Calorimetric readout of Superfluid ^{4}He for sensitivity to dark matter of keV-MeV mass

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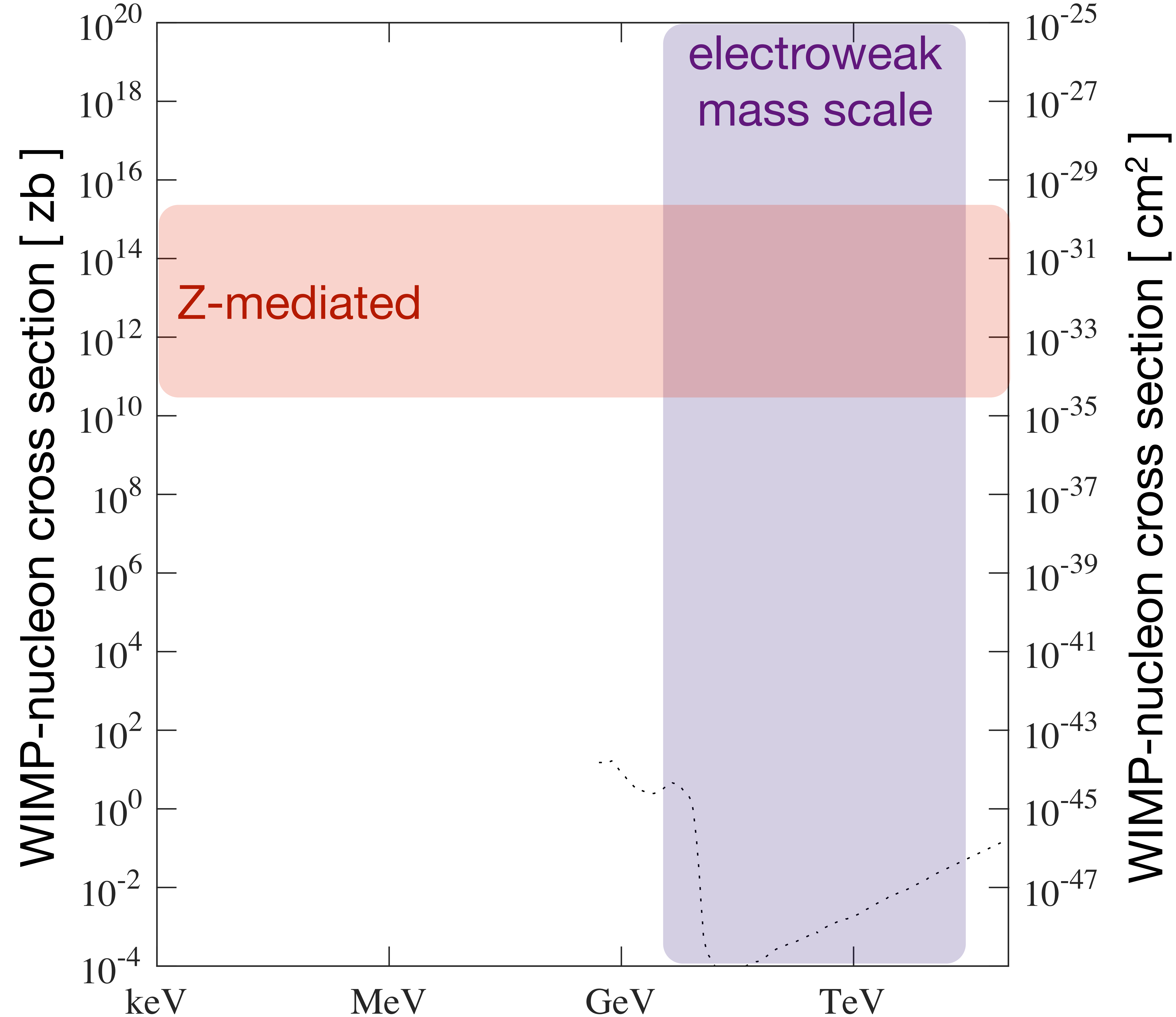
Workshop: Table-Top Experiments with Skyscraper Reach

MIT, Aug 10th, 2017

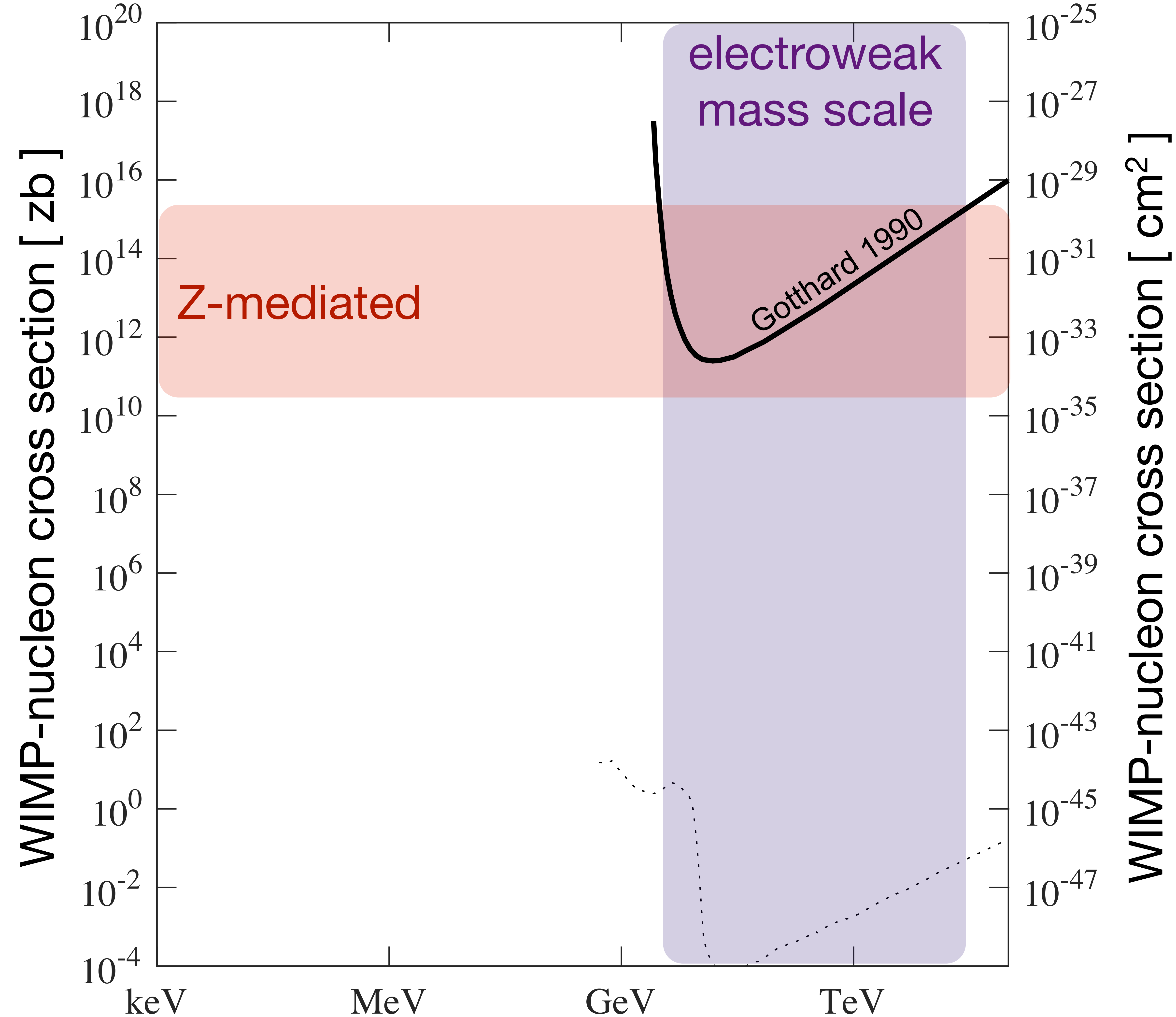
understanding the WIMP as one model among many

The basic WIMP hypothesis
(neutrino-like interactions)



understanding the WIMP as one model among many

The basic WIMP hypothesis
(neutrino-like interactions)
-ruled out by ~1991



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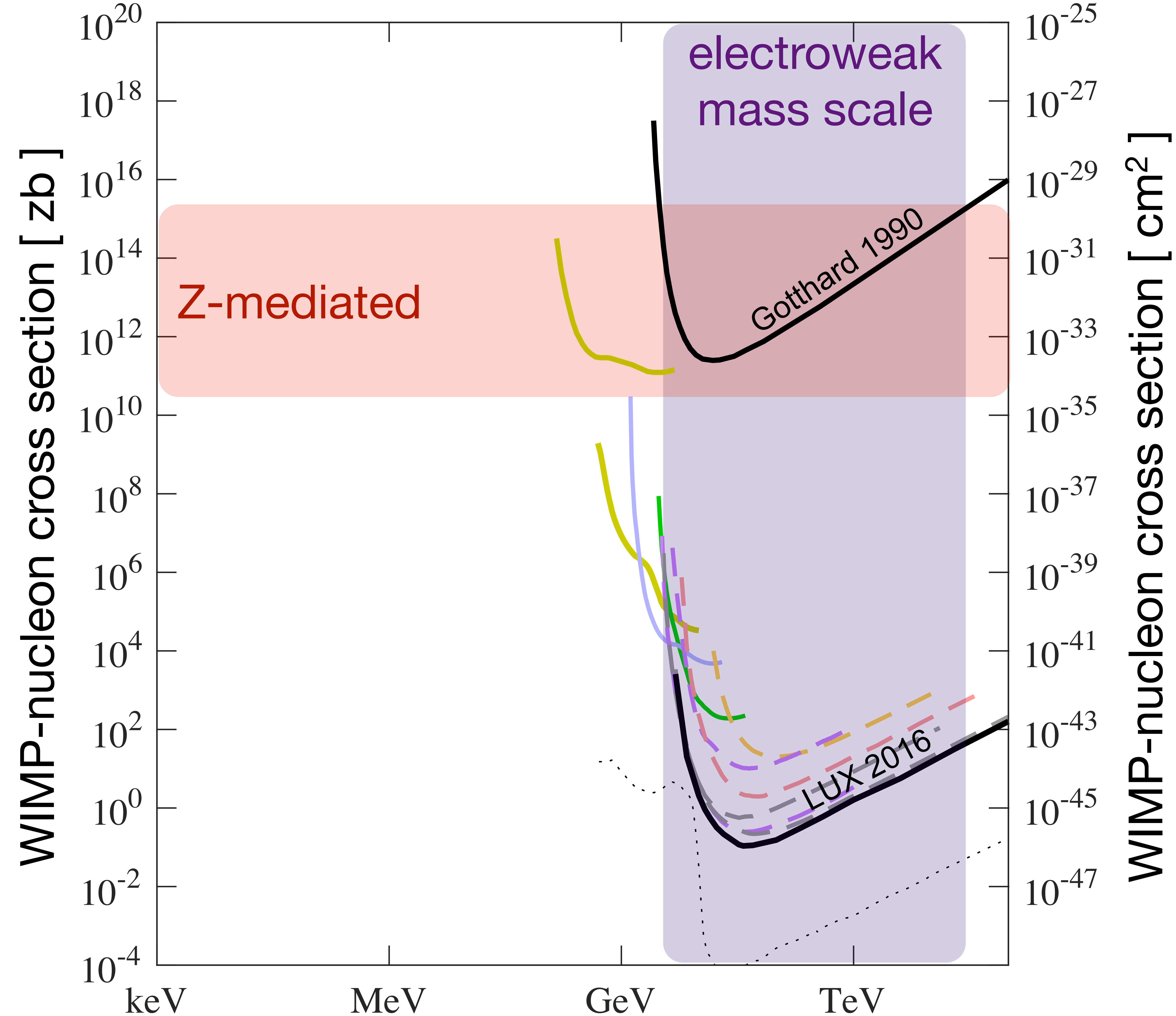

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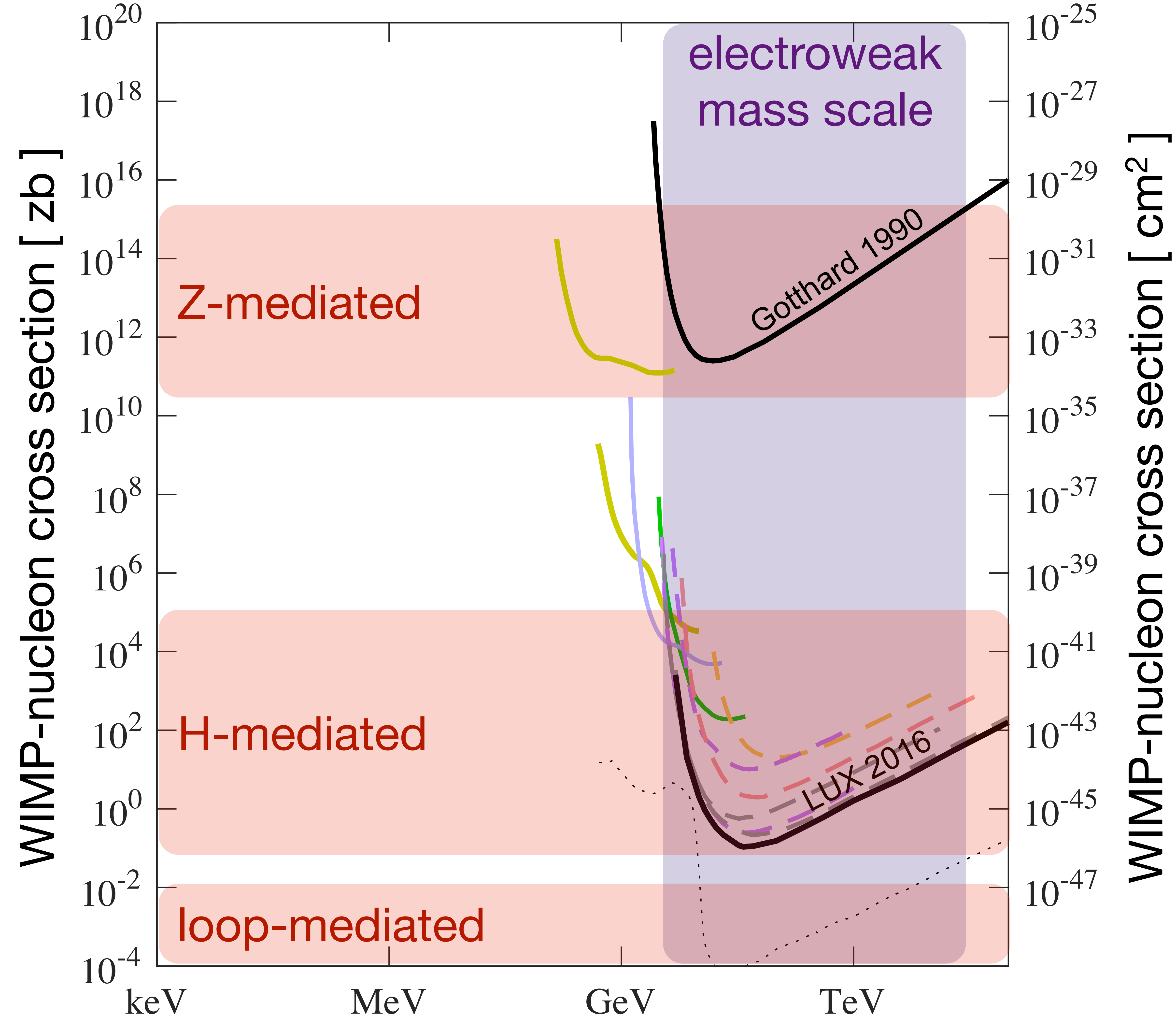
...meaning, we keep broadening the interaction type prior to increasing un-natural versions of weak interaction.



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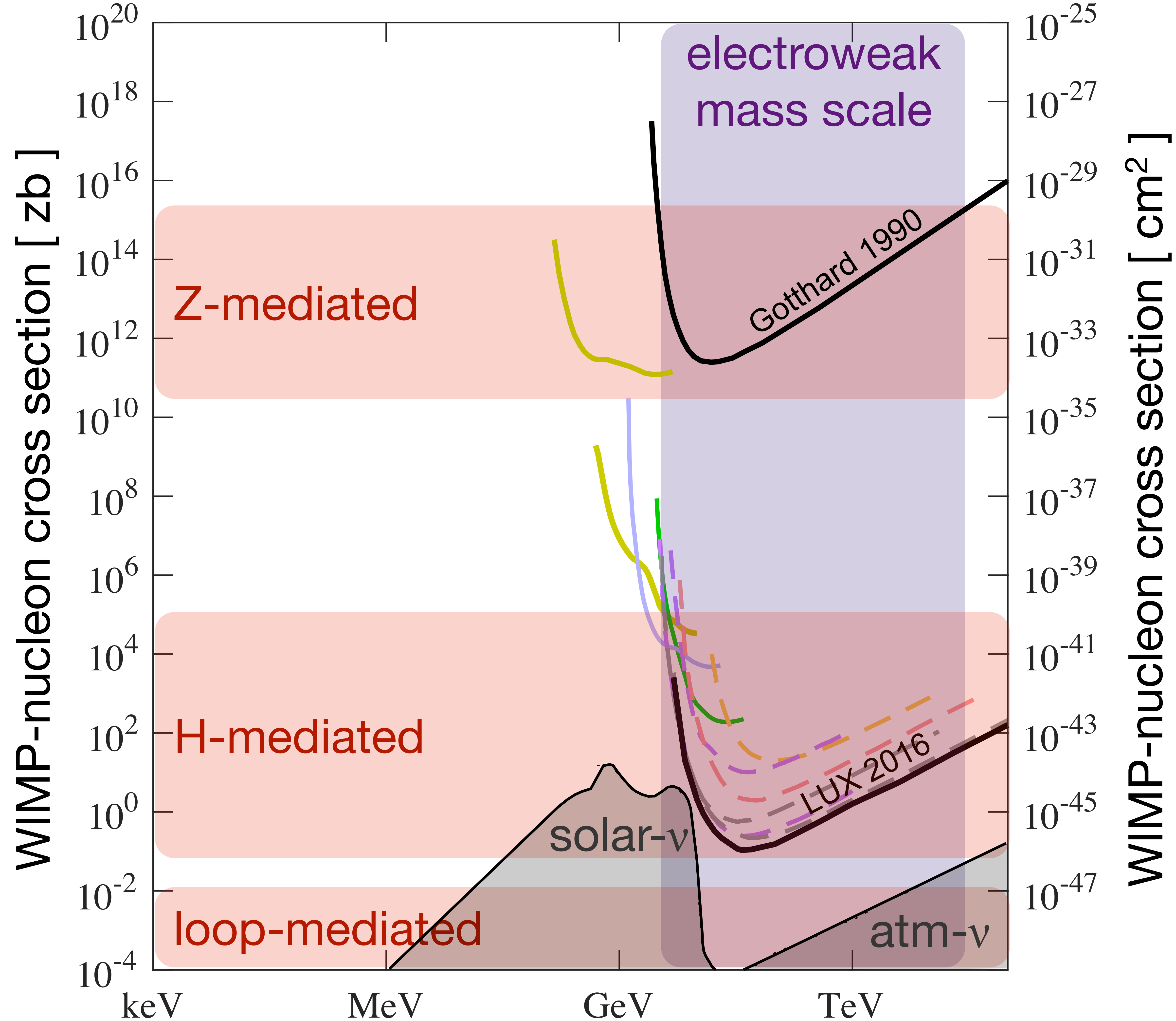
We keep digging down at this same mass range...

...meaning, we keep broadening the interaction type prior to increasing un-natural versions of weak interaction.

Not sustainable for ever:
1. increasingly un-natural
2. unavoidable backgrounds

Time to broaden other priors?



understanding the WIMP as one model among many

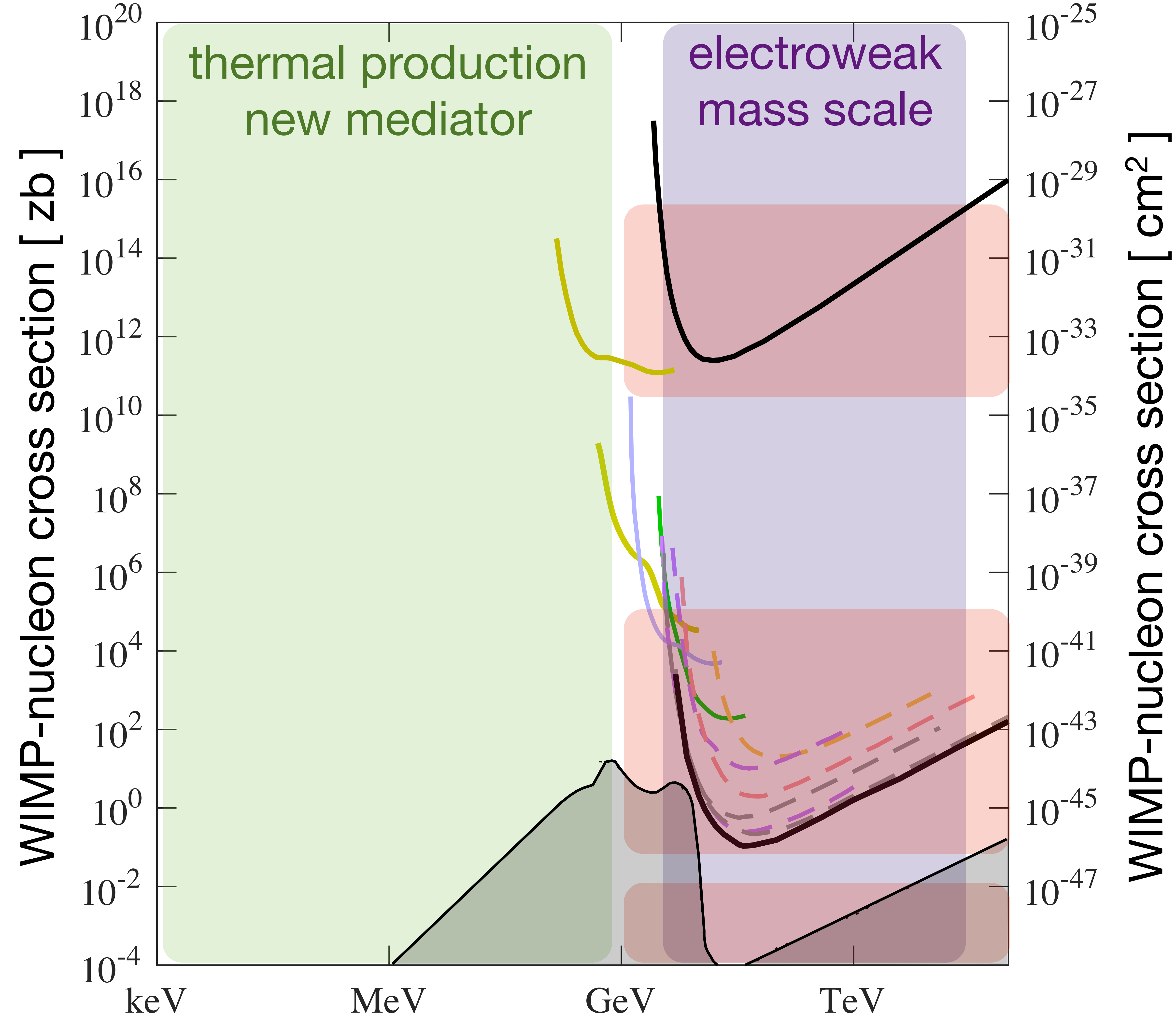
One way to loosen the priors:

