Light WIMP Detection with Liquid Helium

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Light Dark Matter Workshop
University of Michigan
April 16, 2013

Light WIMP Detector Kinematic Figure of Merit

It is more difficult for heavy targets to be sensitive to light WIMPs, since for typical energy thresholds they are only sensitive to a small part of the WIMP velocity distribution. The lower limit of the WIMP-target reduced mass at which a detector can be sensitive is given by

$r_{limit} = 1/v_{esc} * \text{sqrt}\{E_t M_T/2\}$

where v_{esc} is the Galactic escape velocity of 544 km/s, E_t is the energy threshold, and M_T is the mass of the target nucleus. In the limit of small dark matter mass, the reduced mass is the mass of the dark matter particle.

So for reaching sensitivity to small dark matter masses, the kinematic figure of merit is the product of the energy threshold and the target mass, which should be minimized.

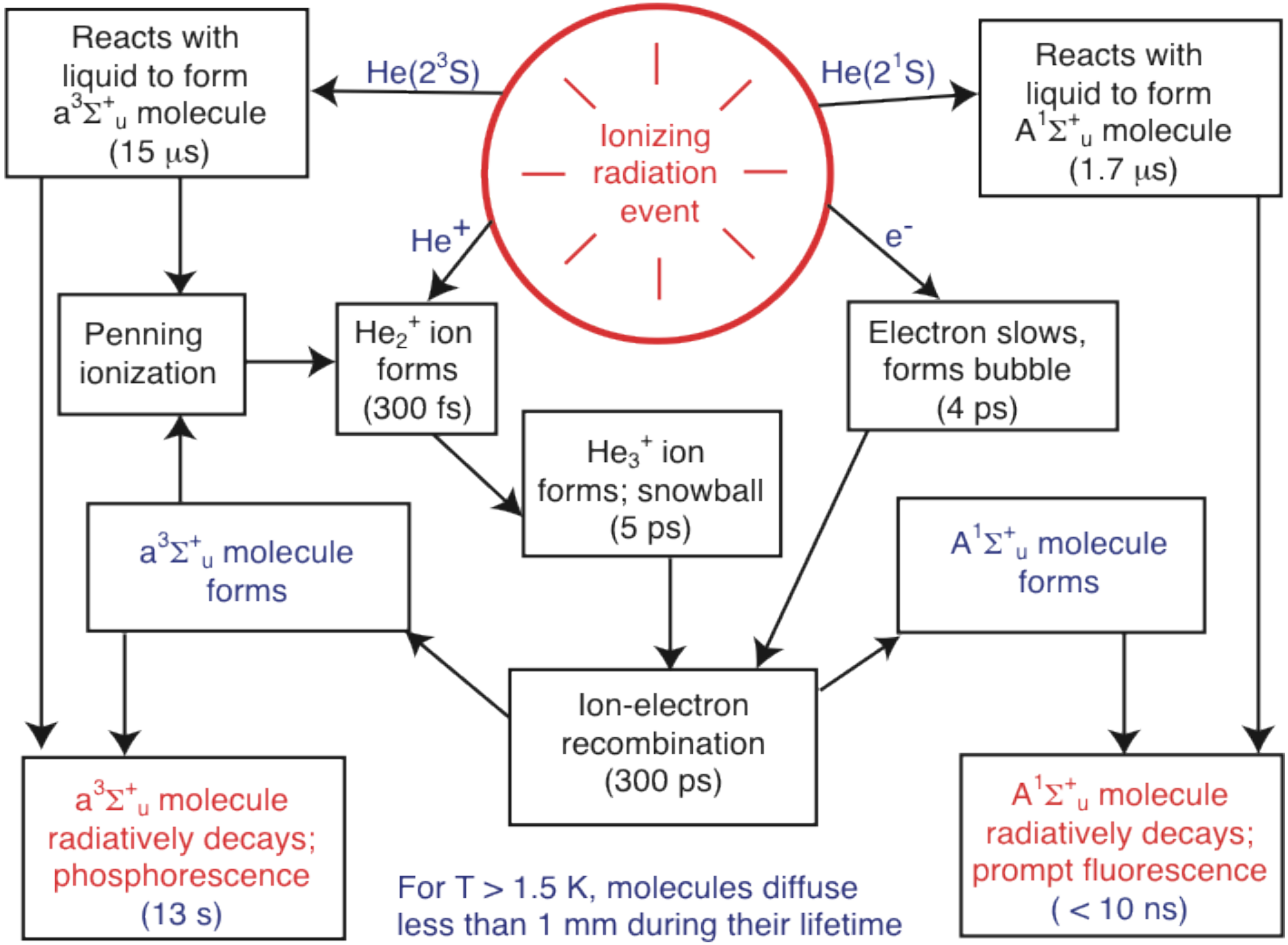
Liquified Noble Gases: Basic Properties

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

Basic philosophy of liquid helium light WIMP experiment (see Guo and McKinsey, arXiv:1302:0534)

- Use multiple signal channels. There are many to choose from in liquid helium. Signal ratios and timing give discrimination power.
  - Prompt scintillation light (S1)
  - Charge (S2)
  - Triplet excimers (S3)
  - Rotons
  - Phonons
- Time projection chamber readout
  - Reject surface events through TPC position reconstruction
  - Reject multiple scatter events with readout timing, position reconstruction
- Include an active veto surrounding the detector
  - Will help to understand and reject gamma and neutron backgrounds
  - Many options (organic scintillator, LNe, LAr, LXe, …)


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)
$A^1\Sigma^+_u$ molecule radiatively decays; prompt fluorescence (< 10 ns)
For T > 1.5 K, molecules diffuse less than 1 mm during their lifetime

