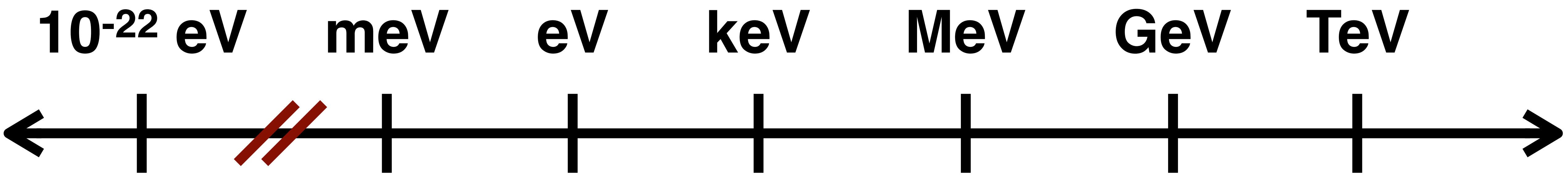
Learning about Dark Sectors with SENSEI

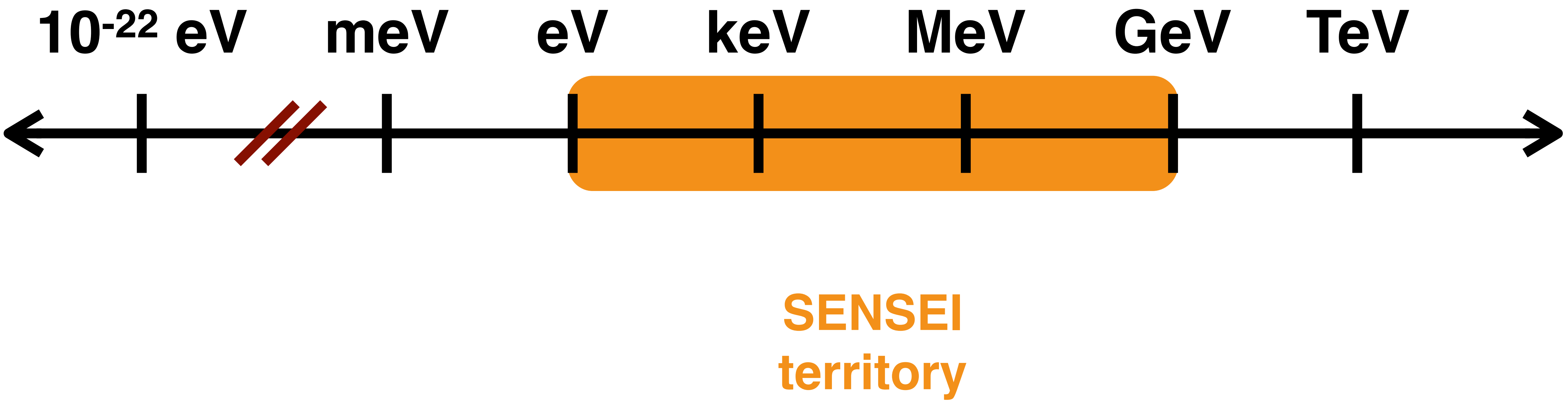
Tien-Tien Yu (CERN)

2017 CKC-CERN Workshop, Jeju Island — June 5, 2017

dark matter candidates



dark matter candidates



SENSEI

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

- fully-depleted 200 micrometer silicon CCD detector
- 4126 x 866 pixels
- operated at 140K
- currently at 1 gram, proposed to 100 grams
- skipper technology: measure charge/pixel multiple times

CERN: Tien-Tien Yu

Fermilab: Javier Tiffenberg, Yann Guardincerri, Miguel Sofo Haro

LBNL: Steve Holland

Stony Brook: Rouven Essig

Tel Aviv University: Tomer Volansky

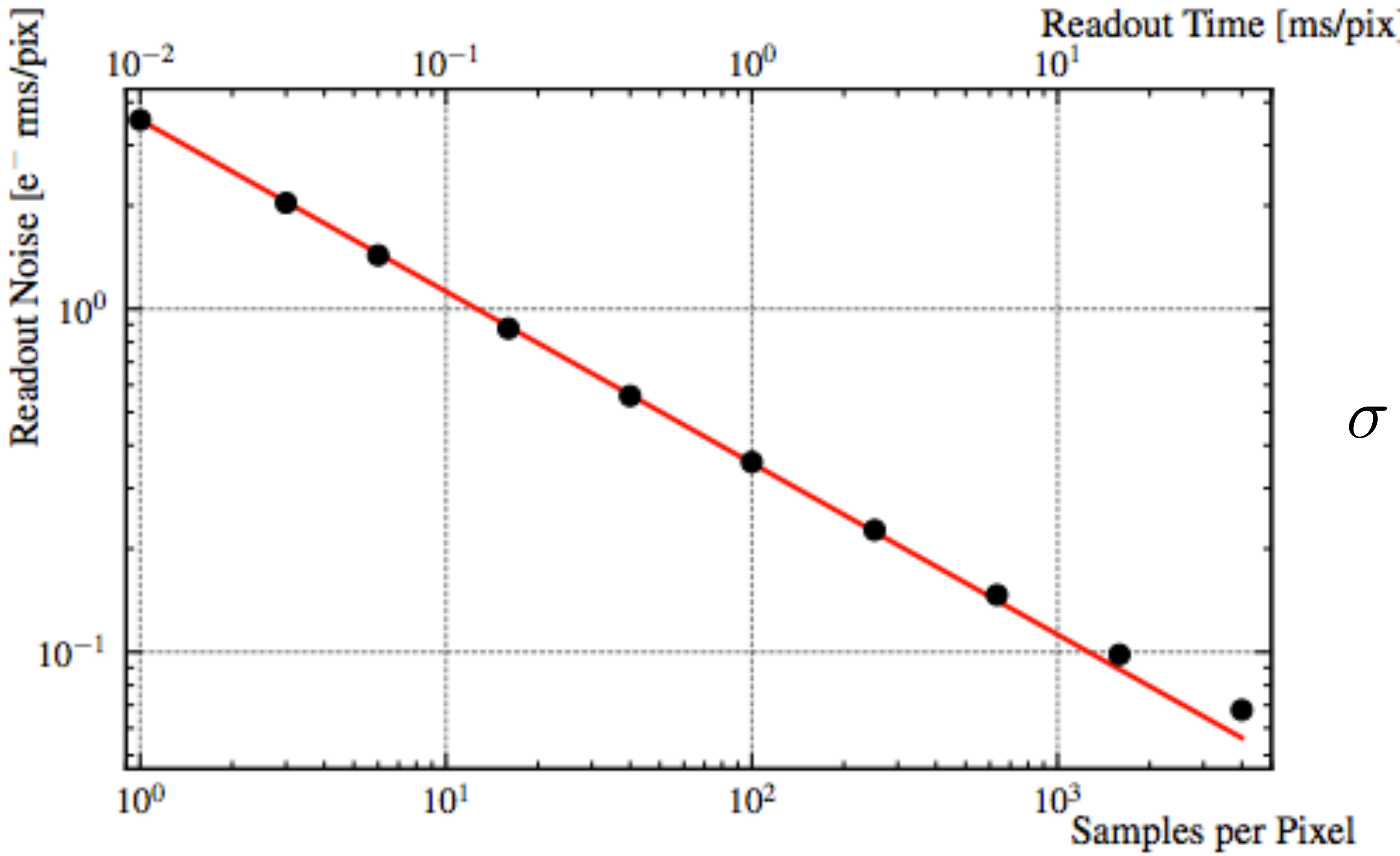
Experimentalists

Theorists

silicon CCDs

- current detectors (i.e. DAMIC) have an 11 electron threshold
- limited by readout noise and dark current

