Light Noble Gases for Light Dark Matter Detection

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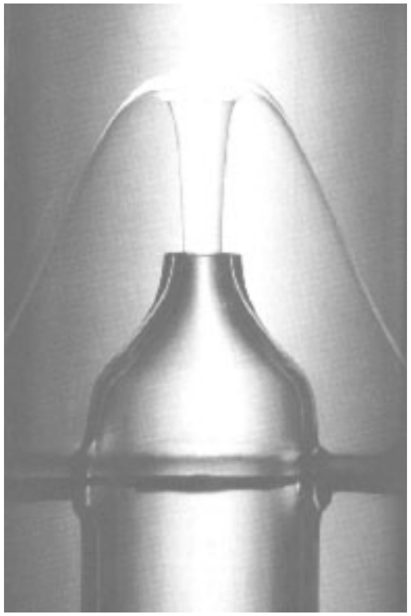


CPAD Workshop

University of Texas, Arlington

October 6, 2015

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 (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

Two topics:

1) Liquid helium-4 for light dark matter detection
2) Doping liquid xenon with light noble gases

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.

Why Helium-4?

- 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 to choose from:
  - Prompt light
  - Delayed triplet excimers
  - Charge
  - Heat (roton and photon quasiparticles)
- Liquid down to 0 K, allowing 100 mK-scale bolometric readout.
- Helium is expected to have robust ionization efficiency, with a forgiving Lindhard factor (high Leff), so nuclear recoil signals should be relatively large.
- Negligible target cost

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

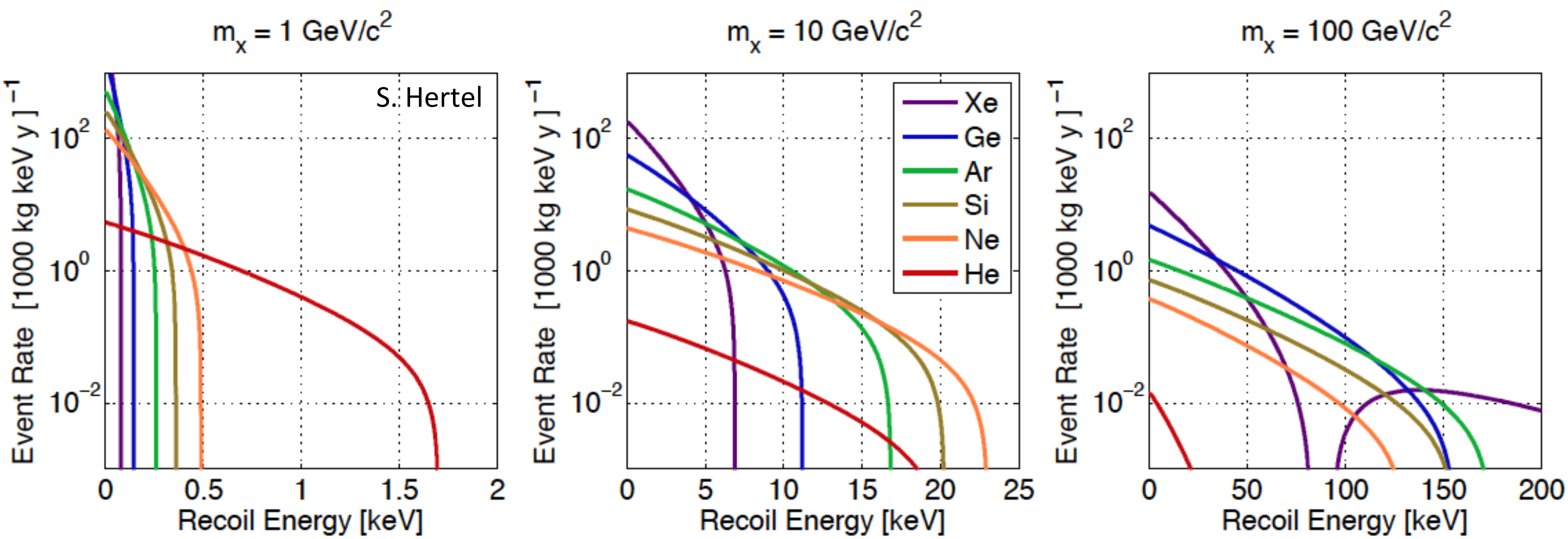
$$r_{limit} = 1/v_{esc} * \mathrm{sqrt}\{E_t M_T/2\}$$

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.

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

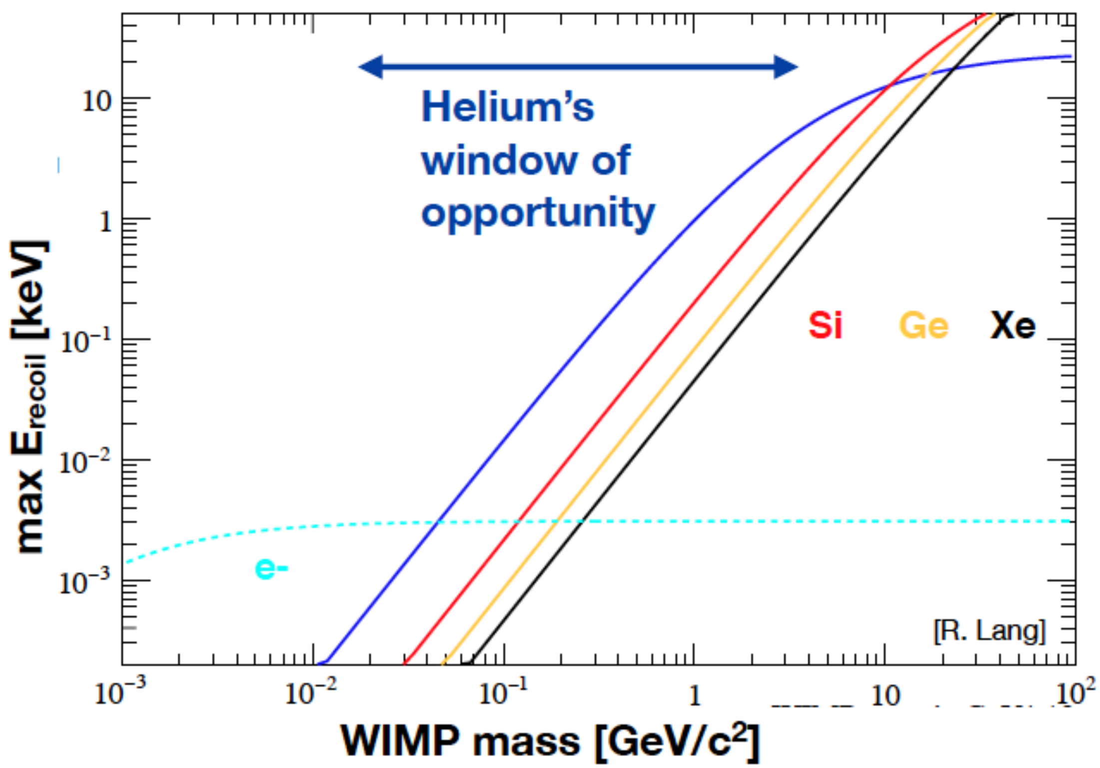


Helium-4 Nuclei: A Natural Match for Light Dark Matter Detection

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

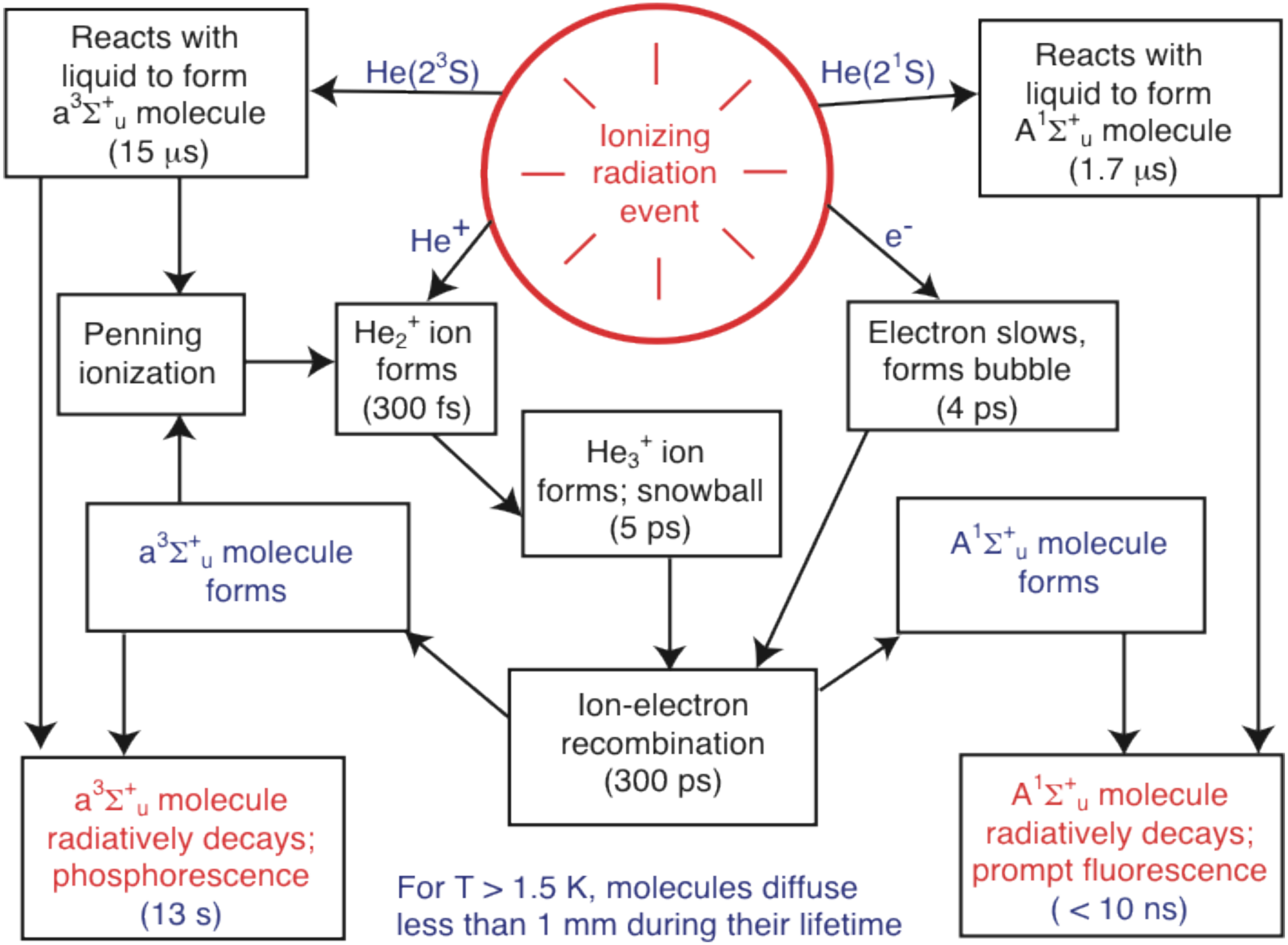


Superfluid helium as a detector material

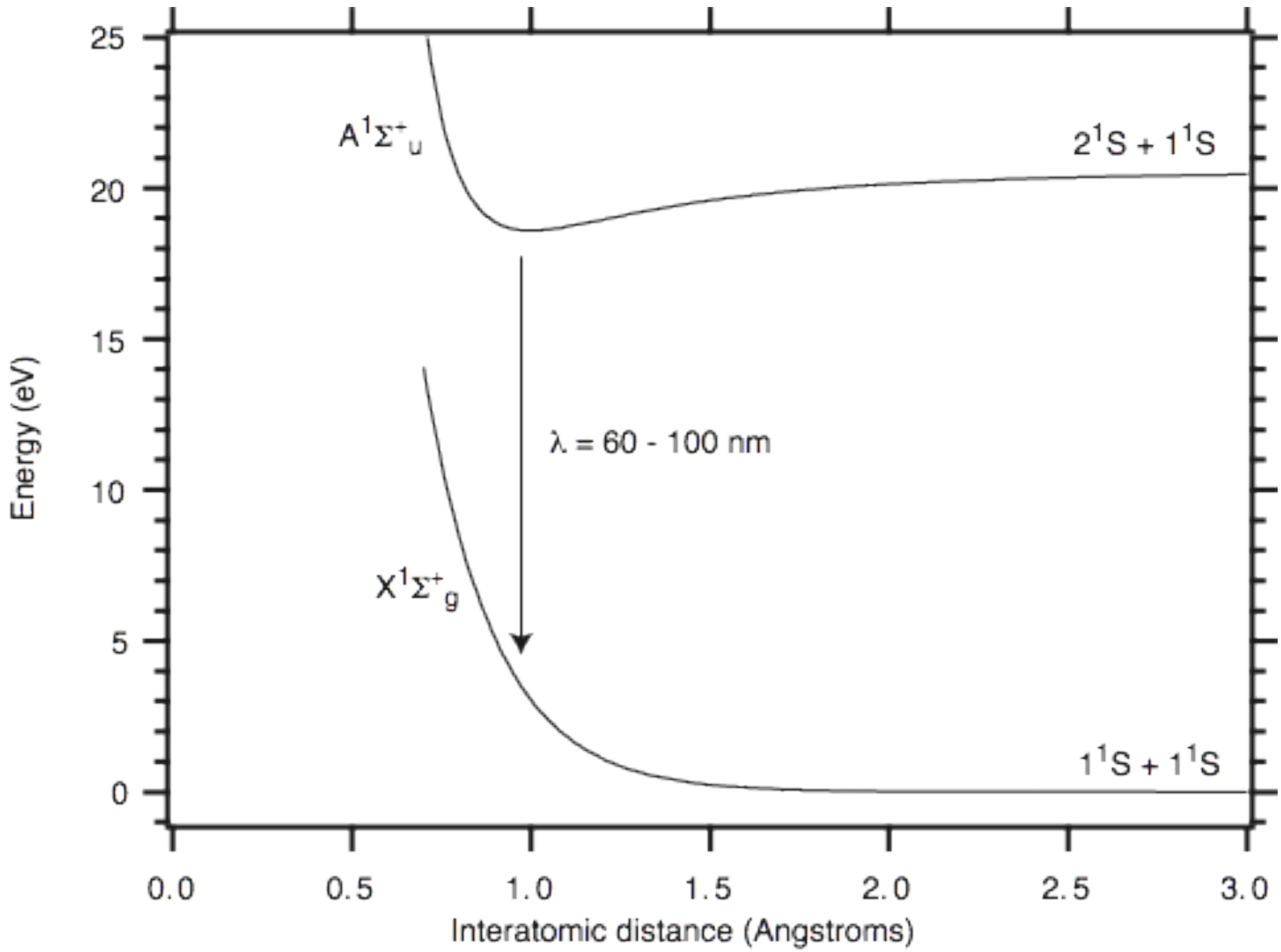
- Used to produce, store, and detect ultracold neutrons. Detection based on scintillation light (S1)
  - Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).
  - Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).

