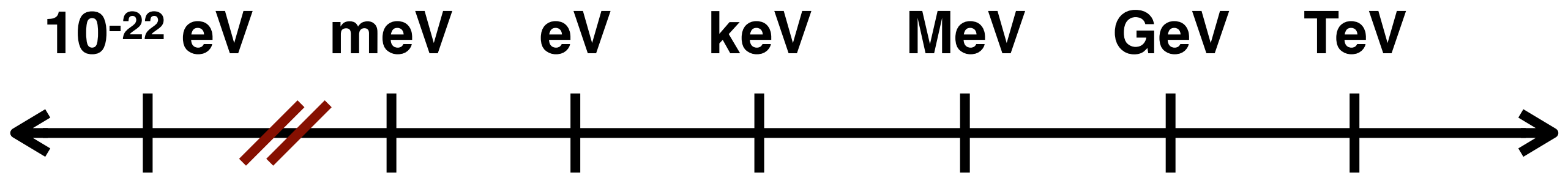


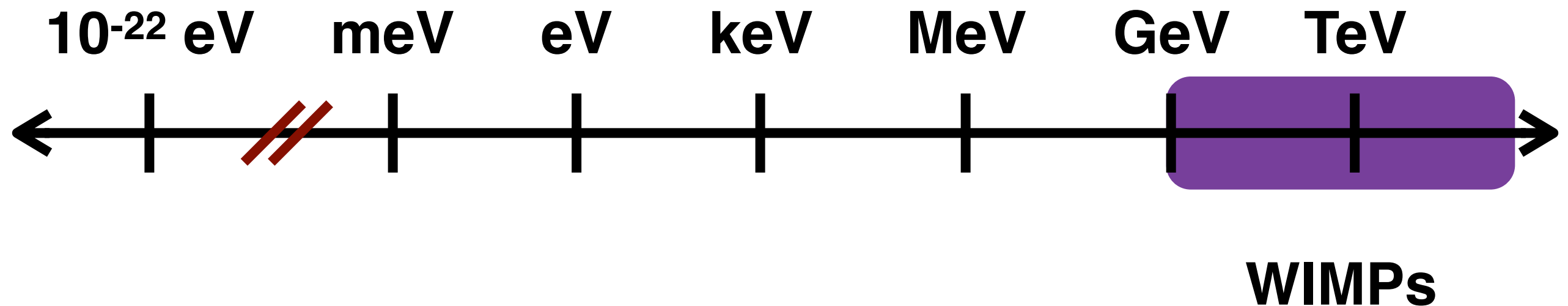
Updates on sub-GeV Dark Matter Direct Detection

Tien-Tien Yu
(University of Oregon)

