A Concept for a Light WIMP Detector Using Superfluid He-4

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(with Wei Guo, Florida State University)

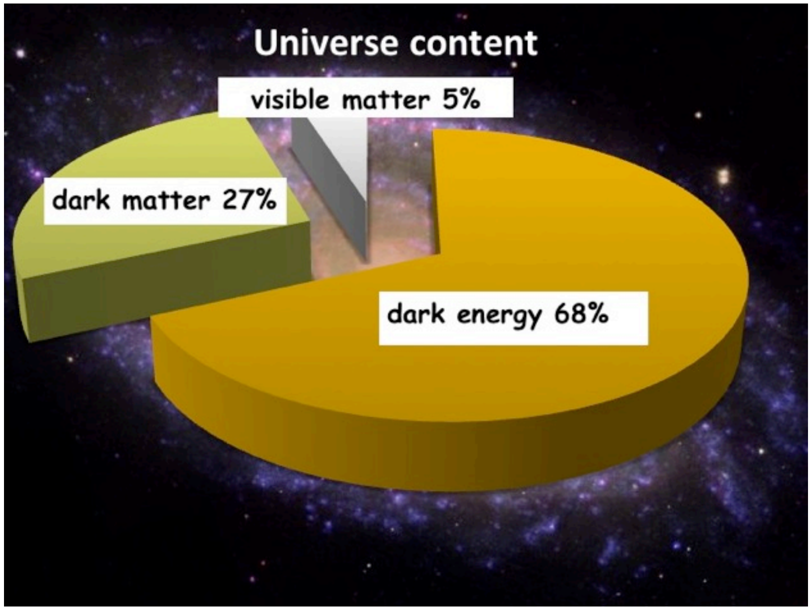
Weak Interaction Discussion Group Seminar
January 28, 2014

Composition of the Universe

The Higgs particle has been discovered, the last piece of the Standard Model.

But as successful as it has been, the Standard Model describes only 5% of the universe. The remaining 95% is in the form of dark energy and dark matter, whose fundamental nature is almost completely unknown.

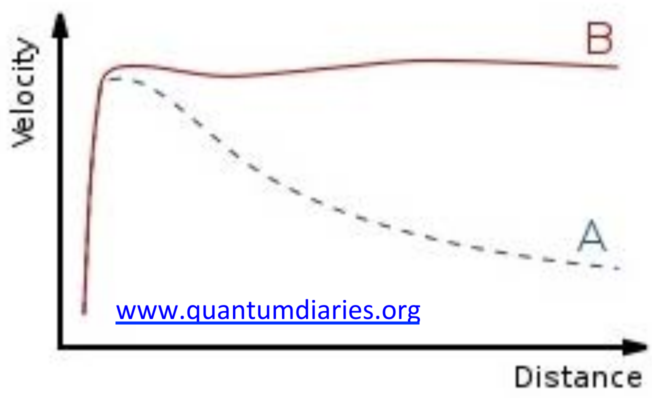
Image: X-ray: NASA/CXC/CfA/M.Markevitch et al.;
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.



www.quantumdiaries.org

Evidence for Dark Matter

Galaxy rotation curves



The cosmic microwave background

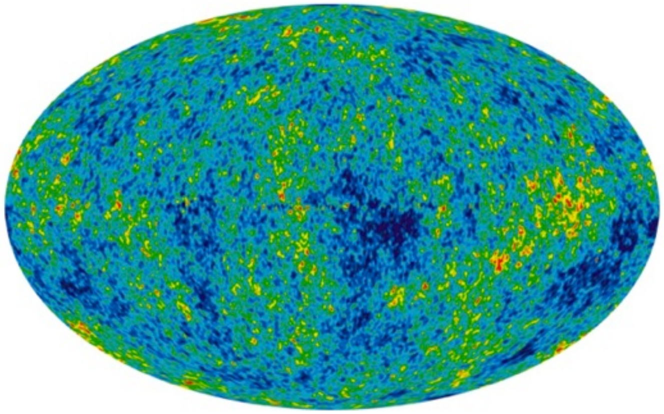


Image: ESA and the Planck collaboration

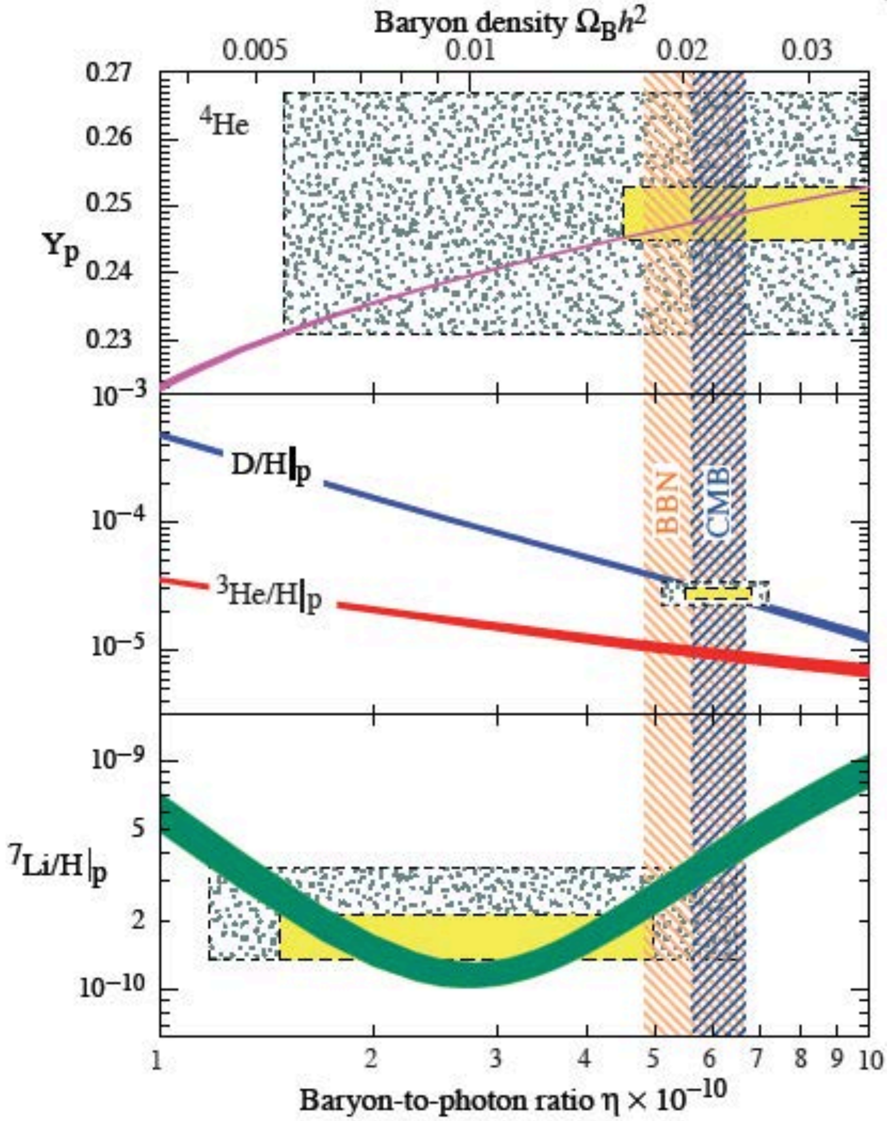
Gravitational lensing

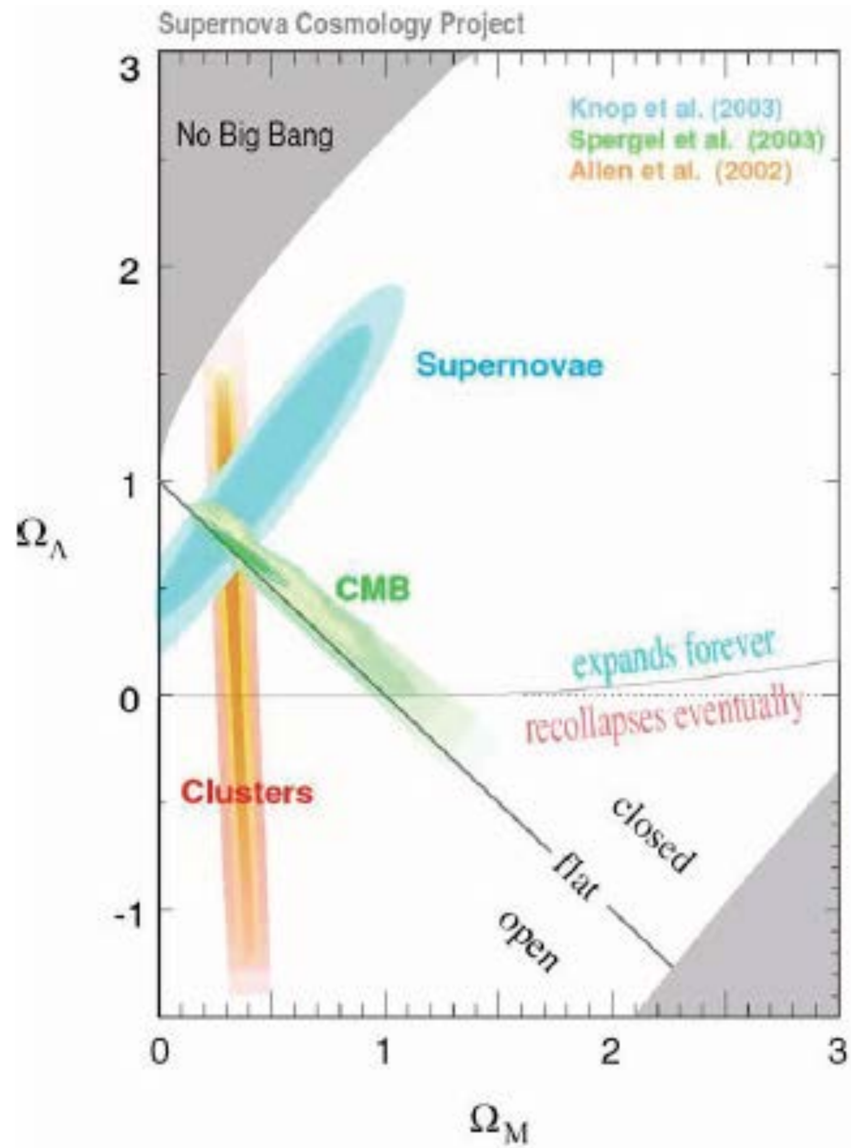
Colley, Turner, Tyson, and NASA

- 27% of the energy composition of the universe
- Properties:
- Stable and electrically neutral
- Non-baryonic
- Non-relativistic
- Estimated local density: 0.3±0.1GeV·cm^{-3}
- Candidates: WIMPs, axions, dark photons,...

Evidence for Dark Matter

Nucleosynthesis determines the density of baryons at early times; the amount of baryonic matter required is far smaller than the total quantity of matter.





Direct Searches for WIMP Dark Matter

Look for anomalous nuclear recoils in a low-background detector

Must be sensitive to event rates of order 1 event/100kg/month or less

$R = N\, r \langle s\, v \rangle$

From $\langle v \rangle$ = 220 km/s, get typical energy deposition of order 10 keV

Key technical challenges:

- Low radioactivity
- Low energy threshold
- Gamma and beta rejection
- Scalability

Detect heat, light, or ionization (or some combination)

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

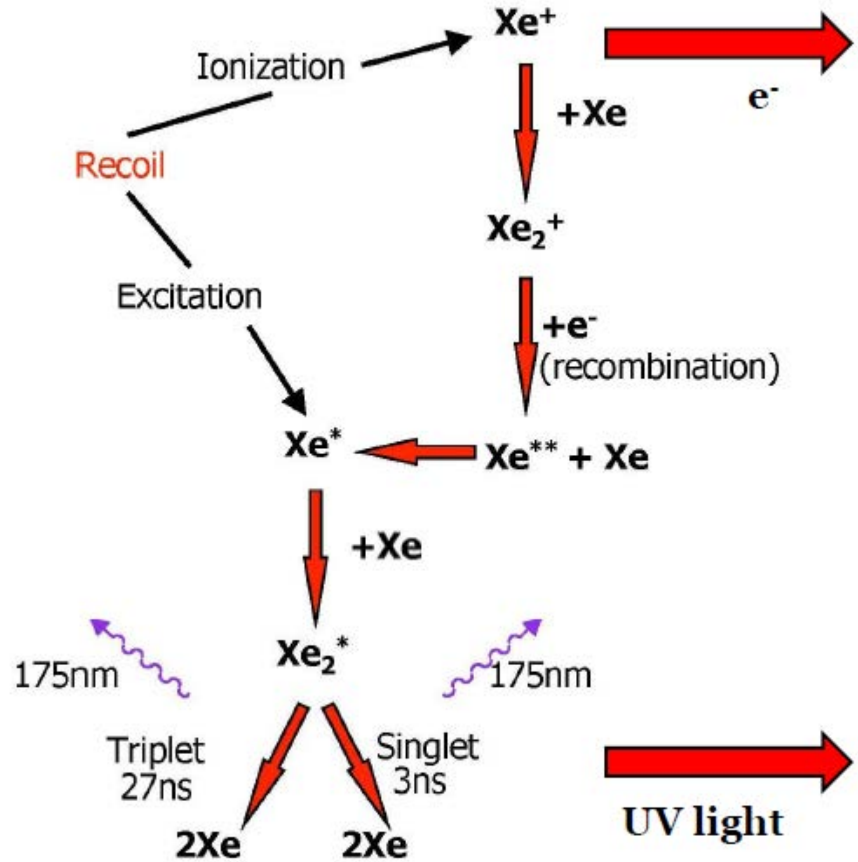
Direct WIMP Detection with Liquid Xenon

- 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)

