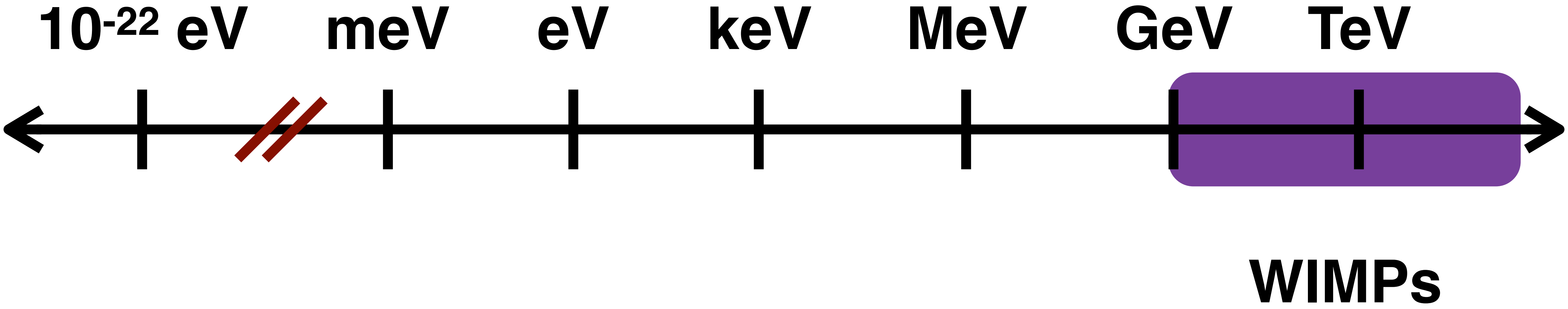
# Dispatches from the sub-GeV Dark Matter Frontier

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

Institute of Mathematics and Physics of the Universe — December 14, 2018

# dark sector candidates



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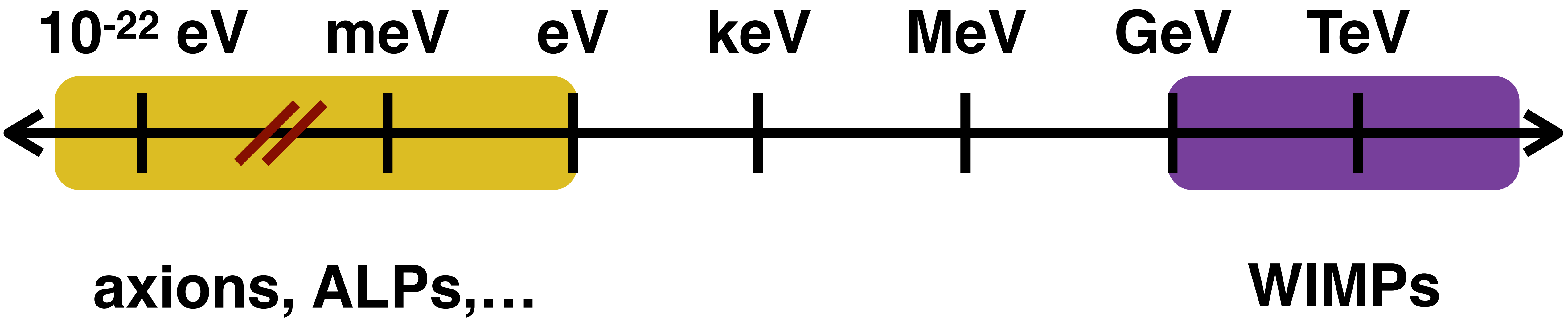

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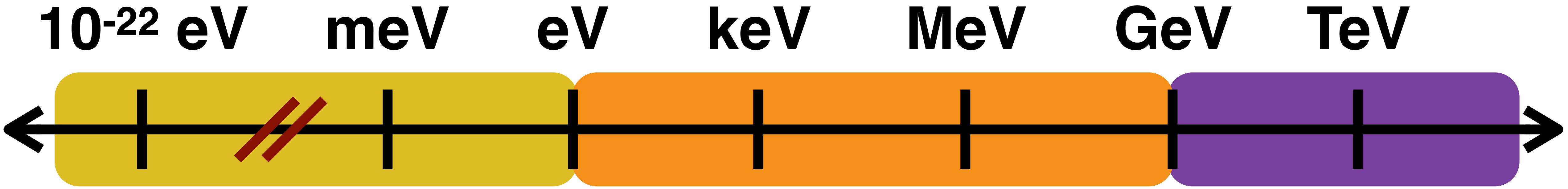
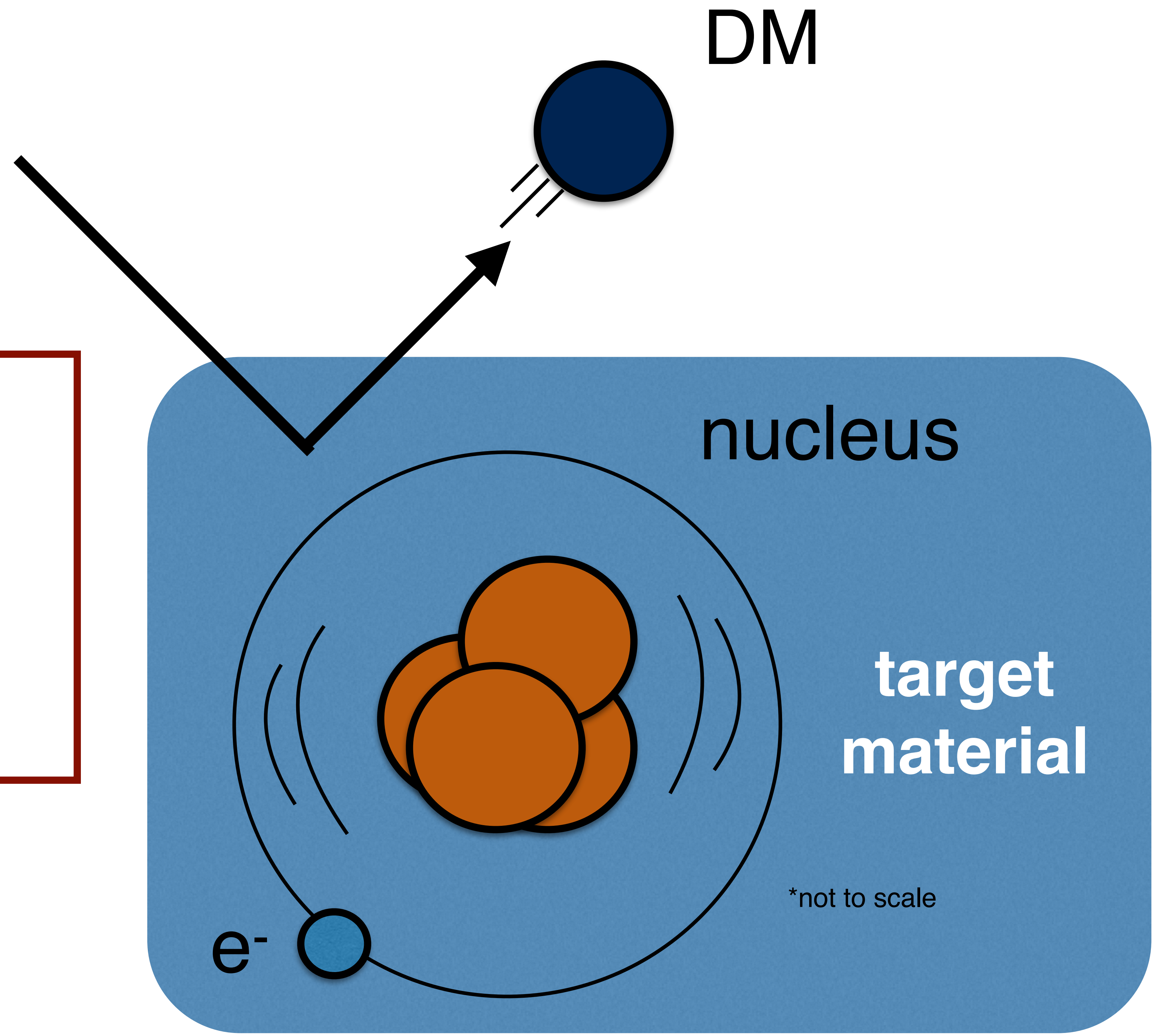


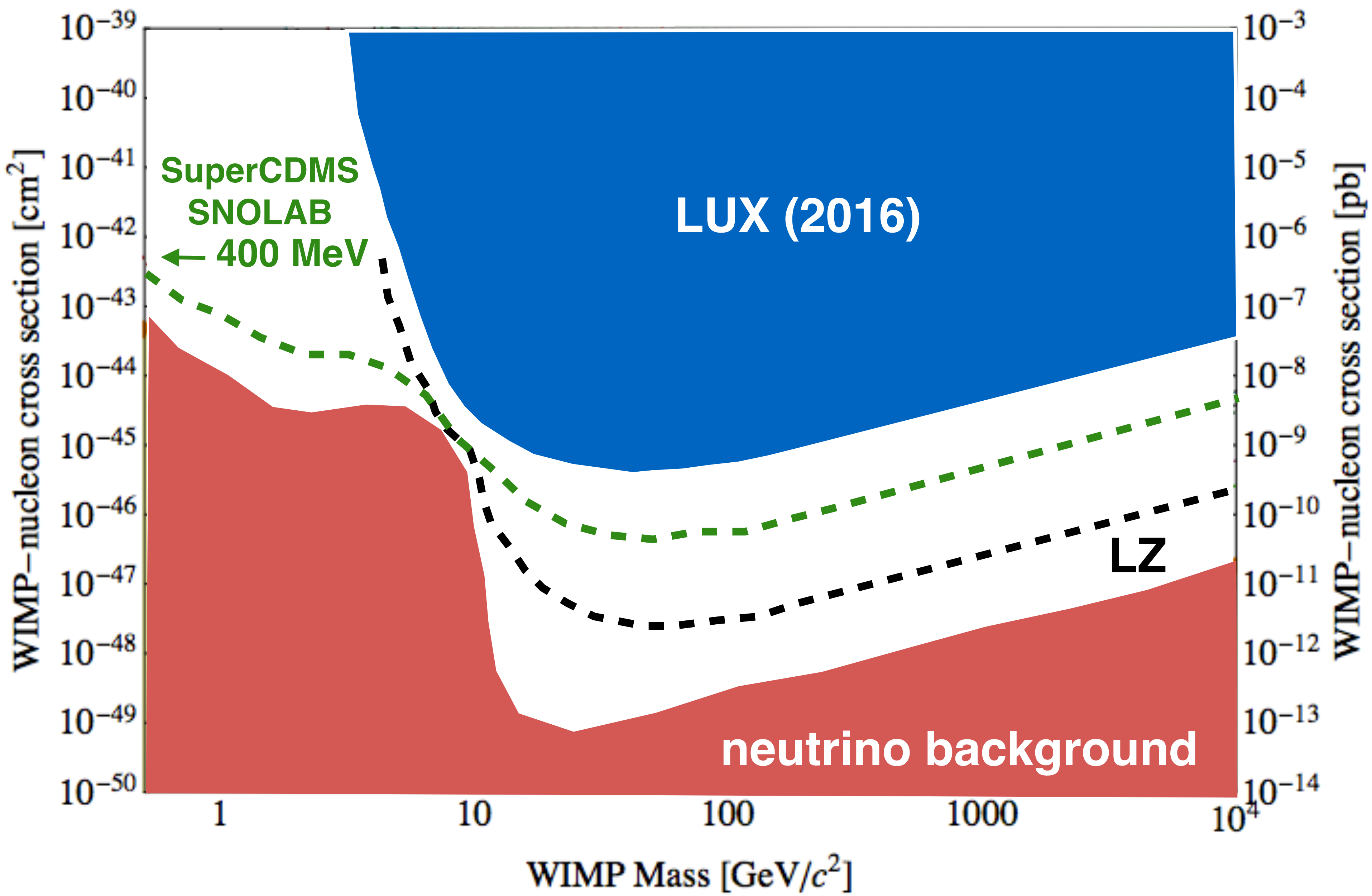

**I will focus here**

# DM direct detection

**signal:**
phonons,
scintillation
photons,
ionization
electrons



# direct detection



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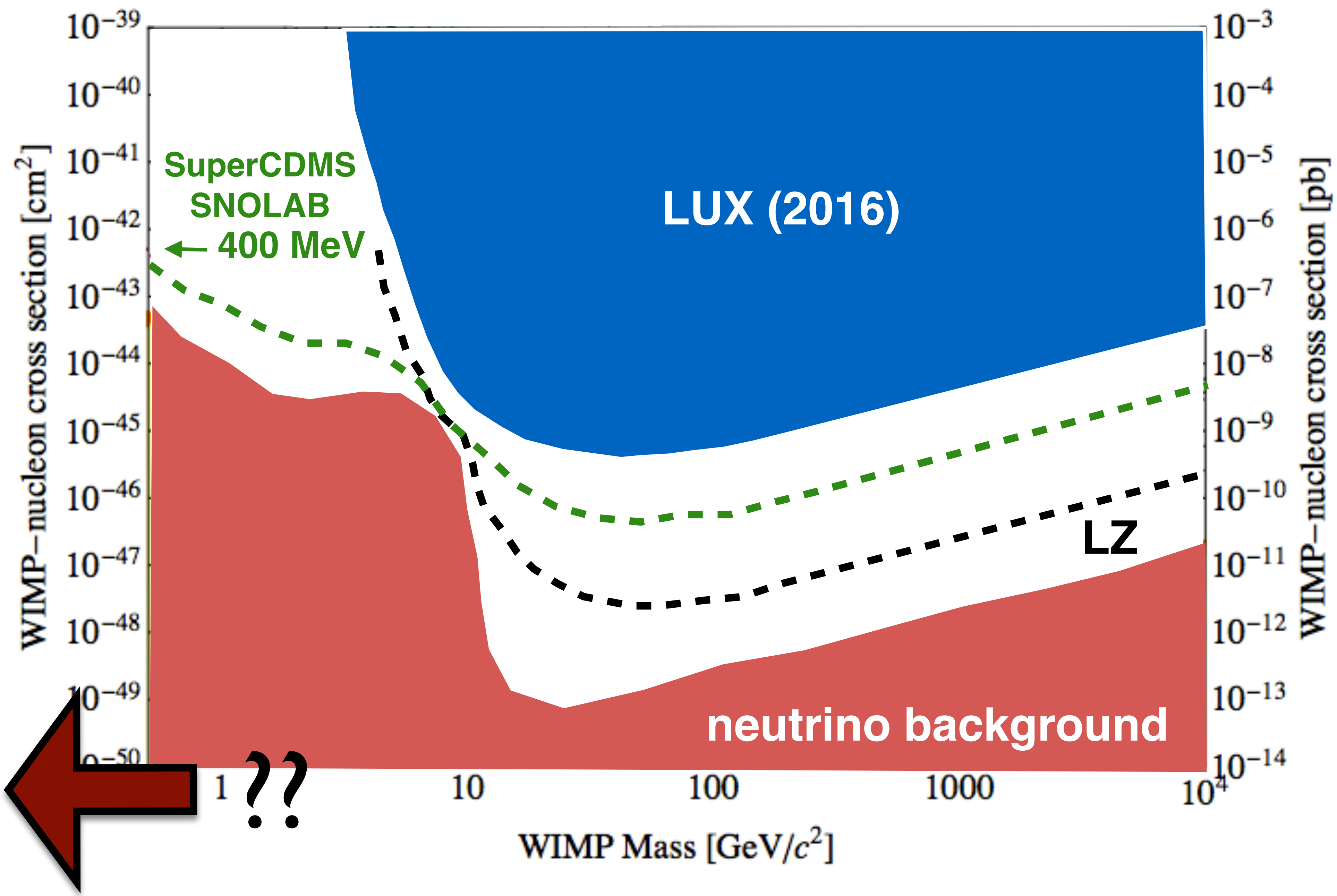
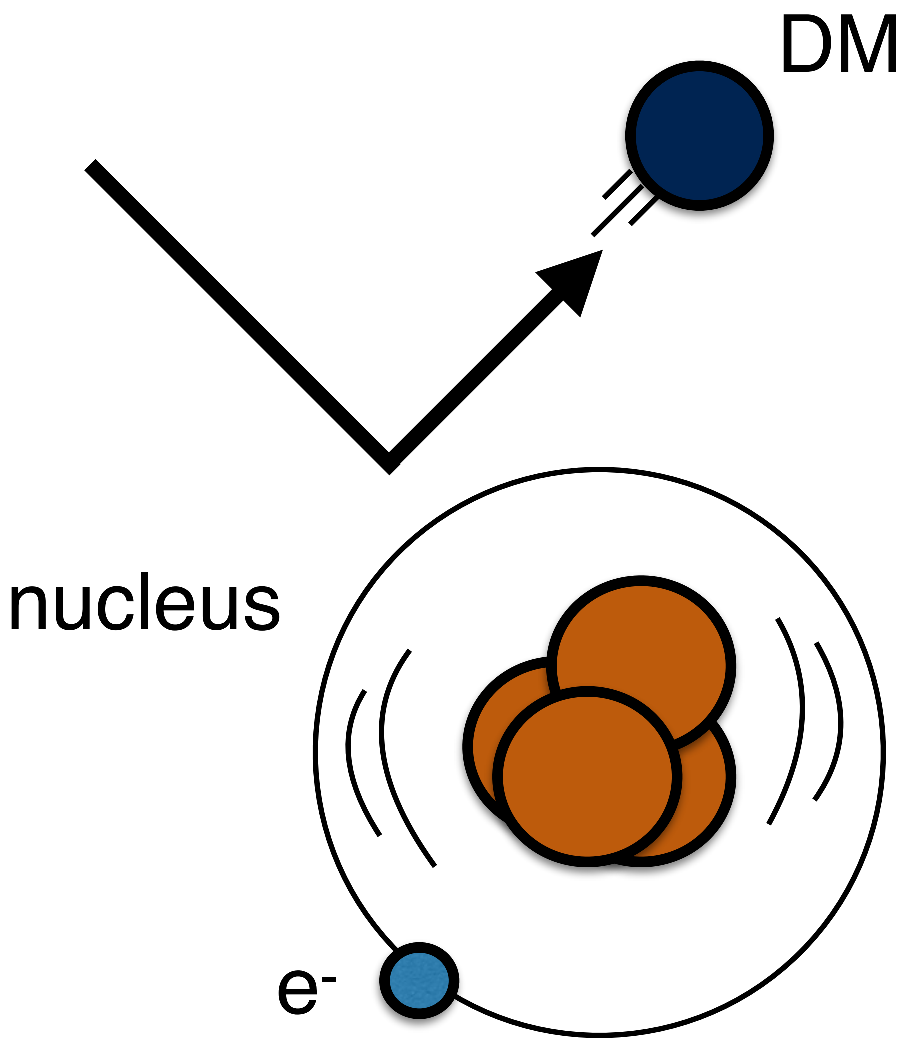
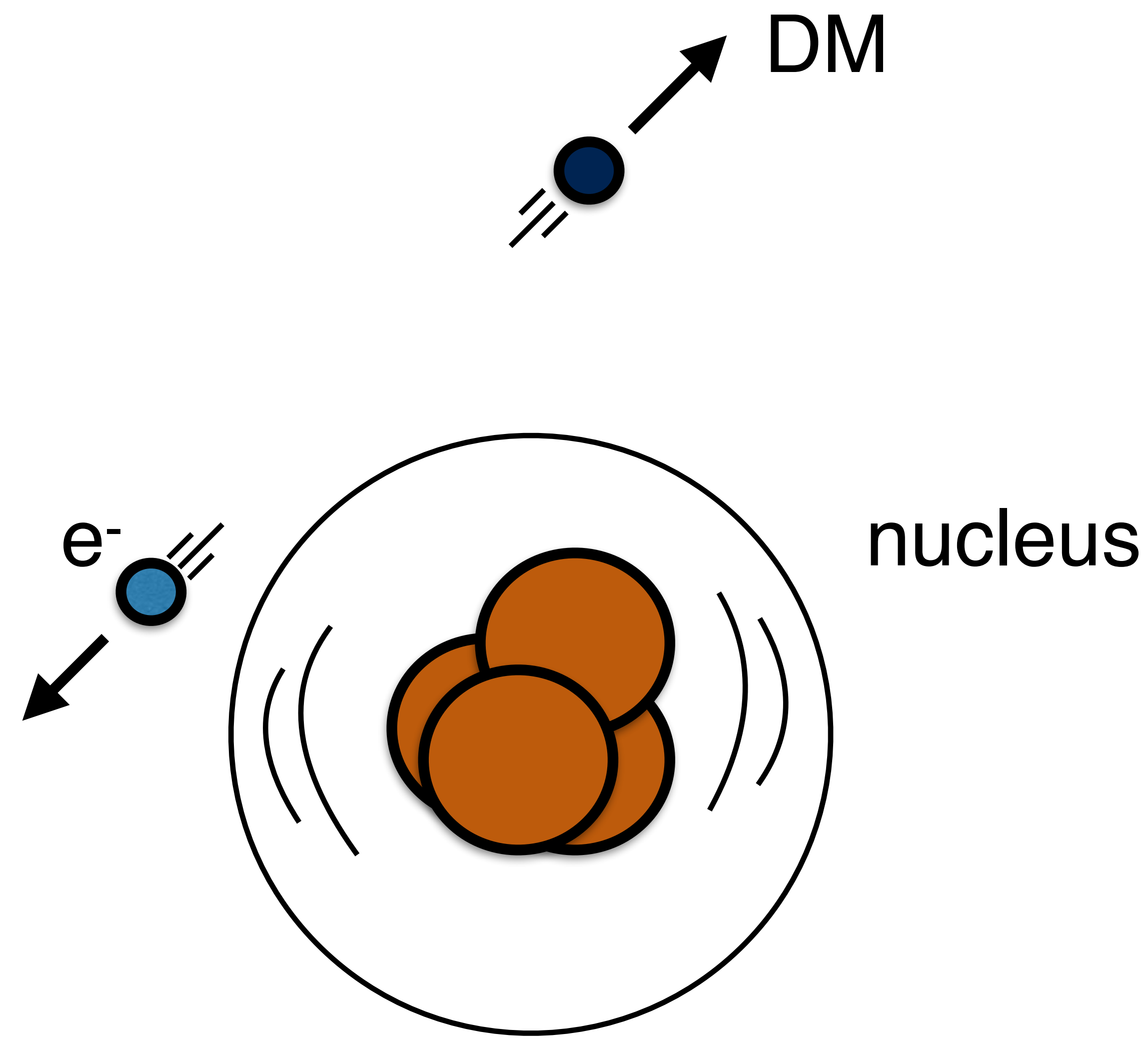




