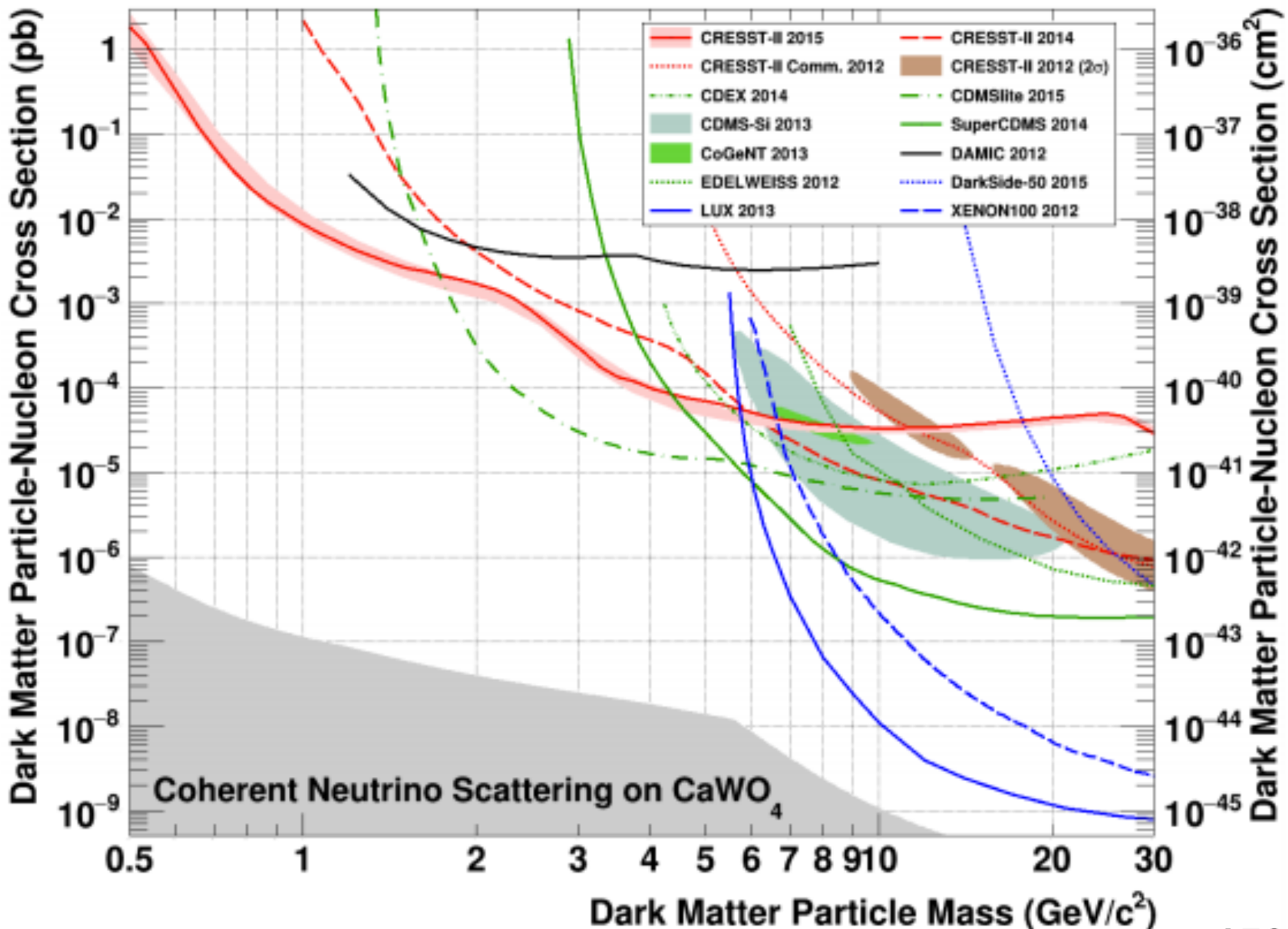
New Directions for DM Direct Detection

Tien-Tien Yu (CERN)

Dark Interactions, BNL - October 4, 2016

Nuclear Recoil



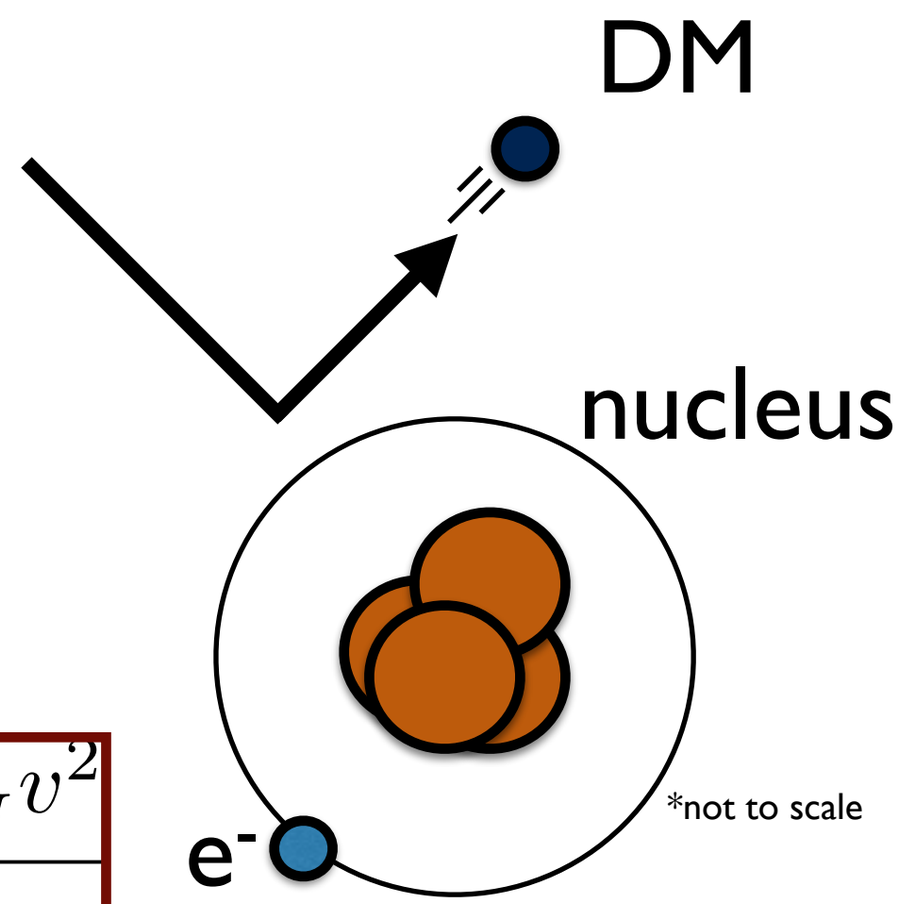
1509.01515

E_{NR} thresholds

LUX: 3 keV

DAMIC: 500 eV

CDMSlite, CRESST: 300 eV

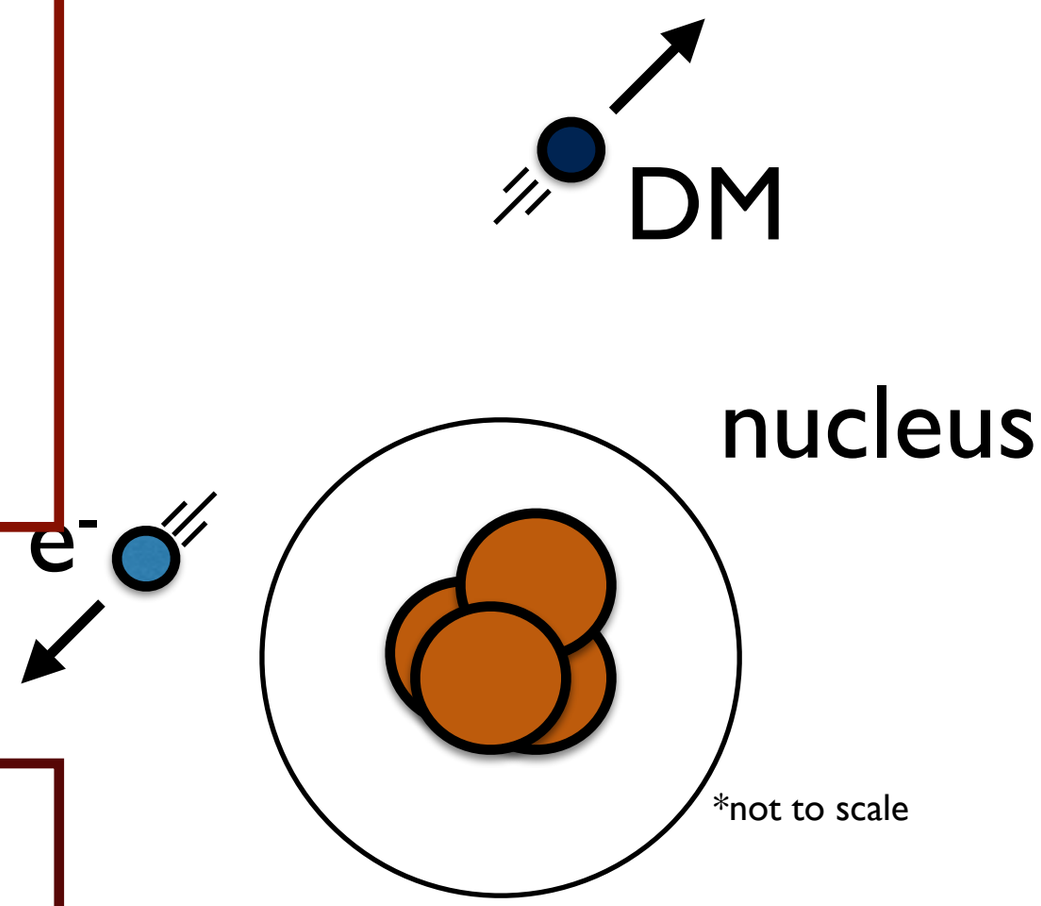


$$E_R = \frac{q^2}{2m_N} \sim \frac{\mu_{\chi N}^2 v^2}{m_N}$$

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

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

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

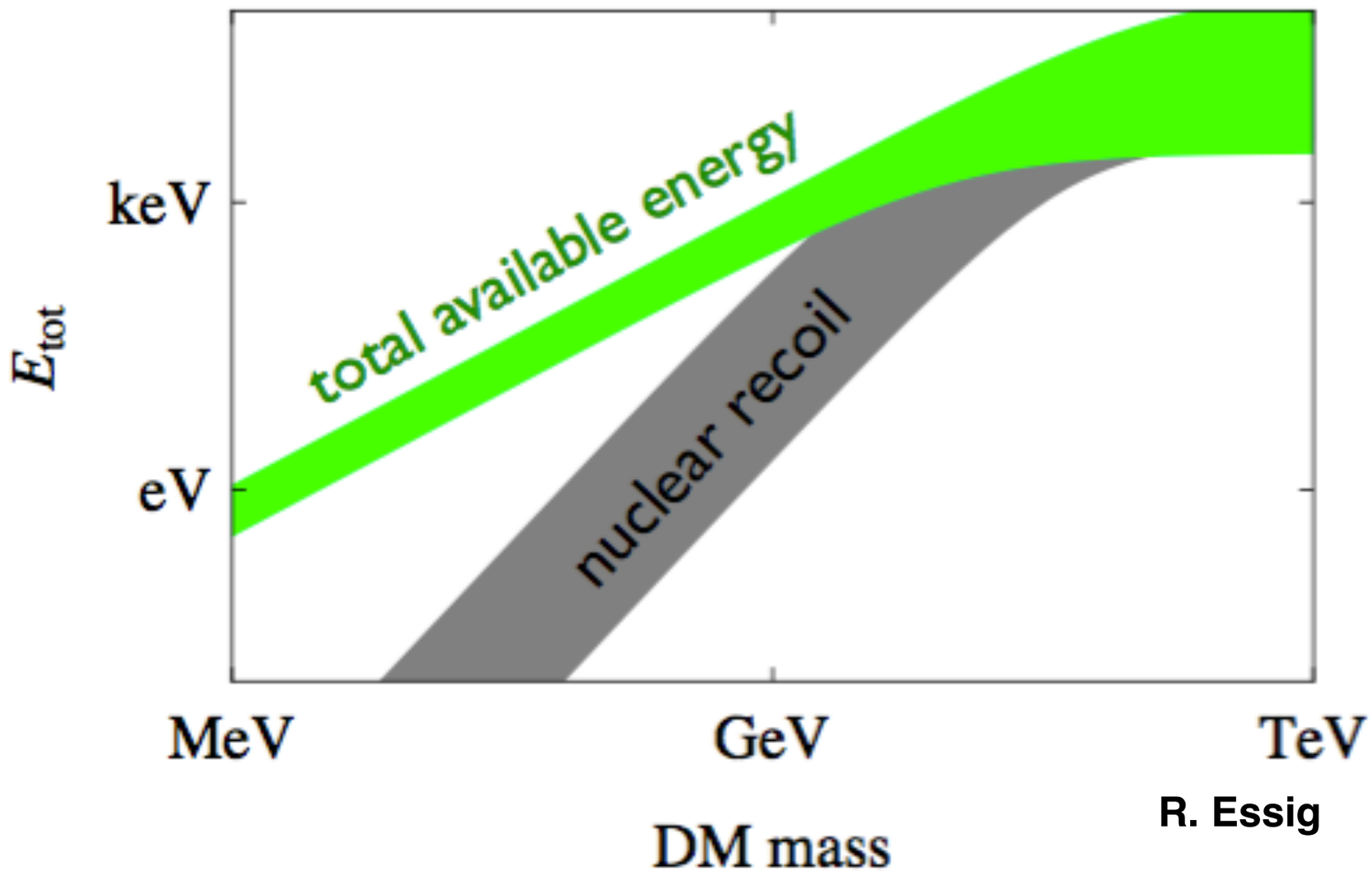
$$\Delta E_e = \vec{q} \cdot \vec{v} - \frac{q^2}{2\mu_{\chi N}}$$

arbitrary-size momentum transfer is possible

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

typical energy transfer

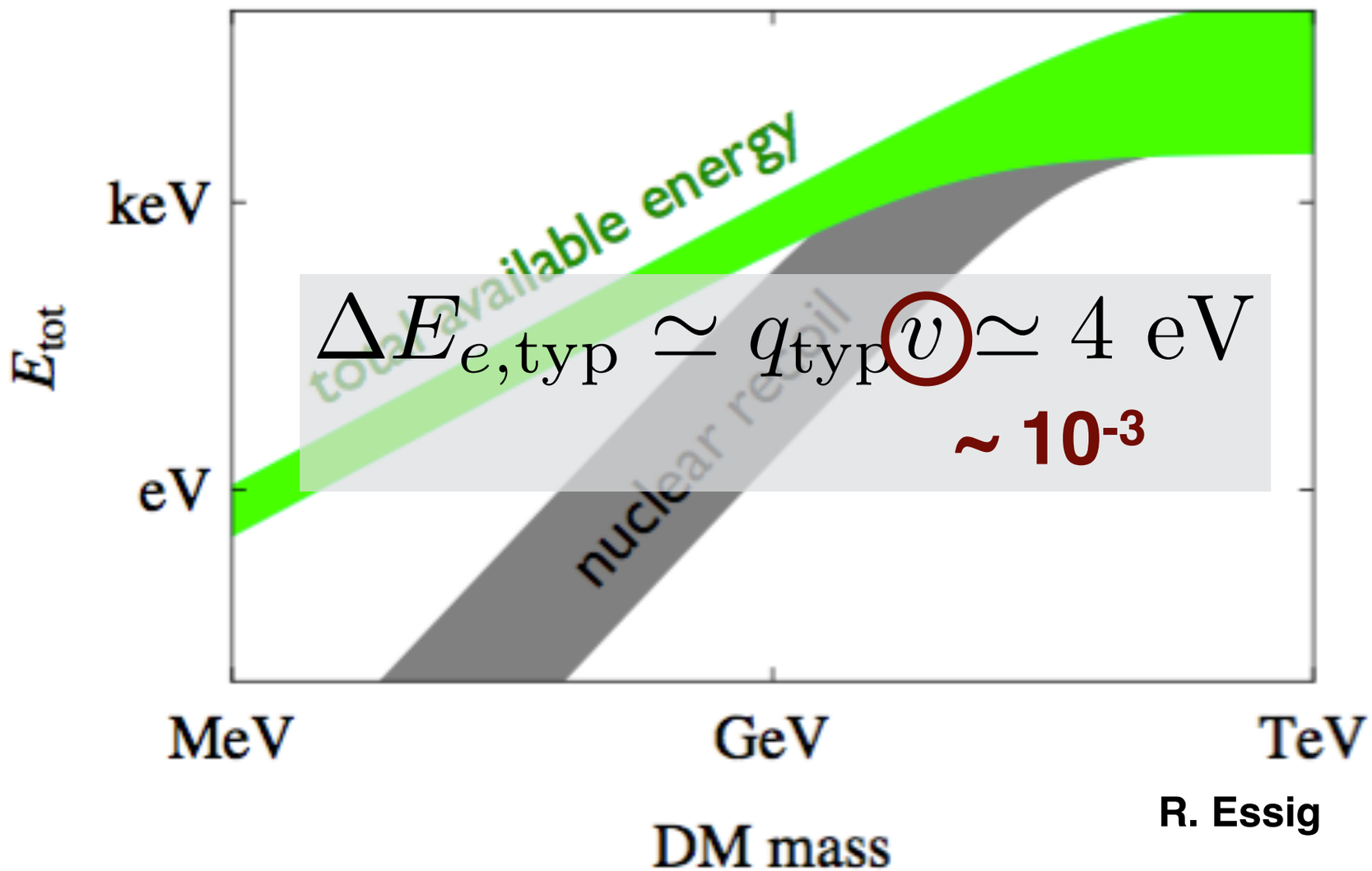
ALL the kinetic energy in the DM-atom collisions is available to excite the electron!



