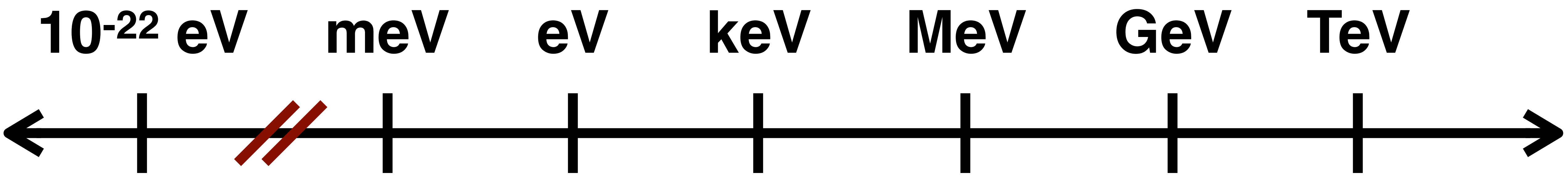
sub-GeV Dark Matter Direct Detection

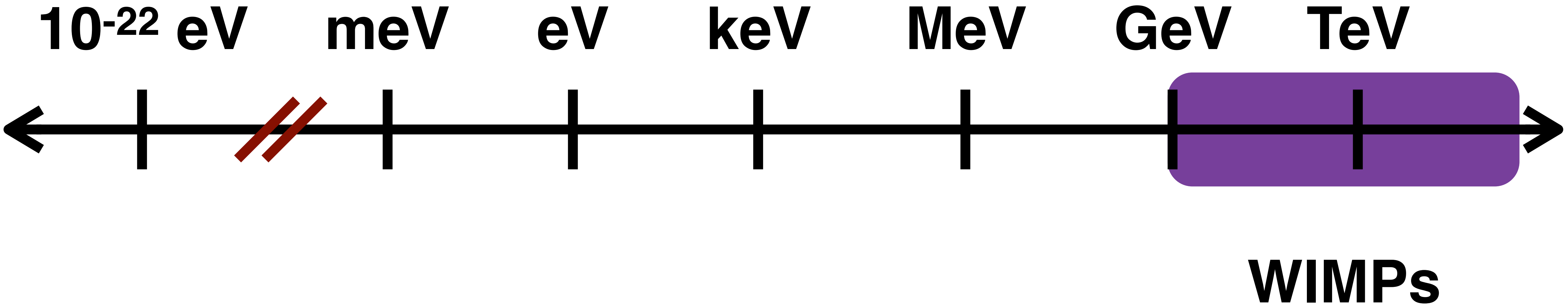
Tien-Tien Yu
(University of Oregon)

Light Dark World 2020 — December (13) 14, 2020

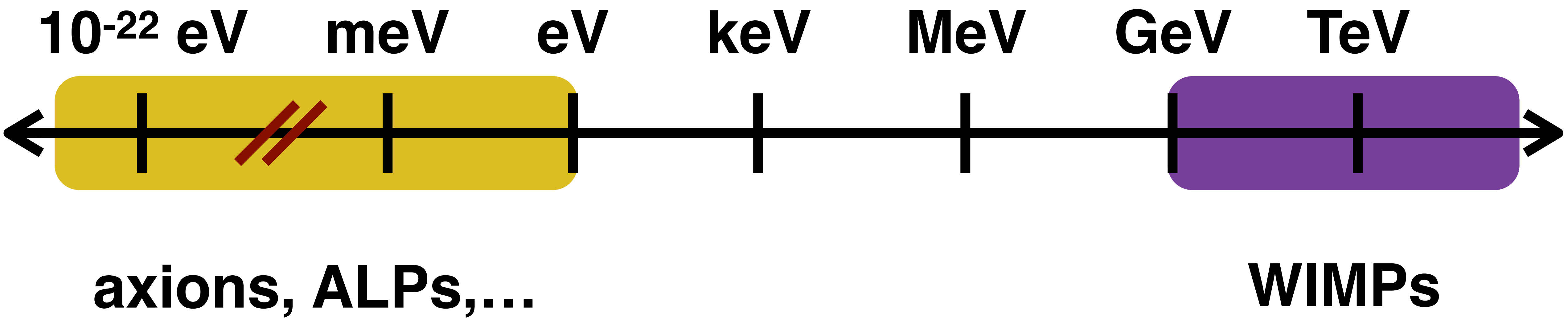
dark matter candidates



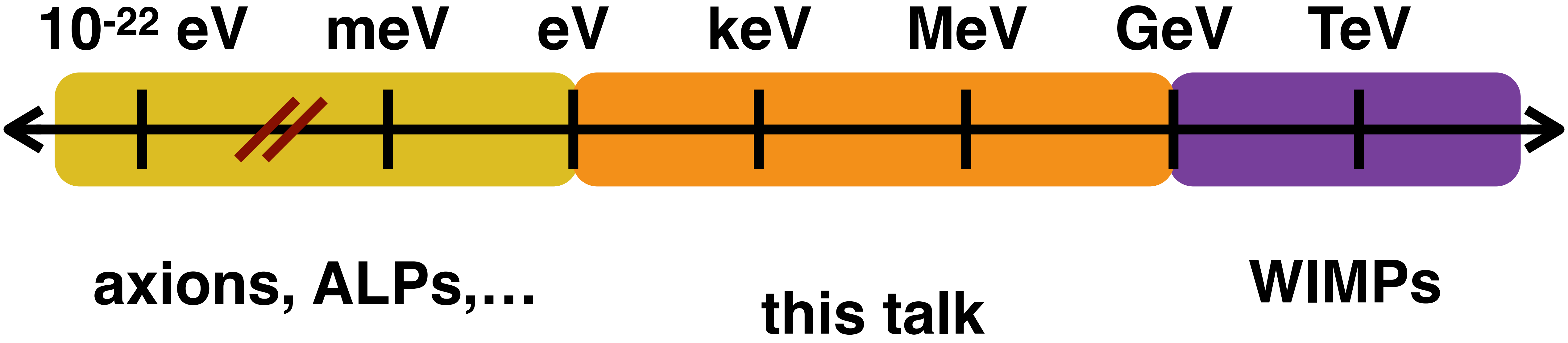
dark matter candidates



dark matter candidates

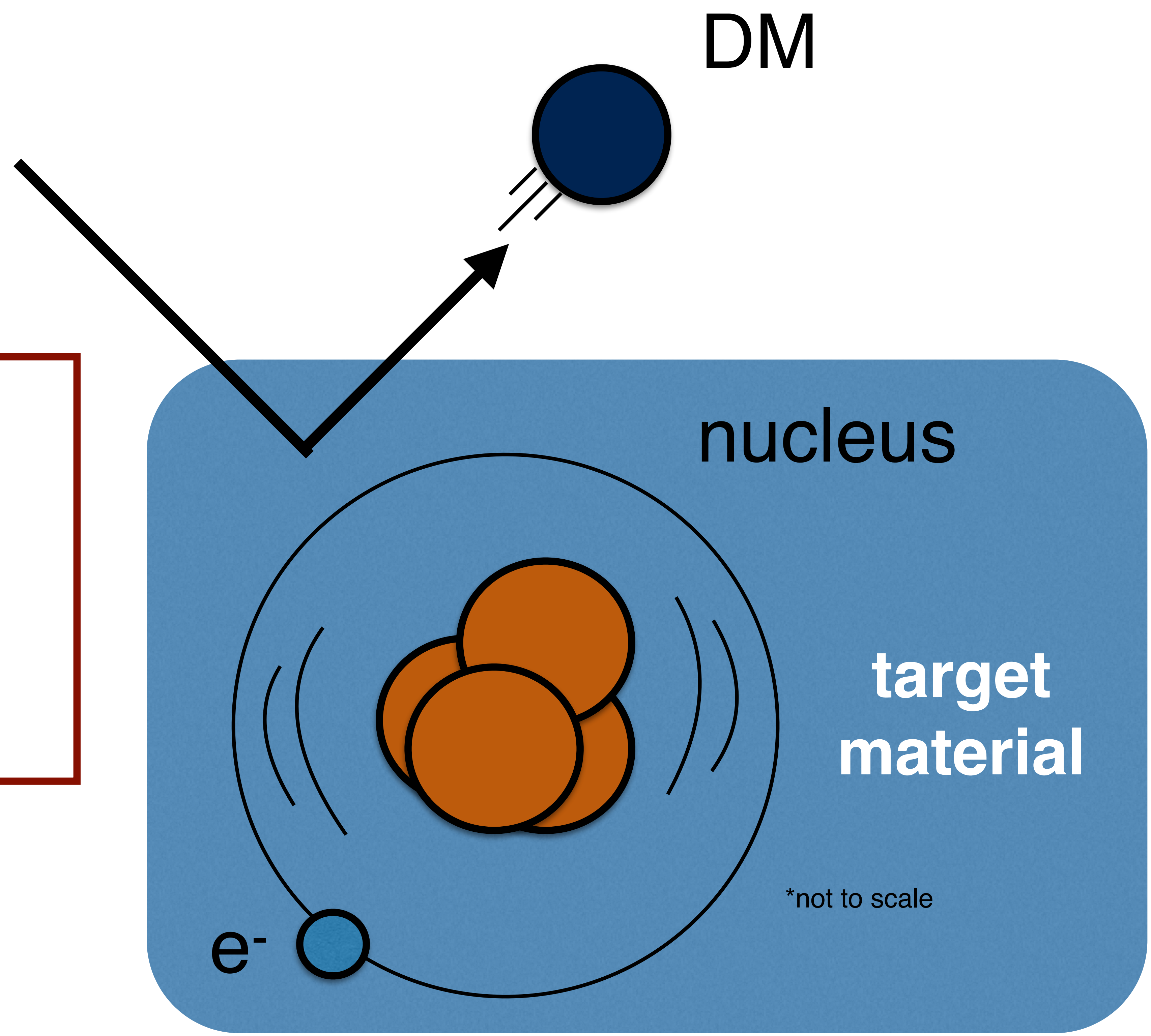


dark matter candidates

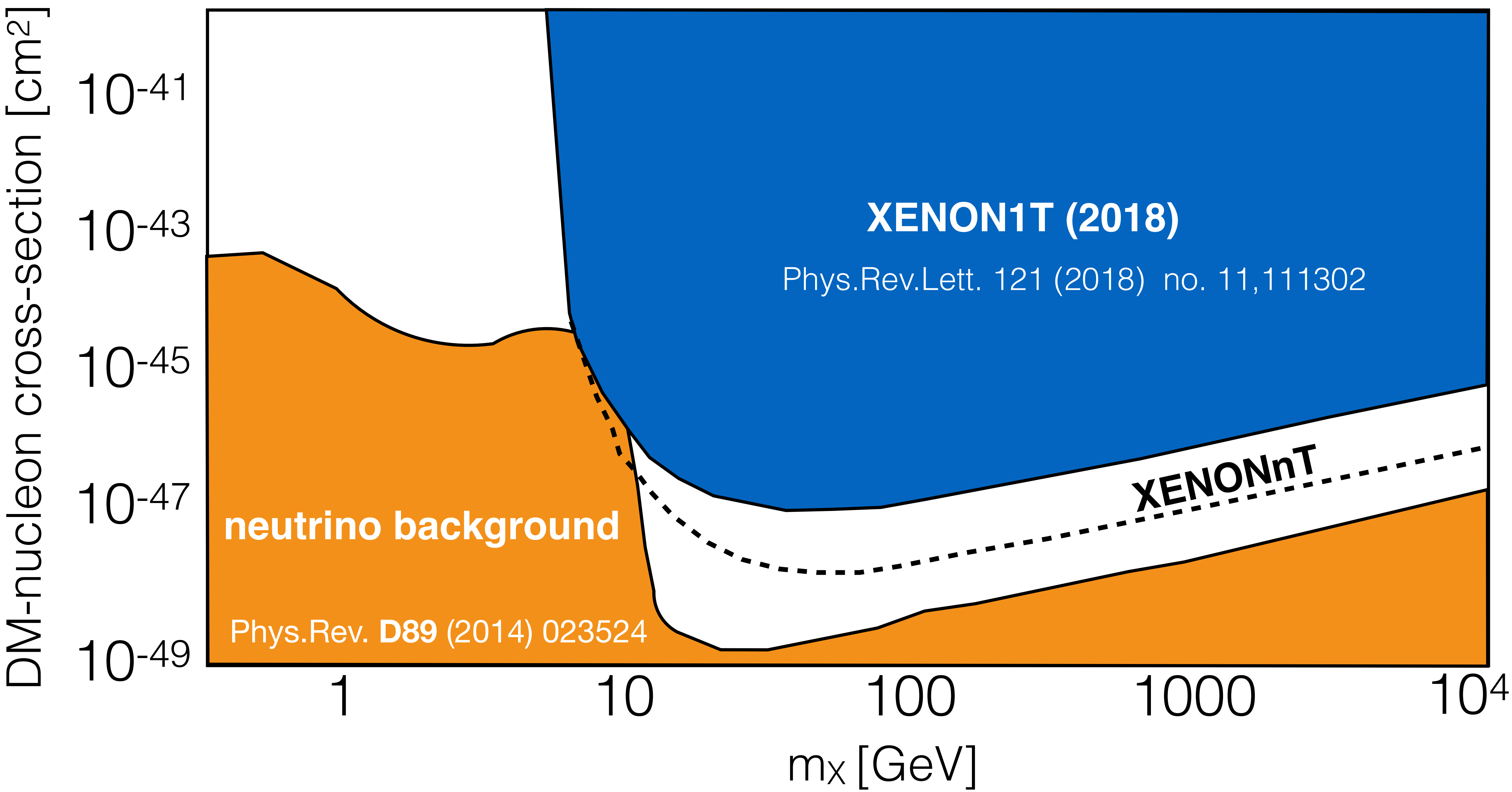


DM direct detection

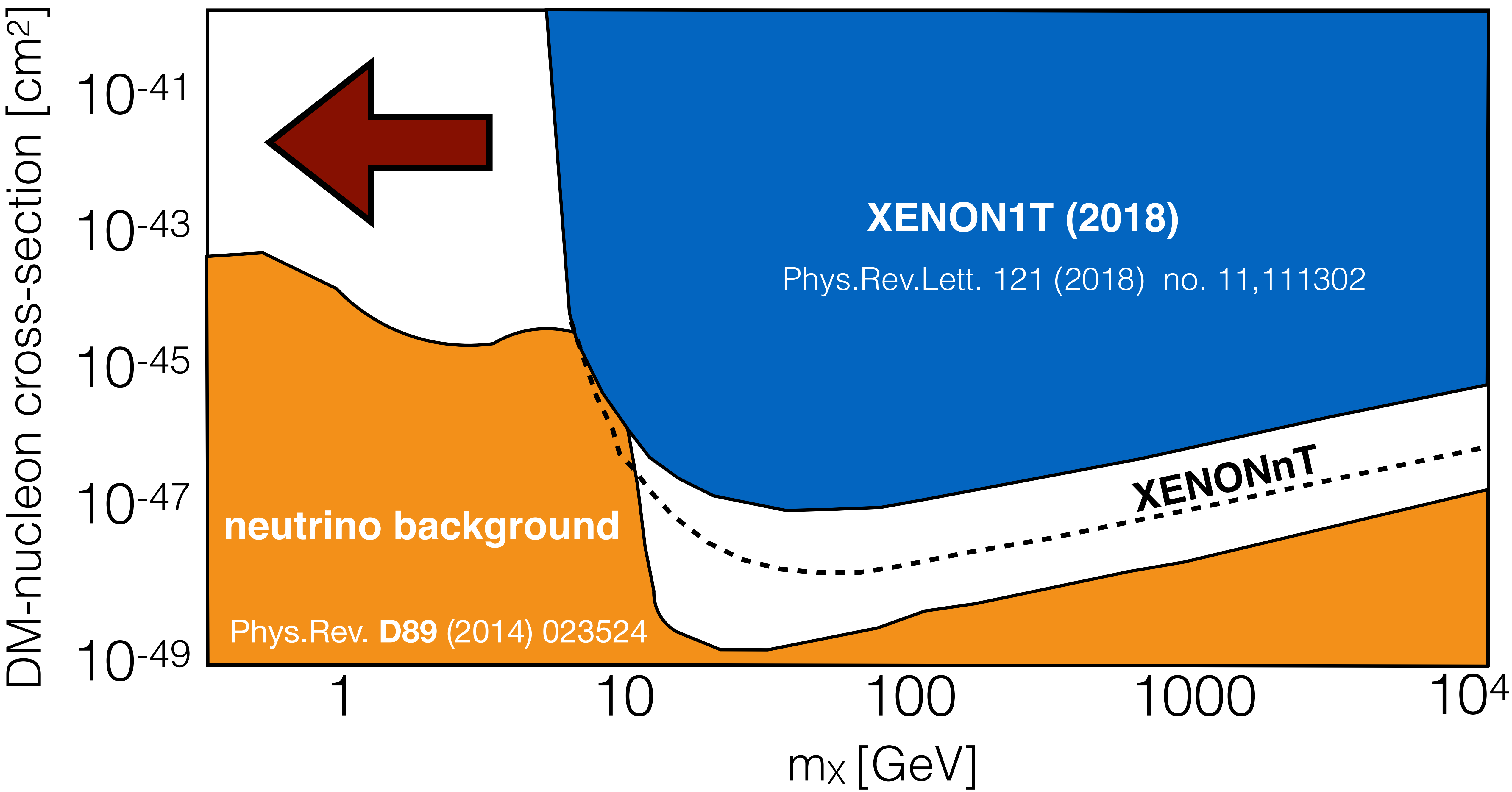
signal:
phonons,
scintillation
photons,
ionization
electrons



direct detection



direct detection



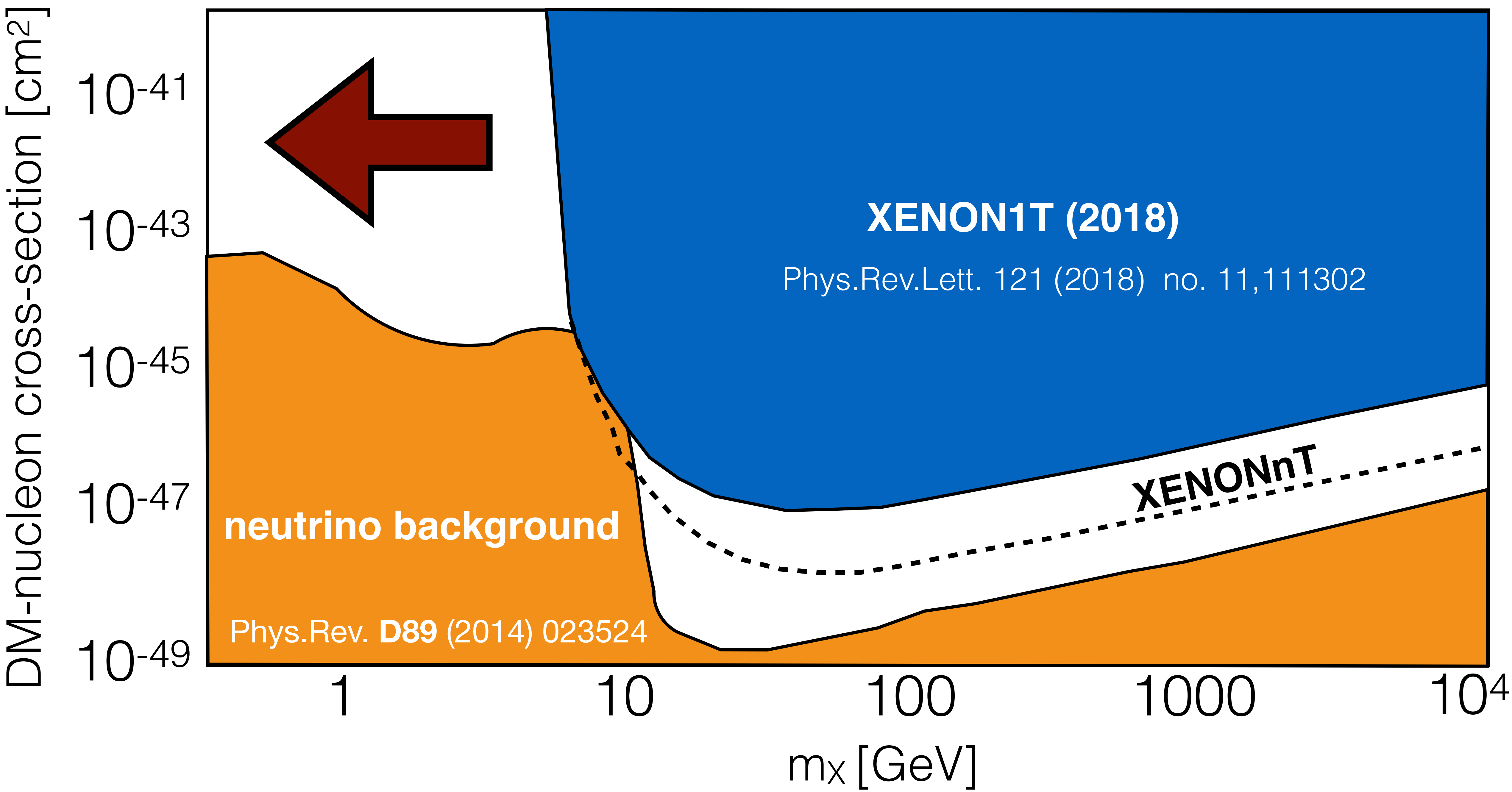
sub-GeV DM direct detection

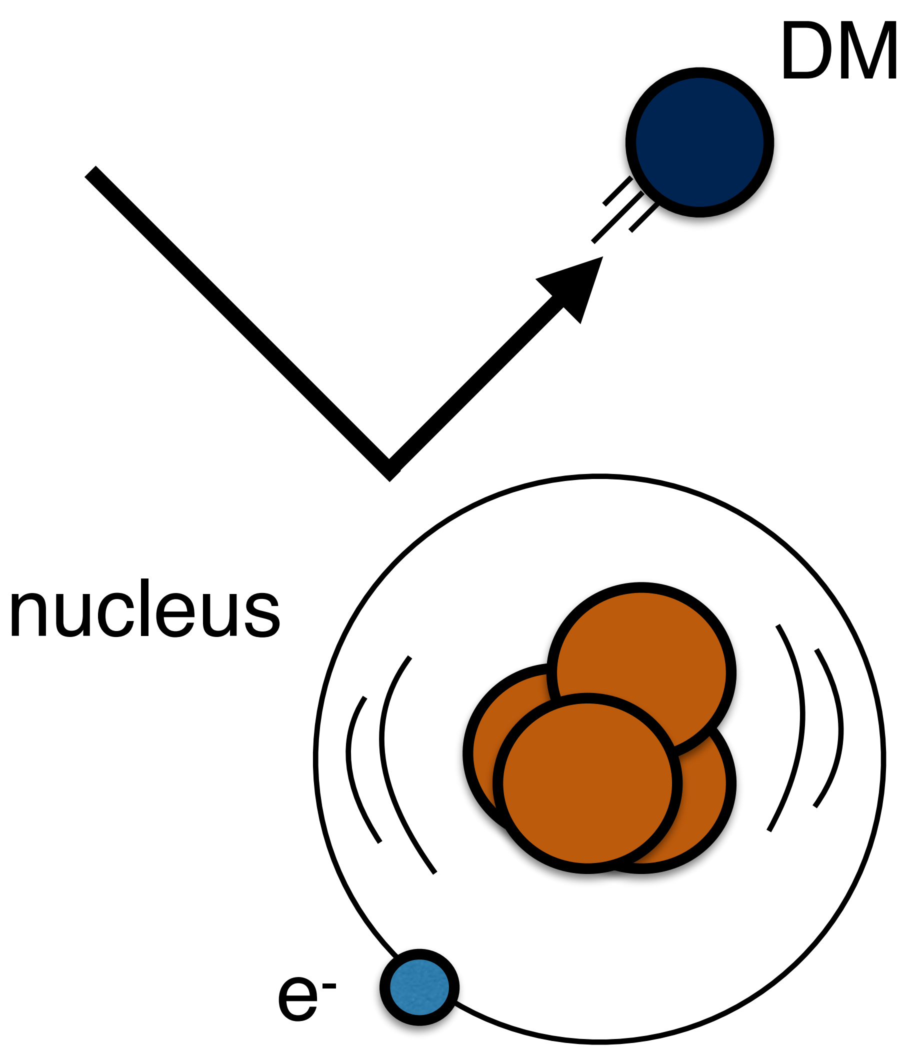
- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
- **Dark matter-nuclear scattering** through the Migdal scattering and bremsstrahlung
- **Absorption** of light dark matter, including axion-like particles and dark photons.
- **Dark matter scattering off collective modes** in molecules and in crystals (including phonons, plasmons and magnons)

sub-GeV DM direct detection

- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
- **Dark matter-nuclear scattering** through the Migdal scattering and bremsstrahlung
- **Absorption** of light dark matter, including axion-like particles and dark photons.
- **Dark matter scattering off collective modes** in molecules and in crystals (including phonons, plasmons and magnons)

