Superfluid ^4He with Calorimetric Readout

U.S. Cosmic Visions: New Ideas in Dark Matter
March 23-25, 2017

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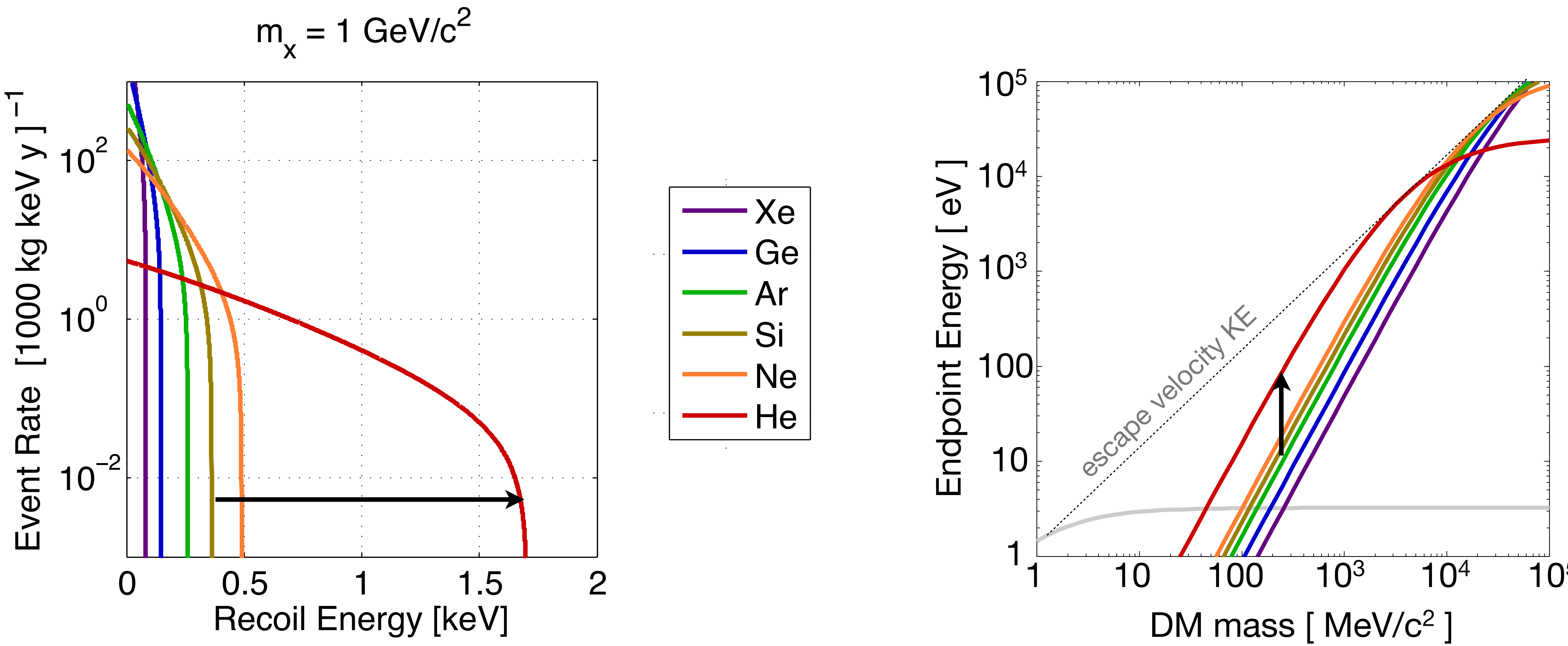
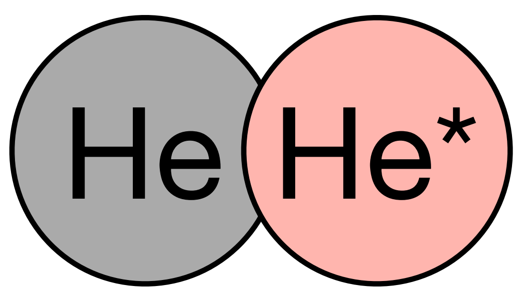
First-order Motivation : Light Baryonic Target



What models are we aiming for? MeV-scale DM with nuclear interactions

LHe Excitations

eV-scale excitations:



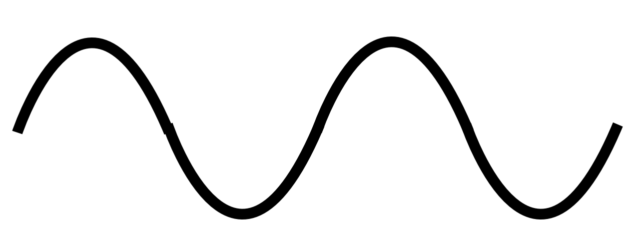
He2* excimers

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)

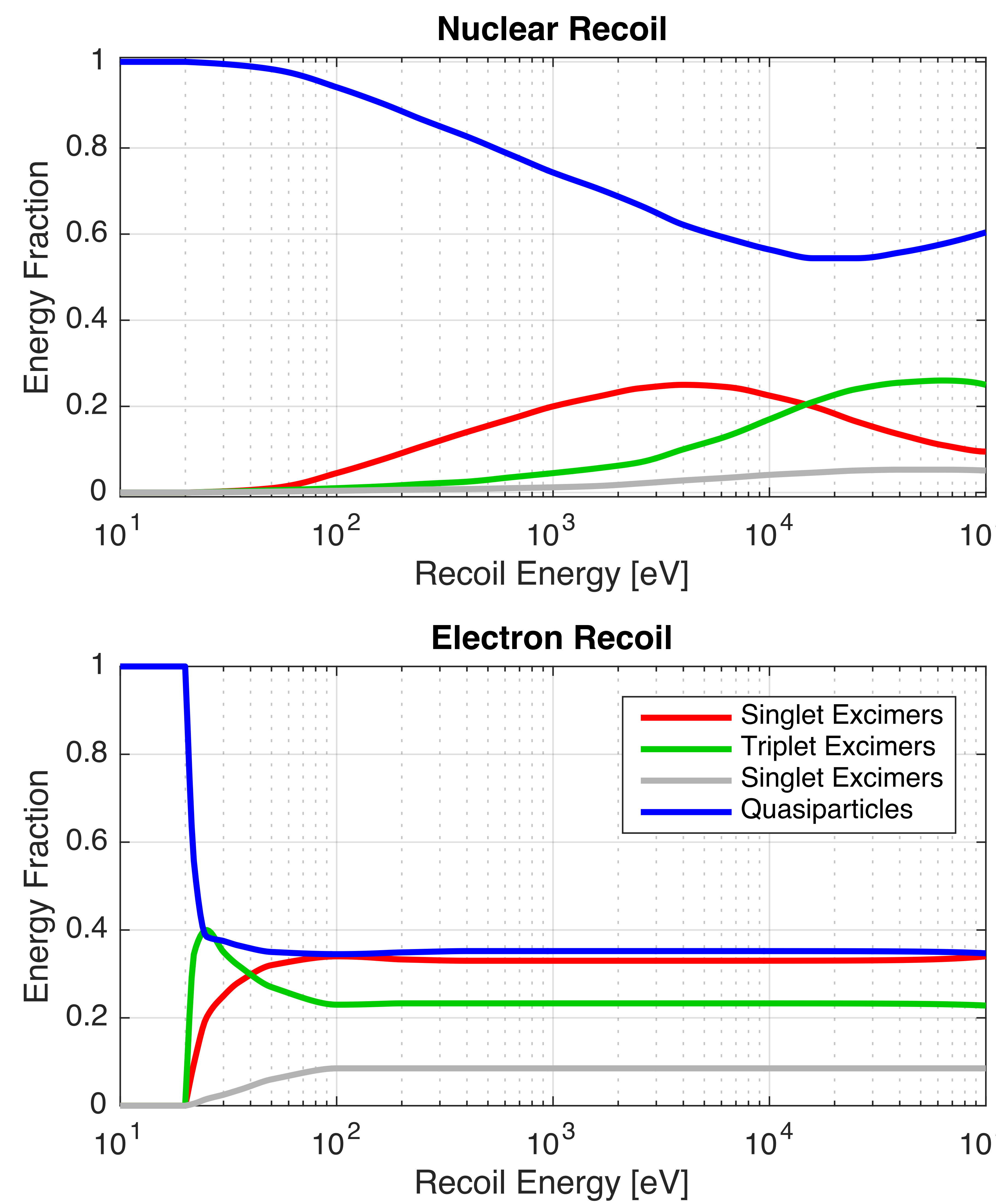
Partitioning Recoil Energy

Partitioning into excitations can be estimated from the ground up, from atomic cross sections.

Here we show the work of George Seidel (next speaker)

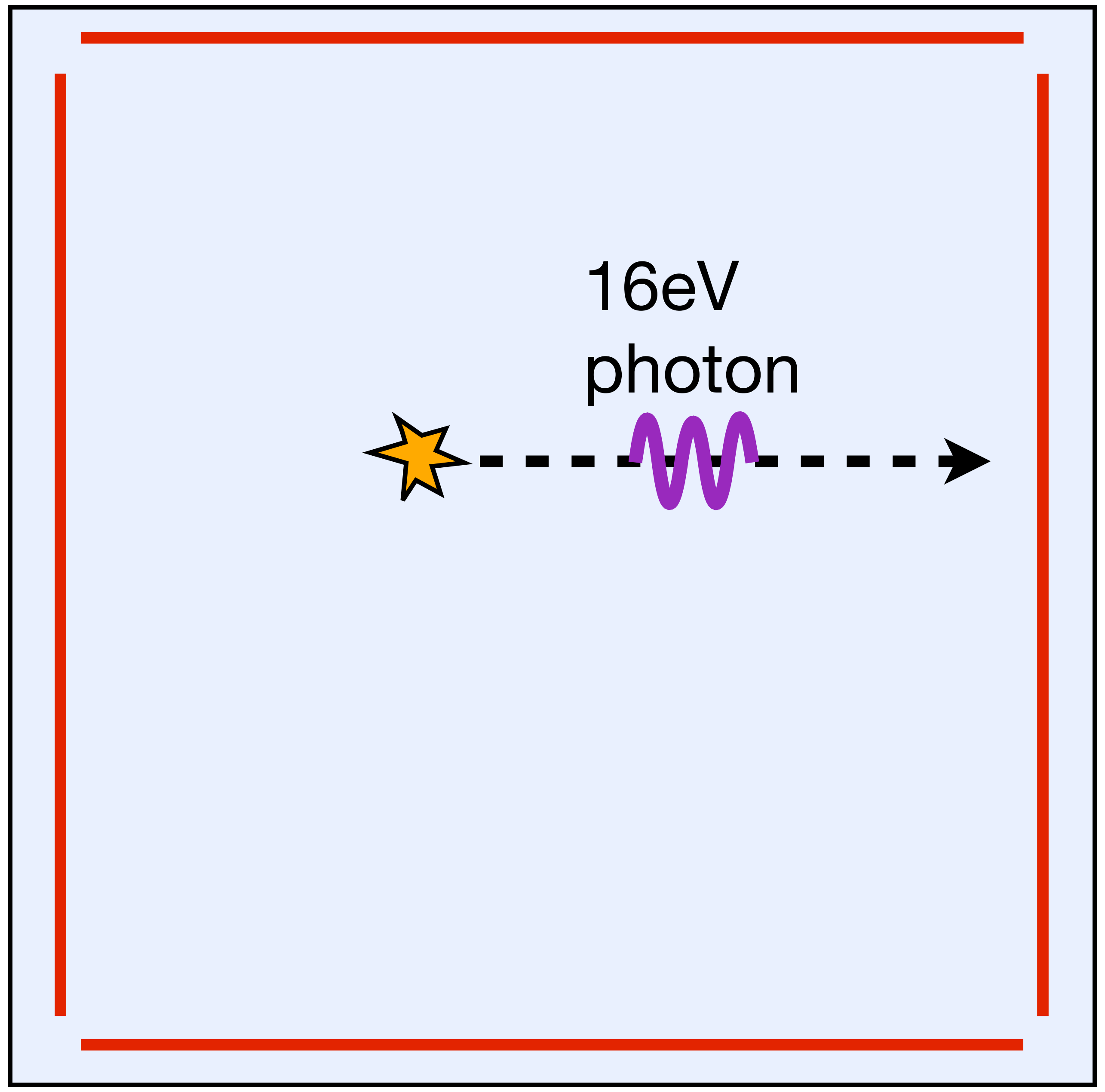
NR and ER have quite different partitioning in a three-way partition (kinetic + triplet + singlet).

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



Reading out Singlet Excitations (16eV photons)

simple detector: box with calorimetry inside



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 to non-phonon excitations (eg, Al quasiparticles)

Photon counting easy
4pi coverage easy

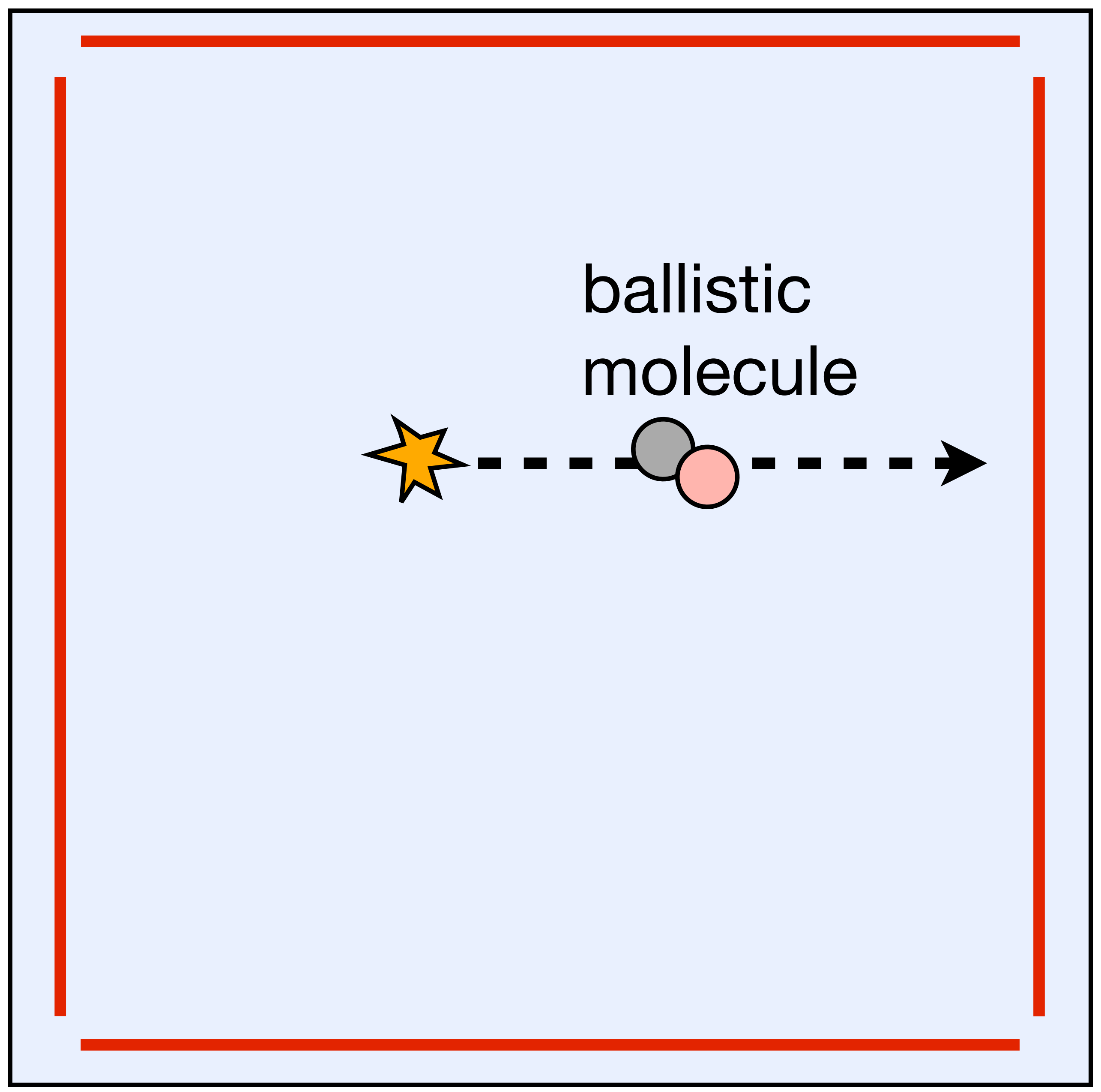
Reading Out Triplet Excitations (ballistic molecules)

simple detector: box with calorimetry inside

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



Reading Out Triplet Excitations (ballistic molecules)

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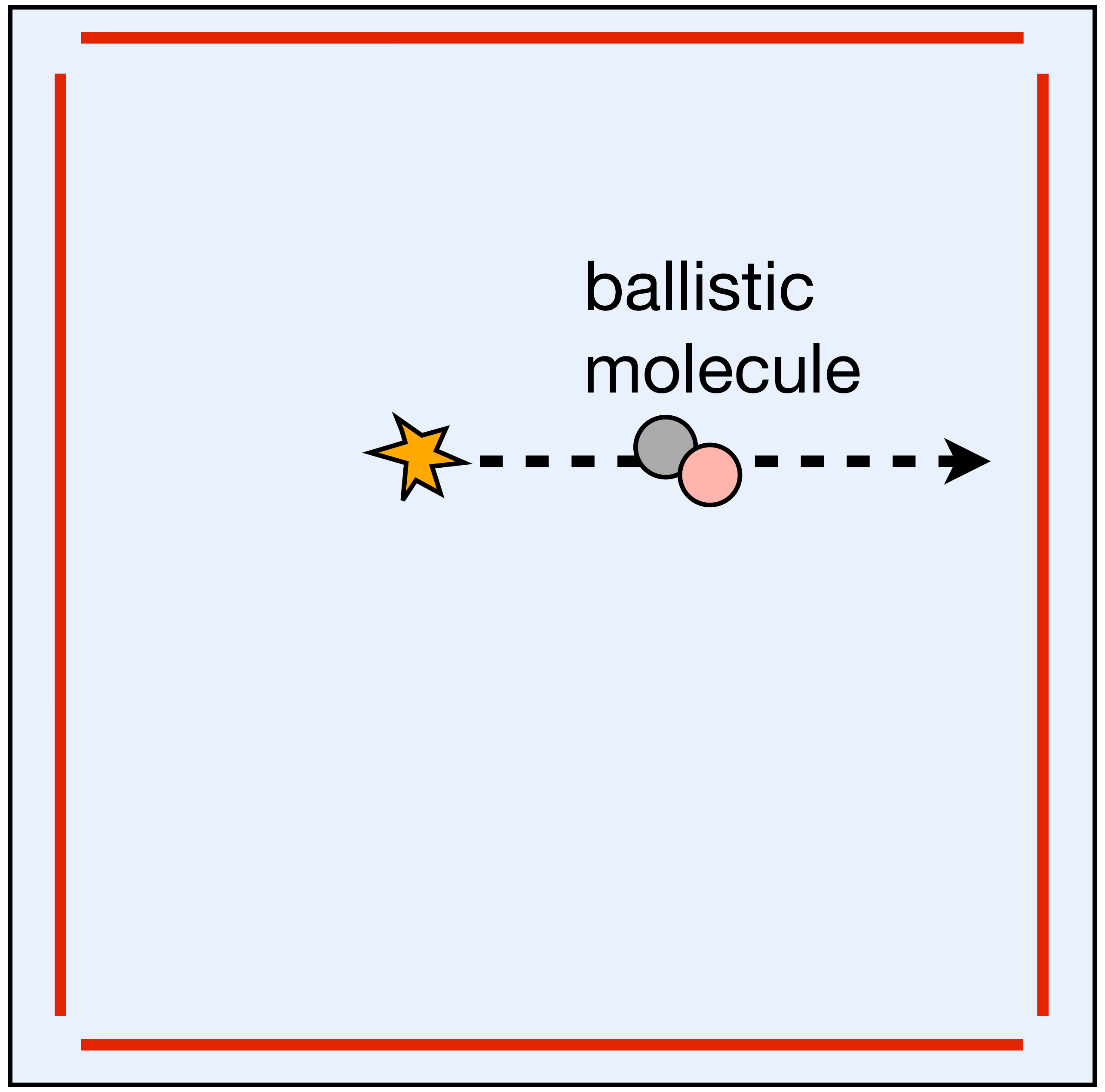

