Light Dark Matter Detection with Transition Edge Sensors

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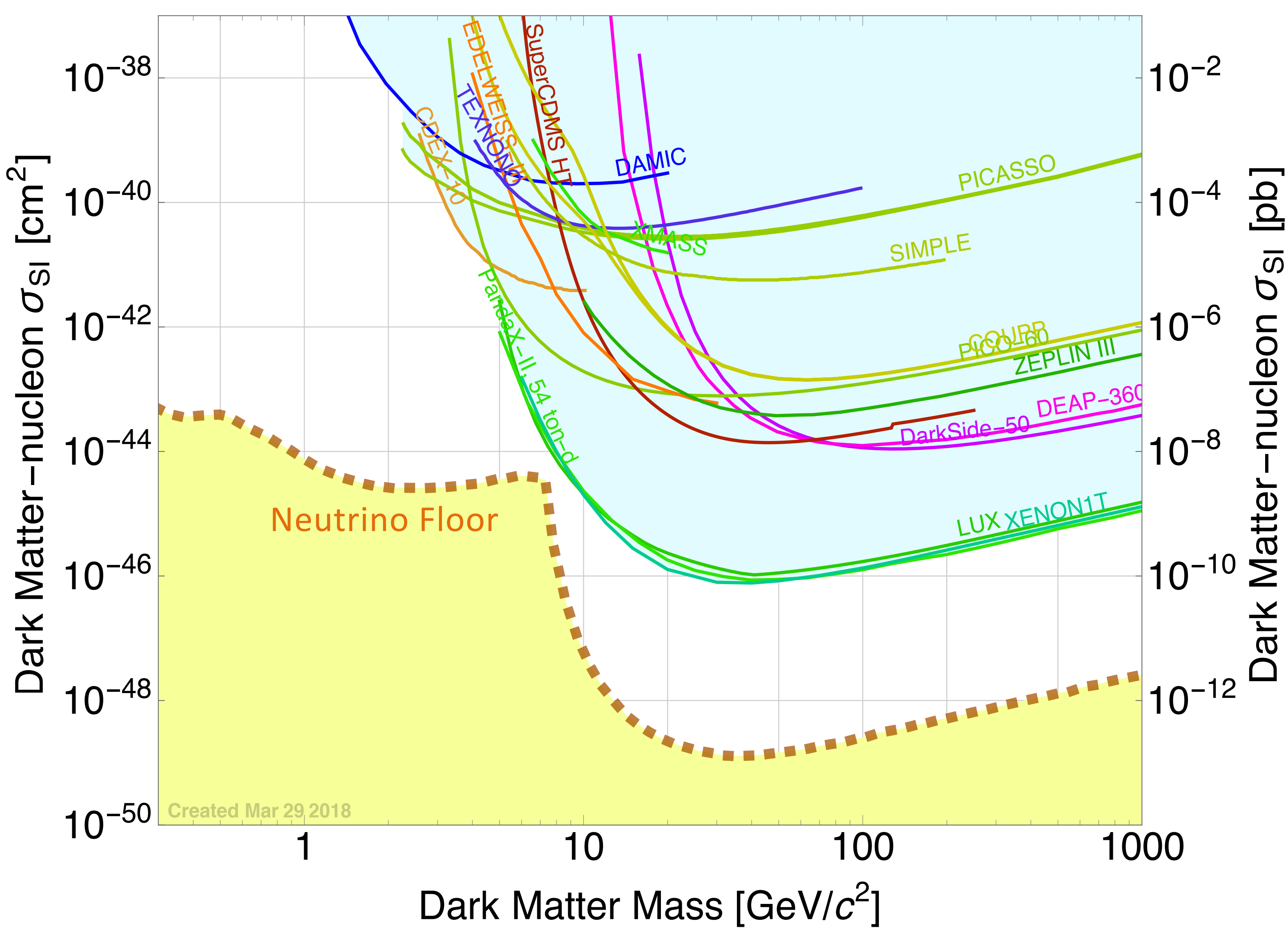
Berkeley
UNIVERSITY OF CALIFORNIA

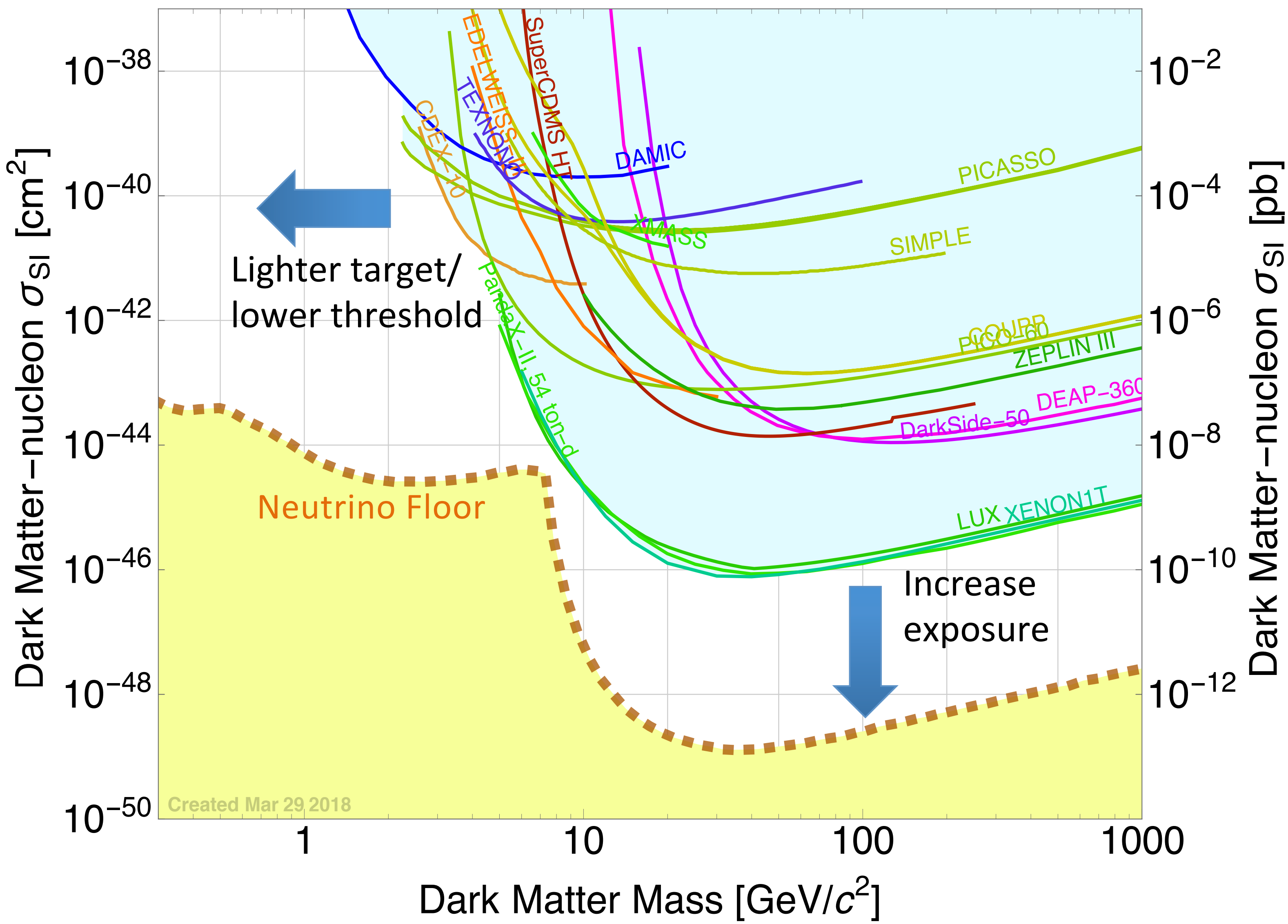
BERKELEY LAB

New Probes for Physics Beyond the Standard Model
Kavli Institute for Theoretical Physics
April 10, 2018

Dark Matter Nuclear Recoils: Current Landscape



Dark Matter Nuclear Recoils: Future Directions

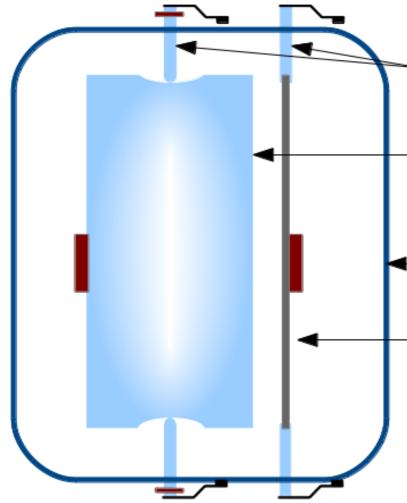


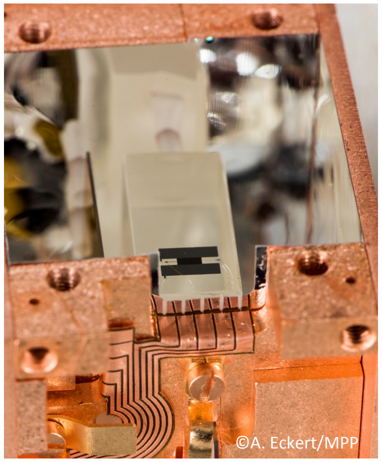
CRESST-III low threshold detectors

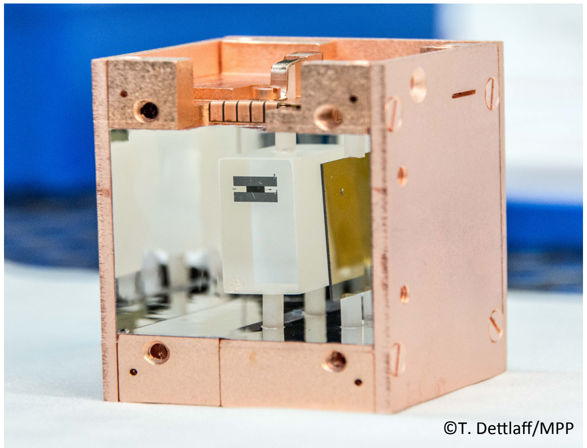
Detector layout optimized for low mass dark matter
Radical reduction of dimension

- Cuboid crystals of (20×20×10)mm^3 (≈**24g**)
- Self grown crystals **≈3 counts/(keV kg day)**
- **100 eV threshold**
- Fully scintillating housing
- Instrumented sticks

Veto surface related background

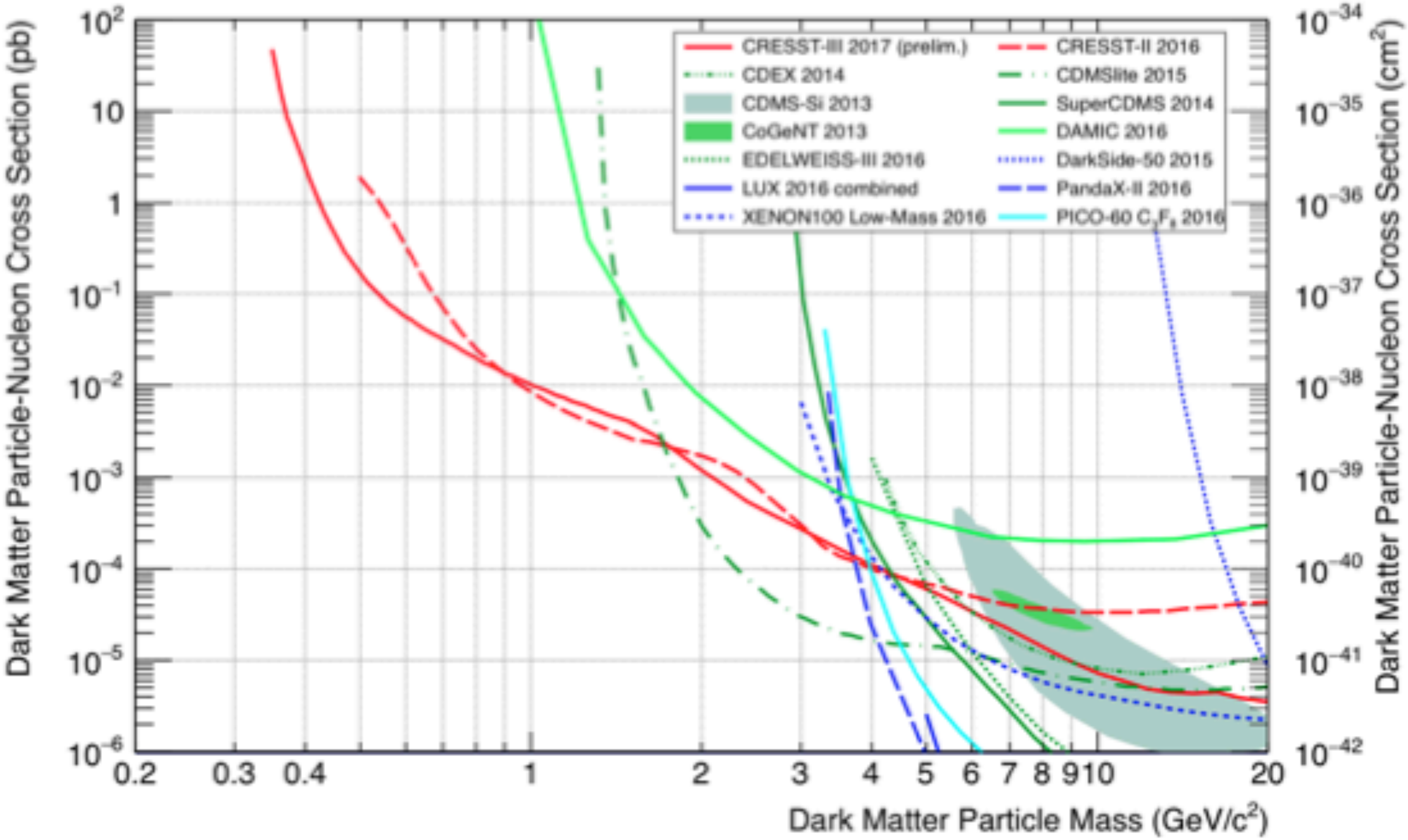






From F. Petricca, Direct Dark Matter search with the CRESST-III Experiment", TAUP 2017

