

Some Recent Progress in Direct Detection of sub-GeV Dark Matter

Rouven Essig

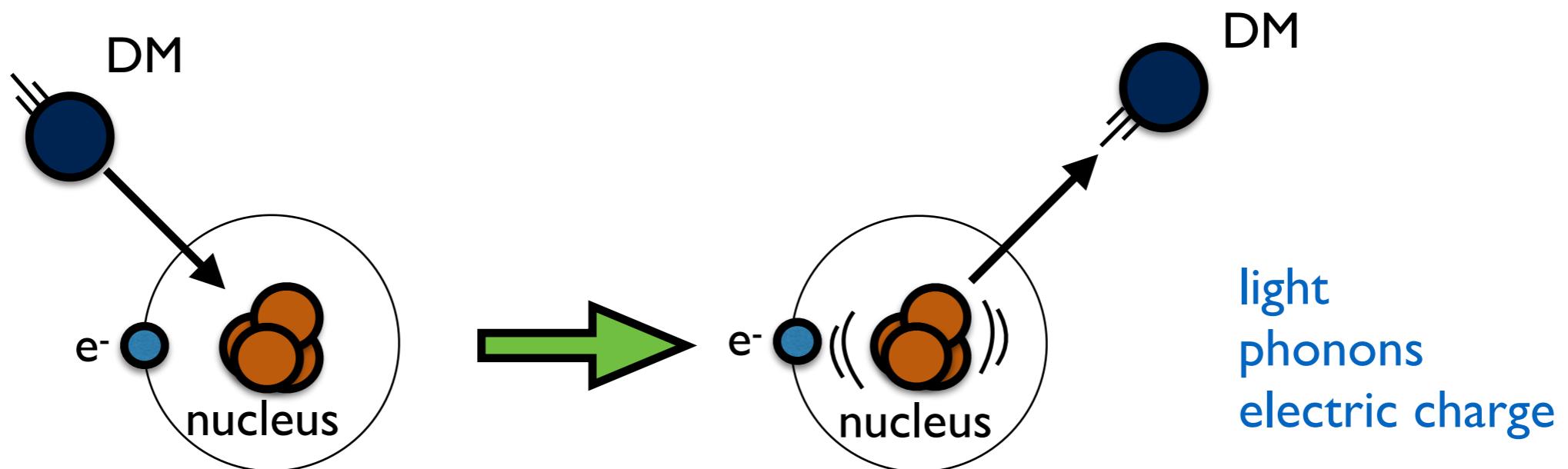
Yang Institute for Theoretical Physics



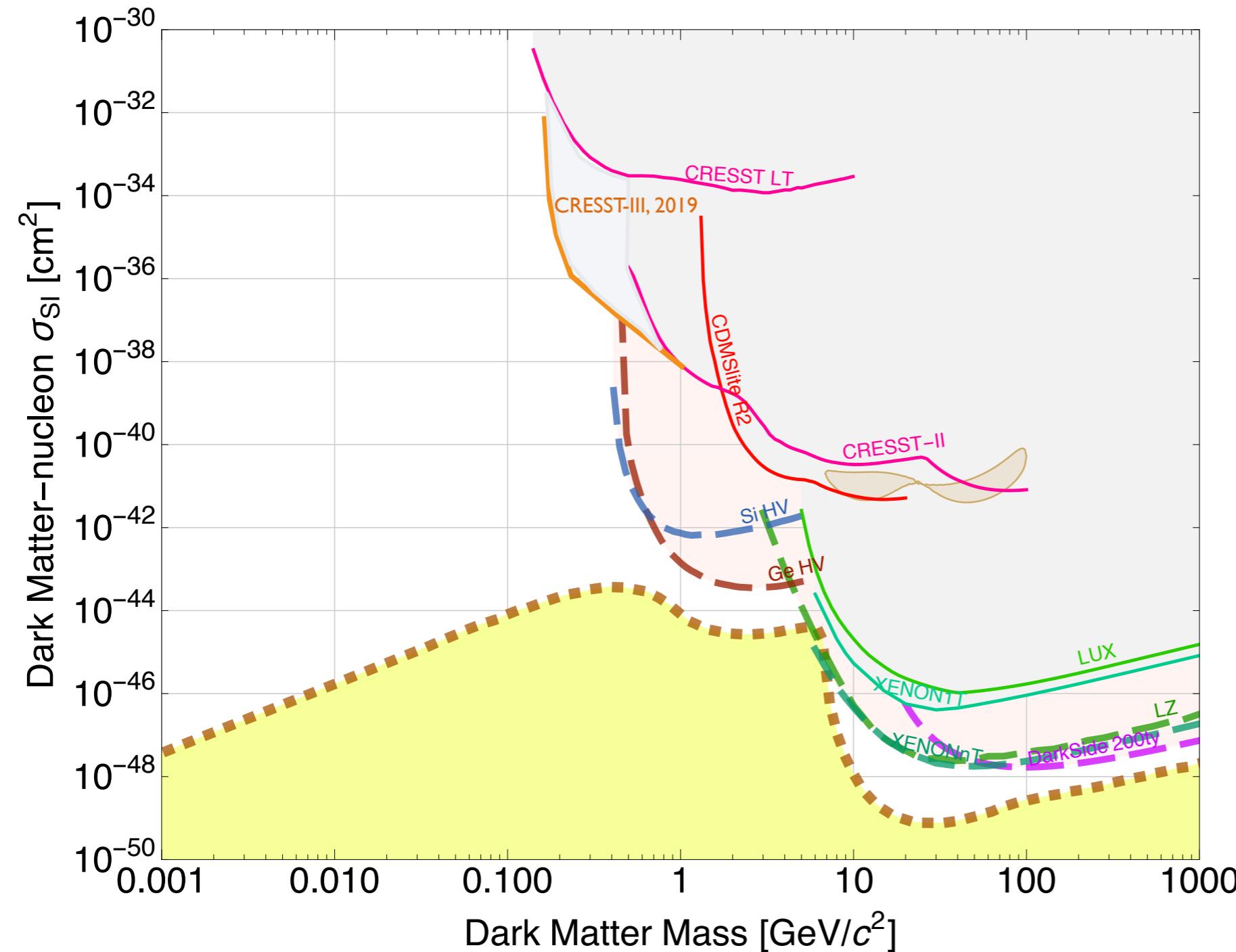
GGI, September 25, 2019

Traditional Direct Detection strategy:

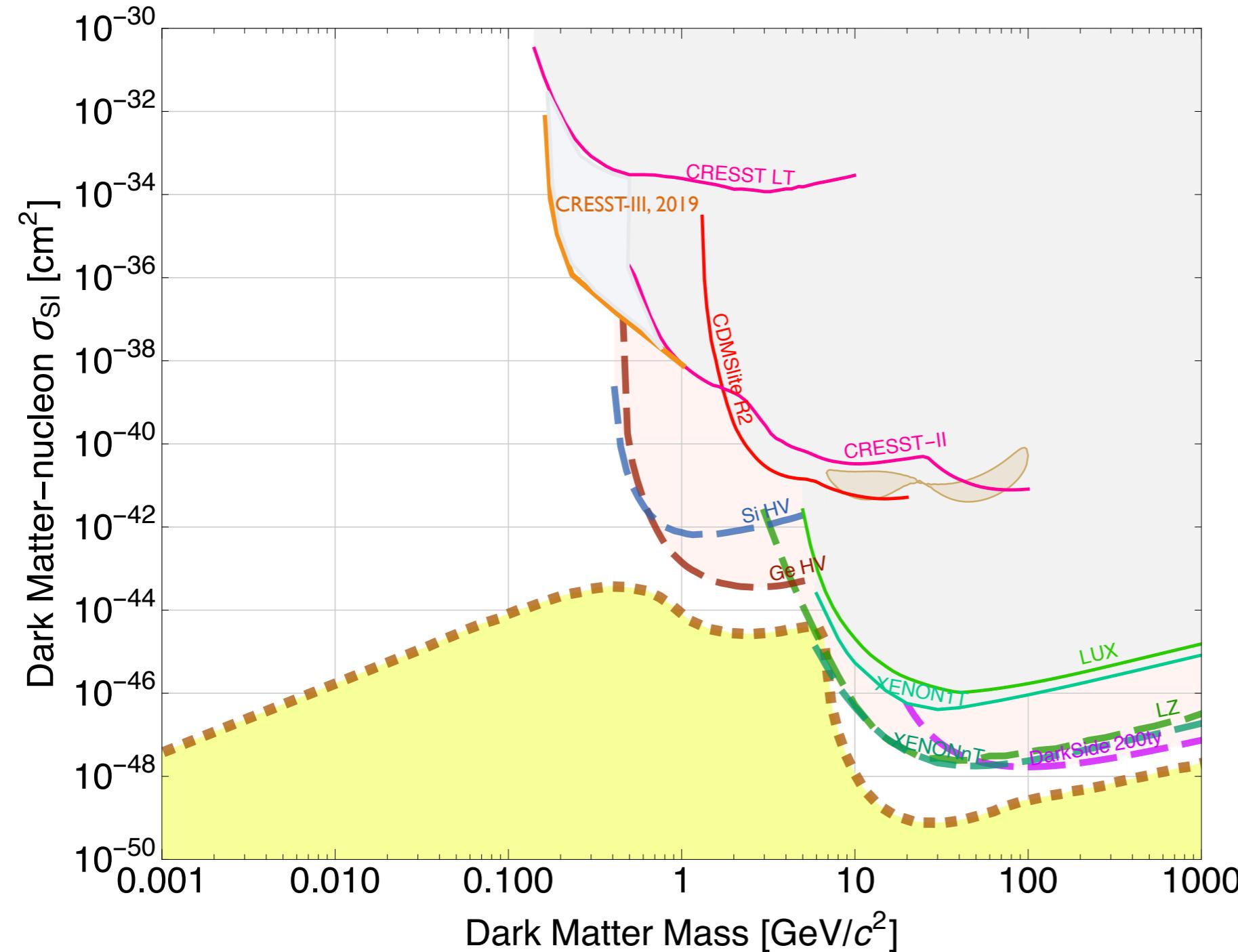
look for nuclear recoils from
elastic WIMP-nucleus scattering



Constraints & projections from elastic nuclear recoils

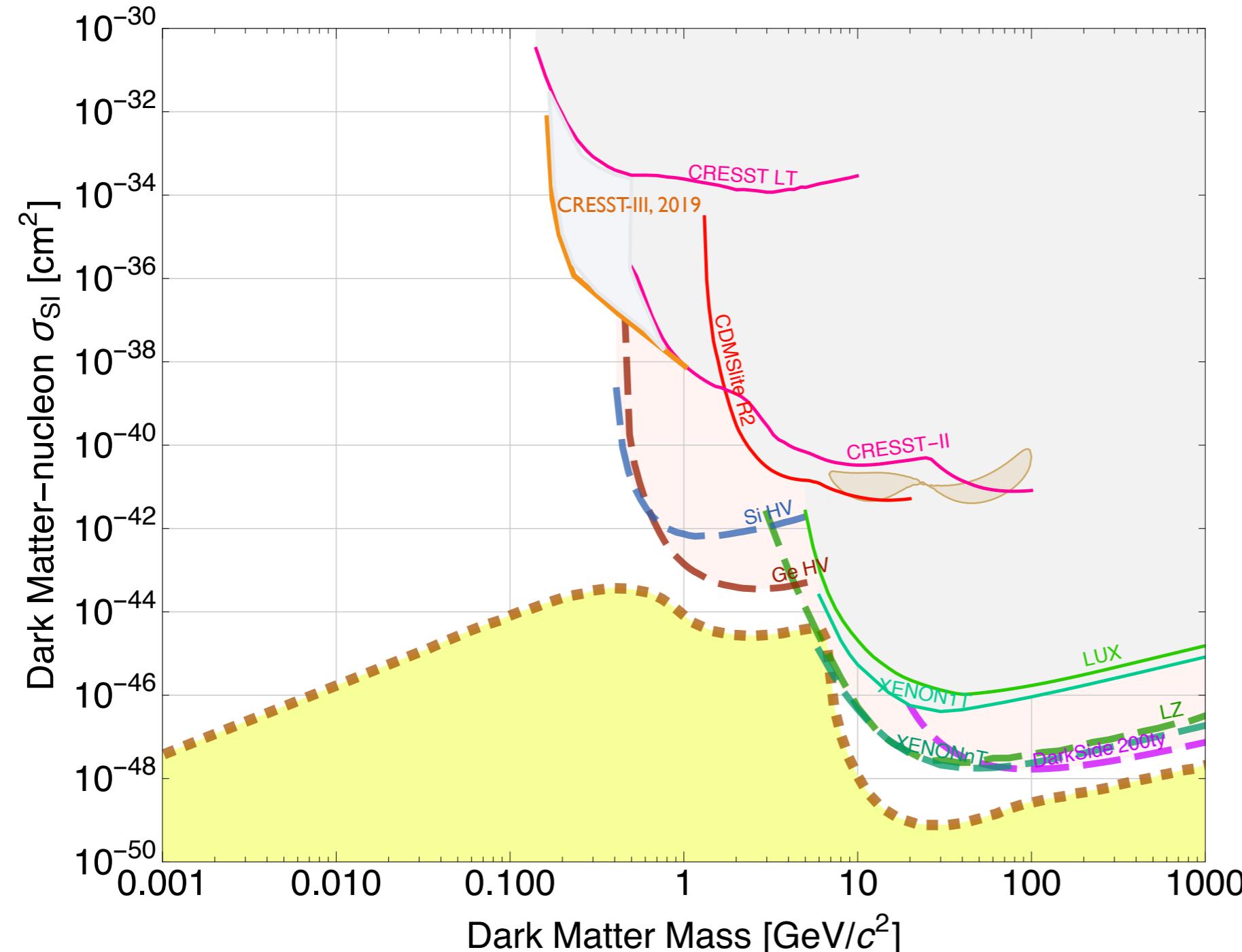


Constraints & projections from elastic nuclear recoils



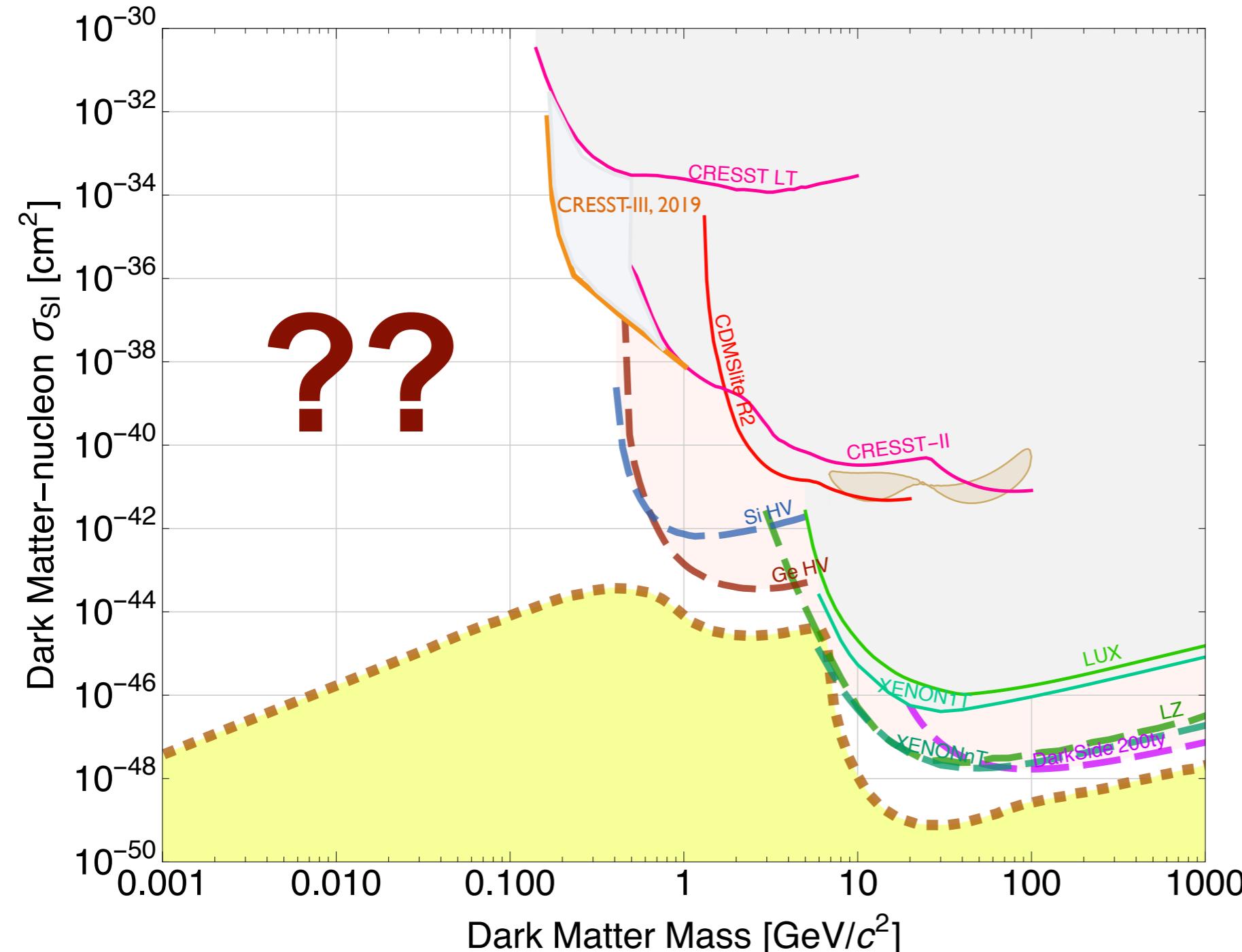
- dozens of experiments over last several decades

Constraints & projections from elastic nuclear recoils



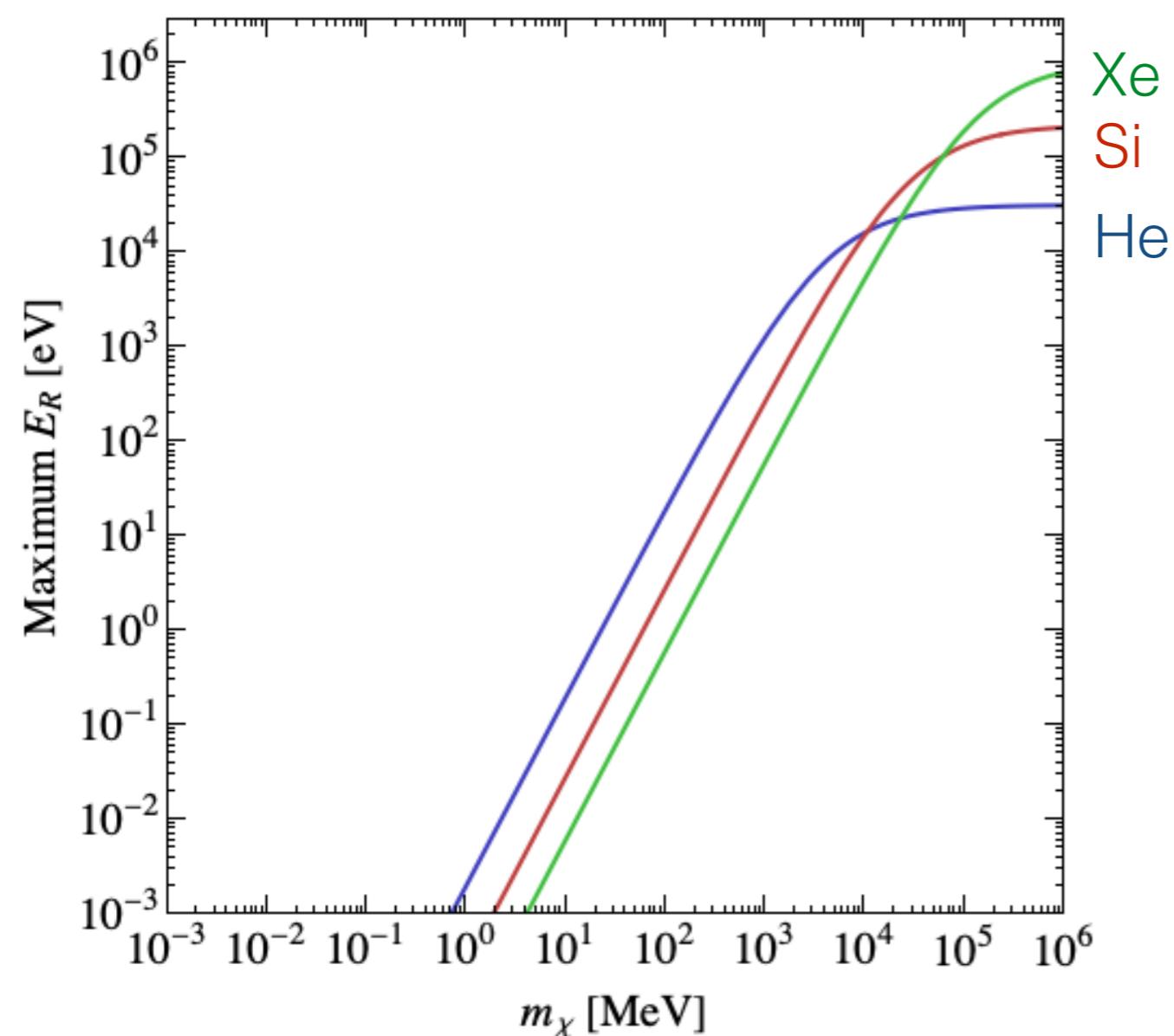
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- WIMP searches well-established with multi-ton-scale experiments taking data soon

Constraints & projections from elastic nuclear recoils



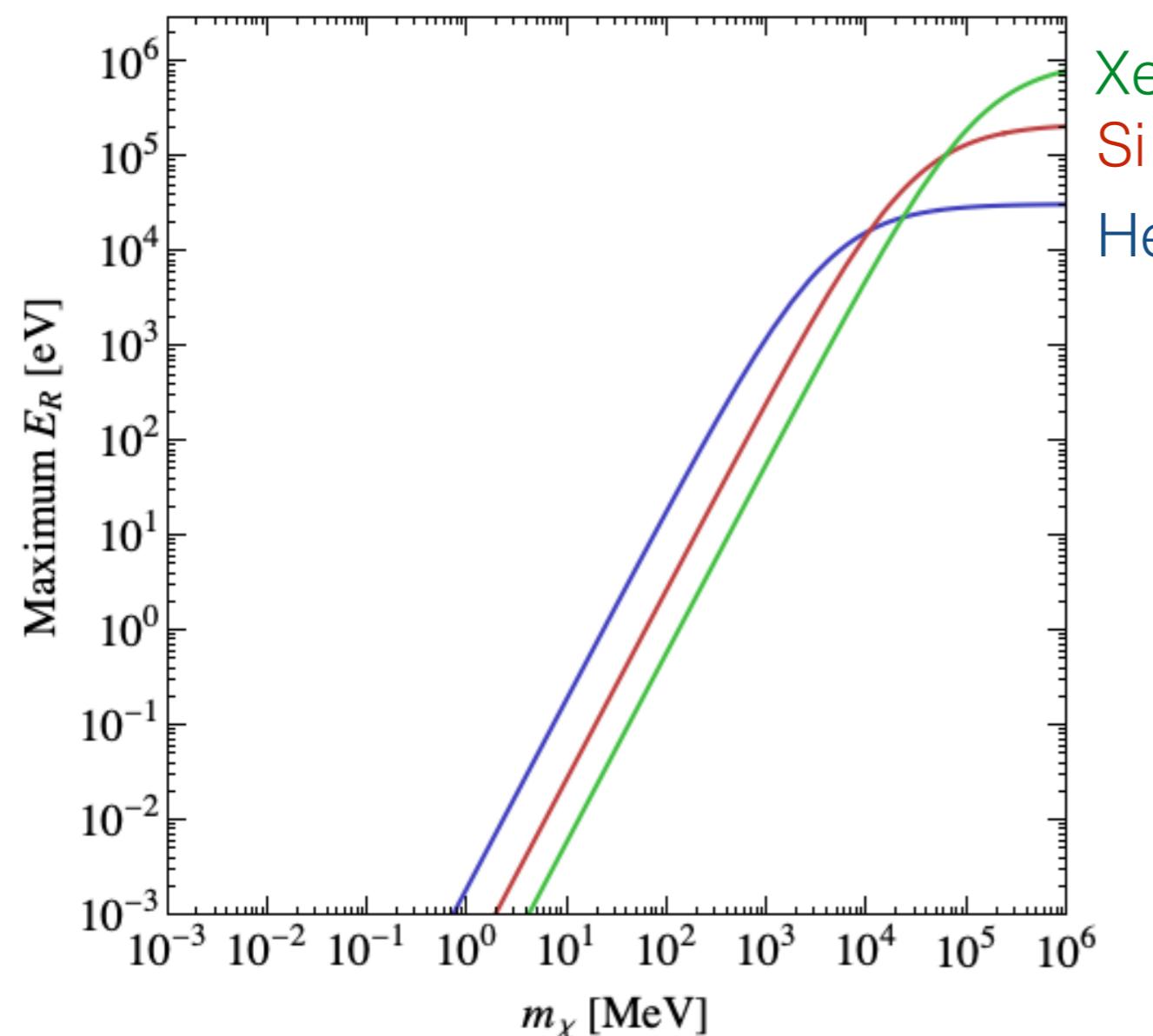
- dozens of experiments over last several decades
- WIMP searches well-established with multi-ton-scale experiments taking data soon
- How probe lower masses?

Probing sub-GeV DM w/ elastic nuclear recoils

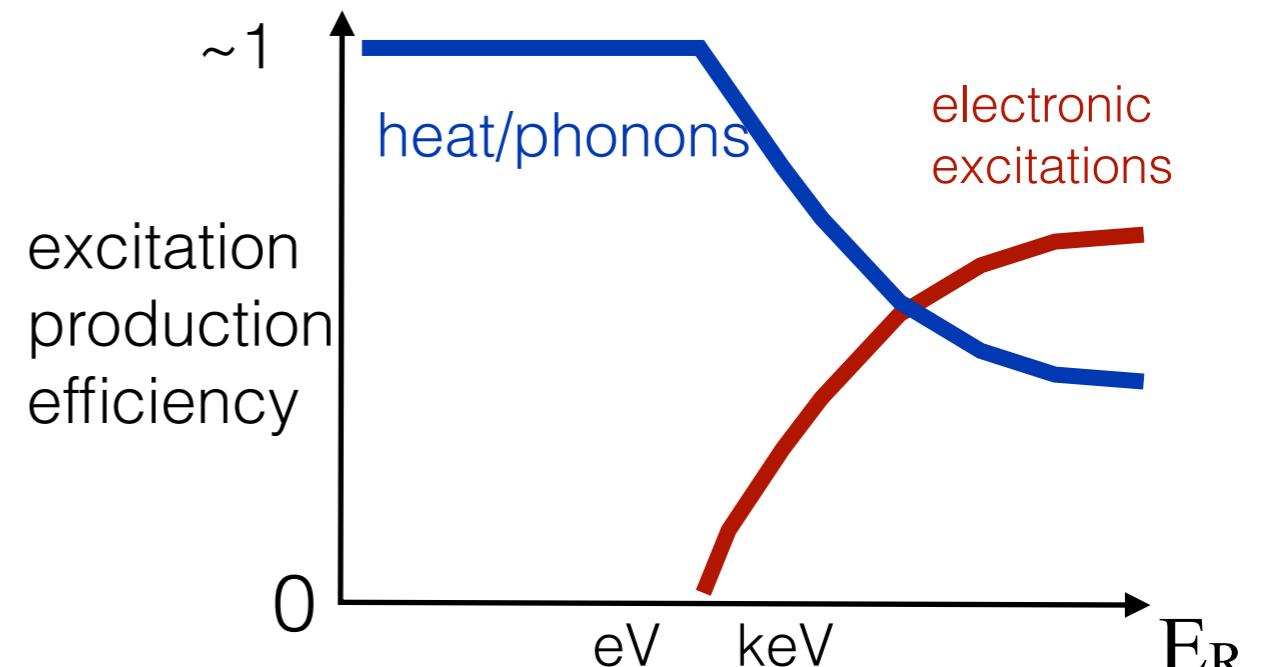


$$E_{\text{NR}} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \approx \frac{2m_\chi^2 v_\chi^2}{m_N}$$

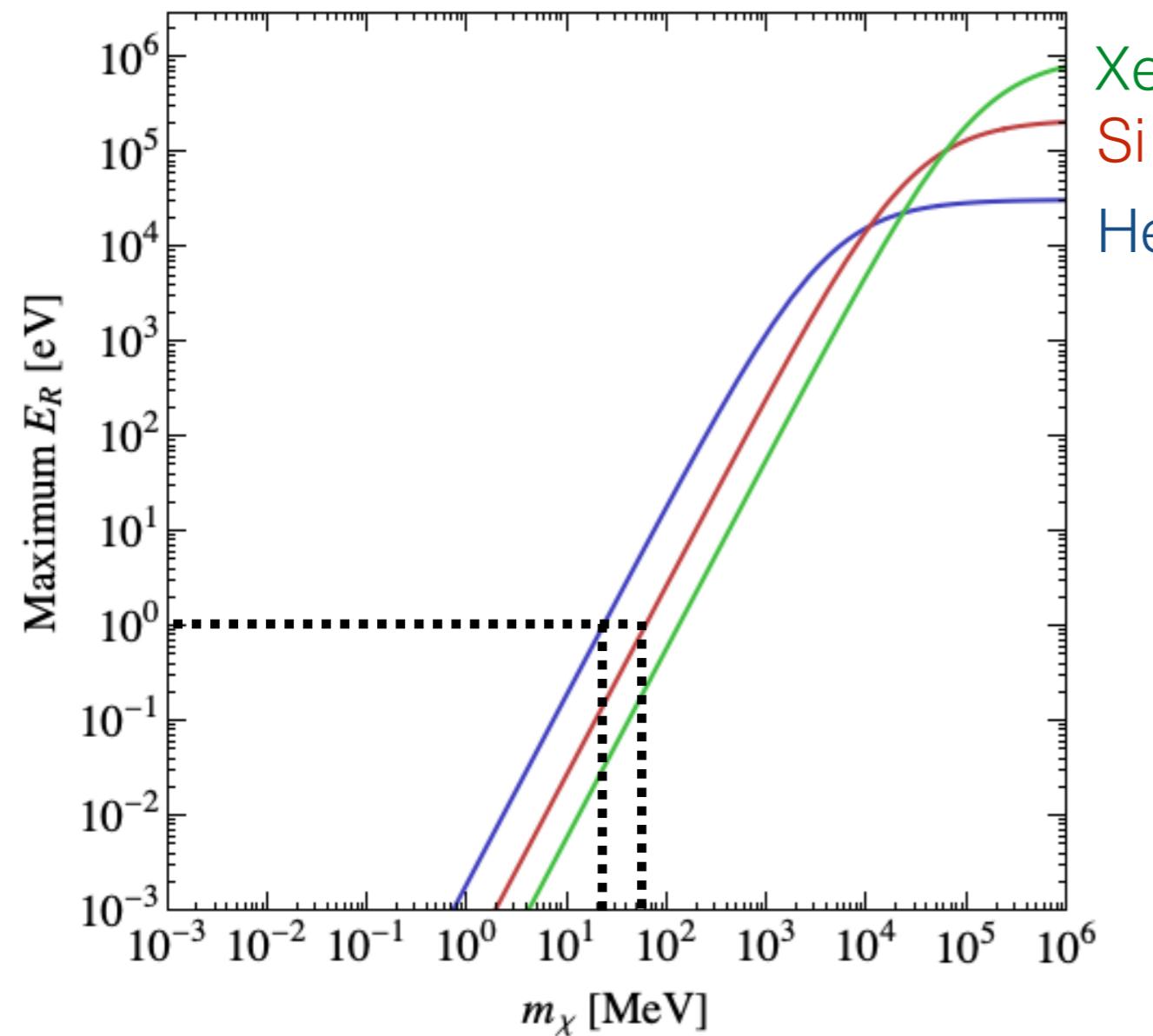
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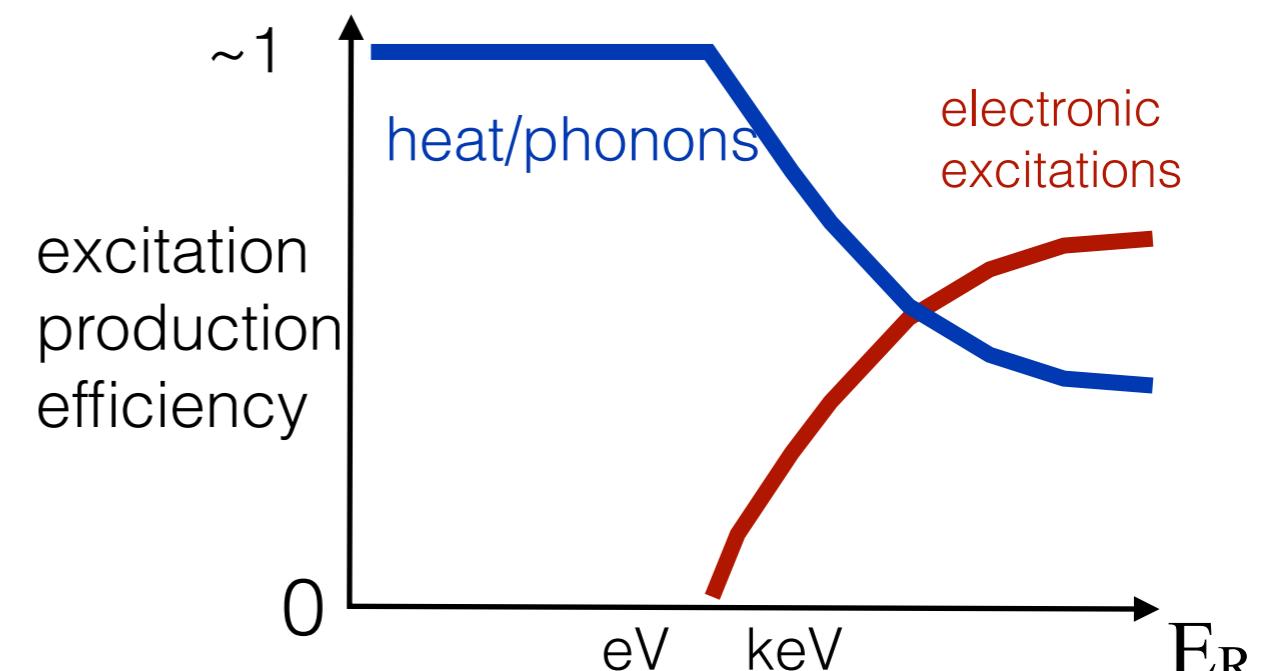
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Probing sub-GeV DM w/ elastic nuclear recoils



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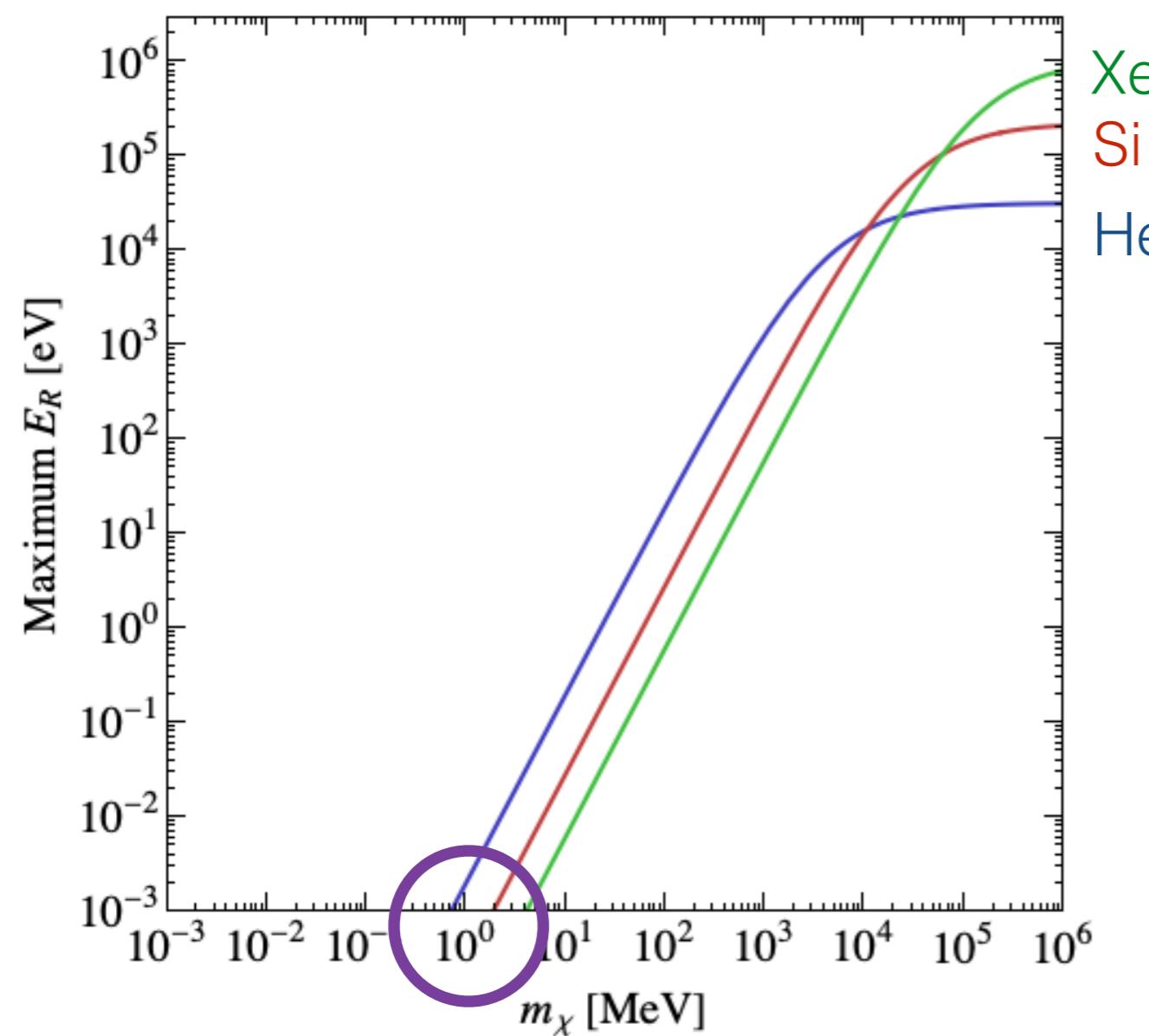


