# Light Noble Gases for Light Dark Matter Detection

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# The Noble Liquid Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense.

Easily purified

- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields

- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors

# 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 |

# Why helium?

- 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.
- Superfluid helium offers multiple signals
  - Prompt light
  - Delayed triplet excimers
  - Charge
  - Heat (rotons/photons)
- You need at least 2 signals to have nuclear recoil/electron recoil discrimination, both to reject ER backgrounds, but also to have a separate handle on signal in the face of unexpected backgrounds. In real experiments, discrimination is crucial, as you can see from the history of the field.
- Should have robust ionization efficiency, with a forgiving Lindhard factor (high Leff), so nuclear recoil signals should be relatively large. THESE HAVE NEVER BEEN MEASURED.

# 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)

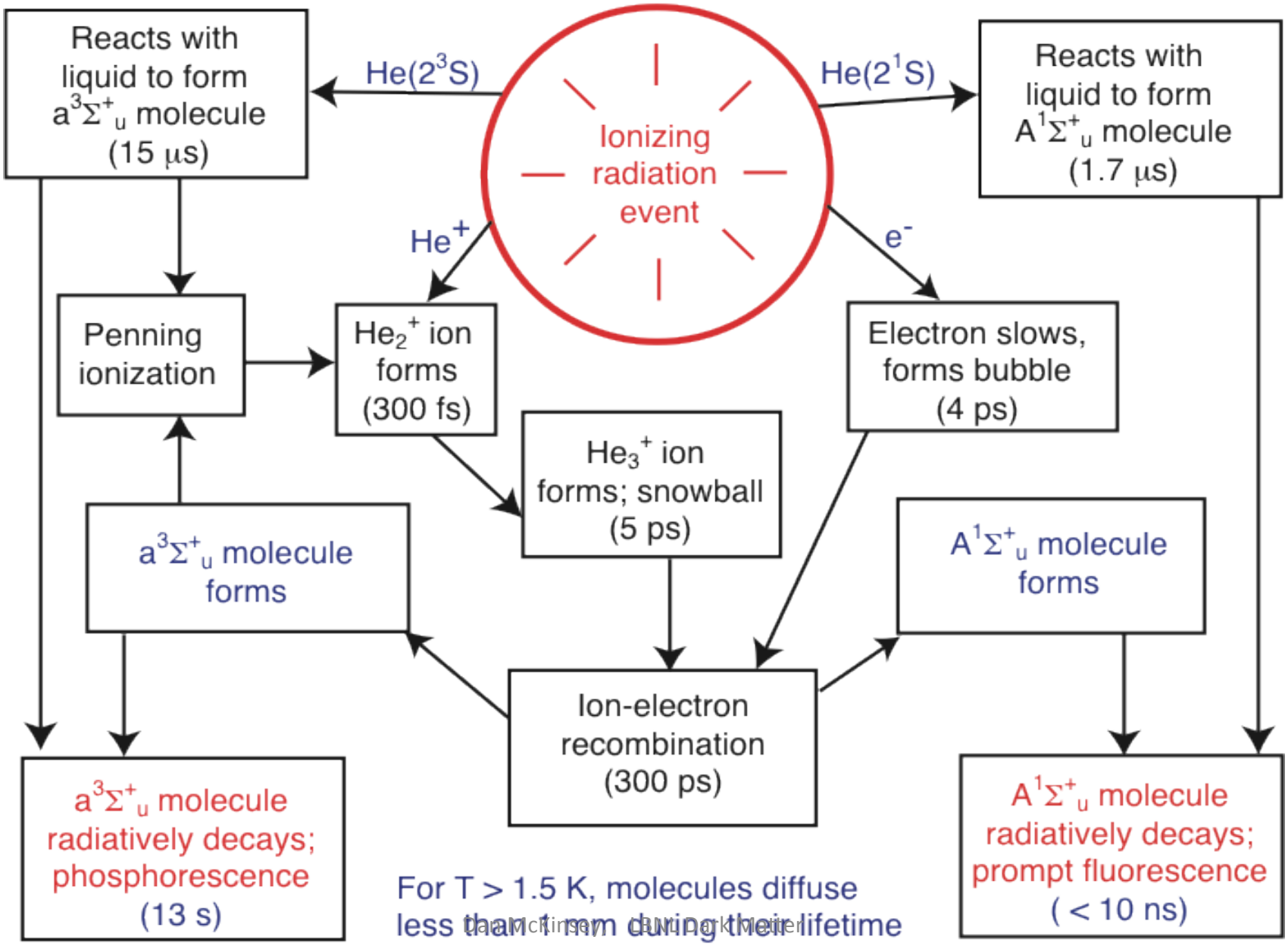
# Light WIMP Detector Kinematic Figure of Merit

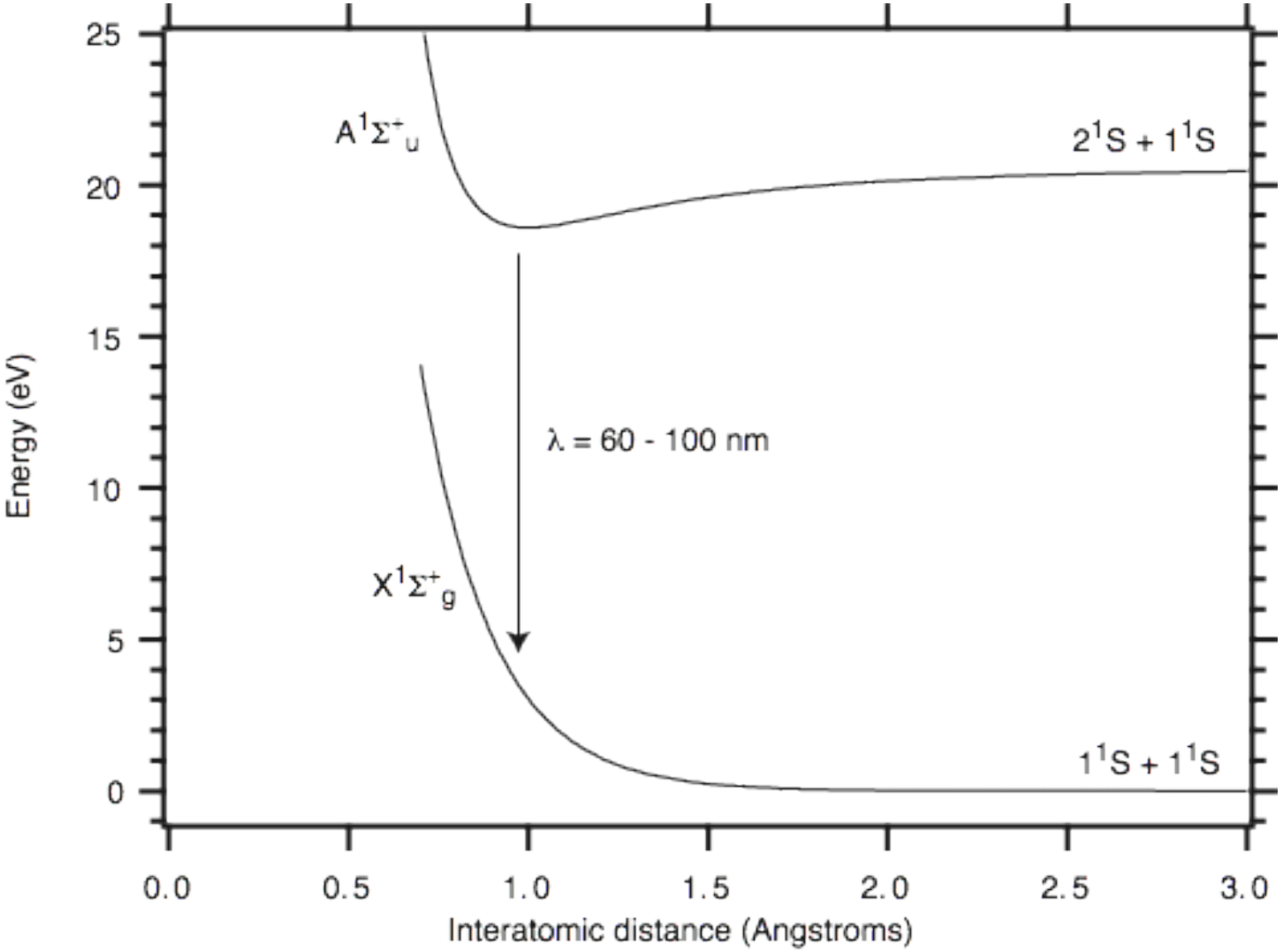
It is more difficult for heavy targets to be sensitive to light WIMPs, since for typical energy thresholds they are only sensitive to a small part of the WIMP velocity distribution. The lower limit of the WIMP-target reduced mass at which a detector can be sensitive is given by

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

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.