Superfluid helium as a detector material

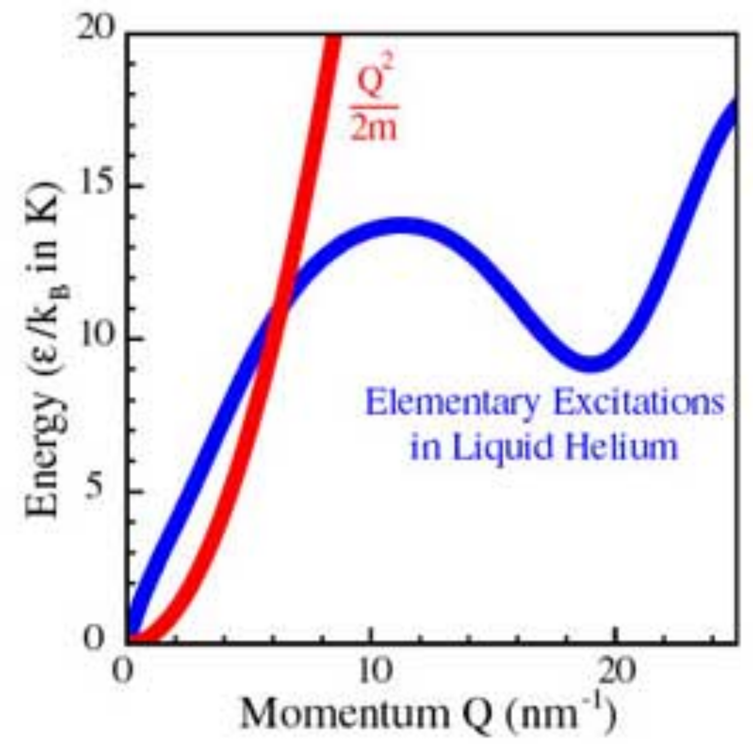
- Used to produce, store, and detect ultracold neutrons. Detection based on scintillation light (S1)
  - Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).
  - Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).

- 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).

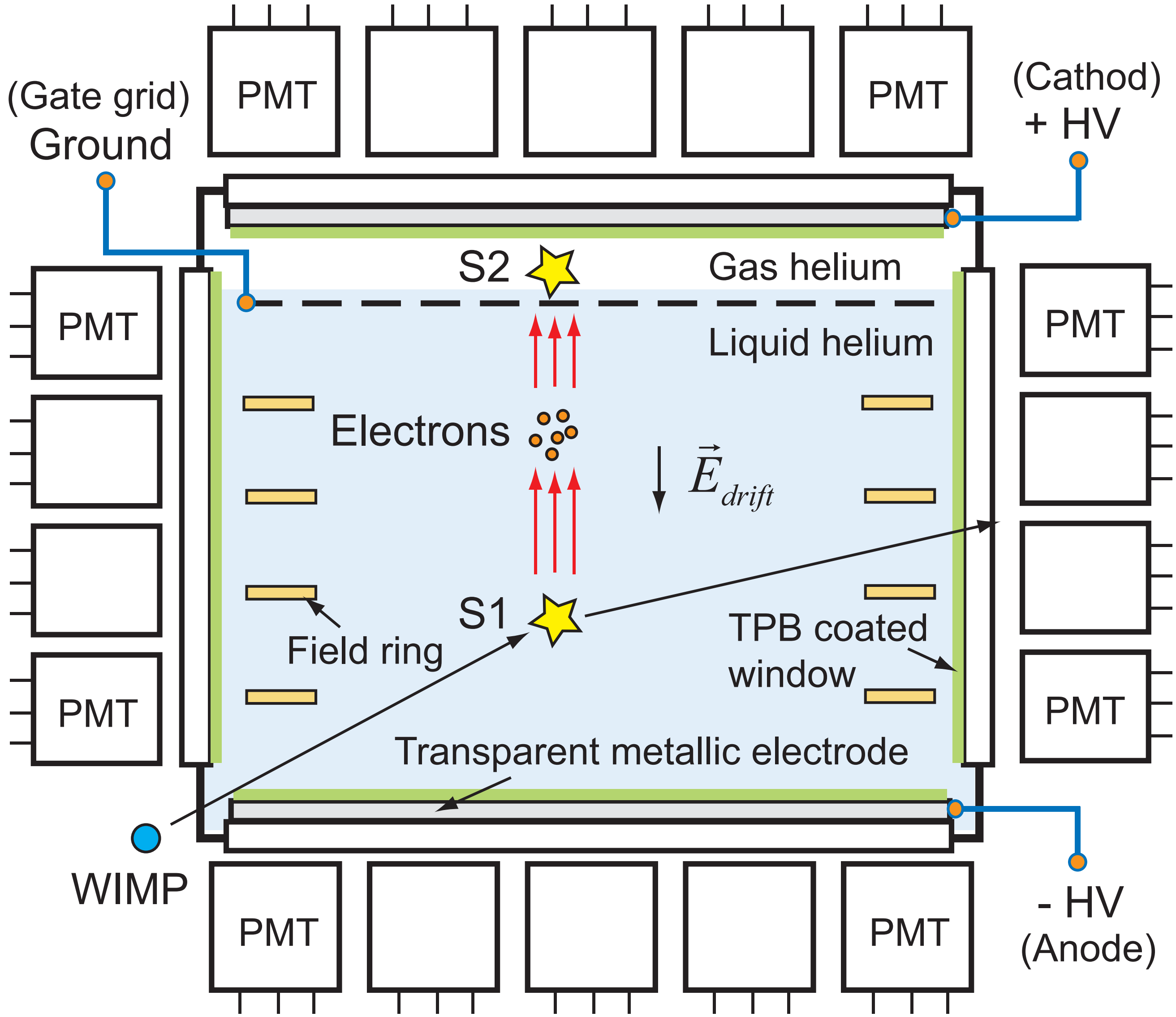
- Proposed for WIMP detection with superfluid He-3 at 100 microK (MACHe3): F. Mayet et al, Phys. Lett. **B 538**, 257C265 (2002)