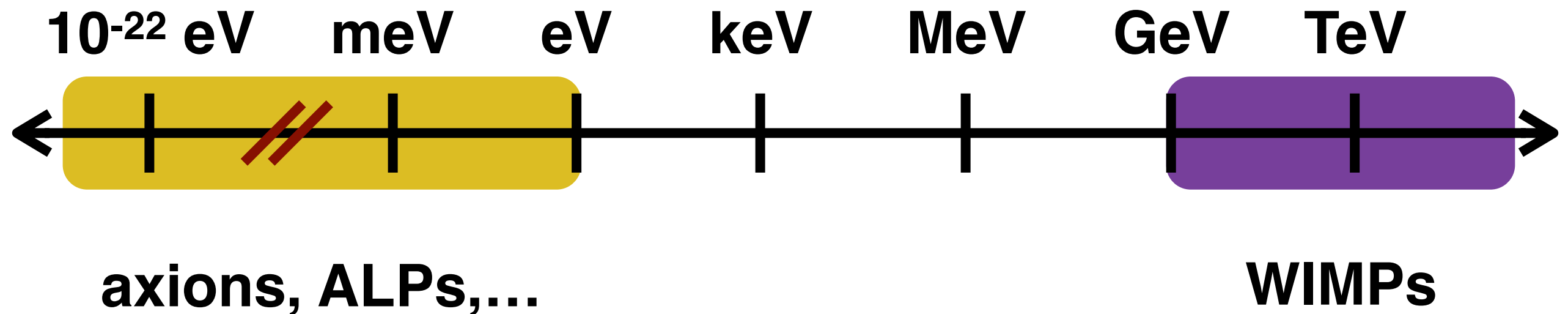
dark matter candidates



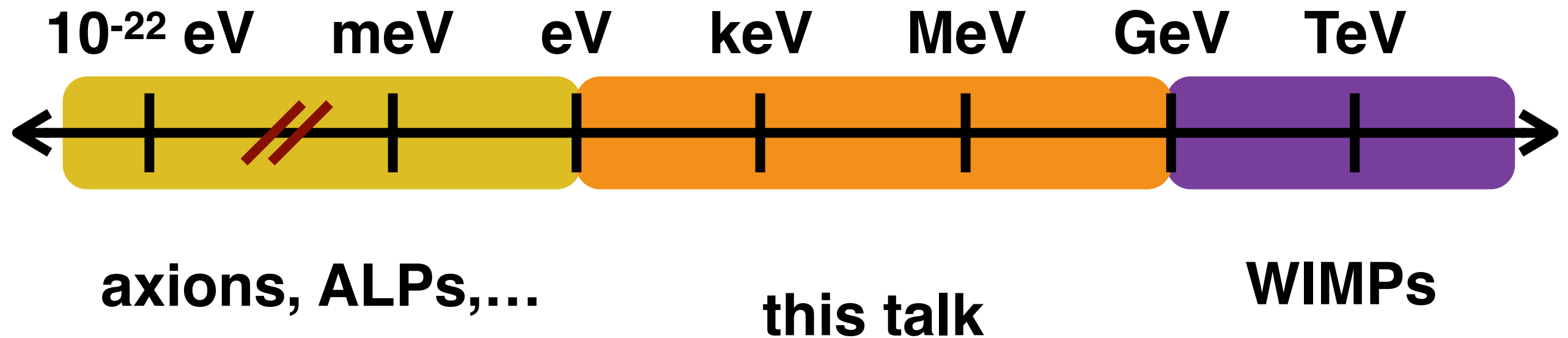
dark matter candidates



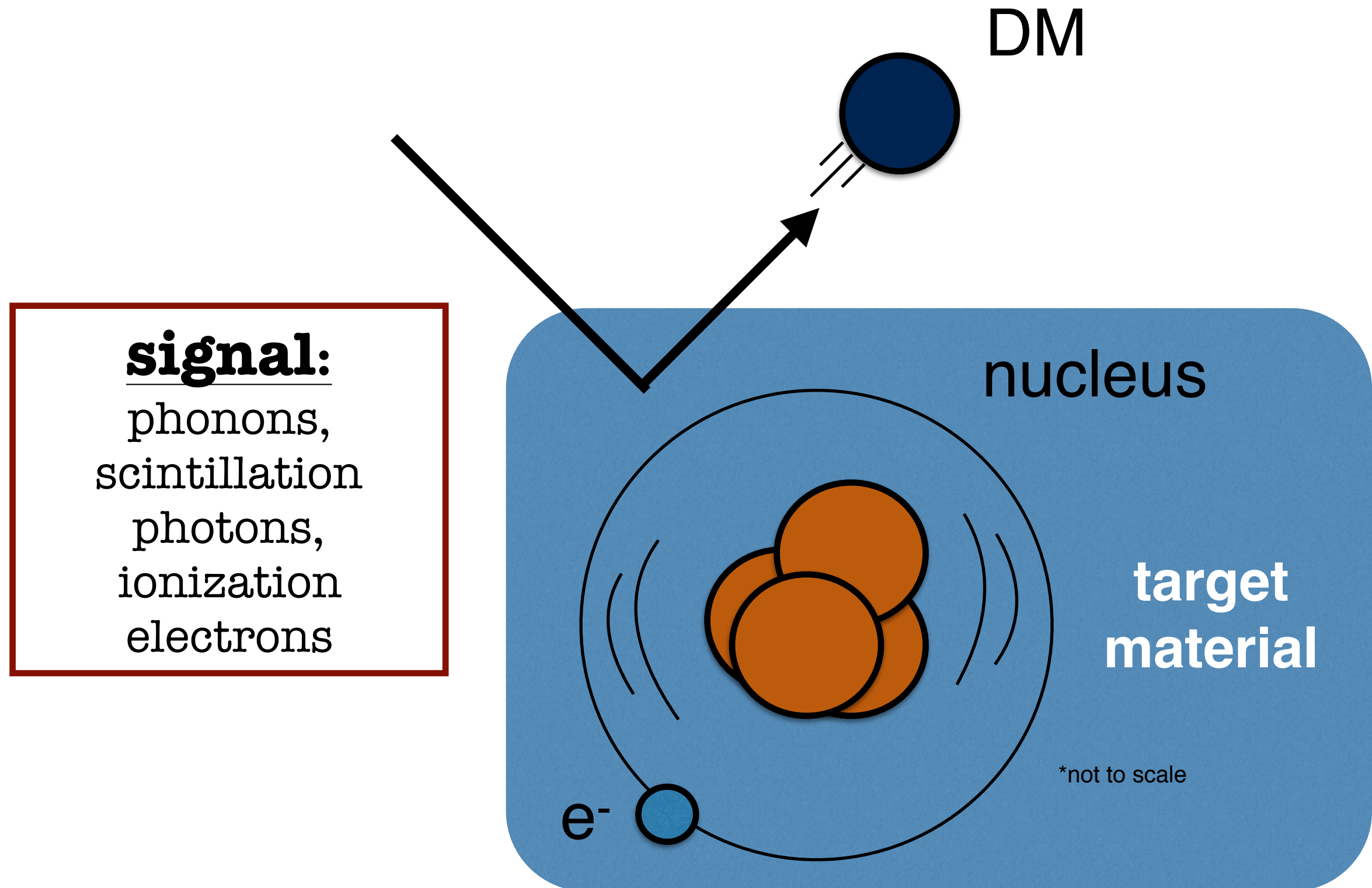
dark matter candidates



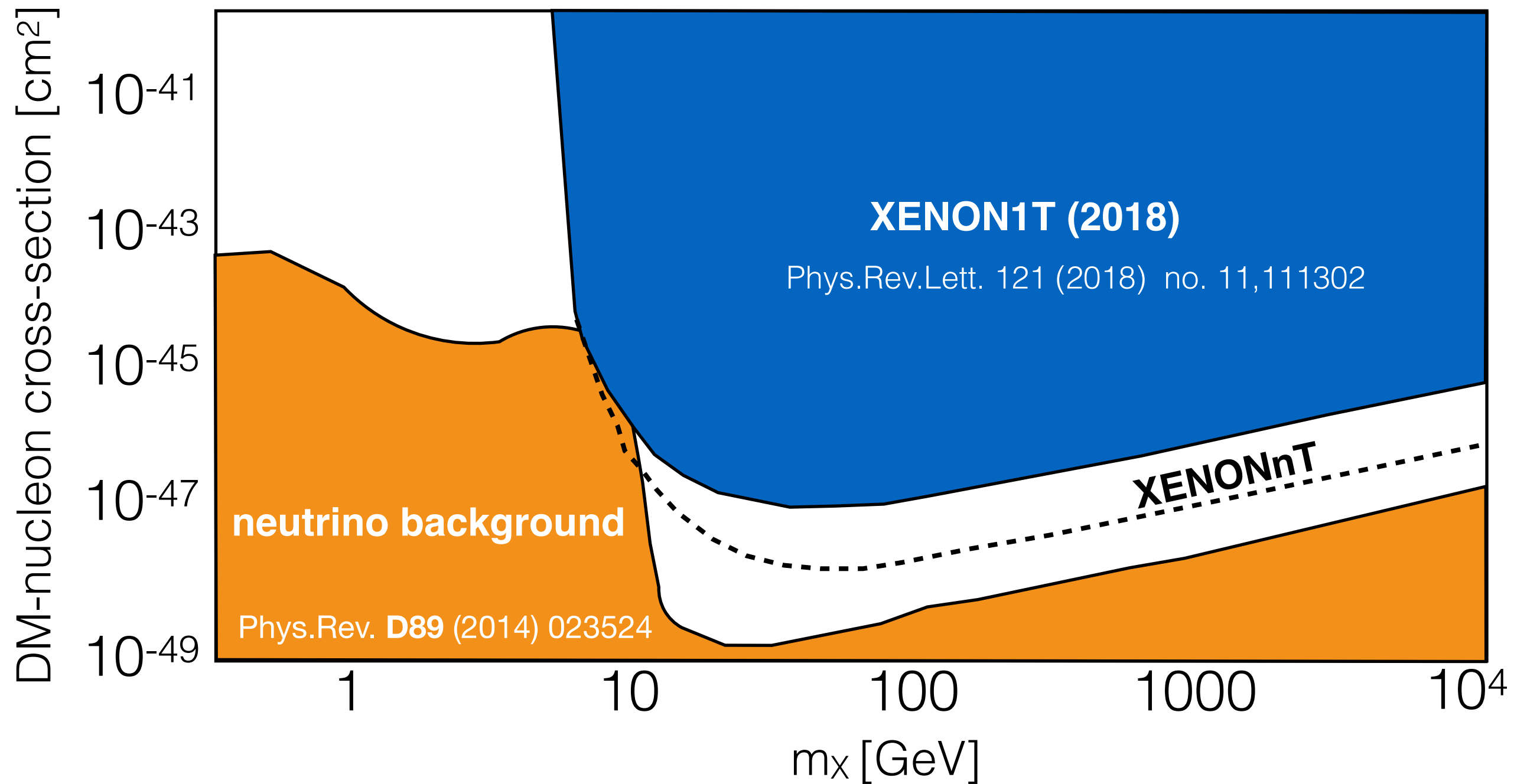
dark matter candidates



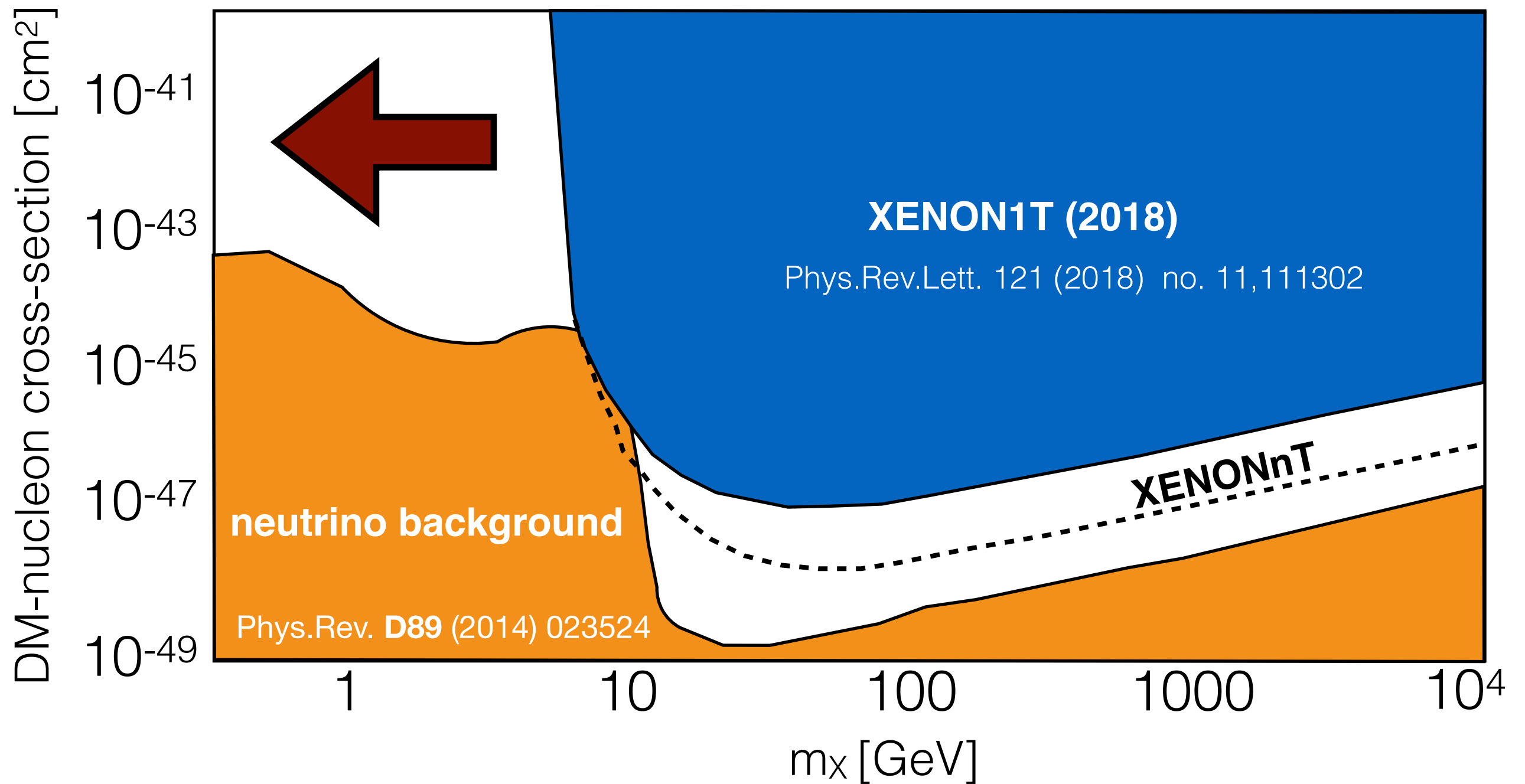
DM direct detection



direct detection



direct detection



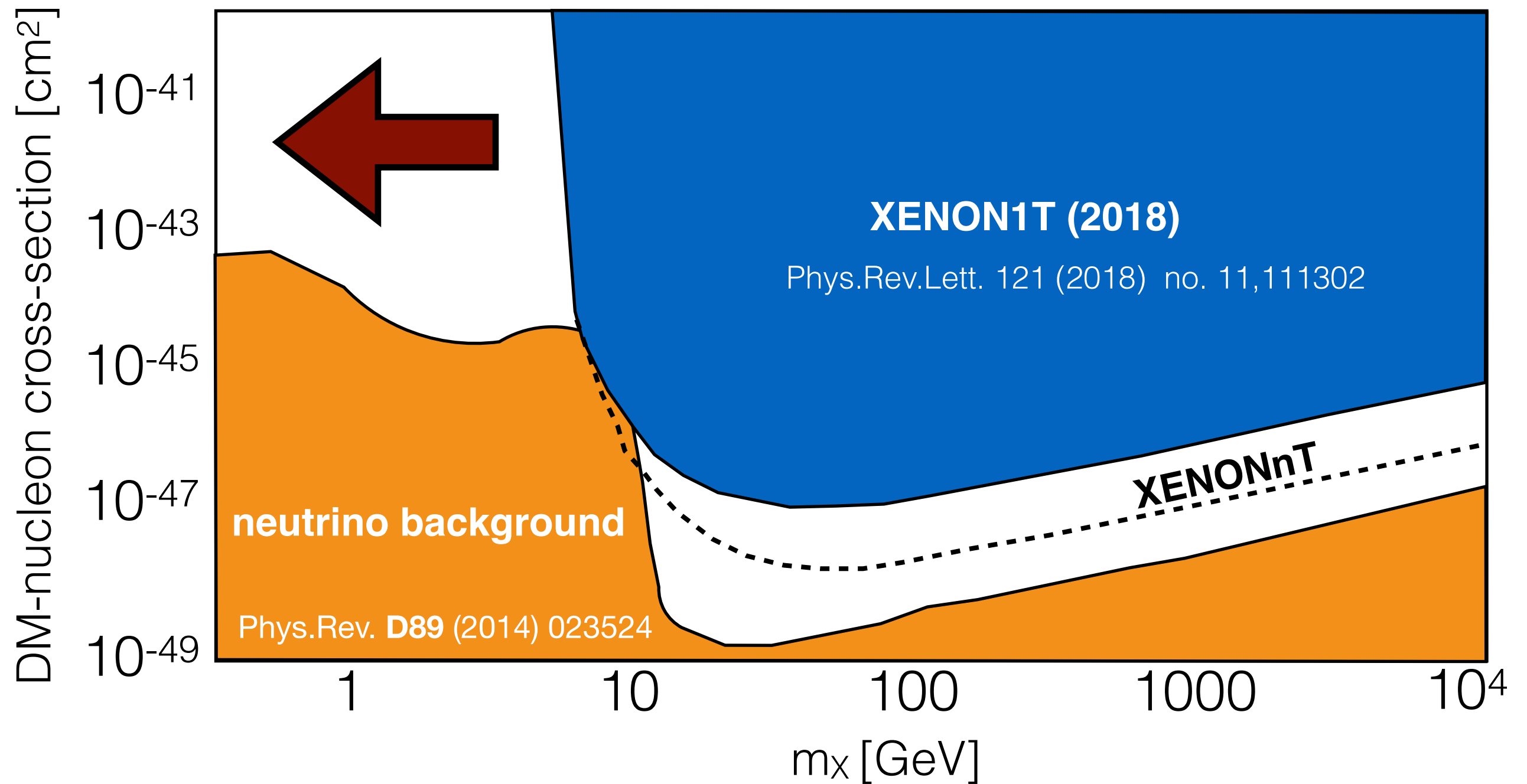
sub-GeV DM direct detection

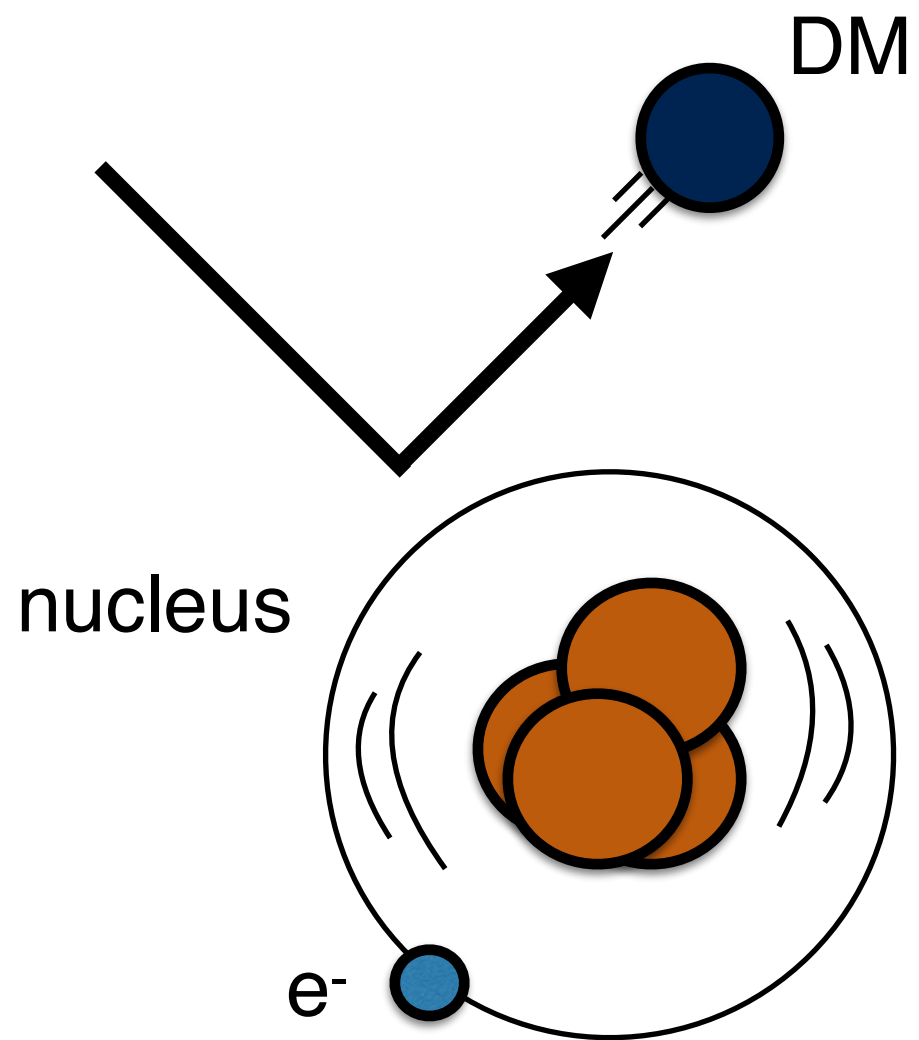
- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
- **Dark matter-nuclear scattering** through the Migdal scattering and bremsstrahlung
- **Absorption** of light dark matter, including axion-like particles and dark photons.
- **Dark matter scattering off collective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

sub-GeV DM direct detection

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direct detection

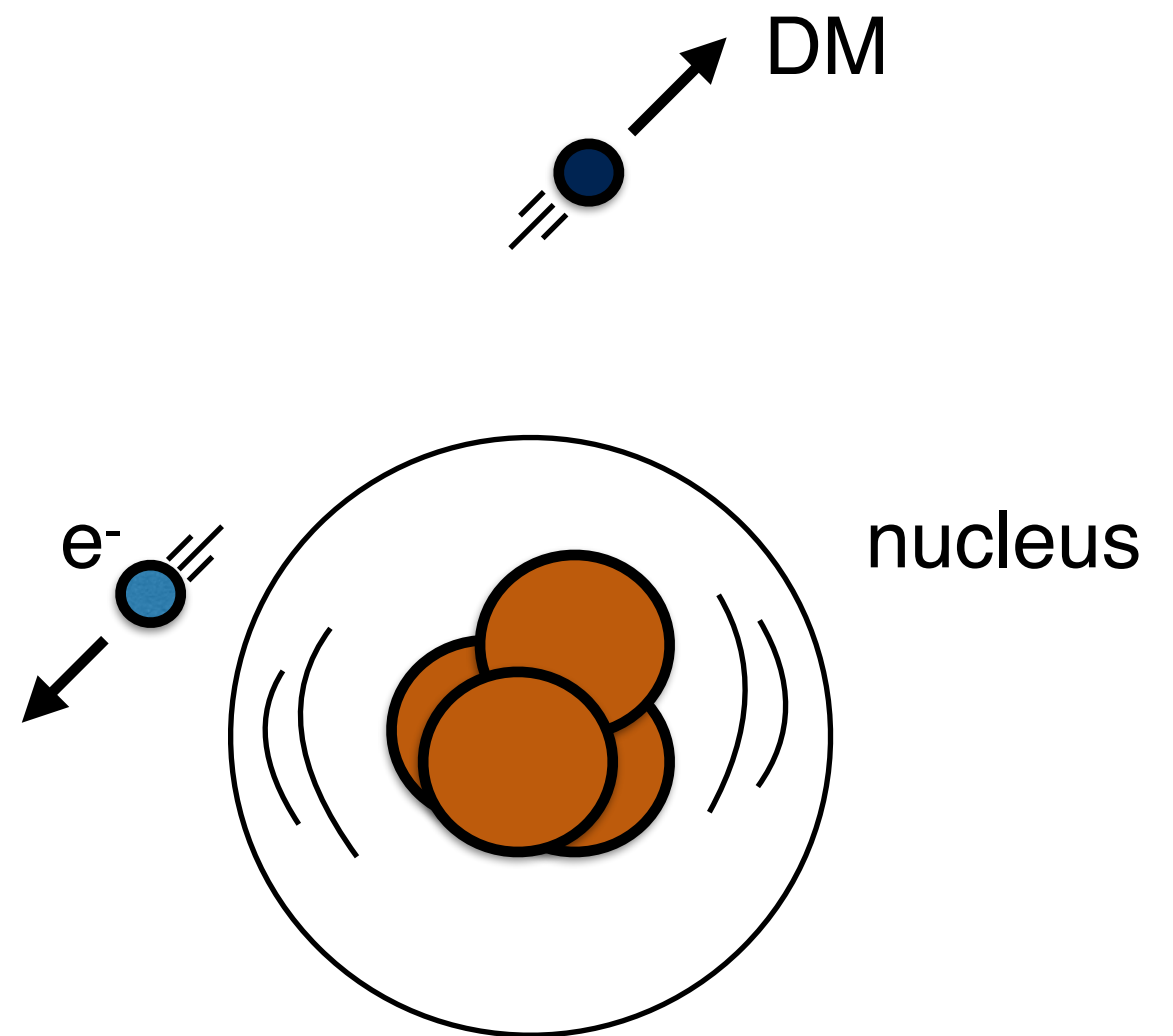




$$E_R = \frac{q^2}{2m_N}$$

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

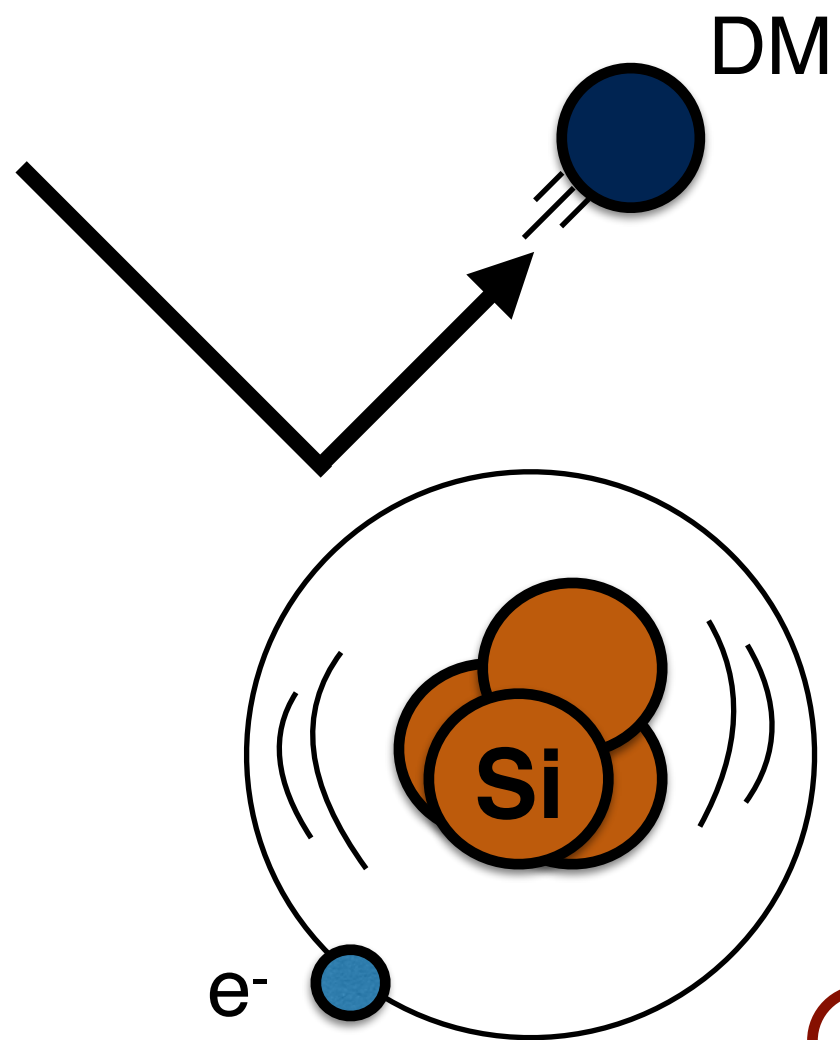
DM-nuclear scattering



$$E_R = \vec{q} \cdot \vec{v} - \frac{q^2}{2\mu_{\chi N}}$$

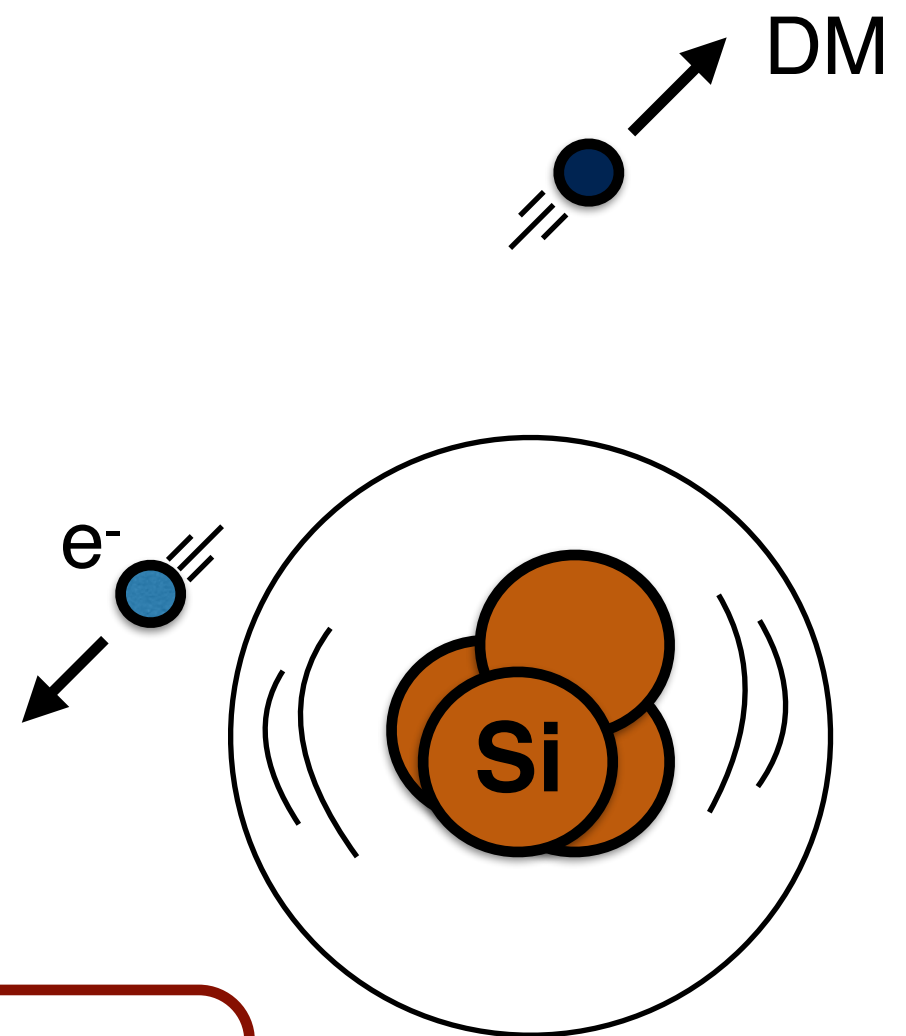
$$\sim \frac{1}{2} \text{ eV} \times \left(\frac{m_\chi}{\text{MeV}} \right)$$

