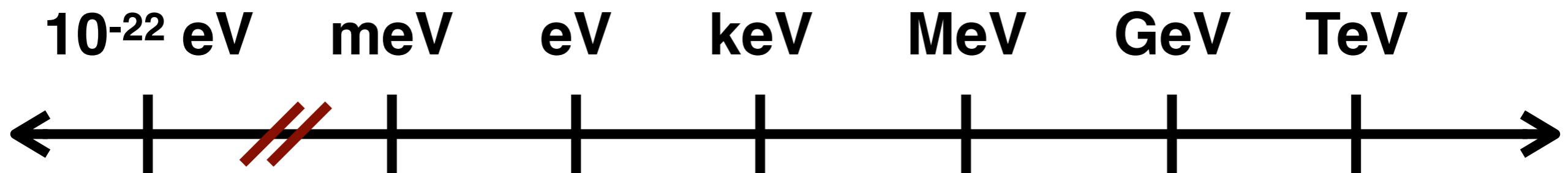


Searching for sub-GeV Dark Matter with SENSEI

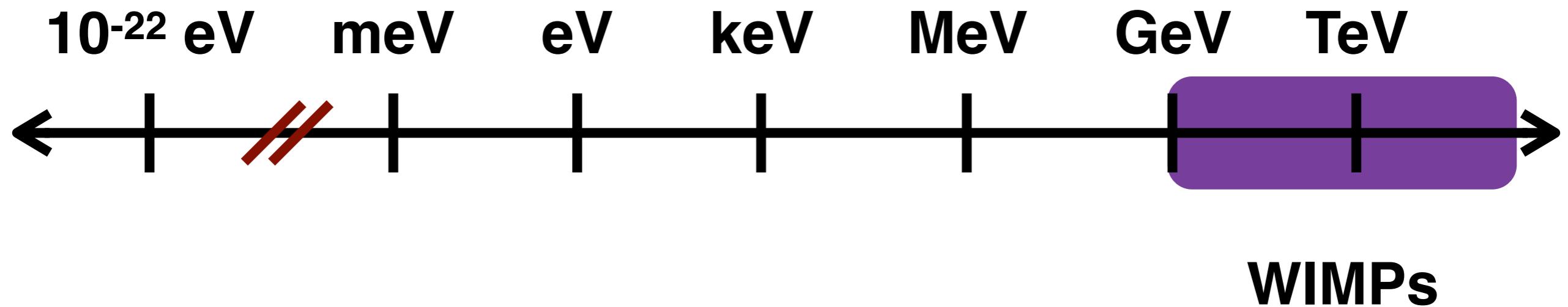
**Tien-Tien Yu
(University of Oregon)**

Low Energy Recoils from Deep Underground – September (25)26, 2020

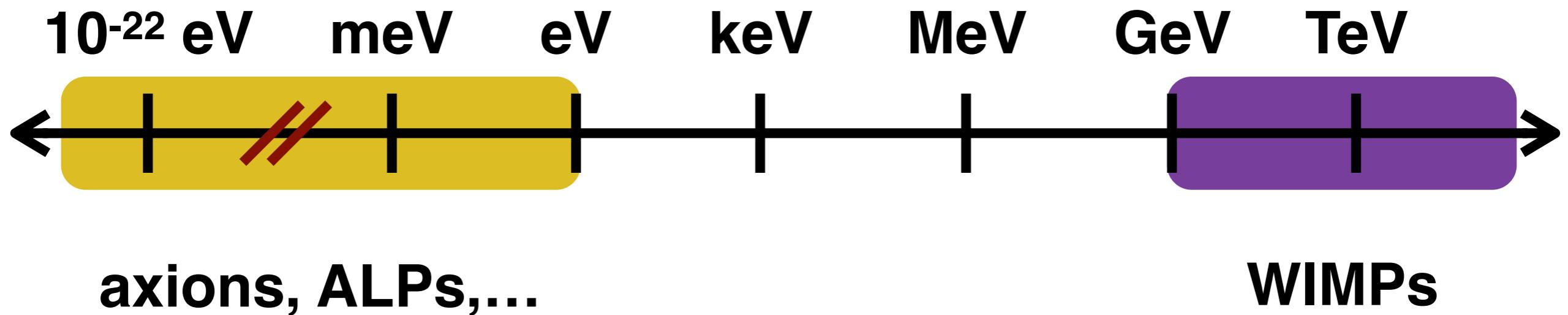
dark matter candidates



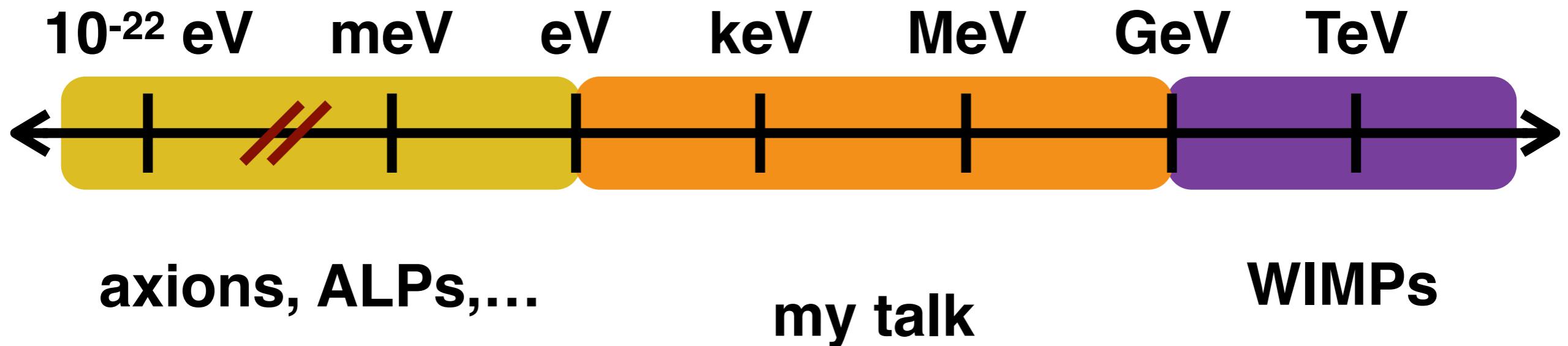
dark matter candidates



dark matter candidates

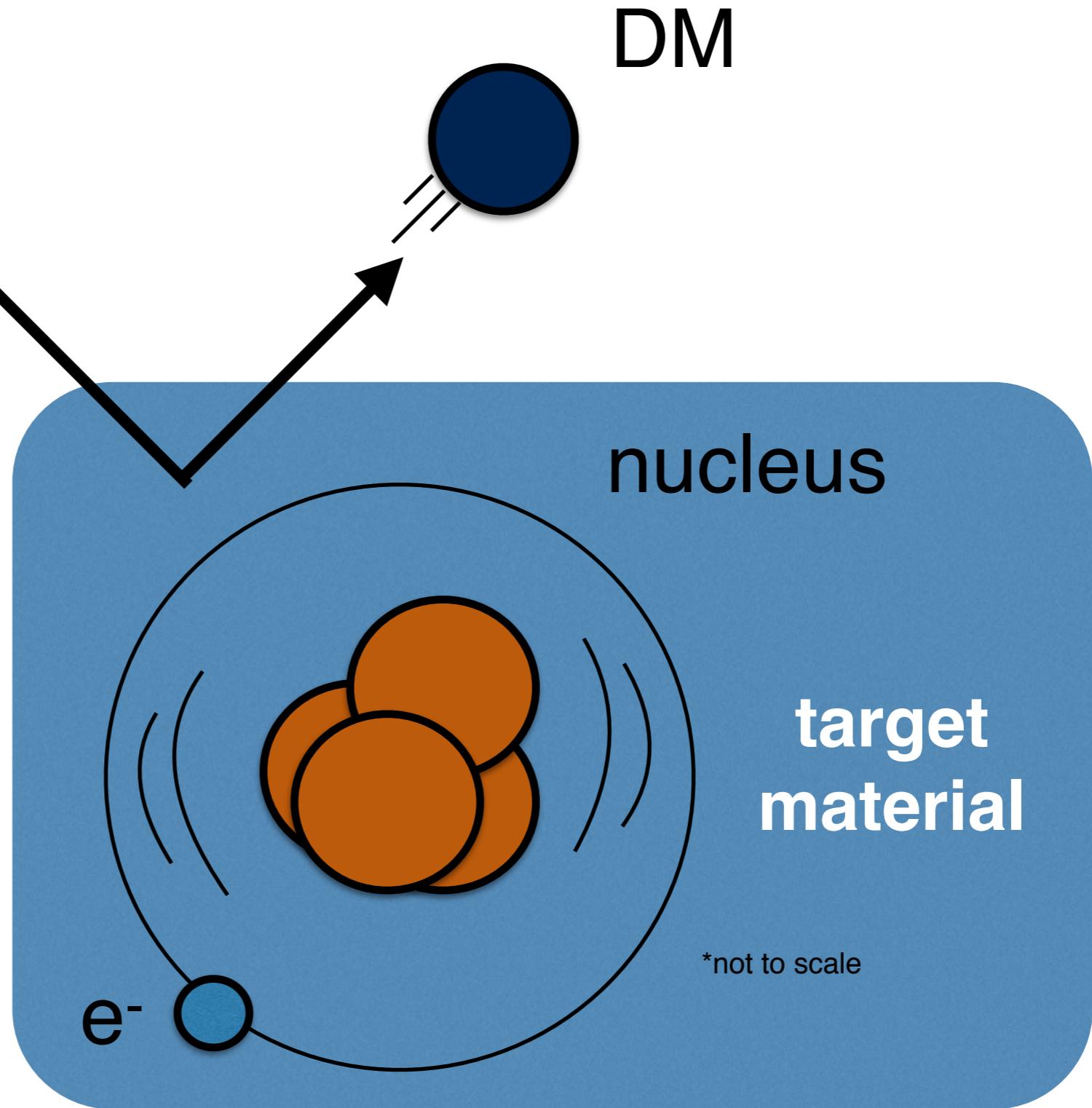


dark matter candidates

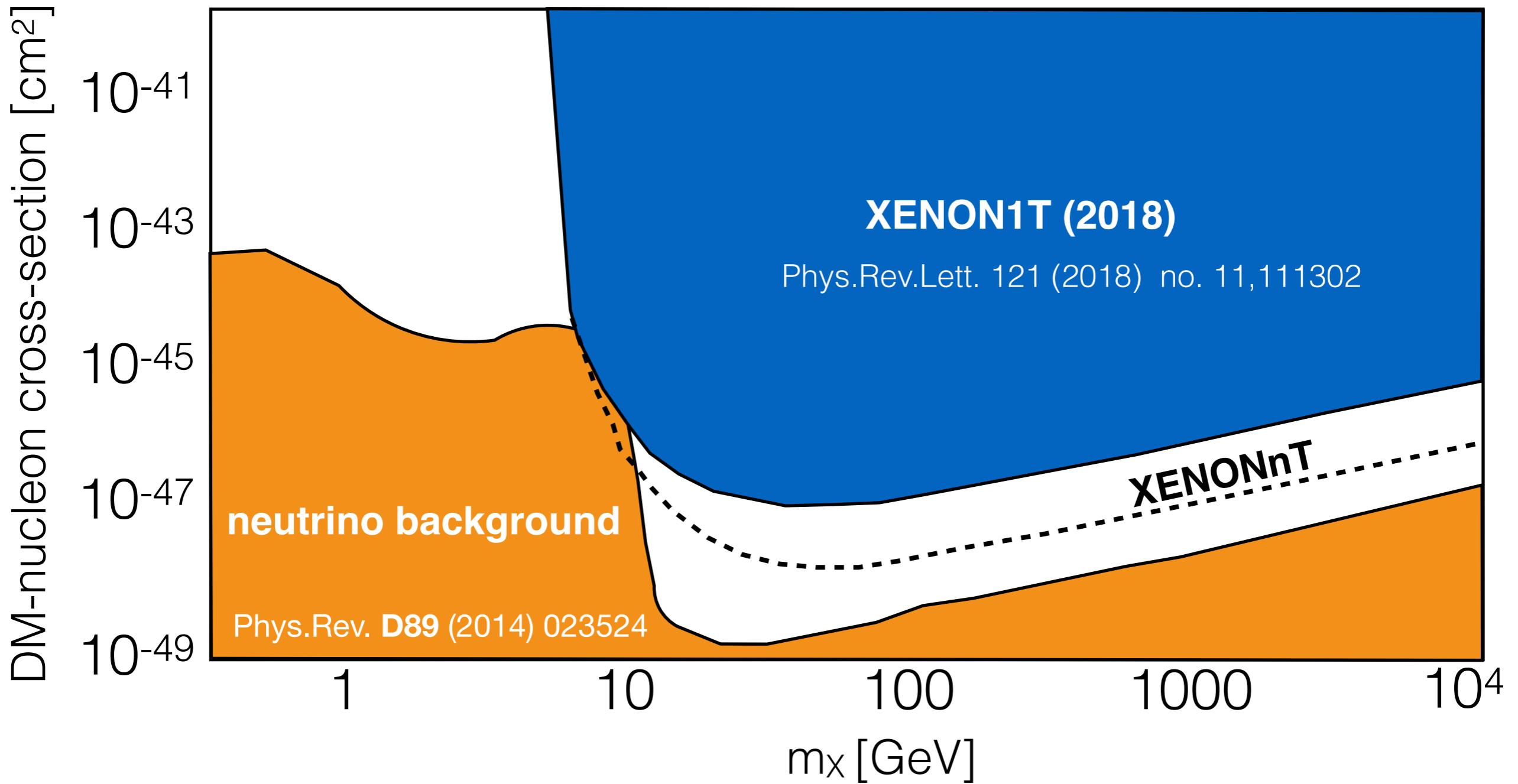


DM direct detection

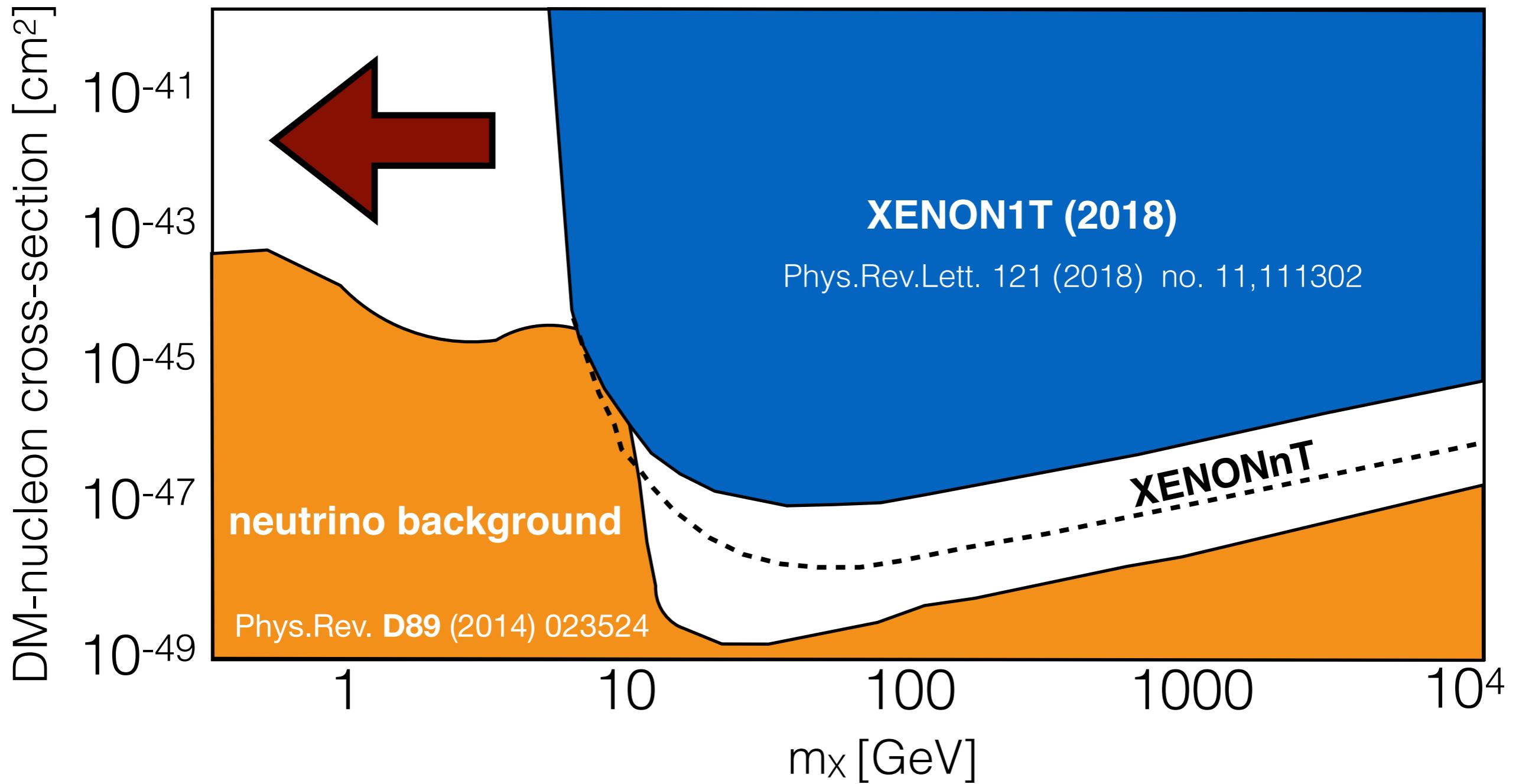
signal:
phonons,
scintillation
photons,
ionization
electrons



direct detection



direct detection



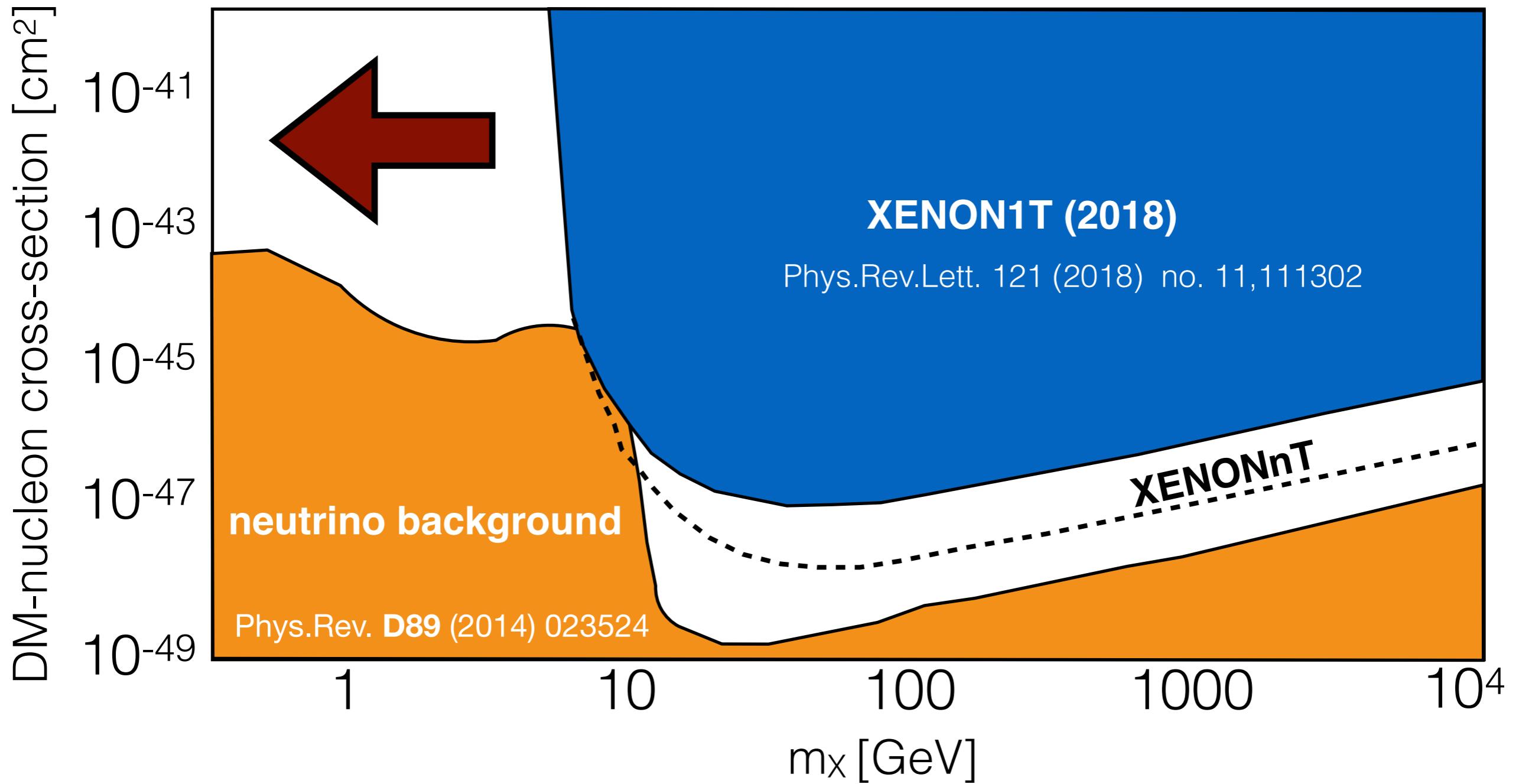
sub-GeV DM direct detection

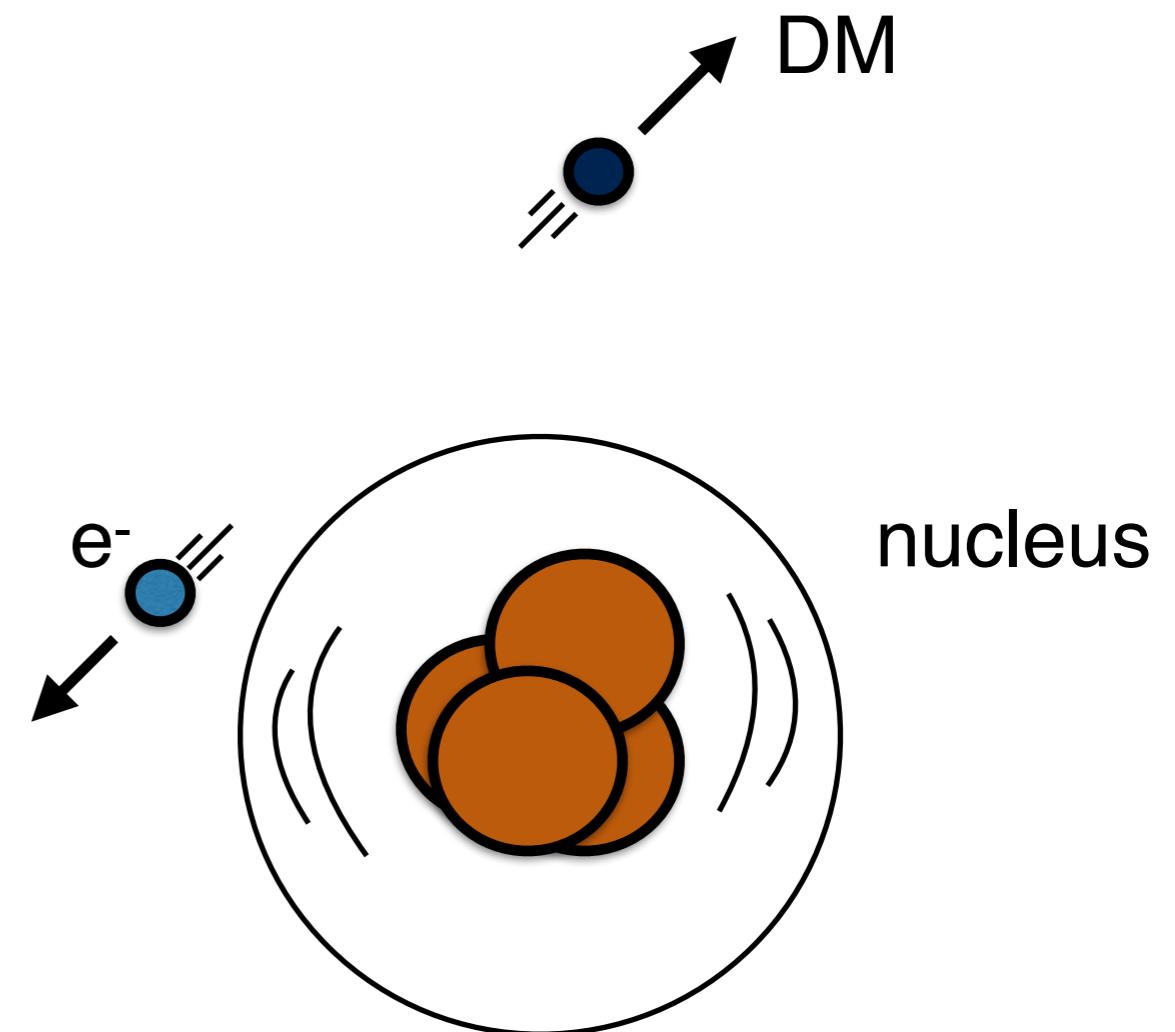
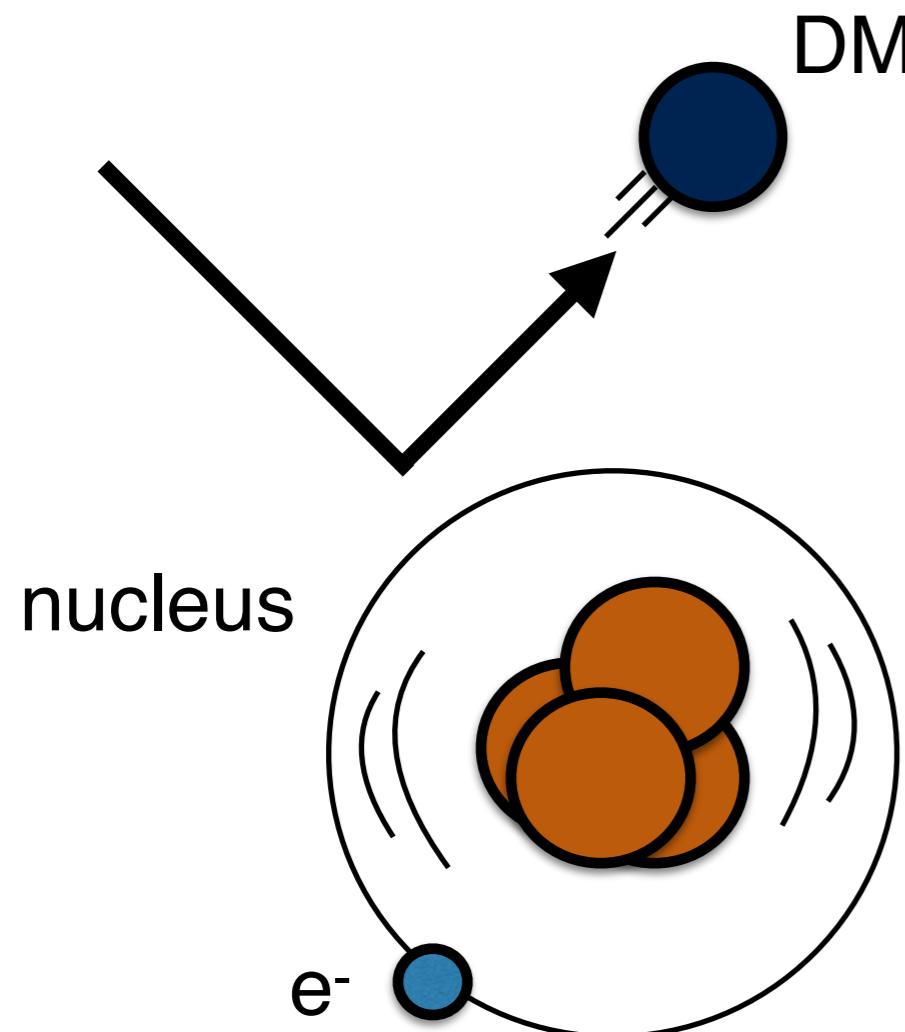
- **Dark matter-electron scattering** in noble liquids, semiconductors, and organic molecules
- **Dark matter-nuclear scattering** through the Migdal scattering and bremsstrahlung
- **Absorption** of light dark matter, including axion-like particles and dark photons.
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sub-GeV 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)

