The next decade in the Direct Detection of sub-GeV Dark Matter

Rouven Essig

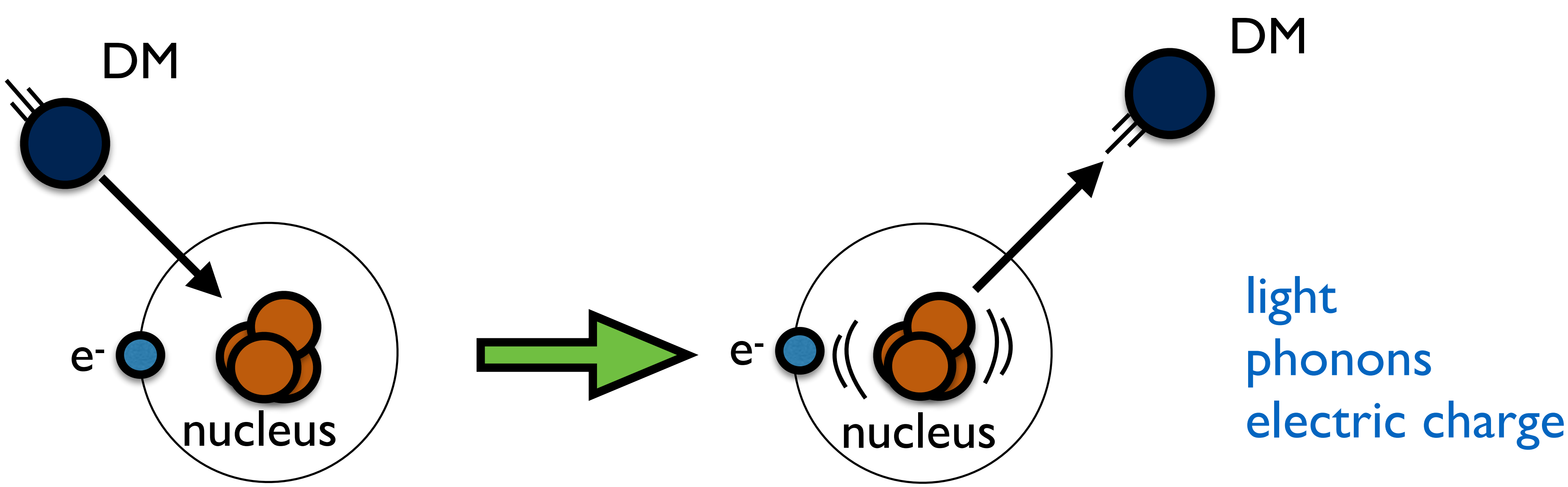
Yang Institute for Theoretical Physics

Stony Brook University

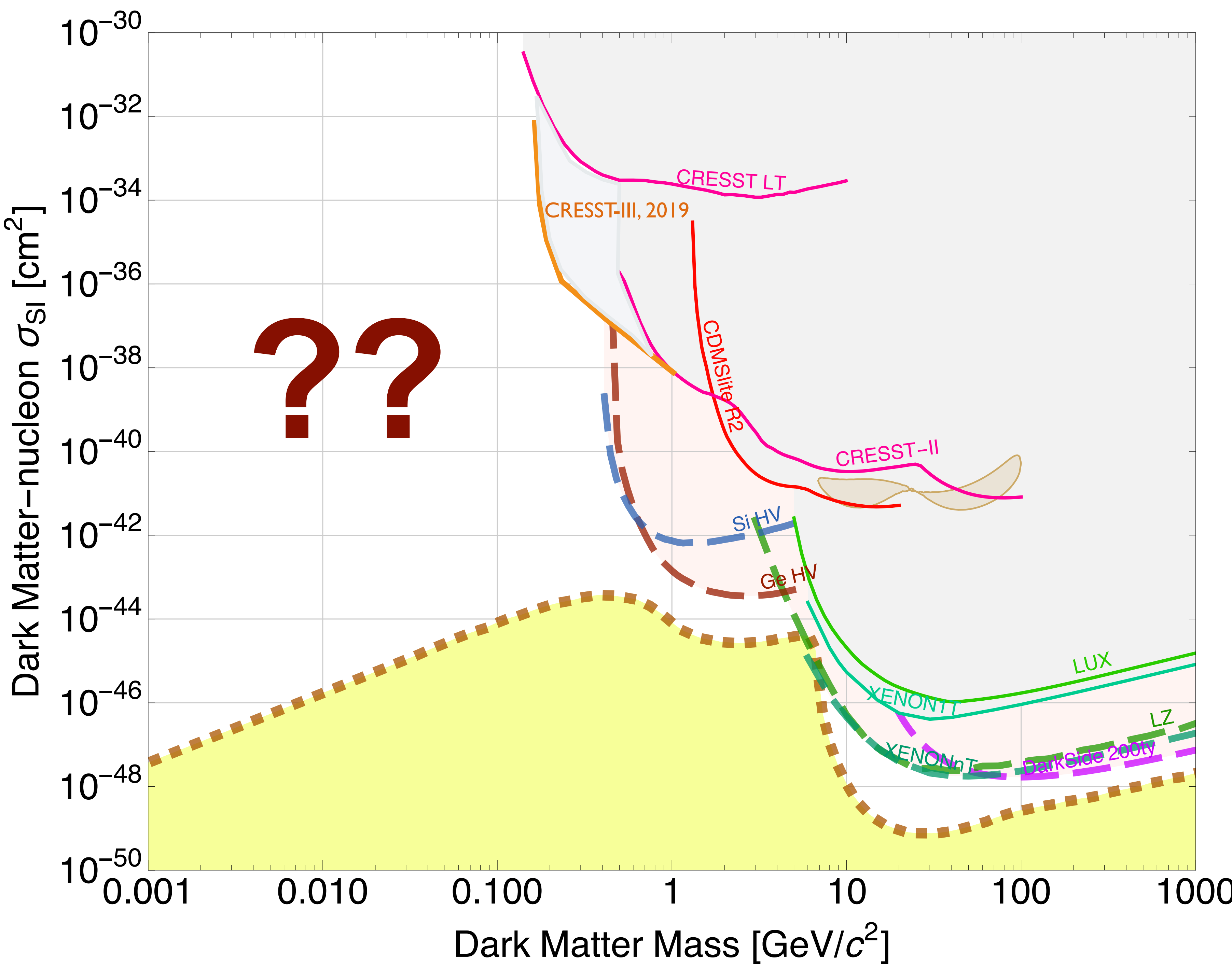
Cosmic Controversies, Chicago, Oct 7, 2019

Traditional Direct Detection strategy:

look for nuclear recoils from
elastic WIMP-nucleus scattering



Constraints & projections from elastic nuclear recoils

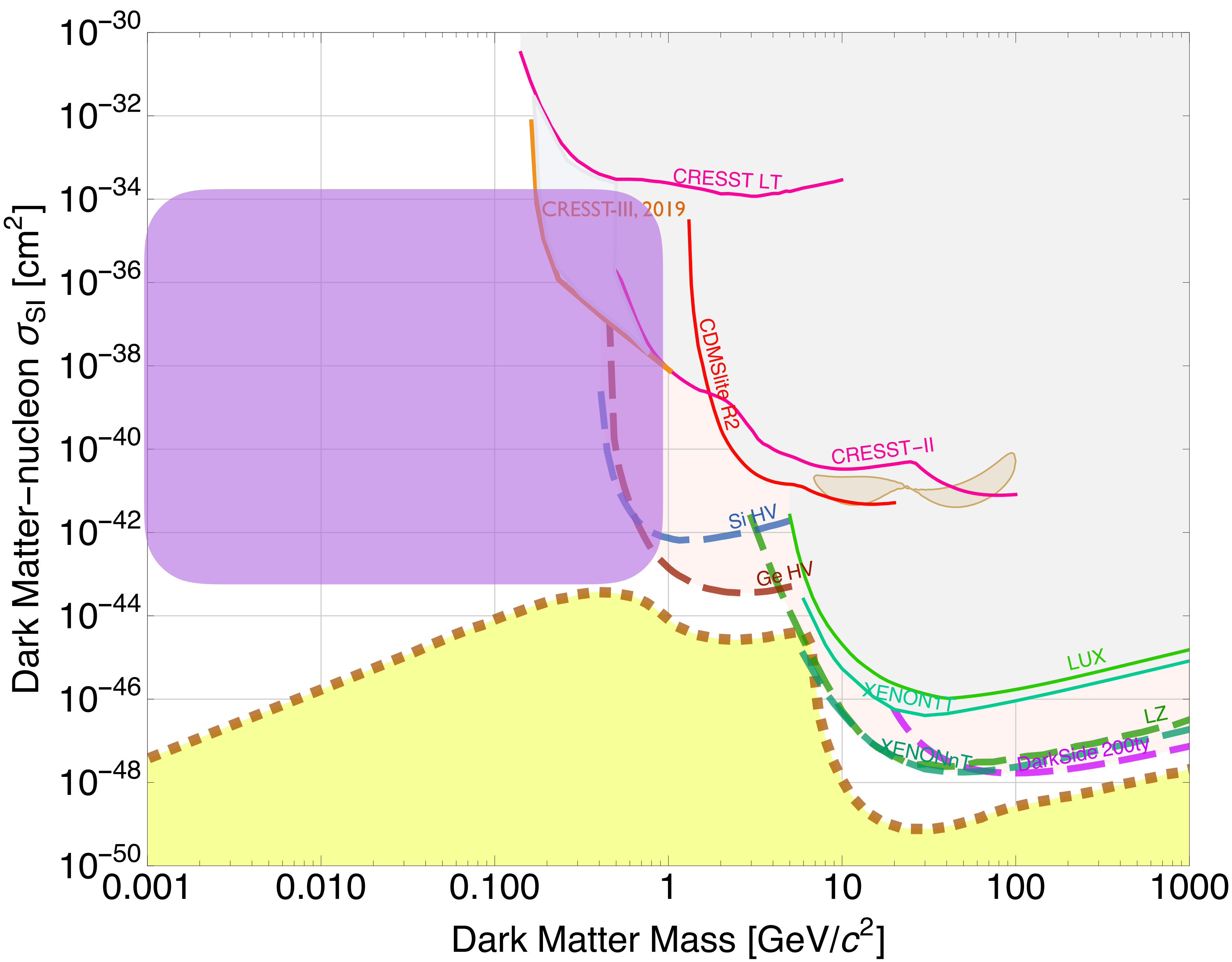


- dozens of experiments over last several decades
- WIMP searches well-established with multi-ton-scale experiments taking data soon
- How probe lower masses?

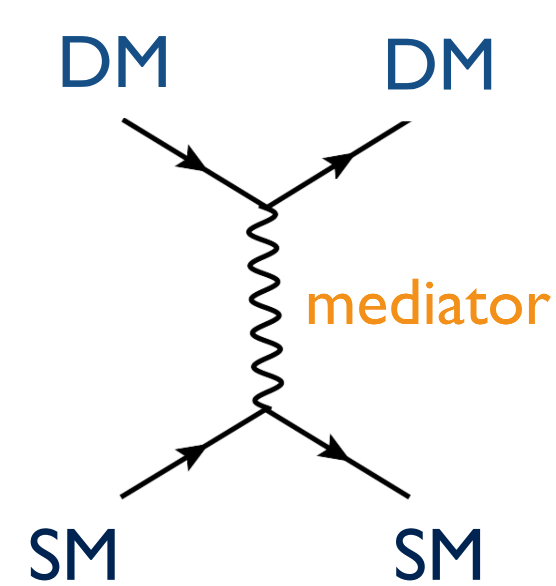
large regions of unexplored parameter space!

Limit plotter: Saab & Figueroa

Several Well-Motivated Hidden-sector DM Candidates



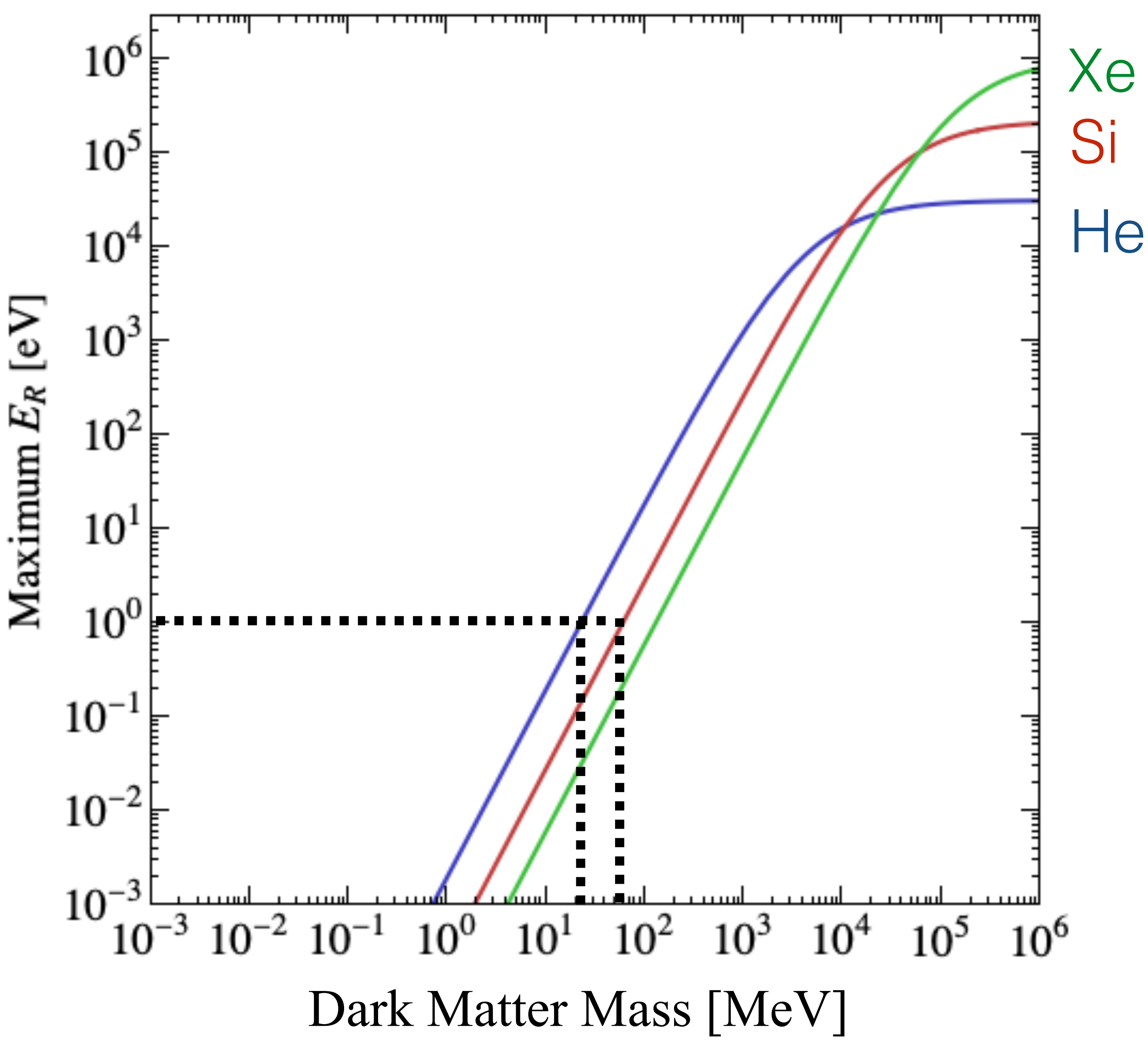
Can obtain relic abundance from freeze-out, an initial asymmetry, freeze-in, SIMP, ELDER…



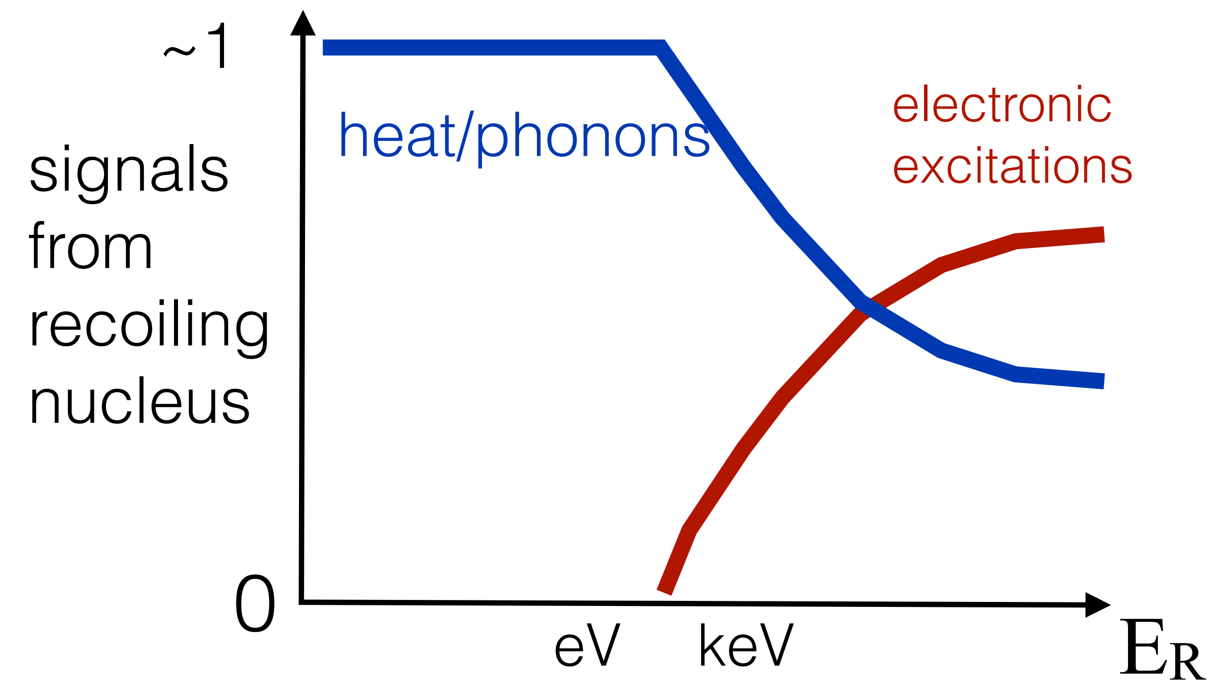
need to probe nuclear <u>and</u> electron interactions