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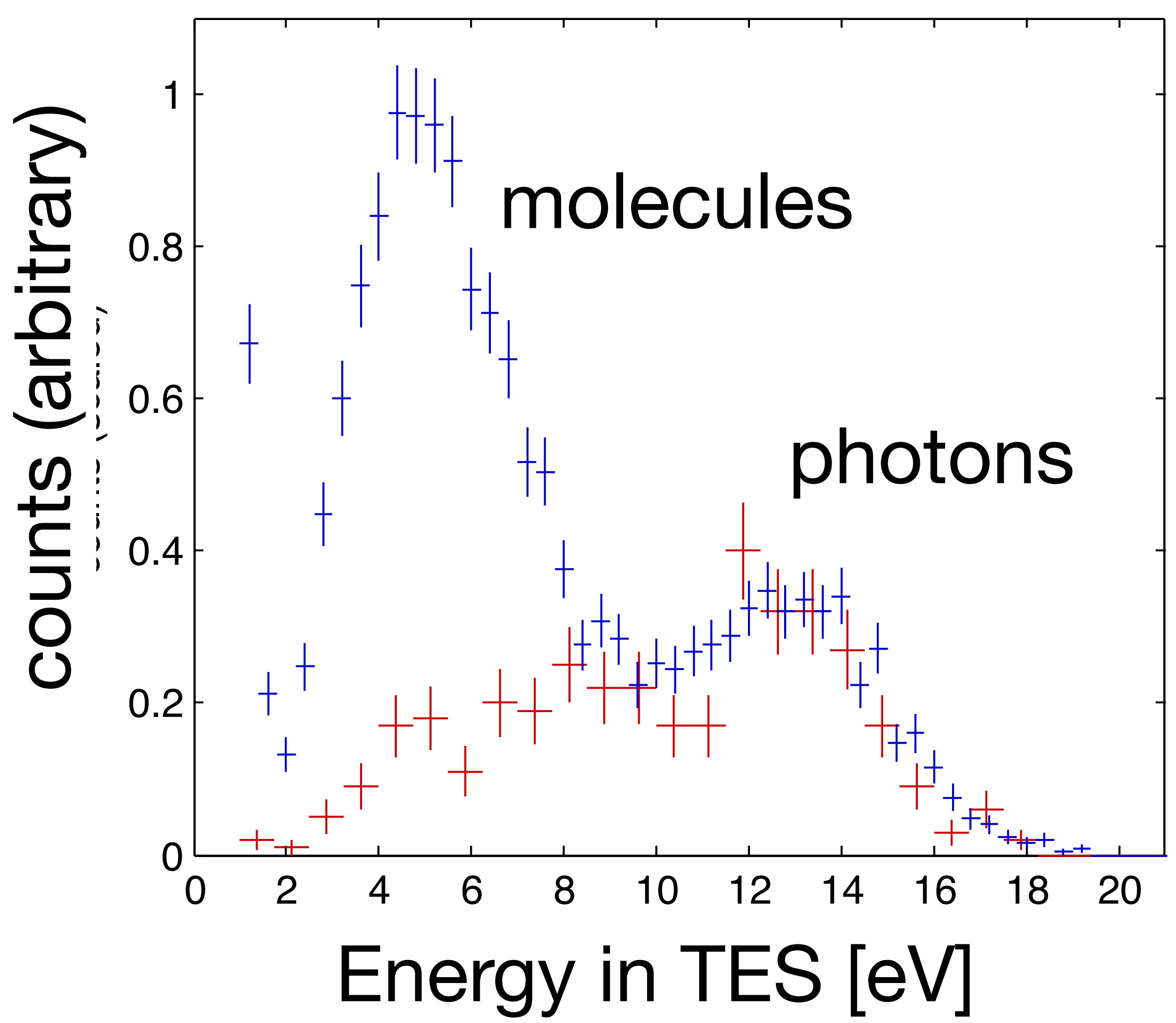


Journal of Low Temperature Physics

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

https://arxiv.org/abs/1605.00694

^{4}He Quasiparticles

The most relevant points:

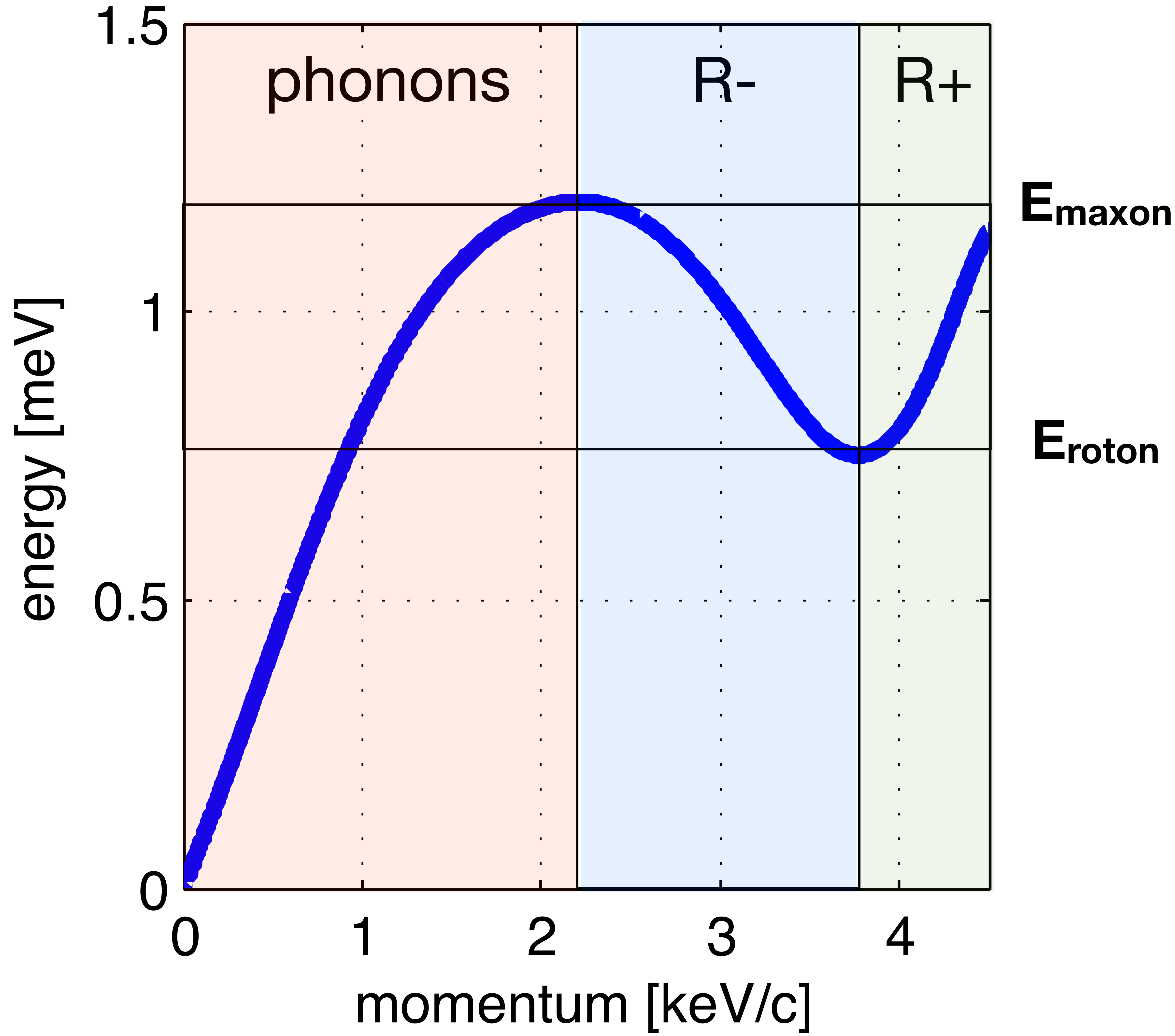
Ignore the nomenclature, no angular momentum.
(think "phonons+weird phonons")

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

Not on a crystal lattice (isotropic dispersion)

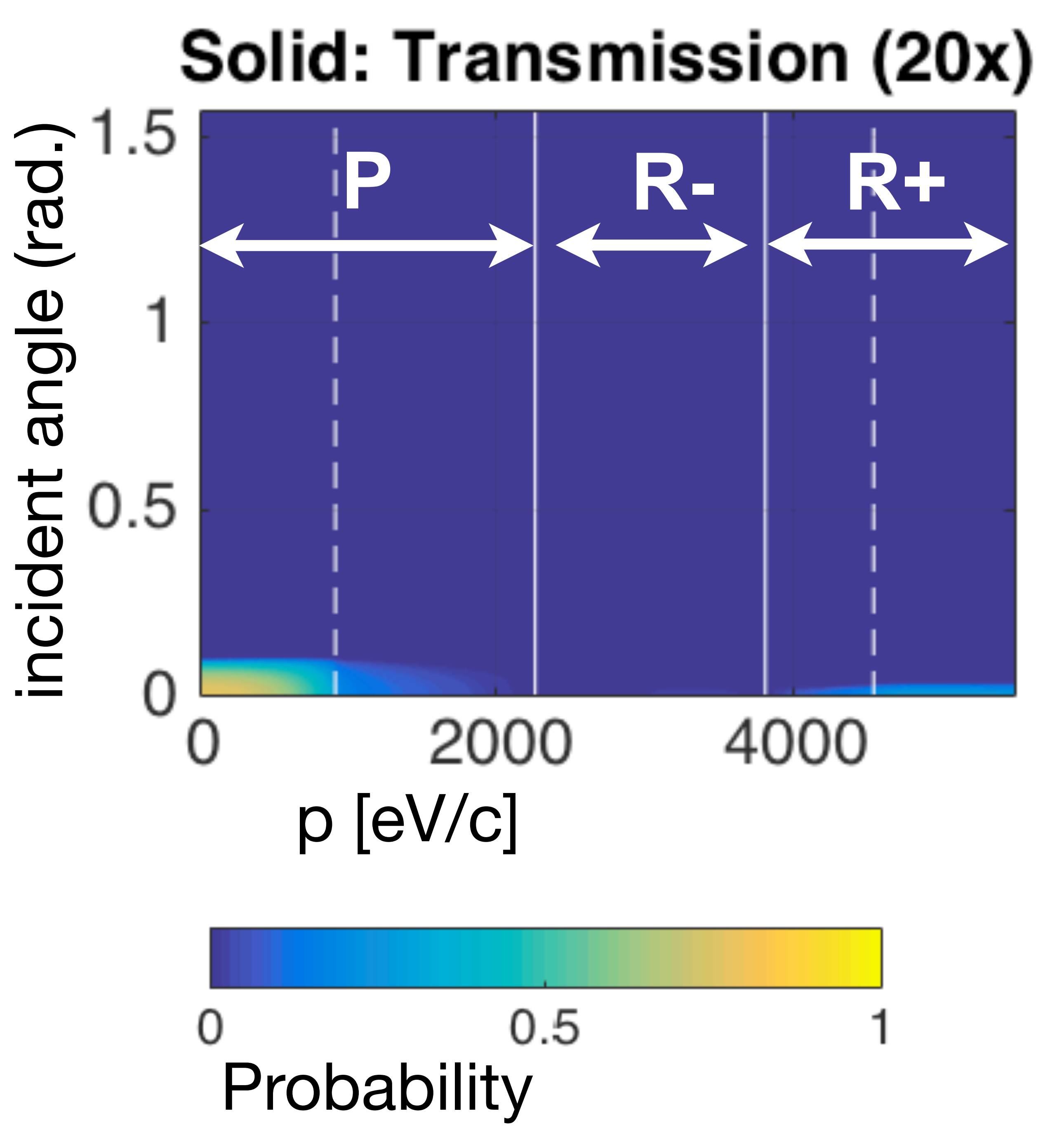
Multiple 'flavors' with distinguishing characteristics:
- slope is velocity
- R- propagation opposite to momentum

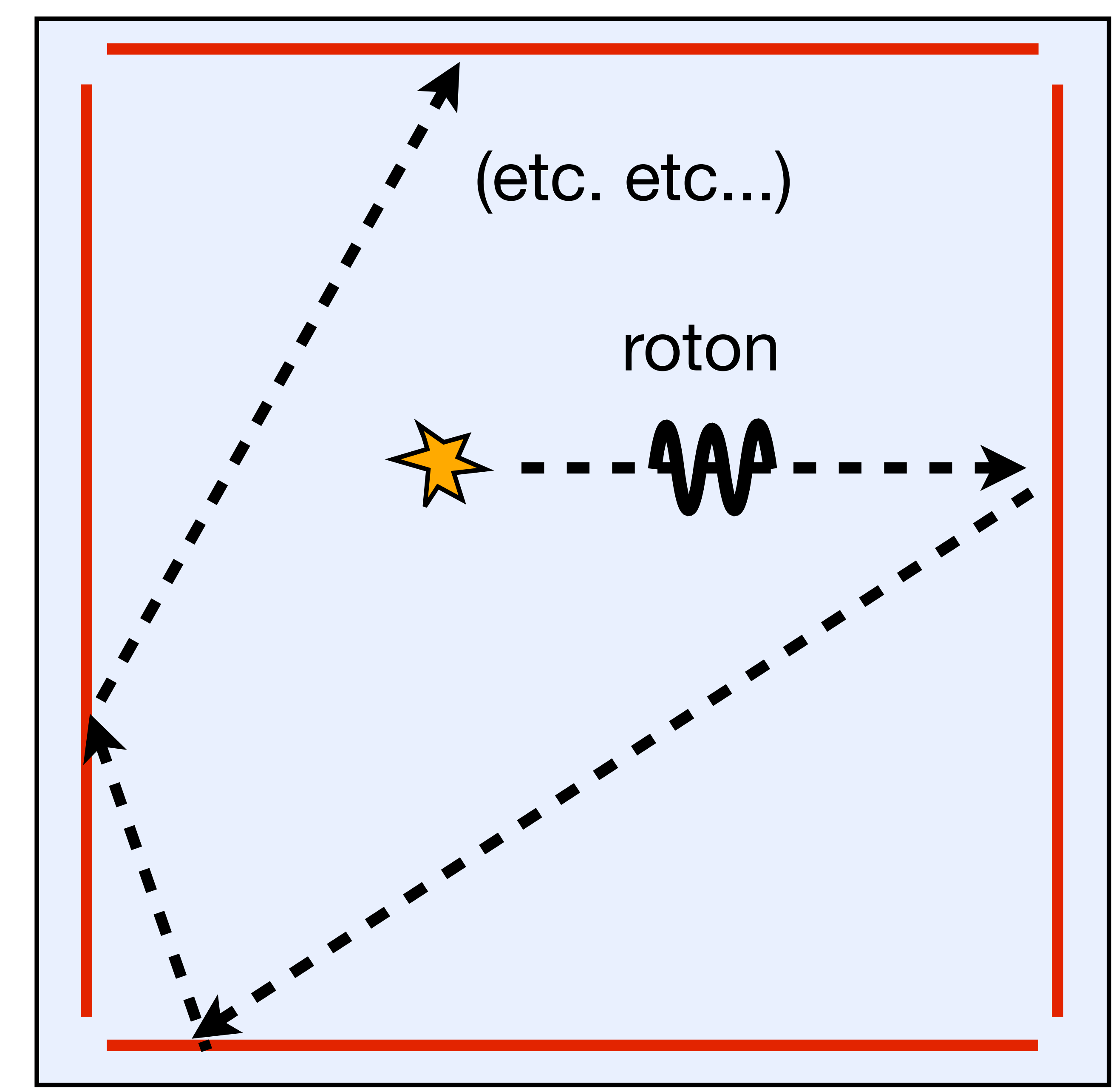
Perfectly ballistic
Decay forbidden
(both assuming $T_{LHe} \lesssim 50$mK and no ^{3}He)



Reading Out ^{4}He Quasiparticles

crossing into solid extremely suppressed
(Kapitza resistance)





