Overview of Light Dark Matter Direct Detection

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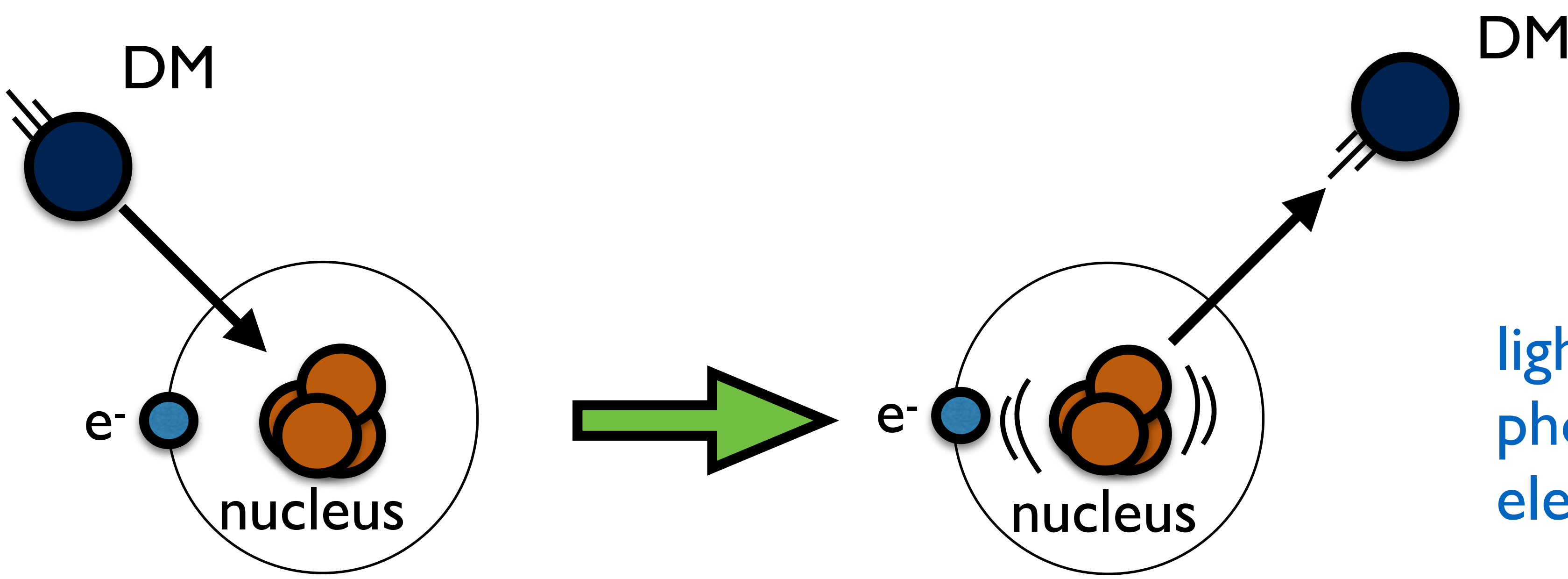
Light Dark Matter @ Accelerators (LDMA), Venice, Nov 20, 2019

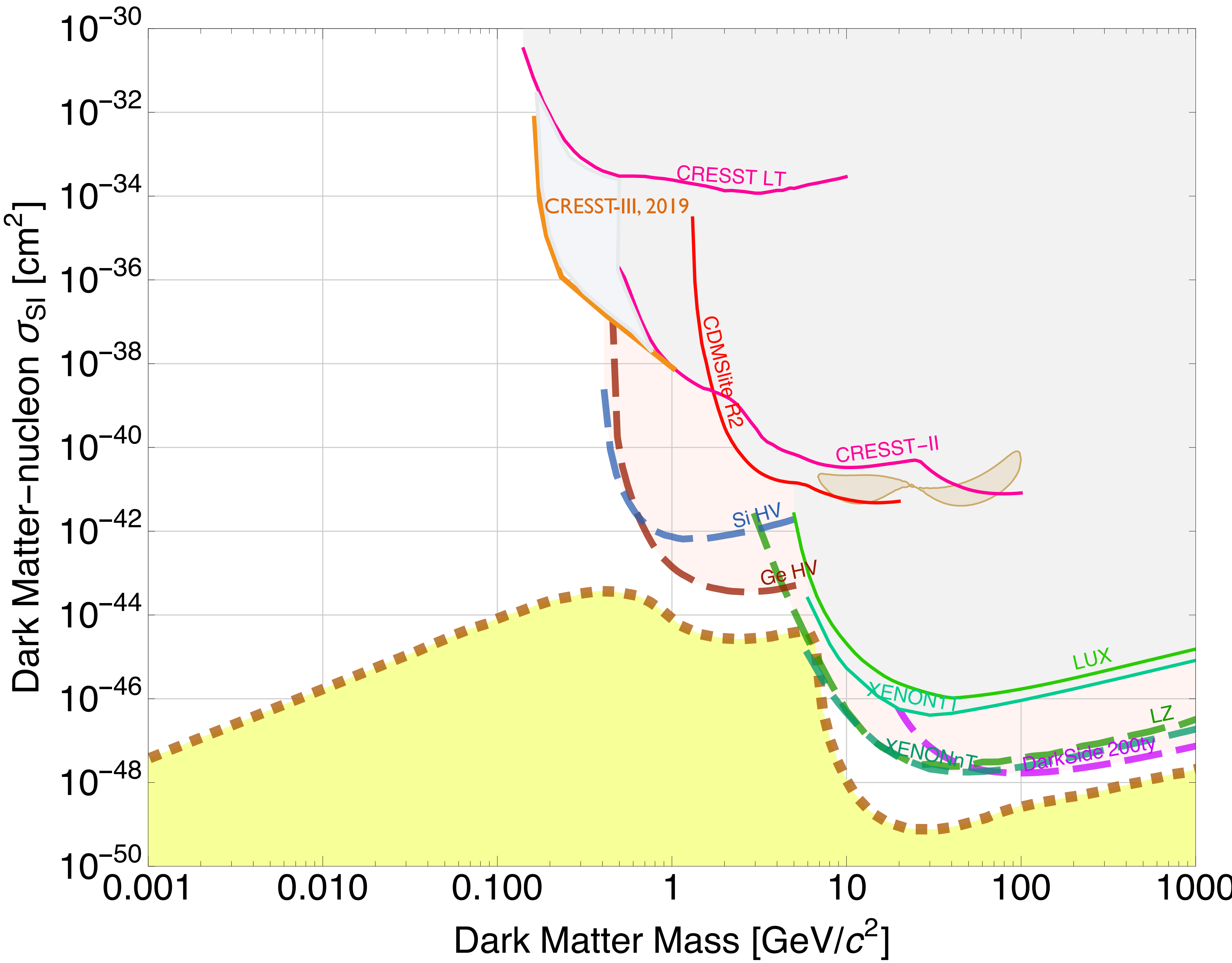
Traditional Direct Detection strategy:

look for nuclear recoils from
elastic WIMP-nucleus scattering



light
phonons
electric charge

Constraints & projections from elastic nuclear recoils



- dozens of experiments over last several decades
- WIMP searches well-established with multi-ton-scale experiments taking data soon

Limit plotter: Saab & Figueroa

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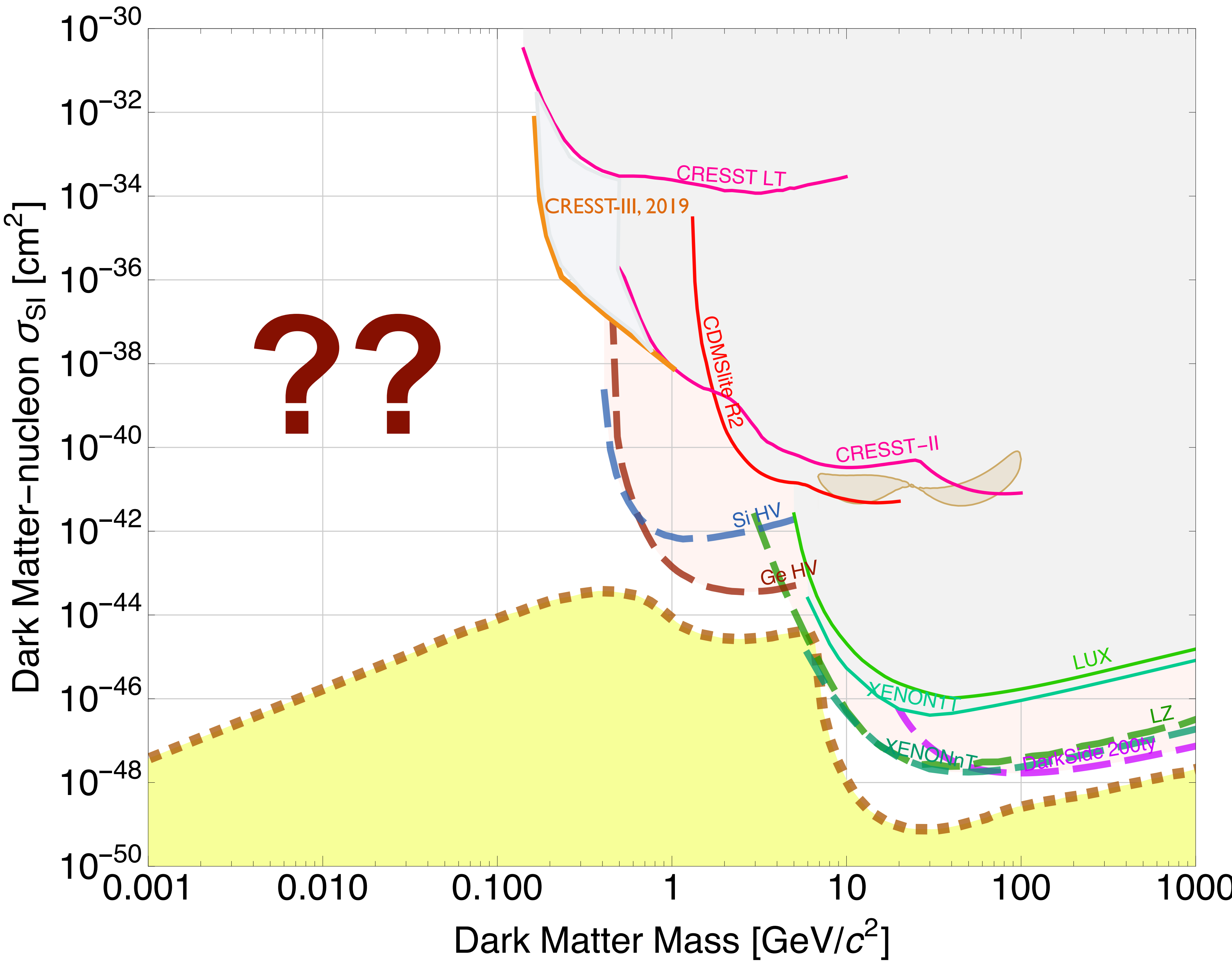

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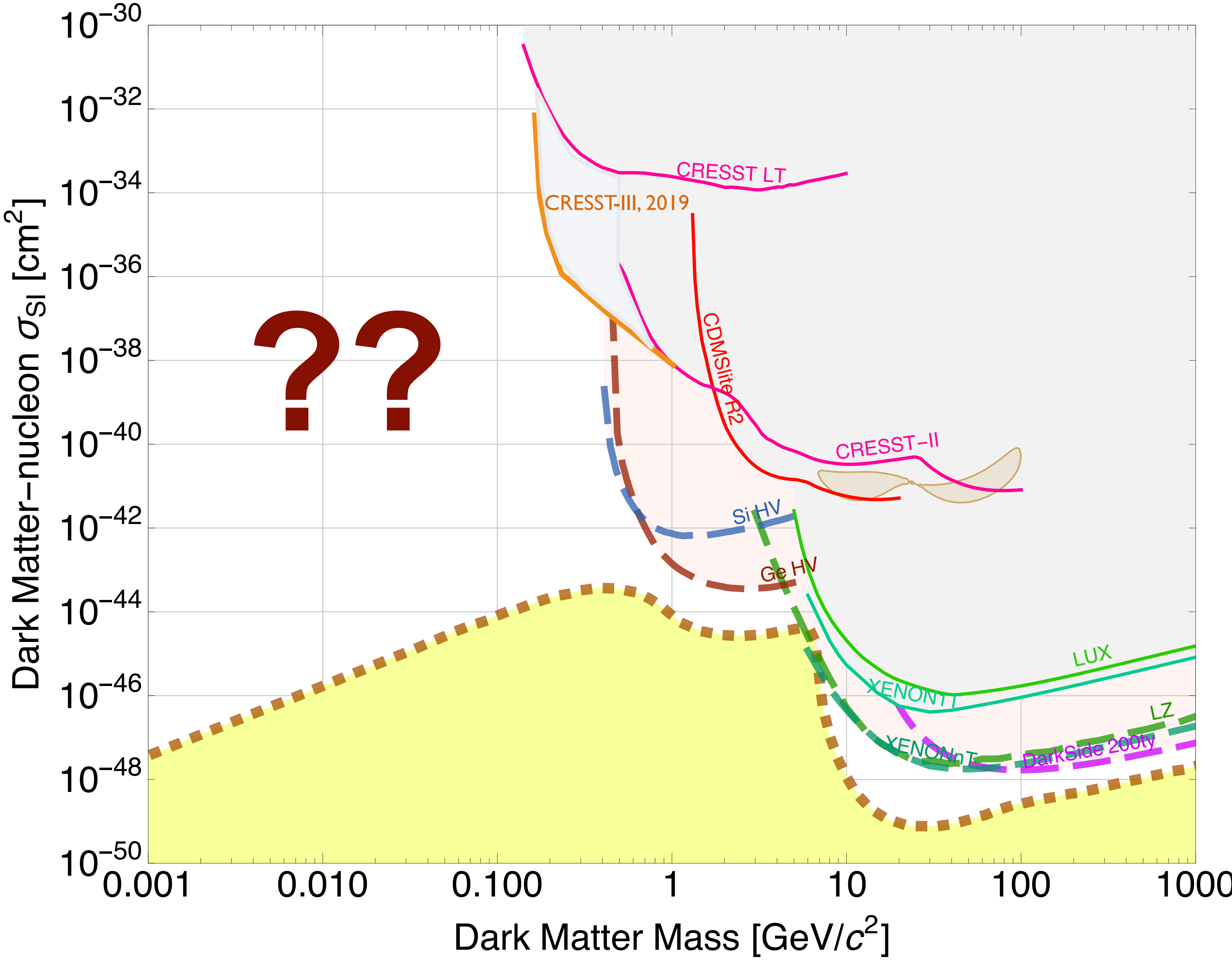

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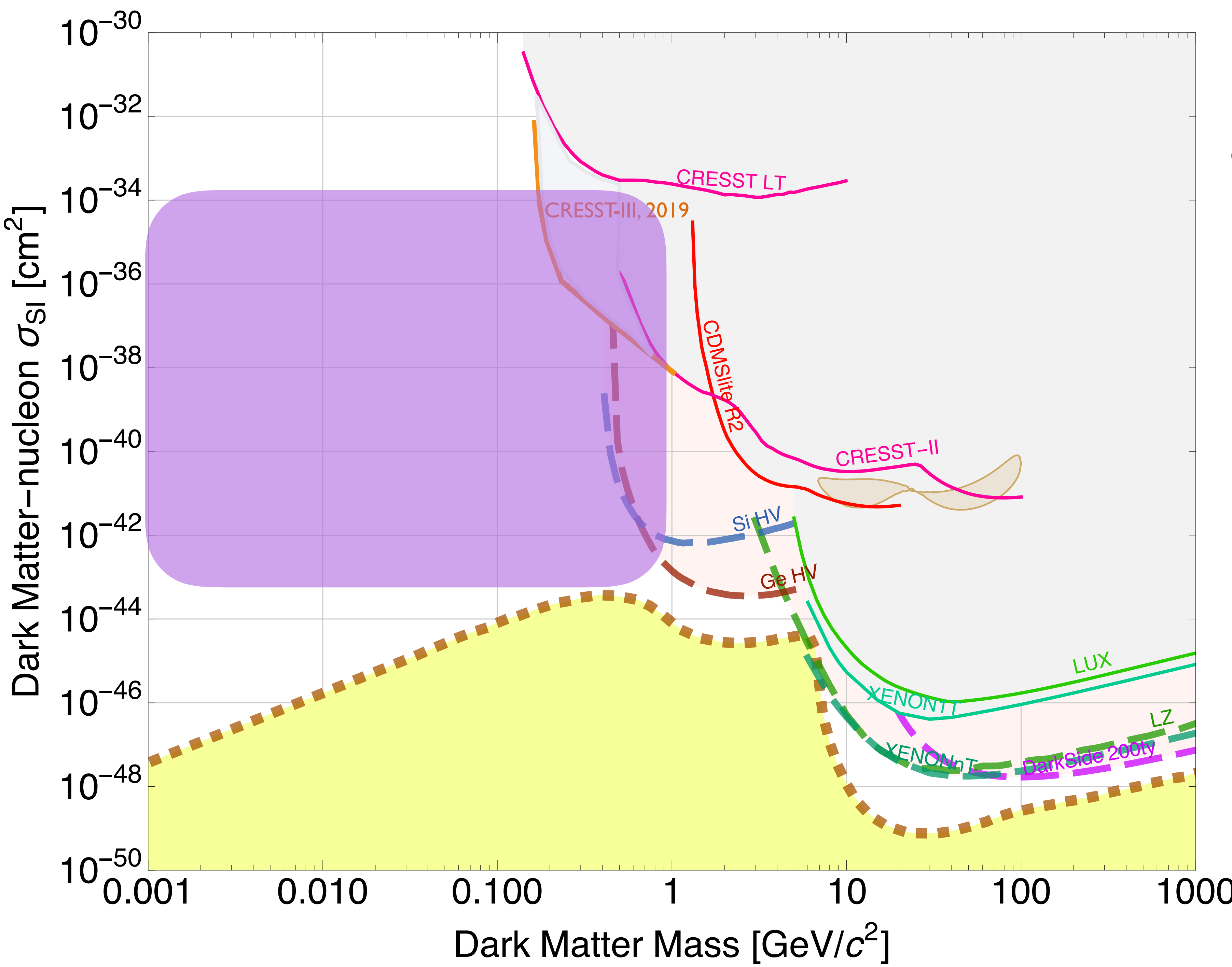
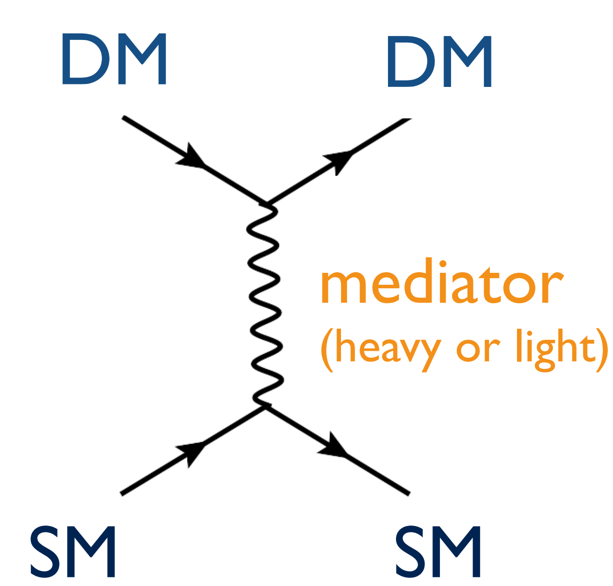
large regions of unexplored parameter space!

Limit plotter: Saab & Figueroa

Several Well-Motivated Hidden-sector DM Candidates



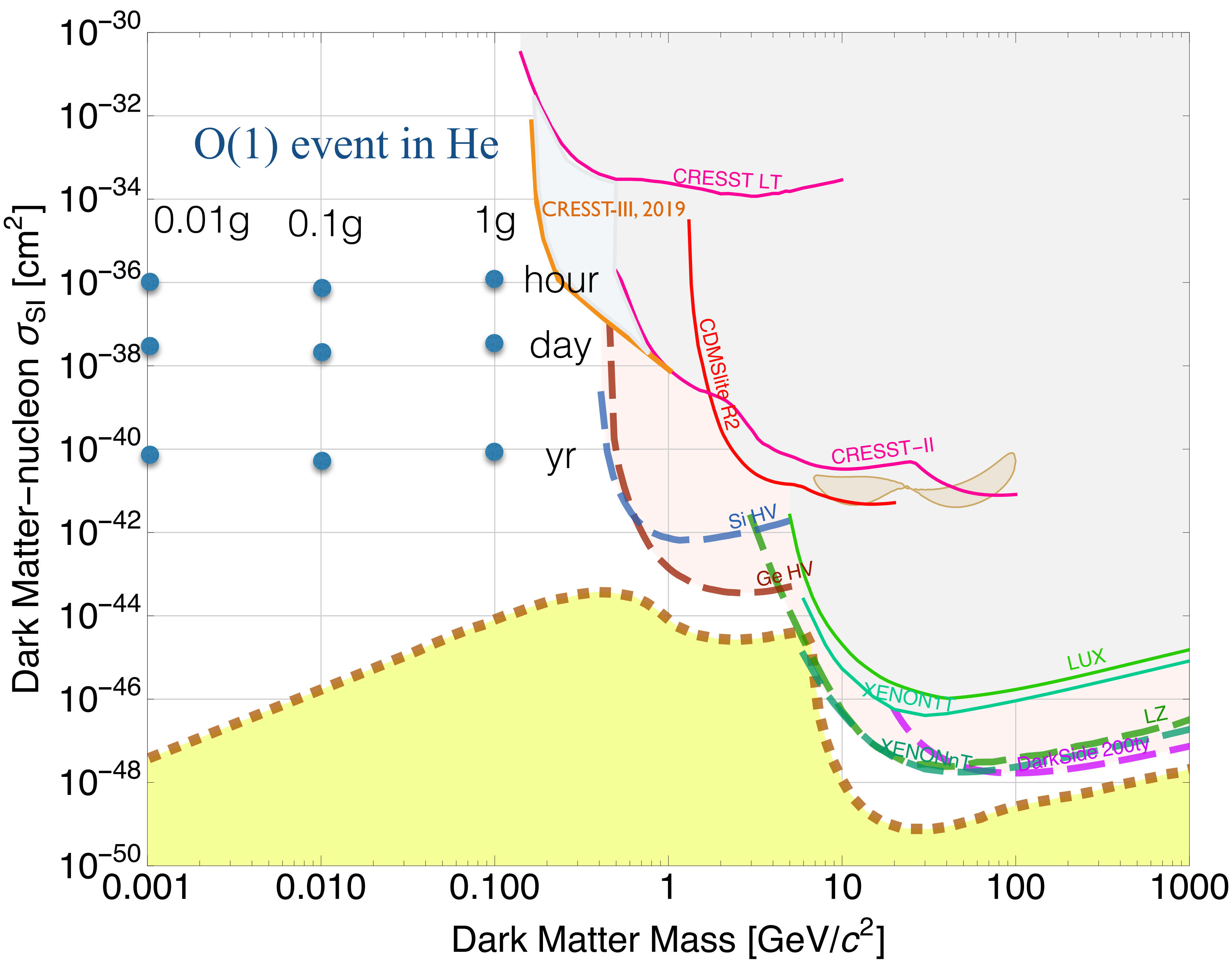
Can obtain relic abundance from freeze-out, an initial asymmetry, freeze-in, SIMP, ELDER, co-scattering…



need to probe nuclear and electron interactions

Limit plotter: Saab & Figueroa

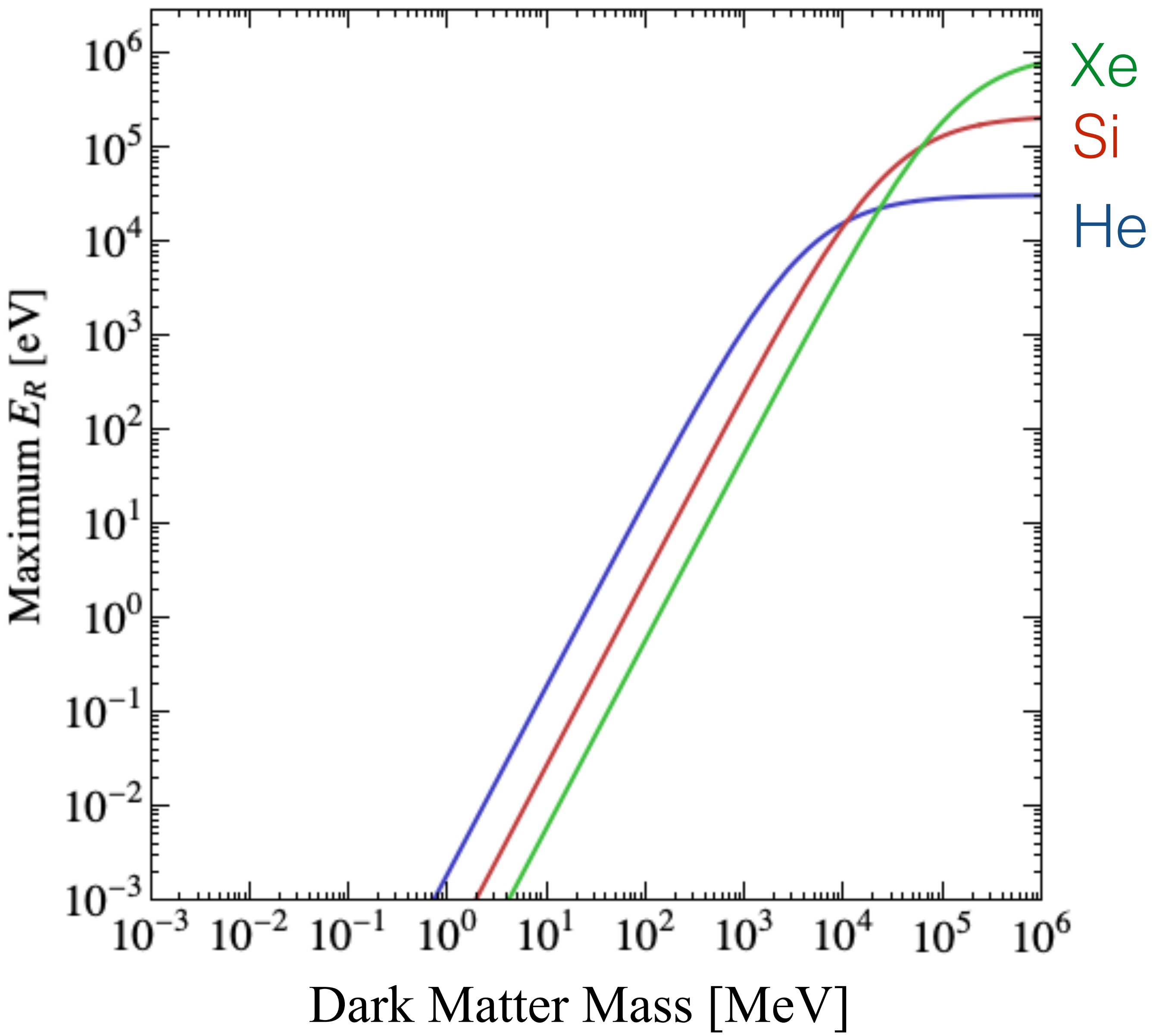
Why small experiments can (in principle) probe orders of magnitude of new sub-GeV DM parameter space



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

Limit plotter: Saab & Figueroa

Probing sub-GeV DM w/ elastic nuclear recoils



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

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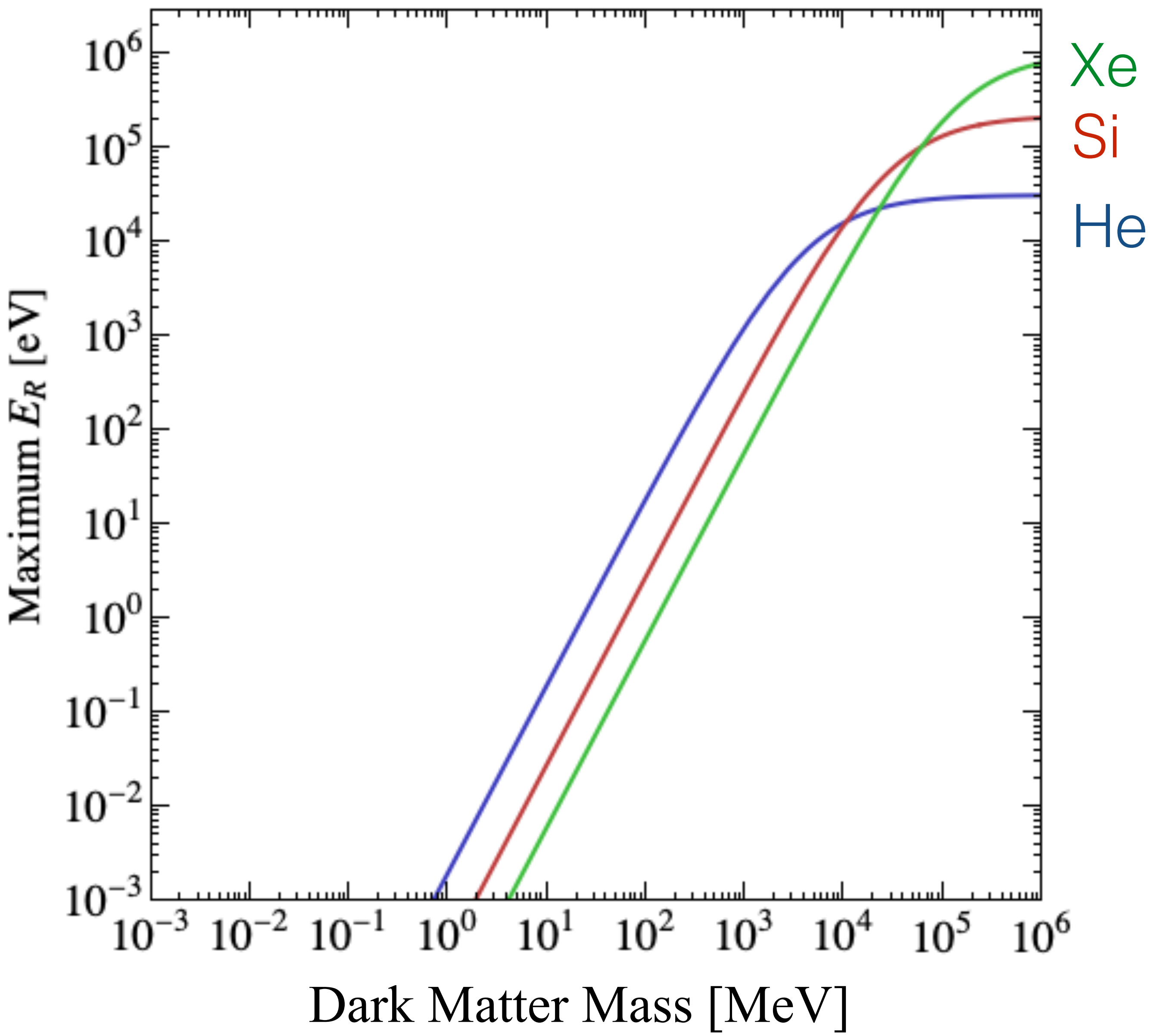

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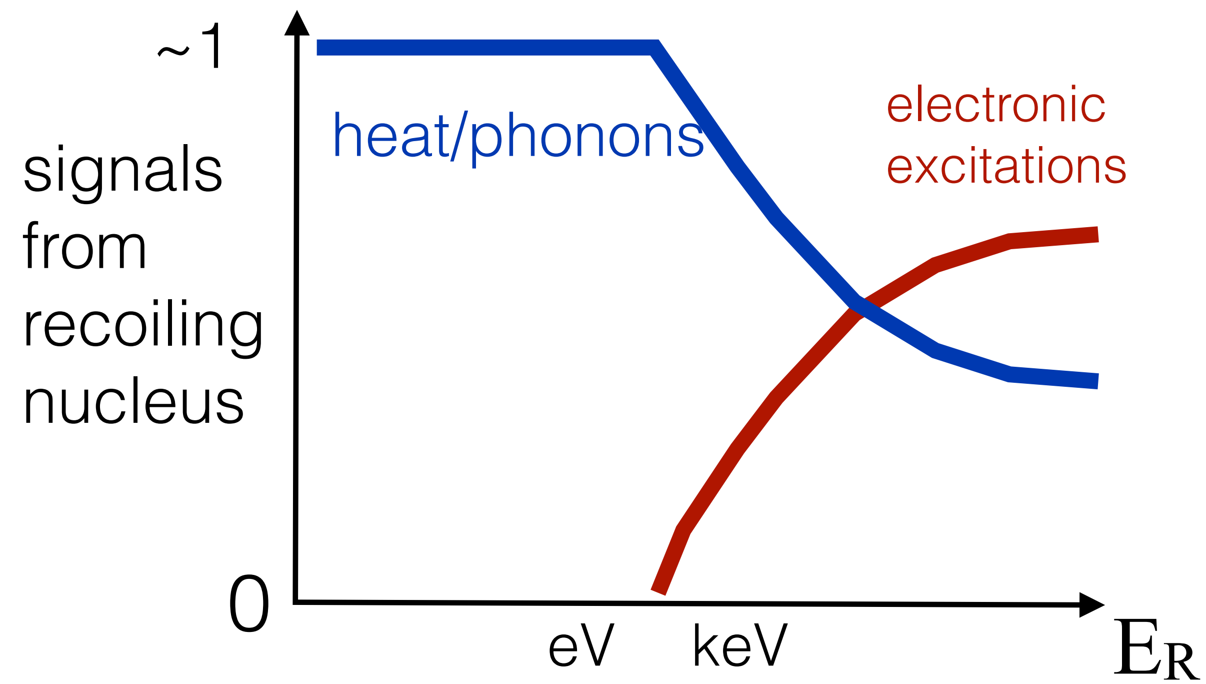

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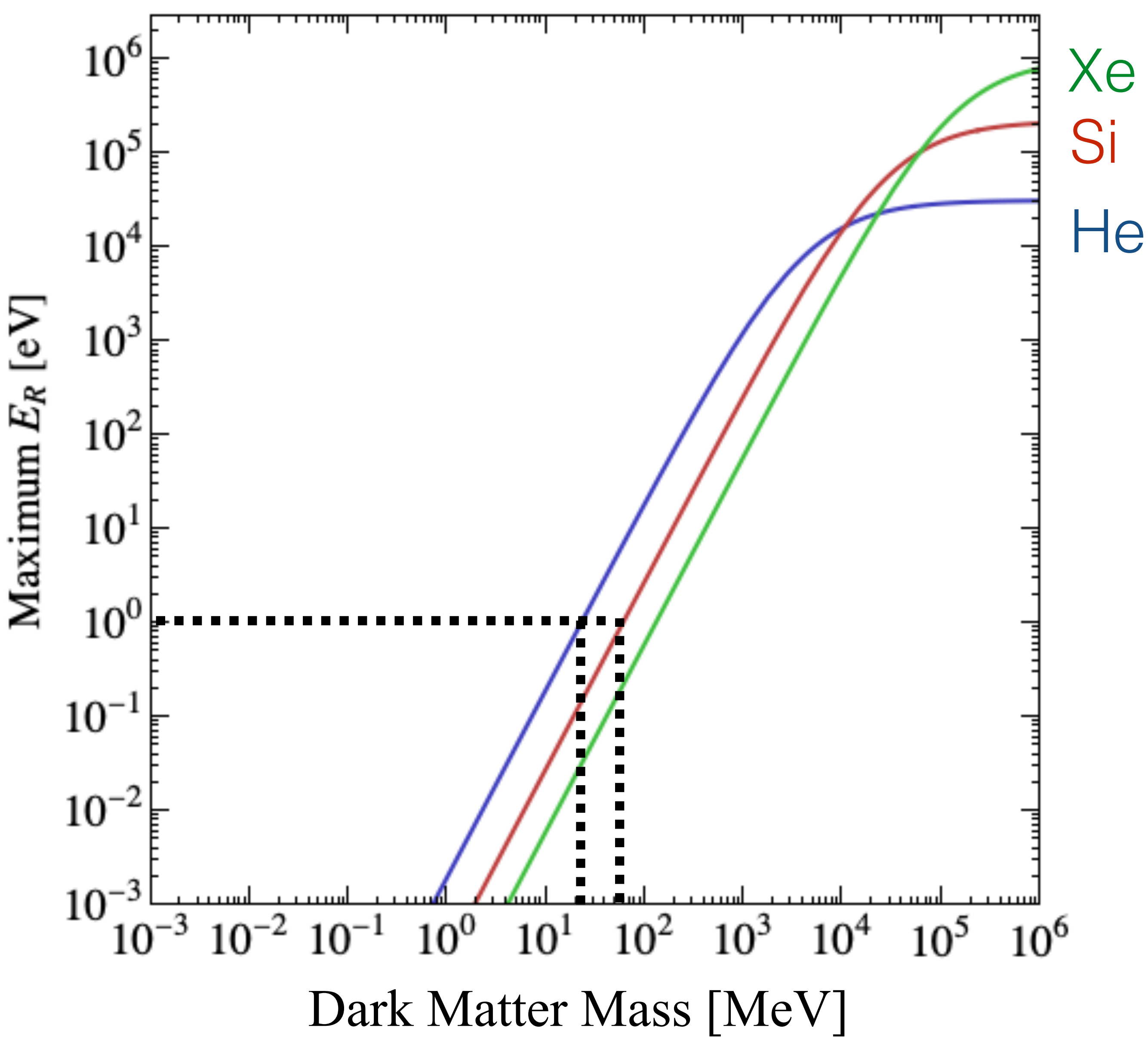