Limit plotter: Saab & Figueroa

Probing sub-GeV DM w/ elastic nuclear recoils



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

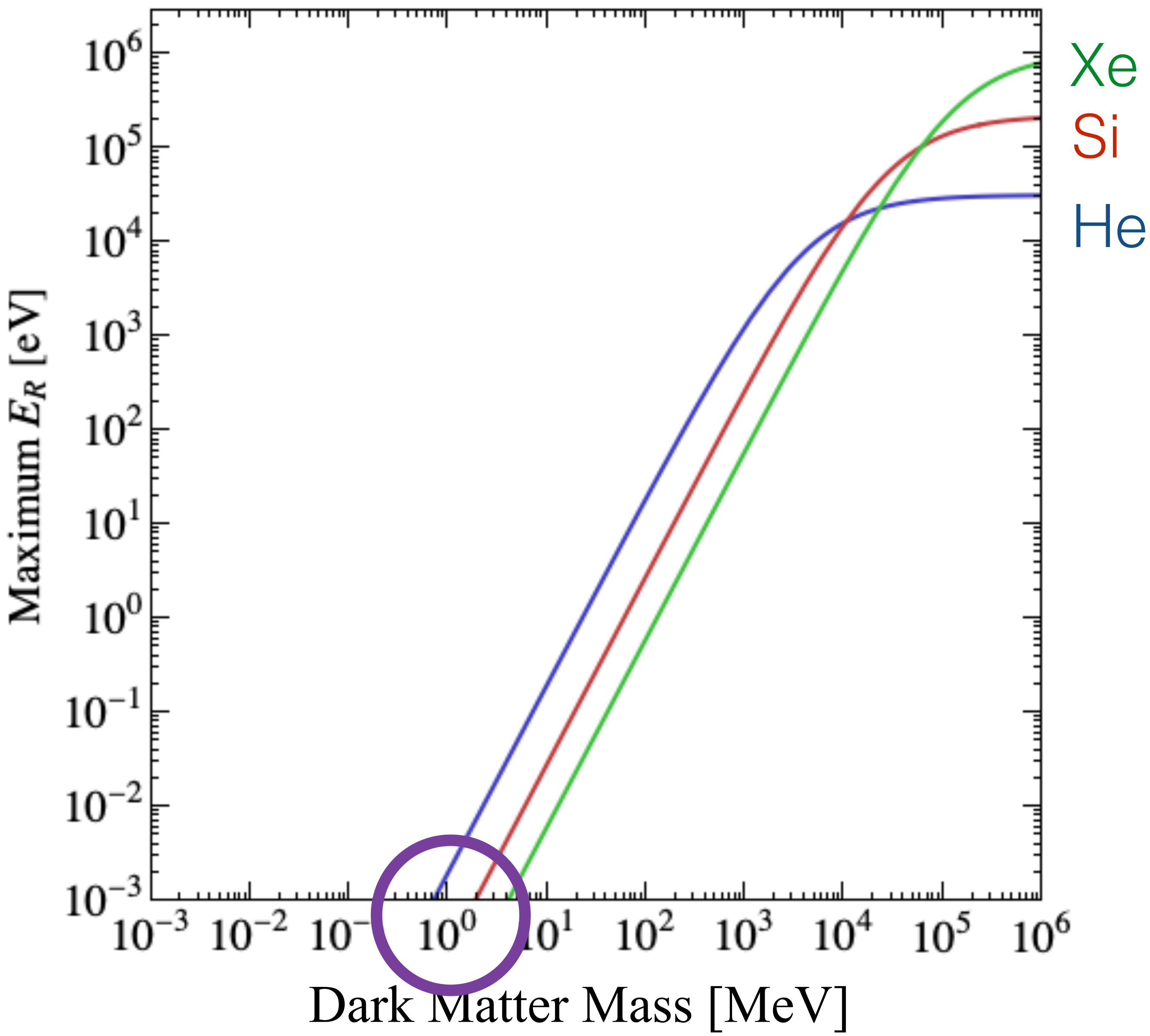


- will soon have phonon detectors w/ O(1 eV) sensitivity

$\Longrightarrow$ 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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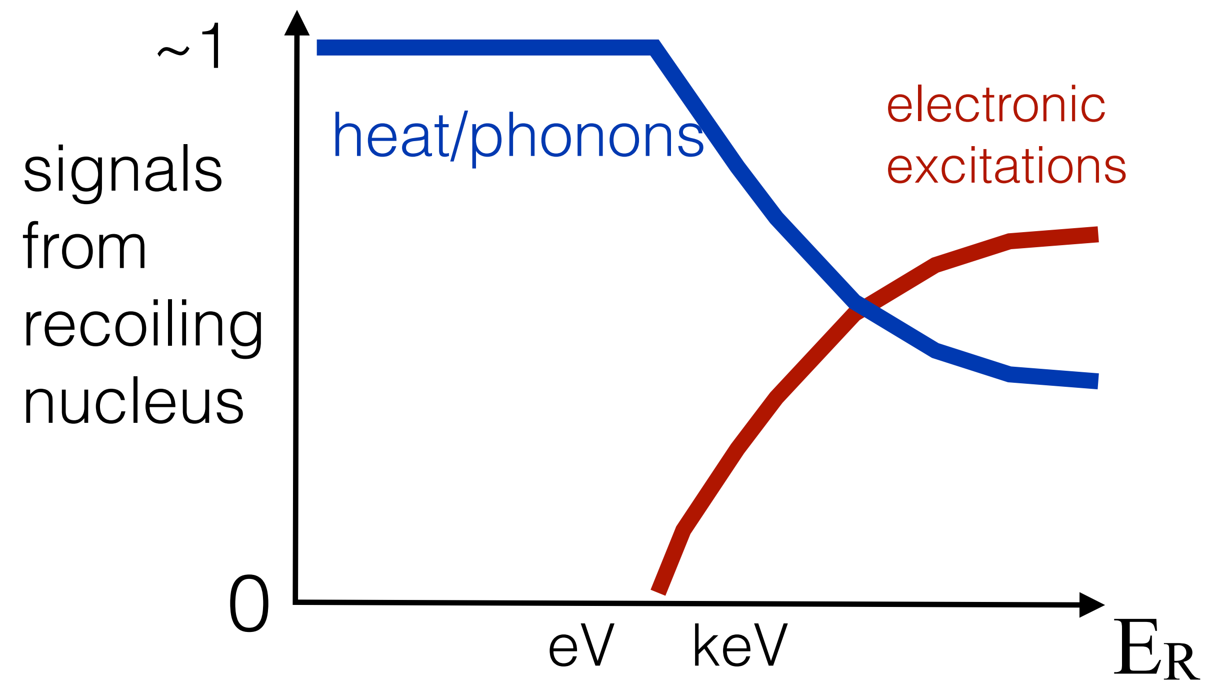

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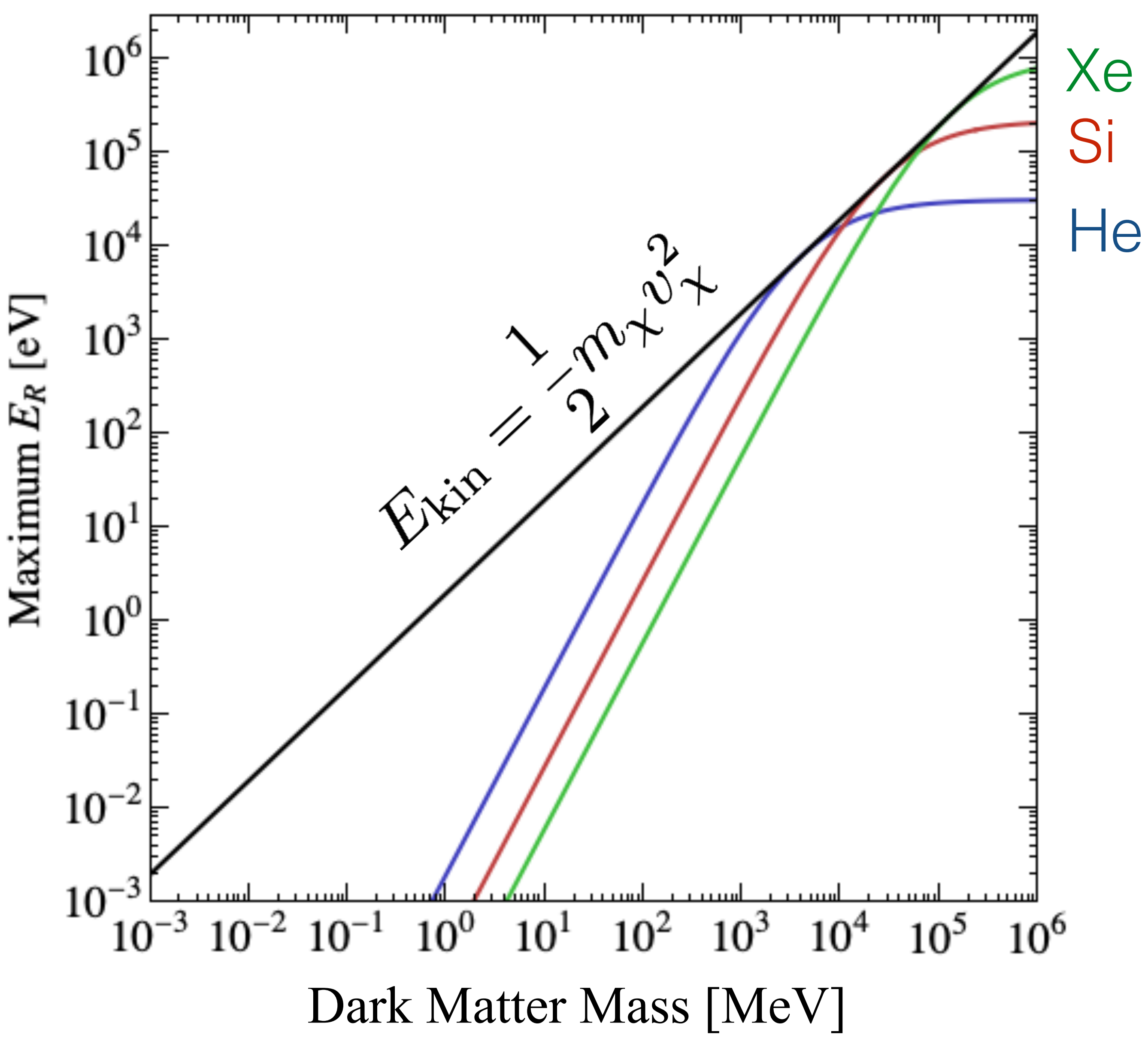
- ultimate sensitivity, to a single ~1 meV phonon, probes 1 MeV DM

Probing sub-GeV DM w/ elastic nuclear recoils

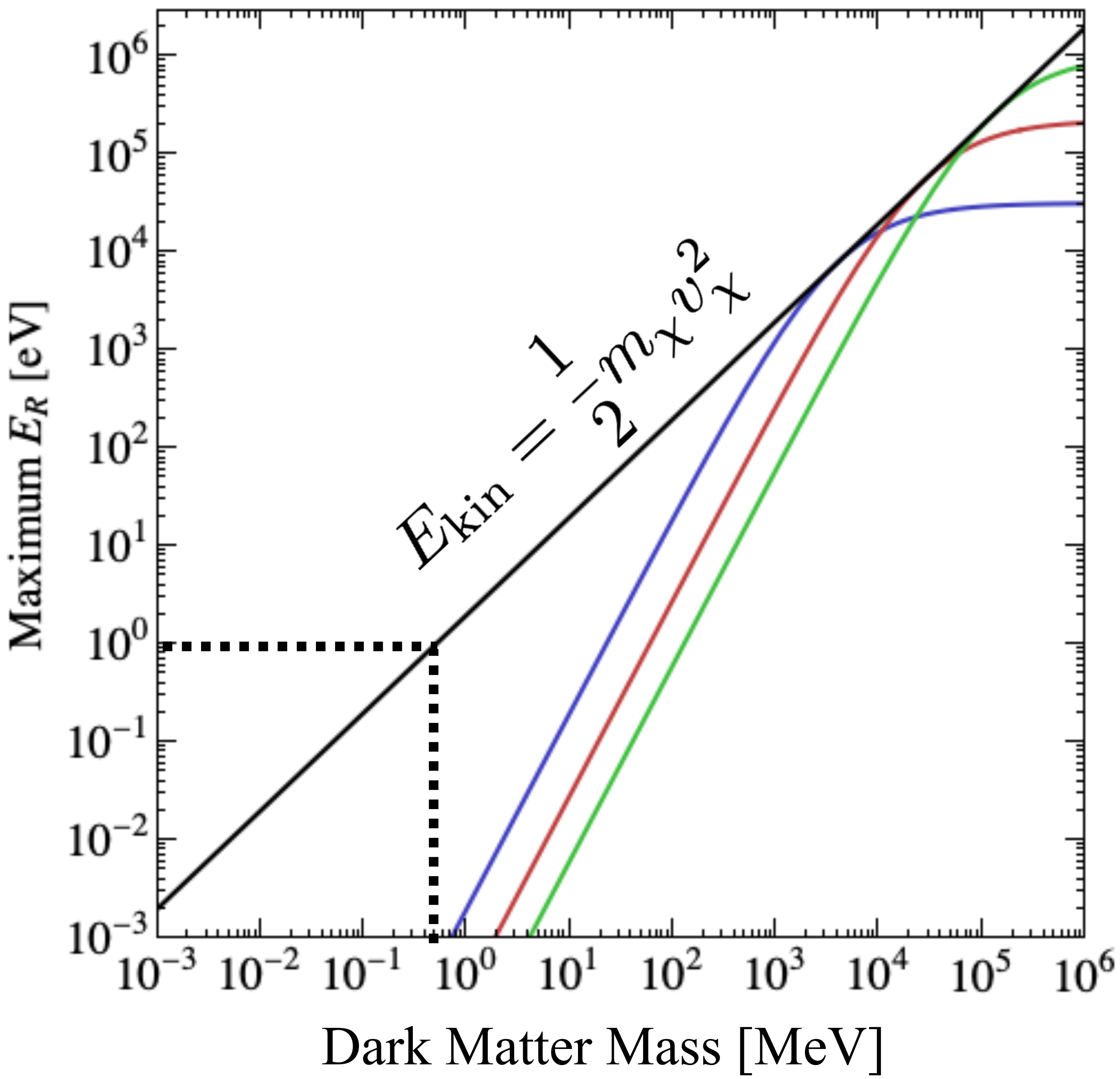


$$E_{\text{NR}} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \simeq \frac{2m_\chi^2 v_\chi^2}{m_N}$$

But note:

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

To probe DM ≪ GeV, look for signals from "inelastic" processes



- Can transfer O(1) of E_{kin}
- A detector sensitive to:
  - 1 eV, probes ~500 keV DM (already demonstrated!)

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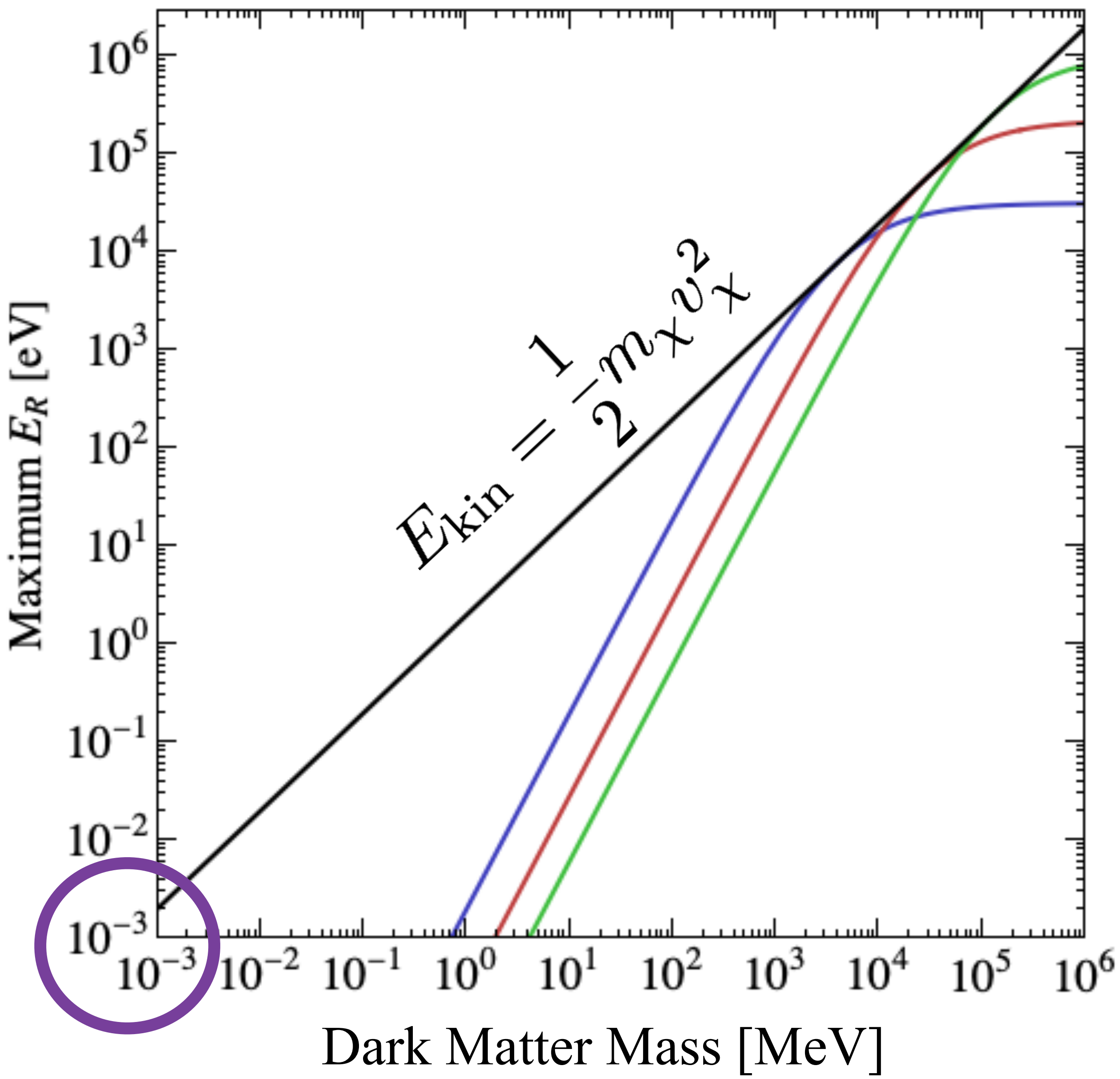

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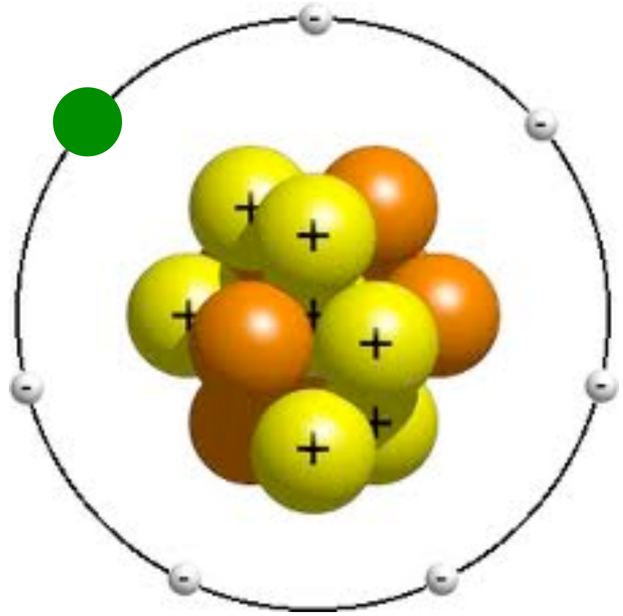
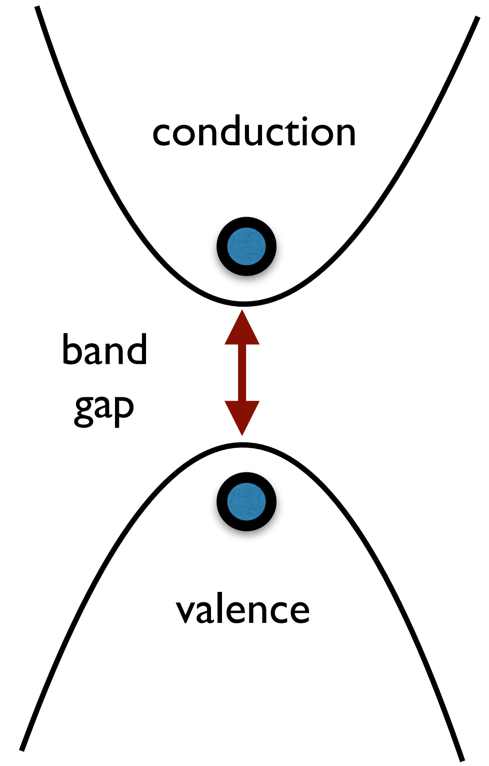
Some Inelastic Processes giving $E_{\max} \sim (1/2) m_\chi v_\chi^2$

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

RE, Mardon, Volansky





see also:
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

noble liquids	semiconductors
$E_{\text{binding}} \sim 10$ eV	$E_{\text{binding}} \sim 1$ eV
$m_{\text{threshold}} \sim 5$ MeV	$m_{\text{threshold}} \sim 500$ keV

Typically produces a signal of only one to a few electrons

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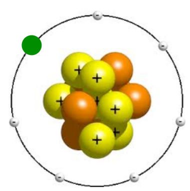
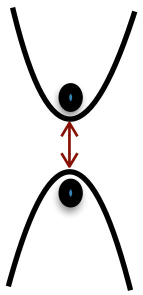
RE, Mardon, Volansky

Measuring small ionization signals is already demonstrated!