R. Essig

typical energy transfer

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



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

~ 10^{-3}

R. Essig

ingredients

particle physics

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

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

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

ingredients

astrophysics

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

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

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

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

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

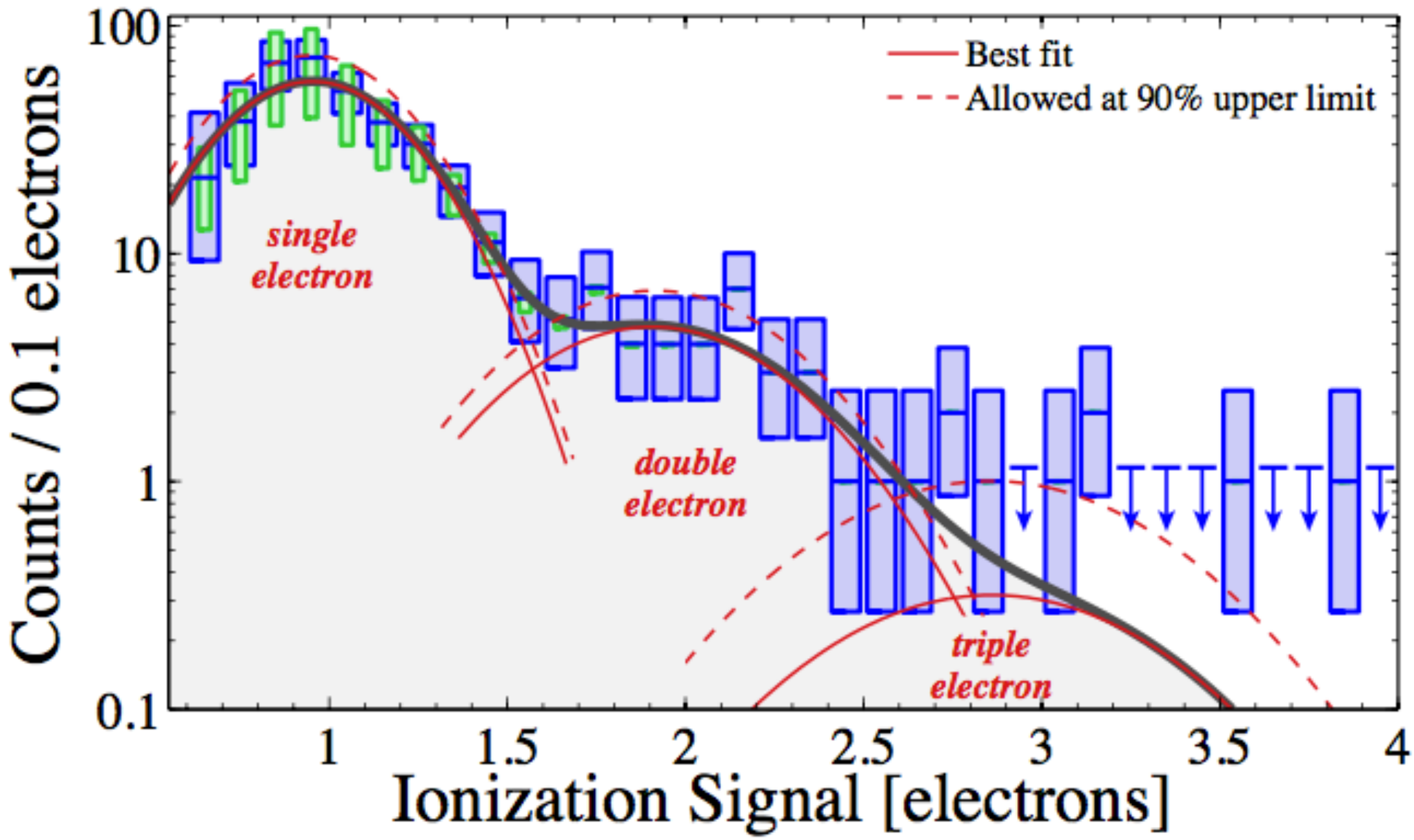
number of target nuclei per unit mass

energy threshold

General goals and challenges

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

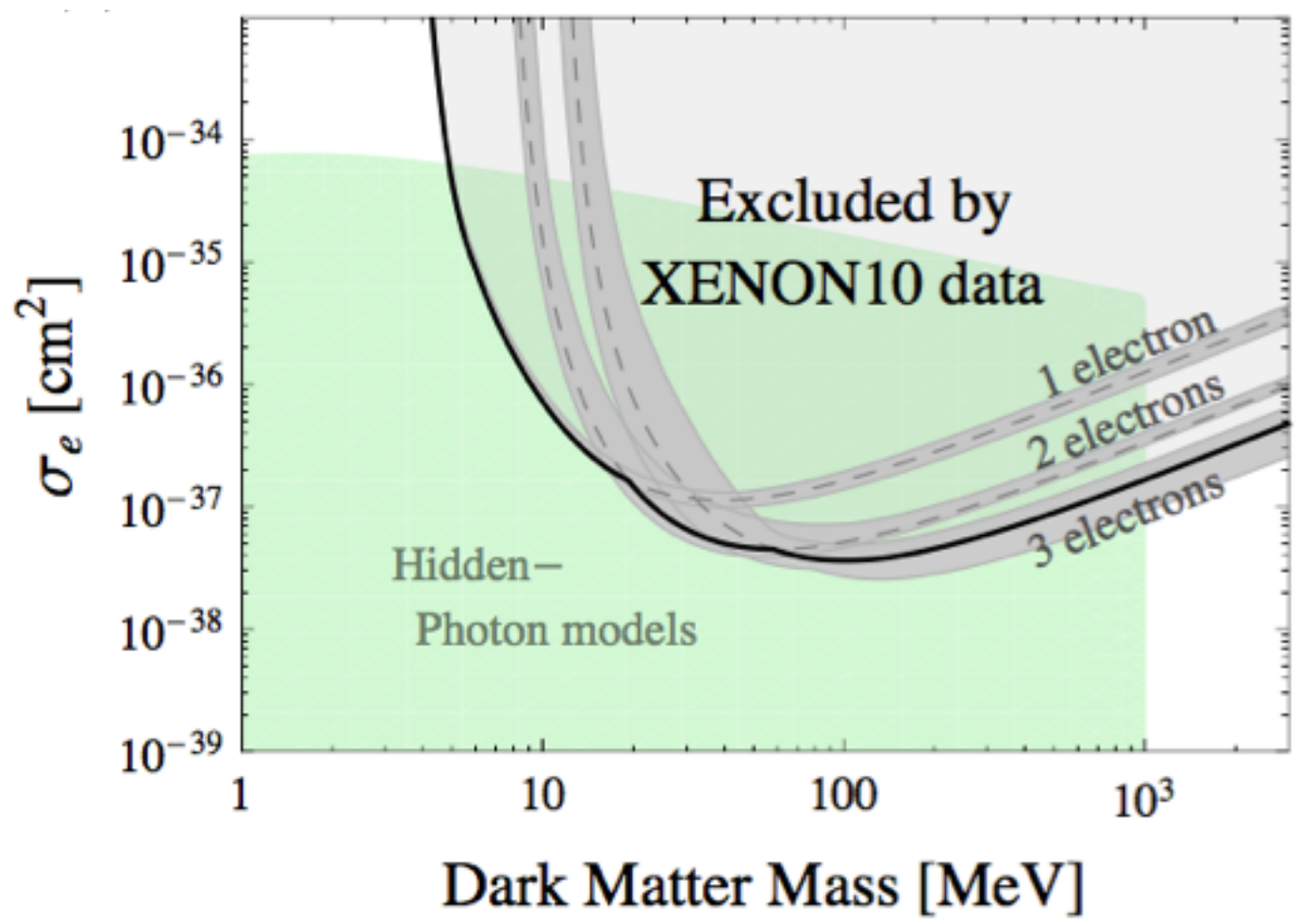
XENON10

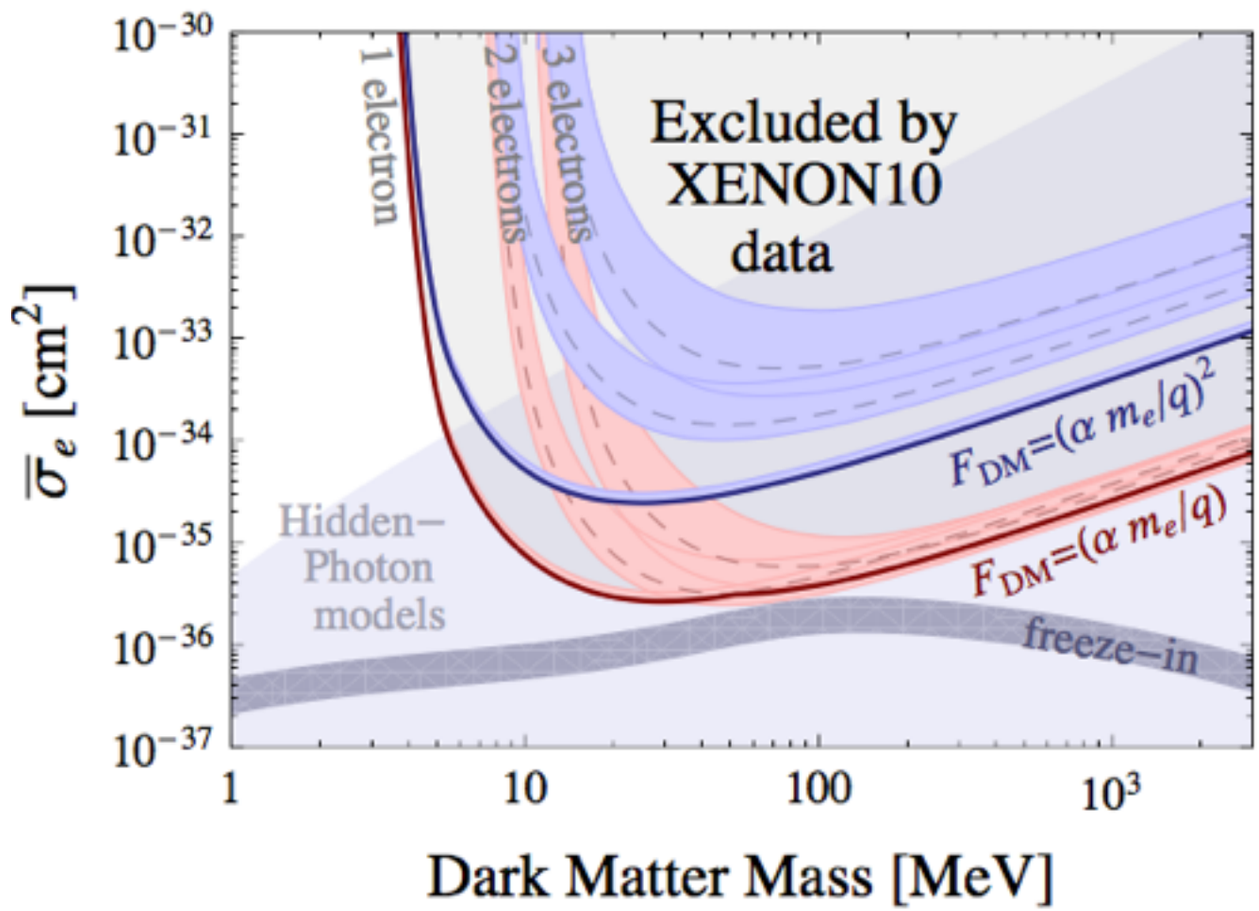


Essig, Manalaysay, Mardon, Sorenson, Volansky

Phys.Rev.Lett. **109** (2012) 021301

XENON10





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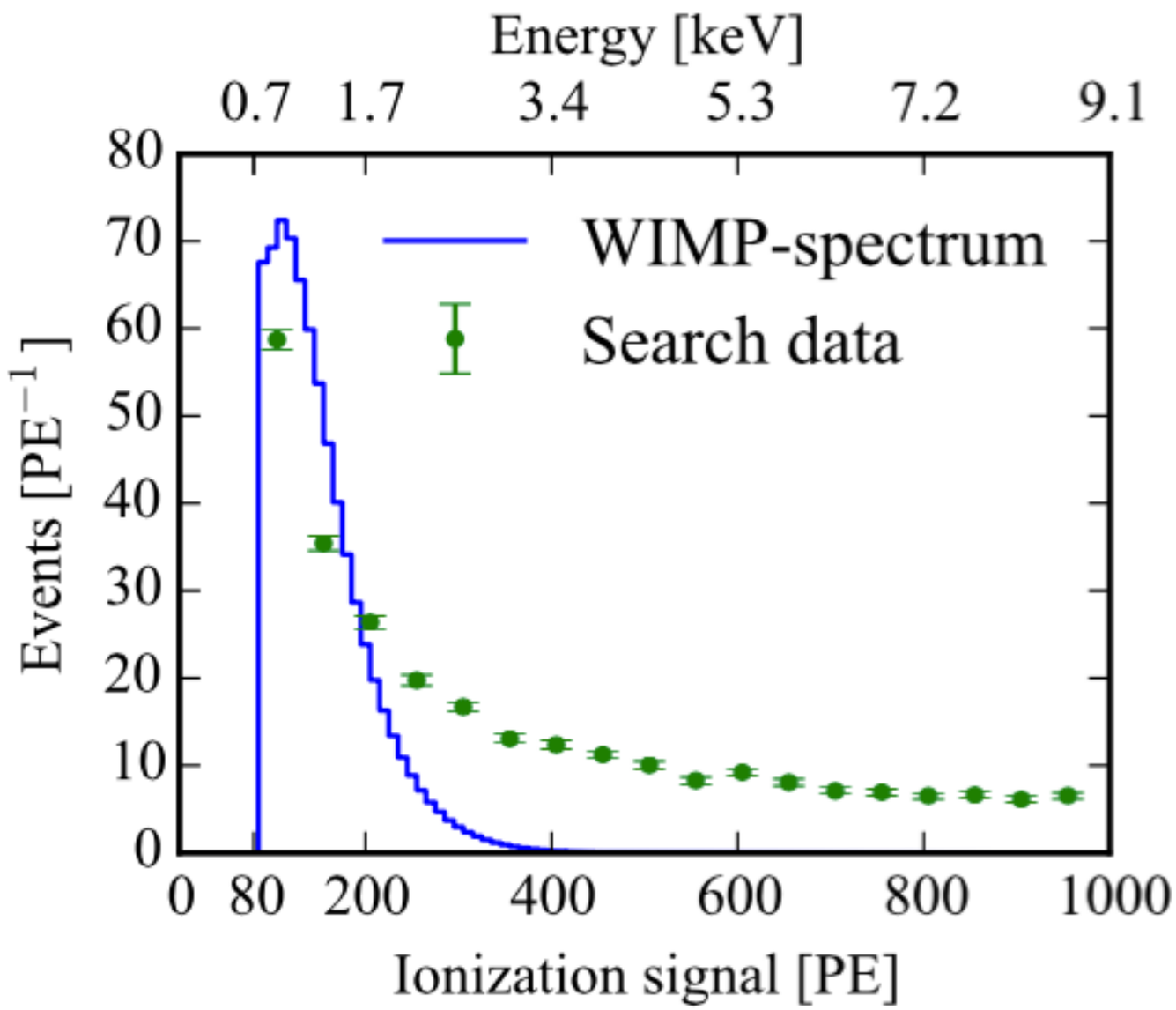
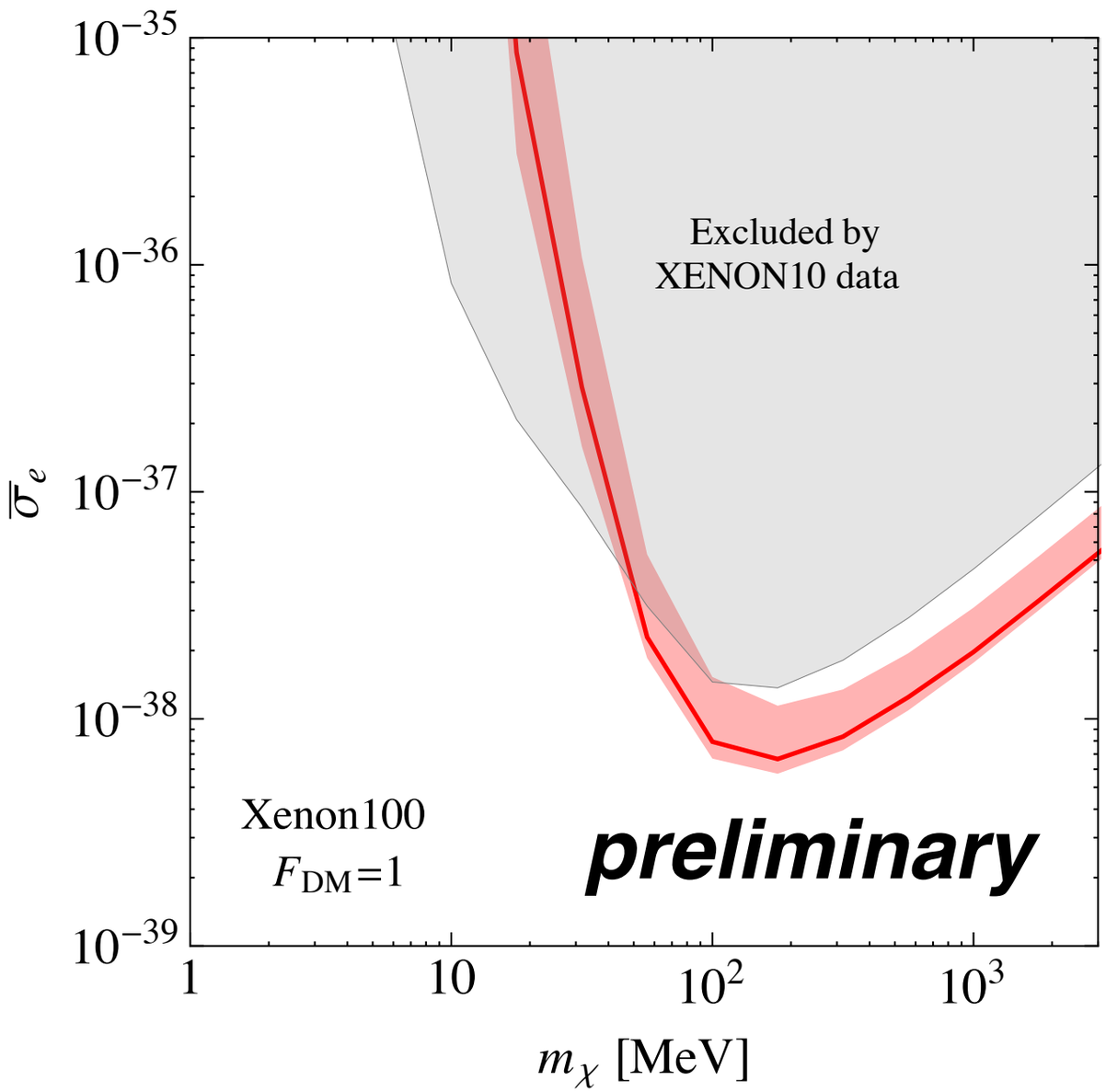
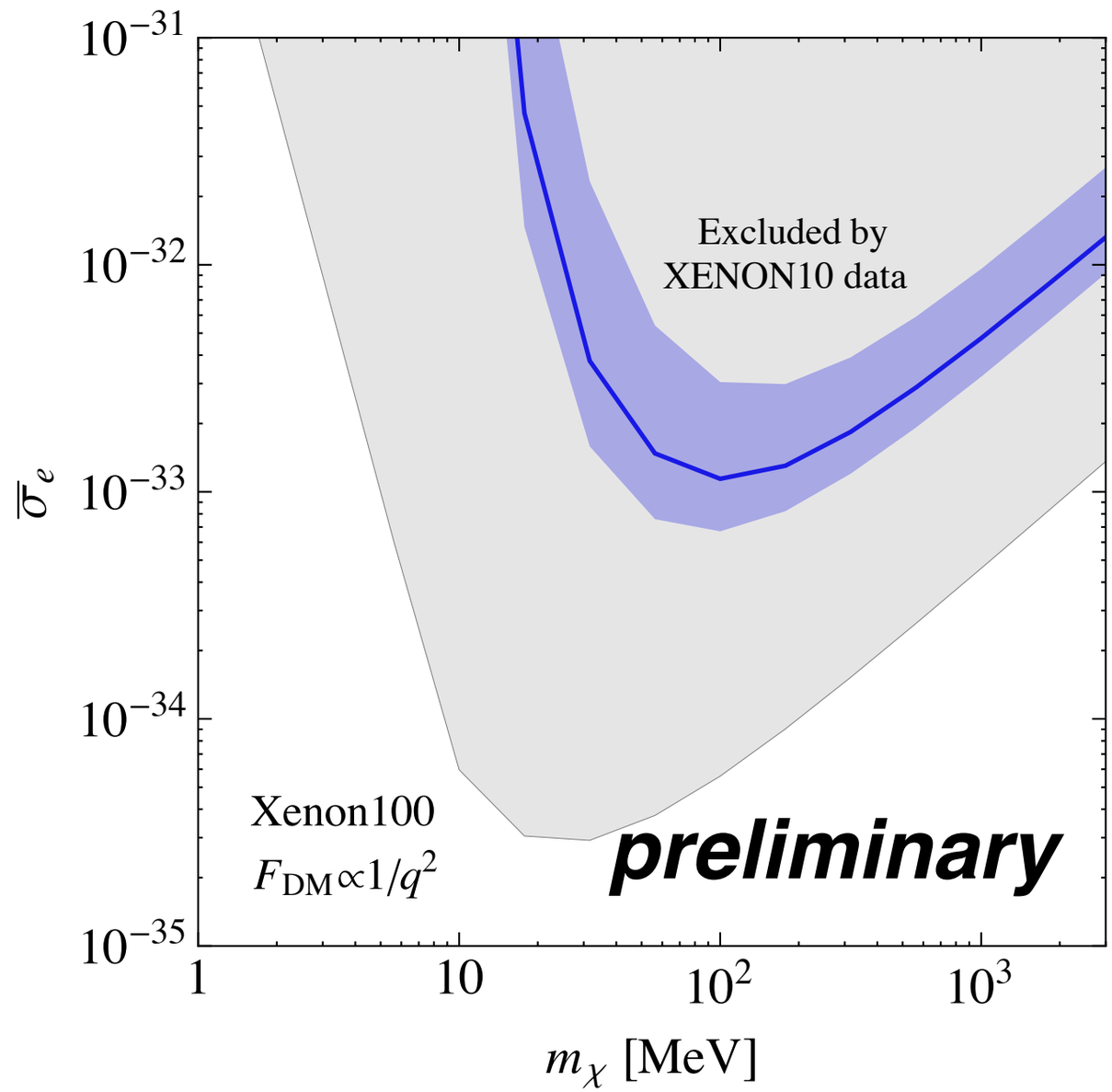
XENON100



