New Ideas for sub-GeV Dark Matter Direct Detection

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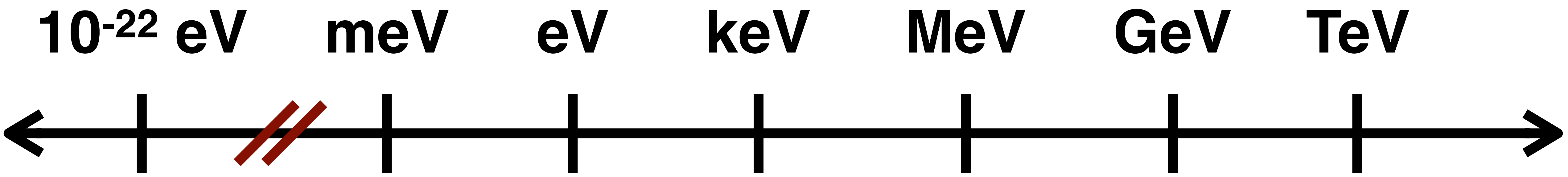
(CERN & University of Oregon)

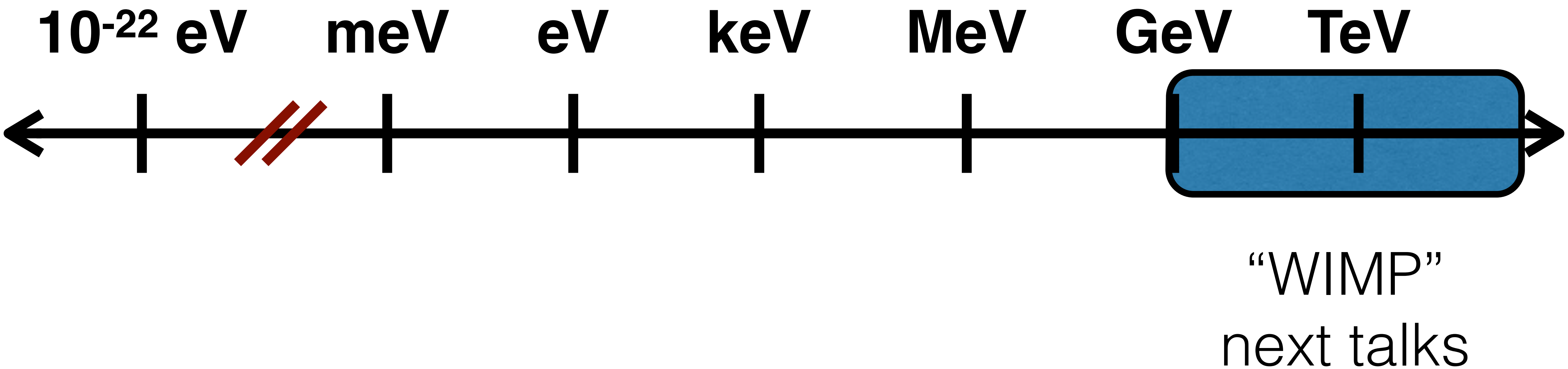
UCLA Dark Matter 2018

February 21, 2018

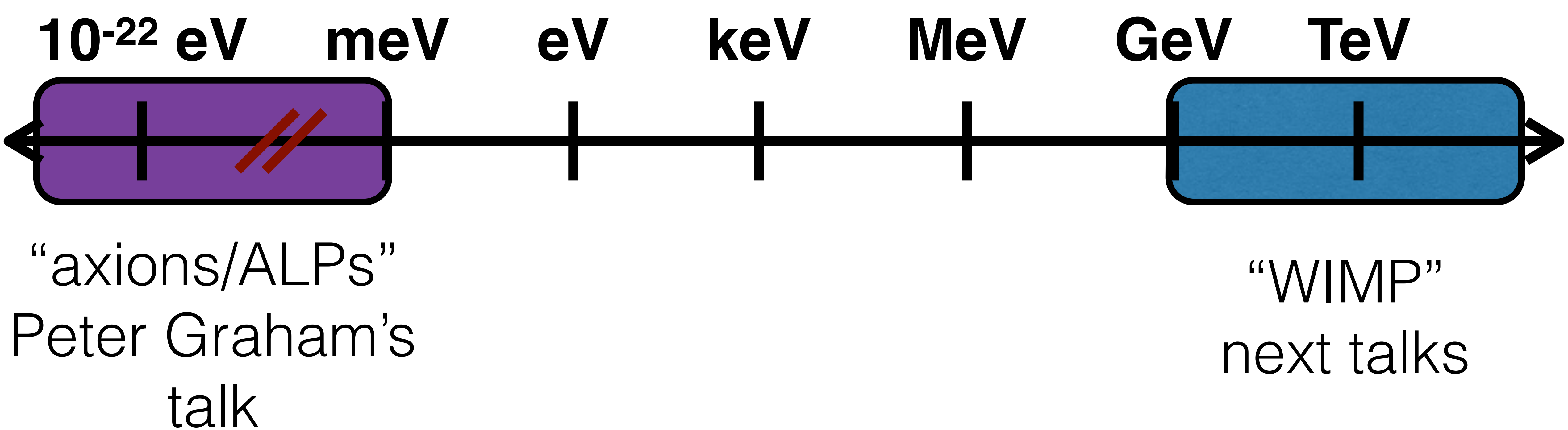
dark matter candidates



dark matter candidates



dark matter candidates



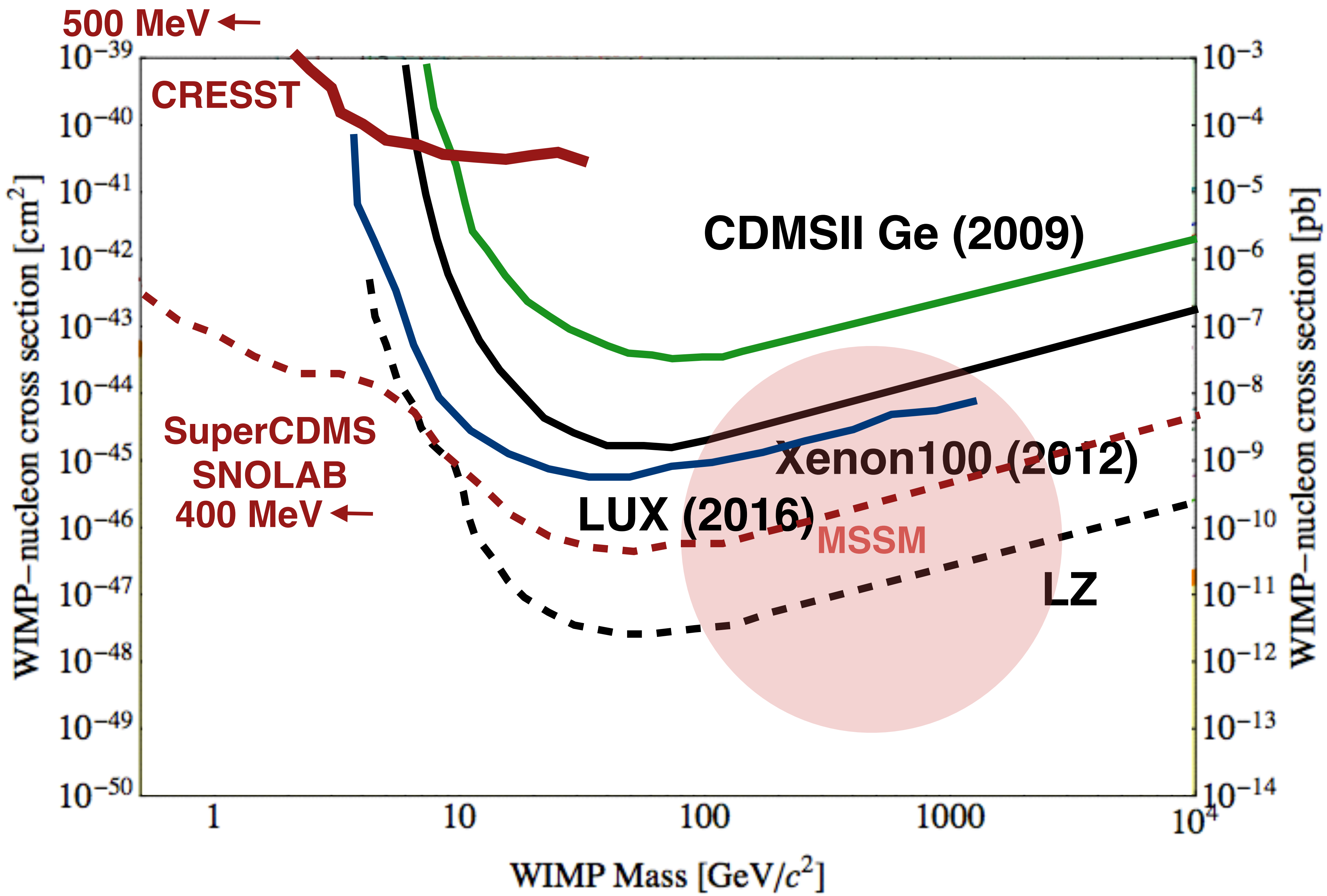
challenges for meV-GeV DM direct detection

fundamental challenge:

need enough **energy transfer**
from DM-target interaction
to create a detectable **signal**