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

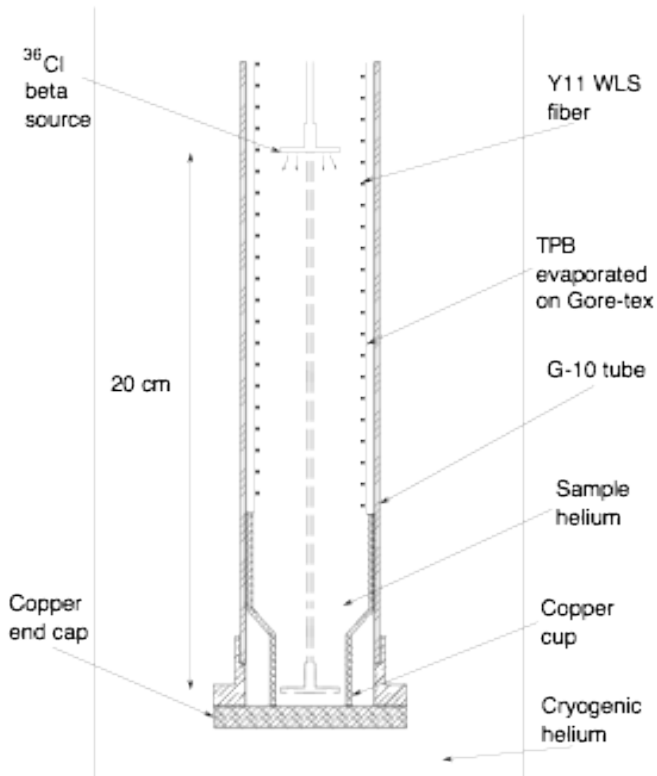

25
20
15
10
5
0
Energy (eV)
$A^1\Sigma^+_u$
$2^1S + 1^1S$
λ = 60 - 100 nm
$X^1\Sigma^+_g$
$1^1S + 1^1S$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Interatomic distance (Angstroms)

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)



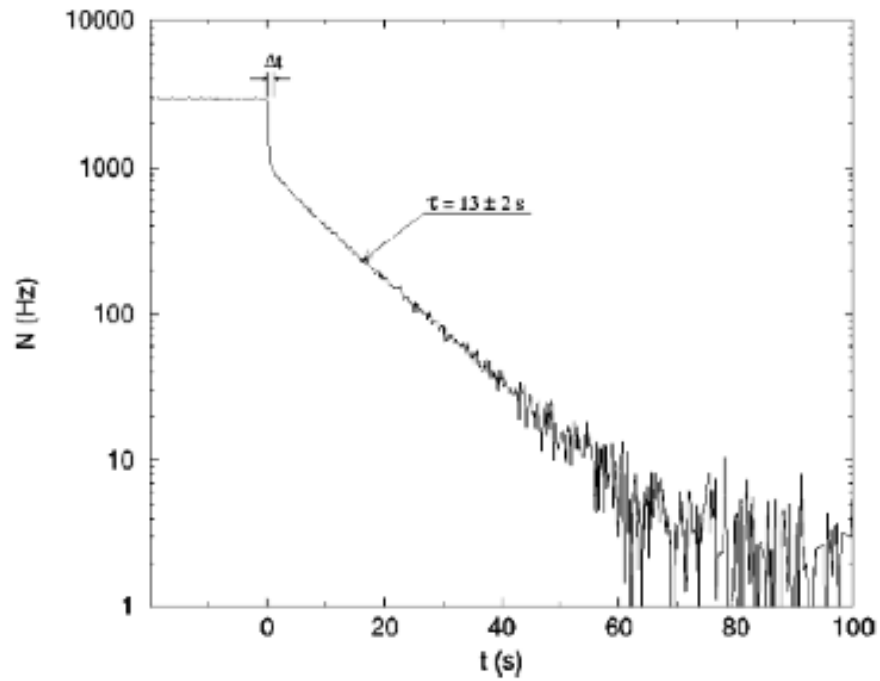
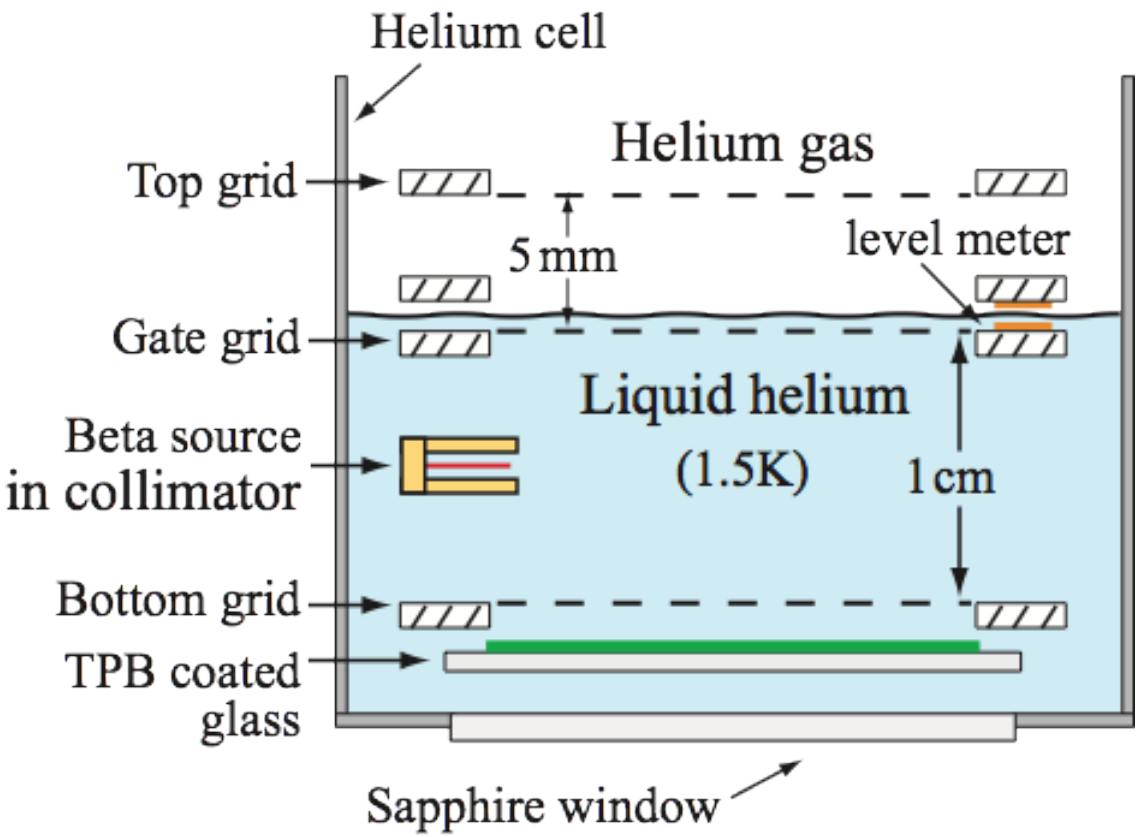




FIG. 2. Count rate $N$ of detected $He_2(a\,^3\Sigma_u^+)$ decays versus time. A $^{36}$Cl $\beta$ source is placed in the center of the detection region and then removed in a time $\Delta t < 1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate $\tau$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

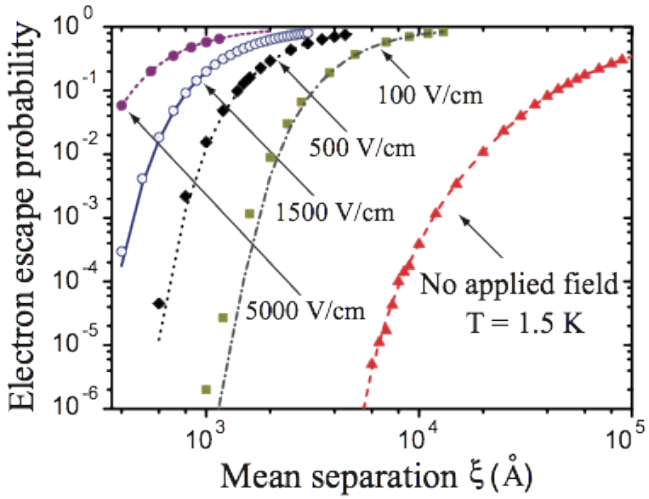
Work at Yale on charge yield in superfluid helium
(W. Guo et al, Journal of Instrumentation **7**, P01002 (2012).)

