Fundamentals of Direct Detection

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New Directions in the Search for Light Dark Matter Particles
Fermilab
June 4, 2019

Caveats/Apologies

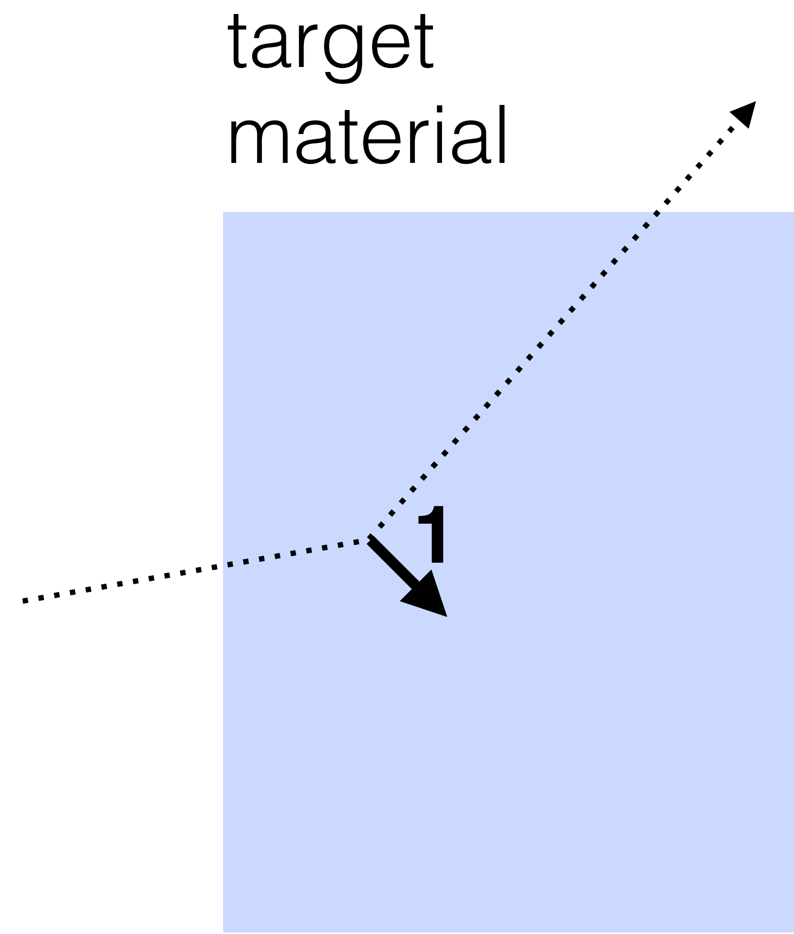
- Giving an intro-level talk to a room full of experts…

  My goal: tell you things you already know.

- I'm not unbiased…

- Not educated enough to give an intelligent talk on ultralight DM
  (restricting myself to keV-MeV-GeV mass scale)

The big-picture game

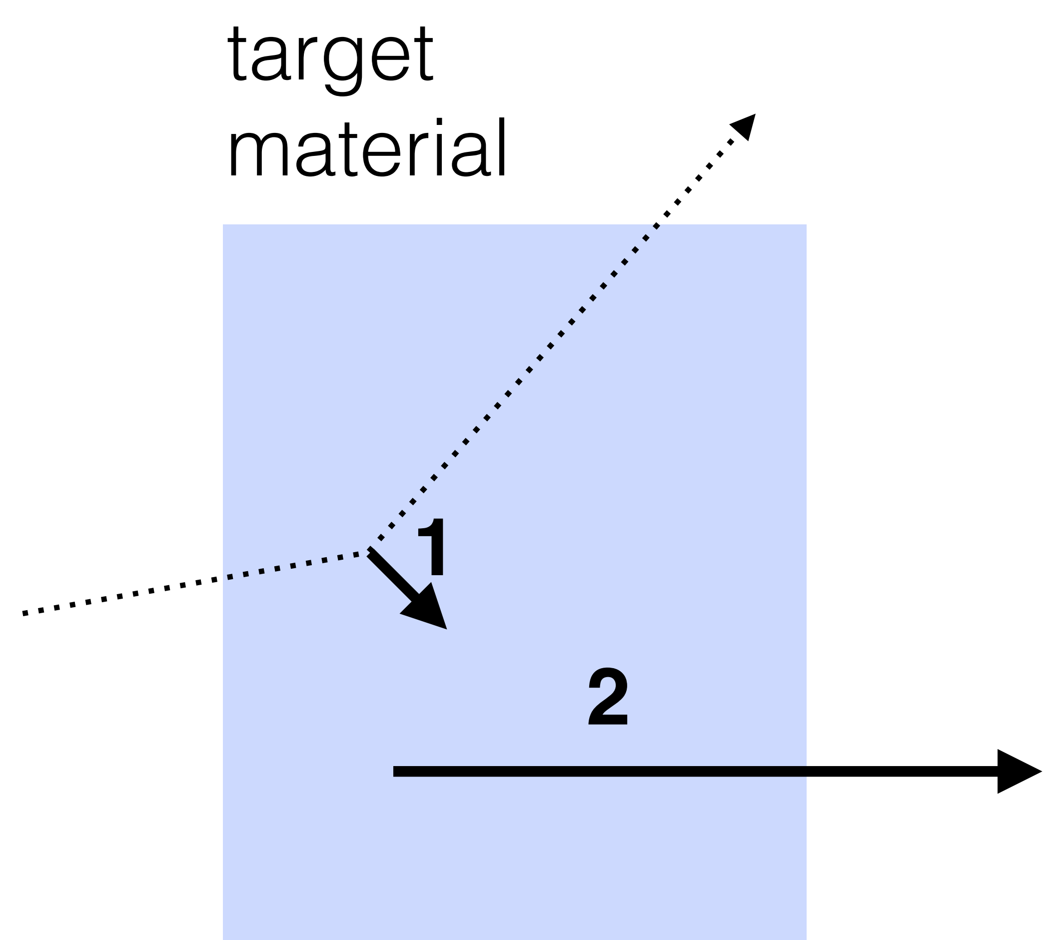


1) find *initial* material excitations that

maximize DM interaction probability

maximize deposited energy

The big-picture game



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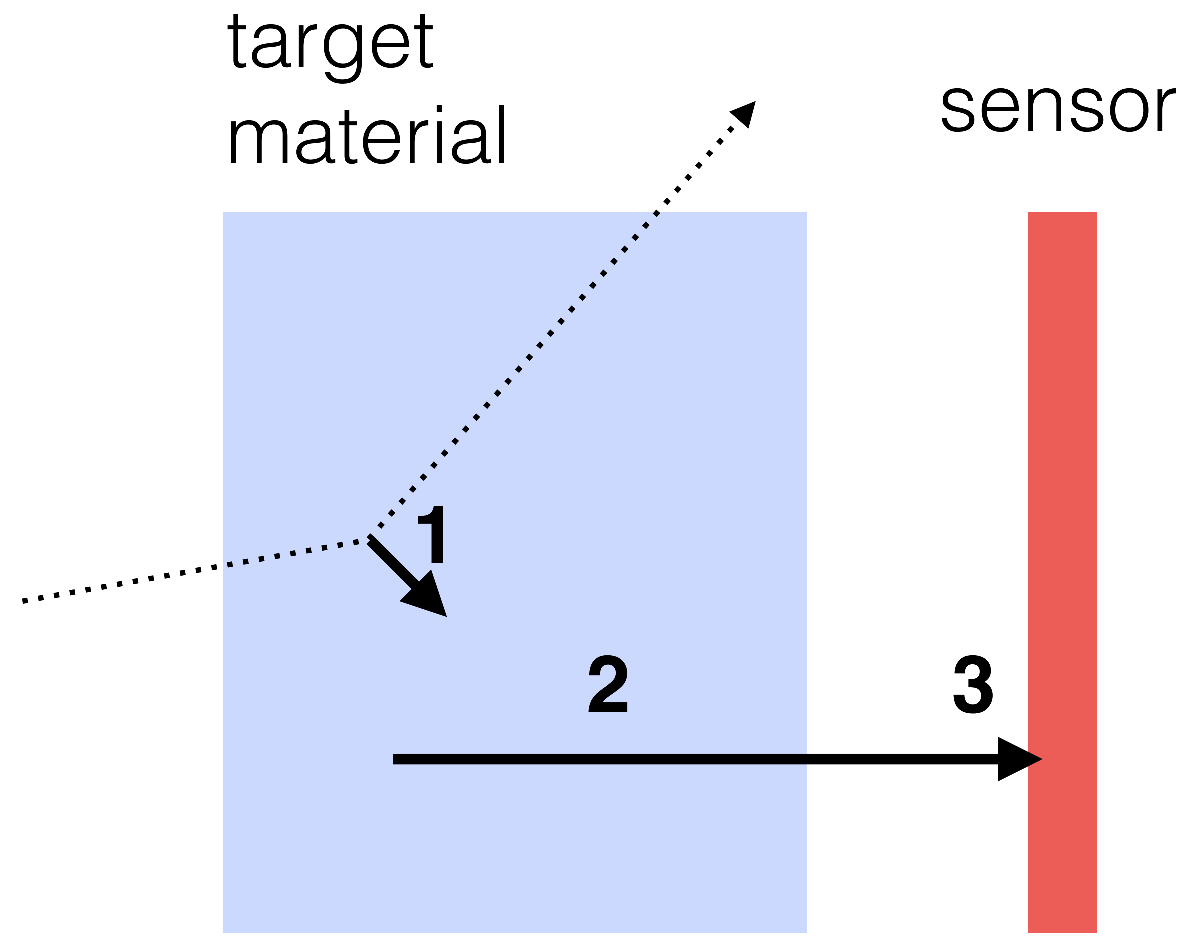

