Title: Dark Matter Detection with Liquid Xenon and Liquid Helium

Date: Sep 24, 2011 12:00 PM

URL: http://pirsa.org/11090087

Abstract: TBA

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

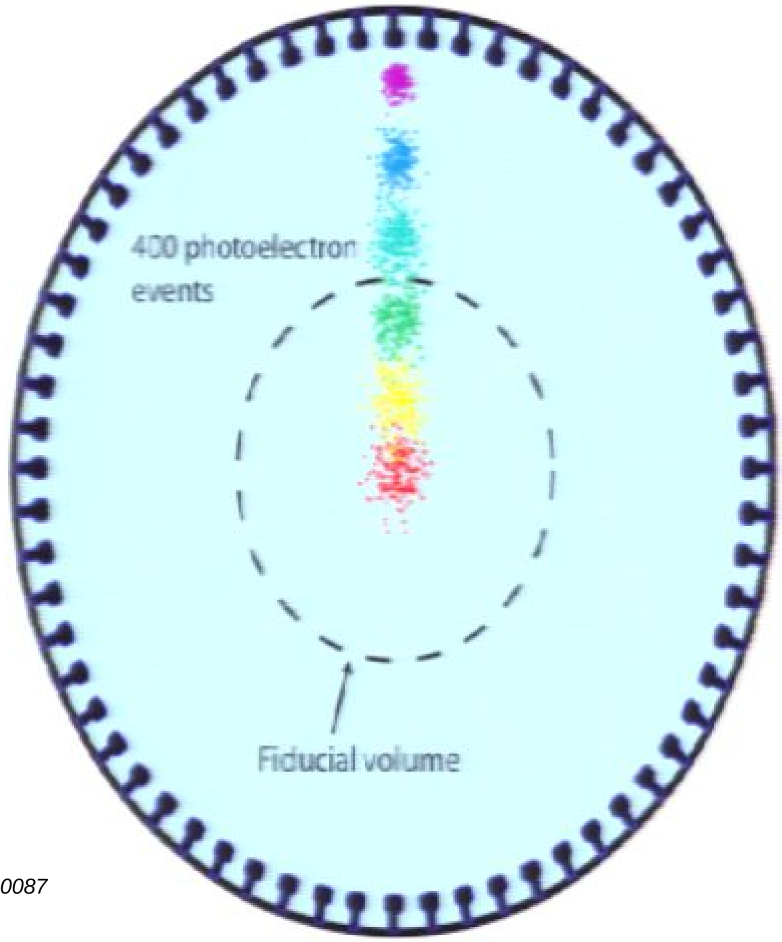
Bright scintillators

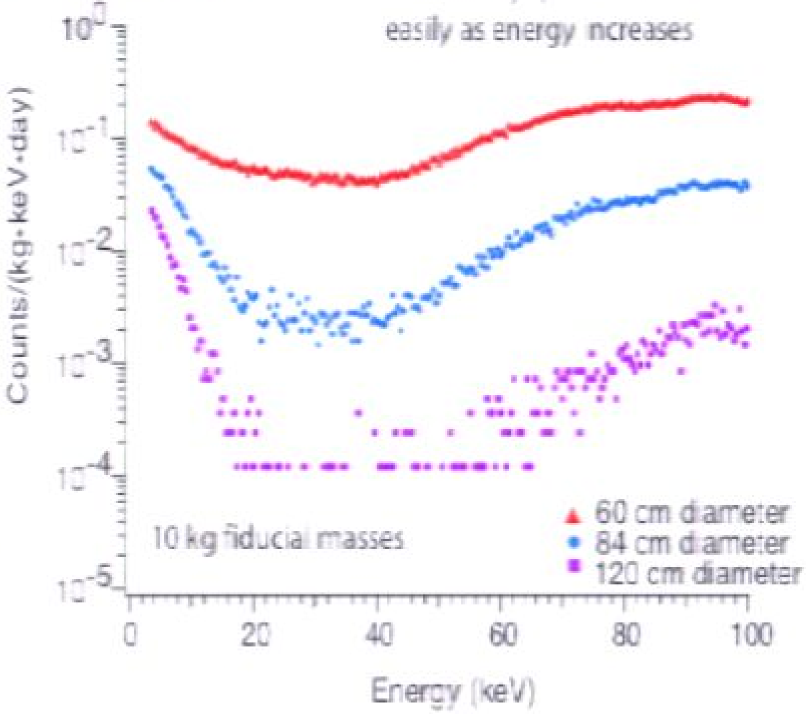
	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	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

Background reduction through self-shielding and position resolution

There is an energy mismatch between penetrating gamma rays (~MeV) and low energy events of interest. High energy gammas must penetrate fiducial volume, scatter, and escape without depositing too much energy, in order to mimic a WIMP.

Background scales as exp{-(detector diameter)/(scattering length)}



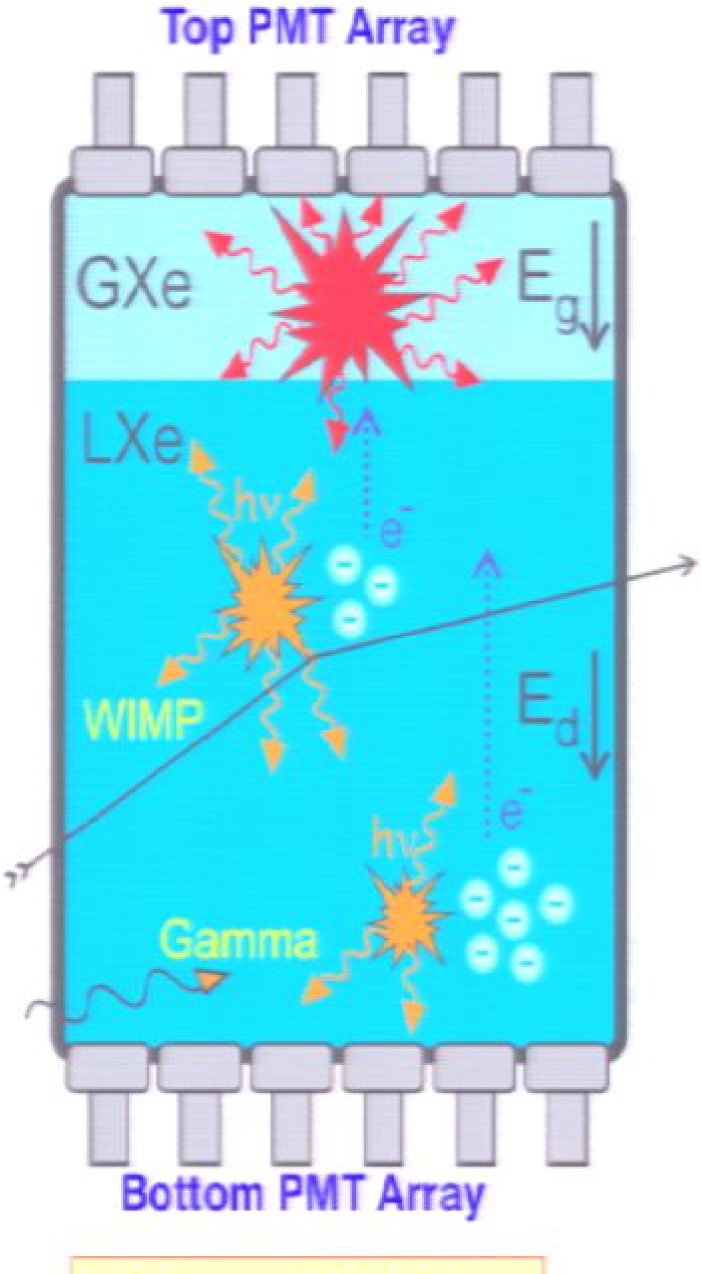


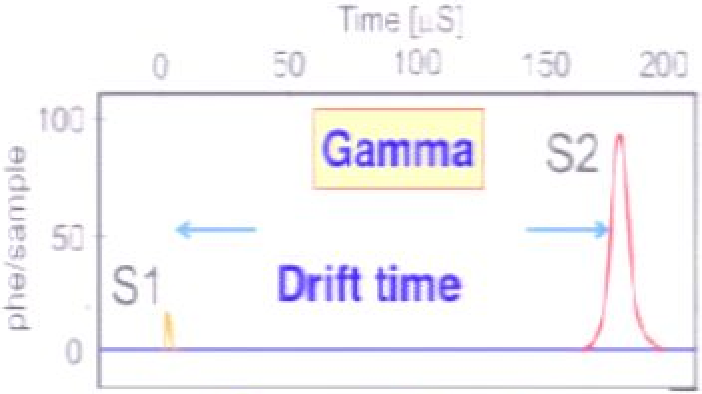
Gamma rays penetrate more easily as energy increases

Based on PMT hit pattern
Maximum likelihood algorithm
Incorporates scattering, wavelength shifter

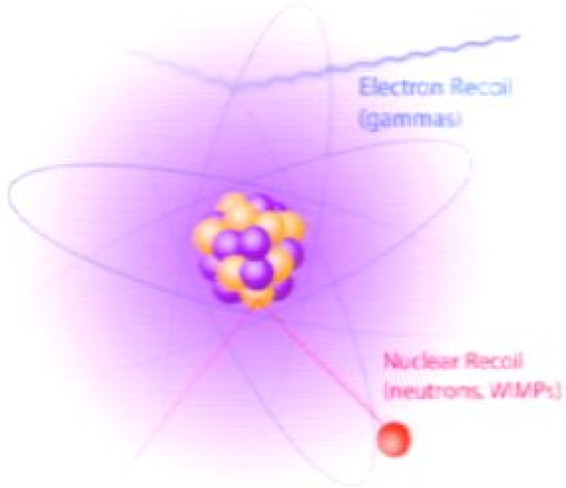
K.J. Coakley and D.N. McKinsey,
Astroparticle Physics 22, 355 (2005).