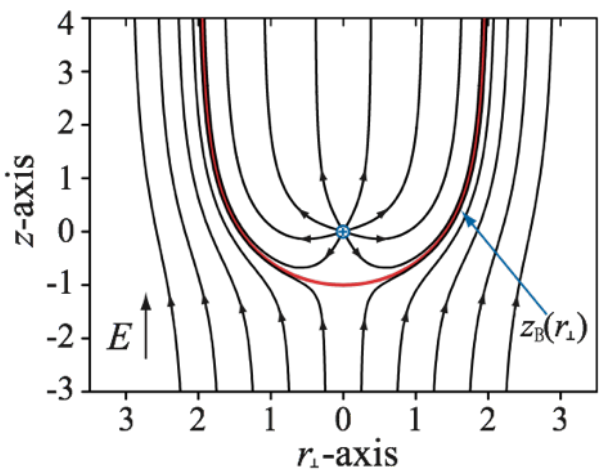


# Data from charge yield measurement

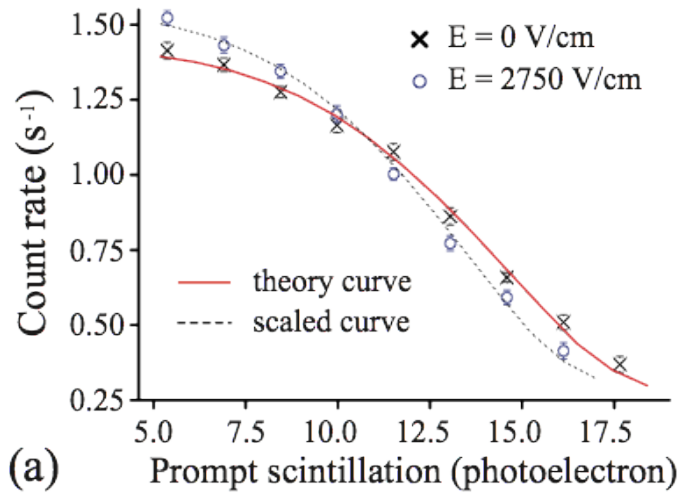
5 kV/cm will give 23% ionization extraction at higher LHe temperatures (1-2 K)
(compare to 30-50 kV/cm in n-edm experiment)

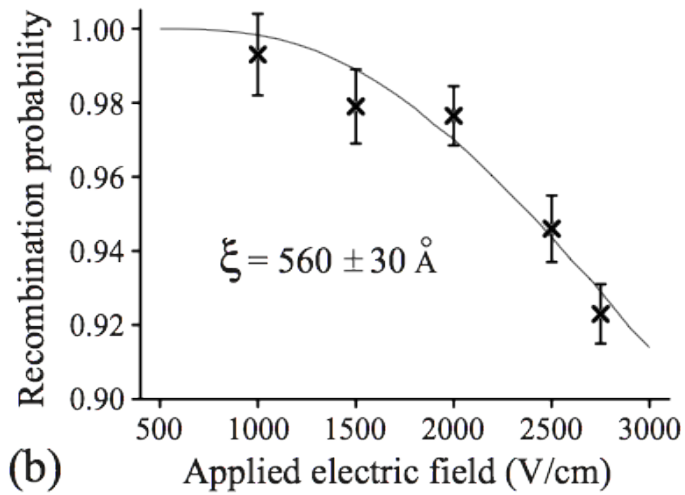
Monte Carlo results



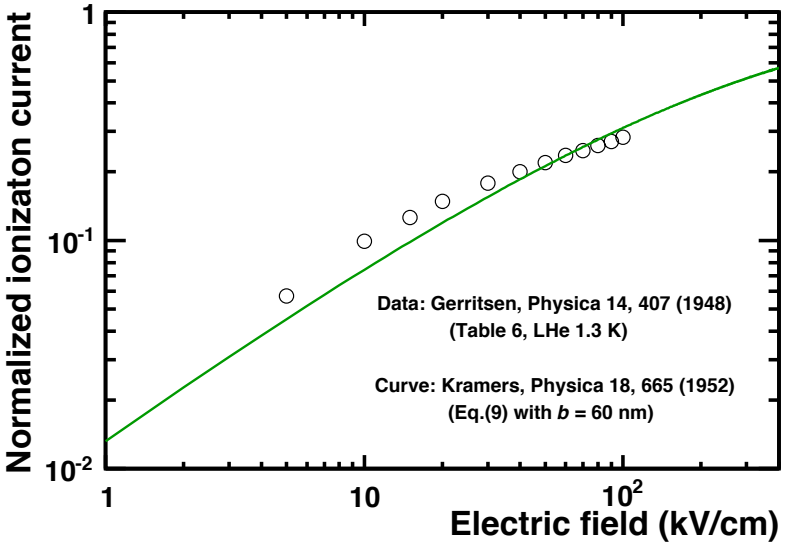

Experimental data

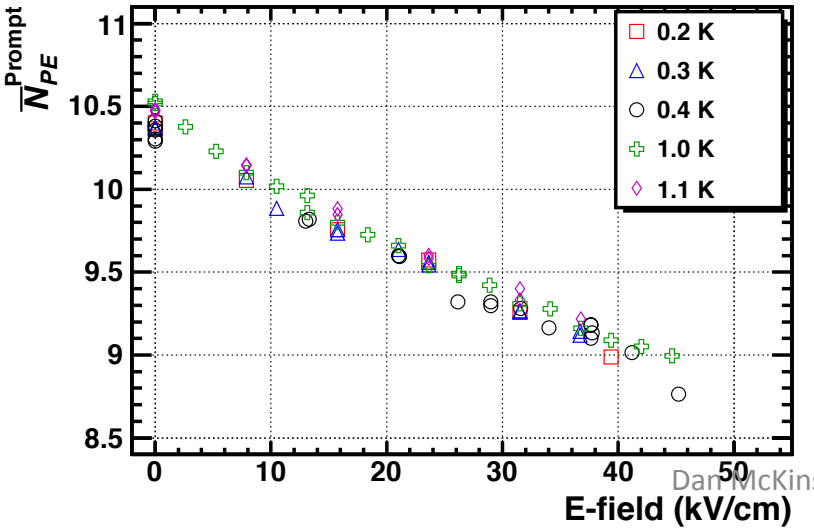


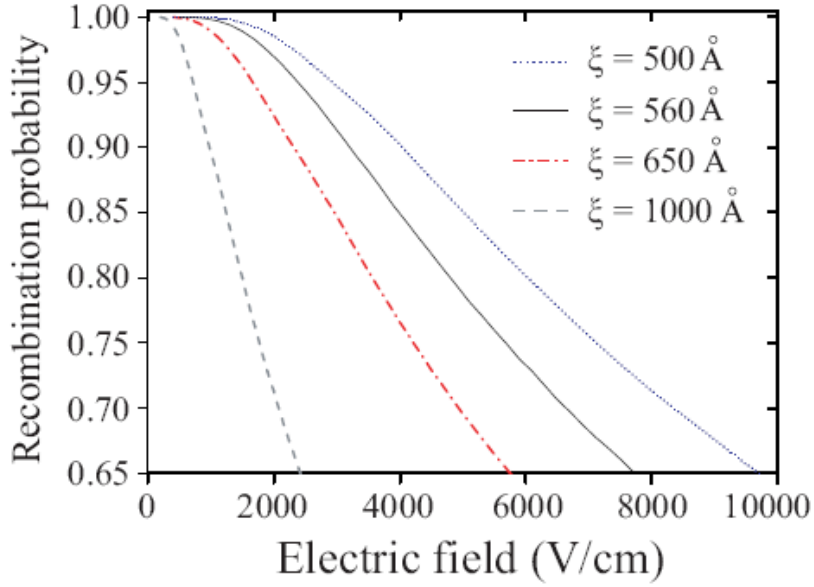
# Helium scintillation vs. electric field

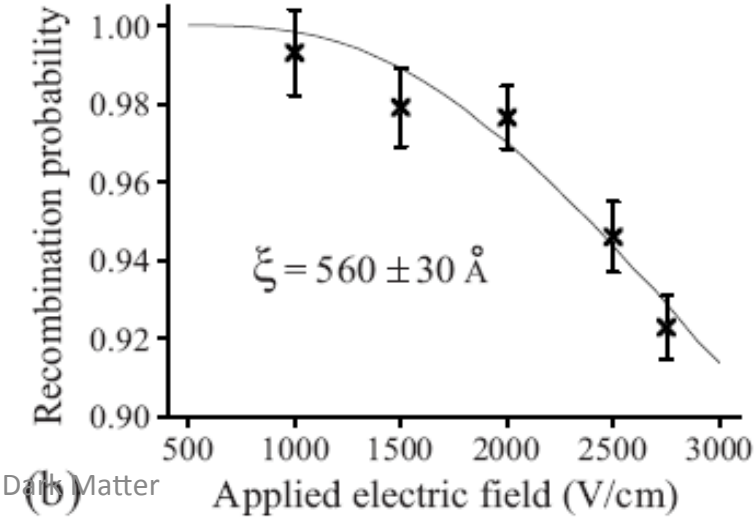
Alpha scintillation yield vs. applied field, T. Ito et al, 1110.0570