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

crossing into solid extremely suppressed
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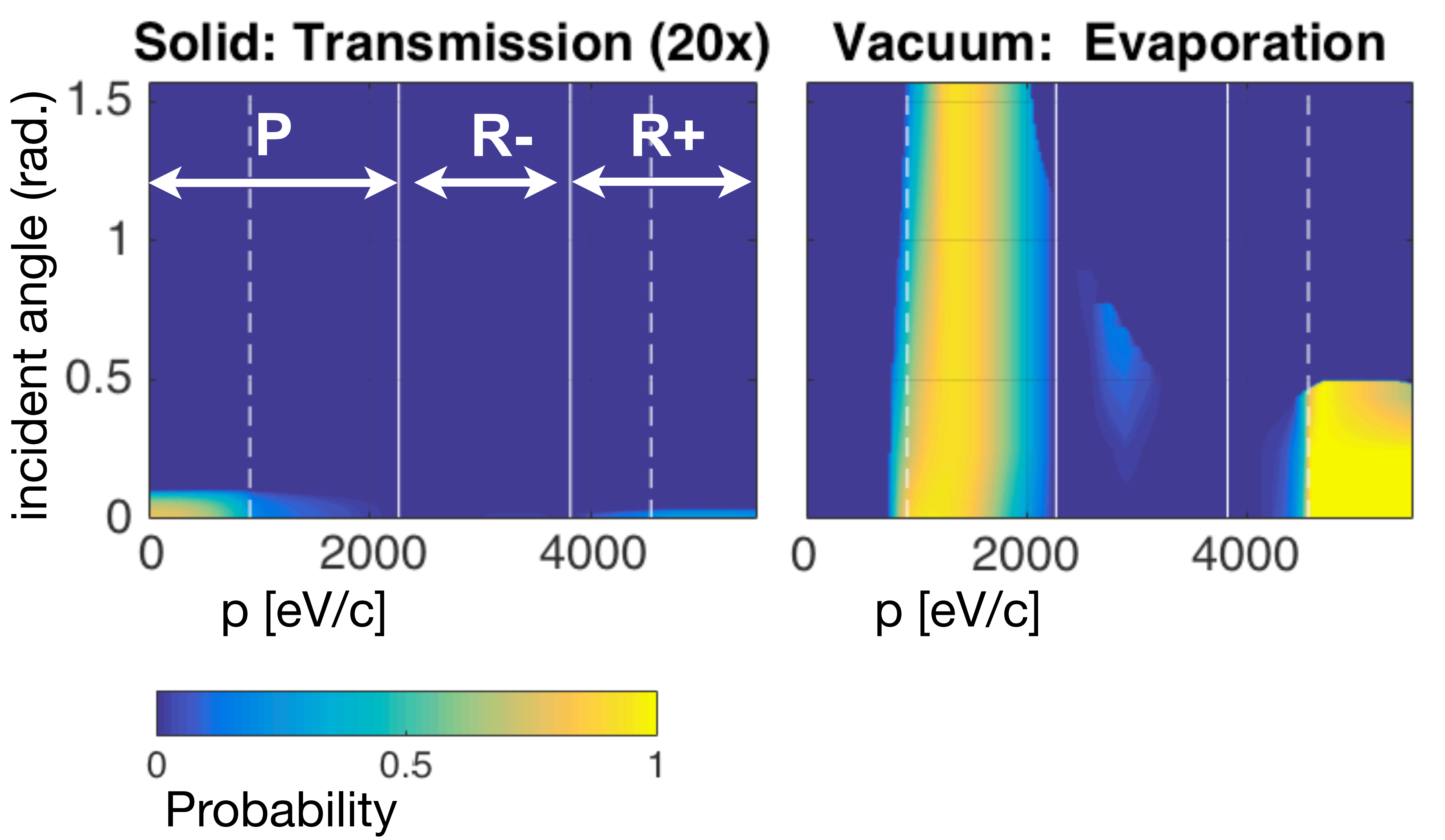
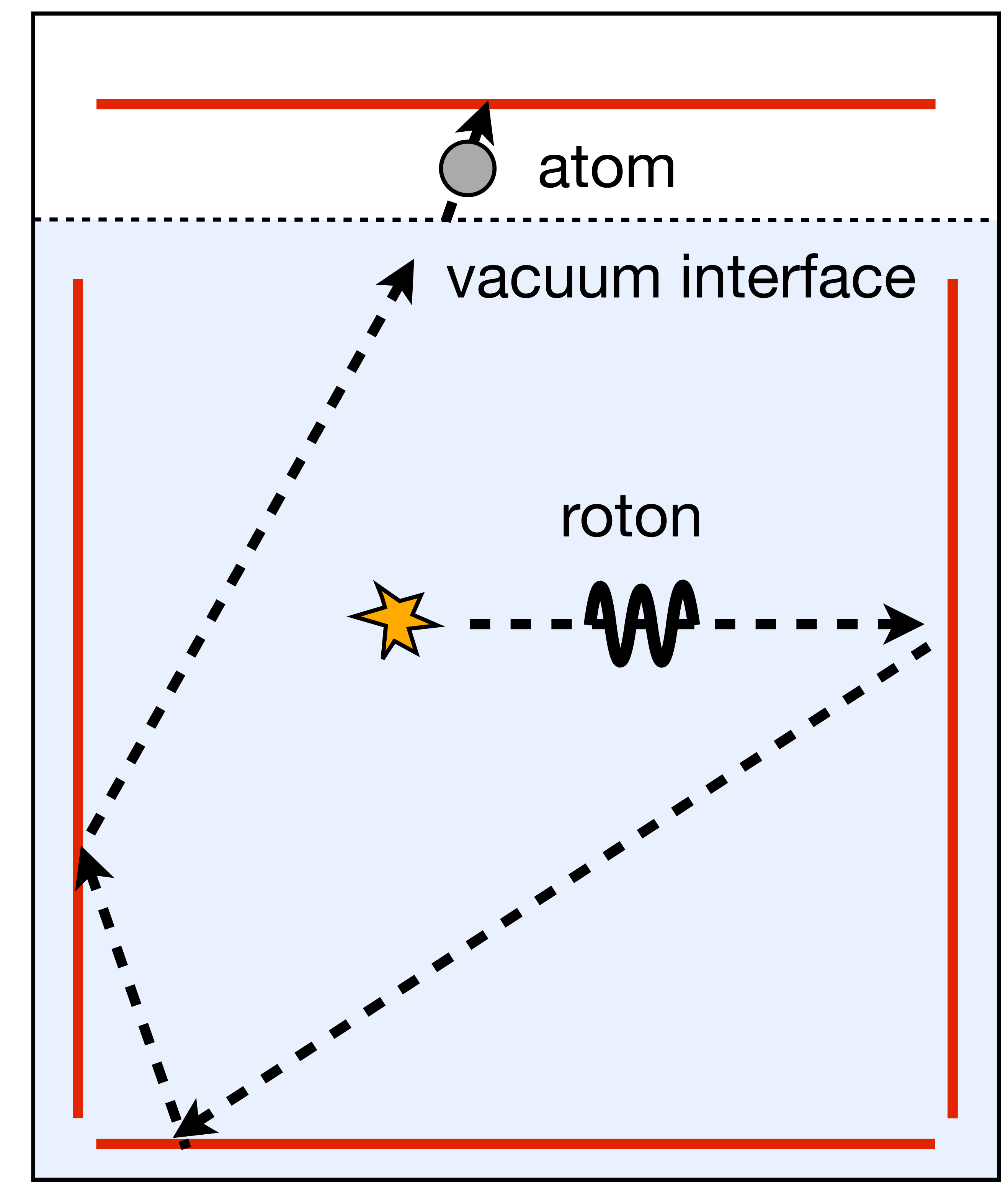
...saved by significant probability
of single-atom evaporation at vacuum





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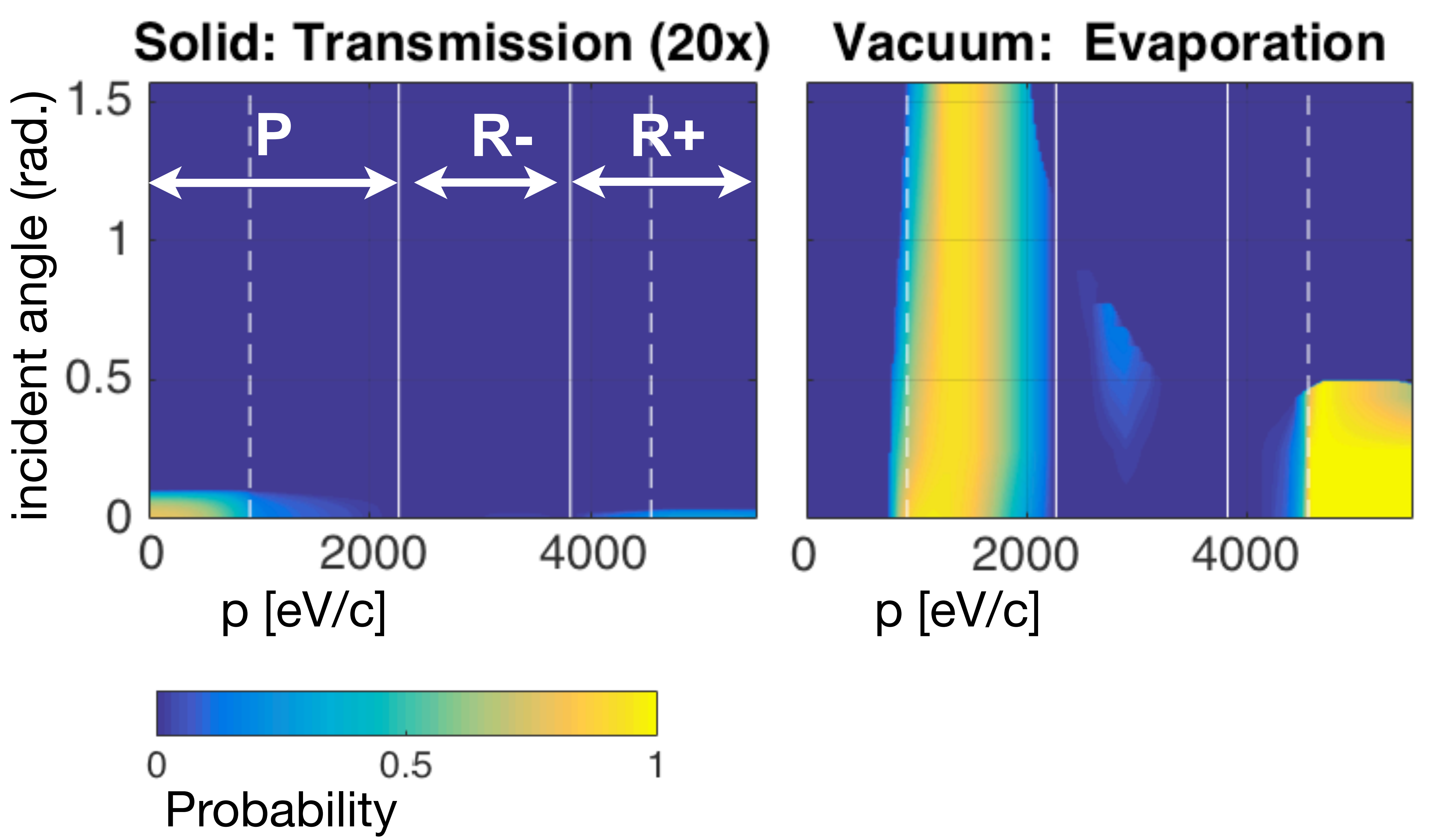
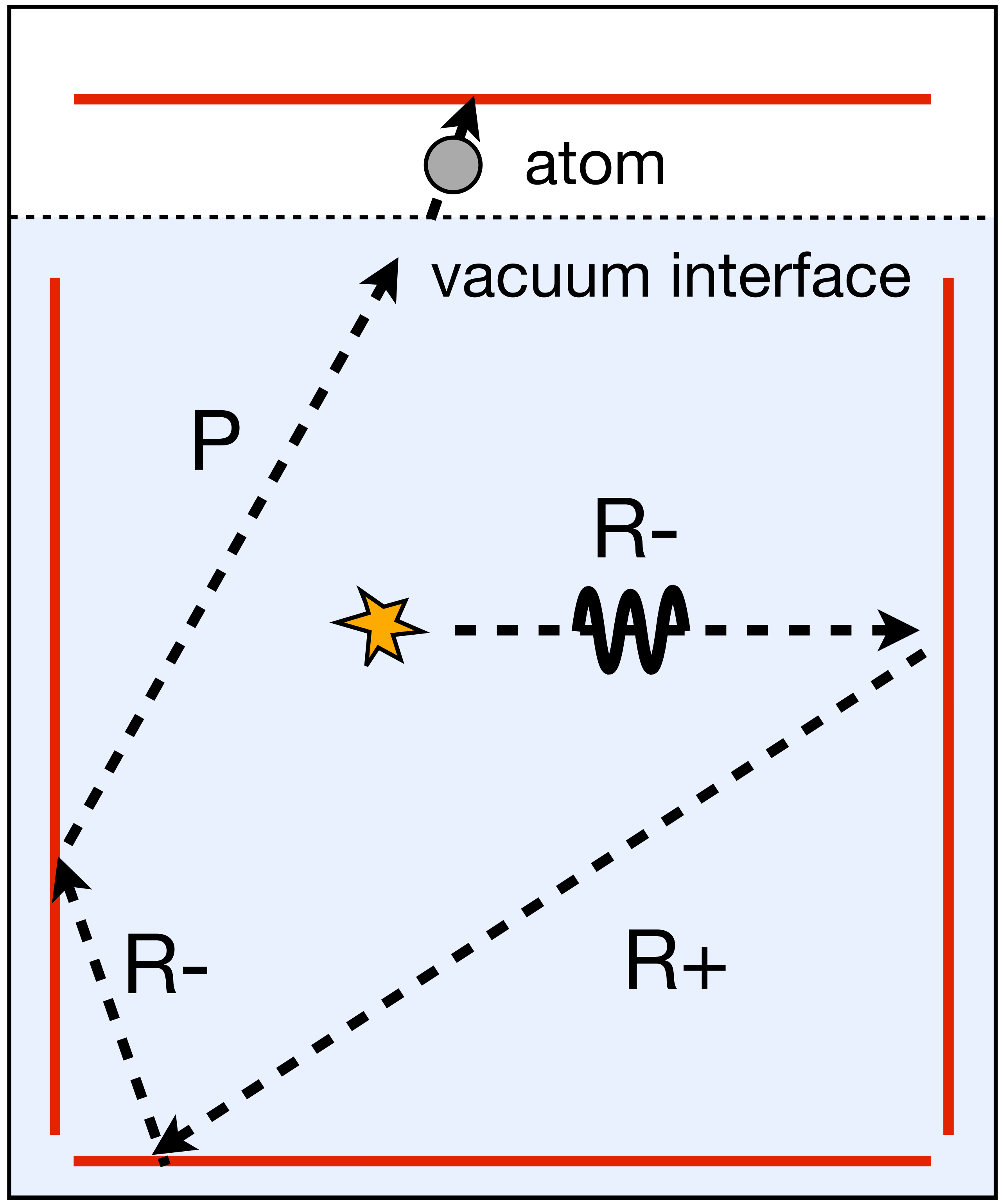
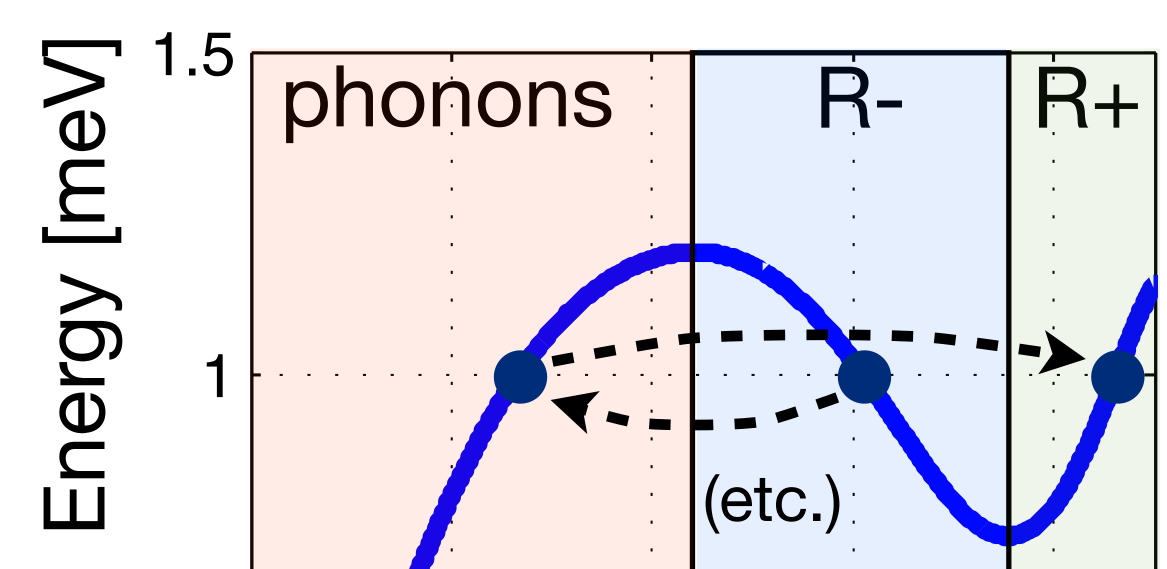
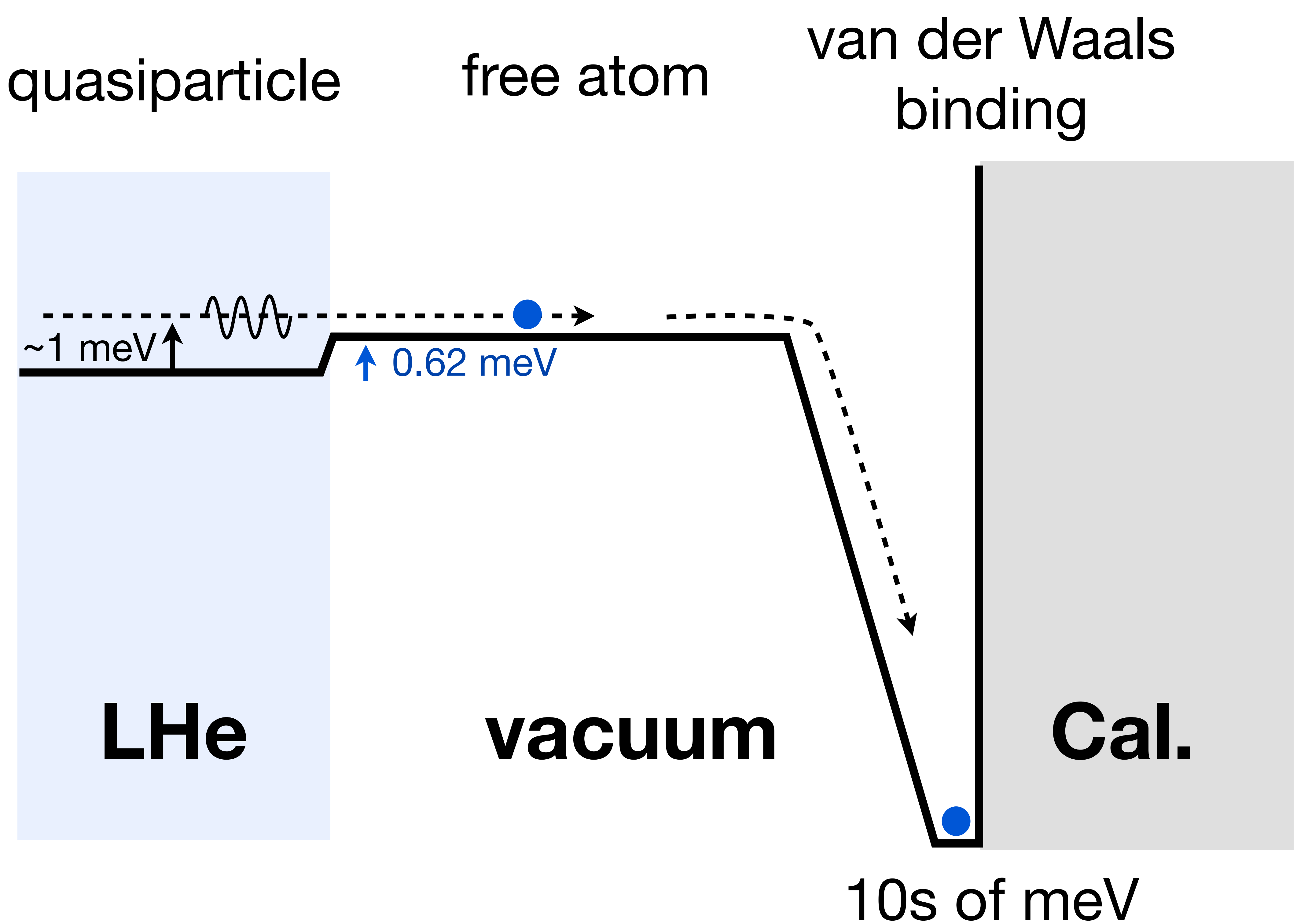






Reading Out ^{4}He Quasiparticles (quantum evaporation)

