Superfluid Helium for Light Dark Matter Detection

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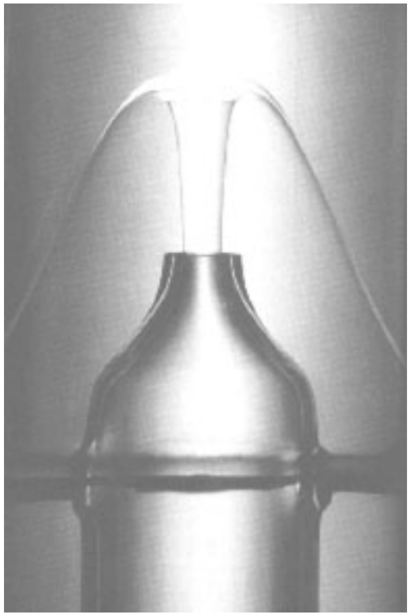


Dark Sectors Workshop
SLAC
April 29, 2016

Outline

This talk:

- Some history, context
- Some advantages of superfluid helium
- Signals in superfluid helium
- Energy partitioning
- Some detector concepts

Next talk (Scott Hertel)

- Some recent TES measurements with superfluid helium
- Phonon/roton reflection and detection
- Light/heat based ER vs NR discrimination
- Dark counts

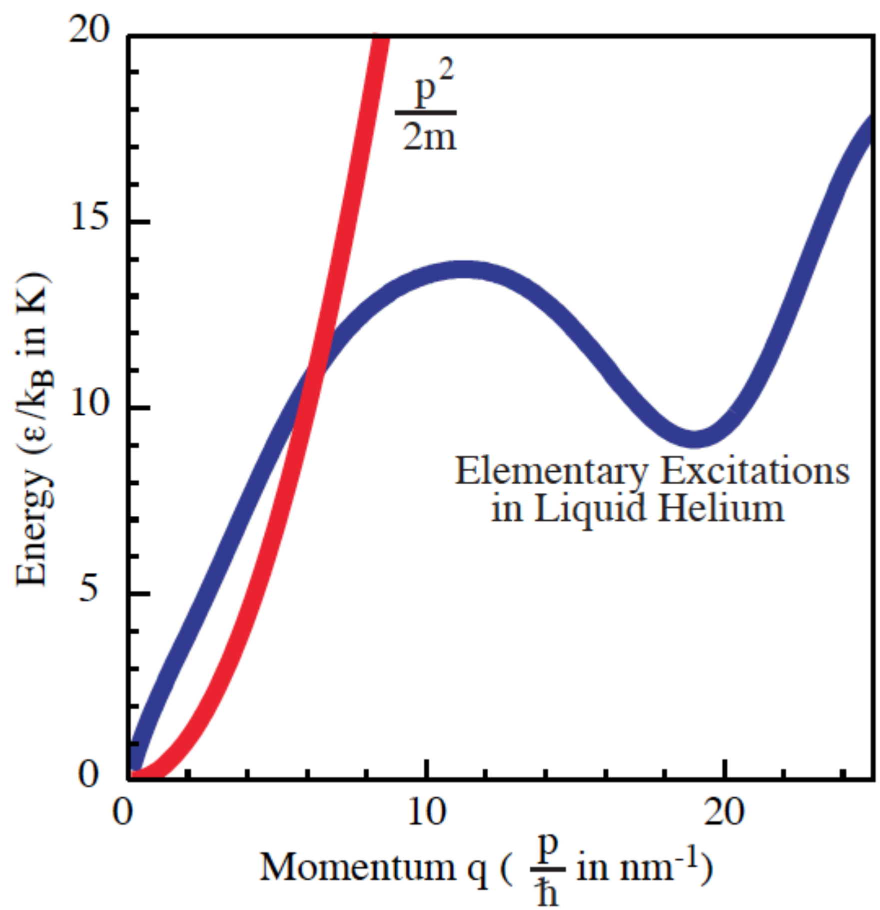
Liquified Noble Gases: Basic Properties

Dense and homogeneous
Do not attach electrons, heavier noble gases give high electron mobility
Easy to purify (especially lighter noble gases)
Inert, not flammable, very good dielectrics
Bright scintillators

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

Superfluid helium-4 as a detector material

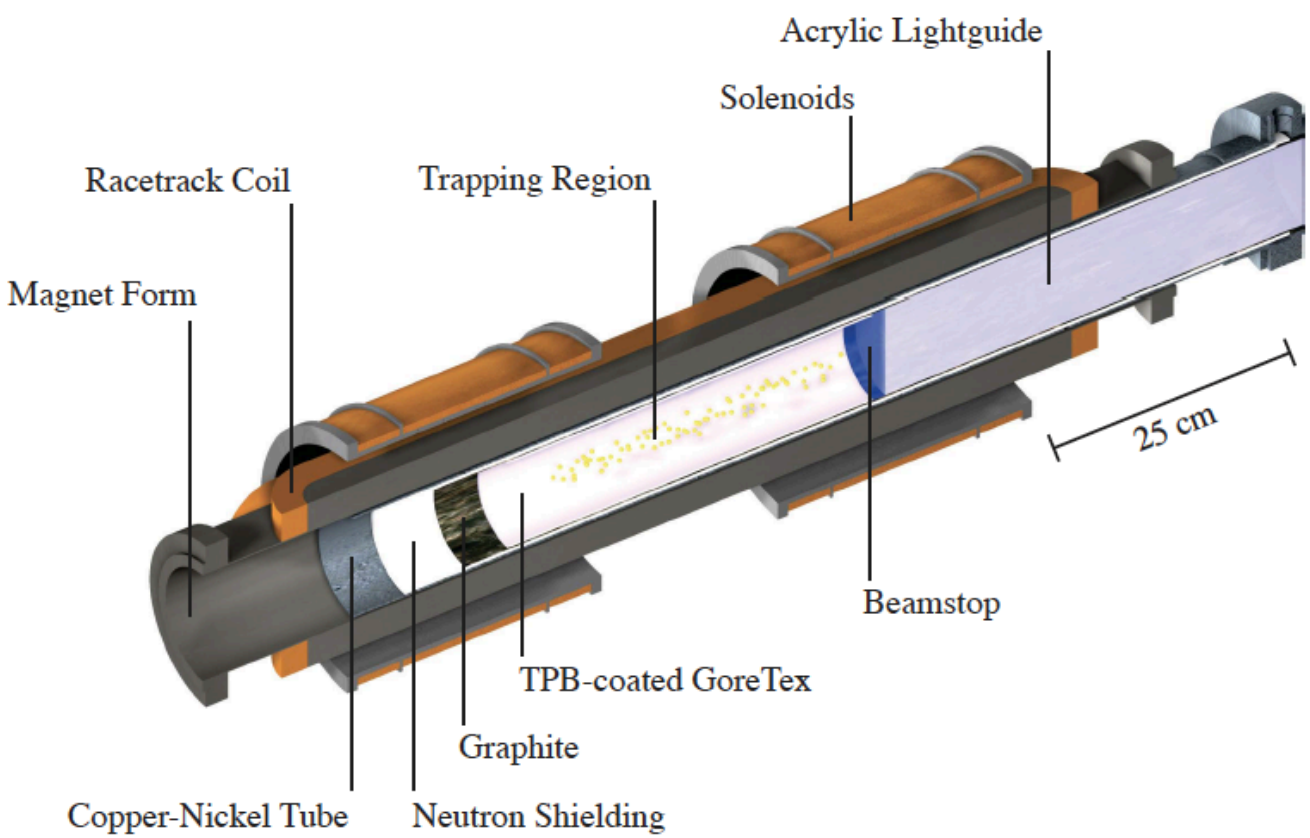
- Used to produce, store, and detect ultracold neutrons.
  - Production based on "superthermal effect": direct production of phonons by cold neutrons, allowing the neutrons to scatter to 100 neV-scale energies and be captured by magnetic fields or material bottles.
  - Can store the neutrons within the superfluid helium; neutrons cannot absorb on He-4.
  - Detection based on scintillation light.



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).