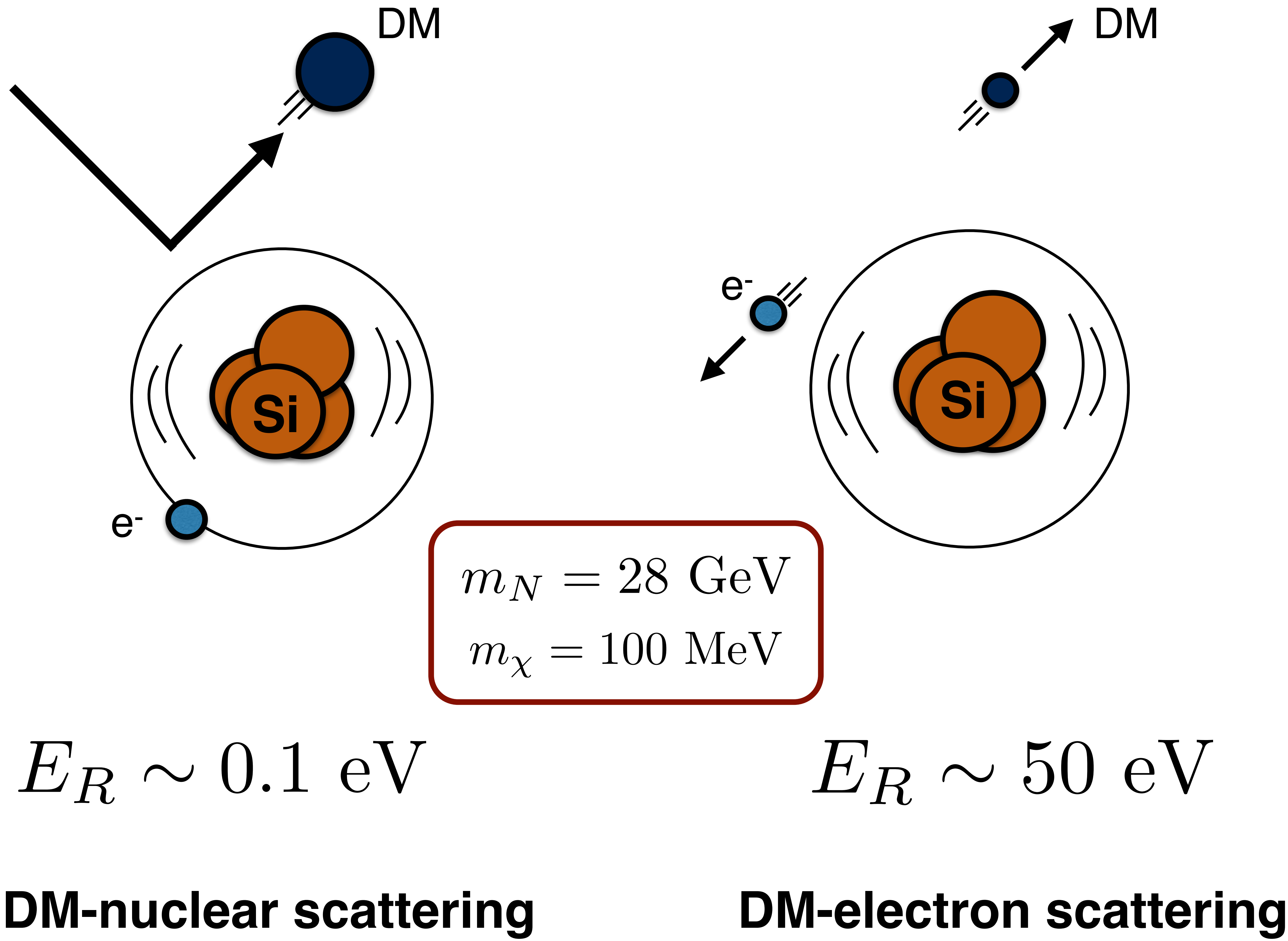

$$E_R = \frac{q^2}{2m_N} \simeq 50\ \mathrm{keV} \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_N}\right)$$

**DM-nuclear scattering**




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

**DM-electron scattering**


DM
e-
Si
DM
e-
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

**calculation**

# ingredients for rate

astrophysics

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

$$\eta(v_{min}) = \int_{v_{min}} \frac{\mathrm{d}^3 v}{v} f_{MB}(\vec{v})$$

Maxwell-Boltzmann

$$v_{min} = \frac{E_R + E_B}{q} + \frac{q}{2m_\chi}$$

# ingredients for rate

**particle physics**

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

$$\overline{\sigma}_e = \frac{\mu_{\chi e}^2}{16\pi m_\chi^2 m_e^2}\overline{|\mathcal{M}_{\chi e}(q)|^2}_{q^2=\alpha^2 m_e^2}$$

$$F_{DM}(q) \simeq \begin{cases} 1 & \textit{heavy mediator} \\ \frac{\alpha m_e}{q} & \textit{electric dipole moment} \\ \frac{\alpha^2 m_e^2}{q^2} & \textit{light mediator} \end{cases}$$

# ingredients for rate

**material dependent**

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

$$|f(k,q)|^2 = \left|\int d^3x\psi_f^*(\vec{x})\psi_i(\vec{x})e^{i\vec{q}\cdot\vec{x}}\right|^2$$

wave-function overlap between initial and final electron states

probability of going from state i to i'

# scattering rate

detector astrophysics

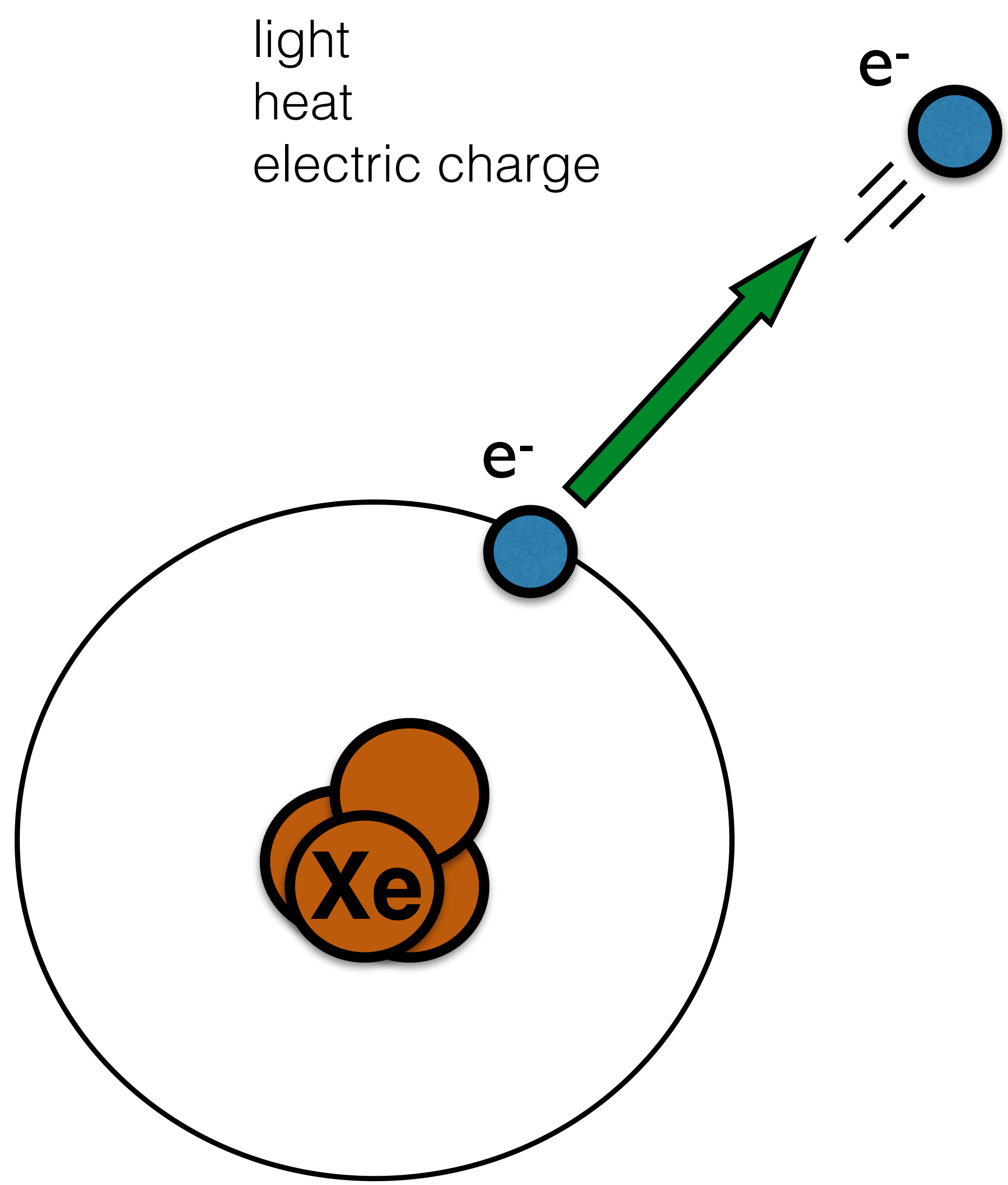
$$\frac{\mathrm{d}\langle\sigma v\rangle}{\mathrm{d}\ln E_R} = \frac{\overline{\sigma}_e}{8\mu_{\chi e}^2}\int q\ \mathrm{d}q |f(k,q)|^2 |F_{DM}(q)|^2 \eta(v_{min})$$

particle physics

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

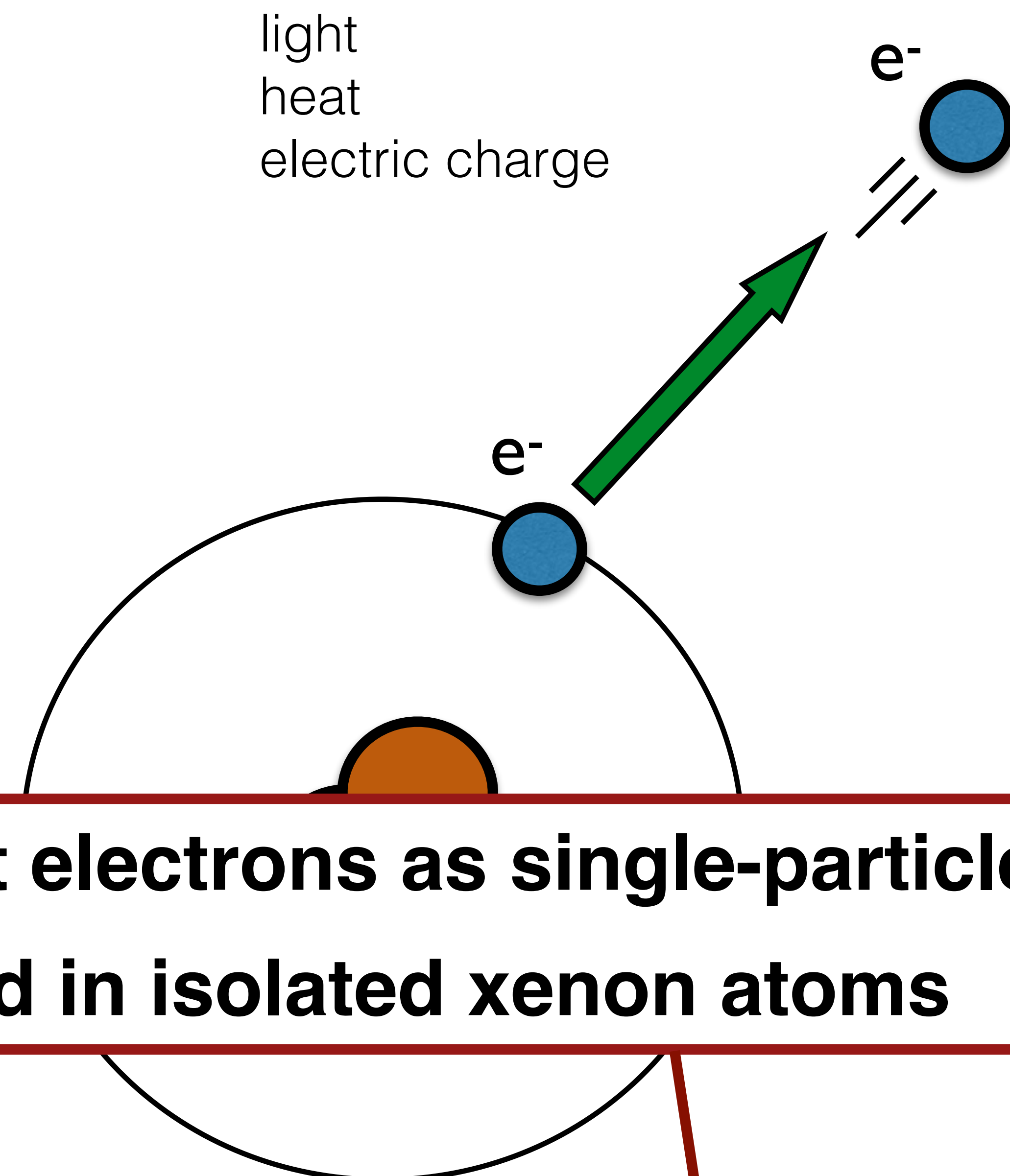
**R = number of events/time/volume**

**liquid xenon**




$$|f(k,q)|^2 = \left| \int d^3x \psi_f^*(\vec{x}) \psi_i(\vec{x}) e^{i\vec{q}\cdot\vec{x}} \right|^2$$

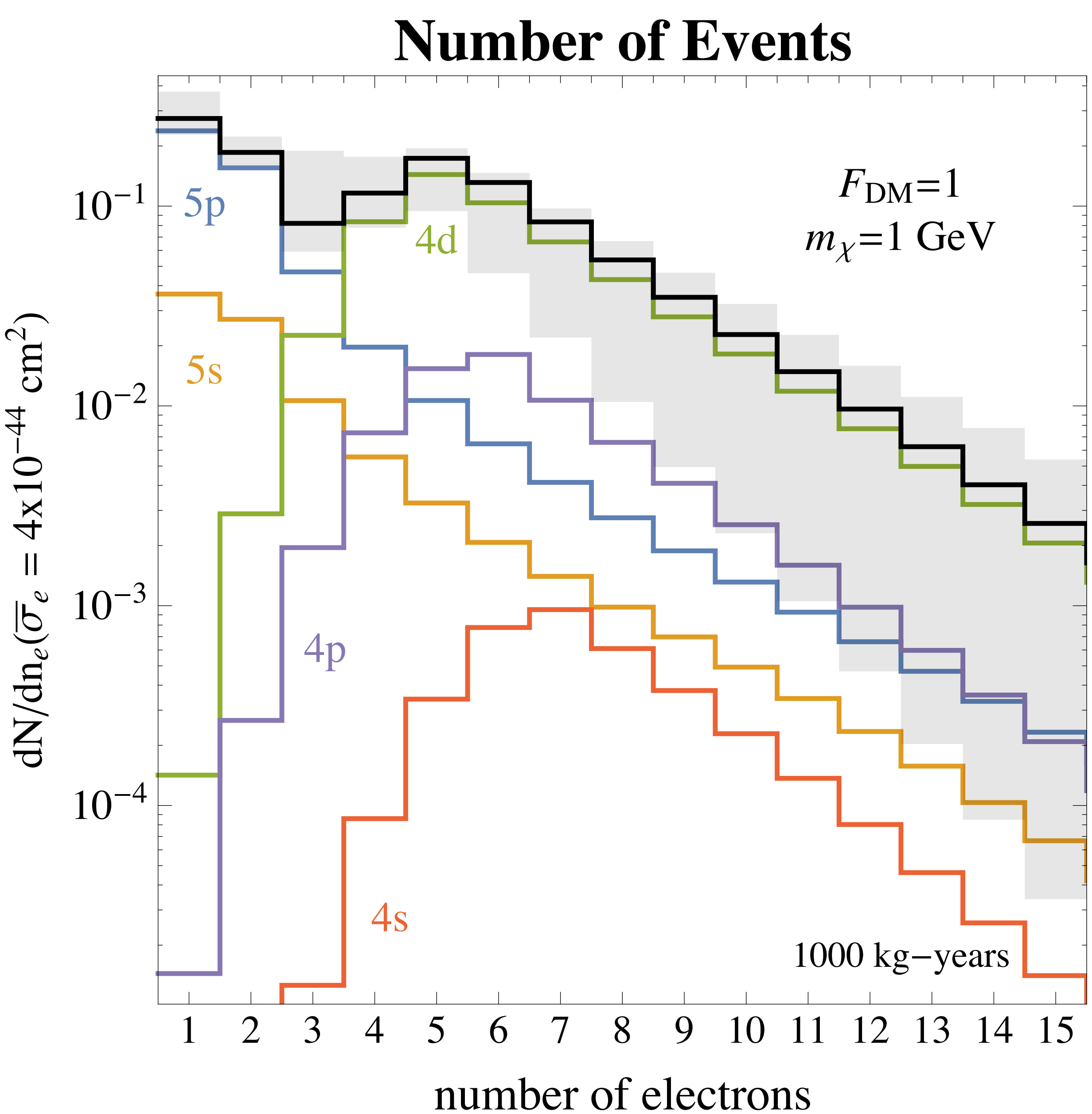
**liquid xenon**




**treat the target electrons as single-particle states bound in isolated xenon atoms**

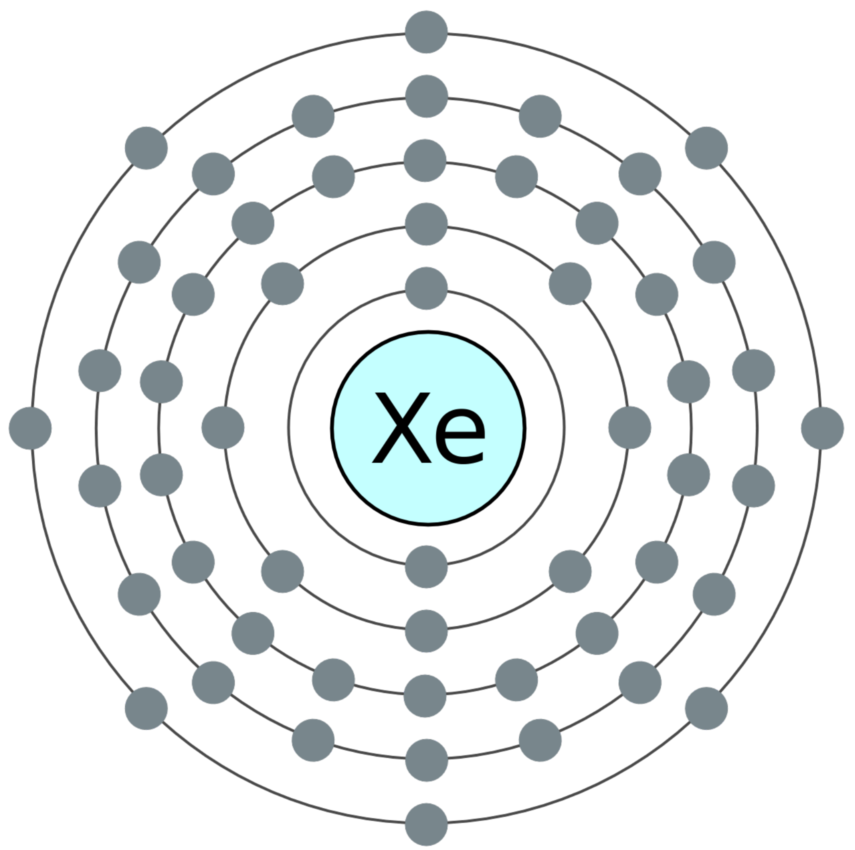
$$|f(k,q)|^2 = \left| \int d^3x \psi_f^*(\vec{x}) \psi_i(\vec{x}) e^{i\vec{q}\cdot\vec{x}} \right|^2$$