→ van der Waals gain



Typical helium-solid binding energy: ~10meV

Can imagine thin layer of graphene-fluorine: 42.9meV

~1 meV roton energy -> ~40 meV observation

-> x40 gain

reference for helium binding to graphene-fluoride:

http://iopscience.iop.org/article/10.1088/0953-8984/25/44/443001/meta

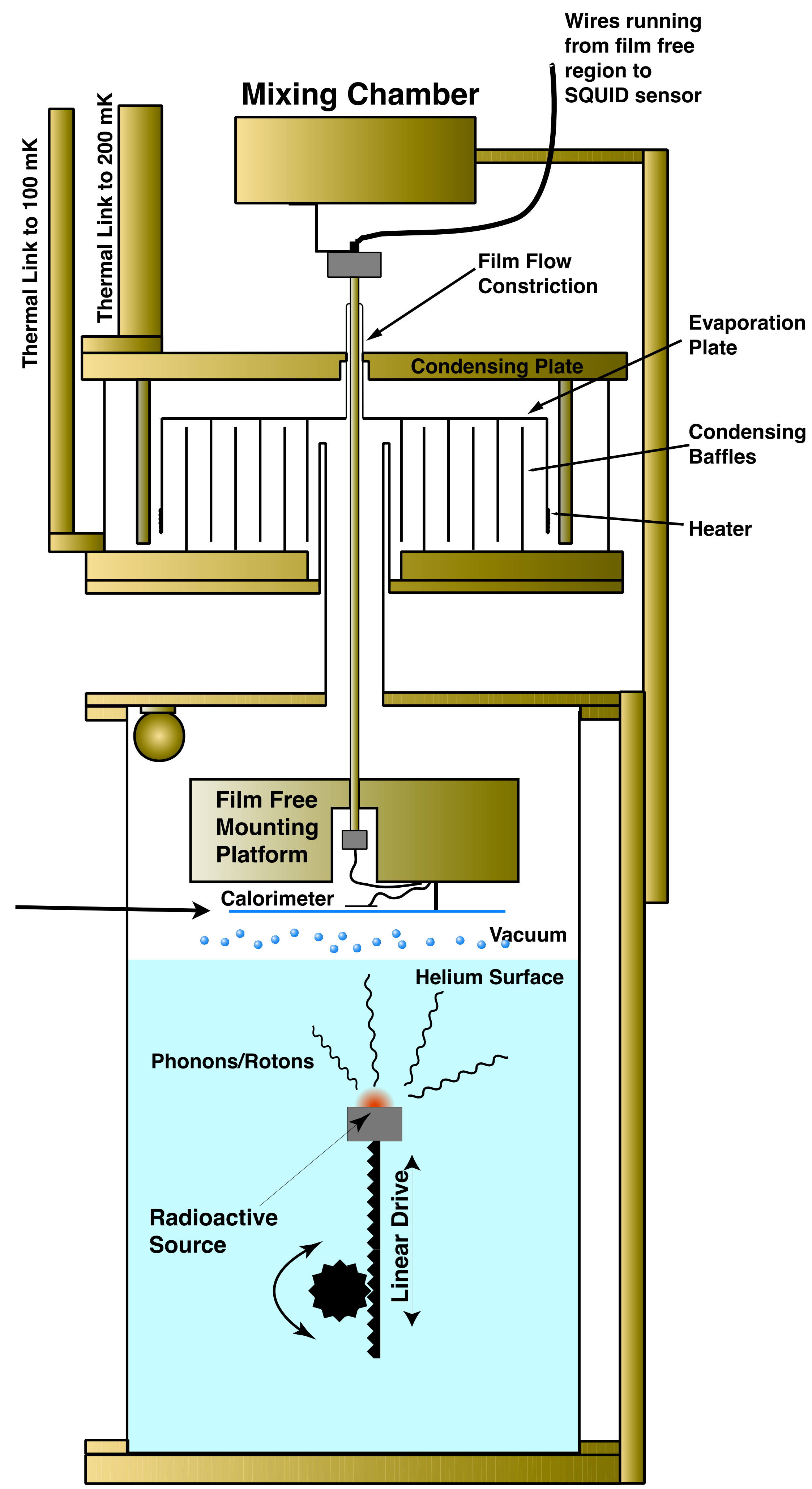
‘Shovel Ready’ Technology Years Ago

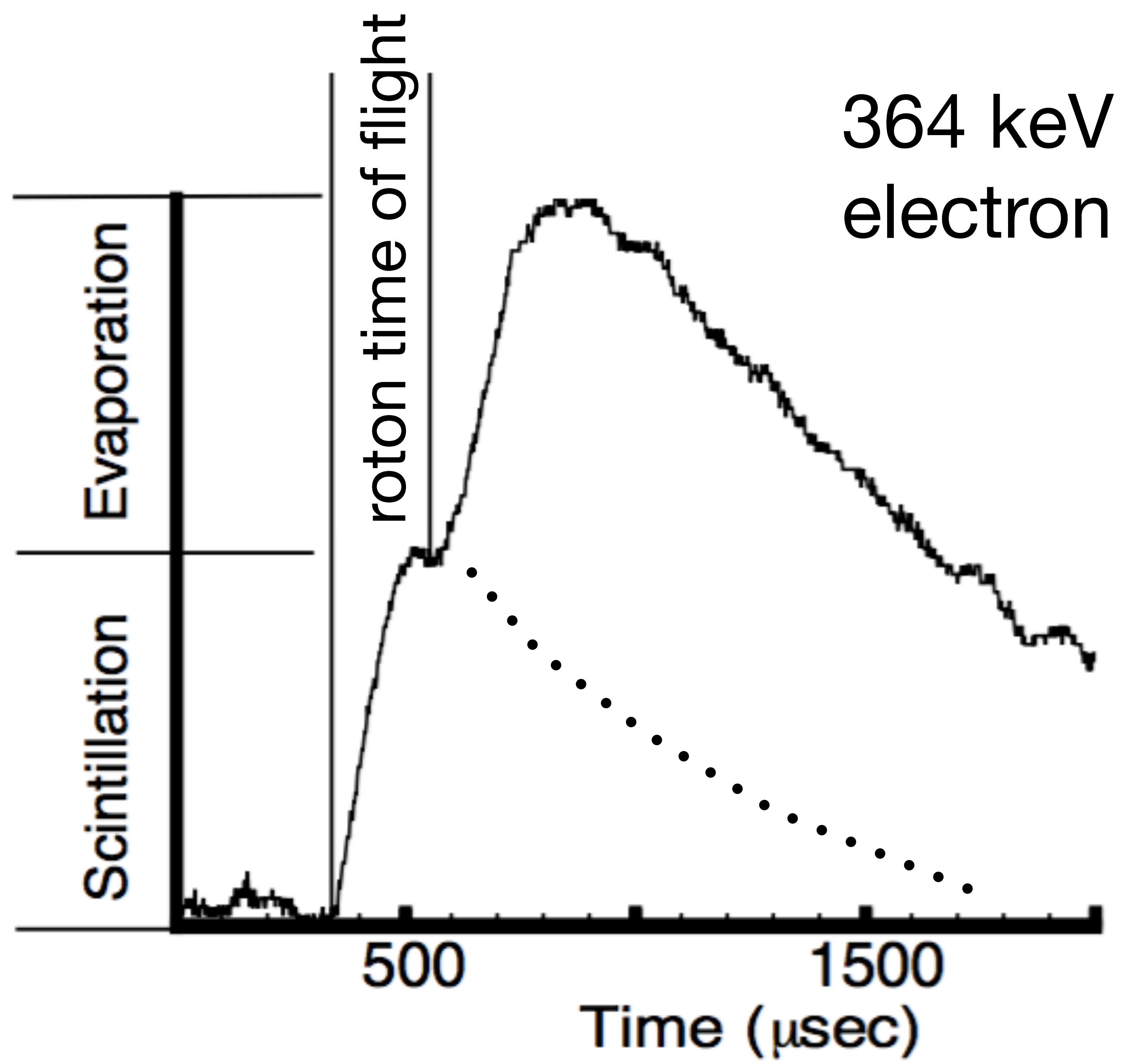
R&D for the proposed HERON pp neutrino observatory

He film burner

wafer calorimeter
single TES channel

kg-scale
LHe mass



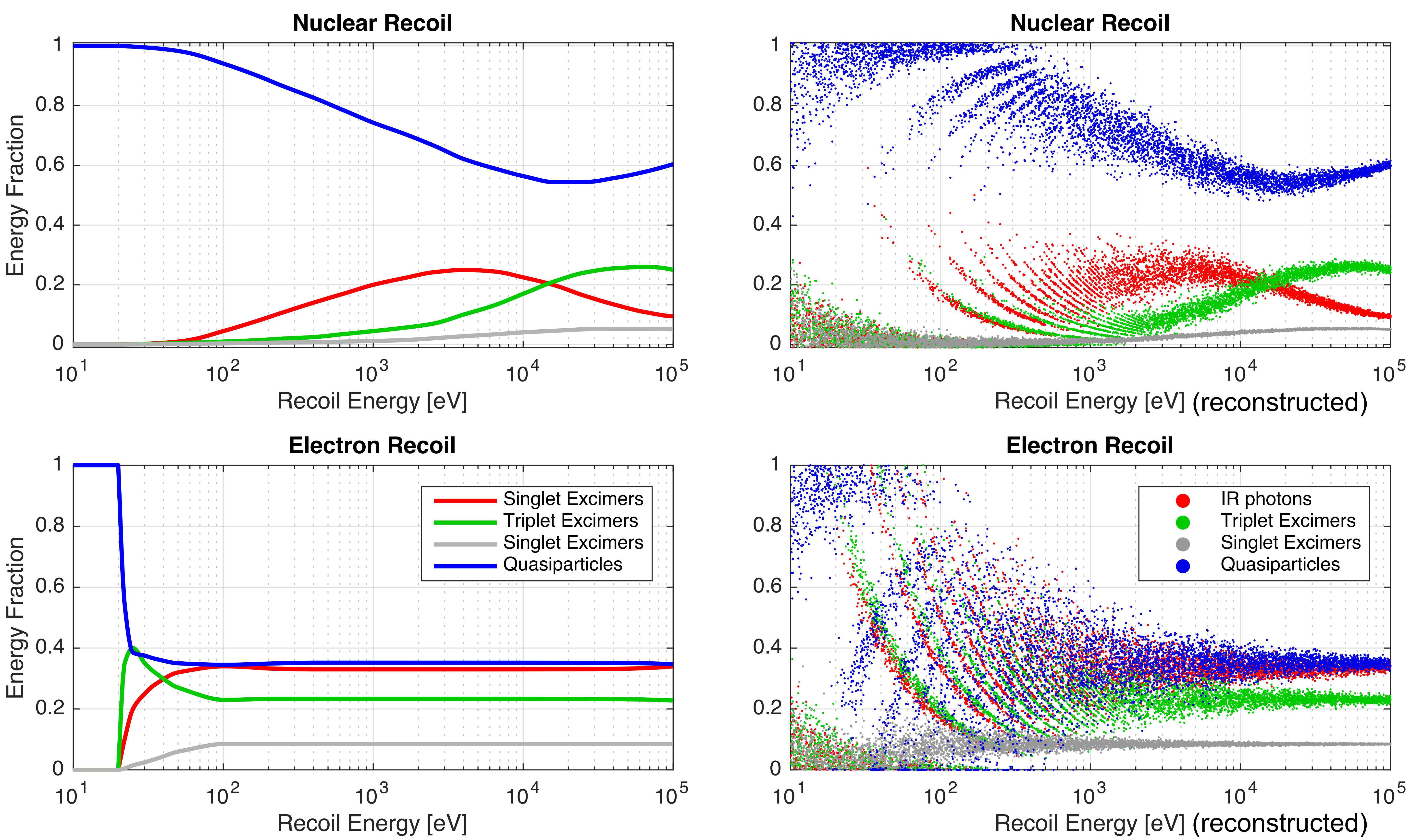


now: light dark matter motivates
+improved eV-threshold calorimetry

ER/NR discrimination using excimer production

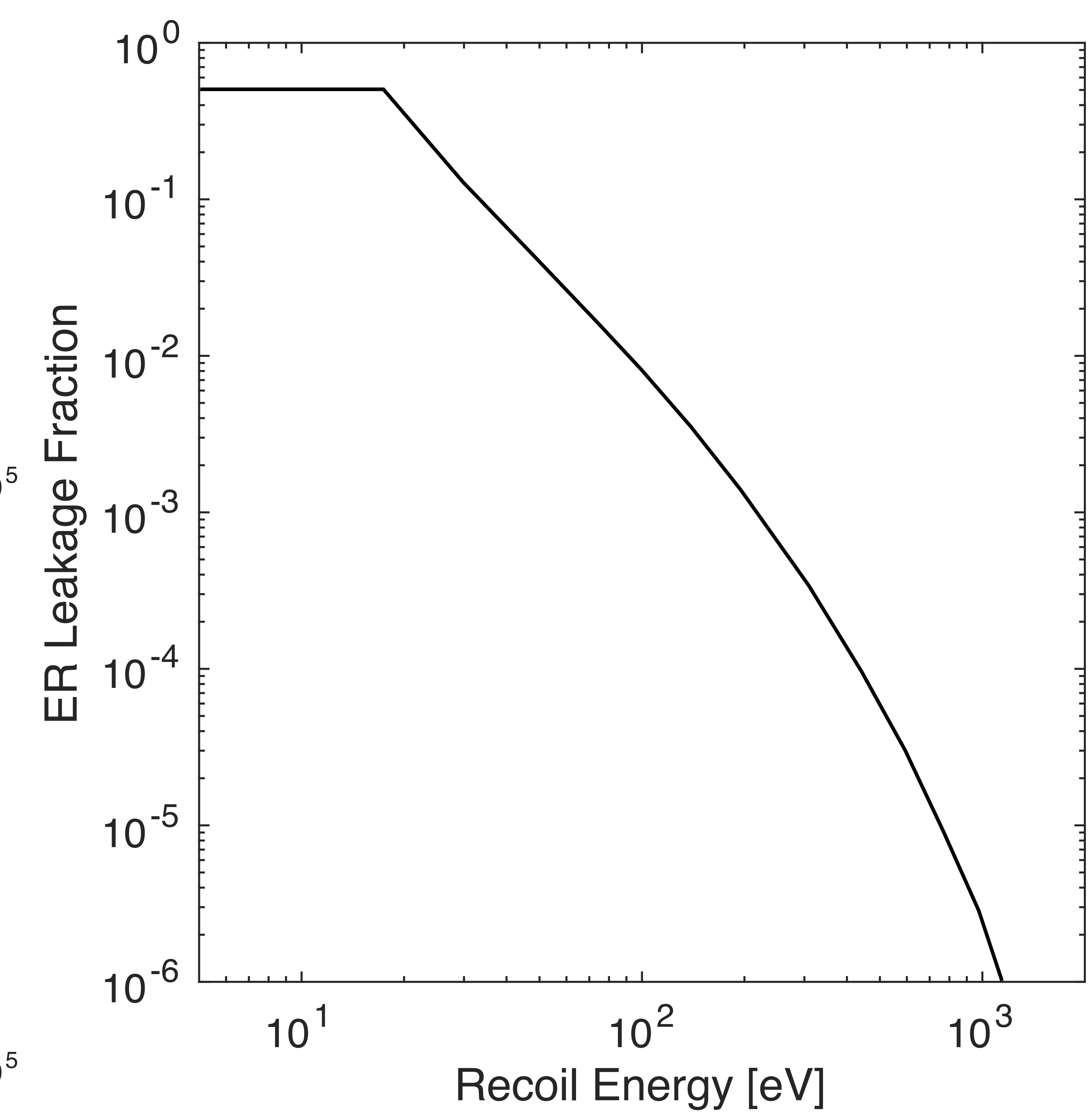
Toy MC detection efficiencies:

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, 1keV range)



Expected Backgrounds

backgrounds included:

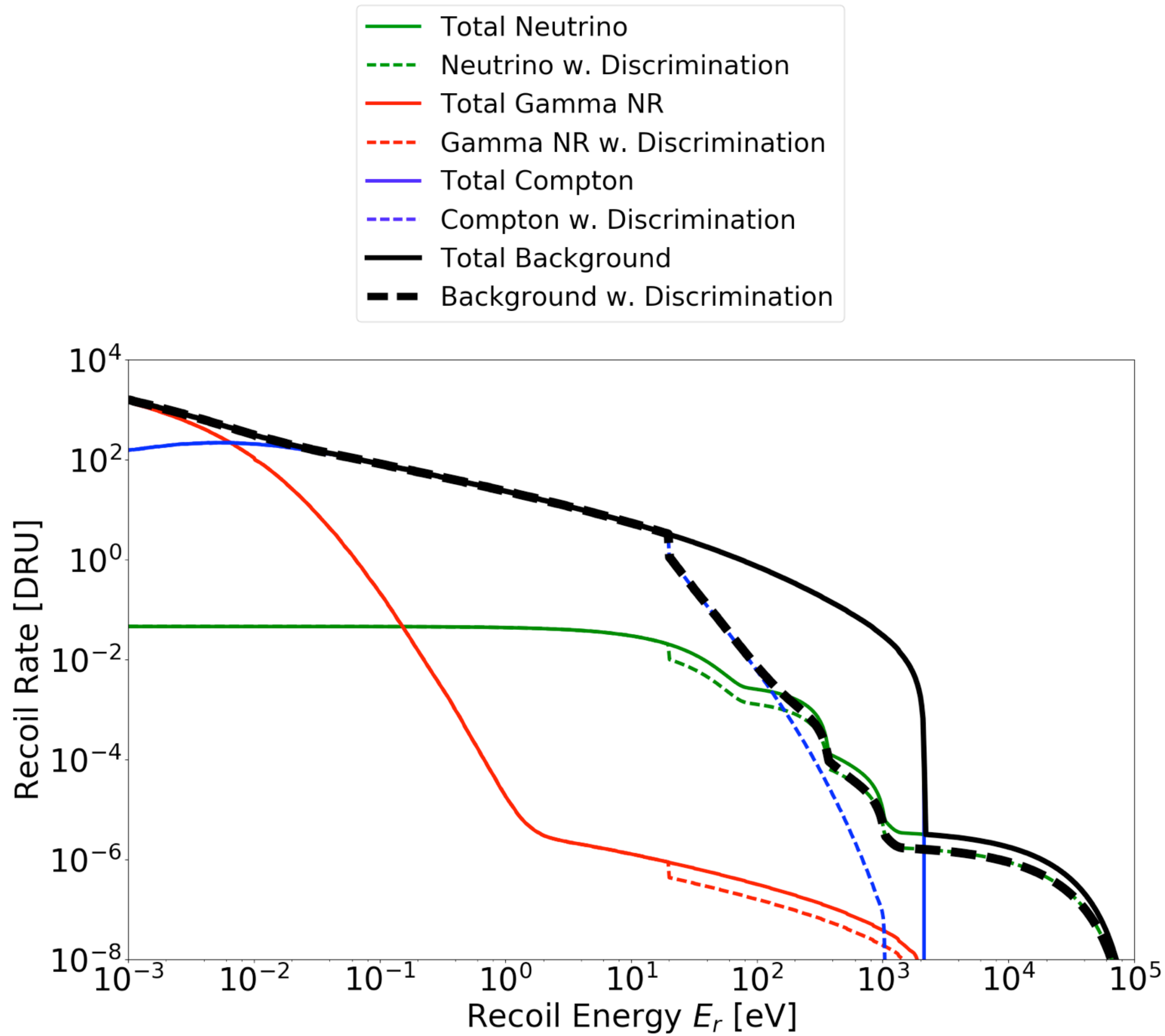
-neutrino nuclear coherent scattering
-gamma backgrounds copy
 SuperCDMS & DAMIC projections
  https://arxiv.org/abs/1610.00006
-note: LHe is naturally itself radiopure

two details:

-excimers allow ER discrimination (>20eV)
-newly-discussed gamma-NR included
  Robinson   Phys. Rev. D 95, 021301 (2017)

arguments for low 'detector' backgrounds:

-low-mass calorimeter, easy to hold
-target mass highly isolated from environment
 (superfluid: friction-free interfaces)