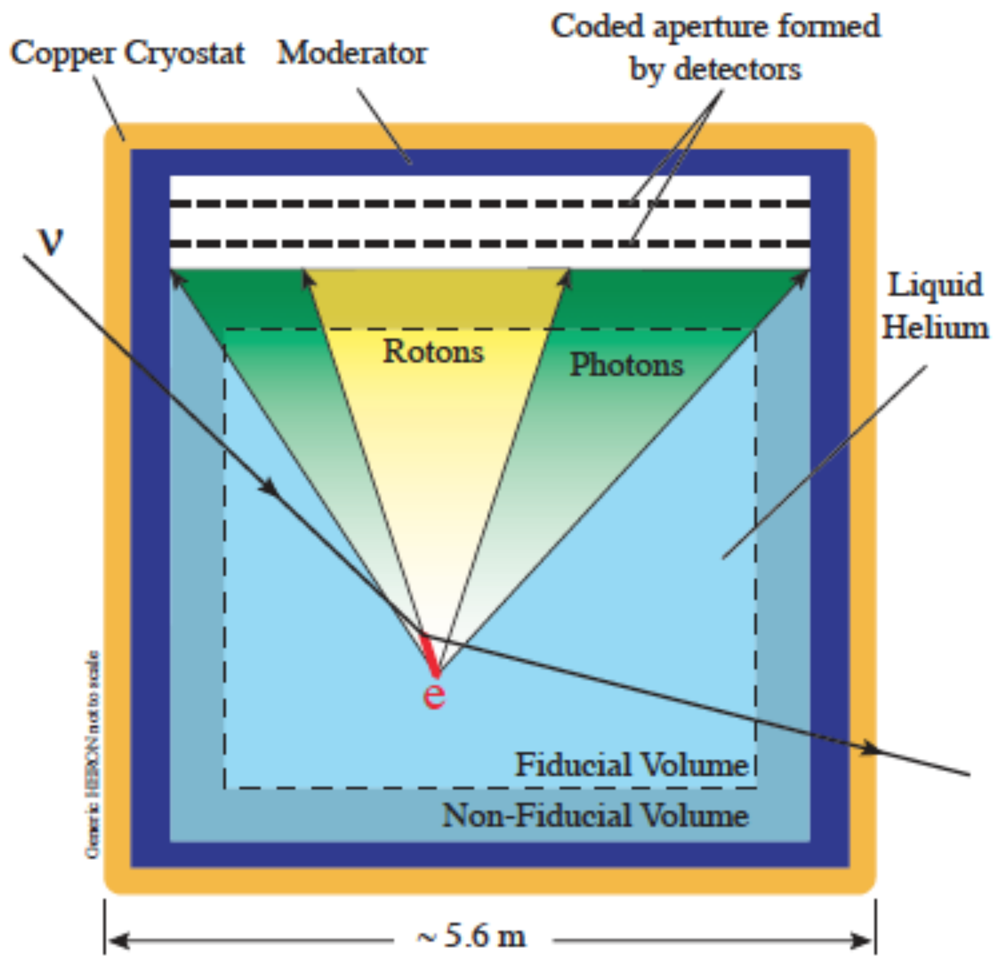
Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).



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.



Why Superfluid Helium for Low-mass Dark Matter Detection?

- Kinematic matching with light dark matter candidates.
  - Pull the energy depositions up in energy, to above threshold.
  - Gain access to more of the WIMP velocity distribution, for a given energy threshold.
  - New: access to extremely low mass dark matter through multi-excitation production, back-to-back jets (see K.Zurek talk, arXiv:1604.08206).
- Superfluid helium offers multiple signals to choose from, and to separate dark matter signal from backgrounds (both electron recoils and detector backgrounds).
  - Prompt light
  - Delayed triplet excimers
  - Charge
  - Heat (roton and photon quasiparticles)

Why Superfluid Helium?

- 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 (high Leff), so nuclear recoil scintillation signals should be relatively large.
- Negligible target cost
- 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 ER background below 14 eV.
- Impurities easily removed, and will fall out of the superfluid.

The importance of discrimination

It is highly advantageous to have at least 2 signal channels with different ER and NR response.

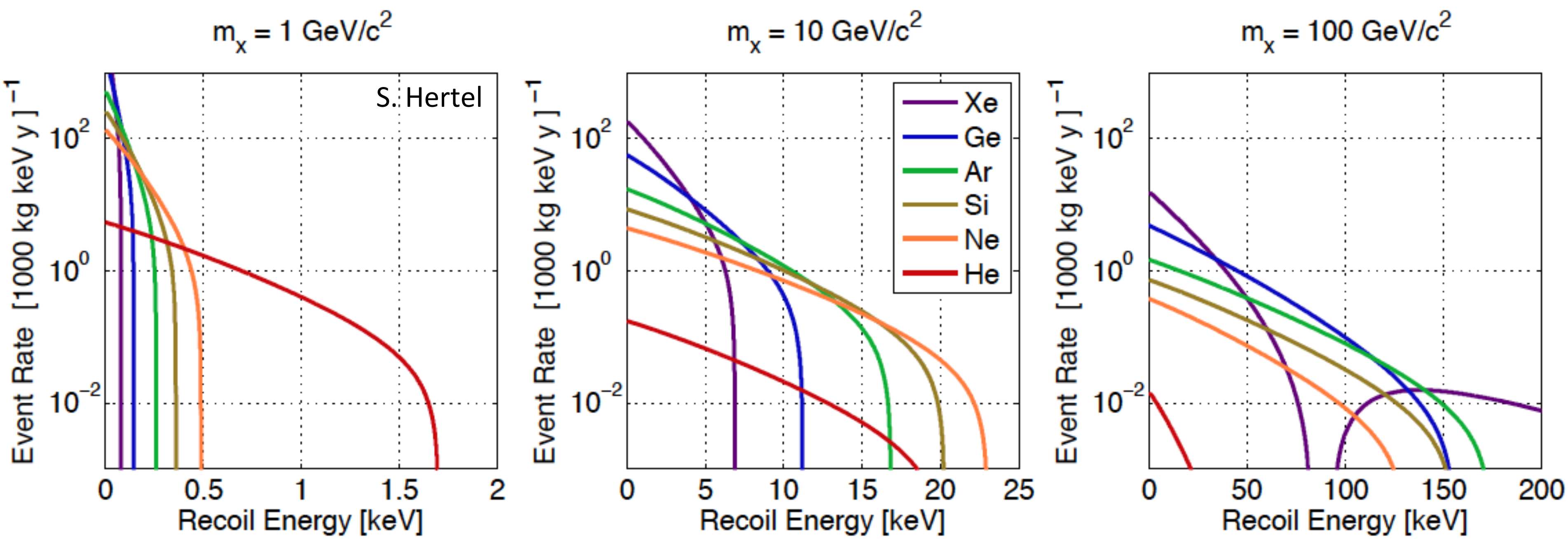
This is to allow nuclear recoil/electron recoil discrimination, both to reject ER backgrounds, but also to have a separate handle on NR signal in the face of unexpected backgrounds. In real experiments, discrimination is crucial, as you can see from the history of the field.

ER/NR discrimination is also critical for discovery of dark matter interactions.

The concepts presented here all use multiple signal channels to allow ER/NR discrimination, while maintaining excellent signal strength.