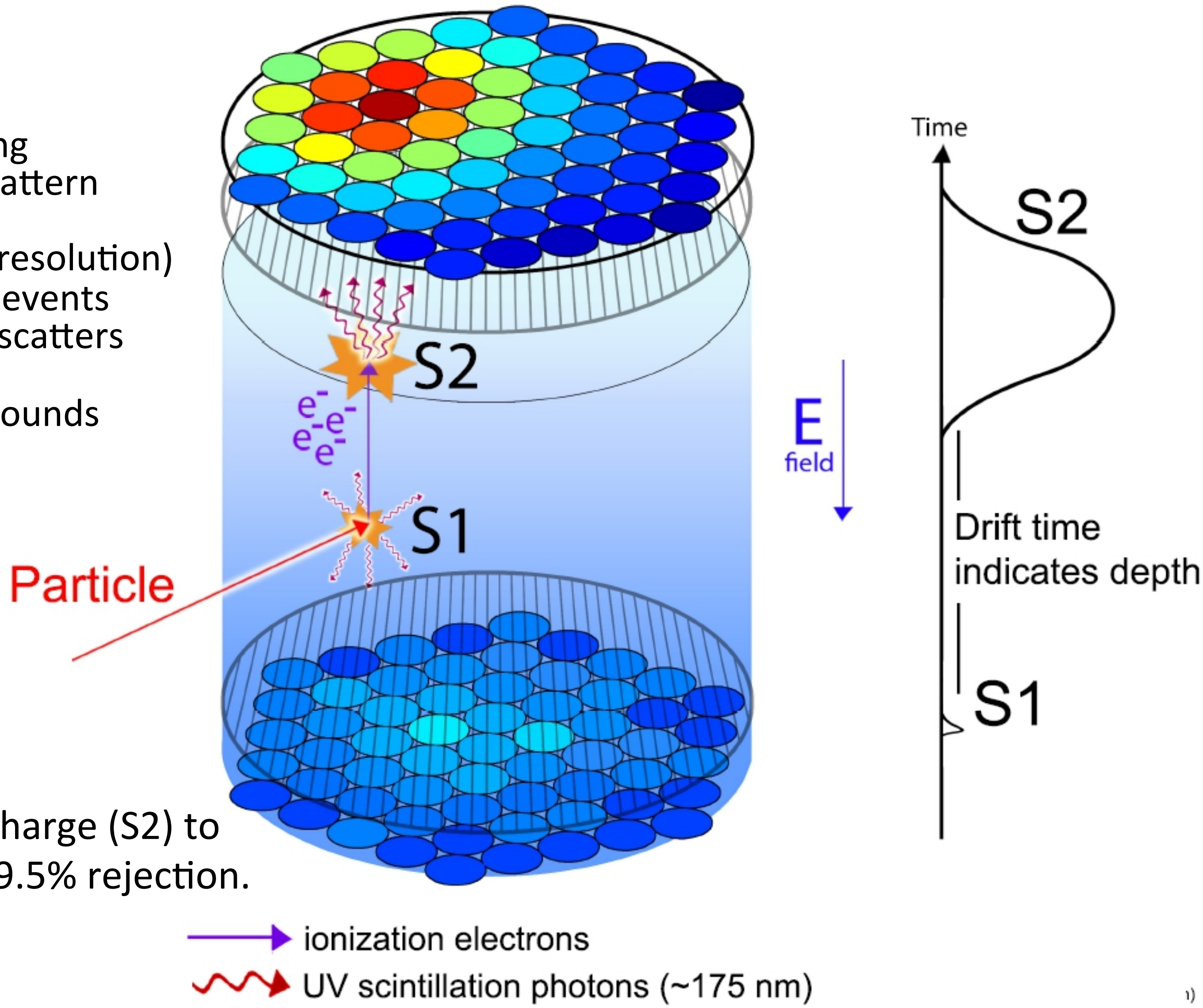


LUX Is a Two-phase Xenon WIMP Detector

Z position from S1 – S2 timing
X-Y positions from S2 light pattern

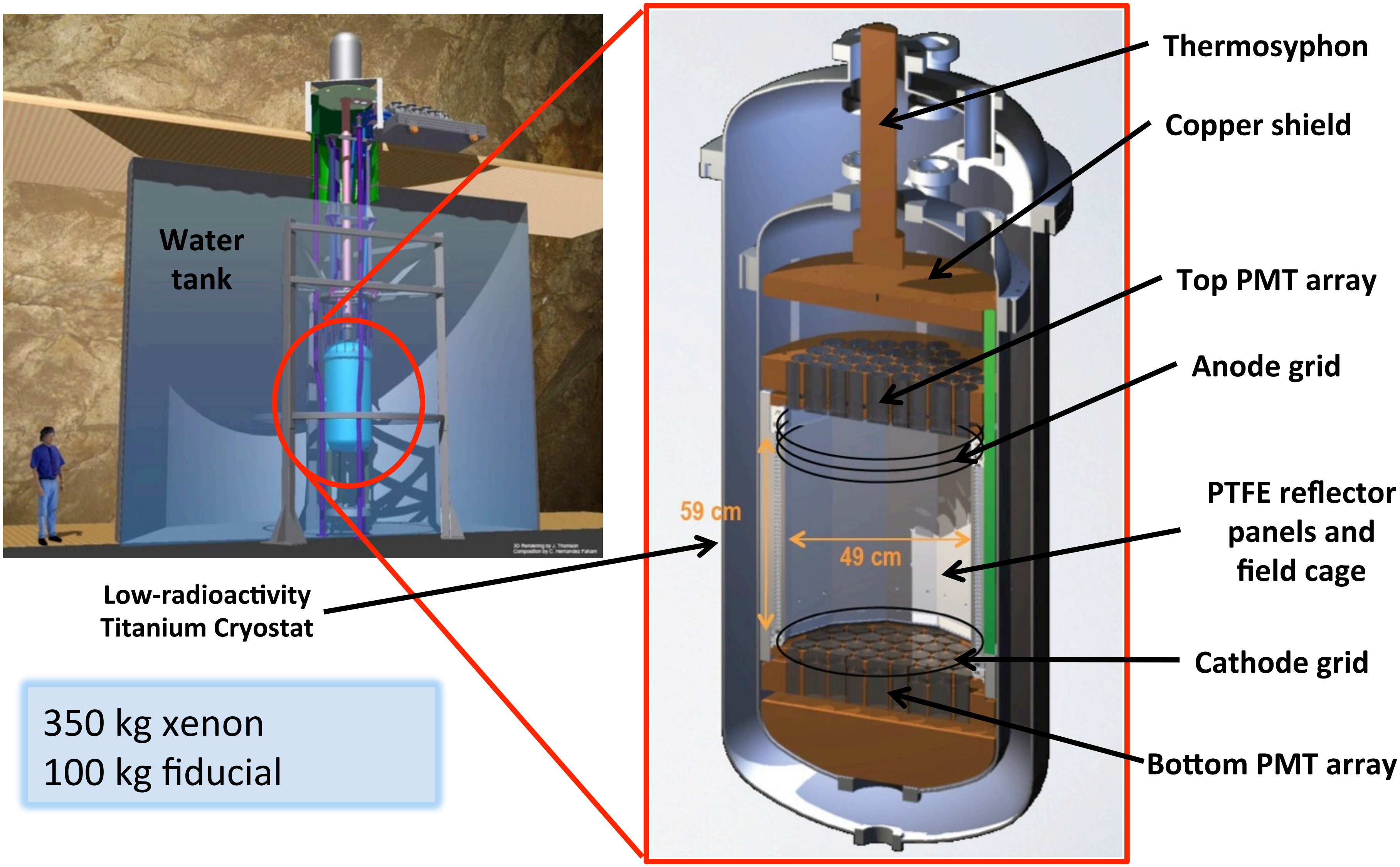
Excellent 3D imaging (~mm resolution)
- eliminates edge events
- rejects multiple scatters

Gamma ray, neutron backgrounds
reduced by self-shielding



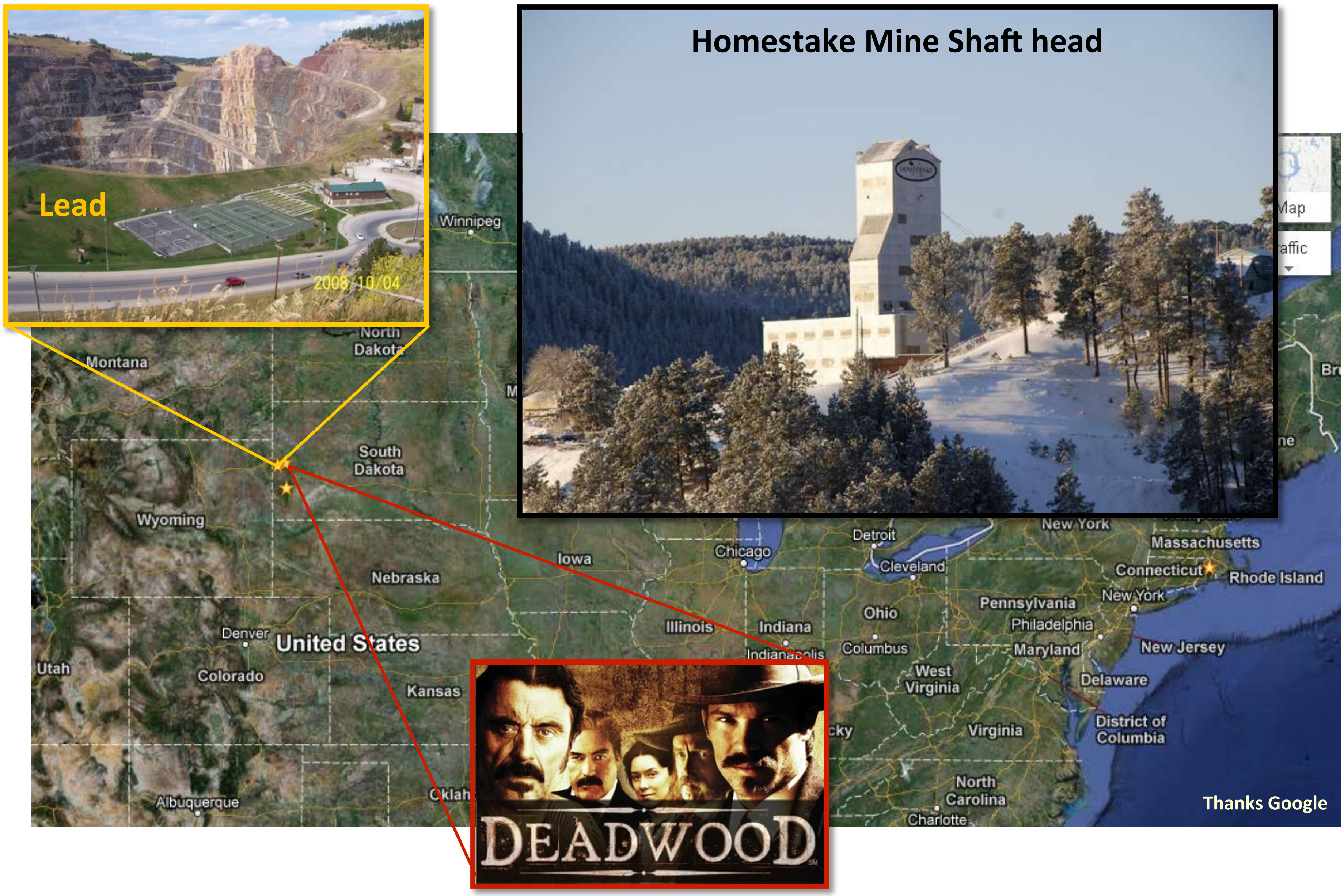
Reject gammas, betas by charge (S2) to
light (S1) ratio. Expect > 99.5% rejection.

