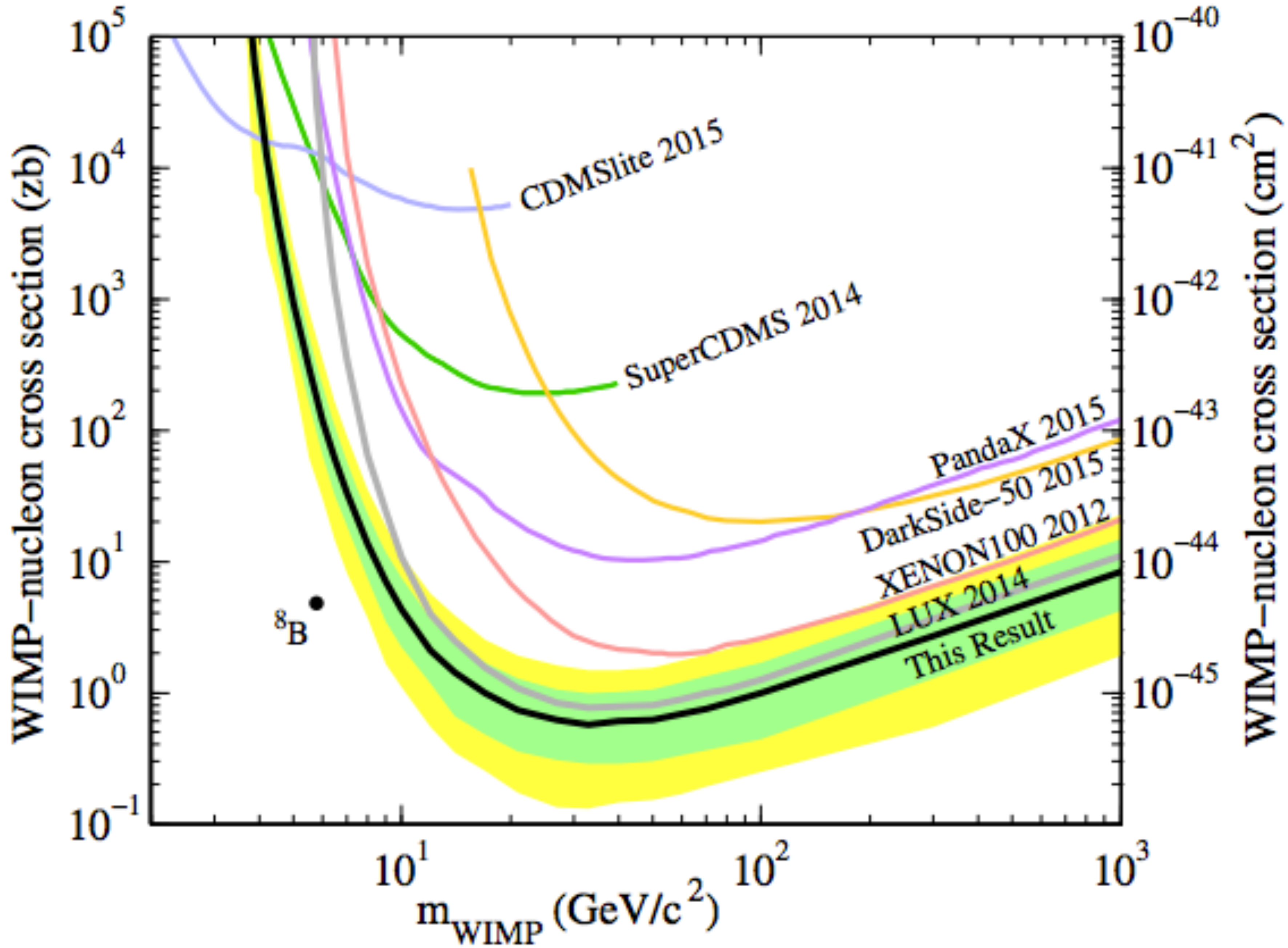
New Directions for DM Direct Detection

Tien-Tien Yu (CERN)

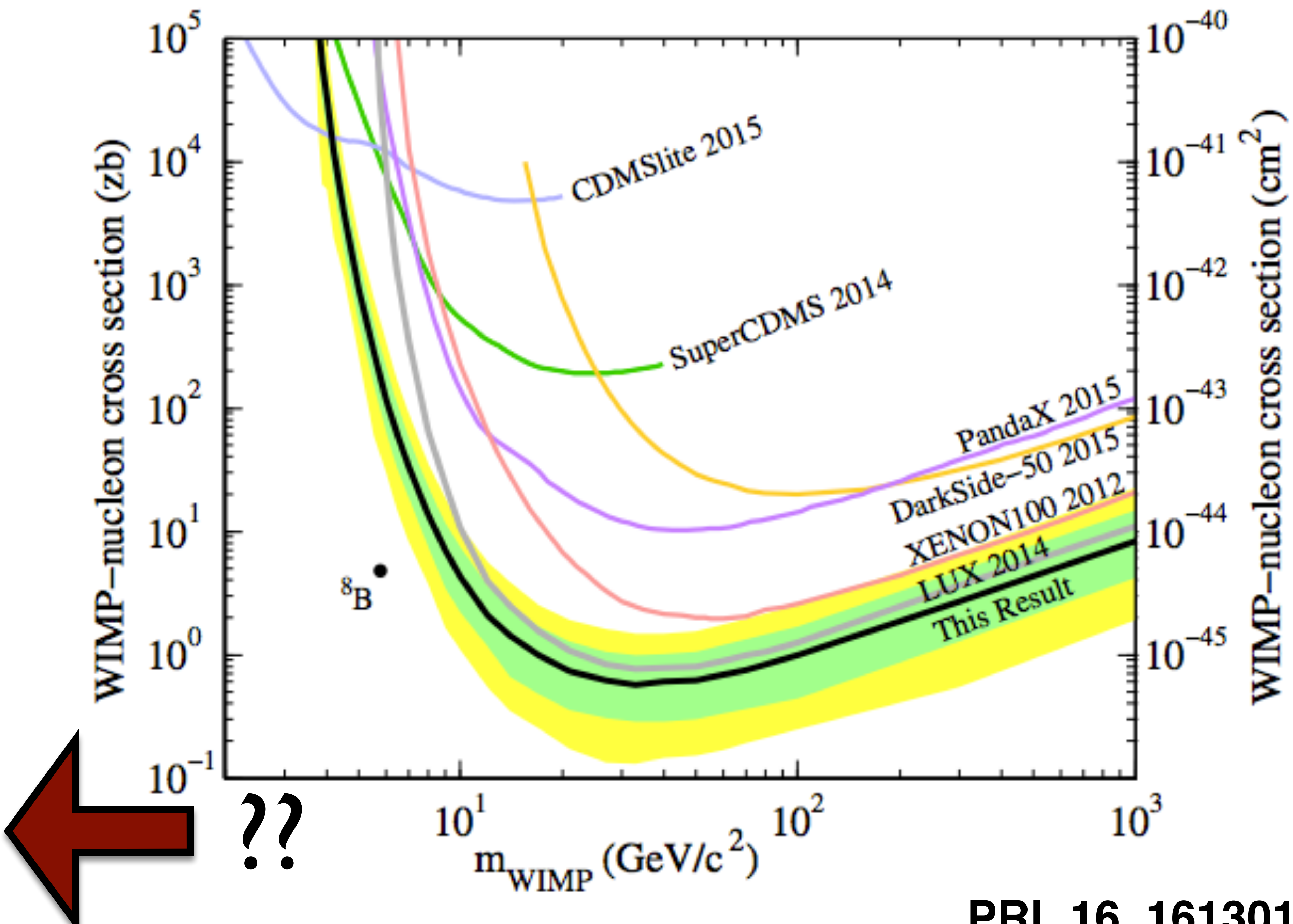
Invisibles16, Orto Botanico Padova - September 15, 2016

Nuclear Recoil



PRL 16, 161301 (2016)

Nuclear Recoil



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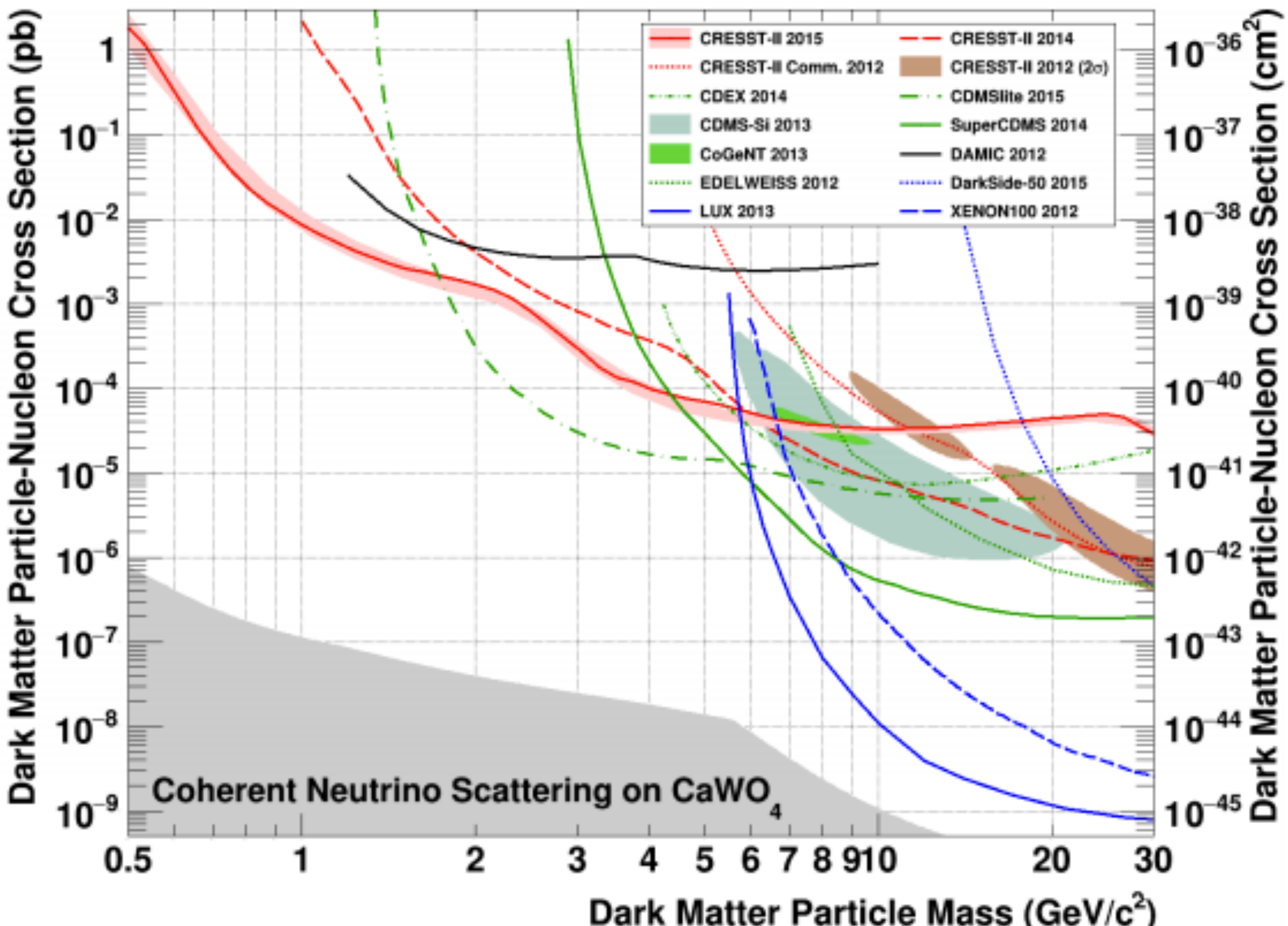
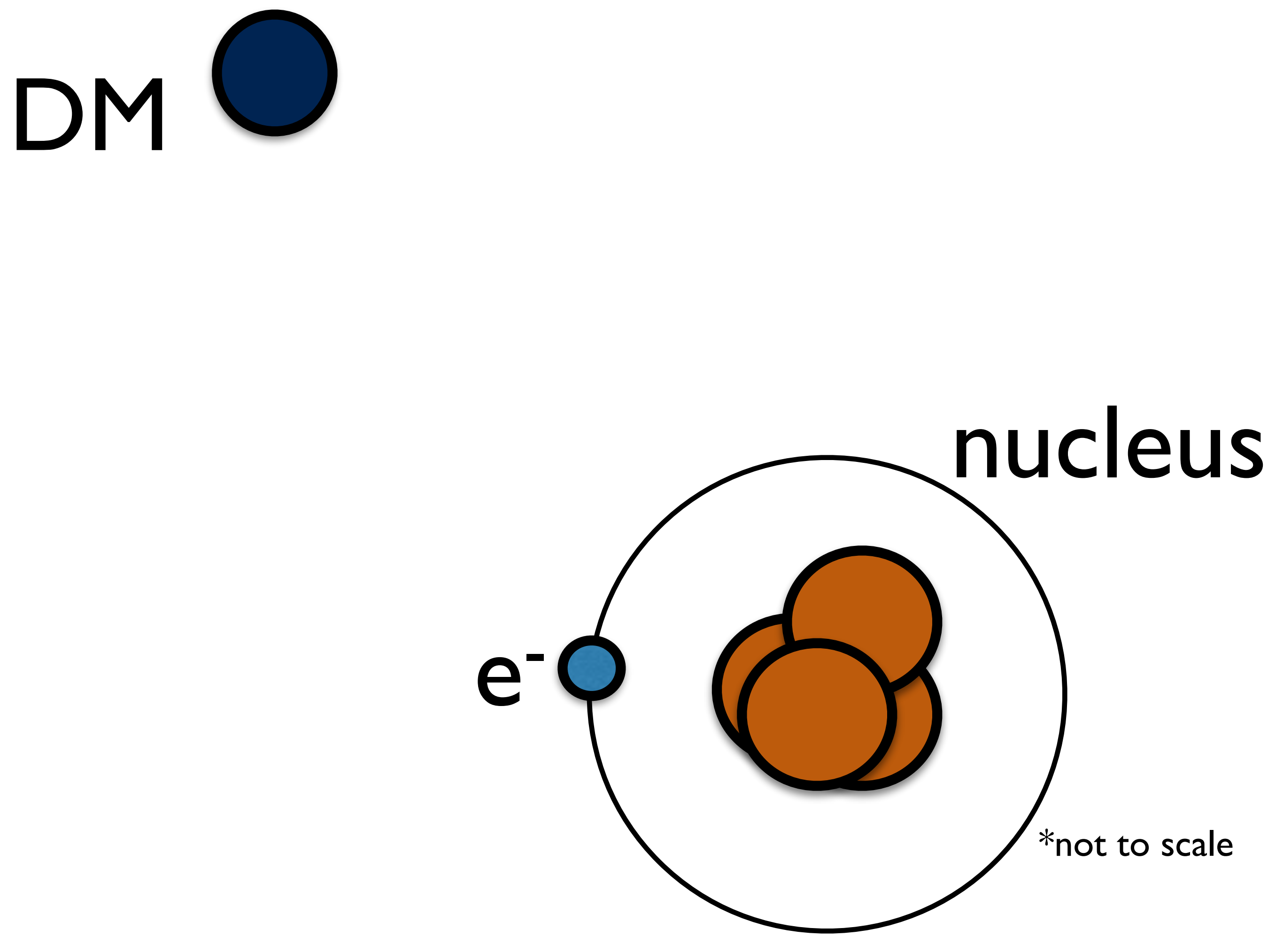
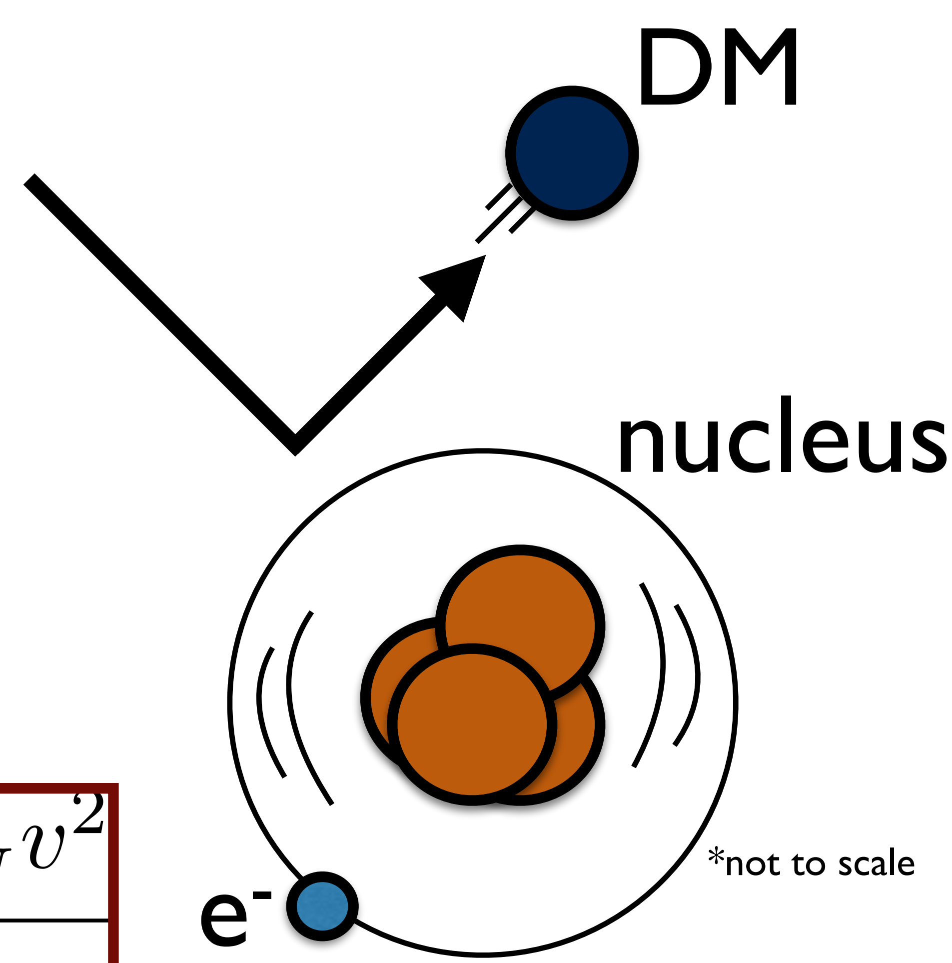
Nuclear Recoil



1509.01515


DM
nucleus
e-
*not to scale



$$E_R = \frac{q^2}{2m_N} \sim \frac{\mu_{\chi N}^2 v^2}{m_N}$$

signal:

