# Light WIMP Detection with Liquid Helium

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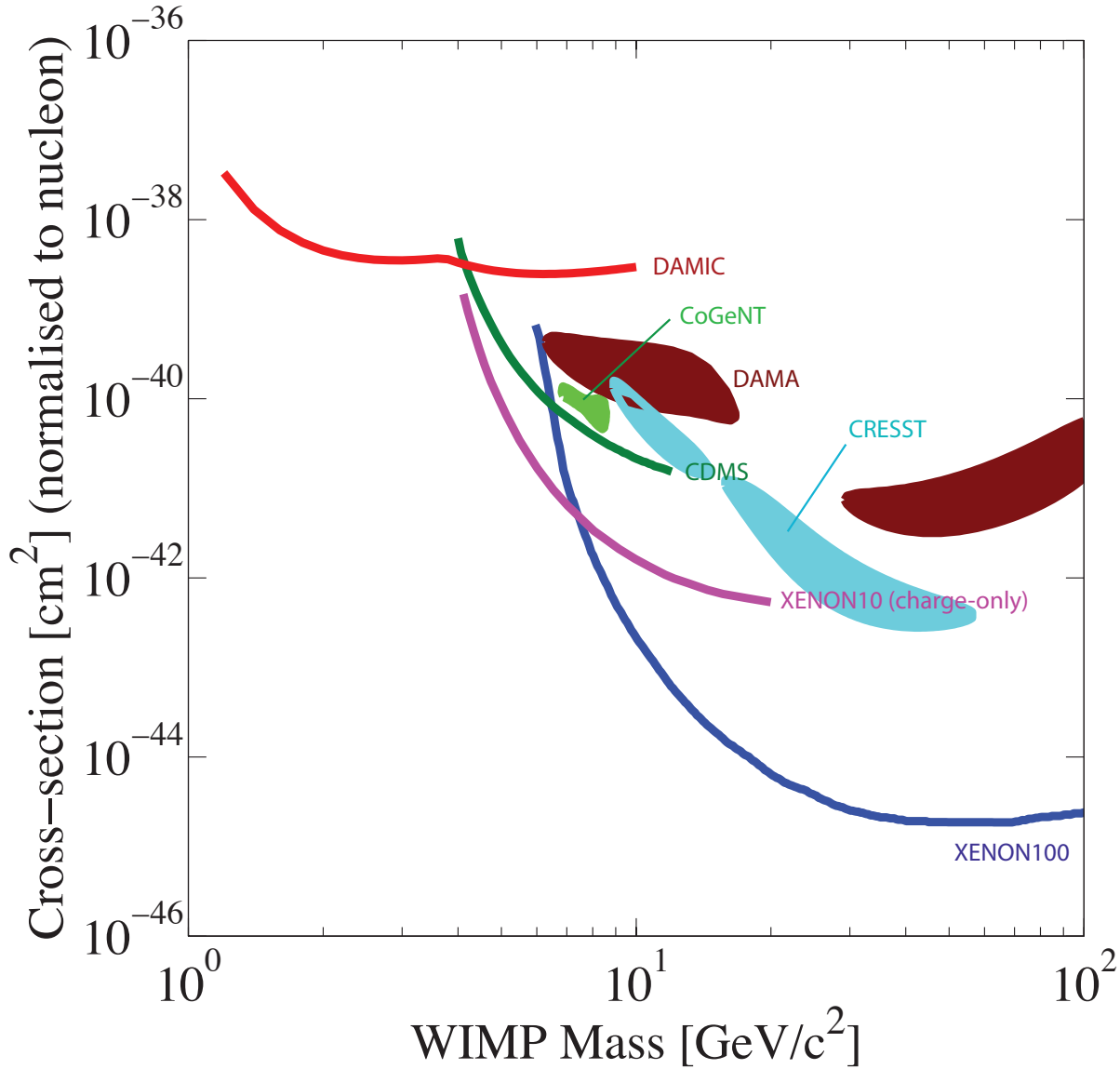
# The current situation for light WIMPs



# 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

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

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.

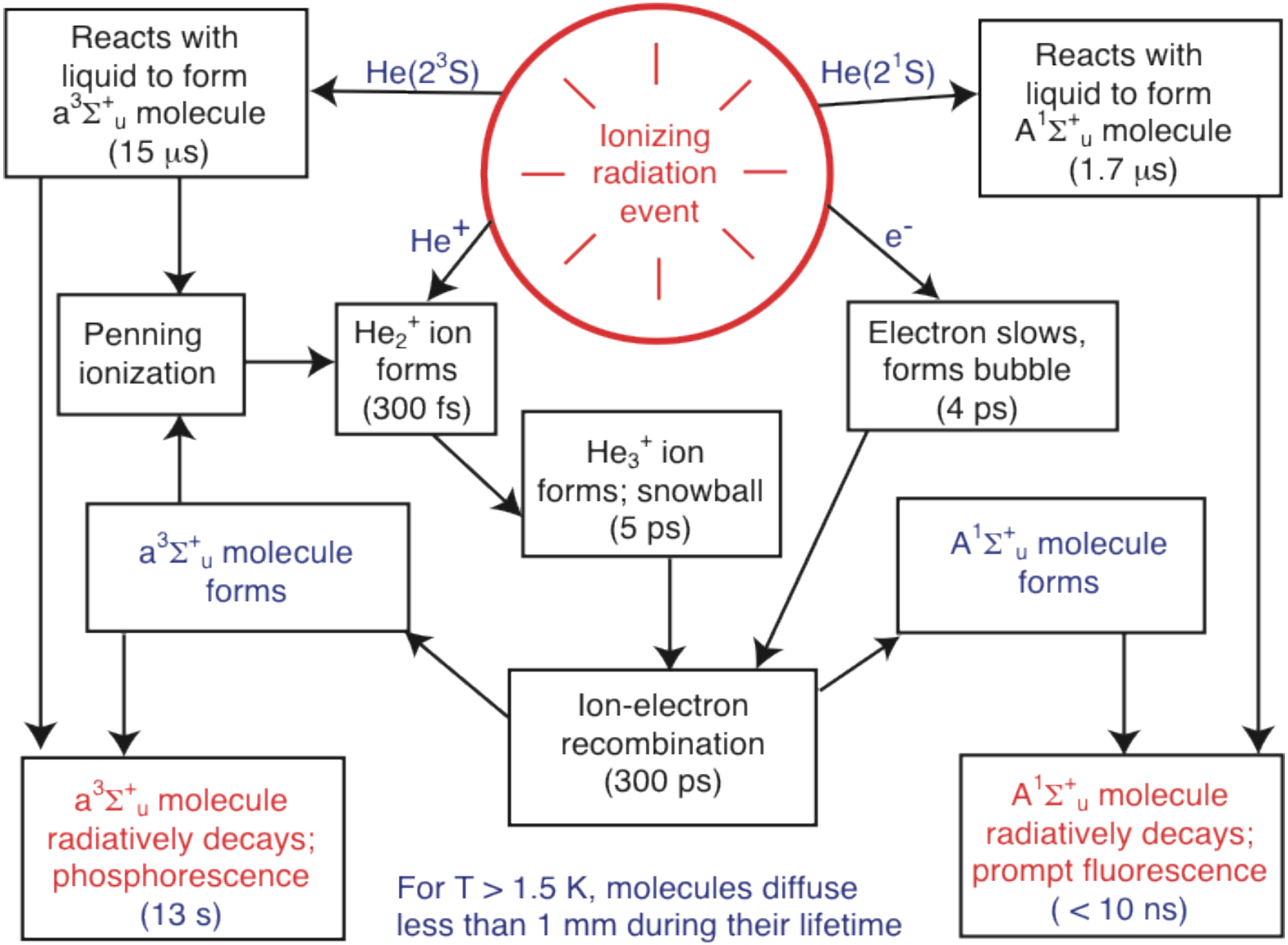
So for reaching sensitivity to small dark matter masses, the kinematic figure of merit is the product of the energy threshold and the target mass, which should be minimized.

