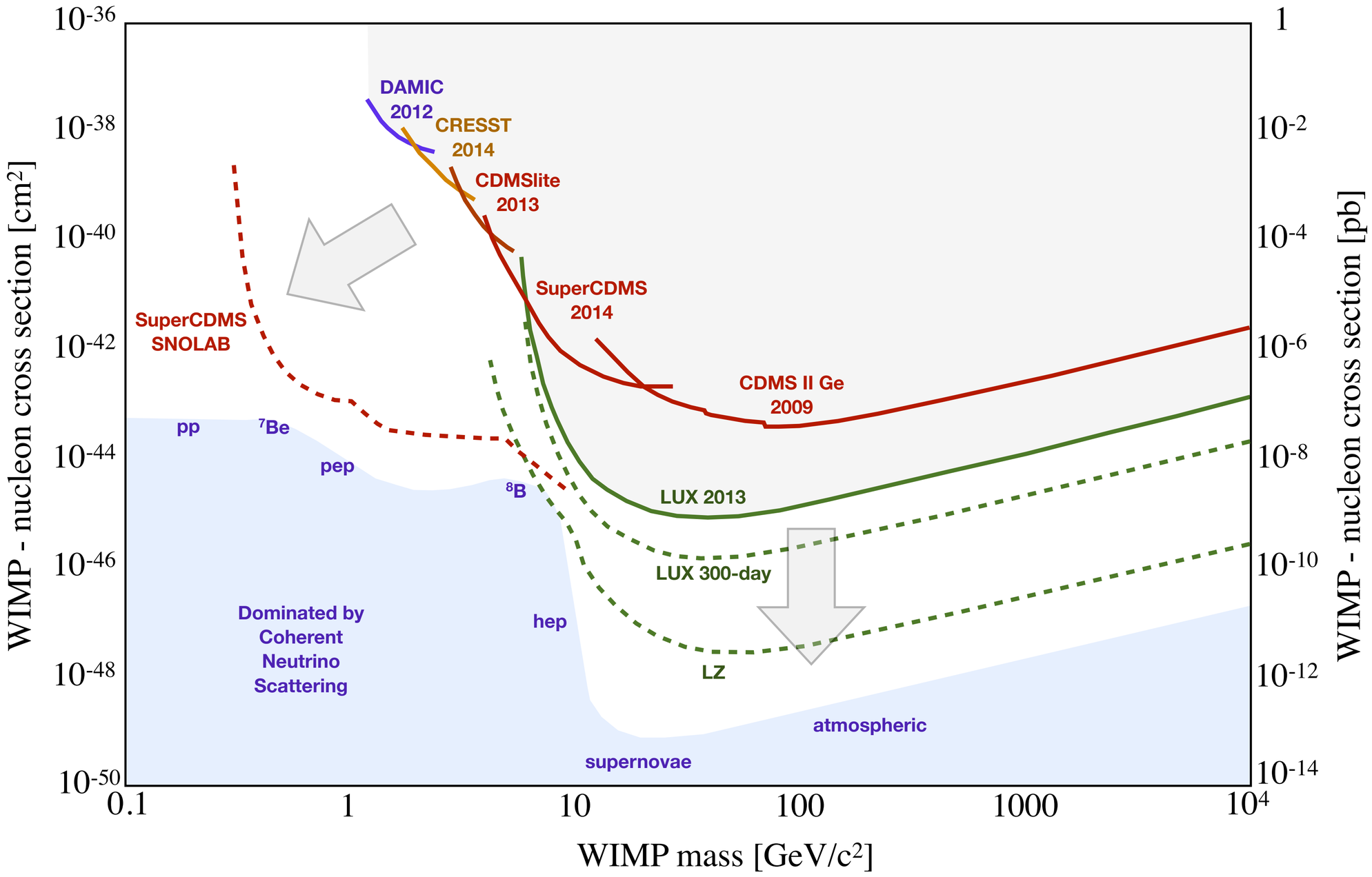
Superfluid Helium
a Unique Detector Material for Low Energies

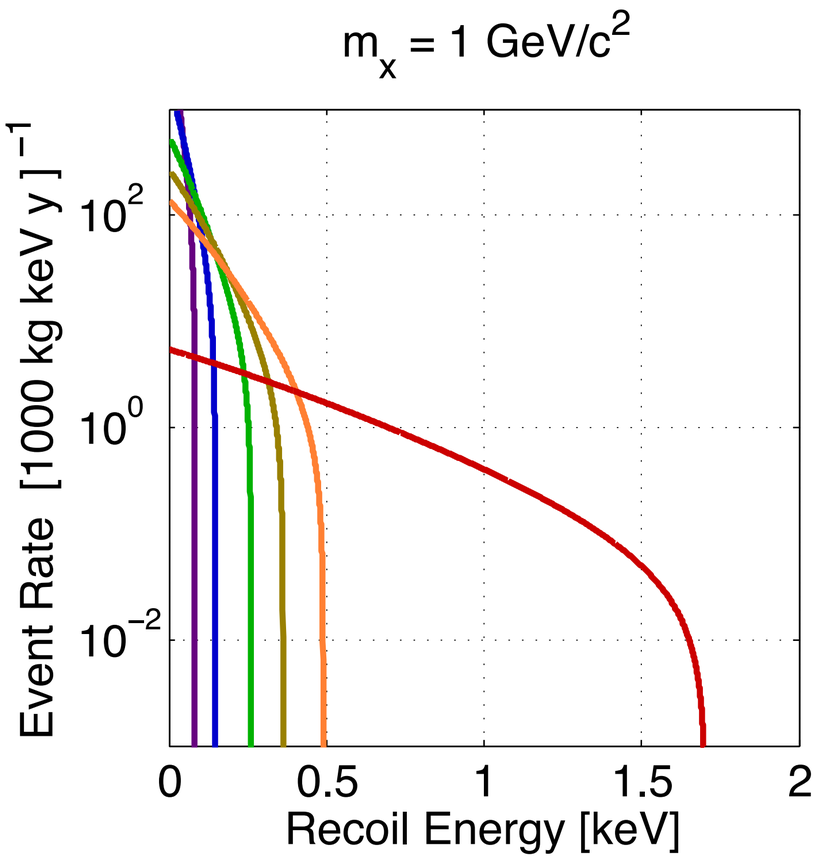
Berkeley Workshop on
Dark Matter Detection
June 9th, 2015
Scott Hertel (Yale)

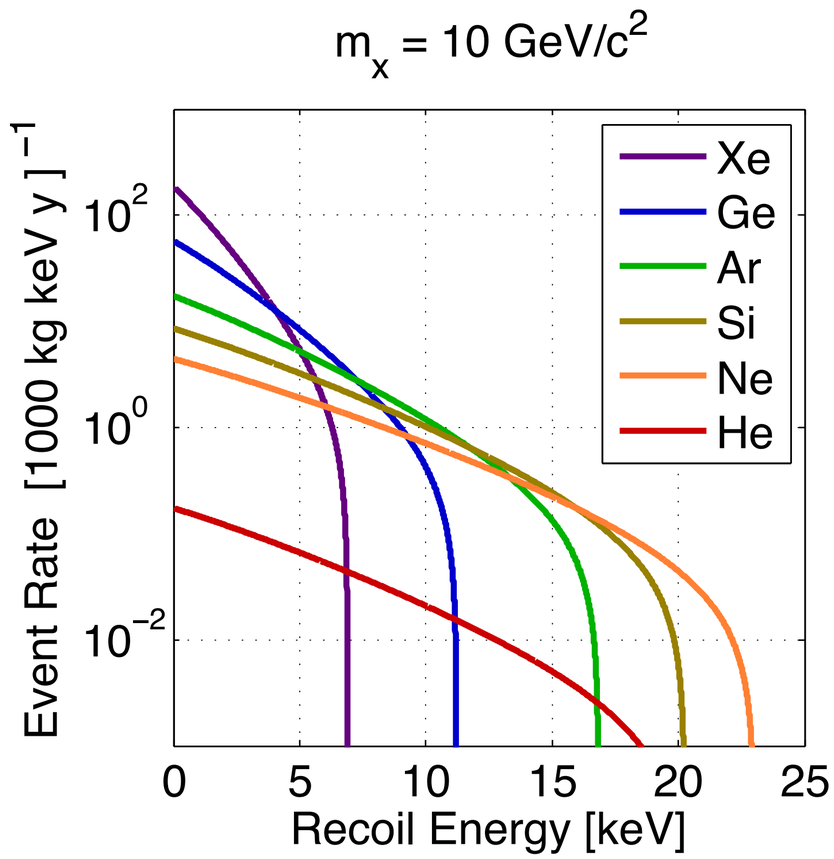

DAMIC
2012
CRESST
2014
CDMSlite
2013
SuperCDMS
2014
SuperCDMS
SNOLAB
CDMS II Ge
2009
LUX 2013
LUX 300-day
LZ
pp
7Be
pep
8B
hep
Dominated by
Coherent
Neutrino
Scattering
atmospheric
supernovae
WIMP - nucleon cross section [cm2]
WIMP - nucleon cross section [pb]
WIMP mass [GeV/c2]
10-36
10-38
10-40
10-42
10-44
10-46
10-48
10-50
1
10-2
10-4
10-6
10-8
10-10
10-12
10-14
0.1
1
10
100
1000
104

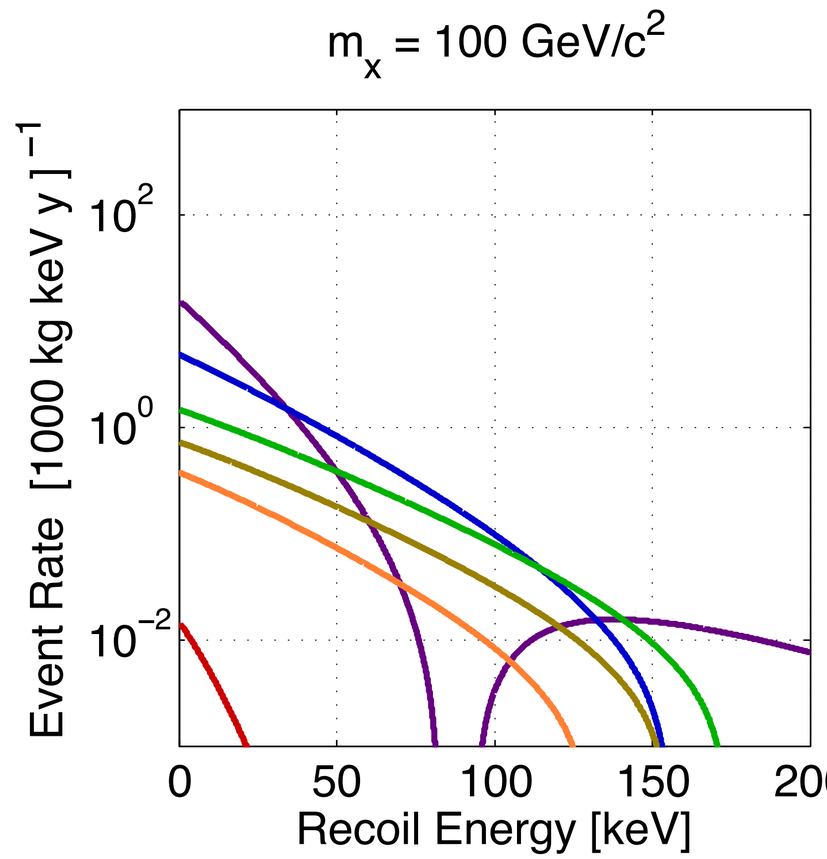
light nuclei:

lose total WIMP recoil rate (~$A^2\mu^2$)

gain rate above some threshold



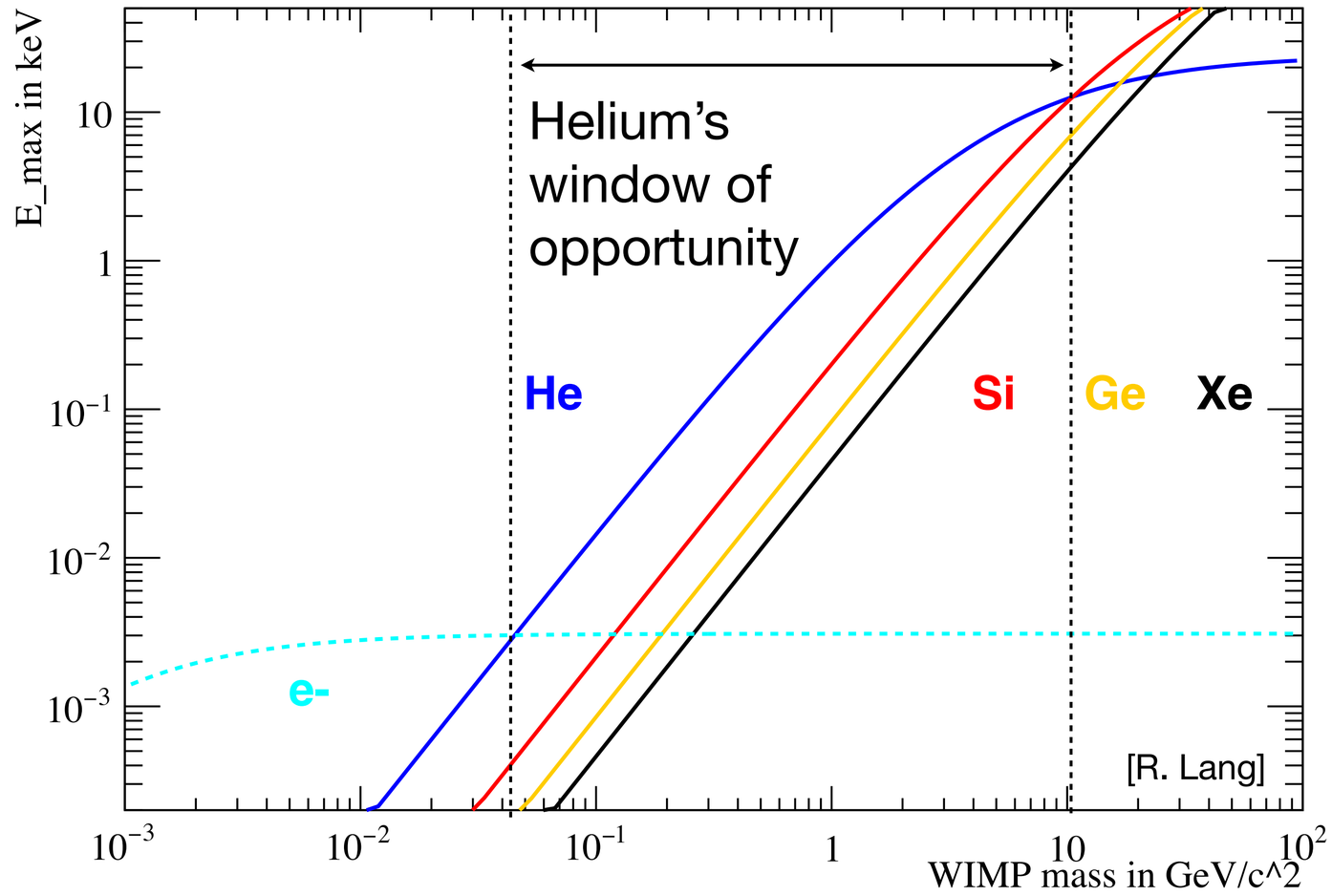




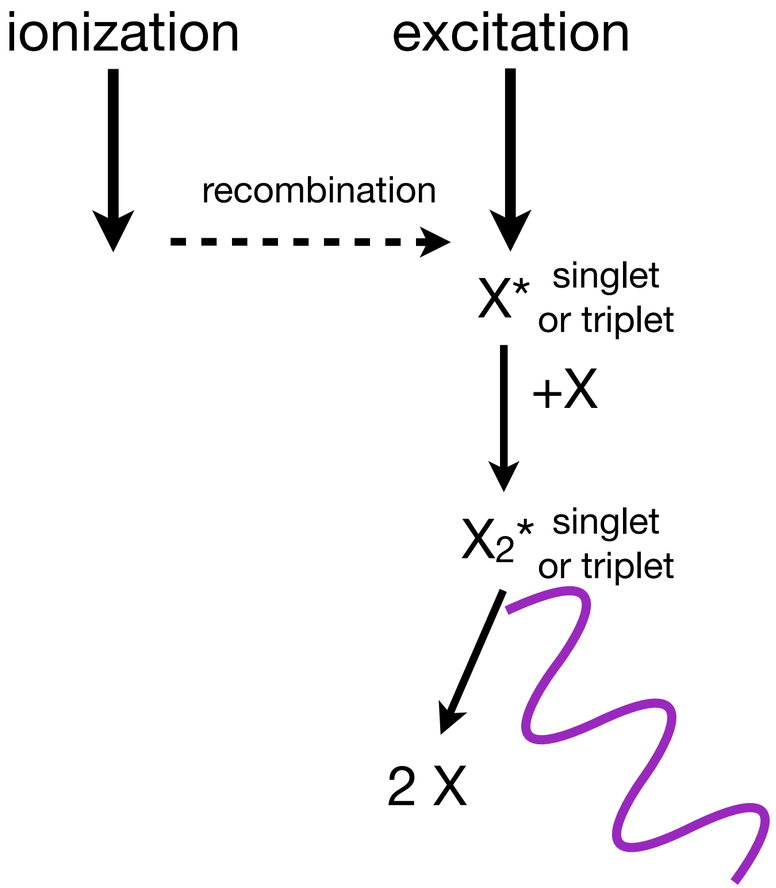
another view: maximum possible nuclear recoil energy for various targets for various WIMP masses