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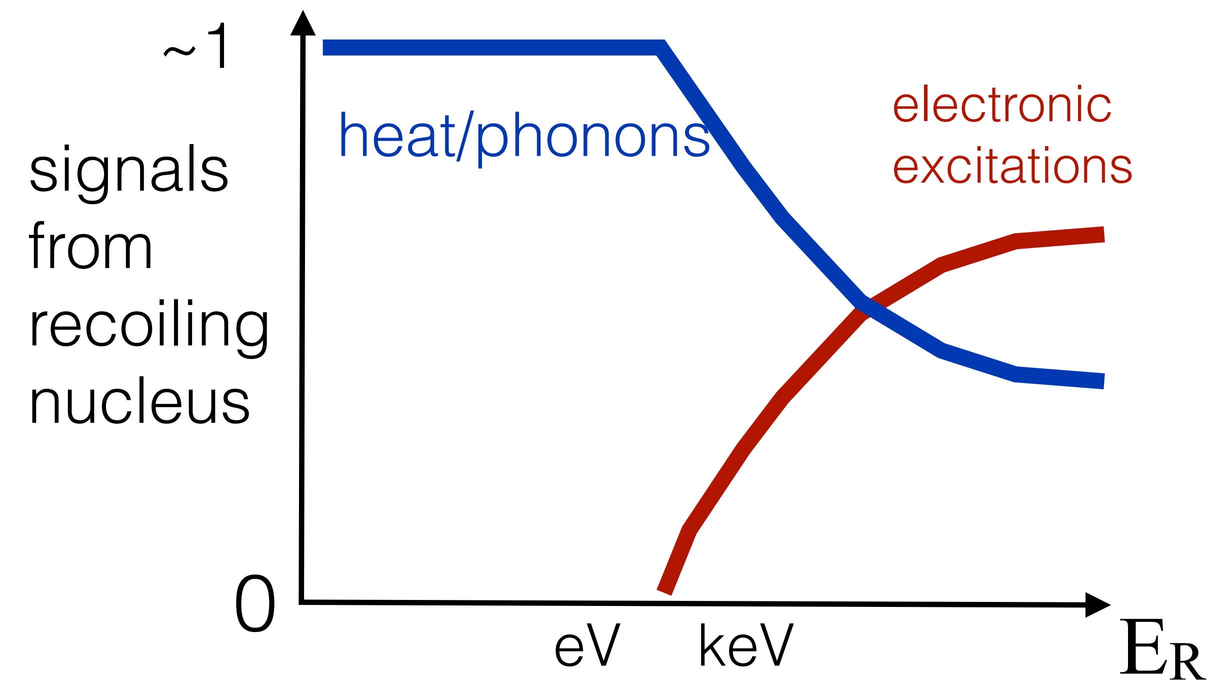
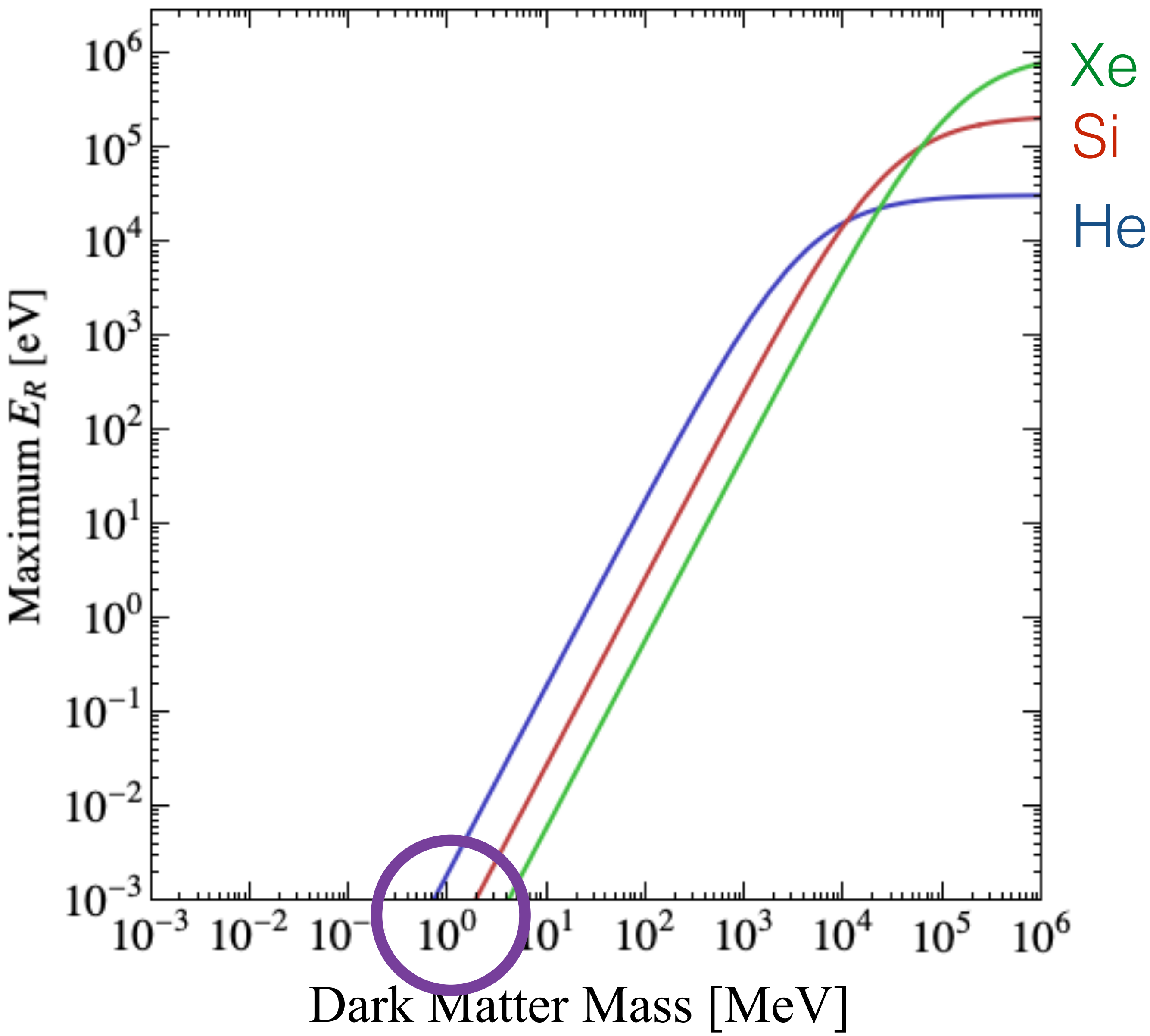


- will soon have phonon detectors w/ O(1 eV) sensitivity

$\Longrightarrow$ probe 20-50 MeV DM

e.g. M. Pyle et.al. (DoE BRN report)
Hertel, Biekert, Lin, Velan, McKinsey (Superfluid ^{4}He)

Probing sub-GeV DM w/ elastic nuclear recoils



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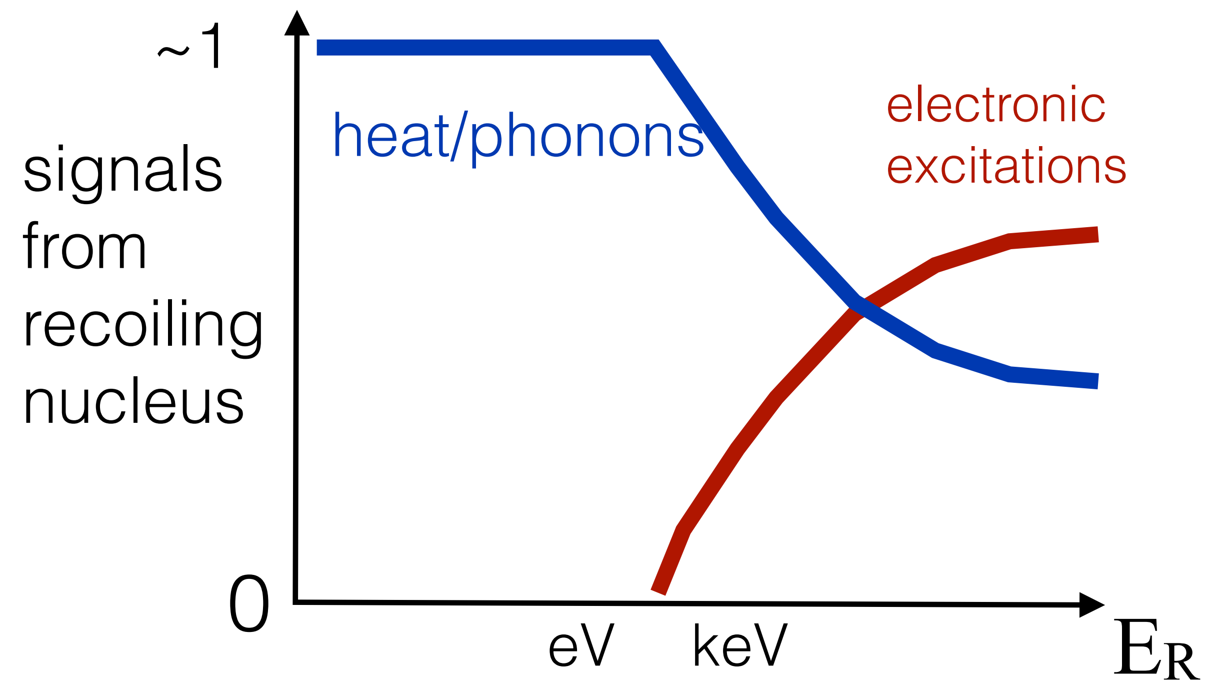

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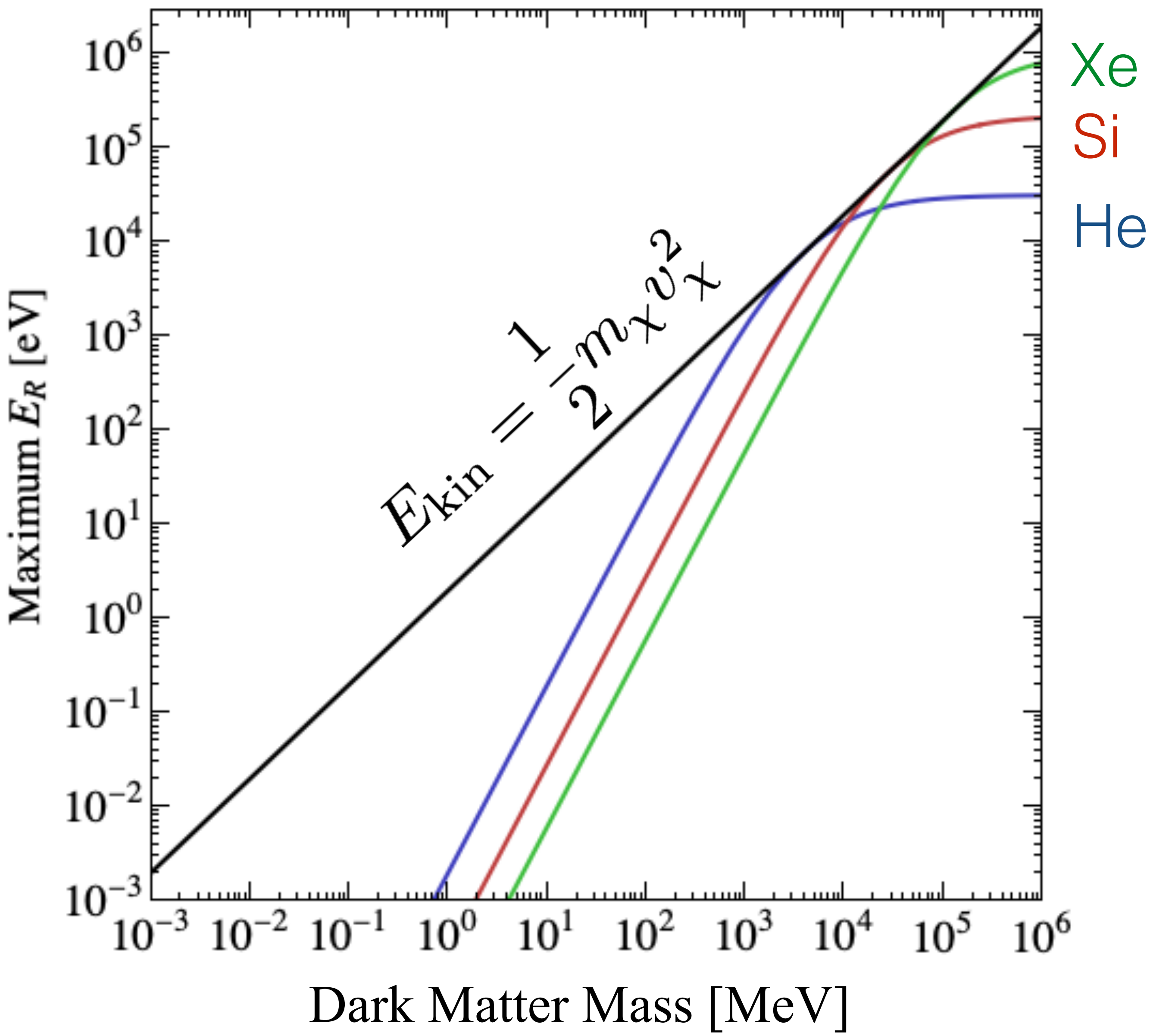

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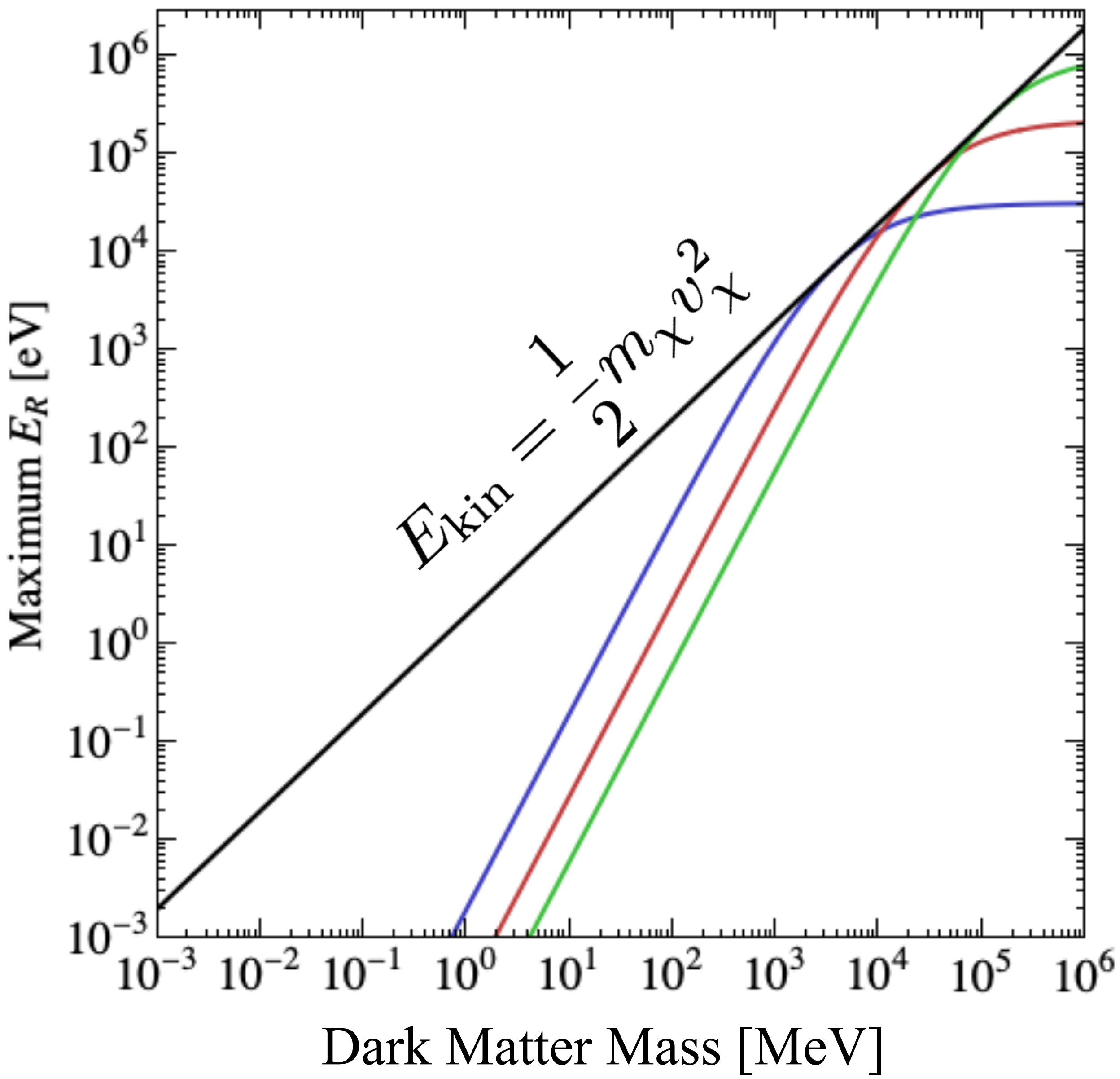
But note:

$$E_{\rm kin} \gg E_R$$

A promising approach to probe DM≪GeV: look for signals from "inelastic" processes



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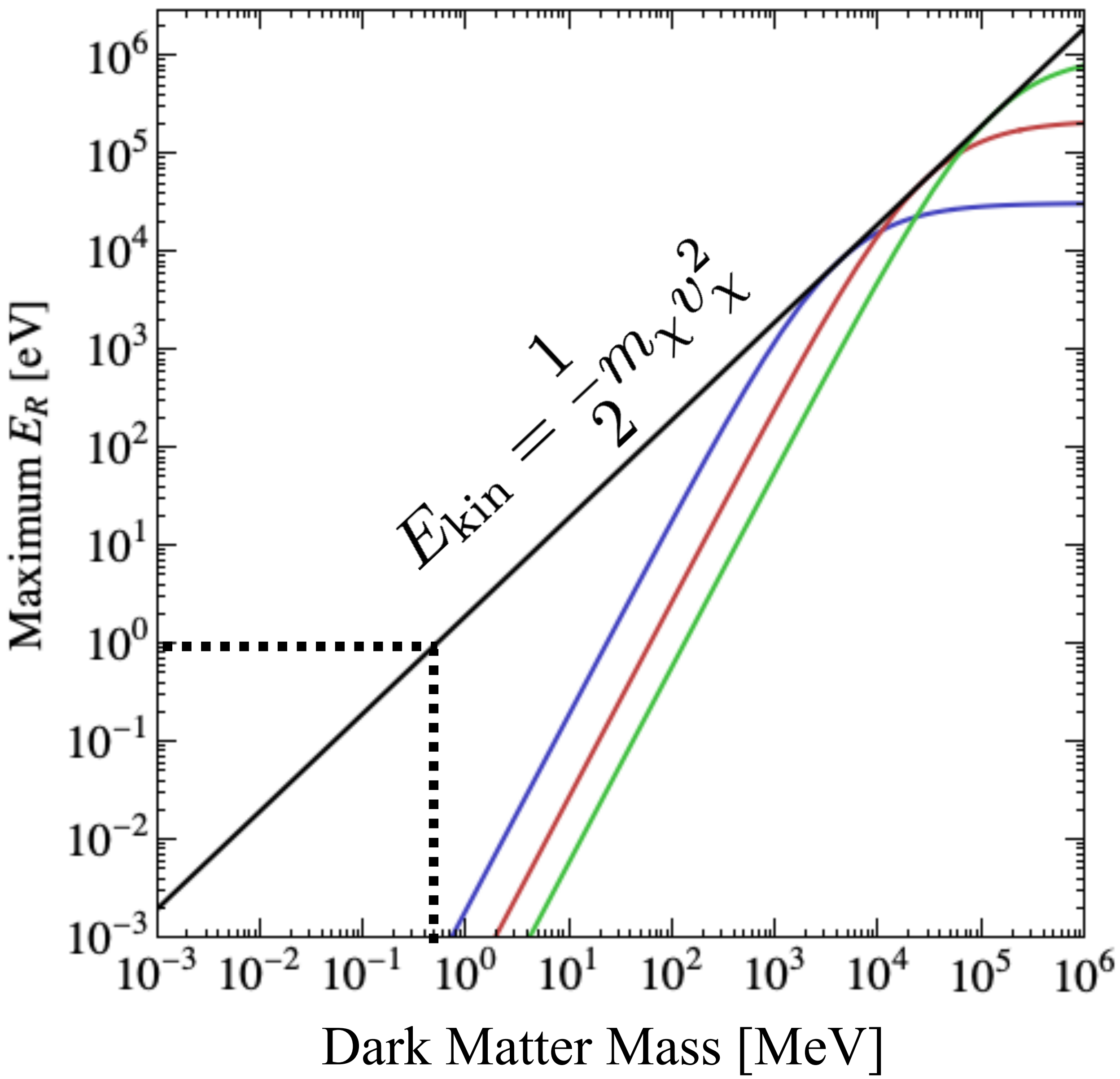

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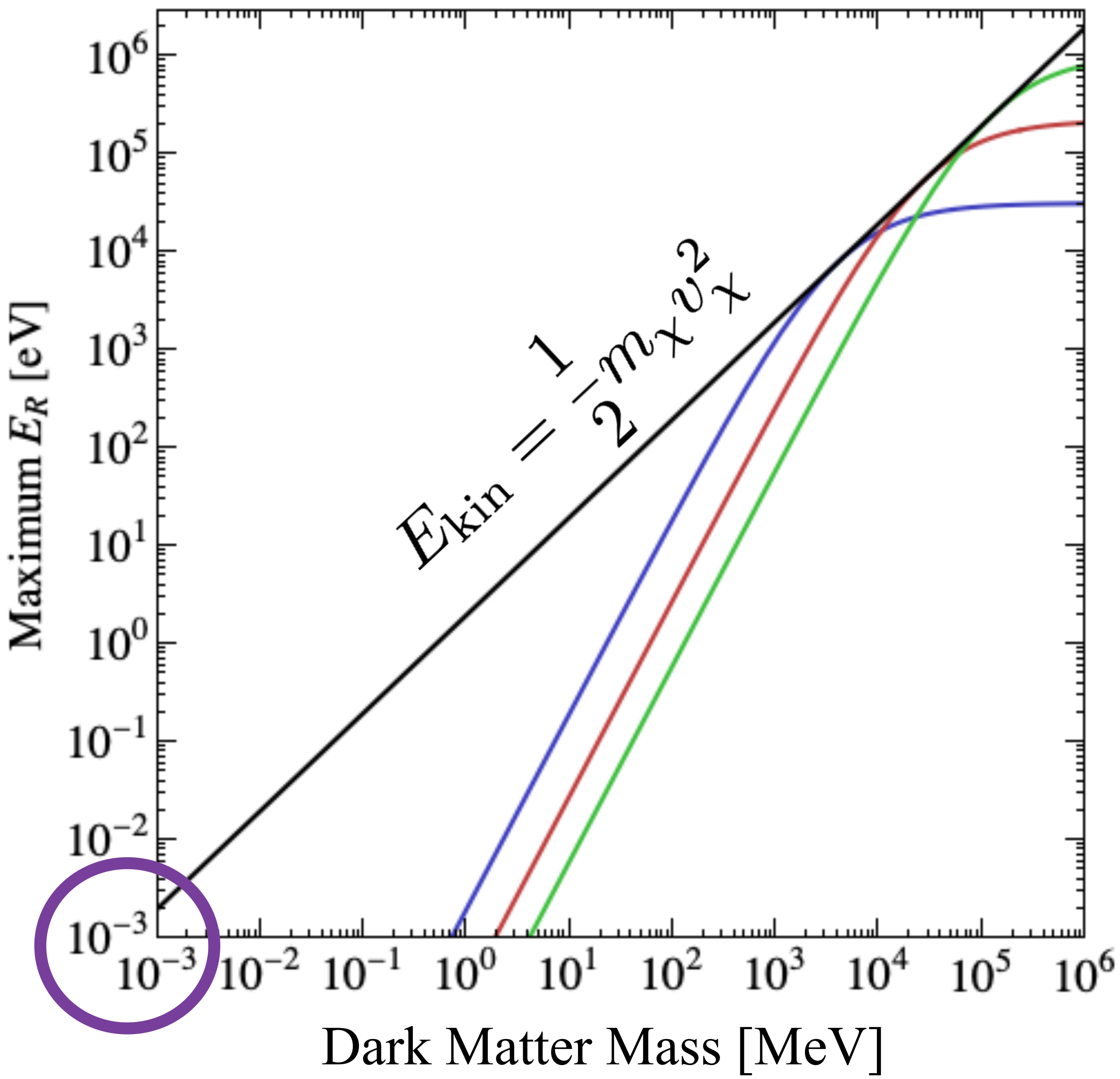

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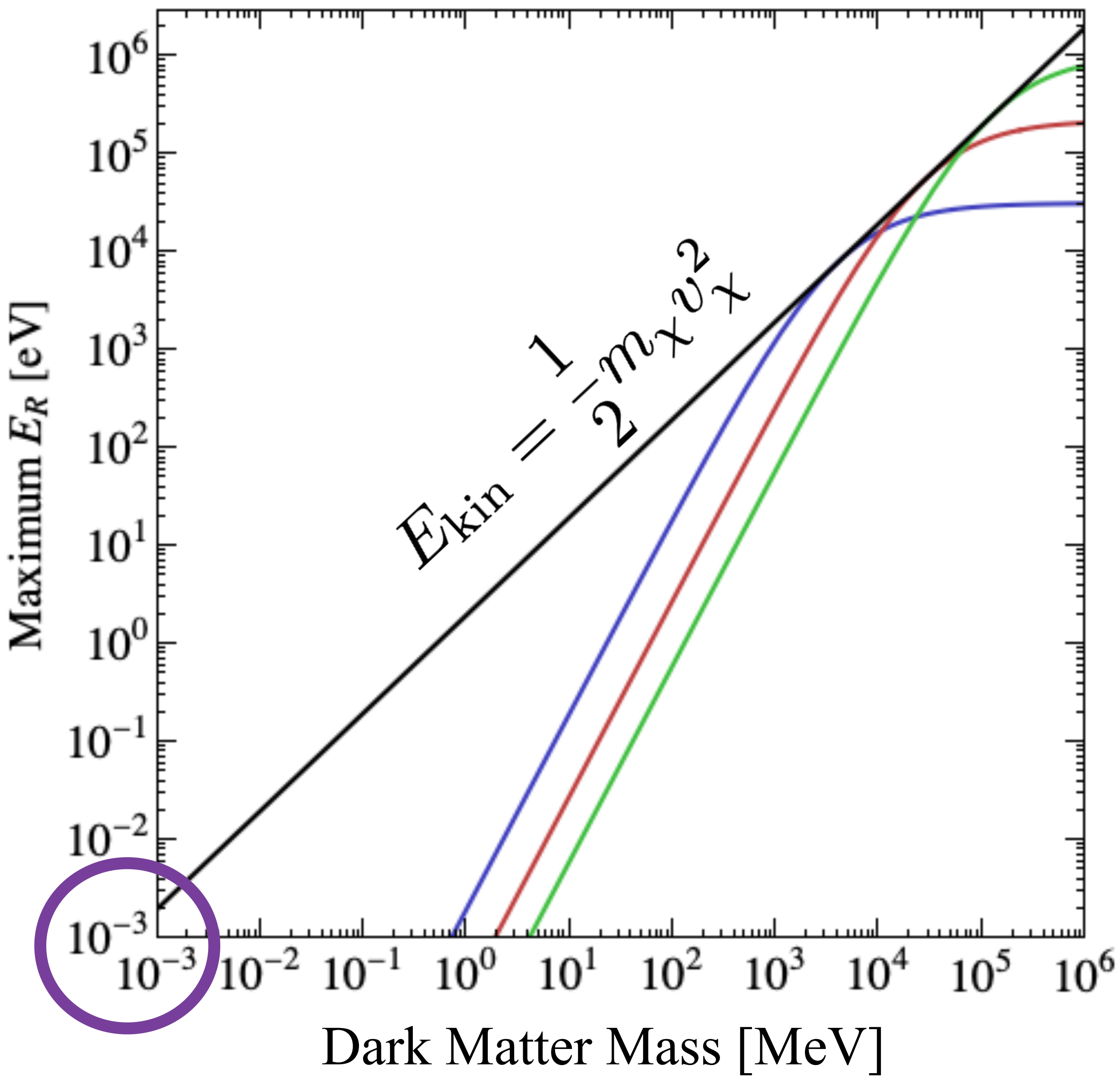

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Many theoretical detection concepts over past few years…
detector R&D and experiments are trying to catch up…

Some Inelastic Processes giving $E_{\mathrm{max}} \sim (1/2) m_\chi v_\chi^2$

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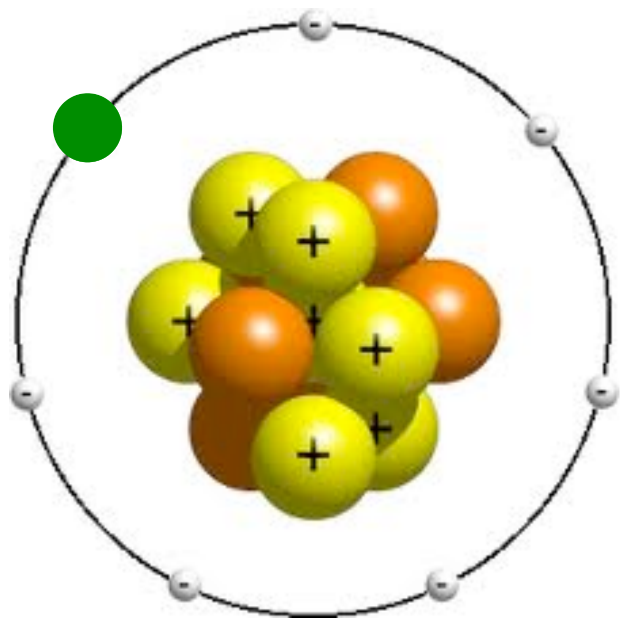
Electron excitation/ionization in e.g. noble-liquids or semiconductors (DM-electron scattering)

RE, Mardon, Volansky



noble liquids

$E_{binding} \sim 10$ eV

$m_{threshold} \sim 5$ MeV

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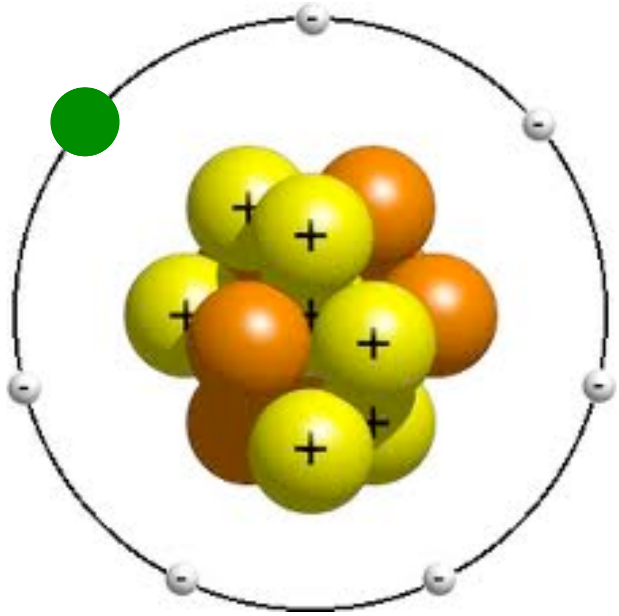

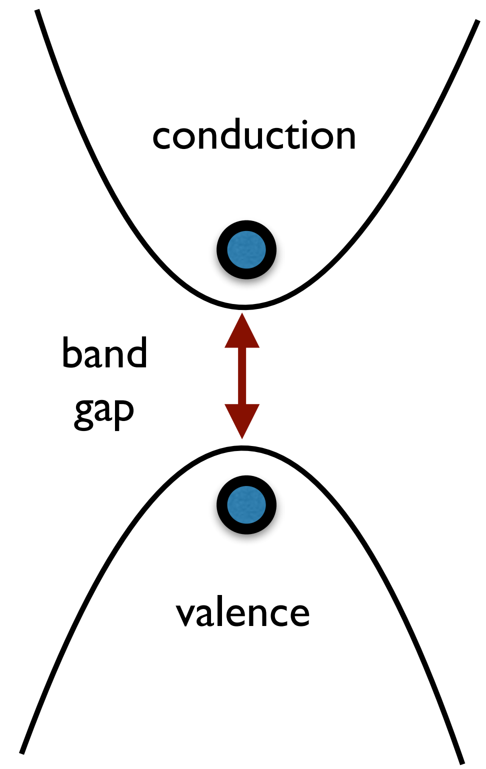

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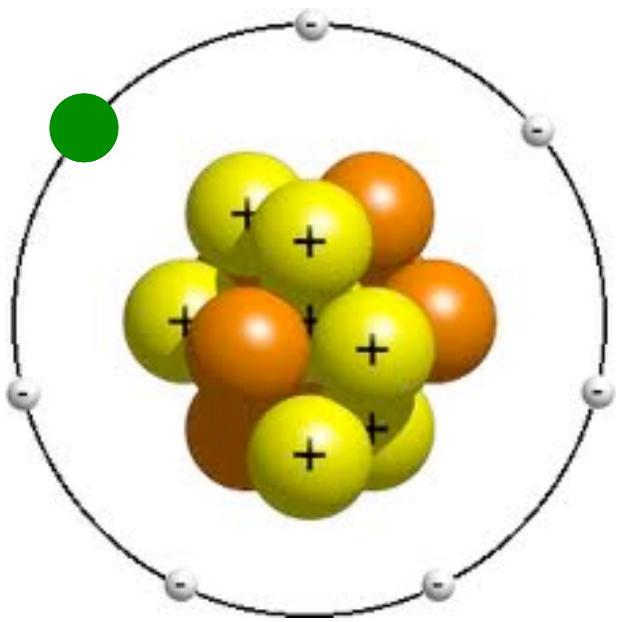