- 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).



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)


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

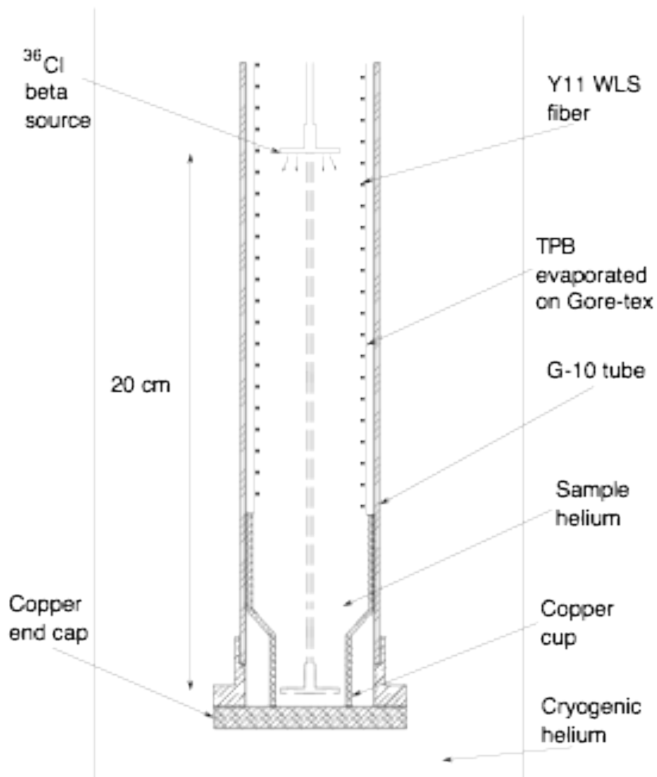
PHYSICAL REVIEW A VOLUME 59, NUMBER 1 JANUARY 1999

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)



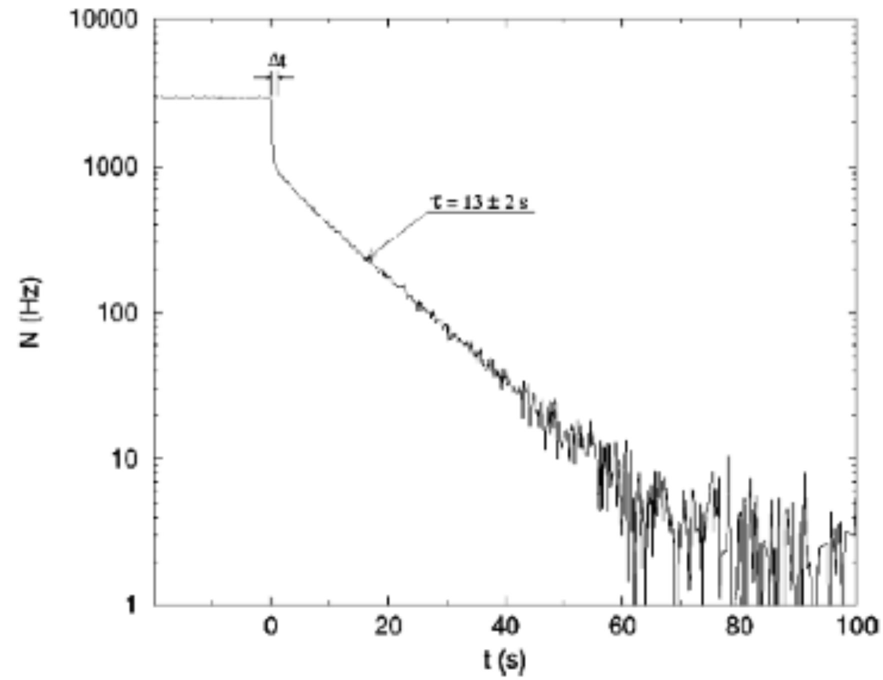
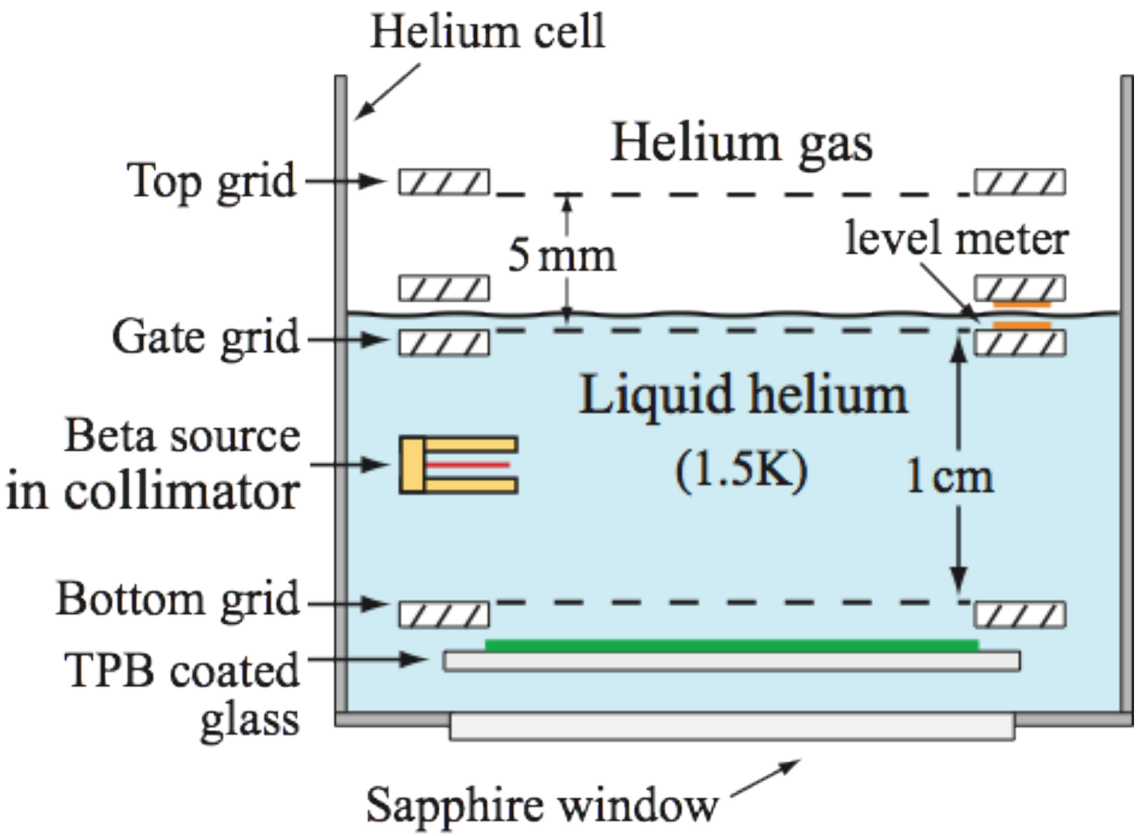


FIG. 2. Count rate N of detected $He_2(a\,^3\Sigma_u^+)$ decays versus time. A ^{36}Cl β source is placed in the center of the detection region and then removed in a time $\Delta t<1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate τ of 13 ± 2 s.

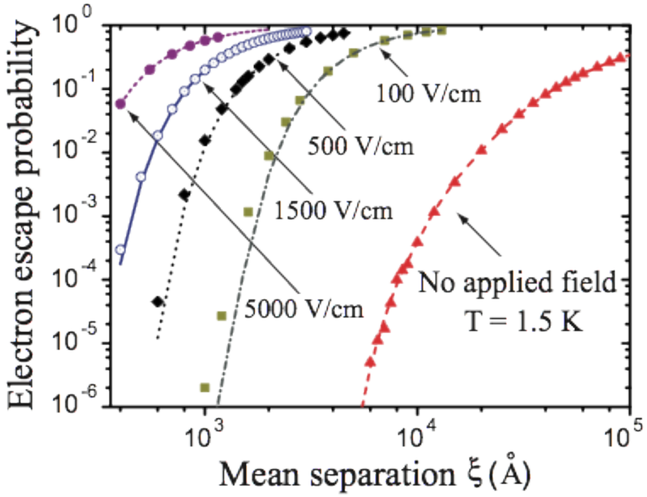
Recent work on charge yield in superfluid helium
(W. Guo et al, Journal of Instrumentation **7**, P01002 (2012).)

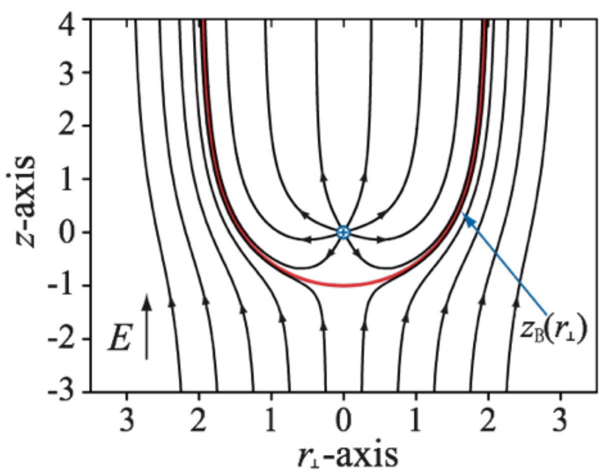


Data from charge yield measurement

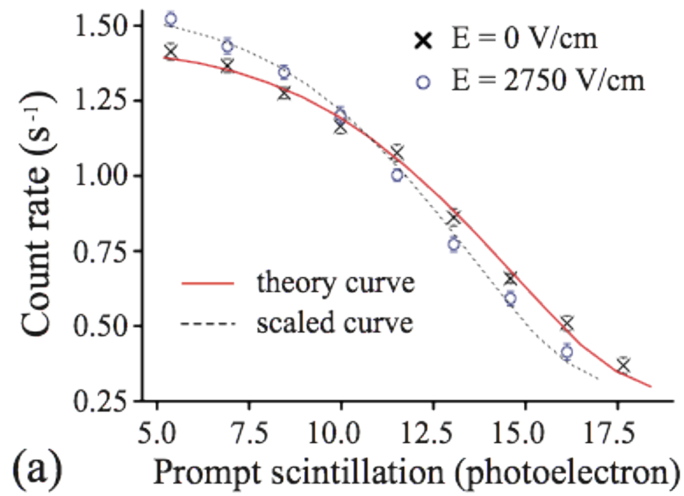
5 kV/cm will give 23% ionization extraction at higher LHe temperatures (1-2 K)
(compare to 30-50 kV/cm in n-edm experiment)