depends on process
and
detector setup

DM-nucleon elastic scattering

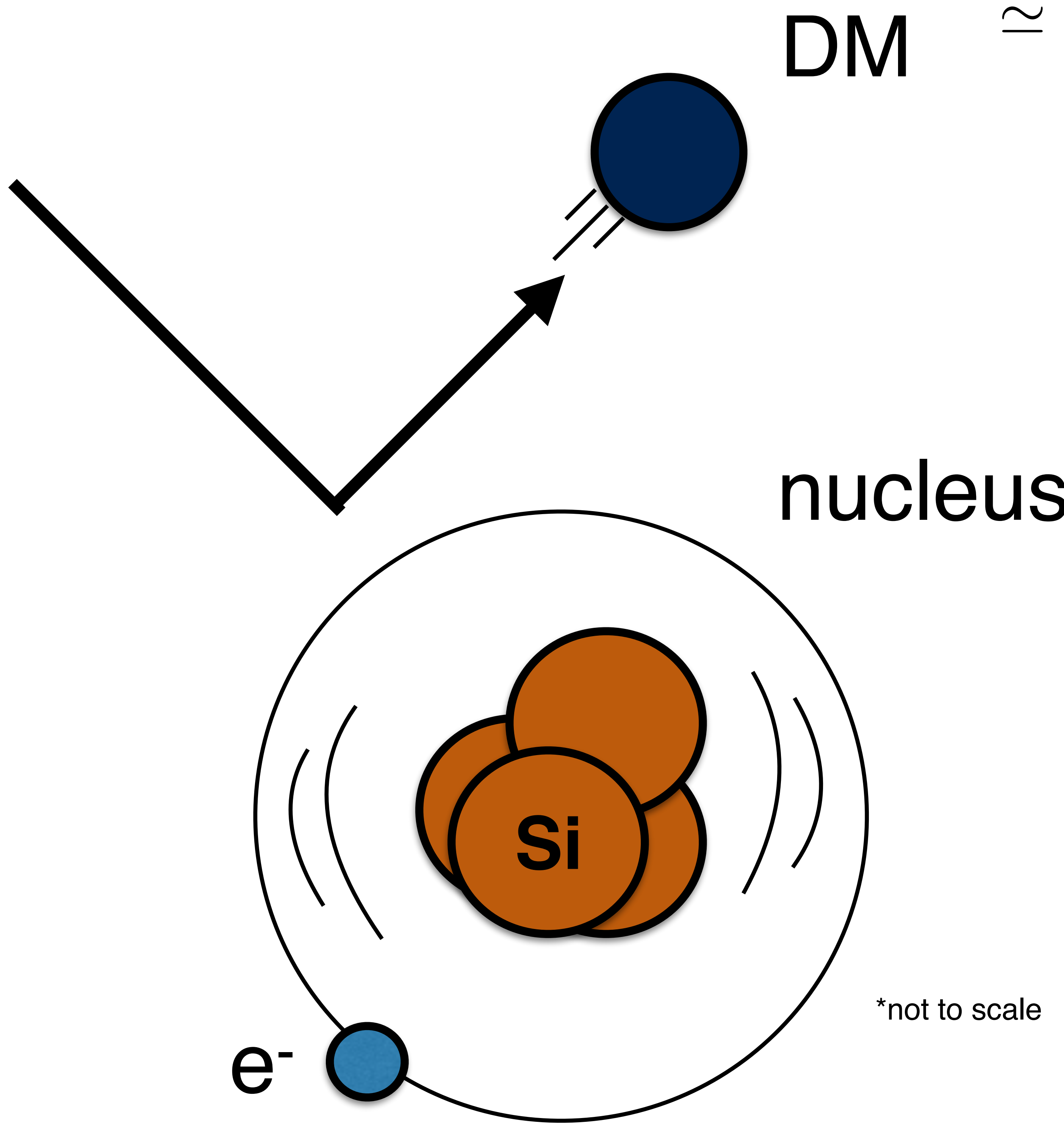


$$E_R = \frac{q^2}{2m_N}$$

momentum transfer

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

nucleus mass



$$m_N = 28 \text{ GeV}$$

$$m_\chi = 100 \text{ GeV}$$

$$E_R \sim 100 \text{ keV}$$

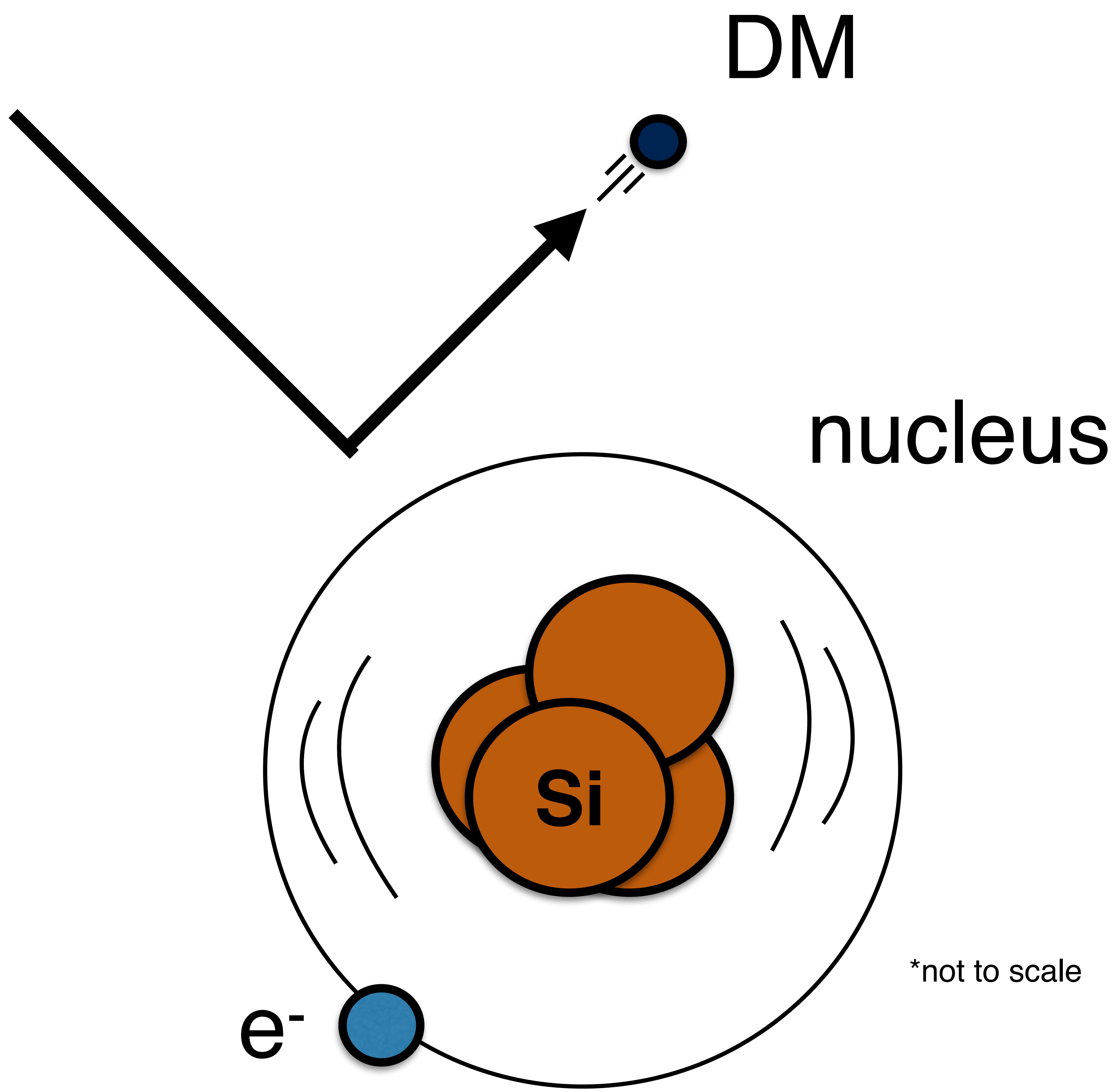
available for detection

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

momentum transfer

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

nucleus mass



$$m_N = 28 \text{ GeV}$$

$$m_\chi = 100 \text{ MeV}$$

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

available for detection

detecting sub-GeV DM in 2 easy steps

1. increase amount of detectable energy

2. decrease energy threshold or increase sensitivity

detecting sub-GeV DM in 2 easy steps

1. increase amount of detectable energy

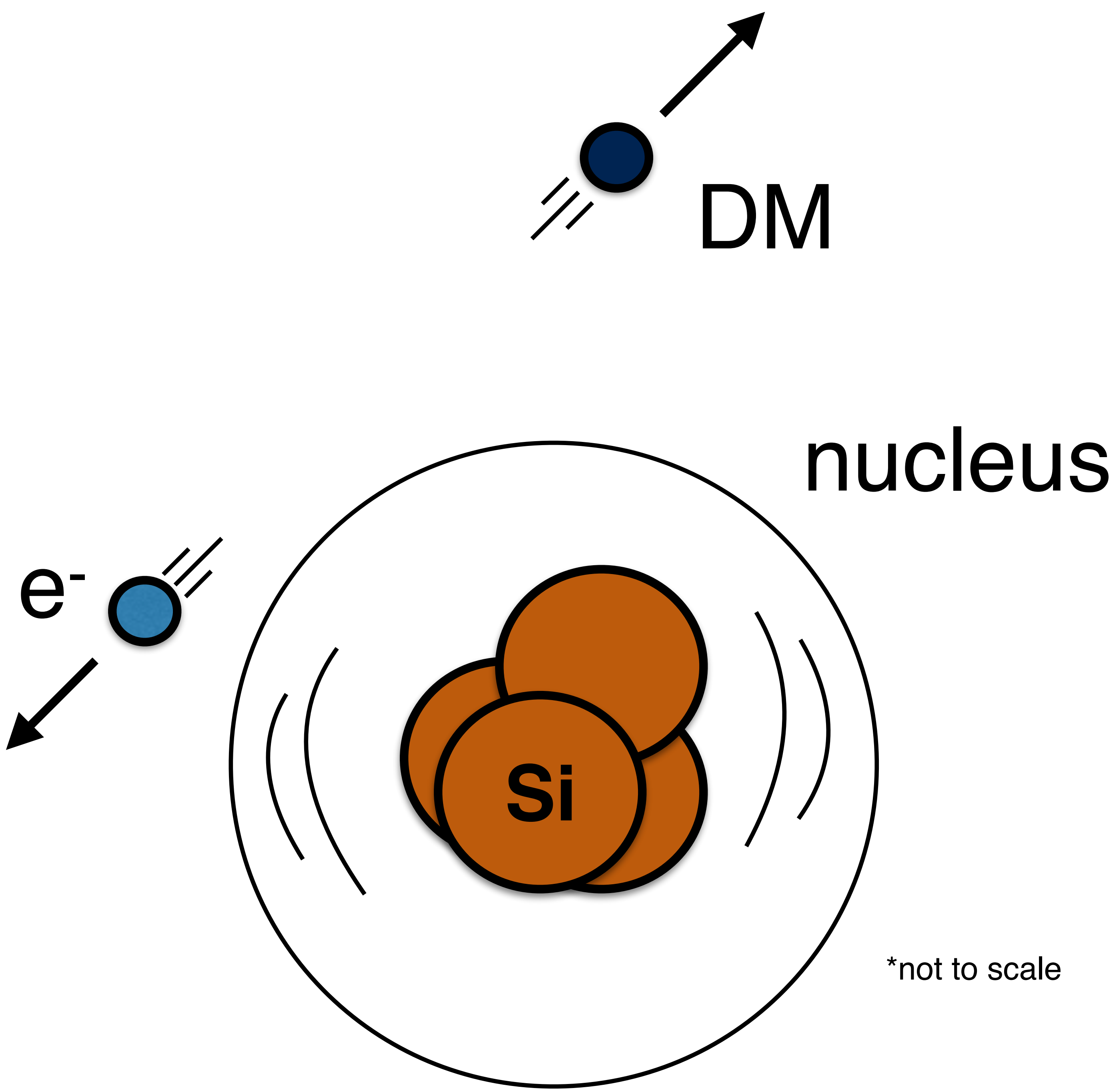
consider different physical processes

2. decrease energy threshold or increase sensitivity

consider a variety of materials

Bernard Sadoulet's talk

DM-electron scattering



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

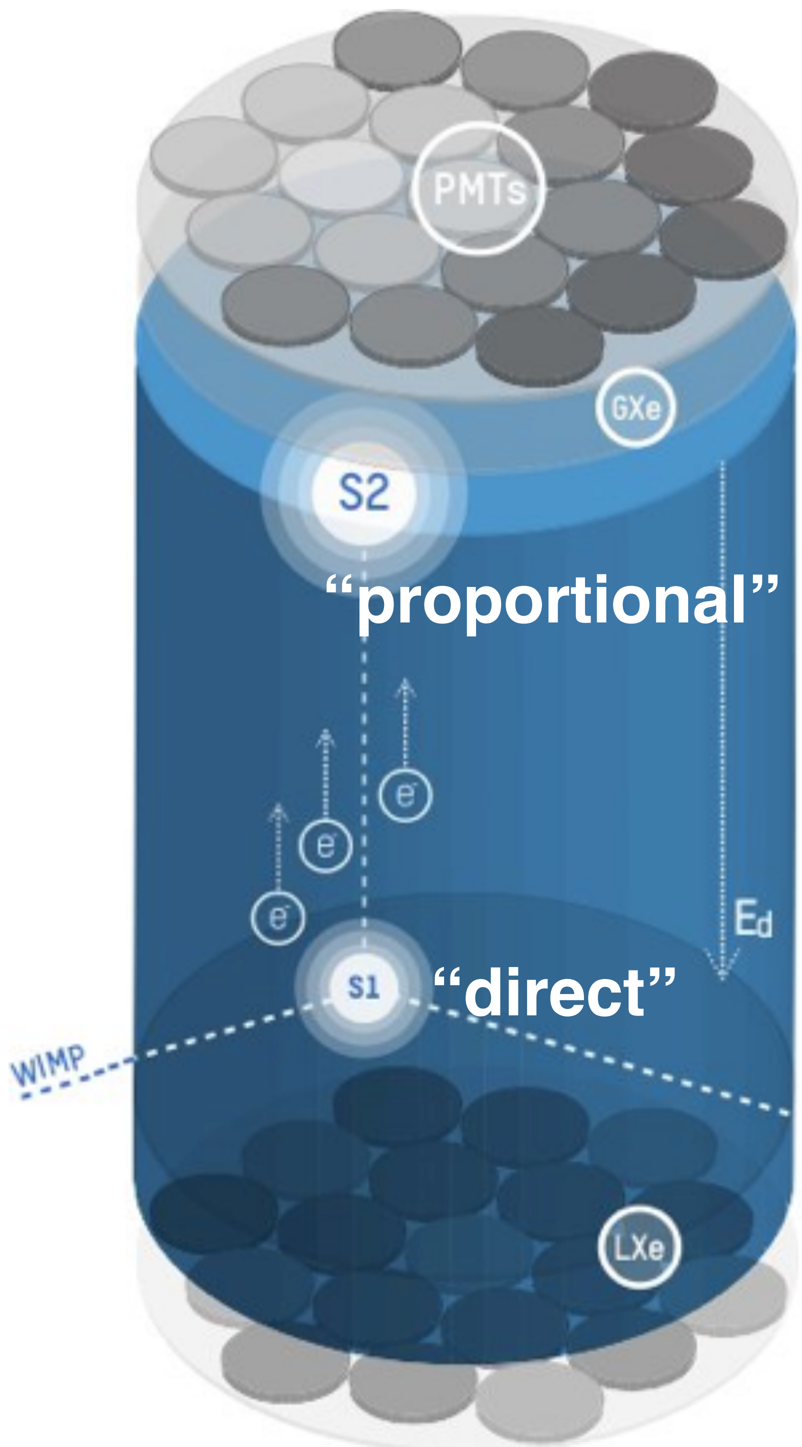
$$m_N = 28\ \text{GeV}$$

$$m_\chi = 100\ \text{MeV}$$

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

available for detection

Liquid Xenon



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

i.e. XENON10, XENON100, XENON1T, LUX, UA(1)’