readout noise



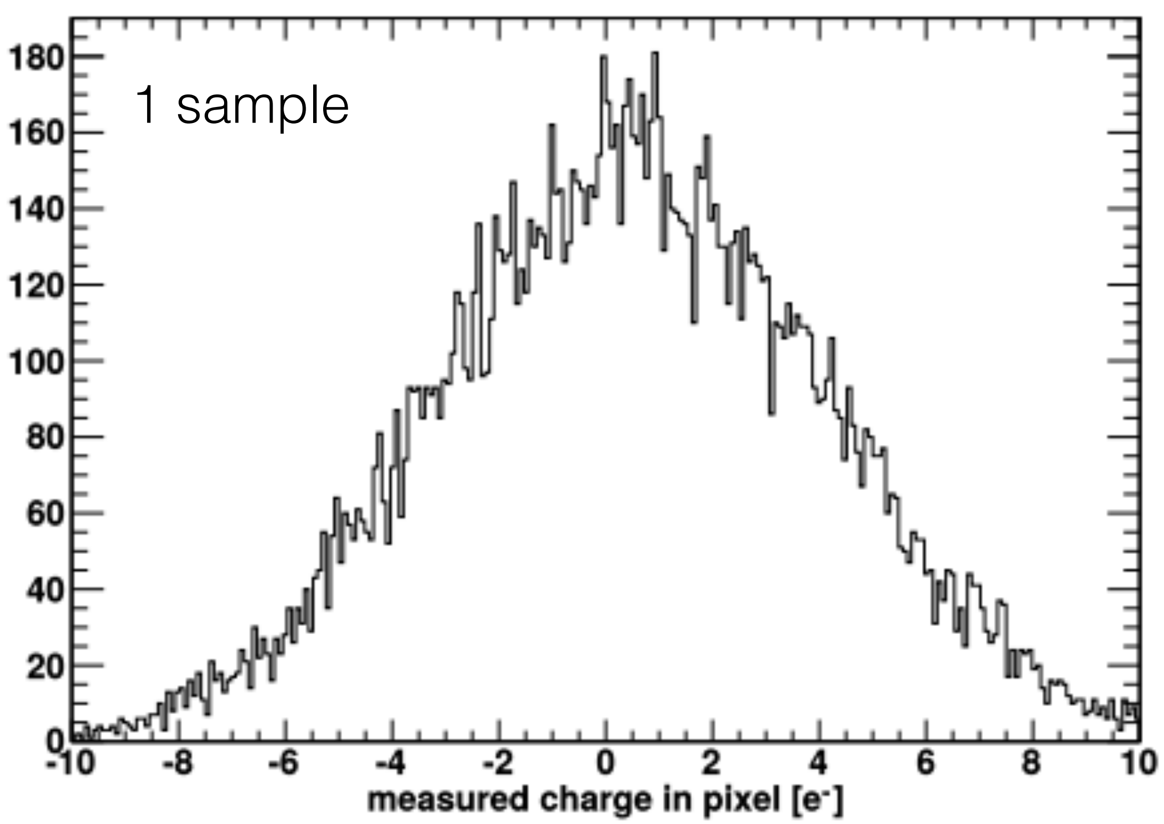
$$\sigma = \frac{\sigma_1}{\sqrt{N}}$$

reduce readout noise by increasing readout time

skipper readout

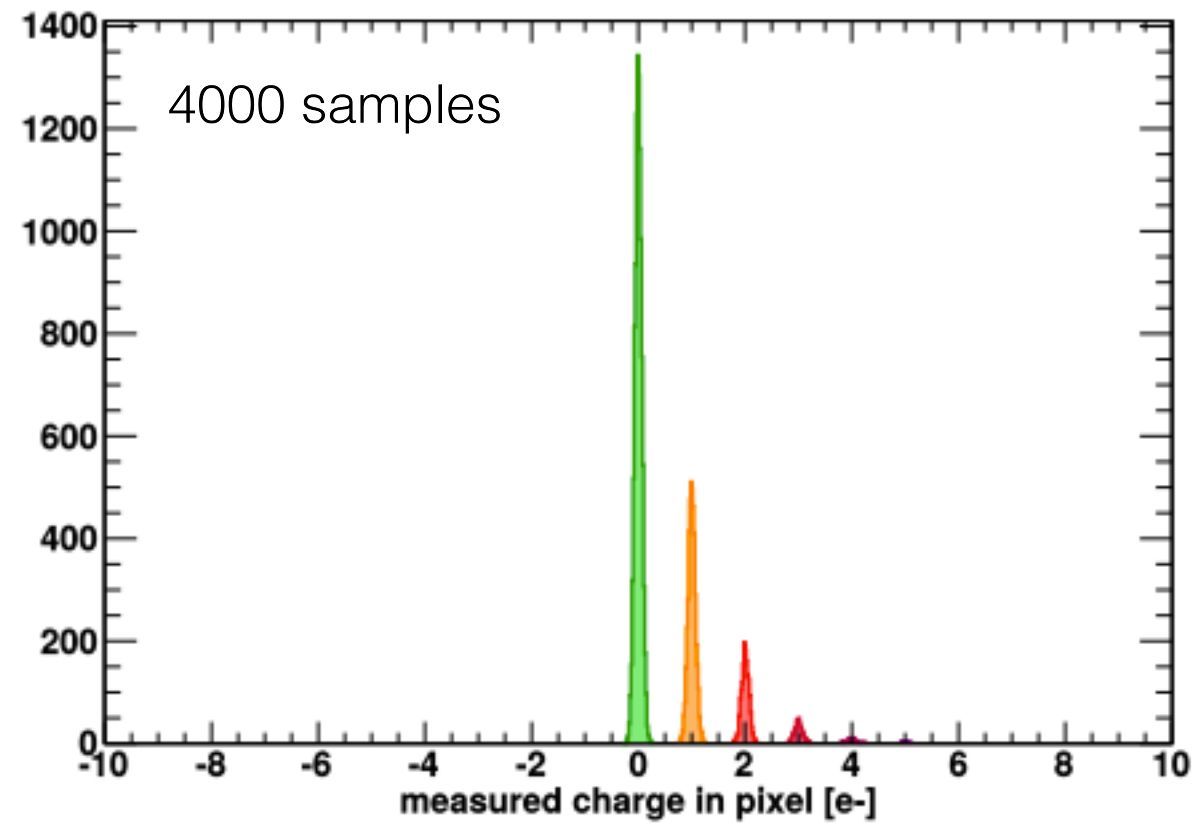
standard CCD

Readout-noise: 3.5 e RMS



skipper CCD

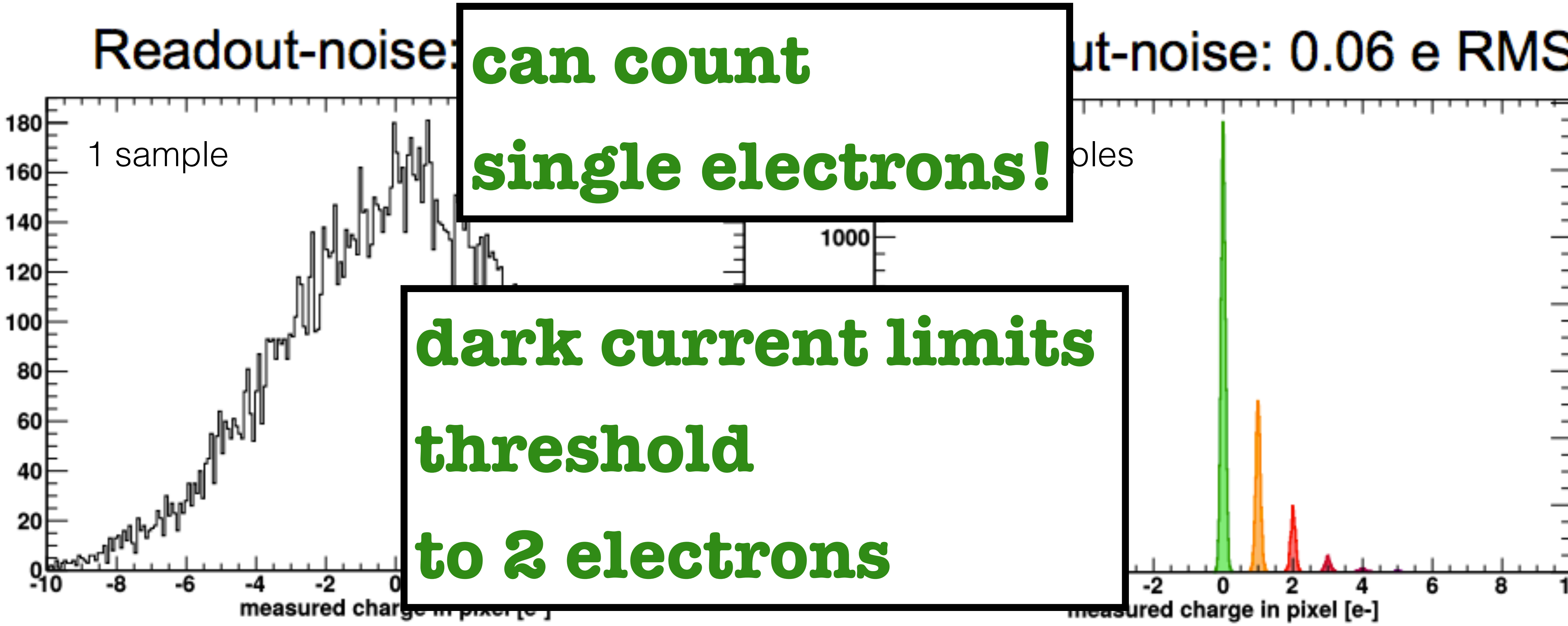
Readout-noise: 0.06 e RMS



Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, Volansky, TTY [1706.00028]

skipper readout

standard CCD | skipper CCD

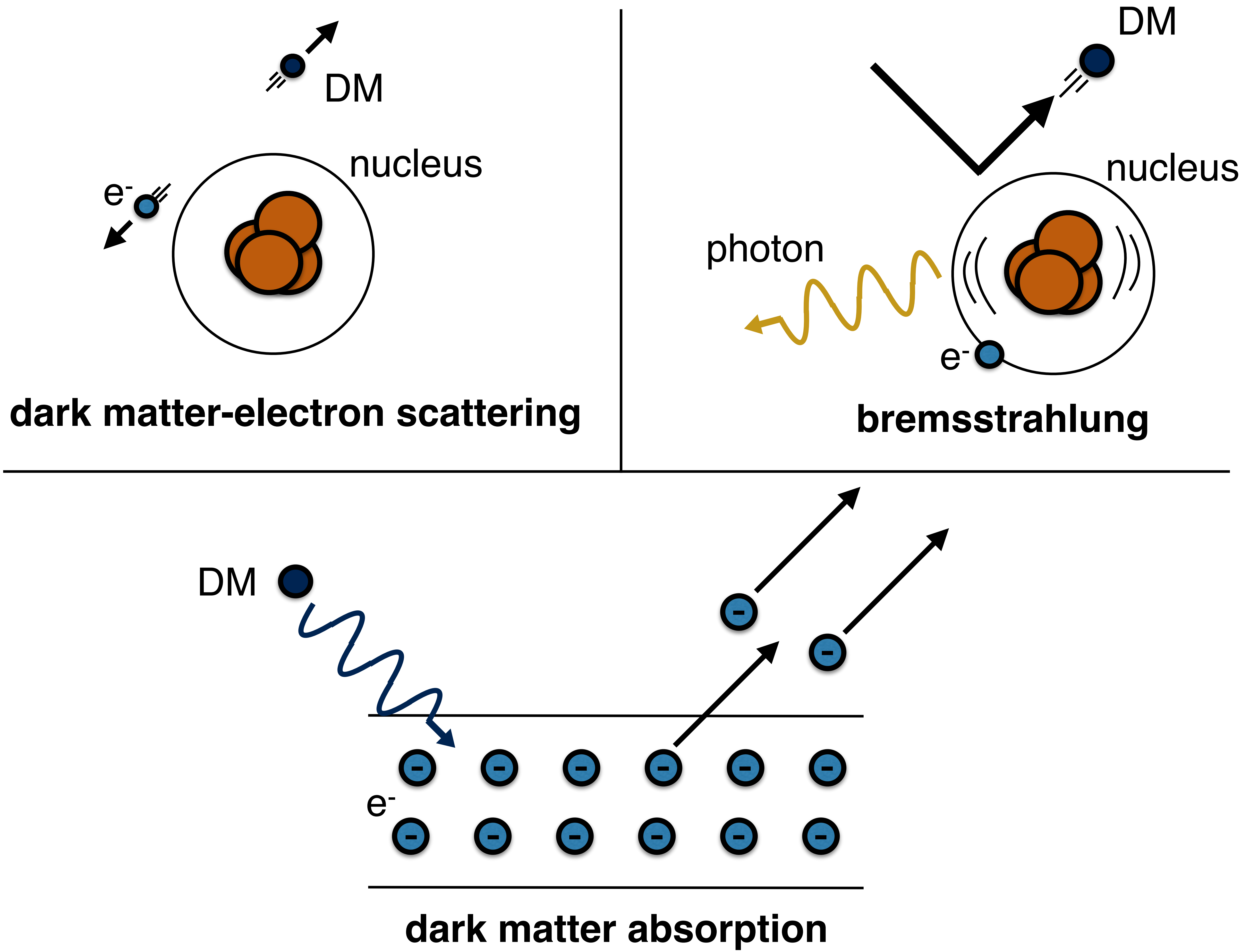


can count single electrons!

dark current limits threshold to 2 electrons

Tiffenberg, Sofo-Haro, Drlica-Wagner, Essig, Guardincerri, Holland, Volansky, TTY [1706.00028]

applications to
dark sector physics


DM
nucleus
e-
dark matter-electron scattering
DM
nucleus
photon
e-
bremsstrahlung
DM
e-
dark matter absorption

dark matter-electron scattering

scattering rate

solid state

astrophysics

$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q |f(k,q)|^2 |F_{DM}(q)|^2 \eta(v_{min})$$

particle physics

local DM density

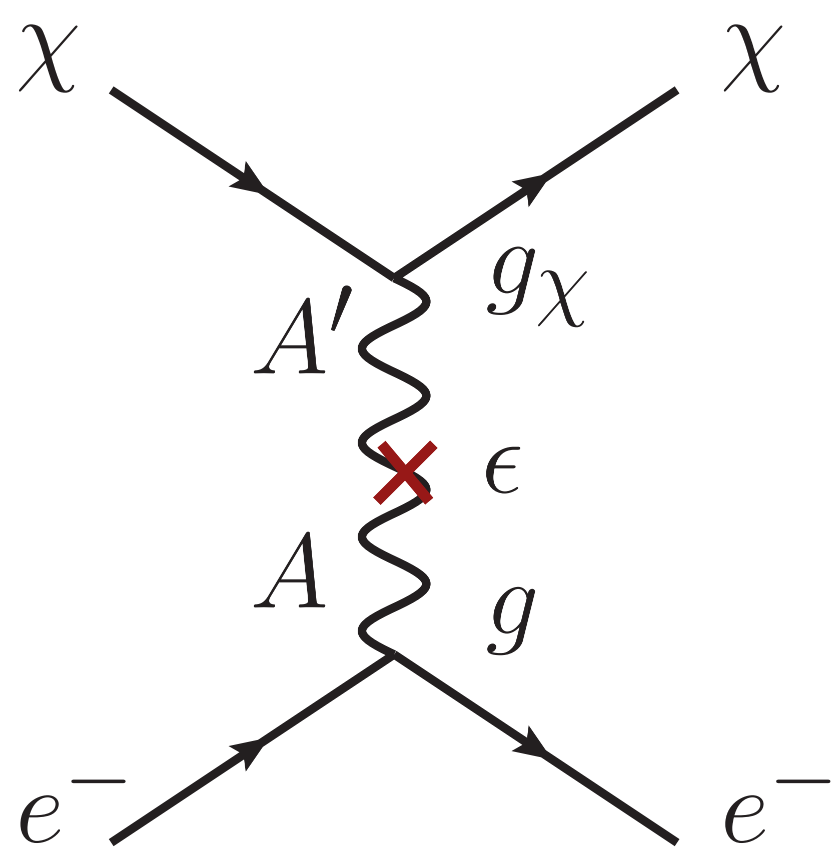
$$R = N_T \frac{\rho_\chi}{m_\chi}\int_{E_{R,cut}} \mathrm{d}\ln E_R \frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R}$$