The LUX Detector



350 kg xenon
100 kg fiducial

The Sanford Laboratory at Homestake



Davis Campus – Summer 2012


June 15


July 6


June 25

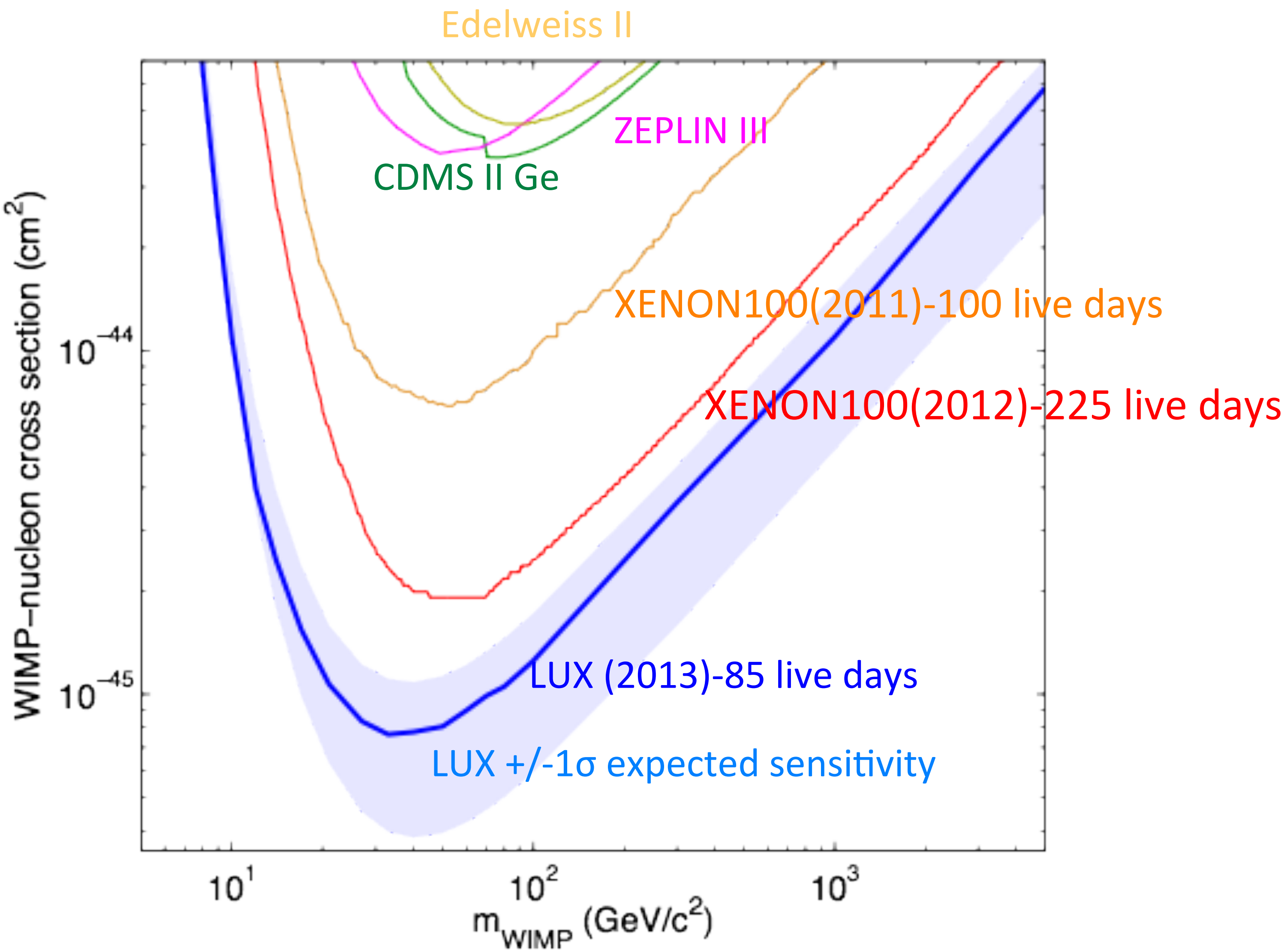

June 29


August 25

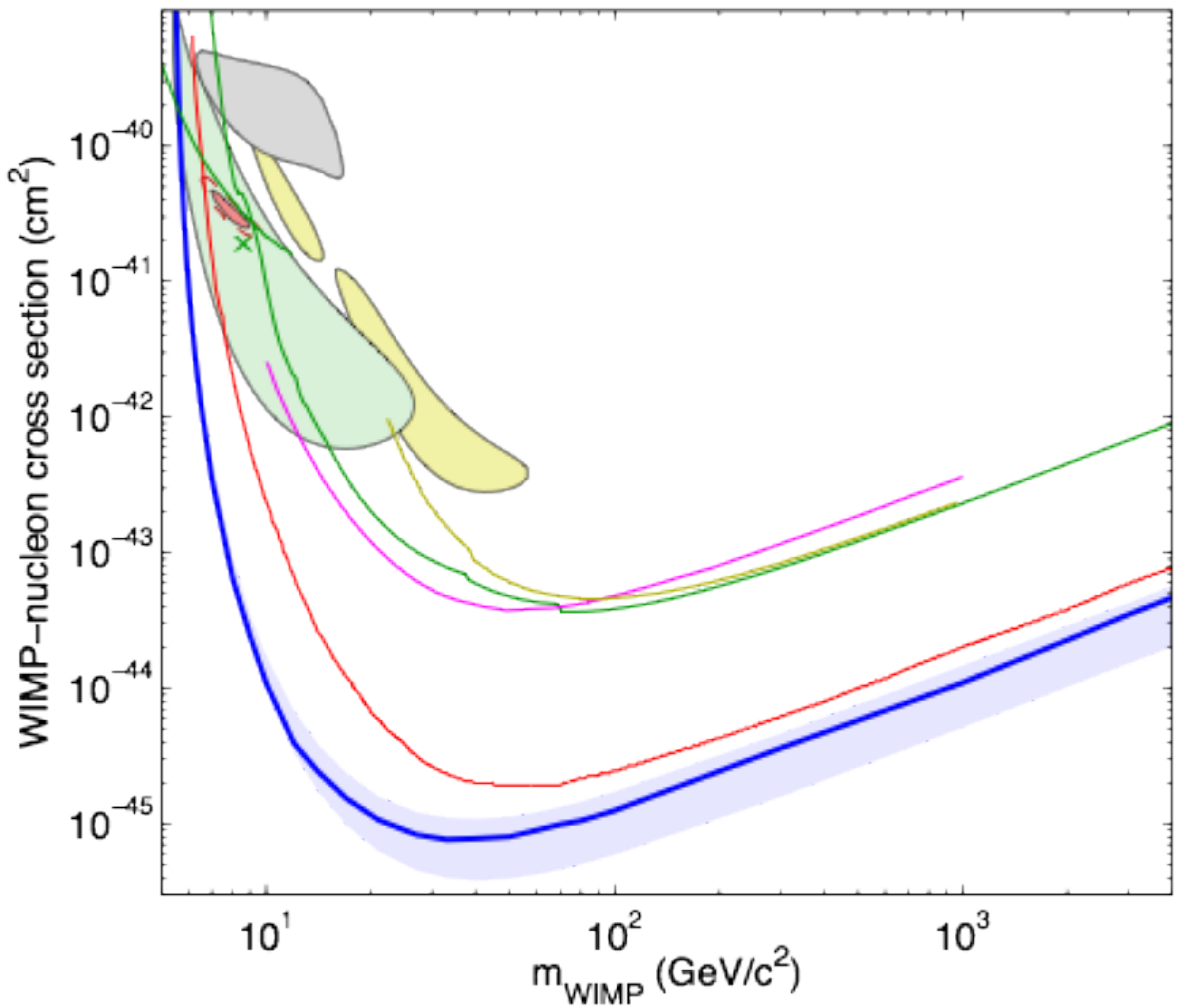

July 12

Davis Campus – September 2012

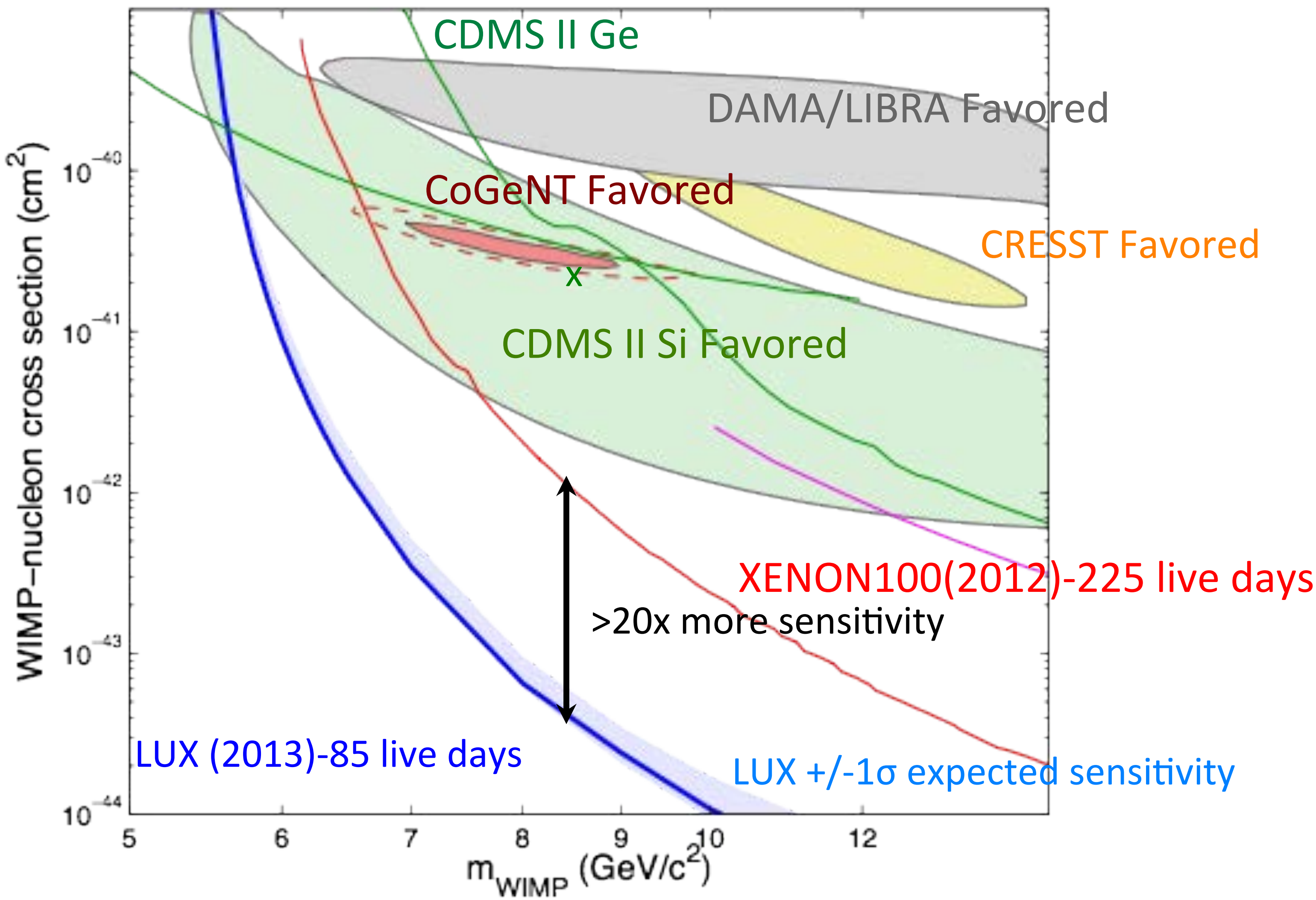
Spin Independent Sensitivity Plots



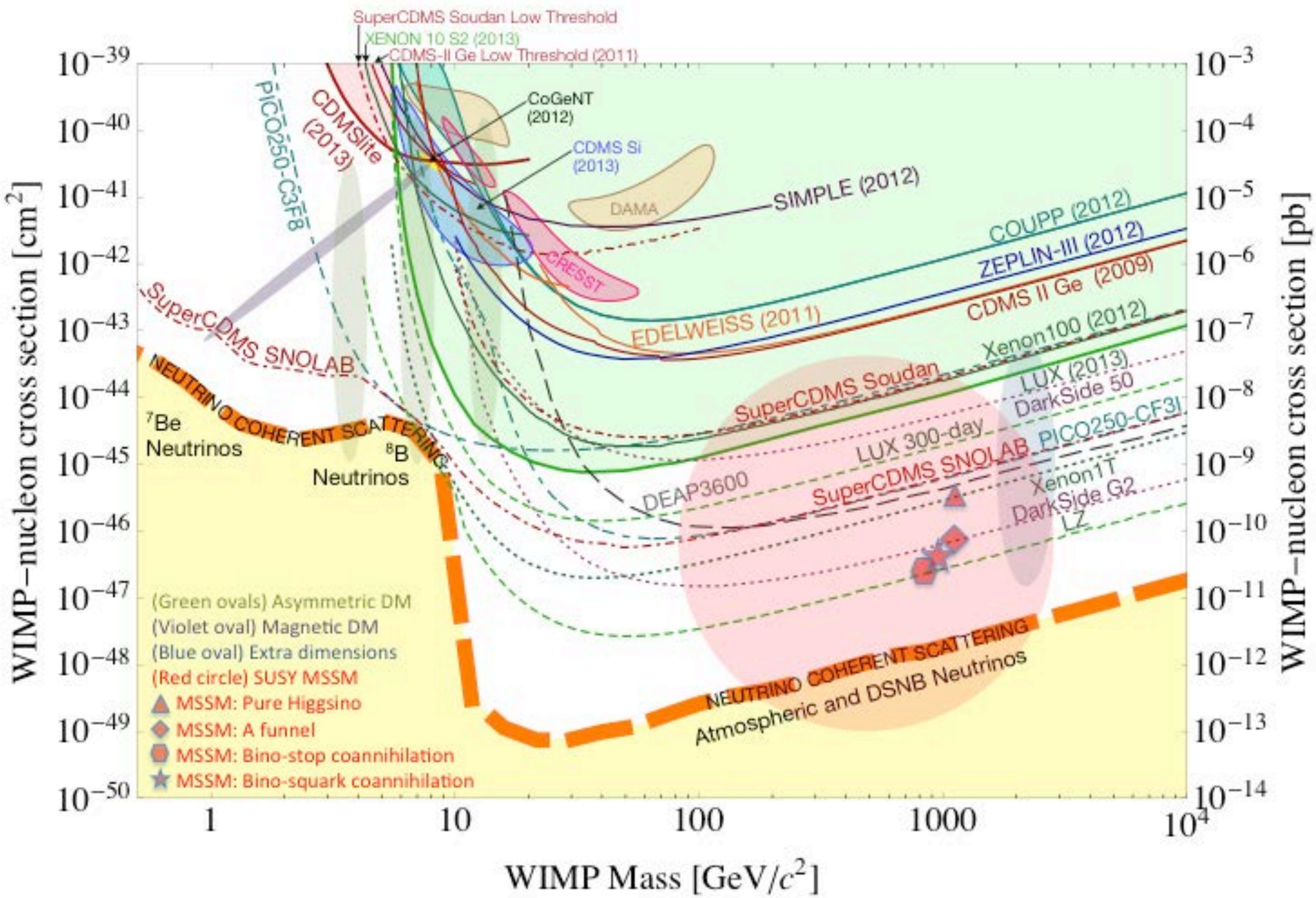
Spin Independent Sensitivity Plots



Low Mass WIMPs - Fully excluded by LUX

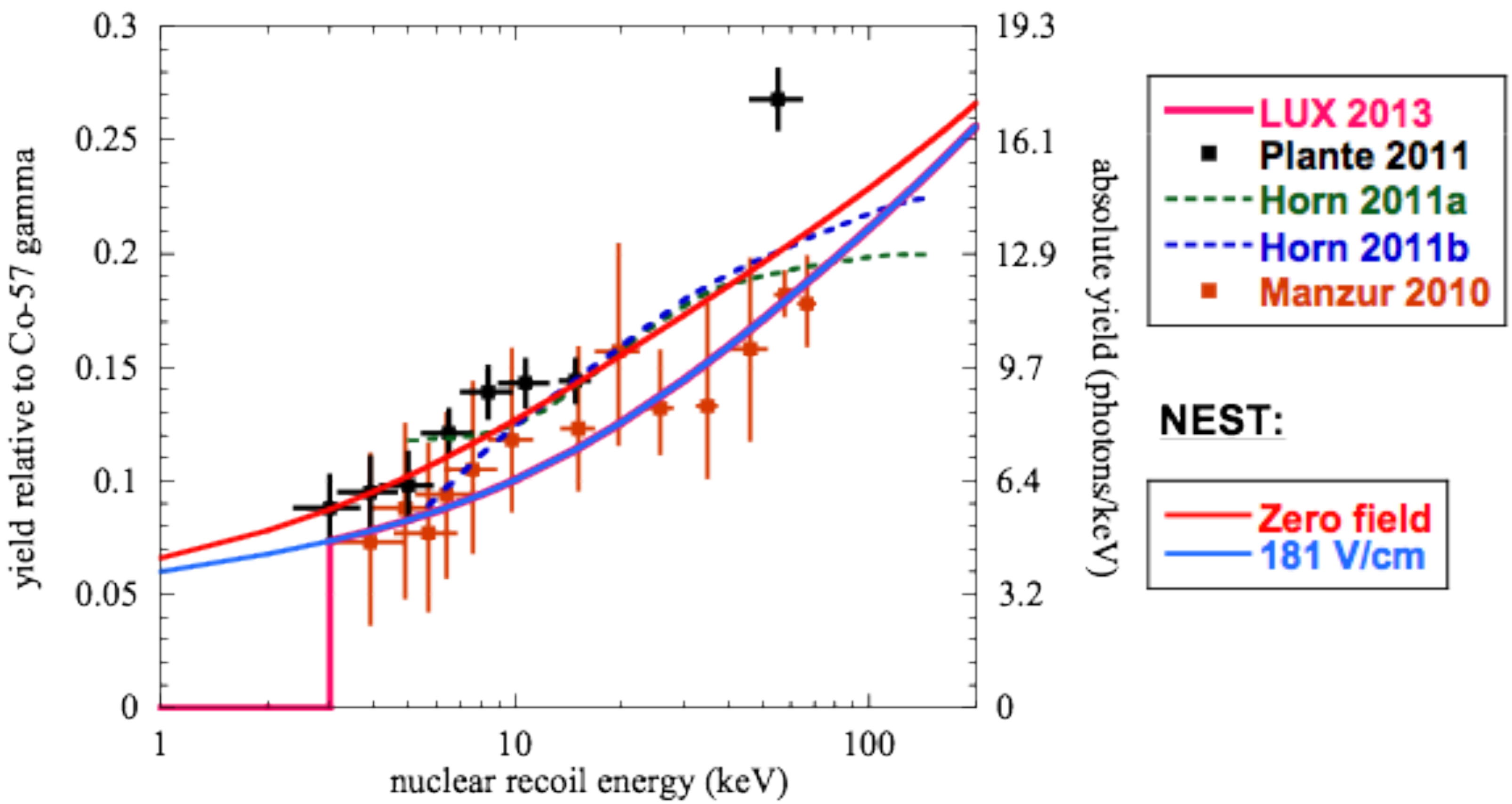


Spin-Independent Limits, as of Oct. 30



Light and Charge Yields in LUX

- Modeled Using Noble Element Simulation Technique (NEST).
- NEST based on canon of existing experimental data.
- **Artificial cutoff in light and charge yields assumed below 3 keVnr, to be conservative**.
- Includes predicted electric field quenching of light signal, to 77-82% of the zero field light yield



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.
  - More information for light WIMP events, allowing better discrimination, position resolution, etc.
- If there is a real WIMP signal, compare helium signal spectrum to that from other targets to learn about the WIMP mass.
- Should have robust ionization efficiency, with a forgiving Lindhard factor (high Leff), so nuclear recoil signals should be relatively large.
- Get away from current paradigm in experimental WIMP physics, which is to aim for 100 GeV, and go for the best cross-section sensitivity. How many experiments do we need, all focused on 100-1000 GeV?
- Low-energy anomalies are (in my opinion) likely all due to poorly understood backgrounds (extraordinary claims require extraordinary evidence), but have had the beneficial effect of widening the theoretical discussion, with many plausible and exciting models invented.
- We need to look under every rock for the dark matter!

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.

Theories of light WIMPs

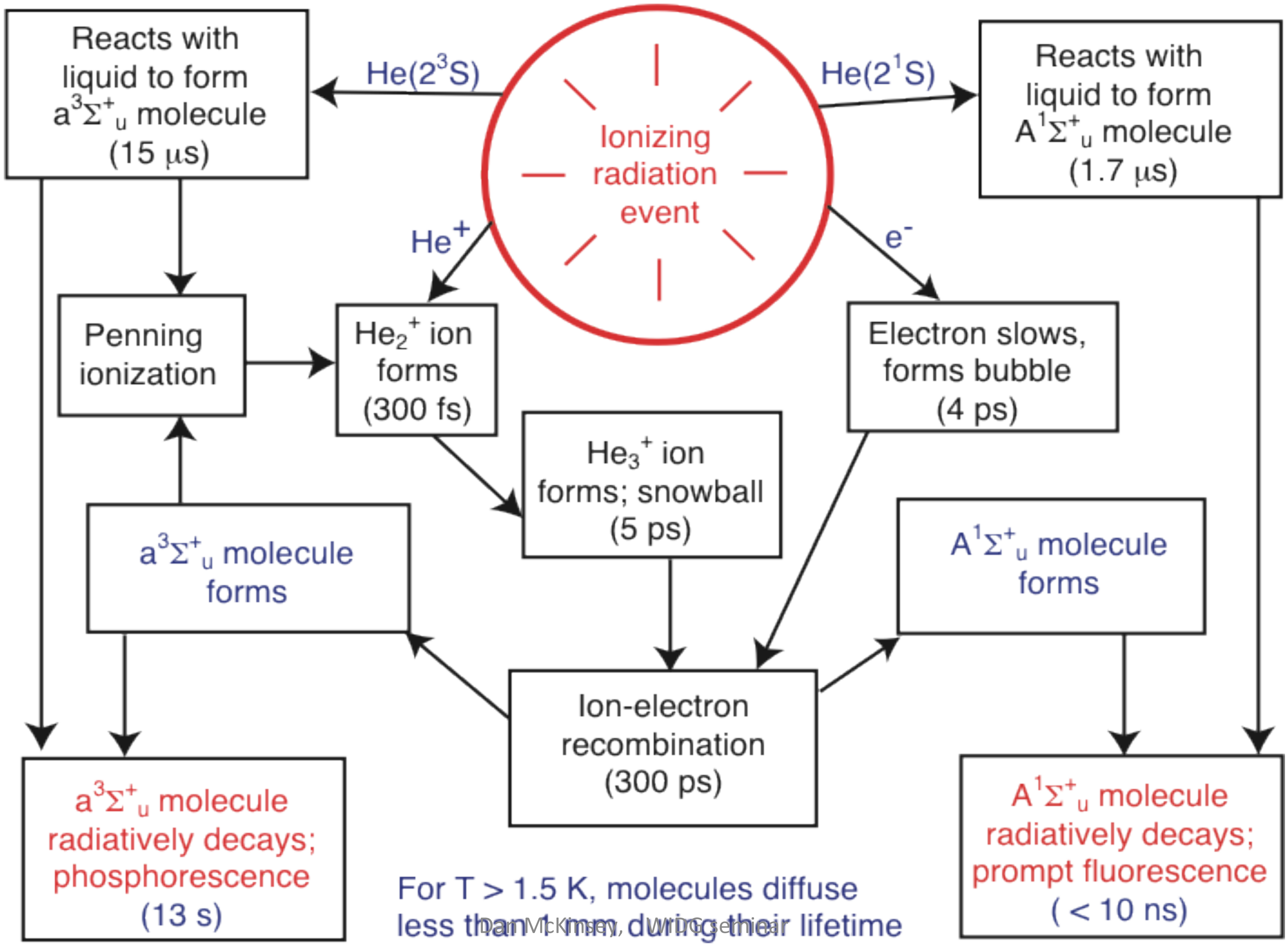
- NMSSM: J. F. Gunion, D. Hooper, B. McElrath, Phys. Rev. D73, 015011 (2006); [hep-ph/0509024] A. Bottino, F. Donato, N. Fornengo et al., Phys. Rev. D67, 063519 (2003) [hep-ph/0212379]; Phys. Rev. D69, 037302 (2004) [hep-ph/0307303]; Phys. Rev. D72, 083521 (2005) [hep-ph/0508270]; Phys. Rev. D78, 083520 (2008) [arXiv:0806.4099 [hep-ph]]; Phys. Rev. D81, 107302 (2010) [arXiv:0912.4025 [hep-ph]];
- Asymmetric dark matter: D. E. Kaplan, M. A. Luty and K. M. Zurek, Phys. Rev. D 79, 115016 (2009) [arXiv:0901.4117 [hep-ph]], J. Shelton and K. M. Zurek, Phys.Rev.D82:123512,2010
- Light WIMPs in MSSM: Eric Kuflik, Aaron Pierce, and Kathryn M. Zurek, Phys.Rev.D81:111701,2010, arXiv:1003.0682
- "WIMPless DM": J. L. Feng, J. Kumar, Phys. Rev. Lett. 101, 231301 (2008) [arXiv:0803.4196 [hep-ph]]; J. Feng, J. Kumar, and L. Strigari Phys. Lett. B 670, 37 (2008) [arXiv:0806.3746 [hep-ph]].
- Singlet scalars: C. P. Burgess, M. Pospelov and T. ter Veldhuis, Nucl. Phys. B 619, 709 (2001) [arXiv:hep-ph/0011335]. S. Andreas, T. Hambye and M. H. G. Tytgat, JCAP 0810, 034 (2008) [arXiv:0808.0255 [hep-ph]]. Y. G. Kim and S. Shin, JHEP 0905, 036 (2009) [arXiv:0901.2609 [hep-ph]].
- Dark sectors with kinetic mixing: M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B 662, 53 (2008) [arXiv:0711.4866 [hep-ph]]. D. Hooper and K. M. Zurek, Phys. Rev. D 77, 087302 (2008) [arXiv:0801.3686 [hep-ph]]. K. M. Zurek, Phys. Rev. D 79, 115002 (2009) [arXiv:0811.4429 [hep-ph]].
- "Mirror matter": R. Foot, Int. J. Mod. Phys. D 13, 2161 (2004) [arXiv:astroph/0407623]. R. Foot, Phys. Rev. D 78, 043529 (2008) [arXiv:0804.4518 [hep-ph]].

Superfluid helium as a detector material

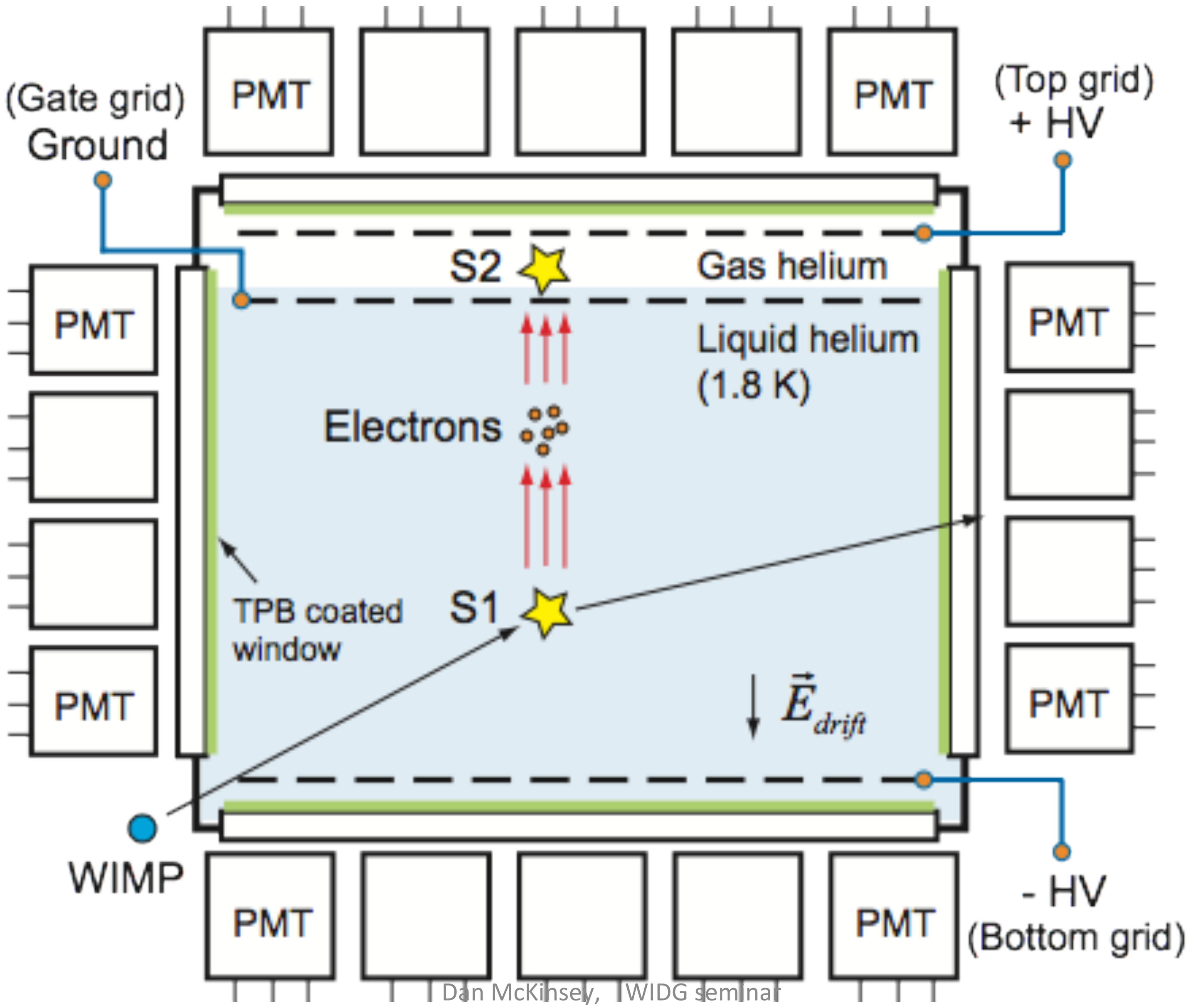
- Used to produce, store, and detect ultracold neutrons. Detection based on scintillation light (S1)
  - Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).
  - Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).