Helium-4 Nuclei: A Natural Match for Light Dark Matter Detection

Lose overall recoil rate as A^2, but gain rate above some energy threshold

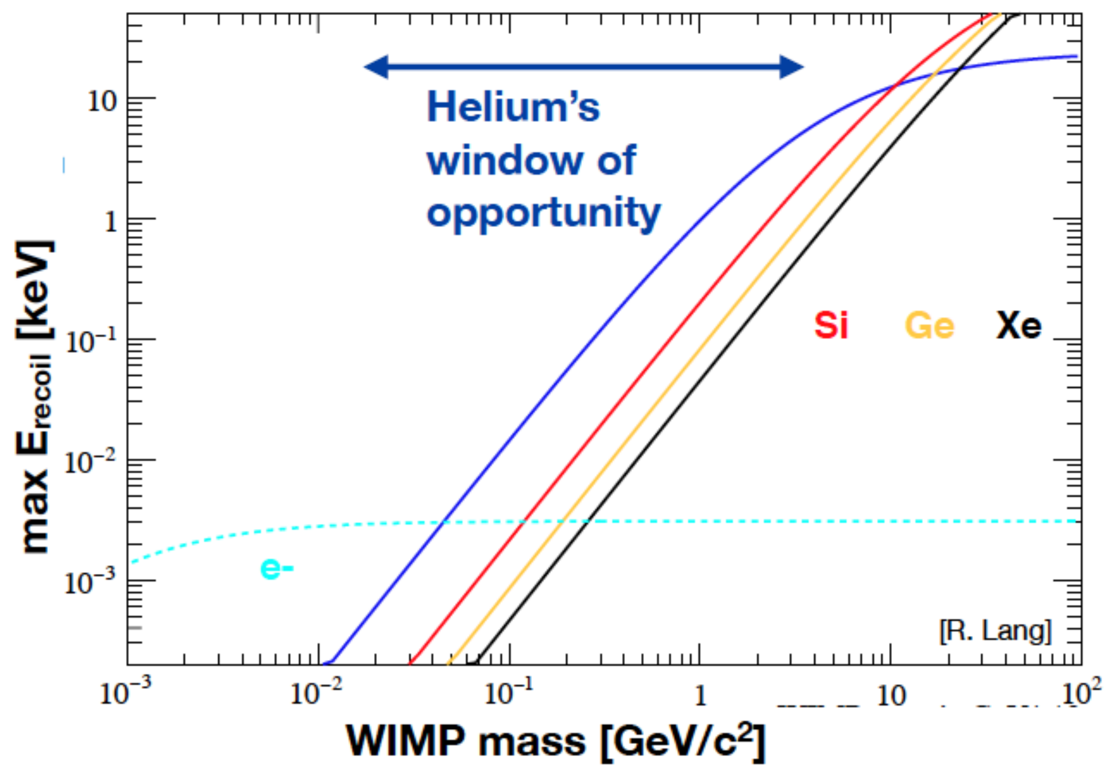


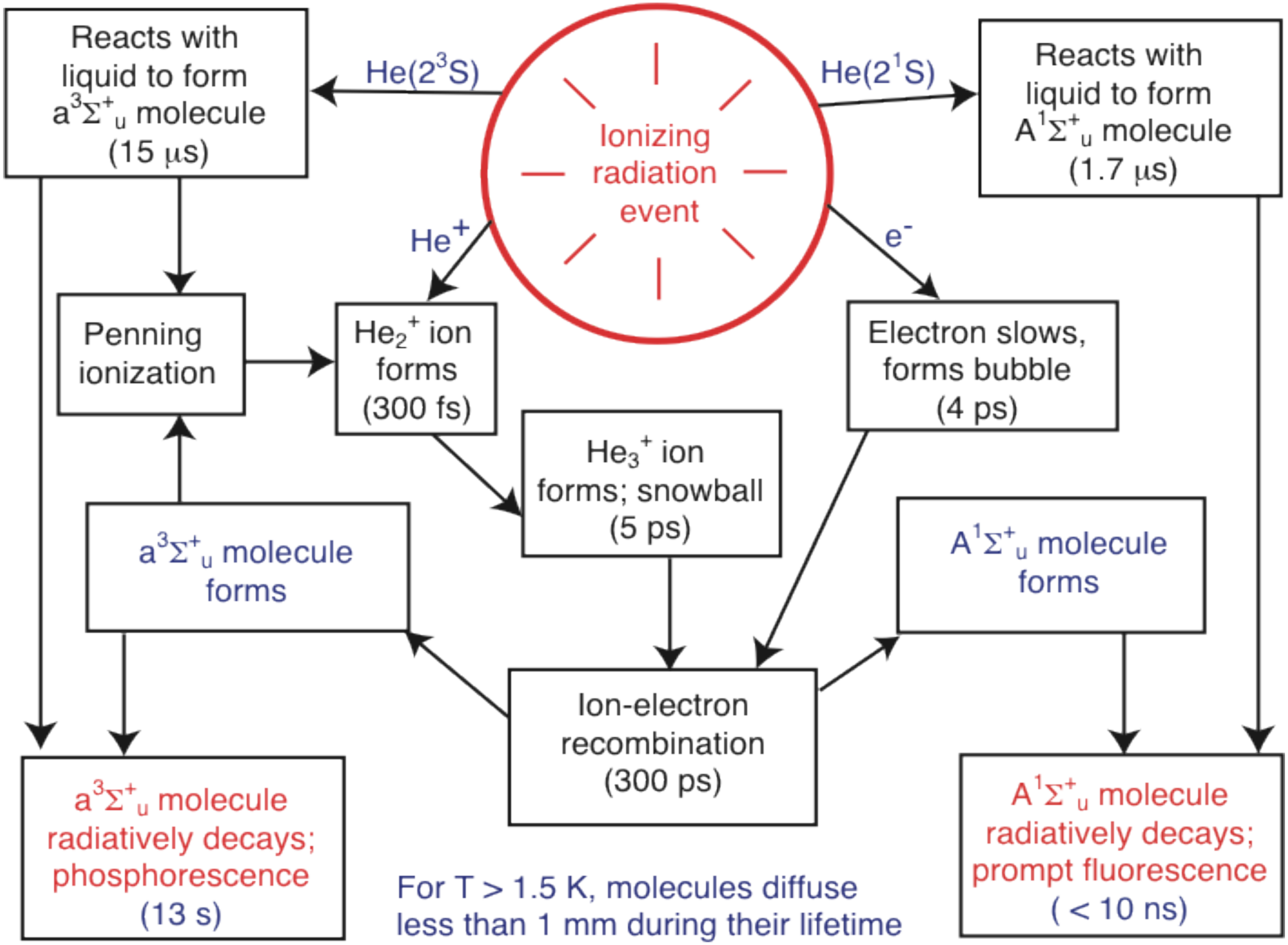
Helium-4 Nuclei: A Natural Match for Light Dark Matter Detection

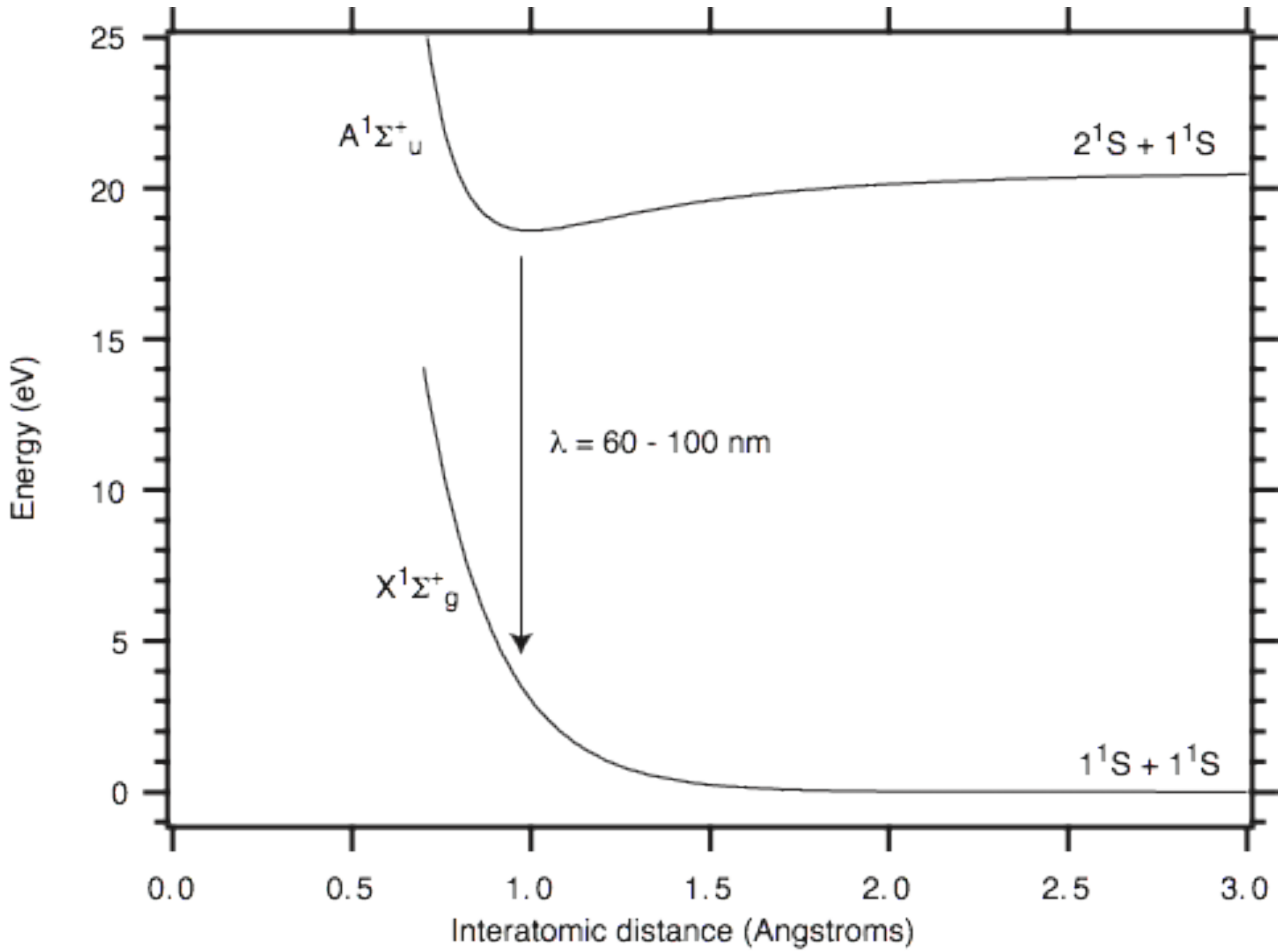
Another view: maximum recoil energy for various targets, as a function of WIMP mass.

$$\max E_{recoil} = KE_x \left(\frac{4\, m_t\, m_x}{(m_t + m_x)^2} \right)$$

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




Reacts with liquid to form $a^3\Sigma^+_u$ molecule (15 μs)
He(2^3S)
Ionizing radiation event
He(2^1S)
Reacts with liquid to form $A^1\Sigma^+_u$ molecule (1.7 μs)
He^+
e^-
Penning ionization
He_2^+ ion forms (300 fs)
Electron slows, forms bubble (4 ps)
He_3^+ ion forms; snowball (5 ps)
$a^3\Sigma^+_u$ molecule forms
$A^1\Sigma^+_u$ molecule forms
Ion-electron recombination (300 ps)
$a^3\Sigma^+_u$ molecule radiatively decays; phosphorescence (13 s)
For T > 1.5 K, molecules diffuse less than 1 mm during their lifetime
$A^1\Sigma^+_u$ molecule radiatively decays; prompt fluorescence (< 10 ns)



25
20
15
10
5
0
Energy (eV)
A1Σ+u
2¹S + 1¹S
λ = 60 - 100 nm
X1Σ+g
1¹S + 1¹S
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Interatomic distance (Angstroms)

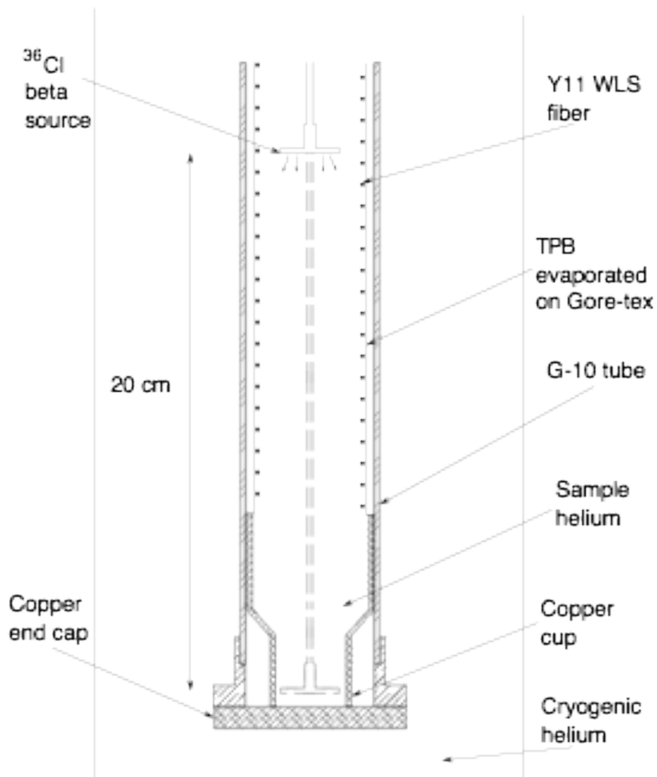
PHYSICAL REVIEW A VOLUME 59, NUMBER 1 JANUARY 1999

Radiative decay of the metastable $He_2(a\,^3\Sigma_u^+)$ molecule in liquid helium