# XENON




**Essig, Volansky, TTY [1703.00910]**

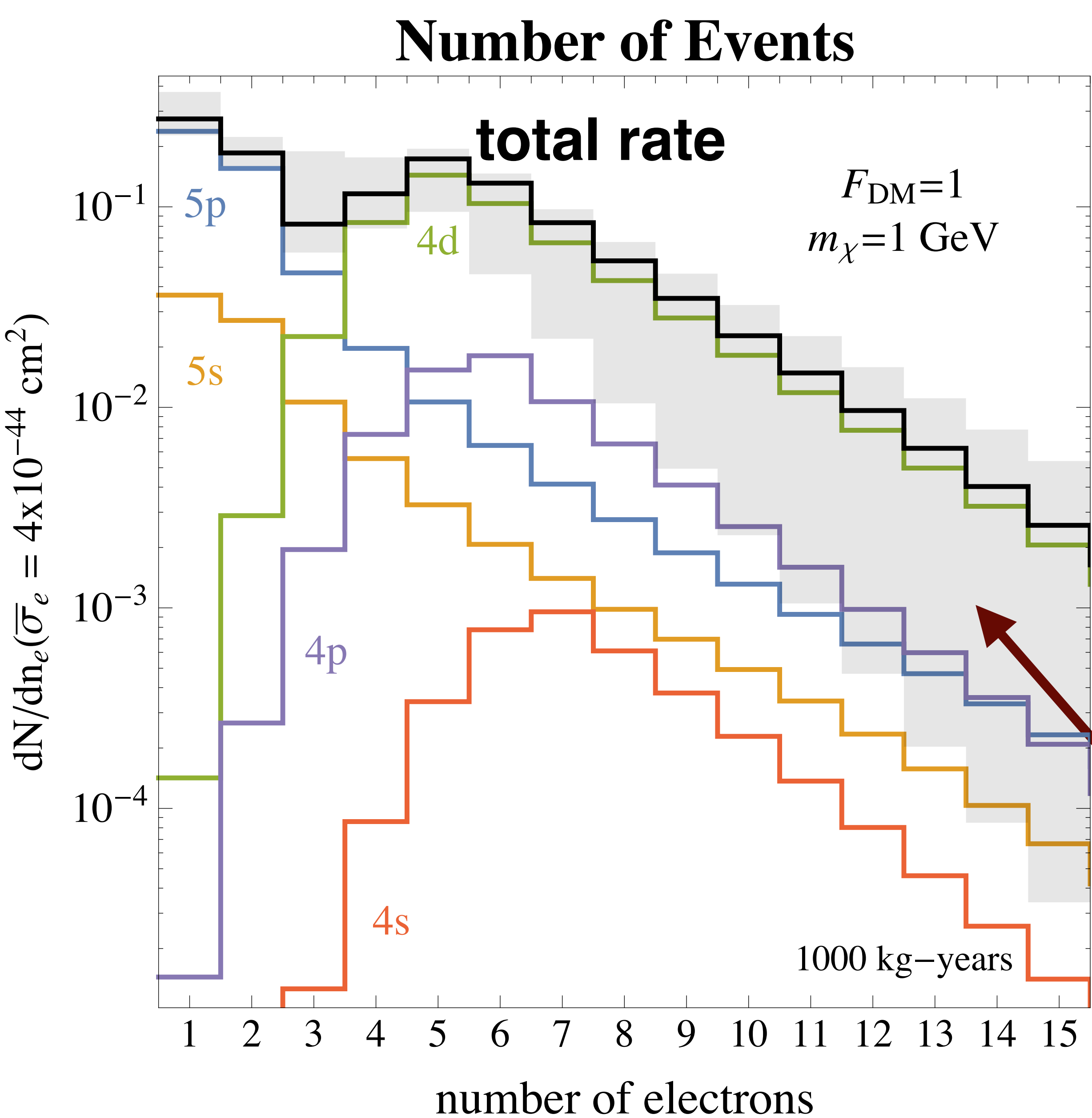
54: Xenon




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

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

# XENON

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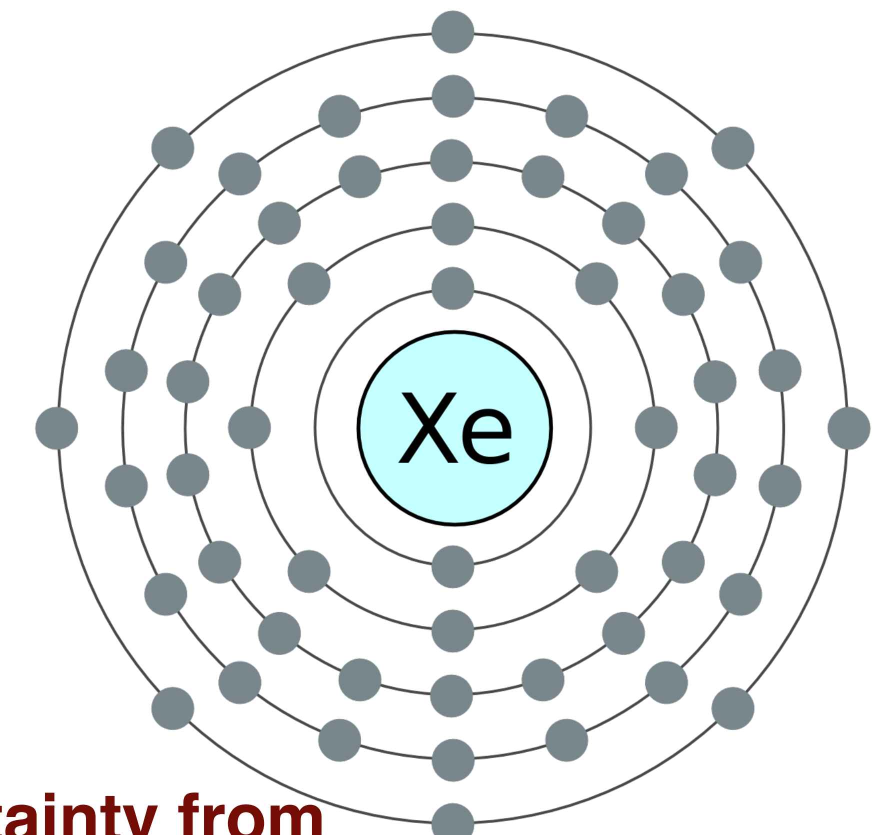
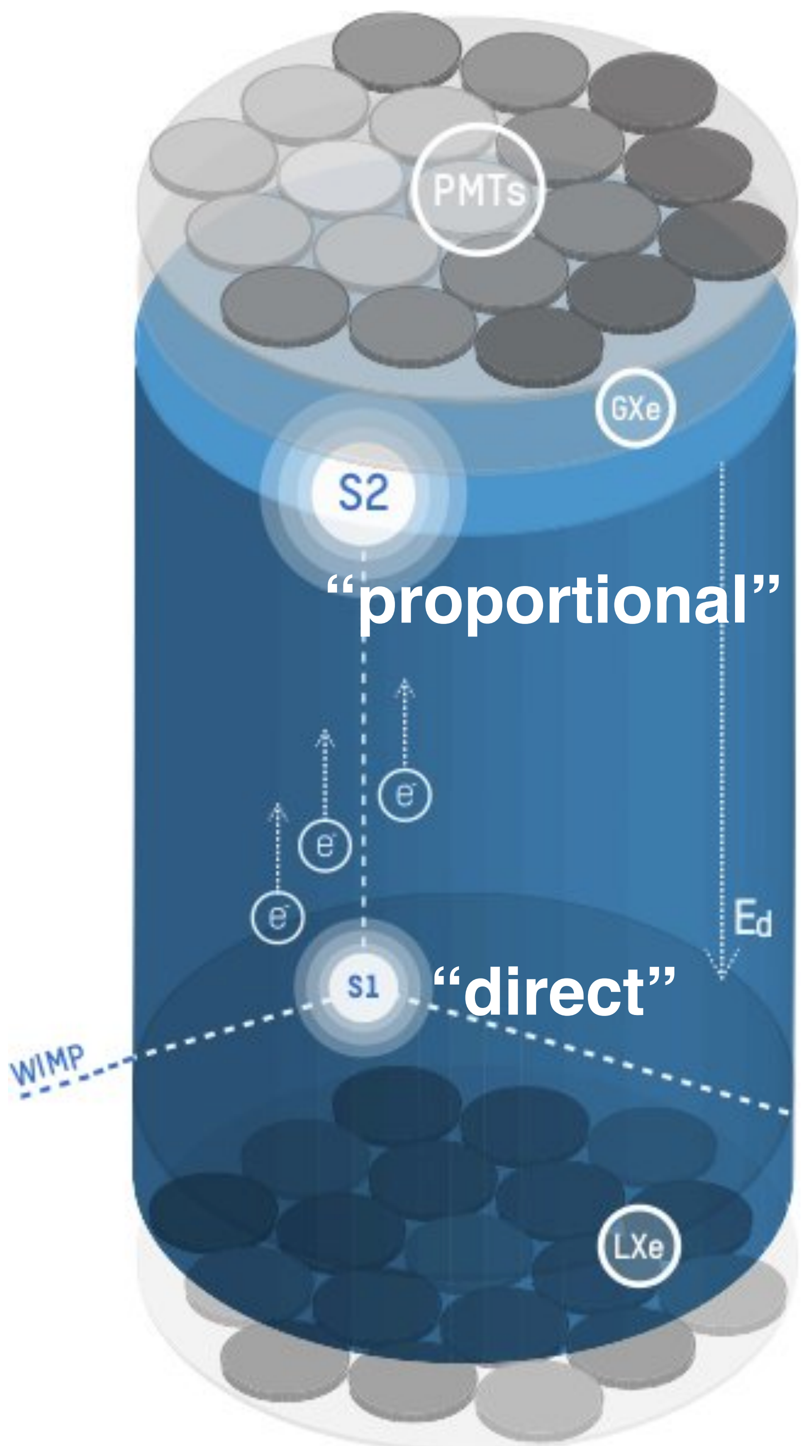



