

HeRALD: direct detection with superfluid ^4He

He Roton Apparatus
for Light Darkmatter

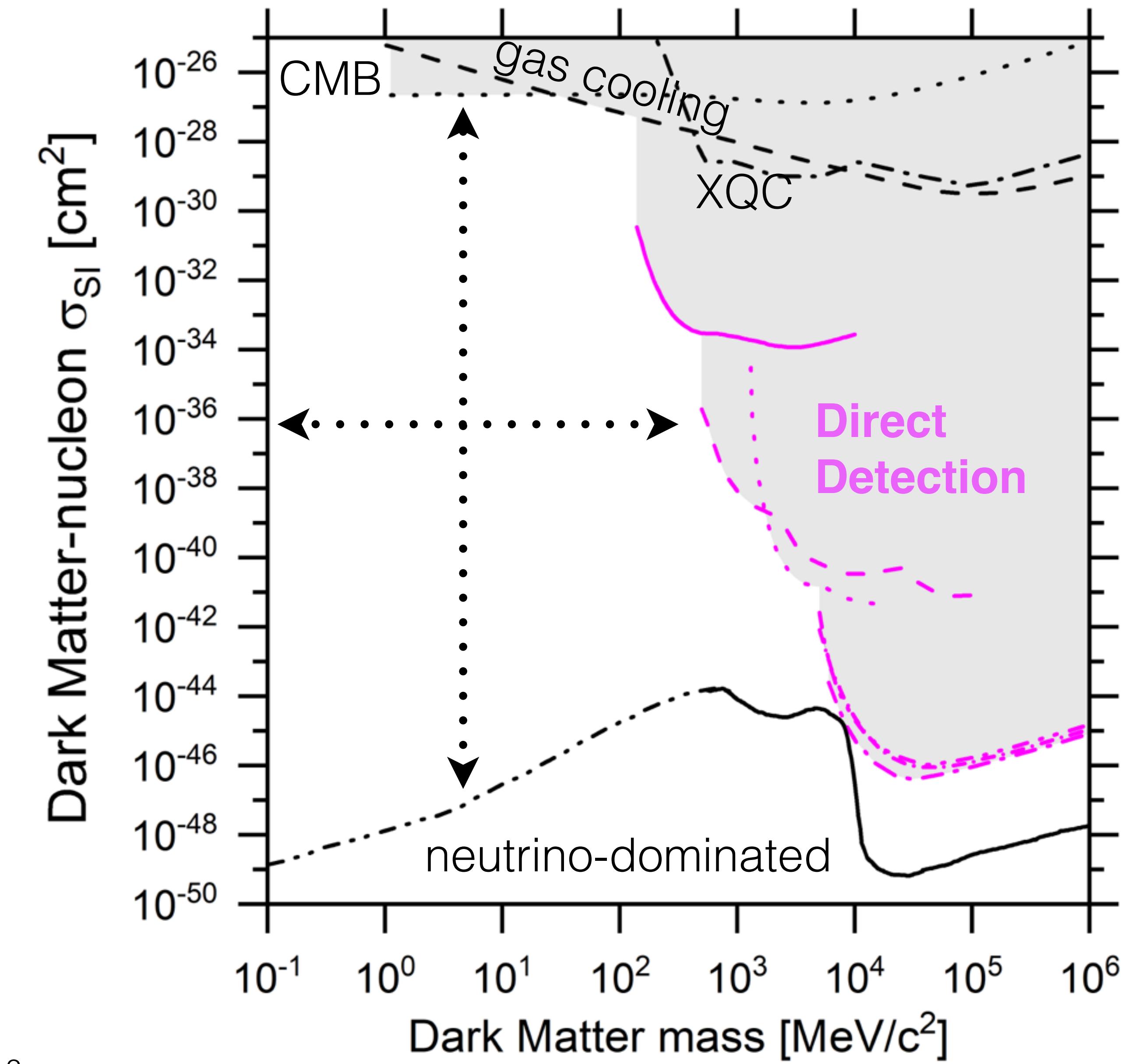
UMASS
AMHERST

Berkeley
UNIVERSITY OF CALIFORNIA

Scott Hertel
IDM 2018

Superfluid ^4He : top-level summary

Difficult Goal: keV-MeV scale mass
hadronic interactions
(typically a phonon-only regime)

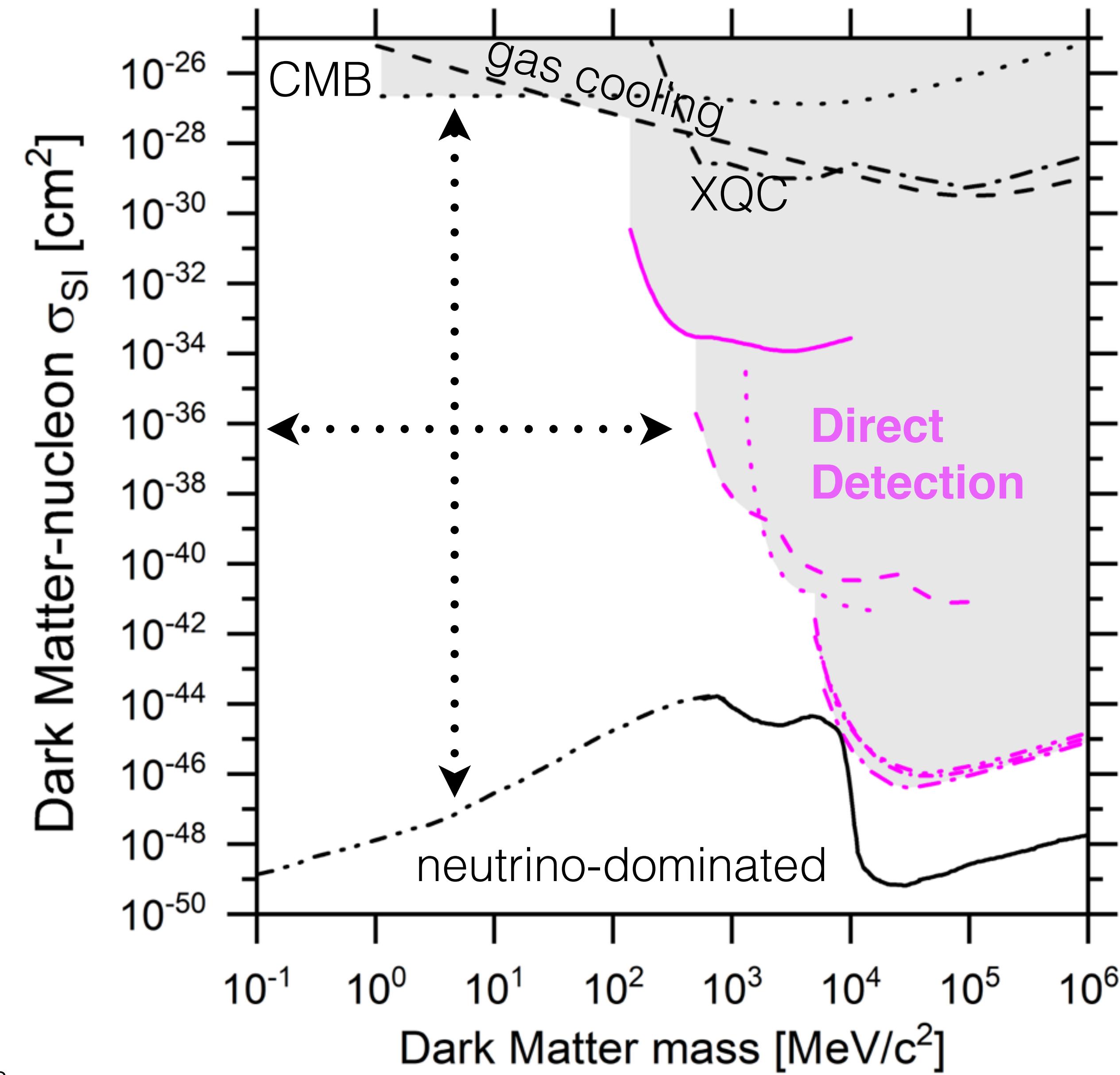


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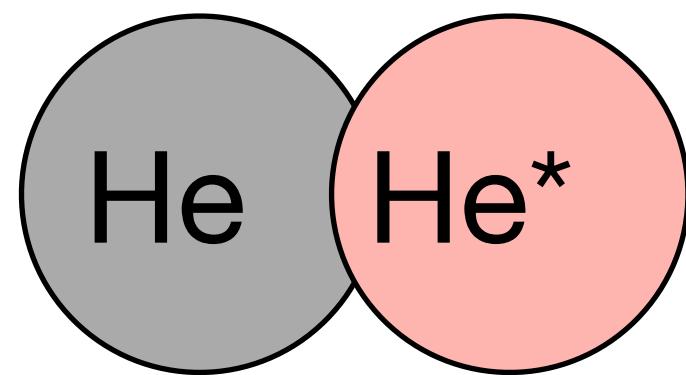
4He Target:

1. Low-mass (enhancement of energy scale)
2. Superfluid supports phonon-like excitations (plus, diatomic excimers like any noble)
3. mK temperature allows bolometric sensing (sensors with no dark rate)
4. Isotopically pure material (^3He removal ‘easy’)
5. Unique vibrational isolation from environment



Atomic excitations in ${}^4\text{He}$

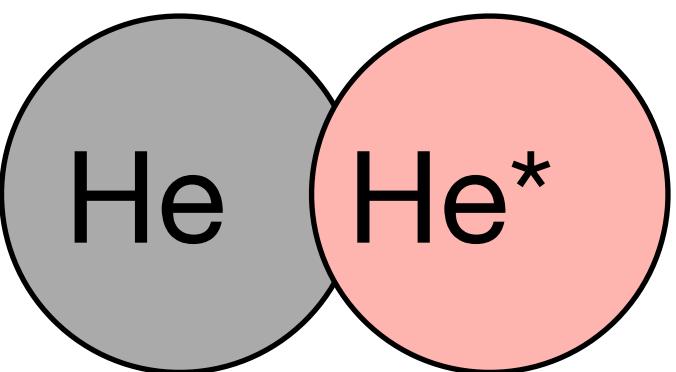
To first order, same as other nobles



$\sim 16 \text{ eV}$

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To second order....

Singlet state

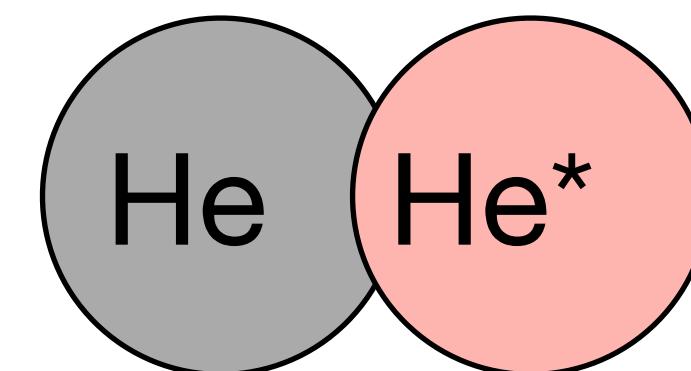
ns decay timescale

observable as scintillation

EUV, no reflection possible

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Triplet state

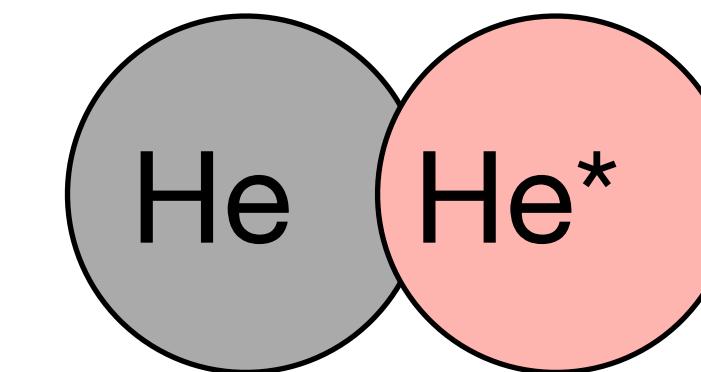
13s half-life (!)

ballistic in superfluid, $\sim 10\text{m/s}$

quenches on solid surface

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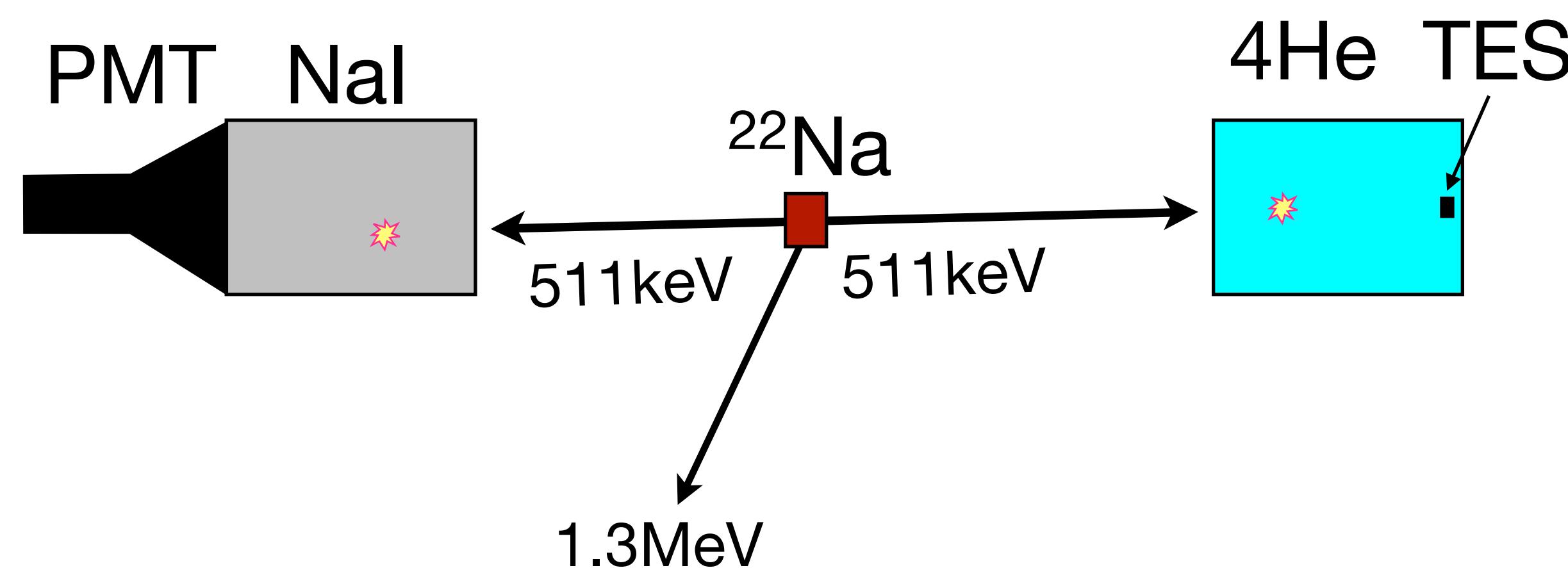
Assuming 4π coverage by eV-threshold calorimetry, both states sensed with $\sim 100\%$ efficiency.