D. N. McKinsey, C. R. Brome, J. S. Butterworth, S. N. Dzhosyuk, P. R. Huffman, C. E. H. Mattoni, and J. M. Doyle
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

R. Golub and K. Habicht
Hahn-Meitner Institut, Berlin-Wannsee, Germany

(Received 27 July 1998)



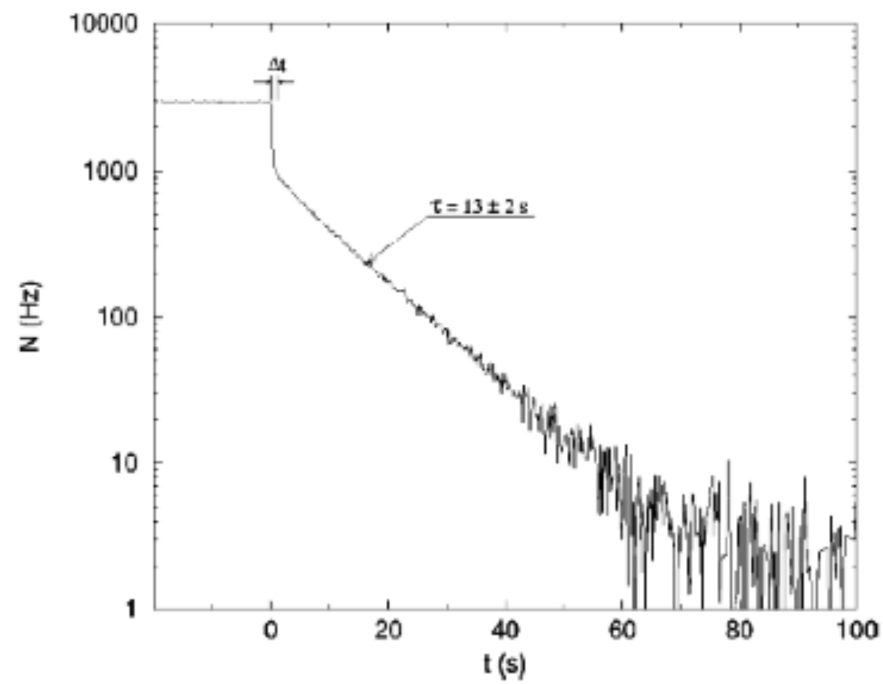
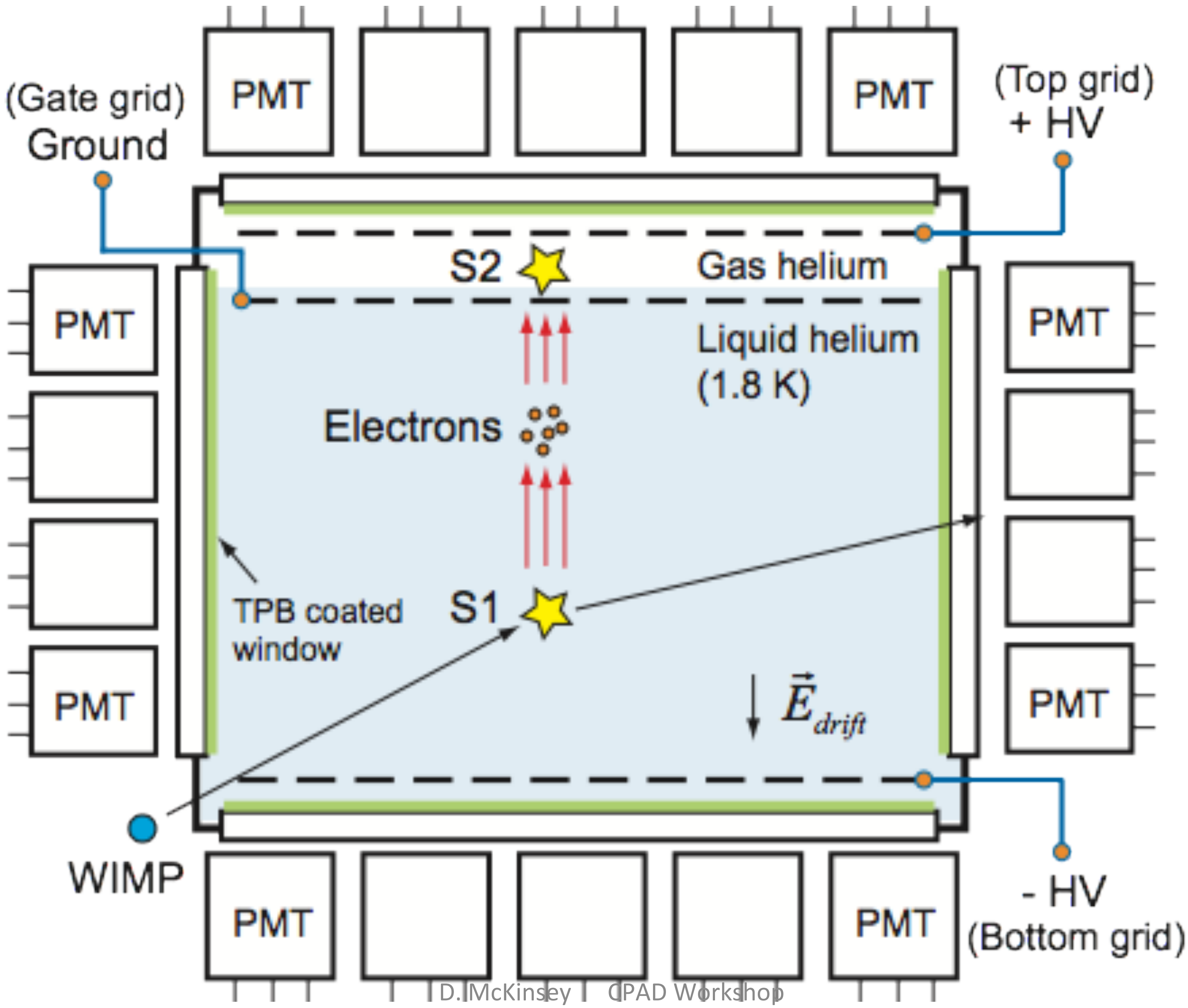


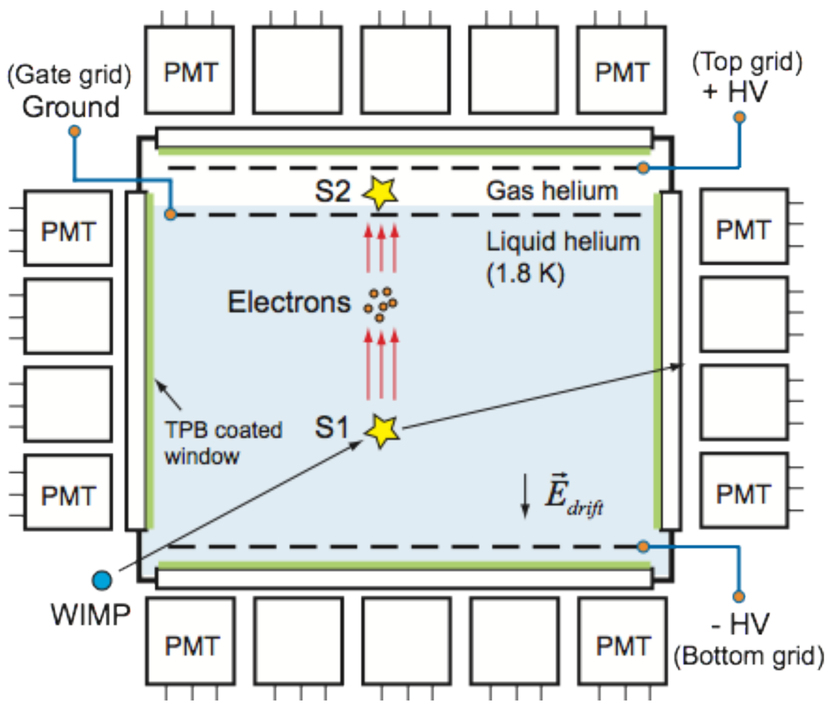
FIG. 2. Count rate N of detected $He_2(a\,^3\Sigma_u^+)$ decays versus time. A ^{36}Cl β source is placed in the center of the detection region and then removed in a time $\Delta t < 1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate τ of 13 ± 2 s.