number of target nuclei per unit mass

energy threshold

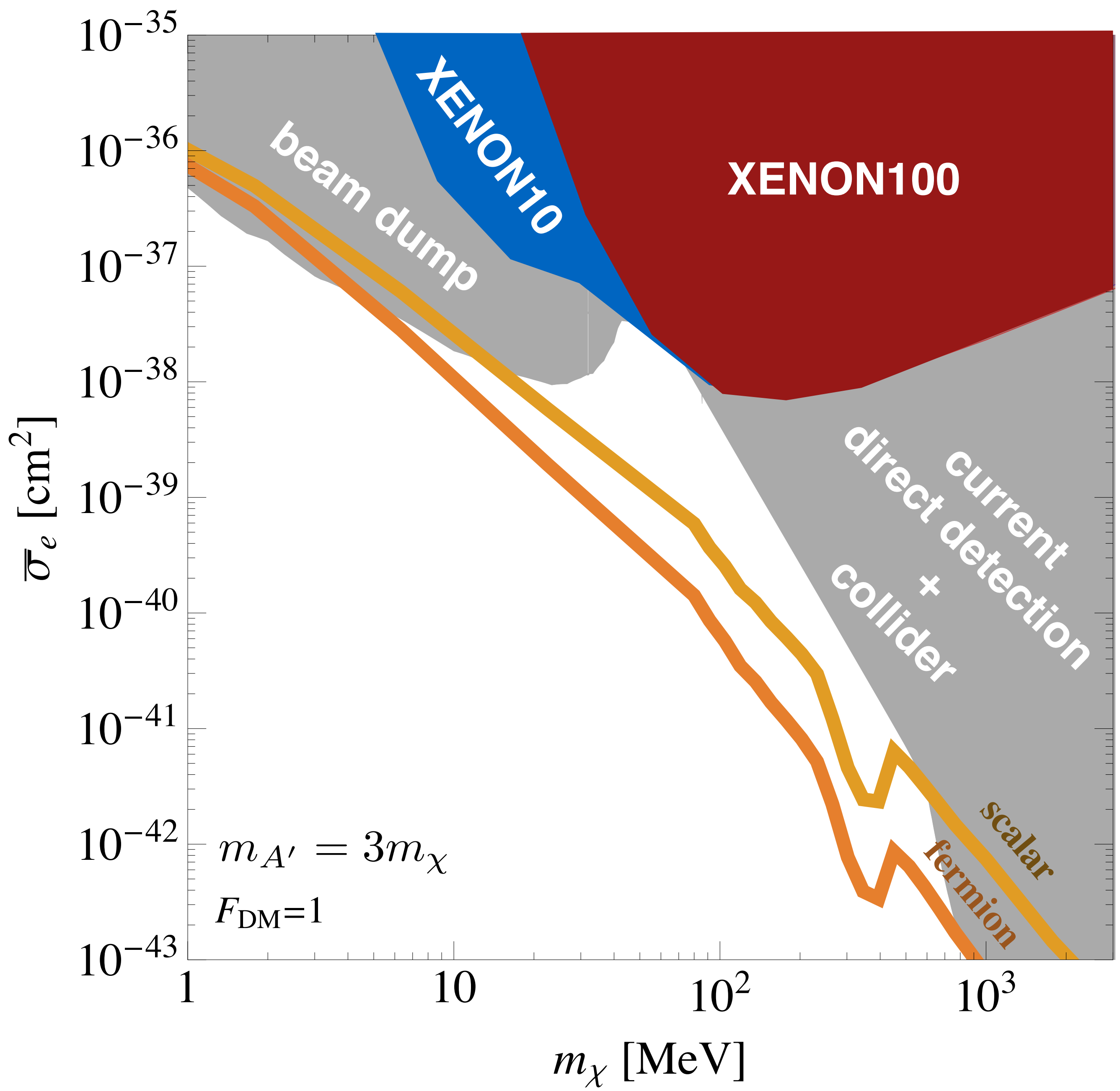
A Model: Hidden Photon

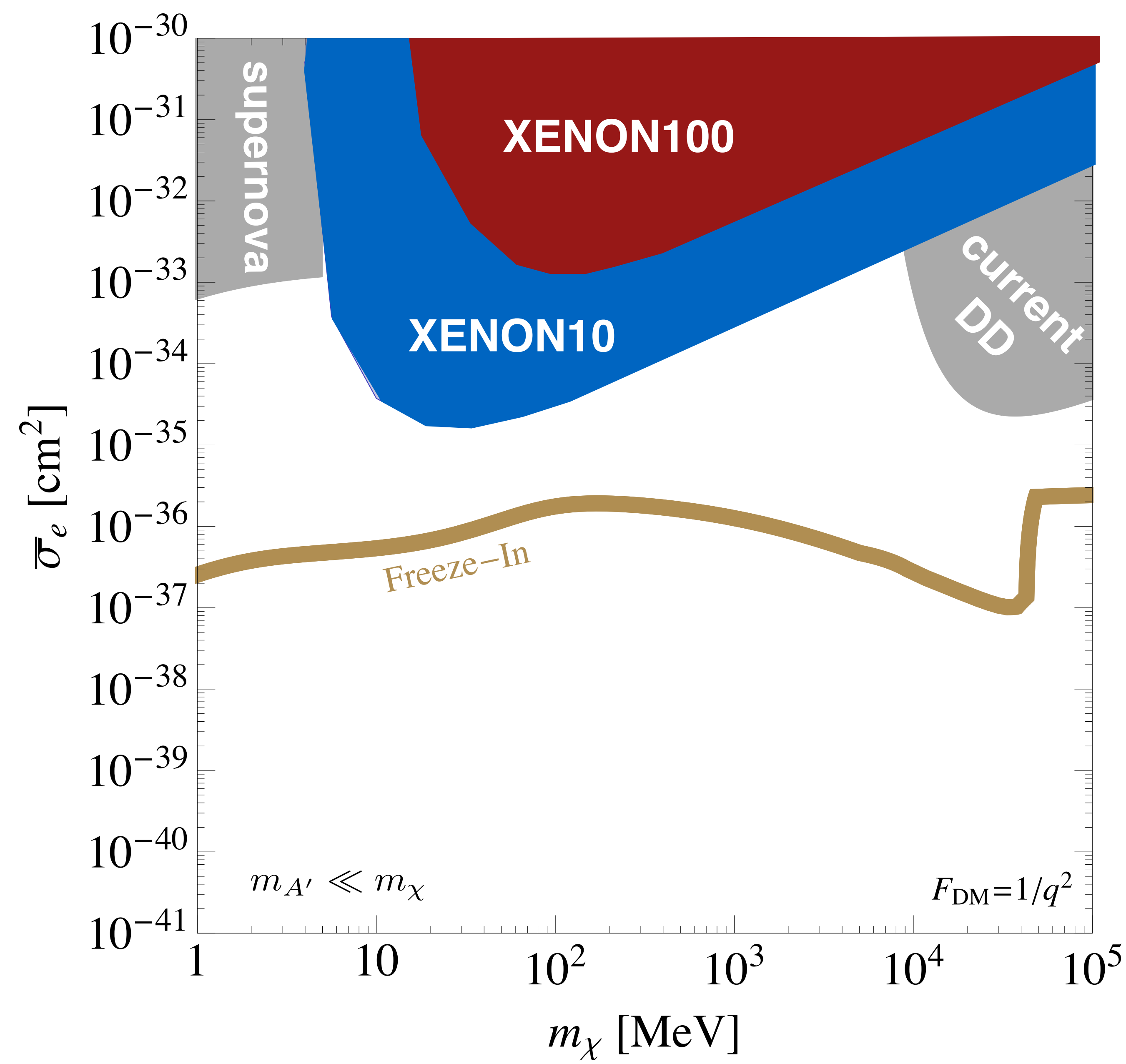
$$\mathcal{L} = F_{\mu\nu}^2 + {F'}_{\mu\nu}^2 + m_{A'}^2 A_\mu'^2 + g_\chi J_\chi^\mu A'_\mu + g J_e^\mu (A_\mu + \epsilon A'_\mu)$$



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

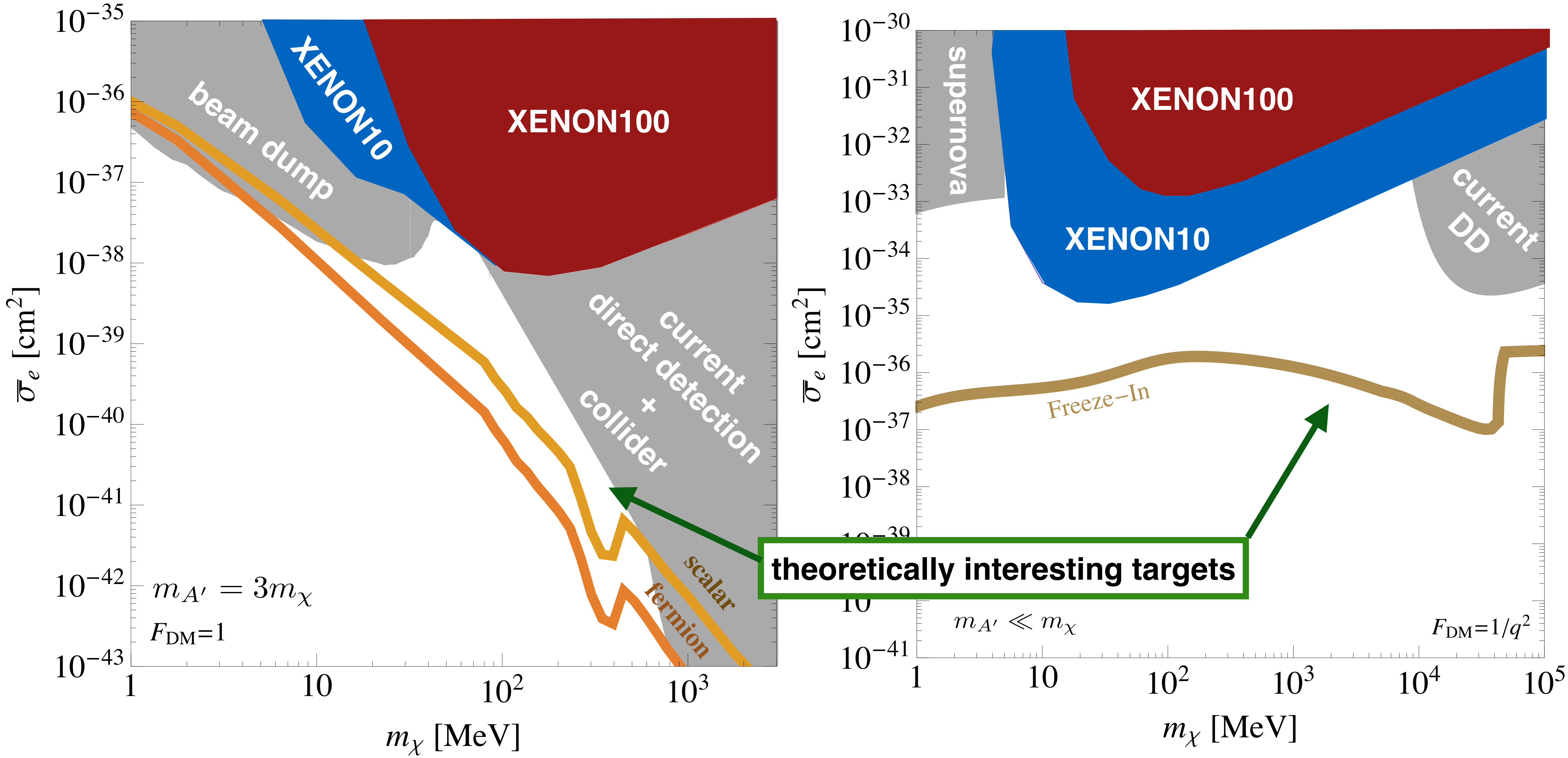
dark photon





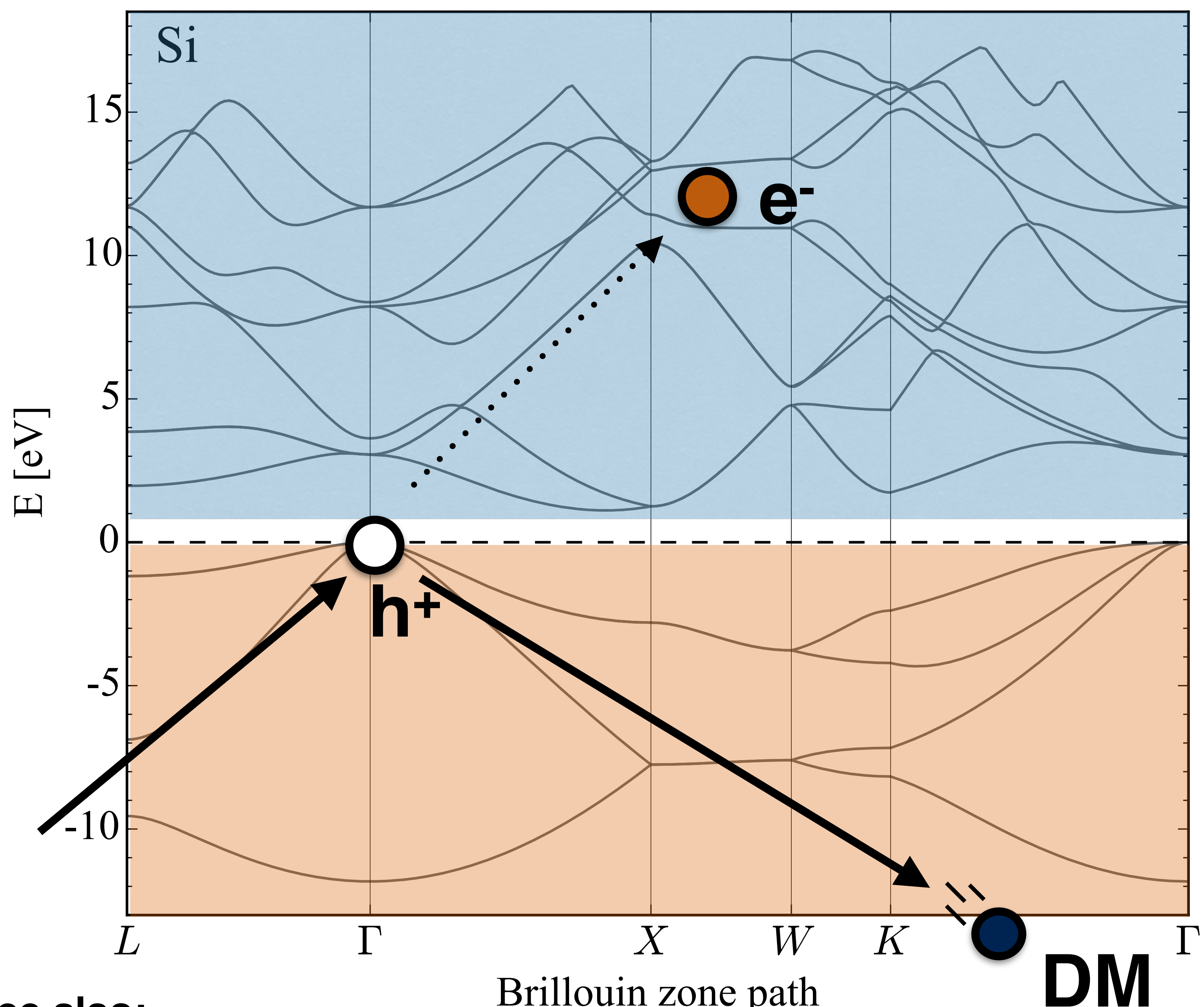
Essig, Volansky, TTY [1703.00910]

dark photon



Essig, Volansky, TTY [1703.00910]

semiconductor targets

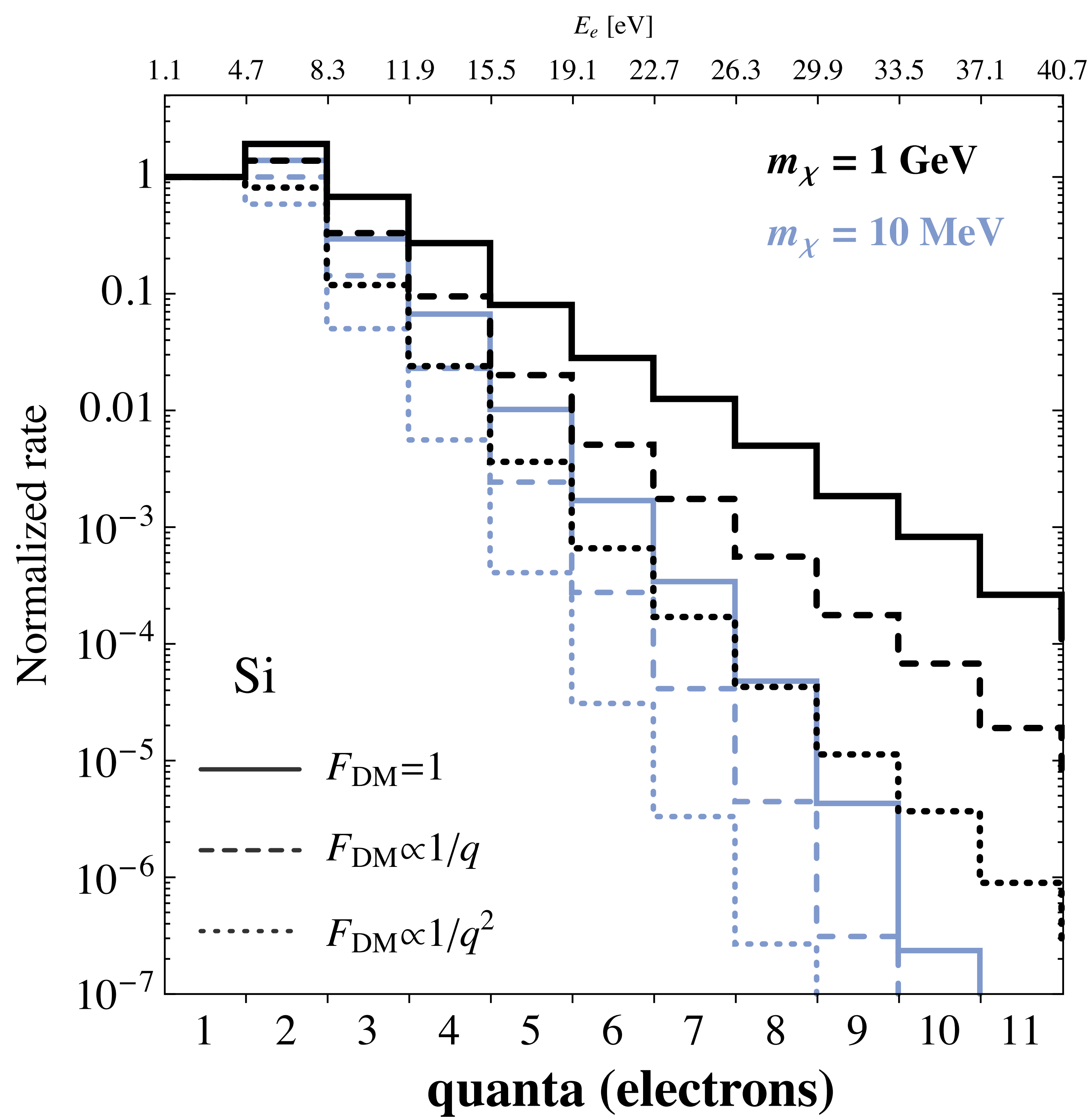


detect the electron(s)

see also:

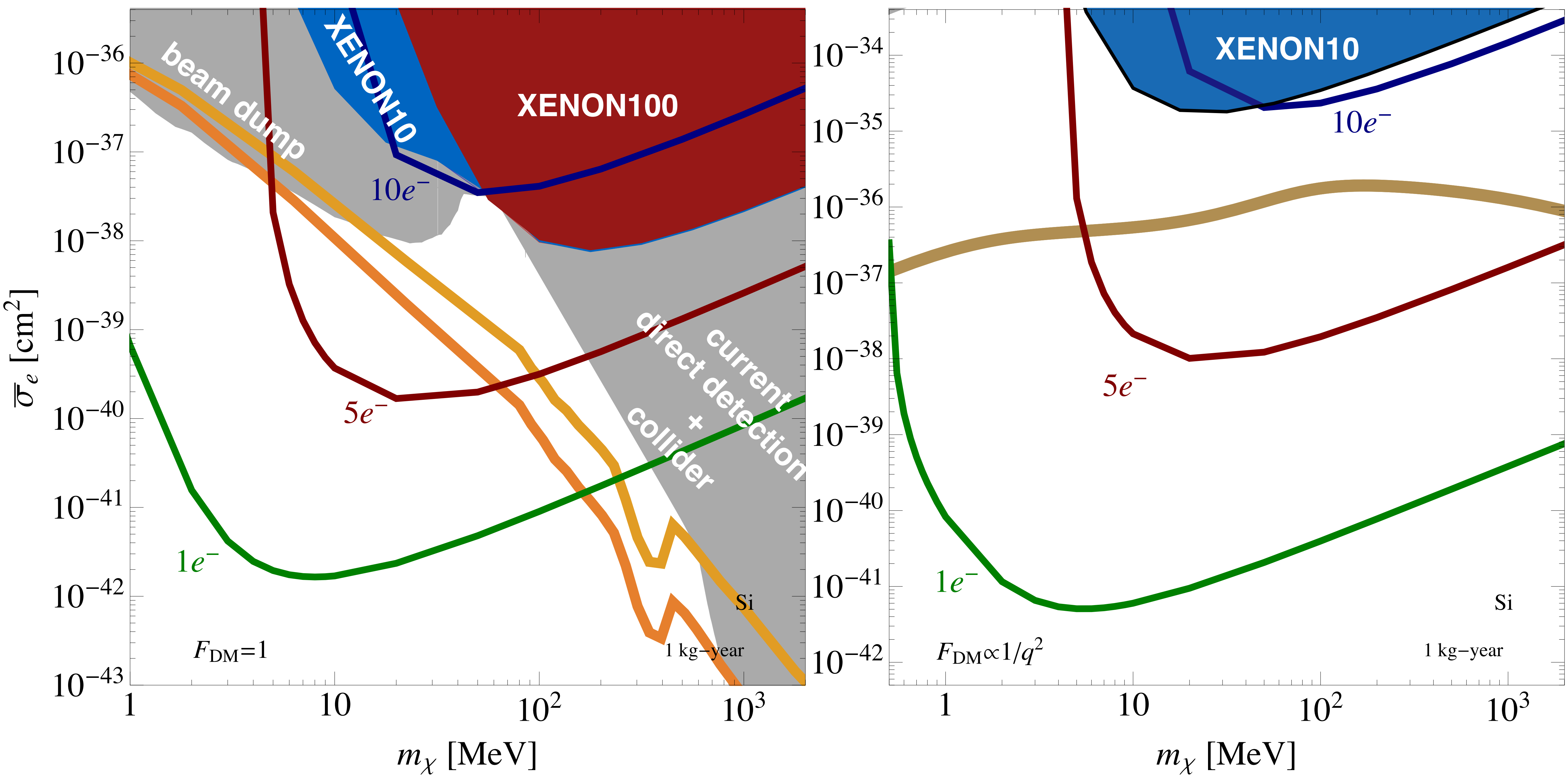
Essig, Mardon, Volansky [1108.5383] Phys.Rev. D85 (2012) 076007
Graham, Kaplan, Rajendran, Walters [1203.2531] Phys.Dark Univ. 1 (2012) 32-49
Lee, Lisanti, Mishra-Sharma, Safdi [1508.07361] Phys.Rev. D92 (2015) 083517

silicon



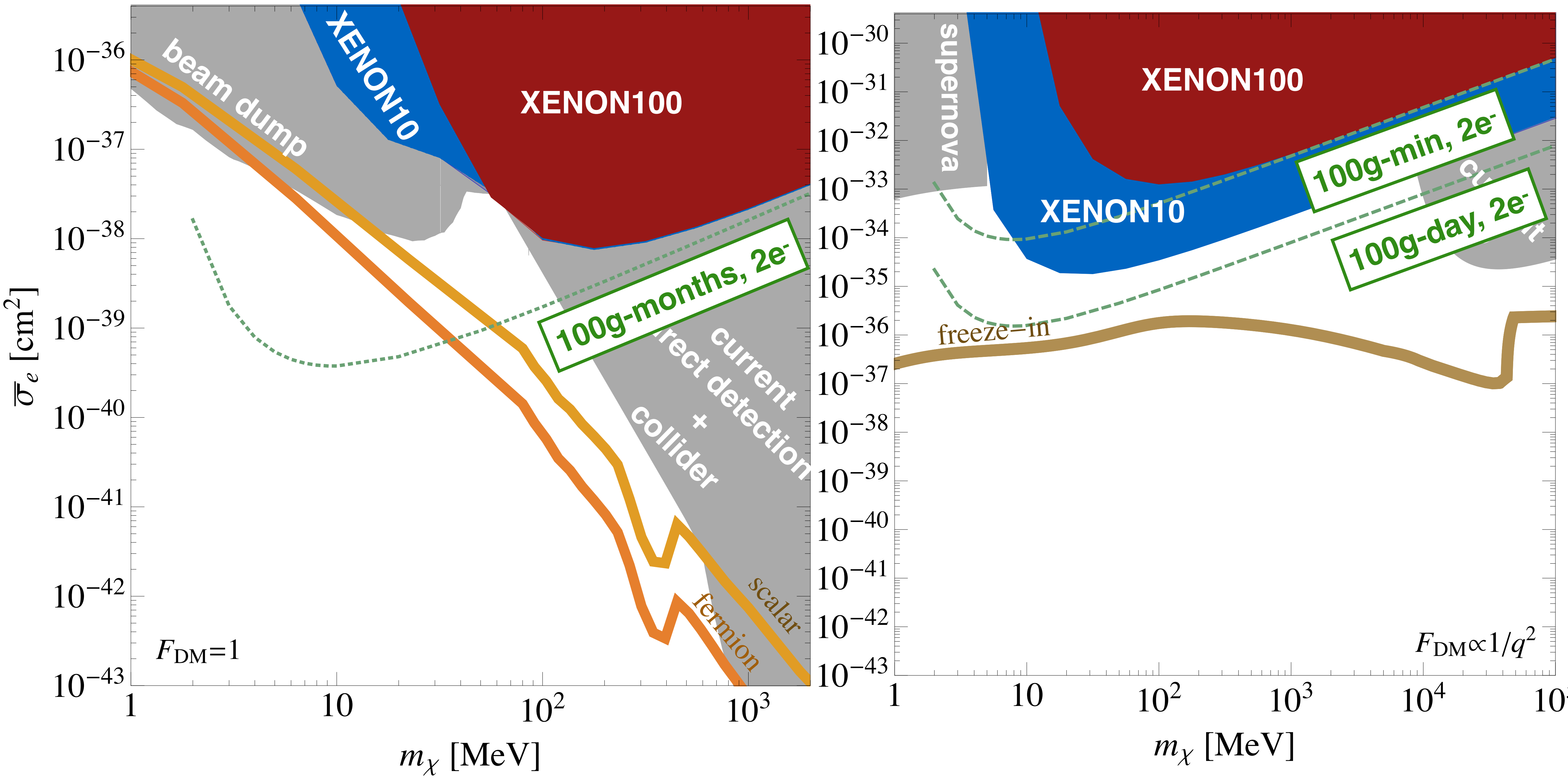
Essig, Fernandez-Serra, Mardon, Soto, Volansky, TTY [1509.01598]

silicon

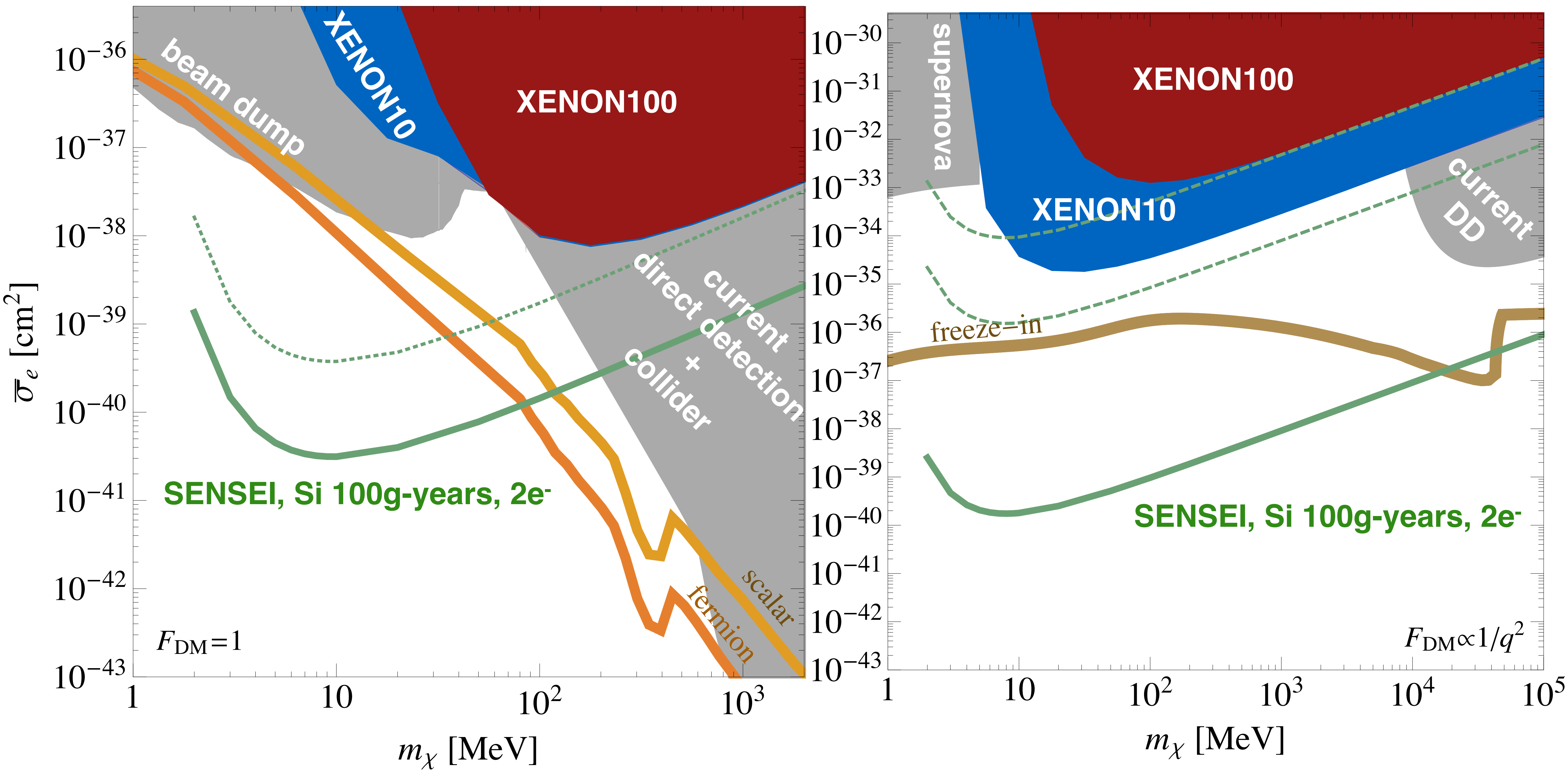


Essig, Fernandez-Serra, Mardon, Soto, Volansky, TTY [1509.01598]