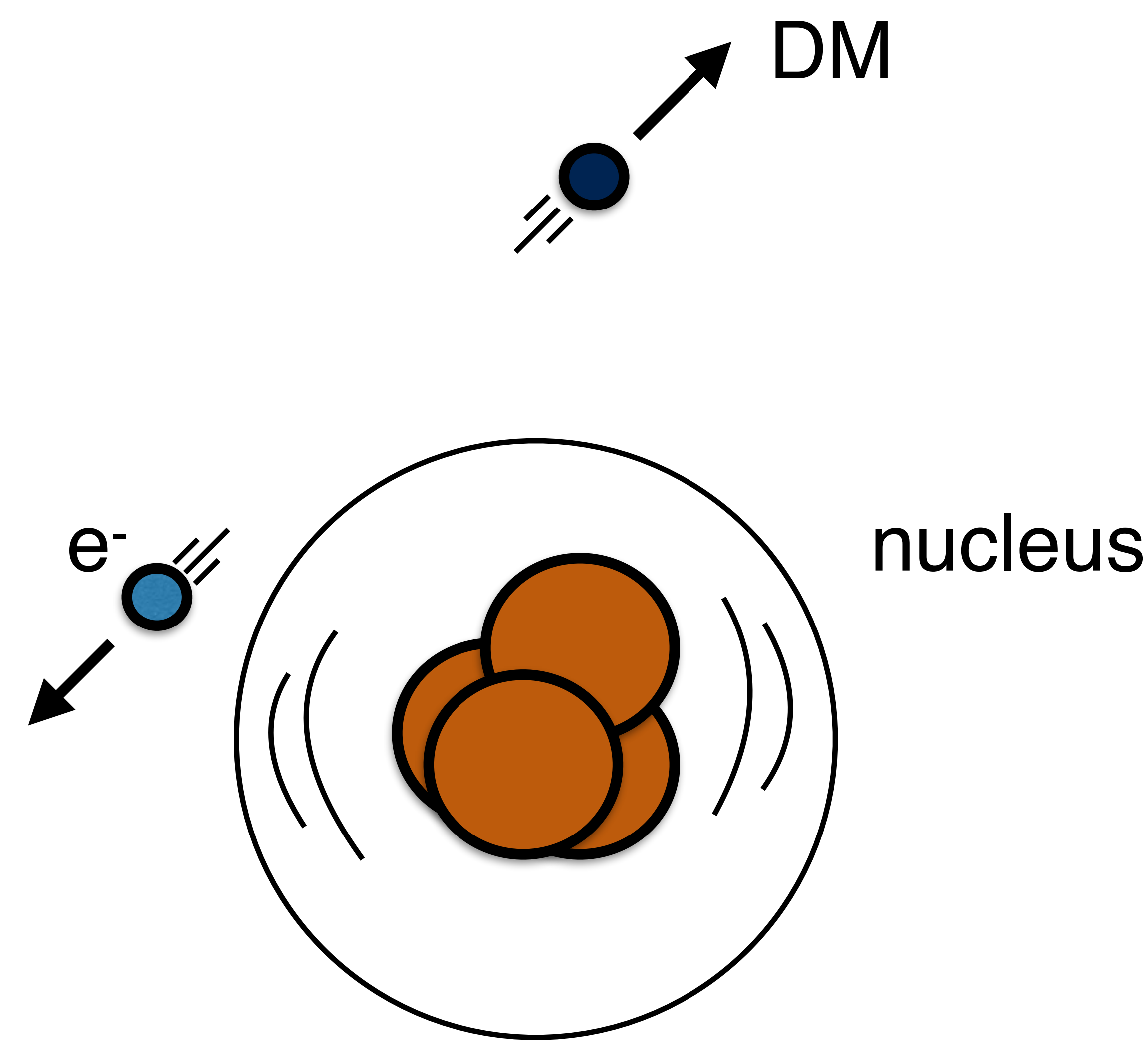
direct detection





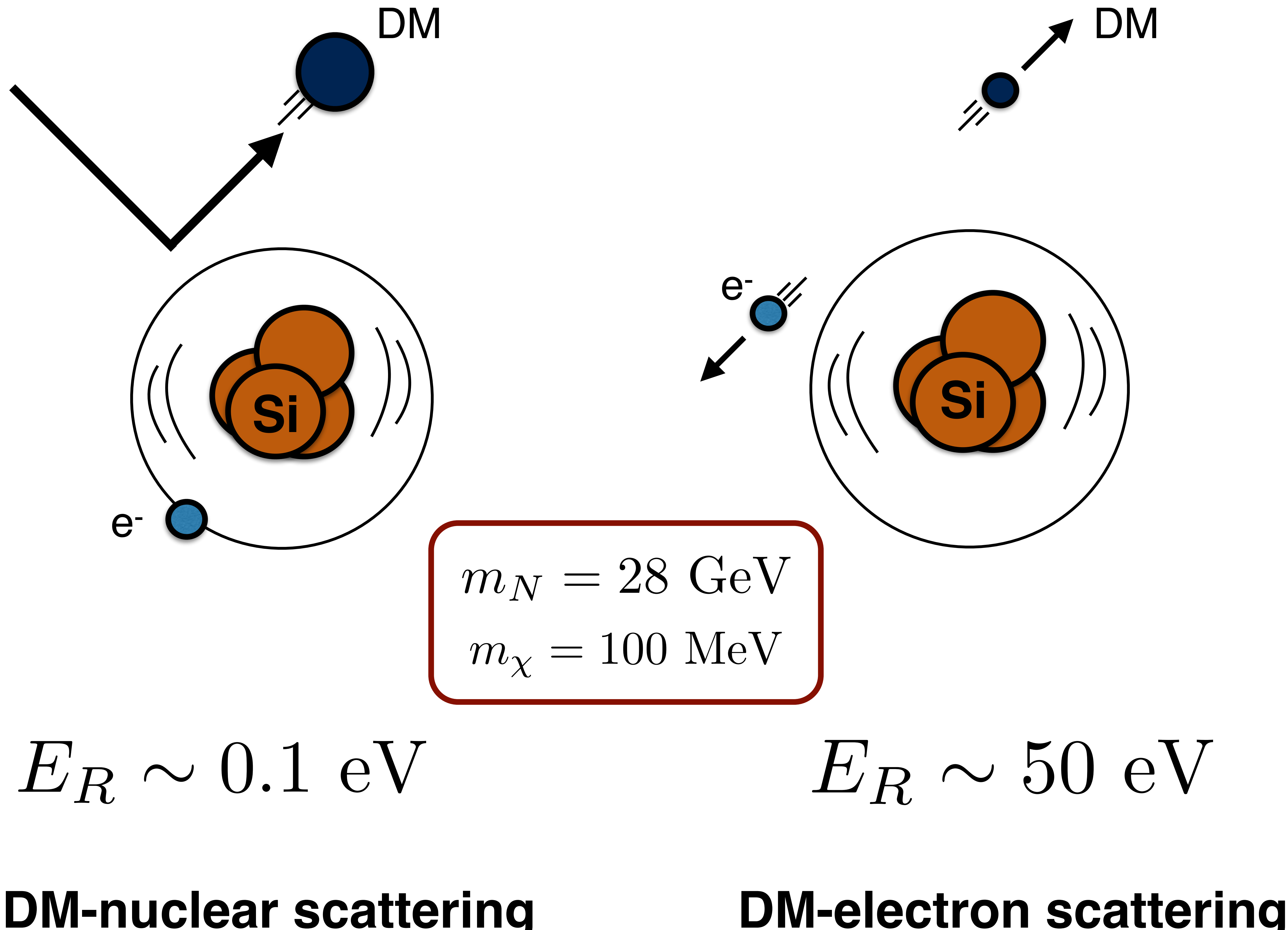
$$E_R = \frac{q^2}{2m_N}$$
$$\simeq 50 \text{ keV} \left(\frac{m_\chi}{100 \text{ GeV}}\right)^2 \left(\frac{100 \text{ GeV}}{m_N}\right)$$

DM-nuclear scattering

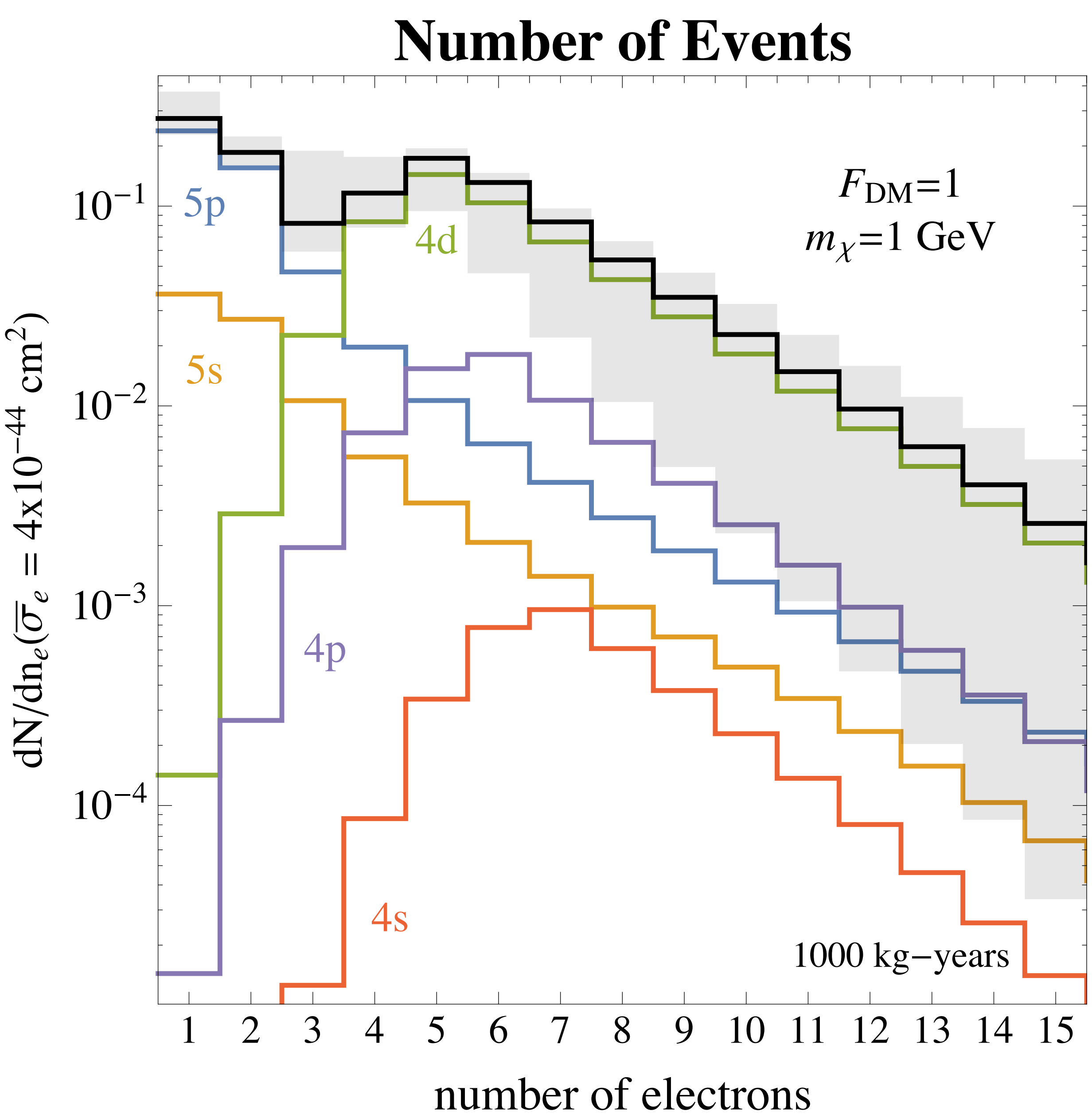


$$E_R = \vec{q} \cdot \vec{v} - \frac{q^2}{2\mu_{\chi N}}$$
$$\sim \frac{1}{2} \text{eV} \times \left(\frac{m_\chi}{\text{MeV}}\right)$$

DM-electron scattering

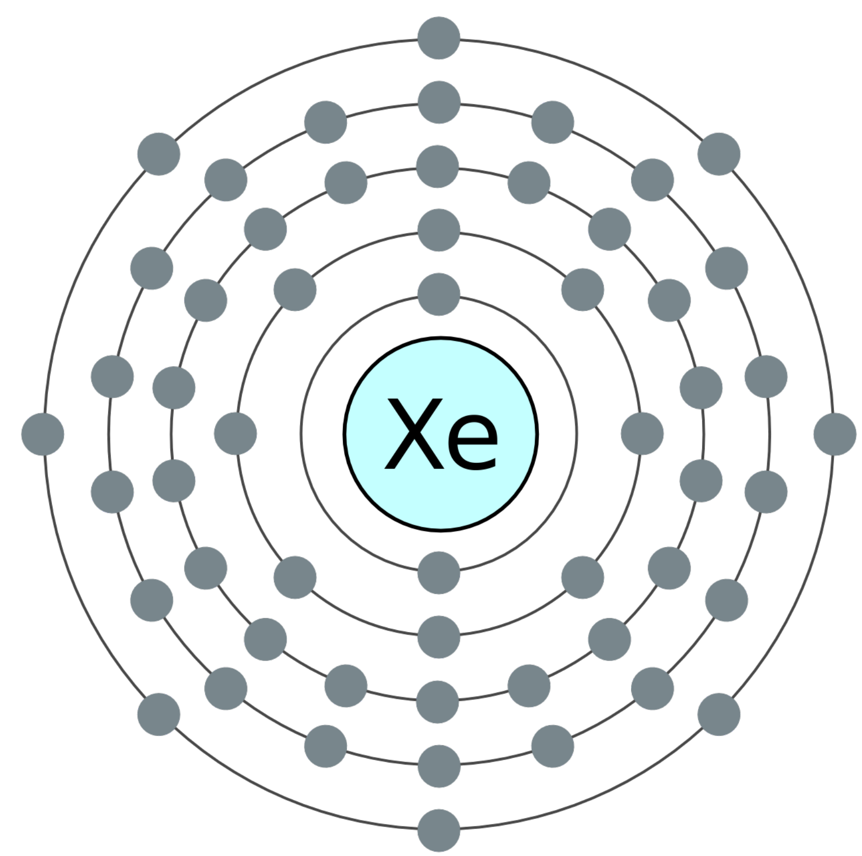

DM
DM
e-
e-
Si
Si
$m_N = 28$ GeV
$m_\chi = 100$ MeV
$E_R \sim 0.1$ eV
$E_R \sim 50$ eV
DM-nuclear scattering
DM-electron scattering

XENON



Essig, Volansky, TTY [1703.00910]

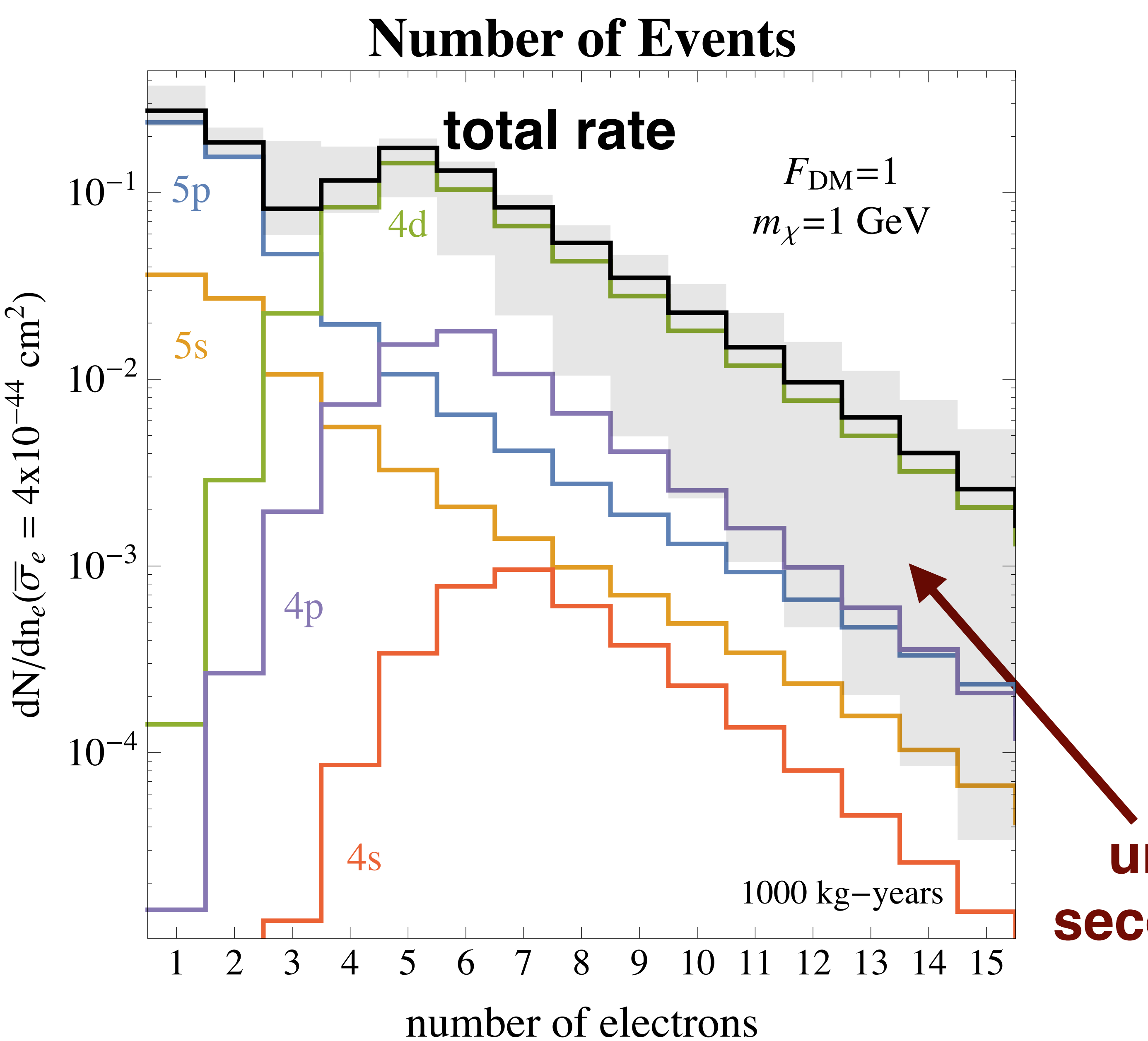
54: Xenon

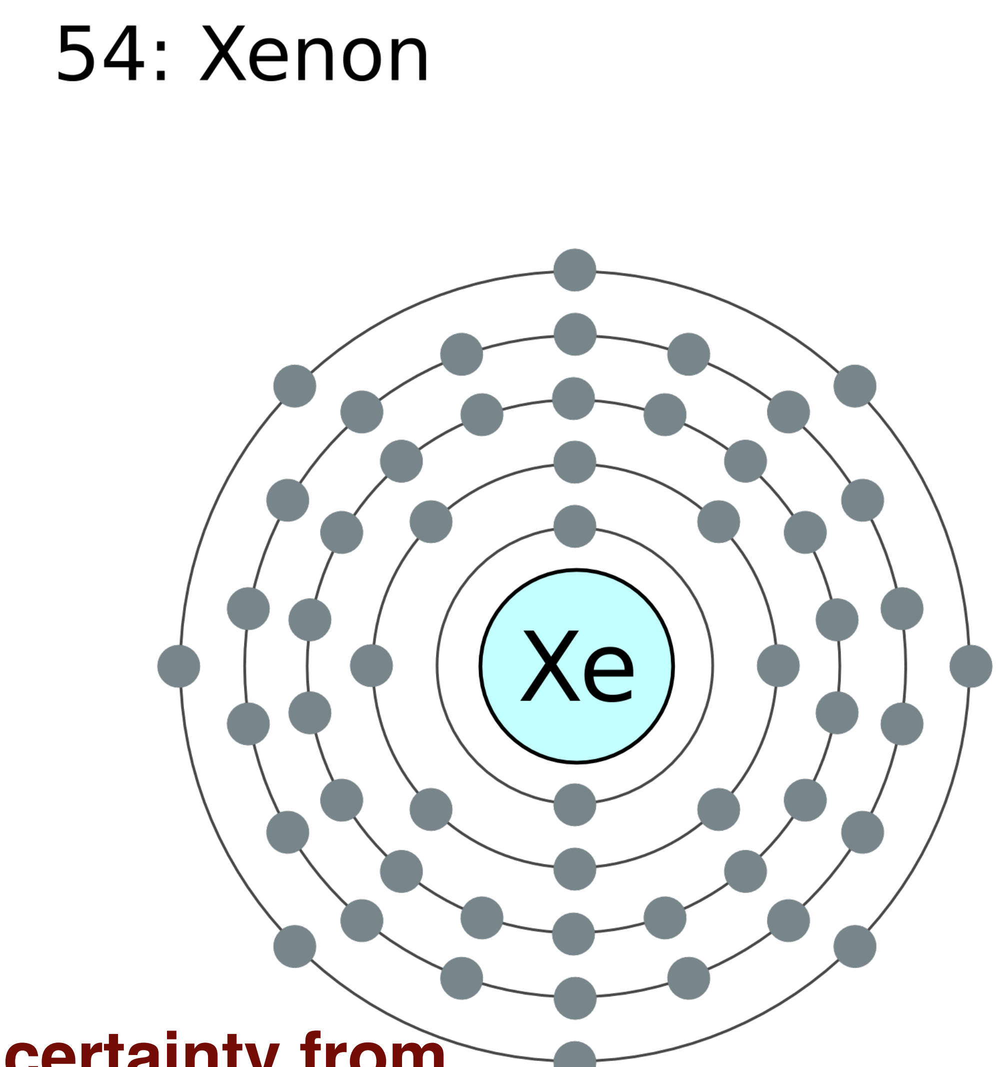


http://commons.wikimedia.org/wiki/Category:Electron_shell_diagrams

Electron configuration:
[Ar] 3d10 4s2 4p6 4d10 5s2 5p6

XENON

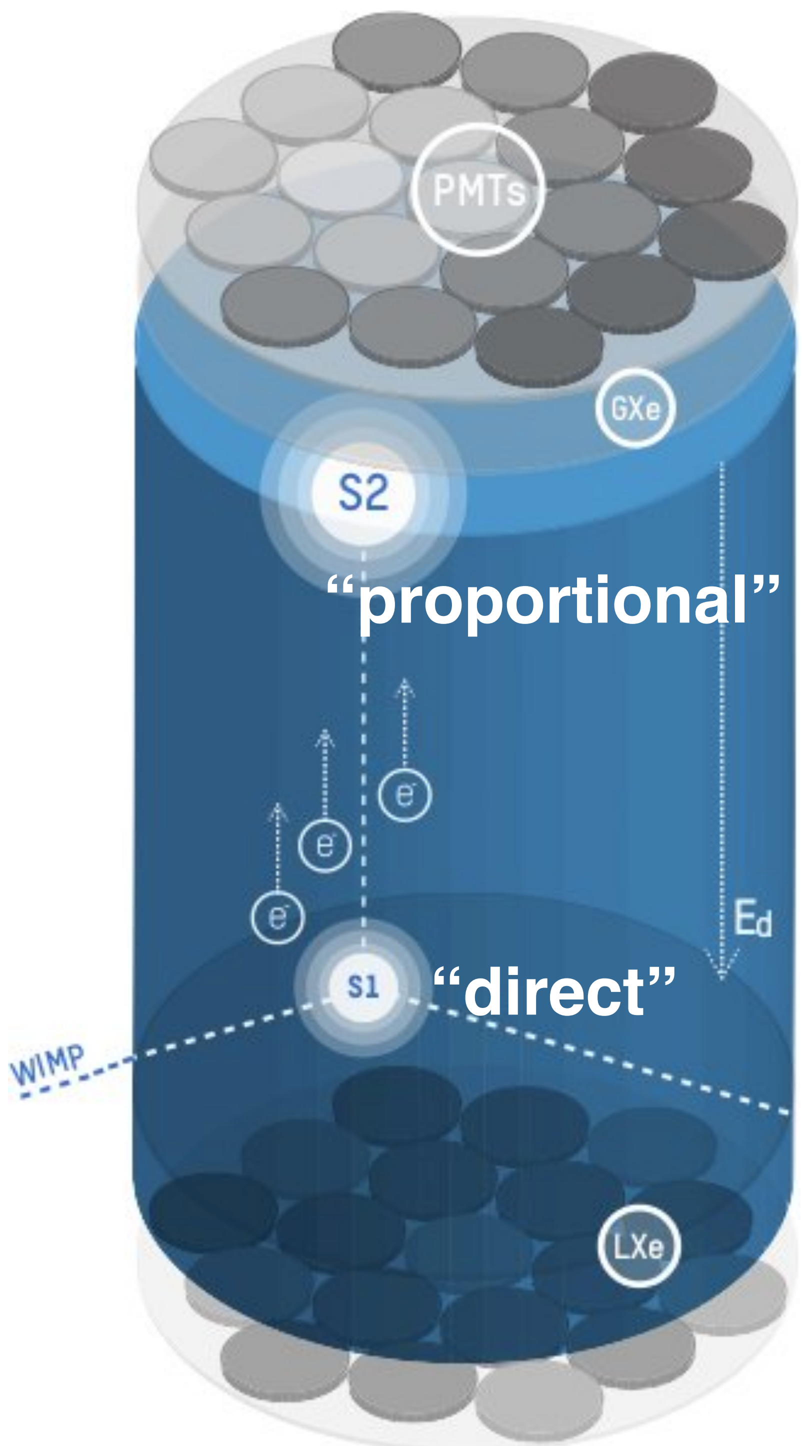




Electron configuration:
[Ar] 3d10 4s2 4p6 4d10 5s2 5p6

Essig, Volansky, TTY [1703.00910]