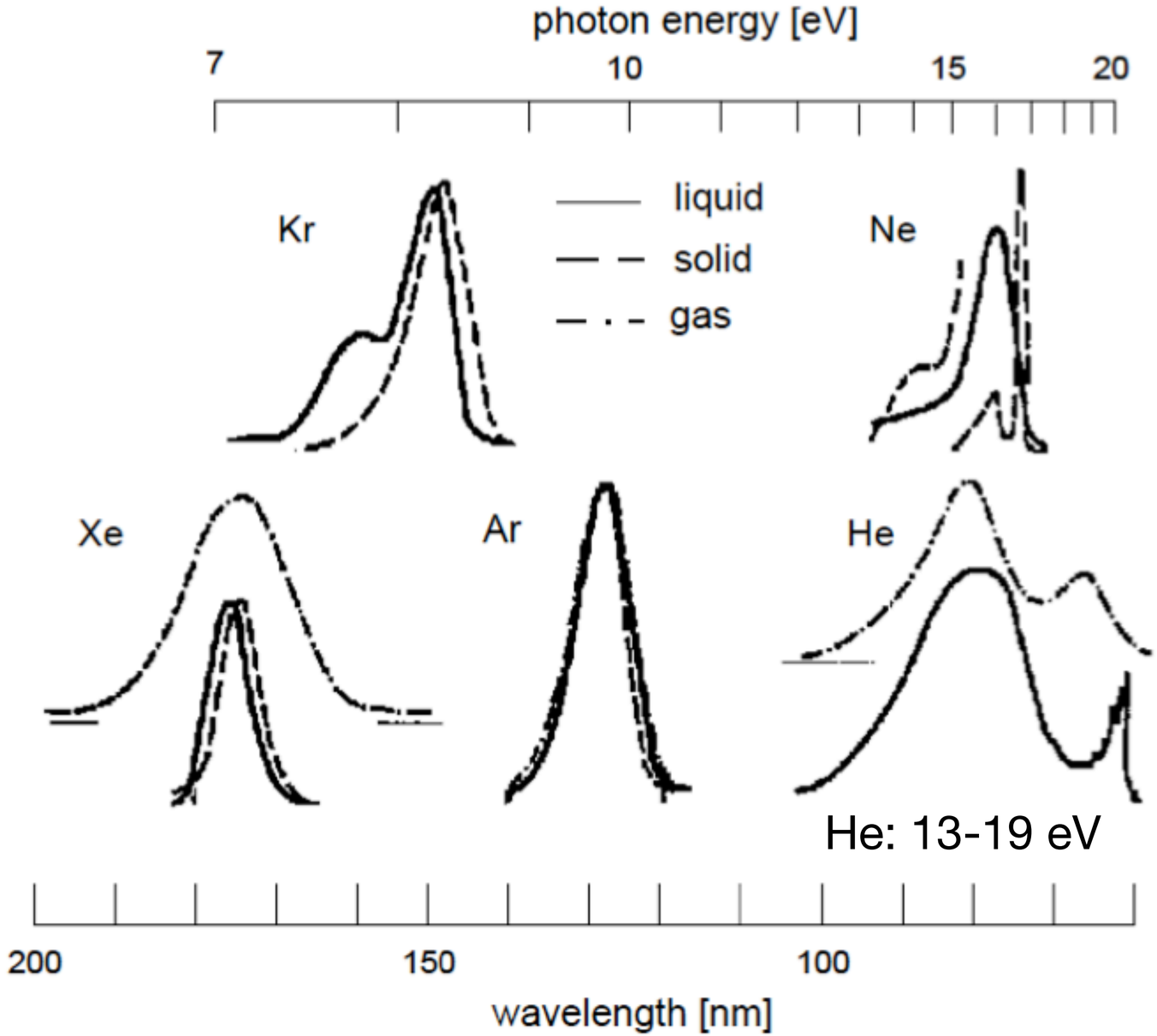
$$\mathrm{maxE_{recoil}} \;=\; \mathrm{KE_x}\left(\frac{4\ m_t\, m_x}{(m_t + m_x)^2}\right)$$

here,
v_x = galactic escape velocity, 540 km/s
nuclear form factors completely ignored
electron's atomic state similarly ignored



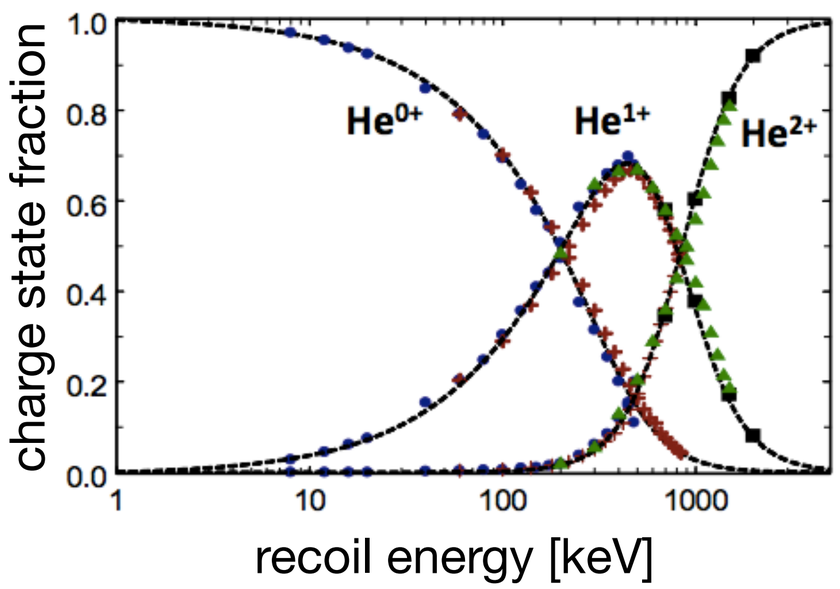
noble liquid scintillation

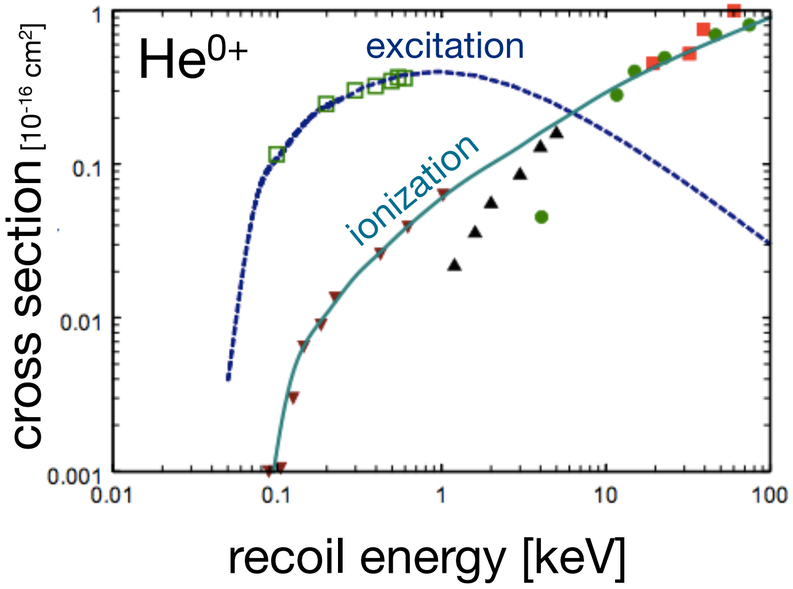


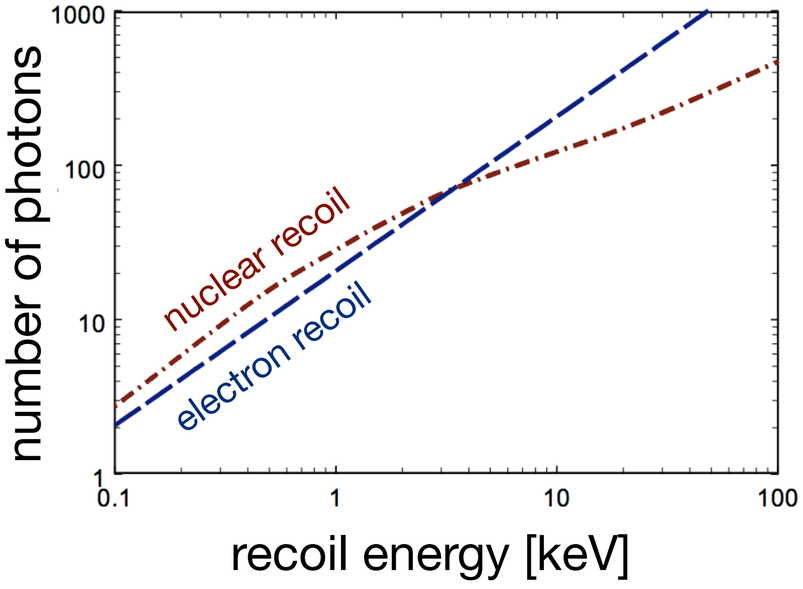


He scintillation yield

A 100eV nuclear recoil will produce a few photons from singlet decay.

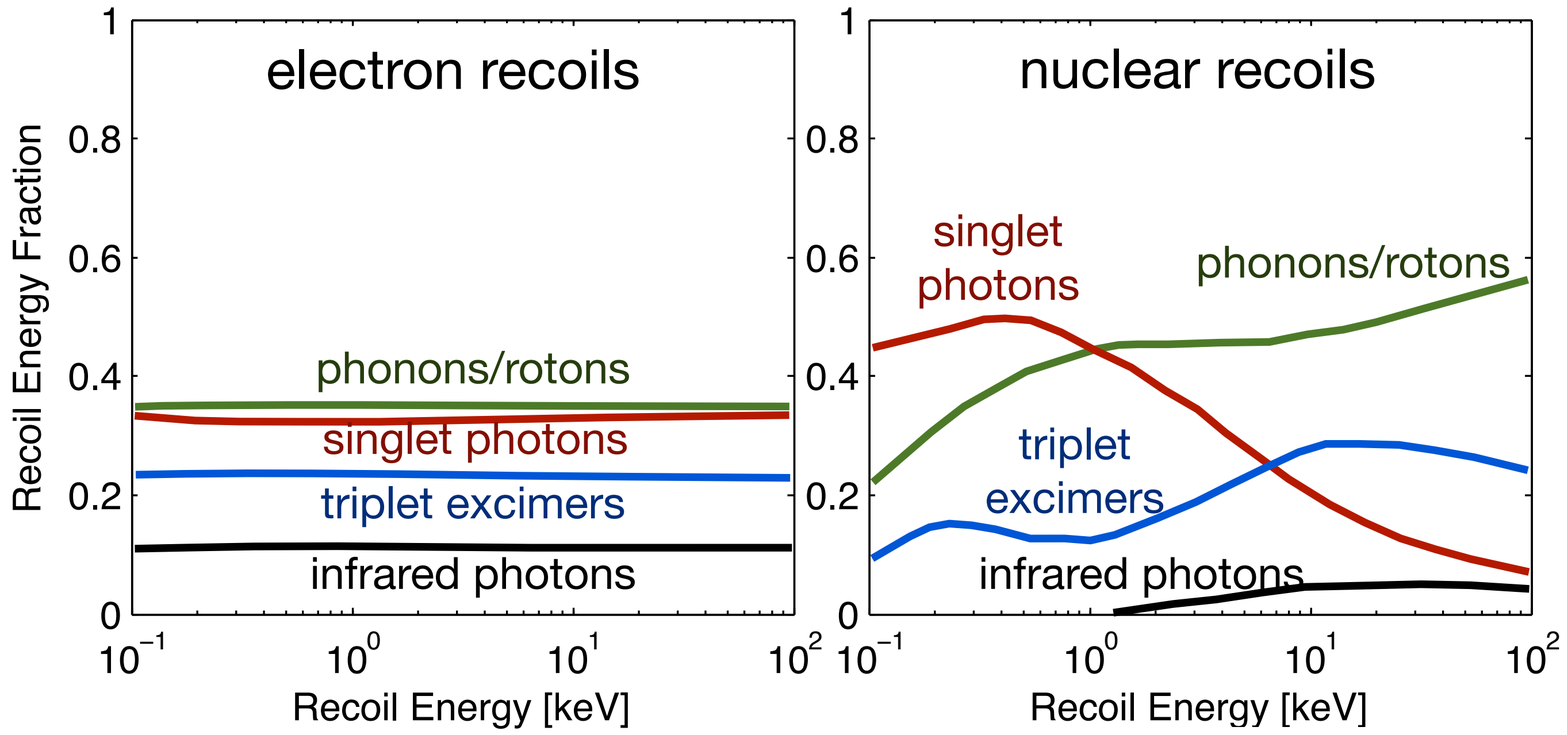






Energy splitting among channels

(rough estimates by George Seidel)



triplet excimers

	scintillation wavelength [nm]	triplet excimer lifetime [us]
He	80	1.3e6
Ne	78	15
Ar	125	1.6
Kr	150	0.09
Xe	175	0.03

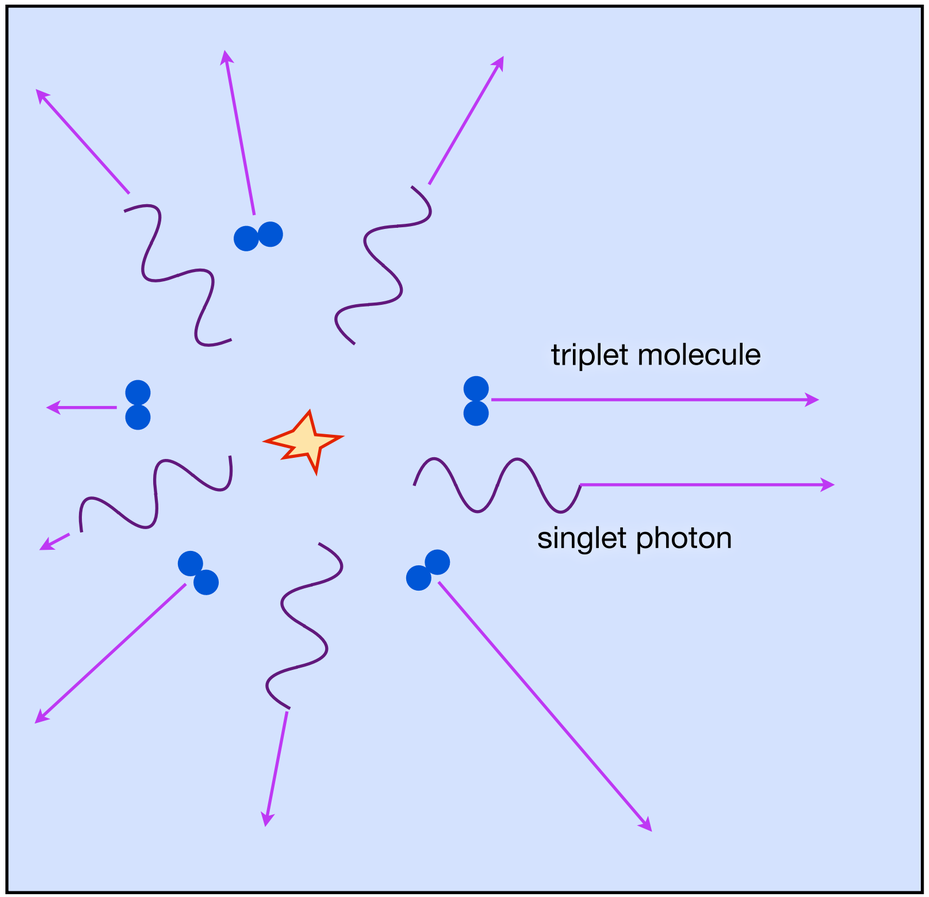
seconds lifetime

-> triplet will represent lost energy
or worse, a near-constant single photon background

can we measure the triplet excimers without waiting?

Triplet Excimers in Superfluid

ballistic
~10 m/s



Triplet Excimers in Superfluid

ballistic
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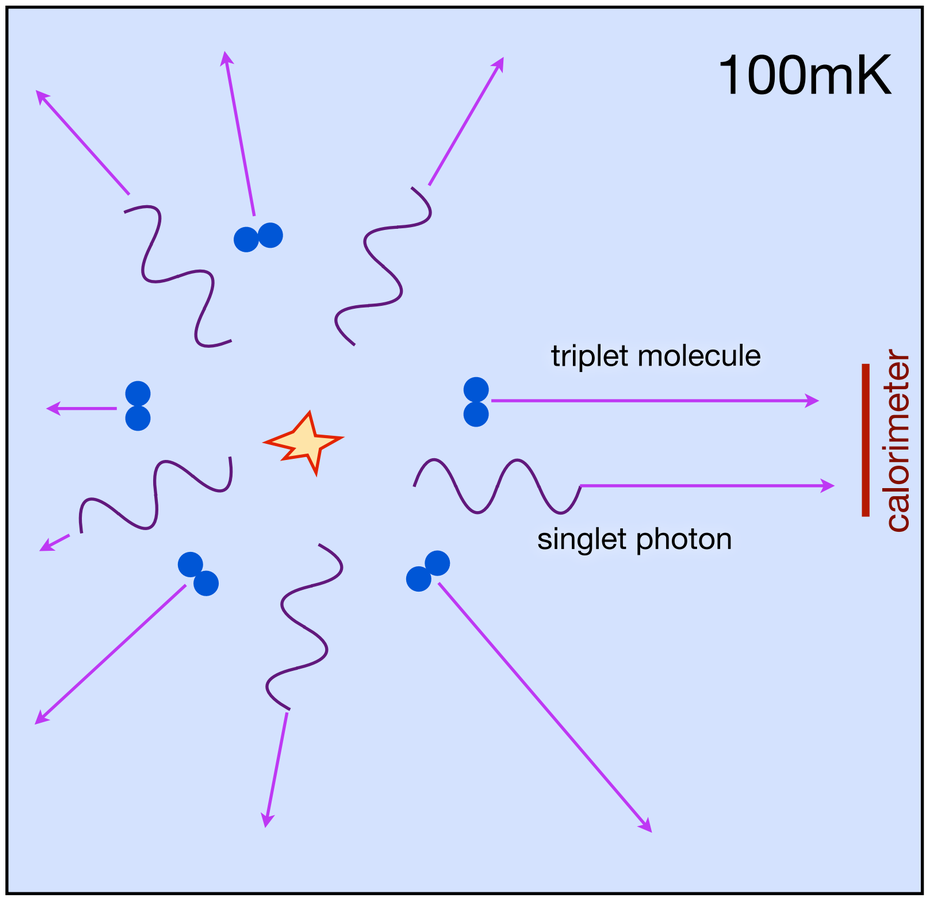
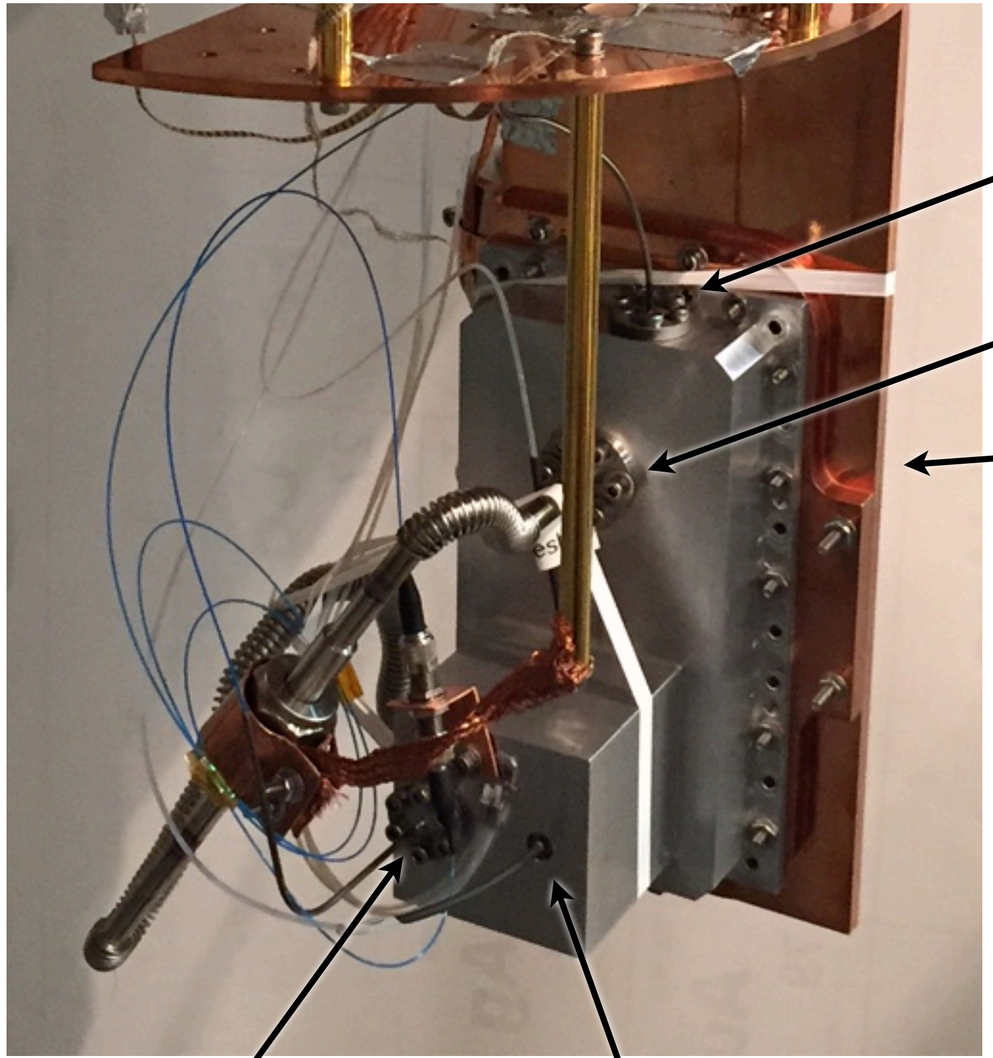
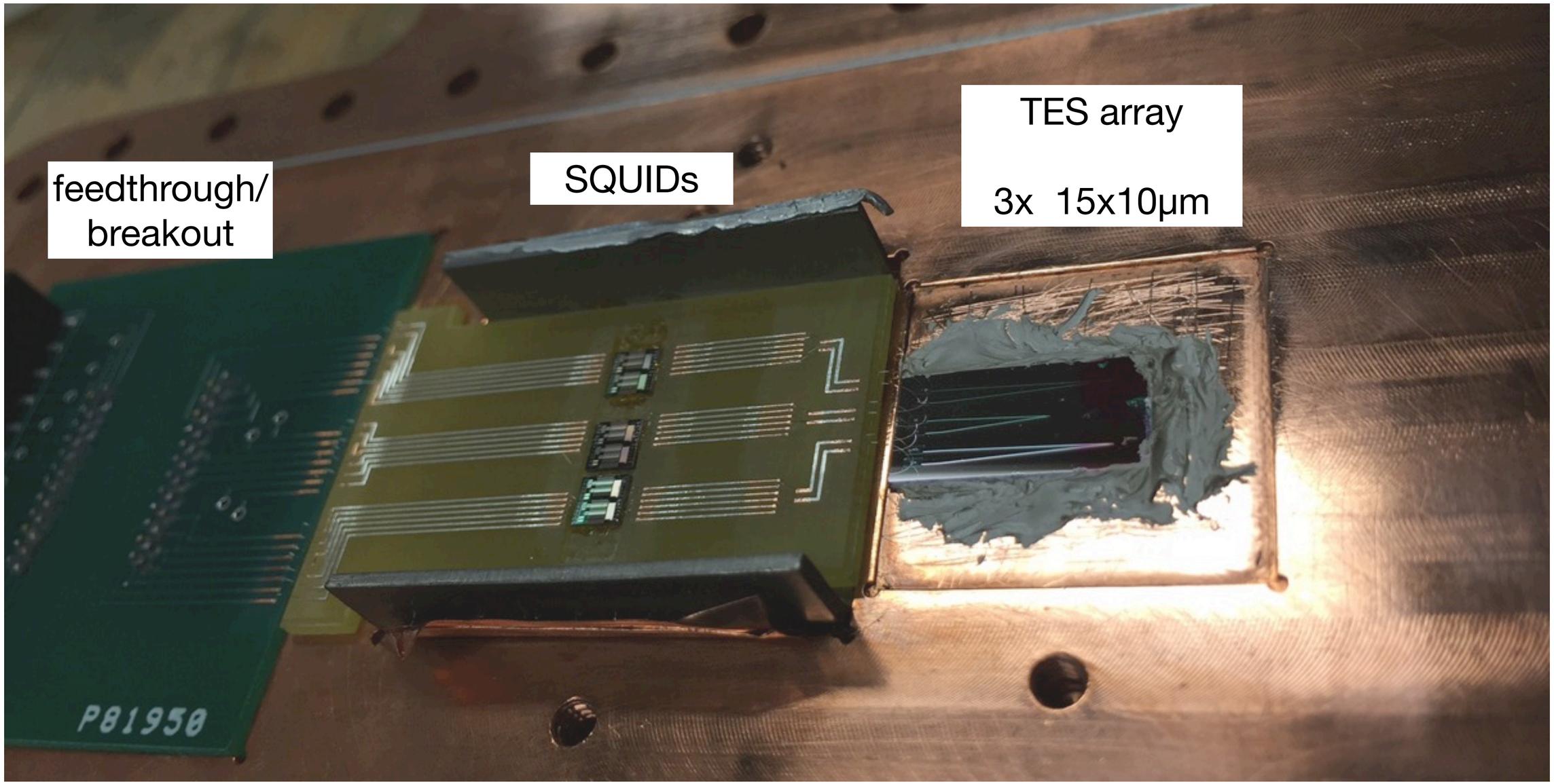