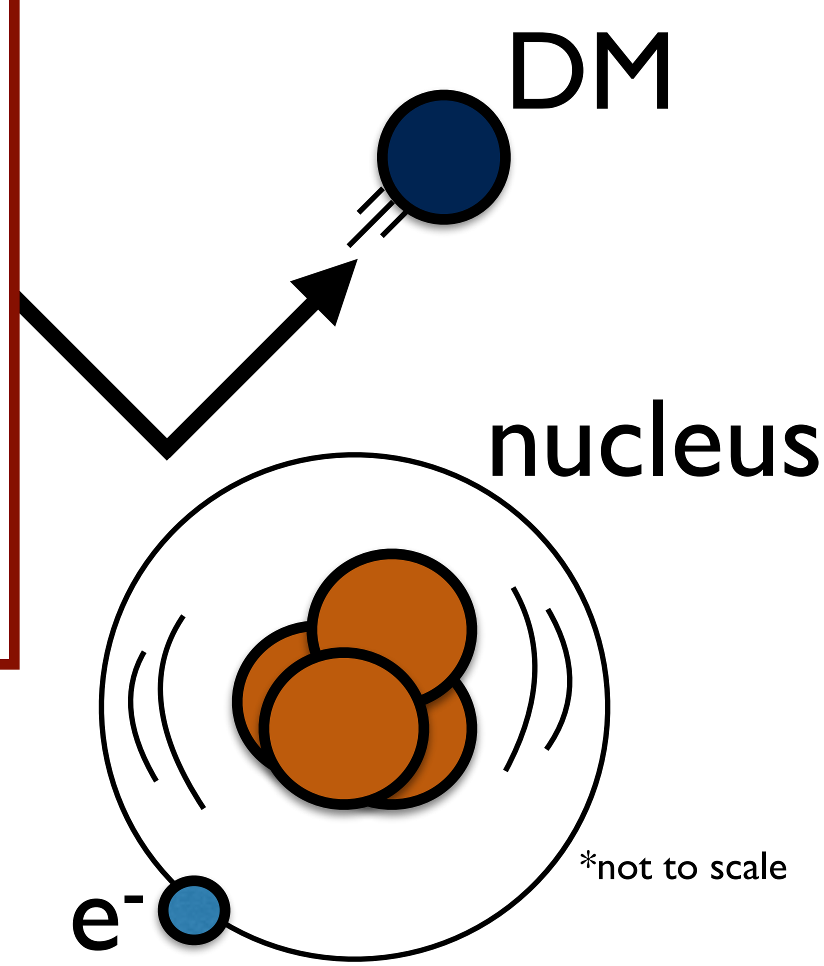
heat

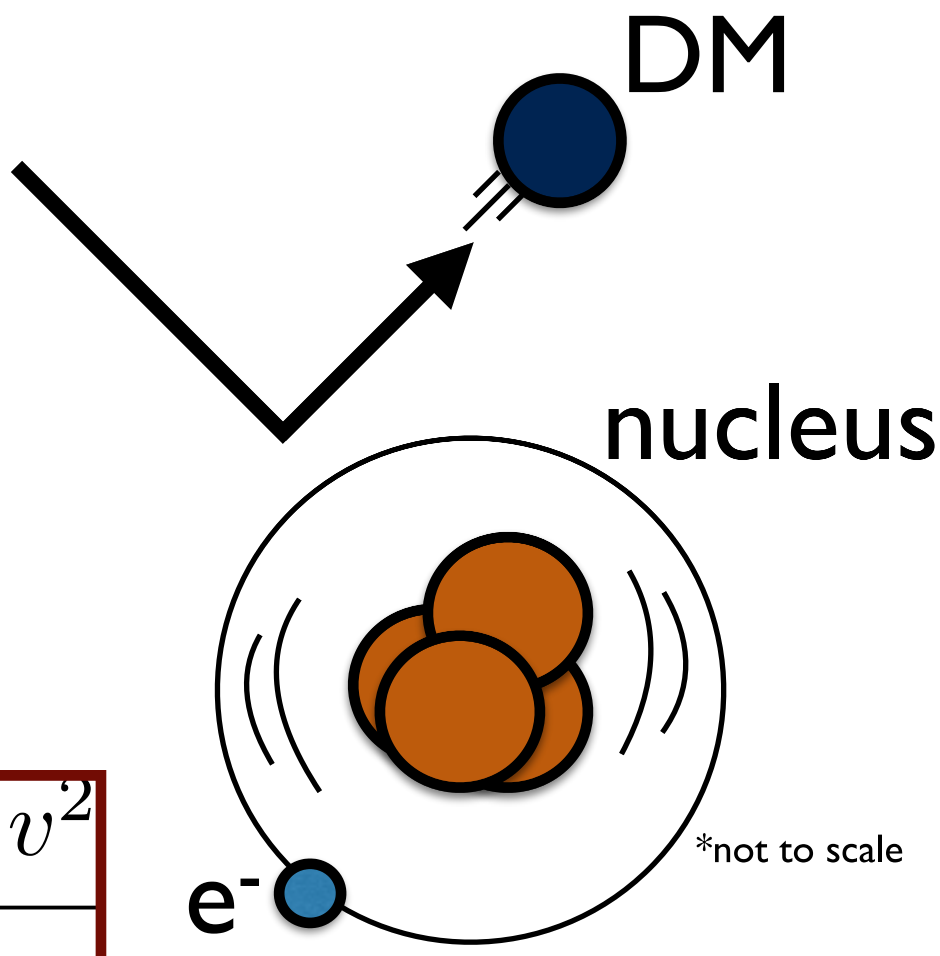
phonons

scintillation photons

ionization electrons

$$E_R = \frac{q^2}{2m_N} \sim \frac{\mu_{\chi N}^2 v^2}{m_N}$$





$$E_R = \frac{q^2}{2m_N} \sim \frac{\mu_{\chi N}^2 v^2}{m_N}$$

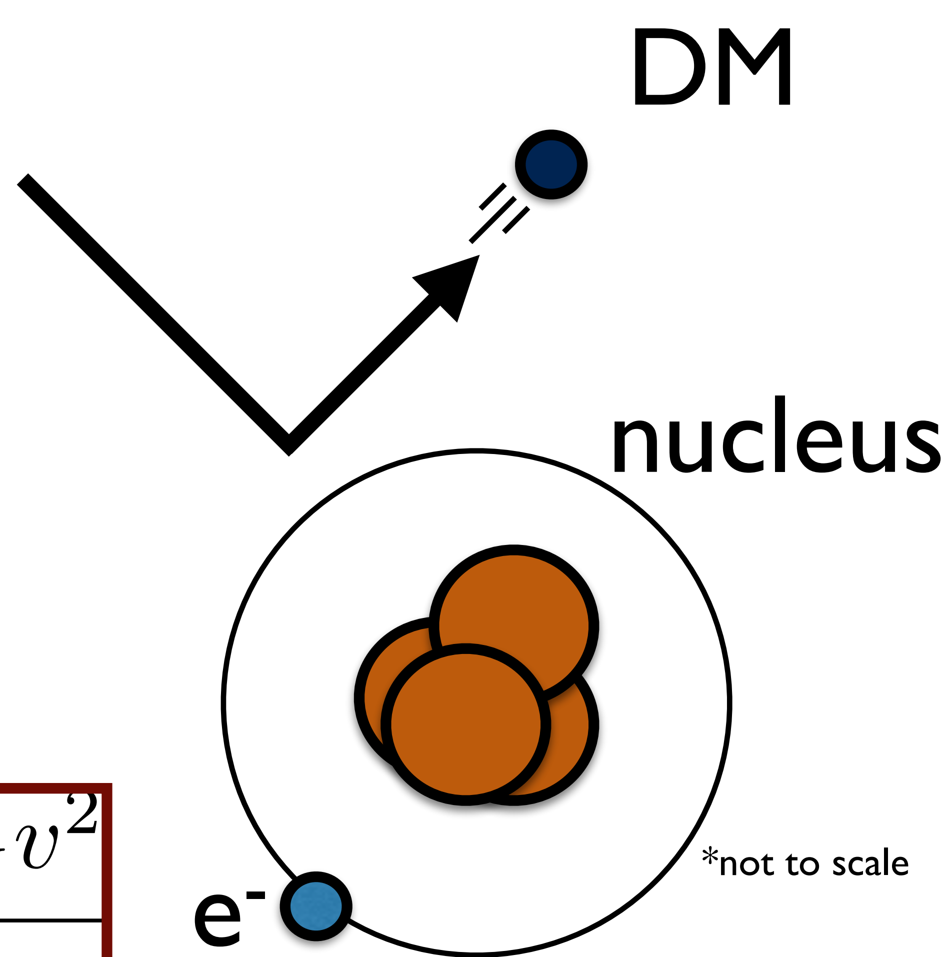
$m_\chi = 100\ \text{GeV}, E_R \sim 100\ \text{keV}$

E_{NR} thresholds

LUX: 3 keV

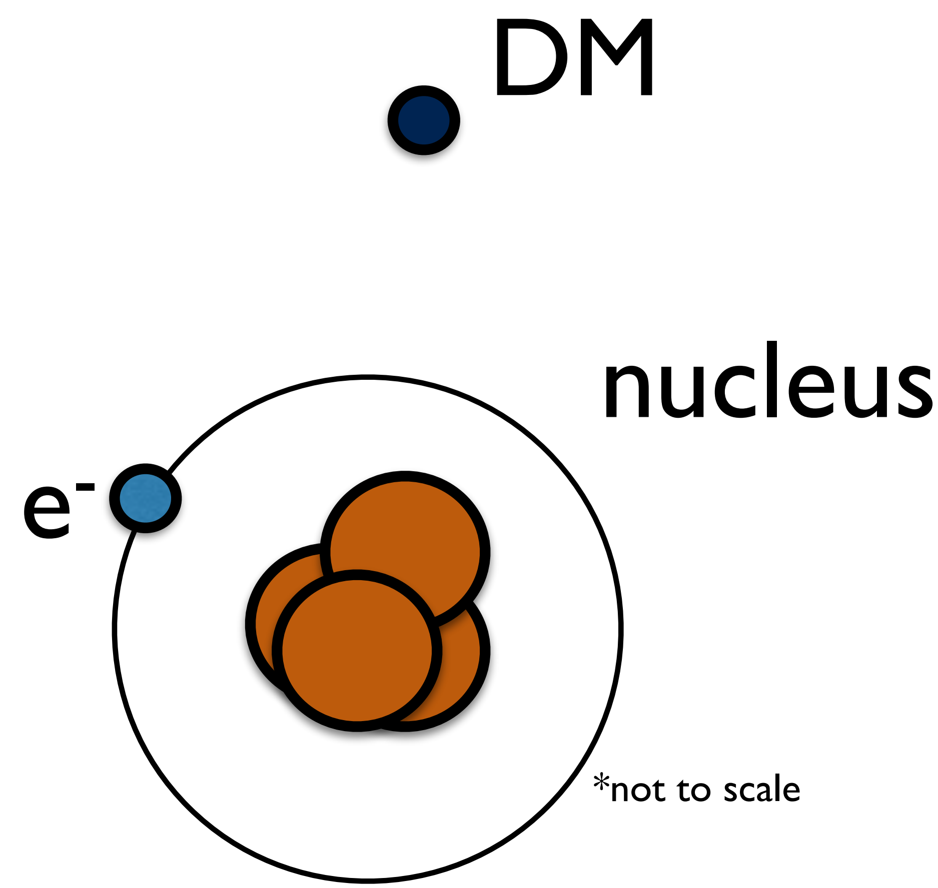
DAMIC: 500 eV

CDMSlite, CRESST: 300 eV



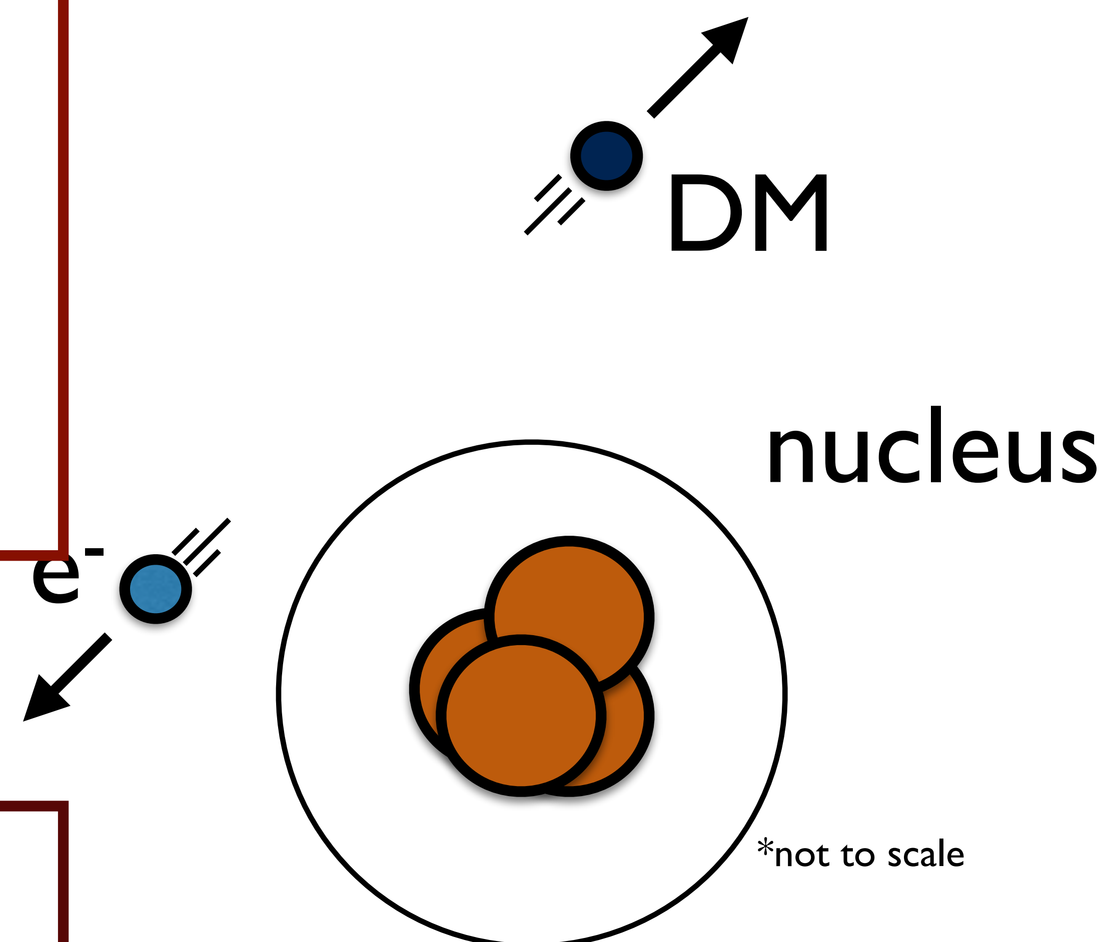
$$E_R = \frac{q^2}{2m_N} \sim \frac{\mu_{\chi N}^2 v^2}{m_N}$$

$$m_\chi = 100 \text{ MeV}, E_R \sim 1 \text{ eV}$$



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

signal:
a few ionized electrons or scintillation photons



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

$$m_\chi = 100\ \mathrm{MeV},\ E_R \sim 50\ \mathrm{eV}$$

typical momentum transfer

typical size of the momentum transfer is set by the electron's momentum

$$q_{\rm typ} \simeq m_e v_e \sim Z_{\rm eff}\,\alpha m_e$$

~ 4 keV

This requires *q* on tail of e- wave function or DM velocity!

typical energy transfer

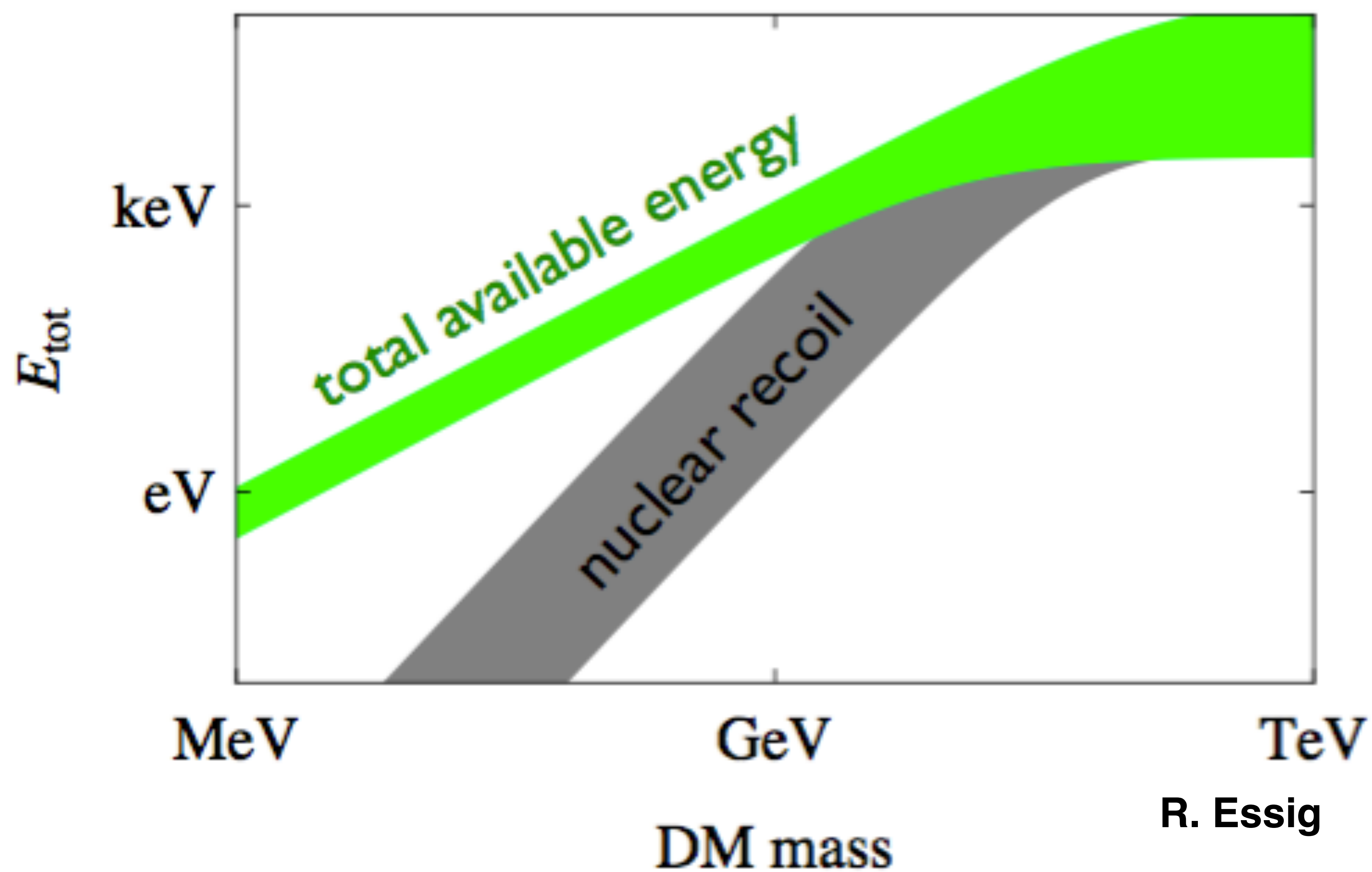
$$\Delta E_e = \vec{q} \cdot \vec{v} - \frac{q^2}{2\mu_{\chi N}}$$