1) **retain assumption of thermal production**
2) **stop assuming we already know all the force mediators**

First order effects:

- more unknowns (more theories)
- thermal production works down to ~keV mass scale (note: new ‘freeze-in’ modes)
- light mediators avoid standard collider searches

understanding the WIMP as one model among many



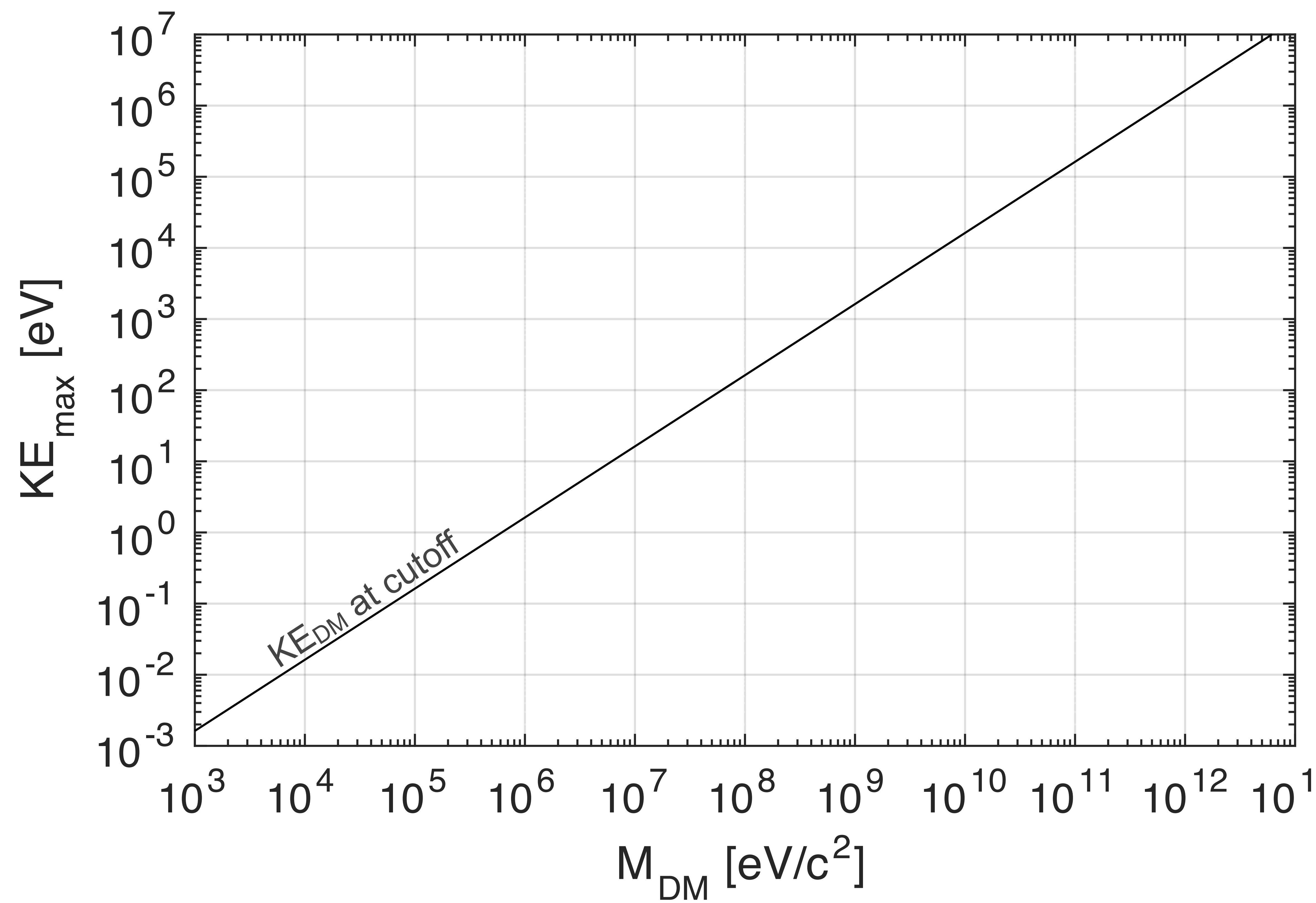
DM kinetic energies

DM particle velocities cut off by (local) escape velocity: $v_{max} \simeq 540$ km/s

$KE_{max} \simeq 1/2 \ m_{DM} \ v_{max}^2$

proportionality of
m_{DM} to KE_{max}

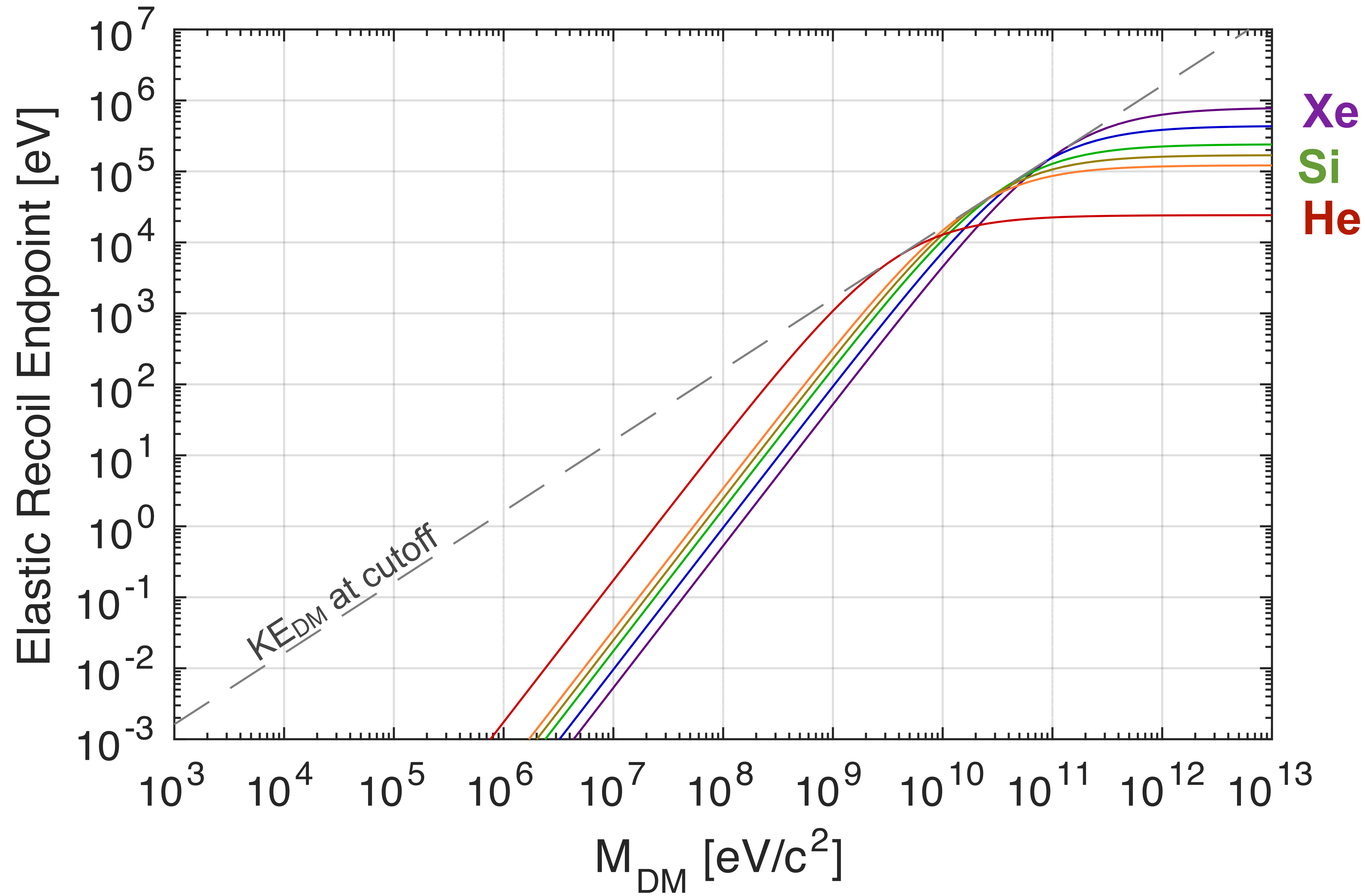
MeV/c^2 ➔ eV
GeV/c^2 ➔ keV
TeV/c^2 ➔ MeV



nuclear recoil energies

when $m_{DM} \simeq m_{target}$, efficient coupling of KE_{DM} into target

order-GeV mass → order-keV recoil endpoint energies
order-MeV mass → order-meV recoil endpoint energies



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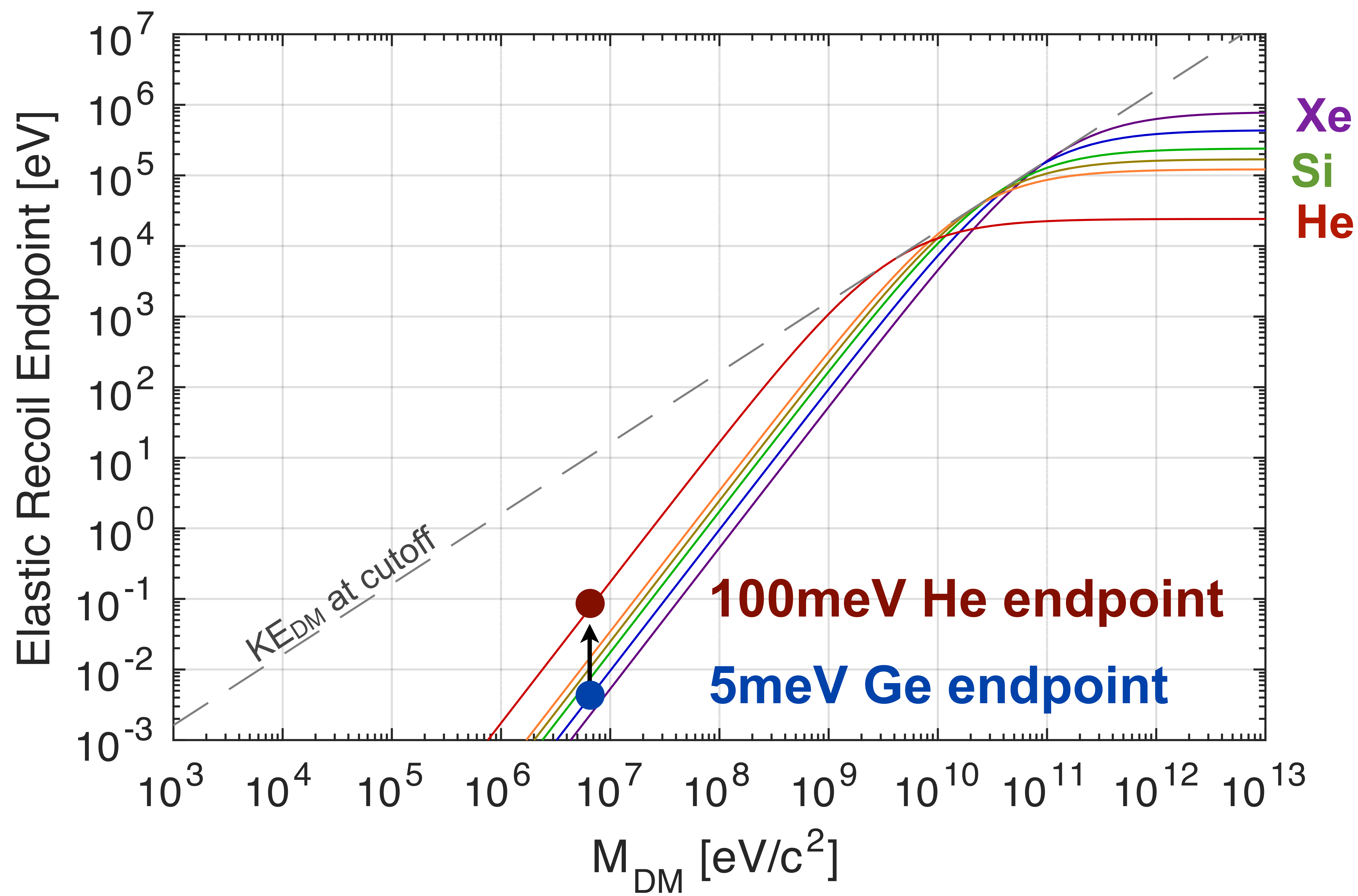

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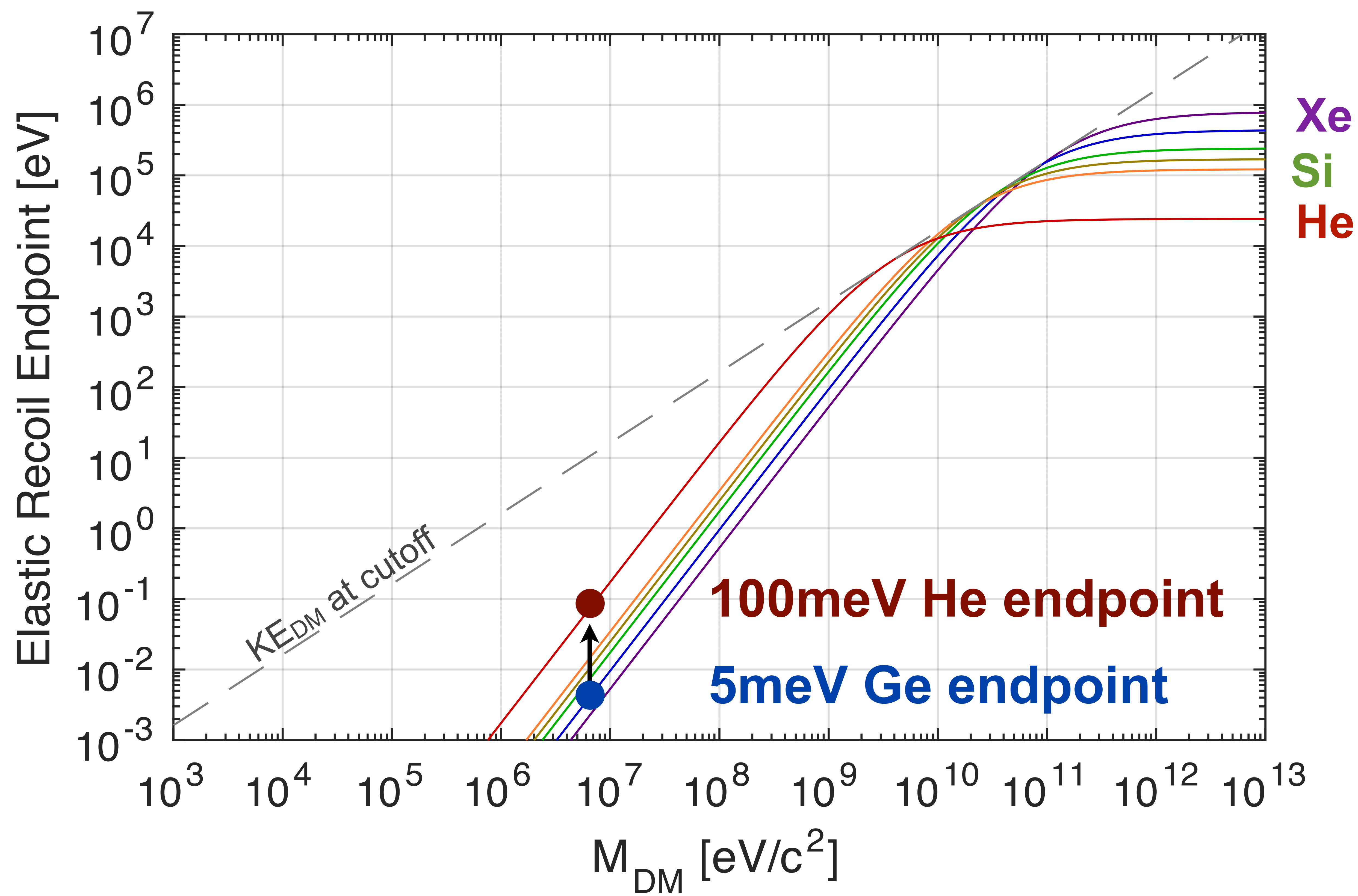
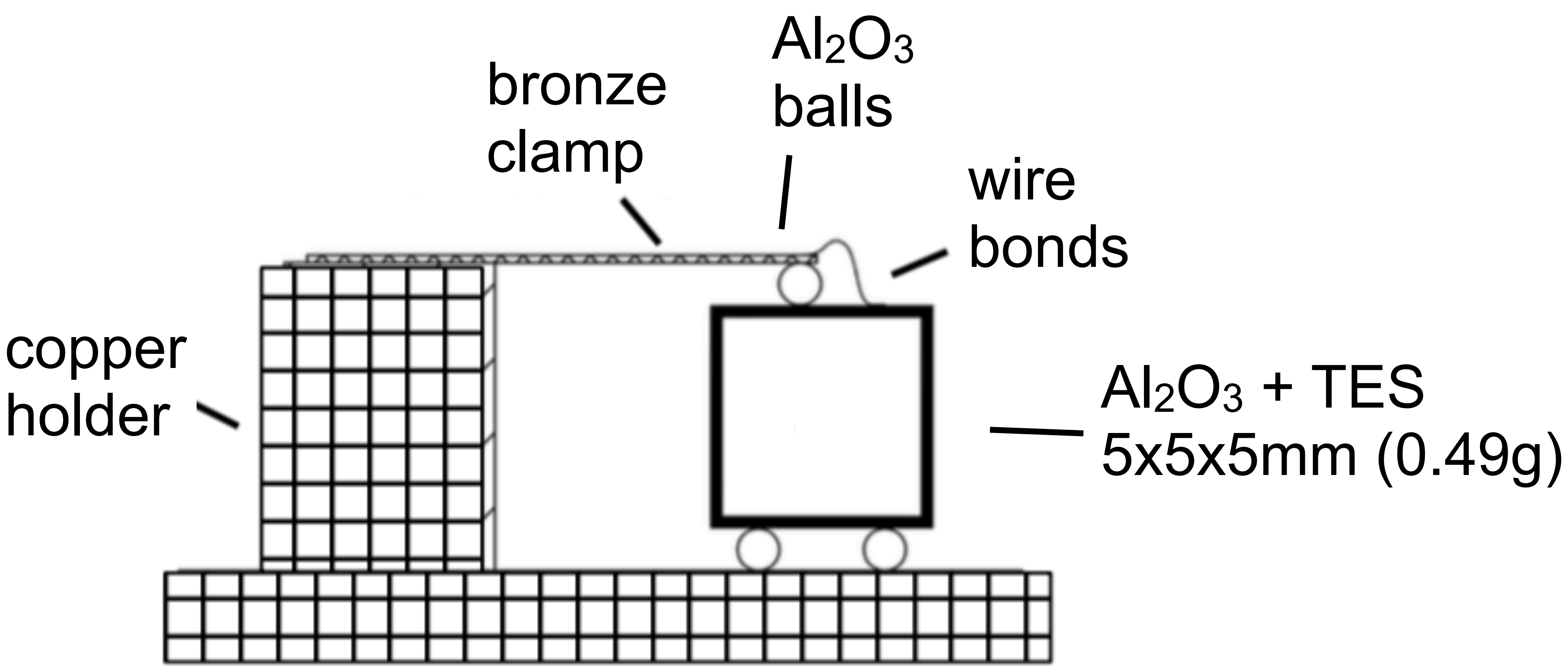
two punchlines:

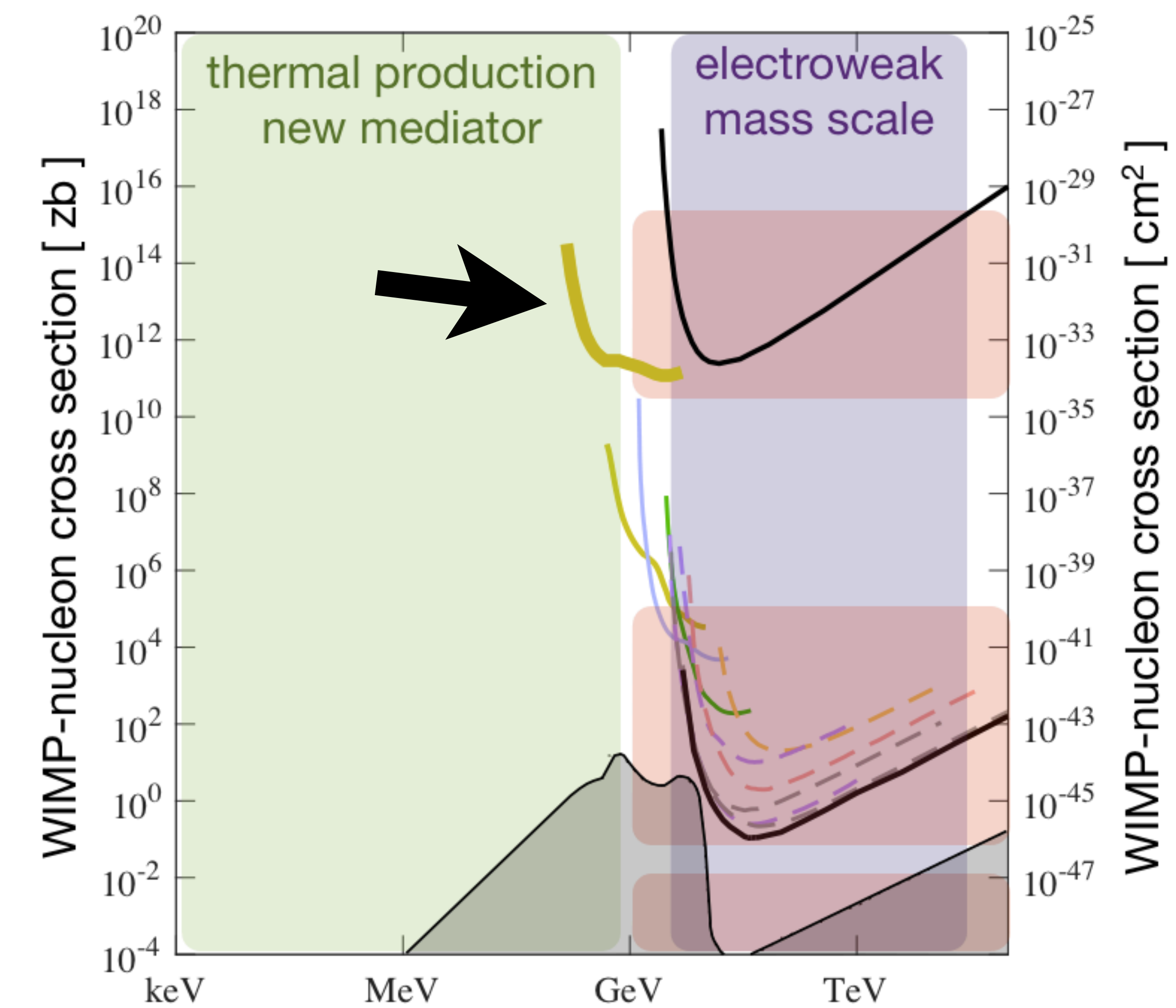
1) light target particle desirable
2) meV-scale excitations desirable