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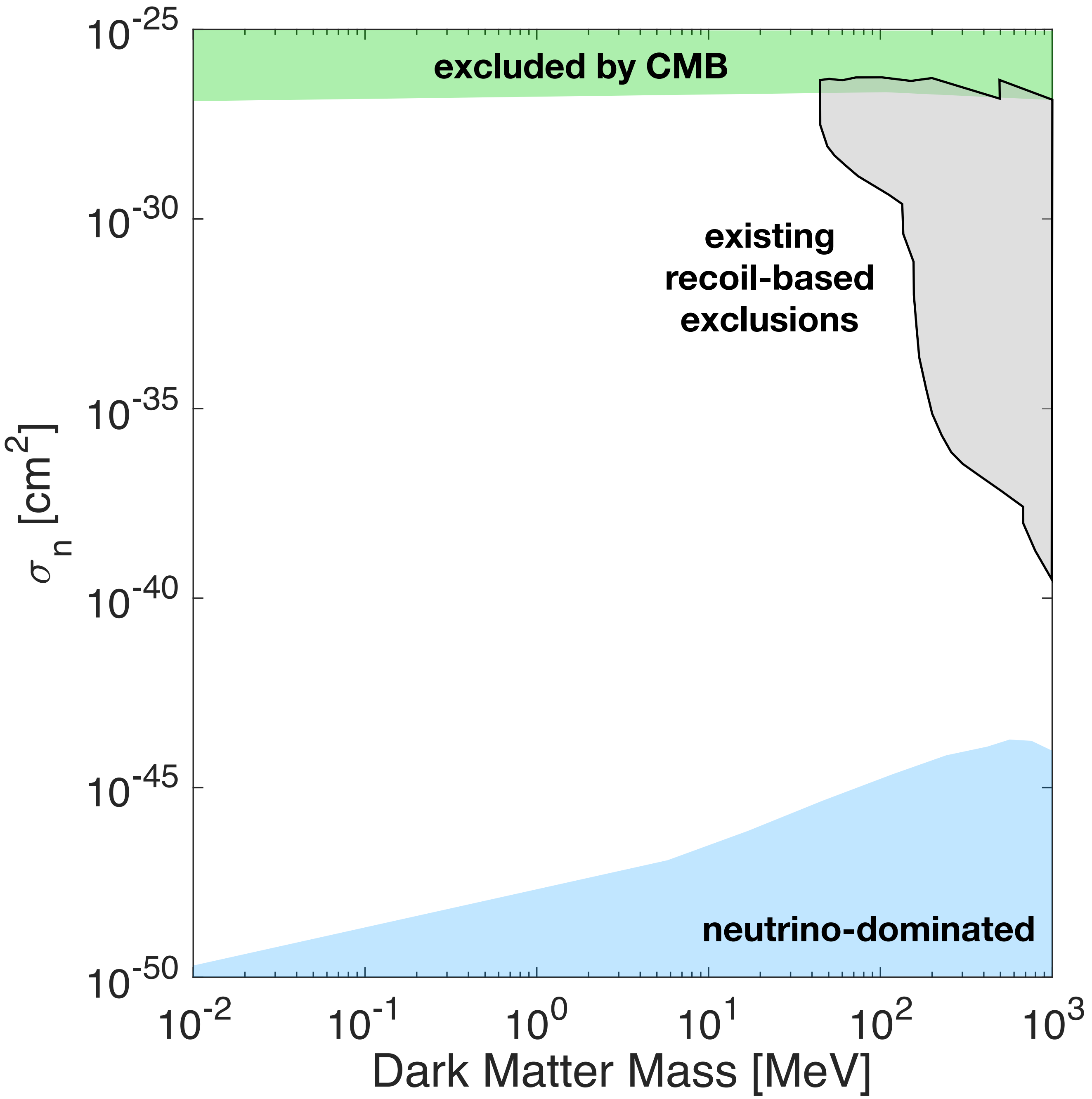


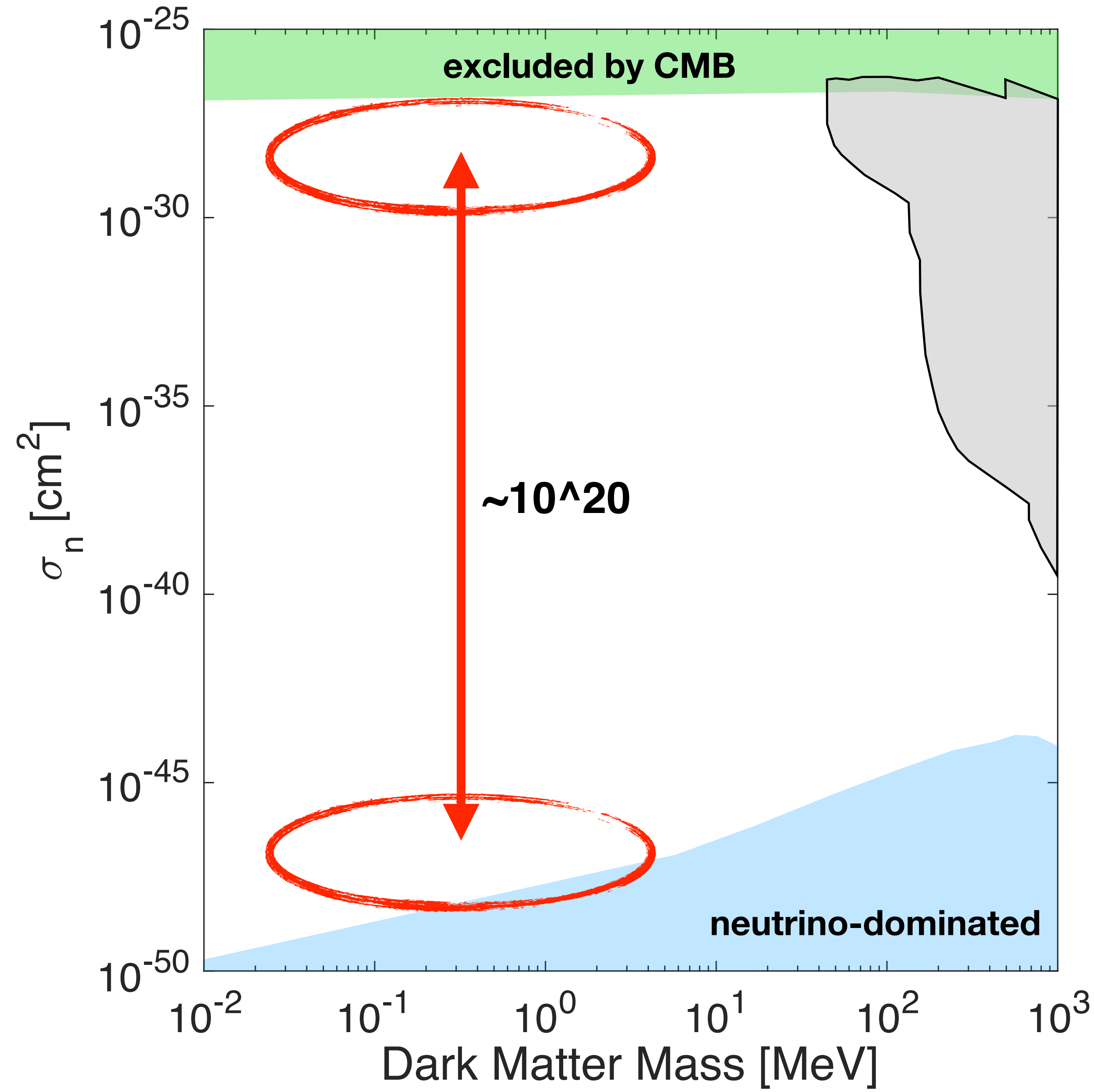
referencing the standard heavy-mediator nuclear recoil space for a moment…

The big-picture game

exposure is `easy'