arbitrary-size momentum transfer is possible

$$\Delta E_e \leq \frac{1}{2}\mu_{\chi N} v^2$$

typical energy transfer

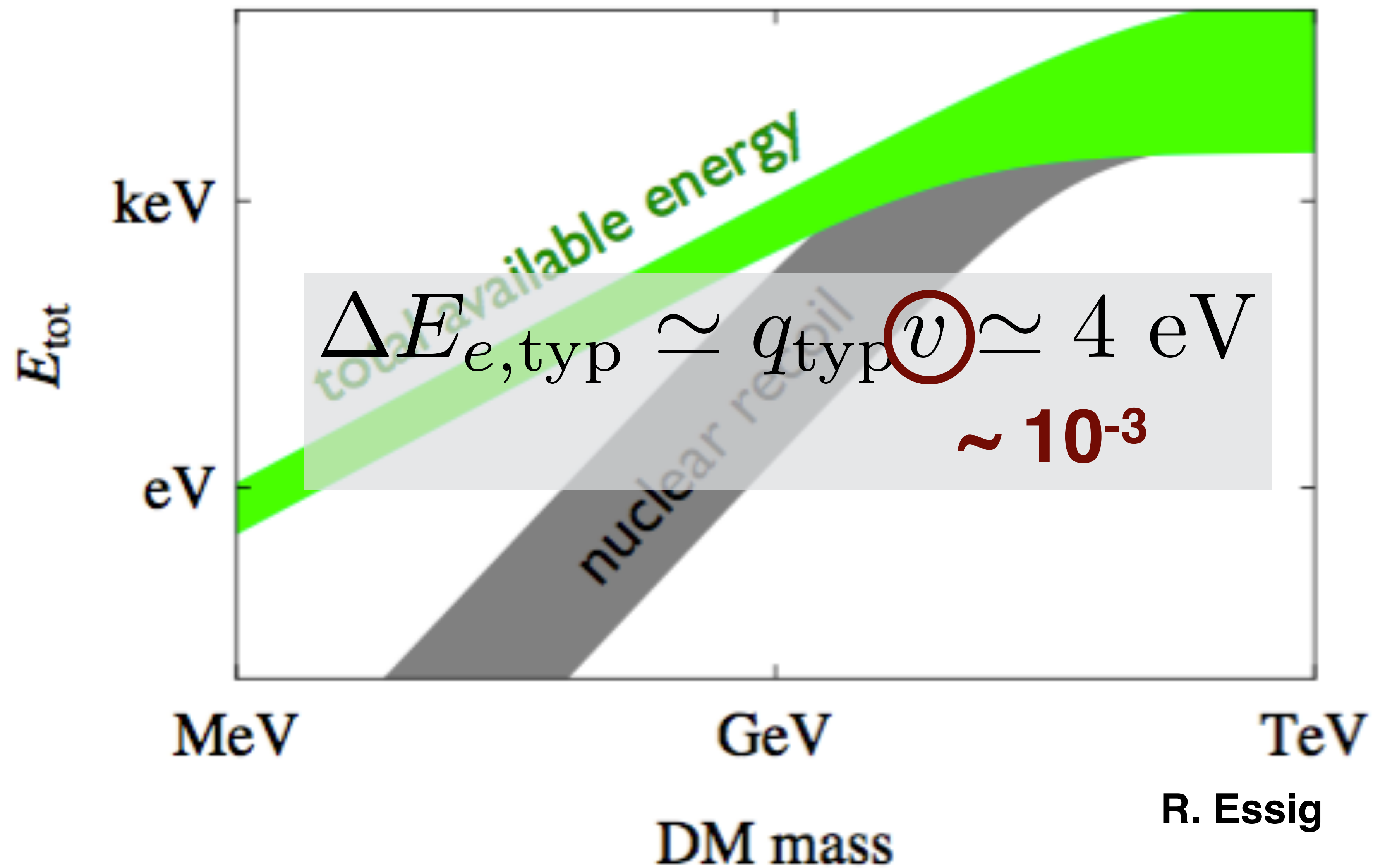
ALL the kinetic energy in the DM-atom collisions is available to excite the electron!



R. Essig

typical energy transfer

ALL the kinetic energy in the DM-atom collisions is available to excite the electron!



$$\Delta E_{e,\text{typ}} \simeq q_{\text{typ}} v \simeq 4 \text{ eV}$$

v **~ 10^{-3}**

R. Essig

ingredients

particle physics

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

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

$$\sigma(q) = \overline{\sigma}_e \times |F_{DM}(q)|^2$$

ingredients

astrophysics

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

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

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

ingredients

material dependent

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

$$\left|f_{i\to i'}(\vec{q},\vec{k})\right|^2 = \frac{V}{(2\pi)^3}\int_{\mathrm{BZ}}\mathrm{d}^3k'\left|\int \mathrm{d}^3x\,\psi^*_{i',\vec{k}'}(\vec{x})\psi_{i,\vec{k}}(\vec{x})e^{i\vec{q}\cdot\vec{x}}\right|^2$$

probability of going from state i to i’

ingredients

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

local DM density

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

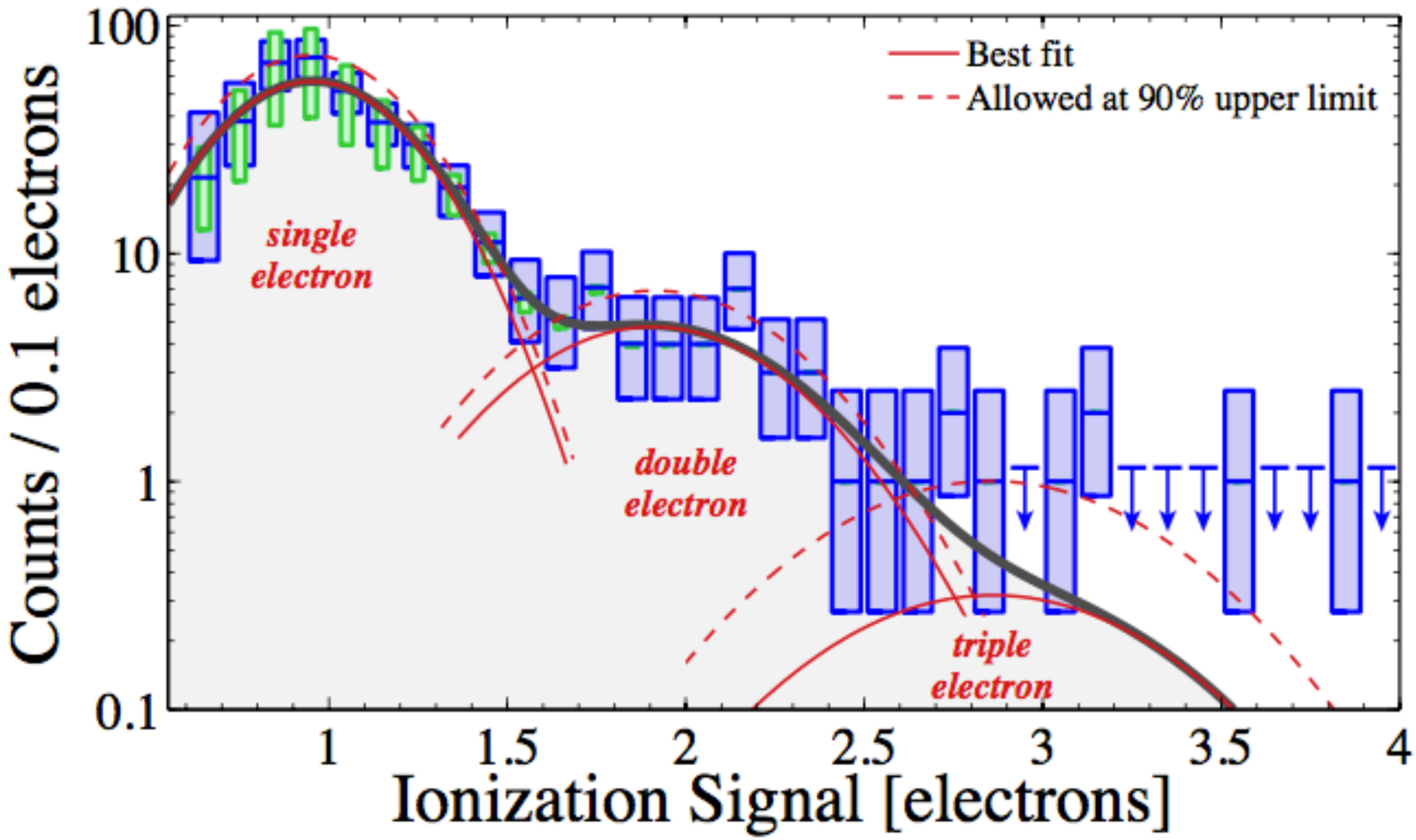
number of target nuclei per unit mass

energy threshold

General goals and challenges

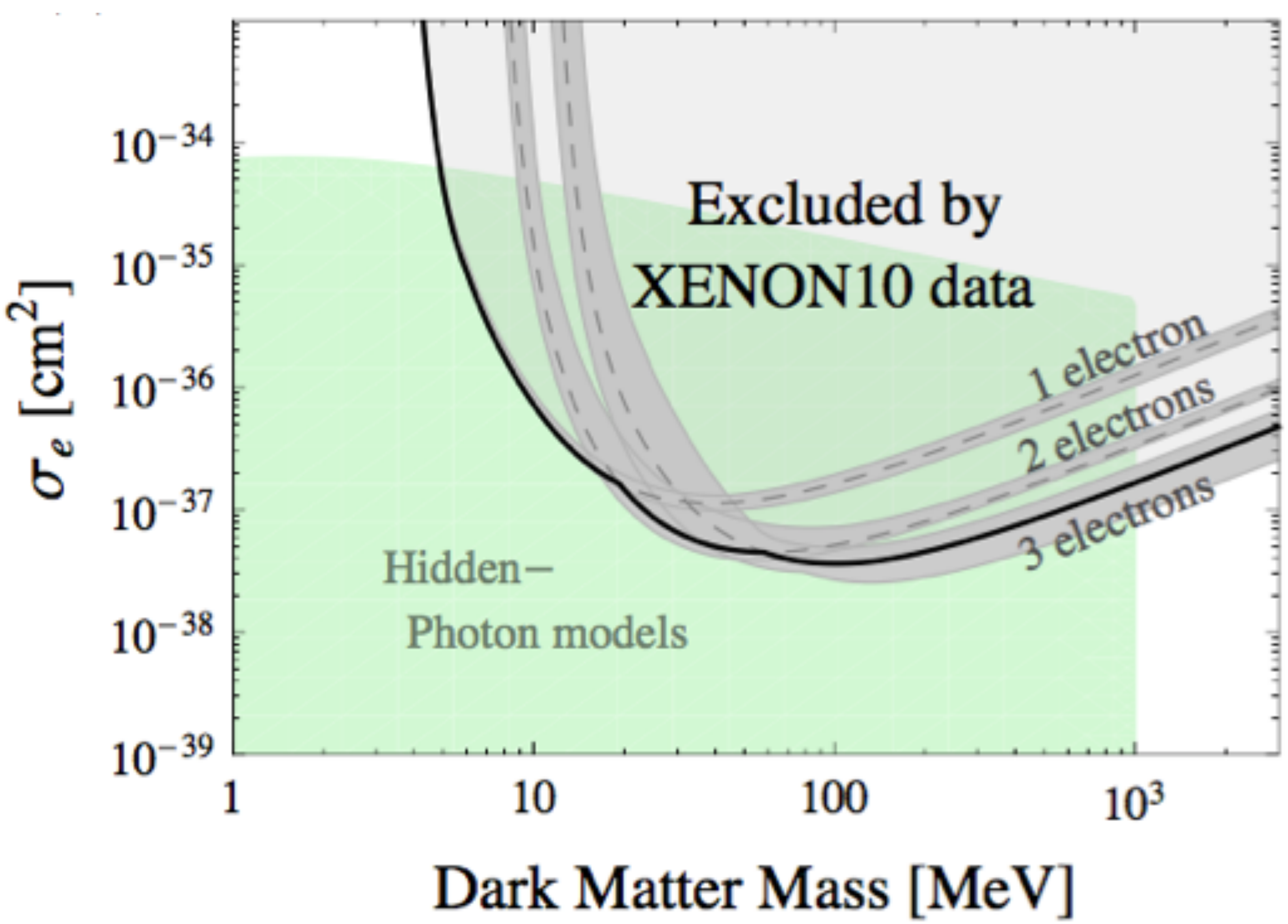
- DM mass reach $m_\chi \gtrsim 250 \text{ keV} \times \frac{\Delta \text{E}}{1 \text{ eV}}$
- Backgrounds
- Signal vs. Background discrimination
- material fabrication and experimental design

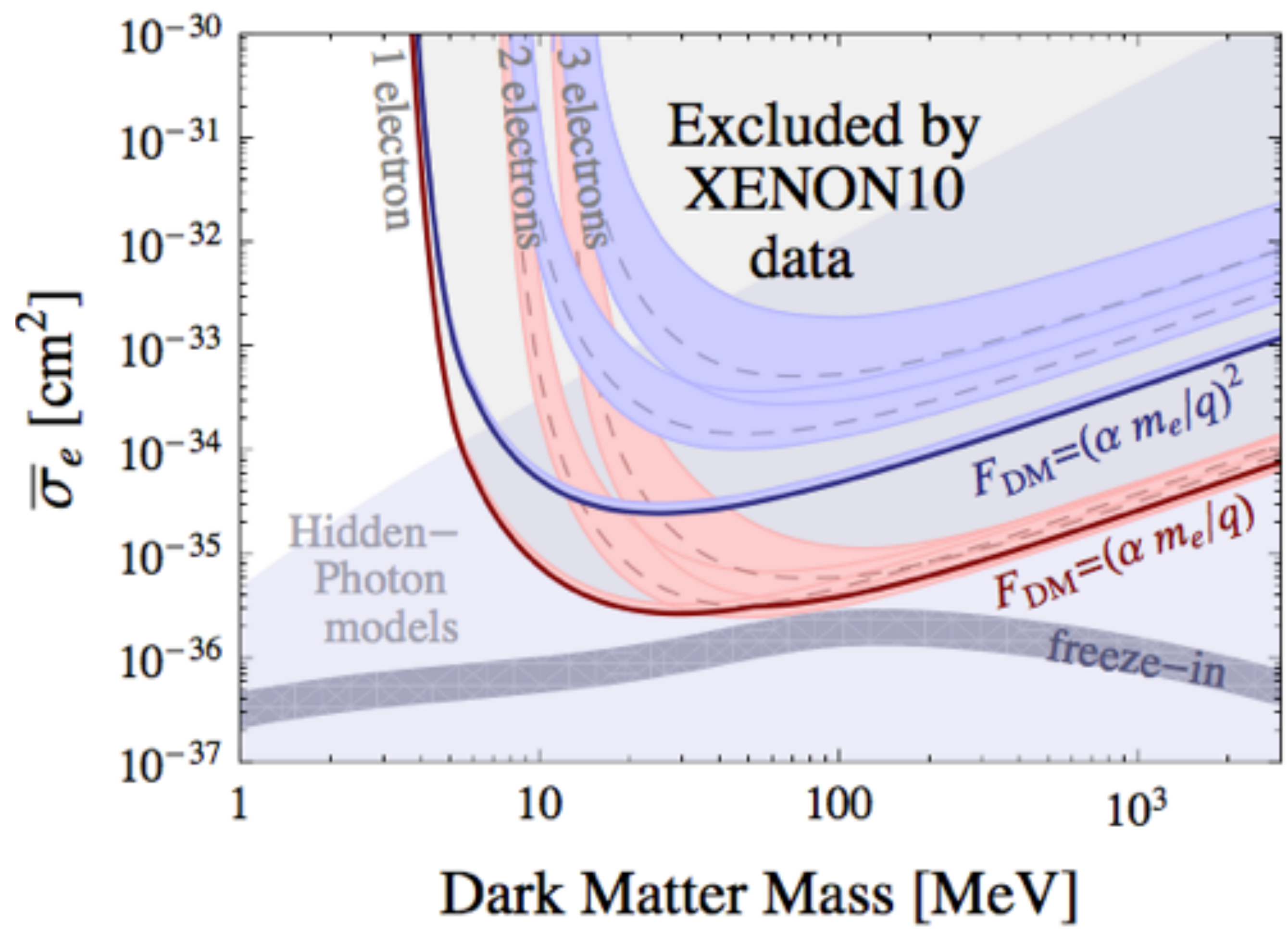
Xenon10



Essig, Manalaysay, Mardon, Sorenson, Volansky [1104.3088]

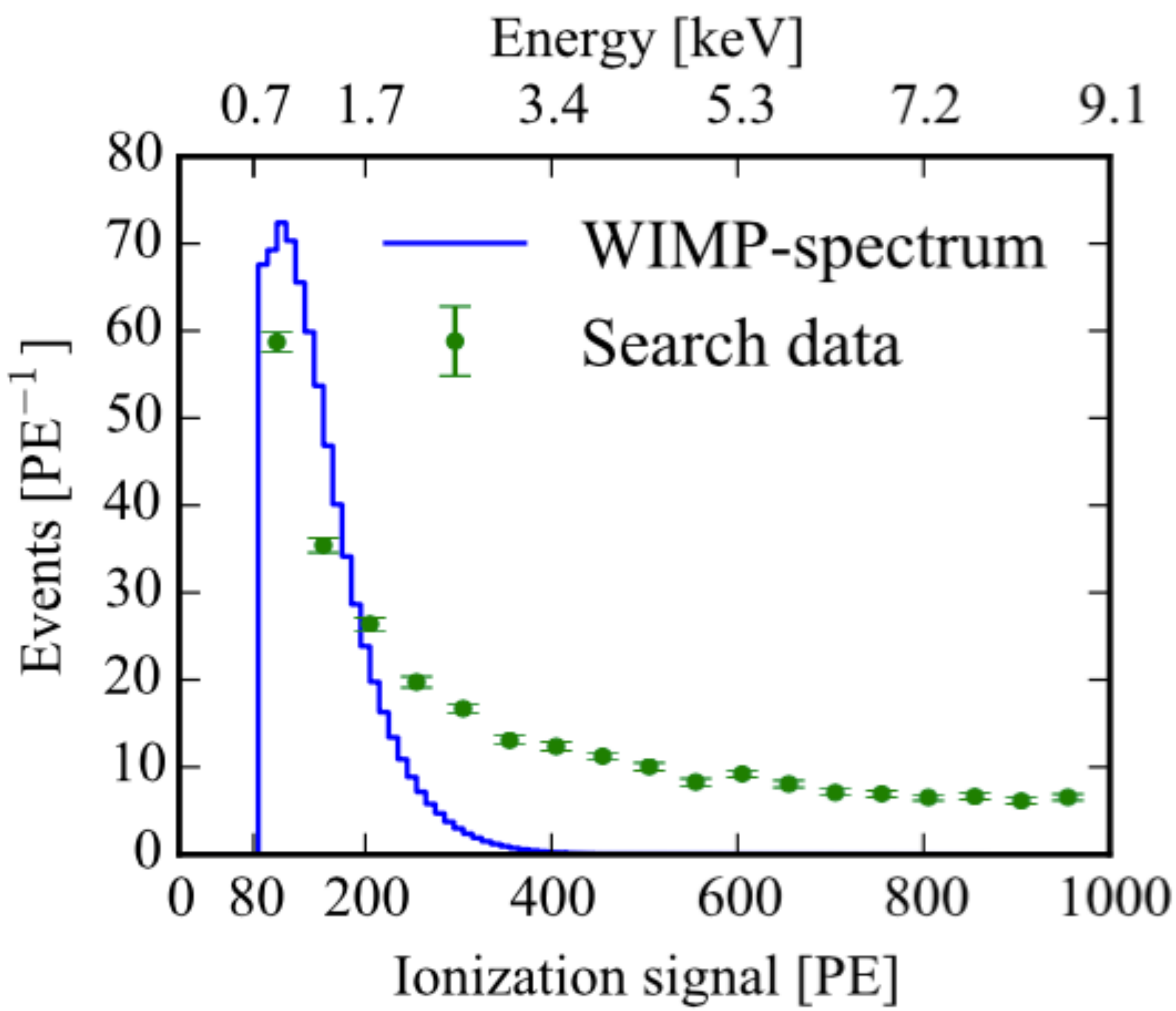
Xenon10





Essig, Manalaysay, Mardon, Sorenson, Volansky [1104.3088]