direct detection





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

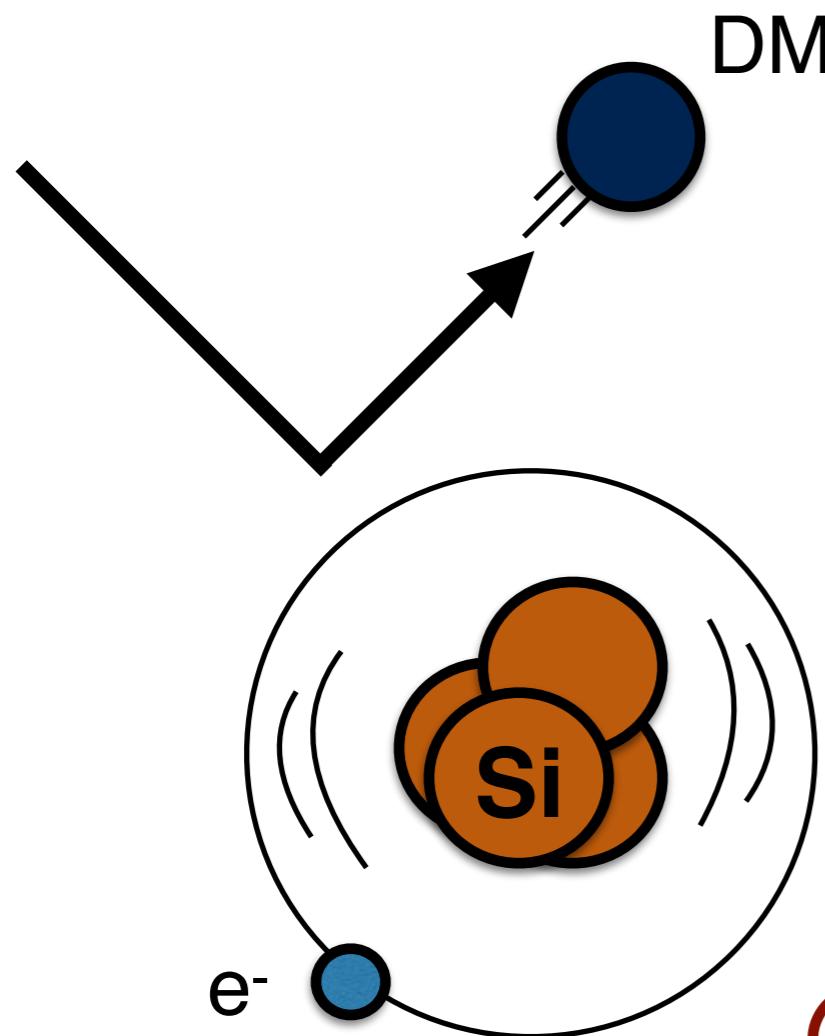
$$\simeq 50 \text{ keV} \left(\frac{m_\chi}{100 \text{ GeV}} \right)^2 \left(\frac{100 \text{ GeV}}{m_N} \right)$$

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

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

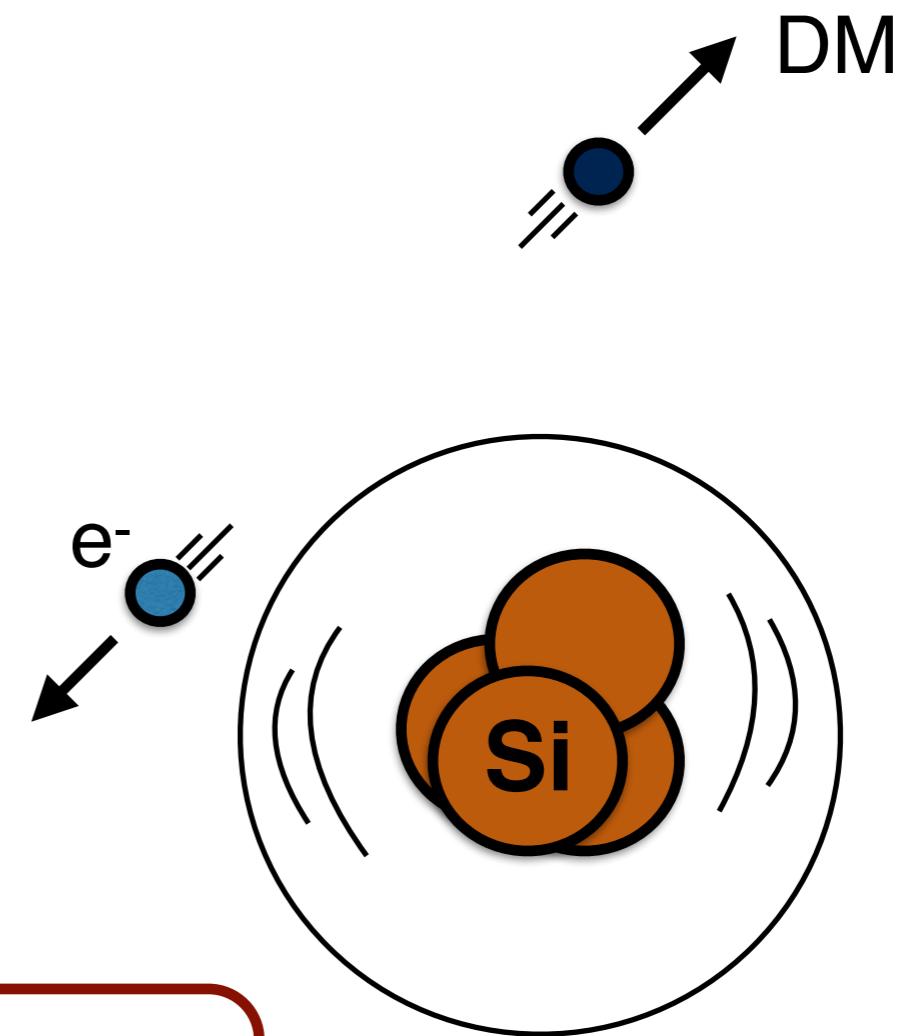
DM-nuclear scattering

DM-electron scattering



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

DM-nuclear scattering

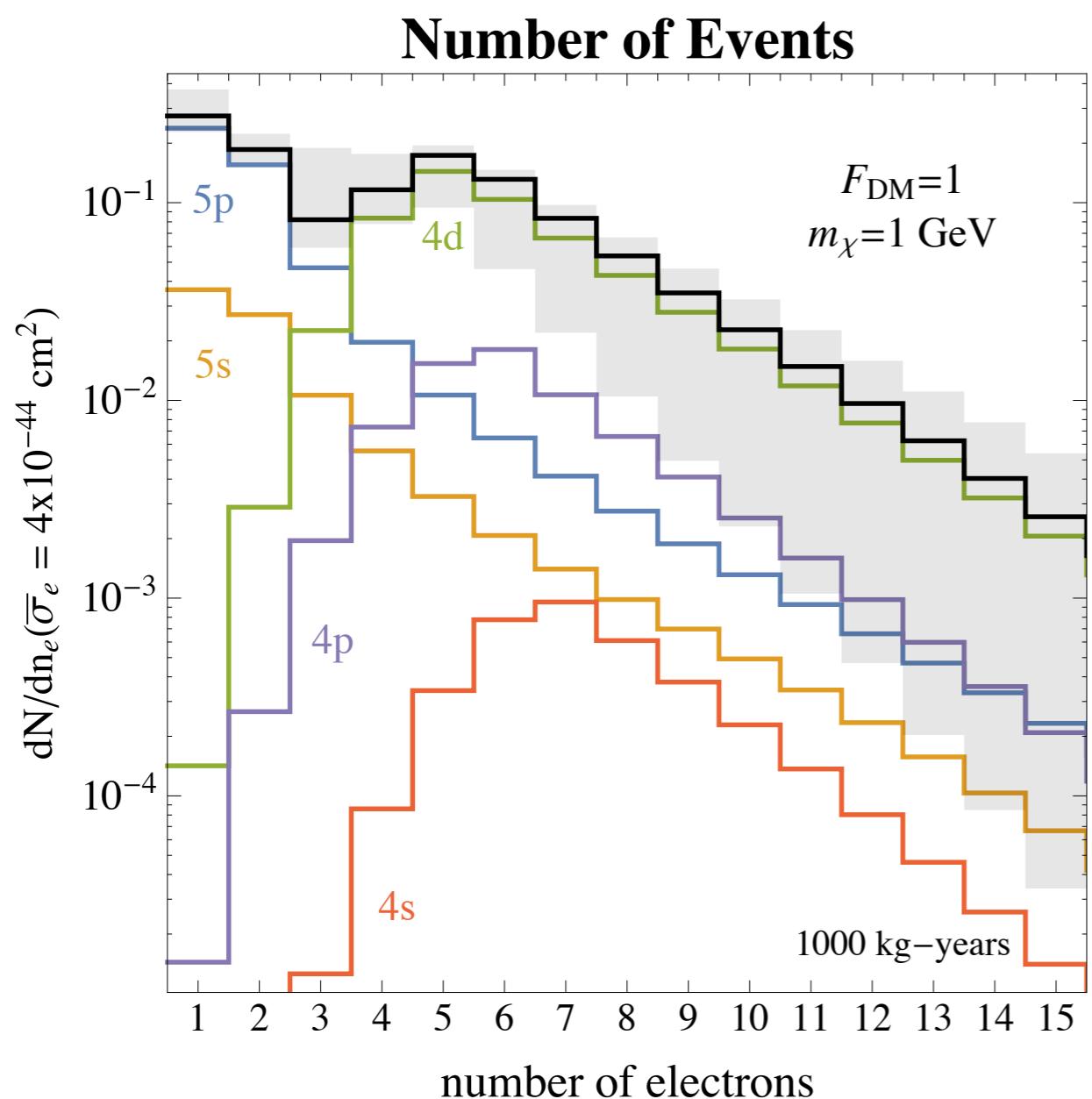


$$E_R \sim 50 \text{ eV}$$

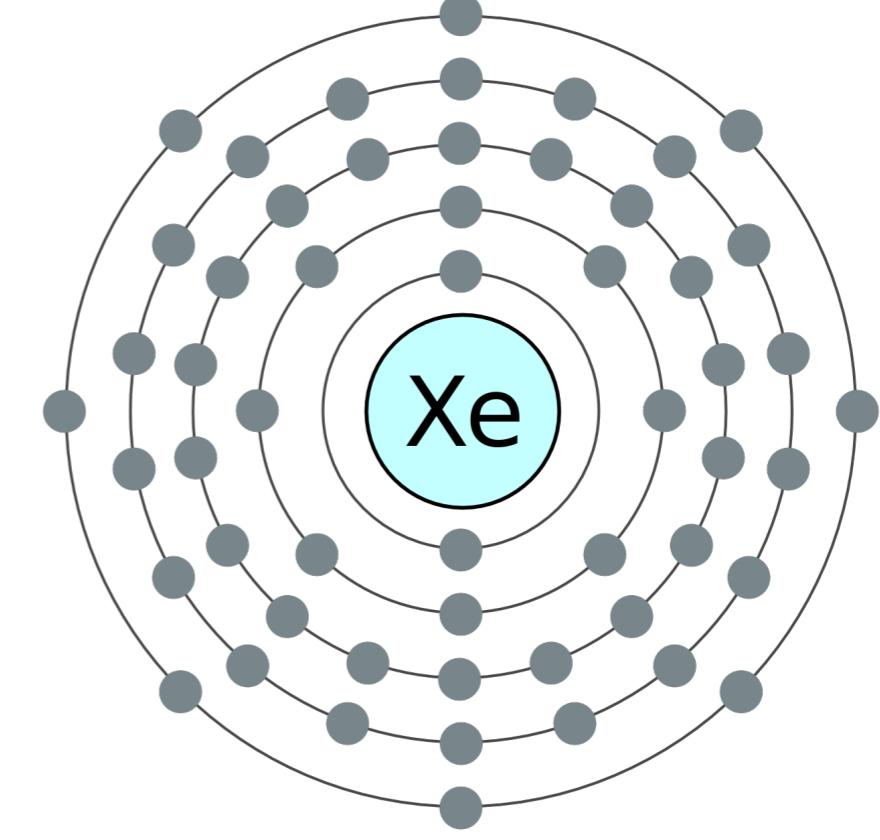
DM-electron scattering

$$\begin{aligned} m_N &= 28 \text{ GeV} \\ m_\chi &= 100 \text{ MeV} \end{aligned}$$

XENON



54: Xenon

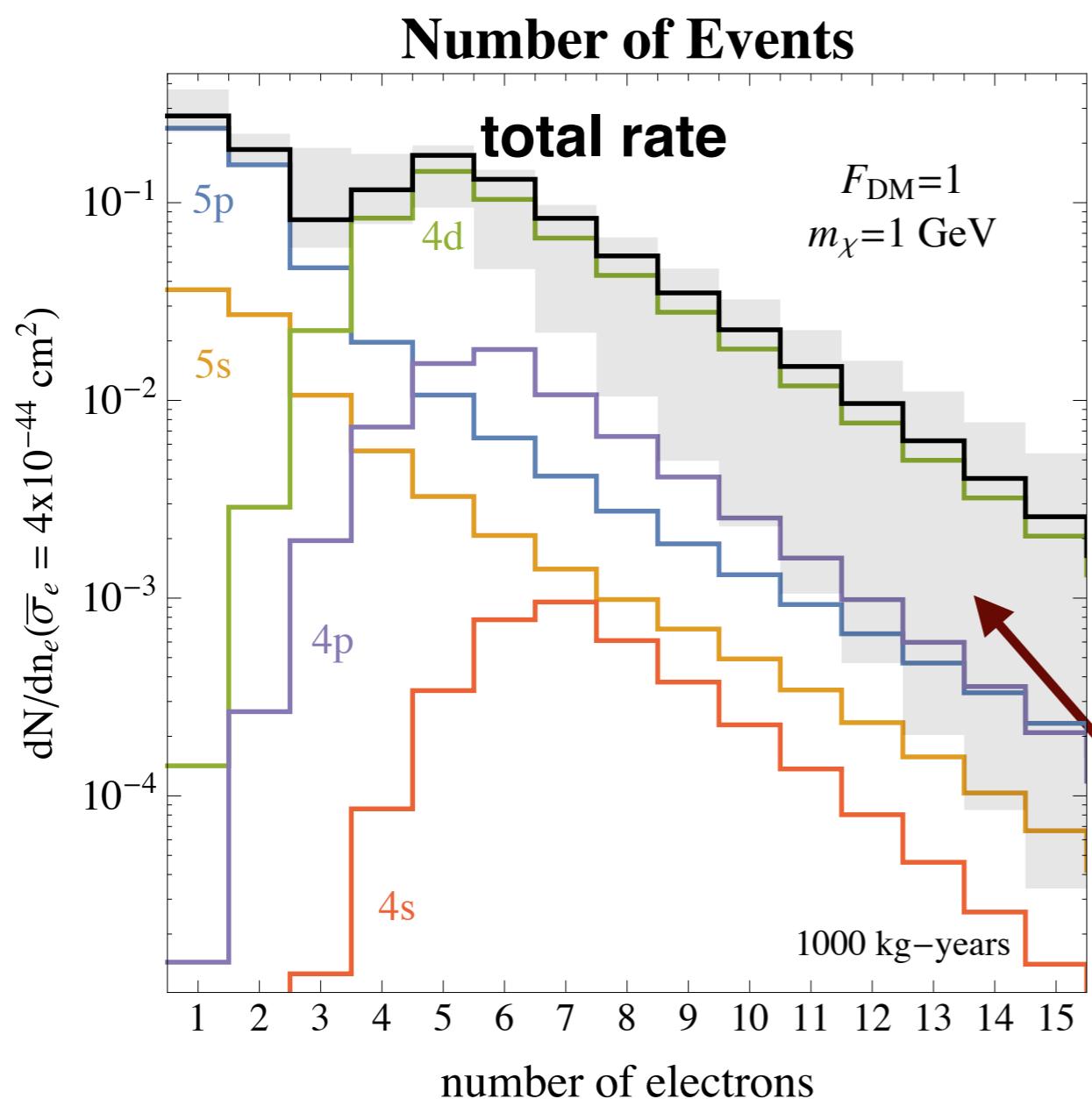


http://commons.wikimedia.org/wiki/Category:Electron_shell_diagrams

Essig, Volansky, TTY [1703.00910]

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

XENON

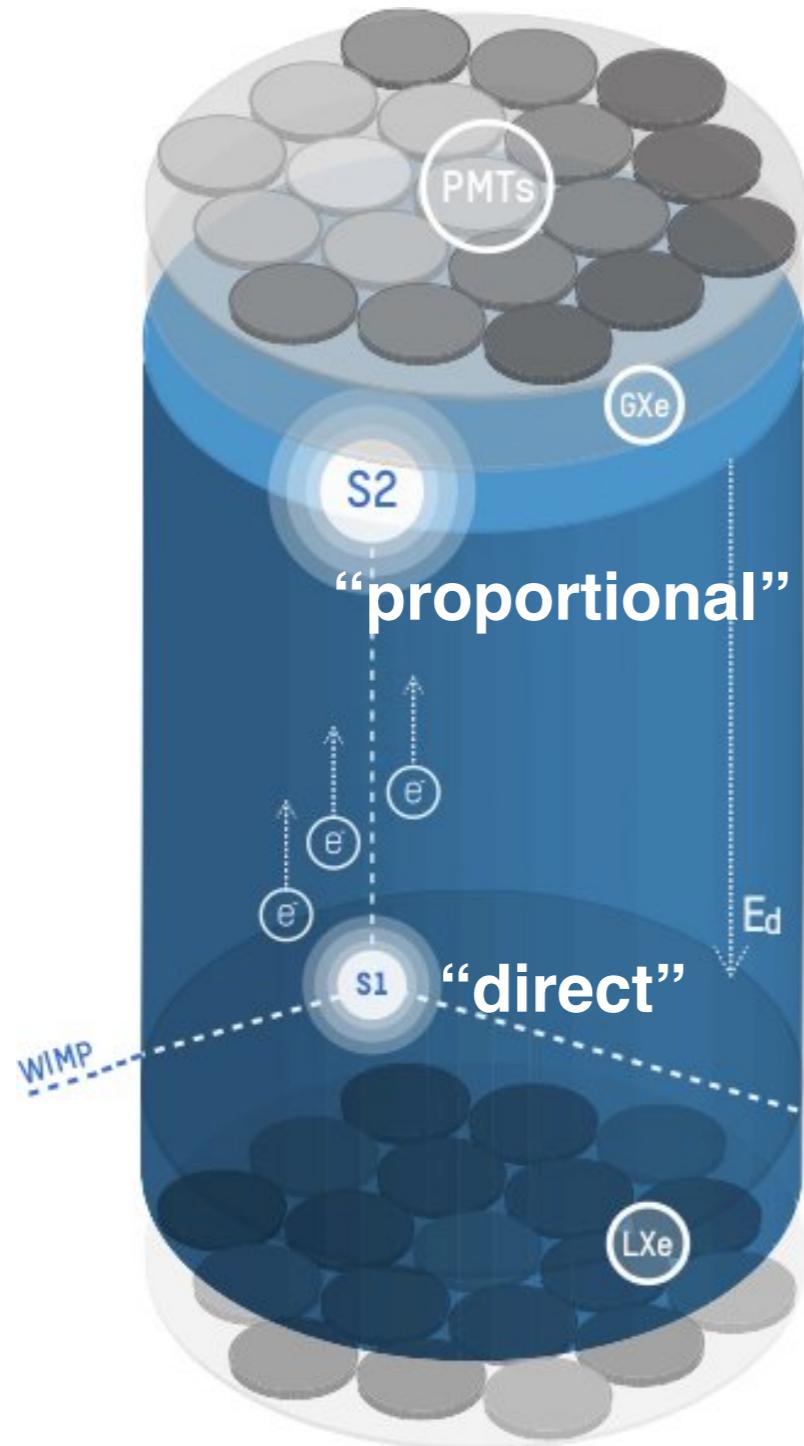


54: Xenon

**uncertainty from
secondary ionization
modeling**

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

Liquid Xenon/Argon



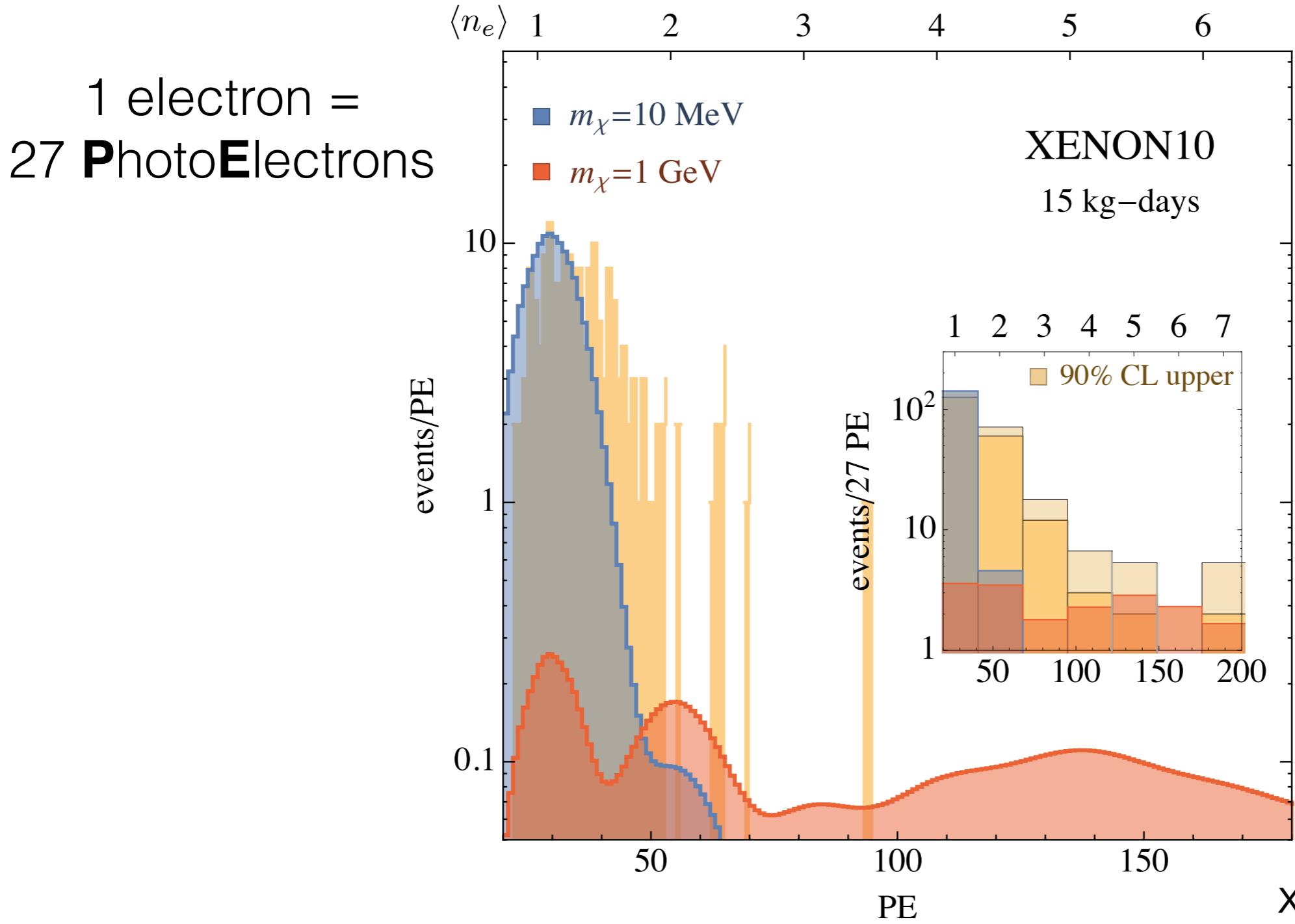
i.e. XENON10, XENON100, XENON1T, LUX,
DarkSide...