Liquid Xenon/Argon



https://commons.wikimedia.org/wiki/File:2phaseTPC_b.jpg

i.e. XENON10, XENON100, XENON1T, LUX, DarkSide…

DM-electron scattering

=

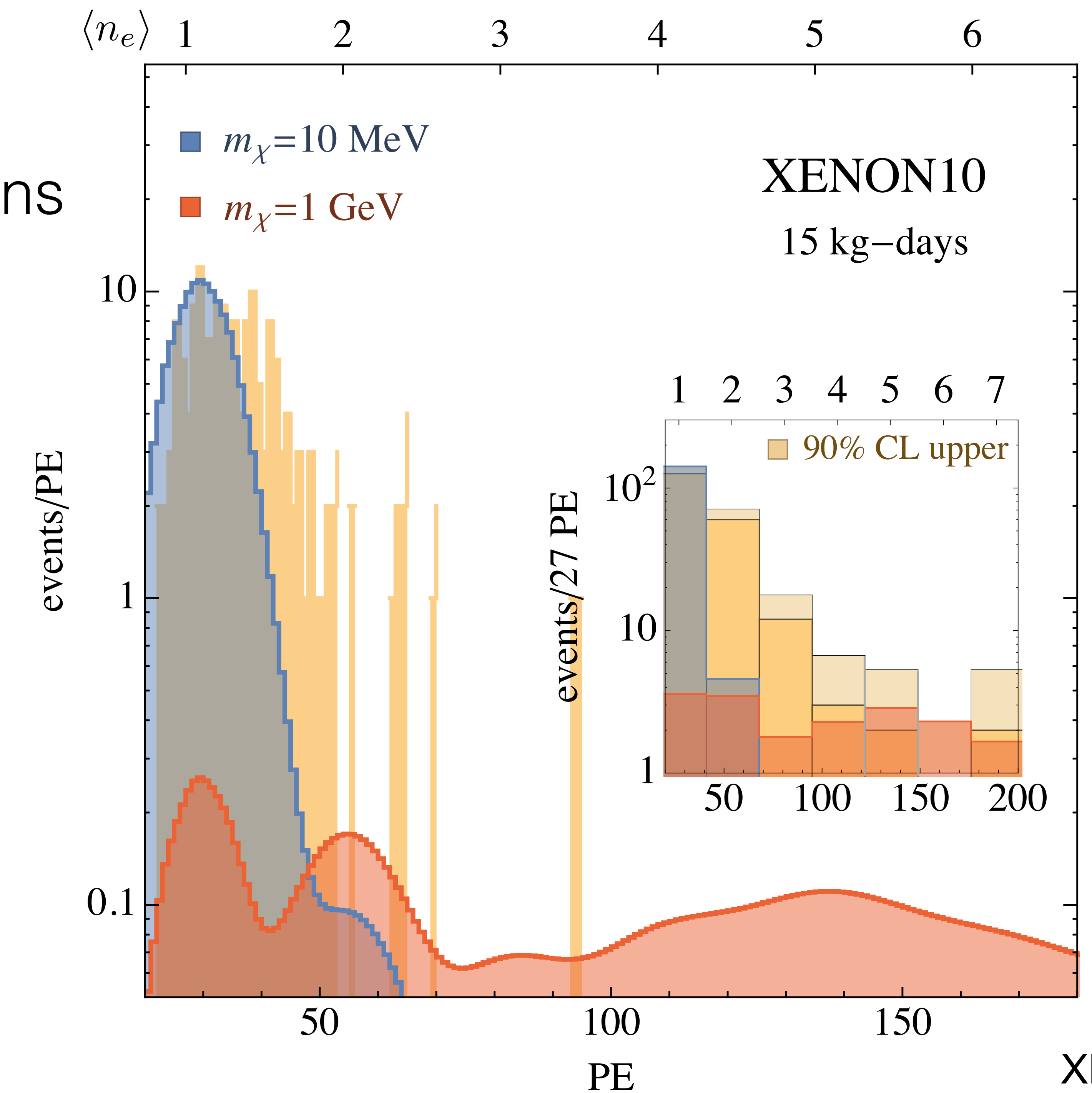
S2 only signal

sensitive to ~10 eV energy depositions

measures **P**hoto**E**lectrons

XENON10

1 electron =
27 **P**hoto**E**lectrons

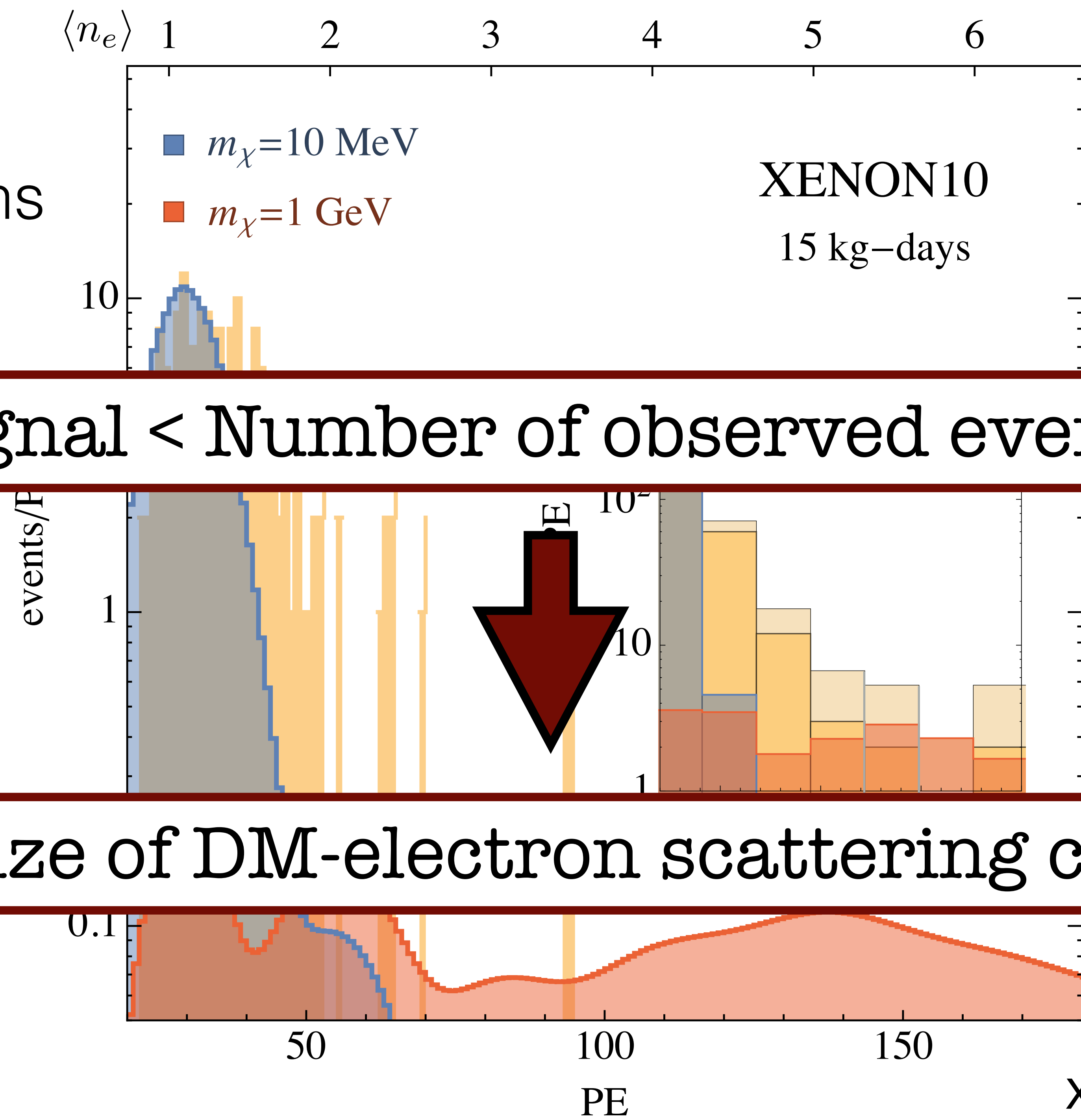


XENON10 Collaboration
Phys.Rev.Lett. **110** (2013) 249901

Essig, Volansky, TTY [1703.00910]

XENON10

1 electron =
27 **P**hoto**E**lectrons



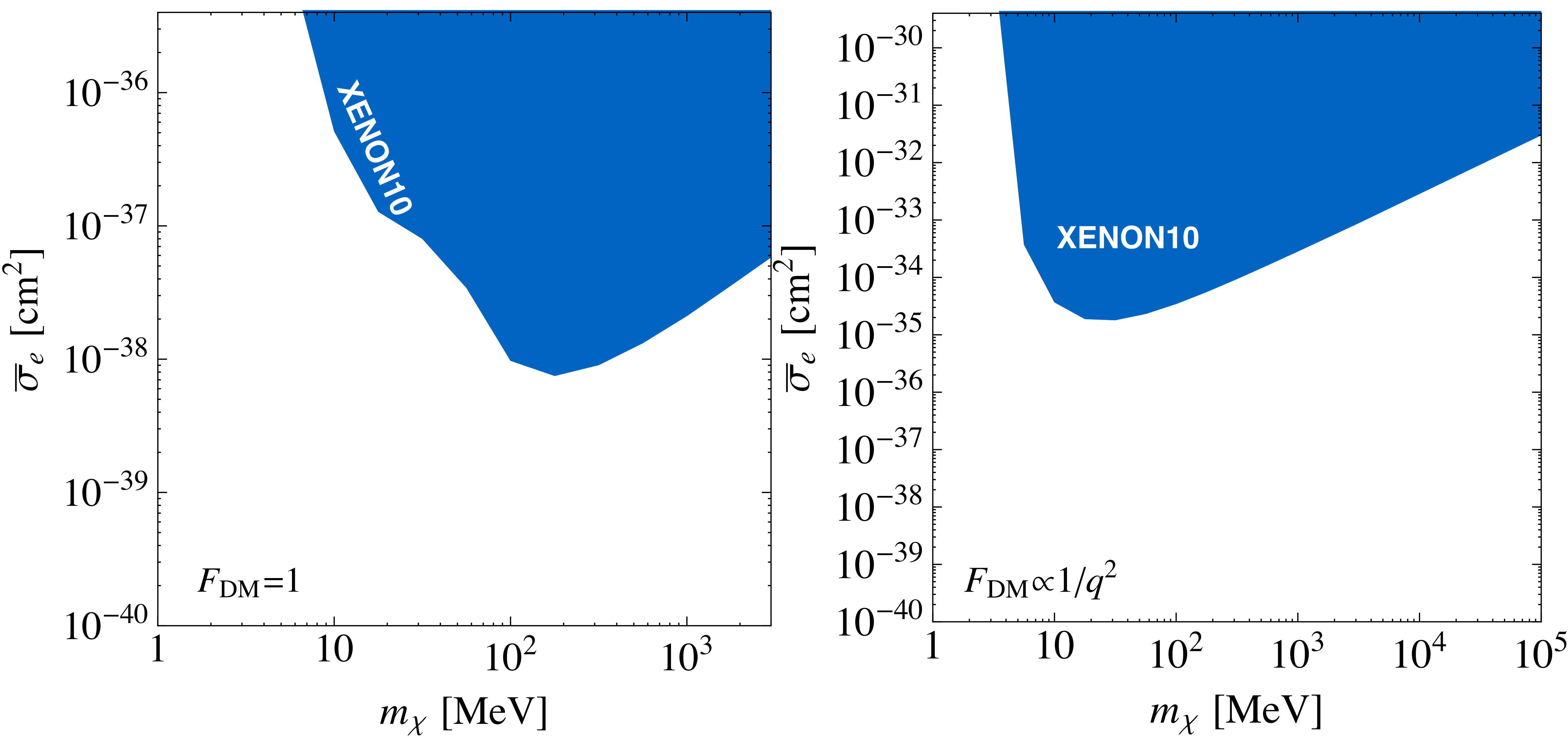
signal < Number of observed events

constrain size of DM-electron scattering cross-section

XENON10 Collaboration
Phys.Rev.Lett. **110** (2013) 249901

Essig, Volansky, TTY [1703.00910]

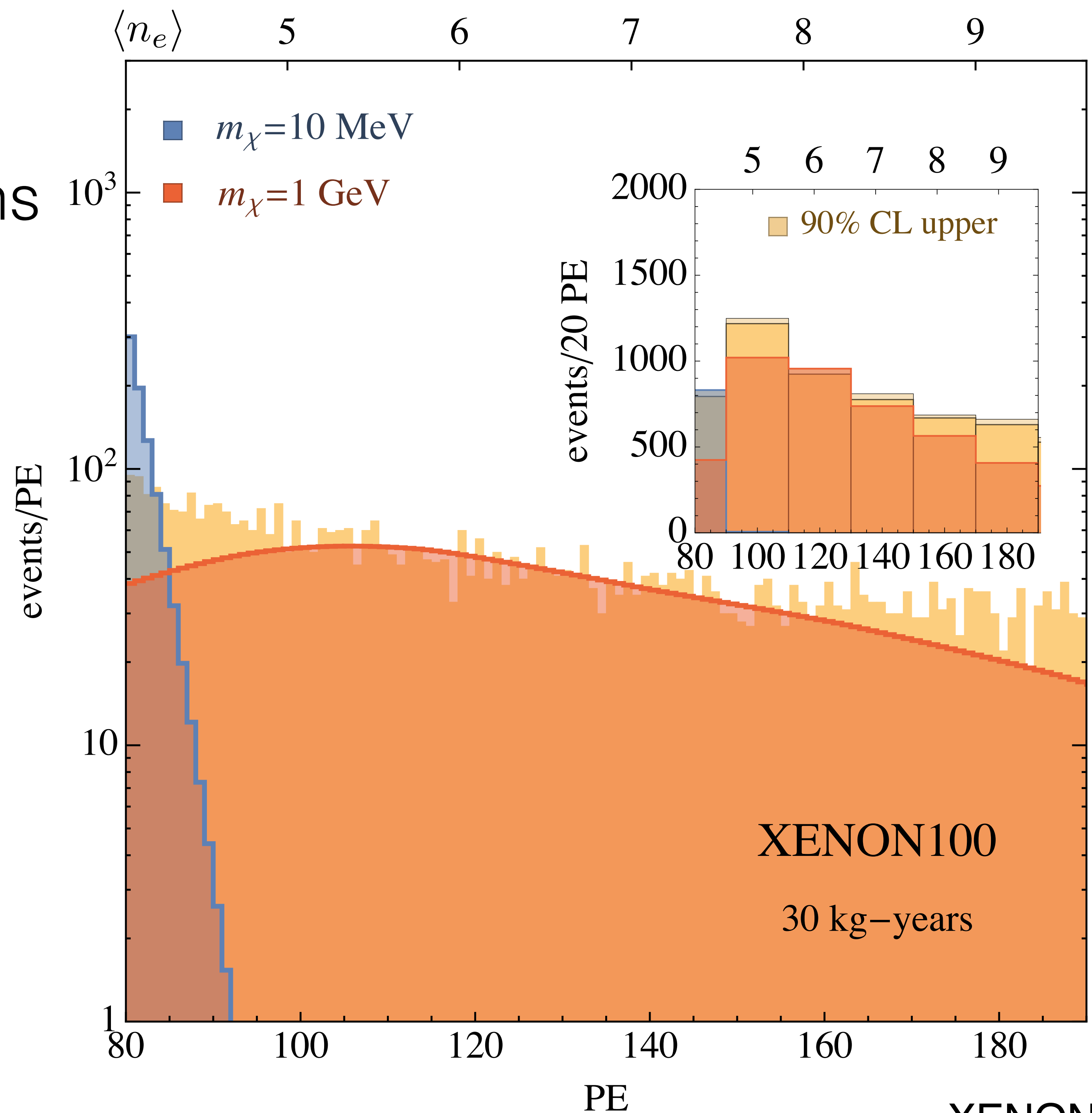
XENON



Essig, Volansky, TTY [1703.00910]

XENON100

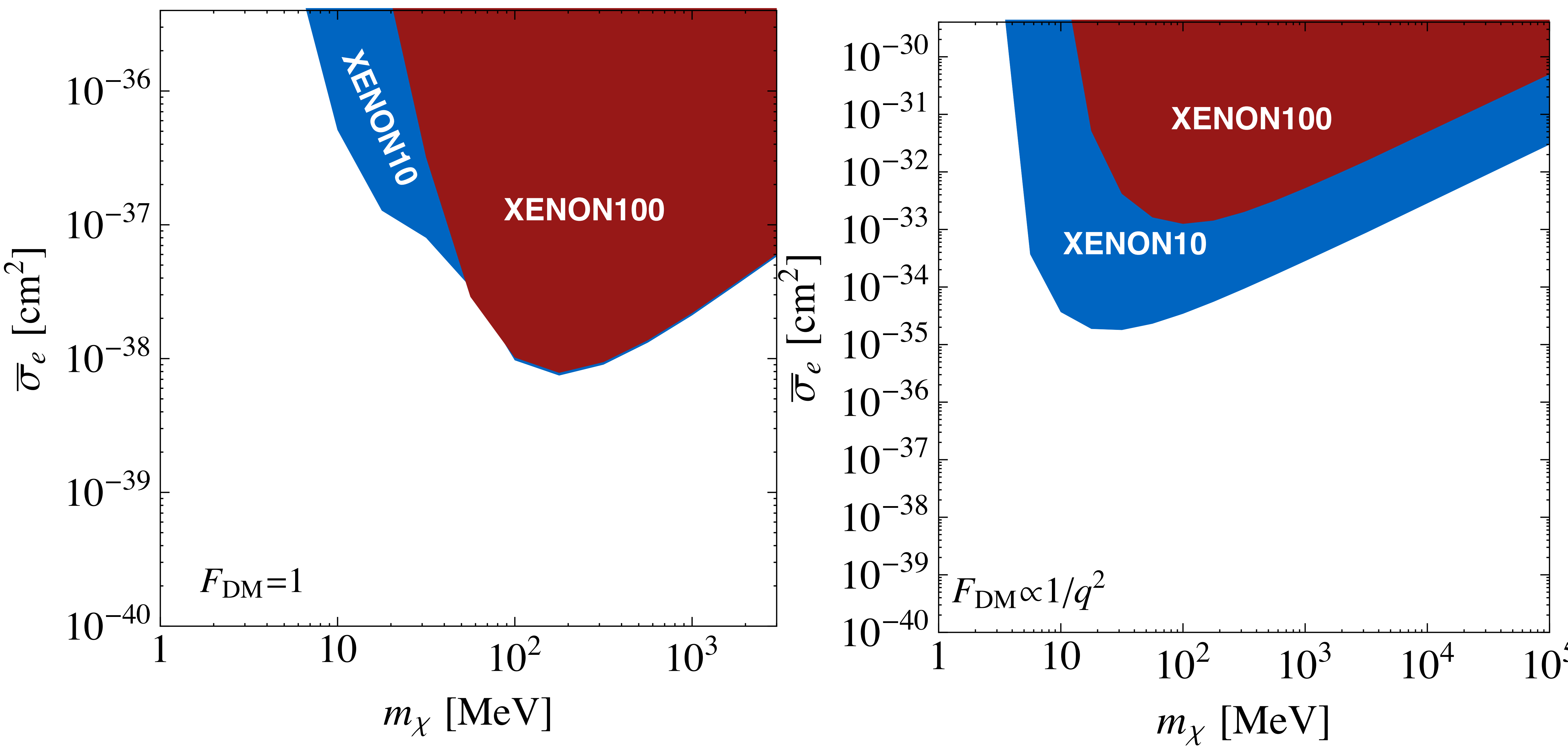
1 electron =
20 **P**hoto**E**lectrons



Essig, Volansky, TTY [1703.00910]

XENON100 collaboration
Phys.Rev. D94 (2016) no.9, 092001

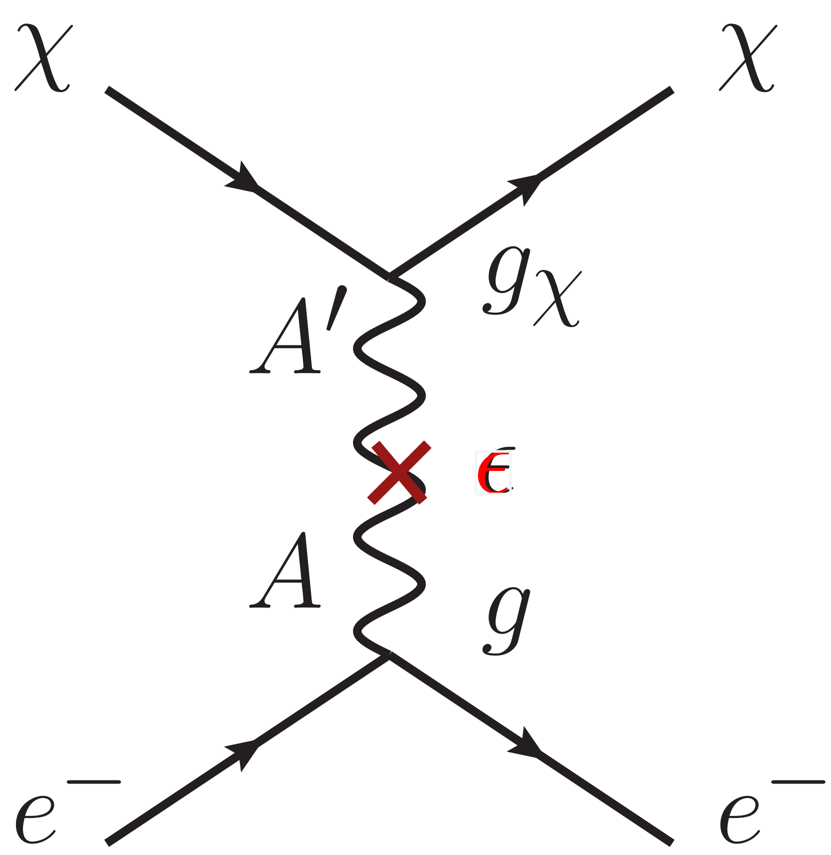
XENON



Essig, Volansky, TTY [1703.00910]

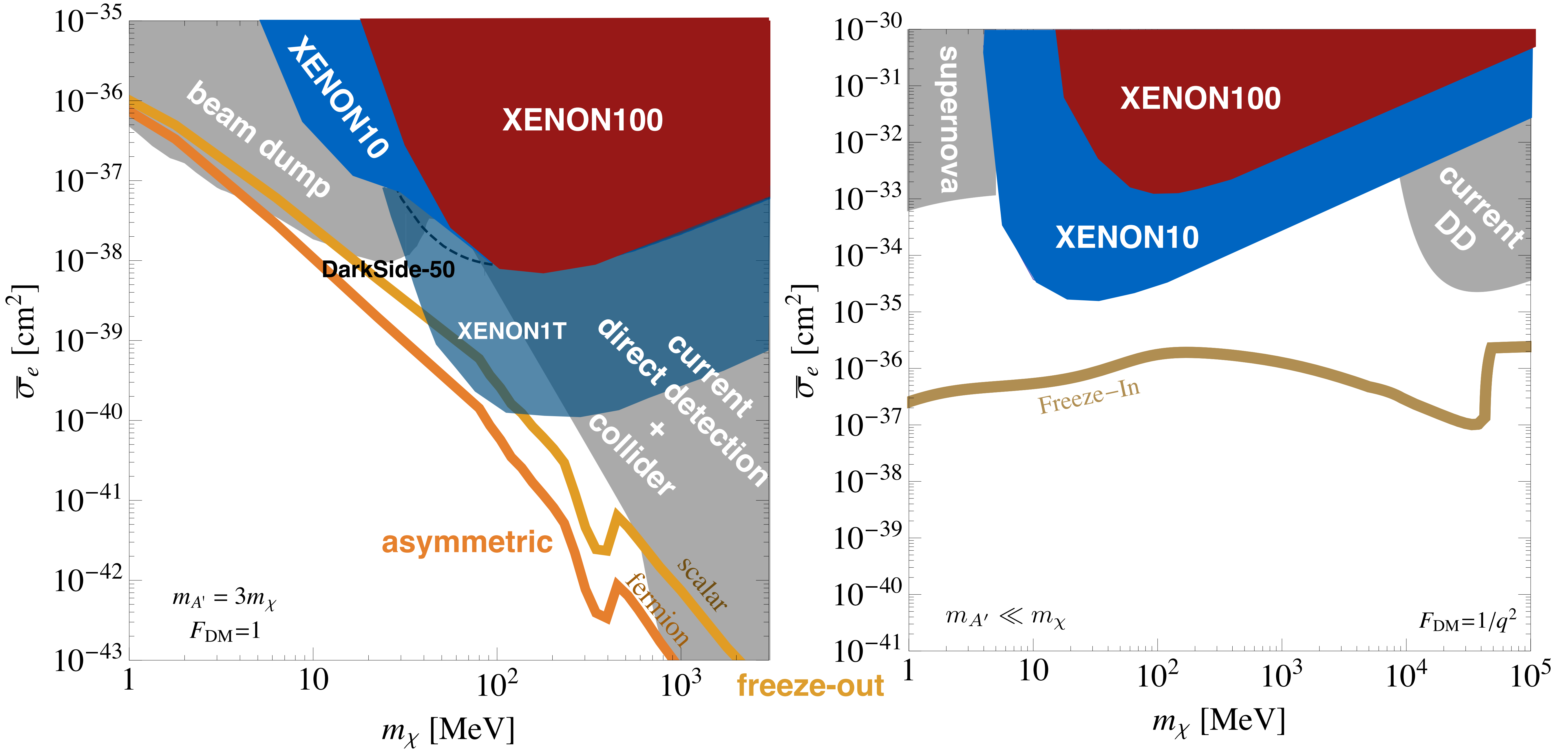
a model: dark photon

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^{\mu}A'_{\mu}$$



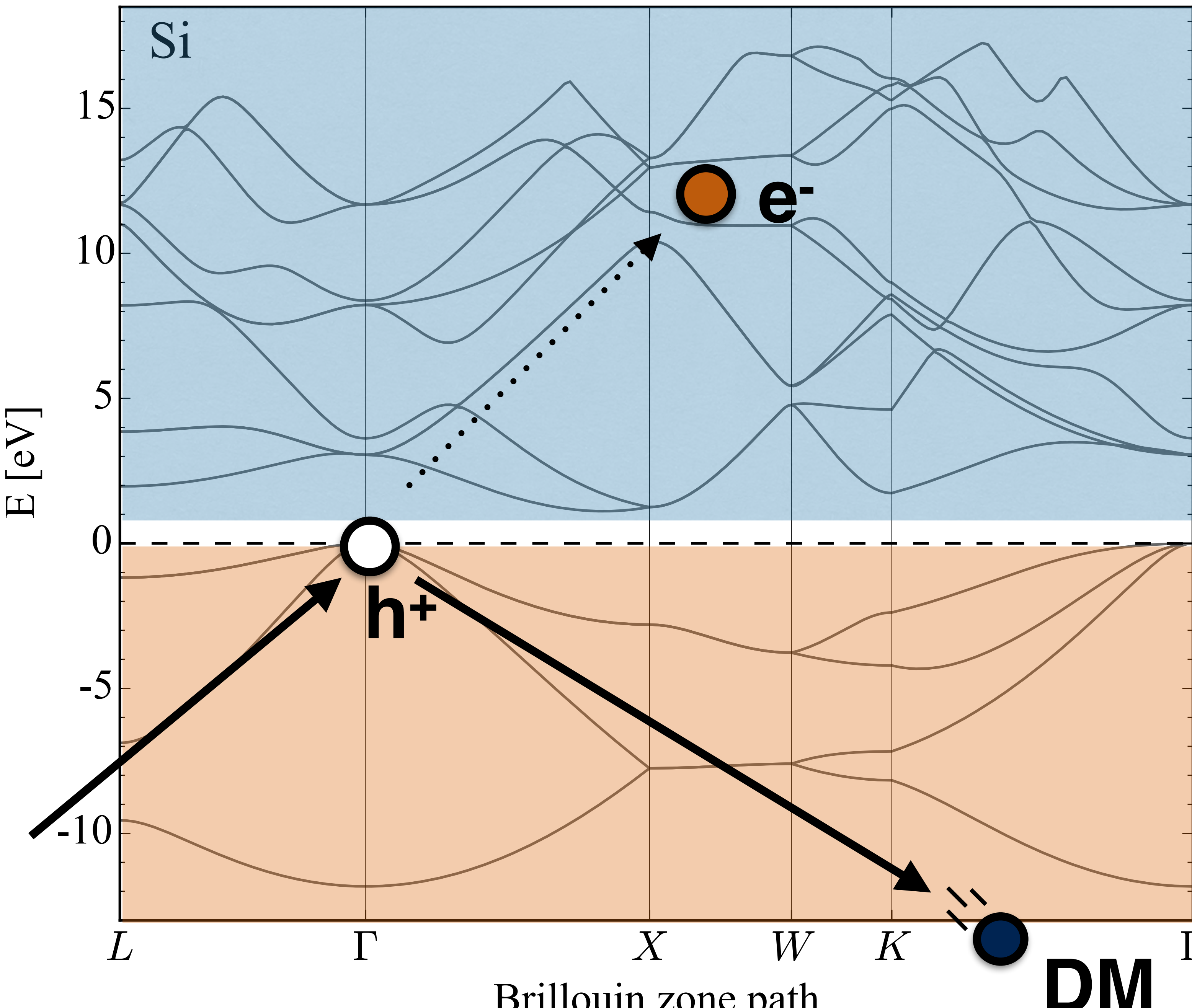
$$F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2} \simeq \begin{cases} 1\,, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}\,, & m_{A'} \ll \alpha m_e \end{cases}$$