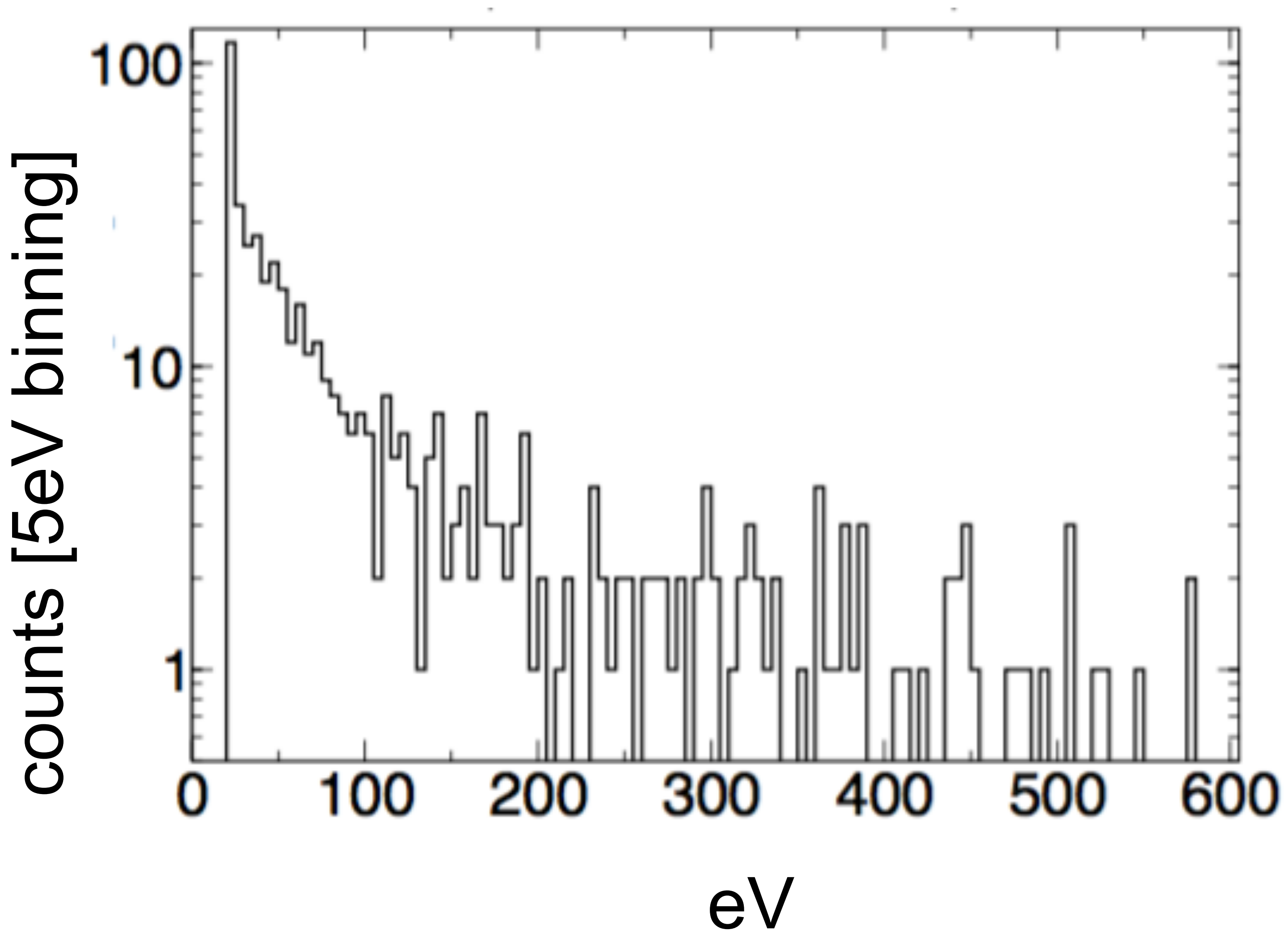


the recent cresst/ν-cleus example

arXiv:1707.06749v2







20 eV threshold (on oxygen → 140 MeV mass threshold)
2.27h exposure
above ground, no shielding, with ~0.2Bq Fe55 source

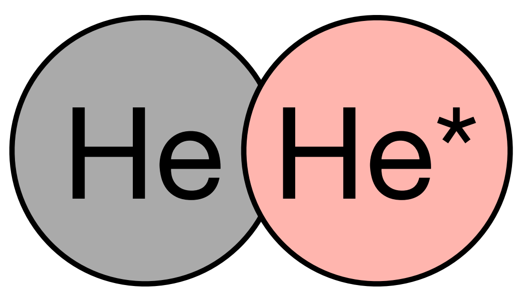
my two cents: we are entering new regime

- sensitivity: energy *threshold* matters more than target *mass*
- backgrounds: dark counts & noise matter more than radiogenics

ie, we are entering the tabletop regime of this workshop

Excitations in superfluid ^4He

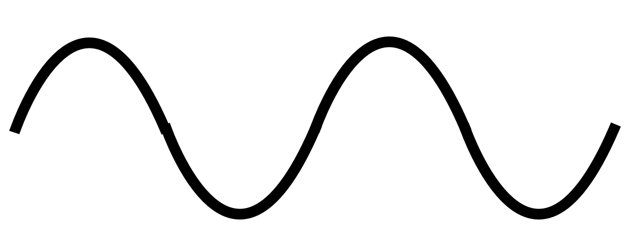
eV-scale excitations:



Excimers (He_2^*)

singlet: ~ns halflife (observable as scintillation)
triplet: 13s halflife (observable as ballistic molecules)
(+ a little IR from excitations to higher atomic states)

meV-scale excitations:



phonons, R- rotons, R+ rotons
(observable as athermal evaporation)

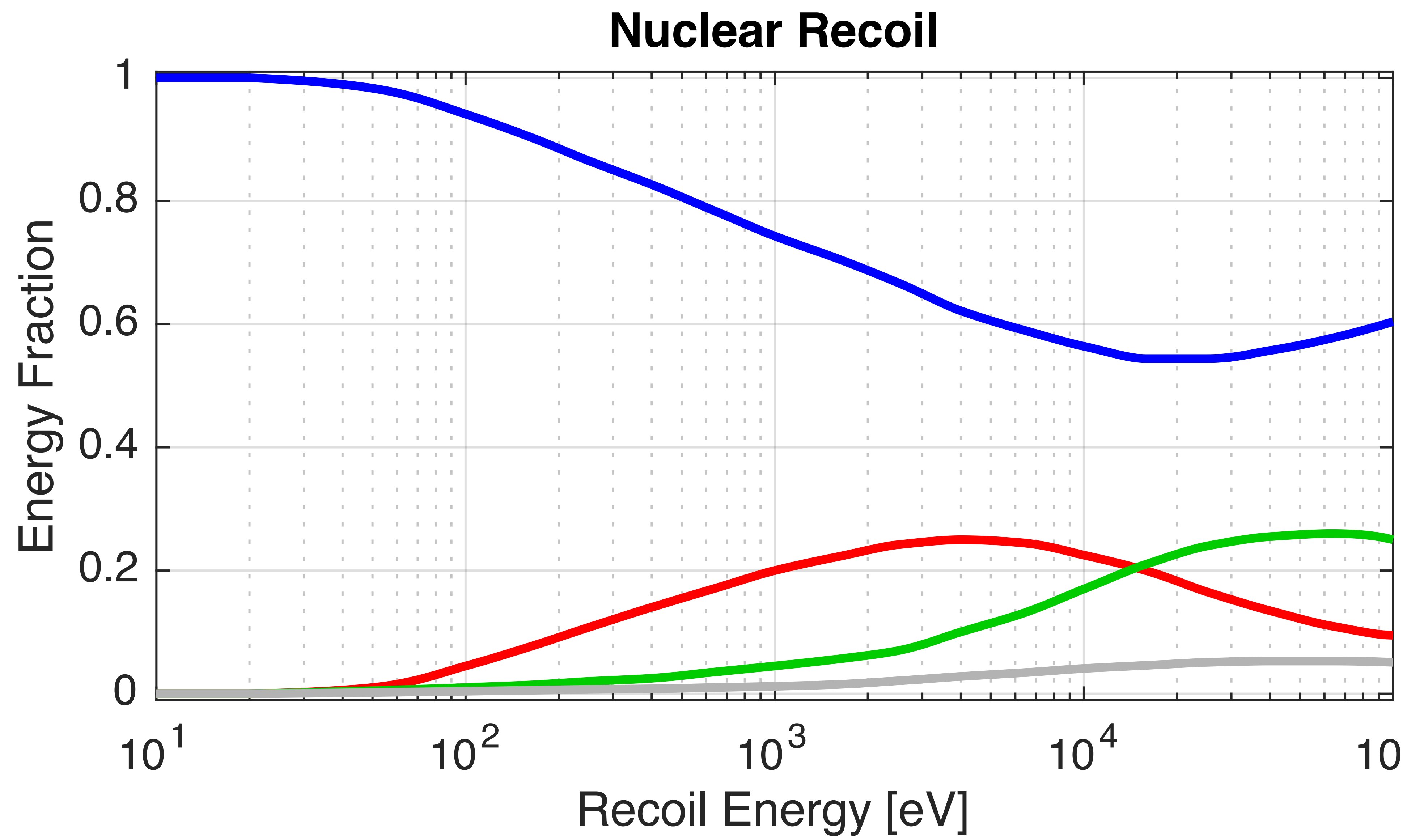
Excitations in superfluid ^{4}He : partitioning

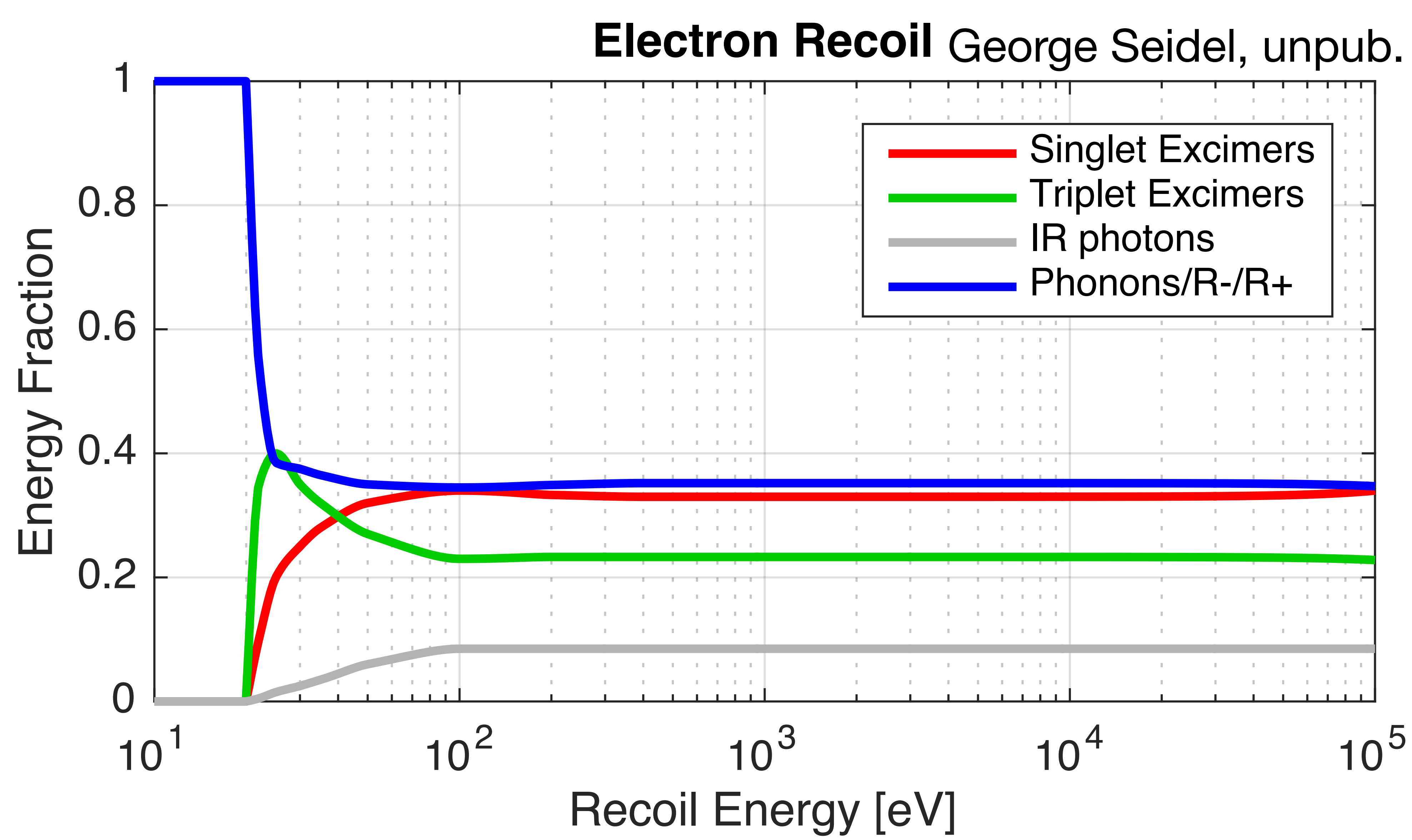
4He: atomic cross sections well measured, well understood.

Recoil energy partitioning can be estimated from the ground up.

NR and ER have quite different partitioning in a three-way partition (kinetic + triplet + singlet).

Beauty of calorimetric sensors:
All recoil energy appears as observable excitations.





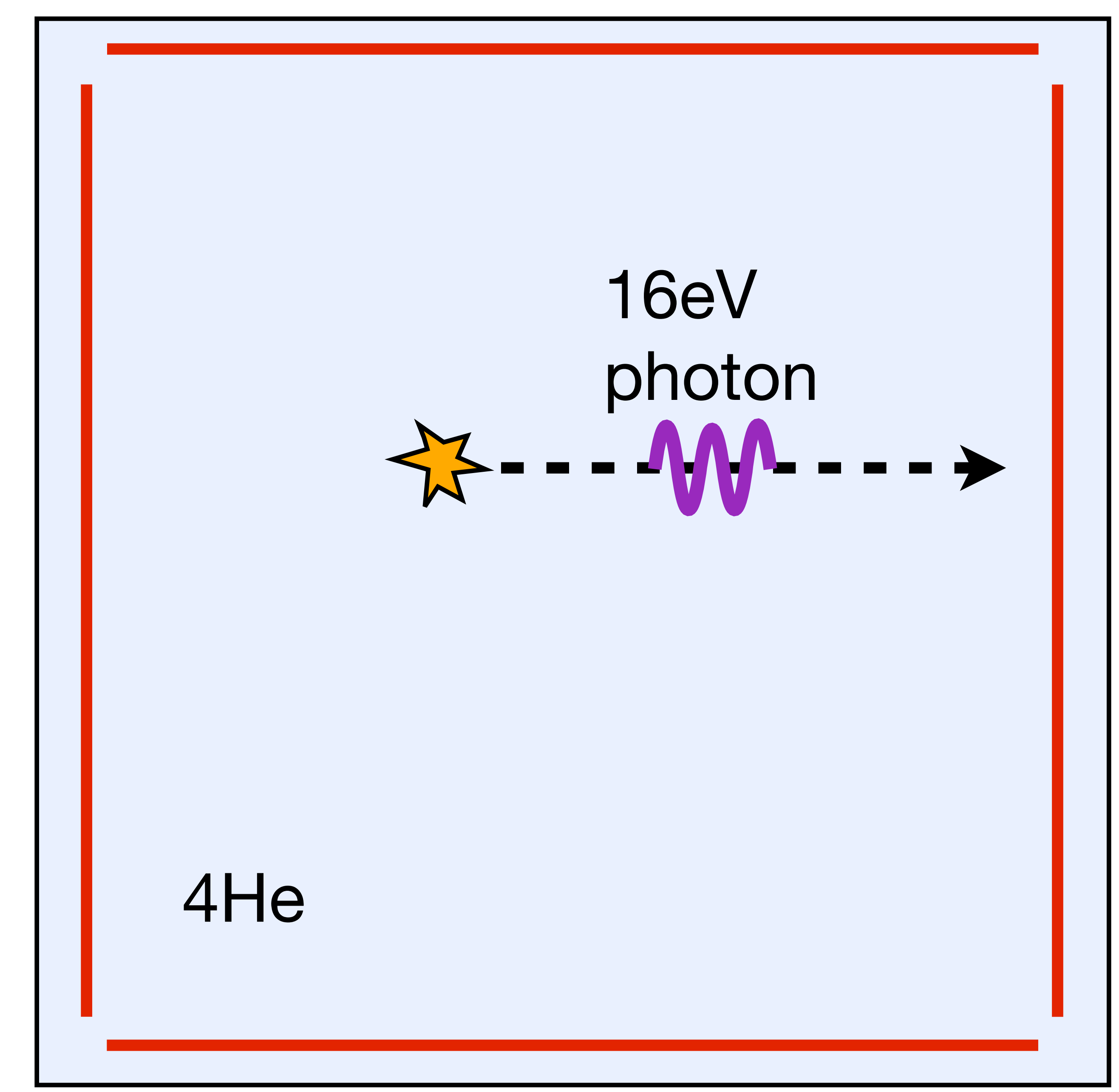
Reading out Singlet Excitations (16eV photons)

Detecting photons is a standard calorimetry application.

Operating calorimetry in LHe: less standard.
Possible, thanks to

1) huge LHe-solid Kapitza resistance
2) fast conversion of photon energy in calorimeter to trapped excitations (eg, Al quasiparticles)

simple detector: box with calorimetry inside



Reading Out Triplet Excitations (ballistic molecules)

Superfluid ➔ friction-free ballistic propagation

Touching a solid supplies mechanism for decay

Some fraction of energy appears in surface
- -energy transferred through electron exchange (not phonons)
- -fraction dependent on material's electron density of states

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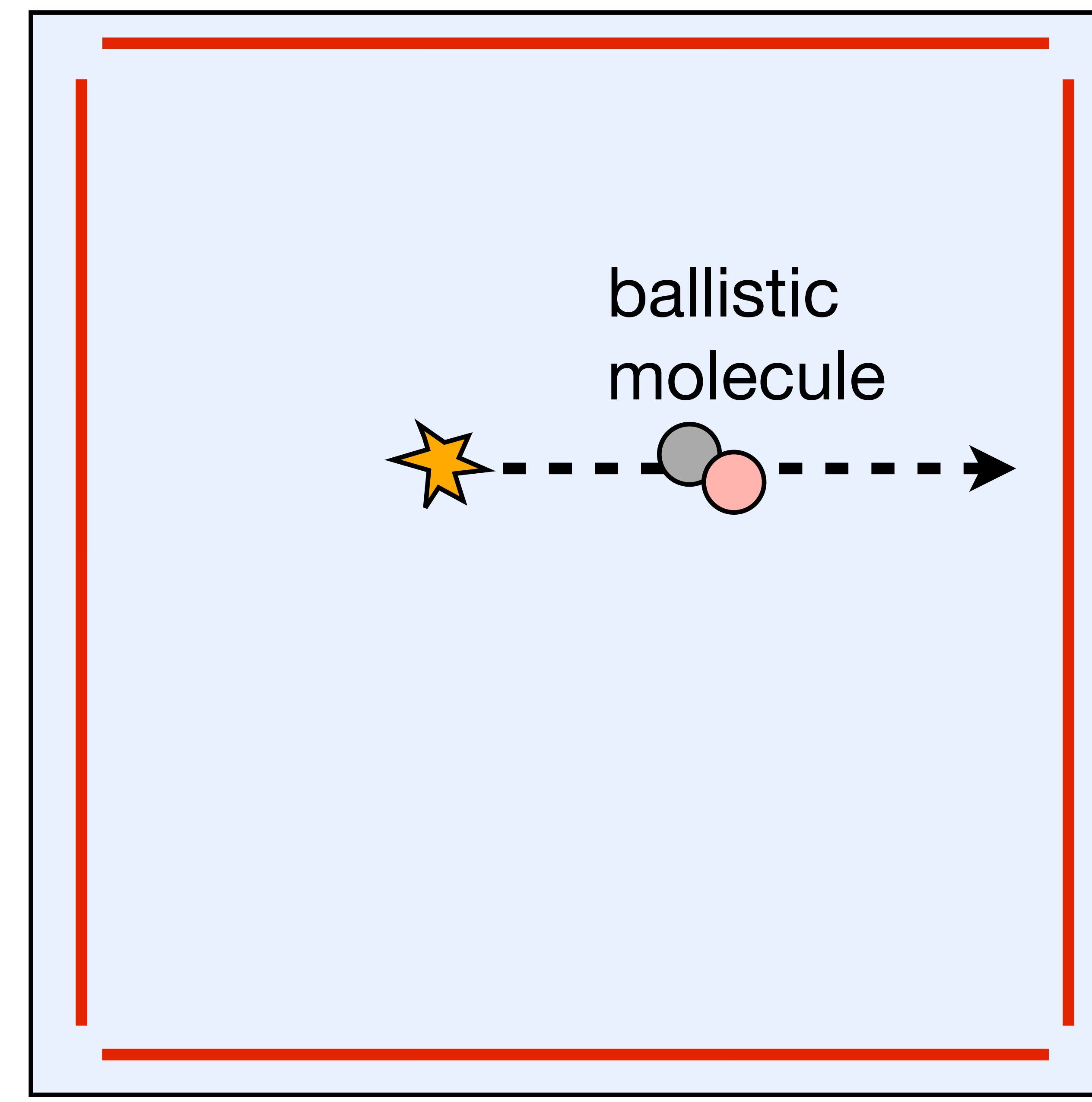