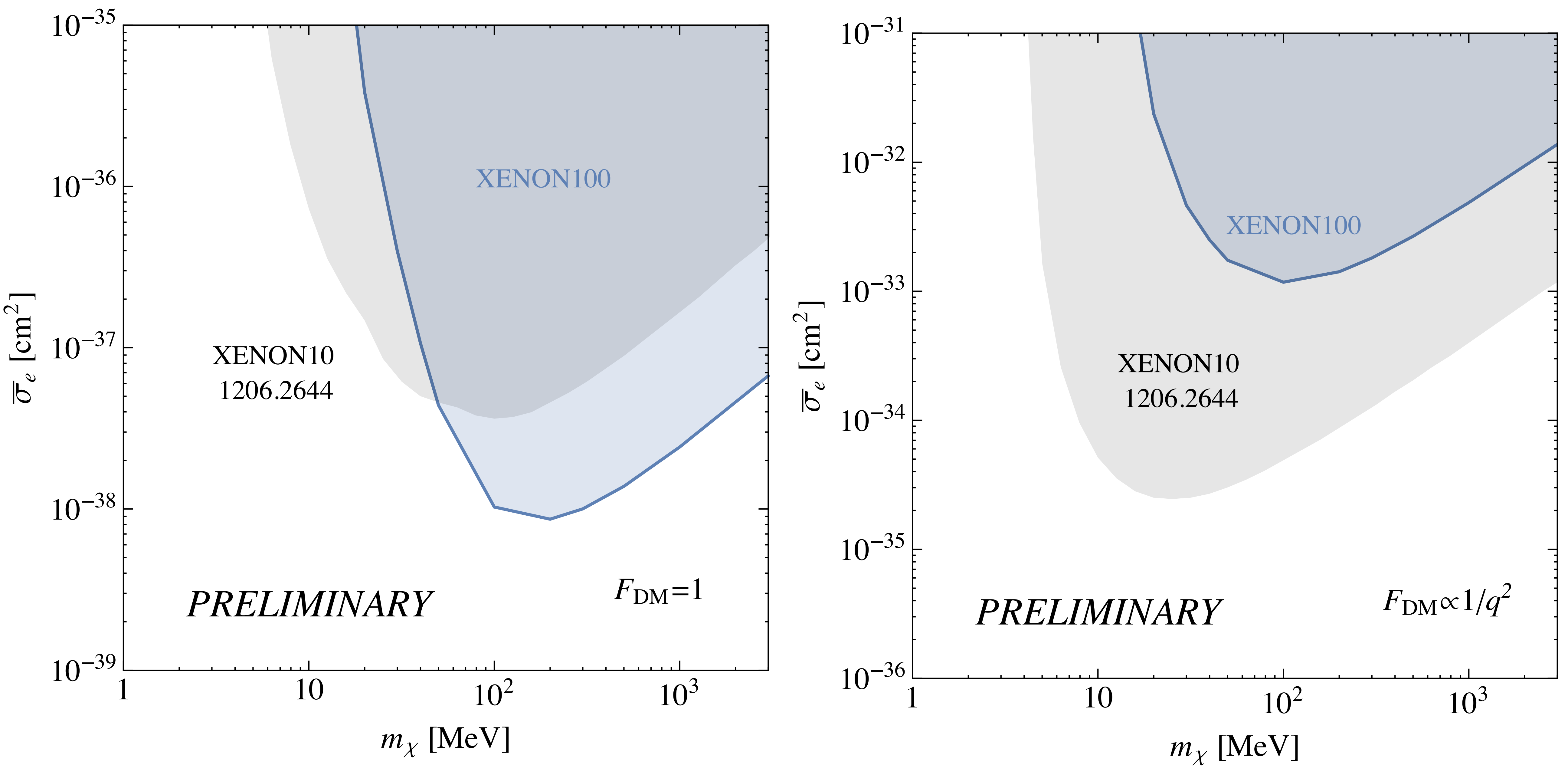
Xenon100



1605.06262

Essig, Mardon, Volansky TTY, *in preparation*

Xenon100

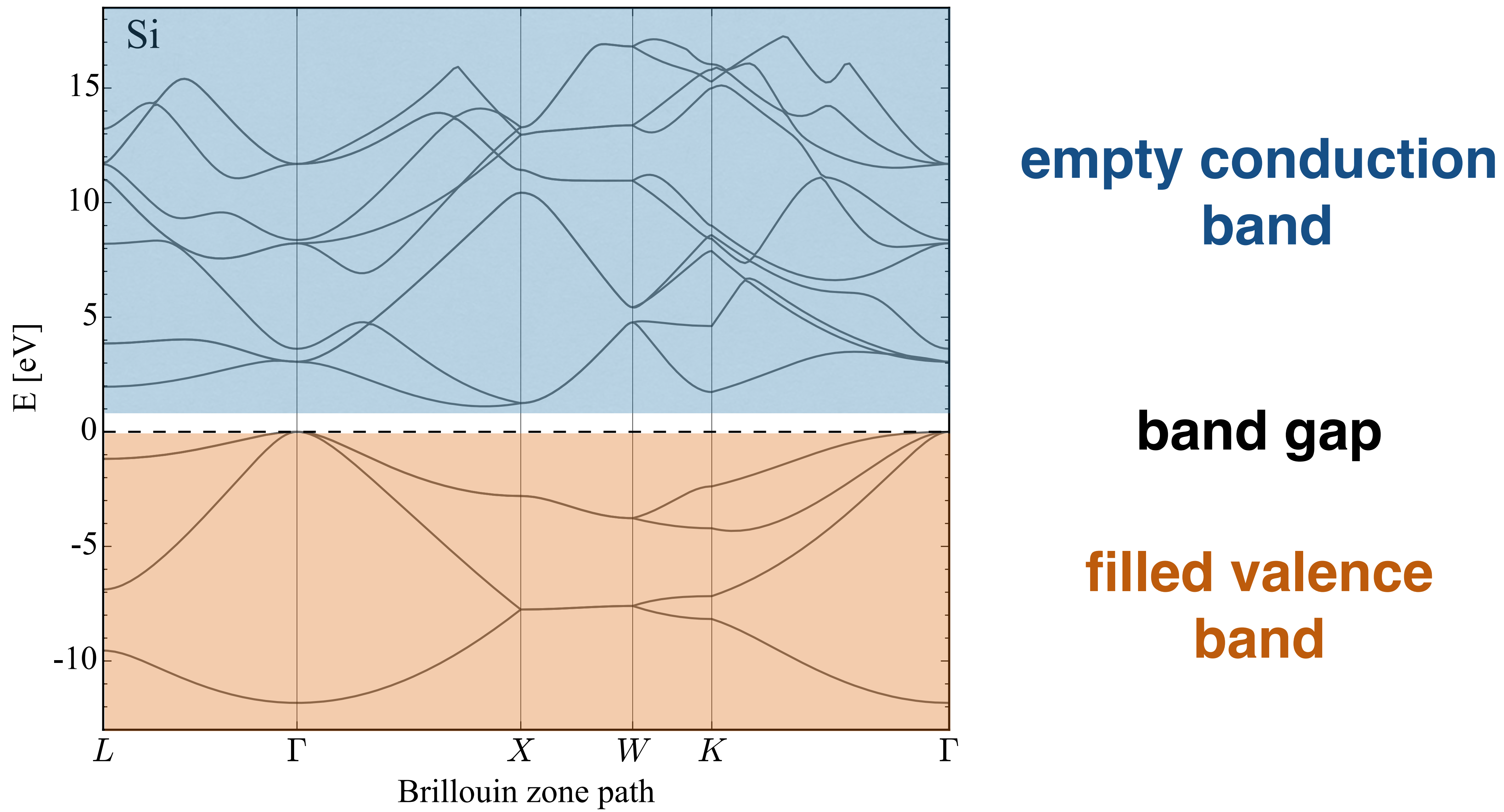


Essig, Mardon, Volansky TTY, *in preparation*

challenges

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

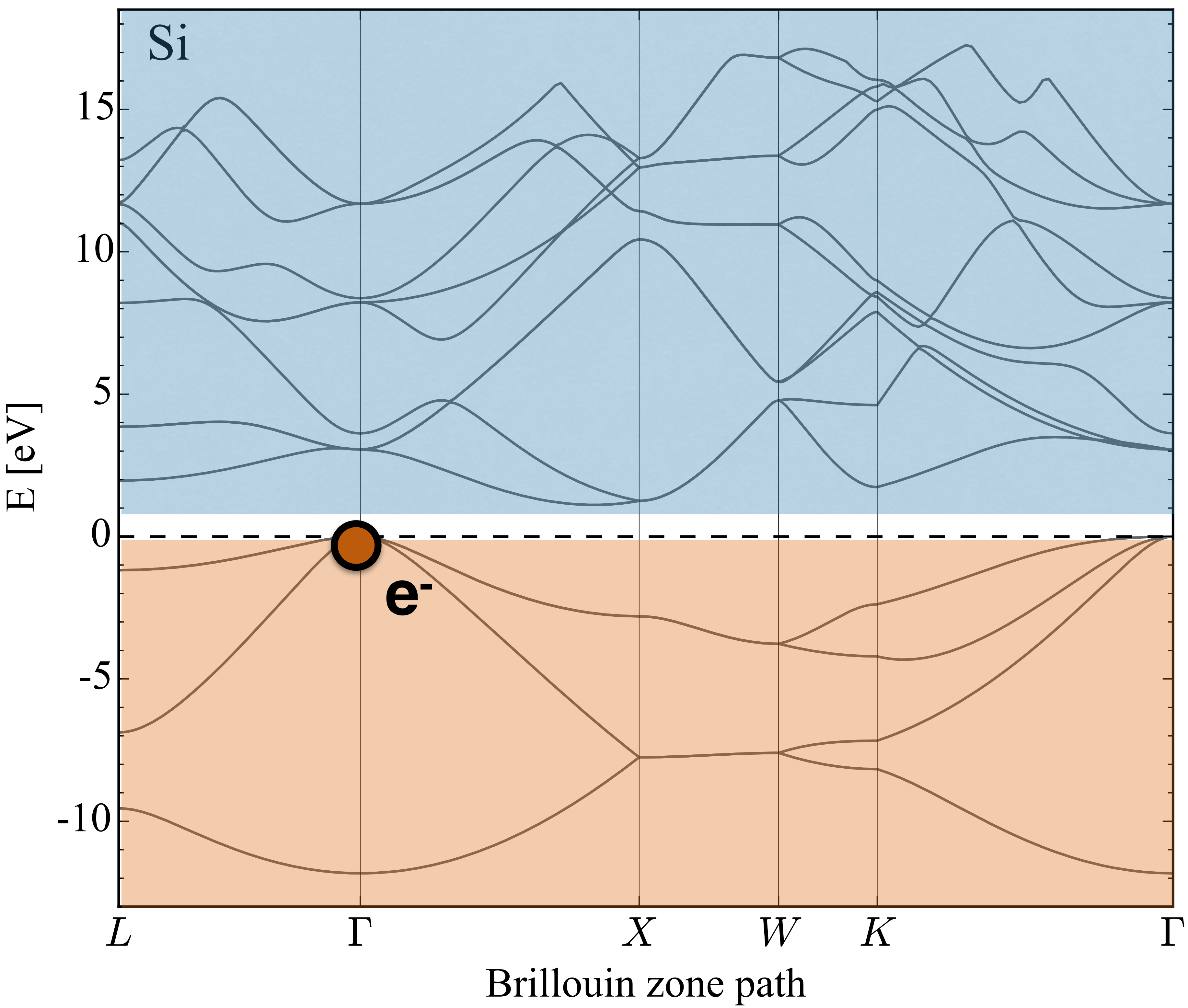
Semiconductor targets



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

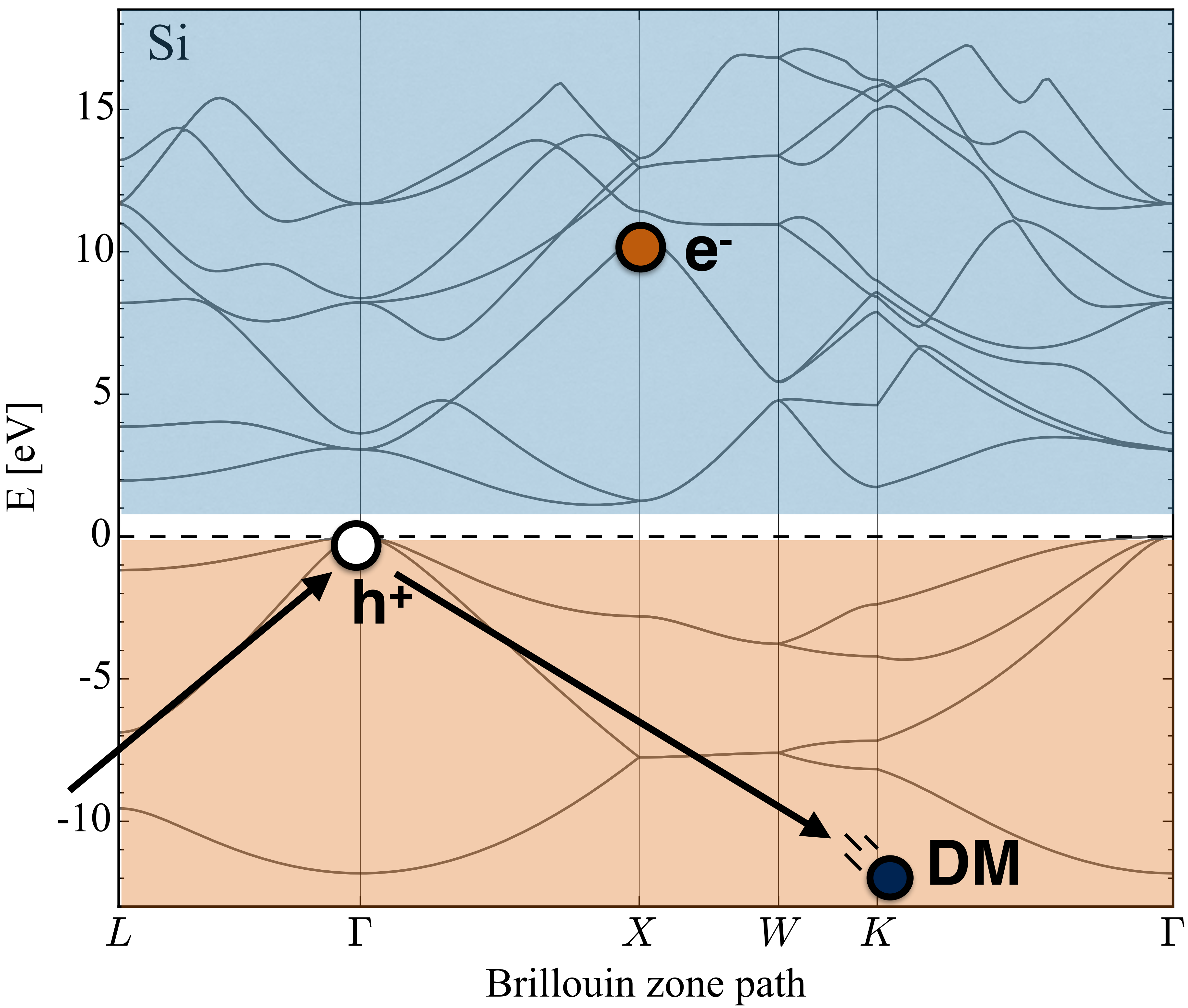
Semiconductor targets



band gap [eV]

Ge	0.67
Si	1.1
GaAs	1.5
NaI	5.9
CsI	6.4

Semiconductor targets



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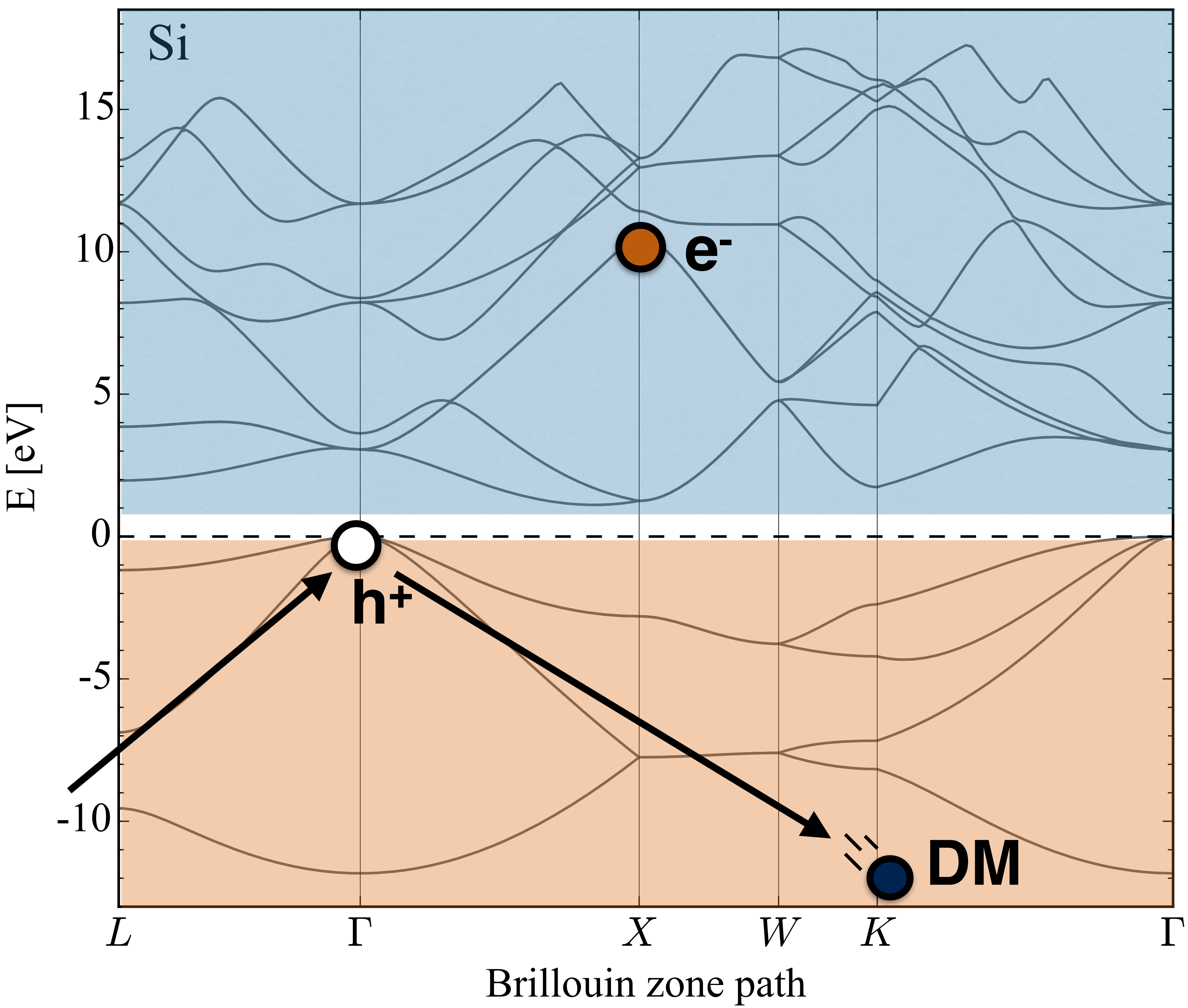
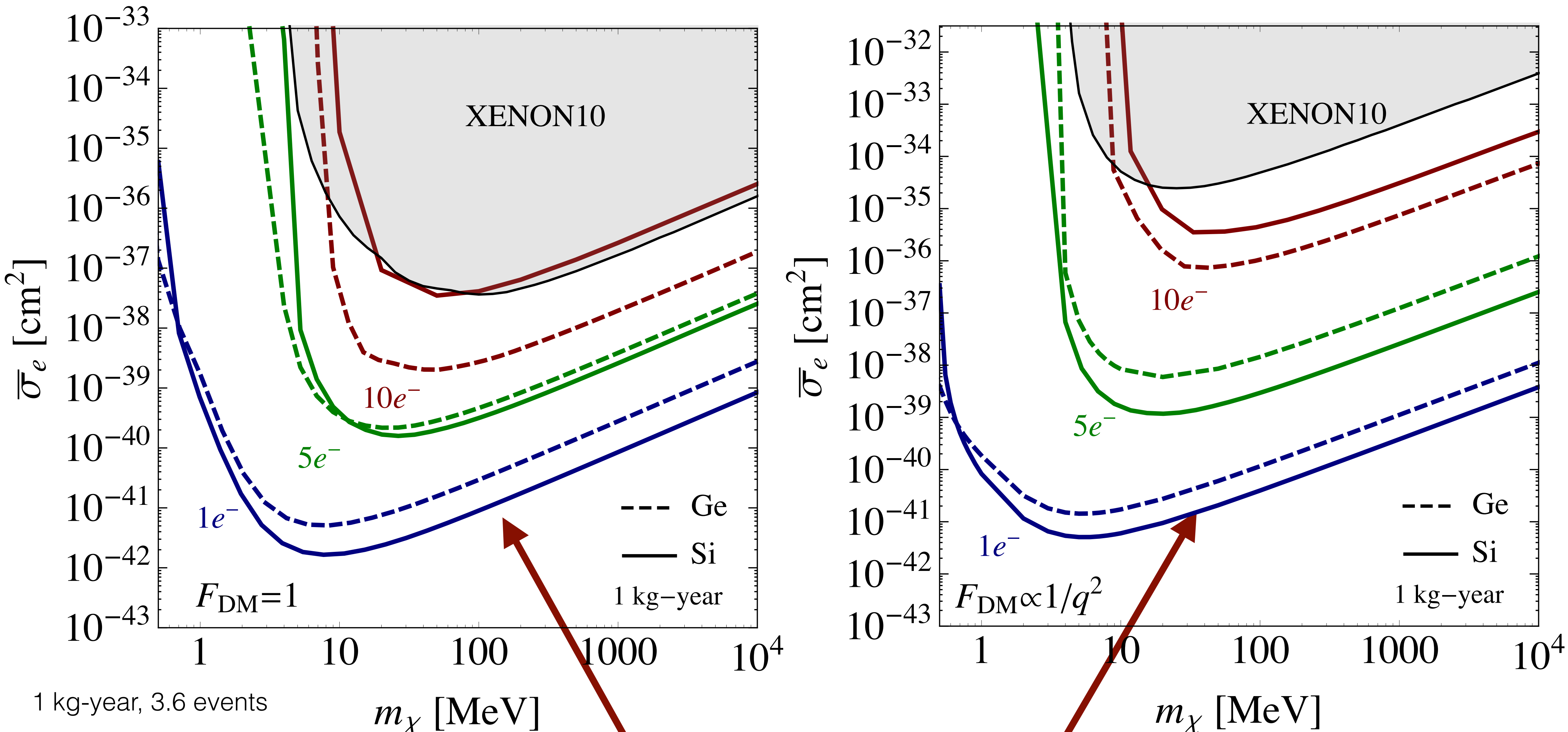
Semiconductor targets