# Energy threshold and backgrounds

- Naïve to ever assume that trigger threshold is equal to analysis threshold.
- Analysis threshold must be high enough that sufficient information is gathered from the event to allow background rejection, such as from:
  - Electron recoil events from gamma ray Compton scattering
  - Neutron scattering events
  - Internal radioactive contamination
  - Surface events, in which only part of event energy is detected
  - "eV-scale" physics, like exciton relaxation, single electrons, …
  - etc.
- If you want good cross-section sensitivity, then multiple signal channels are necessary to distinguish signal from the many lurking background sources. This has been made abundantly clear from the history of direct detection experiments.
- Active vetos can also be effective, to allow backgrounds to be better understood and/or rejected.

# 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

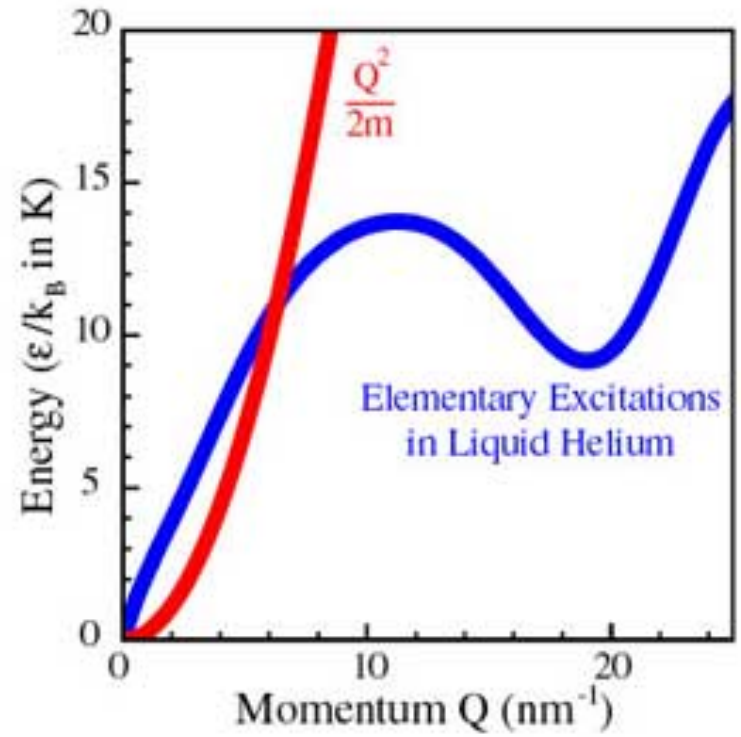
- Used to produce, store, and detect ultracold neutrons. Detection based on scintillation light (S1)
  - Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).
  - Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).

- 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, store, and detect ultracold neutrons
- Very high electric fields achieved, ~ 50 kV/cm, for neutron edm projects