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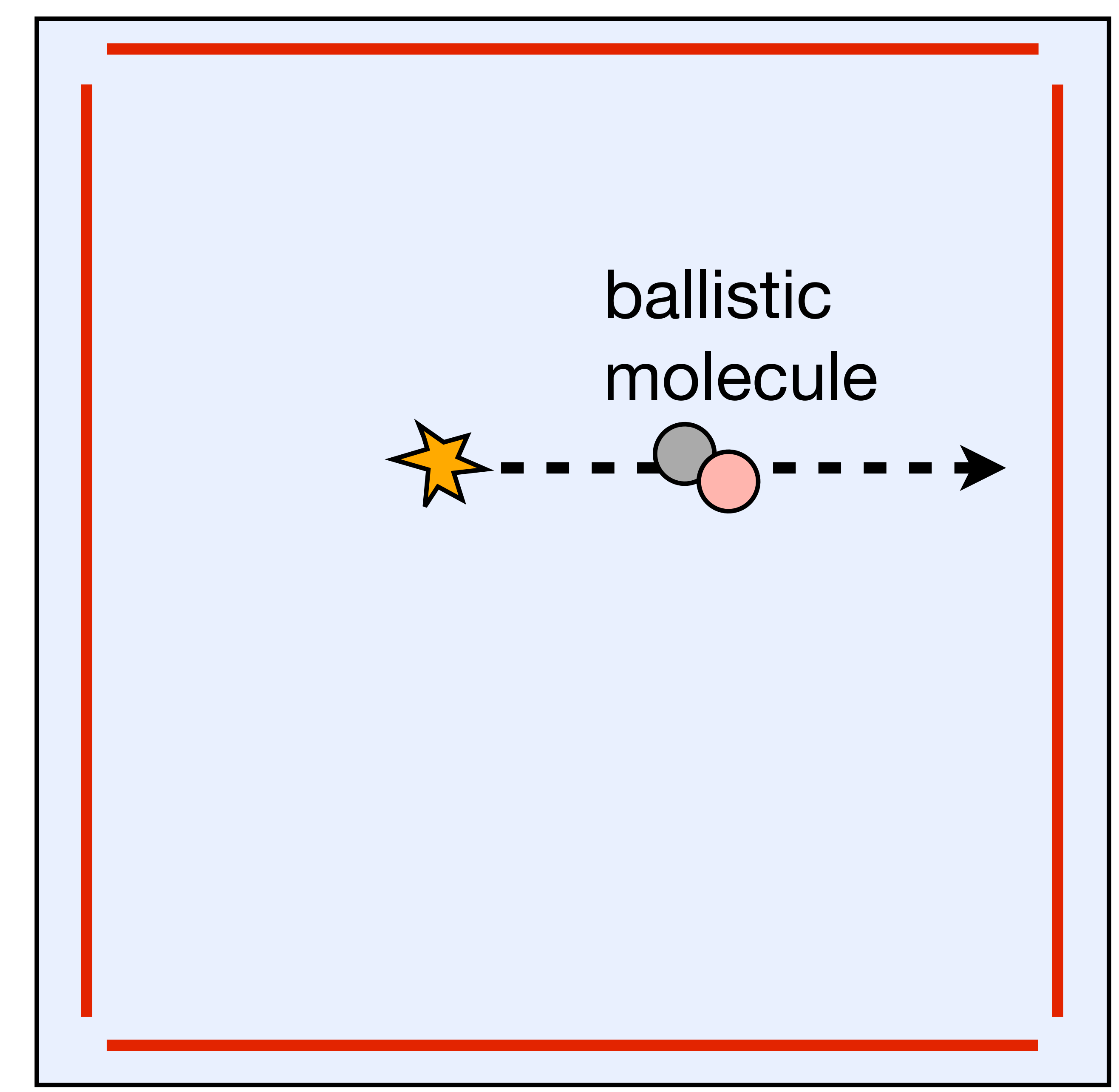
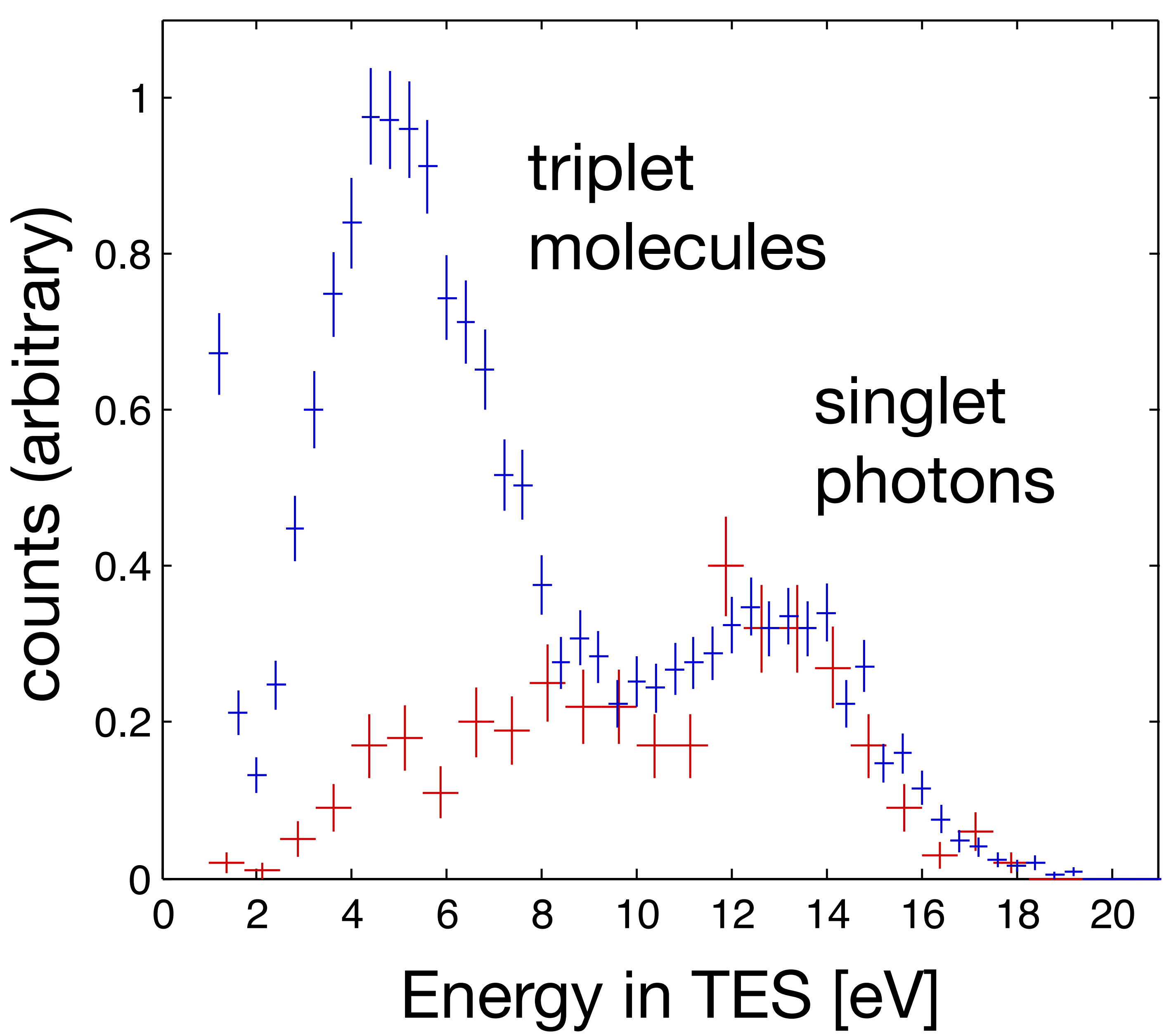




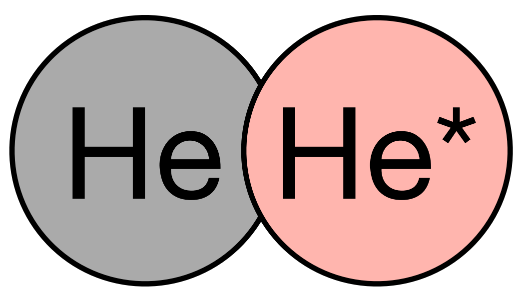
Journal of Low Temperature Physics

February 2017, Volume 186, Issue 3, pp 183–196

https://arxiv.org/abs/1605.00694

Excitations in superfluid ^4He

eV-scale excitations:



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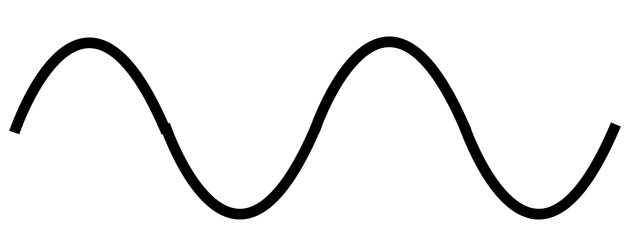


phonons, R- rotons, R+ rotons

(observable as athermal evaporation)

^{4}He Quasiparticles

Things to know:

meV-scale (hear 'MeV-scale DM'...)

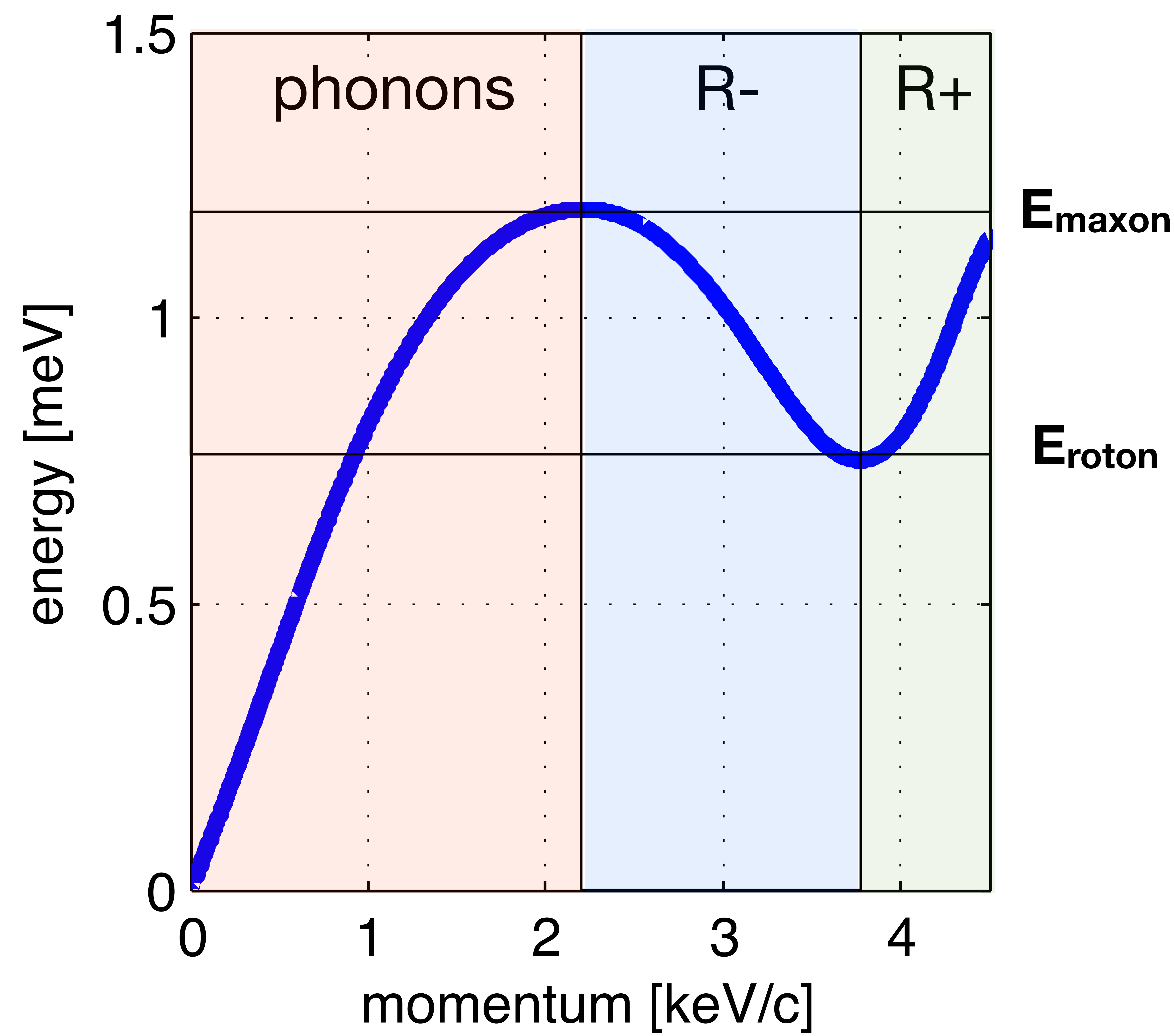
Not on a crystal lattice (isotropic dispersion)

Ballistic propagation

Most downconversions forbidden

Multiple 'flavors' with distinguishing characteristics:
- slope is velocity
- R- propagation opposite to momentum

Below atomic excitation energy, *all* recoil energy appears in these kinetic modes

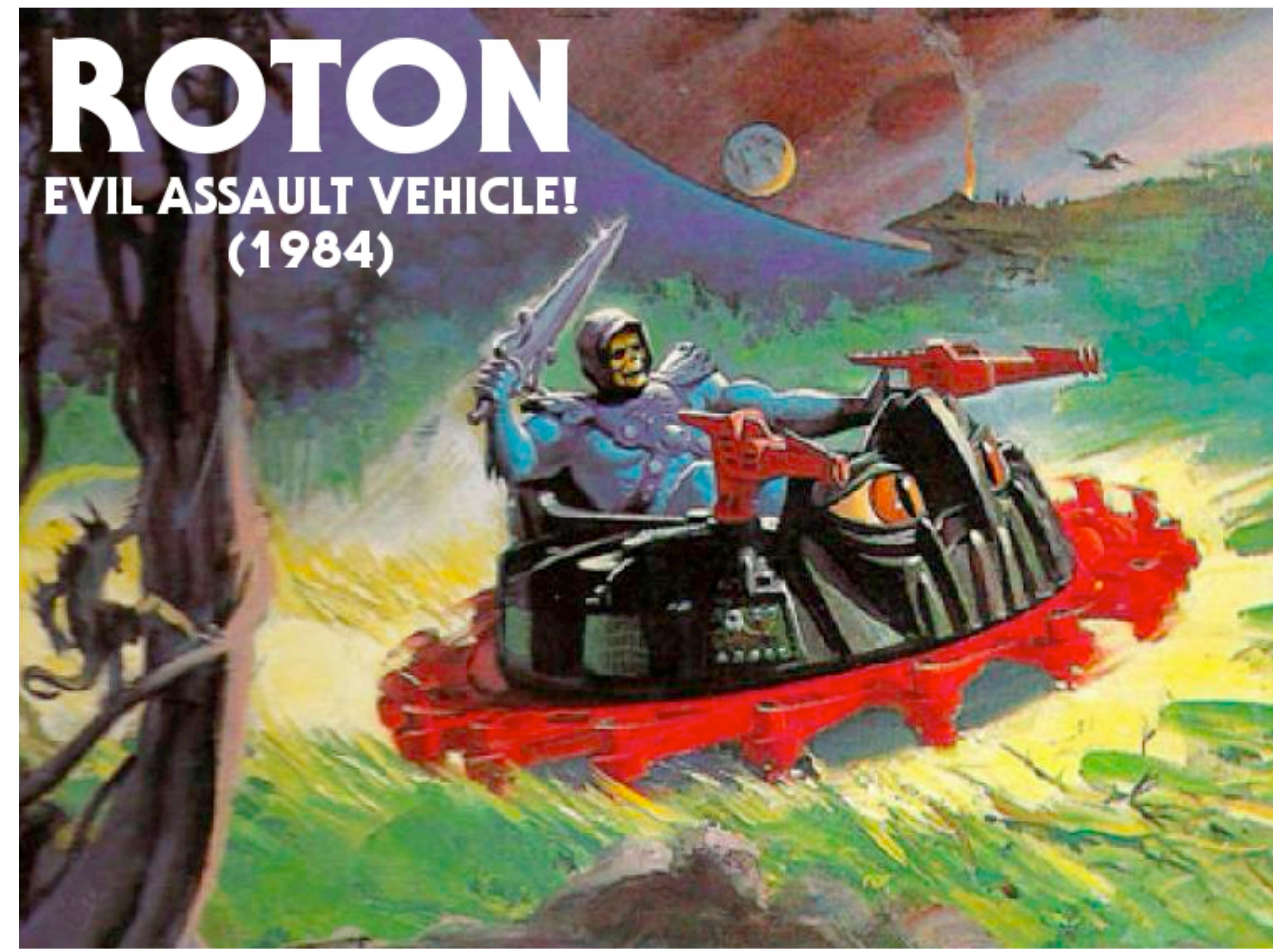


^{4}He Quasiparticles

Don't let the word 'roton' distract you.

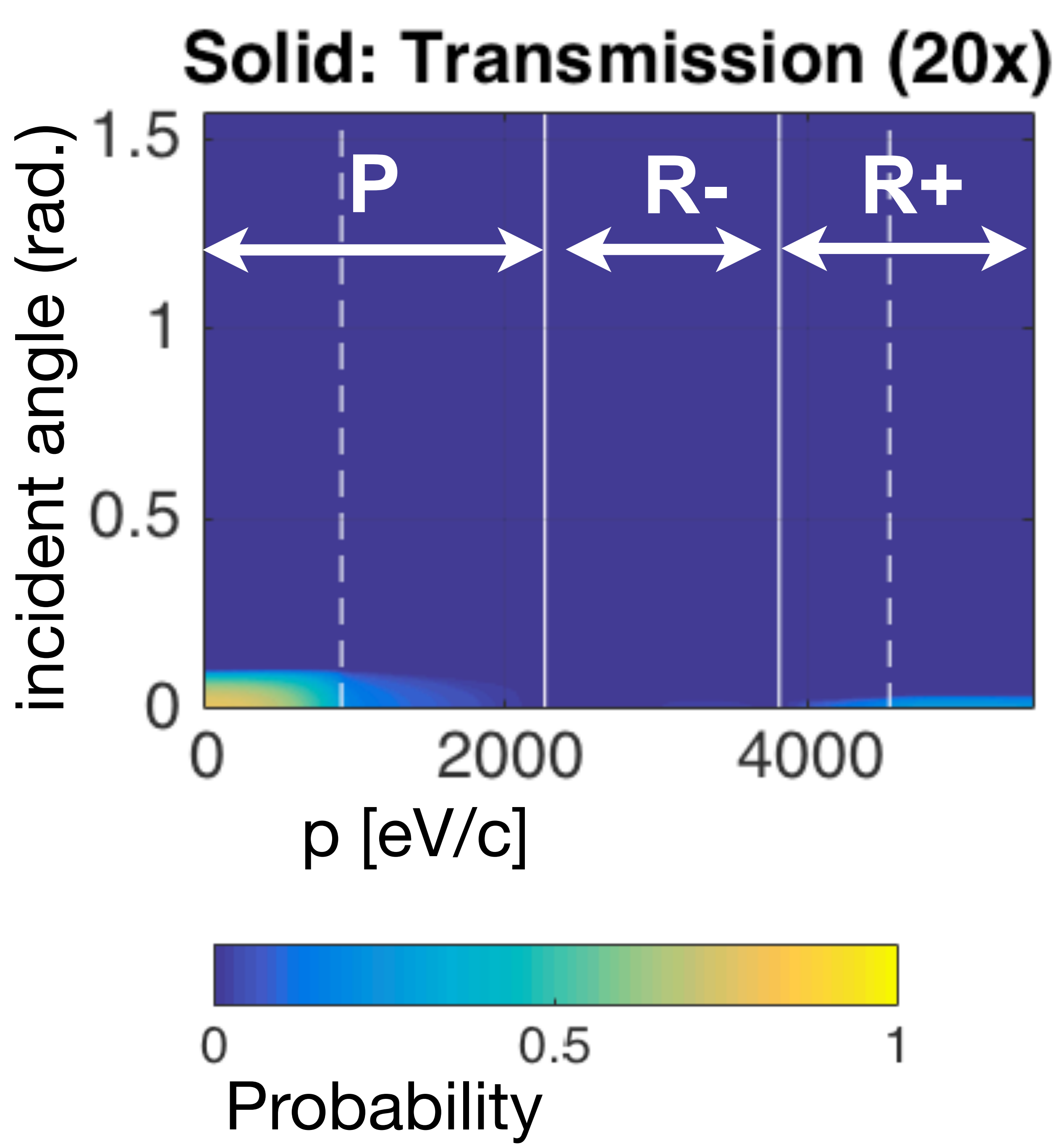
Illustration is incorrect in two ways:
- -rotons are few-atom-scale kinetic excitations
- -rotons do not carry angular momentum.