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

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

Semiconductor targets

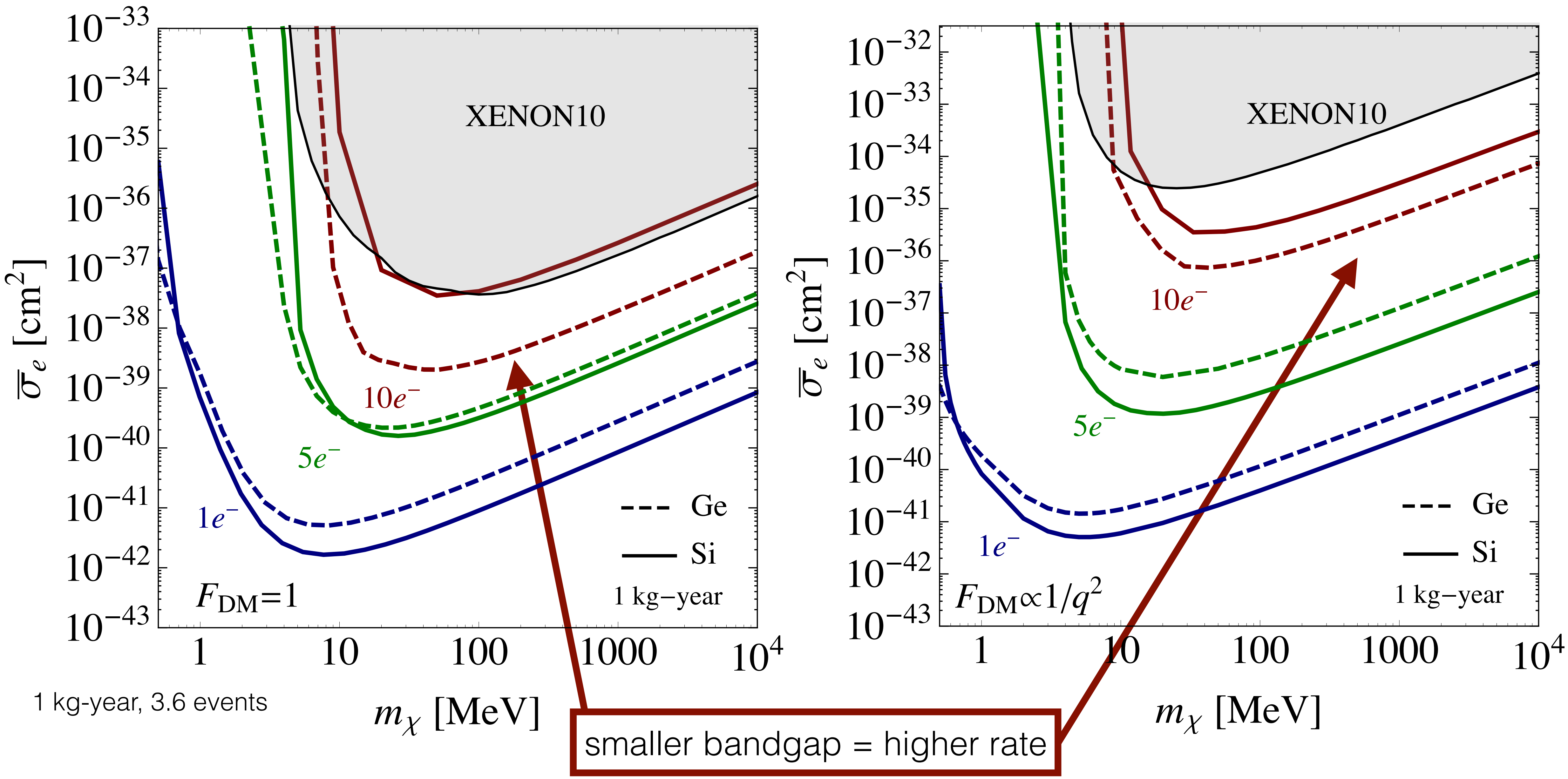


1 kg-year, 3.6 events

smaller atomic mass = more electrons per target mass

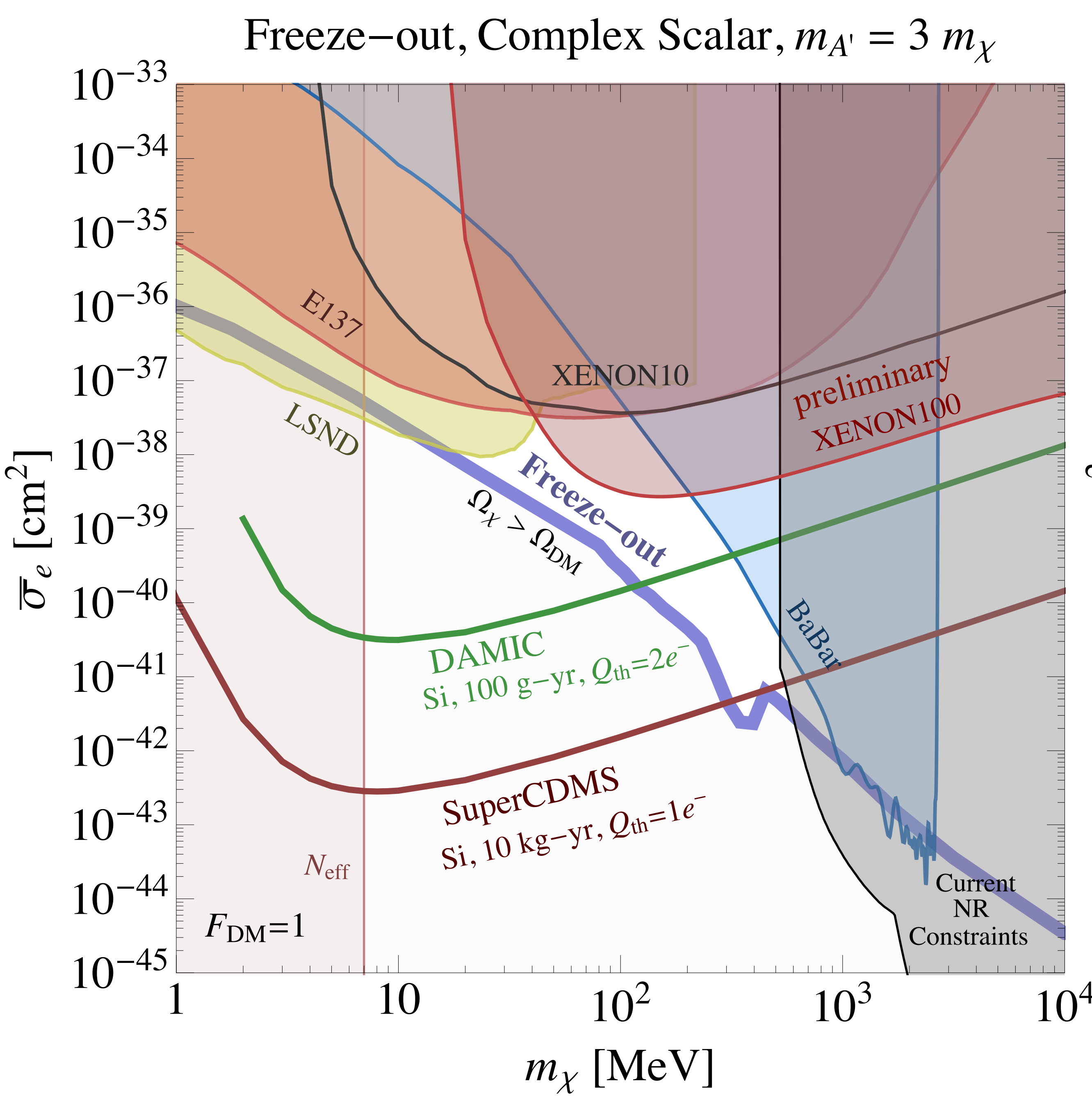
Si wins at high masses and low thresholds

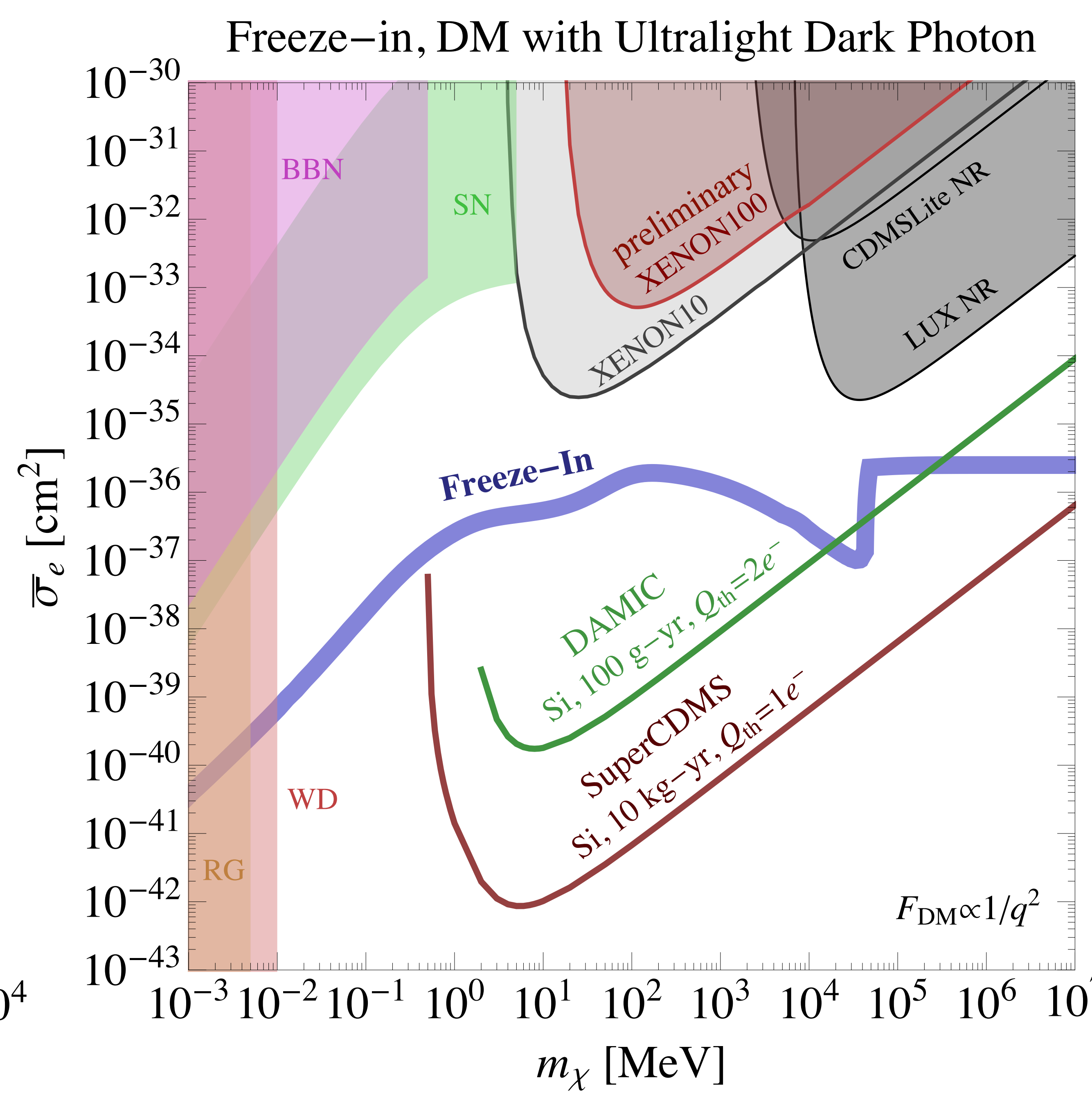
Semiconductor targets



Ge wins at low masses and high thresholds

Semiconductor targets



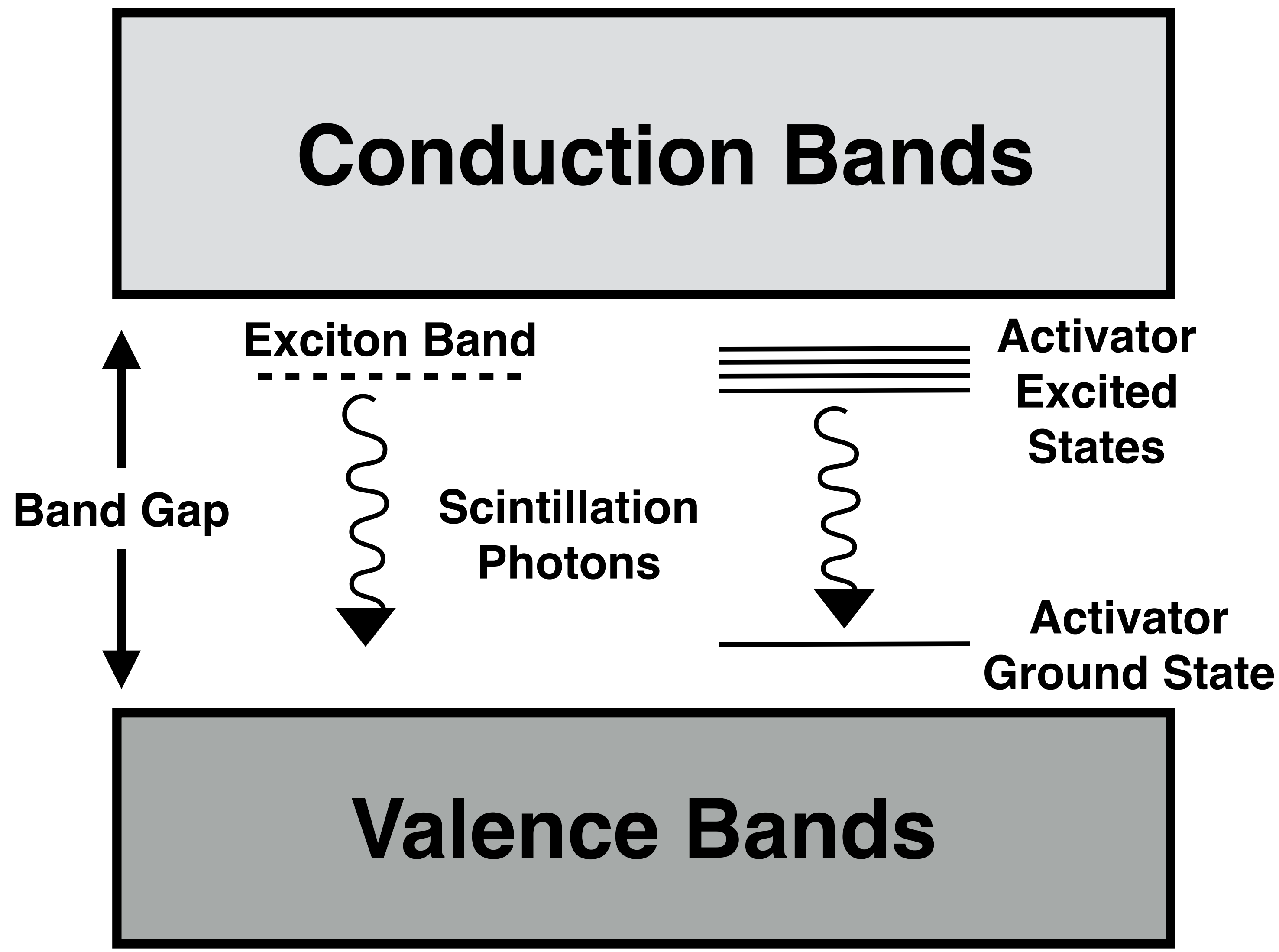


challenges

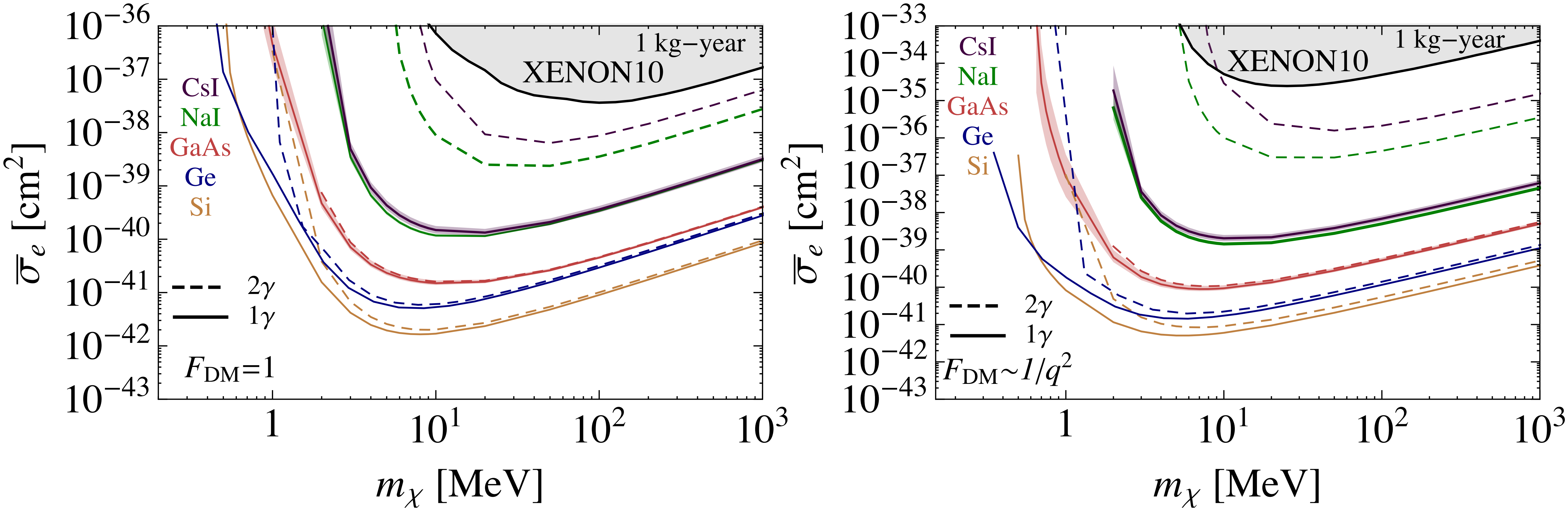
- readout noise
- E-field used to drift the electrons may produce dark current — fundamentally limits the sensitivity

scintillators

A scintillator is a material that, when struck by an incoming particle, absorb its energy re-emits the absorbed energy in the form of light



scintillators



Derenzo, Essig, Massari, Soto, TTY [1607.01009]