SENSEI reach



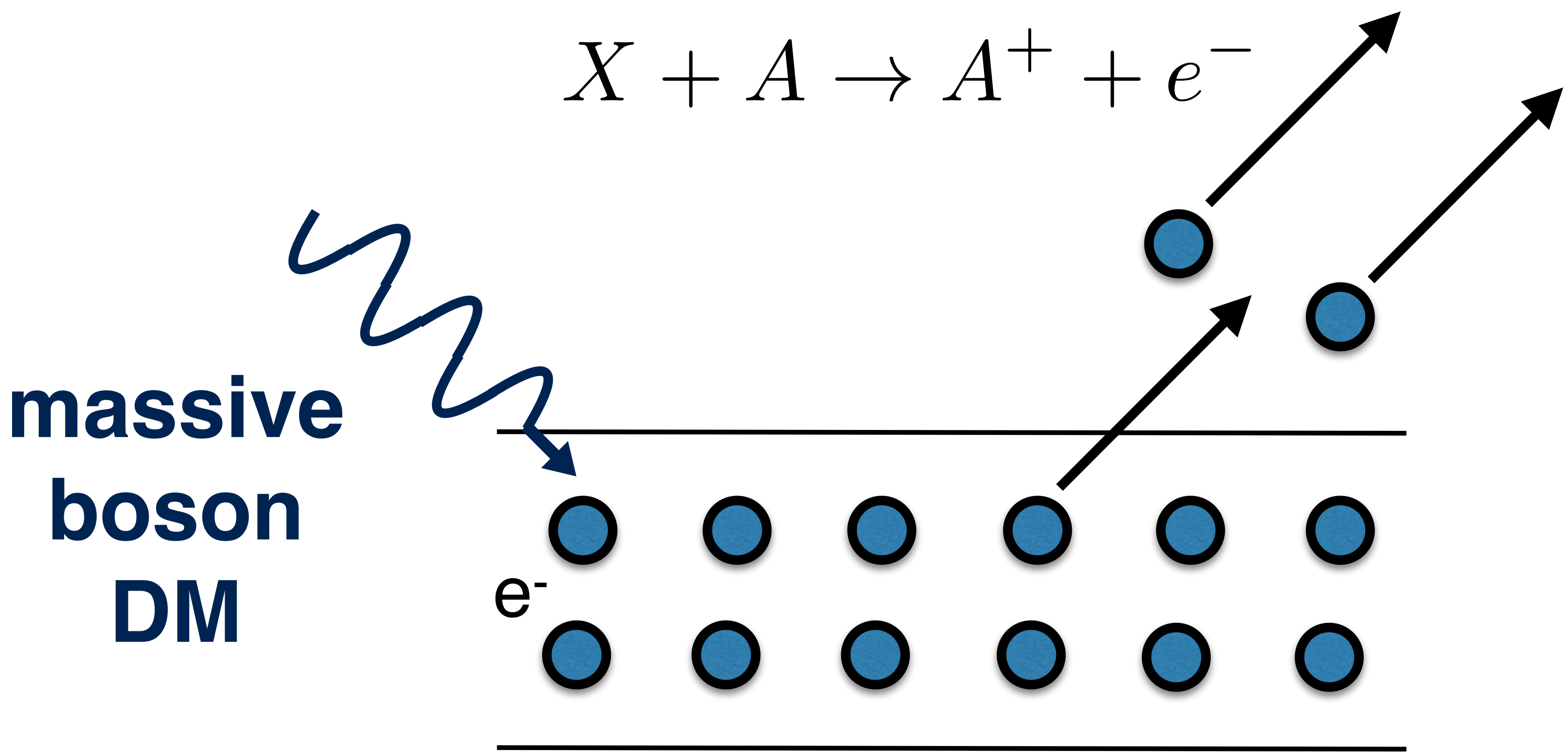
SENSEI reach



dark matter absorption

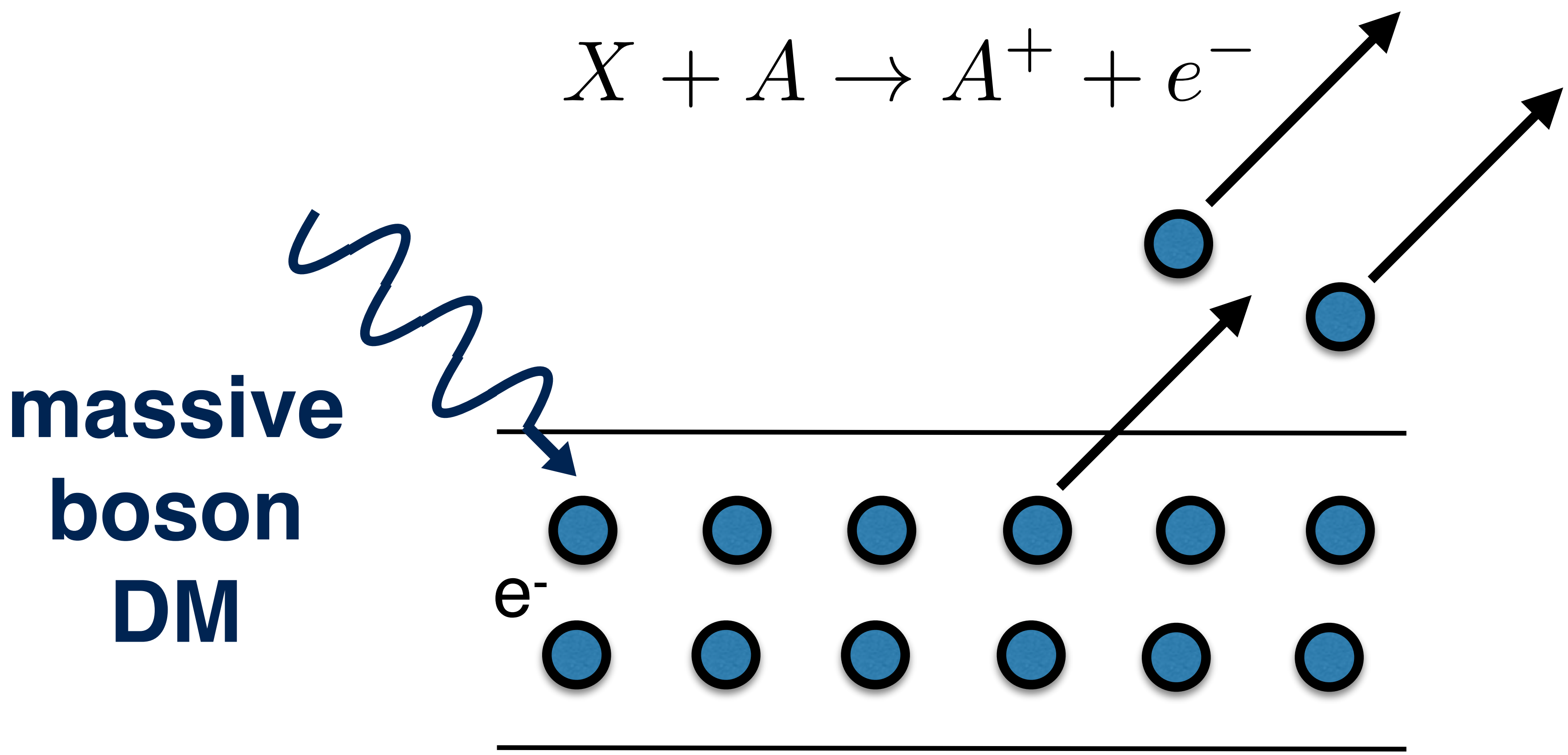
photoelectric effect

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



absorb all of the energy the incoming dark matter

photoelectric effect



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

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

photon absorption rate

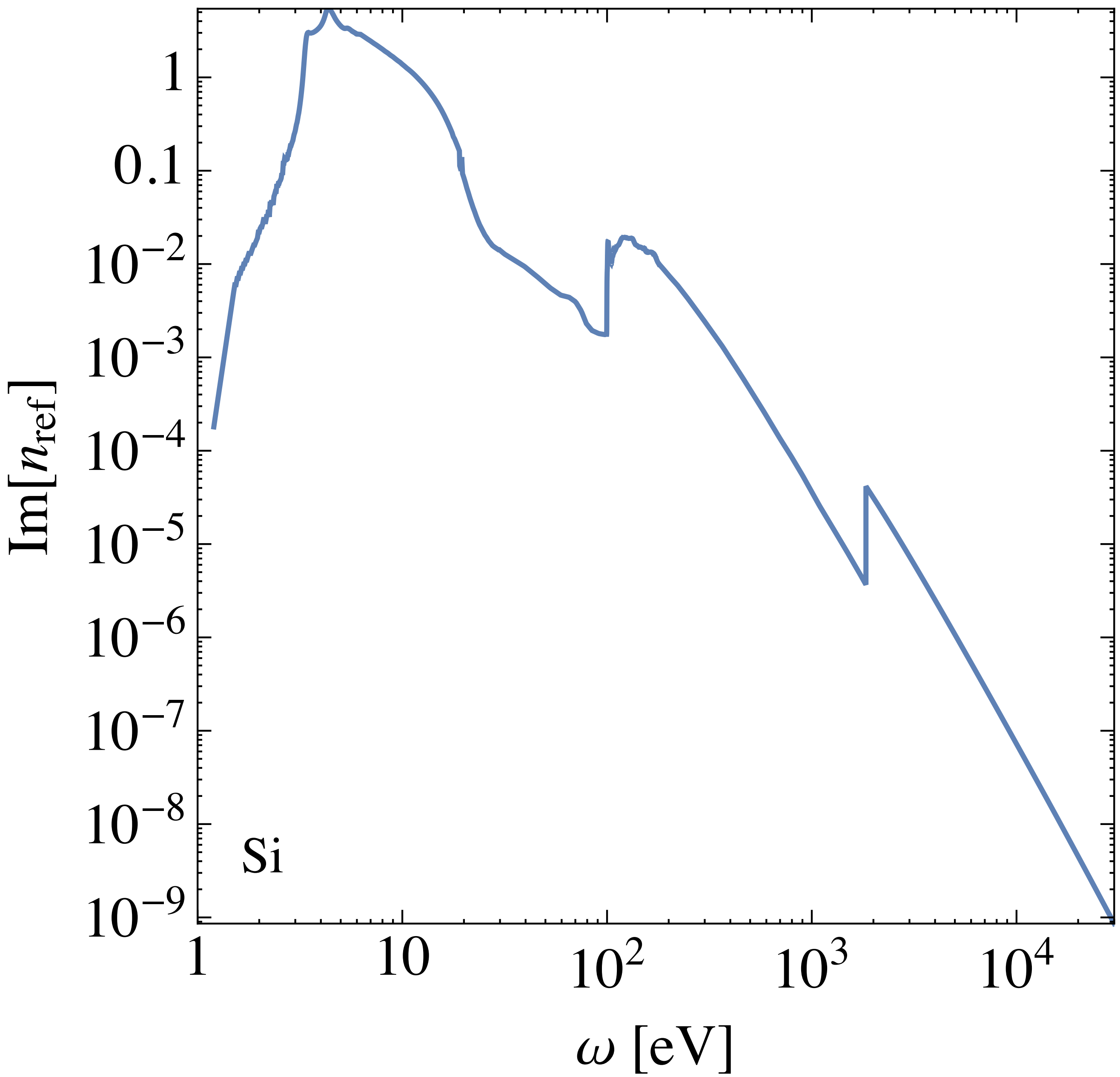
$$\langle n_e \sigma_{\rm PE} v_{\rm rel} \rangle = \frac{\mathrm{Im}\ \Pi_{\rm T,L}}{\omega}$$

$$\Pi_T = \Pi_L \simeq \omega^2 (1 - n_{\rm refr}^2)$$

material dependent

$$\langle n_e \sigma_{\rm PE} v_{\rm rel} \rangle \simeq \omega (1 - \mathrm{Im}\ n_{\rm refr}^2)$$

index of refraction



http://henke.lbl.gov/

shape depends on electronic structure

axion(-like) absorption

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + i g_{aee} a \bar{e} \gamma_5 e$$

“axioelectric effect”

↓

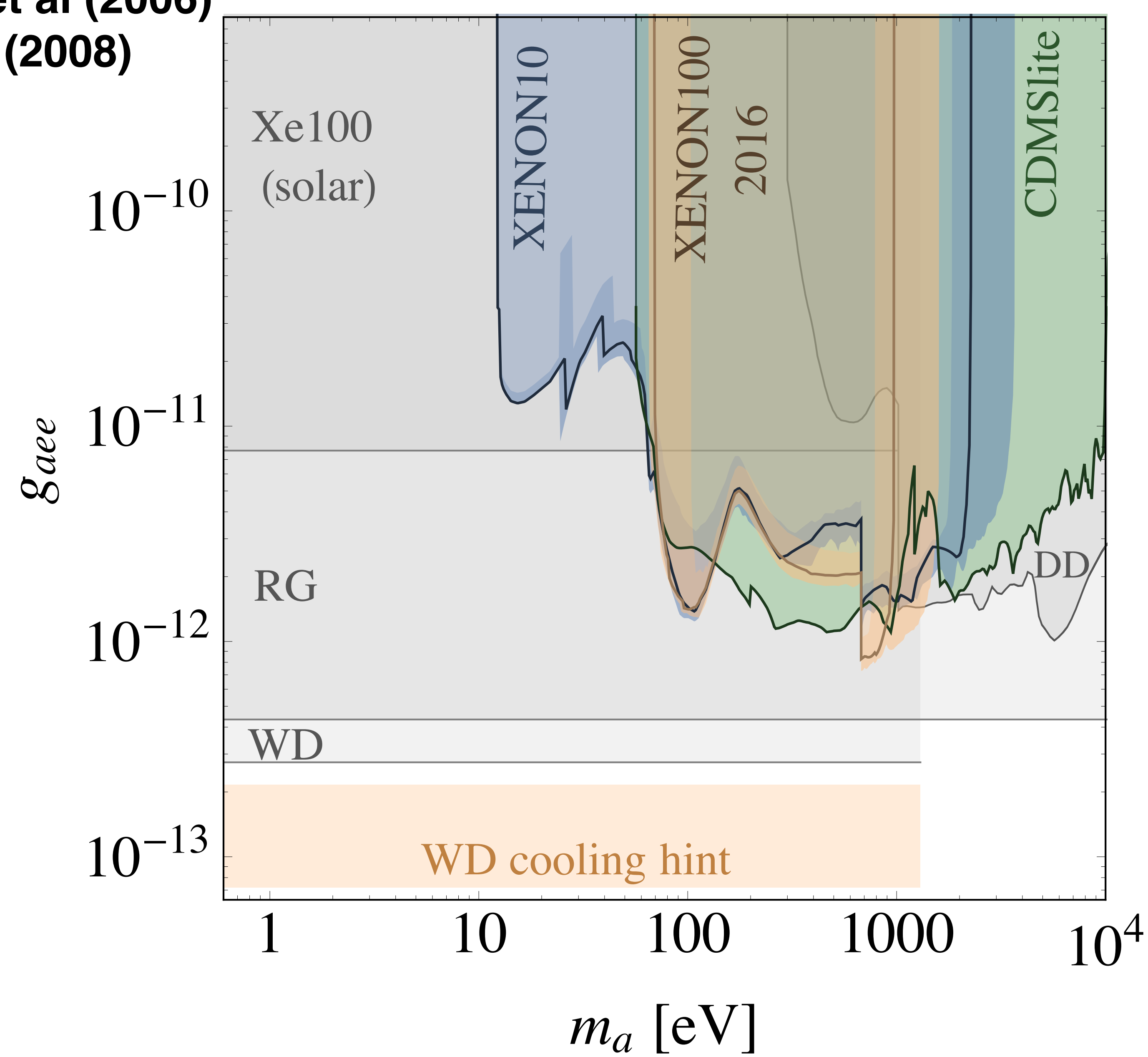
$$\sigma_{\rm AE}(E) v_a \simeq \sigma_{\rm PE}(E) \frac{3}{4} \frac{g_{aee}^2}{4\pi\alpha_{\rm EM}} \frac{E^2}{m_e^2} \left(1 - \frac{1}{3} v_a^{2/3}\right)$$