Superfluid helium for ultracold neutrons

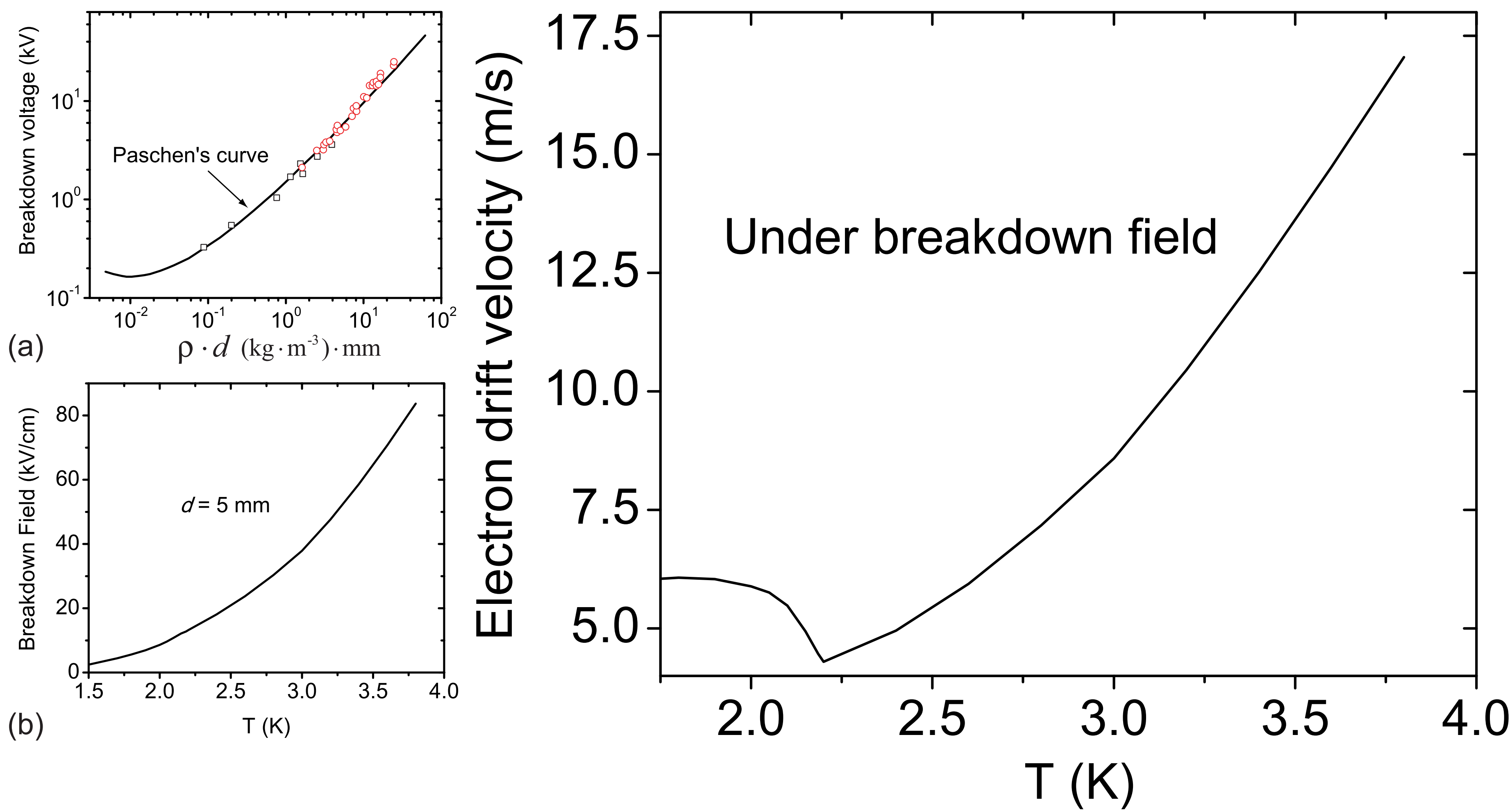
- Superfluid helium used to produce and store ultracold neutrons.
- Ultracold neutrons detected through helium scintillation.
- Very high electric fields achieved, ~ 75 kV/cm, for neutron edm projects.



Light WIMP Detector Concept



Electron drift speed in two-phase He



How to detect the charge signal?

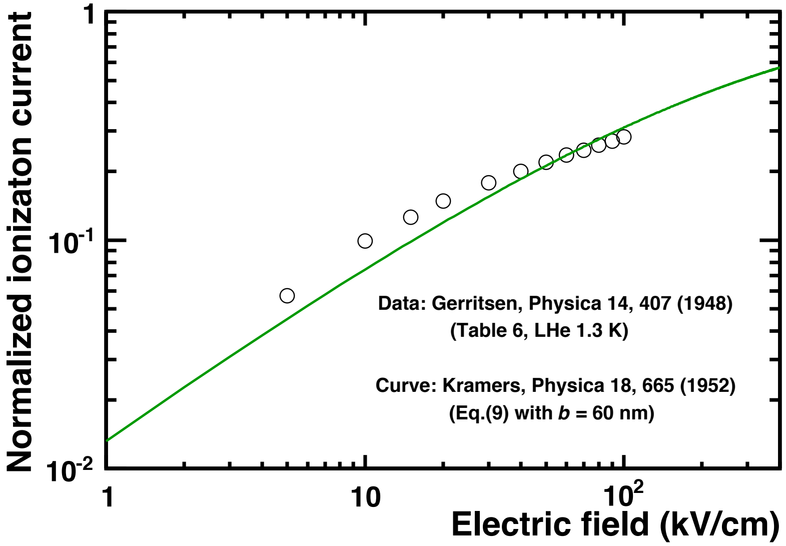
Many options:

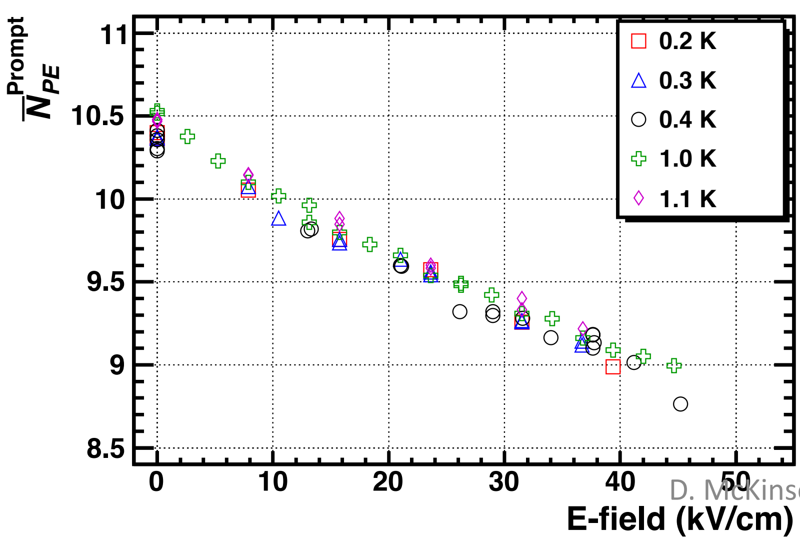
- Proportional scintillation and PMTs (like in 2-phase Xe, Ar detectors)
- Gas Electron Multipliers (GEMs) or Thick GEMS, detect light produced in avalanche.
- Micromegas, detect avalanche light.
- Thin wires in liquid helium. This should generate electroluminescence at fields ~1-10 MV/cm near wire, and is known to happen in LAr and LXe.
- Roton emission by drifting electrons (should be very effective at low helium temperature, analogous to Luke phonons in CDMS).

Charge will drift at ~ 1 cm/ms velocities. Slower than LAr/LXe, but pileup manageable for low background rates.

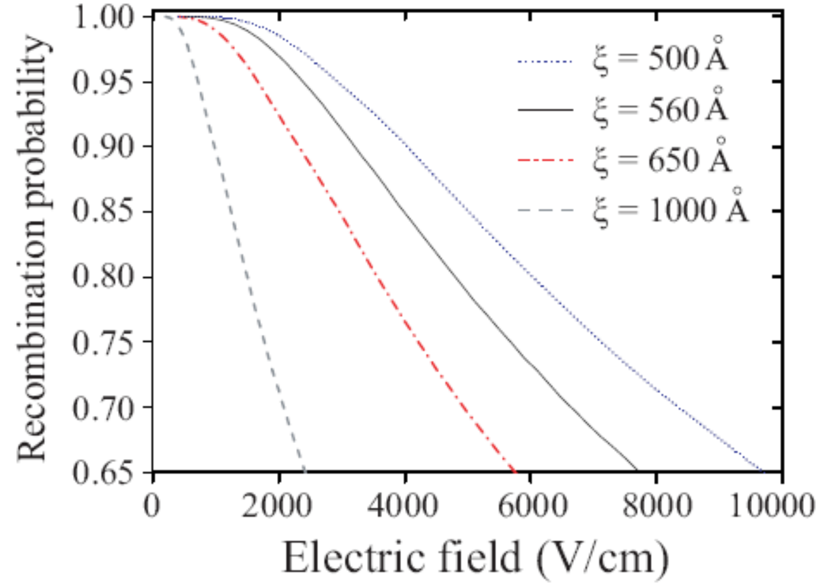
Helium scintillation vs. electric field

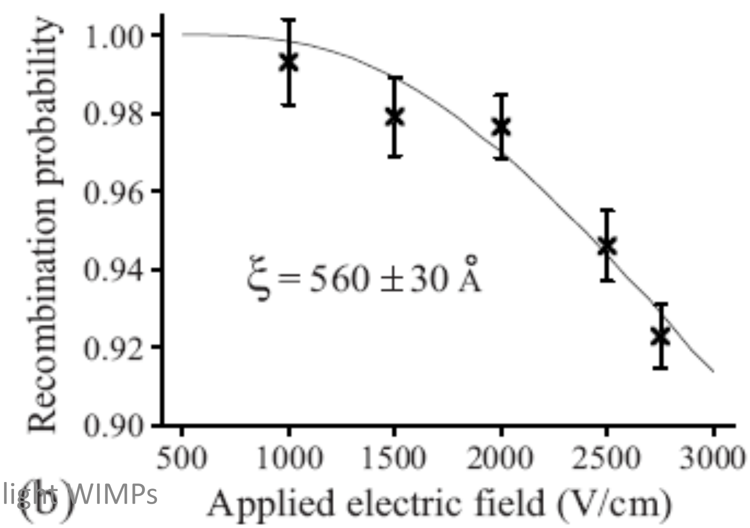
Alpha scintillation yield vs. applied field, T. Ito et al, 1110.0570

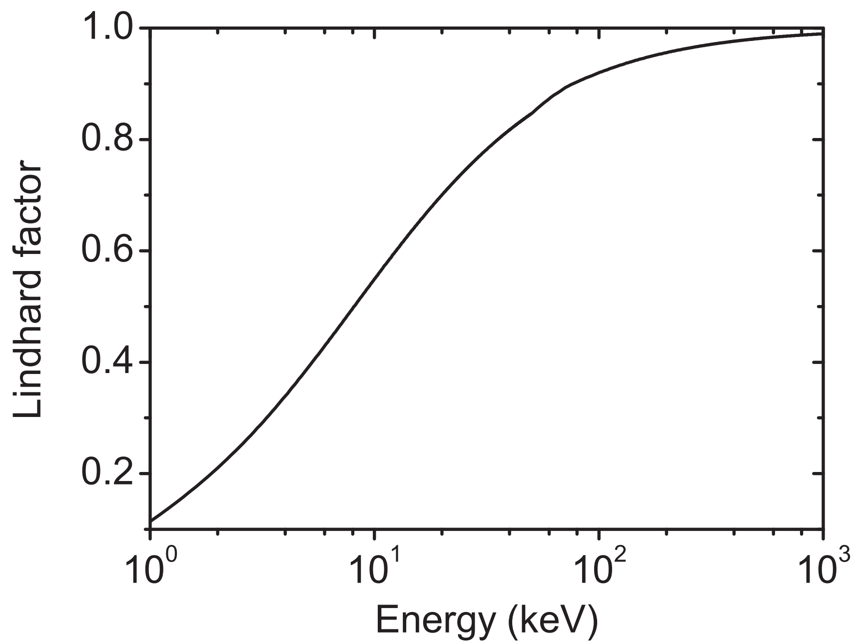




Beta scintillation field quenching: W. Guo et al, JINST 7, P01002 (2012)