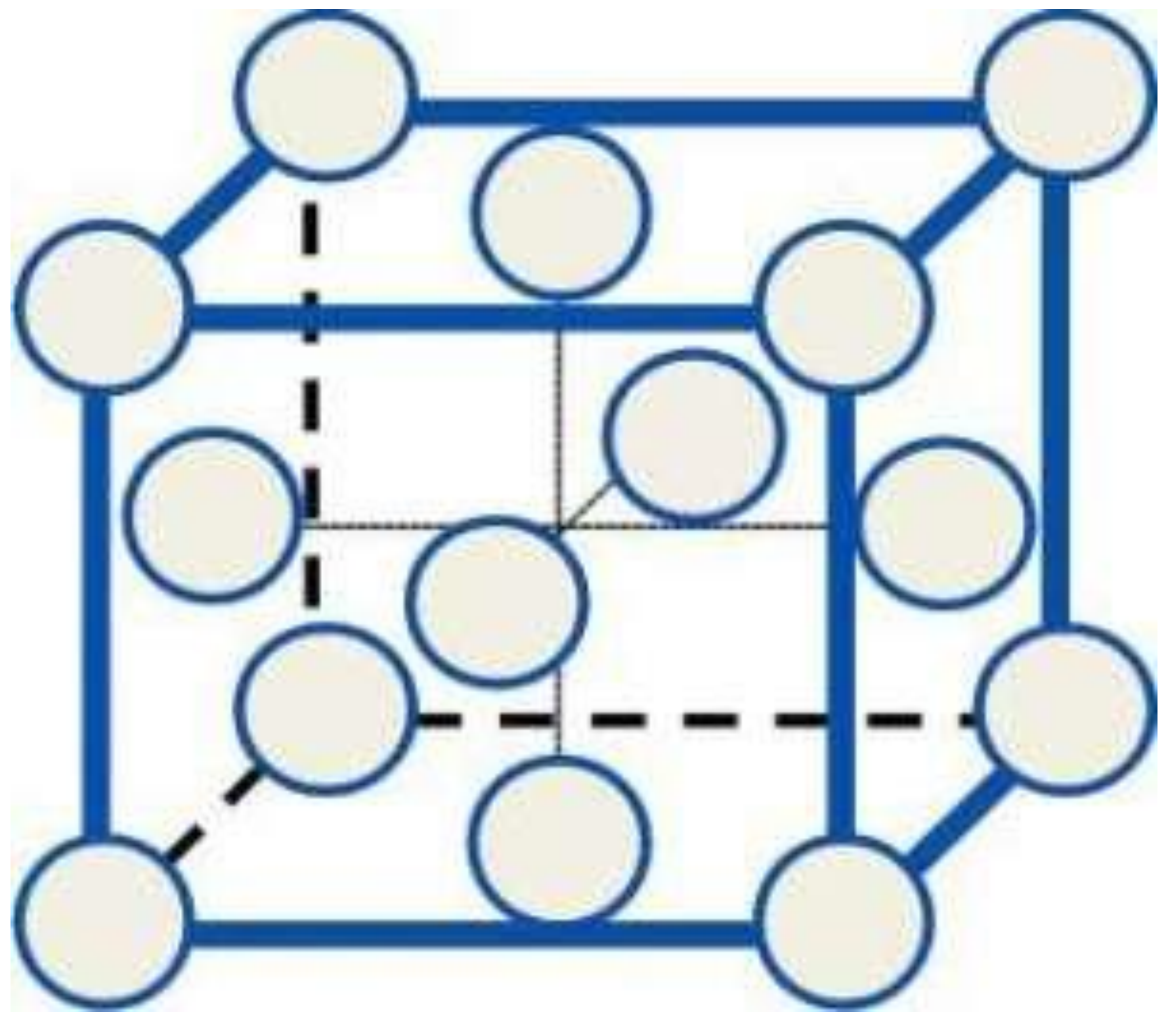
challenges

- contaminants in detector material
- needs large area photon detectors (proposals in progress)
- afterglow

signal vs. background discrimination

- variety of materials and techniques
- annual modulation
- directionality (daily modulation)

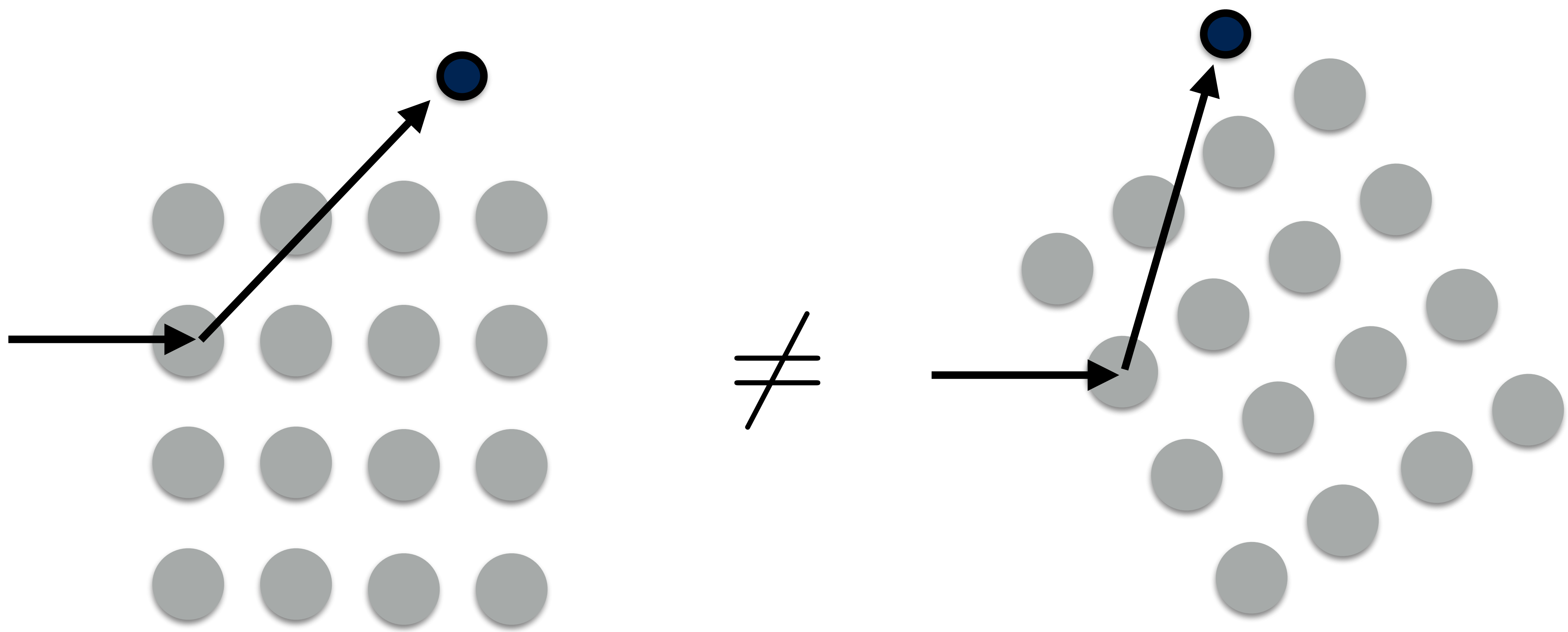
directionality



Department for Materials Research, Risø DTU

Essig, Mardon, Soto, TTY (in preparation)

directionality

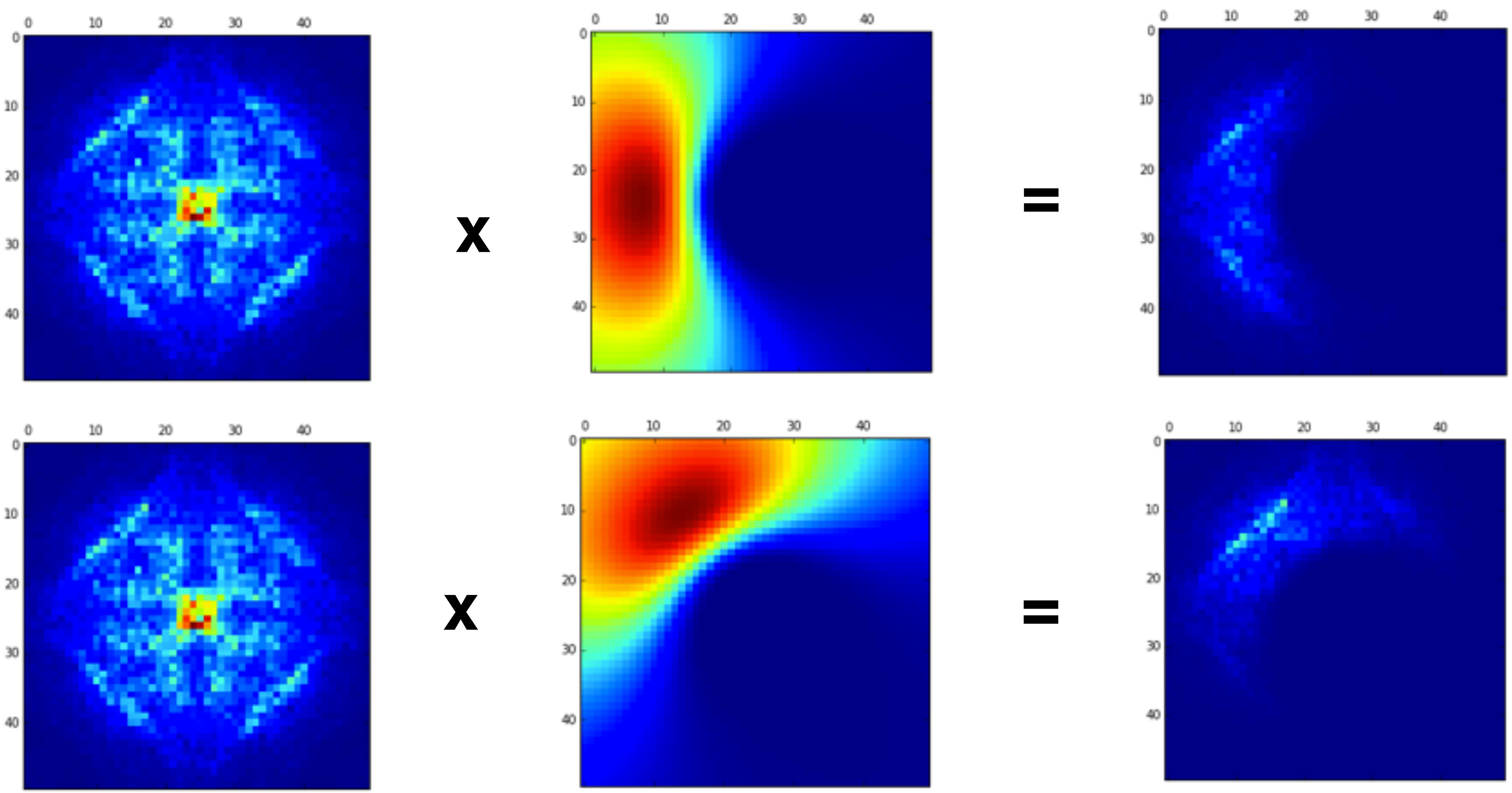


Essig, Mardon, Soto, TTY (in preparation)

directionality

GaAs form factor

halo function

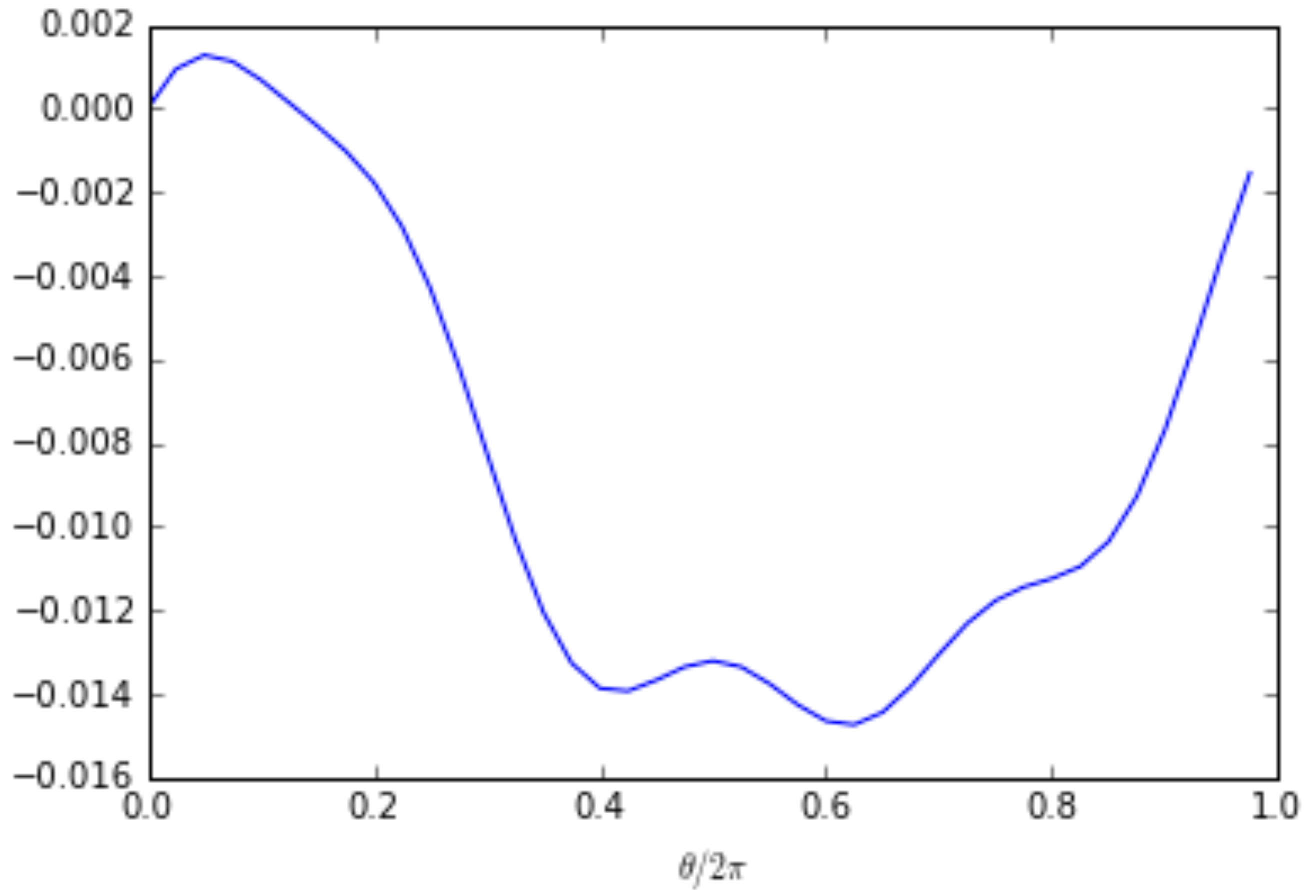


Essig, Mardon, Soto, TTY (in preparation)

very preliminary

directionality

GaAs, mDM=10 MeV



Essig, Mardon, Soto, TTY (in preparation)

very preliminary

other ideas

- chemical bond breaking —   [1608.02940]
- 2D targets — graphene [1606.08849], carbon nanotubes [1412.8213,1602.03216]
- superconductors — [1504.07237, 1512.04533]
- superfluid helium — [1604.08206]
- ????