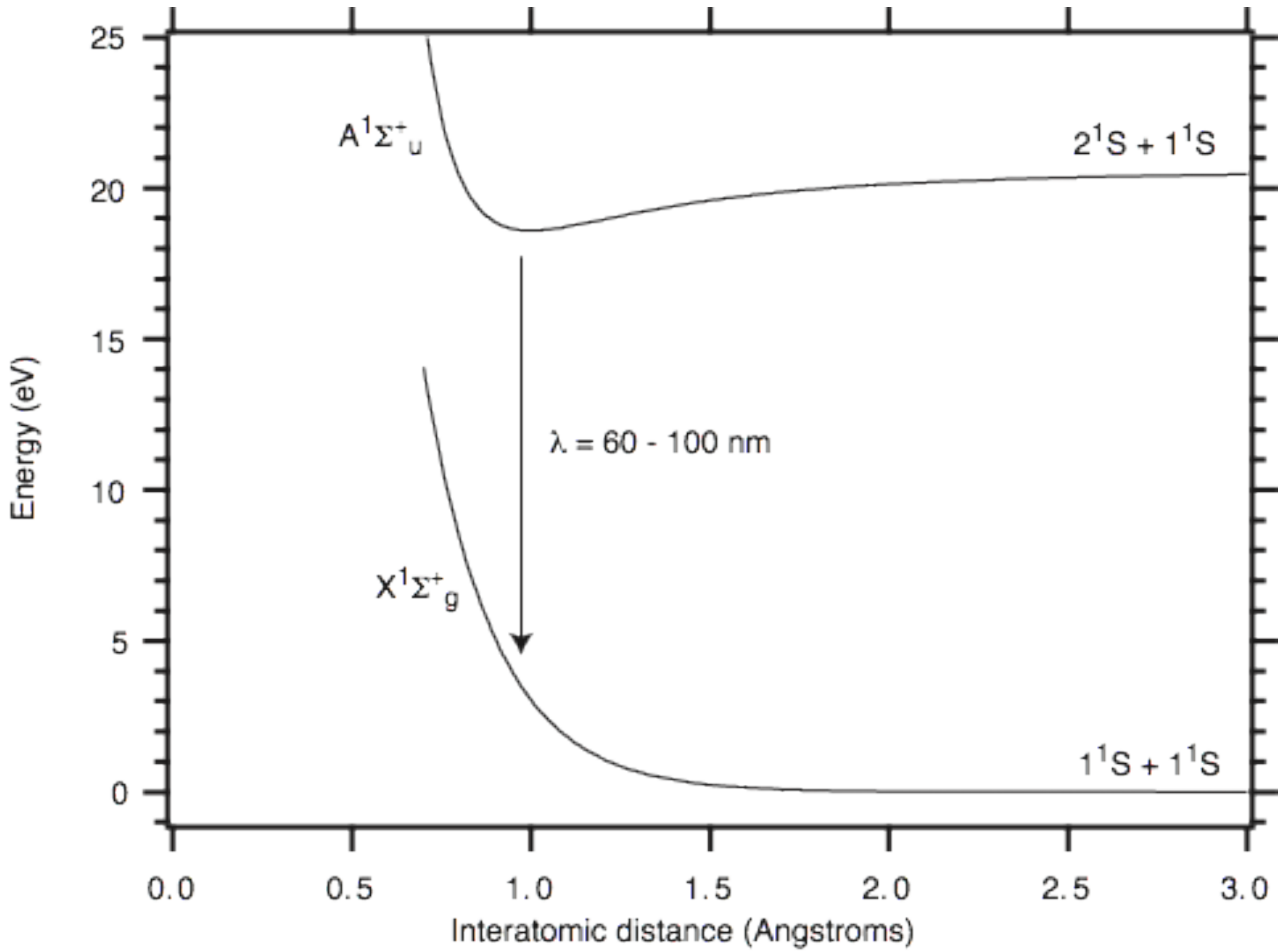
- Proposed for measurement of pp solar neutrino flux using roton detection (HERON): R.E. Lanou, H.J. Maris, and G.M. Seidel, Phys. Rev. Lett. **58**, 2498 (1987).

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

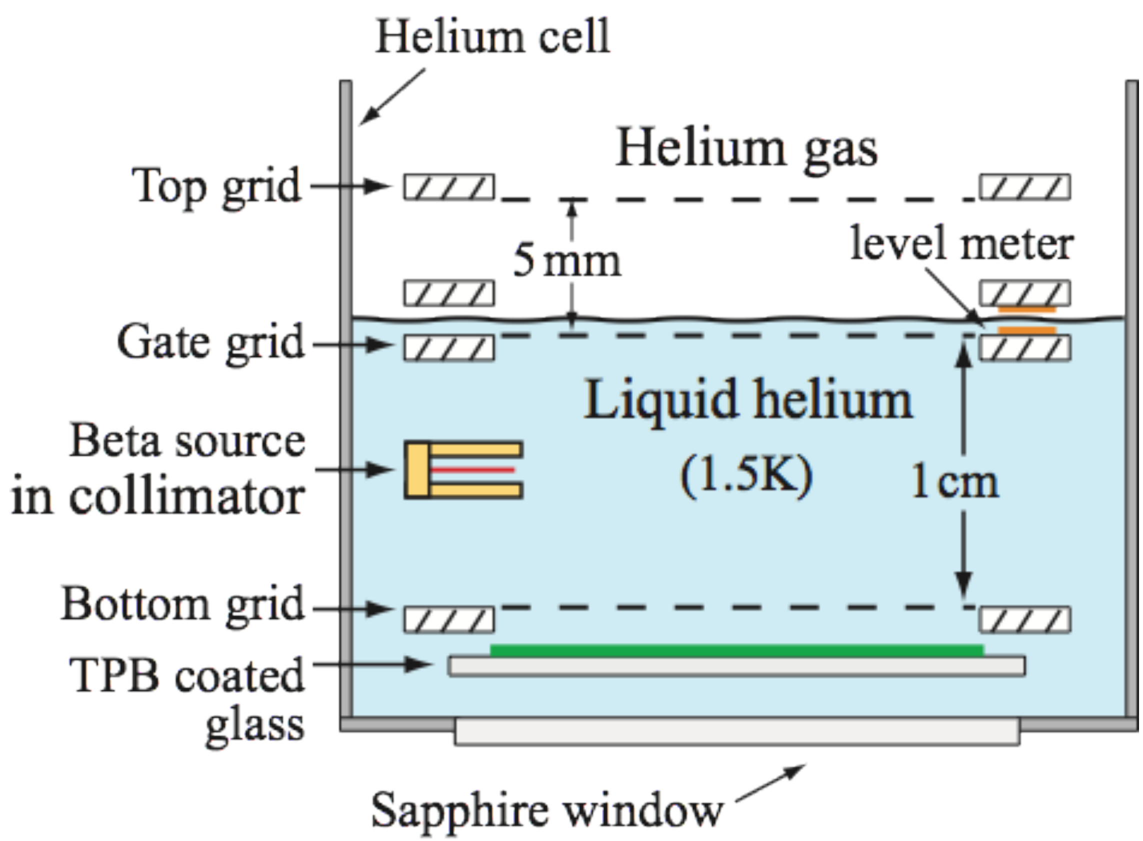

Ionizing radiation event
$He(2^3S)$
$He(2^1S)$
He^+
e^-
Reacts with liquid to form $a^3\Sigma^+_u$ molecule (15 μs)
Reacts with liquid to form $A^1\Sigma^+_u$ molecule (1.7 μs)
Penning ionization
He_2^+ ion forms (300 fs)
He_3^+ ion forms; snowball (5 ps)
Electron slows, forms bubble (4 ps)
$a^3\Sigma^+_u$ 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

Light WIMP Detector Concept




Energy (eV)
25
20
15
10
5
0
$A^1\Sigma^+_u$
$2^1S + 1^1S$
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)

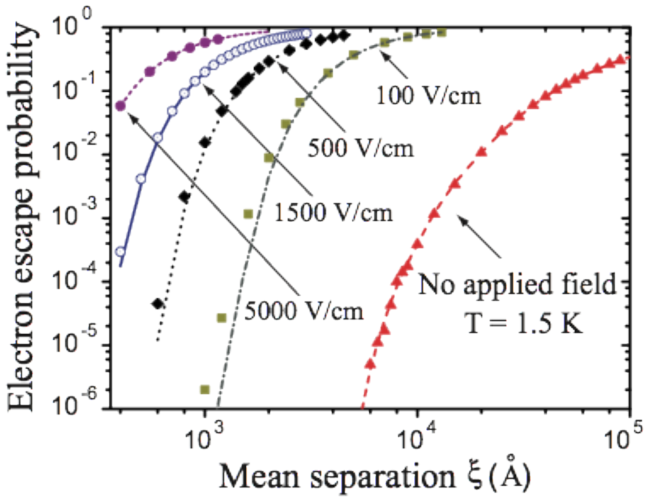
Work at Yale on charge extraction in superfluid helium
(W. Guo et al, Journal of Instrumentation **7**, P01002 (2012).)

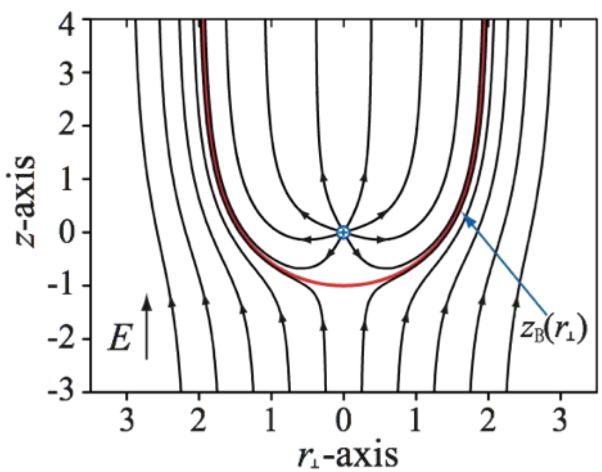


Data from charge extraction measurement

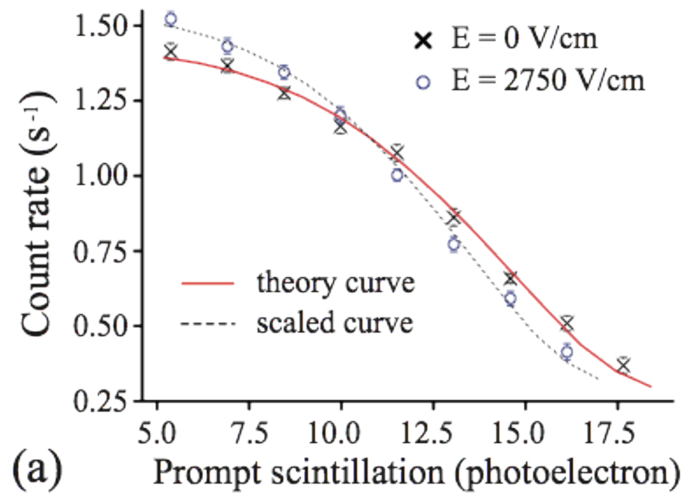
5 kV/cm will give 23% ionization extraction at higher LHe temperatures (1-2 K)
(compare to 30-50 kV/cm in n-edm experiment)

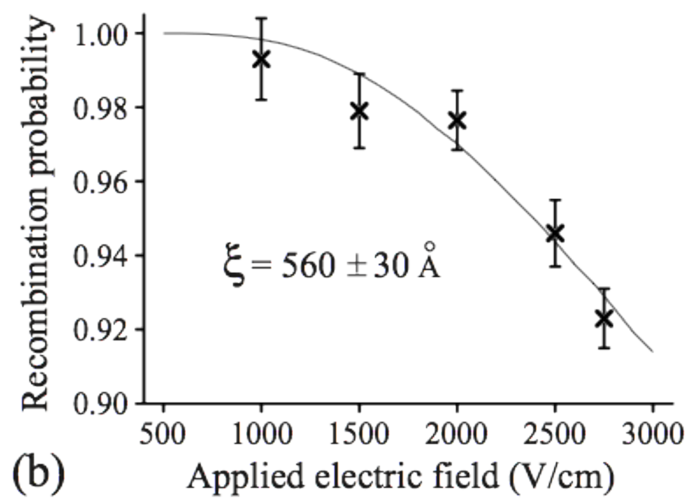
Monte Carlo results





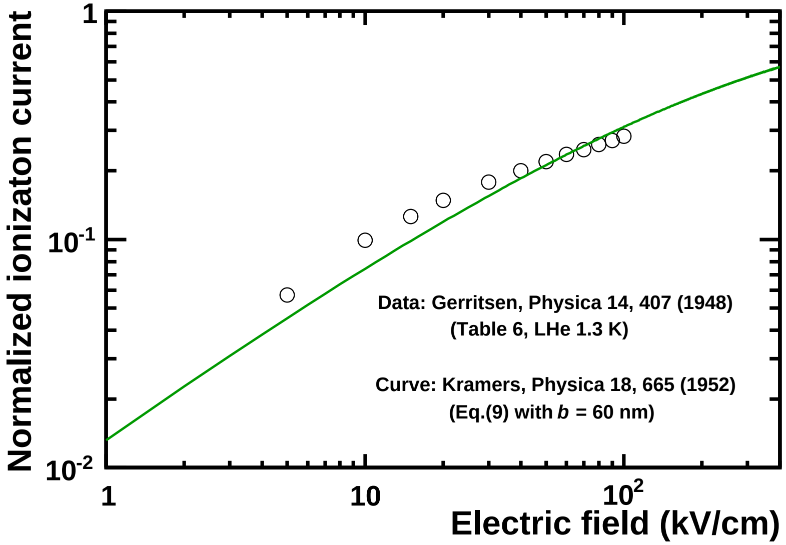
Experimental data

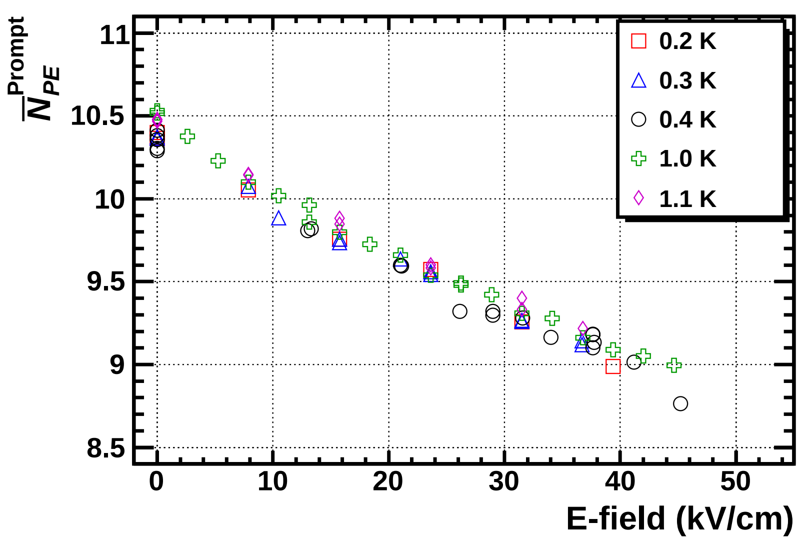




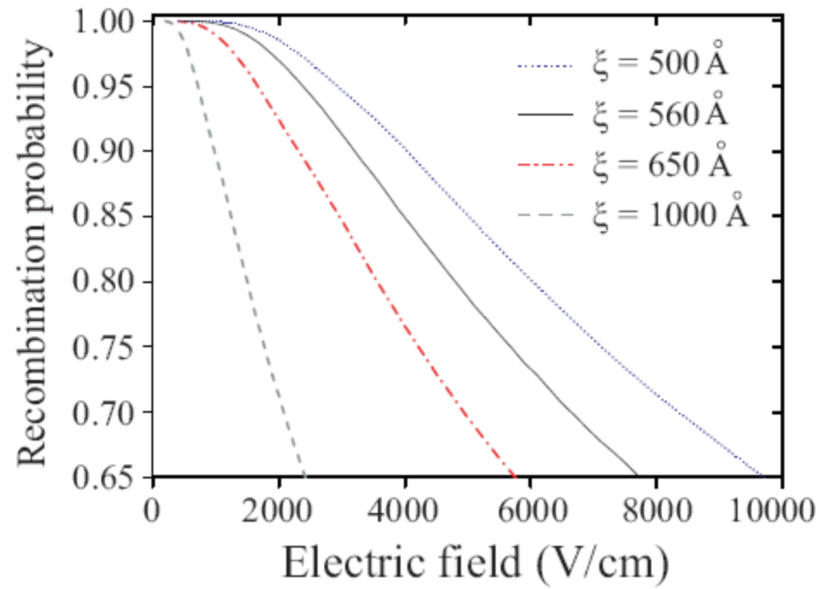
Helium scintillation vs. electric field

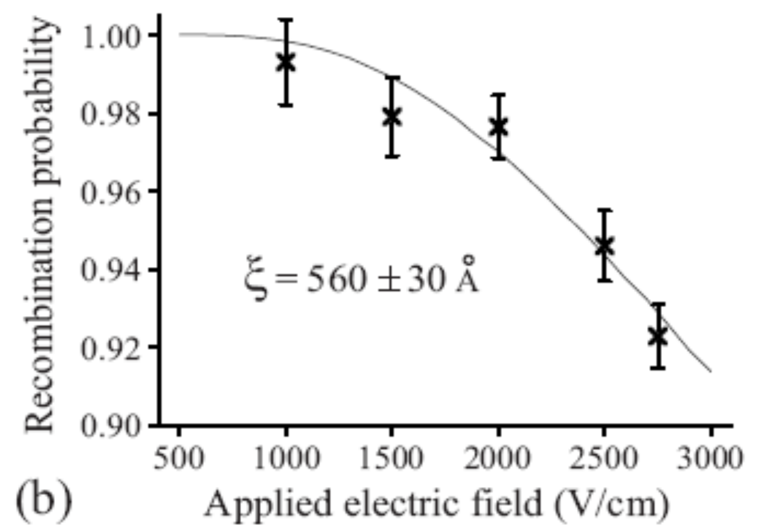
Alpha scintillation yield vs. applied field, T. Ito et al, 1110.0570





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





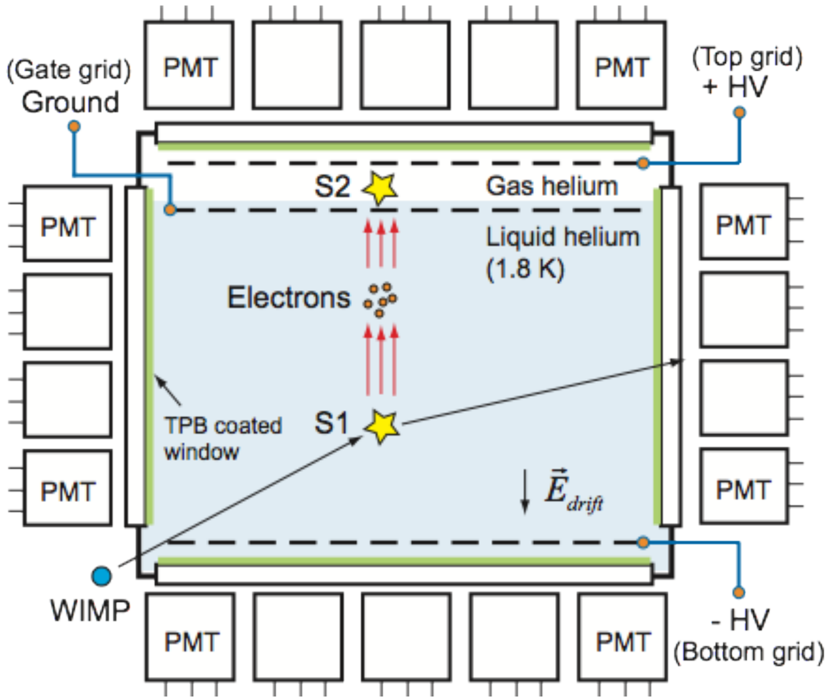
How to detect the charge signal?