Atomic excitations in ^4He

Bolometric sensing demonstrator

arxiv:1605.00694

expectations going in:

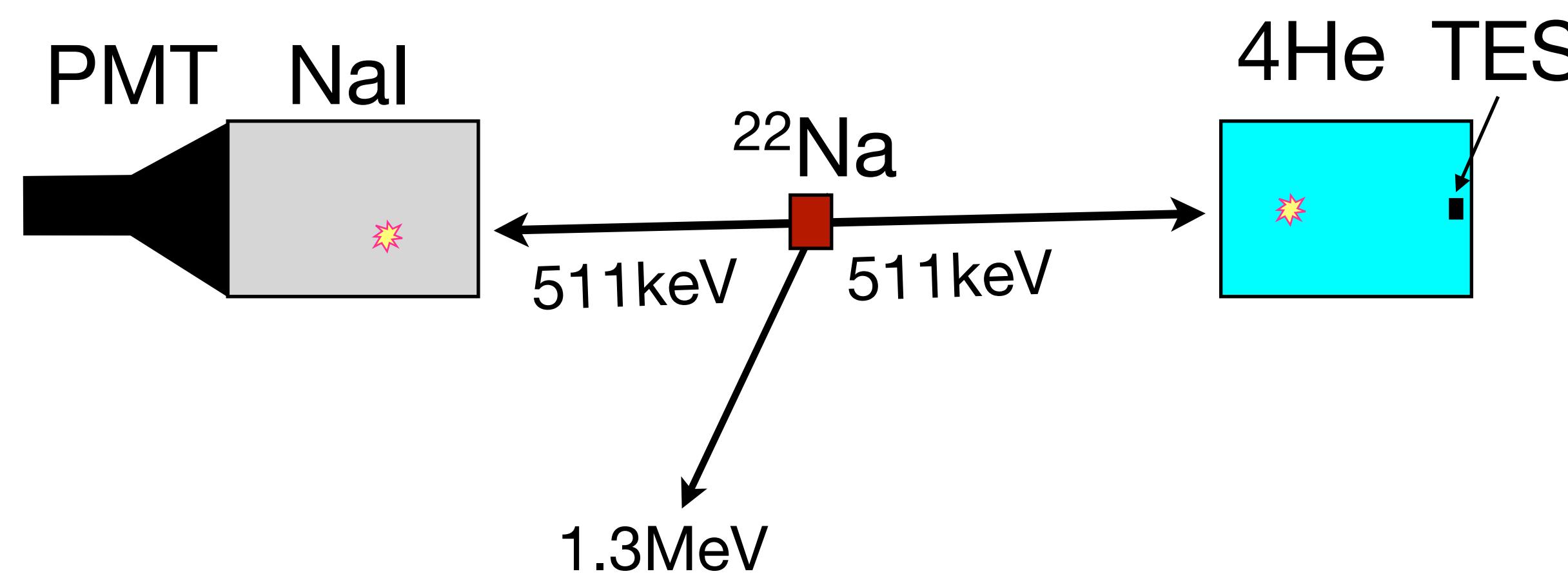


- max 1 signal quantum per recoil (microscopic TES area)
- singlet photons coincident with Nal
- triplet molecule quenches delayed

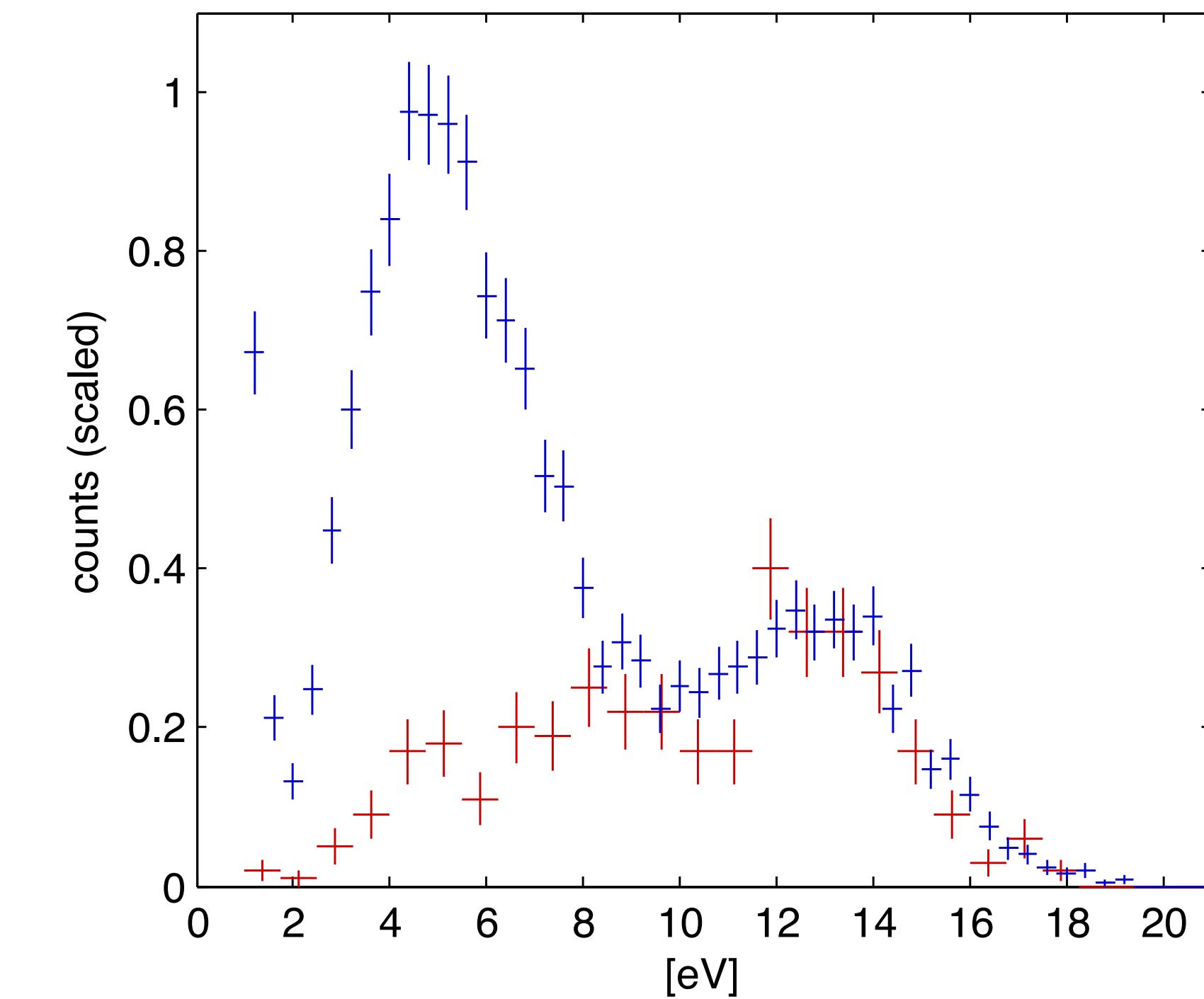
Atomic excitations in ^4He

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arxiv:1605.00694



red: Nal-coincident (singlet photons only)
blue: non-coincident (photons + triplet molecules)

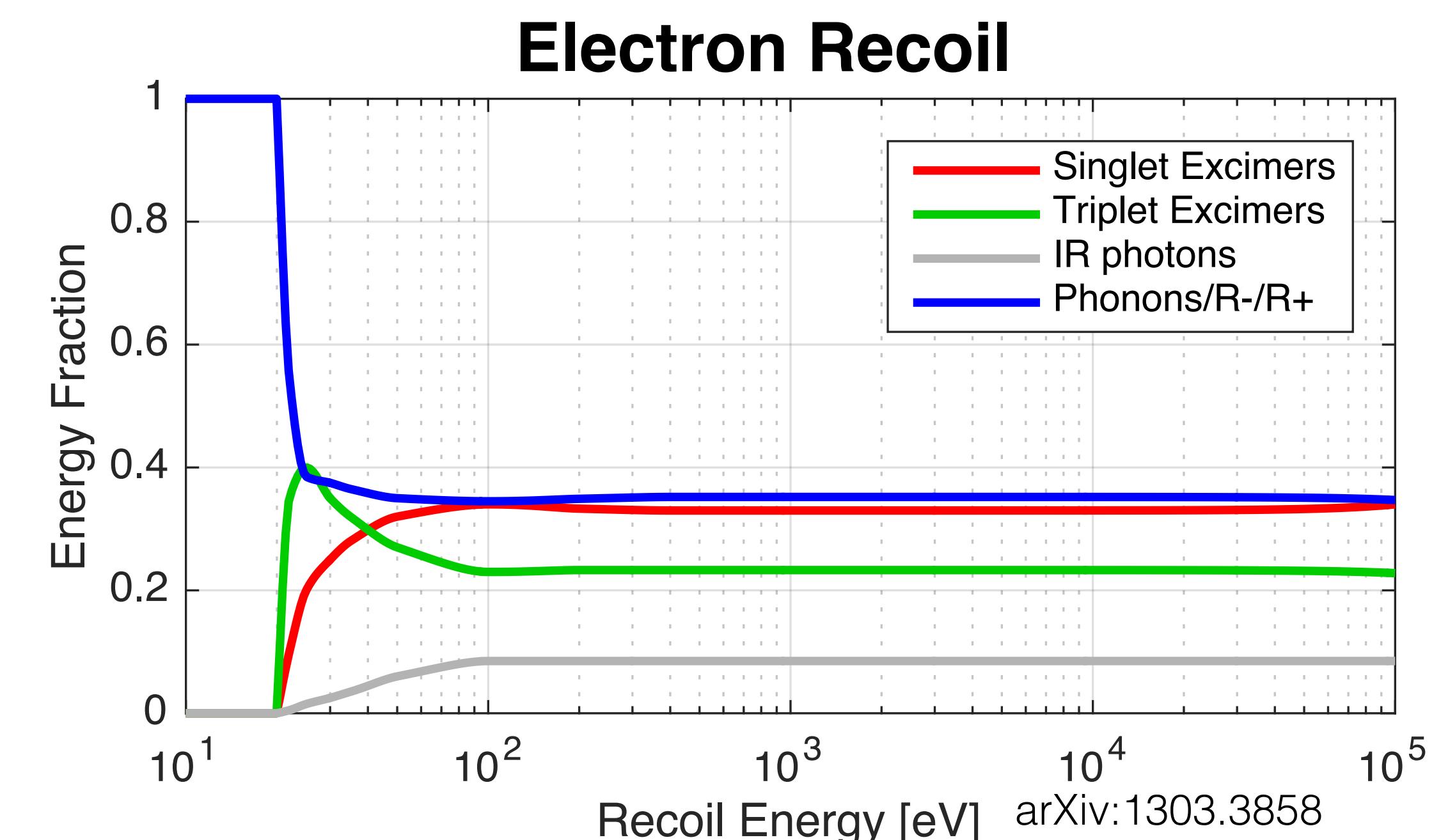
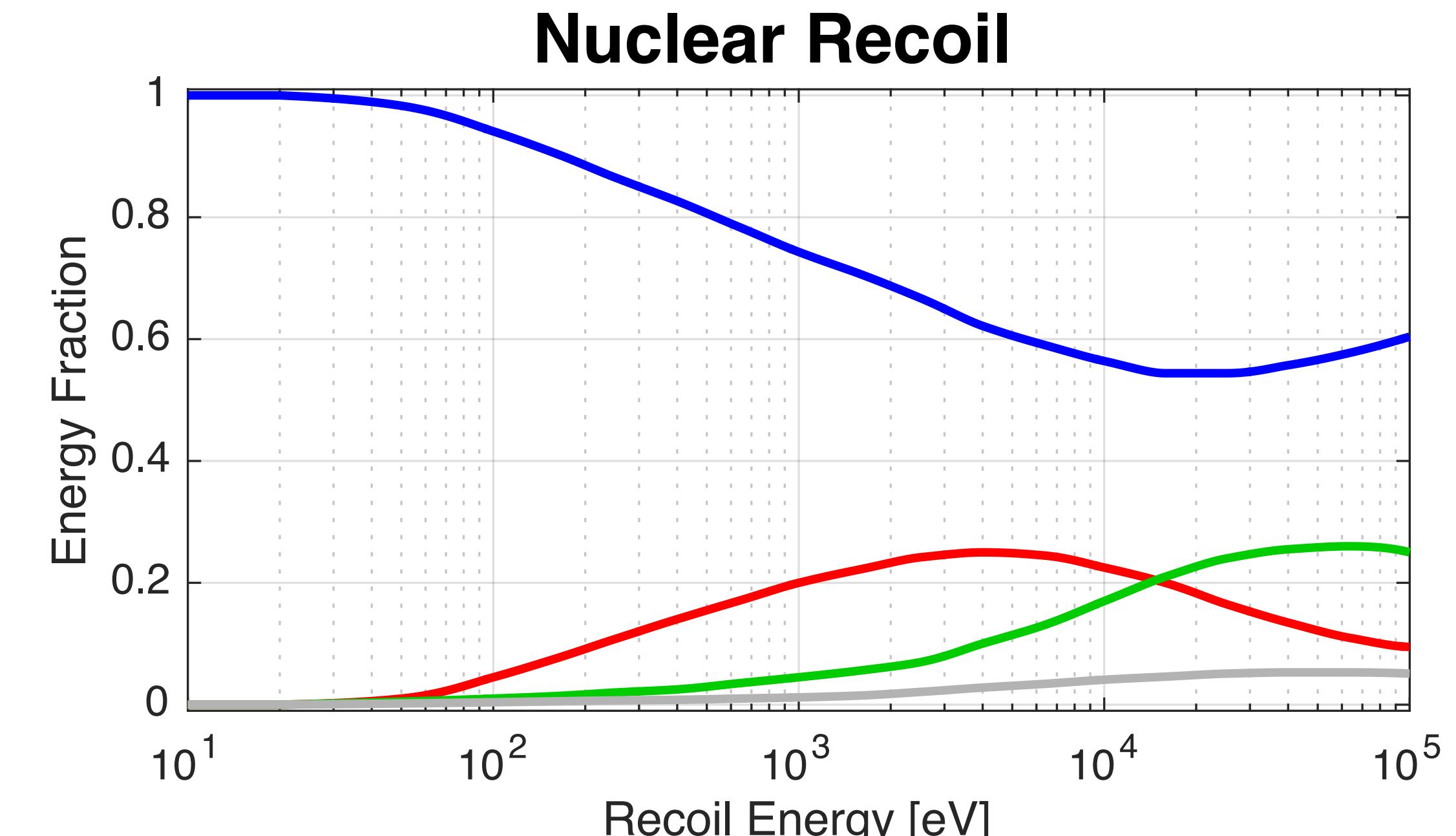