- ongoing work towards $\mathcal{O}(\text{cm}^2)$ -size phonon detector w/ $\mathcal{O}(1 \text{ eV})$ sensitivity

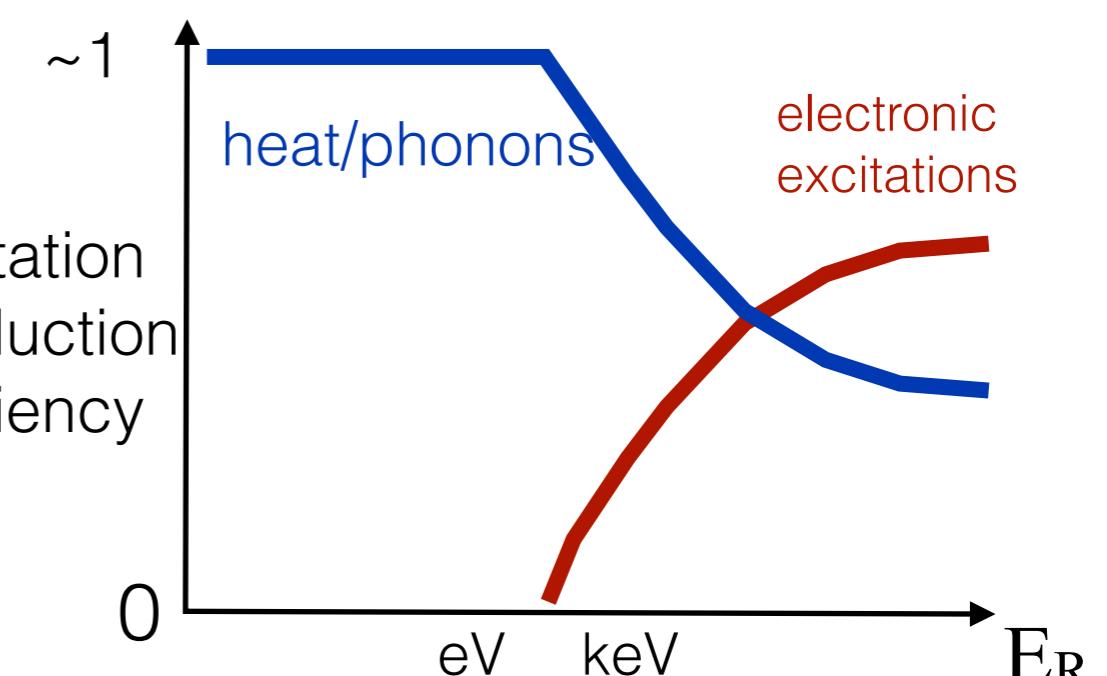
⇒ probe 20-50 MeV DM

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

Probing sub-GeV DM w/ elastic nuclear recoils

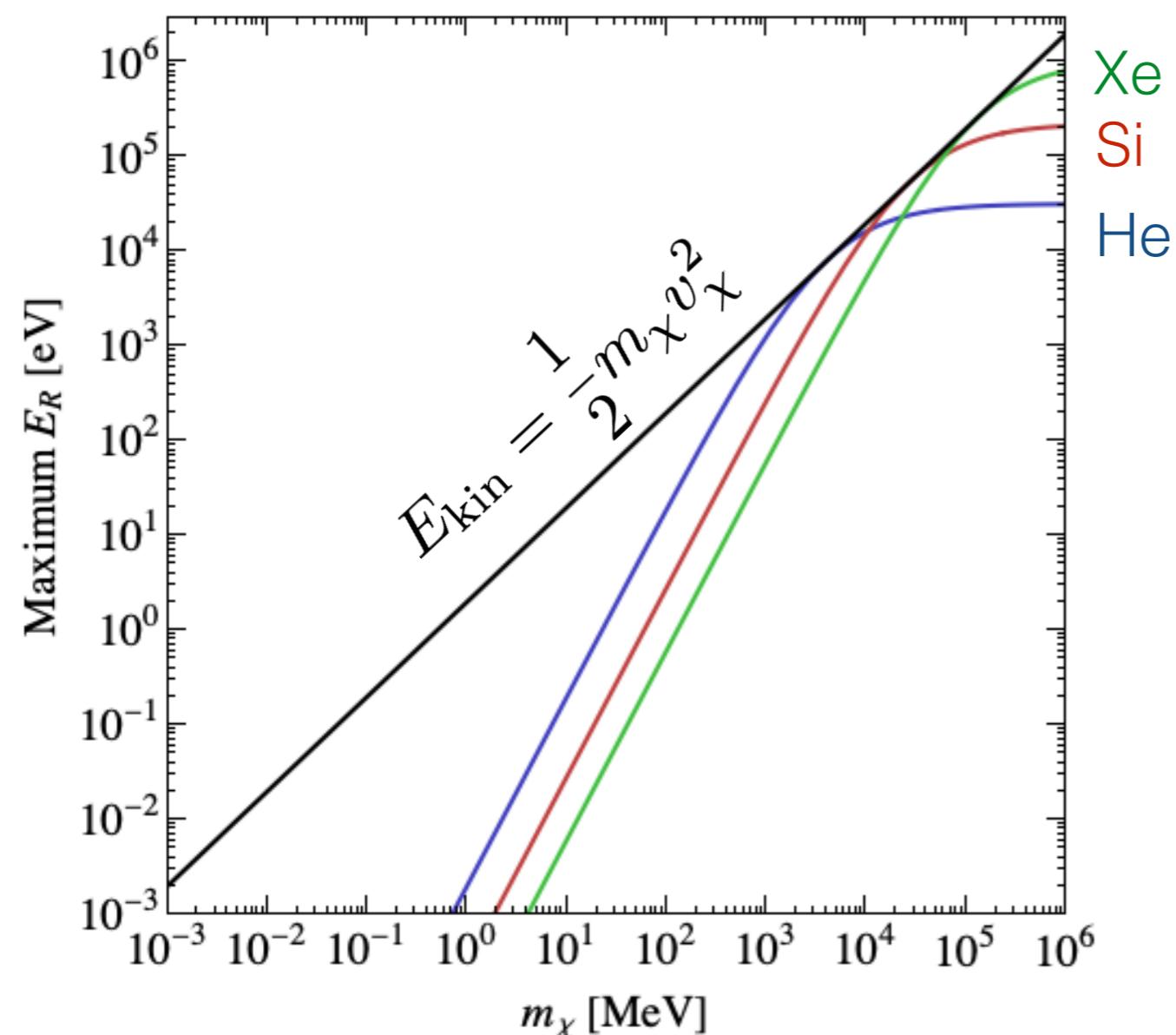


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- ultimate sensitivity, to a single $\sim 1 \text{ meV}$ phonon, probes 1 MeV DM

Probing sub-GeV DM w/ elastic nuclear recoils

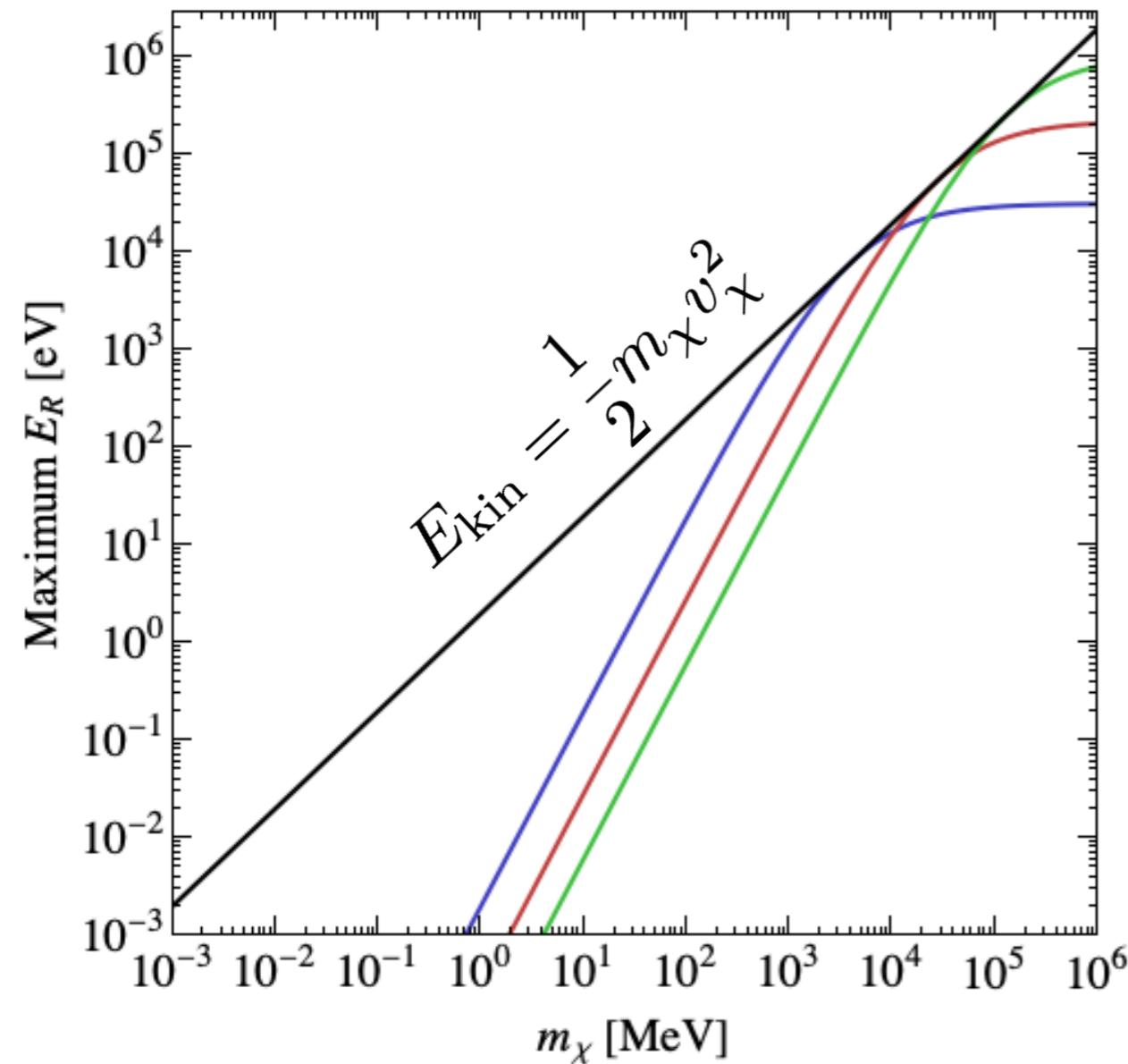


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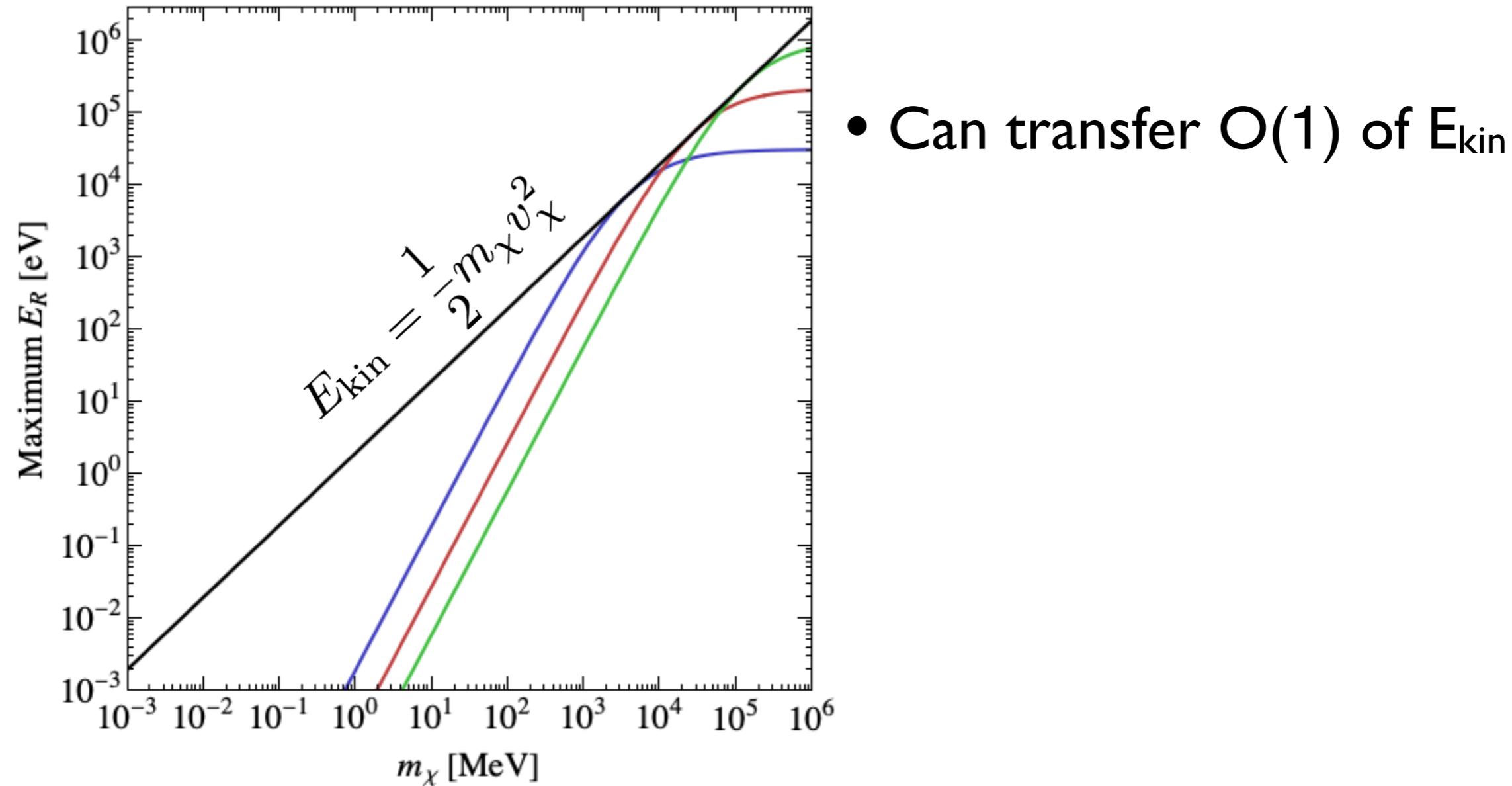
But note:

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

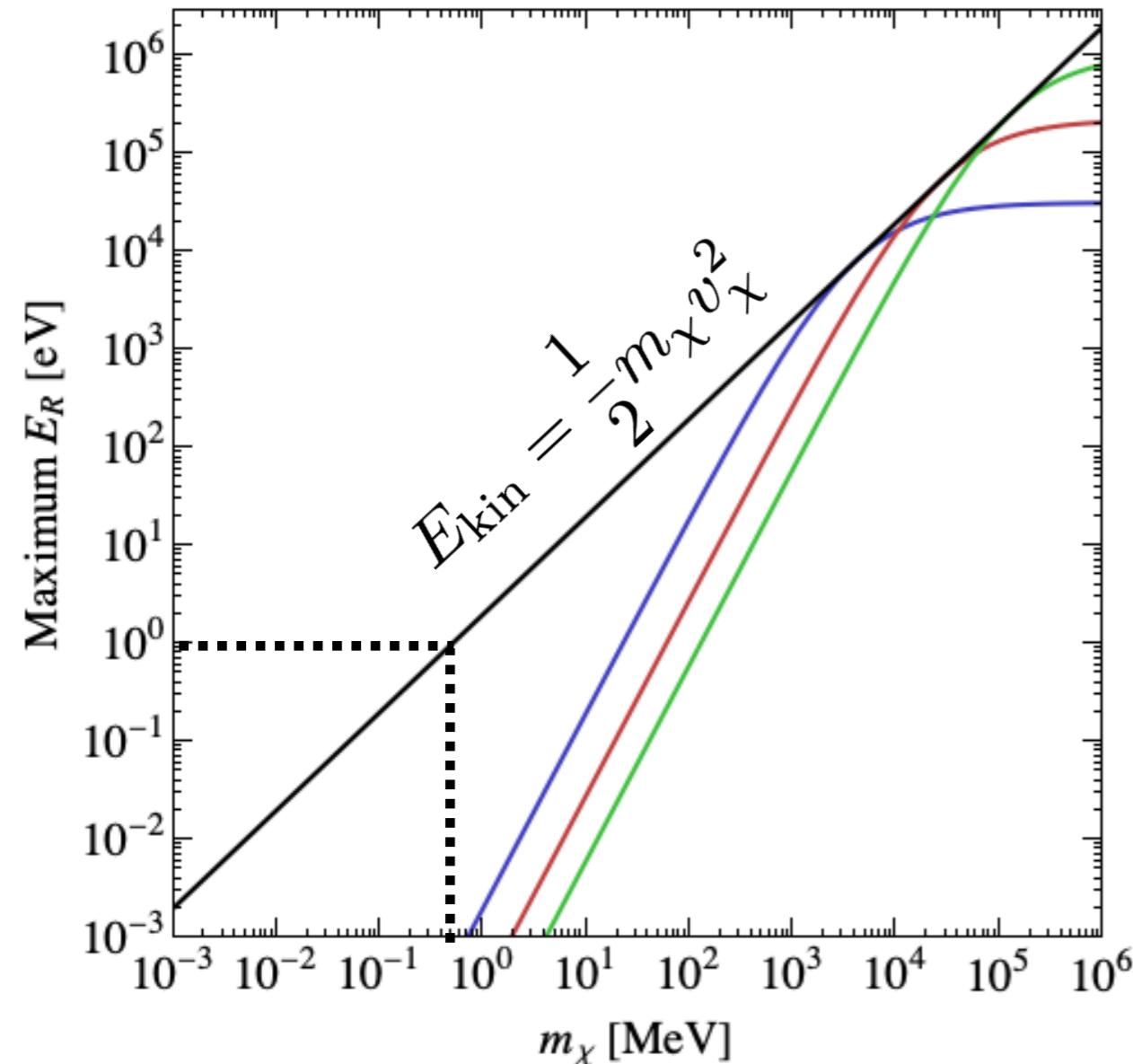
To probe DM \ll GeV, look for signals from “inelastic” processes



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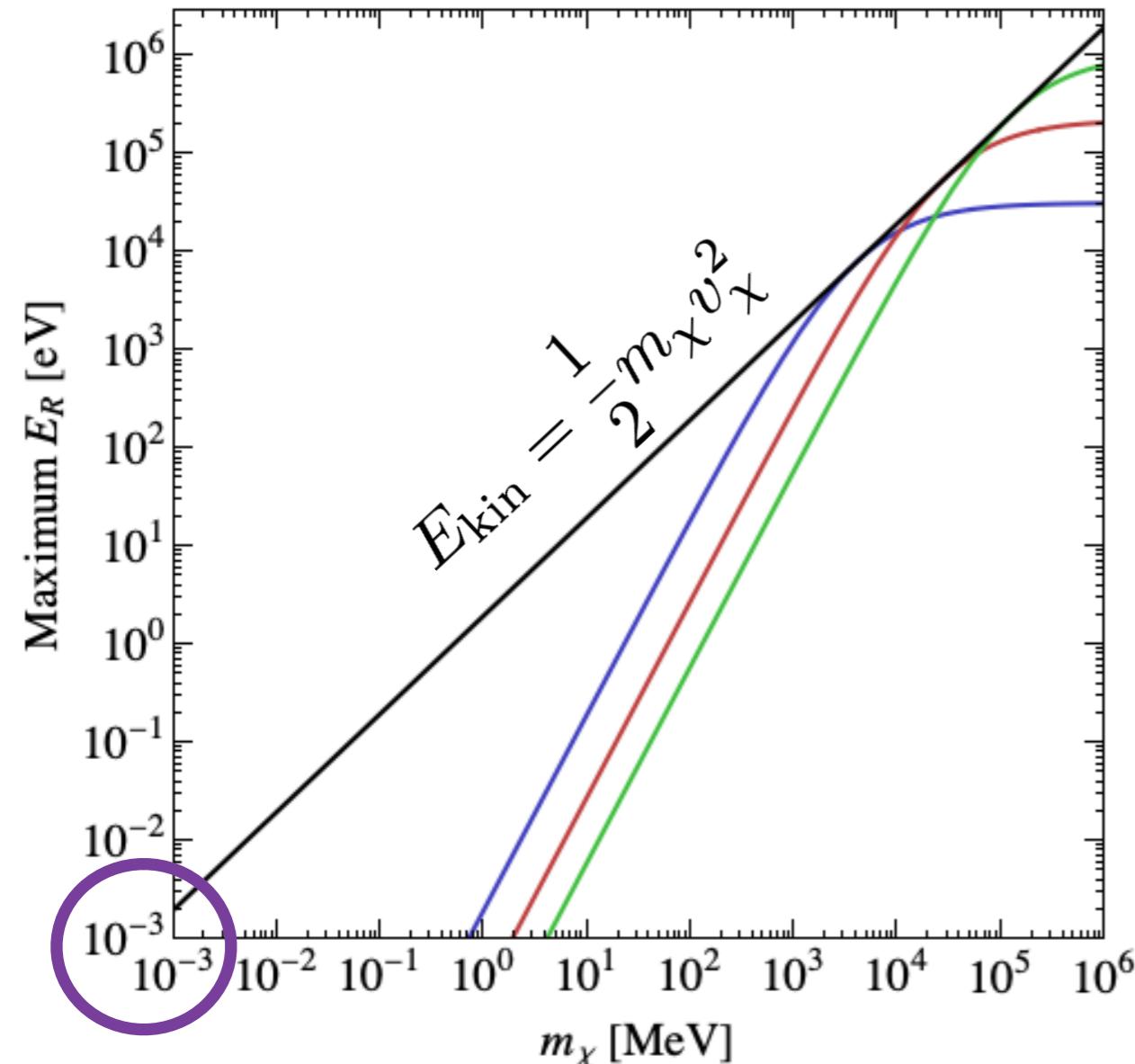


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- Can transfer O(1) of E_{kin}
- A detector sensitive to:
 - 1 eV, probes \sim 0.5 MeV DM
(already demonstrated!)

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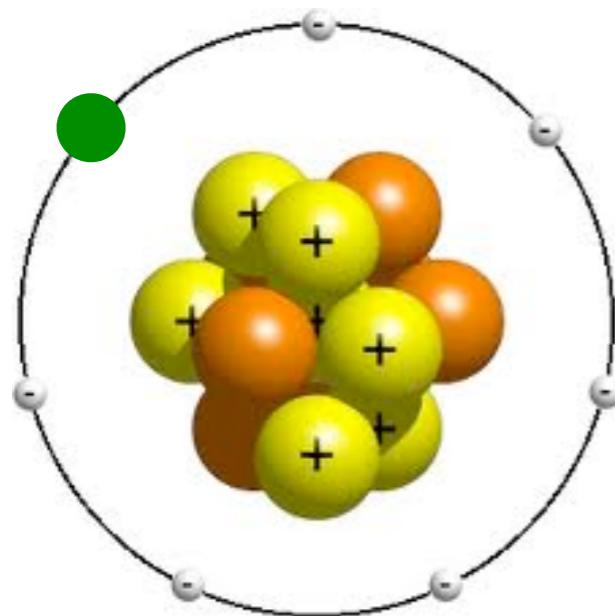
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Some Inelastic Processes giving $E_{\max} \sim (1/2)m_\chi v_\chi^2$

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- Electron excitation/ionization in noble-liquids, semiconductors, or scintillators (DM-e)

RE, Mardon, Volansky, 2011



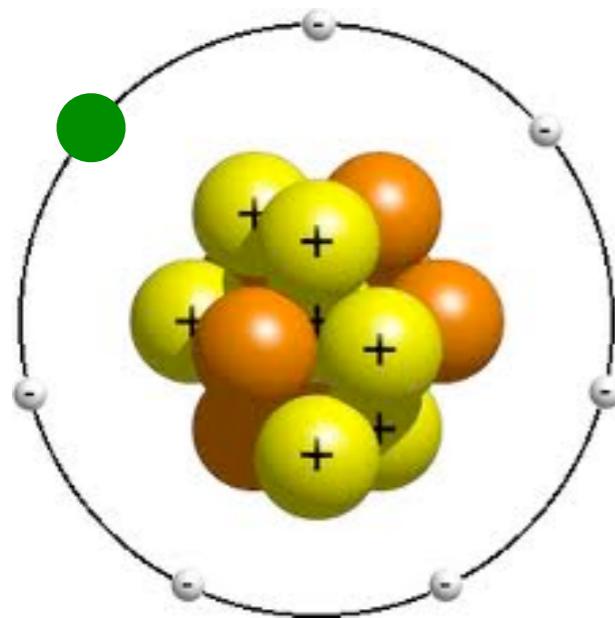
noble liquids

$E_{\text{binding}} \sim 10 \text{ eV}$
 $m_{\text{threshold}} \sim 5 \text{ MeV}$

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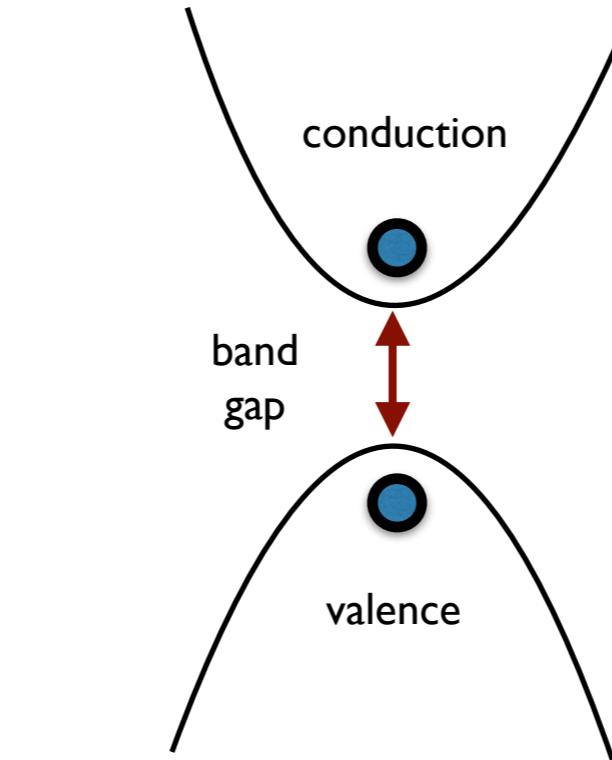
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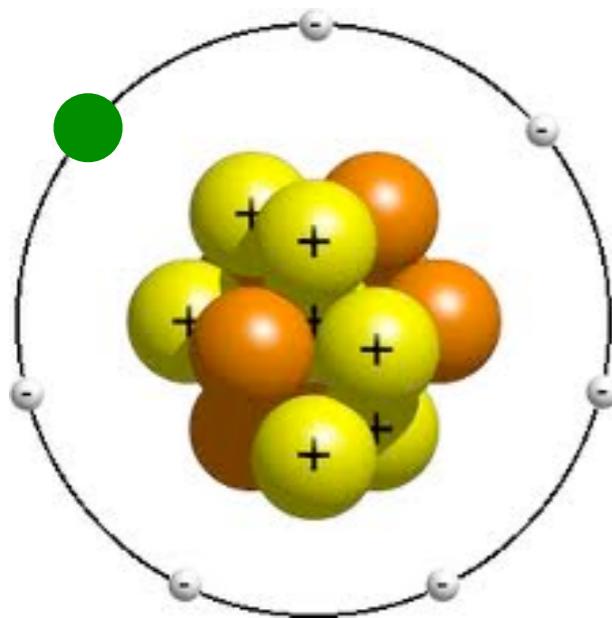
semiconductors
scintillators

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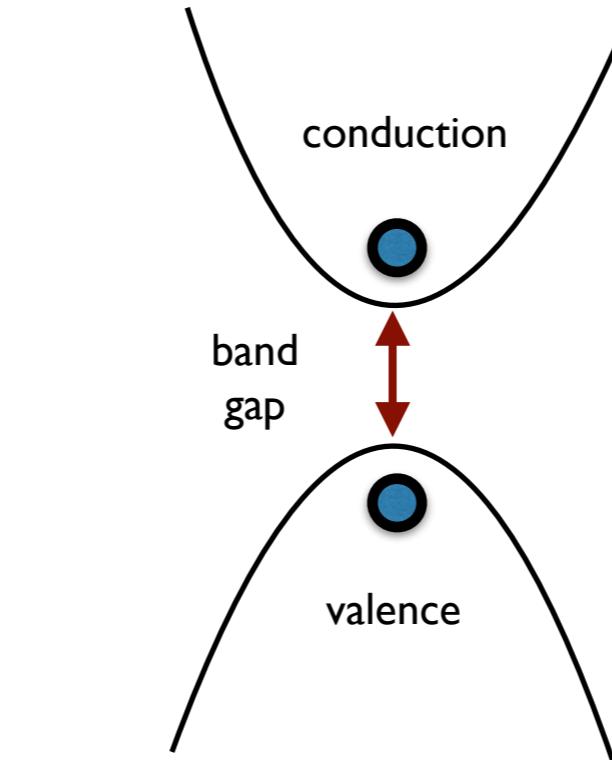
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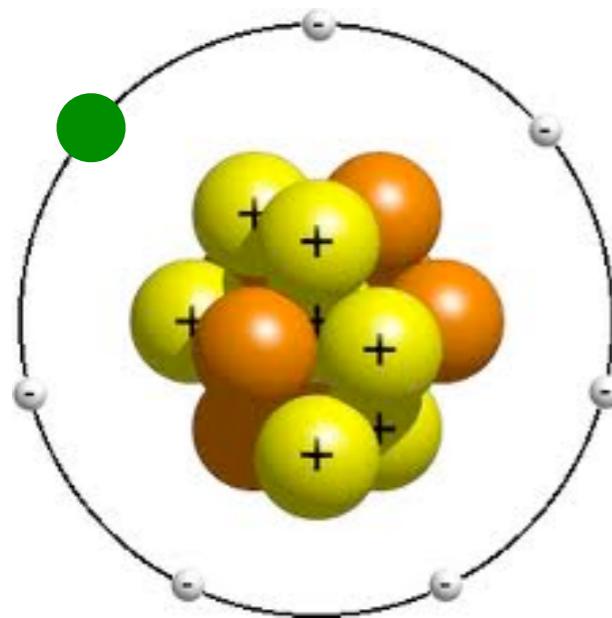
see also:

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, Sholapurkar, Yu
Emken, RE, Kouvaris, Sholapurkar
Derenzo, Bourret, Hanrahan, Bizarri
Lee, Lisanti, Mishra-Sharma, Safdi

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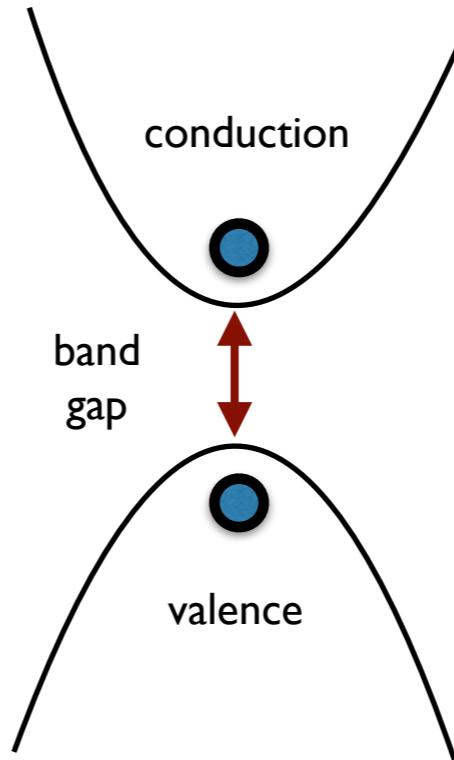
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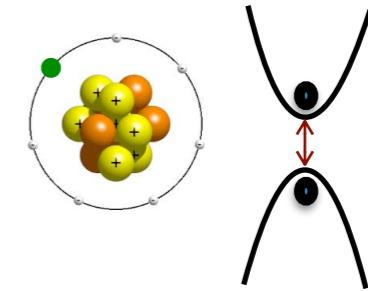
Typically produces a signal of only one to a few e-/γ

see also:

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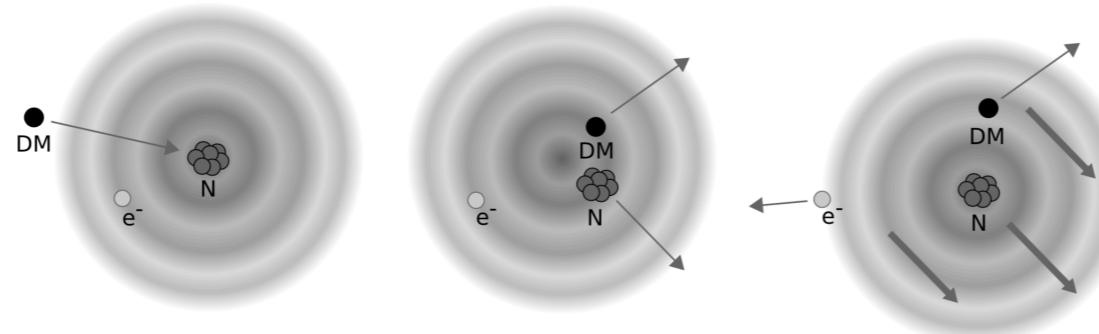
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- Electron excitation/ionization in noble-liquids, semiconductors, or scintillators (DM-e)



RE, Mardon, Volansky, 2011

- Electrons from Migdal effect (DM-N)



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

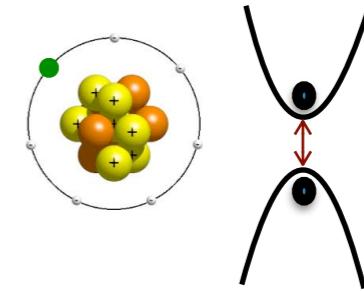
Fig. credit: Dolan, Kahlhoefer, McCabe

RE, Pradler, Sholapurkar, Yu

Baxter, Kahn, Krnjaic

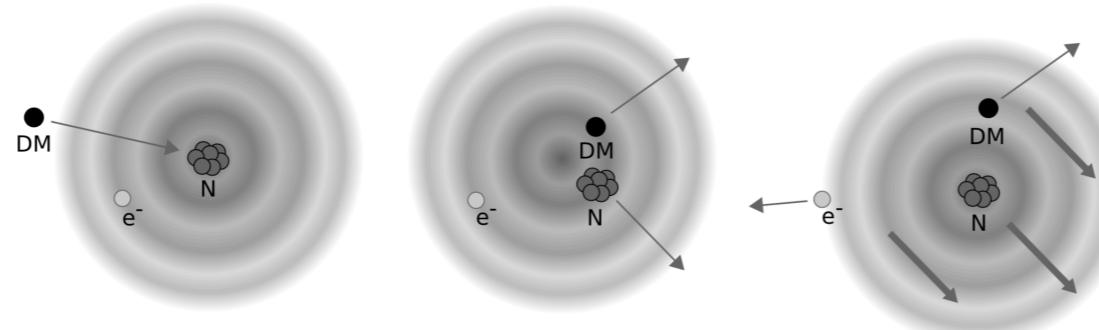
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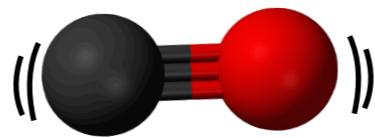
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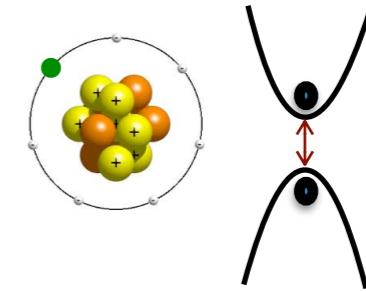
- Molecular excitations (DM-N)