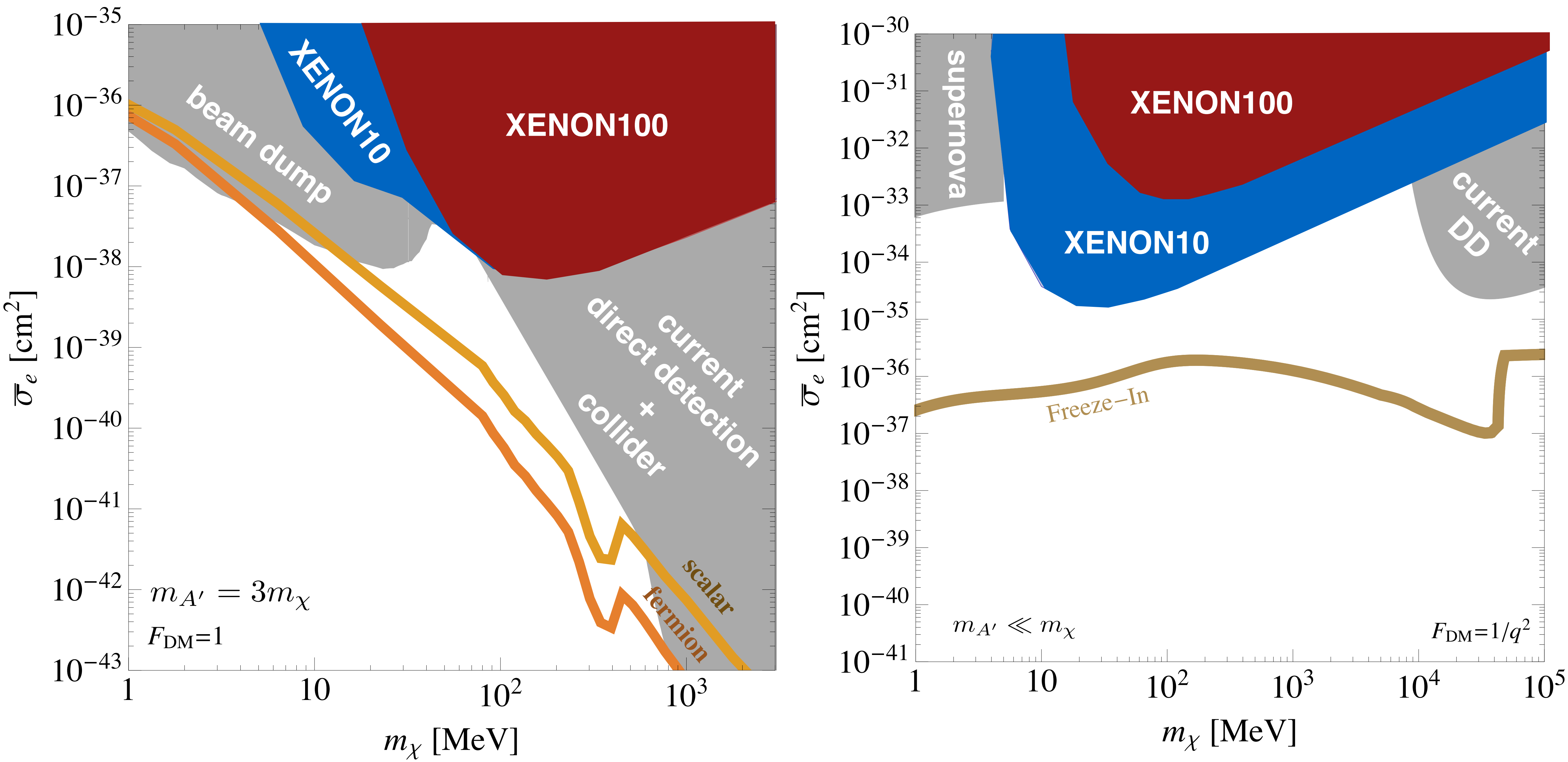
DM-electron scattering
=
S2 only signal

sensitive to ~10 eV energy depositions

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

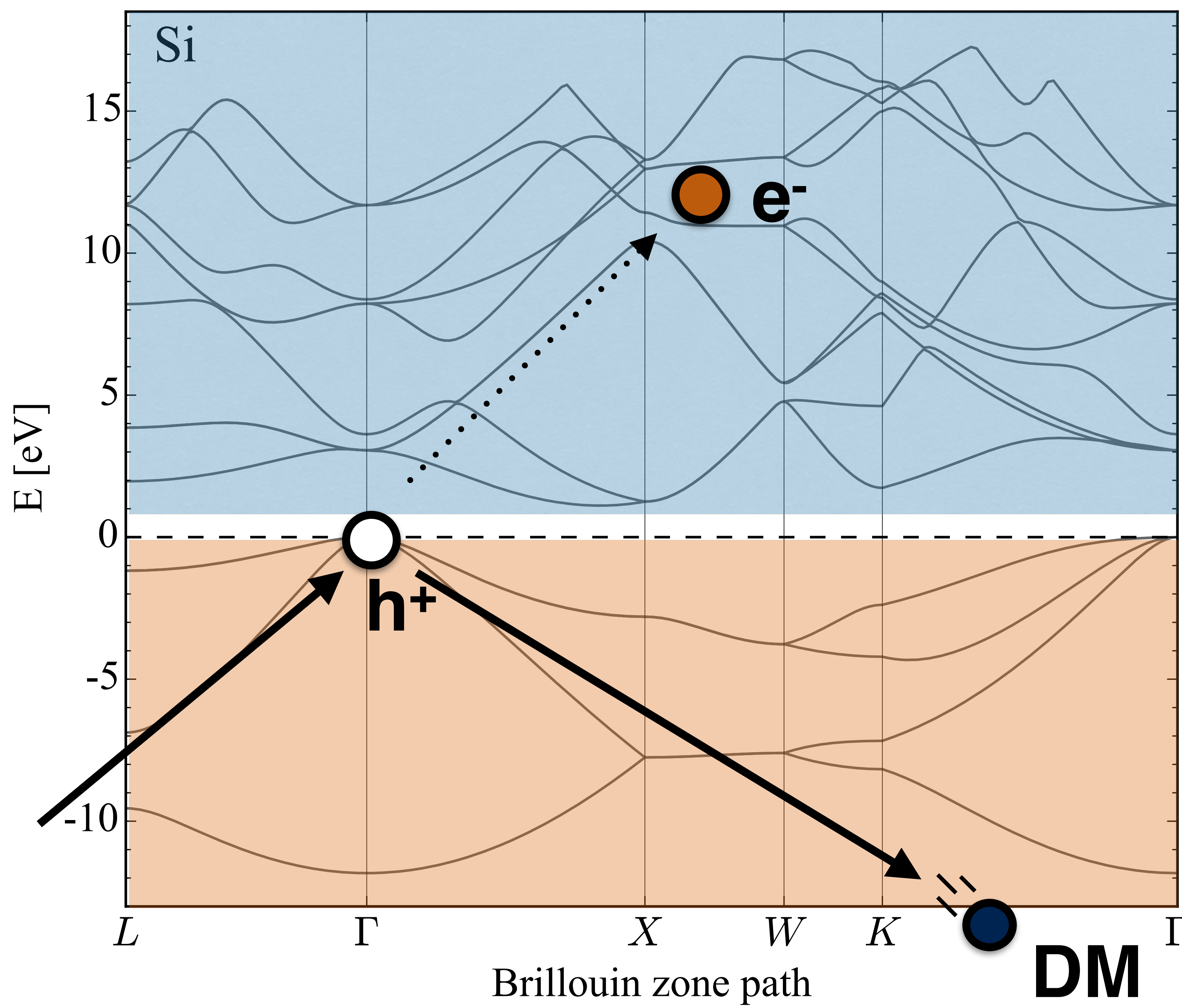
Cristiano Galbiati’s & Elena Aprile’s talks

DM-electron scattering



Essig, Volansky, TTY [1703.00910]

semiconductor targets



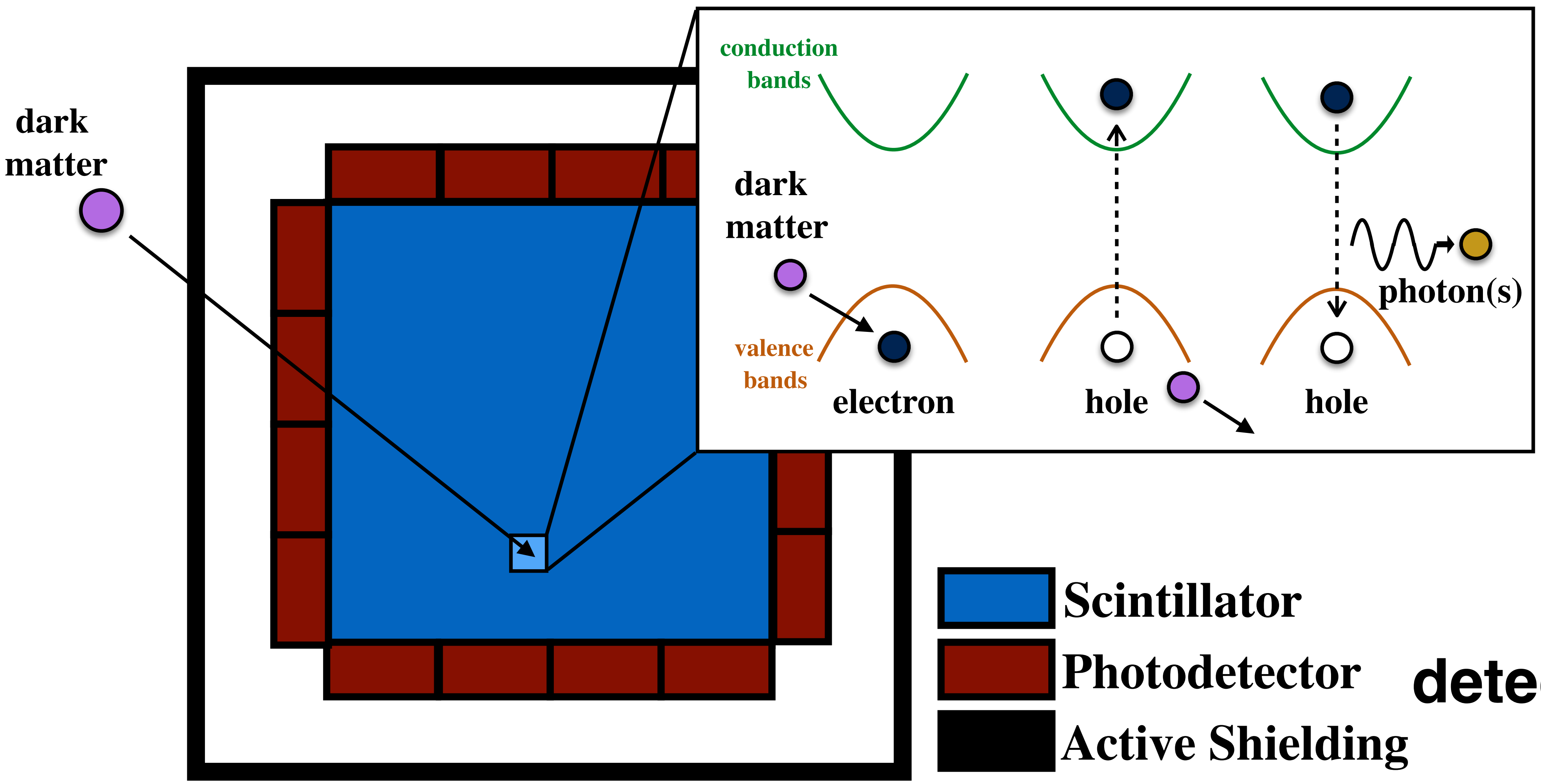
detect the electron(s)

sensitive to ~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]

scintillators



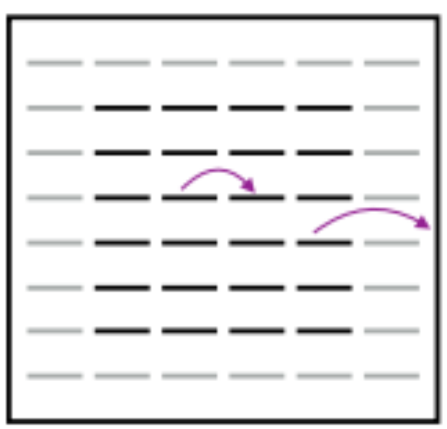
detect the photon(s)

