Probing Sub-GeV Dark Matter with Superfluid Helium

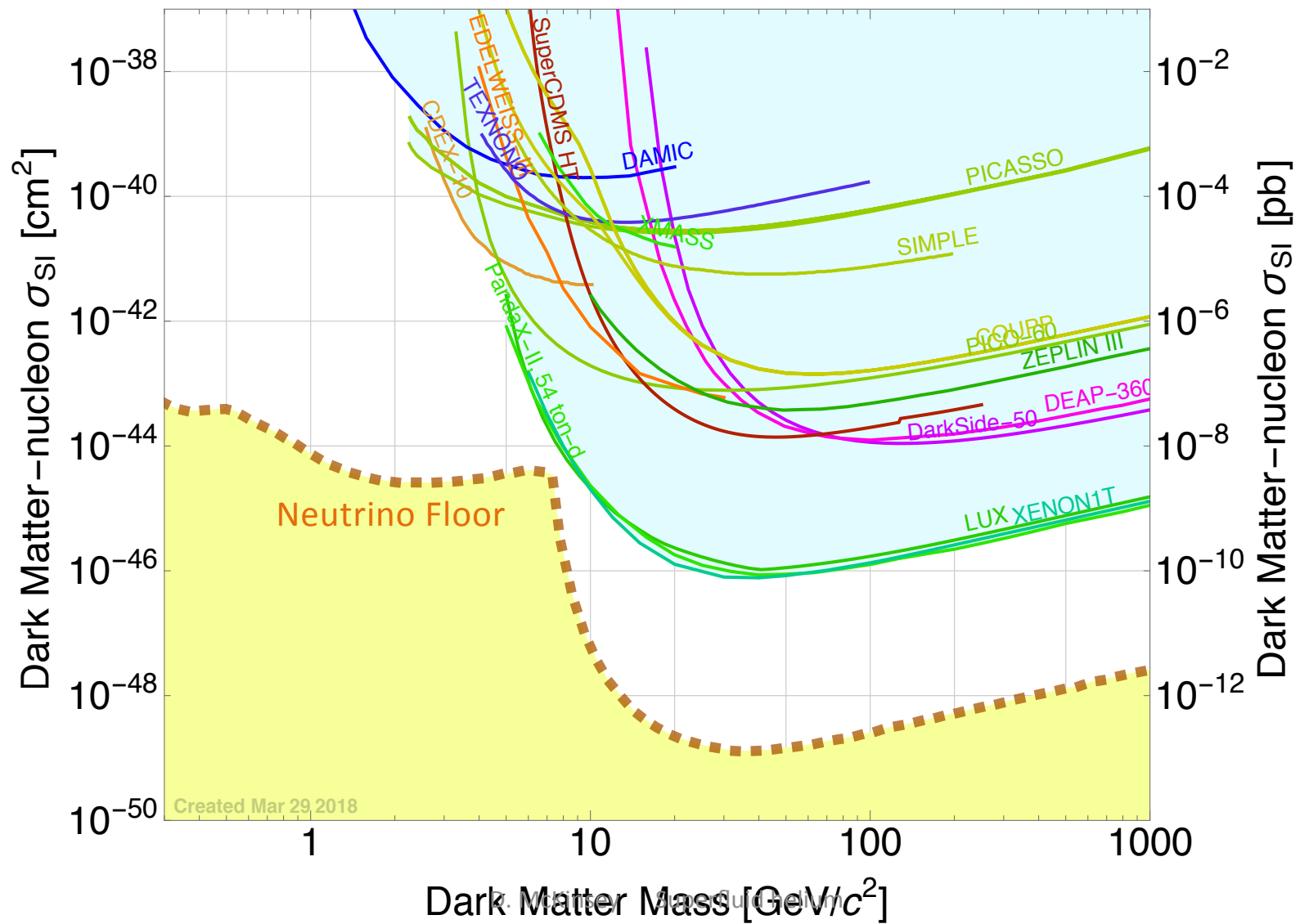## Daniel McKinsey
UC Berkeley and LBNL

(with Scott Hertel (UMass Amherst), Andreas Biekert, Junsong Lin, Vetri Velan)
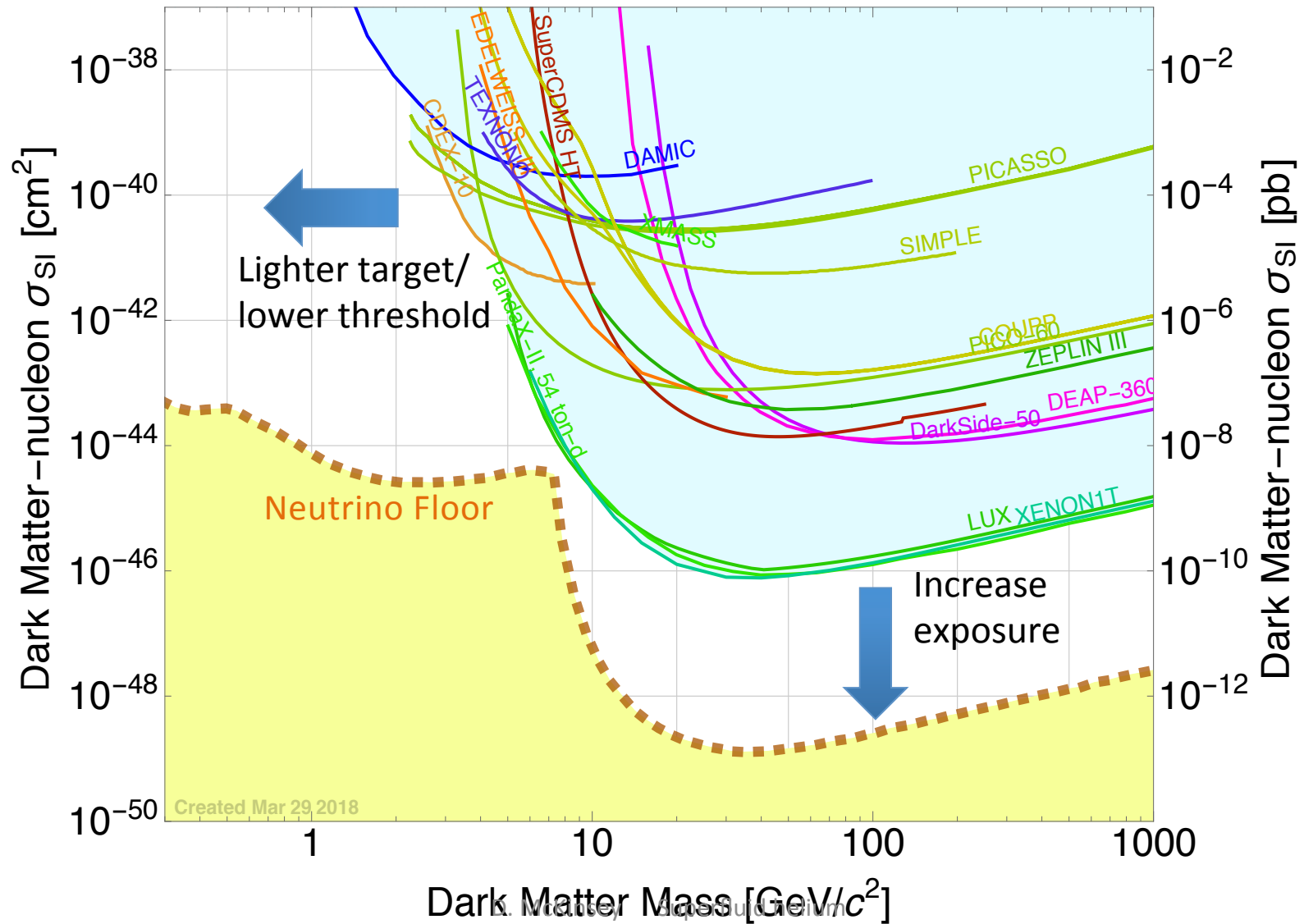
Berkeley
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CIPANP 2018
Palm Springs
May 29, 2018

Dark Matter Nuclear Recoils: Current Landscape

Dark Matter−nucleon σ_{SI} [cm^2] vs. Dark Matter Mass [GeV/c^2]; Dark Matter−nucleon σ_{SI} [pb]

Curves labeled: CRESST-10, EDELWEISS, TEXONO, SuperCDMS HT, DAMIC, PandaX-II 54 ton-d, XMASS, PICASSO, SIMPLE, COUPP, PICO-60, ZEPLIN III, DarkSide-50, DEAP-3600, LUX, XENON1T, Neutrino Floor
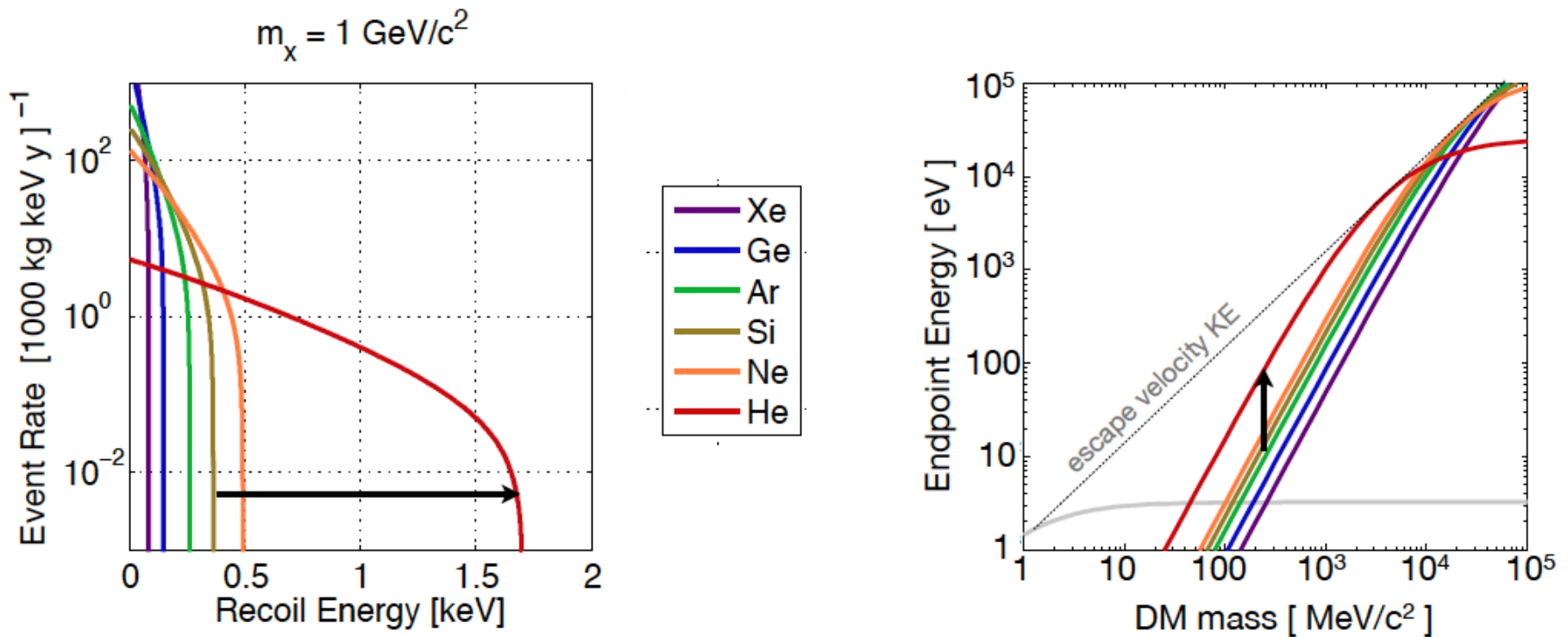
Created Mar 29 2018