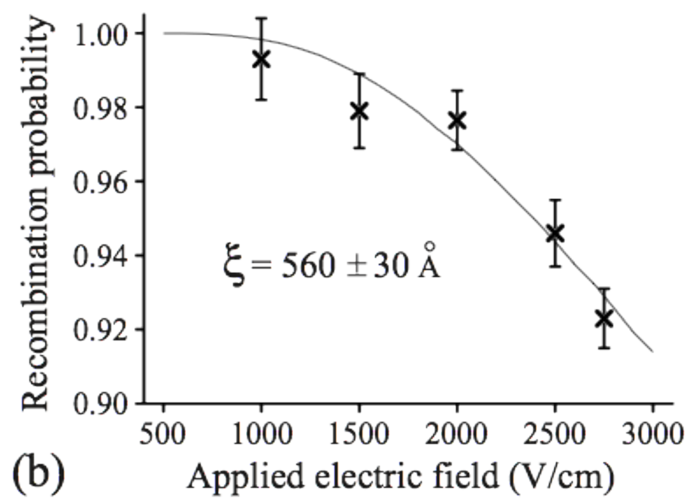
Monte Carlo results





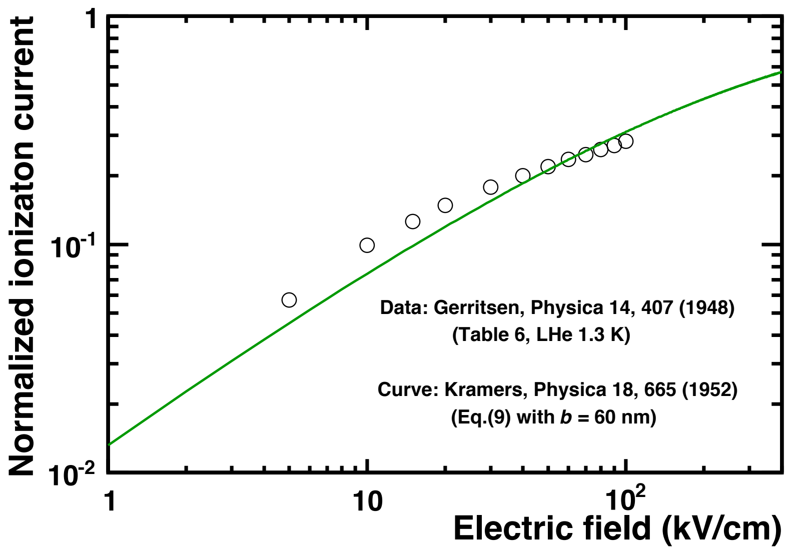
Experimental data

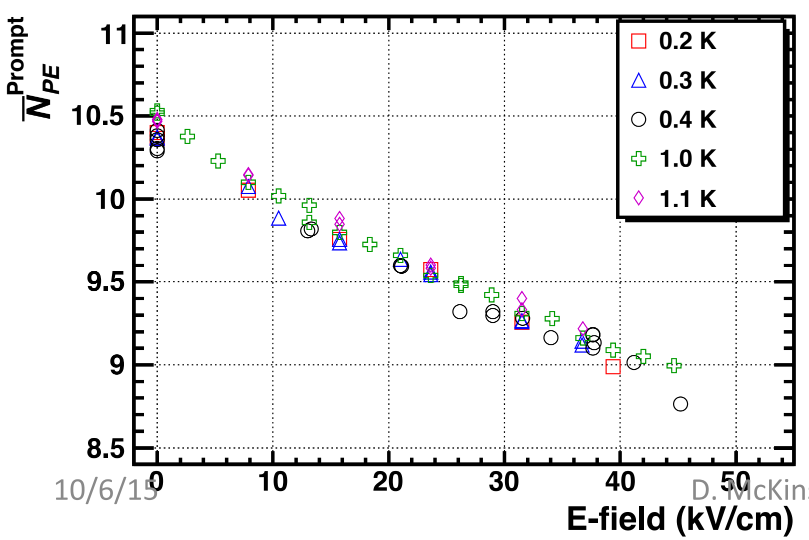




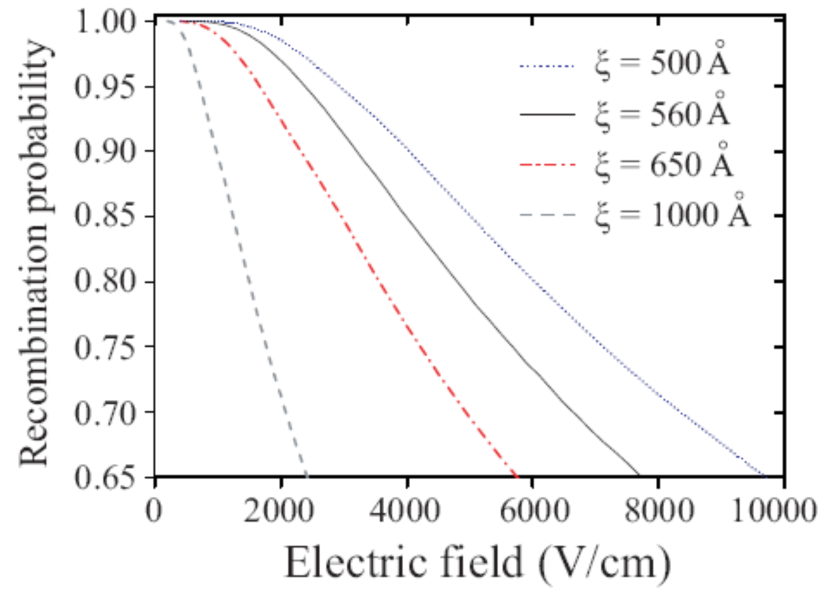
Helium scintillation vs. electric field

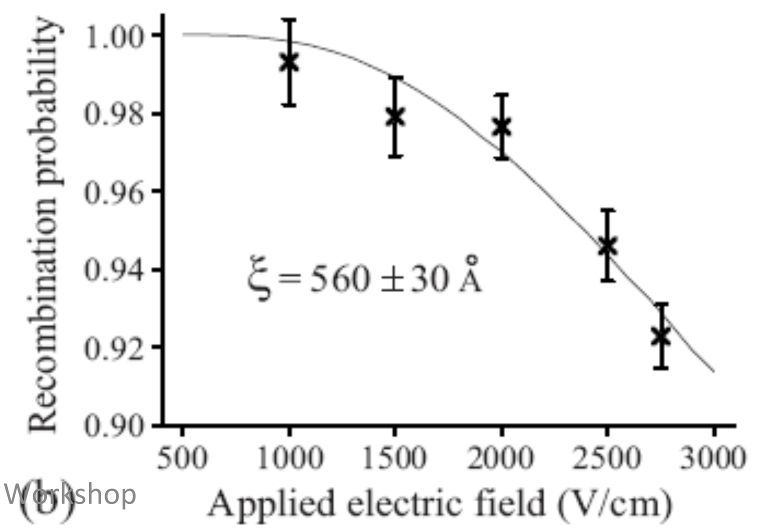
Alpha scintillation yield vs. applied field, T. Ito et al, 1110.0570





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





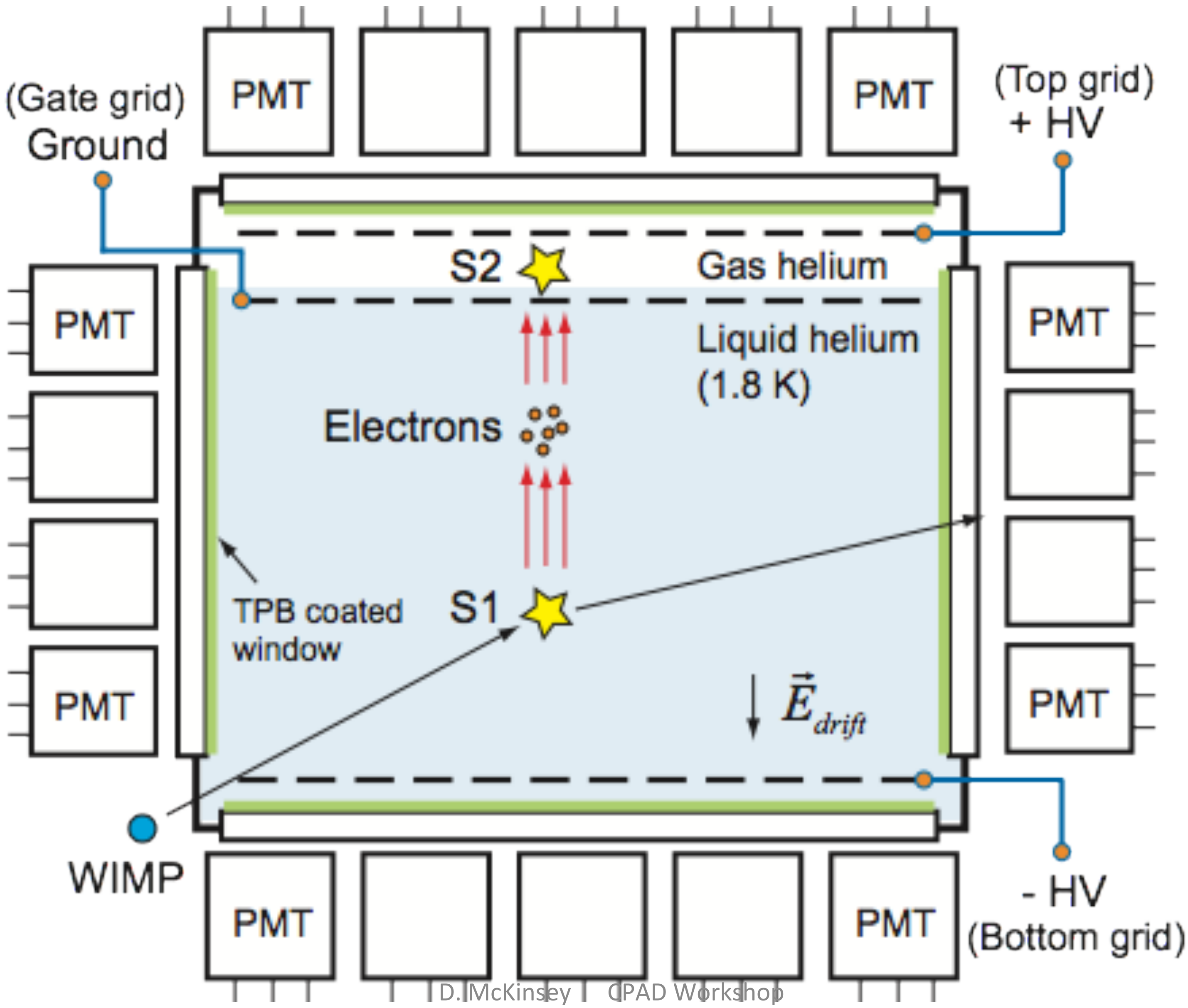
How to detect the charge signal?

Many options:

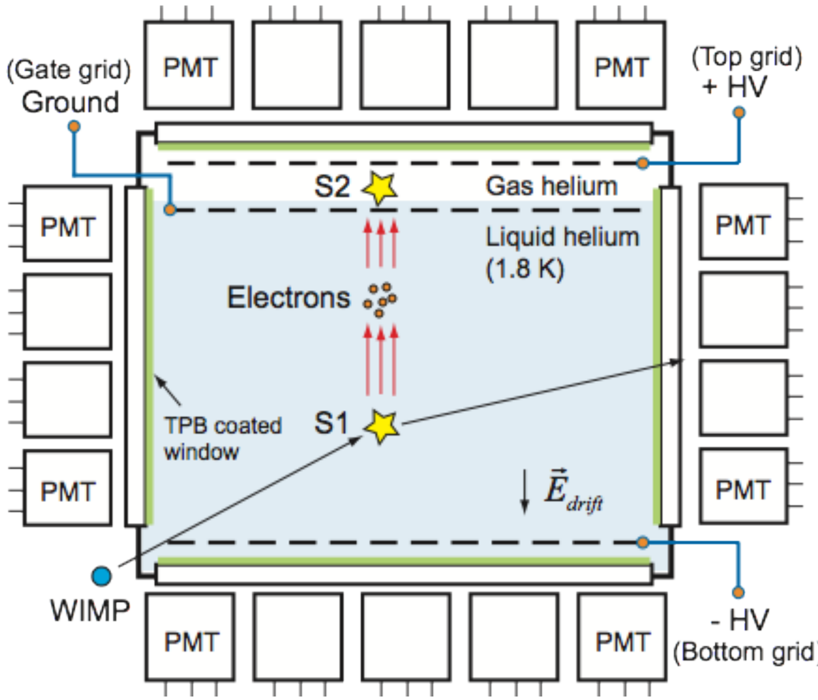
- Proportional scintillation and PMTs (like in 2-phase Xe, Ar detectors)
- Gas Electron Multipliers (GEMs) or Thick GEMS, detect light produced in avalanche.
- Thin wires in liquid helium. This should generate electroluminescence at fields ~1-10 MV/cm near wire, and is known to happen in LAr and LXe.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

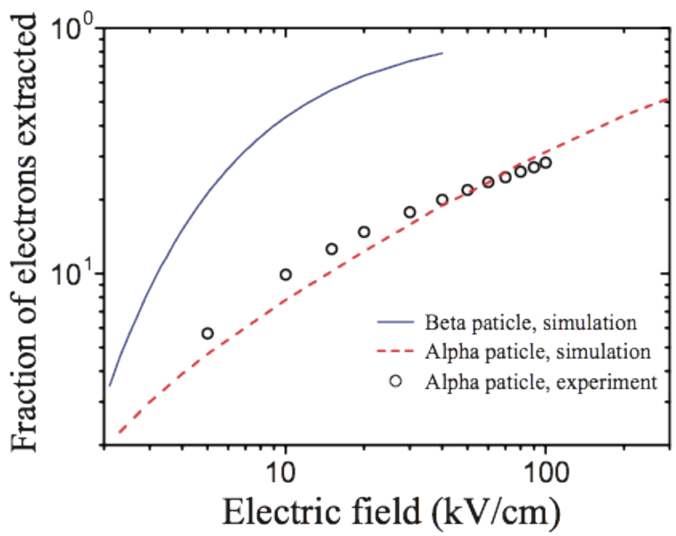
Charge will drift at ~ 1 cm/ms velocities. Slower than LAr/LXe, but pileup manageable for low background rates.

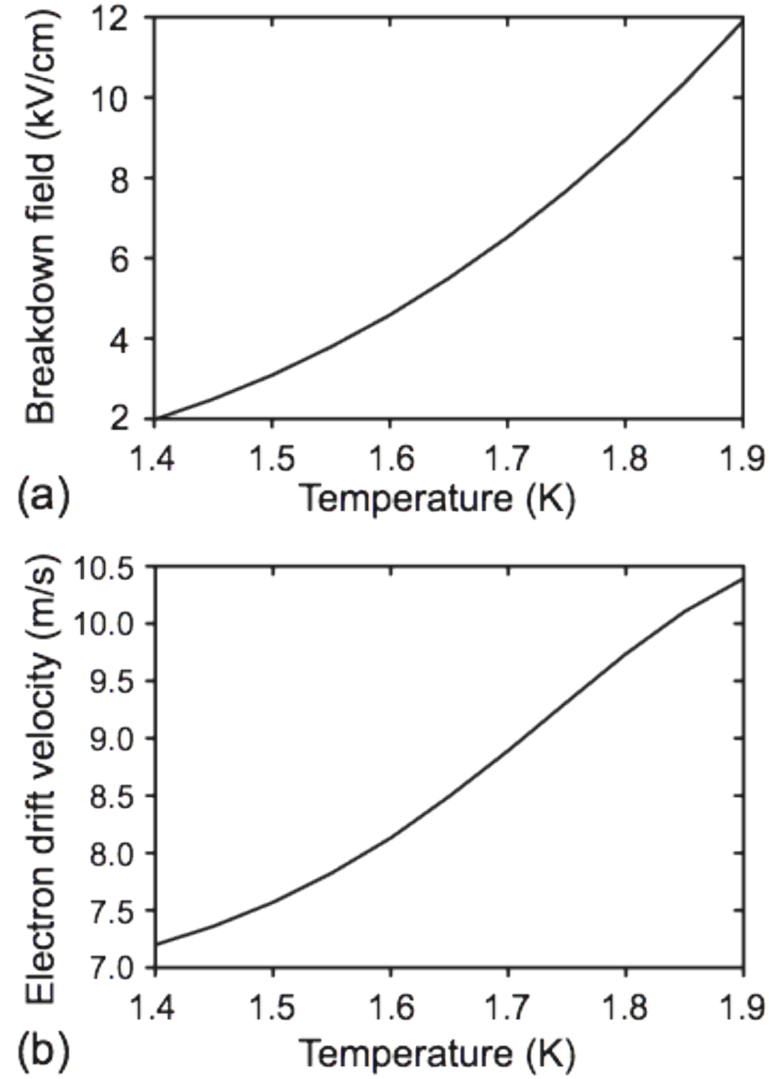
Light WIMP Detector Concept #1: Two-Phase Helium



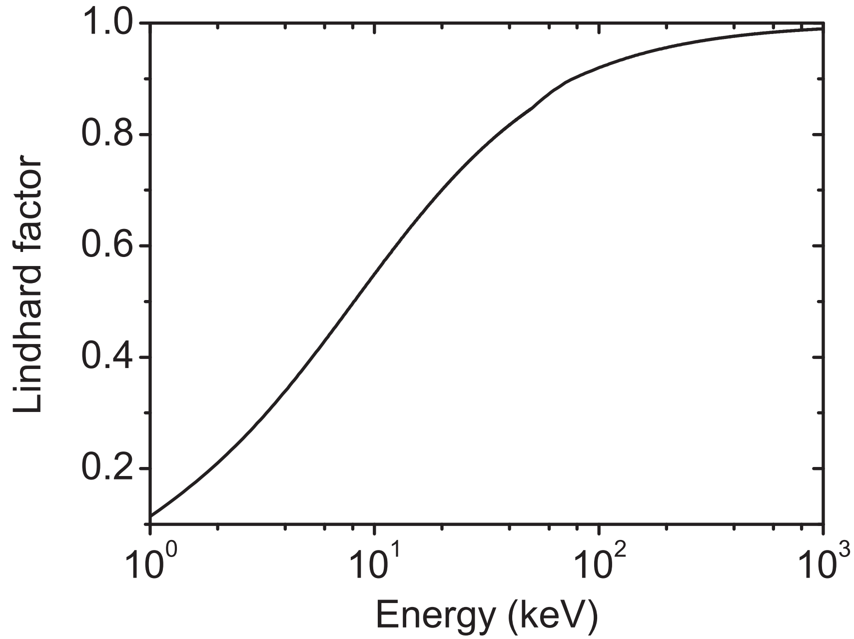
A two-phase helium detector; salient properties