**uncertainty from secondary ionization modeling**

**Essig, Volansky, TTY [1703.00910]**

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

# a XENON detector




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

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

**DM-electron scattering**

**=**

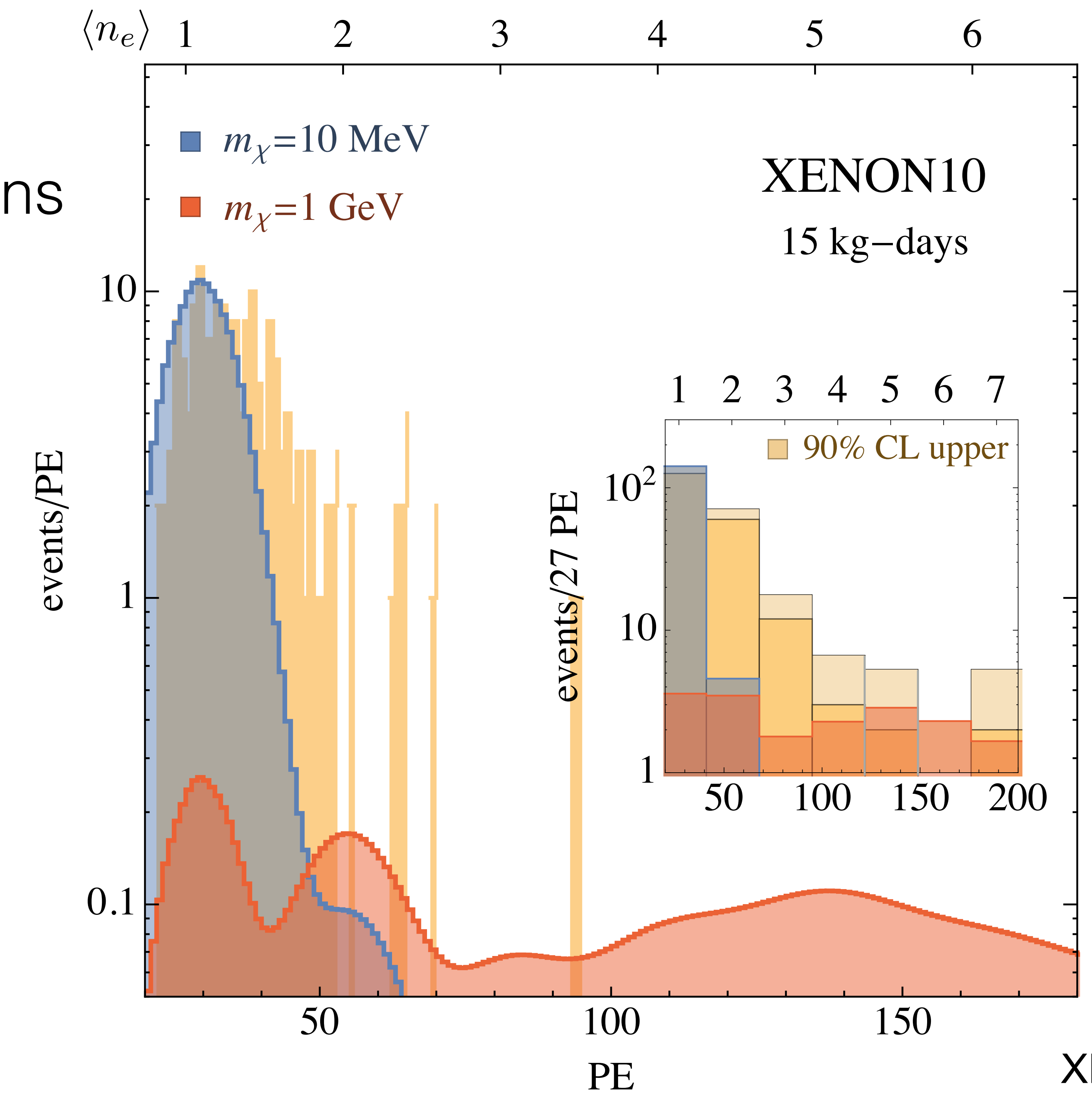
**S2 only signal**

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

*can also do this with LAr detectors like DarkSide

# XENON10

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

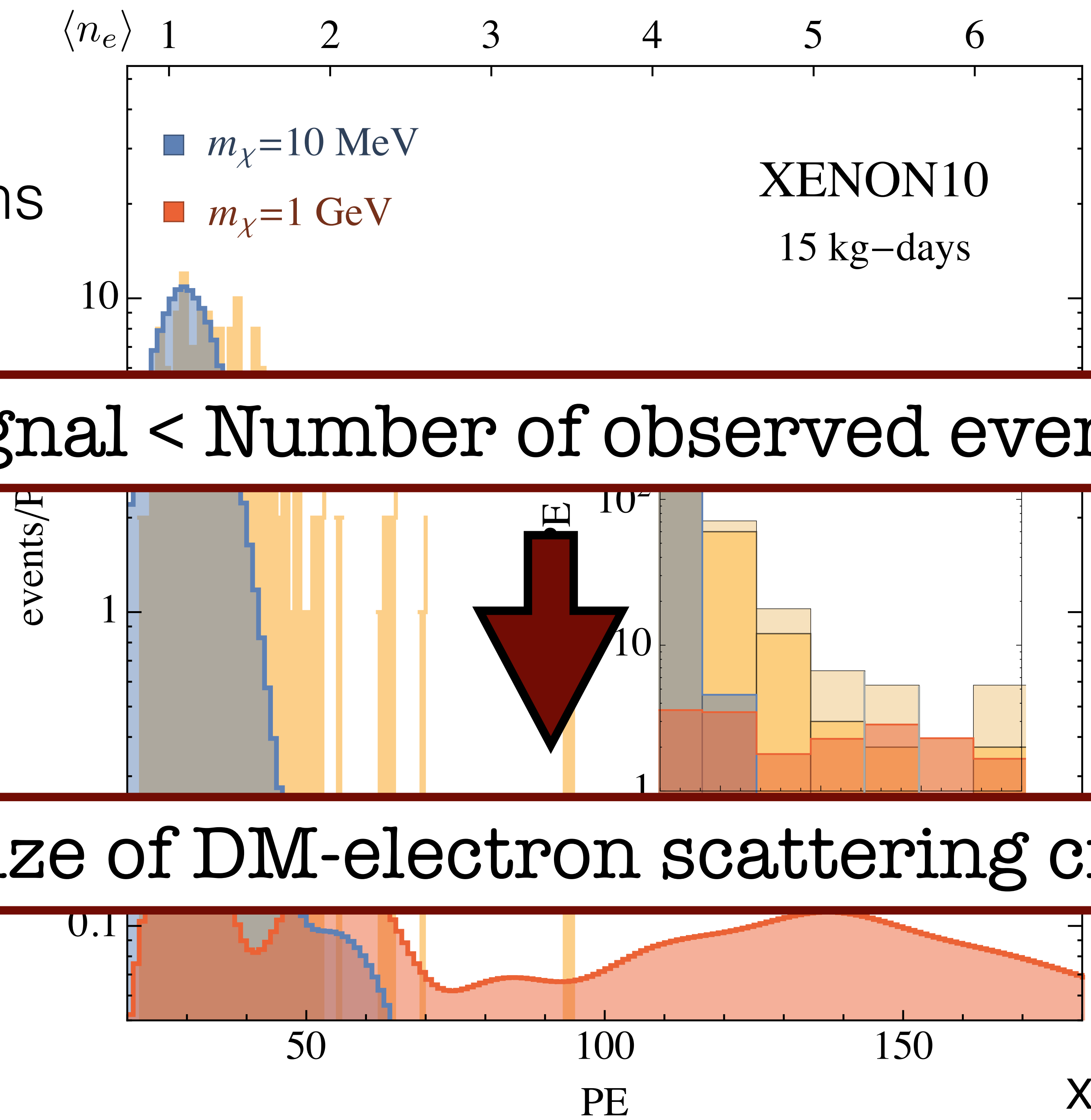



XENON10 Collaboration
Phys.Rev.Lett. **110** (2013) 249901

**Essig, Volansky, TTY [1703.00910]**

# XENON10

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



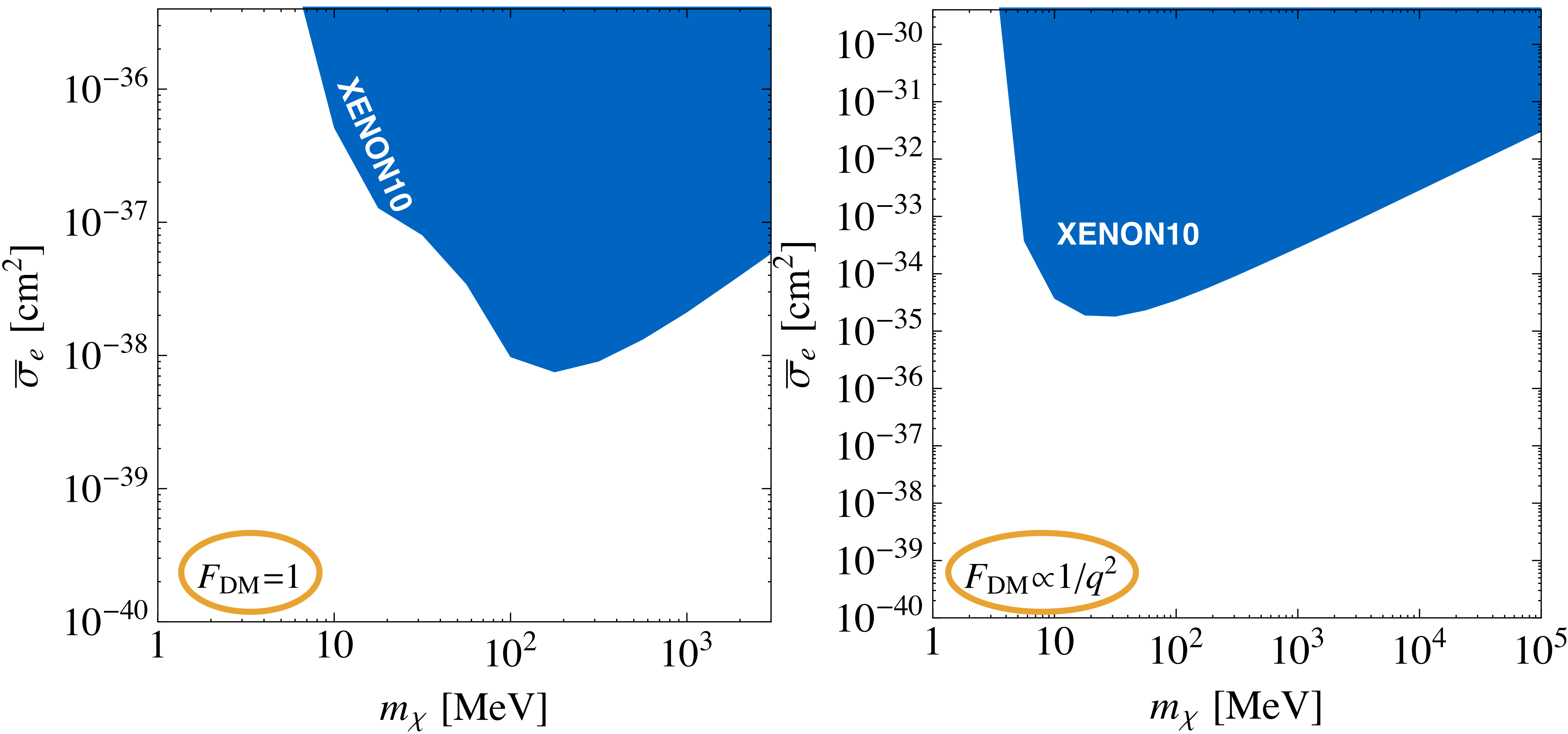

signal < Number of observed events

constrain size of DM-electron scattering cross-section

**Essig, Volansky, TTY [1703.00910]**

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

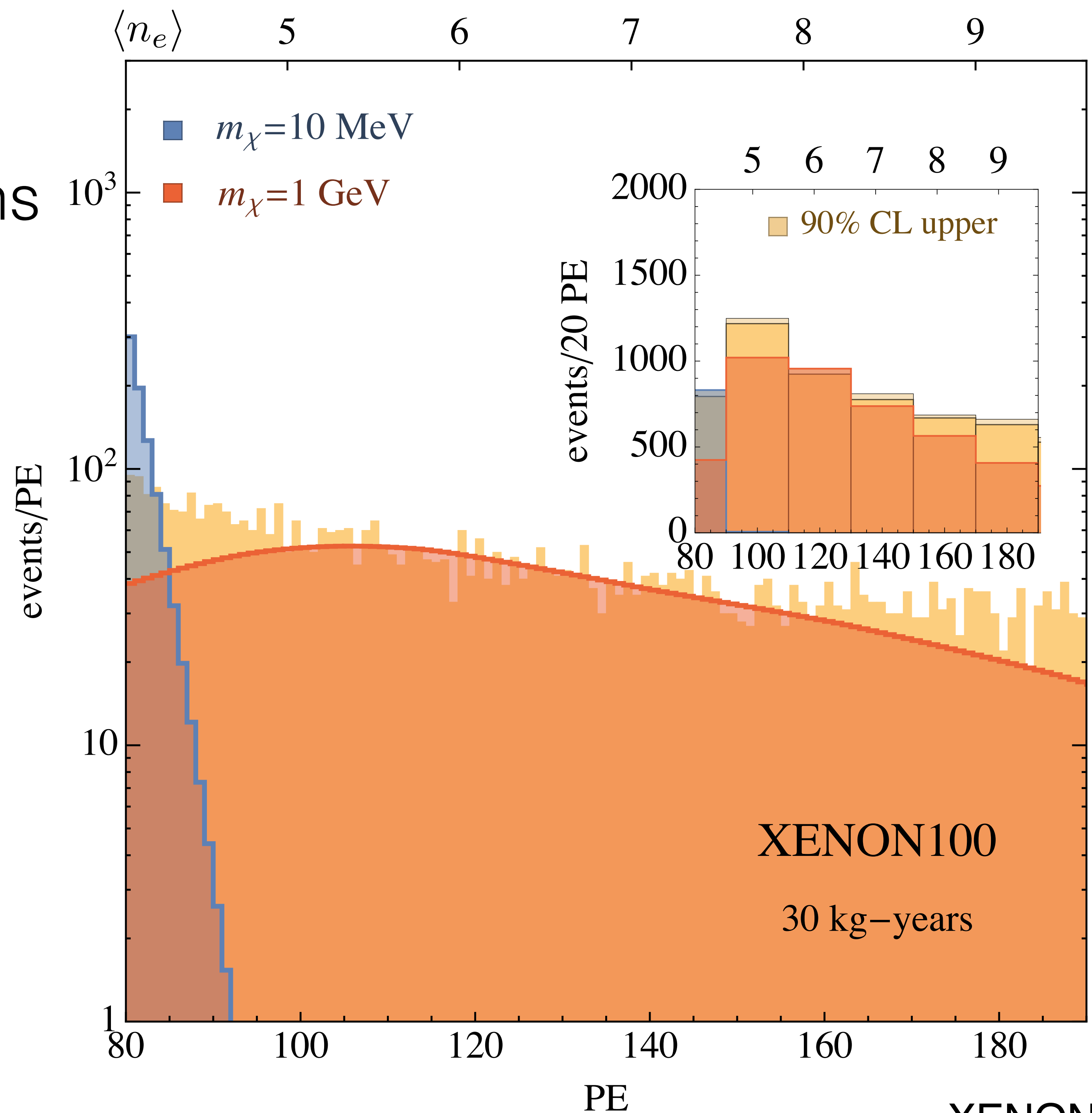
# XENON




**Essig, Volansky, TTY [1703.00910]**

# XENON100

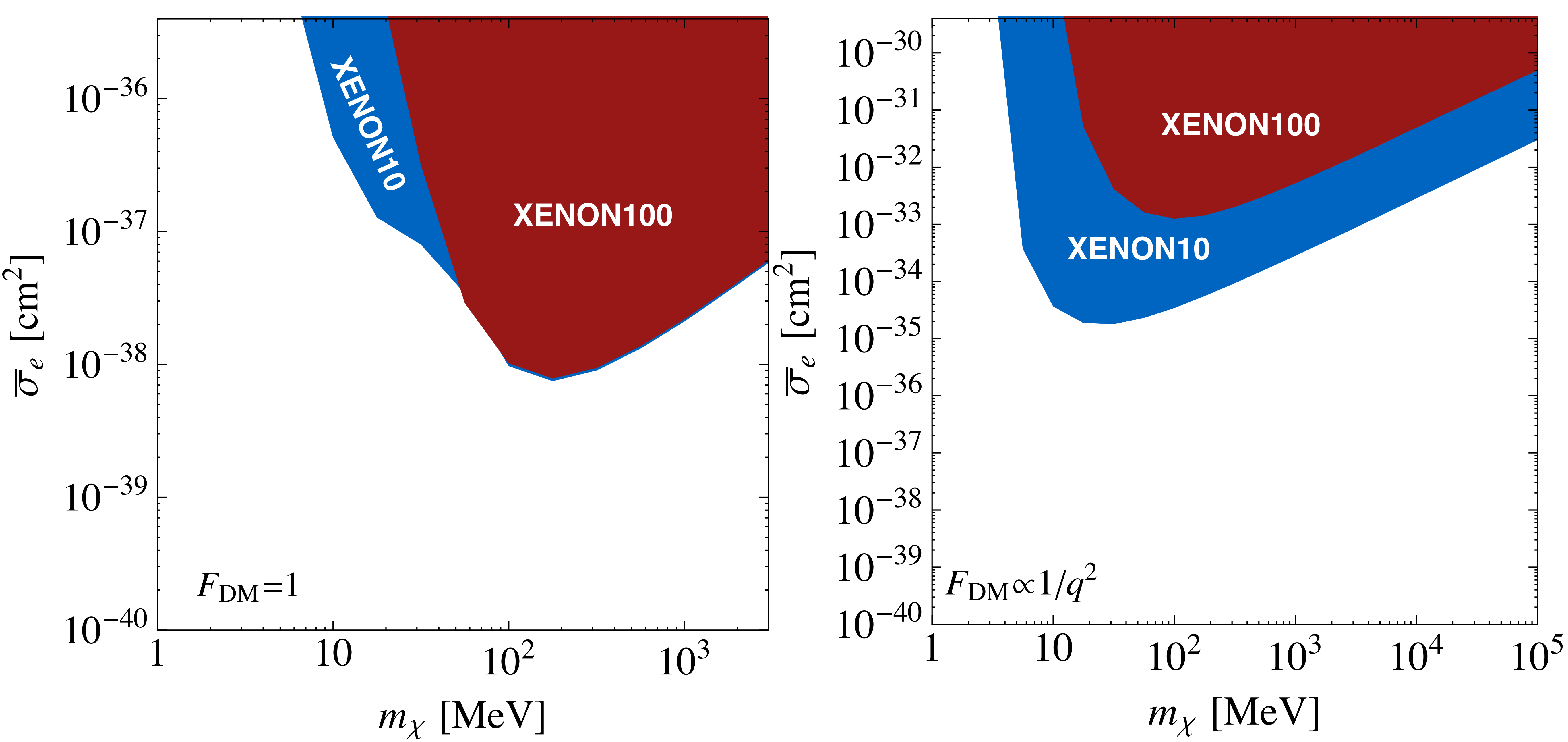
1 electron =
20 **P**hoto**E**lectrons




**Essig, Volansky, TTY [1703.00910]**

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

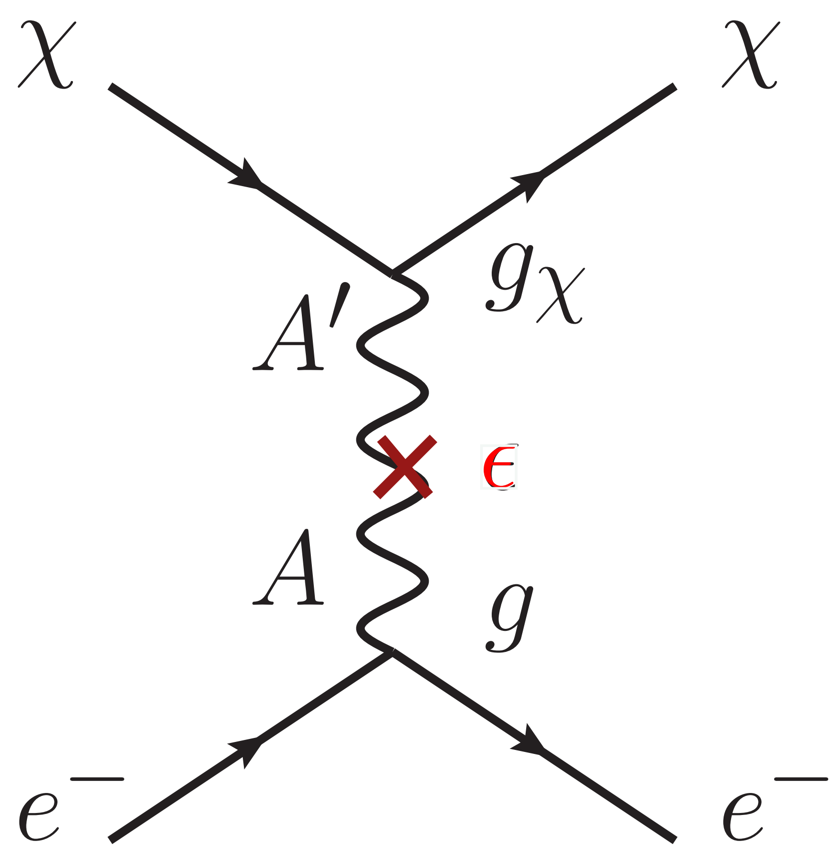
# XENON




**Essig, Volansky, TTY [1703.00910]**

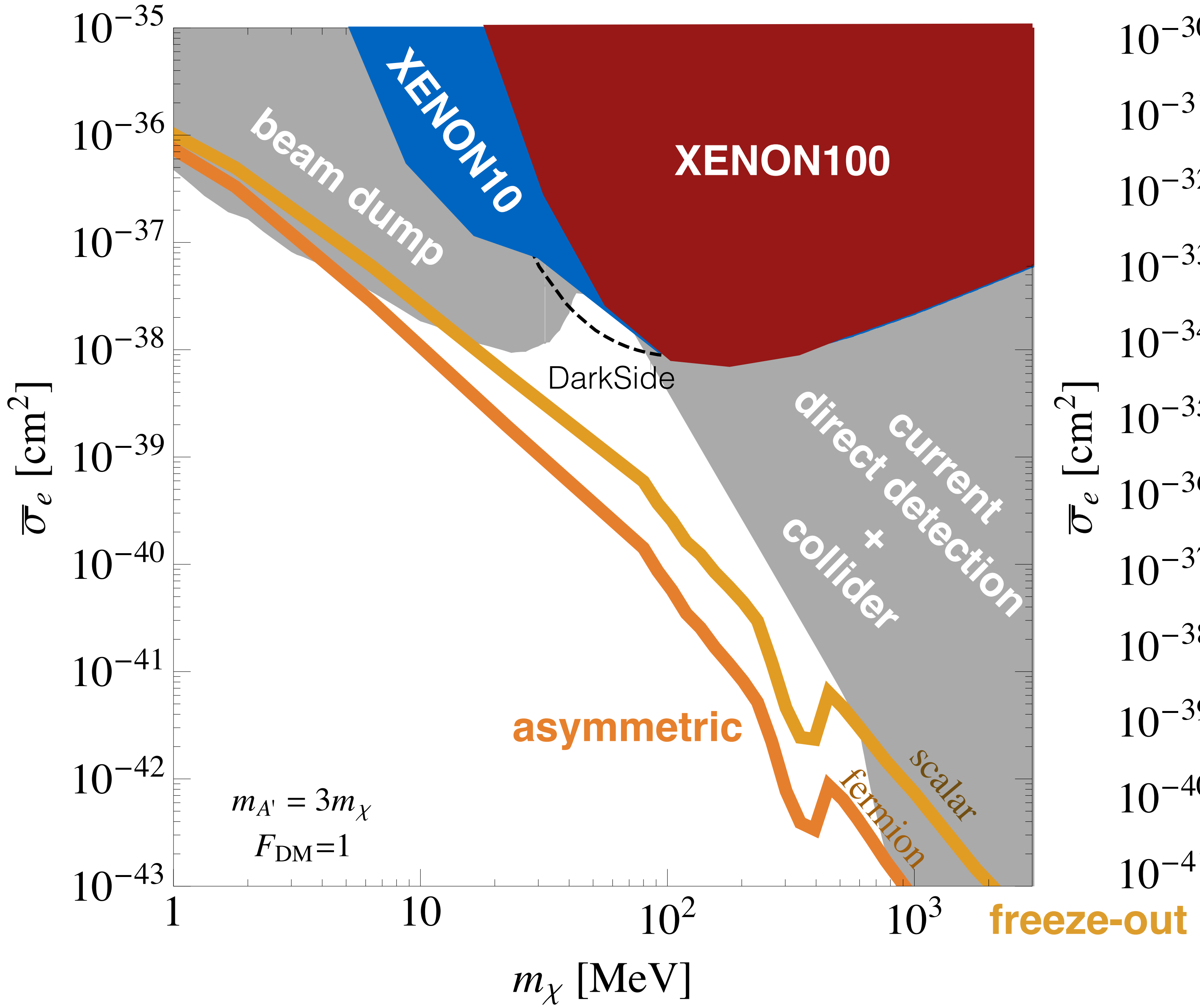
# a model: dark photon

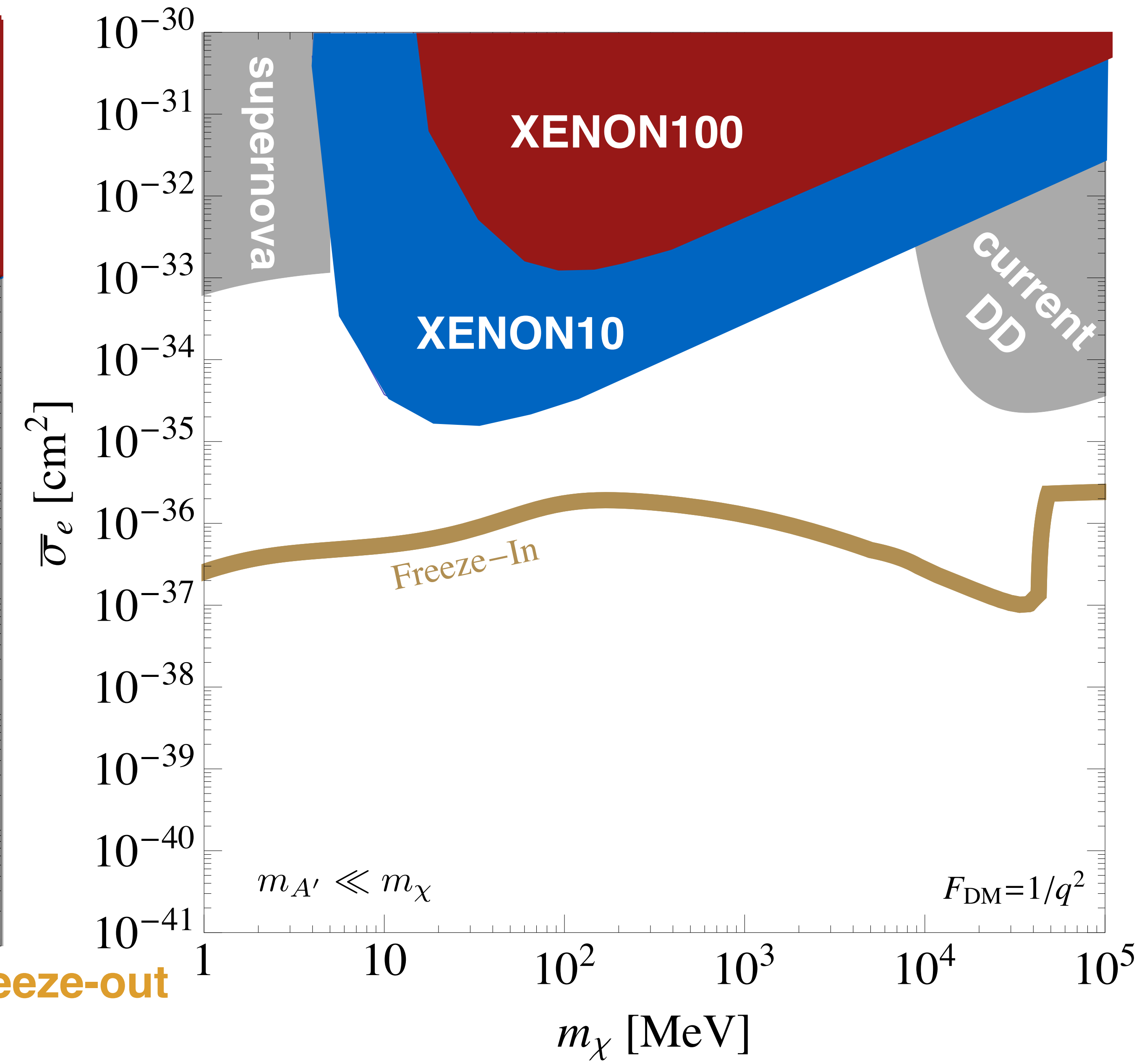
$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^{\mu}A'_{\mu}$$




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

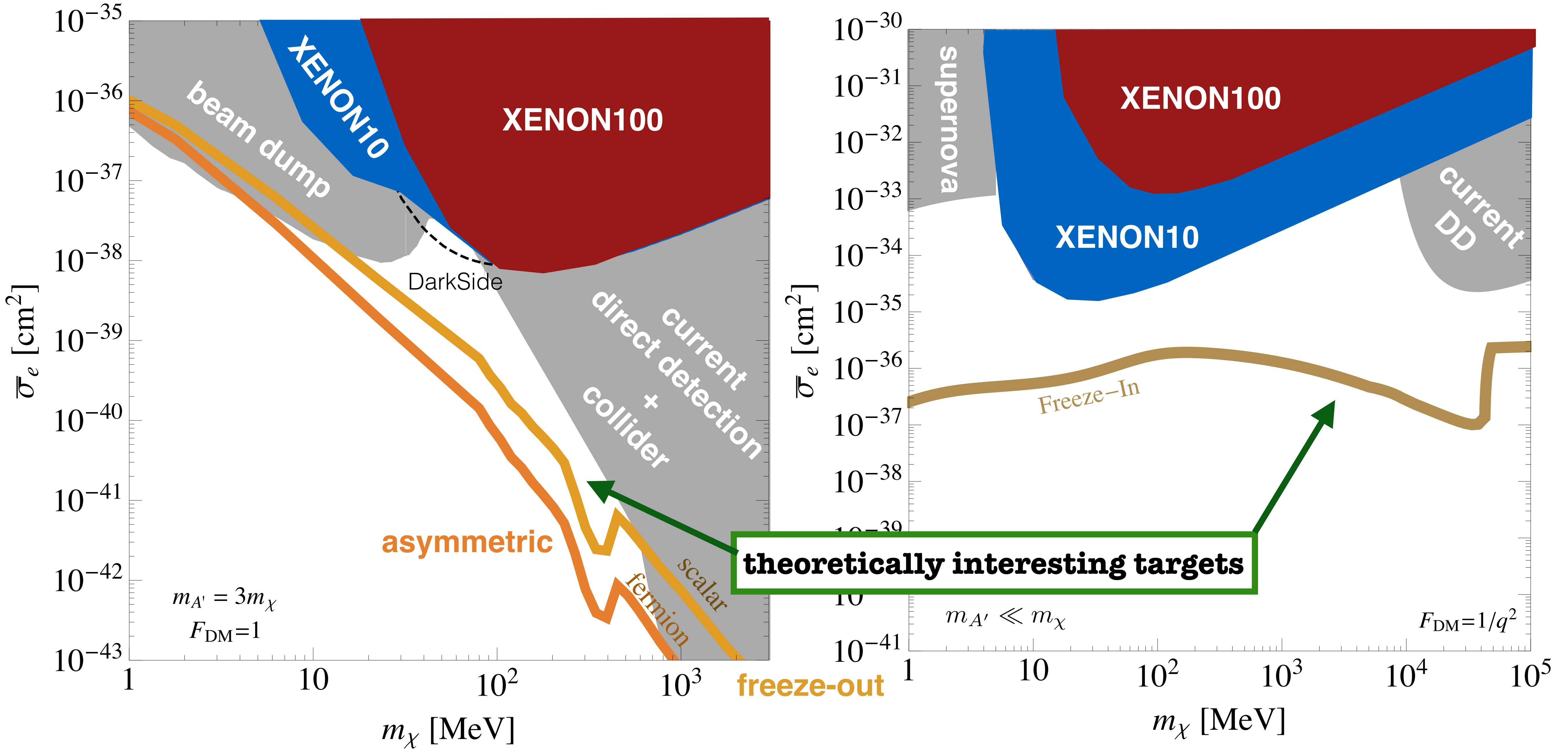
# dark photon




**Essig, Volansky, TTY [1703.00910], DarkSide Collaboration [1802.06998]**

# dark photon




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

# challenges

- detector specific backgrounds
  - $e^-$ gets trapped in liquid-gas interface and is later released
- ionization energy (12.1 eV) limits DM mass reach to few MeV

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  - $e^-$ gets t liquid-gas interface and is later re
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have different detector setup

# challenges

- detector specific backgro
  - $e^-$ gets t... iquid-gas interface ... is later re...
- ionization energy ... ass reach to few MeV

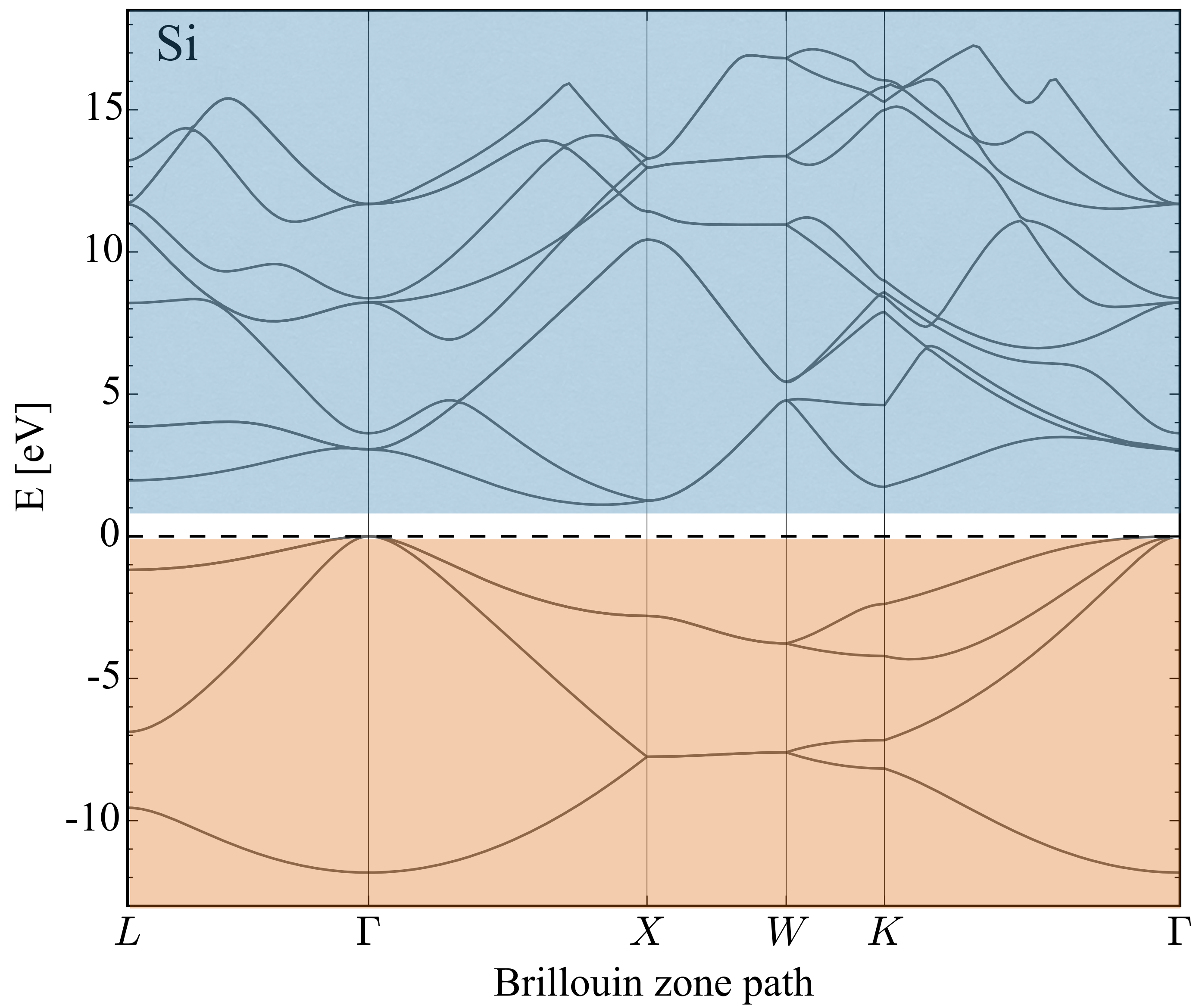
have different detector setup

find a material with smaller ionization energy

# electron energy

- noble gases: $\Delta E_e \sim 10 \text{ eV}$
- semiconductors: $\Delta E_e \sim 1 \text{ eV}$