1605.06262

XENON100



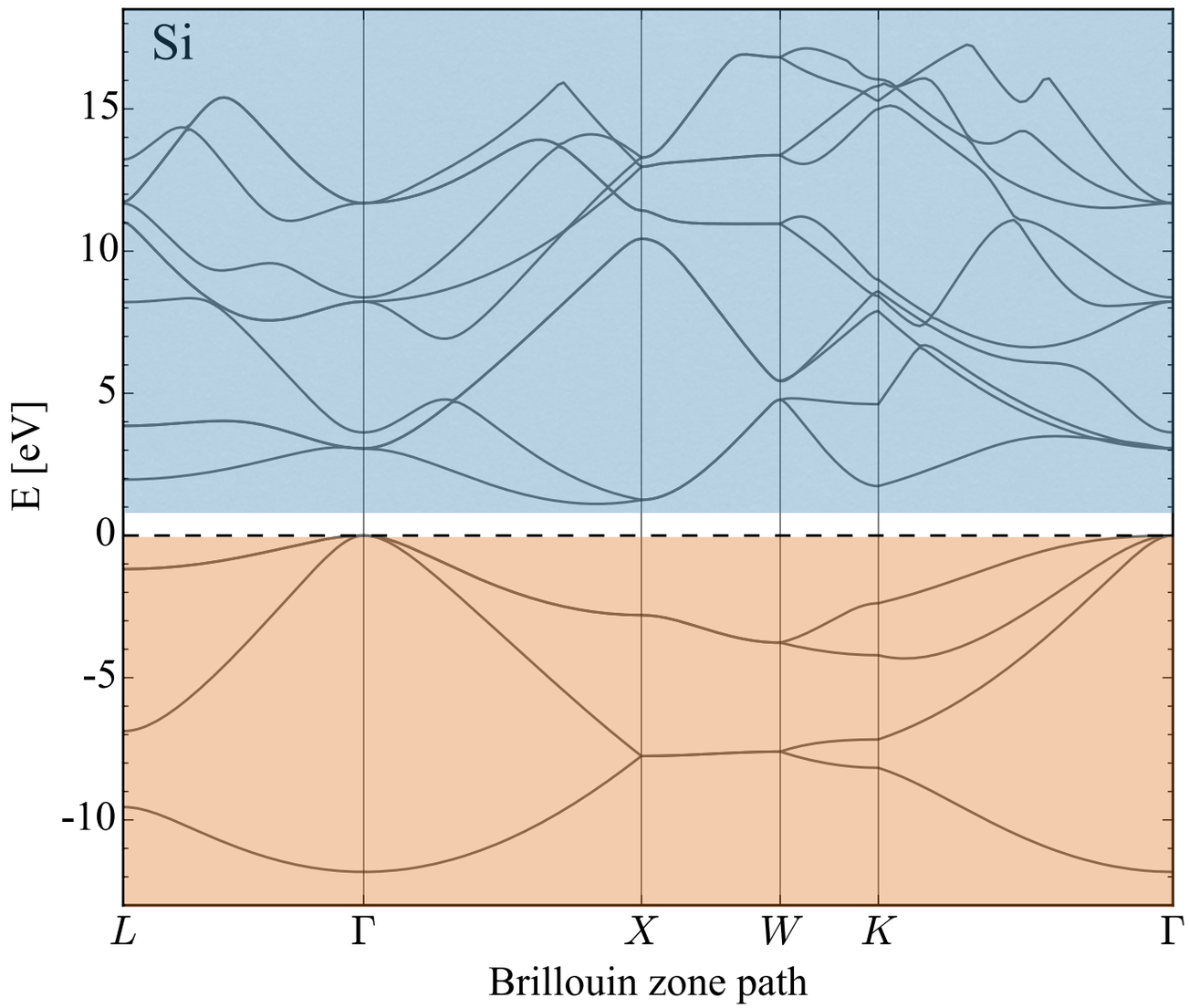


Essig, Mardon, Volansky, TTY, *in preparation*

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



empty conduction band

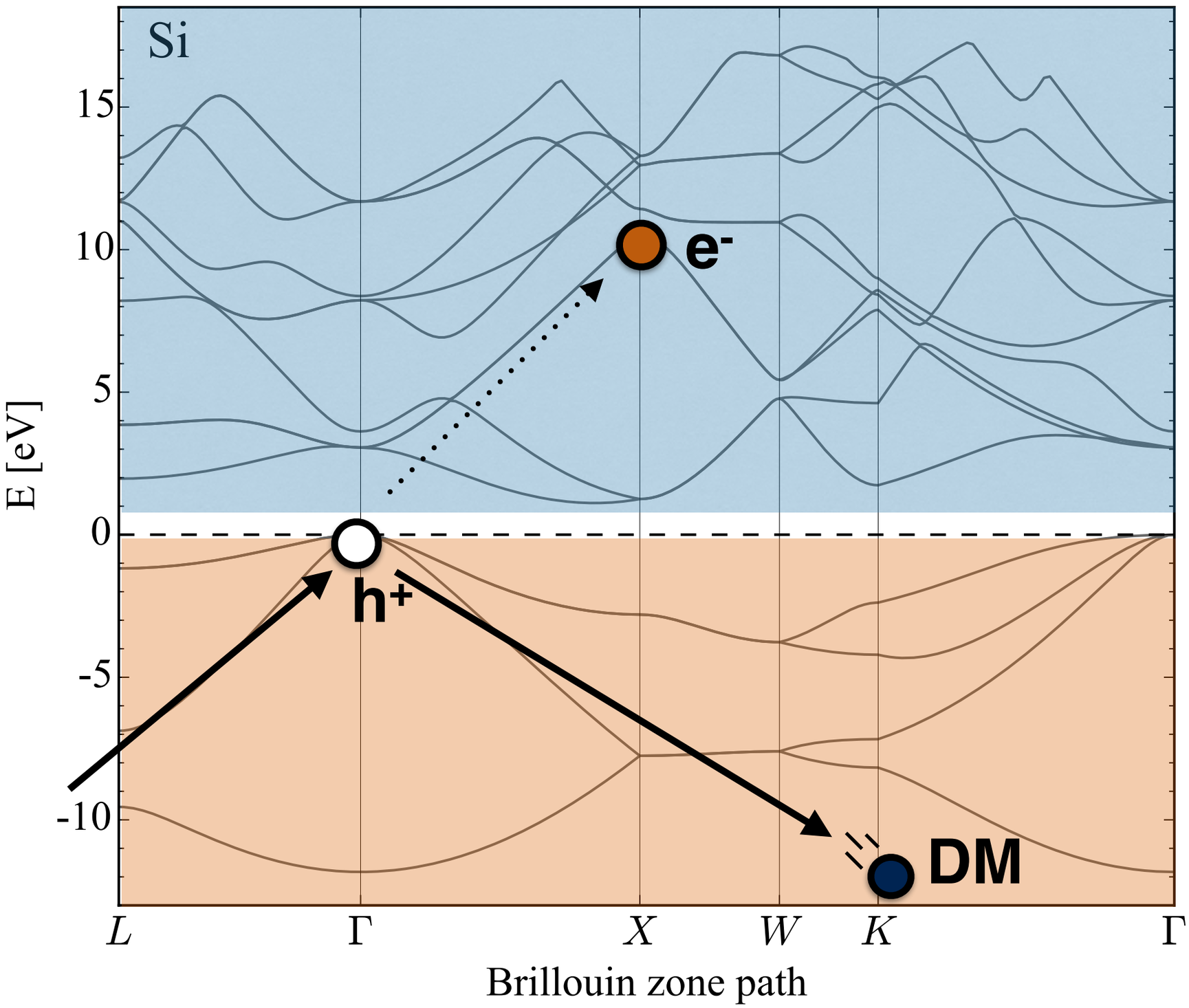
band gap

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

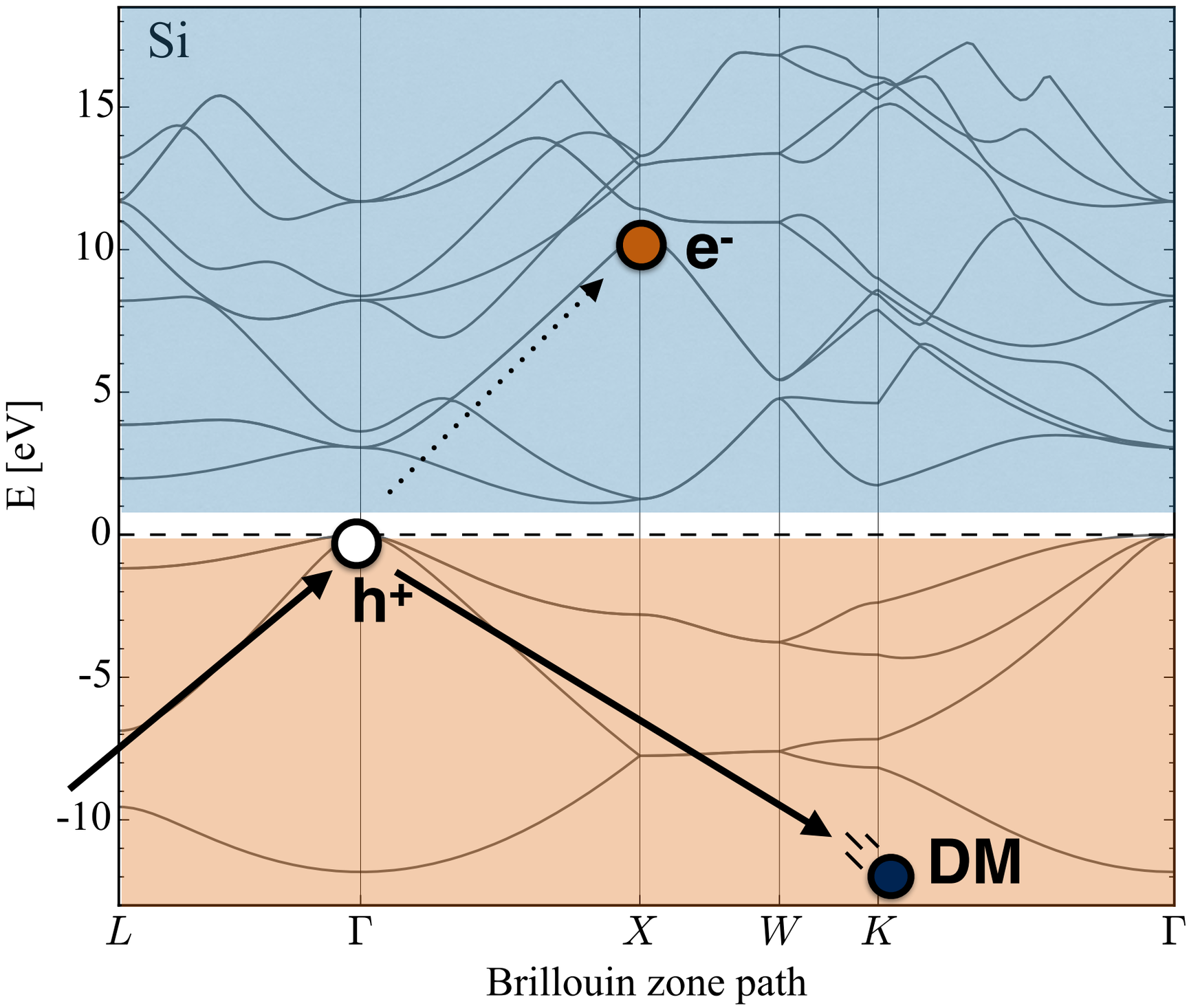
Semiconductor targets



band gap [eV]

Ge	0.67
Si	1.1
GaAs	1.5
NaI	5.9
CsI	6.4

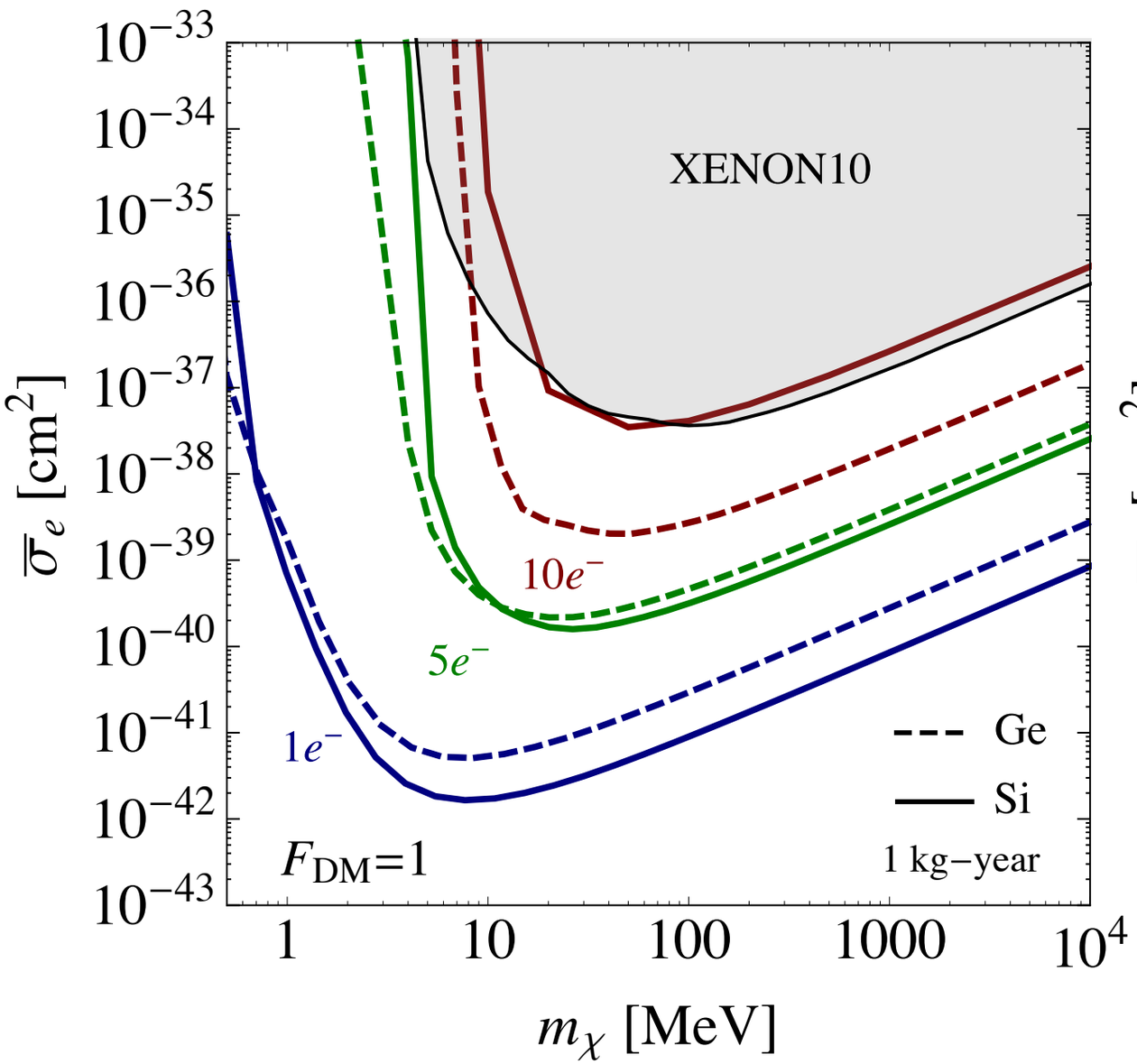
Semiconductor targets

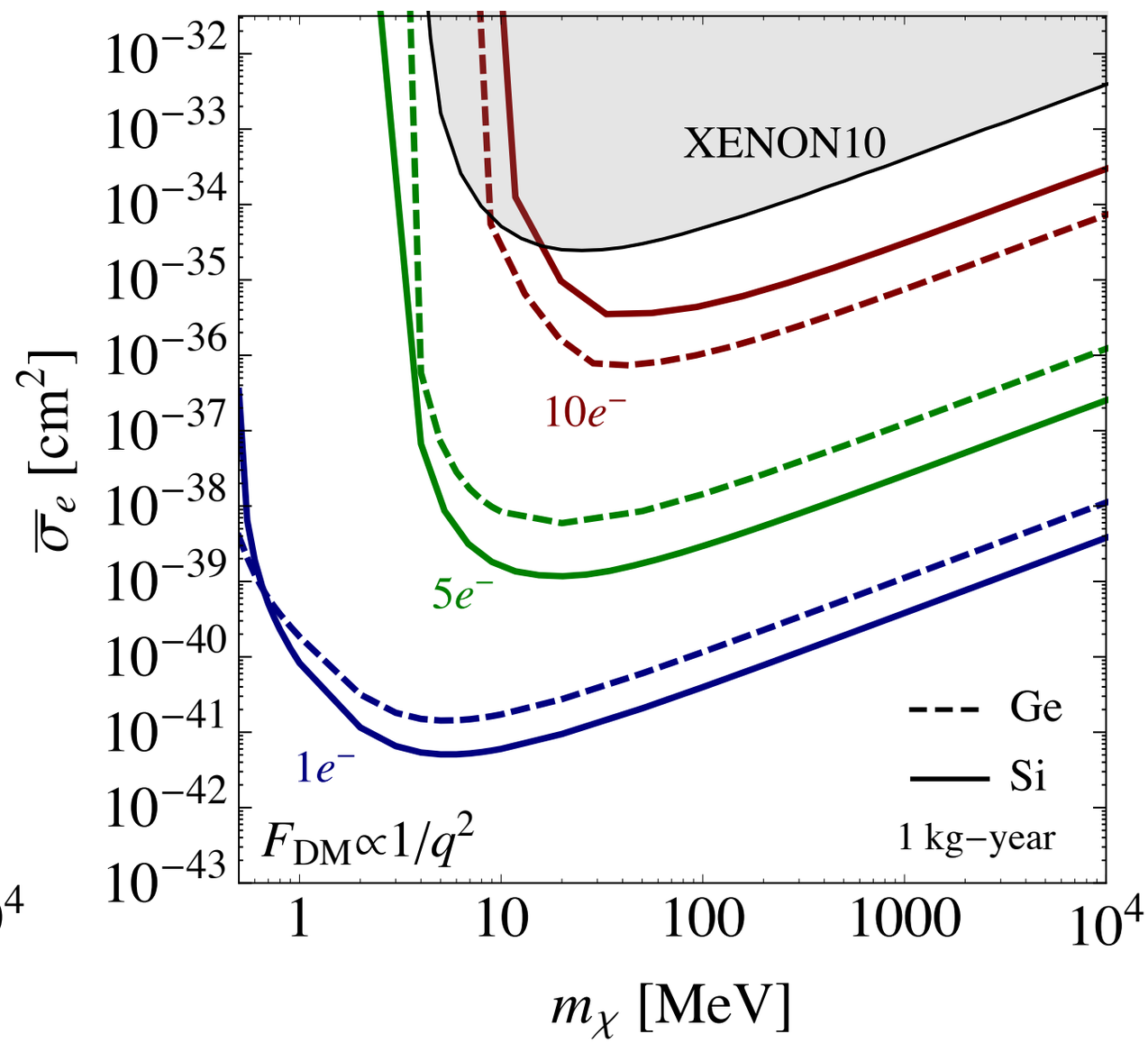


apply an electric field and extract the electron(s) "ionization"