RE, Perez-Rios, Ramani, Slone

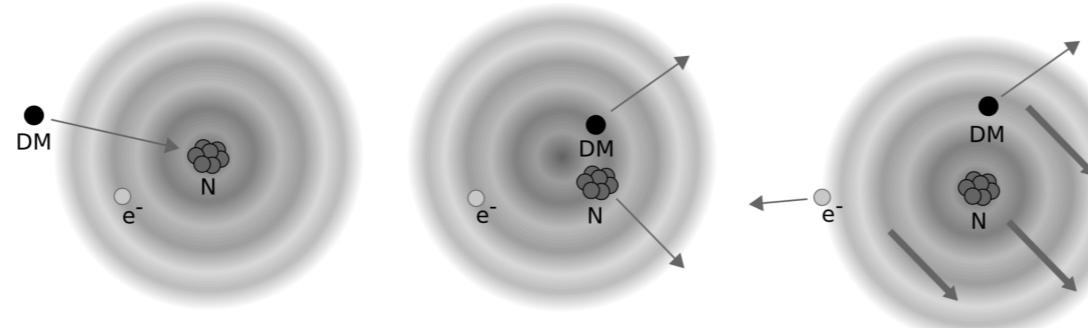
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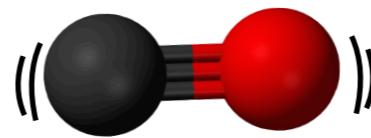
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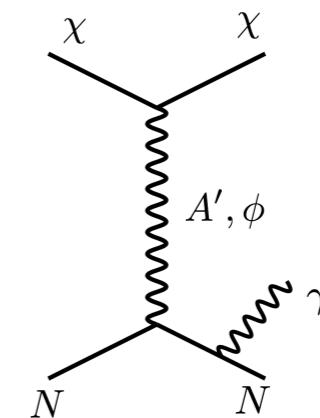
Baxter, Kahn, Krnjaic

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RE, Perez-Rios, Ramani, Slone

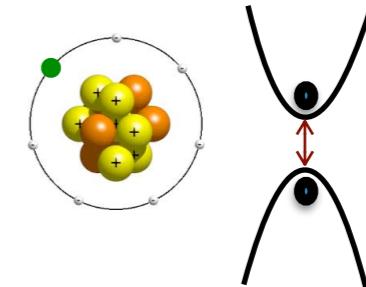
- Photon from bremsstrahlung (DM-N)



Kouvaris, Pradler

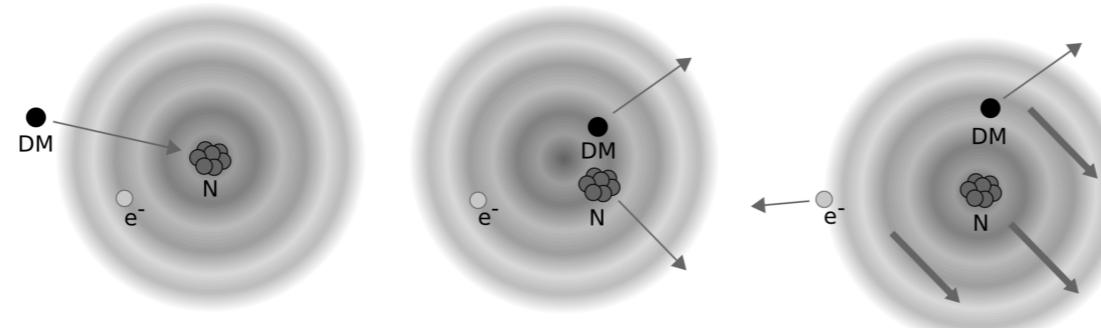
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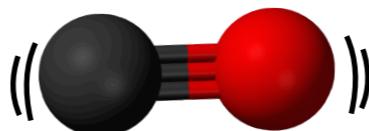
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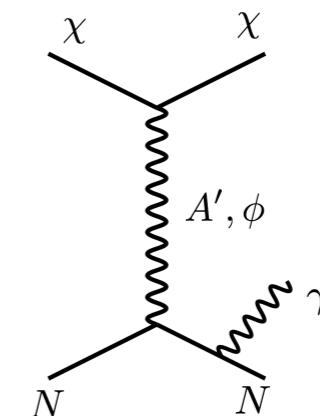
Baxter, Kahn, Krnjaic

- Molecular excitations (DM-N)



RE, Perez-Rios, Ramani, Slone

- Photon from bremsstrahlung (DM-N)



Kouvaris, Pradler

- Optical phonons in polar materials (DM-phonon)

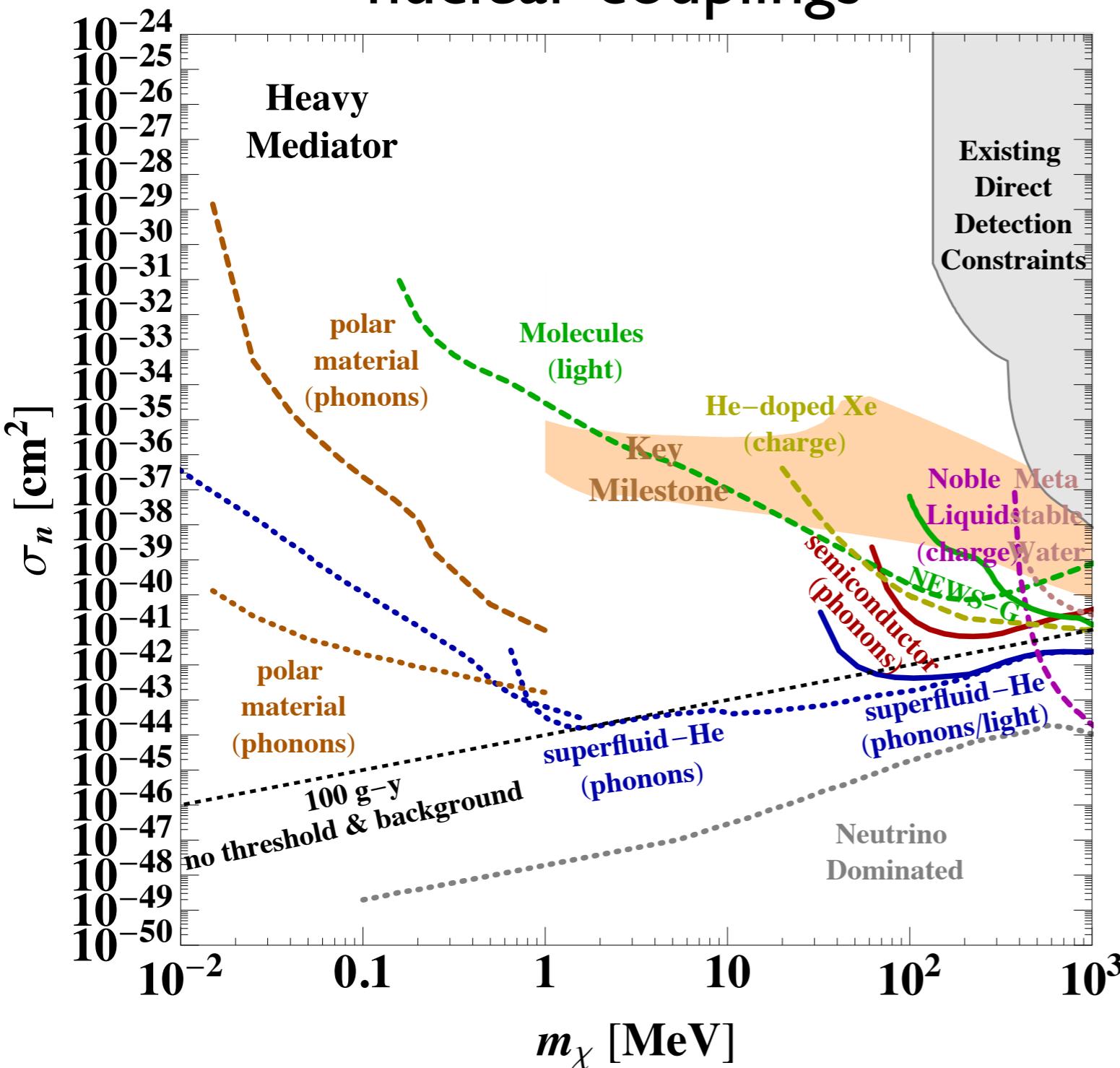
see Simon Knapen's talk

Knapen, Lin, Pyle, Zurek

Many new direct-detection ideas

from DoE High-Energy Physics Basic Research Needs Report

nuclear couplings

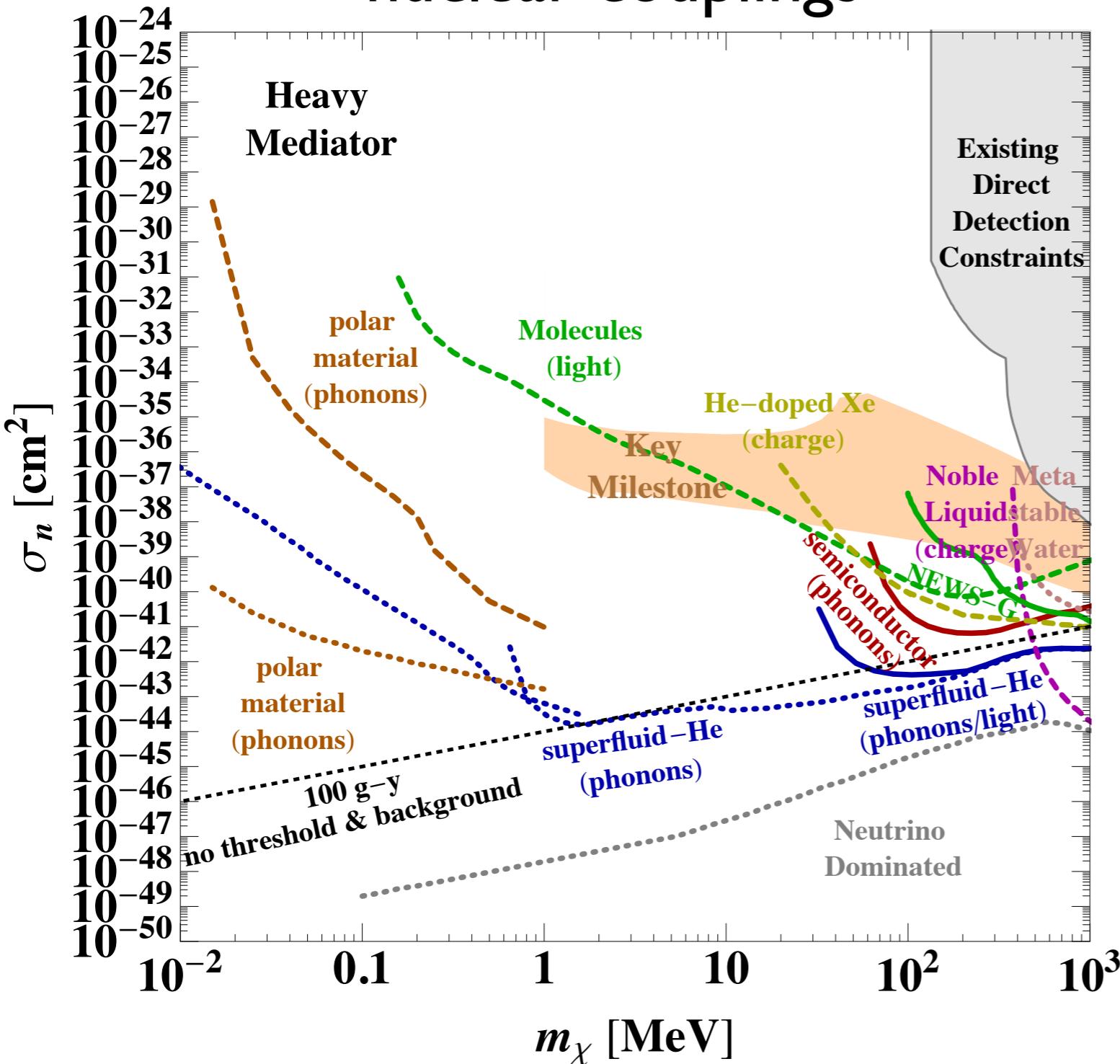


- solid: ready for development
- dashed: some R&D needed
- dotted: long term

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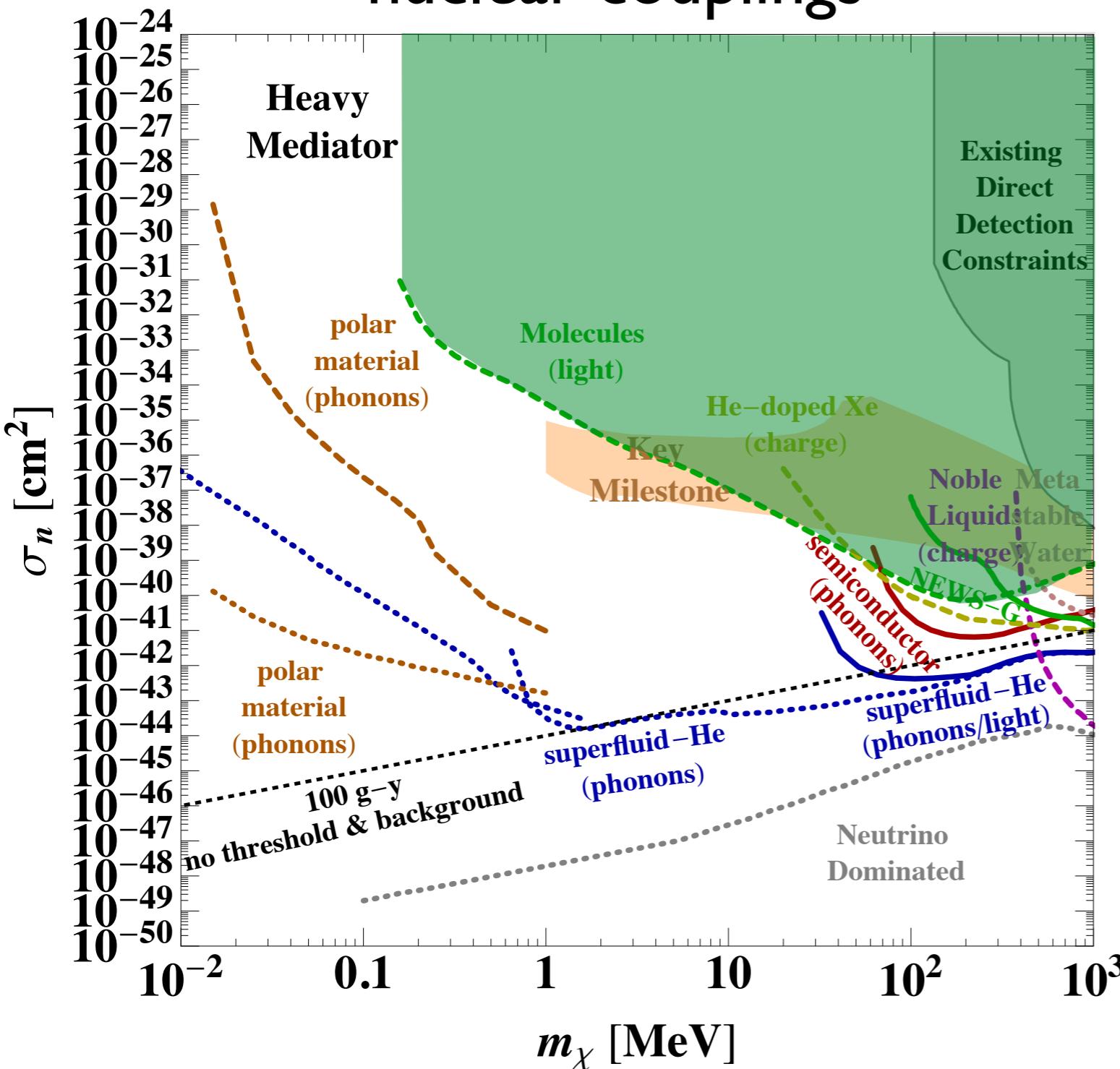
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doesn't include projections for
Bremsstrahlung, Migdal effect, etc

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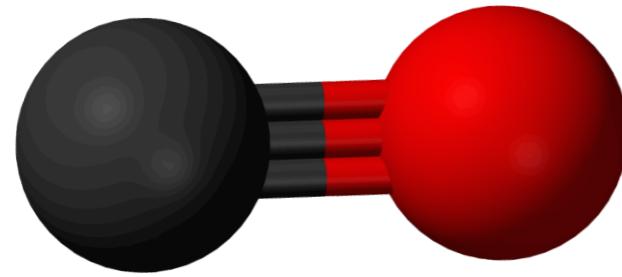
RE, Perez-Rios, Ramani, Sloane
(1907.07682)

A recent idea:
Molecular Excitations

spin-independent &
spin-dependent sensitivity
(see backup slides for more details)

Direct Detection of Spin-(In)Dependent Nuclear Scattering via Molecular Excitations

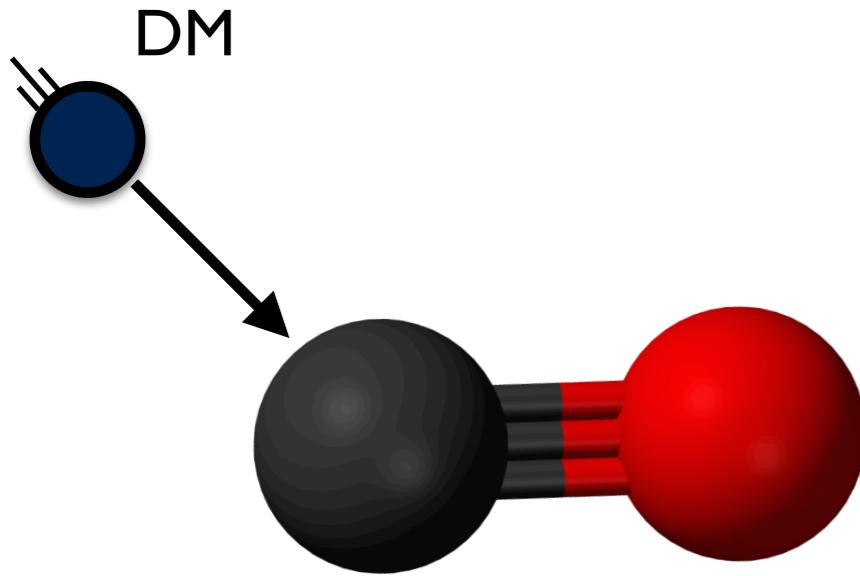
RE, Perez-Rios, Ramani, Slone



e.g. carbon monoxide

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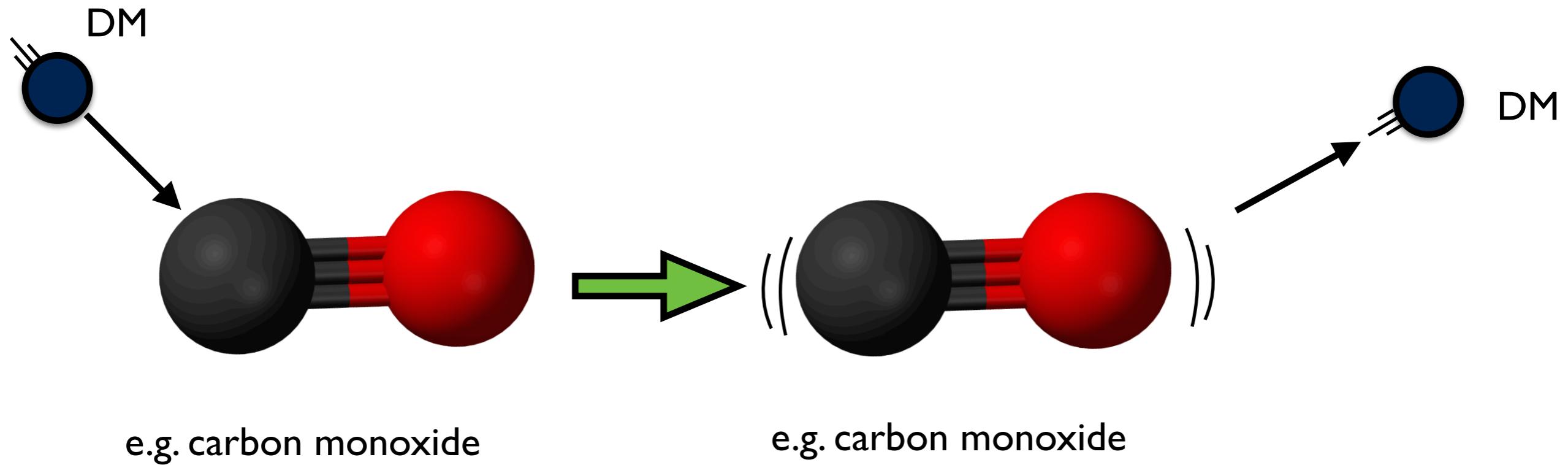
RE, Perez-Rios, Ramani, Slone



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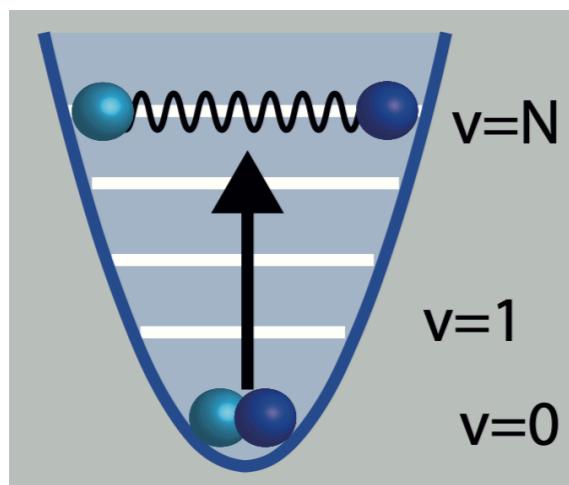
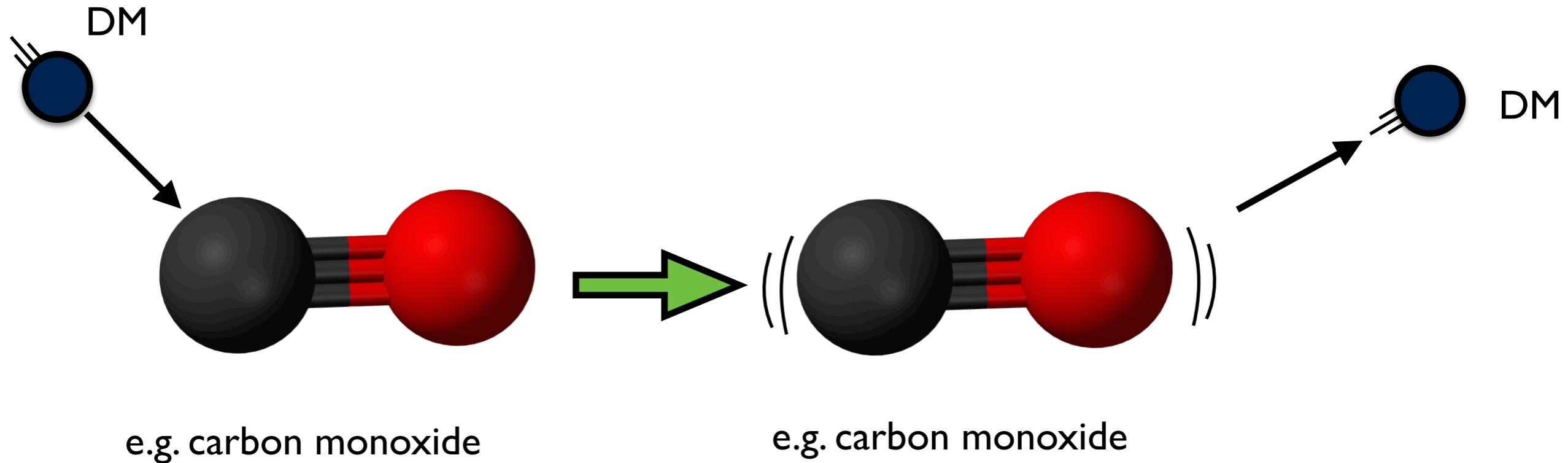
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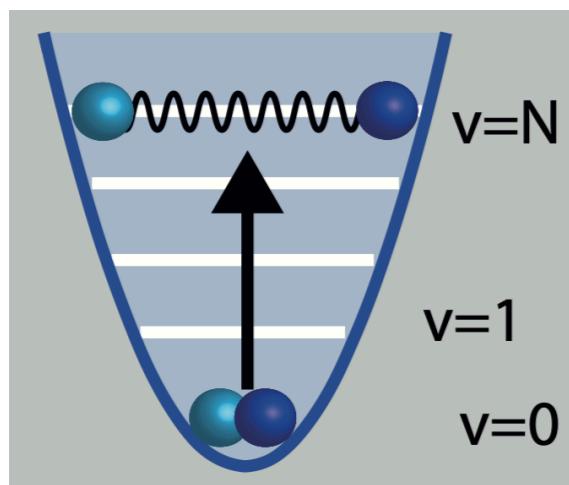
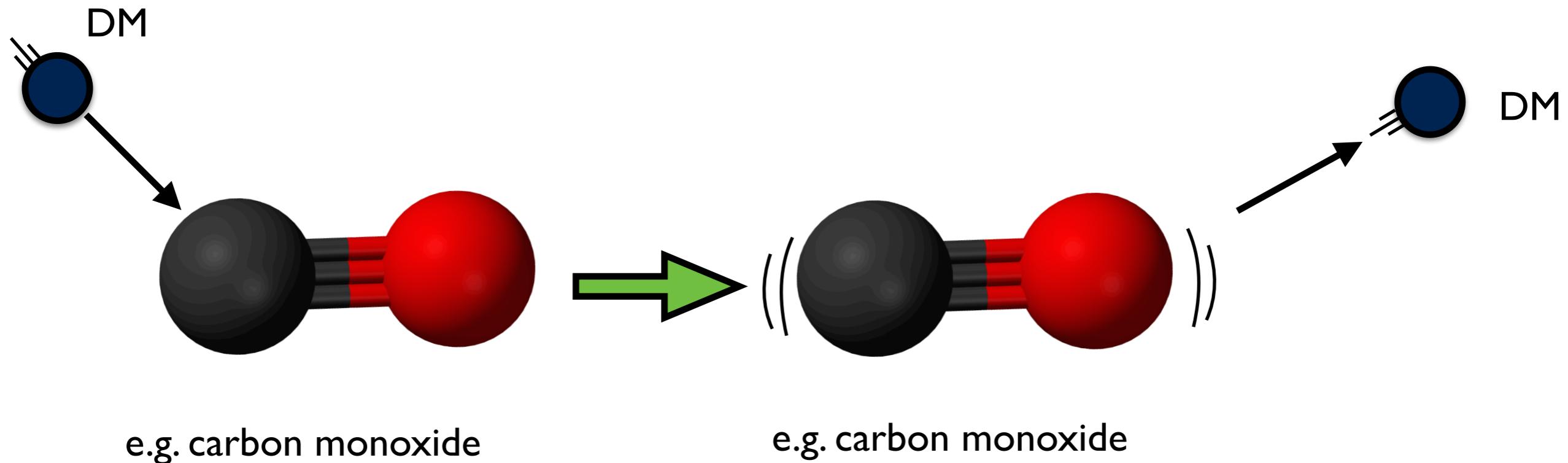
RE, Perez-Rios, Ramani, Slone



DM can transfer good fraction of its kinetic energy
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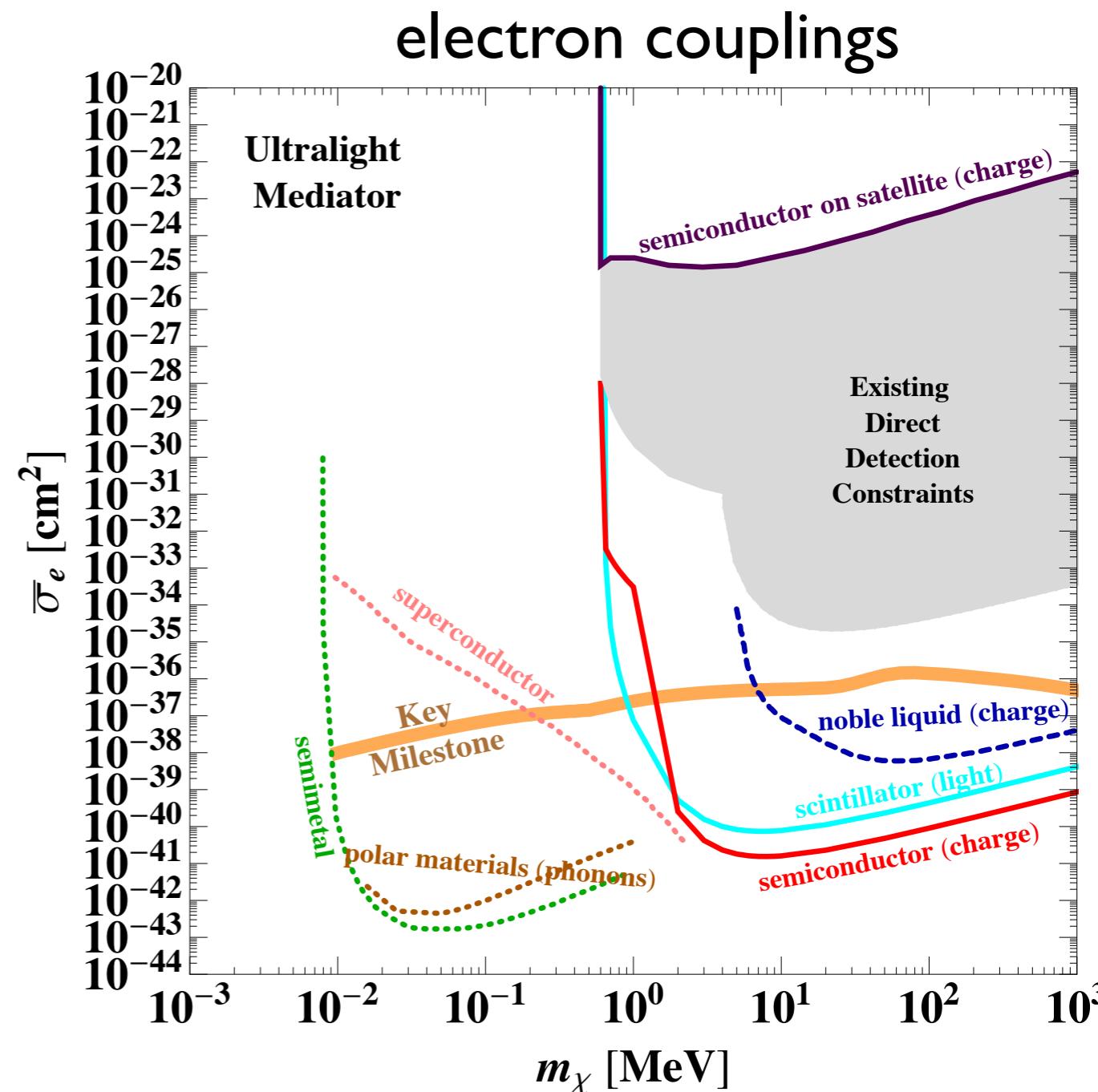
DM can transfer good fraction of its kinetic energy & excite a vibrational state $\mathcal{O}(250 \text{ meV} - 5 \text{ eV})$

as molecule relaxes to ground state get multiple photons of energy $\mathcal{O}(100-250 \text{ meV})$; detect w/ e.g. SNSPDs

Many new direct-detection ideas

from DoE High-Energy Physics Basic Research Needs Report

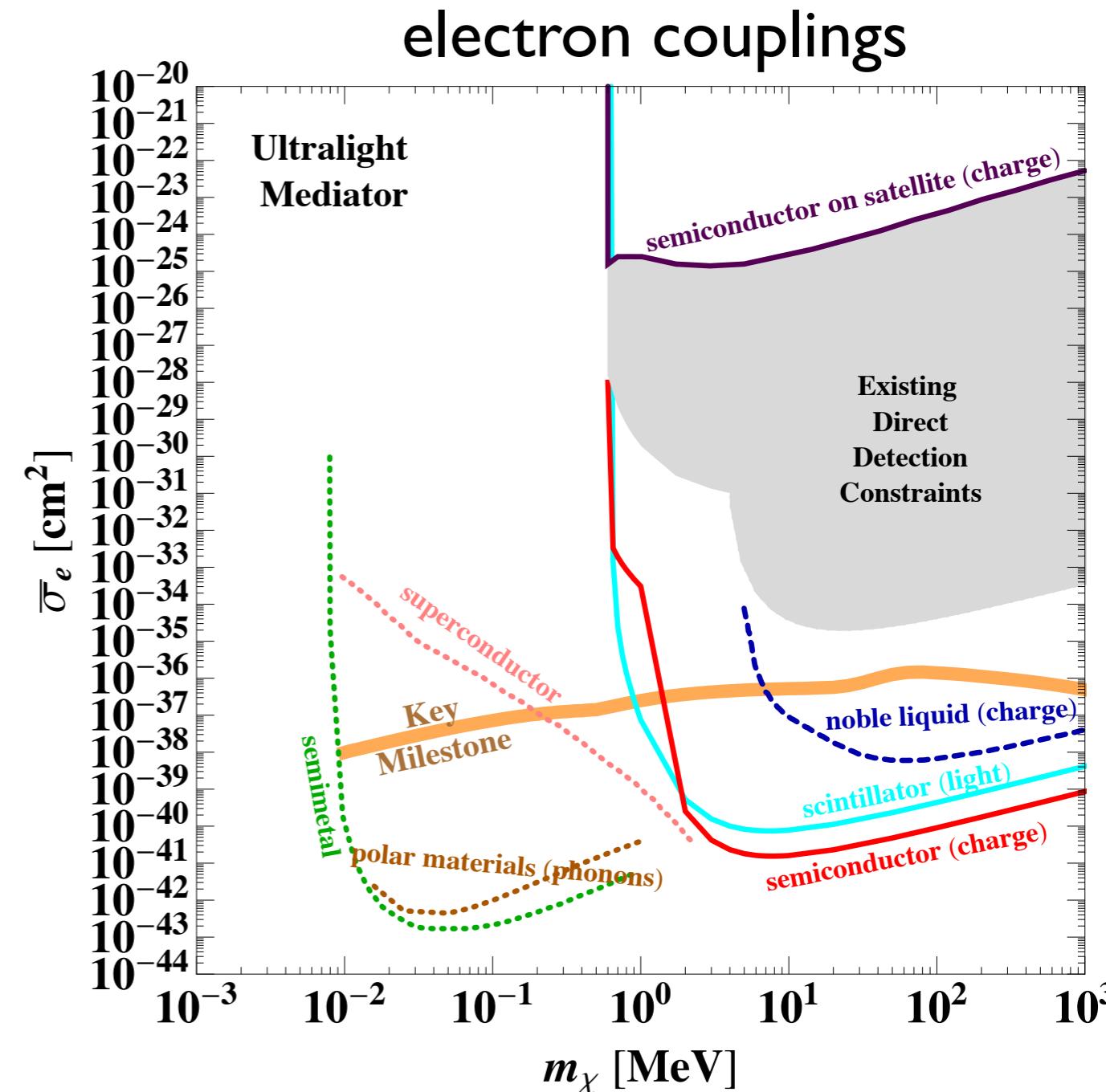
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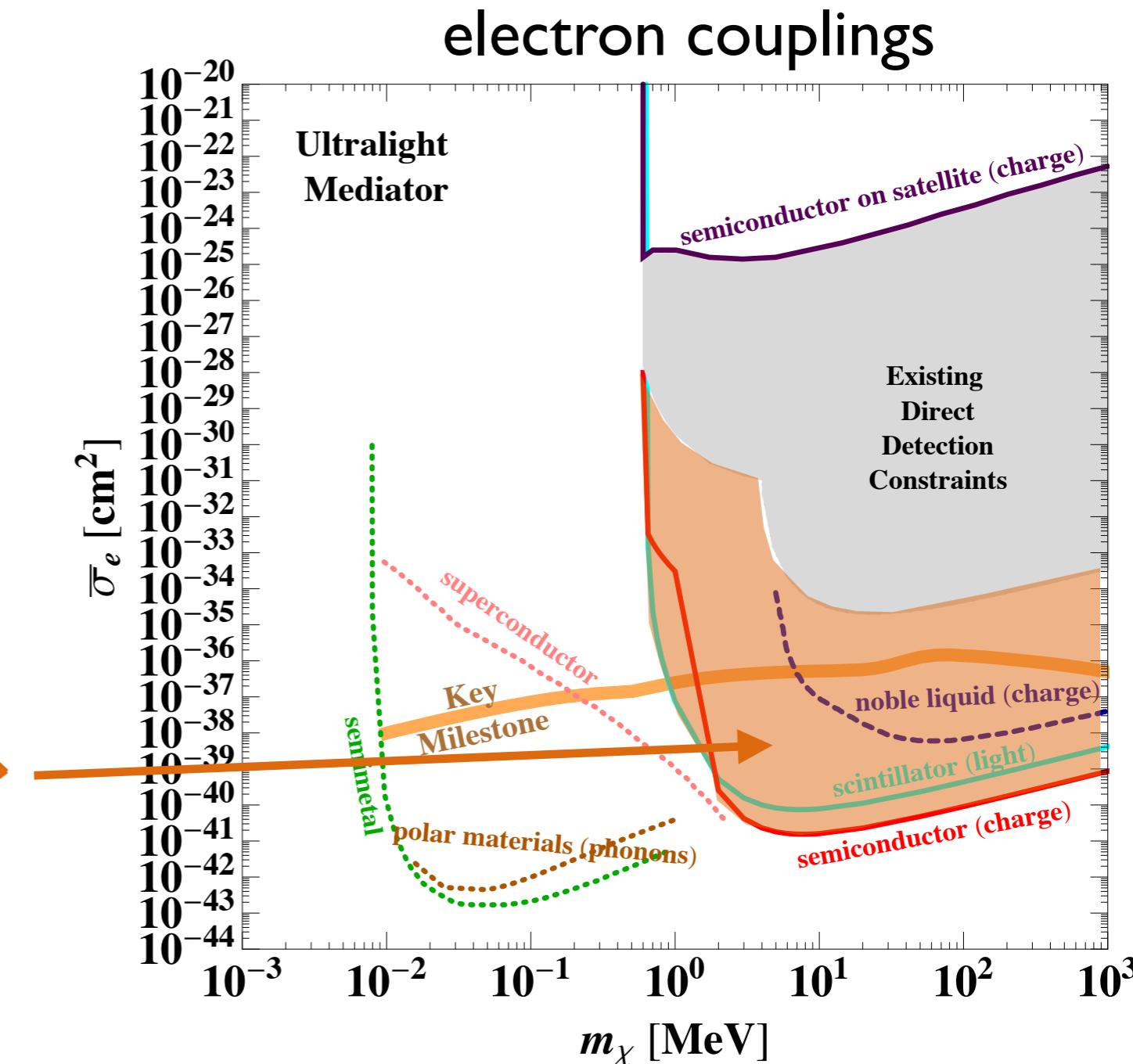
Many new direct-detection ideas