# semiconductor targets




empty conduction band

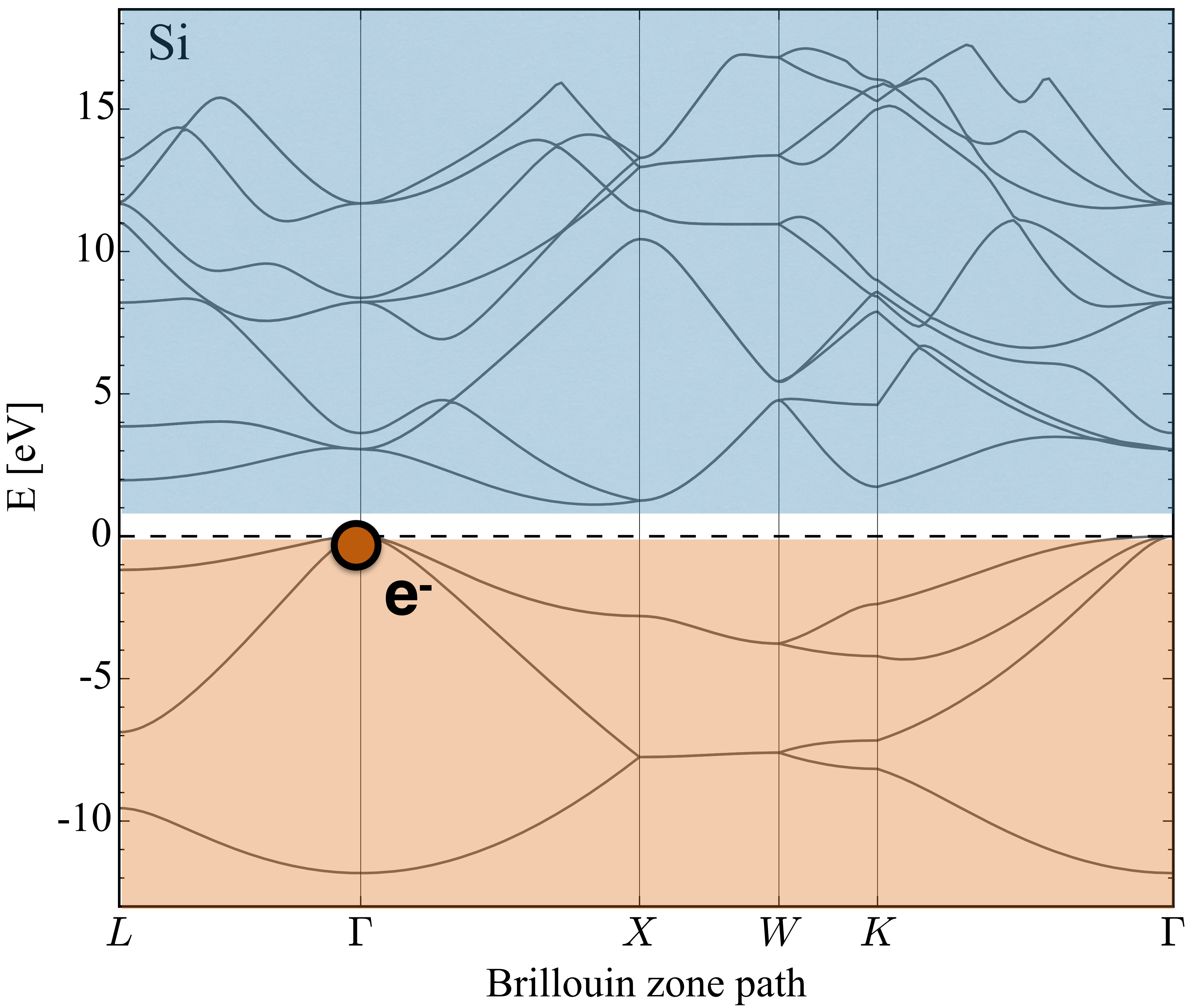
band gap

filled valence band

**Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598] JHEP 1605 (2016) 046**

**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**

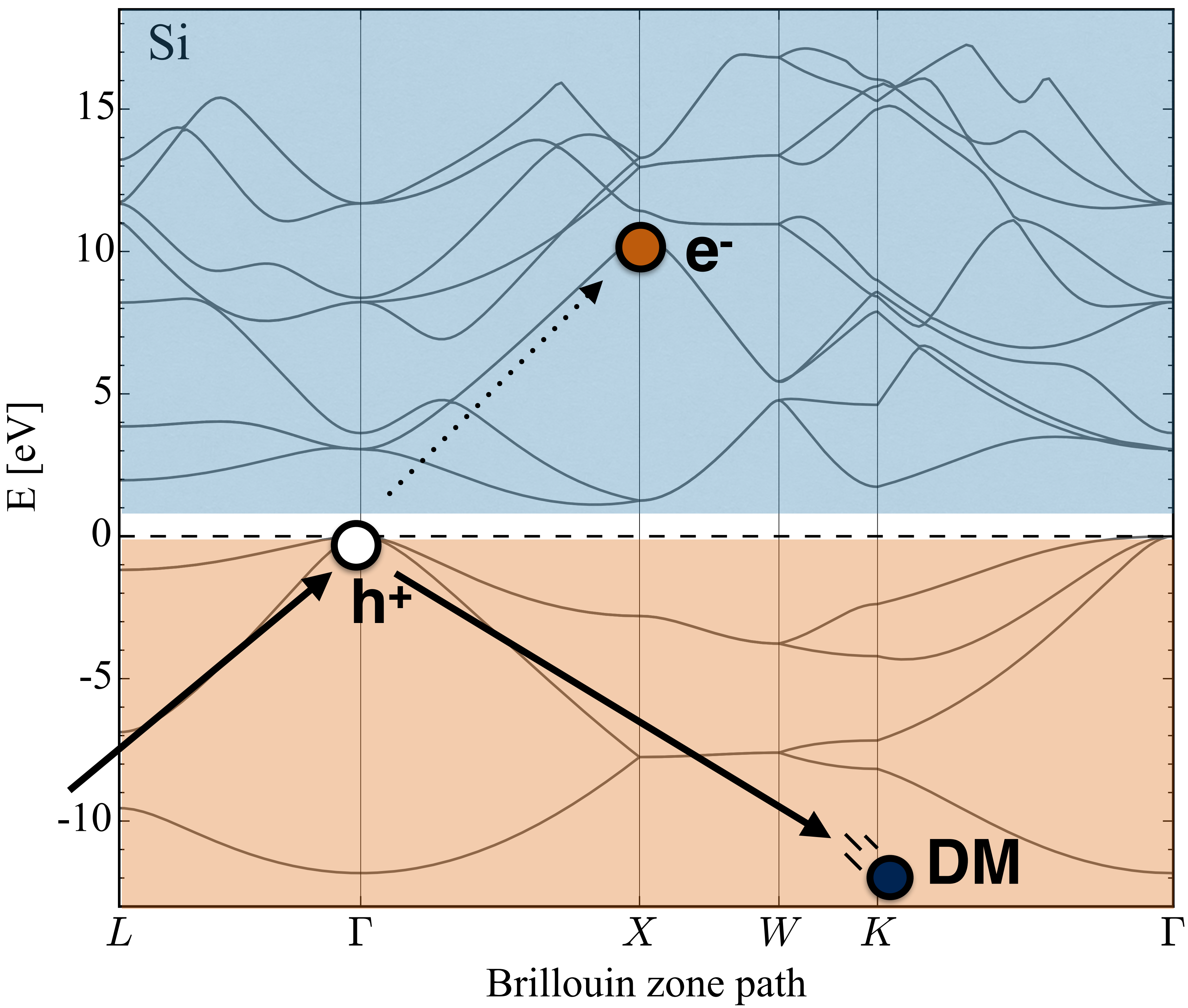
# semiconductor targets




**band gap [eV]**

| | |
|---|---|
| Ge | 0.67 |
| Si | 1.1 |
| GaAs | 1.5 |
| NaI | 5.9 |
| CsI | 6.4 |

# semiconductor targets

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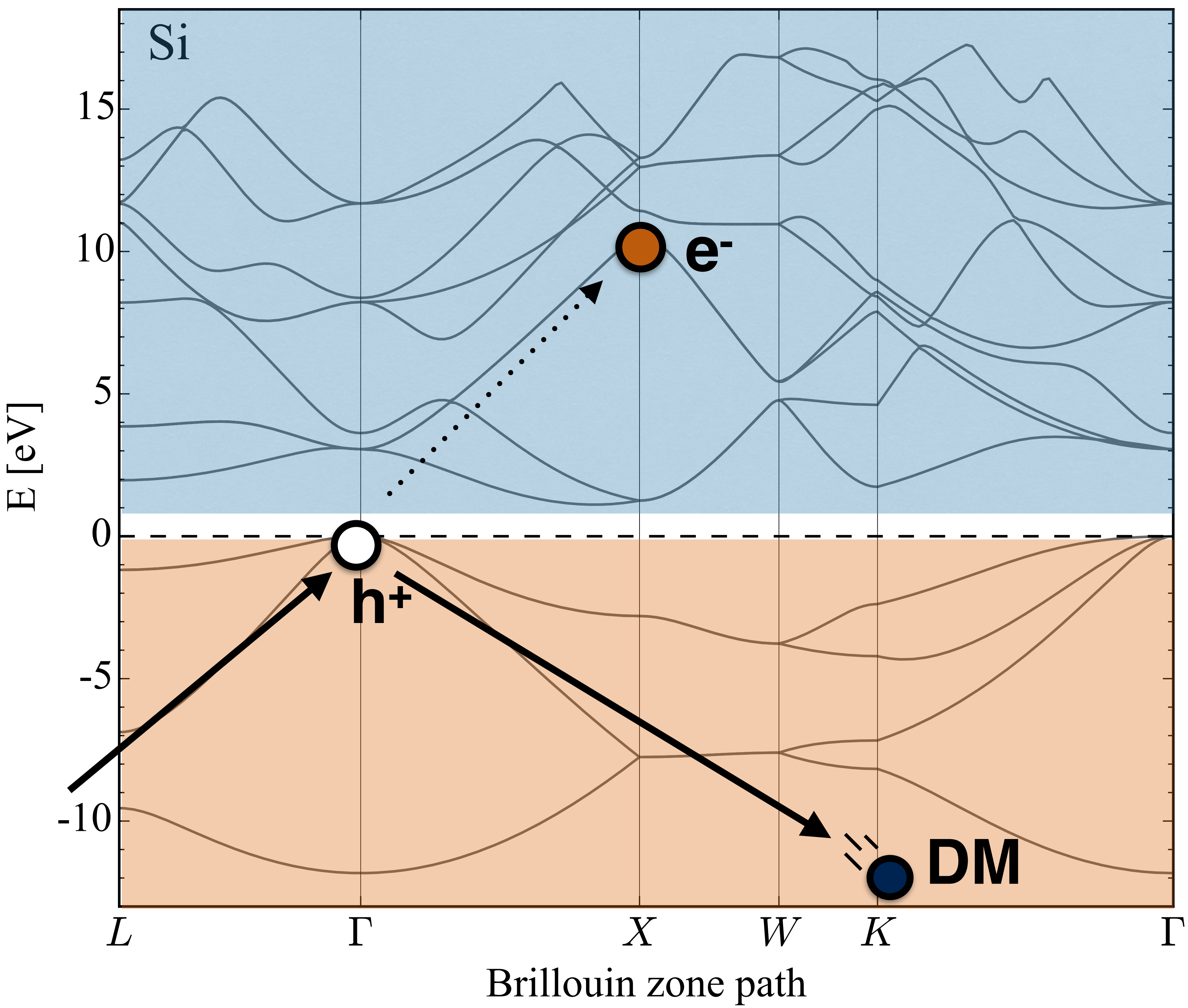
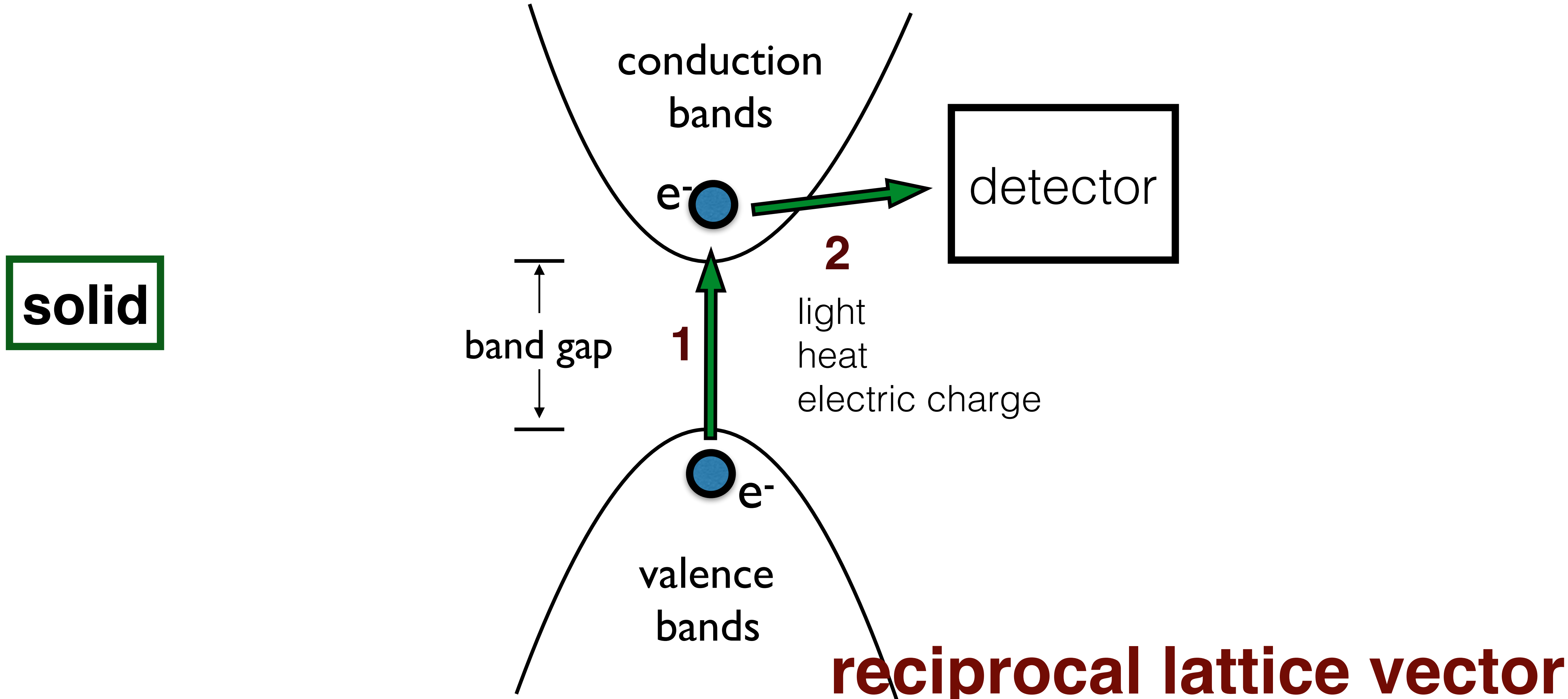



**apply an electric field and extract the electron(s) "ionization"**

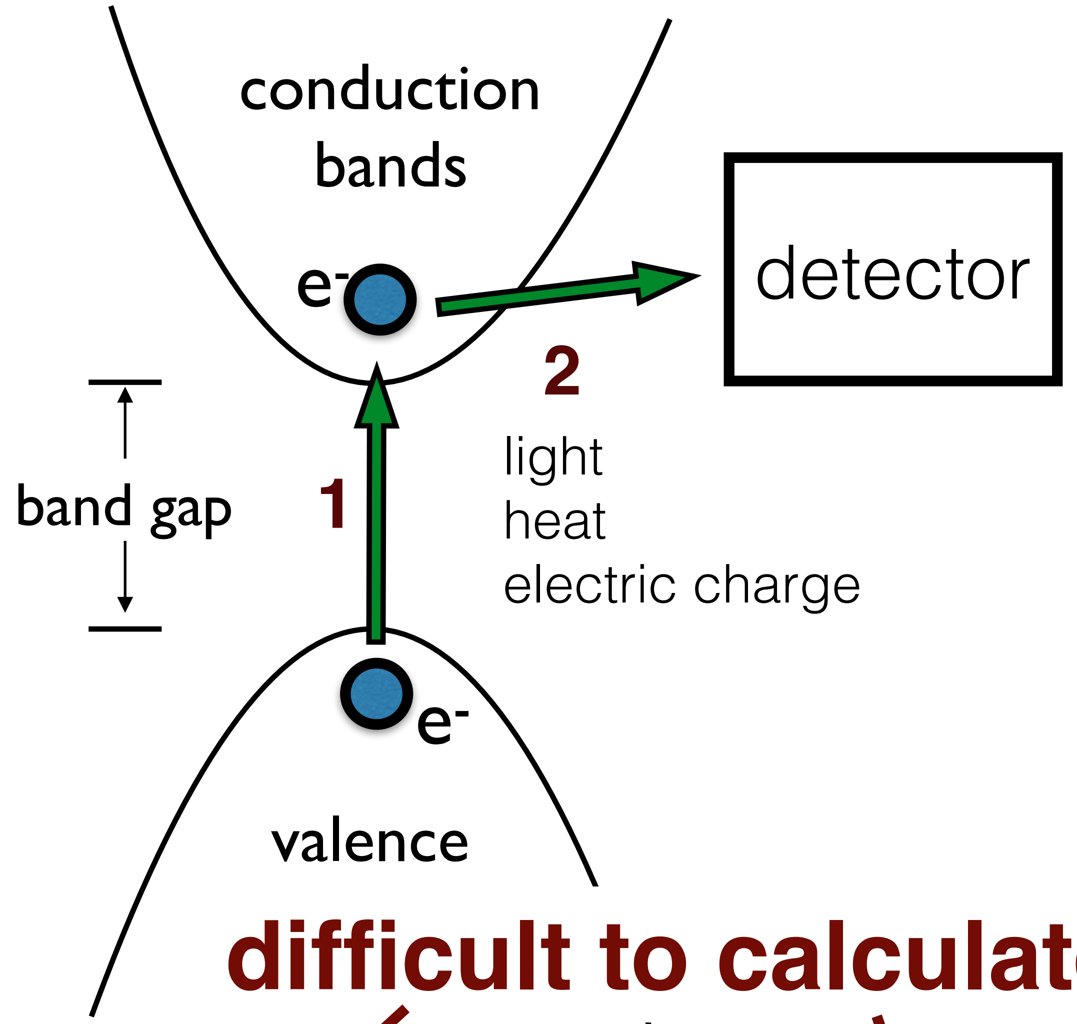
**e-/h+ recombine to produce photon(s) "scintillation"**




$$\left|f_{i\to i'}(\vec{q},\vec{k})\right|^2 = \left|\sum_G \psi^*_{i'}(\vec{k}+\vec{G}+\vec{q})\psi_i(\vec{k}+\vec{G})\right|^2$$

**electrons in a solid are part of a complicated, many-body system**

**solid**




**difficult to calculate these**

$$\left| f_{i \rightarrow i'}(\vec{q}, \vec{k}) \right|^2 = \left| \sum_G \psi^*_{i'}(\vec{k} + \vec{G} + \vec{q}) \psi_i(\vec{k} + \vec{G}) \right|^2$$

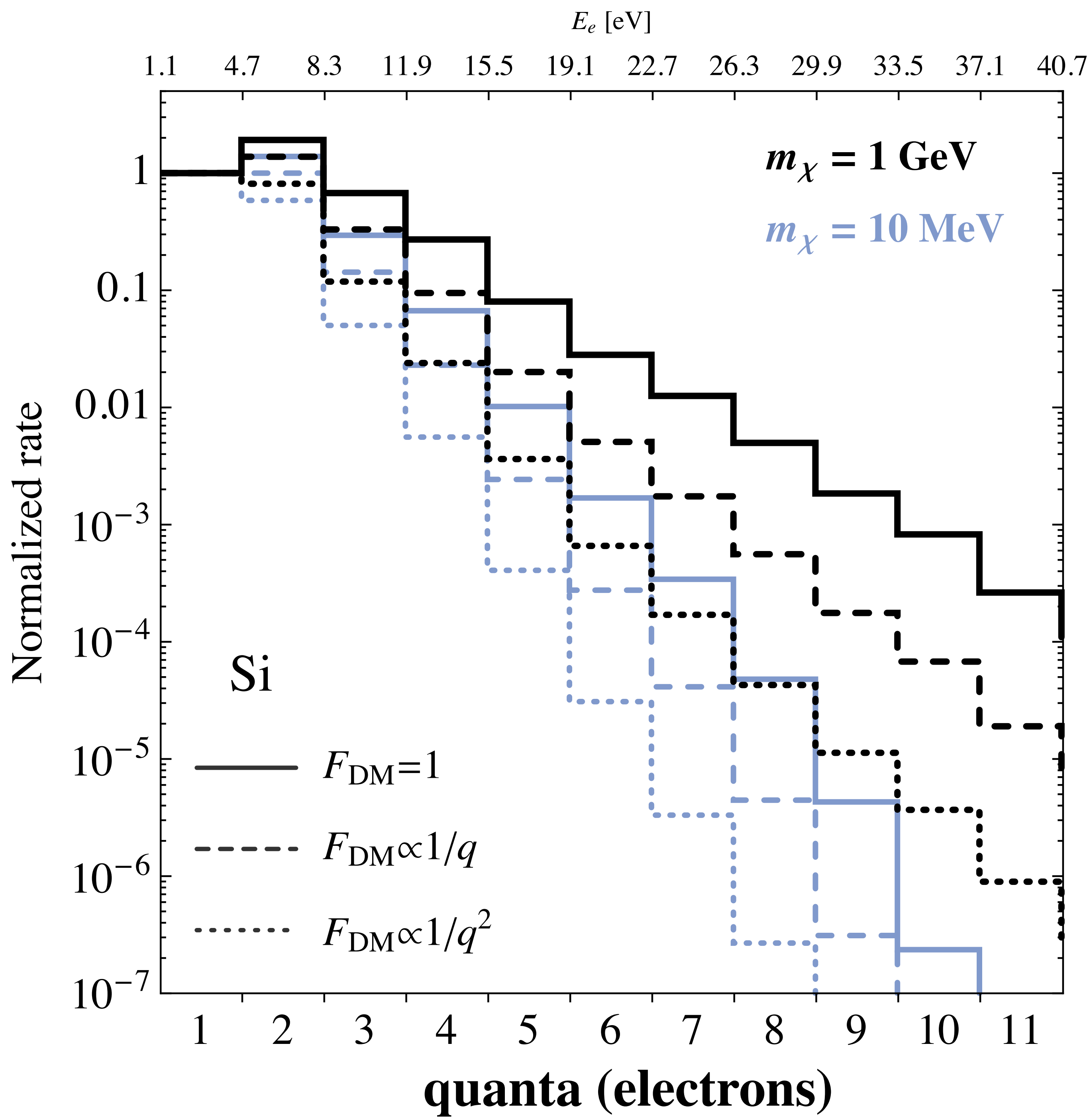
**electrons in a solid are part of a complicated, many-body system**

http://www.quantum-espresso.org/

- open source code for calculating electronic structure
- module QEdark calculates form factor:

http://ddldm.physics.sunysb.edu/

# threshold dependence




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

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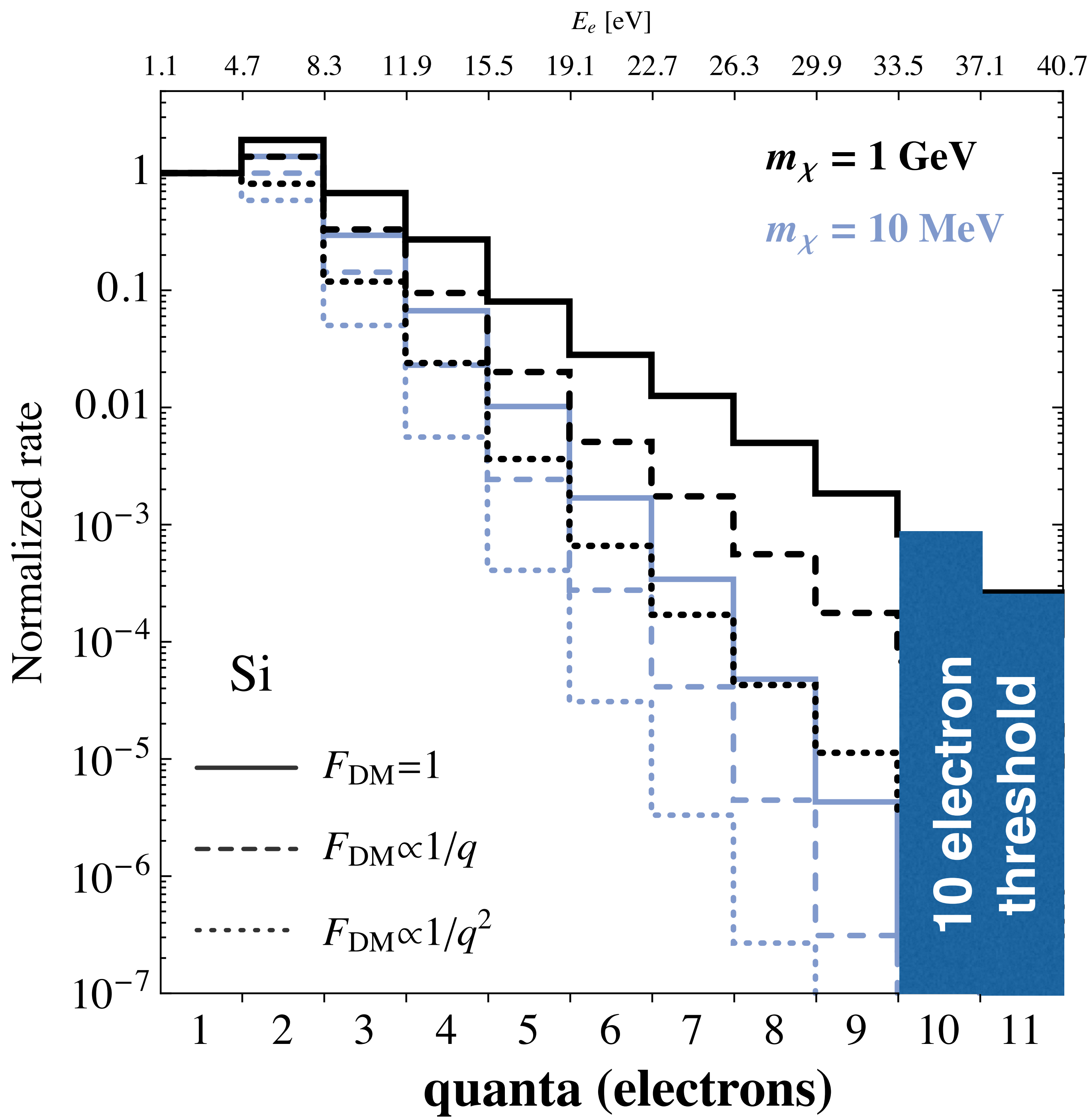