DM-electron scattering
=
S2 only signal

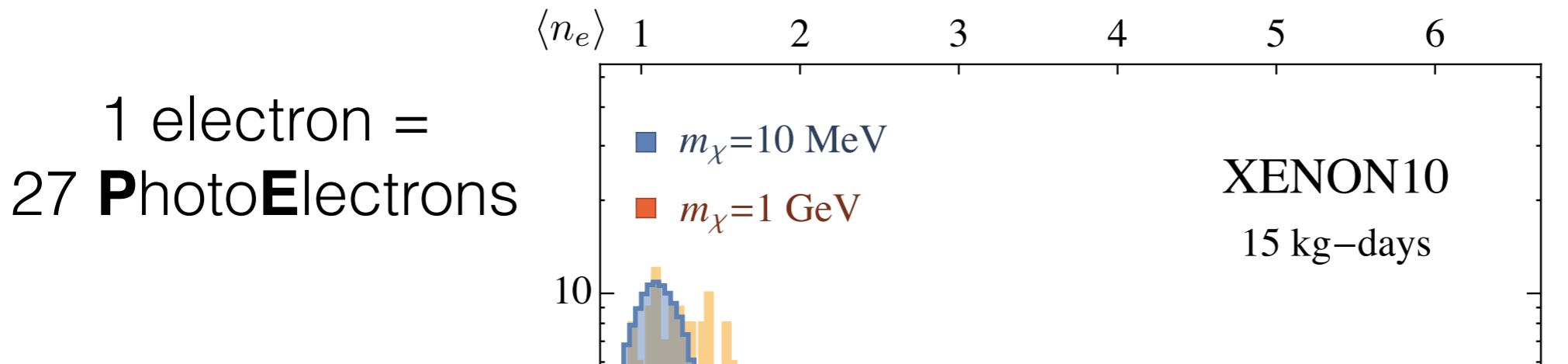
sensitive to ~10 eV energy depositions

measures PhotoElectrons

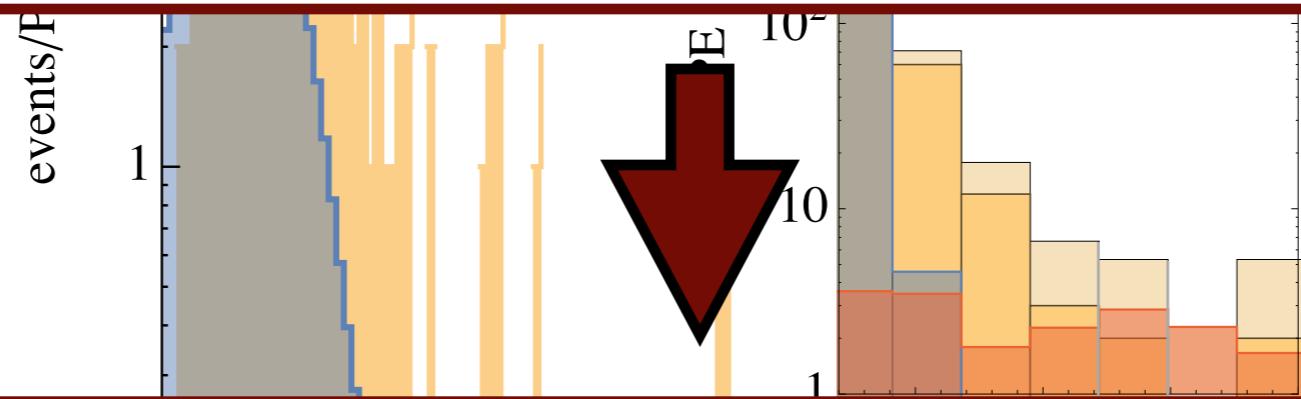
XENON10



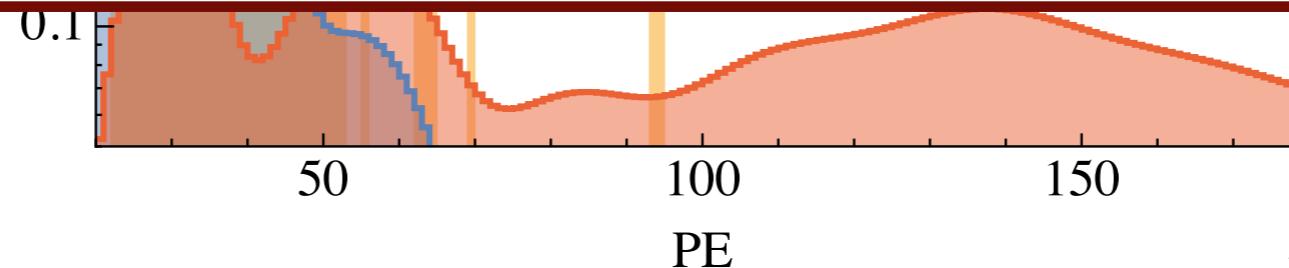
XENON10



signal < Number of observed events



constrain size of DM-electron scattering cross-section

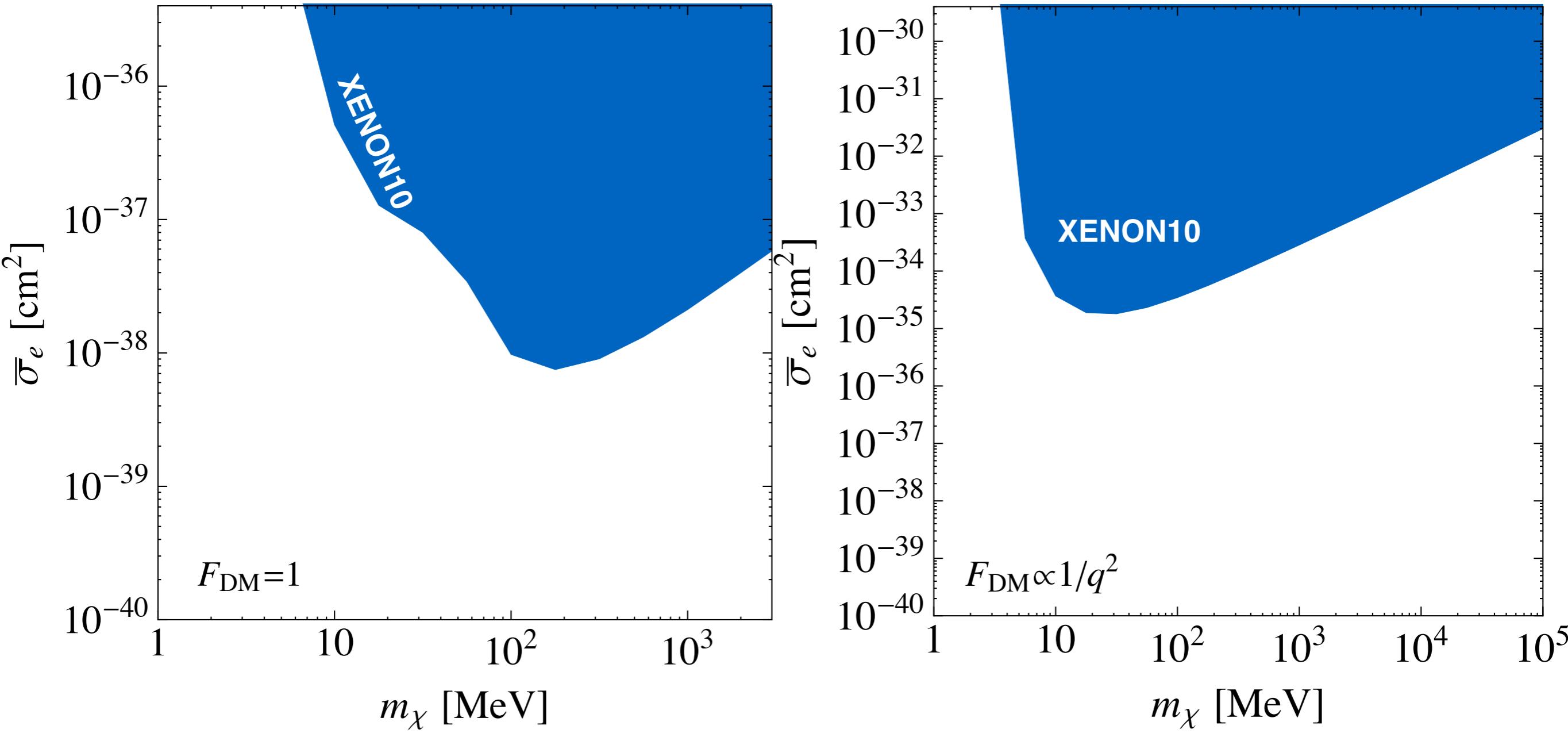


XENON10 Collaboration

Essig, Volansky, TTY [1703.00910]

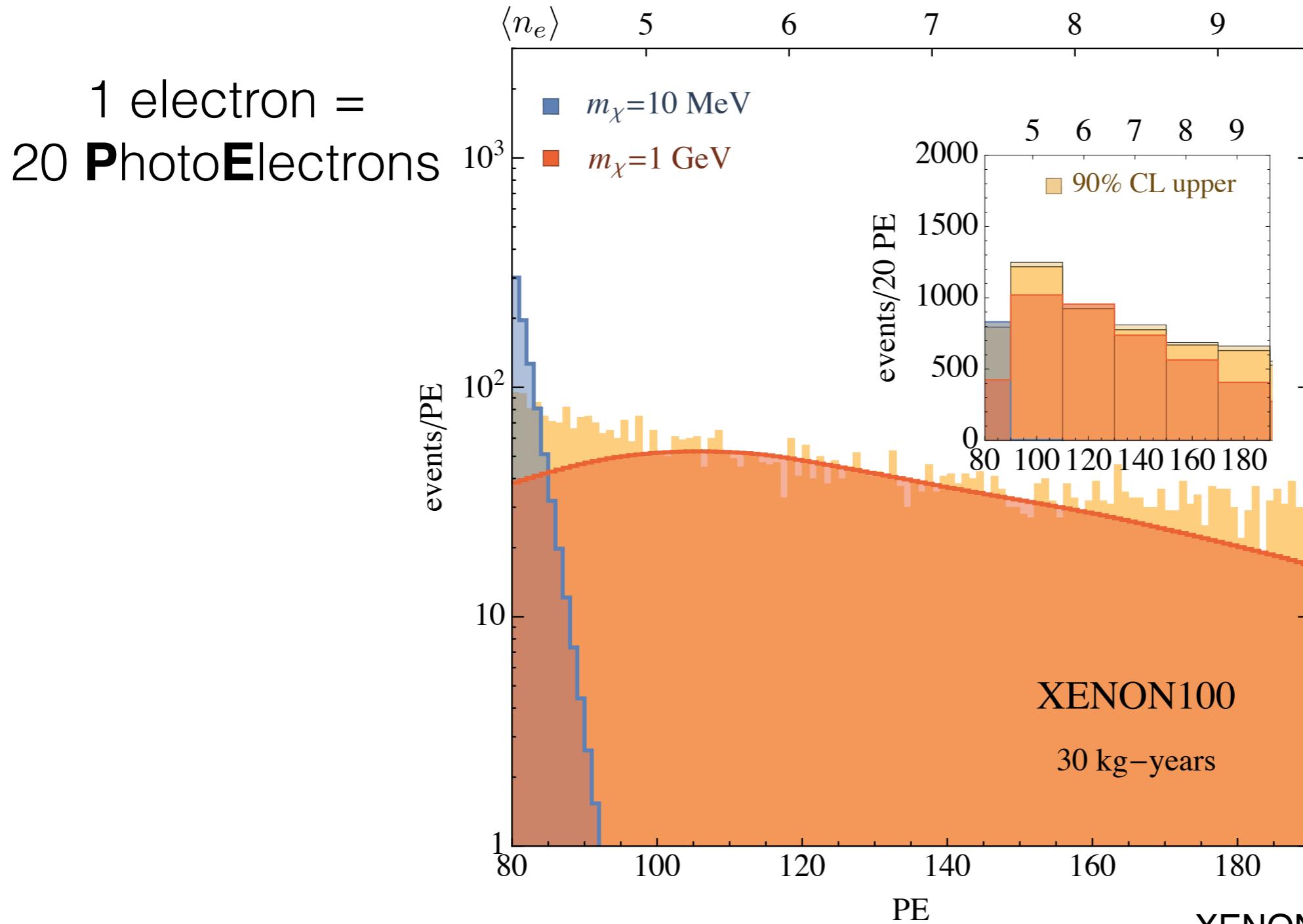
Phys.Rev.Lett. 110 (2013) 249901

XENON



Essig, Volansky, TTY [1703.00910]

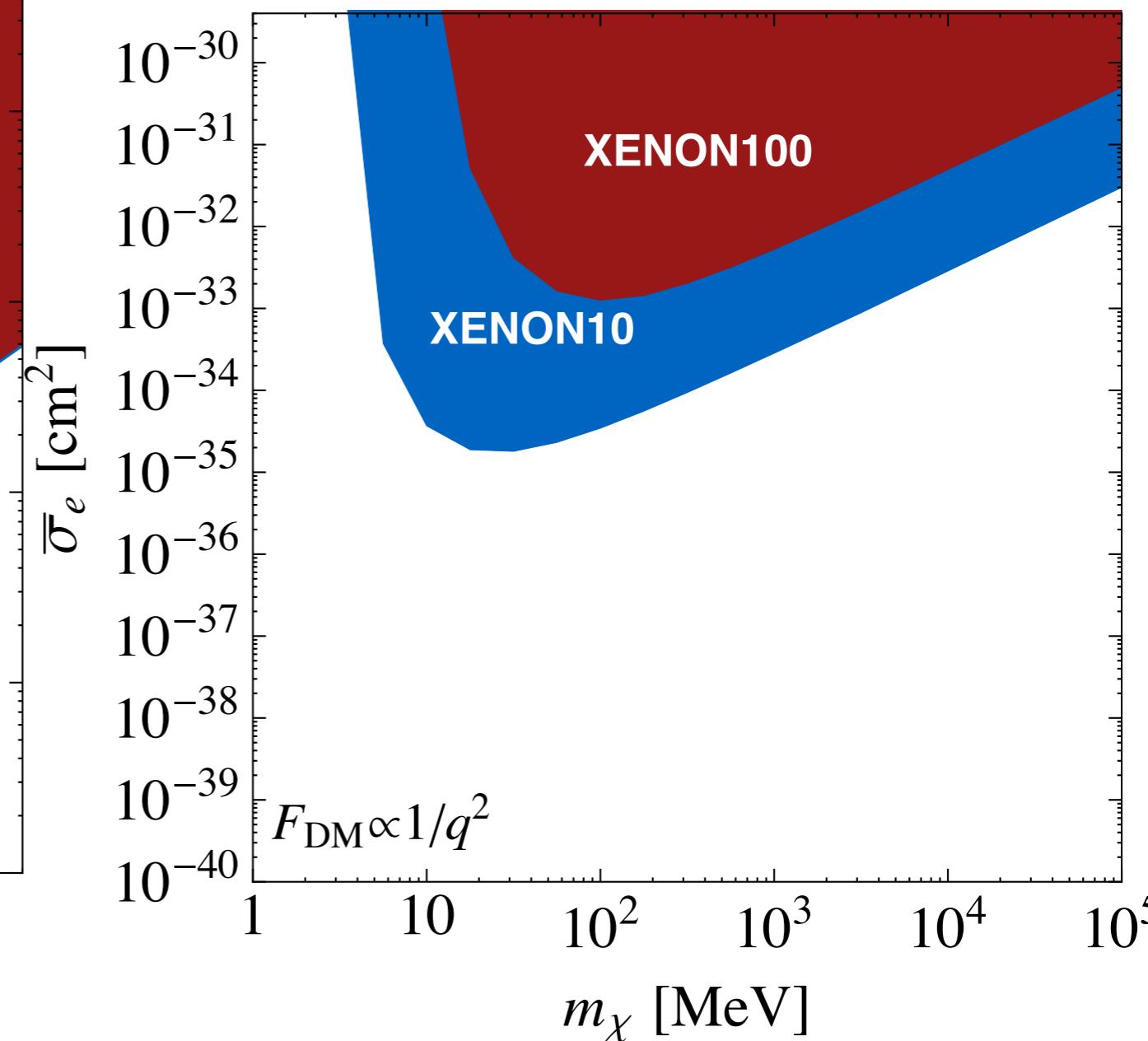
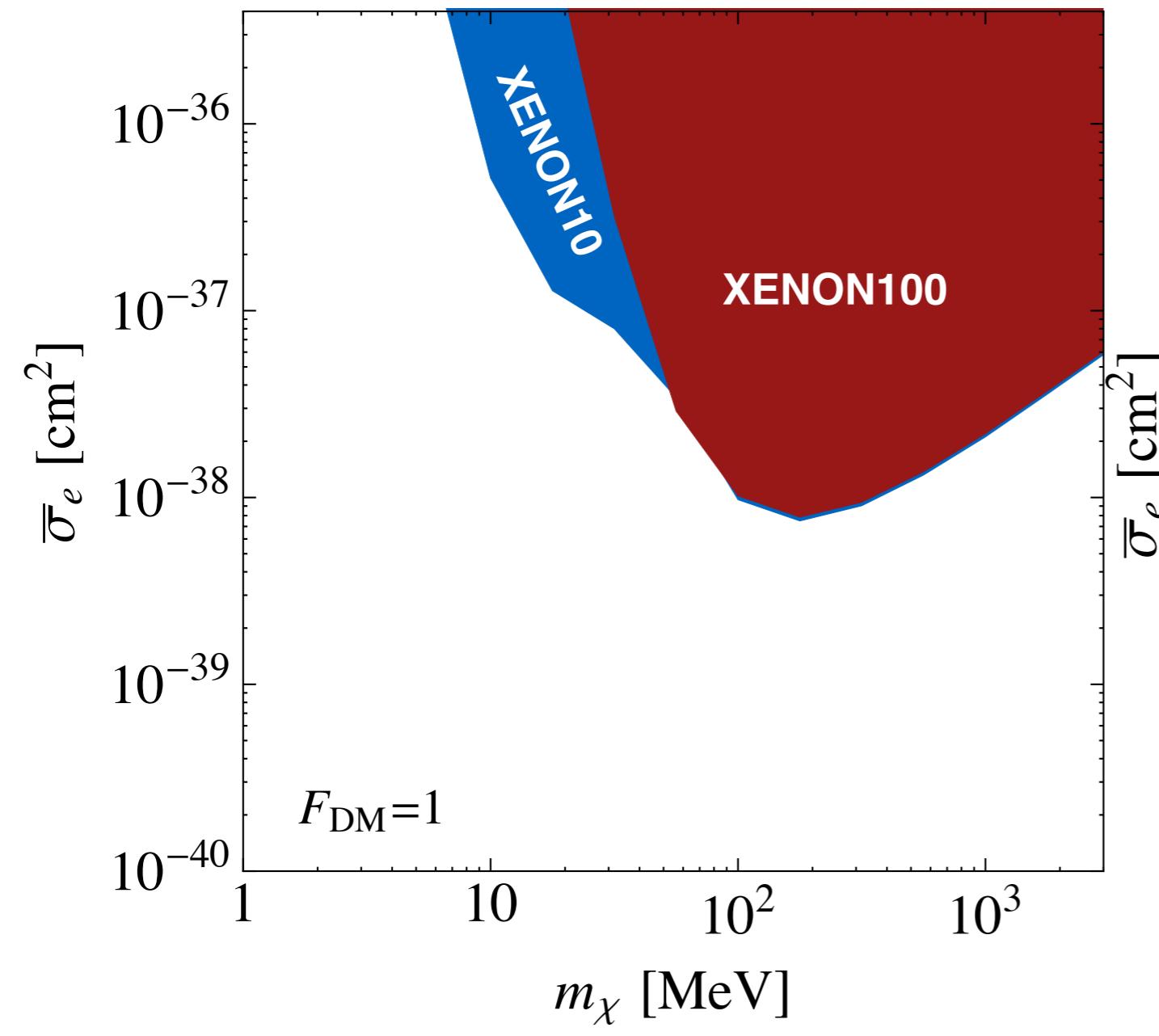
XENON100



Essig, Volansky, TTY [1703.00910]

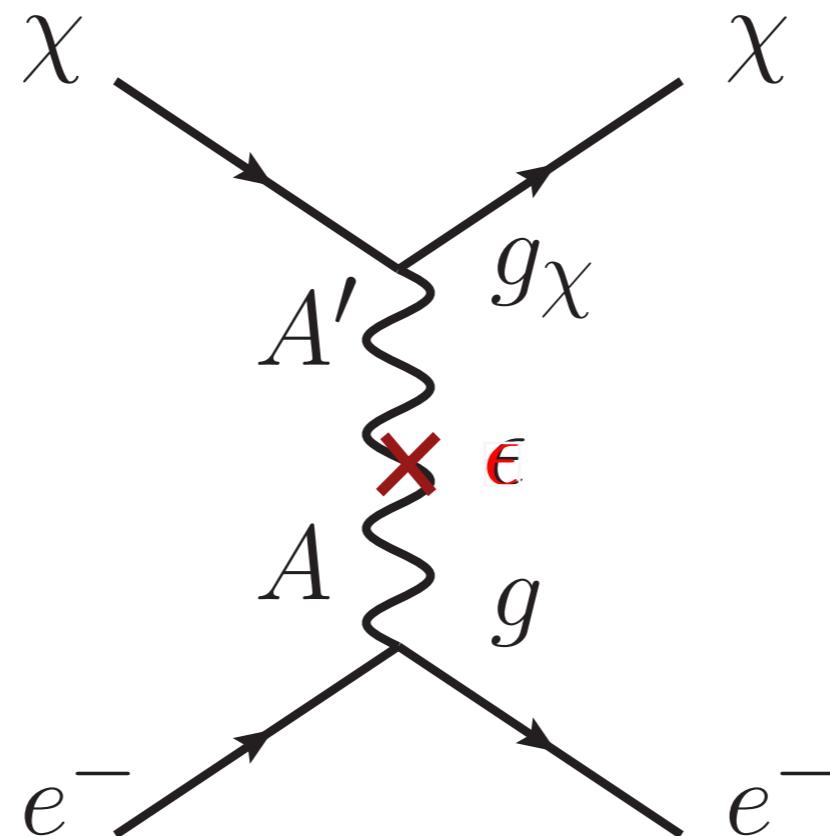
XENON100 collaboration
Phys.Rev. D94 (2016) no.9, 092001