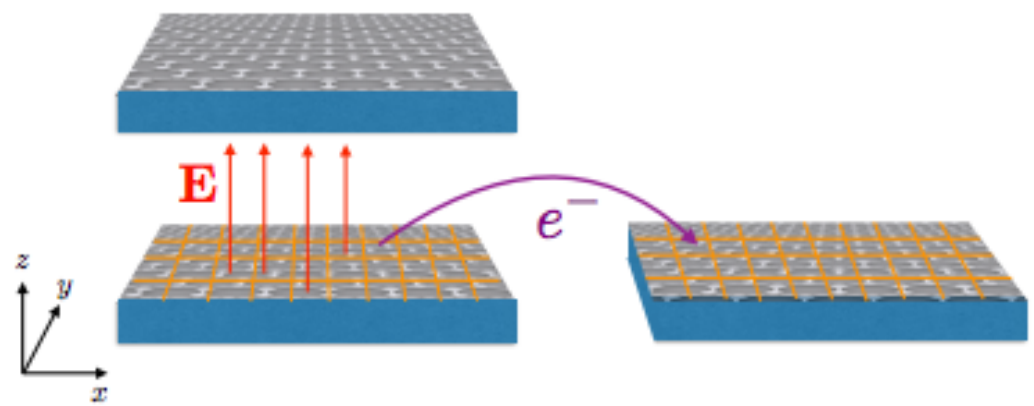
sensitive to ~eV energy depositions

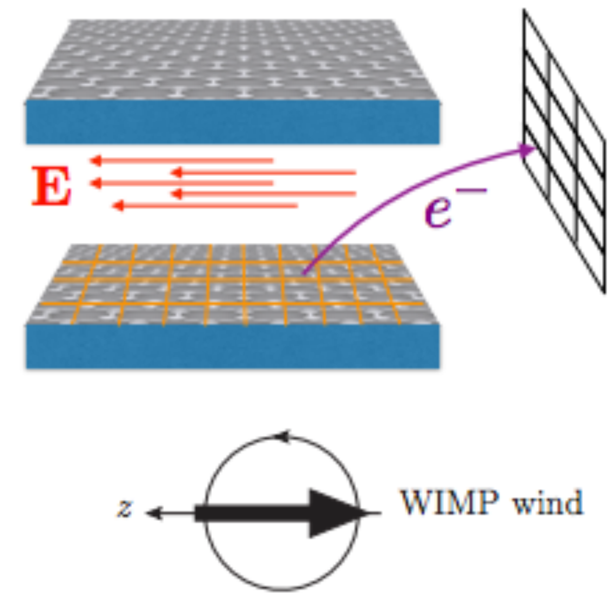
i.e. GaAs, NaI, CsI

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

graphene and carbon nanotubes



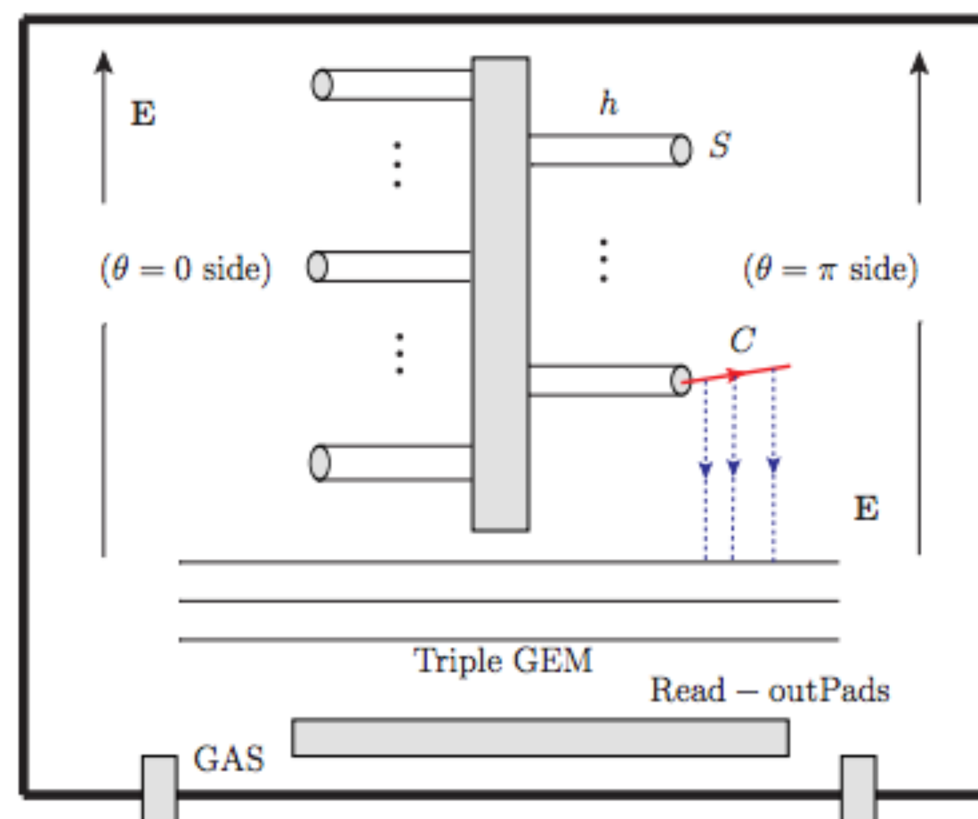




$$\Phi \simeq 4.3 \text{ eV}$$

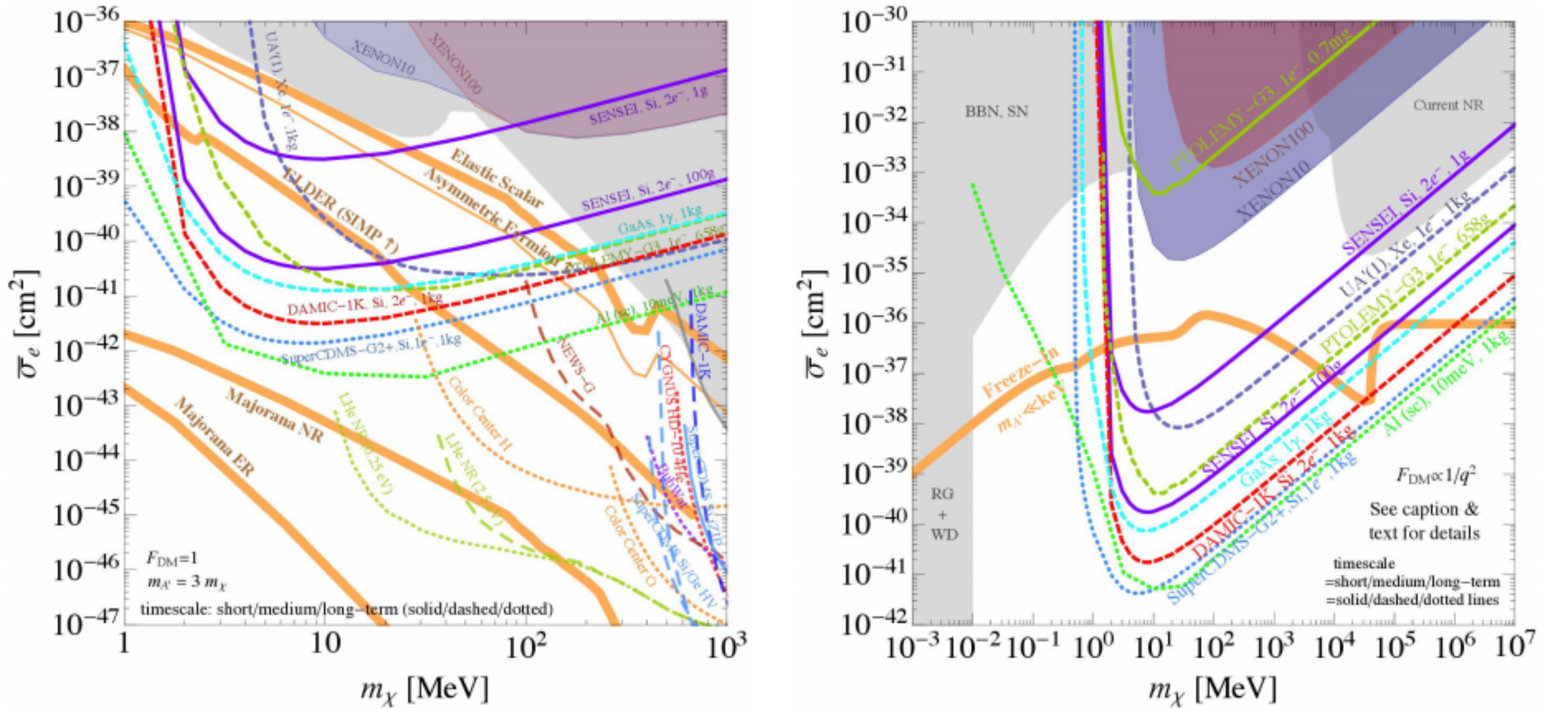
work function = minimum energy to eject an electron

has directional sensitivity!



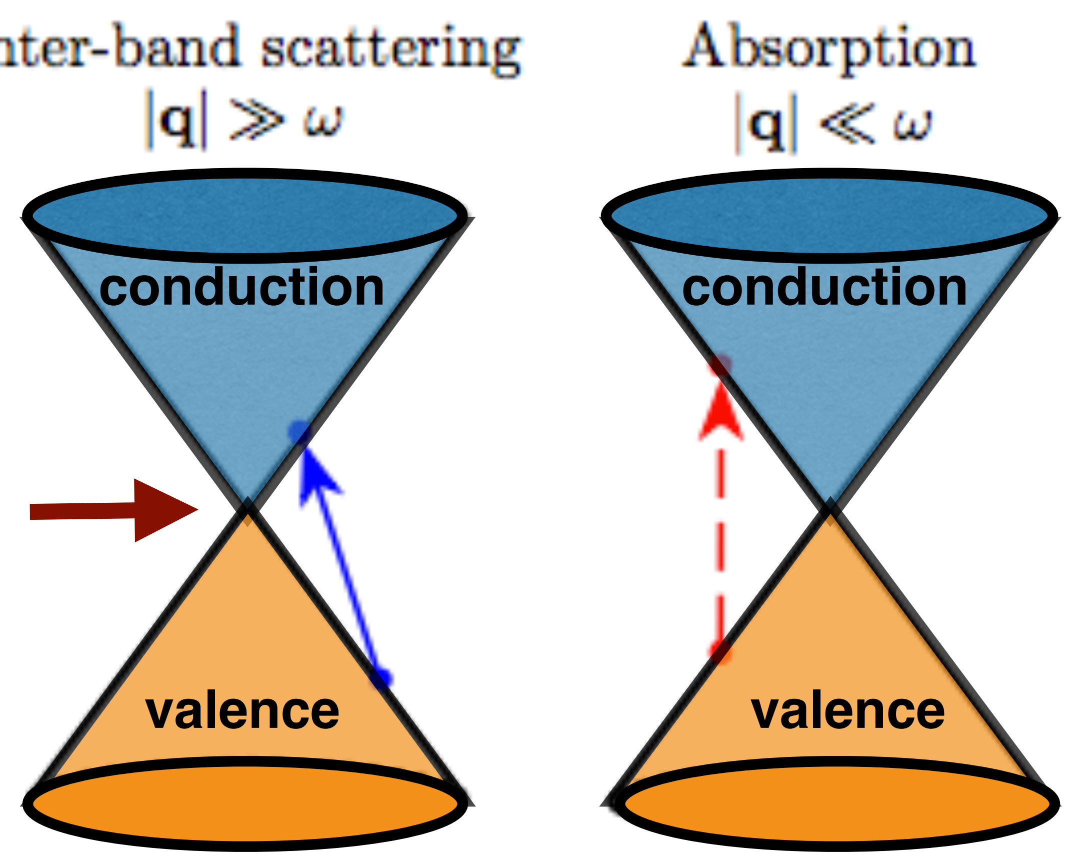
Hochberg, Kahn, Lisanti, Tully, Zurek [1606.08849]
Capparelli, Cavoto, Mazzilli, Polosa [1412.8213]
Cavoto, Luchetta, Polosa [1706.02487]

MeV-GeV DM-e scattering



US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report [1707.04591]

dirac materials



can have zero or very small gap ~meV

characterized by linear low-energy dispersion relationship, $E \sim v_F\, l$

sensitive to ~meV energy depositions
i.e. $ZrTe_5$

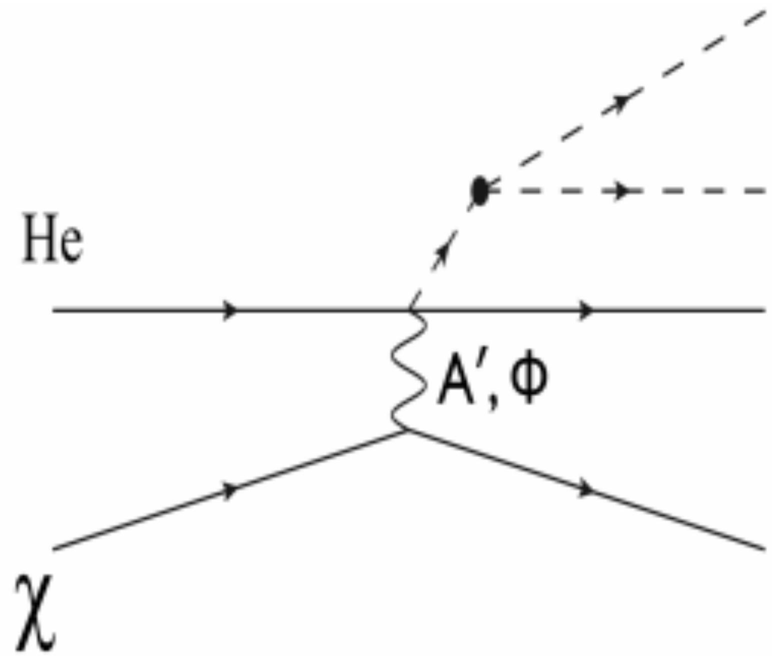
Hochberg, Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin, Liu, Weber, Neaton [1708.08929]

optical phonons

- DM interacts with optical phonons through dipole moment
- sensitive to ~30-100 meV energy depositions
- optical phonons exist in polar materials, i.e. GaAs, sapphire