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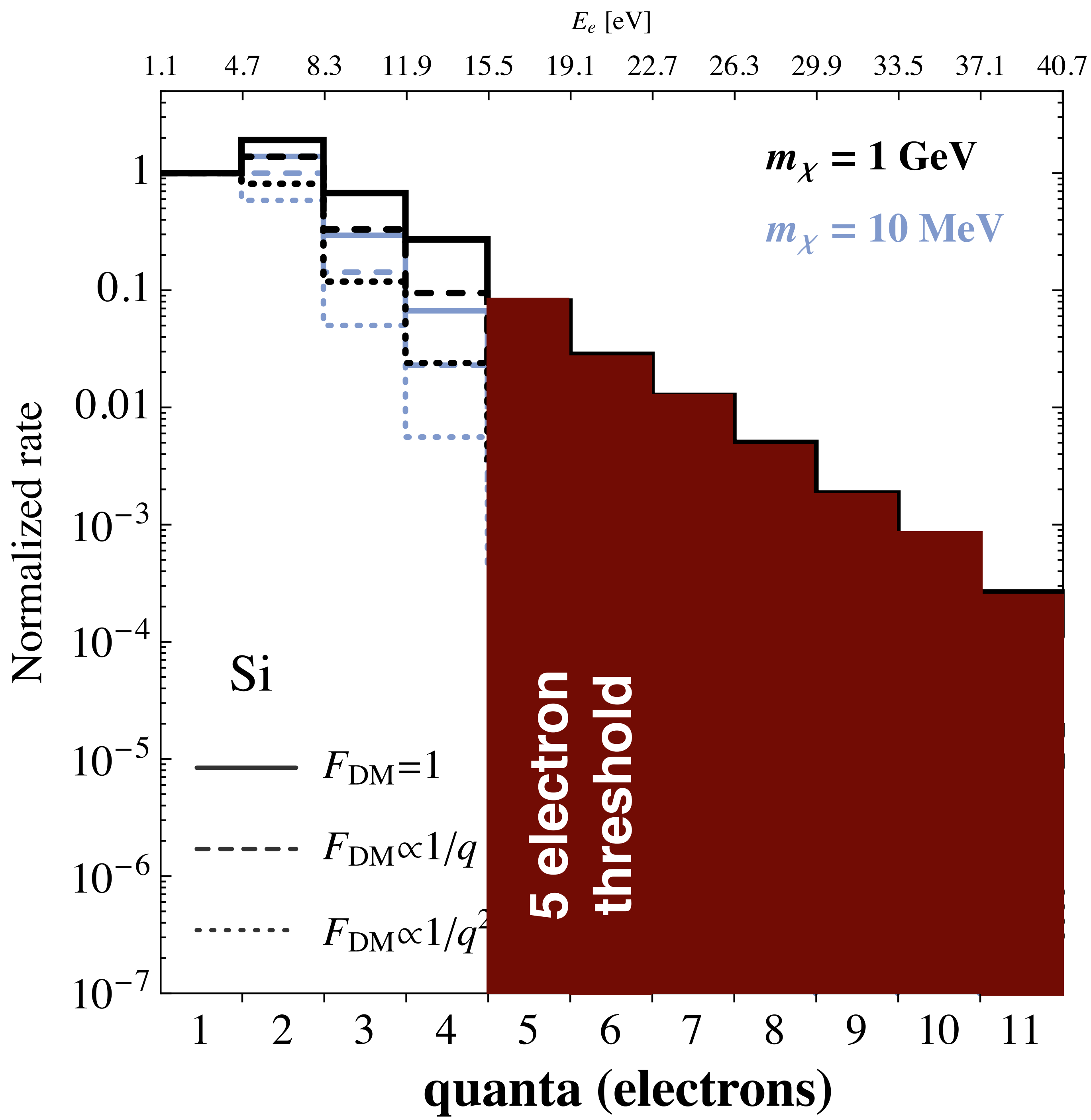


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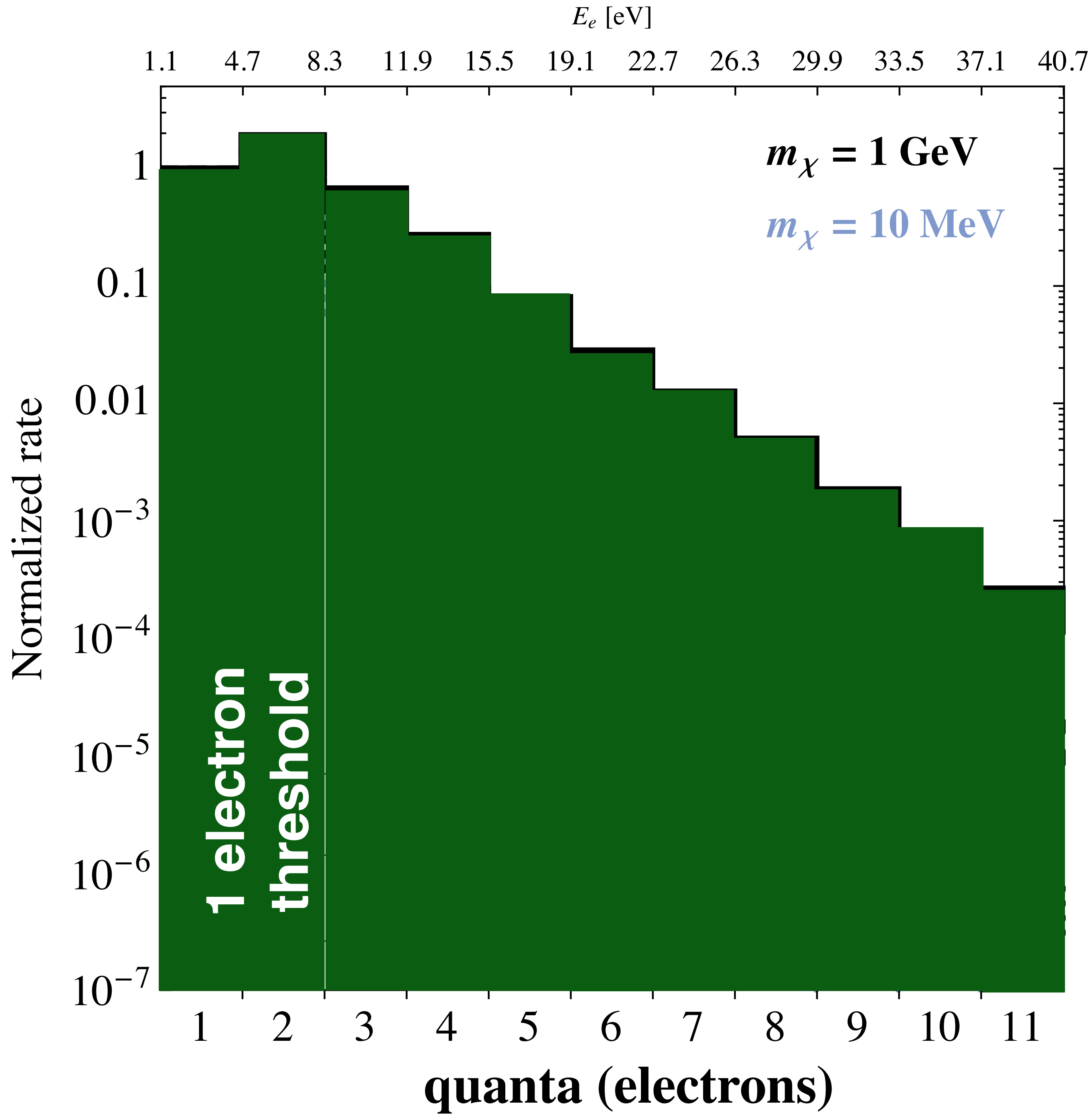


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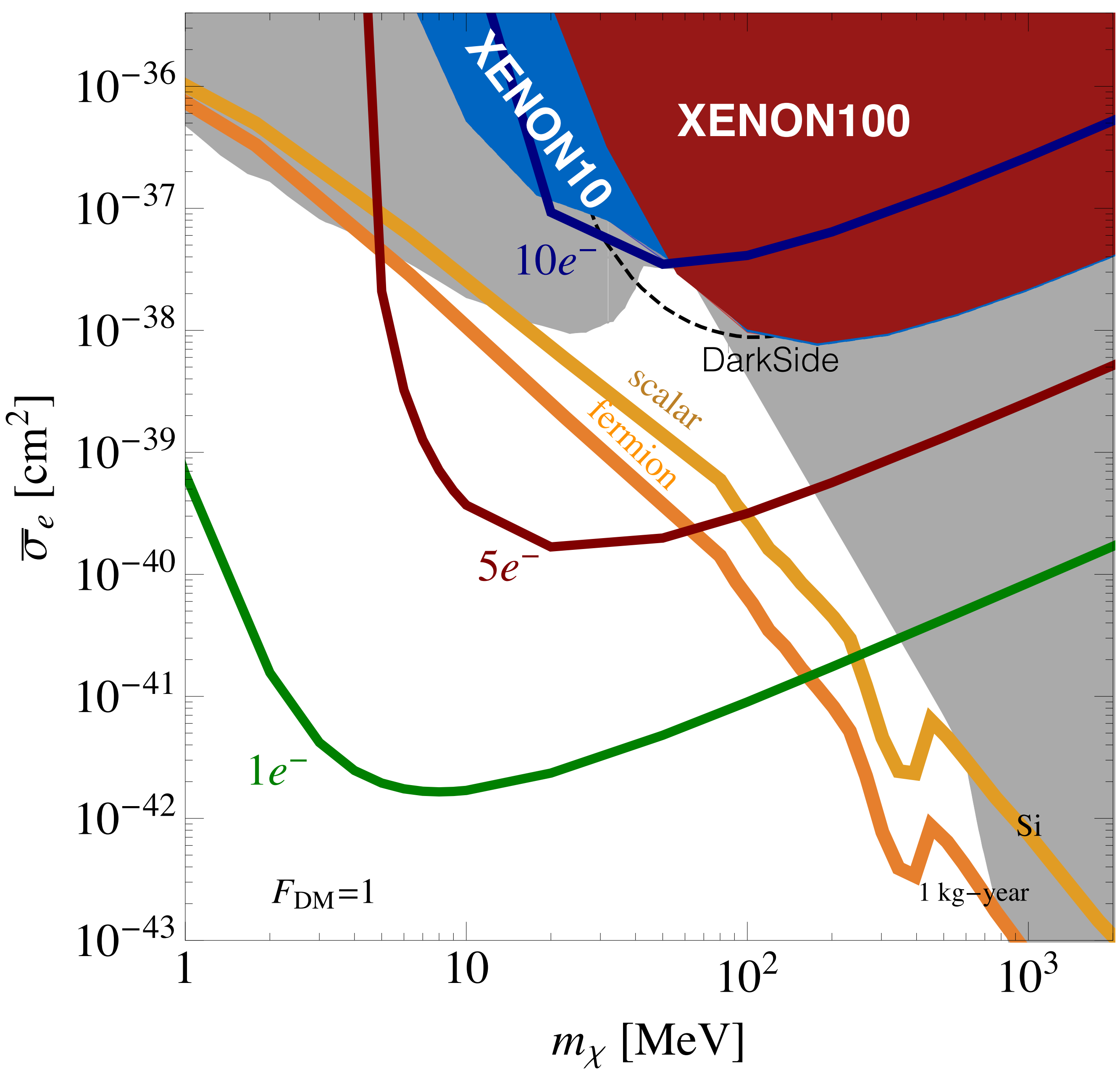


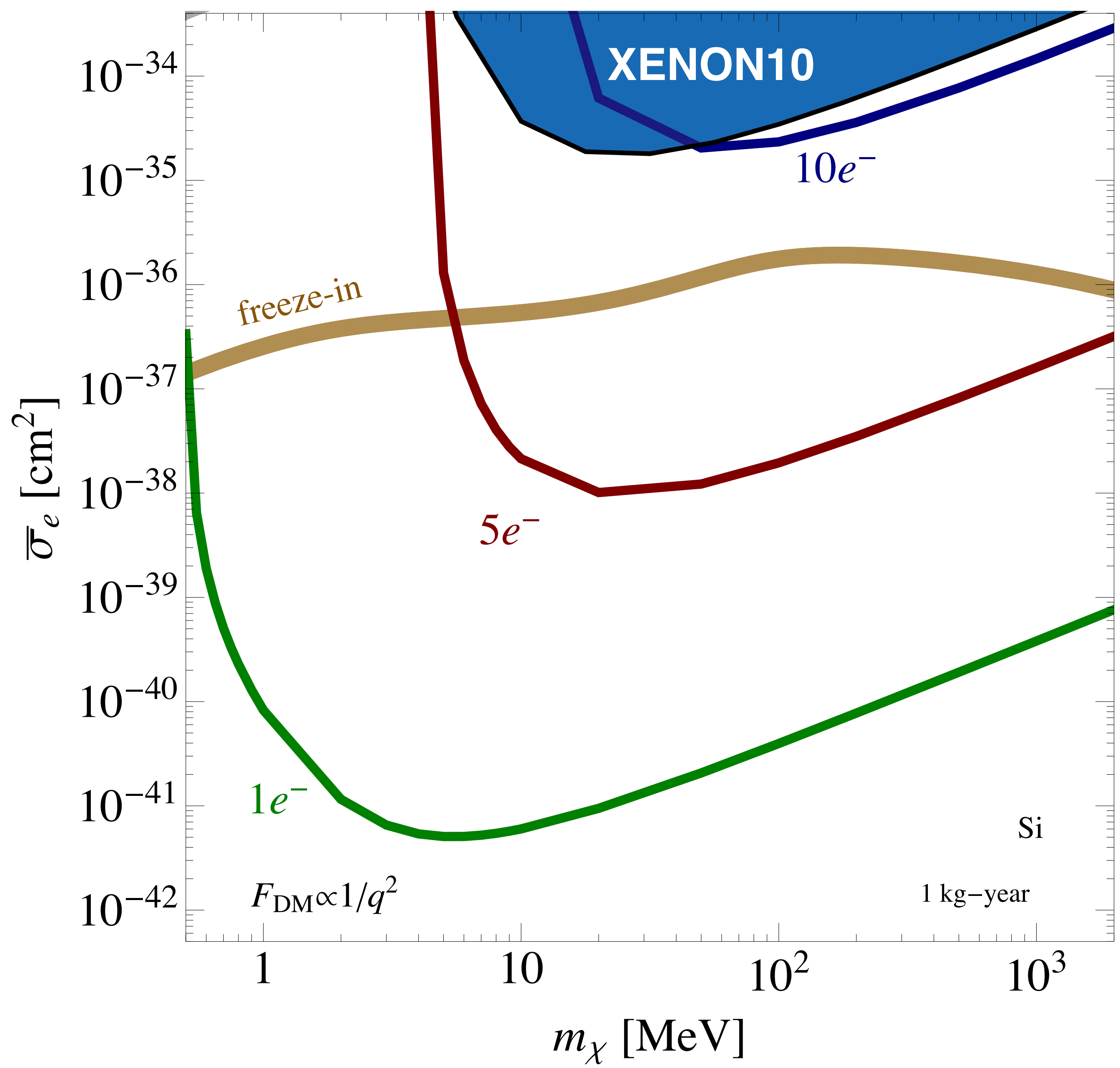


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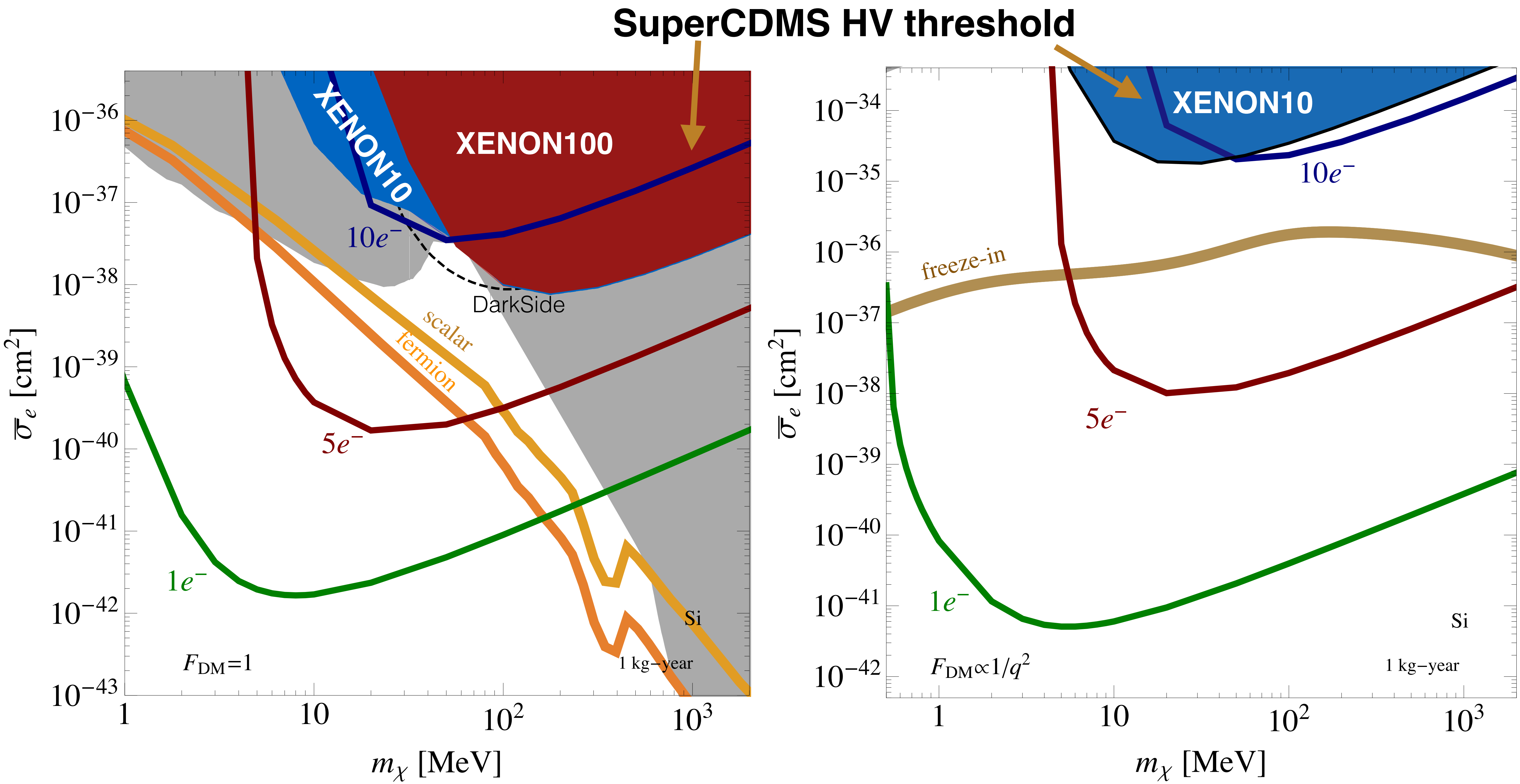