XENON



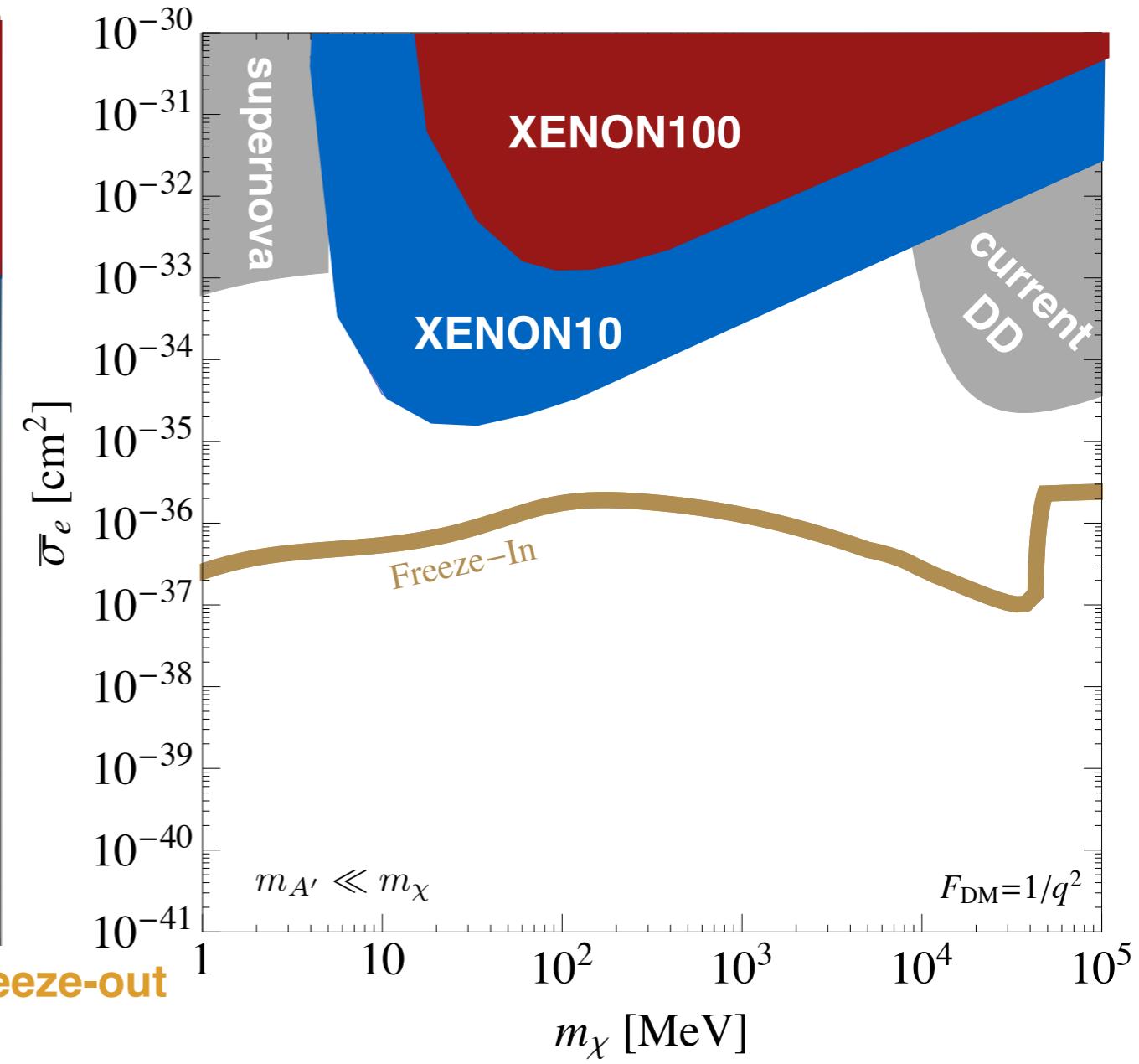
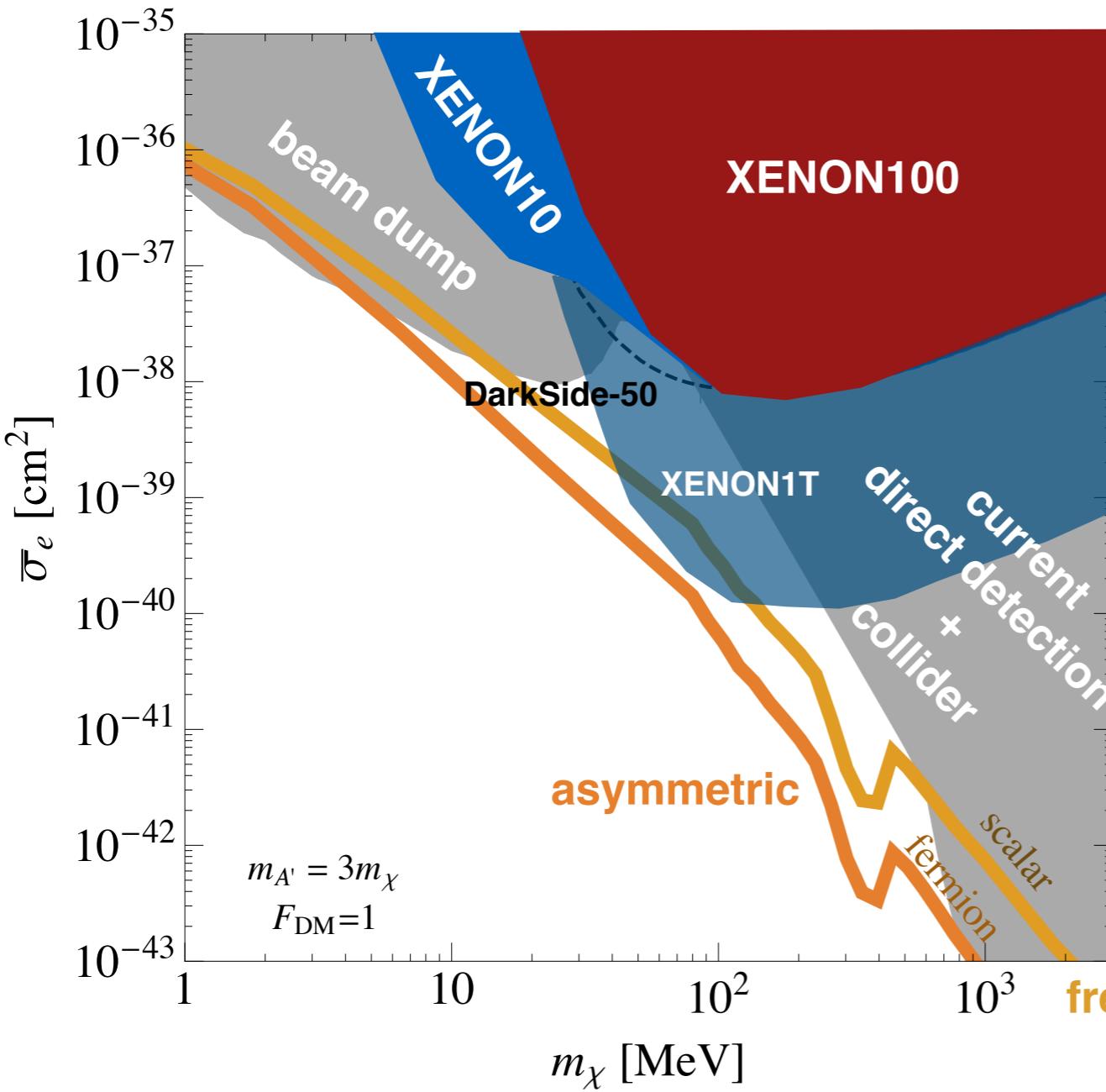
a model: dark photon

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

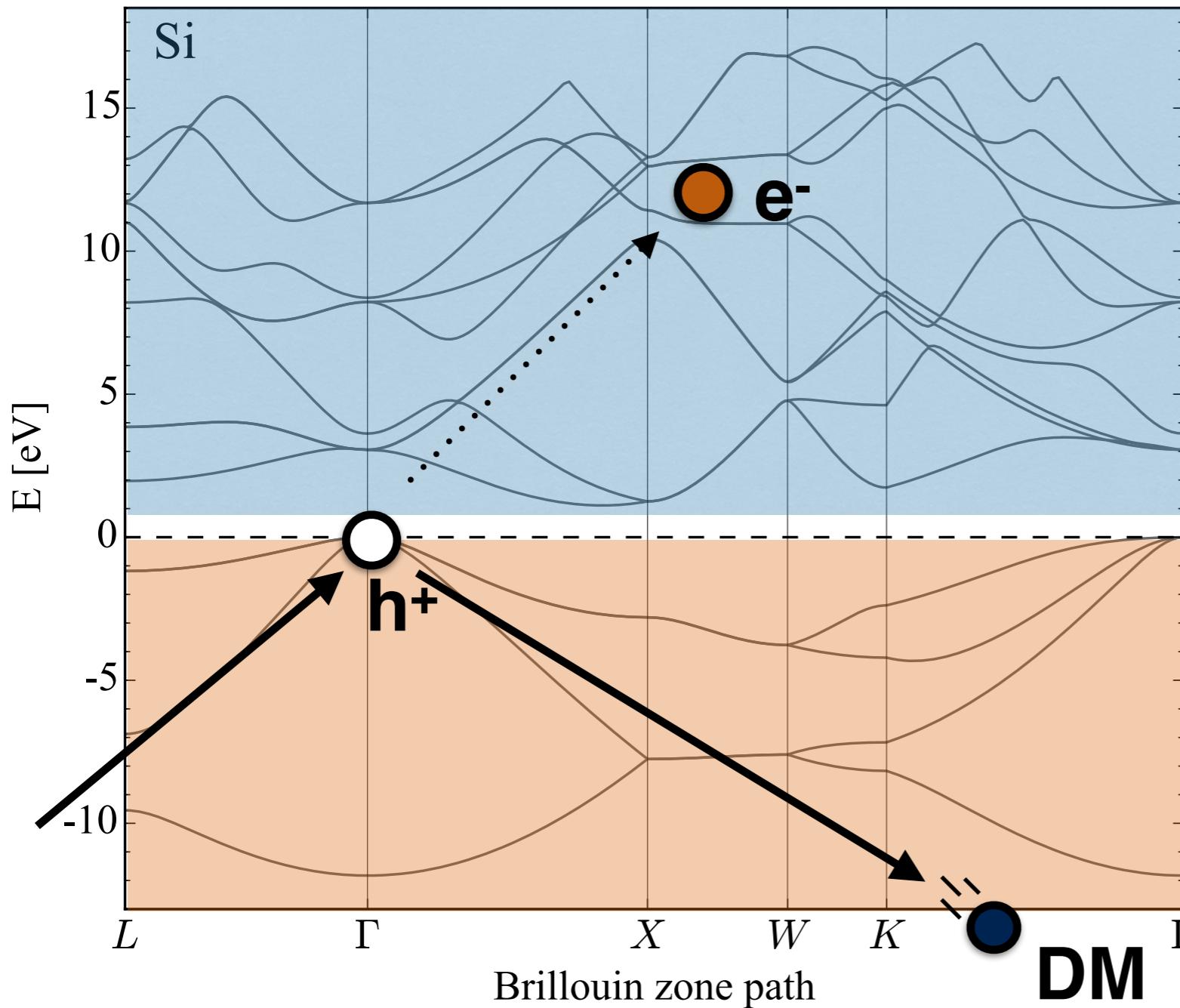


$$F_{DM}(q) = \frac{m_{A'}^2 + \alpha^2 m_e^2}{m_{A'}^2 + q^2} \simeq \begin{cases} 1, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}, & m_{A'} \ll \alpha m_e \end{cases}$$

dark photon



semiconductor targets



detect the electron(s)

sensitive to \sim eV energy
depositions

i.e. silicon,
germanium

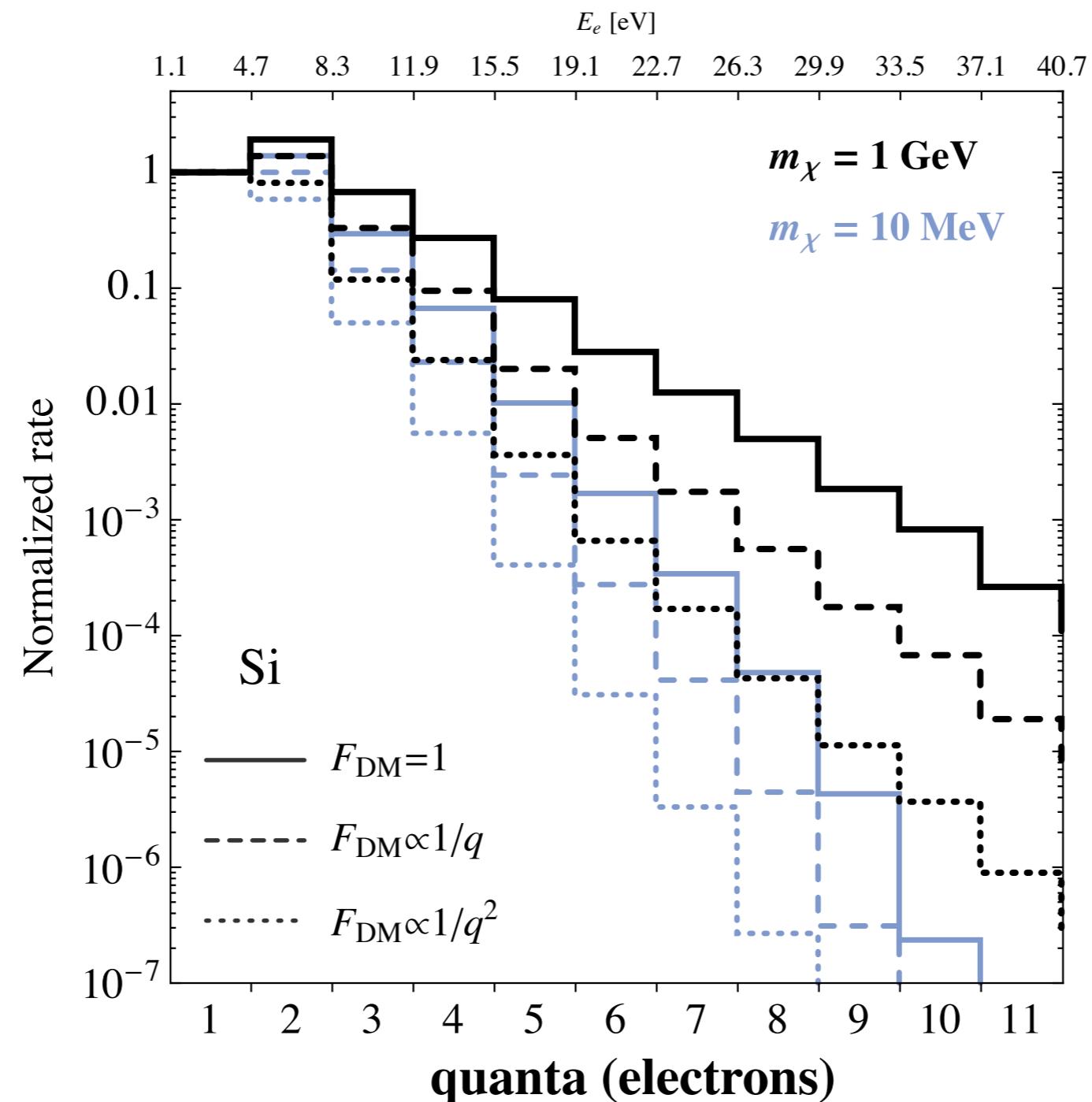
Essig, Mardon, Volansky [1108.5383]

Graham, Kaplan, Rajendran, Walters [1203.2531]

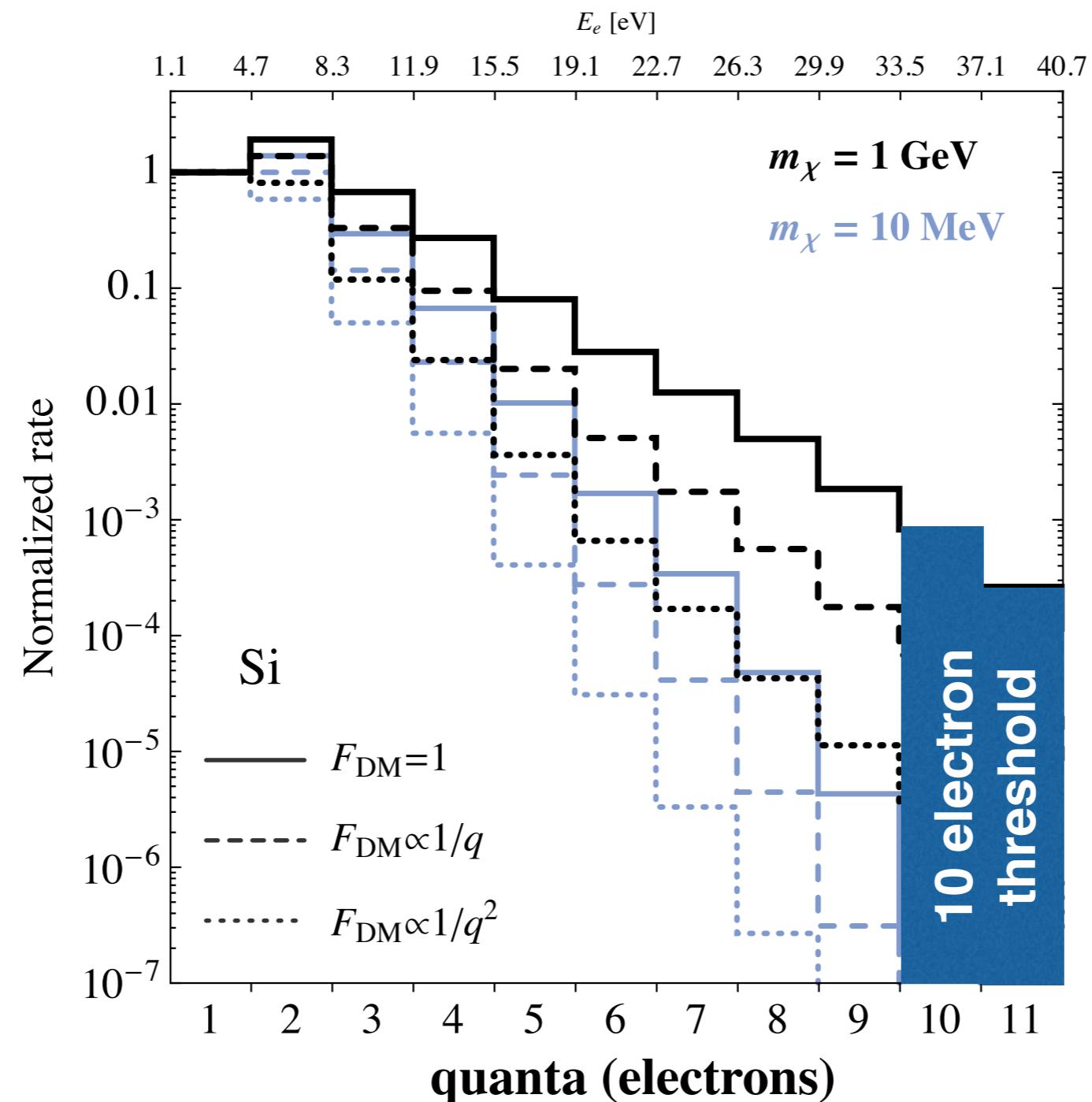
Lee, Lisanti, Mishra-Sharma, Safdi [1508.07361]