Atomic excitations in ^4He

Excimer Yield

In the ^4He case, excitation cross sections well-measured
(atomic beam experiments)

NR and ER yields predicted to be impressively high...
and impressively *different*.



Atomic excitations in ${}^4\text{He}$

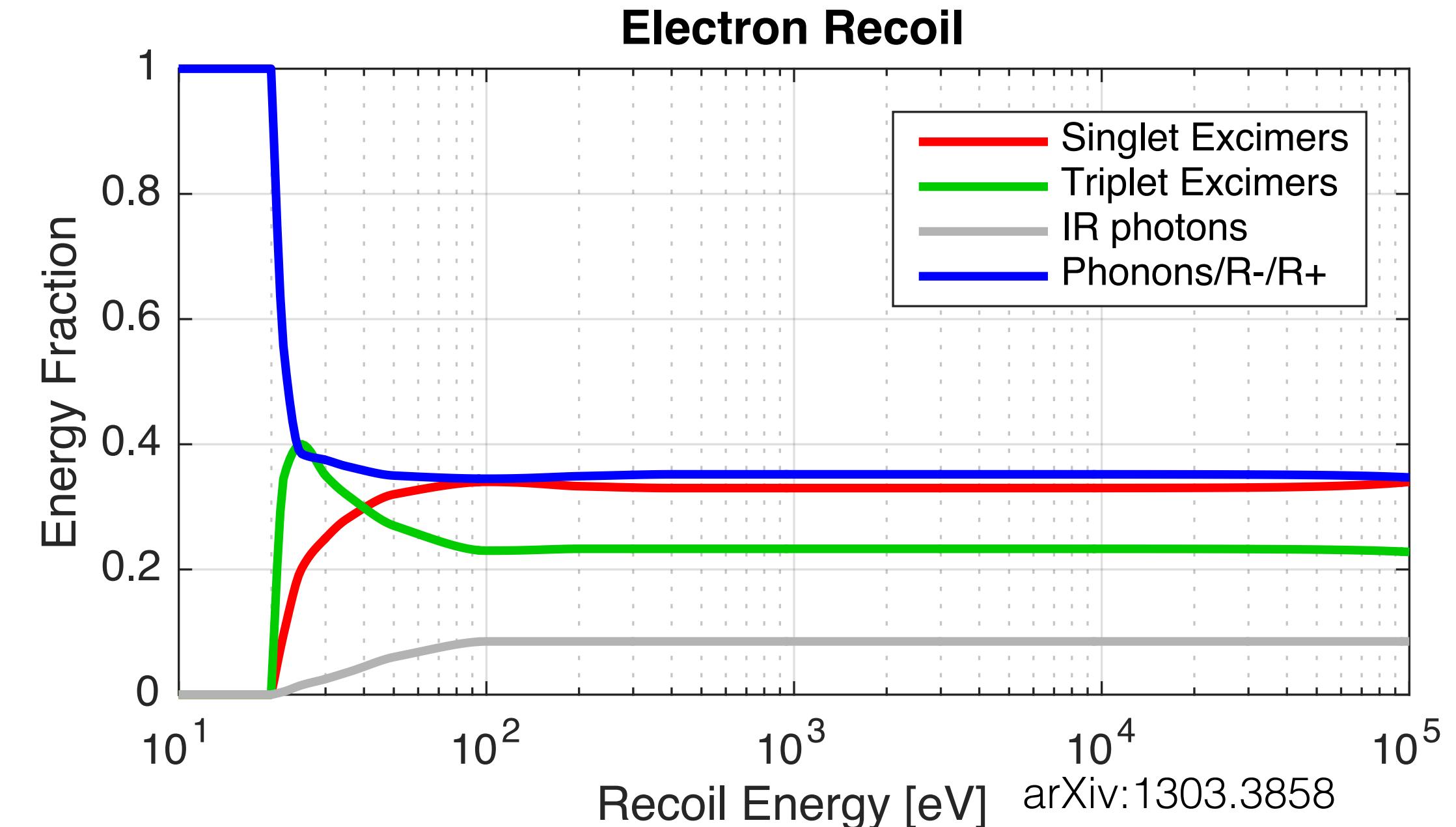
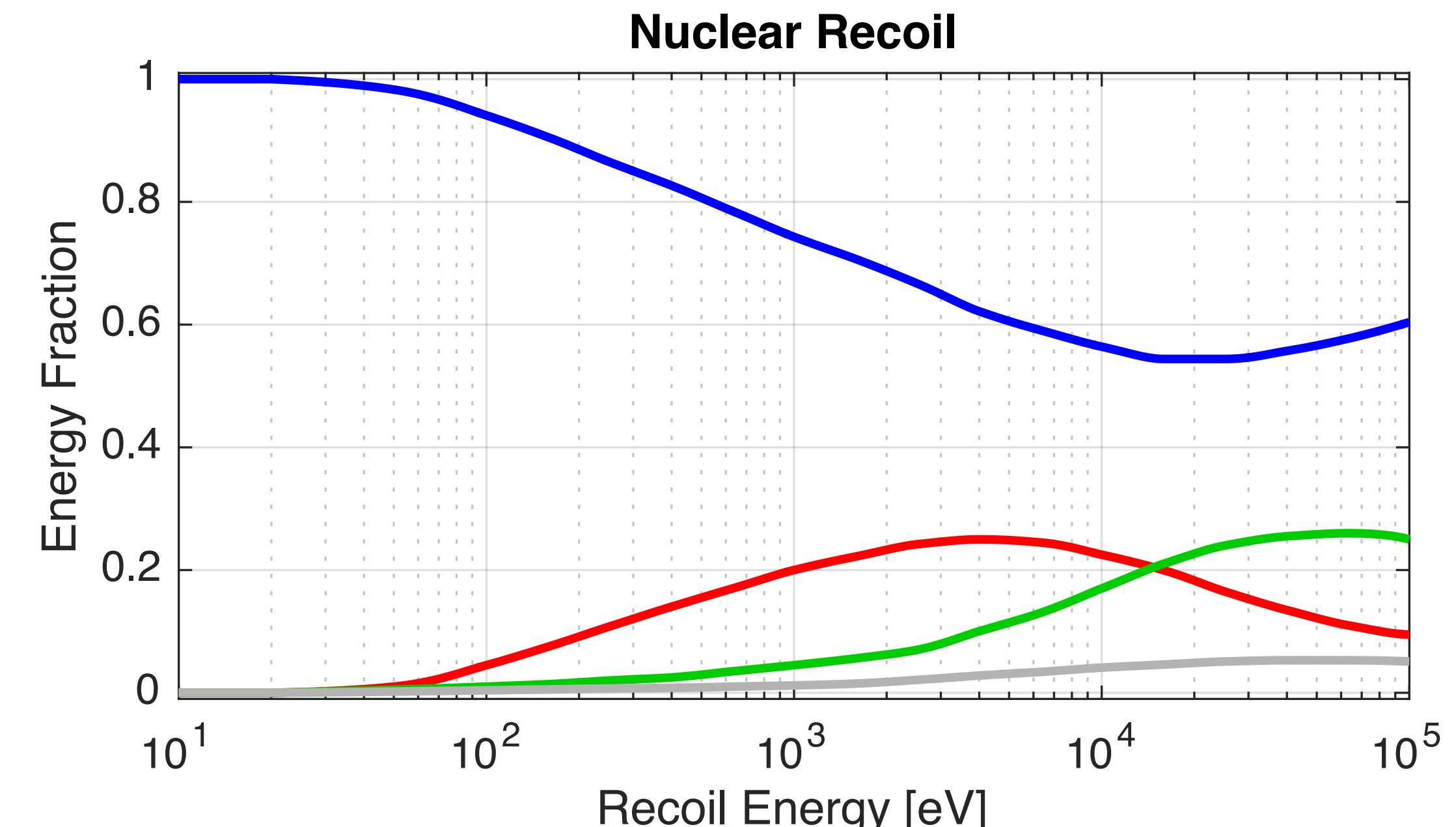
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next step: measure

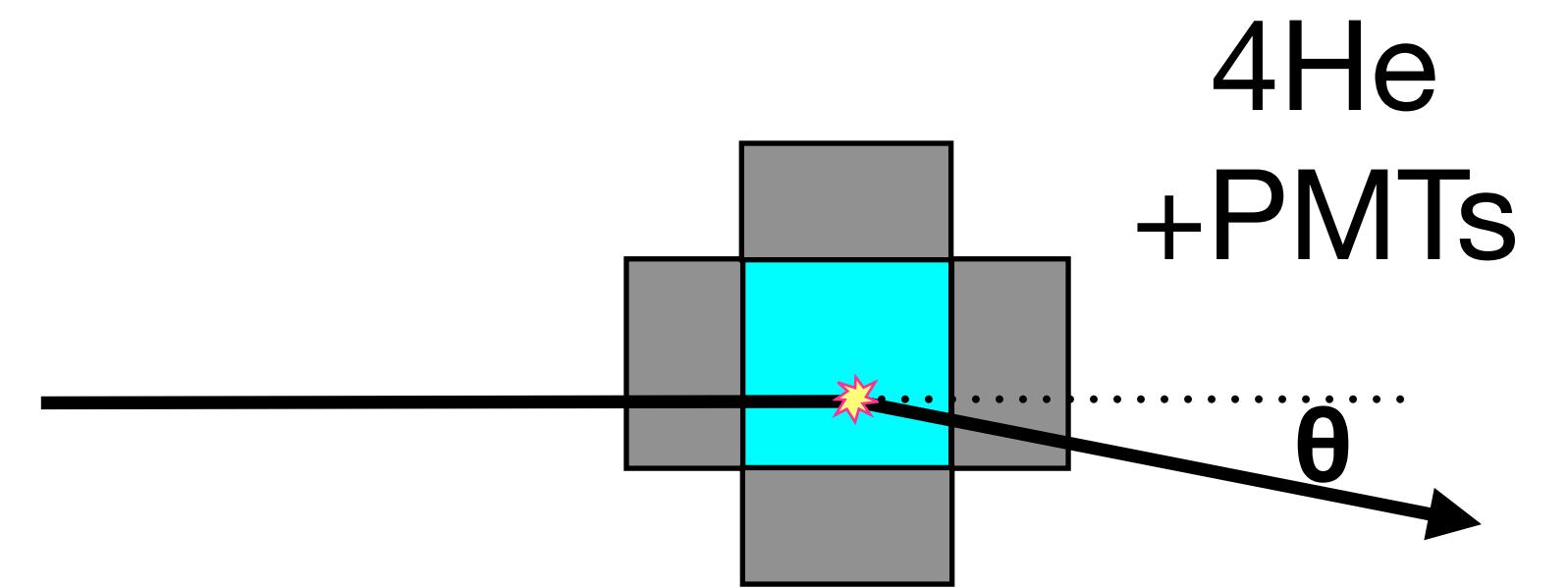


Atomic excitations in ${}^4\text{He}$

Nuclear recoil scintillation yield measurement

Now assembling at UCBerkeley

'Standard' method: pulsed DD neutron source
measured recoil angle



4π coverage using 1" square PMTs
HV supplied using cold Cockcroft-Walton
TPB wavelength-shifter coating



Kinetic excitations in ${}^4\text{He}$

Basic Information

meV-scale (hear ‘MeV-scale DM’)