Reason 1

all rates are interesting



The big-picture game

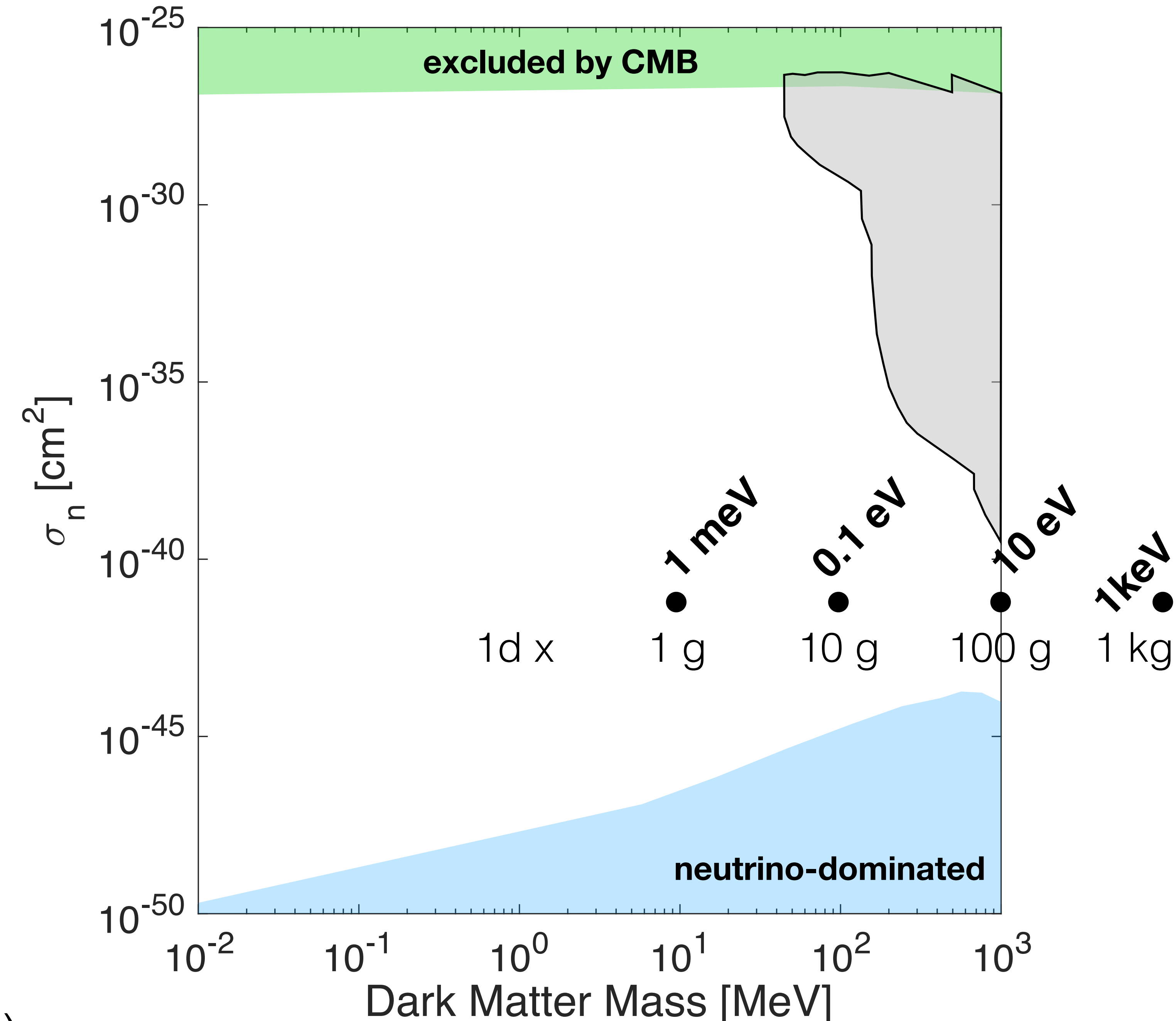
exposure is `easy'

Reason 2

number density ~ [particle mass]$^{-1}$
~flux
~interaction rate

with high rate:mass ratio…
radioactive backgrounds a focus
(along with discrimination technology)

➜threshold



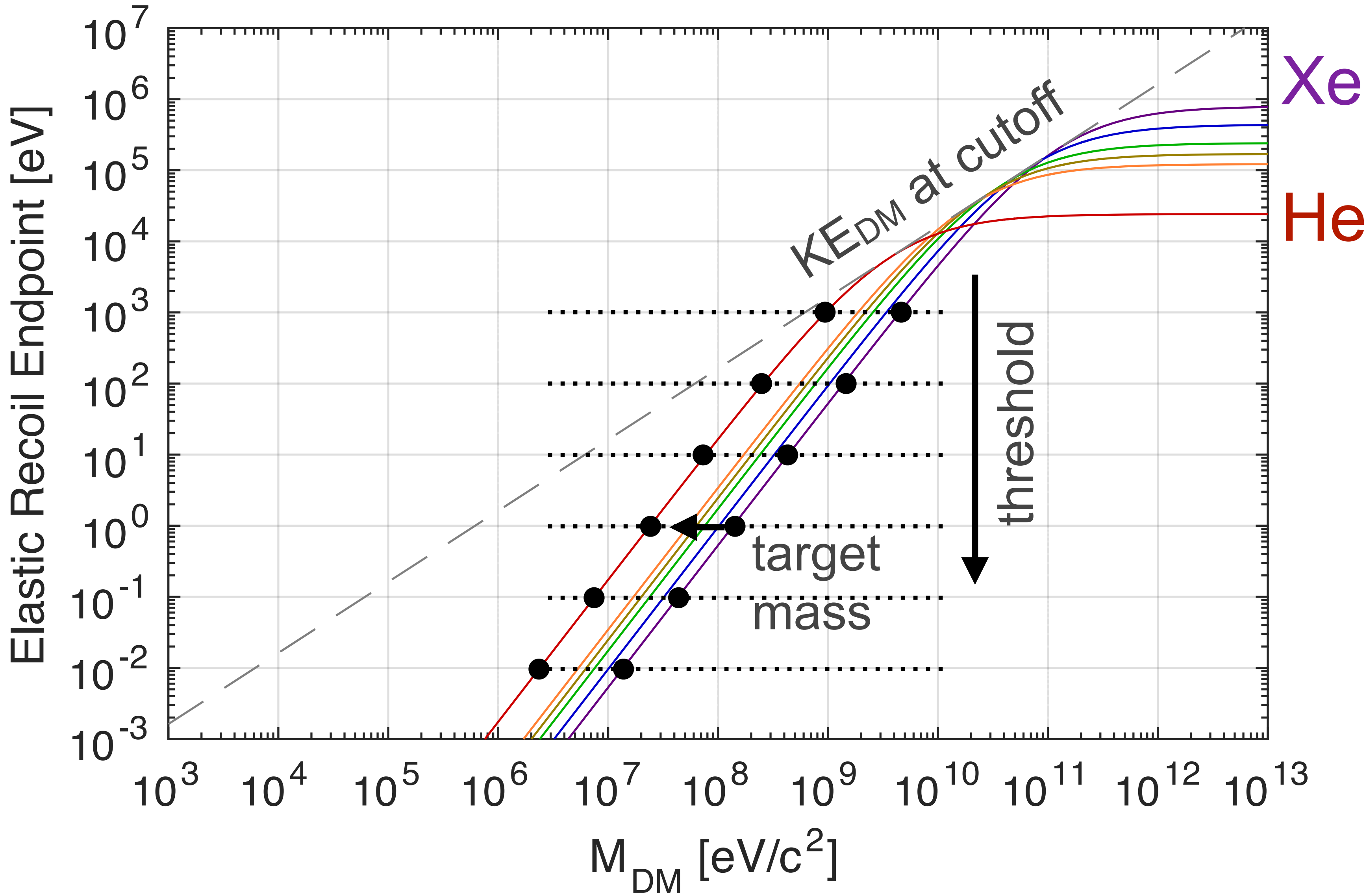
assuming heavy nuclei… if He say, shifted up and to the left

kinematics

nuclear recoils are increasingly poor at accepting recoil energy

example statement:
if M_{DM}=1MeV,
then max KE_{DM}=~1eV,
but max E_{NR} only ~1meV

takeaways:
1) Below 1GeV, masses increasingly mis-matched.
2) factor of ~10 benefit moving to lightest nuclei. (emphasis should still be on threshold)

