Direct Detection of Low-Mass Dark Matter

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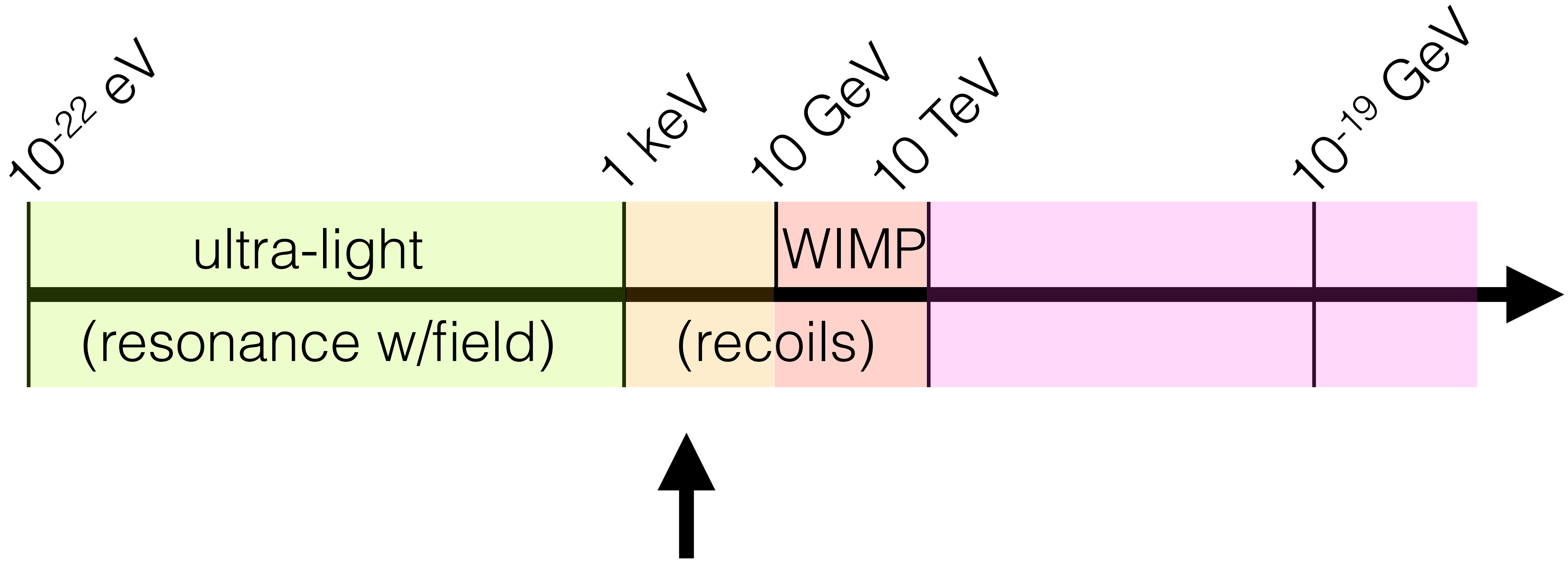
Dark Interactions: Perspectives from Theory and Experiment
Brookhaven National Laboratory
October 2, 2018

Caveats/Apologies

-for many topics, I am not nearly the expert in this room

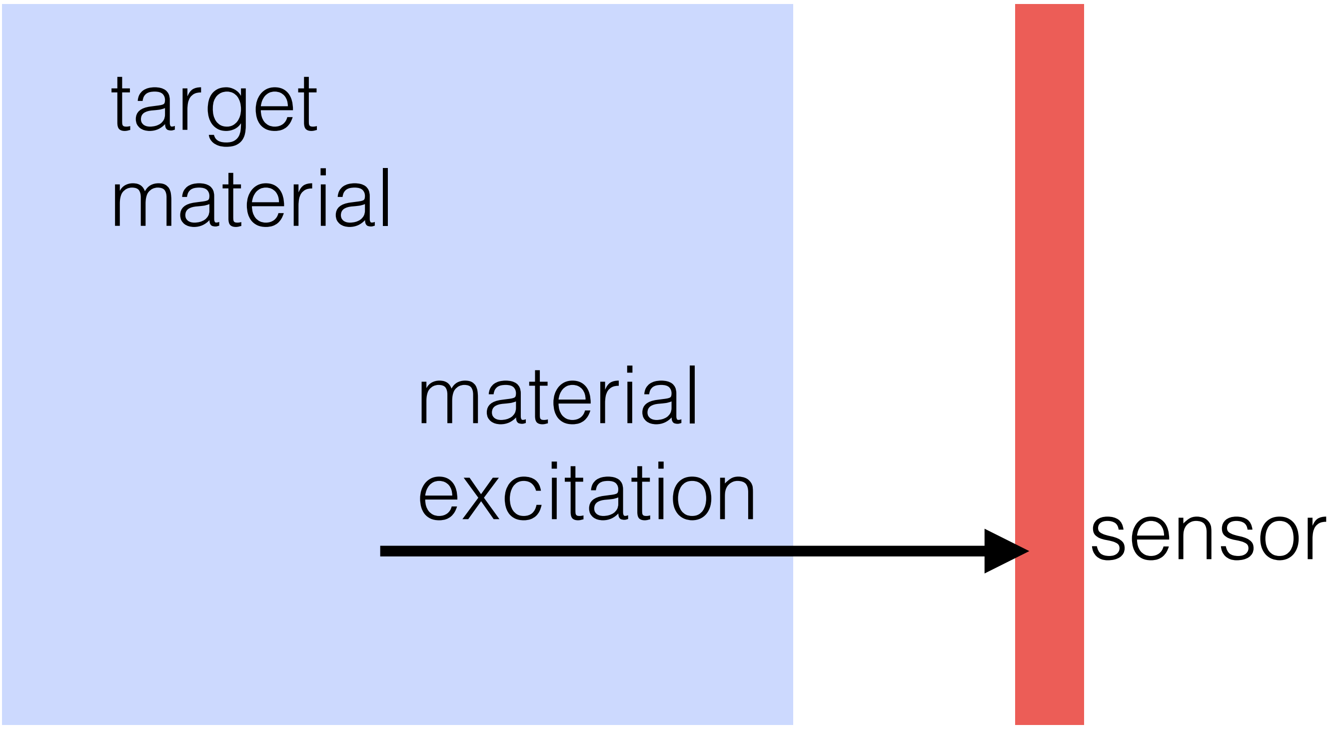
-many biases in what I think is important

-not educated enough to give an intelligent talk on ultralight DM



This talk: detection strategies
for low-energy particle recoils

Big picture



the low-mass direct detection game:

find material excitations that

are efficiently produced by recoils

efficiently propagate to sensors

find sensors that

efficiently detect excitations

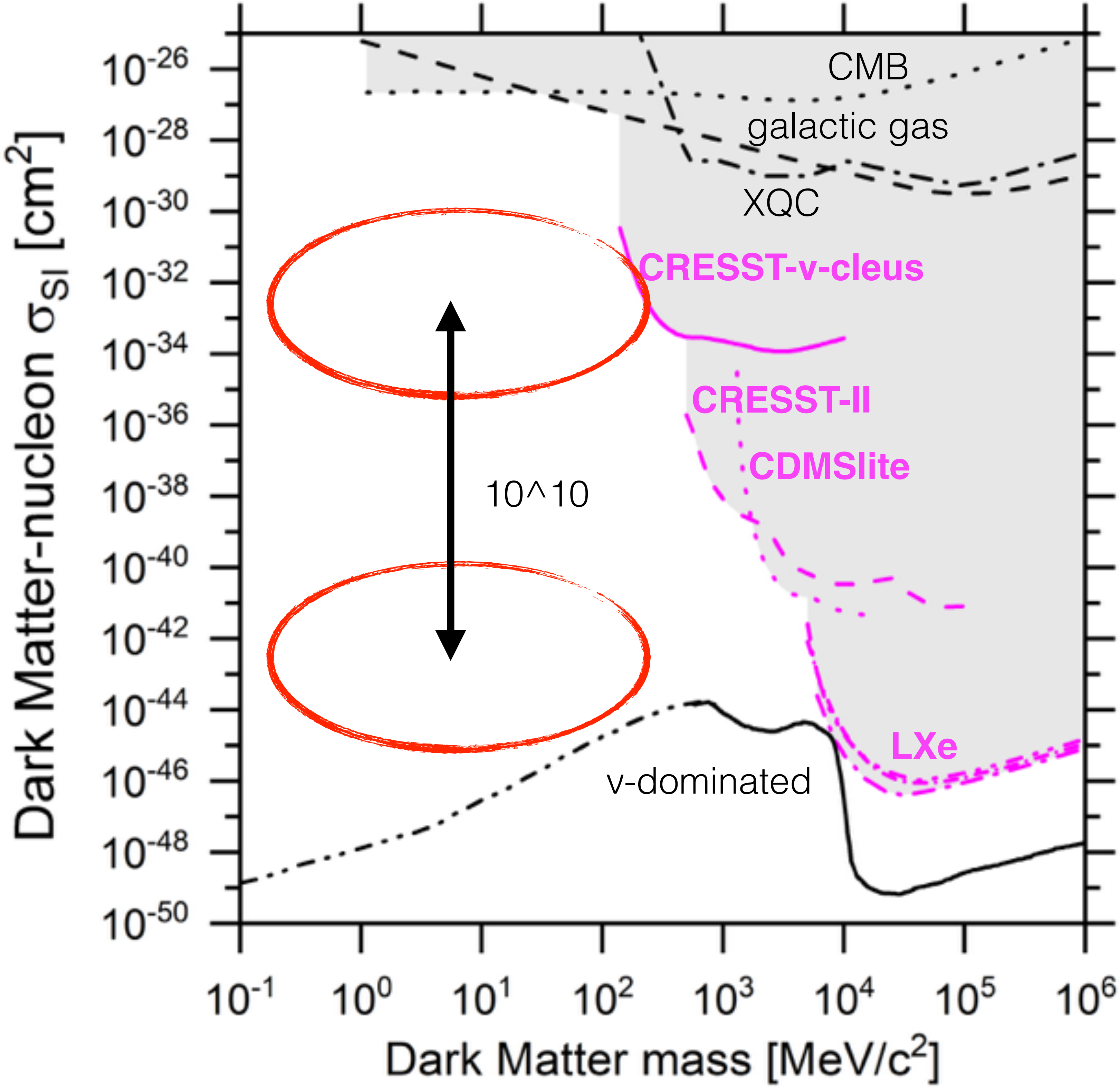
don’t produce false signals

Big picture

exposure is `easy' in this regime

Reason 1

all rates are interesting



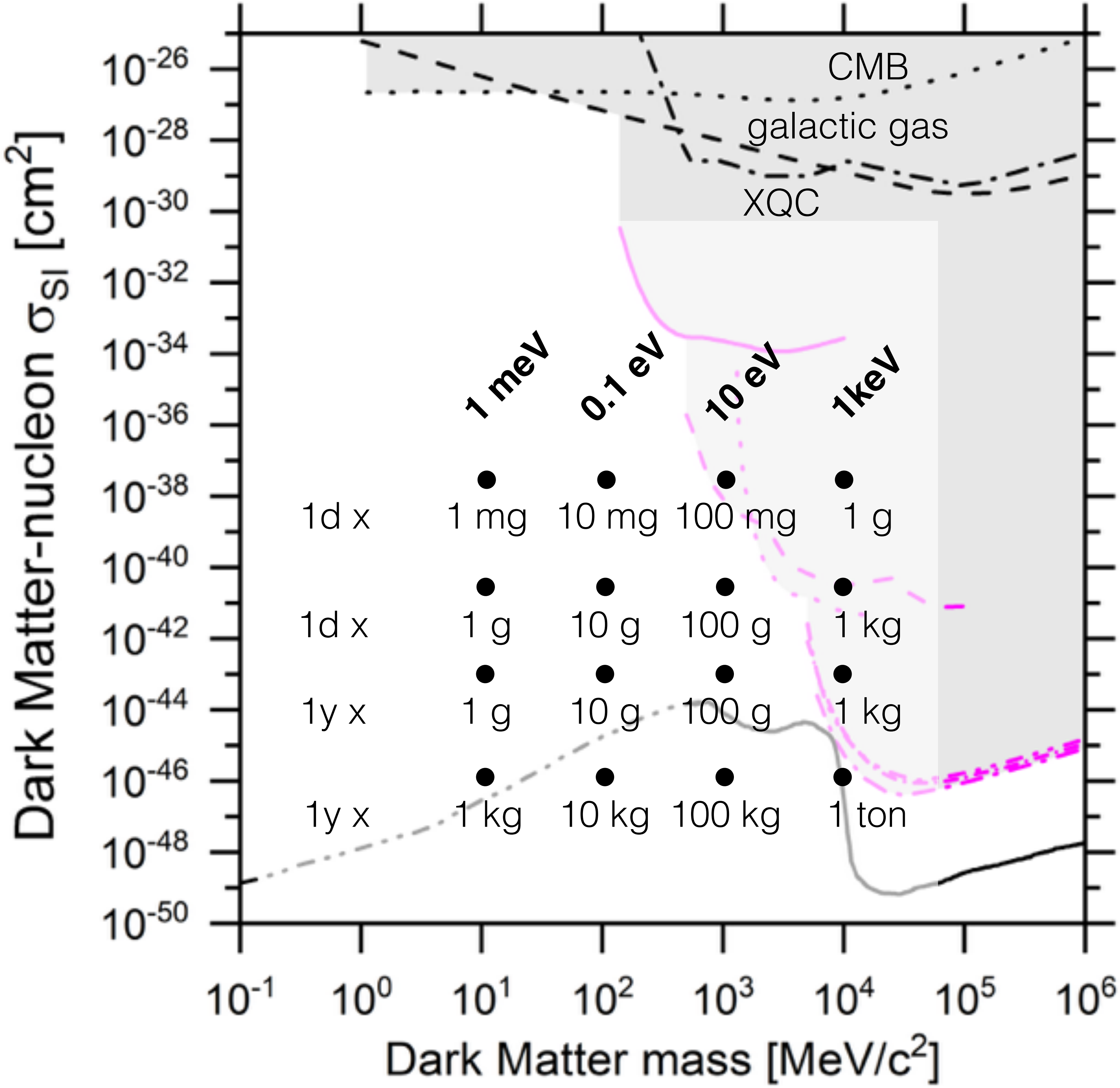
Big picture

exposure is `easy’ in this regime

Reason 2

Rate per kg
~ DM number density
~ [DM particle mass]$^{-1}$

~~exposure~~
➜threshold



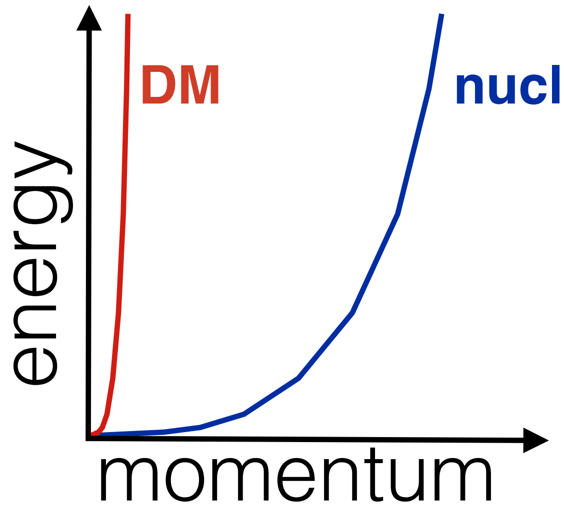
assuming heavy nuclei… if He say, shifted up and to the left

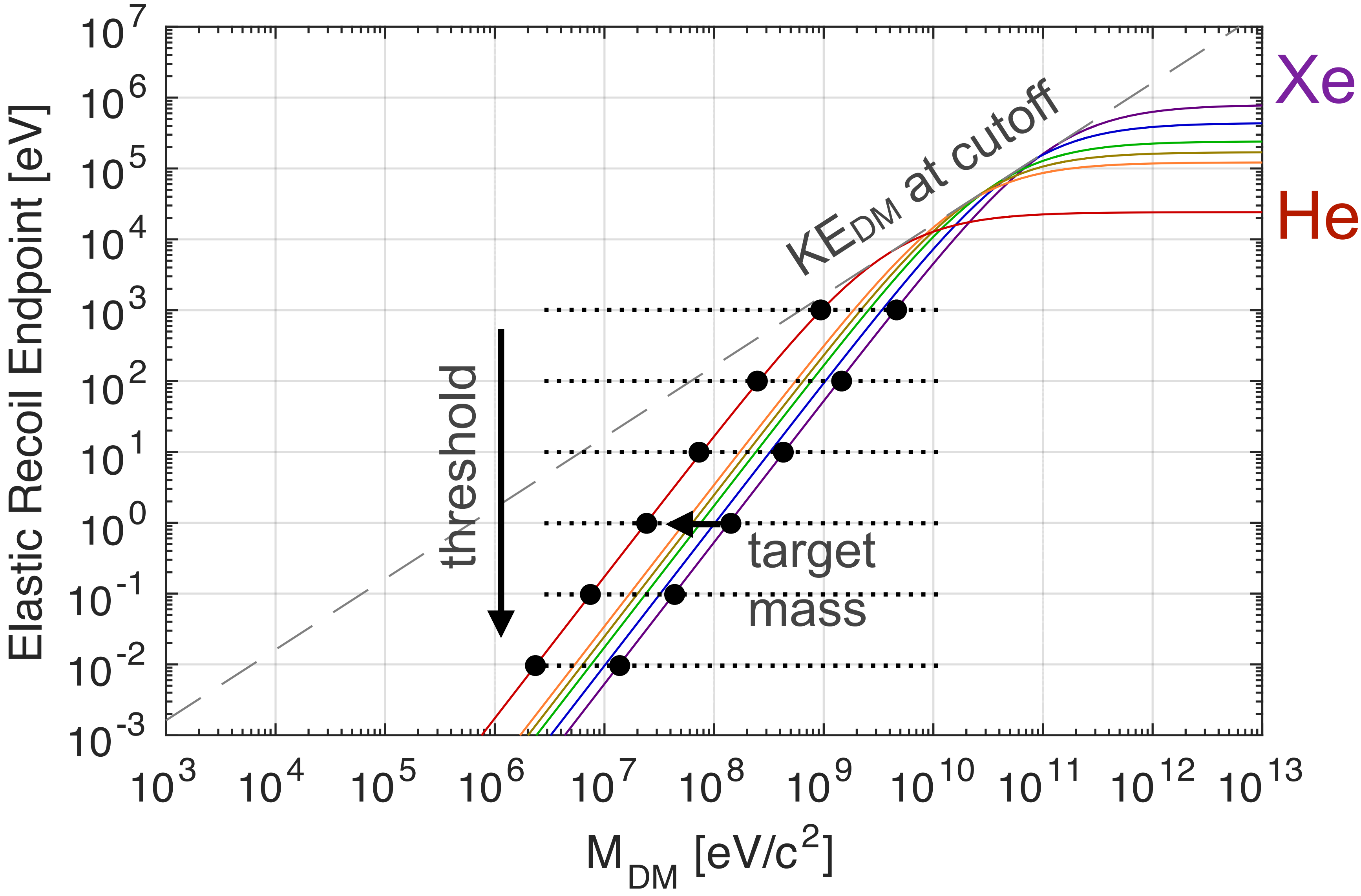
Big picture

nuclear recoils are increasingly poor at accepting recoil energy

threshold,
threshold,
threshold,
and target mass

mismatch ('impedance')
in dispersion relation





Big picture

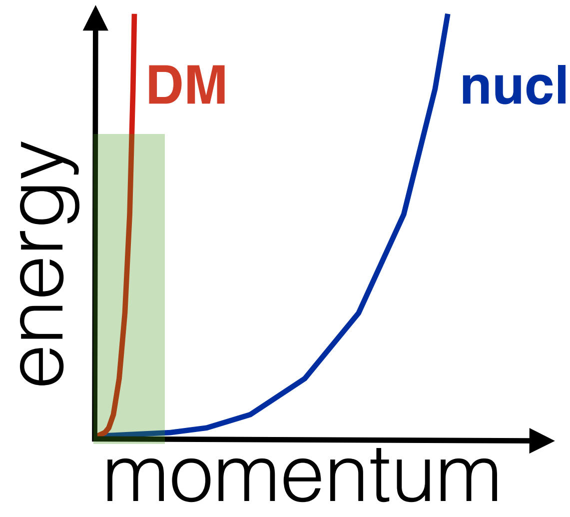
lower momentum-per-energy excitations to the rescue

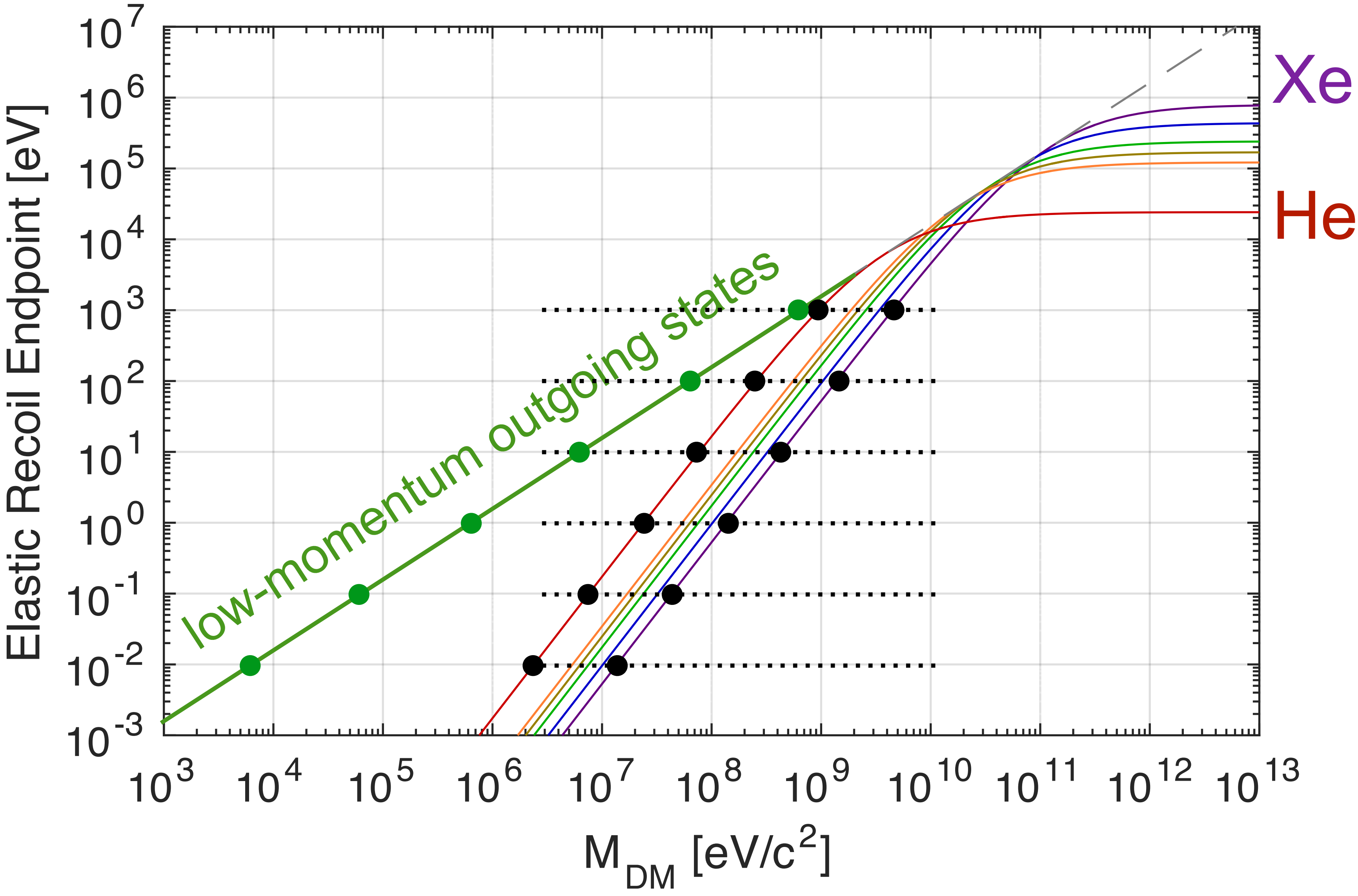
enable sensitivity to low-mass DM, typically with significant suppression

examples:

- atom + photon (brems.)
- back-to-back phonons
- optical phonons

mismatch ('impedance')
in dispersion relation



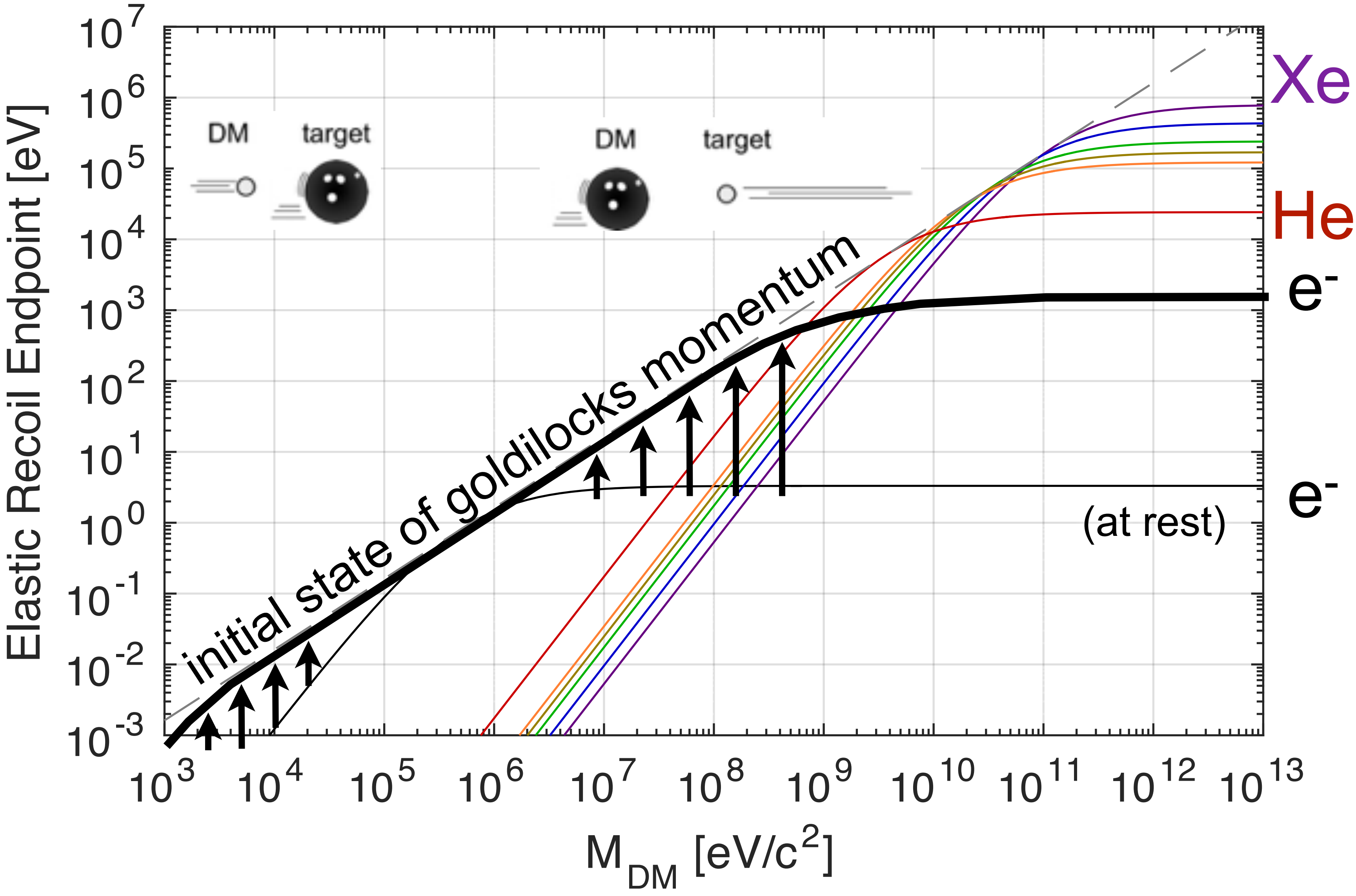


Big picture

electron targets: two kinematic benefits

1) lower target mass (of course)
2) not at rest (wide range of initial momentum states)

probability of high-efficiency recoil: highly dependent on electron momentum distribution.



large-area calorimetry: a universal sensor

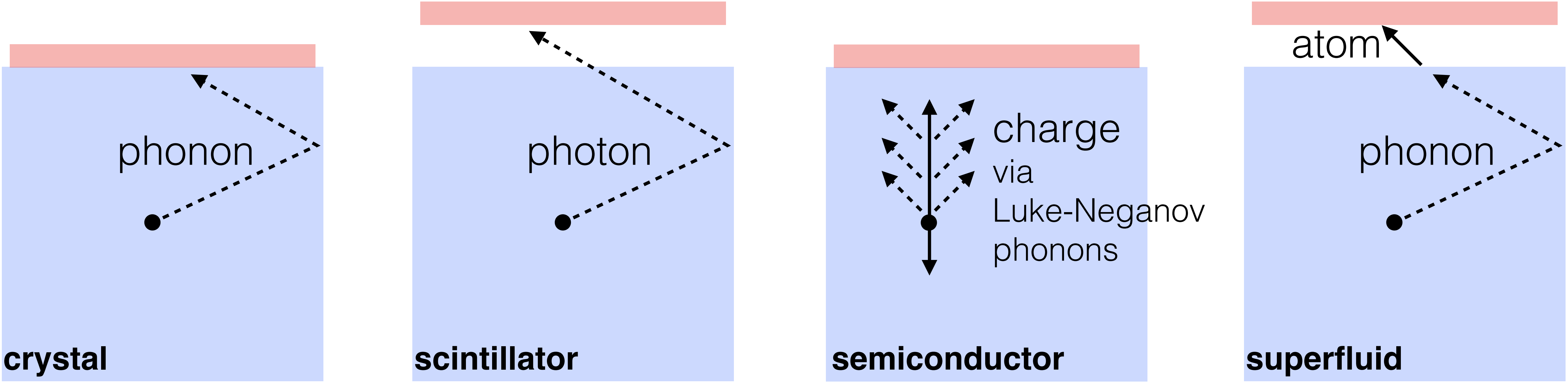
large-area calorimetry: a universal sensor

The promise:

arXiv:1503.01200

If we believe naive scaling laws… meV thresholds (on macroscopic absorbers) appear possible.

This sensor can observe a wide variety of excitations from a wide variety of target materials.



The challenge:

Do the sensor scaling laws actually hold up, particularly with temperature?

What new low-energy material processes will we discover?

large-area calorimetry: a universal sensor

Thermal

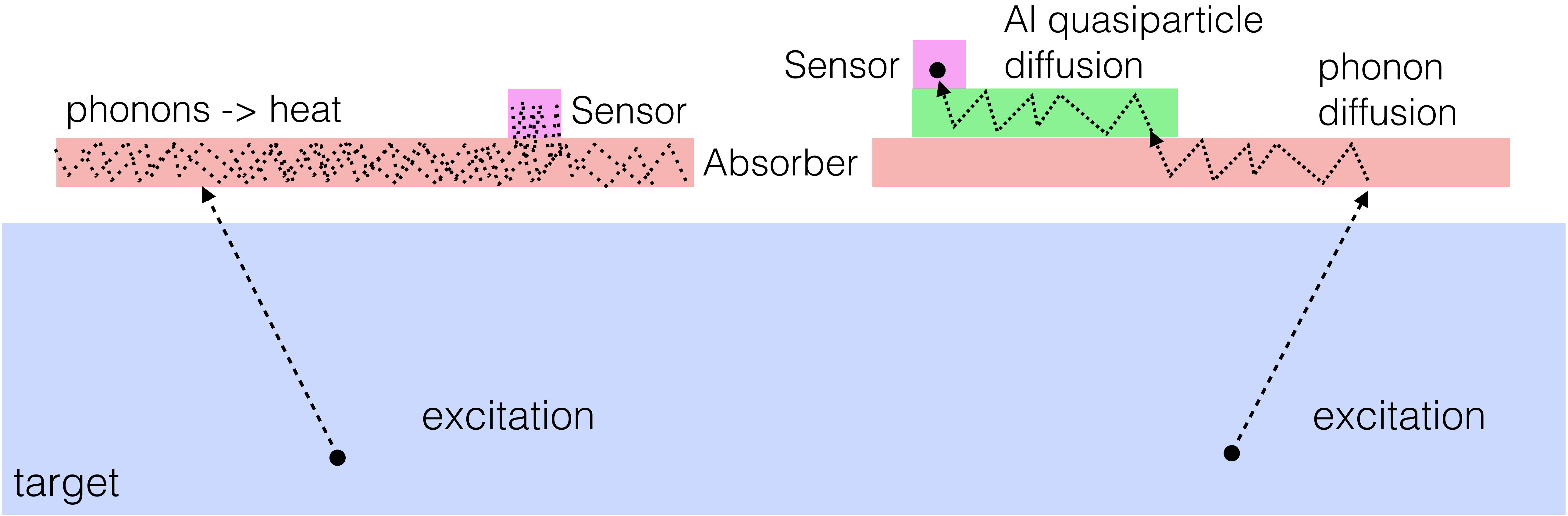
-technically simpler
  -fewer sensors per area
  -less sensitive to interface variation

-slow timescales (order-ms)
  -less information

Athermal

-technically harder
  -more sensors per area
  -more sensitive to interface variation

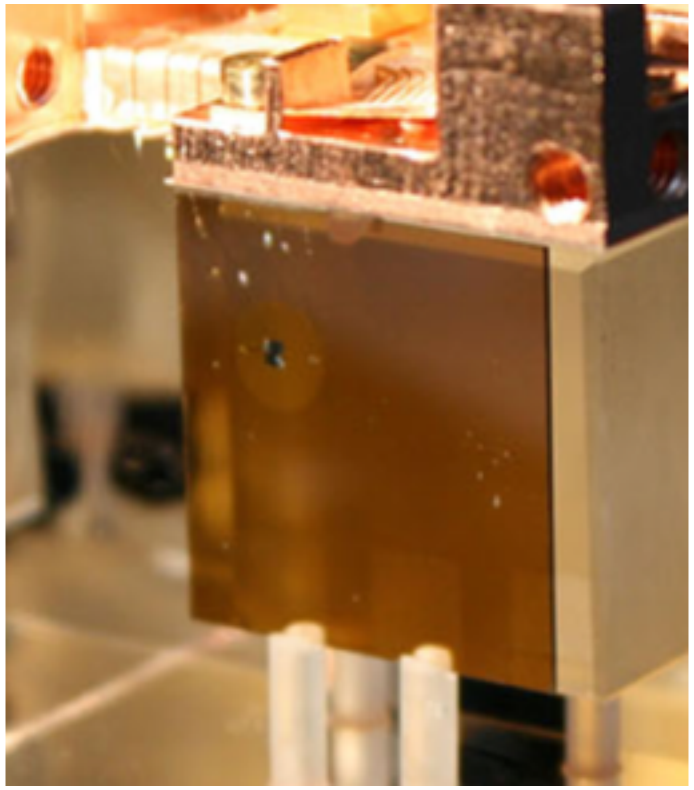
-faster timescales (order-μs)
  -more information



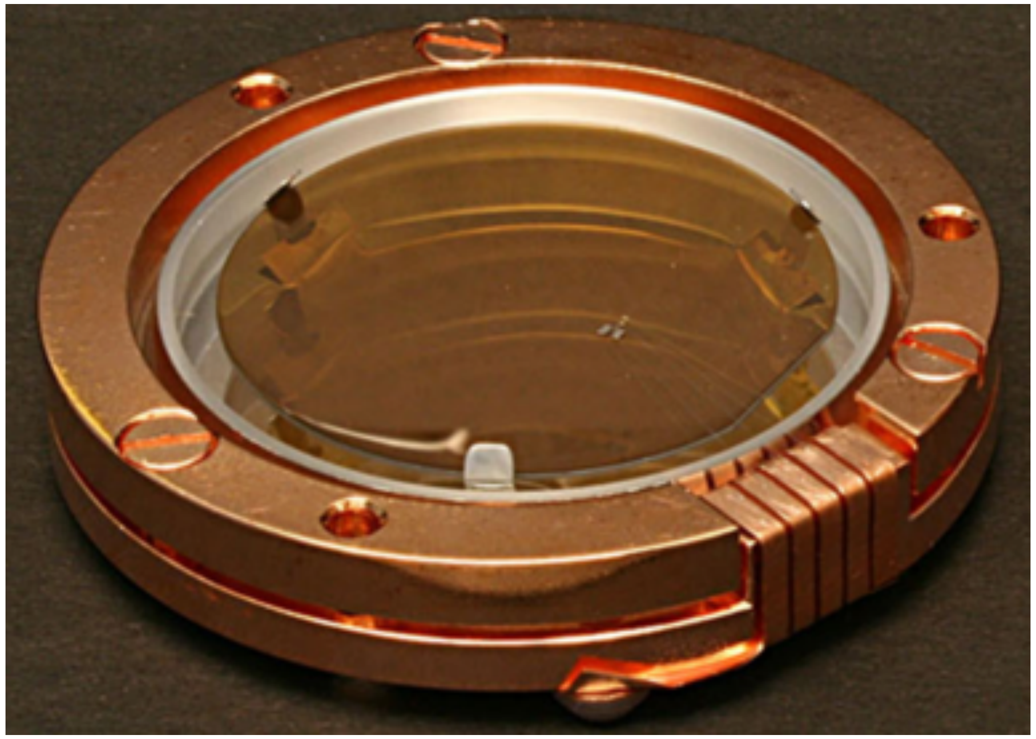
in both cases: key design goal is to match sensor bandwidth to signal timescales