DM-electron scattering



$$E_R \sim 0.1 \text{ eV}$$

DM-nuclear scattering



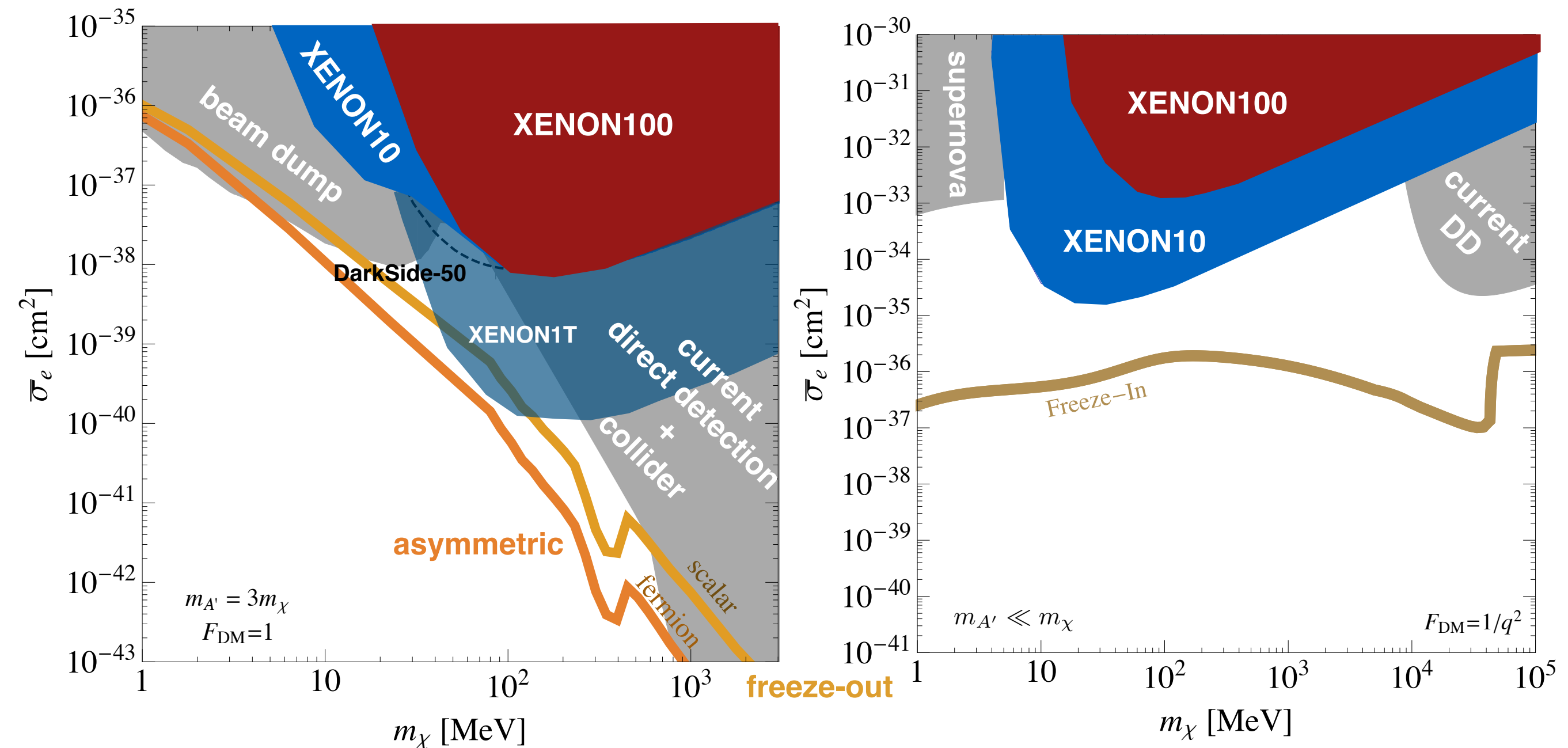
$$E_R \sim 50 \text{ eV}$$

DM-electron scattering

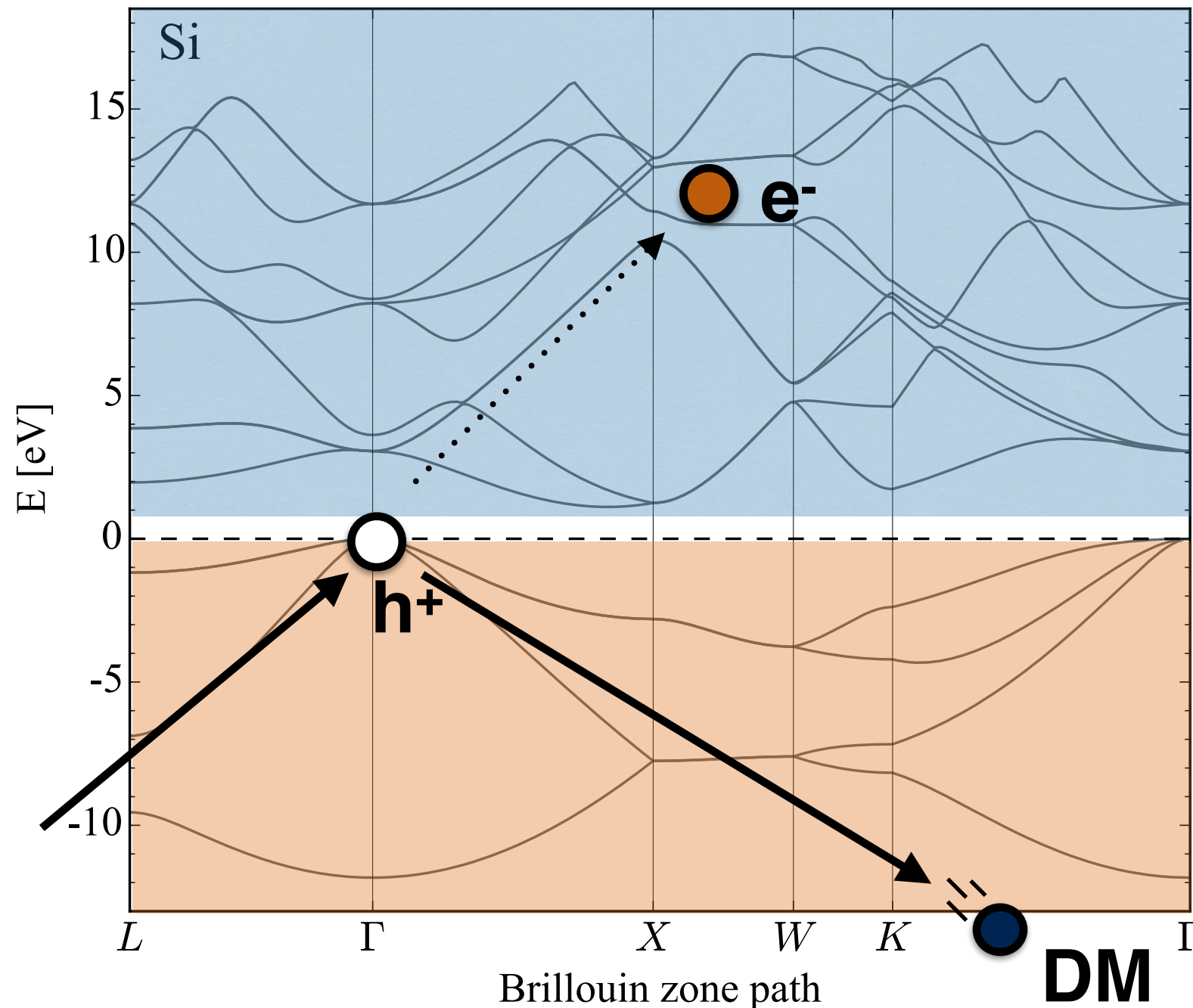
$$m_N = 28 \text{ GeV}$$

$$m_\chi = 100 \text{ MeV}$$

dark photon



semiconductor targets



detect the electron(s)

sensitive to $\sim$ eV energy depositions

**i.e. silicon,
germanium**

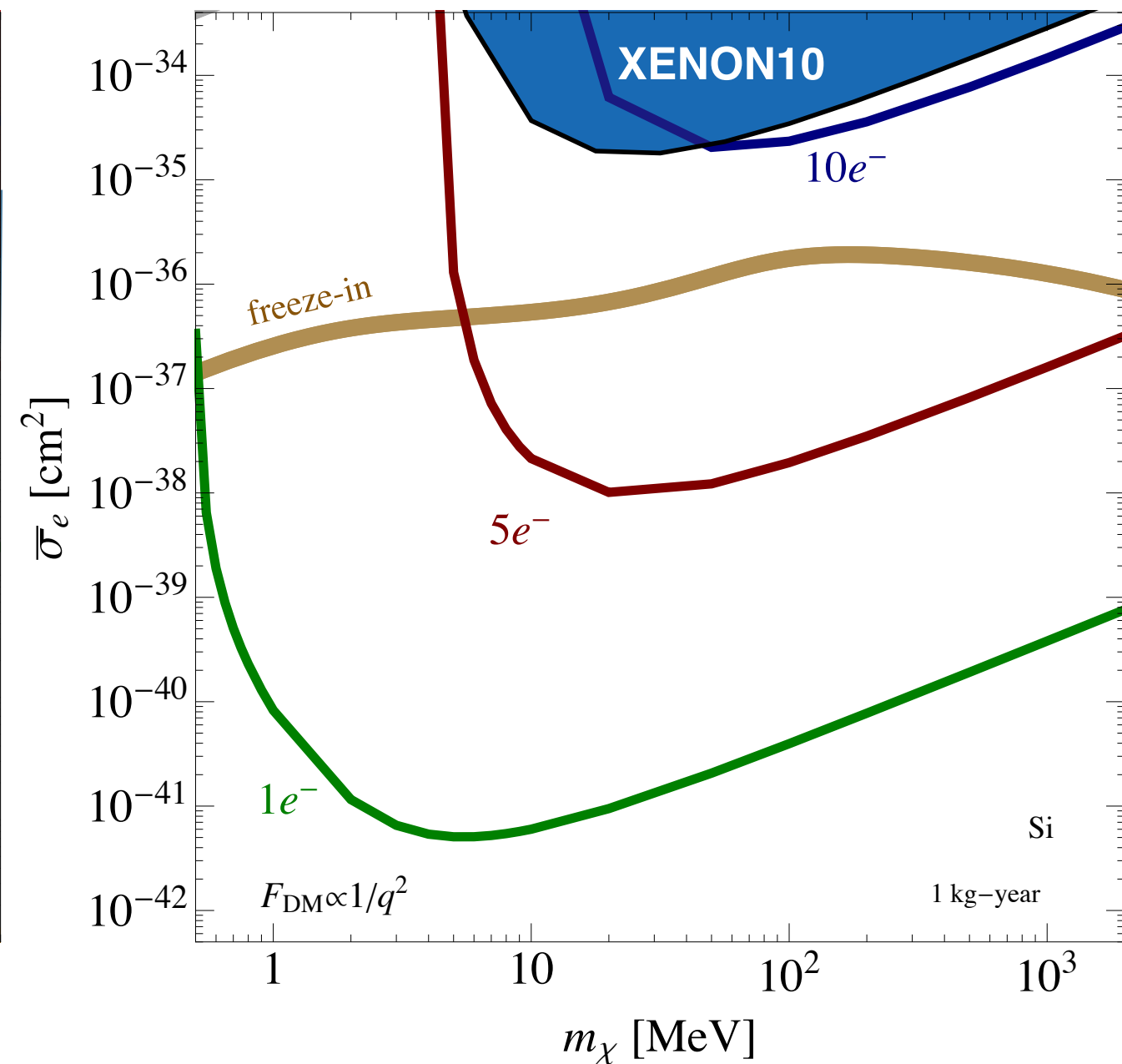
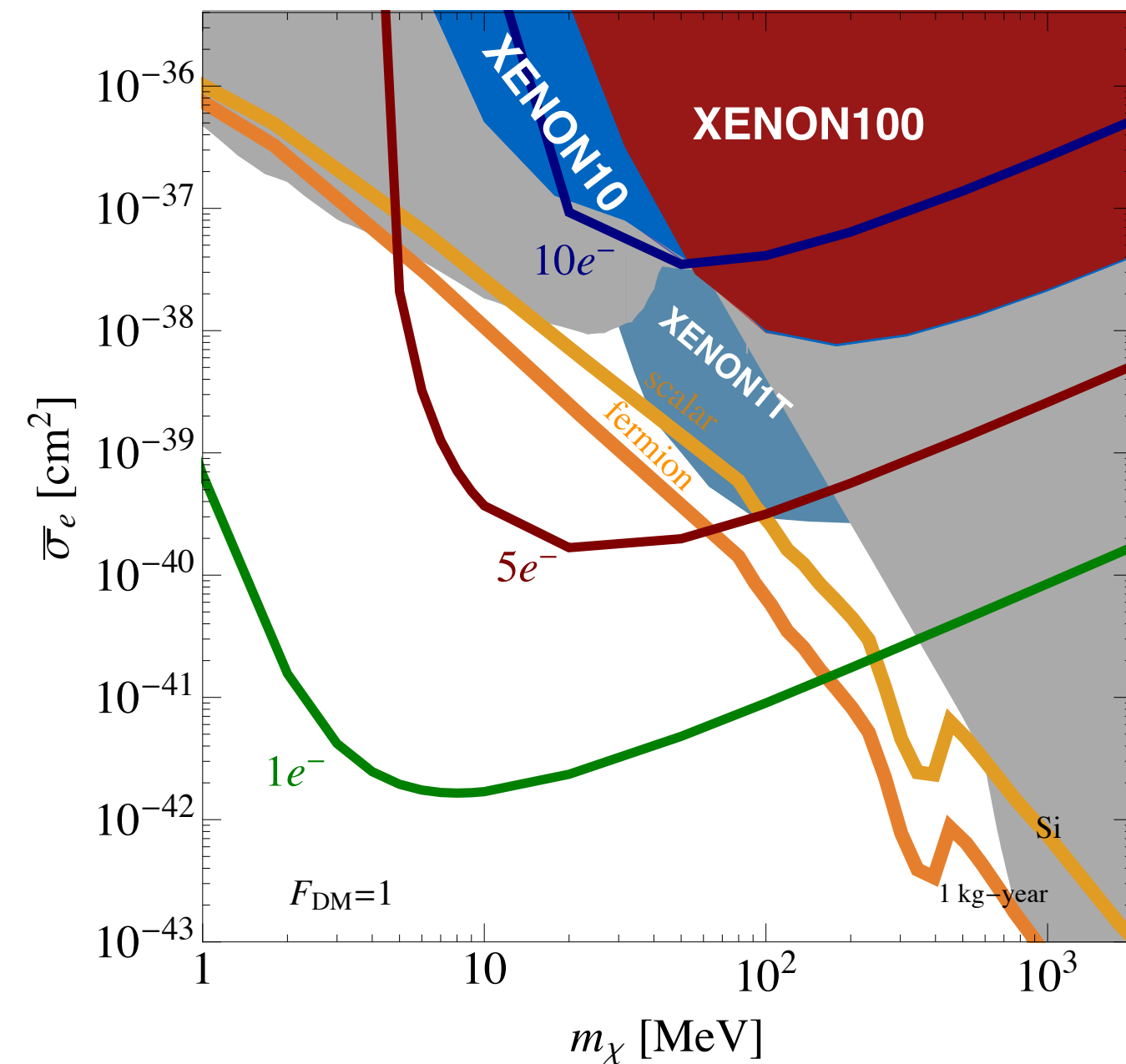
Essig, Mardon, Volansky [1108.5383]

Graham, Kaplan, Rajendran, Walters [1203.2531]