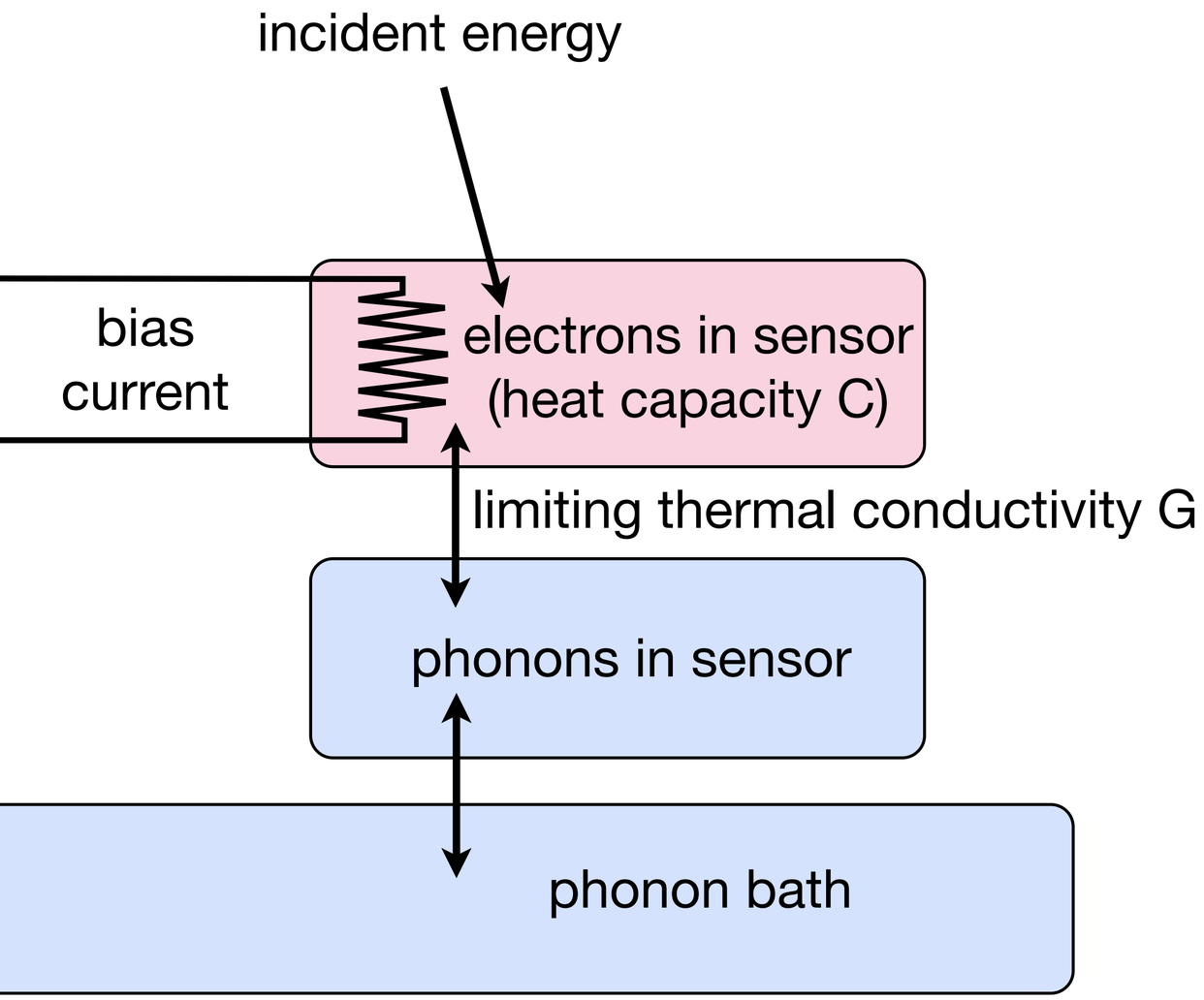


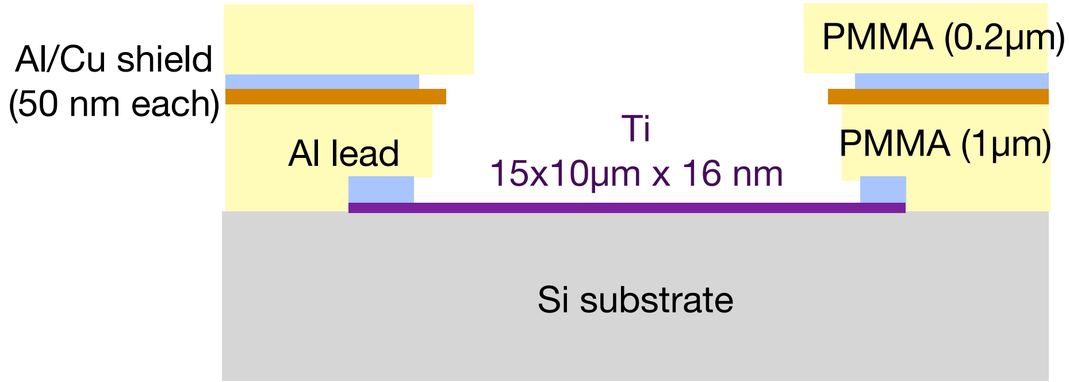
liquid volume:
135ml
(17g, 100 lstp)

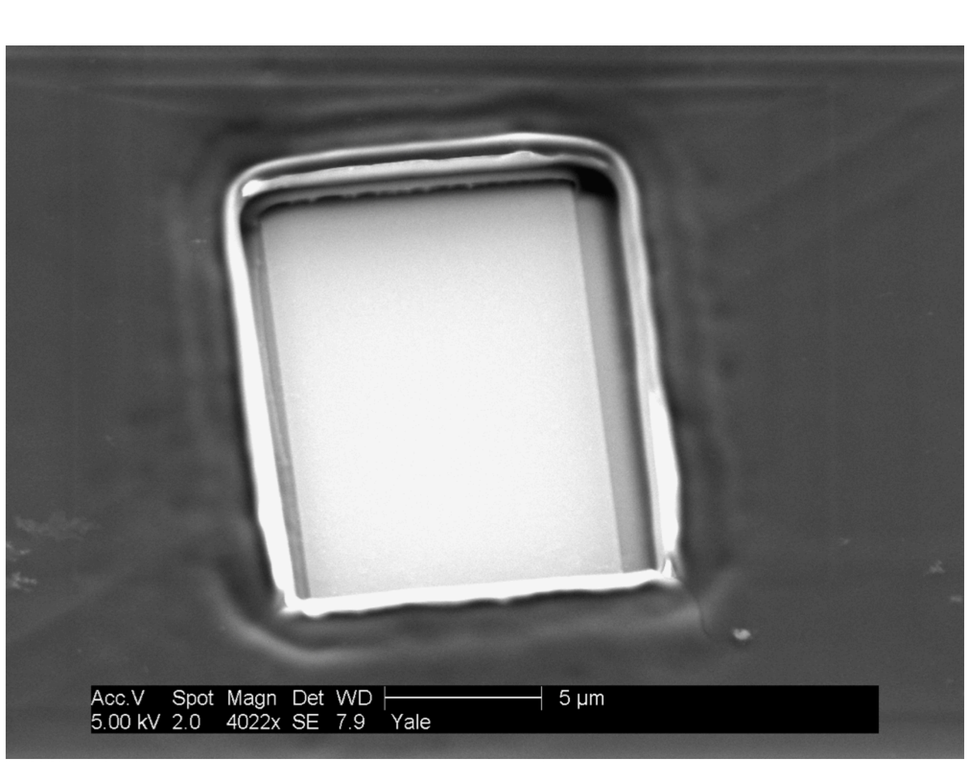
the detector plane



Our Transition Edge Sensors

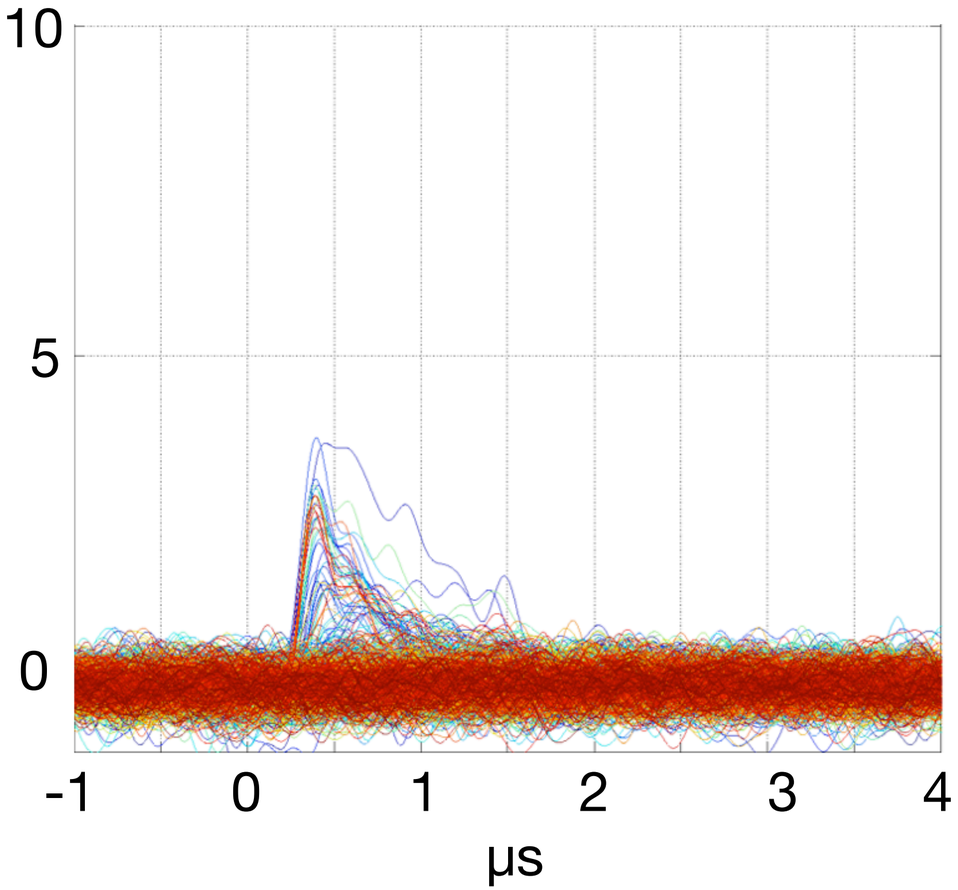


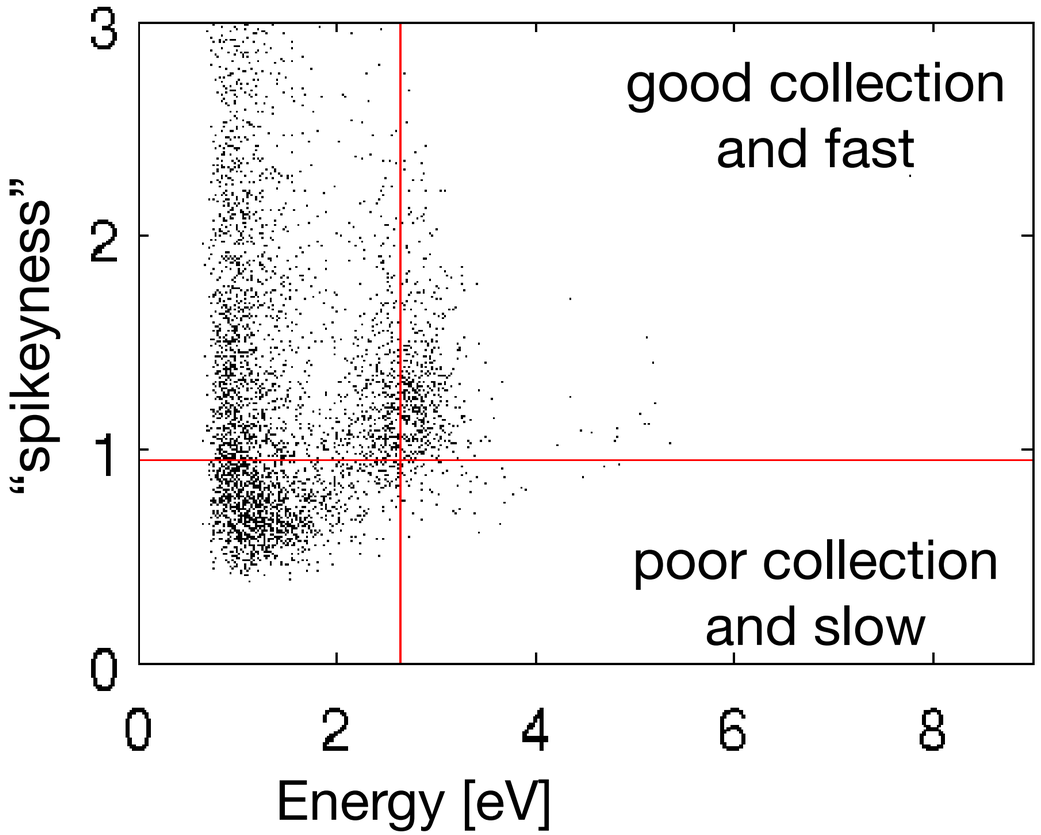




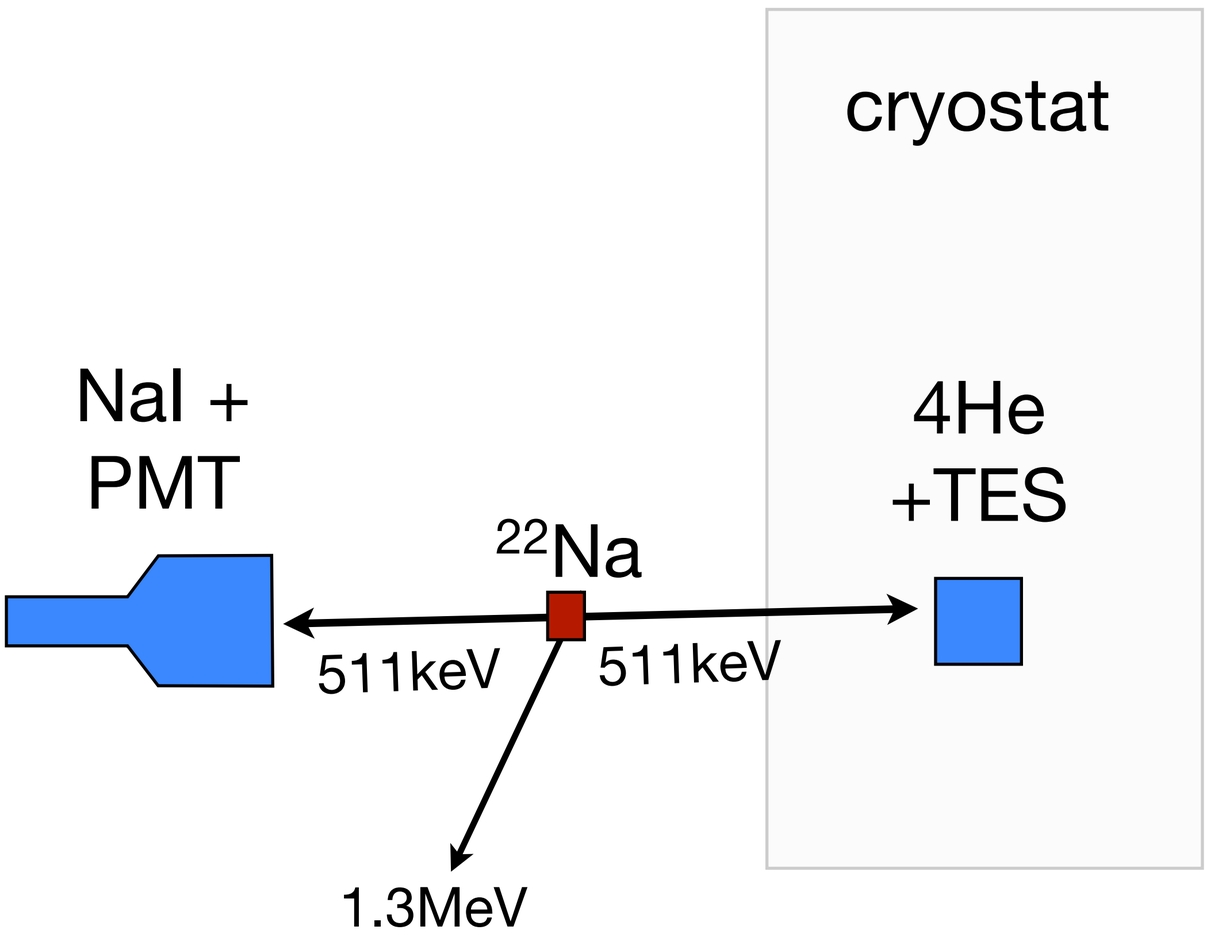
device response: calibrating with 2.64 eV photons