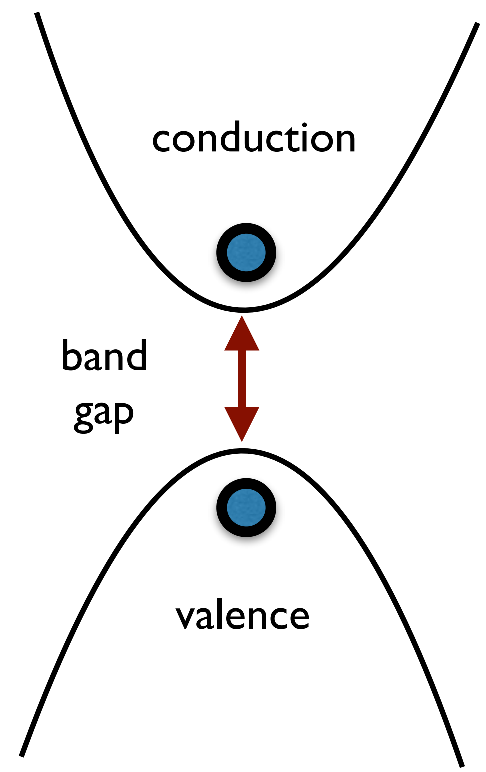

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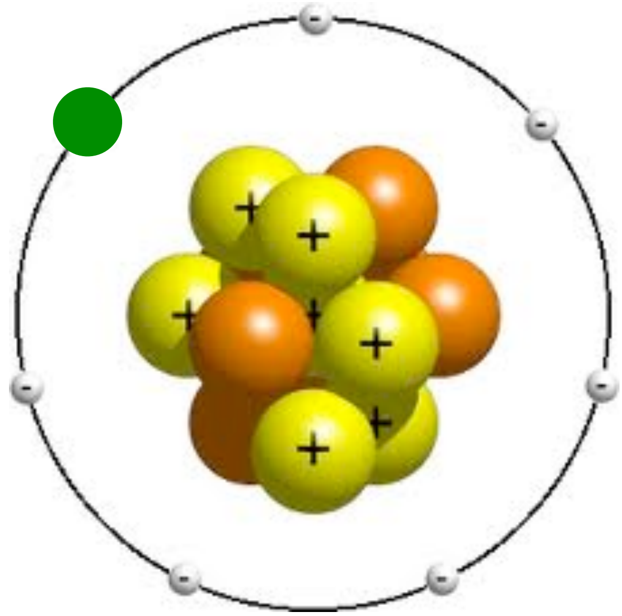

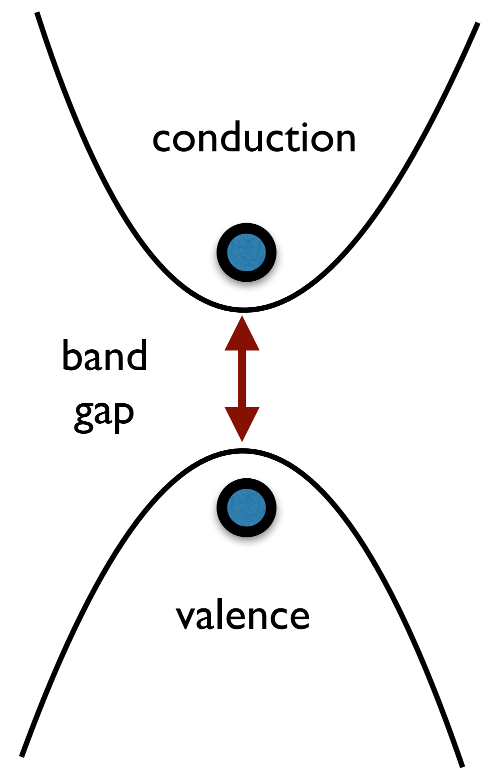

<u>see also:</u>
Graham, Kaplan, Rajendran, Walters
RE, Manalaysay, Mardon, Sorensen, Volansky
RE, Fernandez-Serra, Mardon, Soto, Volansky, Yu
Derenzo, RE, Massari, Soto, Yu
RE, Volansky, Yu
RE, Sholarpurkar, Yu
Emken, RE, Kouvaris, Sholarpurkar
Derenzo, Bourret, Hanrahan, Bizarri
Lee, Lisanti, Mishra-Sharma, Safdi

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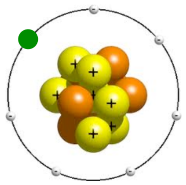

two-phase TPCs
(XENON10/100/1T, DarkSide-50)

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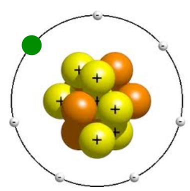

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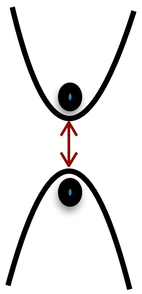

Skipper-CCDs (SENSEI)
TES (SuperCDMS)
DEPFET (DANAE)

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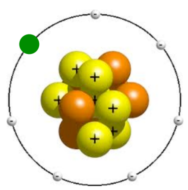

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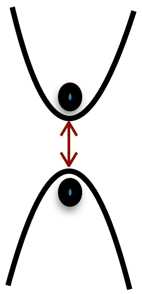

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Planned experiments include

LBECA
DarkSide-LowMass

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DAMIC-M (1 kg Skipper)
OSCURA (10 kg Skipper)

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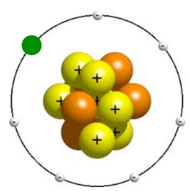

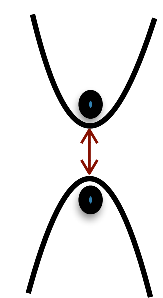

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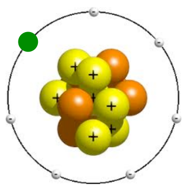

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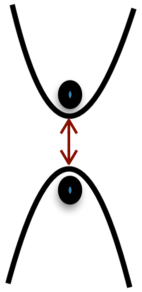
(also see talks by S. Davini, S. Reichard)



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Electrons from Migdal effect (DM-<u>nucleus</u> scattering)

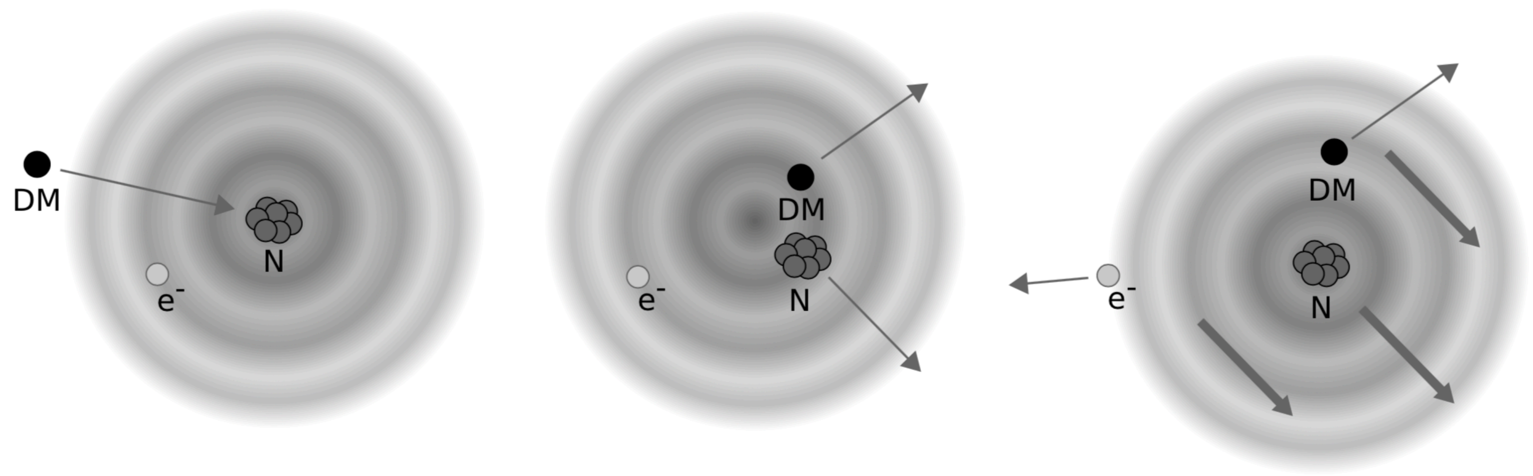

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Fig. credit: Dolan, Kahlhoefer, McCabe

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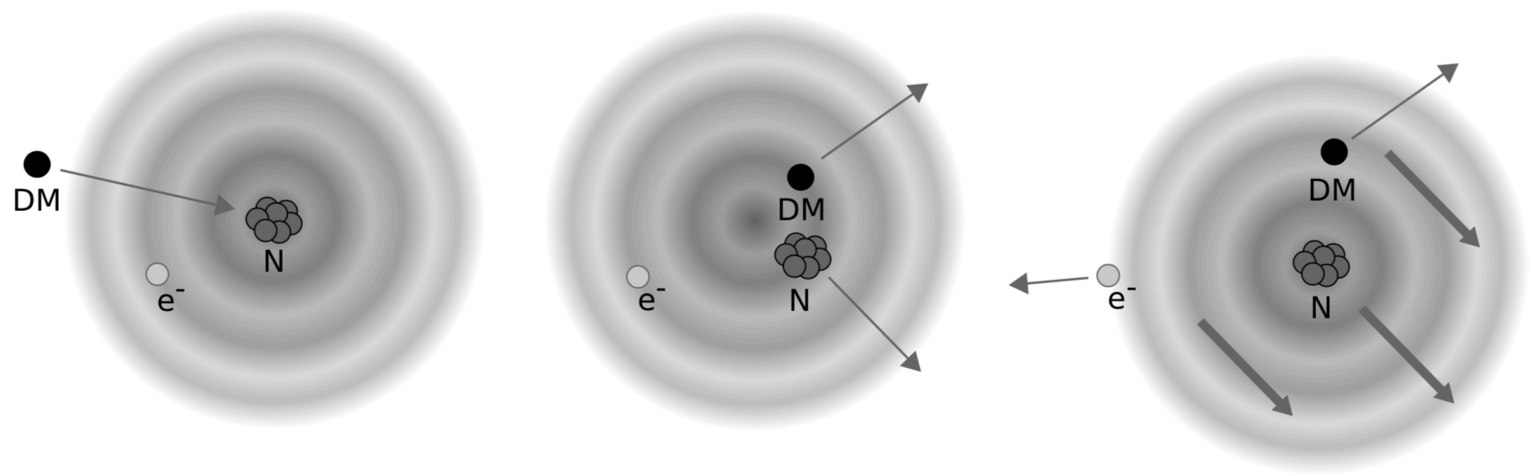

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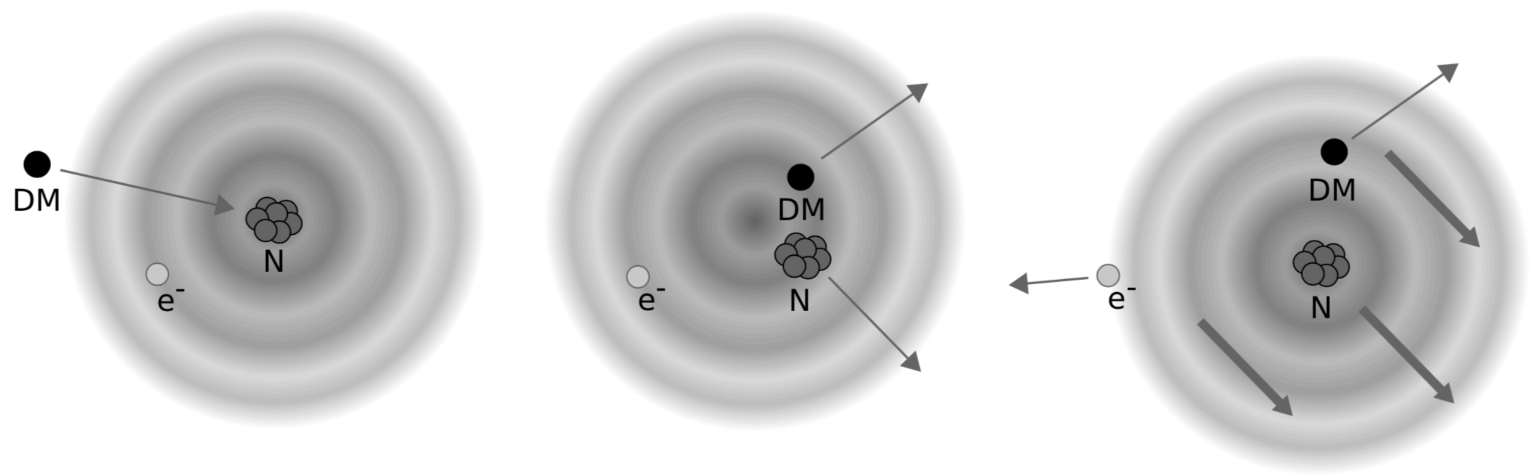

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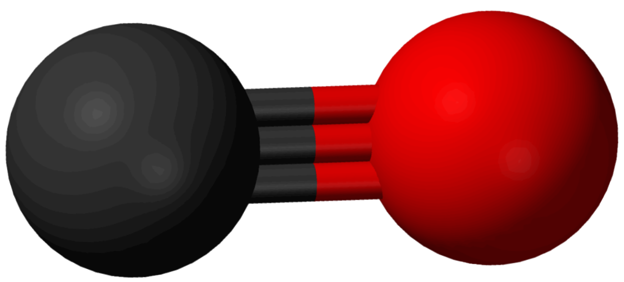
A detector sensitive to small ionization signals will be sensitive to both DM-e and DM-N interactions (w/ same mass threshold!)

Some Inelastic Processes giving $E_{\max} \sim (1/2) m_\chi v_\chi^2$

Molecular Excitations (DM-nucleus scattering)

RE, Perez-Rios, Ramani, Slone (2019)



e.g. carbon monoxide

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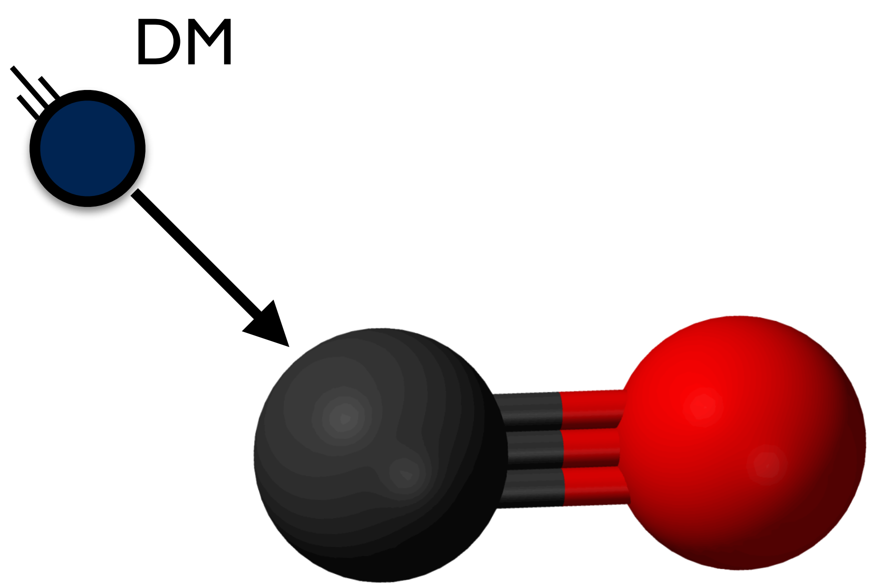

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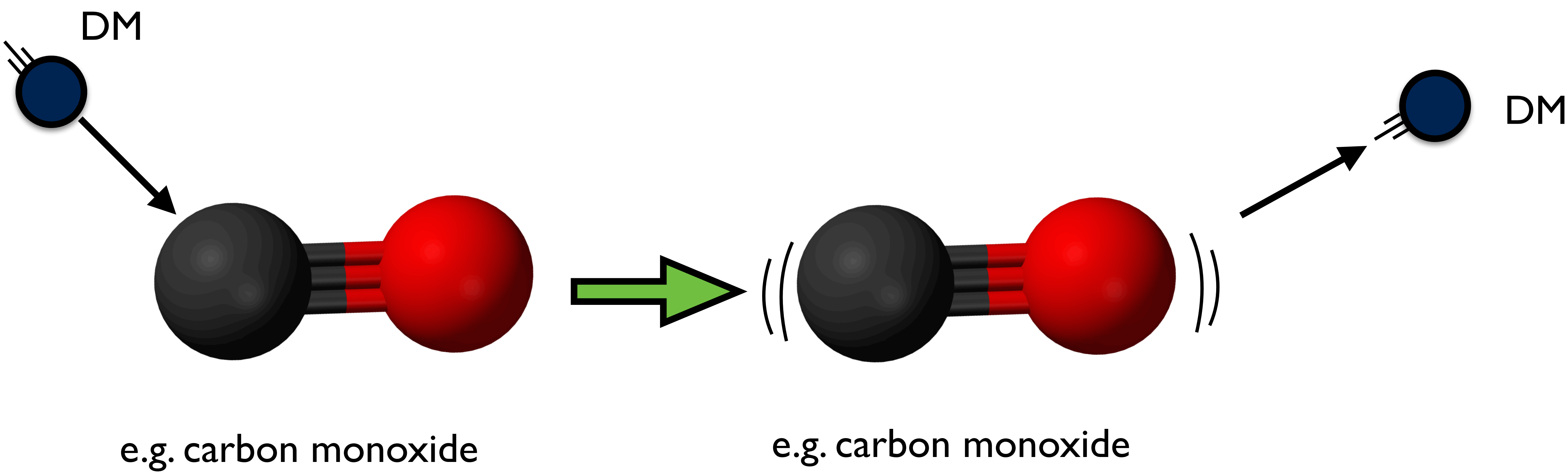

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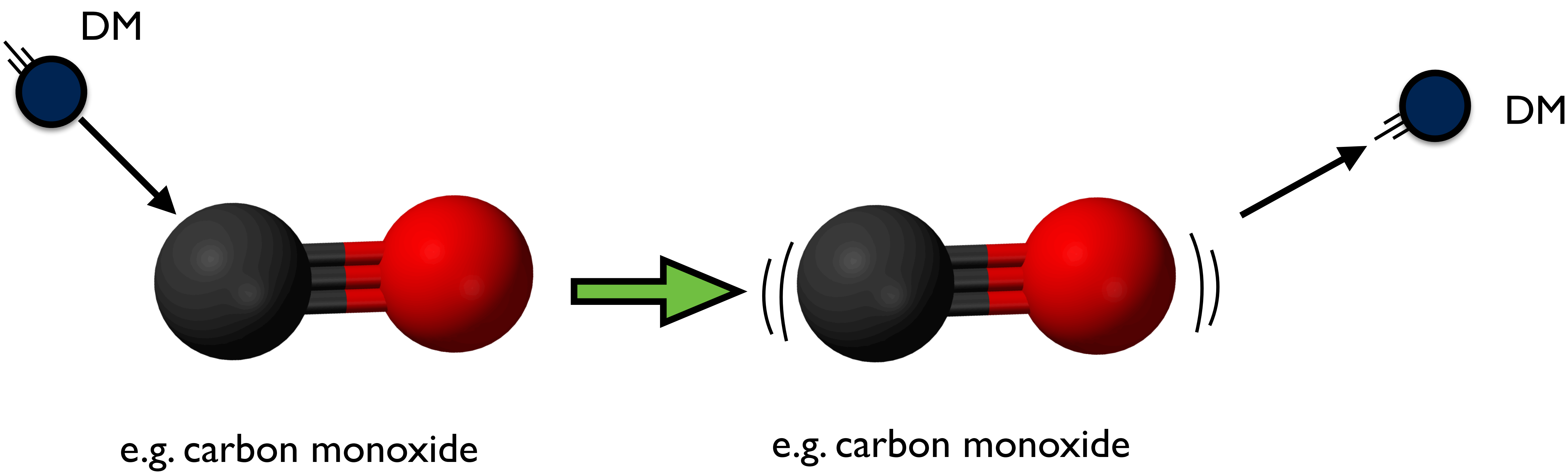

Excited molecule relaxes to ground state emitting <u>multiple</u> photons of energy O(100-250 meV);

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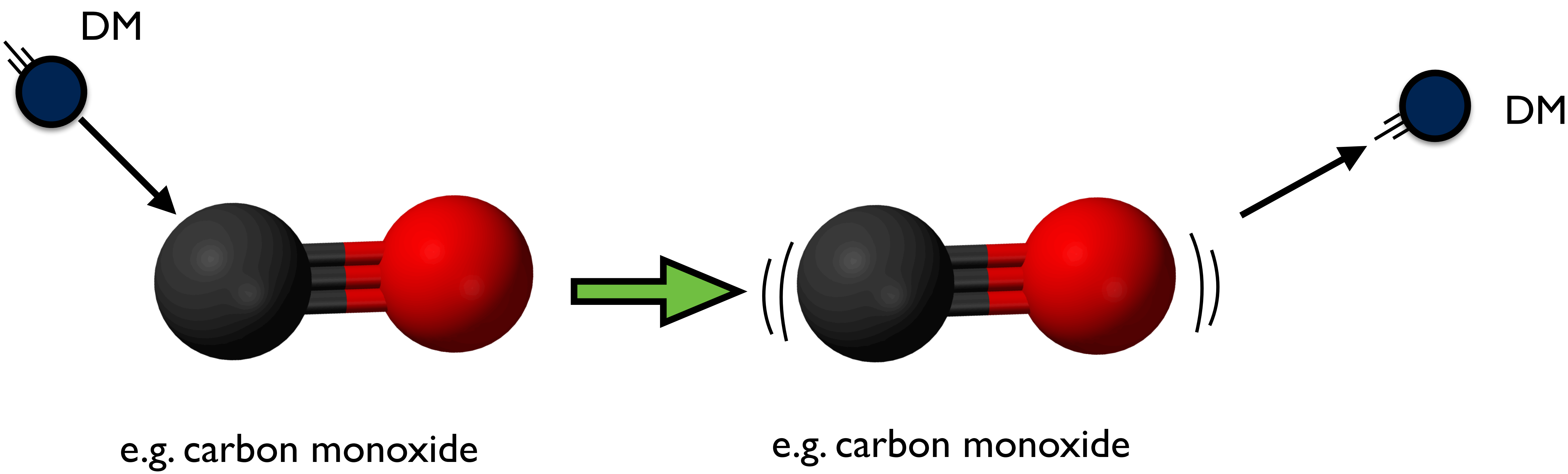

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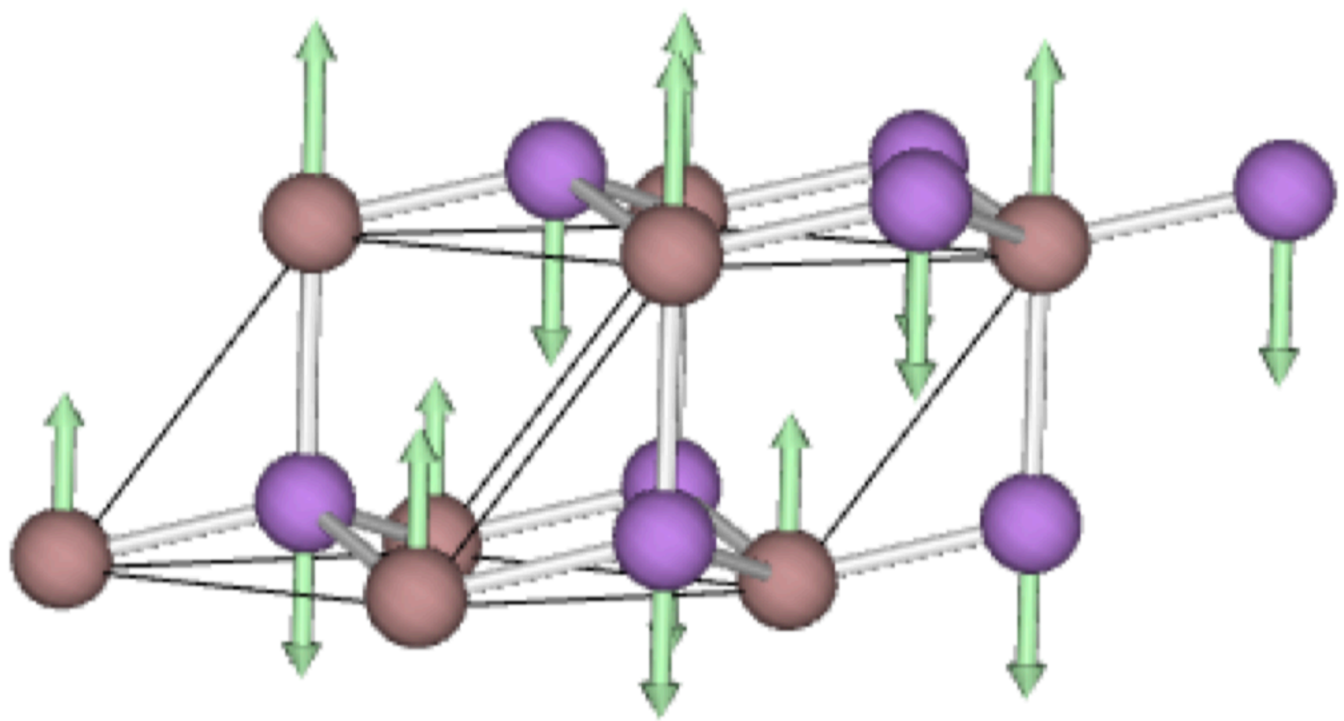
R&D needed to create large-area photodetectors sensitive to O(100 meV) photons, using e.g. SNSPDs, TES, or MKIDS

Some Inelastic Processes giving $E_{\max} \sim (1/2)m_\chi v_\chi^2$

Create optical phonons in polar materials,
e.g. GaAs, sapphire (DM-phonon scattering)

Knapen, Lin, Pyle, Zurek
Griffin, Knapen, Lin, Zurek

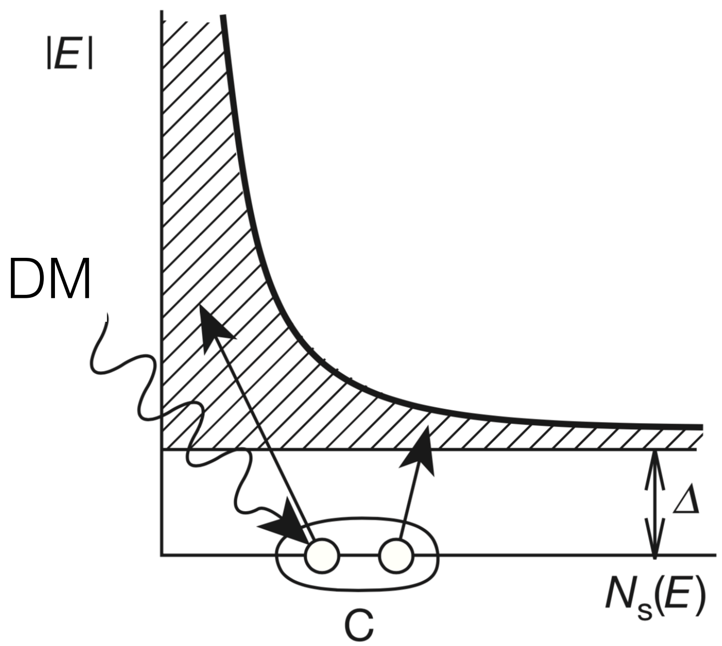


typically produces phonons with energy of 10's of meV

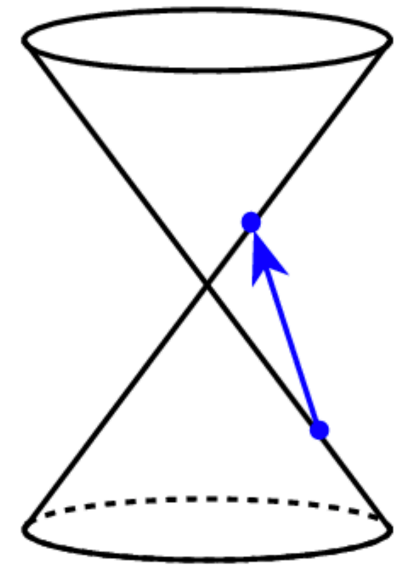
R&D needed to improve phonon sensors (e.g. TES)

Some Inelastic Processes giving $E_{\rm max} \sim (1/2) m_\chi v_\chi^2$

Electron scattering in low-gap materials, e.g. superconductors, Dirac materials



superconductors



Dirac materials

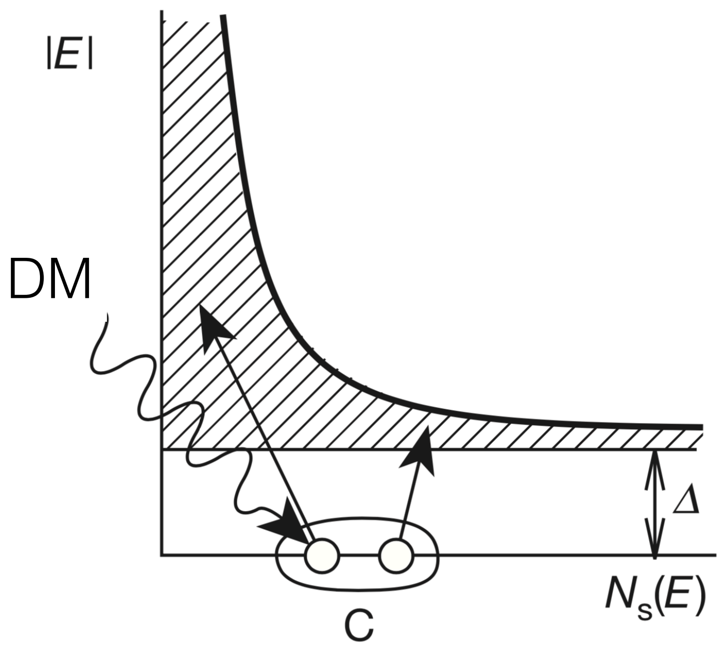
Hochberg, Zhao, Zurek
Hochberg, Pyle, Zhao, Zurek
Hochberg, Lin, Zurek
Hochberg, Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin, Liu, Weber, Neaton

$E_{\rm binding} \sim$ few meV

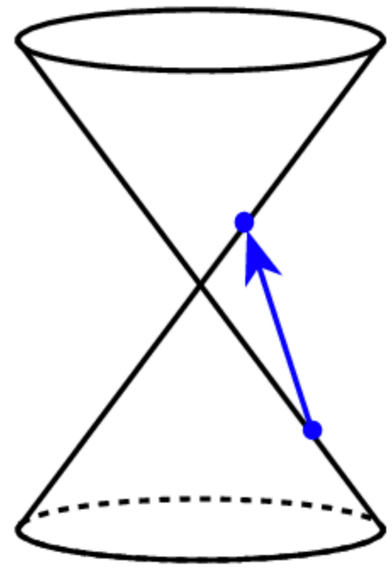
$m_{\rm threshold} \sim$ keV

Some Inelastic Processes giving $E_{\max} \sim (1/2) m_\chi v_\chi^2$

Electron scattering in low-gap materials, e.g. superconductors, Dirac materials



superconductors



Dirac materials

Hochberg, Zhao, Zurek
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Hochberg, Lin, Zurek
Hochberg, Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin, Liu, Weber, Neaton

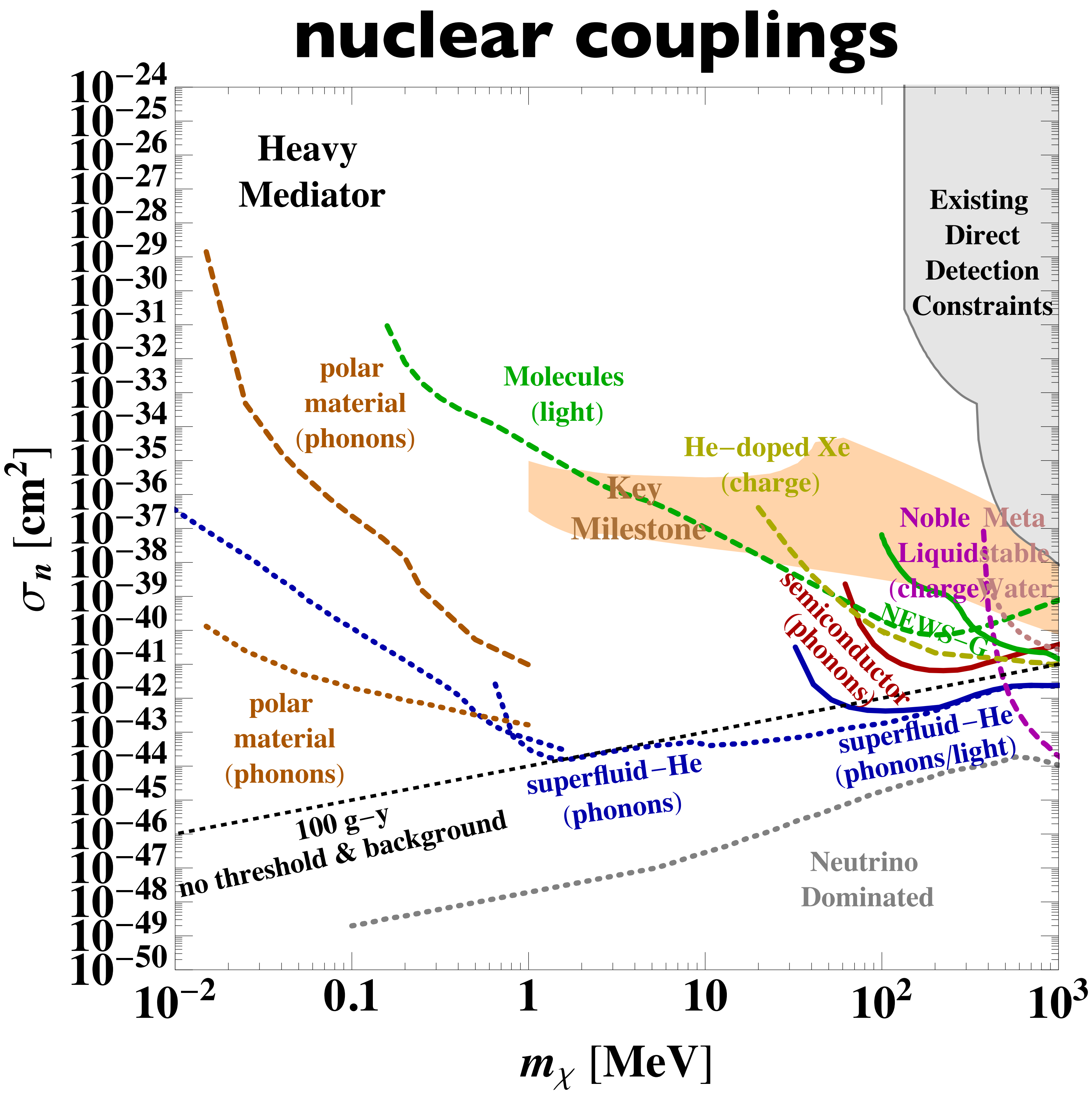
$E_{binding}$~few meV

$m_{threshold}$~ keV

R&D needed to enhance/measure ~meV signals

The next decade in sub-GeV DM direct-detection

from DoE High-Energy Physics Basic Research Needs Report

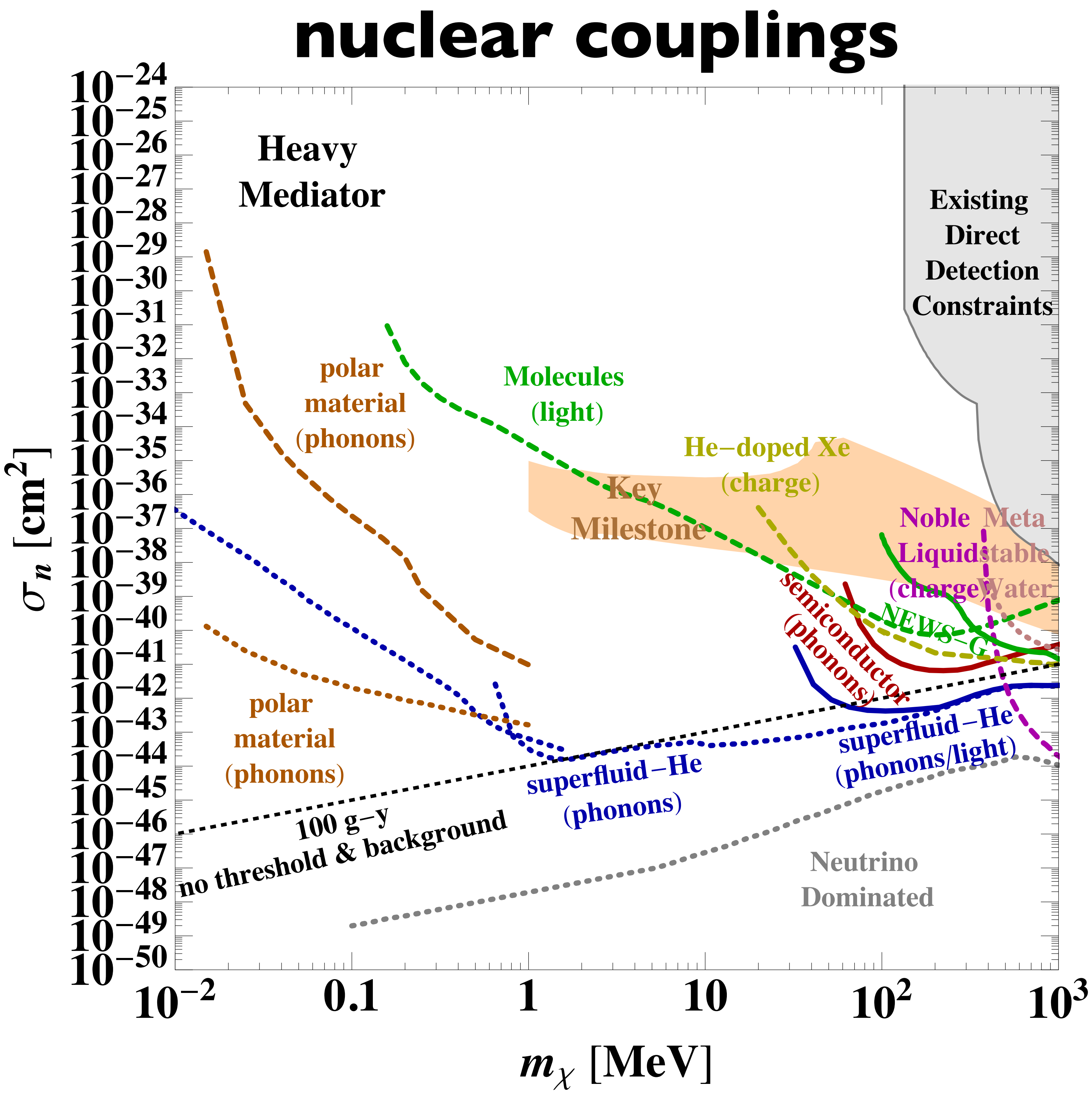


Ideas exist to probe vast new regions of parameter space

- solid: ready for development
- dashed: short-term R&D
- dotted: long-term R&D

The next decade in sub-GeV DM direct-detection

from DoE High-Energy Physics Basic Research Needs Report



(doesn't include projections for e.g. Migdal effect)