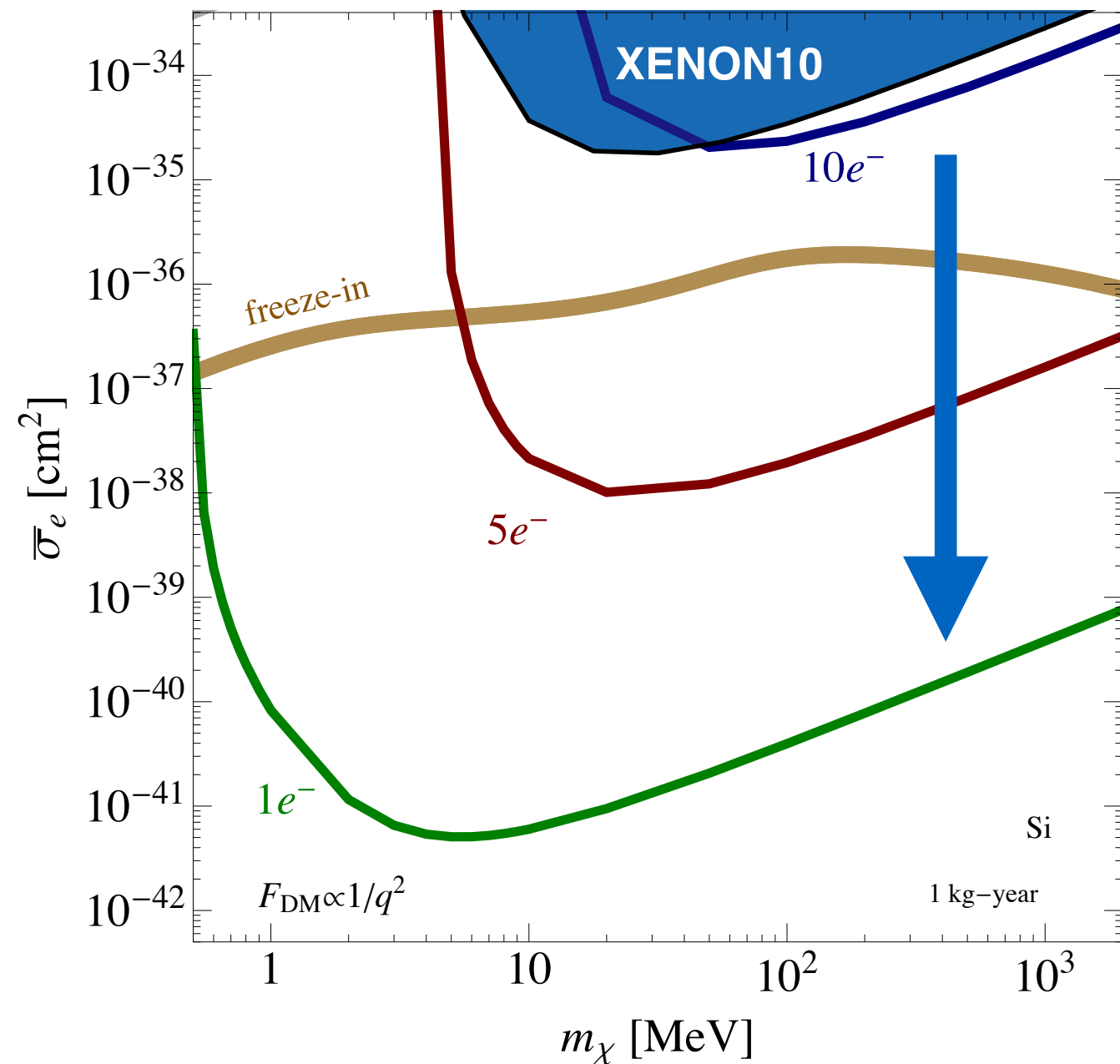
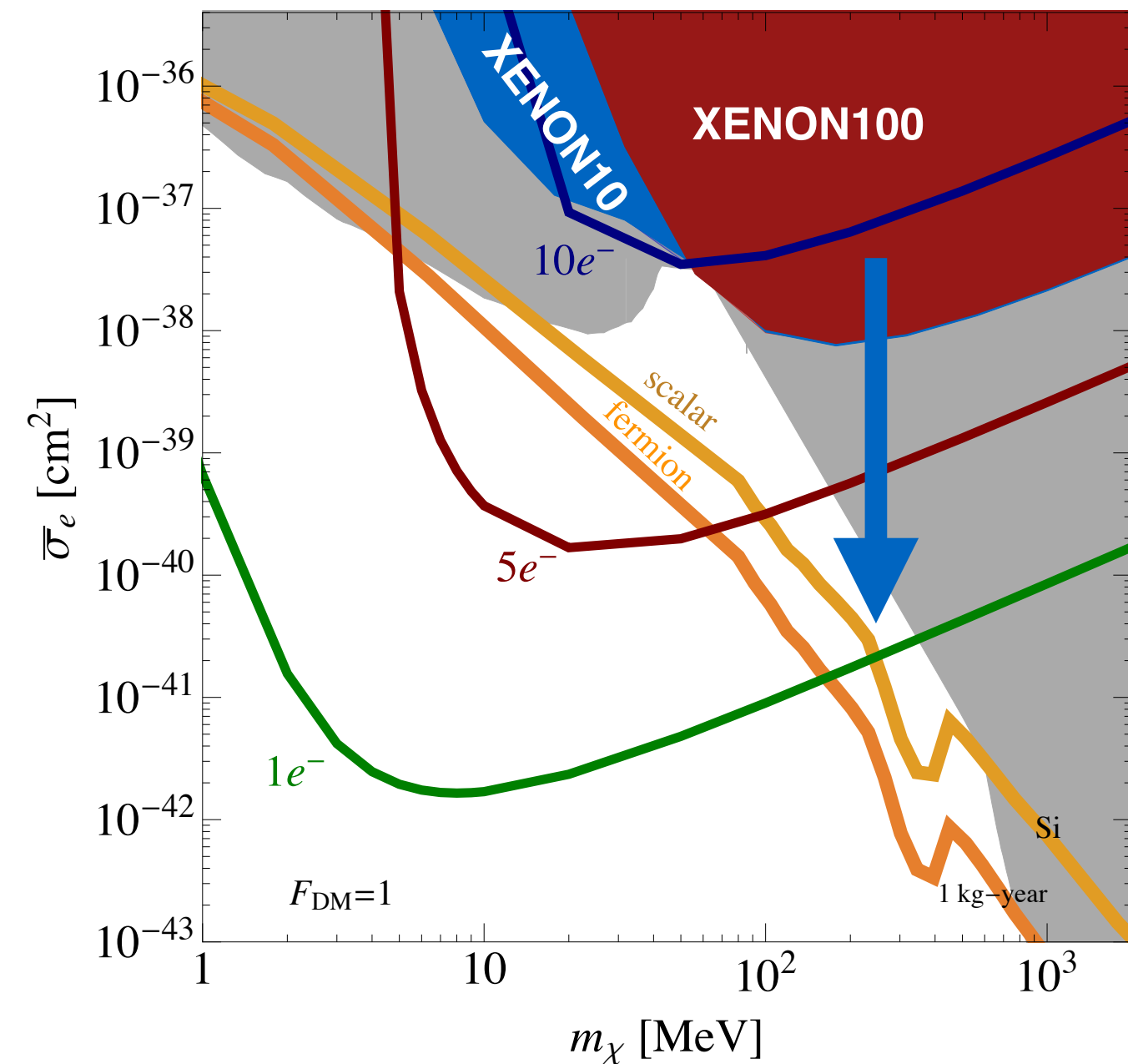
Lee, Lisanti, Mishra-Sharma, Safdi [1508.07361]

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

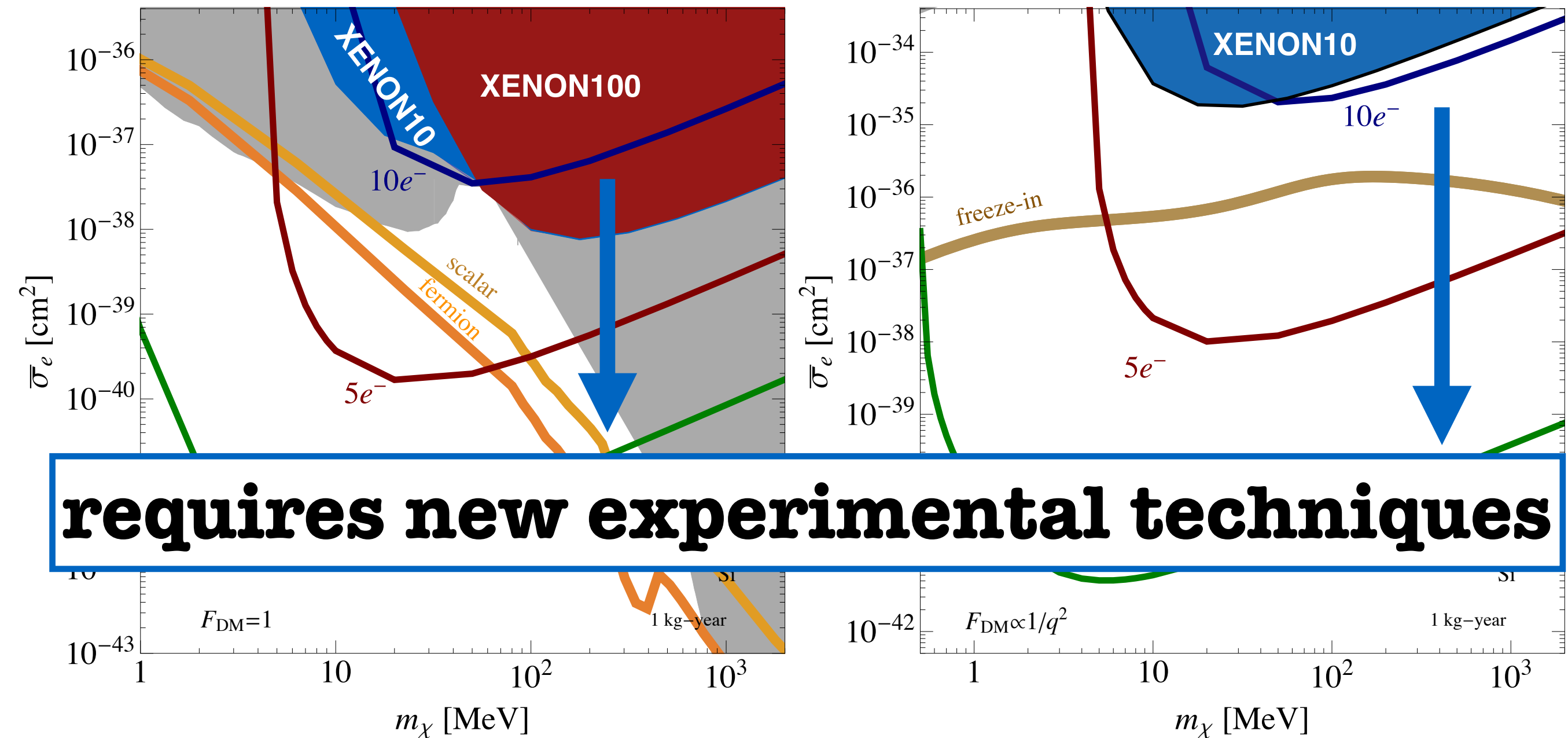
threshold dependence



threshold dependence



threshold dependence





Fermilab

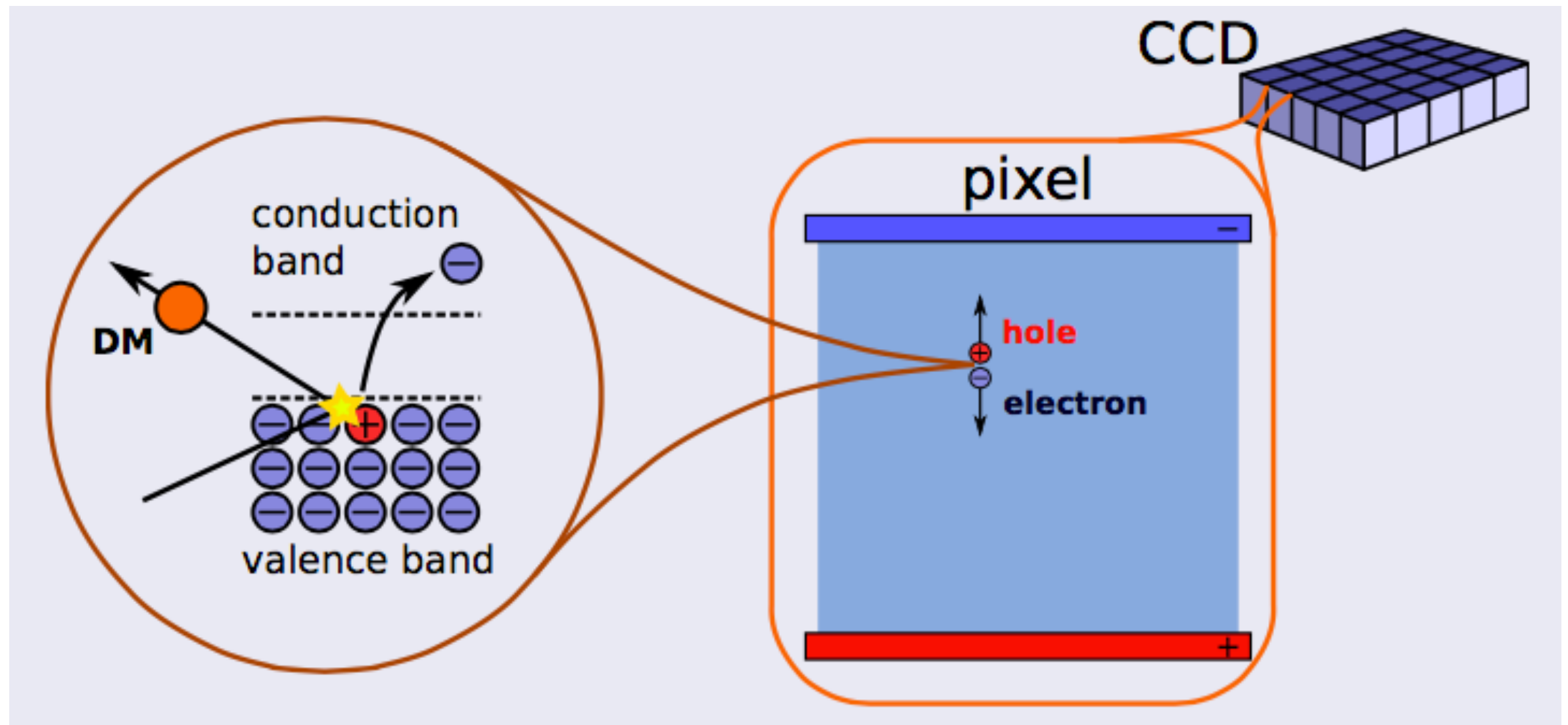
SENSEI



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

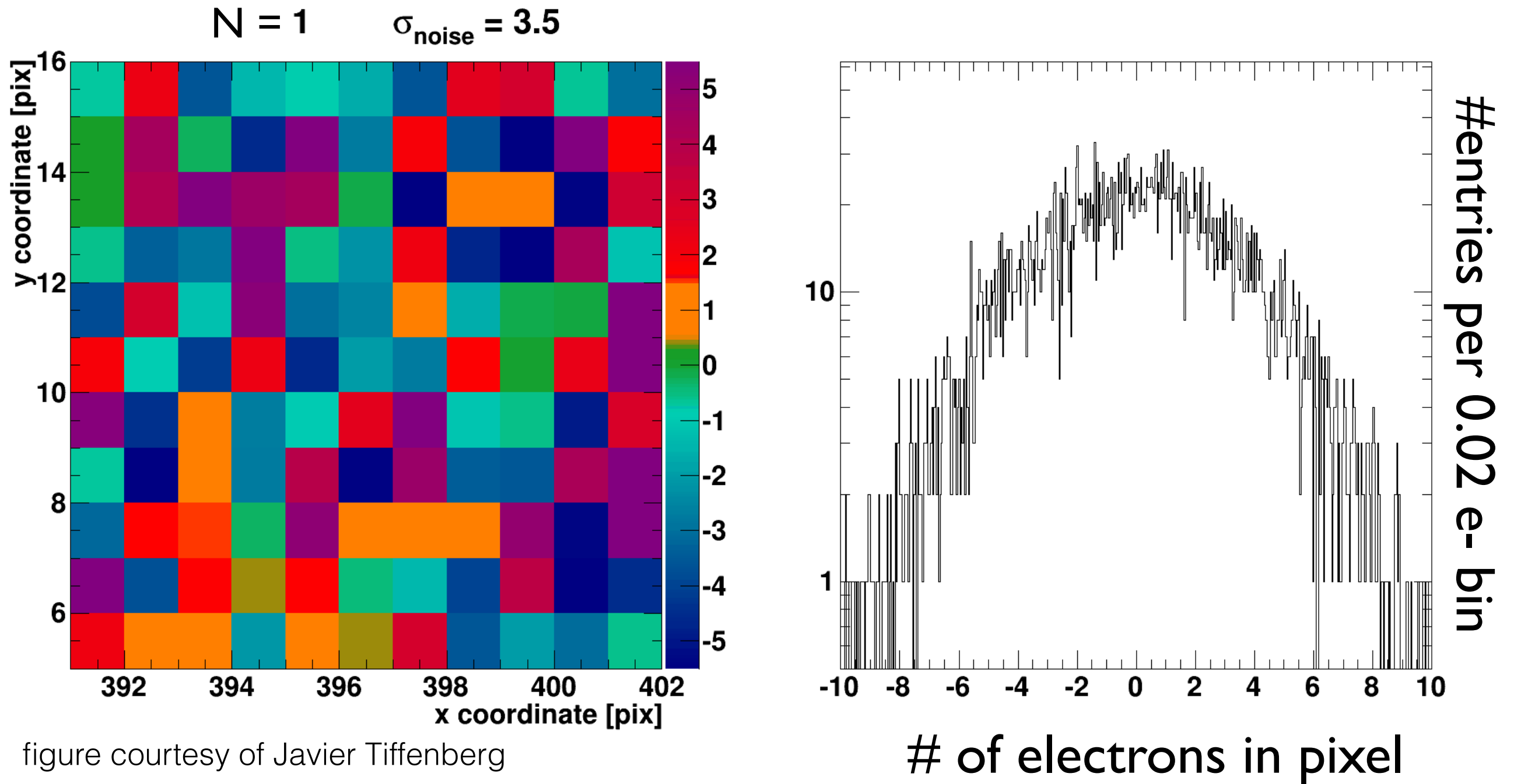


silicon CCD detector



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

of electrons vs. N

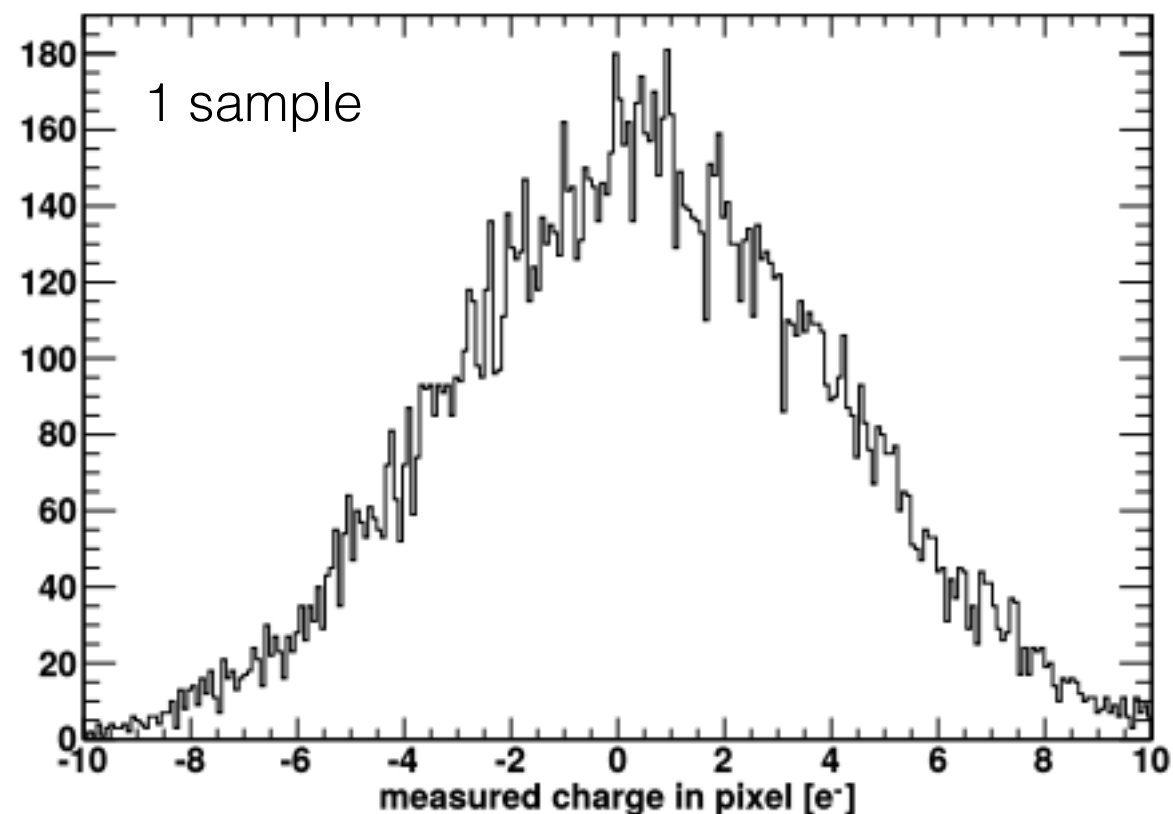


Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig,
Guardincerri, Holland, Volansky, TTY
Phys.Rev.Lett. 119 (2017) 13, 131802 [1706.00028]