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

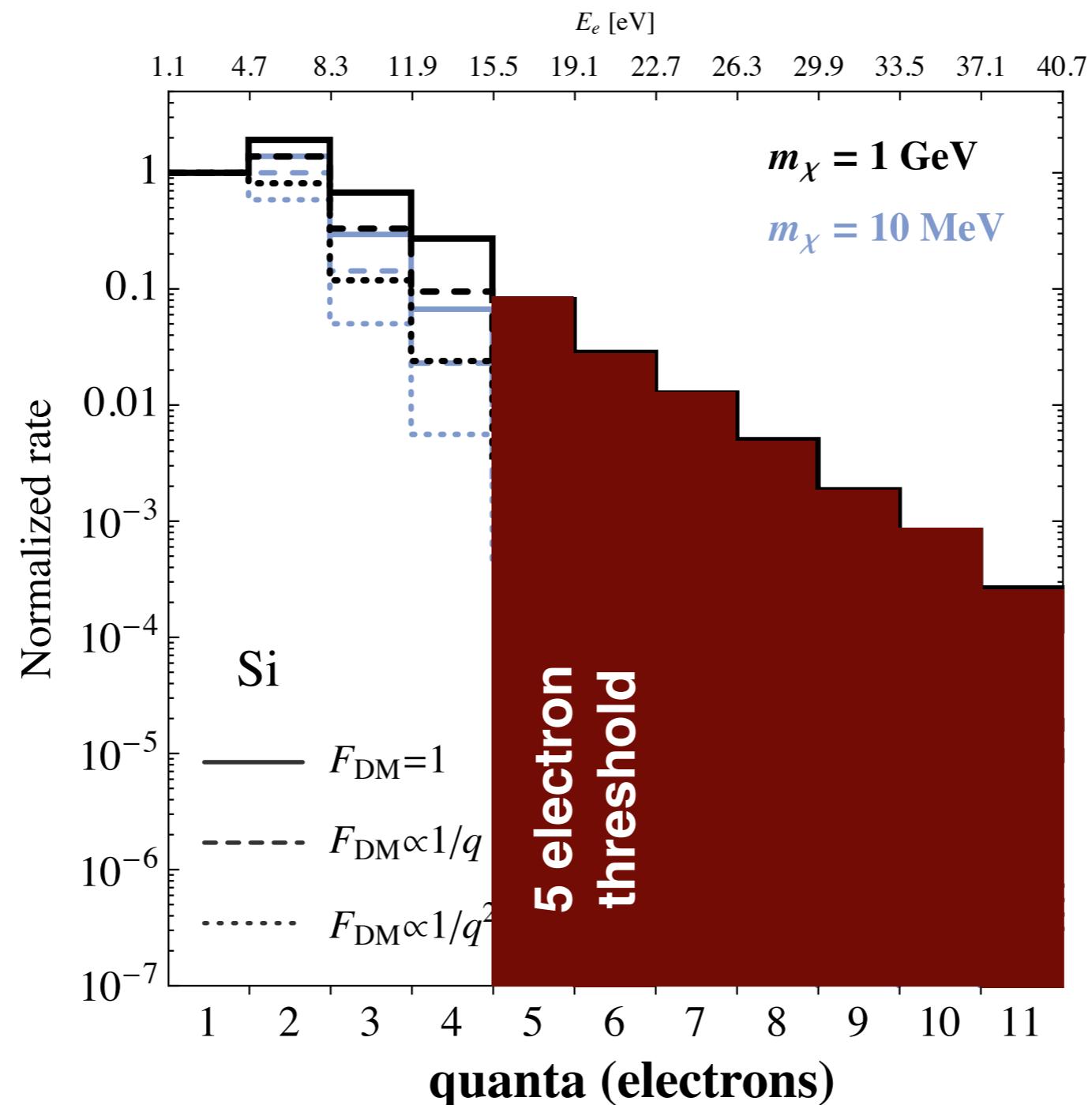
threshold dependence



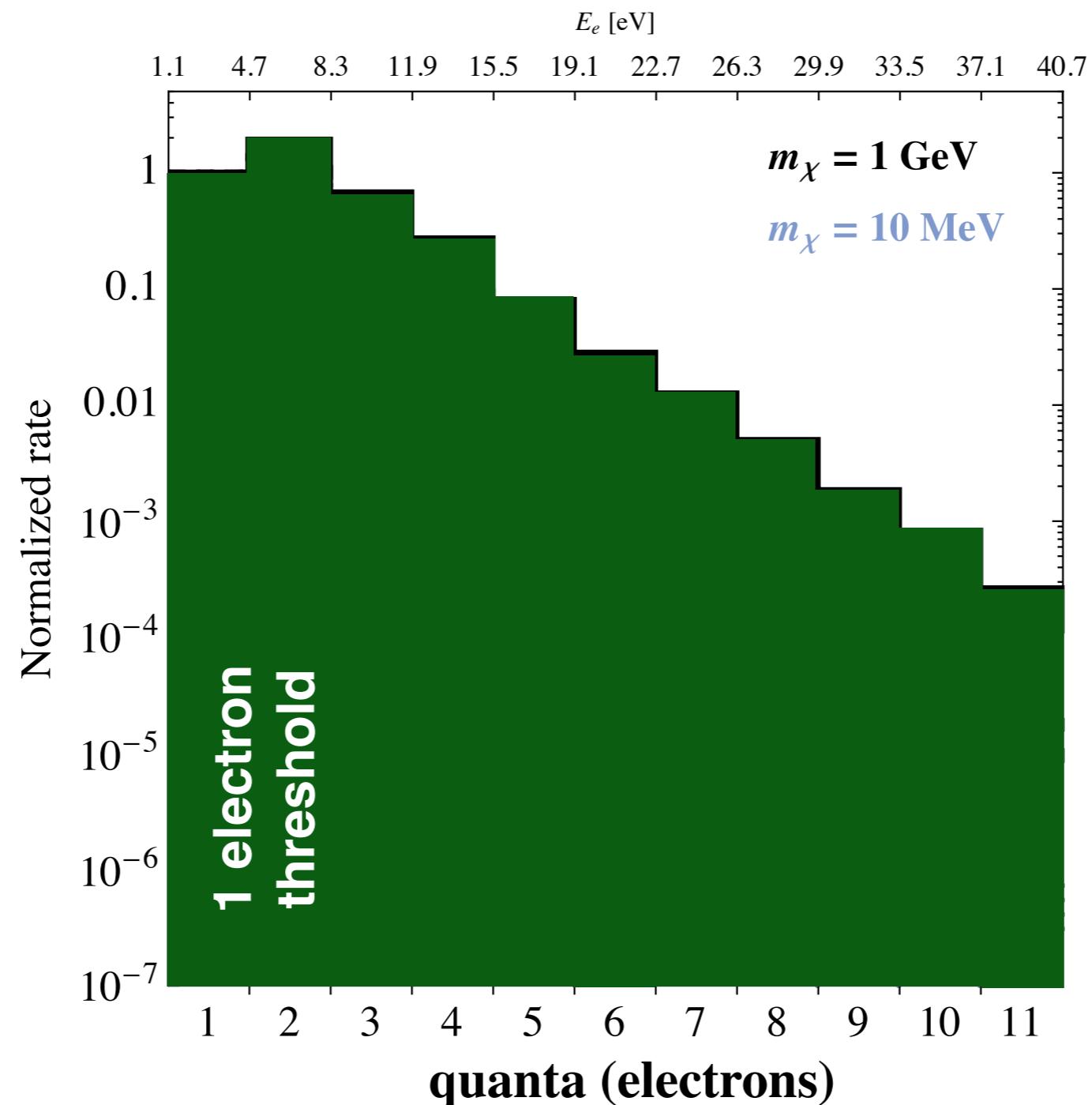
threshold dependence



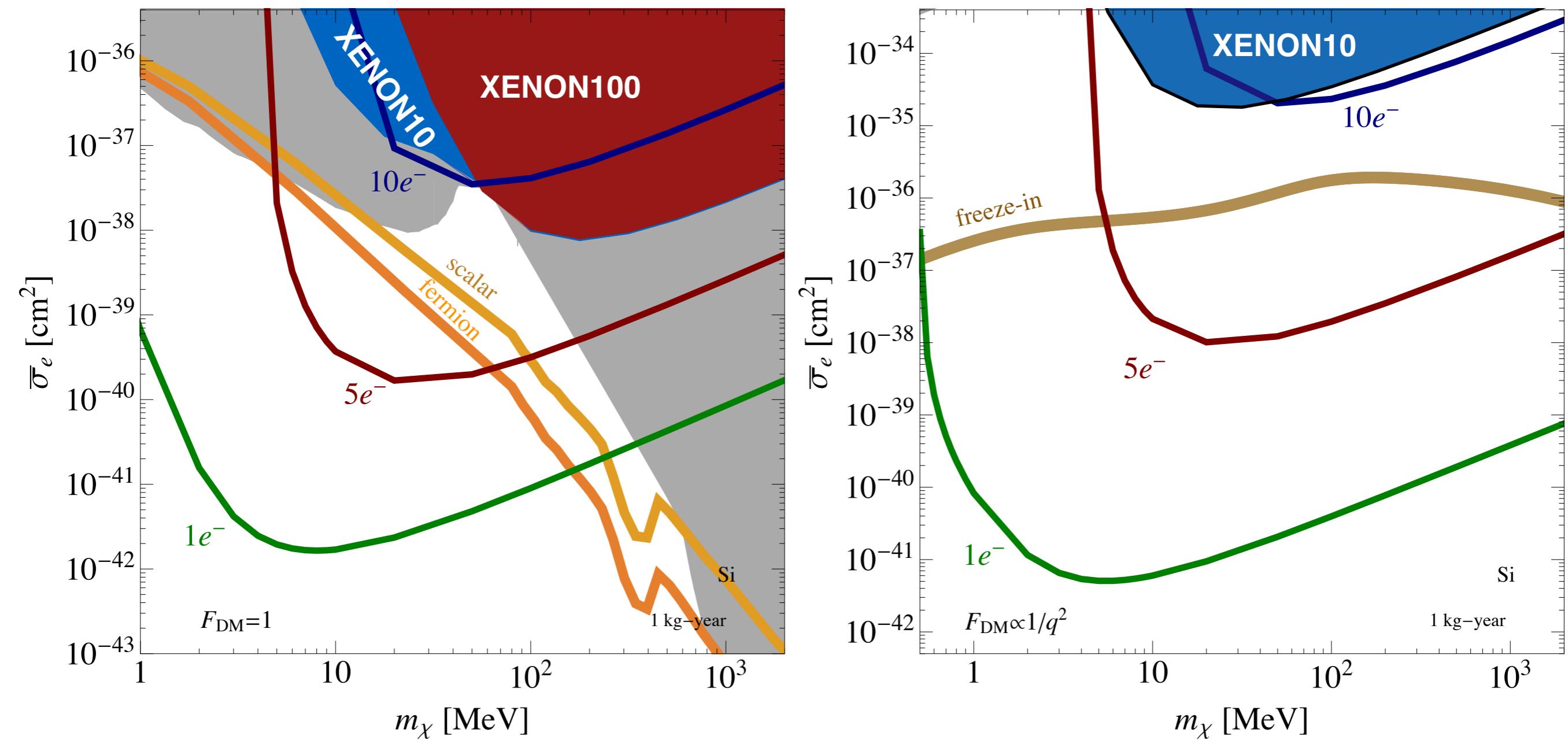
threshold dependence



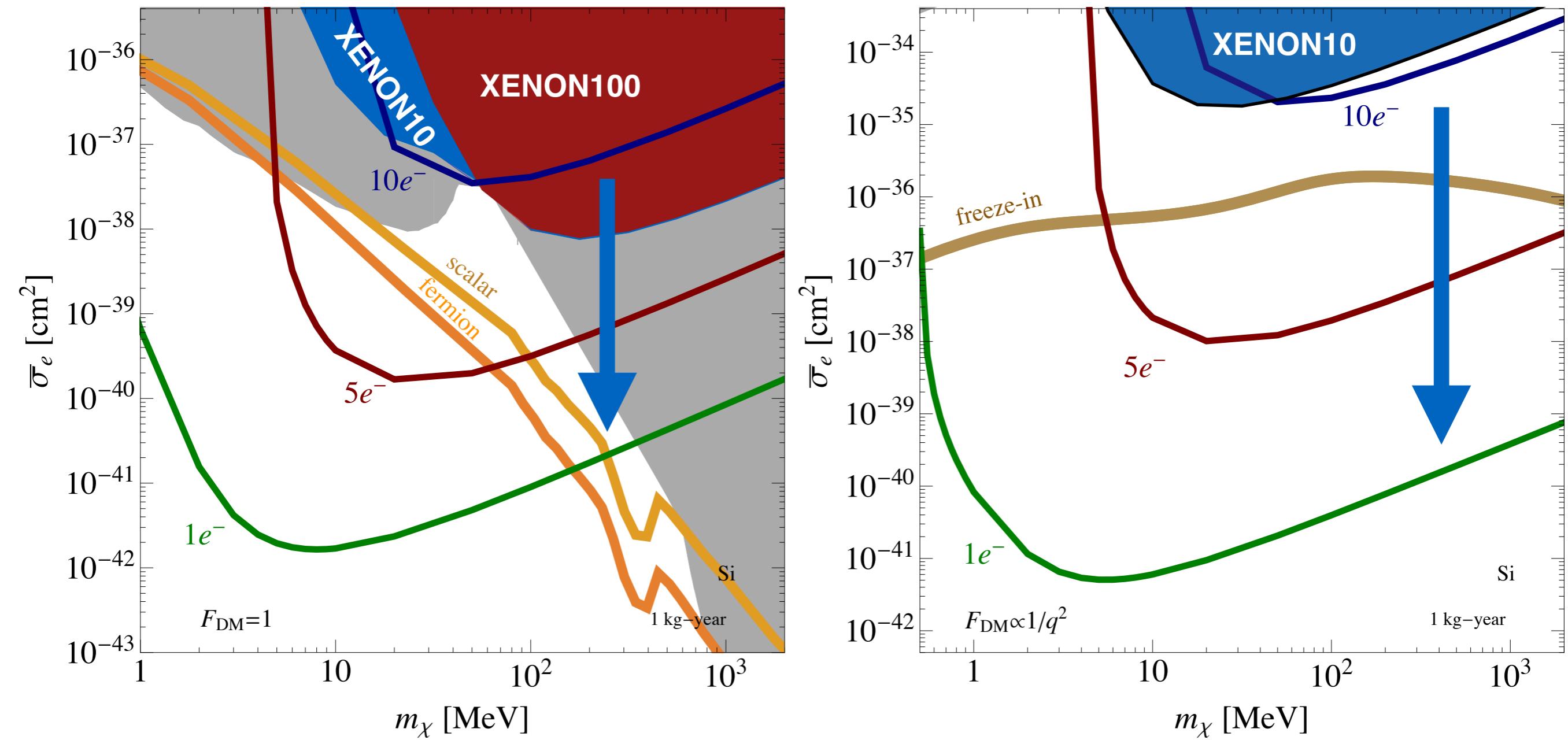
threshold dependence



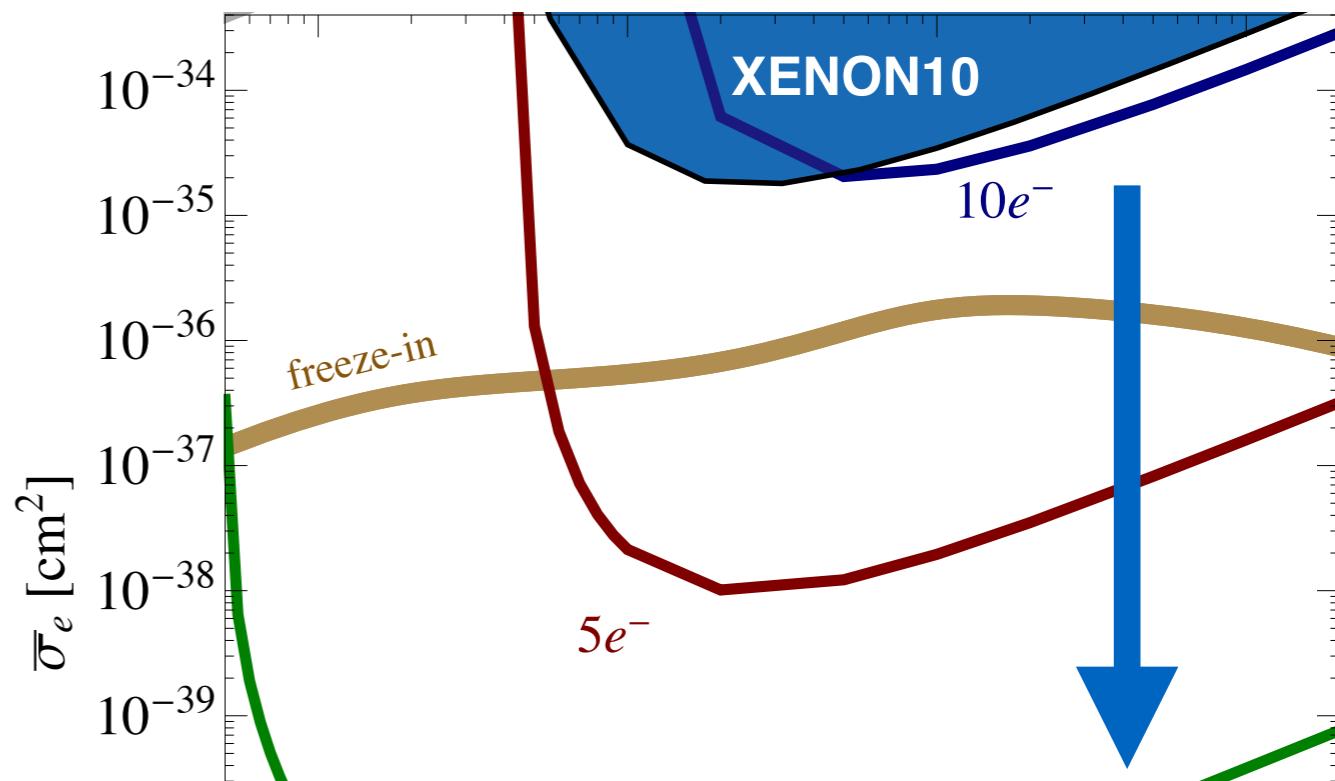
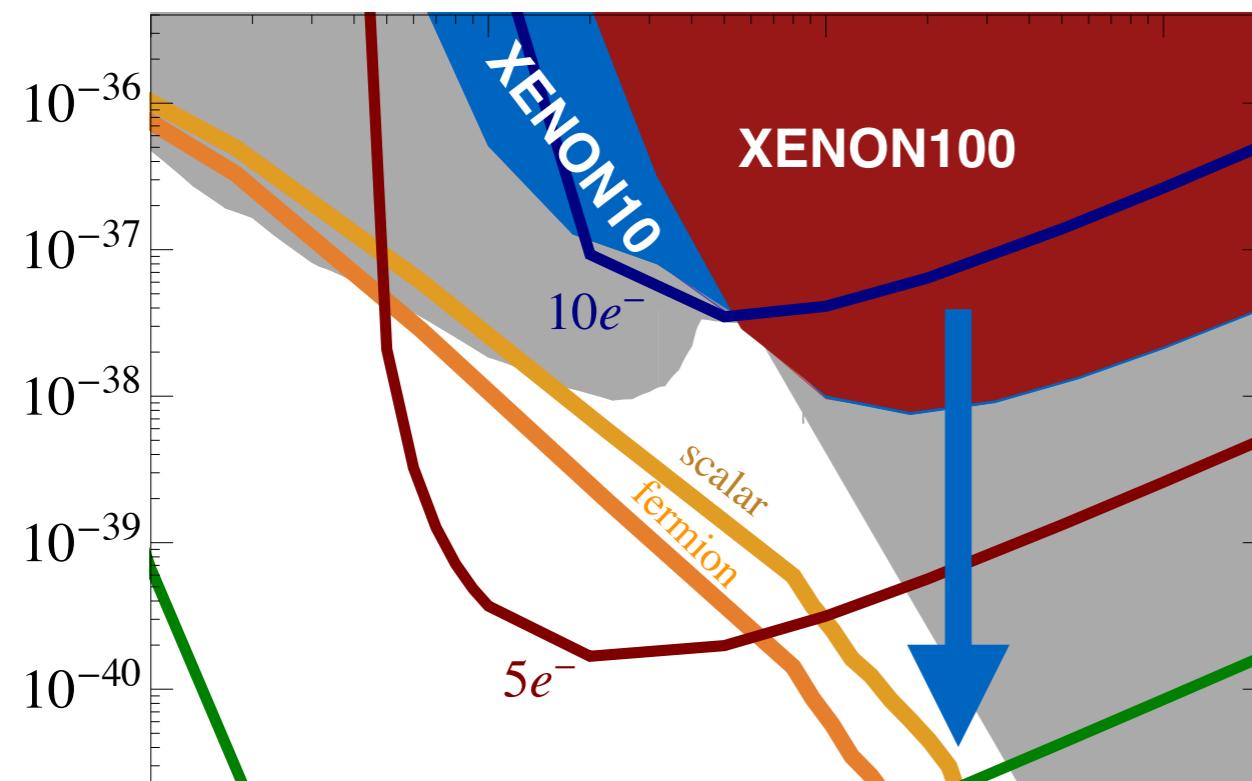
threshold dependence



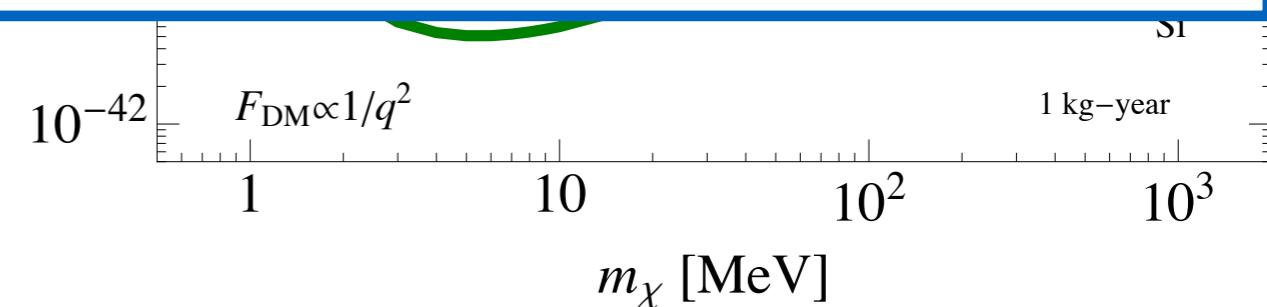
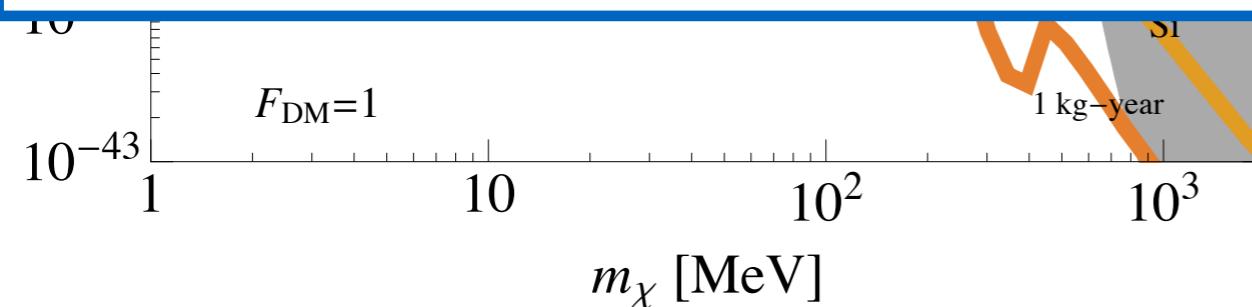
threshold dependence