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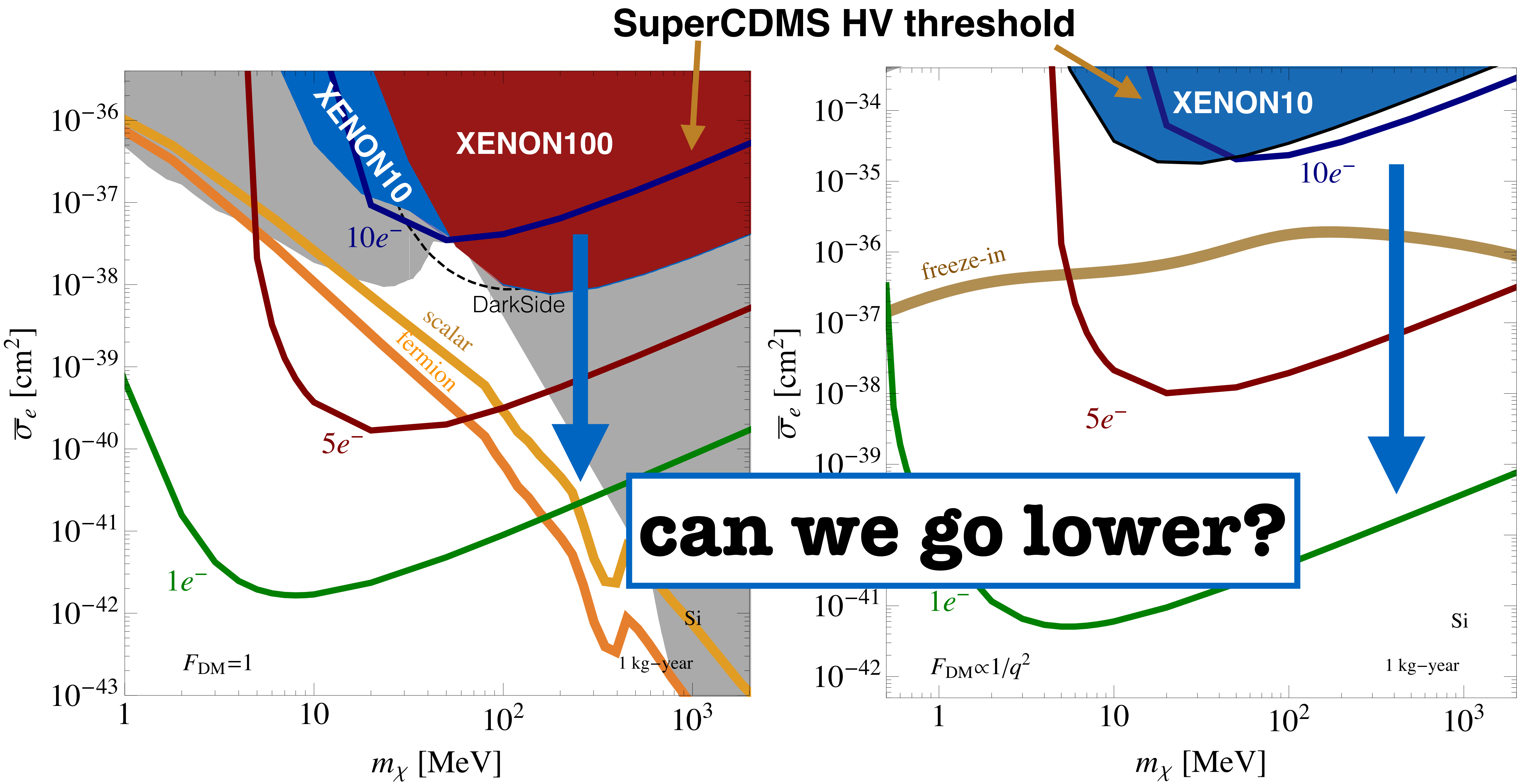



Essig, Fernandez-Serra, Mardon, Soto, TTY [1509.01598]

# SENSEI

**S**ub-**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

Comisión Nacional de Energía Atómica

Fermilab

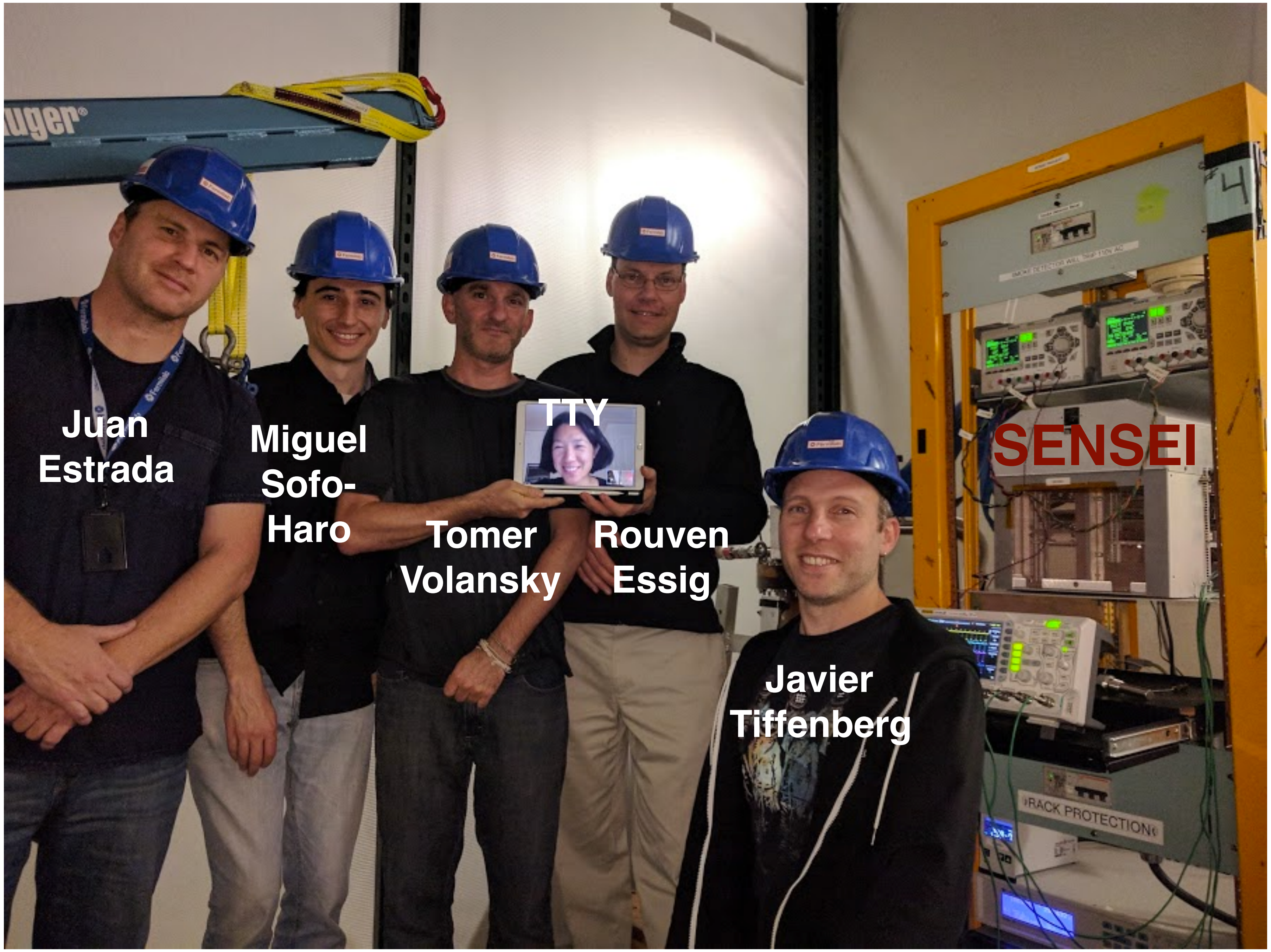
UNIVERSITY OF OREGON

Stony Brook University

TEL AVIV UNIVERSITY

# SENSEI

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



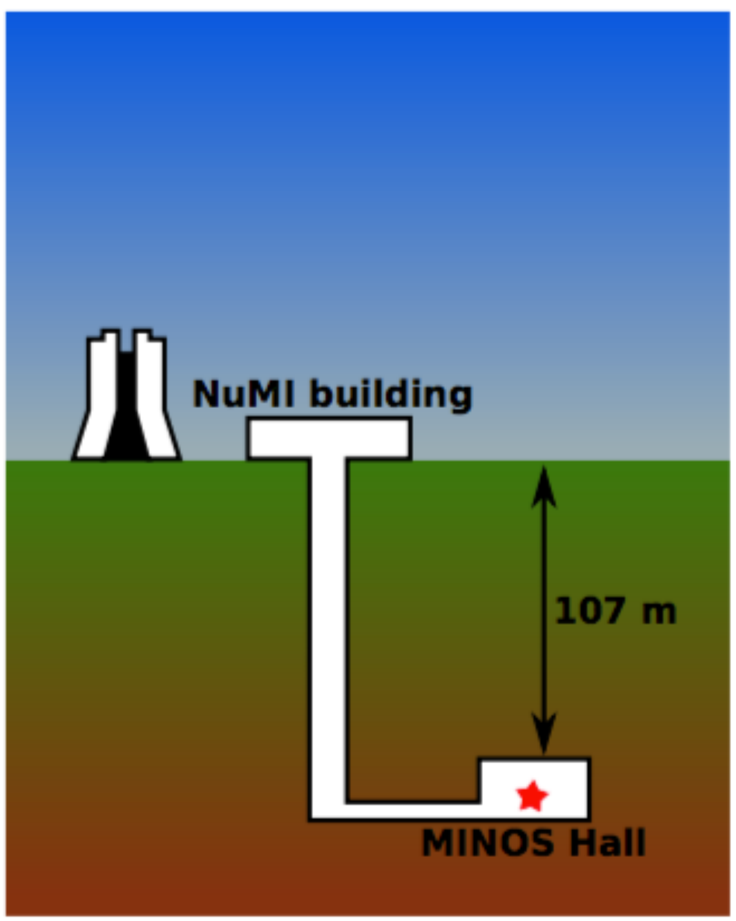

+ **Guillermo Fernandez Moroni**
+ **Michael Crisler**
+ **Erez Etzion**
+ **Liron Barak**
+ **students + postdocs**