Knapen, Lin, Pyle, Zurek [1712.06598]

superfluid helium



DM couples to **collective** quasiparticle modes

(phonons, rotons, maxons)

sensitive to meV-eV energy depositions

neutral atom → small polarizability
not great for models of dark photons

DM-nucleon scattering

Schutz, Zurek [1604.08206]
Knapen, Lin, Zurek [1611.06228]

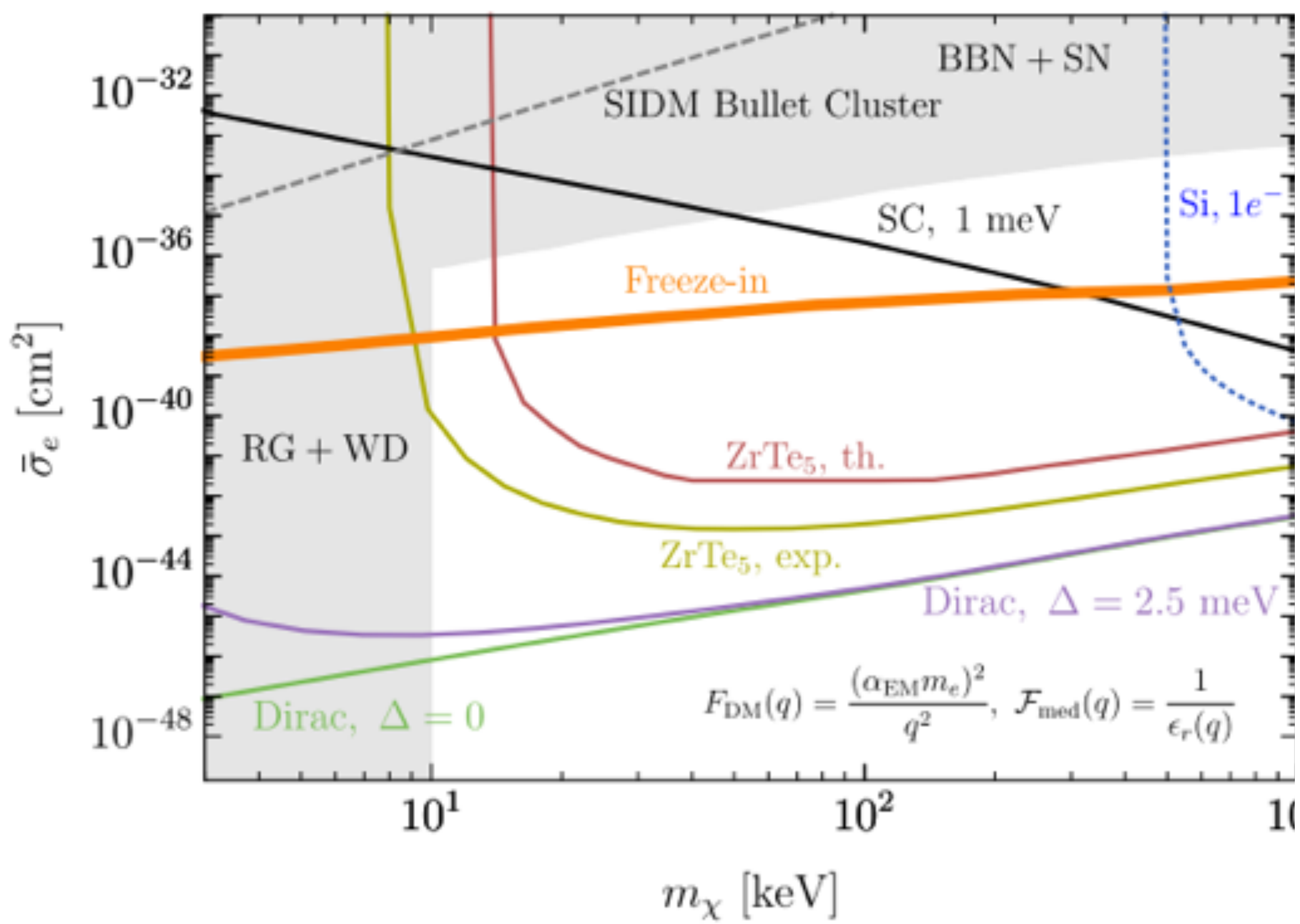
superconductors

- superconductor: material with zero electrical resistance below a critical temperature
- DM interaction breaks cooper pairs, which releases energy
- sensitive to ~meV energy depositions
- i.e. aluminum

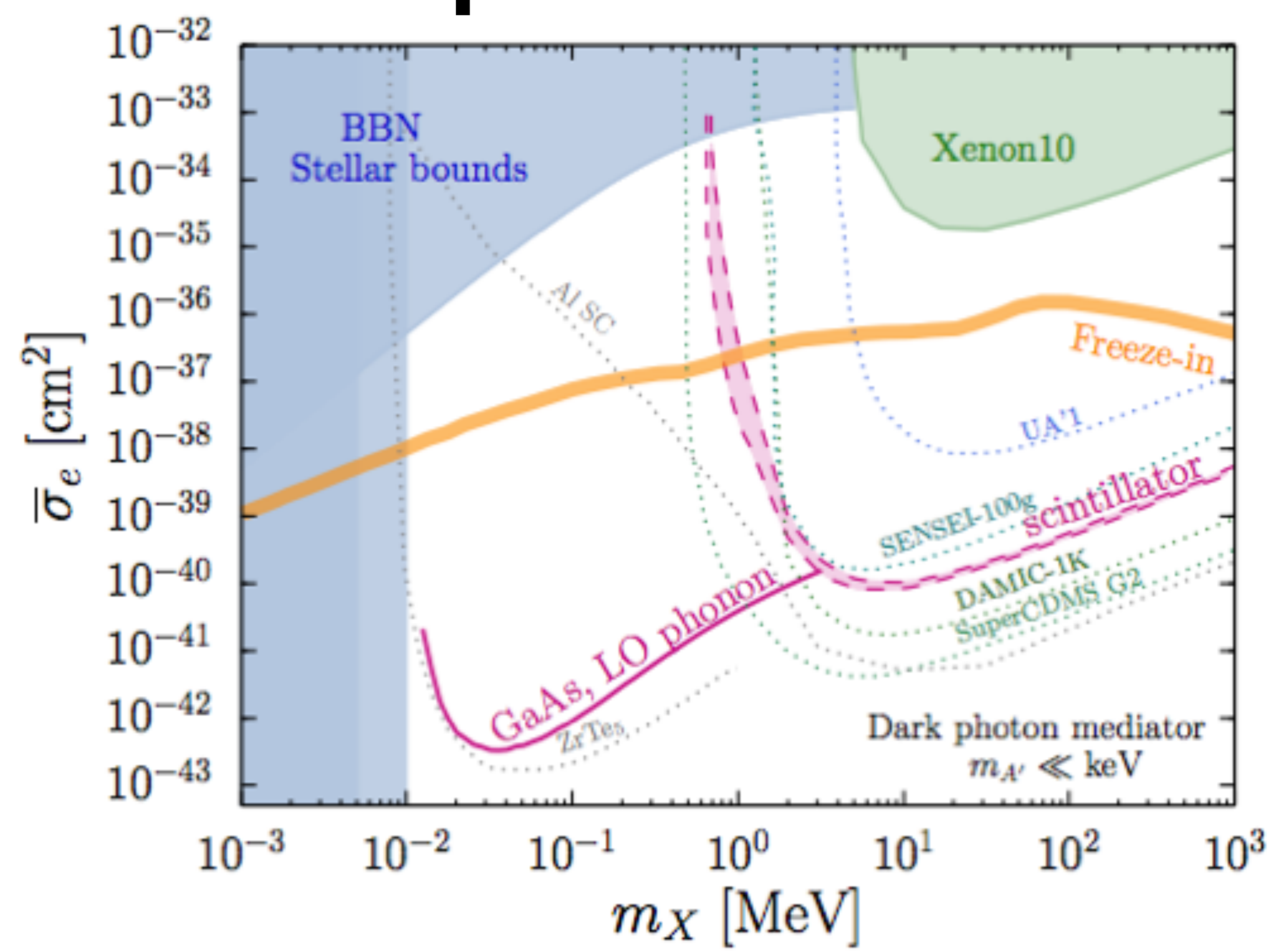
Hochberg, Zhao, Zurek [1504.07237]
Hochberg, Pyle, Zhao, Zurek [1512.04533]
Hochberg, Lin, Zurek [1604.06800]

sub-MeV DM scattering

Dirac Metals



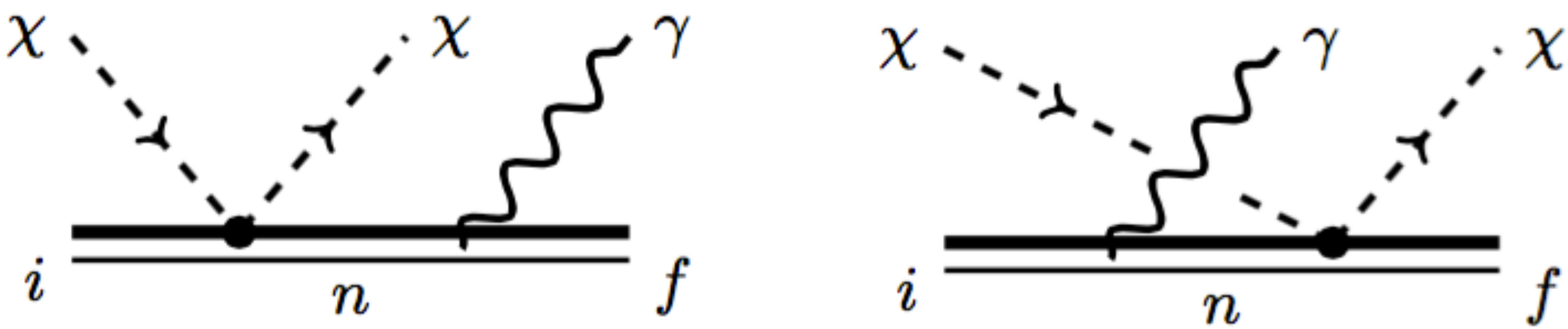
Optical Phonons, superconductors



Hochberg, Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin, Liu, Weber, Neaton [1708.08929]

Knapen, Lin, Pyle, Zurek [1712.06598]

DM-nucleon scattering + photon

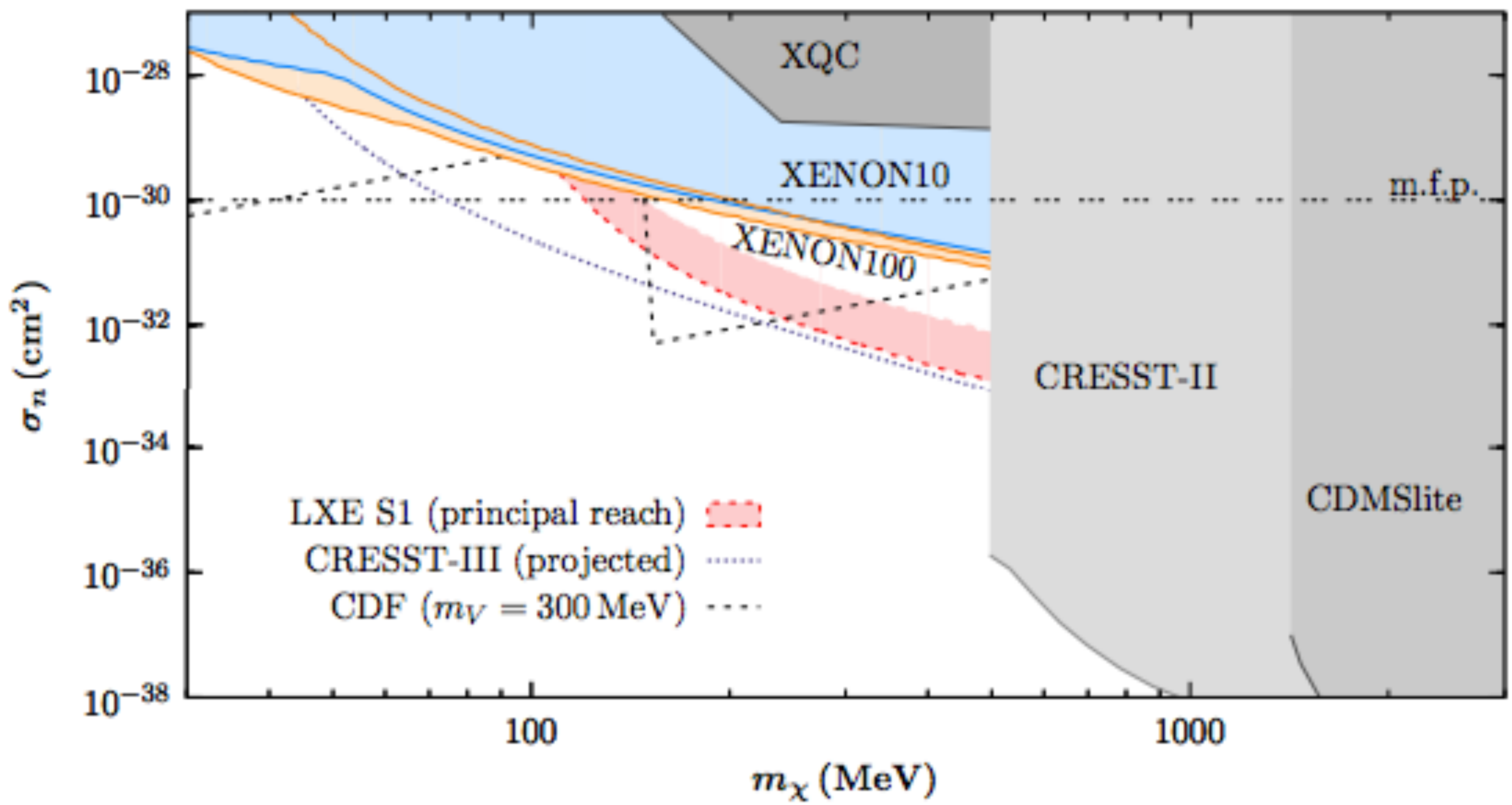


$$d\sigma = |V_{fi}|^2 \frac{\omega^2 d\omega d\Omega_K}{(2\pi)^3} \times d\sigma_{\rm el}$$