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

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

Planned experiments include

LBECA

SENSEI (100 g)
DAMIC-M (1 kg)
10 kg Skipper-CCD detector

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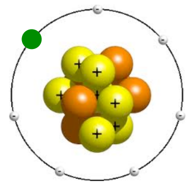

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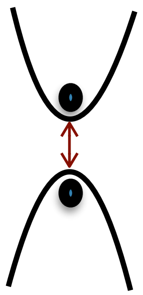

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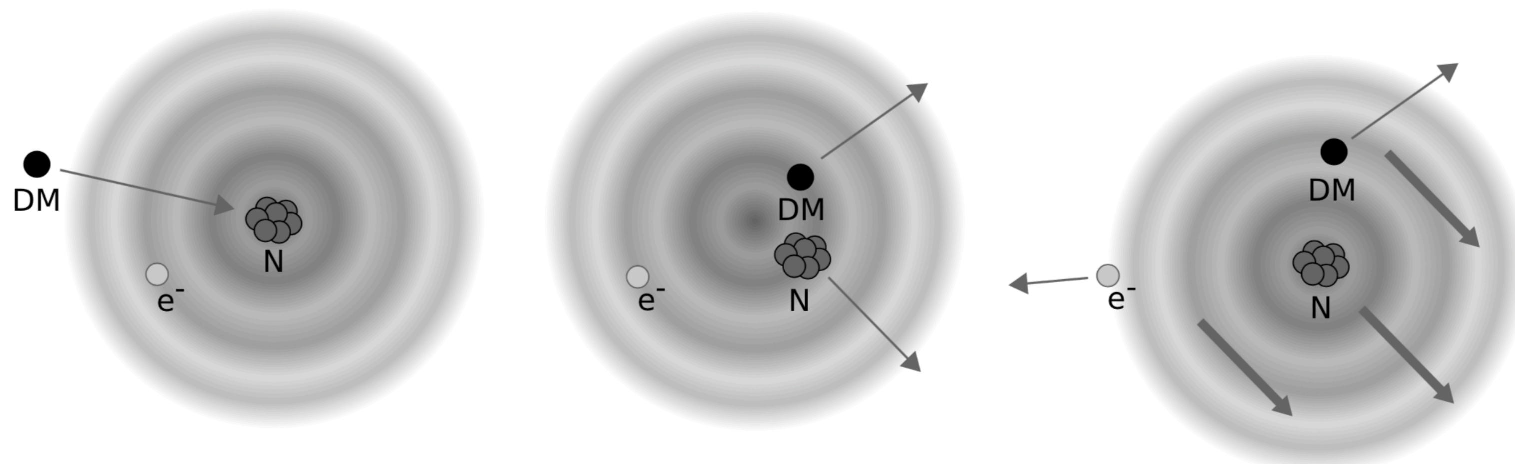
Electrons from Migdal effect (DM-nucleus scattering)



e.g. Vergados, Ejiri 2004;
Ibe, Nakano, Shoji, Suzuki 2017

Fig. credit: Dolan, Kahlhoefer, McCabe

RE, Pradler, Sholapurkar, Yu

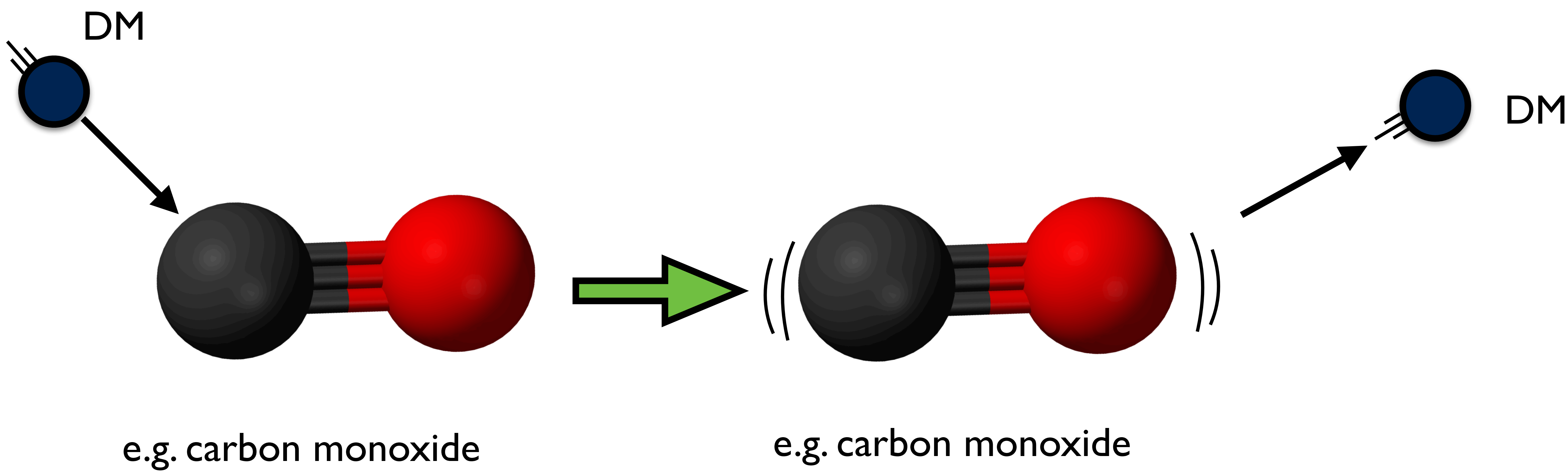
Baxter, Kahn, Krnjaic

A detector sensitive to small ionization signals will be sensitive to <u>both</u> DM-e <u>and</u> 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)



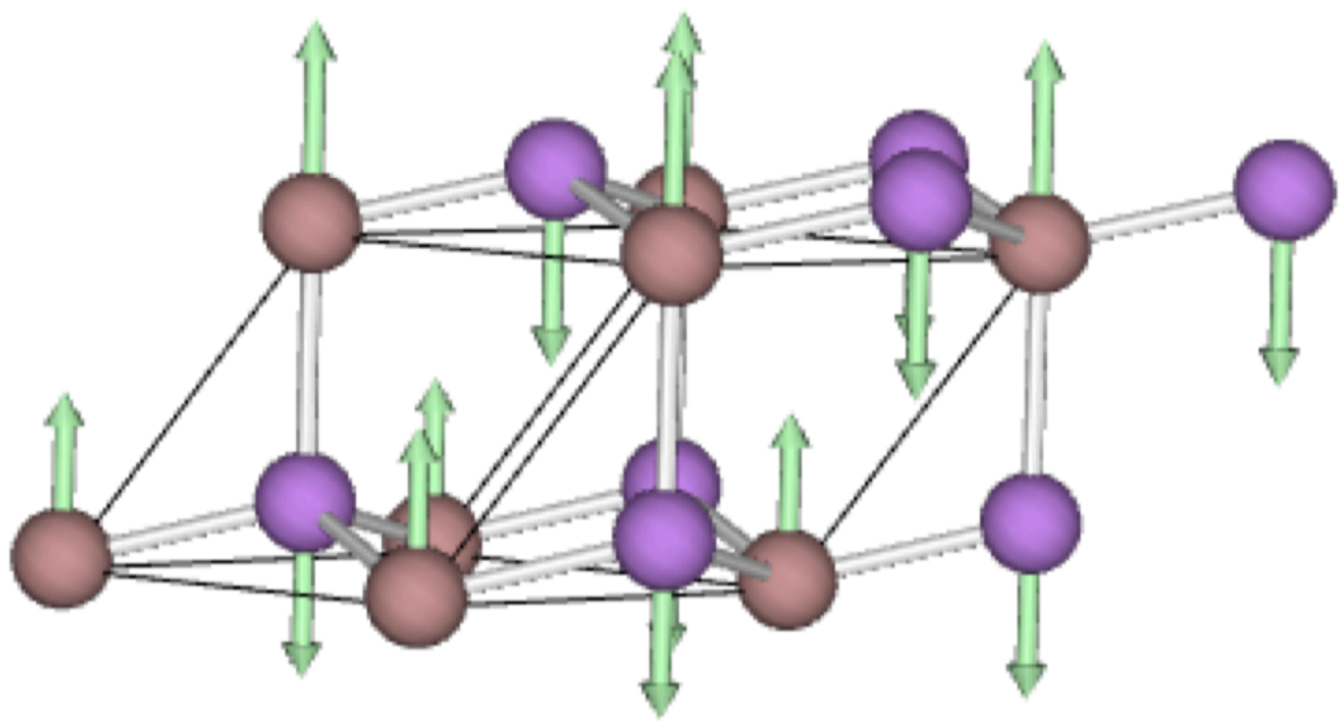
Excited molecule relaxes to ground state emitting
<u>multiple</u> photons of energy O(100-250 meV);
detect w/ ultrasensitive photodetectors

probe spin-independent <u>and</u> spin-dependent interactions

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)

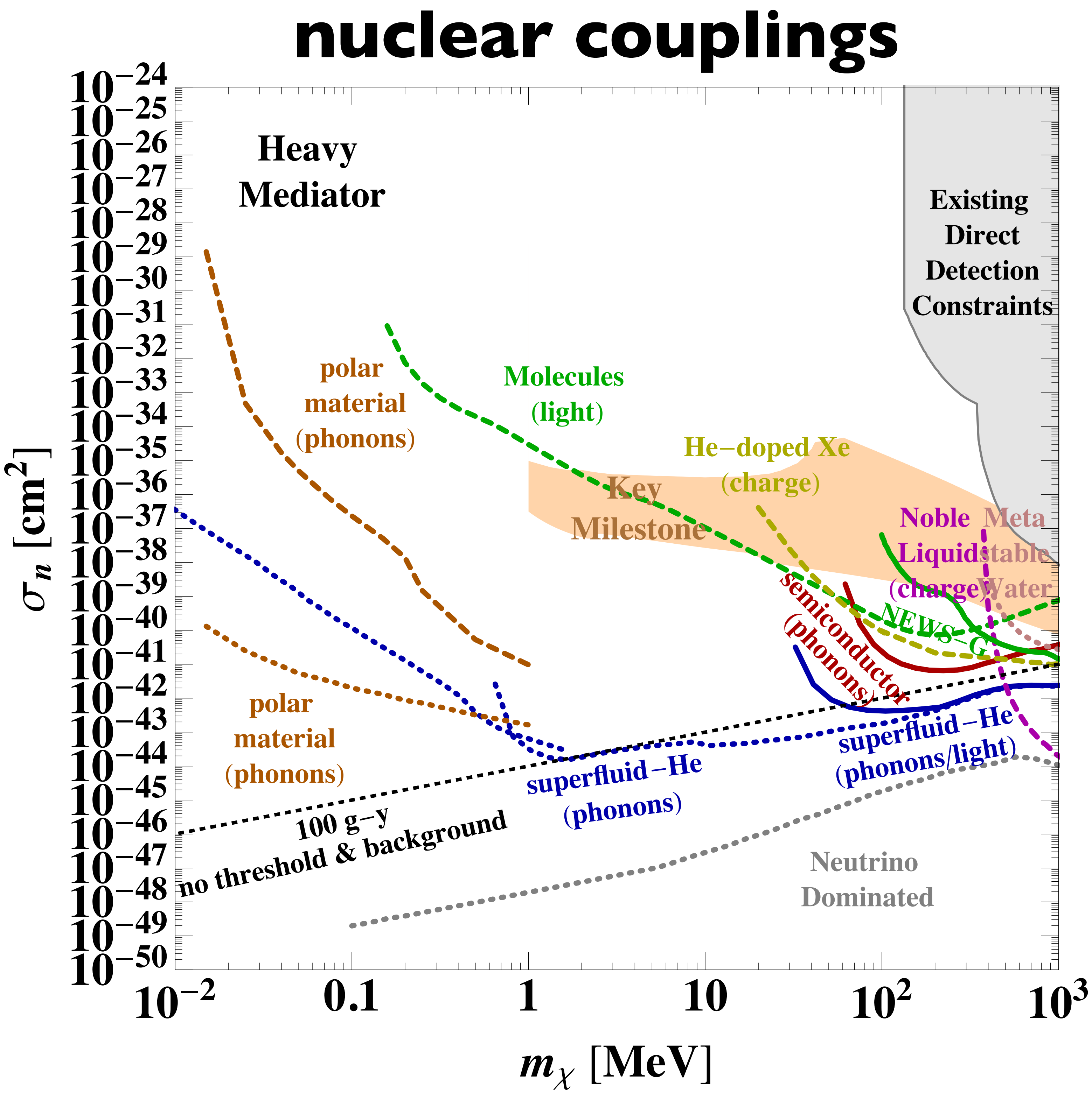
Knapen, Lin, Pyle, Zurek
Griffin, Knapen, Lin, Zurek



probe sub-MeV DM if have sensitivity to 10's of meV of phonons

The next decade in sub-GeV DM direct-detection

from DoE High-Energy Physics Basic Research Needs Report



New detection concepts & technological advances enable exploration of vast new regions of parameter space

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

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

The next decade in sub-GeV DM direct-detection

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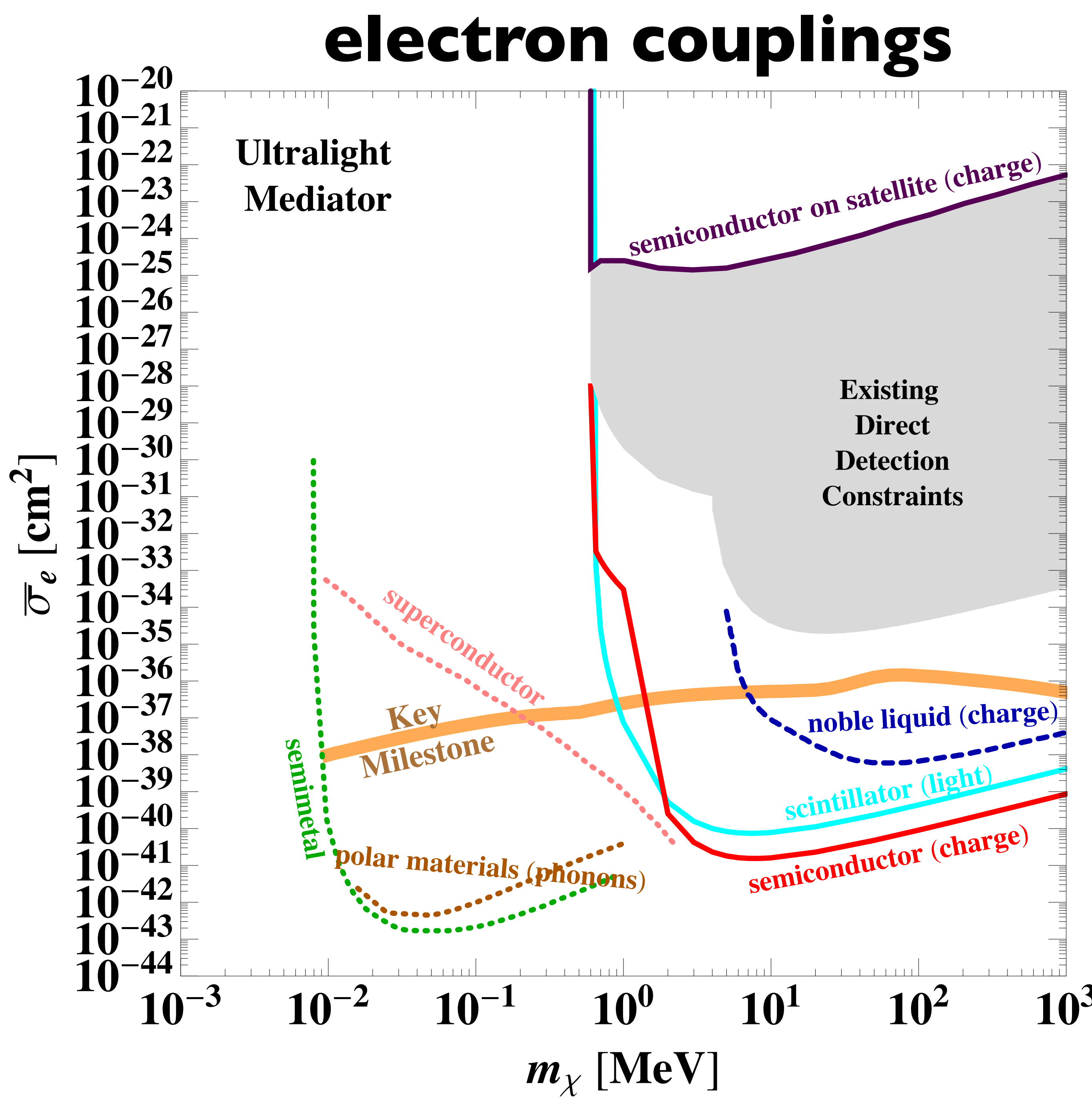

The next decade in sub-GeV DM direct-detection

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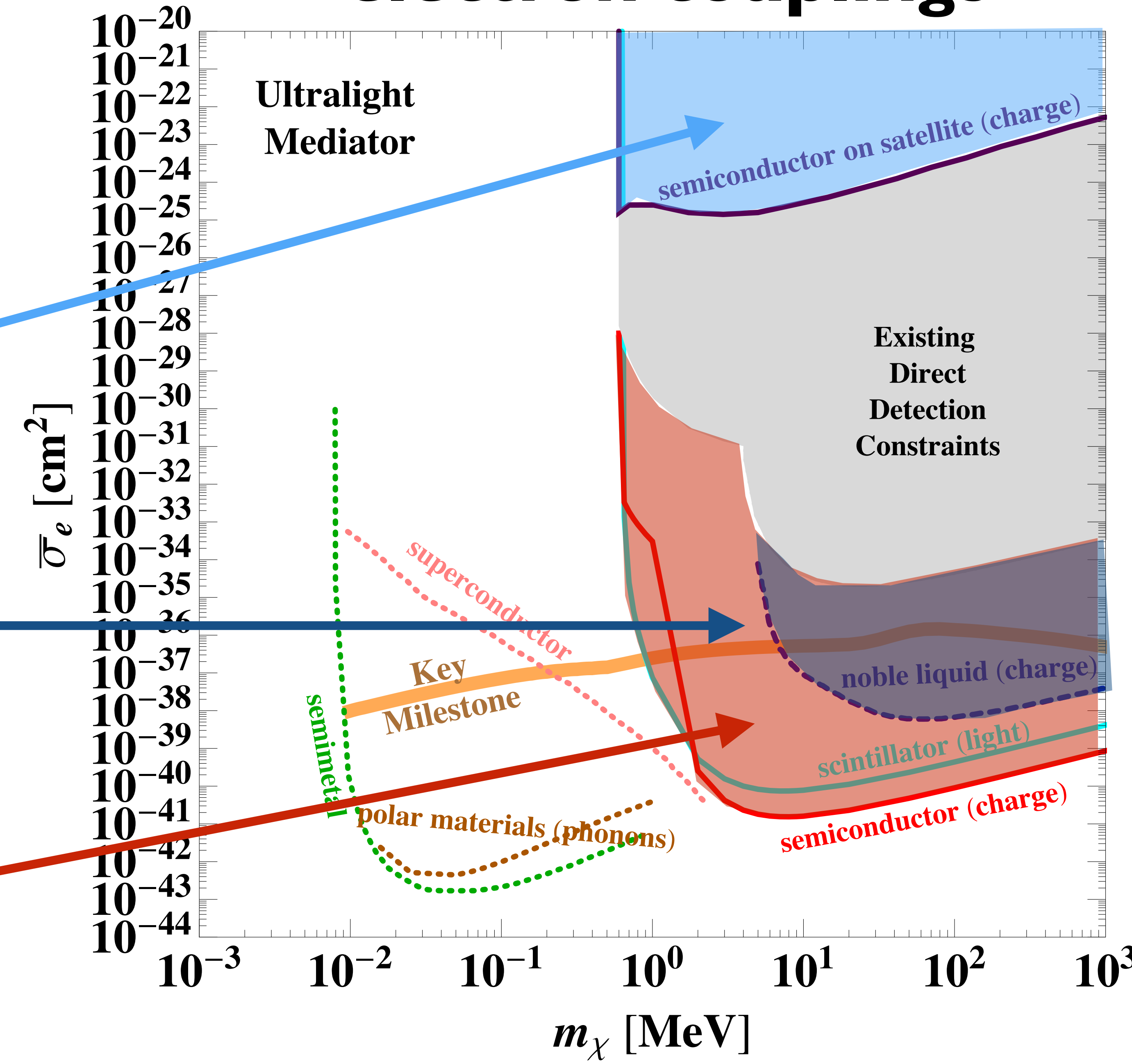
Some experiments ready soon:

Skipper-CCD on balloon/satellite
(see backup slides)

LBECA (liquid Xe)
(see backup slides)

SENSEI
(silicon Skipper CCDs)

electron couplings



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

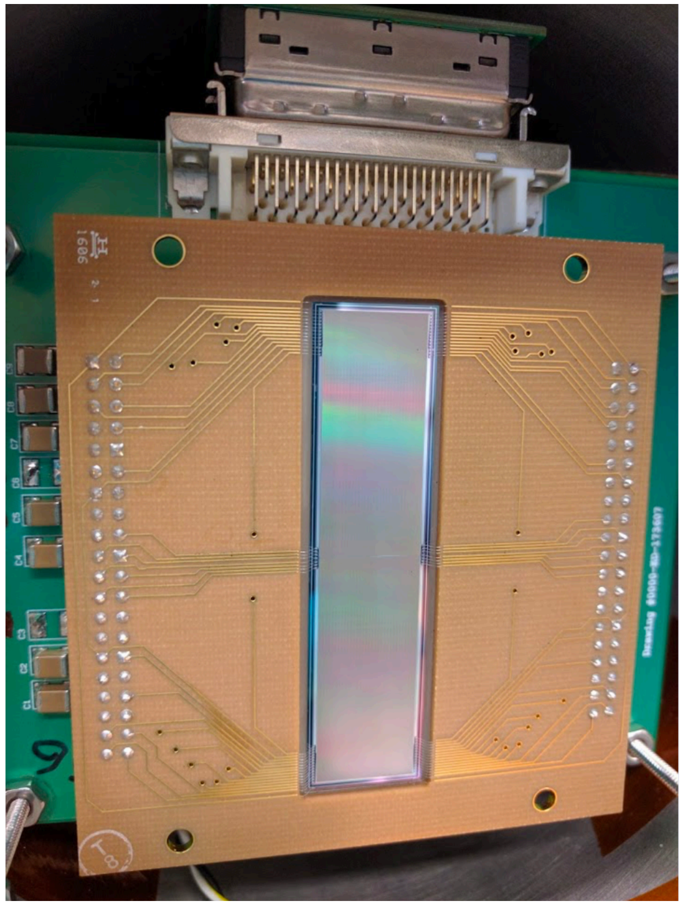
U. Oregon:

- T.-T. Yu

Fully funded by Heising-Simons Foundation & Fermilab

Detection Concept

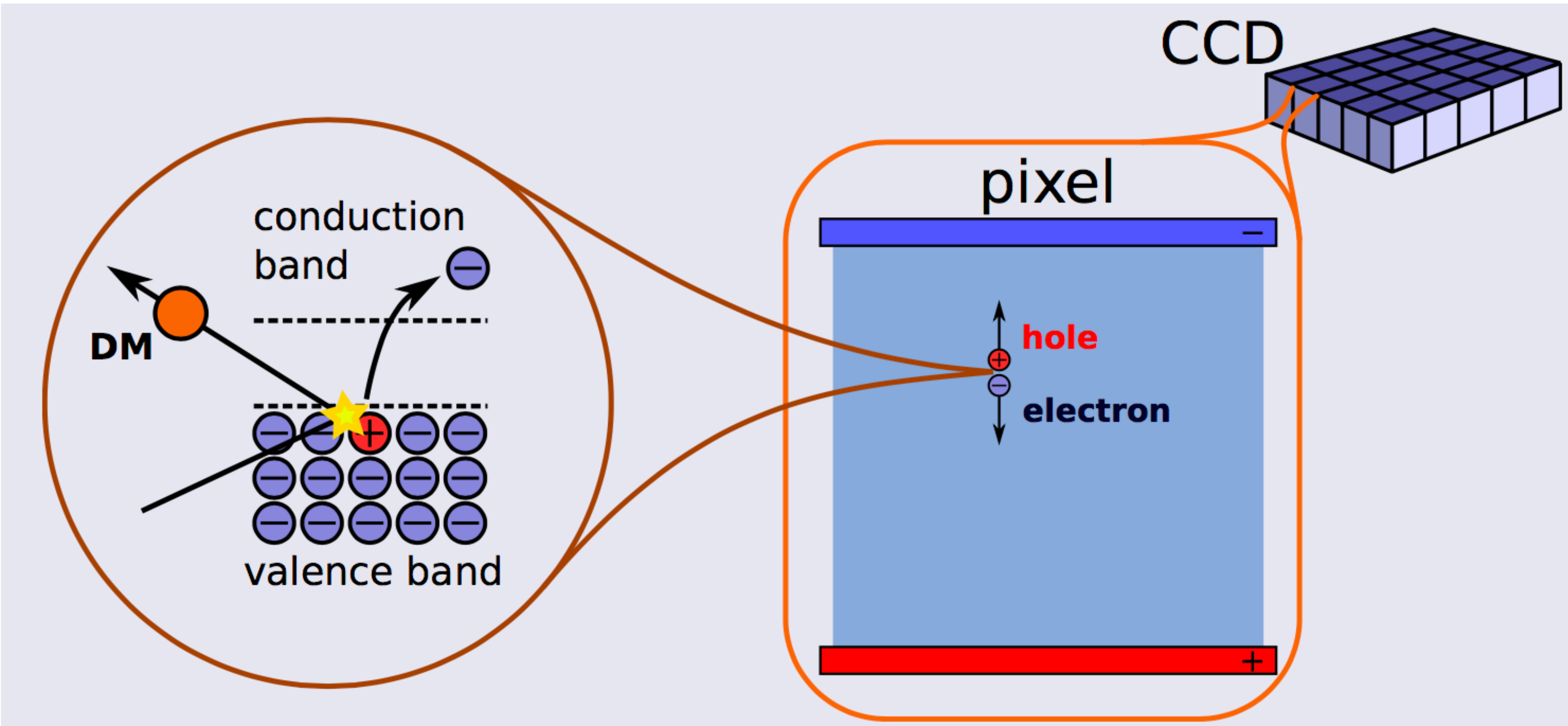
silicon Skipper-CCD



~million pixels

developed in collaboration
between FNAL & LBNL
MicroSystems Lab

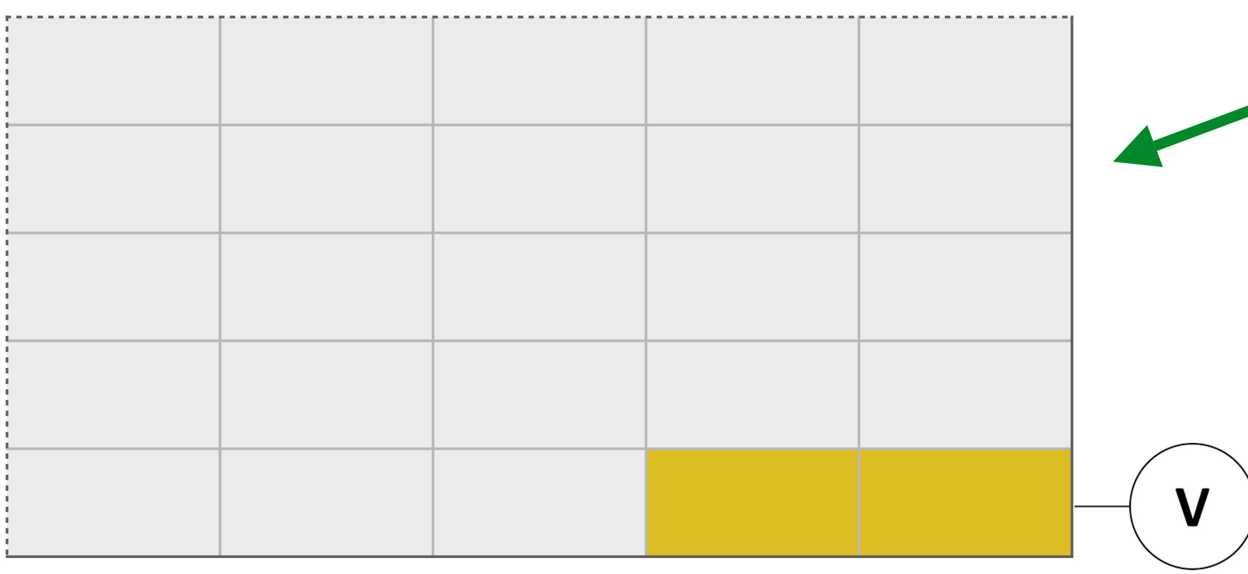
Detection Concept



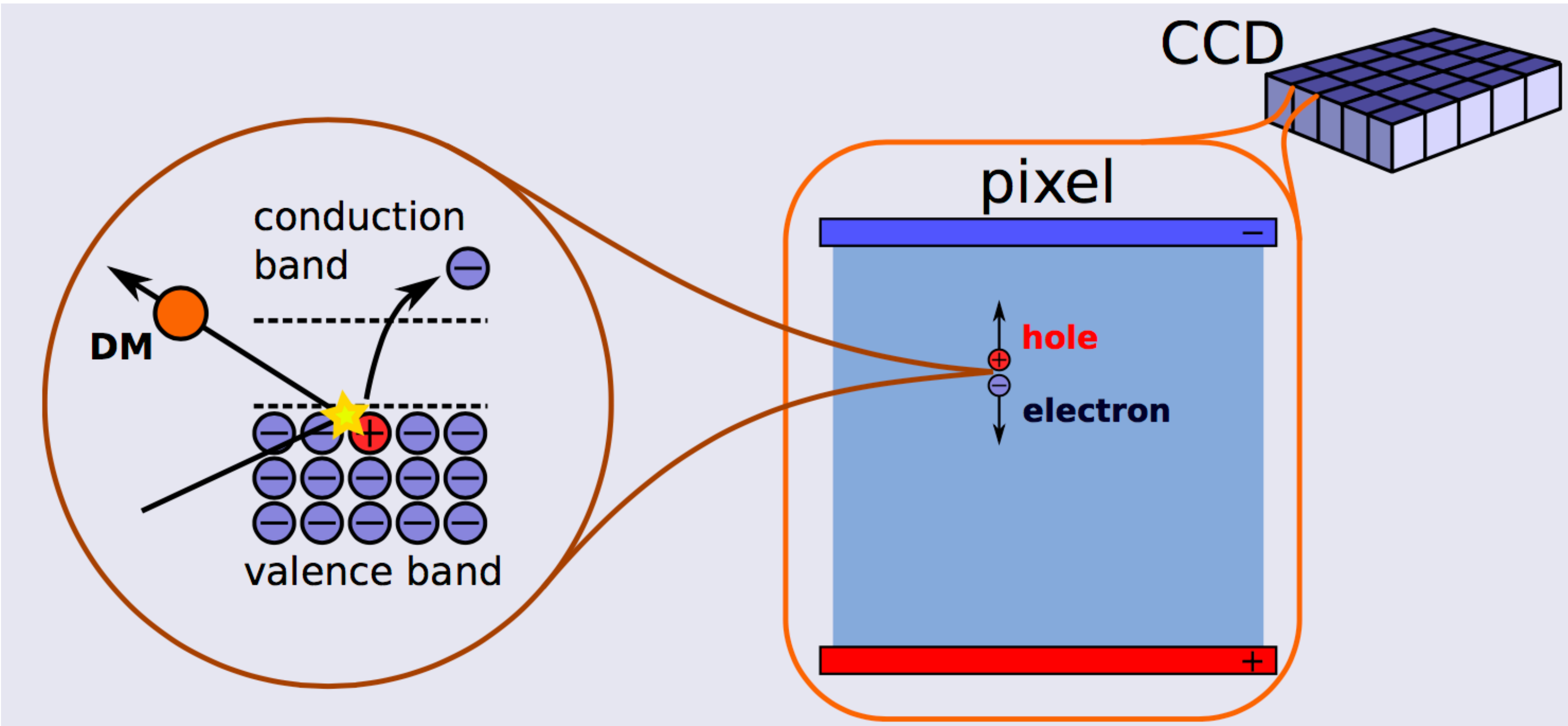
DM typically creates only
one or a few electrons per pixel

silicon Skipper-CCD

~million pixels



Detection Concept



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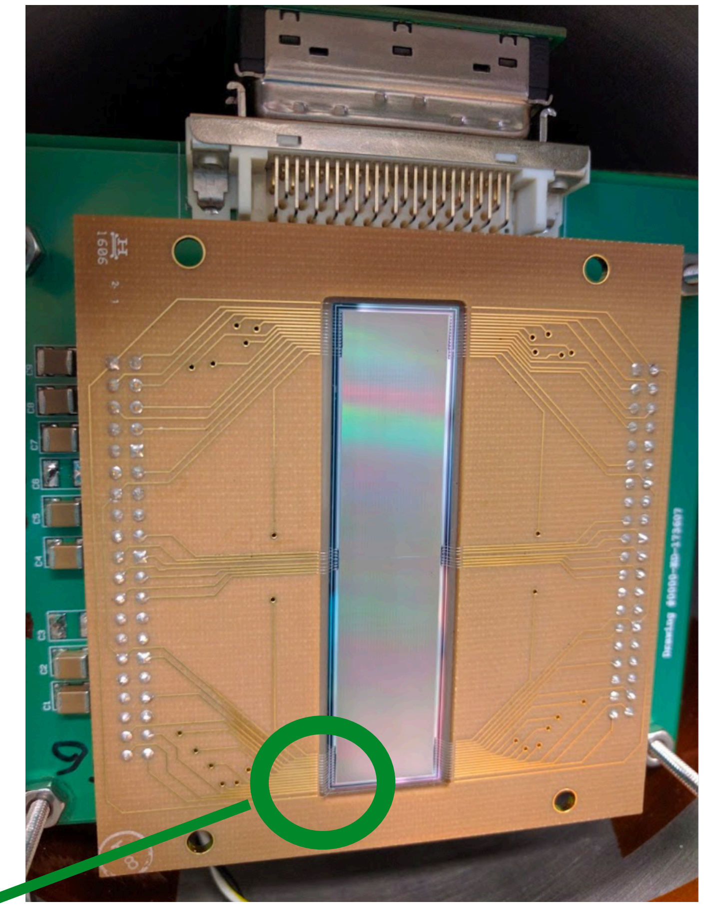

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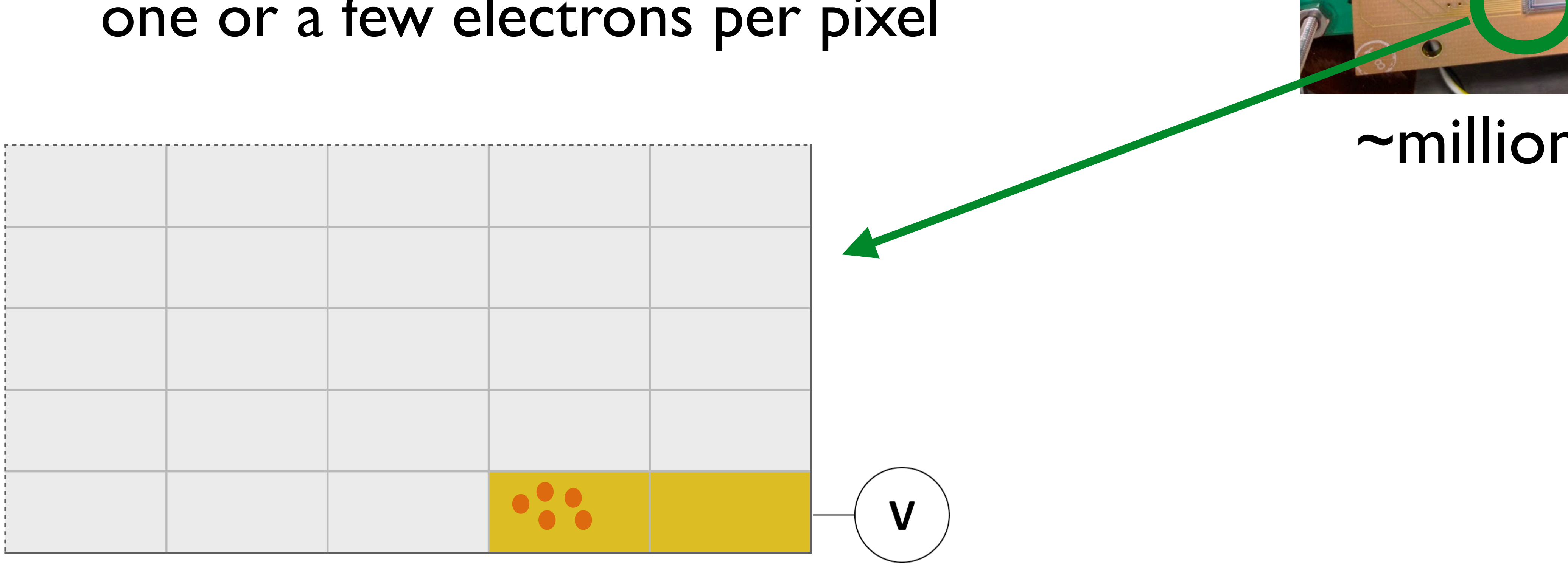

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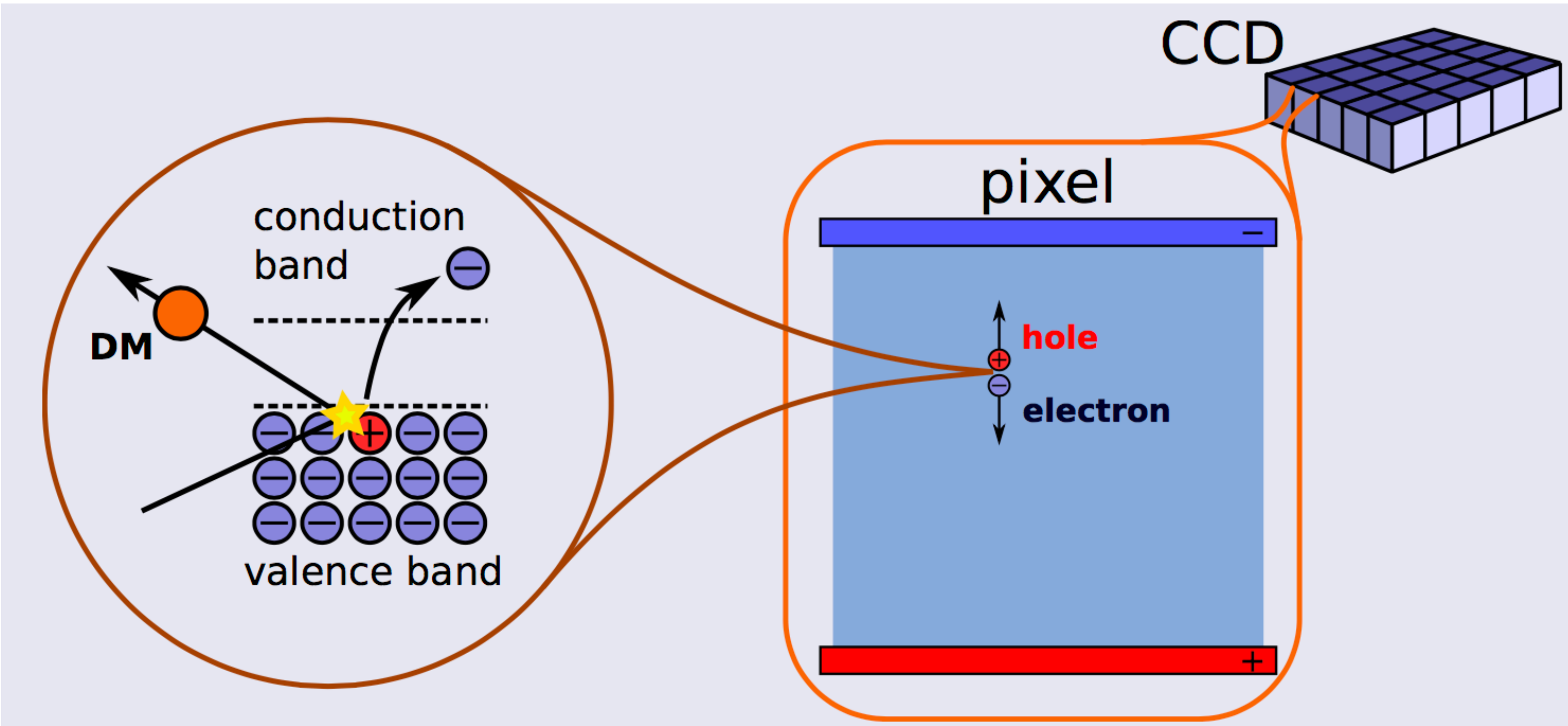