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LBECA
(liquid xenon)

SENSEI
(silicon Skipper CCDs)



Many new direct-detection ideas

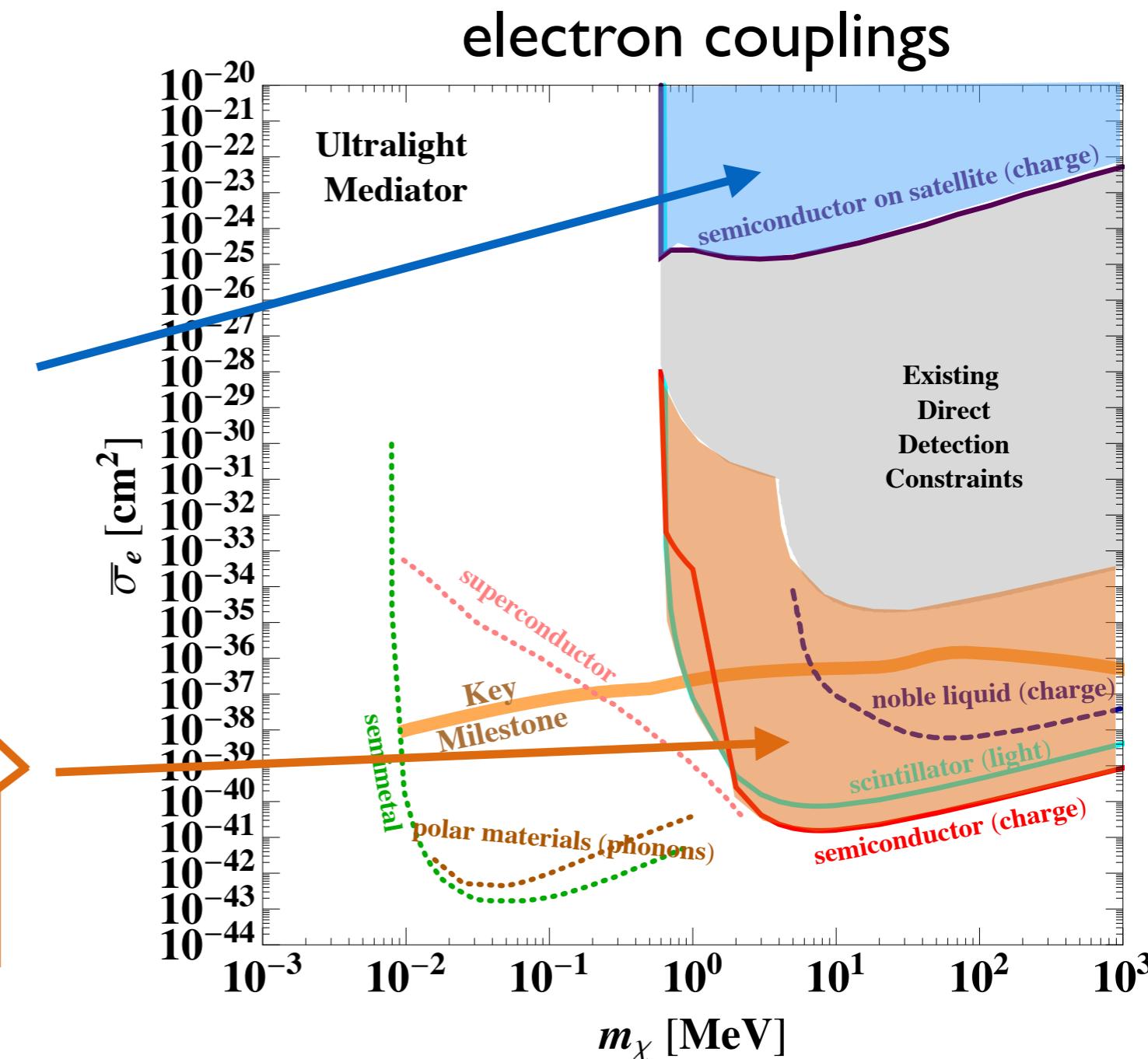
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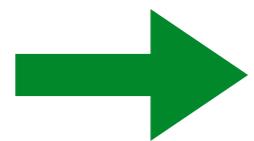
Skipper-CCD on balloon/satellite

LBECA (liquid xenon)

SENSEI (silicon Skipper CCDs)



Outline



- LBECA (liquid xenon)
- SENSEI (silicon Skipper-CCDs)
- Satellite/balloon-borne Skipper-CCD

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

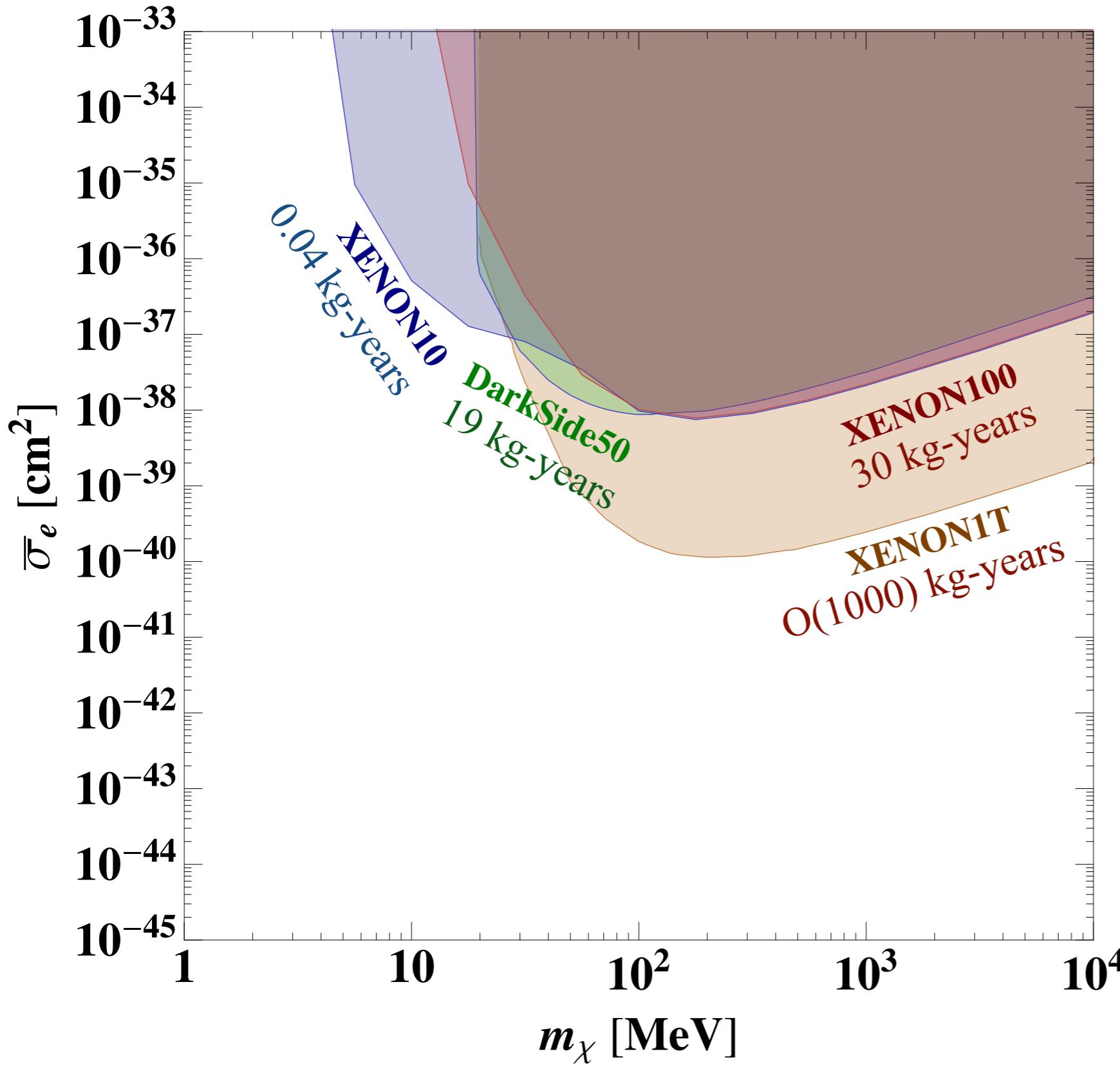
UC San Diego:

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

R&D partially funded by US DoE



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

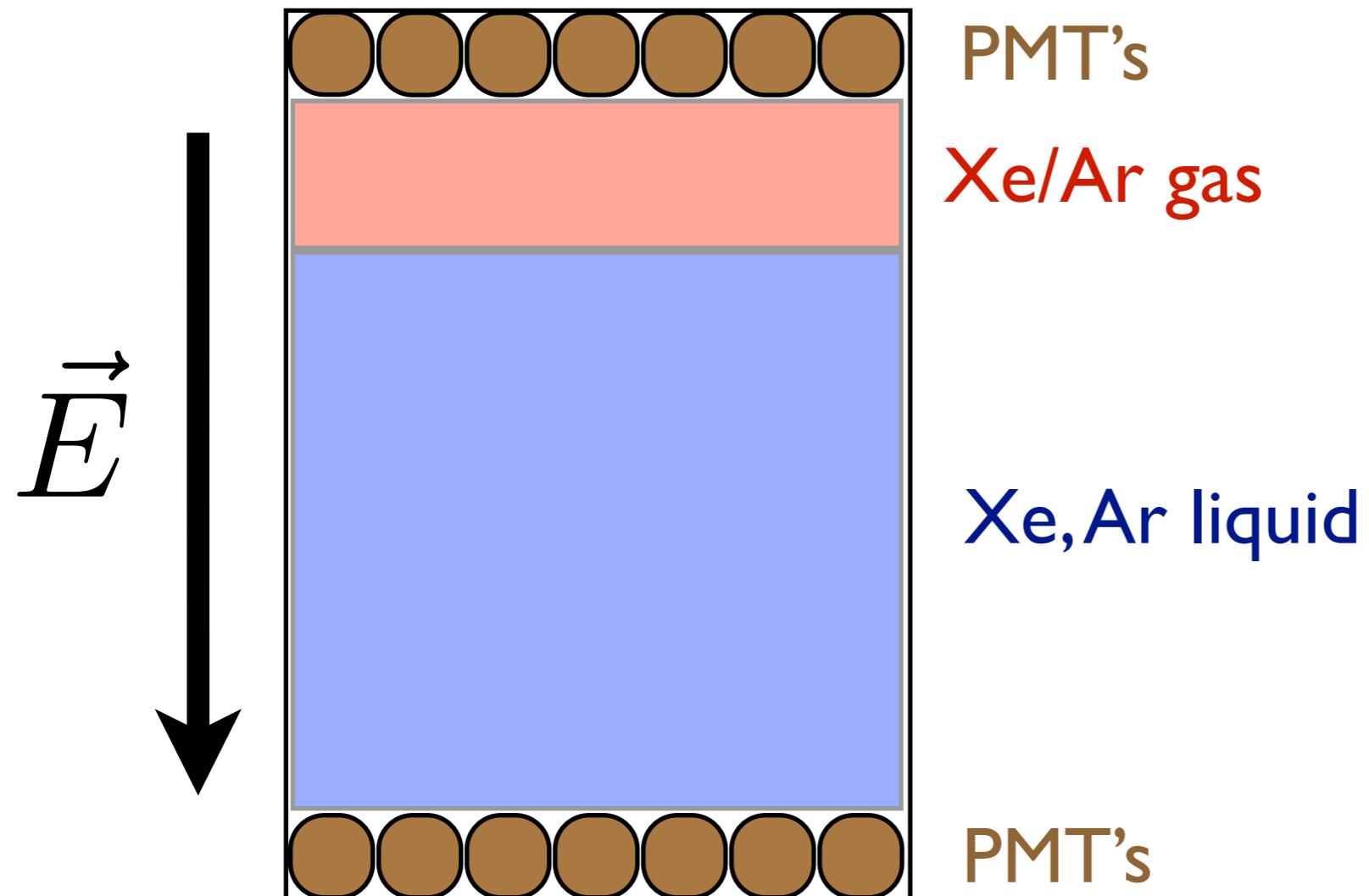
XENON10: 1104.3088

XENON100: 1605.06262

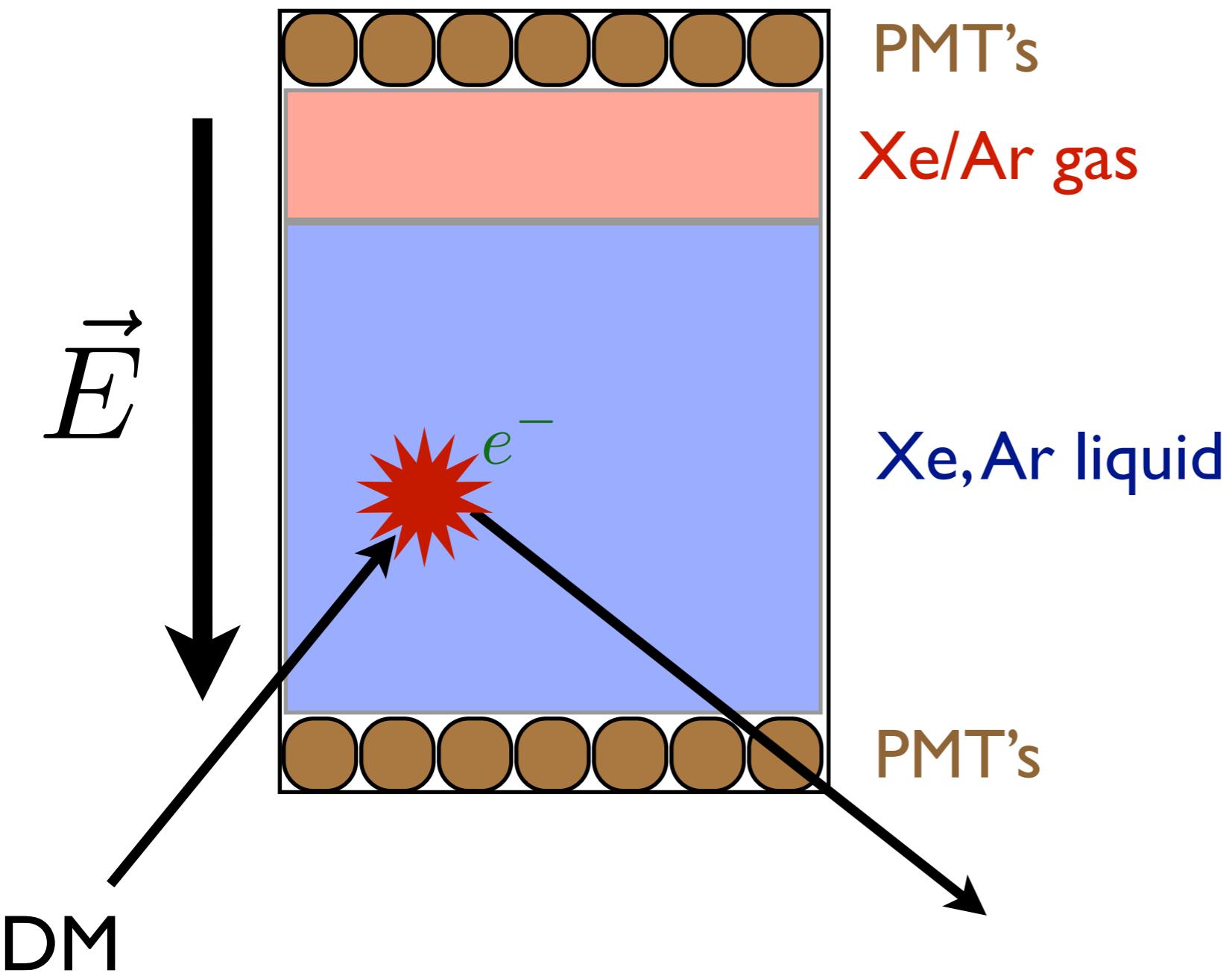
DarkSide-50: 1802.06998

XENON1T: 1907.11485

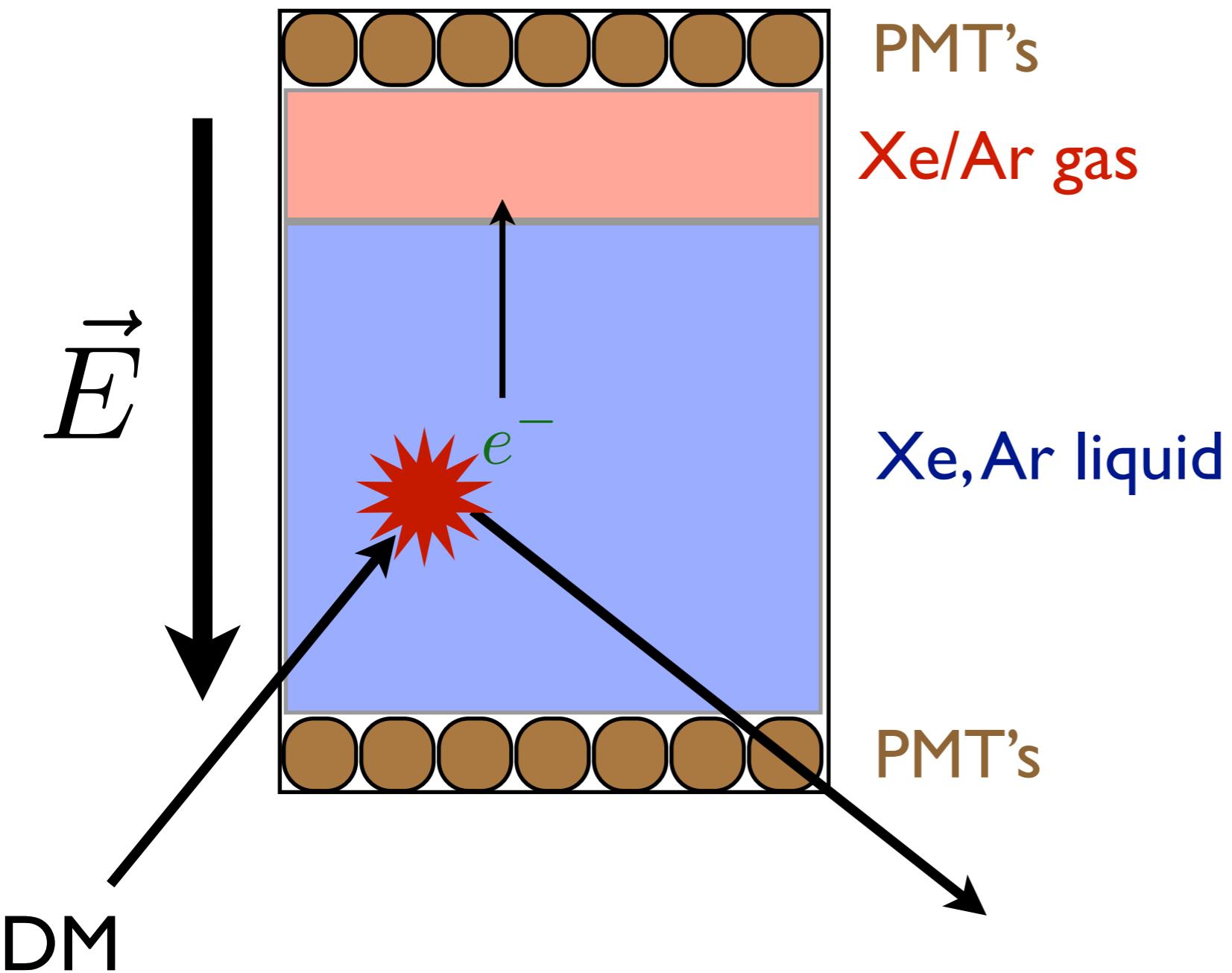
Detection Concept



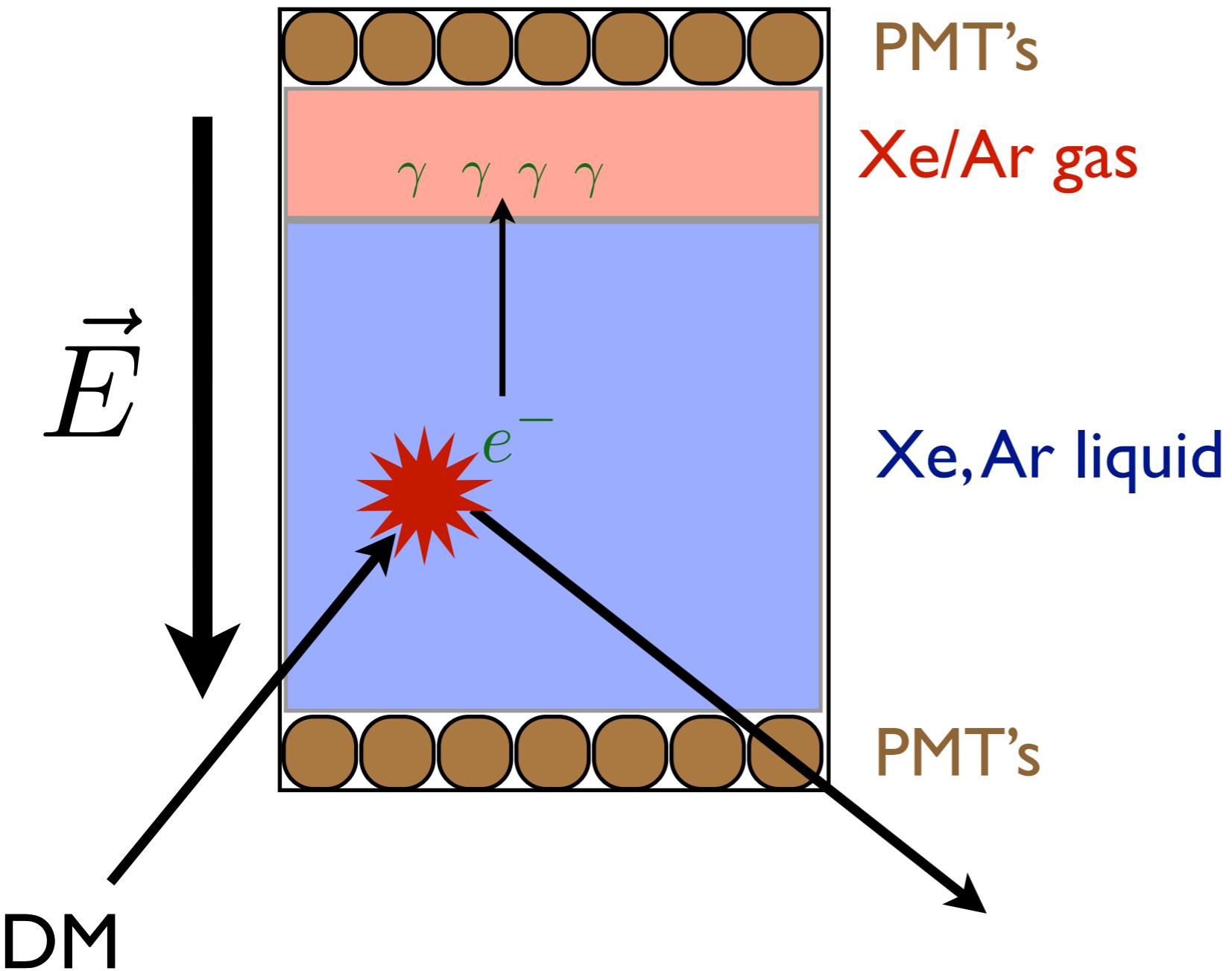
Detection Concept



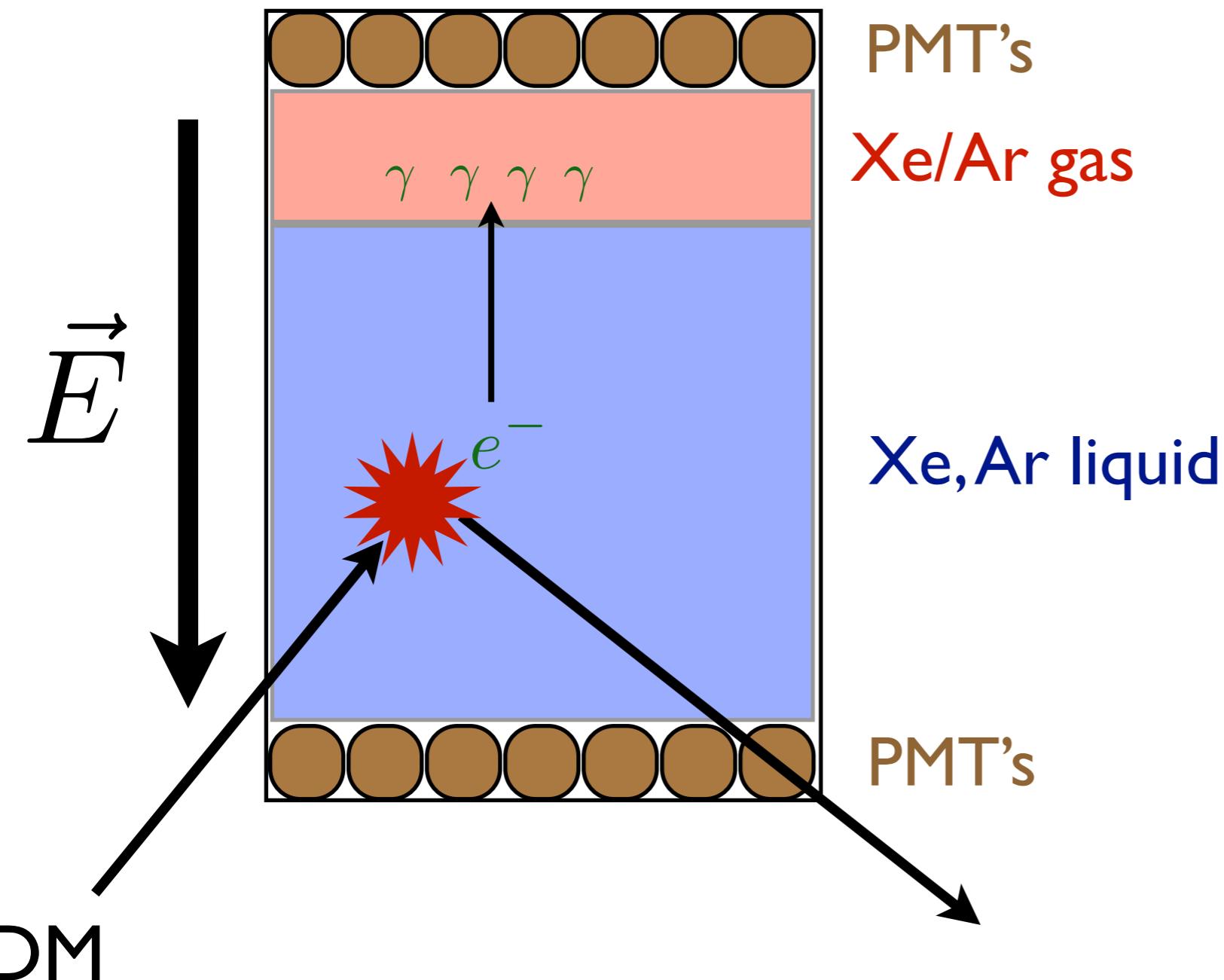
Detection Concept



Detection Concept



Detection Concept

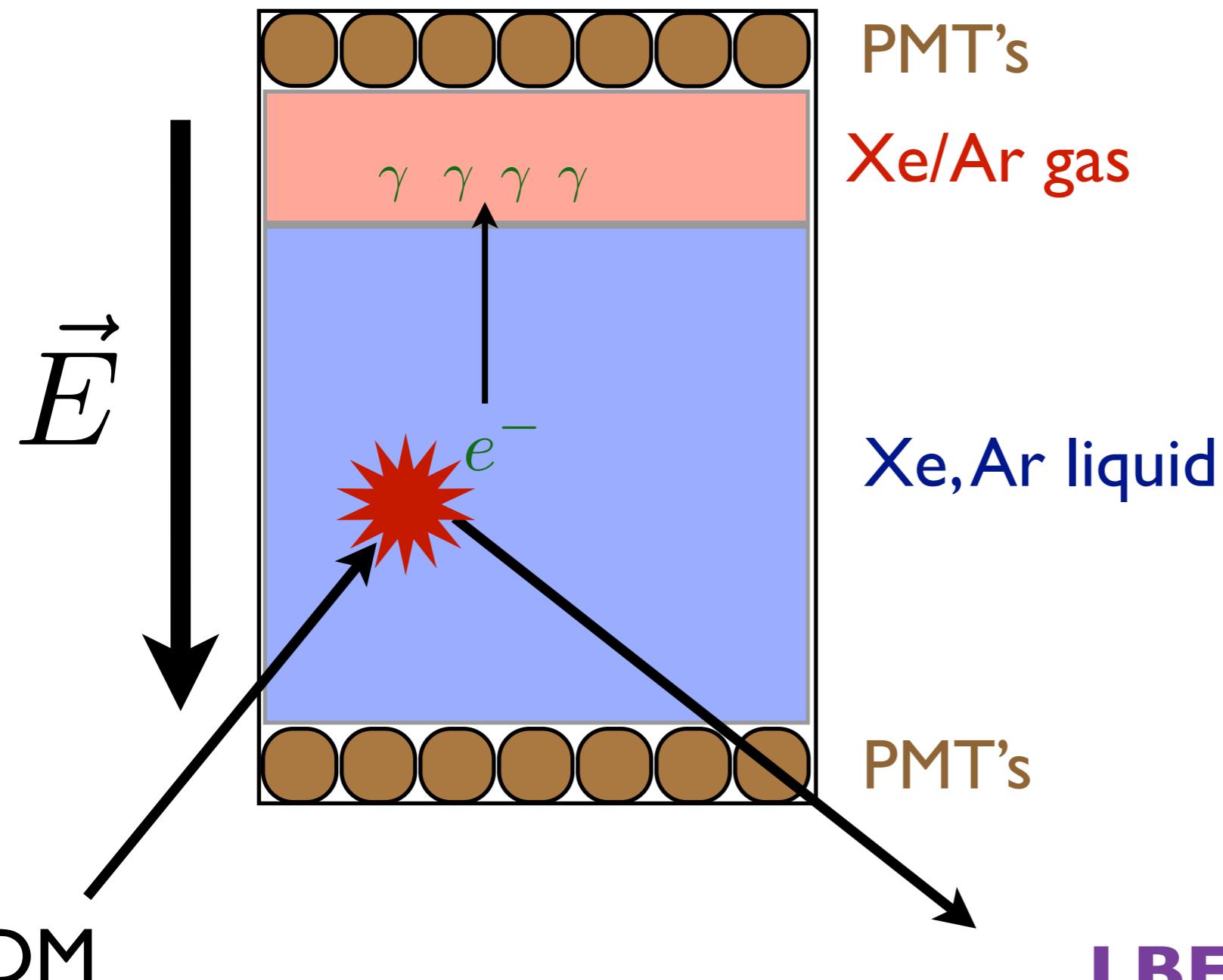


Sensitive to single electrons!

But large backgrounds:

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

Detection Concept



PMT's

Xe/Ar gas

Xe, Ar liquid

PMT's

DM

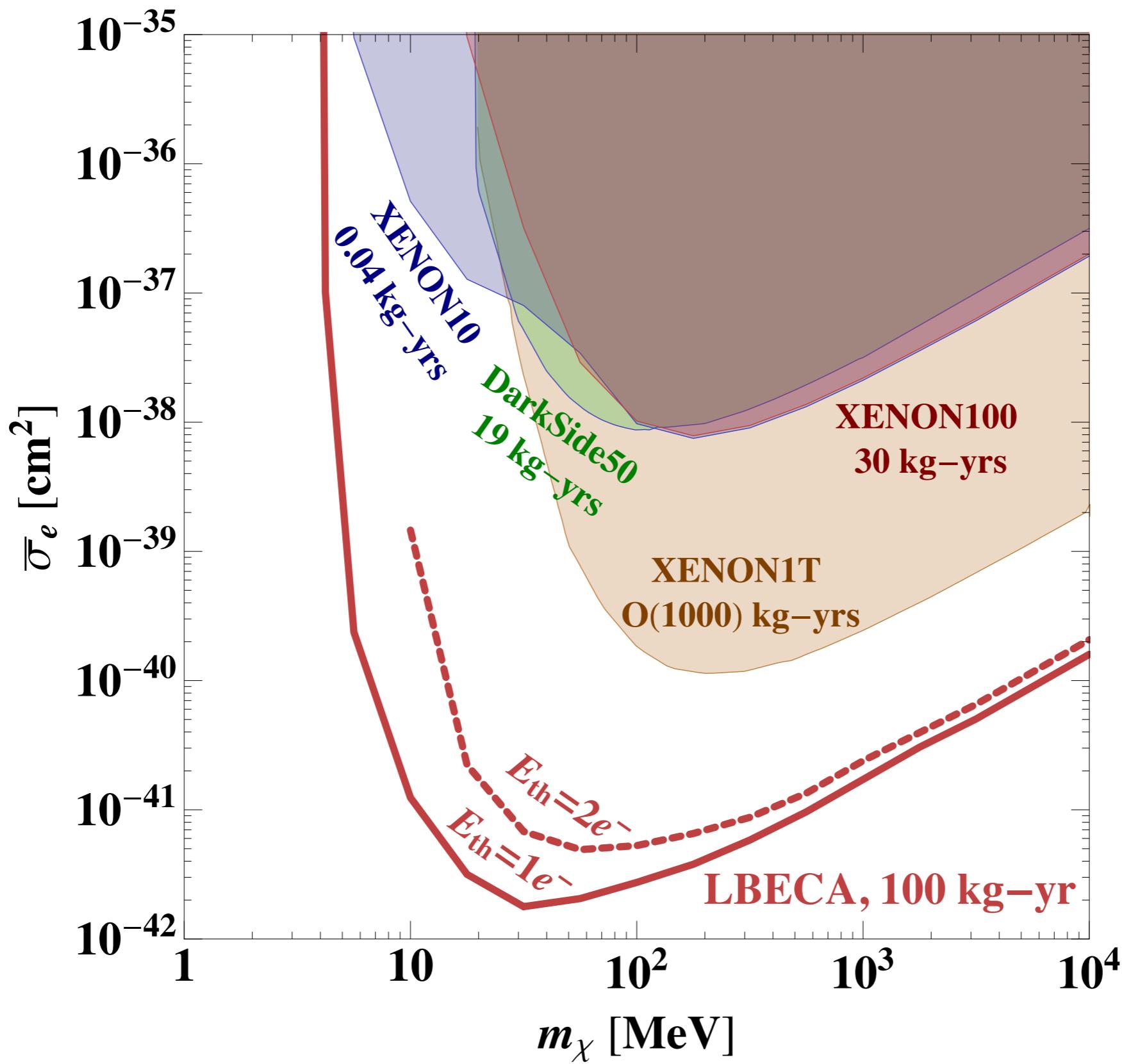
Sensitive to single electrons!