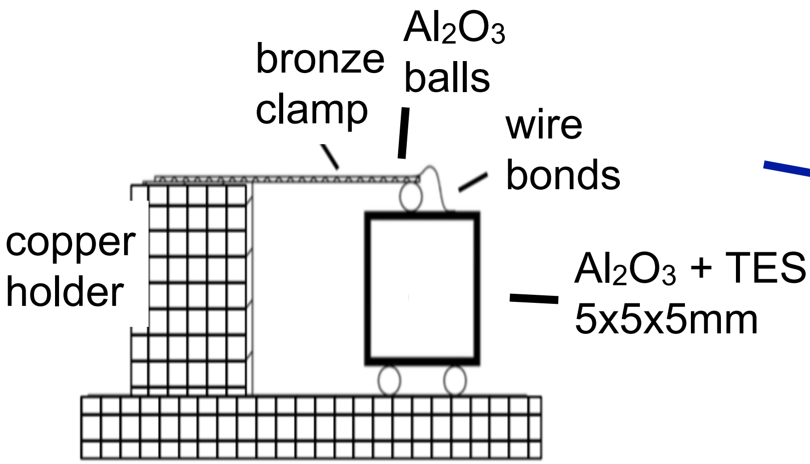
Latest CRESST Limit

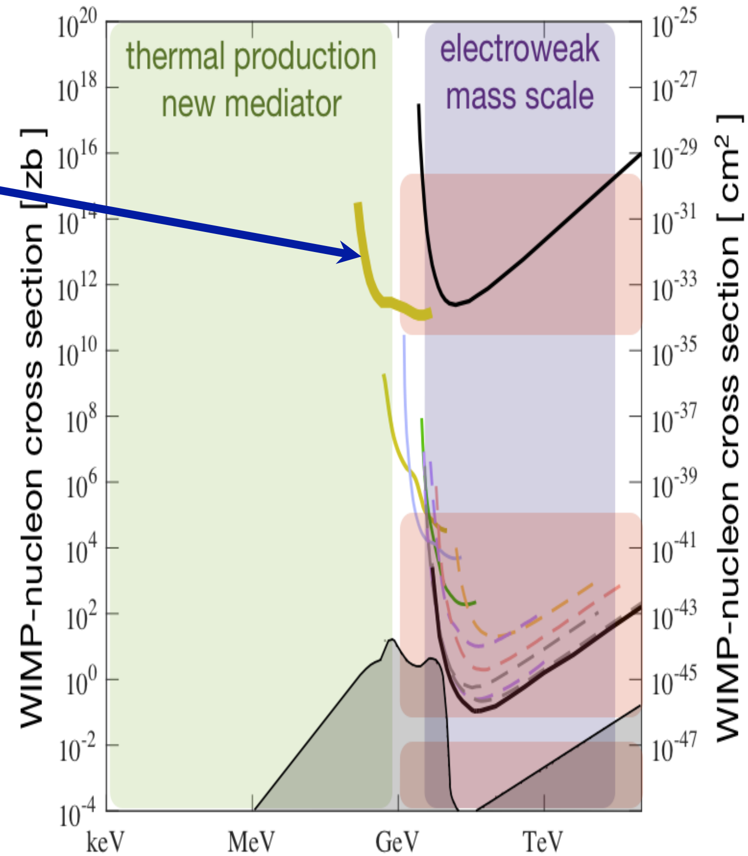


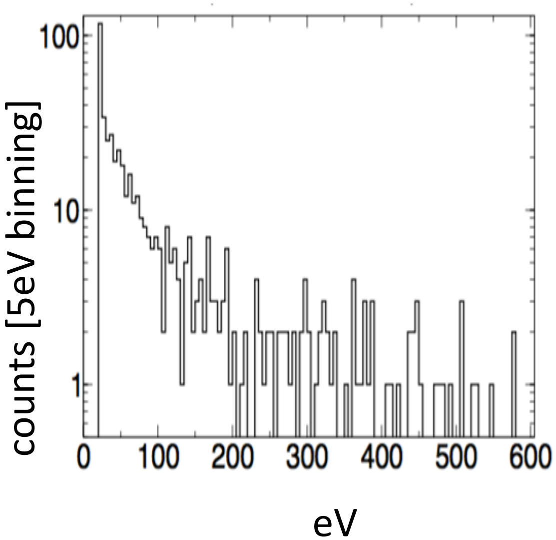
From F. Petricca, Direct Dark Matter search with the CRESST-III Experiment", TAUP 2017

CRESST/ν-cleus

arXiv:1707.06749v2



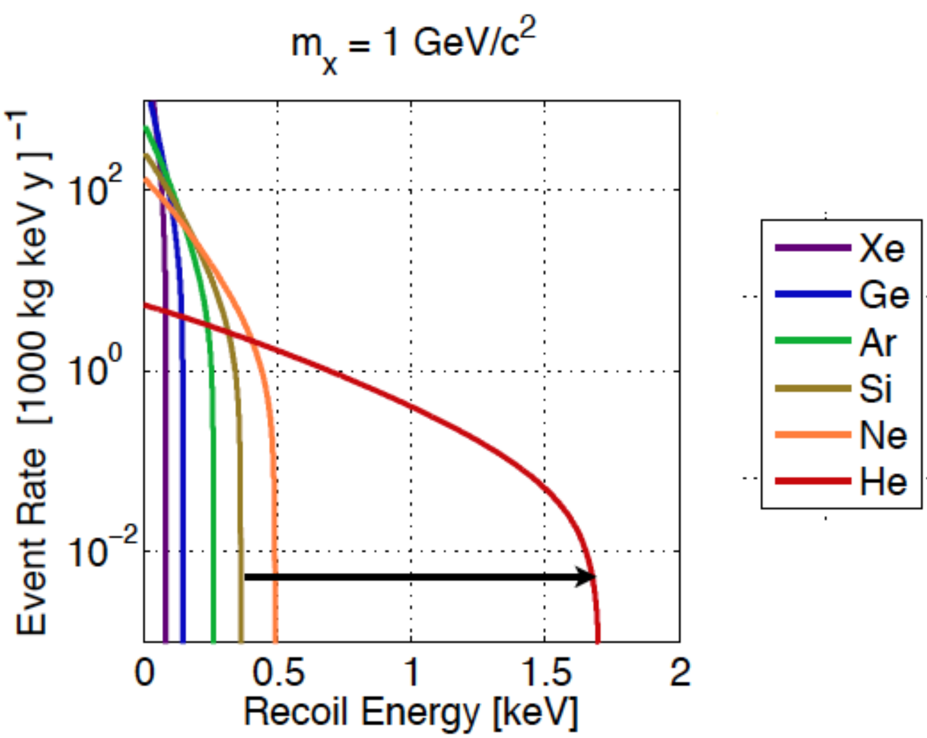


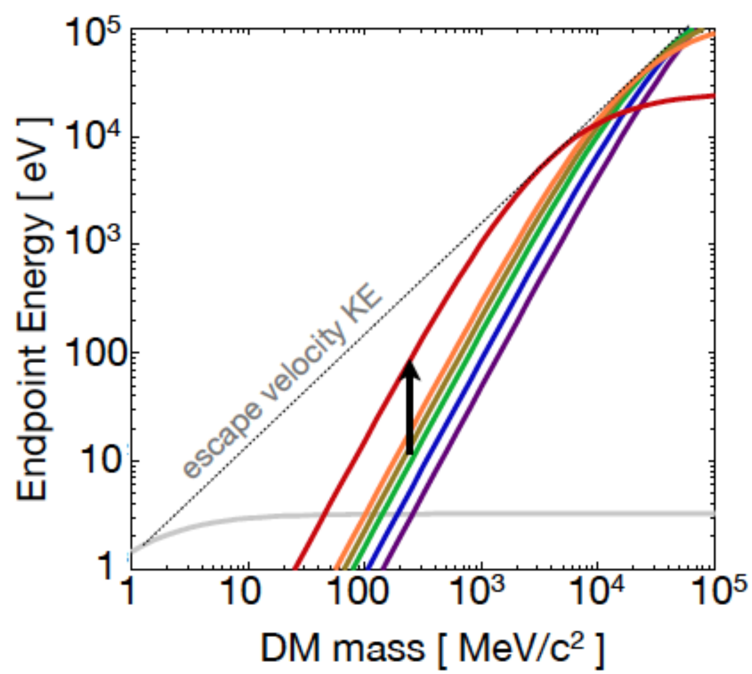


0.49g target
20 eV threshold
2.27h exposure
Above ground, no shielding, with ~0.2Bq Fe55 source
Limit down to 140 MeV dark matter mass!

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.

Keep It Clean

Charley Jordan- Keep It Clean

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:

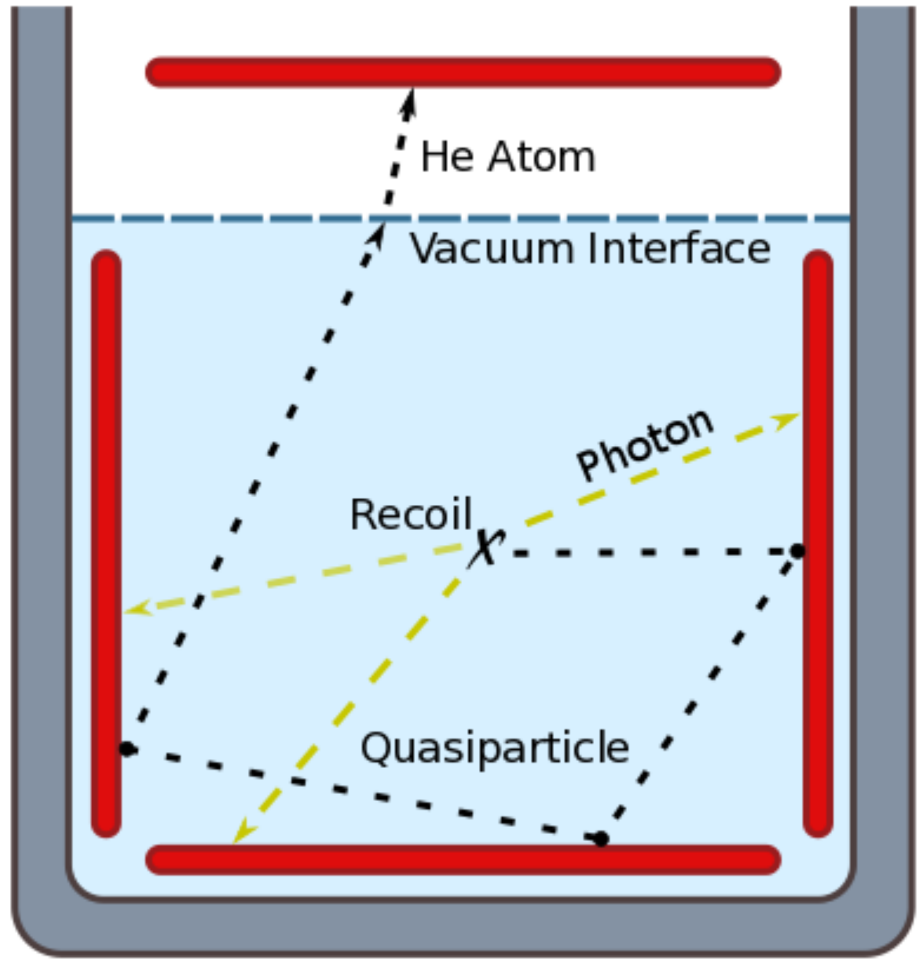
1) Scintillation
2) Ballistic Triplet Excimers
3) Phonons/Rotons

