Liquefied noble gases as targets for light dark matter

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HEFTI Workshop on Light Dark Matter
UC Davis

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

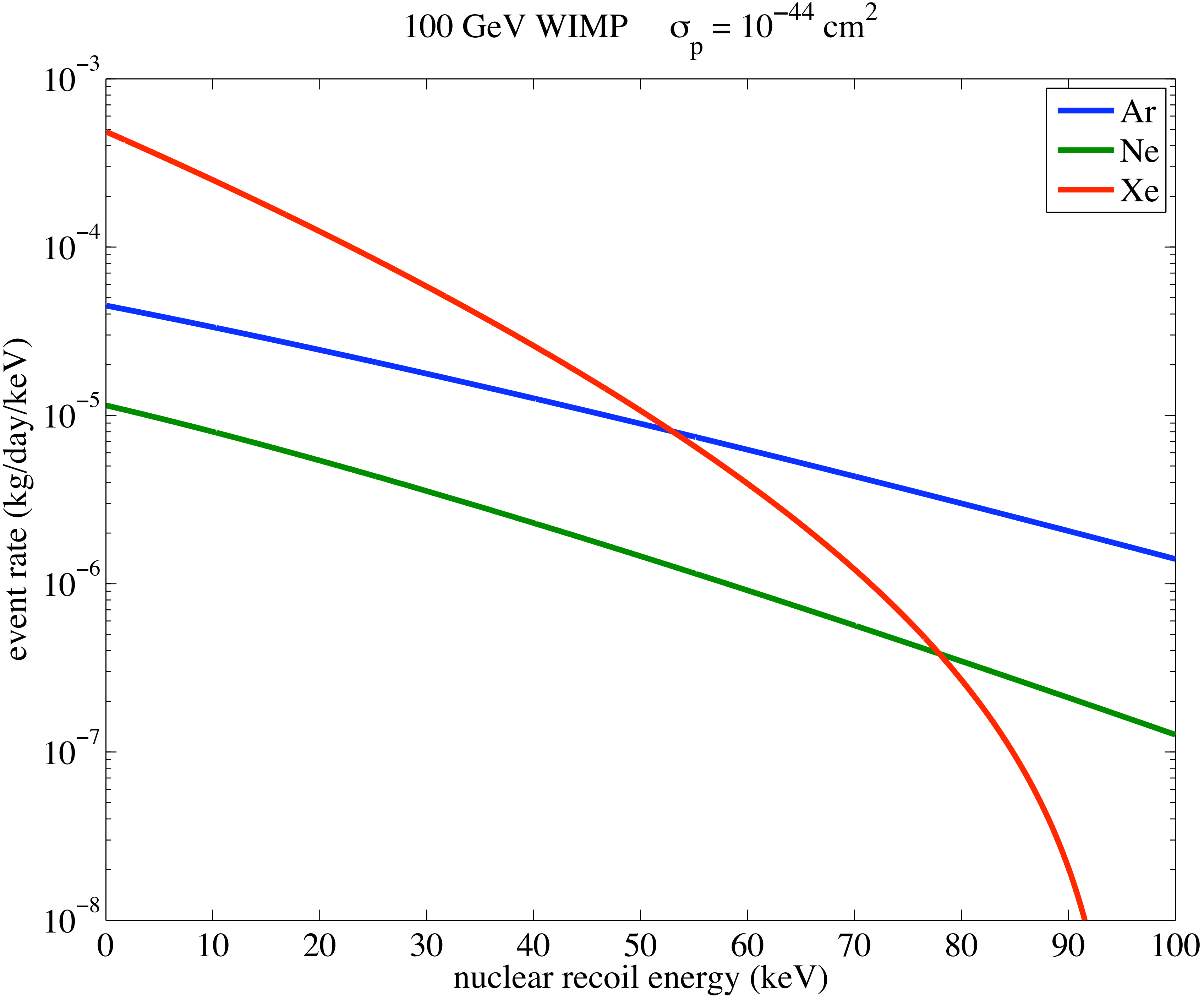
Do not attach electrons, heavier noble gases give high electron mobility

Easy to purify (especially lighter noble gases)