WIMP direct detection: two phase Xe





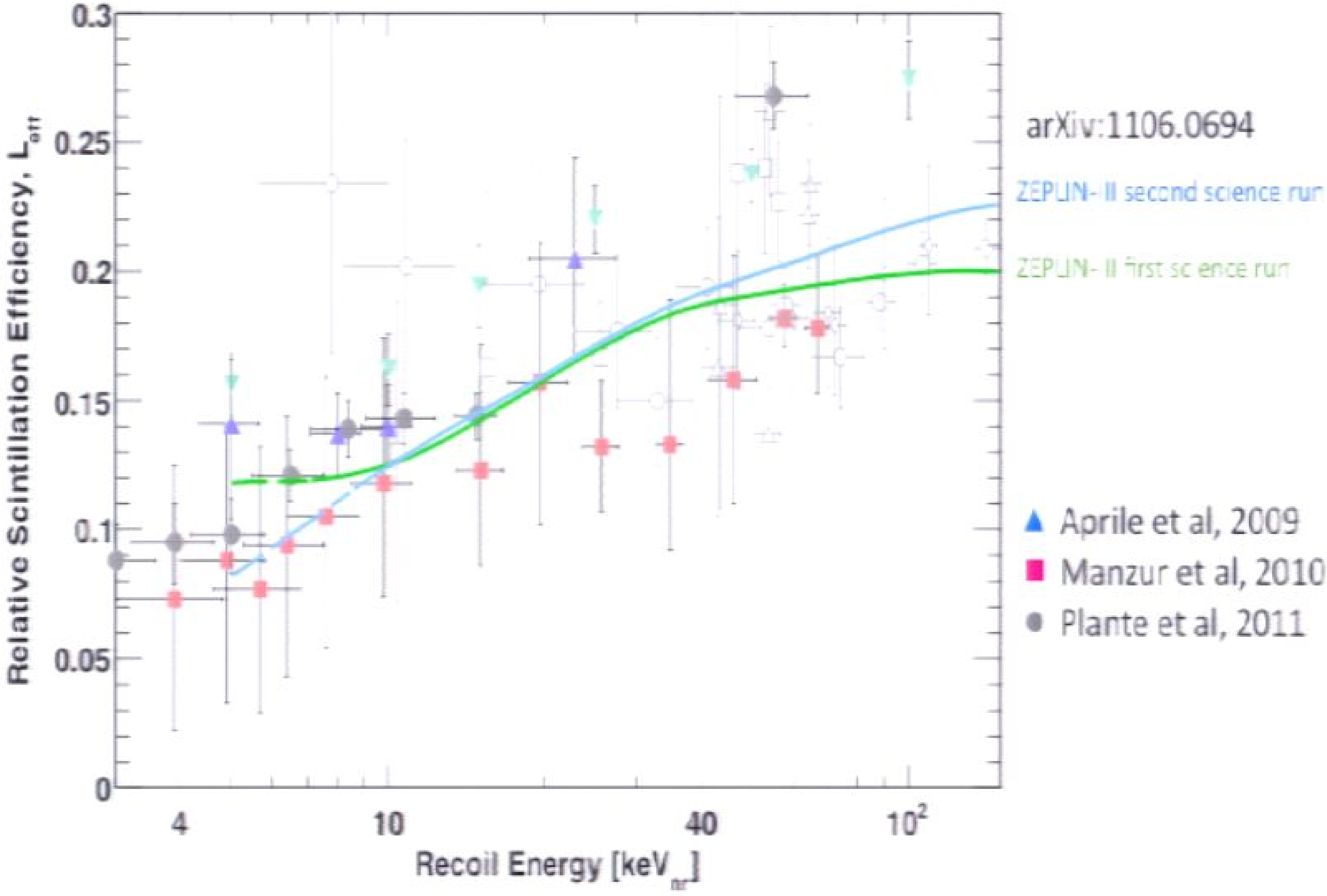
Electron Recoil



Nuclear Recoil

New Leff results from Columbia group and ZEPLIN-III collaboration

Consensus emerging: Leff drops at lower energies

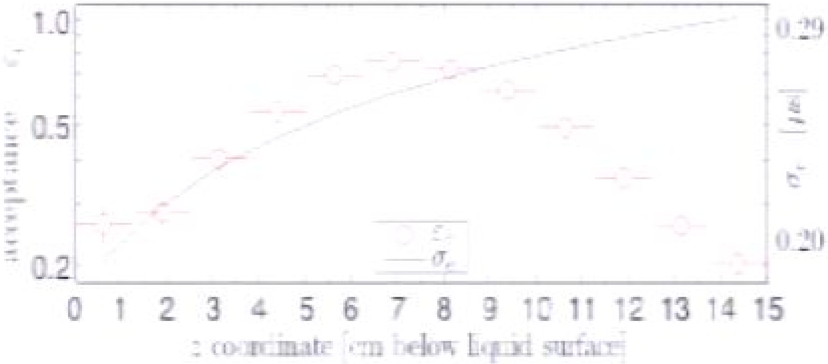


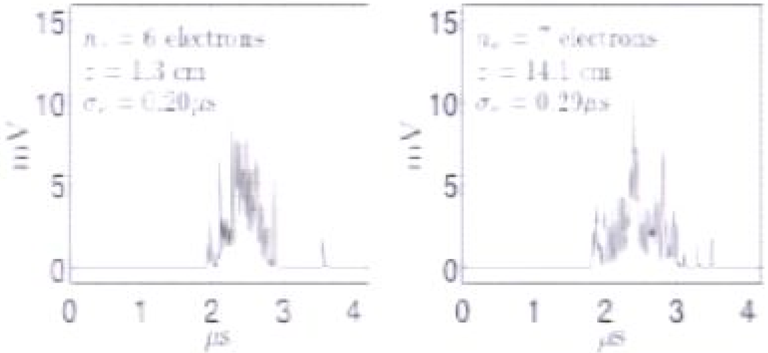
XENON10 charge-only analysis

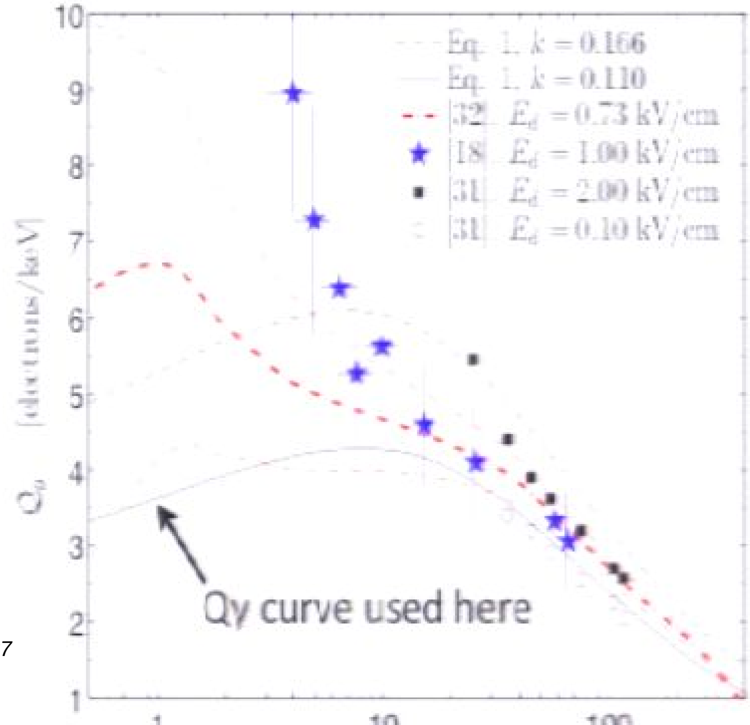
Event depth found by S2 width

Deeper events have more charge diffusion

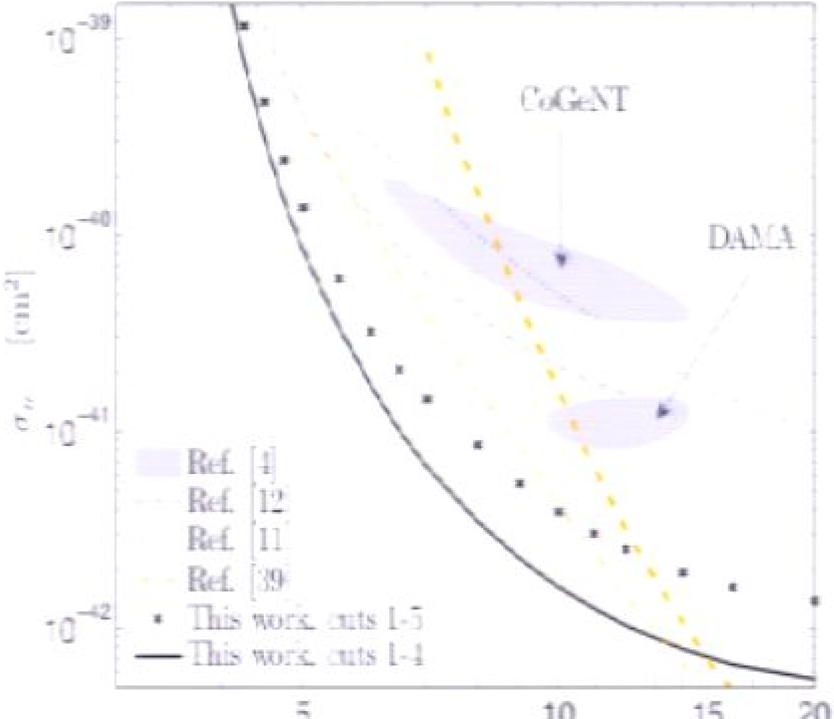
Assumes a sharp cutoff in Qy at 1.4 keV



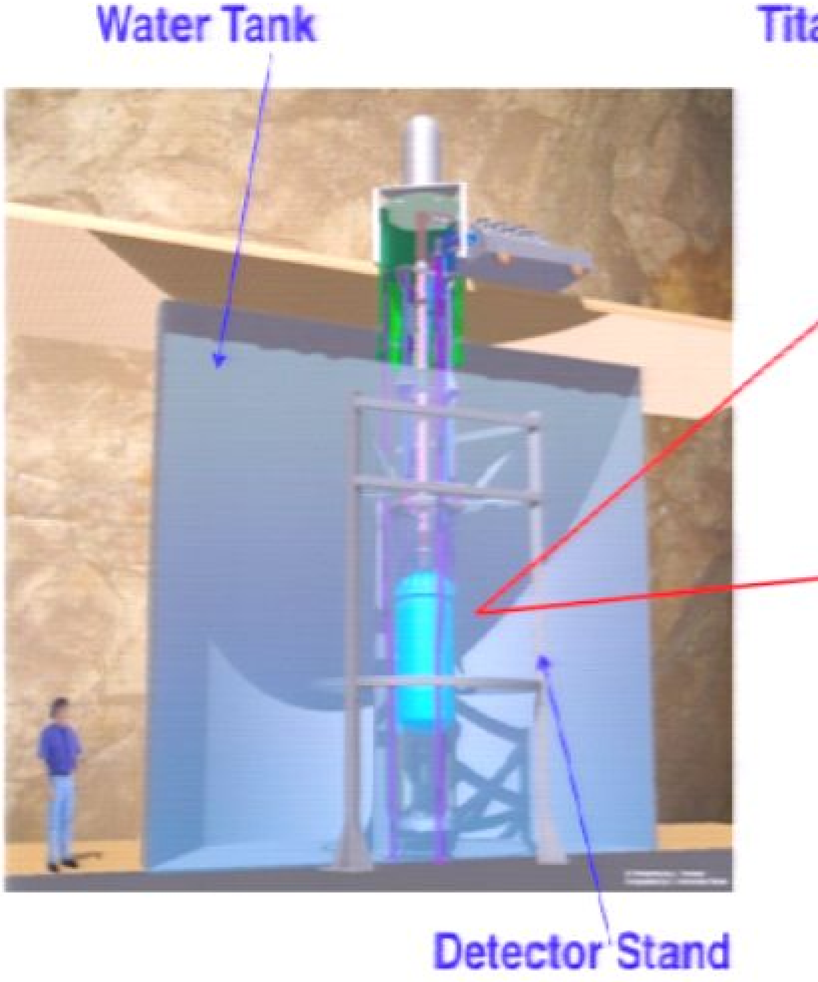


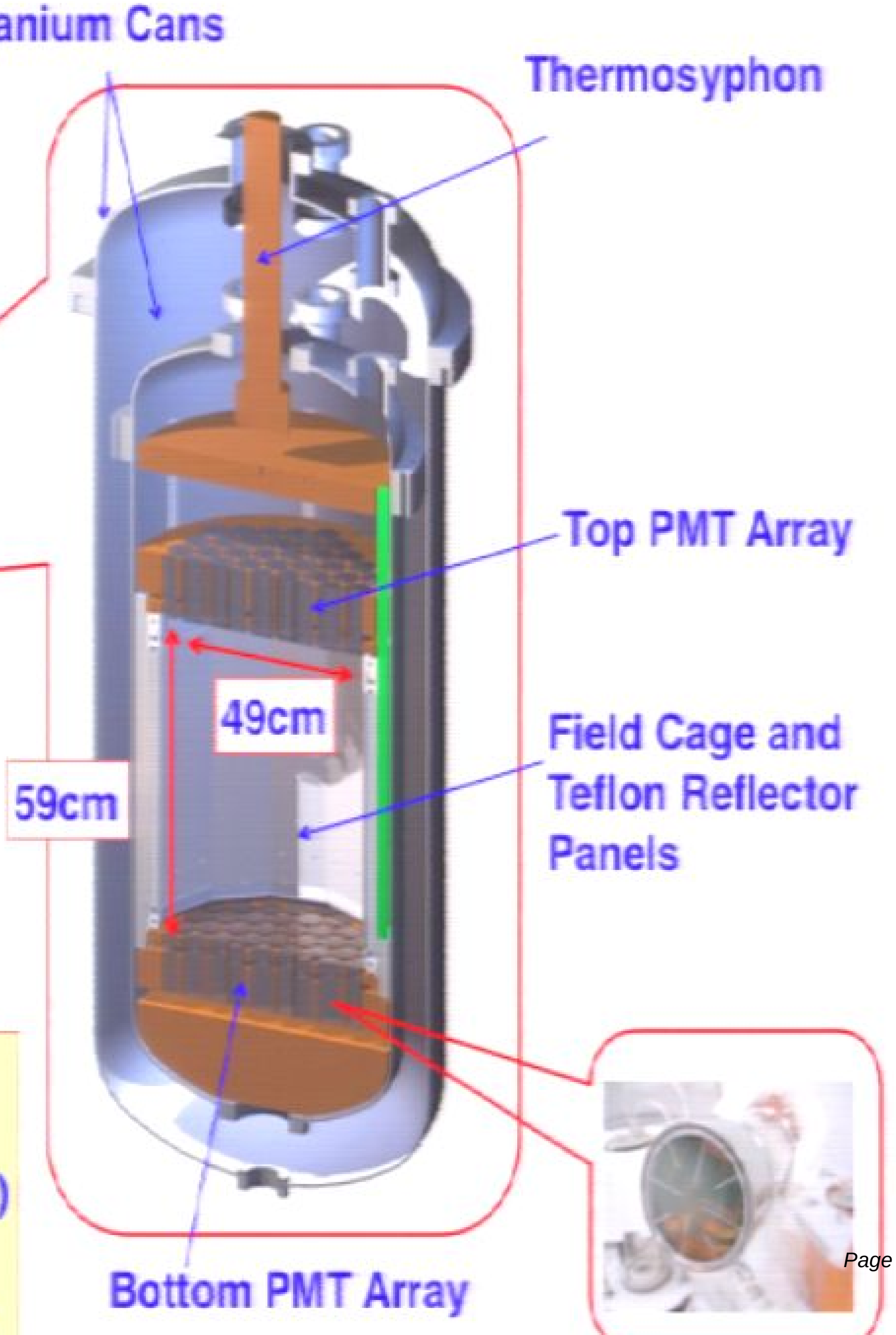


Qy curve used here



LUX Detector





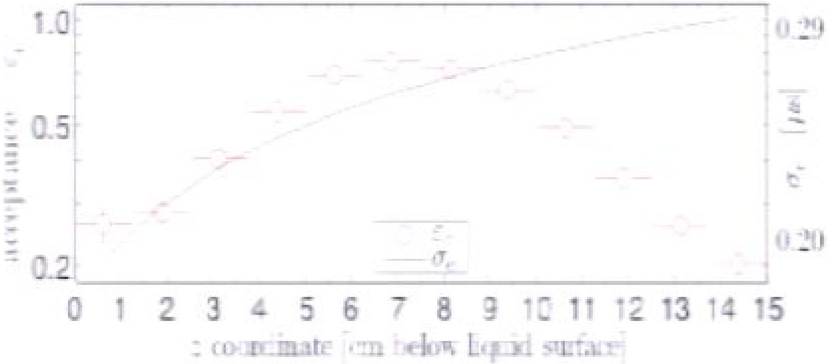
- 350 kg LXe (100 kg fiducial)
- 122 PMTs (QE~30% @ 175nm)
- Low Radioactivity Materials (Ti cryostat)
- Water tank shielding
- >1kW Cooling Power (Thermosyphons)

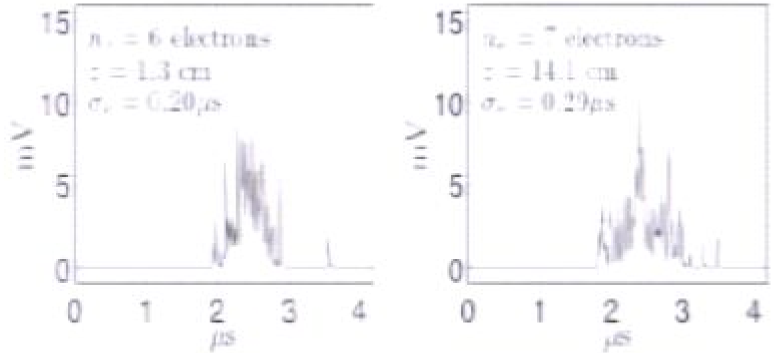
XENON10 charge-only analysis

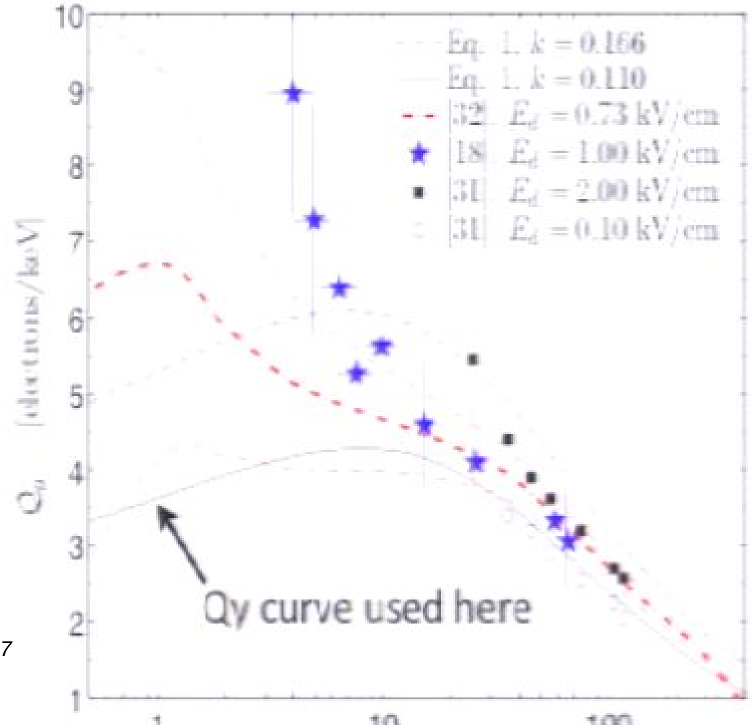
Event depth found by S2 width

Deeper events have more charge diffusion

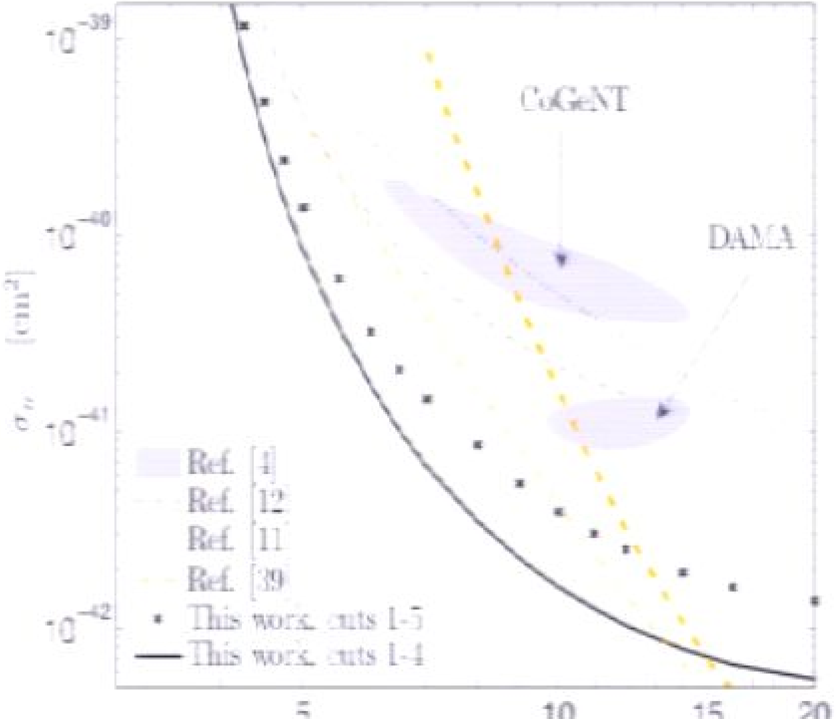
Assumes a sharp cutoff in Qy at 1.4 keV



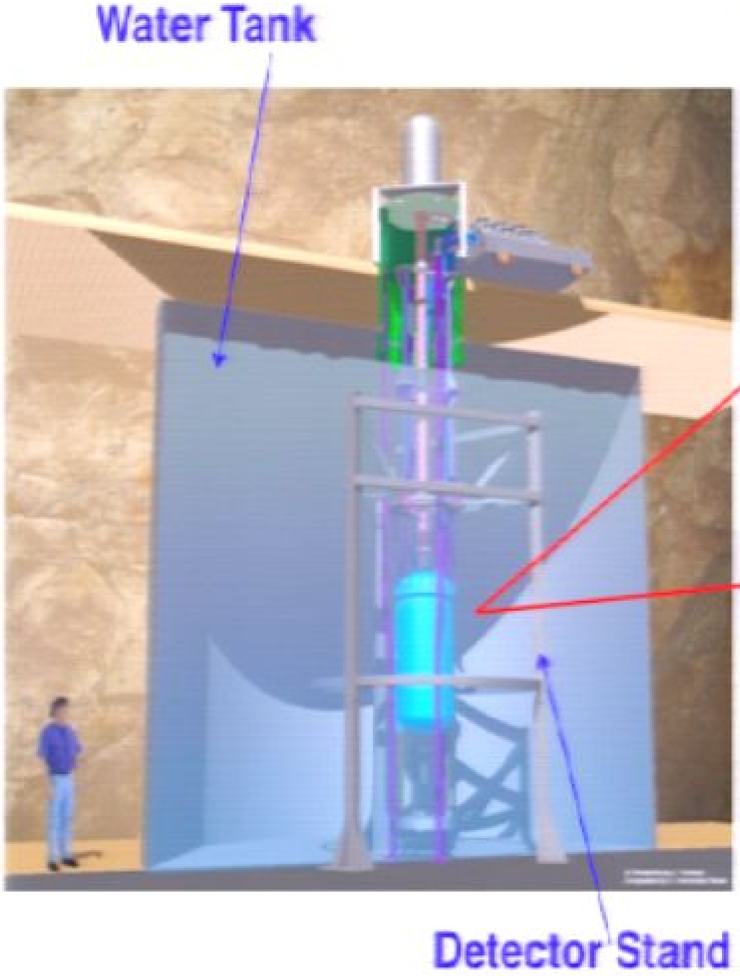


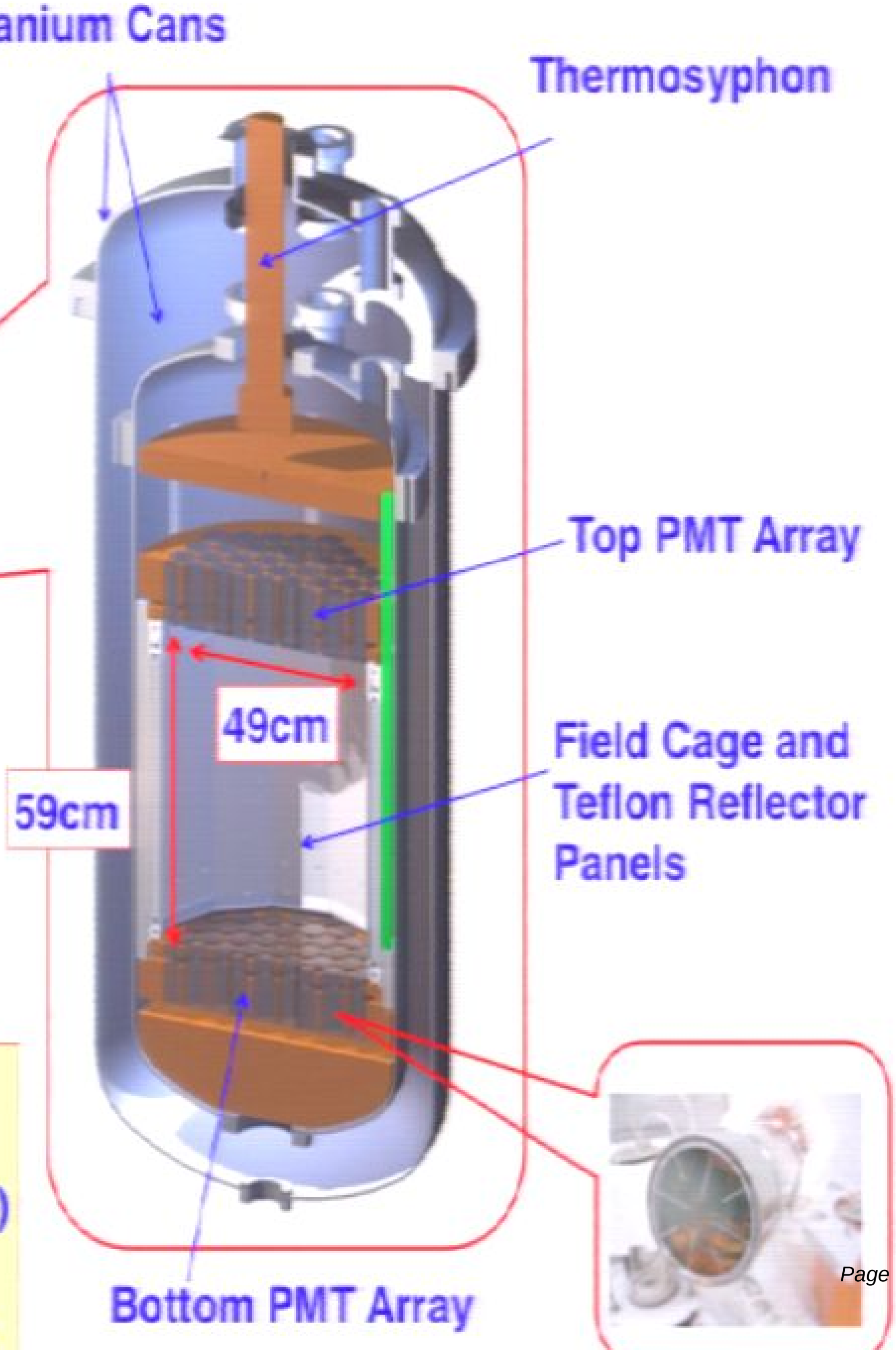


Qy curve used here



LUX Detector

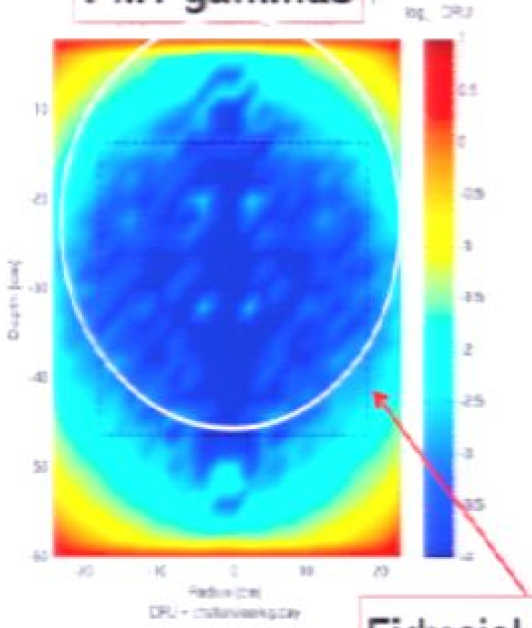




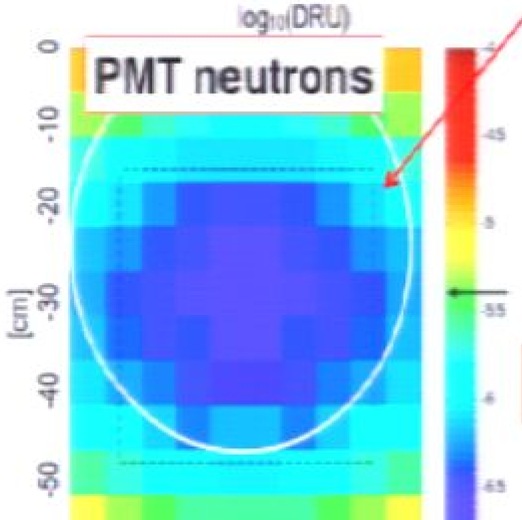
- 350 kg LXe (100 kg fiducial)
- 122 PMTs (QE~30% @ 175nm)
- Low Radioactivity Materials (Ti cryostat)
- Water tank shielding
- >1kW Cooling Power (Thermosyphons)