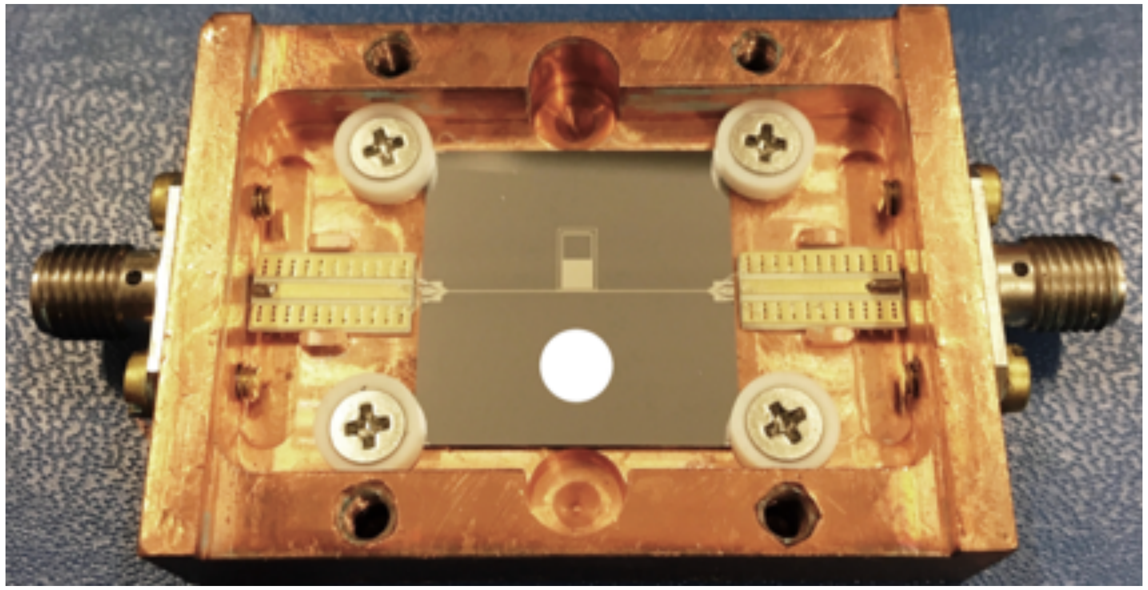
large-area calorimetry: a universal sensor

photo gallery of some thermal or quasi-thermal detectors



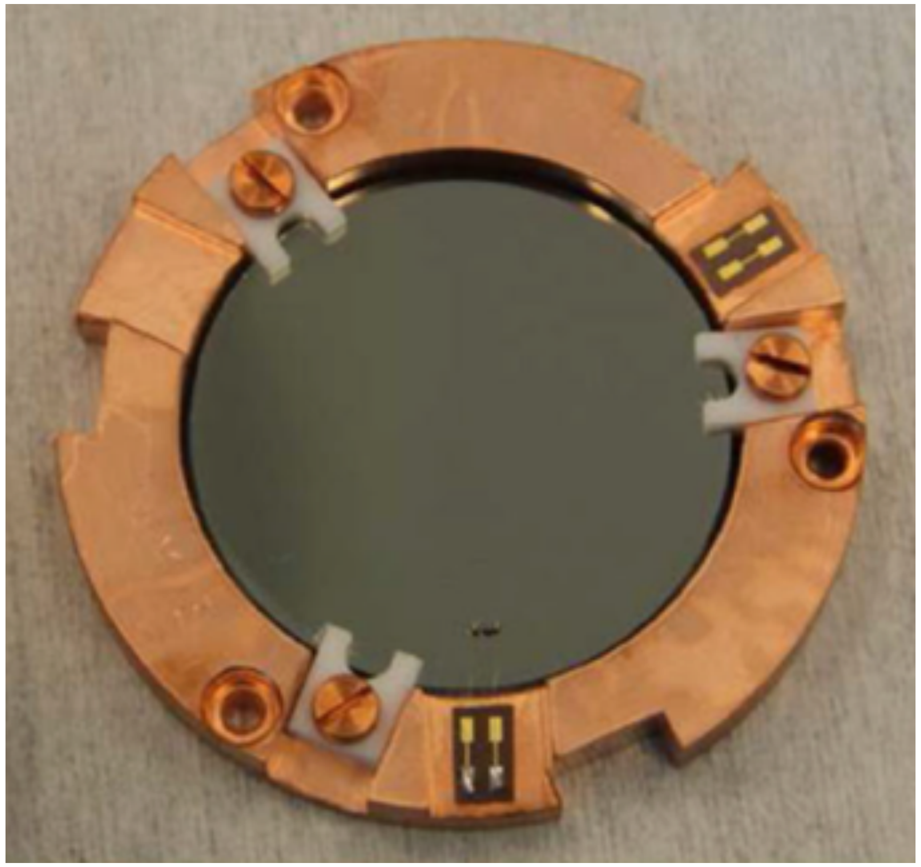
sensor: TES





sensor: KID

sensor: NTD



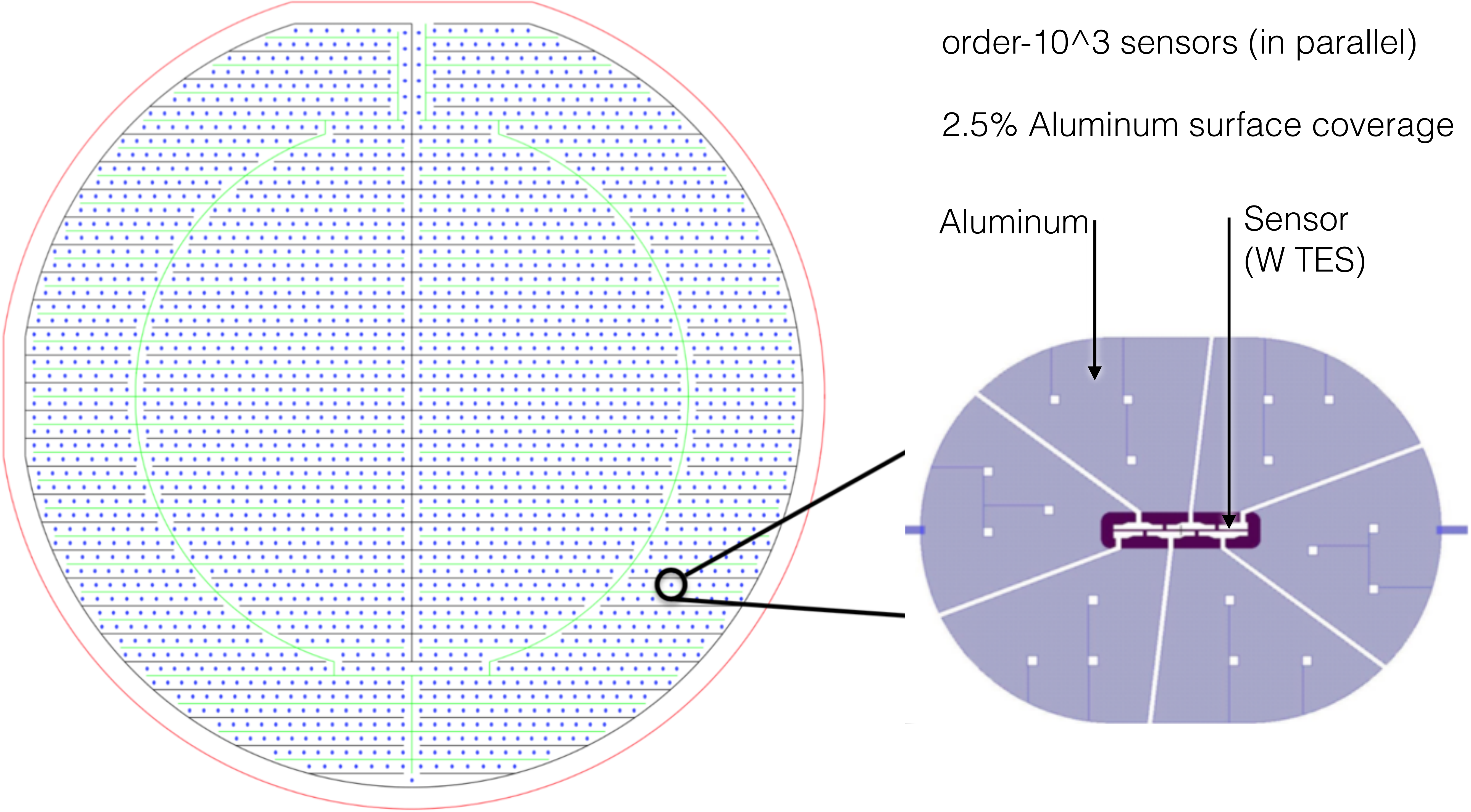
large-area calorimetry: a universal sensor

highly athermal design (ala cdms)

3” diameter Si wafer

order-10^3 sensors (in parallel)

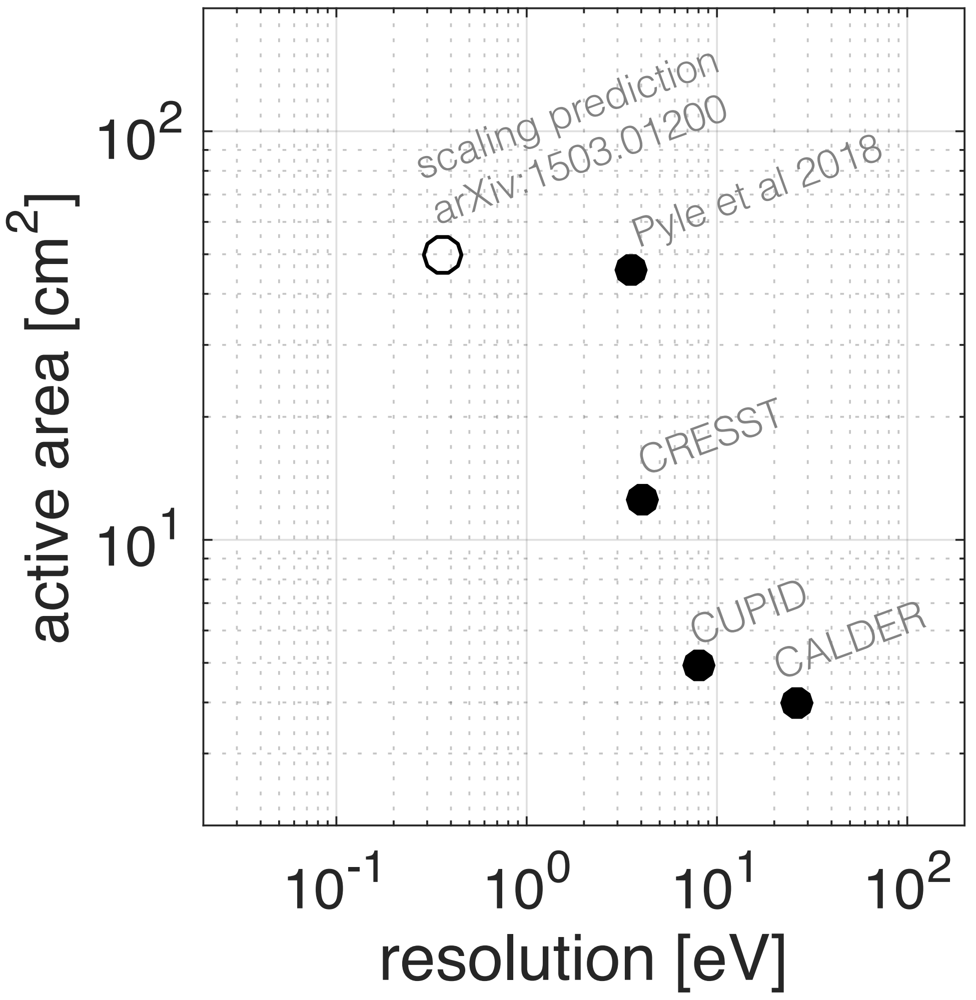
2.5% Aluminum surface coverage



large-area calorimetry: a universal sensor

State of the Field

	Area [cm^2]	Baseline Resolution [eV]	Falltime [ms]	Sensor Type
CALDER 1801.08403	4.0	26	0.8	MKID Al/Ti/Al
CUPID 1704.01758	4.9	7.6	6.4	NTD
CRESST J. Rothe JLTP 18	12.6	4.1	O(1)	TES W, Tc~10-15mK
Pyle et al 2018 talk	45.6	3.5	0.06	TES W, Tc~ 41.5mK