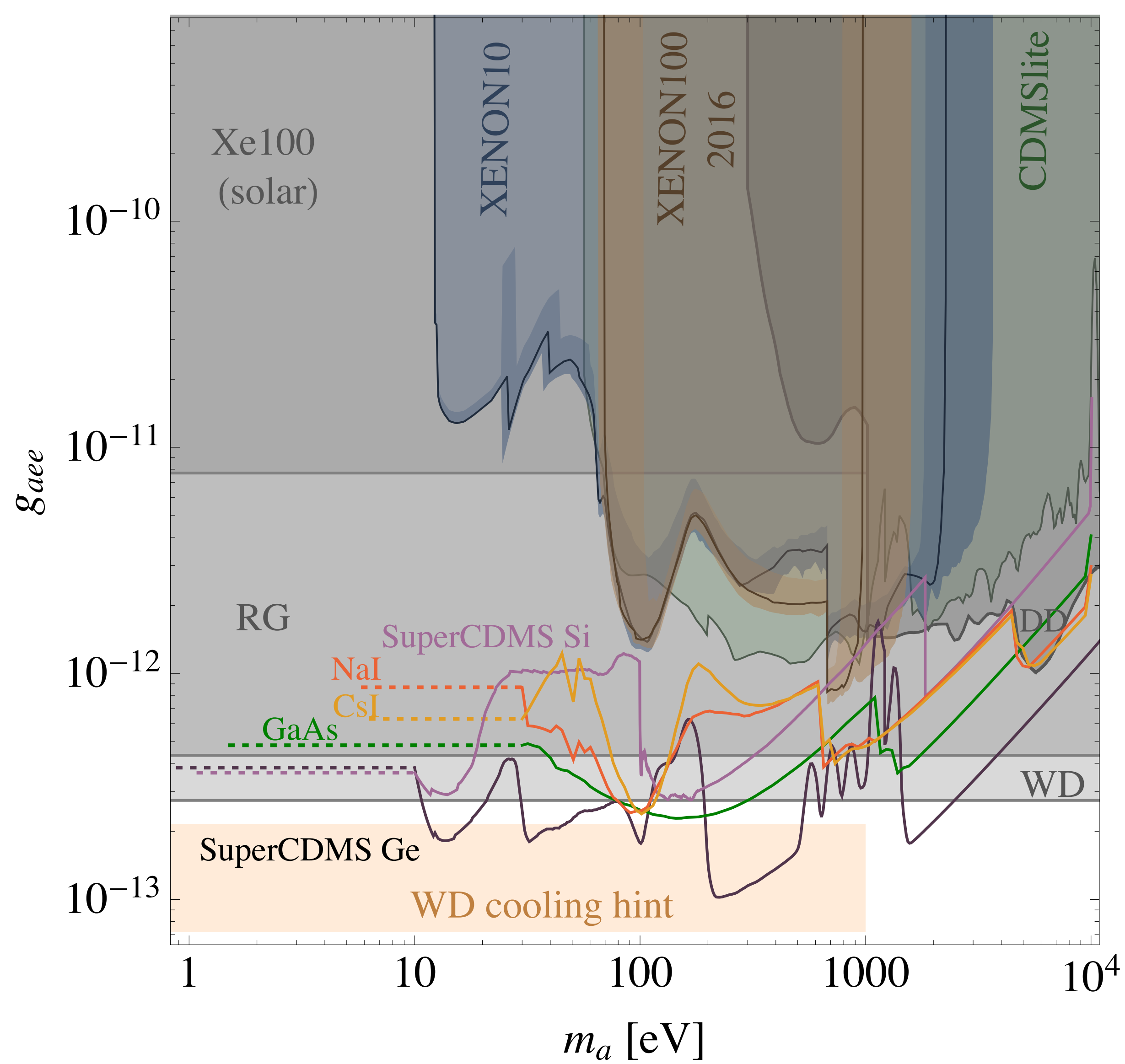
Absorption

- **same experiments** can be used for ultralight (~eV) DM
- consider absorption of DM instead of scattering
- see Tongyan Lin's talk for more details

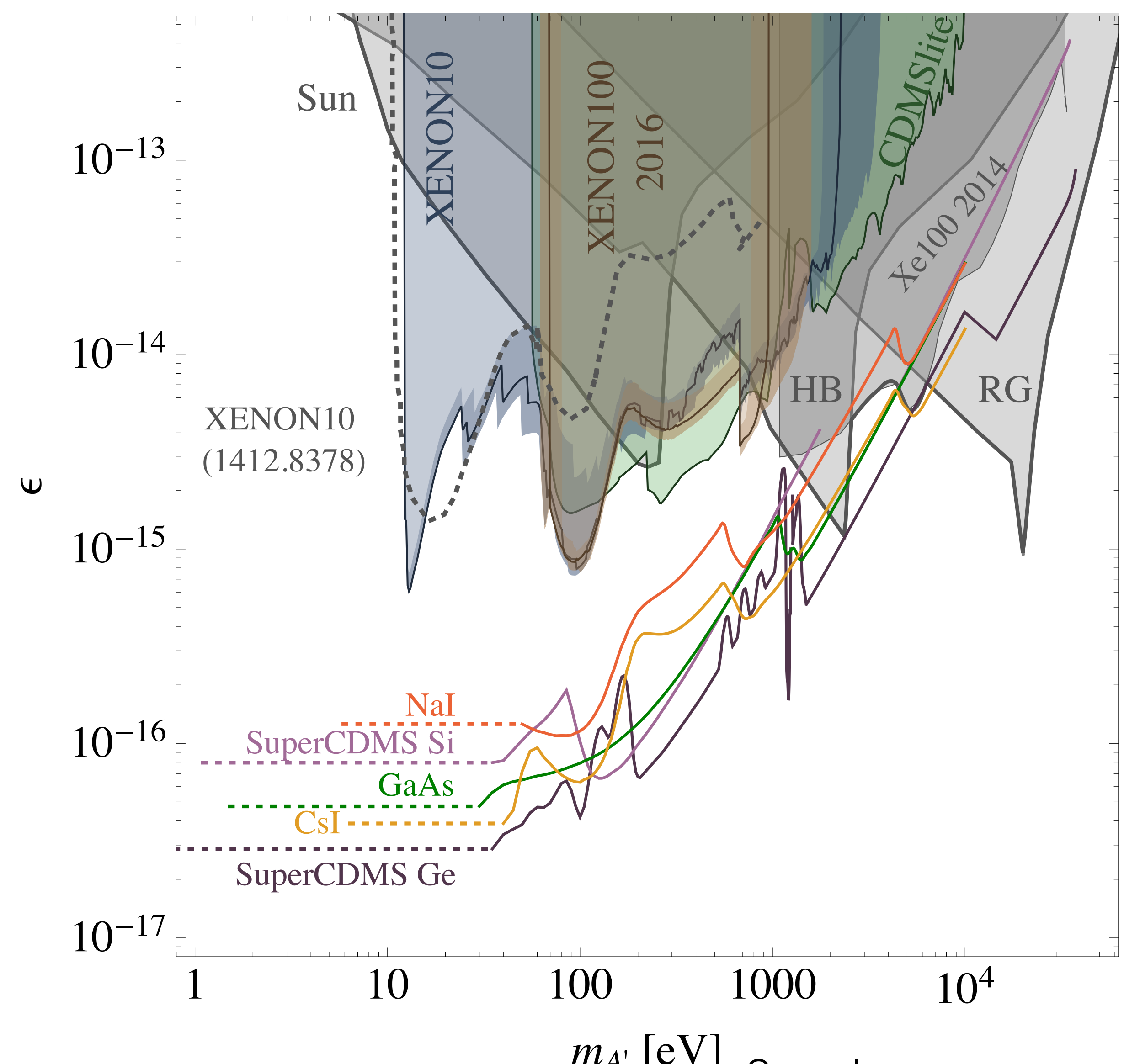
Absorption

See also Raffelt, Redondo,…

axions



dark photons

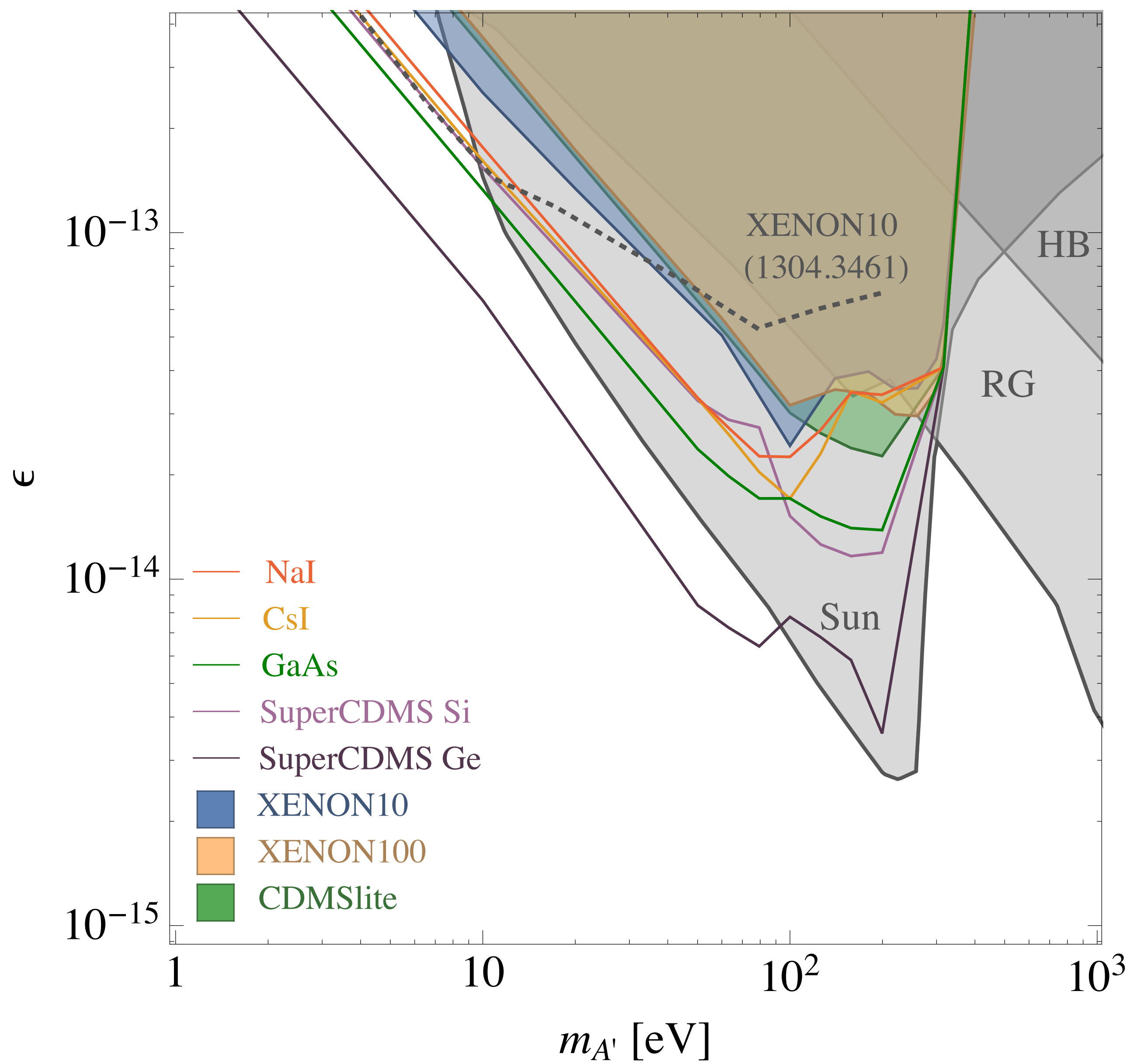


Bloch, Essig, Tobioka, Volansky, TTY [1608.02123]

See also:
An, Pospelov, Pradler, Ritz [1401.8287]
An, Pospelov, Pradler [1309.6599]
Hochberg, Lin, Zurek [1604.06800,1608.01994]

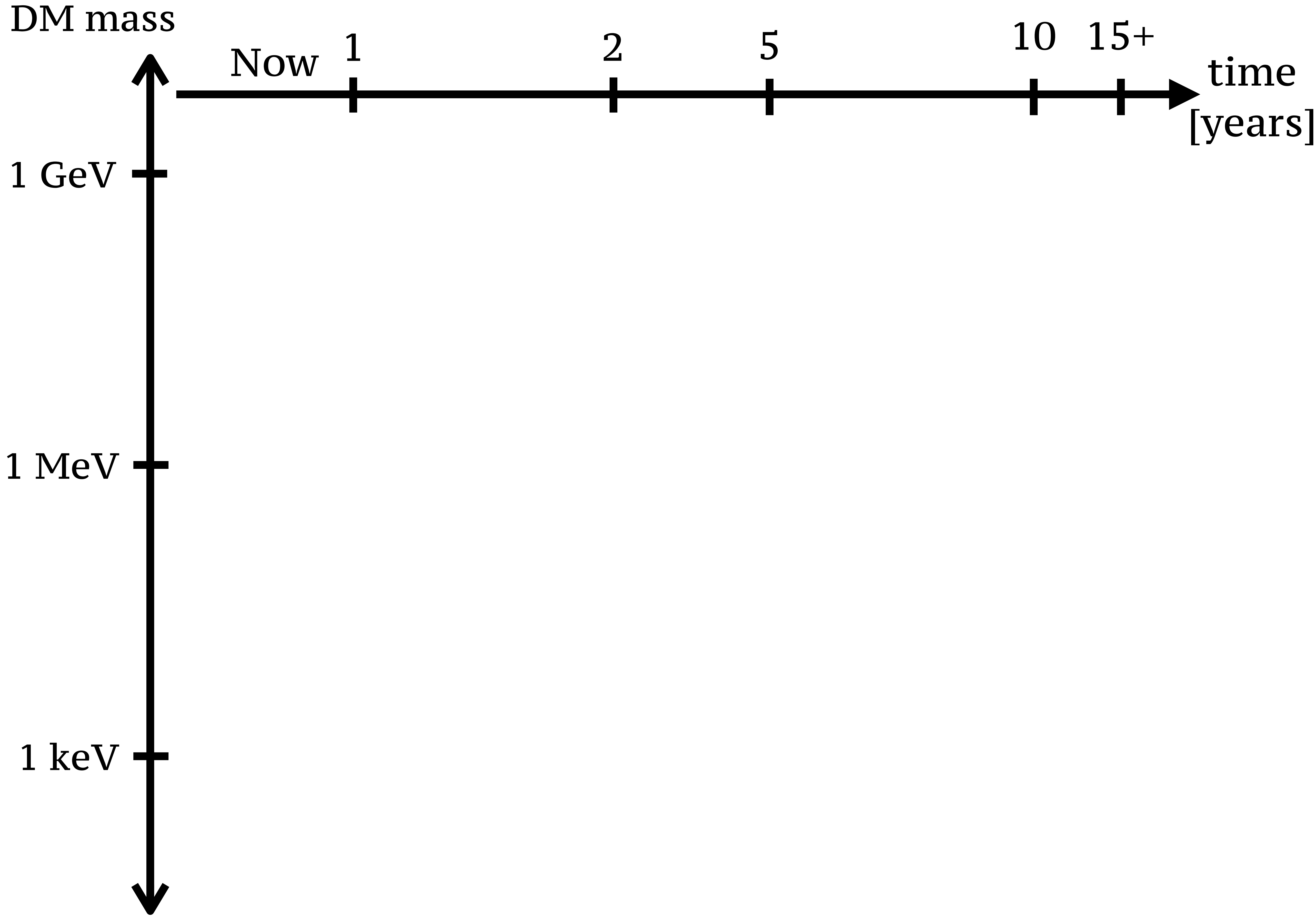
Absorption

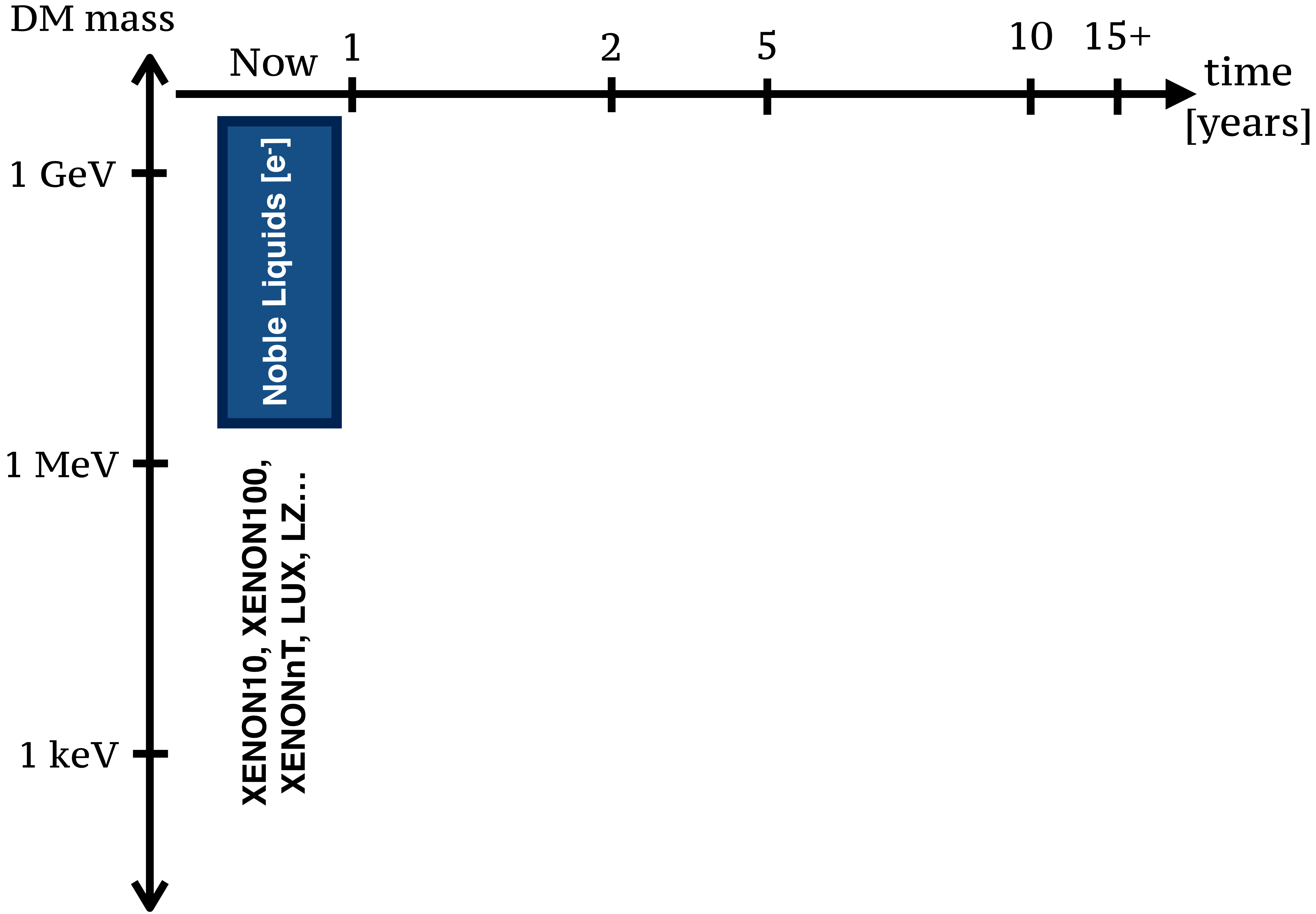
solar dark photons



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

See also
An, Pospelov, Pradler [1304.3461]