Signal: Standard Elastic NR

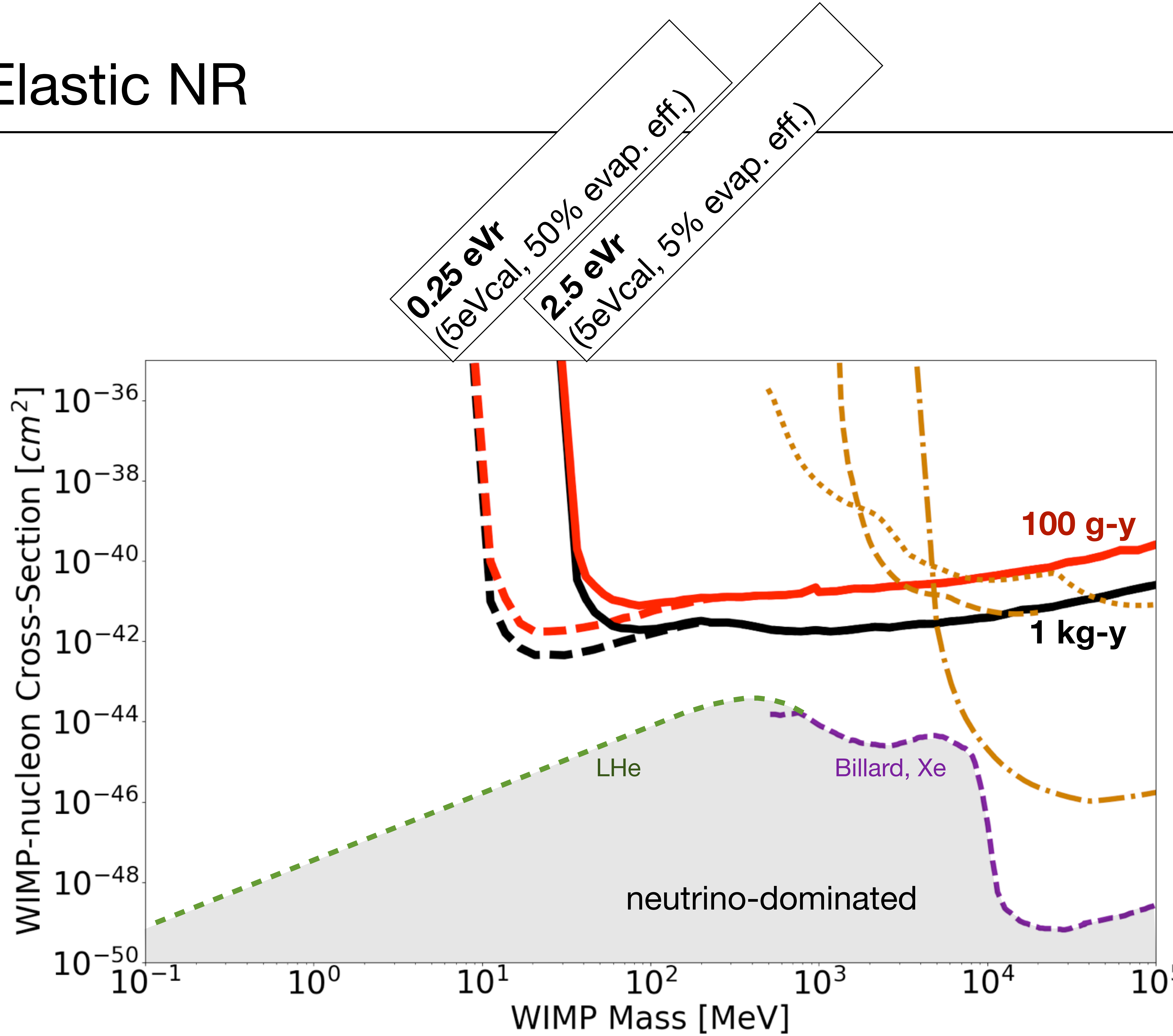
detector parameters assumed

calorimeter threshold of 5eV
(approximately today's abilities)

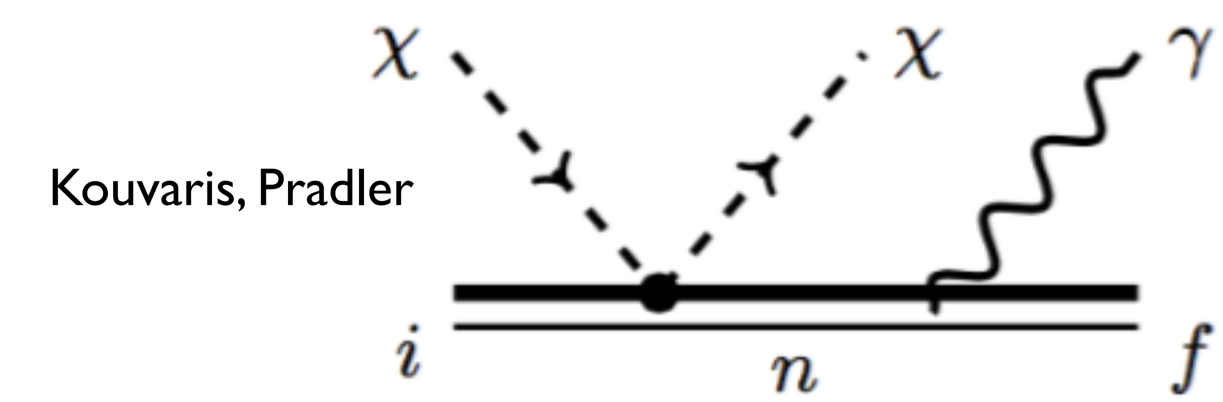
40meV per evaporated atom
(bonding to graphene-fluorine)

5% evaporation efficiency
(already achieved, HERON)

50% evaporation efficiency
(assuming some improvement)



Signal: NR-bremsstrahlung



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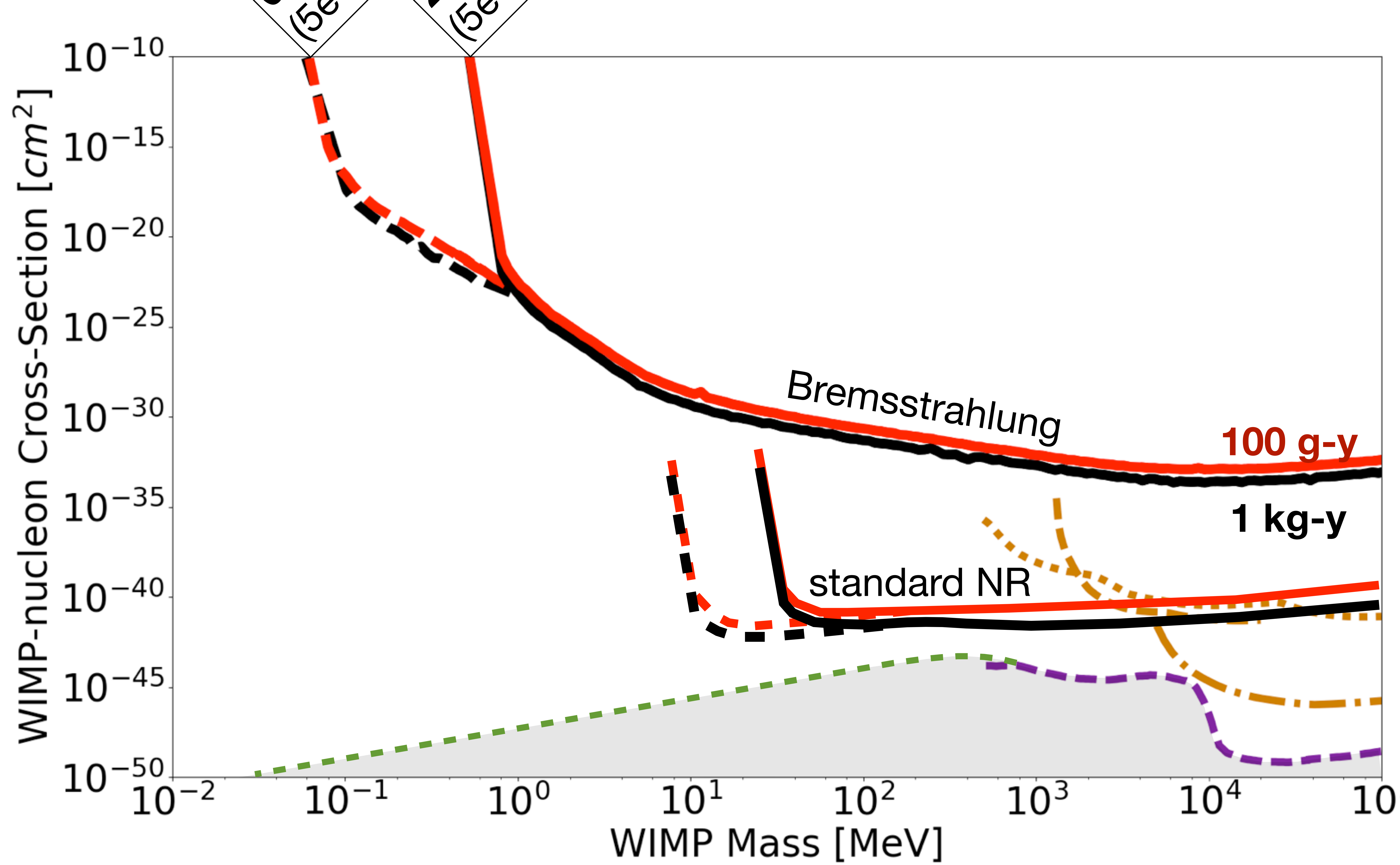
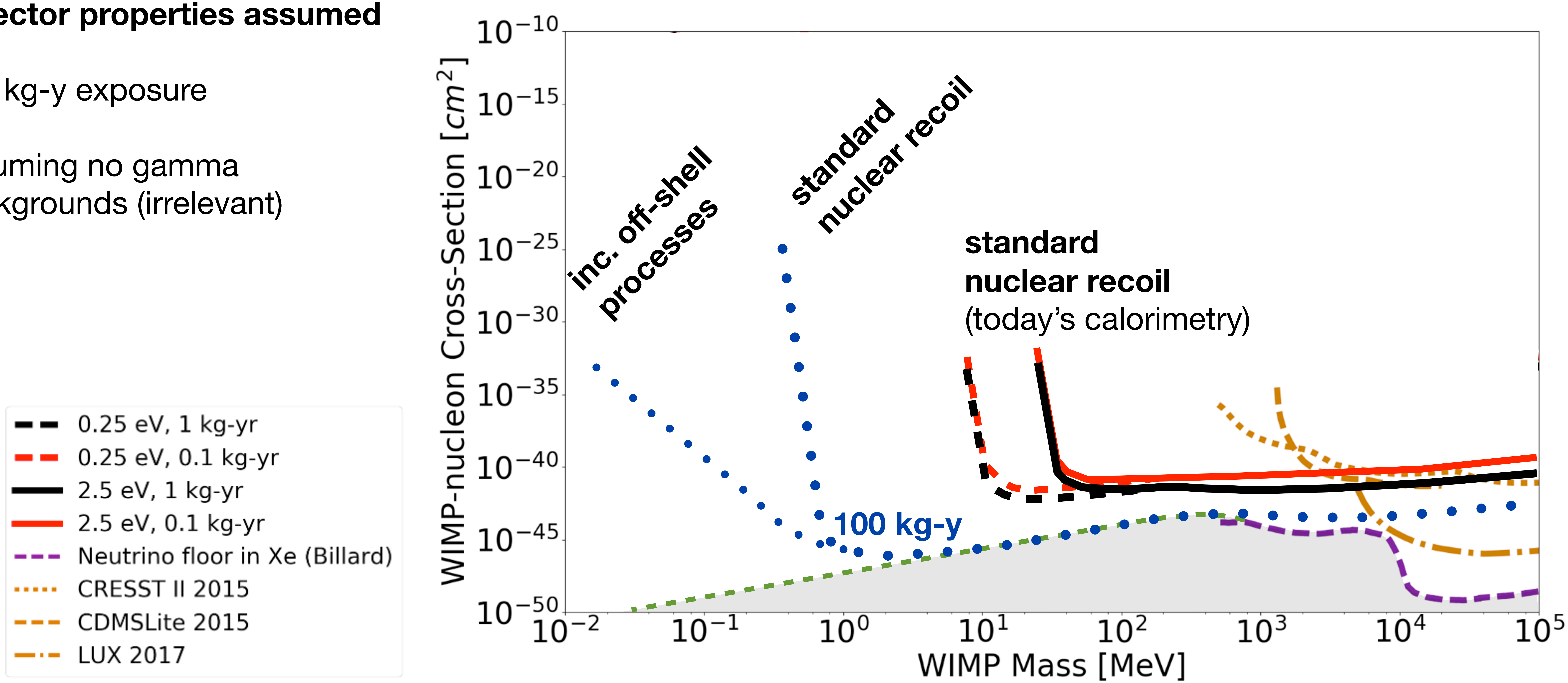


Pushing to Single-Roton Sensitivity

detector properties assumed

100 kg-y exposure

assuming no gamma backgrounds (irrelevant)



A Possible LHe Detector Program

Basic plan:

HERON R&D-like detector underground
(+improved calorimetry)

kg-scale LHe (100g, 10g, still good)
“few” calorimeter channels (<10)
Pb/poly shielding
dry fridge, low manpower operation

Cost: ~$3M

Schedule:

2018 R&D
2019 preliminary design
2020 final design
2020-2022 construction
2022 data-taking

Summary

One of few materials with long-lived observable meV-scale excitations

`Detector backgrounds' : hard to imagine system with lower rate

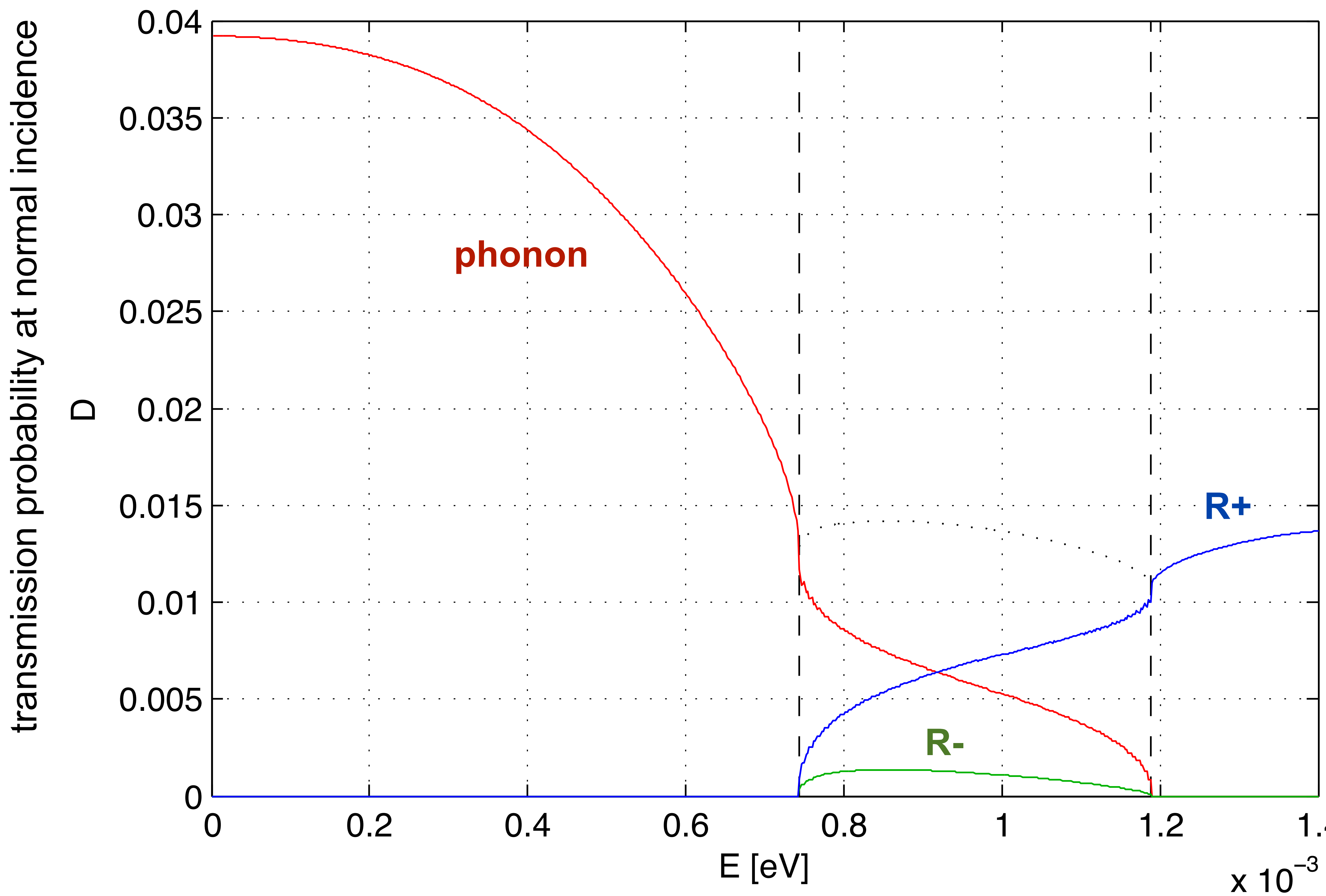
R&D for roton readout largely accomplished
- -HERON R&D for evaporation channel
- -Calorimeter R&D by CDMS, CRESST, etc.

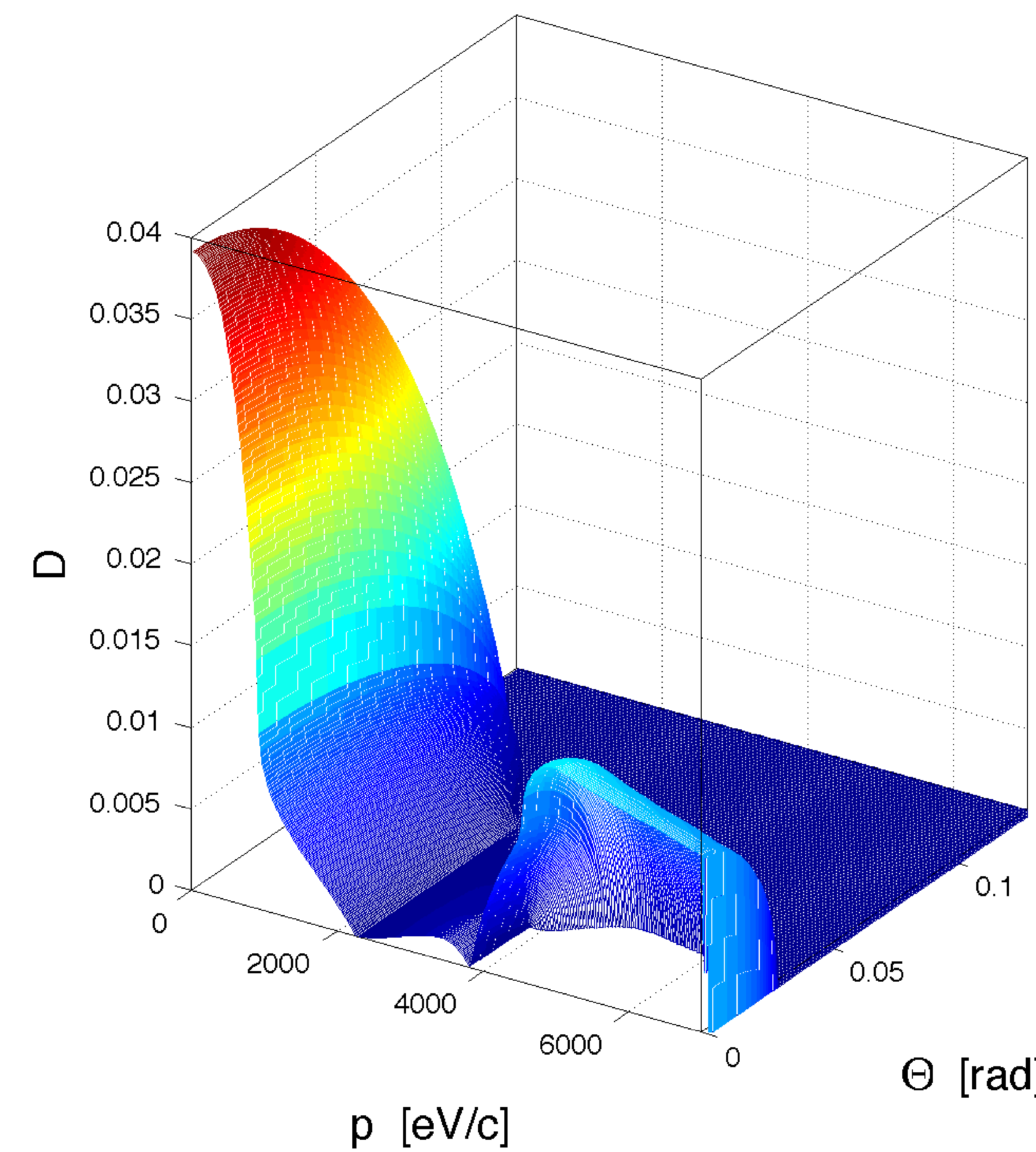
Of the few-million-dollar scale

extra slides

kapitza resistance

Even when kinematically allowed, still only percent-level probability.