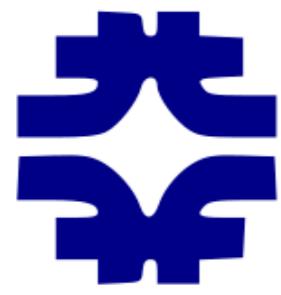


threshold dependence



requires new experimental techniques





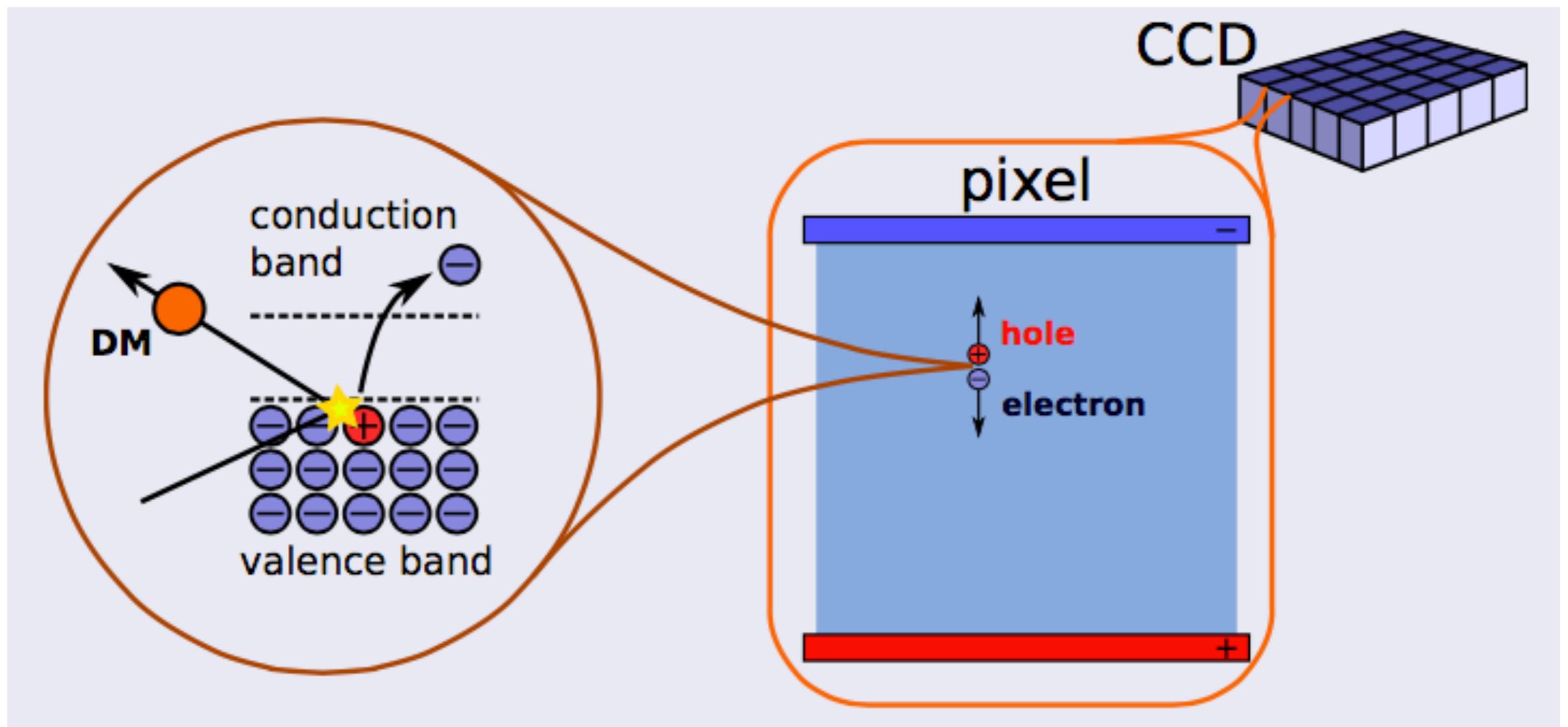
Fermilab

SENSEI

Sub-Electron-Noise Skipper CCD Experimental Instrument



silicon CCD detector



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

of electrons vs. N

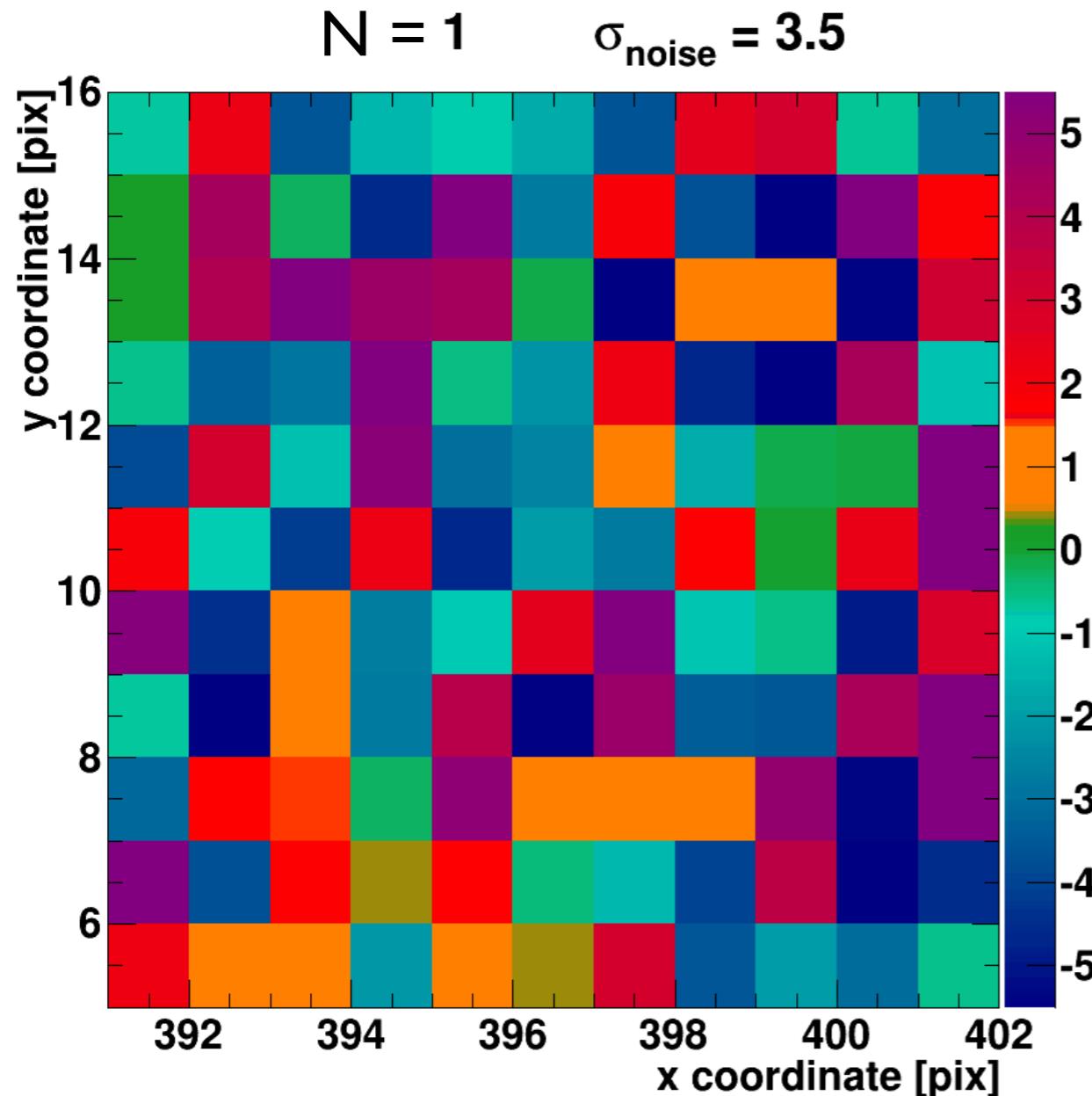
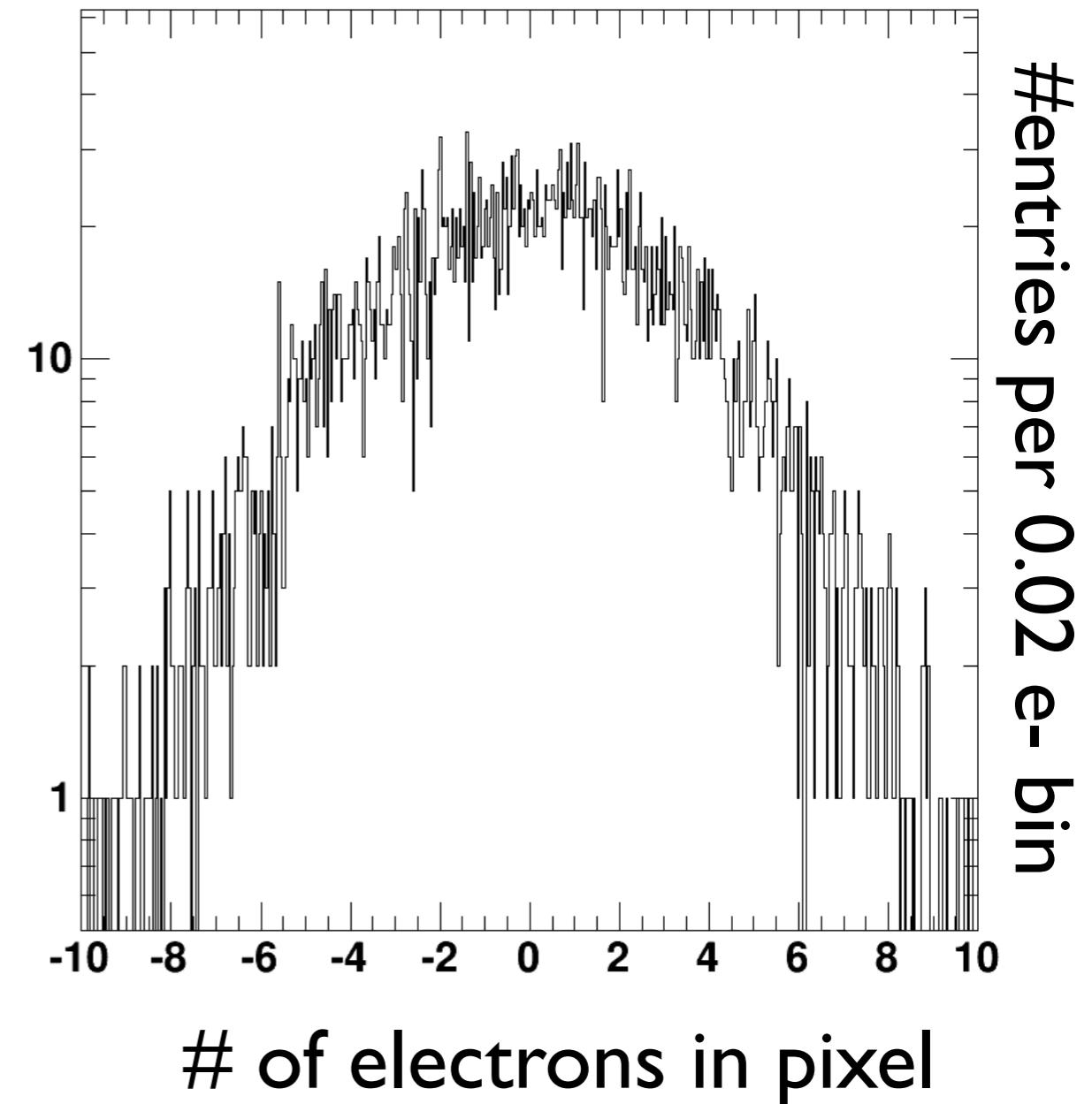


figure courtesy of Javier Tiffenberg

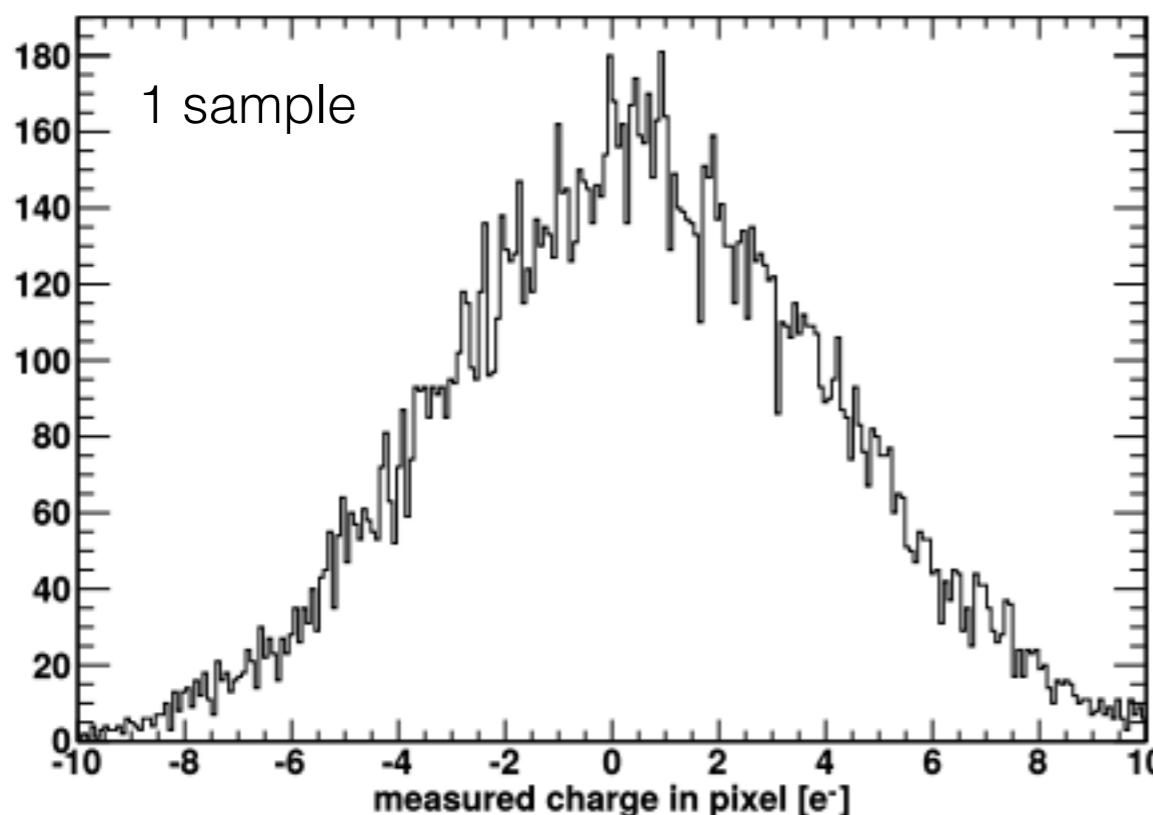


Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig,
Guardincerri, Holland, Volansky, TTY
Phys.Rev.Lett. 119 (2017) 13, 131802 [1706.00028]

skipper readout

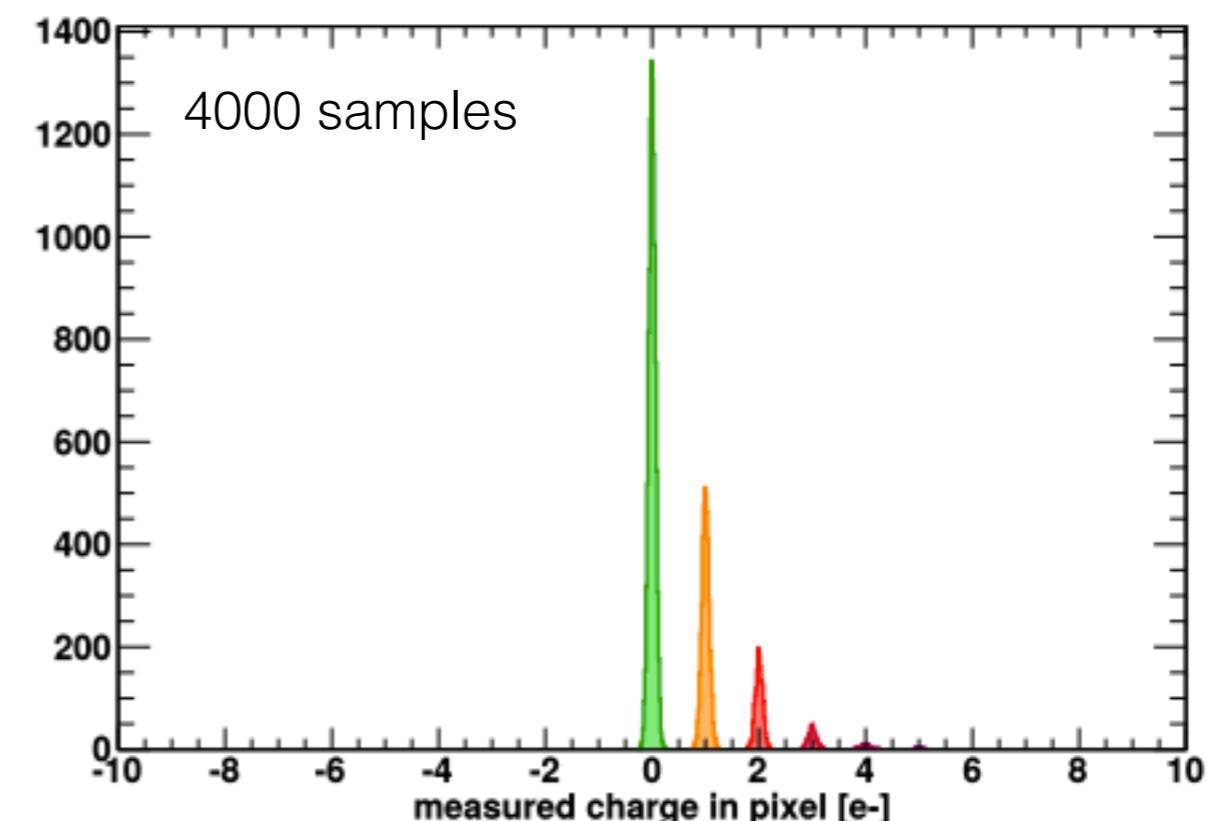
standard CCD

Readout-noise: 3.5 e RMS

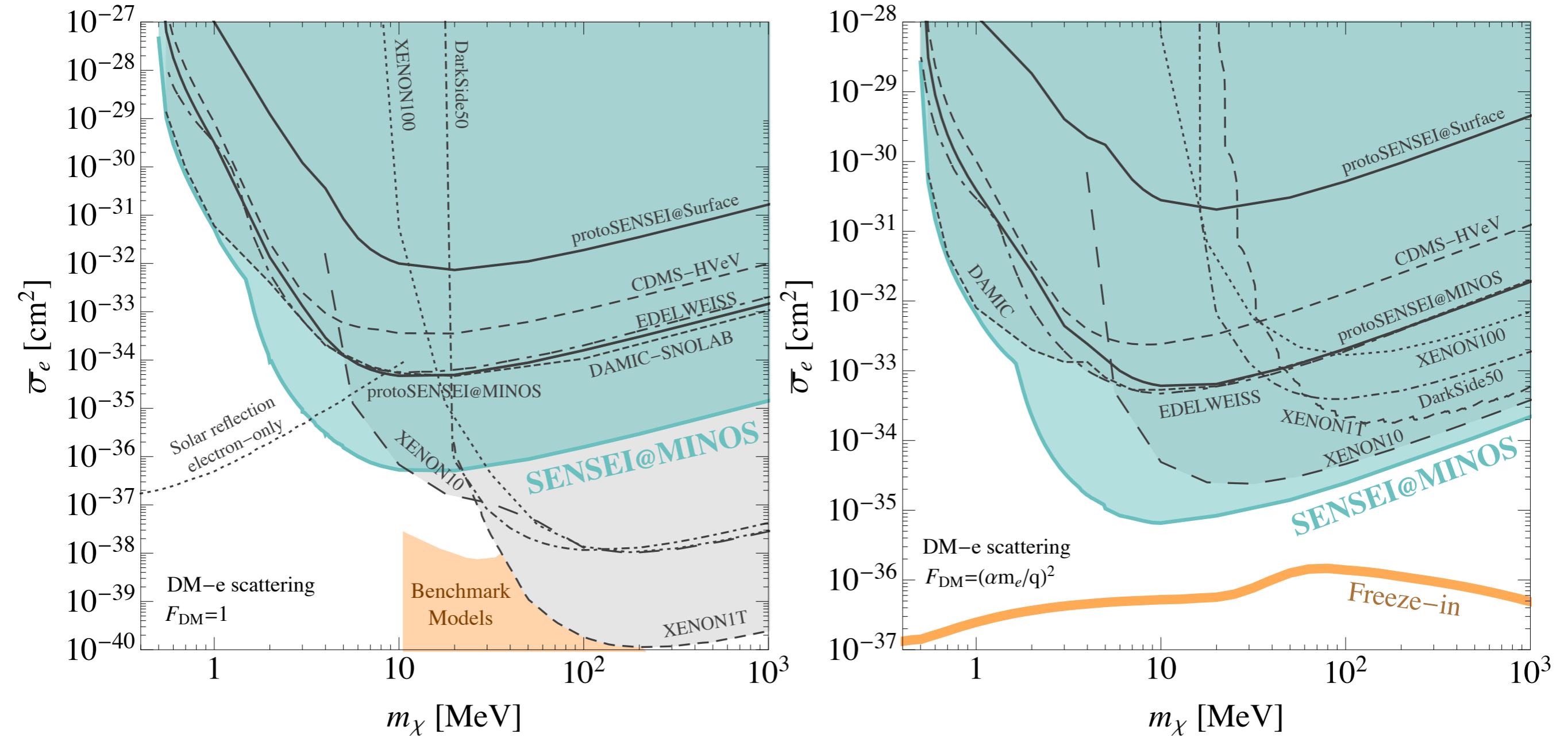


skipper CCD

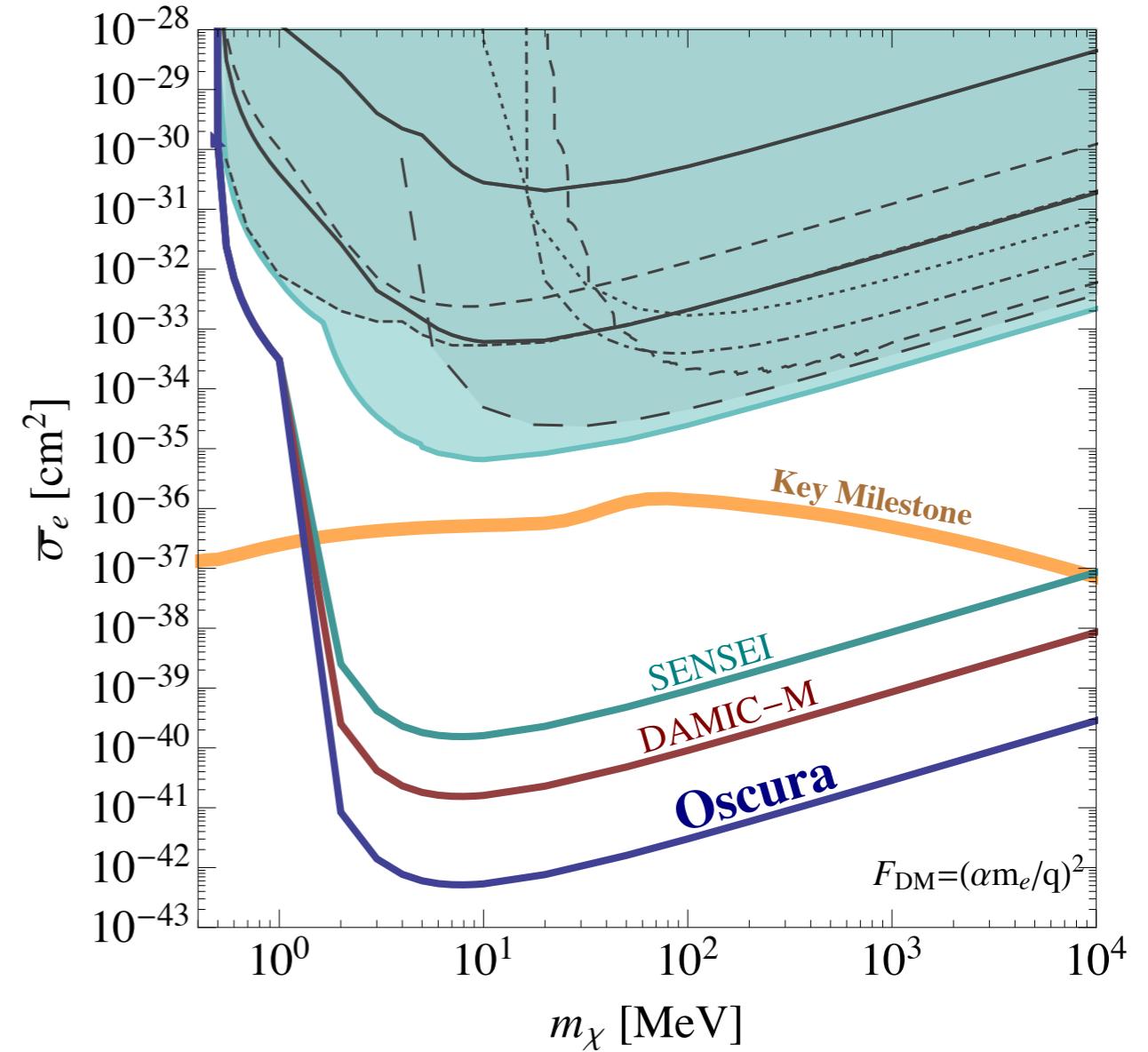
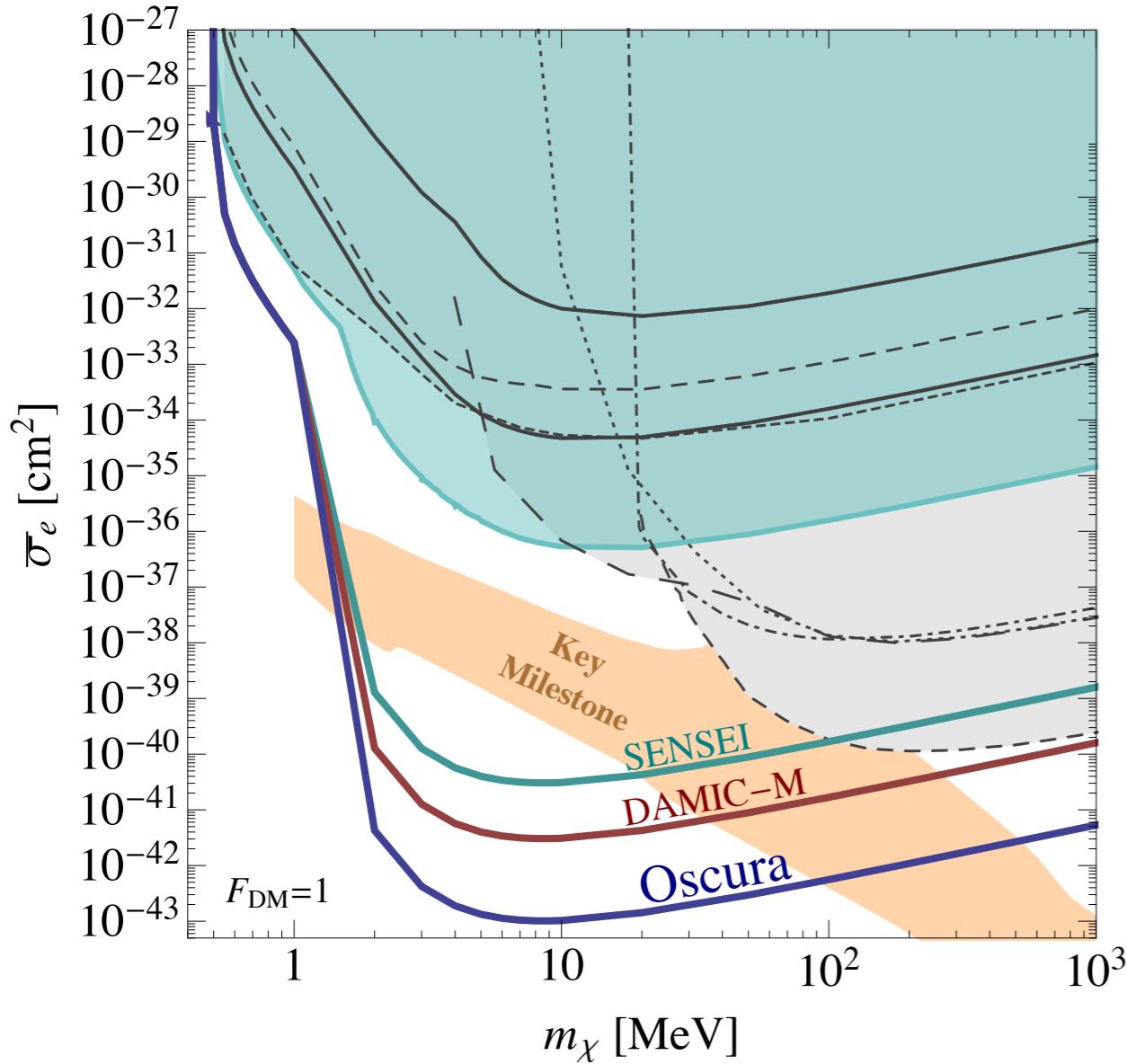
Readout-noise: 0.06 e RMS



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
- **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