signals, one by one

sensing electron recoils

assuming you can sense electron excitations well…

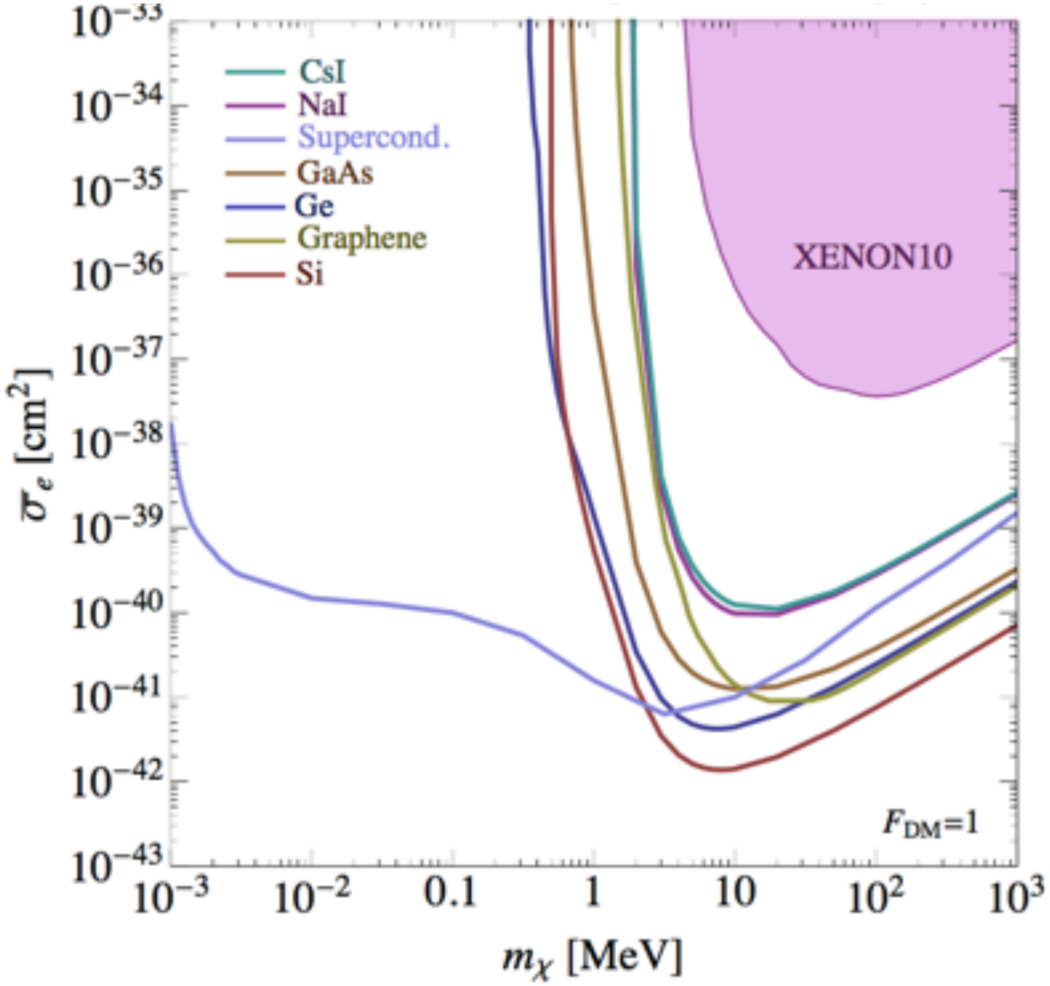
The primary question is: what is the energy of an electronic signal quantum?
The secondary question: what [p,E] states are available, both initial and final?

meV (superconductor)

sub-eV (semiconductor)

few-eV (atomic)

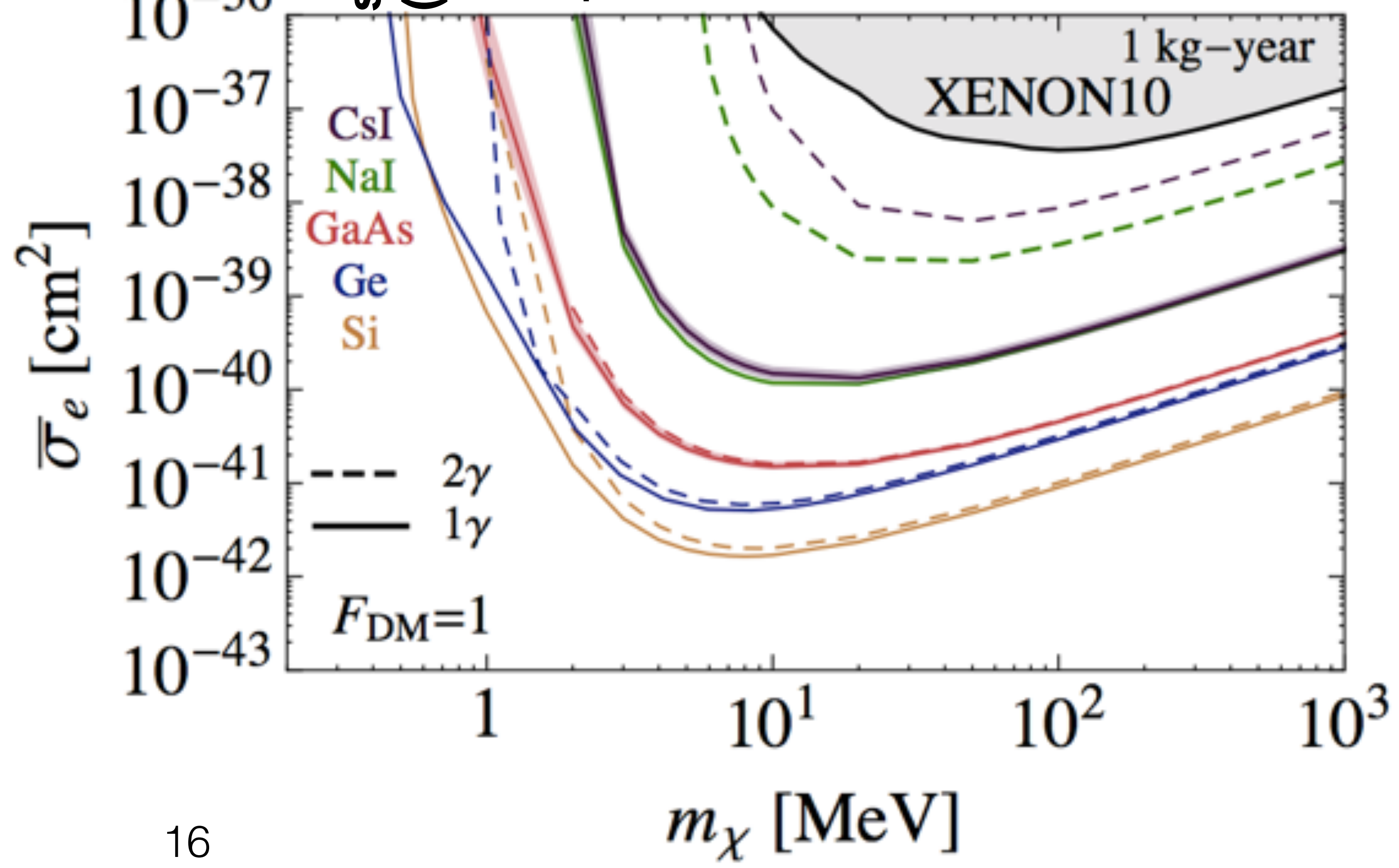
sensing electrons/holes



sub-eV (semiconductor)

few-eV (atomic)

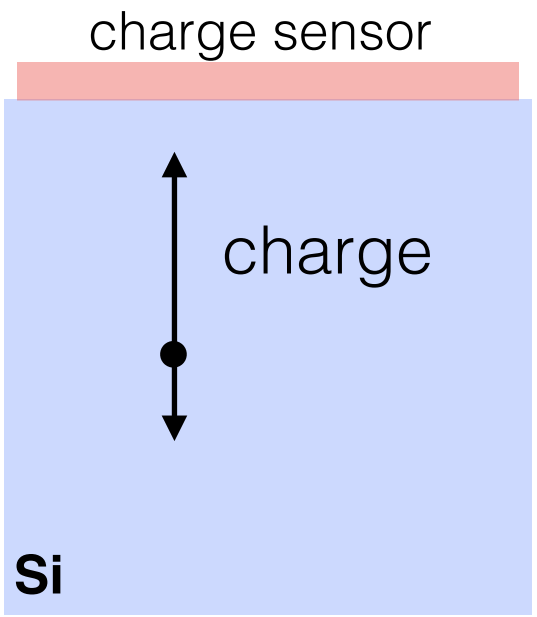
sensing photons



sensing electron recoils

Sensing single semiconductor e-h pairs: a solved problem!

two complementary approaches:

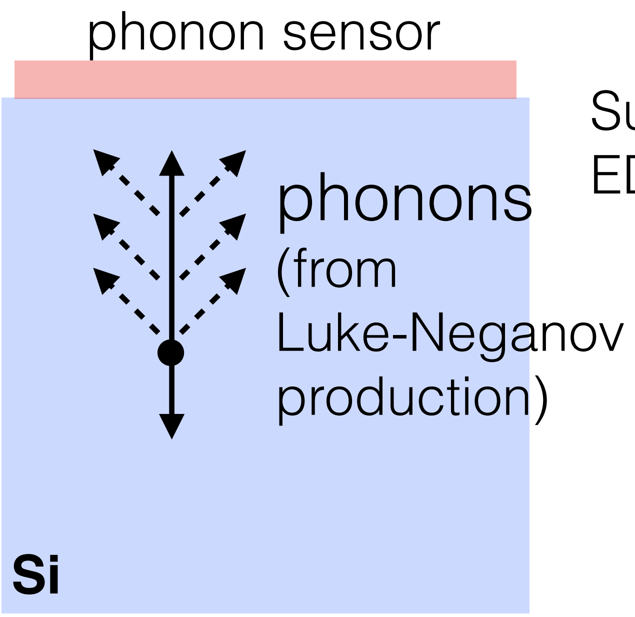


charge sensor

charge

Si

DAMIC
SENSEI



phonon sensor

phonons
(from
Luke-Neganov
production)

Si

SuperCDMS
EDELWEISS

sensing electron recoils

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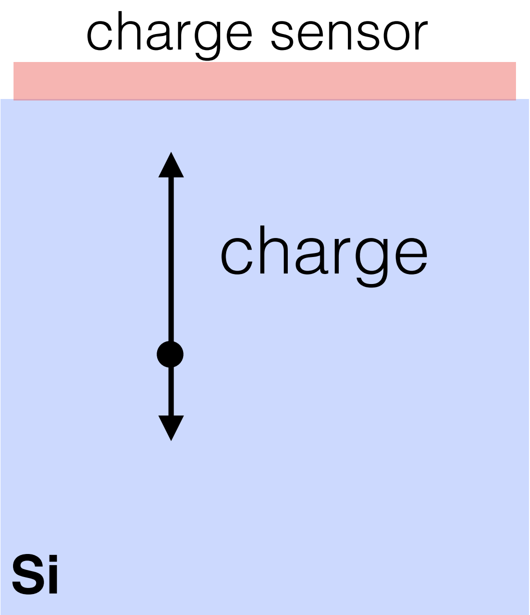
two complementary approaches:



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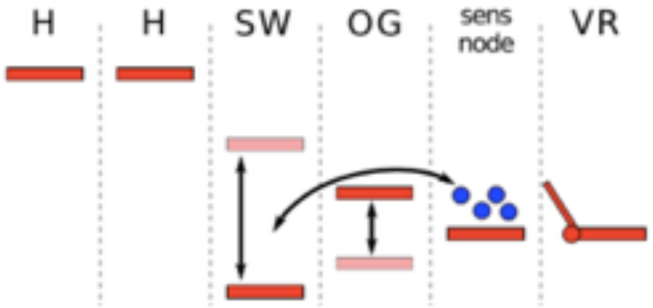
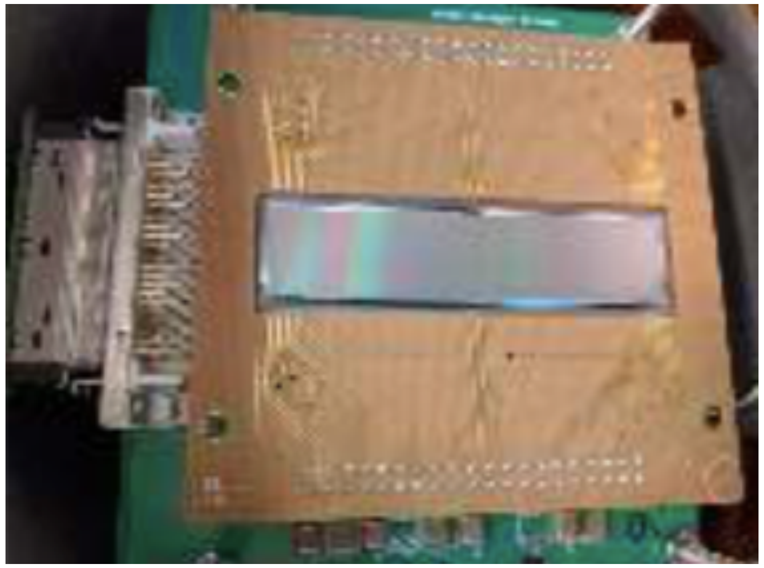
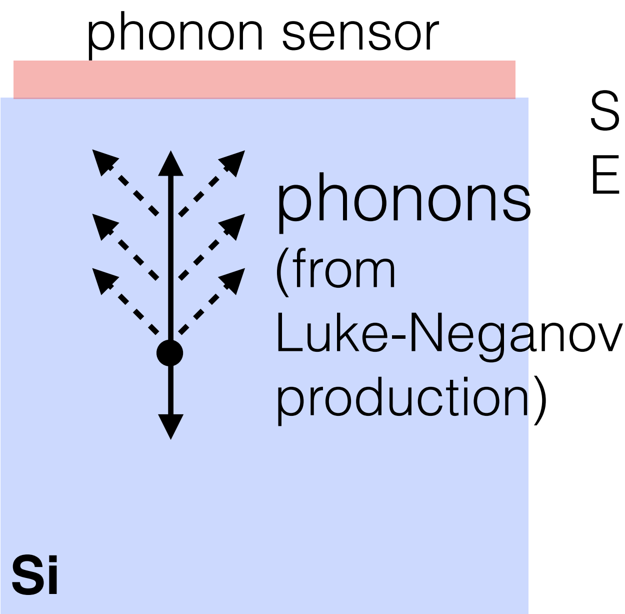


skipper ccd
(repeated sensing)

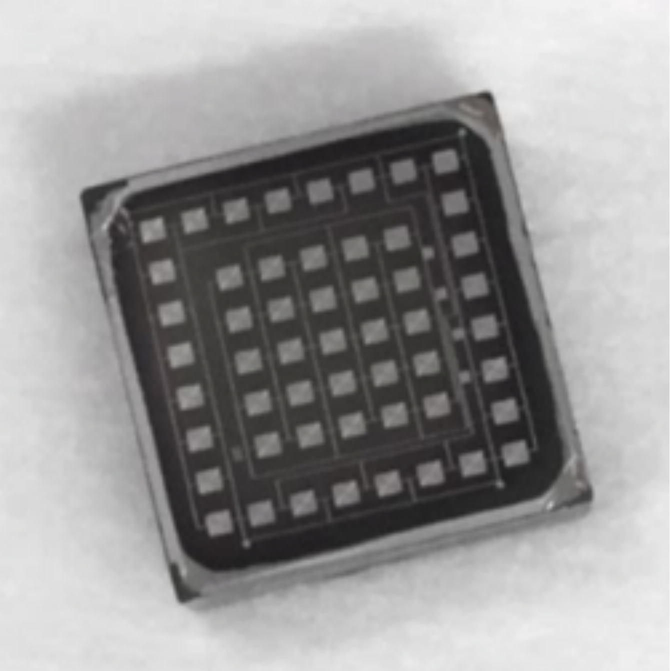
4k x 1k :   0.5g





SuperCDMS
EDELWEISS

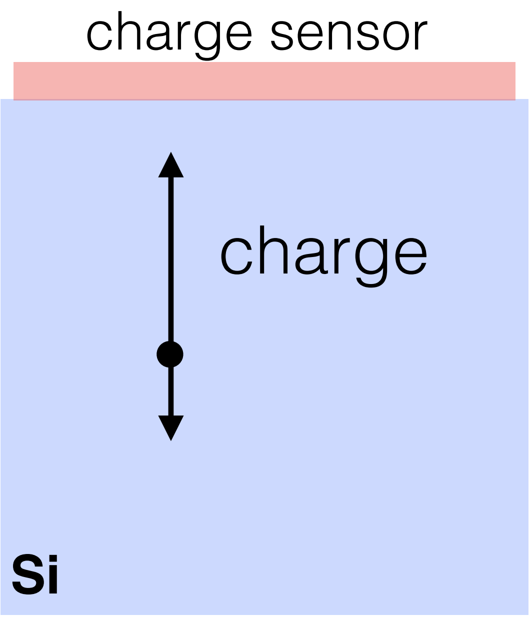
10x10x4 mm :   1g



sensing electron recoils

Sensing single semiconductor e-h pairs: a solved problem!

two complementary approaches:

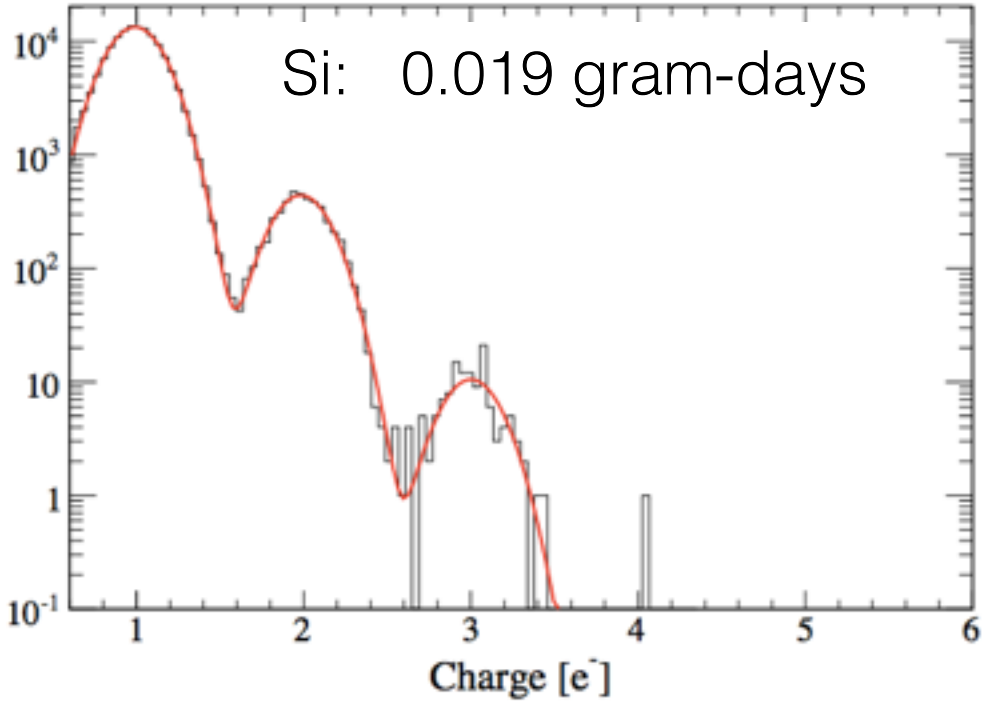


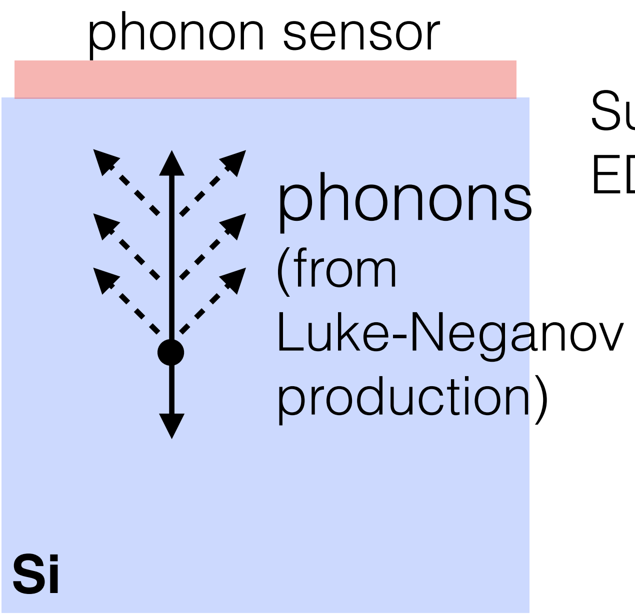
charge sensor

charge

Si

DAMIC
SENSEI





phonon sensor

phonons
(from
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Si

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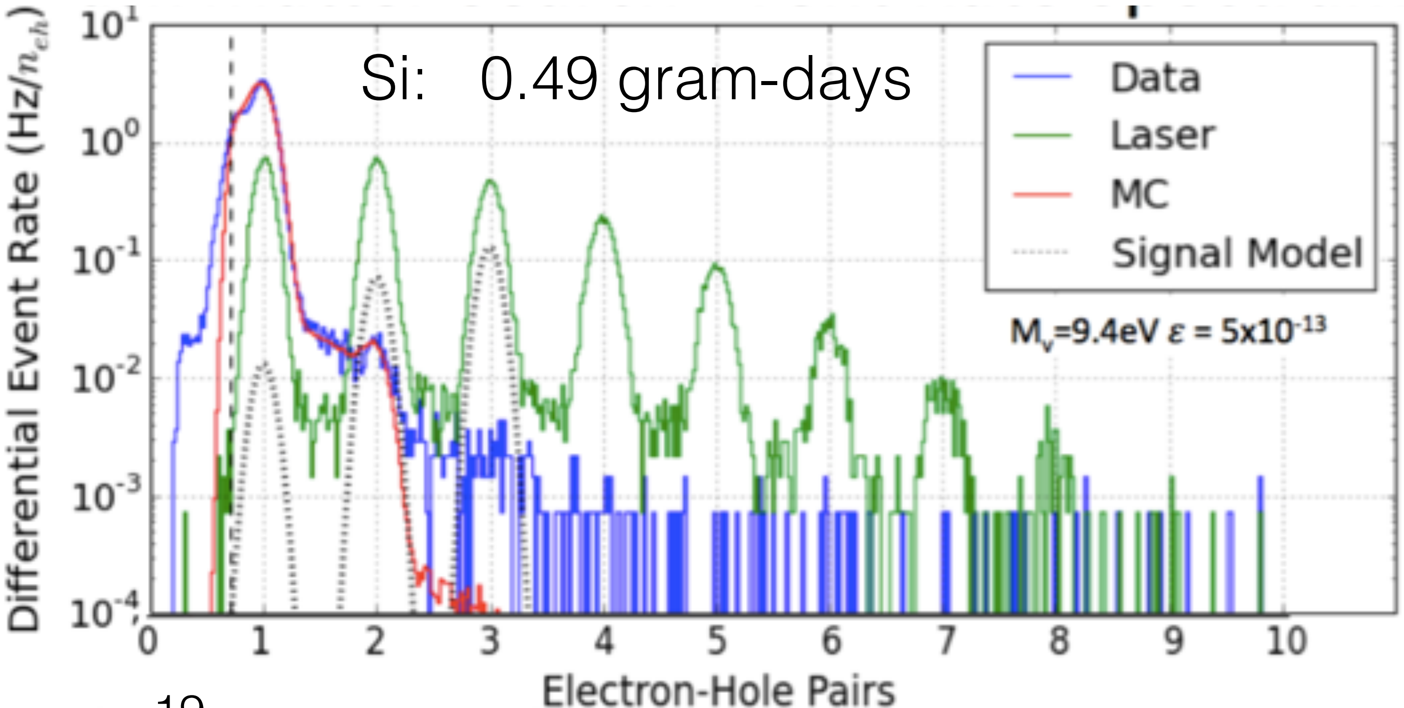
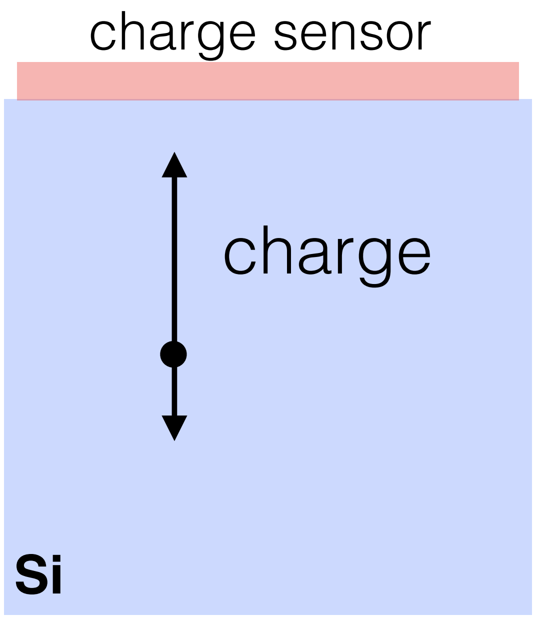
EDELWEISS