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Dark Matter Nuclear Recoils: Future Directions

Helium for light dark matter detection

Light baryonic target with multiple signal channels, including light, charge, triplet excimers, phonons, and rotons.
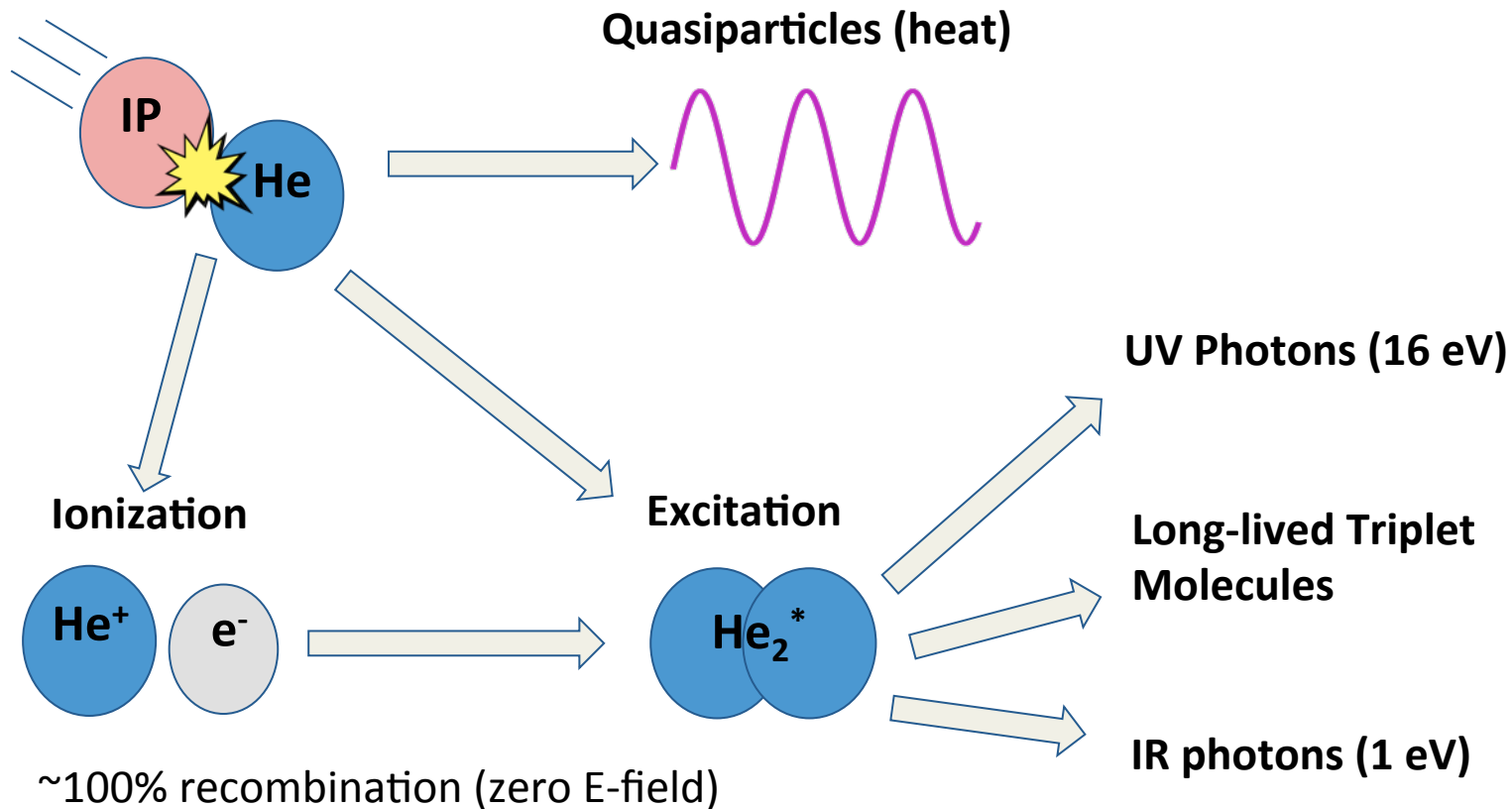(W. Guo and D. N. McKinsey, PRD 87, 115001 (2013).

Why Superfluid Helium-4?

- Liquid down to 0 K, allowing 10-100 mK-scale TES readout.
  - Take advantage of the great advances in TES technology
  - Take advantage of possible ~ 100% detection efficiency for photons, triplet excimers
  - Take advantage of the extremely low vapor pressure of superfluid helium at low temperatures, enabling quantum evaporation-based heat signal amplification.

- Helium is expected to have robust electronic excitation production efficiency, with a forgiving Lindhard factor, so nuclear recoil scintillation signals should be relatively large.

- Negligible target cost

- Low nuclear mass and charge -> low backgrounds from neutrino-nucleus scattering and gamma-nucleus scattering.

- Low vibration sensitivity: As a superfluid, small velocities don't generate excitations.

- Large ionization gap -> less signal quanta per keV than in super-, semiconductors. But no electron recoil background below 16 eV.

- Impurities easily removed from helium using cold traps and getters, and will literally fall out of the superfluid.

Anatomy of a Recoil

Quasiparticles (heat)

IP **He**

Ionization

He$^+$ **e$^-$**

~100% recombination (zero E-field)

Excitation

He$_2$*

UV Photons (16 eV)

Long-lived Triplet Molecules

IR photons (1 eV)

- UV and IR photons detectable as scintillation
- Triplet molecules directly detectable with TES
- Phonons and rotons can be detected with TESs, with some extra work

Superfluid Helium Detector Concept

(S. Hertel, U. Massachusetts, Amherst
Junsong Lin, Andreas Biekert, Vetri Velan, DNM, UC Berkeley)

Initial sensitivity studies, taking neutrino
and gamma ray backgrounds into account:

Signal channels:
      1) Scintillation
      2) Ballistic Triplet Excimers
      3) Phonons/Rotons

No drift field, and no S2 signal
- No worry of few-electron background
- (Though could apply drift field to detect single electrons via roton/phonon production.)

Discrimination using signal ratios

Event position via signal hit patterns

Superfluid helium-4 as a detector material

Proposed for measurement of pp solar neutrino flux using roton detection (HERON): R.E. Lanou, H.J. Maris, and G.M. Seidel, Phys. Rev. Lett. **58**, 2498 (1987).
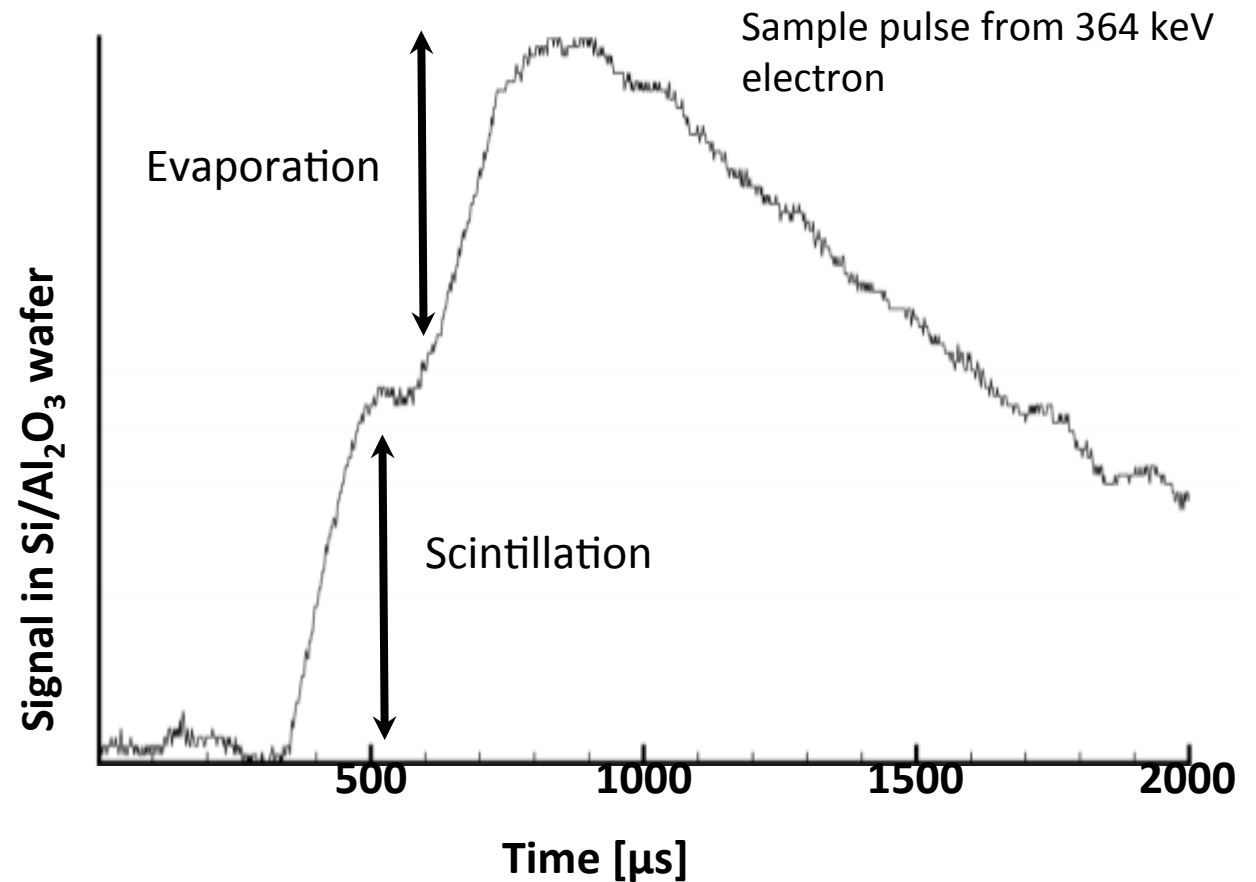
Two signal channels, heat and light. Both measured with a bolometer array.

Also, "HERON as a dark matter detector?" in "Dark Matter, Quantum Measurement" ed Tran Thanh Van, Editions Frontieres, Gif-sur-Yvette (1996)

Concept Demonstrated

- HERON: proposed
  pp neutrino
  observatory
- Pulse at the right
  shows simultaneous
  detection of
  photons and rotons

Sample pulse from 364 keV electron

Evaporation

Scintillation

Signal in Si/Al$_2$O$_3$ wafer

Time [μs]

J. S. Adams et al., AIP Conference Proceedings 533, 112 (2000).
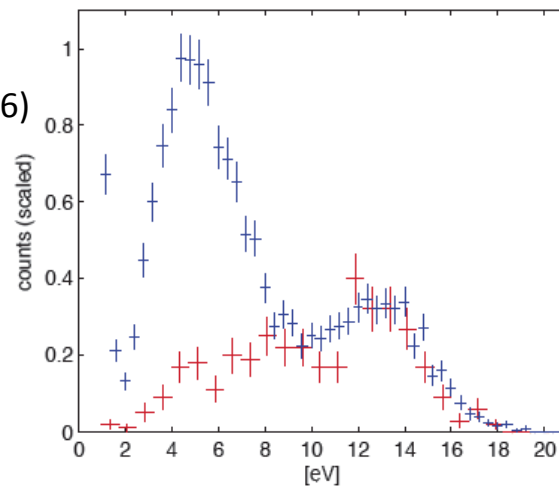Also see: J. S. Adams et al., Physics Letters B 341 (1995) 431-434.