↓

$$R_{\rm ALPs} = 1.9 \times 10^{19} {\rm kg}^{-1} {\rm day}^{-1} \frac{g_{aee}^2}{A} \left(\frac{m_a}{\rm keV}\right) \left(\frac{\sigma_{\rm PE}}{\rm bn}\right)$$

axion(-like) absorption

See also:
Hochberg et al (2016)
Arias et al (2012), Grin et al (2006)
Raffelt (1996), Isern (2008)

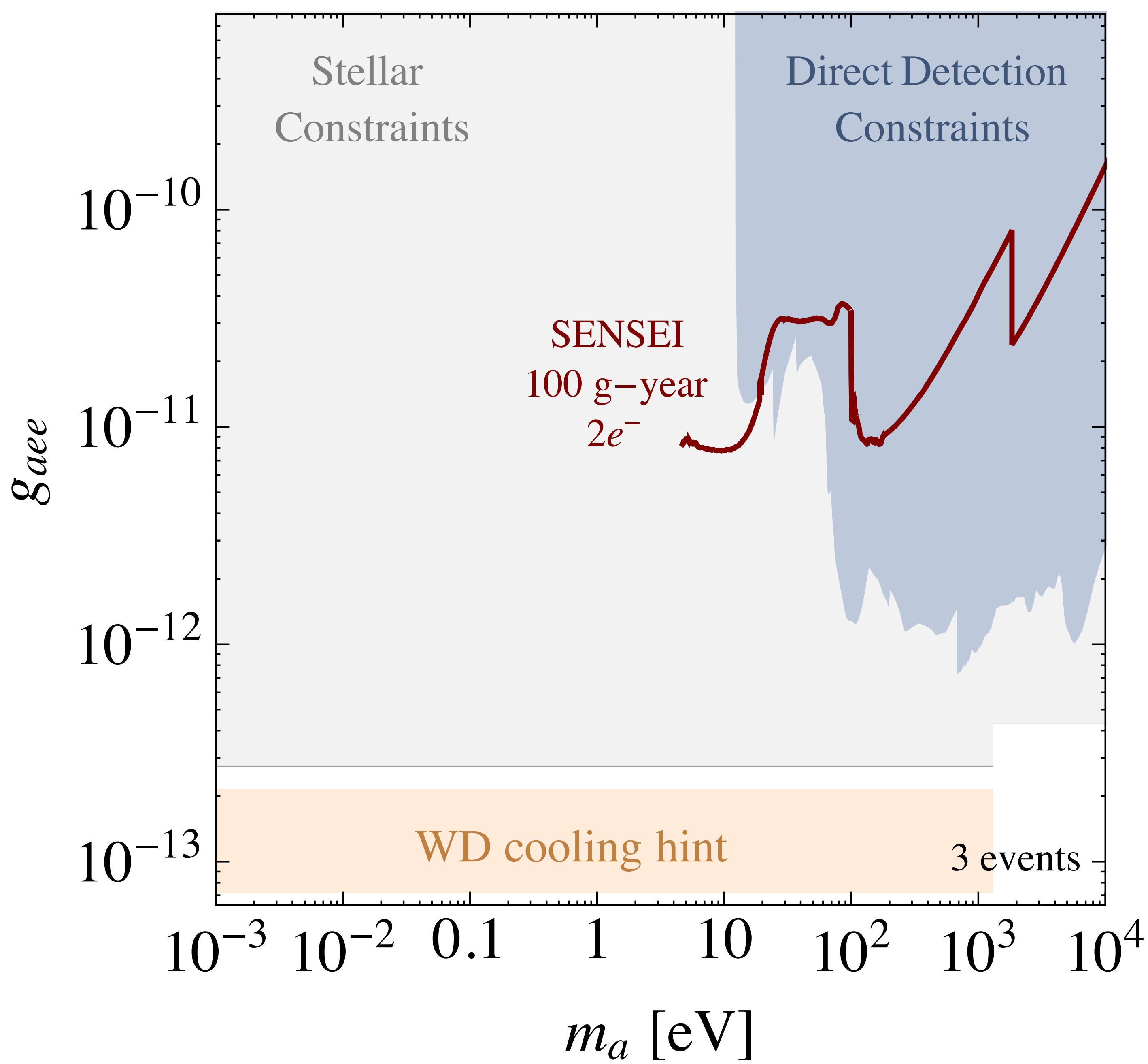


S2-only:
Xenon10 [1104.3088]
Xenon100 [1605.06262]

low e-recoil threshold:
CDMSlite [1509.02448]

Bloch, Essig, Tobioka, Volansky, TTY [1608.02123]

axion(-like) absorption



dark photon absorption

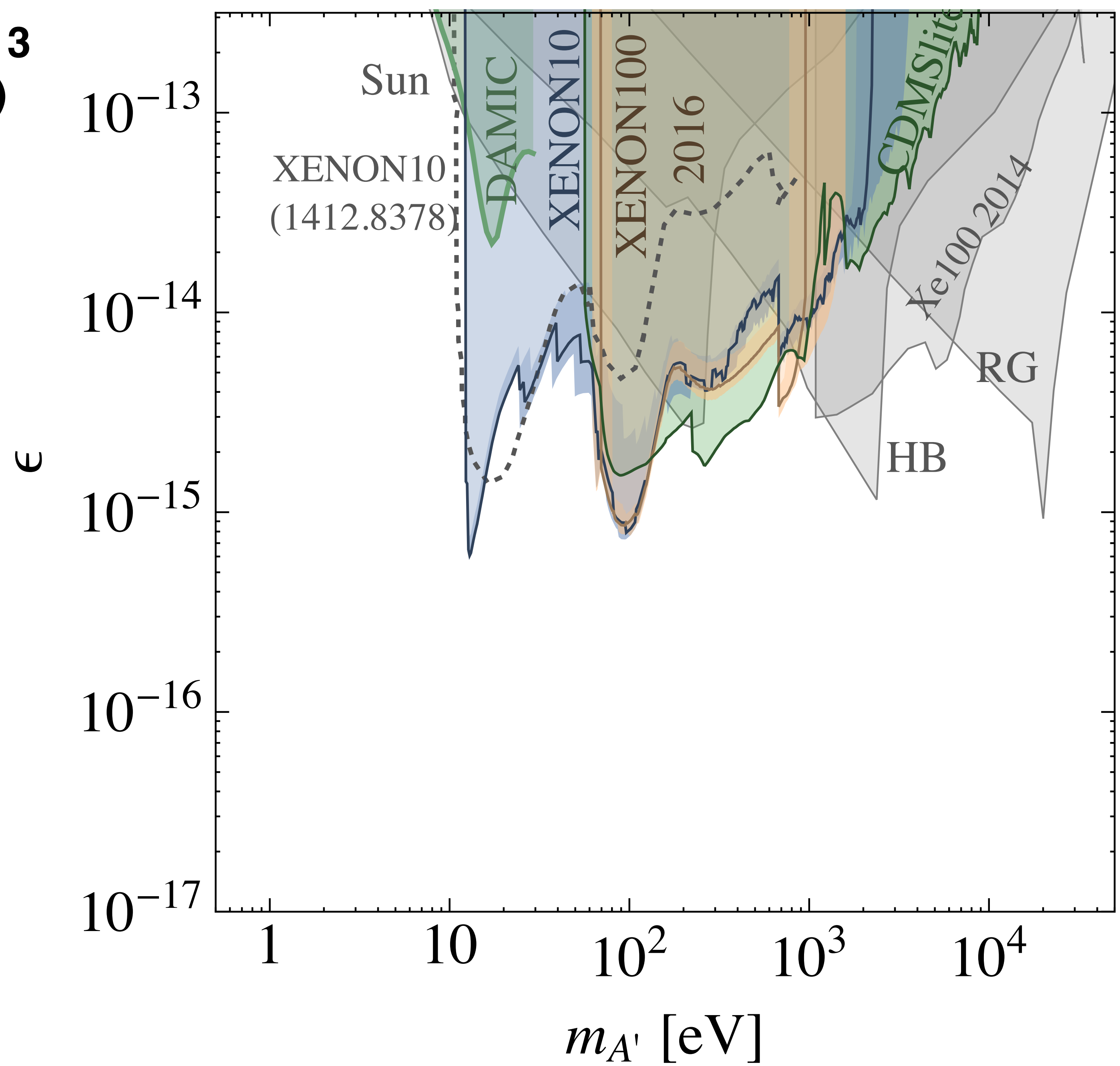
$$\mathcal{L}_{eff} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu + j_\mu A^\mu$$

$$\sigma_X(E_X = m_X)v_{\rm DM} \simeq \epsilon^2 \sigma_{\rm PE}(E = m_X)$$

$$\text{Rate} \simeq \frac{\rho_{\rm DM}}{m_X} \times \epsilon^2 \sigma_{\rm PE}(E = m_X)$$

dark photon dark matter

See also:
An et al 2013, 2014
Redondo & Raffelt 2013
Hochberg et al (2016)



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DAMIC [1607.07410]

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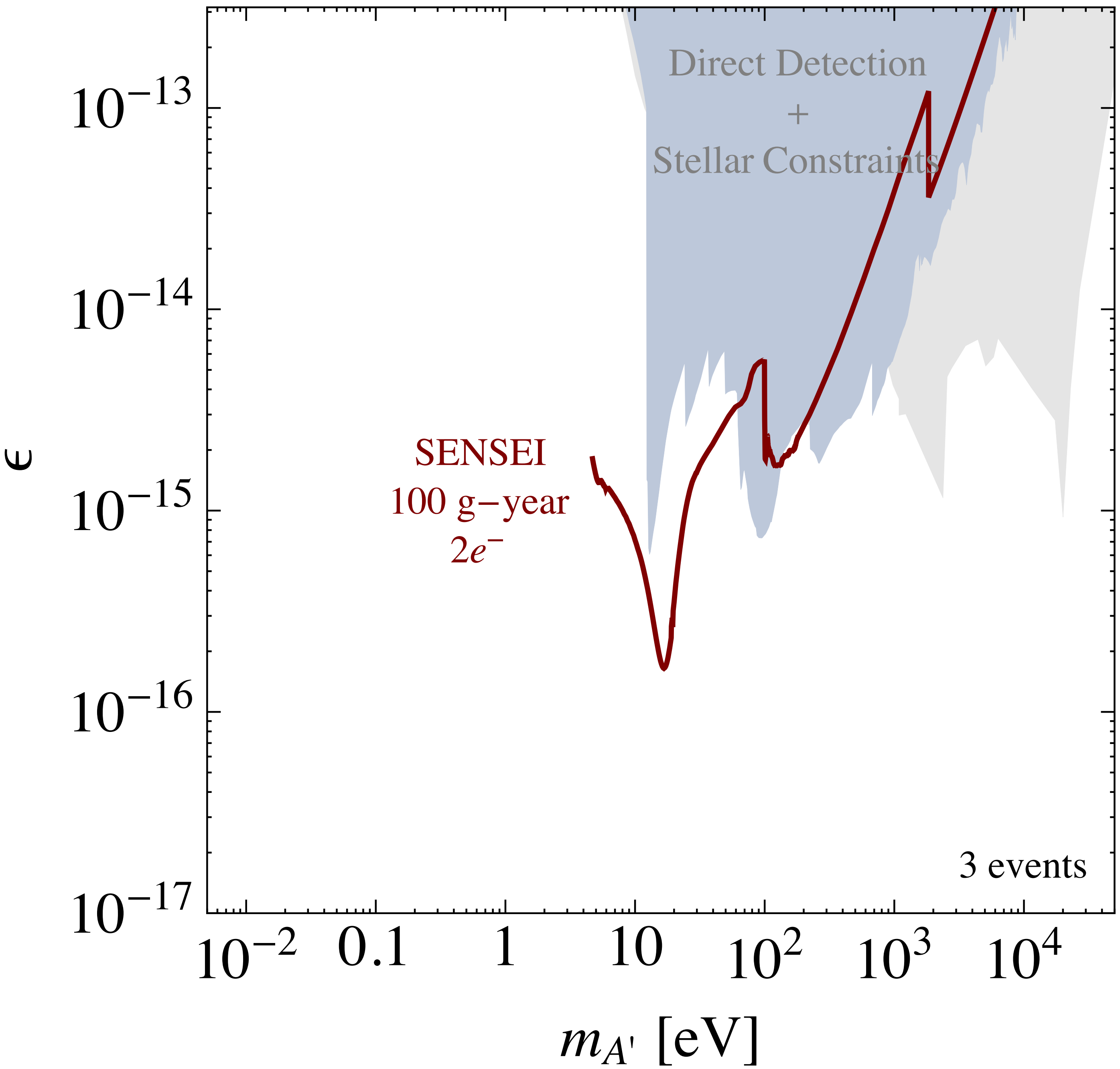
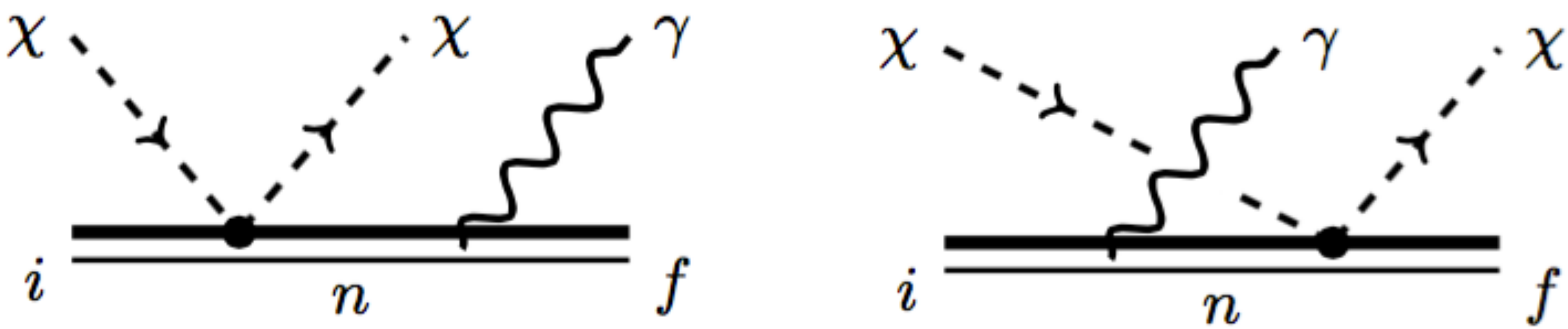
dark photon dark matter