dipole transition element

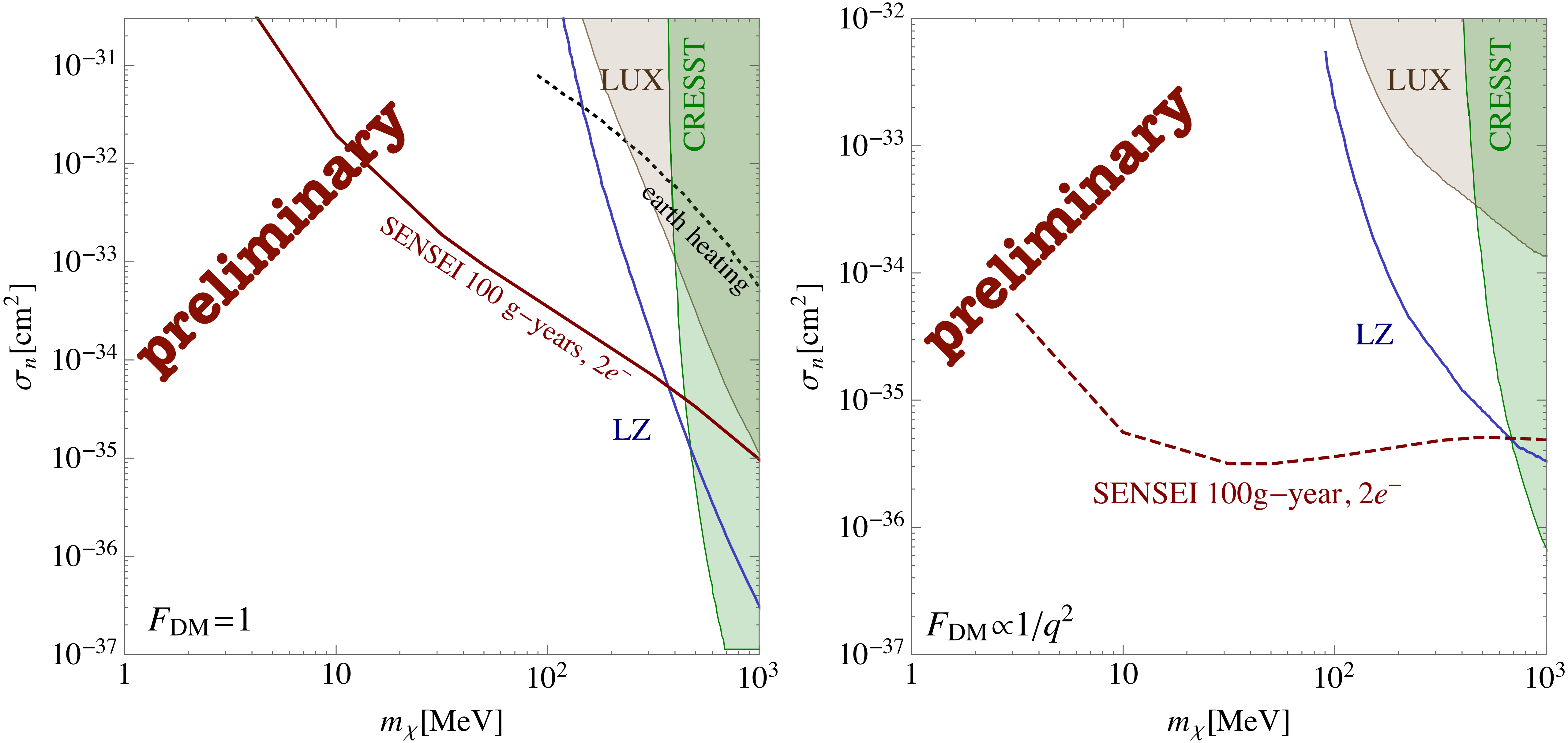
Kouvaris, Pradler [1607.01789]
McCabe [1702.04730]

DM-nucleon scattering + photon



Kouvaris, Pradler [1607.01789]

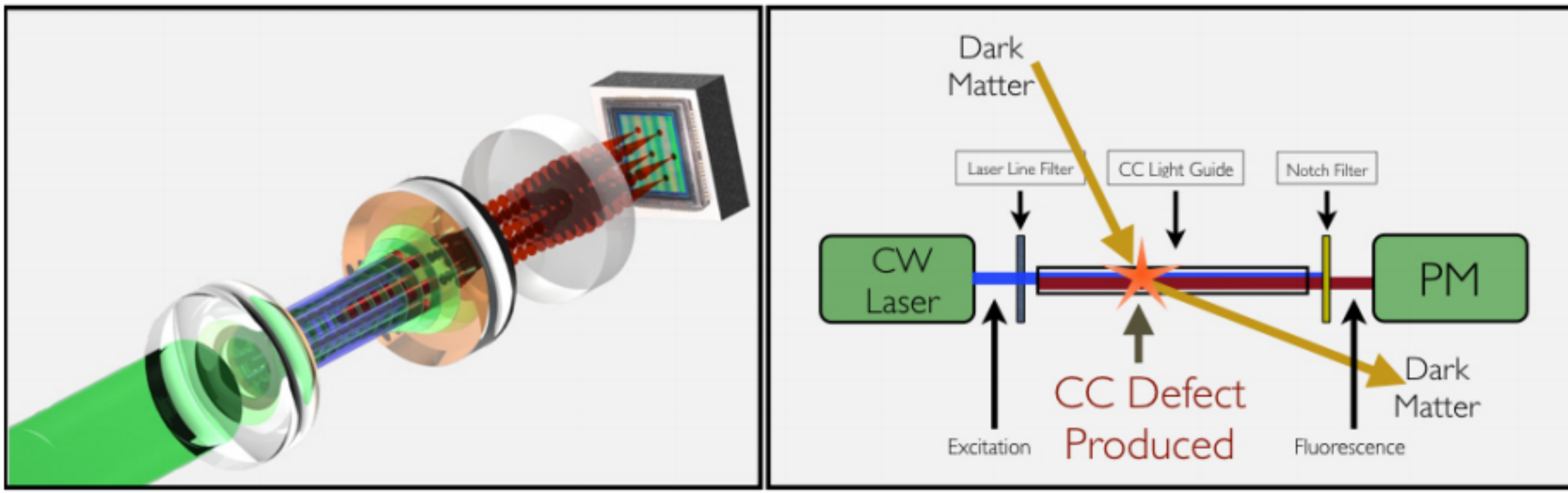
photon emission



SENSEI: A Novel Search for Light Dark Matter, *to appear*

DM interaction triggers a physical or chemical change in target material

color centers

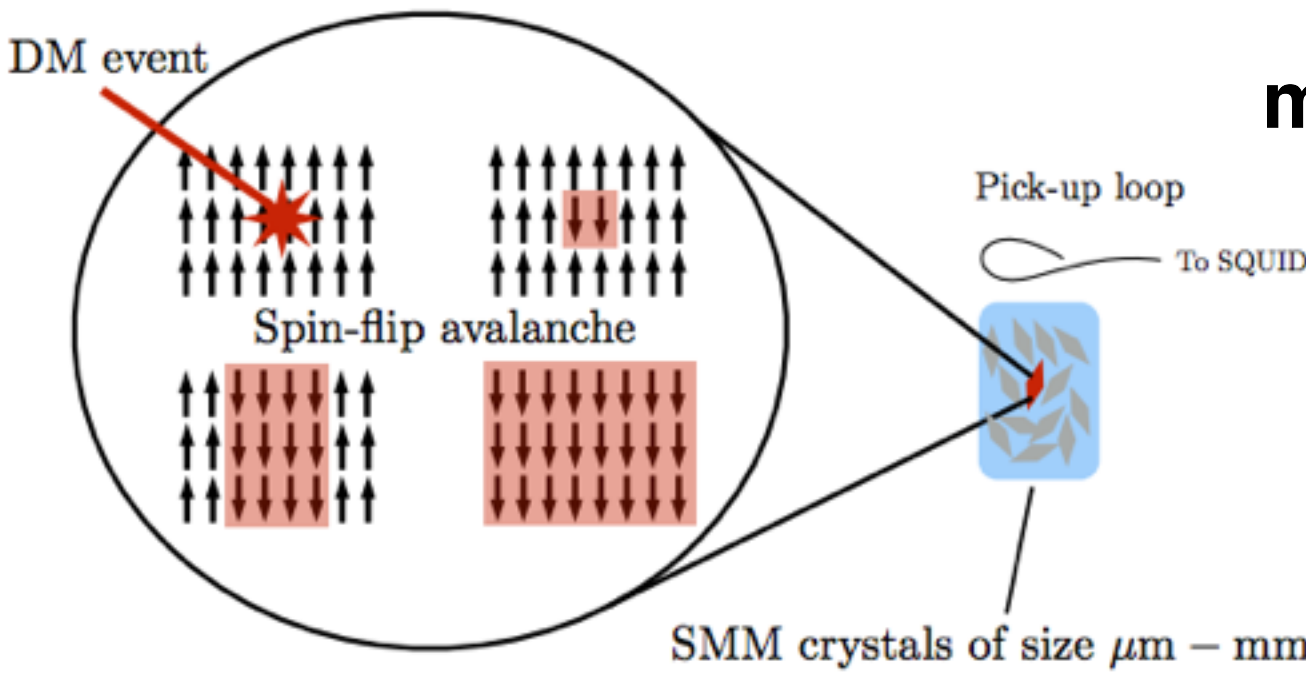


DM interaction creates a long-lived defect in the crystal

sensitive to ~10 eV energy depositions

Budnik, Chesnovsky, Slone, Volansky [1705.03016]

magnetic bubbles



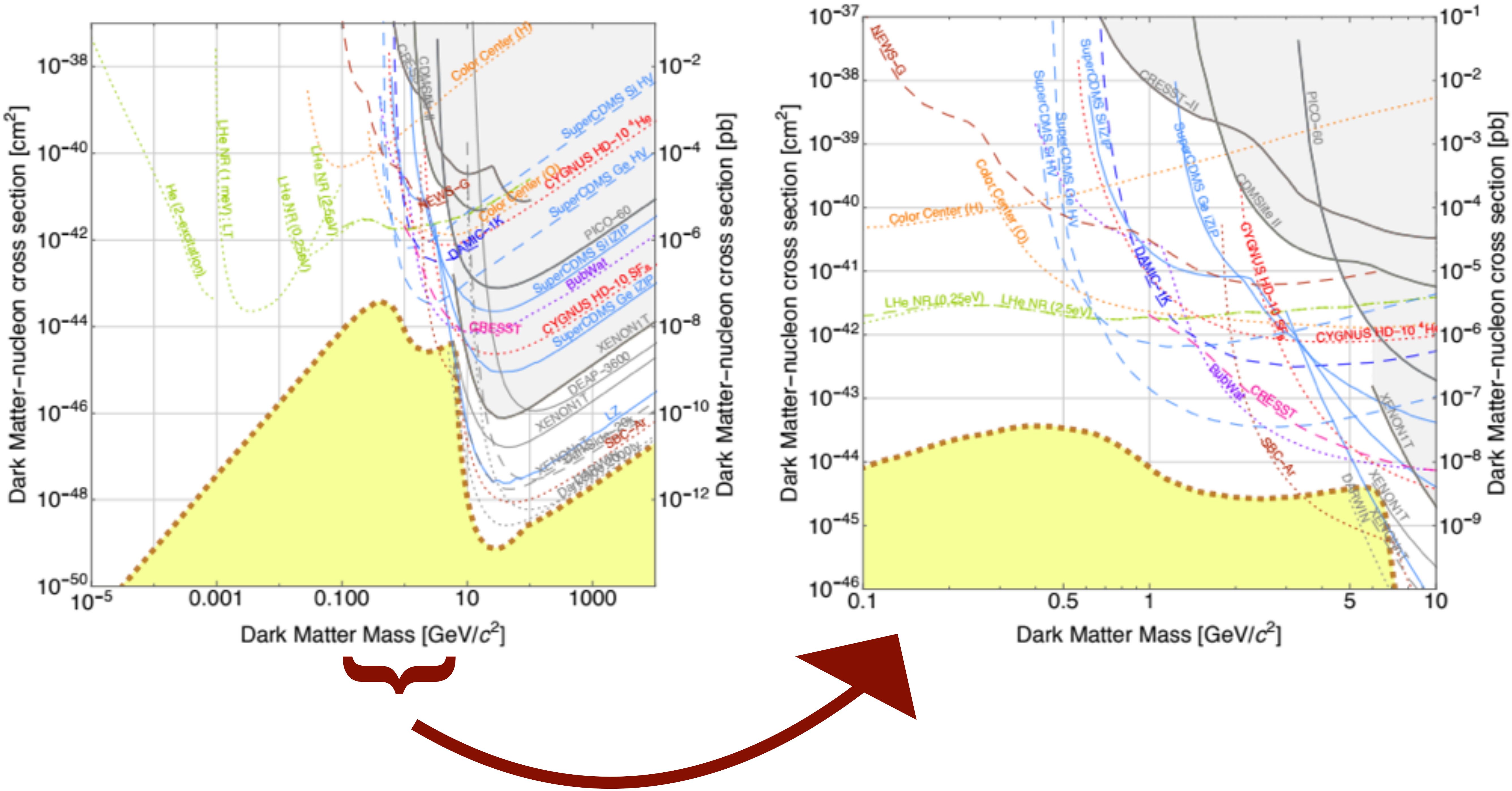
single molecule magnets (SMM) = molecular crystals with molecules that act like tiny, non-interacting magnets

relies on the coherence of interaction event to create a measurable signal

sensitive to 10^{-3} eV-10 eV energy depositions

Bunting, Gratta, Melia, Rajendran [1701.06566]