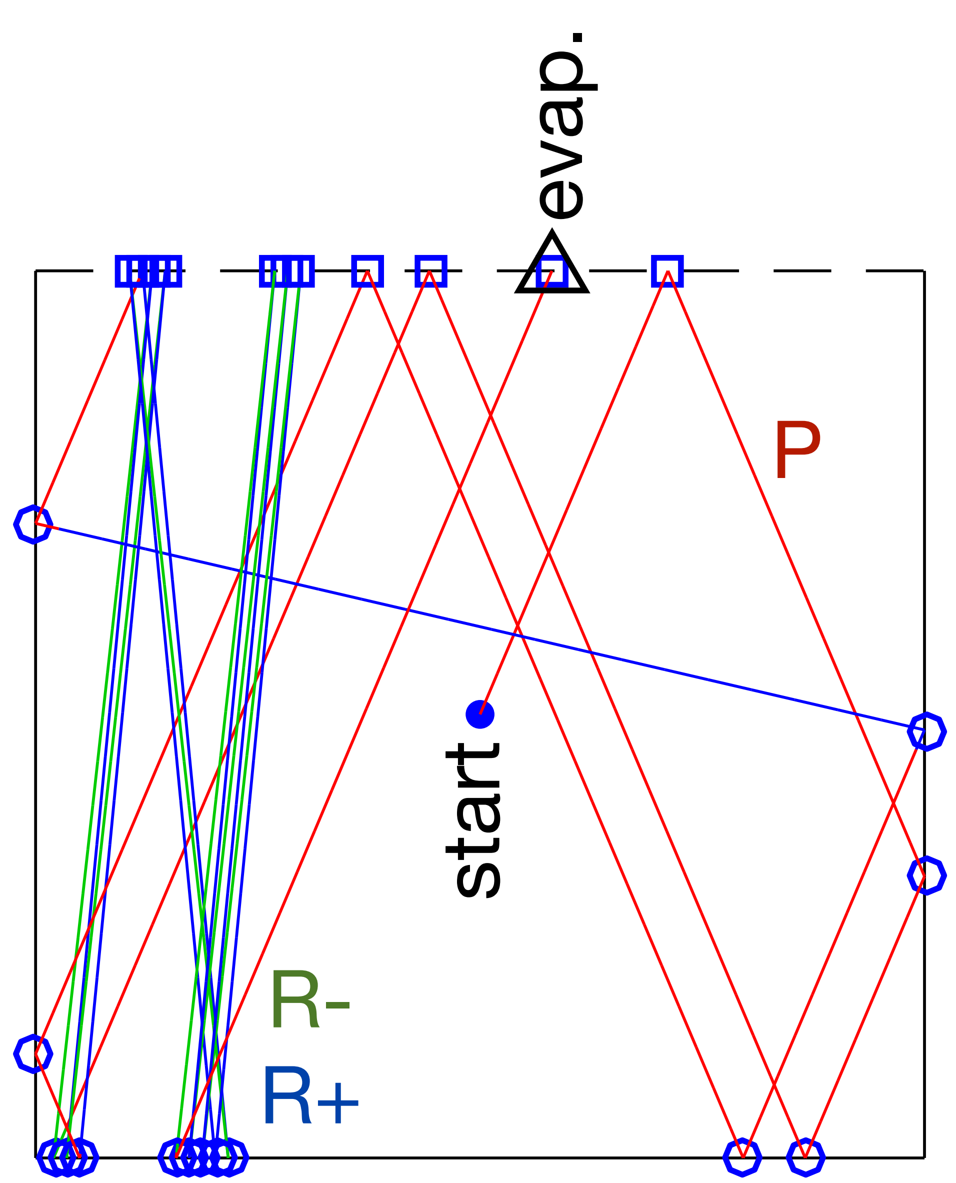




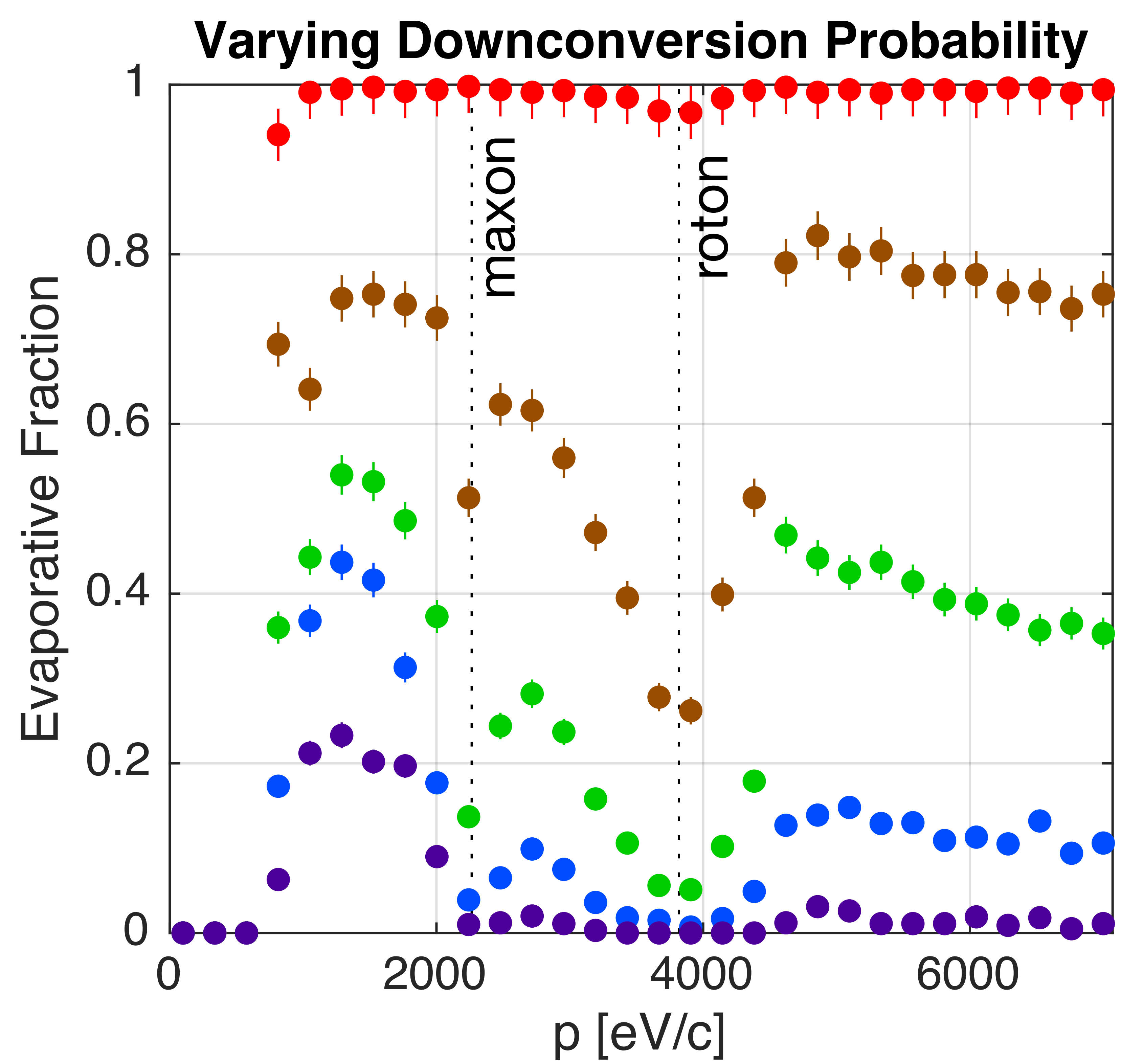
using arXiv:1004.3497v1

bouncing quasiparticles

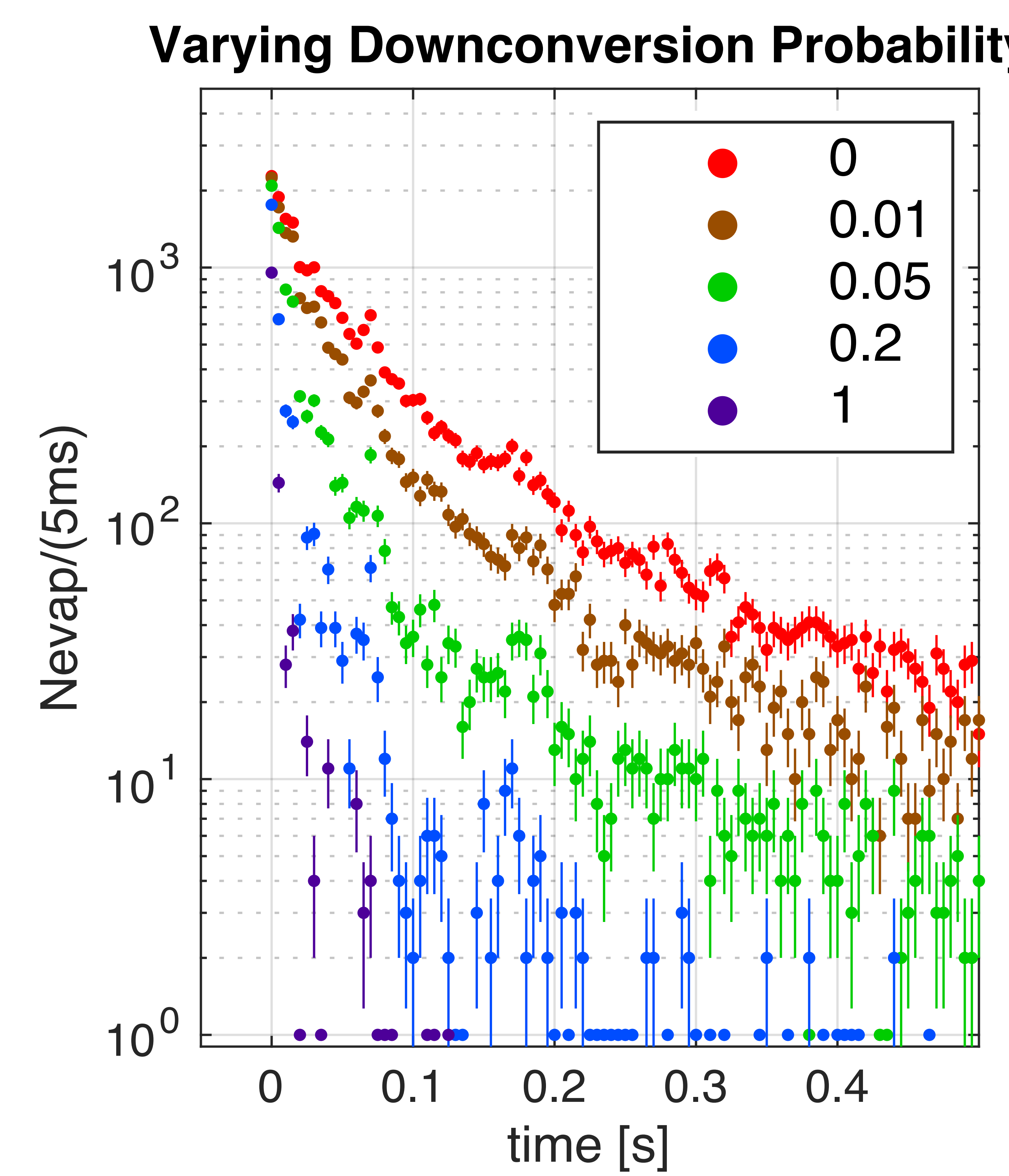
A toy MC was constructed to bounce excitations around a kg-scale volume.



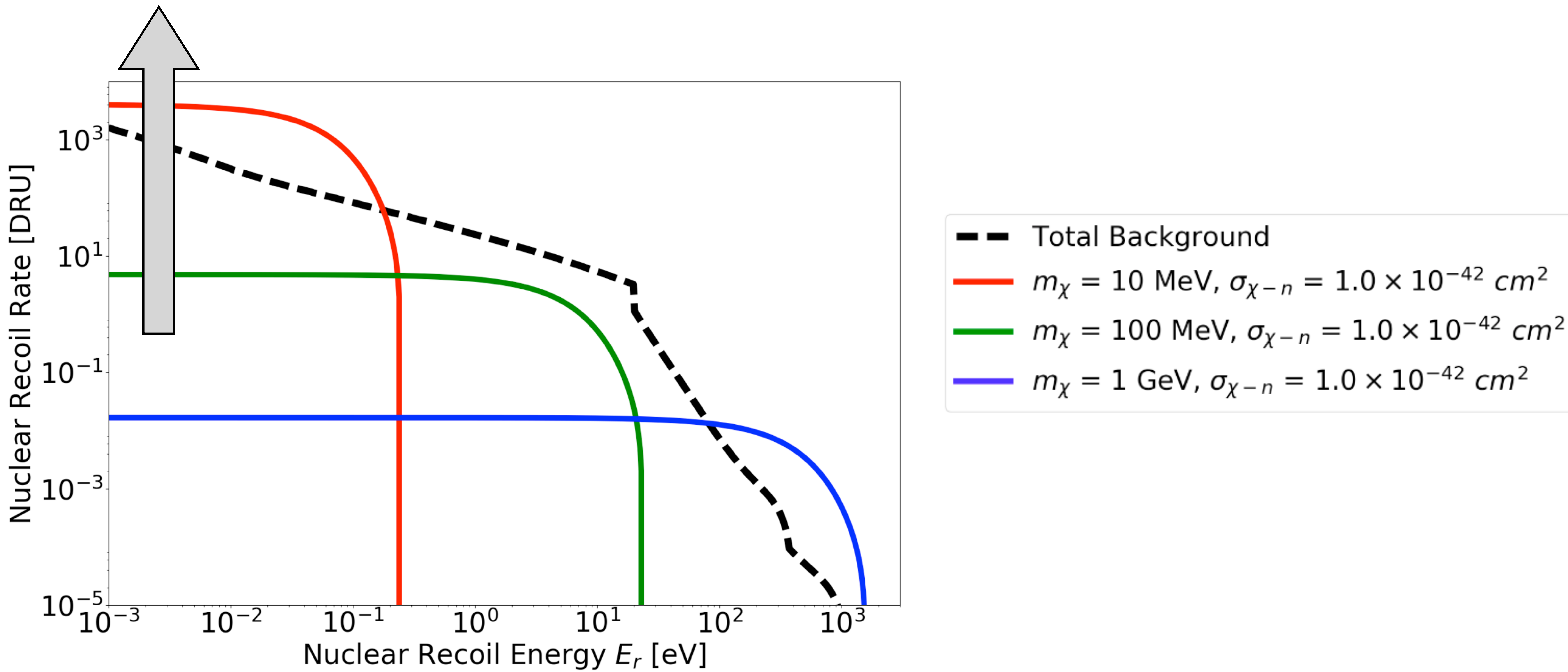
We plot evaporation efficiency as a function of initial momentum and a generic downconversion probability.



Timescales are 10-100ms (depending on downconversion)