dark photon



Essig, Volansky, TTY [1703.00910], DarkSide Collaboration [1802.06998], XENON1T [1907.11485]

semiconductor targets



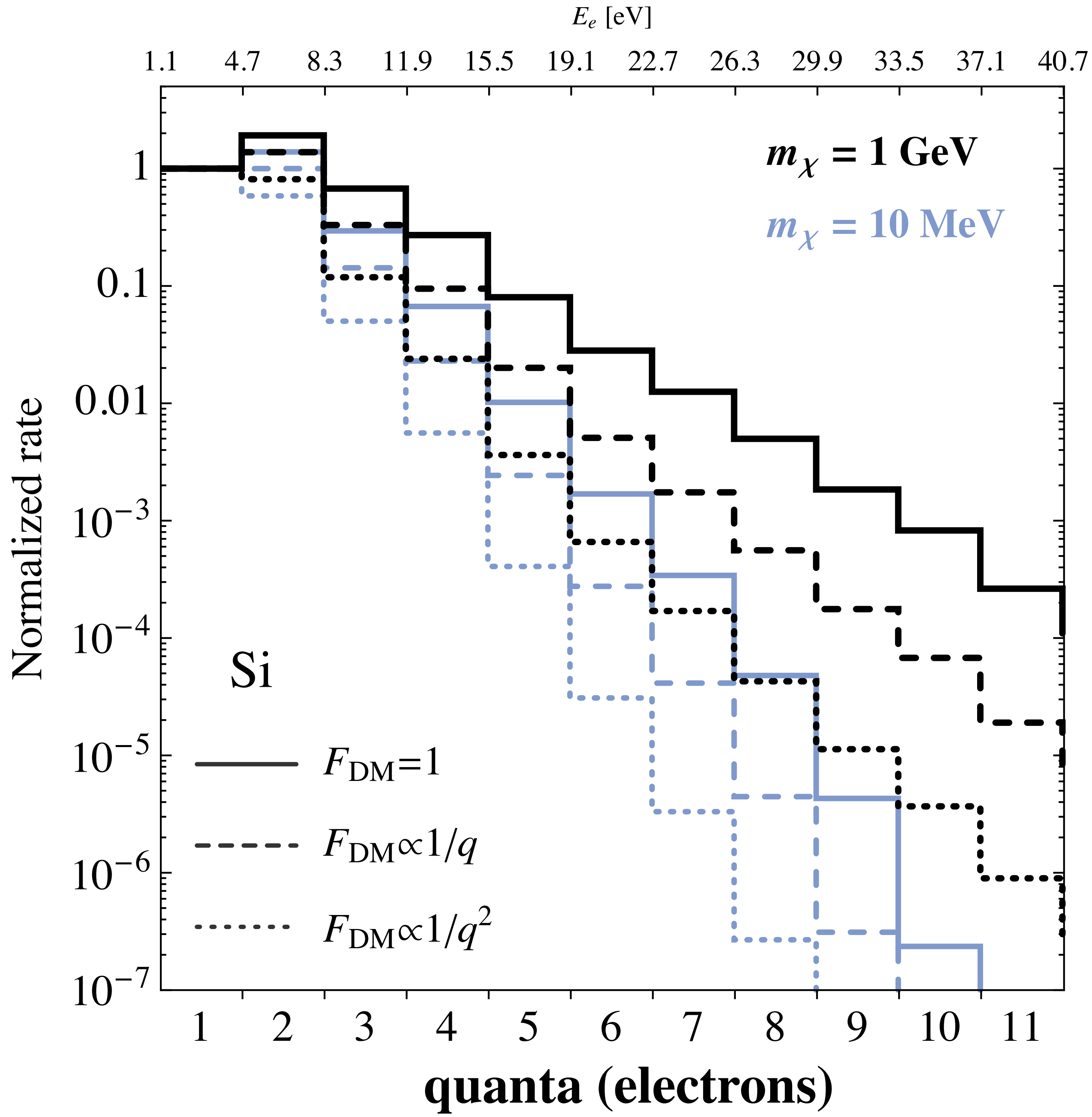
detect the electron(s)

sensitive to ~eV energy depositions

i.e. silicon, germanium

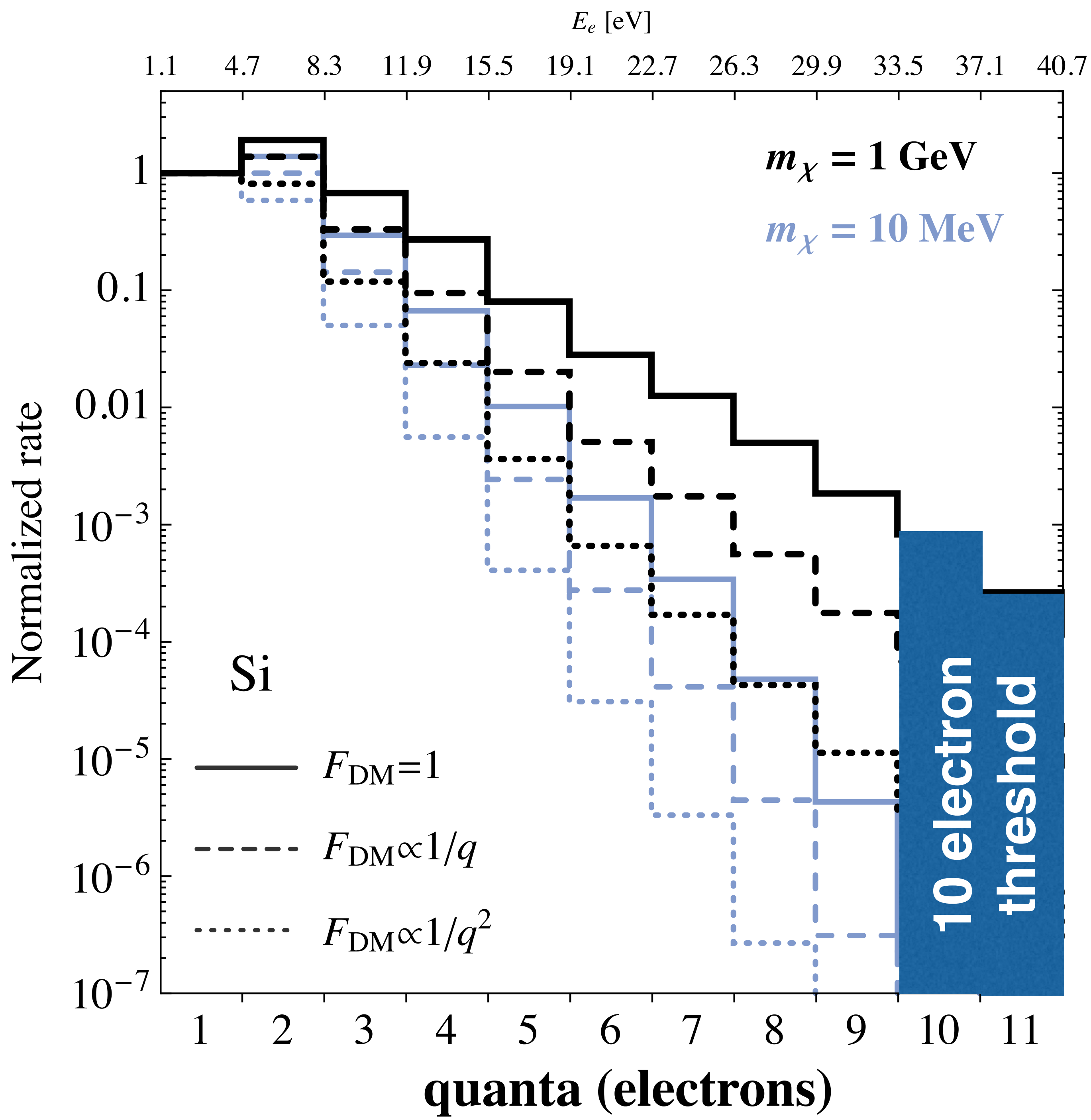
Essig, Mardon, Volansky [1108.5383]
Graham, Kaplan, Rajendran, Walters [1203.2531]
Lee, Lisanti, Mishra-Sharma, Safdi [1508.07361]
Essig, Fernandez-Serra, Mardon, Soto, Volansky, TTY [1509.01598]

threshold dependence



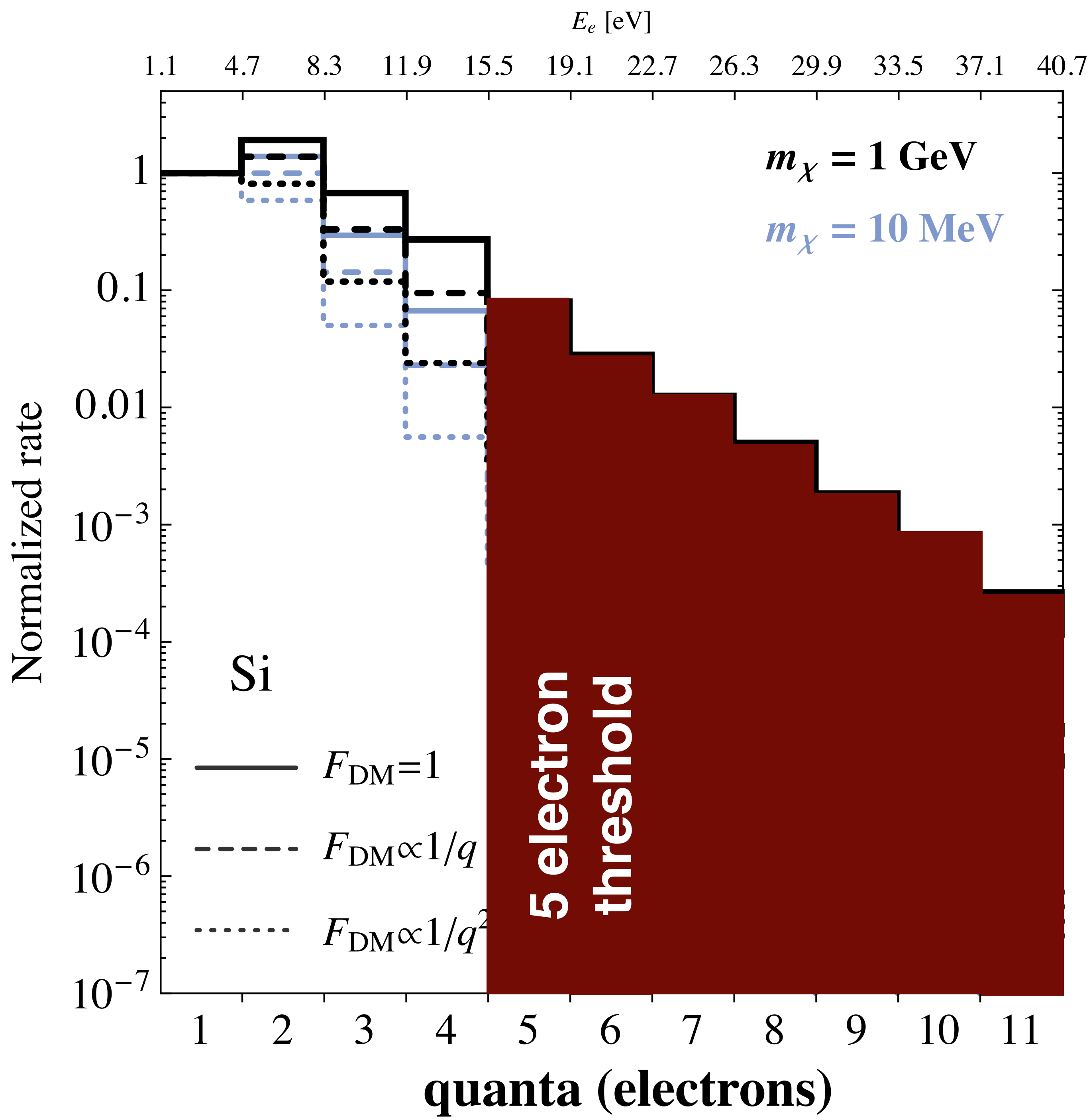
Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

threshold dependence



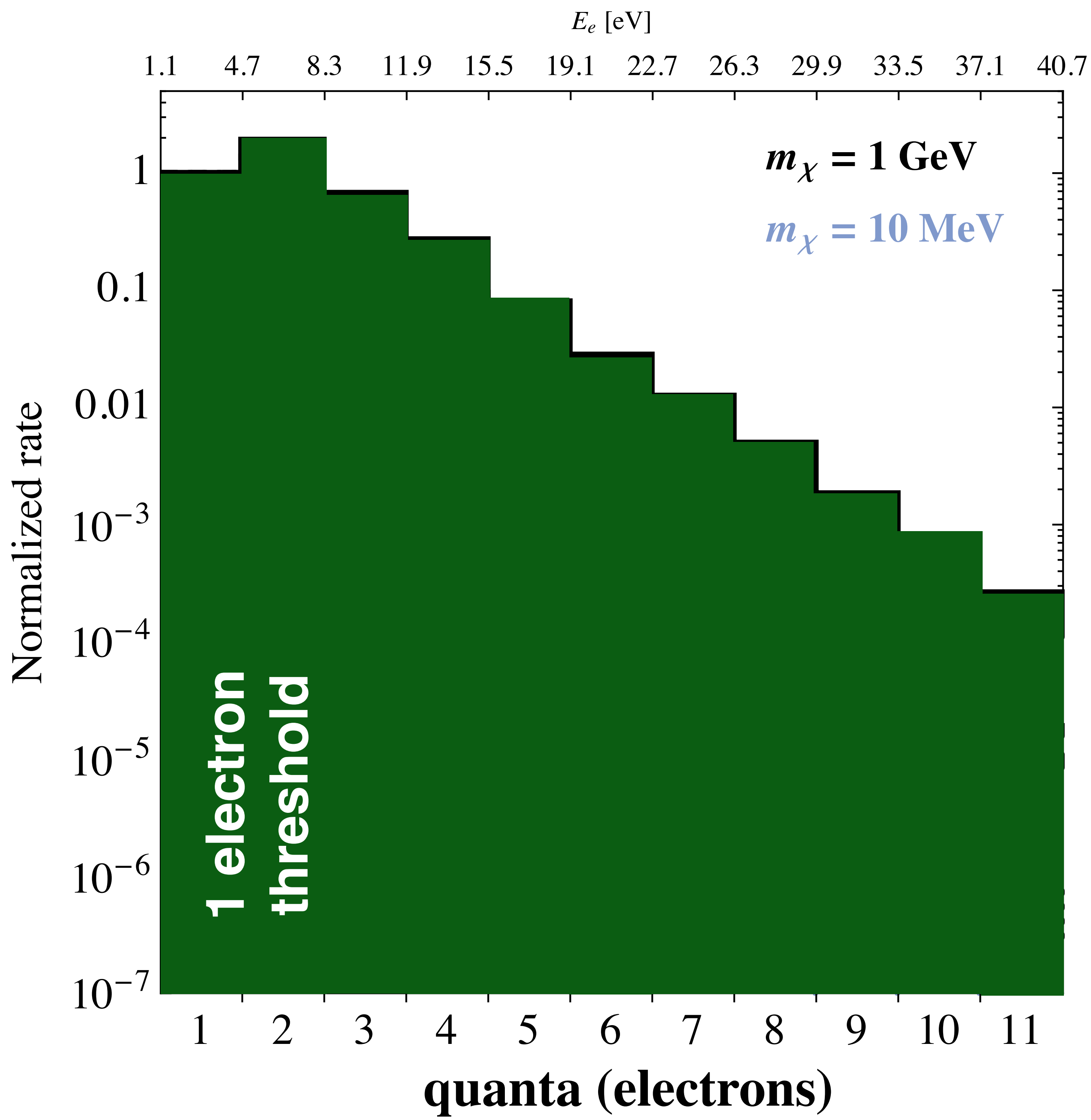
Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

threshold dependence



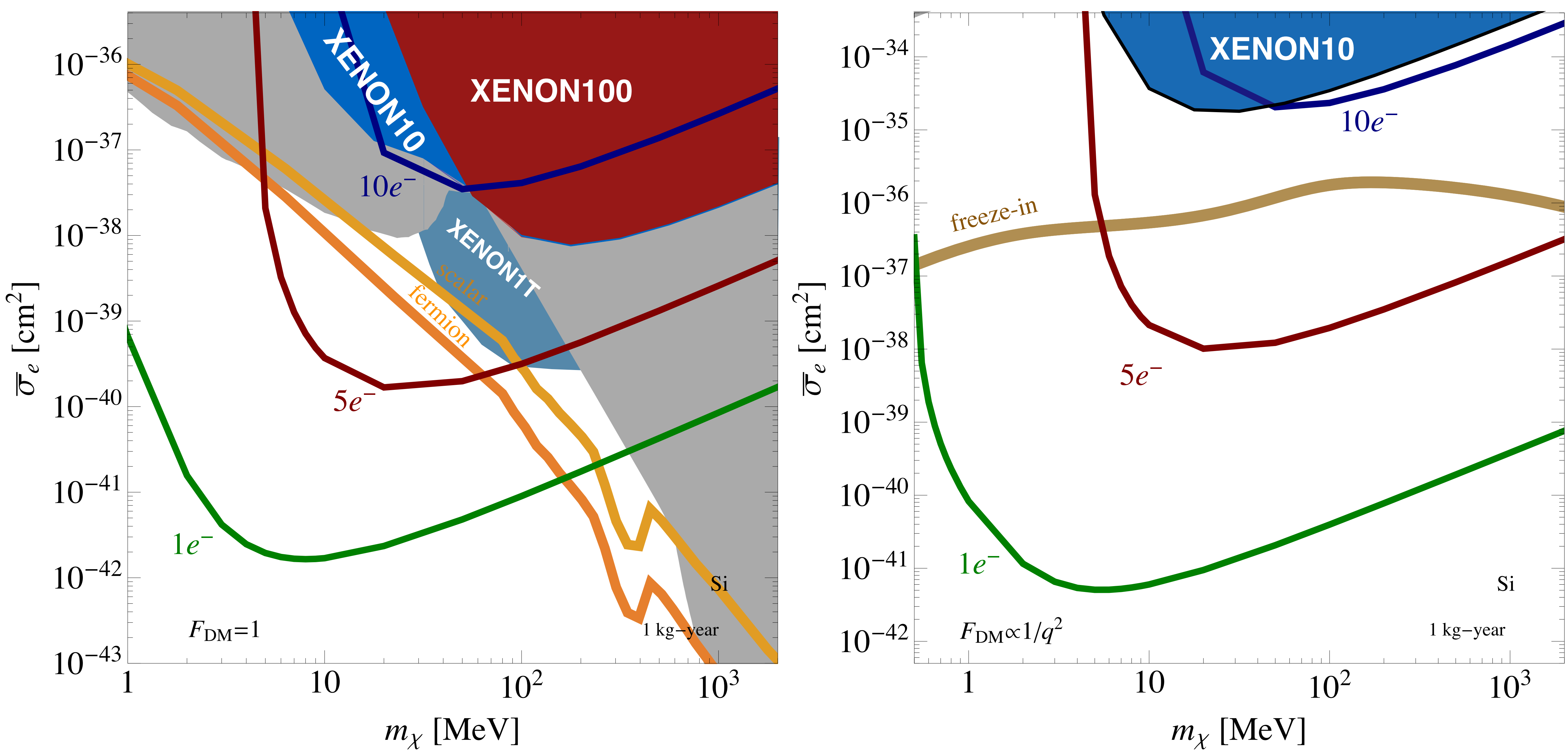
Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

threshold dependence



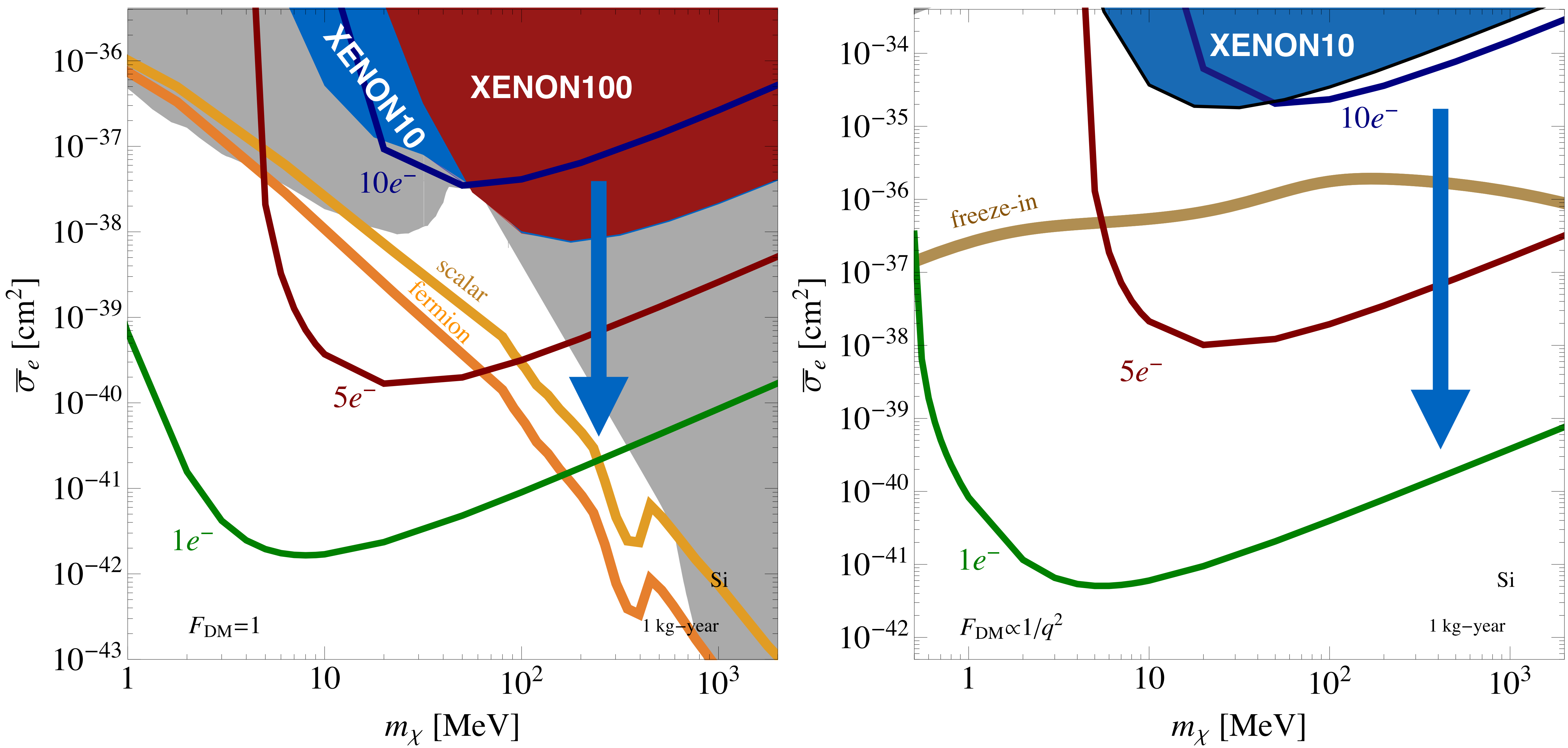
Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

threshold dependence



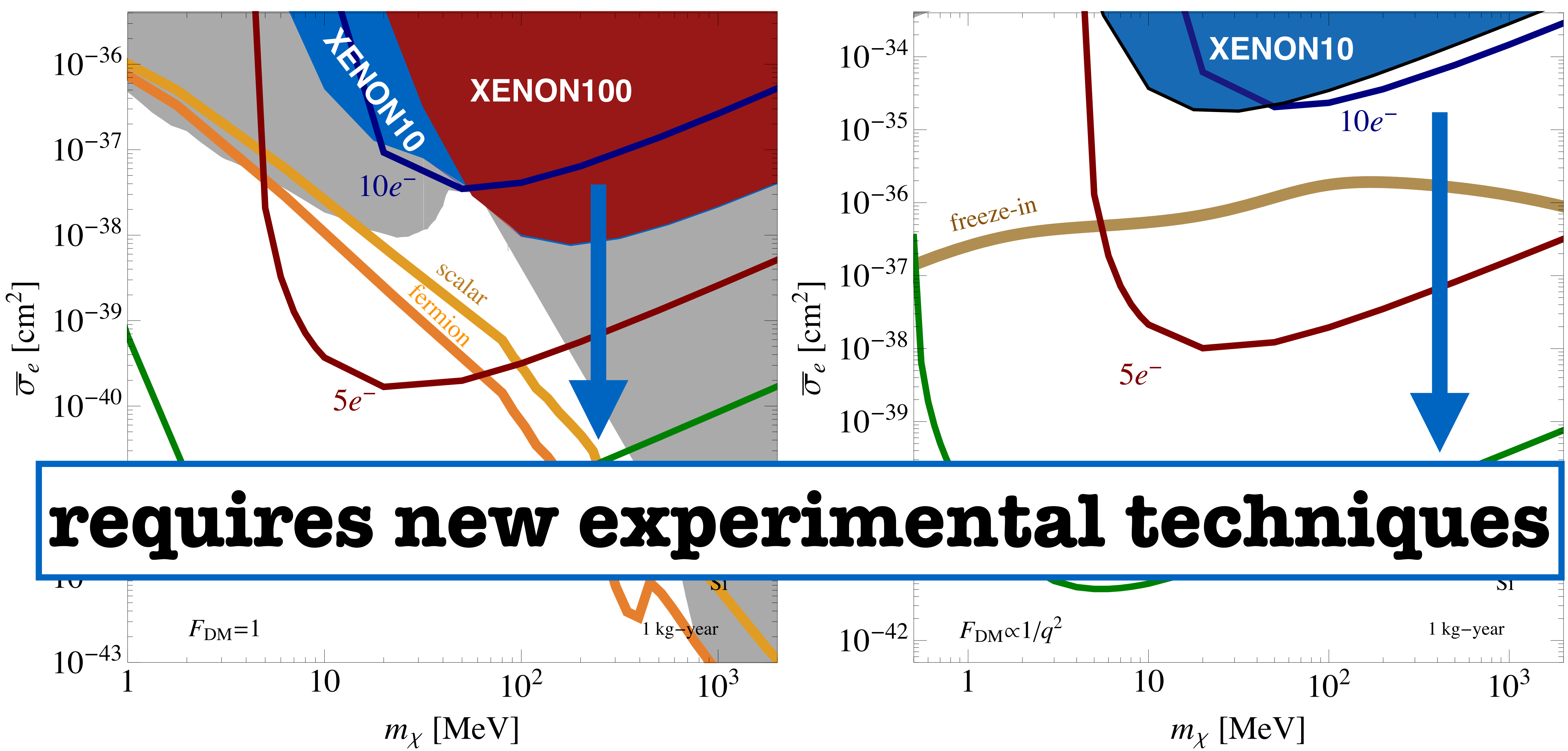
Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

threshold dependence



Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

threshold dependence



requires new experimental techniques

Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

challenges

- computation of form factors — utilize solid state codes and run on a cluster
- reaching 1-2 electron thresholds
  - **readout noise** — can minimize by increasing time of readout
  - E-field used to drift the electrons may produce **dark current** — fundamentally limits the sensitivity