Trickery: Xe self shielding

PMT gammas

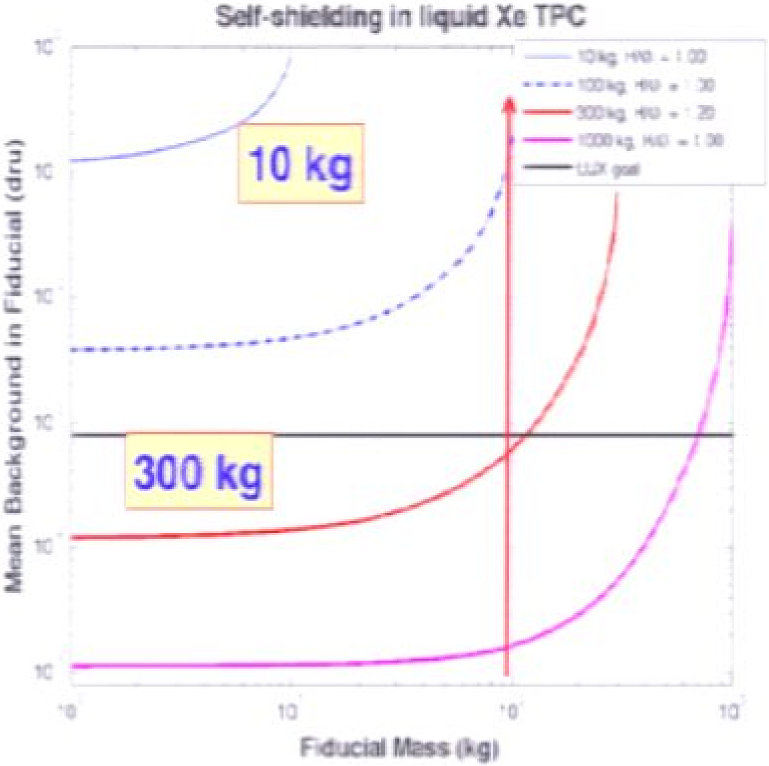


Fiducial volume



PMT neutrons

PMTs are dominant background source



10 kg

300 kg

We benefit a lot from scaling up

Expect <0.5 nuclear/electron-recoils in 100 days

The LUX Collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
Monica Pangilinan	Postdoc
Jeremy Chapman	Graduate Student
Carlos Hernandez Faham	Graduate Student
David Malling	Graduate Student
James Verbus	Graduate Student

Case Western

Thomas Shutt	PI, Professor
Dan Akerib	PI, Professor
Mike Dragowsky	Research Associate Professor
Carmen Carmona	Postdoc
Ken Clark	Postdoc
Tom Coffey	Postdoc
Karen Gibson	Postdoc
Adam Bradley	Graduate Student
Patrick Phelps	Graduate Student
Chang Lee	Graduate Student
Kati Pech	Graduate Student

Harvard

Masahiro Morii	PI, Professor
Michal Wlasenko	Postdoc
John Oliver	Electronics Engineer

Lawrence Berkeley + UC Berkeley

Bob Jacobsen	Professor
Jim Siegrist	Professor
Bill Edwards	Engineer
Joseph Rasson	Engineer
Mia Ihm	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Group
Dennis Carr	Mechanical Technician
[illegible]kaz	Staff Physicist
Peter Sorensen	Postdoc

Collaboration was formed in 2007 and fully funded by DOE and NSF in 2008.

UC Santa Barbara

Harry Nelson	PI, Professor
Dean White	Engineer
Susanne Kyre	Engineer

LIP Coimbra

Isabel Lopes	PI, Professor
Jose Pinto da Cunha	Assistant Professor
Vladimir Solovov	Senior Researcher
Luiz de Viveiros	Postdoc
Alexander Lindote	Postdoc
Francisco Neves	Postdoc
Claudio Silva	Postdoc

SD School of Mines

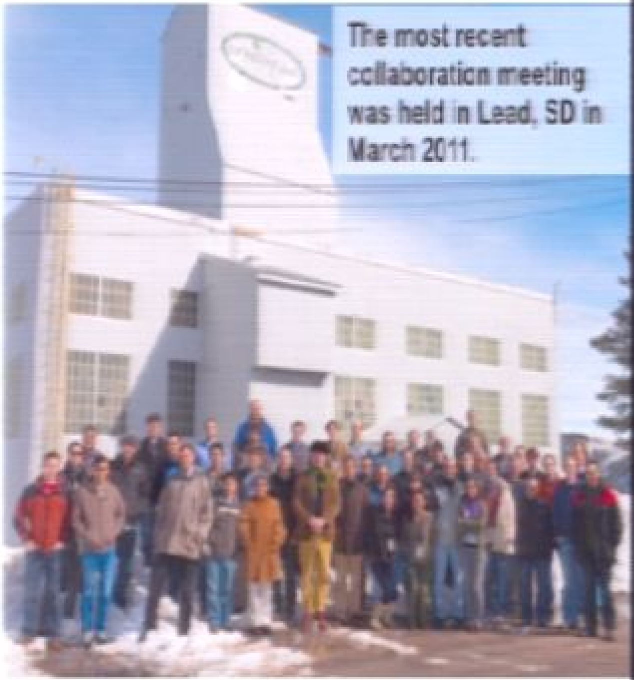
Xinhua Bai	PI, Professor; Physics Group Leader
Mark Hanhardt	Graduate Student

Texas A&M

James White	PI, Professor
Robert Webb	Professor
Rachel Mannino	Graduate Student
Tyana Stiegler	Graduate Student
Clement Sofka	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Robert Svoboda	Professor
Richard Lander	Professor
Britt Holbrook	Senior Engineer
John Thomson	Senior Machinist
Matthew Szydagis	Postdoc
Jeremy Mock	Graduate Student



The most recent collaboration meeting was held in Lead, SD in March 2011.

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skulski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Mongkol Moongweluwan	Graduate Student

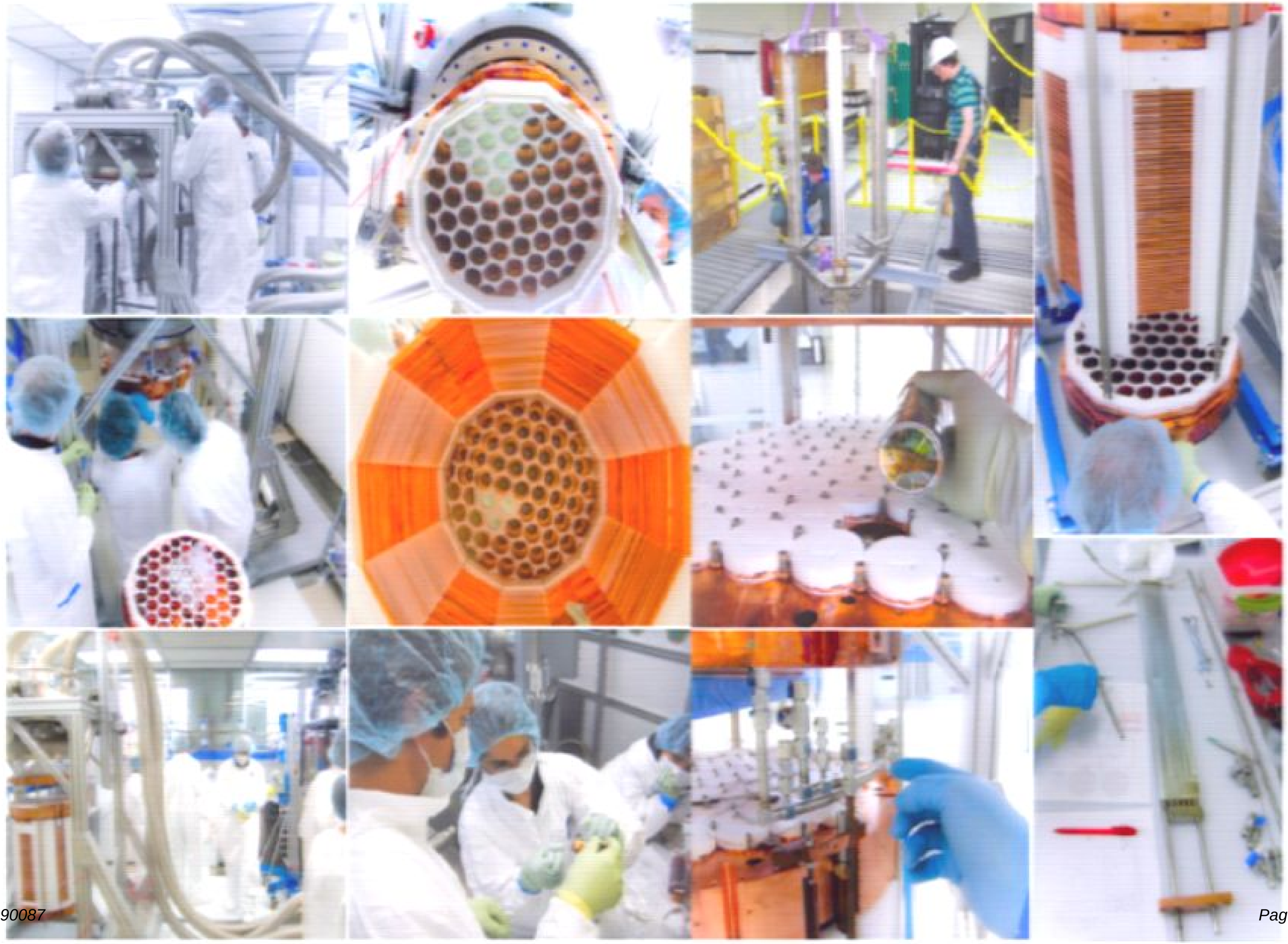
U. South Dakota

Dongming Mei	PI, Professor
Wengchang Xiang	Postdoc
Chao Zhang	Postdoc
Oleg Perevozchikov	Postdoc

Yale

Daniel McKinsey	PI, Professor
Peter Parker	Professor
James Nikkel	Research Scientist
Sidney Cahn	Lecturer/Research Scientist
Alexey Lyashenko	Postdoc