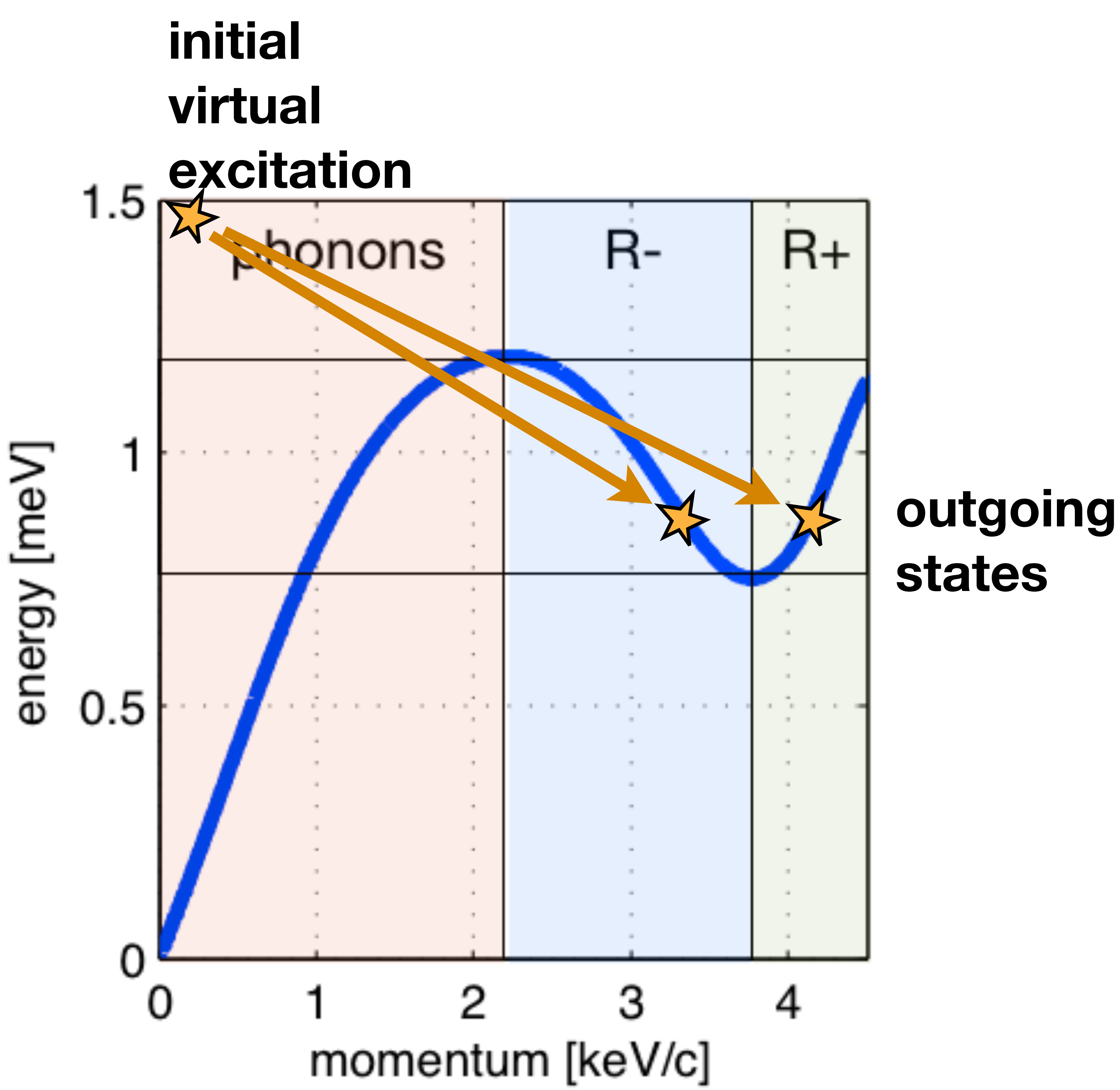


general point: particle backgrounds irrelevant to lowest masses



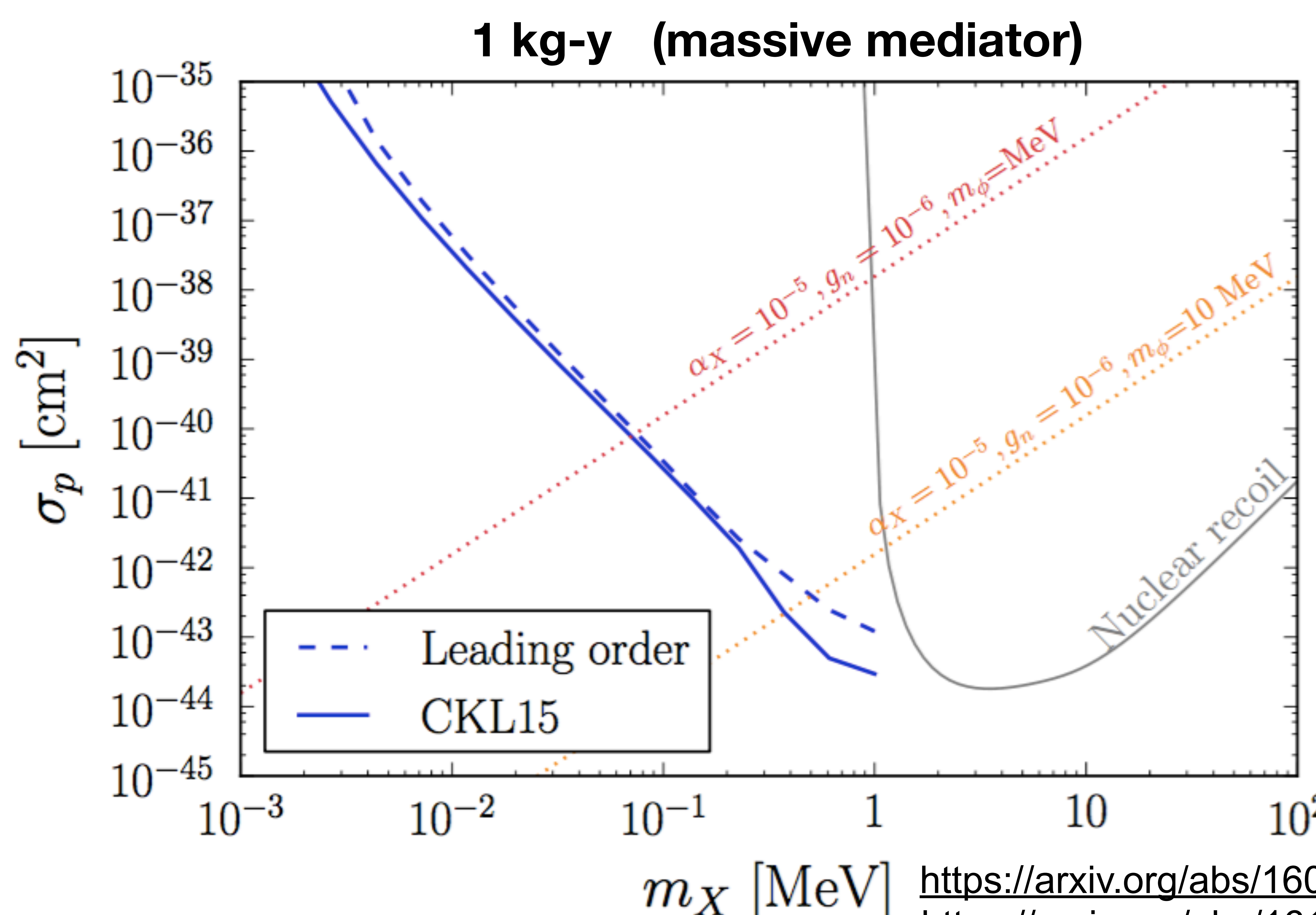
production of “off-shell” excitations

recoil can produce a virtual quasiparticle
(above dispersion curve)



better kinetic branch for light dark matter:
high energy / low momentum

-> MeV threshold reduced into keV range



https://arxiv.org/abs/1604.08206
https://arxiv.org/abs/1611.06228

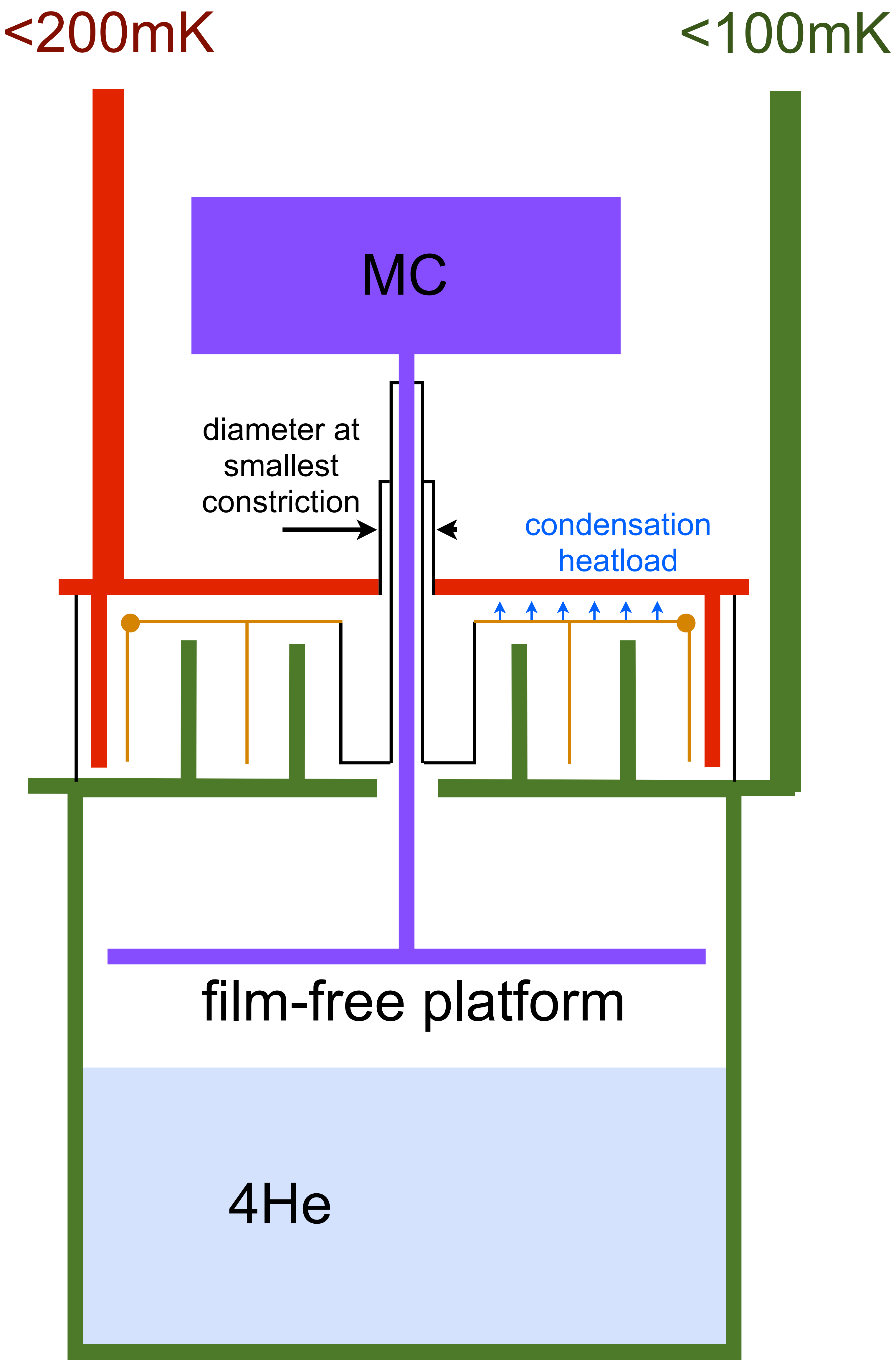
film burner (copied directly from the HERON R&D)

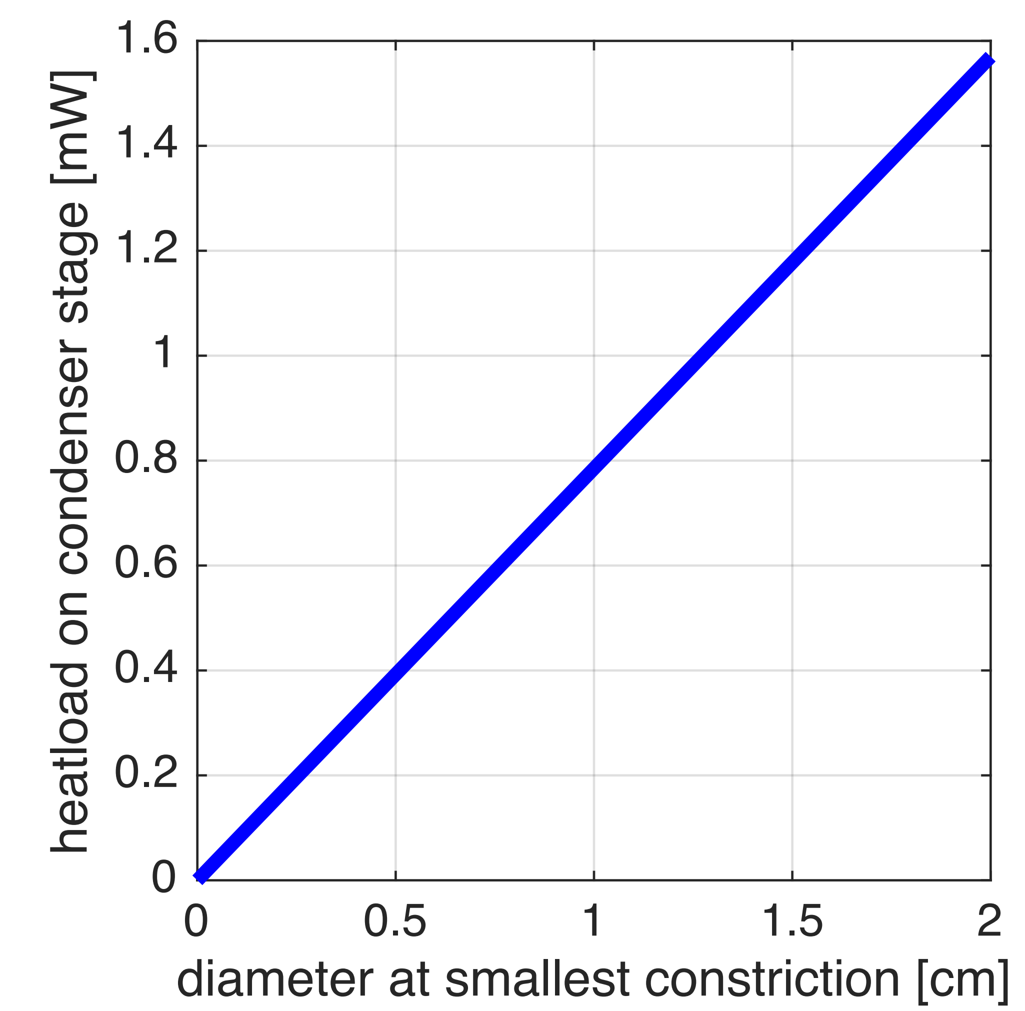
black:
stainless steel for thermal isolation

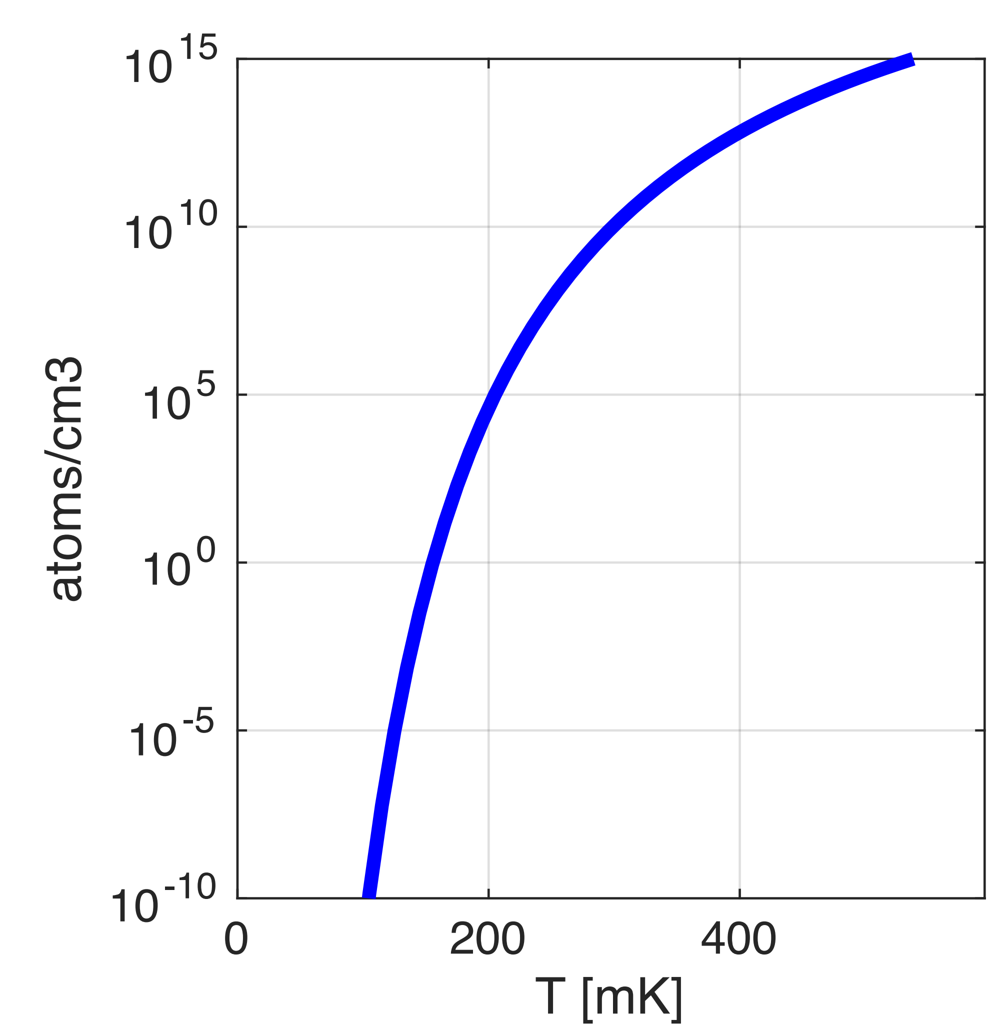
orange:
"evaporator" surface
isolated heated copper at ~500mK
minimal heatload

red:
"condenser" stage
order 1mW of condensation
(for order 1cm-diam film)
order 200 mK (higher temperature produces a higher vapor pressure, which places a condensation heatload on the green stage)

green:
4He bath stage, ideally <100mK
heatload only due to leakage of 4He vapor from the condenser, can be extremely small

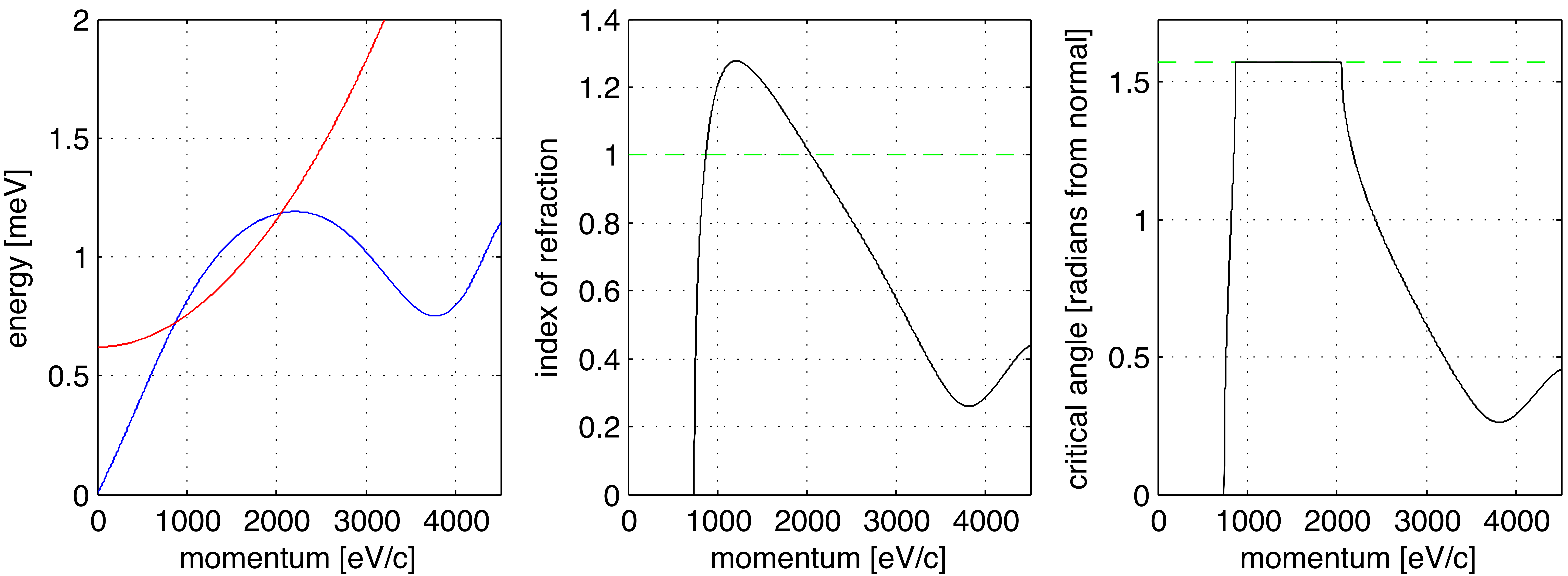






quantum evaporation: kinematically-allowed incident angles

punchline: phonon branch always at a useful angle.
roton branch useful only after translation to phonon branch



below the atomic excitation energy:
can we pull out the qp momentum distribution?