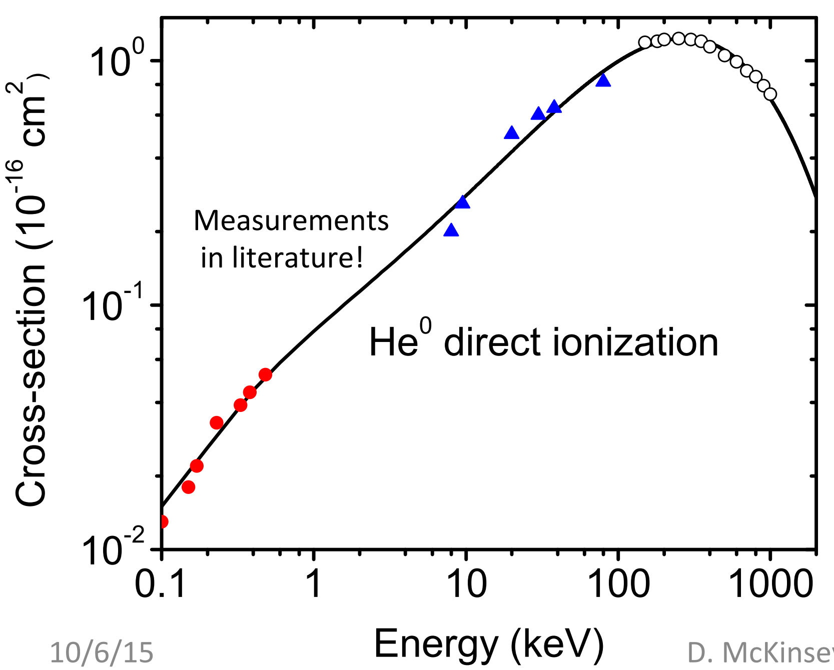
Alpha data: A.N. Gerritsen, Physica 14, 407 (1948).

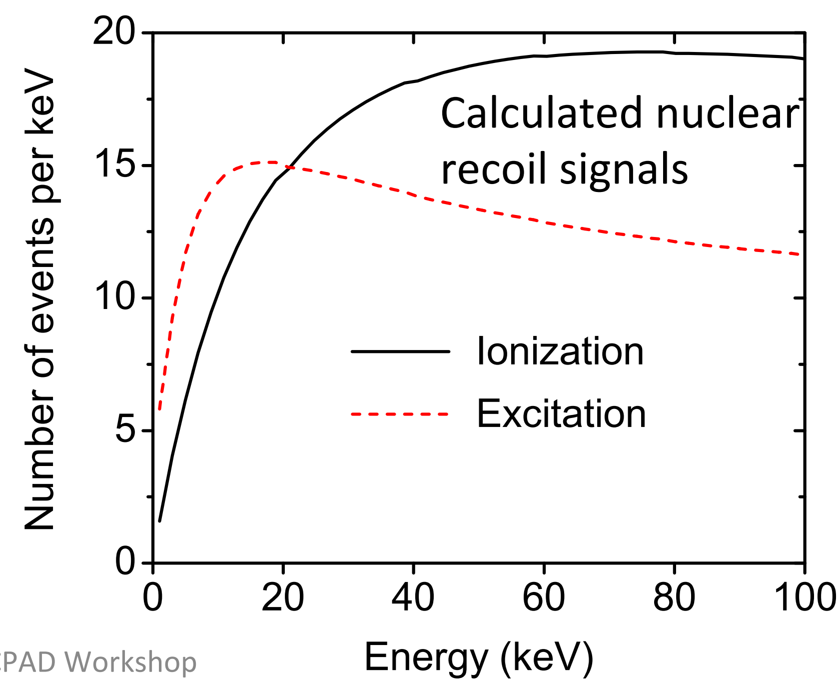


Liquid helium-4 predicted response (Guo and McKinsey, arXiv:1302.0534, Phys. Rev. D 87, 115001 (2013).)

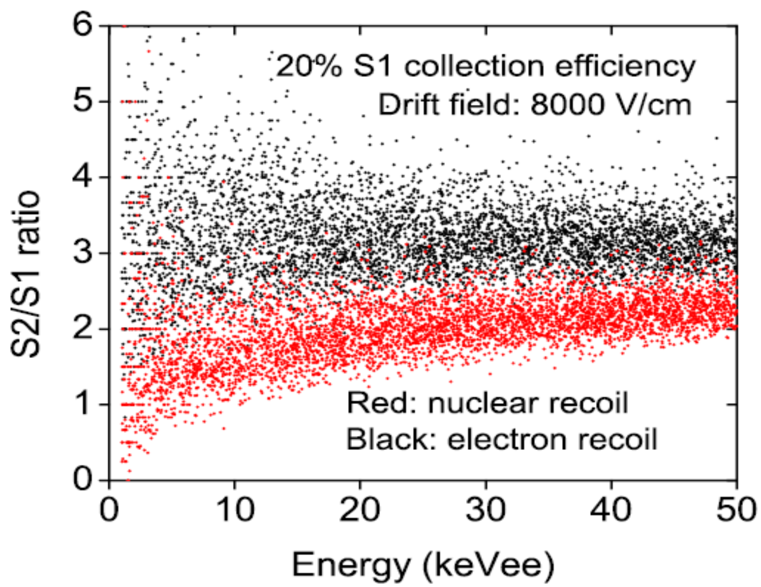
Liquid helium has lower electron scintillation yield for electron recoils (19 photons/keVee)

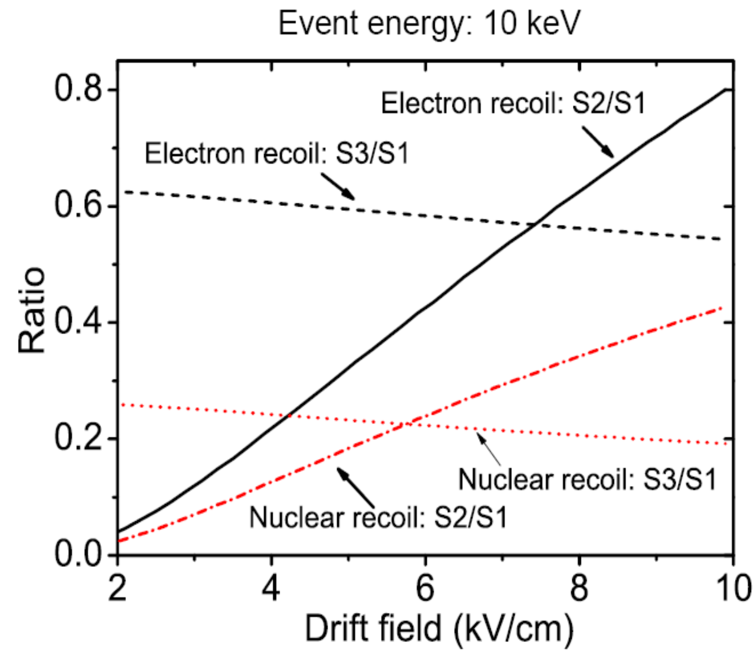
But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity