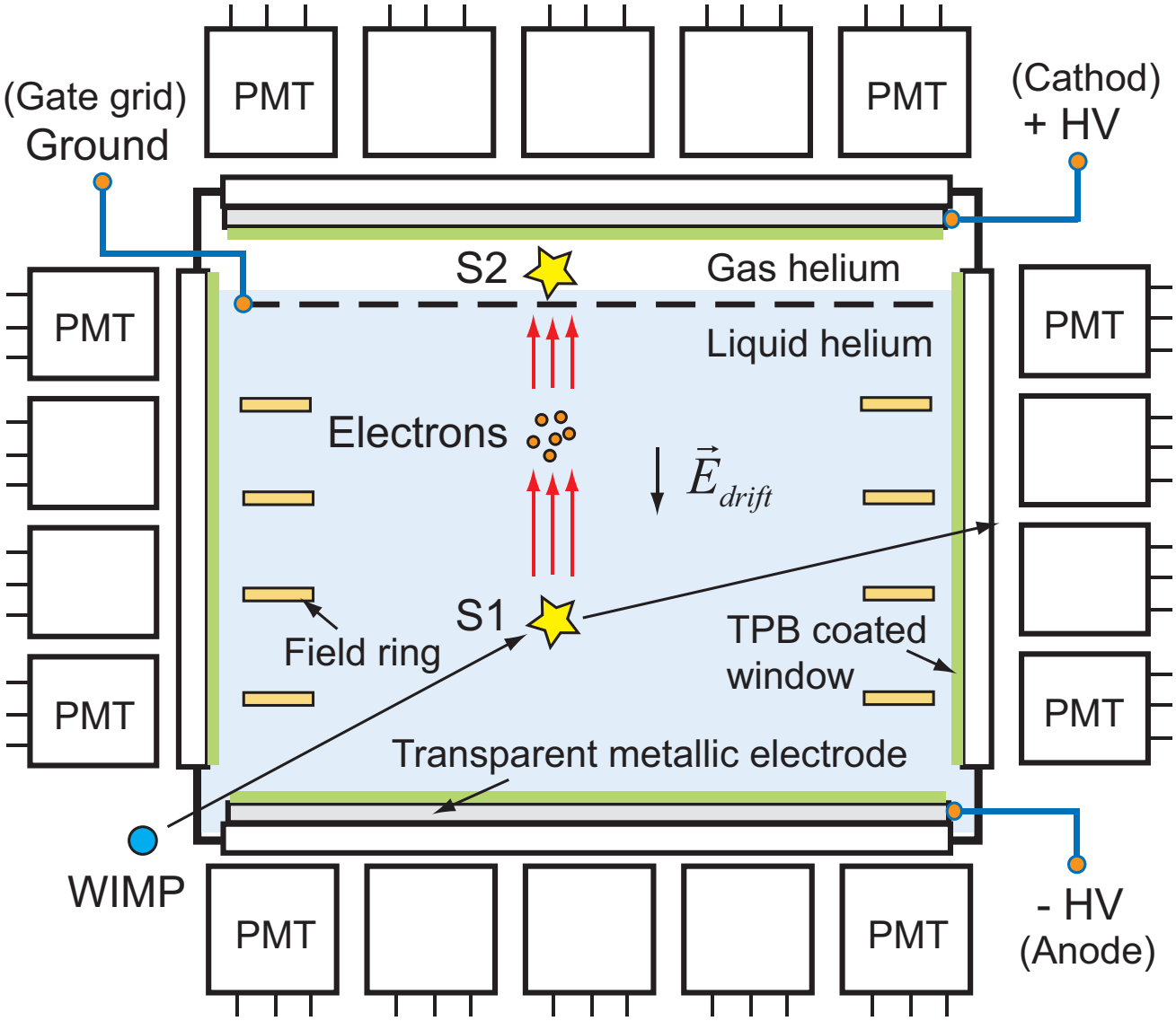


# Liquified Noble Gases: Basic Properties

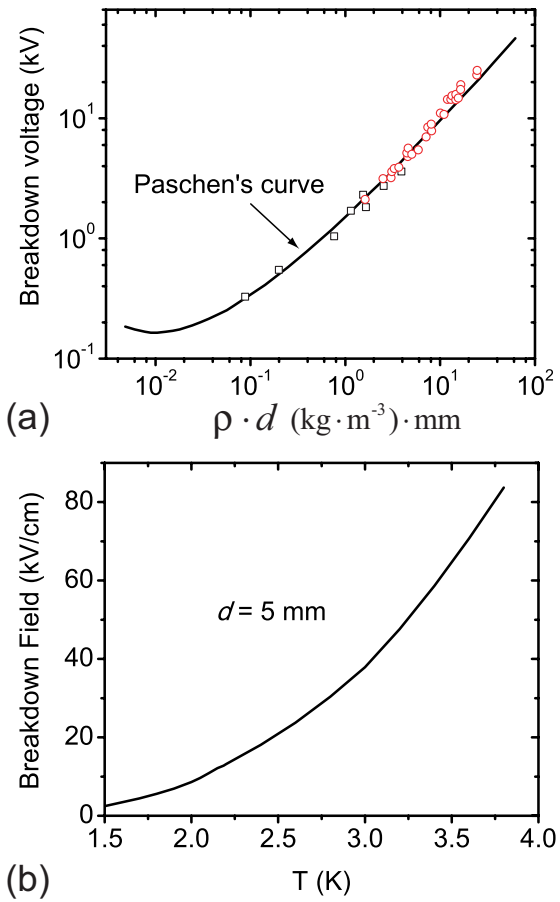
Dense and homogeneous
Do not attach electrons, heavier noble gases give high electron mobility
Easy to purify (especially lighter noble gases)
Inert, not flammable, very good dielectrics
Bright scintillators

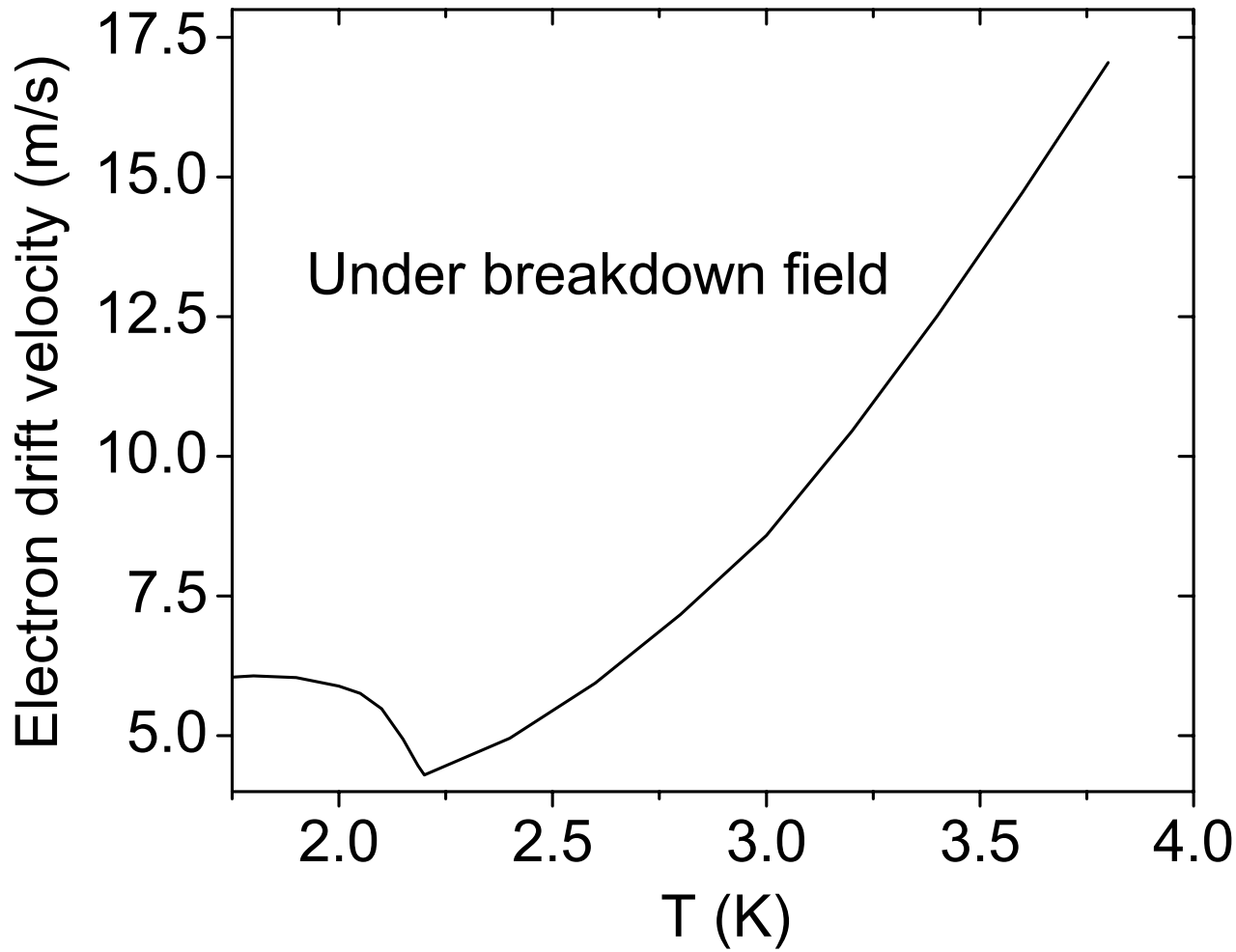
| | Liquid density (g/cc) | Boiling point at 1 bar (K) | Electron mobility ($cm^2/Vs$) | Scintillation wavelength (nm) | Scintillation yield (photons/MeV) | Long-lived radioactive isotopes | Triplet molecule lifetime ($\mu s$) |
|---|---|---|---|---|---|---|---|
| LHe | 0.145 | 4.2 | low | 80 | 19,000 | 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 |