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

Example: Sensitivity of LBECA



Outline

- LBECA (liquid xenon)
- • SENSEI (silicon Skipper-CCDs)
- Satellite/balloon-borne Skipper-CCD

The SENSEI Collaboration



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



Stony Brook
University



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

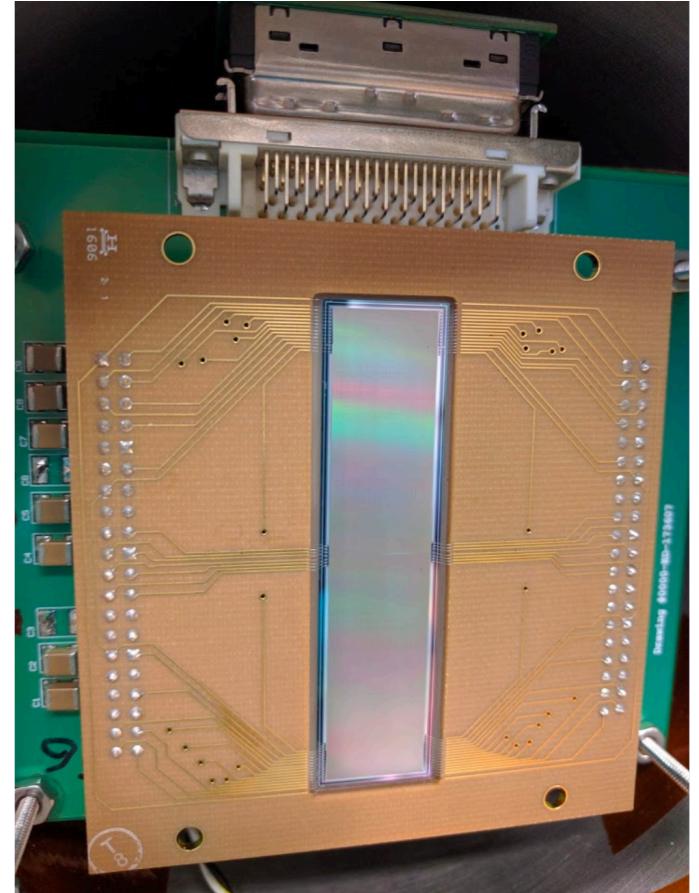
Fully funded by Heising-Simons Foundation & Fermilab



Detection Concept

Detection Concept

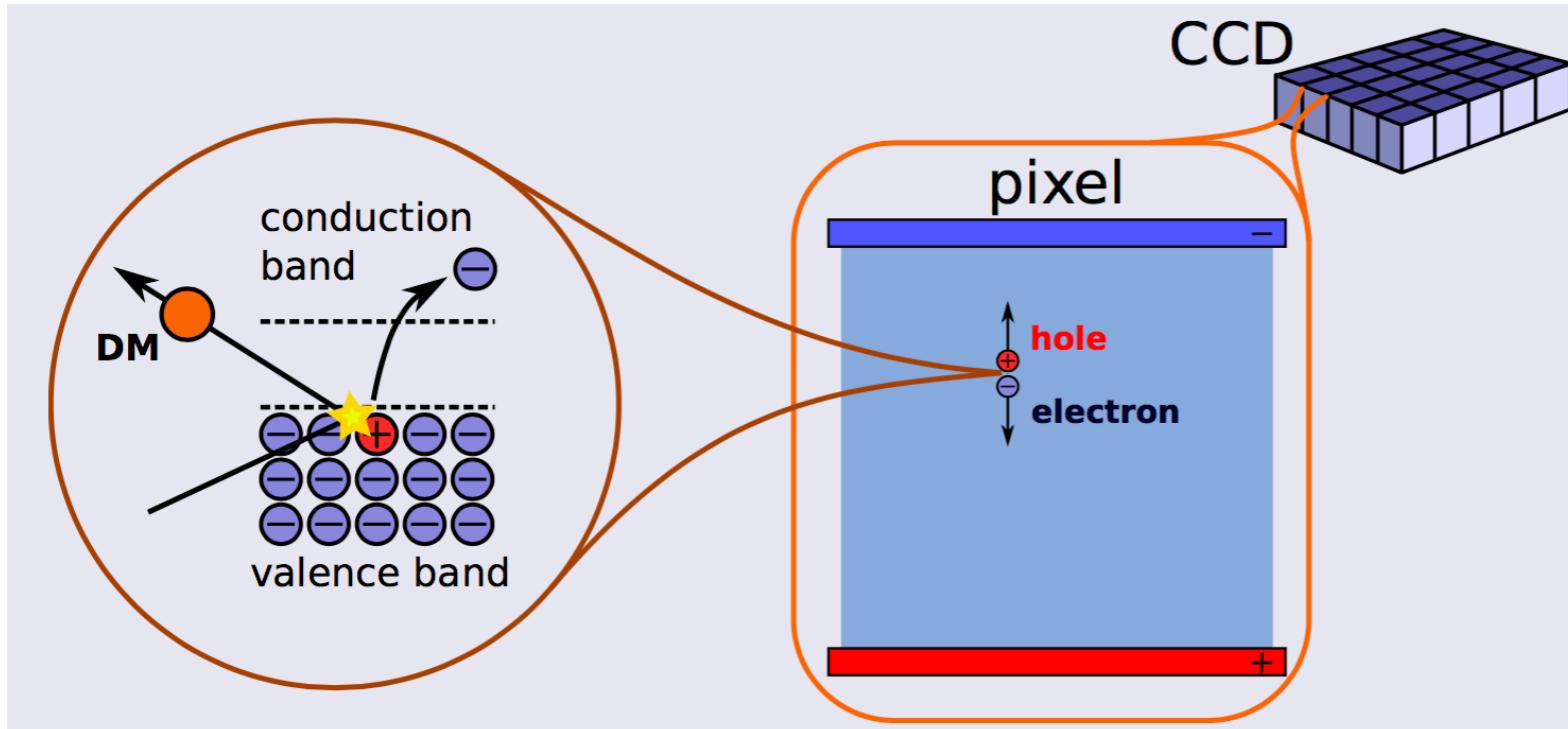
silicon Skipper-CCD



~million pixels

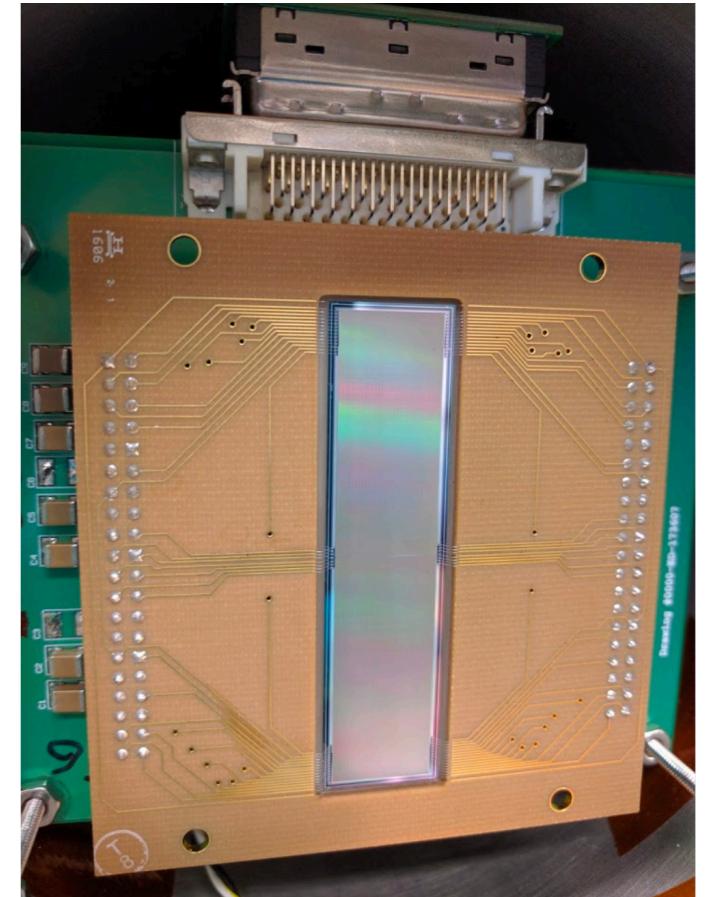
developed in collaboration
between FNAL & LBNL
MicroSystems Lab

Detection Concept



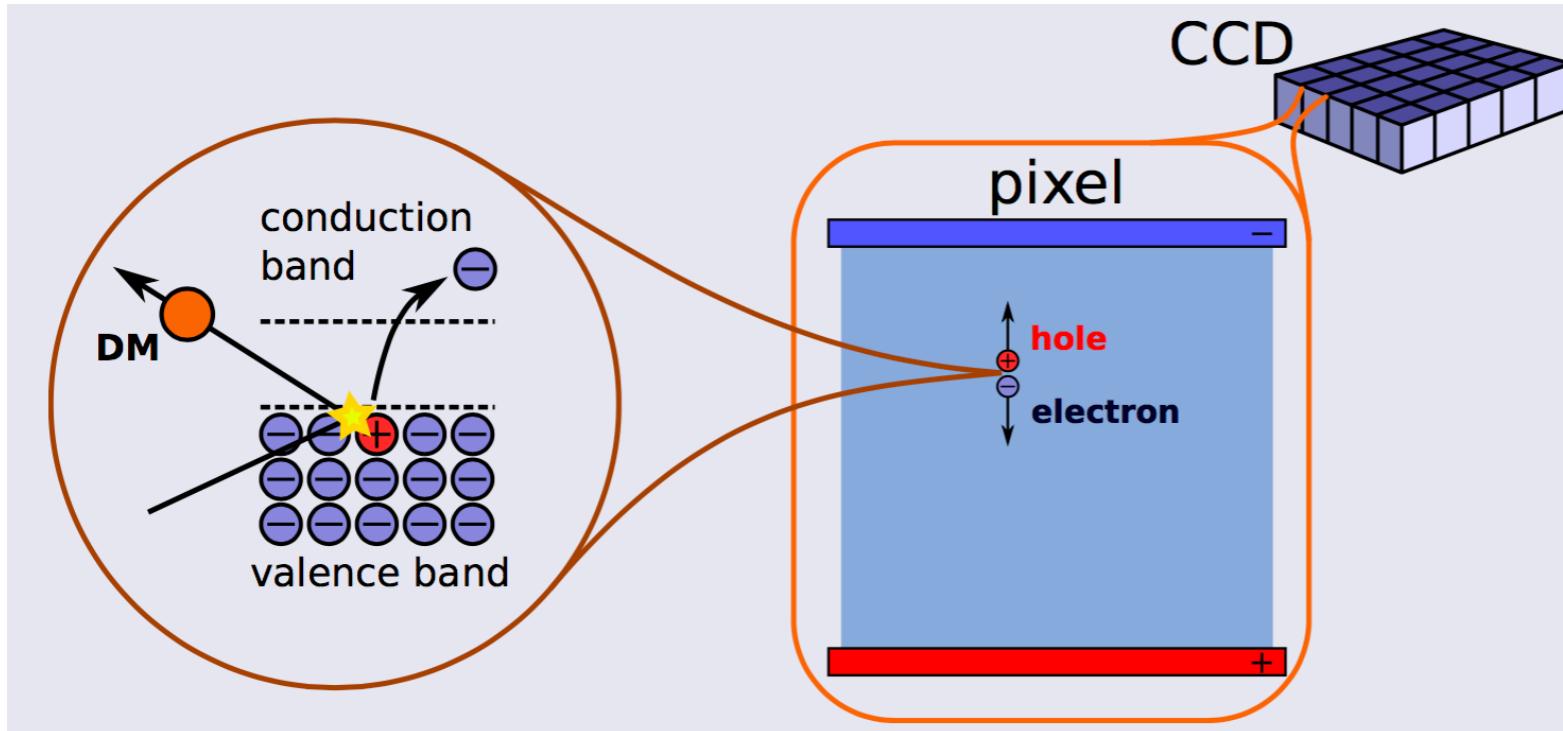
DM typically creates only
one or a few electrons/pixel

silicon Skipper-CCD



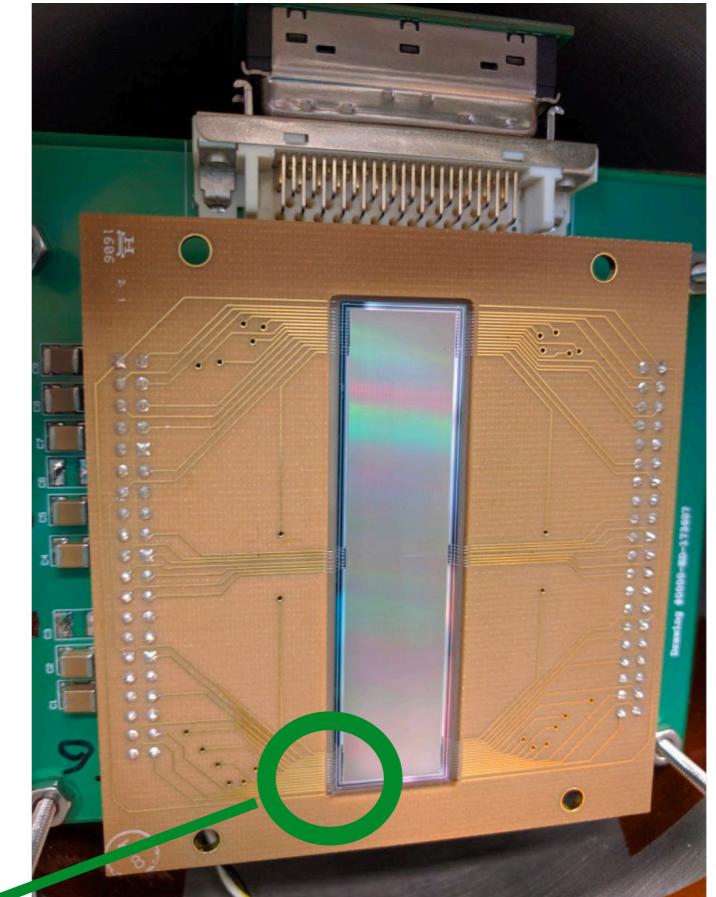
~million pixels

Detection Concept

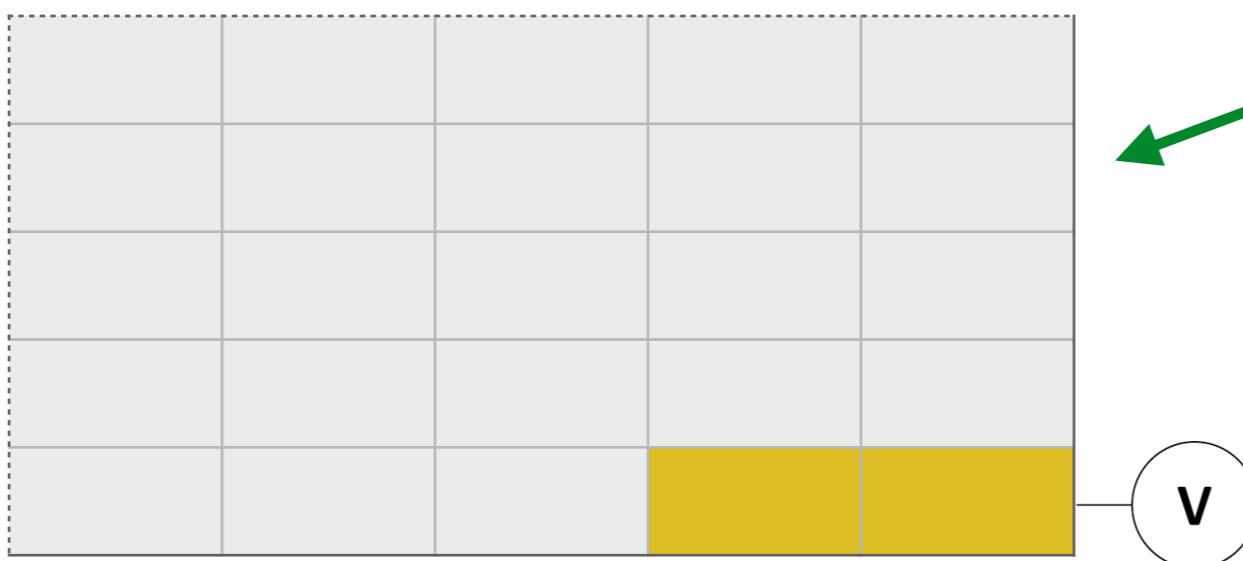


DM typically creates only
one or a few electrons/pixel

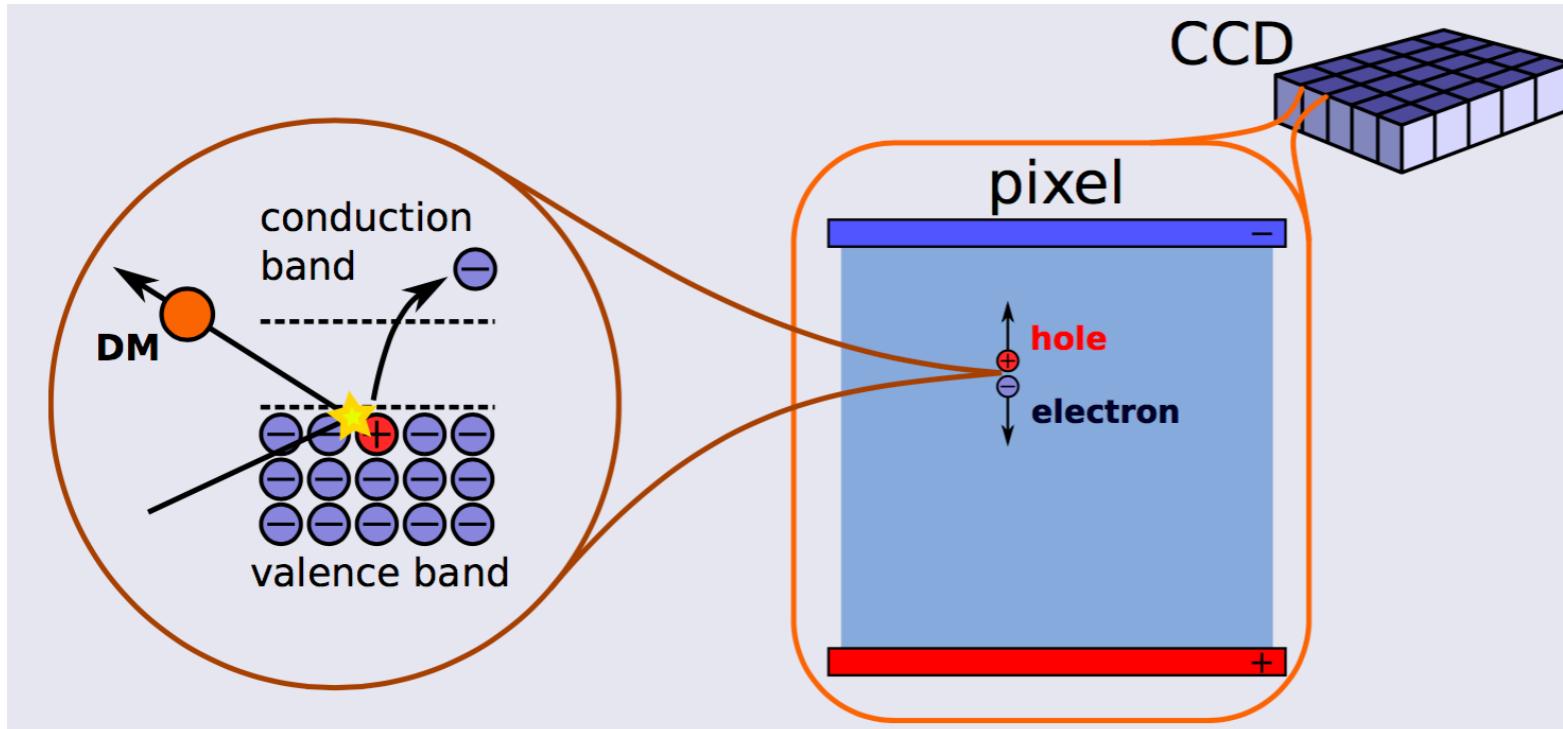
silicon Skipper-CCD



~million pixels

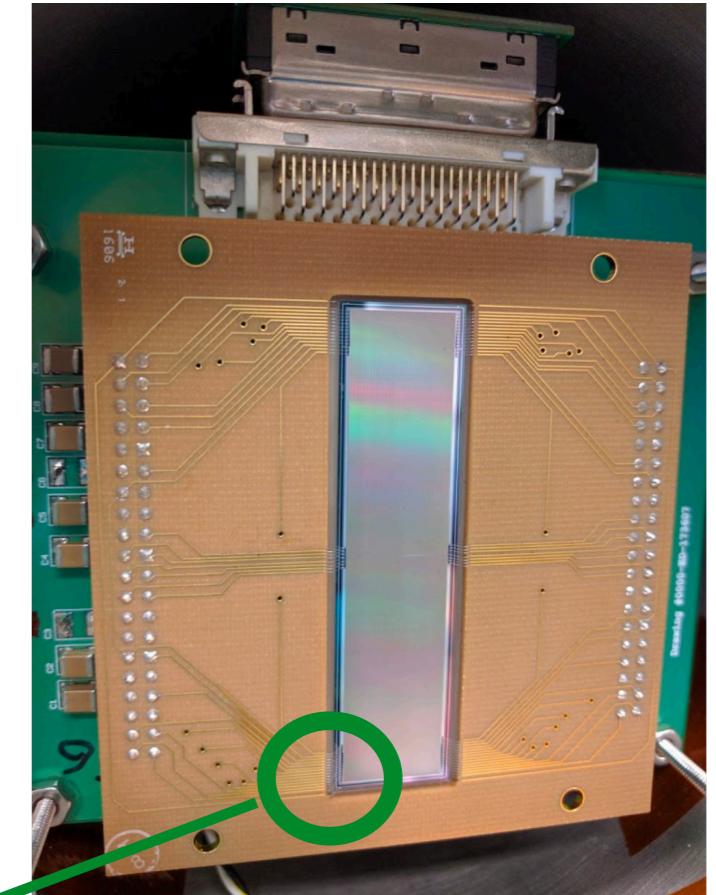


Detection Concept

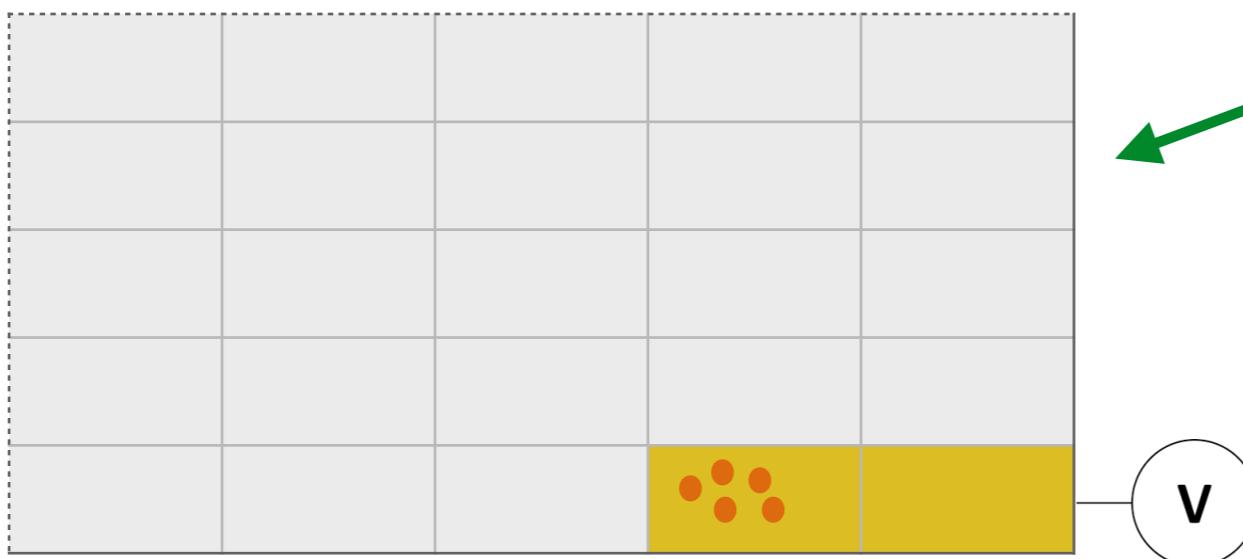


DM typically creates only
one or a few electrons/pixel

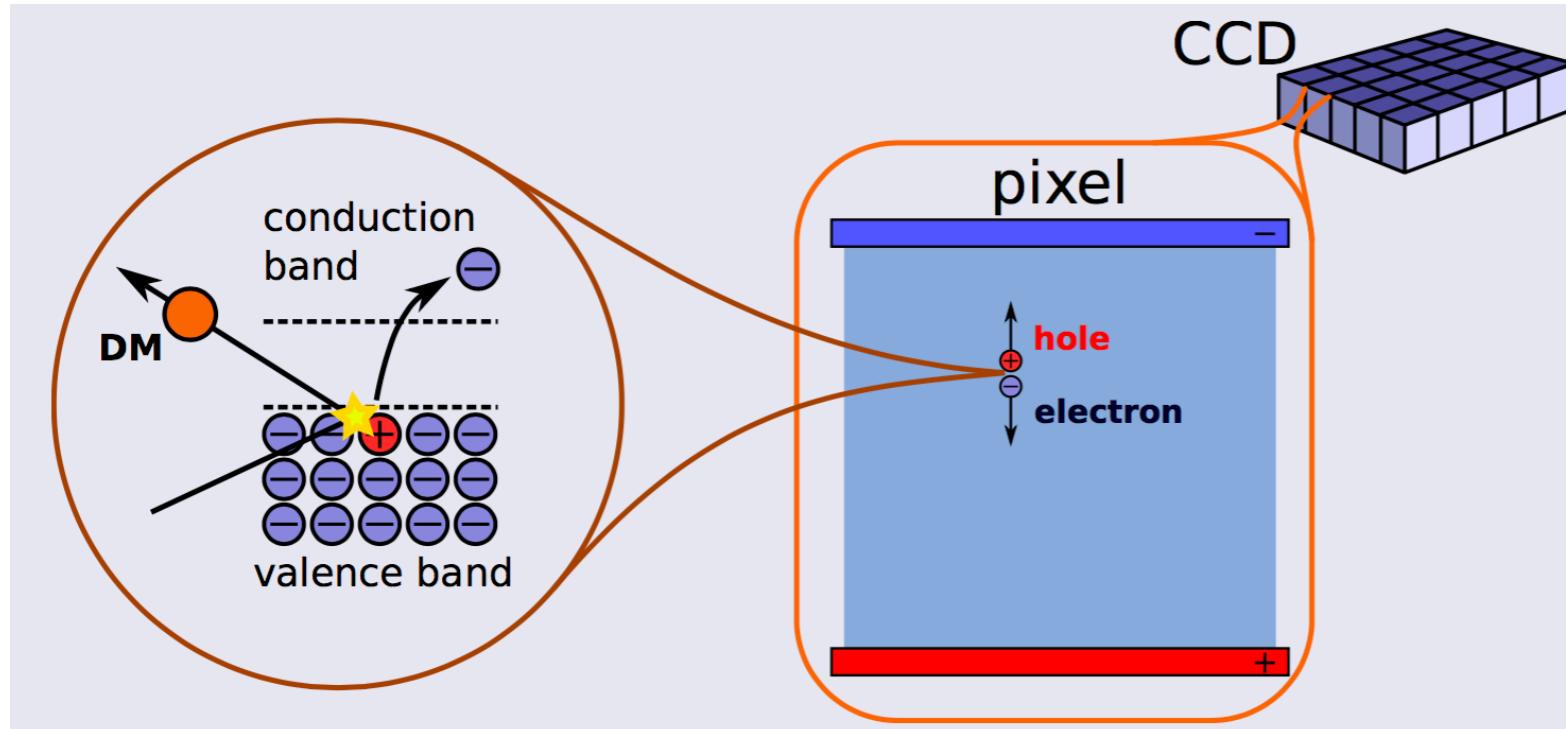
silicon Skipper-CCD



≈million pixels



Detection Concept

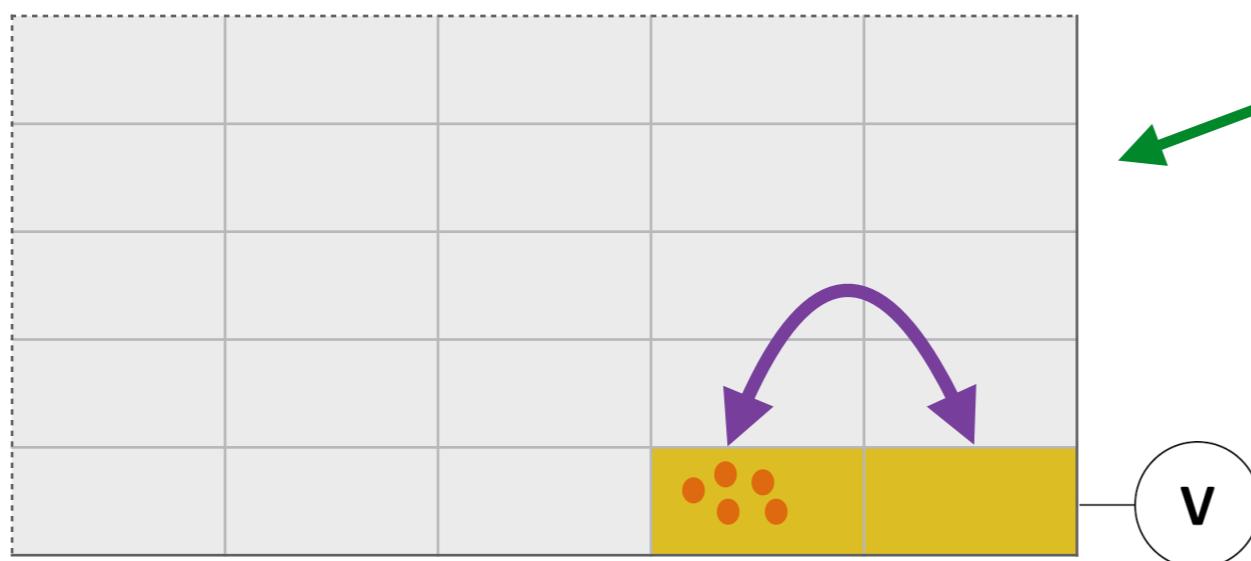


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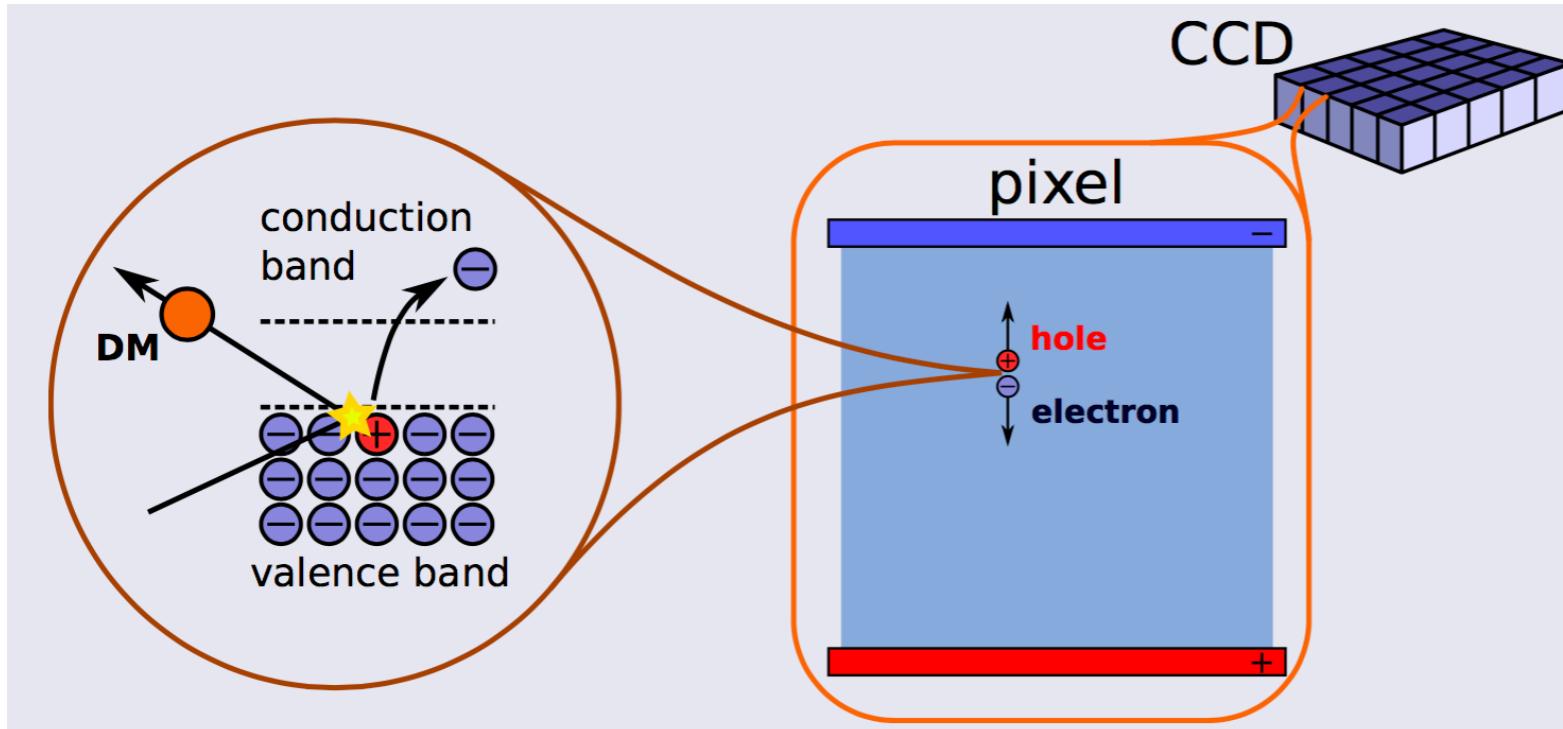


~million pixels



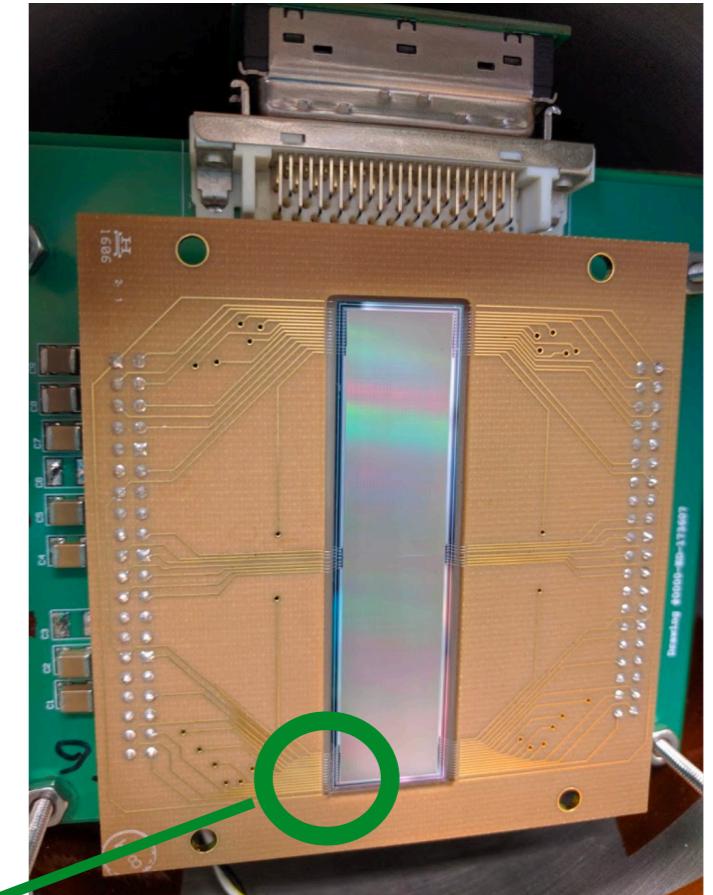
repeatedly
measure charge to
lower noise