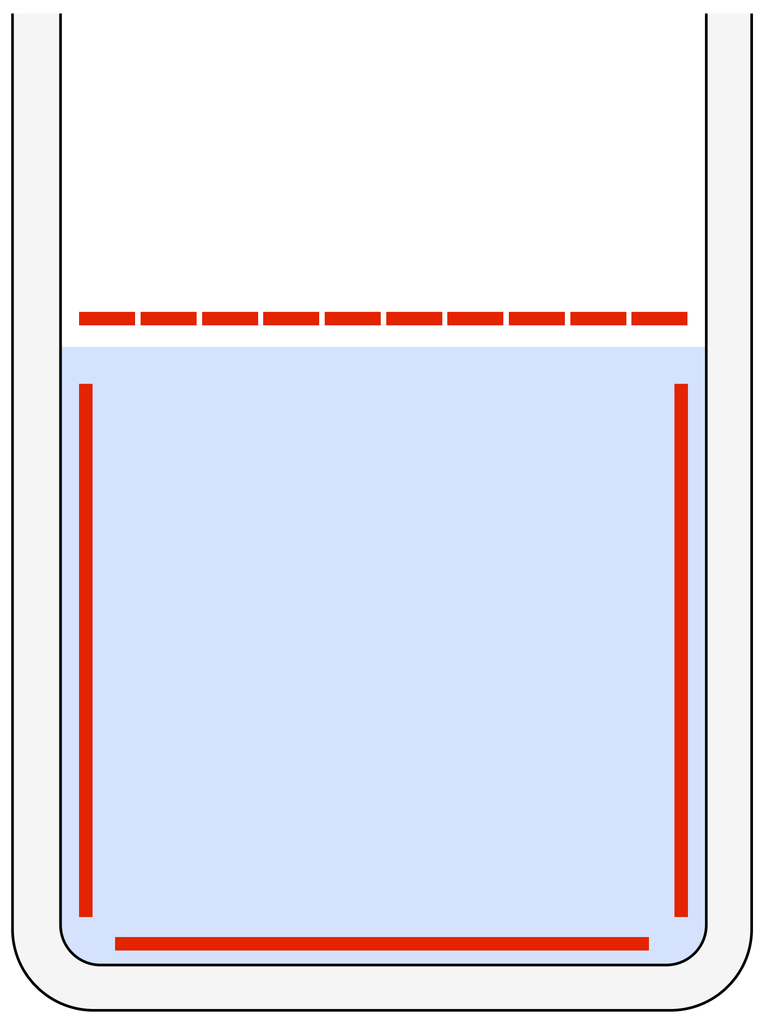
nuclear recoil quasiparticle momentum spectrum: not understood, not measured

BUT: initially-produced population is self-interacting.
easy to imagine that qp distribution cools, dependent on dE/dx

information 1: ratio above/below evaporation threshold

information 2: arrival timing & pulseshape (use $v_{(p)}$)

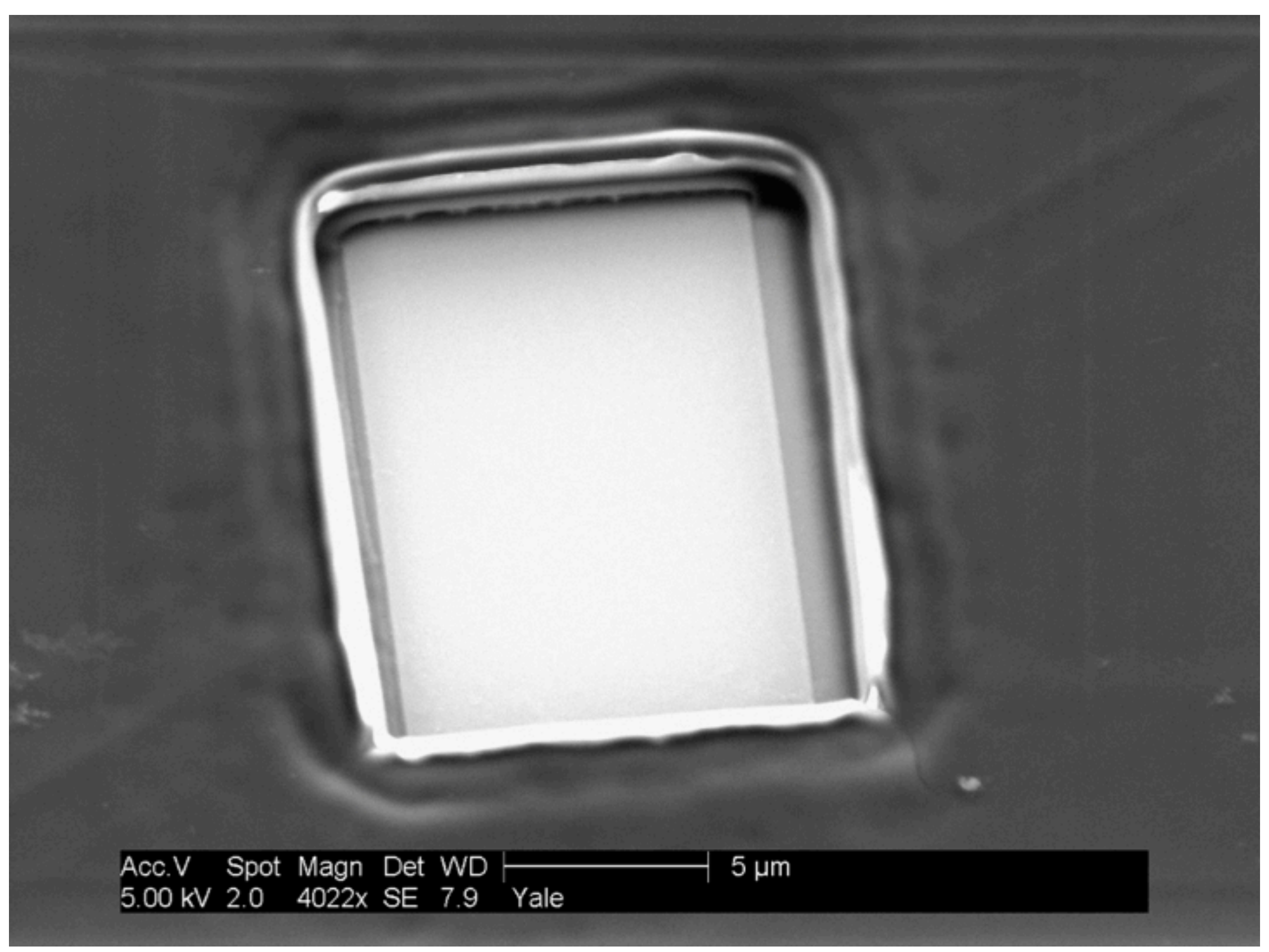
information 3: use evaporative refraction angle distributions

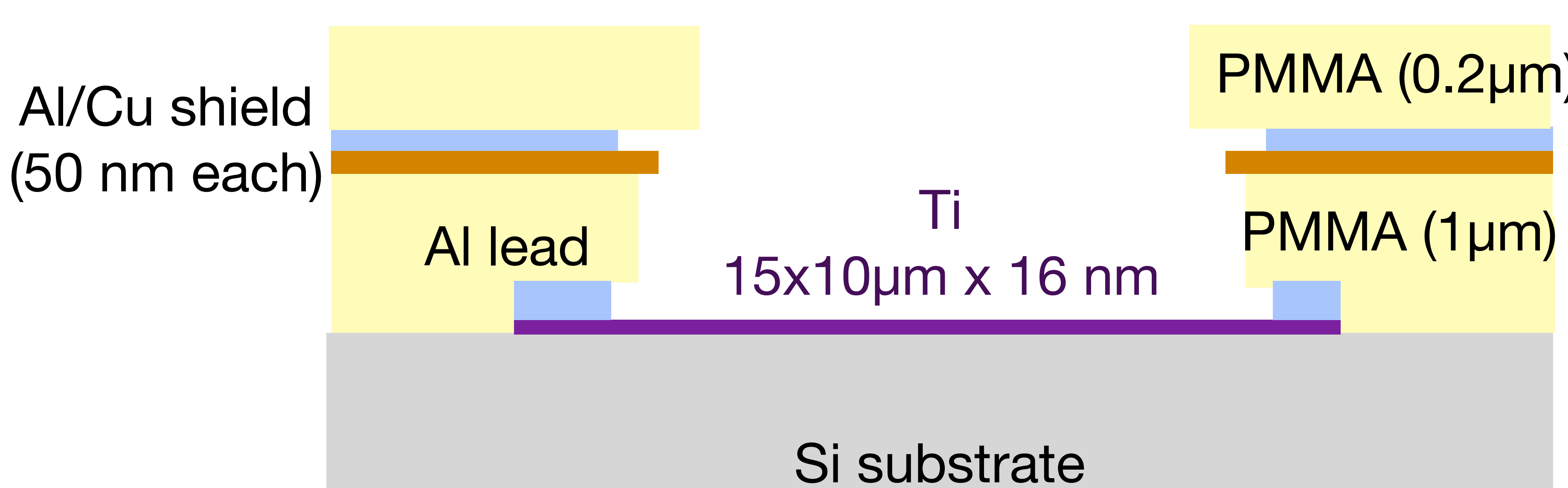


Some details on the Yale experiment

Of course the surrounding material was acting as a collection surface of variable collection efficiency.

To enhance resolution, we shielded the surrounding surface using layers of insulator and metal.

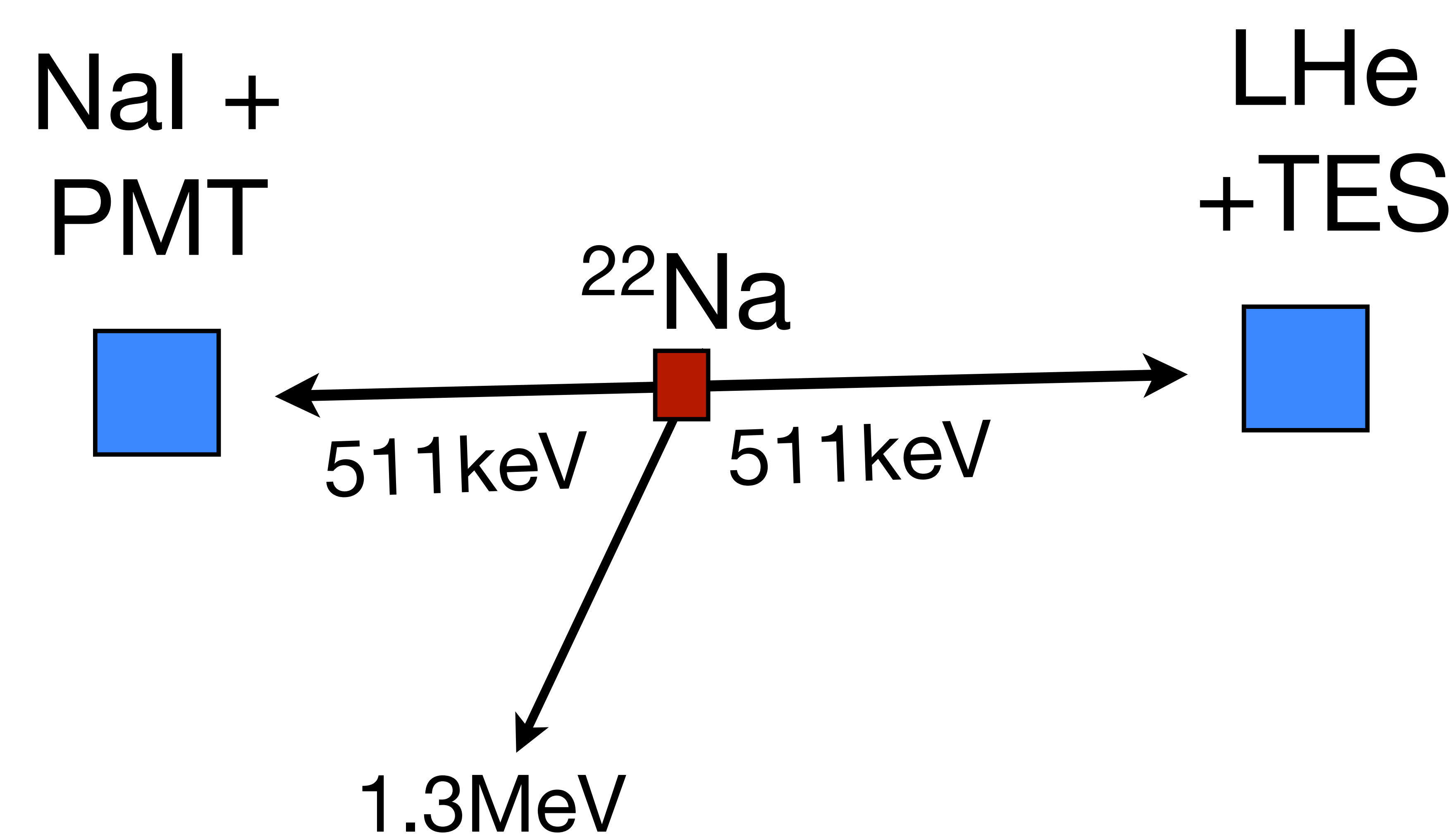




We employed an essential trick to group triggers into categories:

PMT-coincident: prompt (singlet photon)

non-coincident: delayed (triplet molecule) (+untagged photons)

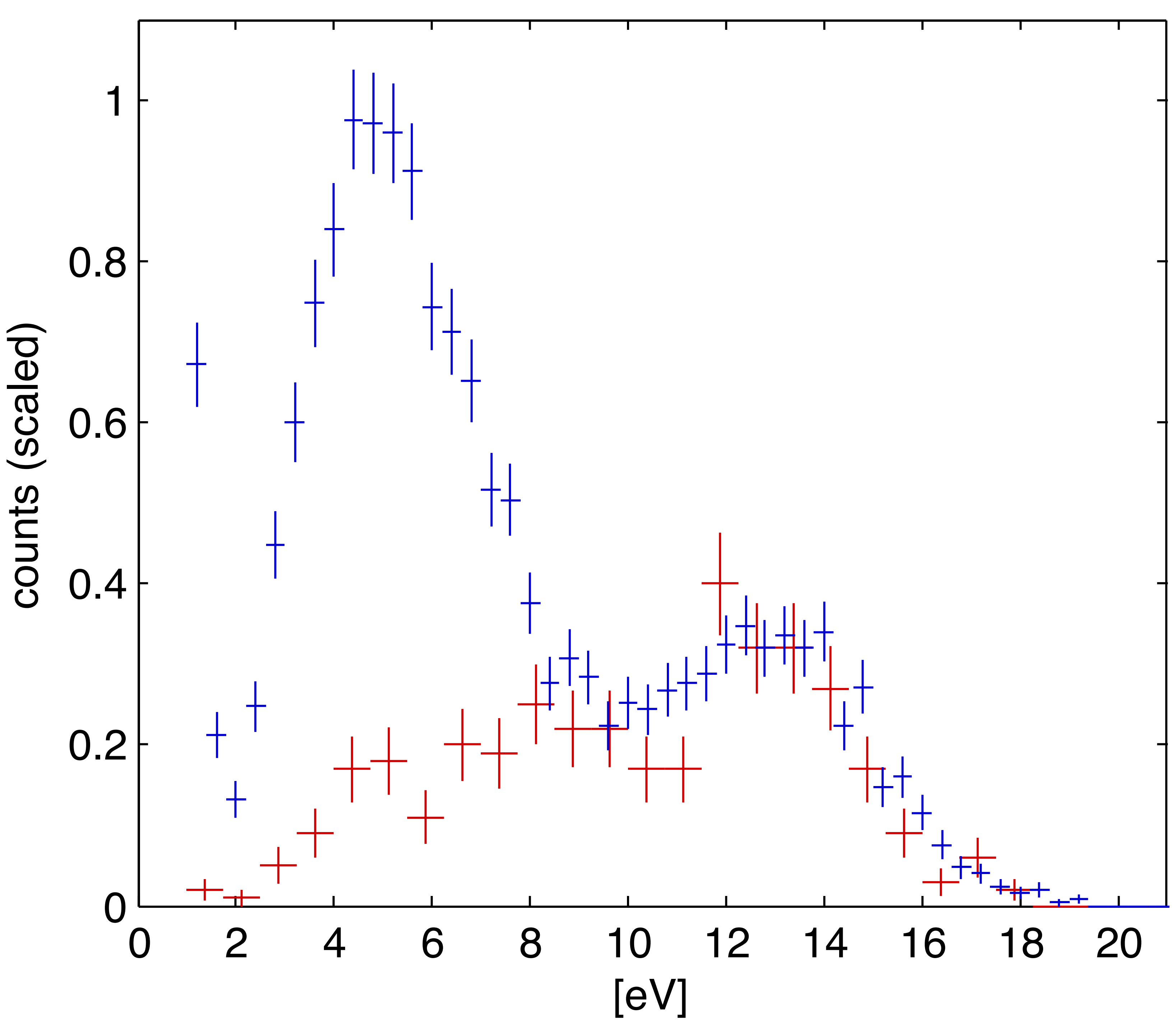


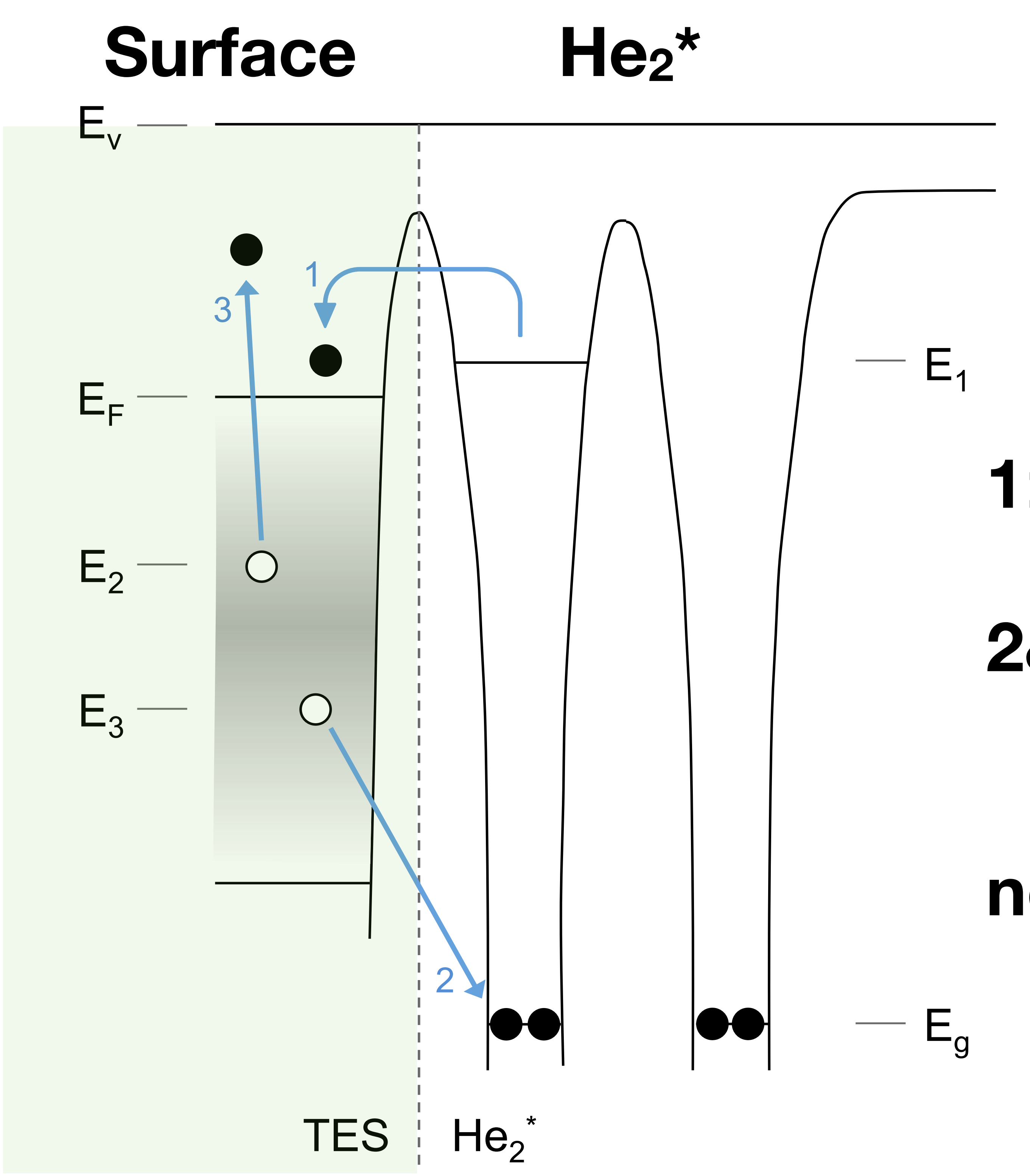
triplet excimer quench signal

Observation: \`prompt‘ population shows peak near expected energy, with a degraded tail.
\`delayed‘ population shows a new peak at a few eV.

Conclusion: triplet excimers drop some fraction of their energy into the calorimeter surface.
the excimer decays through electron exchanges with surface

red: photons only
blue: photons + triplet molecules





arxiv:1605.00694

1: resonant ionization

2&3: auger neutralization
(auger energy lost)

not shown: electrons falling into the holes (what we see)