DM-nucleon interactions



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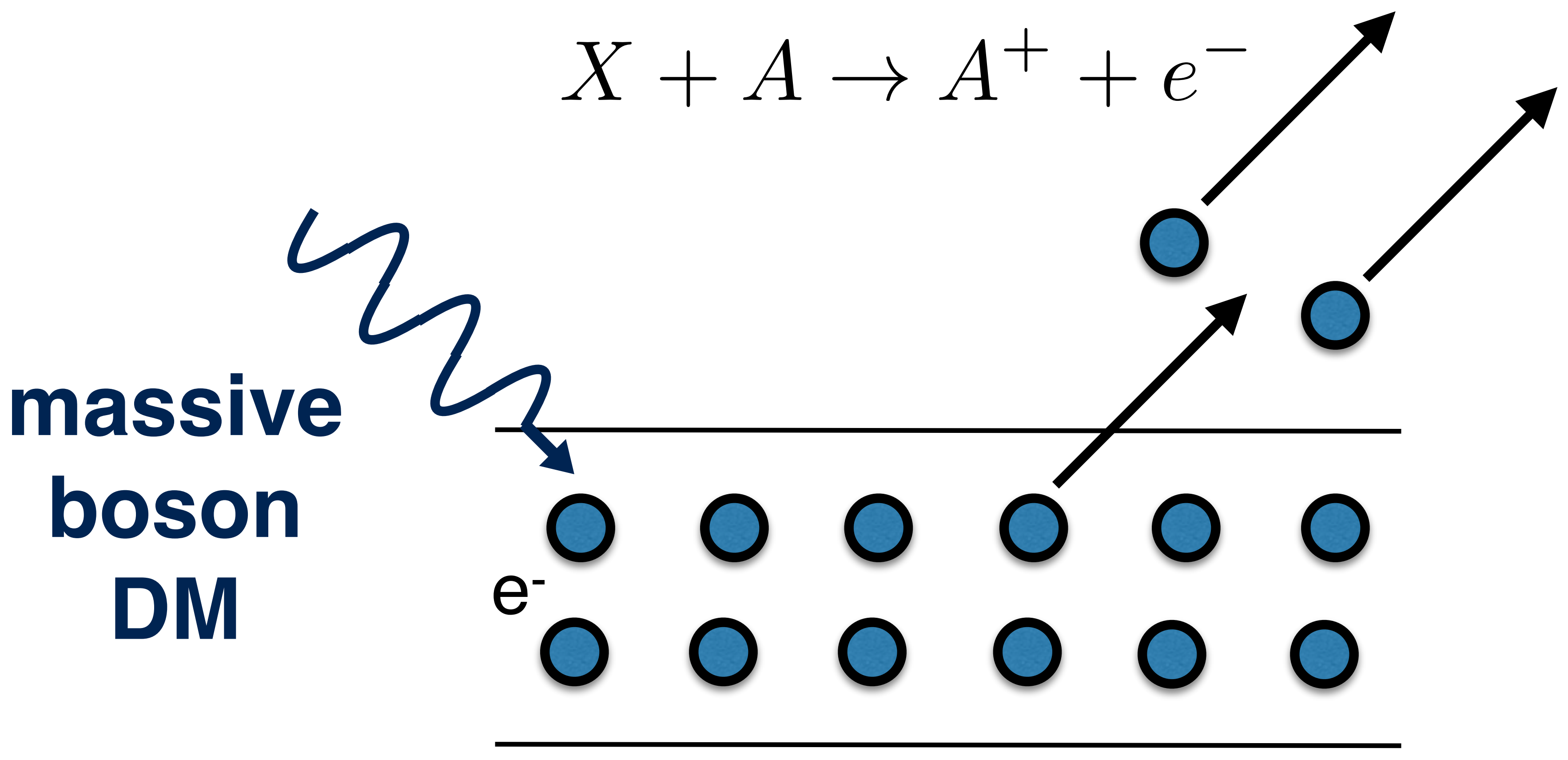
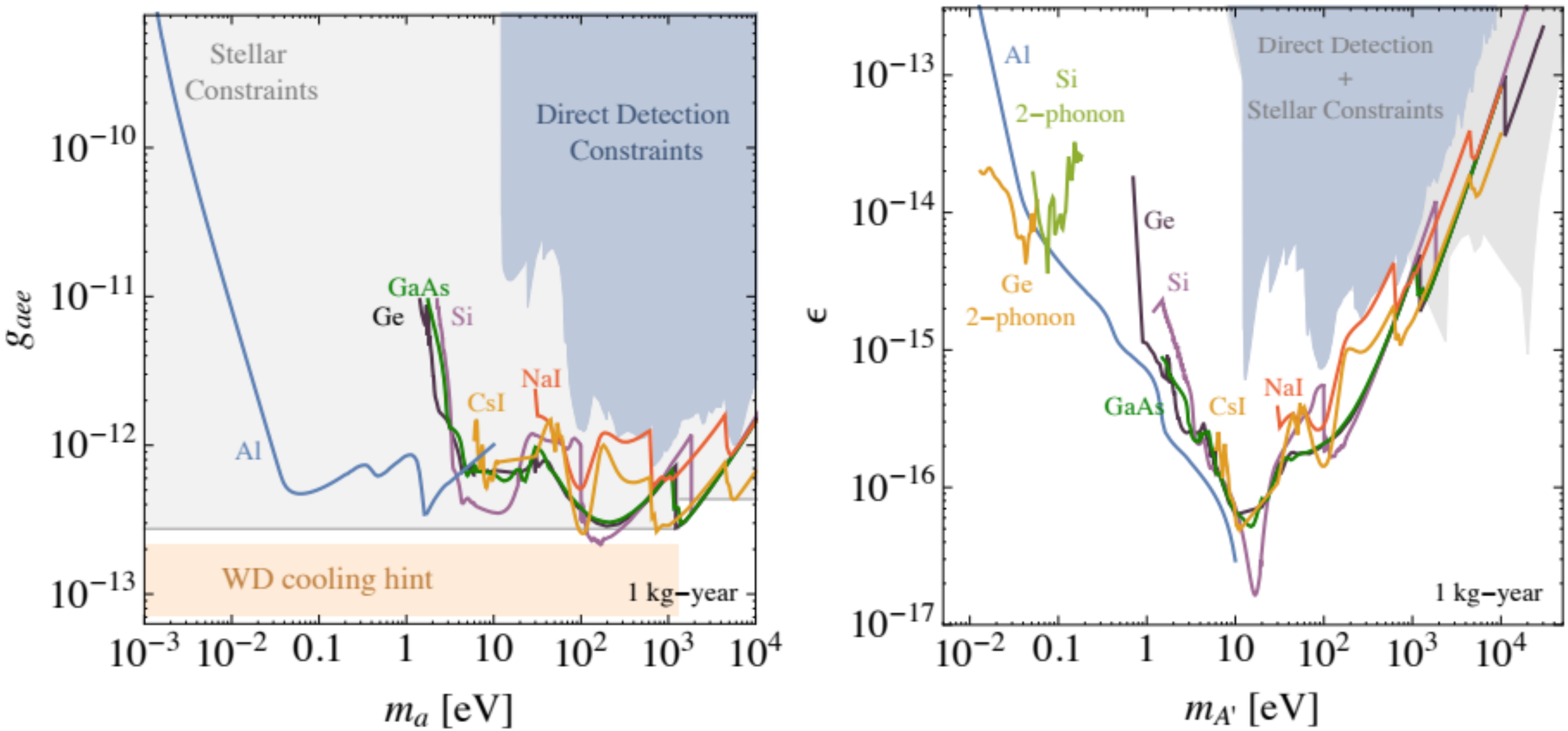
photoelectric effect

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



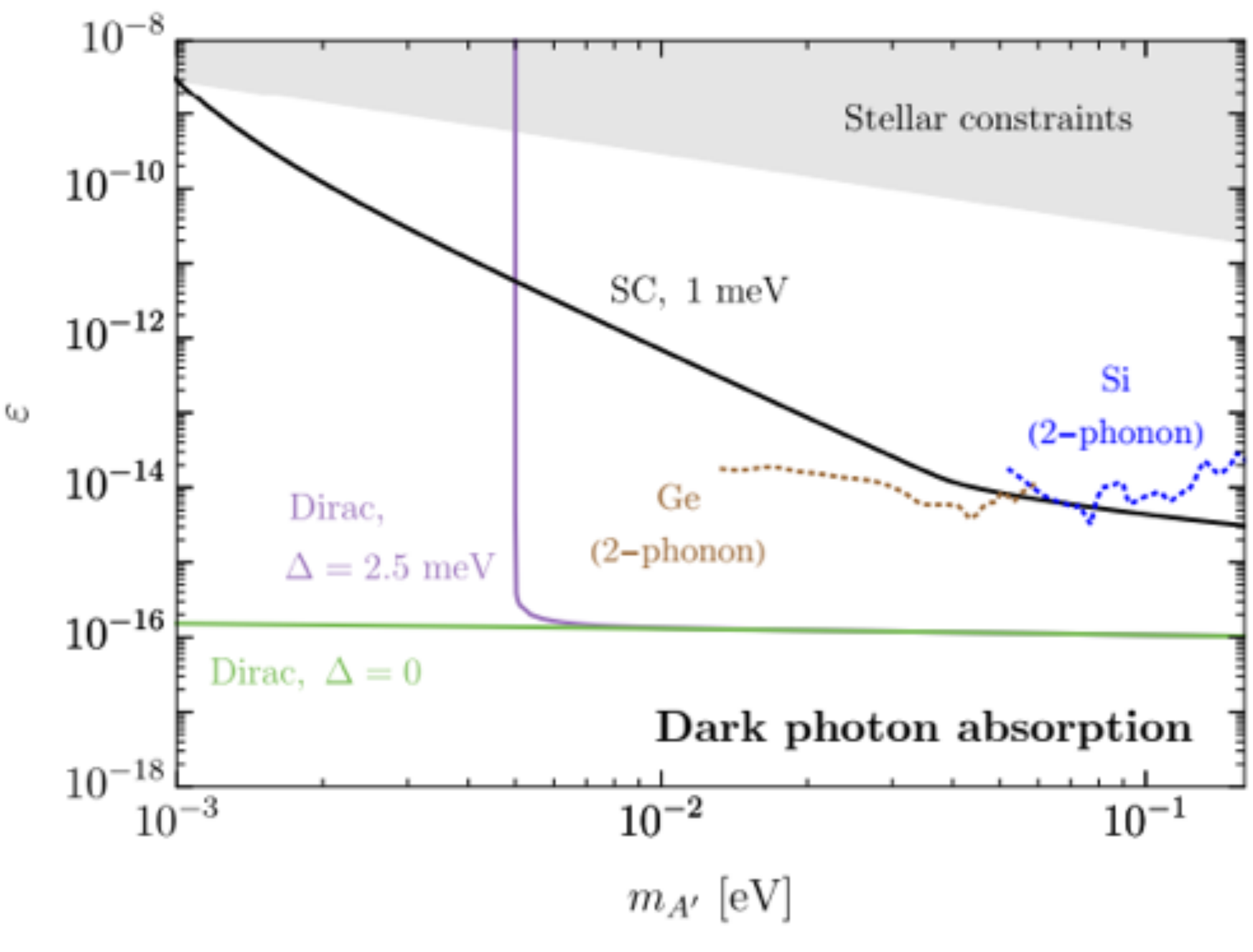
absorb all of the energy
the incoming dark matter