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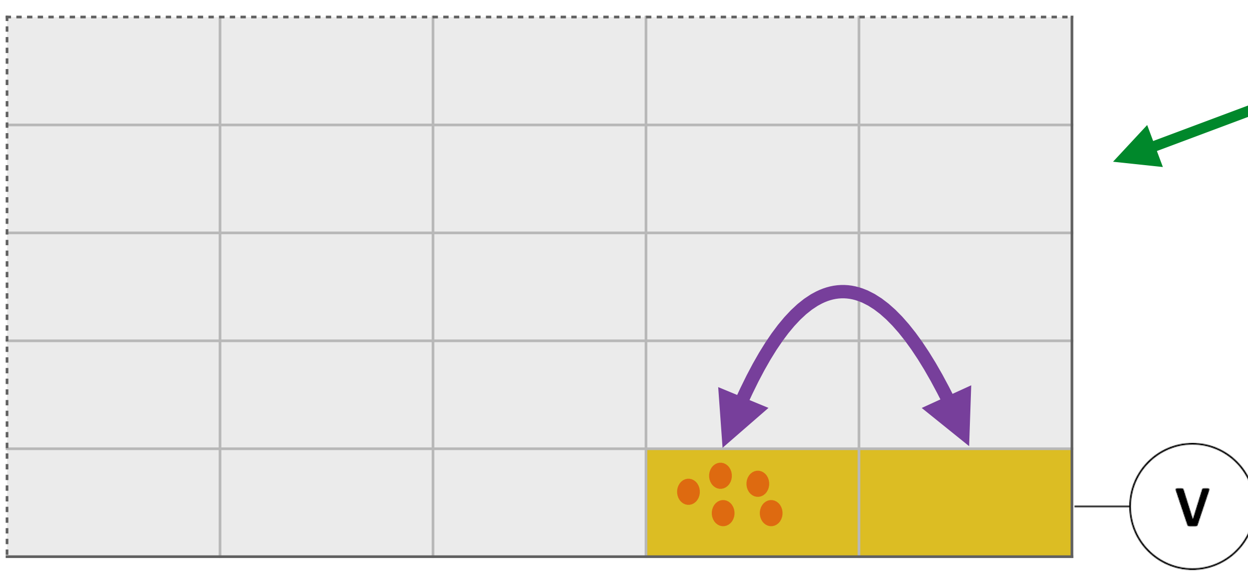
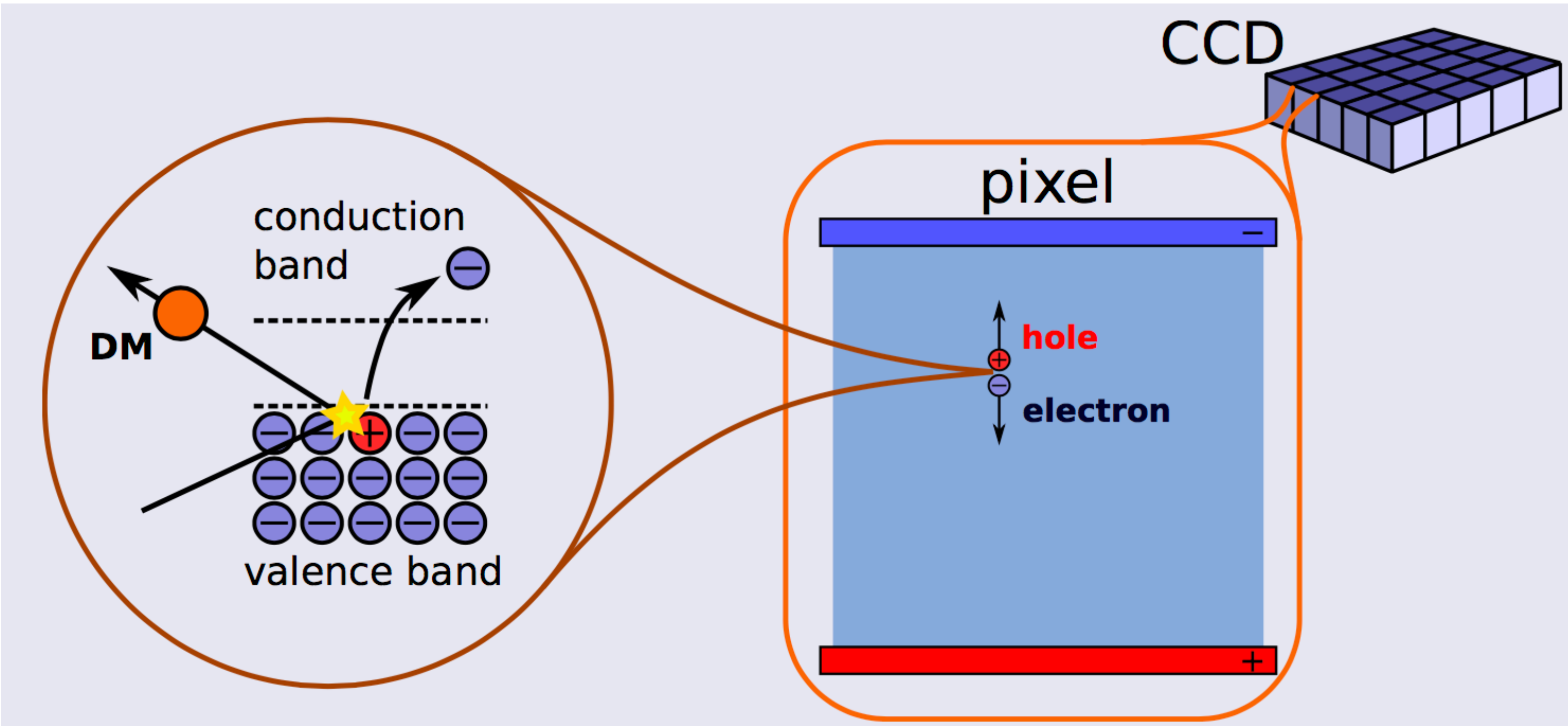


repeatedly measure charge
to achieve sub-electron
readout noise

Detection Concept



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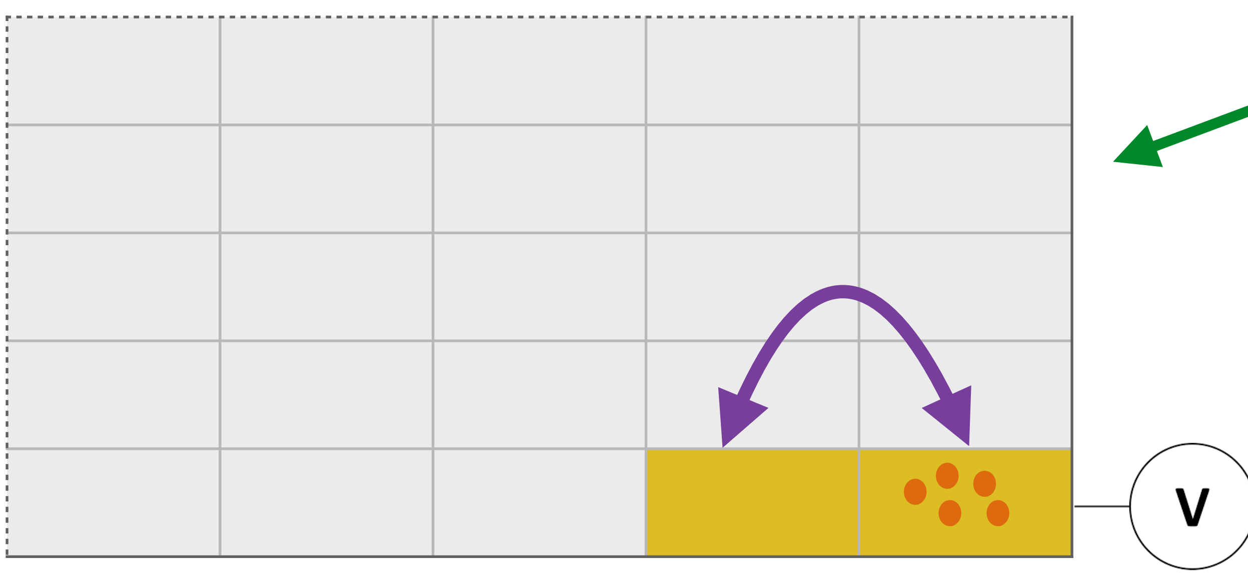

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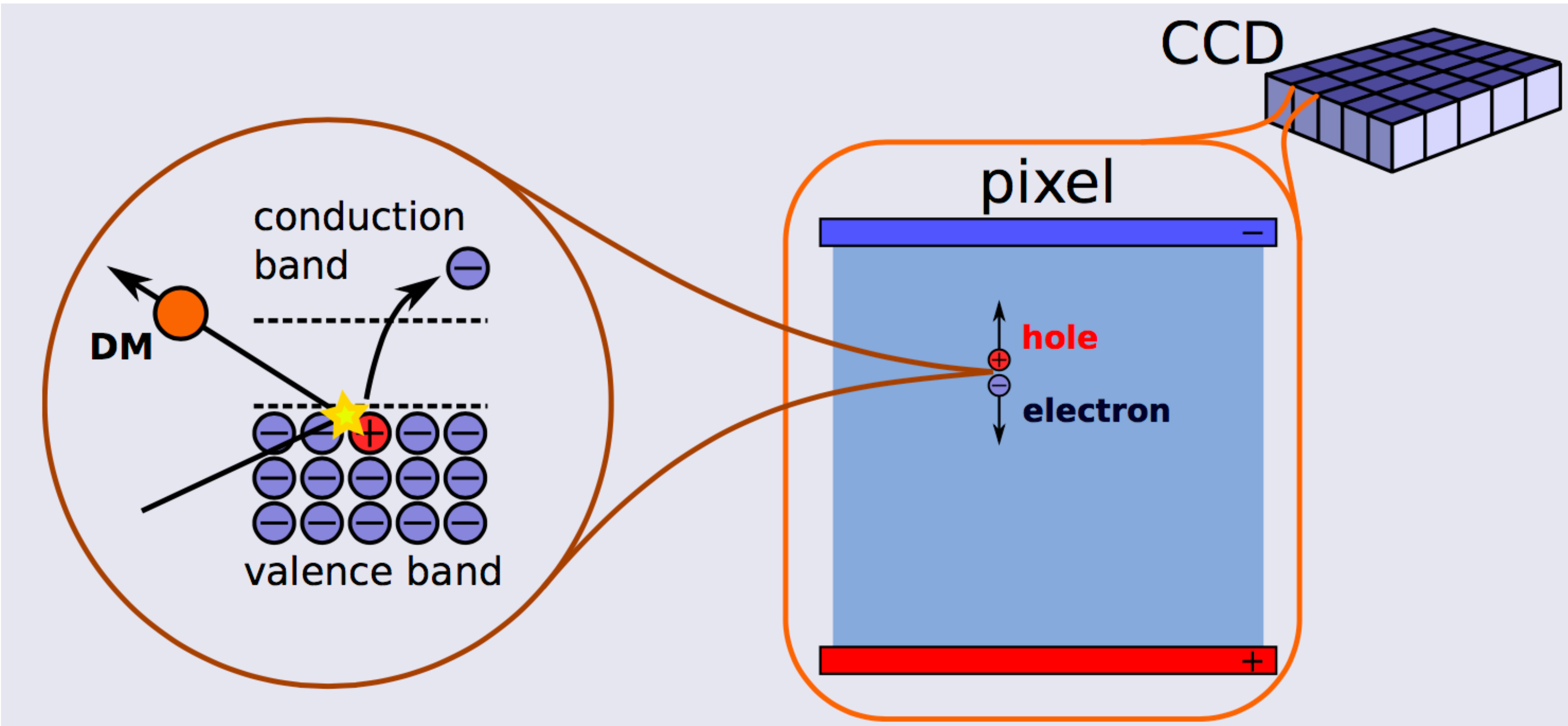

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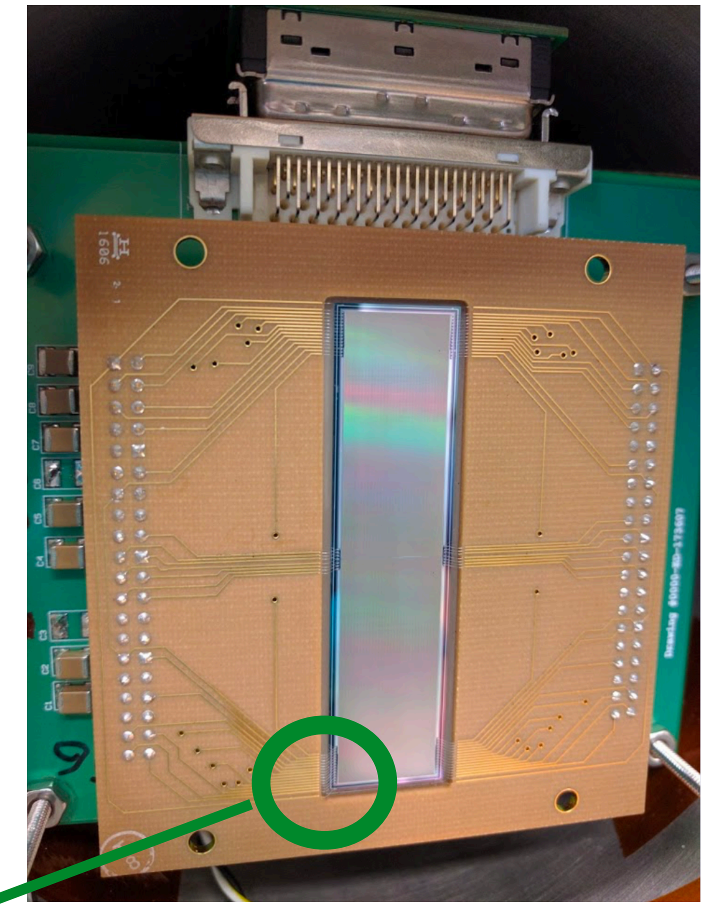

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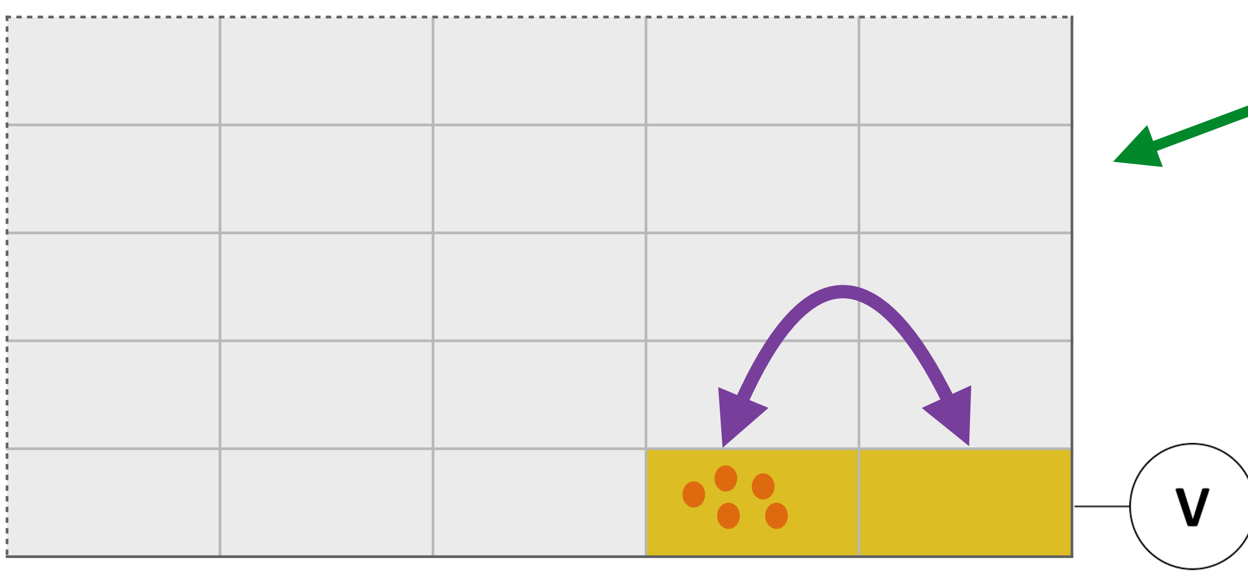

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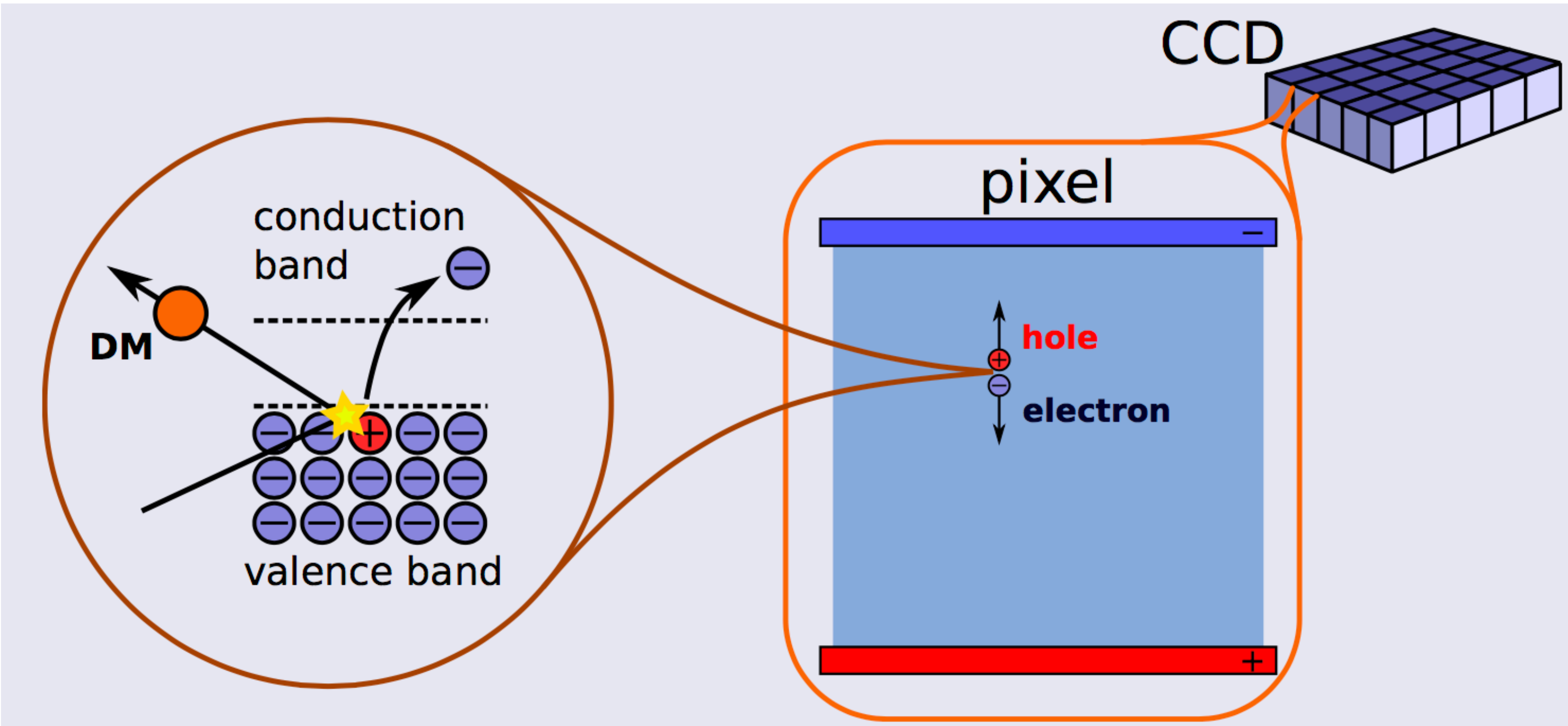