Reading Out Singlet Excitations (16 eV Photons)

Detecting photons is a simple calorimetry application. Operating calorimetry in LHe: less standard. Possible thanks to:
- Huge LHe-solid Kapitza resistance
- Fast conversion of photon energy to
    non-phonon excitations
    (e.g. Al quasiparticles)

Triplet excimers may also be read out using the same calorimetry!

F. Carter et al,
J Low Temp Phys (2016)
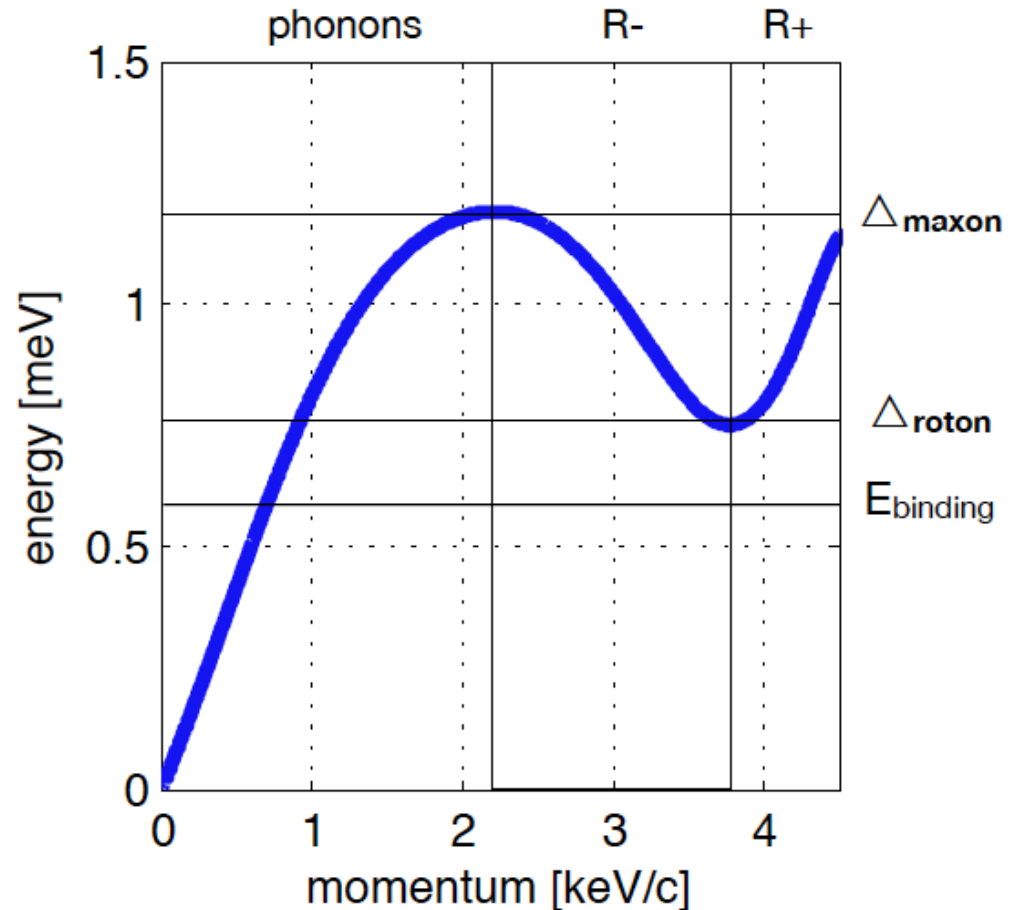arXiv:1605.00694

Simple detector: box with calorimetry inside

Phonons and Rotons

Superfluid supports vibrational modes (some non-intuitive).

Ballistic, ~150 m/s.

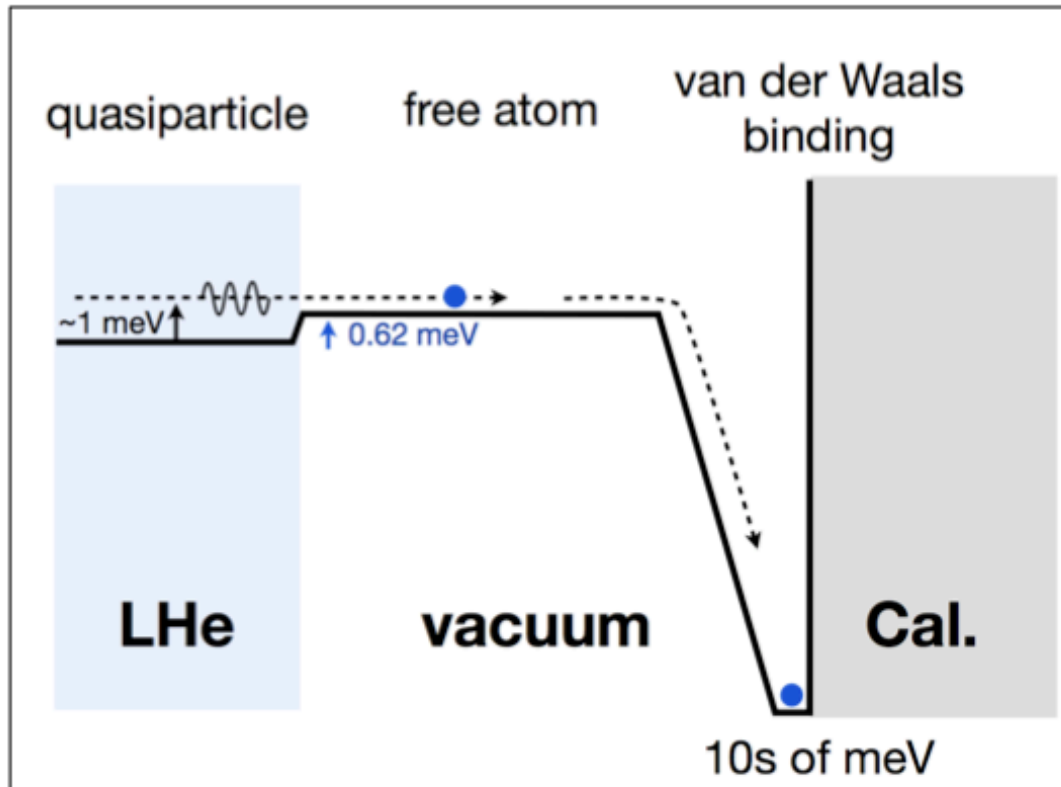Enormous Kapitza resistance, i.e. *tiny* probability of crossing into solid.

Few downconversion pathways.

Most signal expected in R- and R+ rotons, with absorption probability on walls measured to be 2.8 x 10^{-3}.
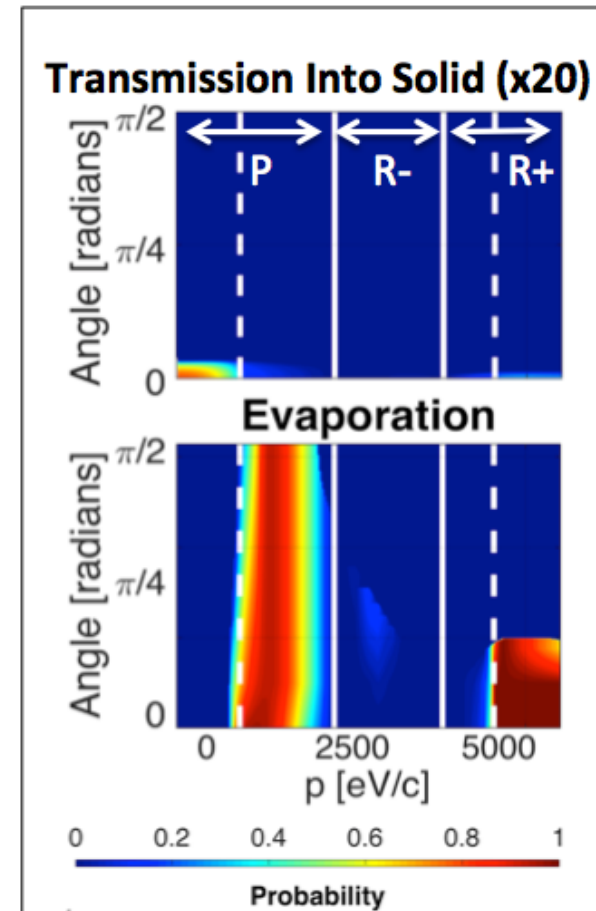See Brown and Wyatt, J. Phys.: Condens. Matter 15, 4717 (2003).

Quantum evaporation from superfluid helium – vacuum interface

Heat amplification from desorption – adsorption process
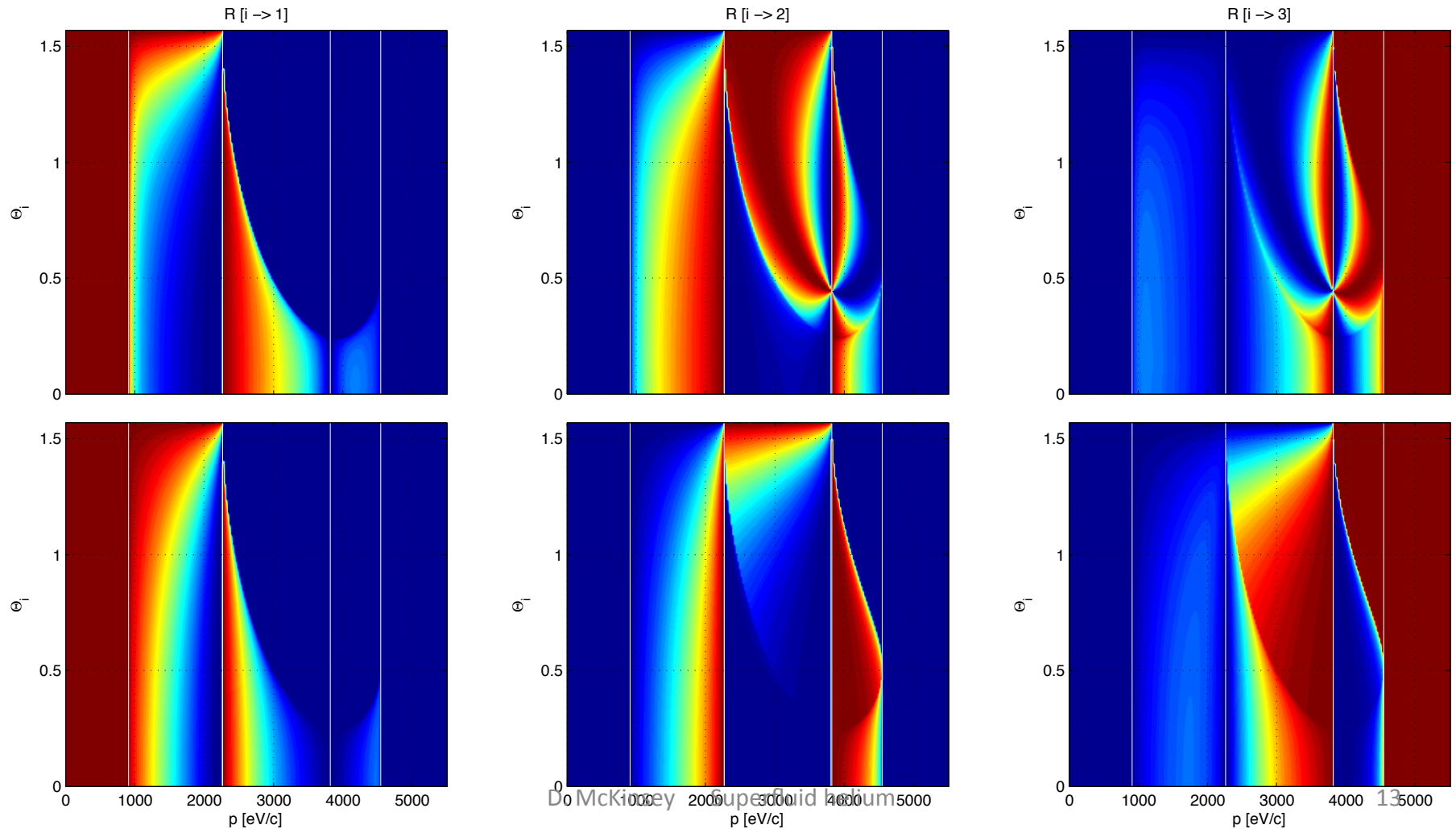Adsorption gives 10-40 meV depending on surface