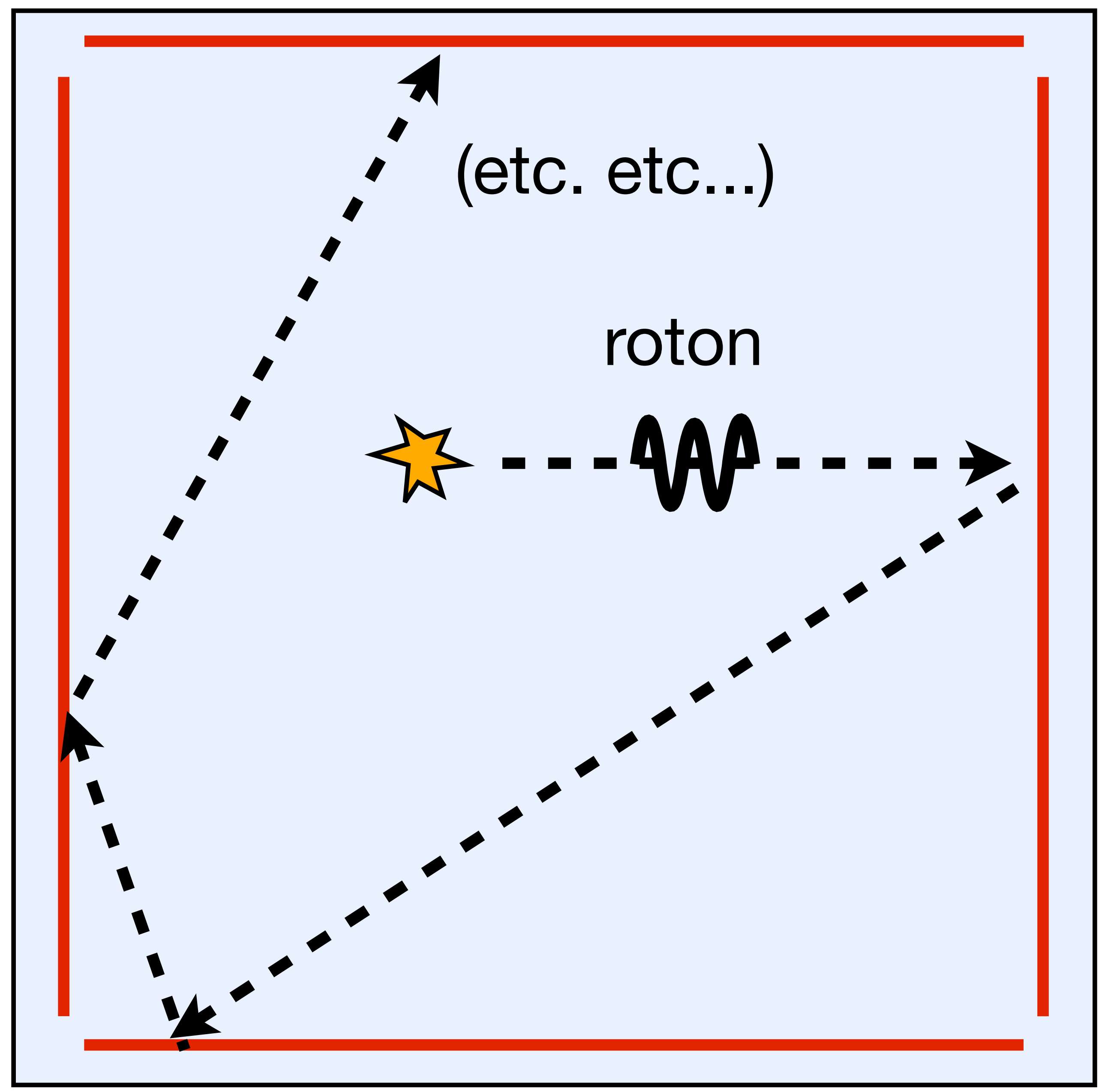
sufficient shorthand:
rotons are "high-momentum phonons"



Reading Out ^{4}He Quasiparticles

crossing into solid extremely suppressed
(Kapitza resistance)





Reading Out ^{4}He Quasiparticles (quantum evaporation)

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...saved by significant probability
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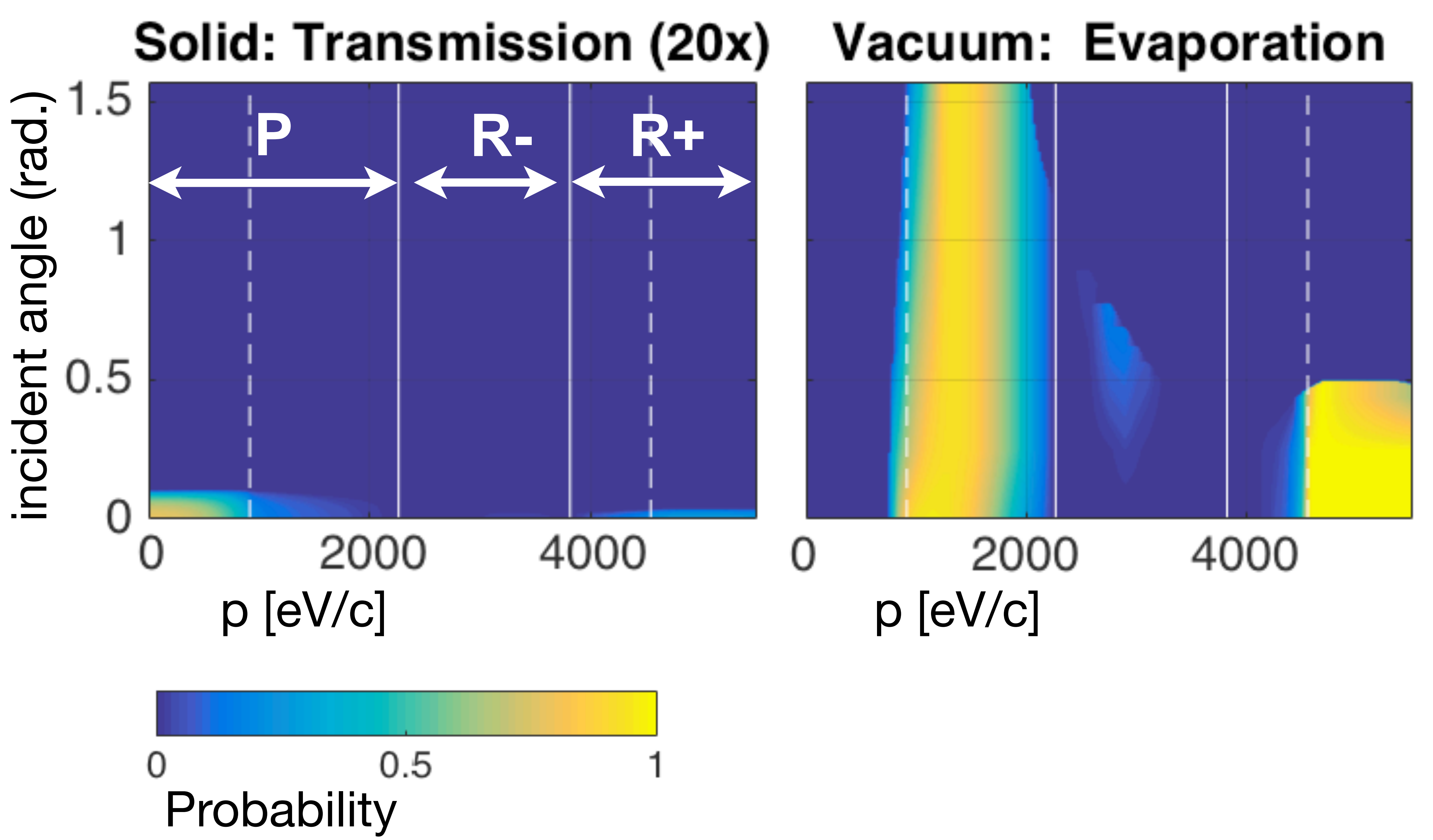

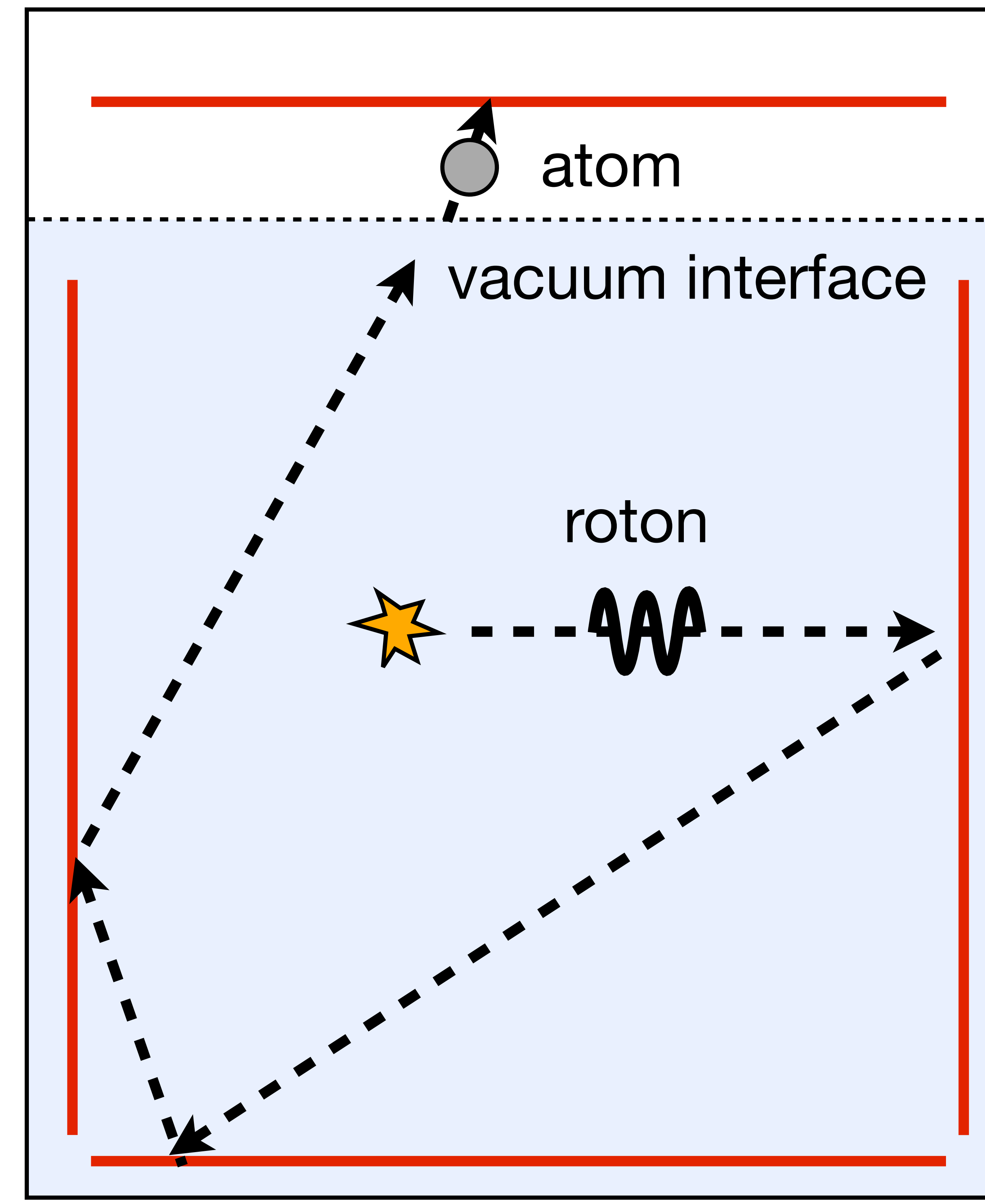

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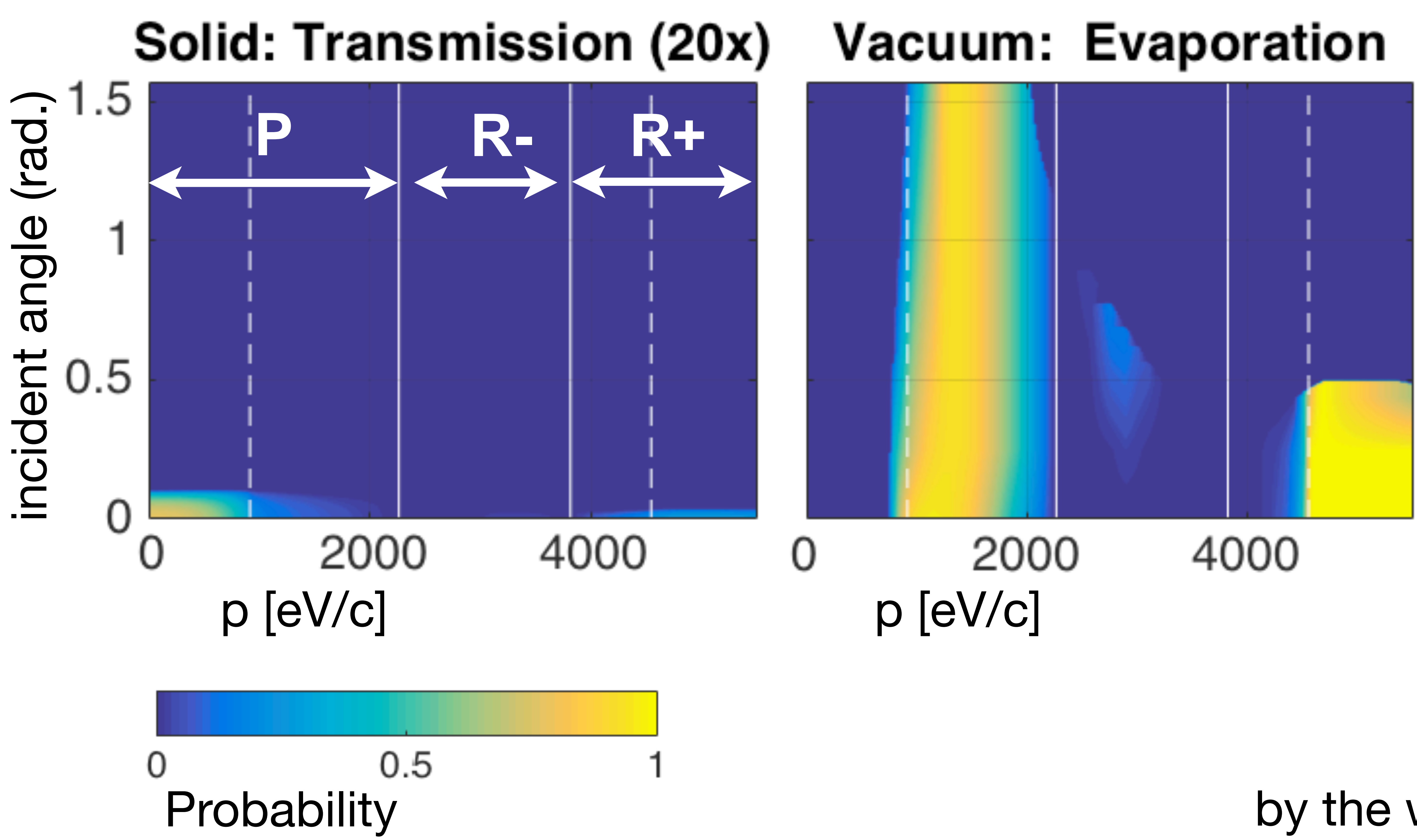
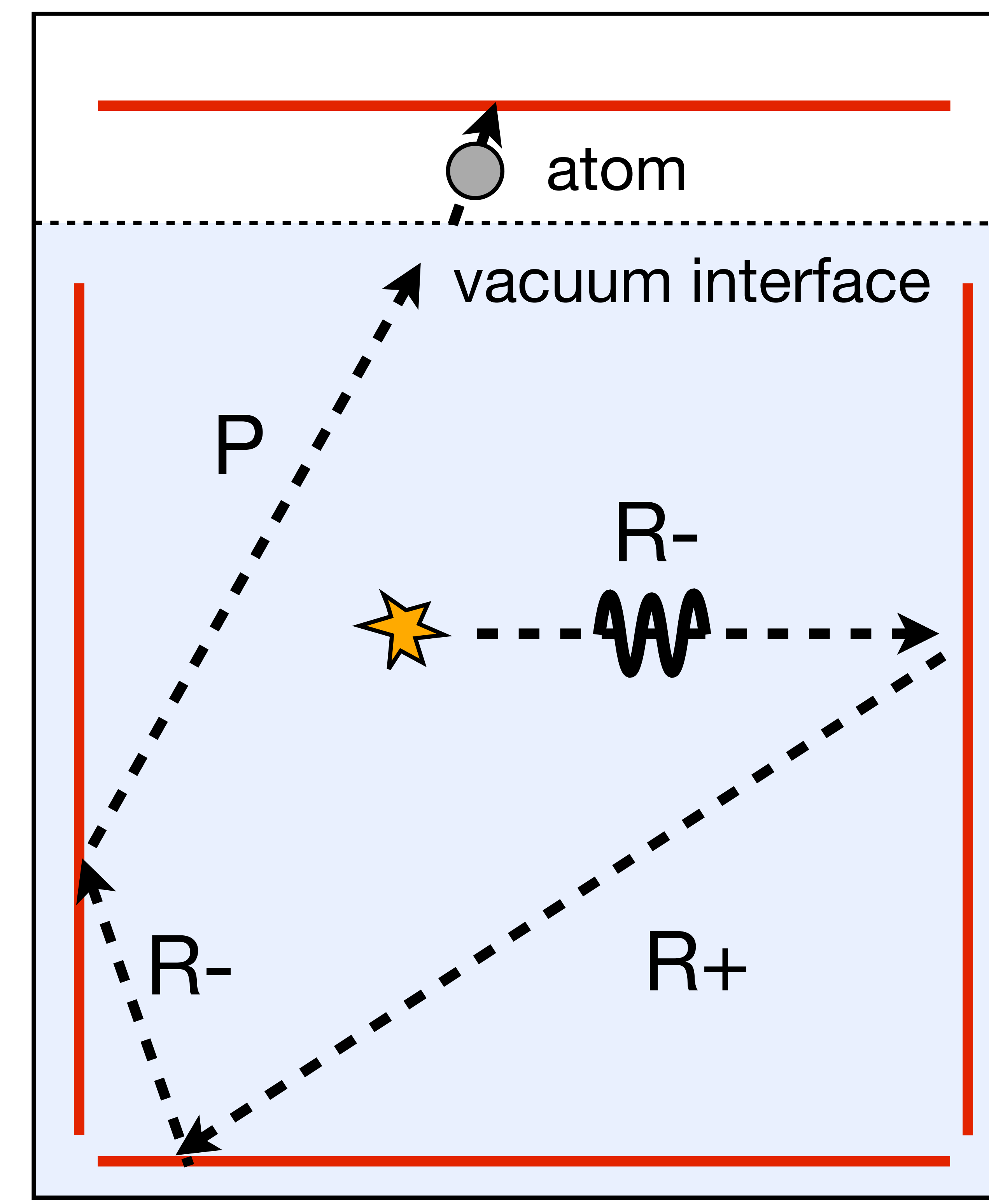
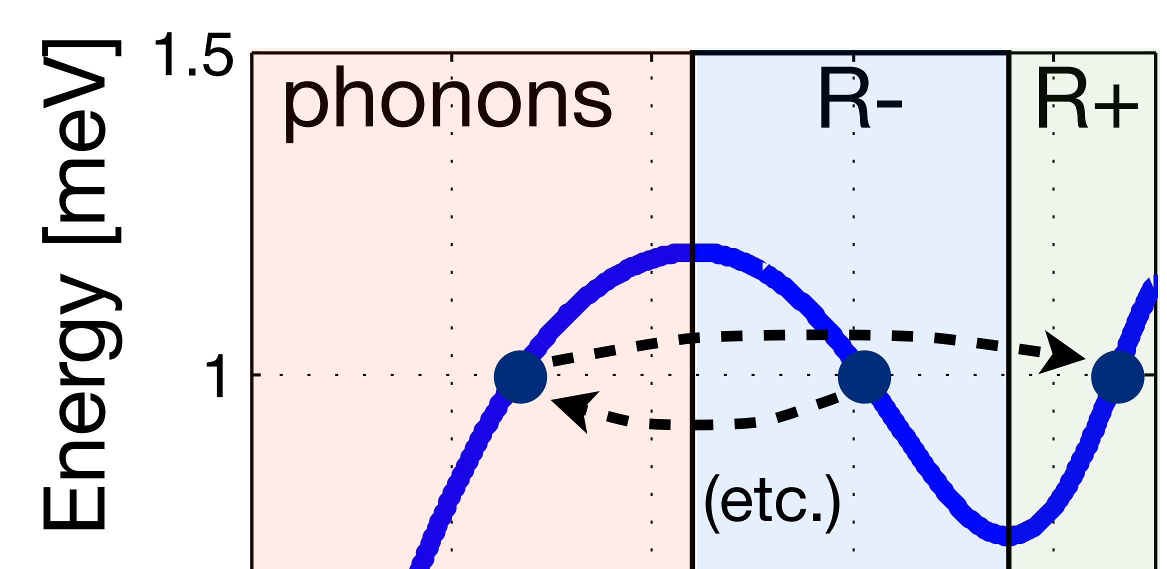


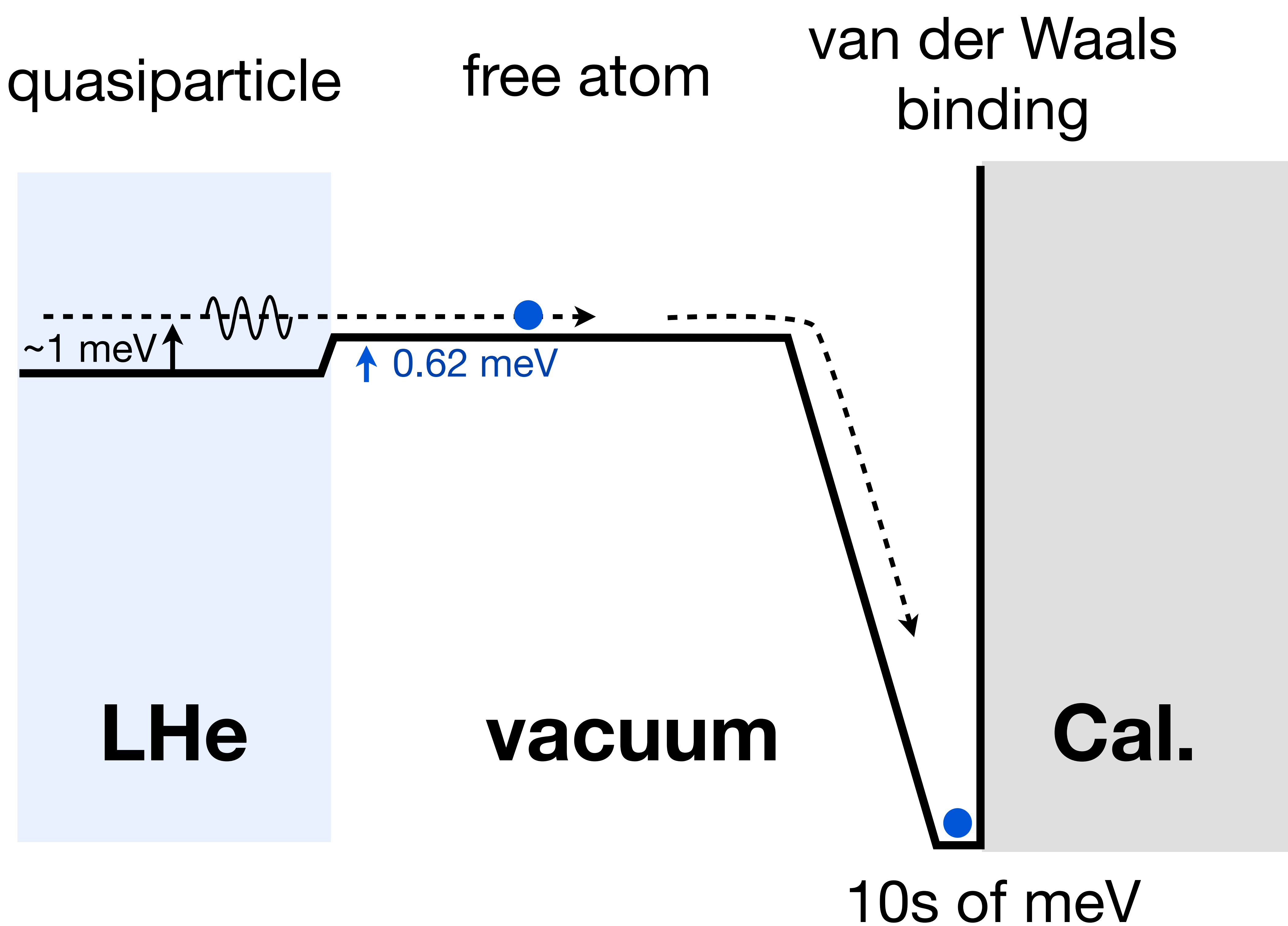


by the way:



Reading Out ^{4}He Quasiparticles (quantum evaporation)