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

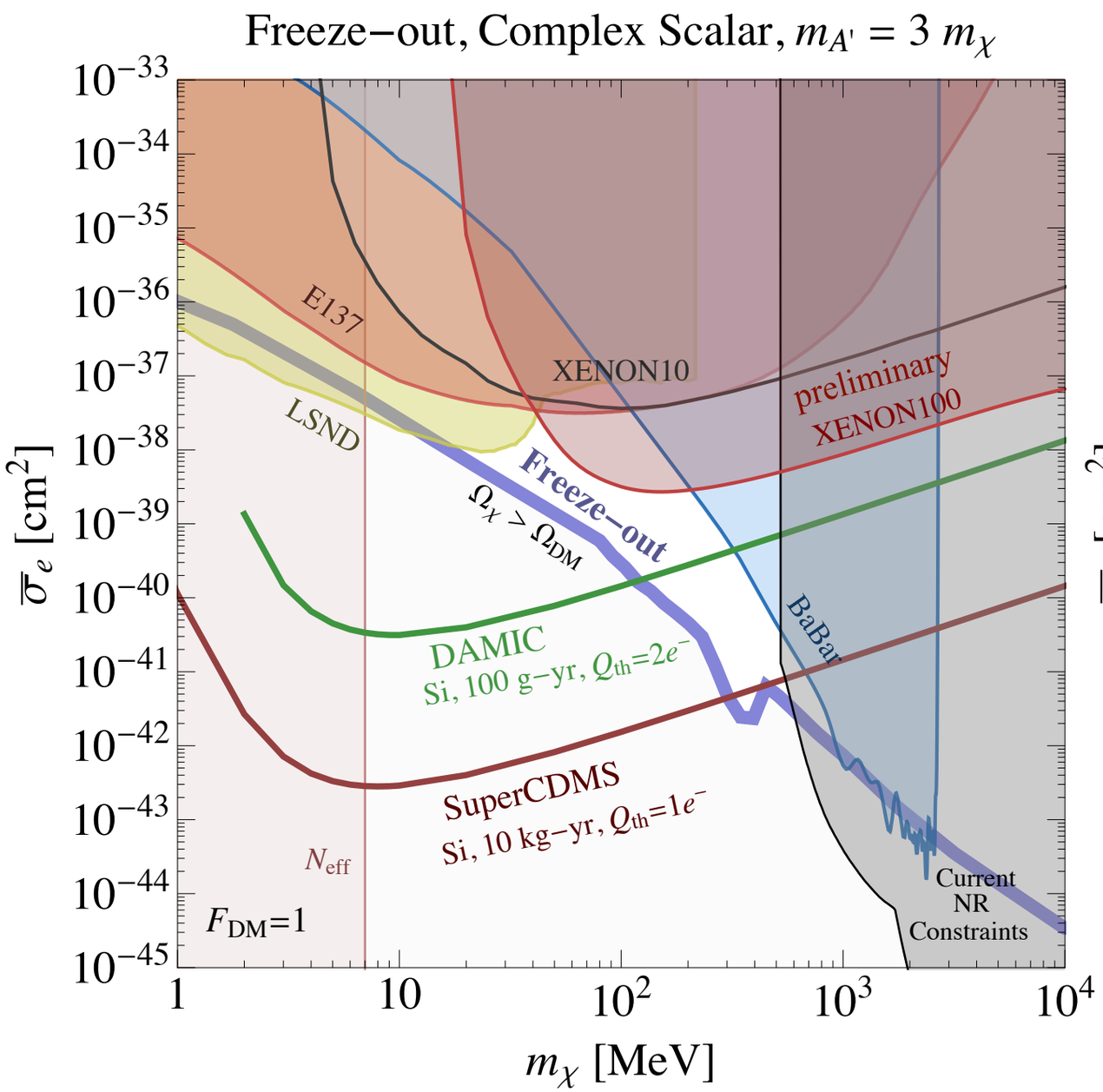
ionization signal

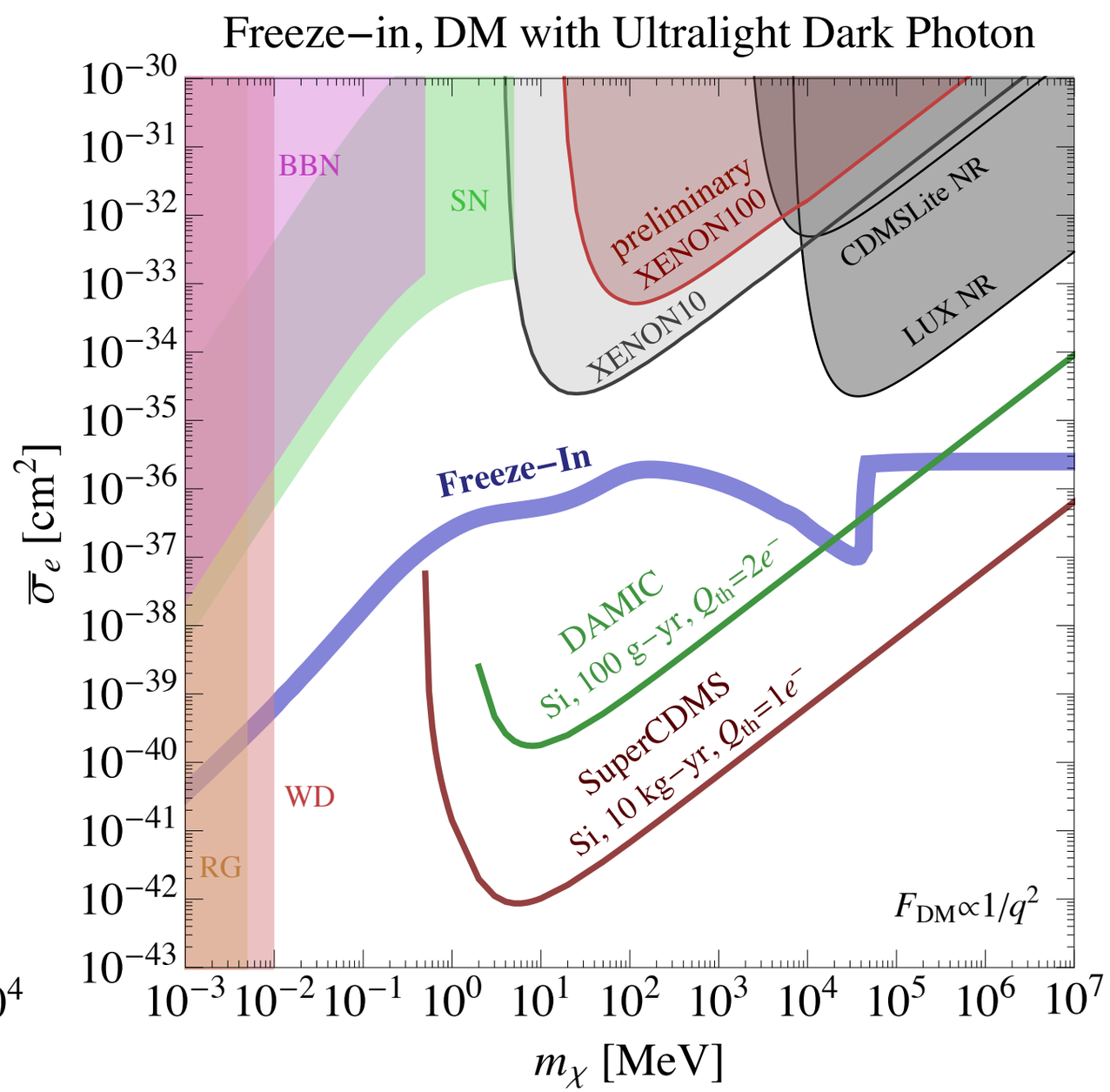




1 kg-year, 3.6 events

ionization signal





challenges

- readout noise — can minimize by increasing time of readout (ongoing with FNAL group)
- E-field used to drift the electrons may produce dark current — fundamentally limits the sensitivity

challenges

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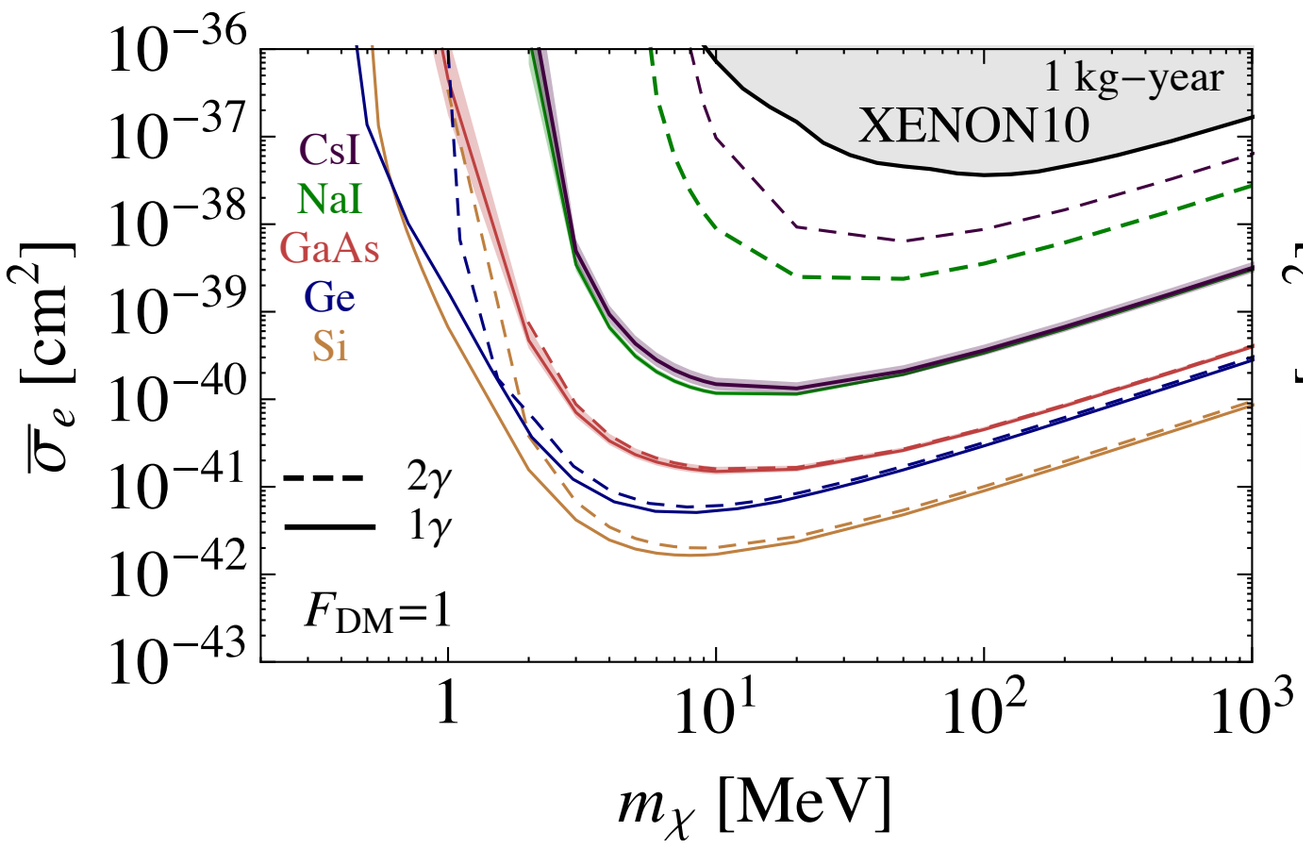
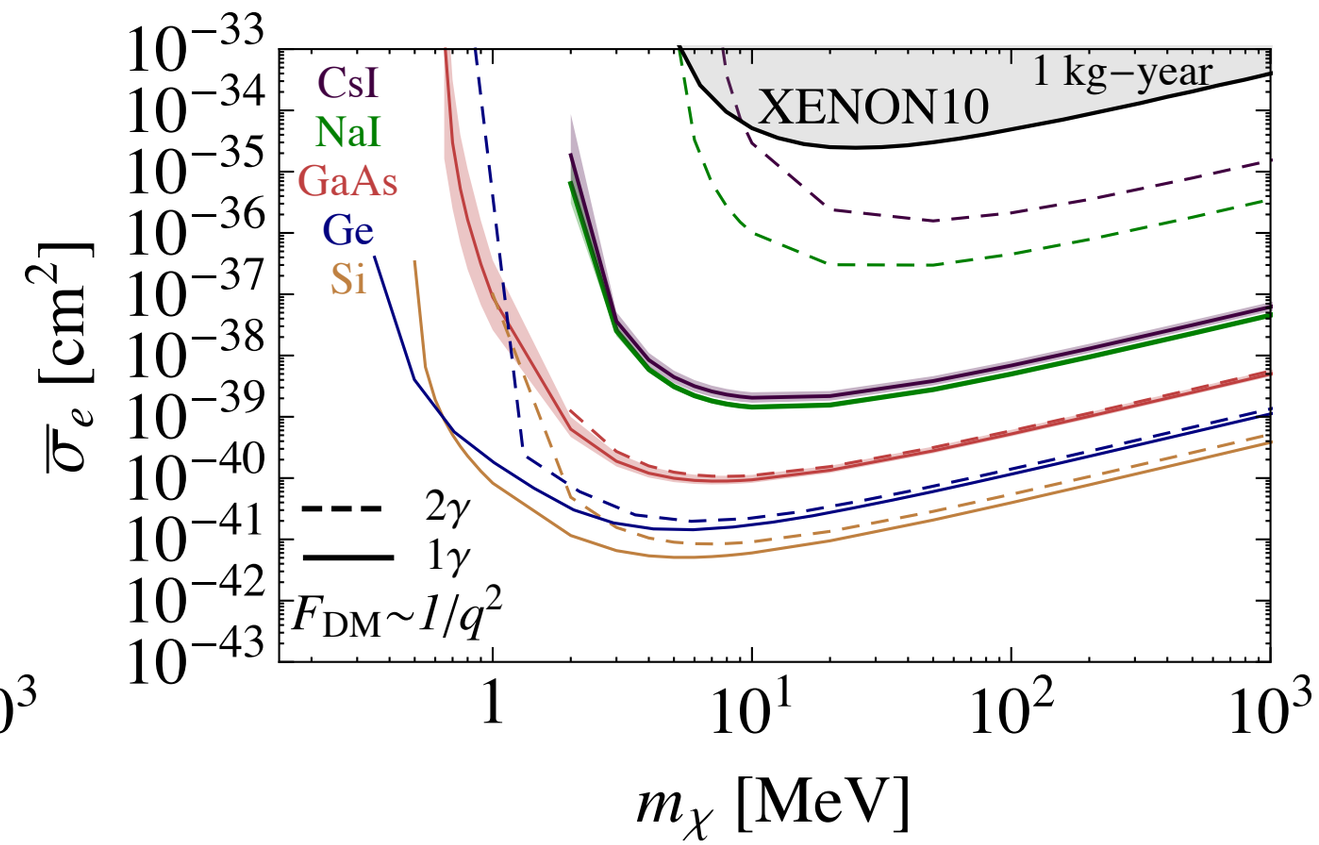
- E-field used to drift the electrons may produce dark current — fundamentally limits the sensitivity

specific to ionization experiments!

scintillator signal





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

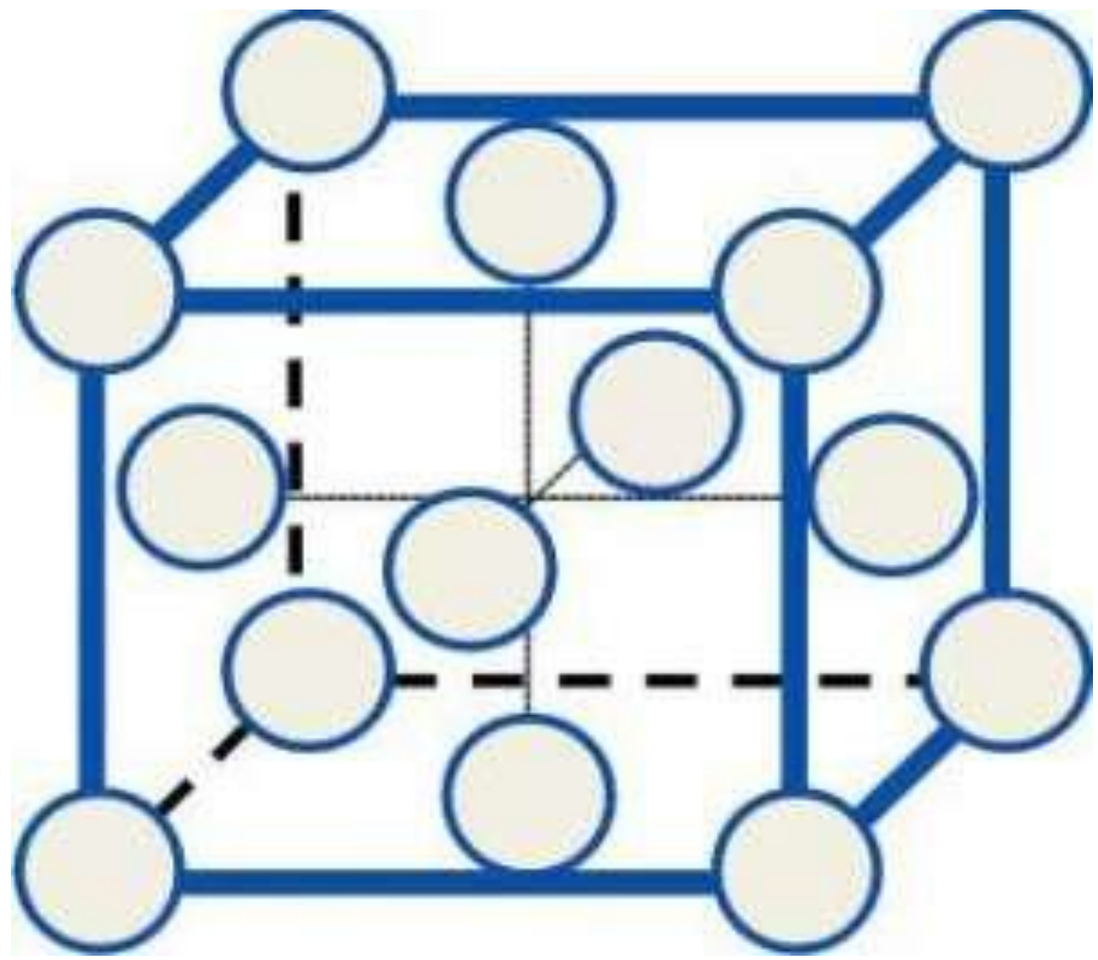
challenges

- 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)