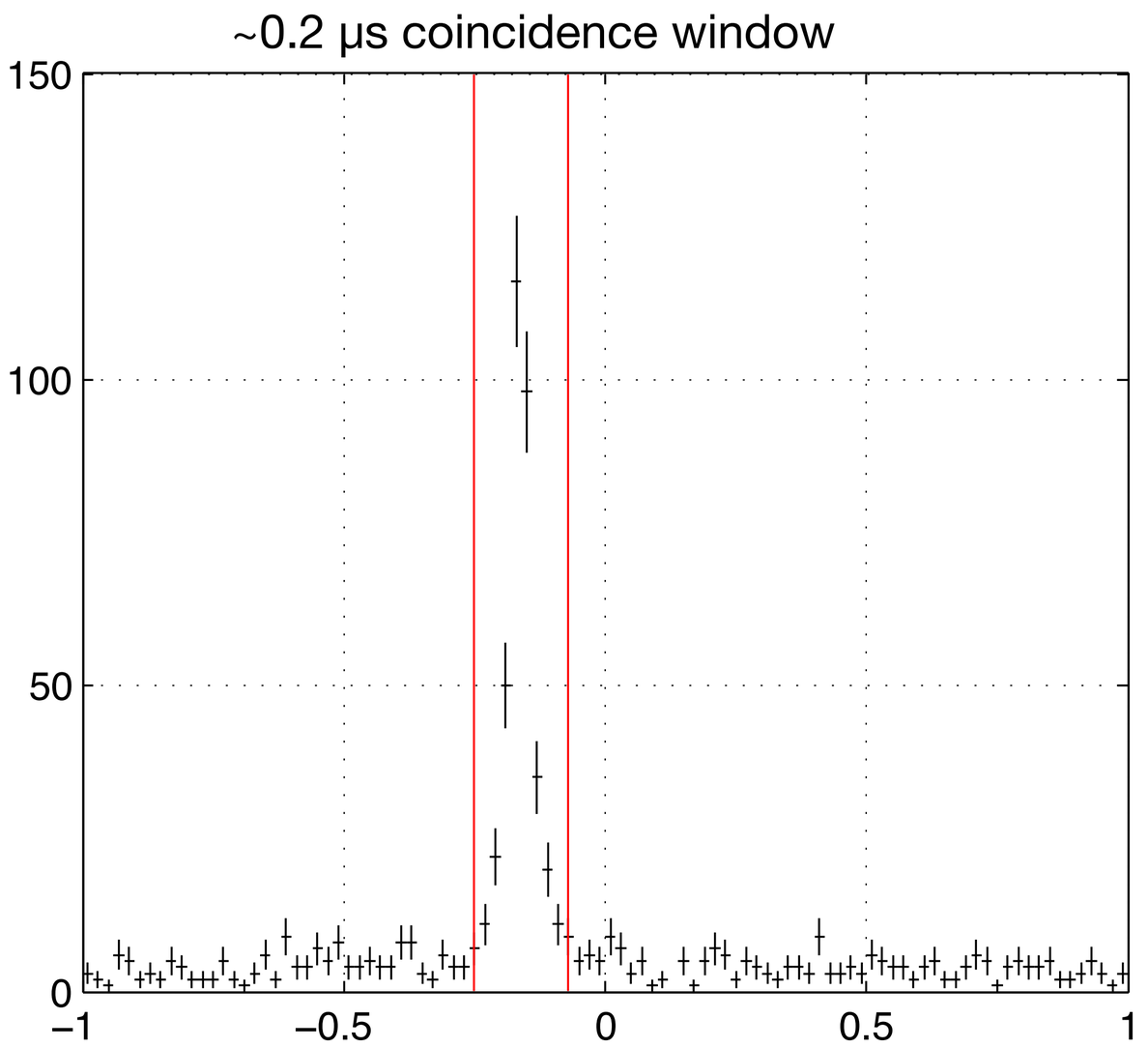
power into electron system [eV/μs]



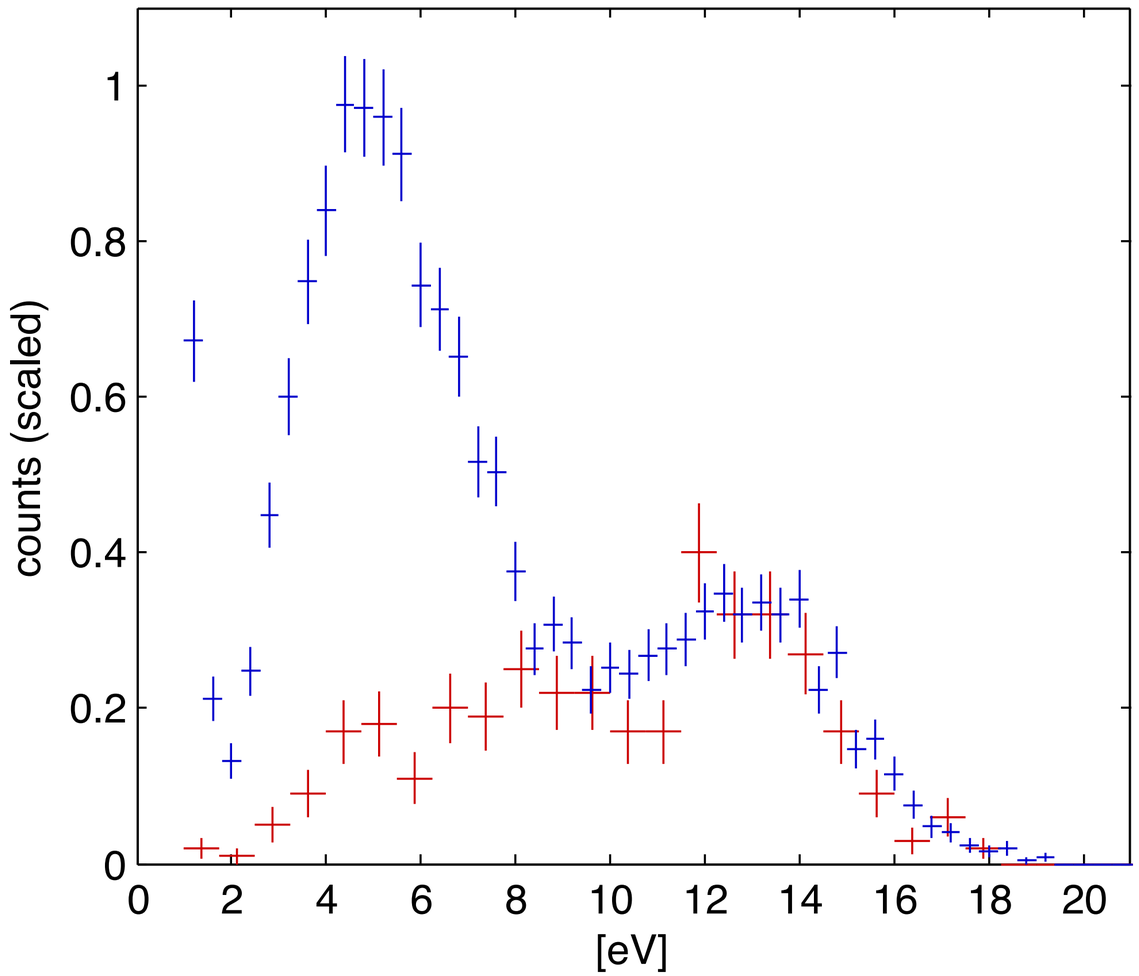


^{22}Na coincidence
tags prompt singlet decay





prompt and delayed spectra



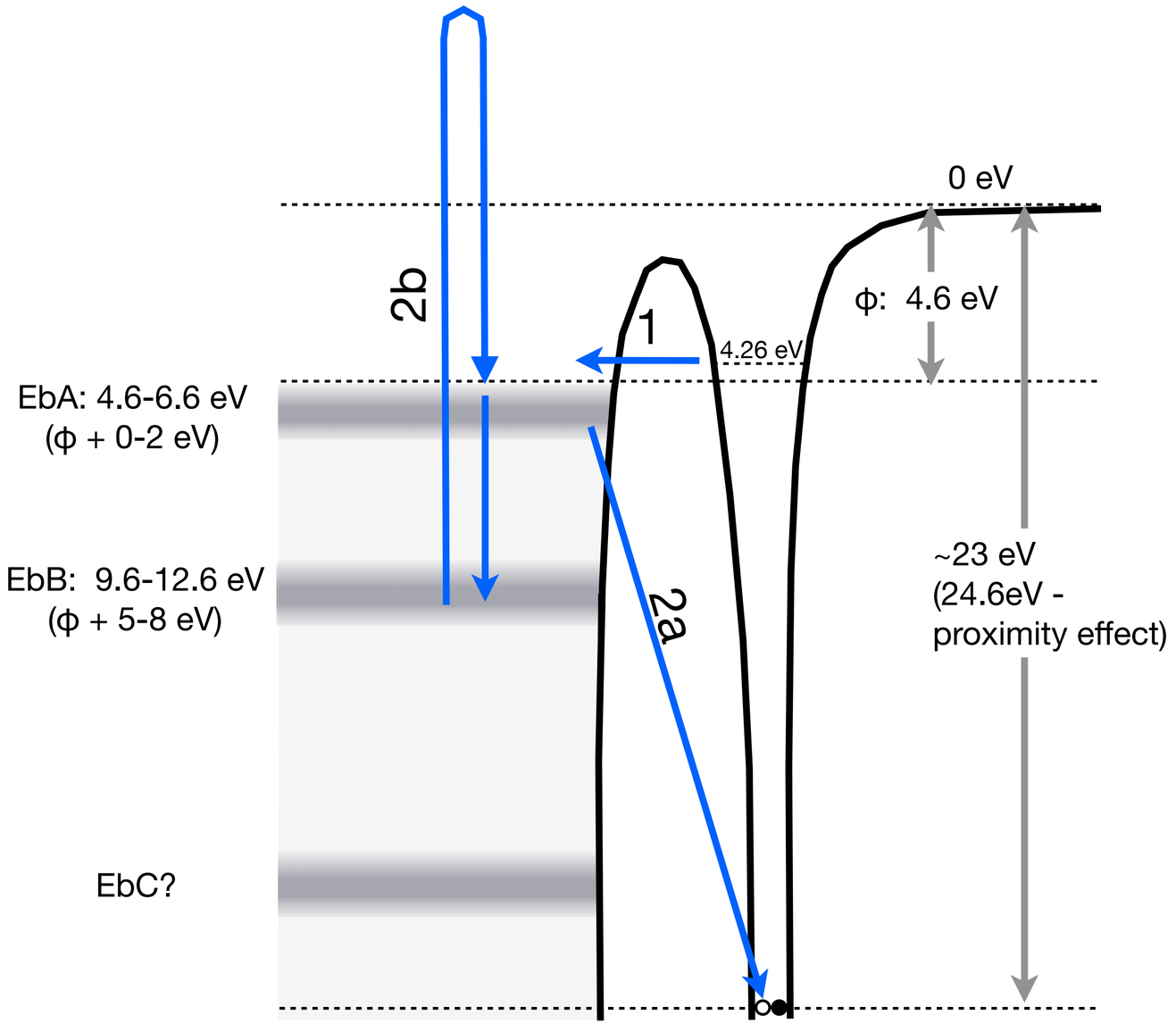
PMT-coincident:
prompt singlet photons only

PMT anti-coincident:
mixture of singlet photons
and **triplet quenching**

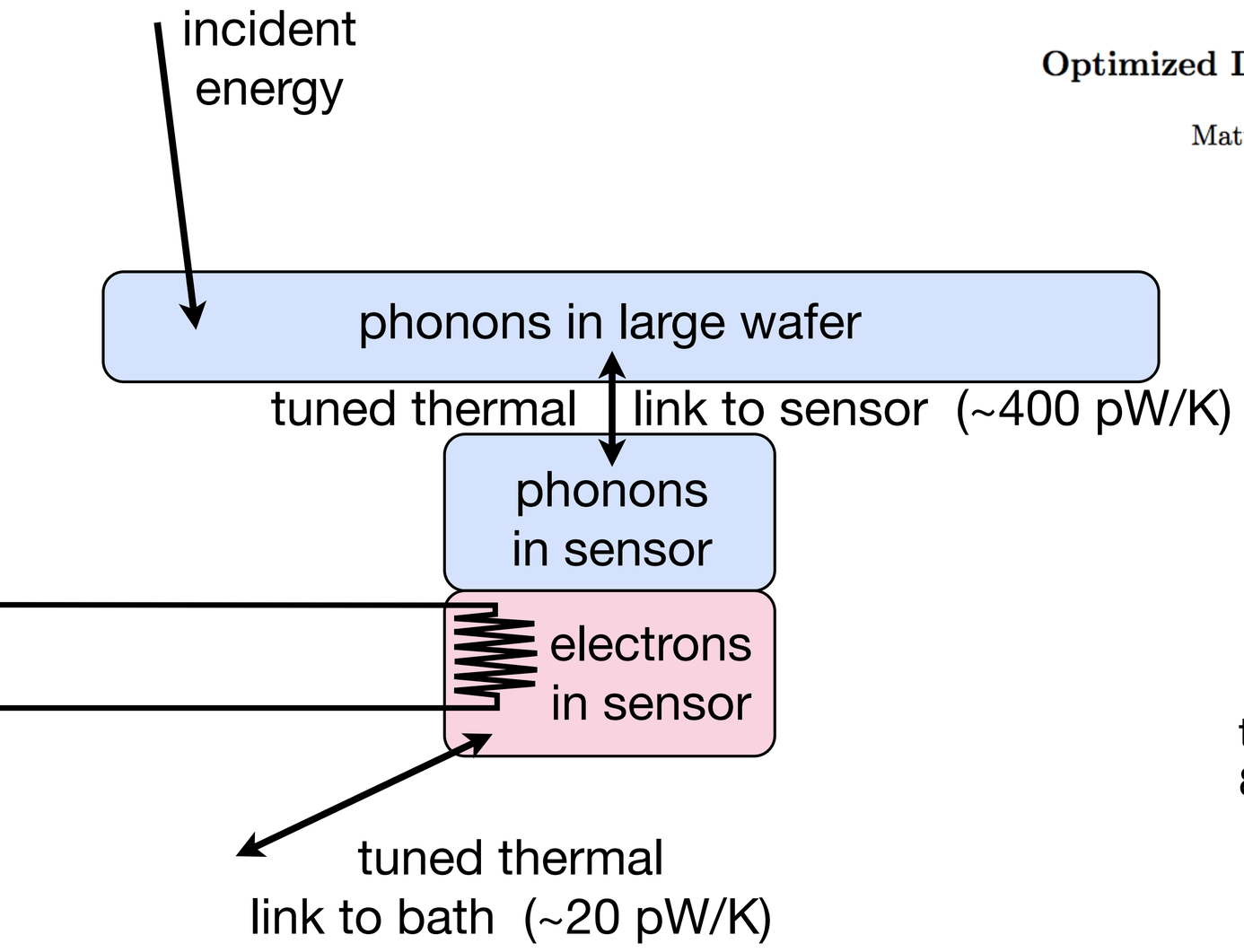
starting to understand the quench physics

1) **resonant ionization** of the excimer (excimer electron finds vacancy in metal)

2) **auger neutralization** of ionized excimer (metal electron falls into excimer, and spits out an Auger)



next step : large collection areas and high collection efficiency



Optimized Designs for Very Low Temperature Massive Calorimeters

Matt Pyle,[1,*] Enectali Feliciano-Figueroa,[2] and Bernard Sadoulet[1]
[1] *Physics Department, University of California Berkeley*
[2] *Physics Department, Massachusetts Institute of Technology*
(Dated: February 2, 2015)