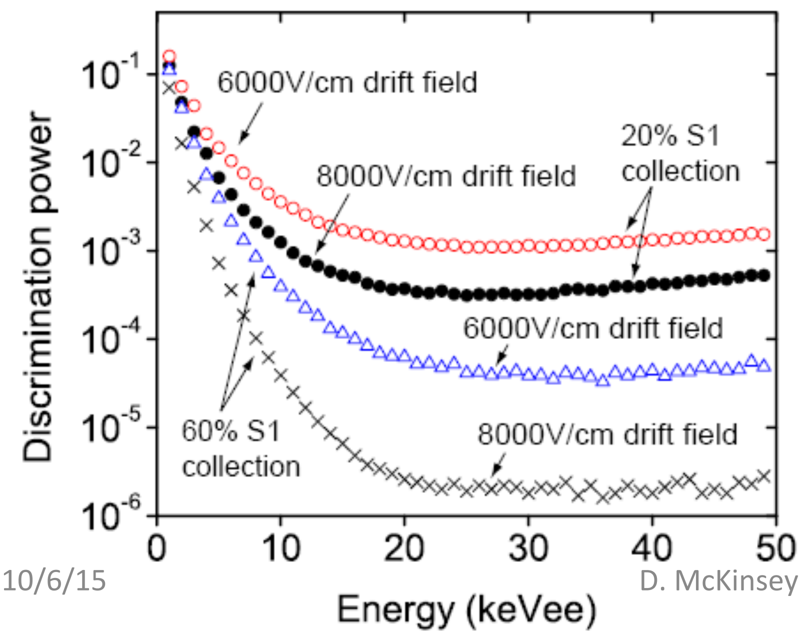


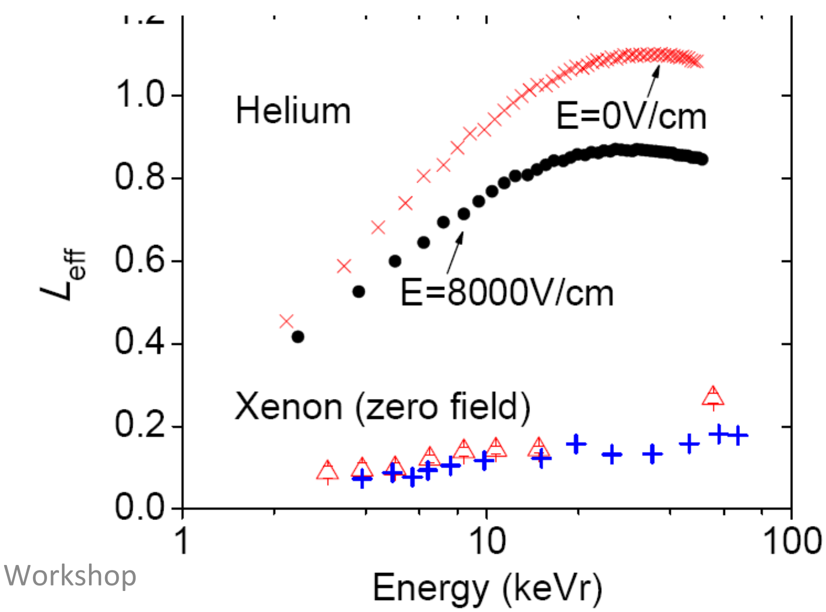


Predicted nuclear recoil discrimination and signal strengths in liquid helium

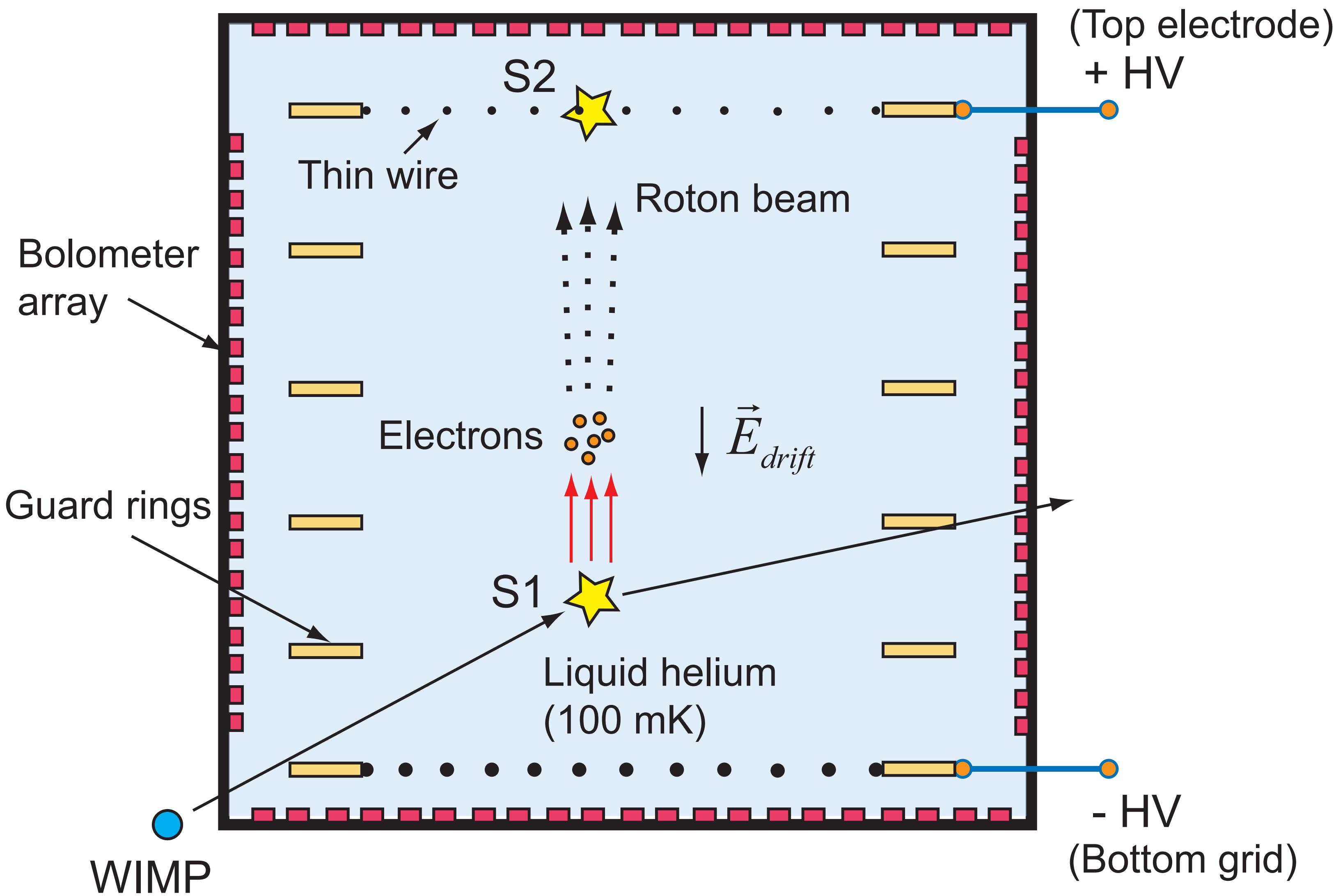








Concept #2: A Light WIMP Detector with 20 bar superfluid helium at ~ 100 mK

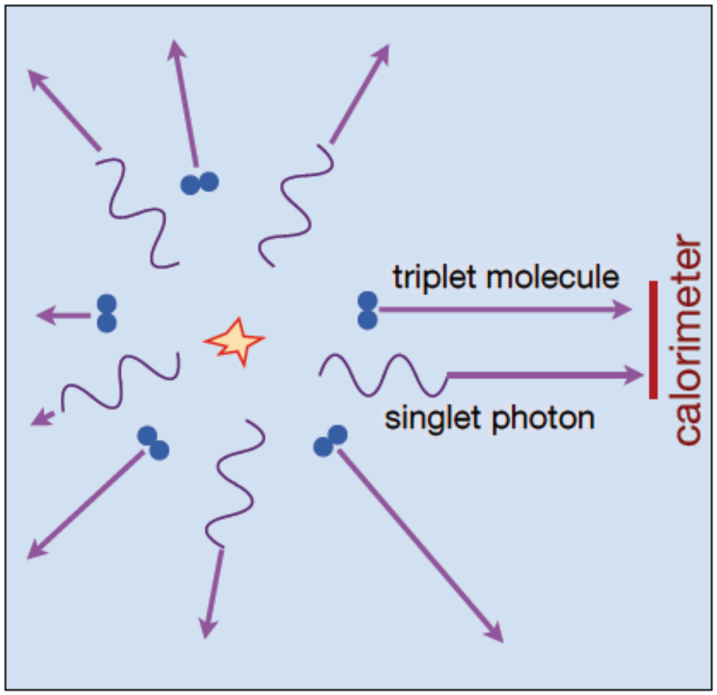


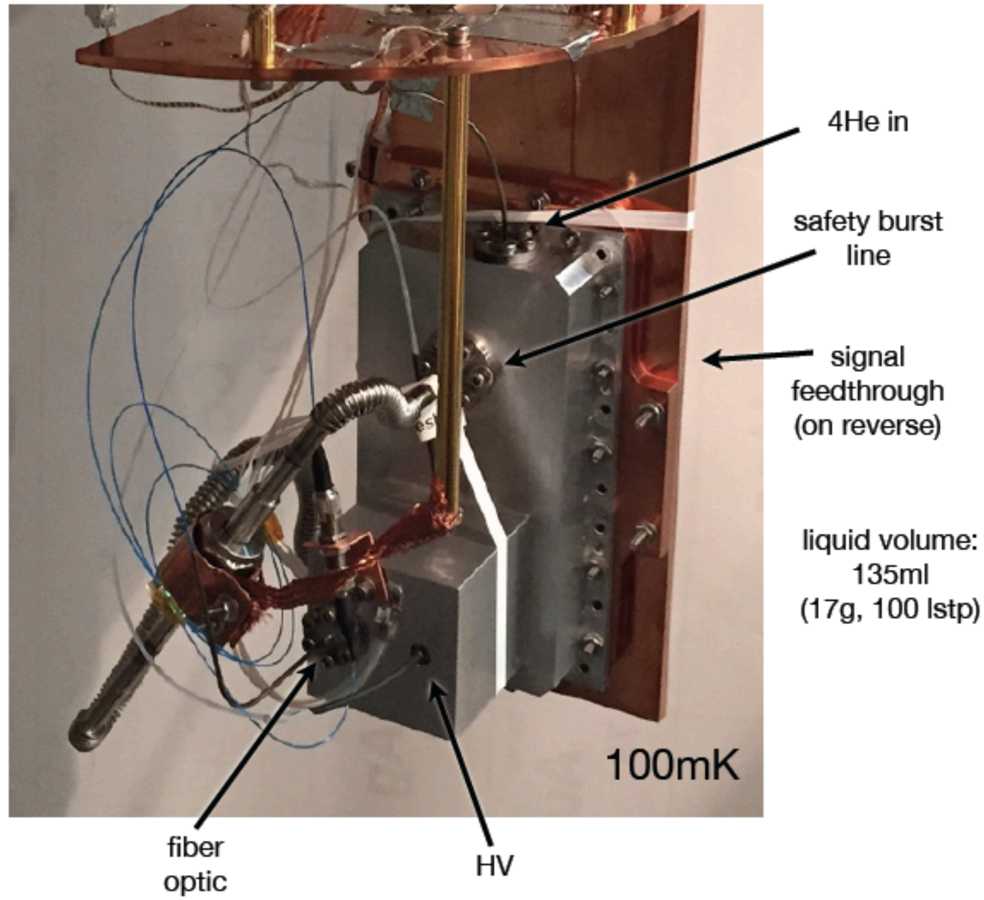
How to detect S3 (helium molecules)?

Again, many options:

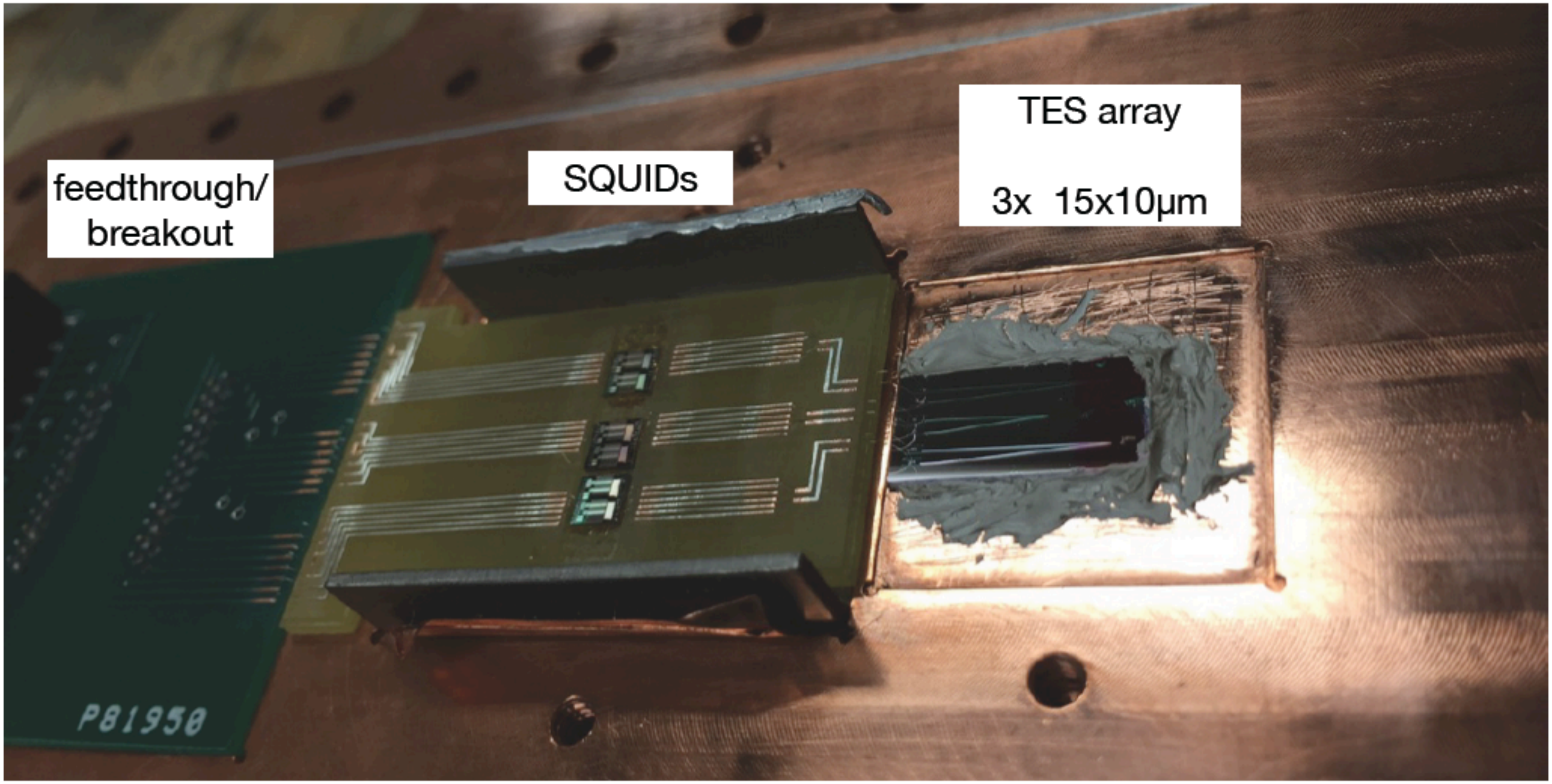
- Laser-induced fluorescence (though will require lots of laser power and be slow)
- Drift molecules with heat flux, then quench on low work function metal surface to produce charge, which is then detected the same way as S2 (though heat flux drift will require lots of cooling power).
- Detect with bolometer 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 S3!

Recent Demonstration Experiments:
Bolometrtic Detection of Superfluid Helium Scintillation and Triplet Excimers