# Light WIMP Detector Concept



# Electron drift speed in two-phase He



# How to detect the charge signal?

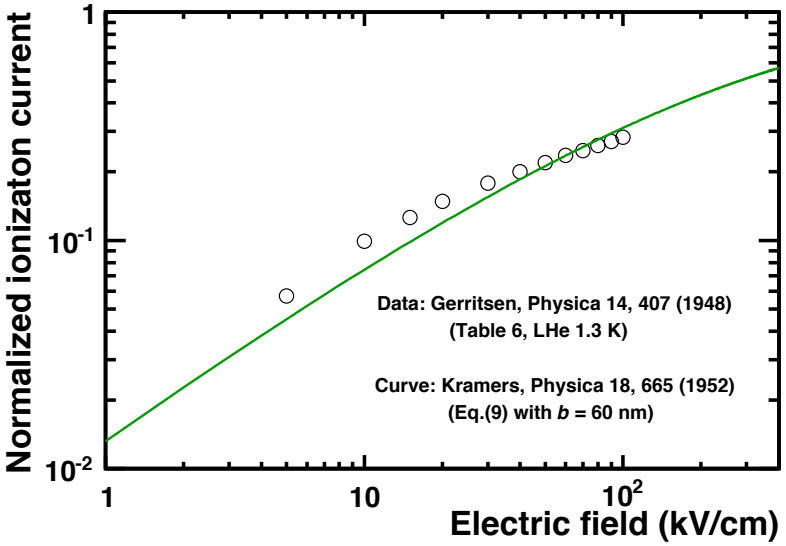
Many options:

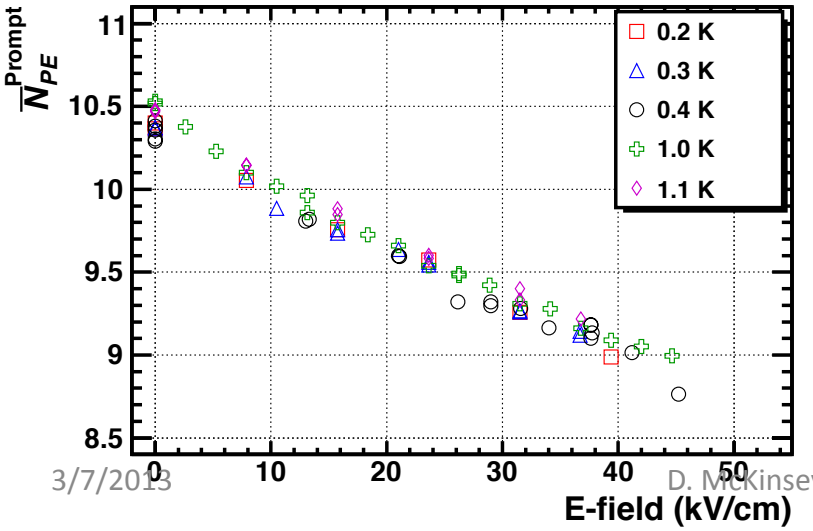
- Proportional scintillation and PMTs (like in 2-phase Xe, Ar detectors)
- Gas Electron Multipliers (GEMs) or Thick GEMS, detect light produced in avalanche.
- Micromegas, detect avalanche light.
- Thin wires in liquid helium. This should generate electroluminescence at fields ~1-10 MV/cm near wire, 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.

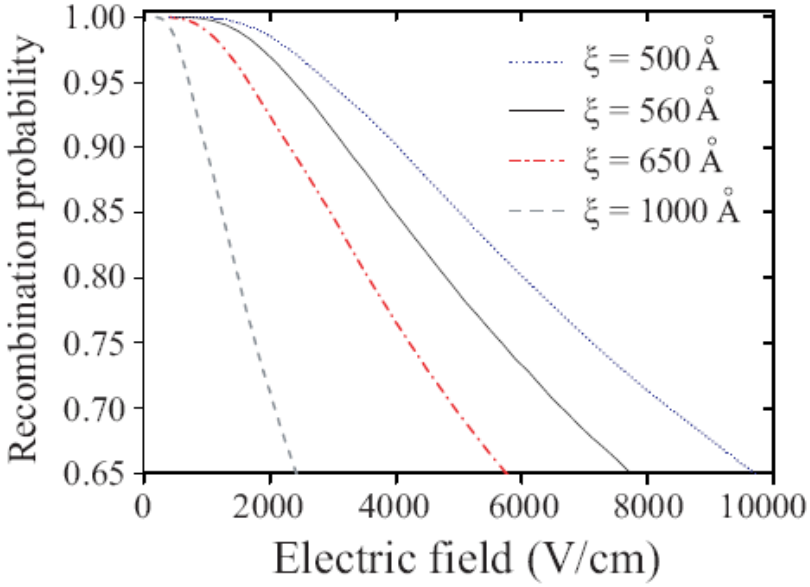
# Helium scintillation vs. electric field

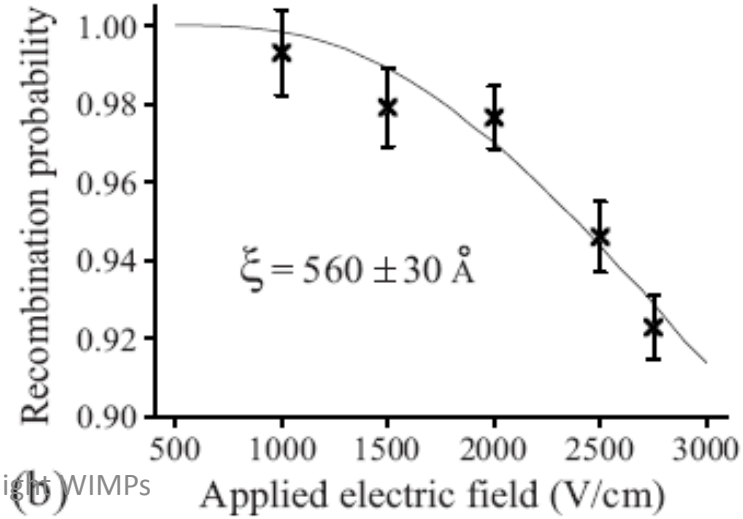
Alpha scintillation yield vs. applied field, T. Ito et al, 1110.0570