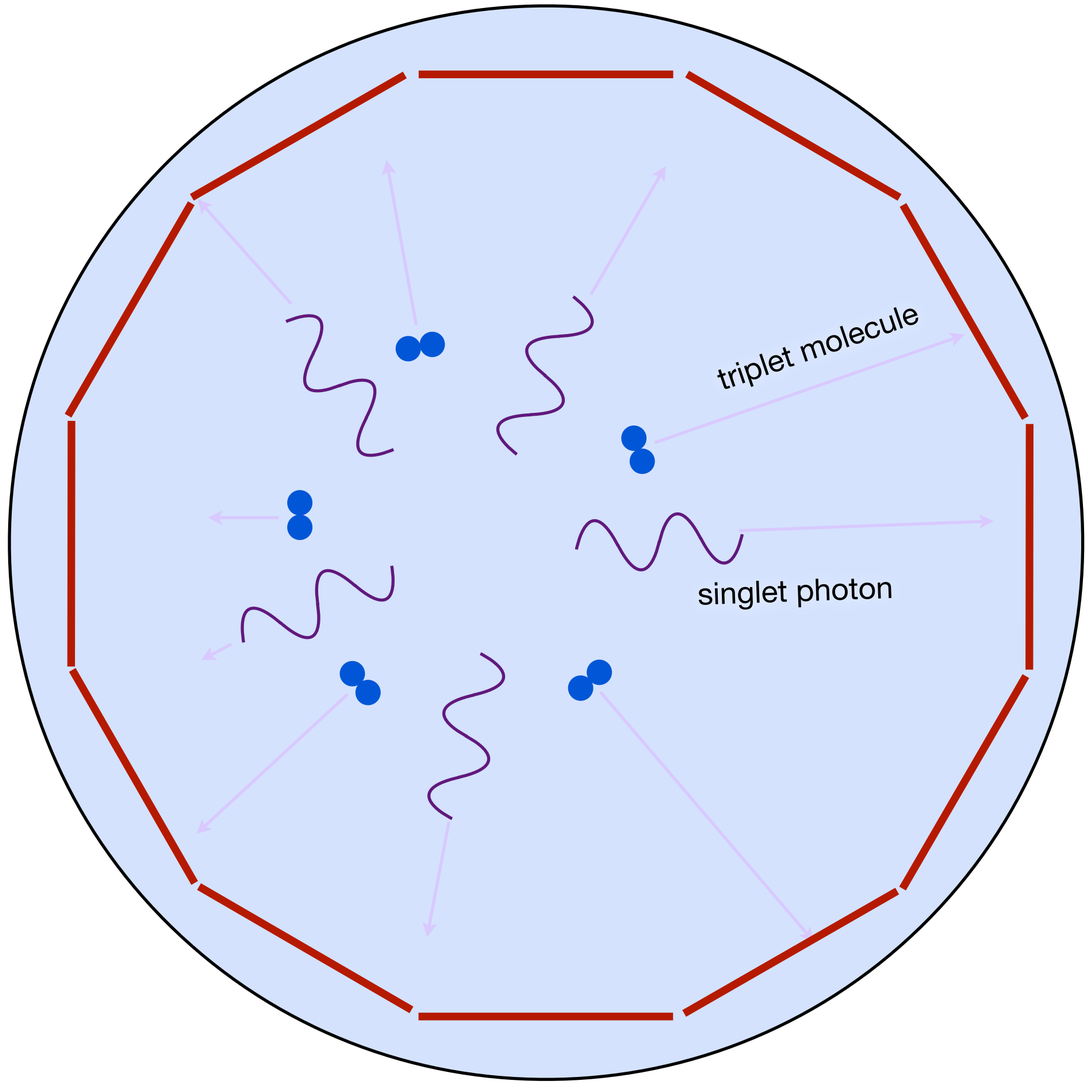
80 mm diameter Si wafer
tungsten TES (10mK)
0.36 eV predicted resolution

thermal links to superfluid are minuscule
80mm Si wafer: $G_{absorber\text{-}bath}$ = **~0.15 pW/K**

one can imagine a 100%-efficient triplet-singlet detector

ton-scale

few-hundred-eV threshold



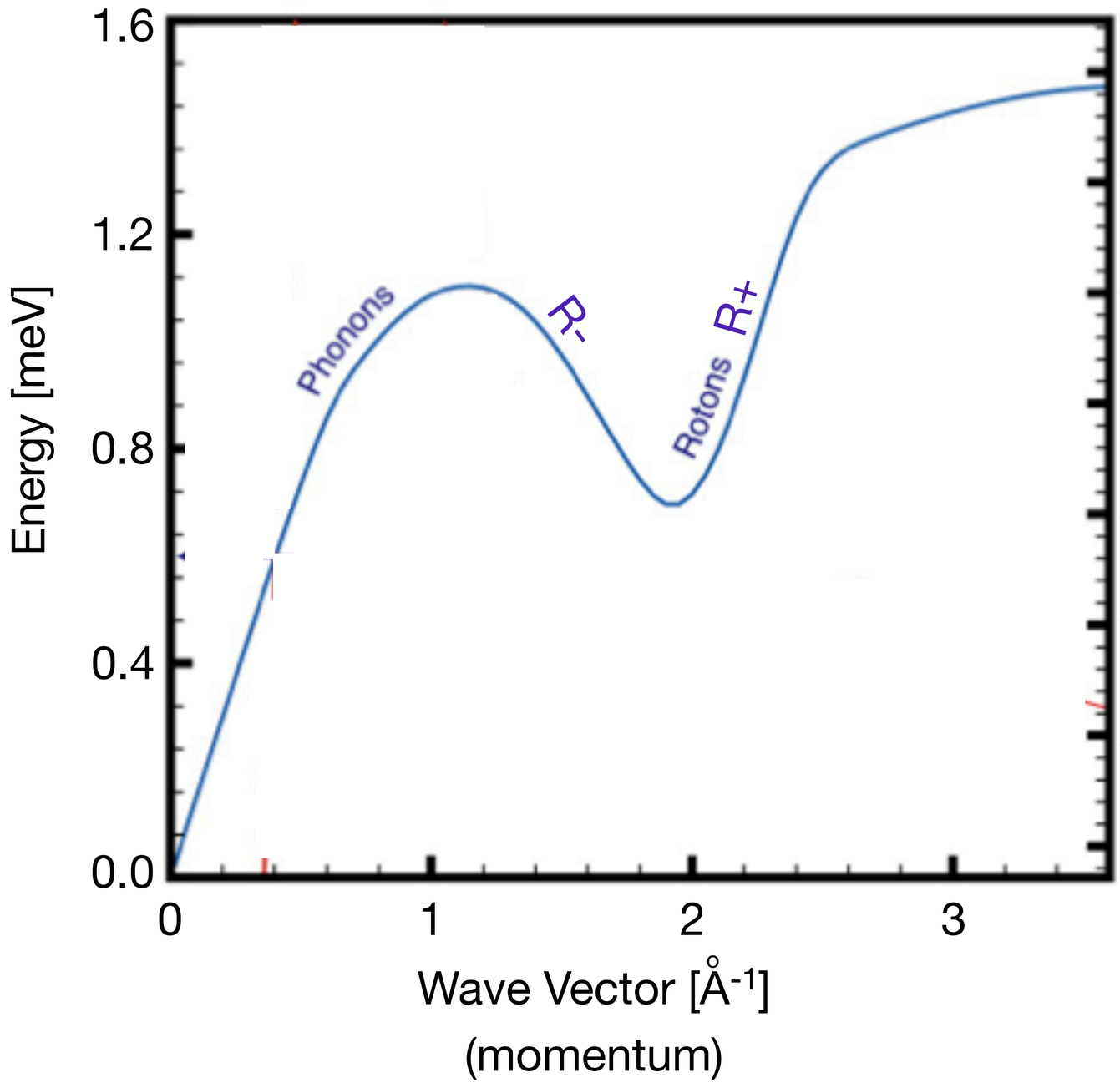
phonons and rotons

superfluid supports vibration
(some non-intuitive)

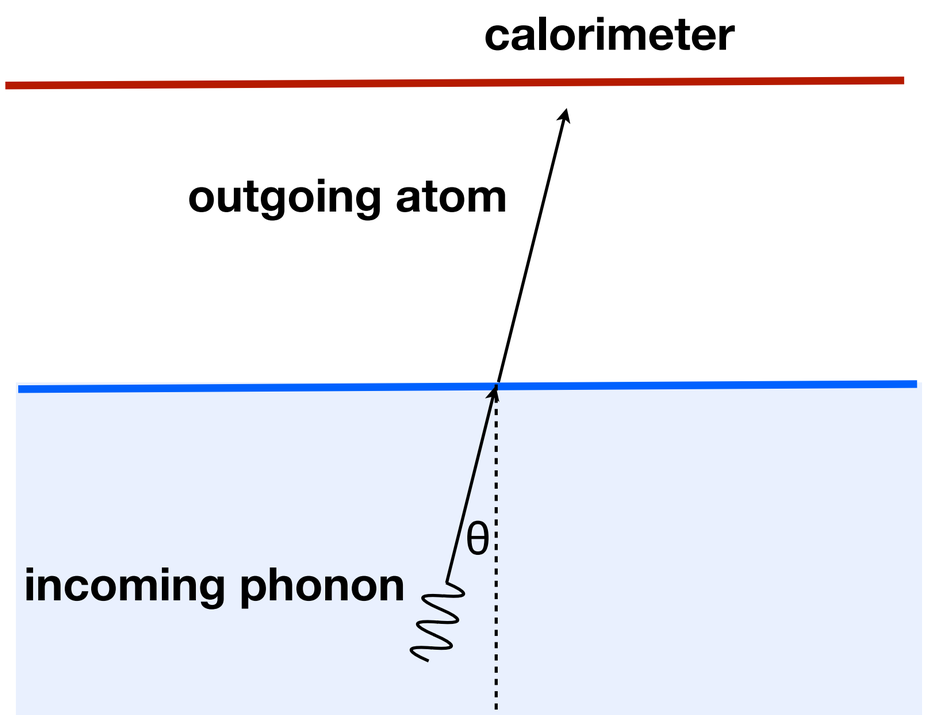
ballistic, ~150m/s

enormous Kapitza resistance,
i.e. *tiny* probability of crossing into solid
(~1% per interaction)

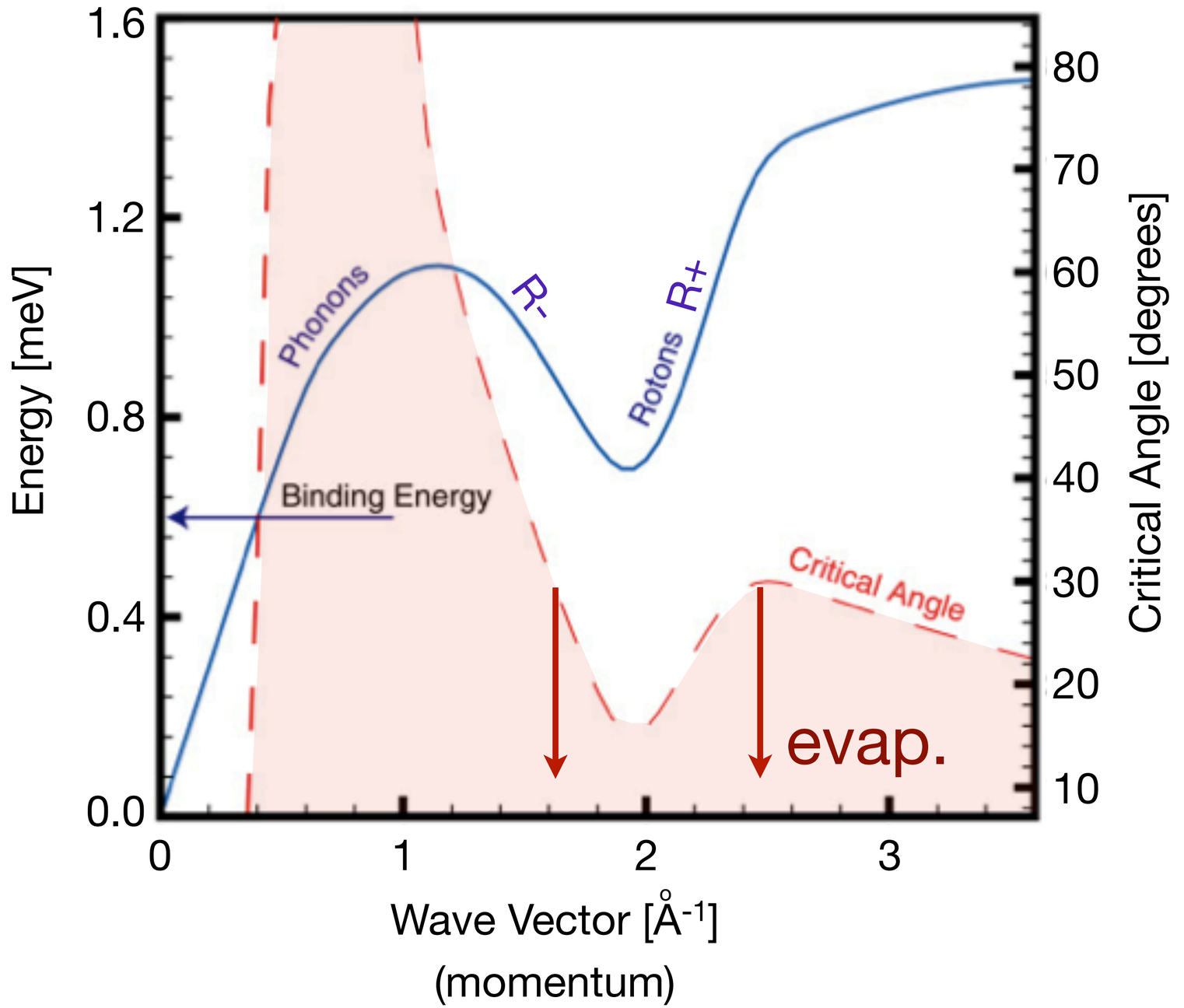
few downconversion pathways



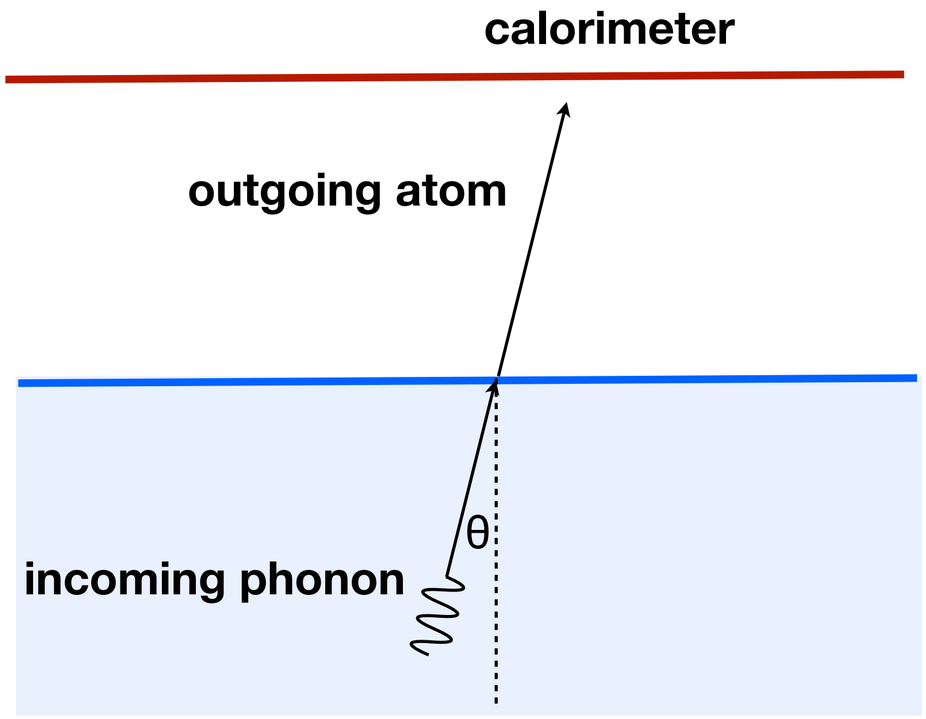
athermal evaporation



chance per interaction high: ~25%
-> nearly all phonon/roton energy will end up as athermal evaporation



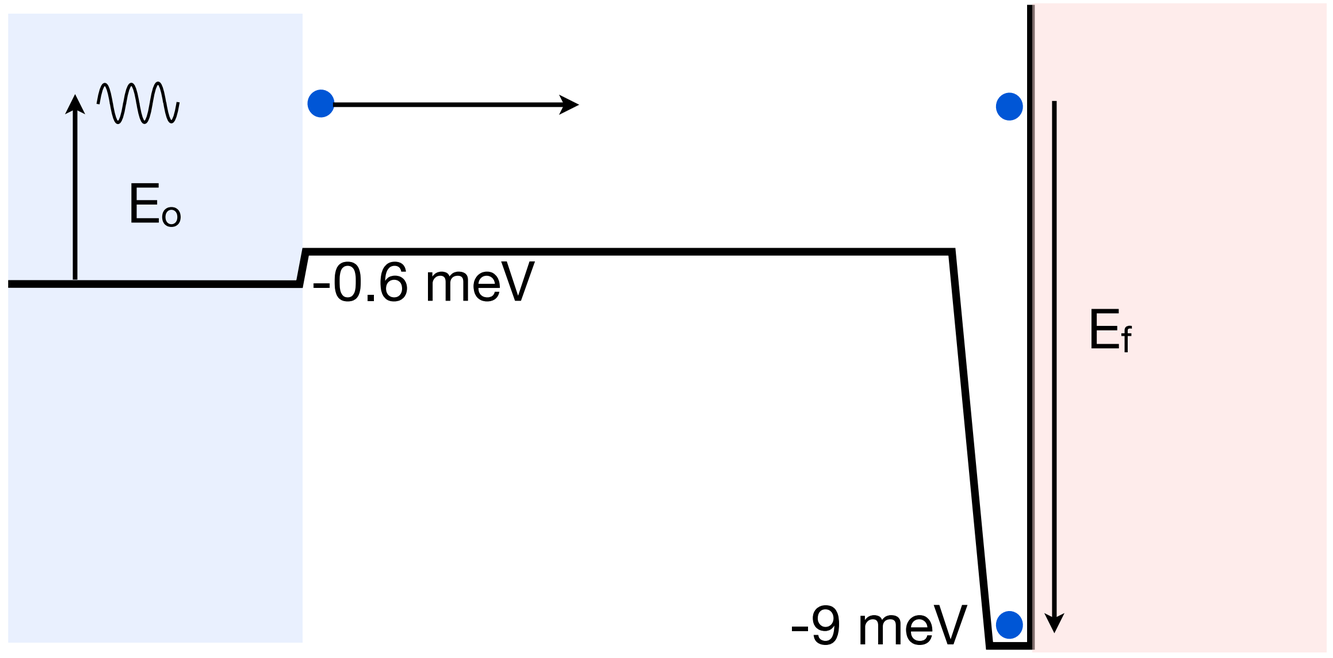
athermal evaporation



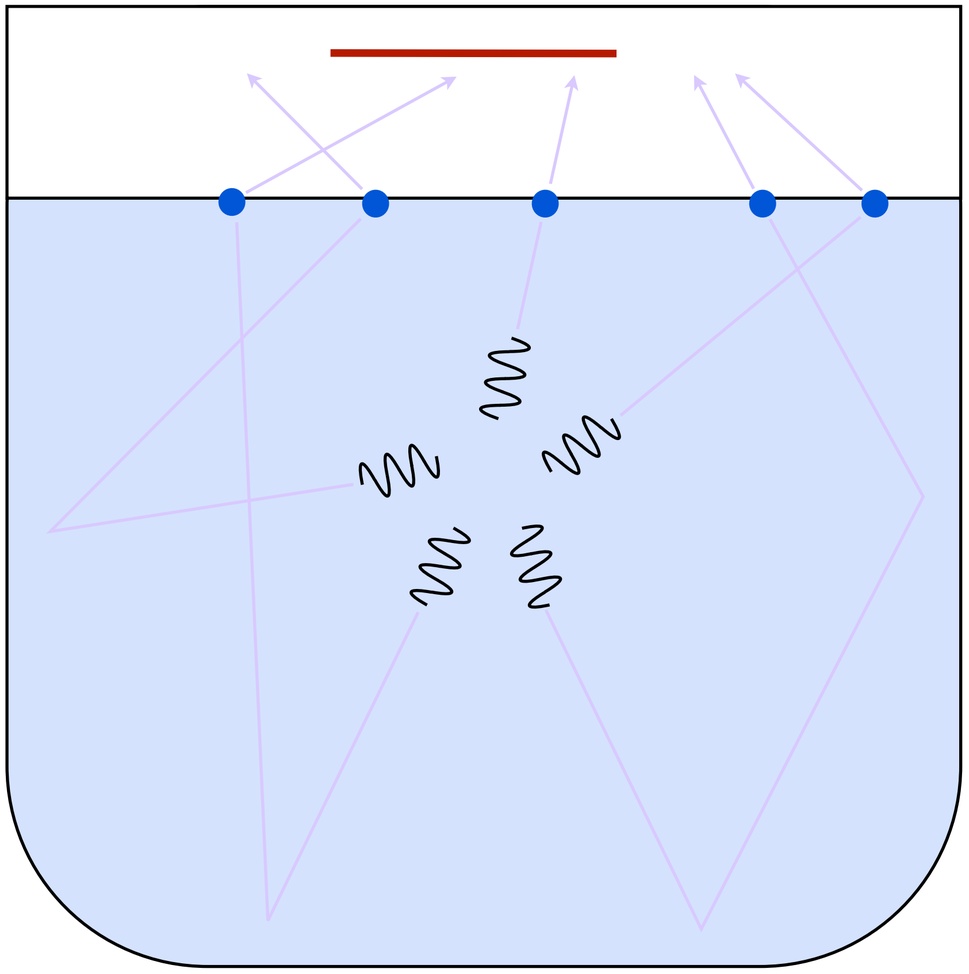
chance per interaction high: ~25%
-> nearly all phonon/roton energy
will end up as athermal evaporation