skipper readout

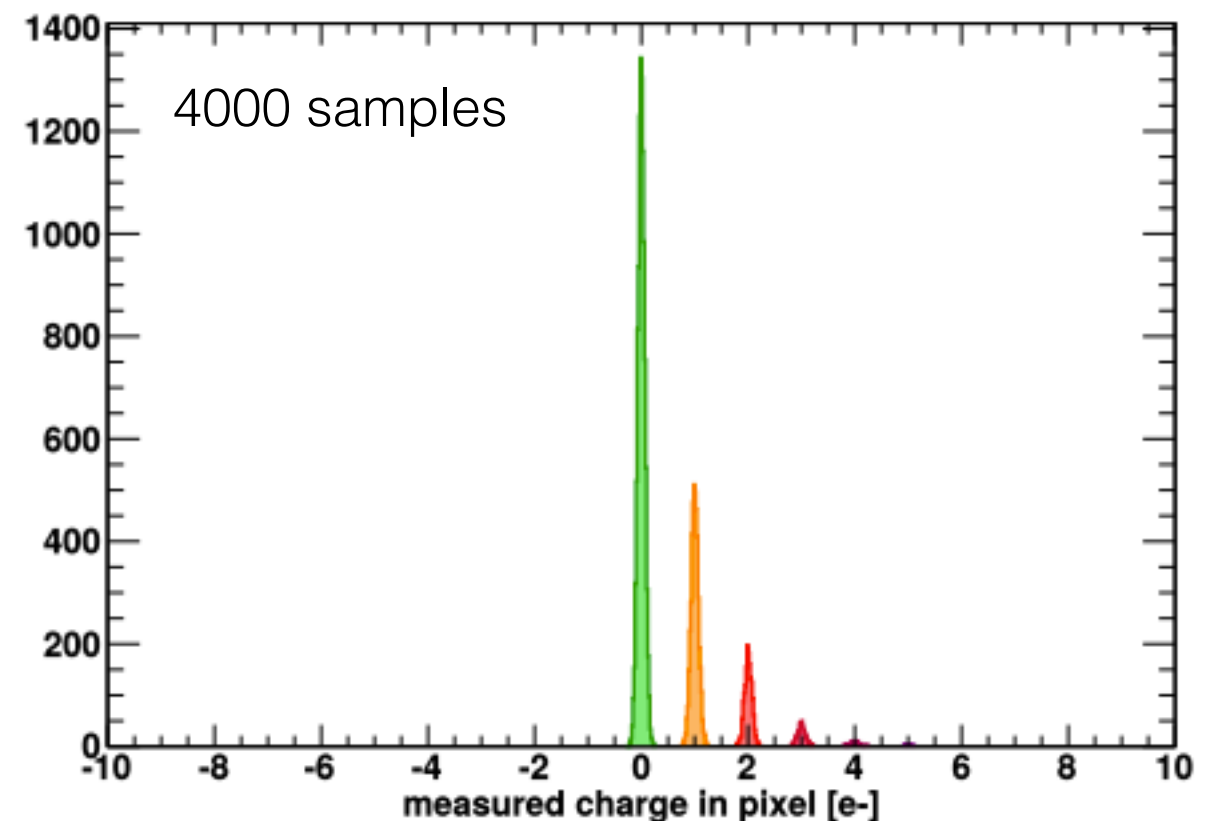
standard CCD

Readout-noise: 3.5 e RMS



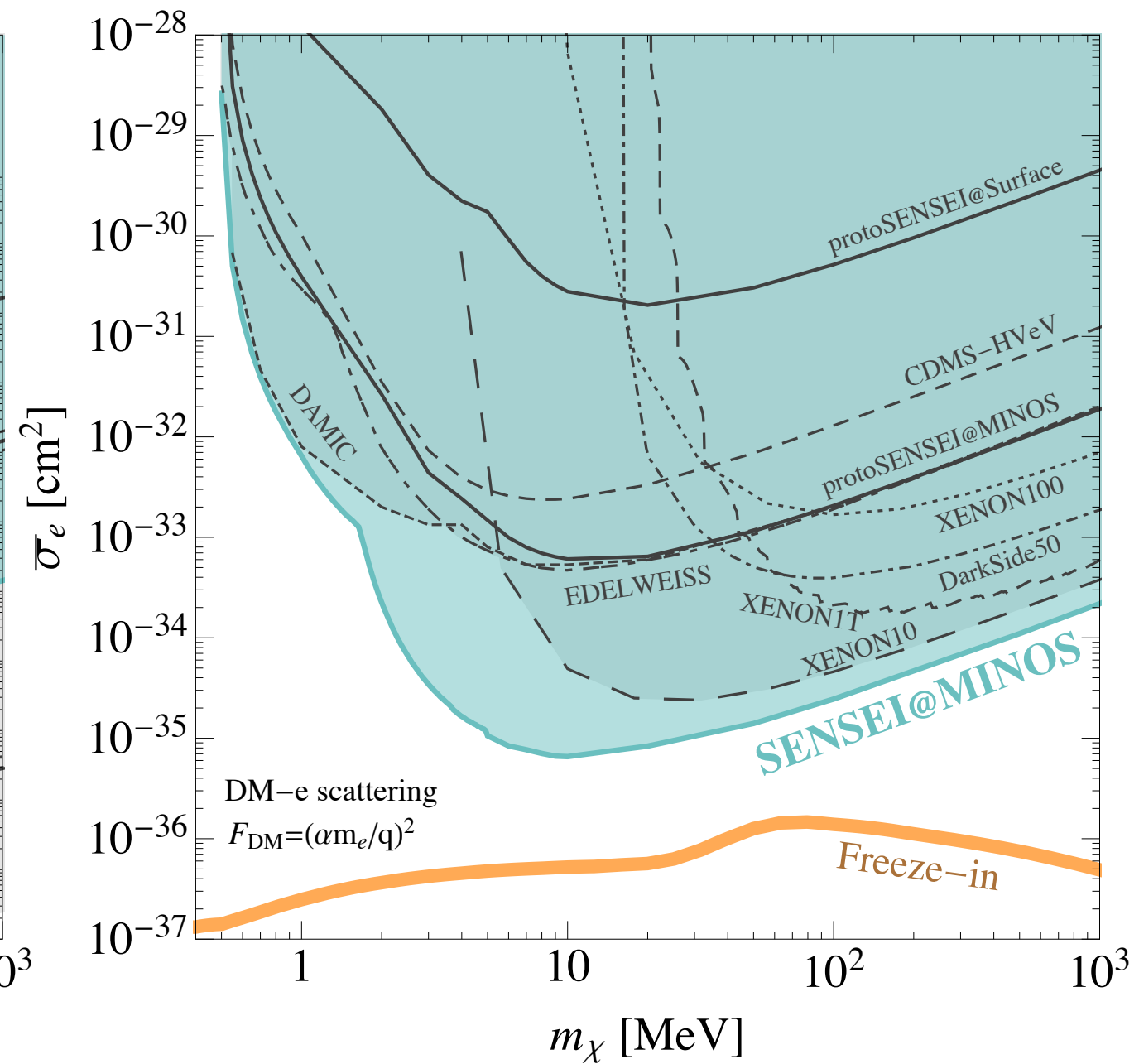
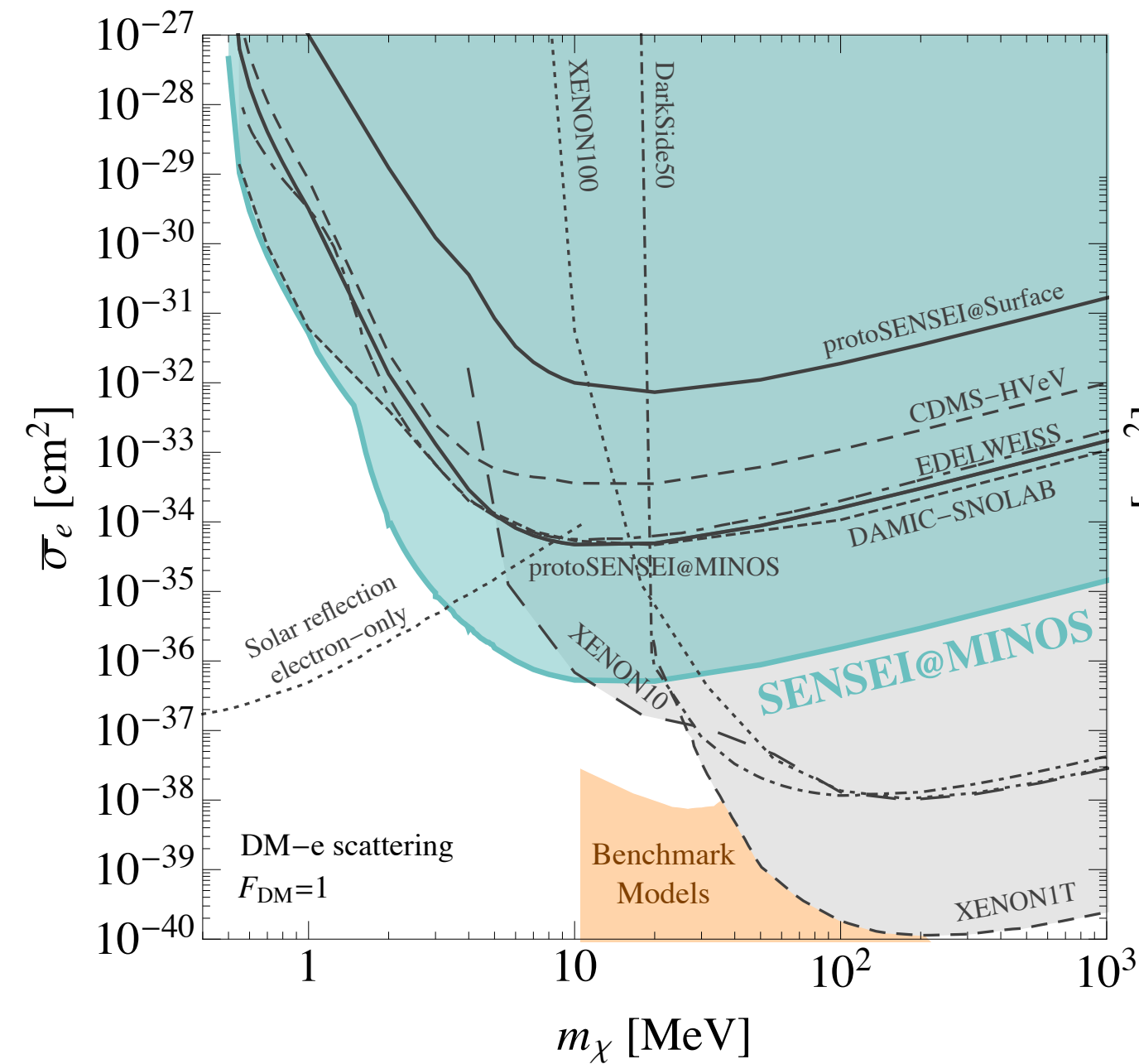
skipper CCD

Readout-noise: 0.06 e RMS

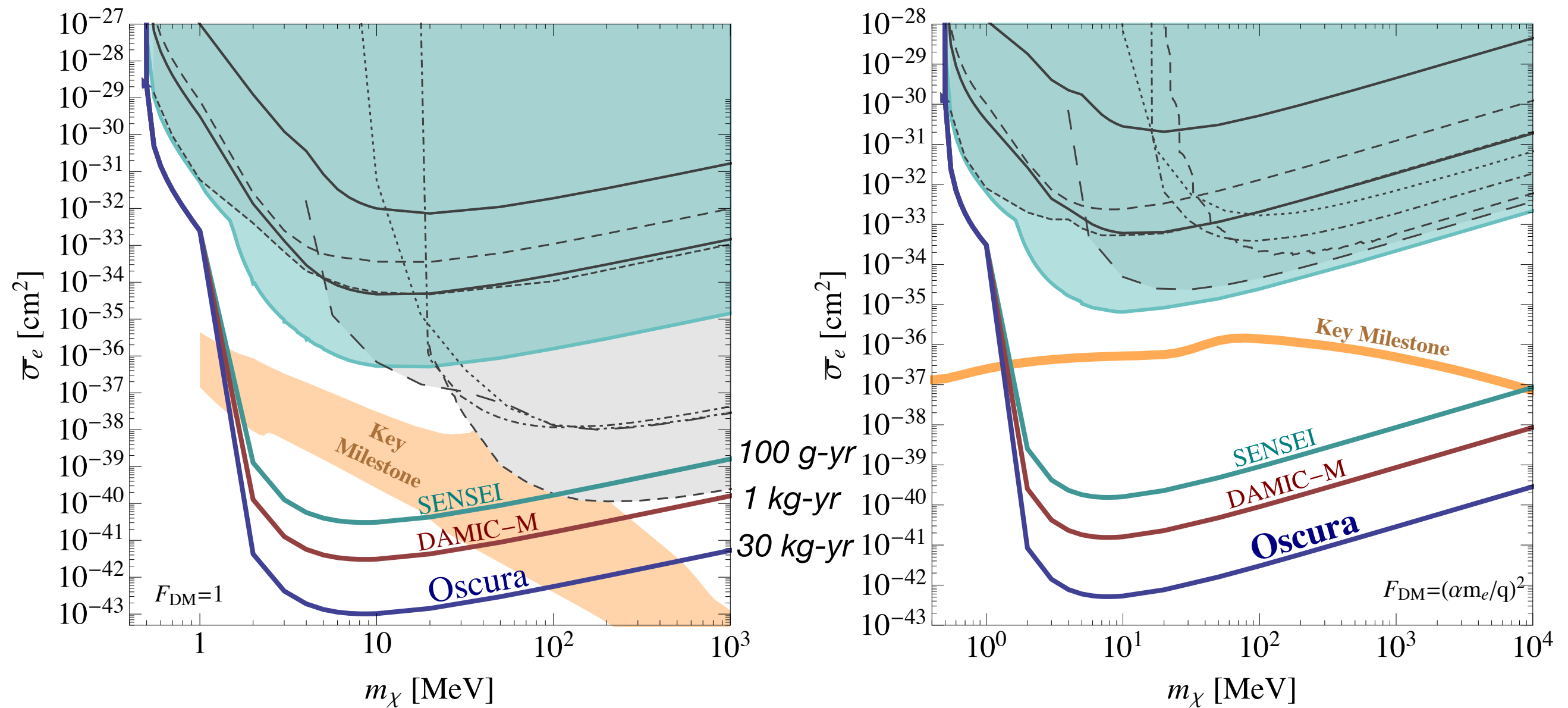


Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig,
Guardincerri, Holland, Volansky, TTY
Phys.Rev.Lett. 119 (2017) 13, 131802 [1706.00028]

DM-electron scattering



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
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- **Dark matter scattering off collective modes** in molecules and in crystals (including phonons, plasmons and magnons)