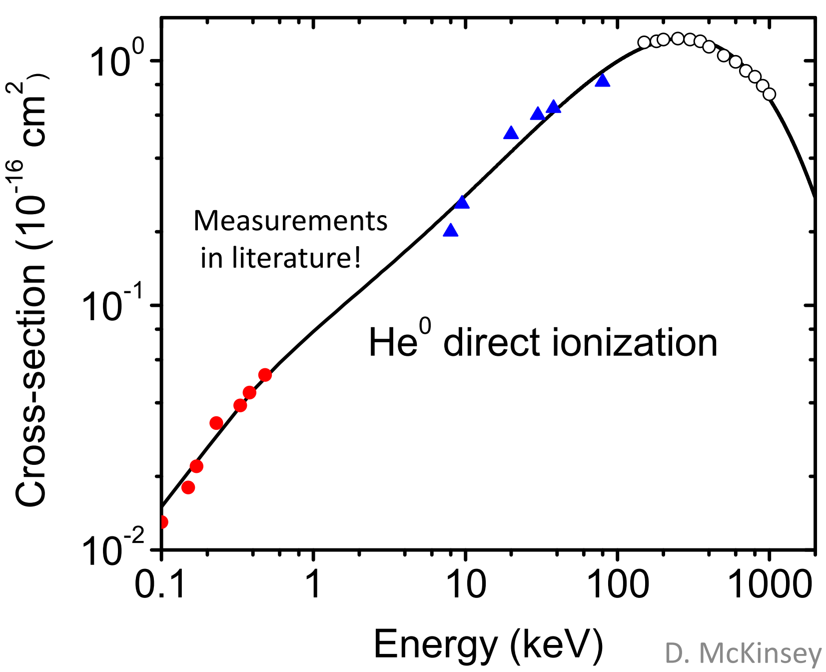


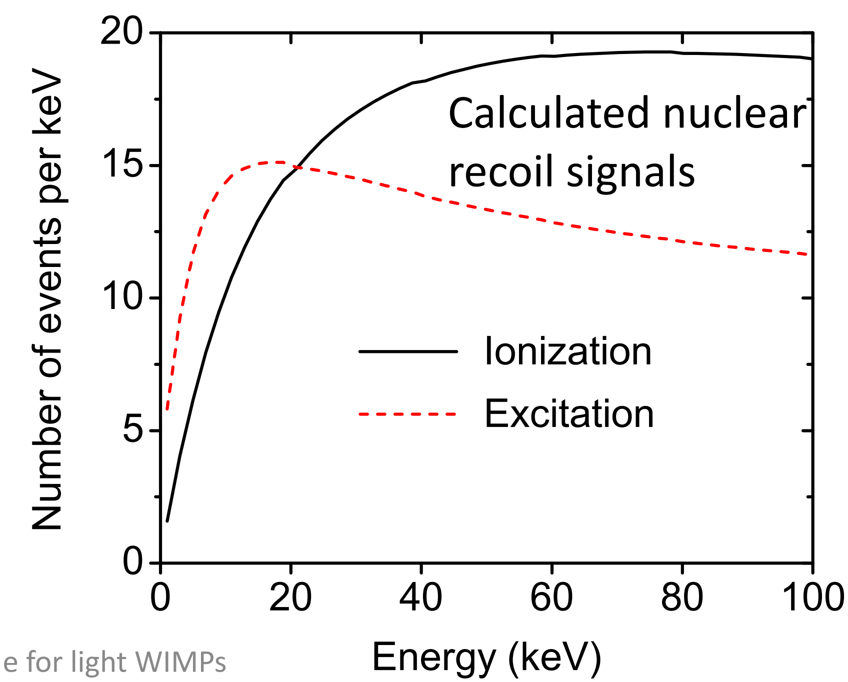


Liquid helium-4 predicted response (Guo and McKinsey, arXiv:1302.0534)

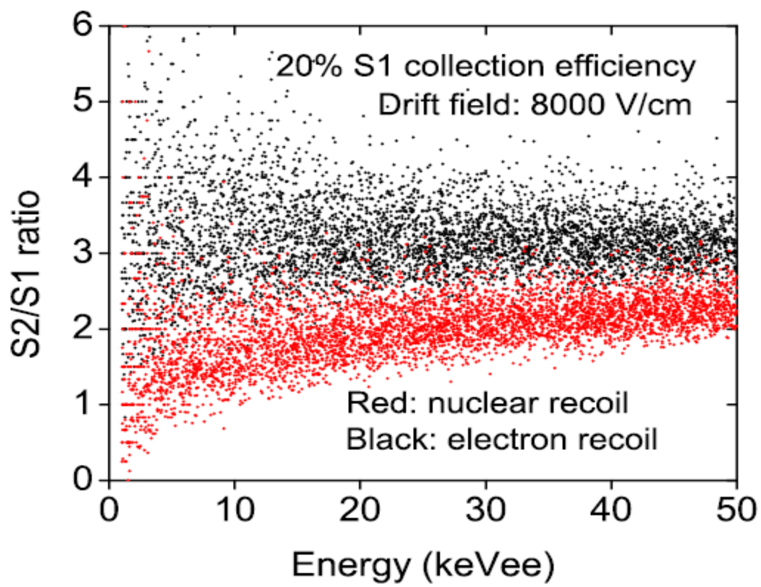
Lower electron scintillation yield (19 photons/keVee)