amplification *before* sensing

for typical 1meV roton/phonon,
gain of ~10x in energy



athermal evaporation



sounds crazy,
but demonstrated by HERON

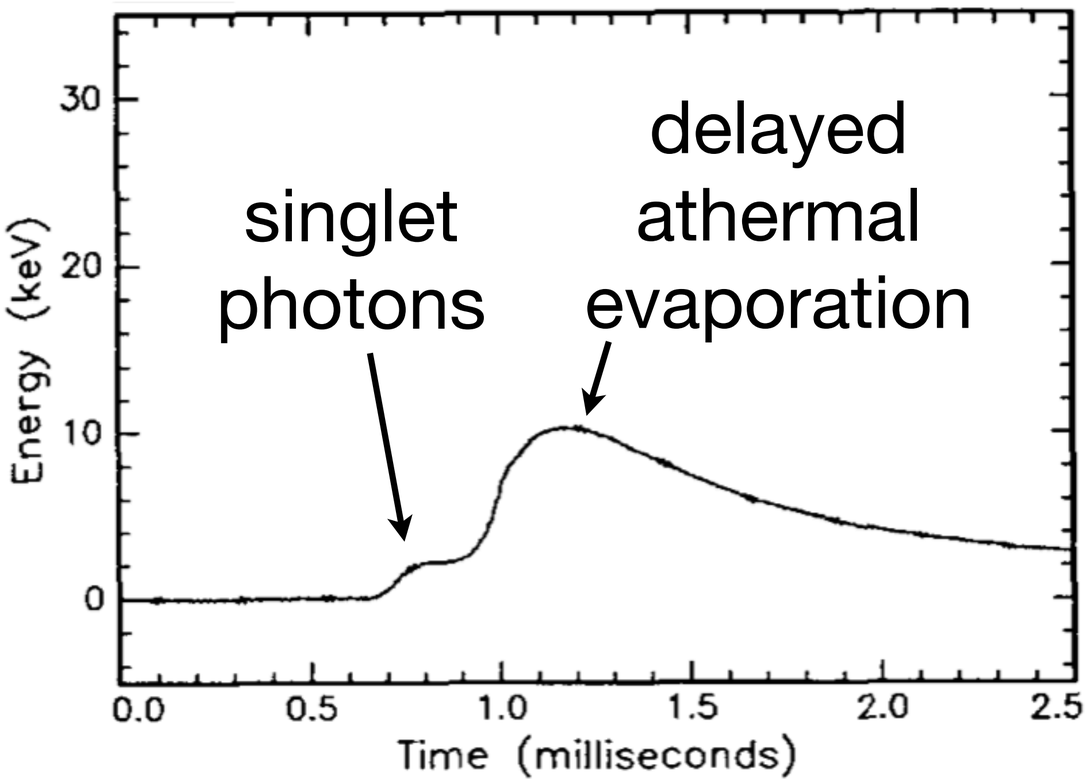
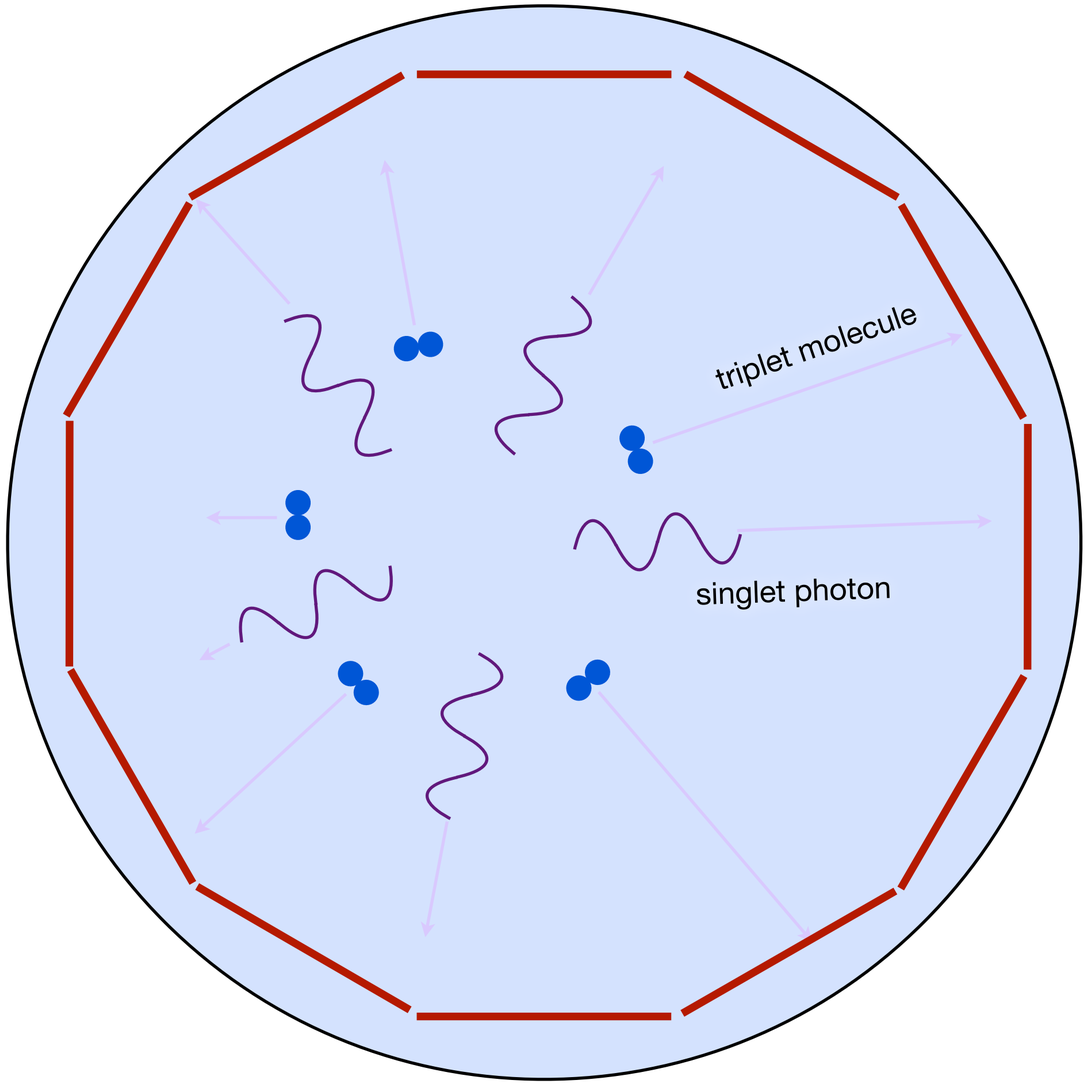
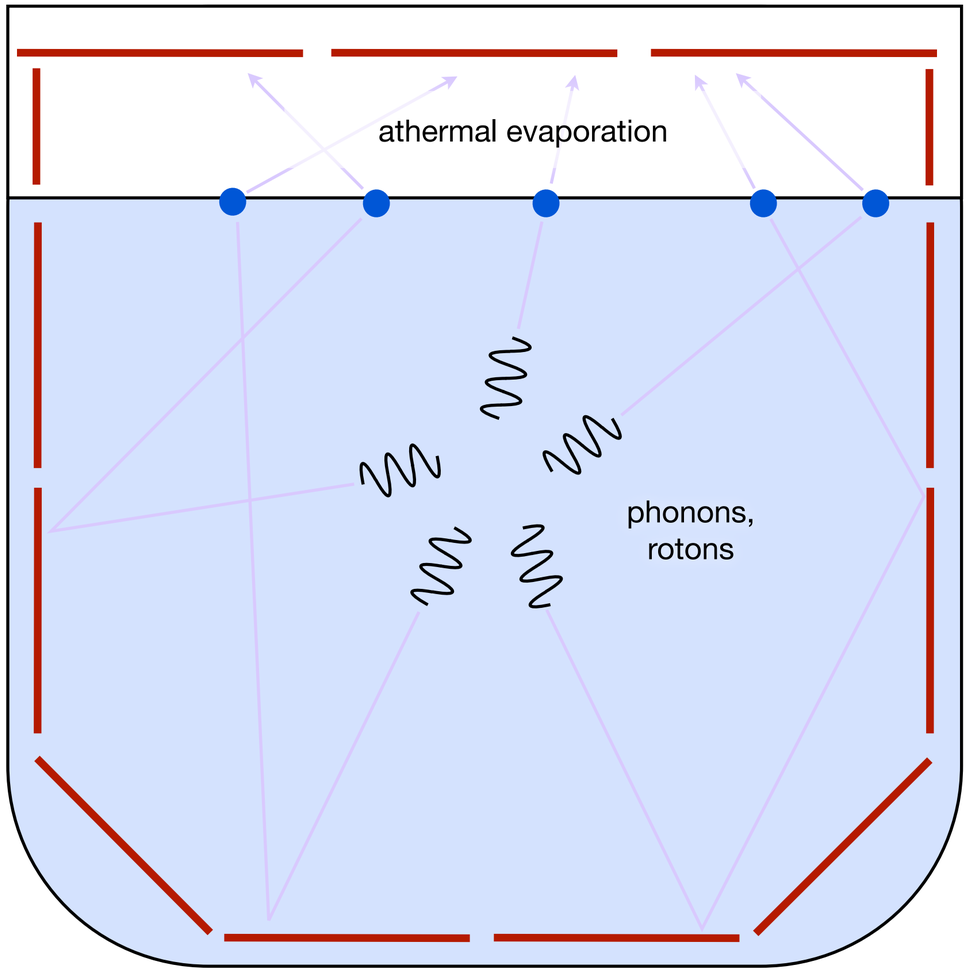


Fig. 2. (a) The calorimeter response (average of about 100 events) when an α particle is stopped in liquid helium. The collimated α tracks are (a) parallel and (b) perpendicular to the liquid surface.

add vacuum, gain a 3rd powerful channel



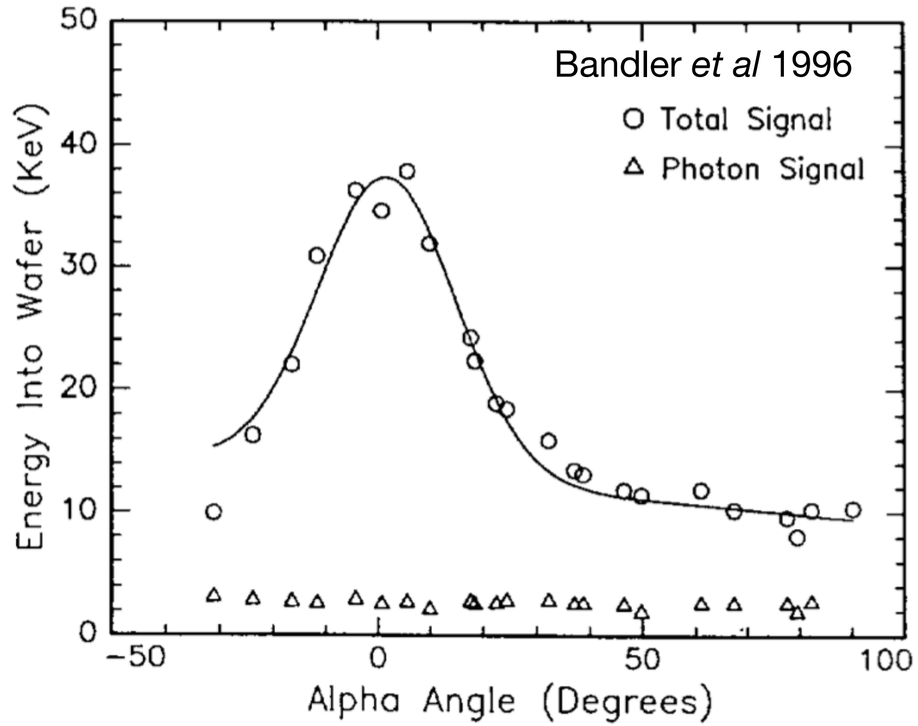
1 eV recoil
1 eV of phonons/rotons
75% above evaporation threshold? (guess)
75% result in evaporation? (guess)
~ **5eV heat** in vacuum calorimeters?