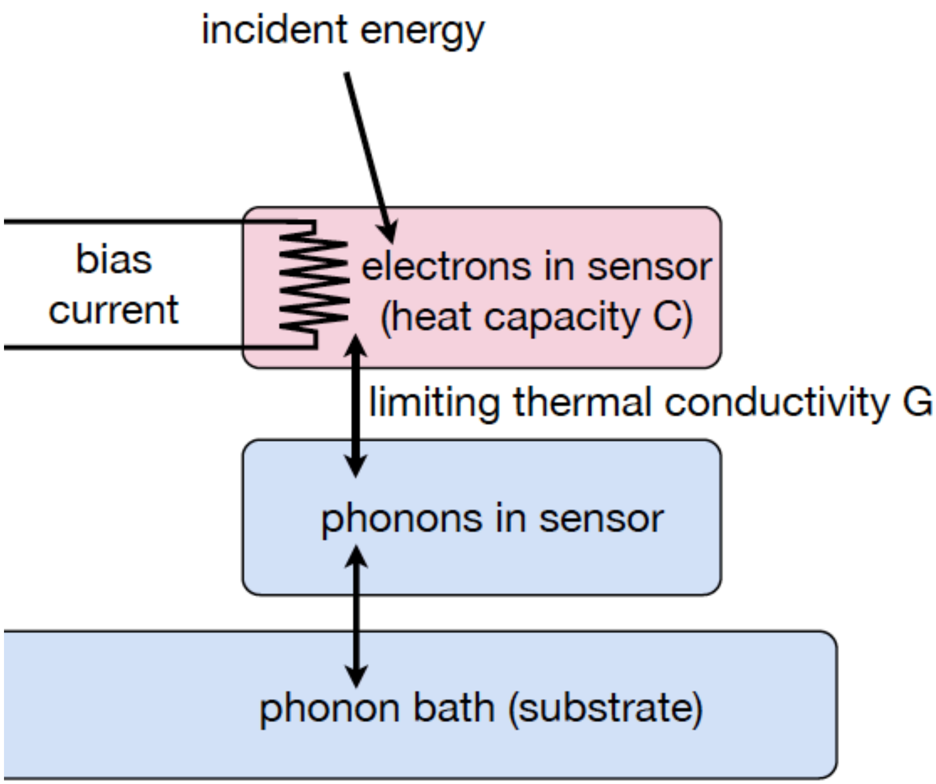


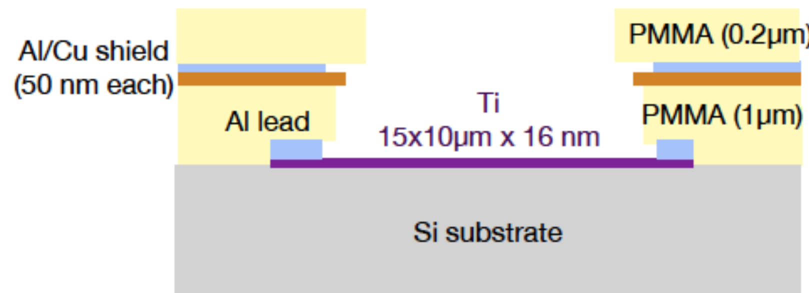


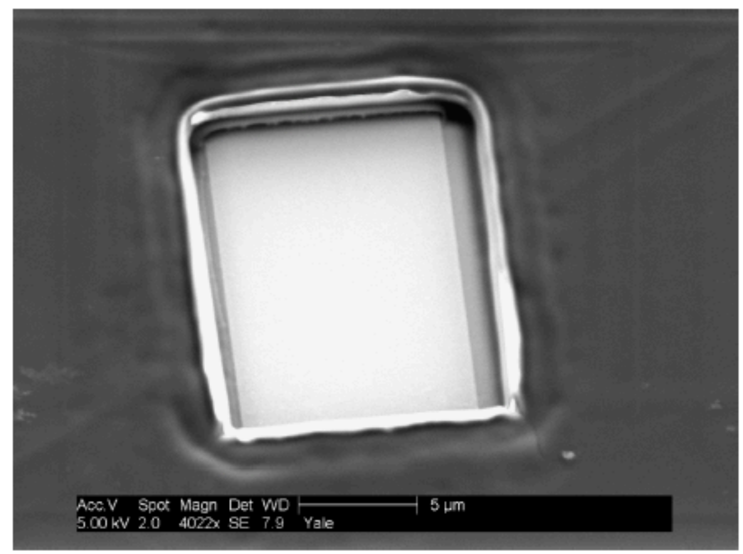
Detector Plane



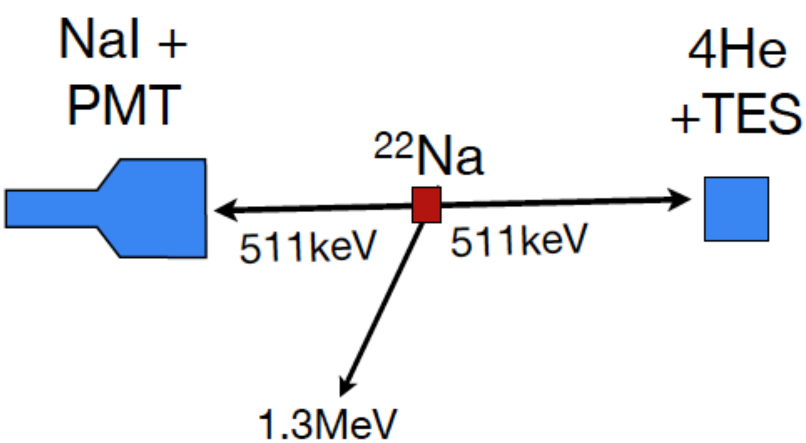
Transition Edge Sensors

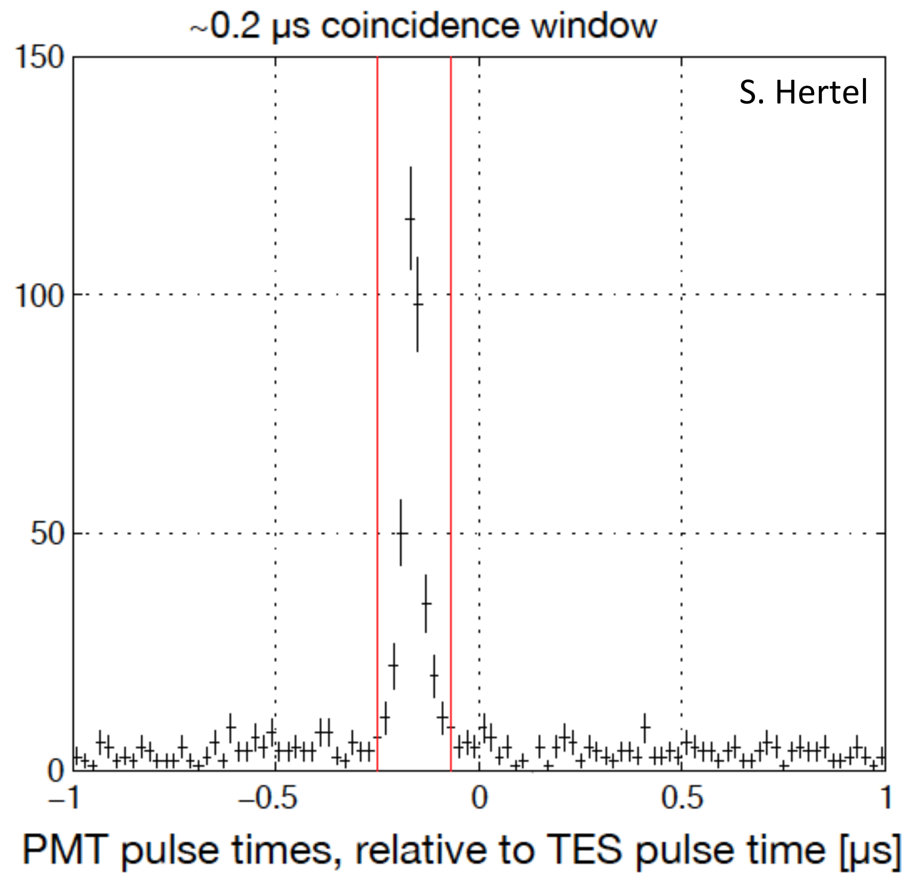




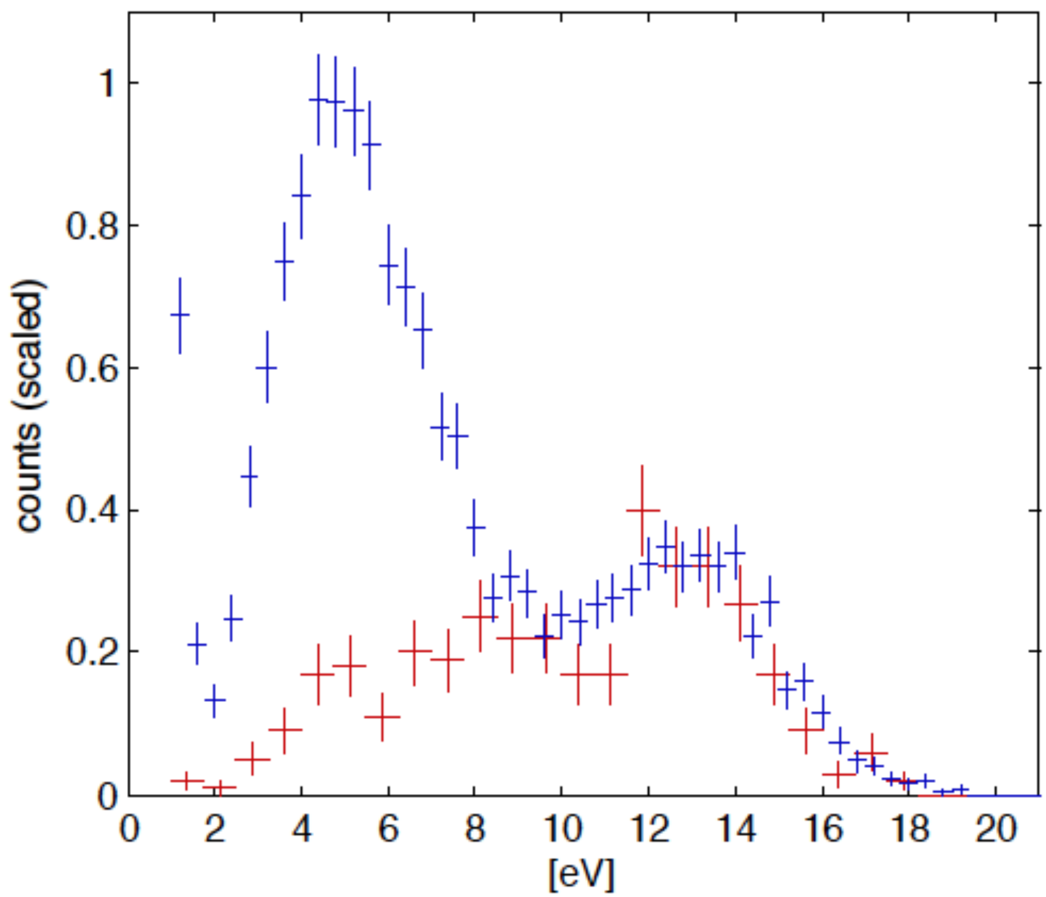


^{22}Na Coincidence tags prompt helium response (singlet decay)





prompt and delayed spectra

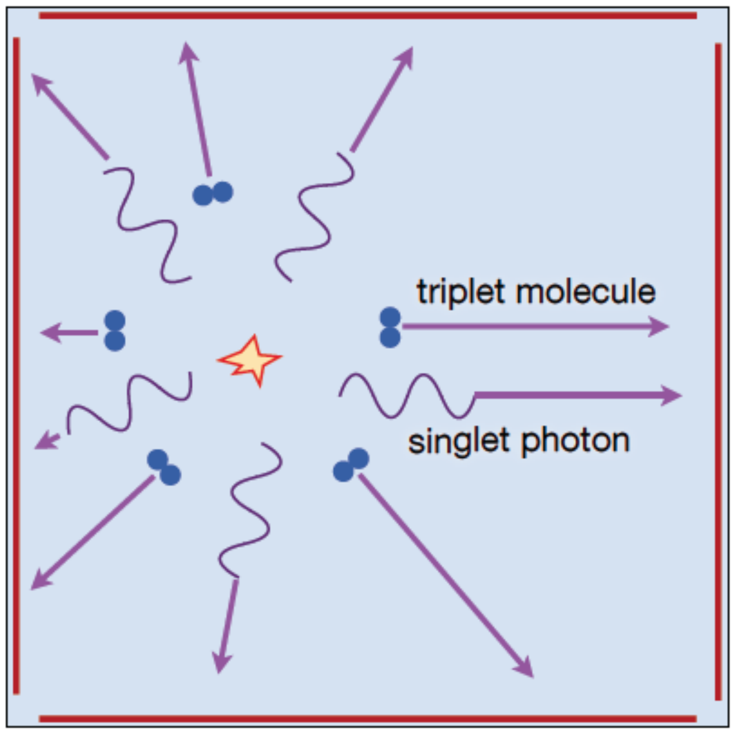


PMT-coincident:
prompt singlet photons only

PMT anti-coincident:
mixture of singlet photons
and **triplet quenching**

Next Step: A Photon & Excimer Detector with High Bolometer Coverage

Goals: Measure ER, NR signal yields at low energies



~ 1-cm cube with 6 wafer calorimeters

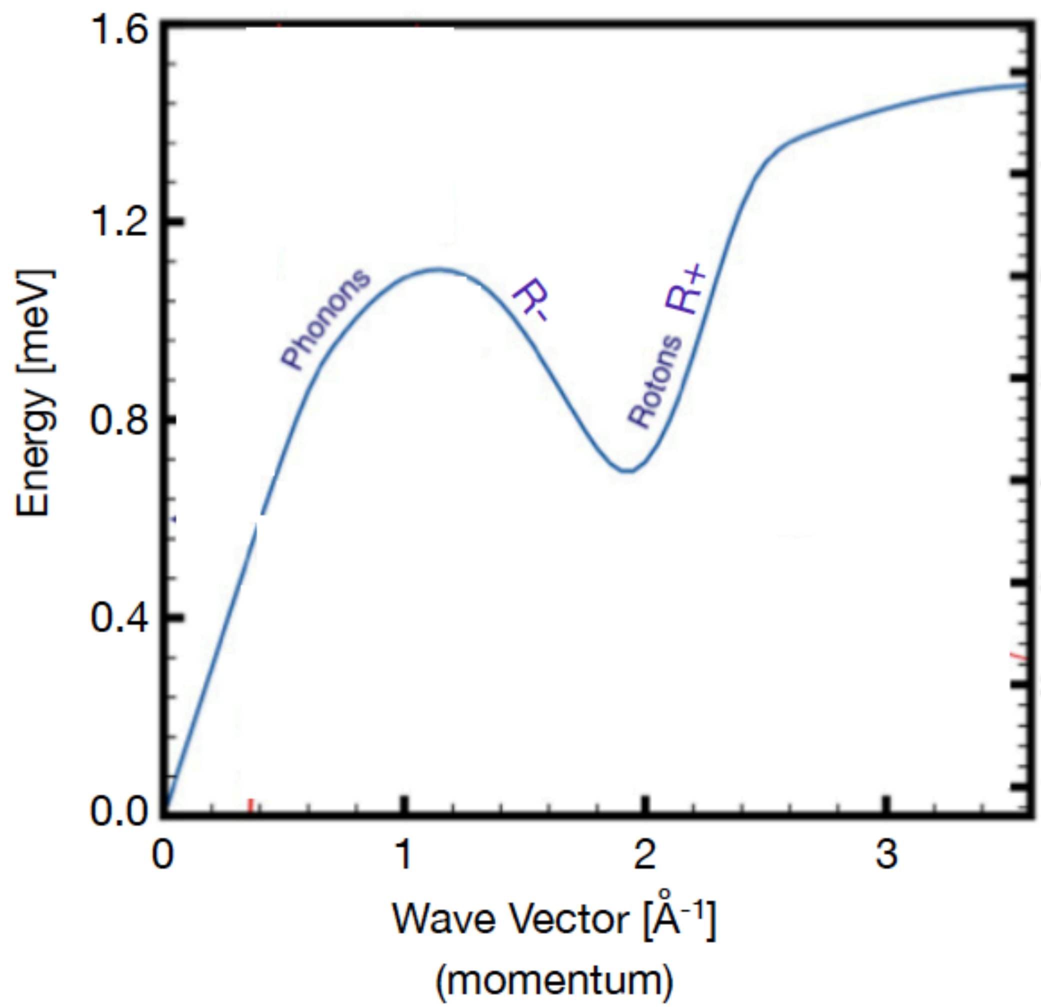
phonons and rotons

superfluid supports vibration
(some non-intuitive)

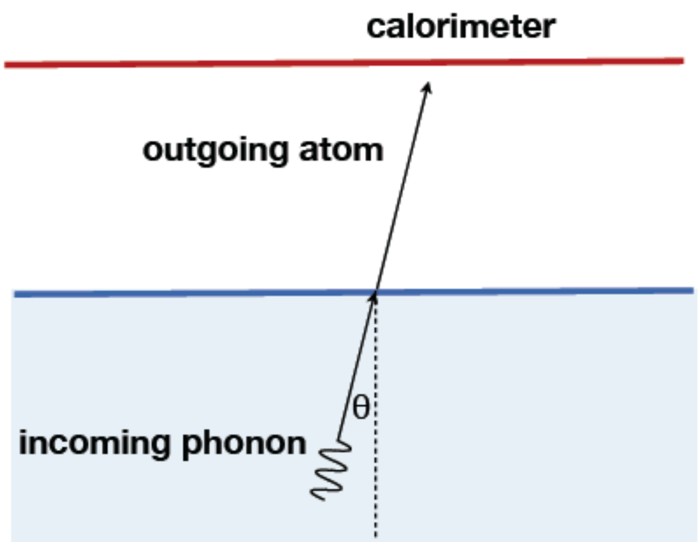
ballistic, ~150m/s

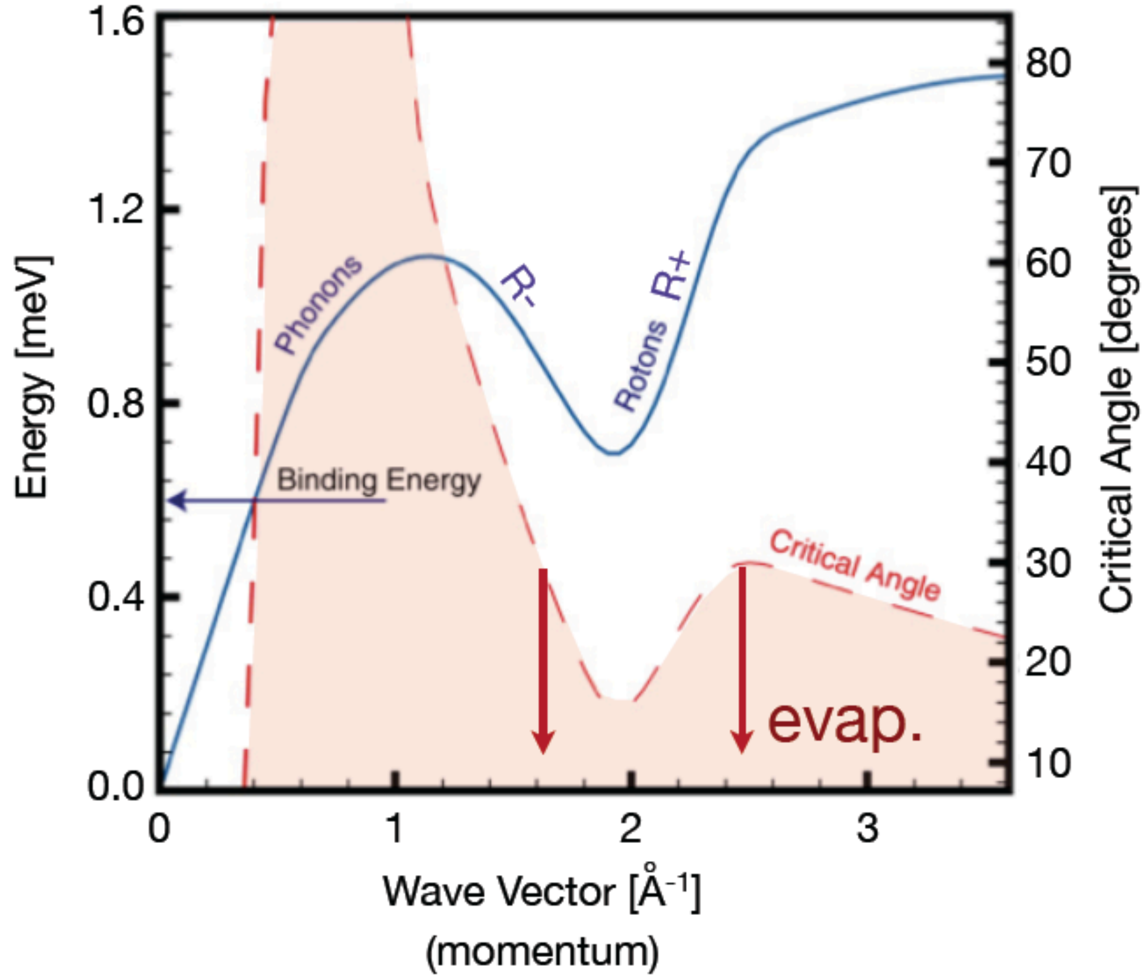
enormous Kapitza resistance,
i.e. *tiny* probability of crossing into solid
(~1% per interaction)