Phonons and rotons can change type when reflecting from surfaces

Calculations based on Tanatarov et al., arXiv:1004.3497

refection mode-change probabilities
(blue=0, red=1)

upper three: solid interface
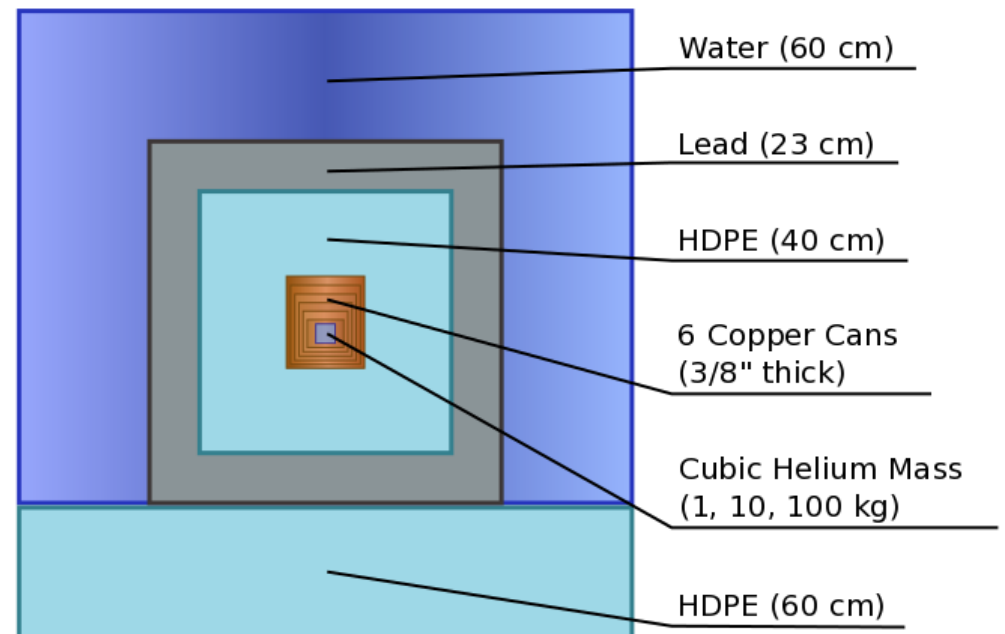lower three: vacuum interface

Expected Backgrounds

Backgrounds included:

- Neutrino nuclear coherent scattering
- Gamma-ray electron recoil backgrounds (similar to SuperCDMS)
- Note: Helium itself is naturally radiopure, and easily purified of contaminants
- Gamma-ray nuclear recoil backgrounds (see Robinson, PRD 95, 021301 (2017)

Arguments for low "detector" backgrounds:

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

Water (60 cm)

Lead (23 cm)

HDPE (40 cm)

6 Copper Cans (3/8" thick)

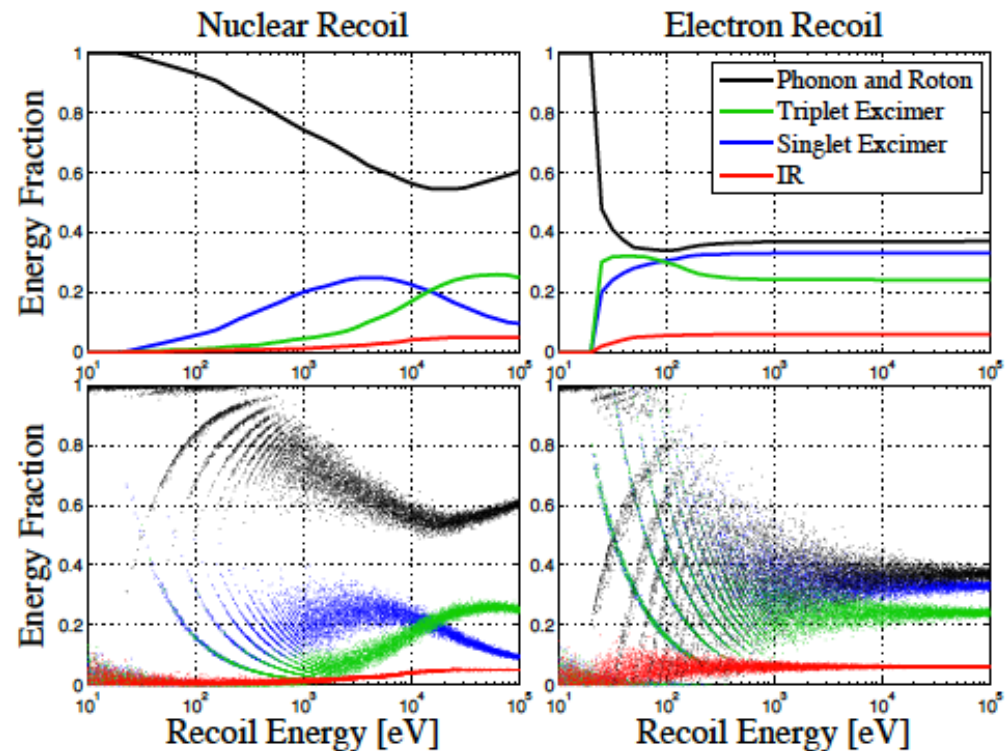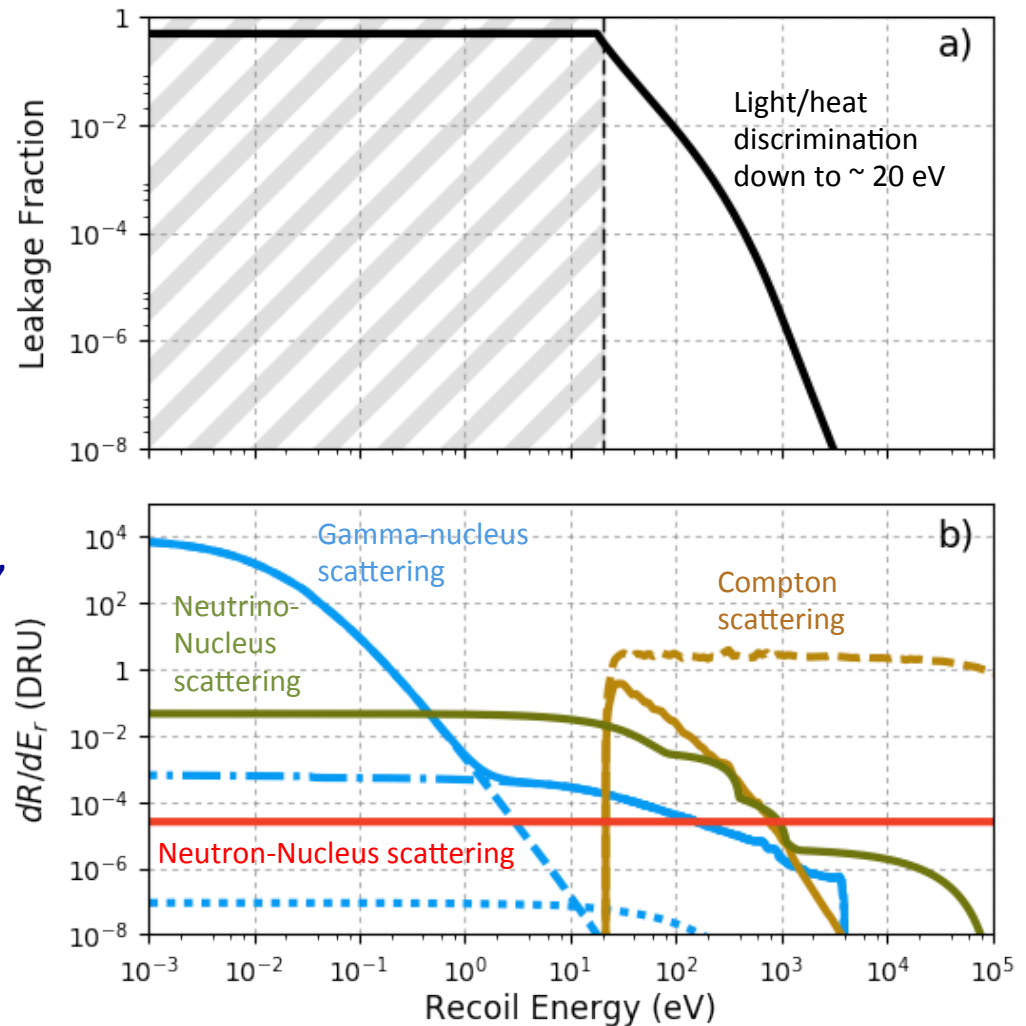Cubic Helium Mass (1, 10, 100 kg)

HDPE (60 cm)

Electron recoil / nuclear recoil discrimination

Toy Monte Carlo detection efficiencies:

- singlet UV photons: 0.95 (4pi coverage by calorimetry)
- Triplet excimers: 5/6 (only solid surfaces)
- IR photons: 0.95 (similar to UV photons)

Excellent predicted discrimination at sub-keV energies

Expected Backgrounds

Backgrounds included:

- Neutrino nuclear coherent scattering
- Gamma-ray electron recoil backgrounds (similar to SuperCDMS)
- Note: Helium itself is naturally radiopure, and easily purified of contaminants
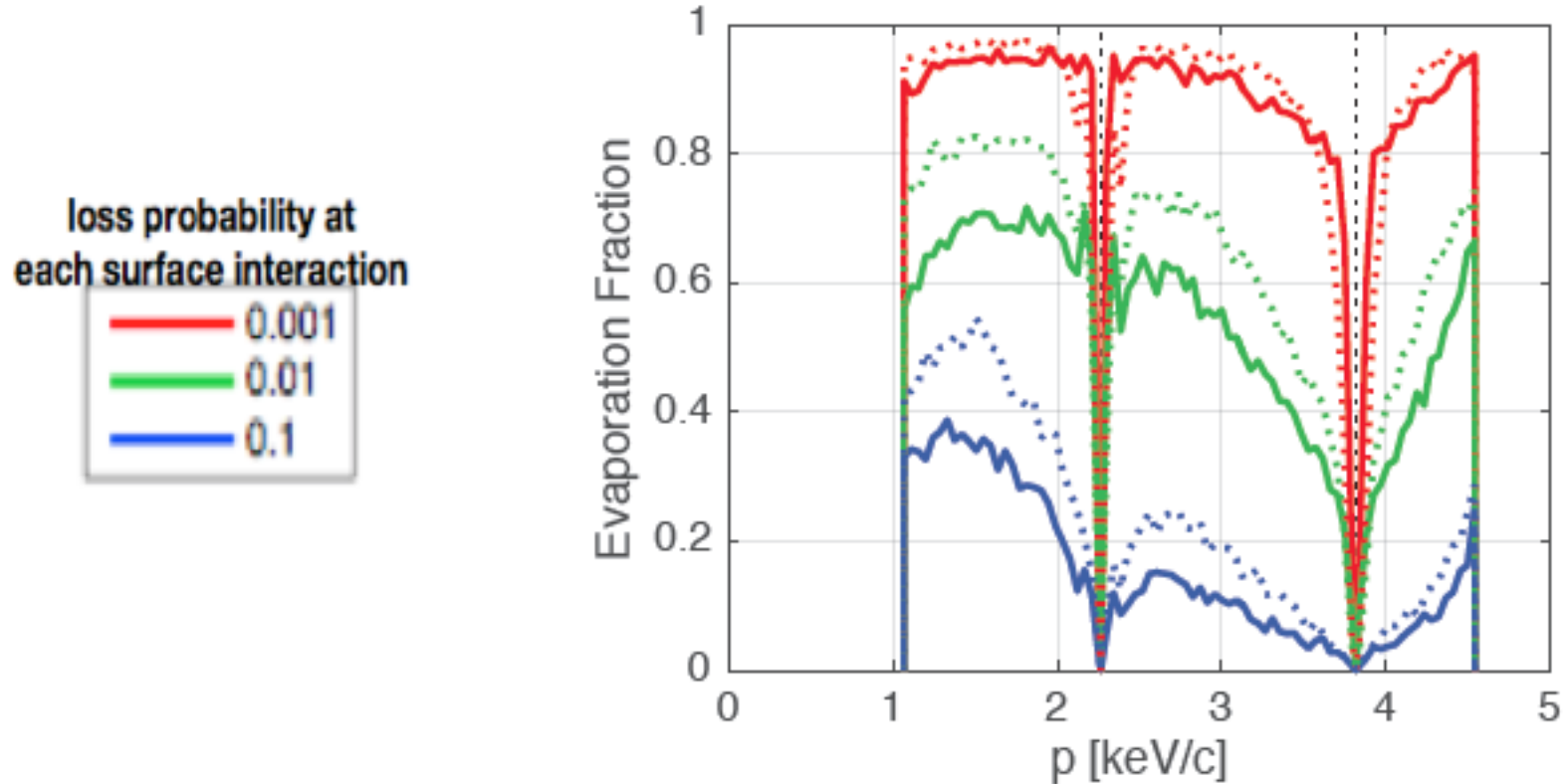- Gamma-ray nuclear recoil backgrounds (see Robinson, PRD 95, 021301 (2017)

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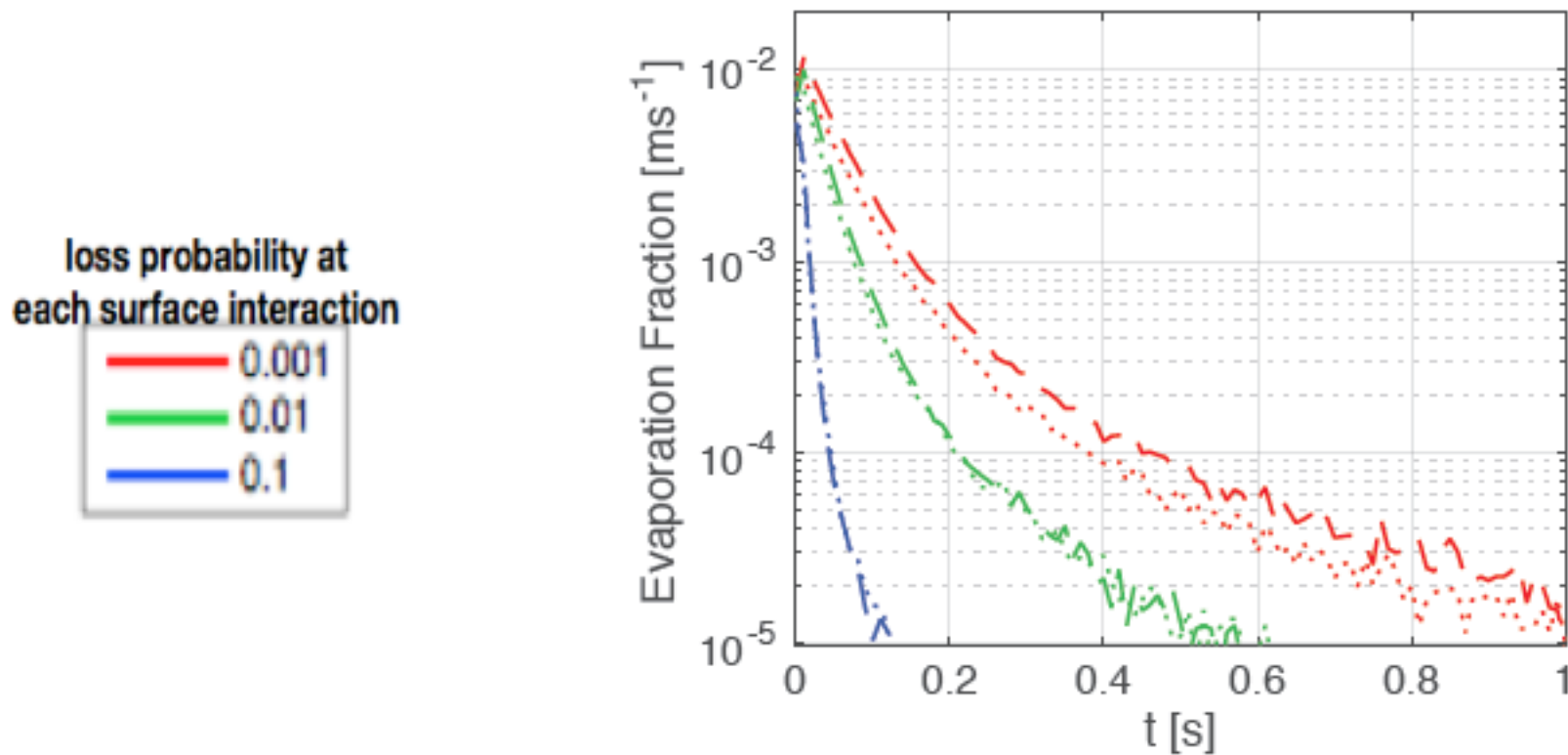
Phonon and Roton Monte Carlo Studies

Below are shown Monte-Carlo-determined efficiencies of detecting quasiparticles (phonons or rotons) as a function of quasiparticle momentum, for varying surface absorption probabilities (0.001 to 0.1)

loss probability at each surface interaction
— 0.001
— 0.01
— 0.1

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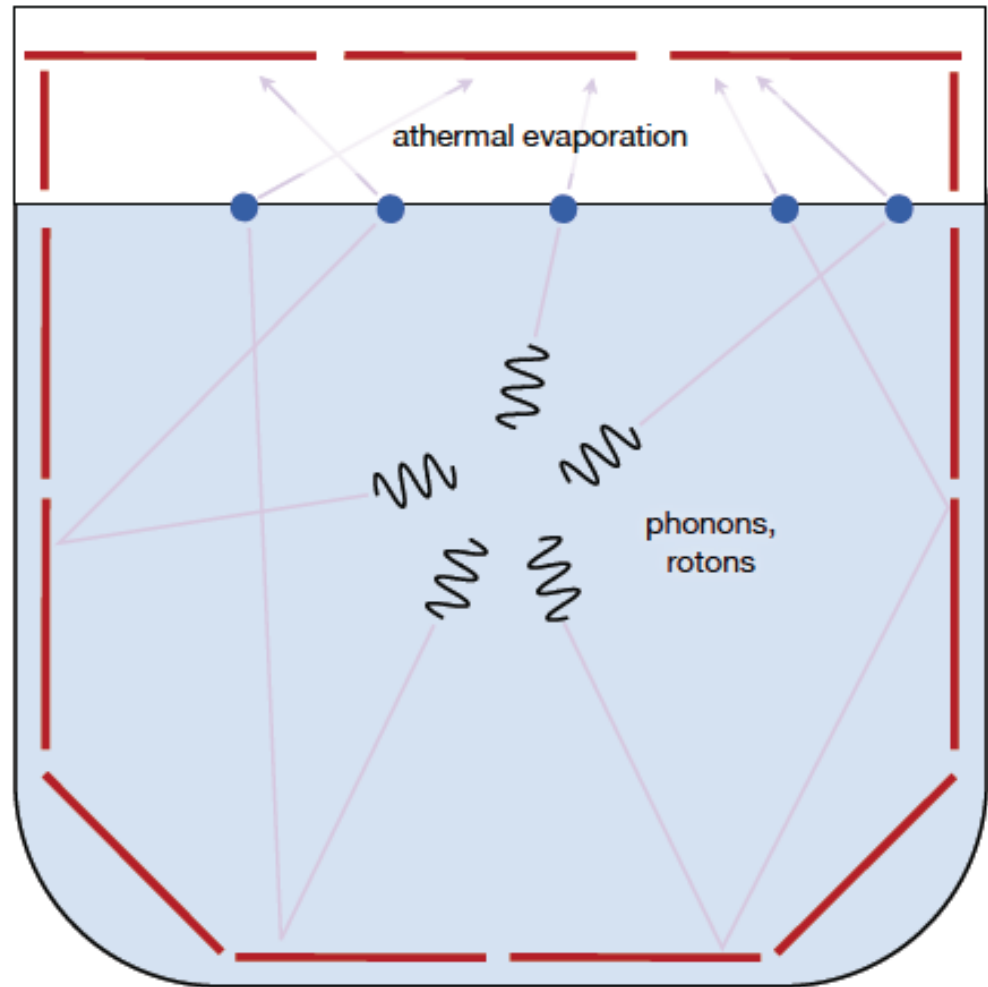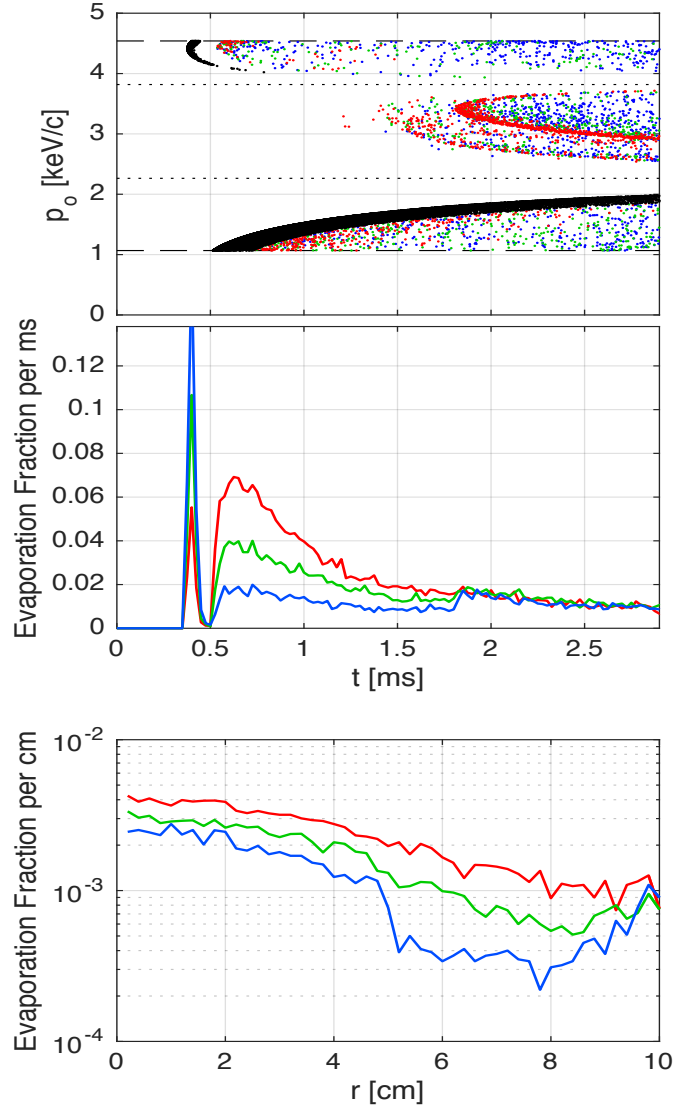— 0.001
— 0.01
— 0.1