dark matter bremsstrahlung

dark matter-nuclear scattering



$$d\sigma = |V_{fi}|^2 \frac{\omega^2 d\omega d\Omega_K}{(2\pi)^3} \times d\sigma_{\rm el}$$

dipole transition element

see also:
Kouvaris, Pradler [1607.01789]
McCabe [1702.04730]

photon emission cross-section

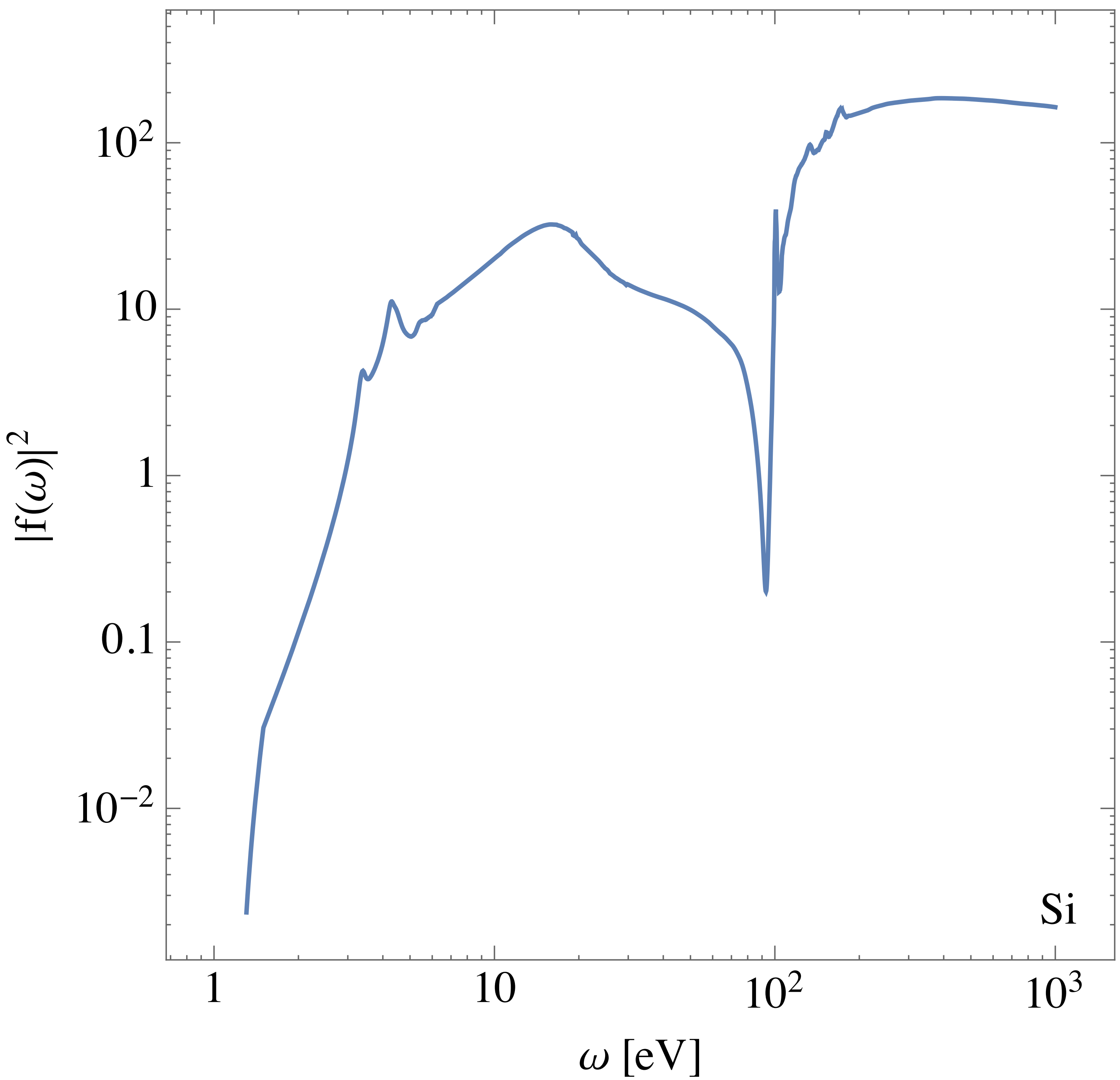
$$\frac{d\sigma}{d\omega dE_R} = \frac{4\alpha}{3\pi\omega}\frac{E_R}{m_N}|f(\omega)|^2 \times \frac{d\sigma}{dE_R}\Theta(\omega_{\mathrm{max}-\omega})$$

atomic scattering factor

$$\frac{d\sigma}{dE_R} = \frac{A^2\sigma_n m_N}{2\mu_n^2 v^2}|F_{\mathrm{DM}}(q)|^2$$

elastic DM-nucleus cross-section

atomic scattering factor



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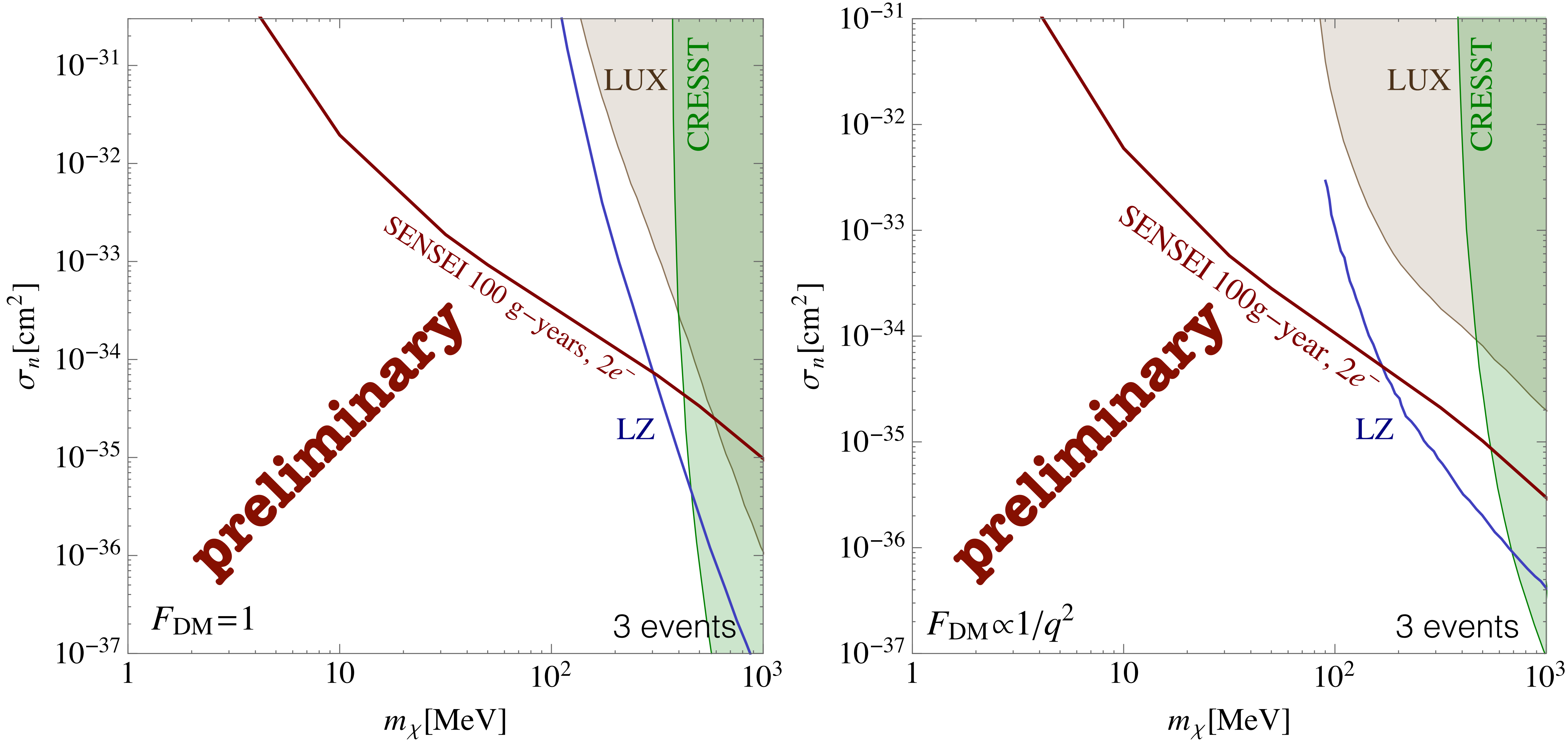
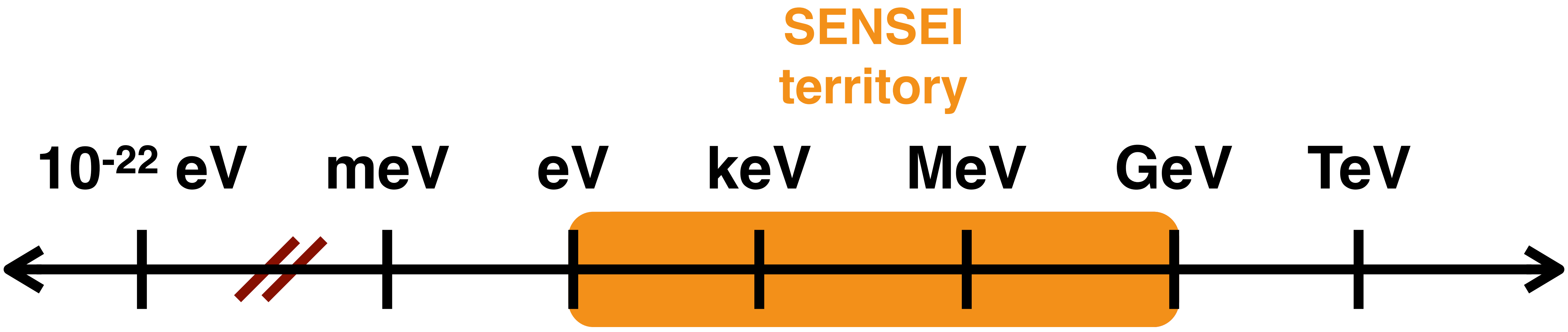
shape depends on electronic structure