Fermilab

SENSEI

HEISING-SIMONS
FOUNDATION

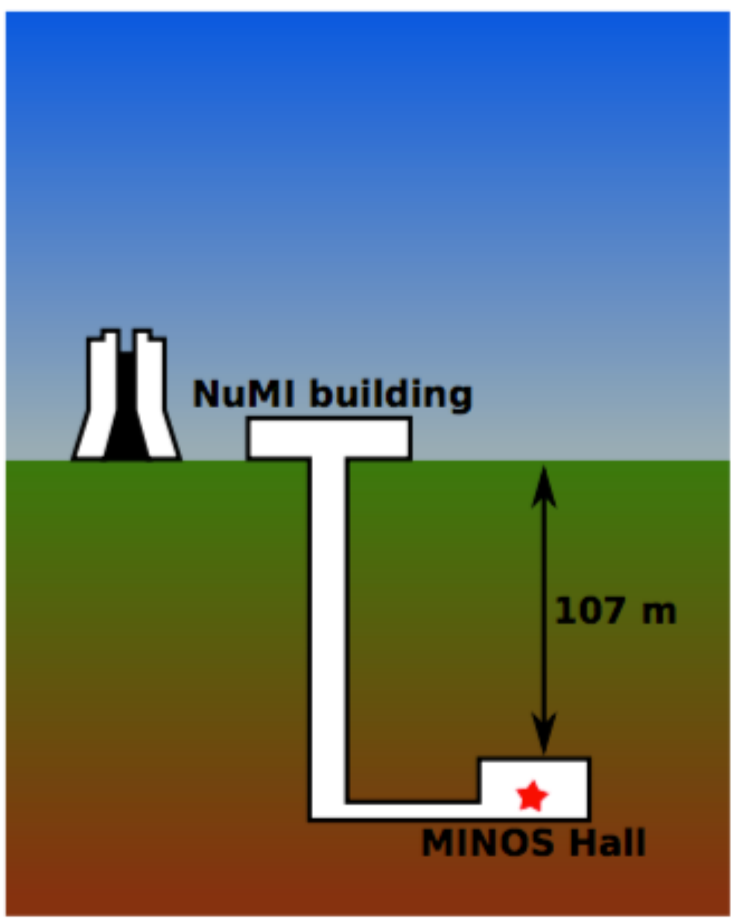
Sub-**E**lectron-**N**oise **S**kipper CCD **E**xperimental **I**nstrument

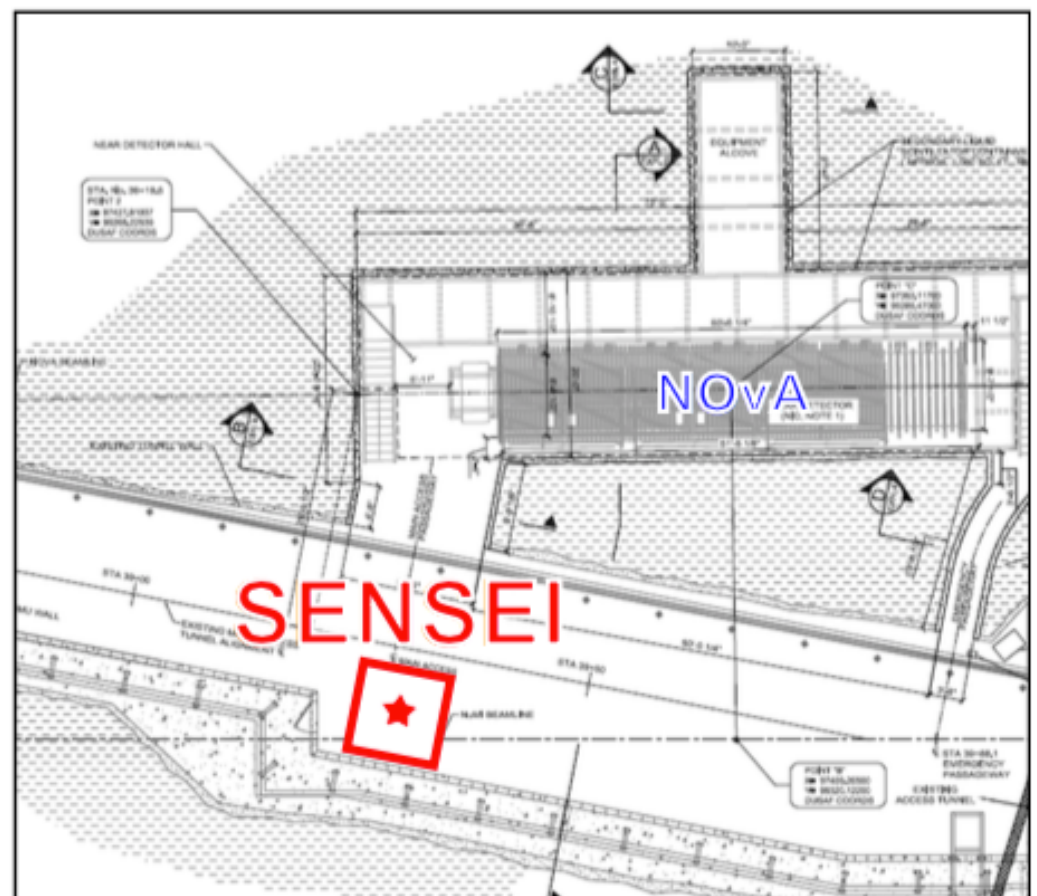
SENSEI

Sub-**E**lectron-**N**oise **S**kipper CCD **E**xperimental **I**nstrument

Whats next: Installation @MINOS & low radiation package

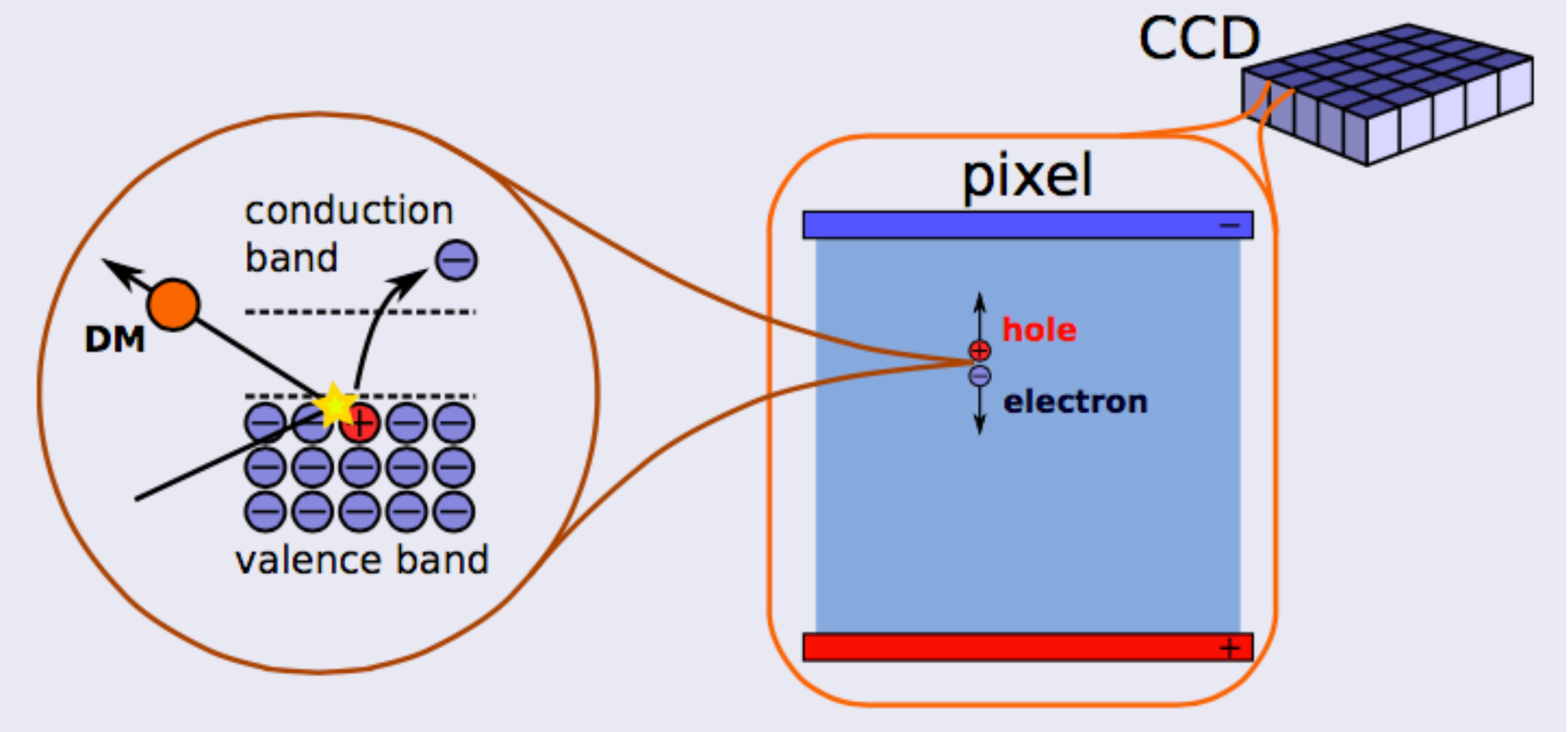
Technology demonstration: installation at shallow underground site





J. Tiffenberg

silicon CCD detector



requires very low noise!
two sources: readout, dark current

of electrons vs. N

$N = 1$ $\sigma_{noise} = 3.5$

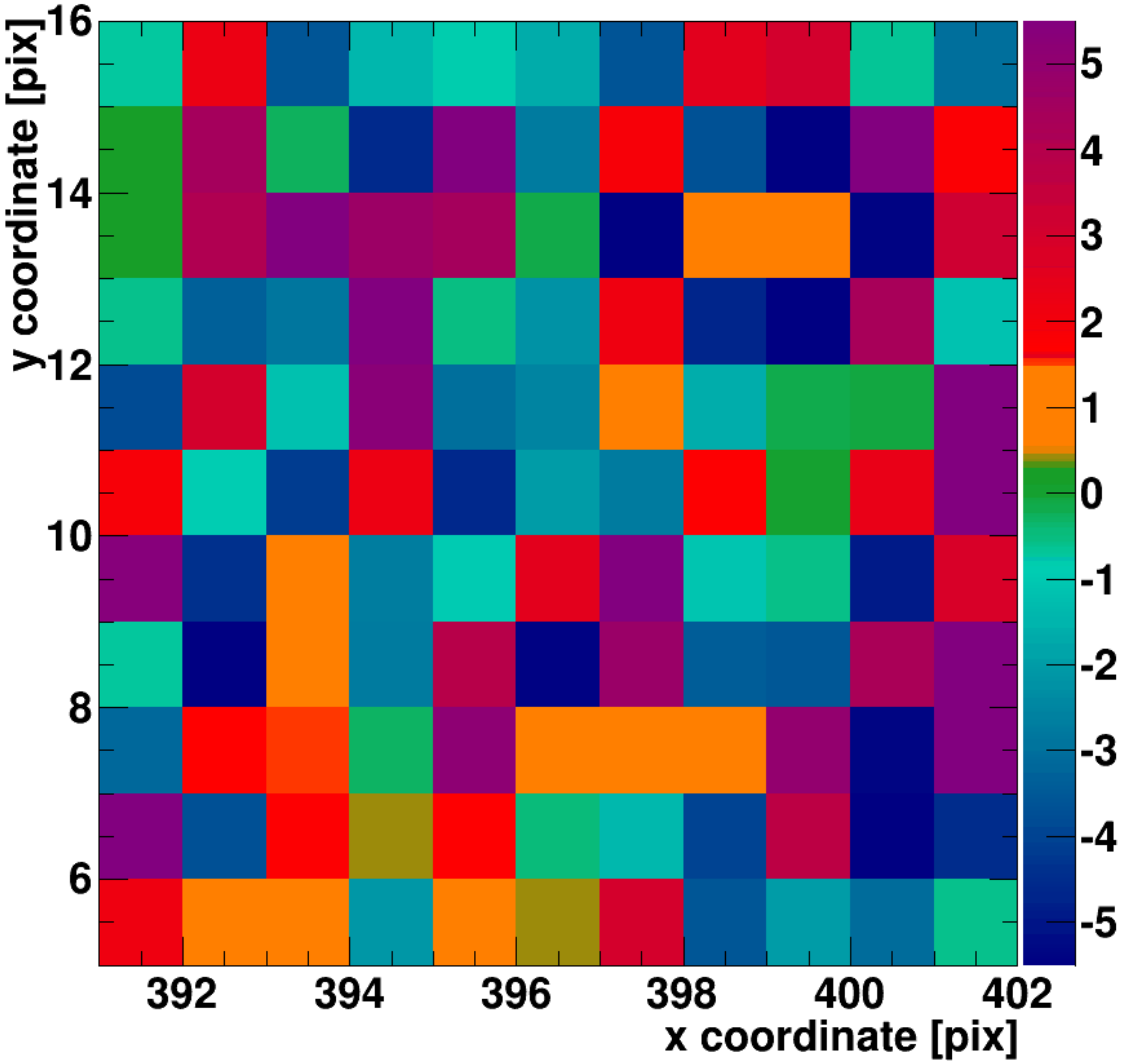
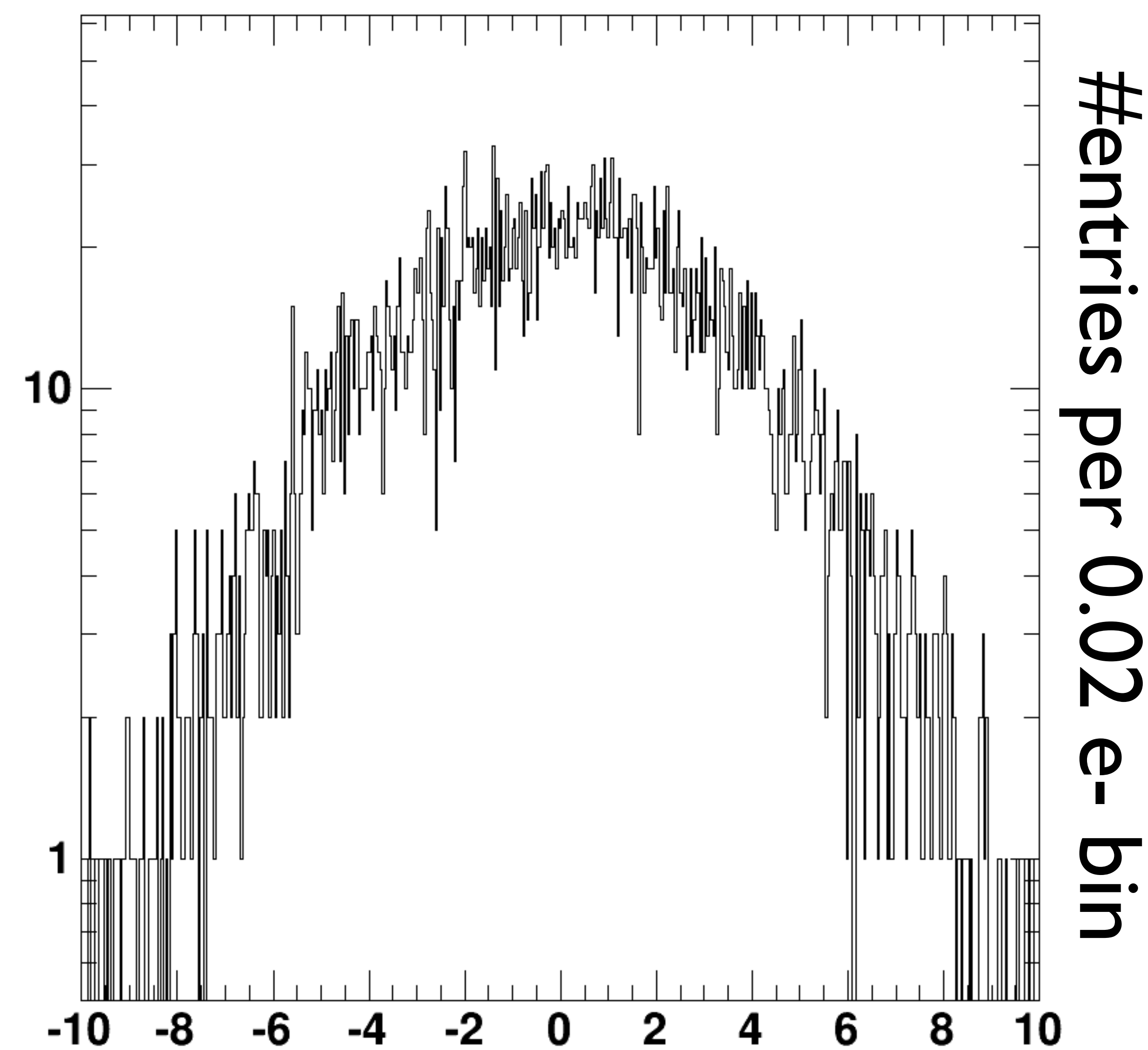


figure courtesy of Javier Tiffenberg

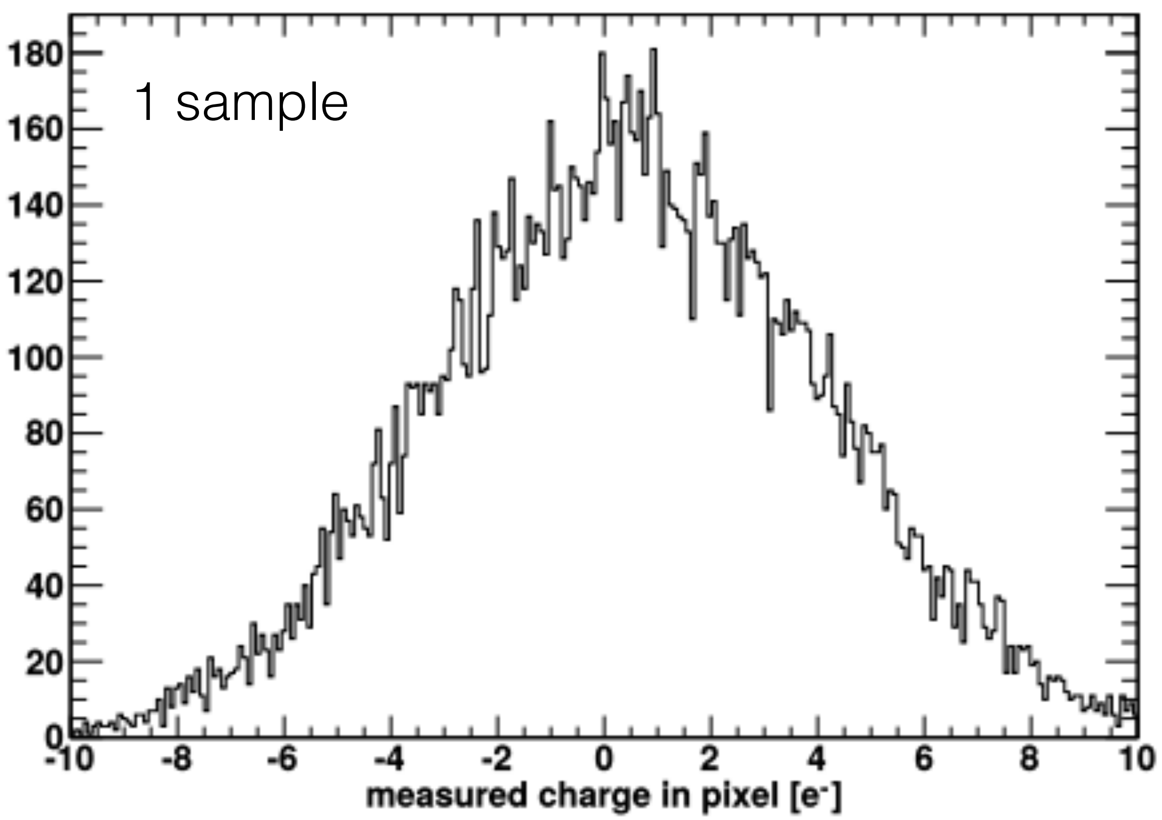


Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig,
Guardincerri, Holland, Volansky, TTY
***Phys.Rev.Lett.* 119 (2017) 13, 131802 [1706.00028]**