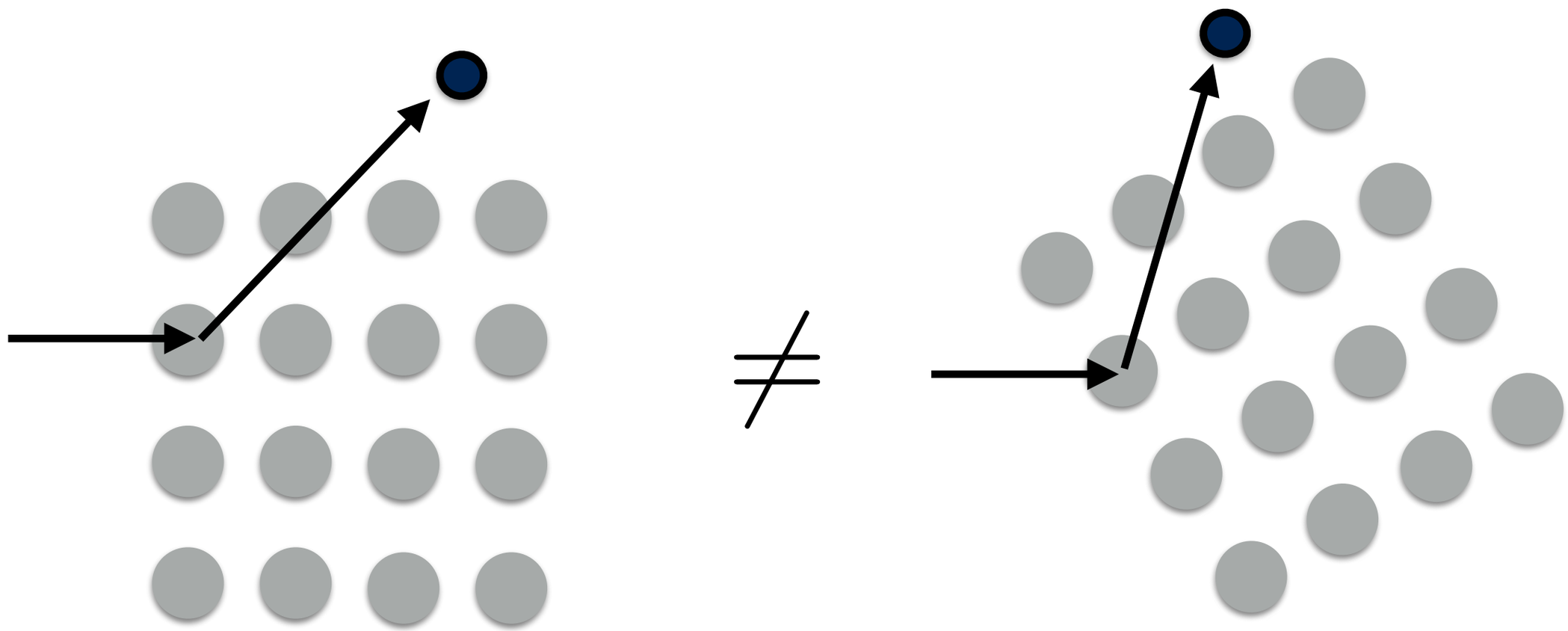
directionality



Department for Materials Research, Risø DTU

Essig, Mardon, Soto, TTY (in preparation)

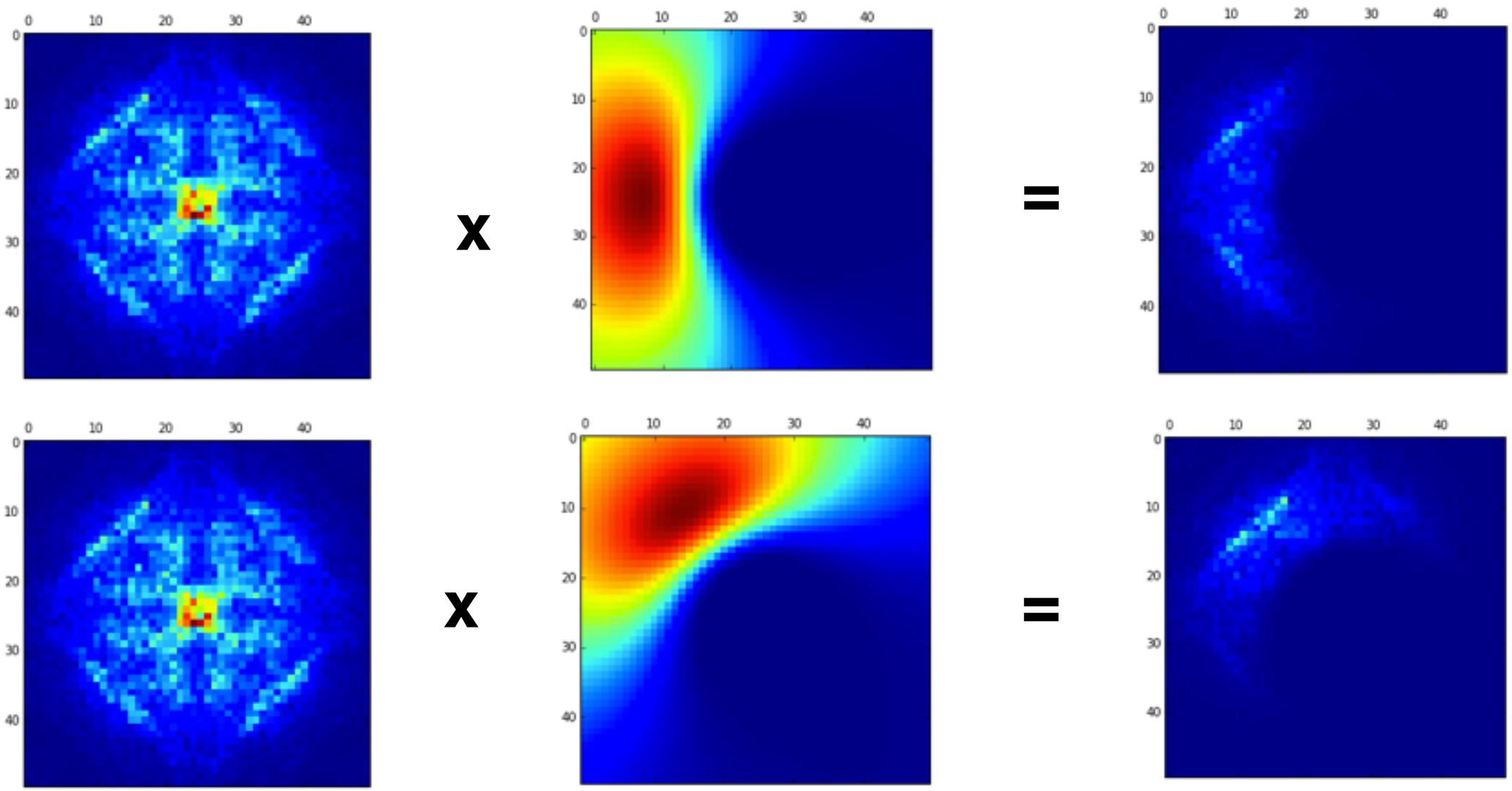
directionality



Essig, Mardon, Soto, TTY (in preparation)

directionality

GaAs form factor **halo function**

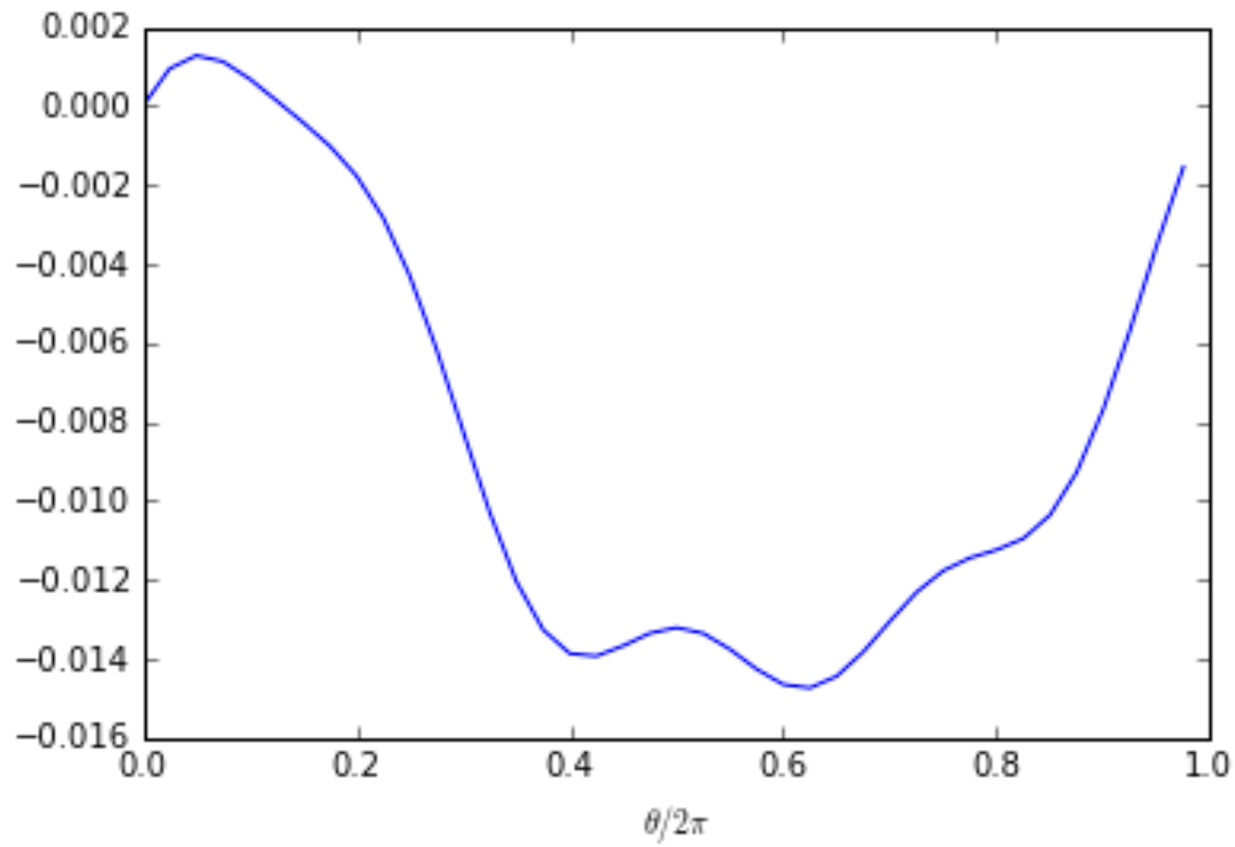


Essig, Mardon, Soto, TTY (in preparation)

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]
- ????

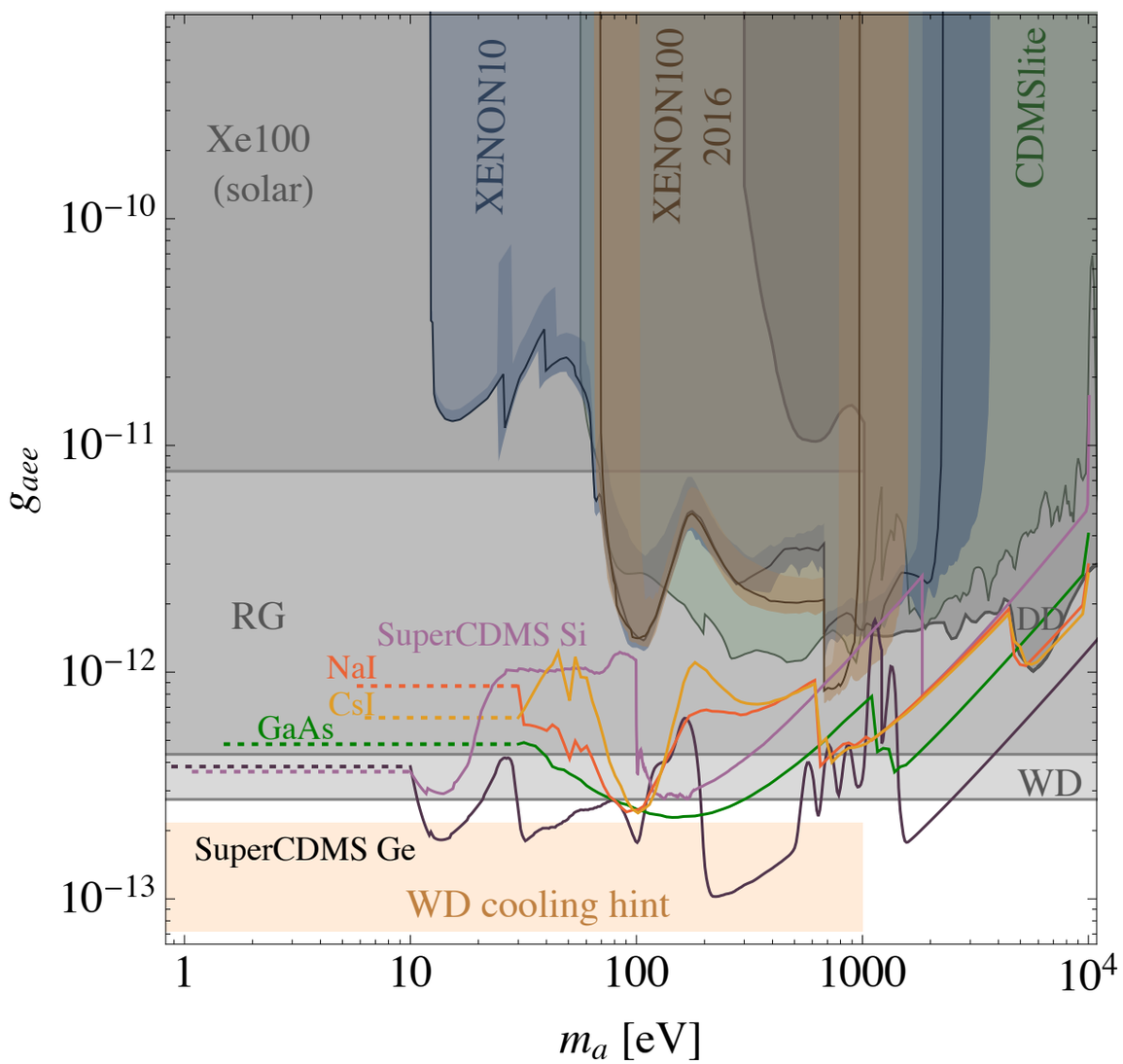
Absorption

- **same experiments** can be used for down to ~eV DM
- consider absorption of DM instead of scattering