Sanford Lab Surface Facility

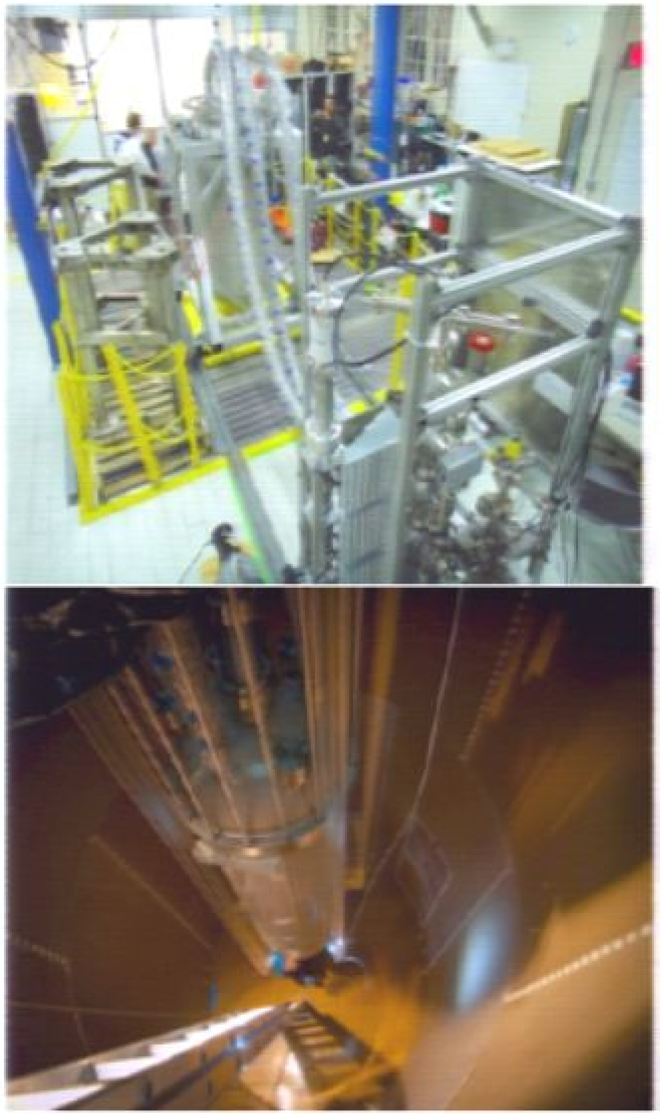


LUX Program Timeline

LUX 0.1

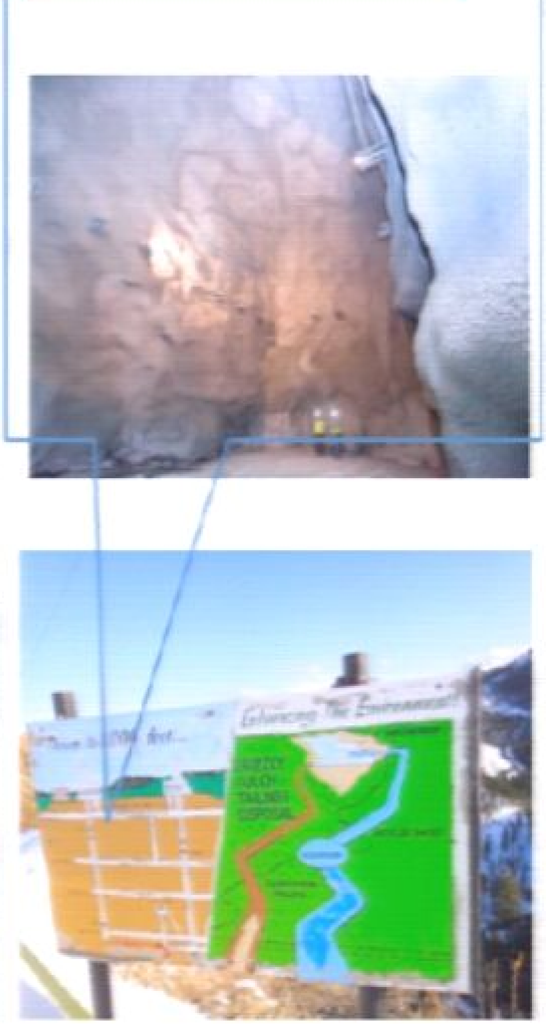
2007 - 2009

LUX Surface Run



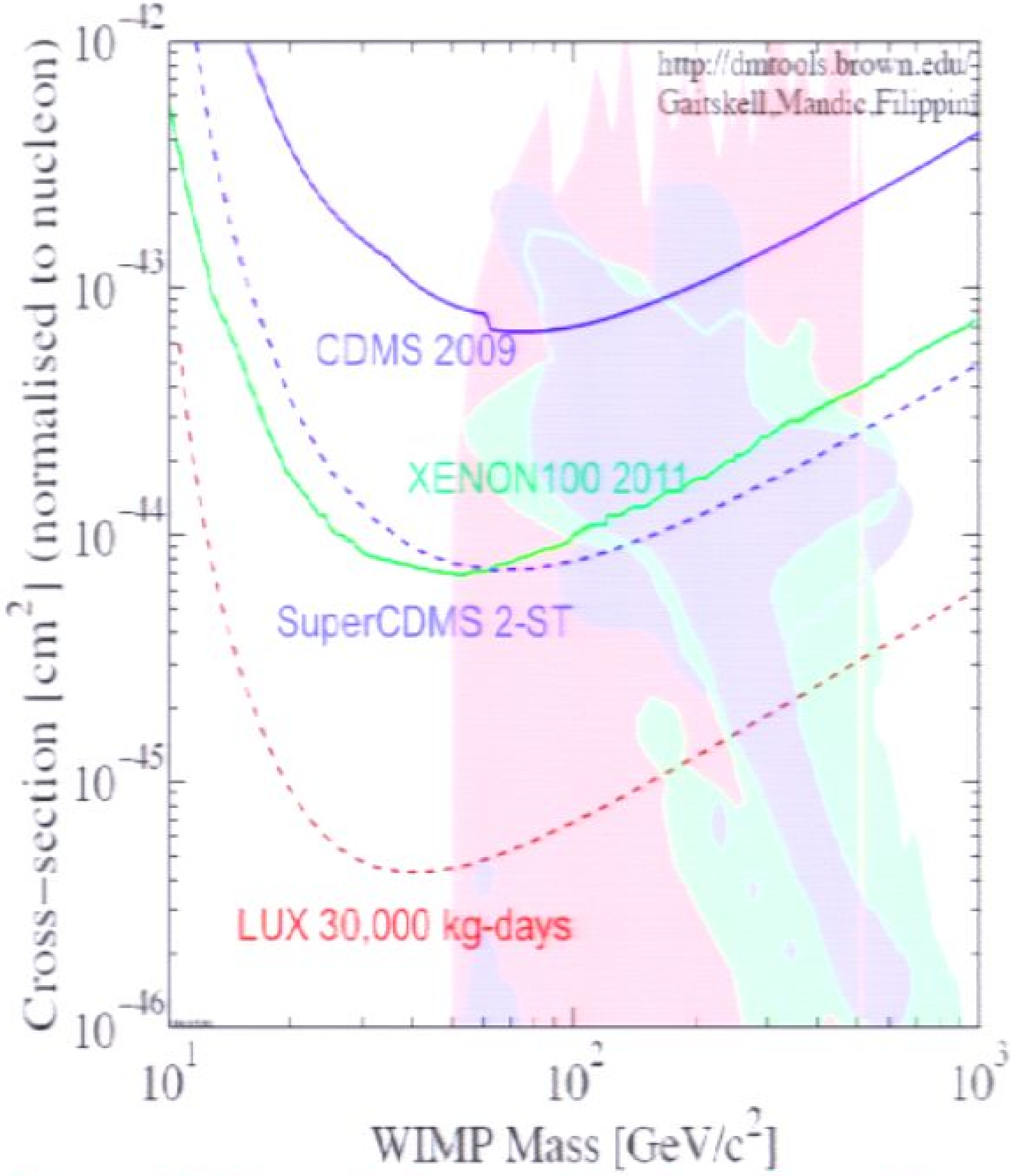
2010 - 2011

LUX DM Search Run



2012+

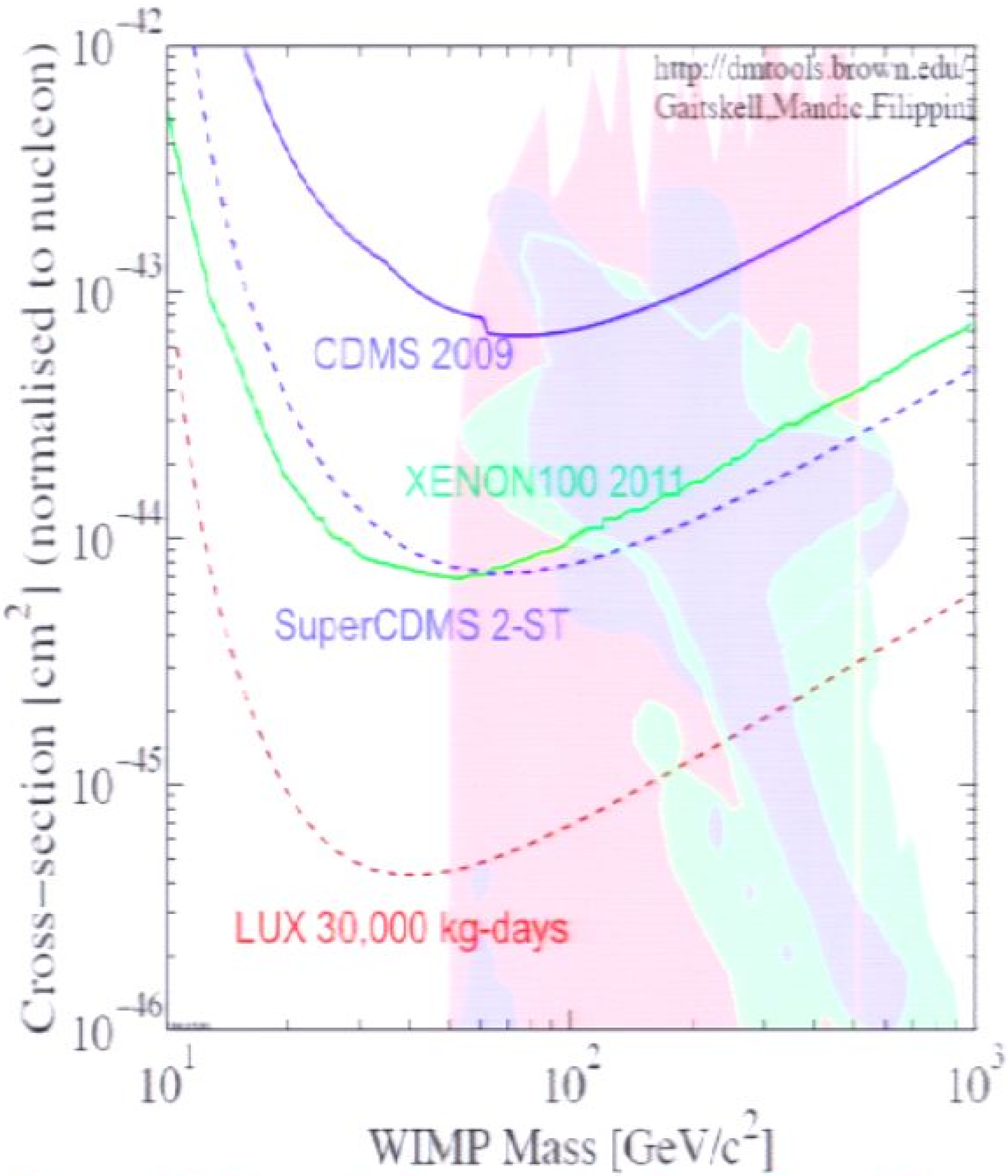
LUX dark matter sensitivity

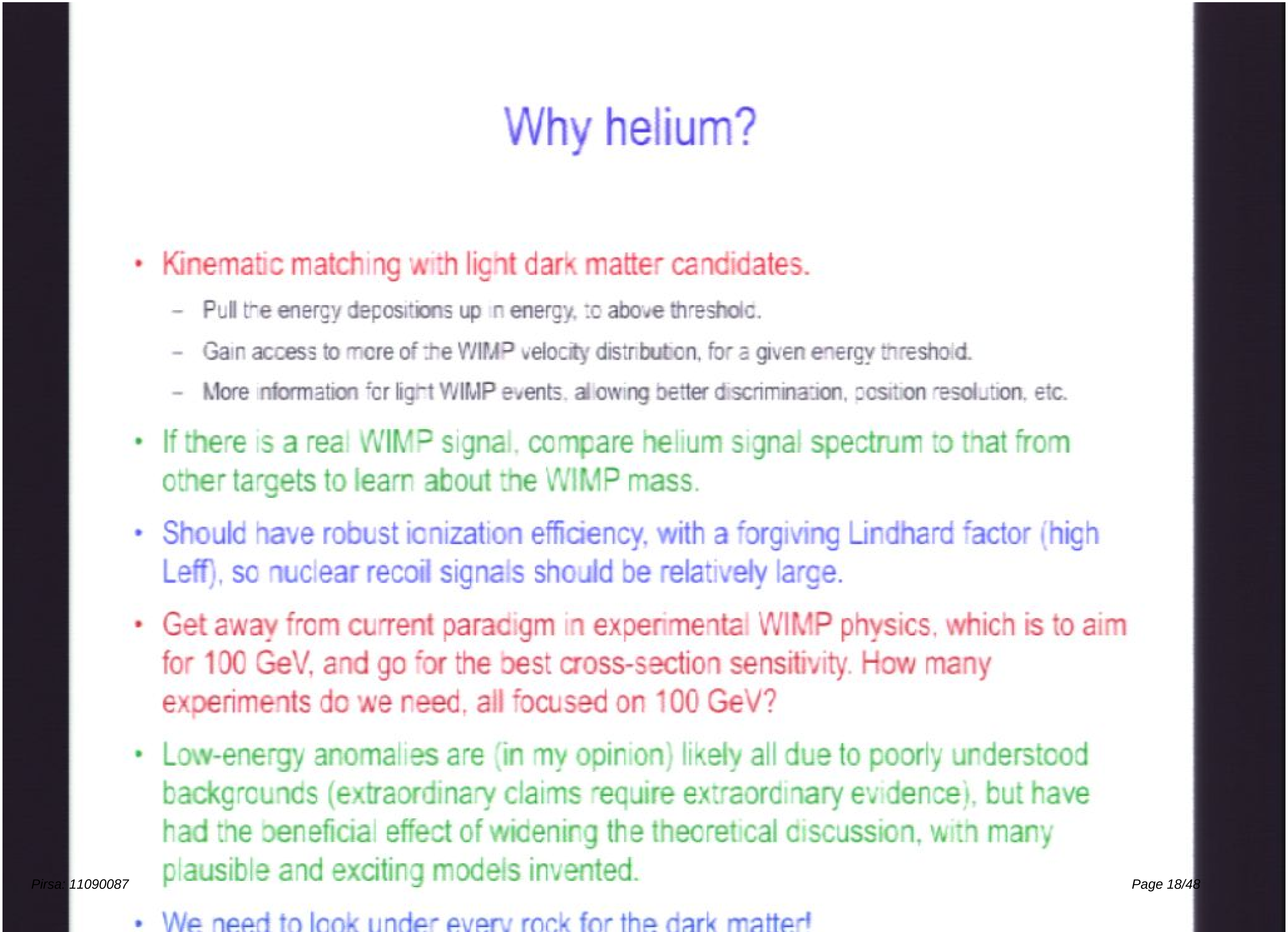


Why helium?

- 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 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!

LUX dark matter sensitivity





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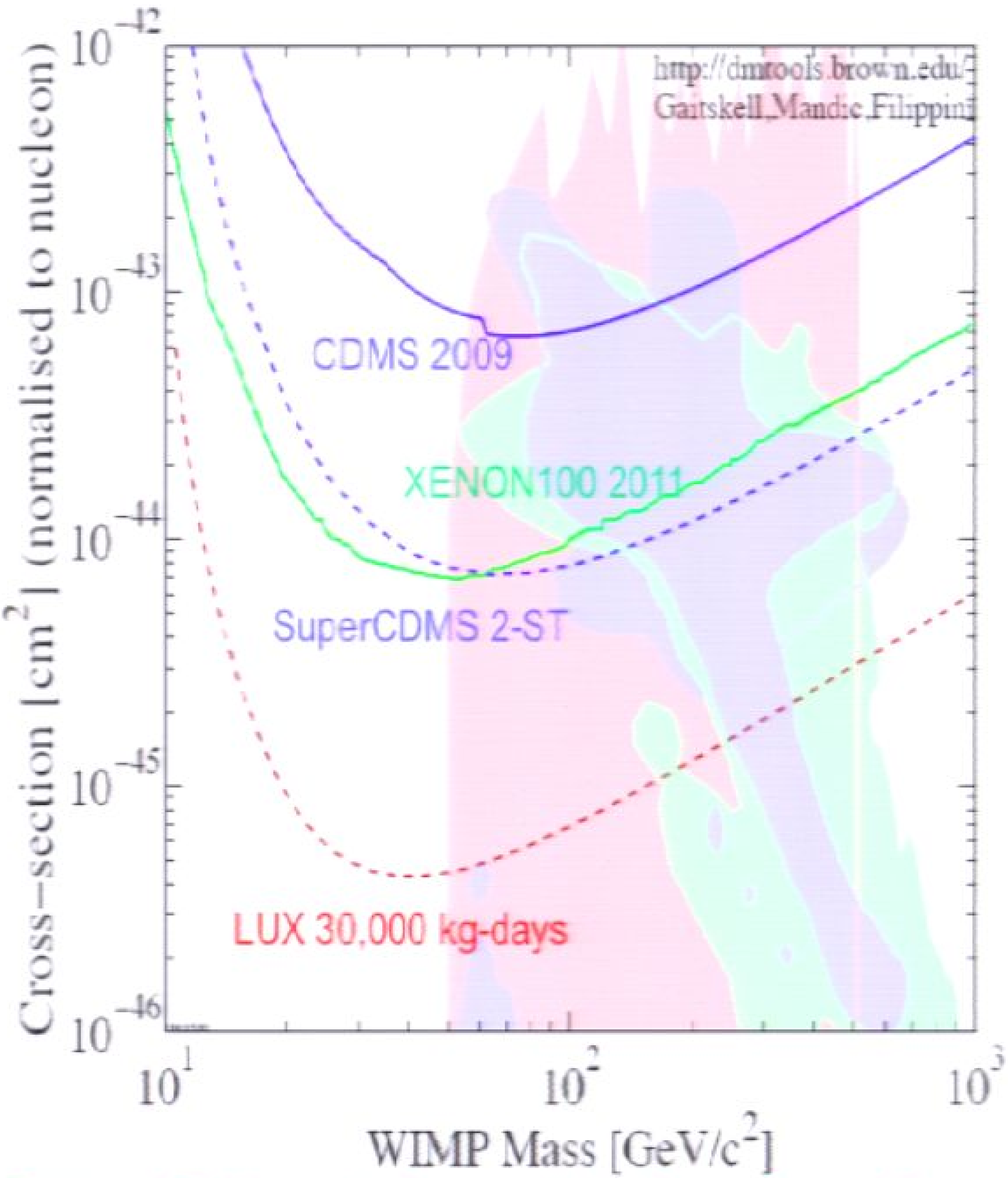

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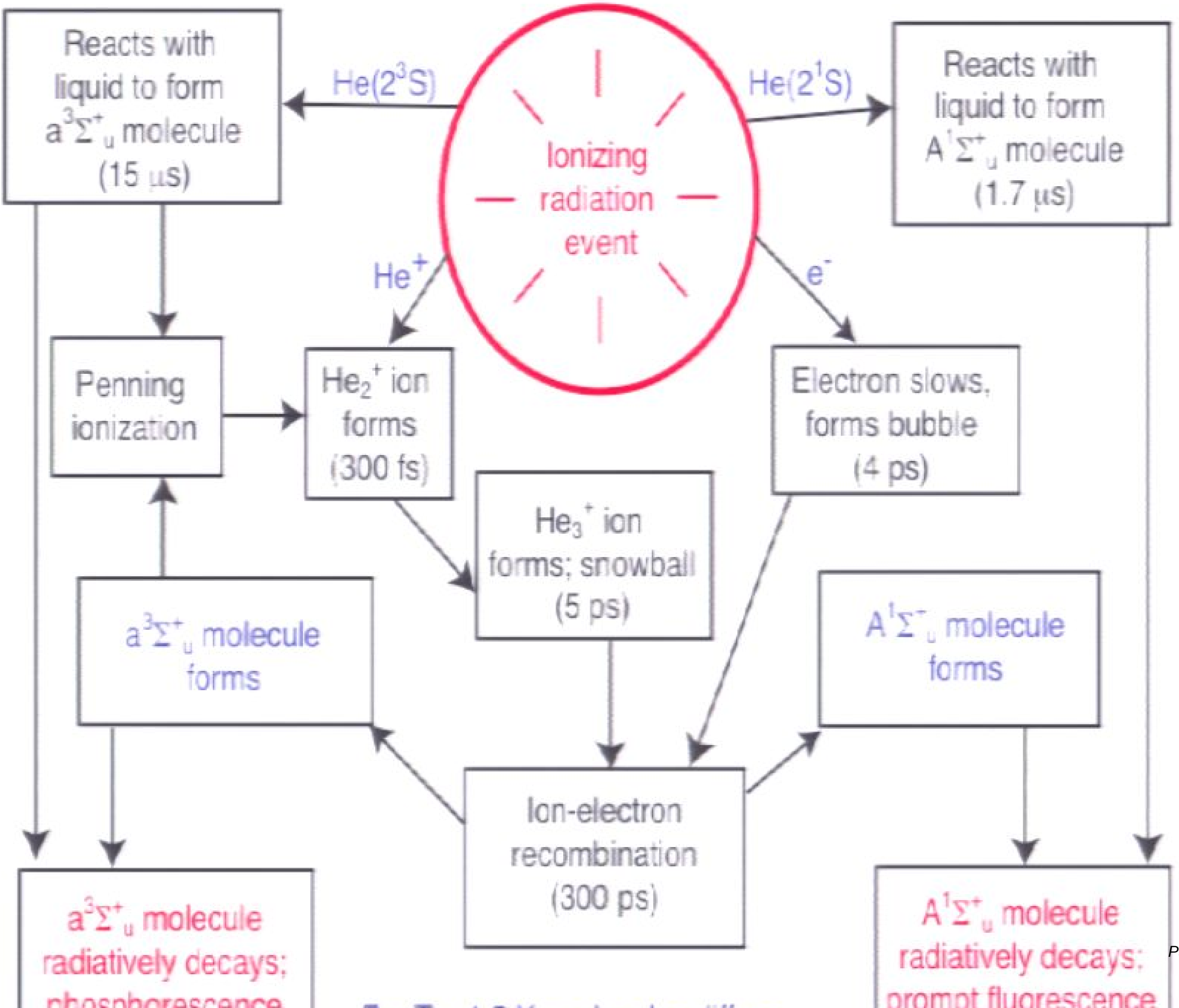
Superfluid helium as a detector material

- 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)

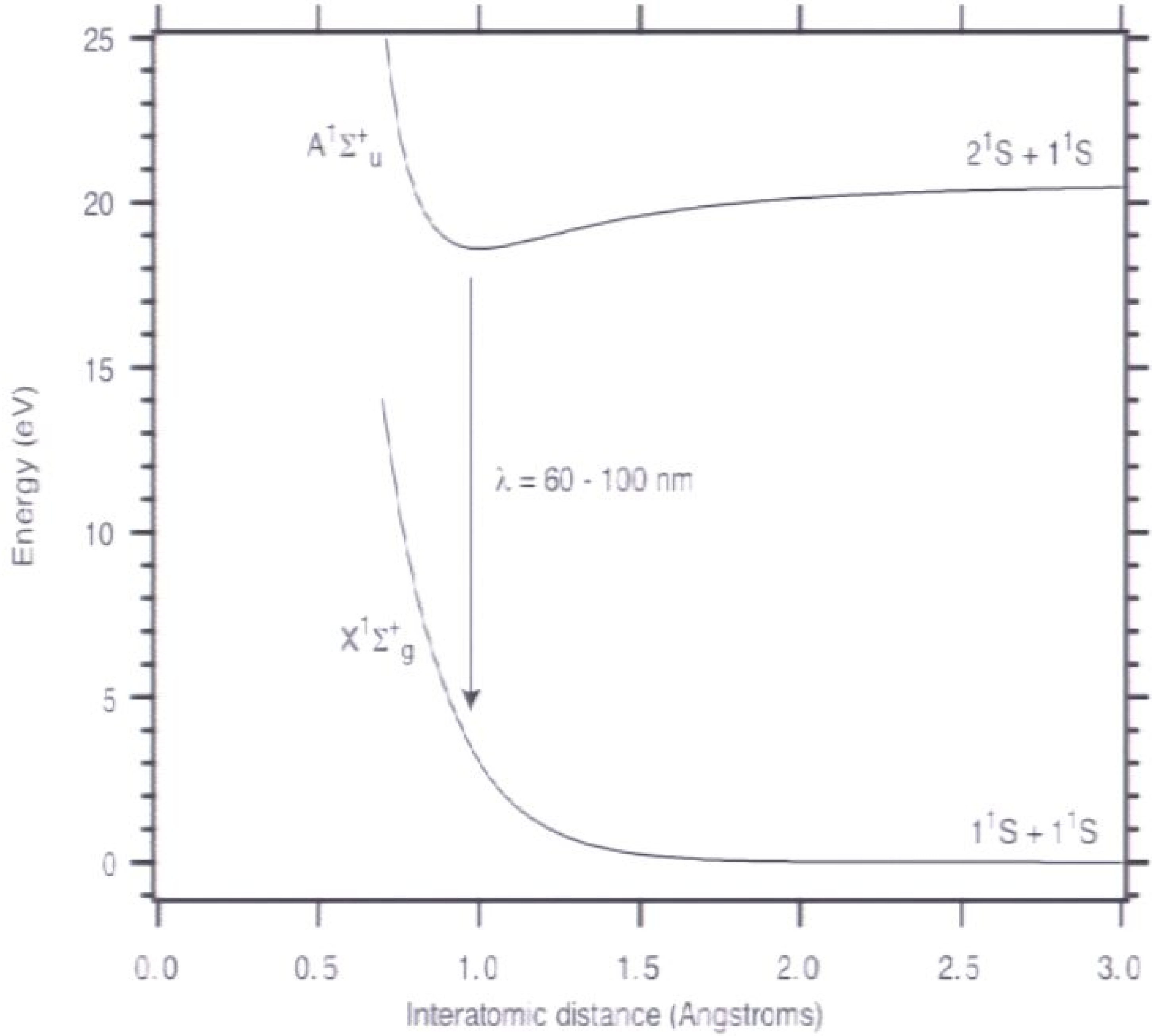
$a^3\Sigma^+_u$ molecule forms

$A^1\Sigma^-_u$ molecule forms

Ion-electron recombination (300 ps)

$a^3\Sigma^+_u$ molecule radiatively decays; phosphorescence

$A^1\Sigma^+_u$ molecule radiatively decays; prompt fluorescence



25
20
15
10
5
0
Energy (eV)
$A^1\Sigma^+_u$
$2^1S + 1^1S$
$\lambda = 60 - 100$ 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)

Liquid helium for light dark matter detection

Concept: A liquid helium time projection chamber (LHe-TPC)

Advantages of LHe include good kinematics for light WIMPs,
extremely effective purification, homogeneous detector volume,
no long-lived isotopes.