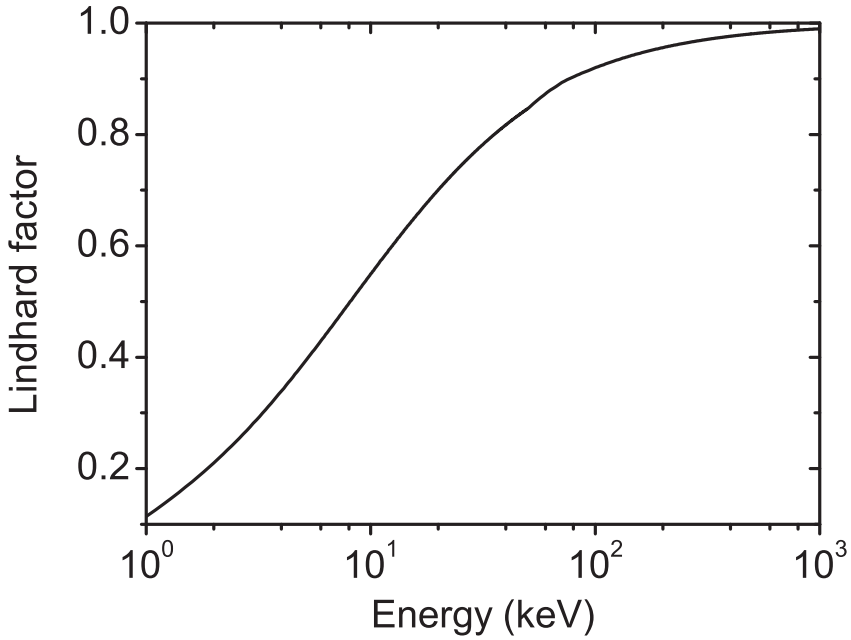



Beta scintillation field quenching: W. Guo et al, JINST 7, P01002 (2012)



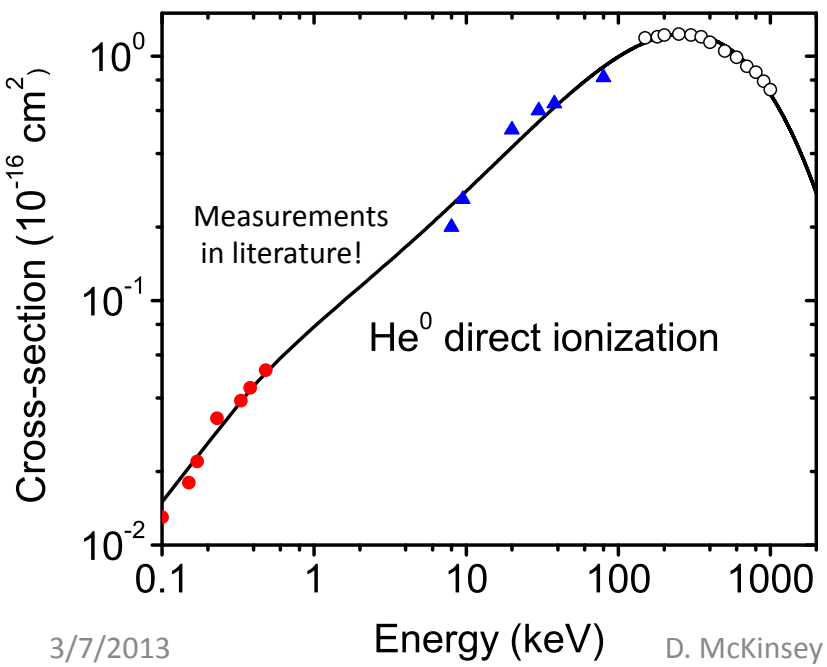



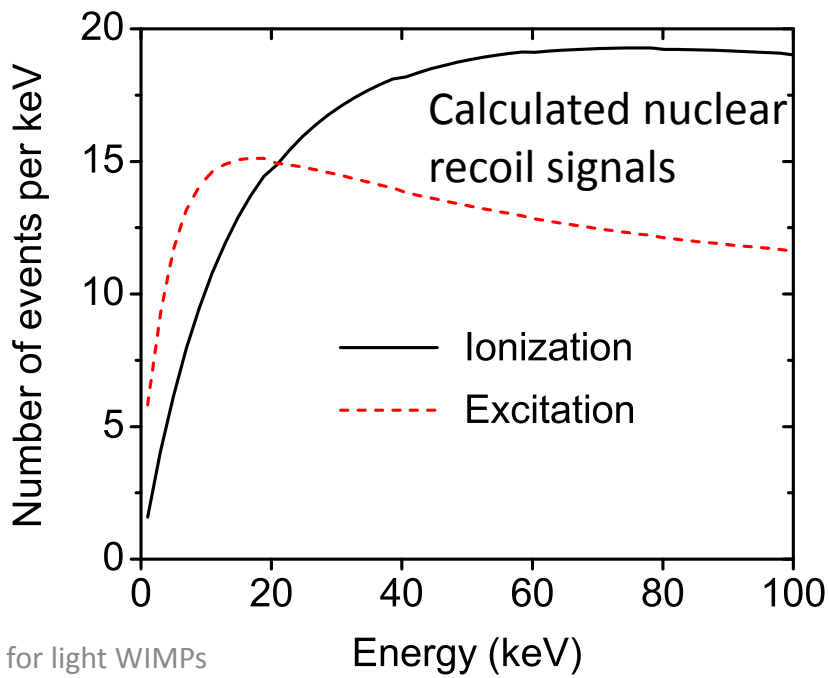



Liquid helium-4 predicted response (Guo and McKinsey, arXiv:1302.0534)