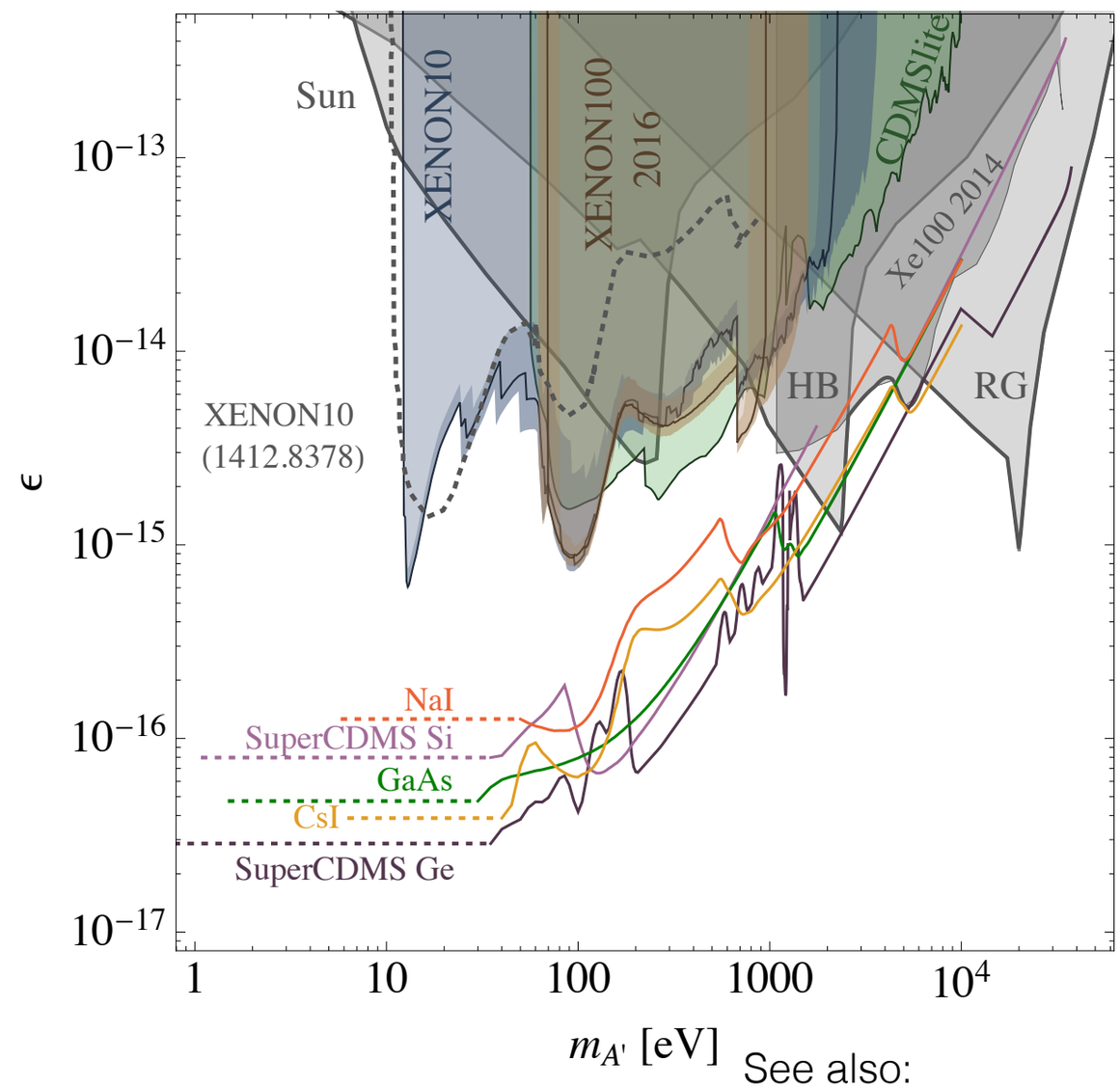
Absorption

See also Jaeckel, Raffelt, Redondo…

axions



dark photons

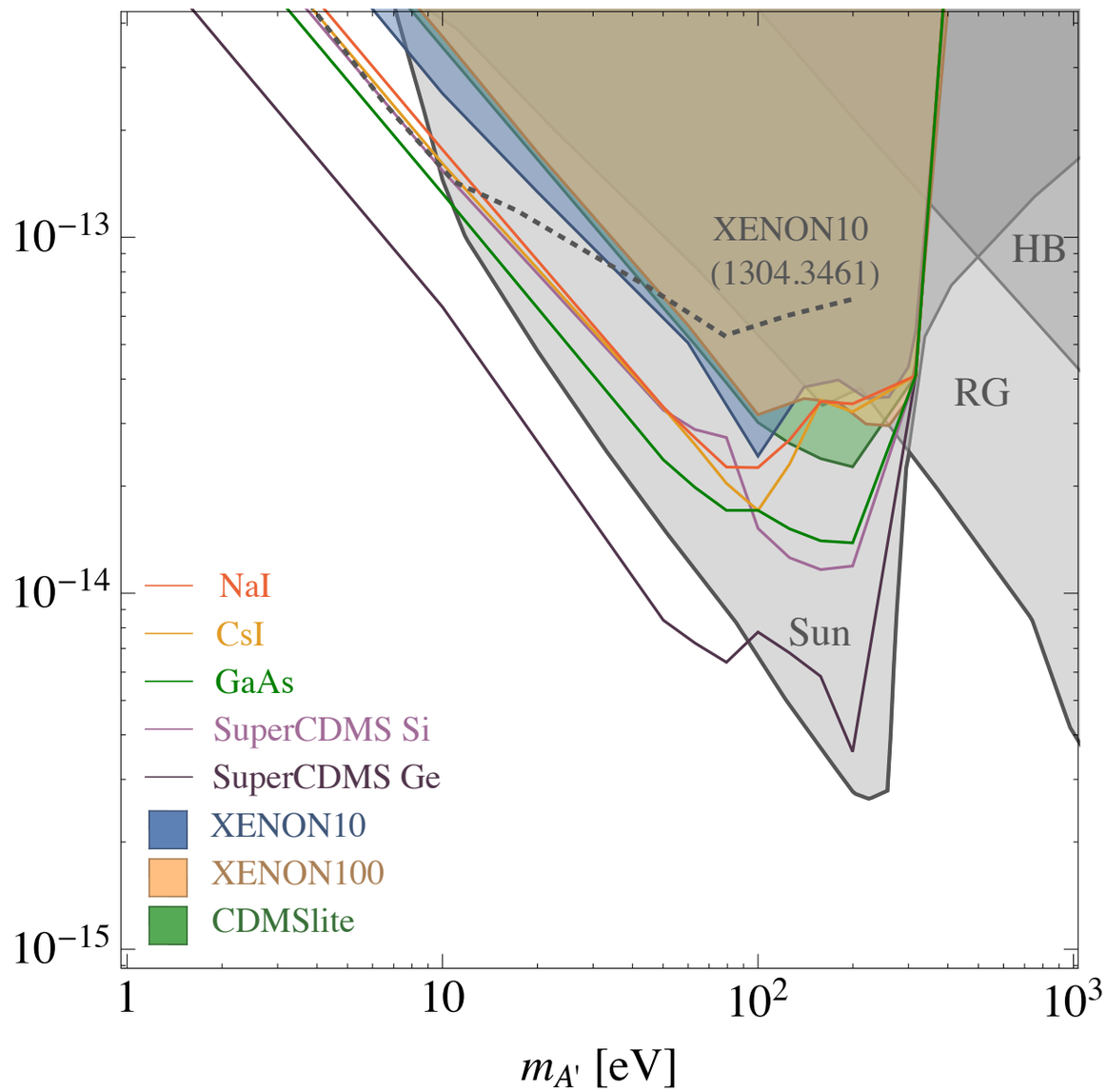


Bloch, Essig, Tobioka, Volansky, TTY [1608.02123]