Detection Concept

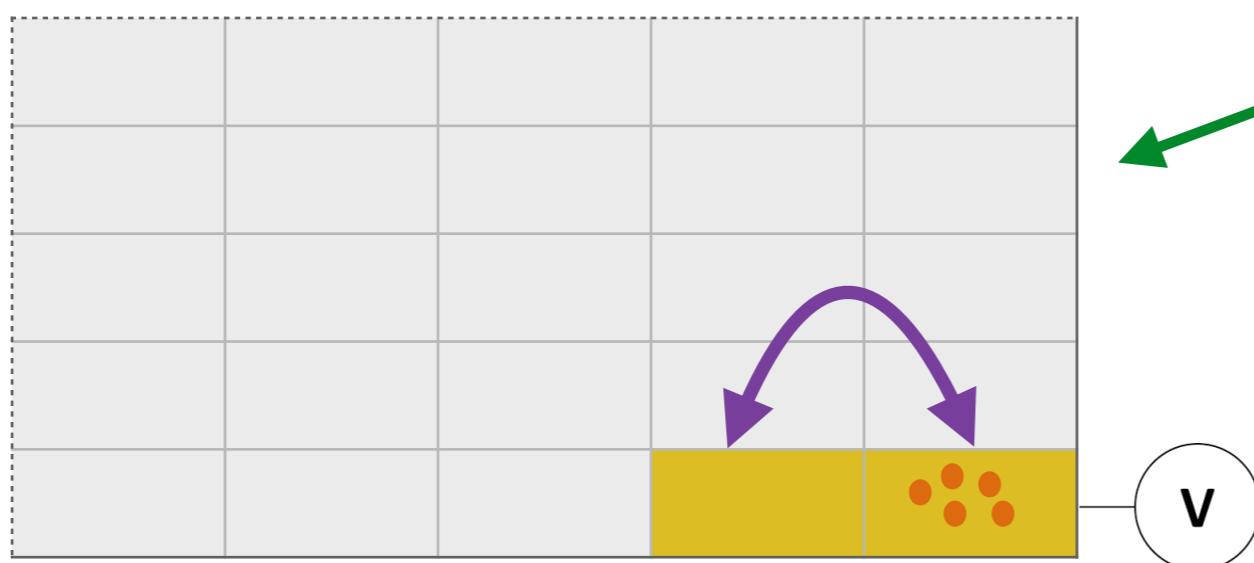


DM typically creates only
one or a few electrons/pixel

silicon Skipper-CCD

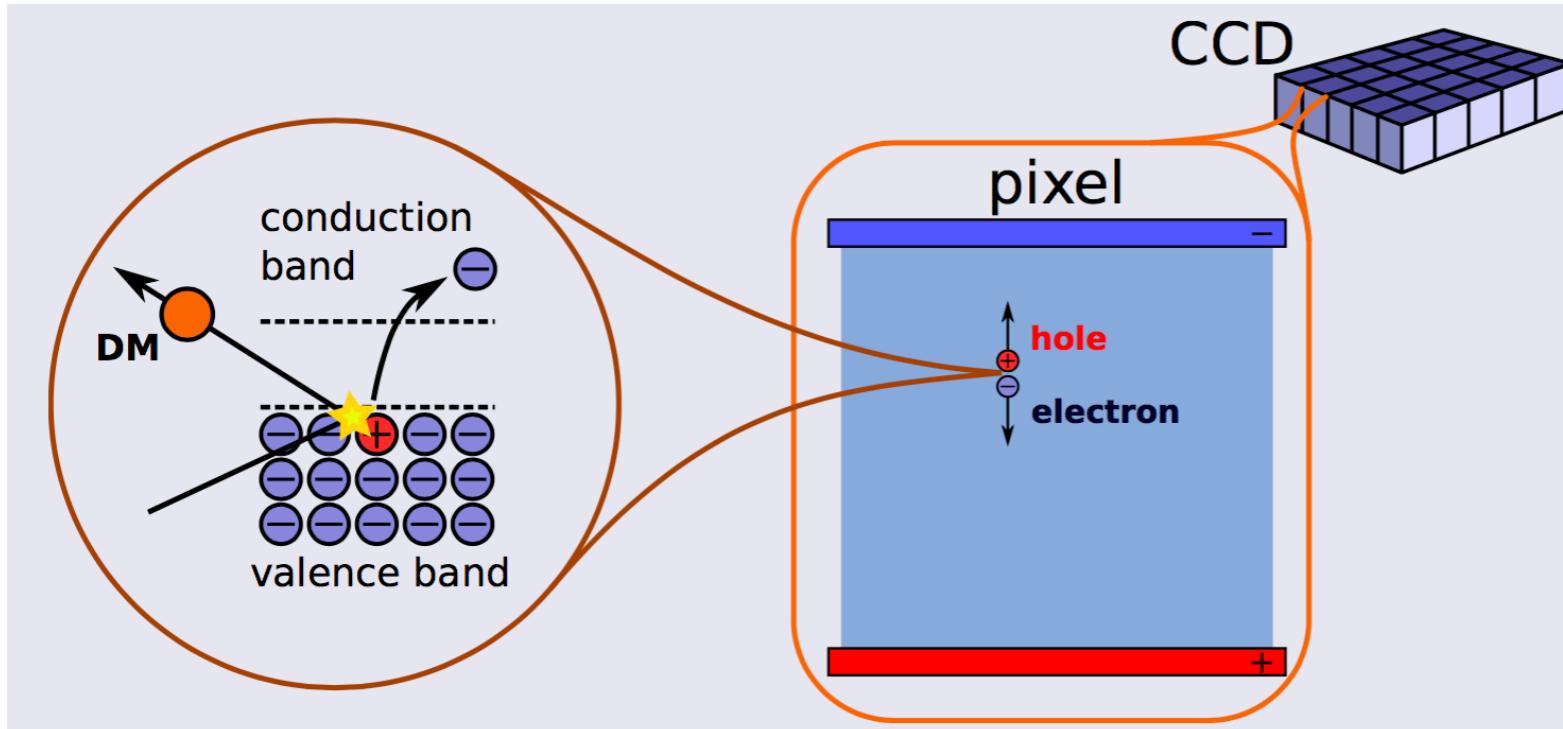


~million pixels



repeatedly
measure charge to
lower noise

Detection Concept

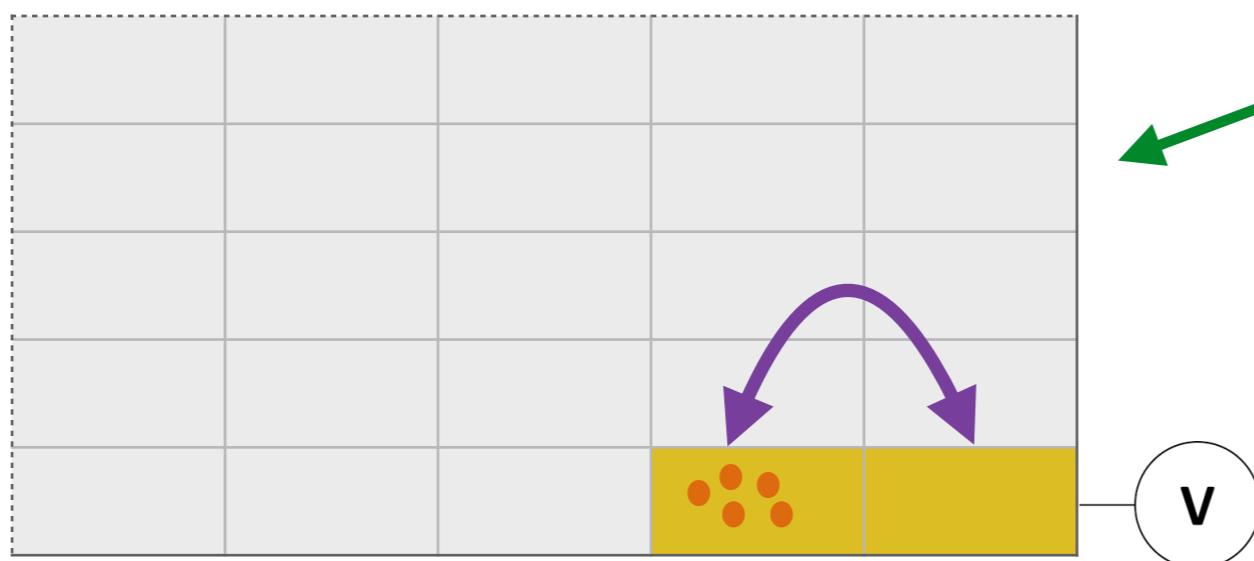


DM typically creates only
one or a few electrons/pixel

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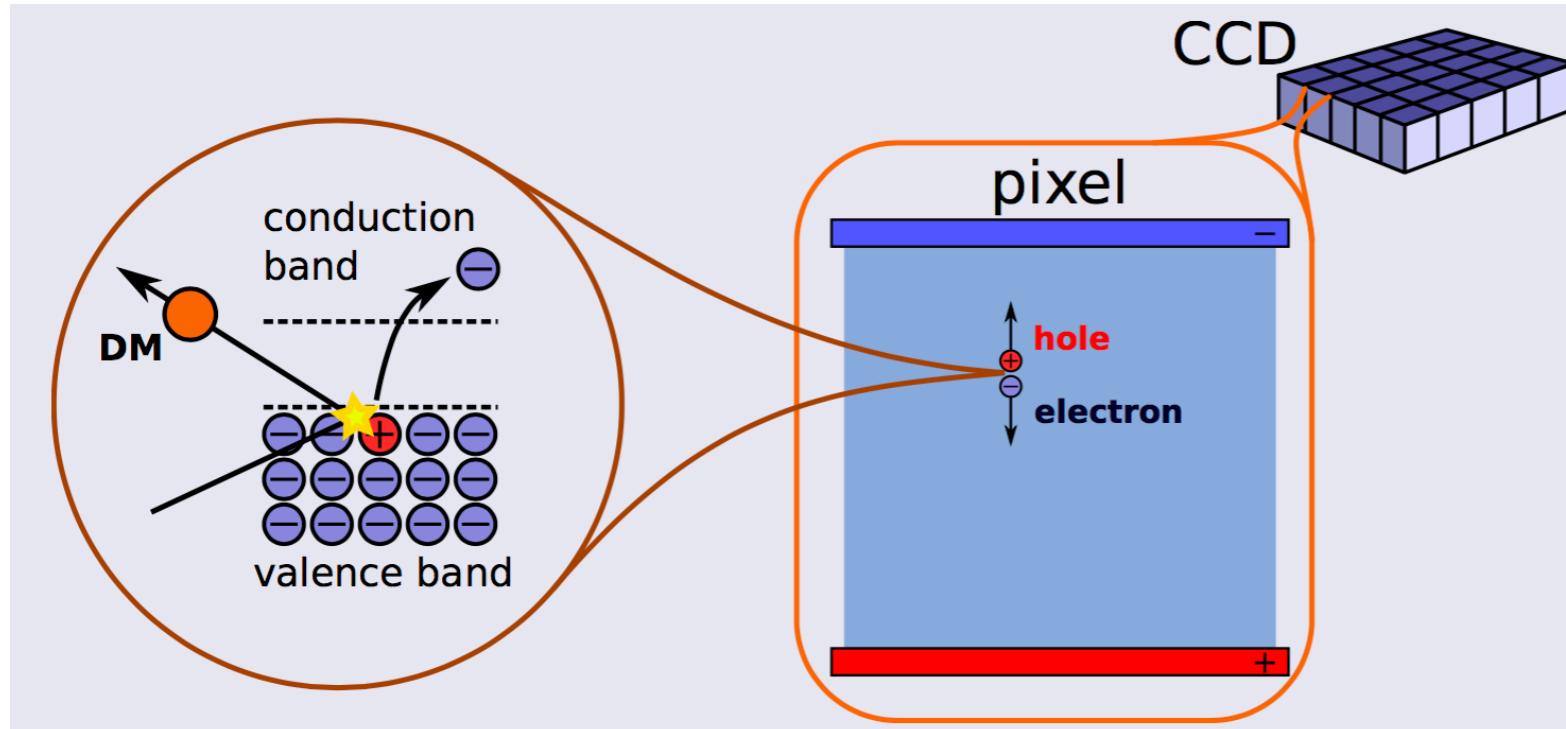


~million pixels



repeatedly
measure charge to
lower noise

Detection Concept

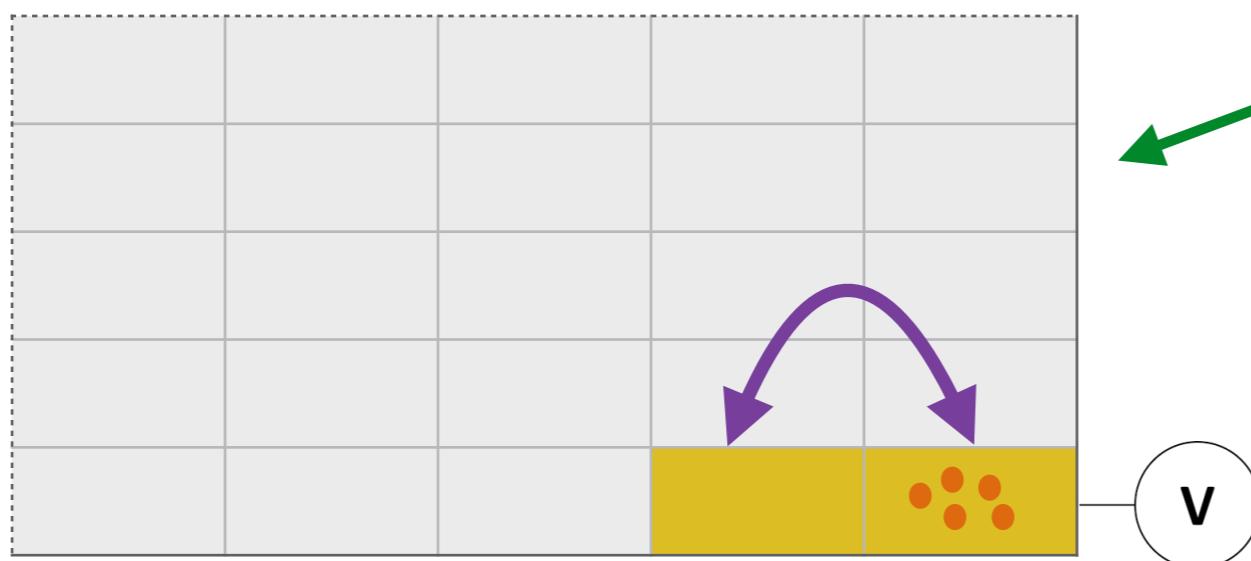


DM typically creates only
one or a few electrons/pixel

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~million pixels

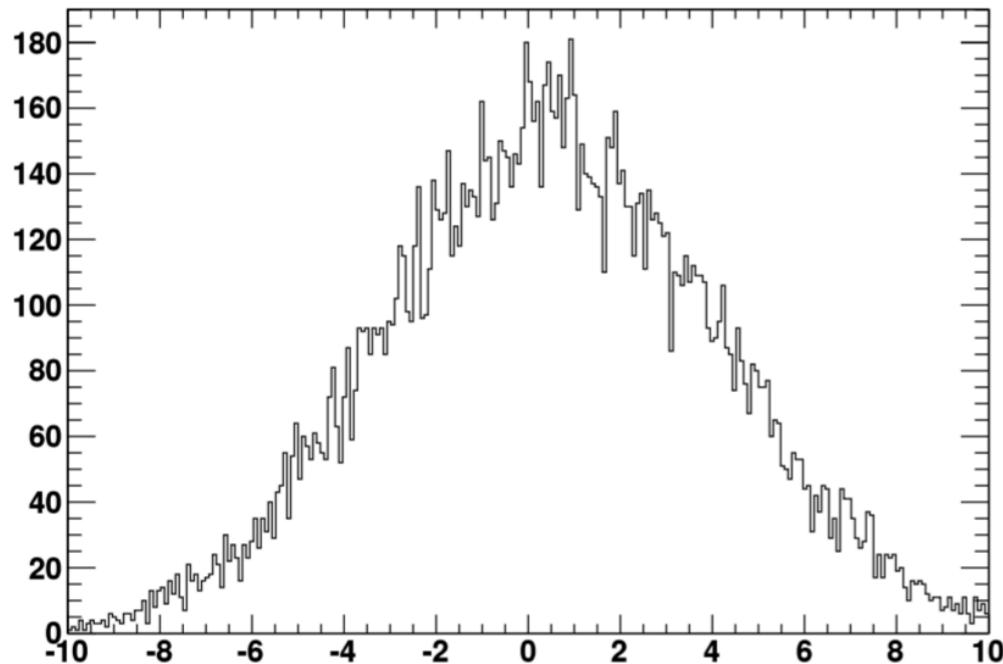


repeatedly
measure charge to
lower noise

Skipper-CCD can count individual electrons, w/ \sim zero noise

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

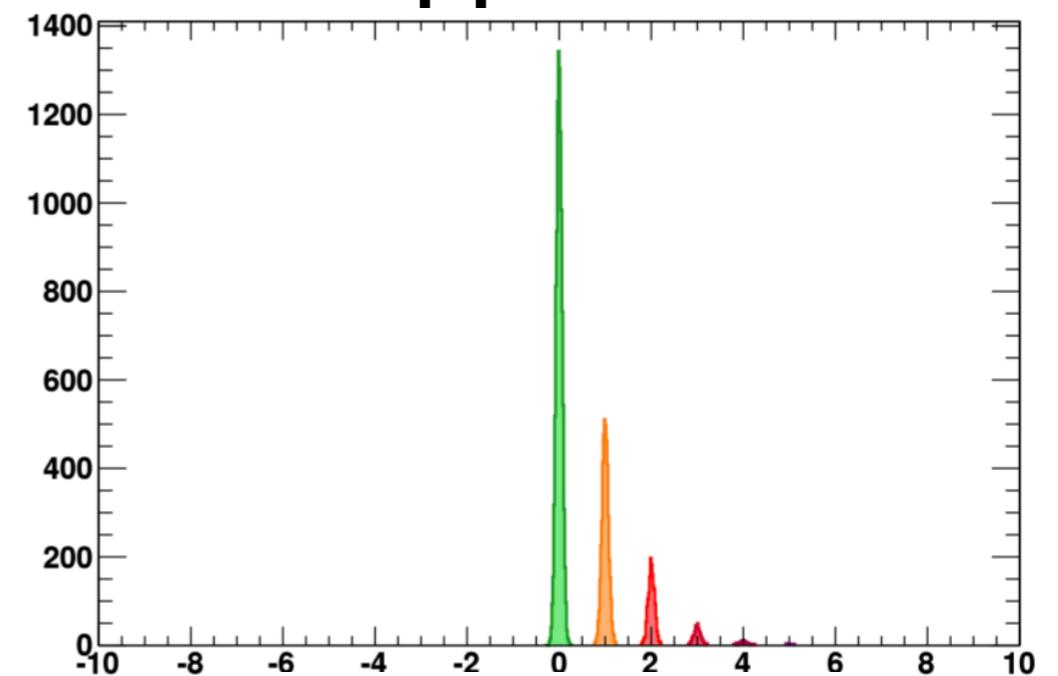
ordinary CCD



electron-hole pairs

rms noise ~ 3 e⁻
(single measurement)

Skipper CCD



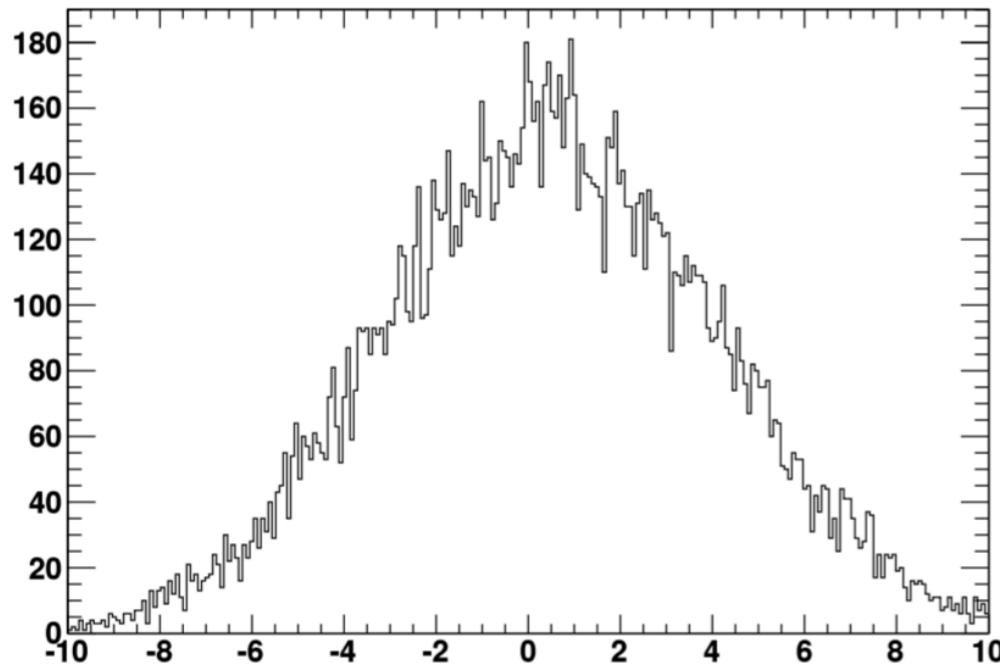
electron-hole pairs

rms noise ~ 0.06 e⁻ !
(repeated measurements)

Skipper-CCD can count individual electrons, w/ \sim zero noise

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

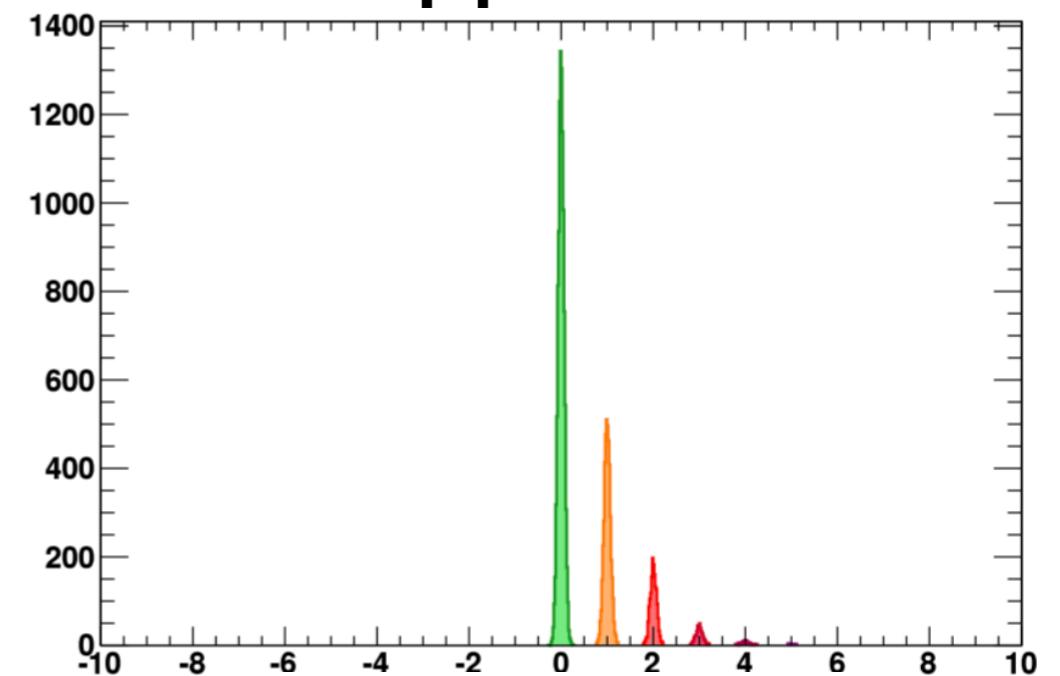
ordinary CCD



electron-hole pairs

rms noise ~ 3 e⁻
(single measurement)

Skipper CCD



electron-hole pairs

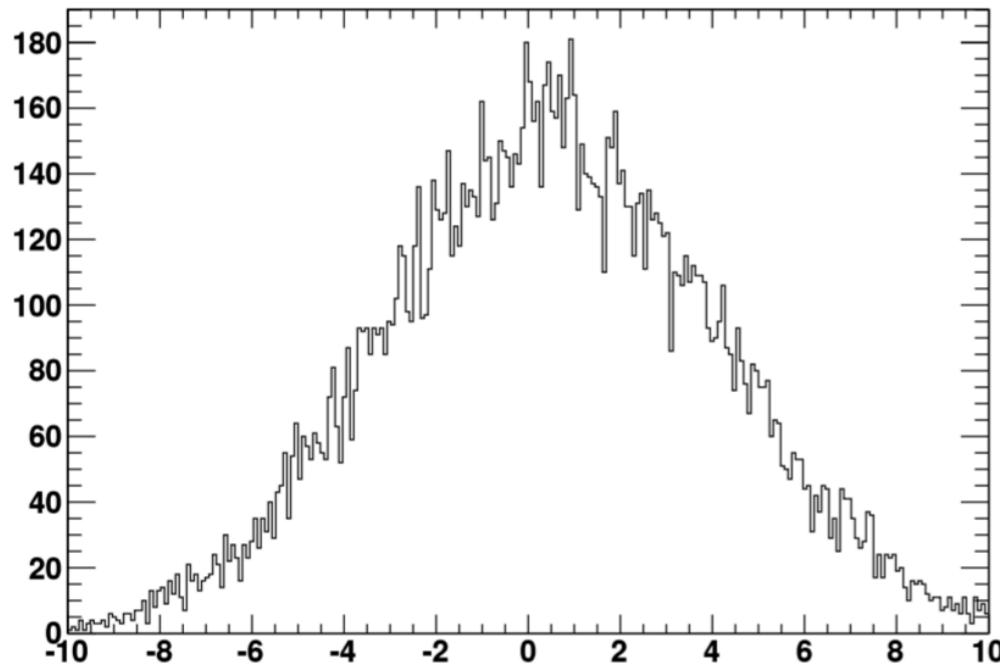
rms noise ~ 0.06 e⁻ !
(repeated measurements)

demonstrated by SENSEI Collaboration in a Fermilab LDRD
project using small (~ 0.1 gram) prototype Skipper-CCDs

Skipper-CCD can count individual electrons, w/ \sim zero noise

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

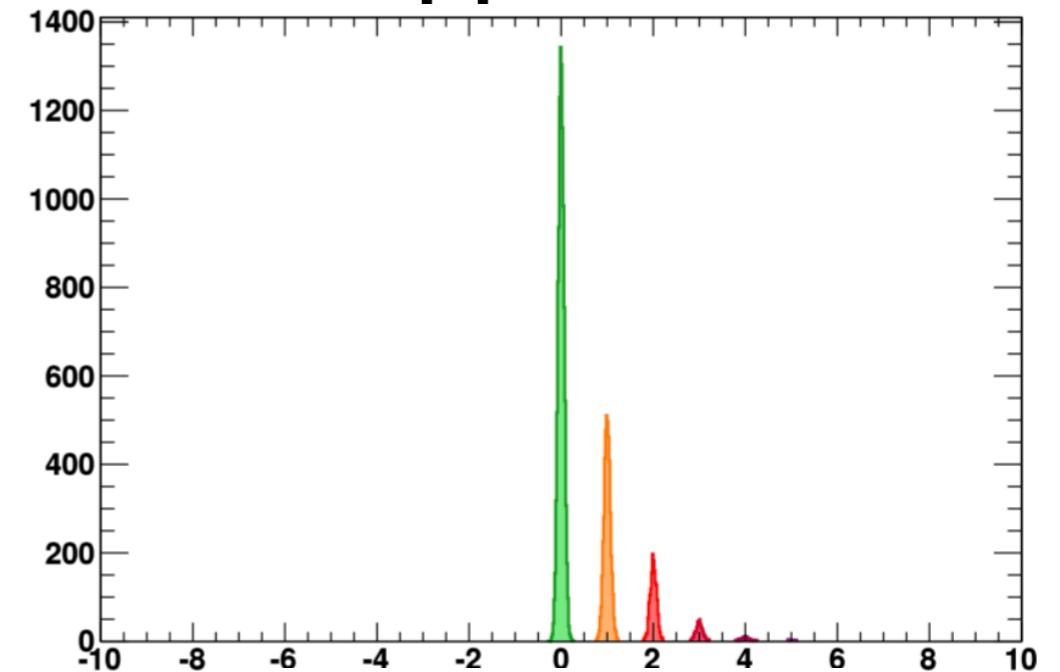
ordinary CCD



electron-hole pairs

rms noise ~ 3 e-
(single measurement)

Skipper CCD



electron-hole pairs

rms noise ~ 0.06 e- !
(repeated measurements)

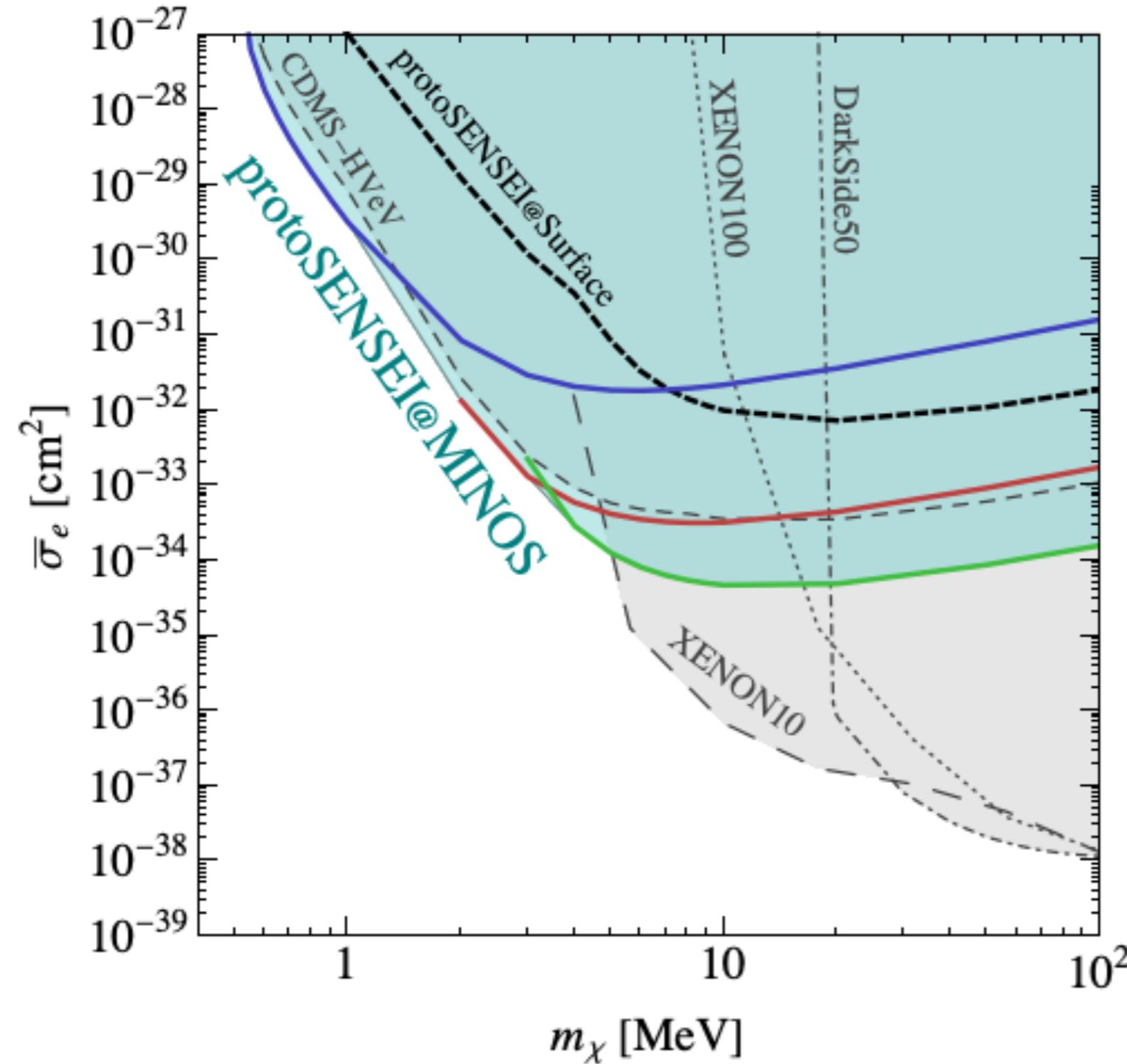
demonstrated by SENSEI Collaboration in a Fermilab LDRD project using small (~ 0.1 gram) prototype Skipper-CCDs

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

SENSEI DM constraints from a (tiny) prototype operating on surface & ~100m underground near MINOS cavern at Fermilab

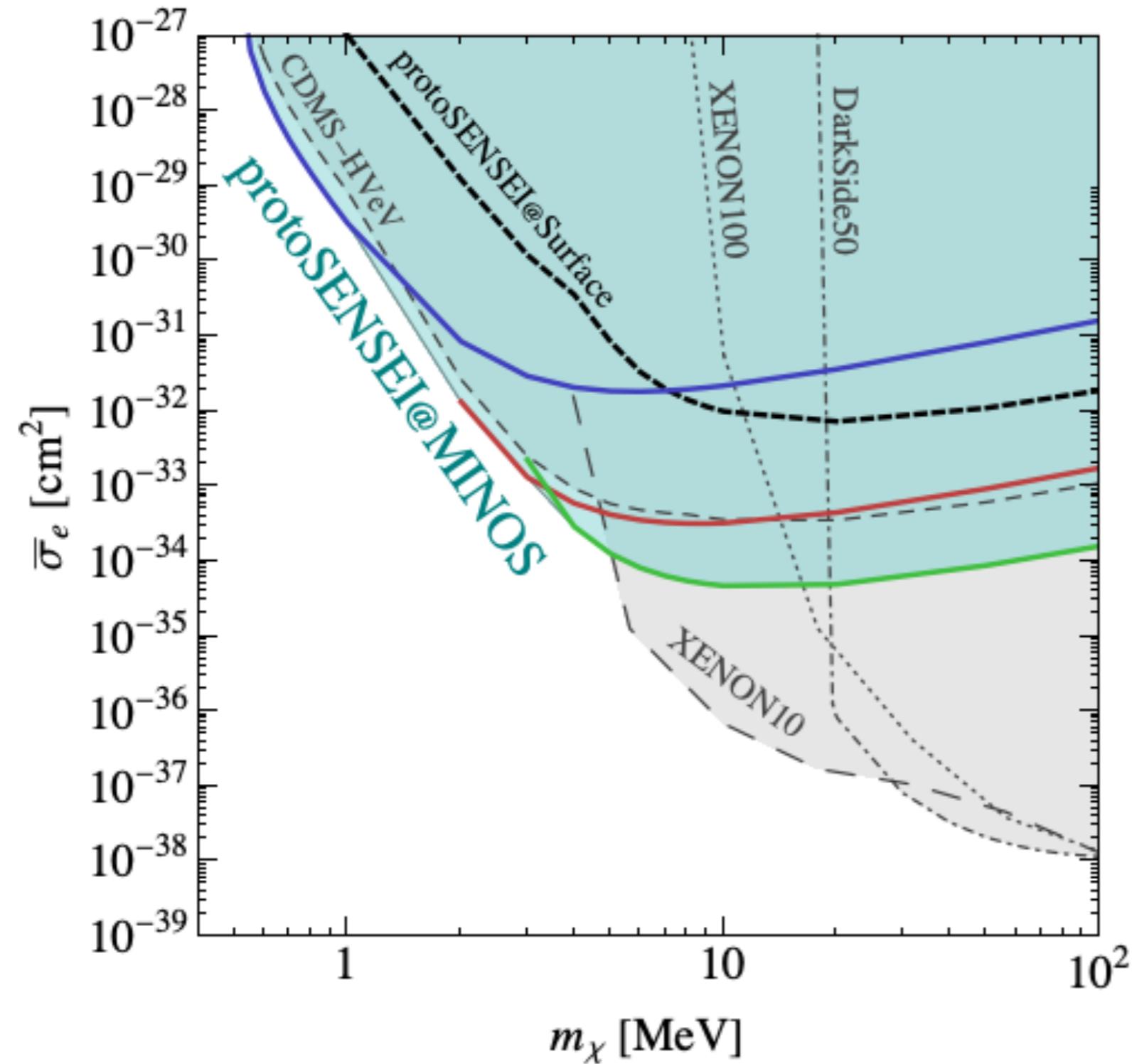
SENSEI Collaboration,
1804.00088 & 1901.10478, PRL

- exposure ~ 0.02 gram-days &
 ~ 0.246 gram-days, respectively



SENSEI DM constraints from a (tiny) prototype operating on surface & ~100m underground near MINOS cavern at Fermilab

SENSEI Collaboration,
1804.00088 & 1901.10478, PRL

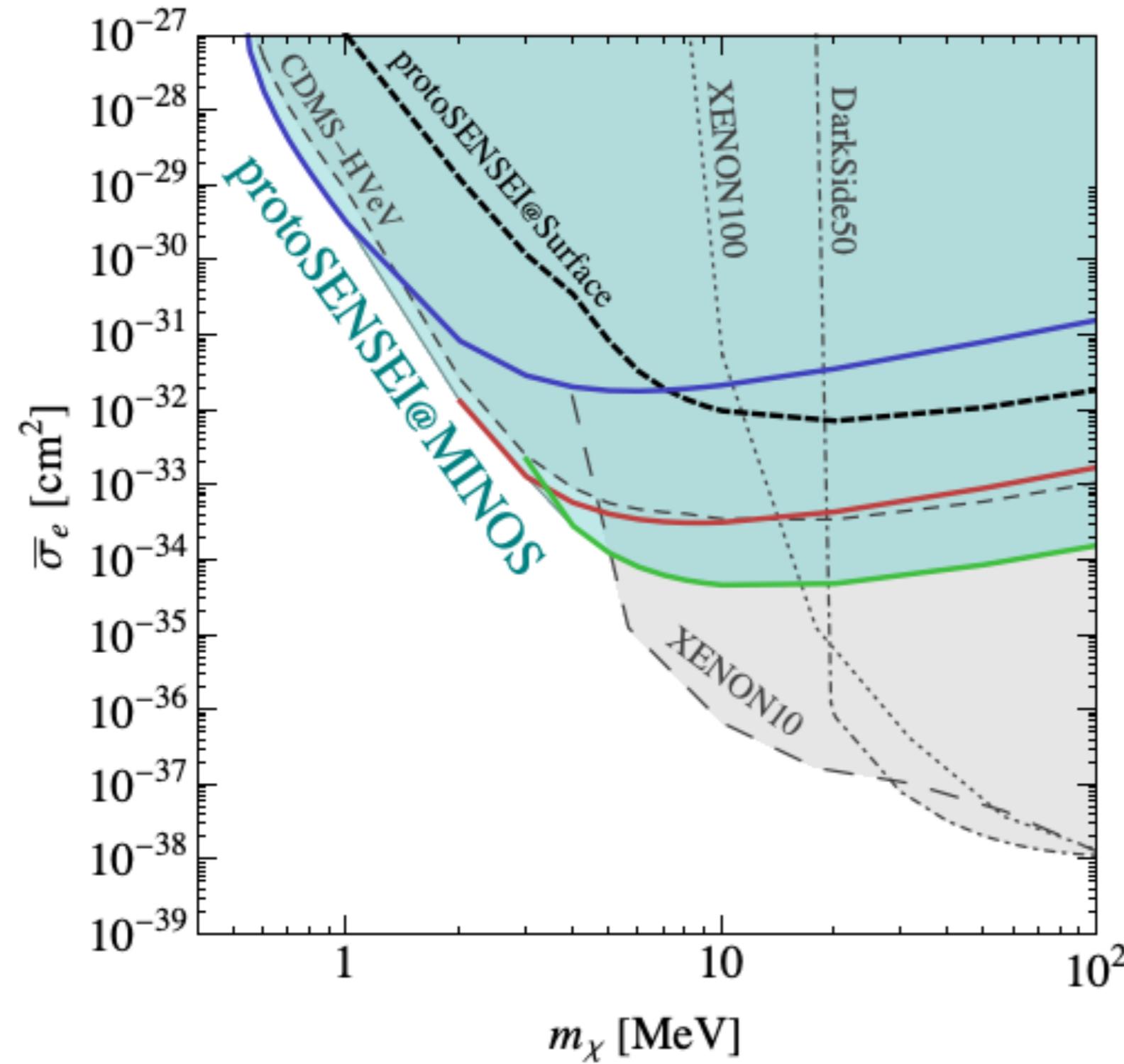


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SENSEI DM constraints from a (tiny) prototype operating on surface & ~100m underground near MINOS cavern at Fermilab