Heat-only Readout?
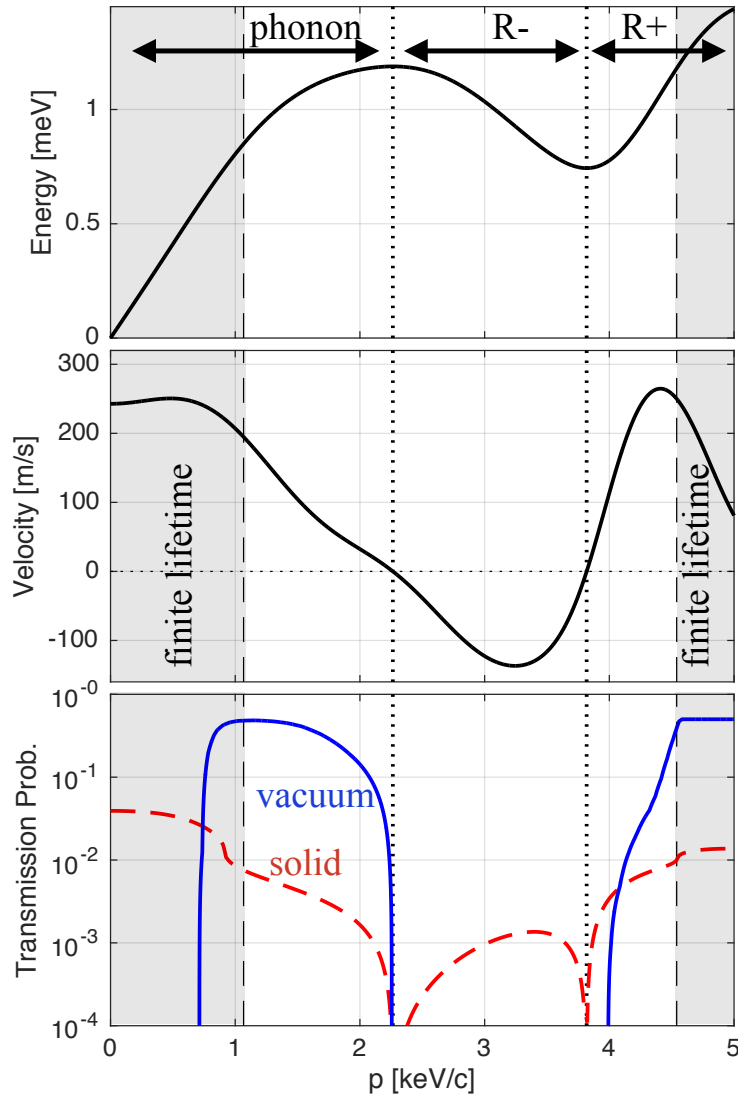
Signal channels:

Phonons

Rotons

Energies in principle down to ~ 1 meV.

Discrimination using roton/phonon signal ratios likely. Electron recoils, detector effects, nuclear recoils likely create different roton/ phonon distributions, with resulting differences in signal timing.

Position reconstruction using signal hit patterns

athermal evaporation

phonons, rotons

Background vs Signal Discrimination with Phonon/Roton Timing?

0 bounces
1 bounce
2 bounces
3 bounces

p^0

p^1

p^2

Possible stages of a superfluid helium program

Generation 1: "shovel ready"
10 eVr threshold, 1 kg-y
  Assuming 40 meV per He atom (graphene-fluorine)
  20 eV calorimeter threshold w/ 5% evap. efficiency

Generation 2: "feasible after R&D"
100 meVr threshold, 10 kg-y
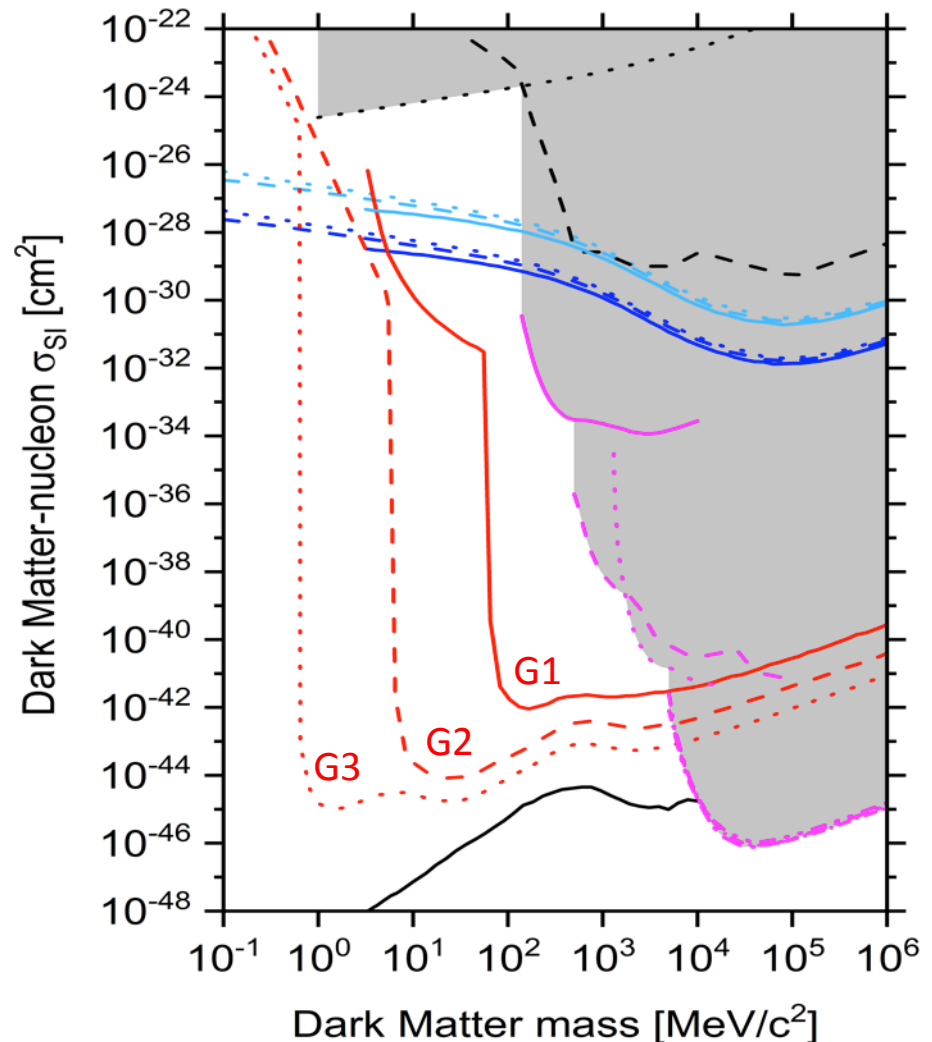 Assuming 40 meV per He atom (graphene-fluorine)
  1 eV calorimeter threshold w/ 25% evap. Efficiency
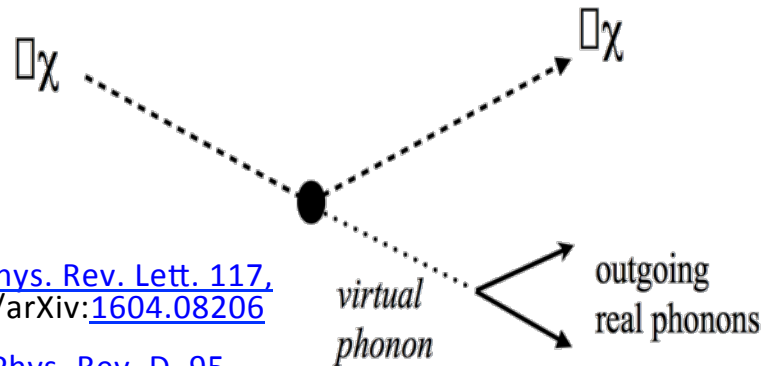
Generation 3: "theoretically possible"
1 meVr threshold, 100 kg-y
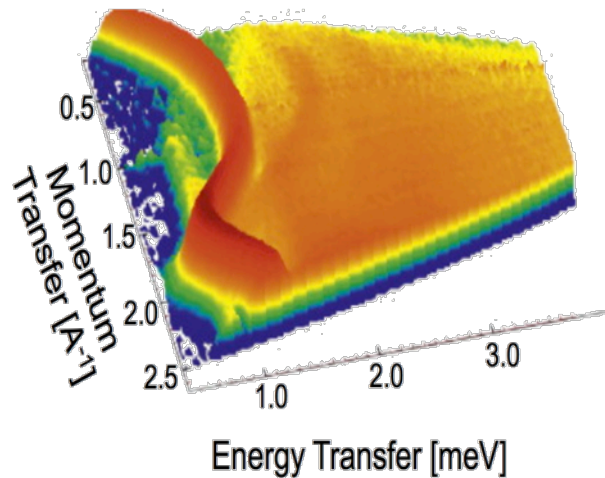 Limit of single-atom counting
  (~40 meV calorimeter threshold)