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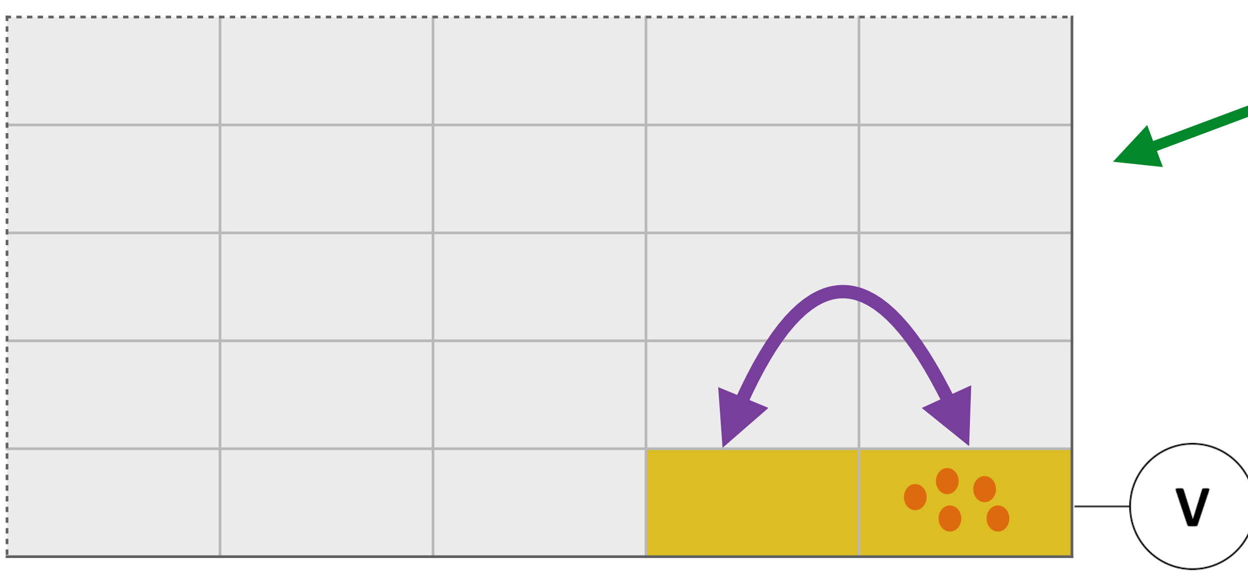
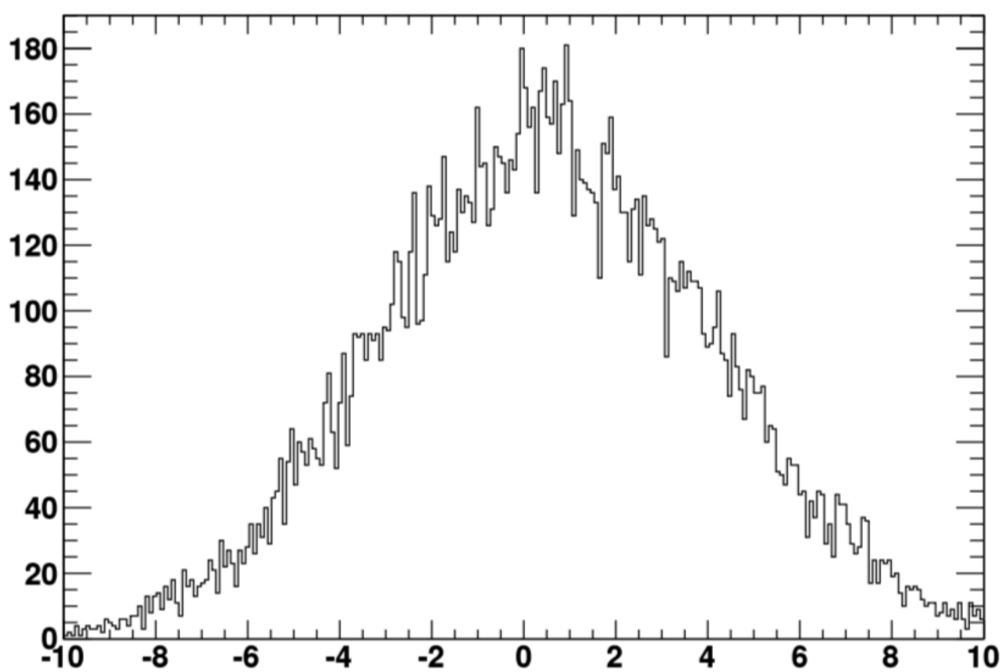


repeatedly measure charge
to achieve sub-electron
readout noise

Can count individual electrons, w/ ~zero noise

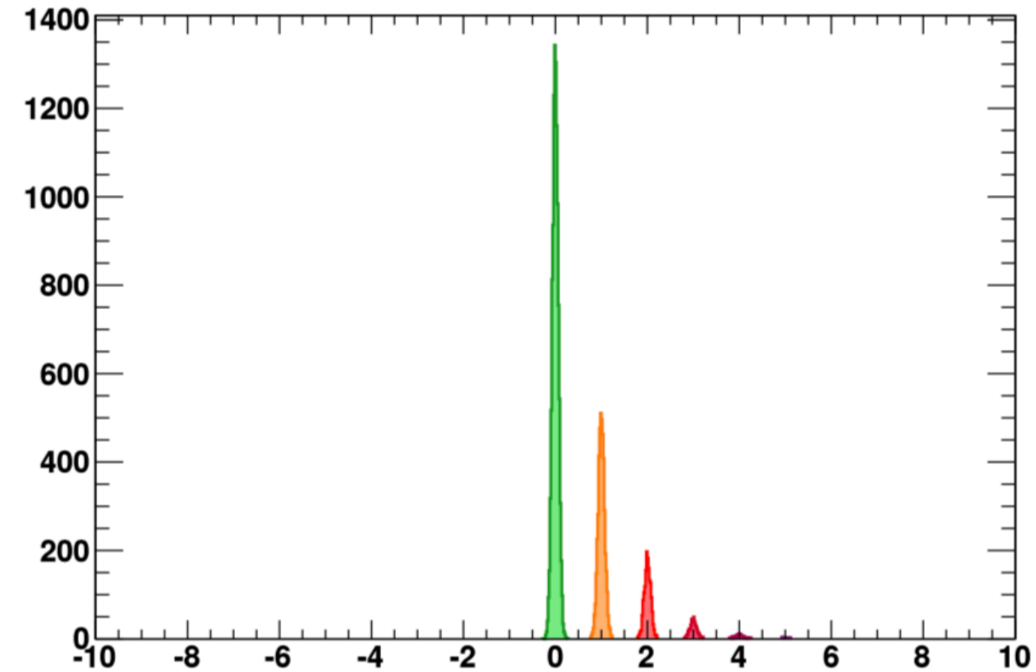
Tiffenberg, Sofo-Haro, Drlica-Wagner, RE, Guardincerri, Holland, Volansky, Yu (1706.00028, PRL)

Si: traditional CCD



electron-hole pairs

Si: Skipper-CCD



electron-hole pairs

rms noise ~3 e^-
(single measurement)

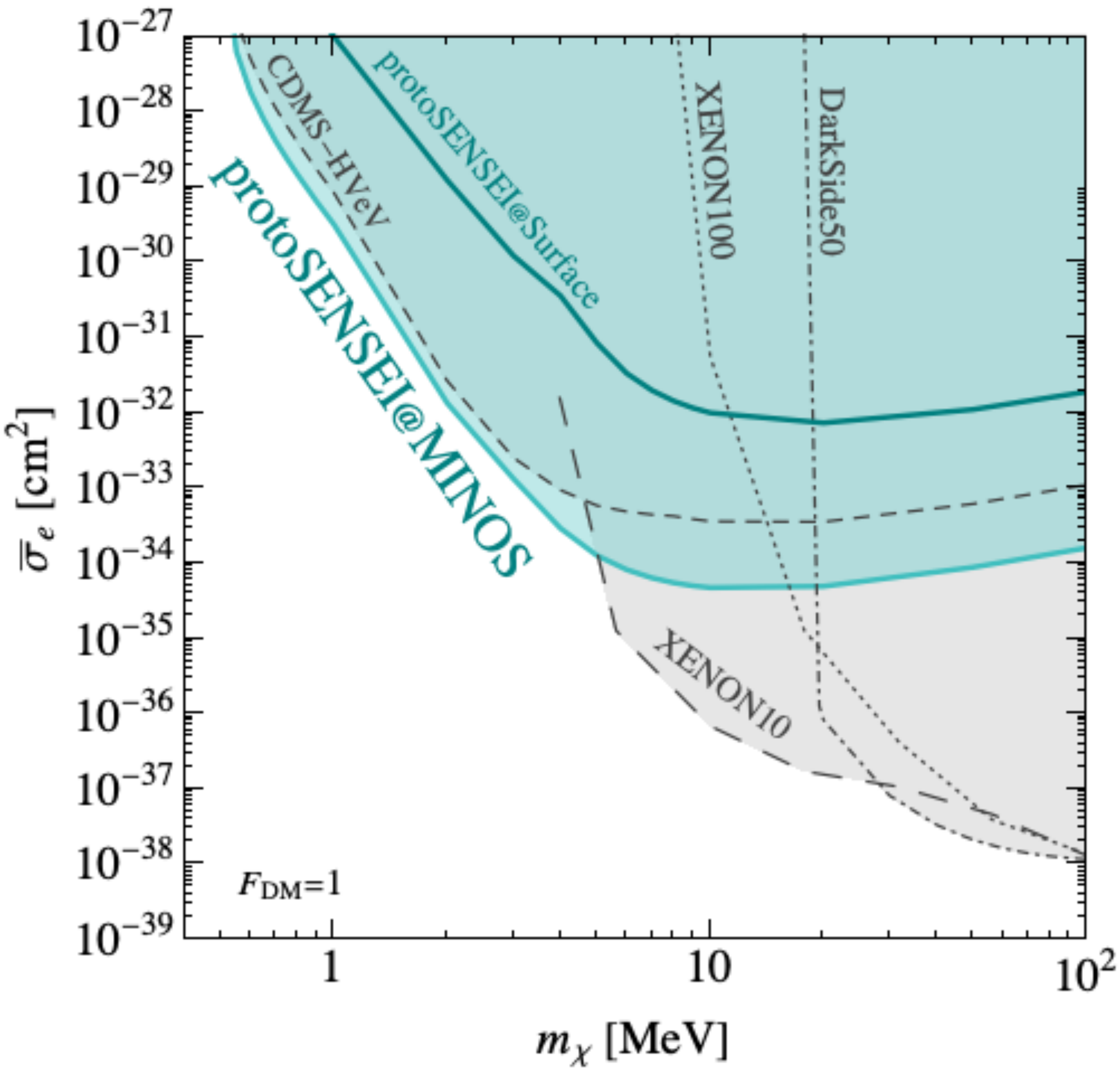
rms noise ~0.06 e^- !
(repeated measurements)

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

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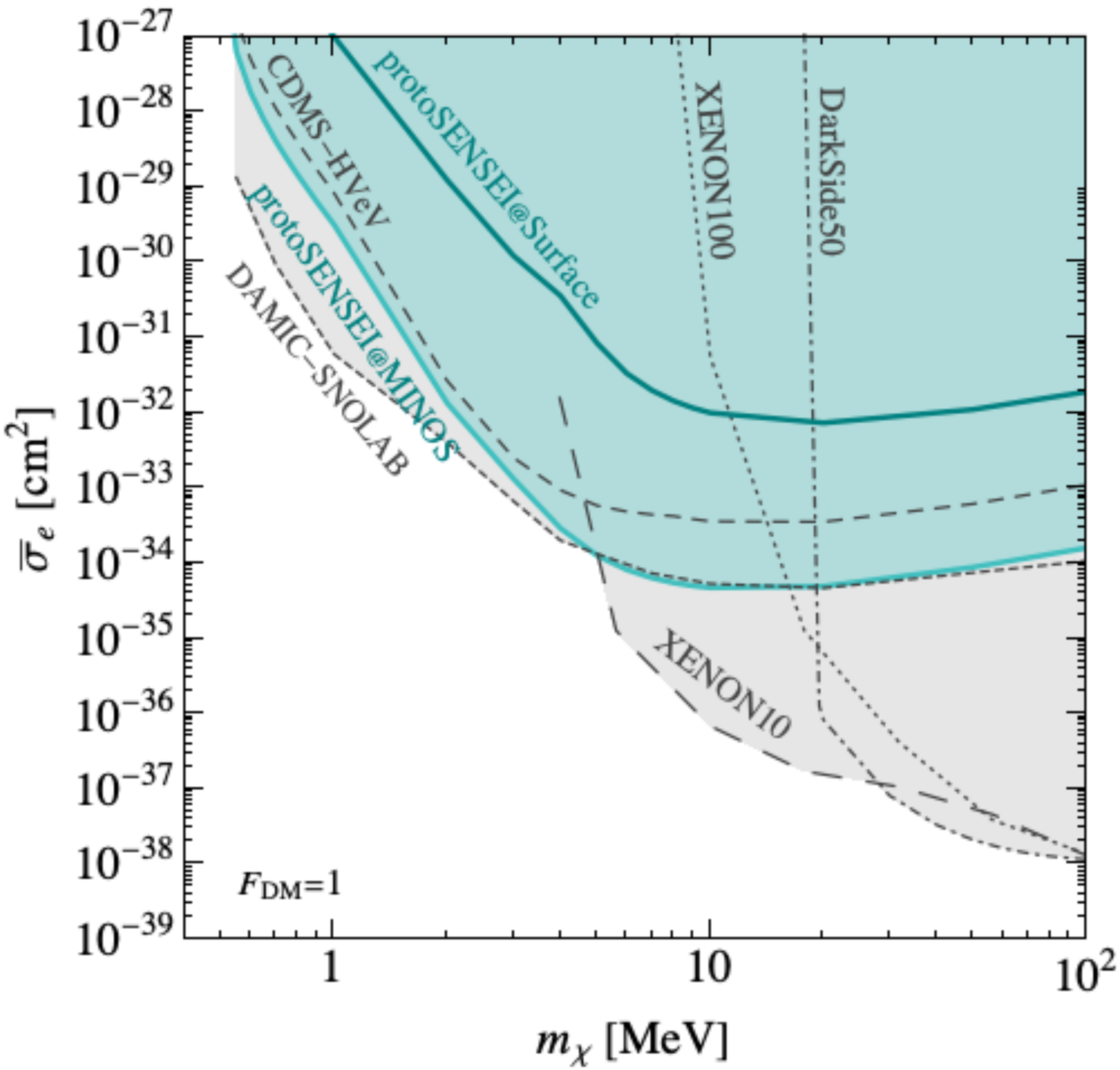

- tiny exposures:
  surface: ~0.02 gram-days
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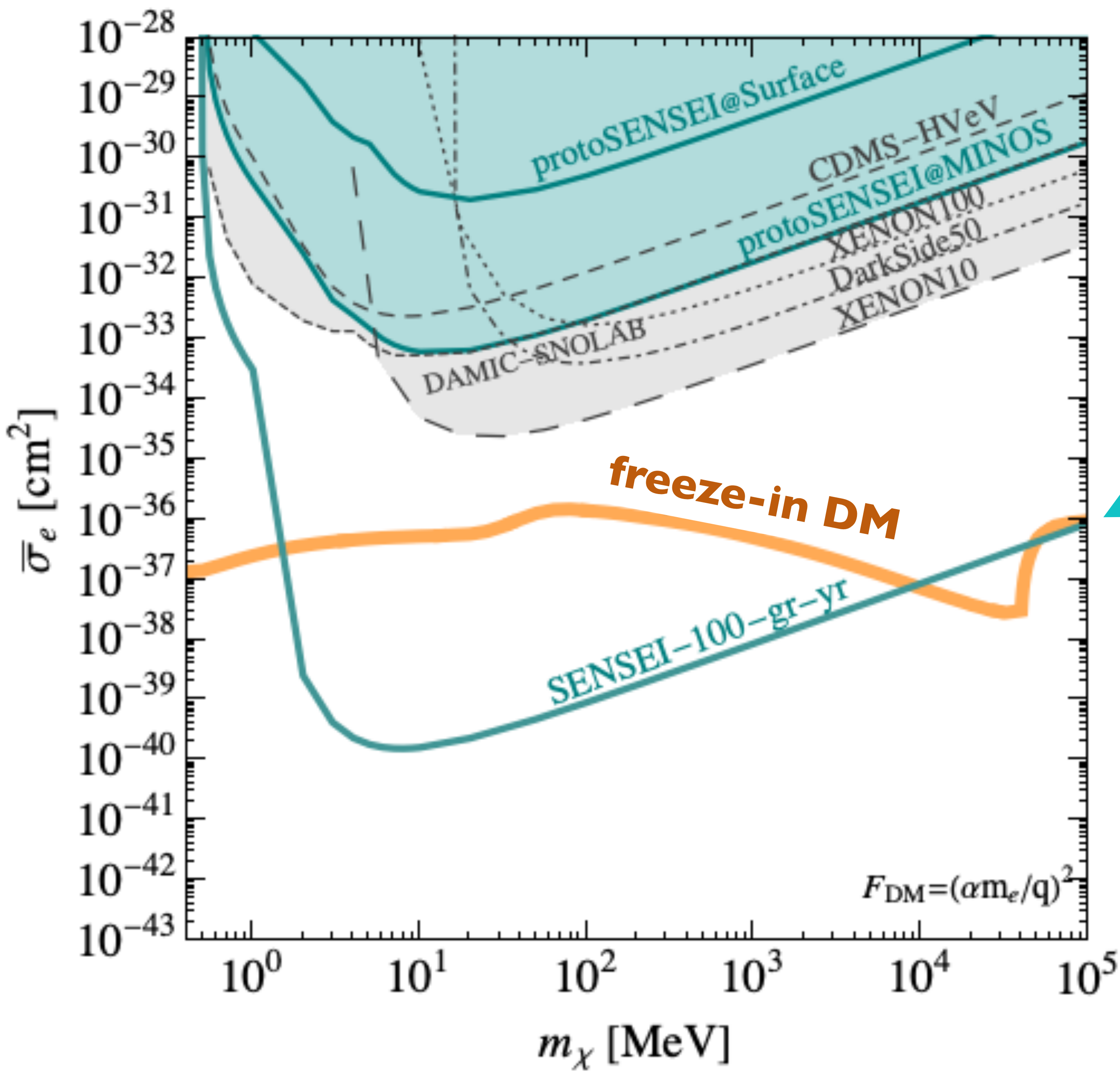
DAMIC@SNOLAB
(w/ ordinary CCDs w/ high-quality silicon, 200 gram-days)