Ideas exist to probe vast new regions of parameter space

- solid: ready for development
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The next decade in sub-GeV DM direct-detection

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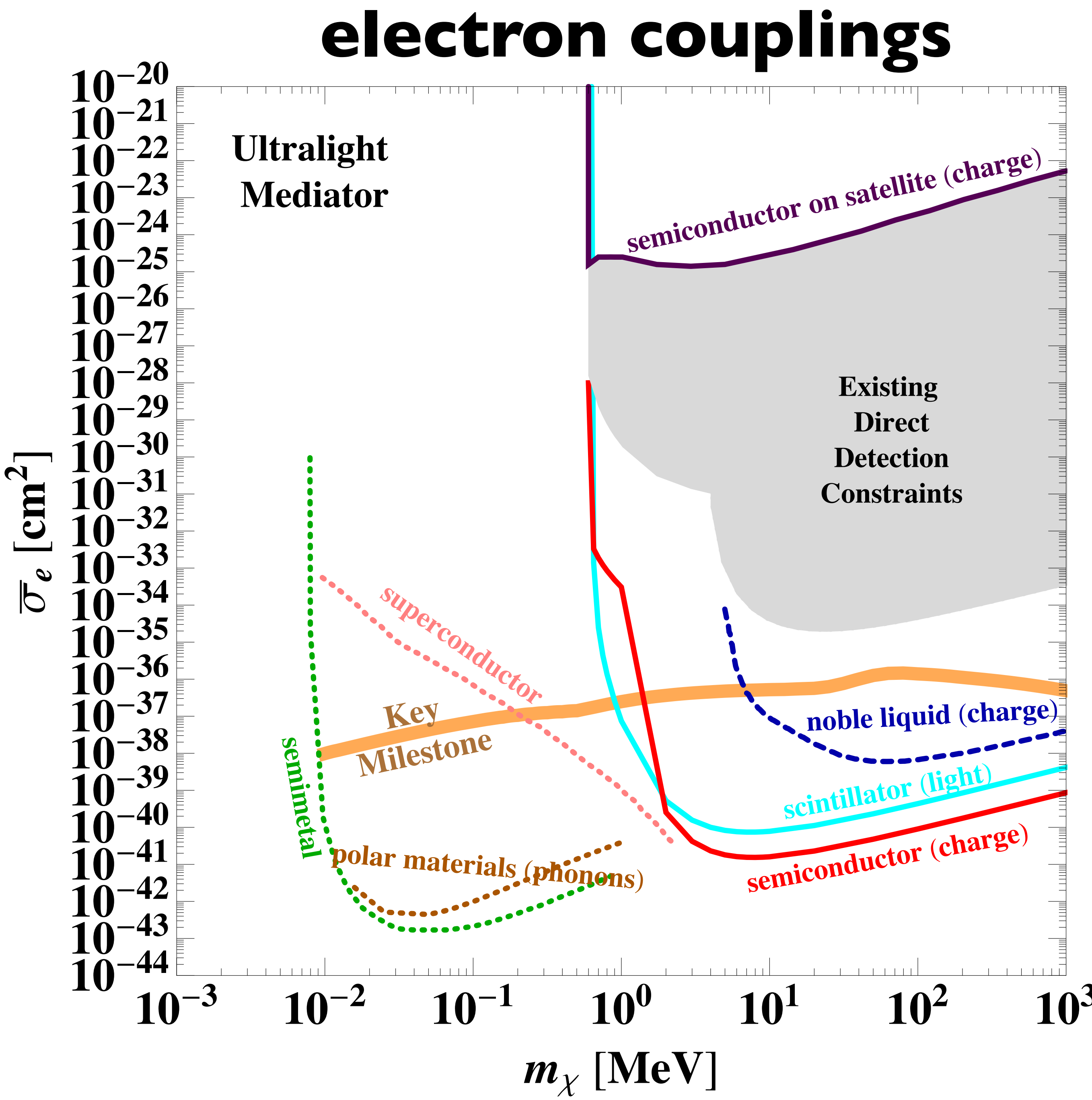
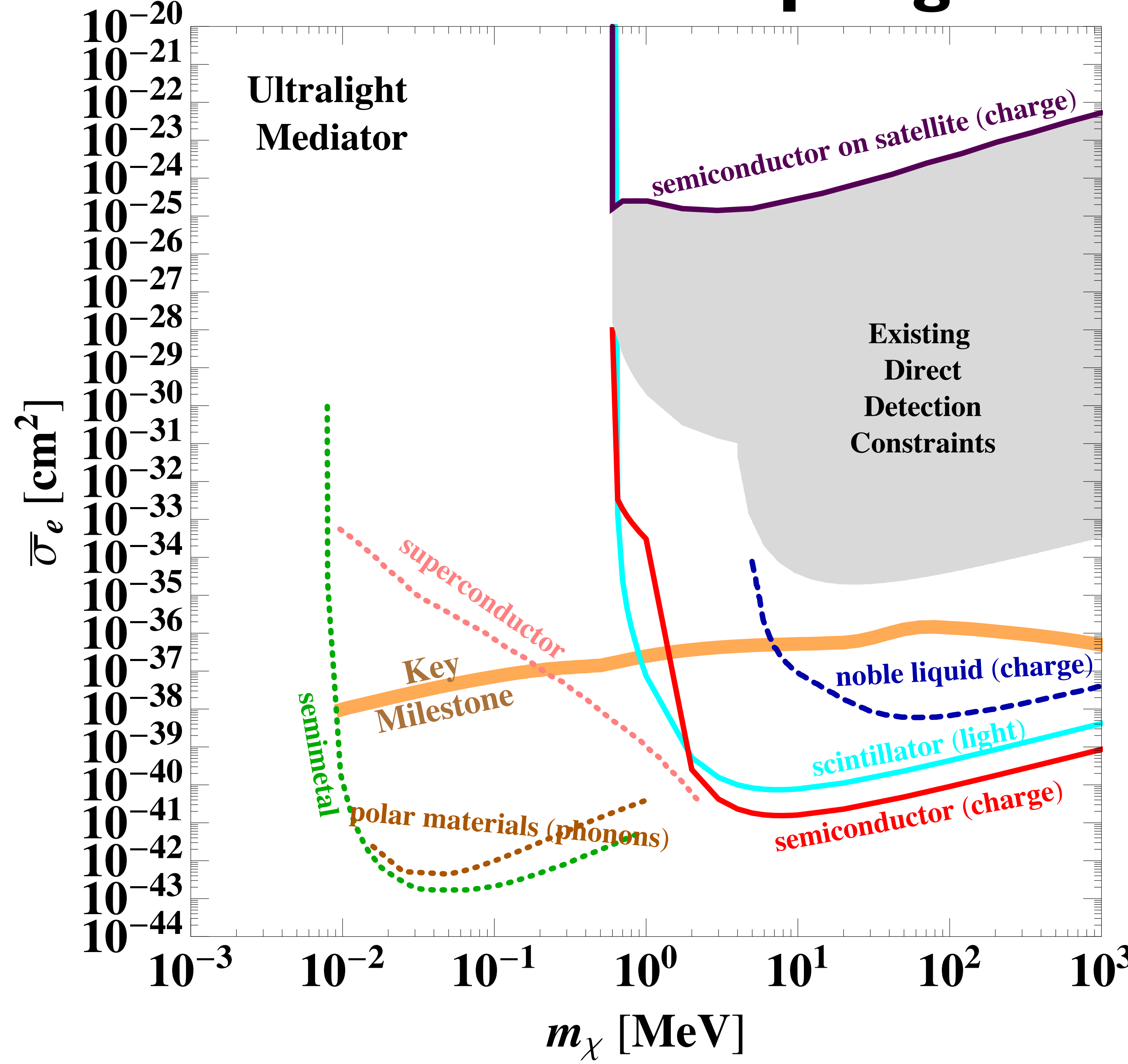


The next decade in sub-GeV DM direct-detection

from DoE High-Energy Physics Basic Research Needs Report

Some experiments ready soon:

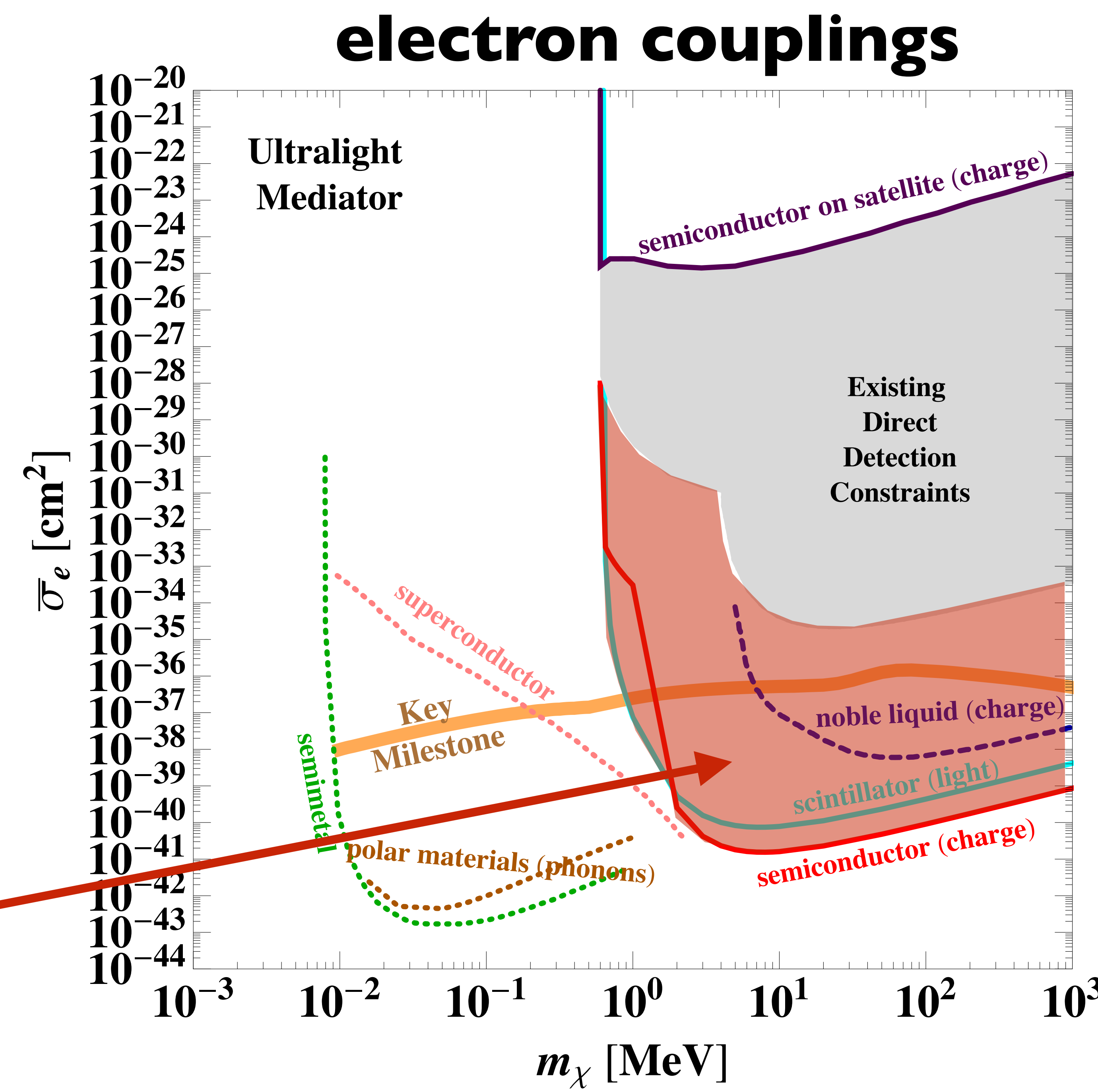
electron couplings



The next decade in sub-GeV DM direct-detection

from DoE High-Energy Physics Basic Research Needs Report

Some experiments ready soon:



SENSEI

(silicon Skipper CCDs)

(brief)

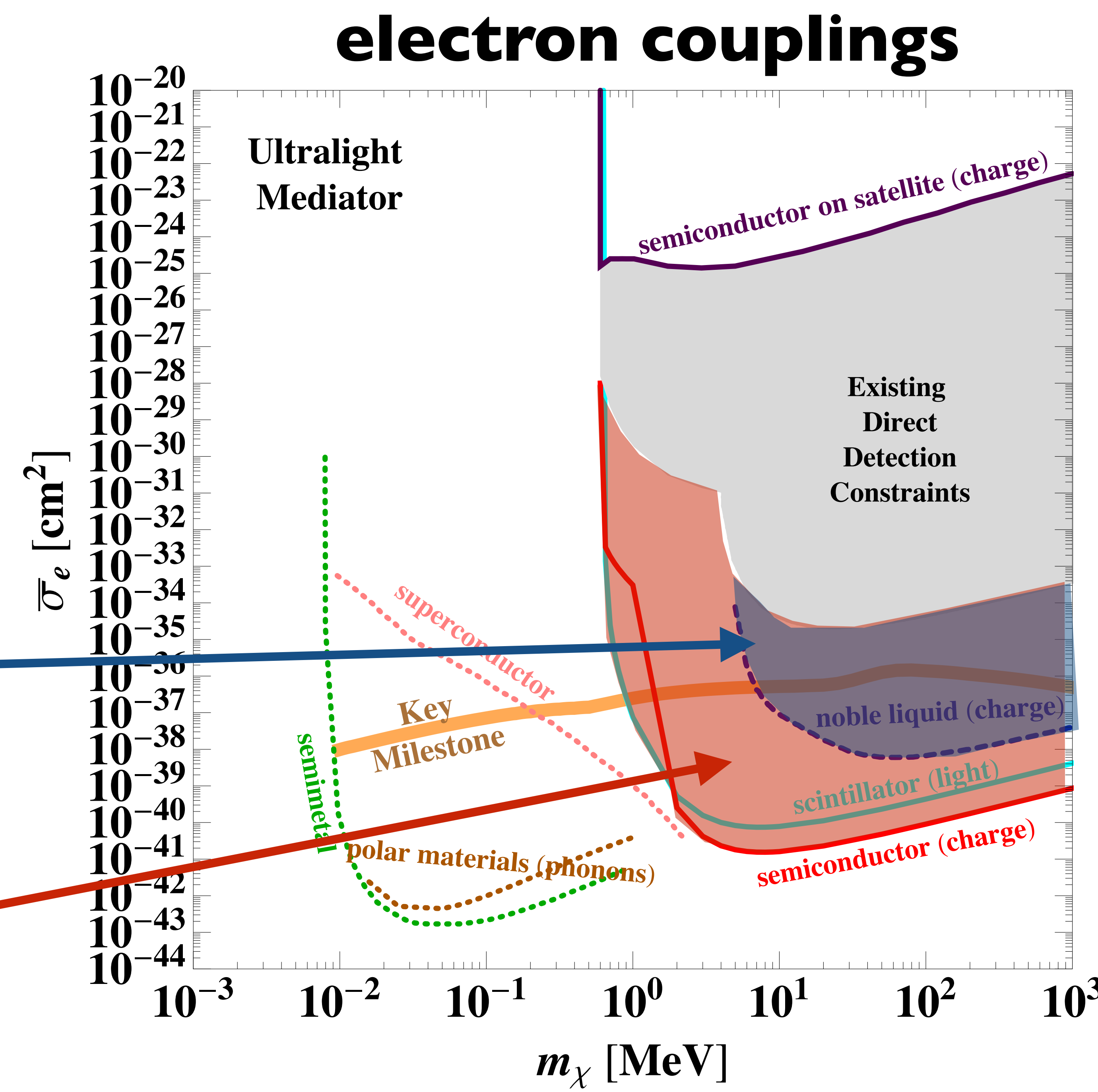
The next decade in sub-GeV DM direct-detection

from DoE High-Energy Physics Basic Research Needs Report

Some experiments ready soon:

LBECA (liquid Xe)
(very brief)

SENSEI
(silicon Skipper CCDs)
(brief)



The next decade in sub-GeV DM direct-detection

from DoE High-Energy Physics Basic Research Needs Report

Some experiments ready soon:

Skipper-CCD on balloon/satellite

(see backup slides)

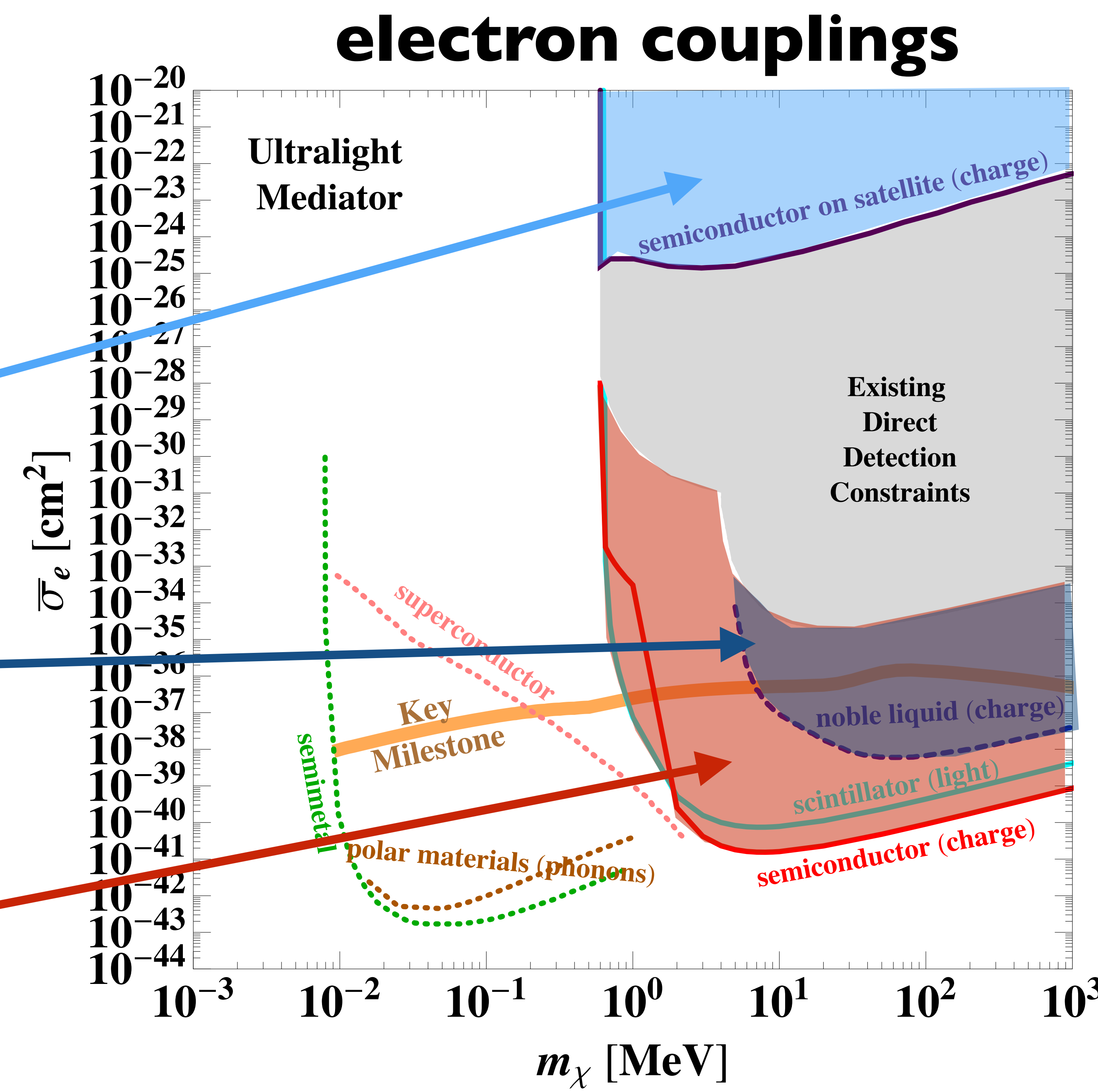
LBECA (liquid Xe)

(very brief)

SENSEI

(silicon Skipper CCDs)

(brief)



The LBECA Collaboration

"Low Background Electron Counting Apparatus"

BERKELEY LAB Lawrence Livermore National Laboratory PURDUE UNIVERSITY Stony Brook University UC San Diego

LBNL:

- P. Sorensen

LLNL:

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

Purdue

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

Stony Brook:

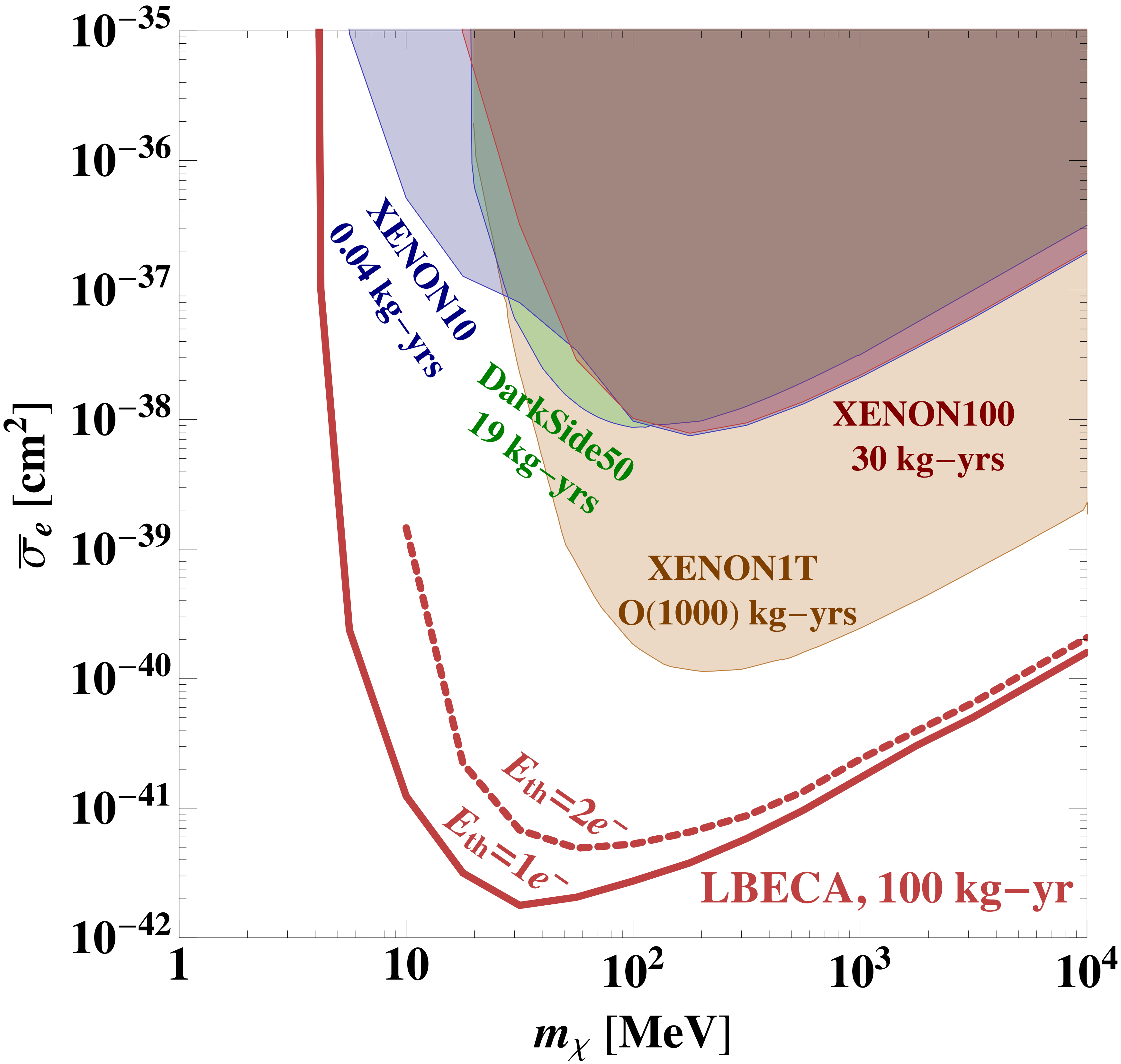
- R. Essig, M. Fernandez-Serra, C. Zhen

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

The SENSEI Collaboration

"Sub-Electron-Noise Skipper-CCD Experimental Instrument"

The SENSEI Collaboration

"Sub-Electron-Noise Skipper-CCD Experimental Instrument"

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:

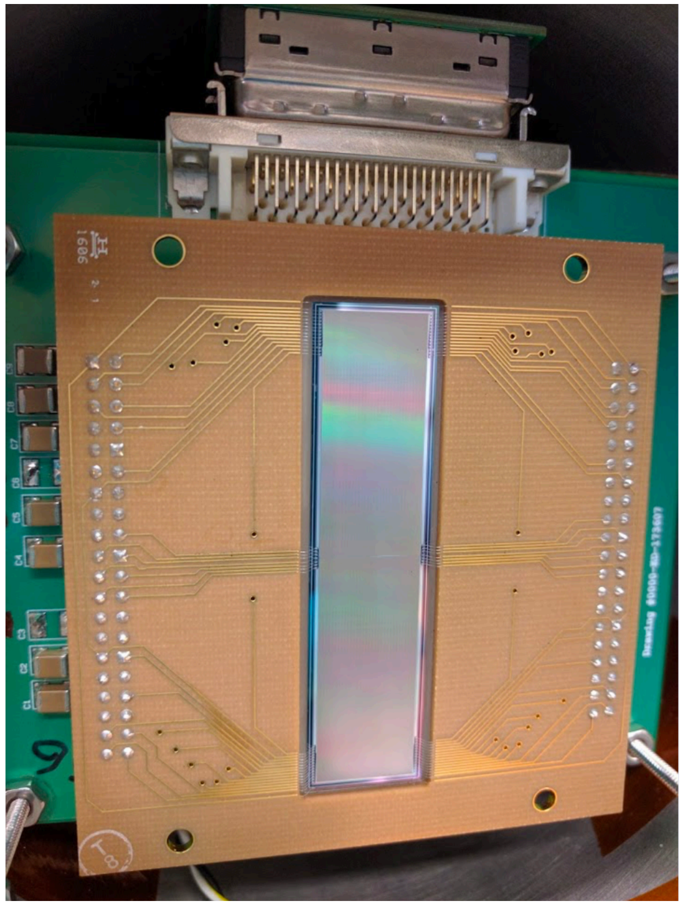
- T.-T. Yu

Fully funded by Heising-Simons Foundation & Fermilab

Detection Concept

Detection Concept

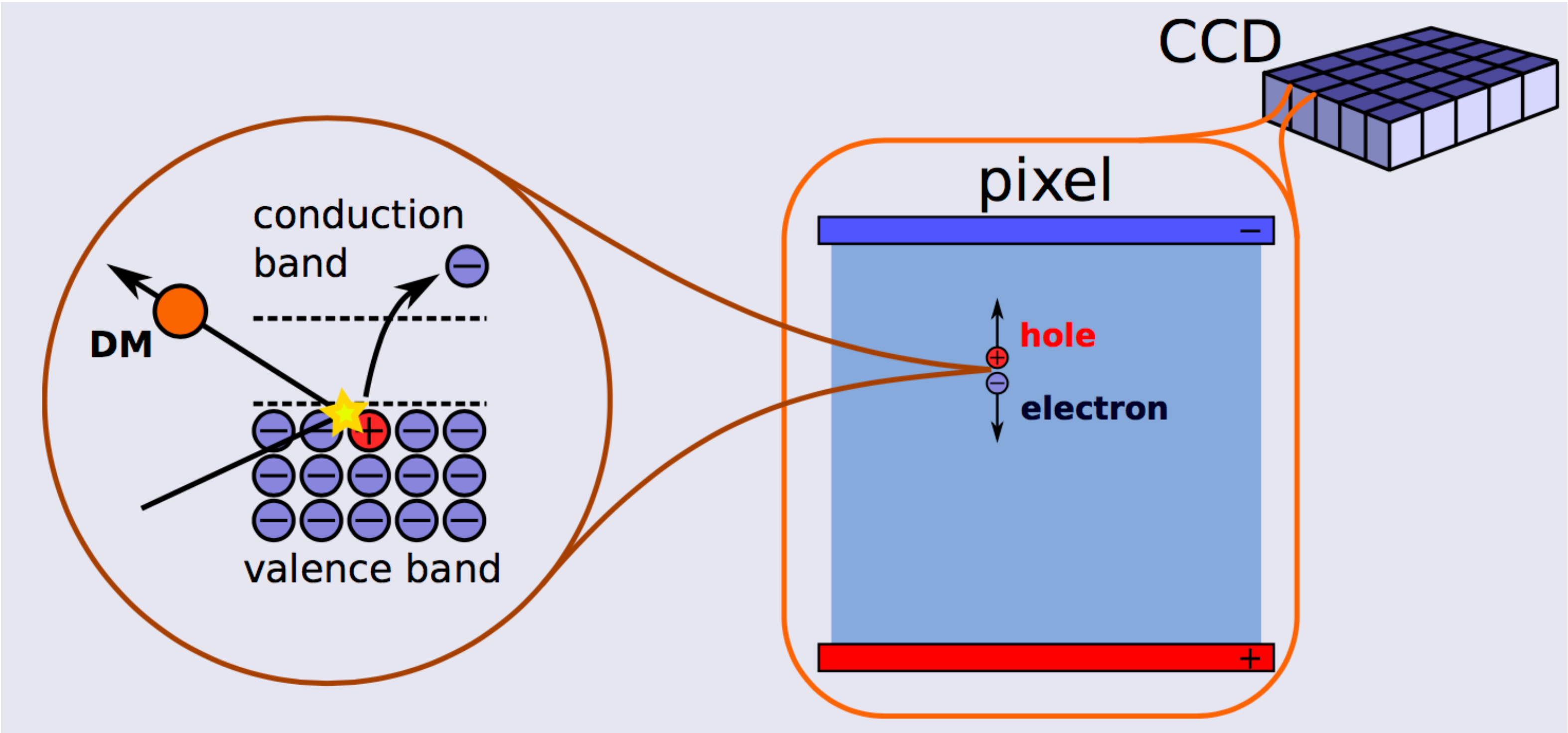
silicon Skipper-CCD



~million pixels

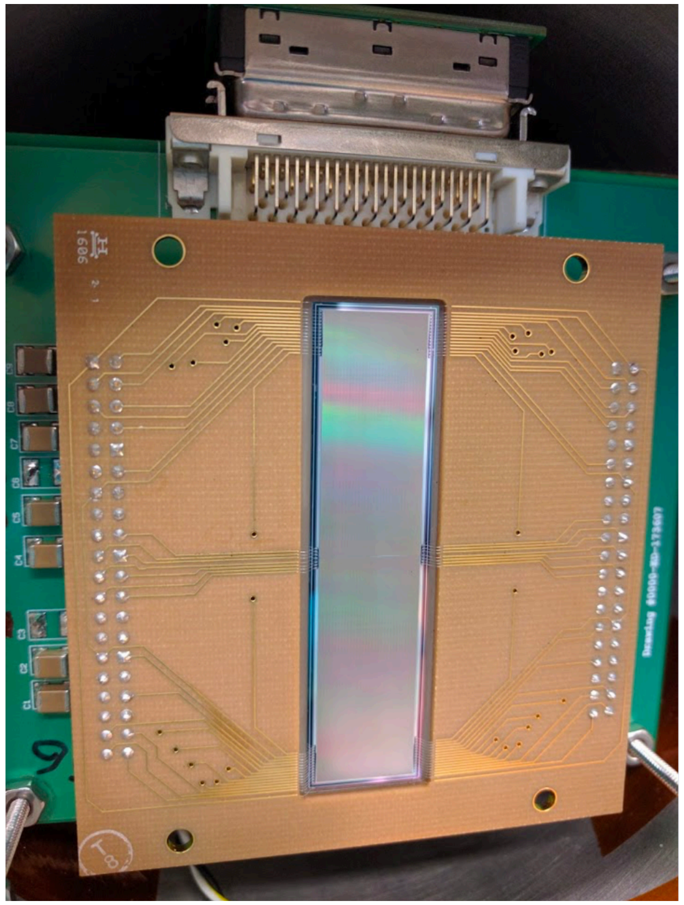
developed in collaboration
between FNAL & LBNL
MicroSystems Lab