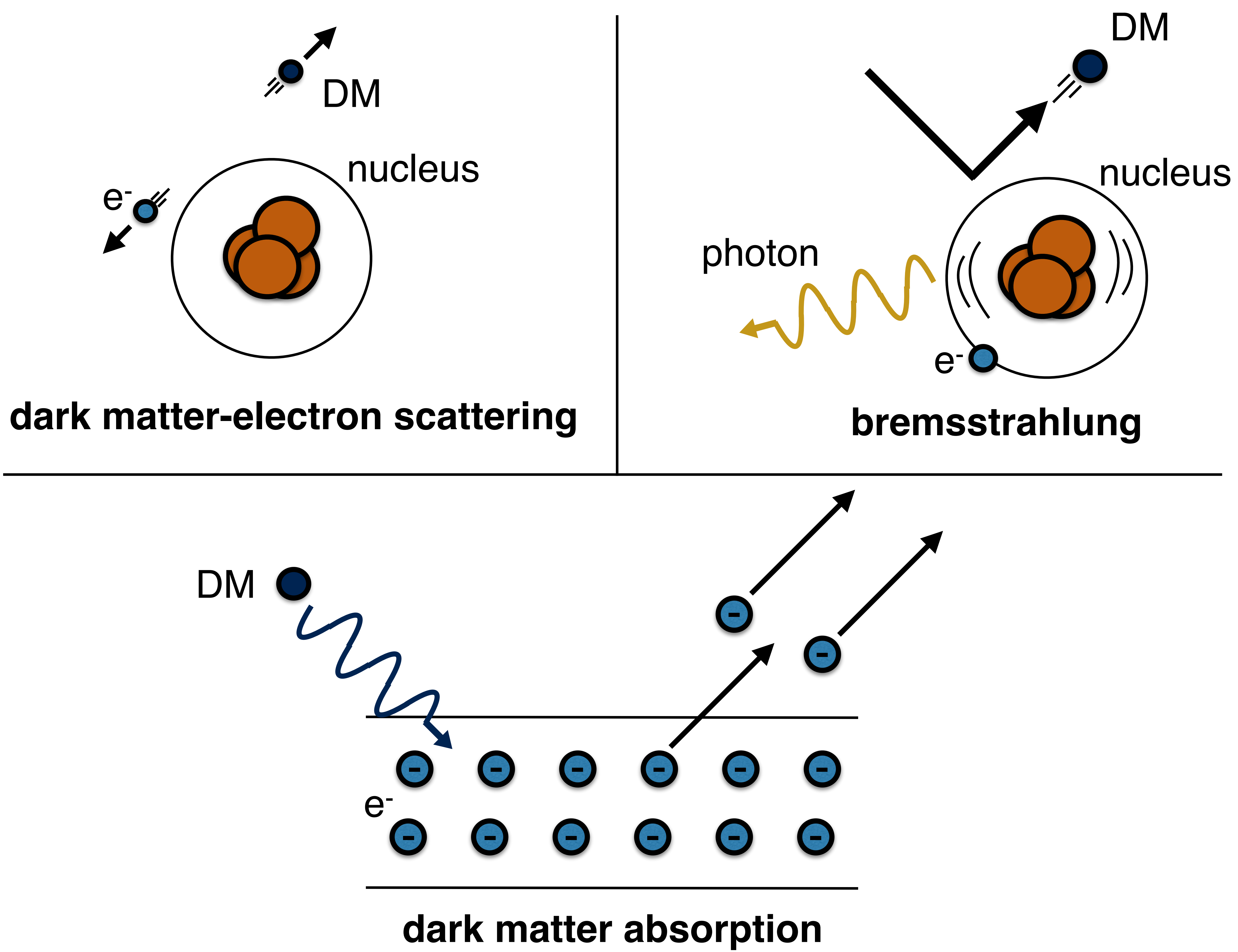
dark matter-nucleon scattering



R. Essig, X. Wang, TTY, *in preparation*

dark matter candidates

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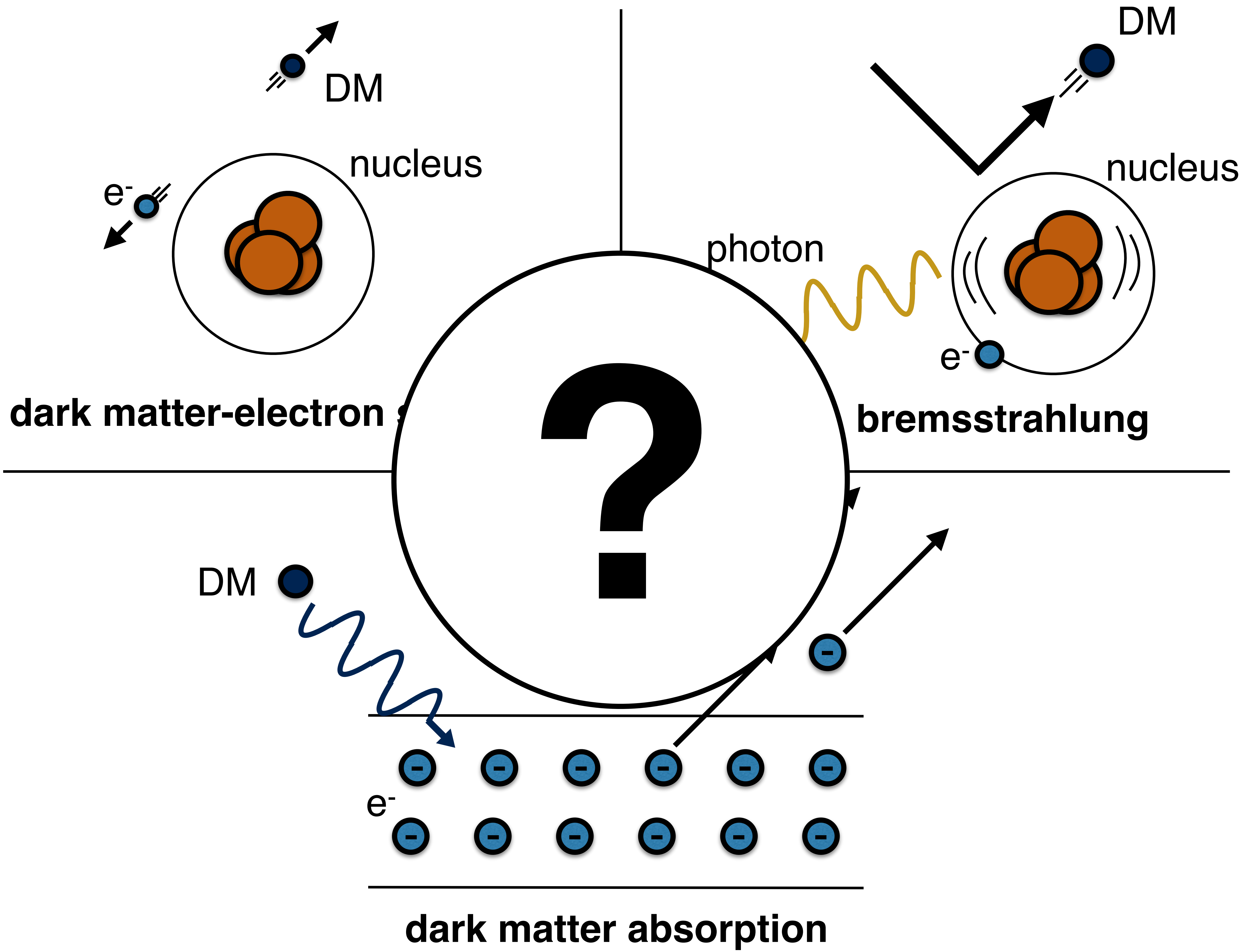
dark matter absorption

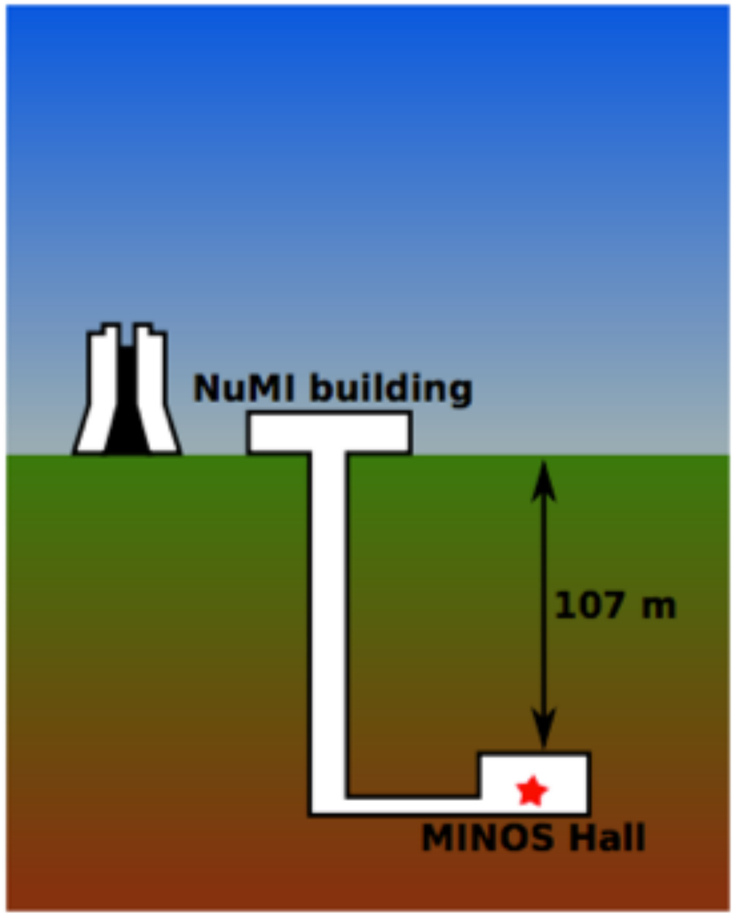

DM
nucleus
e-
dark matter-electron s
DM
nucleus
photon
e-
bremsstrahlung
?
DM
e-
dark matter absorption

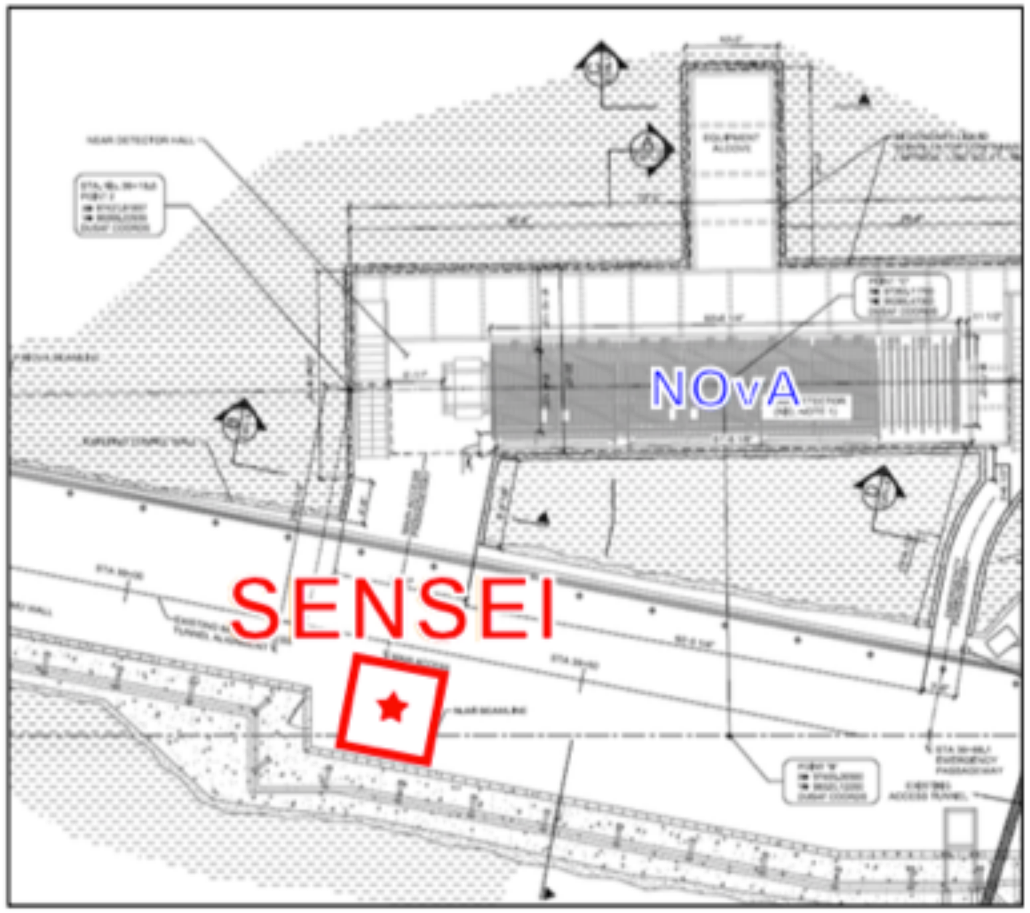
extras

SENSEI

Whats next: Installation @MINOS & low radiation package

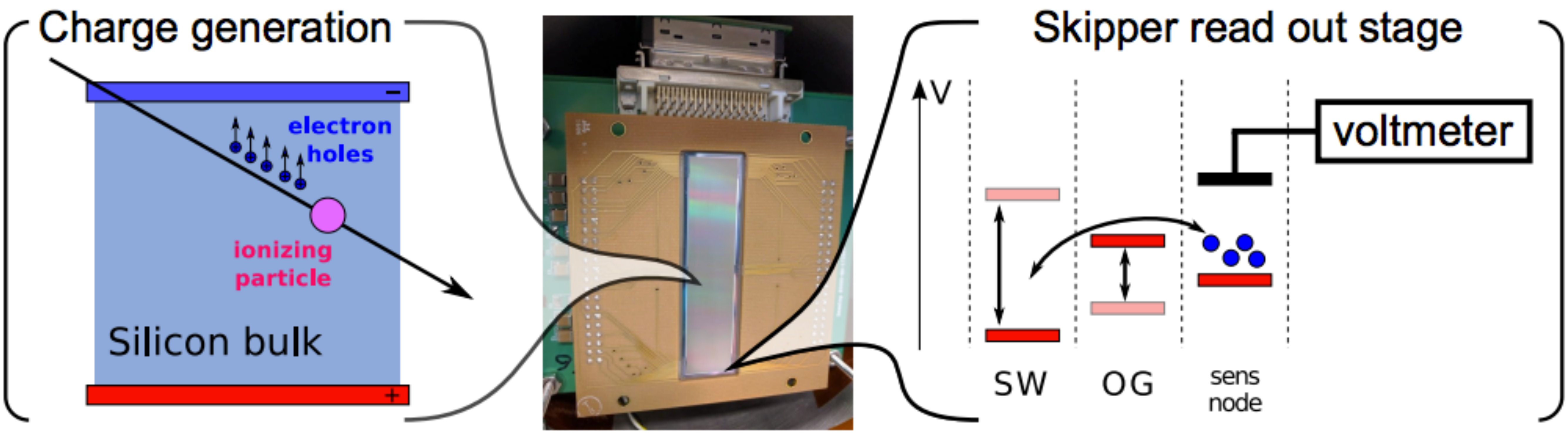
Technology demonstration: installation at shallow underground site

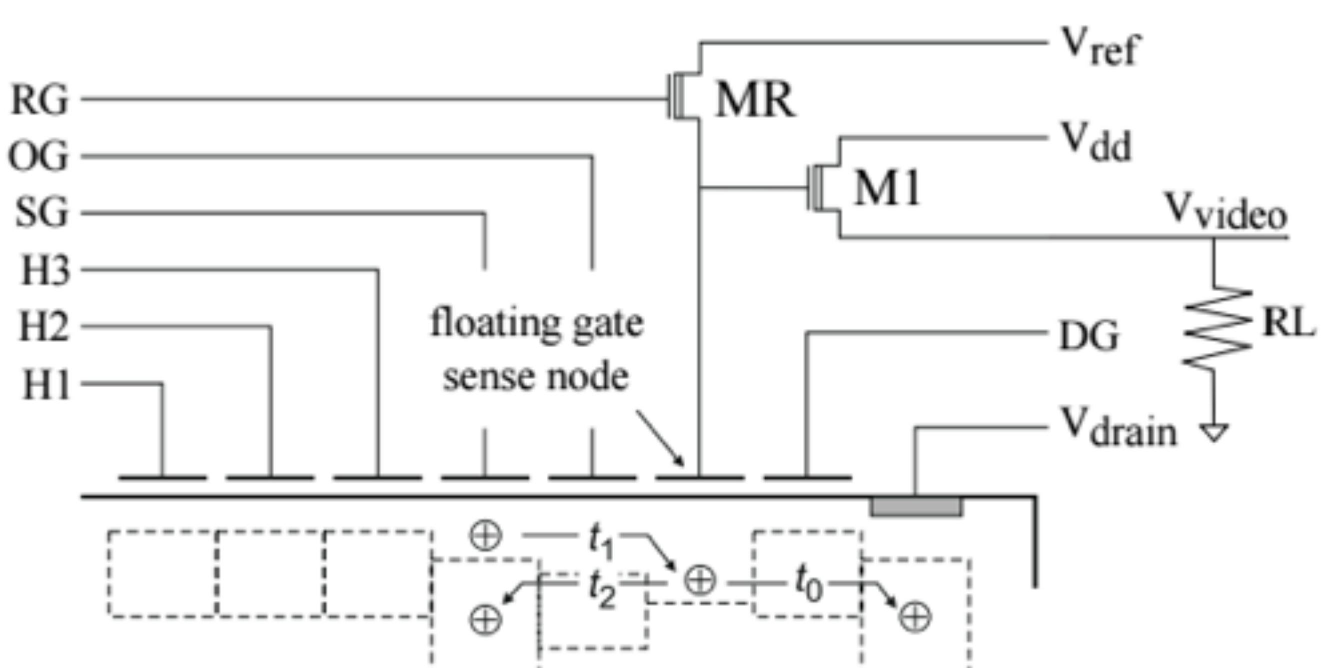




Fermilab J. Tiffenberg

skipper readout





non-destructive readout!

J. Tiffenberg, M. Sofo-Haro,
A. Drlica-Wagner, R. Essig,
Y. Guardincerri, S. Holland,
T. Volansky, TTY
[1706.00028]