Higher Order Phonon Processes

Schutz et al., Phys. Rev. Lett. 117, 121302 (2016)/arXiv:1604.08206

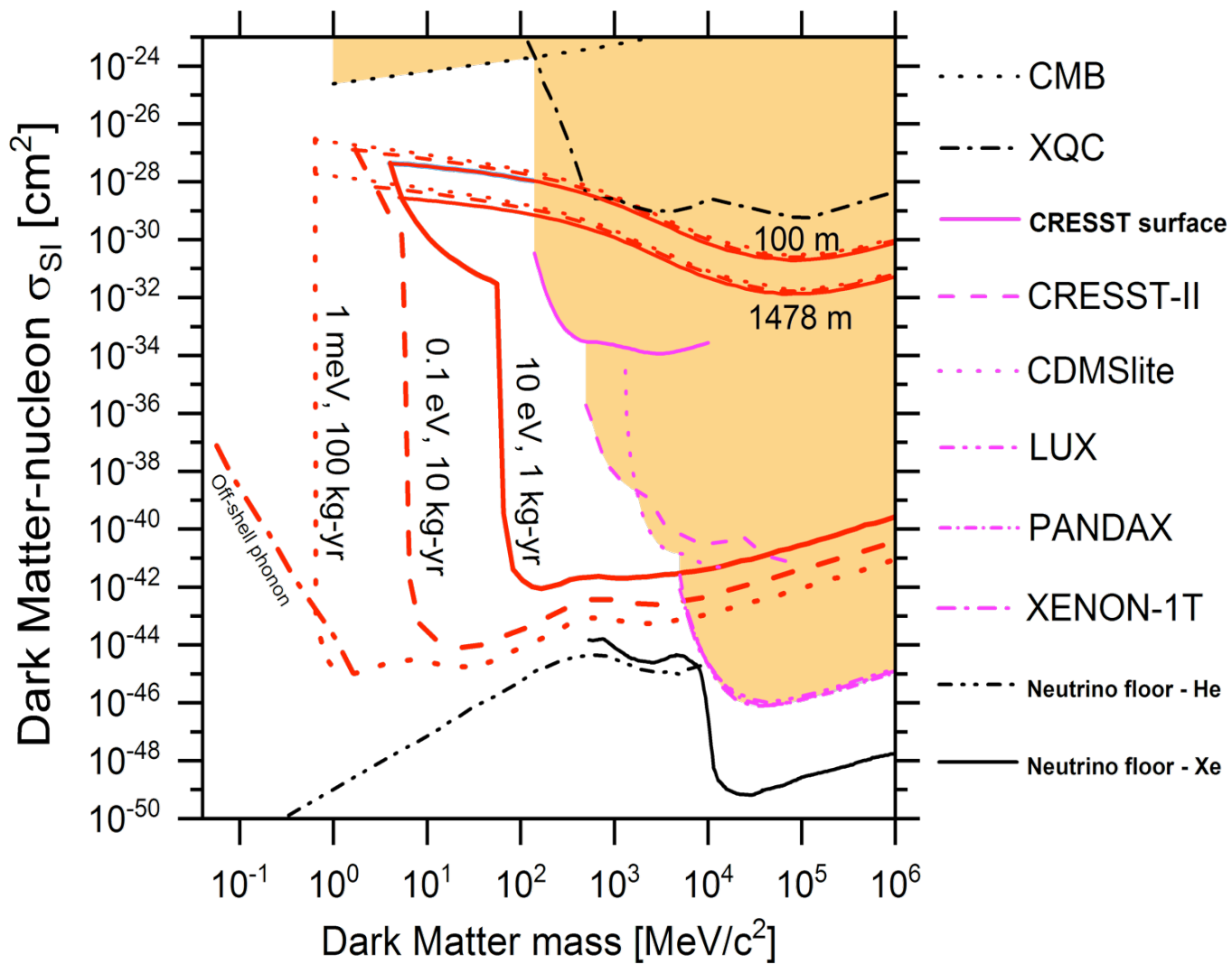Knapen et al., Phys. Rev. D. 95, 056019 (2017)/arXiv:1611.06228

- Virtual phonons not limited to dispersion relation.
- Process allows sensitivity to keV-scale warm DM
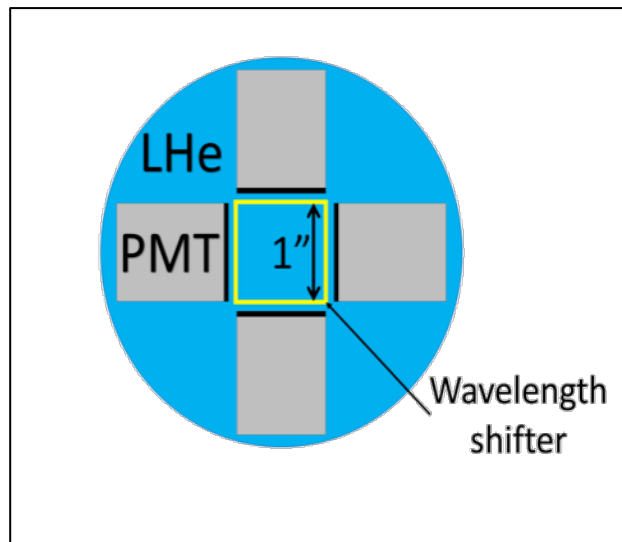- Two-phonon process experimentally observed in neutron scattering (below)

Visualization from: Nucl. Instr. Meth. Phys. Res. A 611, 259-262 (2009)/ arXiv:0811.4332

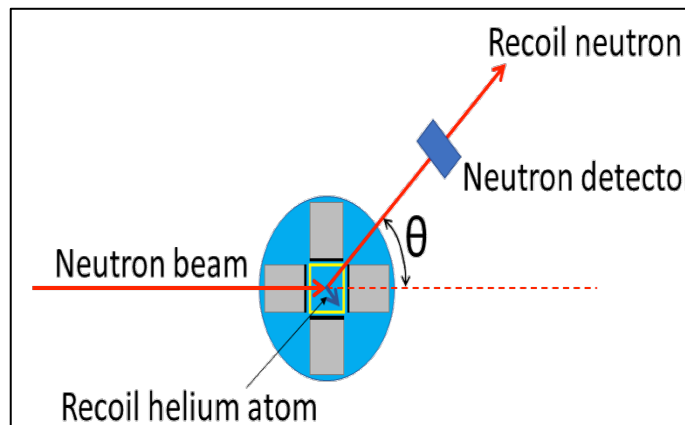Measured in: Gibbs et al., J. Phys.: Condens. Matter 11, 603-628 (1999)

Projected Sensitivity – nuclear recoils

Next Steps

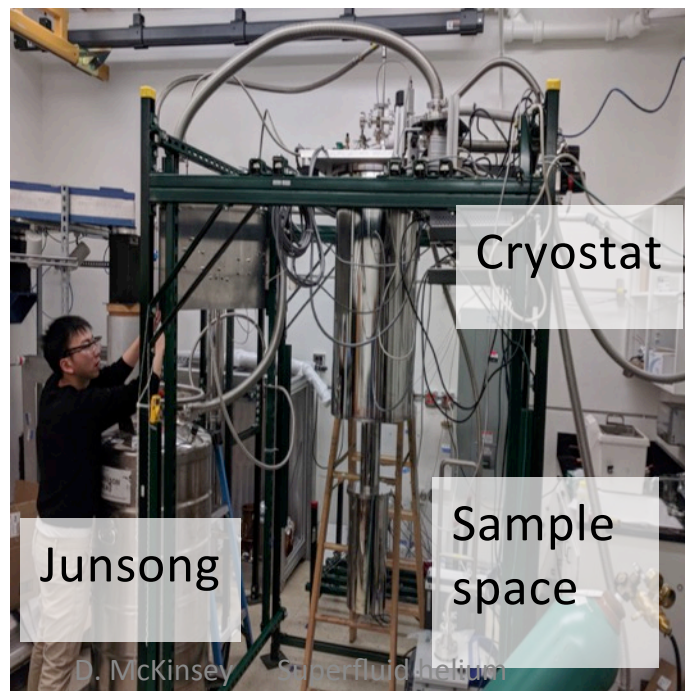LHe
PMT | 1"
Wavelength shifter

Recoil neutron
Neutron detector
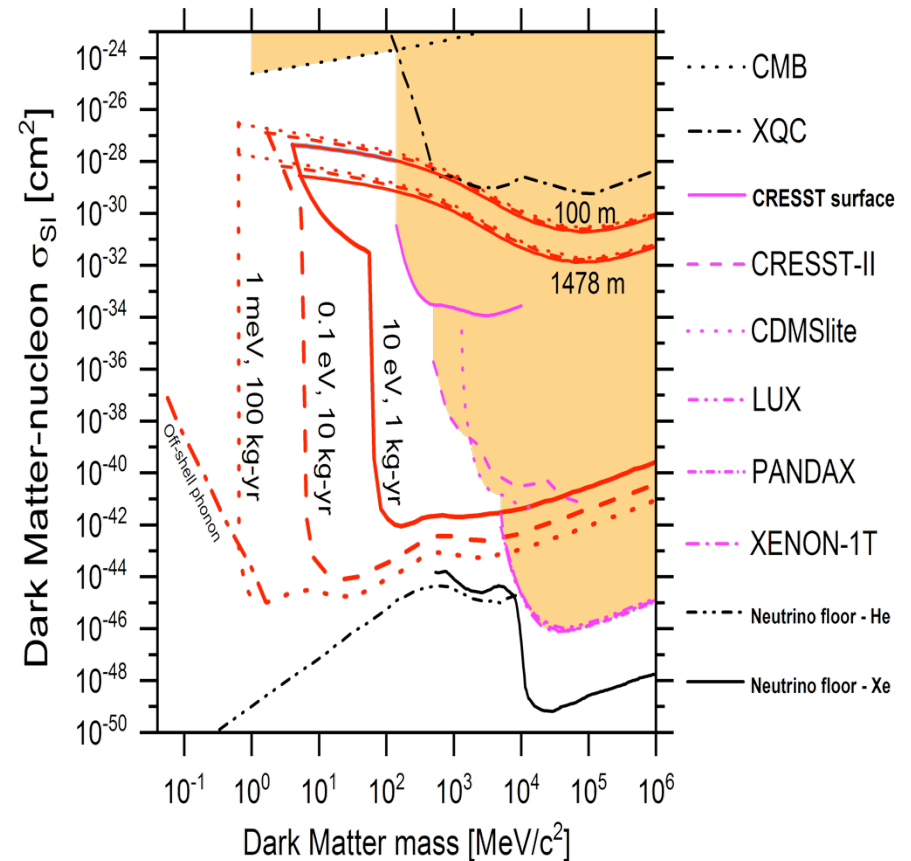θ
Neutron beam
Recoil helium atom

Now: Measure scintillation light yield from low energy nuclear recoils in superfluid helium

Also: Dilution refrigerator instrumentation studies (UCB + UMass)

Right: Successful cool down to 1.5 K!