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



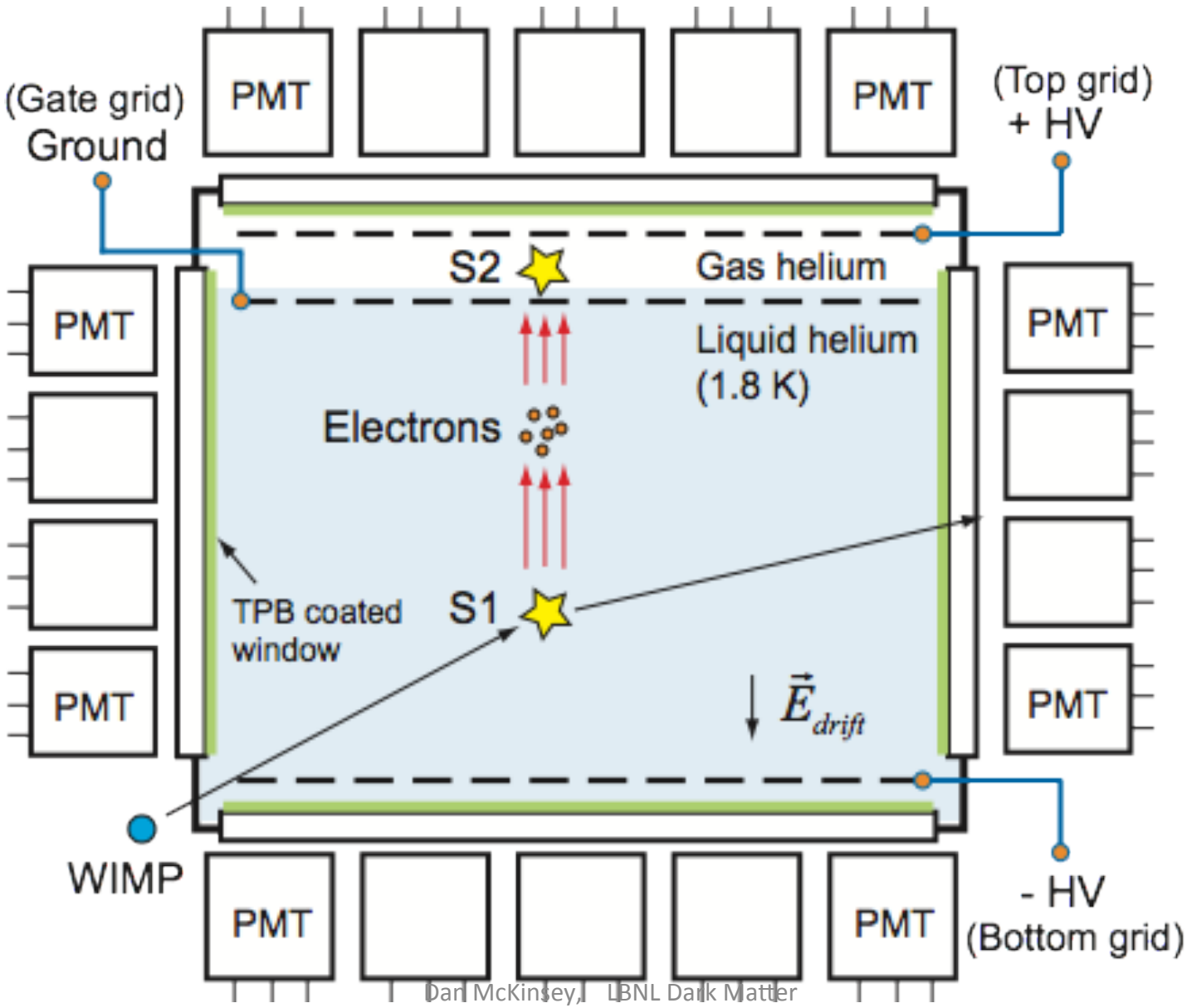
# How to detect the charge signal?

## Many options:

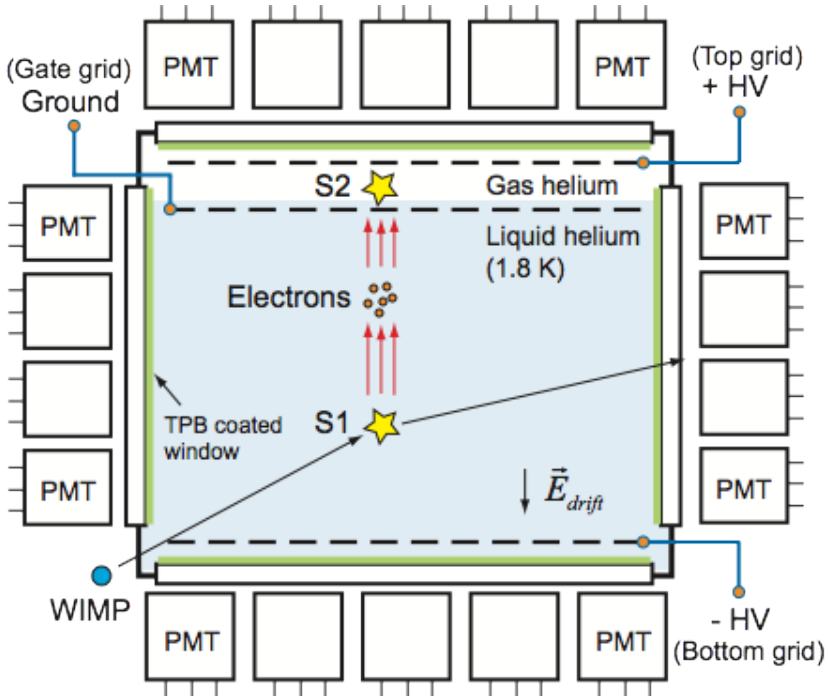
- Proportional scintillation and PMTs (like in 2-phase Xe, Ar detectors)
- Gas Electron Multipliers (GEMs) or Thick GEMS, detect light produced in avalanche.
- Thin wires in liquid helium. This should generate electroluminescence at fields ~1-10 MV/cm near wire, and is known to happen in LAr and LXe.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

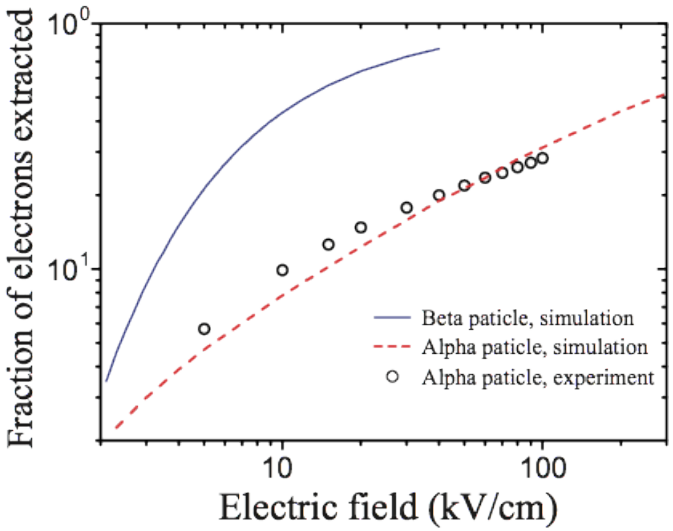
Charge will drift at ~ 1 cm/ms velocities. Slower than LAr/LXe, but pileup manageable for low background rates.

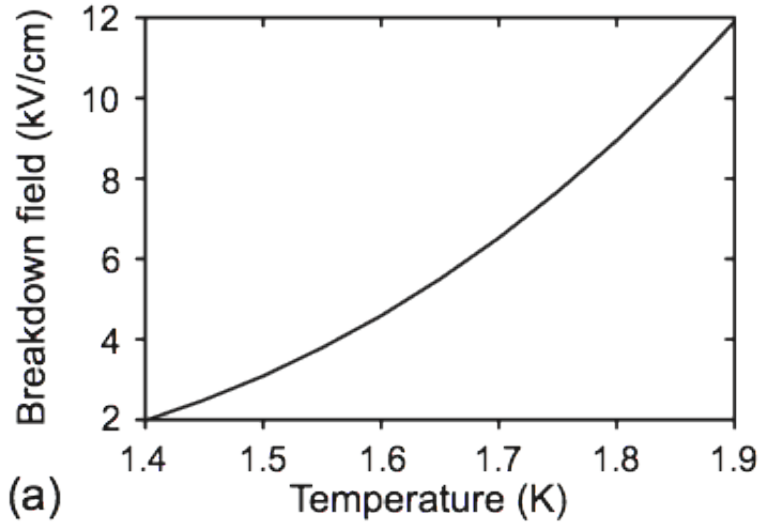
# Light WIMP Detector Concept #1: Two-Phase Helium