SENSEI Collaboration,
1804.00088 & 1901.10478, PRL



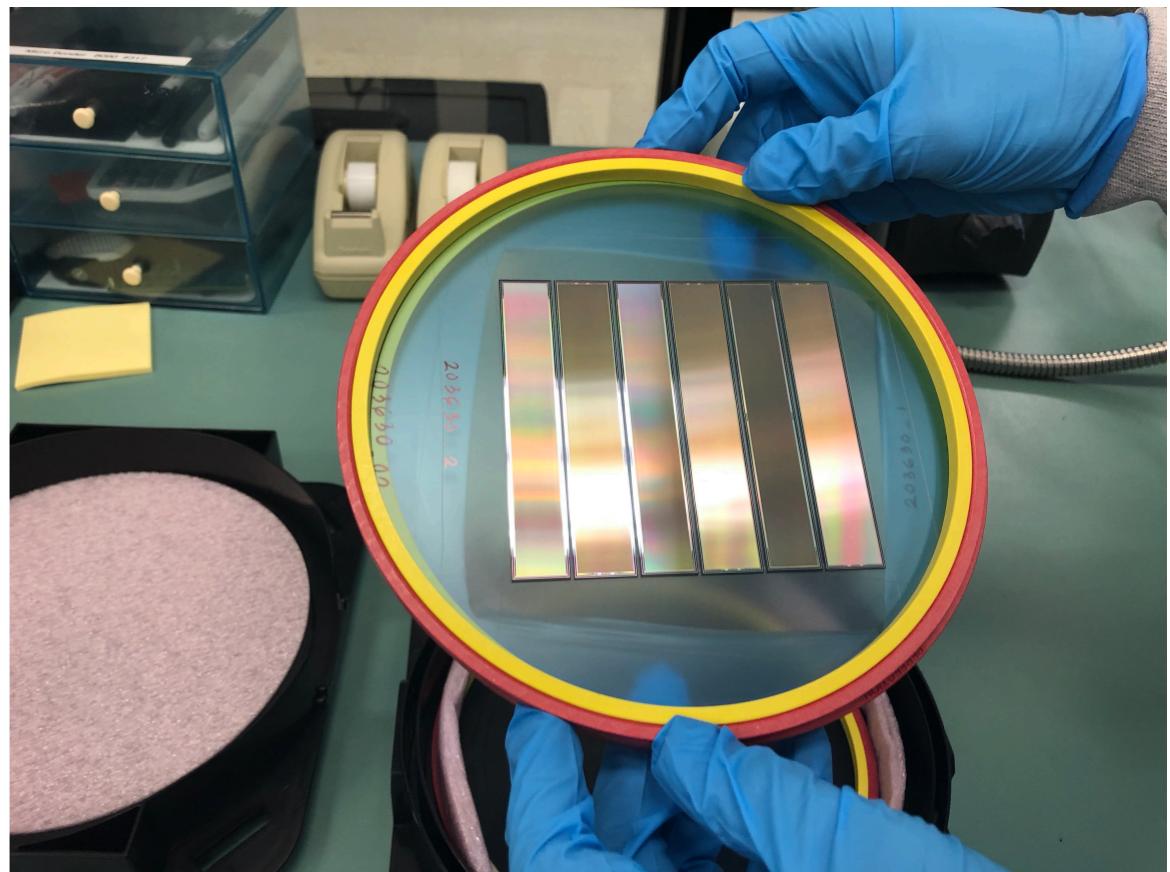
- exposure ~ 0.02 gram-days &
 ~ 0.246 gram-days, respectively

DAMIC@SNOLAB (w/ ordinary CCDs, 200 gram-days) recently improved bound below 5 MeV (due to high-quality silicon & low dark counts)

see 1907.12628

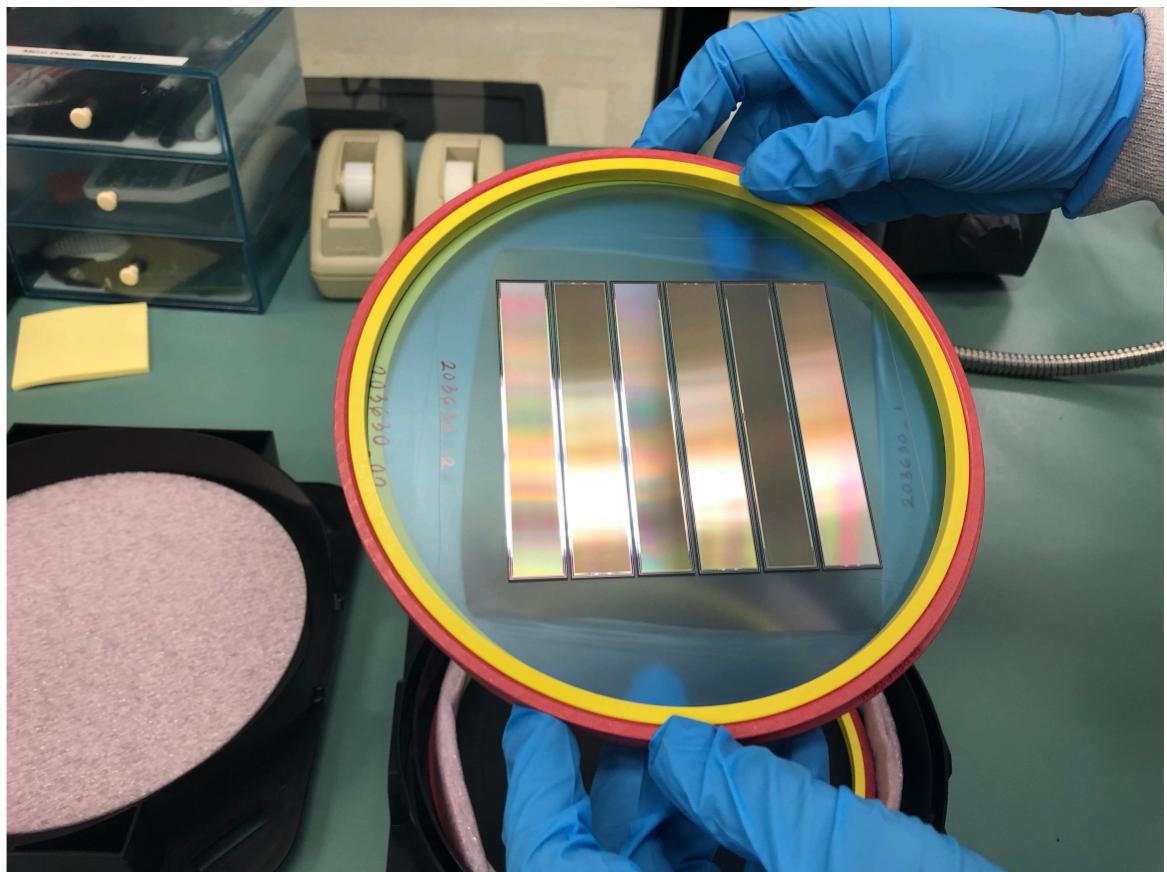
SENSEI: Goals & Current Status

deploy ~100 grams of new
(and bigger) Skipper CCDs



SENSEI: Goals & Current Status

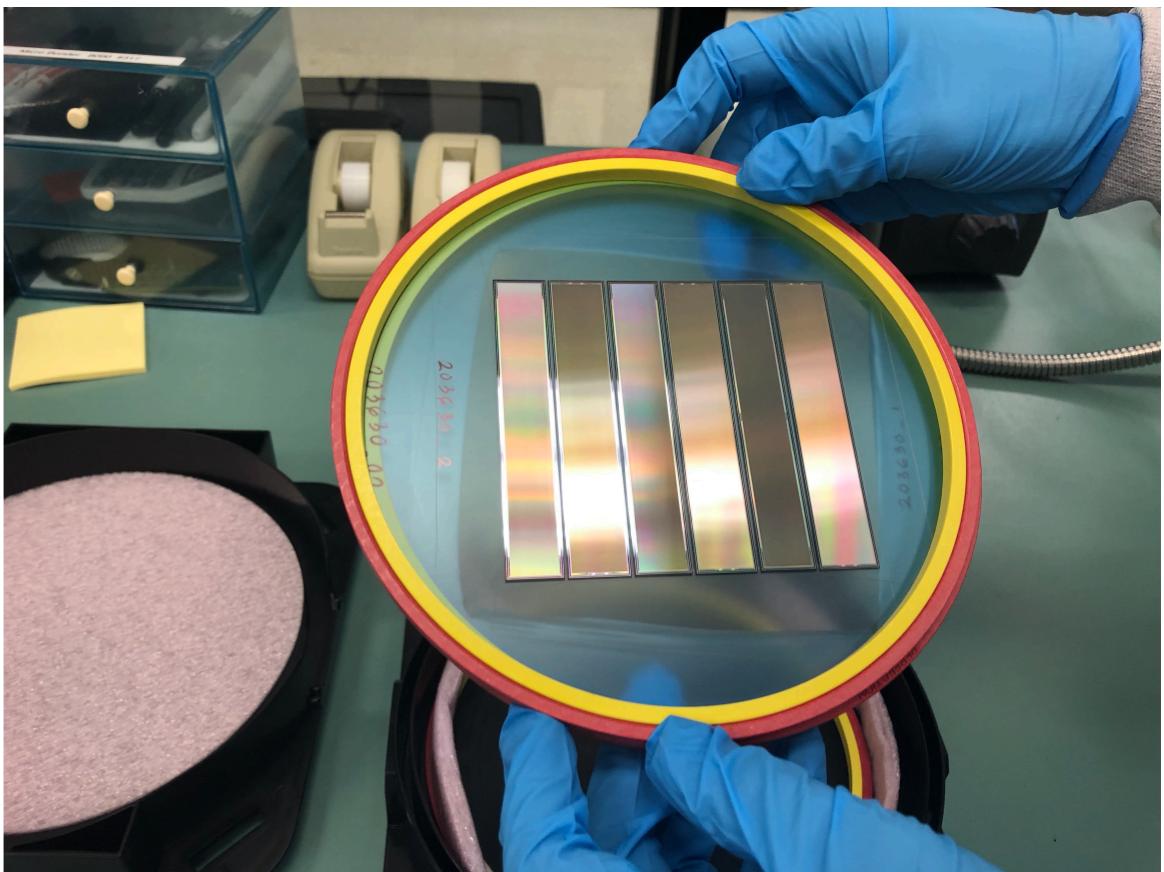
deploy ~100 grams of new
(and bigger) Skipper CCDs



- new Skipper-CCDs are in hand and being tested

SENSEI: Goals & Current Status

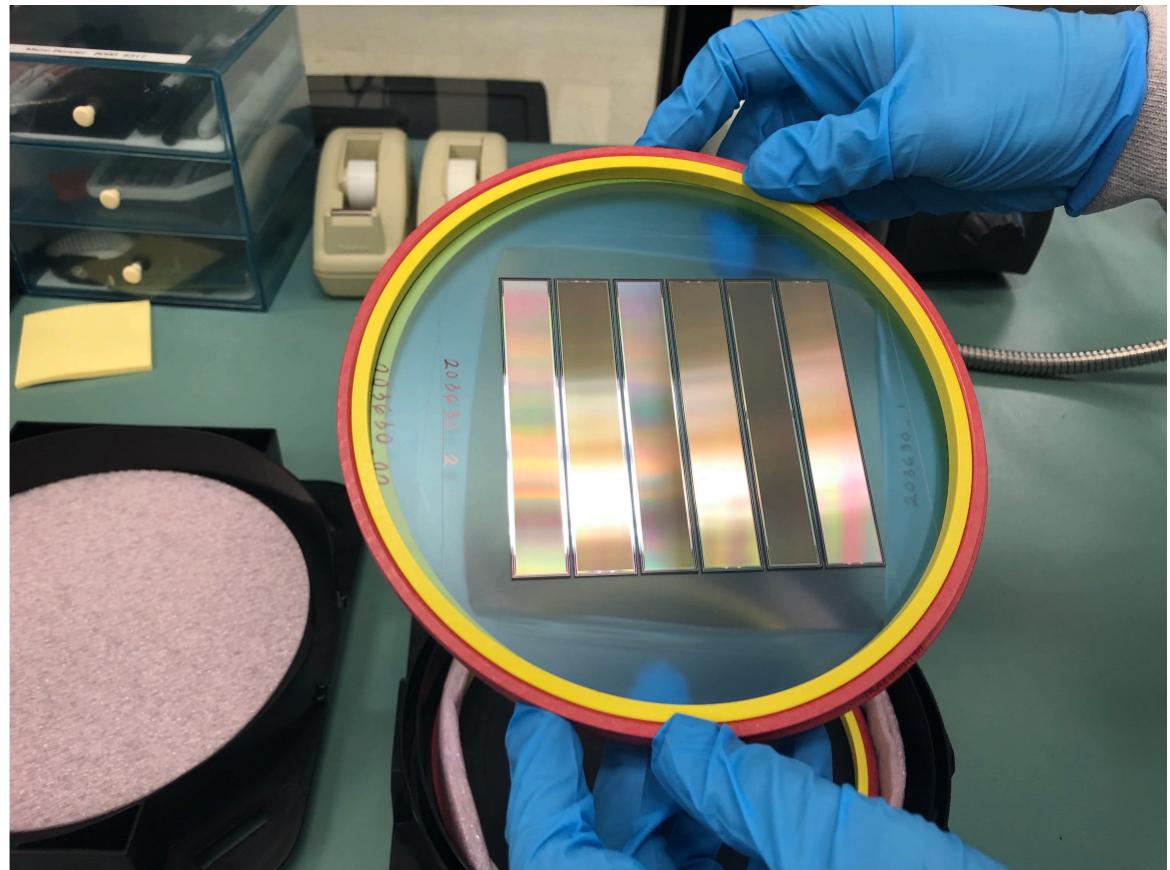
deploy ~100 grams of new
(and bigger) Skipper CCDs



- new Skipper-CCDs are in hand and being tested
- staged approach:

SENSEI: Goals & Current Status

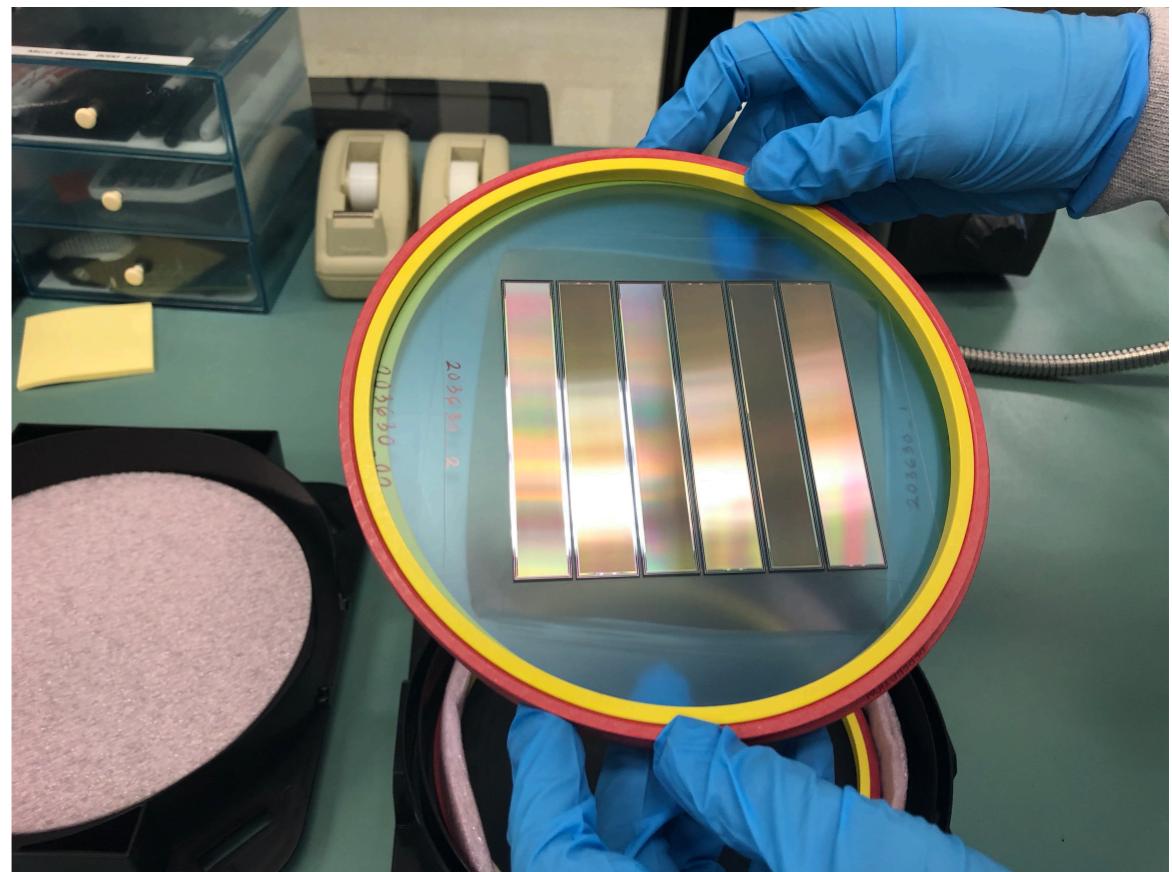
deploy ~100 grams of new
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- new Skipper-CCDs are in hand and being tested
- staged approach:
 - ~10 grams, first at MINOS, then at SNOLAB
(this year→early 2020)

SENSEI: Goals & Current Status

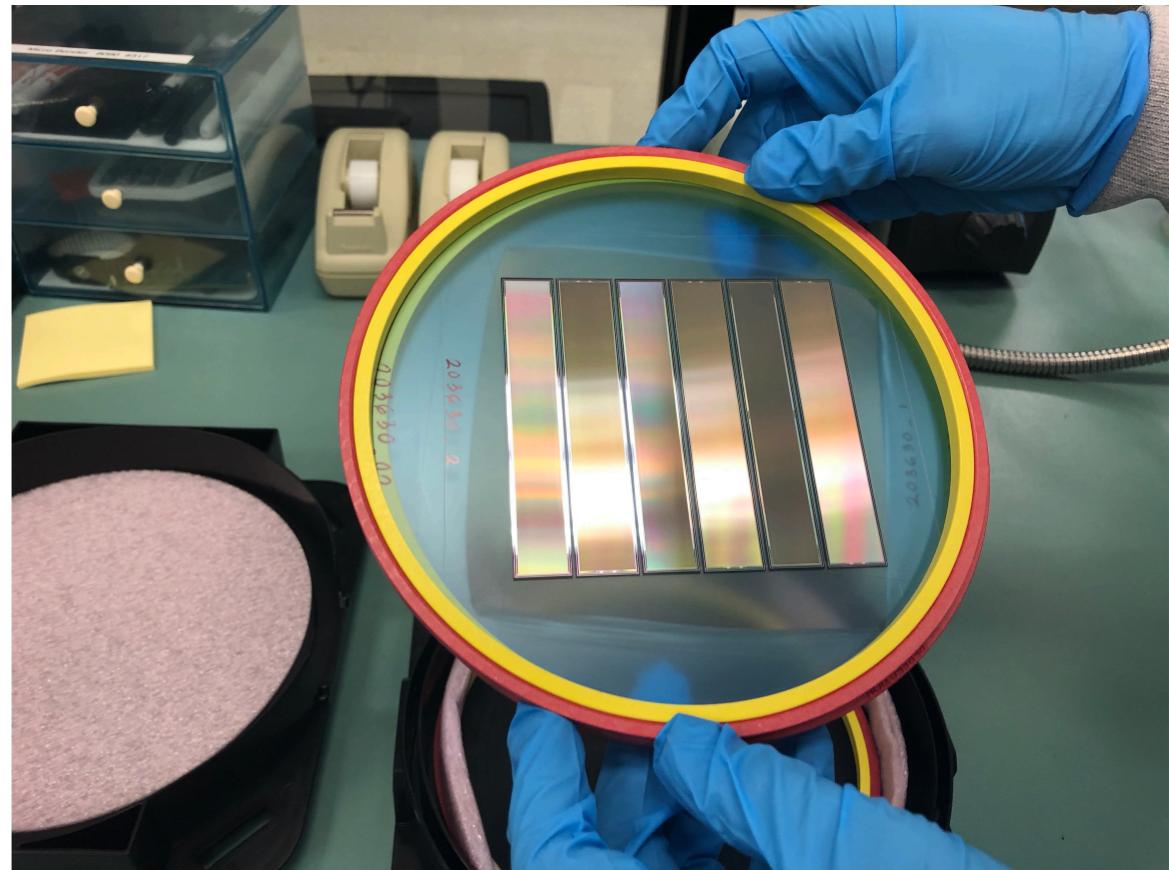
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 - 2020: ~100 g at SNOLAB

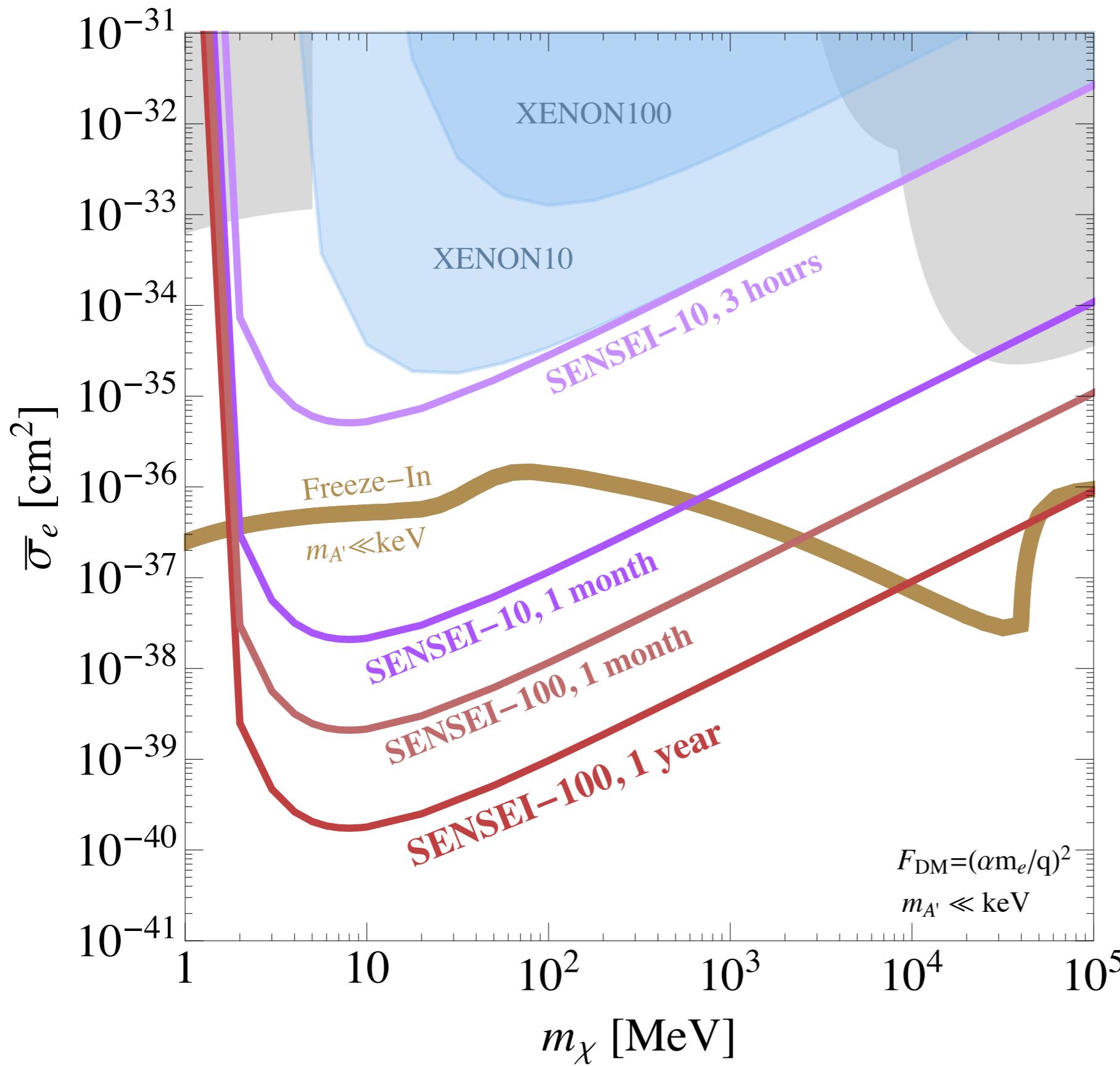
SENSEI: Goals & Current Status

deploy ~100 grams of new
(and bigger) Skipper CCDs



- new Skipper-CCDs are in hand and being tested
- staged approach:
 - ~10 grams, first at MINOS, then at SNOLAB
(this year→early 2020)
 - 2020: ~100 g at SNOLAB
 - received “Deployment Approval” from SNOLAB yesterday

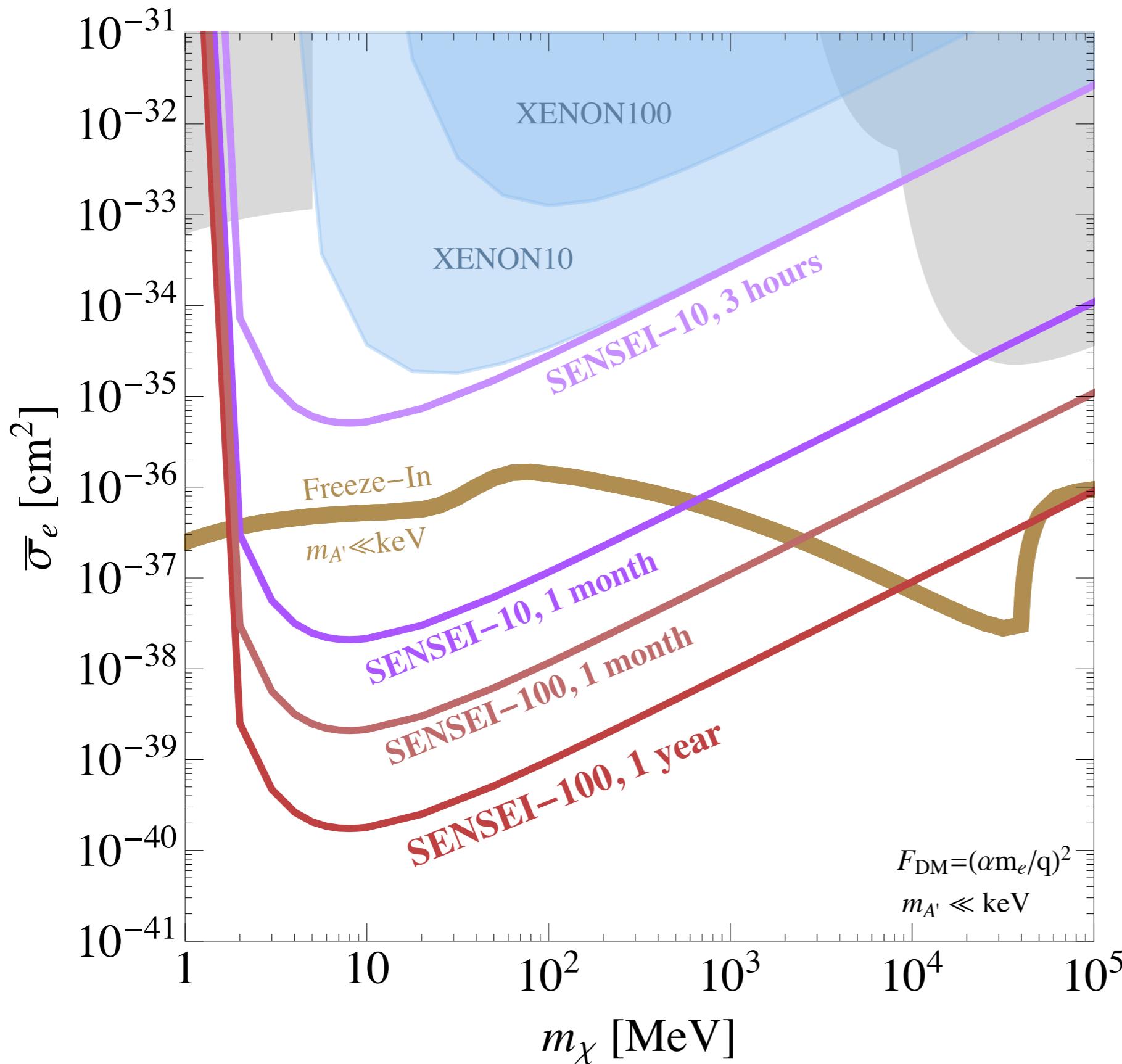
Example SENSEI sensitivity: freeze-in DM



mediator: “ultralight”
dark photon

$$\bar{\sigma}_e \propto \frac{1}{q^4}$$

Example SENSEI sensitivity: freeze-in DM



mediator: “ultralight”
dark photon

$$\bar{\sigma}_e \propto \frac{1}{q^4}$$

freeze-in model

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

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

SENSEI: backgrounds

SENSEI: backgrounds

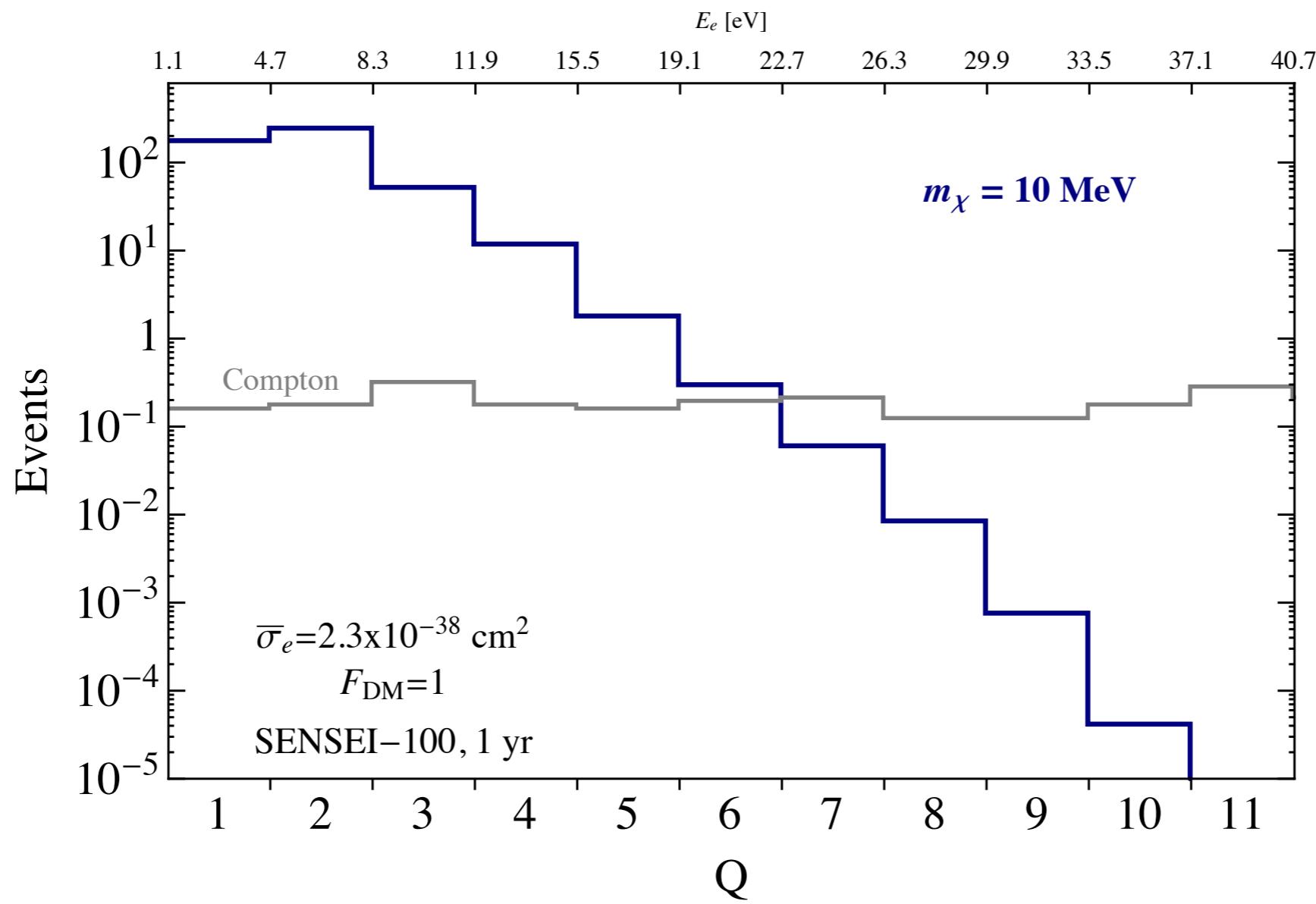
- Readout noise: irrelevant

SENSEI: backgrounds

- Readout noise: irrelevant
- Solar neutrinos: irrelevant RE, Sholapurkar, Yu

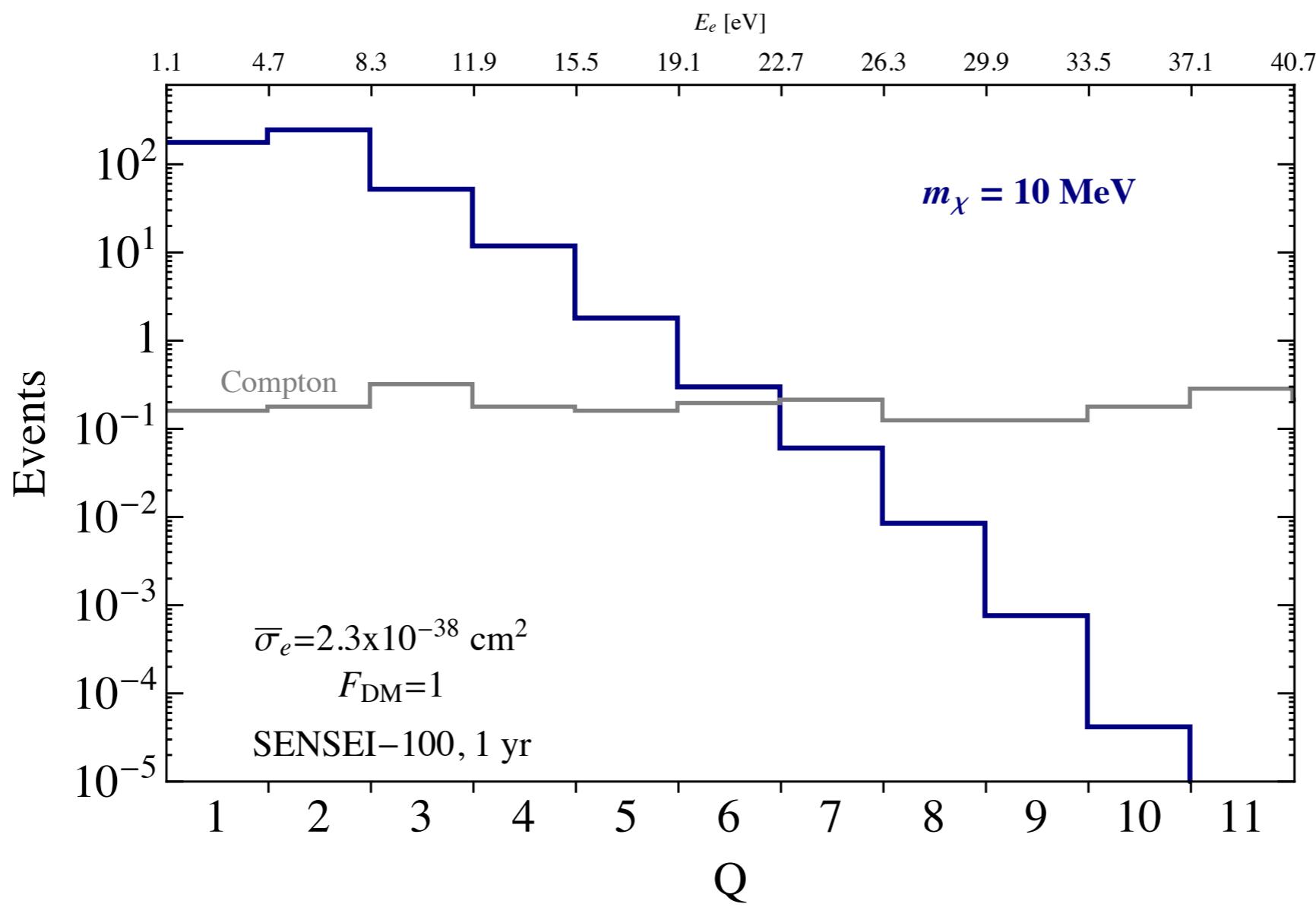
SENSEI: backgrounds

- Readout noise: irrelevant
- Solar neutrinos: irrelevant RE, Sholapurkar, Yu
- Radiogenic backgrounds: <1 event