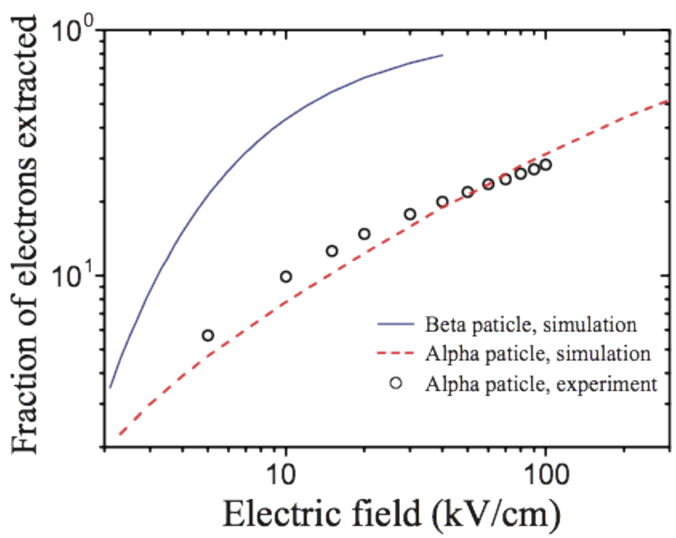
Light WIMP Detector Concept #1: Two-Phase Helium

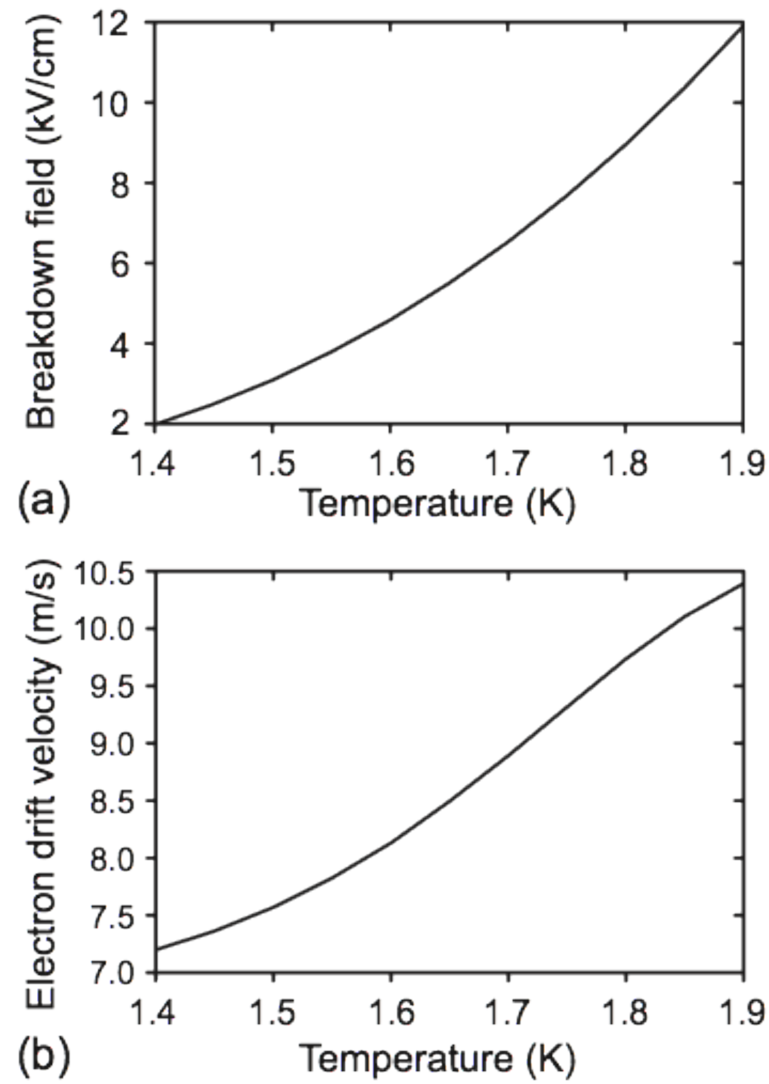
Energies down to ~ 1 keV



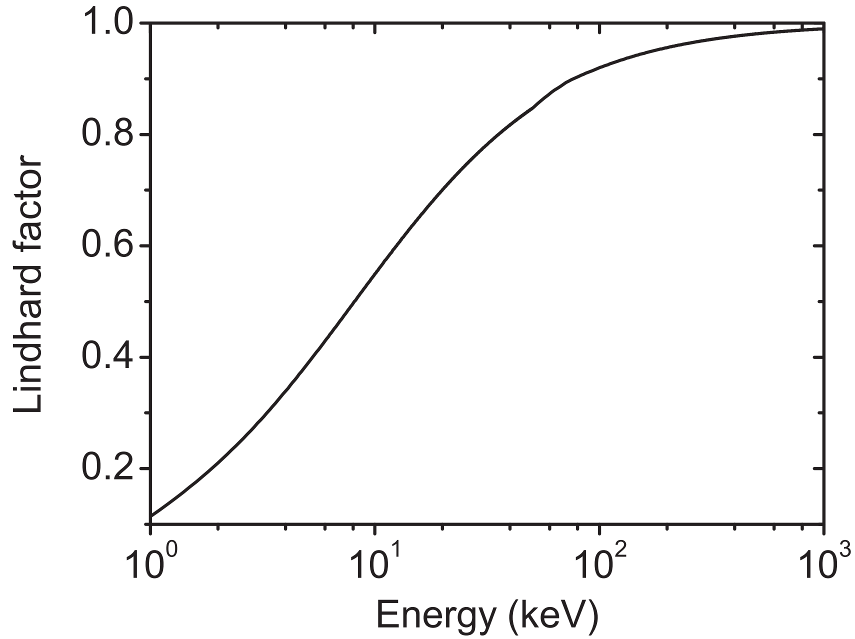
A two-phase helium detector; salient properties







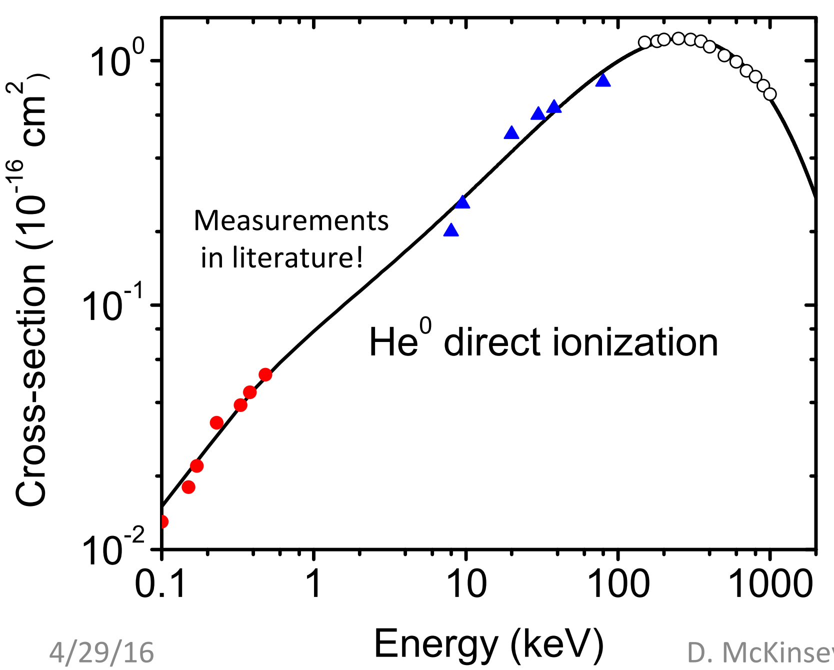
Alpha data: A.N. Gerritsen, Physica 14, 407 (1948).

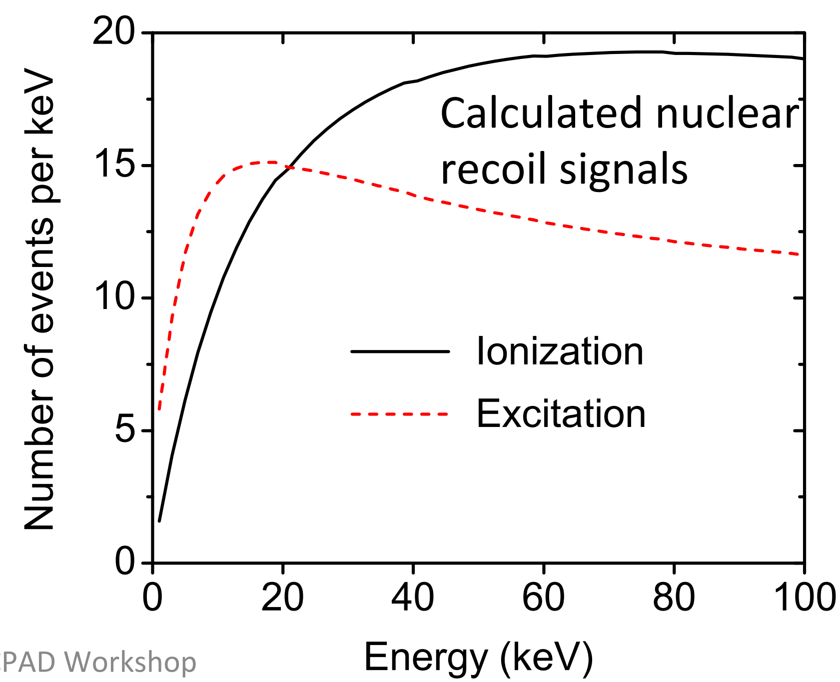


Liquid helium-4 predicted response (Guo and McKinsey, arXiv:1302.0534, Phys. Rev. D 87, 115001 (2013).)