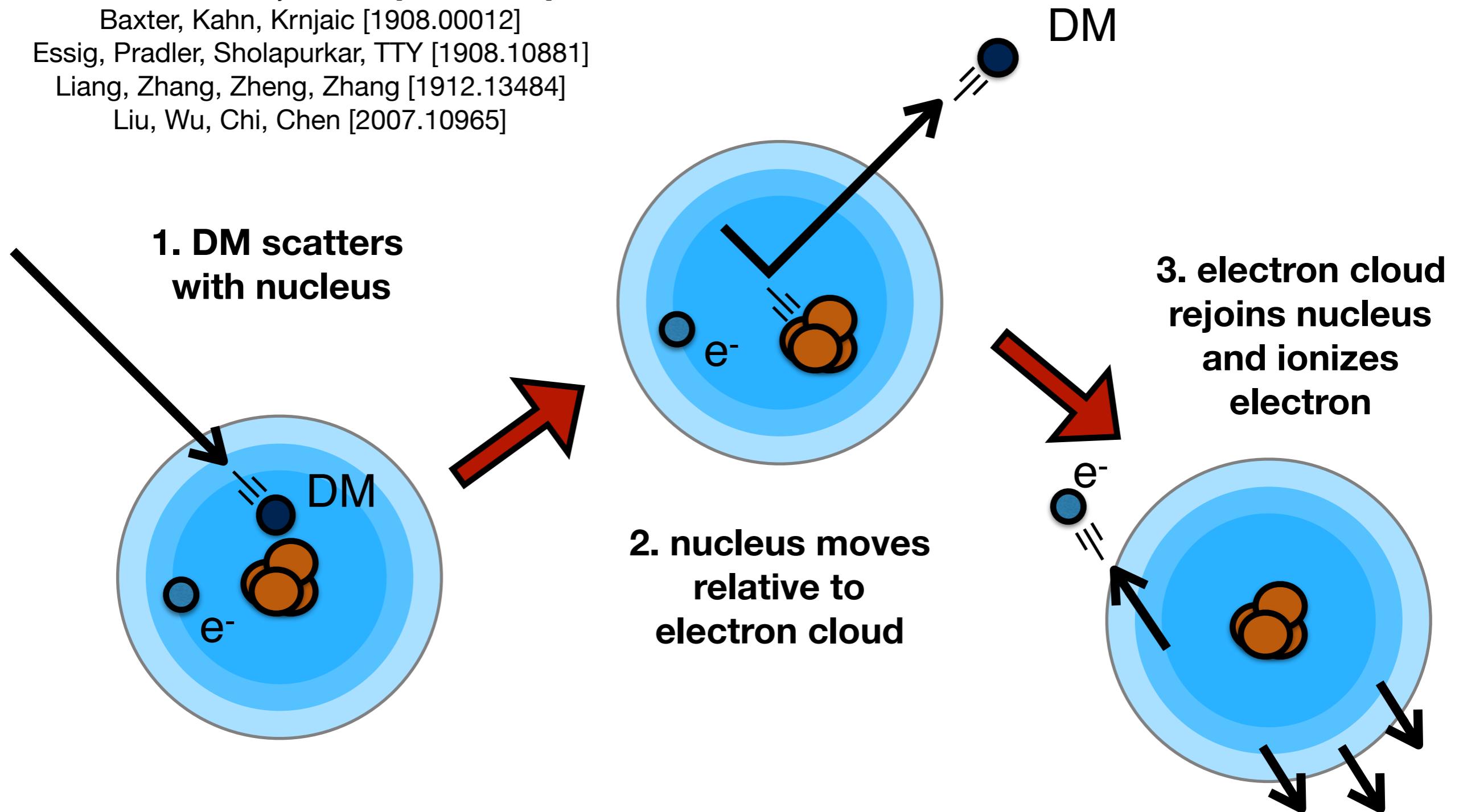
Ibe, Nakano, Shoji, Suzuki [1707.07258]

Baxter, Kahn, Krnjaic [1908.00012]

Essig, Pradler, Sholapurkar, TTY [1908.10881]

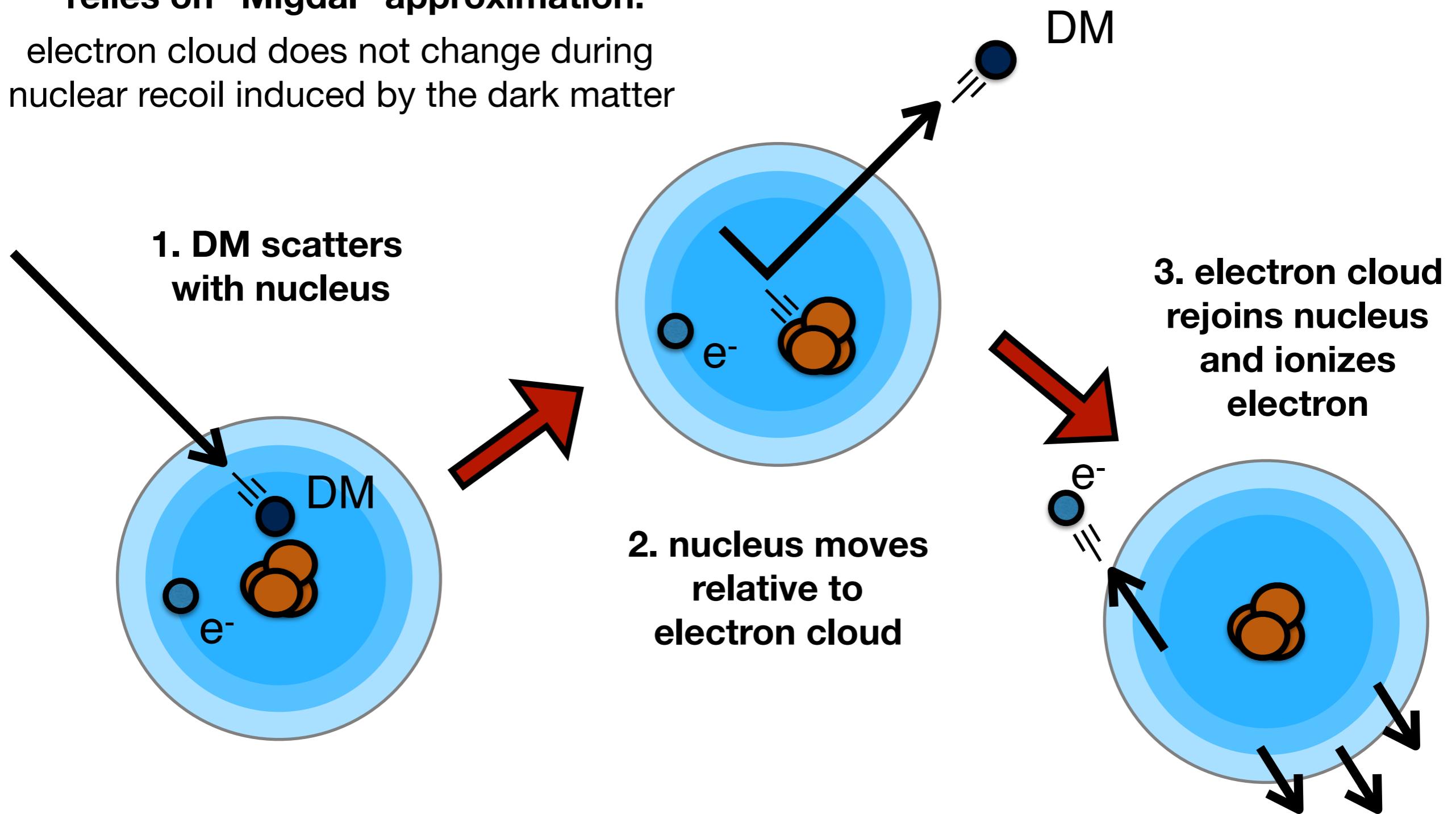
Liang, Zhang, Zheng, Zhang [1912.13484]

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

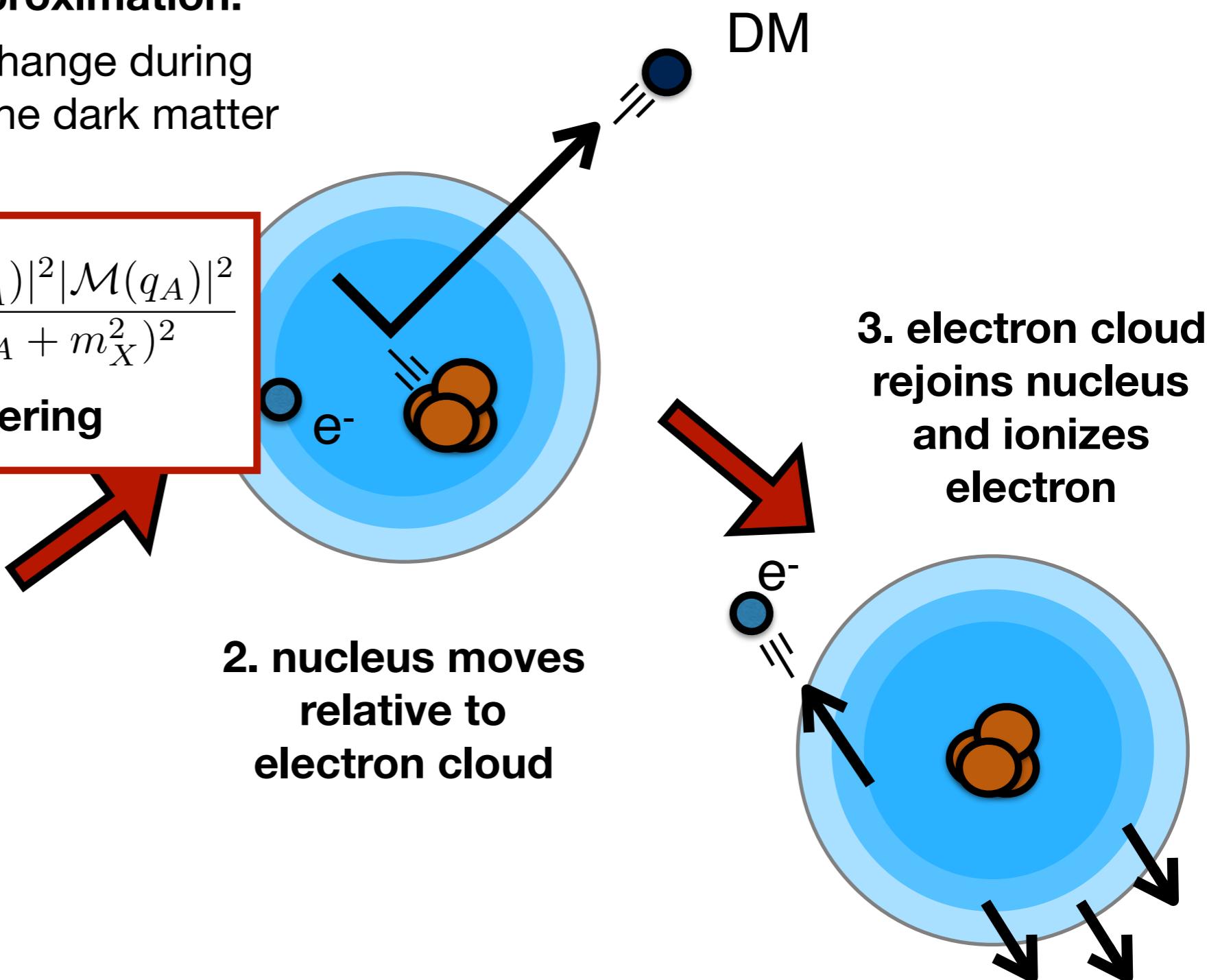
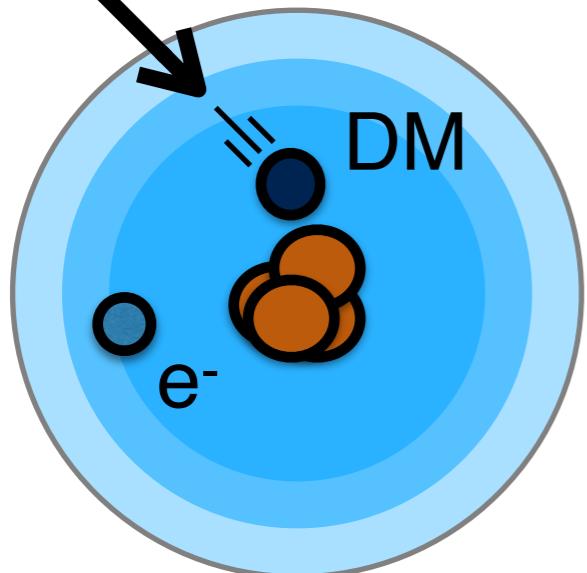


“Migdal” scattering

* relies on “Migdal” approximation:
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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:

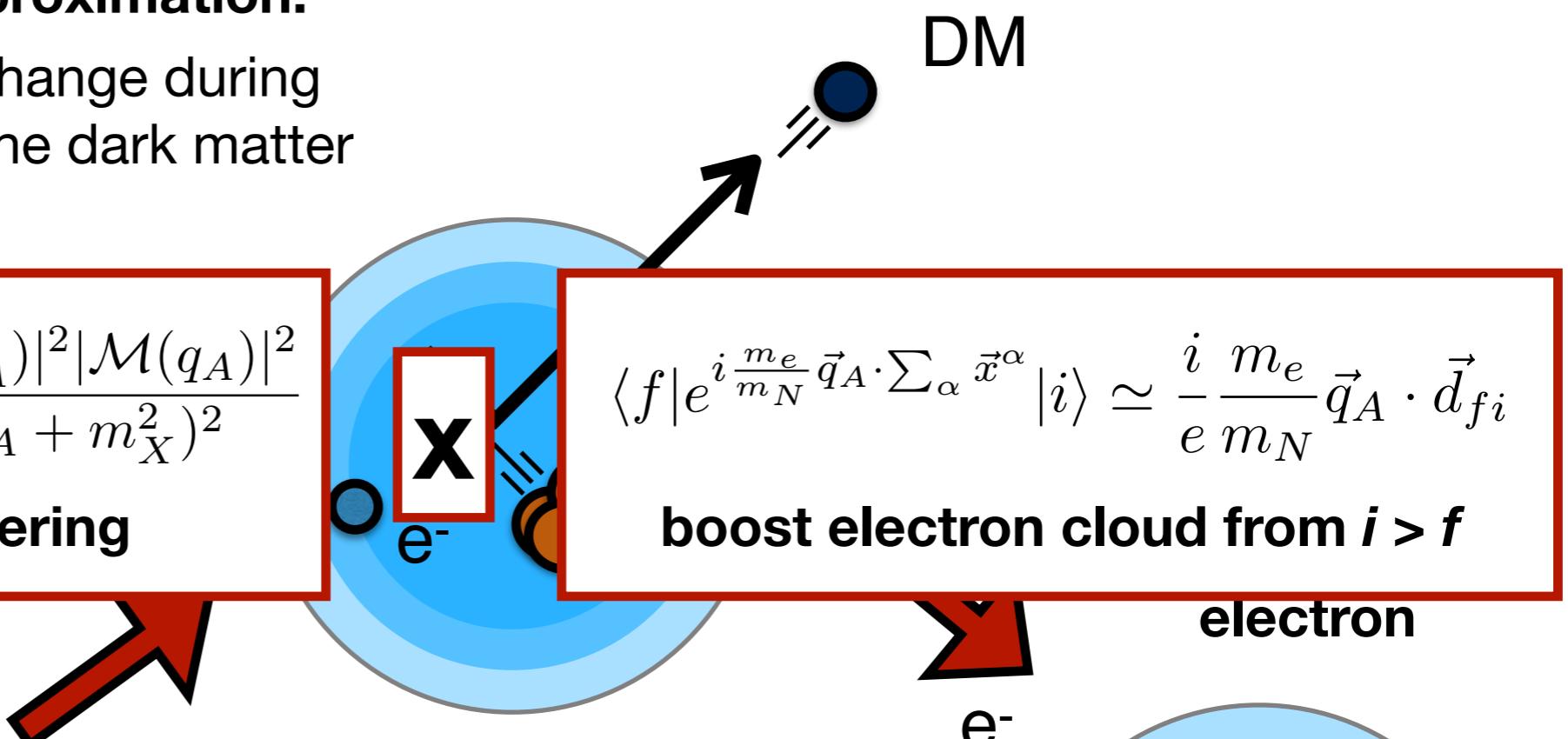
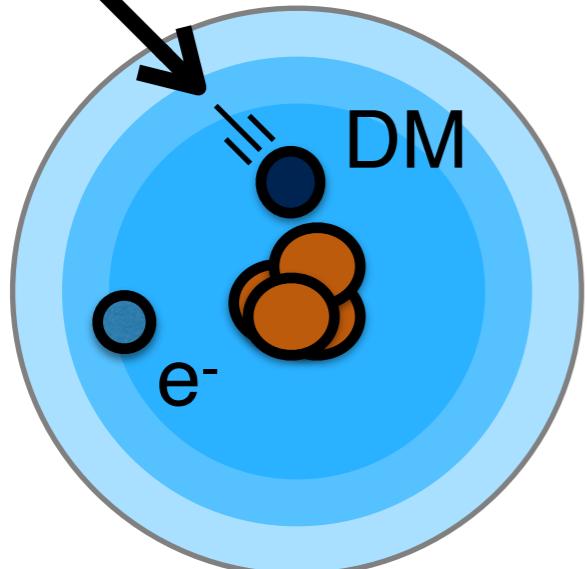
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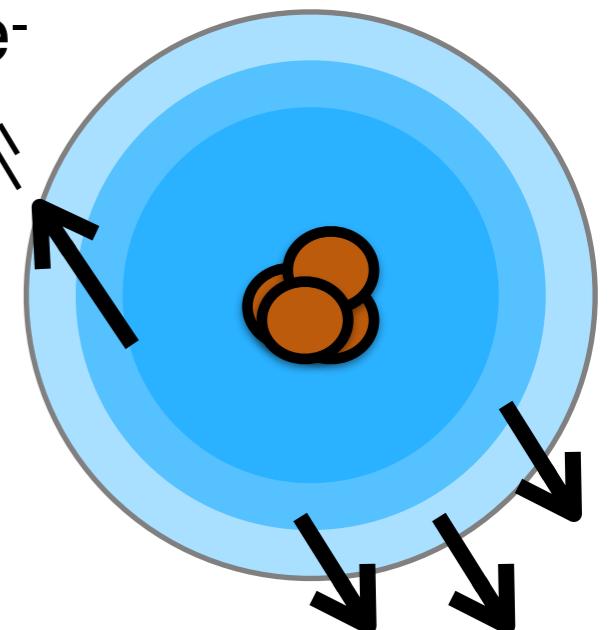
DM-nucleus scattering

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

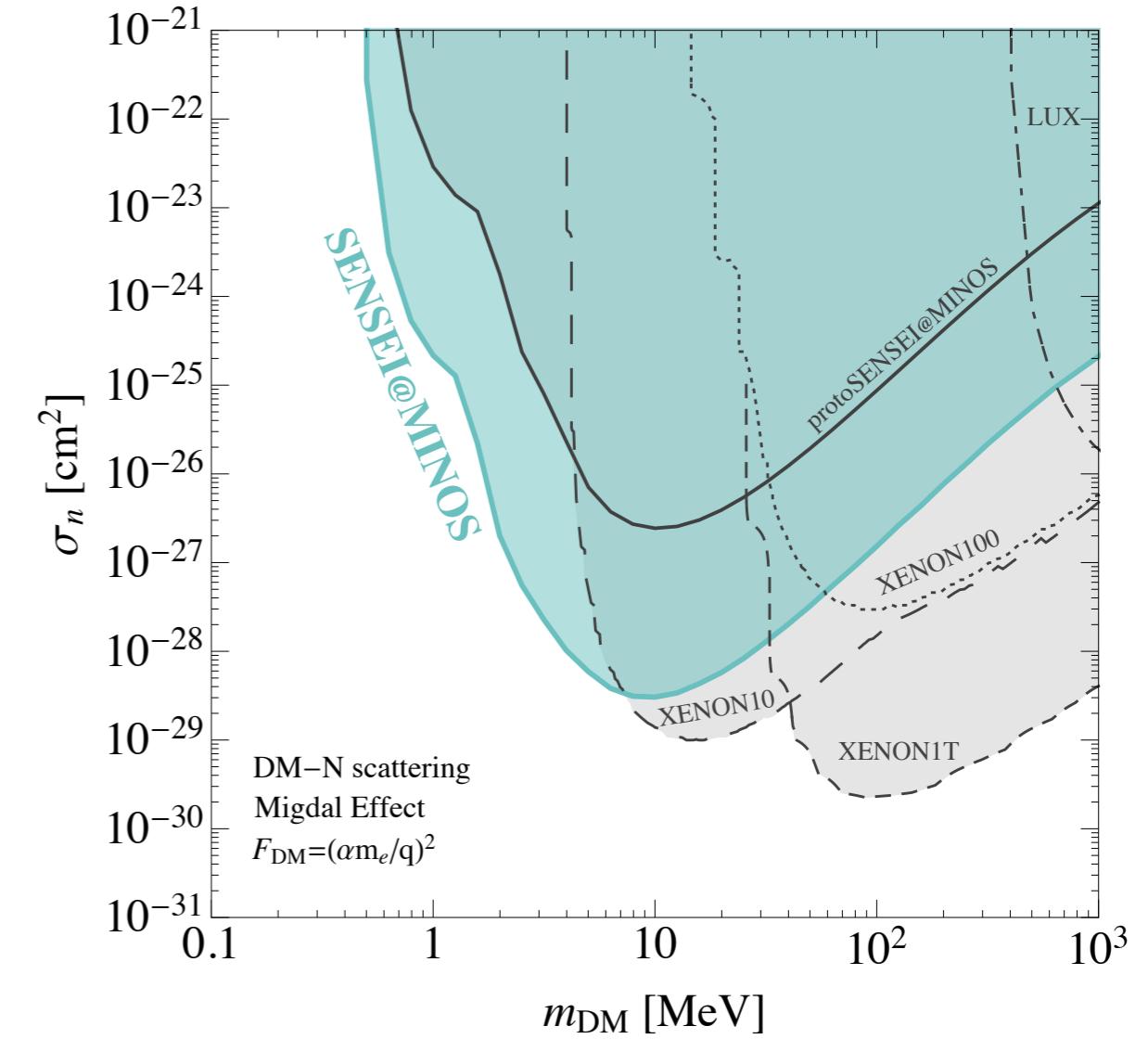
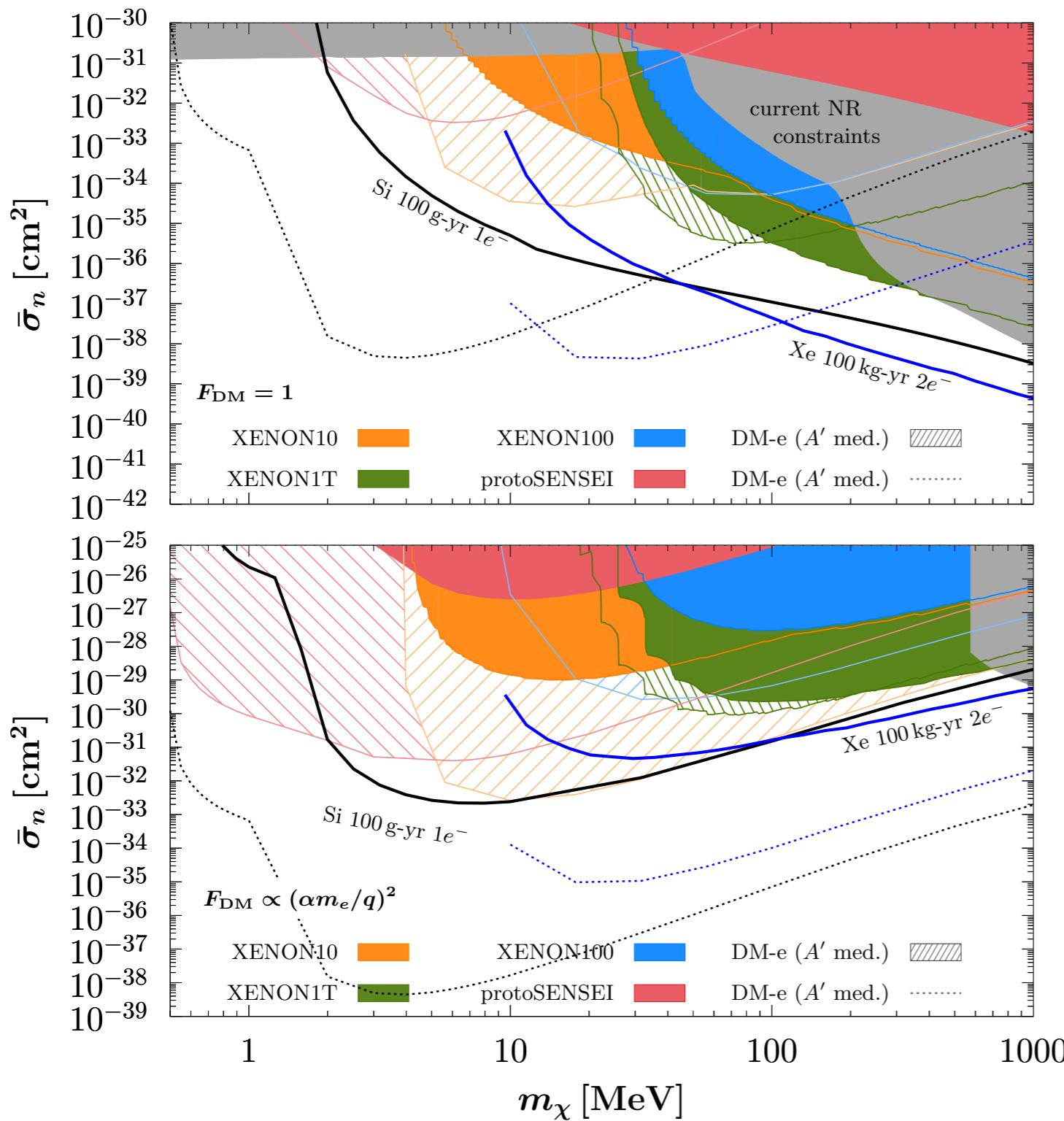
boost electron cloud from $i > f$