skipper readout

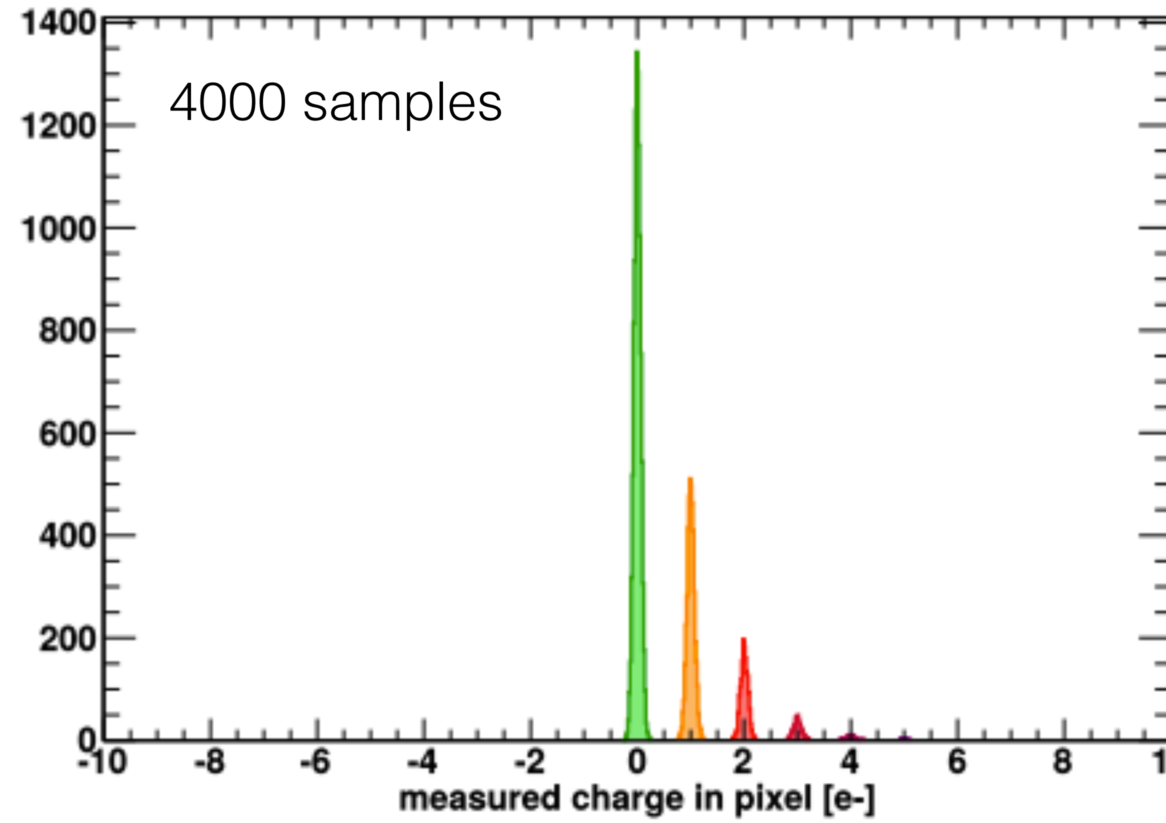
standard CCD

Readout-noise: 3.5 e RMS



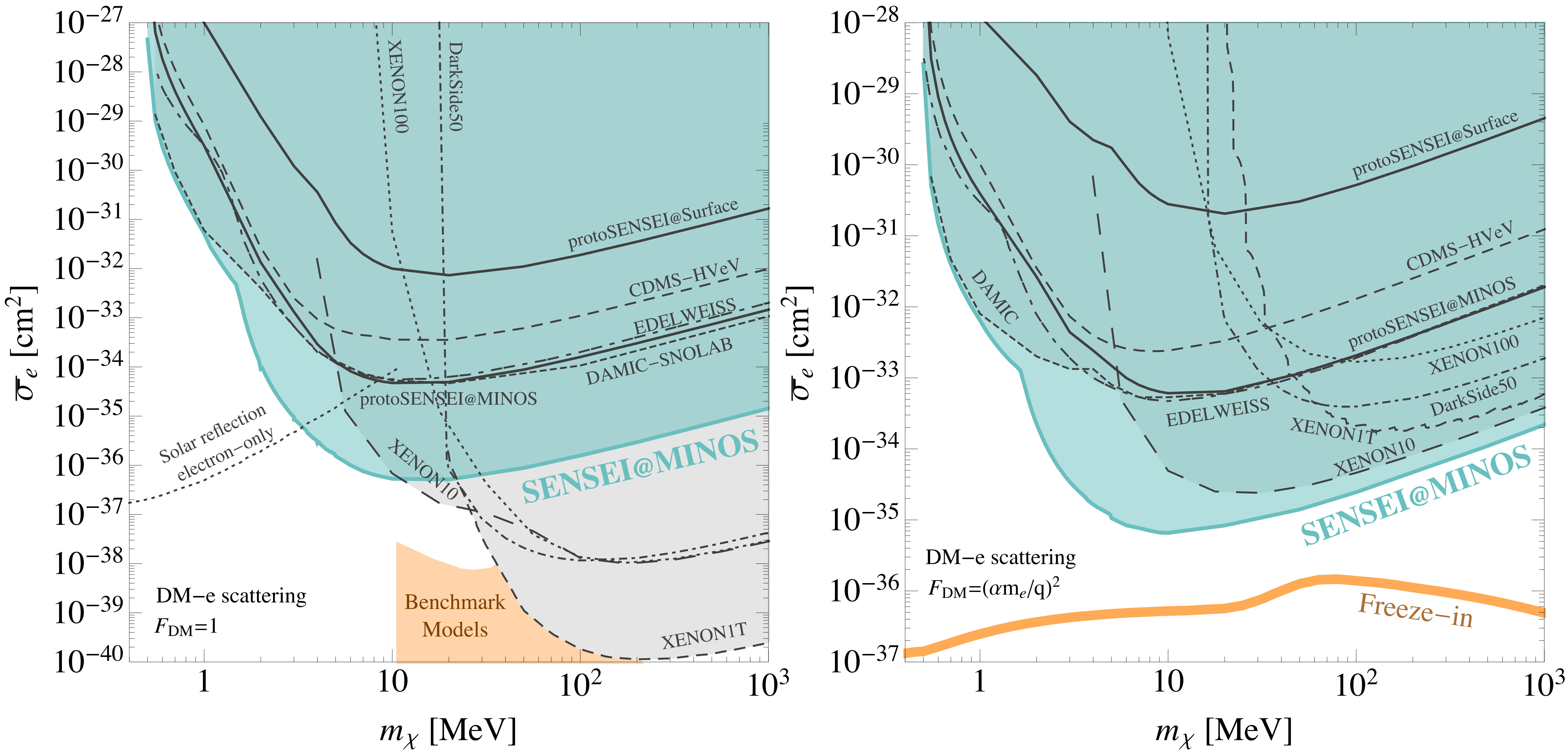
skipper CCD

Readout-noise: 0.06 e RMS



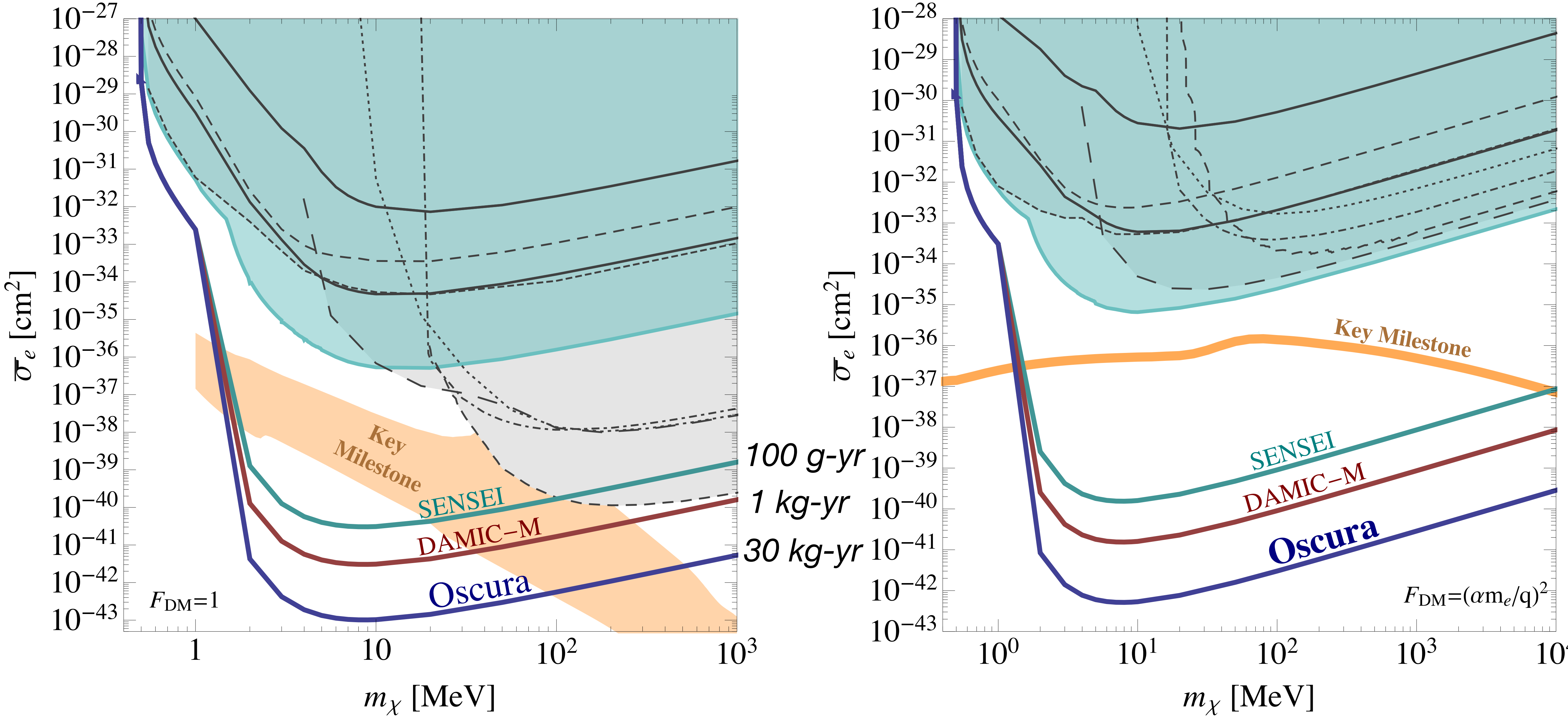
Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig,
Guardincerri, Holland, Volansky, TTY
***Phys.Rev.Lett.* 119 (2017) 13, 131802 [1706.00028]**

DM-electron scattering



SENSEI collaboration [arXiv:2004.11378], *Phys.Rev.Lett.* 125 (2020) 17, 171802 - *Editors' Suggestion*

DM-electron scattering



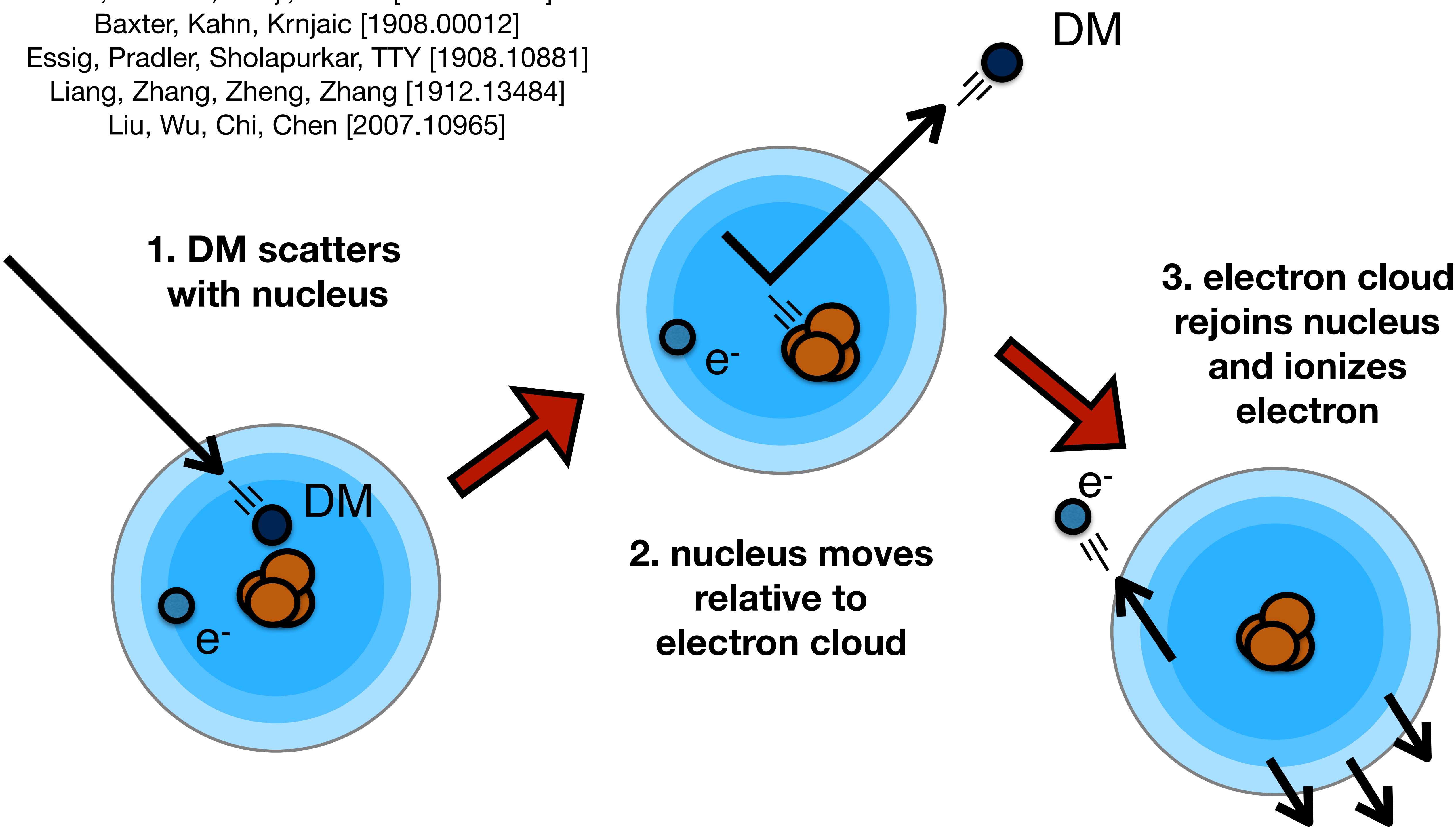
Projections for future Si Skipper-CCD experiments

sub-GeV DM direct detection

- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
- **Dark matter-nuclear scattering** through the Migdal scattering and bremsstrahlung
- **Absorption** of light dark matter, including axion-like particles and dark photons.
- **Dark matter scattering off collective modes** in molecules and in crystals (including phonons, plasmons and magnons)

“Migdal” scattering

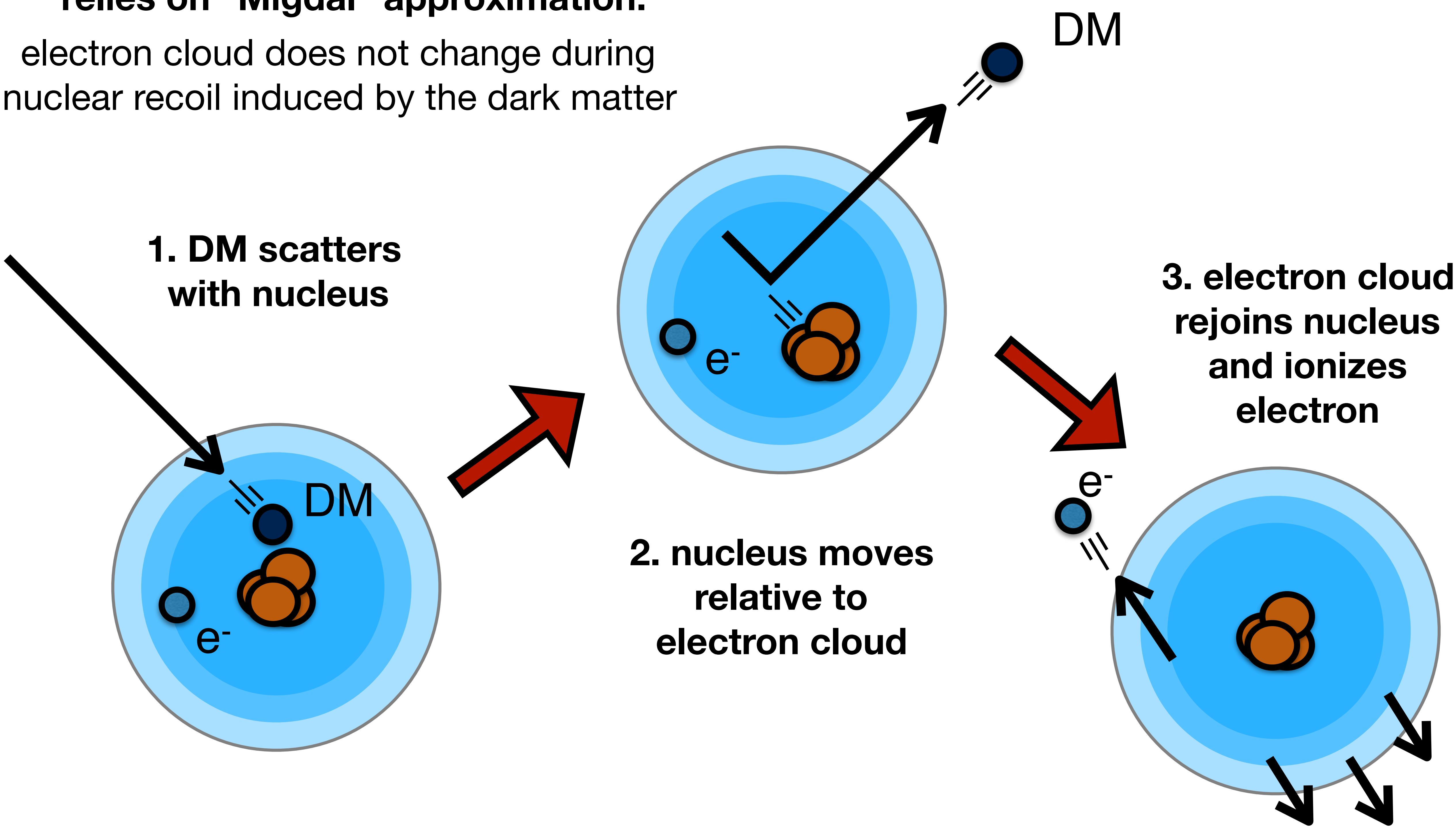
Ibe, Nakano, Shoji, Suzuki [1707.07258]
Baxter, Kahn, Krnjaic [1908.00012]
Essig, Pradler, Sholapurkar, TTY [1908.10881]
Liang, Zhang, Zheng, Zhang [1912.13484]
Liu, Wu, Chi, Chen [2007.10965]



“Migdal” scattering

***relies on “Migdal” approximation:**

electron cloud does not change during nuclear recoil induced by the dark matter



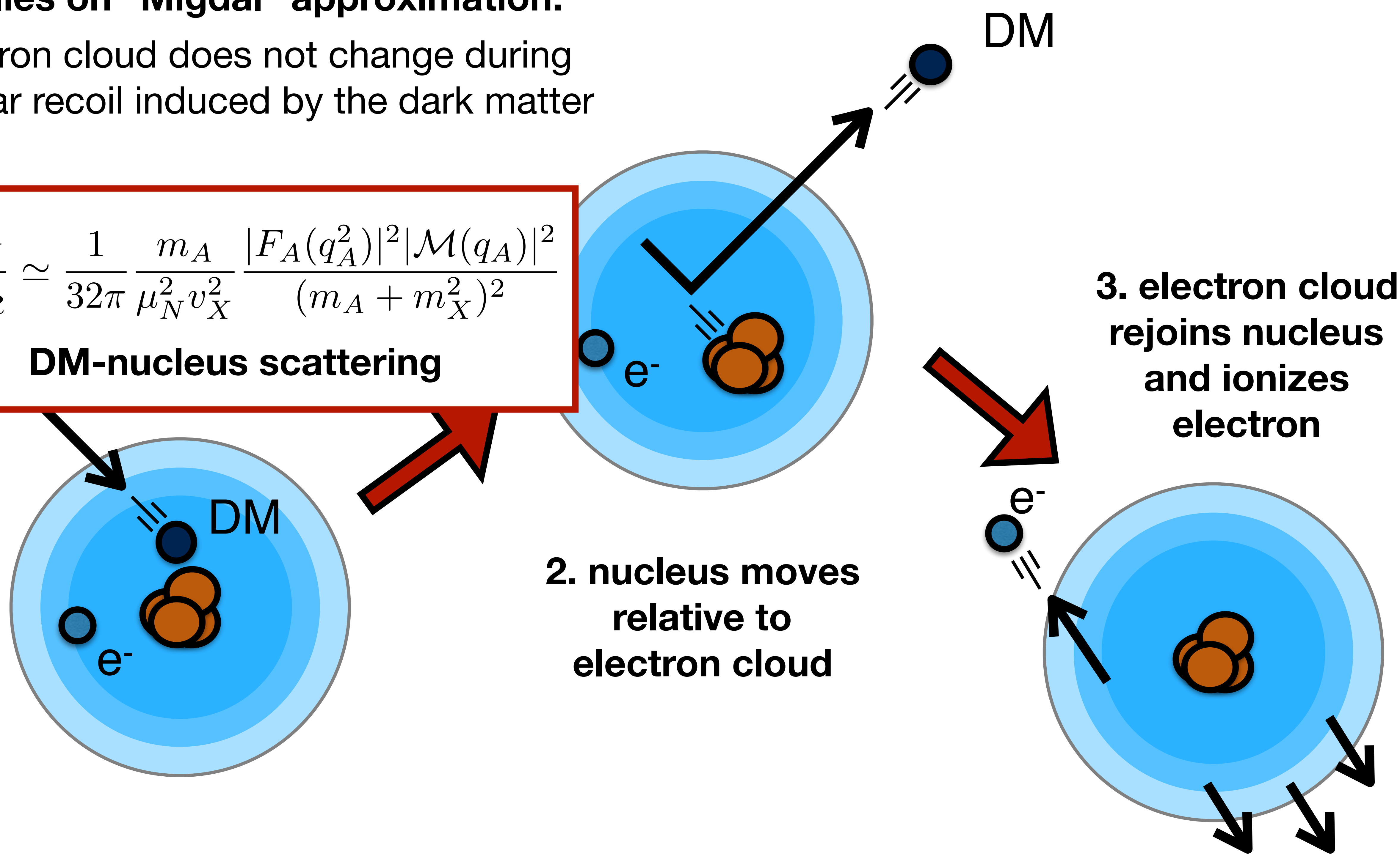
“Migdal” scattering

***relies on “Migdal” approximation:**

electron cloud does not change during nuclear recoil induced by the dark matter

$$\frac{d\sigma_N}{dE_R} \simeq \frac{1}{32\pi} \frac{m_A}{\mu_N^2 v_X^2} \frac{|F_A(q_A^2)|^2 |\mathcal{M}(q_A)|^2}{(m_A + m_X^2)^2}$$

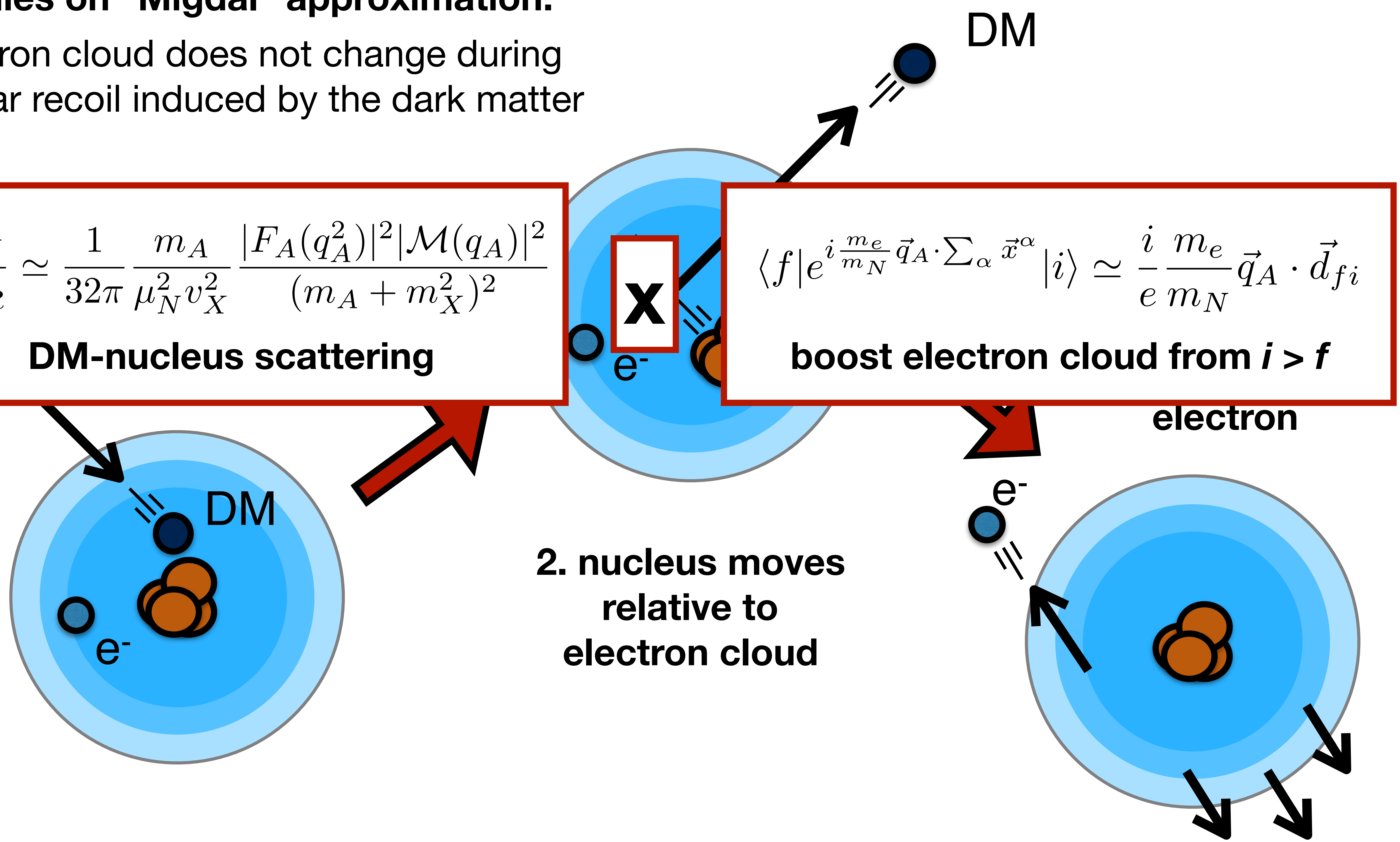
DM-nucleus scattering



“Migdal” scattering

*__relies on “Migdal” approximation:__

electron cloud does not change during nuclear recoil induced by the dark matter



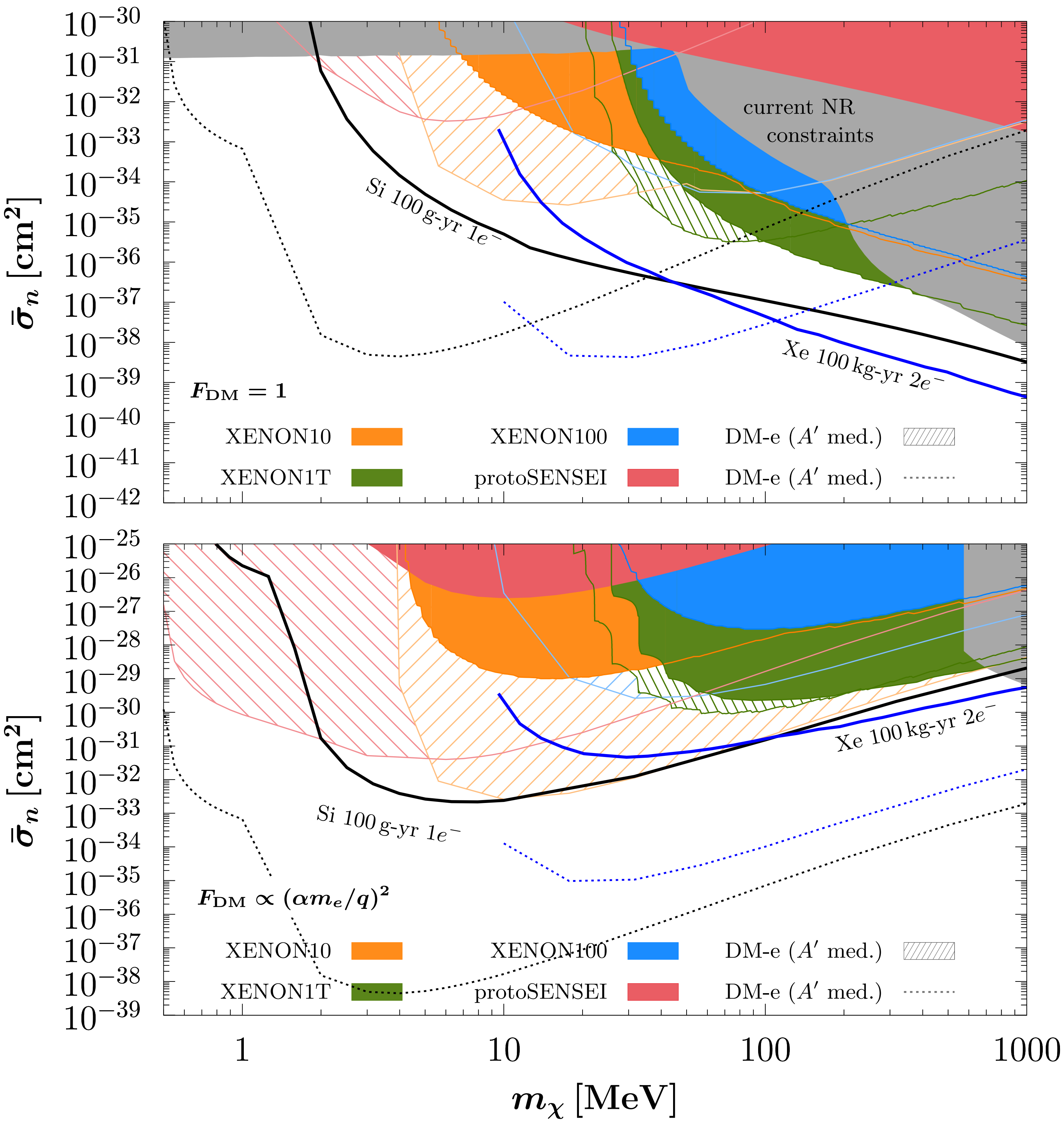
$$\frac{d\sigma_N}{dE_R} \simeq \frac{1}{32\pi}\frac{m_A}{\mu_N^2 v_X^2}\frac{|F_A(q_A^2)|^2|\mathcal{M}(q_A)|^2}{(m_A+m_X^2)^2}$$