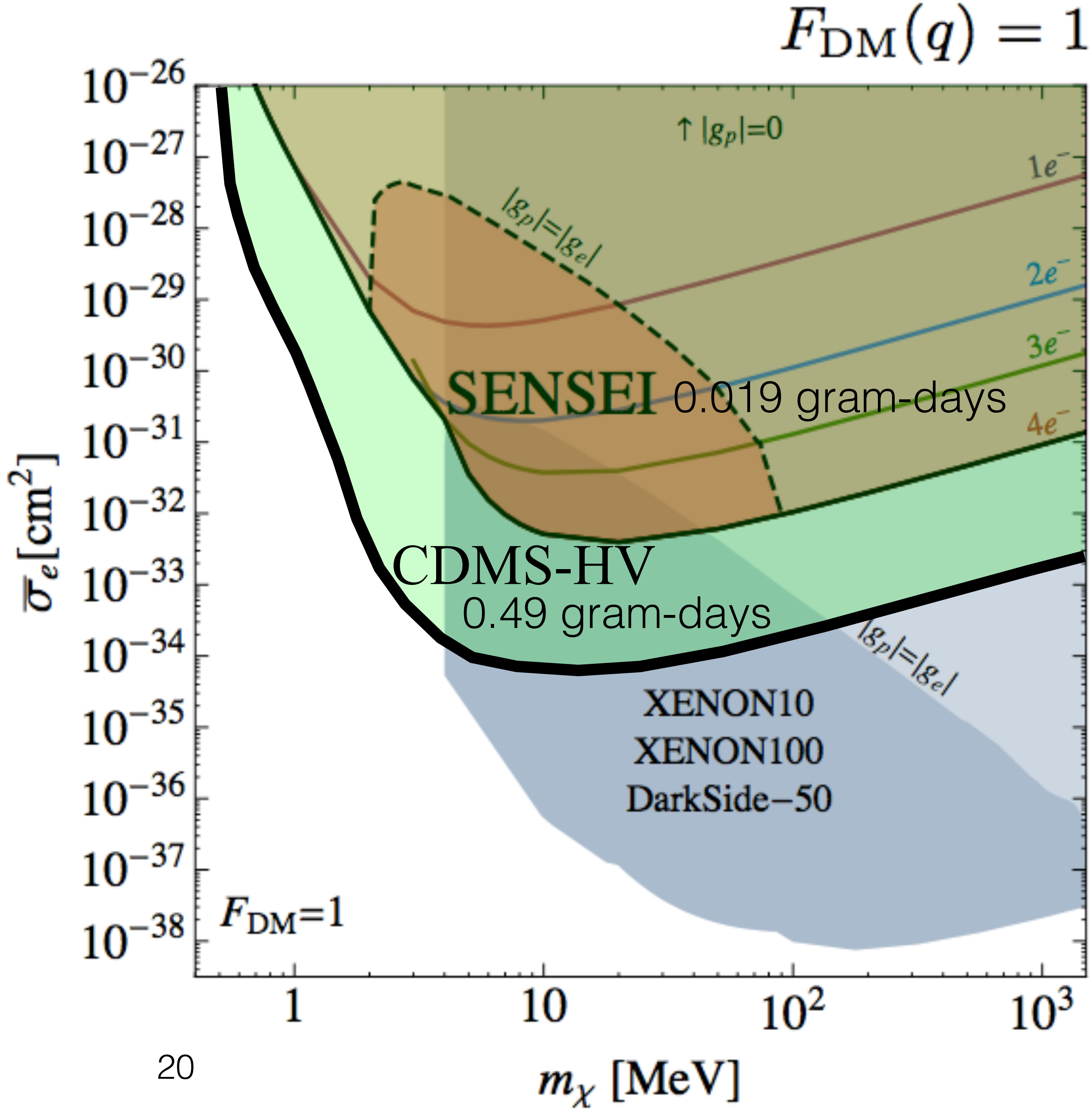
sensing electron recoils

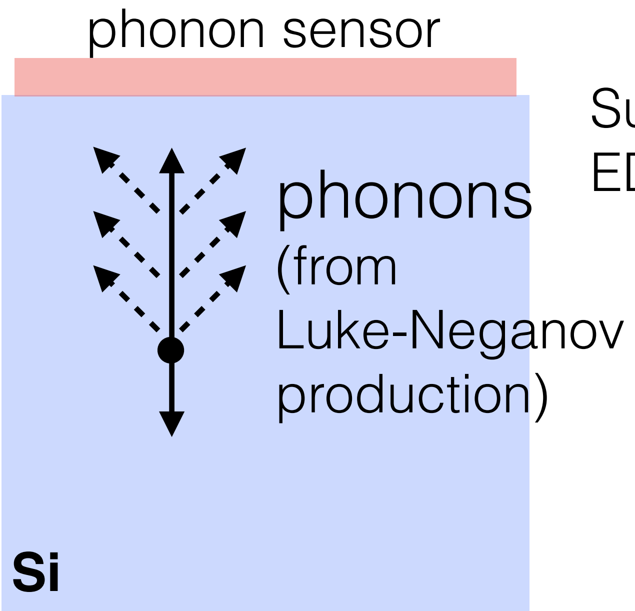
Sensing single semiconductor e-h pairs: a solved problem!

two complementary approaches:



DAMIC
SENSEI





SuperCDMS
EDELWEISS

sensing electron recoils

arXiv:1607.01009, 1802.09171

doing the same thing via photons…. why bother?
- -easier to scale mass to kg or even ton-scale
- -No need to *apply* potential energies to the target (potential for even lower dark counts)

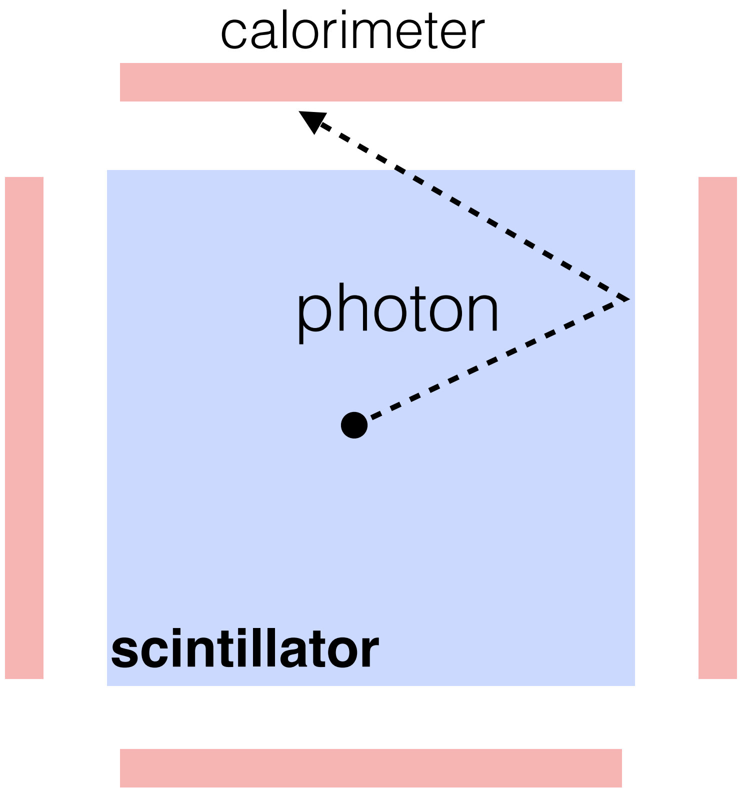
photon sensor goals:

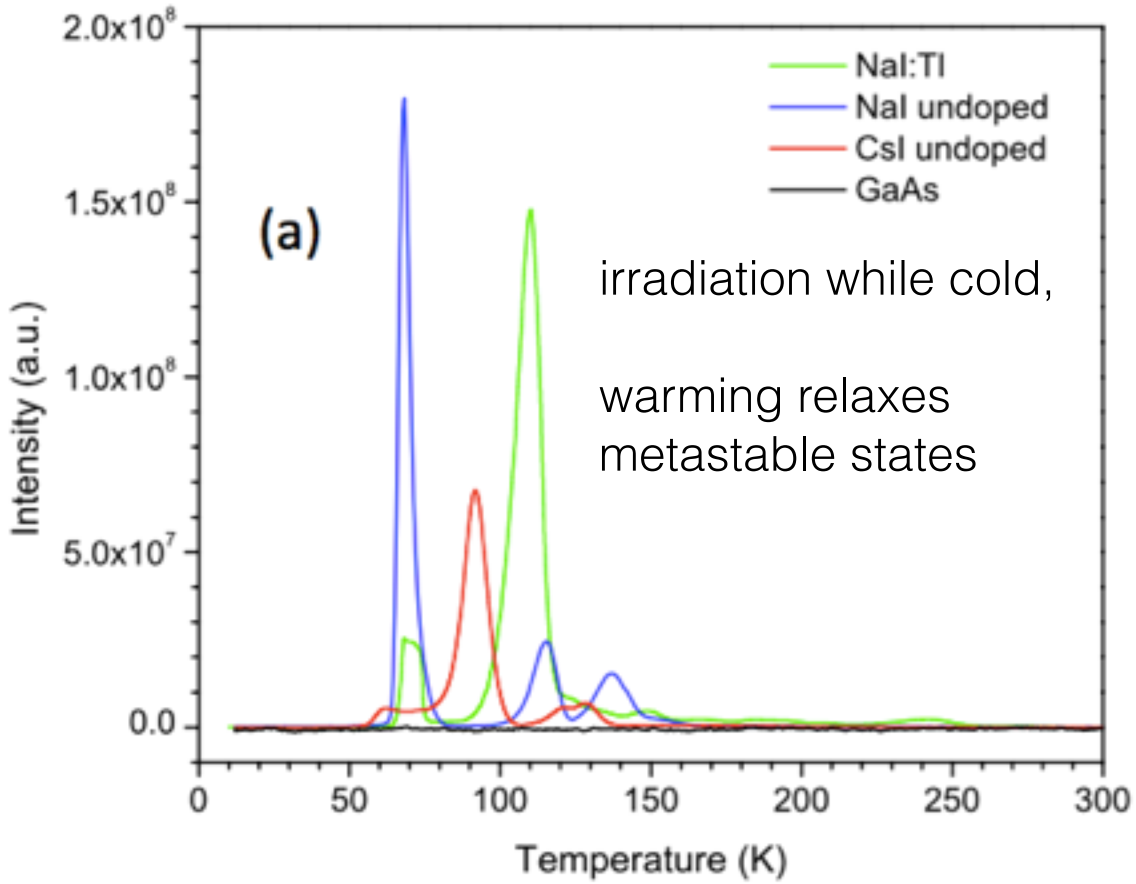
photon-counting
4pi coverage
efficiency ~1
dark count ~0

(calorimetry)

crystal goals:

low band-gap (CsI: 6eV, GaAs: 1.5eV)
photon energy just under that (GaAs: 1.3eV)
high quantum efficiency (GaAs: 60%)
low dark counts (GaAs: so far so good)





irradiation while cold,

warming relaxes metastable states

sensing electron recoils

What electron excitations are available below the eV scale?