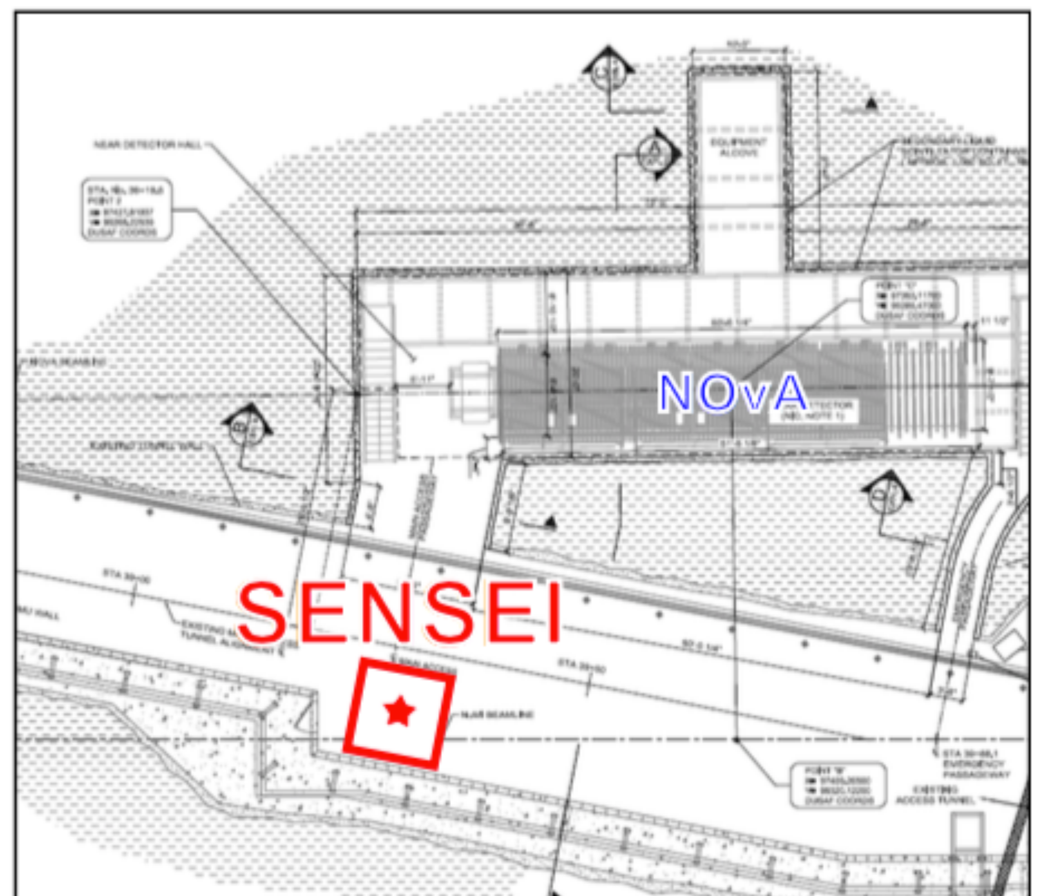
# SENSEI

**S**ub-**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

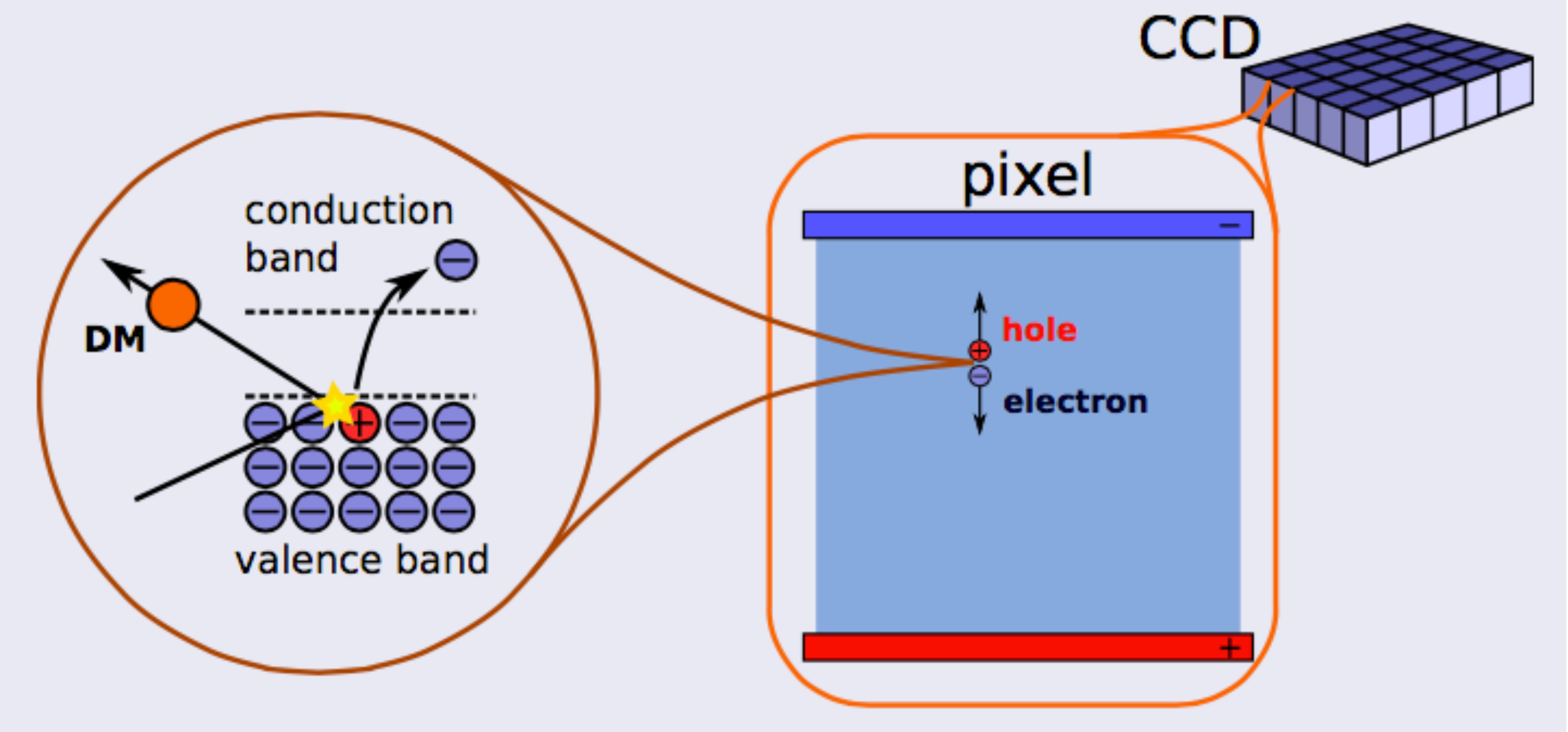





J. Tiffenberg

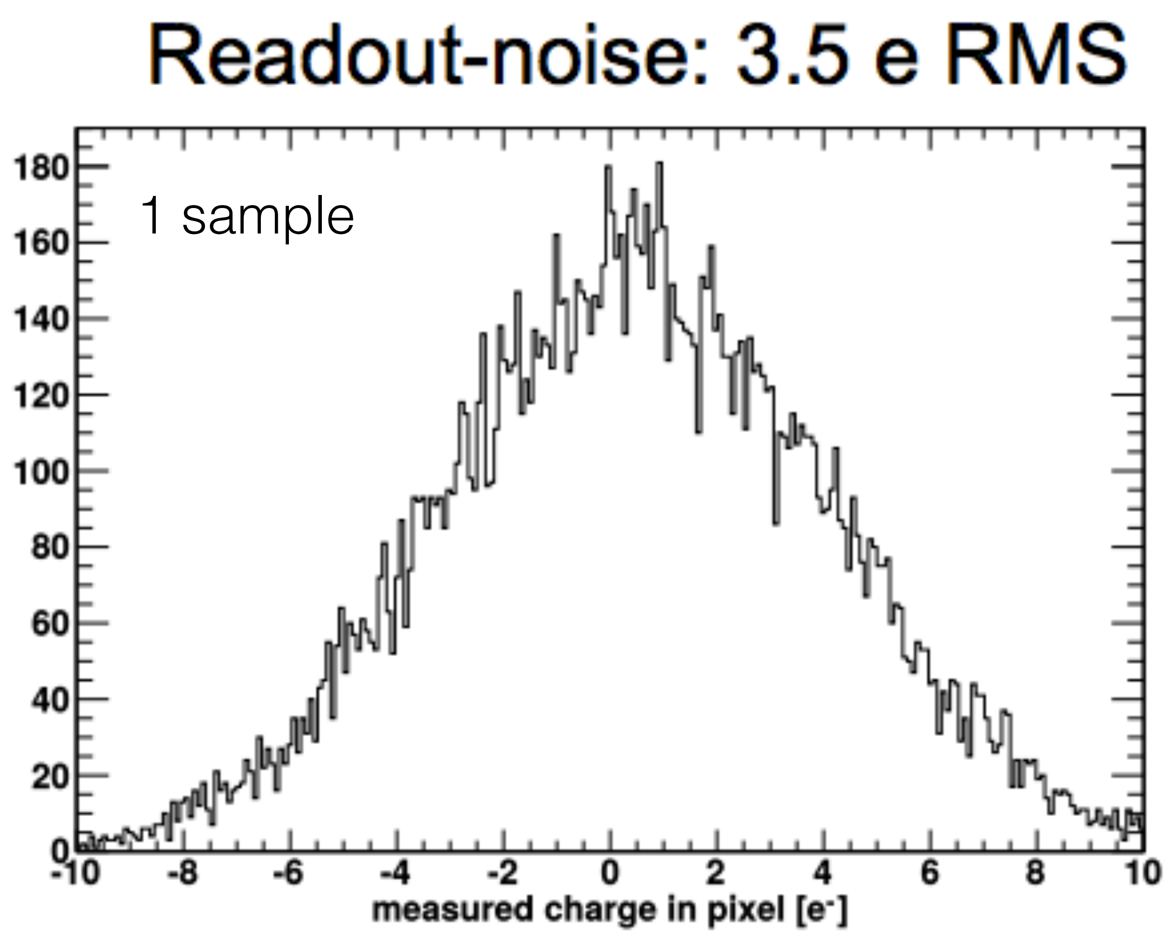
# silicon CCD detector



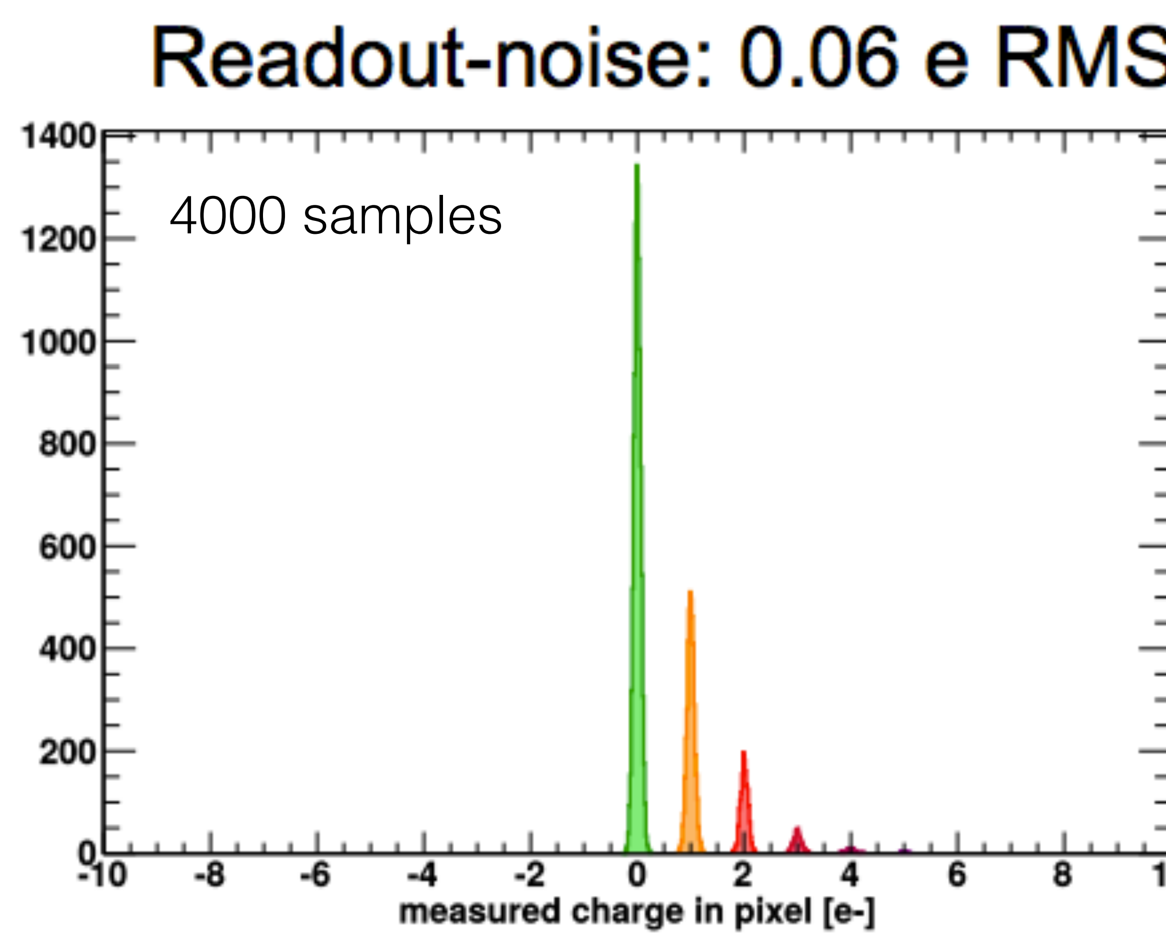

**requires very low noise!**
**two sources: readout, dark current**

# skipper readout

## standard CCD



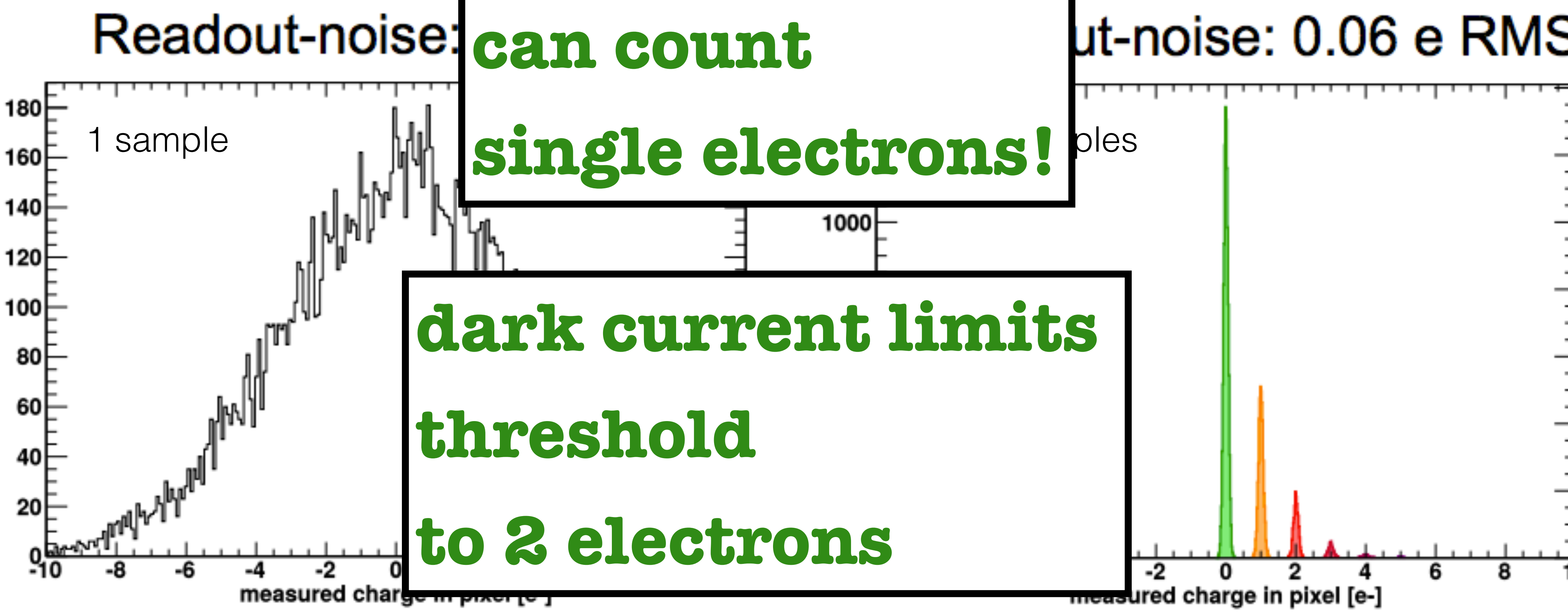

## skipper CCD




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

# skipper readout

**standard CCD** | **skipper CCD**

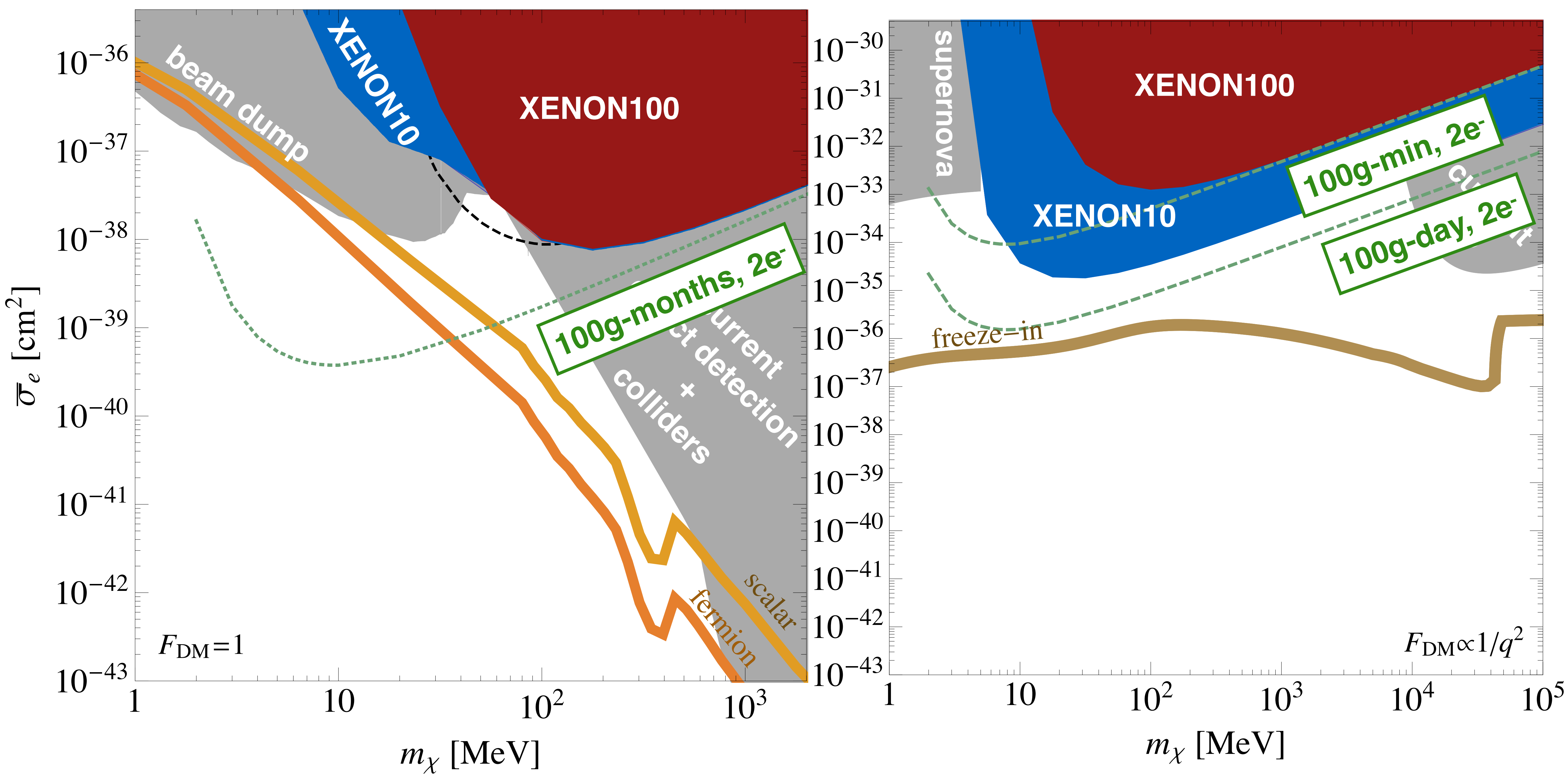



**can count single electrons!**

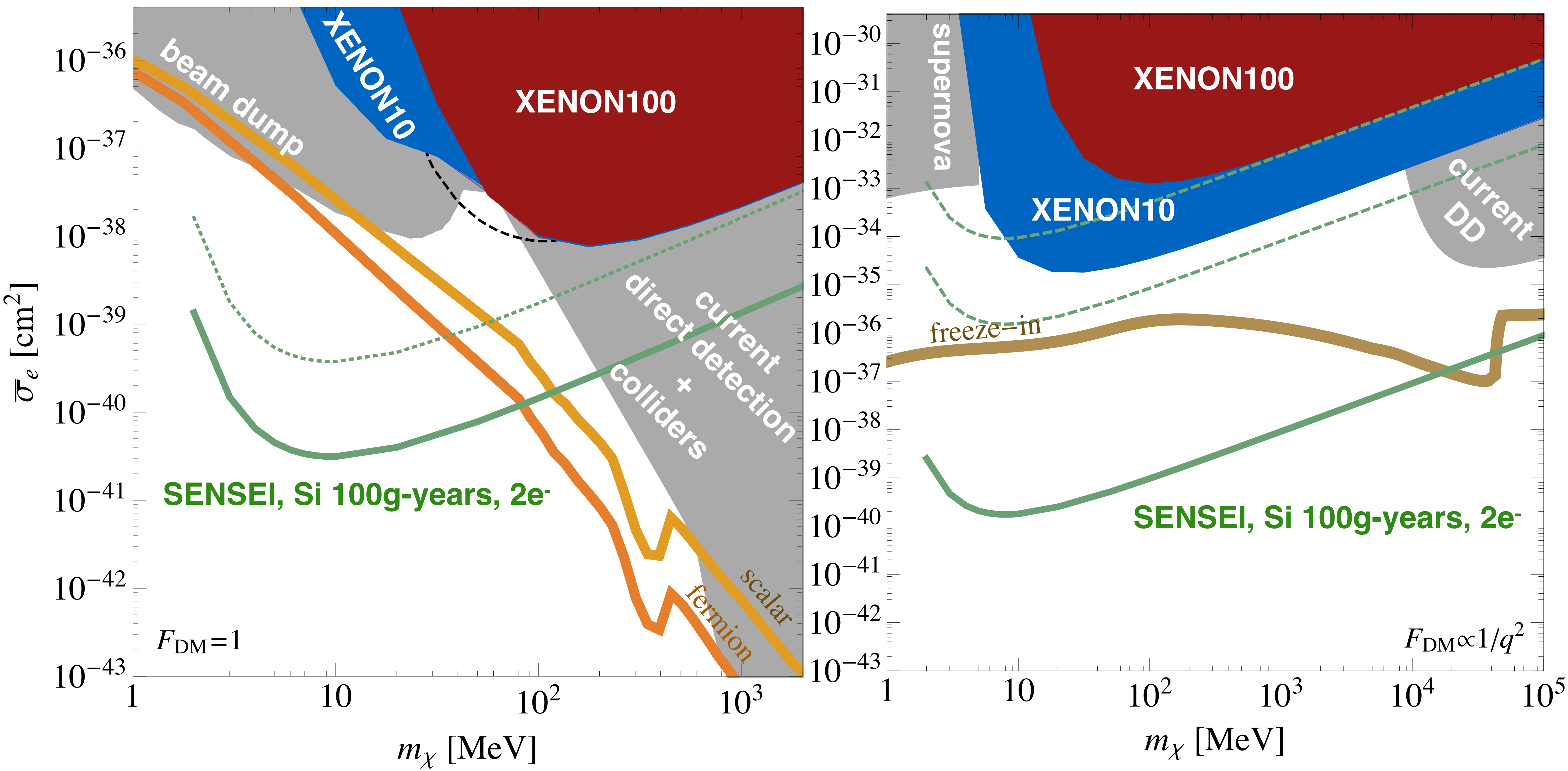
**dark current limits threshold to 2 electrons**

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

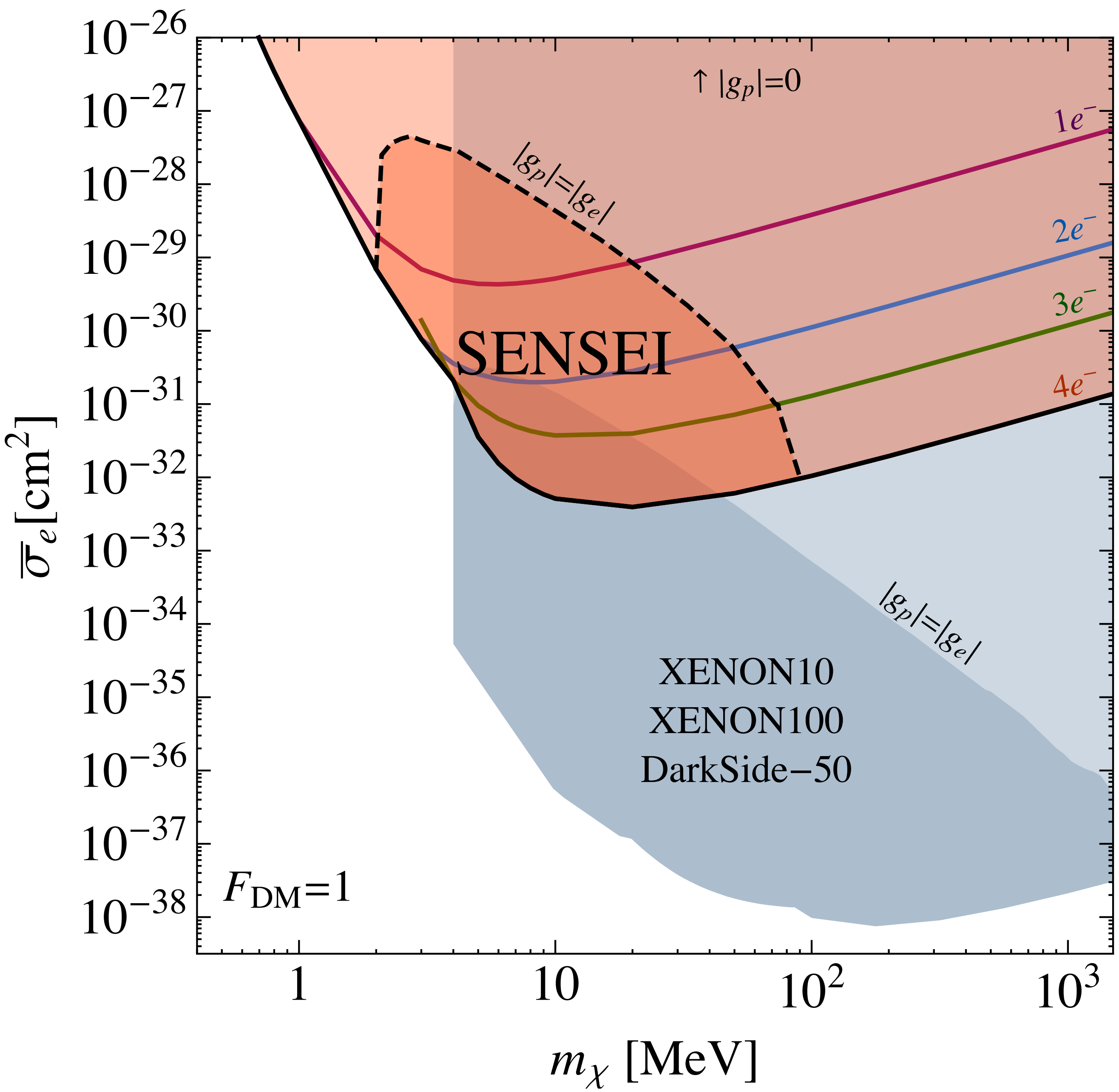
# SENSEI projections

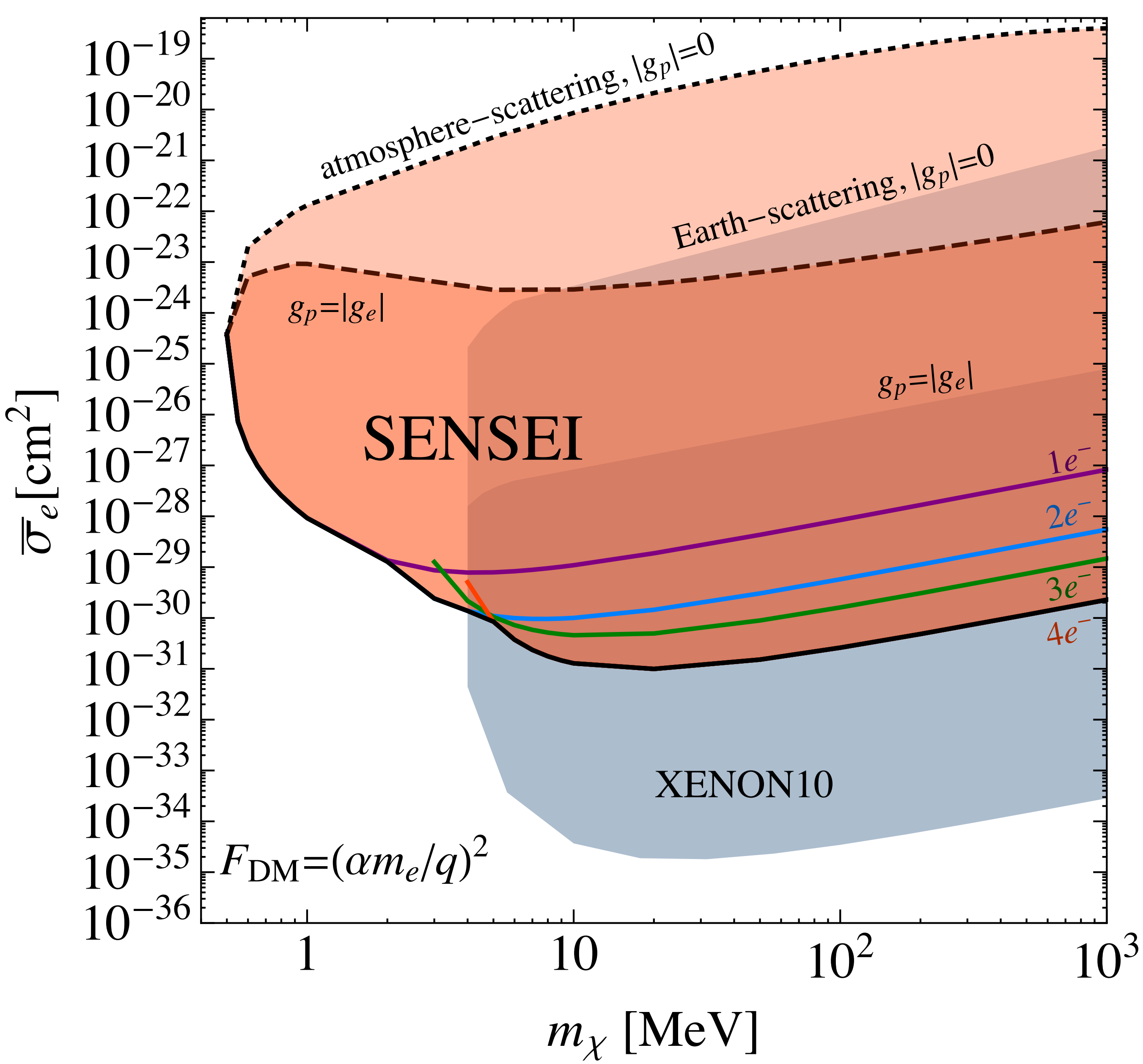


# SENSEI projections



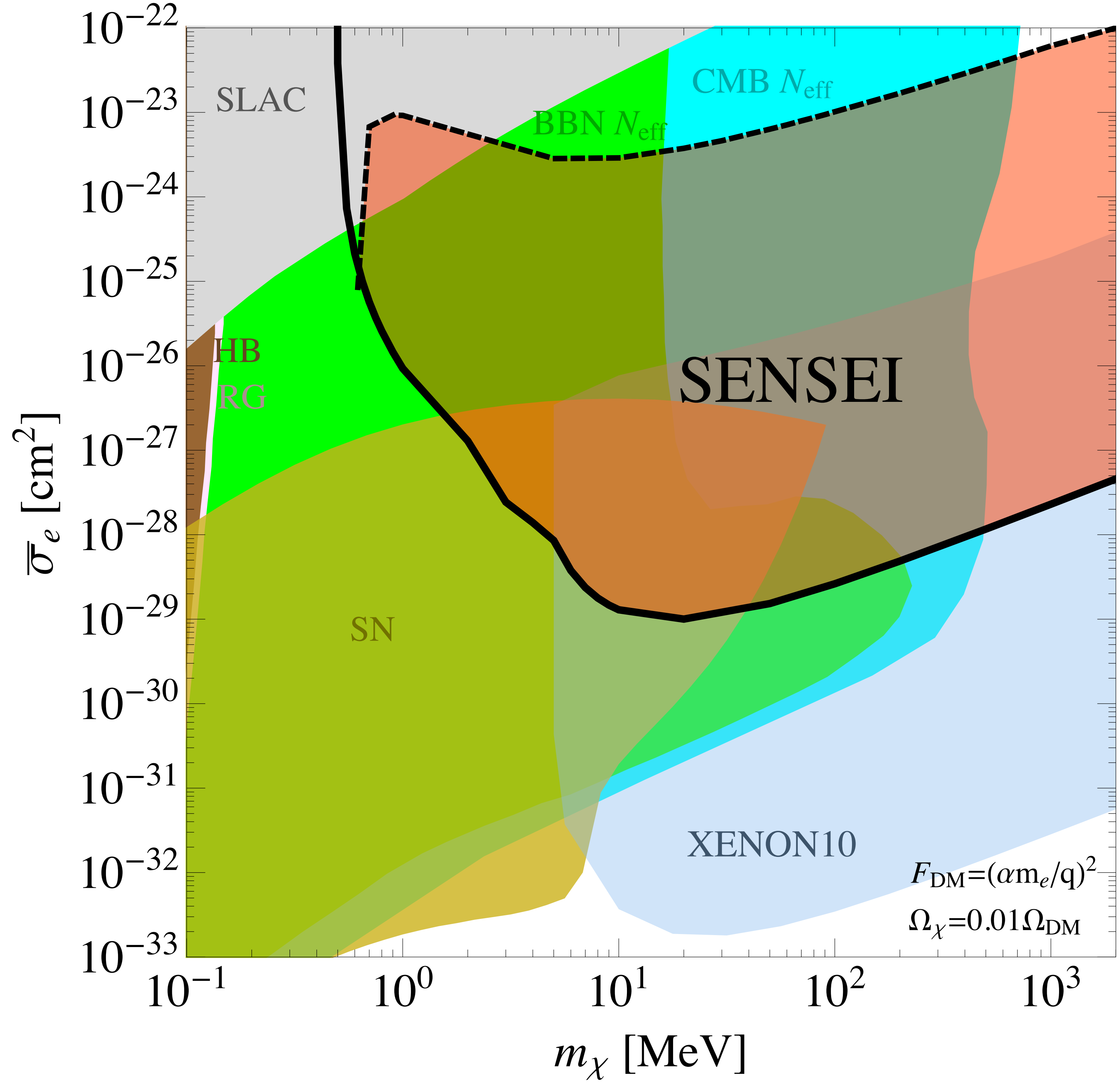
# surface run at FNAL




0.019 gram-days

# surface run at FNAL



# future of SENSEI

- new results with 0.188 g-days of exposure coming very soon!
- begin deployment of 10 g detector at SNOlab early 2019
- ultimate science goal of 100g-years of exposure expected by end of 2021