“Migdal” scattering

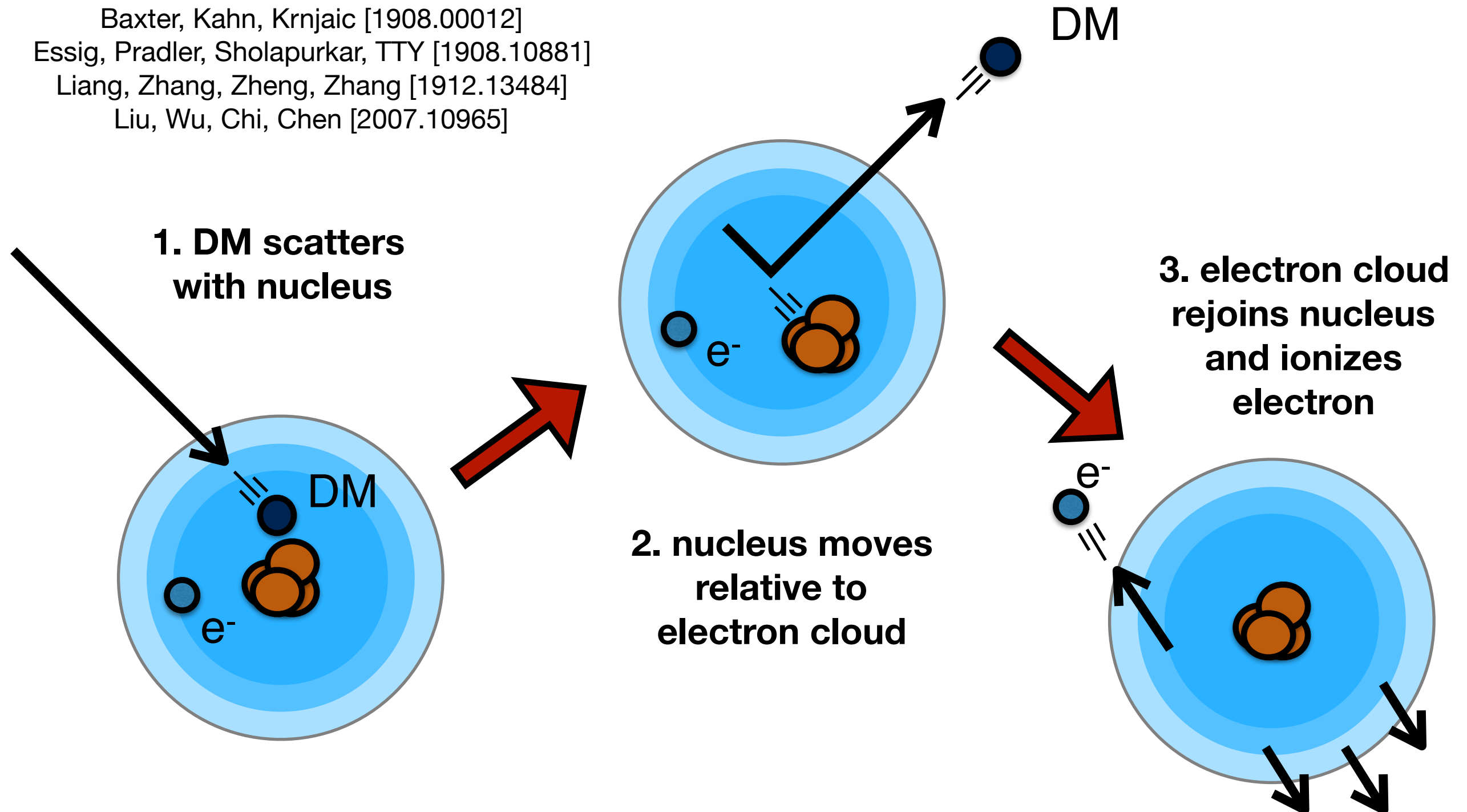
Ibe, Nakano, Shoji, Suzuki [1707.07258]

Baxter, Kahn, Krnjaic [1908.00012]

Essig, Pradler, Sholapurkar, TTY [1908.10881]

Liang, Zhang, Zheng, Zhang [1912.13484]

Liu, Wu, Chi, Chen [2007.10965]

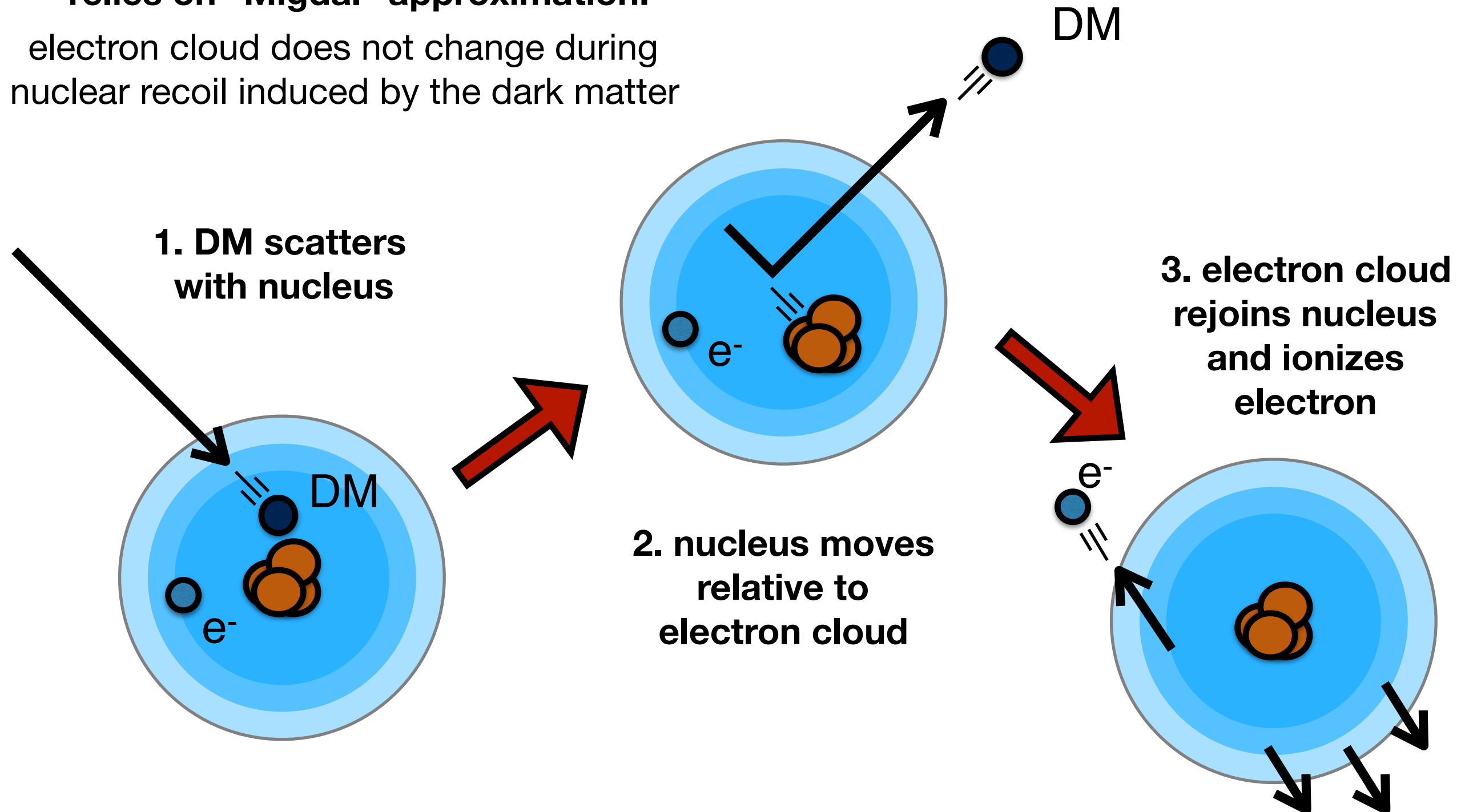


“Migdal” scattering



relies on “Migdal” approximation:

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



“Migdal” scattering

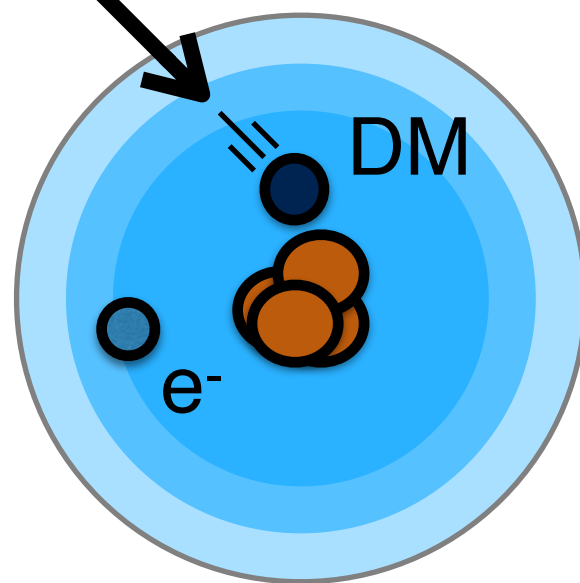


relies on “Migdal” approximation:

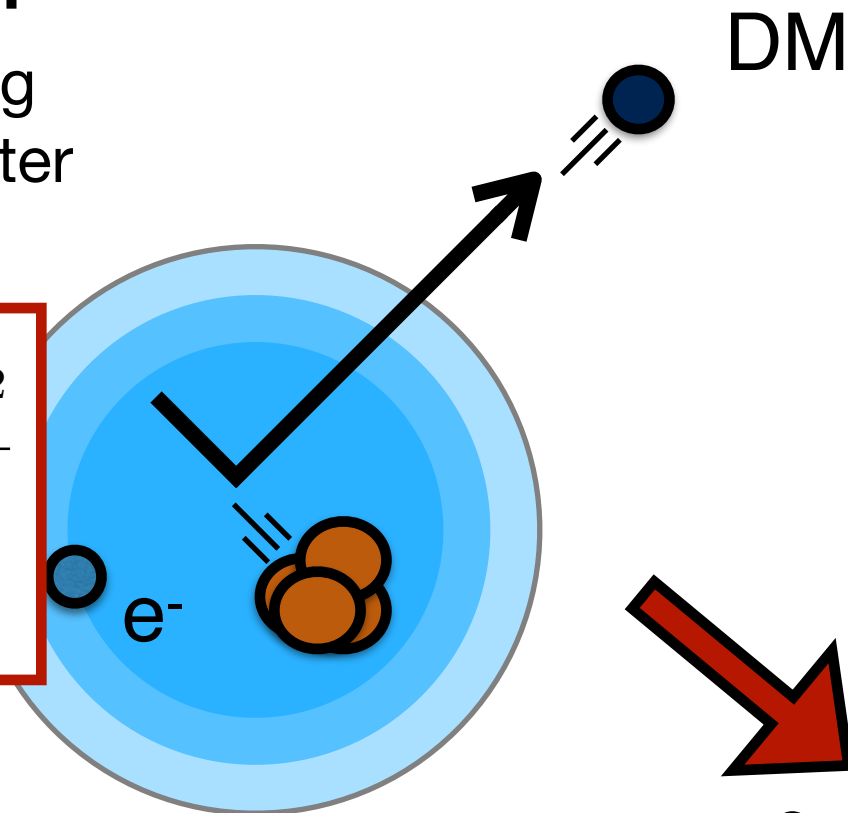
electron cloud does not change during nuclear recoil induced by the dark matter

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

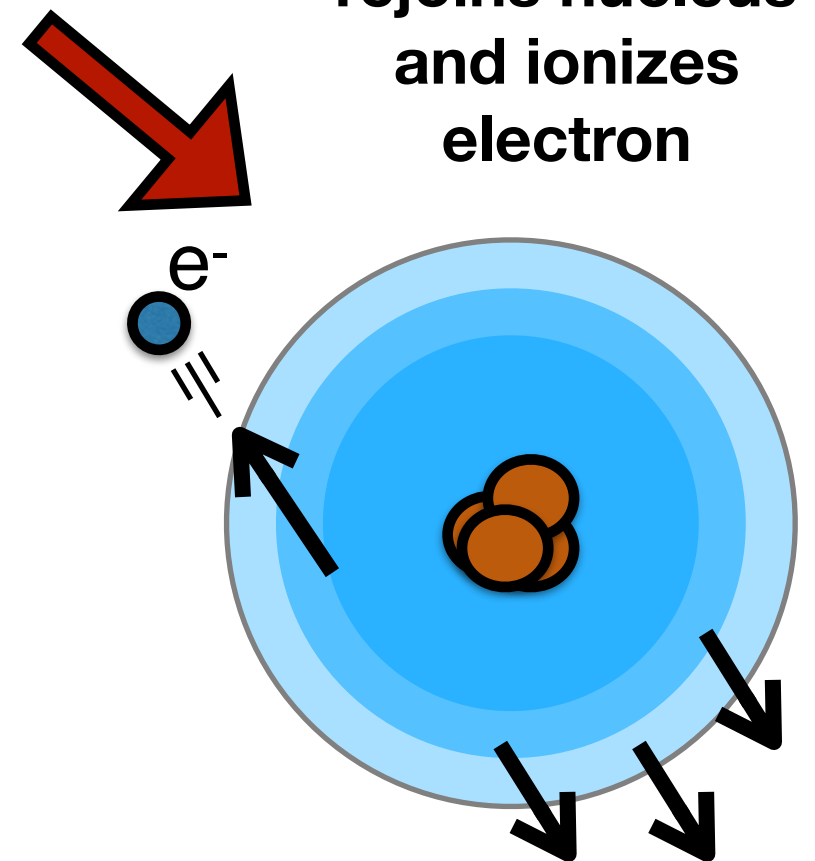
DM-nucleus scattering



2. nucleus moves relative to electron cloud



3. electron cloud rejoins nucleus and ionizes electron



“Migdal” scattering



relies on “Migdal” approximation:

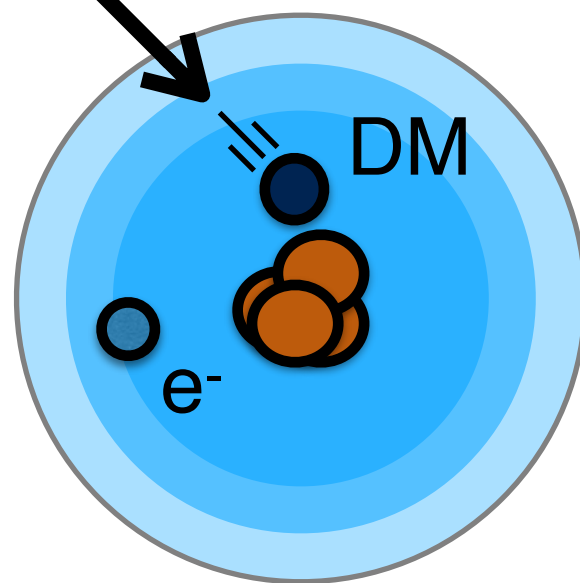
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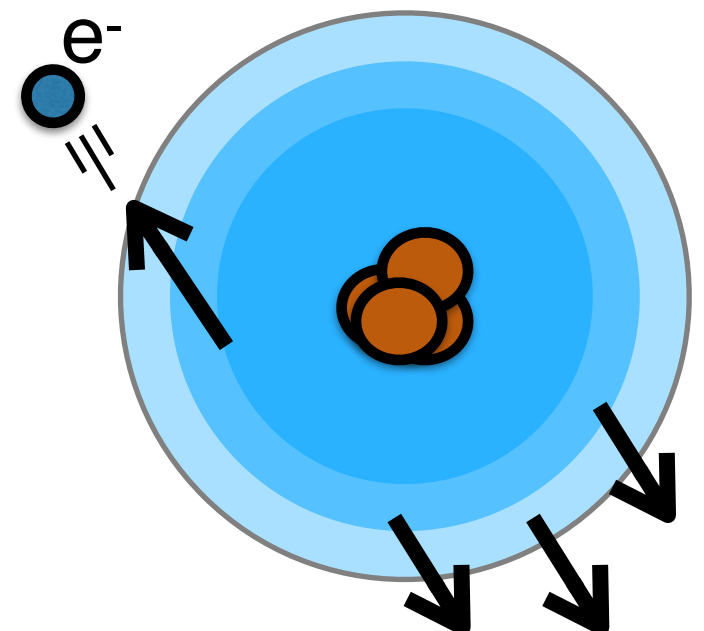
DM-nucleus scattering