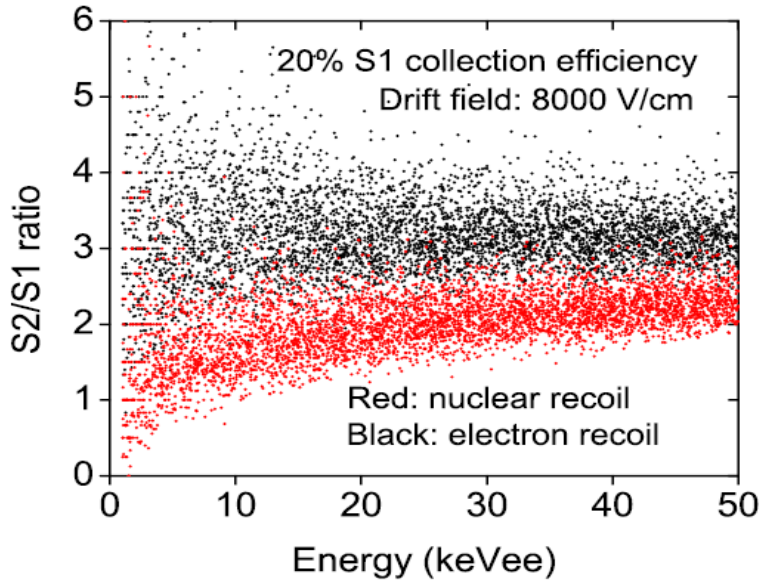
Lower electron scintillation yield (19 photons/keVee)

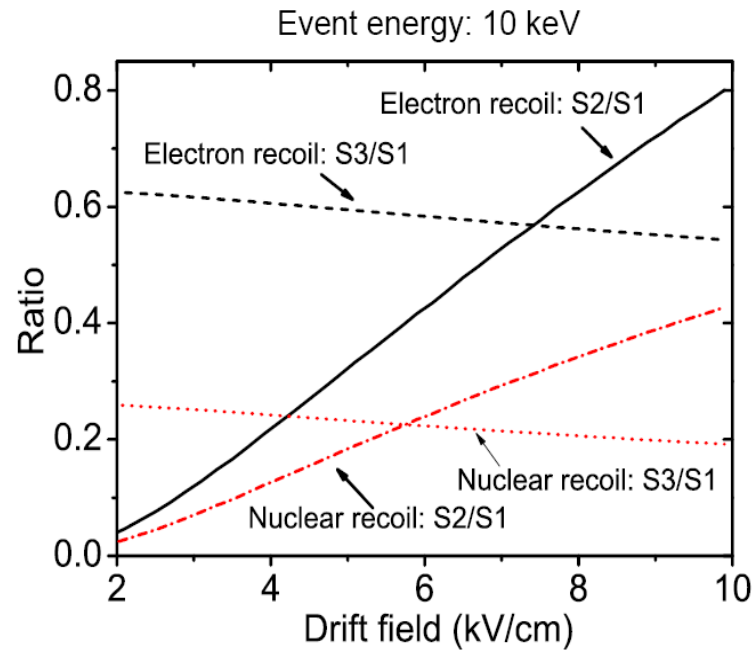
But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity

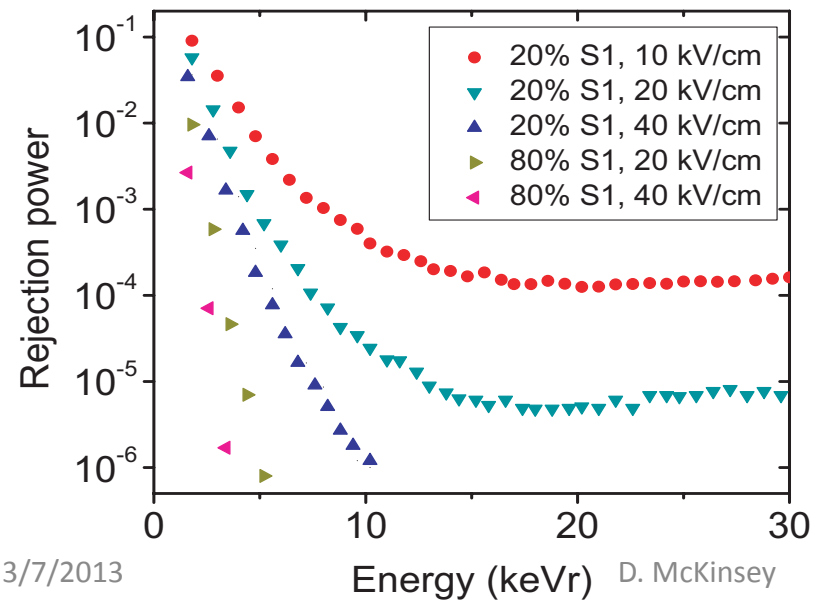


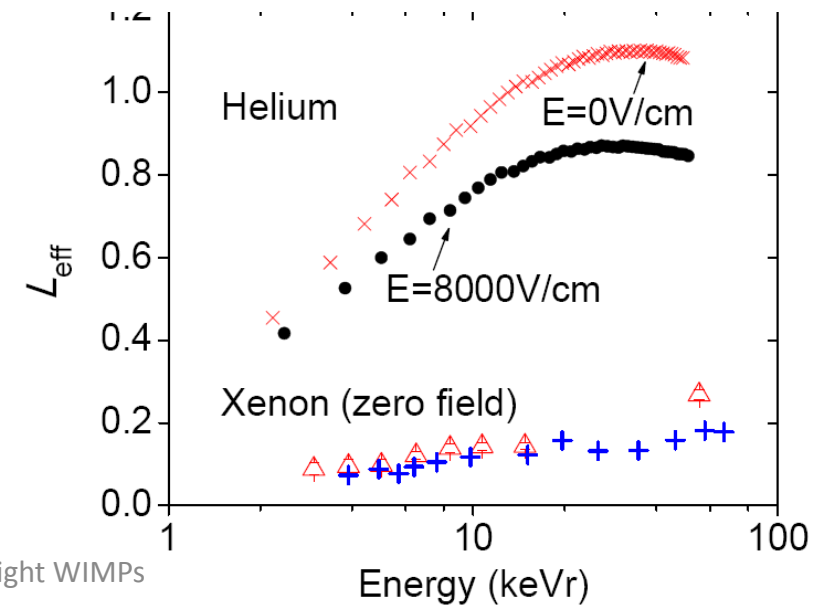



# Predicted nuclear recoil discrimination and signal strengths in liquid helium

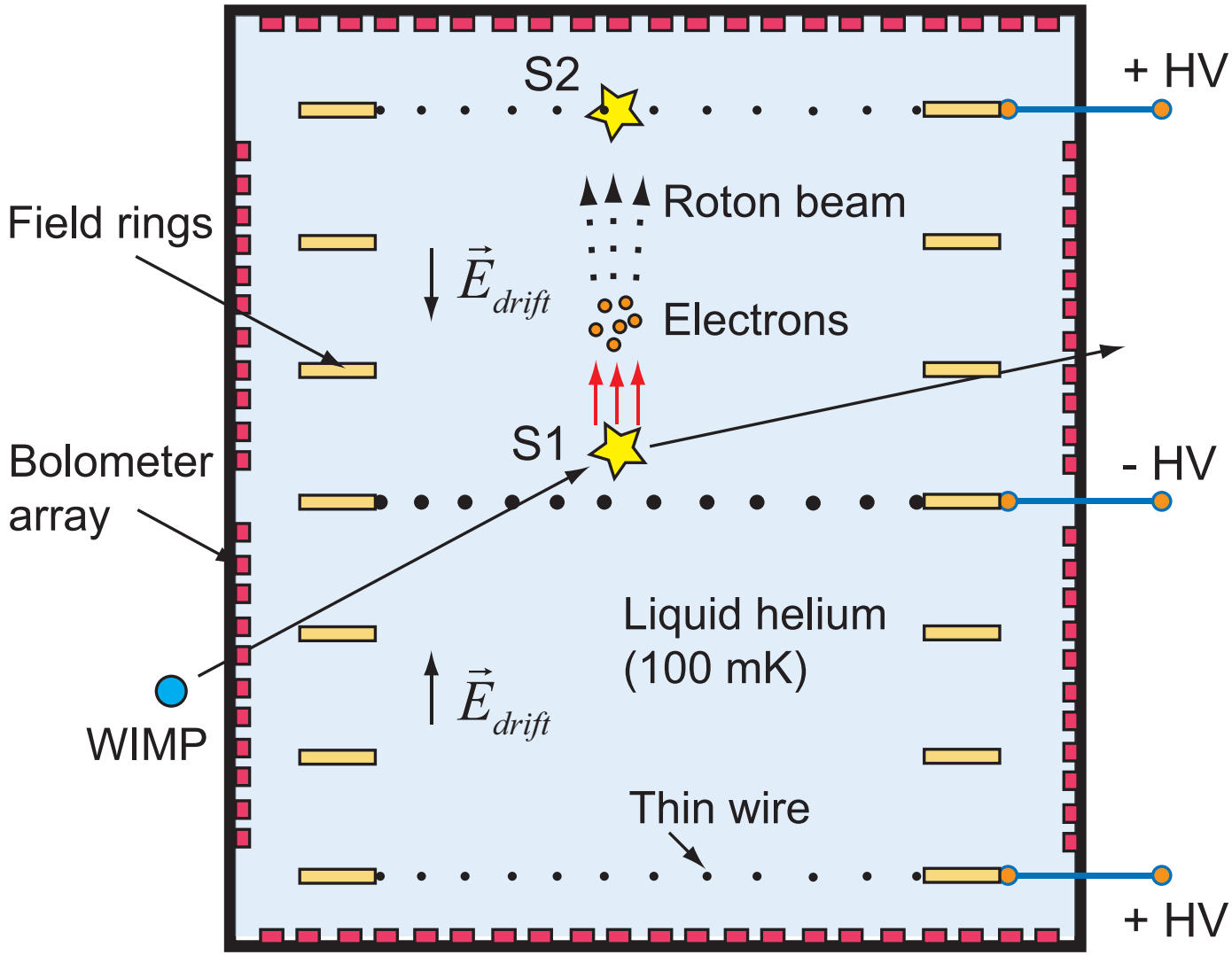


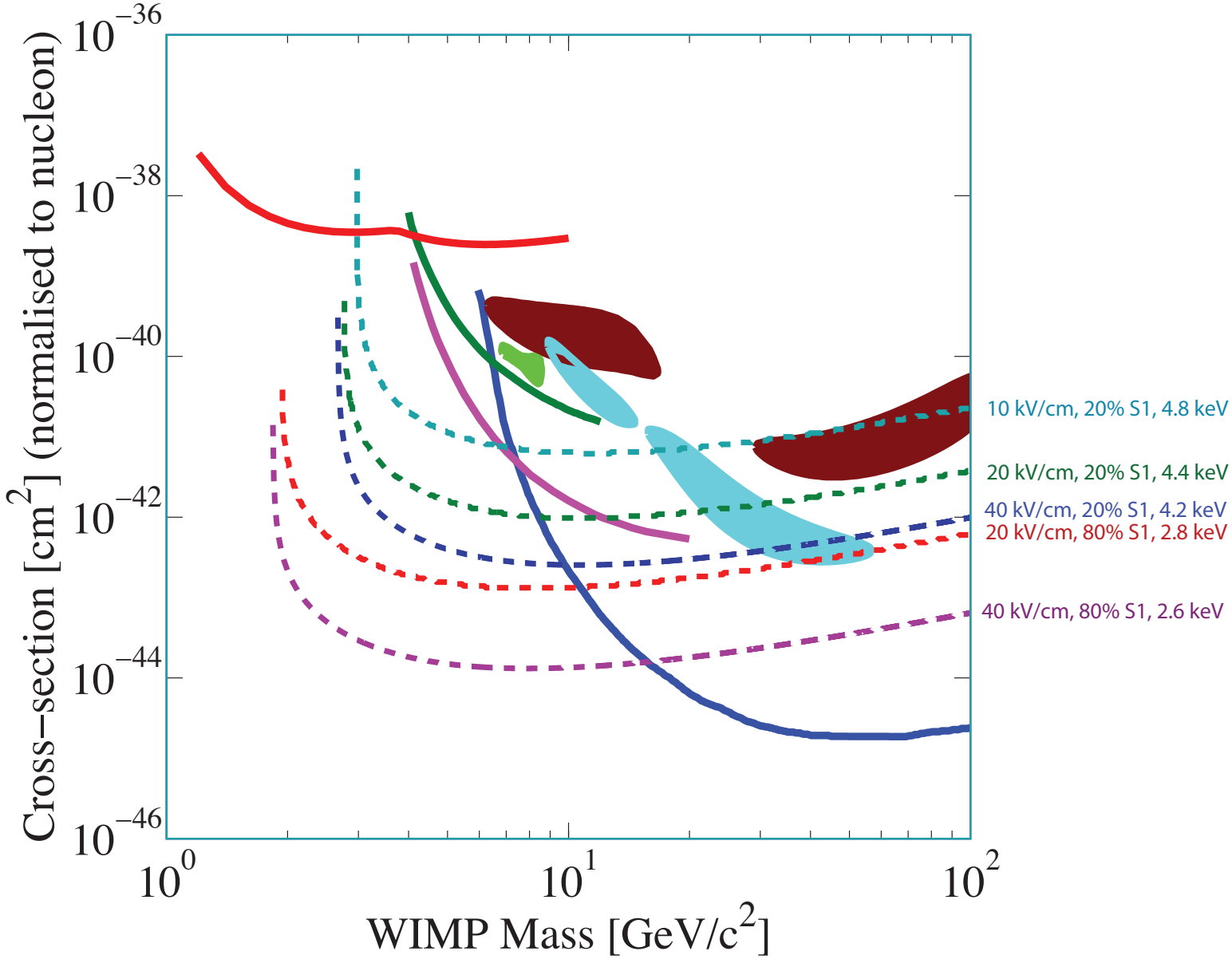



# Concept for a Light WIMP Detector at ~ 100 mK



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



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

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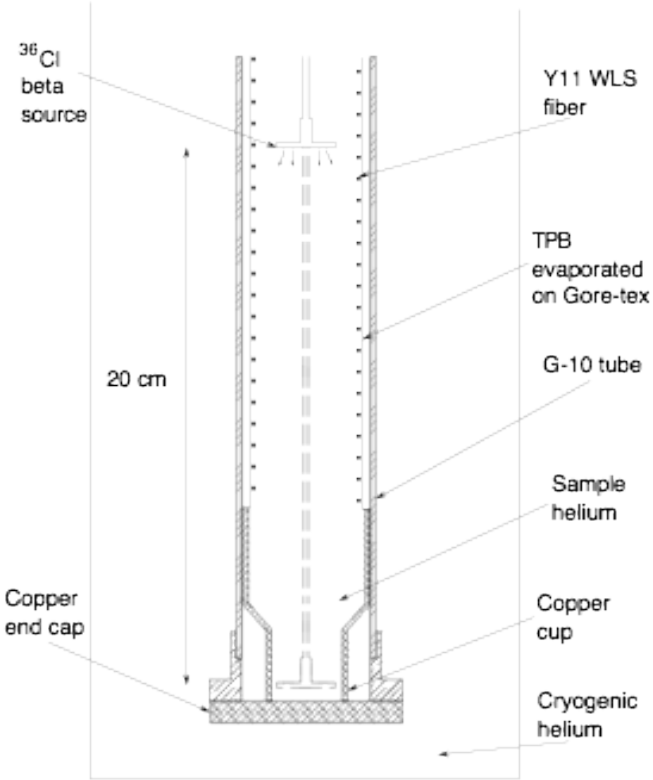
(Received 27 July 1998)



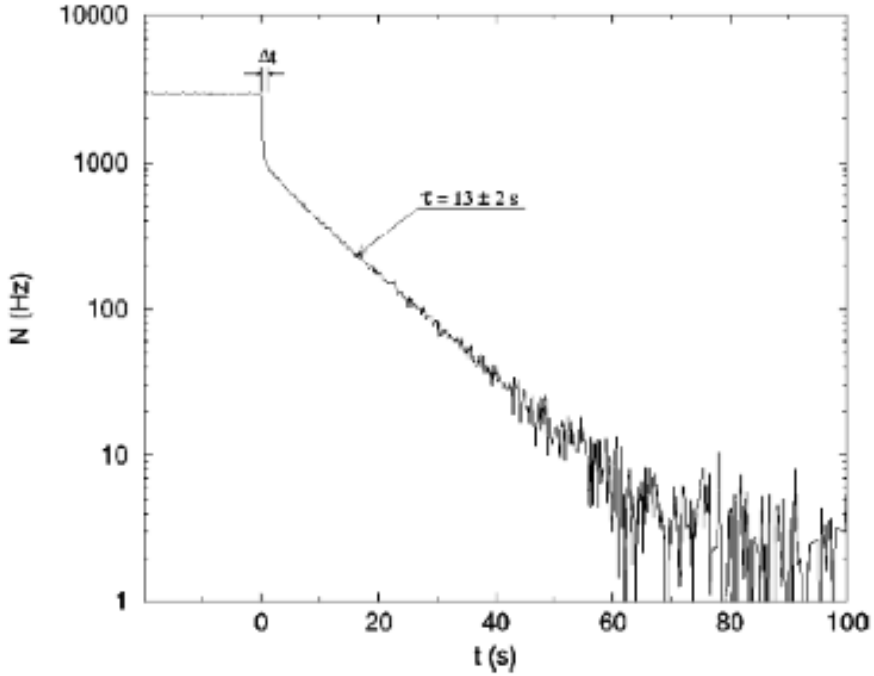




FIG. 2. Count rate $N$ of detected $He_2(a\,^3\Sigma_u^+)$ decays versus time. A $^{36}$Cl $\beta$ source is placed in the center of the detection region and then removed in a time $\Delta t < 1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate $\tau$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

# Question answers:

1) Experiment Status and Target Mass
   - This is an R&D project in the near term; not an operating experiment.
   - Target mass of order 0.1 - 100 kg
2) Fiducial target mass
   - Fiducial mass of order 0.05 - 50 kg
3) Backgrounds after passive and active shielding
   - Assuming gamma Compton scattering background at 1 event/keVee/kg/day. This is likely to be the dominant background. With veto, could knock this down an order of magnitude or so.
   - Neutrons will multiple-scatter in the liquid helium, since He number density is high and cross-sections are in the few barn range. Multiple scatters will give multiple S2 pulses and be rejected. Simulations needed quantify neutron background rejection.