2. nucleus moves
relative to
electron cloud



“Migdal” scattering

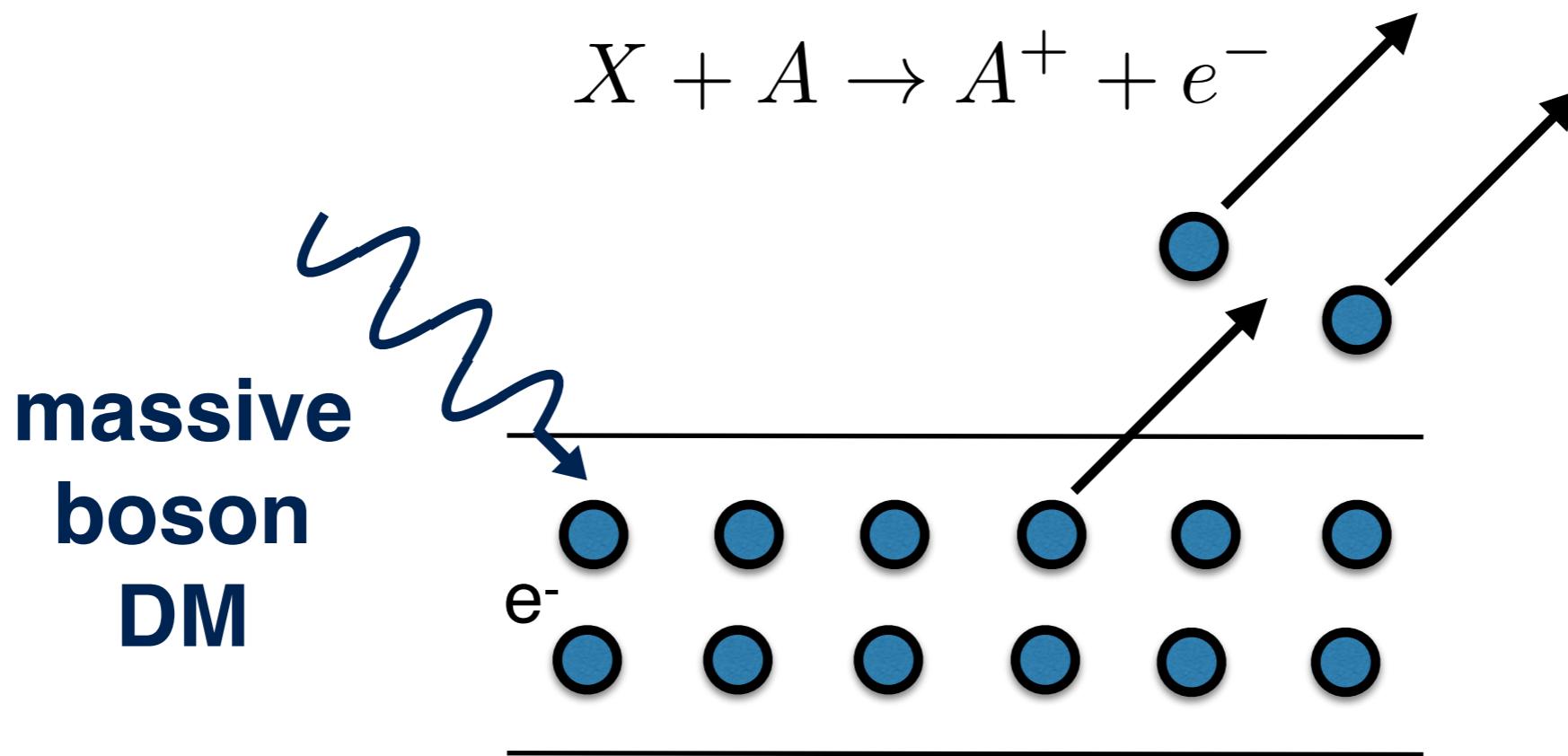


**SENSEI collaboration [arXiv:2004.11378],
accepted to PRL - Editors' Suggestion**

sub-GeV DM direct detection

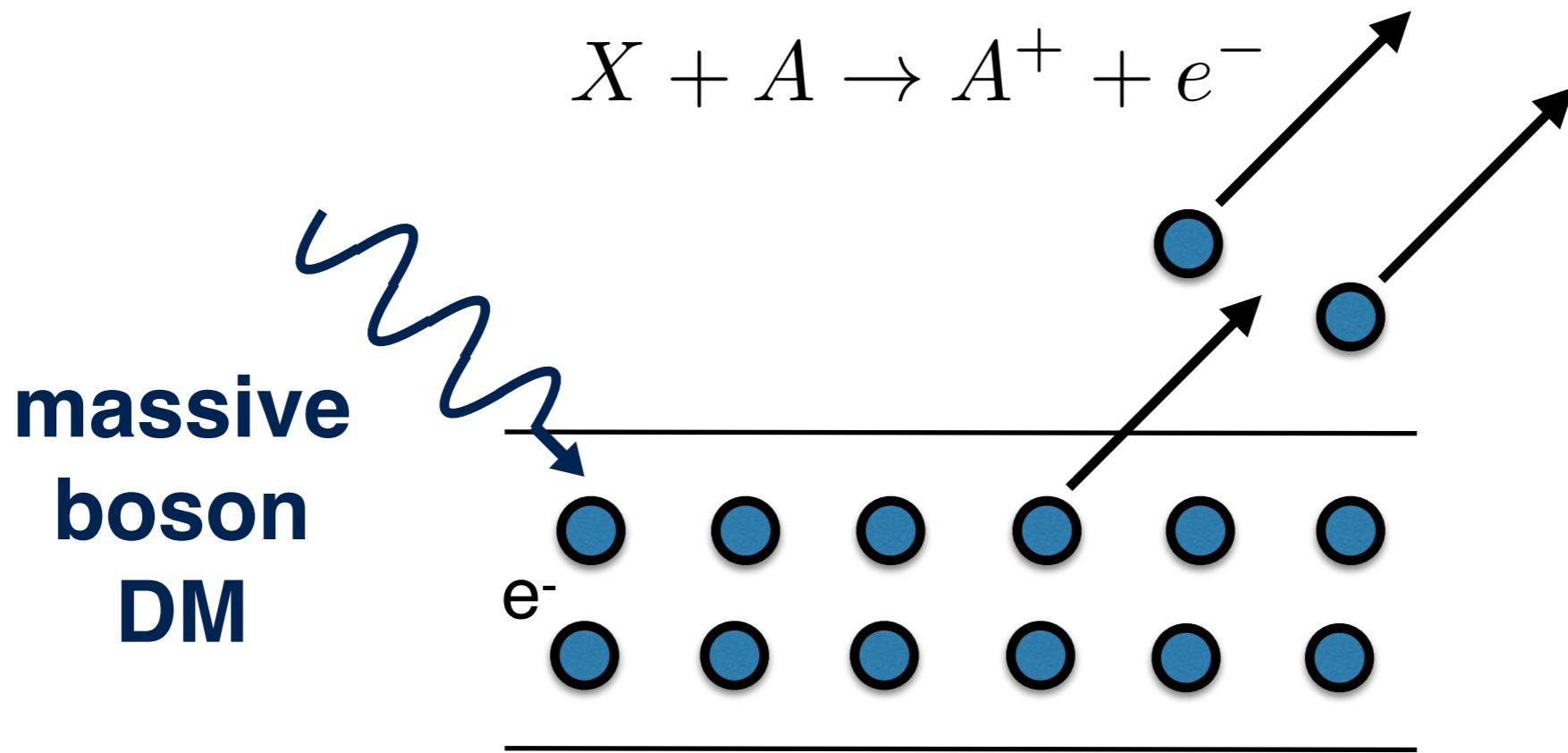
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photoelectric effect



absorb all of the energy
the incoming dark matter

photoelectric effect



photon

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

bosonic dark matter

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

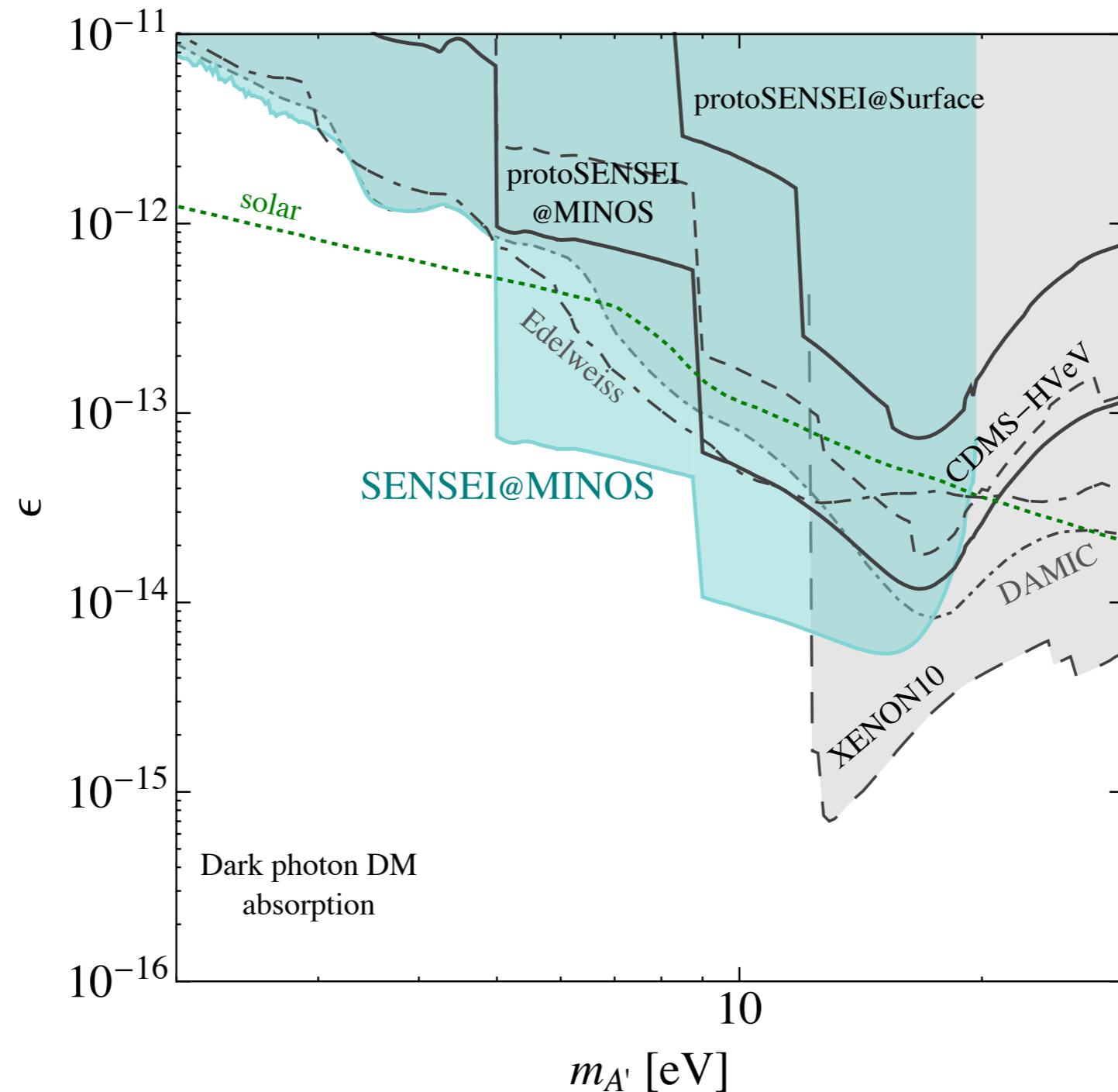
<

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

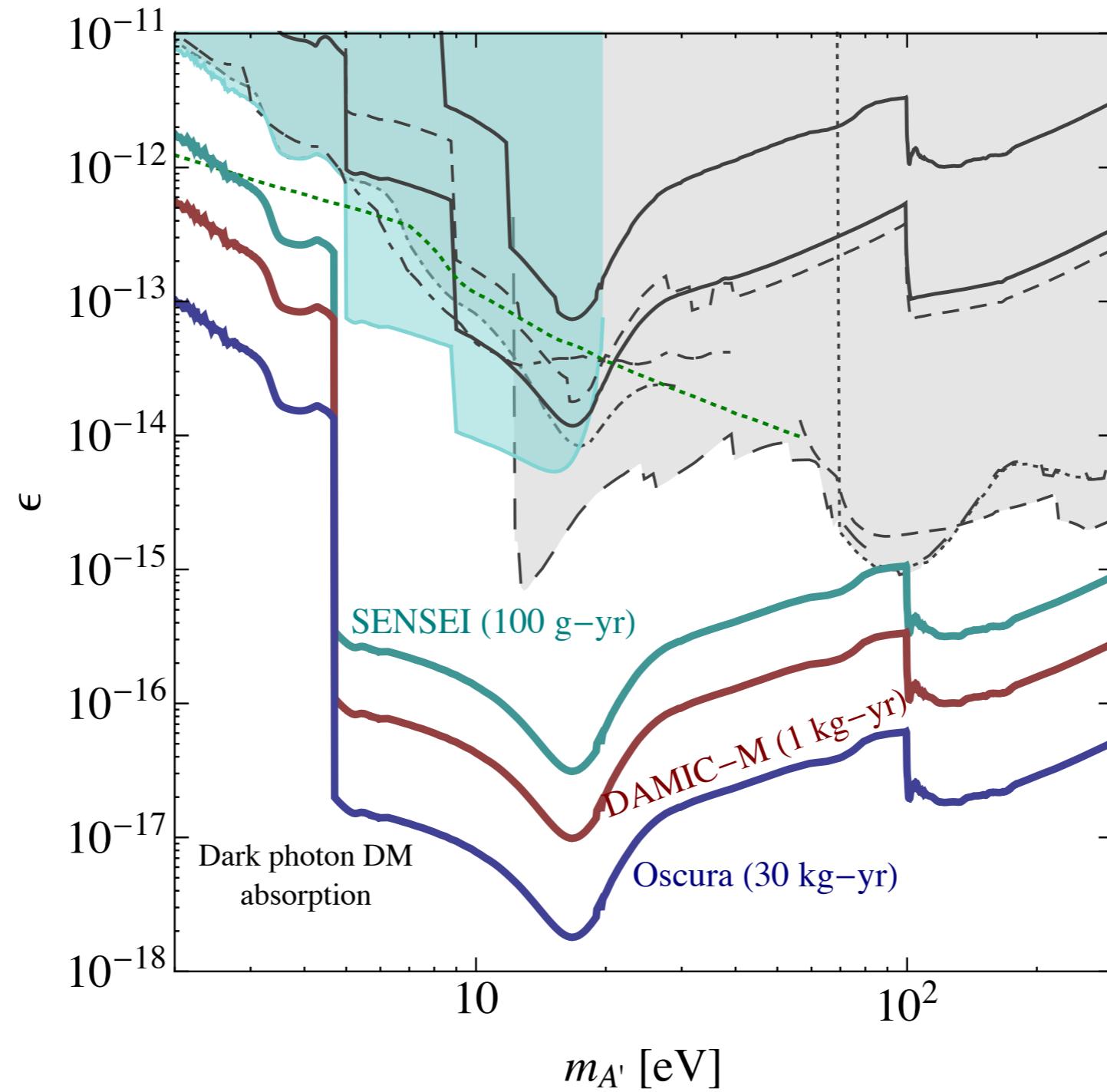
can relate
massive boson
absorption to
photon absorption

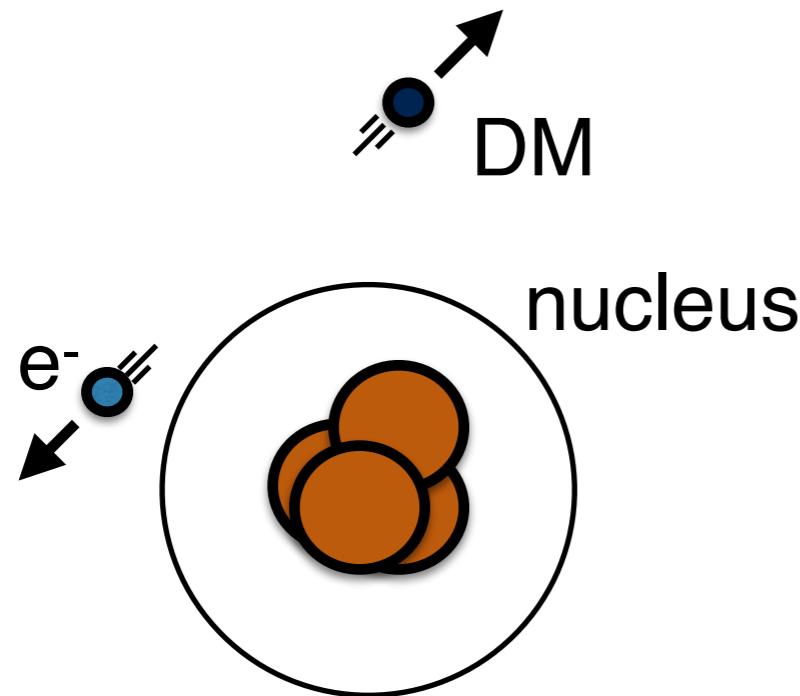
$$\sigma_{DM}(\omega) \propto \sigma_{\text{PE}}(\omega)$$

Dark Photon DM

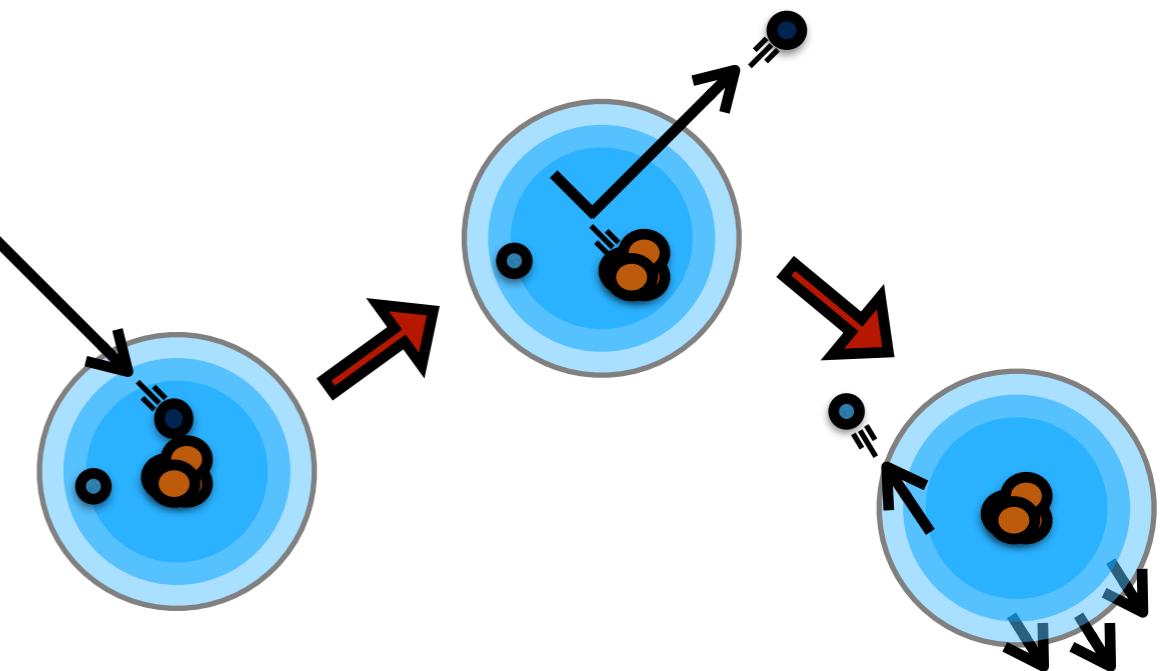


Dark Photon DM

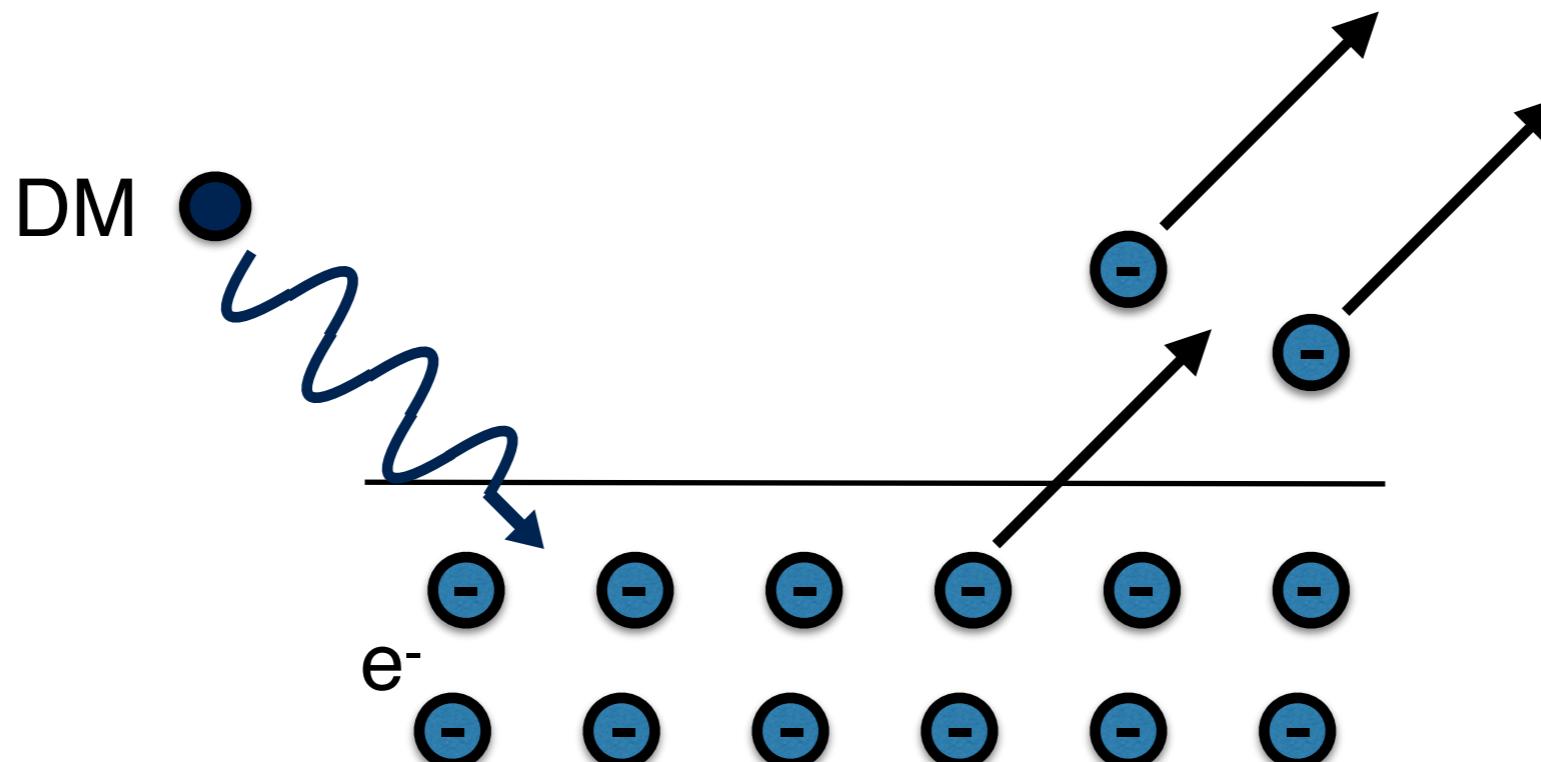




dark matter-electron scattering



dark matter-nucleus scattering



dark matter absorption

sub-GeV DM direct detection

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see Tongyan Lin's talk