→ van der Waals gain



Typical helium-solid binding energy: ~10meV

Higher binding energies exist (graphene-fluorine: 42.9meV)

most recoil energy is in roton modes (DOS ~ p^2)

each 1 meV roton energy becomes ~40 meV observation

→ x40 gain

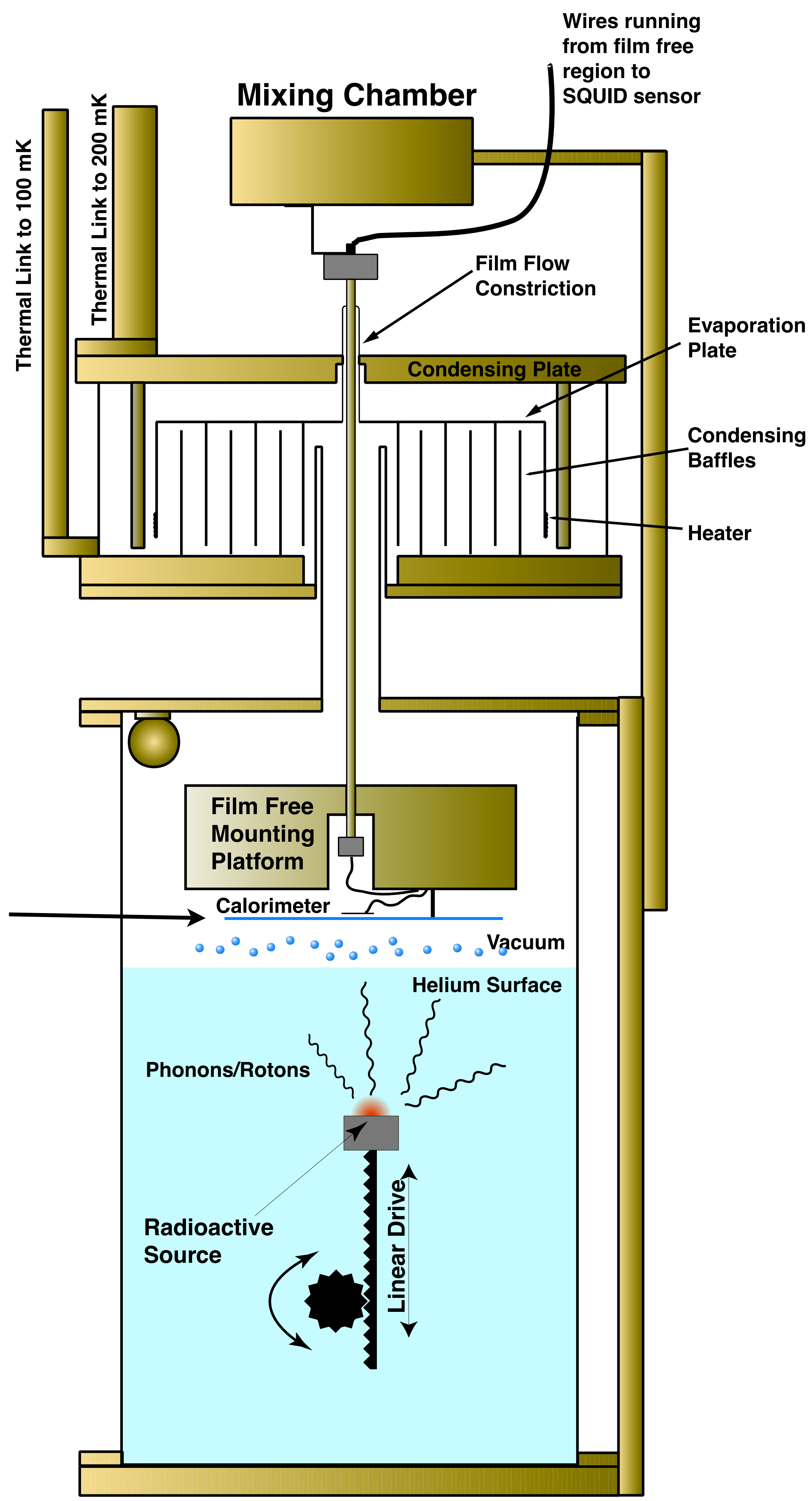
‘Shovel Ready’ Technology Years Ago

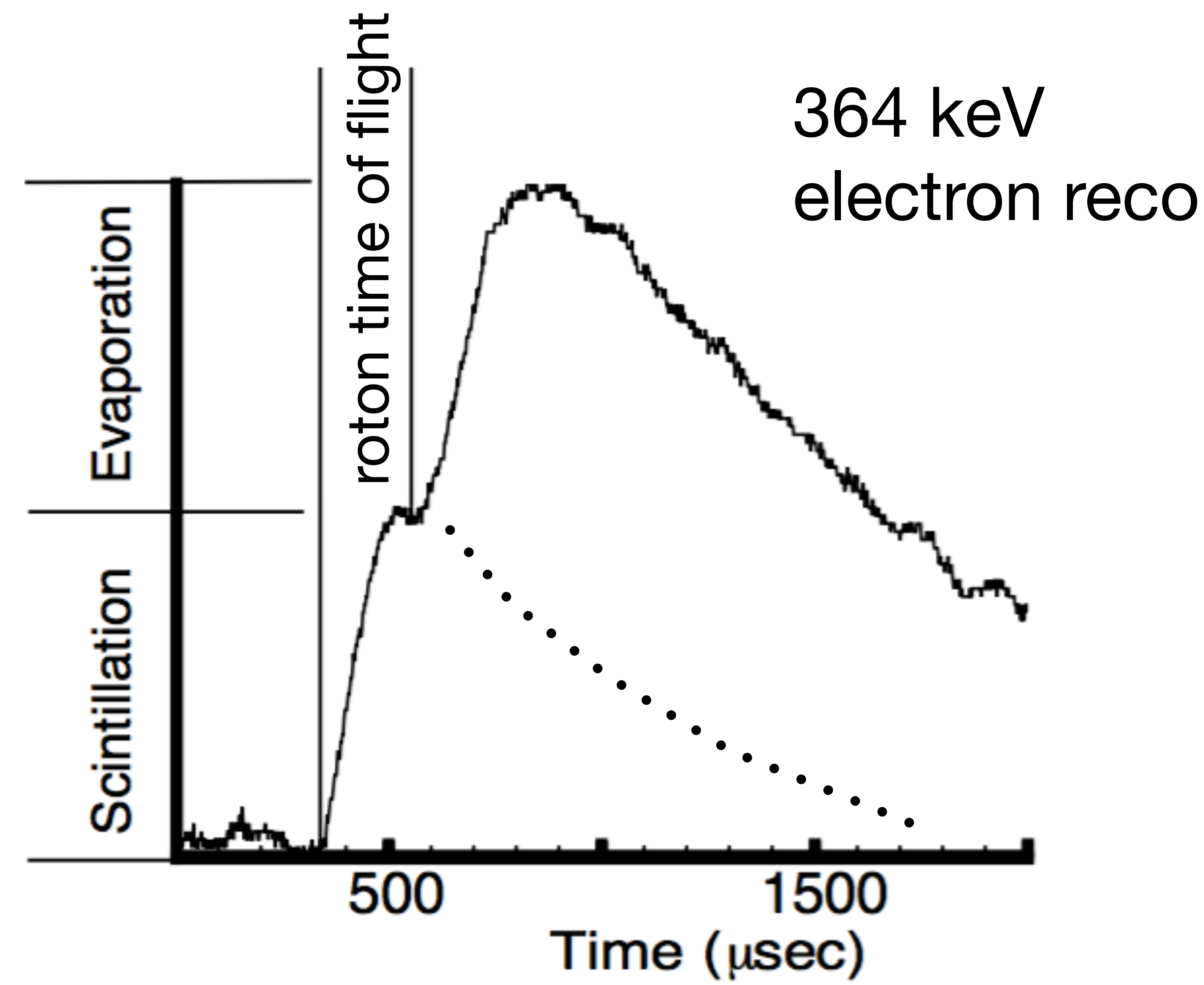
R&D for the proposed HERON pp neutrino observatory

He film burner

wafer calorimeter
single TES channel

kg-scale
LHe mass





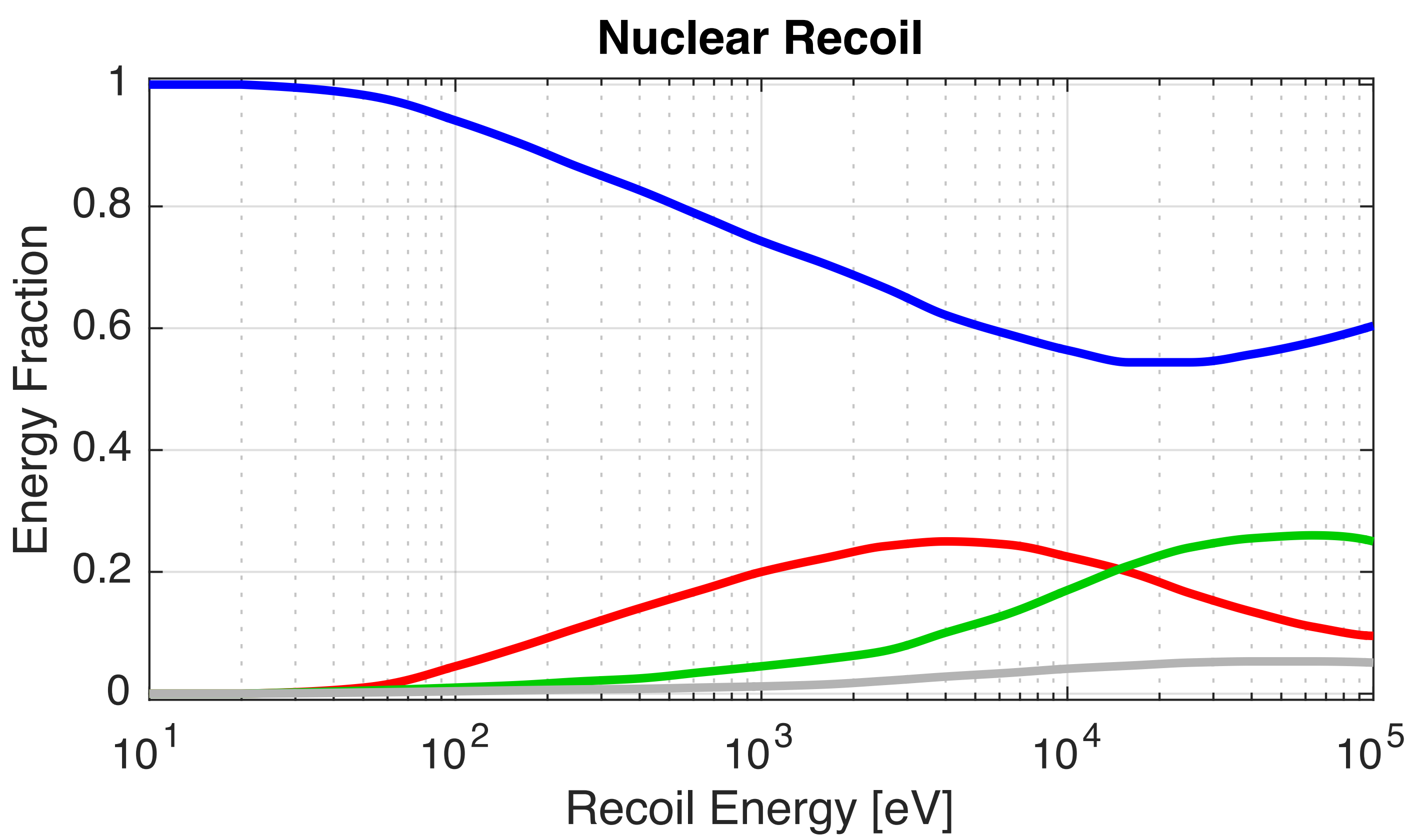
now: technology newly motivated by light dark matter
+ improved calorimetry steadily improving

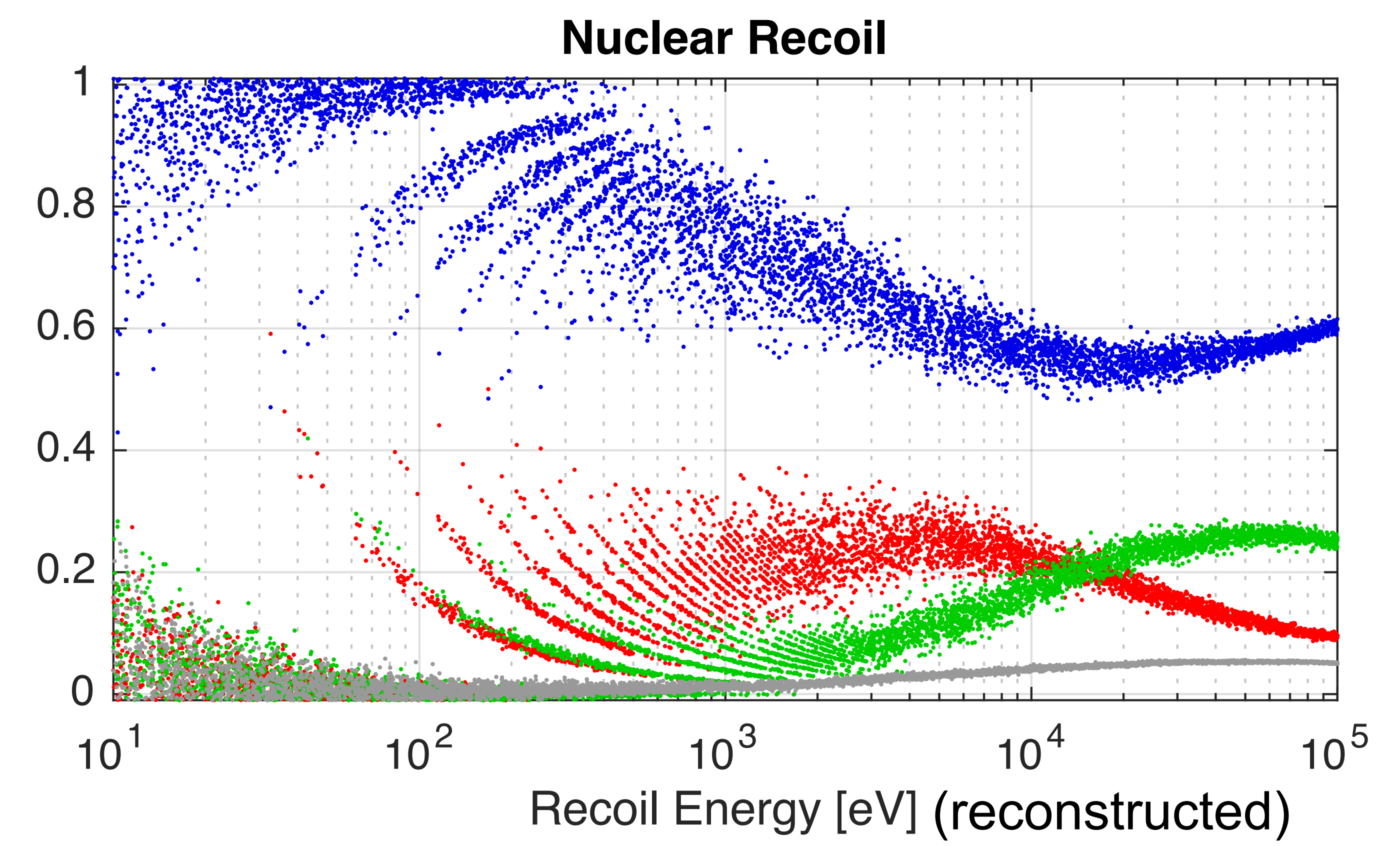
ER/NR discrimination using excimer production

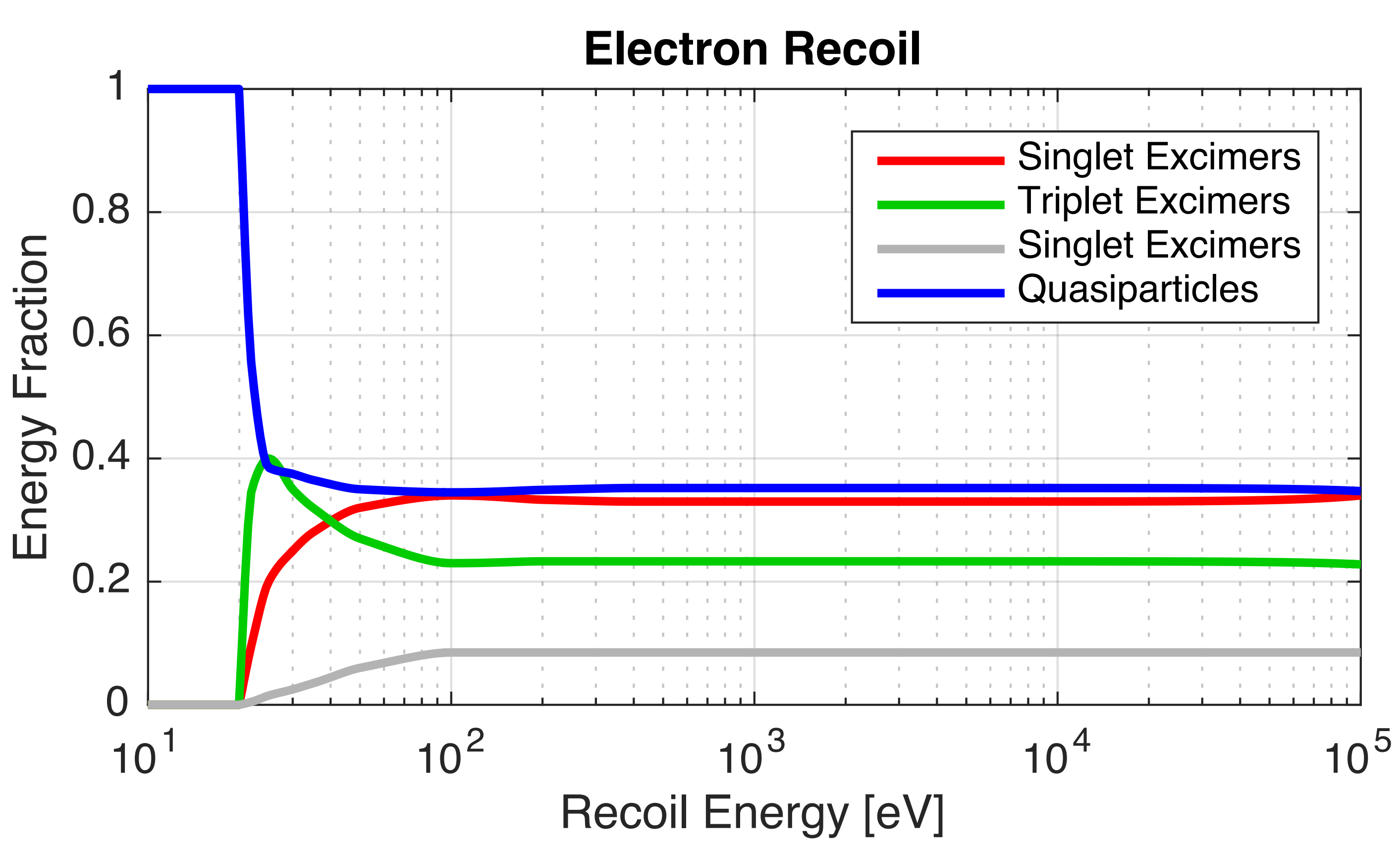
Toy MC

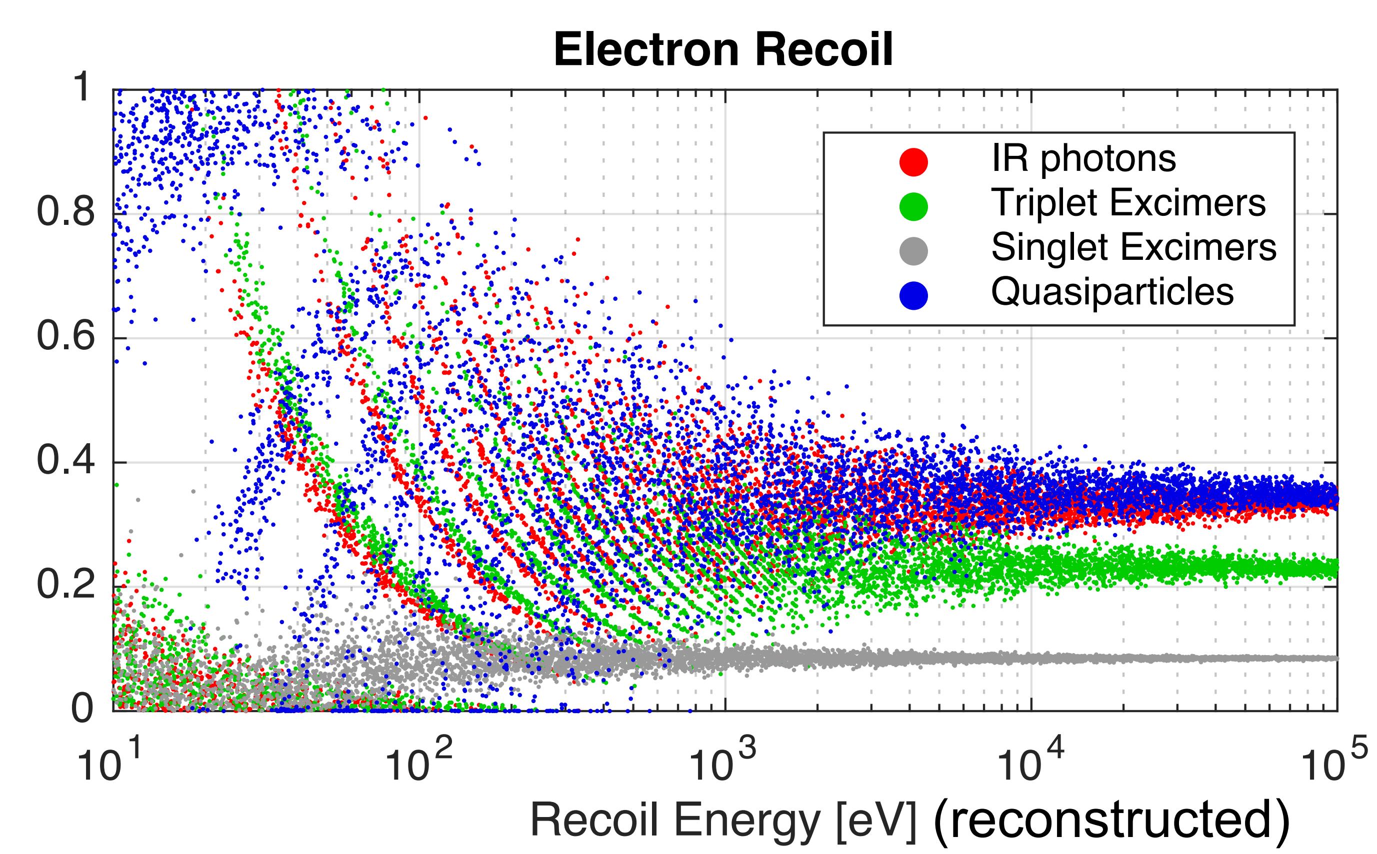
Production Statistics
Assumed Poissonian
(biggest first, remaineder in QP)

Detection Efficiencies
singlet UV photons : 0.95 (4pi coverage by calorimetry)
triplet excimers : 5/6 (only solid interfaces)
IR photons : 0.95 (similar to UV photons)