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

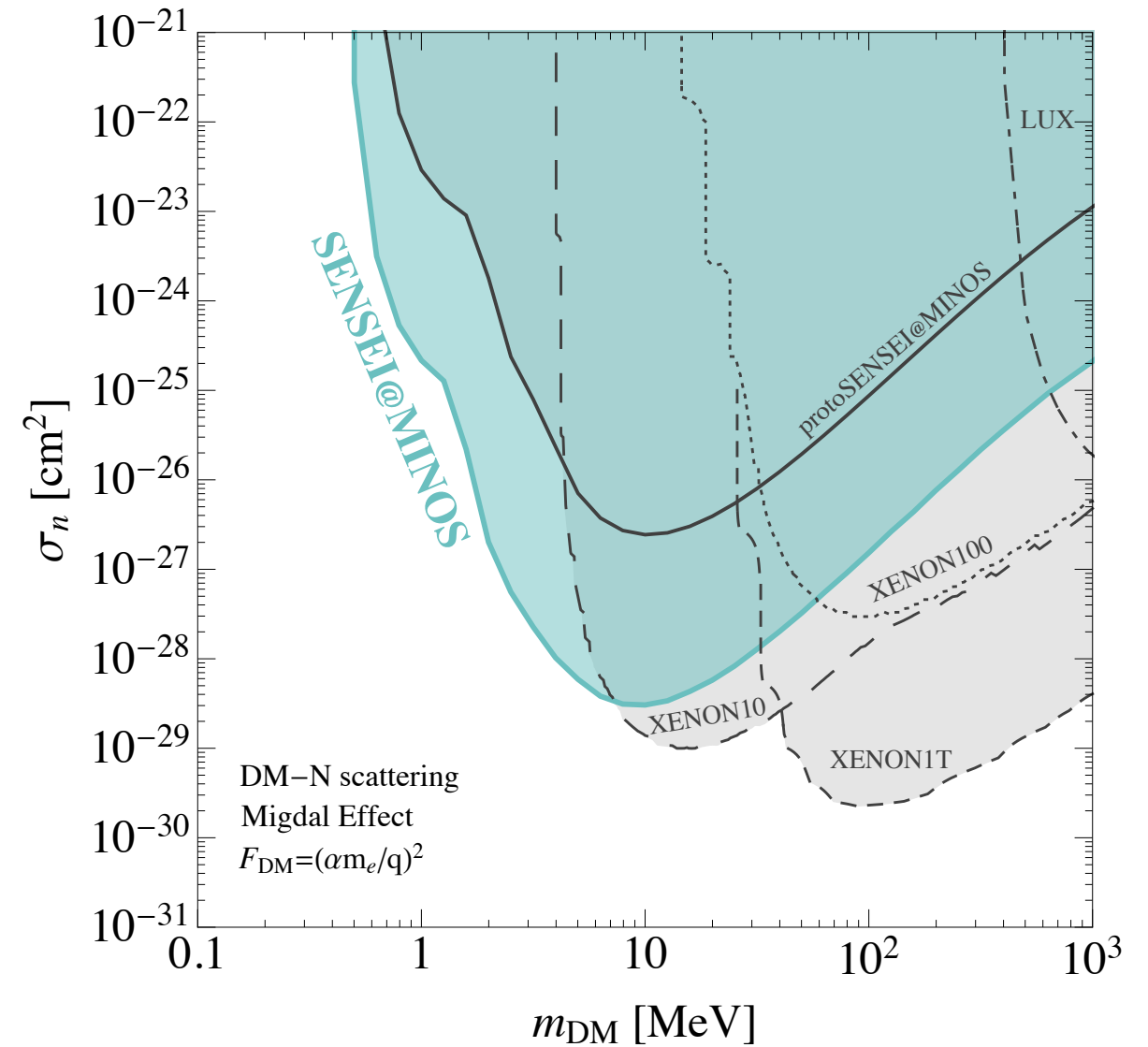
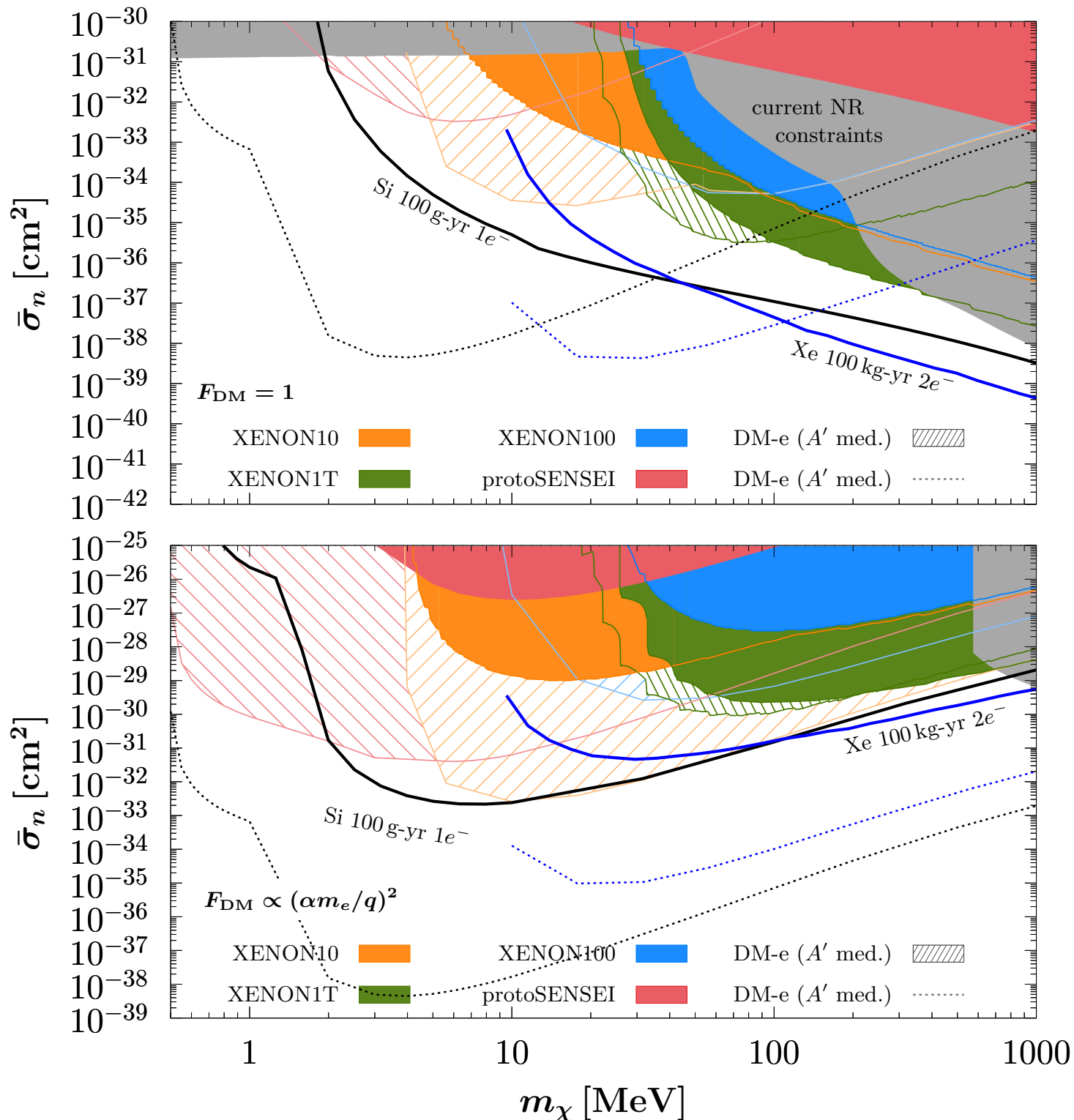
boost electron cloud from $i \rightarrow f$



2. nucleus moves relative to electron cloud



“Migdal” scattering



SENSEI collaboration [arXiv:2004.11378],

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

Editors' Suggestion

“Migdal” scattering

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, $q_0 = \sqrt{2m_N\omega_0}$ 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 increased expectation from elastic scattering, even when the energy threshold is above the single-phonon energy for phonons above the elastic energy. We use a simple model of electronic excitations to argue that ionization signals induced from DM-electron scattering or the Migdal effect. In well-motivated models of dark photon, we show that these signals can probe experimental milestones for cosmological thermal target for Majorana fermion DM.

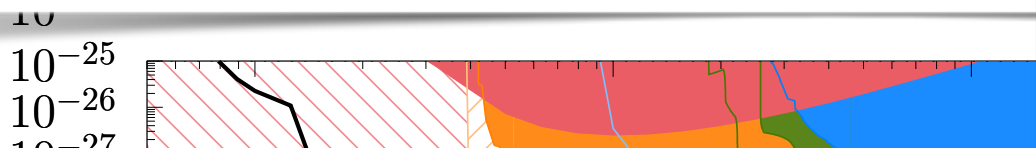
Comments: 6 pages, 3 figures, plus supplementary material

Subjects: High Energy Physics – Phenomenology (hep-ph); Cosmology and Nongalactic Astrophysics (astro-ph.CO)

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 Kozaczk, Tongyan Lin

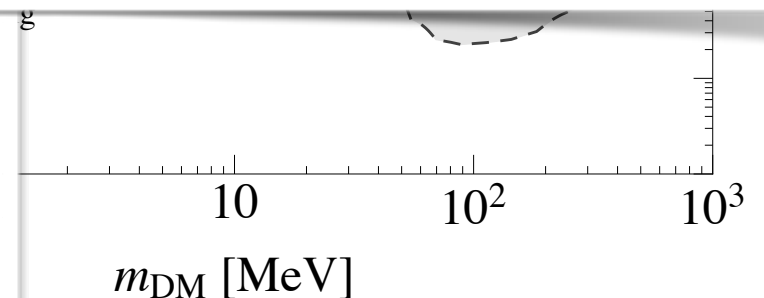
When a nucleus in an atom undergoes a collision, there is a small probability to inelastically excite an electron. This is known as the Migdal effect. In this Letter, we present a first complete derivation of the Migdal effect from dark matter--nucleus scattering in semiconductors, which also accounts 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)



SENSEI collaboration [arXiv:2004.11378],

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

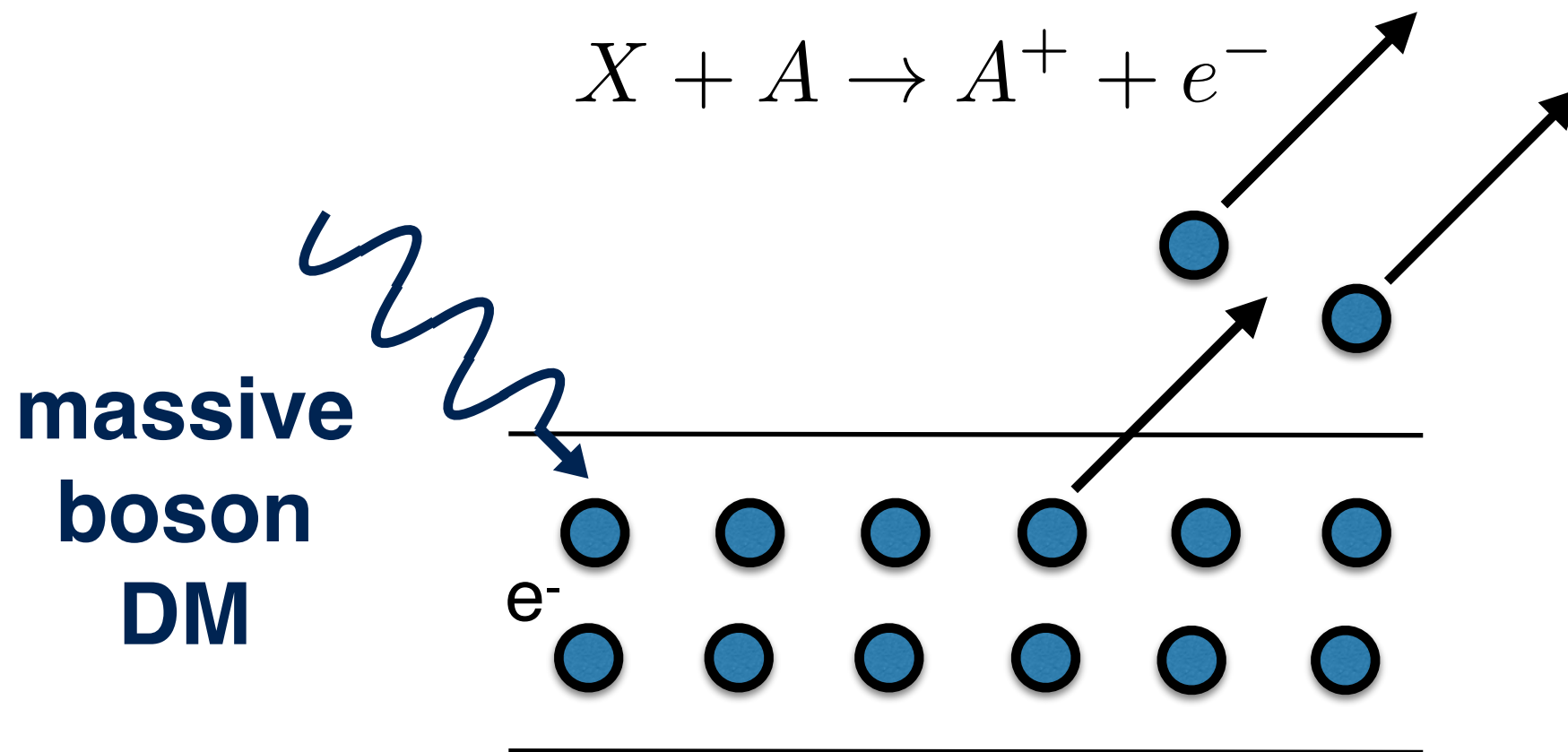
Authors' Suggestion

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

sub-GeV DM direct detection

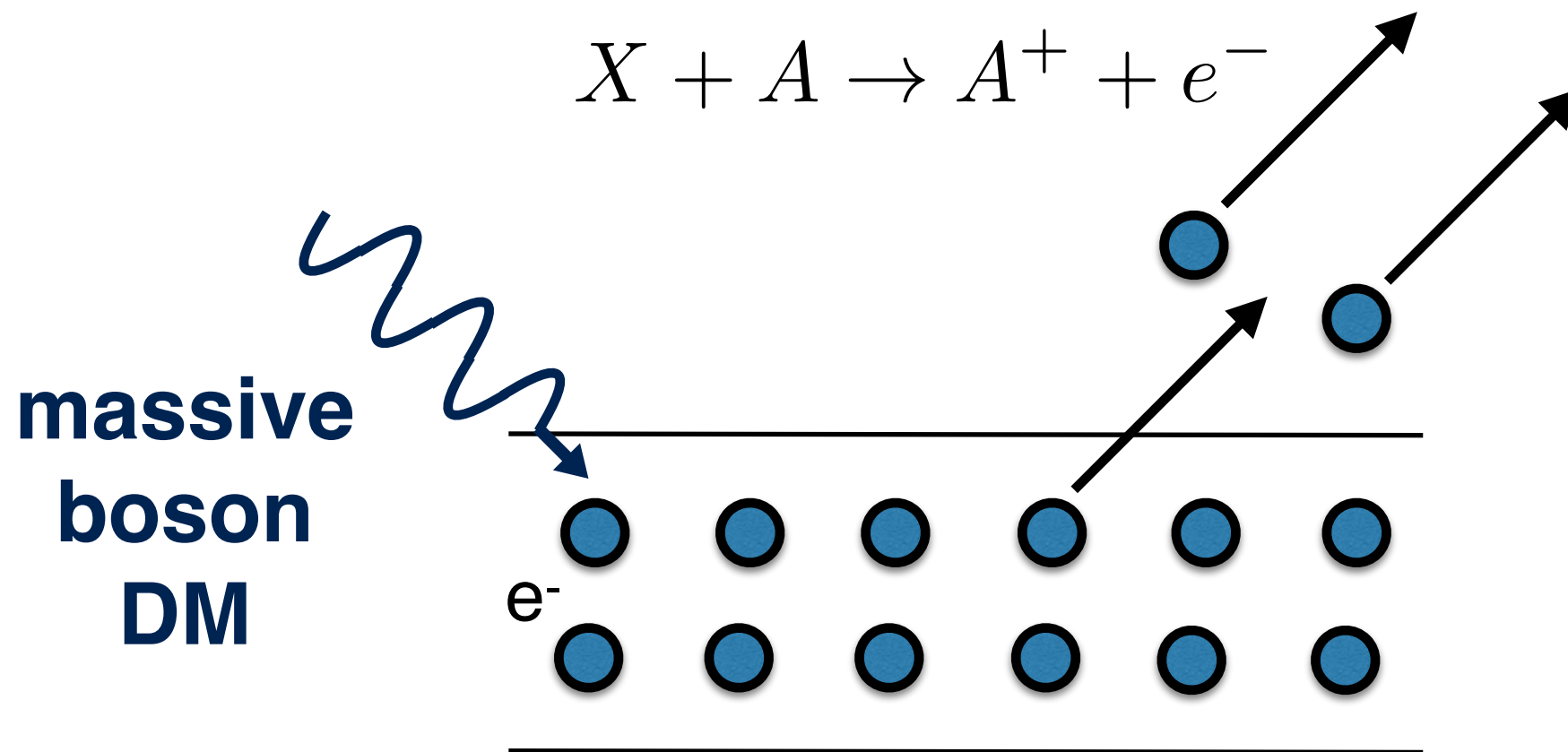
- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
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photoelectric effect