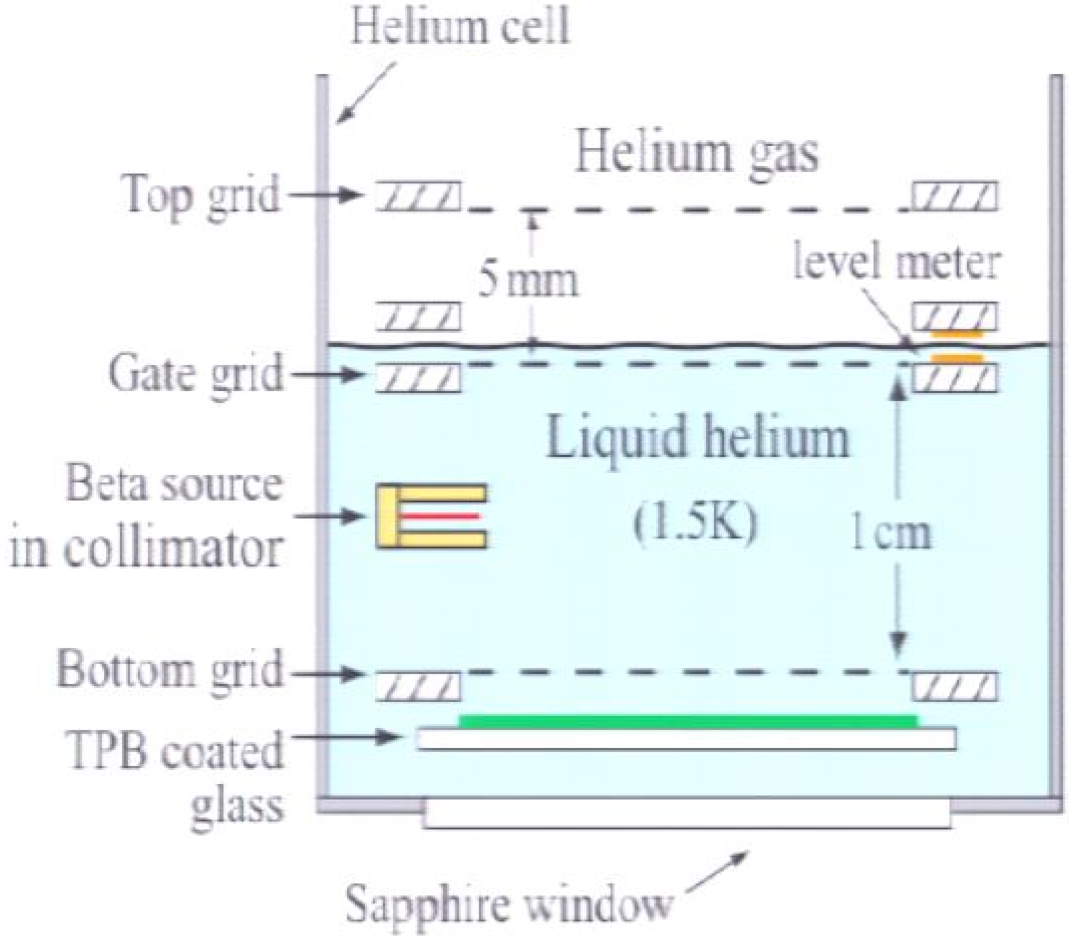
Rich set of signals:
Prompt light (S1)
Drifted electrons (S2)
Triplet helium molecules (S3)
Other signals (S4, S5... from rotons, phonons, quantum turbulence, ...)

For direct dark matter experiments, discrimination is crucial!
S2/S1 should give electron recoil/nuclear recoil discrimination, as in LXe
S1/S3 should give discrimination as well (like pulse-shape discrimination in LAr)
S2/S3 is also plausible

Discrimination needs to be studied: This is not a mature dark matter technology!

Research and development needed on determining the strength of S1, S2, S3
for electron recoils and nuclear recoils, resulting discrimination power,
and the best way to read out these signals

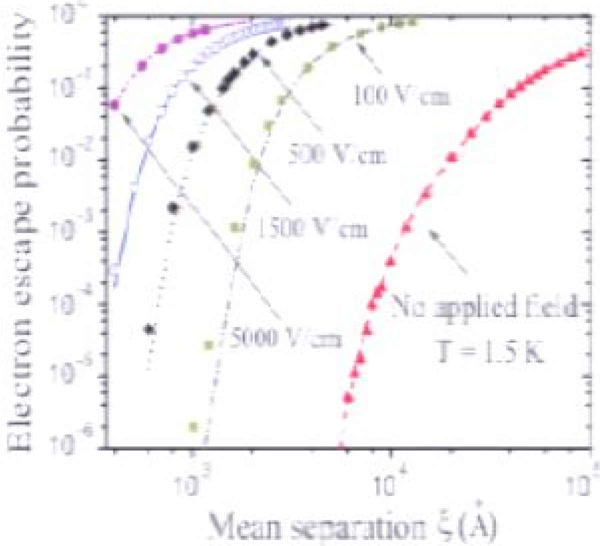
New experimental work at Yale on charge extraction in superfluid helium
(W. Guo et al, expect paper on arXiv next week)

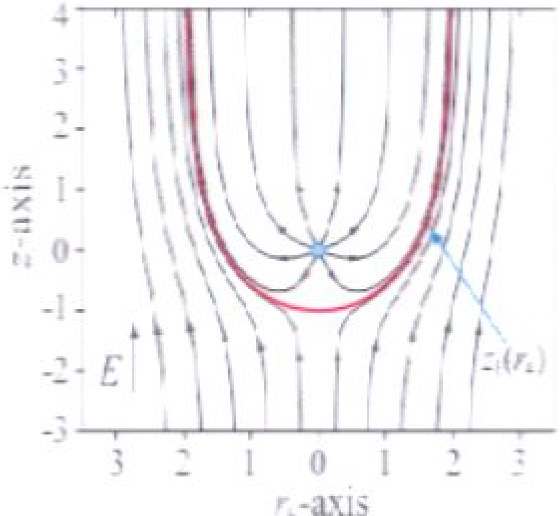


Data from charge extraction measurement

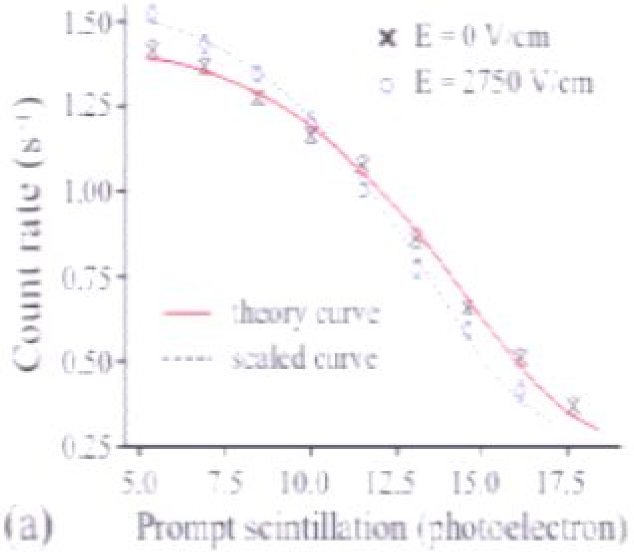
5 kV/cm will give 23% ionization extraction at higher LHe temperatures (1-2 K)
(compare to 30-50 kV/cm in n-edm experiment)

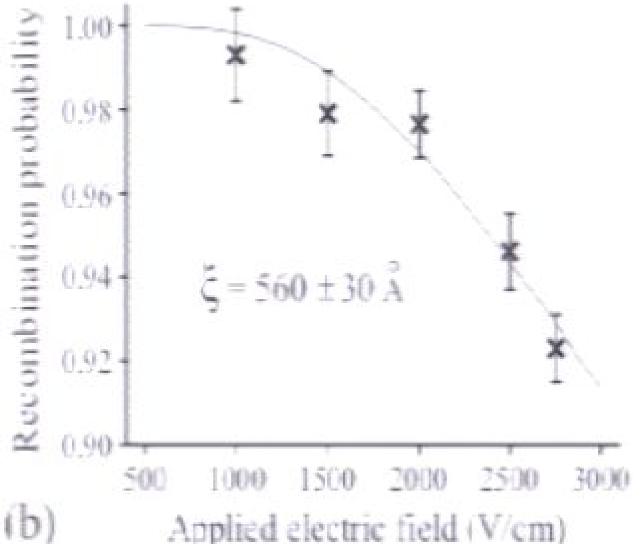
Monte Carlo results





Experimental data





How to detect the charge signal?

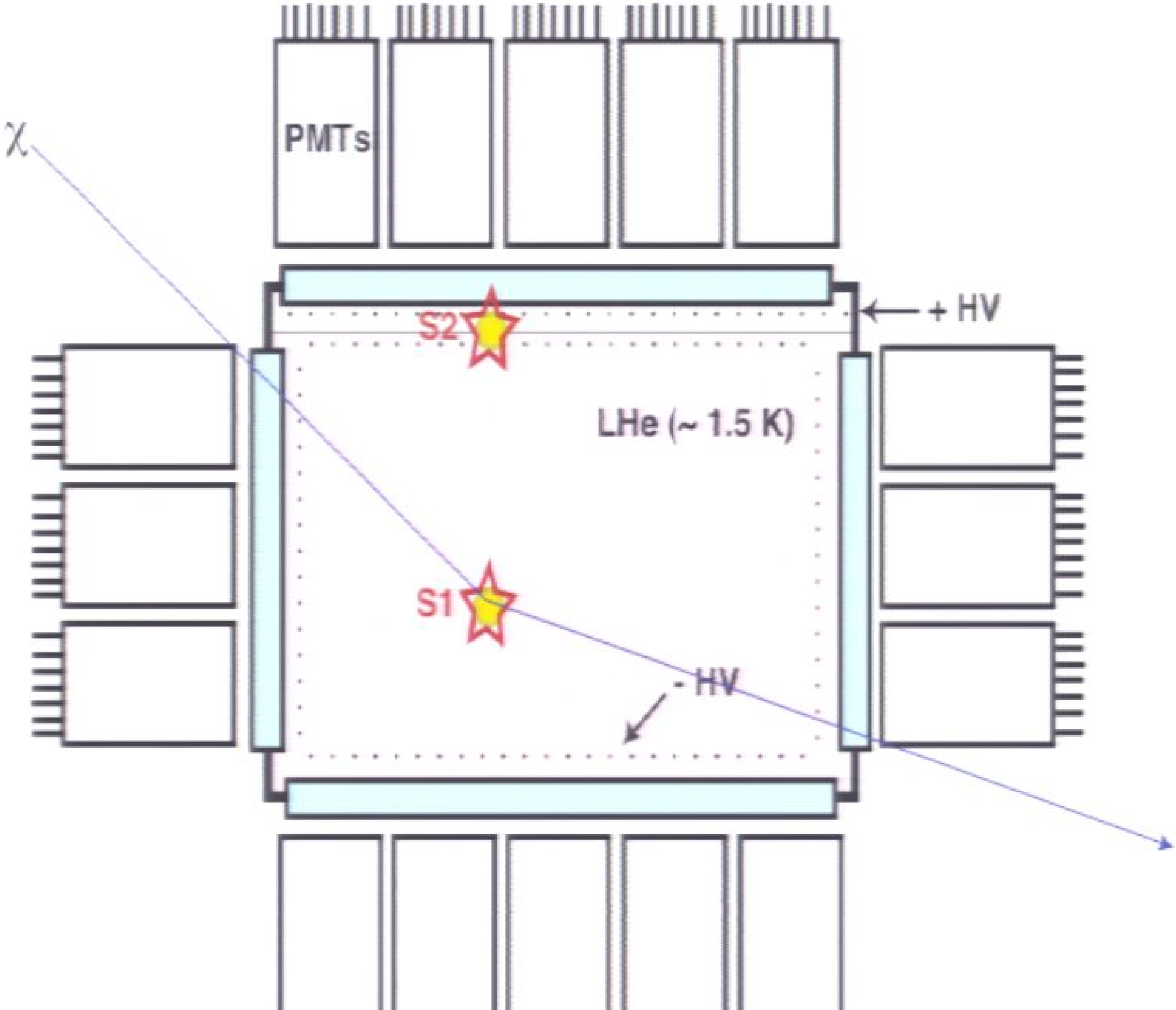
Many options:

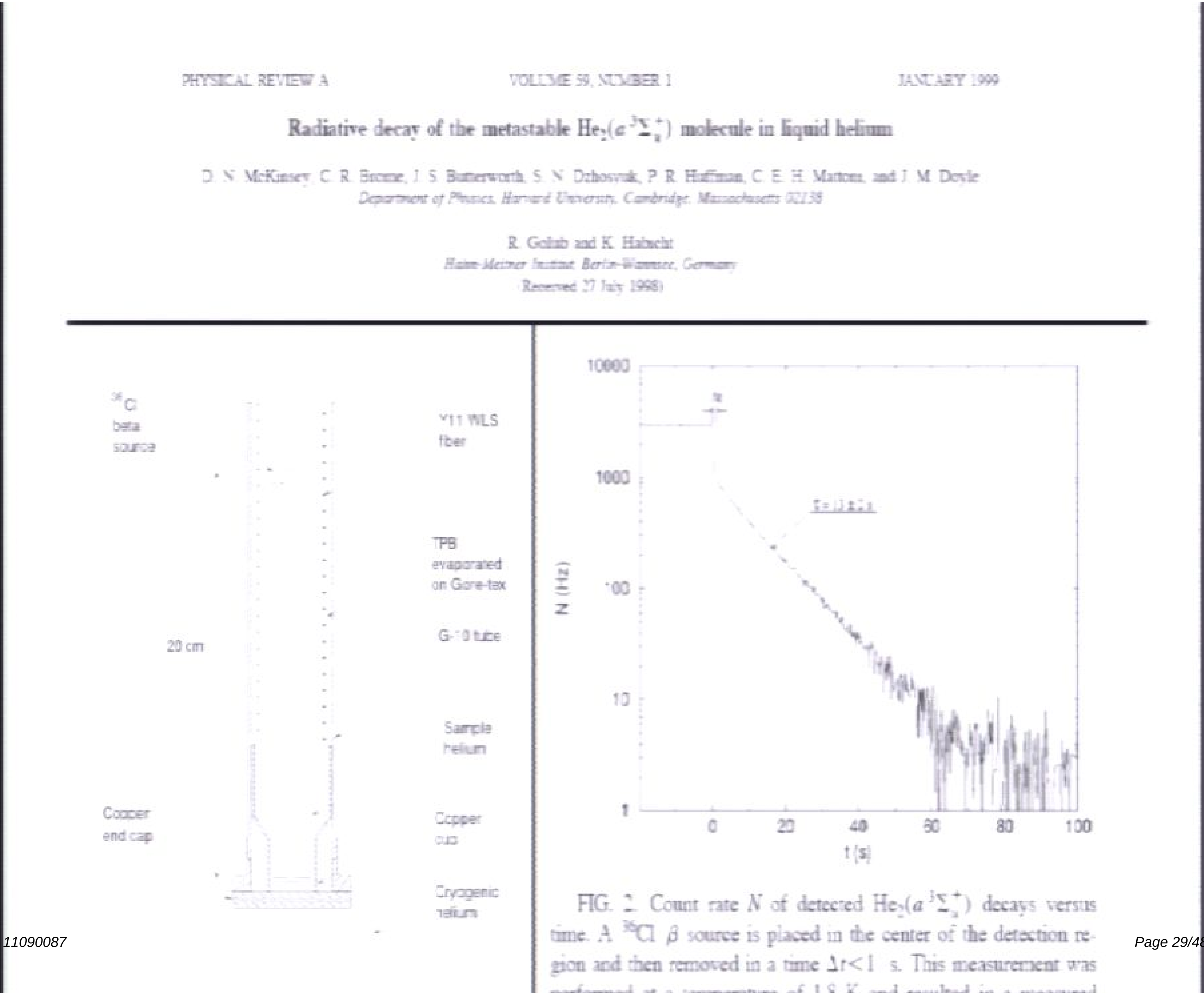
- Proportional scintillation (like in 2-phase Xe, Ar detectors)
- Gas Electron Multipliers (GEMs) or Thick GEMS, detect light produced in avalanche.
- Micromegas, detect avalanche light.
- Thin wires in liquid helium. This should generate electroluminescence at fields ~1-10 MV/cm near wire, and is known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

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

In all cases, use the trick of changing the charge signal into a light signal, read out with the same photodetectors that detect the prompt S1 light

Light WIMP Detector Concept





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

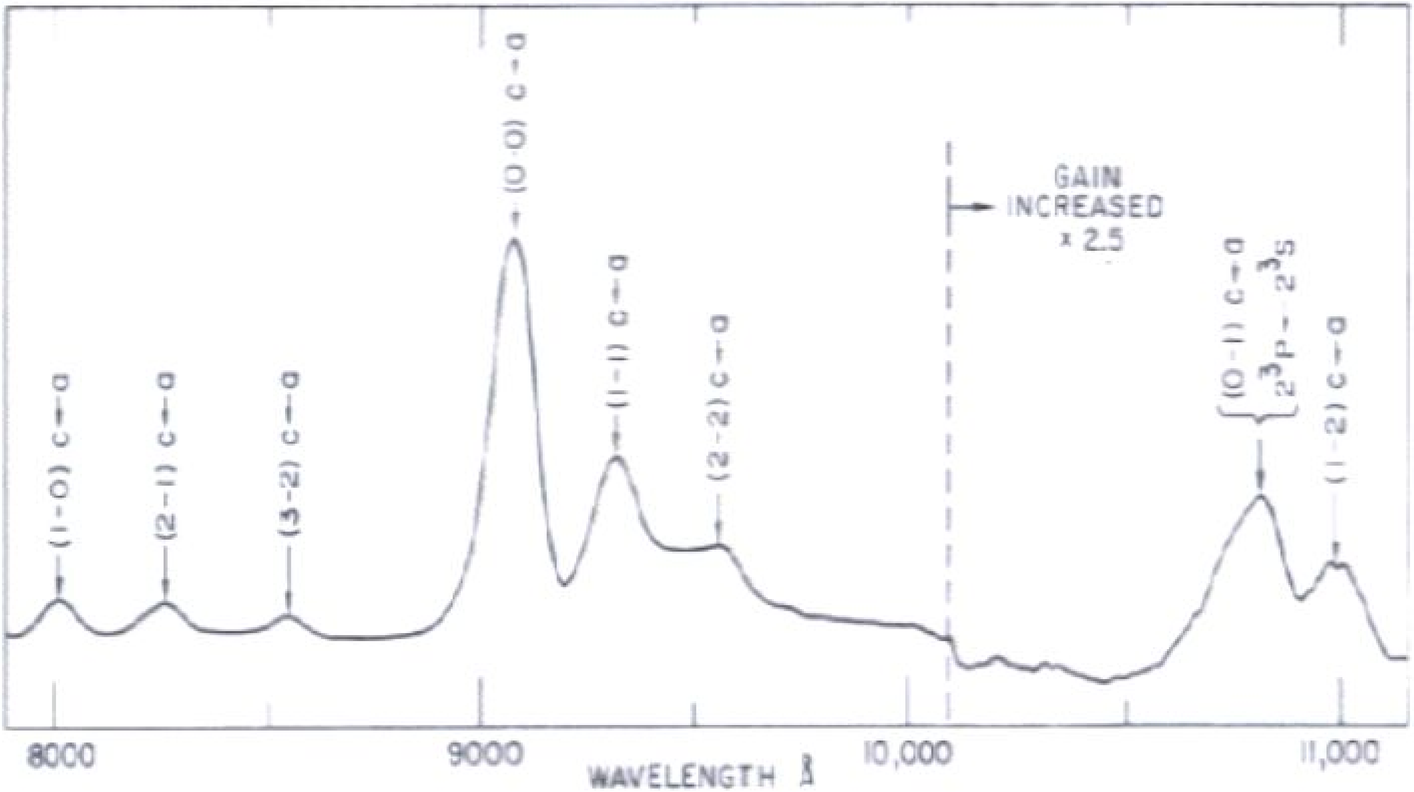
R. Golub and K. Habicht
Hahn-Meitner Institut, Berlin-Wannsee, Germany

(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

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).