No drift field, and no S2 signal

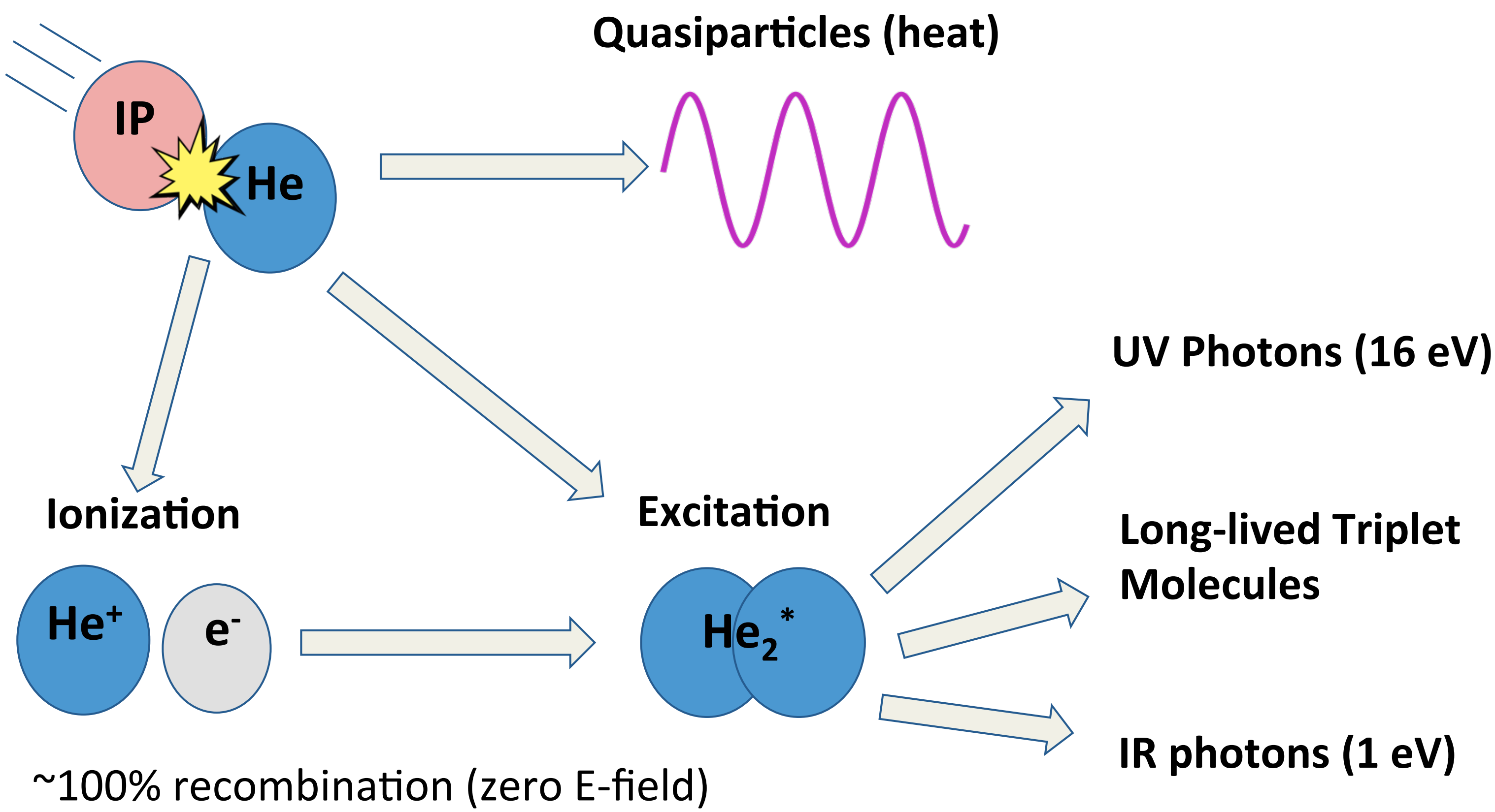
- No worry of few-electron background
- (Though could apply drift field to detect single electrons via roton/phonon production.)

Discrimination using signal ratios

Event position via signal hit patterns



Anatomy of a Recoil

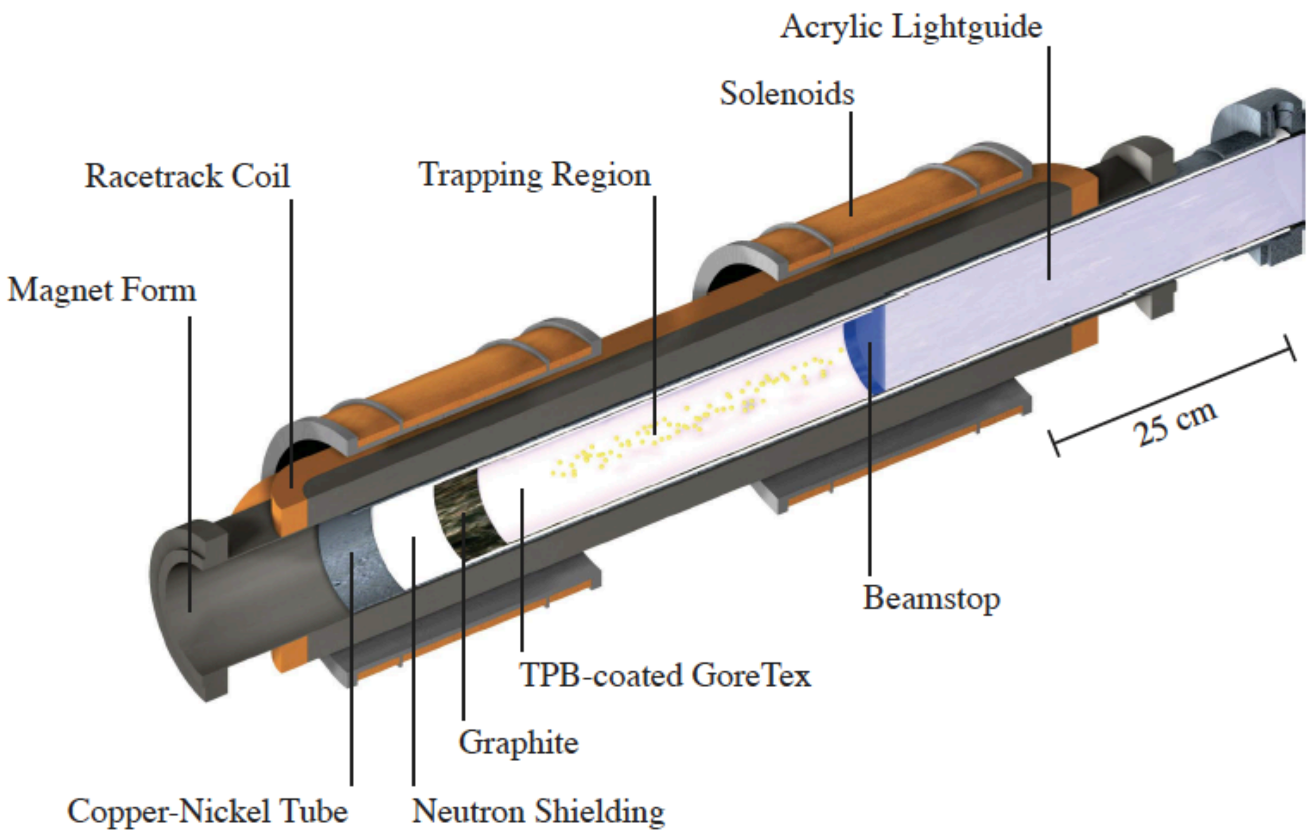


- UV and IR photons detectable as scintillation
- Triplet molecules directly detectable with TES
- Phonons and rotons can be detected with TESs, with some extra work

Superfluid helium-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).

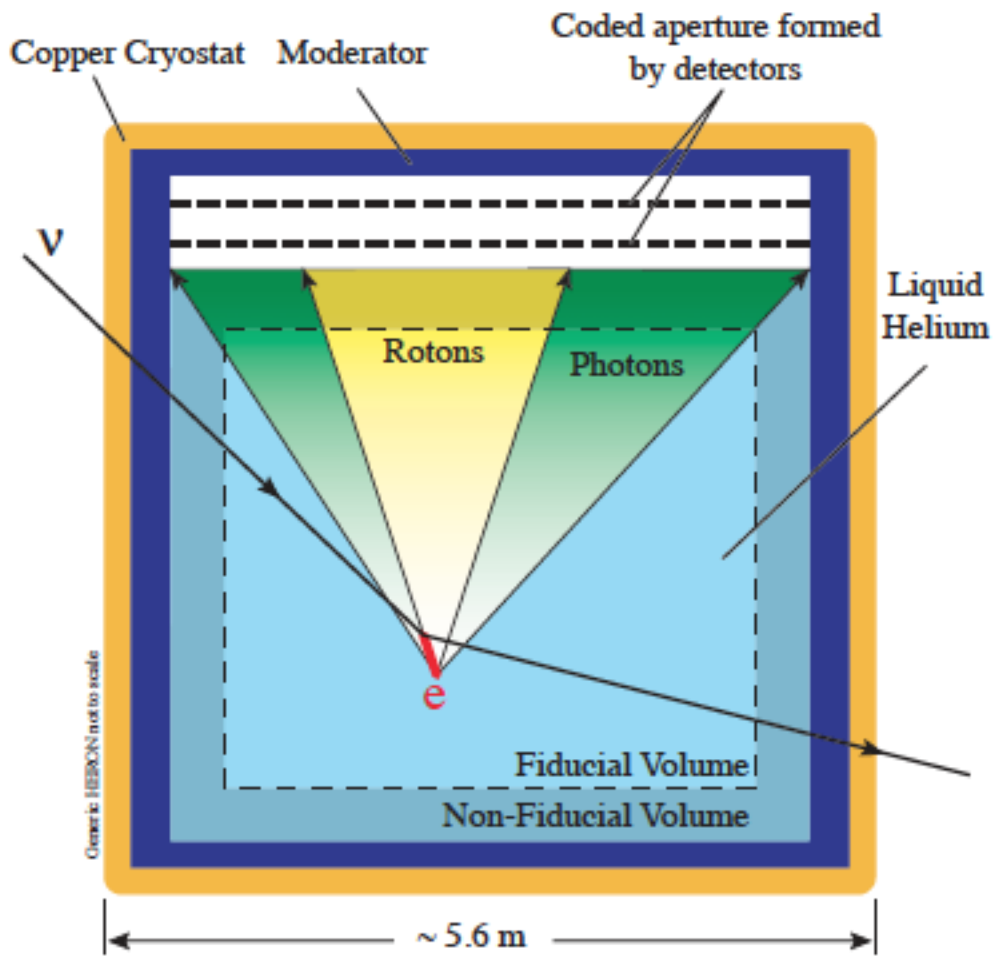


Superfluid helium-4 as a detector material

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).

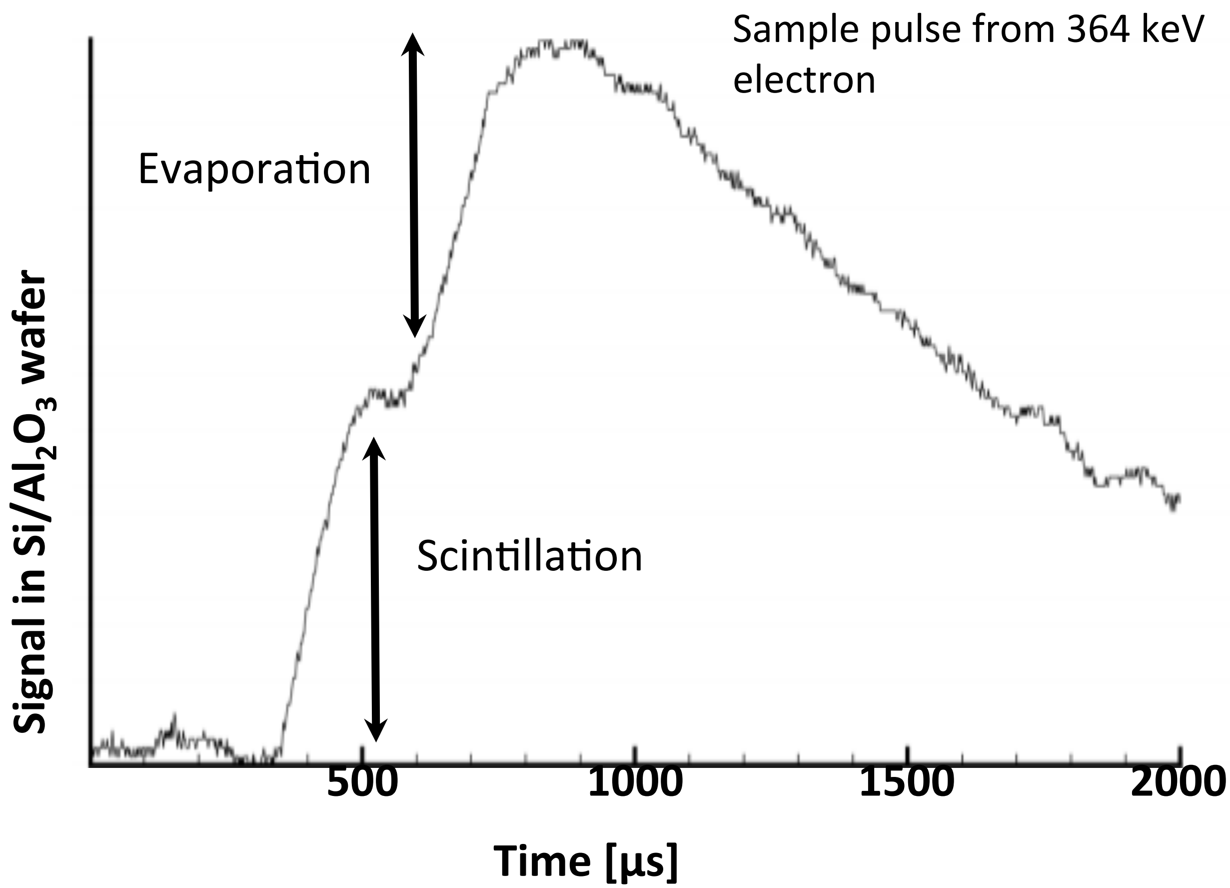
Two signal channels, heat and light. Both measured with a bolometer array.