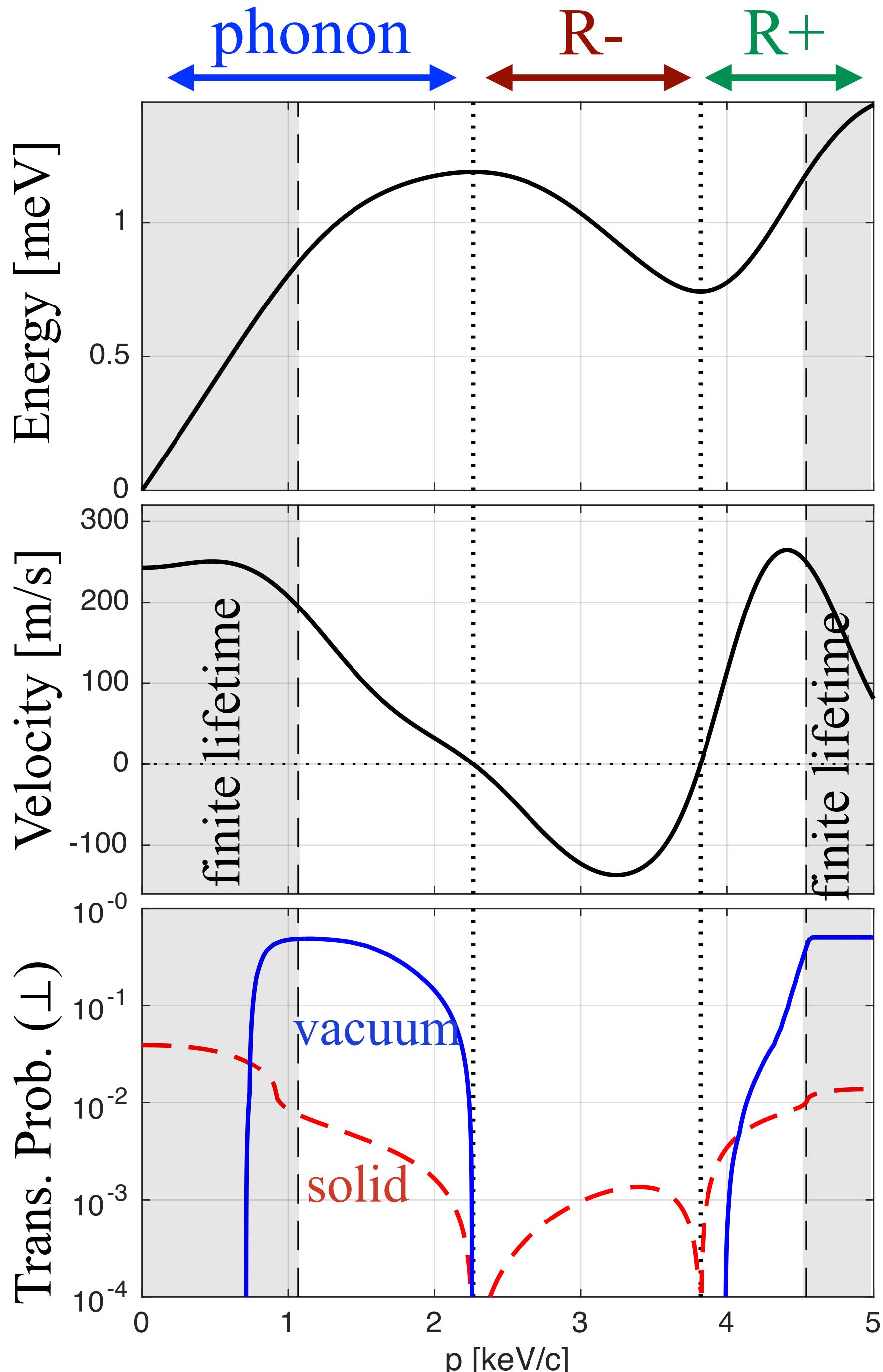
Isotropic medium, ballistic propagation
(if $T \leq 100\text{mK}$ and 3He-free)

Downconversion kinematically forbidden
(over significant momentum range)

Several ‘flavors’, with differing properties

Dispersion relation very different from solid walls
(low transmission prob.)

Reflections frequently change ‘flavor’



Kinetic excitations in ${}^4\text{He}$

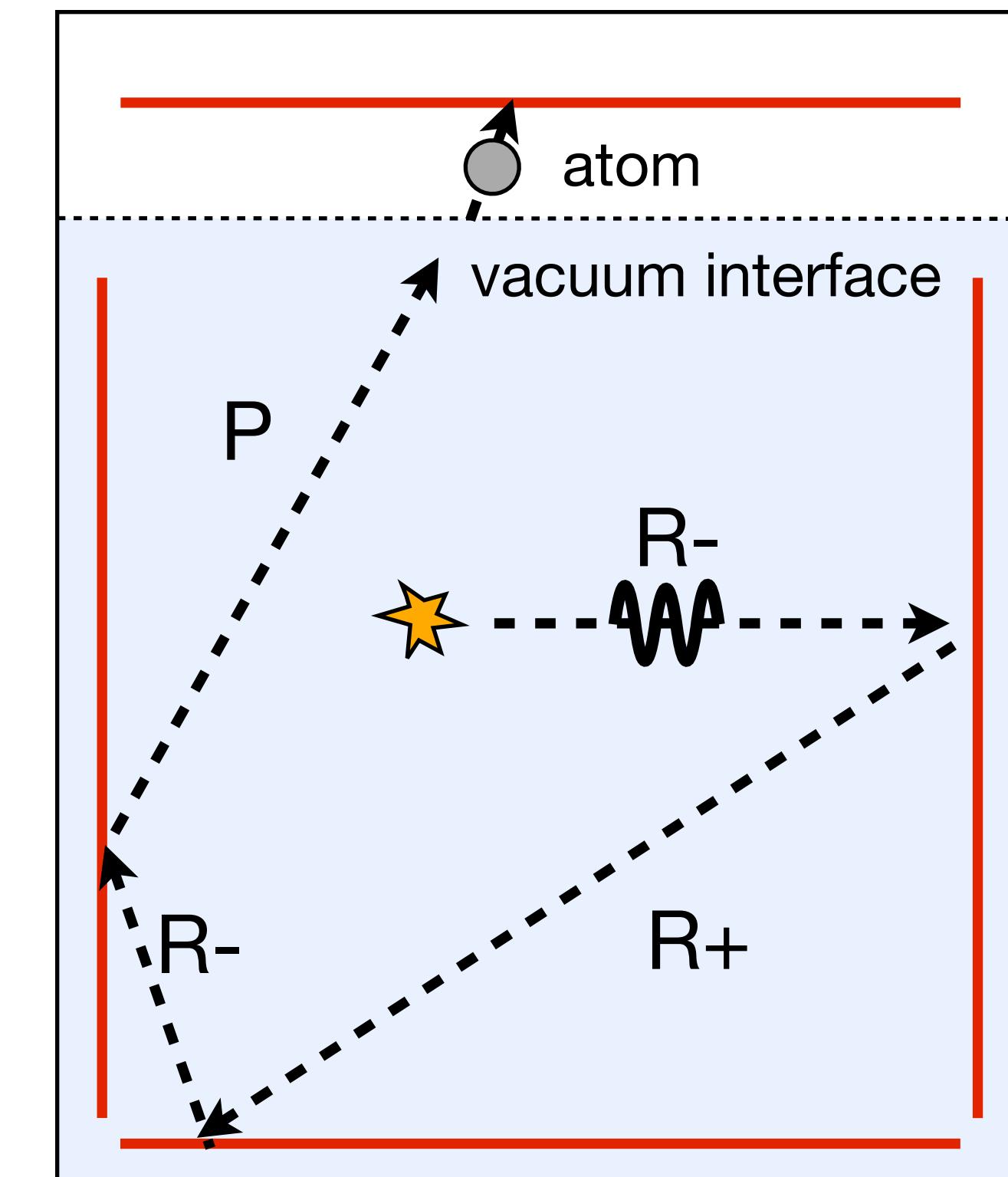
Quantum Evaporation

kinetic excitation -> liberated atom in vacuum

1-to-1 process

significant probability per vacuum-interface-interaction

high fraction of recoil energy appears in this channel
(in theory. one R&D goal: improve the solid reflectivity)



Kinetic excitations in ^4He

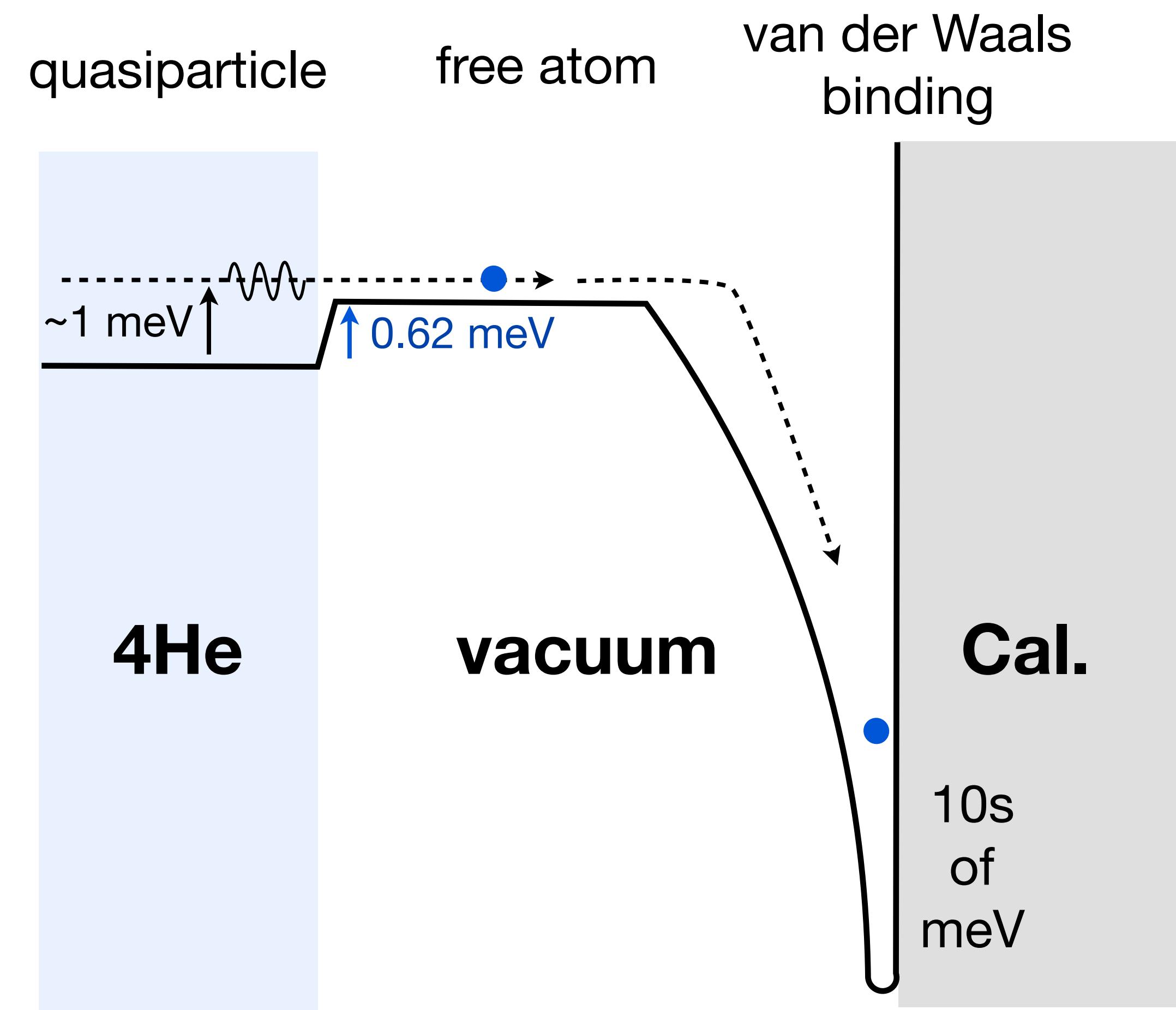
Sensing free ^4He atoms using calorimetry