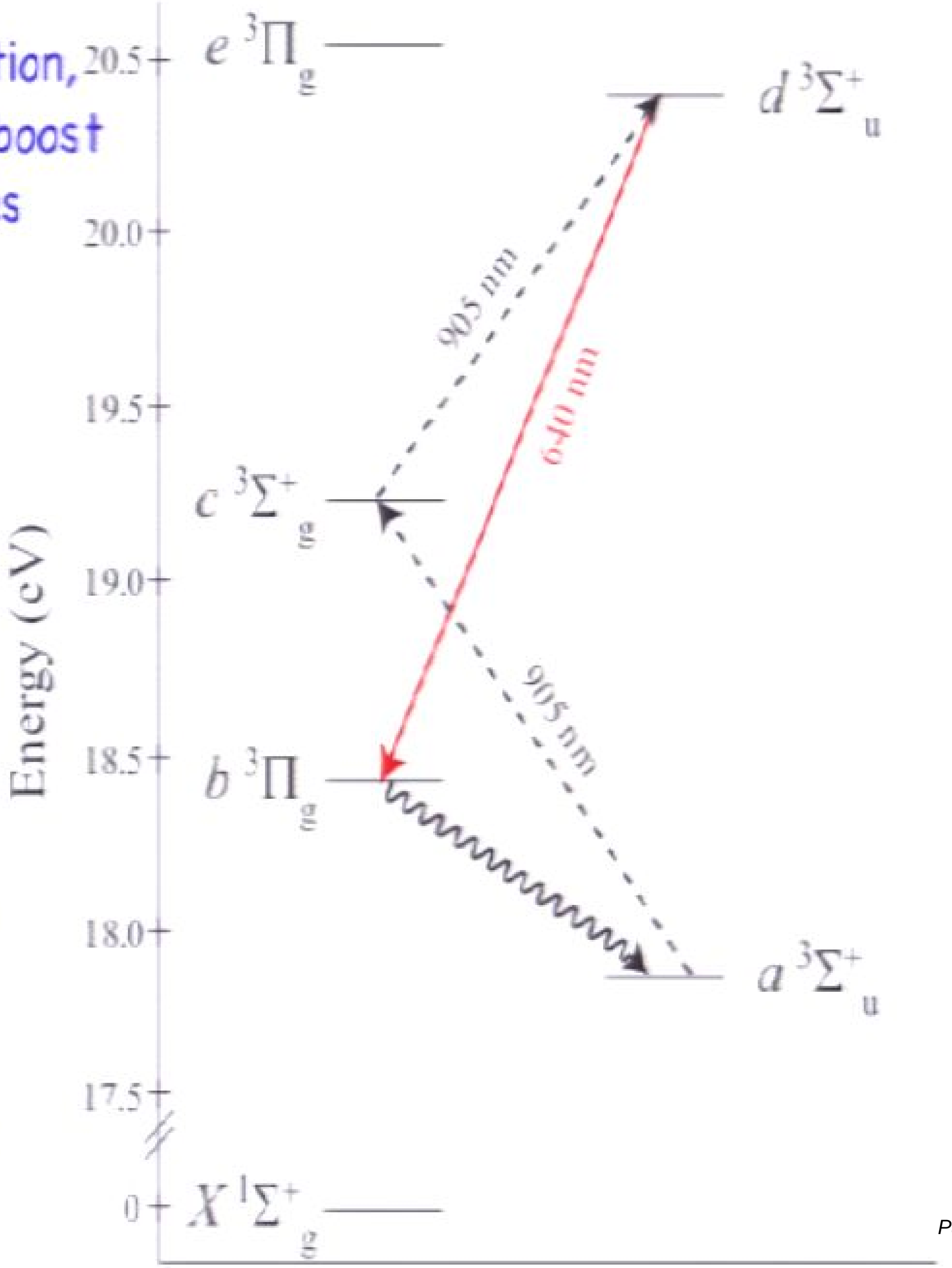
Strong absorption at 910 nm: c–a transition, 0-0 vibrational
Other vibrational transitions visible.

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

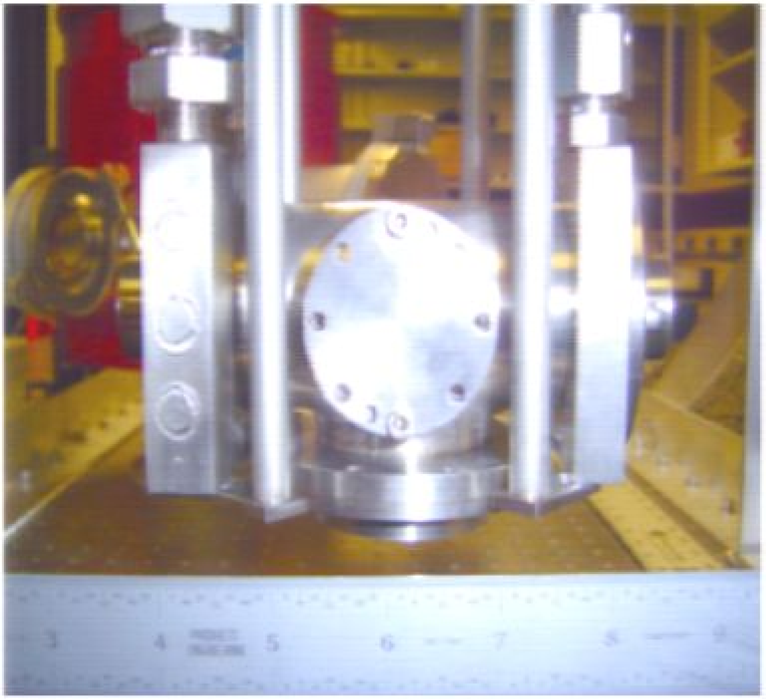
Uses:

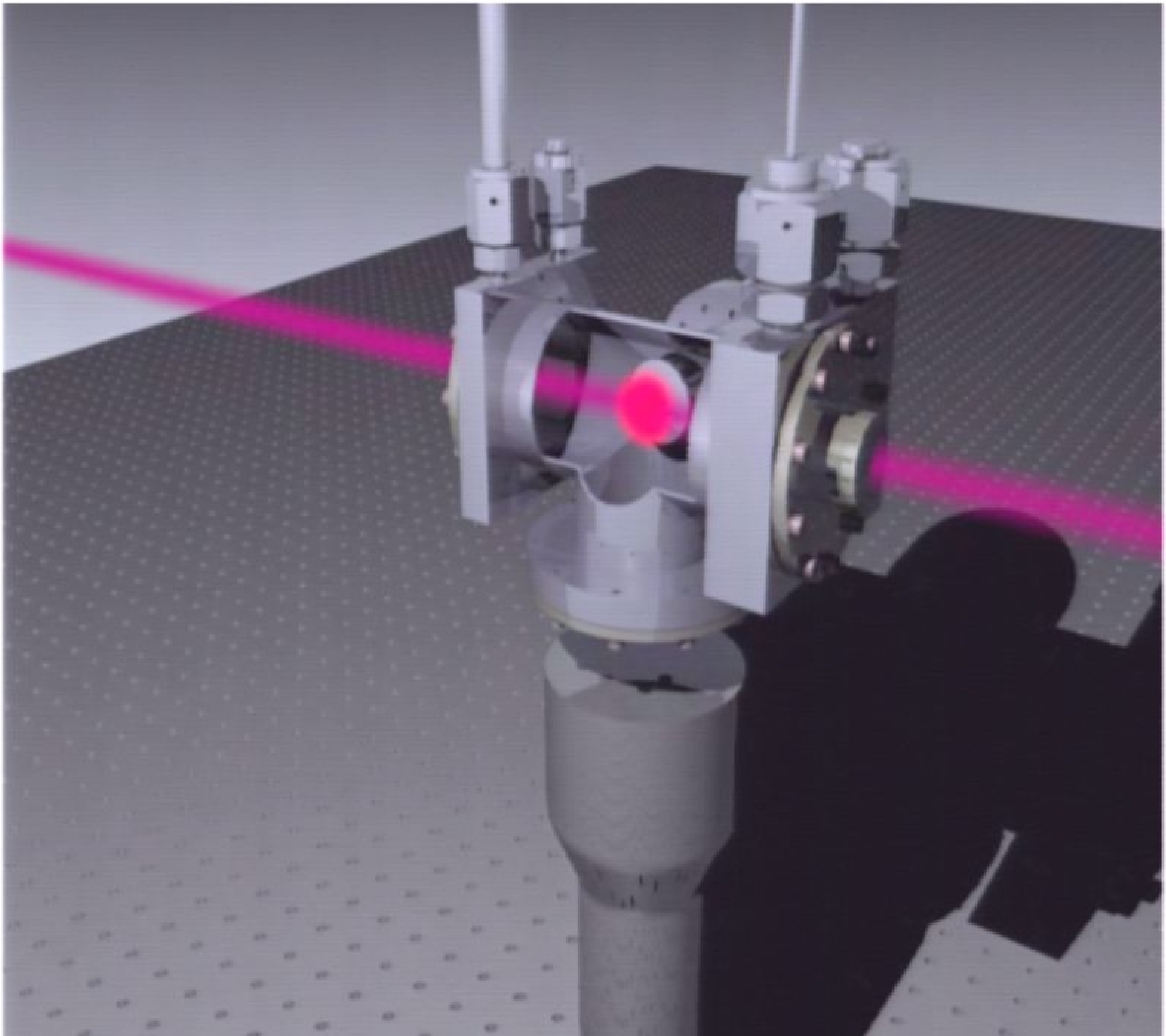
- WIMP detection
- ultracold neutrons
- gamma ray imaging
- Turbulence visualization

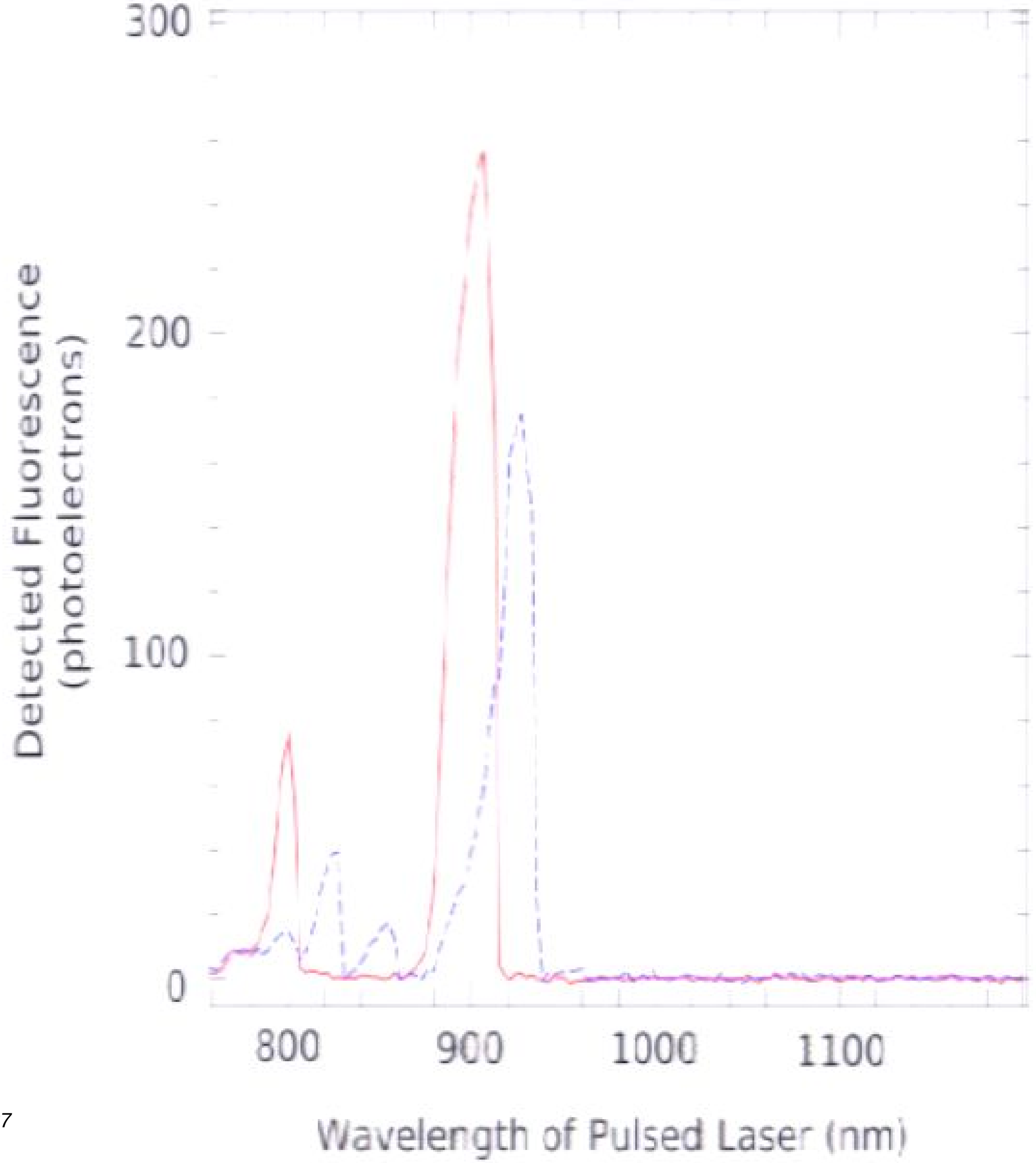
Recent support:
Packard Foundation, DTRA

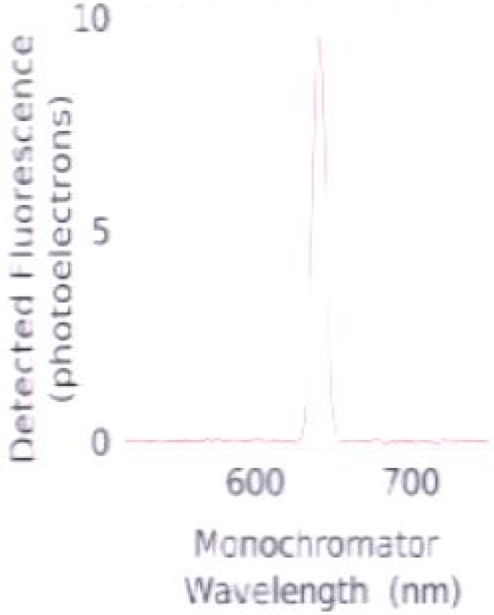


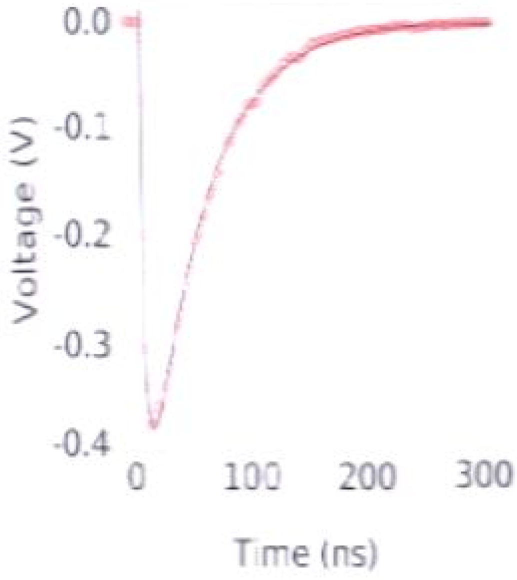
Pumped He-4 system at Yale, with optical access