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



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.

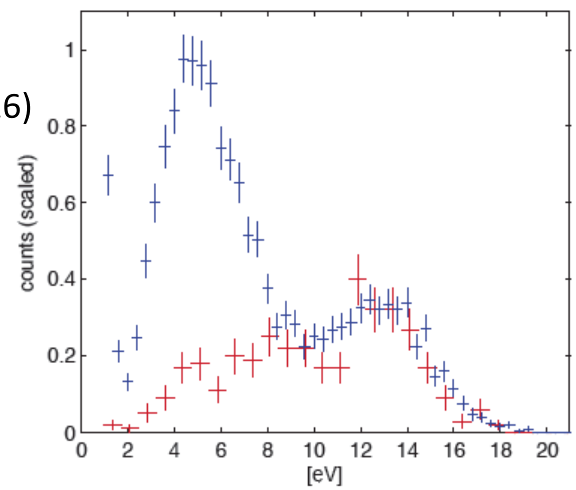
Reading Out Singlet Excitations (16 eV Photons)

Detecting photons is a simple calorimetry application. Operating calorimetry in LHe: less standard. Possible thanks to:

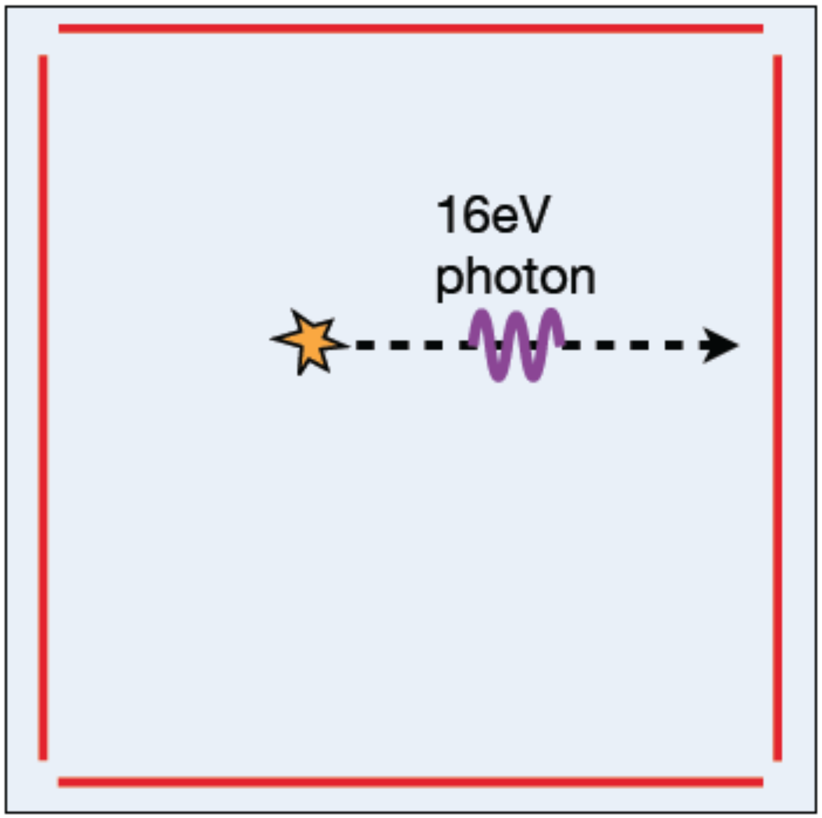
- Huge LHe-solid Kapitza resistance
- Fast conversion of photon energy to non-phonon excitations (e.g. Al quasiparticles)

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

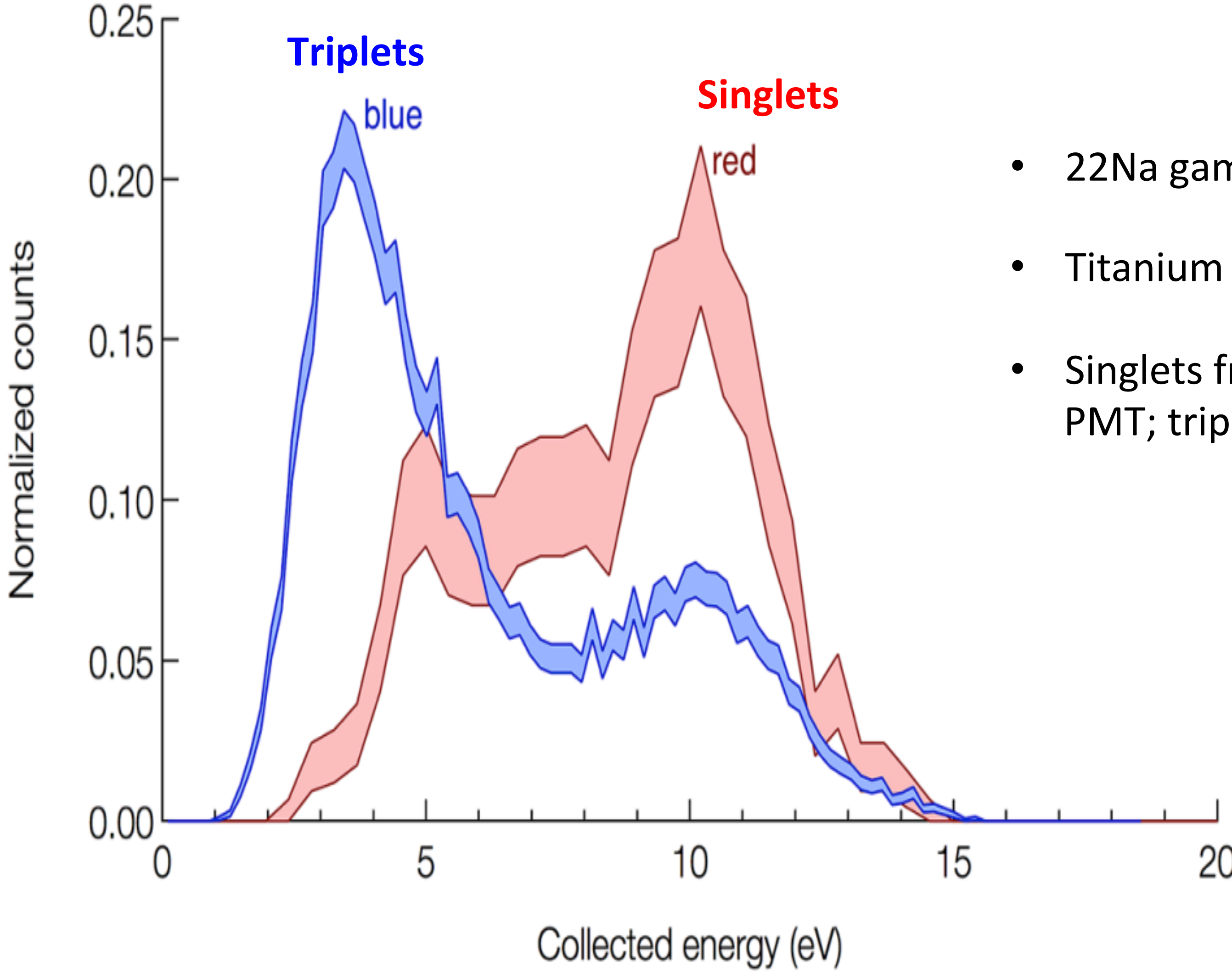
F. Carter et al,
J Low Temp Phys (2016)
arXiv:1605.00694



Simple detector: box
with calorimetry inside



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

Phonons and Rotons

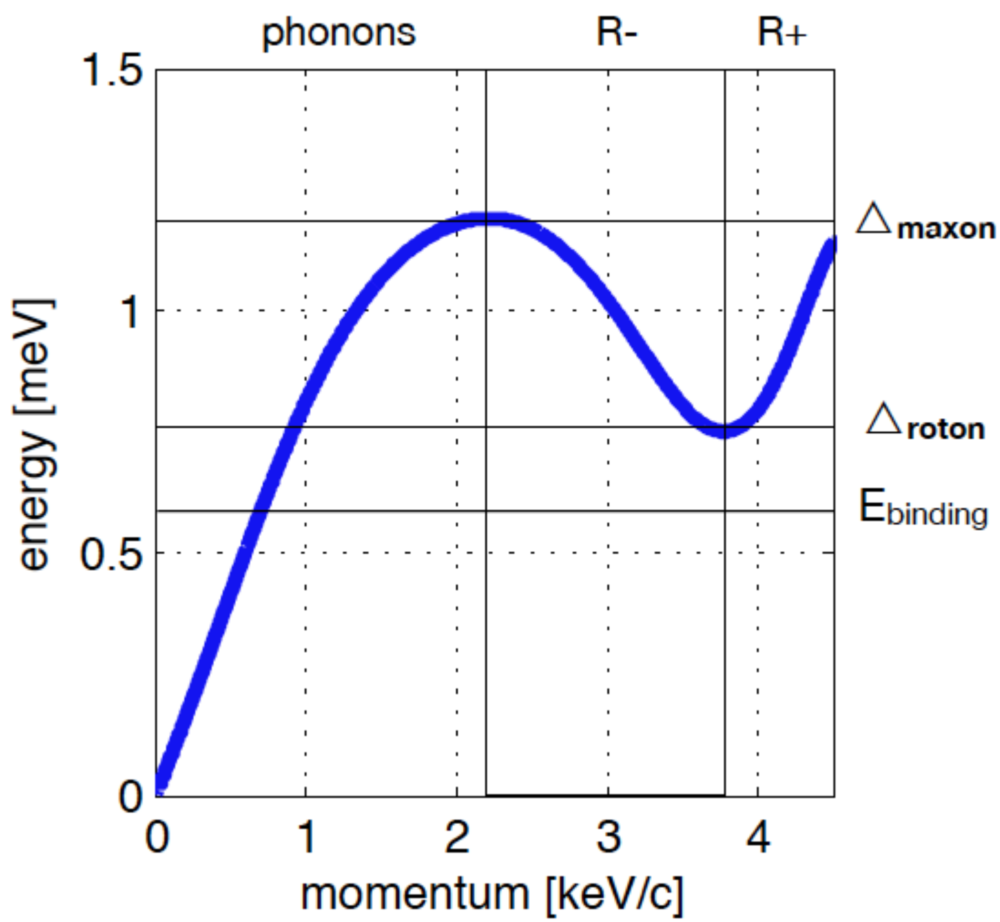
Superfluid supports vibrational modes (some non-intuitive).

Ballistic, ~150 m/s.