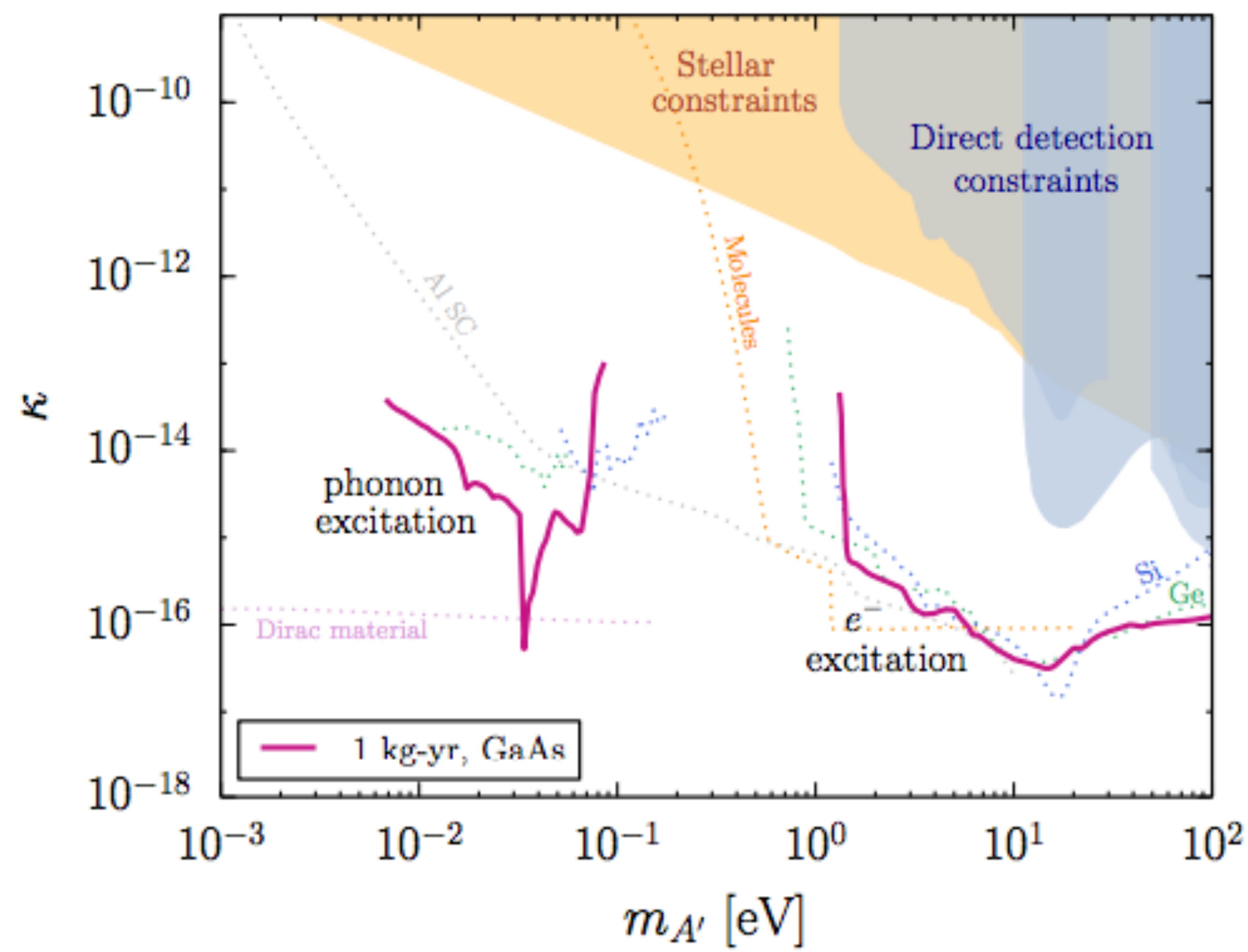
absorption



US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report [1707.04591]

absorption

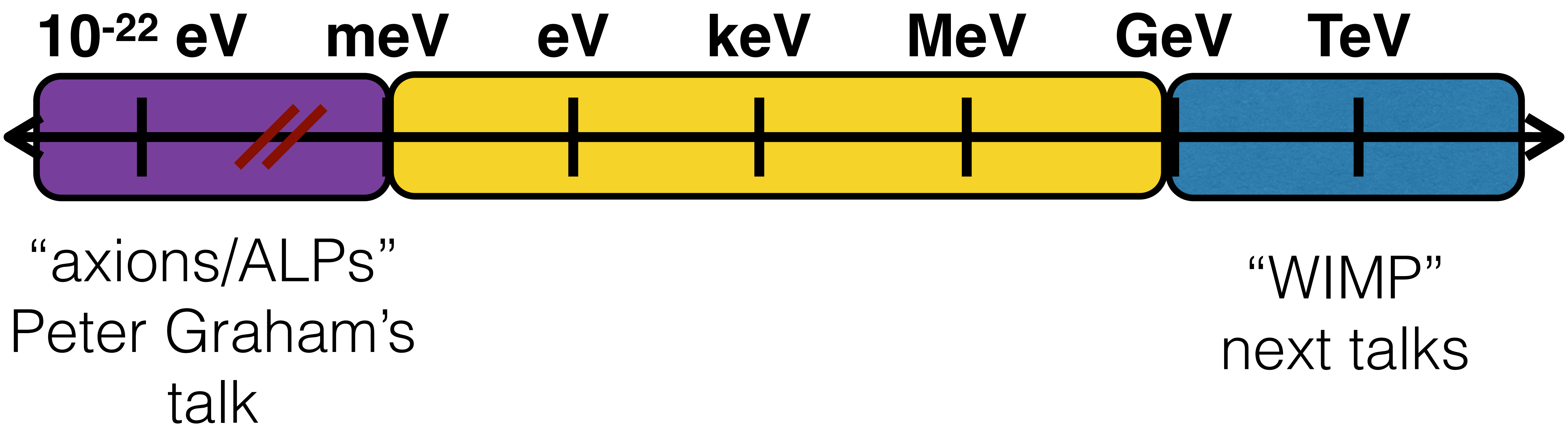




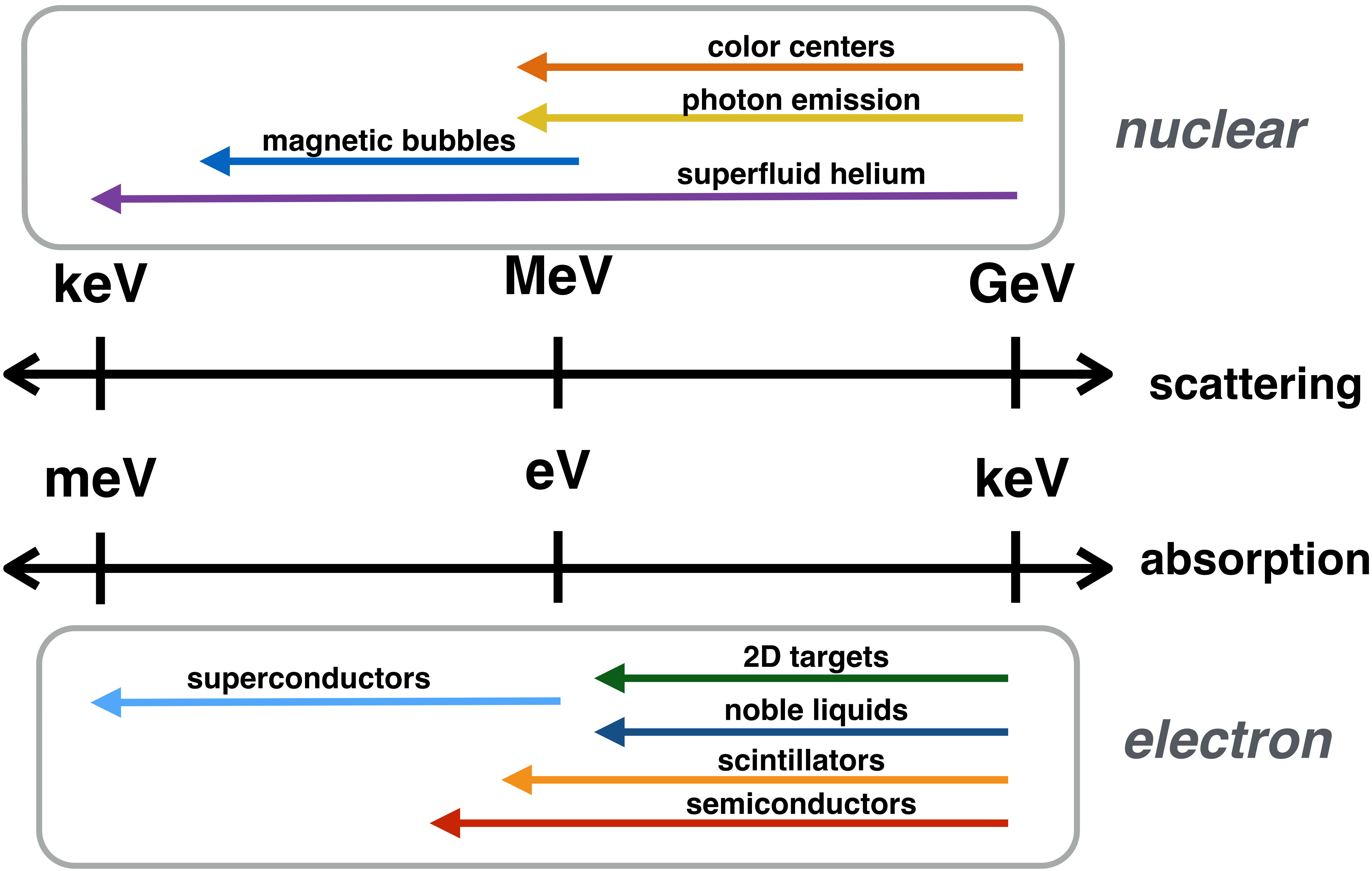
Hochberg, Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin, Liu, Weber, Neaton [1708.08929]

Knapen, Lin, Pyle, Zurek [1712.06598]

dark matter candidates



dark matter candidates



extra: proposed experimental ideas

SENSEI

target material: Si CCD with Skipper readout

processes: DM-e scattering, DM-absorption, DM-n bremsstrahlung

detects: single-few electrons

mass reach: eV-GeV

timeline: running, 2 years to deploy 100g

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

scintillators

target material: GaAs(Si,B)

processes: DM-e scattering, DM absorption

detects: single-few photons

mass reach: MeV-GeV

timeline: R&D effort ongoing

Derenzo, Essig, Massari, Soto, TTY [1607.01009]
+ LBNL Scintillator research group (Derenzo, Bourret-Courchesne, Bizarri)
+ Matt Pyle (UC Berkeley)

polar materials

target material: GaAs, Al_2O_3 (sapphire)

processes: DM-phonon scattering, DM absorption

detects: phonons

mass reach: meV-MeV

timeline: R&D effort ongoing

Knapen, Lin, Pyle, Zurek [1712.06598]

2D carbon

target material: graphene, carbon nanotubes

processes: DM-n scattering, DM-e scattering

detects: carbon ion, electrons

mass reach: MeV-GeV

timeline: 1 yr prototype, 1 yr data

Hochberg, Kahn, Lisanti, Tully, Zurek [1606.08849] — PTOLEMY G3

Capparelli, Cavoto, Mazzilli, Polosa [1412.8213]
Cavoto, Luchetta, Polosa [1706.02487]

carbon nanotubes

superfluid helium

target material: He3

processes: inelastic DM-nucleus scattering

detects: quasiparticles (phonons, rotons)

mass reach: keV-MeV

timeline: 1-3 year R&D, ready to start 2018-2020

Schutz, Zurek [1604.08206]
Knapen, Lin, Zurek [1611.06228]

dirac materials

target material: dirac semimetals ($ZrTe_5$)

processes: DM-absorption, DM-e scattering

detects: electrons

mass reach: meV-MeV

timeline: ???

Hochberg, Kahn, Lisanti, Zurek, Grushin, Ilan, Griffin,
Liu, Weber, Neaton [1708.08929]

color centers

target material: crystals (CaF)

processes: DM-n scattering

detects: photons

mass reach: 10 MeV-GeV

timeline: R&D ongoing

Budnik, Chesnovsky, Slone, Volansky [1705.03016]

magnetic bubbles

target material: SMM (Mn12-acetate)

processes: DM-absorption, DM-e scattering, DM-n scattering

detects: magnetic flux

mass reach: meV-10 eV

timeline: R&D effort ongoing

Bunting, Gratta, Melia, Rajendran [1701.06566]

superconductors

target material: aluminum

processes: DM-e scattering, DM-absorption

detects: phonons

mass reach: meV-10 eV

timeline: 10+ years

Hochberg, Zhao, Zurek [1504.07237]
Hochberg, Pyle, Zhao, Zurek [1512.04533]
Hochberg, Lin, Zurek [1604.06800]