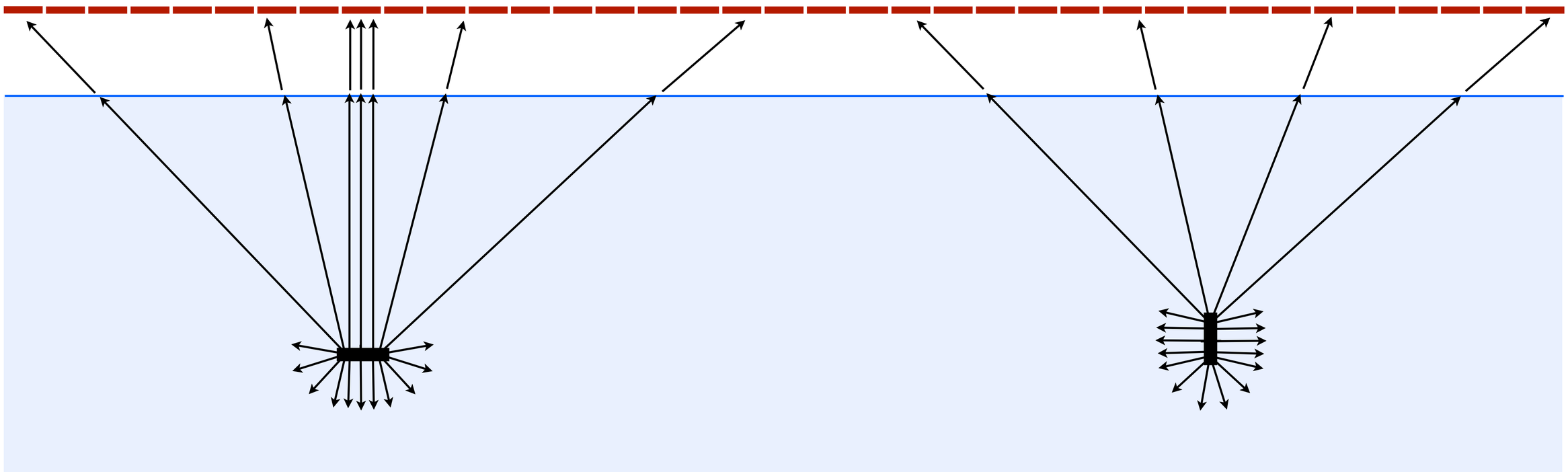


the phonon&roton channel carries track direction information

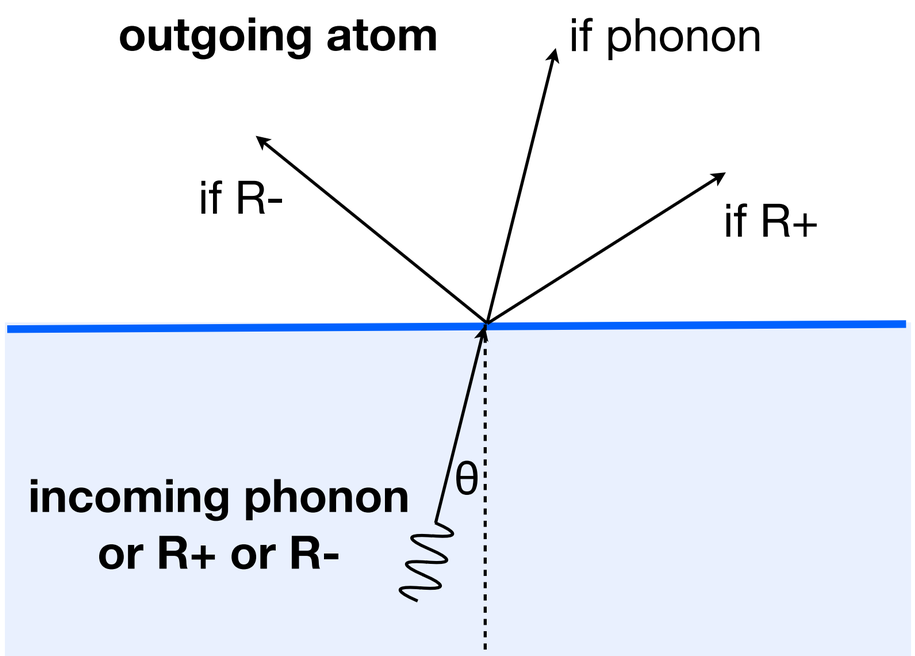
flux emitted normal to track

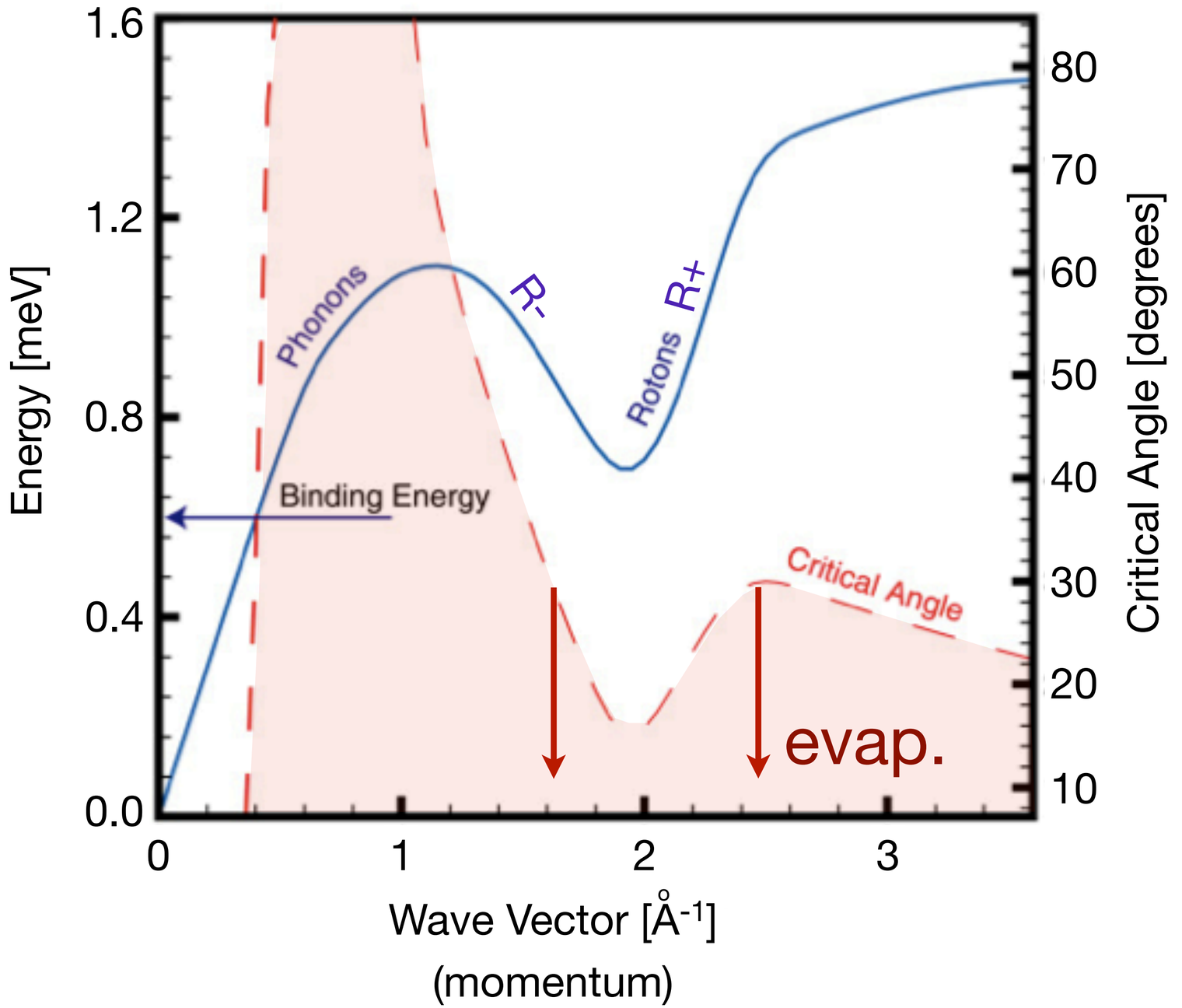
untested energy dependence





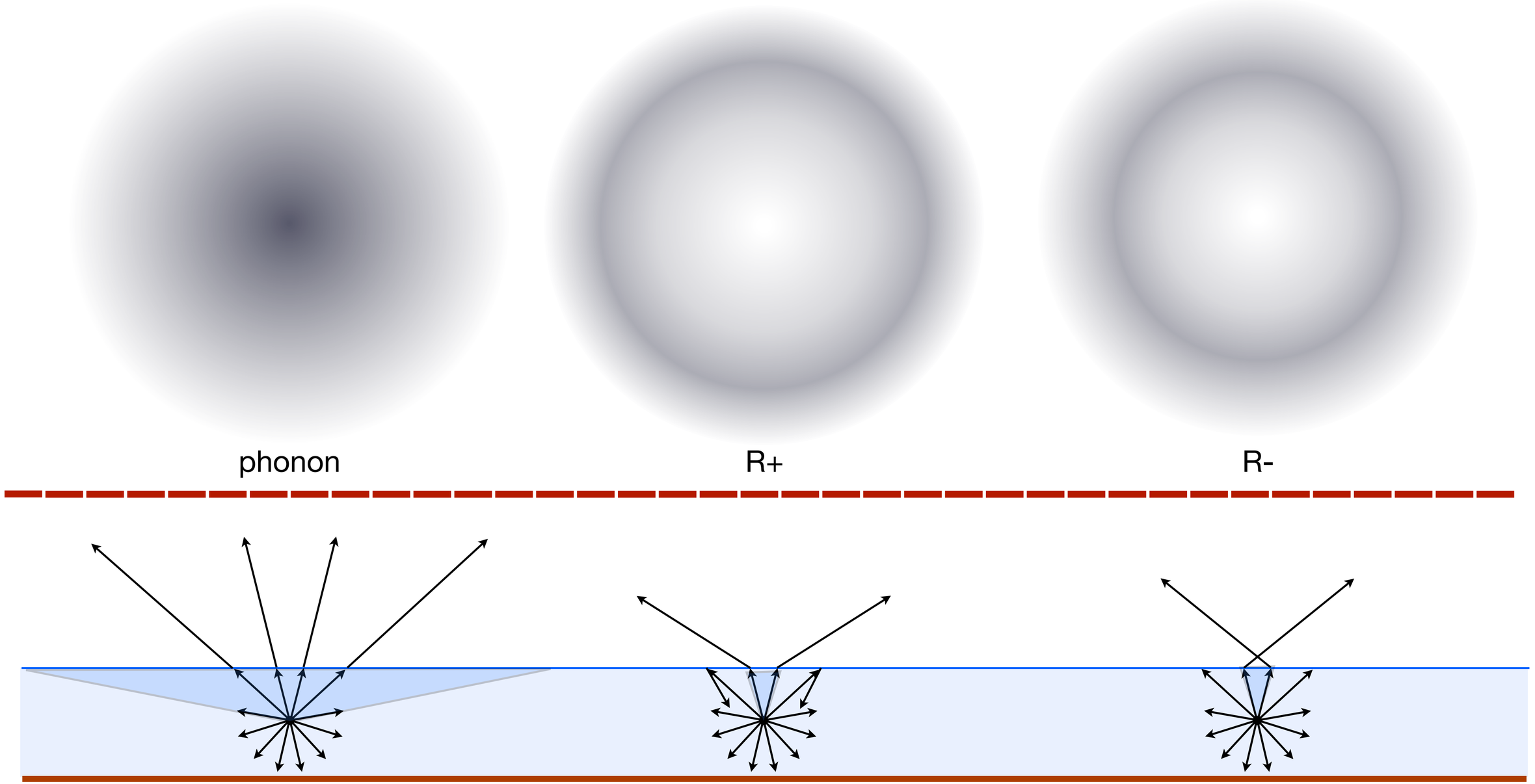
phonons/roton athermal evaporation ‘refractive index’





refractive index and critical angle make the phonon/roton ratio visible

question for experiment: ER/NR discrimination efficiency



WIMP direct detection parameter space

strawman
photon+roton detector

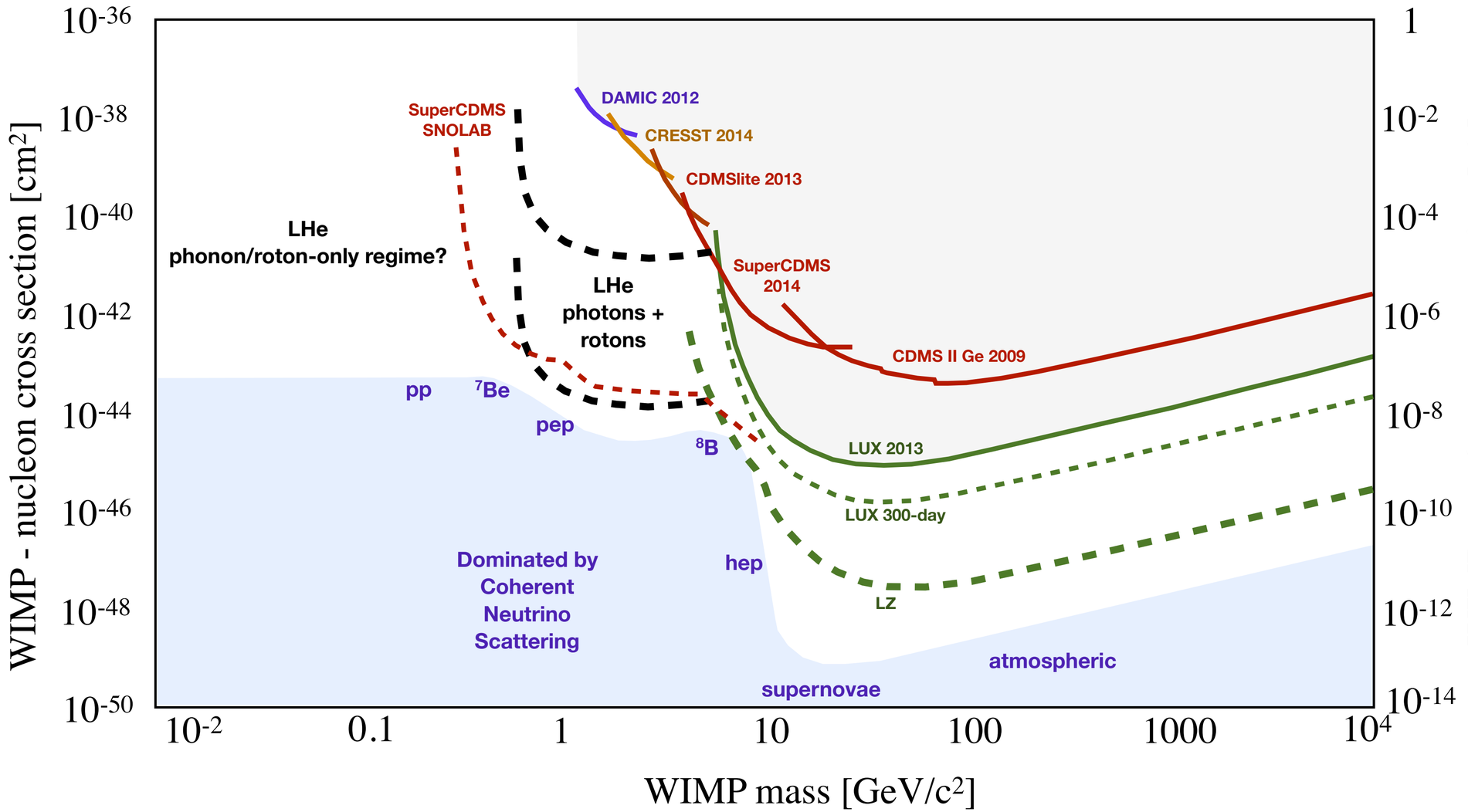
300 eV threshold
(~10 photons, conservative)

1 ER event/keV/kg/day
flat 95% discrimination

two exposures:

20 kg-days
0.4 kg (3.2 liters) for 50 days

20,000 kg-days
55 kg (440 liters) for 1 year



the superfluid miracle

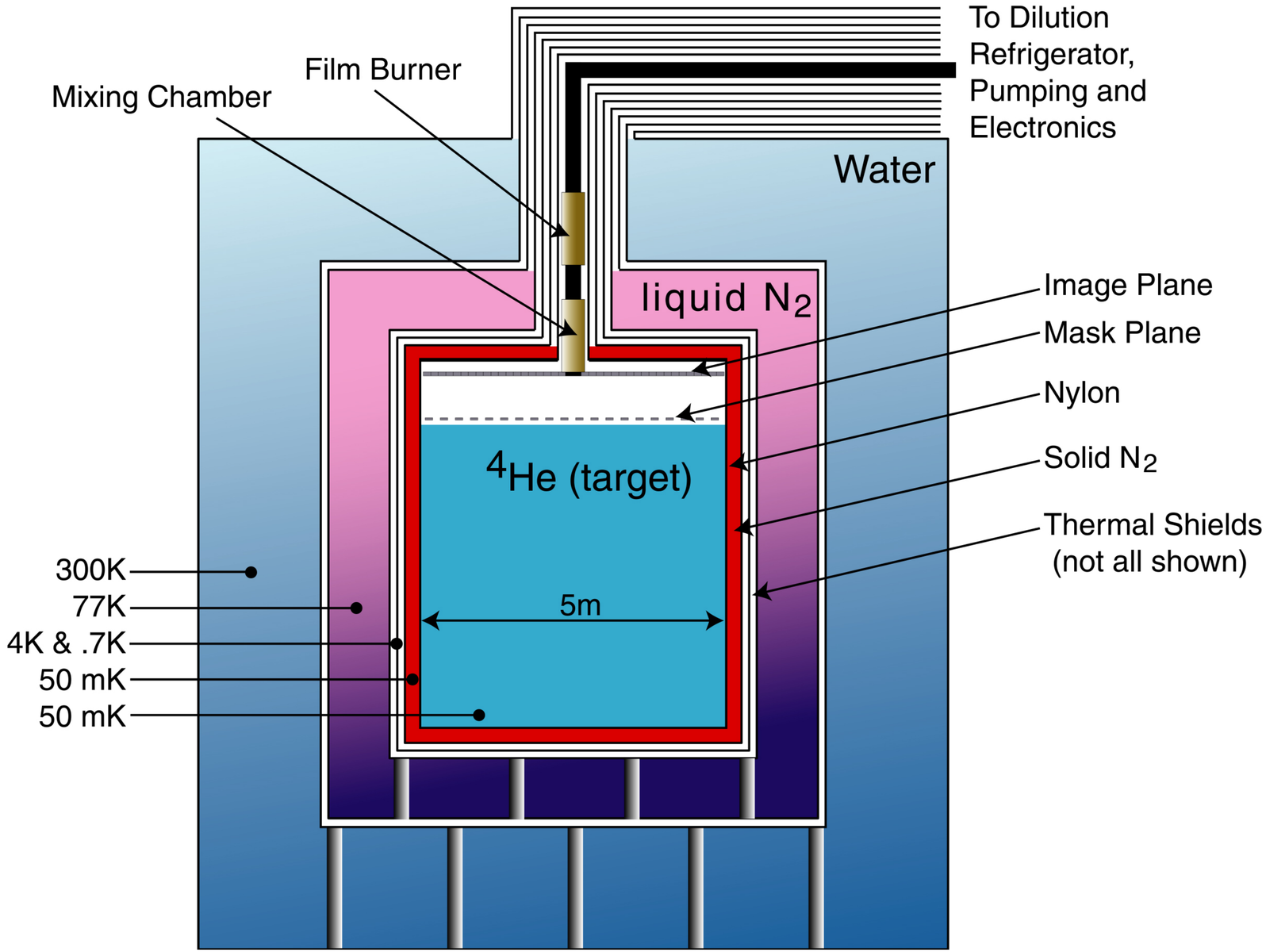
kinematically matched to the low-mass range (effectively boosts recoil energy)
perfect radiopurity for ‘free’
pairable with 100%-efficient sensors due to the mK temperatures

good scintillator (threshold ~100eV?)
singlets & triplets both visible and cleanly separated by triplet drift time

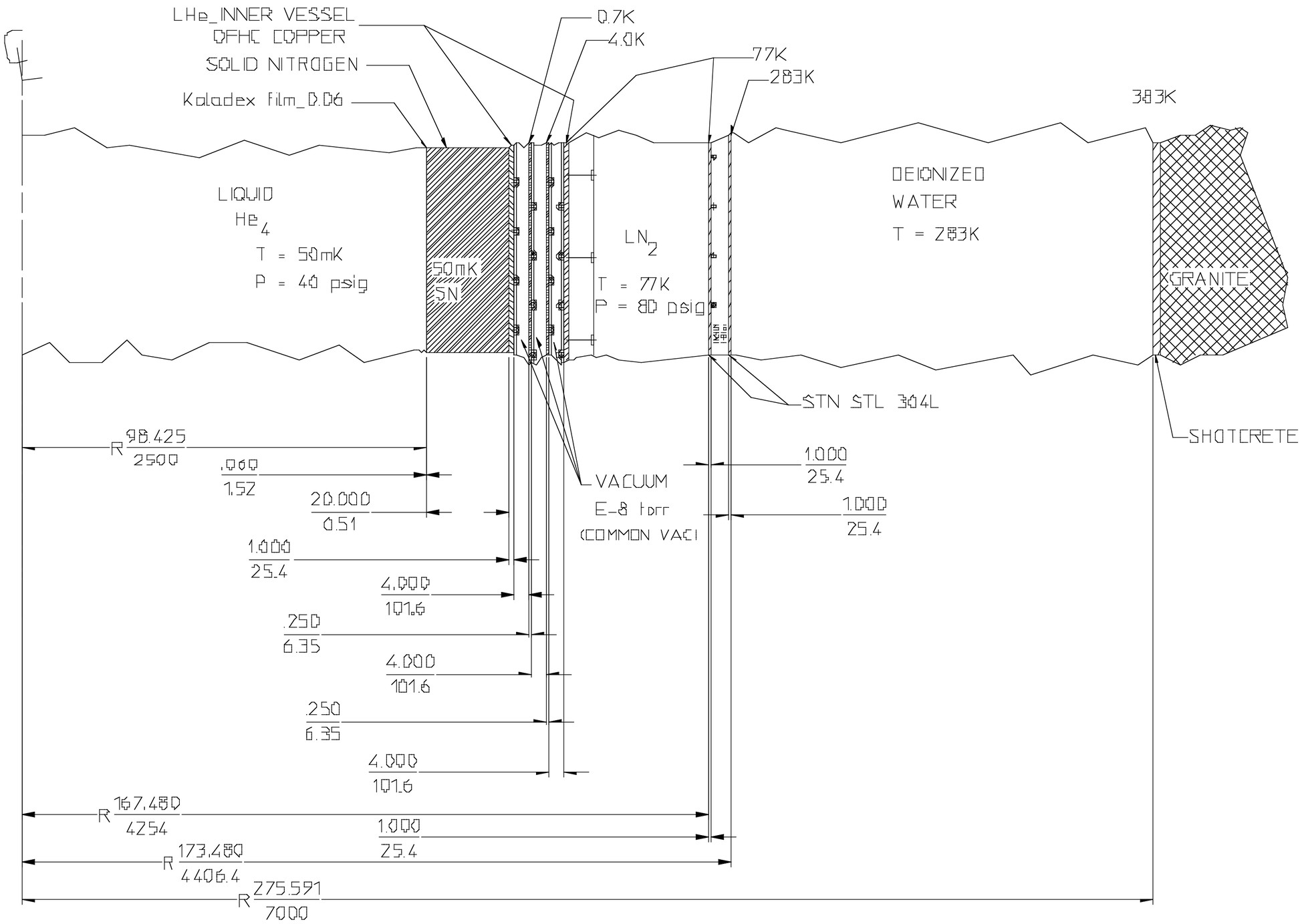
multiple meV excitations (p, R+, R-) possibly containing track orientation & ER/NR information
high detection efficiency
10x amplification before sensing
hard to imagine meV backgrounds (harder than other materials)

extra slides

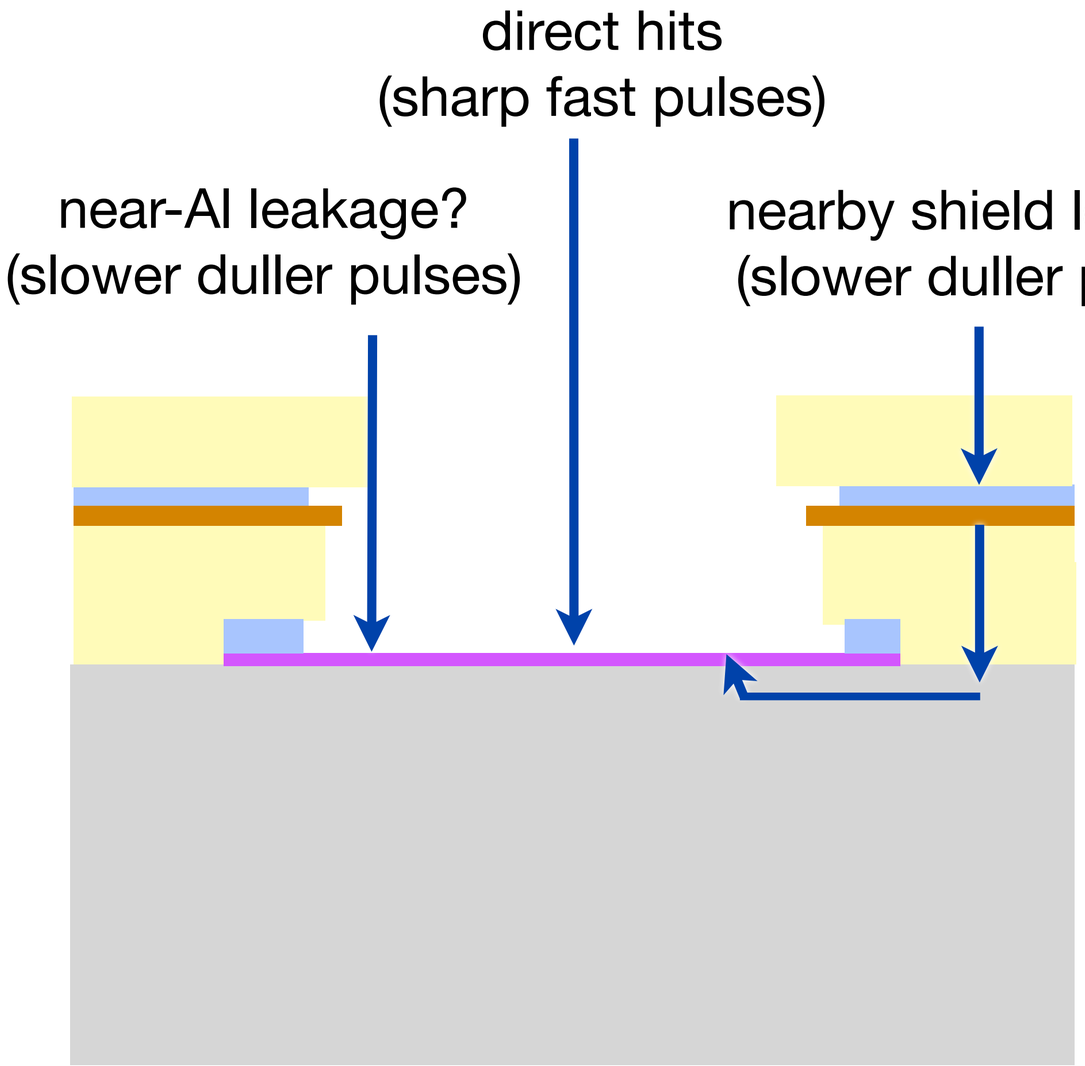
HERON: initial planning for 20 tons of 4He at 50mK