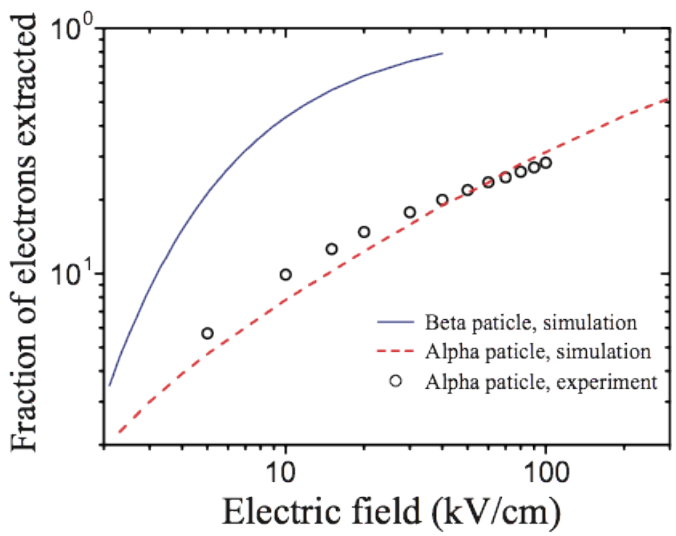
Many options:

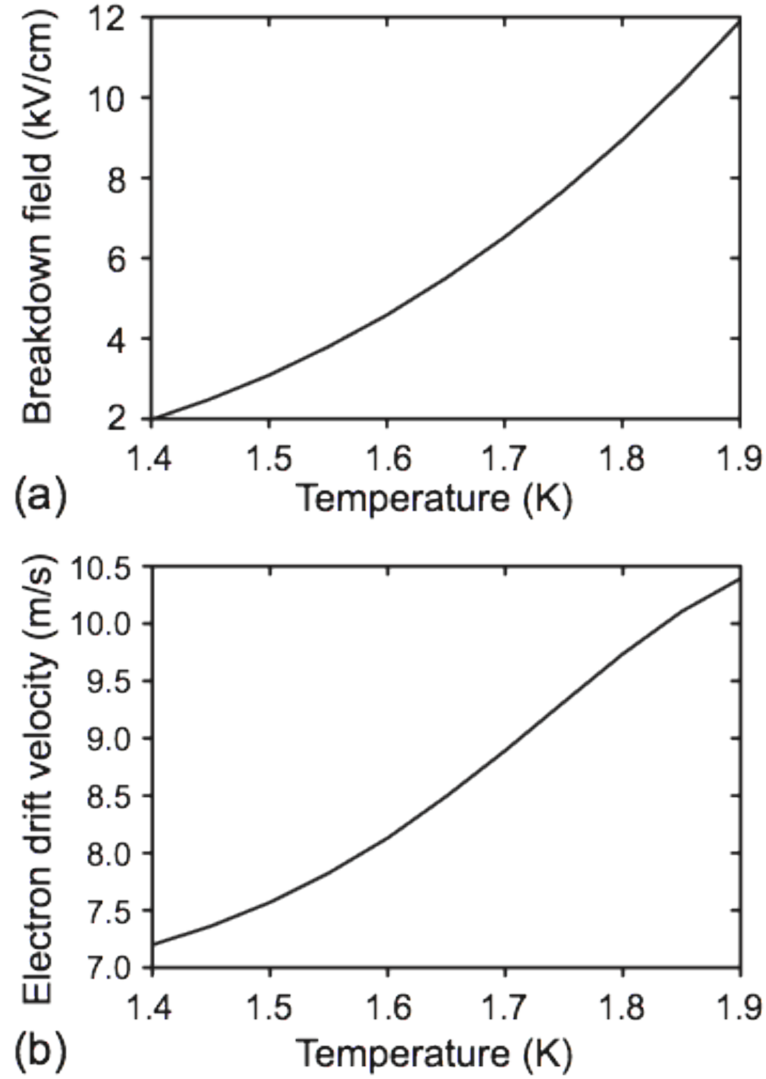
- Proportional scintillation and PMTs (like in 2-phase Xe, Ar detectors)
- Gas Electron Multipliers (GEMs) or Thick GEMS, detect light produced in avalanche.
- Micromegas, detect avalanche light.
- Thin wires in liquid helium. This should generate electroluminescence at fields ~1-10 MV/cm near wire,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

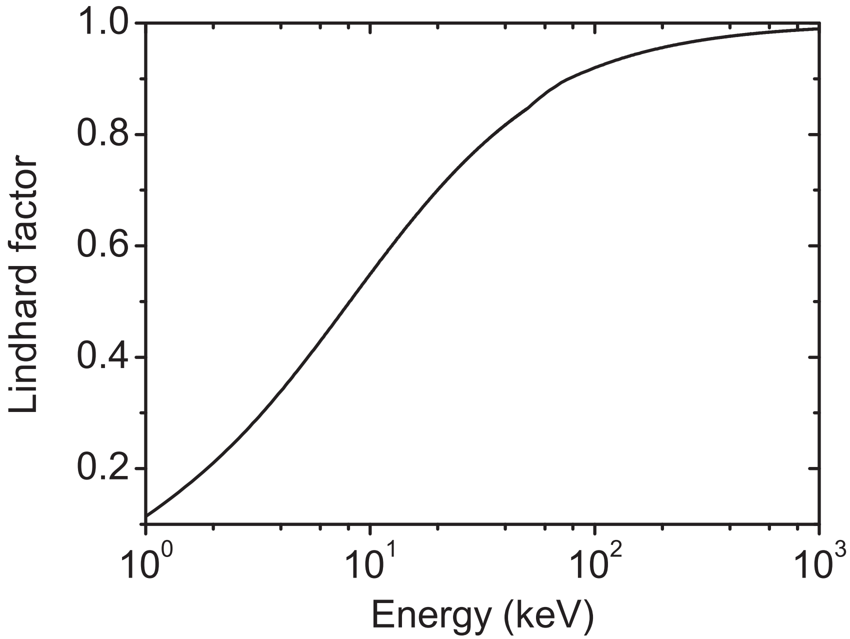
A two-phase helium detector; salient properties







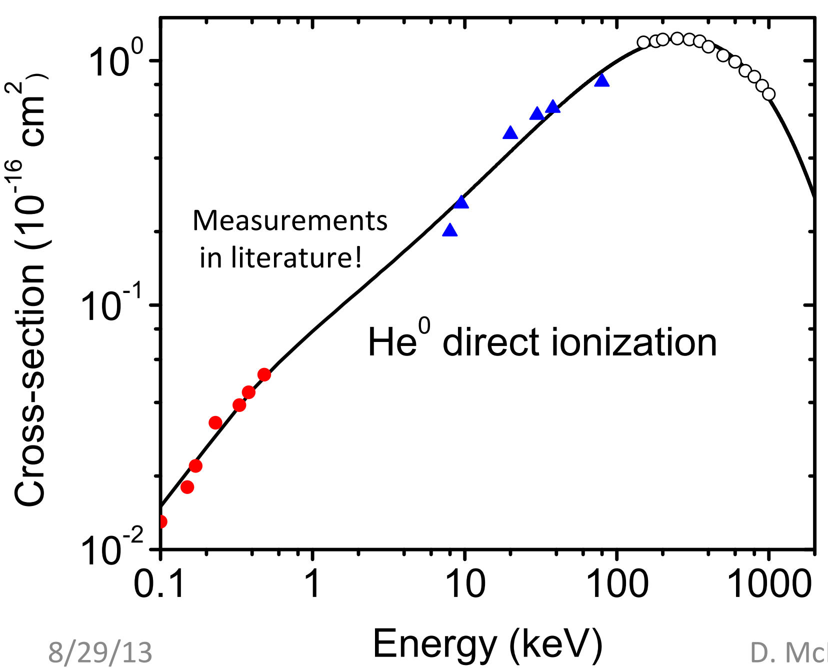
Alpha data: A.N. Gerritsen, Physica 14, 407 (1948).

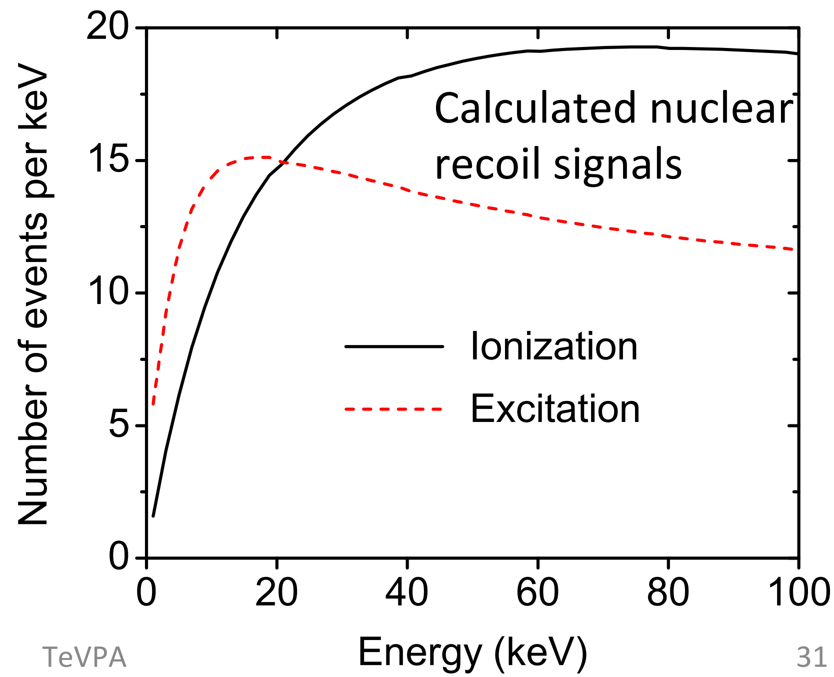


Liquid helium-4 predicted response (Guo and McKinsey, arXiv:1302.0534, Phys. Rev. D 87, 115001 (2013).)

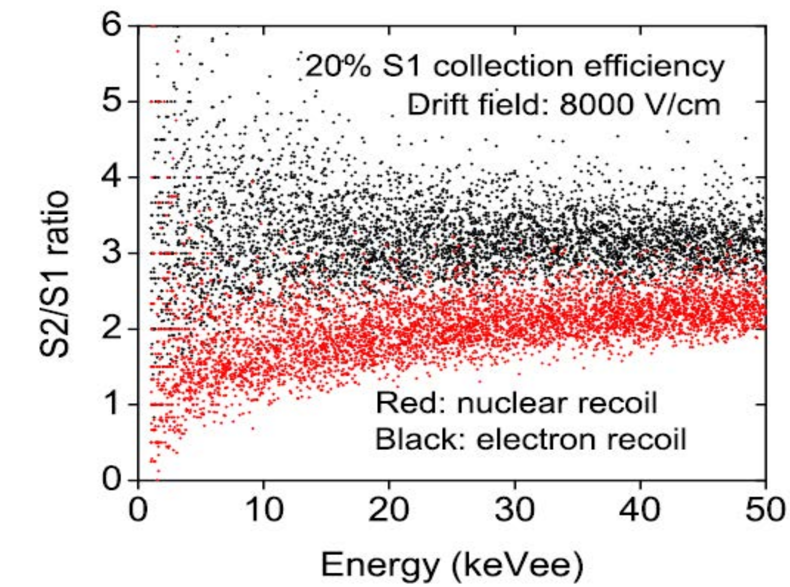
Liquid helium has lower electron scintillation yield for electron recoils (19 photons/keVee)

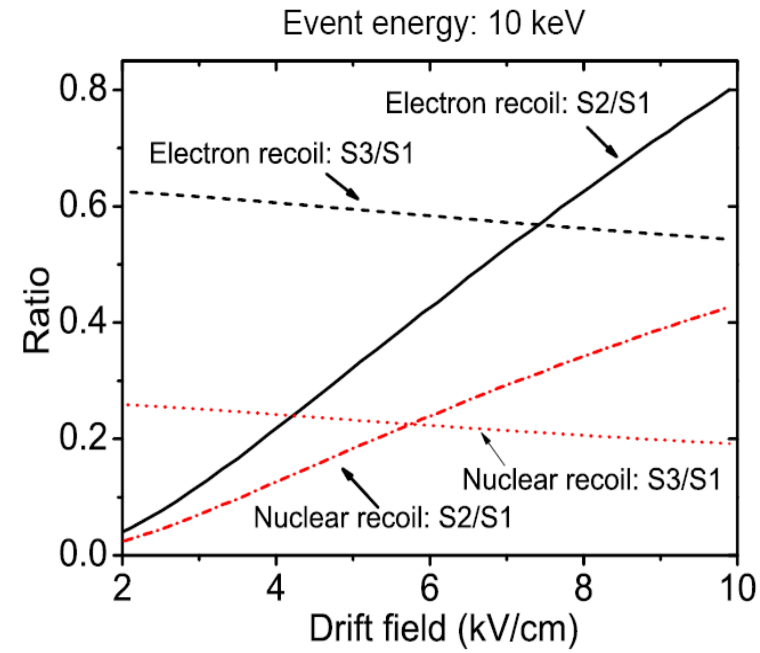
But, extremely high Leff, good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity

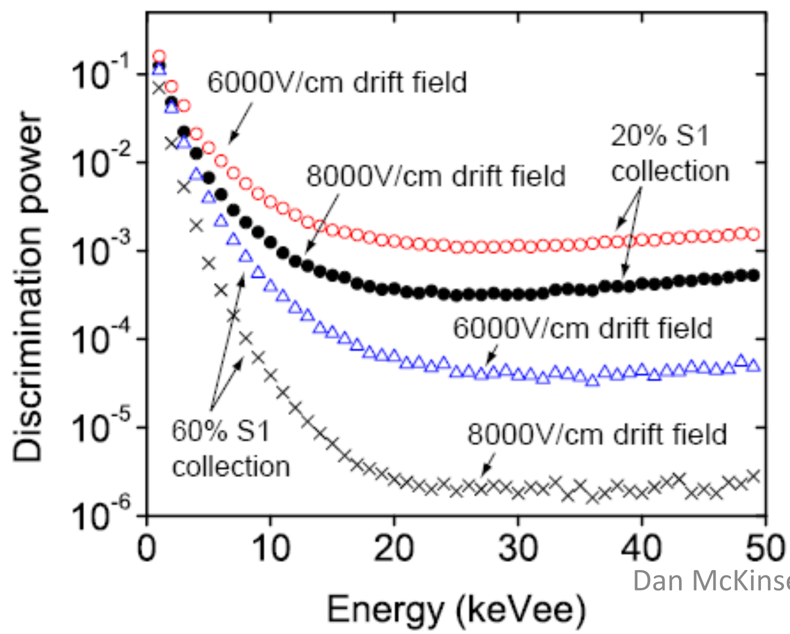


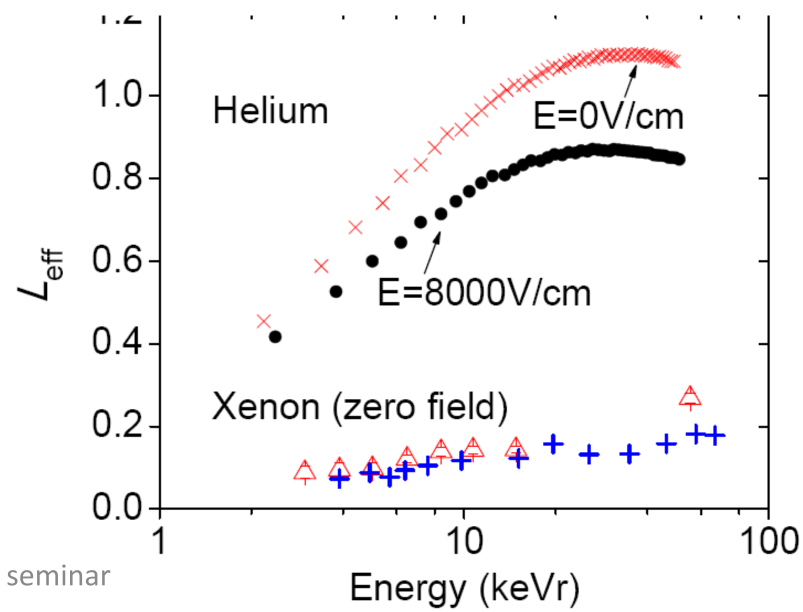


Predicted nuclear recoil discrimination and signal strengths in liquid helium

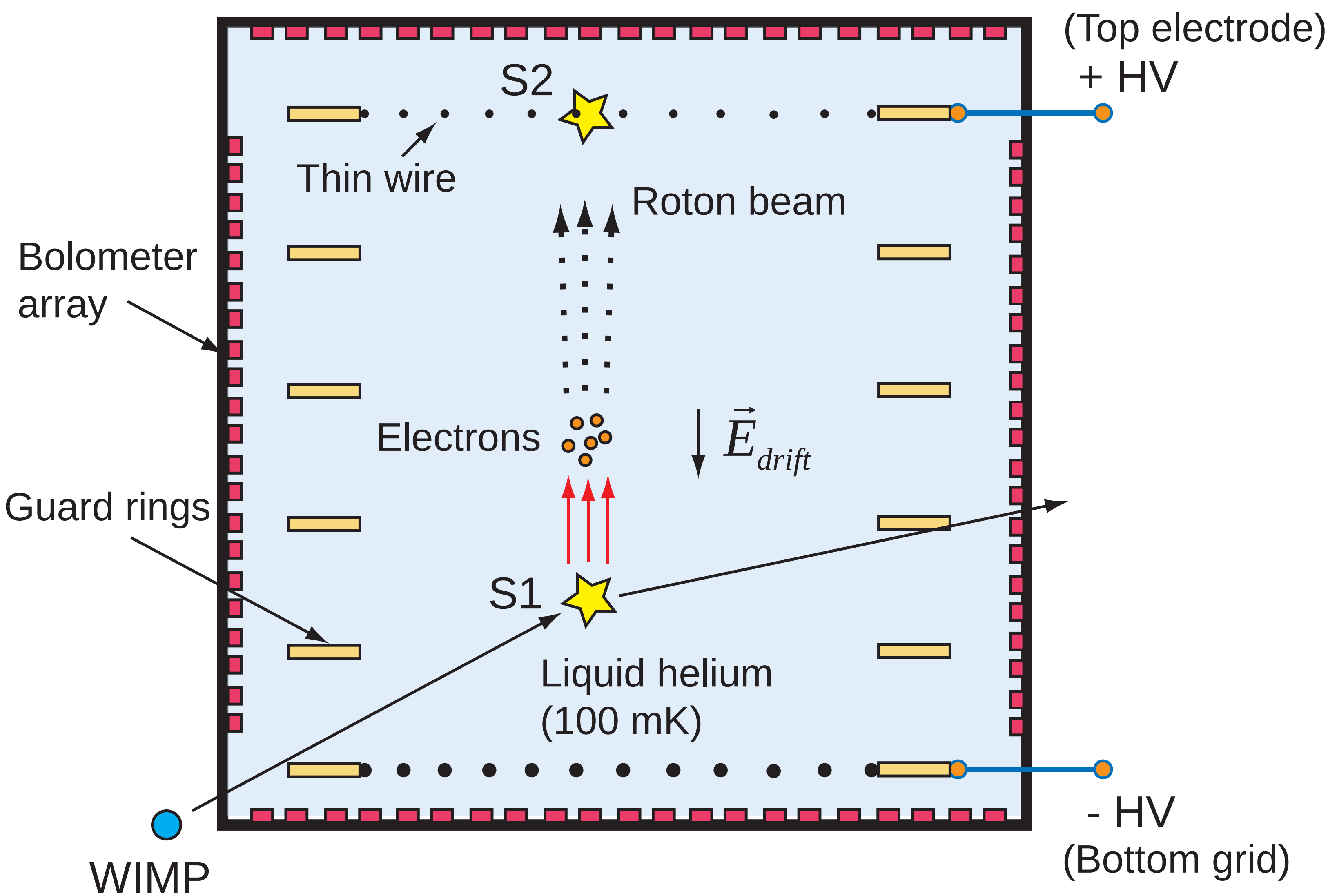




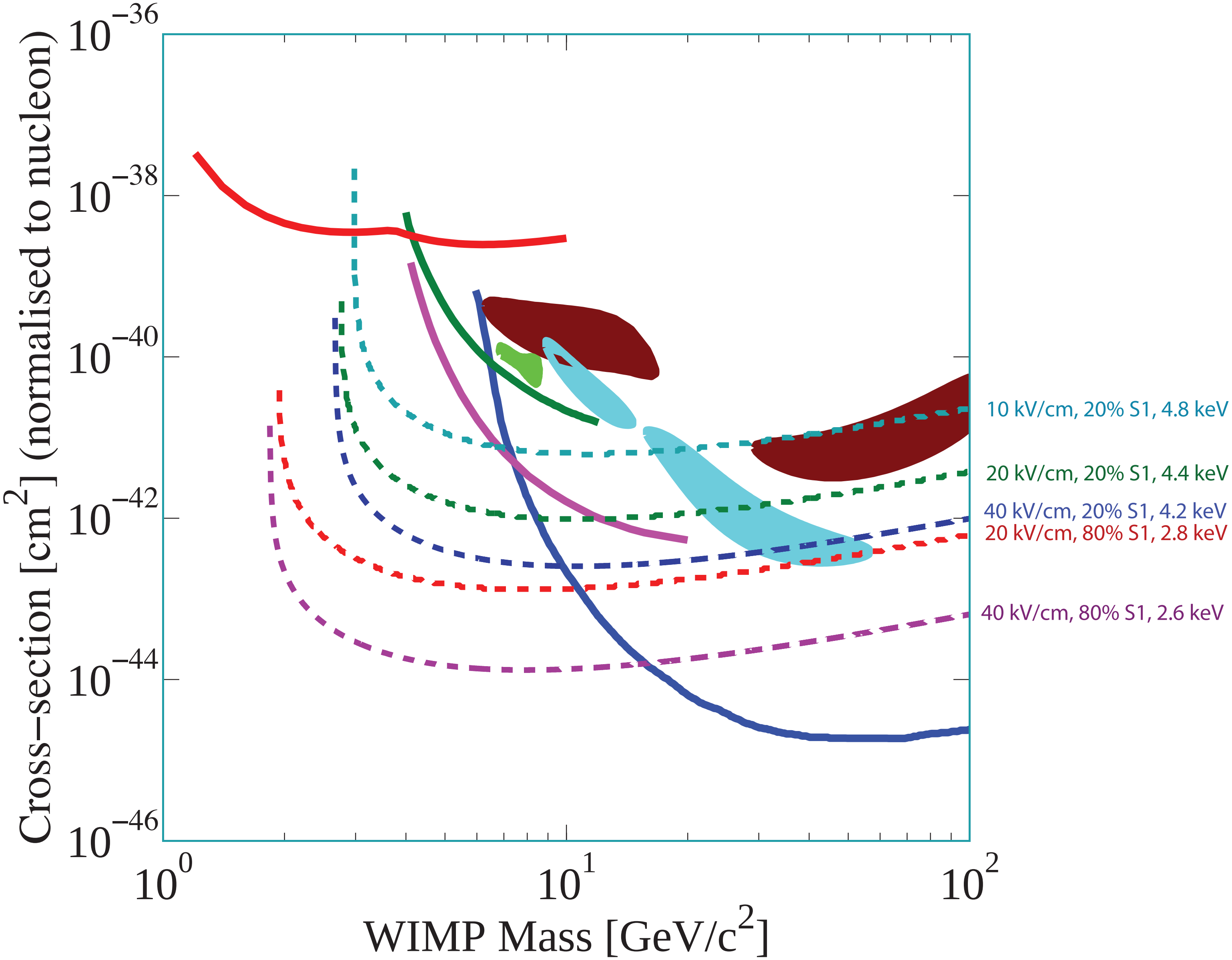




Concept for a Light WIMP Detector at ~ 100 mK



Projected Sensitivity for Liquid Helium



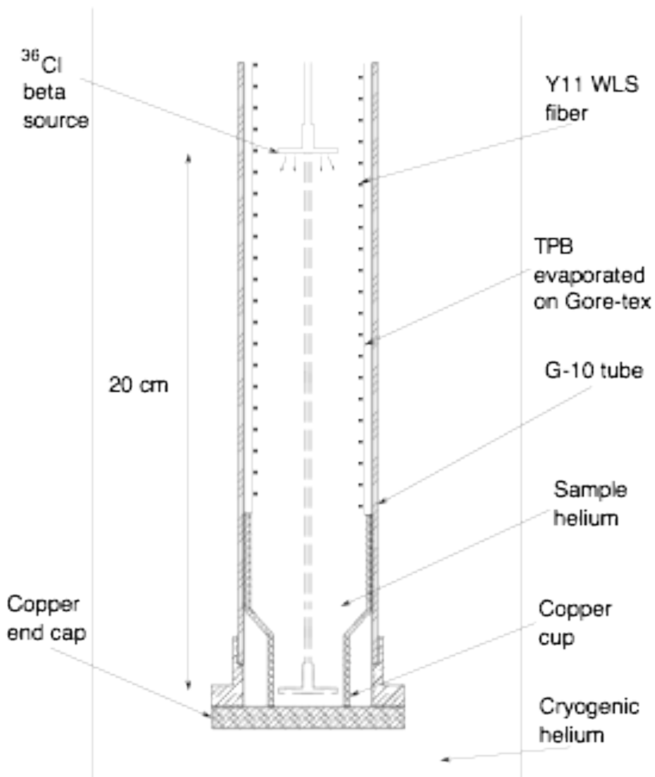
PHYSICAL REVIEW A VOLUME 59, NUMBER 1 JANUARY 1999

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)



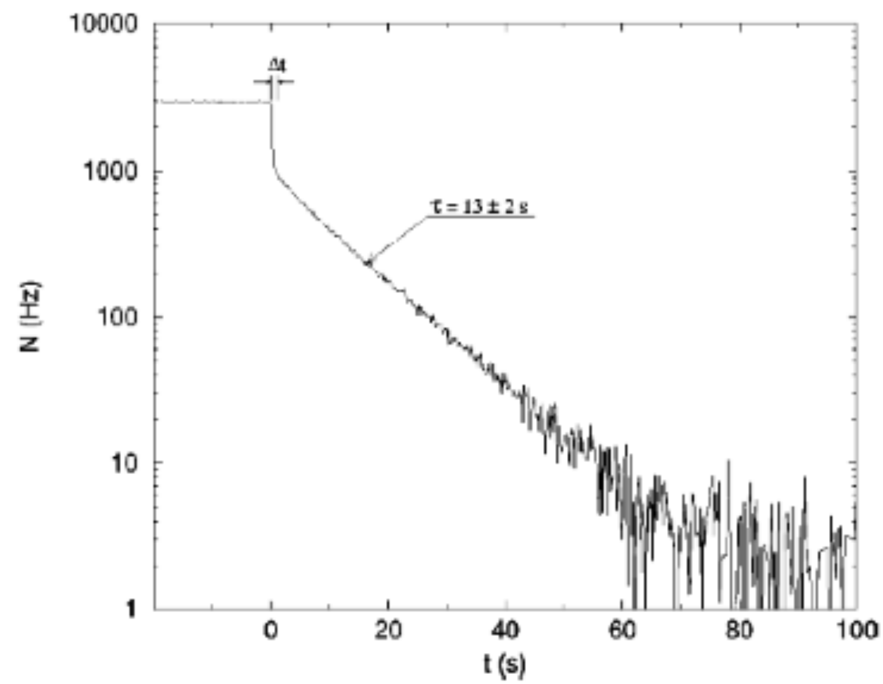
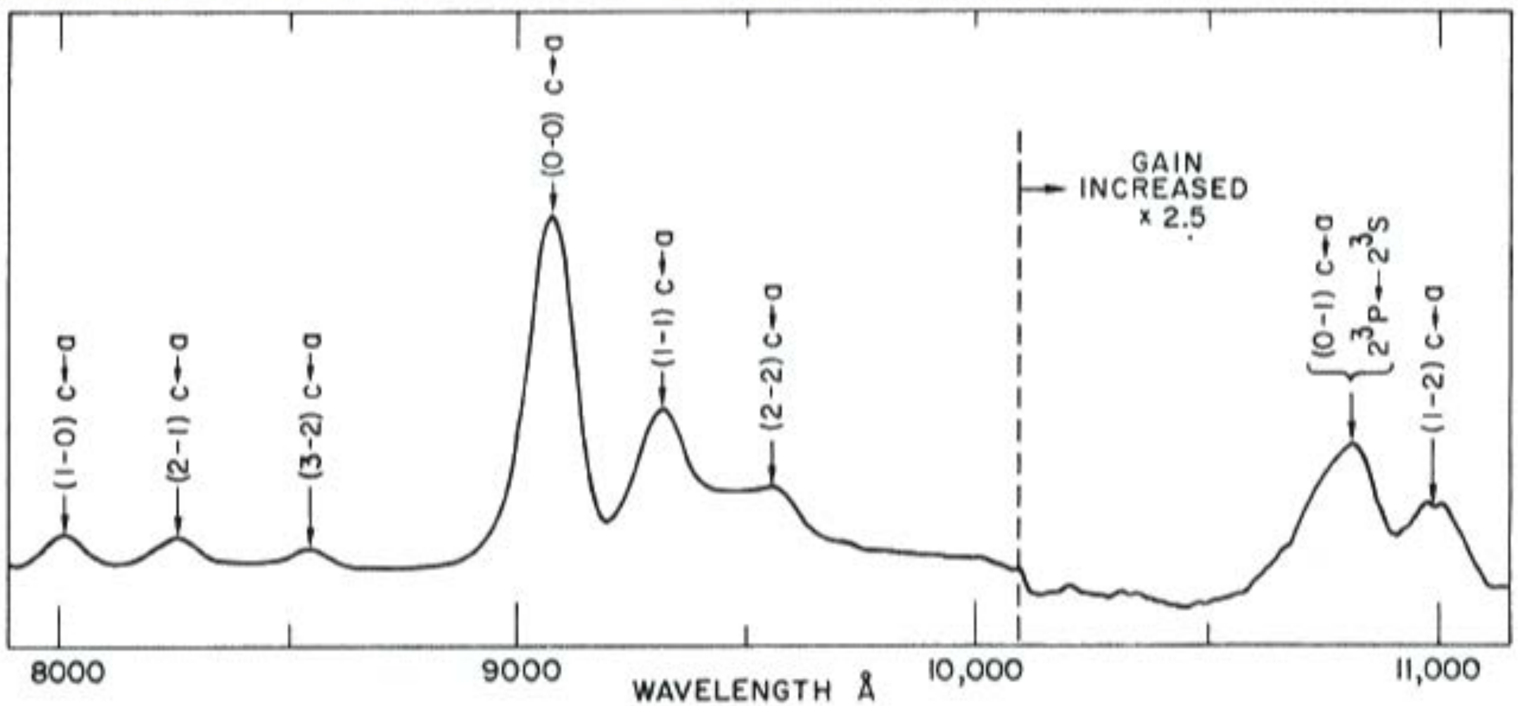


FIG. 2. Count rate N of detected $He_2(a\,^3\Sigma_u^+)$ decays versus time. A ^{36}Cl β source is placed in the center of the detection region and then removed in a time $\Delta t<1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate τ of 13 ± 2 s.

In the 60's and 70's, spectroscopic studies were done on electron-excited LHe.
(Groups of Reif, Walters, Fitzsimmons, and more recently Parshin)
Lines were visible from a long-lived "neutral excitation", identified as triplet He_2

Absorption spectrum of electron-excited liquid helium:



J. C. Hill et al, Phys. Rev. Lett. 26, 1213 (1971).

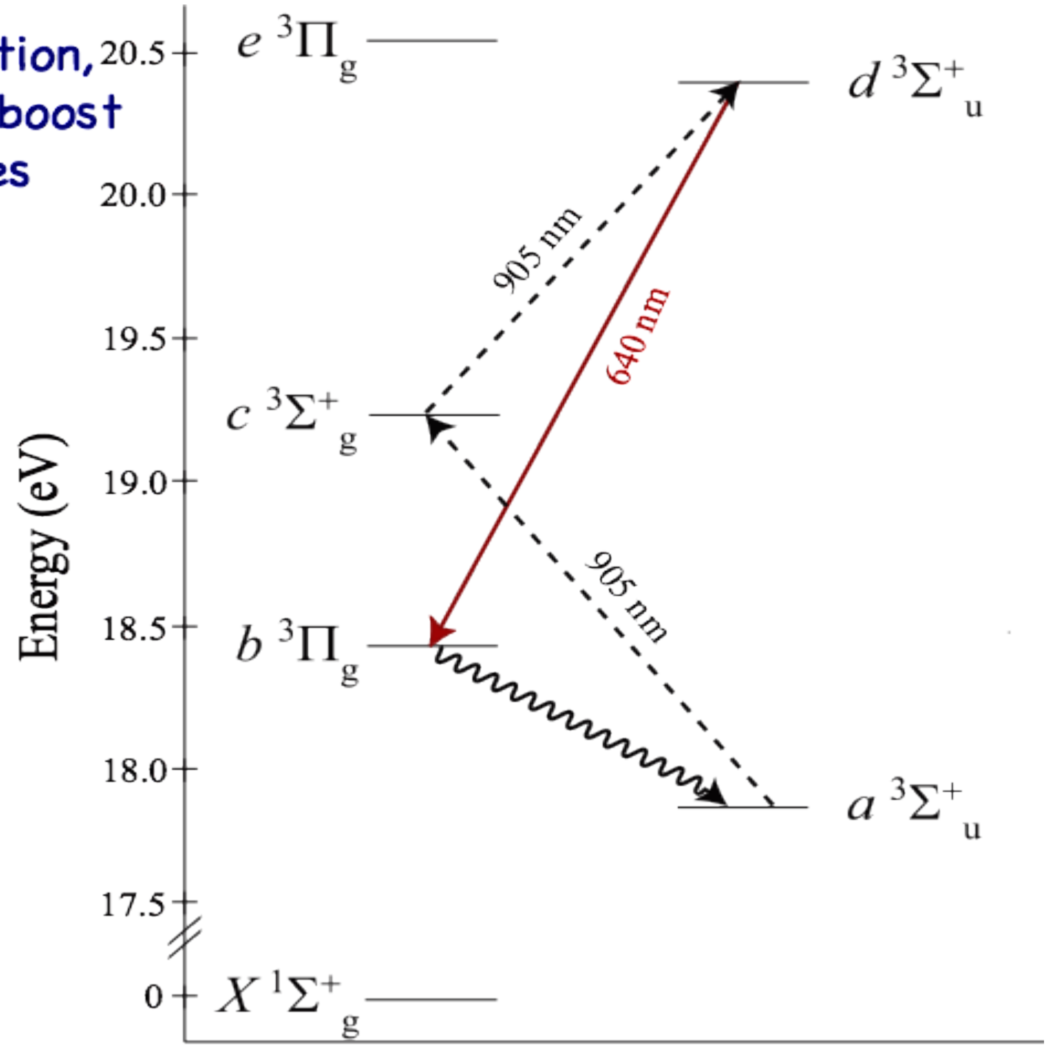
Strong absorption at 910 nm: c-a transition, 0-0 vibrational
Other vibrational transitions visible.
The triplet He_2 molecule exists as a bubble in liquid helium, with radius 0.7 nm.