1907.12628

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

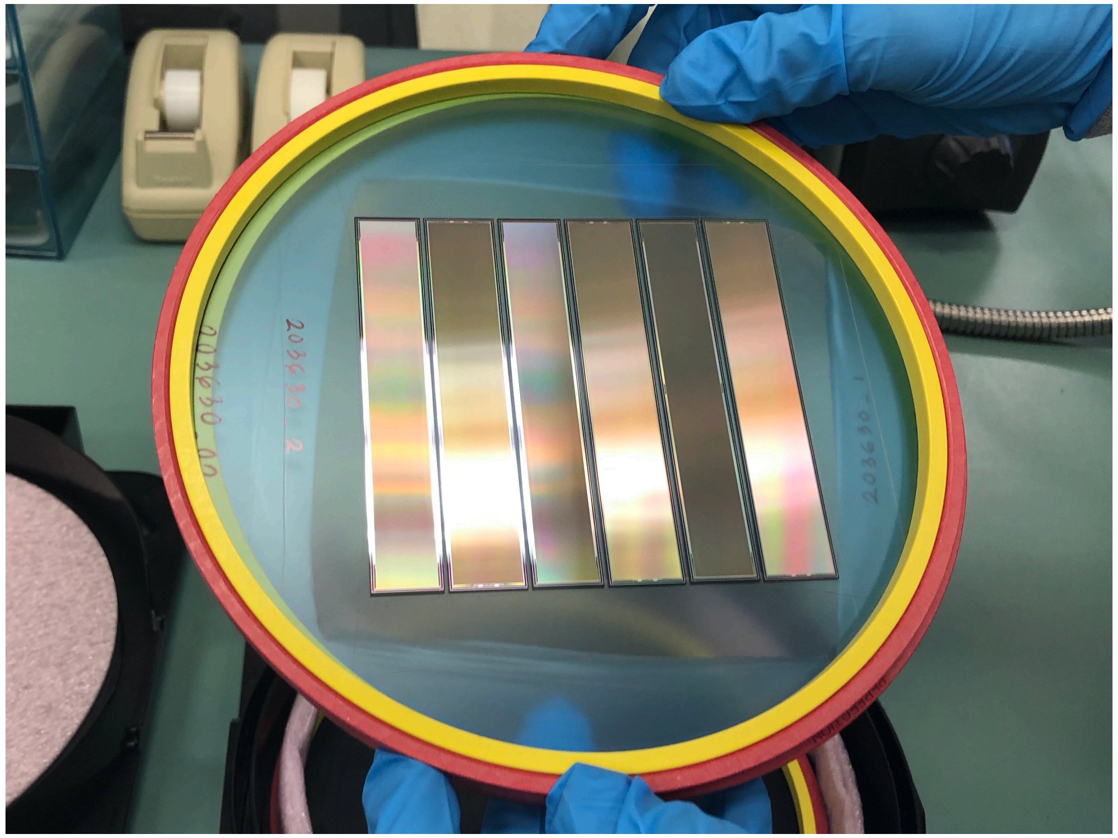


- orange: "freeze-in DM"

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

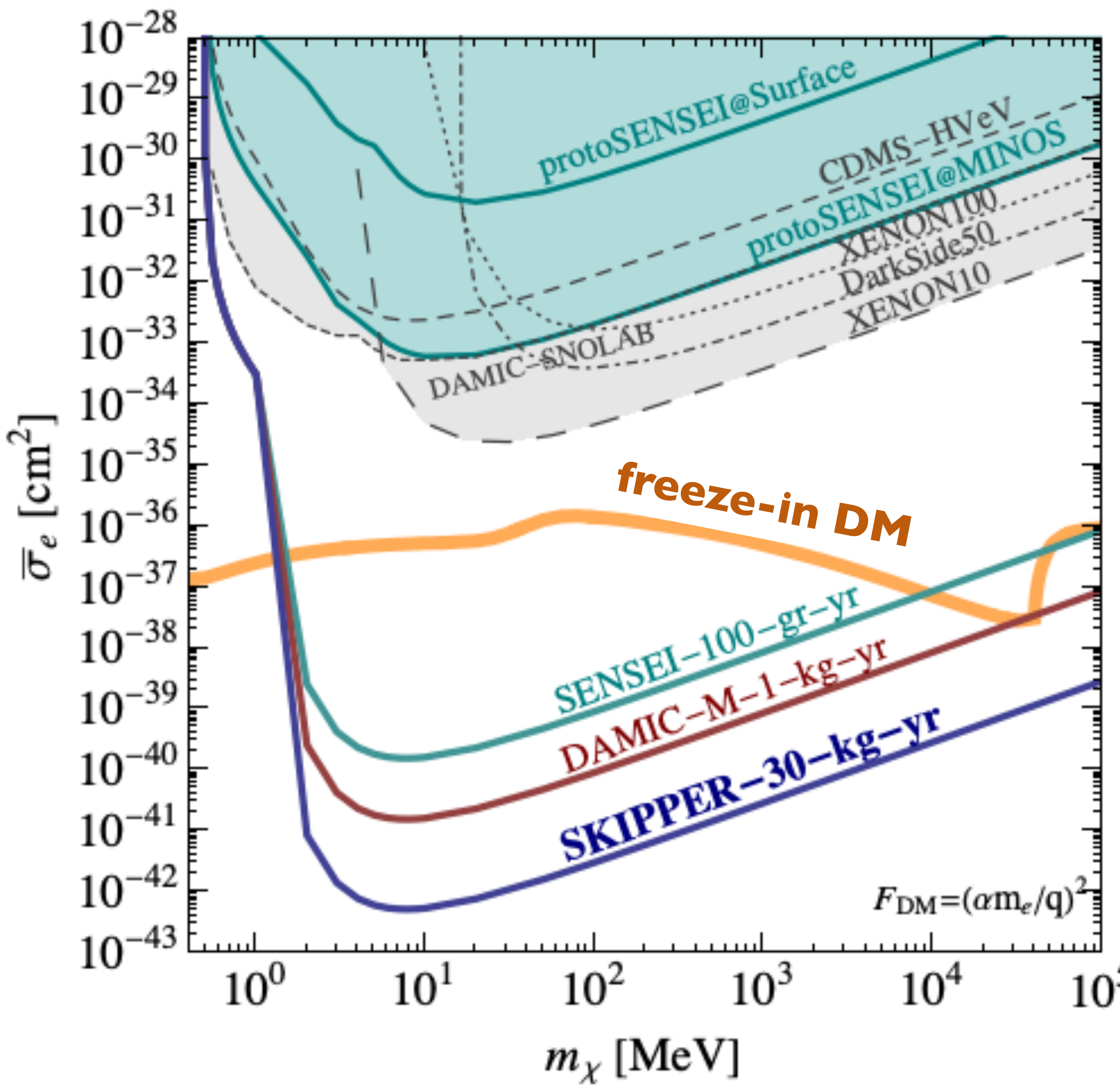
SENSEI: 100 g @ SNOLAB (funded, 2020)

new sensors are already being tested



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

SENSEI & other planned Skipper-CCD detectors



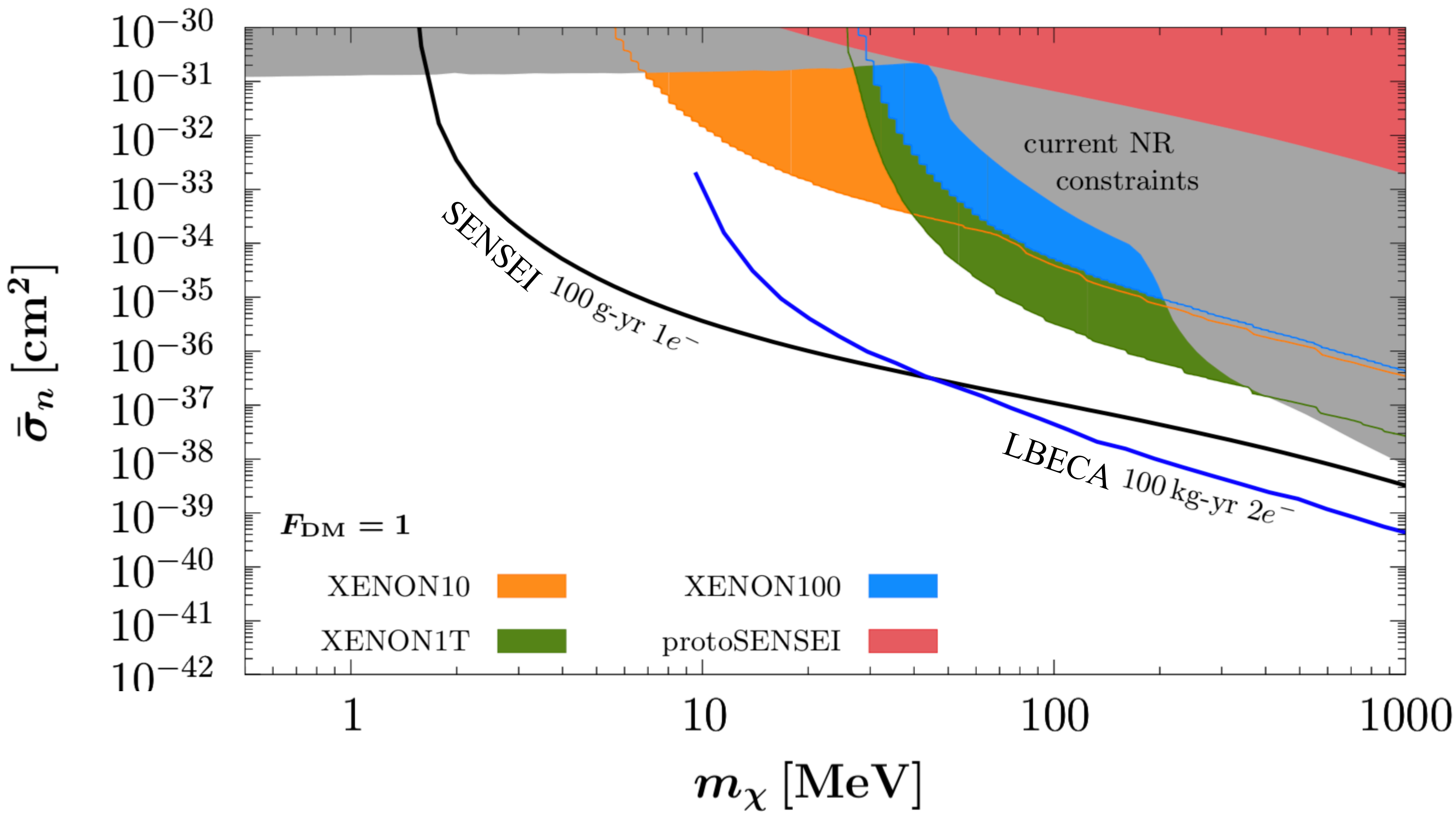
SENSEI: 100 g @ SNOLAB
(funded, 2020)

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

10 kg Skipper-CCD
(R&D funding announced last week by DoE)

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

SENSEI & LBECA have sensitivity also to Nuclear Interactions from Migdal effect



XENON10 sets best limit between 5 to 30 MeV

SENSEI & LBECA expected to improve by orders of magnitude

RE, Pradler, Sholapurkar, Yu

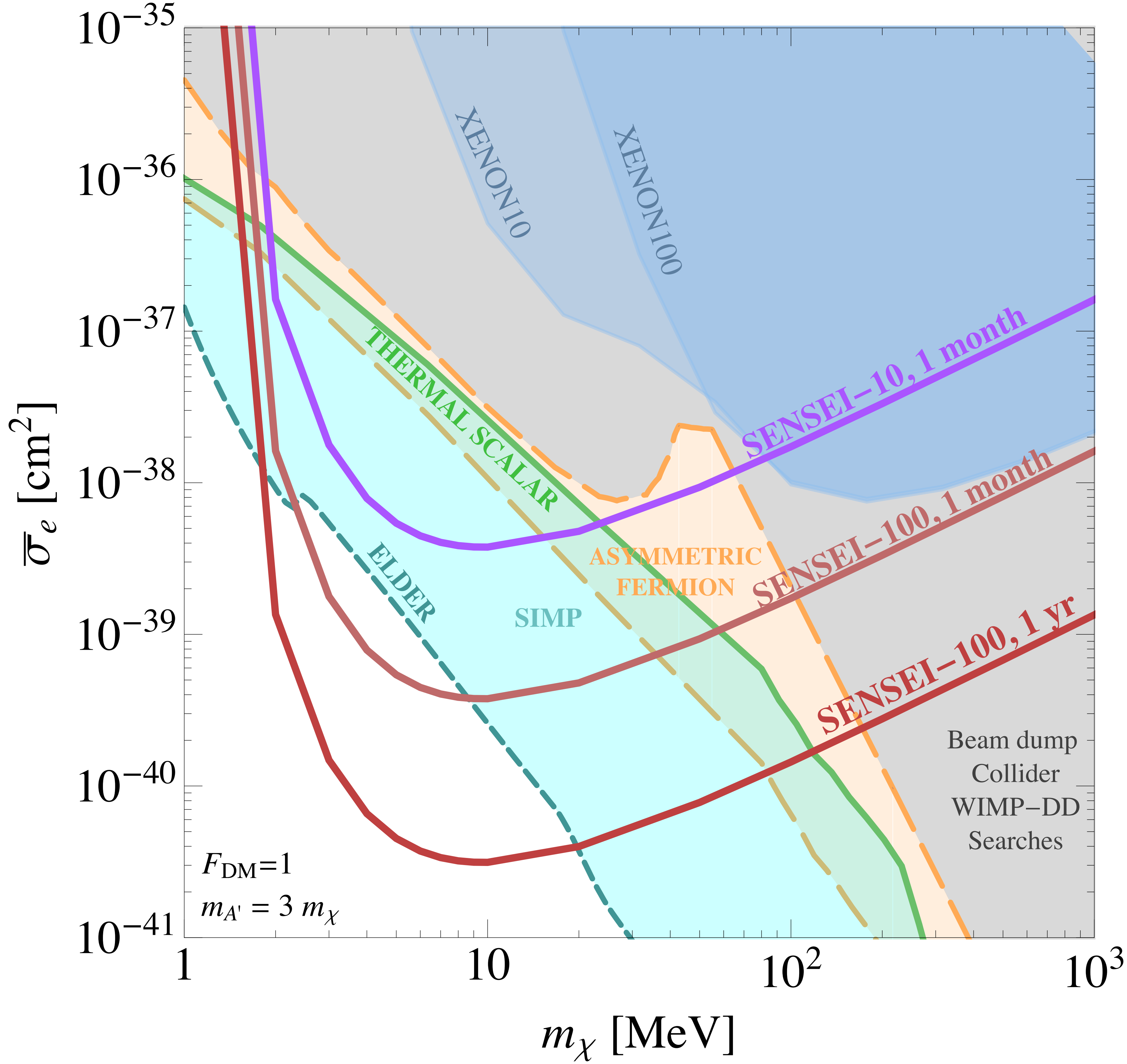
see also Baxter, Kahn, Krnjaic

Summary

- A much wider class of DM models are now actively being considered compared to ~10 years ago, including several well-motivated sub-GeV DM candidates
- Direct detection of sub-GeV DM is now possible, with several competing proposals
- SENSEI and other experiments have first results and will probe vast new regions of uncharted territory in next few years

Thank you!

SENSEI sensitivity to Benchmark Models

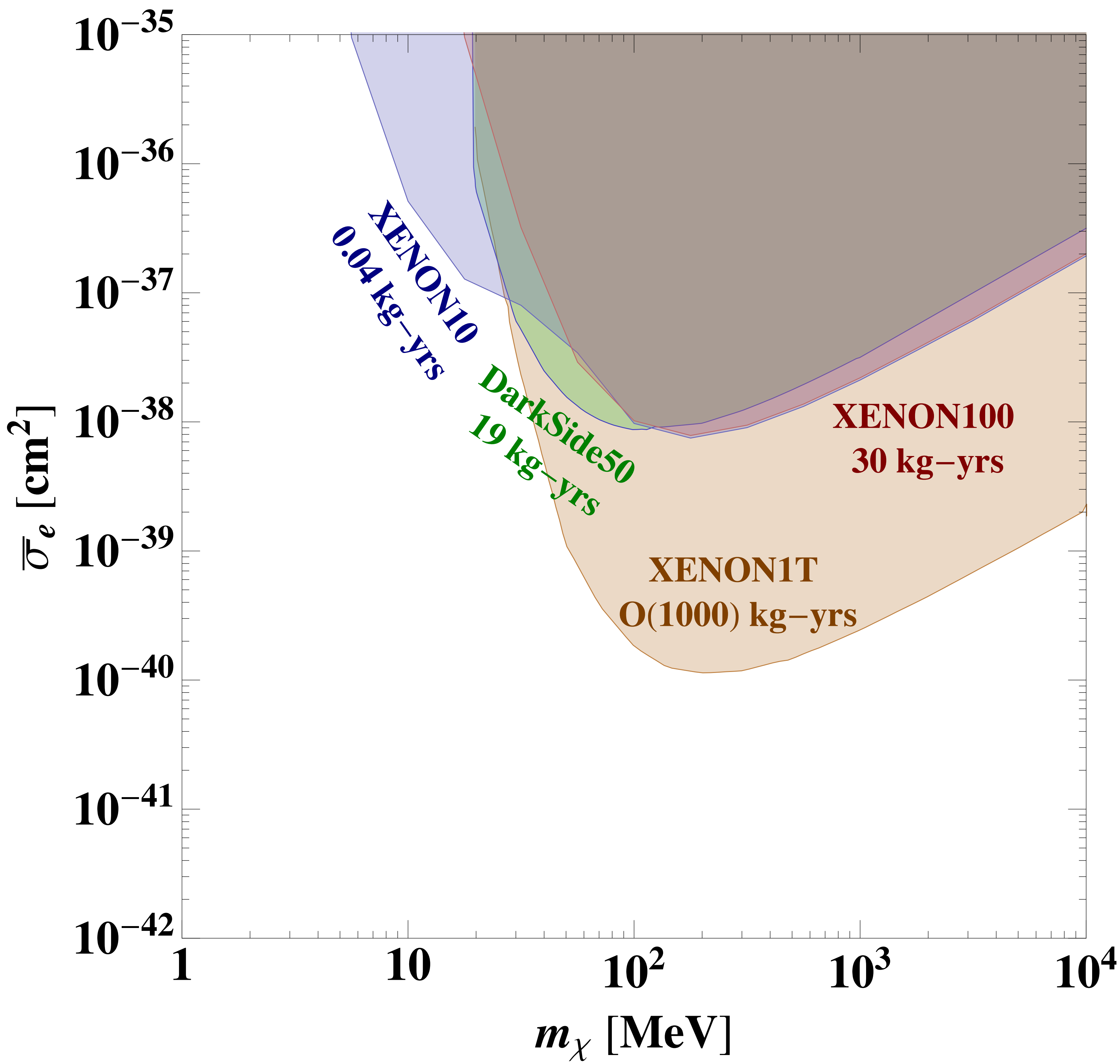


mediator: "heavy" dark photon

Models:

- thermal scalar
- asymmetric fermion
- SIMP
- ELDER

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

The LBECA Collaboration

“Low Background Electron Counting Apparatus”

LBNL:

- P. Sorensen

LLNL:

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

Purdue

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

Stony Brook:

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

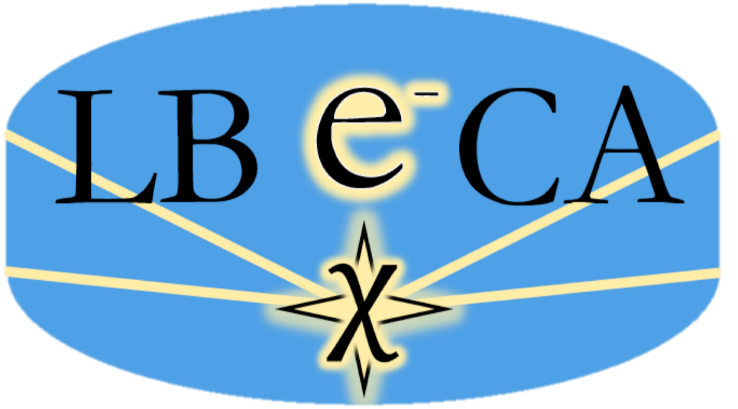
UC San Diego:

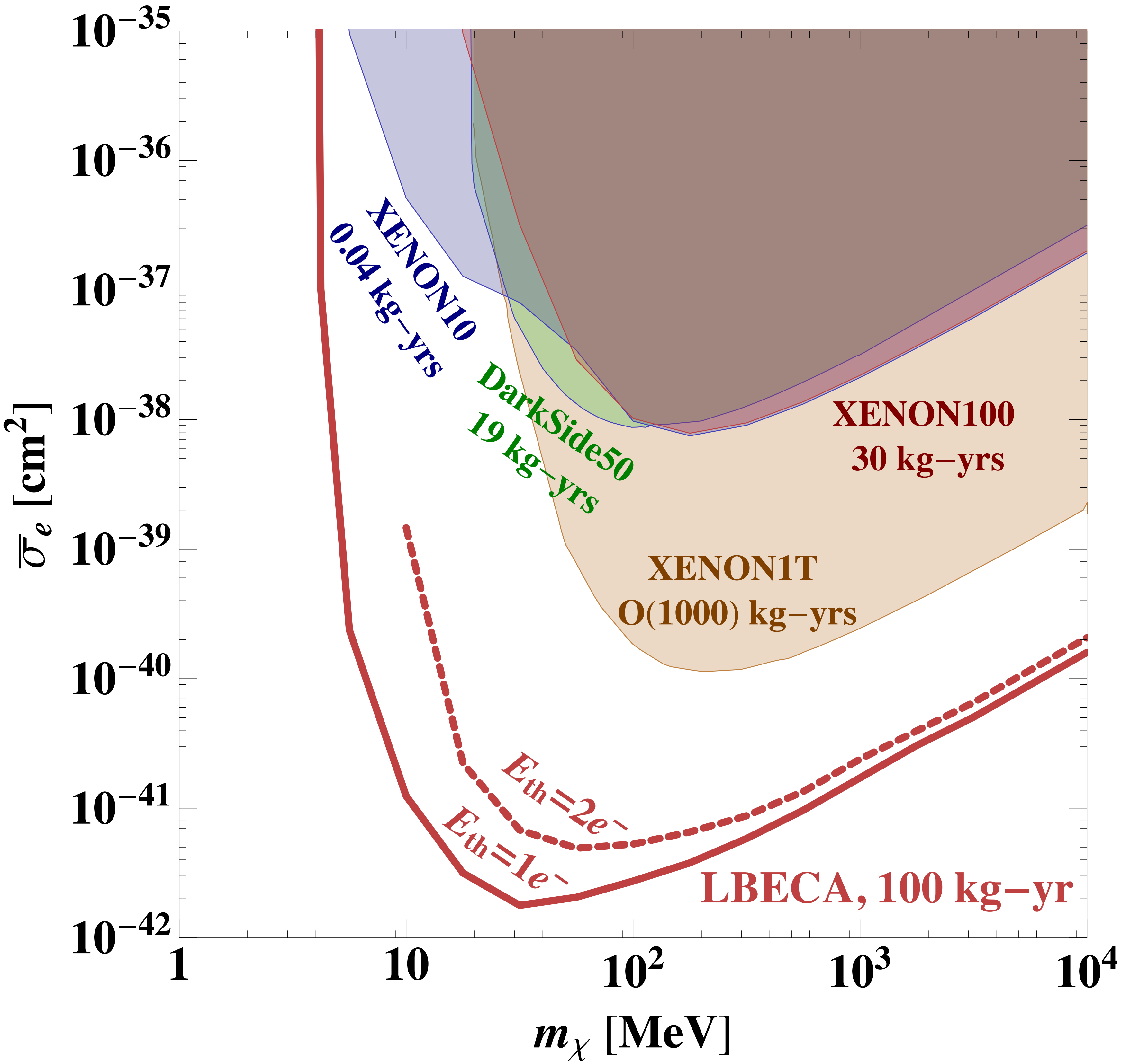
- K. Ni, J. Long, J. Ye

R&D partially funded by US DoE

Proposed Experiment: LBECA

"Low Background Electron Counting Apparatus"





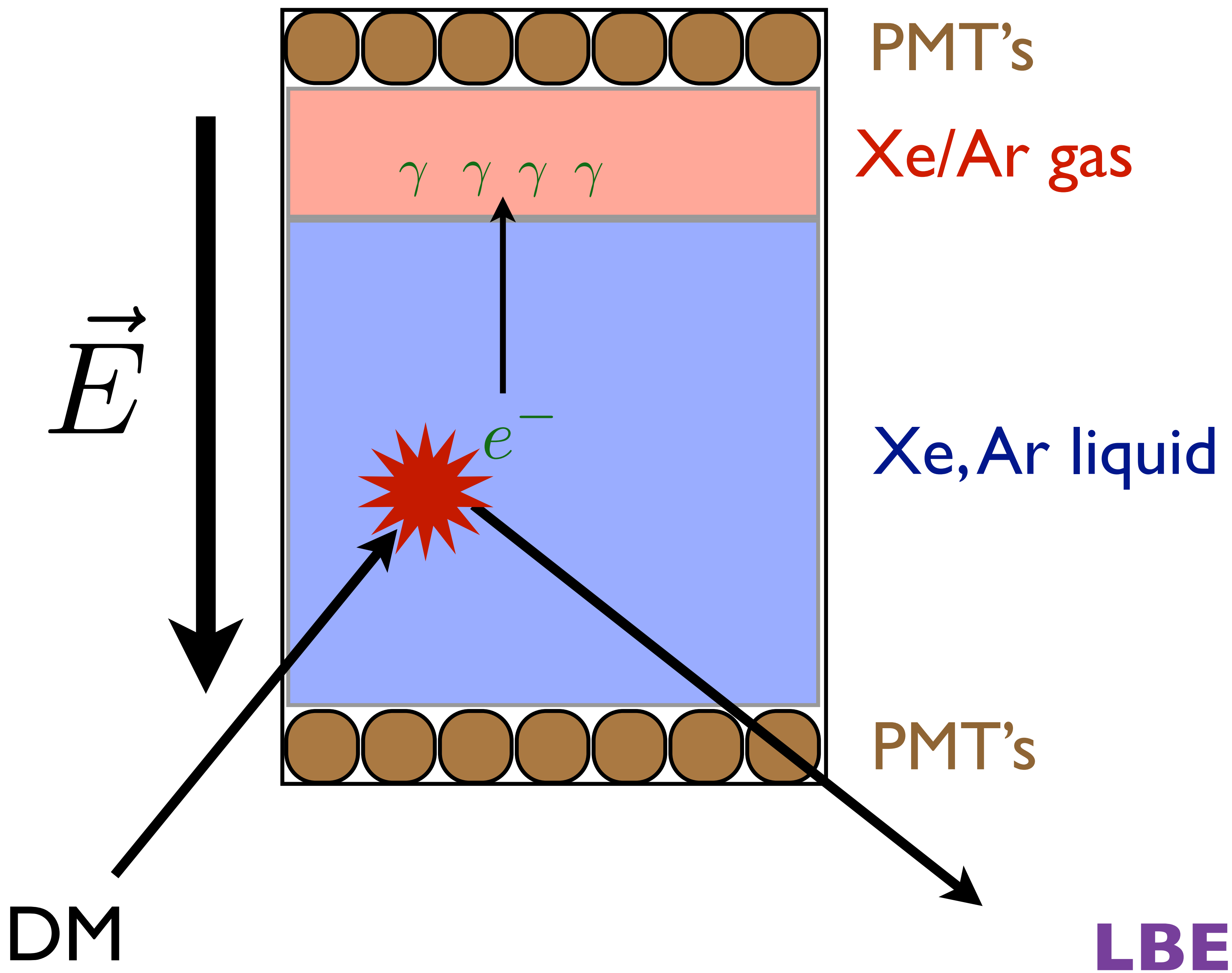
Bernstein, Clark, RE, Fernandez-Serra, Kopec, Lang, Long, Ni, Pereverzev, Sorensen, Xu, Ye, Zhen…

Goal:

100 kg liquid xenon detector w/o backgrounds that have plagued previous detectors

partially funded by DoE Detector R&D program

Detection Concept



Sensitive to single electrons!

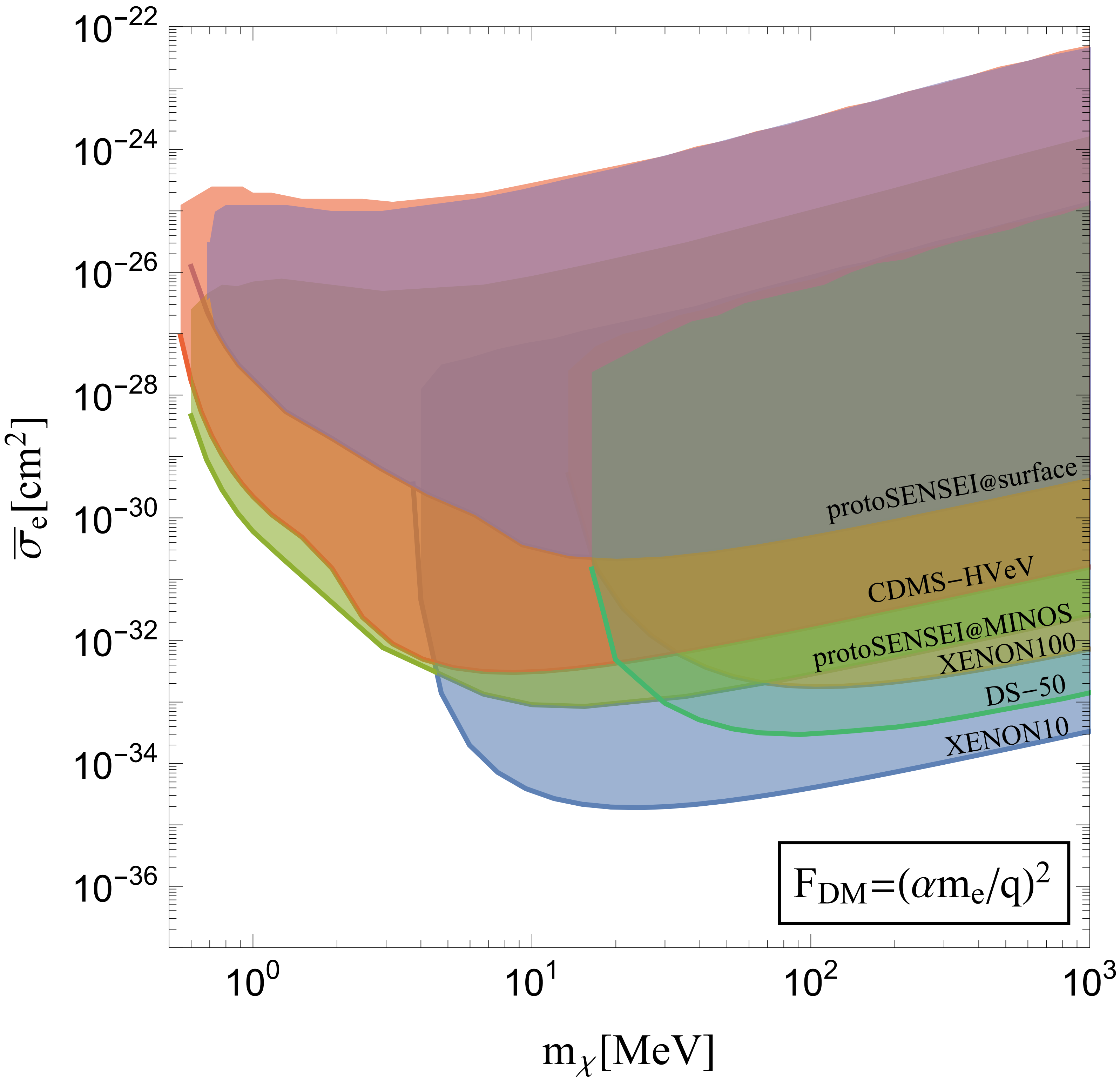
But large backgrounds:

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

LBECA: a ~100 kg detector, ideally w/o these backgrounds

Current bounds on DM w/ large interactions

Emken, RE, Kouvaris, Sholarpurkar

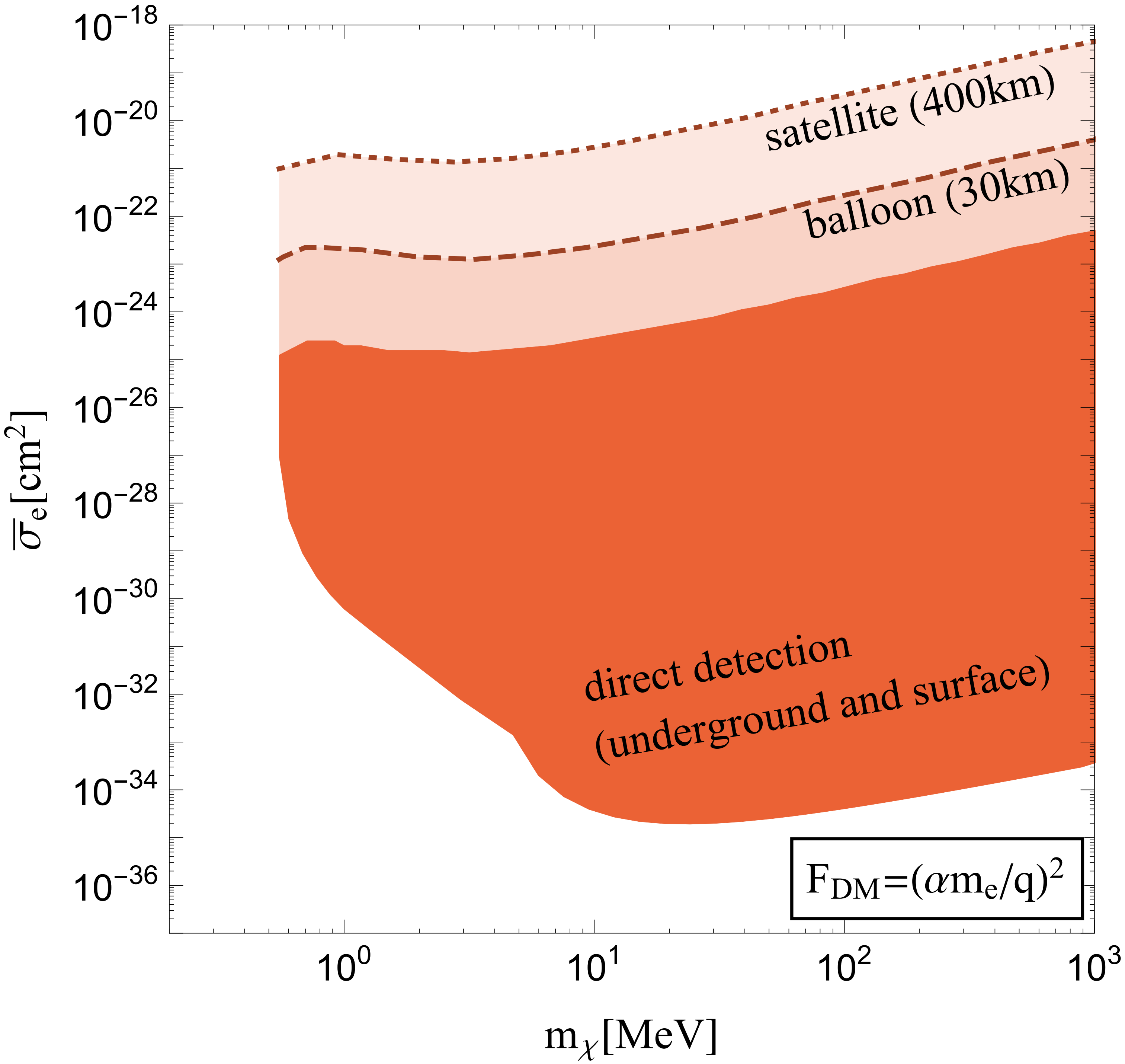


assumes dark photon mediator

Surface data (from prototypes by SENSEI & CDMS-HV) are most constraining at high cross sections

A Skipper-CCD on a satellite or balloon can probe DM with even larger interactions

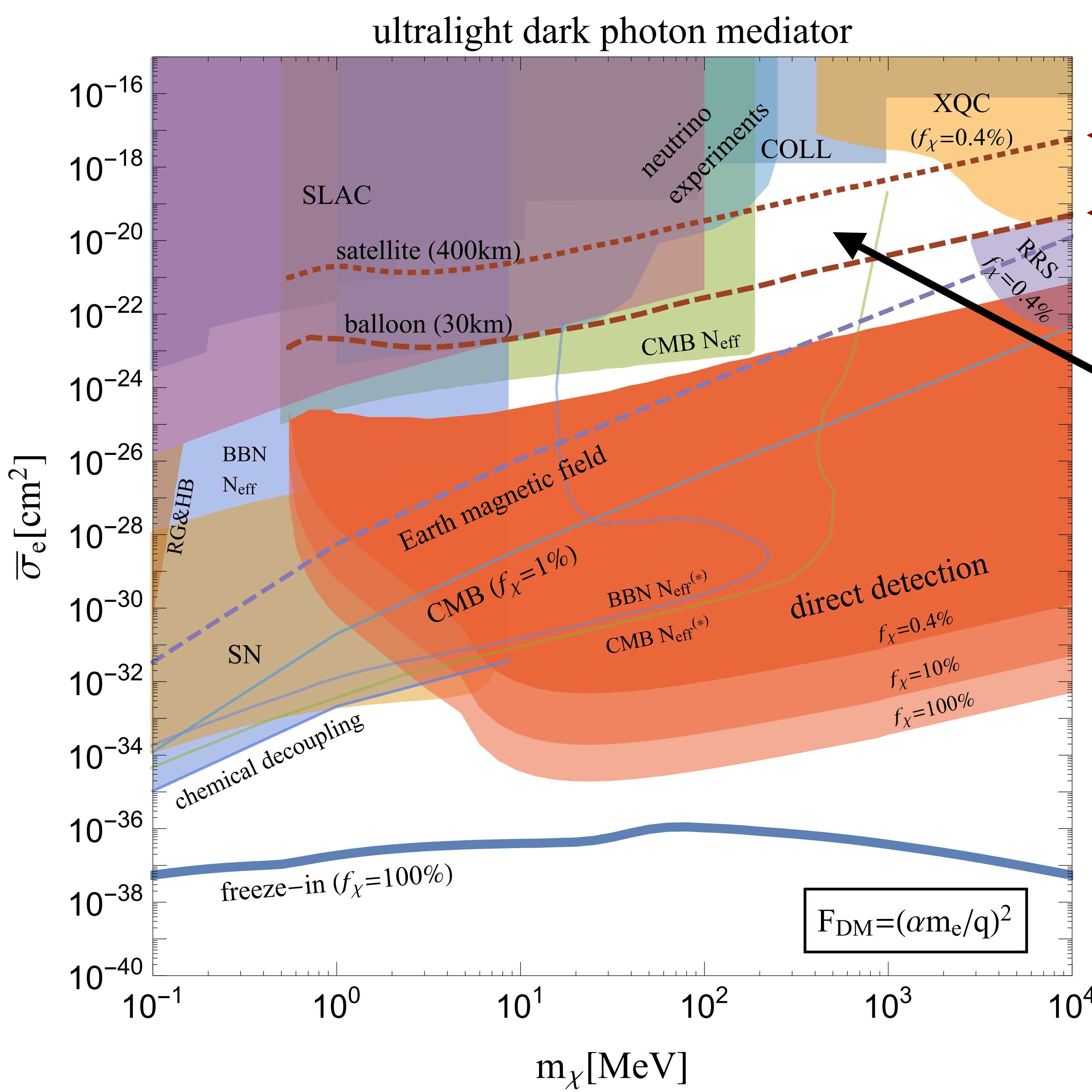
Emken, RE, Kouvaris, Sholarpurkar



Balloon- & satellite-borne detector being explored in collaboration w/ scientists at FNAL & JPL

Is there a DM model w/ such large interactions?

Emken, RE, Kouvaris, Sholarpurkar



satellite

balloon

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