Trick: use van der Waals binding energy as a gain

Typical helium-solid binding energy: $\sim 10\text{ meV}$
(Coating could enhance. graphene-fluorine: 42.9 meV)

each 1 meV excitation becomes ~ 40 meV deposition

→ x40 gain



Expected Backgrounds

'Real' Backgrounds

neutrino nuclear coherent scattering

gamma backgrounds copy SuperCDMS & DAMIC projections (arXiv:1610.00006)

including newly-discussed gamma-NR background

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

Dark Count Backgrounds

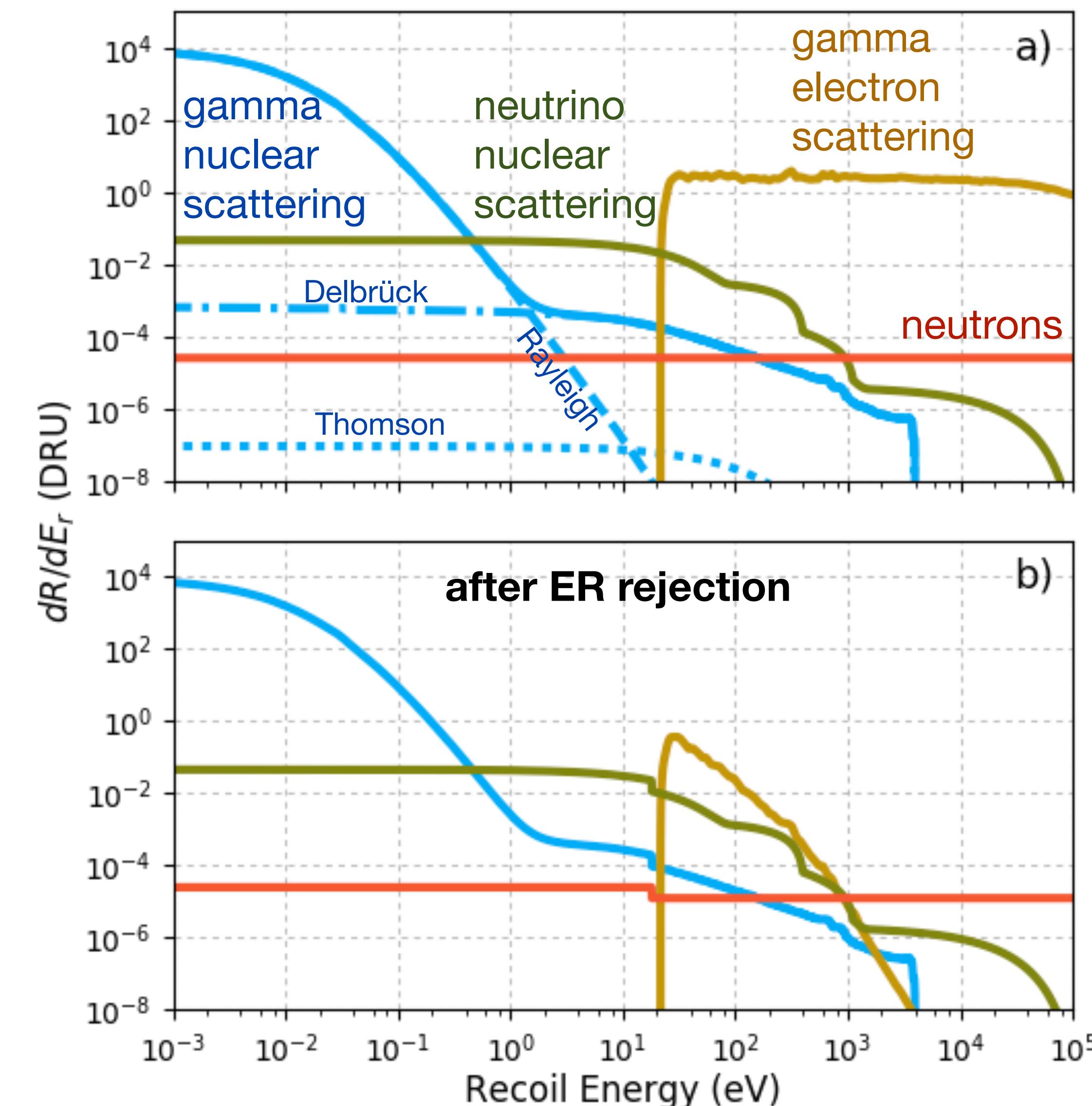
Qualitative arguments for low rate:

calorimetry: no applied potential energies

calorimeter 2D and low mass (clamps not an issue)

superfluid target mass: highly vibrationally isolated

signal interface physics (gap) highly uniform



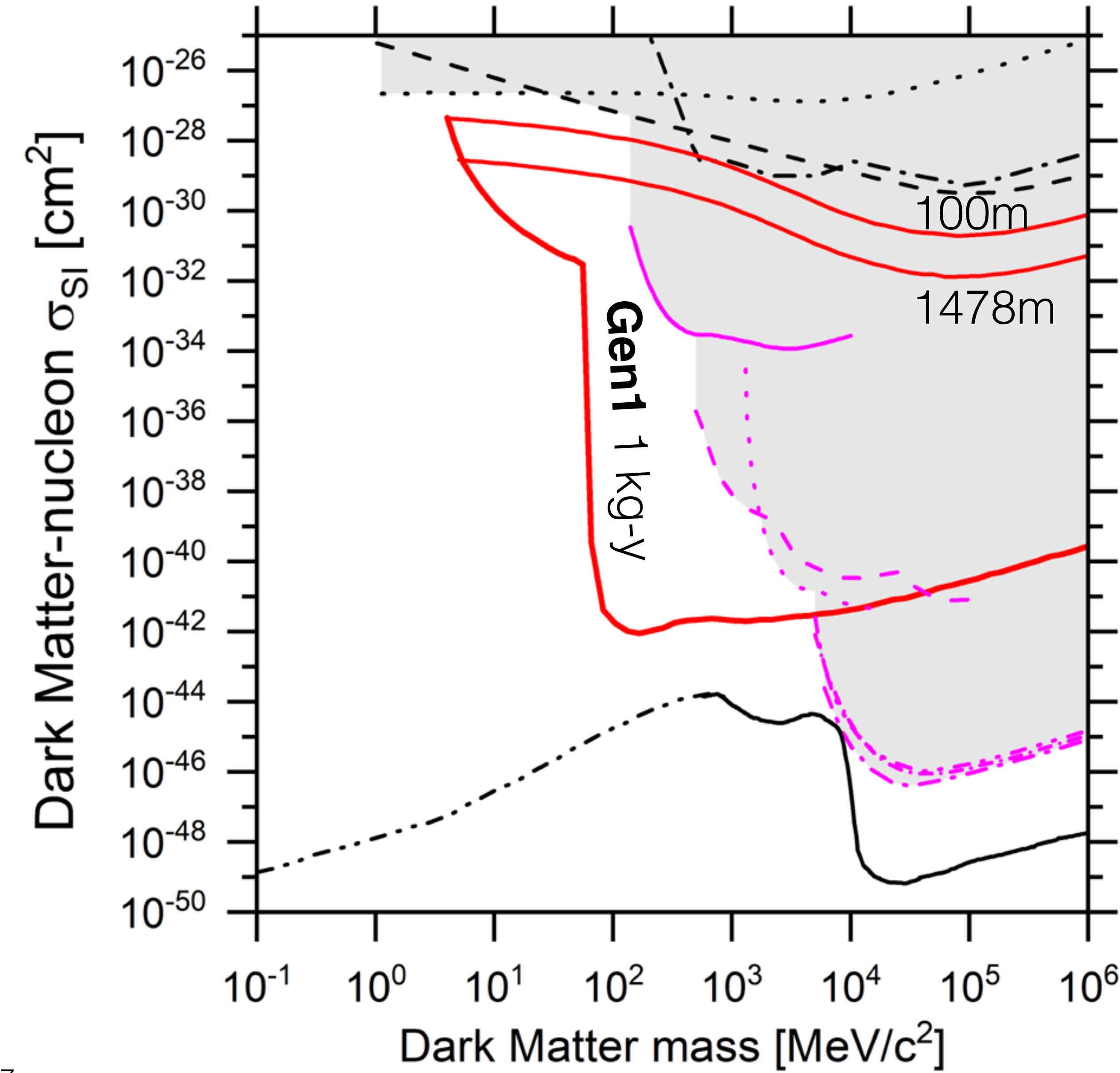
Nuclear recoil sensitivity

We include

- the backgrounds from previous slide
- the effects of earth shielding at two depths
- the NR-bremsstrahlung signal path

Signal amplitude: $E_{\text{cal}} = E_{\text{rec}} \times F_{\text{evap}} \times G$

Calorimeter	Evaporation Fraction	Gain	Resulting Recoil Threshold
Threshold	F _{evap}	G	E _{rec}
E _{cal}	F _{evap}	G	E _{rec}
Gen1	5 eV	0.05	10
			10 eV



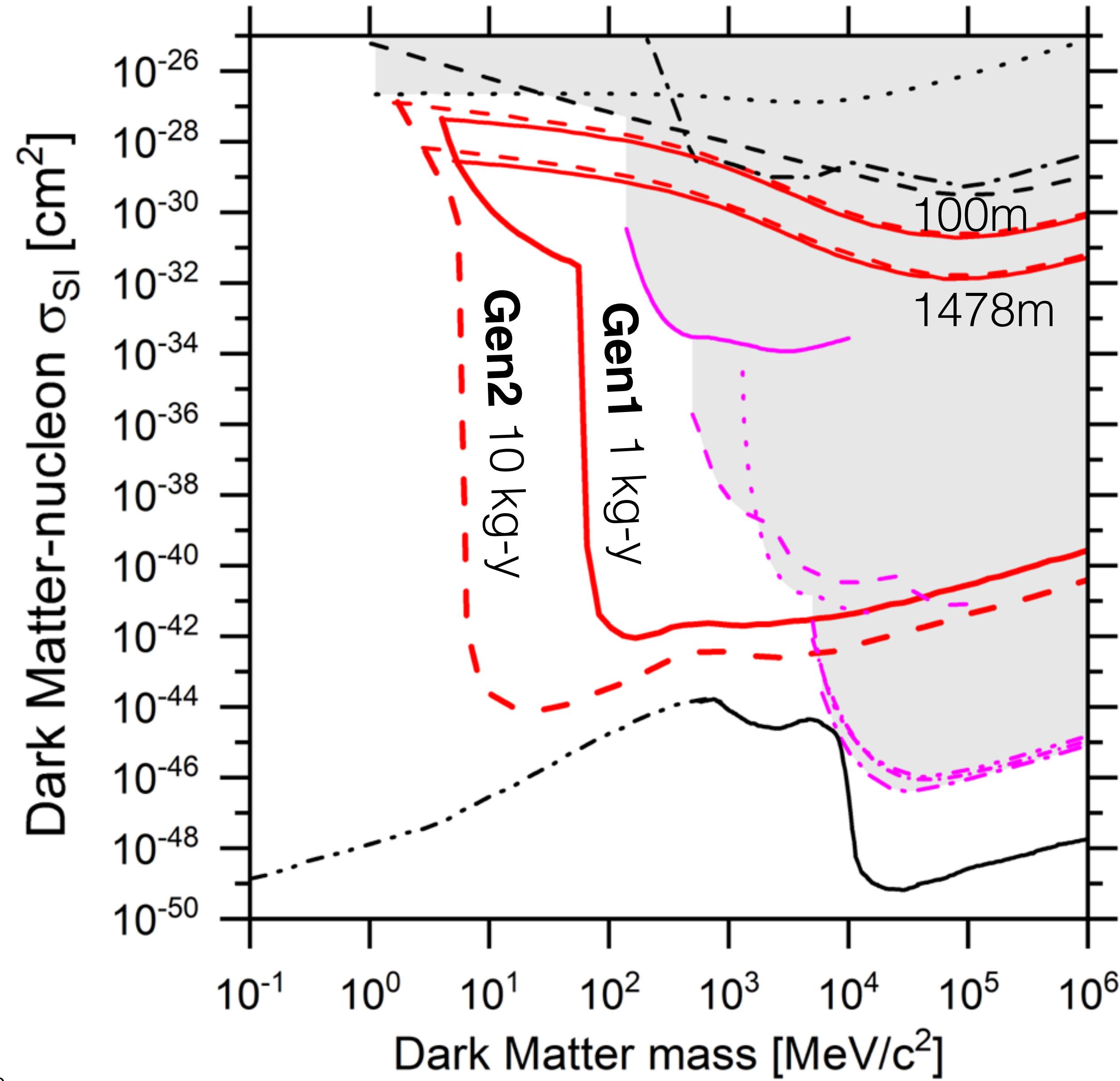
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	Calorimeter Threshold E_{cal}	Evaporation Fraction F_{evap}	Gain G	Resulting Recoil Threshold E_{rec}
Gen1	5 eV	0.05	10	10 eV
Gen2	1 eV	0.25	40	0.1 eV



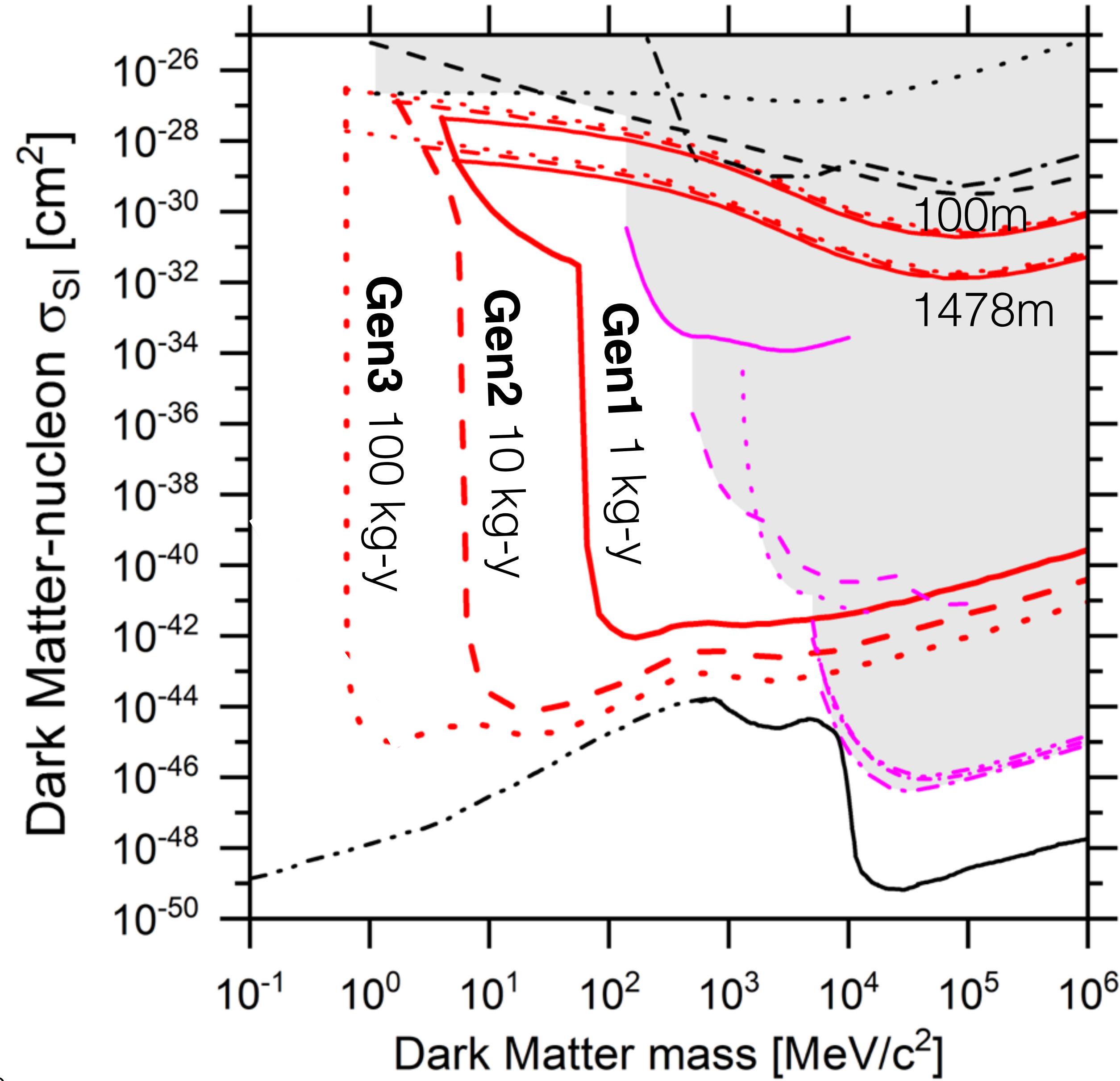
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Gen3	20 meV	0.50	40	1 meV