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

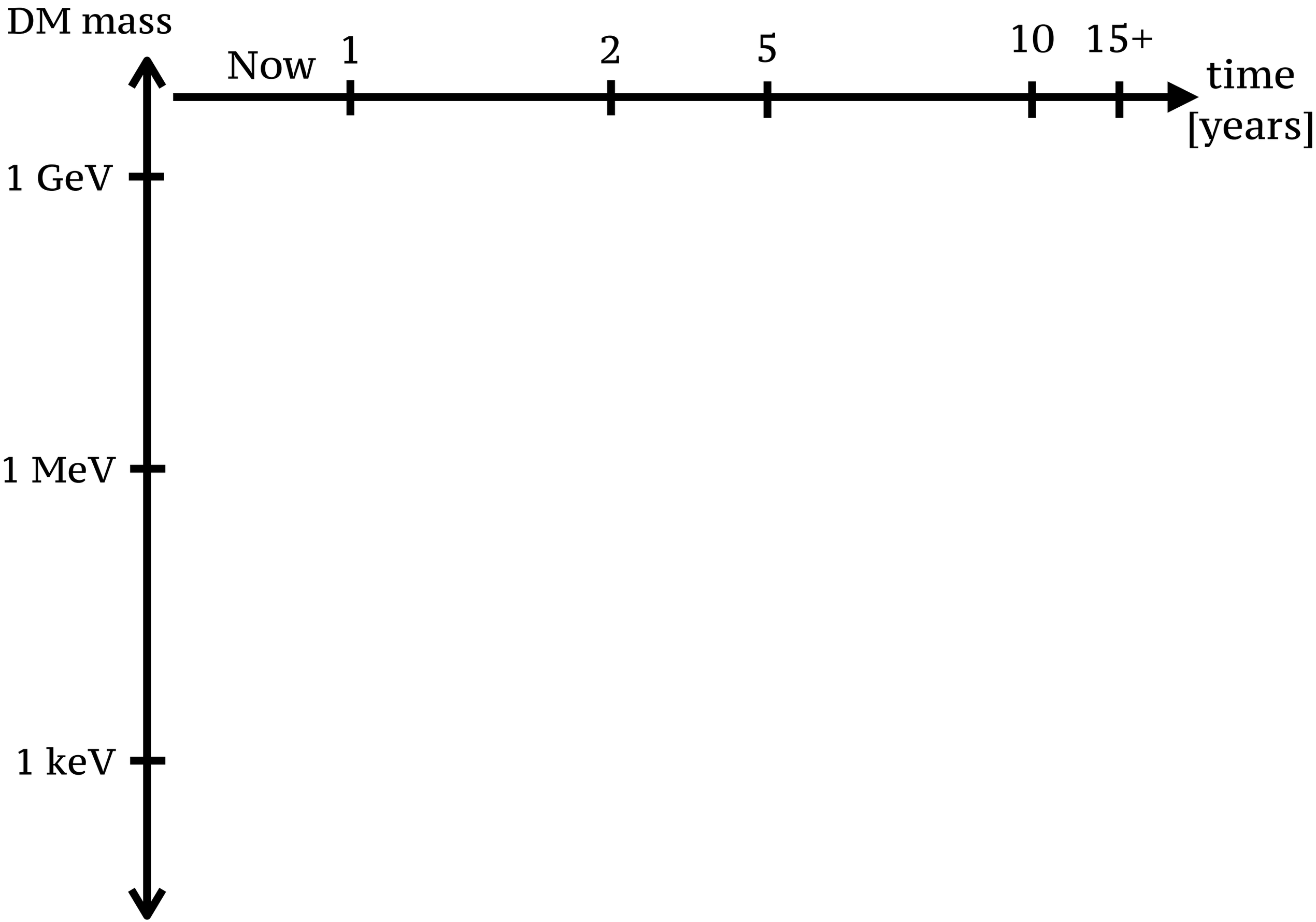
Absorption

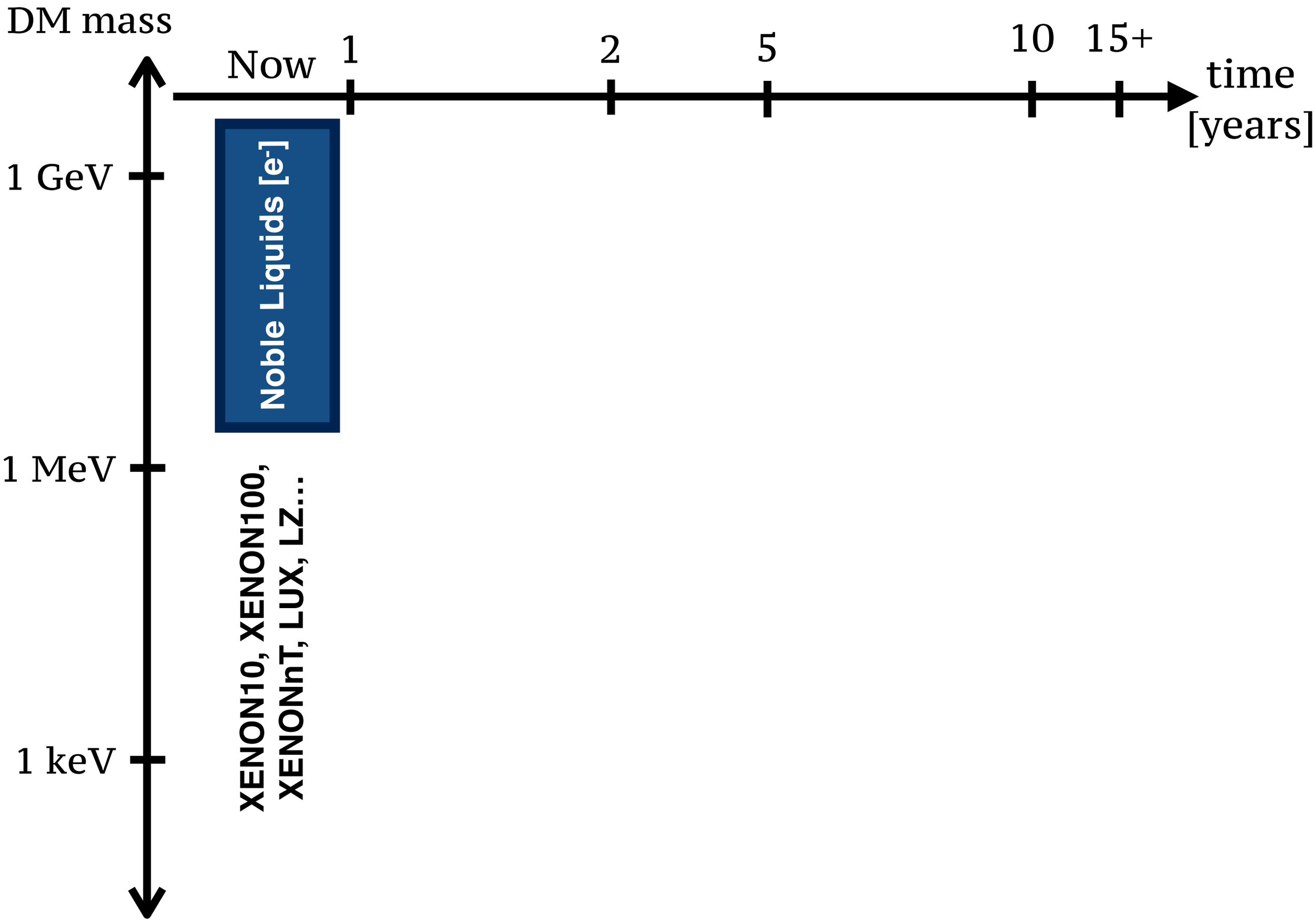
solar dark photons



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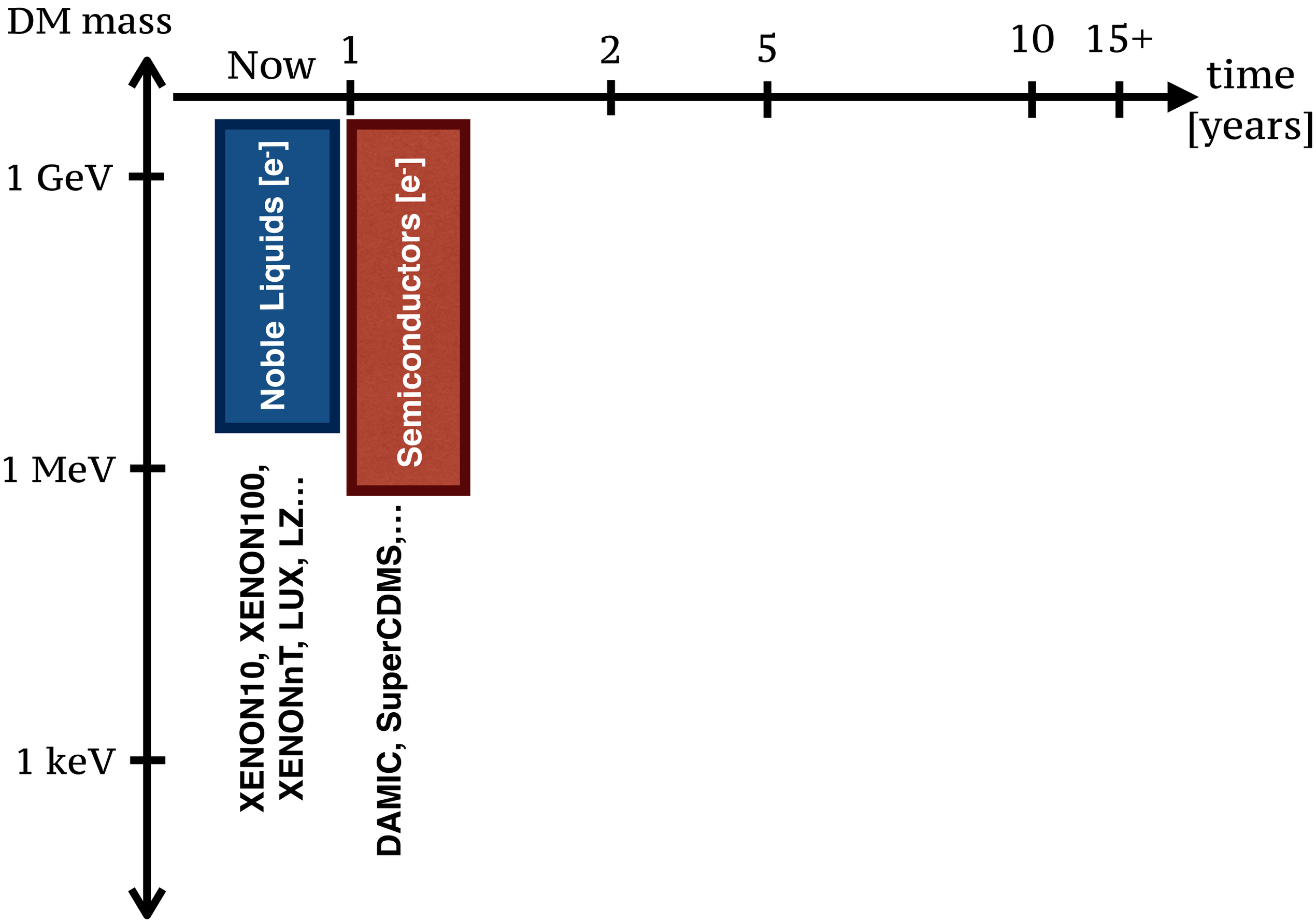
Noble Liquids [e-]
XENON10, XENON100,
XENONnT, LUX, LZ...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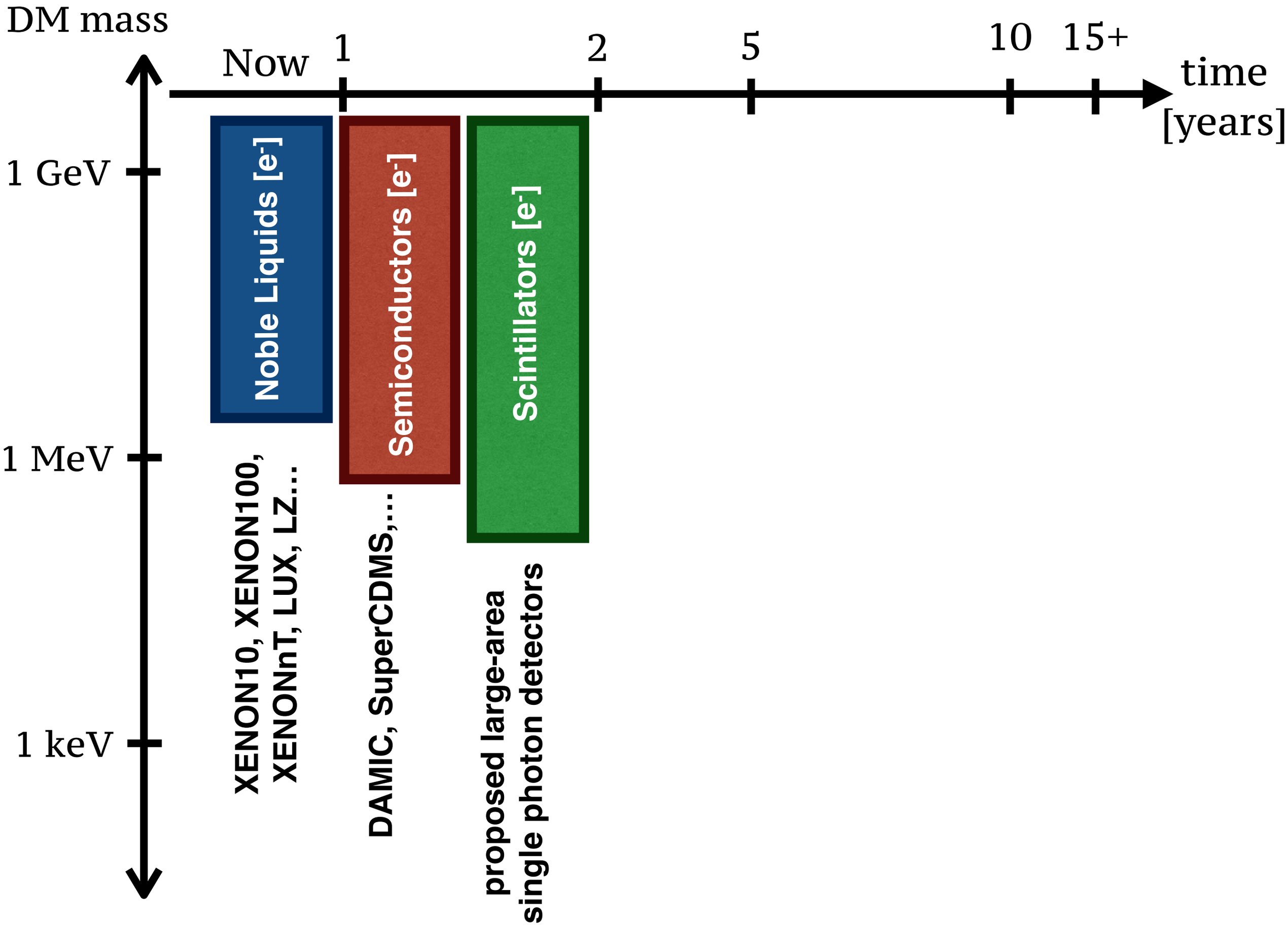
XENON10, XENON100, XENONnT, LUX, LZ…
DAMIC, SuperCDMS,…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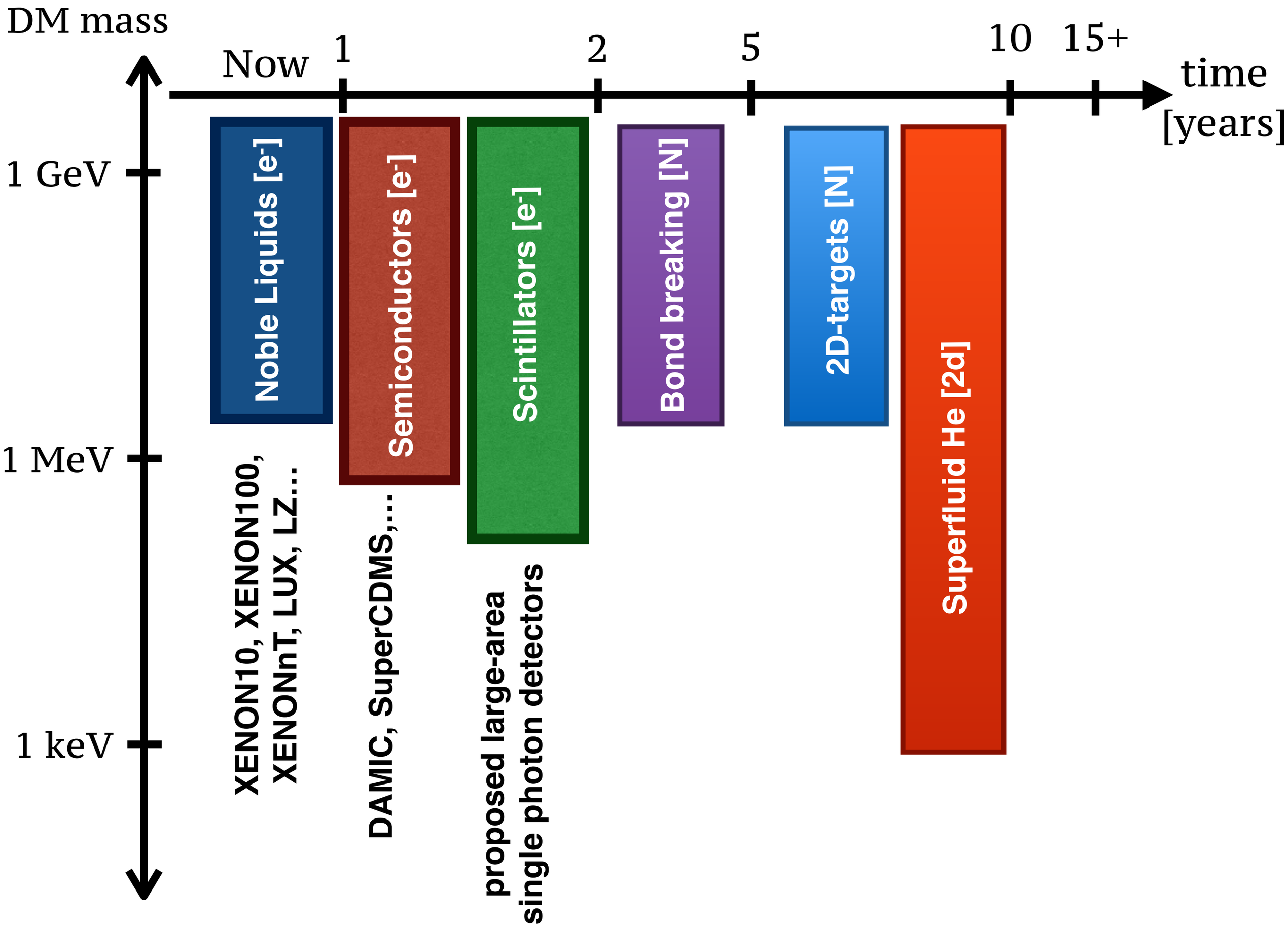
Noble Liquids [e-]
Semiconductors [e-]
Scintillators [e-]
XENON10, XENON100, XENONnT, LUX, LZ...