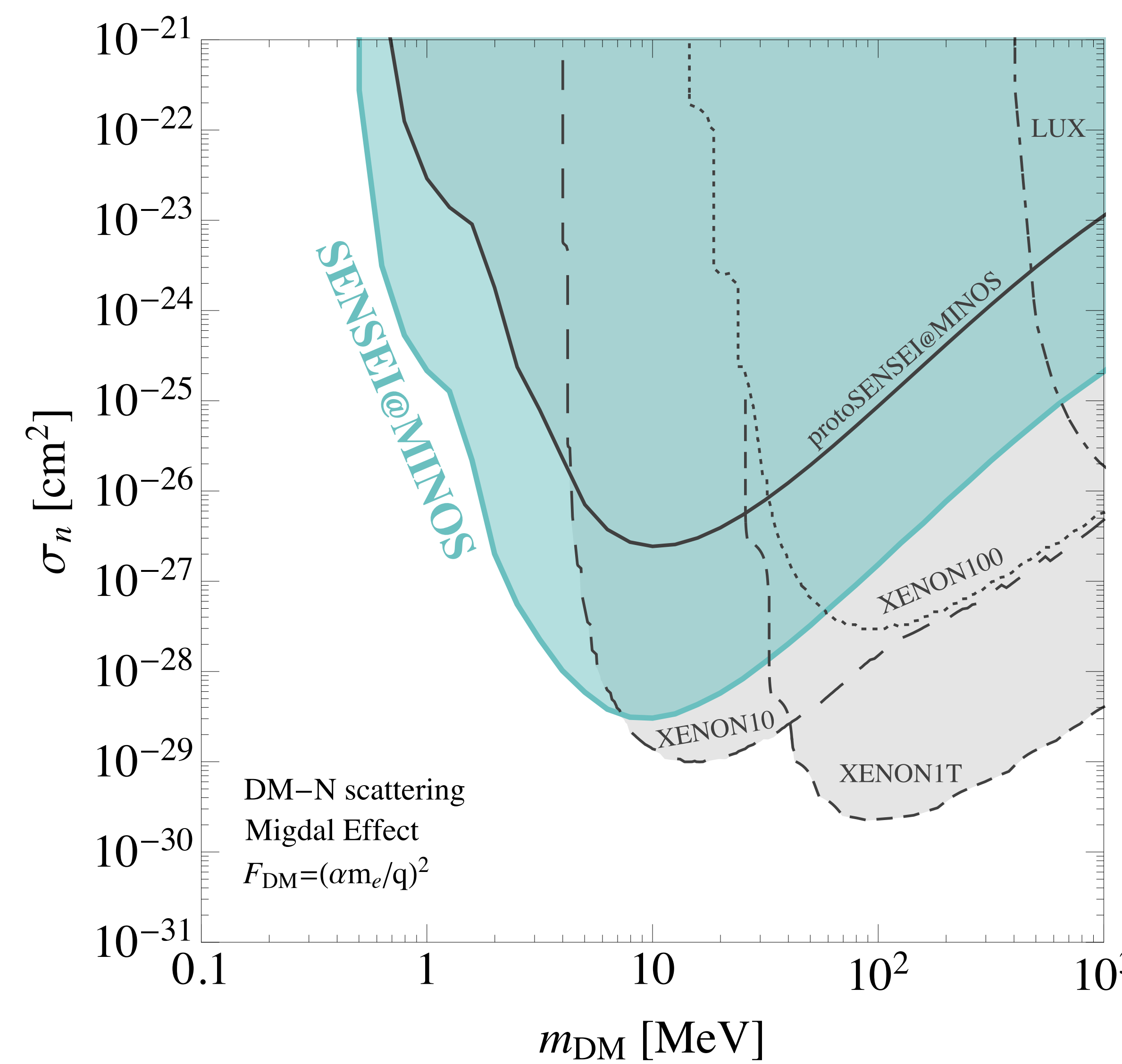
DM-nucleus scattering

$$\langle f|e^{i\frac{m_e}{m_N}\vec{q}_A\cdot\sum_\alpha \vec{x}^\alpha}|i\rangle \simeq \frac{i}{e}\frac{m_e}{m_N}\vec{q}_A\cdot\vec{d}_{fi}$$

boost electron cloud from *i* > *f*

“Migdal” scattering





SENSEI collaboration [arXiv:2004.11378],

***Phys.Rev.Lett.* 125 (2020) 17, 171802**

Editors' Suggestion

Essig, Pradler, Sholapurkar, TTY *Phys.Rev.Lett.* 124 (2020) 2, 021801 [arXiv:1908.10881]

“Migdal” scattering

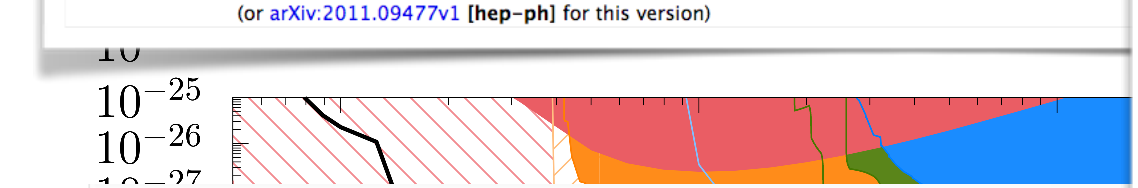
new!

Dark Matter Detection With Bound Nuclear Targets: The Poisson Phonon Tail

Yonatan Kahn, Gordan Krnjaic, Bashi Mandava

Dark matter (DM) scattering with nuclei in solid-state systems may produce elastic nuclear recoil at high energies and single-phonon excitation at low energies. When the dark matter momentum is comparable to the momentum spread of nuclei bound in a lattice, $q_0 = \sqrt{2 m_N \omega_0}$ where m_N is the mass of the nucleus and ω_0 is the optical phonon energy, an intermediate scattering regime characterized by multi-phonon excitations emerges. We study a greatly simplified model of a single nucleus in a harmonic potential and show that, while the mean energy deposited for a given momentum transfer q is equal to the elastic value $q^2/(2m_N)$, the phonon occupation number follows a Poisson distribution and thus the energy spread is $\Delta E = q\sqrt{\omega_0/(2m_N)}$. This observation suggests that low-threshold calorimetric detectors may have significantly inc… expectation from elastic scattering, even when the energy threshold is above the single-phon… for phonons above the elastic energy. We use a simple model of electronic excitations to argu… ionization signals induced from DM-electron scattering or the Migdal effect. In well-motivated… dark photon, we show that these signals can probe experimental milestones for cosmological… thermal target for Majorana fermion DM.

Comments: 6 pages, 3 figures, plus supplementary material
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Cosmology and Nongalactic Astrophysics (…
Report number: FERMILAB-PUB-20-588-T
Cite as: arXiv:2011.09477 **[hep-ph]**
(or arXiv:2011.09477v1 **[hep-ph]** for this version)

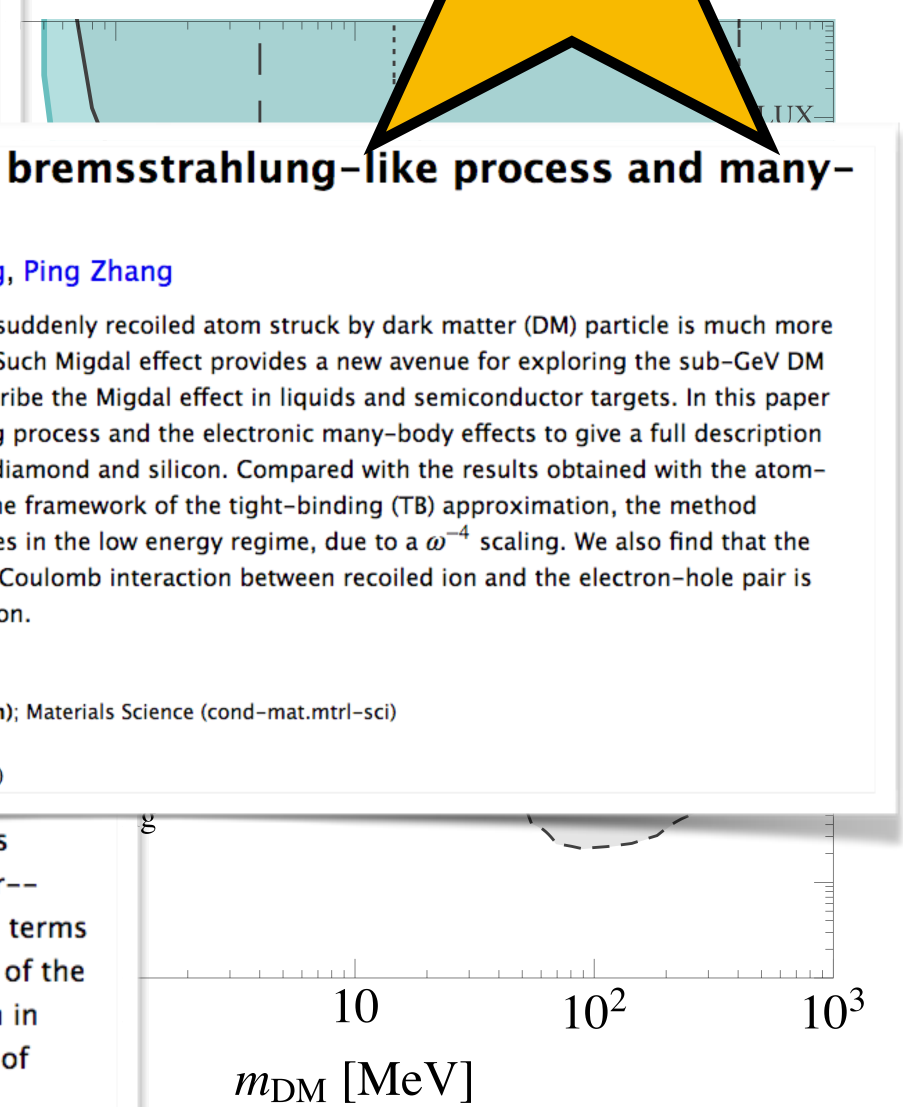


Describing Migdal effect with bremsstrahlung-like process and many-body effects

Zheng-Liang Liang, Chongjie Mo, Fawei Zheng, Ping Zhang

Recent theoretical studies have suggested that the suddenly recoiled atom struck by dark matter (DM) particle is much more likely to excite or lose its electrons than expected. Such Migdal effect provides a new avenue for exploring the sub-GeV DM particles. There have been various attempts to describe the Migdal effect in liquids and semiconductor targets. In this paper we incorporate the treatment of the bremsstrahlung process and the electronic many-body effects to give a full description of the Migdal effect in bulk semiconductor targets diamond and silicon. Compared with the results obtained with the atom-centered localized Wannier functions (WFs) under the framework of the tight-binding (TB) approximation, the method proposed in this study yields much larger event rates in the low energy regime, due to a ω^{-4} scaling. We also find that the effect of the bremsstrahlung photon mediating the Coulomb interaction between recoiled ion and the electron-hole pair is equivalent to that of the exchange of a single phonon.

Comments: 9+5 pages, 6 figures
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; Materials Science (cond-mat.mtrl-sci)
Cite as: arXiv:2011.13352 **[hep-ph]**
(or arXiv:2011.13352v1 **[hep-ph]** for this version)



The Migdal effect in semiconductors

Simon Knapen, Jonathan Kozaczuk, Tongyan Lin

When a nucleus in an atom undergoes a collision, there is a small probability to inelastically excite an electron. This is known as the Migdal effect. In this Letter, we present a first complete derivation of the Migdal effect from dark matter--nucleus scattering in semiconductors, which also accounts for multiphonon production. The rate can be expressed in terms of the energy loss function of the material, which we calculate with density functional theory (DFT) methods. Because of the smaller gap for electron excitations, we find that the rate for the Migdal effect is much higher in semiconductors than in atomic targets. Accounting for the Migdal effect in semiconductors can therefore significantly improve the sensitivity of experiments such as DAMIC, SENSEI and SuperCDMS to sub-GeV dark matter.

Comments: 5+11 pages. Comments welcome
Subjects: **High Energy Physics - Phenomenology (hep-ph)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2011.09496 **[hep-ph]**
(or arXiv:2011.09496v1 **[hep-ph]** for this version)

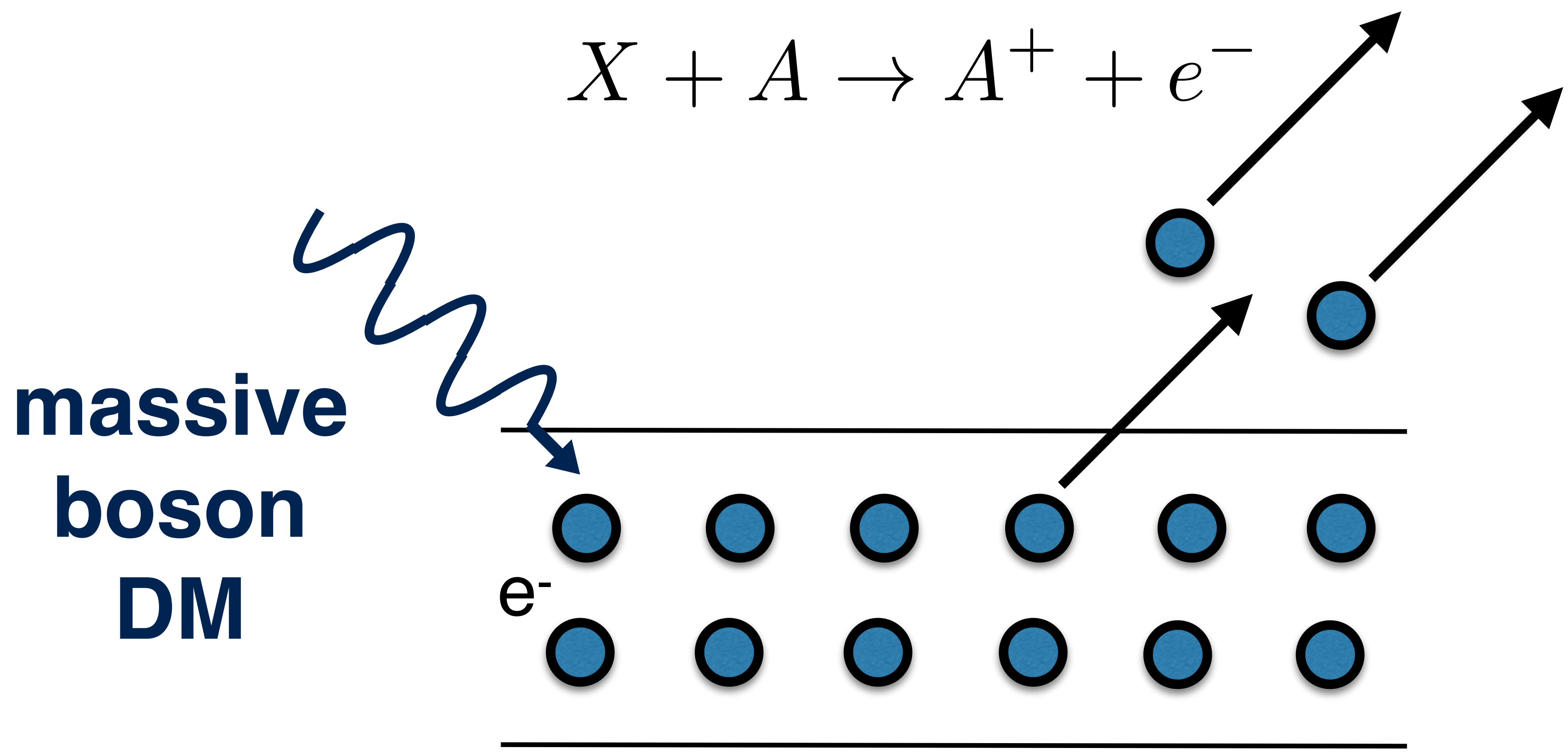
…SEI collaboration [arXiv:2004.11378],
…*.Rev.Lett.* 125 (2020) 17, 171802
…*ors' Suggestion*

Essig, Pradler, Sholapurkar, TTY *Phys.Rev.Lett.* 124 (2020) 2, 021801 [arXiv:1908.10881]

sub-GeV DM direct detection

- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
- **Dark matter-nucleus scattering** through the Migdal scattering and bremsstrahlung
- **Absorption** of light dark matter, including axion-like particles and dark photons.
- **Dark matter scattering off collective modes** in molecules and in crystals (including phonons, plasmons and magnons)

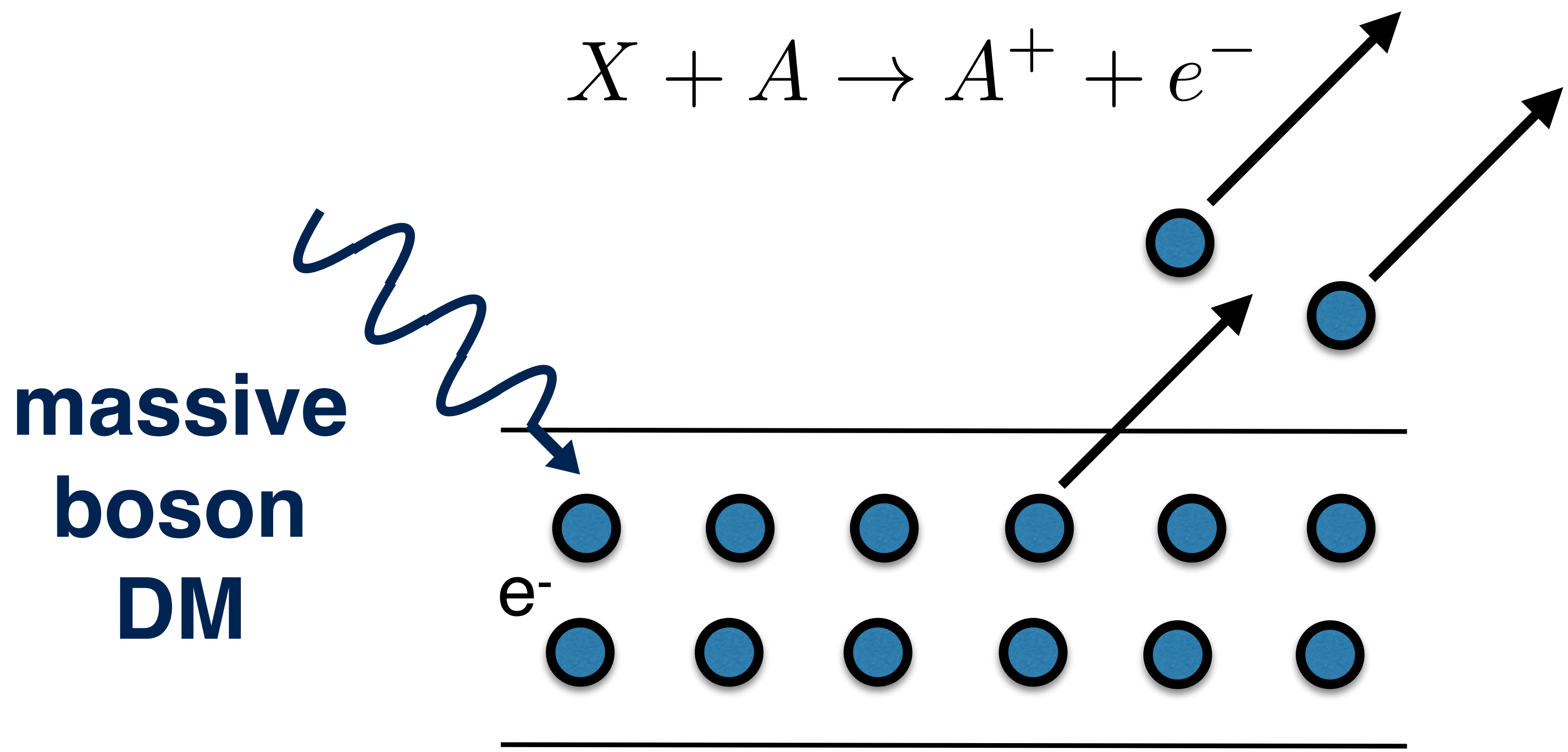
photoelectric effect



**absorb all of the energy
the incoming dark matter**

photoelectric effect

$$X + A \to A^+ + e^-$$



photon

$$|\vec{q}| = \omega$$

bosonic dark matter

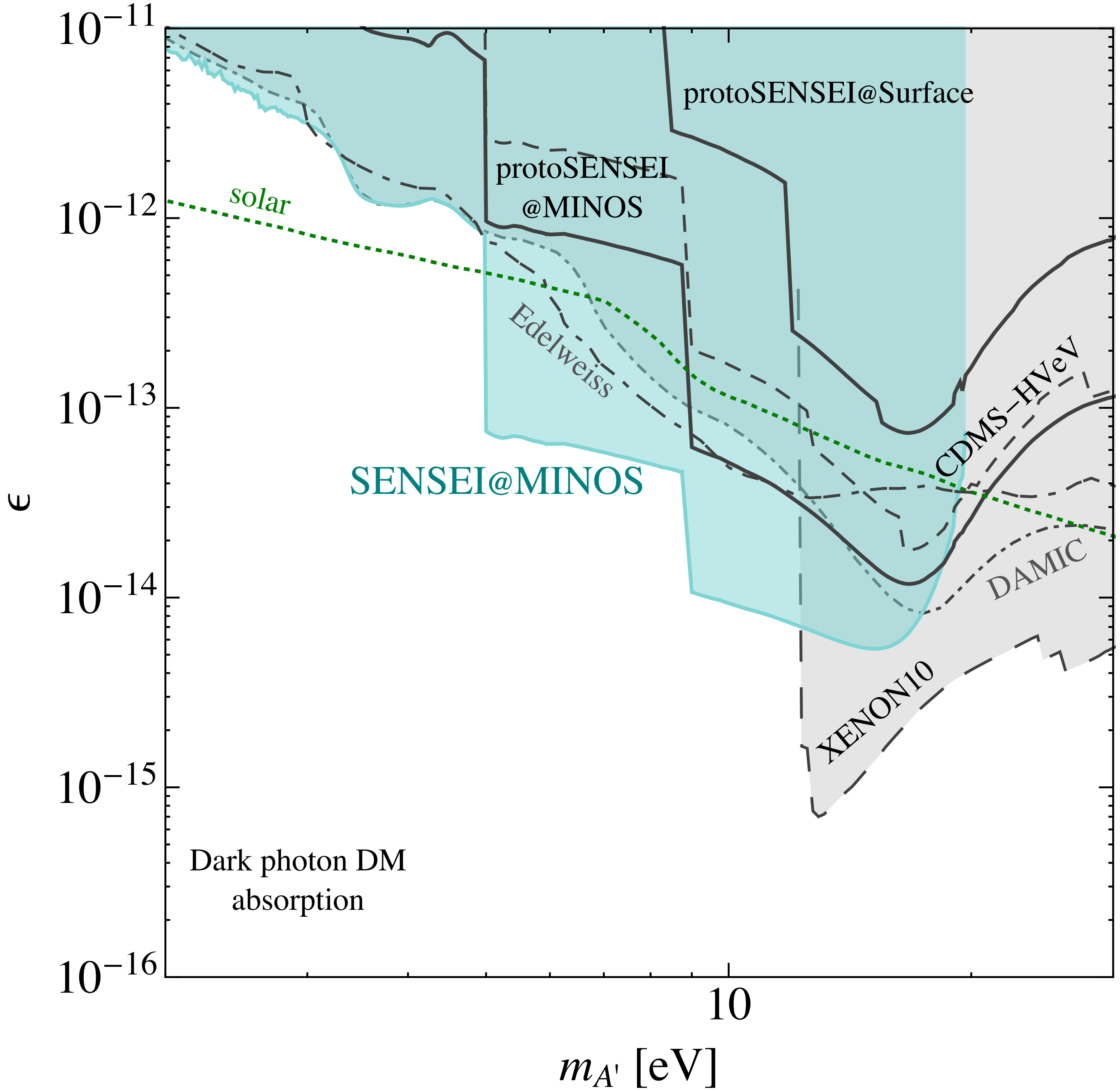
$$|\vec{q}| = m_X v_{\rm DM} \sim 10^{-3}\omega$$

$$< \quad |\vec{q}_e|$$

can relate massive boson absorption to photon absorption

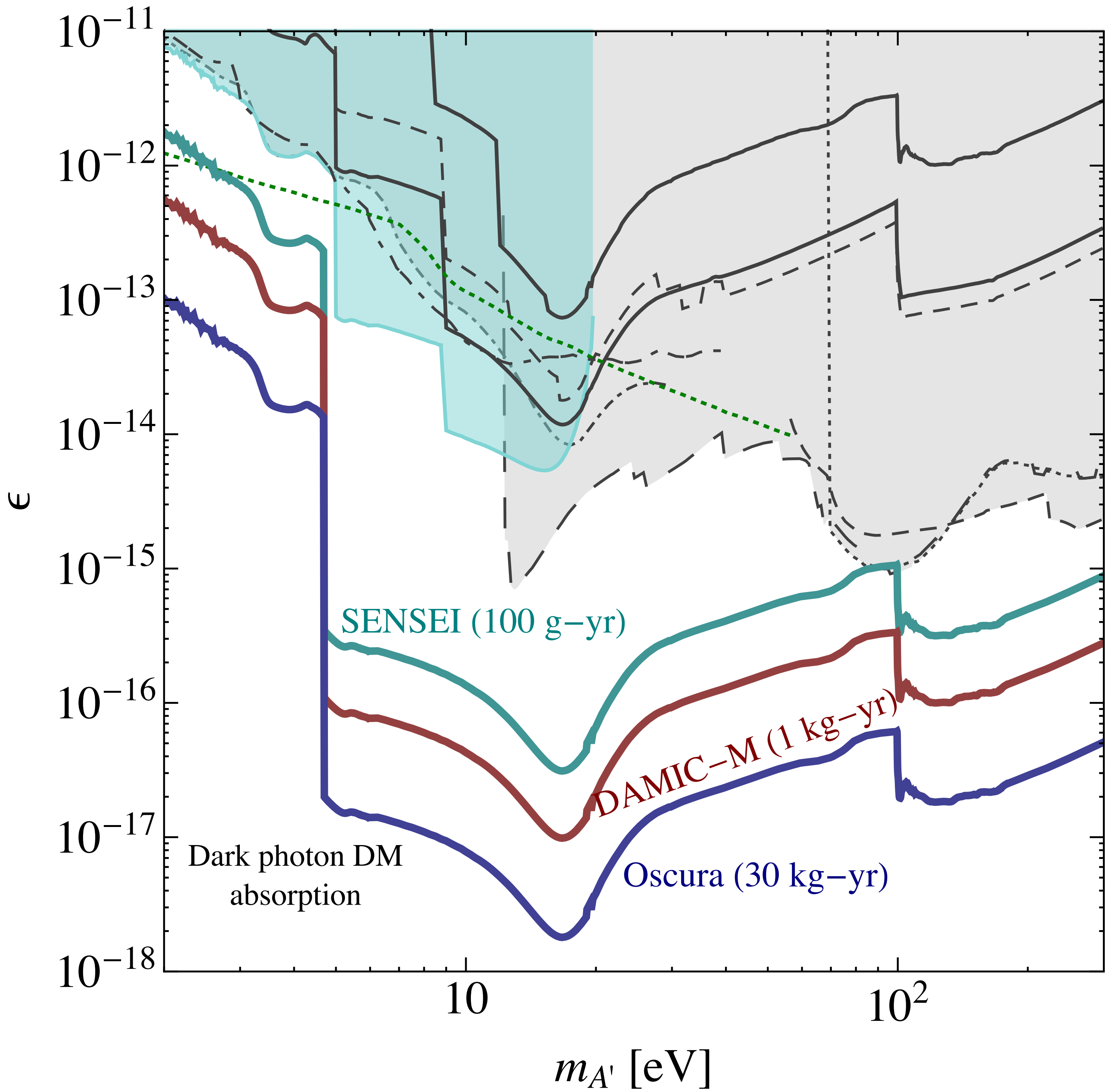
$$\sigma_{DM}(\omega) \propto \sigma_{\rm PE}(\omega)$$