few downconversion pathways



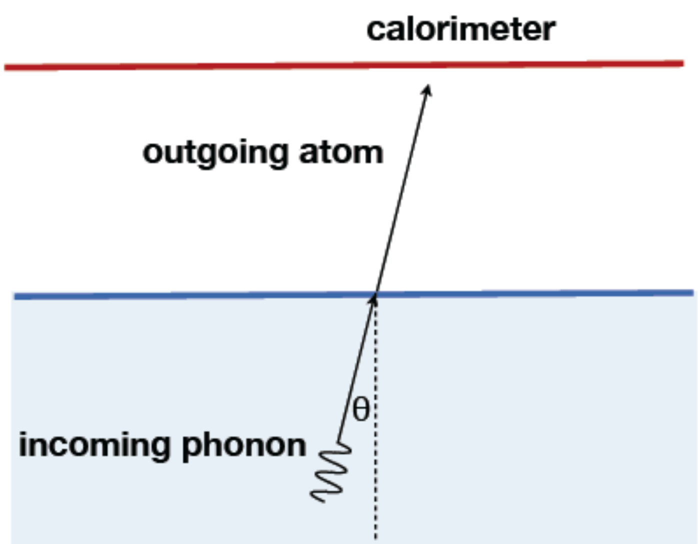
athermal evaporation





chance per interaction high: ~25%
-> nearly all phonon/roton energy will end up as athermal evaporation

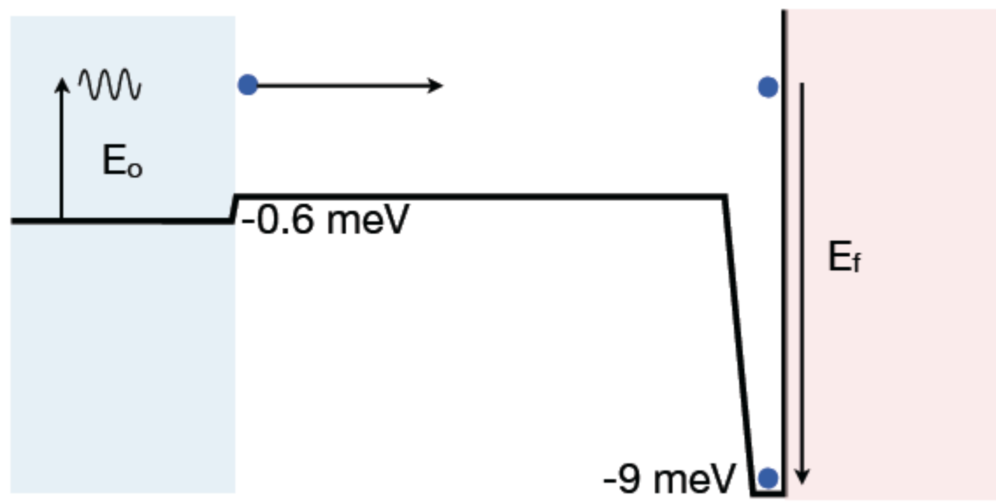
athermal evaporation



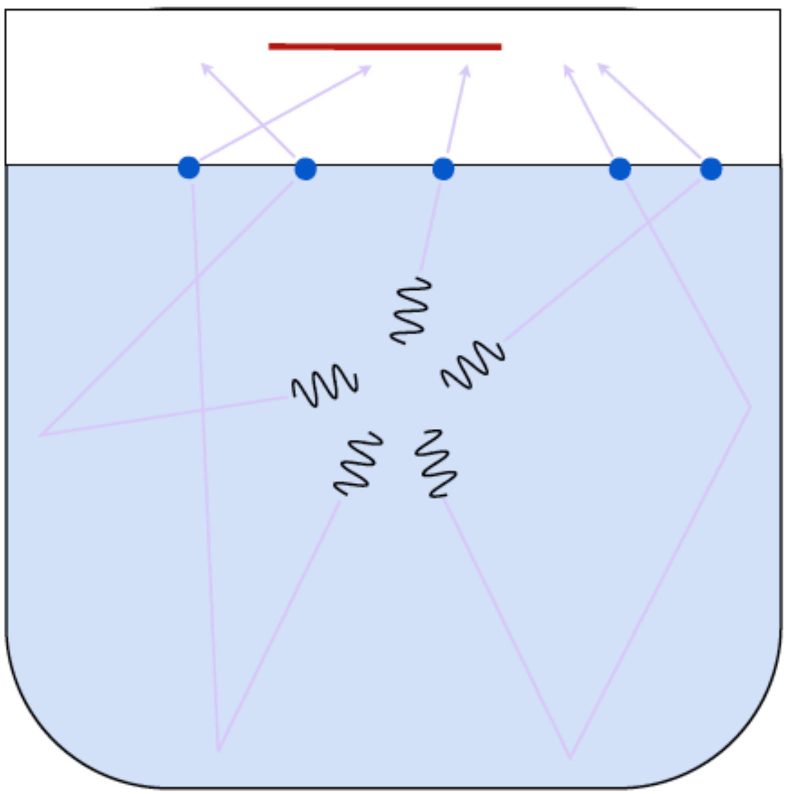
chance per interaction high: ~25%
-> nearly all phonon/roton energy
will end up as athermal evaporation

amplification *before* sensing

for typical 1meV roton/phonon,
gain of ~10x in energy



Athermal Evaporation – Demonstrated by HERON R&D



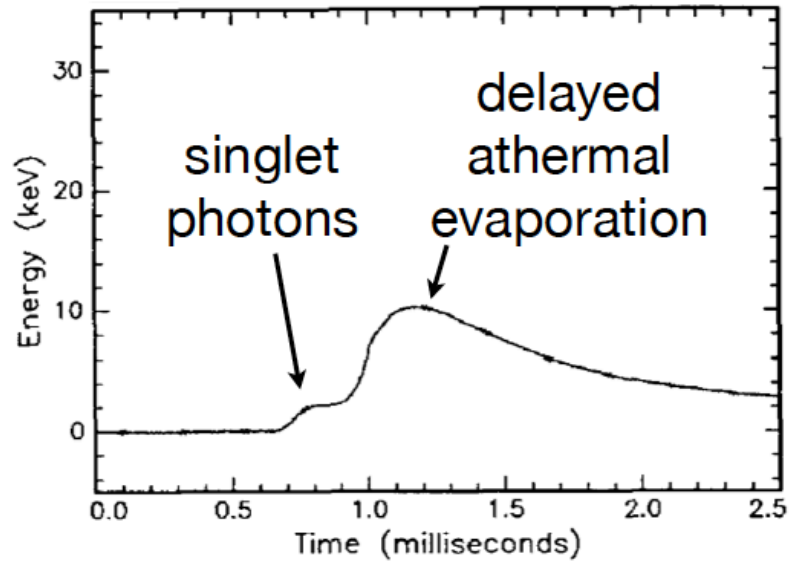


Fig. 2. (a) The calorimeter response (average of about 100 events) when an α particle is stopped in liquid helium. The collimated α tracks are (a) parallel and (b) perpendicular to the liquid surface.

Concept #3

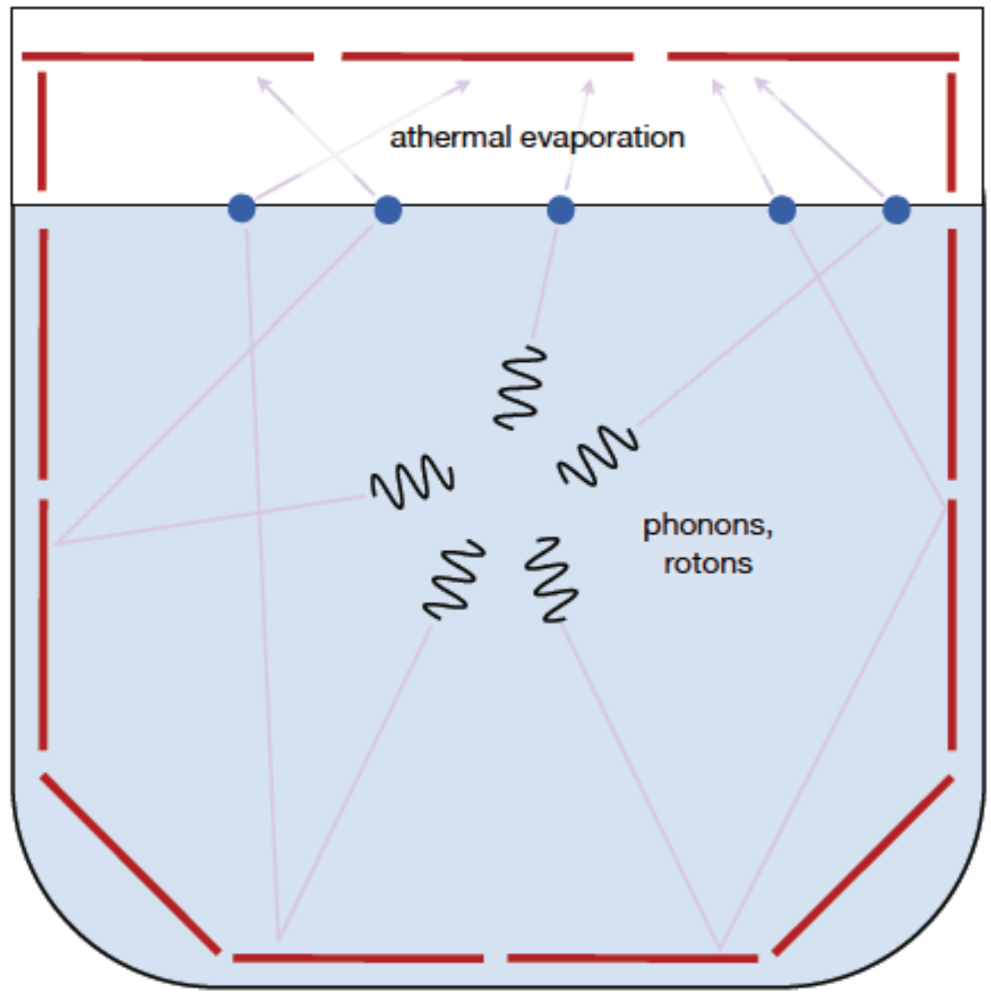
Signal channels:

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

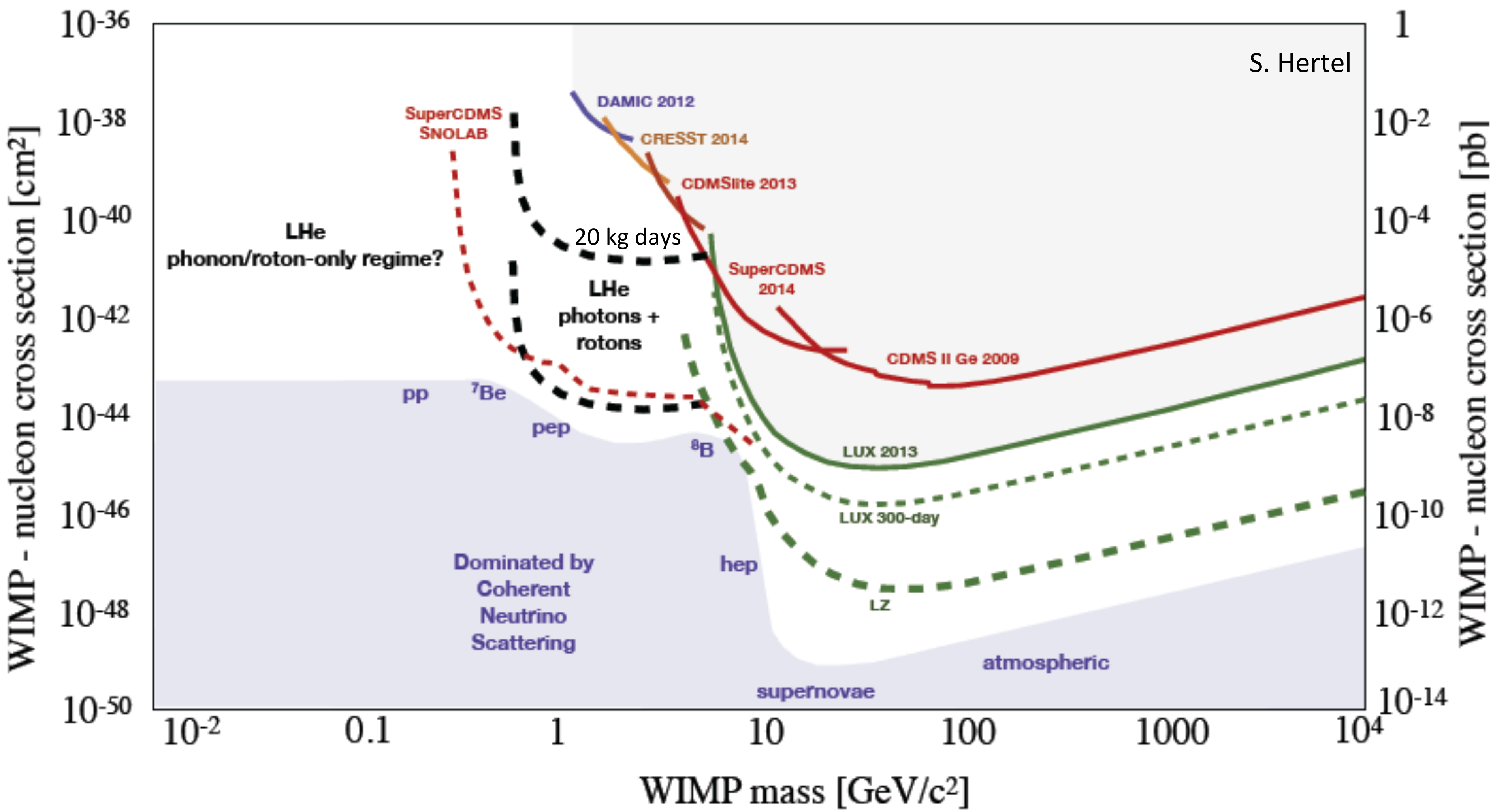
No drift field, and no S2 signal

Discrimination using signal ratios

Position reconstruction using signal hit patterns



Projected Sensitivity



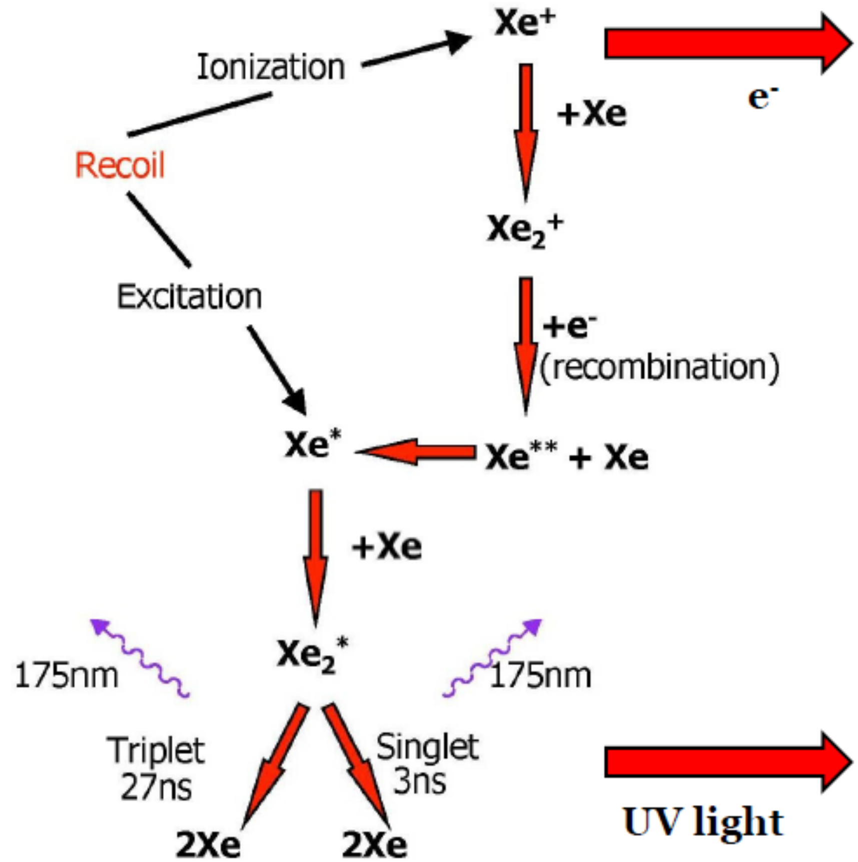
Direct WIMP Detection with Liquid Xenon

- 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)



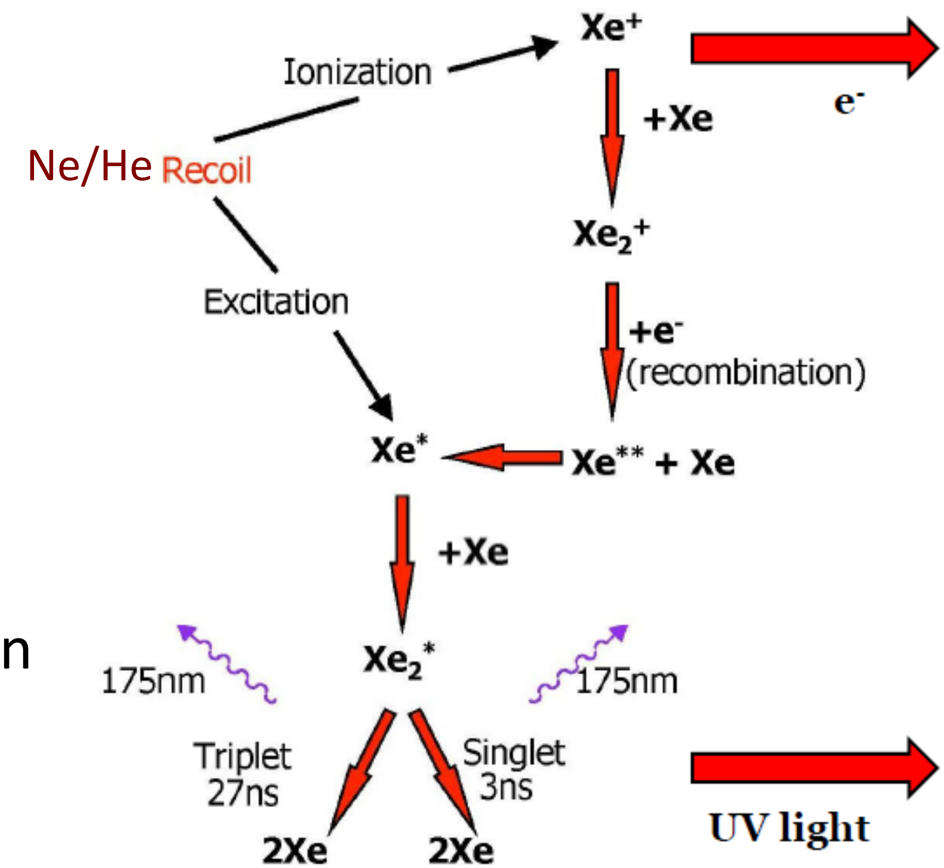
Direct WIMP Detection with Liquid Xenon
^ Neon/Helium-doped

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

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

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

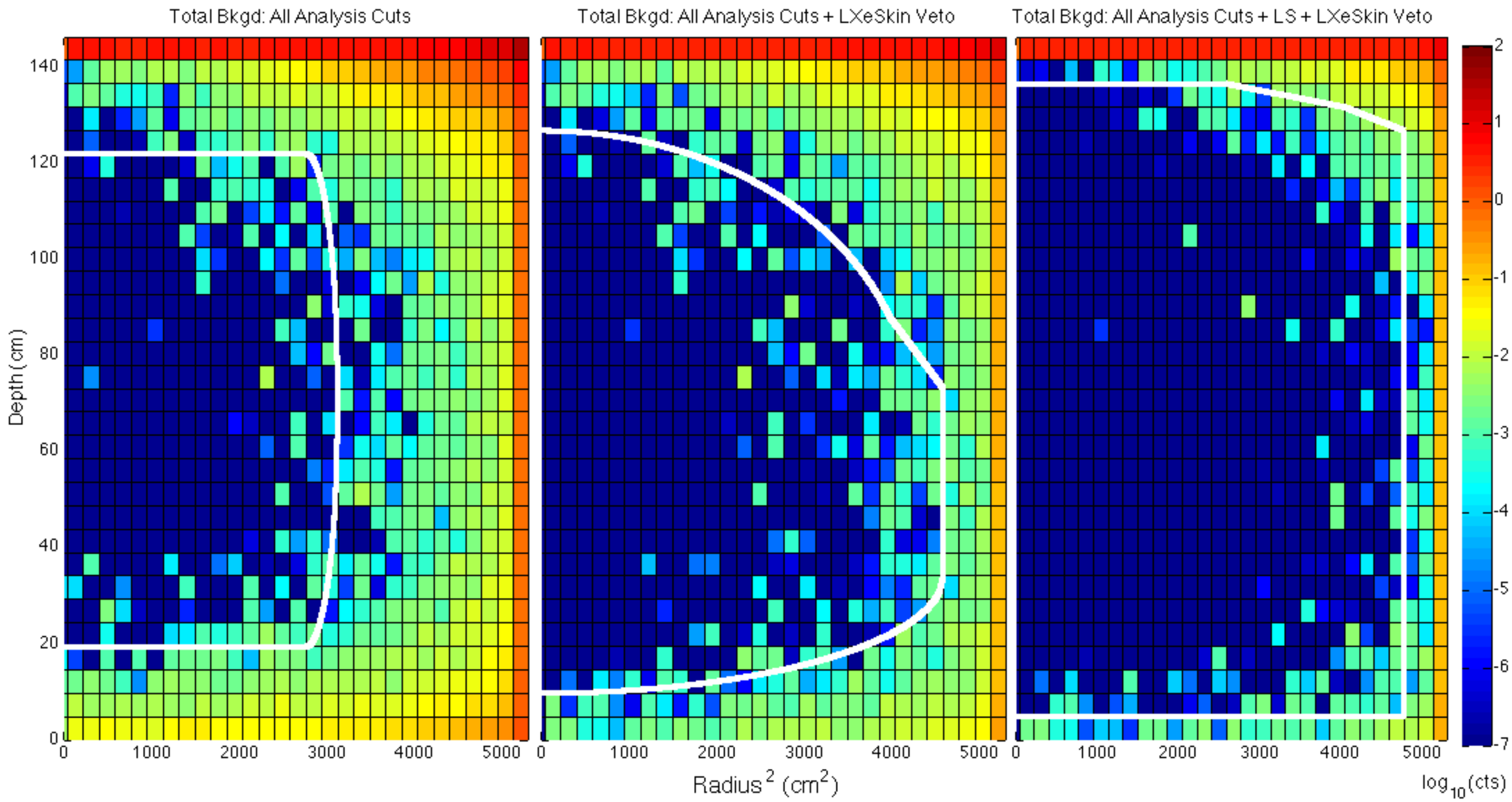
- Recoil energy deposited in three channels:
  - Scintillation (photons)
  - Ionization (charge)
  - Heat (phonons)



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?)

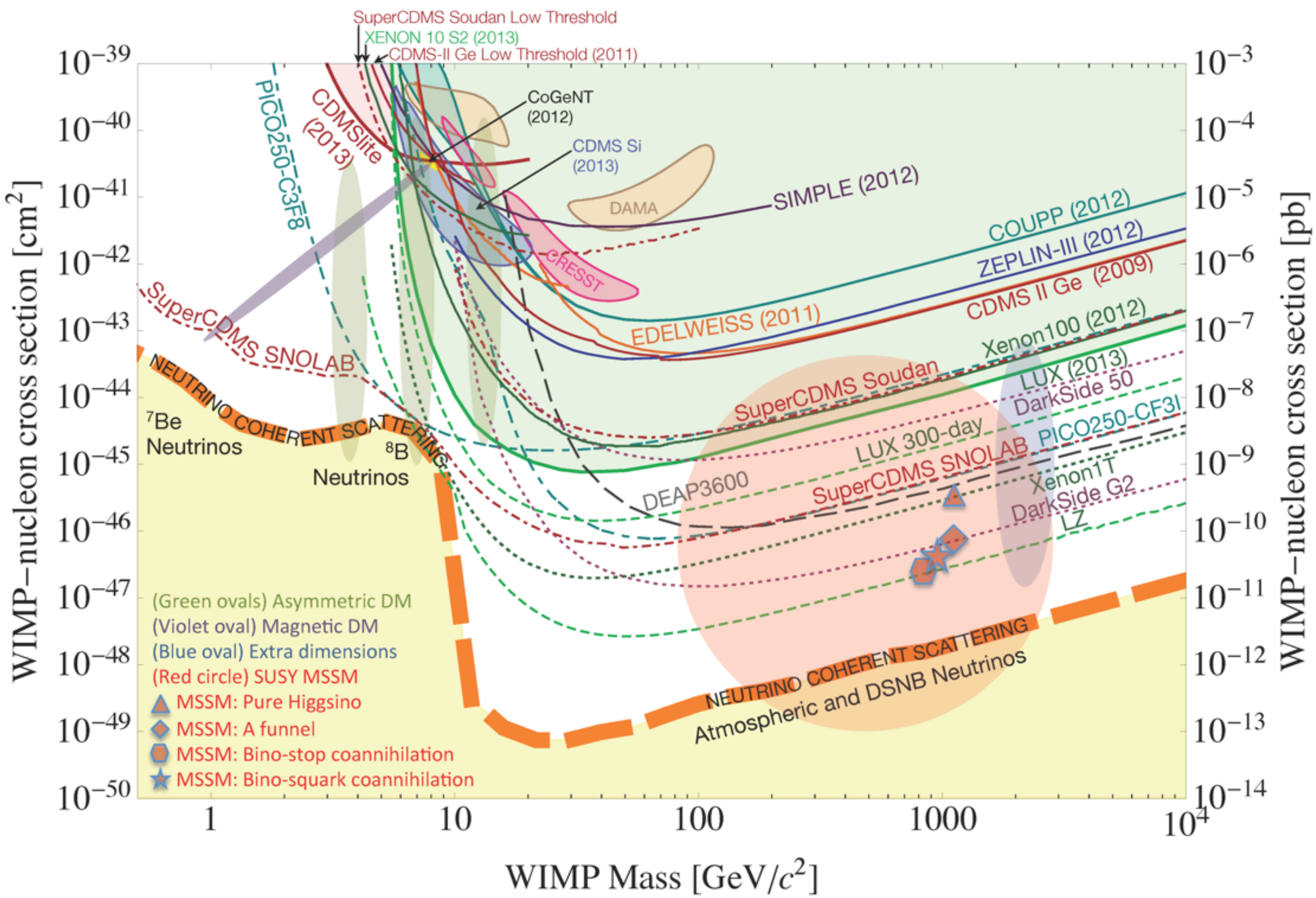
LZ: Self-shielding reduces gamma ray/neutron background to well below neutrinos



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.
  - Effort underway at Fermilab (H. Lippincott)
- 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.
A Happy Coincidence?



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 M_1/M_2, so heat production is diminished and electronic excitation is enhanced. See P. Sigmund, European Physical Journal D **47**, 45 (2008).

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

- Light element doping promises significantly enhanced light and charge yields, at a given recoil energy!
- Calibration will be an interesting challenge – picking out NR yields of the dopant. At a given scatteing angle, dopant signal will be much larger, both because of neutron kinematics and because of favorable light and charge yields.

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.