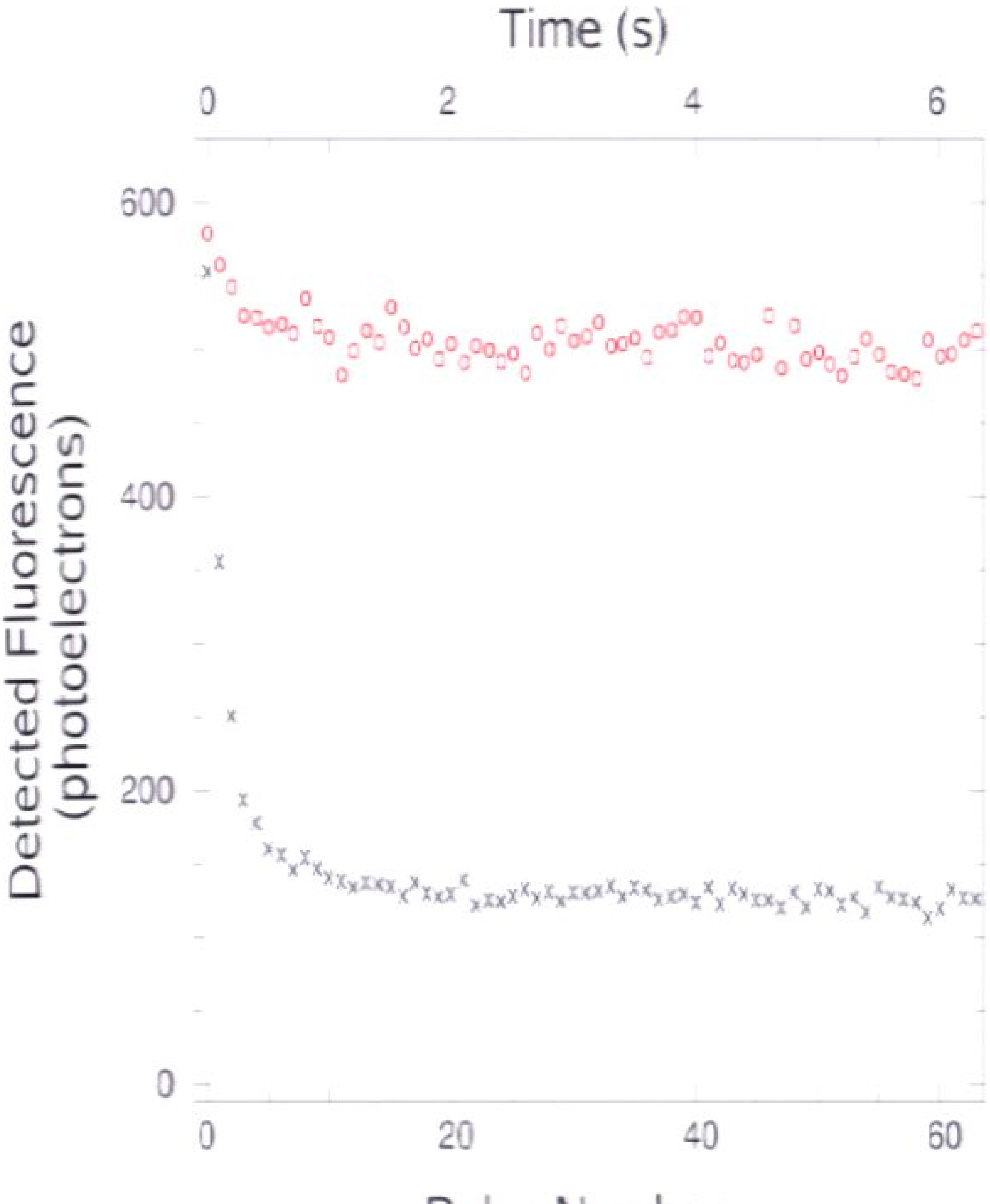




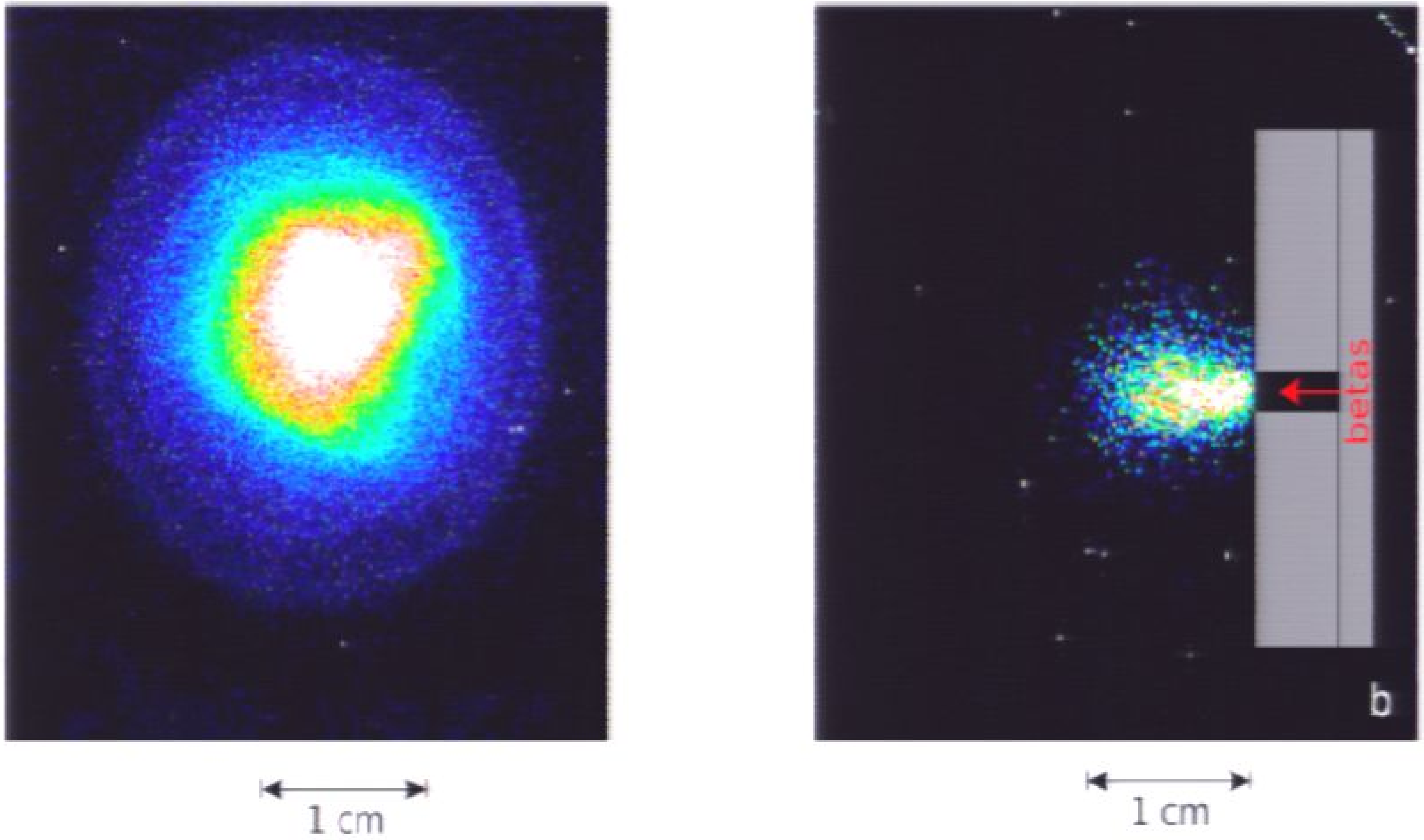

300
200
100
0
800
900
1000
1100
Detected Fluorescence (photoelectrons)
Wavelength of Pulsed Laser (nm)


10
5
0
600
700
Detected Fluorescence (photoelectrons)
Monochromator Wavelength (nm)

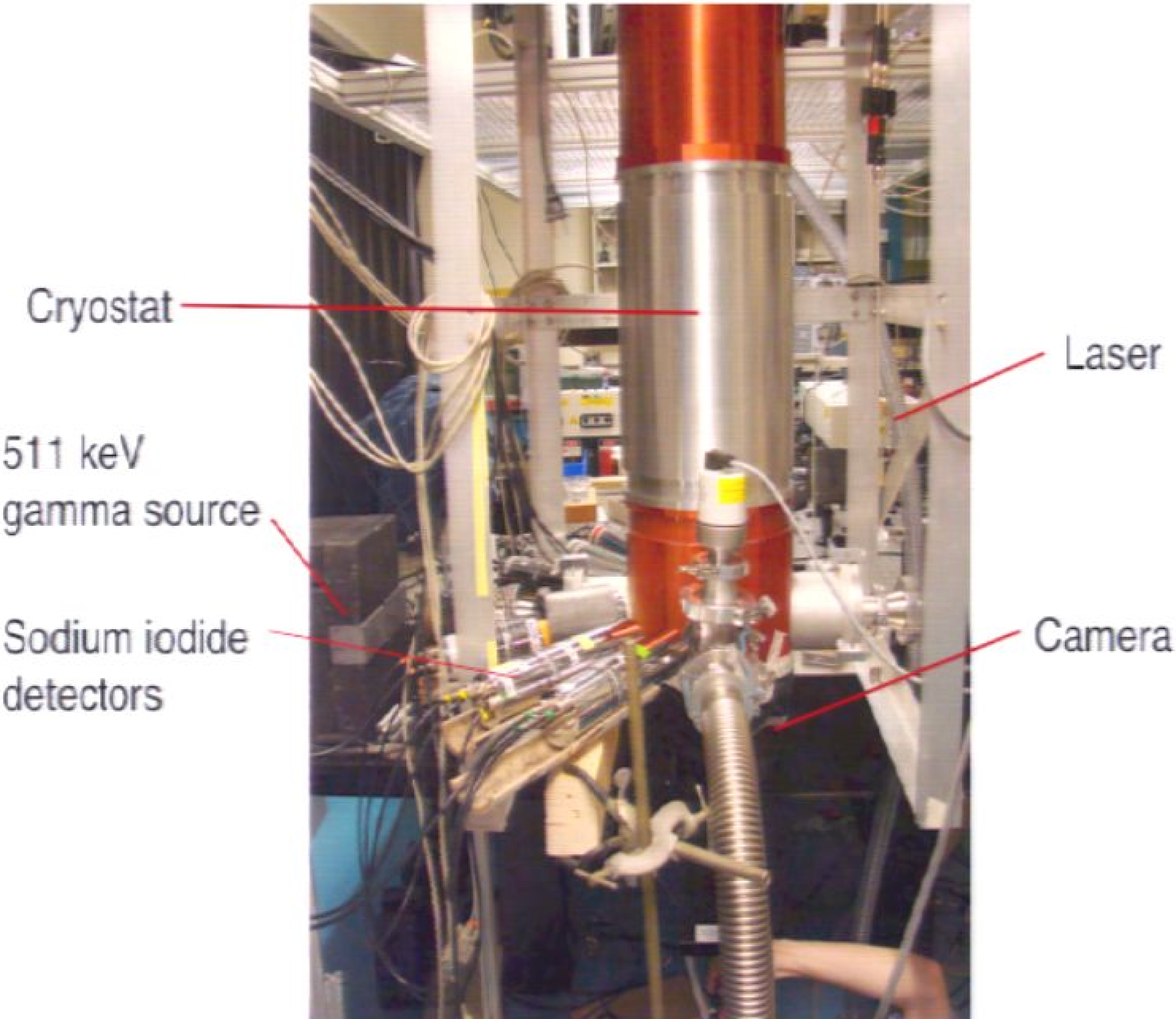

0.0
-0.1
-0.2
-0.3
-0.4
0
100
200
300
Voltage (V)
Time (ns)


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

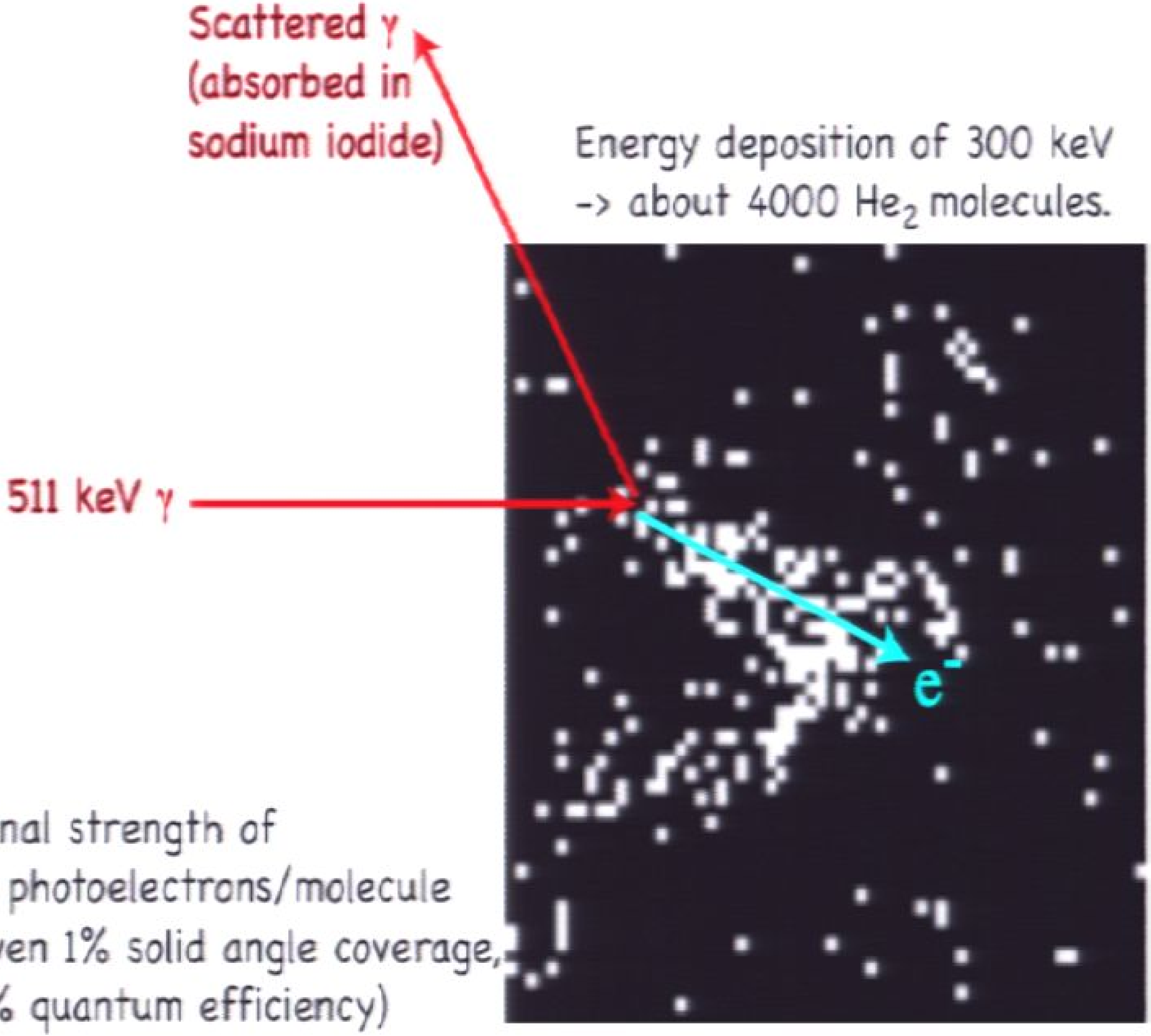
Images of Helium Molecules



Scattering gamma rays in liquid helium

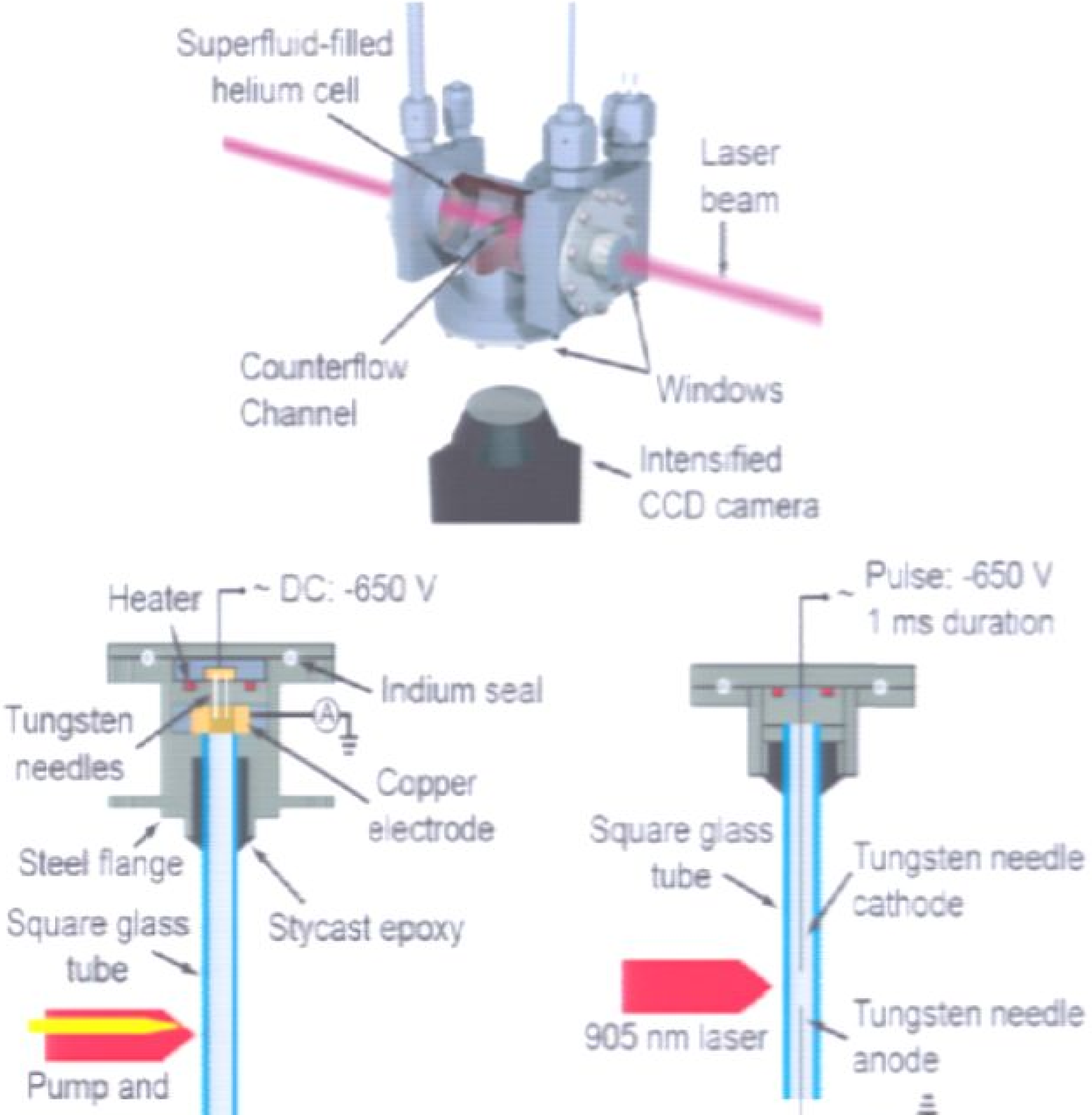


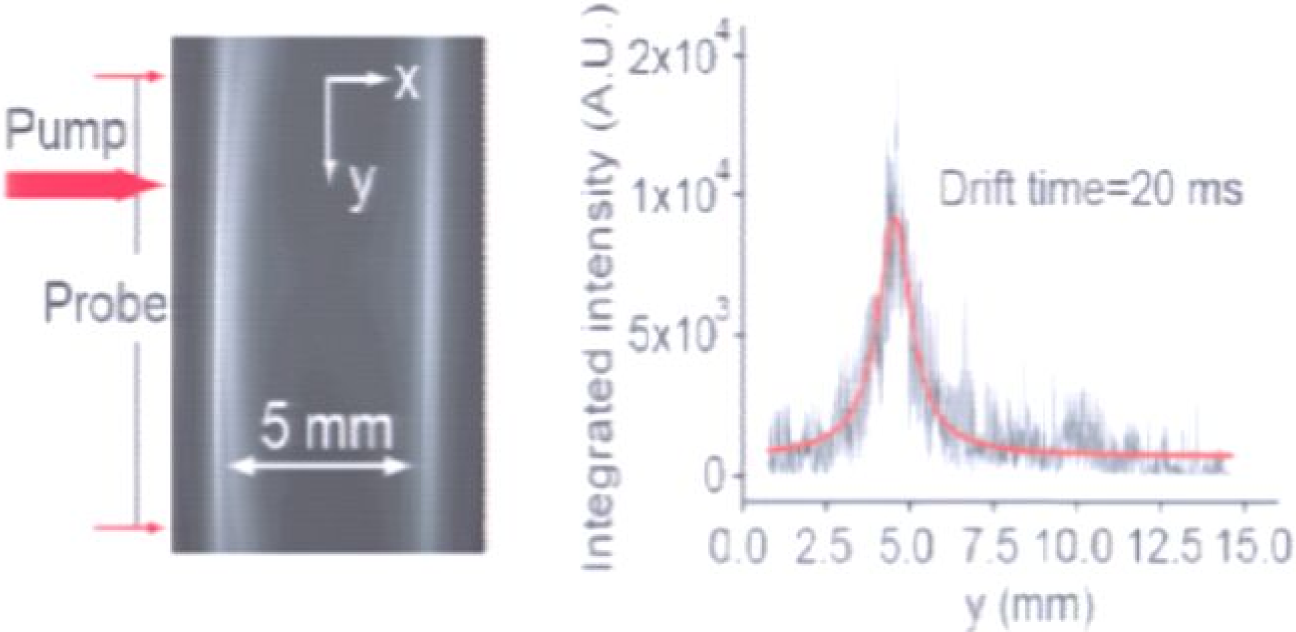
Energy deposition of 300 keV
-> about 4000 He_2 molecules.