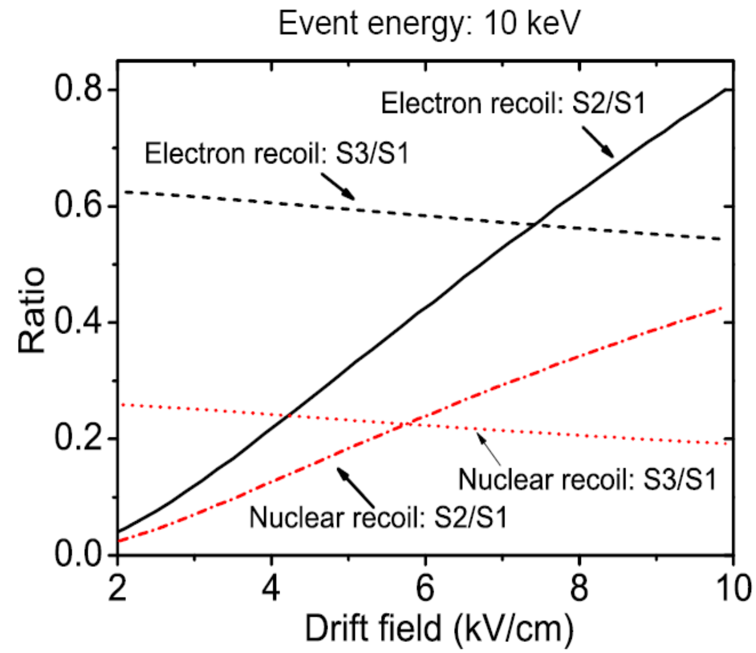
But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity

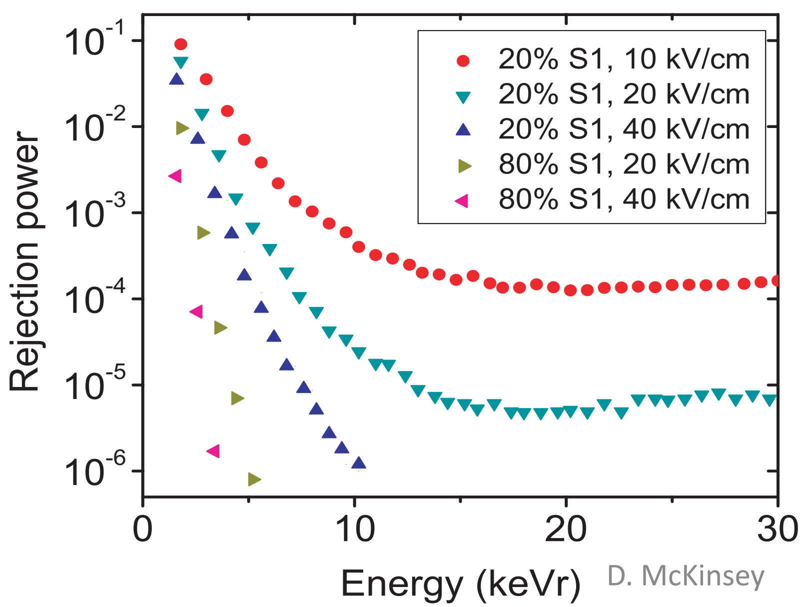


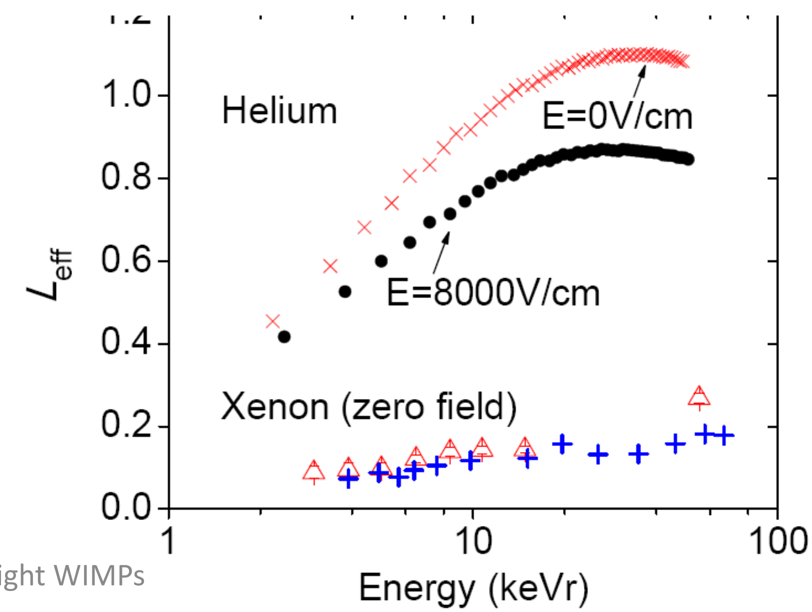


Predicted nuclear recoil discrimination and signal strengths in liquid helium

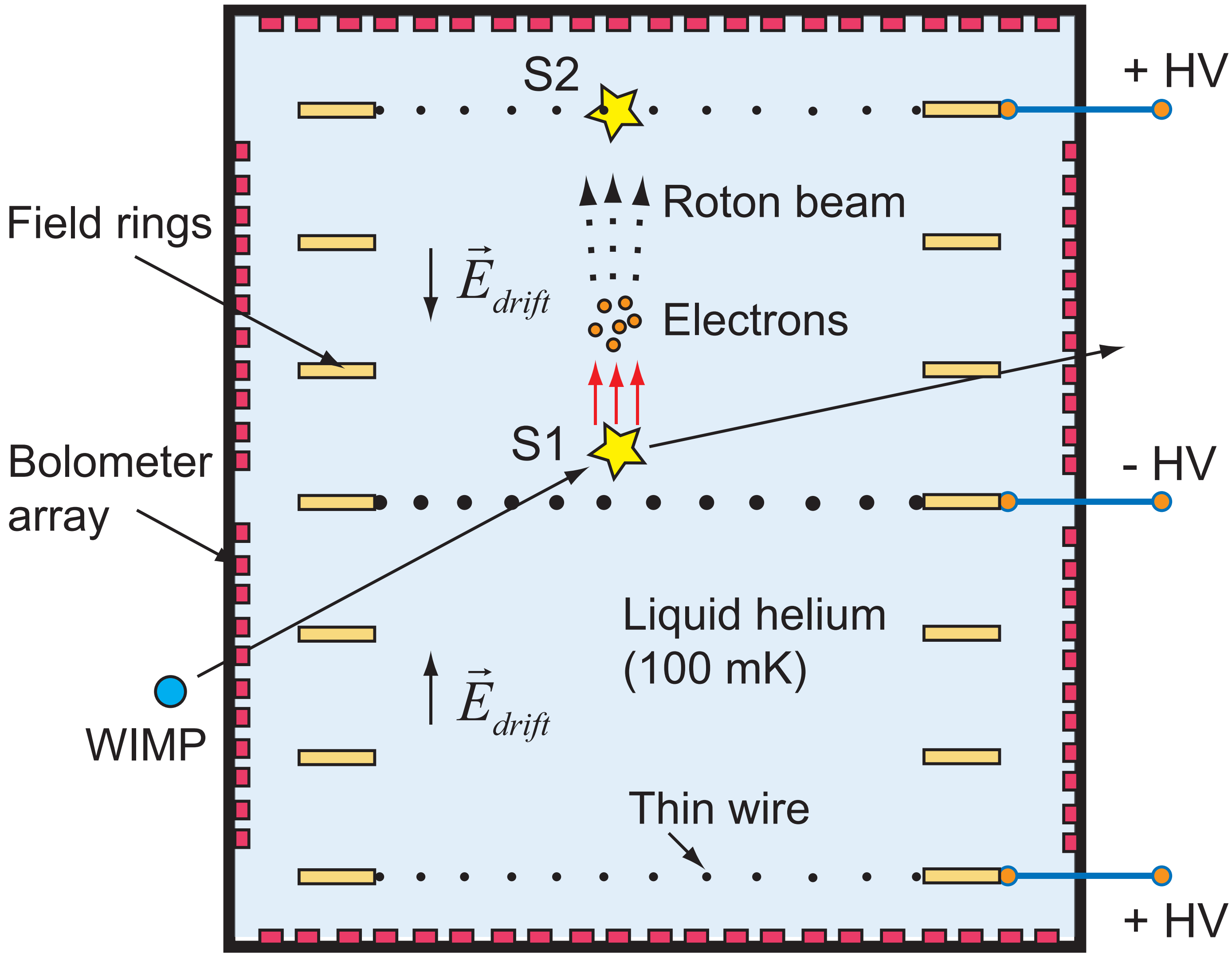




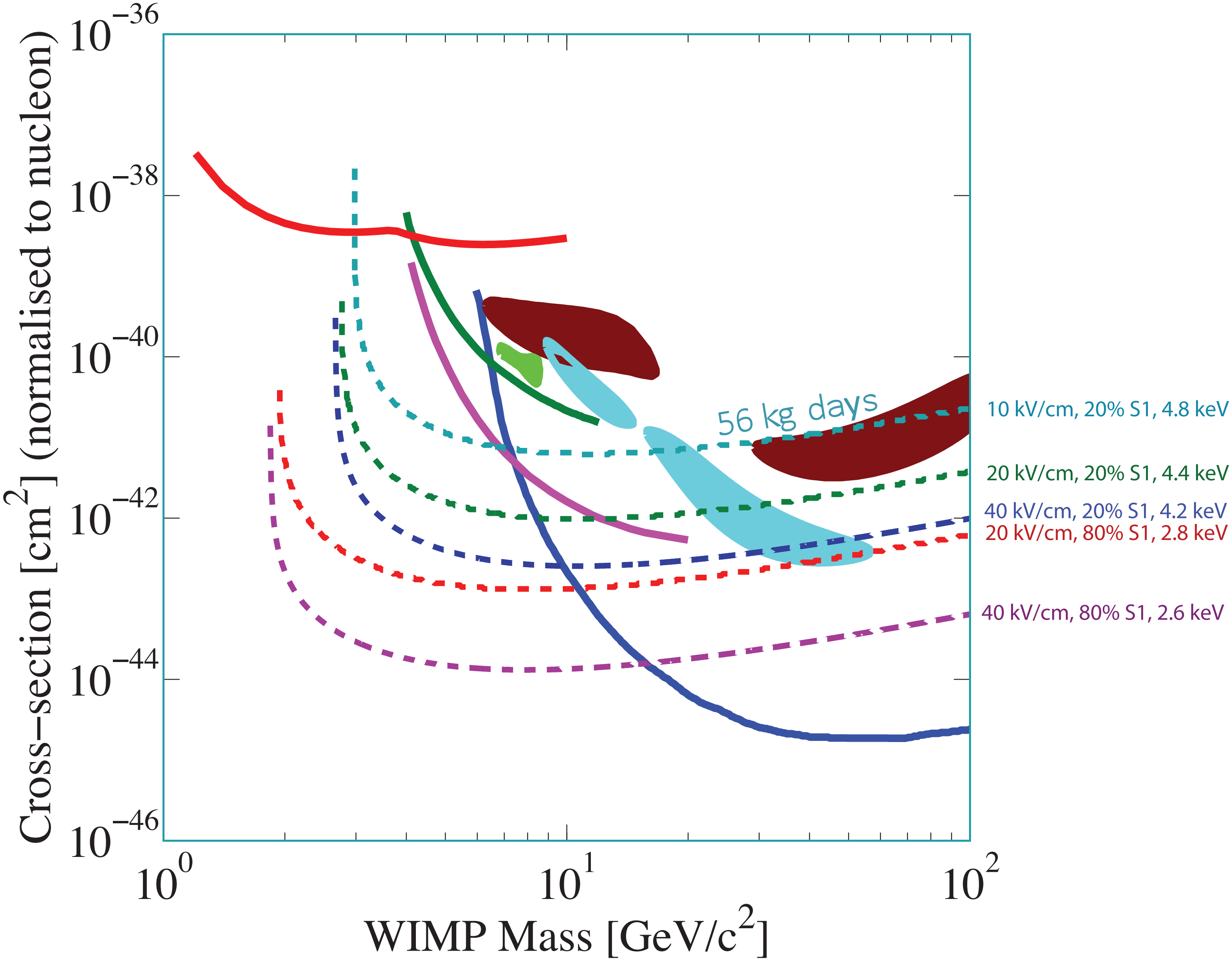




Concept for a Light WIMP Detector at ~ 100 mK



Projected Sensitivity for Liquid Helium (with only charge and S1 readout)