Detection Concept



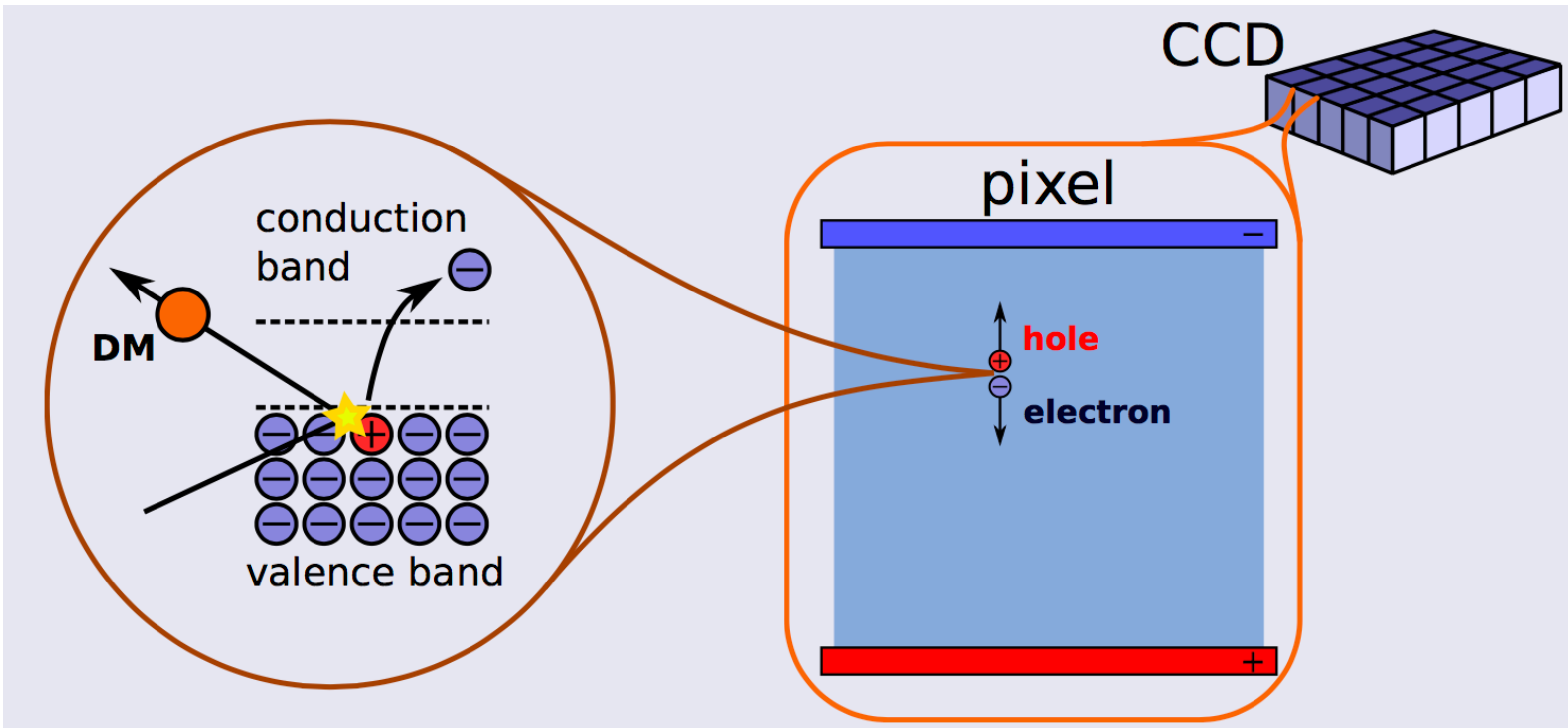
DM typically creates only
one or a few electrons per pixel

silicon Skipper-CCD



~million pixels

Detection Concept



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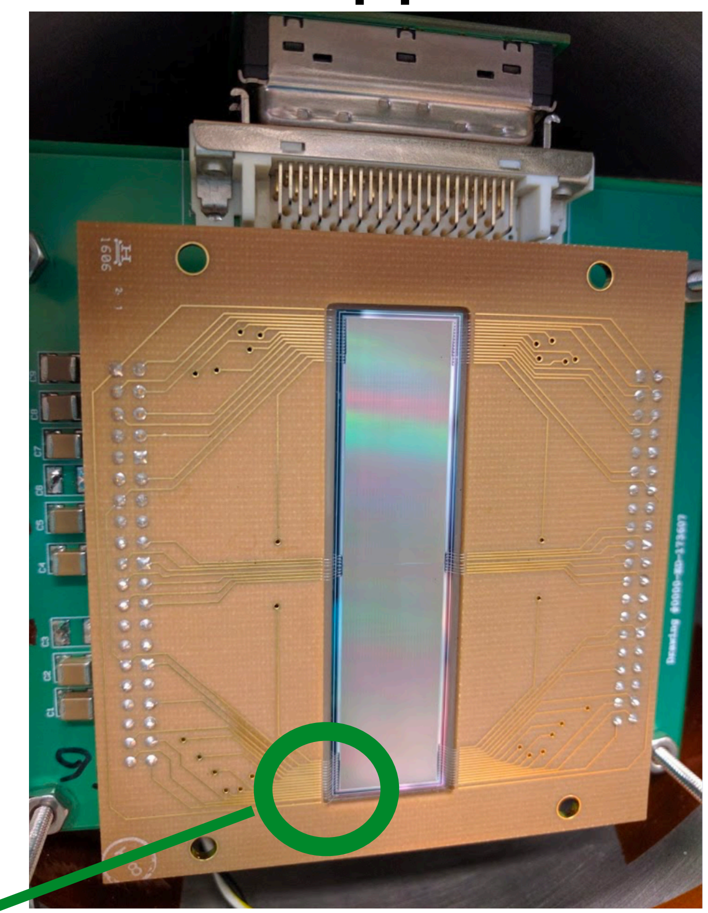
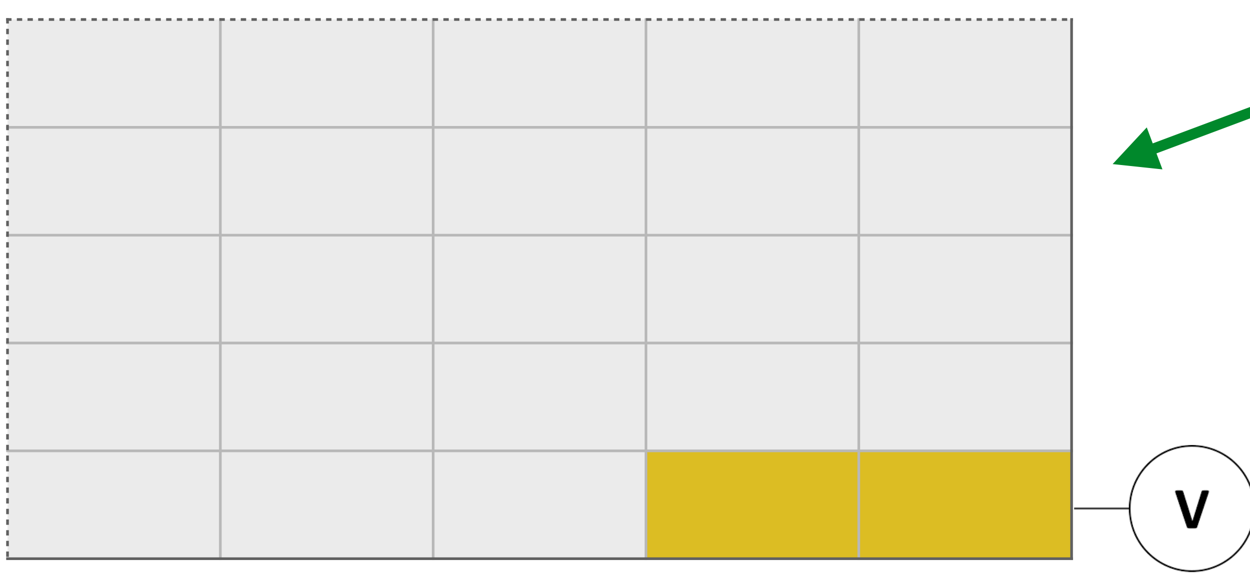
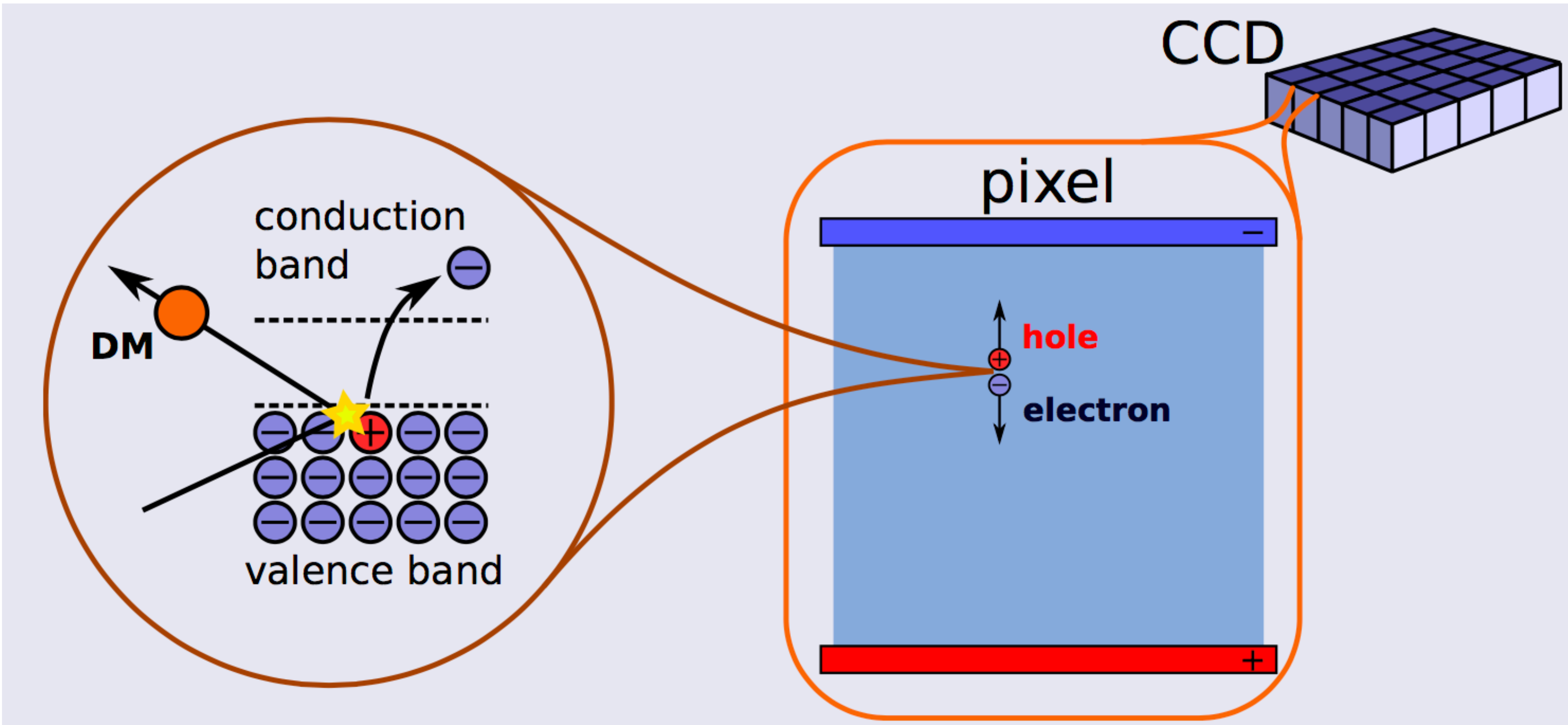


~million pixels



Detection Concept



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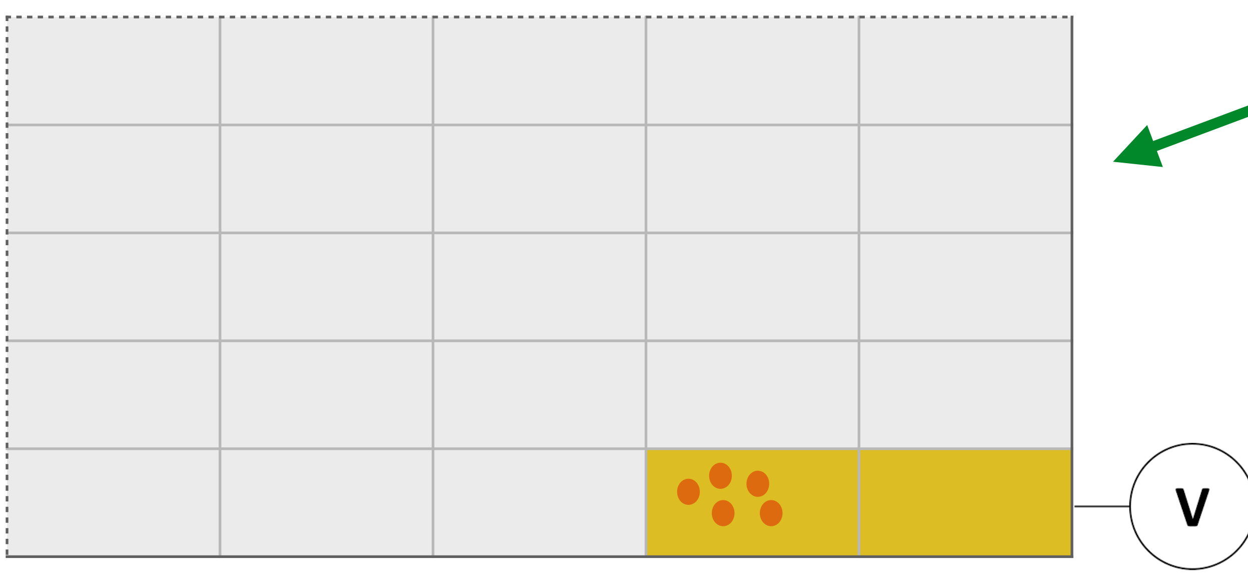
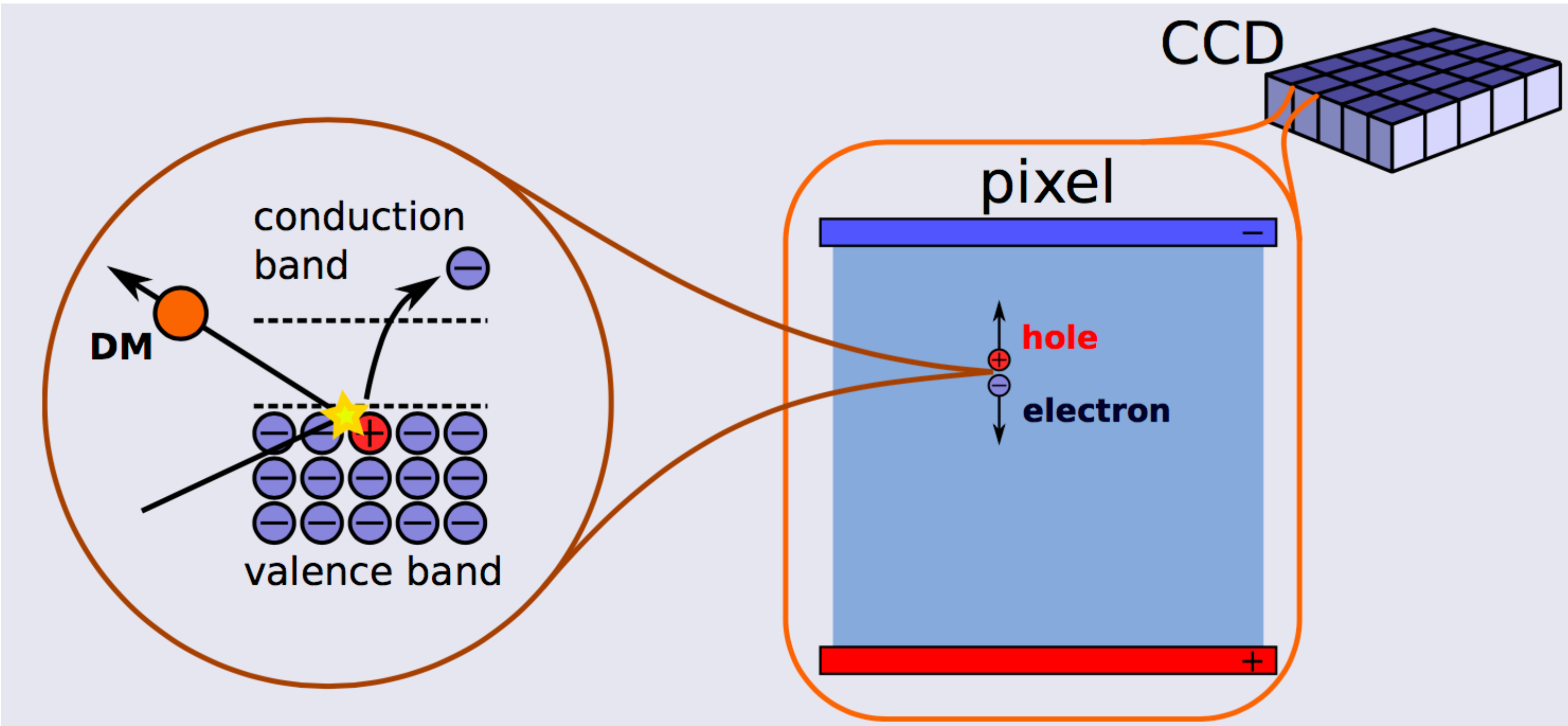


Detection Concept



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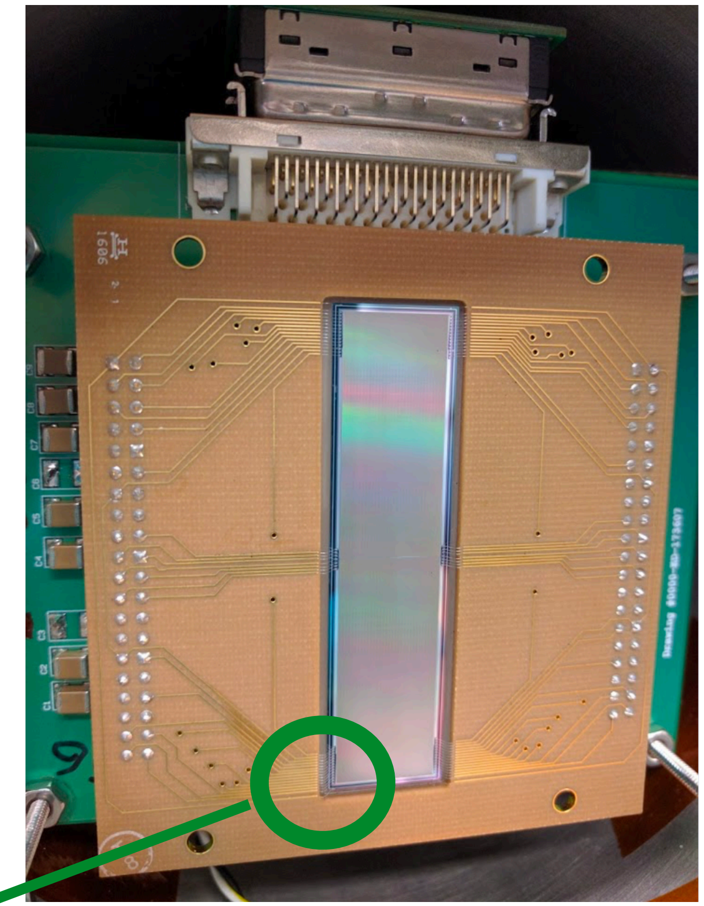
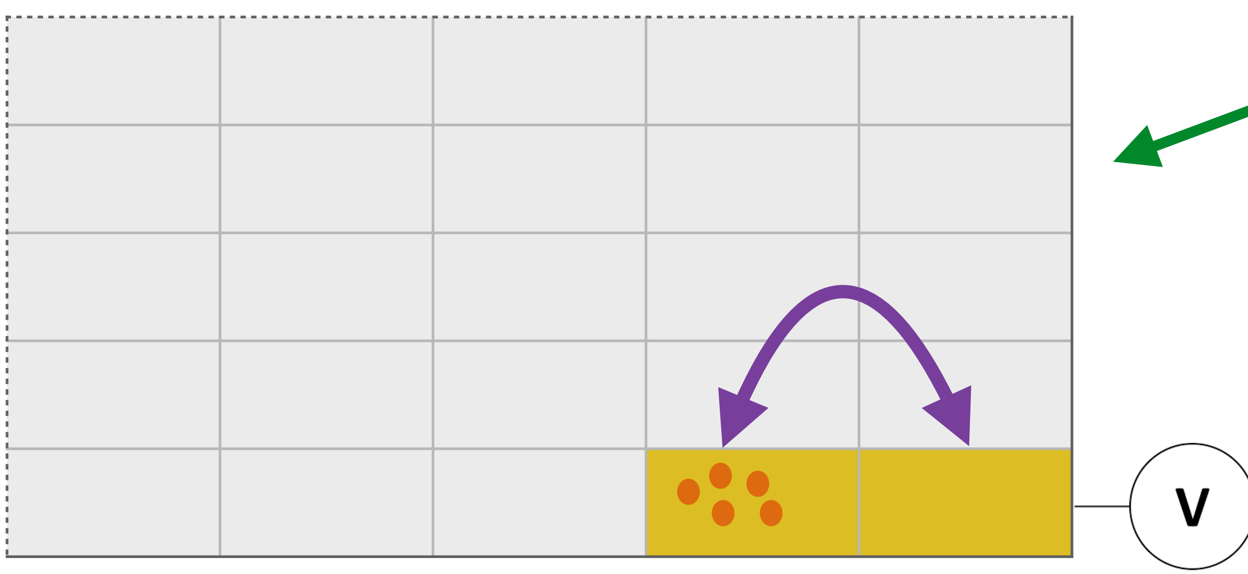
silicon Skipper-CCD

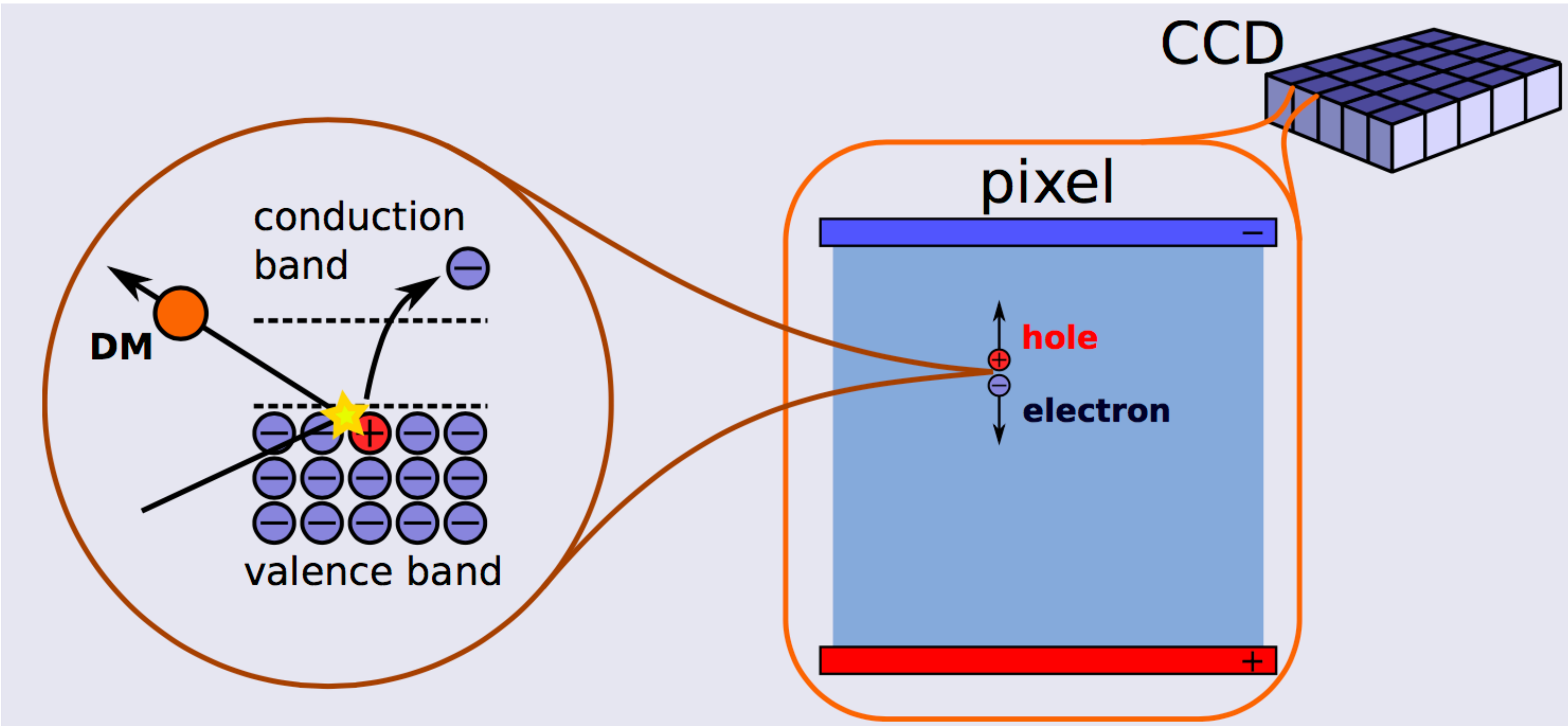


~million pixels



repeatedly measure charge to achieve sub-electron readout noise

Detection Concept



silicon Skipper-CCD

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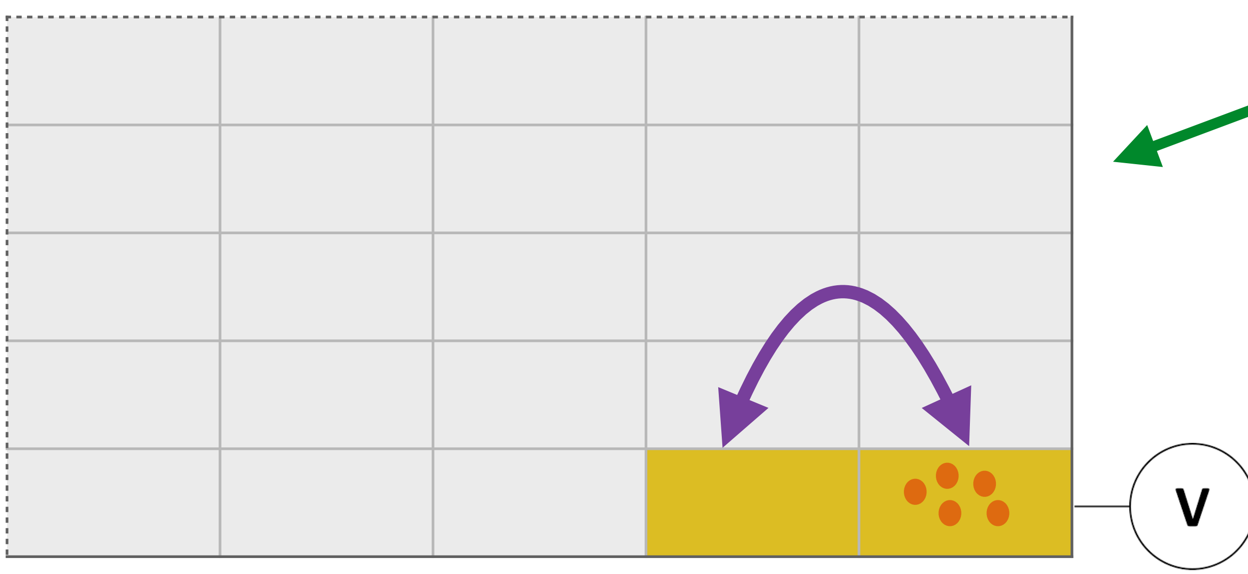

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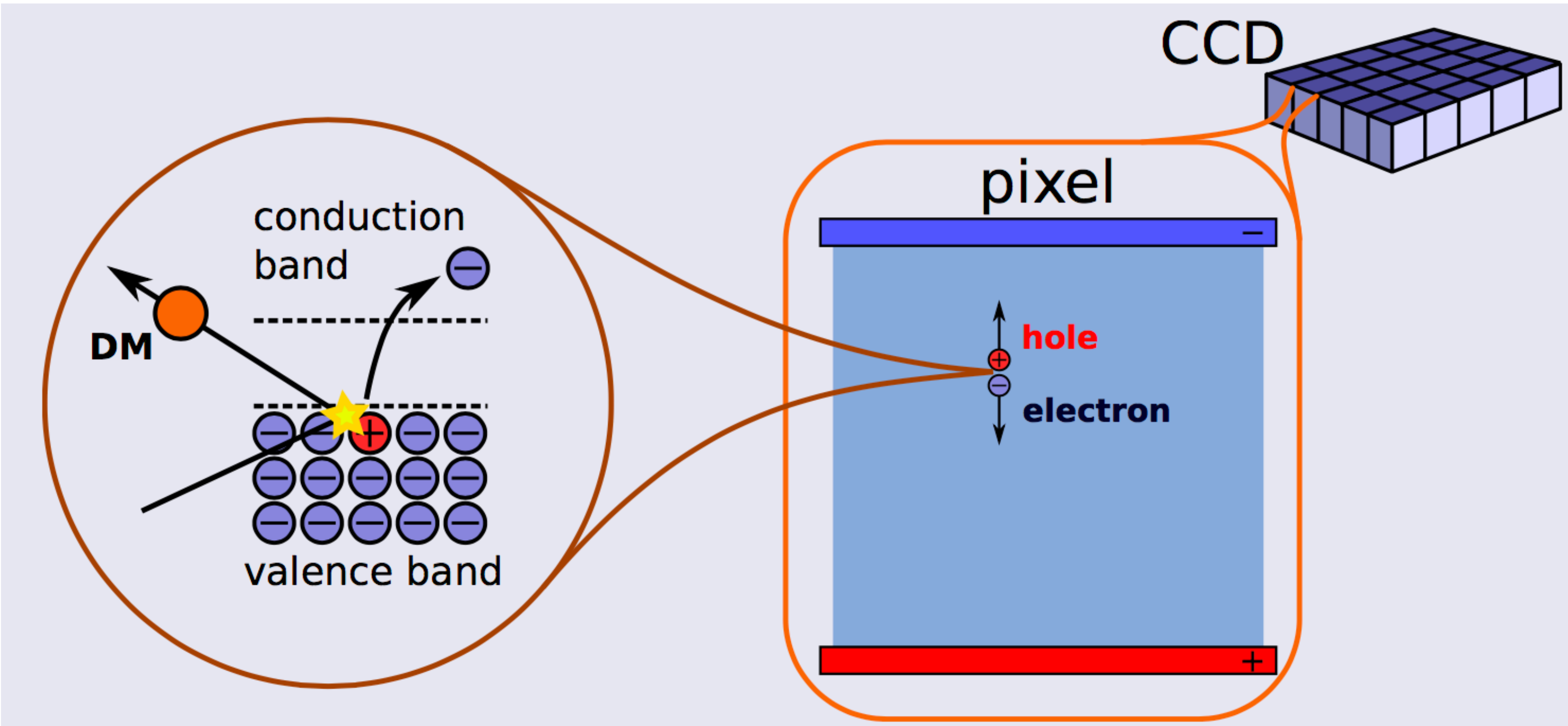
Detection Concept



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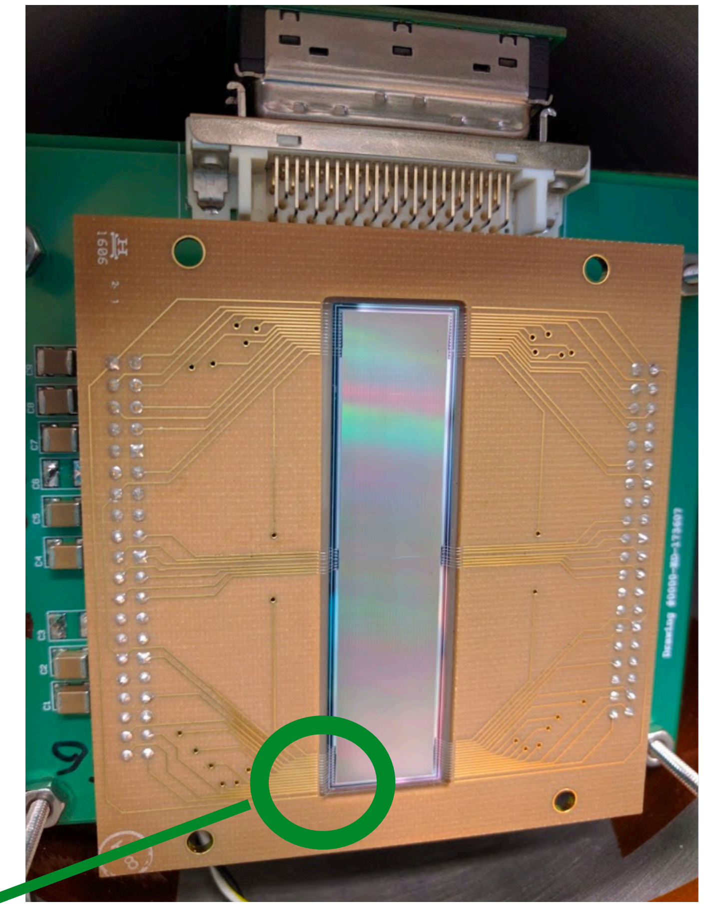
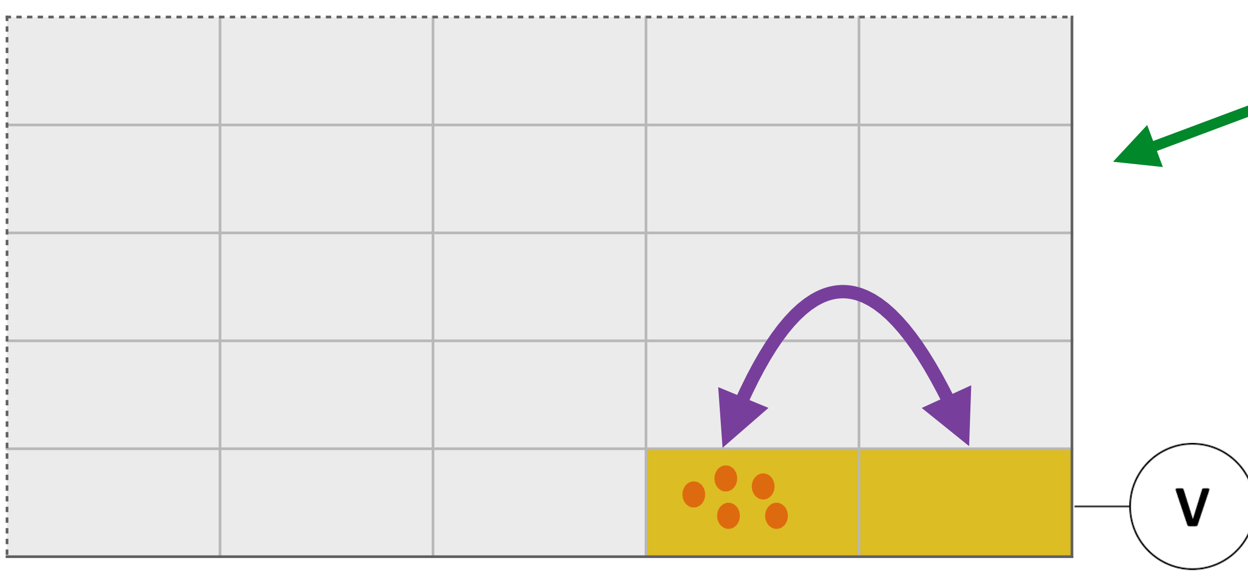
silicon Skipper-CCD