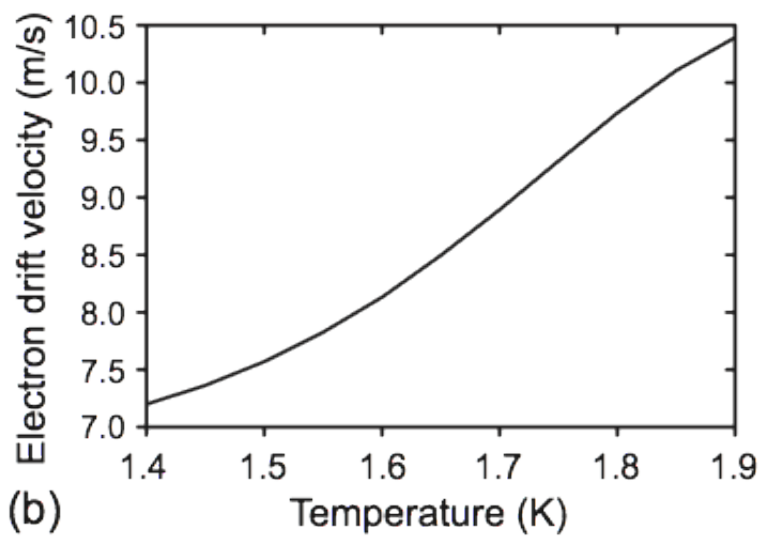


# A two-phase helium detector; salient properties

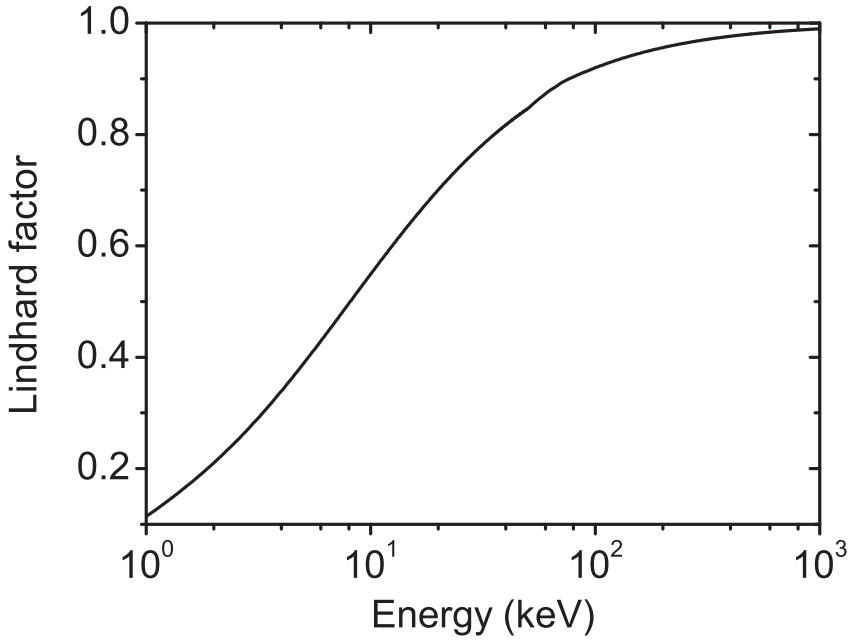


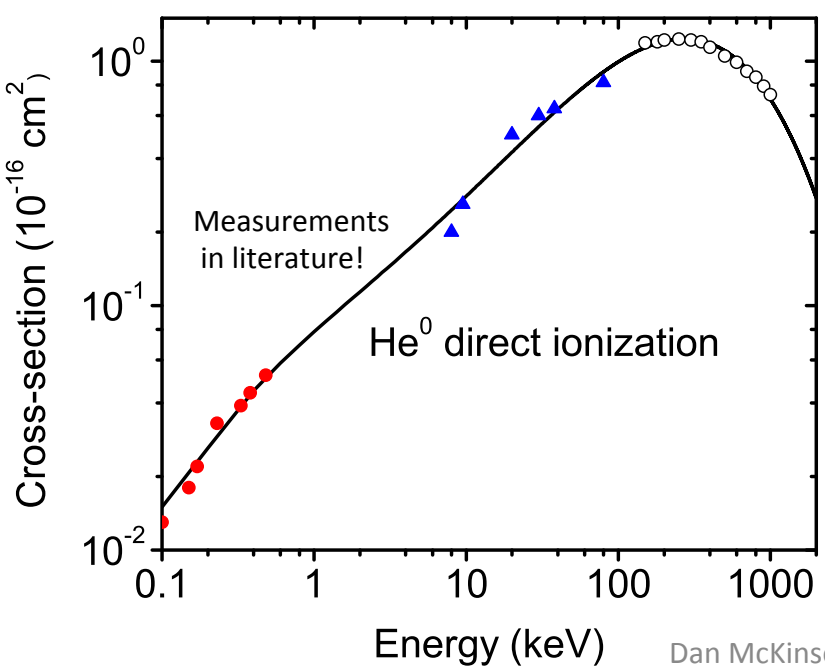

Alpha data: A.N. Gerritsen, Physica 14, 407 (1948)

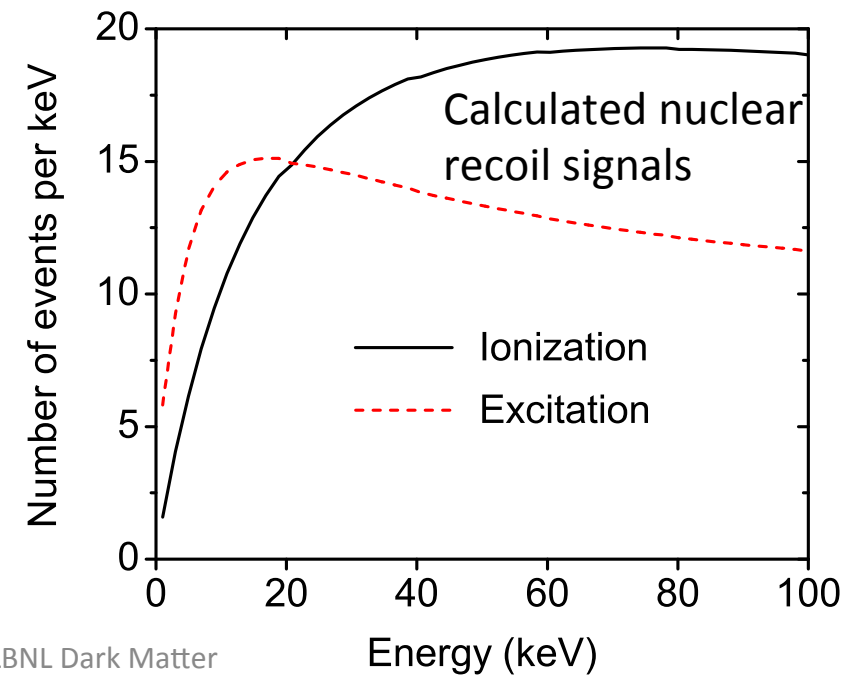



Liquid helium-4 predicted response (Guo and McKinsey, arXiv:1302.0534, Phys. Rev. D 87, 115001 (2013).)

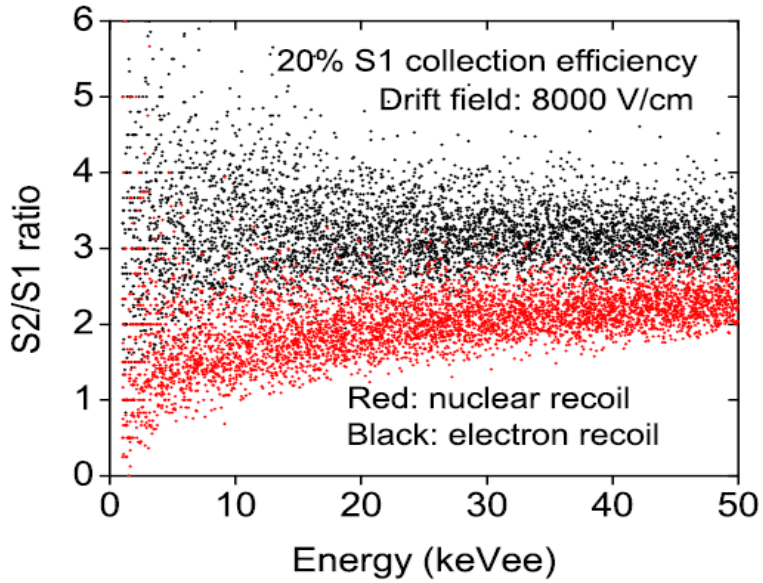
Liquid helium has lower electron scintillation yield for electron recoils (19 photons/keVee)

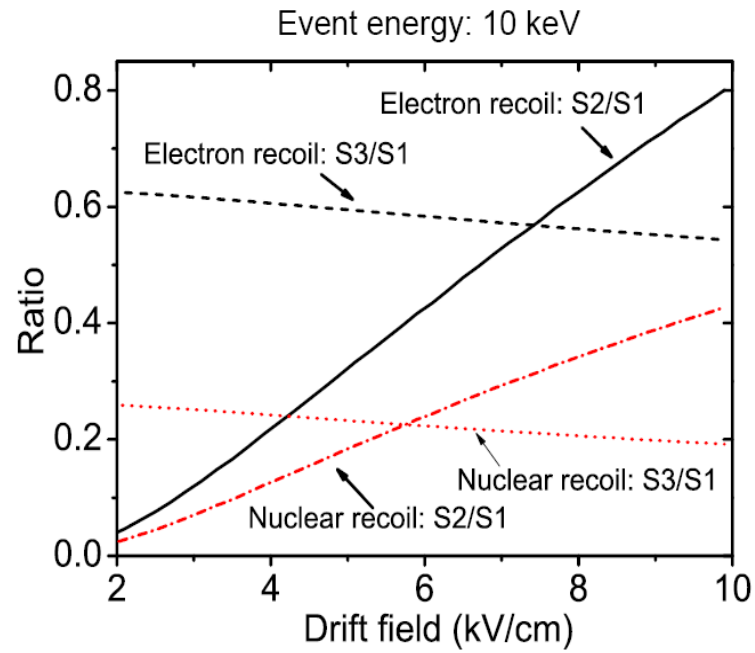
But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity

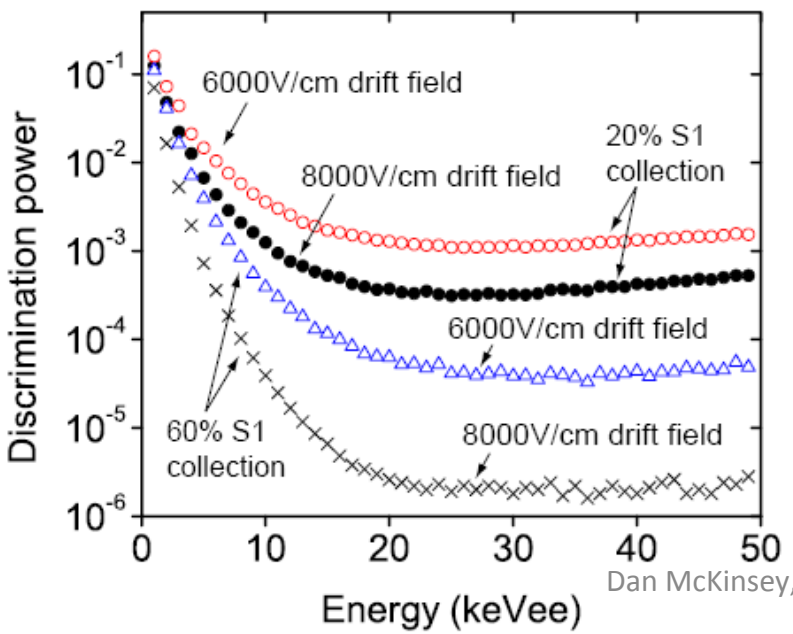


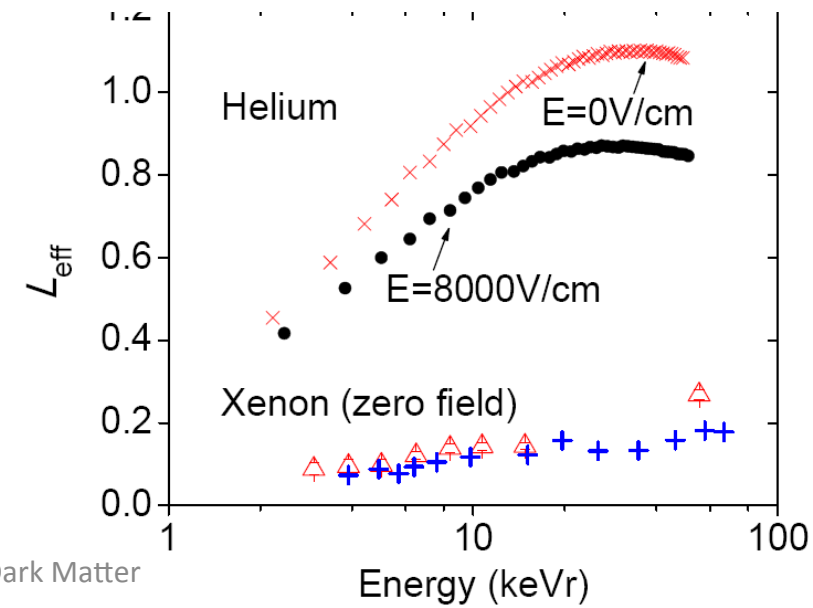



# Predicted nuclear recoil discrimination and signal strengths in liquid helium

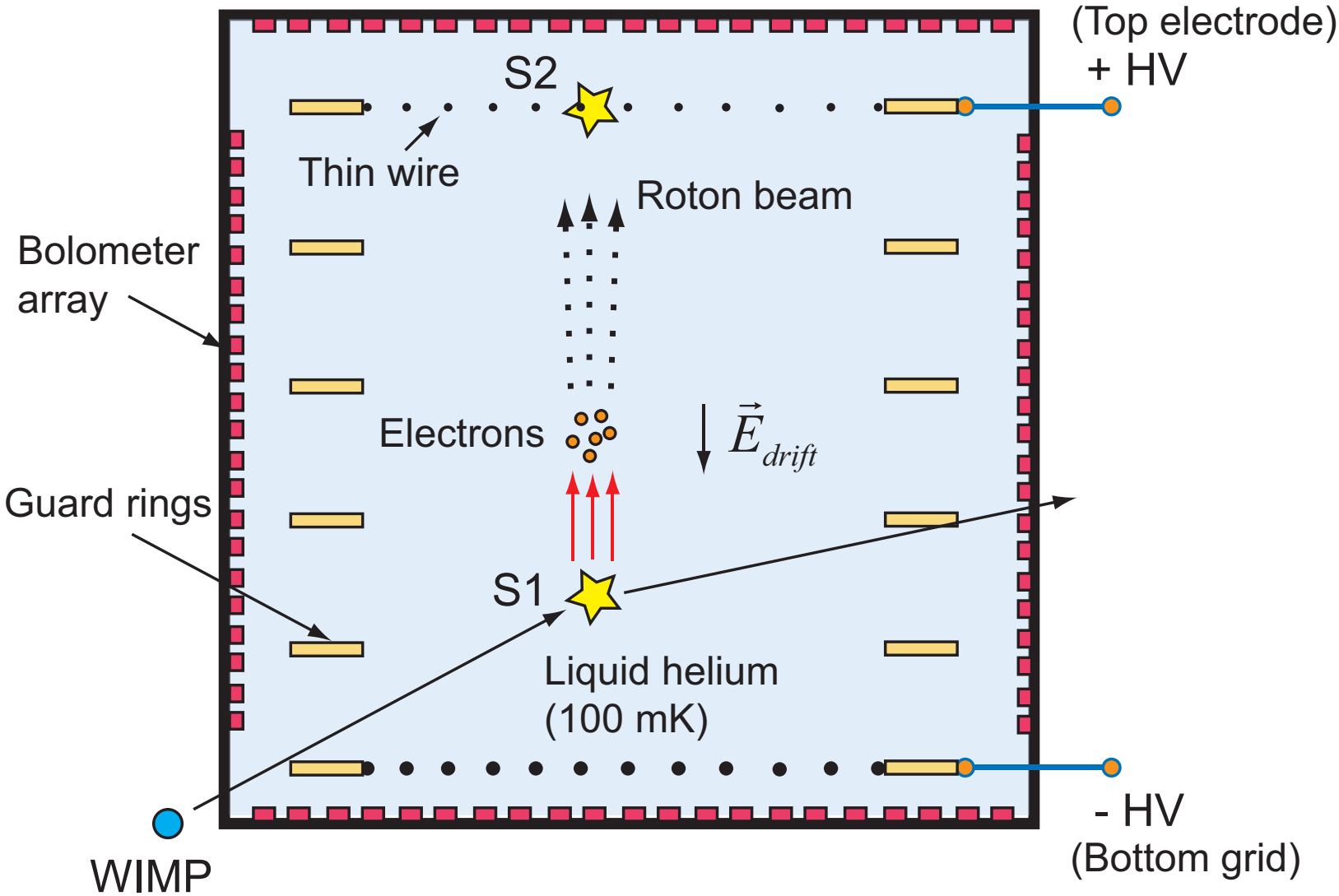


# Concept #2: A Light WIMP Detector with 20 bar superfluid helium at ~ 100 mK

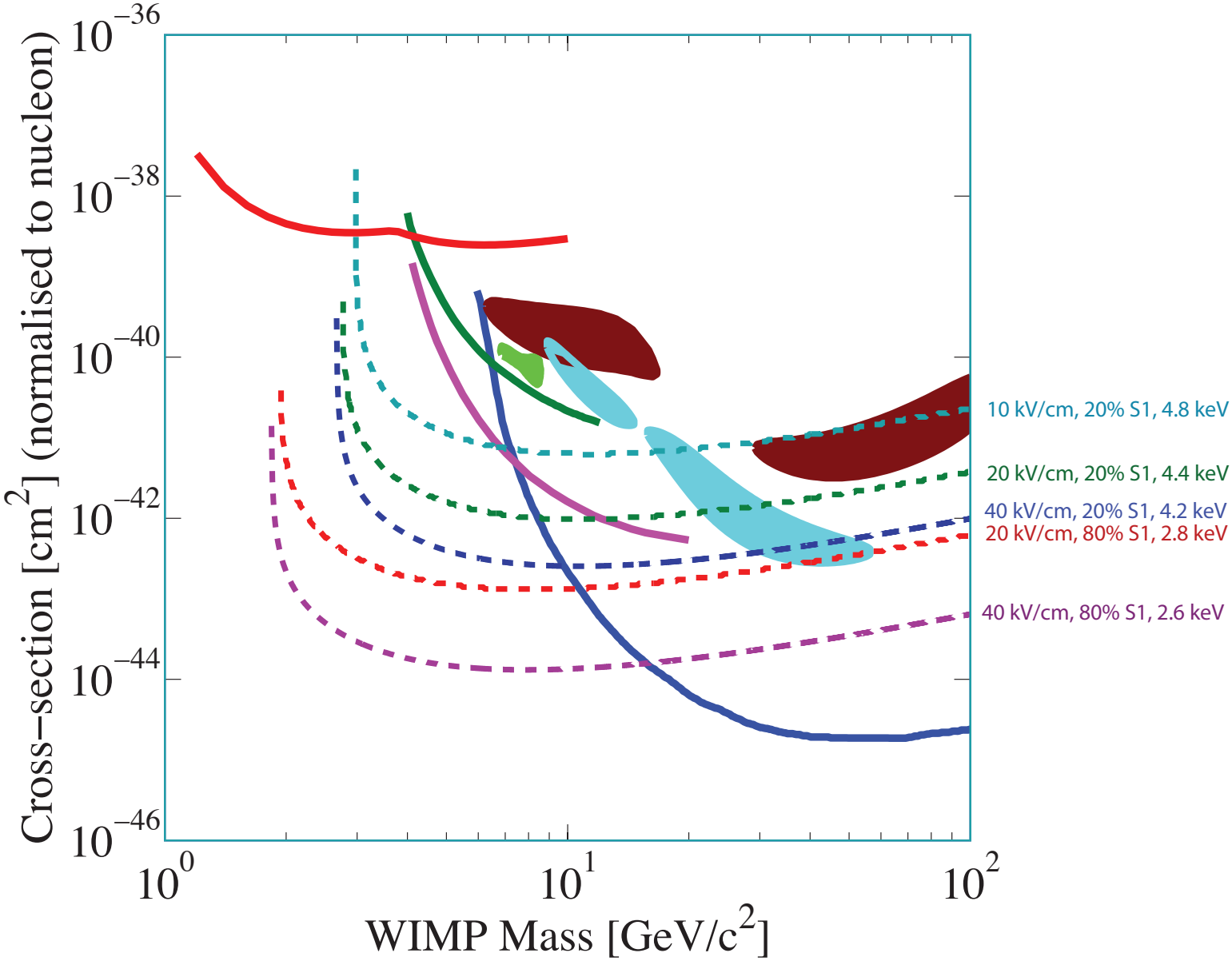


# How to detect S3 (helium molecules)?

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 ~ 1 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!
  - See next talk by Scott Hertel on latest R&D results on this topic.

Projected Sensitivity for Liquid Helium with Light and Charge Readout



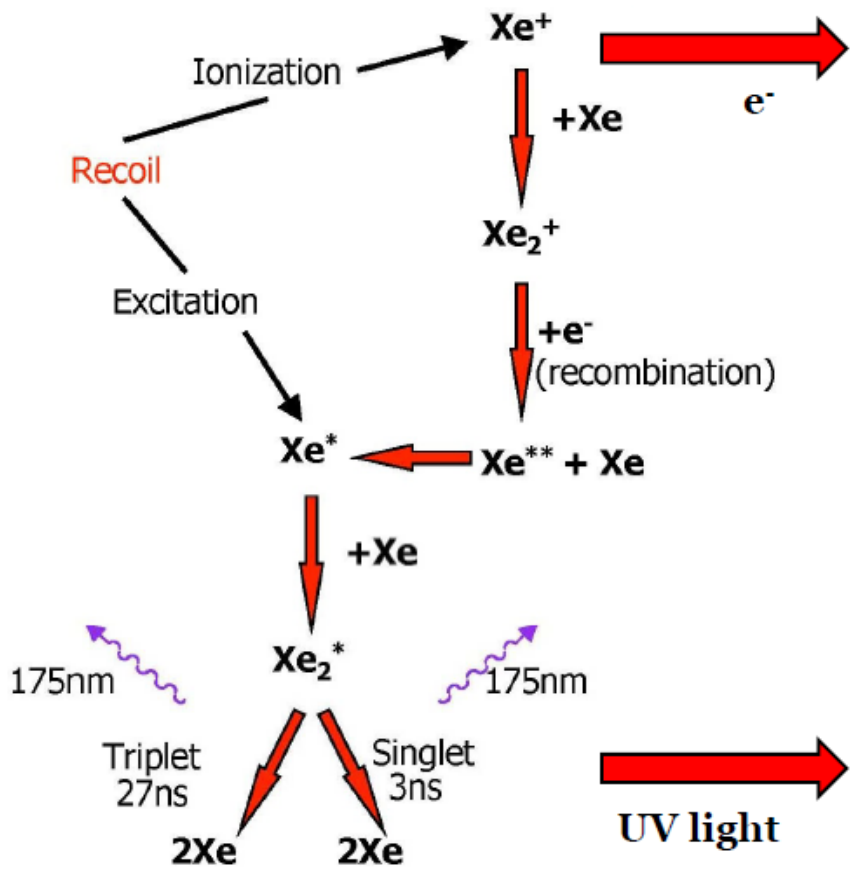
# Direct WIMP Detection with Liquid Xenon

- Goal: observe recoils between a WIMP and a target nucleus