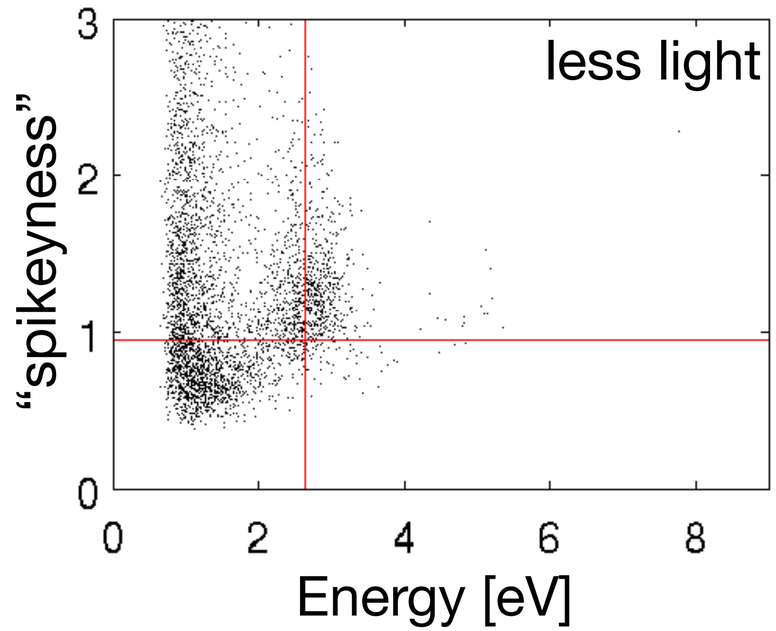


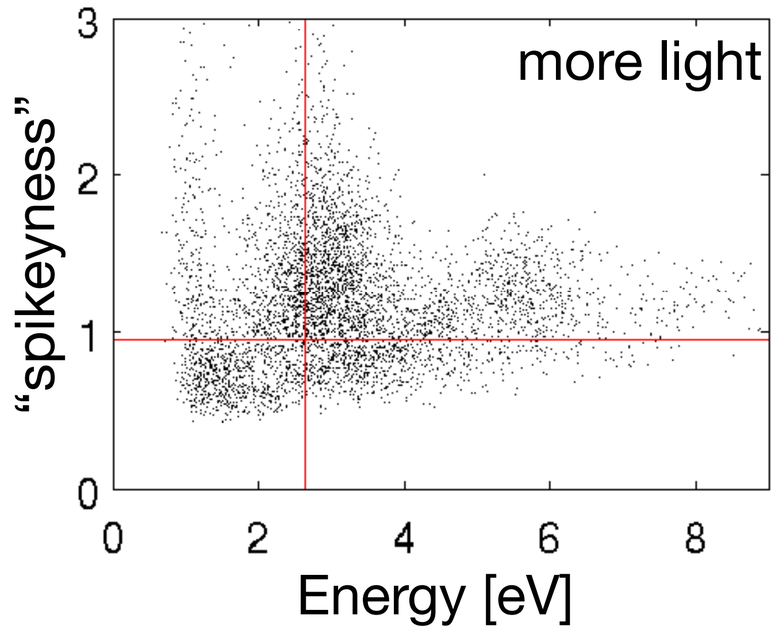
HERON: initial planning for 20 tons of 4He at 50mK



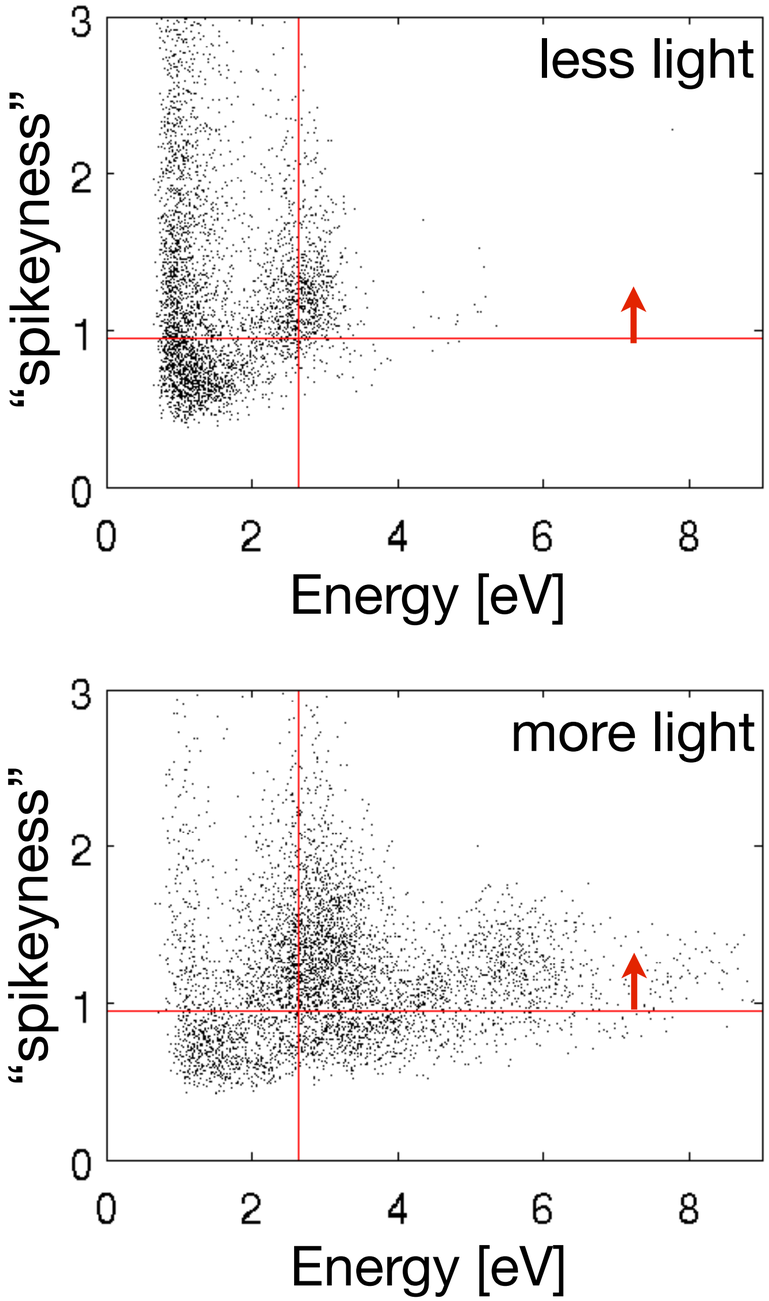
the device is not perfect
... but pulse shape can tag poor collection

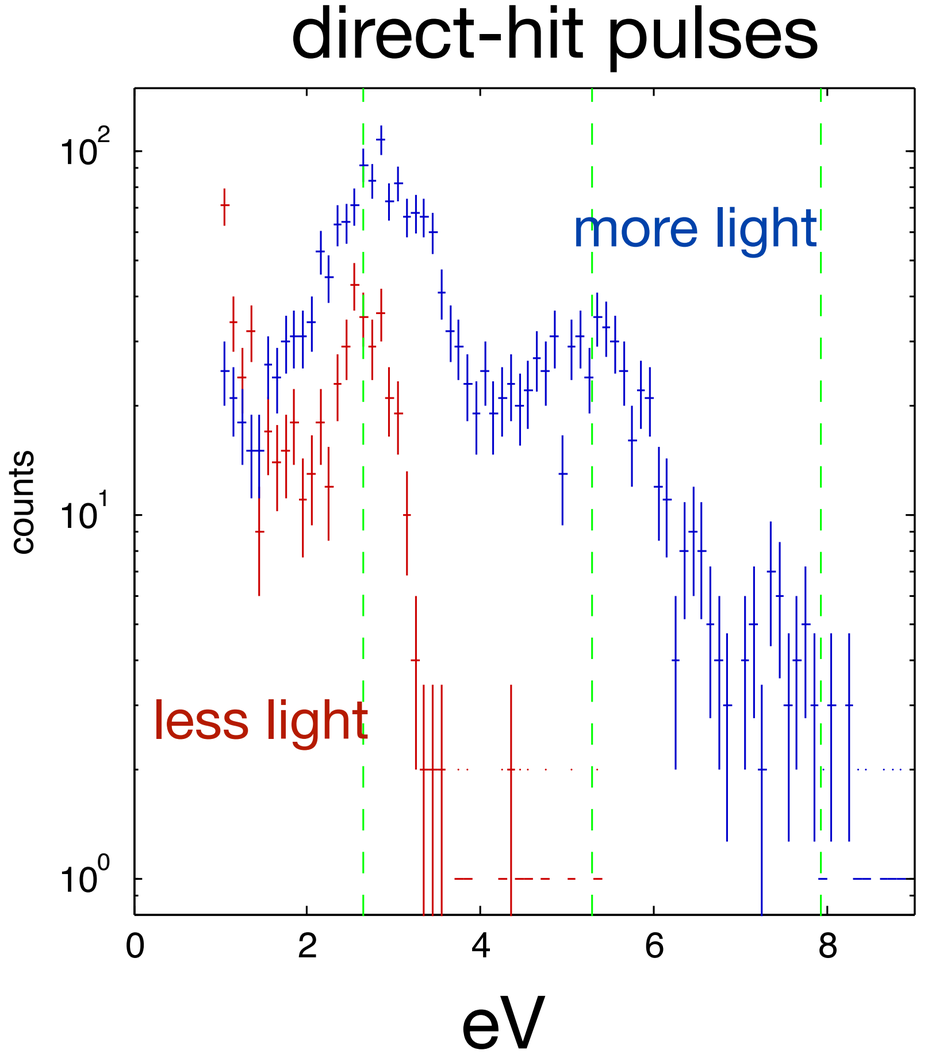






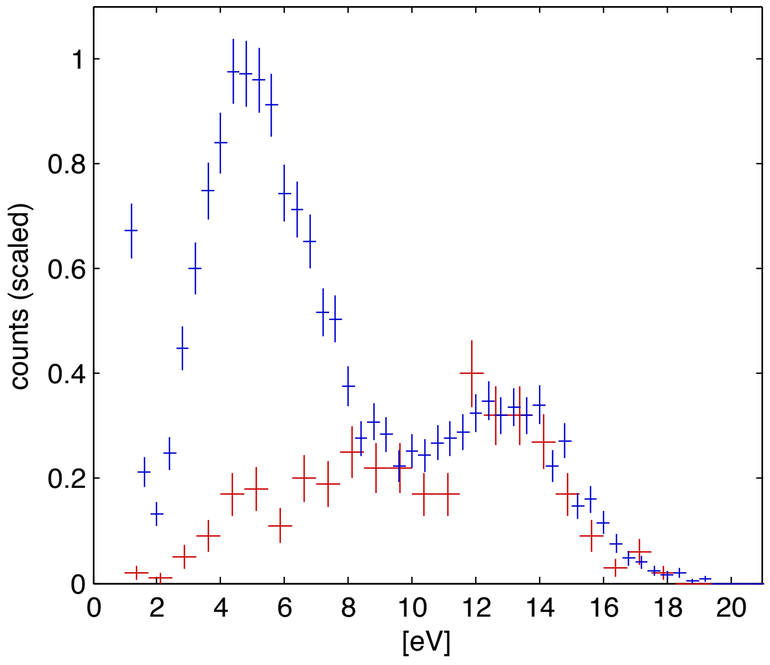
spectra can be made for direct-hit pulses, and photon counting peaks are seen



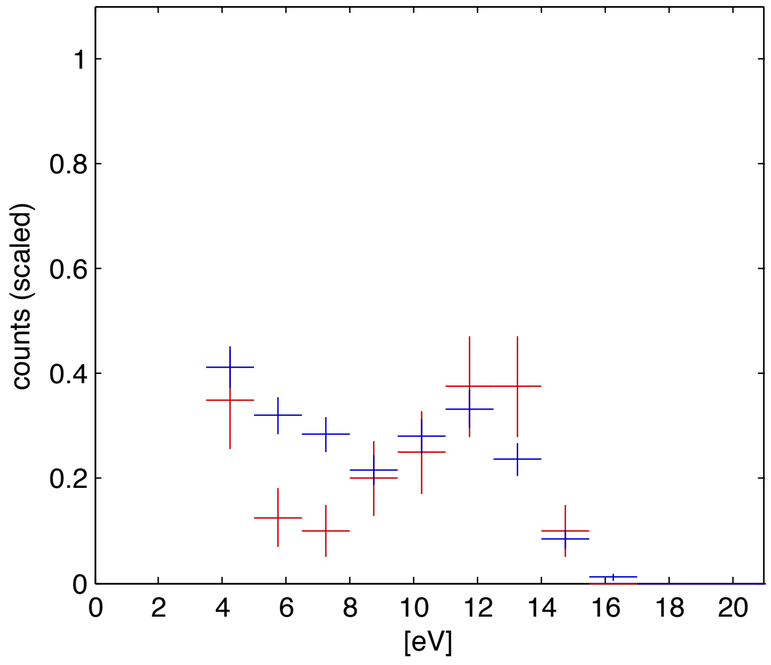


exploring alternate surfaces
(alternate surface density of states)

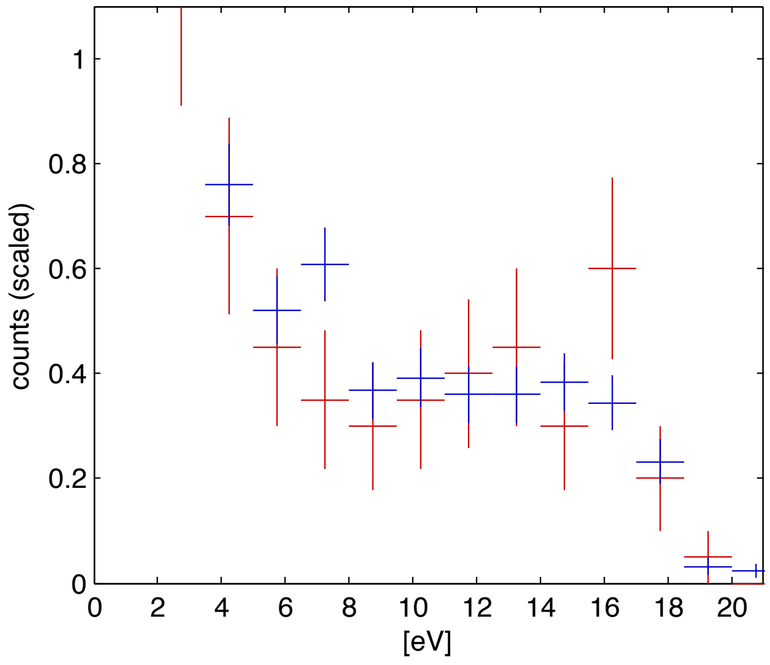
Ti ϕ = 4.3 eV
(some oxidation)



Au ϕ = 5.1 eV
(near-zero oxidation)



Pt ϕ = 6.4 eV
(near-zero oxidation)



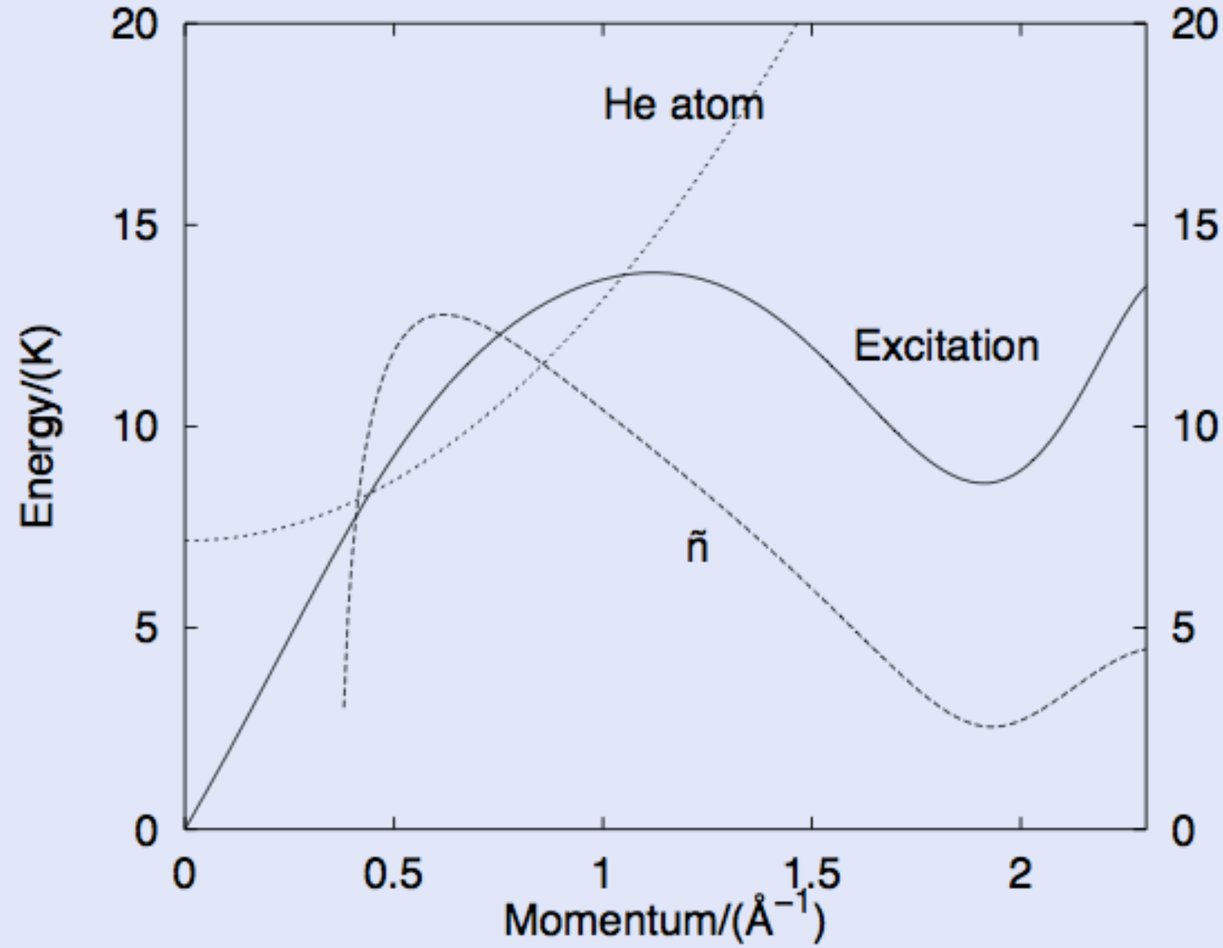


Figure 5: Energy of an elementary excitation, and an atom outside the liquid, and the "Refractive index" plotted against momentum/ $\hbar$.