~million pixels



repeatedly measure charge
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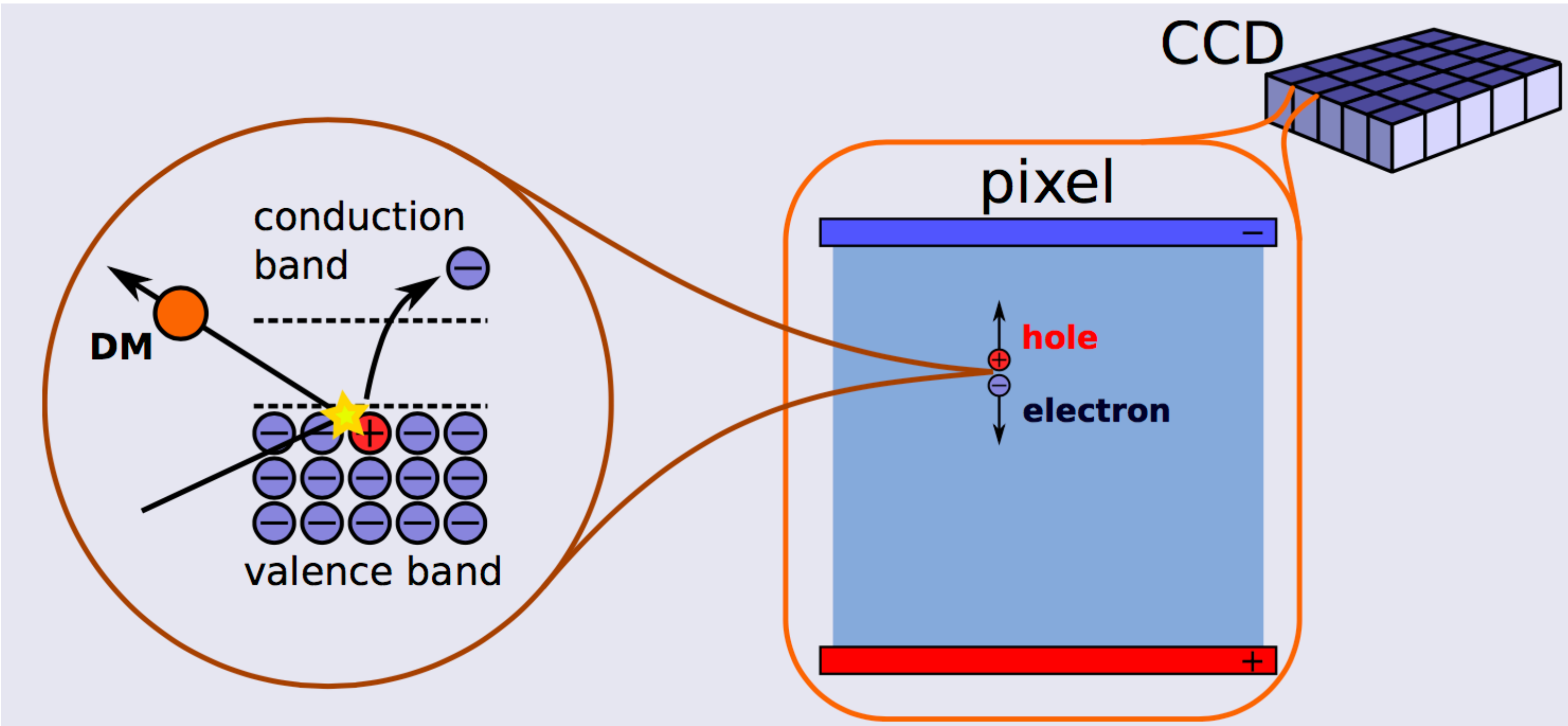
Detection Concept



silicon Skipper-CCD

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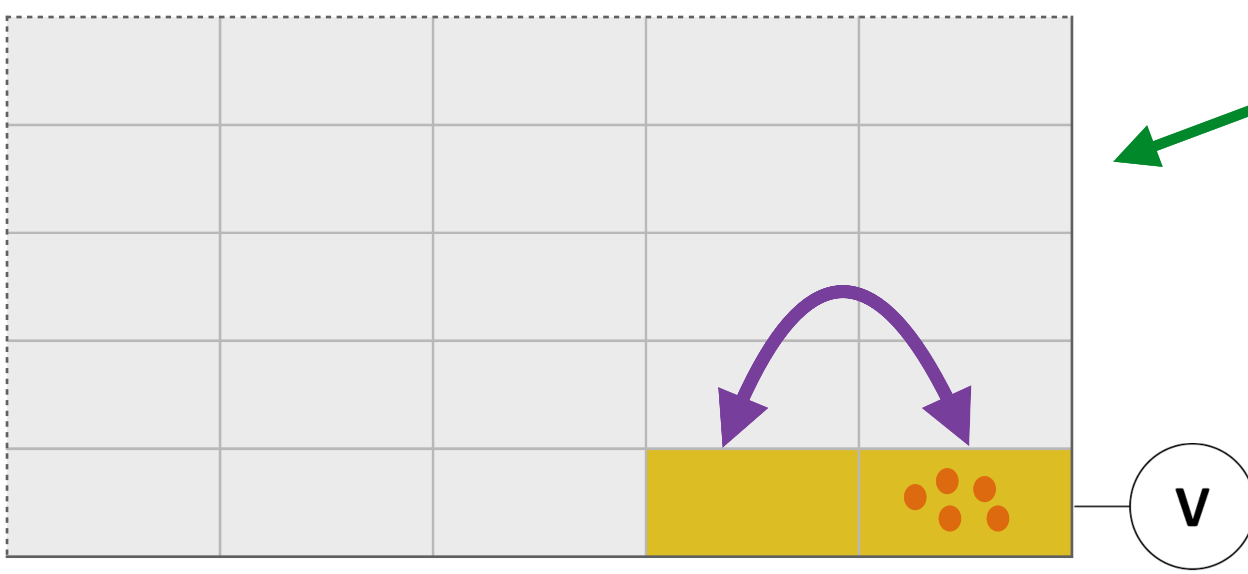
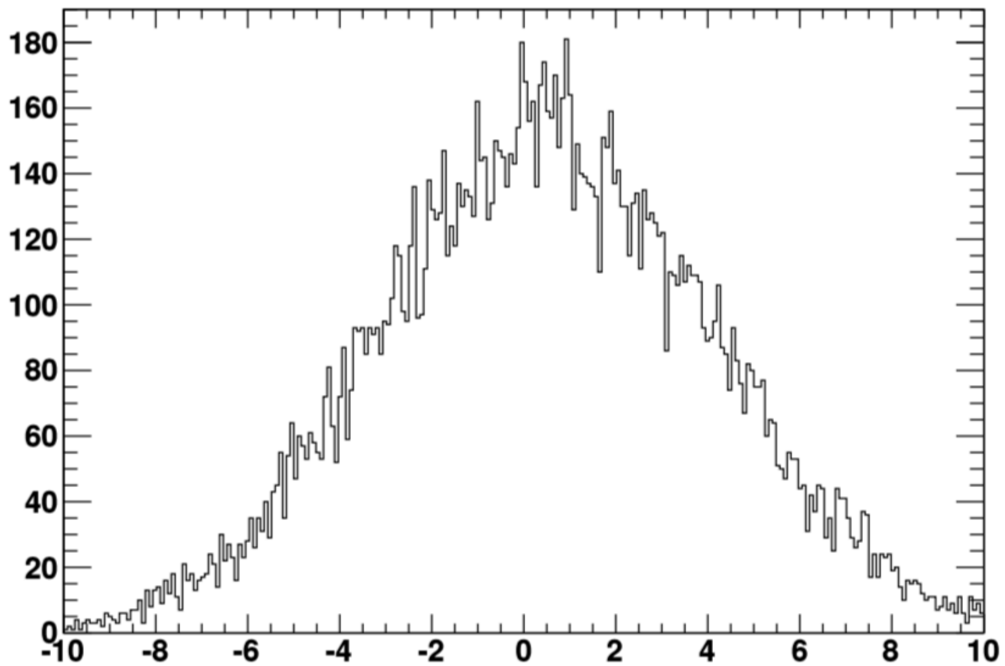


repeatedly measure charge
to achieve sub-electron
readout noise

Can count individual electrons, w/ ~zero noise

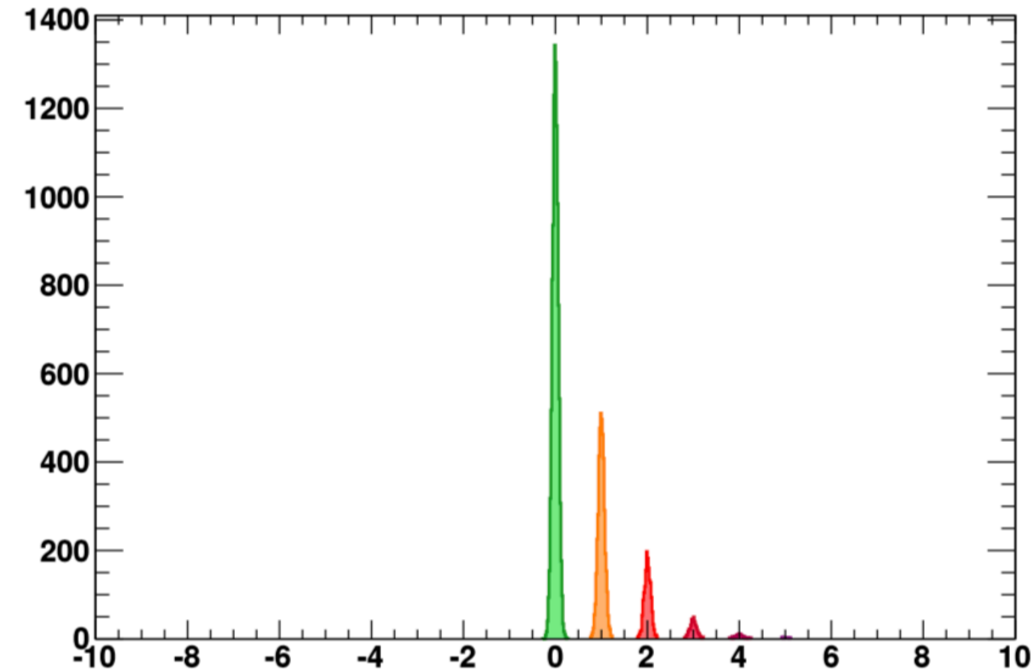
Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, PRL)

Si: traditional CCD



electron-hole pairs

Si: Skipper-CCD



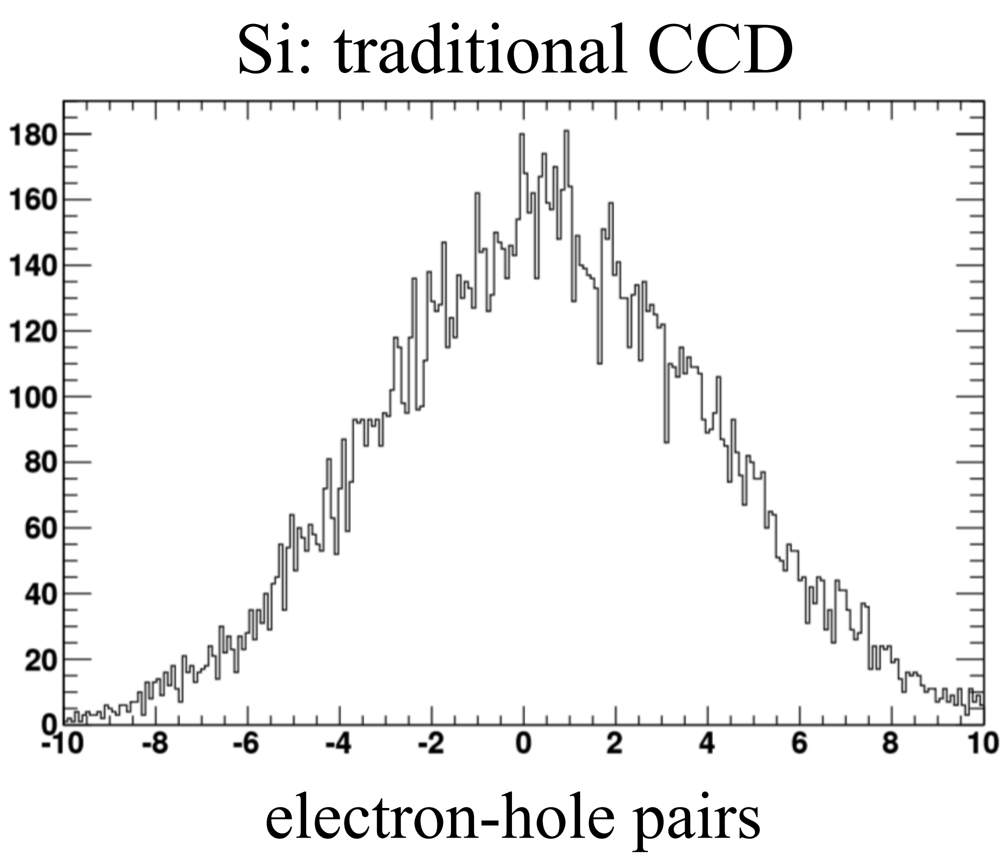
electron-hole pairs

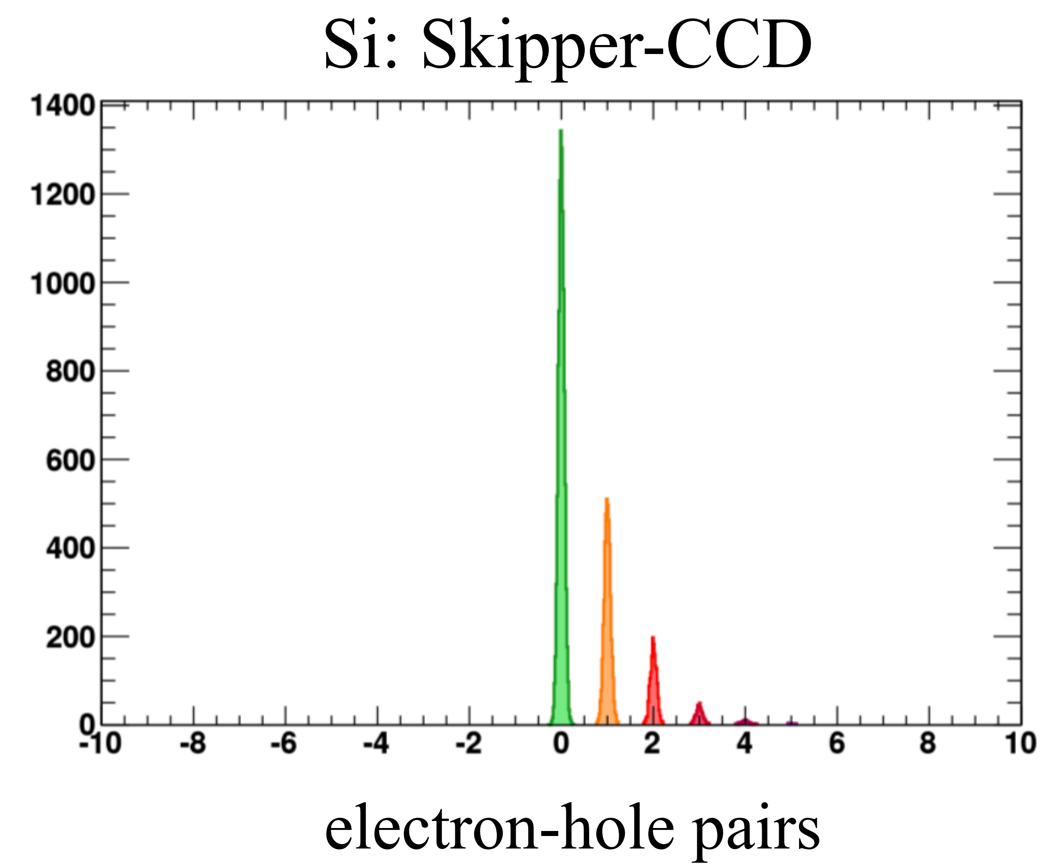
rms noise ~3 e^-
(single measurement)

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

Can count individual electrons, w/ ~zero noise

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





rms noise ~3 e^-
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(repeated measurements)

successfully demonstrated by SENSEI in a Fermilab LDRD project

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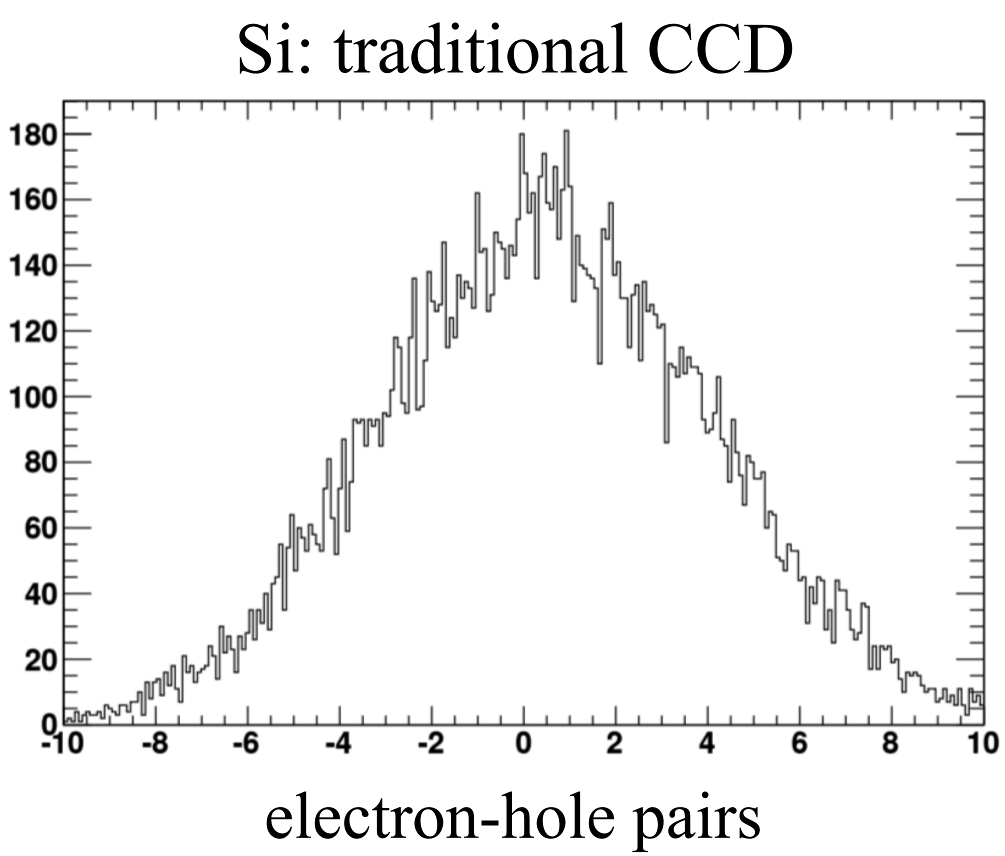
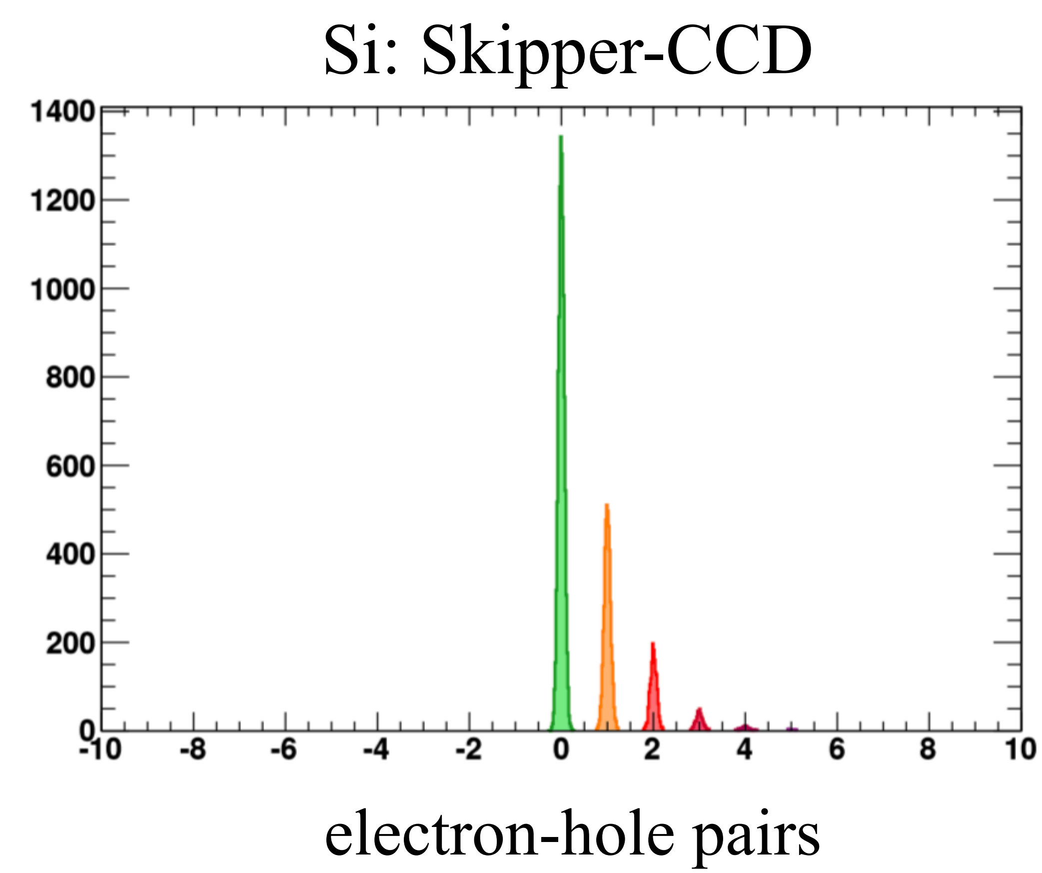
Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, PRL)





rms noise ~3 e^-
(single measurement)

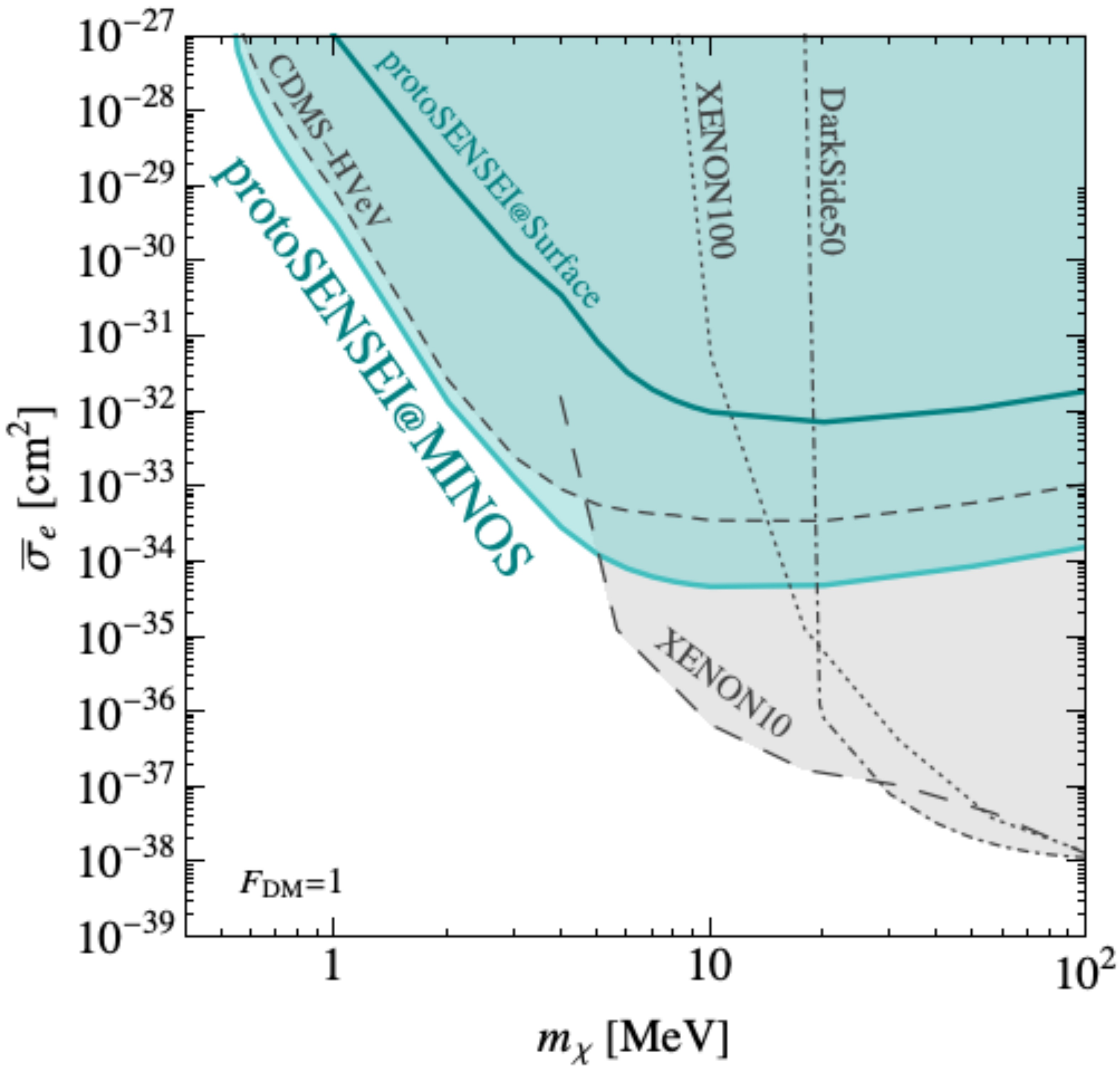
rms noise ~0.06 e^- !
(repeated measurements)

successfully demonstrated by SENSEI in a Fermilab LDRD project

enables a super-sensitive search for DM

SENSEI DM constraints from a ~0.1 gram prototype

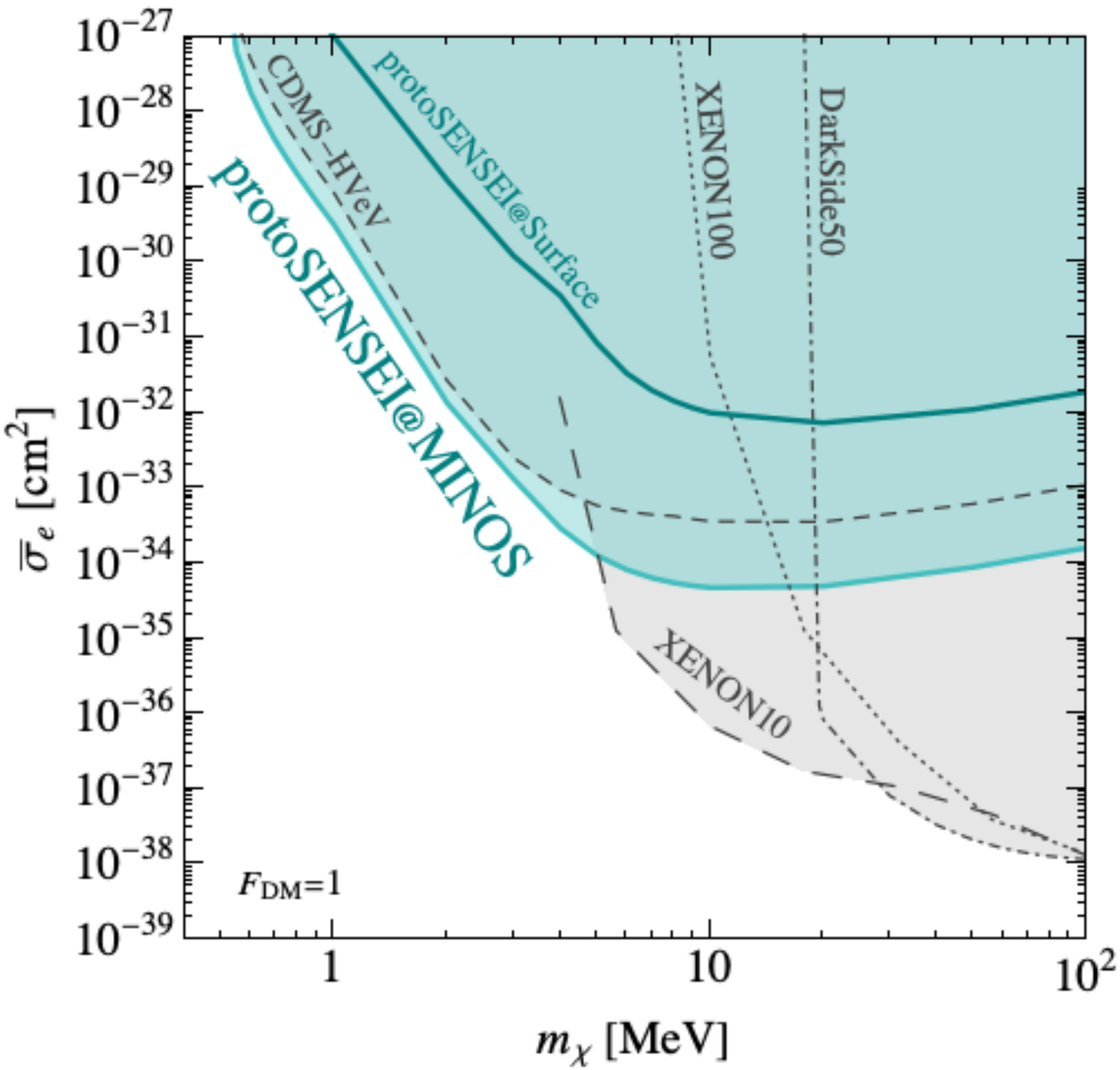
SENSEI Collaboration,
1804.00088 & 1901.10478, PRL



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

SENSEI DM constraints from a ~0.1 gram prototype

SENSEI Collaboration,
1804.00088 & 1901.10478, PRL



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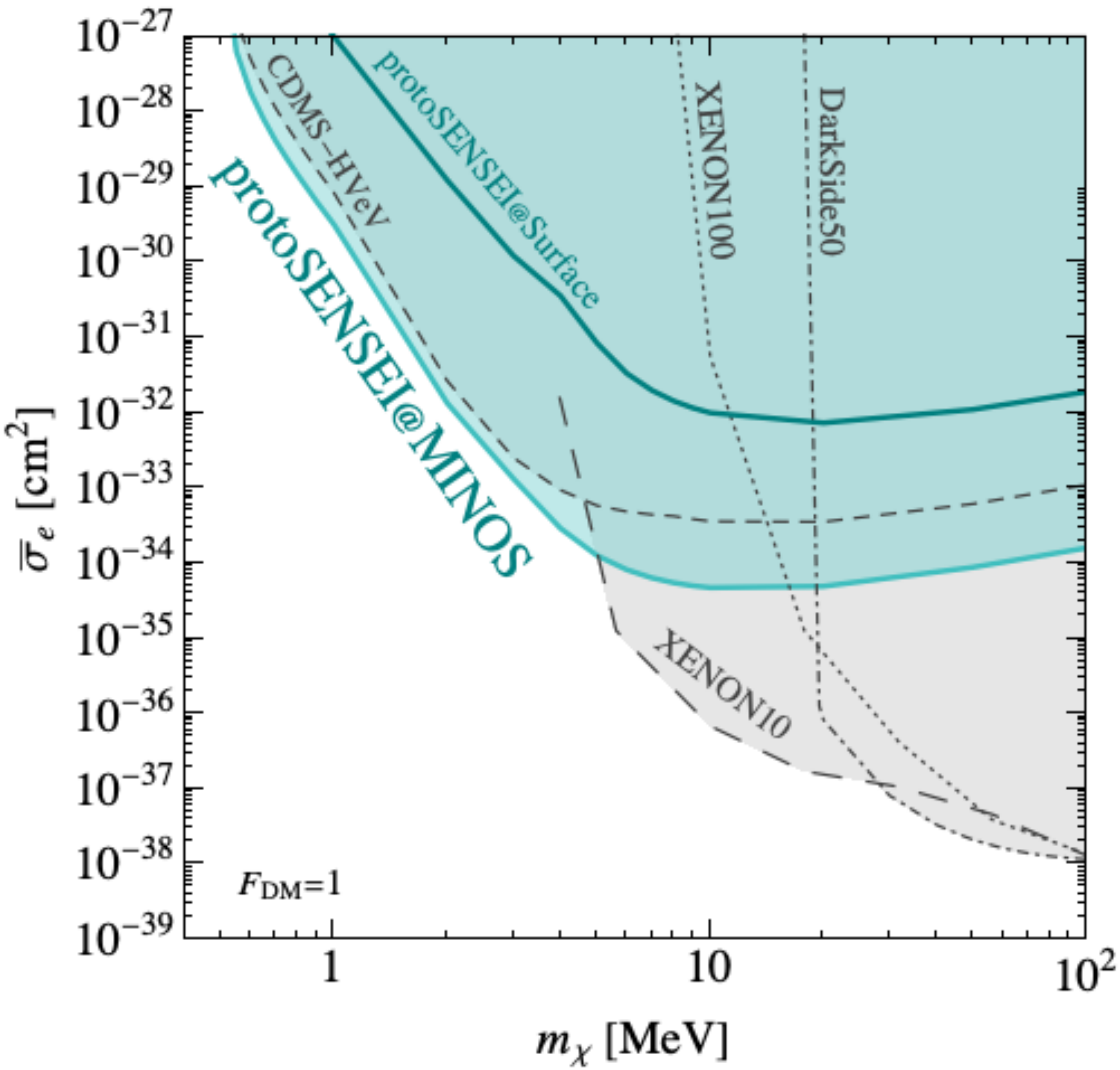
SENSEI DM constraints from a ~0.1 gram prototype