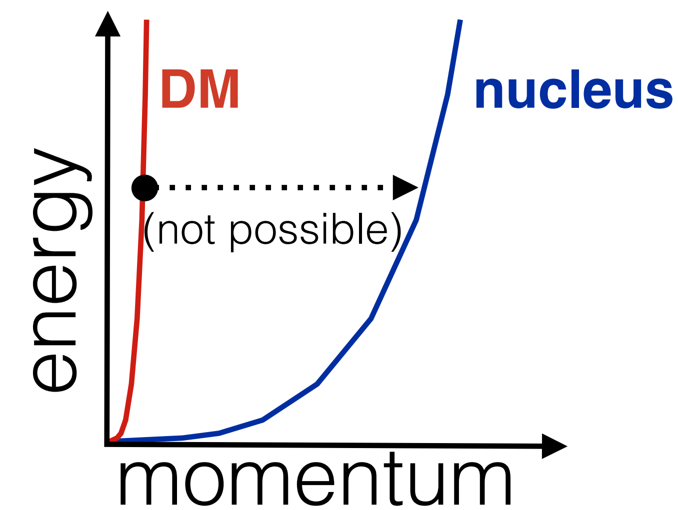


kinematics

nuclear recoils are increasingly poor at accepting recoil energy

put another way:

mismatch (‘impedance’)
in dispersion relation

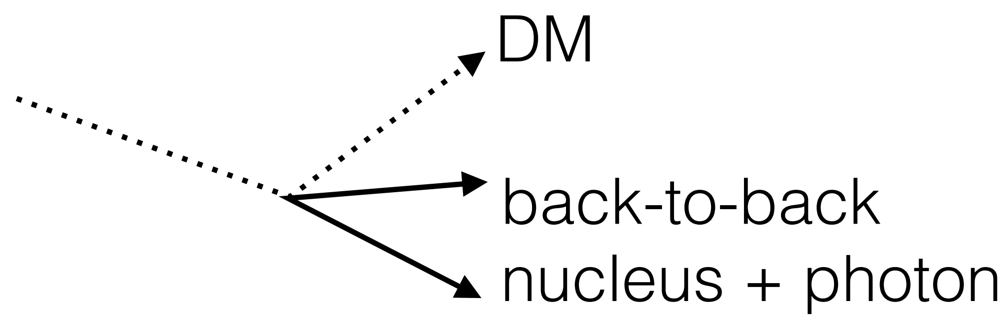


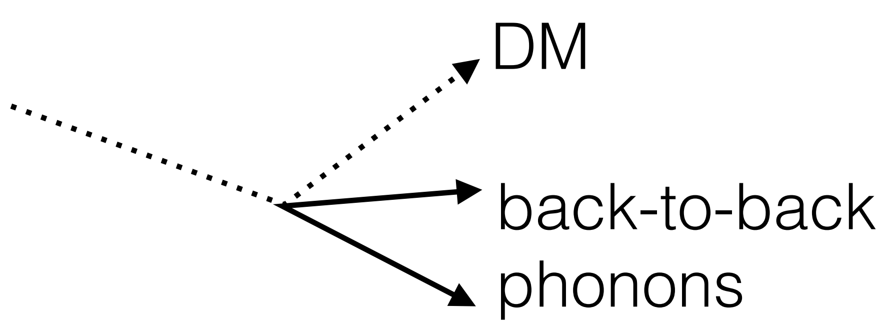
need to find ways to transfer energy without requiring momentum
(aka: need to find material excitations of low/matching effective mass)

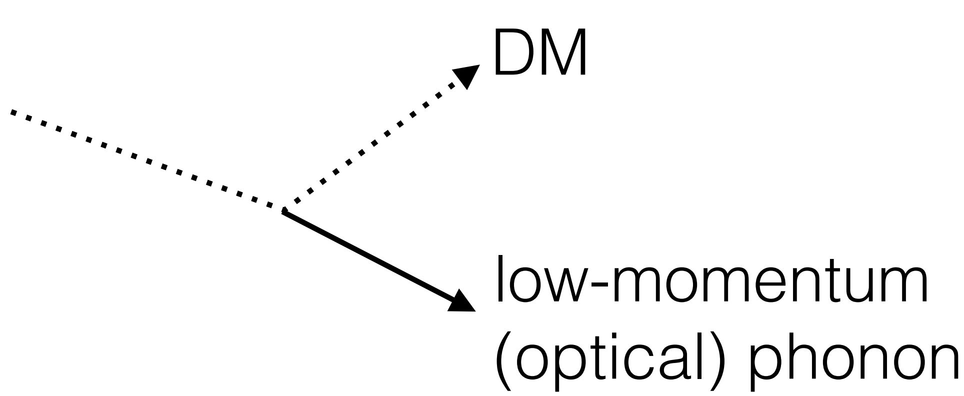
kinematics

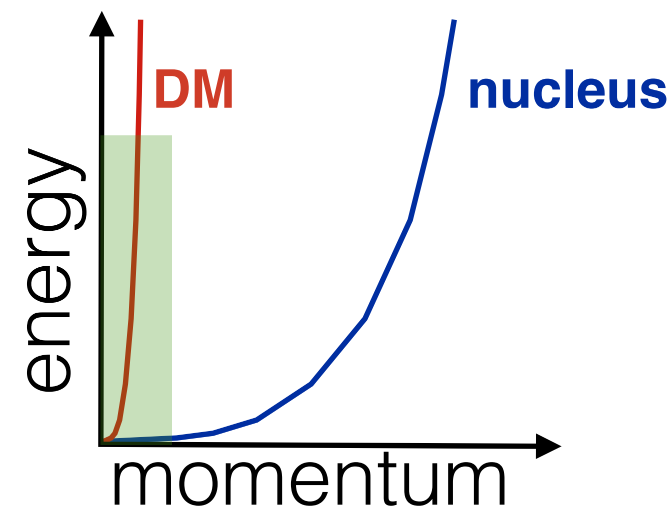
low-momentum (low effective mass) final states to the rescue

examples:









downside:
can be highly suppressed
due to higher complexity

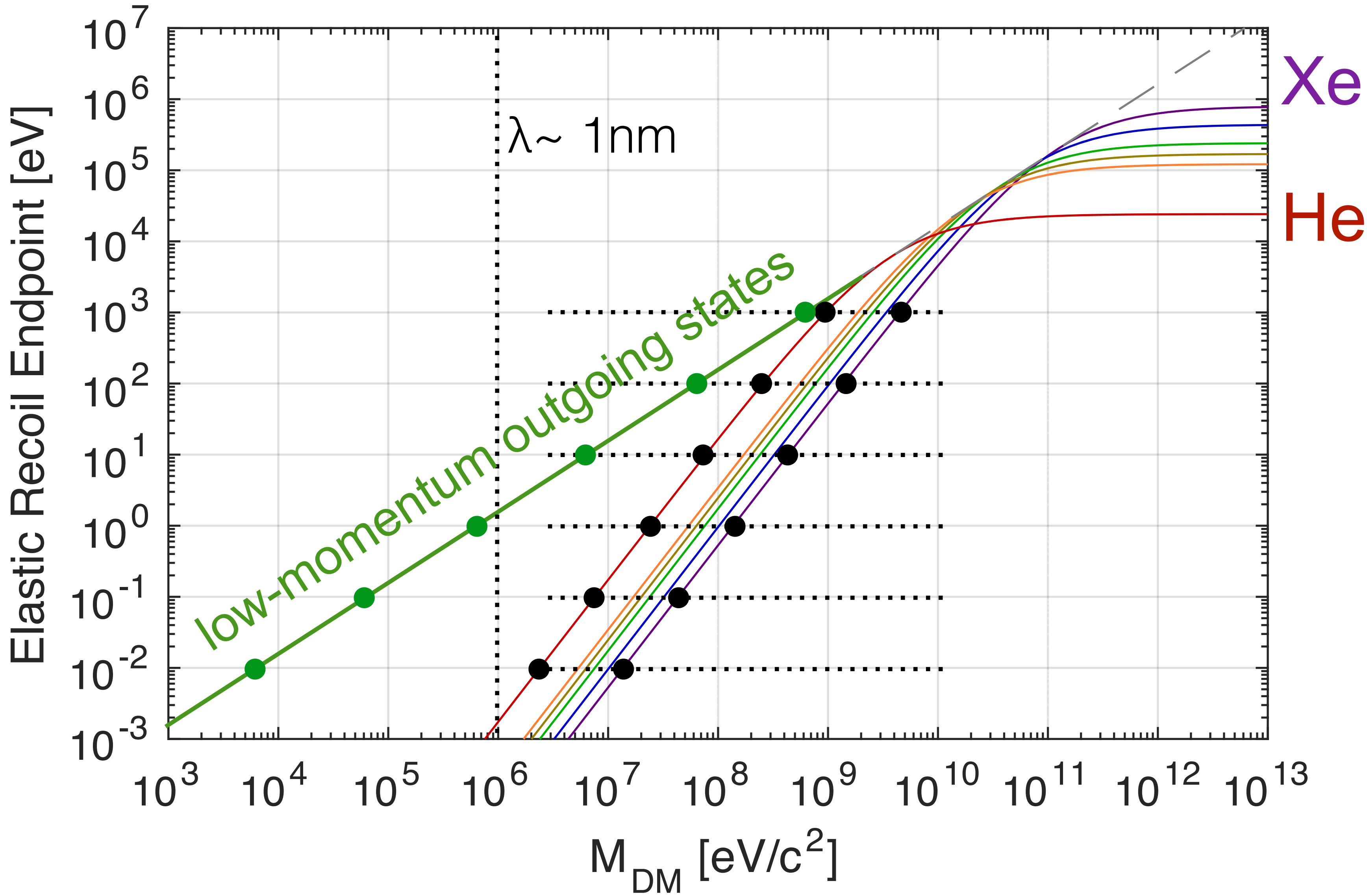
kinematics

low-momentum (low effective mass) final states to the rescue

If one finds a material with excitations of keV effective mass (energy and momentum similar to LDM), can probe to keV mass scale.