Nuclear recoil sensitivity

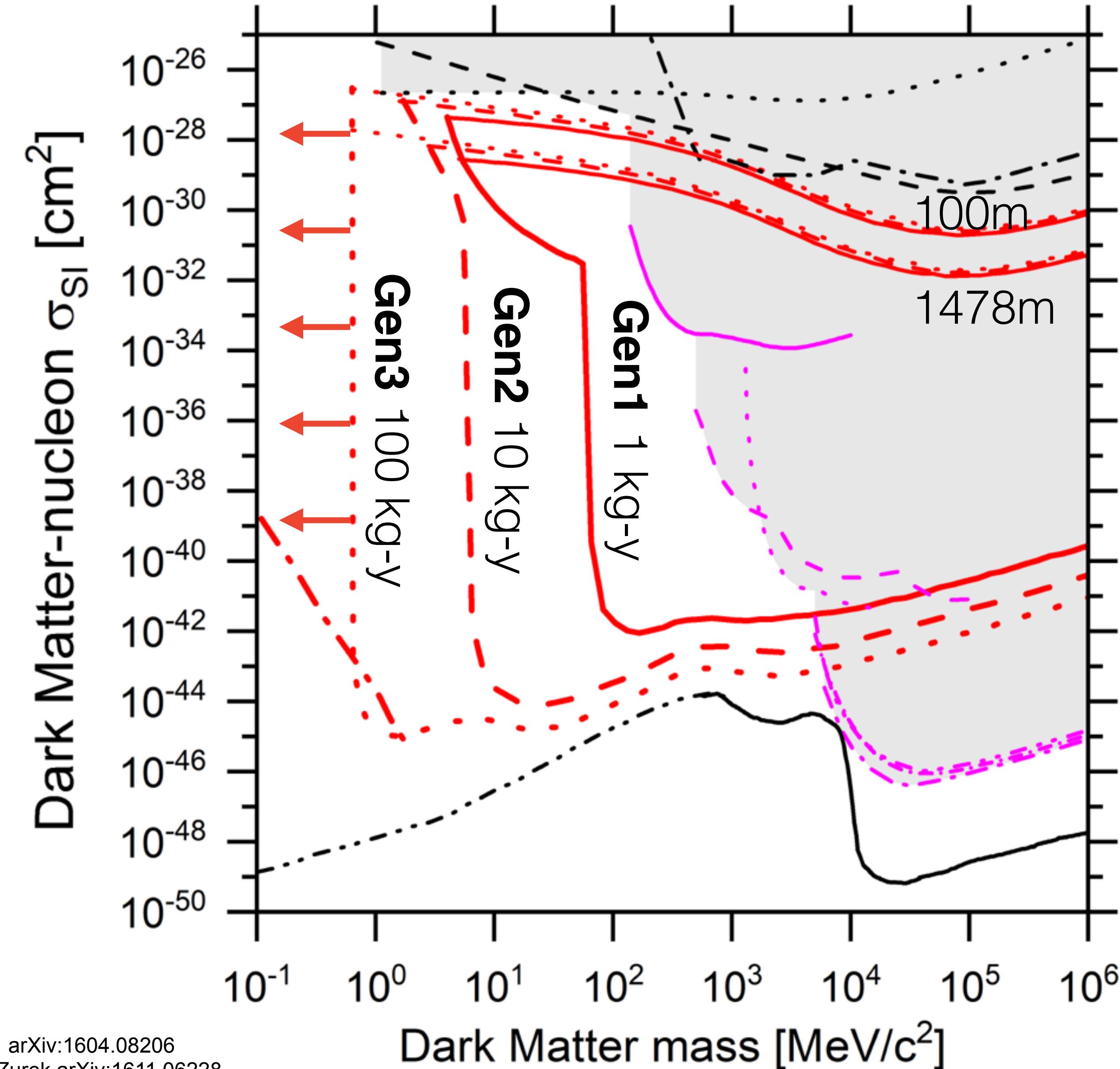
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Gen2	1 eV	0.25	40	0.1 eV
Gen3	20 meV	0.50	40	1 meV

Given single-excitation sensitivity, new diagrams
(w/ off shell rotons) probe keV mass regime.



Summary

The phonon-only detector regime is hard.

Superfluid ^4He offers several advantages to other ideas:

1. Recoil energies enhanced thanks to light nucleus
2. Comparative wealth of excitation information
 - phonon/singlet/triple at $E > 20\text{eV}$
 - $P/R-/R+$ provide recoil information even at meV energies
3. Unique phonon gain method (phonon \rightarrow free atom \rightarrow adhesion)
4. Unique vibrational isolation from environment

supplemental

HERON

Idea Paper: 1987

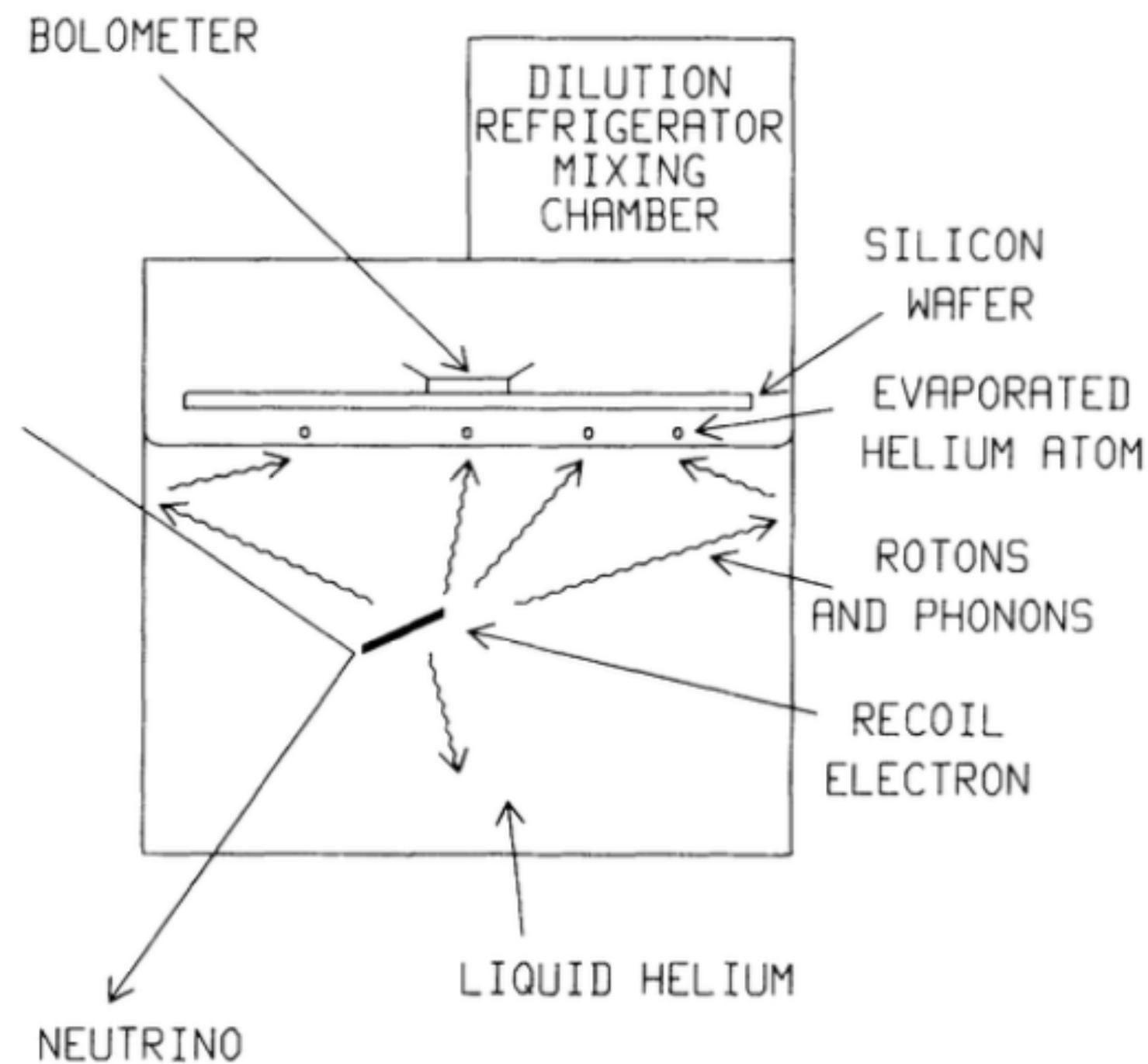
Active R&D for more than 10 years

PHYSICAL REVIEW LETTERS

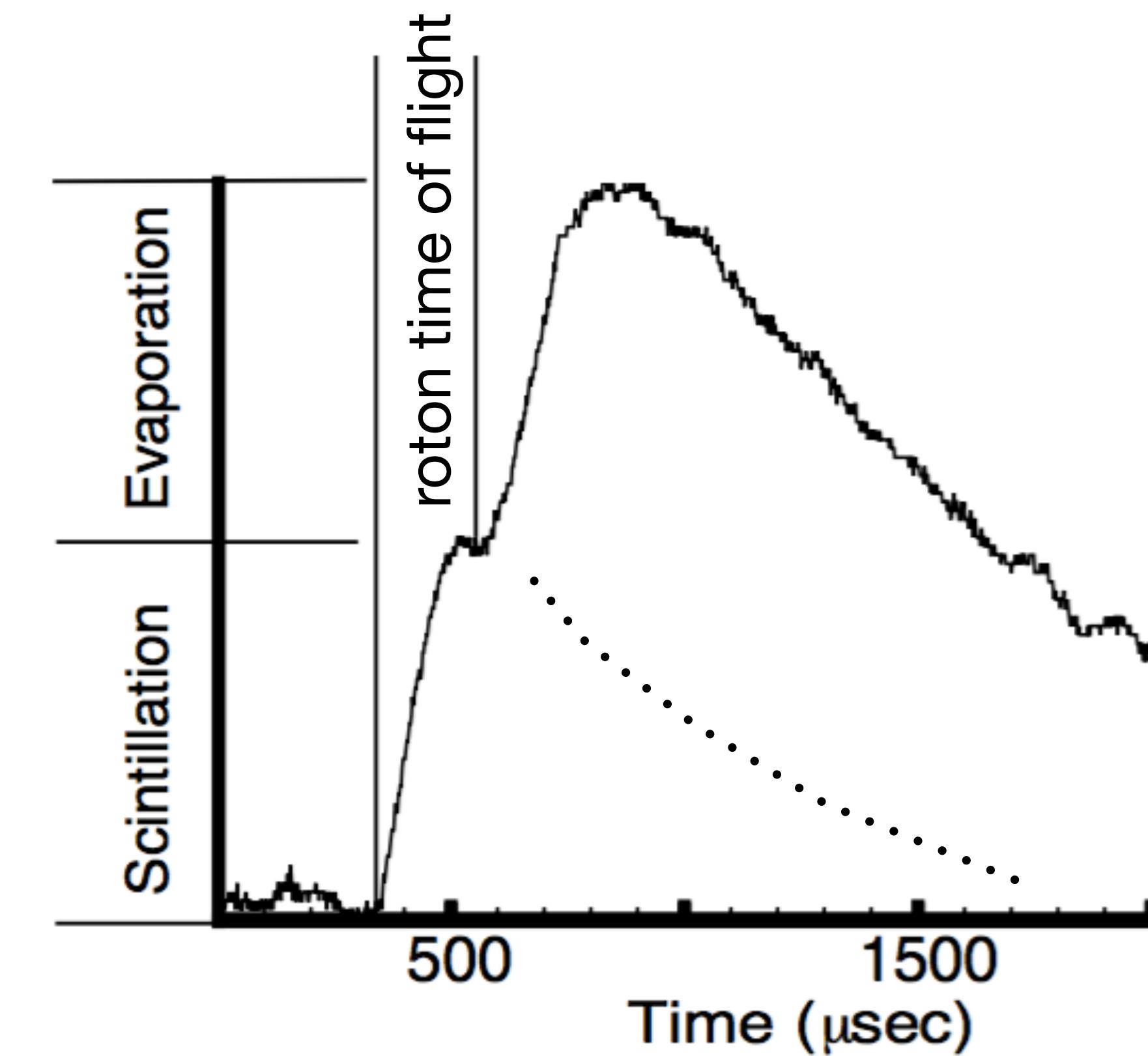
Detection of Solar Neutrinos in Superfluid Helium