1-100 meV gap energies for 1-100 keV dark matter: a couple of the several ideas

superconductors

1512.04533

Al: 0.6meV gap

calorimetric readout
(either of quasiparticles directly, or of phonons from qp decay)

alternative: qp-counting via qubit

requires significant R&D

semi-metals (meV-gap semiconductors)

1708.08929

ZrTe5: few-meV gap, tunable by doping

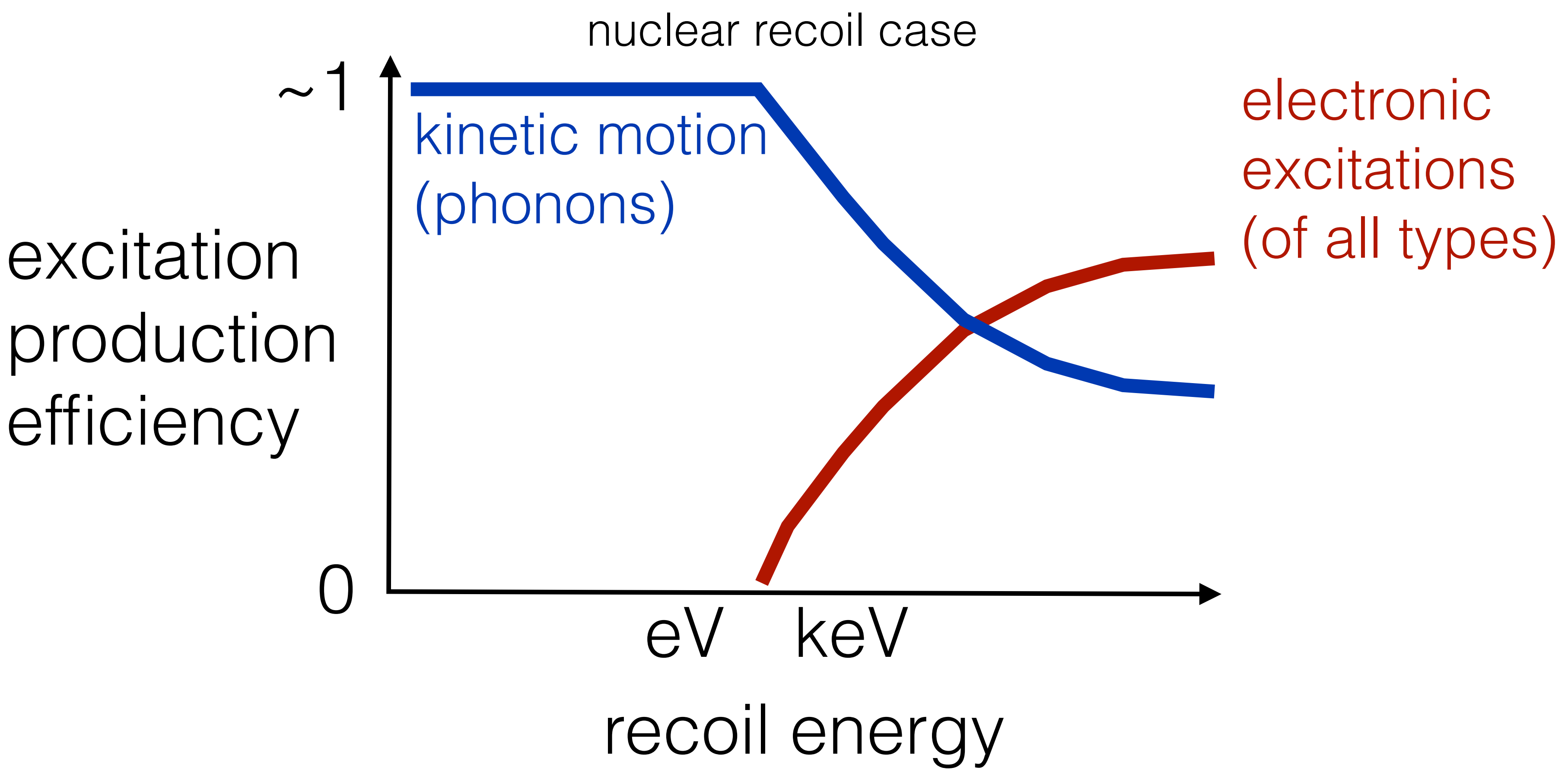
readout unclear, most promising idea is a FET-like resistance change

elephant in the room: what does the dark count do for meV-scale excitations?

sensing nuclear recoils

1) typically, less energy than electron recoil case
   (unless taking advantage of low-momentum-per-E states)

2) typically, low or no energy in the electronic signal quanta
   (plus side: no need to argue about ‘quenching’ anymore…)



sensing nuclear recoils

Generic two-pillar strategy:

1: use excitations of low momentum-per-E

(low-mass nucleus or low-momentum phonon states)

2: push calorimetry threshold as low as possible

(pull energy into calorimeter, match sensor and signal timescales, push Tc down, shrink all heat capacities)

sensing nuclear recoils

crystal target

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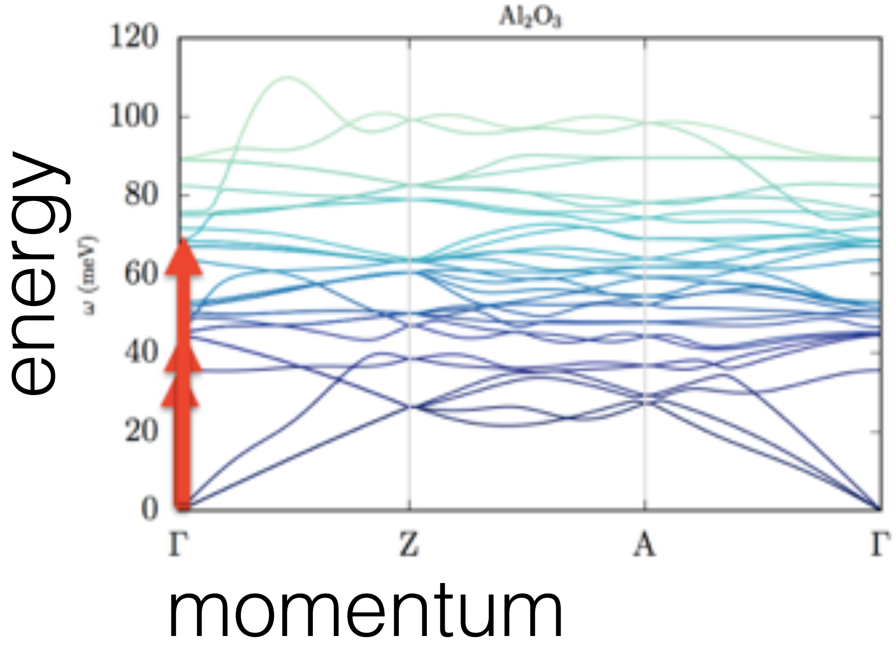
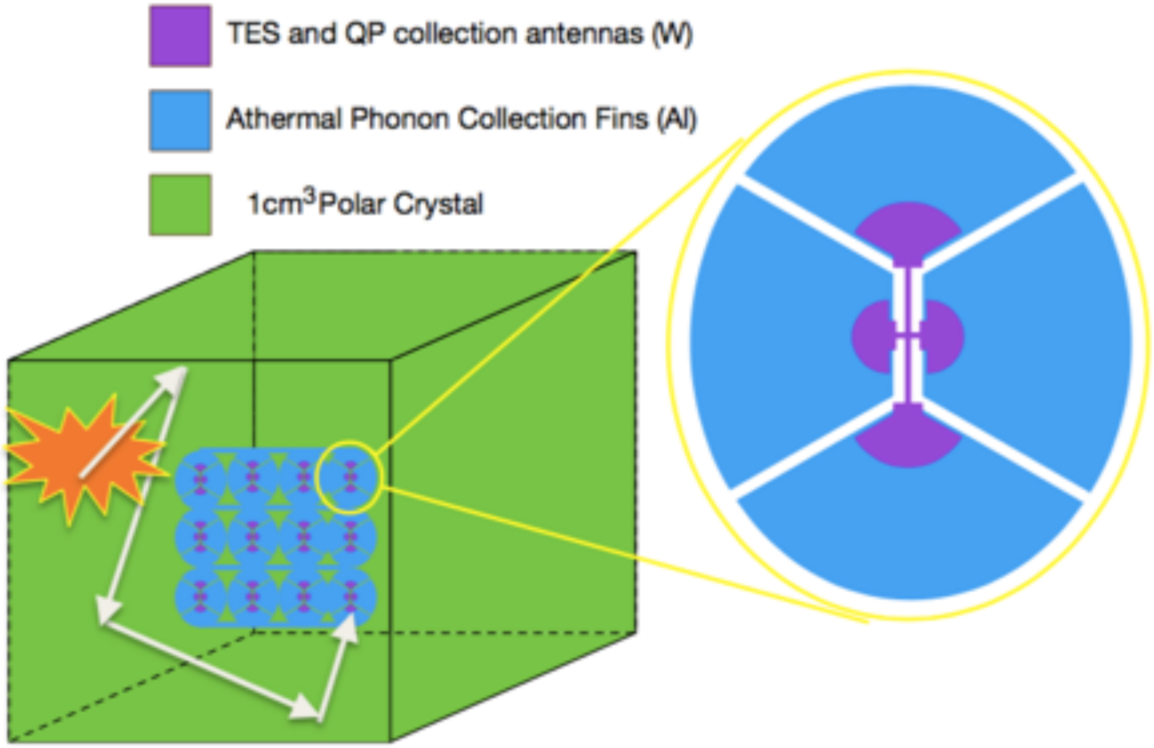




`shovel ready' from M. Pyle:

$$\sigma_E^2 \sim N_{sensor} C_1 T^2$$

~2g
~200 meV sigma

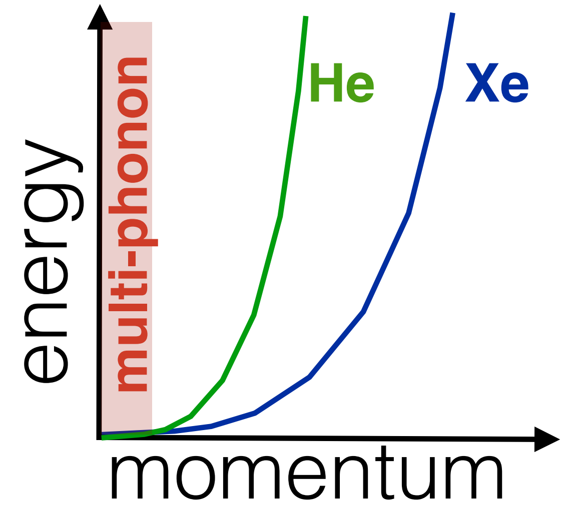
sensing nuclear recoils

superfluid 4He target mass

Two-pillar strategy:

1: use excitations of low momentum-per-E

(low-mass nucleus or low-momentum phonon states)



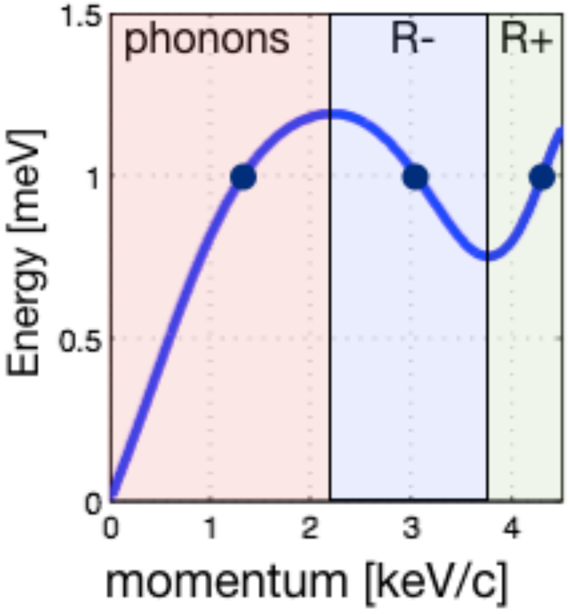
2: push calorimetry threshold as low as possible

plus some other good ideas if you can:

3: distinguishable ‘flavors’ of meV-scale excitations

phonons, R-, R+

(differ in velocity and transmission)

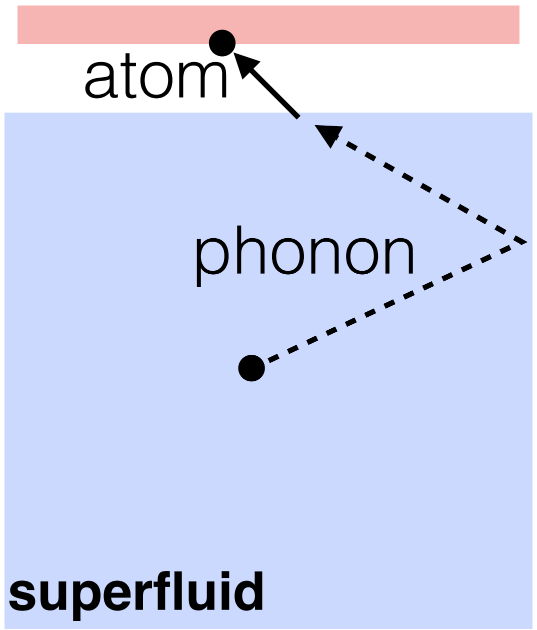


4: amplification of signal before reaching calorimeter

phonon

-> free atom
(quantum evaporation)

-> electrostatic attraction
(gain: x10-40)



summary points

keV-MeV mass range

meV-to-eV threshold requirements
gram (or even smaller) target masses can be world-leading useful
diverse ideas, very fun for an experimentalist

electron recoils

can benefit from electron momentum in bound-state
counting semiconductor e-h pairs: now ready to scale up
counting photons: R&D done, now ready for first exposure
meV-scale excitations: some good ideas, time to be doing this R&D

nuclear recoils

can benefit from optical phonon modes and other low-momentum states
great progress on calorimeter threshold in recent years
continuity with existing NR approaches, plus new phonon modes