(meV threshold)

Remarkable coincidence in DM deBroglie wavelength scale
(similar to lattice spacing)

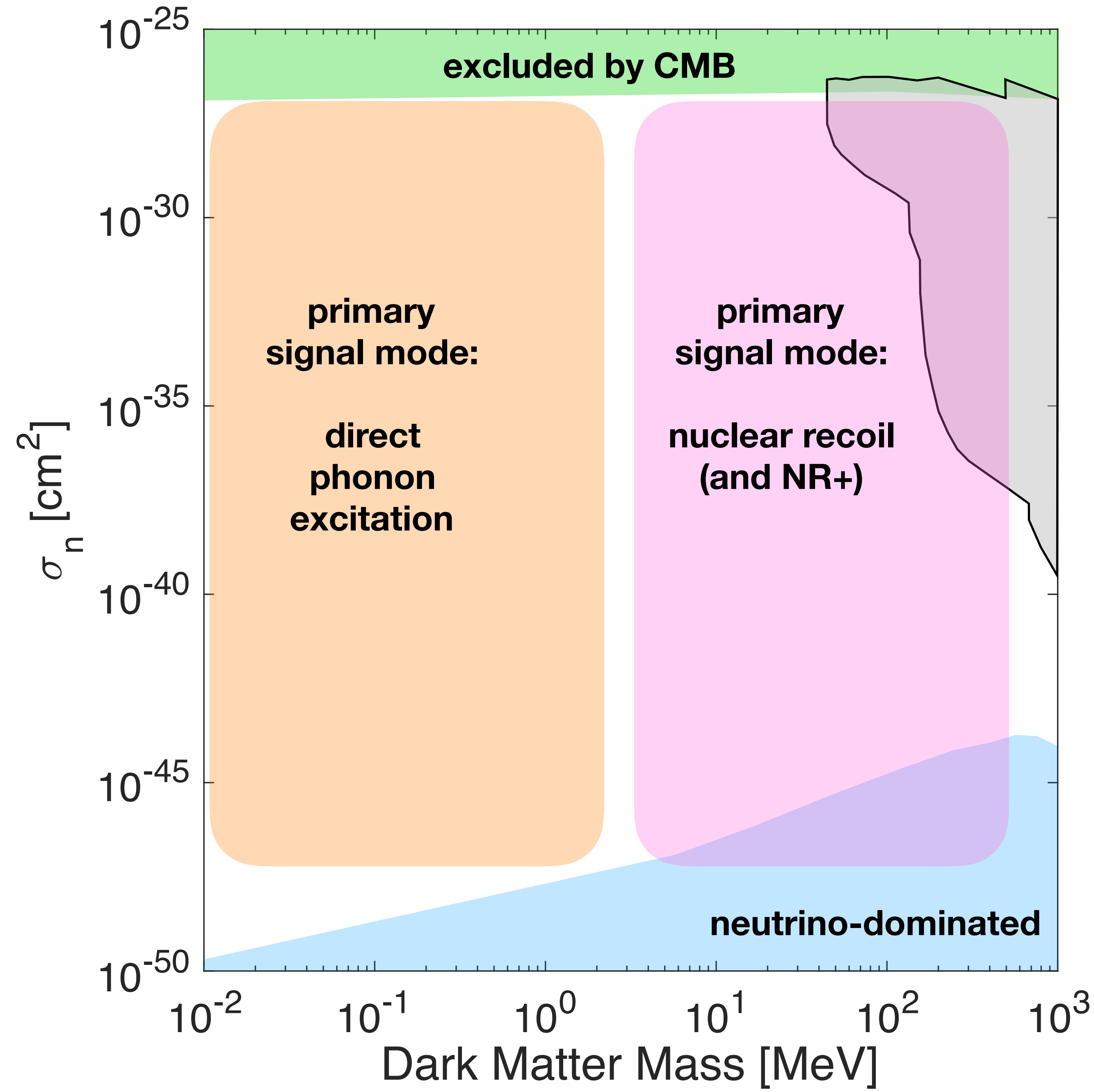


The big-picture game

natural division at ~MeV scale

above MeV: NR still works

below MeV: phonons take over



Big picture

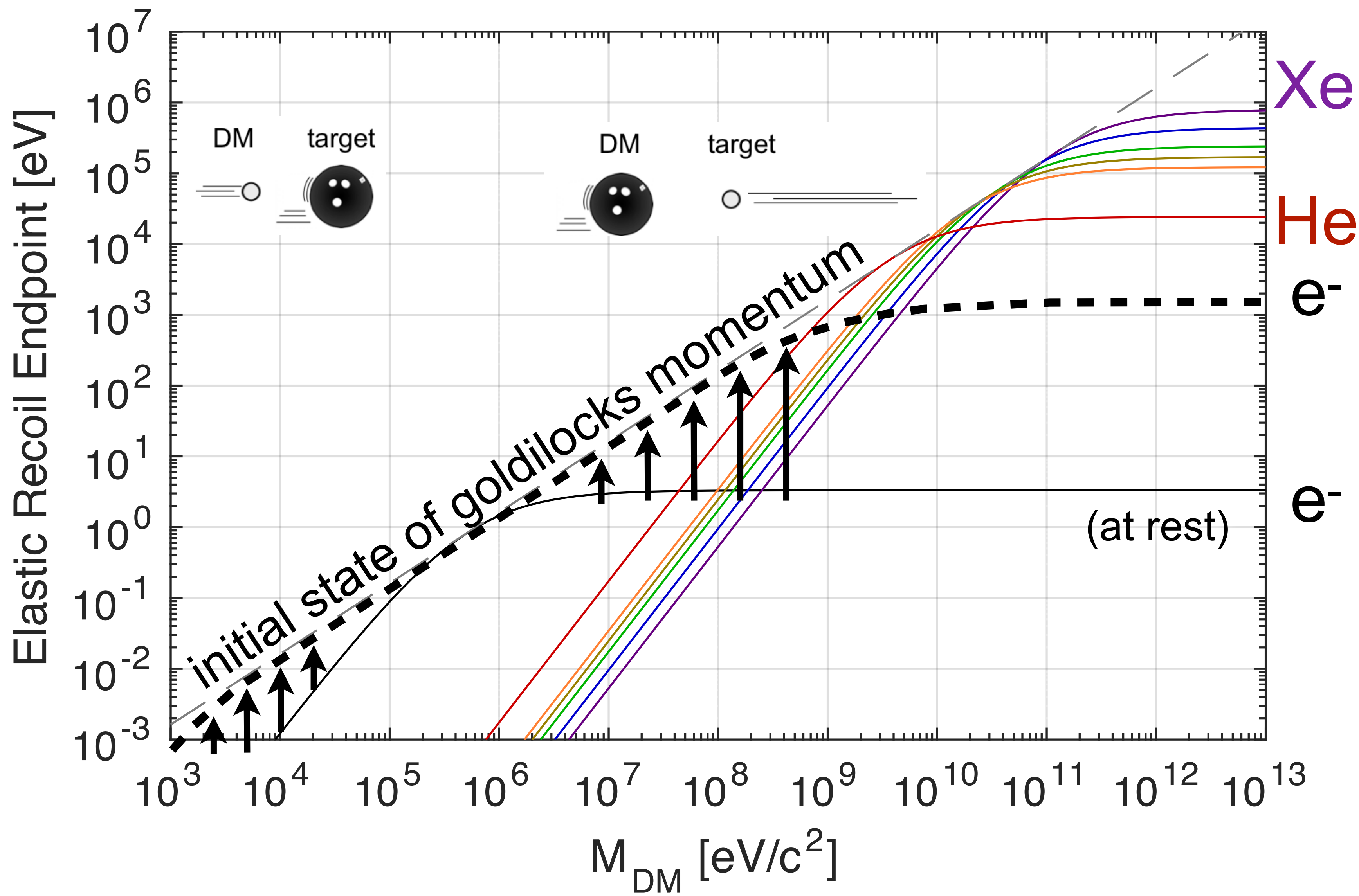
electron scattering to the rescue

1) lower target mass
2) initial non-zero momentum

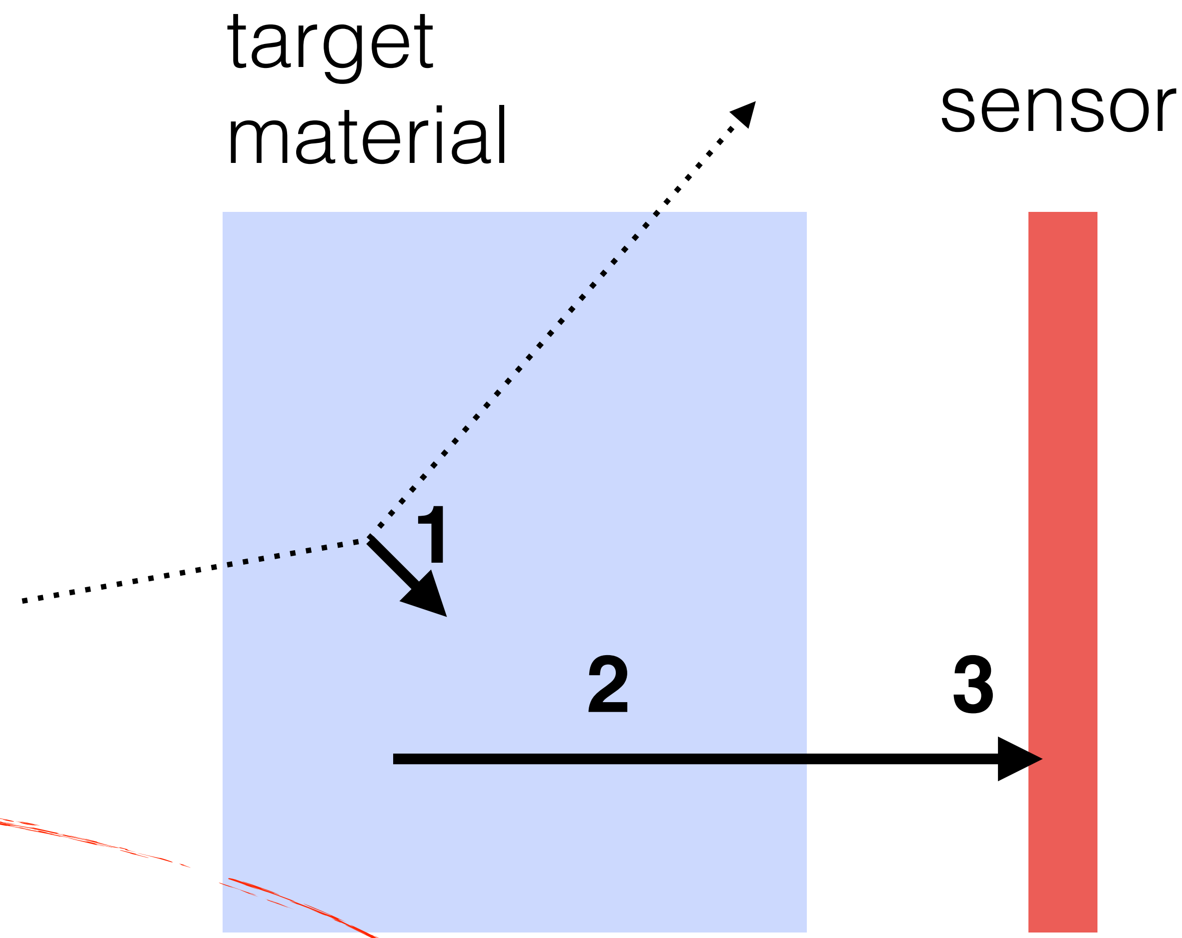
initial momentum distribution enables nearly any [△p,△E]

full energy transfer possible over wide mass range.

but again: large suppression



The big-picture game