Idea: Use 2-photon excitation, fluorescence detection to boost sensitivity to He_2 molecules (D. N. McKinsey et al, PRL 95, 111101 (2005))

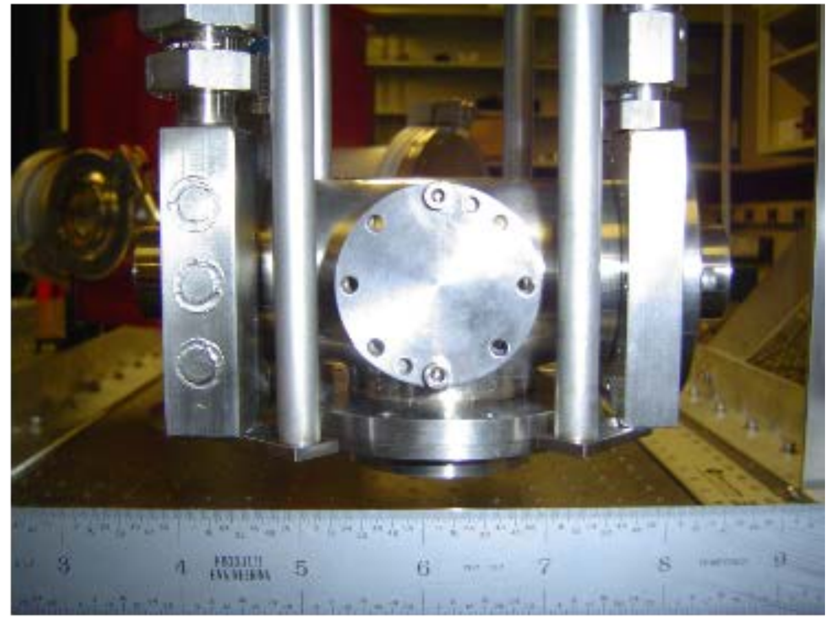
Uses:

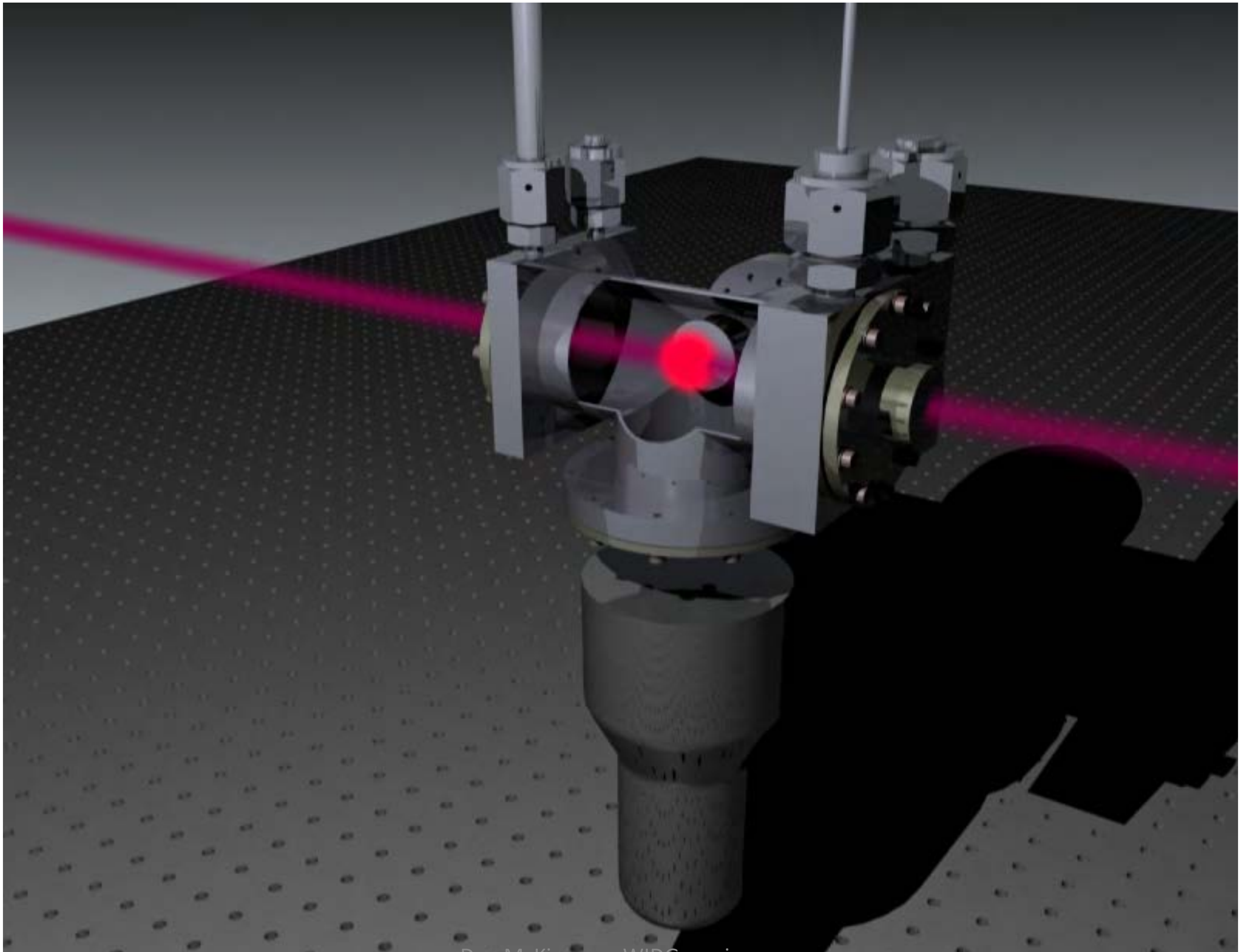
- WIMP detection
- ultracold neutrons
- gamma ray imaging
- Turbulence visualization

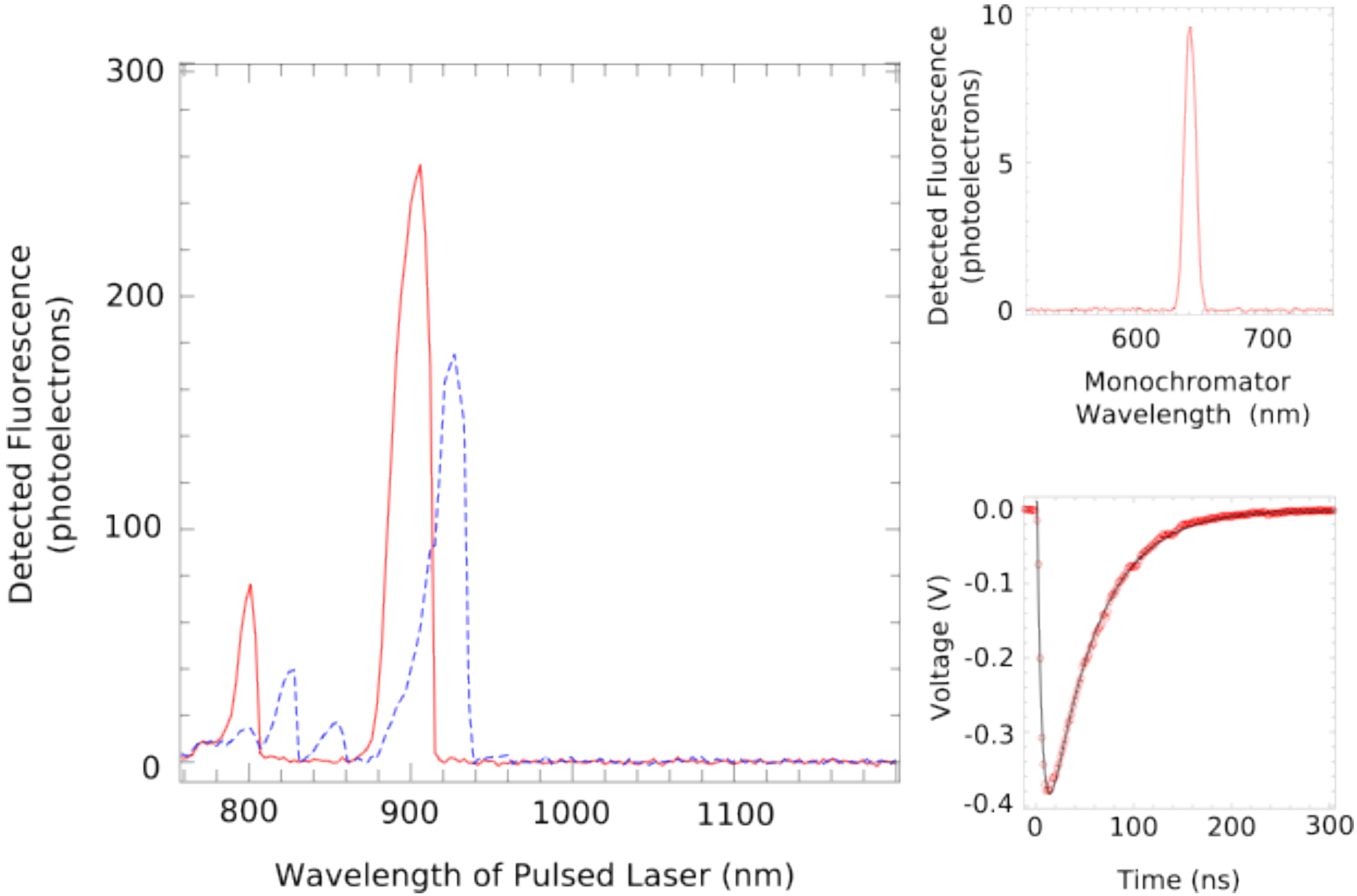
Recent support:
Packard foundation, DTRA

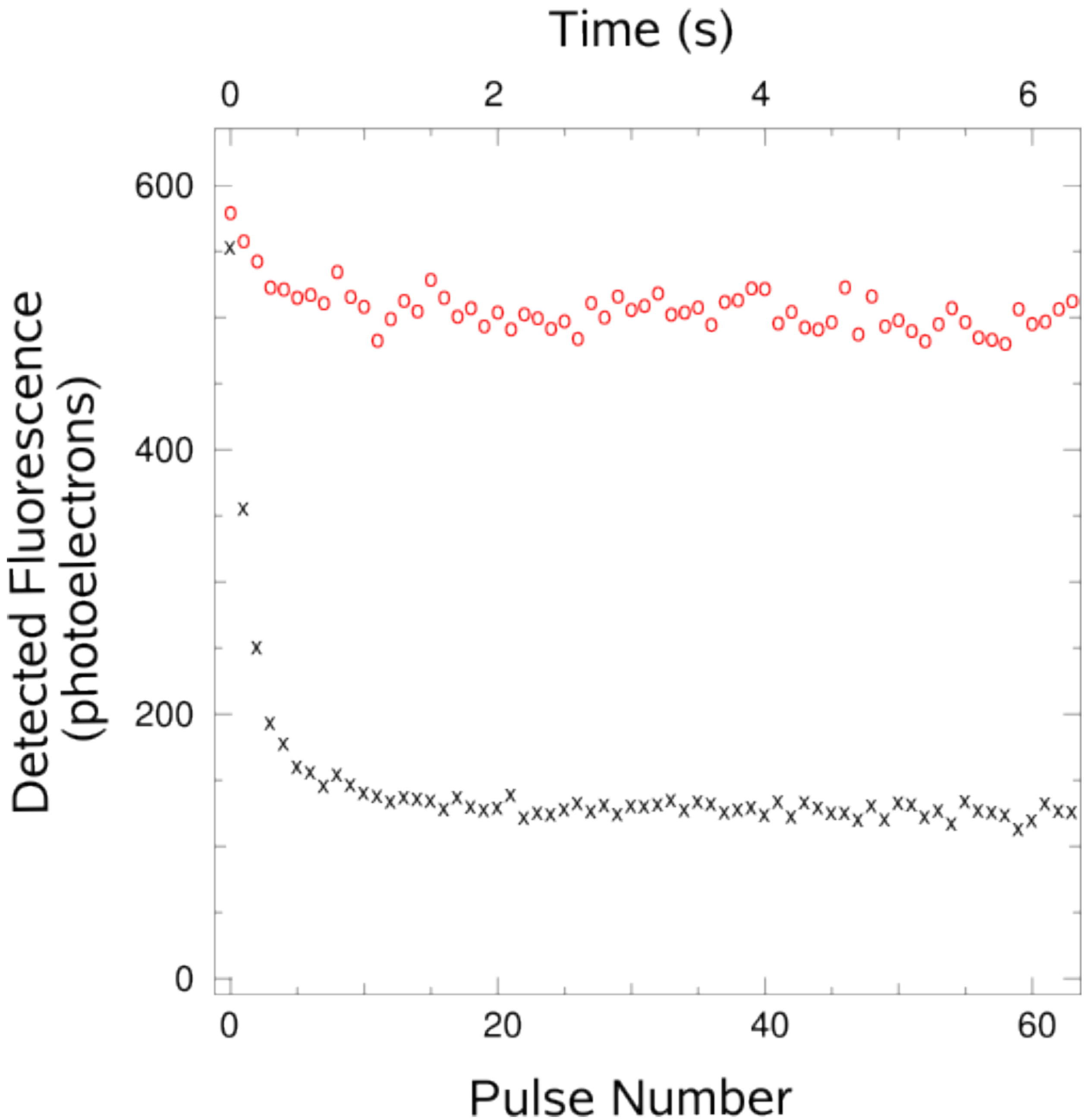


Pumped He-4 system at Yale, with optical access



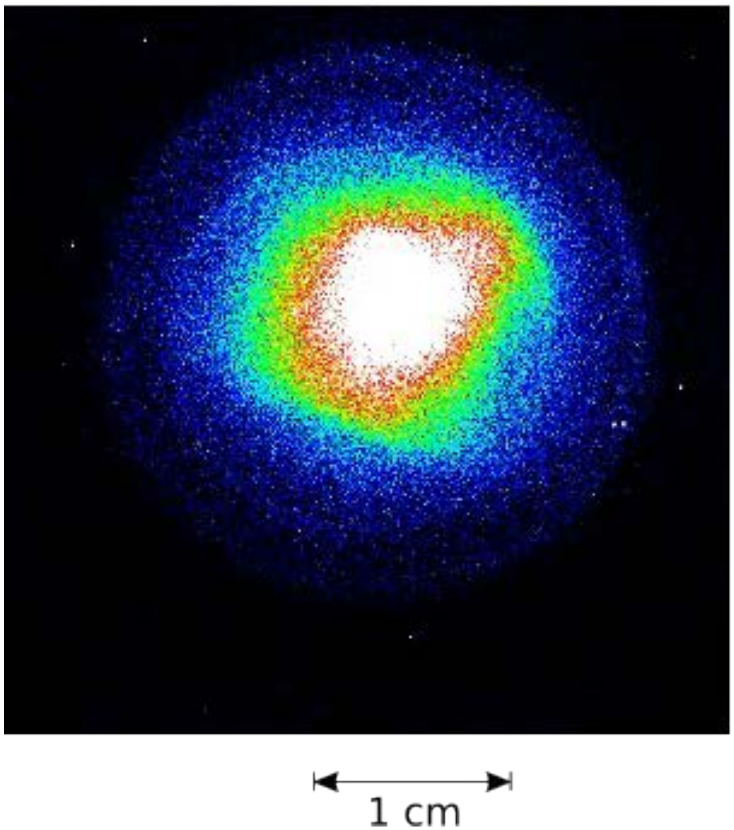


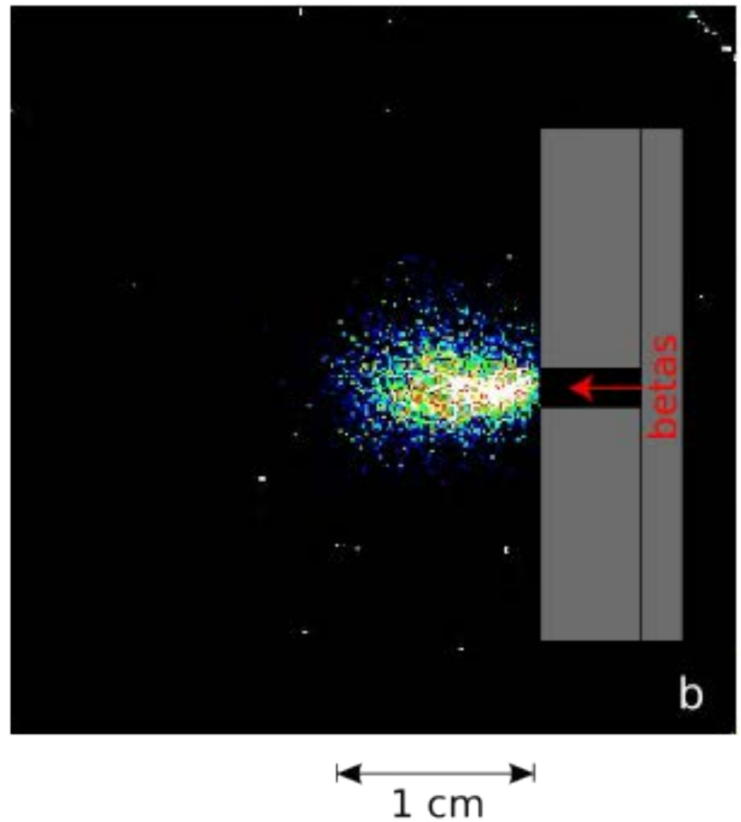

Detected Fluorescence (photoelectrons)
300
200
100
0
800
900
1000
1100
Wavelength of Pulsed Laser (nm)
Detected Fluorescence (photoelectrons)
10
5
0
600
700
Monochromator Wavelength (nm)
Voltage (V)
0.0
-0.1
-0.2
-0.3
-0.4
0
100
200
300
Time (ns)