R. E. Lanou, H. J. Maris, and G. M. Seidel

Department of Physics, Brown University, Providence, Rhode Island 02912
(Received 4 March 1987)



example bolometer trace (364 keV electron)

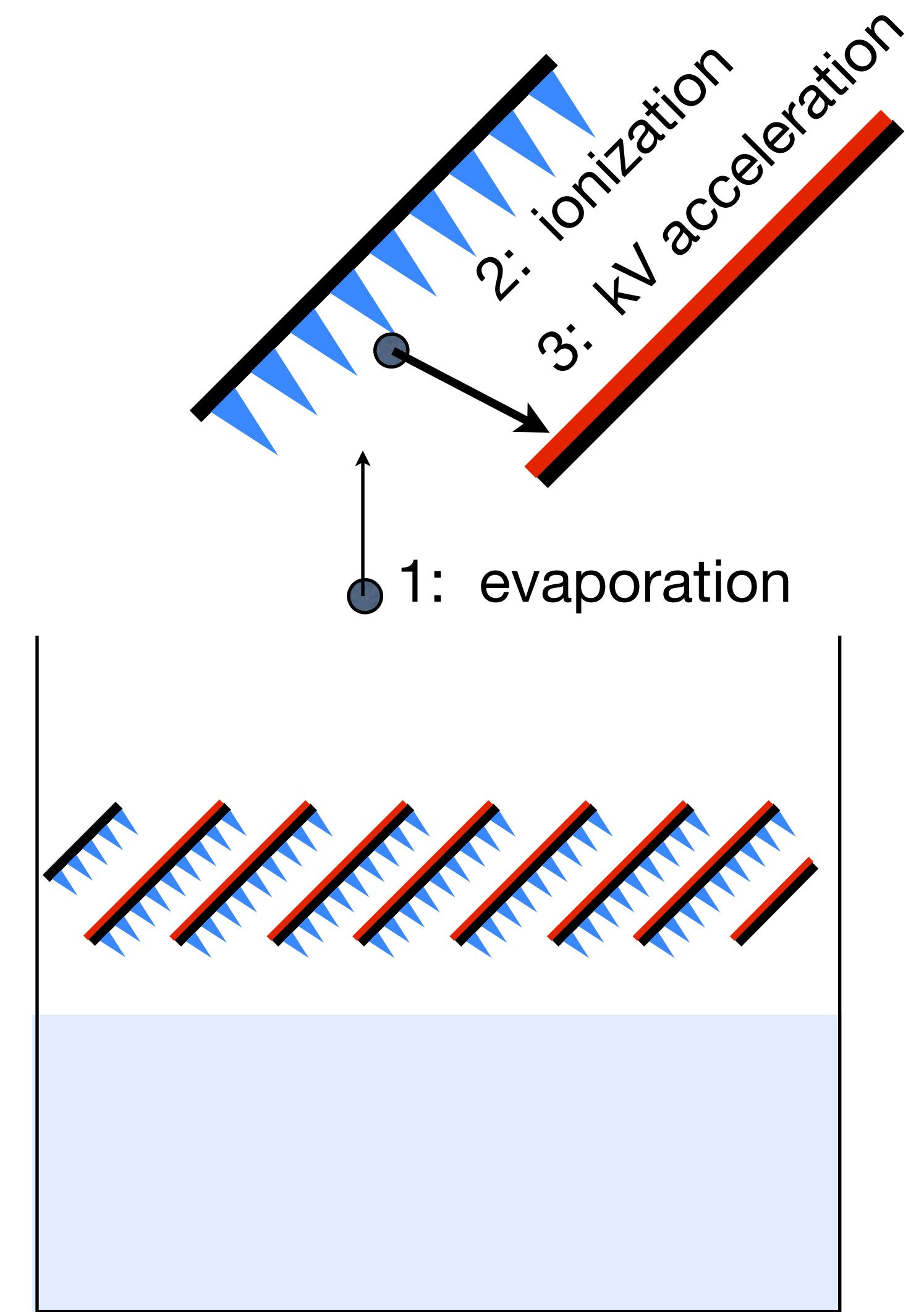
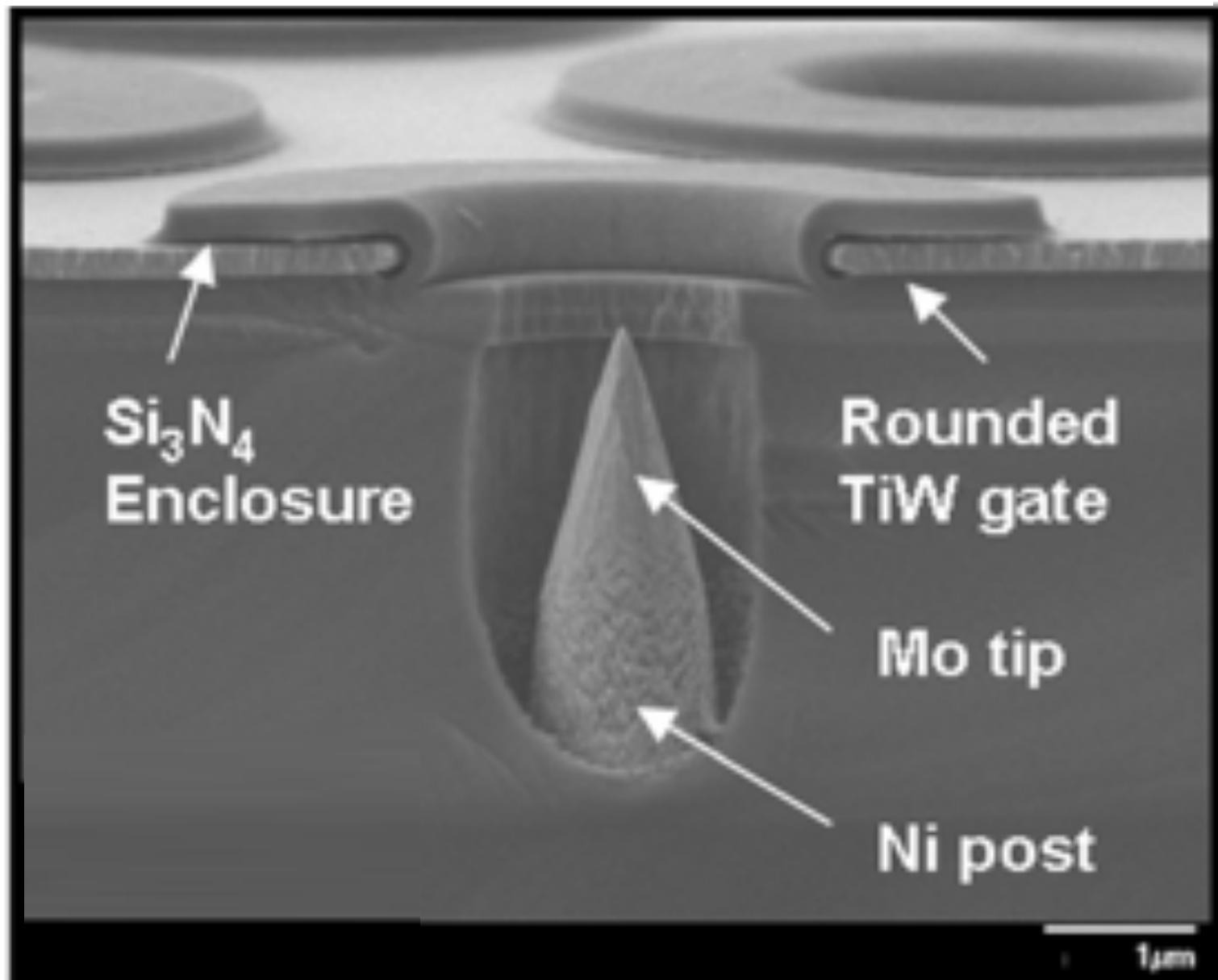


Sensing free ^4He atoms via ionization

arXiv:1706.00117

possibly a faster route to the atom-counting regime

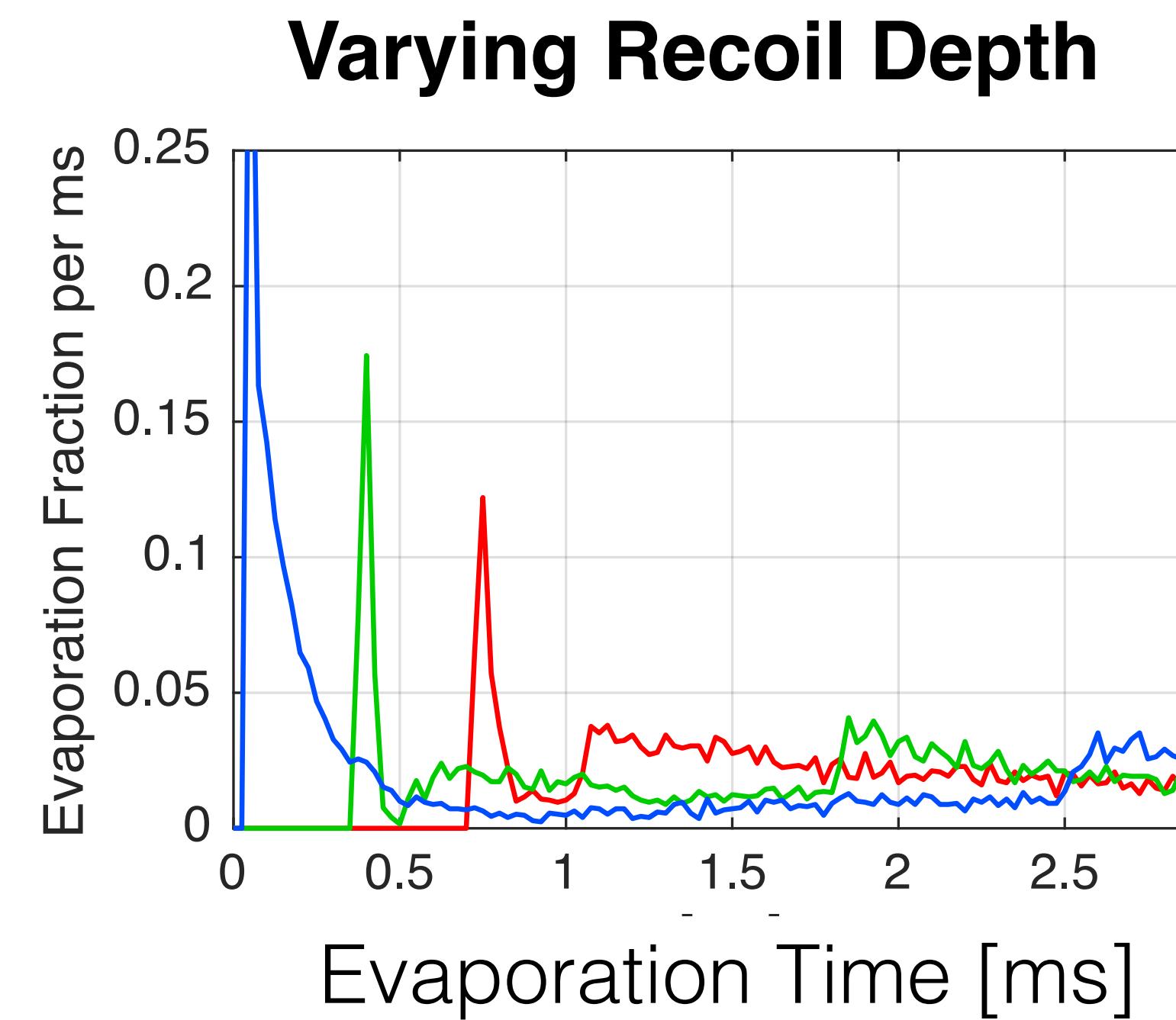
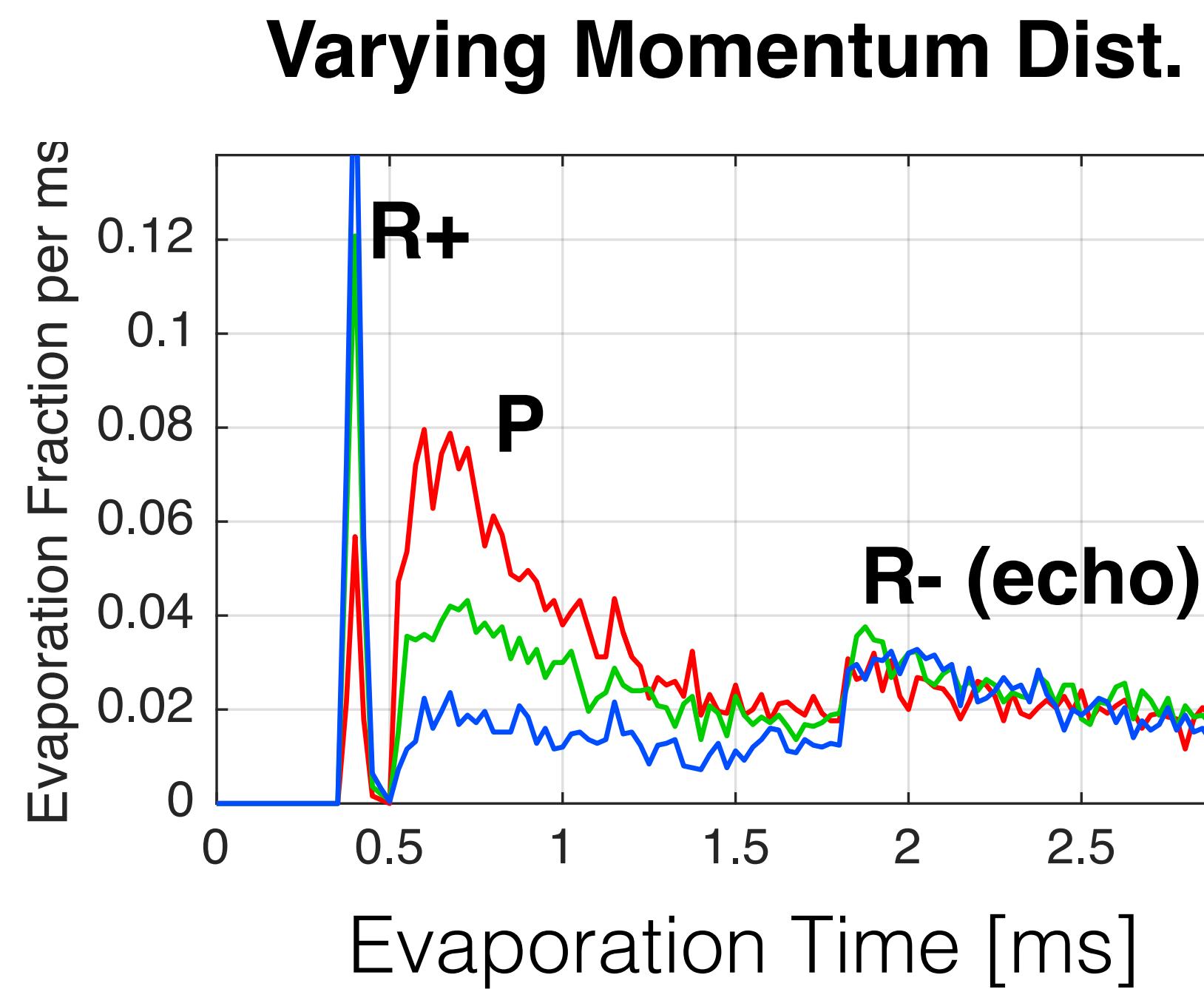
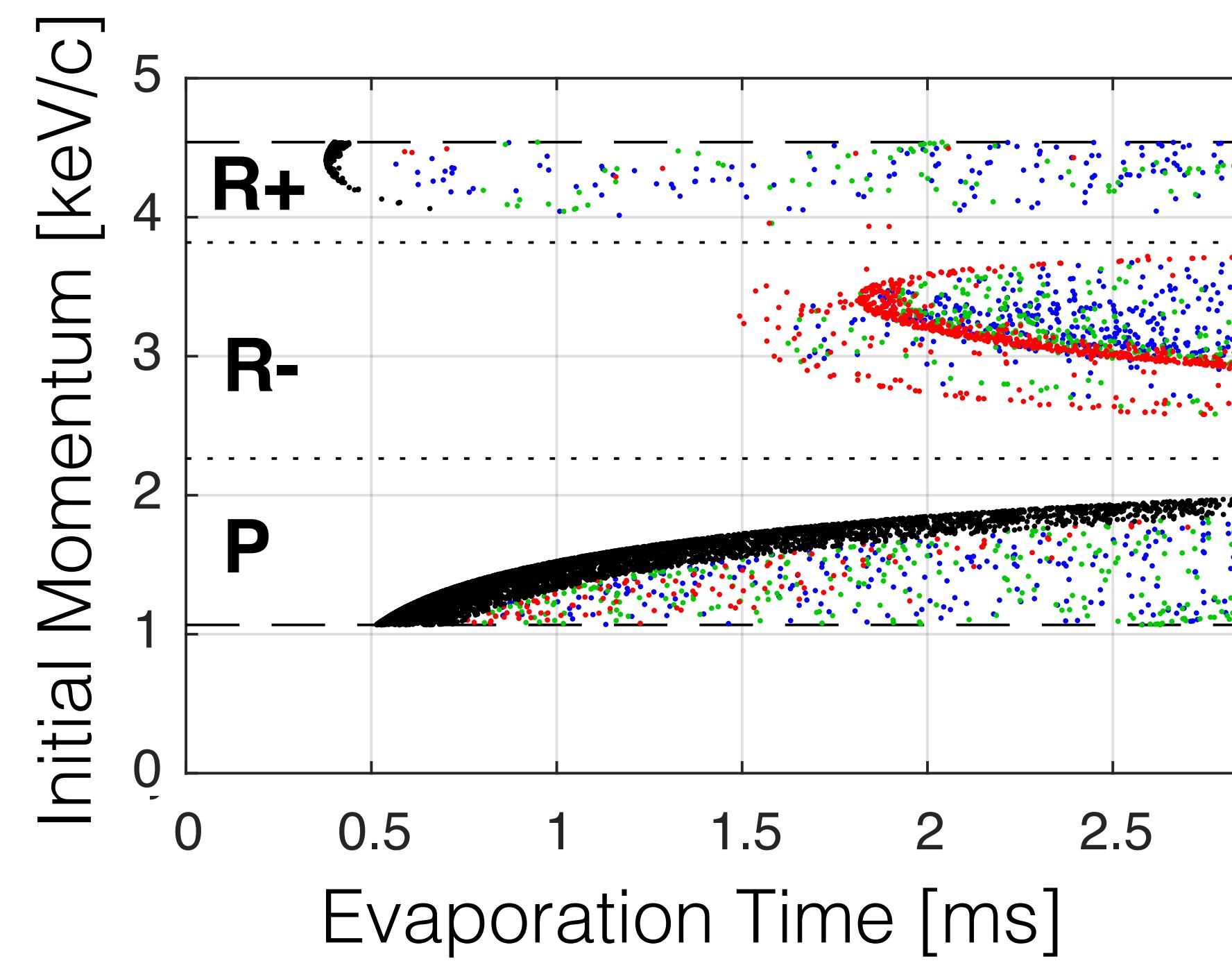
key challenge: HV and dark counts