4) Detector discrimination
   - Discrimination is not yet demonstrated. This is a key R&D goal.
   - S2/S1 discrimination is predicted to give rejection of electron recoil backgrounds. Efficiency depends strongly on electric field and light collection.
5) Energy threshold
   - Energy threshold needs to be quantified. This is a key R&D goal.
   - With S2/S1 discrimination, expect analysis threshold in range of 2-4 keVr.
   - With roton/phonon bolometric readout, could lower this further.

6) Sensitivity versus WIMP mass

- With S1 and S2 readout, at 40 kV/cm drift field, 80% S1 collection, 14,000 kg day exposure, project spin-independent cross-section sensitivites of
  - 1e-43 $cm^2$ at 2 GeV
  - 1e-44 $cm^2$ at 5 GeV
  - 1e-44 $cm^2$ at 10 GeV
- With S3 (triplet molecule) or phonon/roton readout, this could be improved further.

7) Experimental challenges

- High voltages, high light collection
- Bolometric readout for improved performance

8) Annual modulation

- If anomalous events are seen, could certainly build up statistics to look for annual modulation.
- To do this, sufficient detector stability would need to be demonstrated.

9) Unique capabilities

- Light WIMPs!
- For S2 and S1 readout, could consider swapping 4He for 3He to test proton spin-dependent models at low WIMP mass. Expensive!

10) Determining WIMP properties and astrophysical parameters

- If signals are seen by the community, a low-mass target provides one end of the target mass lever arm for determining WIMP mass and mean velocity.