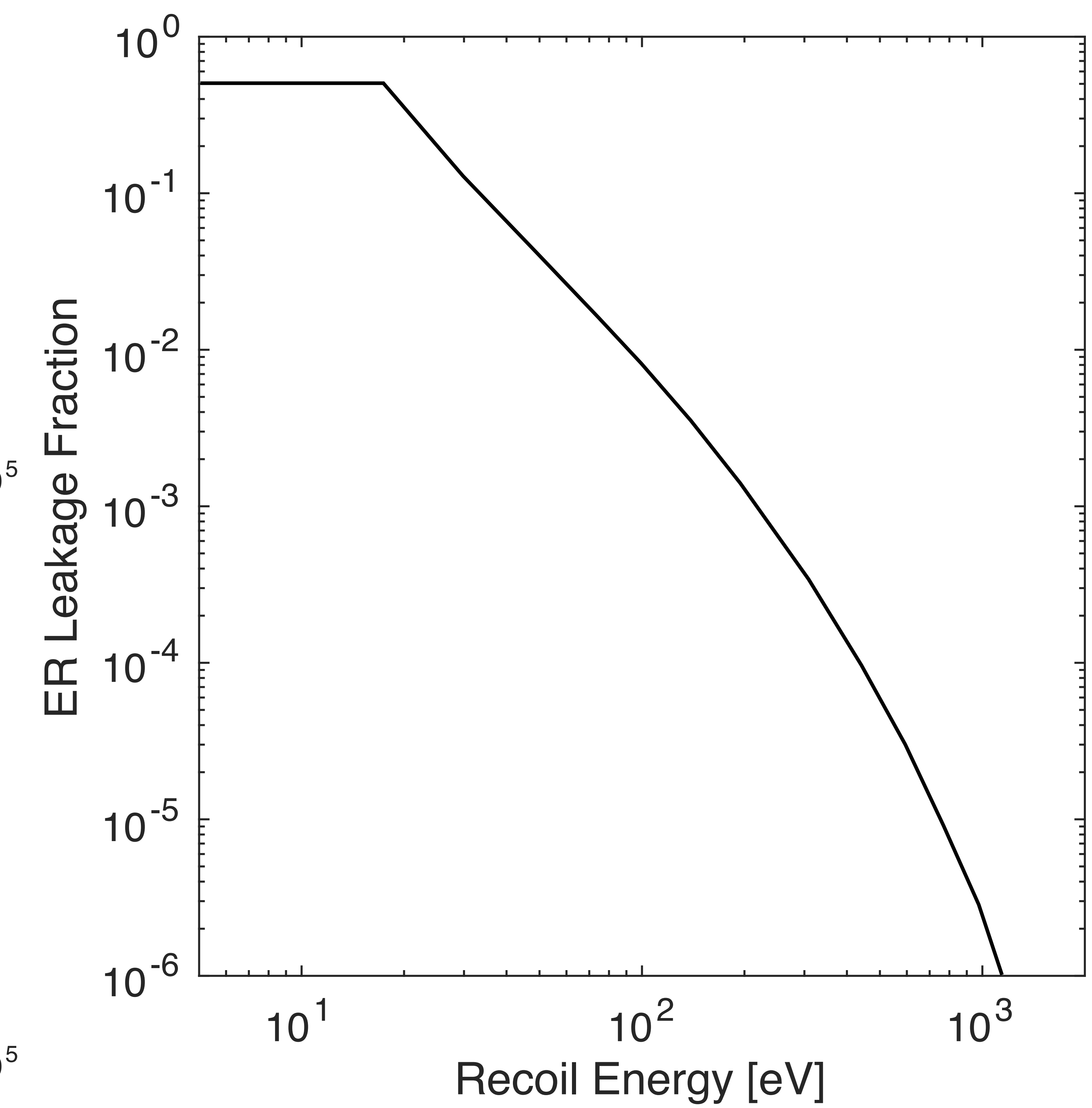






Result:

extreme discrimination
(in `high energy' >100eV range)



Simulated Backgrounds

backgrounds included:

-neutrino nuclear coherent scattering
-gamma backgrounds copy
 SuperCDMS & DAMIC projections

https://arxiv.org/abs/1610.00006

-note: LHe is naturally itself radiopure

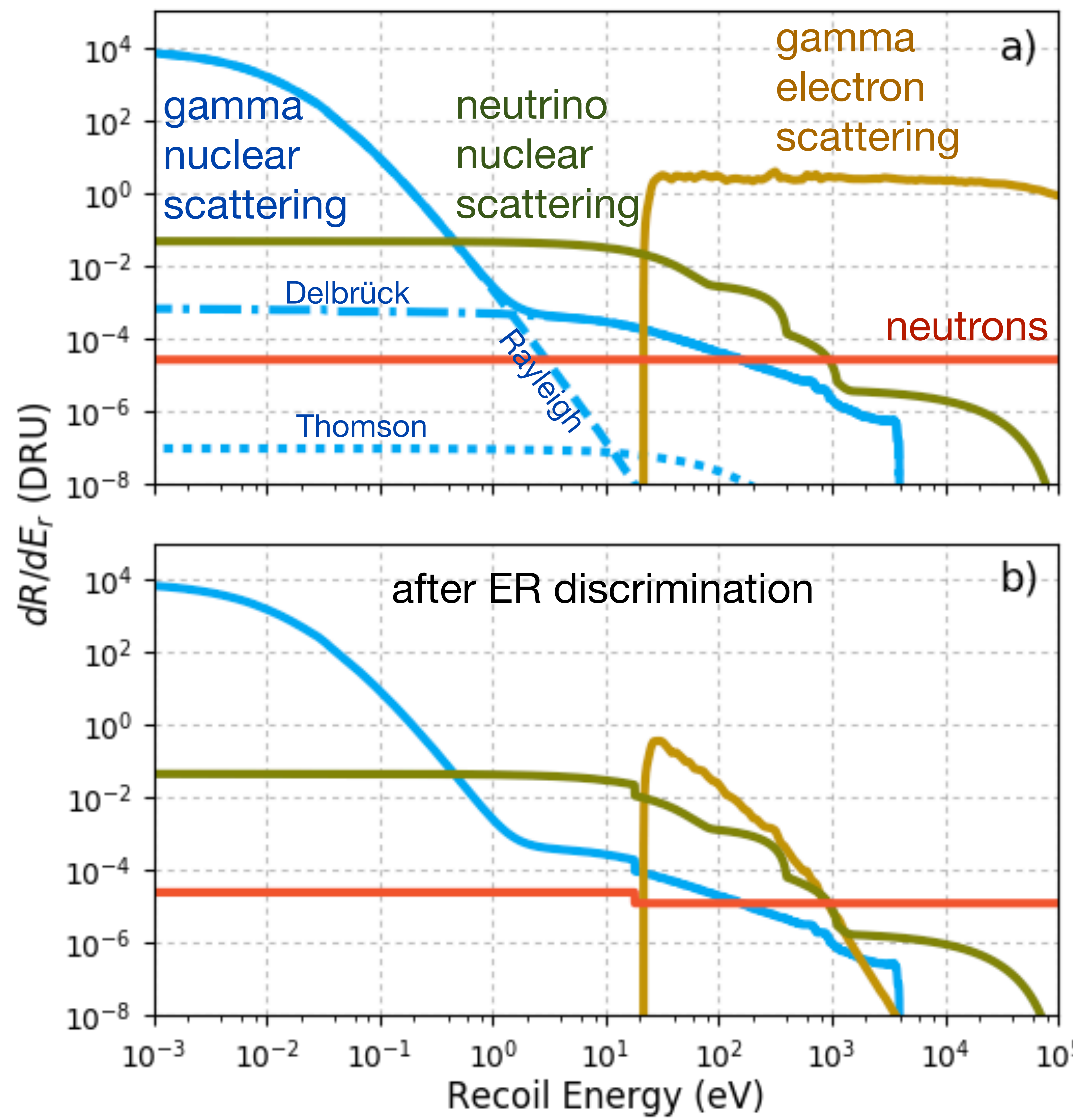
two details:

-excimers allow ER discrimination (>20eV)
-newly-discussed gamma-NR background

Robinson Phys. Rev. D 95, 021301 (2017)

arguments for low dark count rate:

-calorimetry, no applied potential energies
-low-mass calorimeter: low-energy clamps
-superfluid target: highly isolated from environment

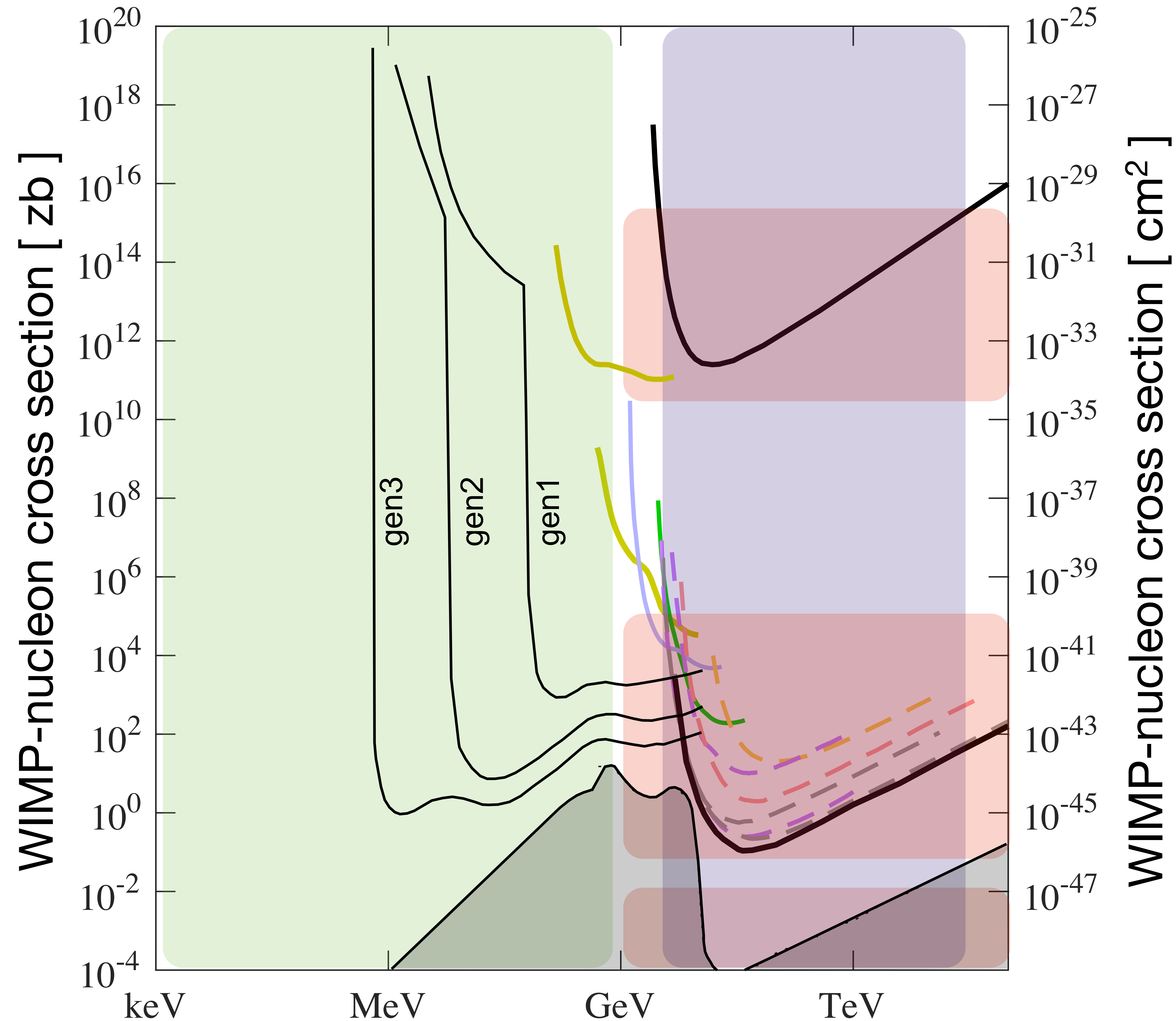


Nuclear Recoil Sensitivity

gen1: “shovel ready”
10 eVr threshold, 1 kg-y
assuming 40meV per evaporated atom (graphene-fluorine)
20 eV calorimeter threshold w/ 5% evap. efficiency

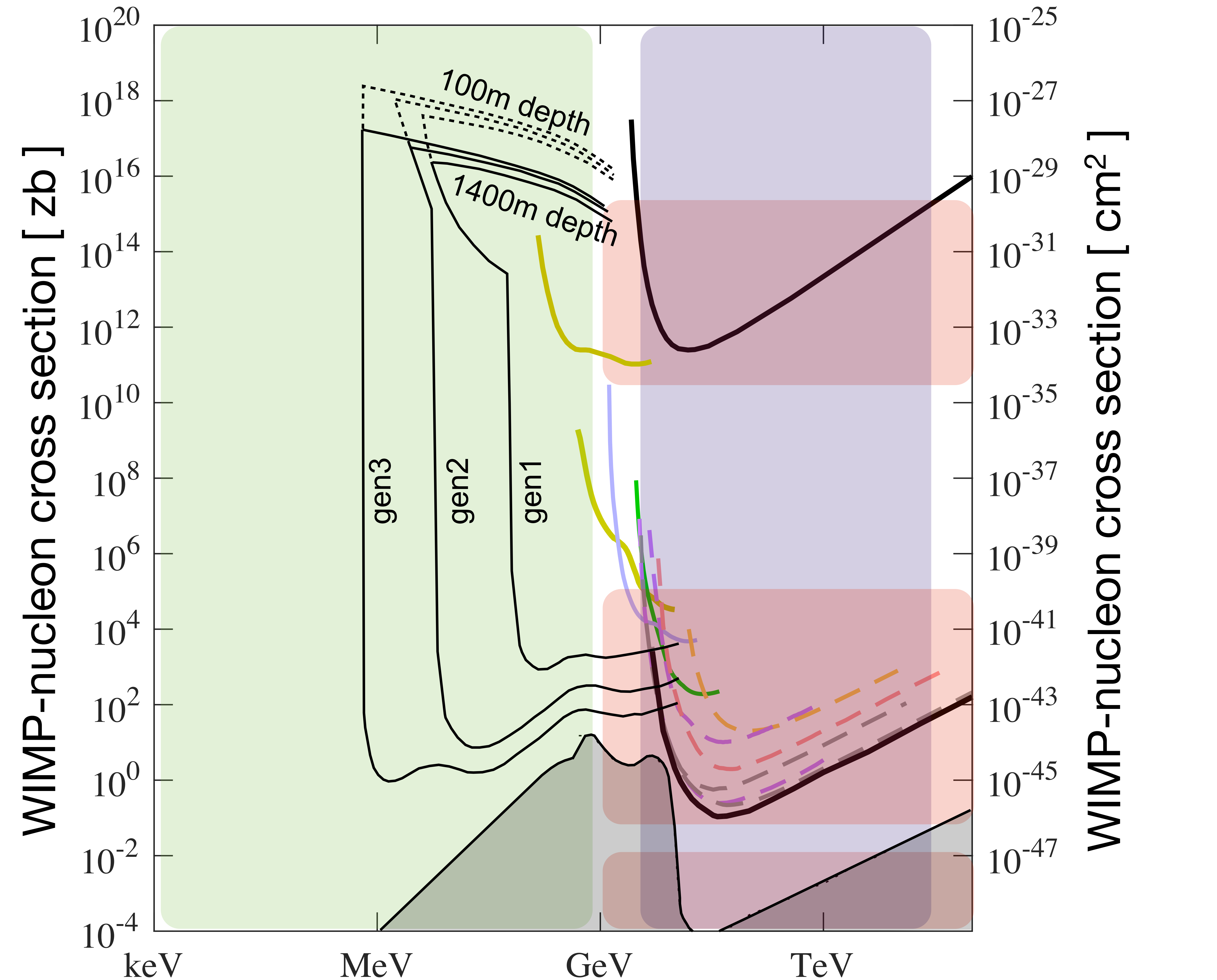
gen2: “feasible after R&D”
100 meVr threshold, 10 kg-y
assuming 40meV per evaporated atom (graphene-fluorine)
1 eV calorimeter threshold w/ 25% evap. efficiency

gen3: “theoretically possible”
1 meVr threshold, 100 kg-y
limit of single-atom counting (~40meV calorimeter threshold)



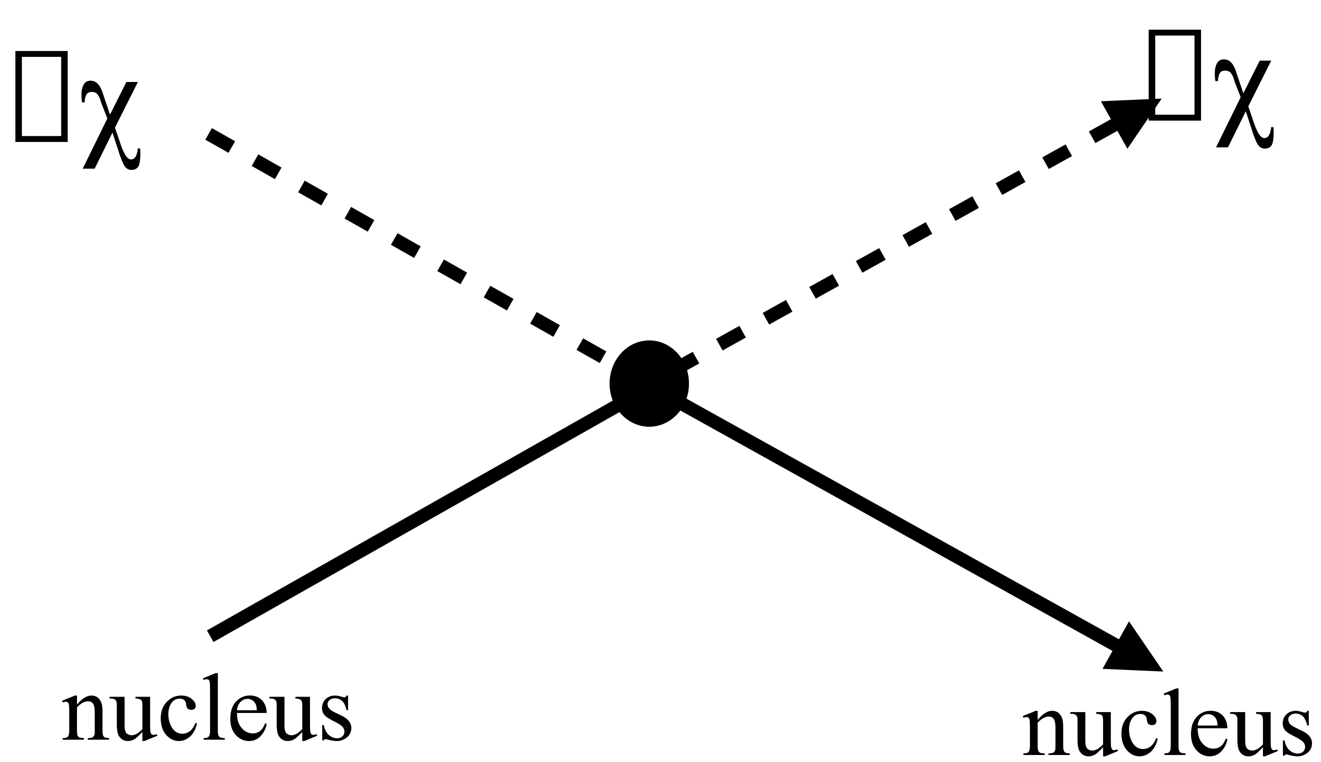
Nuclear Recoil Sensitivity

rarely-considered but newly-relevant:
earth shielding at large cross-sections



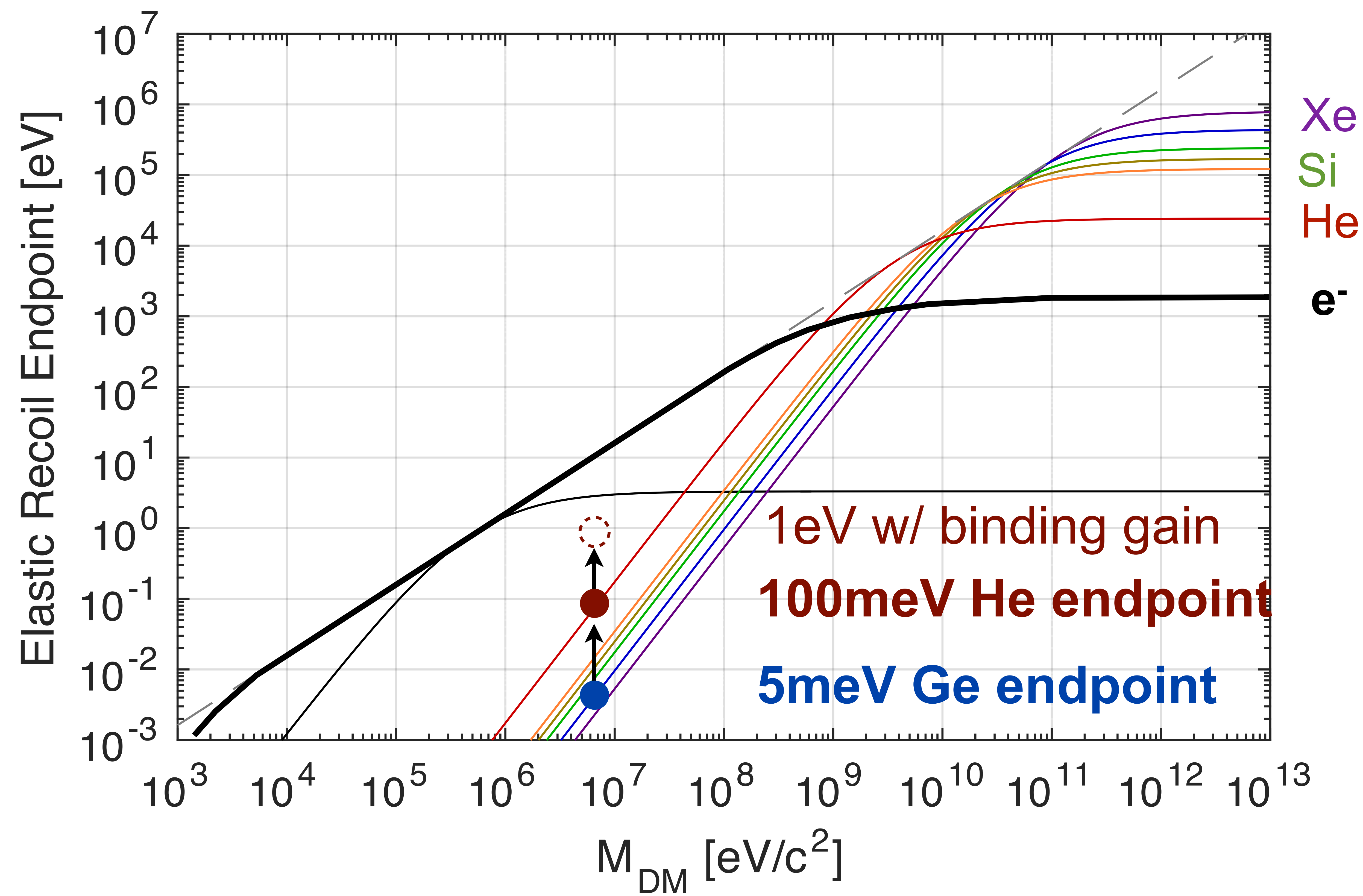
two-body diagram

the nuclear mass (dispersion relation)
is very different from
the DM mass (dispersion relation)

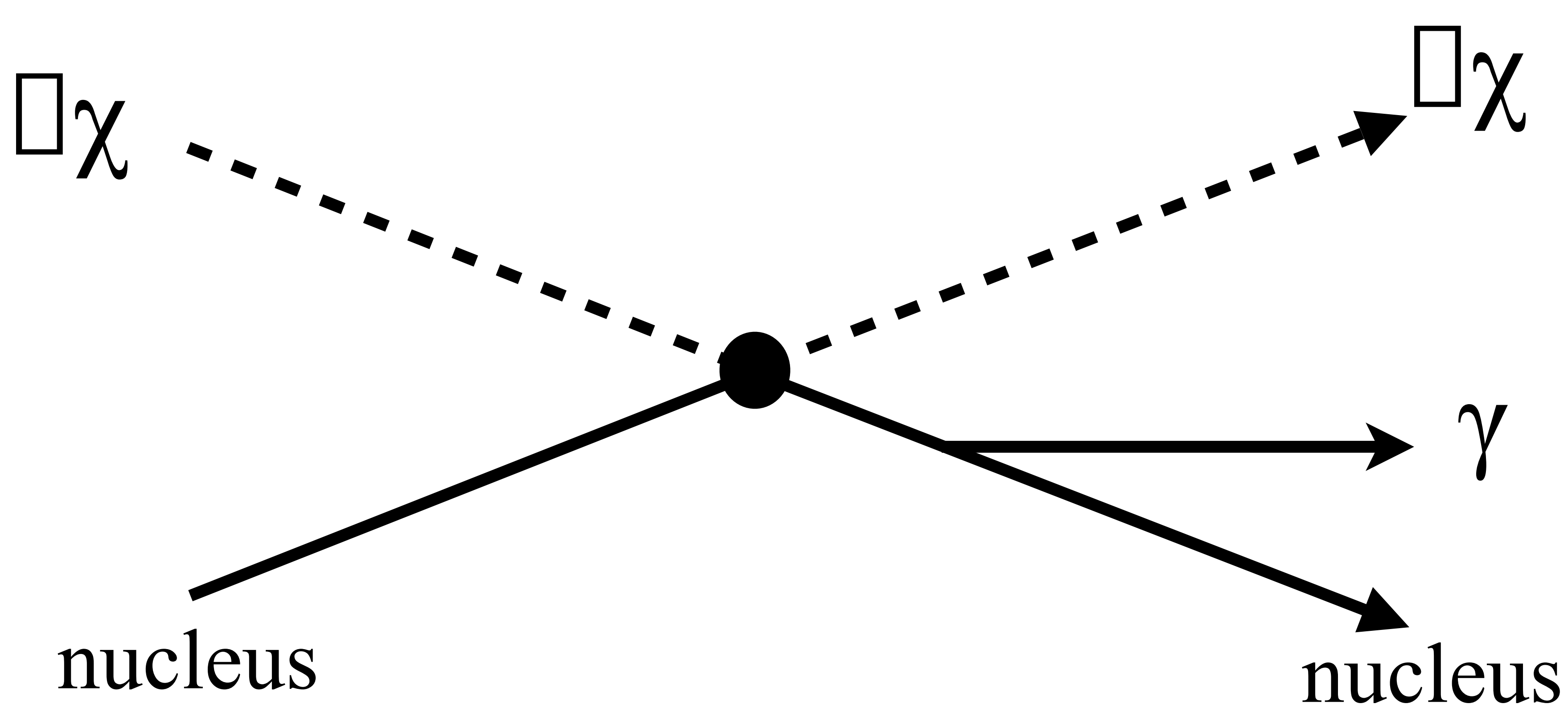


this talk has so far been “we have a mismatch, but we have strategies to mitigate that mismatch.”