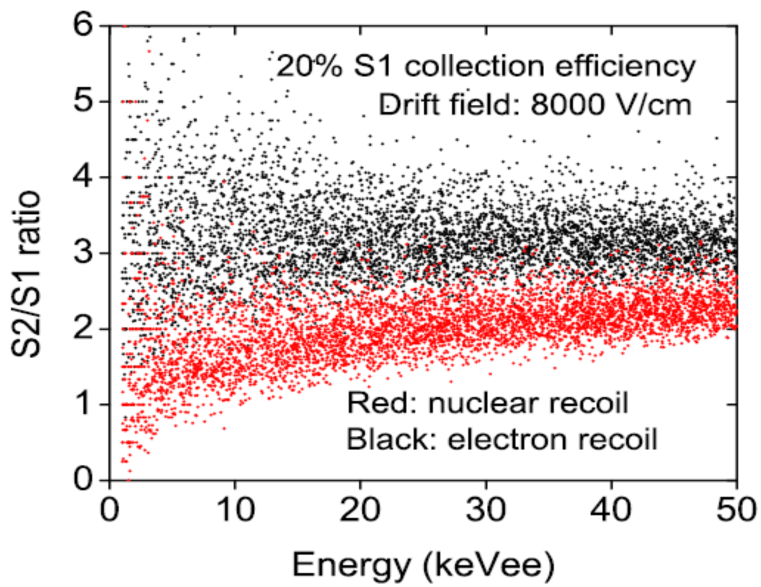
Liquid helium has lower electron scintillation yield for electron recoils (19 photons/keVee)

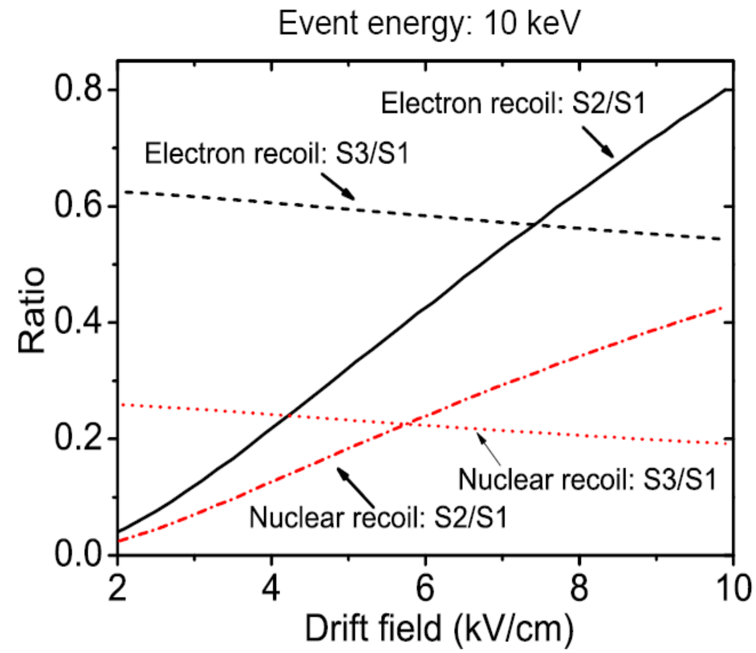
But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity

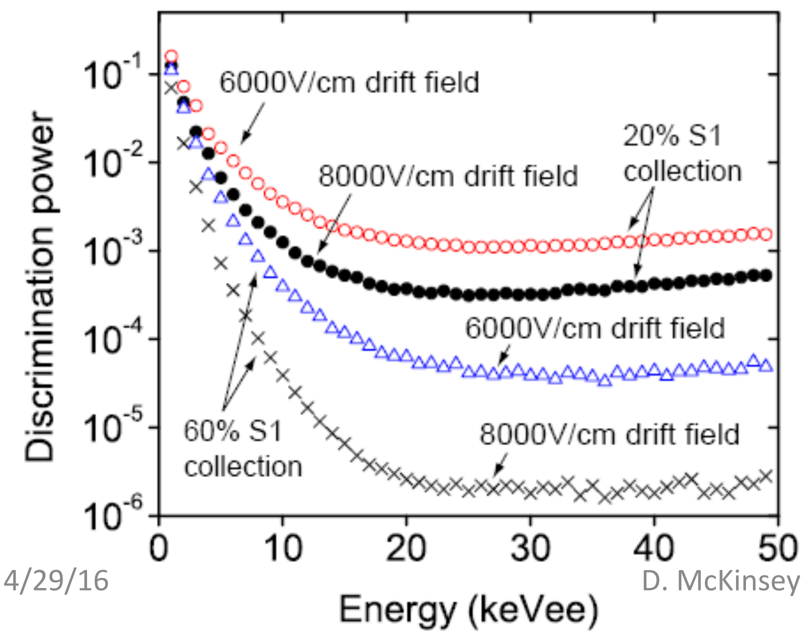


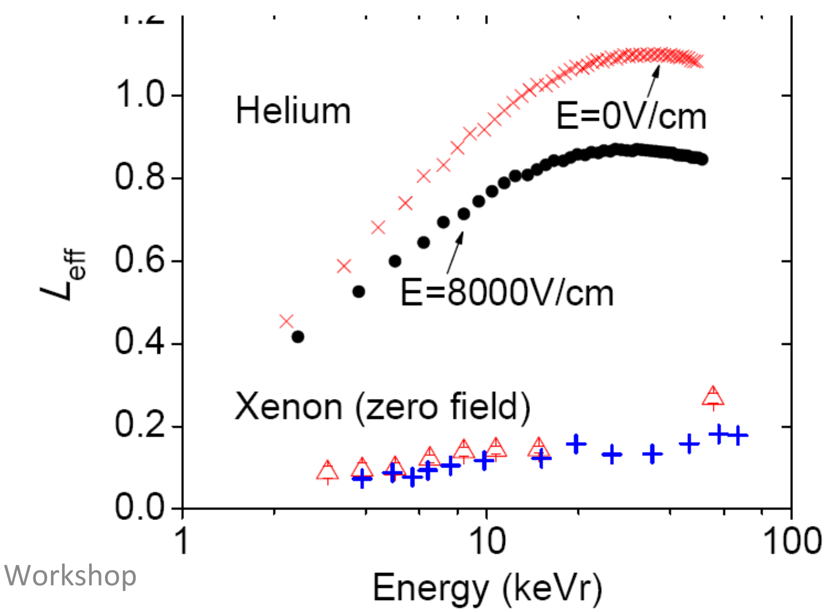


Predicted nuclear recoil discrimination and signal strengths in liquid helium









How to detect triplet helium molecules?

Detect with TES array immersed in superfluid, and let the molecules travel ballistically to be detected (v ~ 1-10 m/s)

- < 1 eV resolution quite possible
- Each molecule has ~ 18 eV of internal energy, which will mostly be released as heat, electronic excitation in TES.
- Note that the same bolometer array could detect both light and triplet excimers!
- Now has been demonstrated experimentally (see S. Hertel talk).

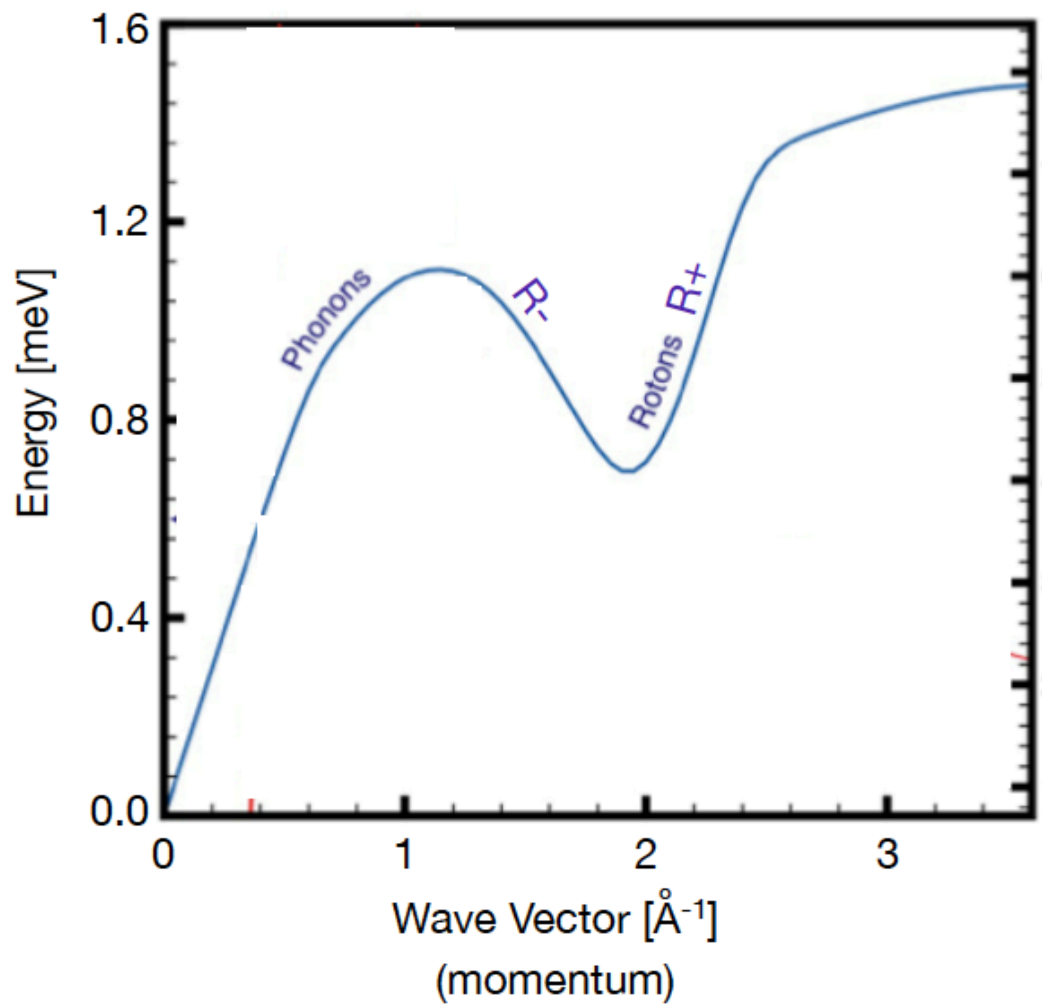
phonons and rotons

superfluid supports vibration
(some non-intuitive)