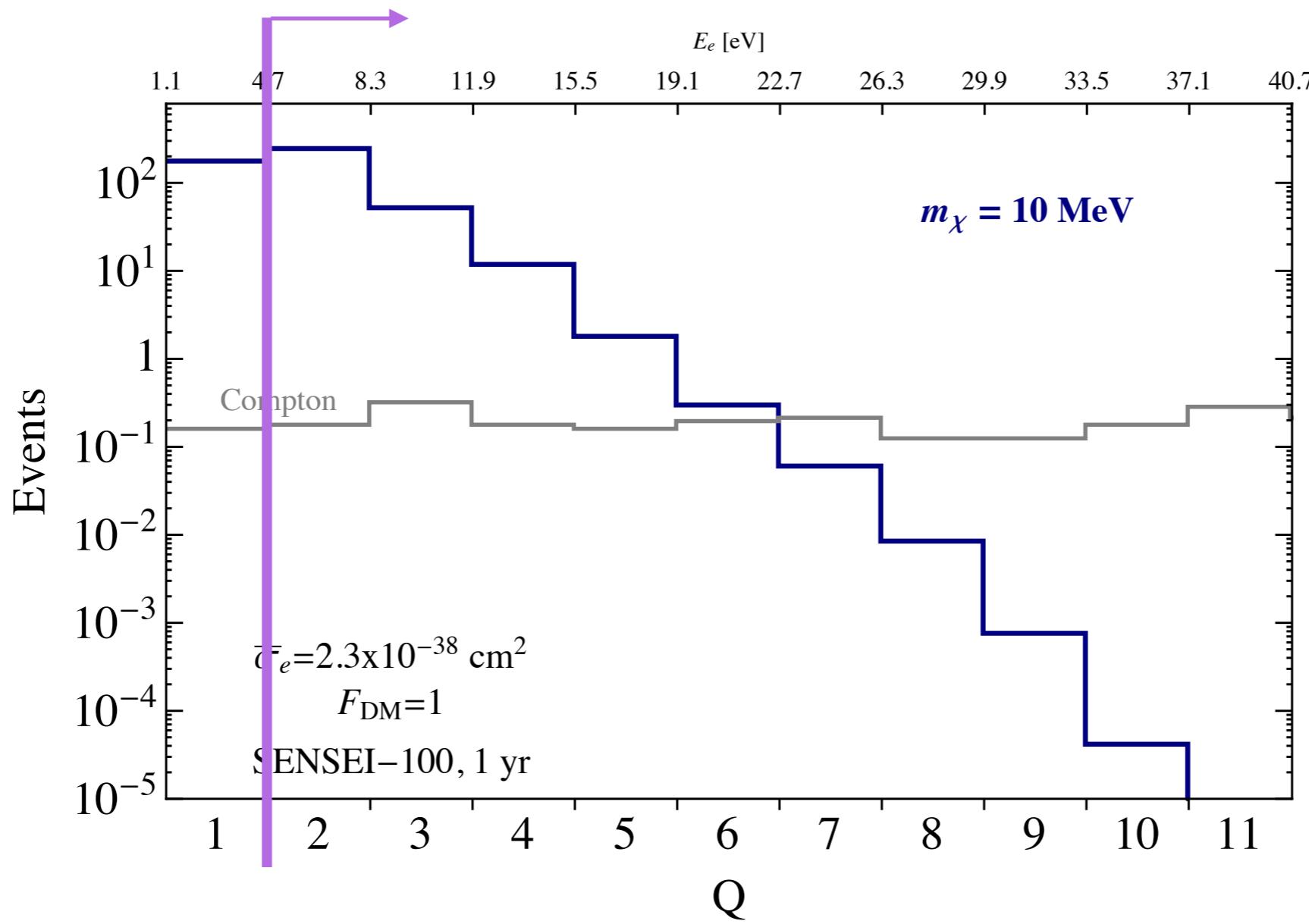
SENSEI: backgrounds

- Readout noise: irrelevant
- Solar neutrinos: irrelevant RE, Sholapurkar, Yu
- Radiogenic backgrounds: <1 event
- *Dark current (thermal fluctuations): limits discovery threshold to 2e⁻ ?*

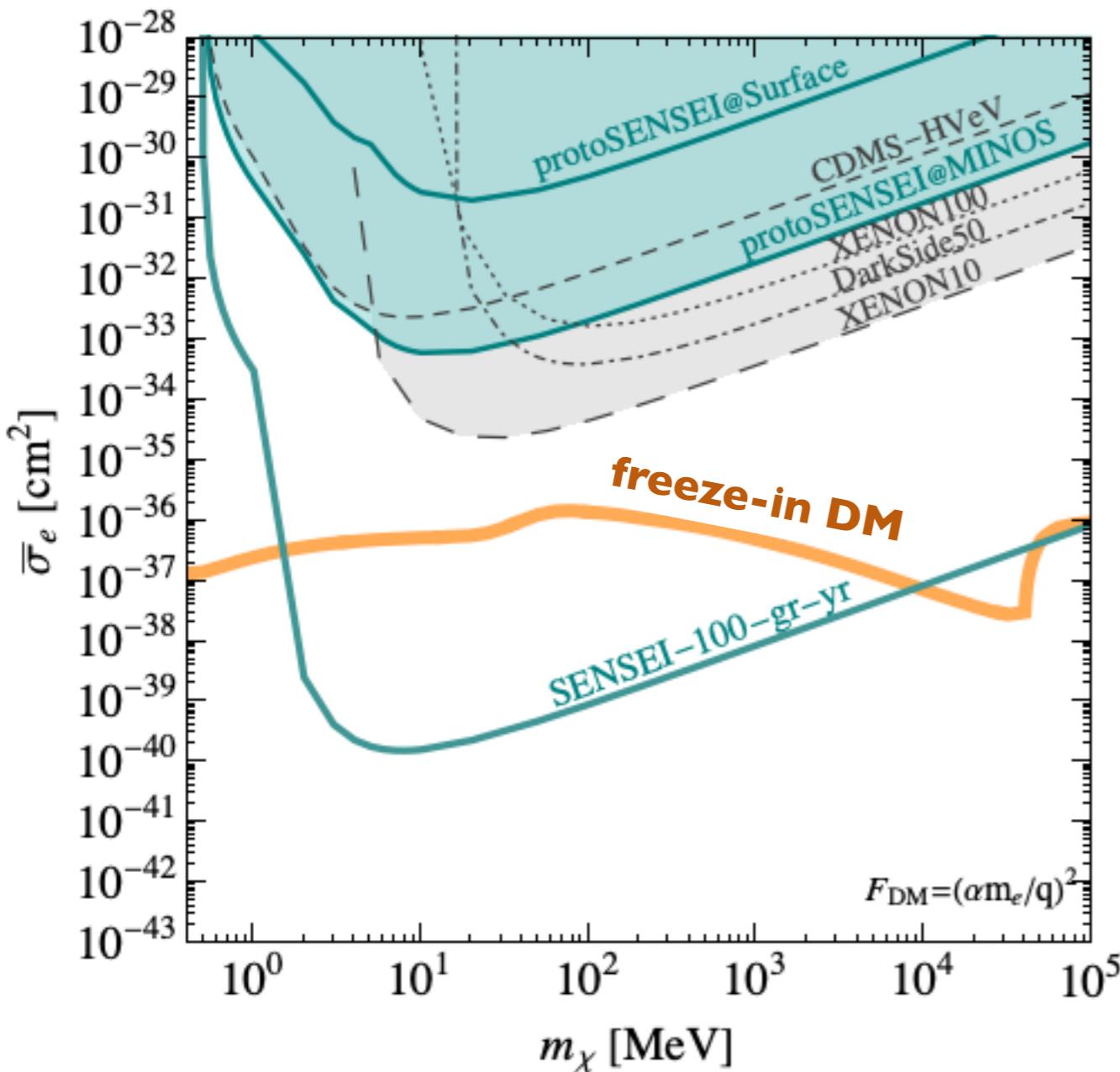


SENSEI: backgrounds

- Readout noise: irrelevant
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- Radiogenic backgrounds: <1 event
- *Dark current (thermal fluctuations): limits discovery threshold to 2e⁻ ?*

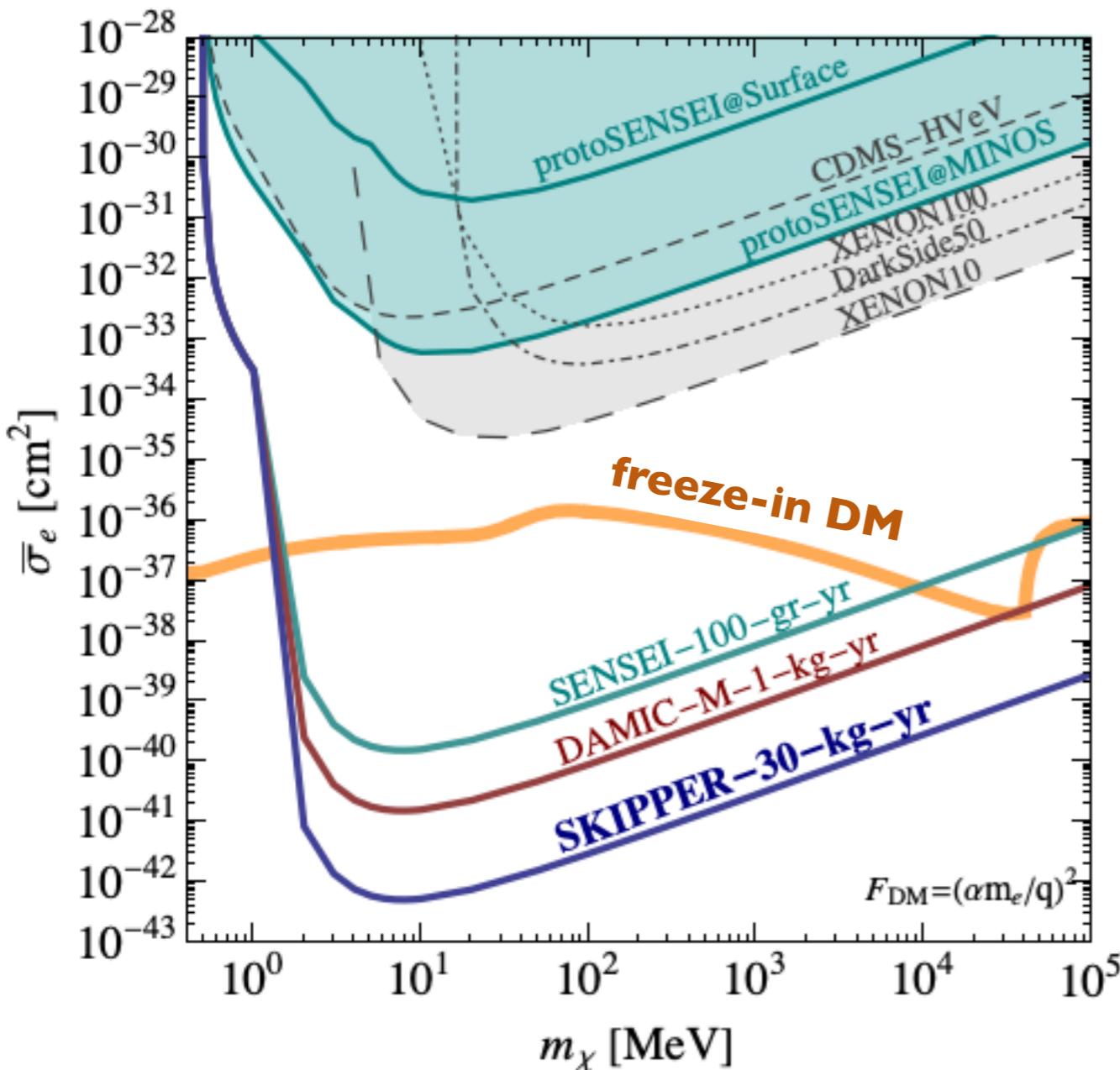


SENSEI + other planned Skipper-CCD detectors



SENSEI: 100 g @ SNOLAB
(funded, 2020)

SENSEI + other planned Skipper-CCD detectors



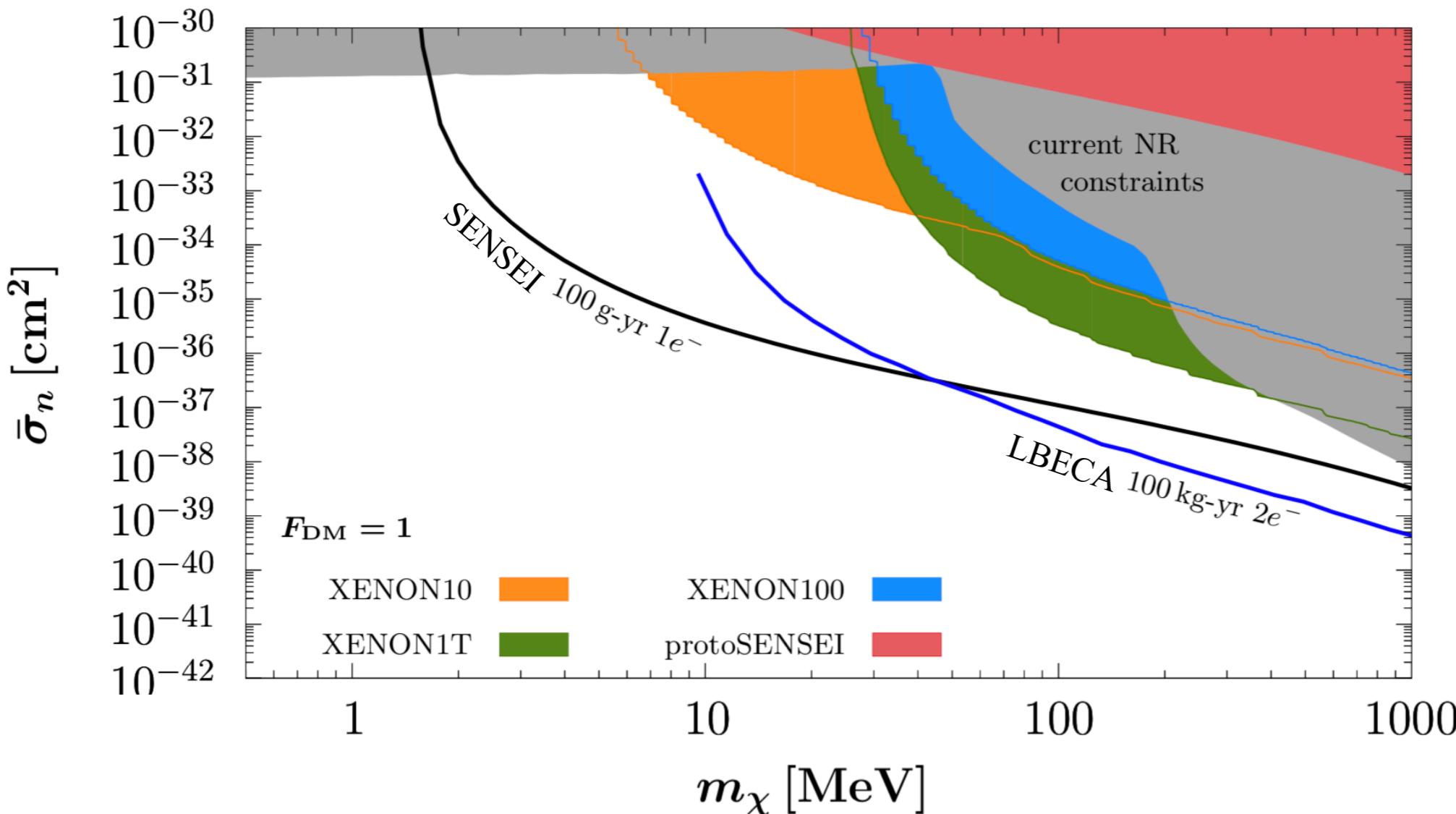
SENSEI: 100 g @ SNOLAB
(funded, 2020)

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

10 kg Skipper-CCD
(will receive R&D funding from US 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



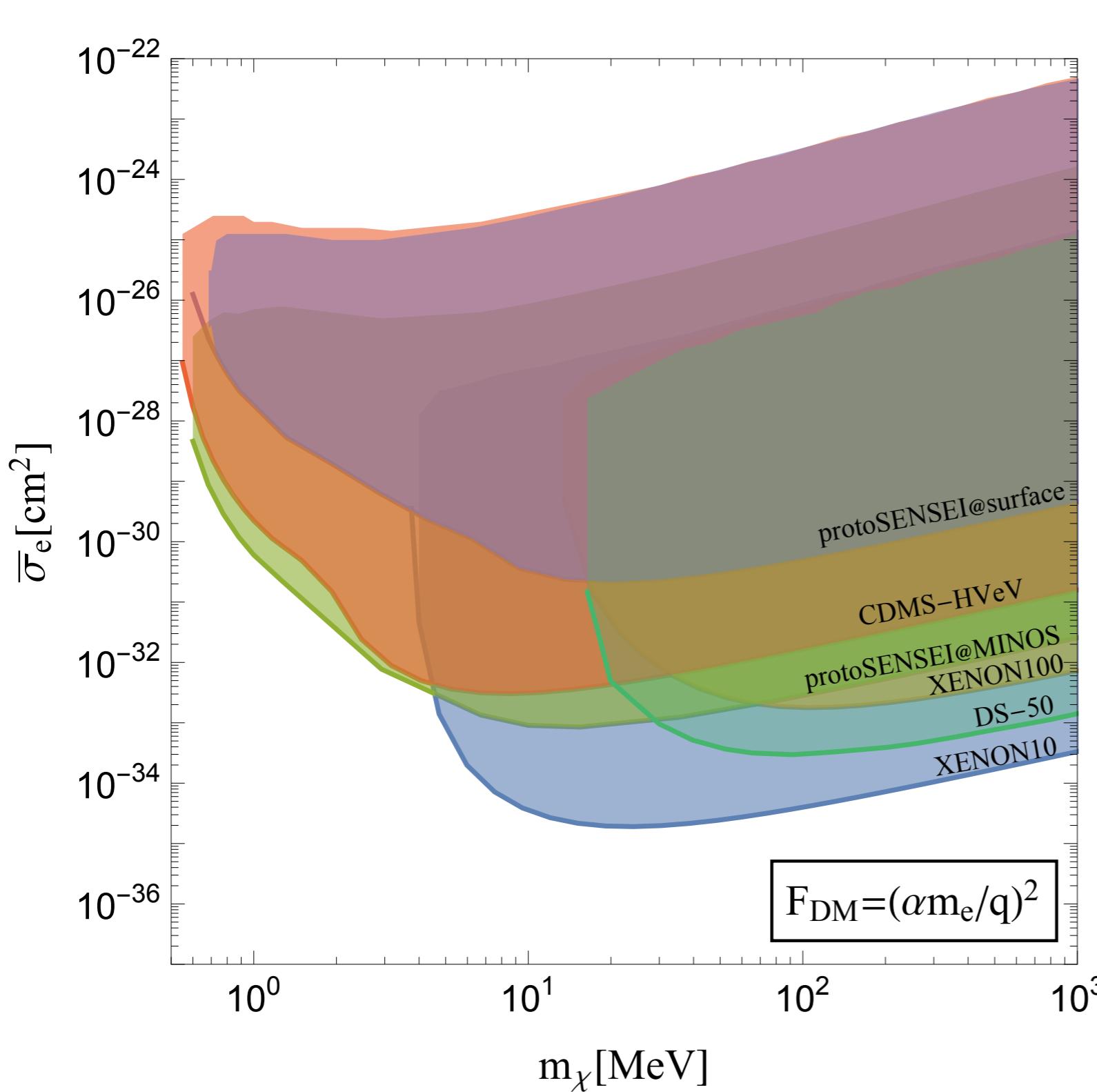
XENON10 sets
best limit between
5 to 30 MeV

First attempt at a
projection for Migdal
effect in silicon
taking into account
band structure

Outline

- LBECA (liquid xenon)
- SENSEI (silicon Skipper-CCDs)
- Satellite/balloon-borne Skipper-CCD

Current bounds on DM w/ large interactions



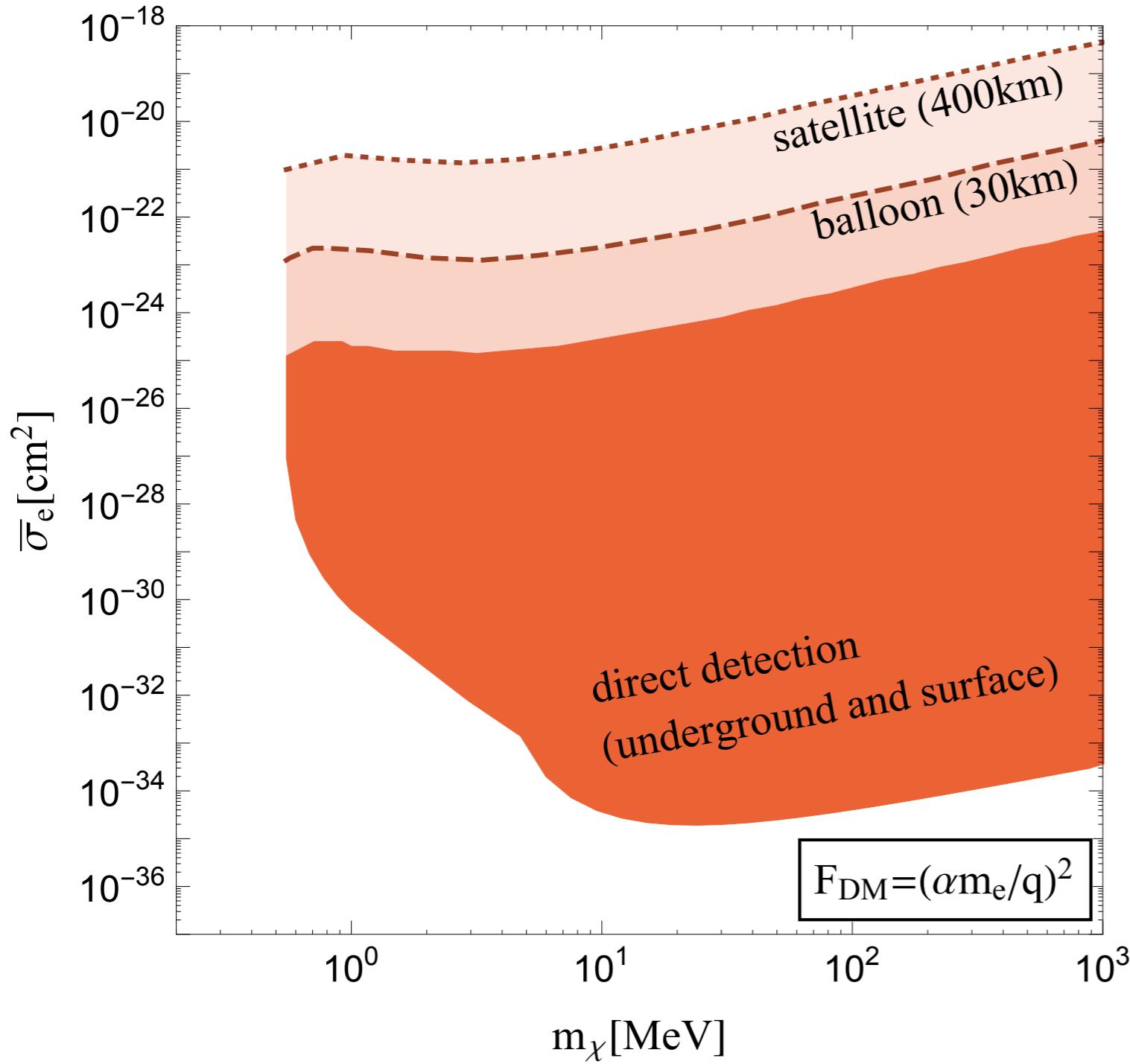
Emken, RE, Kouvaris, Sholapurkar

assumes dark photon mediator

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

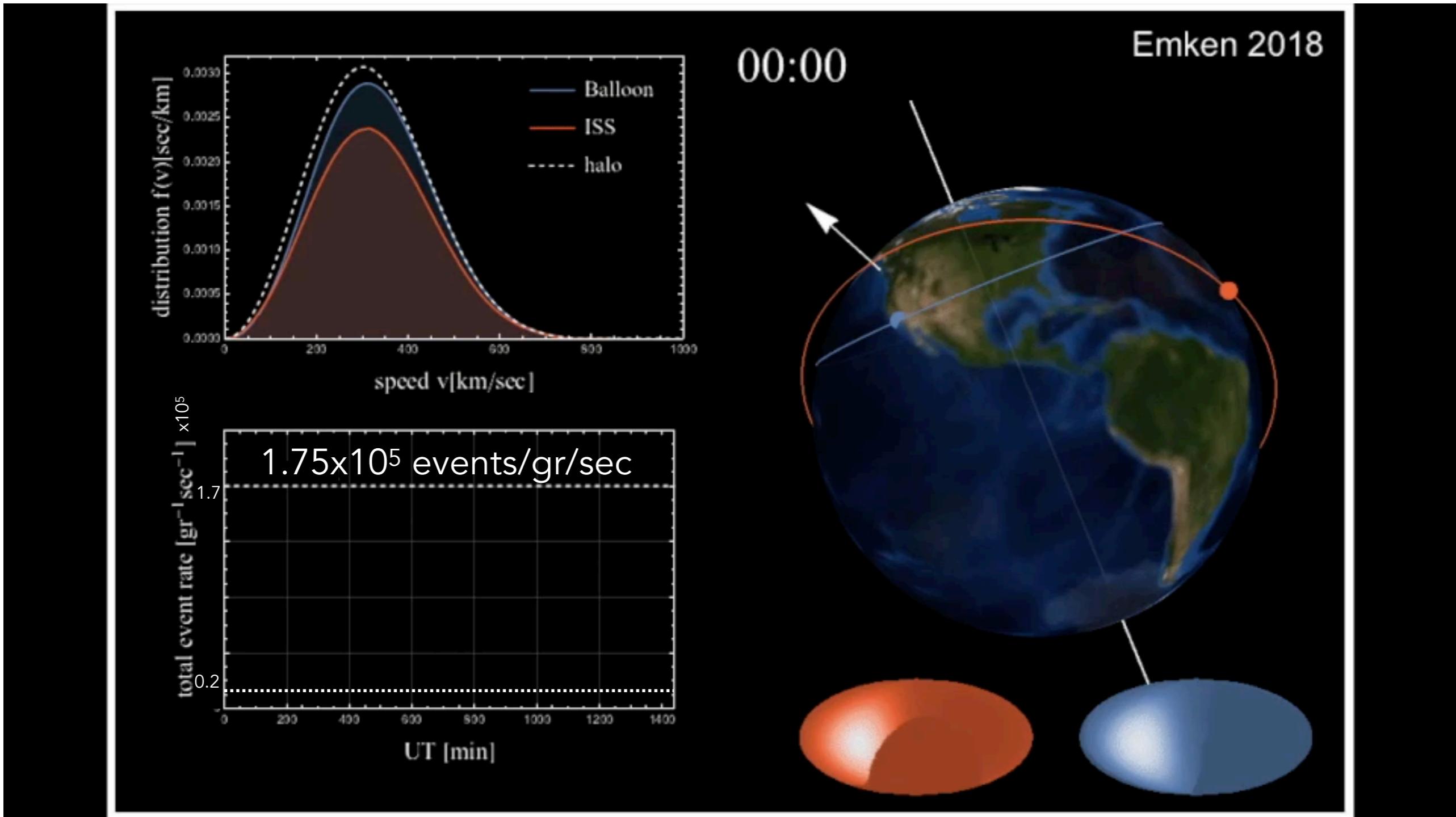
A Skipper-CCD on a satellite or balloon can probe DM with even larger interactions

Emken, RE, Kouvaris, Sholapurkar



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

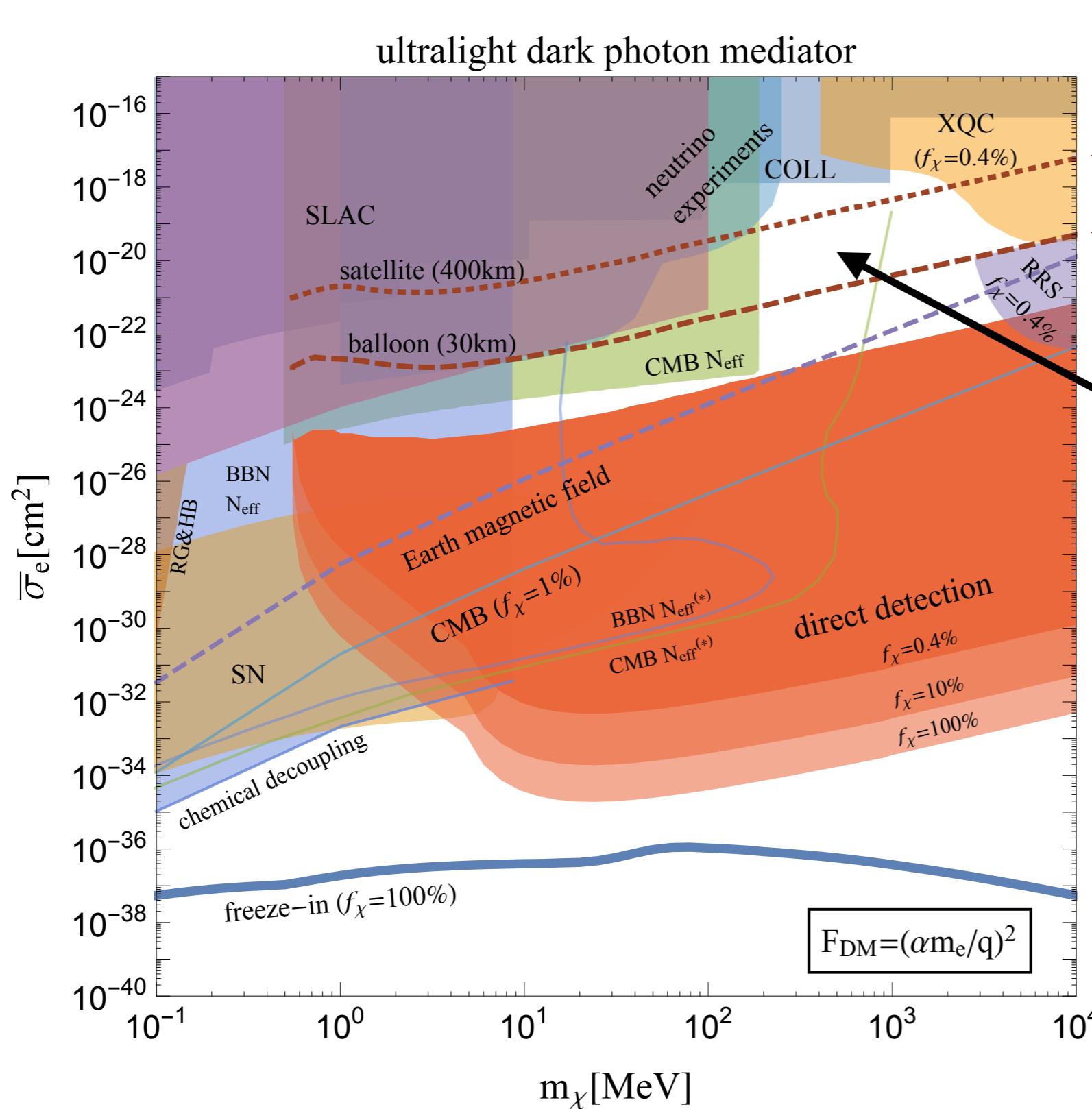
Expect Large Modulation of Signal Rate



A striking signal!

(there are caveats...)

Is there a DM model w/ such large interactions?



Emken, RE, Kouvaris, Sholapurkar

satellite
balloon

Maybe...
a subdominant
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

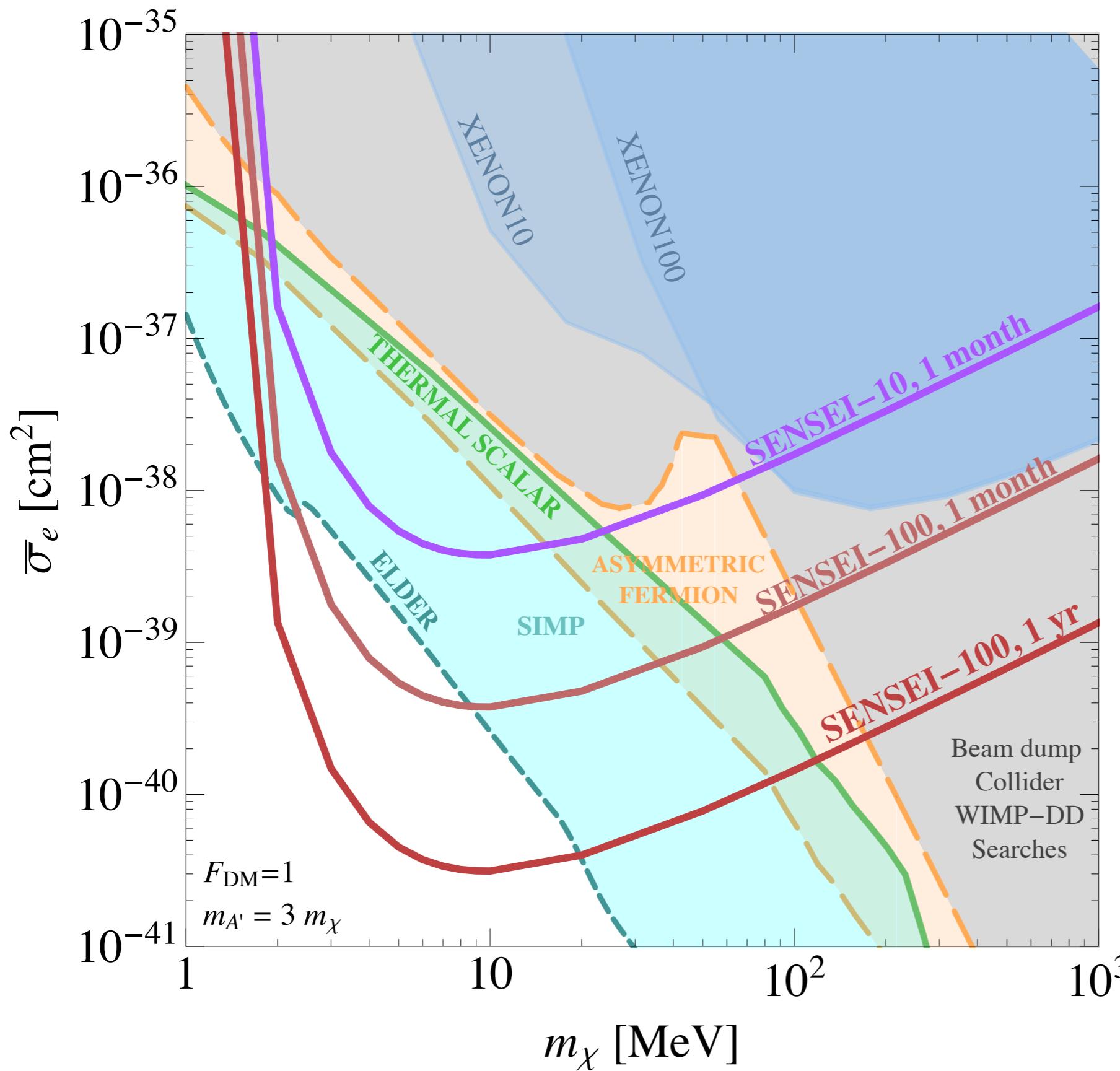
Liu, Outmezguine, Redigolo, Volansky

Summary

- Sub-GeV DM is an active area of research with various competing & complementary concepts & proposals
- A molecular gas target could probe spin-(in)dependent nuclear interactions down to ~ 200 keV
- LBECA (~ 100 kg liquid-xenon) aims to probe DM > 5 MeV, reducing backgrounds that have plagued other noble-liquid detectors
- SENSEI (~ 100 g Skipper-CCDs, funded) has first results and will probe > 500 keV in next $\sim 1\text{--}2$ years; larger detectors have funding
- A Skipper-CCD on a balloon/satellite could probe a possibly unconstrained region for strongly interacting (subdominant) DM

Thank you!

SENSEI sensitivity to Benchmark Models



mediator: “heavy”
dark photon

Models:

- thermal scalar
- asymmetric fermion
- SIMP
- ELDER