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
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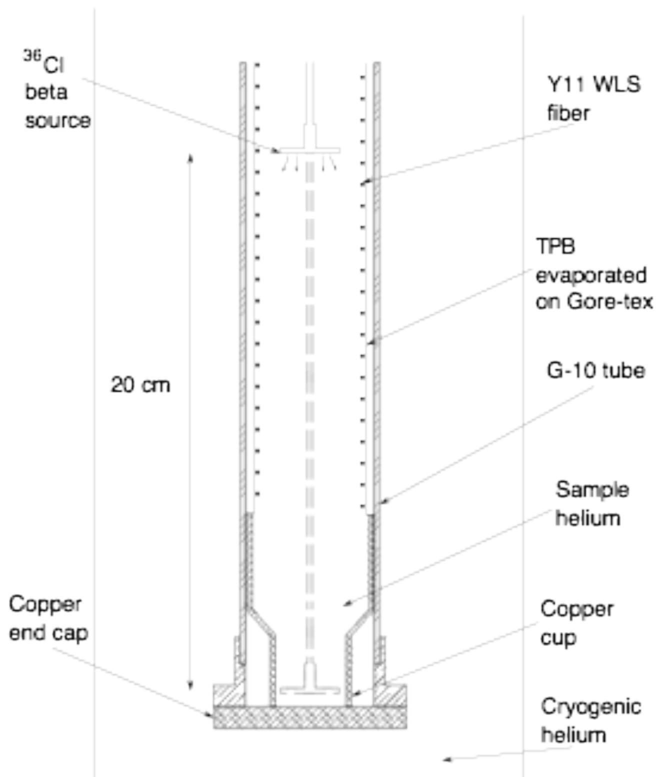
(Received 27 July 1998)



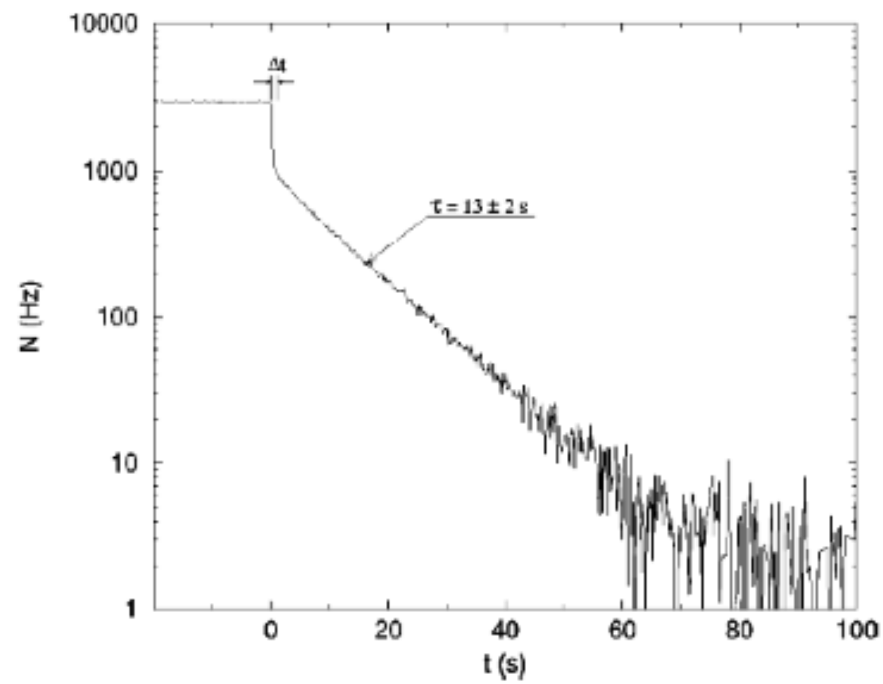


FIG. 2. Count rate N of detected $He_2(a\,^3\Sigma_u^+)$ decays versus time. A ^{36}Cl β source is placed in the center of the detection region and then removed in a time $\Delta t<1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate τ of 13 ± 2 s.

How to detect S3 (helium molecules)?

Again, many options:

- Laser-induced fluorescence (though will require lots of laser power and be slow)
- Drift molecules with heat flux, then quench on low work function metal surface to produce charge, which is then detected the same way as S2 (though heat flux drift will require lots of cooling power).
- Detect with bolometer array immersed in superfluid, and let the molecules travel ballistically to be detected (v ~ few m/s)
  - ~ few eV resolution possible
  - Each molecule has ~ 18 eV of internal energy, which will mostly be released as heat.
  - Note that the same bolometer array could also detect S1 and S2!

Helium for MeV dark matter?

(i.e. how one might reach extremely low energy thresholds)

- Single electron detection
  - Single electrons should be detectable, via electroluminescence or roton emission.
  - What is the single electron rate in a LHe TPC, and how does it compare to XENON10 ~23 electrons/kg day? Does the rate drop significantly with temperature?
  - Noble gases have less electron signal than semiconductors, but this business is mostly about backgrounds.
- Prompt phonon and roton detection
  - Can look at very low energies, using electron signal as a veto. An electron can be made to produce tens of keV of heat by dragging it through the superfluid, pulling any ionizing event well above the energy region of interest.
  - Will roton/phonon ratio give discrimination power? How might one tell rotons and phonons apart? Bolometer pulse shape?

Summary

- The search for light WIMPs is well motivated, but is technically challenging, demanding sophisticated technologies with light target nuclei, low energy thresholds, and low backgrounds.
- Superfluid helium should have many of the advantages of other noble liquid targets, including scalability, position reconstruction and discrimination, but is also predicted to have high nuclear recoil light yield.
- Relatively straightforward implementation likely achievable using PMT readout a la two-phase Xe and Ar, but improved performance and lower energy threshold may be possible with roton/phonon readout.
- Technical overlap with other noble gas detectors, bolometric detectors
- R&D needed!