Dark Photon DM



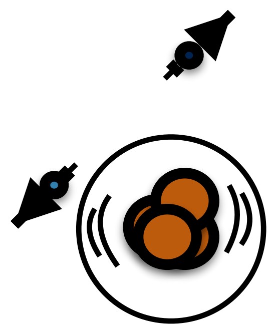
SENSEI collaboration [arXiv:2004.11378], *Phys.Rev.Lett.* 125 (2020) 17, 171802 *- Editors' Suggestion*

Dark Photon DM



theory models

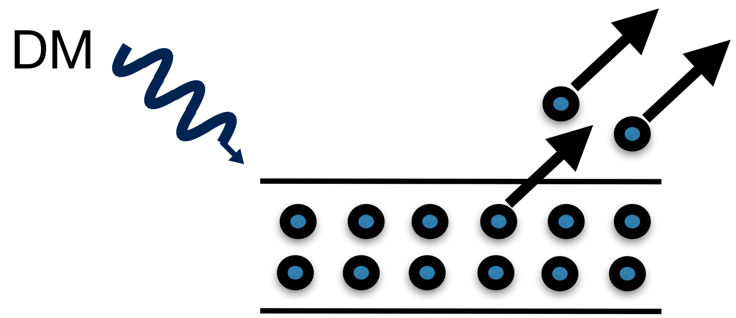
Dark matter-electron scattering



Rate ~ $\overline{\sigma}_e$ x exposure

$$m_\chi \gtrsim 0.3\ \text{MeV} \times \frac{\Delta E_B}{1\ \text{eV}}$$

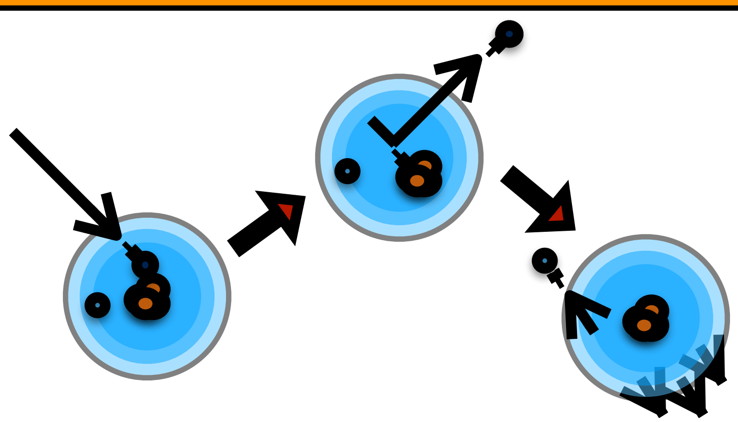
Bosonic dark matter absorption



Rate ~ ε^2 x exposure

$$m_\chi \gtrsim \Delta E_B$$

Dark matter-nuclear scattering



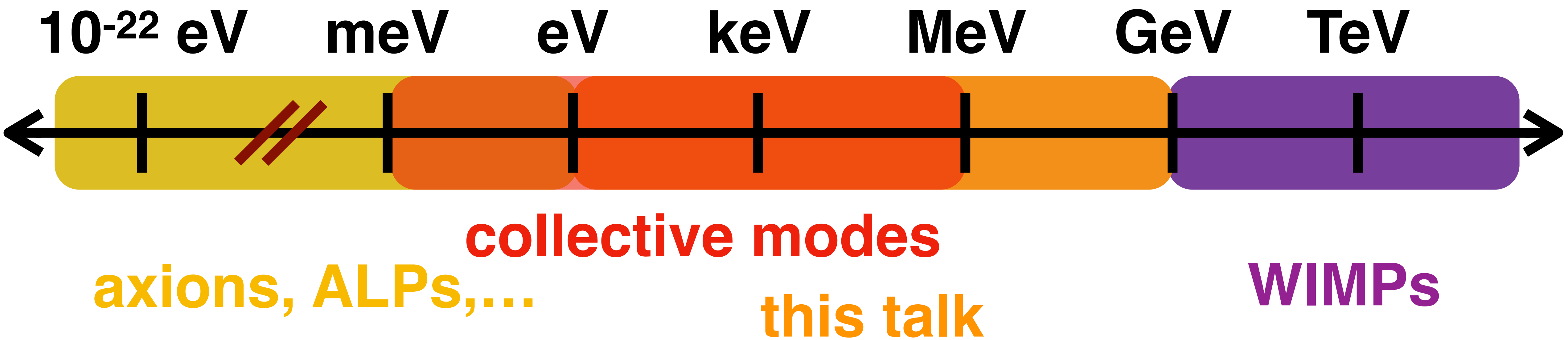
Rate ~ $\overline{\sigma}_n$ x exposure

$$m_\chi \gtrsim 0.3\ \text{MeV} \times \frac{\Delta E_B}{1\ \text{eV}}$$

sub-GeV DM direct detection

- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
- **Dark matter-nuclear scattering** through the Migdal scattering and bremsstrahlung
- **Absorption** of light dark matter, including axion-like particles and dark photons.
- **Dark matter scattering off collective modes** in molecules and in crystals (including phonons, plasmons and magnons)

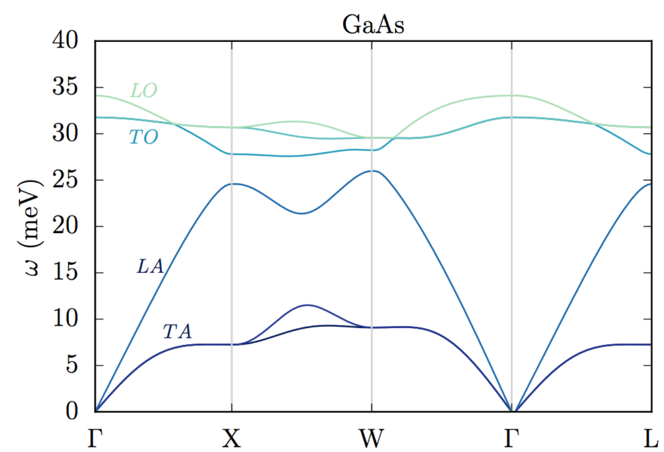
dark matter candidates



collective modes

energy gaps of meV in scale sensitive to sub-MeV DM

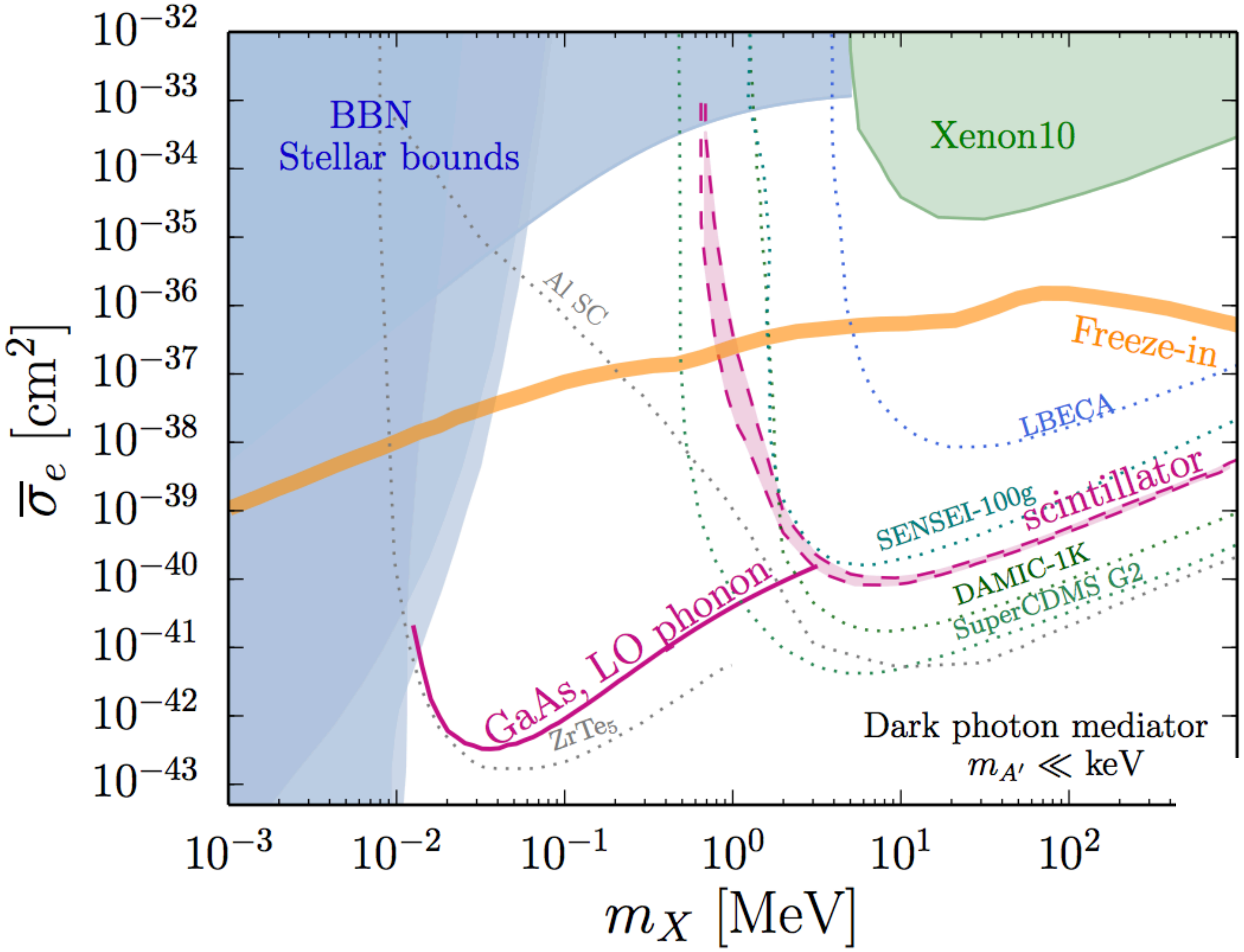
- **phonons**: collective excitation of atoms in a crystal
  - acoustic: “in-phase”
  - optical: “out-of-phase”



Griffin, Knapen, Lin, Zurek
Phys.Rev.D 98 (2018) 11, 115034
[arXiv:1807.10291]

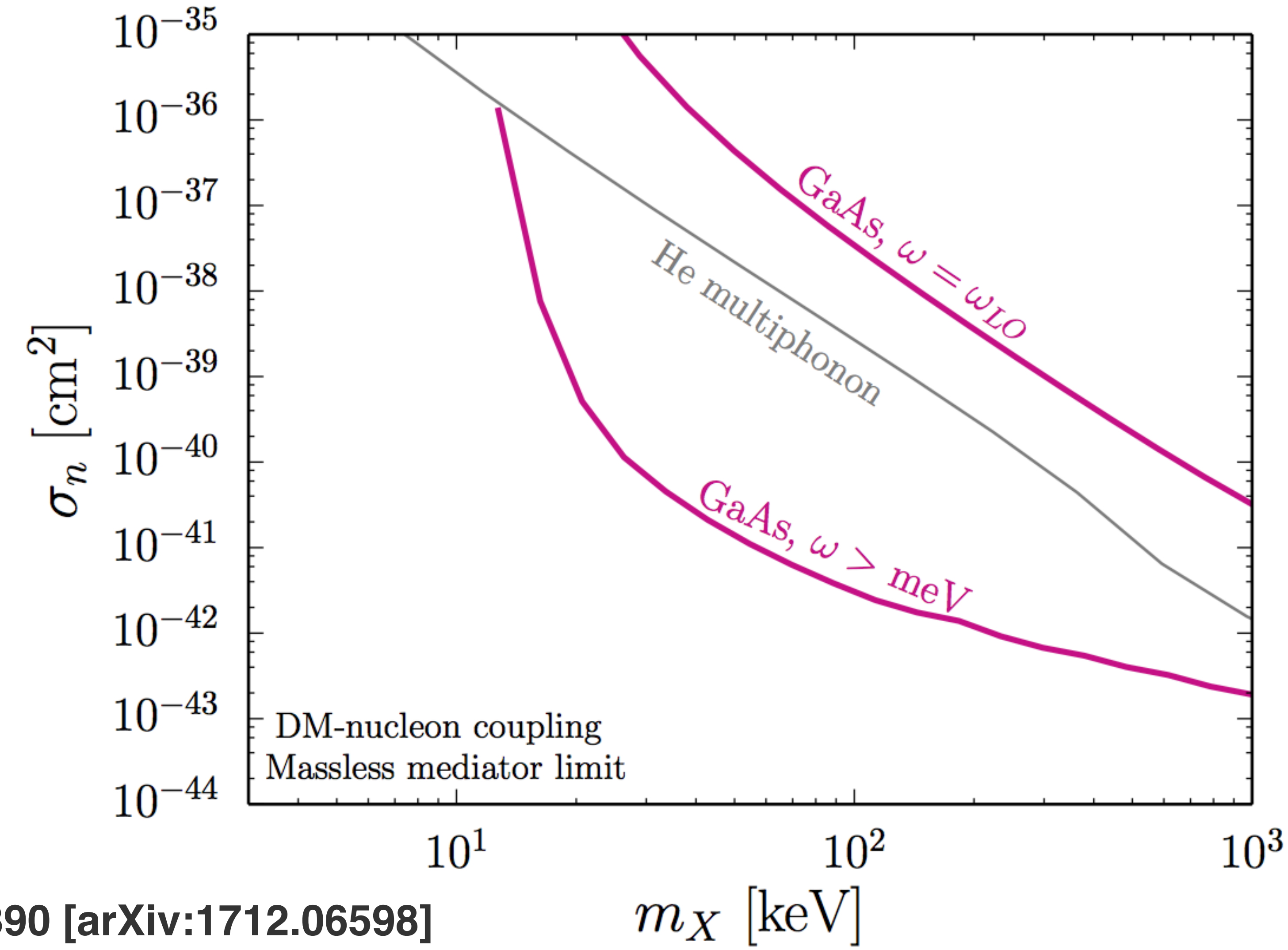
- **magnons**: collective excitation of electron spin
  - sensitive to spin-dependent interactions (DM-coupling to electron spin)
- there are also **plasmons** (collective excitation of electrons)…

see work by e.g. A. Caputo, A. Esposito, E. Geoffray, Y. Kahn, S. Knapen, G. Krnjaic, S. Griffin, T. Lin, T. Melia, A. Mitridate, A. D. Polosa, S. Rajendran, S. Sun,T. Trickle, Z. Zhang, K. Zurek, …



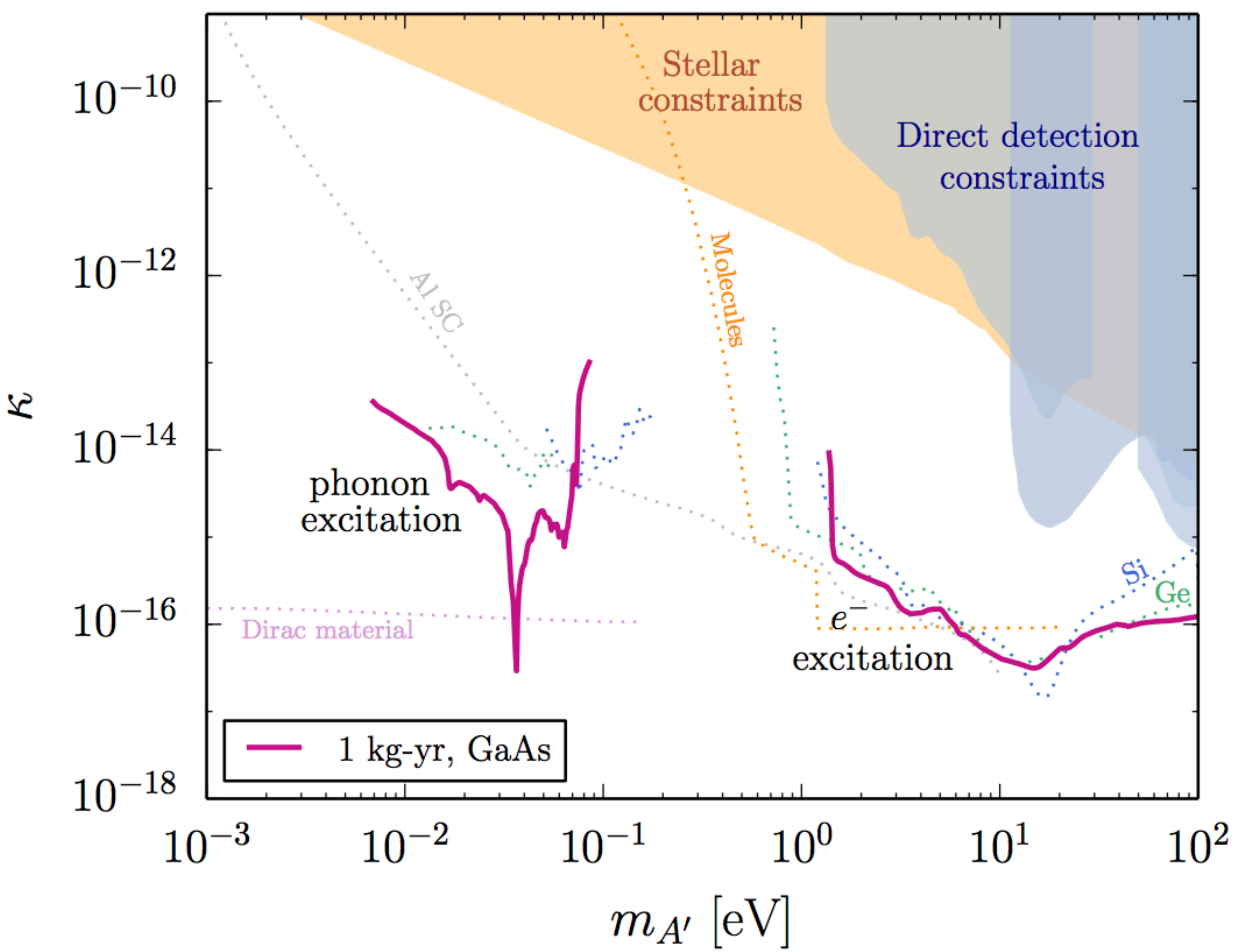
DM-electron interactions

DM-nucleon interactions



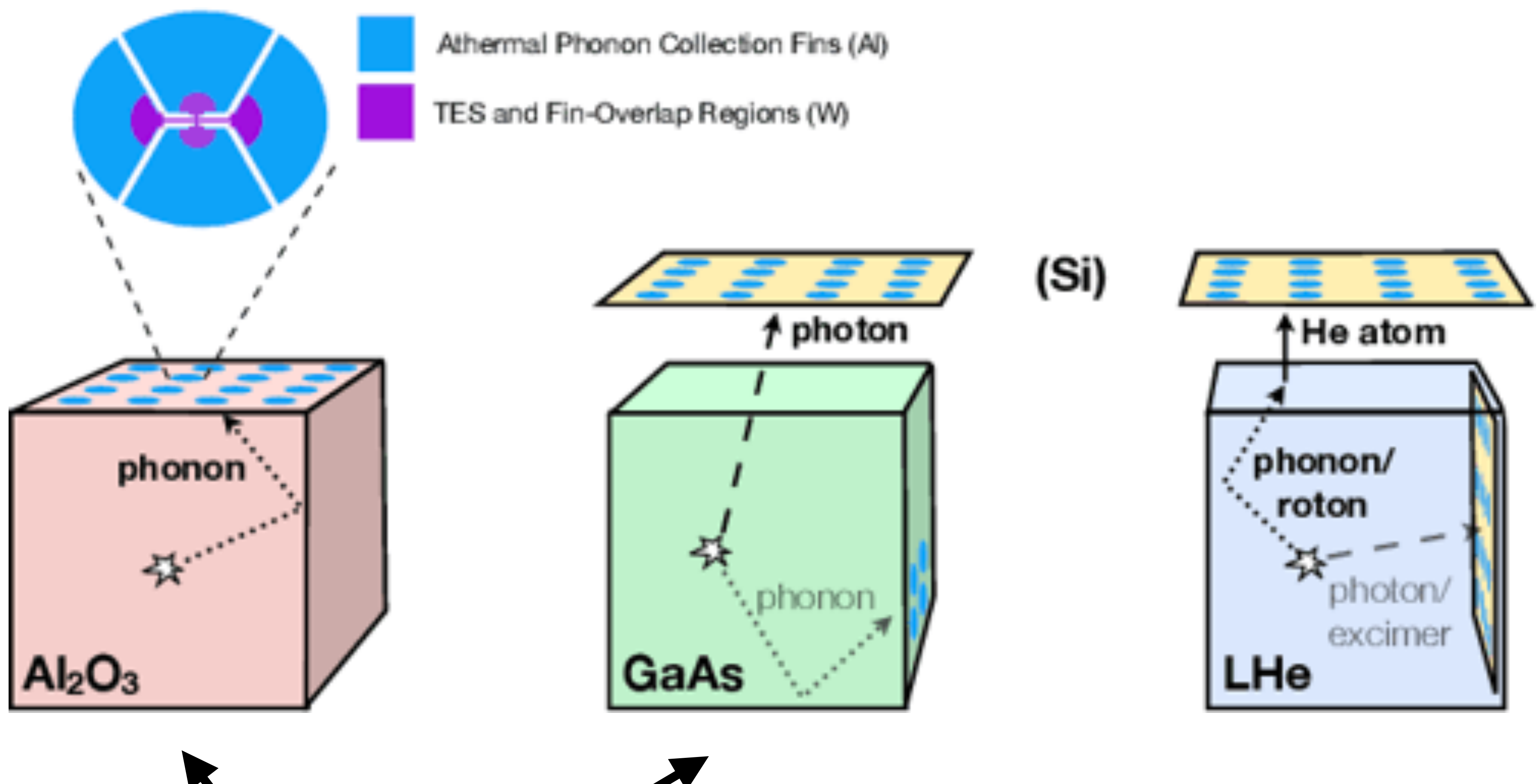
Knapen, Lin, Pyle, Zurek *Phys.Lett.B* 785 (2018) 386-390 [arXiv:1712.06598]

dark photon absorption



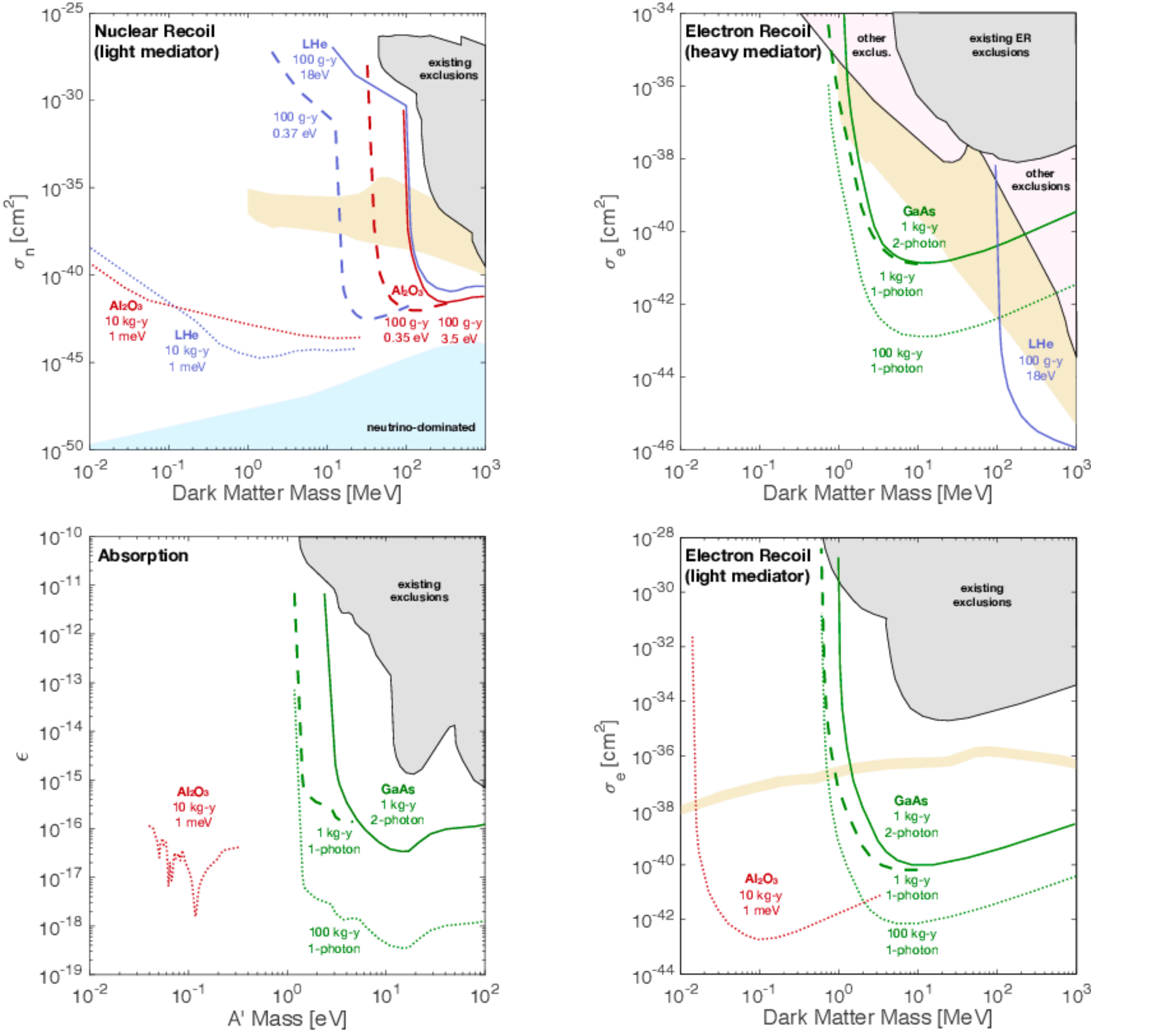
Knapen, Lin, Pyle, Zurek *Phys.Lett.B* 785 (2018) 386-390 [arXiv:1712.06598]

Transition **E**dge **S**ensors with **S**ub-**E**V **R**esolution **A**nd **C**ryogenic **T**argets



SPICE

HeRALD



The TESSERACT Dark Matter Project

dark matter candidates