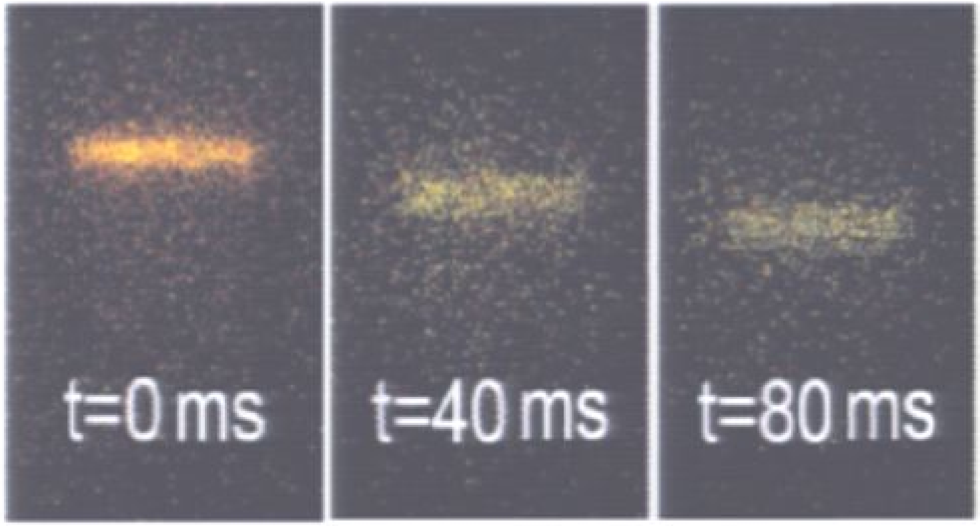


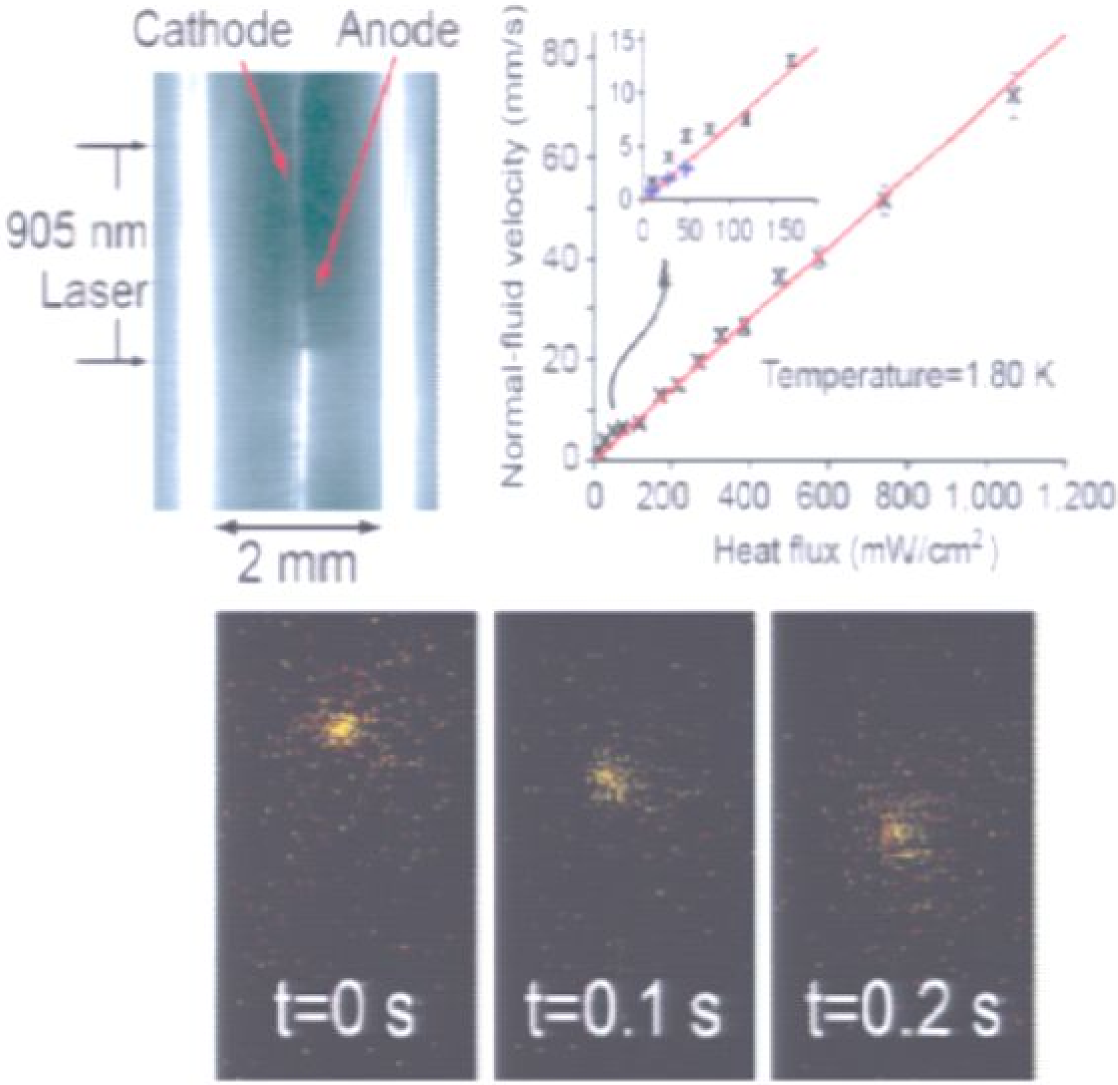
Signal strength of
0.1 photoelectrons/molecule
(given 1% solid angle coverage,
10% quantum efficiency)

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).

Capture of He_2^* Molecules by Vortex Lines in Superfluid ^4He at $T < 0.2K$

D.E. Zmeev[a,e], F. Pakpour[a], P.M. Walmsley[a], A.I. Golov[a], W. Guo[b],
D.N. McKinsey[b], G.G. Ihas[c], W.F. Vinen[d], and P.V.E. McClintock[e]

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[b]Department of Physics, Yale University, New Haven, Connecticut 06520, USA
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[e]Physics Department, Lancaster University, Lancaster LA1 4YB, UK

Motivation

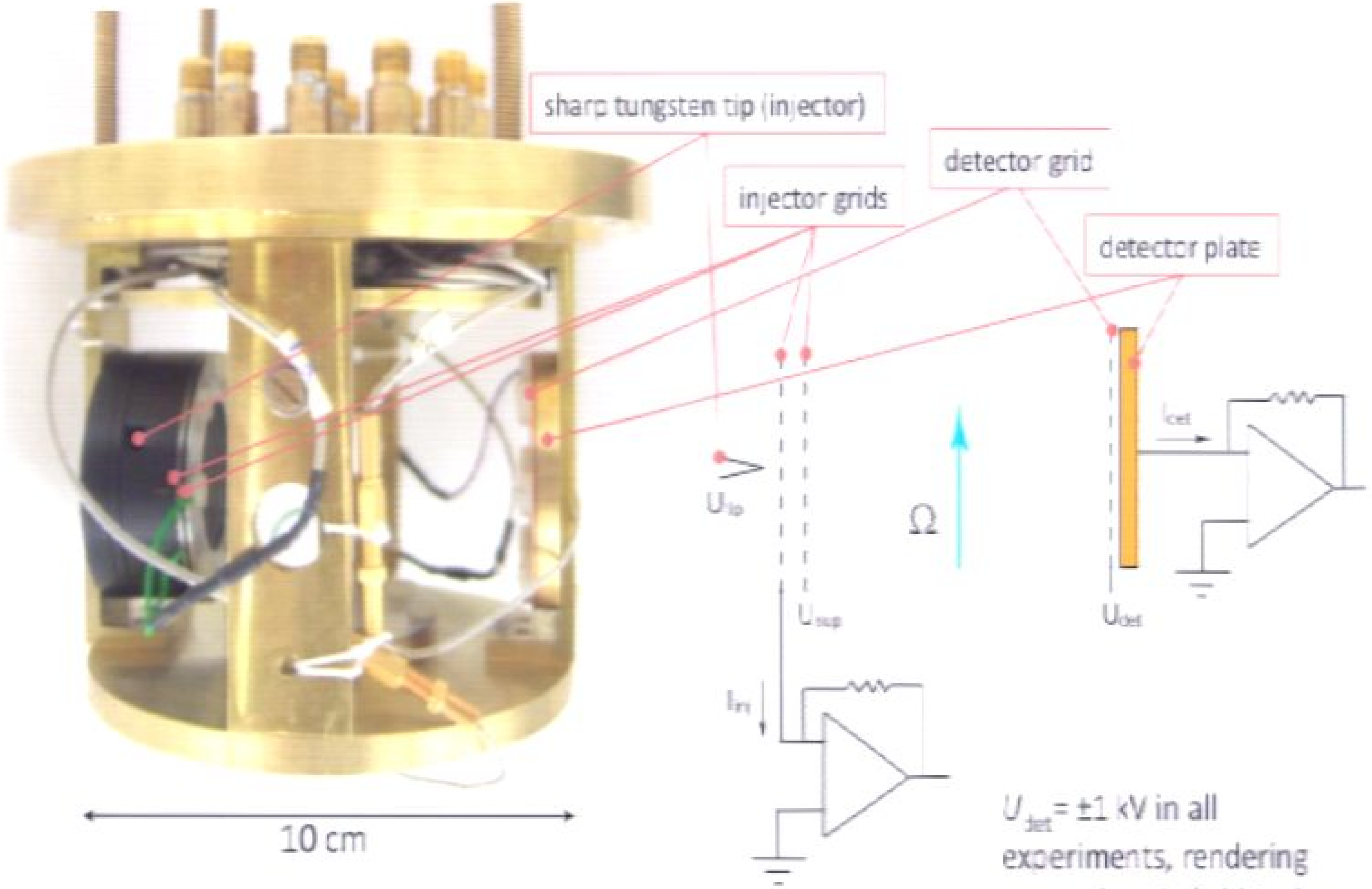
At the moment there is no technique allowing one to visualize quantized vortices in a superfluid in the T→0 limit.

Our goal was to see how effectively the excimers are captured by the vortices. If the excimers can indeed be captured, the vortices can be visualized using the induced fluorescence technique proved successful at Yale University.

The He_2^* molecules are good candidates for the trace particles as they are small and light enough. They are electrically neutral, optically active, can be easily injected.

Visualization of vortices will facilitate measurements of vortex dynamics on a wide range of lengthscales and the energy spectra of different types of quantum turbulence.

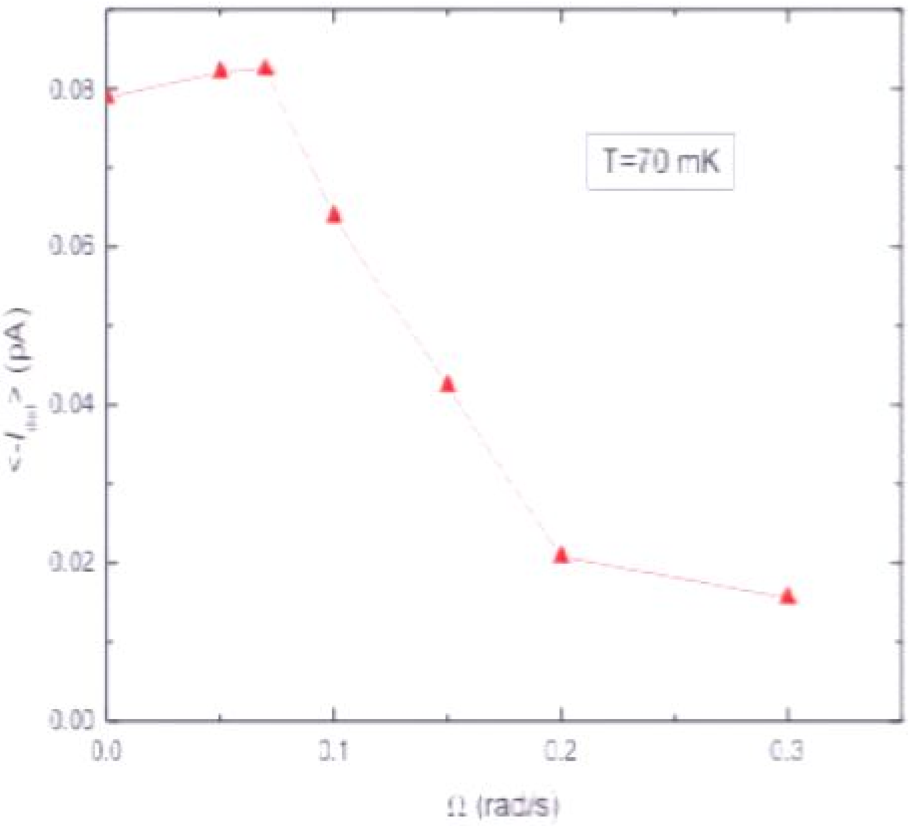
Experimental cell



The cell is filled with liquid helium and can be subjected to rotation

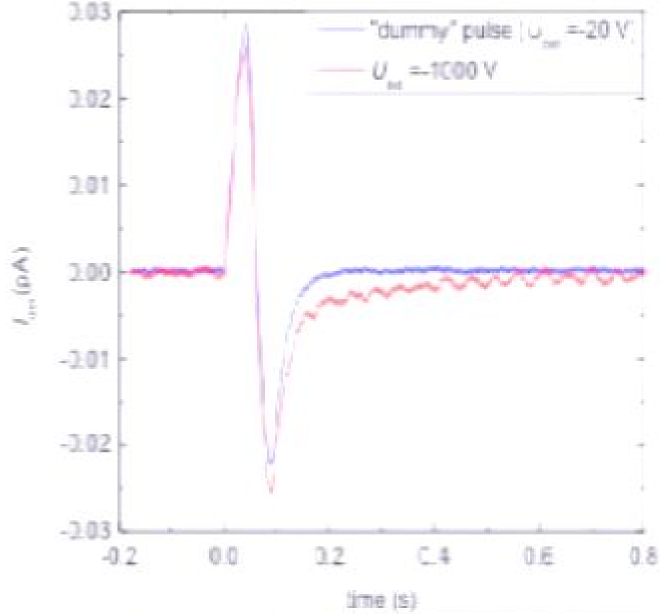
U_{det} = ±1 kV in all experiments, rendering mean electric field in the detection region $E \sim 200$ kV/cm

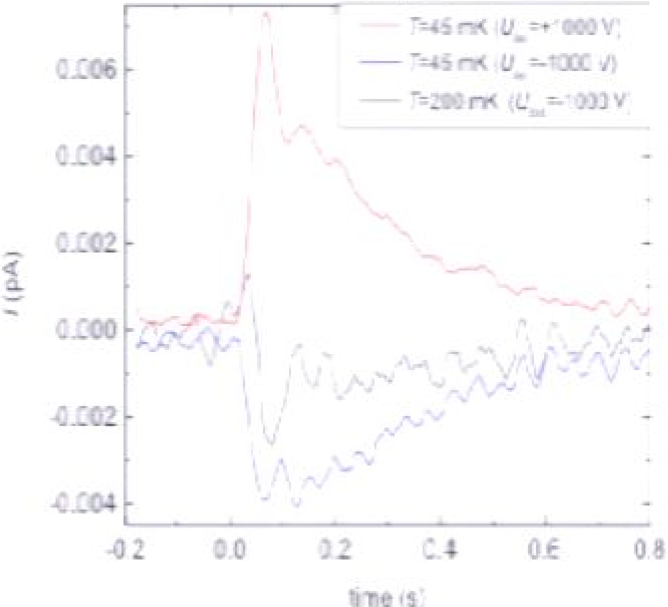
Dependence of the signal on angular velocity



The signal can be almost entirely suppressed by a slow rotation at 0.2 rad/s.
This suggests that the molecules are effectively trapped by vortices.

Pulsed measurements





We were able to observe tiny signals in the pulsed regime. The signals had to be averaged over 3-4 days. The capacitive pick-up had to be subtracted (to do this "dummy" pulses were applied with a low voltage setting on the detector grid).

The pulse length was 90 ms and the pre-amp bandwidth was 20 Hz.

The bottom figure shows signals taken with U_{det}=-1000kV at 45 and 200mK with the pick-up background subtracted.
The arrival time gives estimated velocity of 1 m/s (this corresponds to vortex rings of radii R~0.1 μm).

In accord with the DC measurements, the signal due to the molecules was much smaller at 200 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
  - Temperature must be < 50 mK to keep Kapitza resistance low enough, and allow heat signal to be extracted before it is lost to the liquid helium.
  - 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

- New charge-only technique effective for low-mass WIMPs, will scale up well in future LXe detectors.
- Liquid helium looks promising for light WIMP searches
  - Technology already partially developed for ultracold neutron, pp neutrino, He-3 Kibble-Zurek mechanism projects
  - Lots of signals available (prompt light, charge, triplet molecules, rotons, ...).
  - New Yale results on charge separation show that charge signal may be had with reasonable fields.
  - Needs R&D on nuclear recoil signals, charge, and triplet molecule detection.