DM mass
Now
1
2
5
10
15+
time
[years]
1 GeV
1 MeV
1 keV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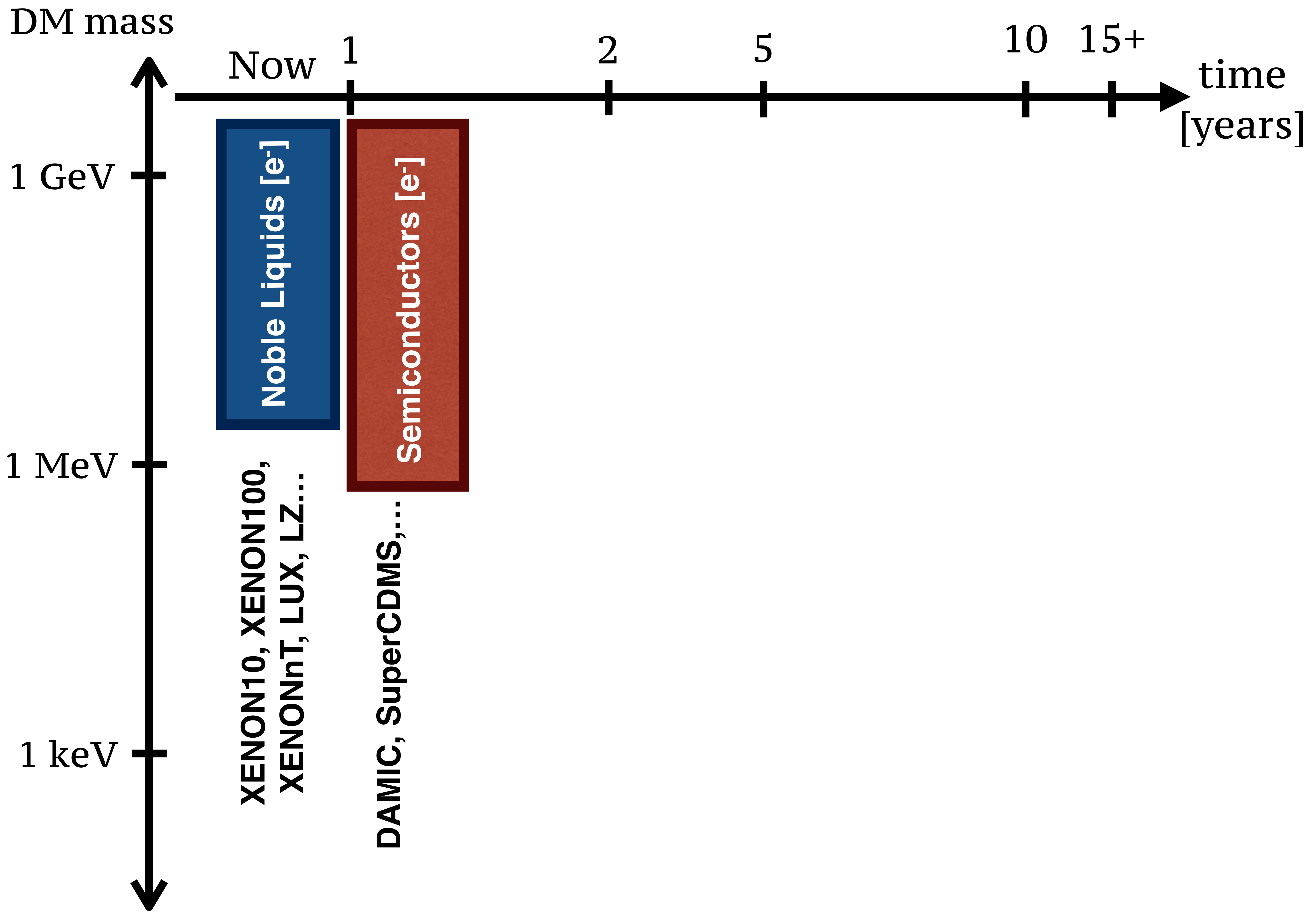
Noble Liquids [e-]
XENON10, XENON100,
XENONnT, LUX, LZ...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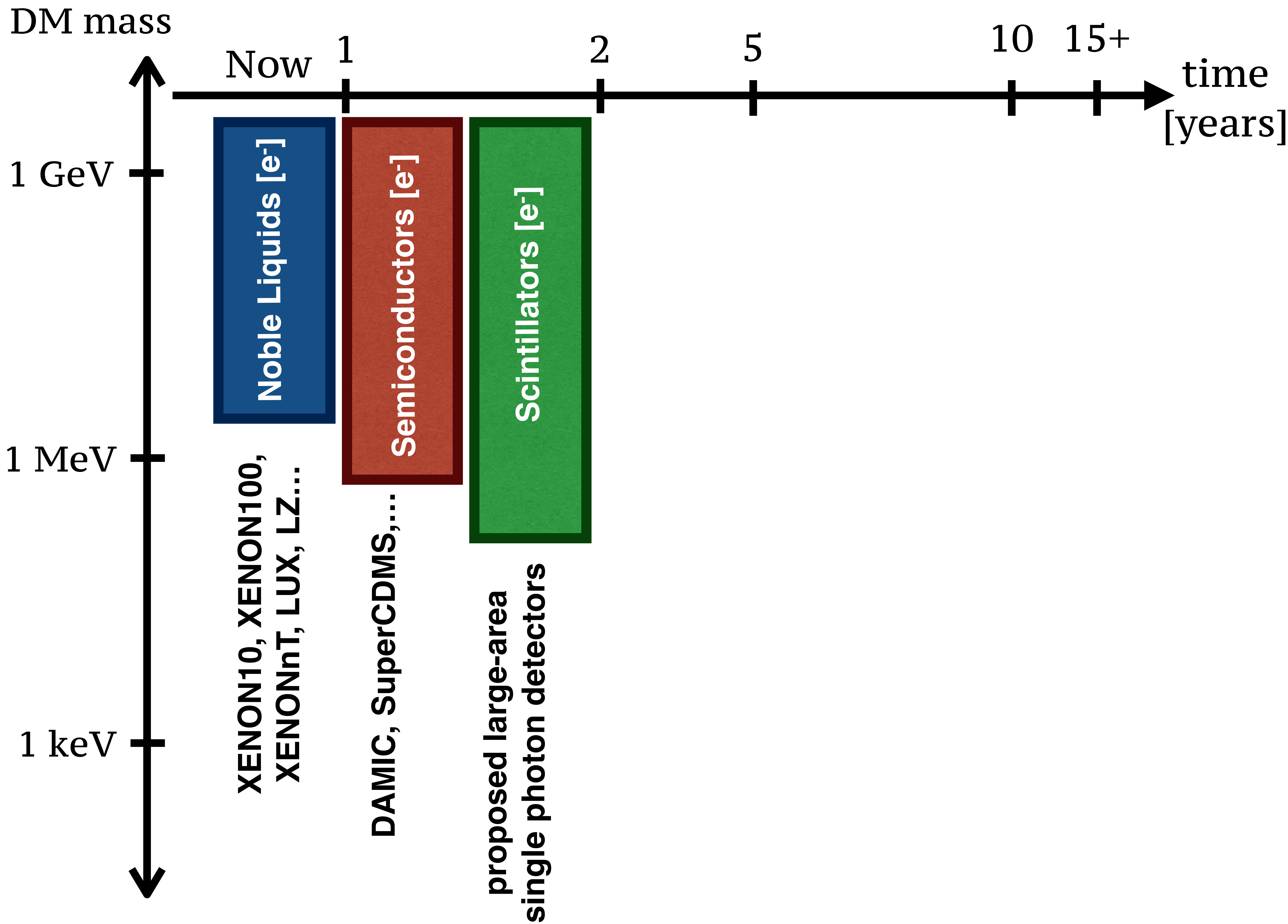
Semiconductors [e-]
DAMIC, SuperCDMS,...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XENON10, XENON100,
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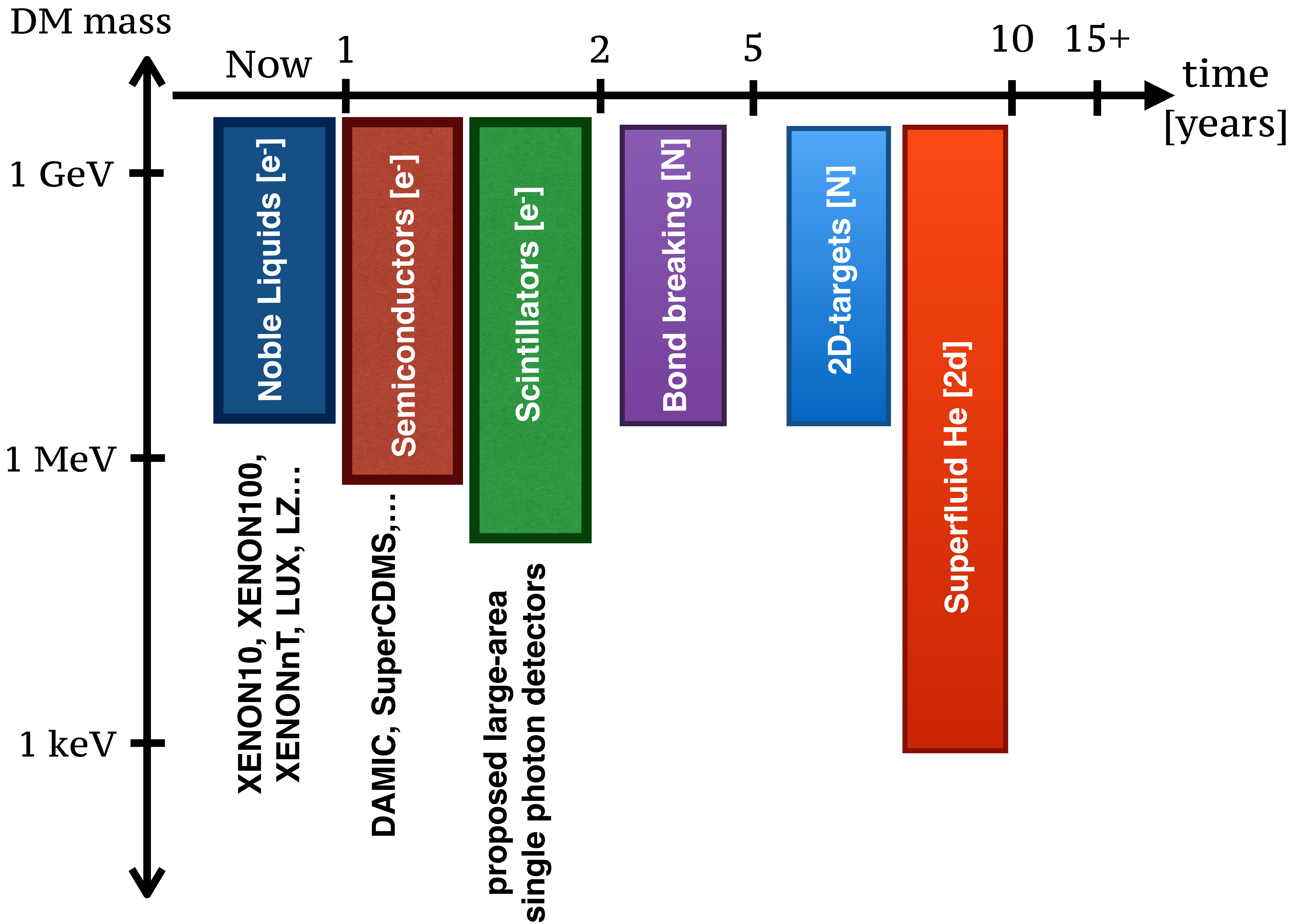
DAMIC, SuperCDMS,....
proposed large-area
single photon detectors



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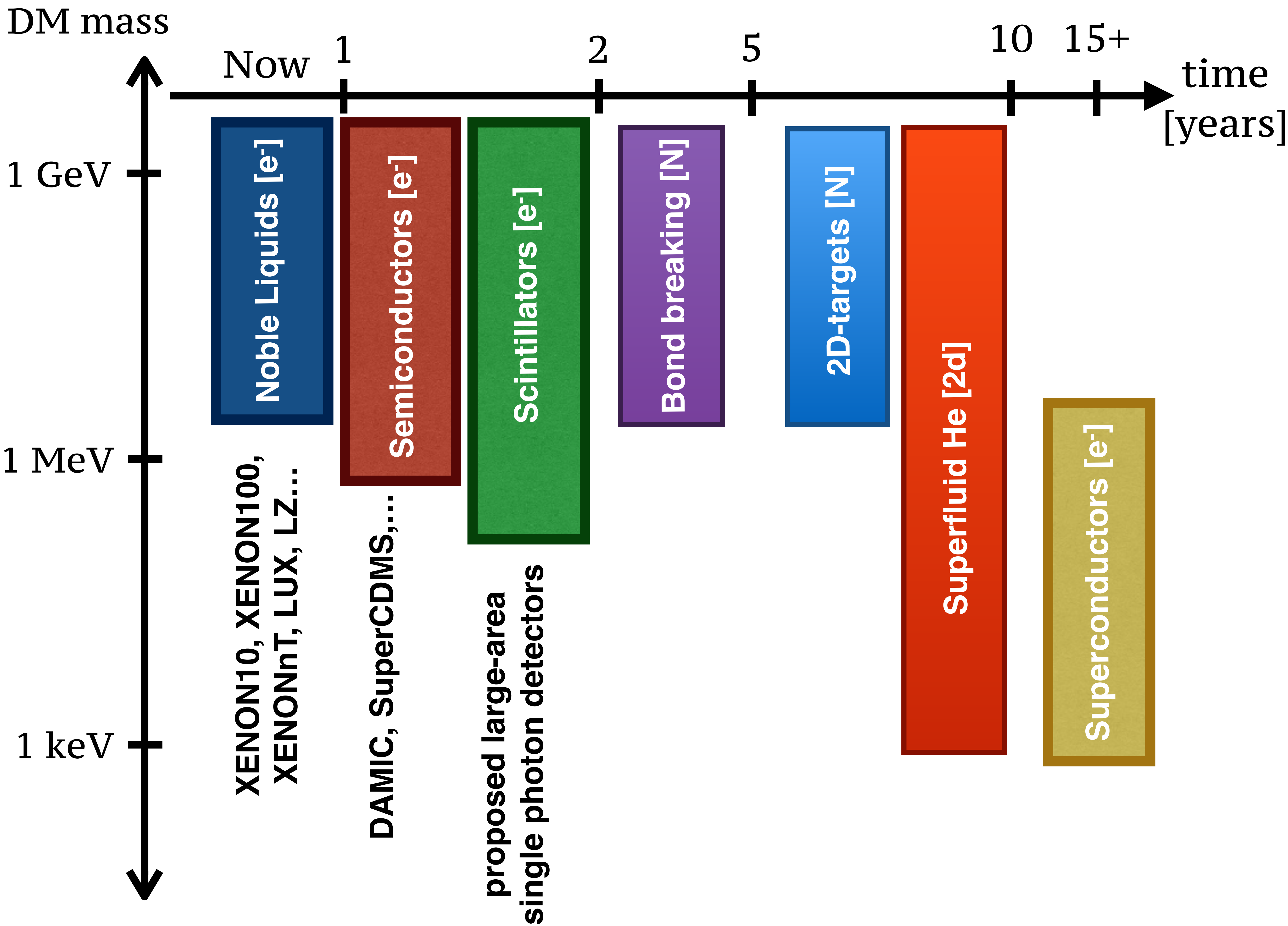
Bond breaking [N]
2D-targets [N]
Superfluid He [2d]
XENON10, XENON100, XENONnT, LUX, LZ...
DAMIC, SuperCDMS,...
proposed large-area single photon detectors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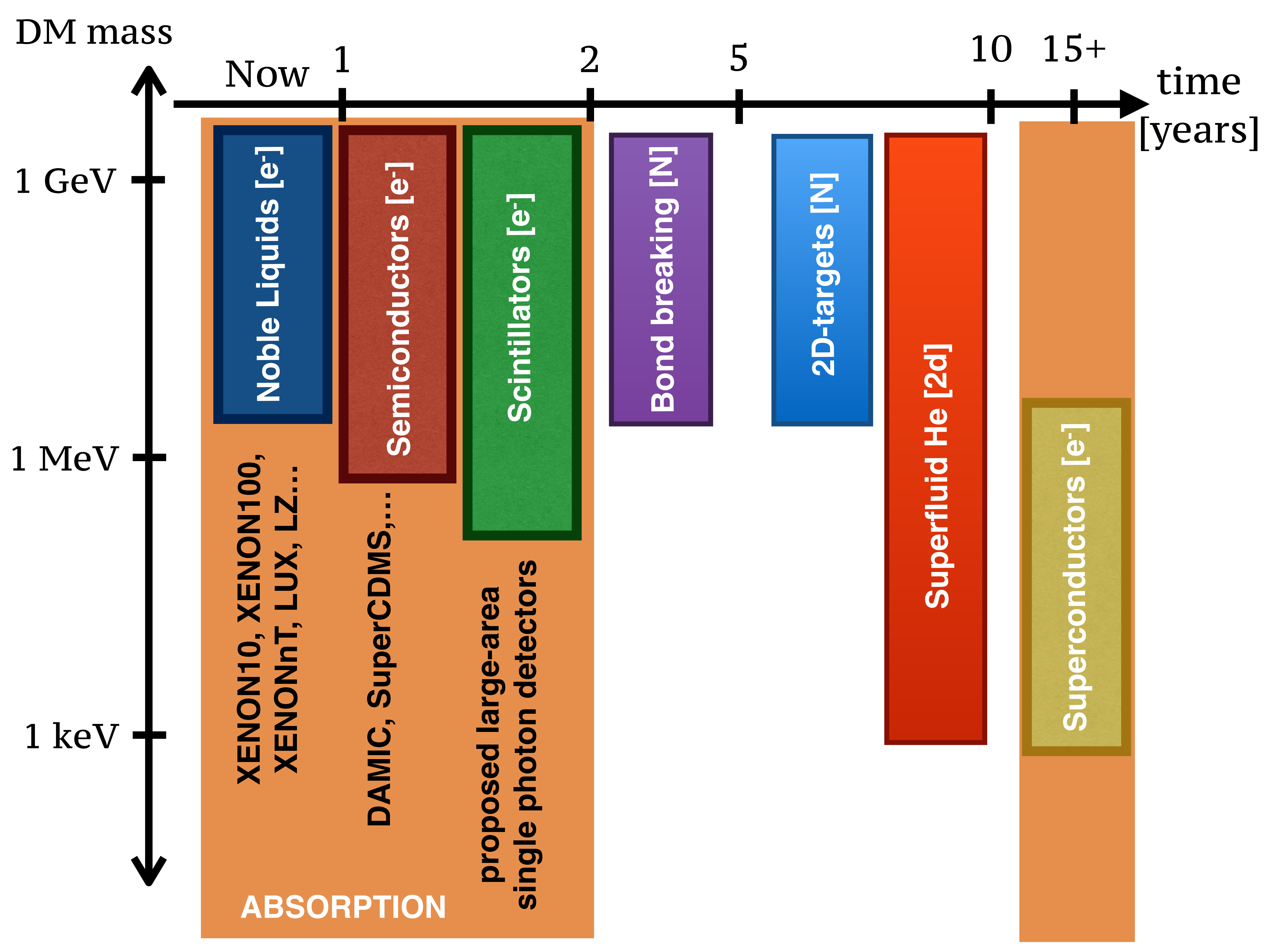
Bond breaking [N]
2D-targets [N]
Superfluid He [2d]
Superconductors [e-]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XENON10, XENON100, XENONnT, LUX, LZ...
DAMIC, SuperCDMS,...
proposed large-area single photon detectors
ABSORPTION

Material	$m_{\mathrm{DM,th}}$ (theoretical)	Technology	Challenges	(Optimistic) Timescale
Noble liquids (Xe, Ar)	few MeV	two-phase TPC	dark counts	existing
Semiconductors (Si, Ge)	$\sim 0.1 - 1$ MeV	CCDs & Calorimeter	dark counts (?)	$\sim 1 - 2$ years
Scintillators (GaAs, NaI, CsI)	$\sim 0.5 - 1$ MeV	Calorimeter: $\sigma_E \sim 0.2$ eV	sensitivity & afterglow (?)	$\lesssim 5$ years
Superconductors (Al)	~ 1 keV	Calorimeter: $\sigma_E \sim 1$ meV	sensitivity & unknown backgrounds	$\sim 10 - 15$ years
Superfluid He (NR)	~ 1 MeV	Calorimeter: $\sigma_E \sim 1$ eV	sensitivity & unknown backgrounds	$\lesssim 5$ years
Bond Breaking	$\sim$ few MeV	color centers	sensitivity & unknown backgrounds	$\lesssim 5$ years
Superfluid He (2-excitation)	~ 1 keV	Calorimeter $\sigma_E \sim 10$ meV	sensitivity & unknown backgrounds	$\sim 5 - 10$ years
2D-targets (graphene)	few MeV	based on PTOLEMY	low exposure, unknown backgrounds	$\sim 5 - 10$ years

Dark Sectors Report: 1608.08632