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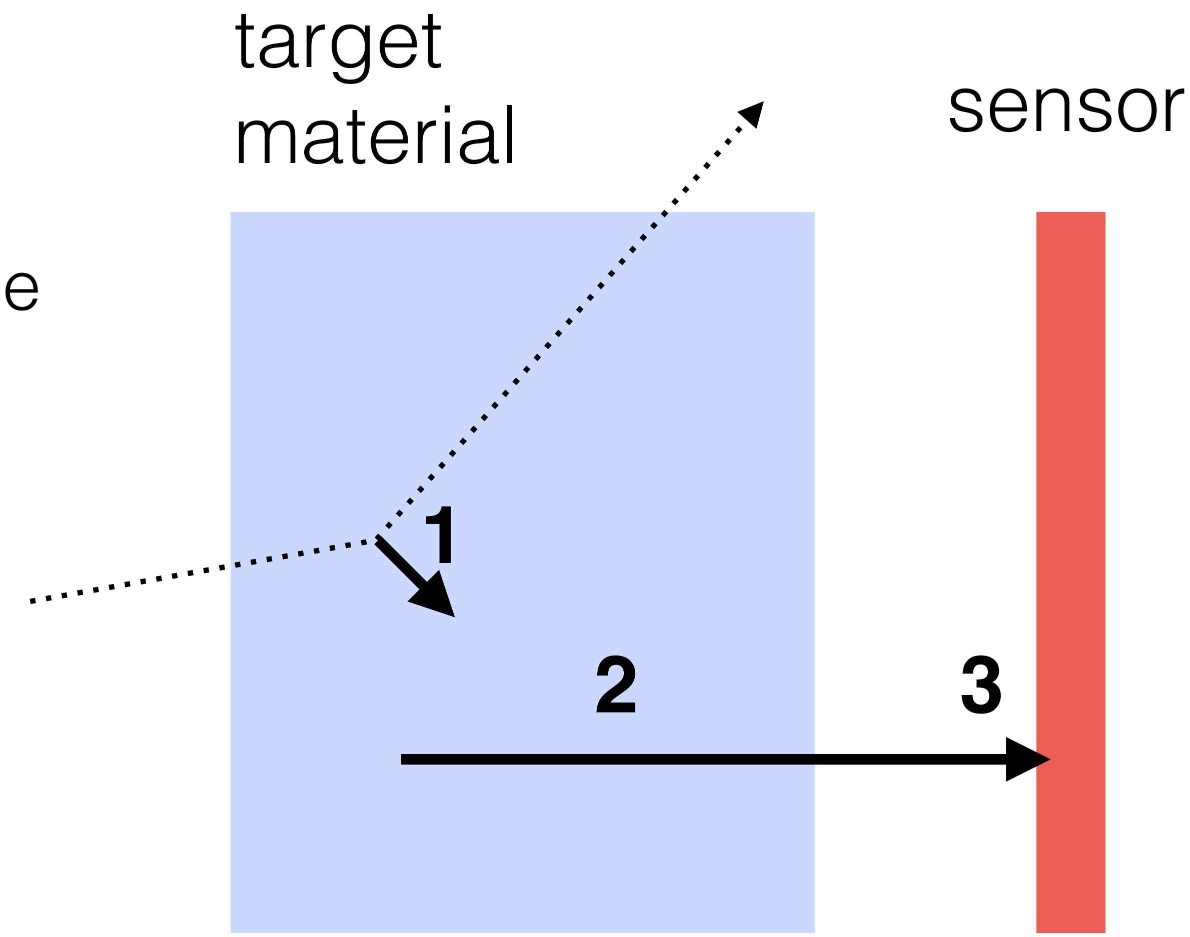
signal carriers



As we've said, the initial excitation (1) might be

recoiling nucleus
recoiling electron
some back-to-back state
optical phonon
…

We (typically) don't see the initial excitation,
we see its (lower-energy) descendants (2)

recoiling nucleus

- *lattice dislocation*
- *movement*: ballistic phonons, heat, phase change

recoiling electron

- *atomic*: ionization, excitation (scintillation)
- *semiconductor*: electron-hole pairs
- *semimetal*: similar, just lower energy
- *superconductor*: quasiparticles (`broken cooper pairs')