SENSEI Collaboration,
1804.00088 & 1901.10478, PRL



- tiny exposures:
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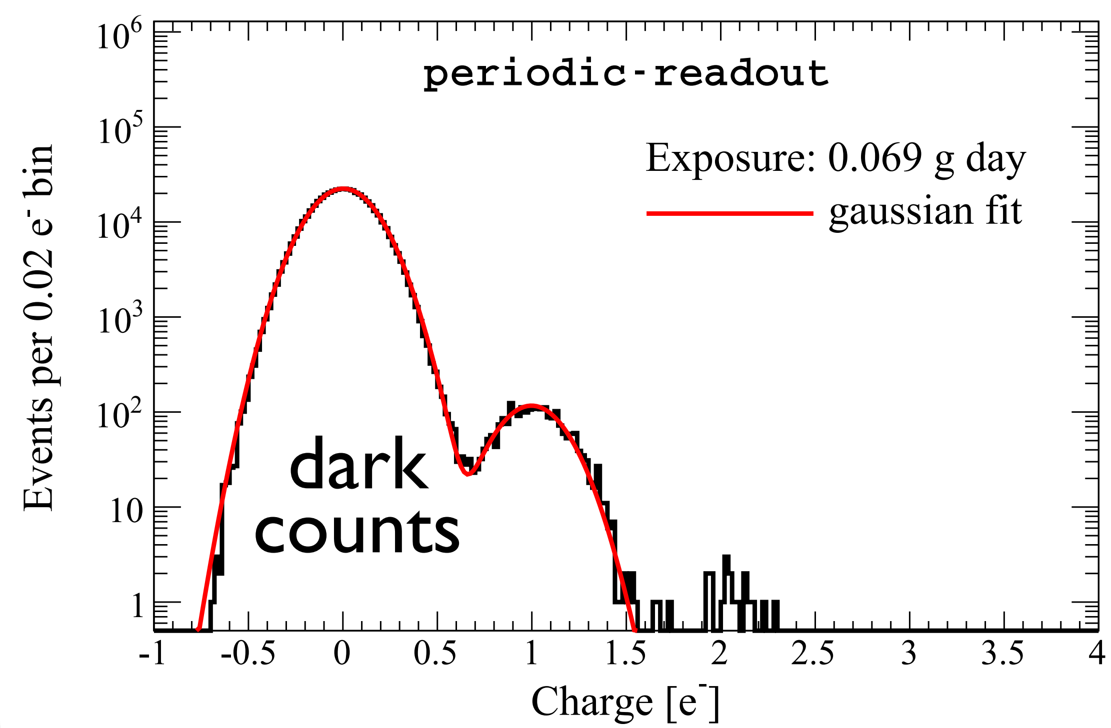
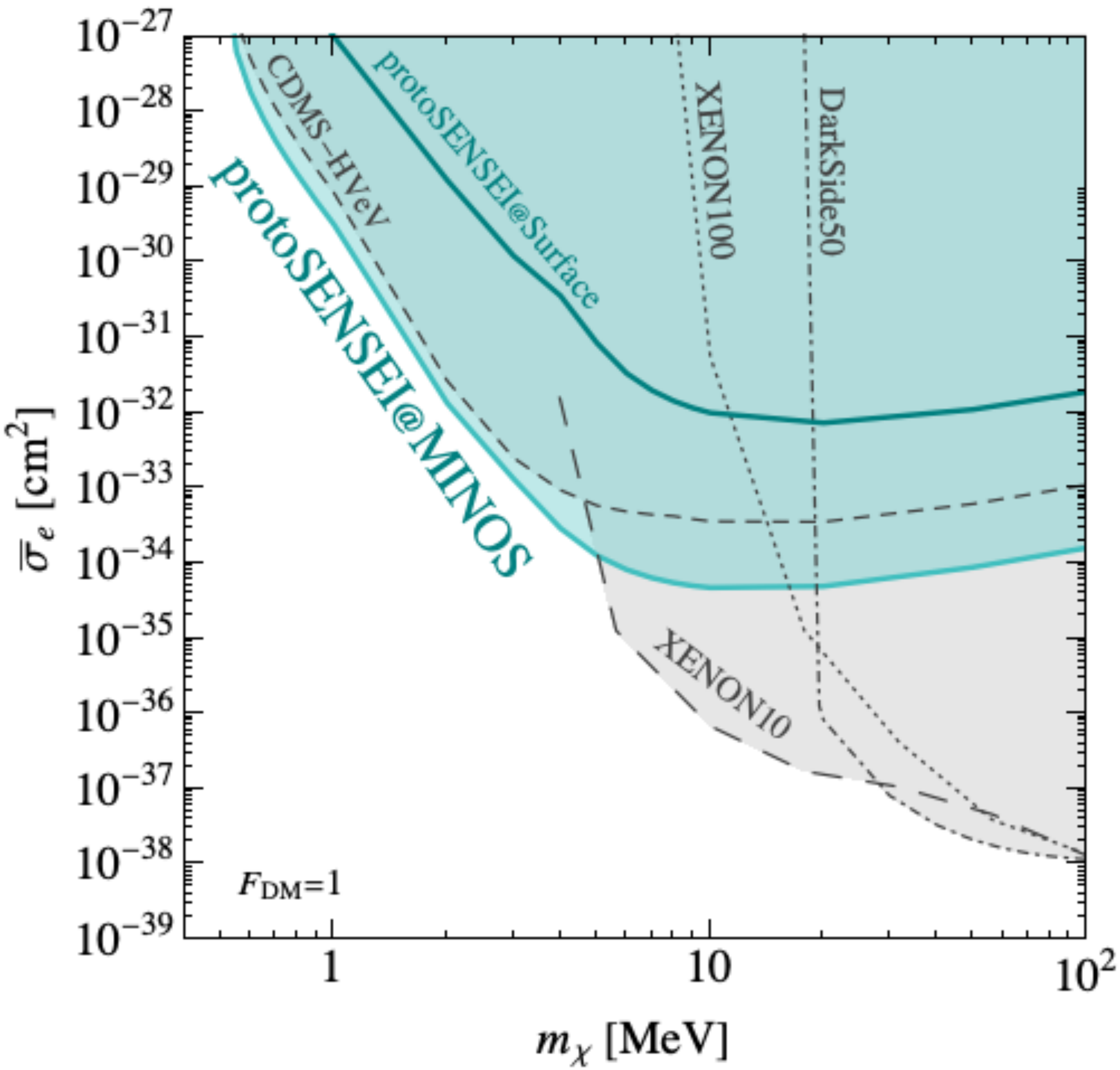
currently limited by exposure (not backgrounds) for $n_e > 2$



SENSEI DM constraints from a ~0.1 gram prototype

SENSEI Collaboration,
1804.00088 & 1901.10478, PRL



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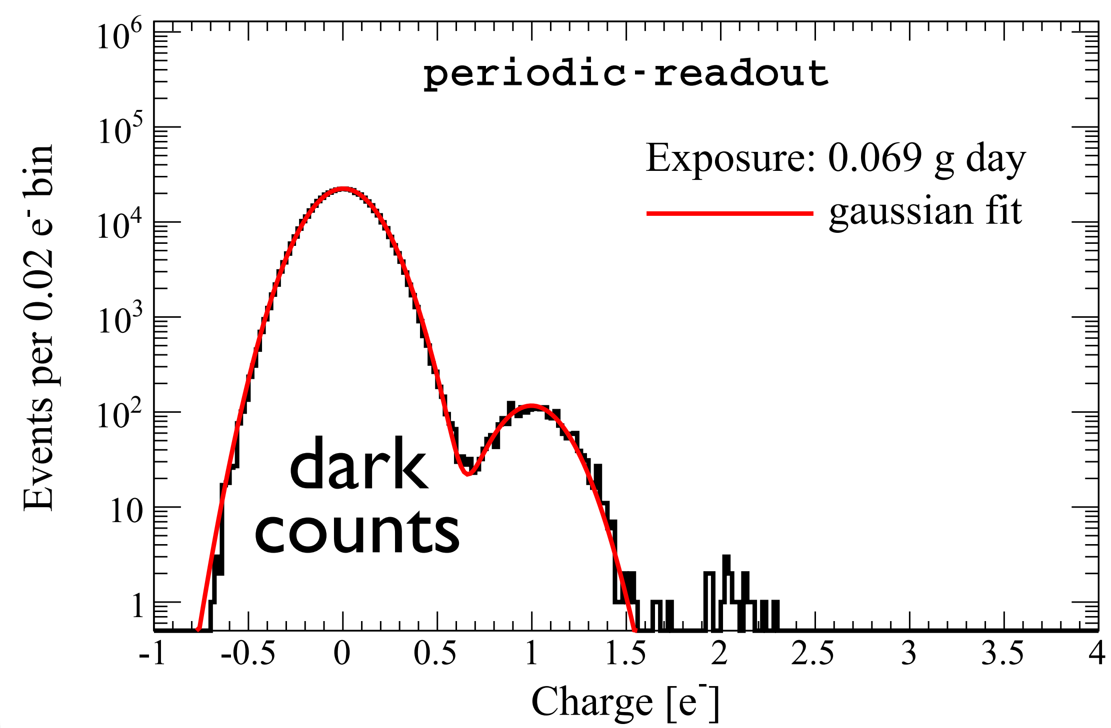
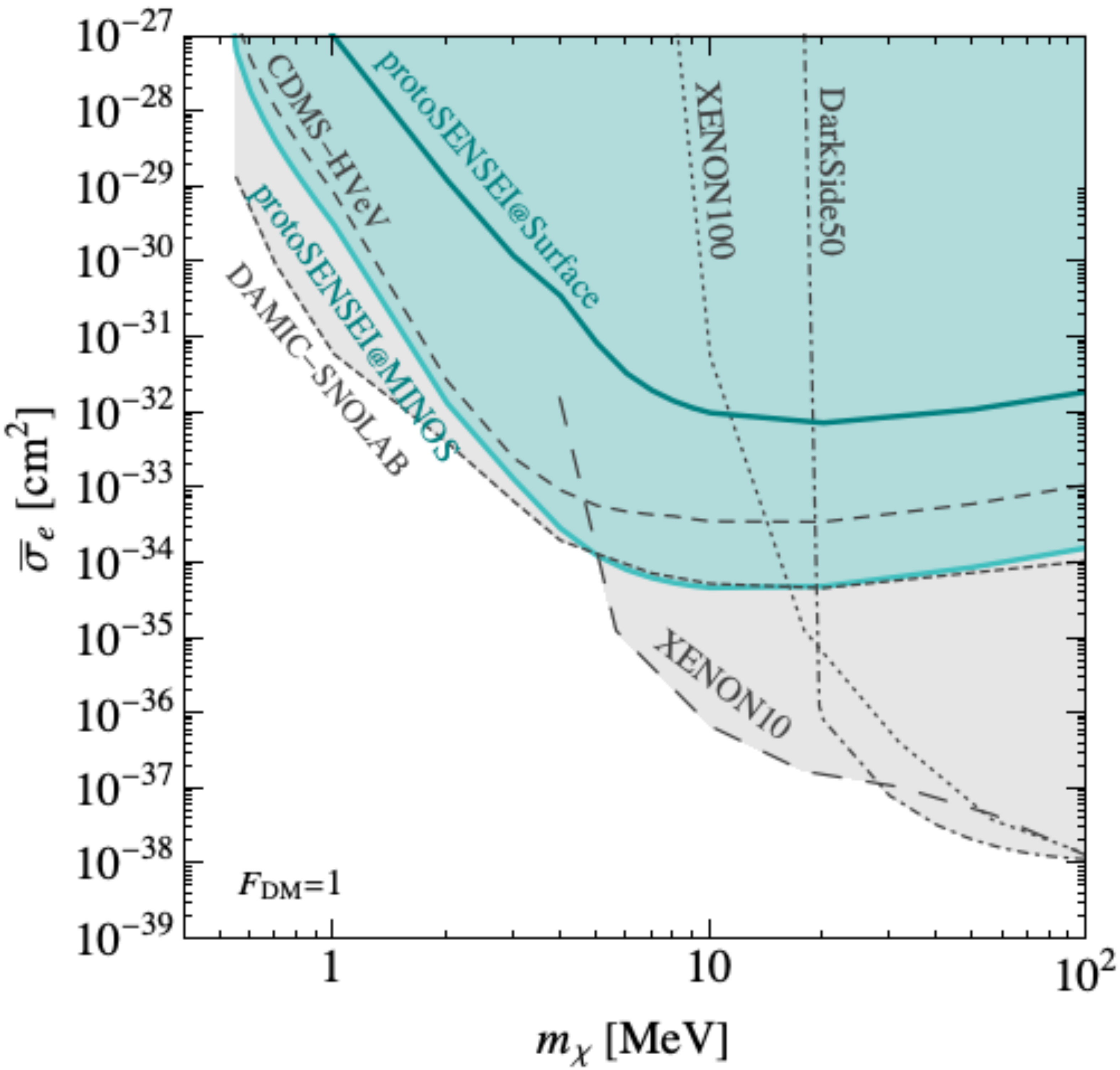


expect even better performance from science-grade sensors

SENSEI DM constraints from a ~0.1 gram prototype

SENSEI Collaboration,
1804.00088 & 1901.10478, PRL



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

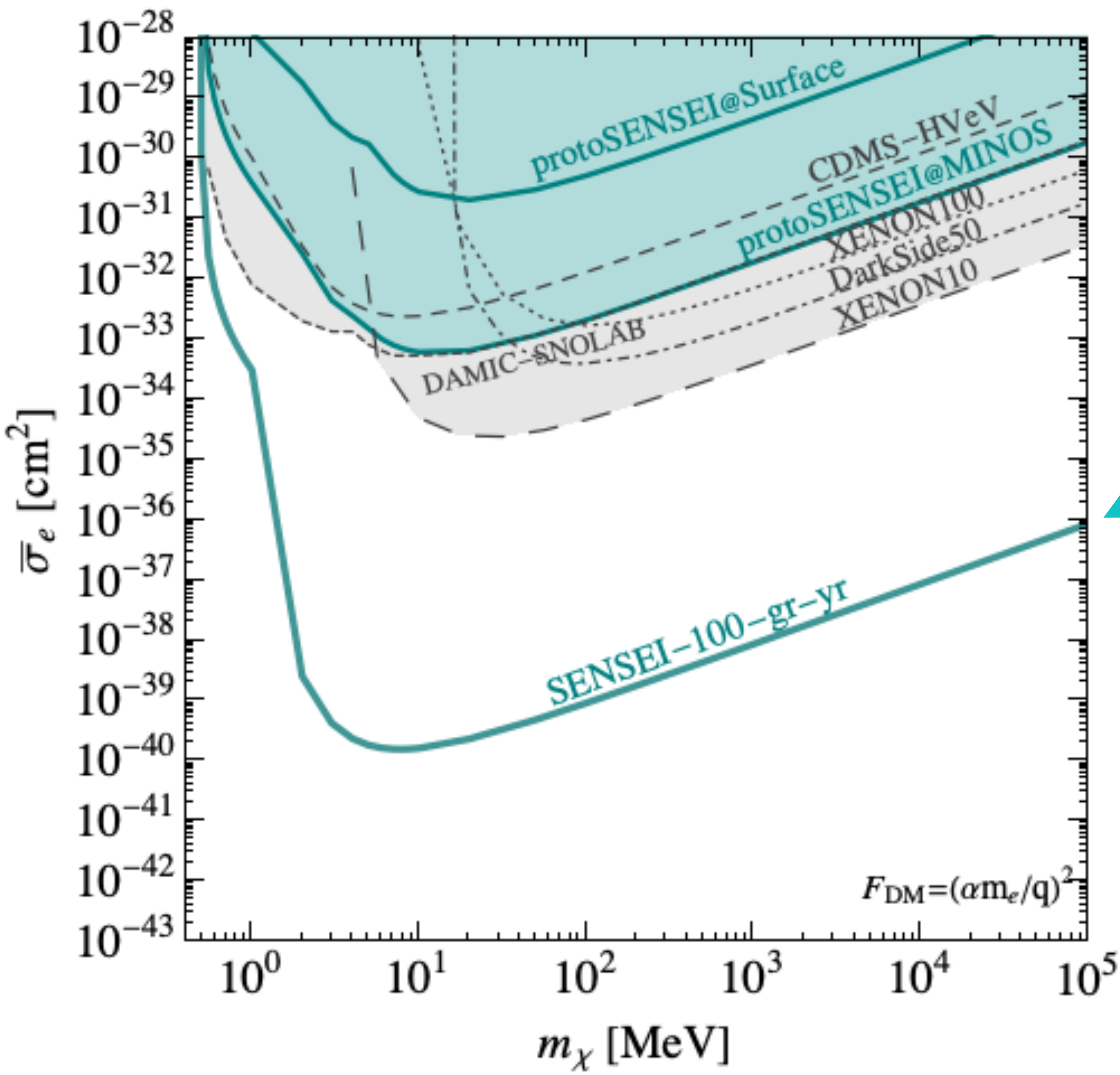
DAMIC@SNOLAB

- uses ordinary CCDs
- have lower dark counts compared to our prototype detectors
- ~200 gram-days

1907.12628

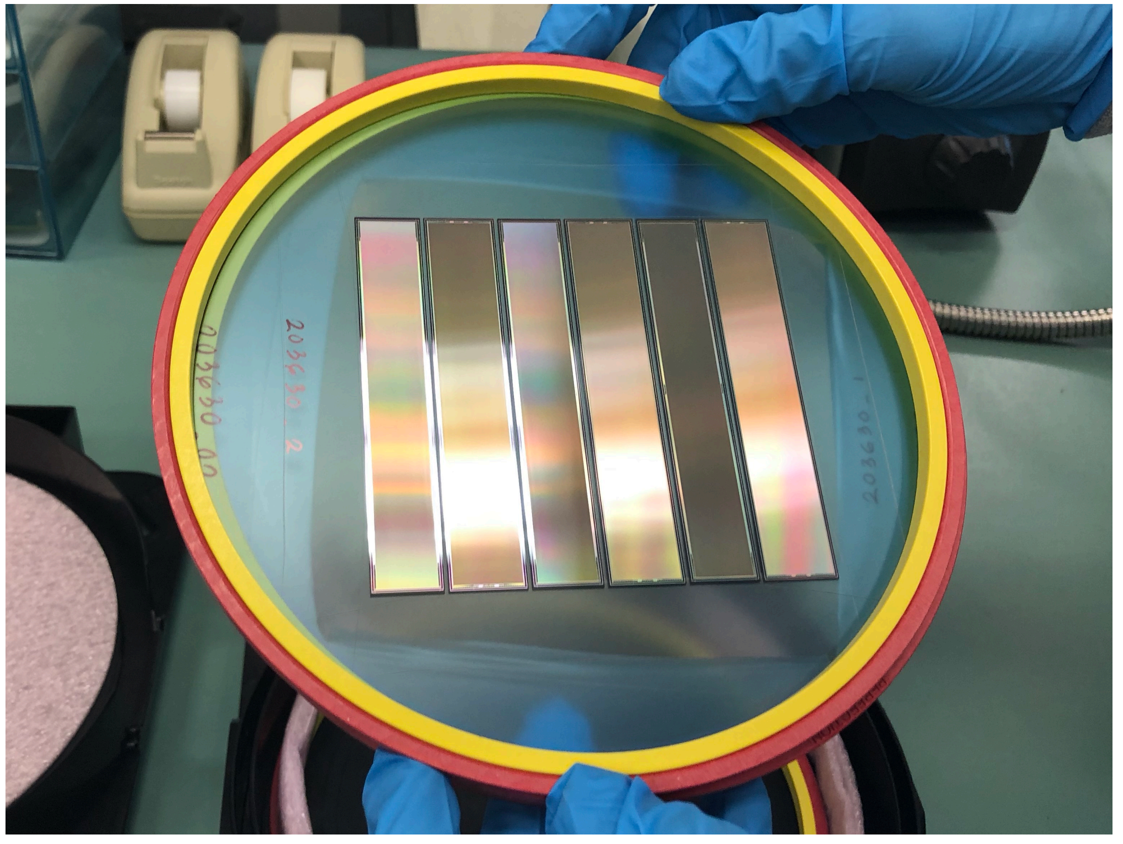
see talk by P. Privitera

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

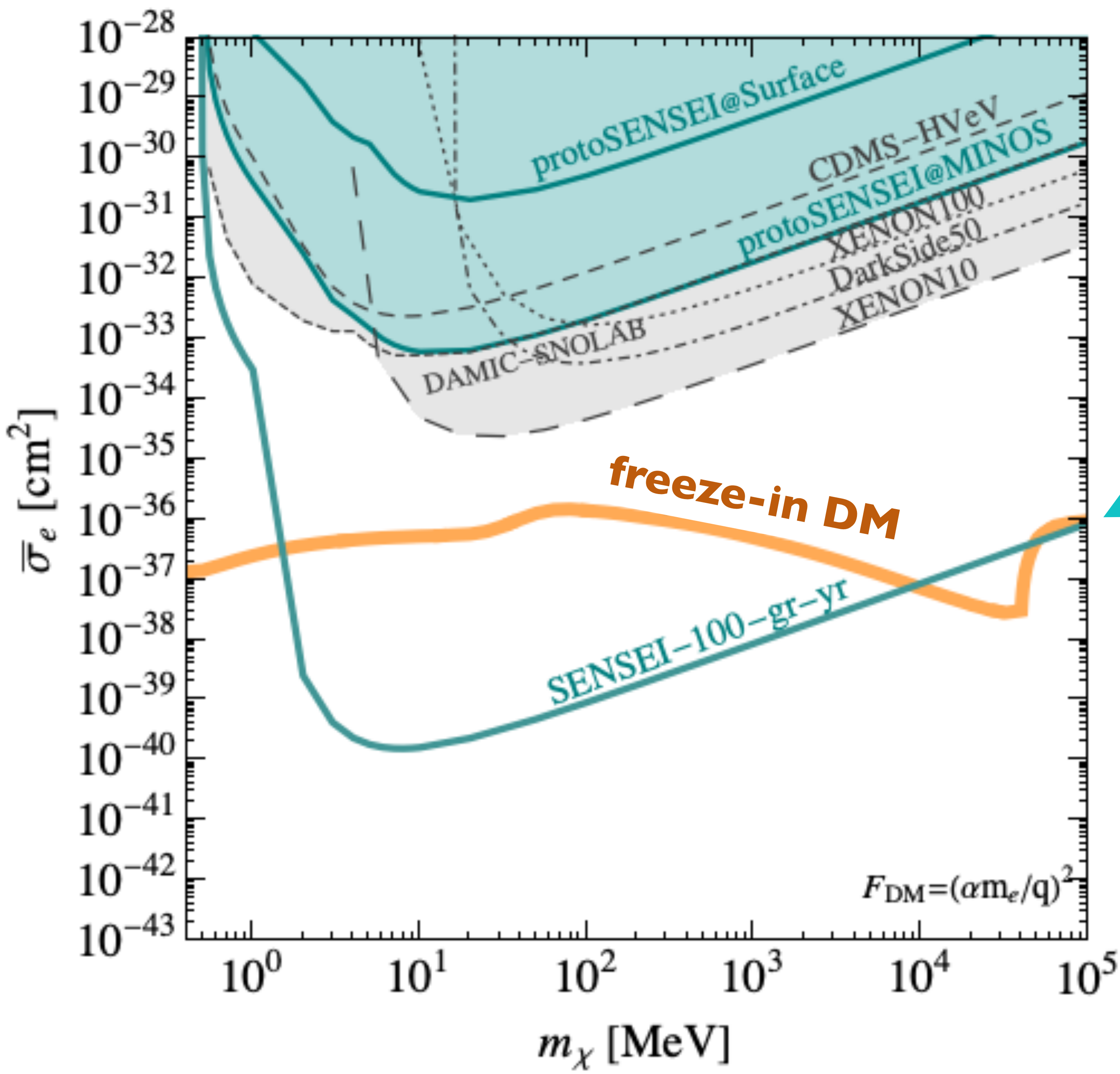


SENSEI: 100 g @ SNOLAB
(funded, 2020)

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
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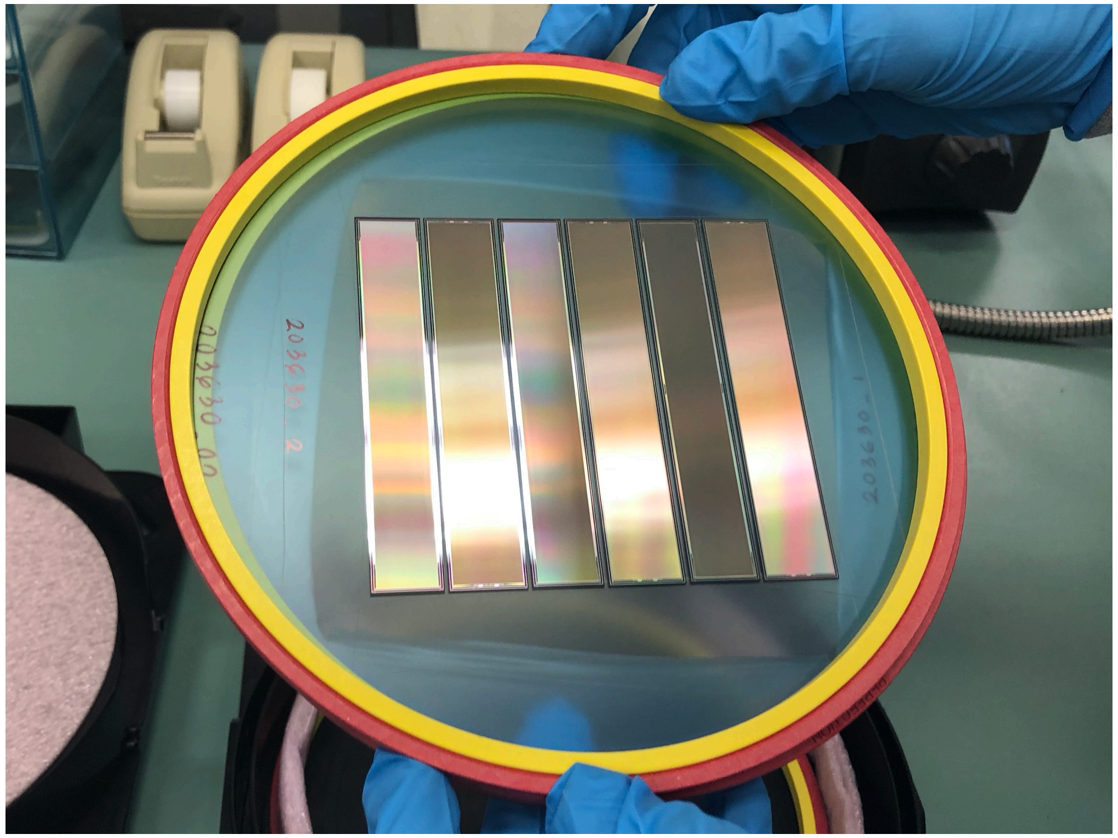
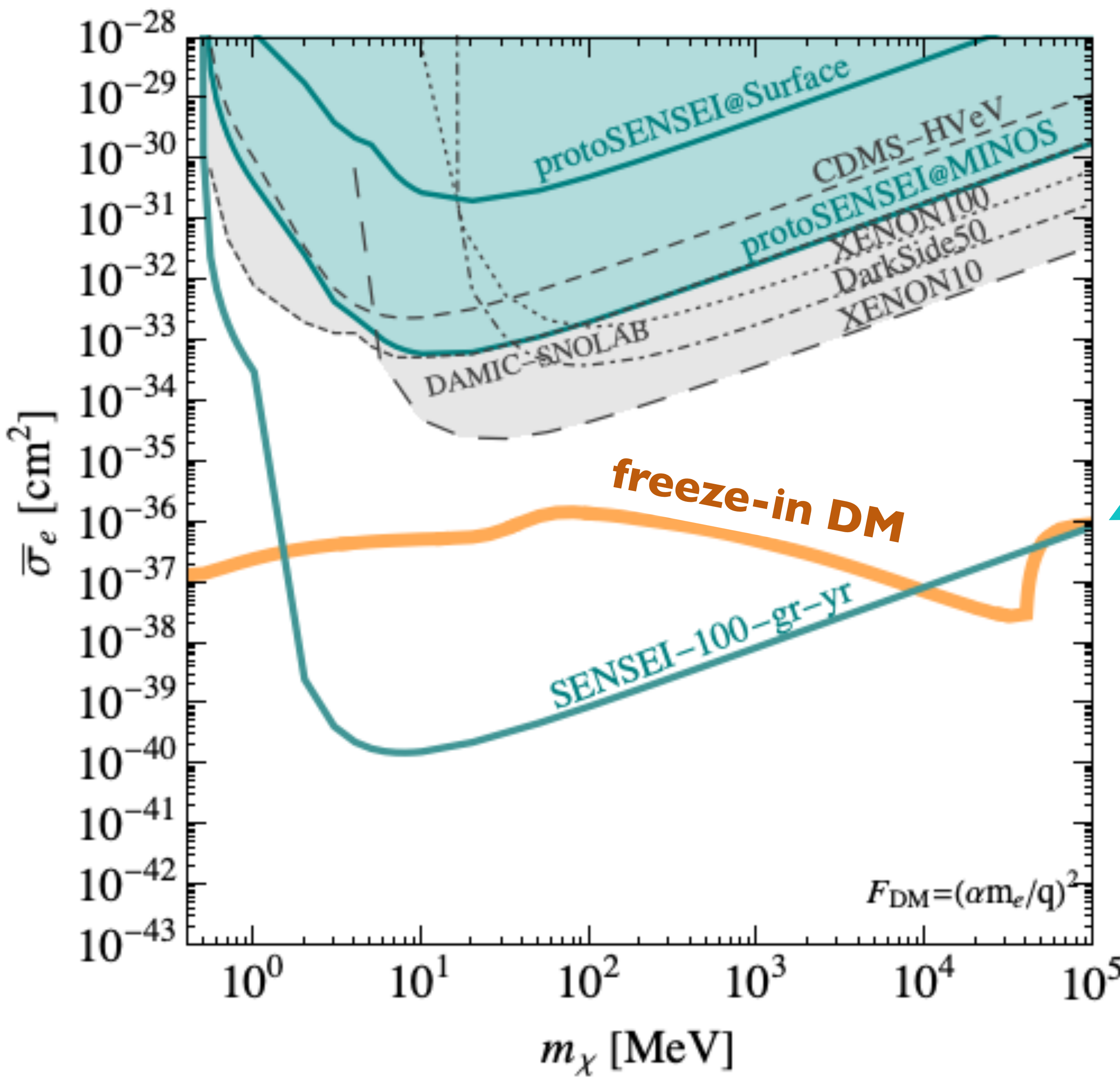


SENSEI projection for 100 g of science-grade Skipper-CCDs



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SENSEI: 100 g @ SNOLAB (funded, 2020)

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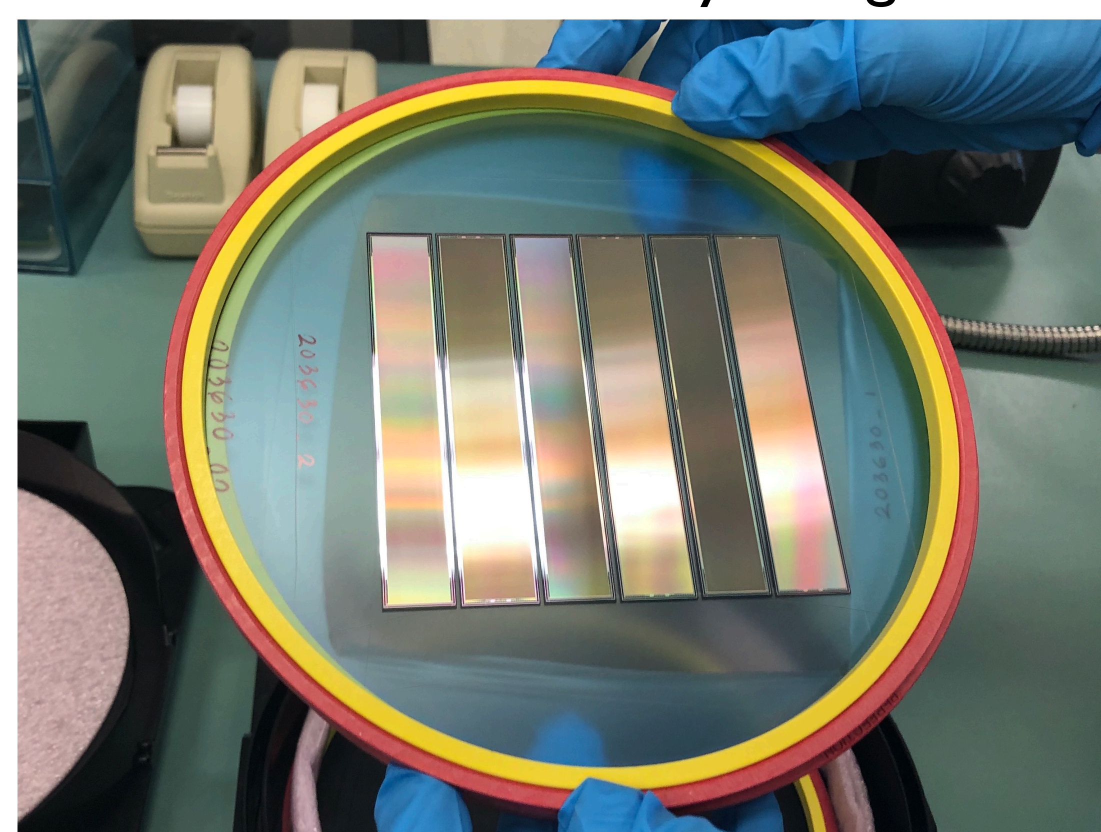
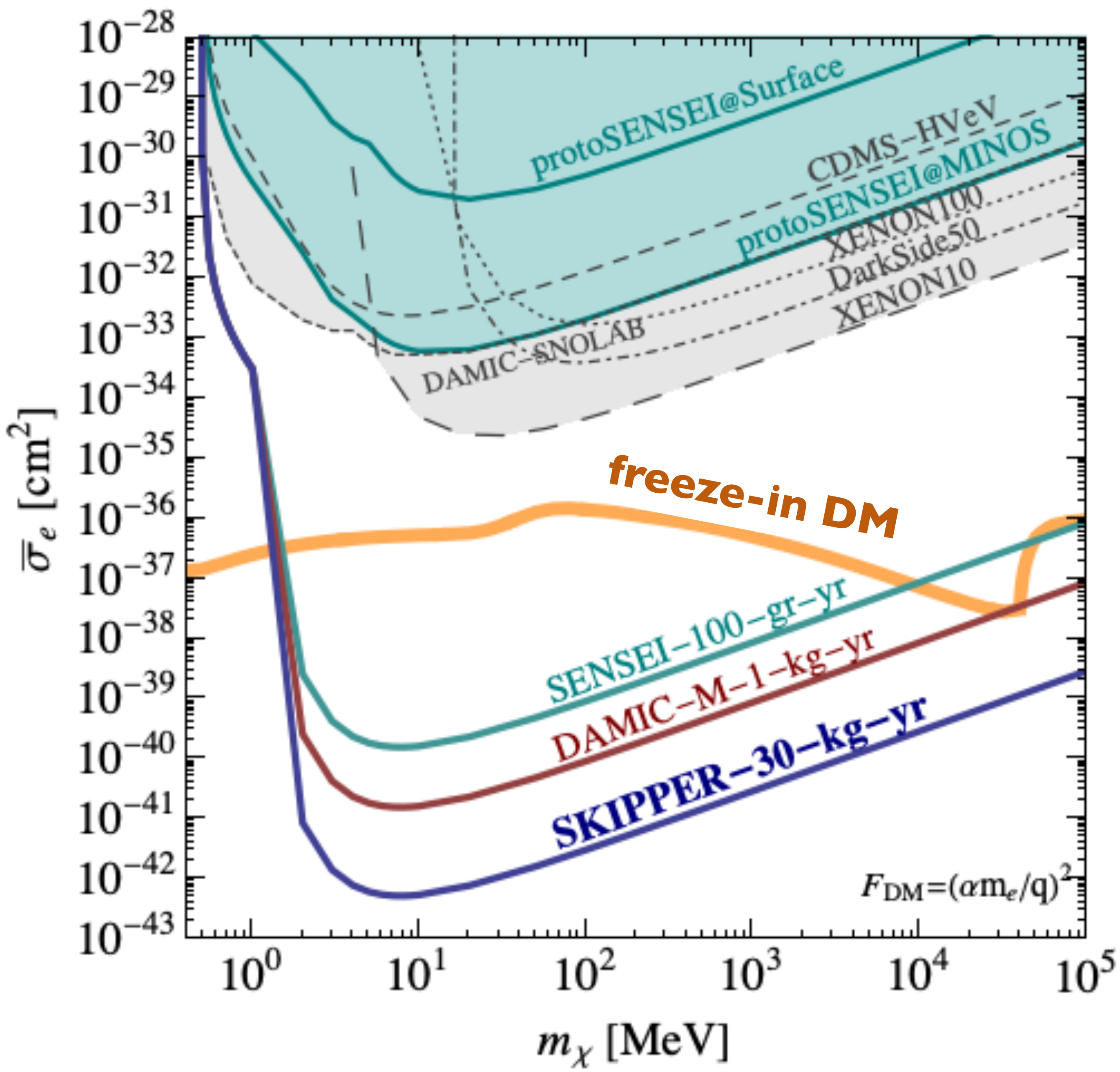


[see backup slides for other models like SIMP, ELDER, freeze-out, asymmetric]

