daniel Egana-Ugrinovic, RE, Mukul Sholapurkar, 2011.13939

Radioactivity & cosmic-ray muons can produce *many* O(eV) photons, by e.g.

- Cherenkov radiation
- Radiative recombination
- Transition radiation*

Photons get absorbed in sensor to produce an electron





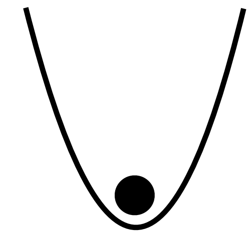
~100s of tracks/g-day at SENSEI, ~10 thousand /g-day at SuperCDMS HVeV

*see also Robinson, 2010.11043

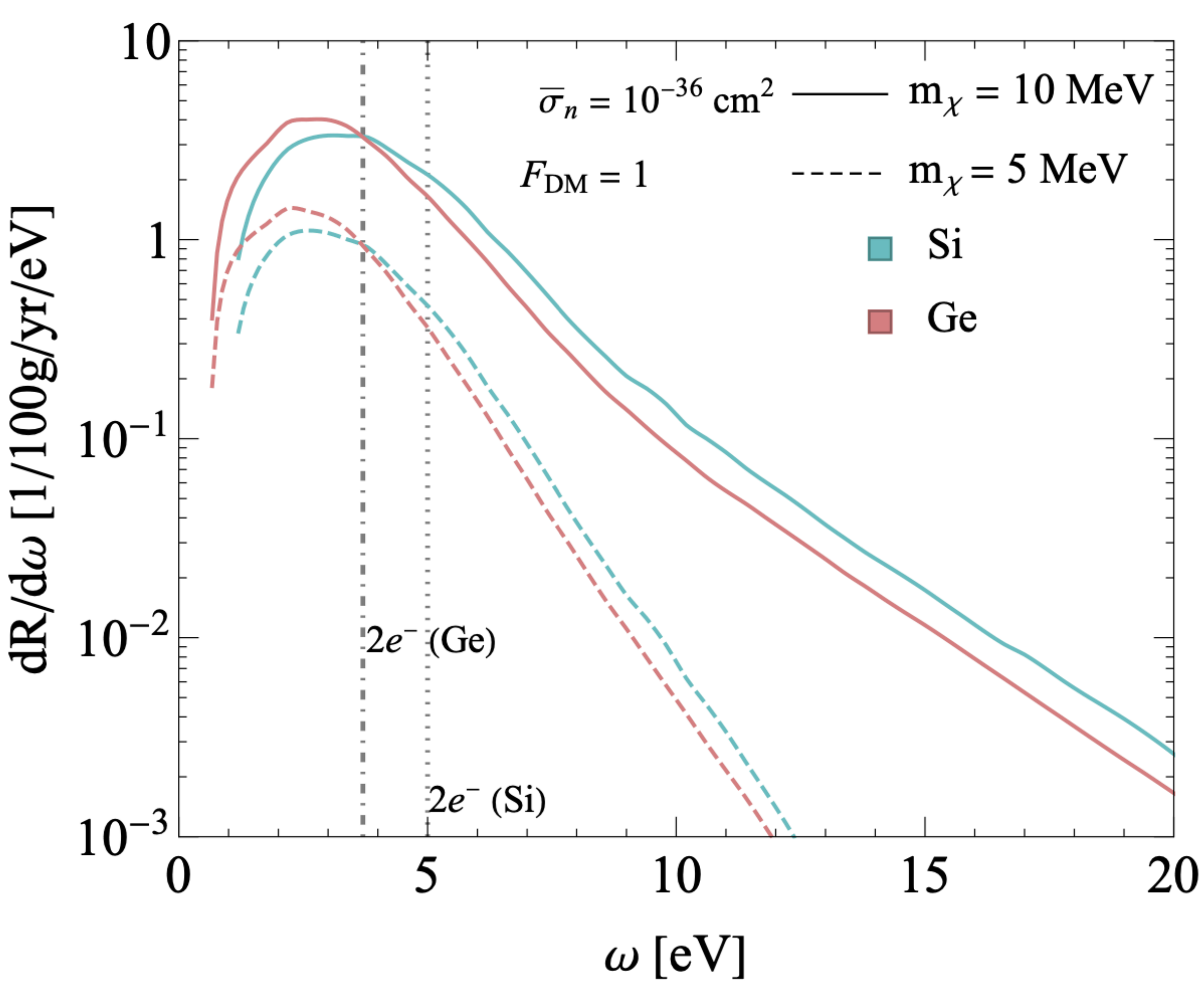
Improved Calculation of Migdal Rates

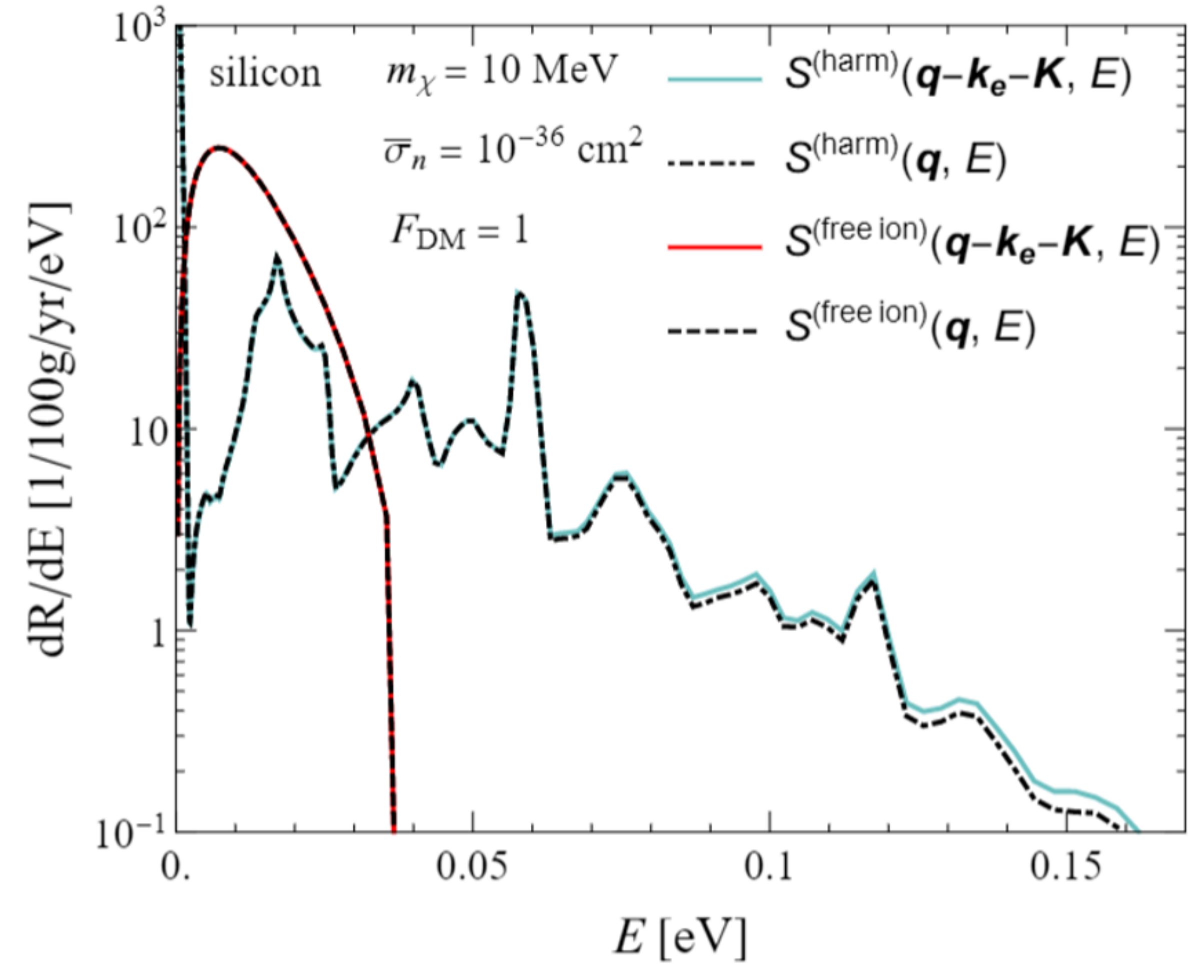
Example: semiconductors

- response of nucleus differs from free nucleus
- use an EFT to reliably calculate Migdal for DM masses $< 100\ \mathrm{MeV}$



Figures from Berghaus, Esposito, RE, Sholapurkar (2210.06490)





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