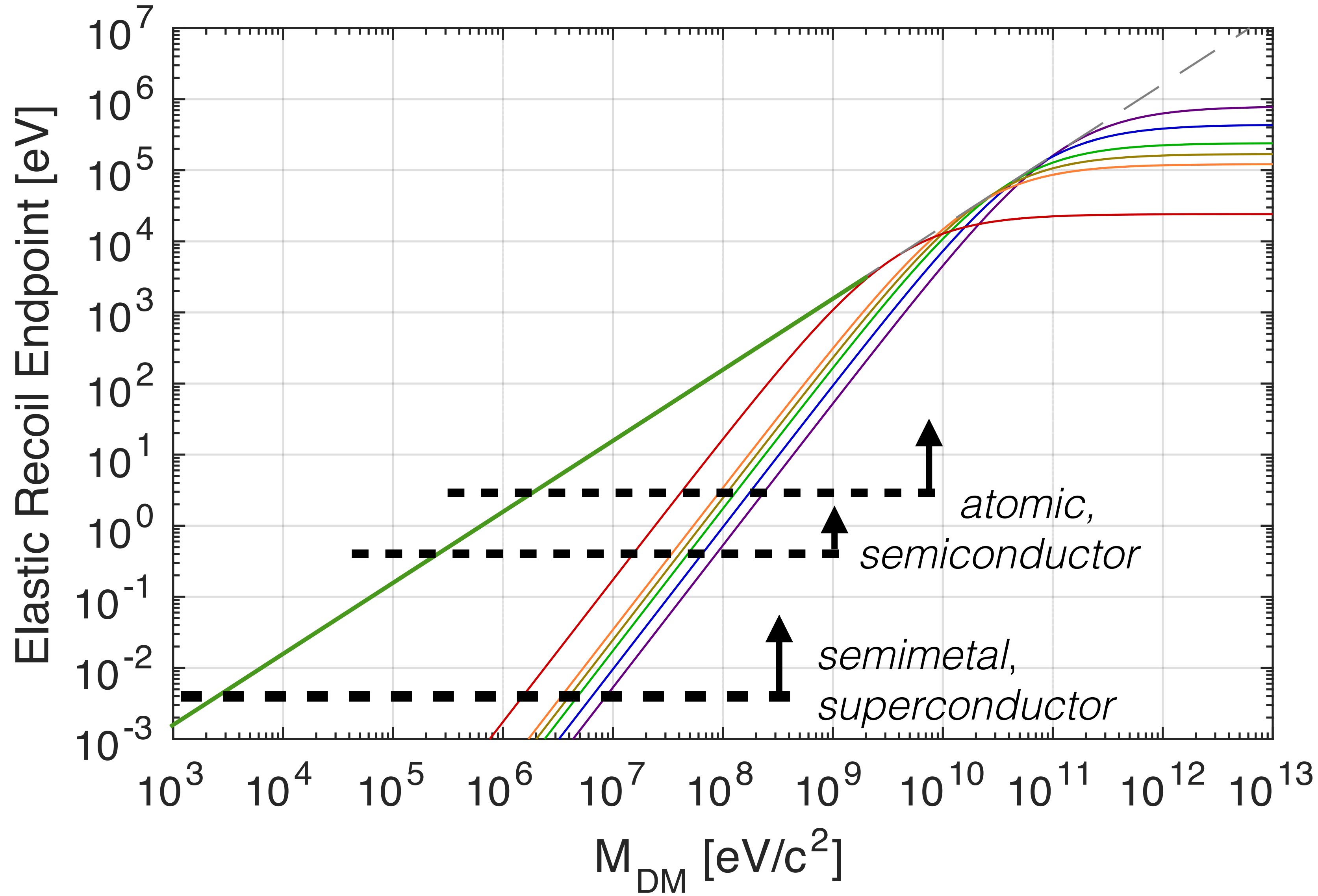
recoiling optical phonon

- lower-energy ballistic phonons

signal carriers

choice of signal carrier sets a threshold

atomic excitation is eV-scale. -> can reach MeV mass
longer term, can think about meV electron gaps -> can reach keV mass



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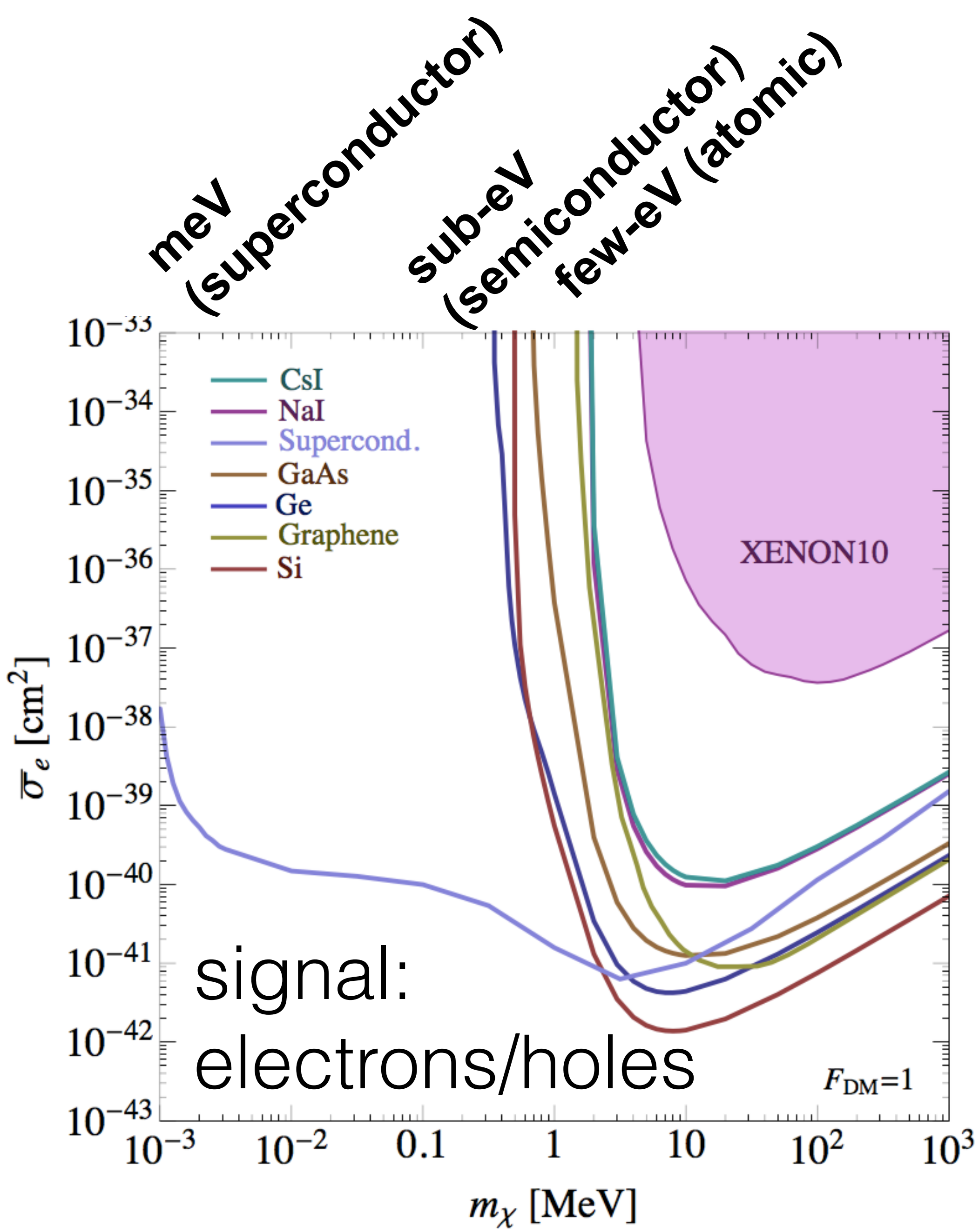
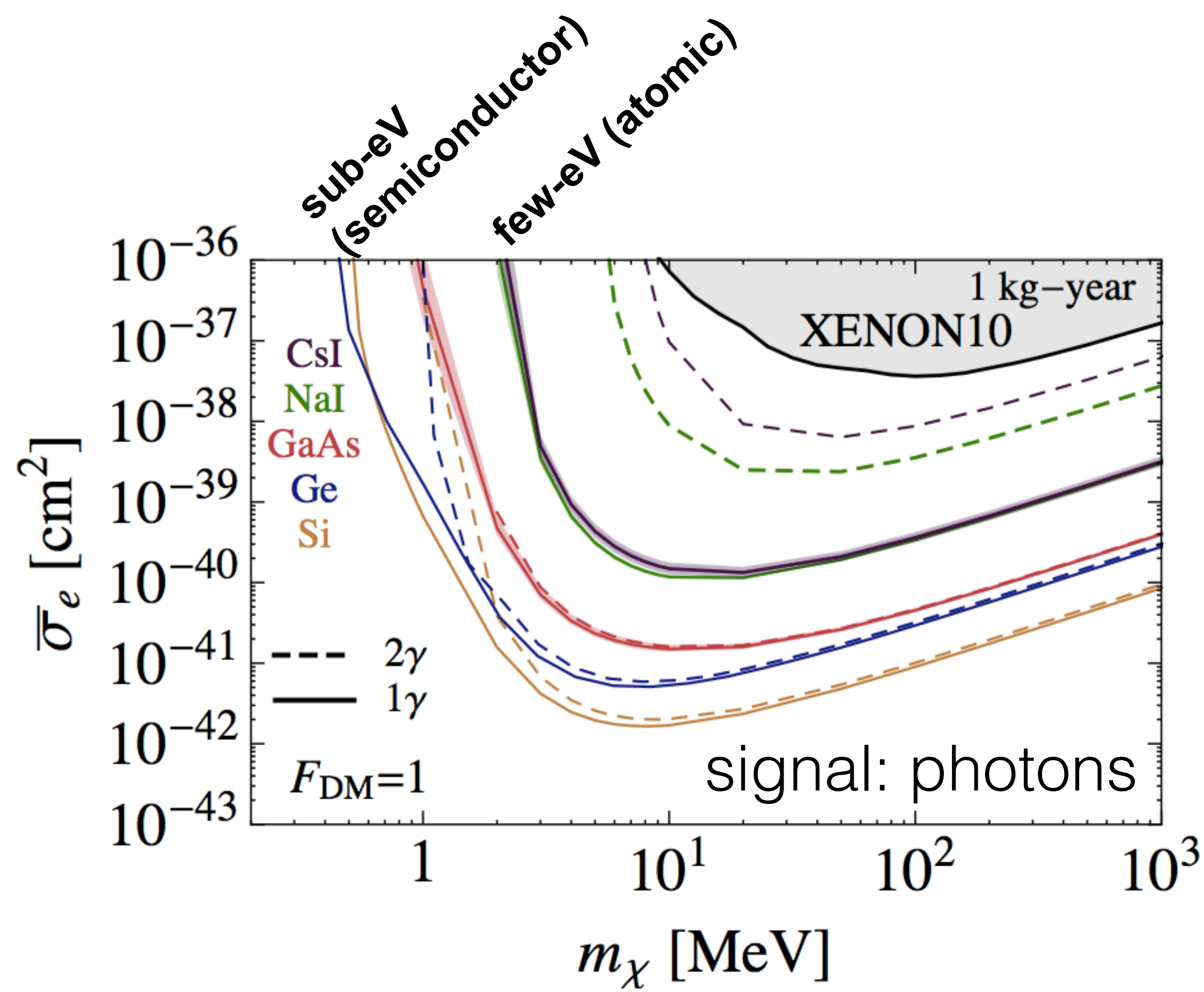
(some similar stories on the nuclear recoil and phonon recoil side)