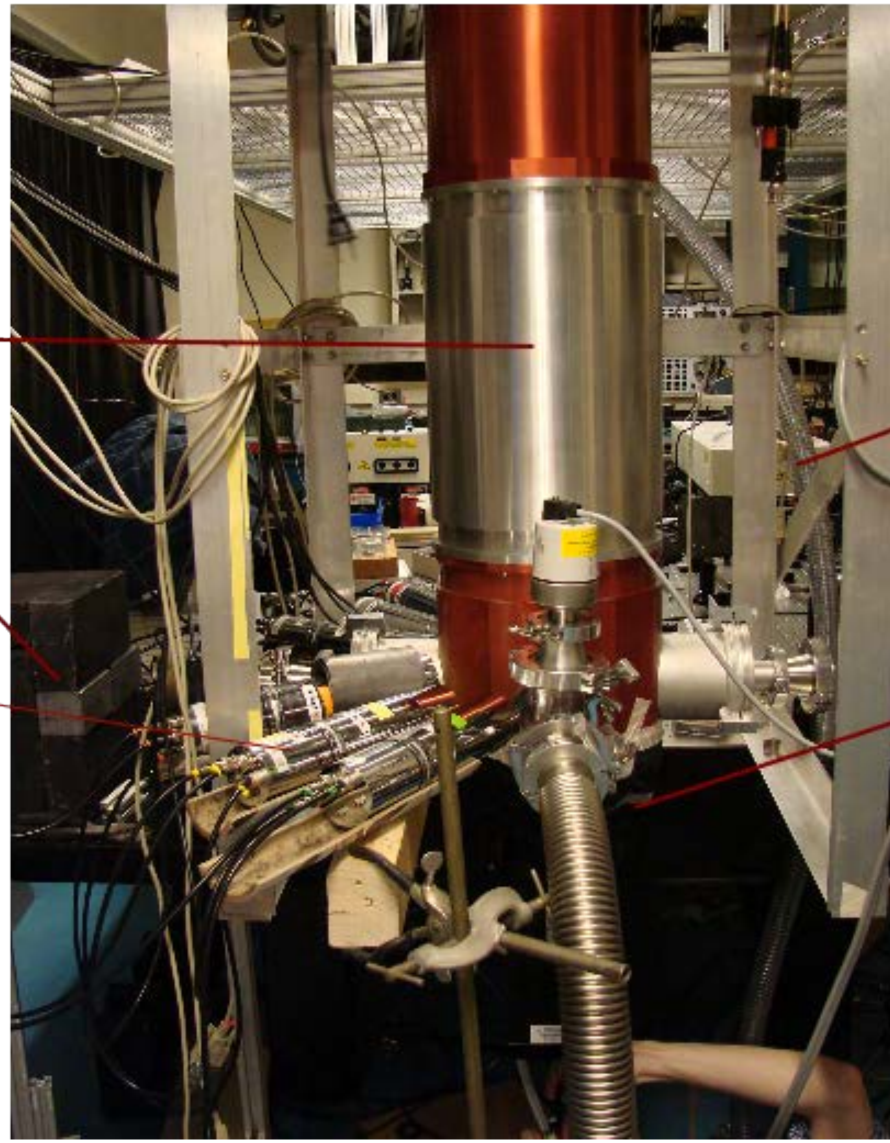
Time (s)
0
2
4
6
600
400
200
0
Detected Fluorescence
(photoelectrons)
0
20
40
60
Pulse Number

Images of Helium Molecules

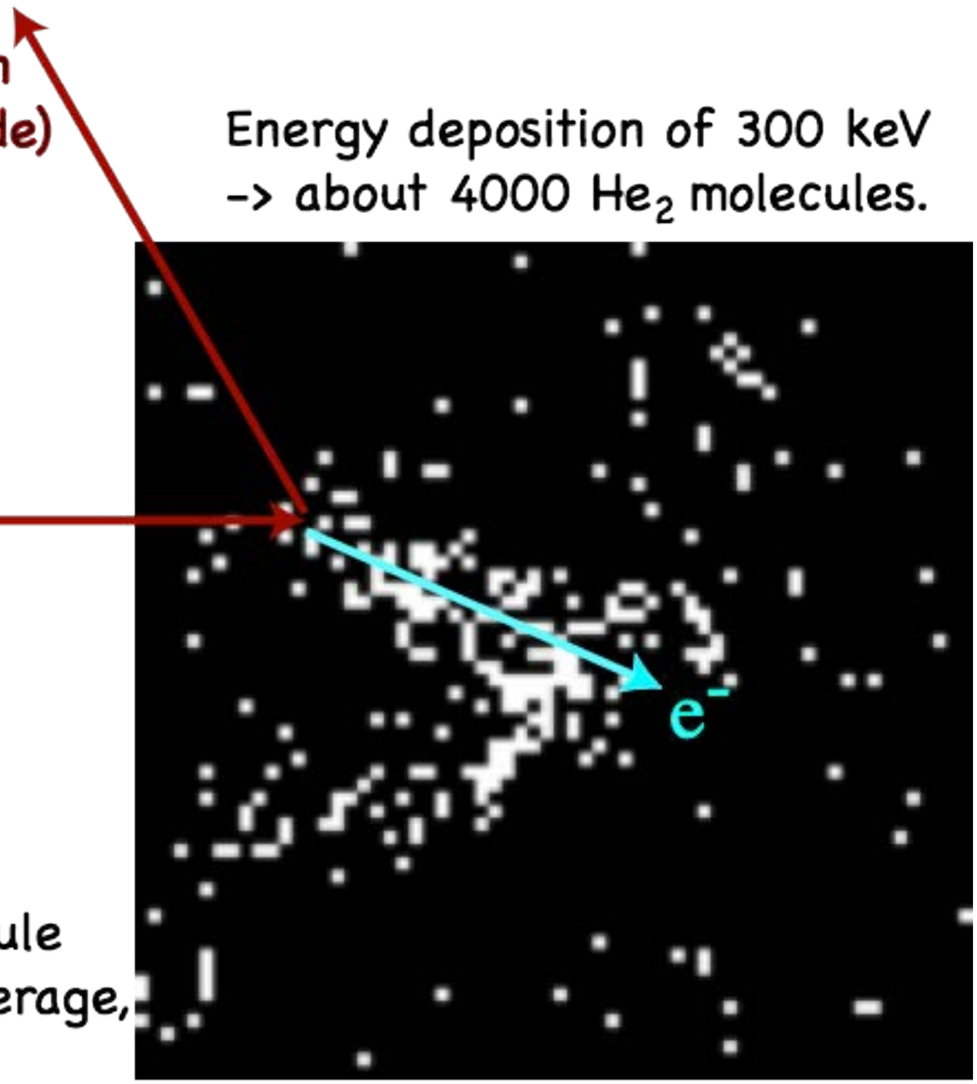




Scattering gamma rays in liquid helium

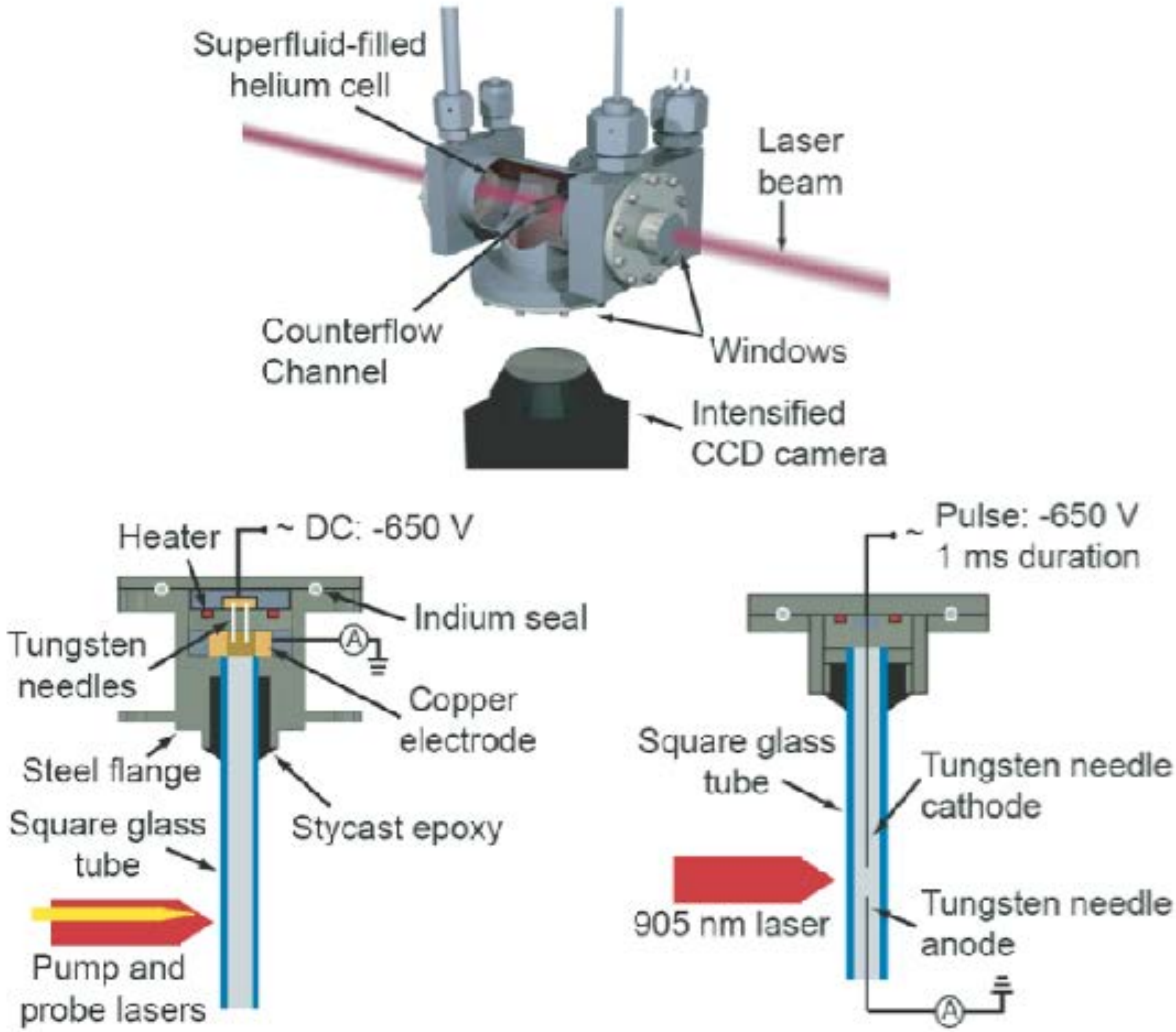


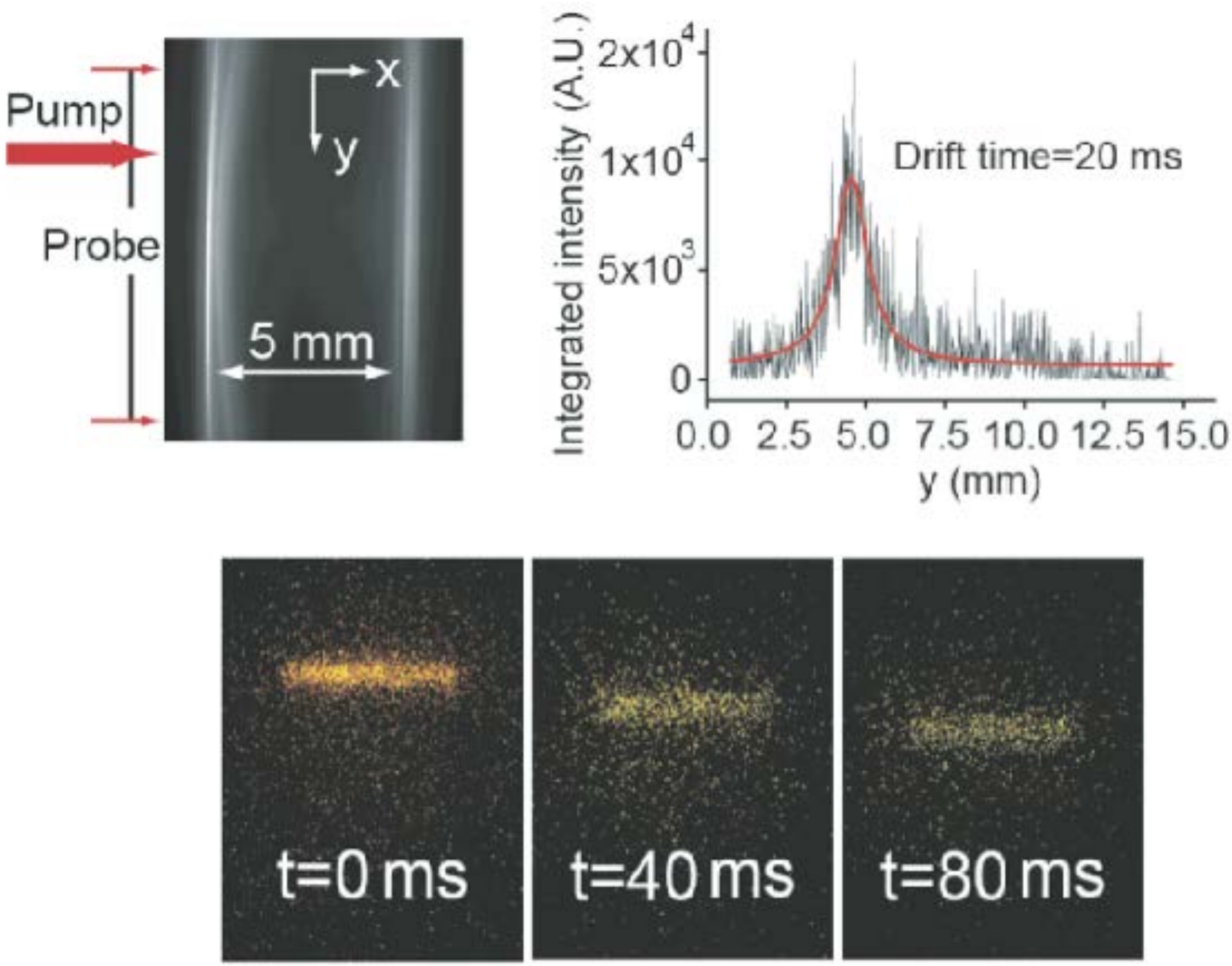
Energy deposition of 300 keV
-> about 4000 He_2 molecules.

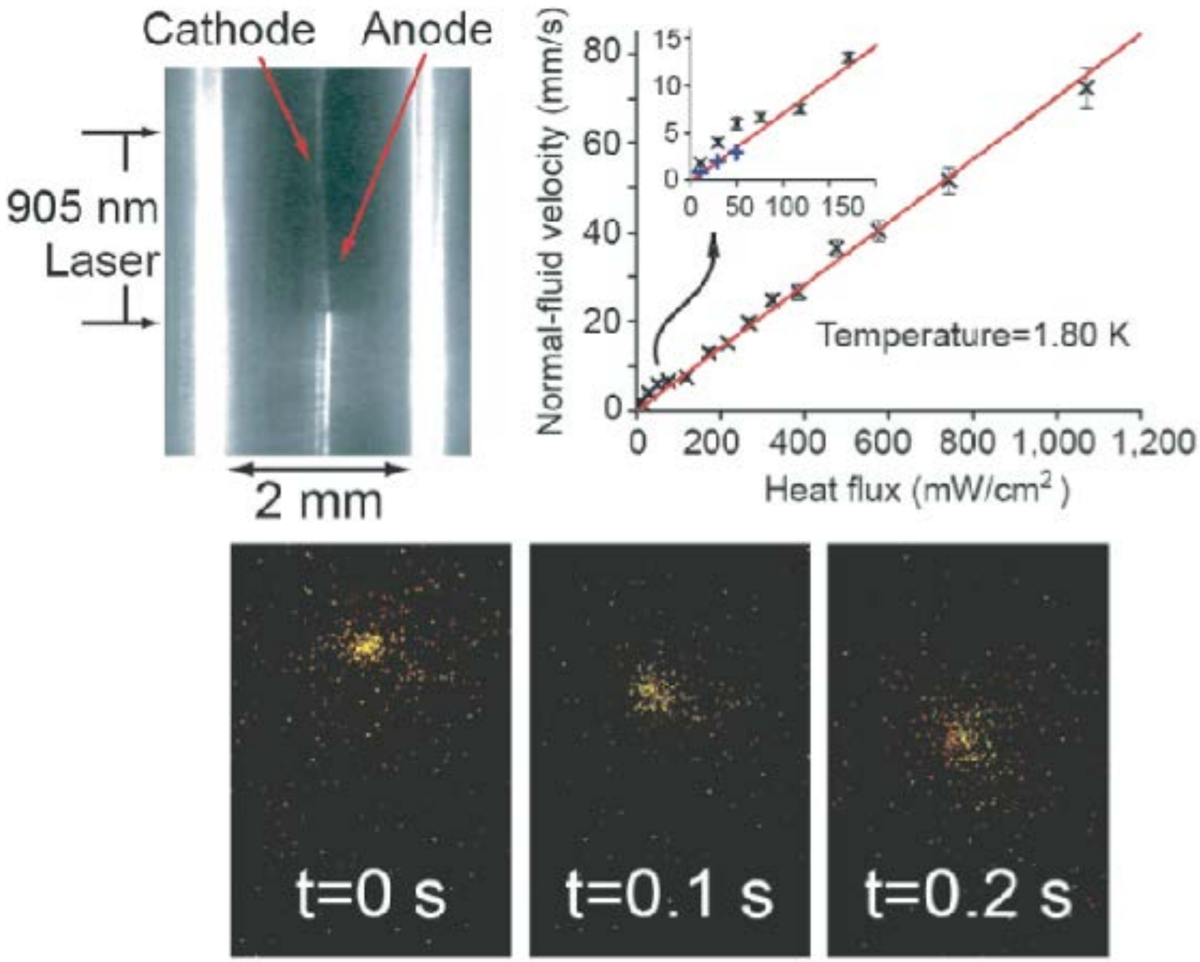


Signal strength of
0.1 photoelectrons/molecule
(given 1% solid angle coverage,
10% quantum efficiency)

Helium molecule tracking experiments (Guo et al, arXiv:1004.2545)




Pump
Probe
x
y
5 mm
Integrated intensity (A.U.)
2x10^4
1x10^4
5x10^3
0
Drift time=20 ms
0.0 2.5 5.0 7.5 10.0 12.5 15.0
y (mm)
t=0 ms
t=40 ms
t=80 ms



W. Guo et al, Phys. Rev. Lett **105**, 045301 (2010).

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!

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 such a detector was presented.
- R&D needed!