SENSEI & other planned Skipper-CCD detectors



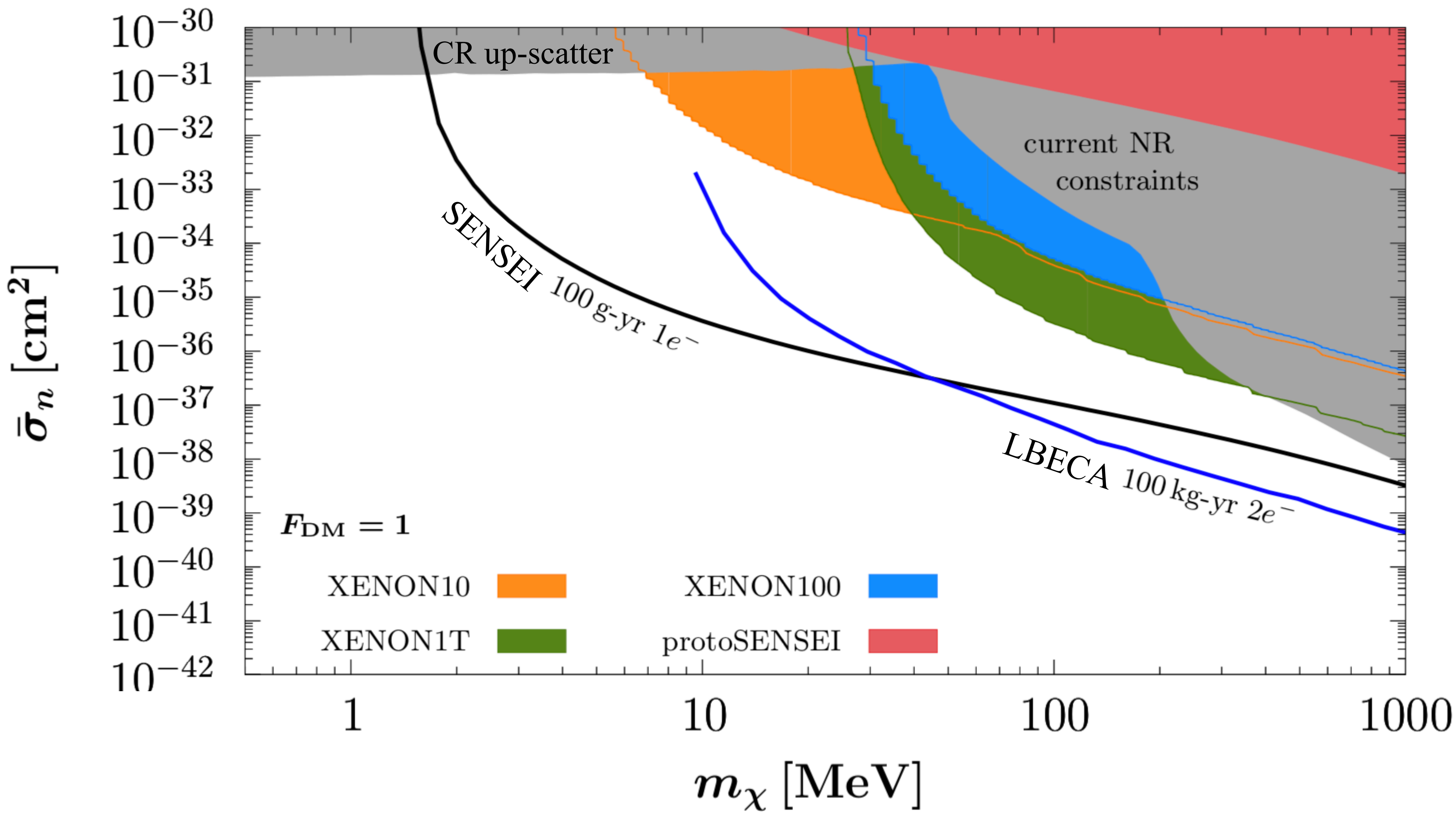
SENSEI: 100 g @ SNOLAB
(funded, 2020)

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

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

J. Estrada, A. Chavarria, RE, B. Loer, P. Privitera;
M. Crisler, M. Fernandez-Serra, R. Saldanha, J. Tiffenberg

Sensitivity to nuclear scattering from Migdal effect



XENON10 sets best limit between 5 to 30 MeV

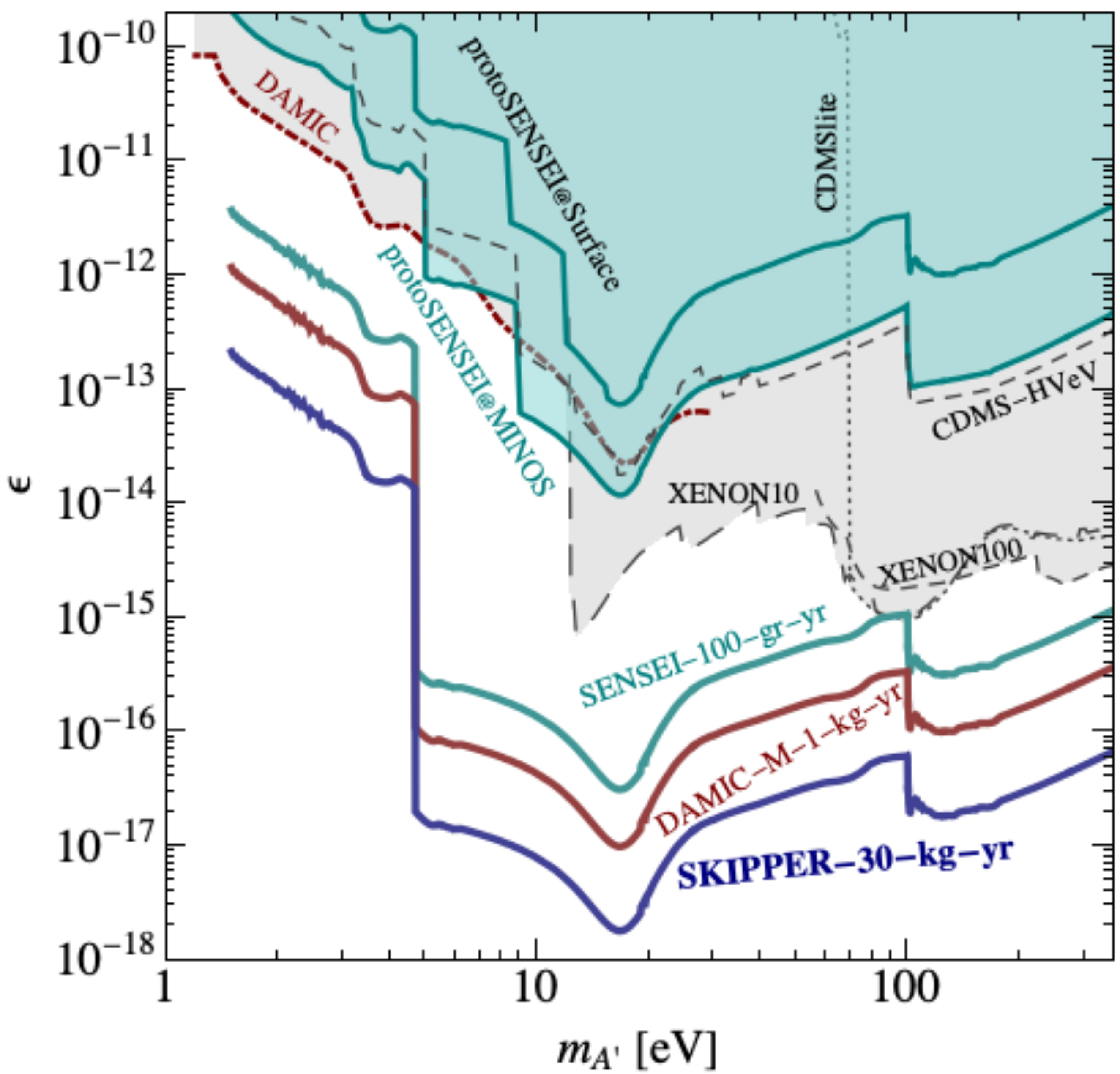
LBECA, SENSEI, DAMIC-M, OSCURA, … will probe orders of magnitude of new parameter space

plot from RE, Pradler, Sholapurkar, Yu

see also Baxter, Kahn, Krnjaic

Absorption of dark photon DM

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



SENSEI: 100 g @ SNOLAB

DAMIC-M: 1 kg gram @ Modane

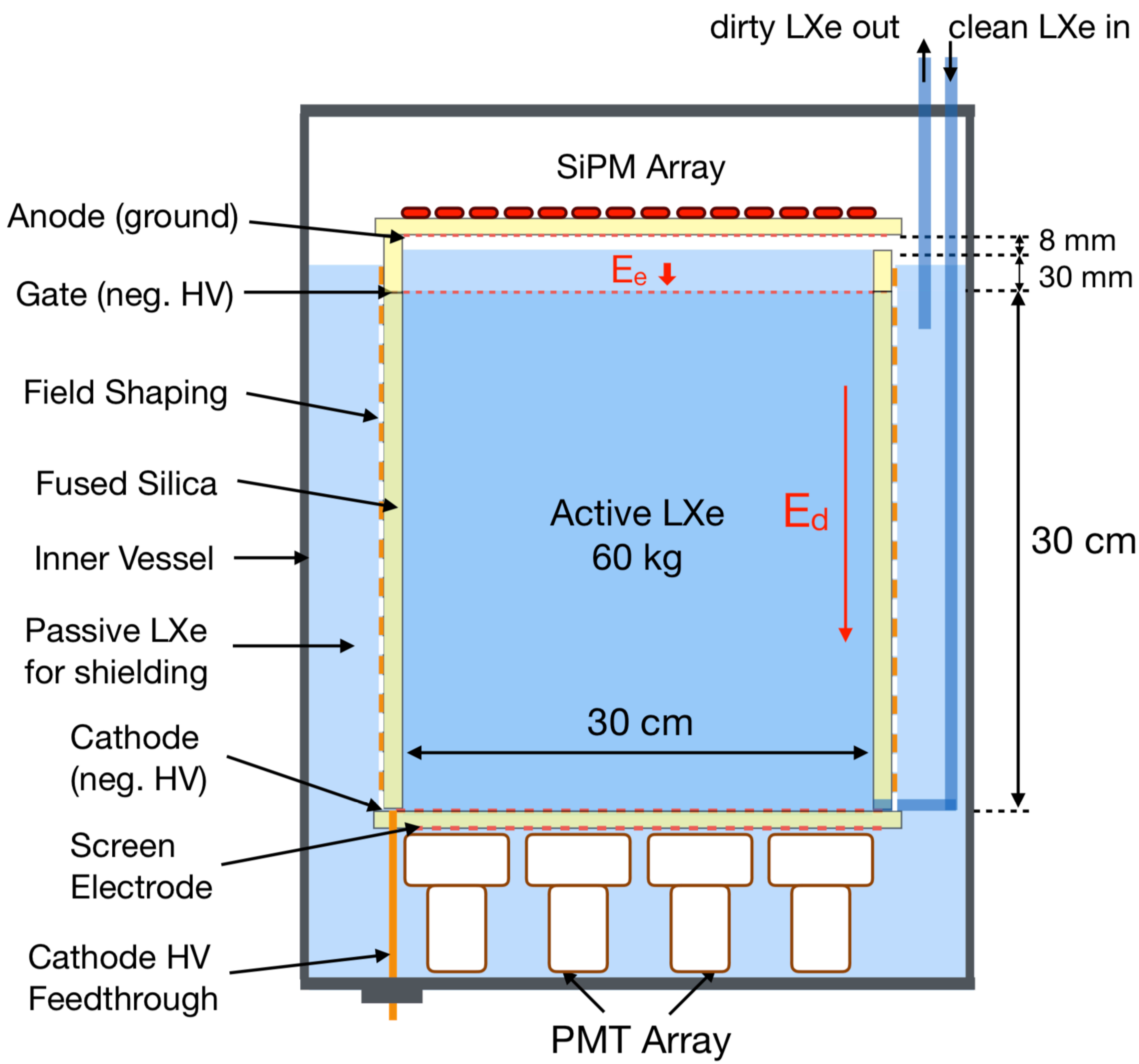
OSCURA: 10 kg

Summary

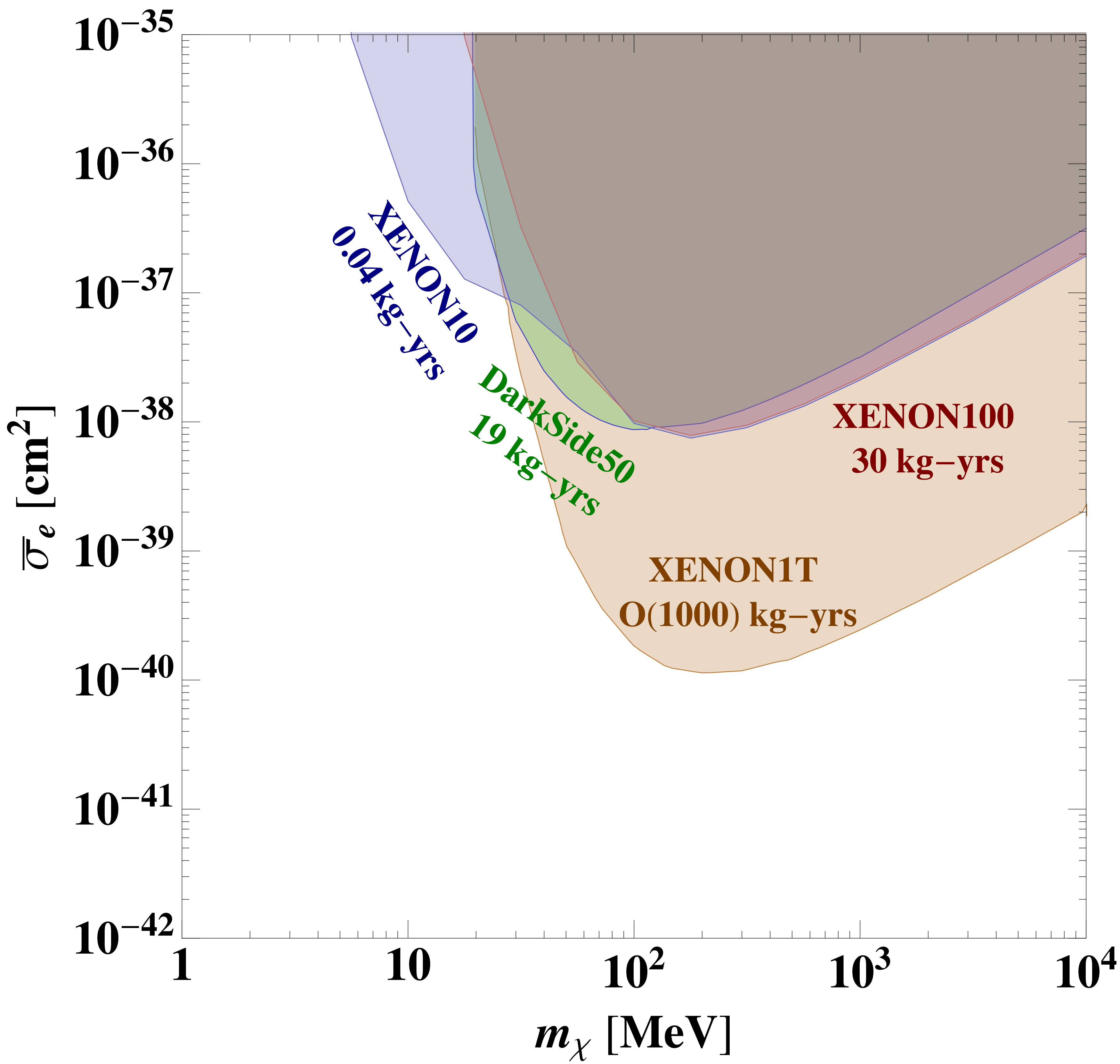
- Direct detection down to ~MeV DM is possible, with significant progress in theory and instrumentation in past <10 years
- Expect SENSEI, DAMIC-M, OSCURA, LBECA, SuperCDMS, … to probe vast regions of uncharted territory in next few years
- Expect Sub-MeV range to open up after further R&D (detection concepts exist)
- Direct detection and accelerator-based searches probe overlapping as well as complementary parameter space; need both to maximize discovery chances and understand DM

Thank you!

LBECA design



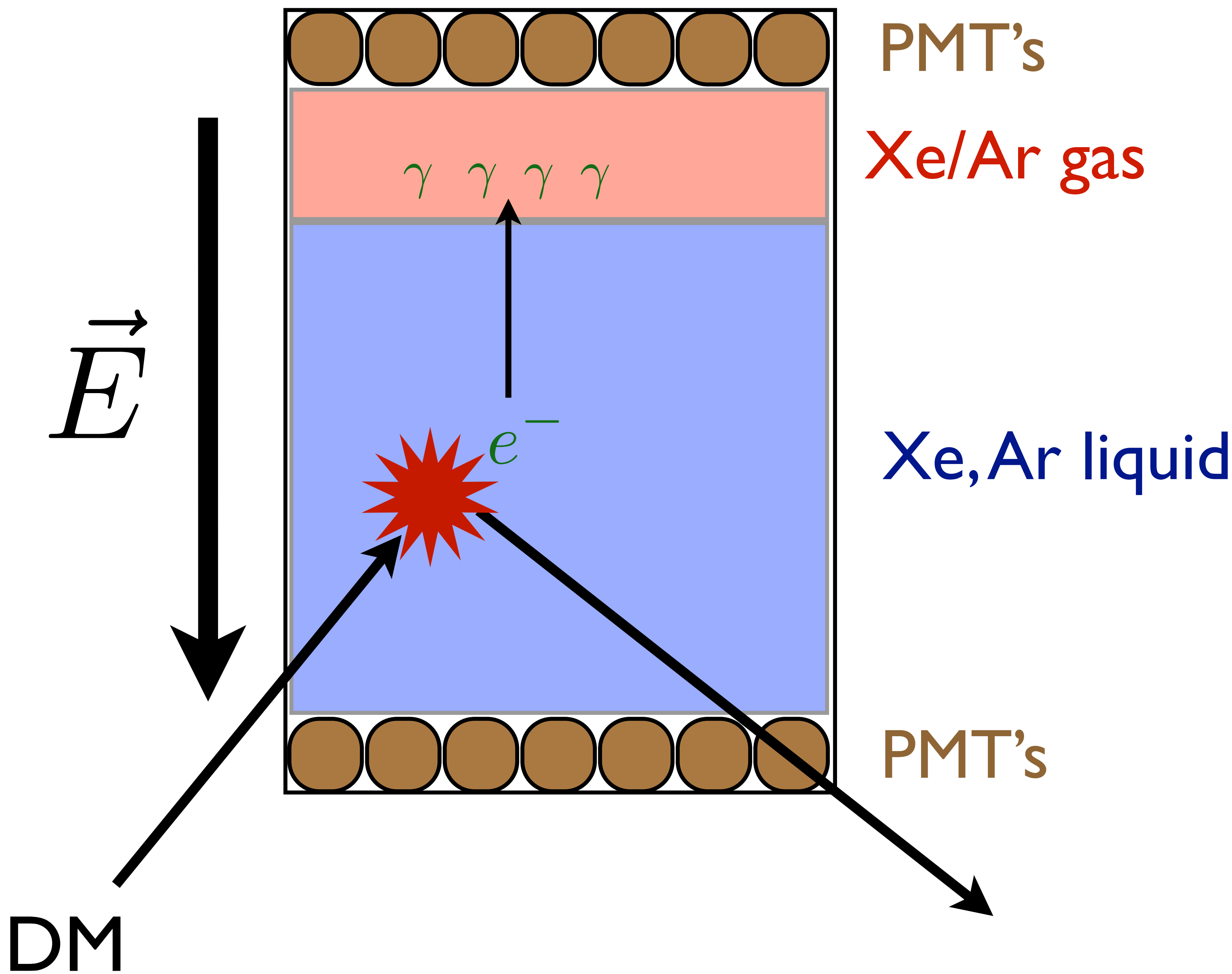
Best current constraints on DM-e⁻ scattering >5 MeV from liquid xenon/argon detectors



RE, Mardon, Volansky, 2011
RE, Manalaysay, Mardon, Sorensen, Volansky, 2012
RE, Volansky, Yu 2017
DarkSide-50, 2018
XENON1T, 2019

XENON10: 1104.3088
XENON100: 1605.06262
DarkSide-50: 1802.06998
XENON1T: 1907.11485

Detection Concept

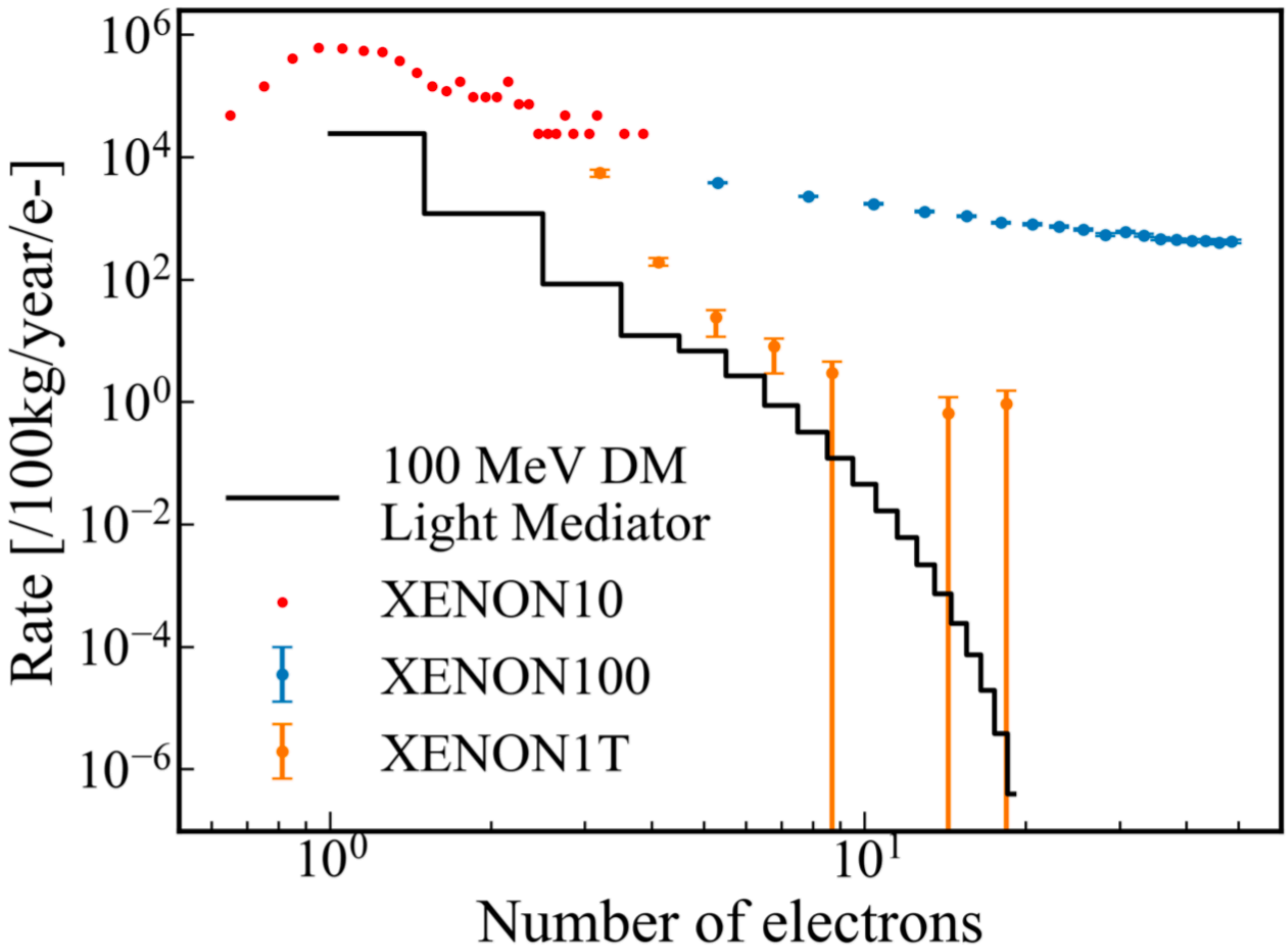


Sensitive to single electrons!

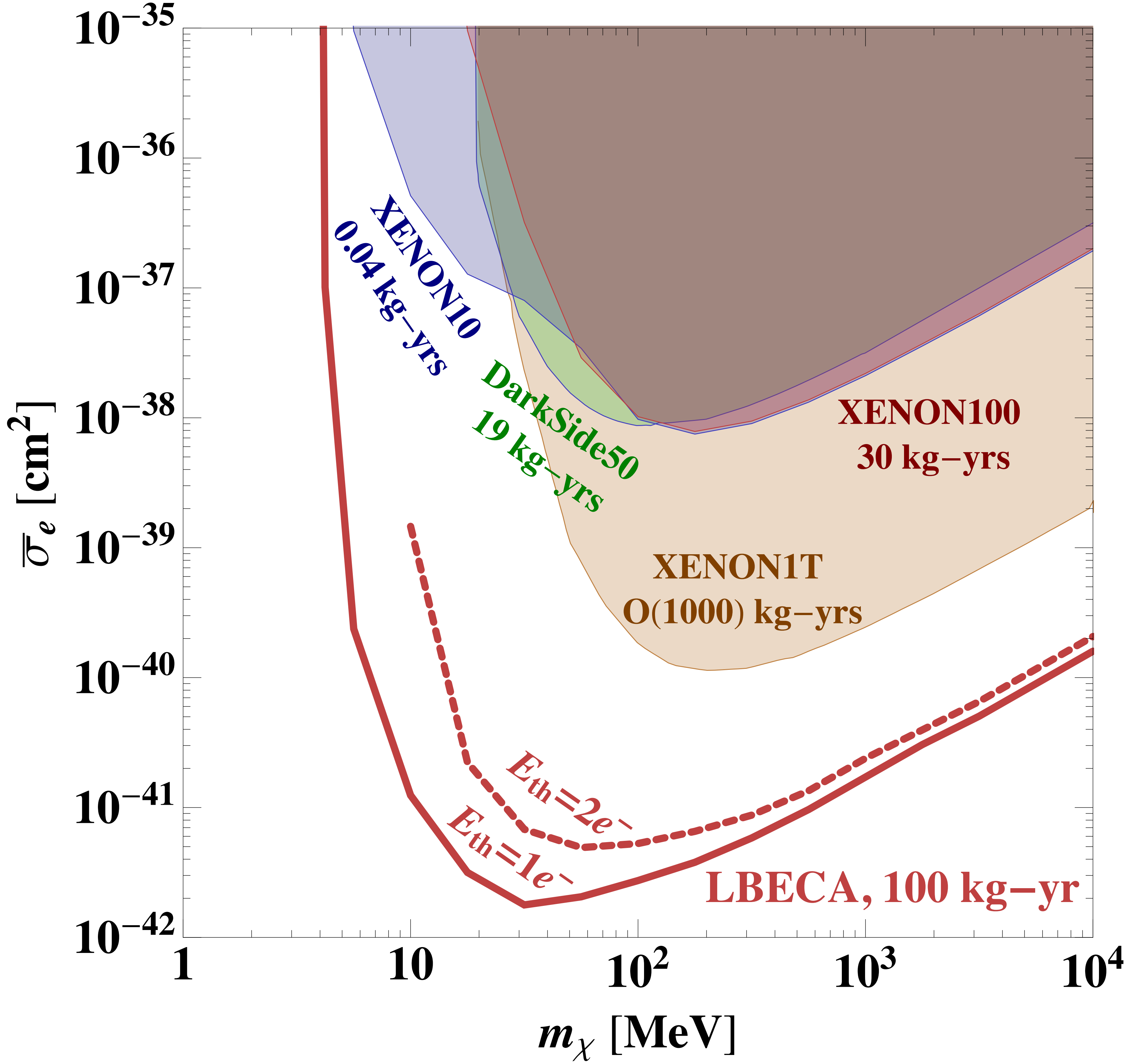
But large backgrounds:

- delayed e^- extraction across liquid-gas interface
- photoionization of negatively charged impurities
- exposed metal surfaces

Current xenon/argon detectors are background limited



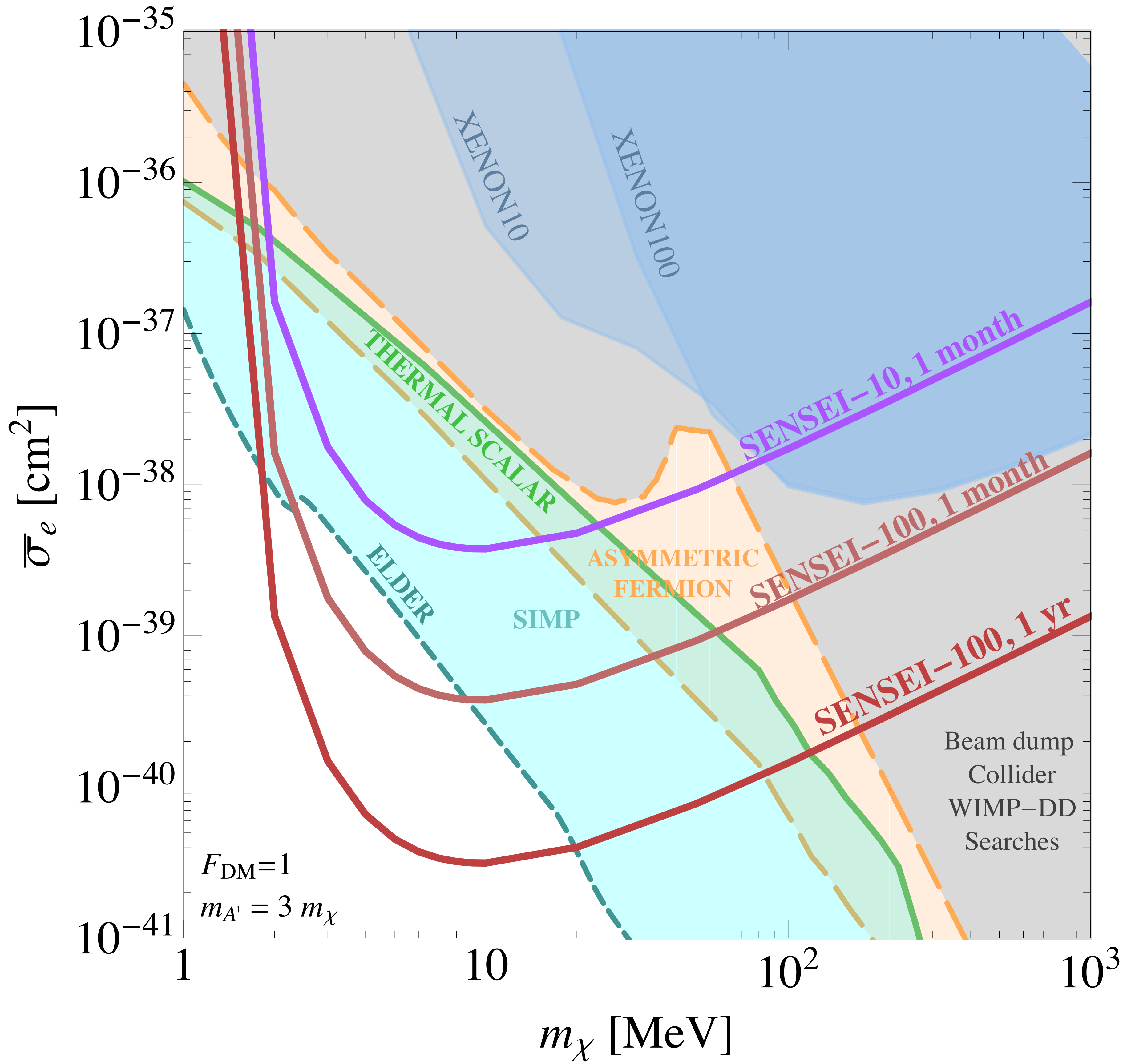
Proposed Experiment: LBECA



Goal:

reduce backgrounds to explore orders of magnitude of new parameter space

SENSEI sensitivity to Benchmark Models



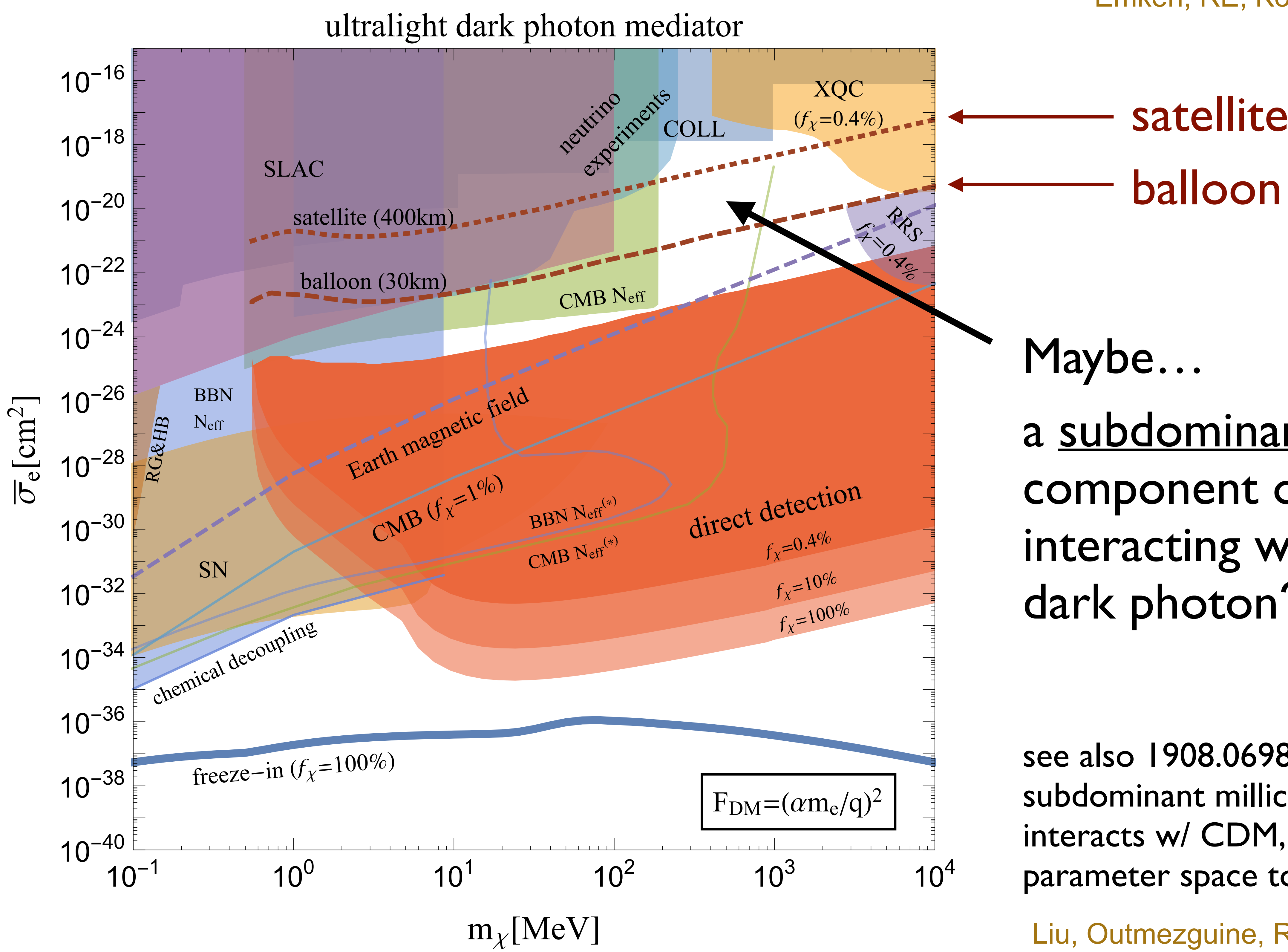
mediator: "heavy" dark photon

Models:

- thermal scalar
- asymmetric fermion
- SIMP
- ELDER
- co-scattering (not shown)

Is there a DM model w/ such large interactions?

Emken, RE, Kouvaris, Sholarpurkar



Maybe…

a <u>subdominant</u> component of DM interacting w/ ultralight dark photon?

see also 1908.06986, in which subdominant millicharged DM interacts w/ CDM, opening up more parameter space to explain EDGES

Liu, Outmezguine, Redigolo, Volansky