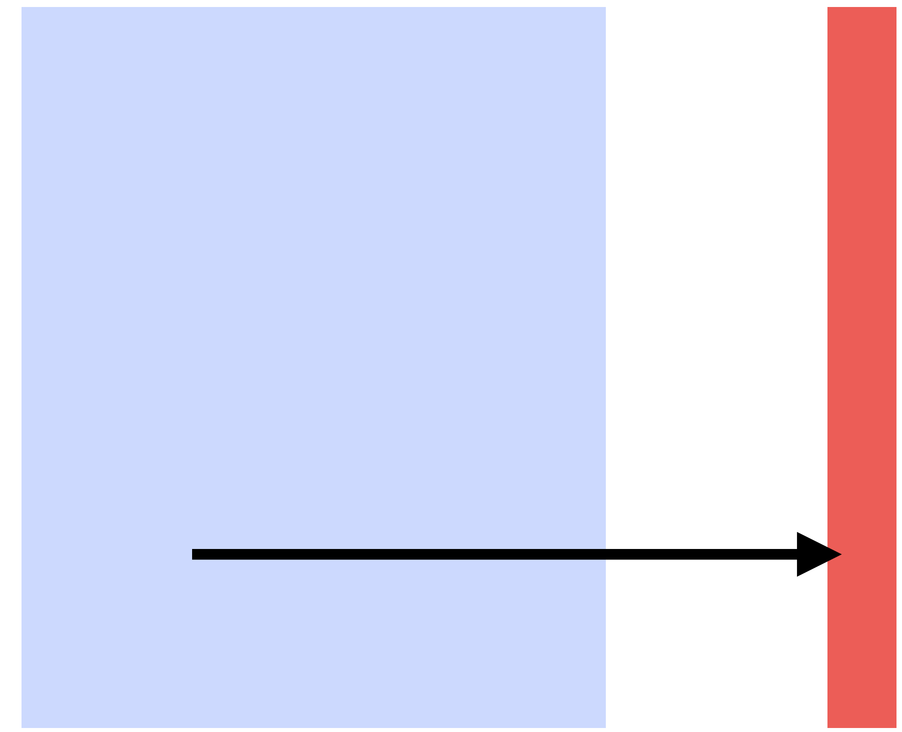
signal carriers

comments on signal carrier mobility

mobility often dictated by a messy world of impurities and defects.

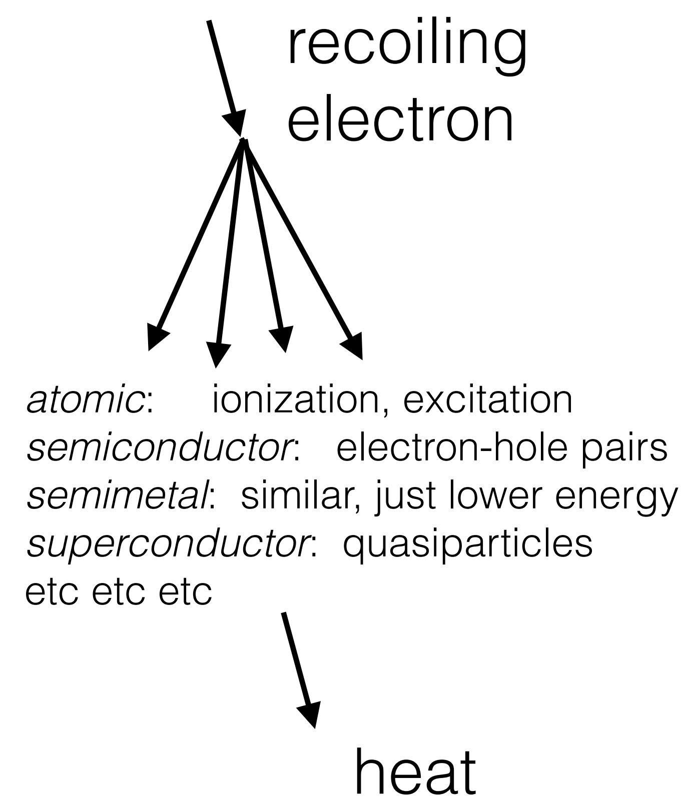
things like
- -impurities
- -lattice defects
- -trapped magnetic flux
- -complexity of interfaces
- -position-dependent gap energy

far from the ‘theorist world’… ;)



when all else fails: continue downconverting all the way (to heat),

and read out a temperature fluctuation.



dark counts / noise

‘dark counts’: spontaneous production of signal quanta by either target or sensor

examples:
single electrons leaking out of PMT photocathode
single electrons leaking across semiconductor contact
single photons emitted by relaxing metastable lattice defects
burst of phonons emitted by slip or crack
etc.

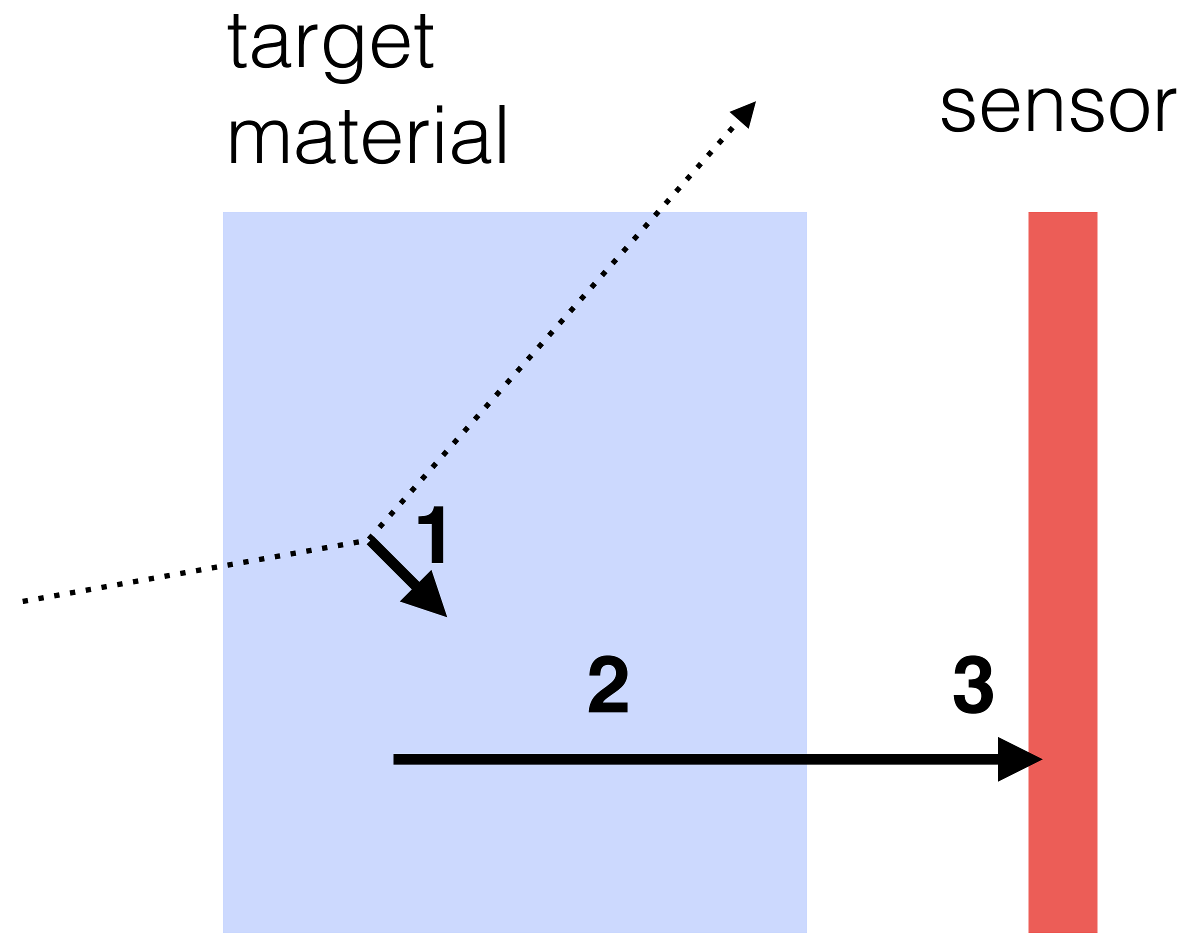
(often expressions of applied potentials)

‘noise’: calorimetry often not in the counting regime. instead limited by
ambient E&M environment
vibration-induced capacitive couplings
undesired thermal links
etc.

In keV-MeV-GeV regime:
Mobility, dark counts, and noise will dominate the experimentalists’ days in lab.

Hard work currently going on these days, plenty of hard work still ahead.

Summary



1) find *initial* excitations that

maximize DM interaction probability

maximize deposited energy ($\triangle$p small)
- use low-mass target particle (options limited)
- use electron's initial momentum
- use multi-component final states
- use low-momentum excitations

2) find *signal* excitations that

are efficiently produced by energy deposits

efficiently transport energy macroscopic distances
- not at all a given

3) find sensors that

efficiently detect excitations

don't produce false signals
- any applied potential has *some* dark rate to minimize

4) let creativity reign

still plenty of room here for
new good ideas at each step