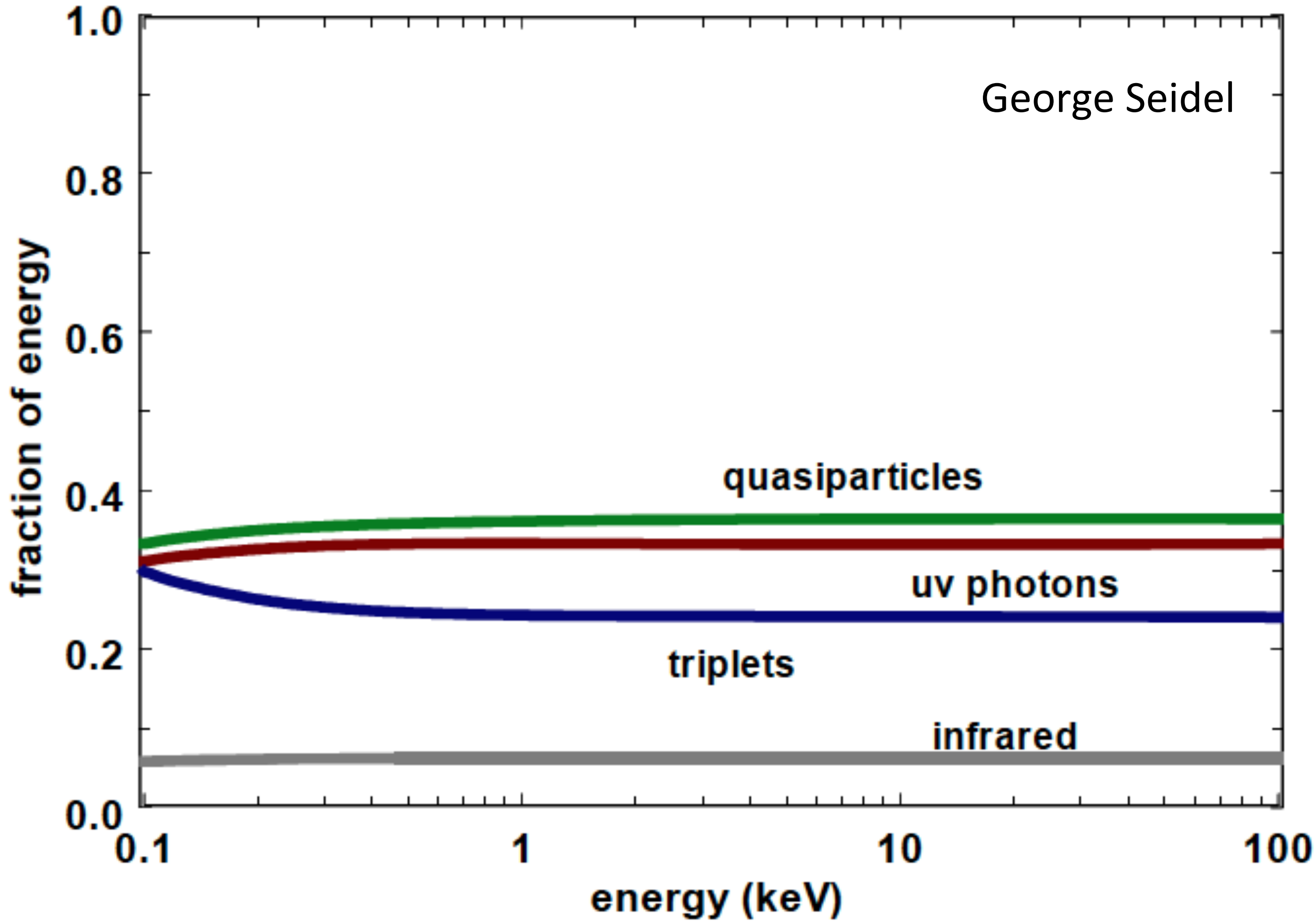
ballistic, ~150m/s

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

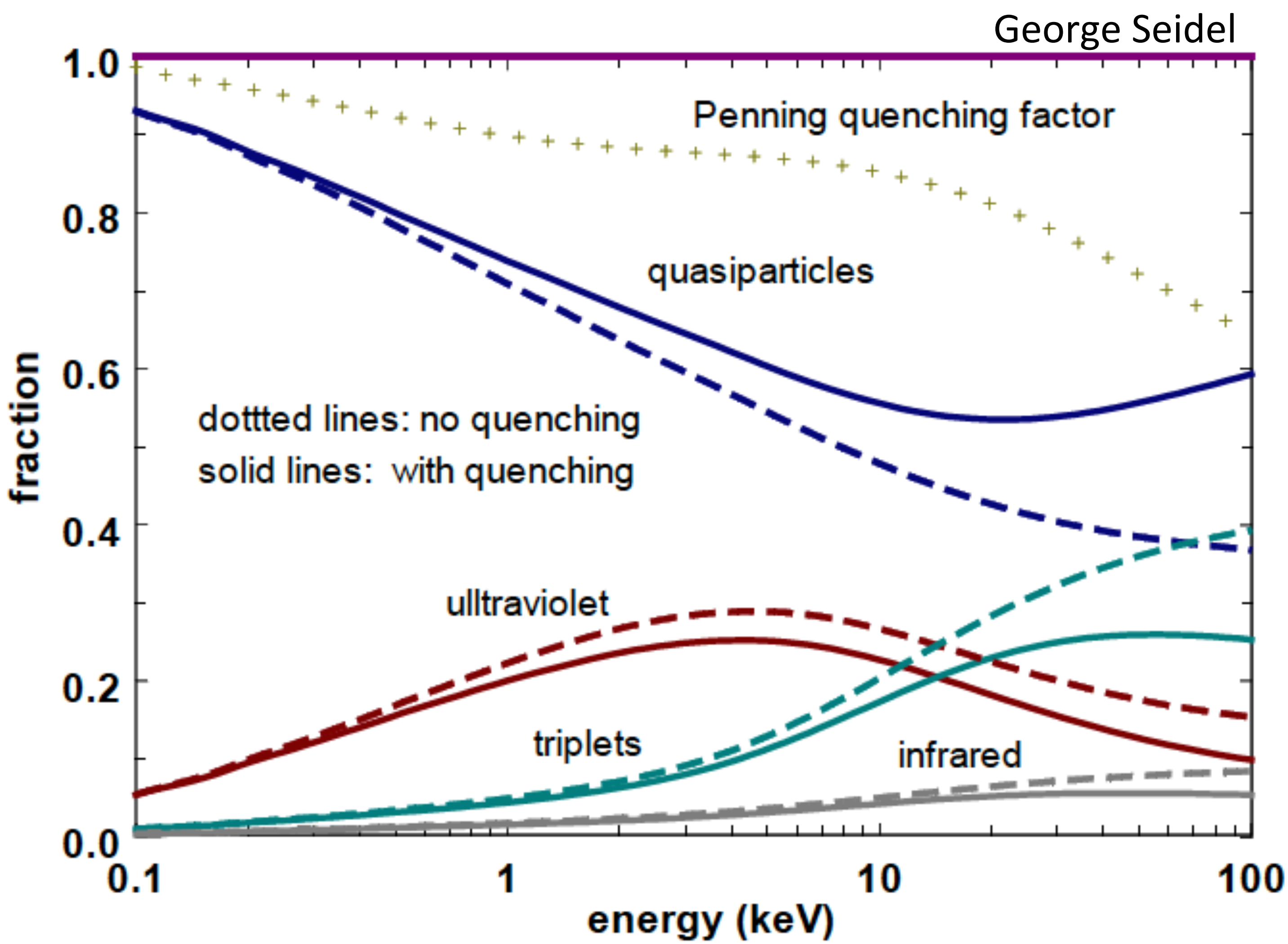
few downconversion pathways



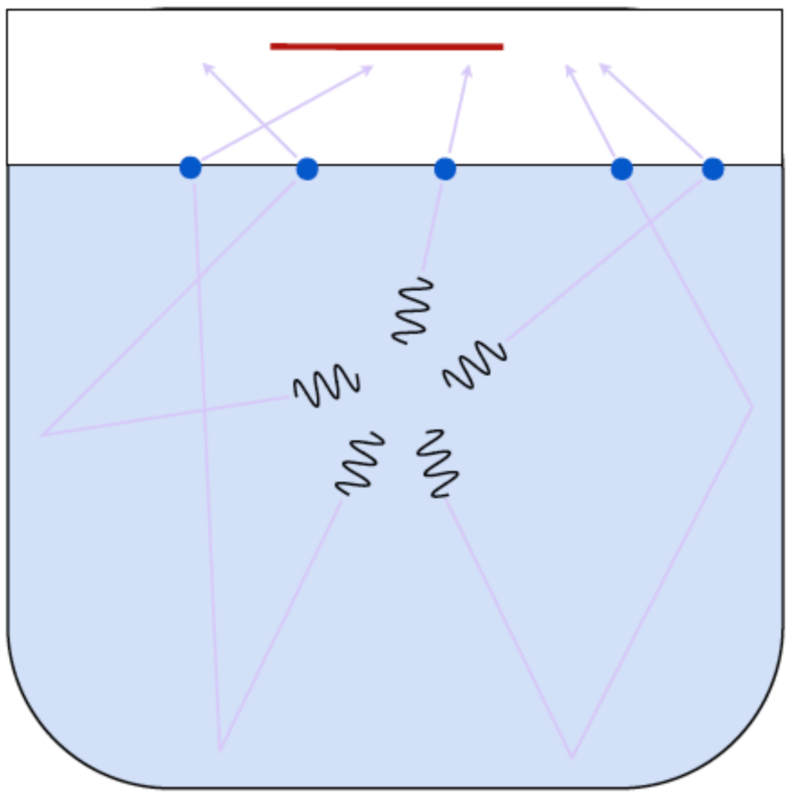
Signal partitioning – electrons recoils



Signal partitioning – nuclear recoils



Athermal Evaporation – Demonstrated by HERON R&D



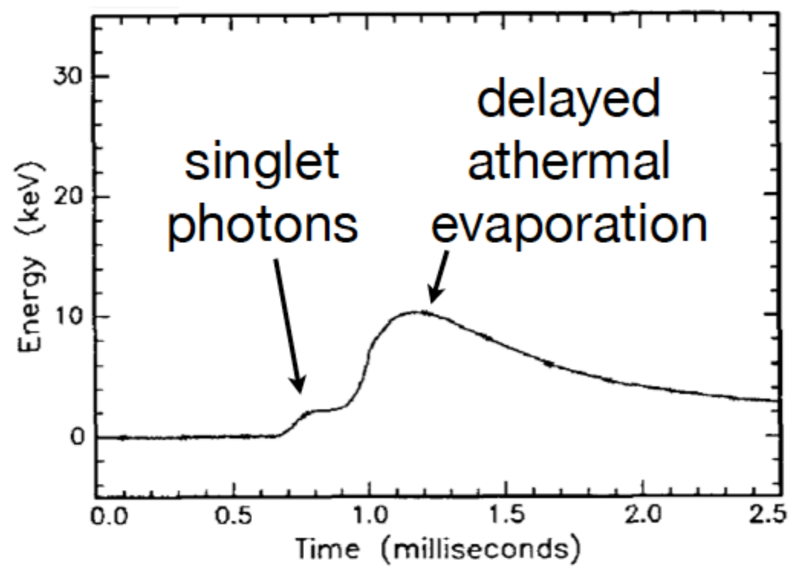


Fig. 2. (a) The calorimeter response (average of about 100 events) when an α particle is stopped in liquid helium. The collimated α tracks are (a) parallel and (b) perpendicular to the liquid surface.

Concept #2

Signal channels:

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

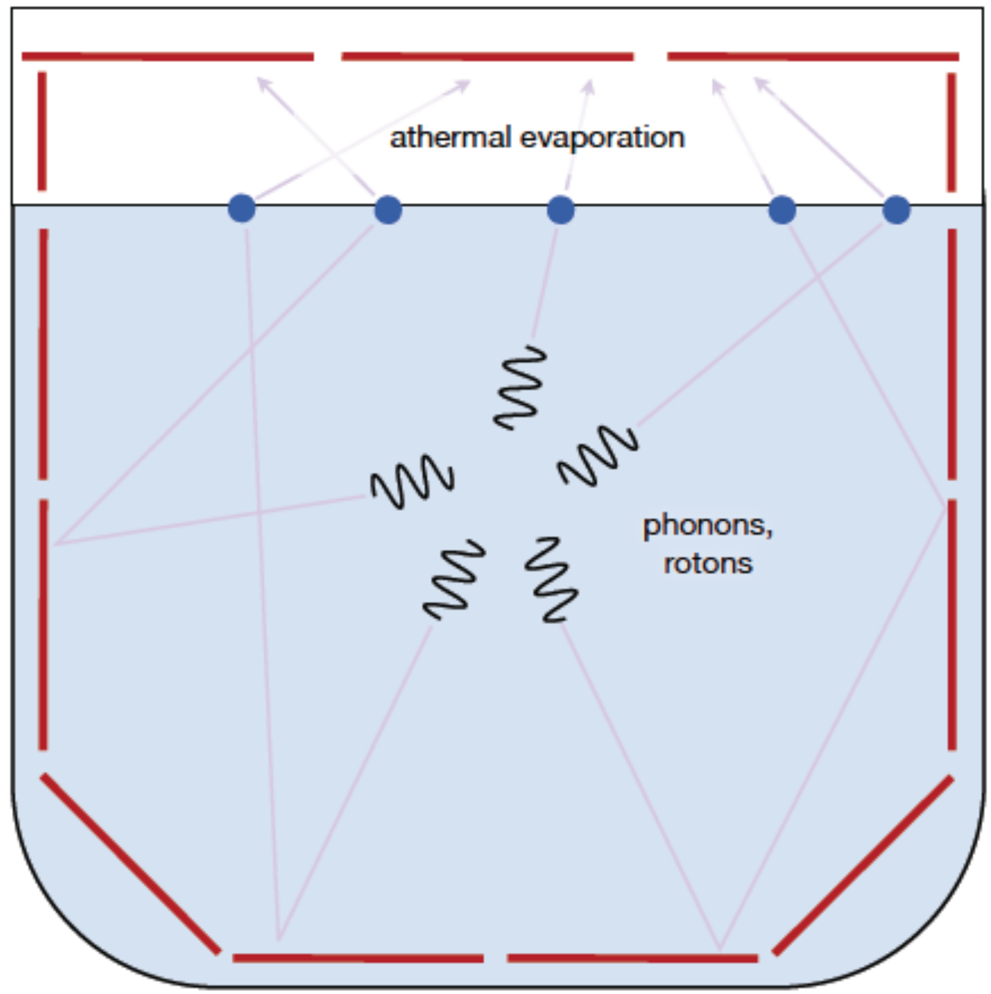
No drift field, and no S2 signal

- no worry of few-electron background
- Position reconstruction via signal hit patterns