~10x energy boost from light nucleus
~10x energy boost from van der Waals gain



three-body option #1: nuclear bremsstrahlung



Kouvaris, Pradler: arXiv:1607.01789
McCabe: arXiv:1702.04730v1

trick:
outgoing [nucleus+γ] can have wide range of [E,p]

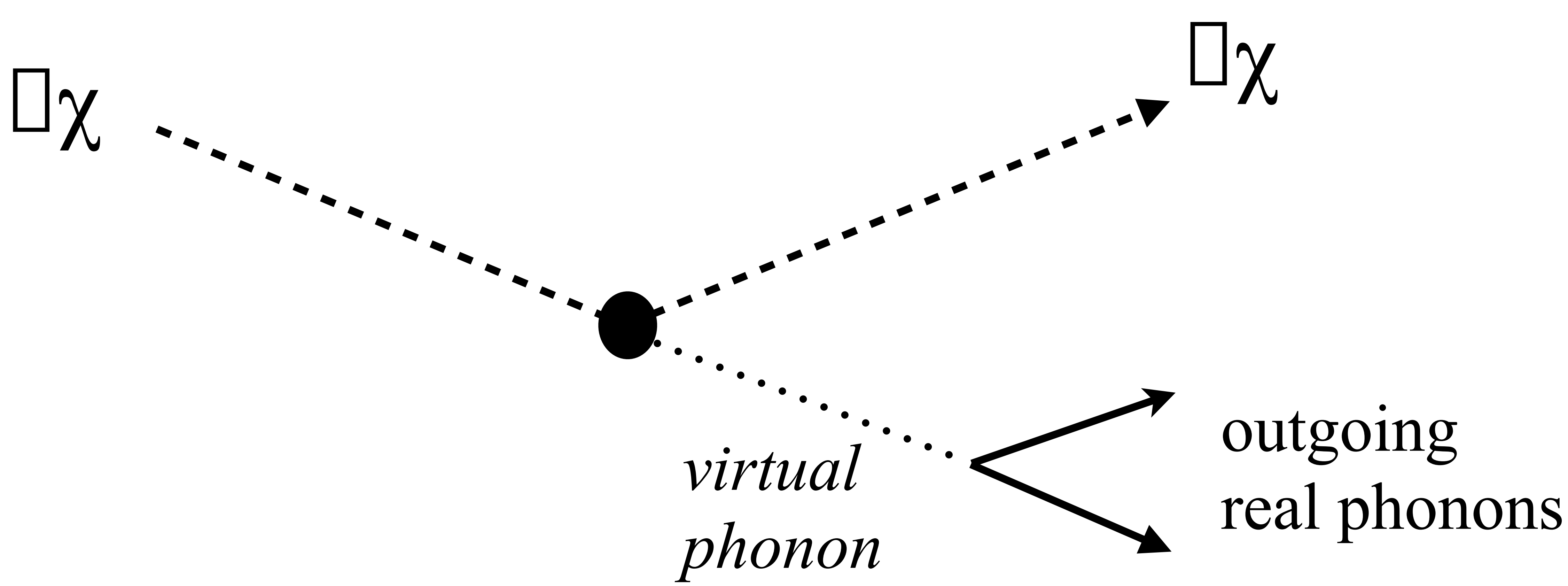
no longer limited to nuclear dispersion relation

what you get:
recoil E can be up to DM KE

(and E_γ can be up to recoil E)

what you pay:
large phase space suppression

three-body option #2: multiple outgoing phonons



Schutz, Zurek: arXiv:1604.08206
Knappen, Lin, Zurek arXiv:1611.06228

trick:
outgoing multi-phonon states can have wide range of [E,p]

no longer limited to phonon dispersion relation

what you get:
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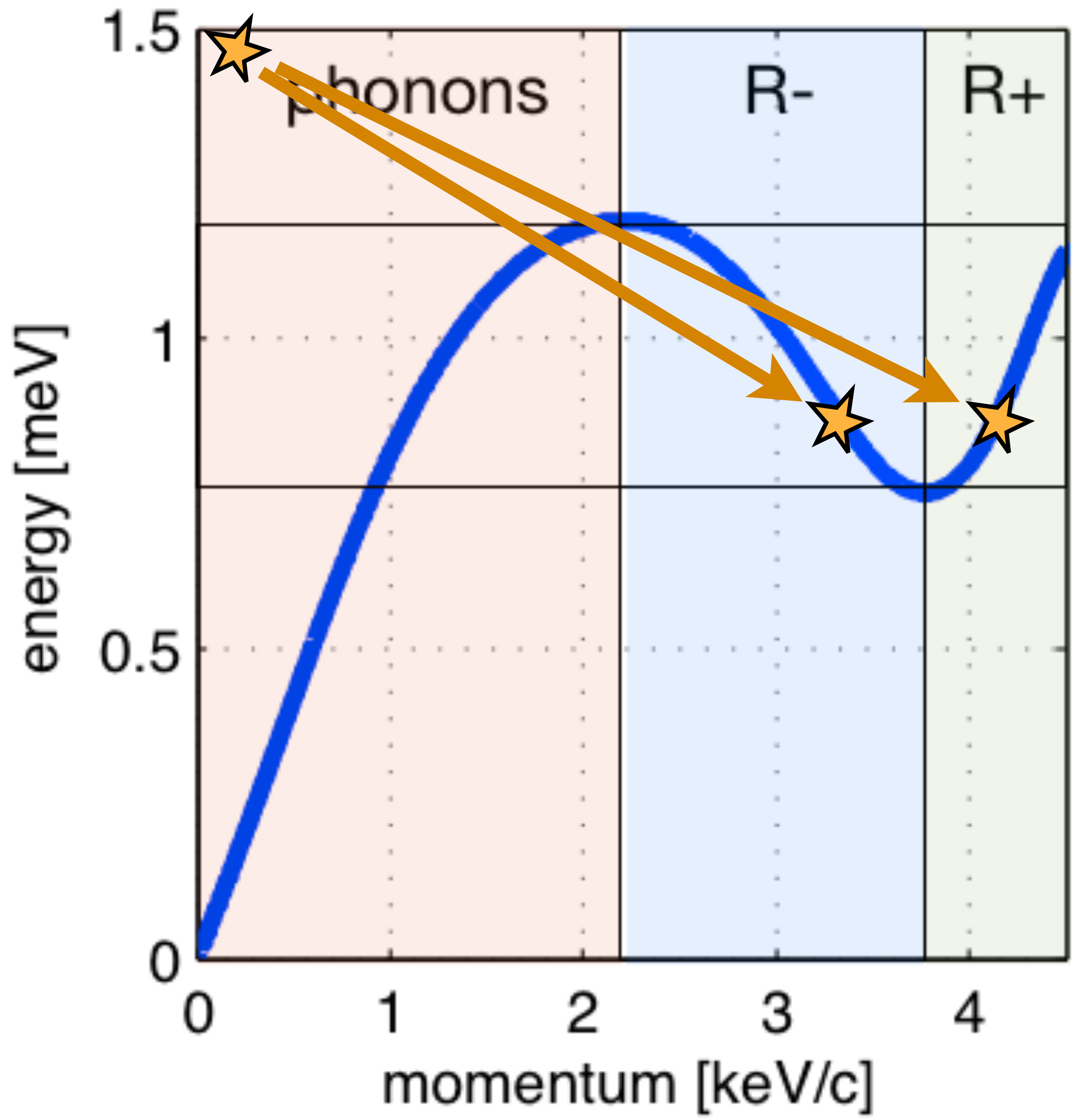
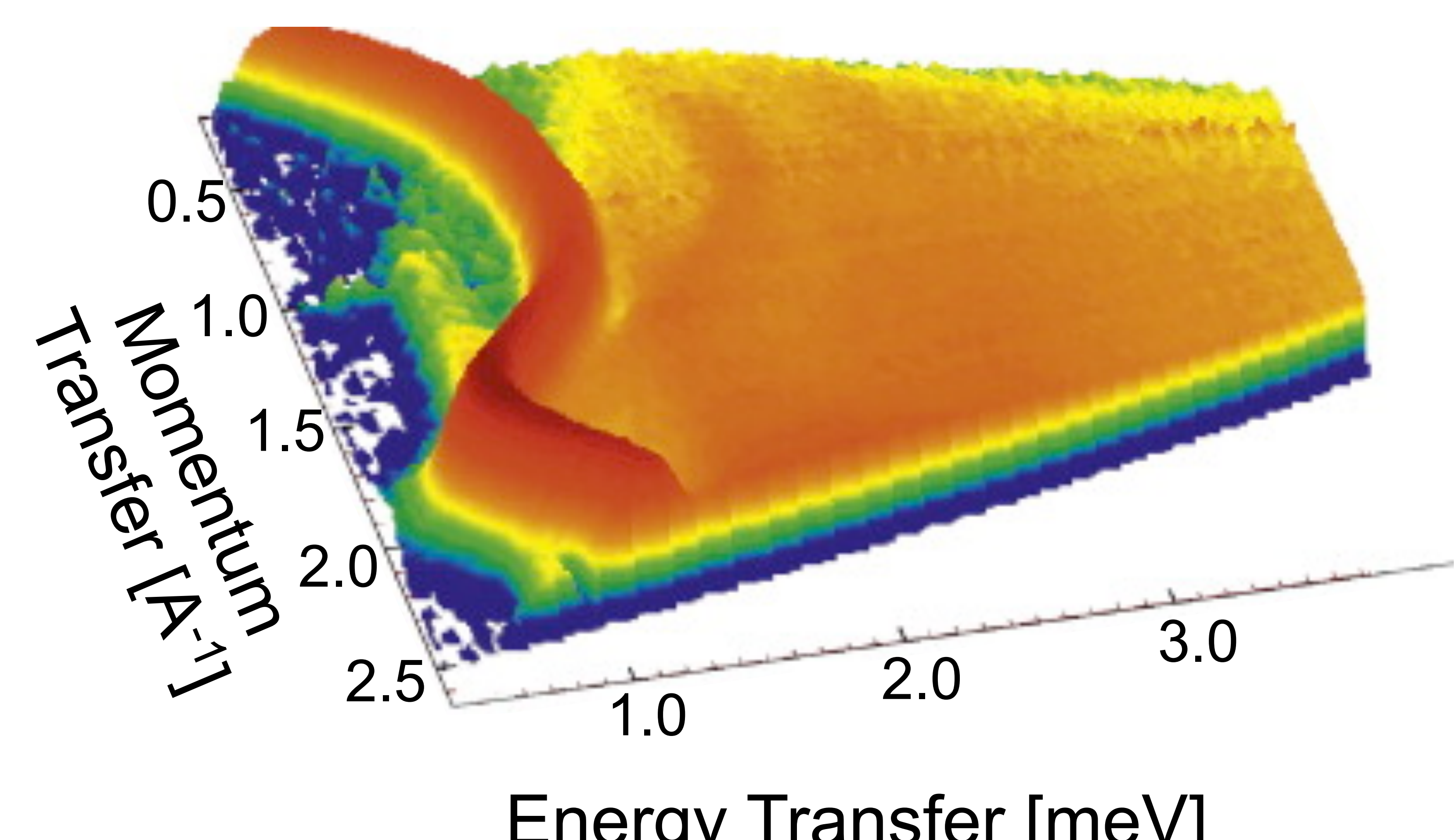
what you pay:
large phase space suppression

three-body option #2: multiple outgoing phonons



as observed in
neutron scattering data



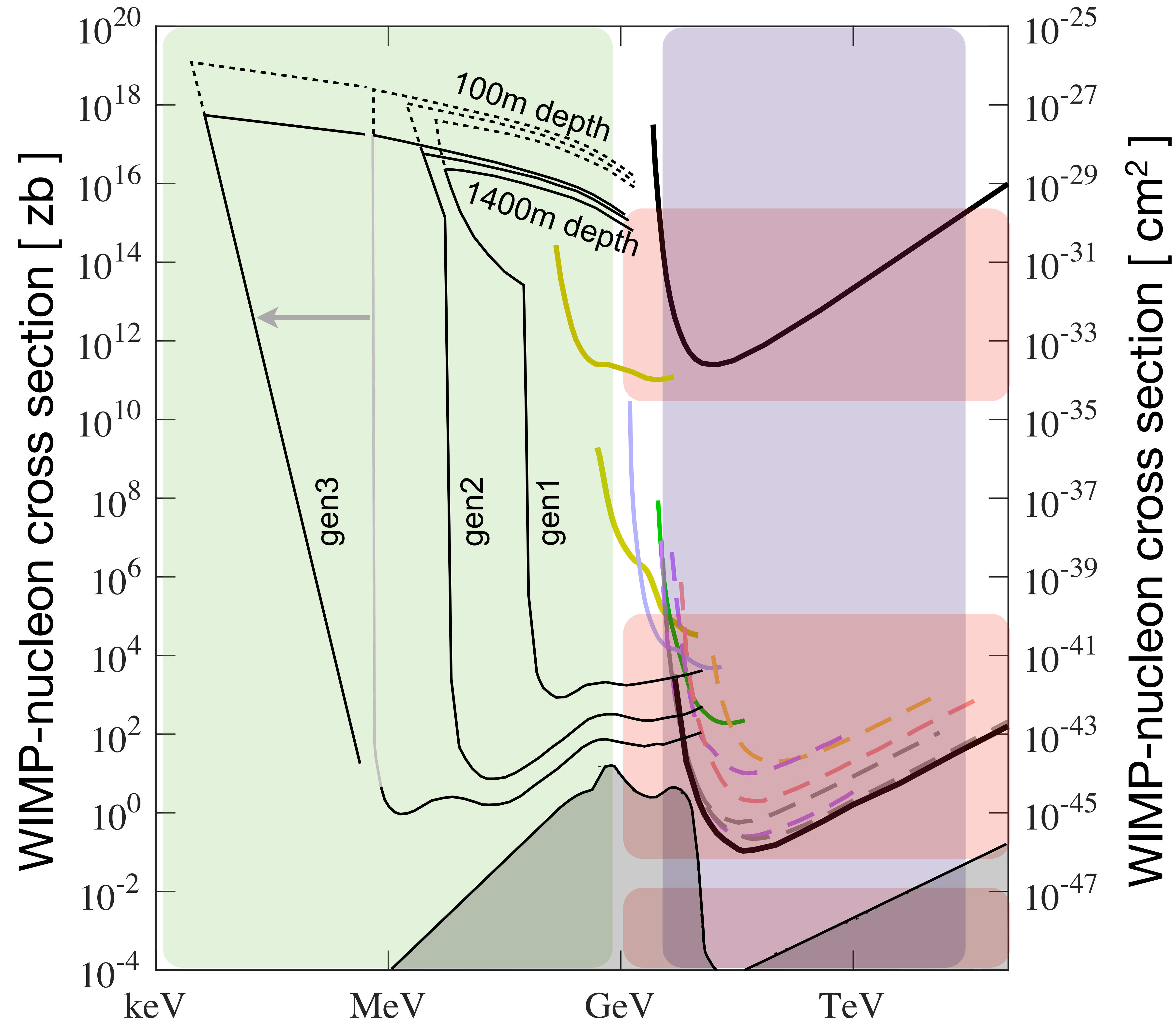
Schmidt-Wellenburg et al
NIMA611 2009 p259

Nuclear Recoil Sensitivity

result of double-roton diagram:

bypass the He atom dispersion relation

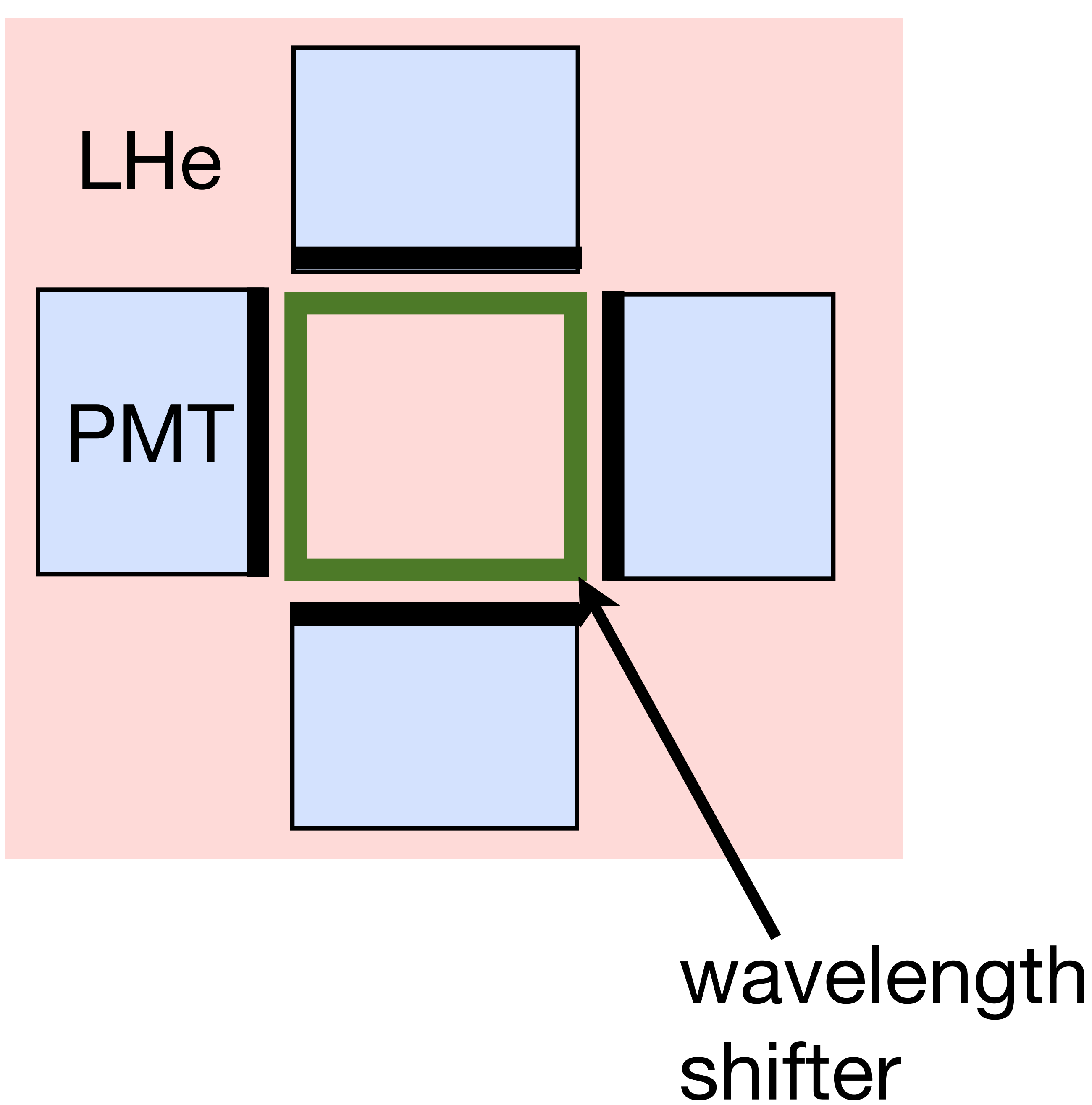
sensitivity to keV-scale masses



starting up some new efforts

McKinsey Group at Berkeley

4He scintillation yield at low energies



Hertel Group at U. Mass. (no table yet)

designing, setting up 4He evaporation channel test bed

goals: evaporation channel R&D
evaporation channel calibration (bring to n facility)
early DM limits from on-campus lab ("*ν*-cleus style")

Summary

Ideal technology for low-mass NR

- -meV-scale long-lived kinetic excitations
- -light-element material
- -suppressed "dark counts" in superfluid

Shovel-ready technology

- -4He evaporation: HERON
- -calorimeters: CDMS, CRESST, etc.

Small and cheap, $1M-scale

- - small target (grams-to-kg)
- - few channels (6+)