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

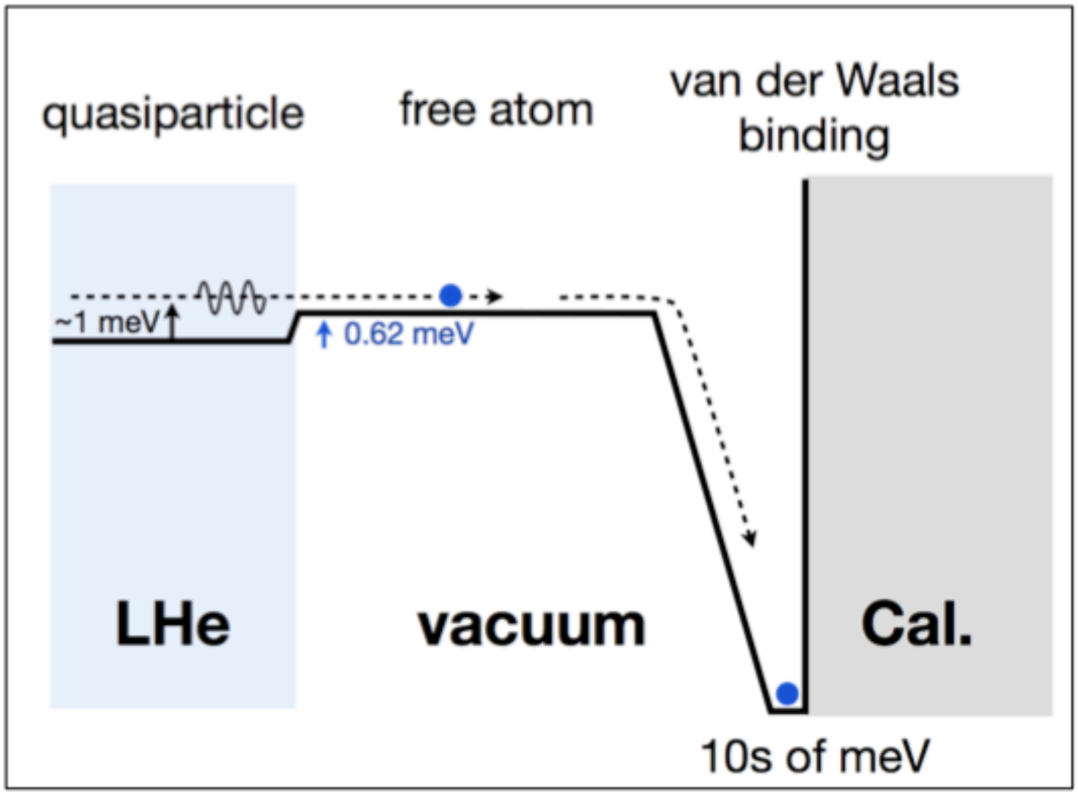
Few downconversion pathways.

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

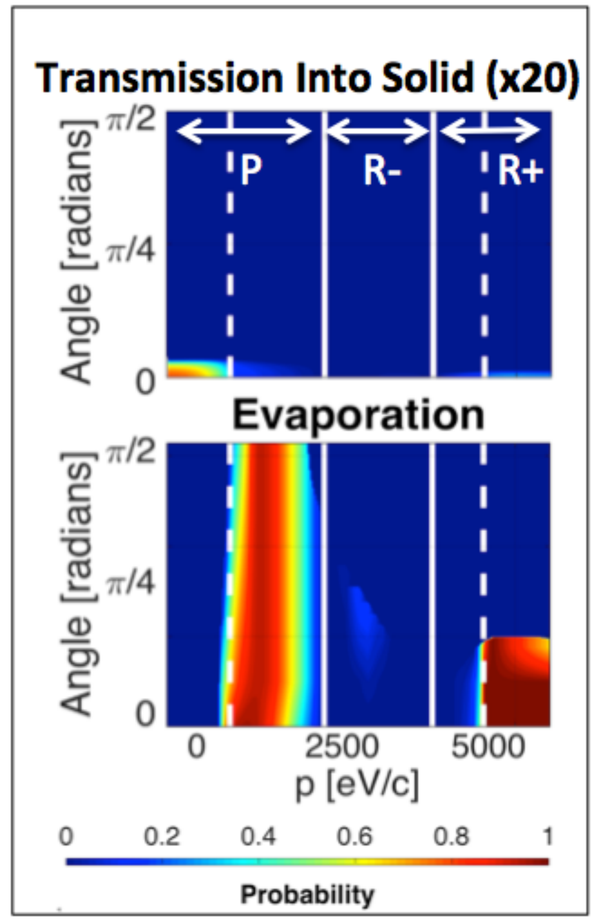


Quantum evaporation from superfluid helium – vacuum interface

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



~10x signal energy enhancement!

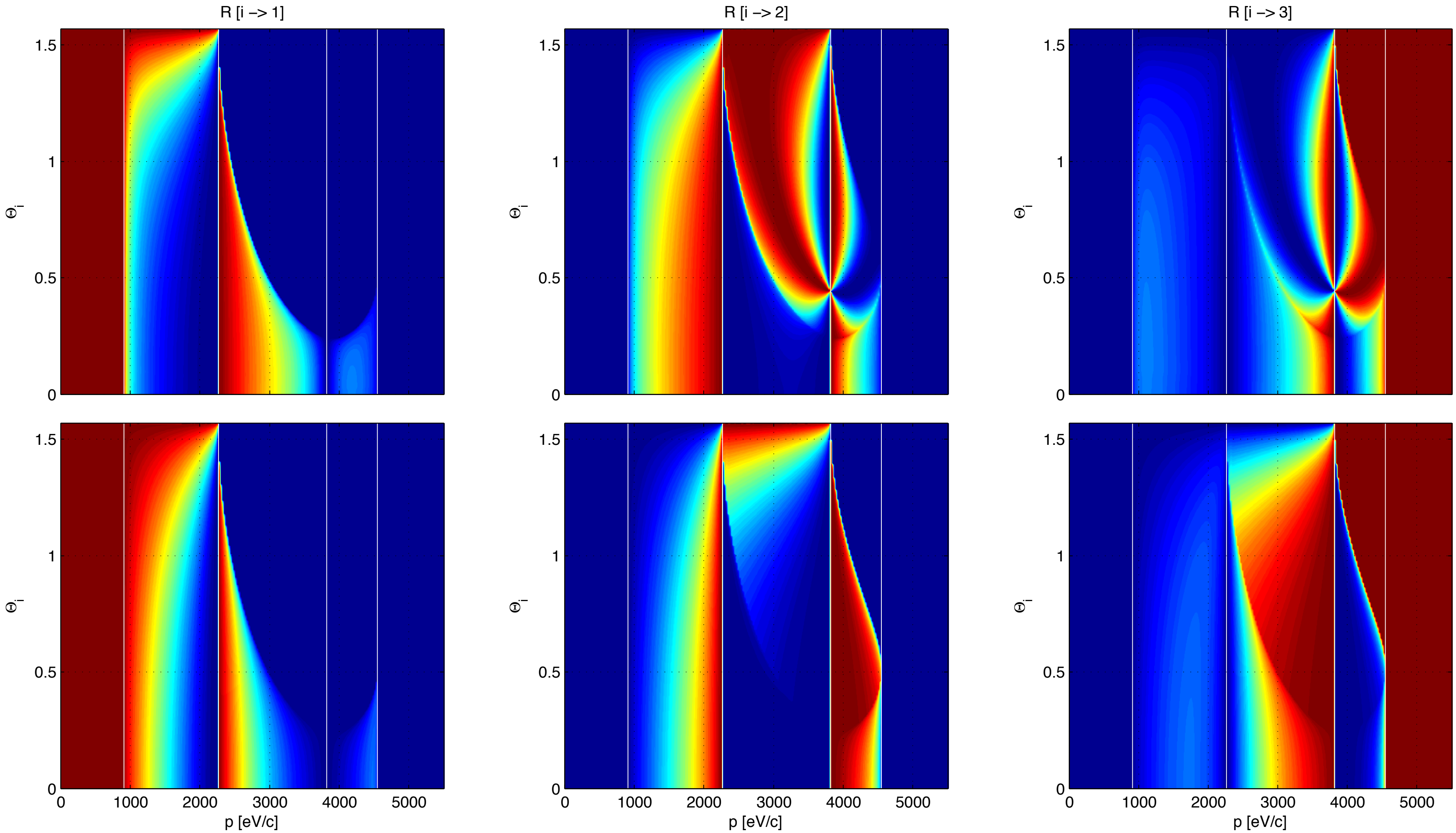


Phonons and rotons can change type when reflecting from surfaces

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

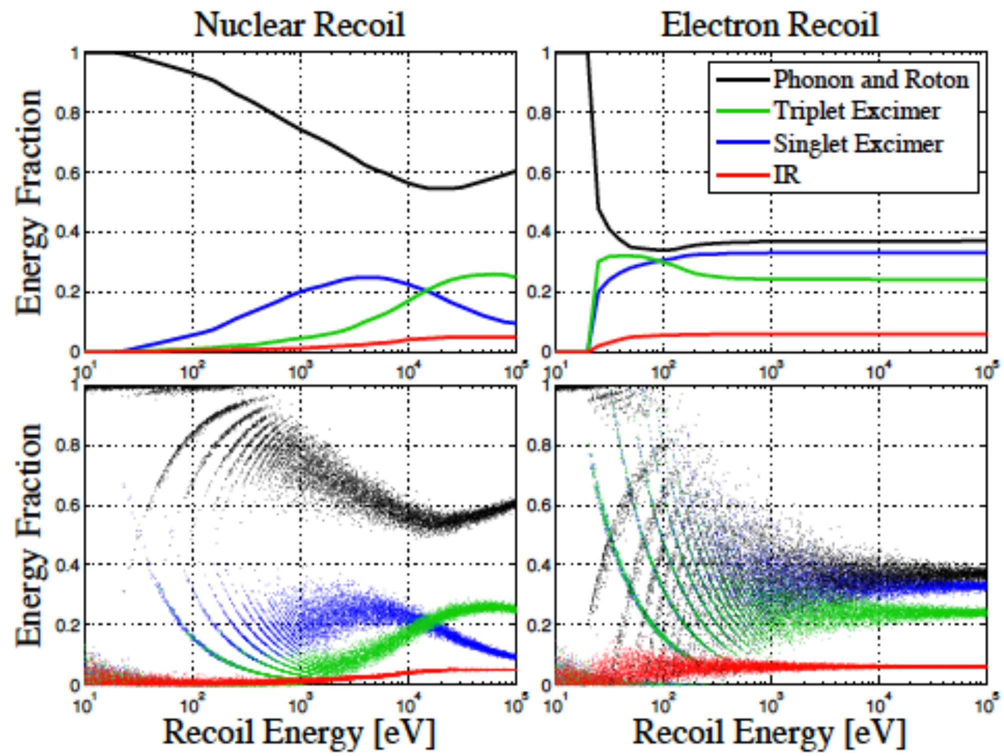


Electron recoil / nuclear recoil discrimination

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)

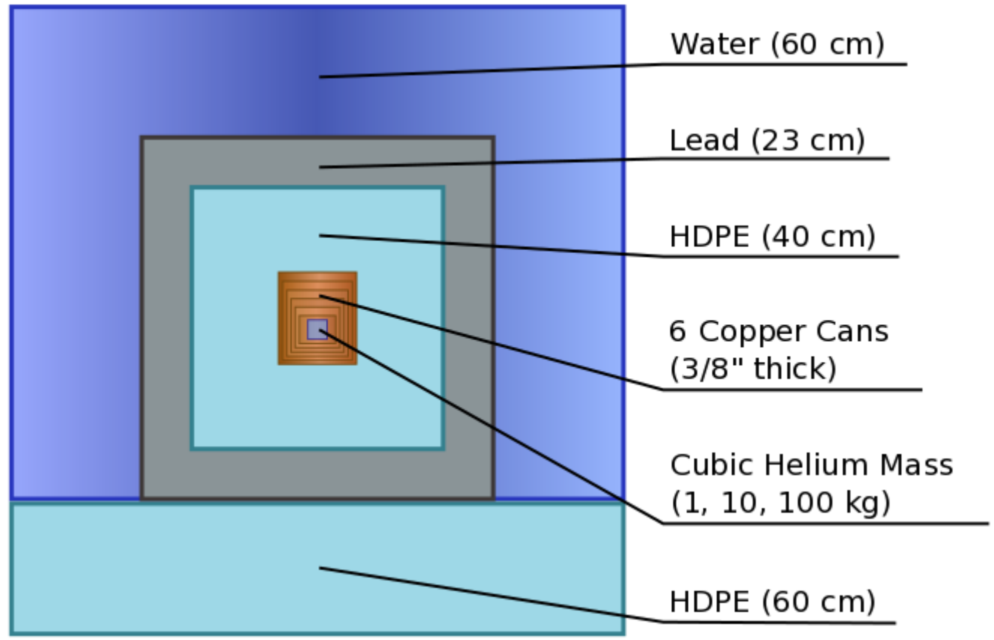
Excellent predicted discrimination at sub-keV energies



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)



Arguments for low "detector" backgrounds:

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

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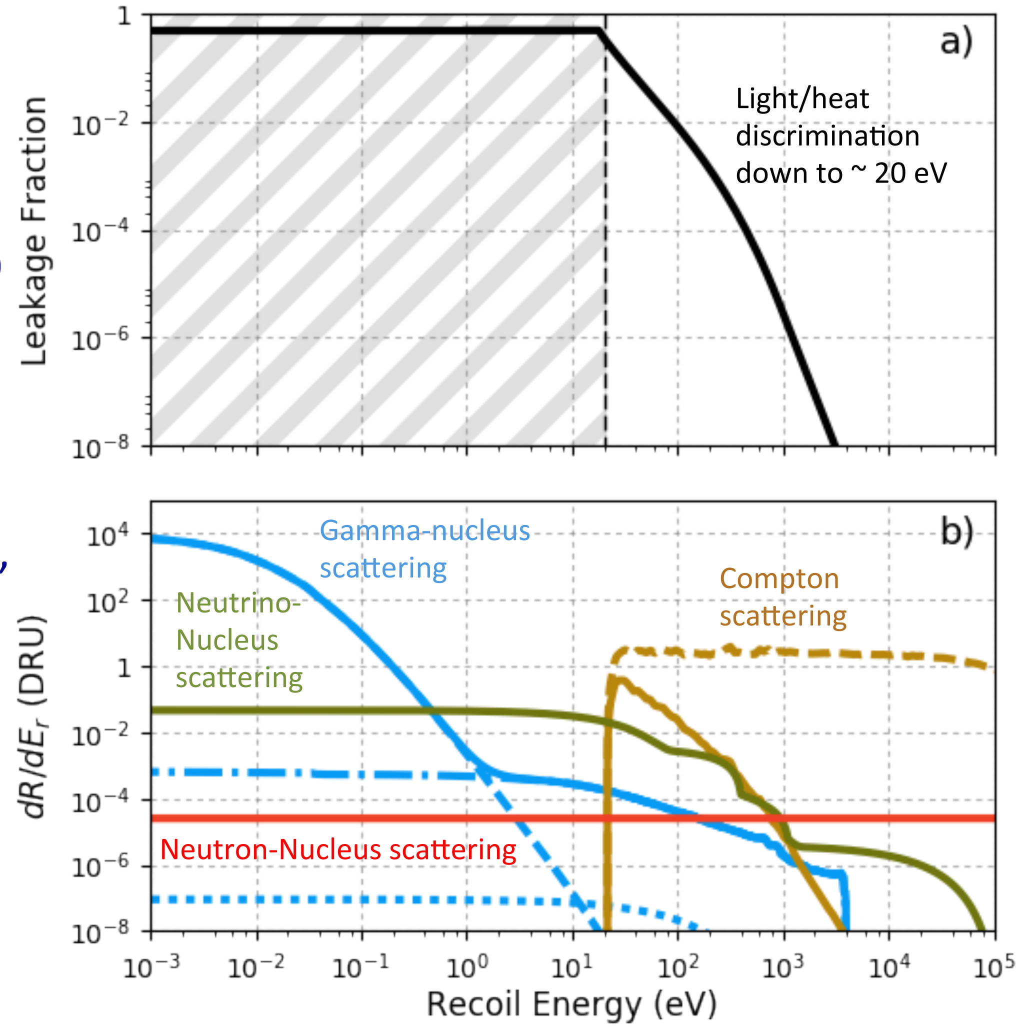
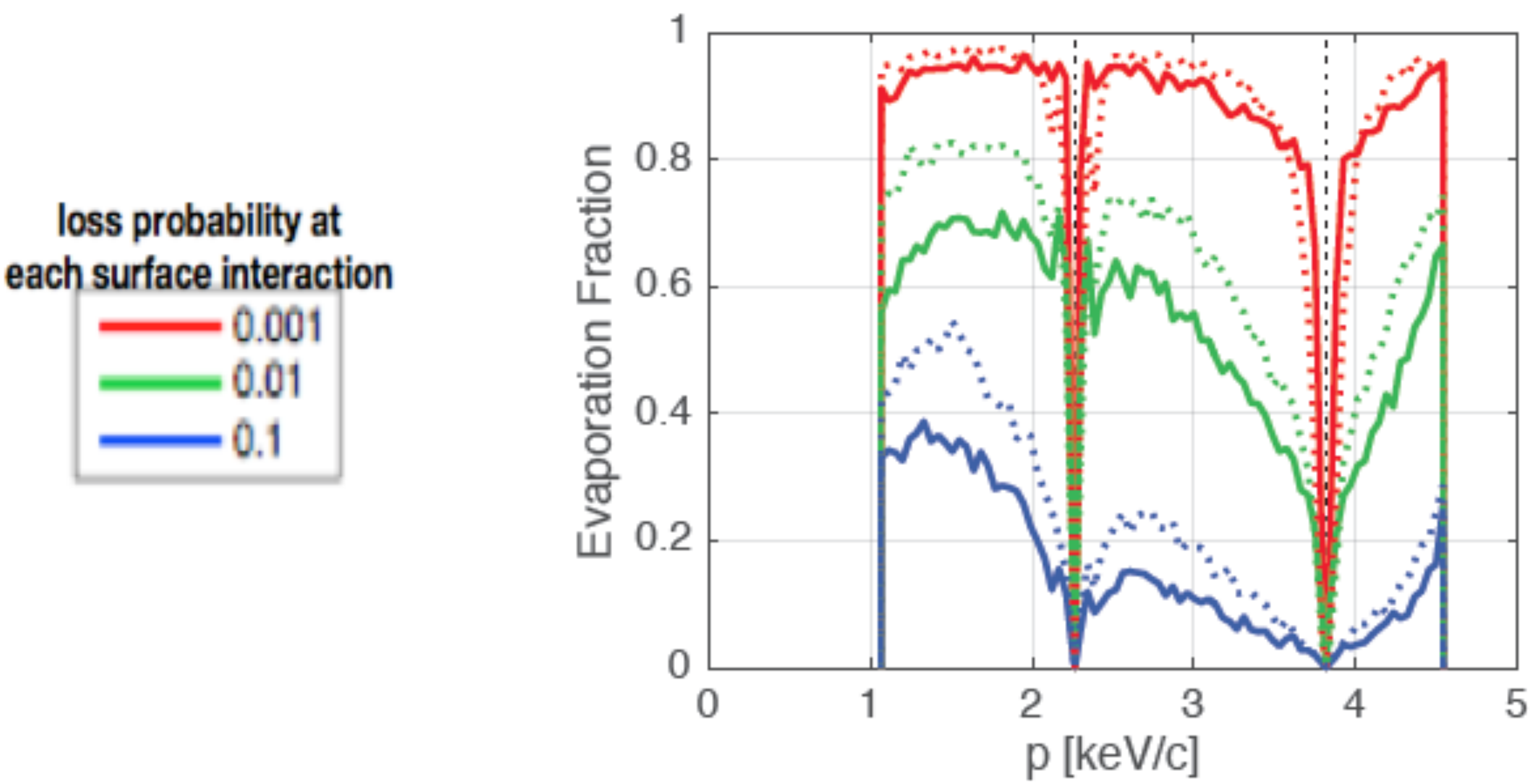


Phonon and Roton Monte Carlo Studies

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)



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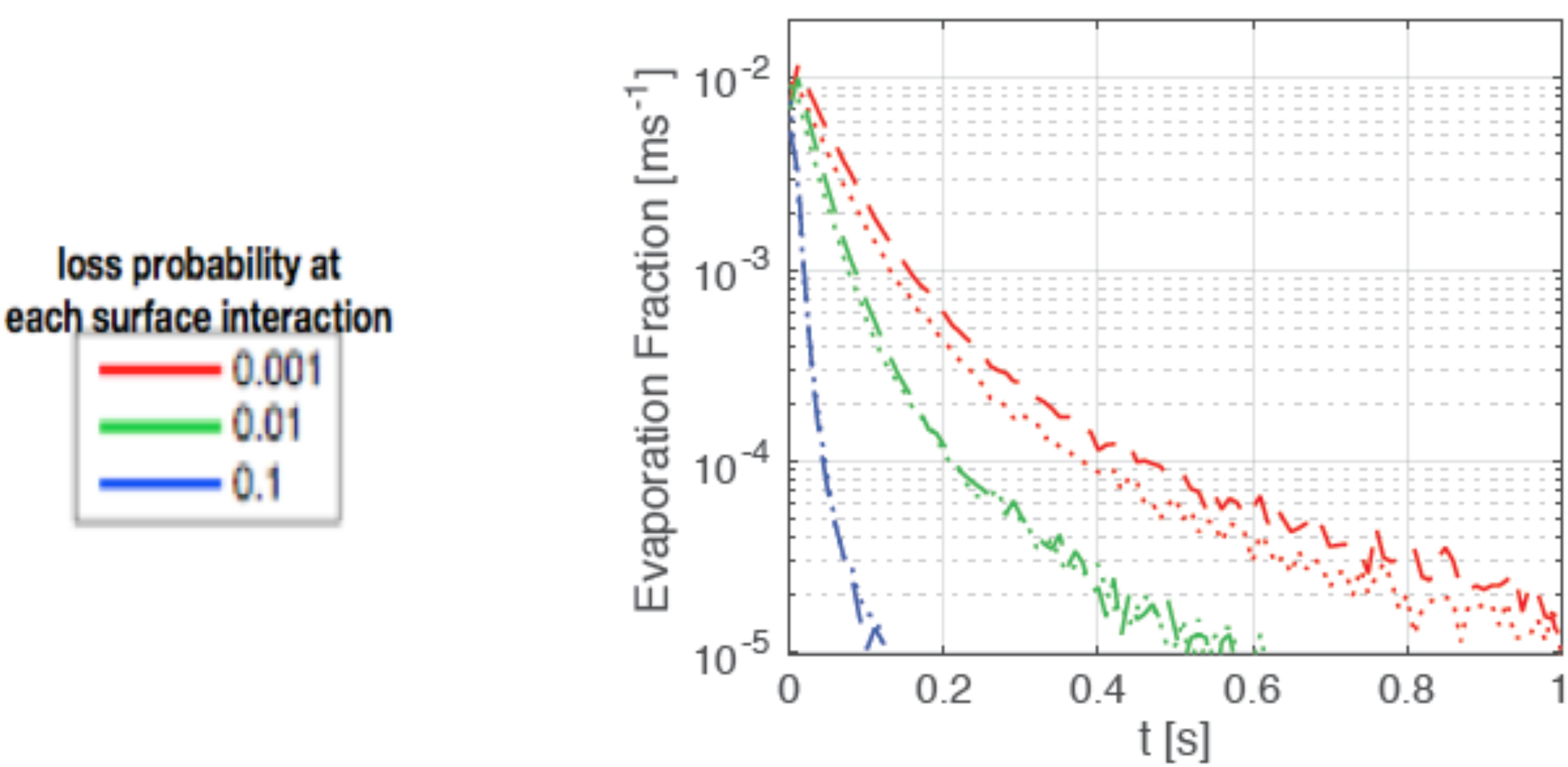


Heat-only Readout?

Signal channels:

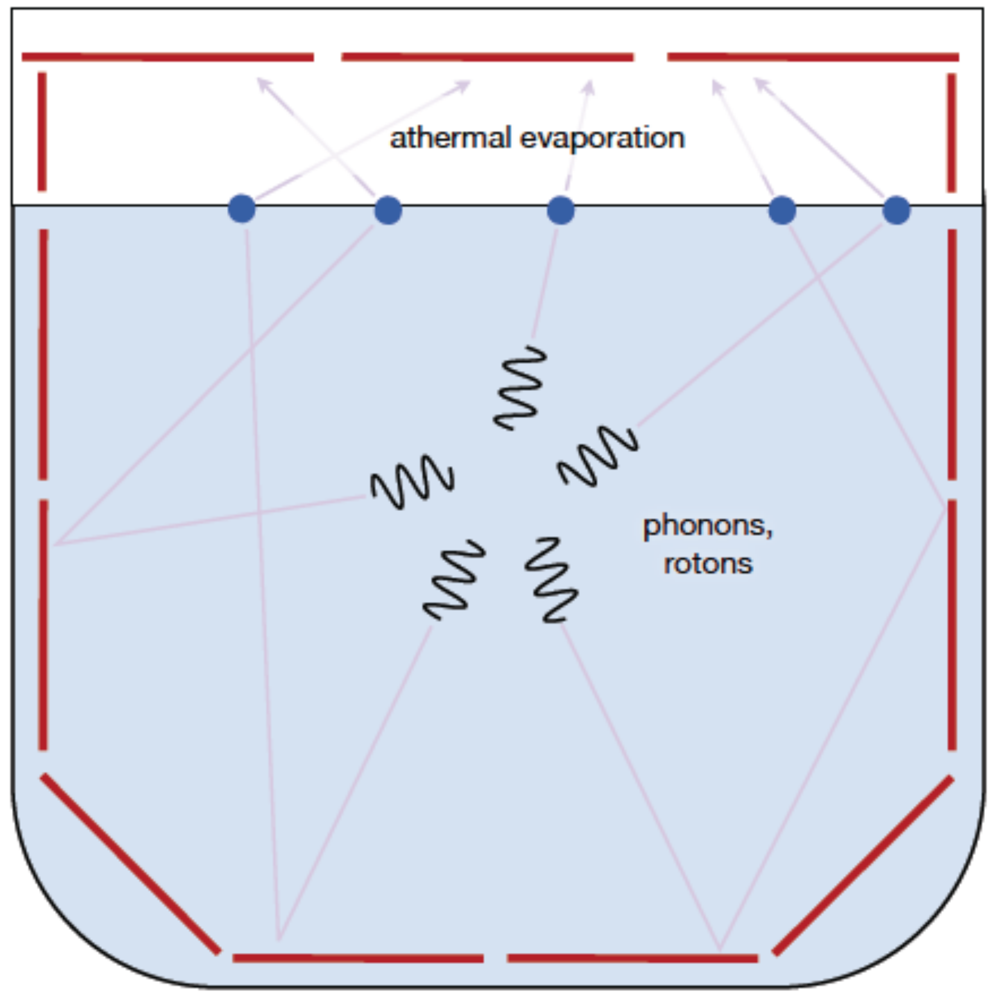
Phonons

Rotons

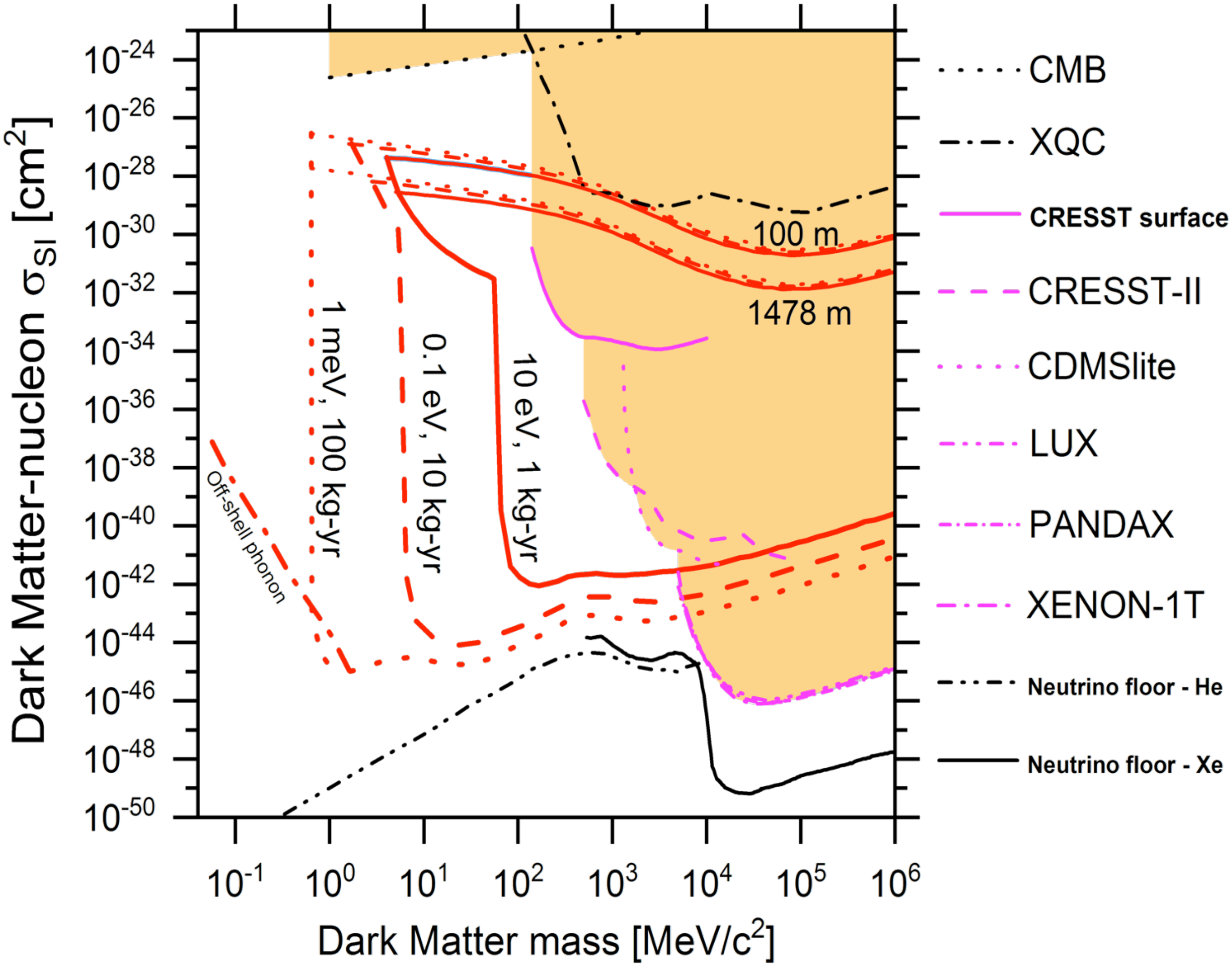
Energies in principle down to ~ 1 meV.

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.

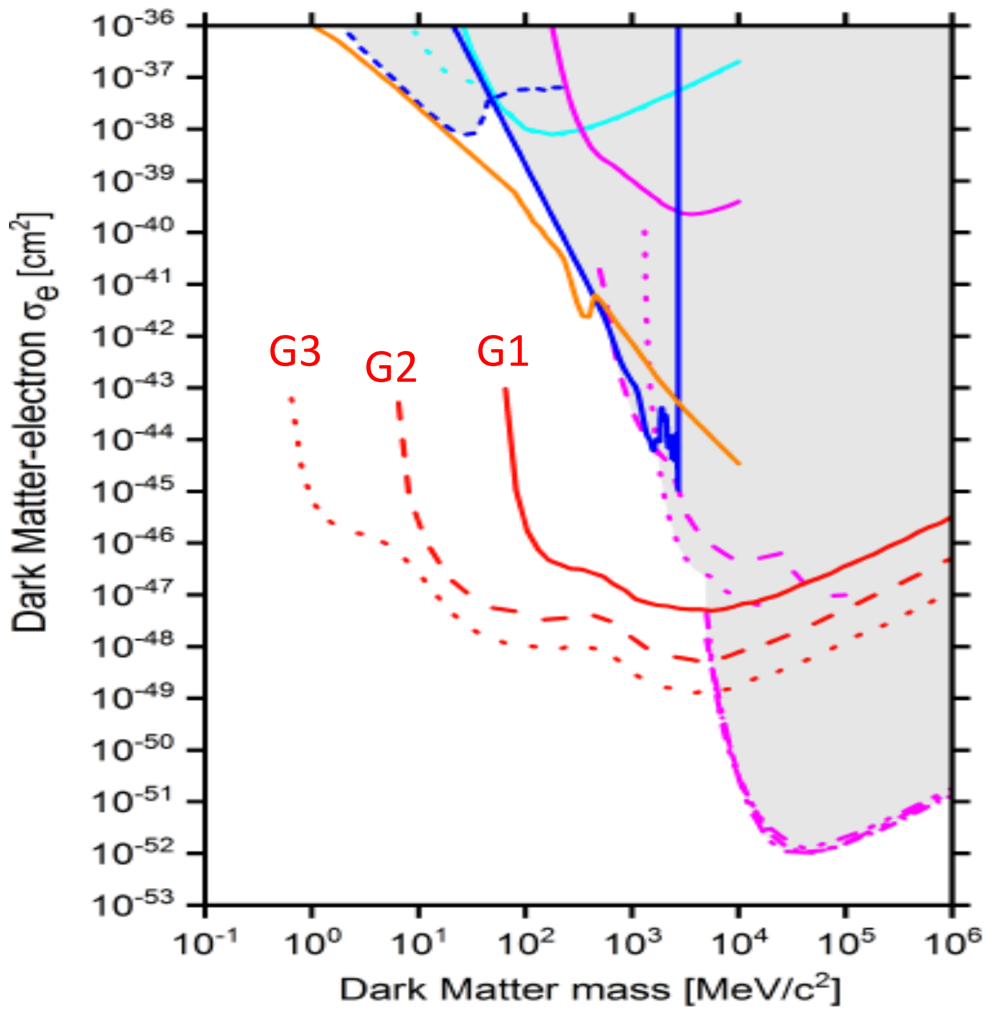
Position reconstruction using signal hit patterns



Projected Sensitivity – nuclear recoils



Projected Sensitivity – dark photon dark matter w/ heavy mediator

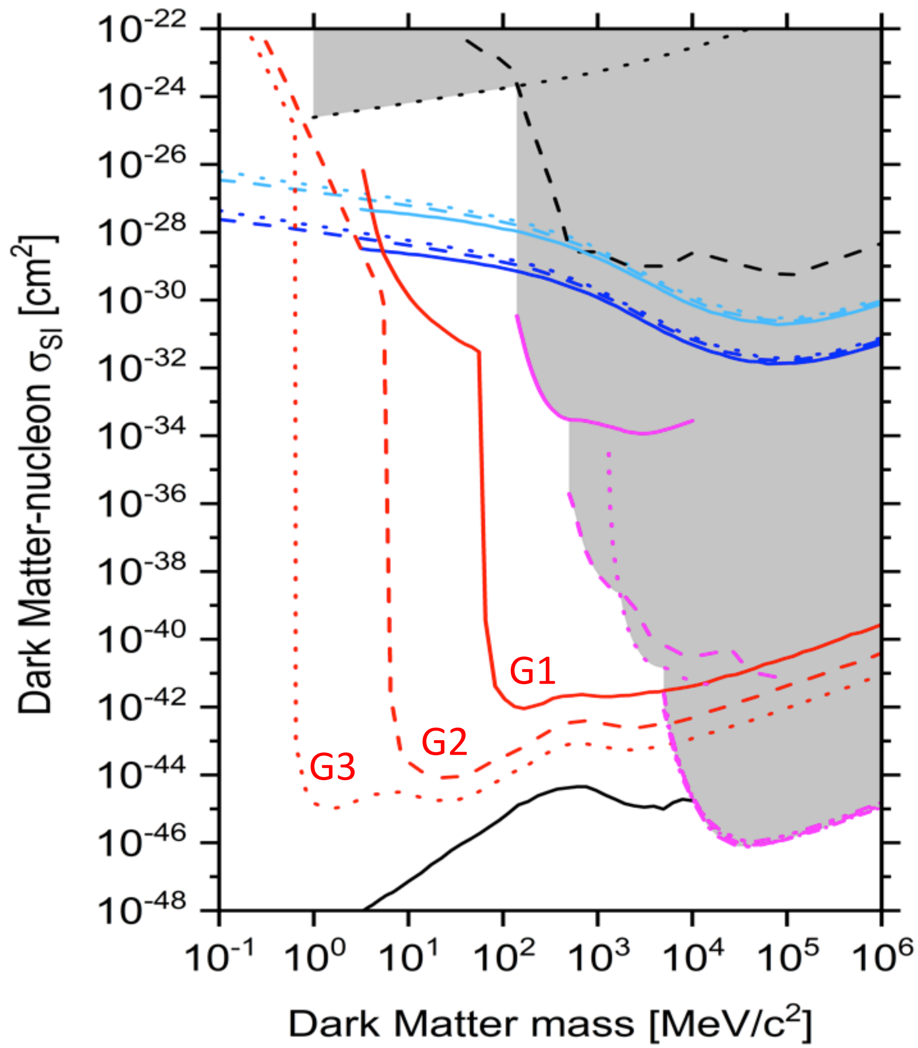


Possible stages of a superfluid helium program

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

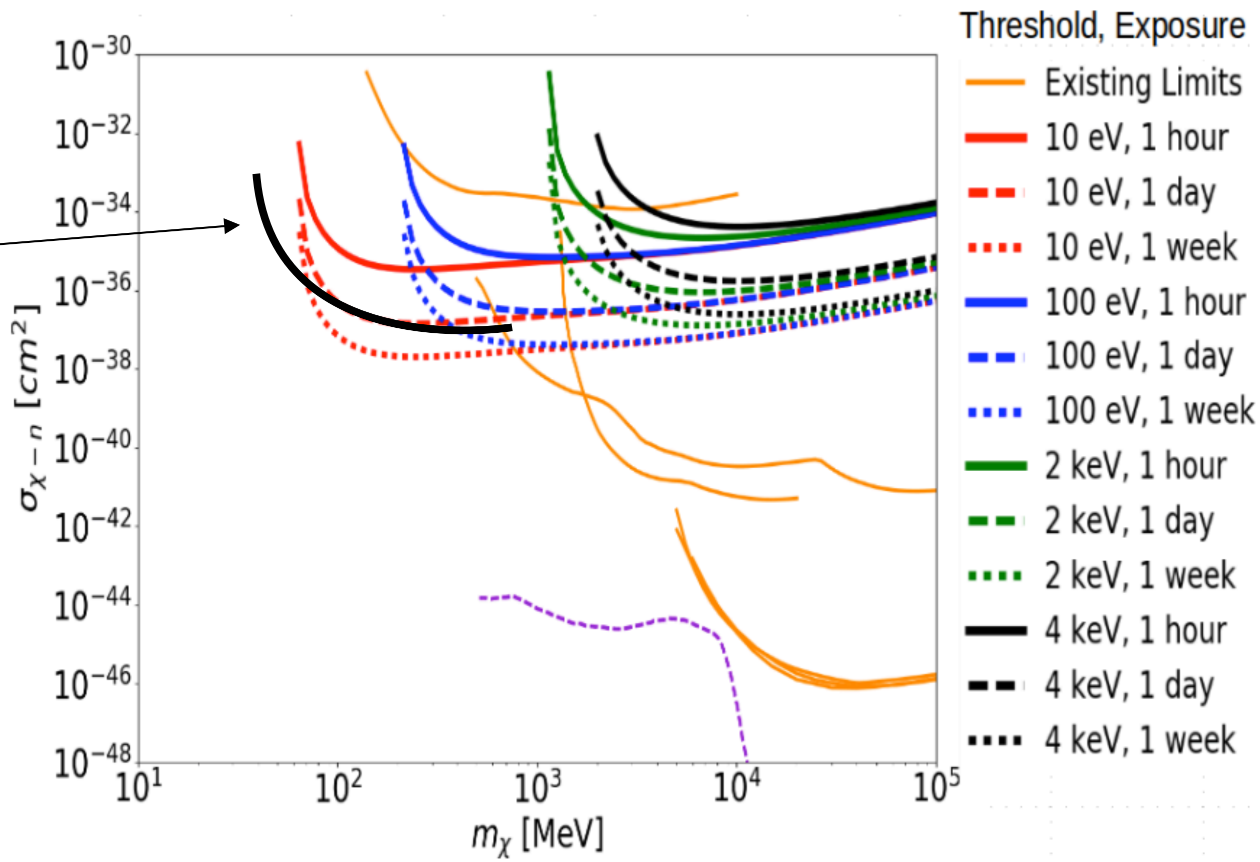
Generation 3: "theoretically possible"
1 meVr threshold, 100 kg-y
Limit of single-atom counting
(~40 meV calorimeter threshold)