DAMIC, SuperCDMS,...
proposed large-area single photon detectors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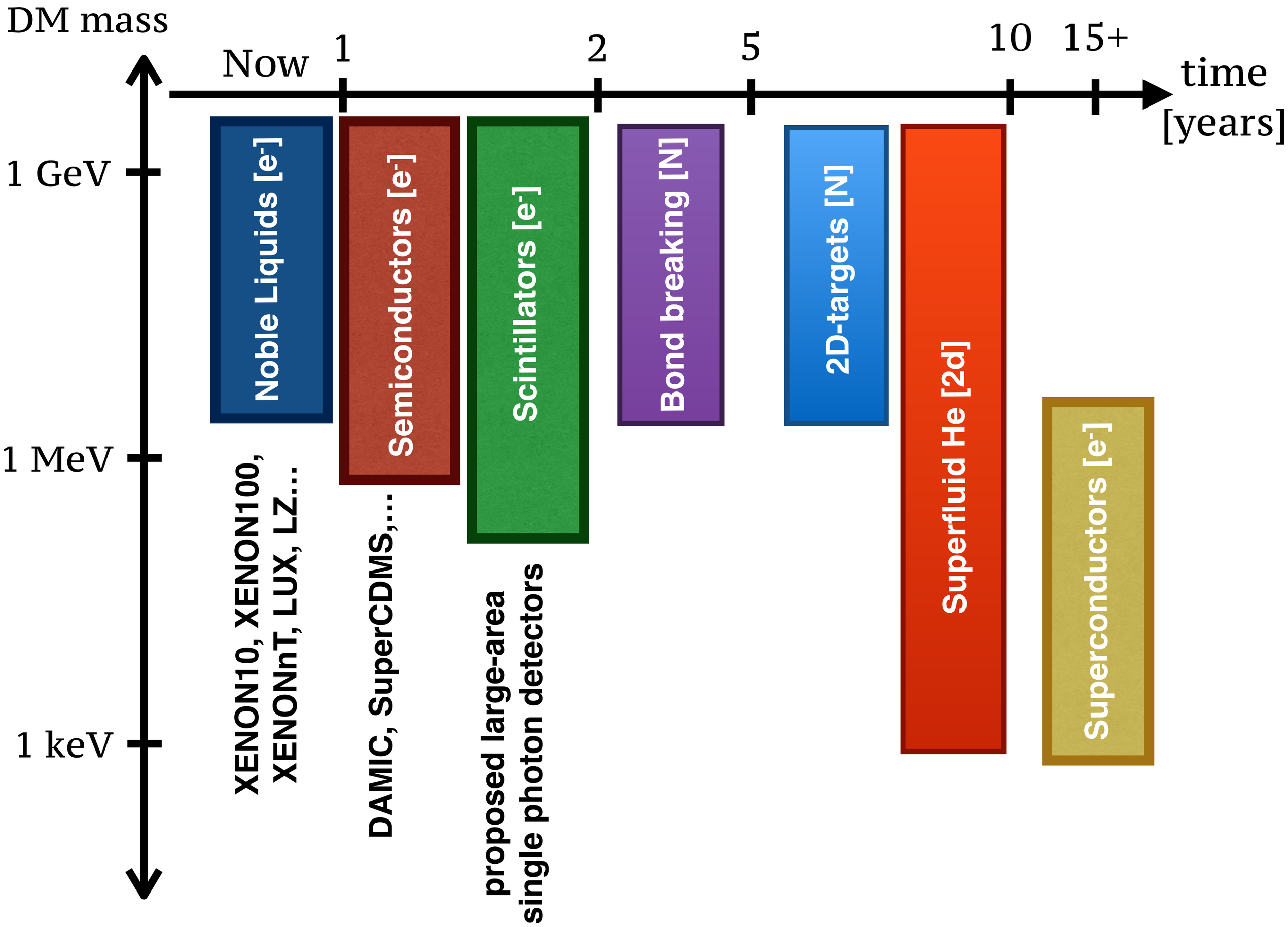
proposed large-area single photon detectors
Bond breaking [N]
2D-targets [N]
Superfluid He [2d]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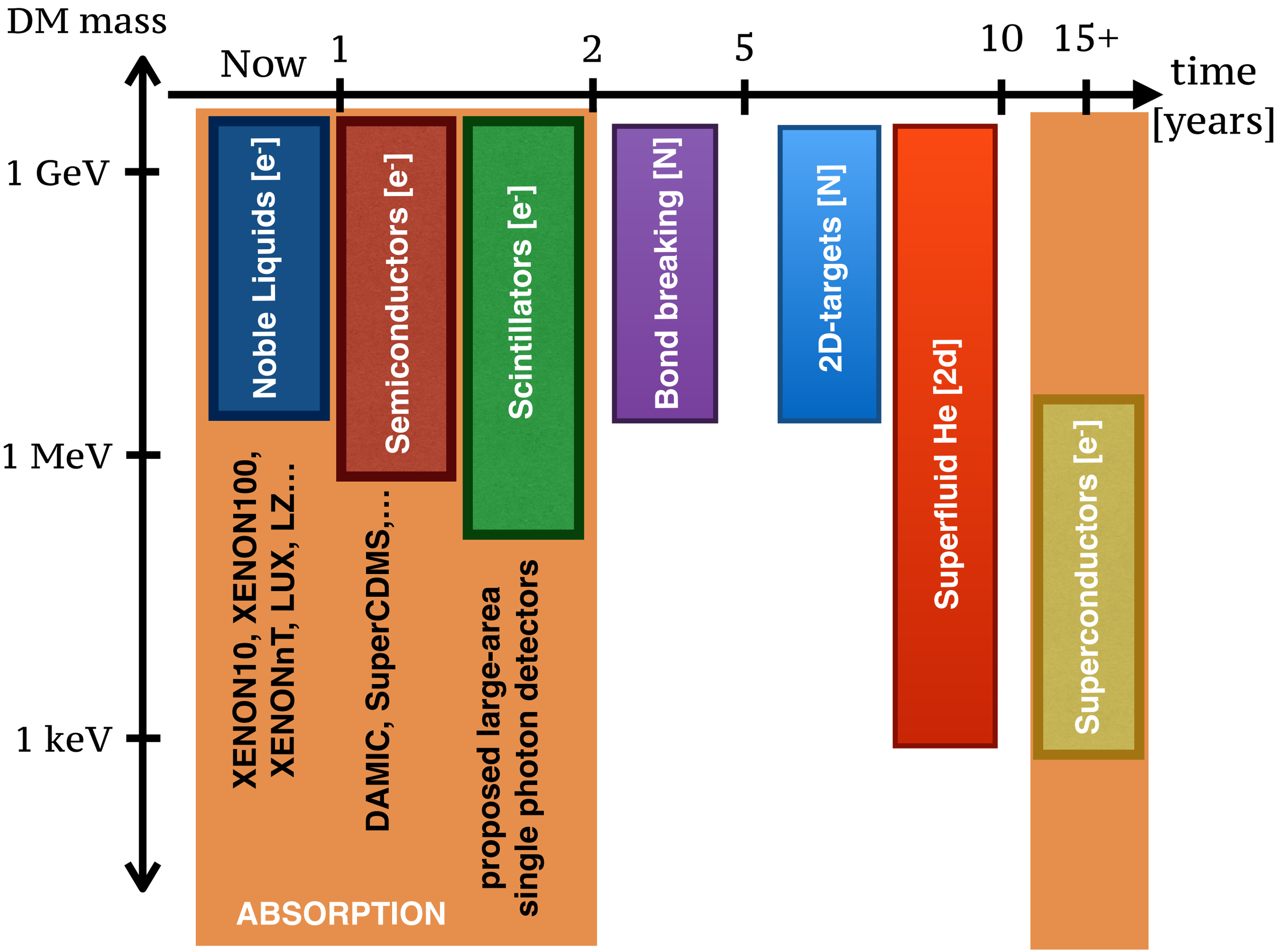
Superconductors [e-]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Scintillators [e-]
Bond breaking [N]
2D-targets [N]
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XENON10, XENON100, XENONnT, LUX, LZ...
DAMIC, SuperCDMS,...
proposed large-area single photon detectors
ABSORPTION