- Equation for WIMP interaction cross section

$$\frac{dN}{dE_R} \propto \left( \frac{e^{-E_R/(E_0 r)}}{E_0 r} \right) \cdot \left( F^2(E_R) \cdot I \right)$$

$$I \propto A^2 \quad \text{(for S.I. interactions)}$$

- Recoil energy deposited in three channels:
  - Scintillation (photons)
  - Ionization (charge)
  - Heat (phonons)



# Direct WIMP Detection with Liquid Xenon

^ Neon/Helium-doped

- Goal: observe recoils between a WIMP and a target nucleus
- Equation for WIMP interaction cross section

$$\frac{dN}{dE_R} \propto \left( \frac{e^{-E_R/(E_0 r)}}{E_0 r} \right) \cdot \left( F^2(E_R) \cdot I \right)$$

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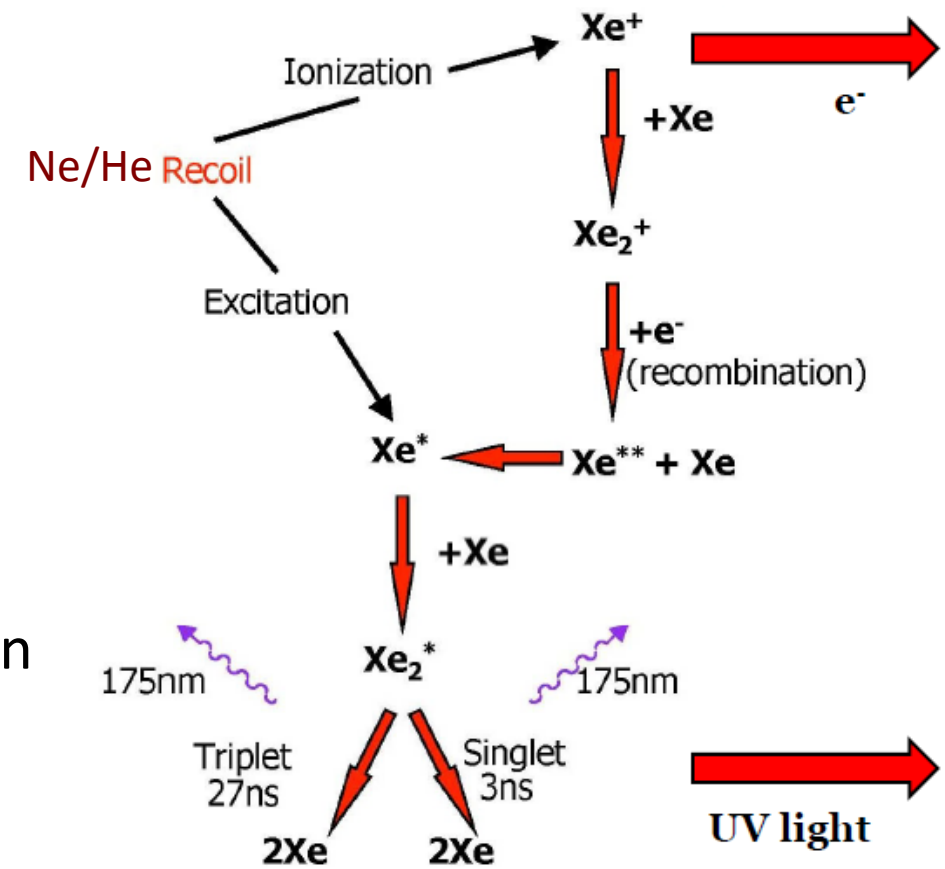
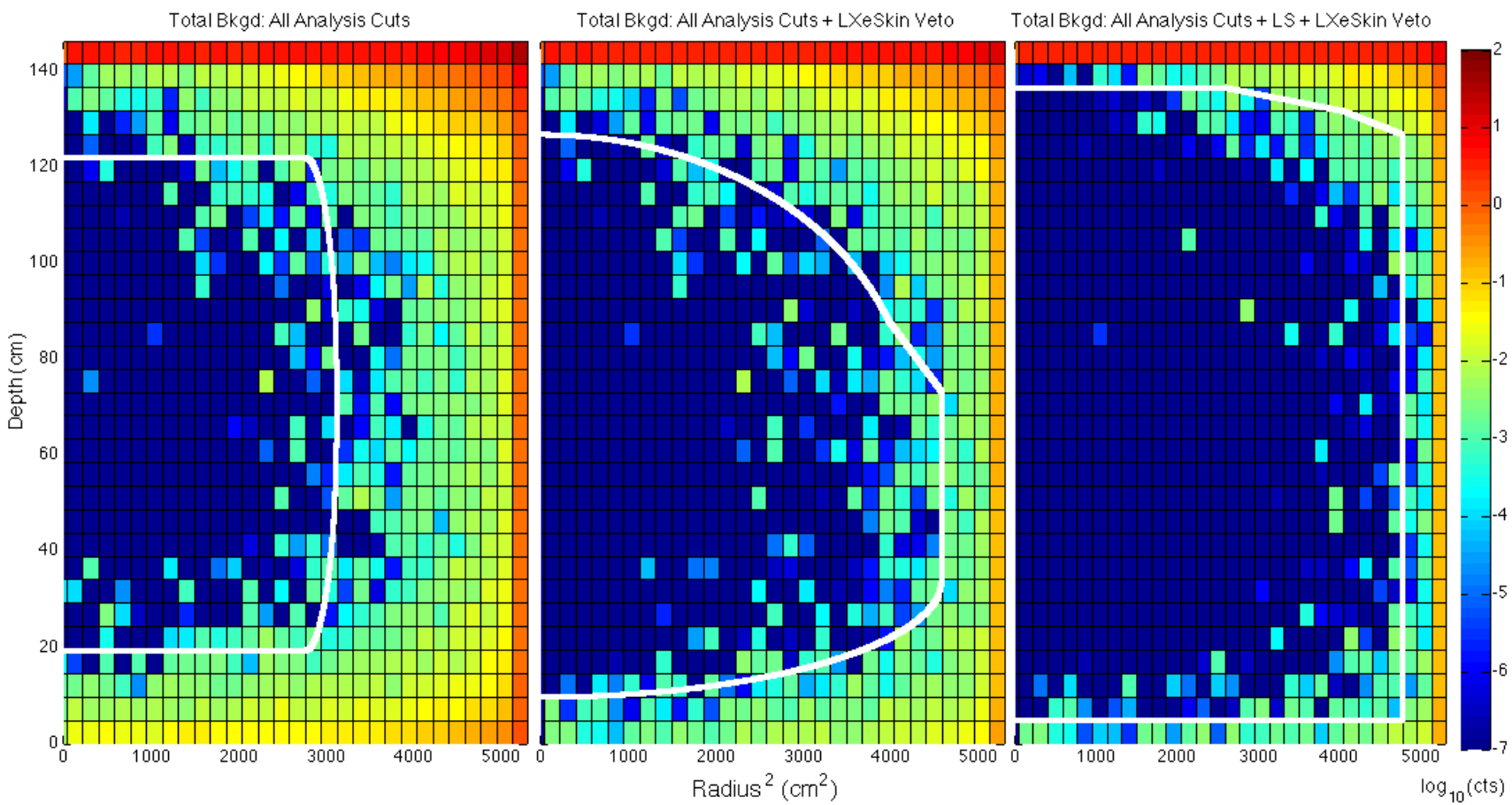