Cryostat

Junsong

Sample space

Superfluid Helium Detector

Leiden (wet, low-vibration) dilution fridge being set up in McKinsey lab at UCB

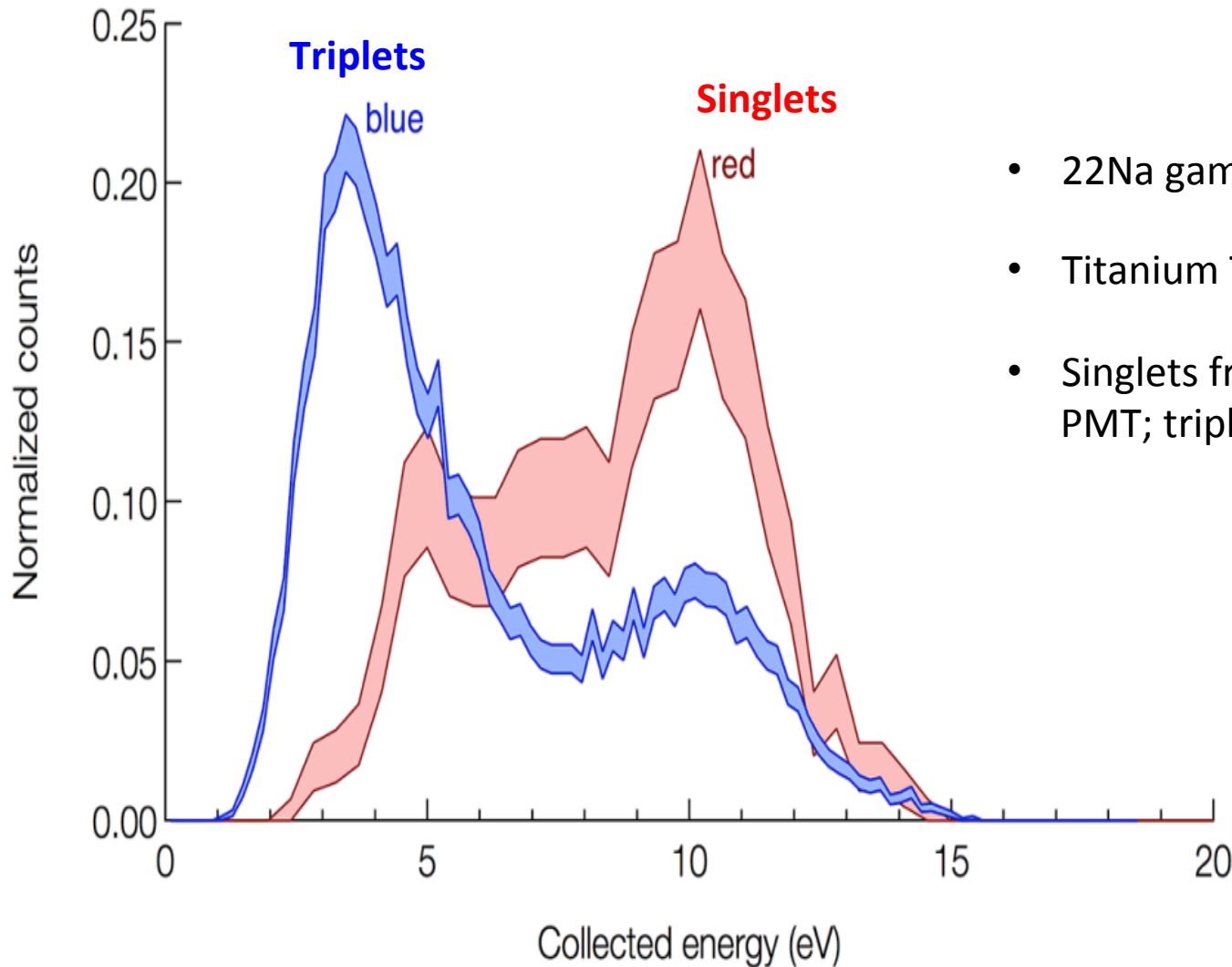First tests being designed, with TES, SQUIDs, helium film burner, shielding

Summary

- Preliminary studies on limits for a dark matter search using superfluid helium are very promising

- Basic technology has been demonstrated

- Future generations aided by current R&D in TES technology by CDMS, CRESST, many others

- Paper imminent!

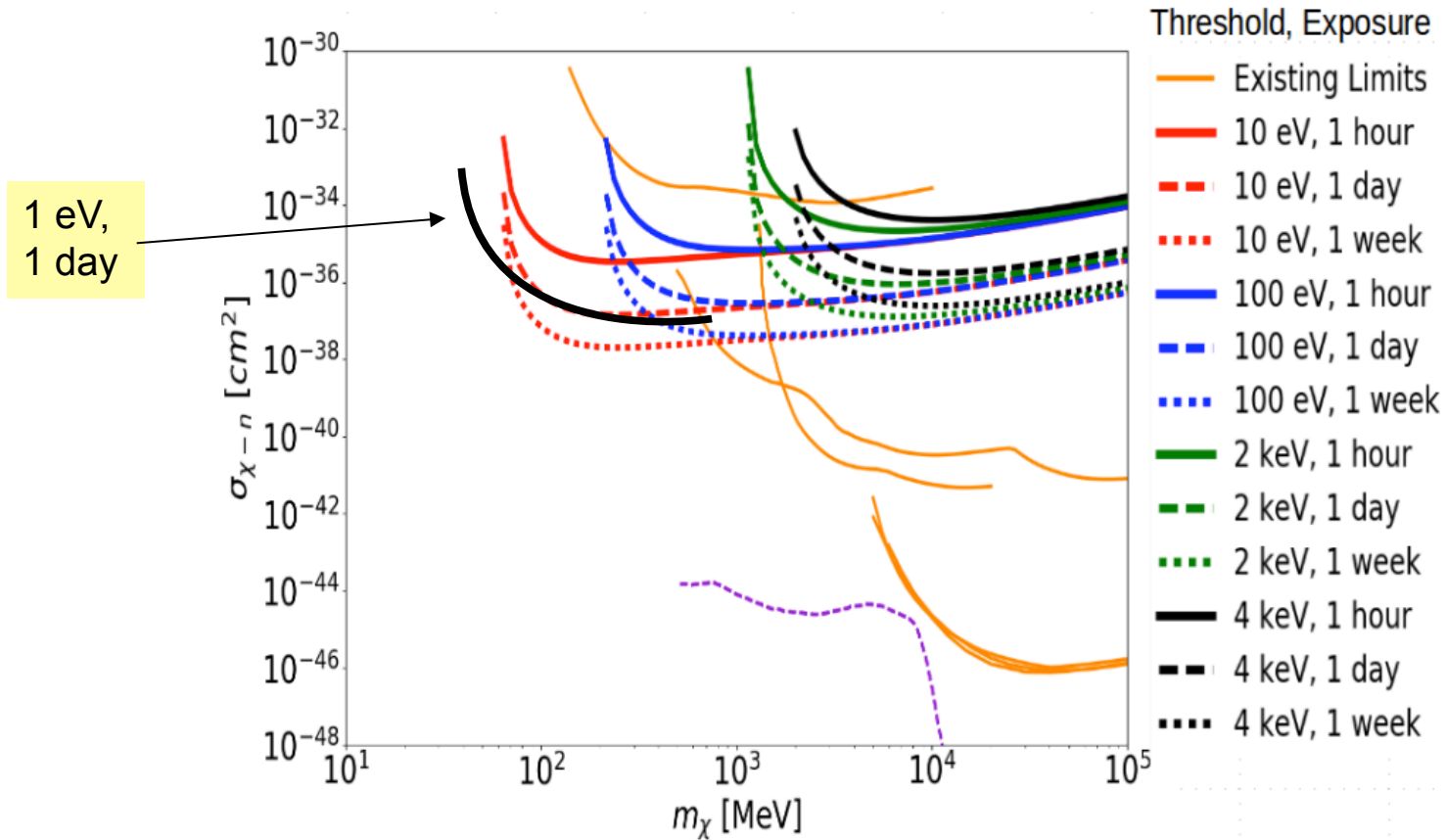- Also stay tuned for instrumentation studies out of UCB and UMass

Ballistic Triplets

- 22Na gamma source

- Titanium TES in 100 mK 4He bath

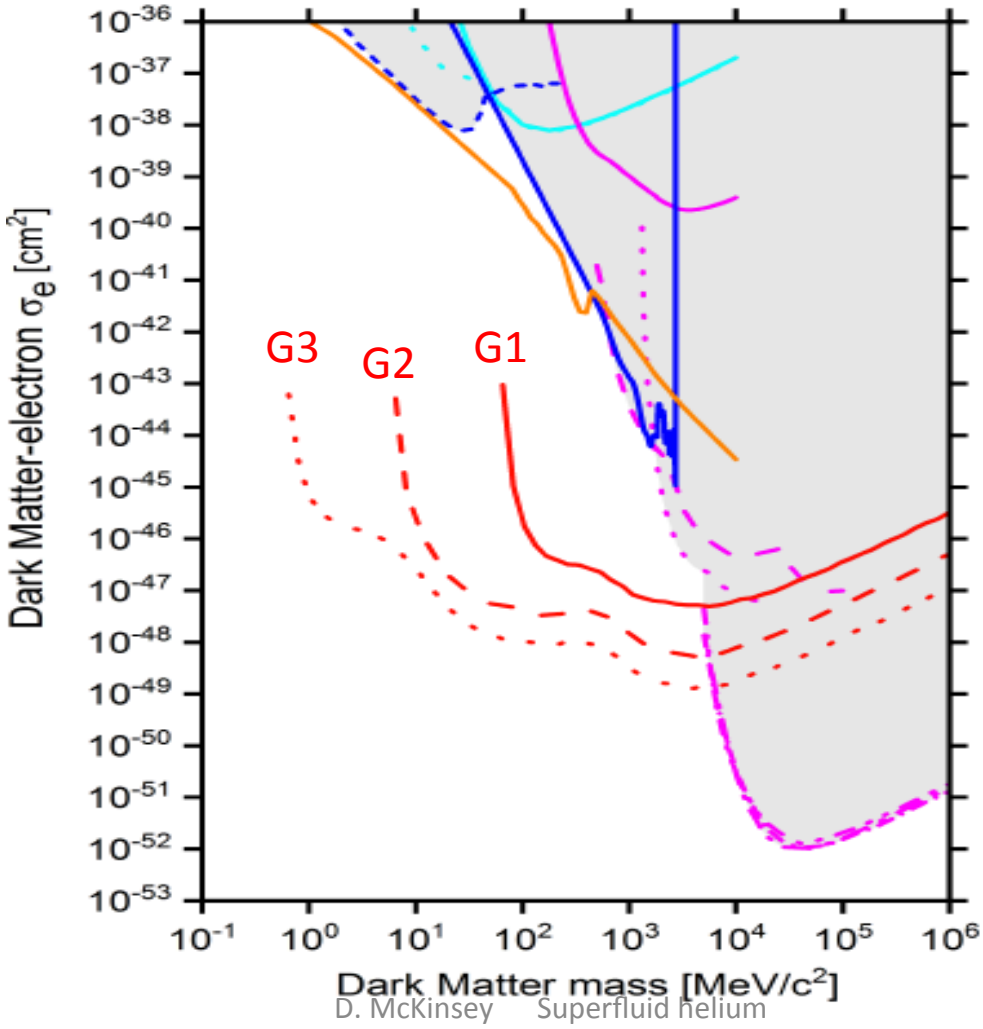- Singlets from TES coincident with PMT; triplets from only TES

Carter, et al., J. Low Temp. Phys. 186(3) 183-196 (2017)/arXiv:1605.00694

LHe reach at the surface

2g LHe on surface. Zero background

Projected Sensitivity – dark matter, with heavy dark photon mediator

Superfluid helium-4 as a detector material

- Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).

Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).