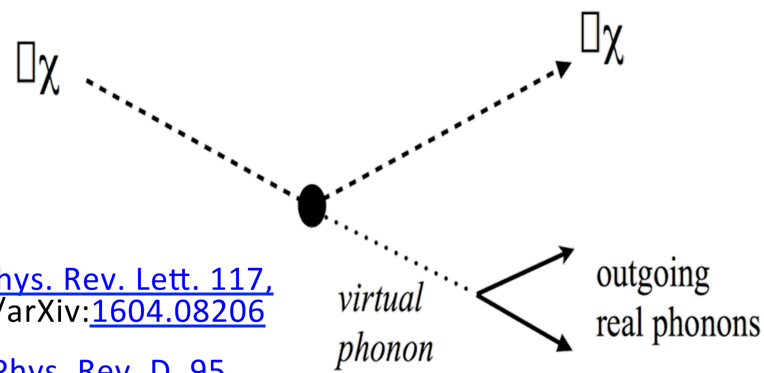
LHe reach at the surface

2g LHe on surface. Zero background

1 eV,
1 day



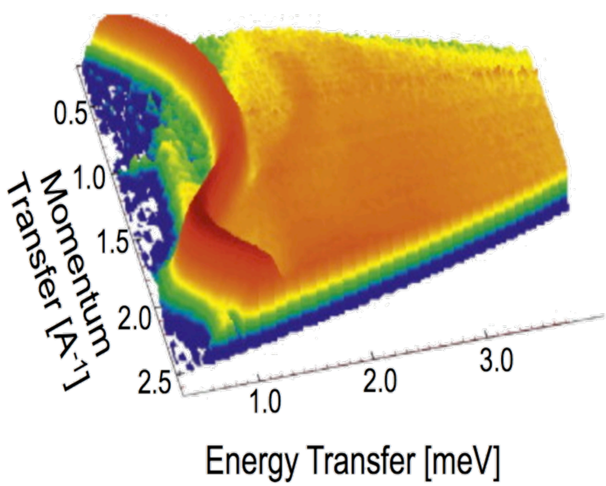
Higher Order Phonon Processes



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

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

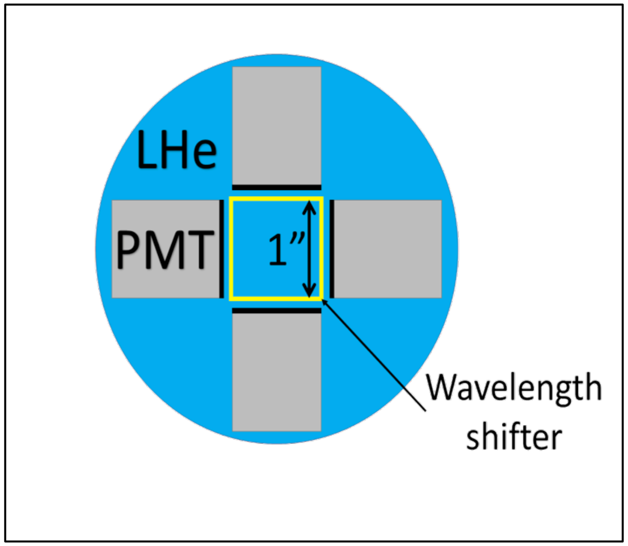
- Virtual phonons not limited to dispersion relation.
- Process allows sensitivity to keV-scale warm DM
- Two-phonon process experimentally observed in neutron scattering (below)

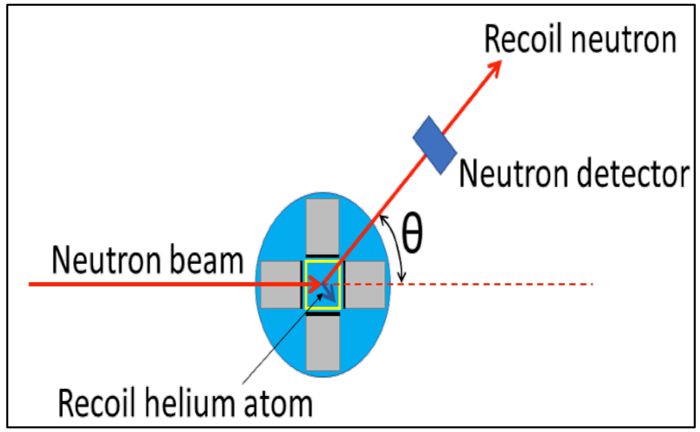


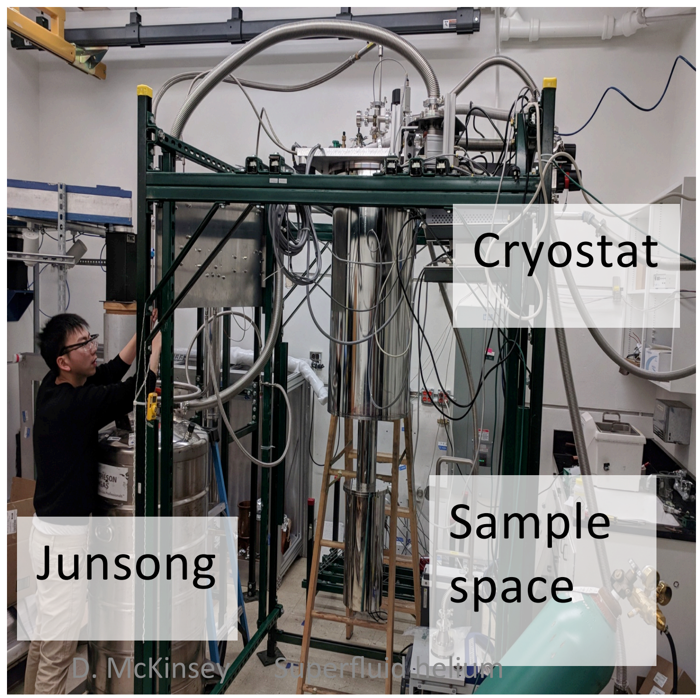
Visualization from: Nucl. Instr. Meth. Phys. Res. A 611, 259-262 (2009)/ arXiv:0811.4332

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

Next Steps







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

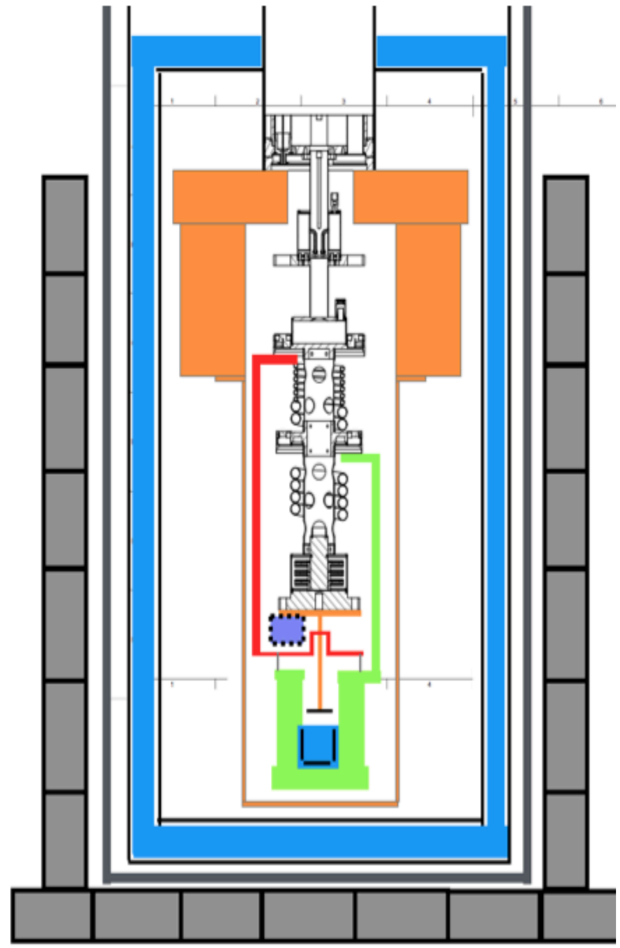
Also: Dilution refrigerator instrumentation studies (UCB + UMass)

Right: Successful cool down to 1.5 K!

Superfluid Helium Detector

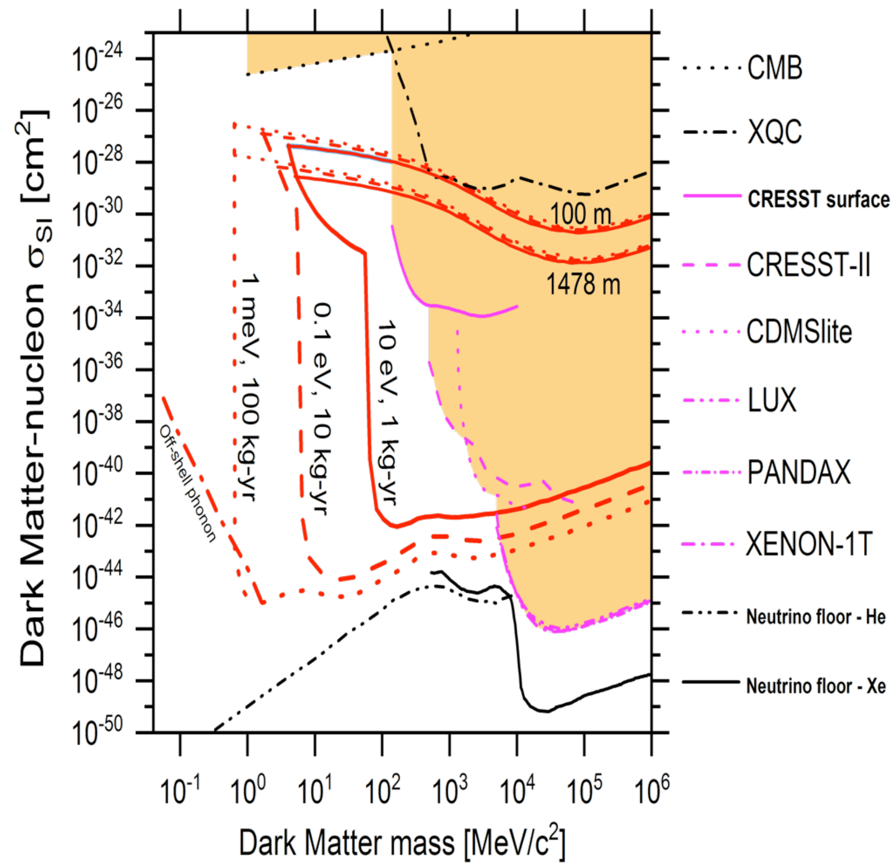
Leiden (wet, low-vibration) dilution refrigerator being set up in McKinsey lab at UCB

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



Backup slides

TES R&D Topics

- Measurement of light, He2*, infrared, phonon, roton yields in superfluid helium for both electron and nuclear recoils. (1 year)

- Optimization of in-vacuum TES array for detection of evaporated helium atoms. The lower the threshold the better, but note:
  - Can extract important science with a ~10 eV threshold, comparable to CRESST. Does not require a revolutionary advance, just experience in detecting low-energy events through helium evaporation. (1 year)
  - Can probe every-lighter dark matter with ever-lower energy thresholds, down to 1 meV. Case for long-term, revolutionary advances in TES technology (2-10 years).

- Optimization of in-liquid TES array for ~100% QE detection of light, He2*. Operation in liquid requires faster readout, likely prefer athermal methods. Photon detector development also useful for detecting electron recoil signals in scintillating crystals like GaAs, NaI. (1 year)

- Longer-term: Optimize surfaces in liquid helium for photon and roton reflectivity, so as to optimize calorimeter signal and aid in lowering energy threshold. (2-10 years).