Could LXe be doped with He or Ne to create a low-background light WIMP target?

- Advantage: spectacular self-shielding ability of LXe.
- Advantage: likely improvement in nuclear recoil ionization and atomic excitation production.
- Advantage: Ne and He are easy to purify and have no long-lived isotopes.
- Advantage: After LXe signal production, Ne and He are essentially standby impurities that shouldn't affect the scintillation spectrum, so existing and well-developed LXe experimental techniques should largely work.
- Disadvantage: low density of Ne or He in LXe; a factor of 8-10 below ideal gas law, so about 4 orders of magnitude lower than the LXe density.
  - BUT, necessary mass is quite small, 4 orders of magnitude less than for heavy WIMPs
- Disadvantage: He and Ne can diffuse into and destroy PMTs.
  - BUT, low temperatures suppress diffusion in glass. Neon is probably fine if added after cooldown, but this need to be tested. Helium would need different light readout (Silicon photomultipliers?)

# LZ: Self-shielding reduces gamma ray/neutron background to well below neutrinos

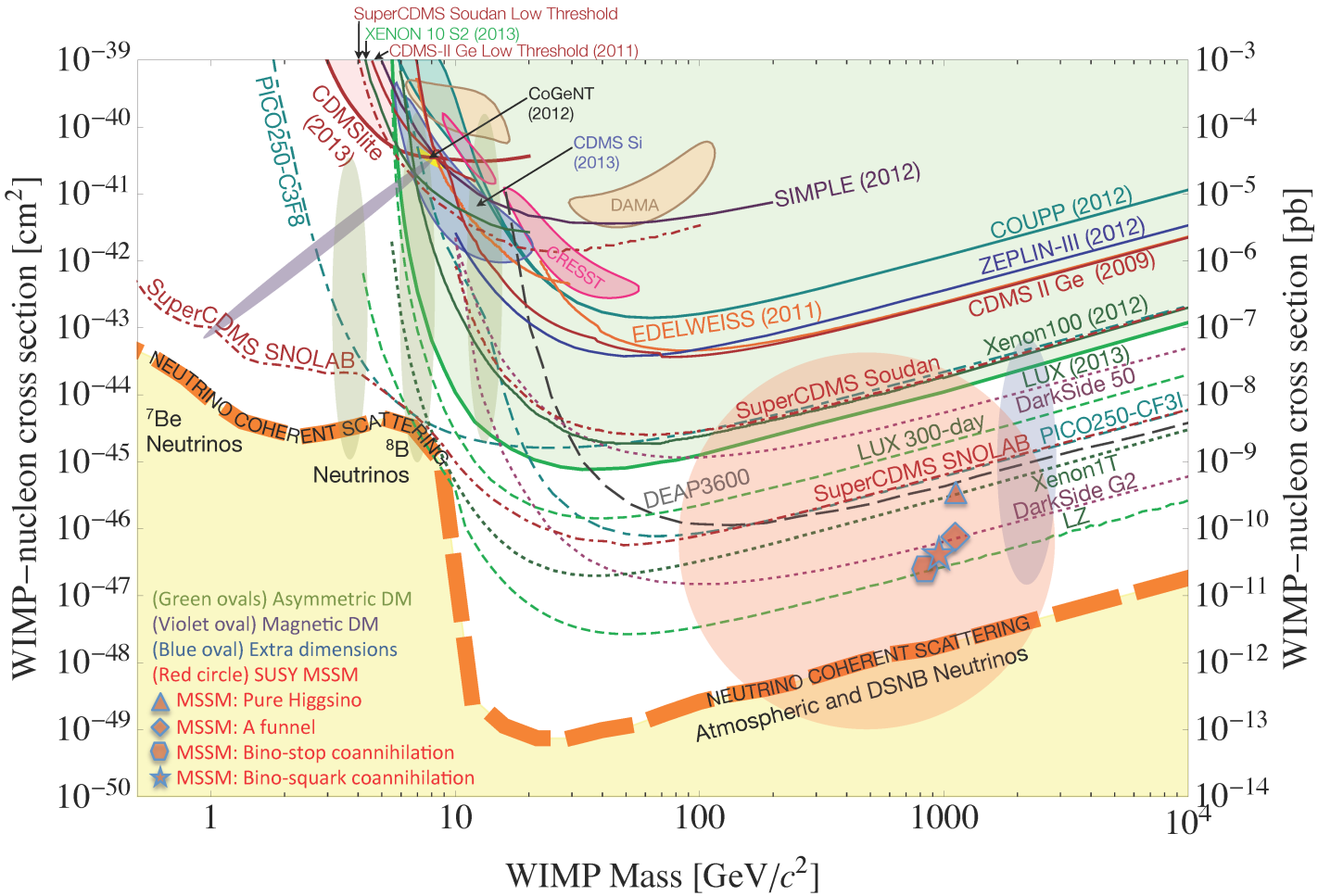


# Neon/Helium density

- Henry coefficients (density in liquid, compared to density in gas above the liquid) for Neon or Helium is LXe are likely 10-20%, based on trend of heavier solutes.
  - But not yet measured, to my knowledge.
- This leads to an order of magnitude lower

  He/Ne density than you might naively calculate from ideal gas law.

Neutrino background is 4 orders of magnitude higher for light dark matter than standard WIMPs.
This is similar to the doping fraction of a light target in LXe




Dan McKinsey, LBNL Dark Matter

# Excitation and Ionization in Doped LXe

- Lindhard theory is less developed when the target nucleus is different from the main target material.
  - Electronic stopping power scales as the projectile velocity, which obviously is higher for light targets than for heavy ones, at a given recoil energy.
- More importantly, the nuclear stopping power for a light target in a heavy one is suppressed by the ratio $Z_1/Z_2$, so heat production is diminished and electronic excitation is enhanced. See P. Sigmund, European Physical Journal D **47**, 45 (2008).

$$M_2 S_{n,1 \text{ in } 2} = M_1 S_{n,2 \text{ in } 1},$$

# 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 has 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.
- A concept for a superfluid helium-based dark matter detector was presented.
- A concept for a LHe or LNe-doped LXe experiment was presented. Likely advantage of high excitation and ionizations yields, but NR measurements are needed.