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

photoelectric effect



photon

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

bosonic dark matter

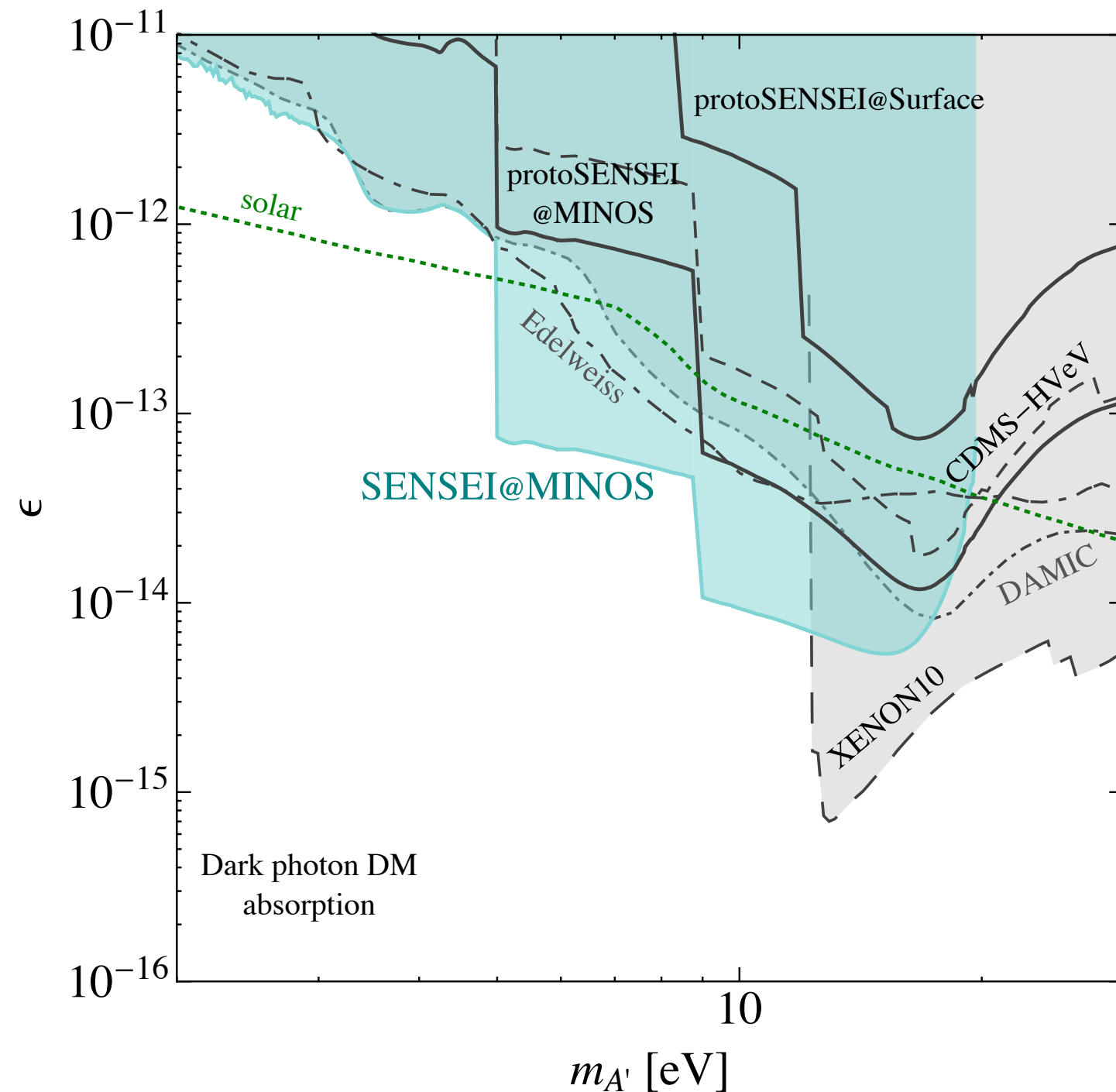
$$|\vec{q}| = m_X v_{\text{DM}} \sim 10^{-3} \omega$$

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

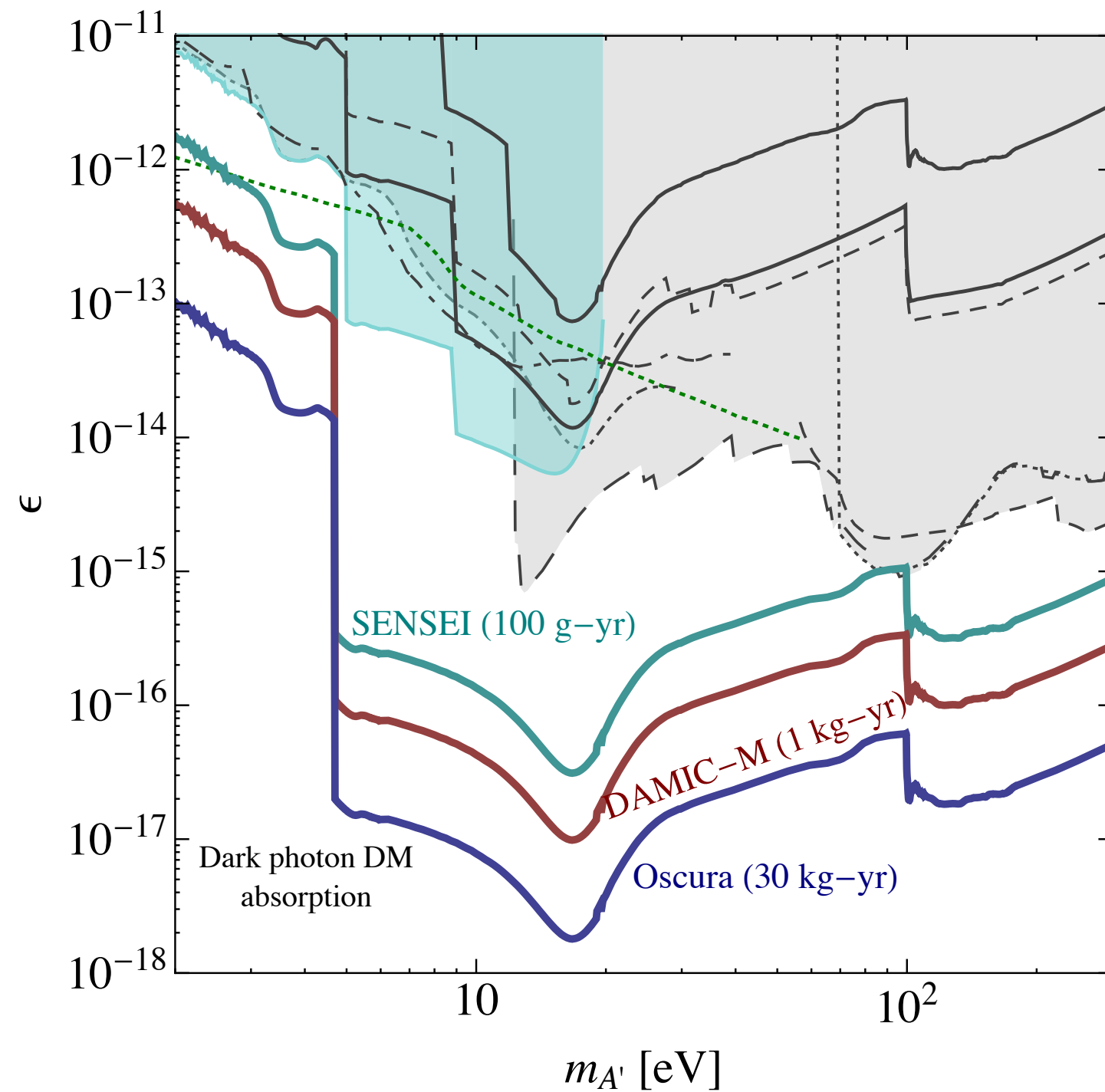
can relate
massive boson
absorption to
photon absorption

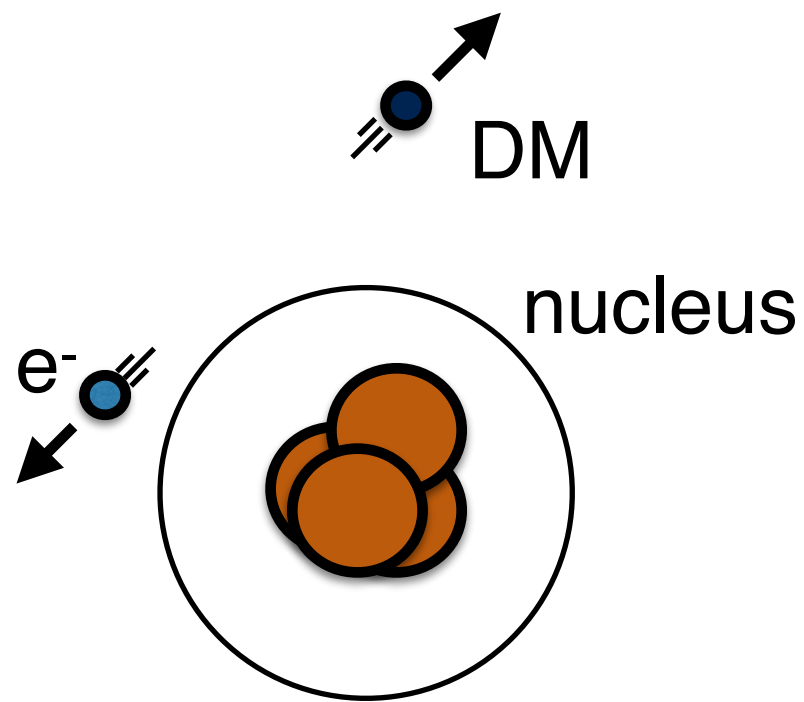
$$\sigma_{\text{DM}}(\omega) \propto \sigma_{\text{PE}}(\omega)$$

Dark Photon DM

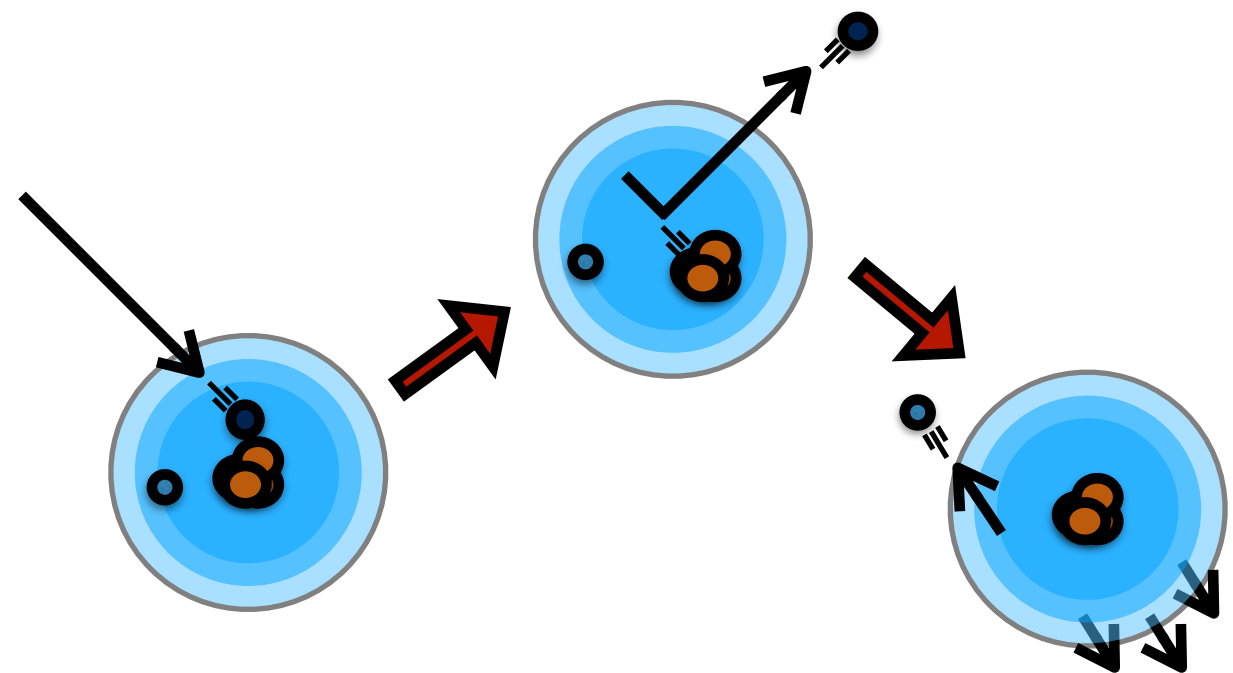


Dark Photon DM

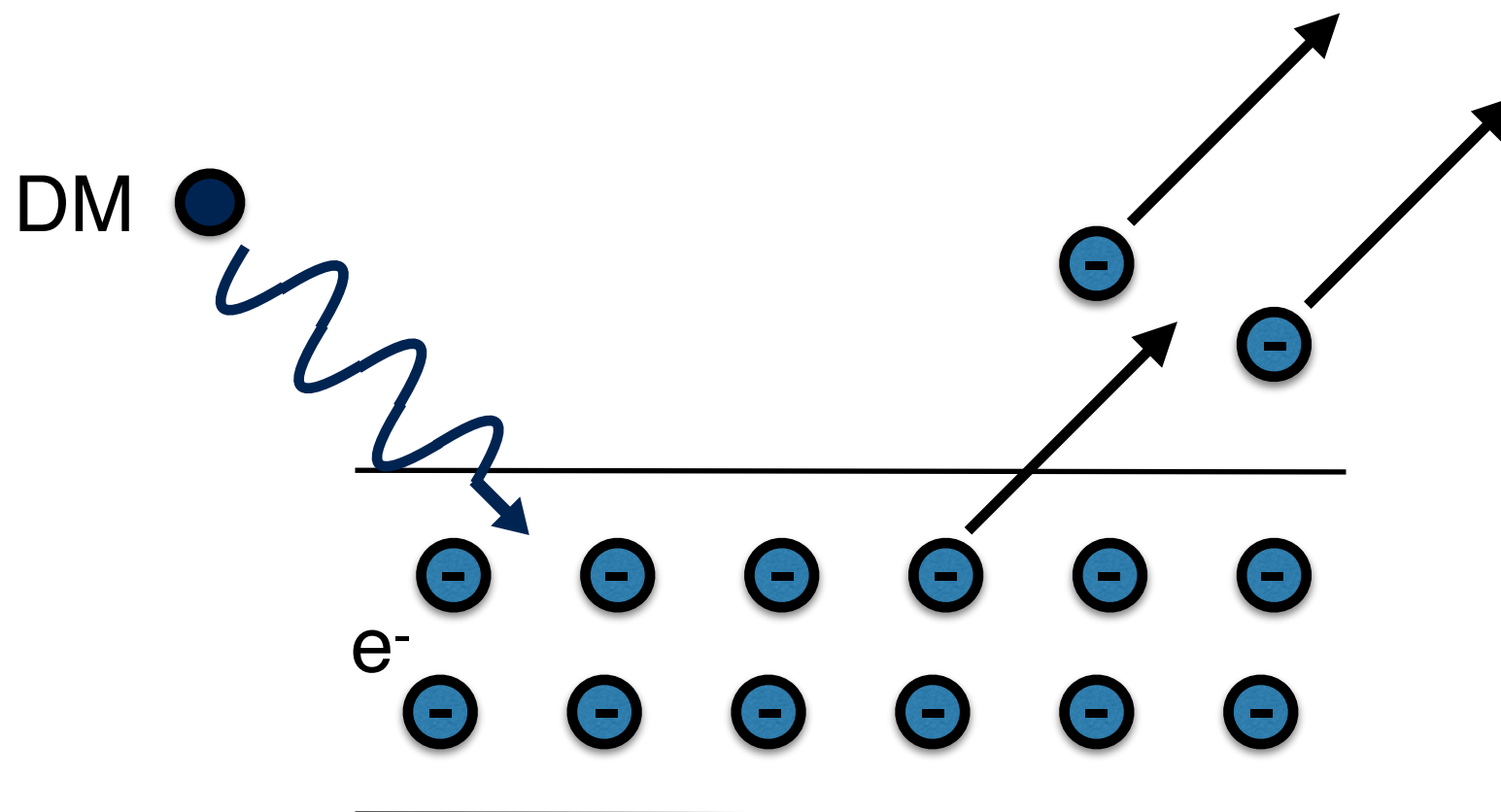




dark matter-electron scattering



dark matter-nucleus scattering

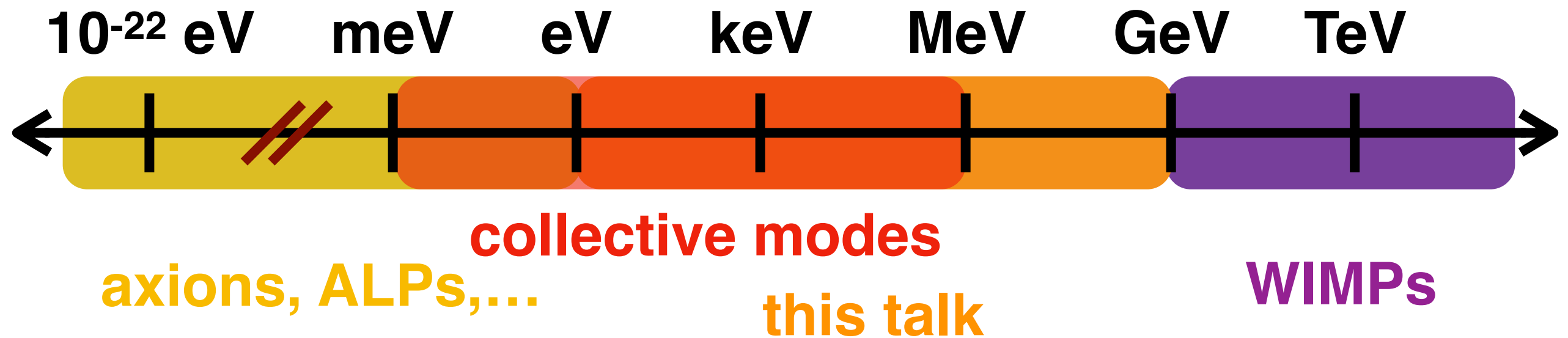


dark matter absorption

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
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- **Dark matter scattering off collective modes** in molecules and in crystals (including phonons, plasmons and magnons)

dark matter candidates



collective modes

- **phonons**: collective excitation of atoms in a crystal
 - acoustic: “in-phase”
 - optical: “out-of-phase”
- **magnons**: collective excitation of electron spin
 - sensitive to spin-dependent interactions (DM-coupling to electron spin)
- sensitivity to $\sim$ keV DM masses
- may require new materials — area of active research
- 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, ...