(simple) MC of phonon propagation

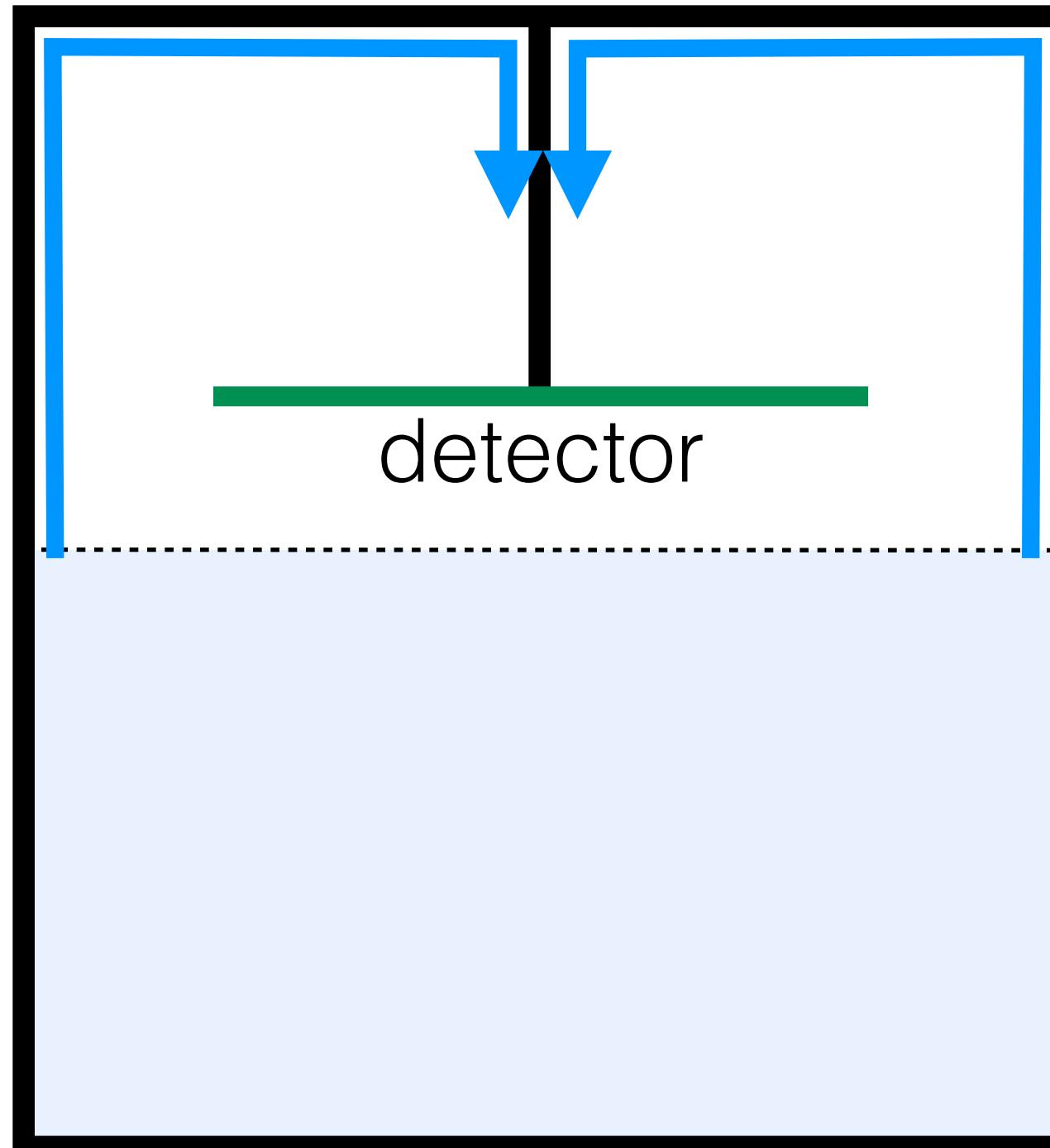
Variety of excitations provides wealth of recoil information

- position
- momentum distribution (recoil type?)



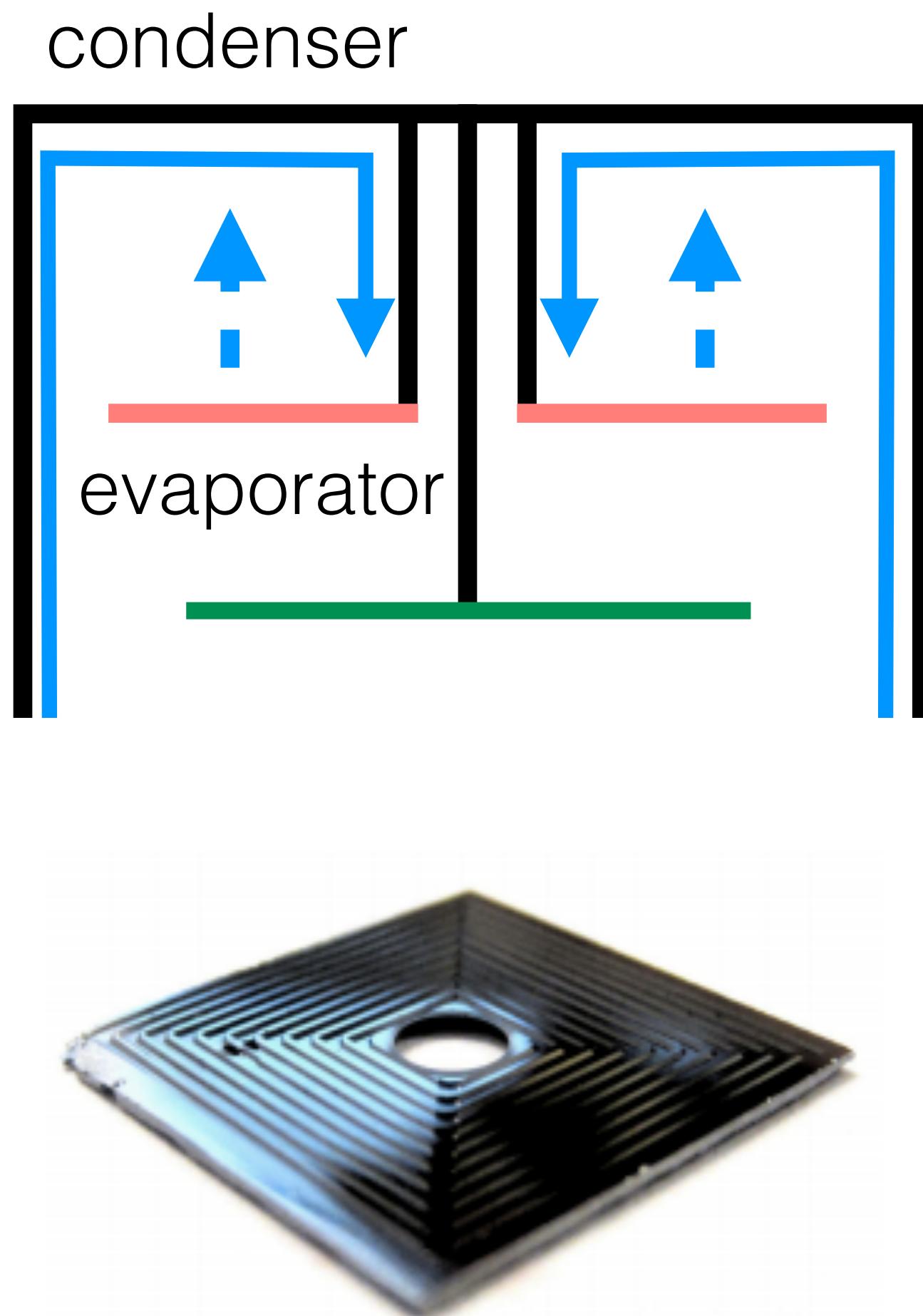
Keeping the calorimeter film-free

The Engineering Challenge:
stop a superfluid film flow



Three methods:

- **Film Burner**
 - tried and true
 - requires heat input
- **Knife Edge** (<10nm radius)
 - never 100% effective
- **Cesium coating** (unoxidized)
 - scary for several reasons



Off-shell phonons

arXiv:1604.08206
arXiv:161106228