- (Though could apply drift field to detect single electrons via roton/phonon production.)

Best for energies down to 300 eV.

Discrimination using signal ratios

Position reconstruction using signal hit patterns



Concept #3

Signal channels:

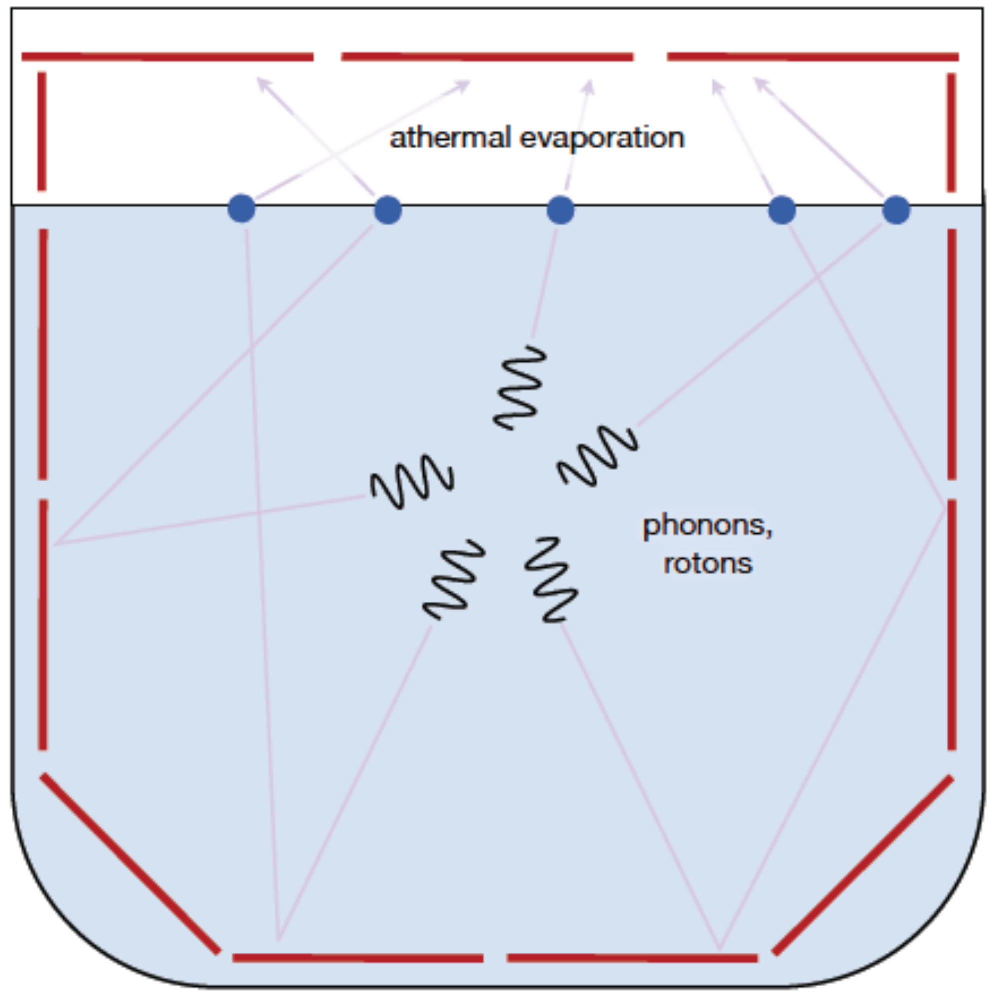
Phonons

Rotons

Energies down to ~ few meV !!

Discrimination using roton/phonon signal ratios likely. Electron recoils, detector effects, nuclear recoils likely create different roton/ phonon distributions.

Position reconstruction using signal hit patterns



Summary

Highest energies: Use charge and light?
Medium energies: Light and heat looks very promising.
Low energies: Use phonons and rotons, likely still have discrimination.

Multiple advantages, this looks like an ideal technology for low-mass dark matter detection.