Inert, not flammable, very good dielectrics

Bright scintillators

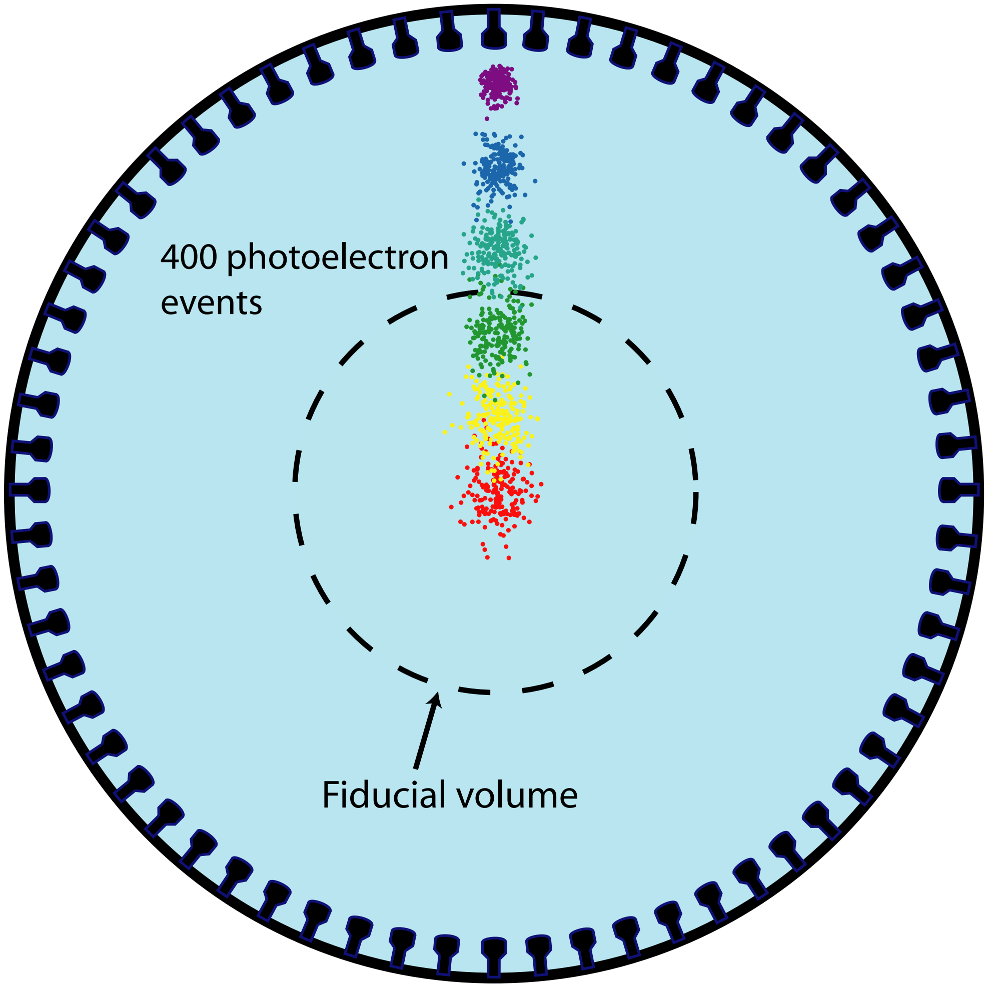
	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125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

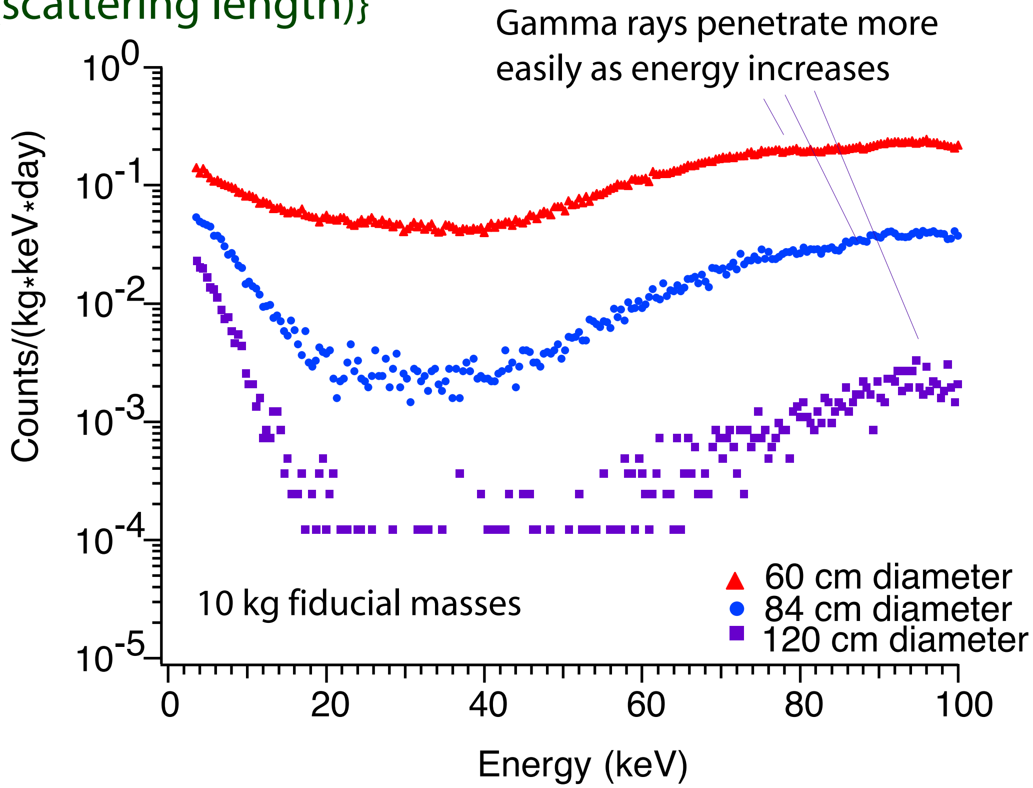

100 GeV WIMP $\sigma_p = 10^{-44}$ cm^2
Ar
Ne
Xe
event rate (kg/day/keV)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
10
20
30
40
50
60
70
80
90
100
nuclear recoil energy (keV)

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)}





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

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

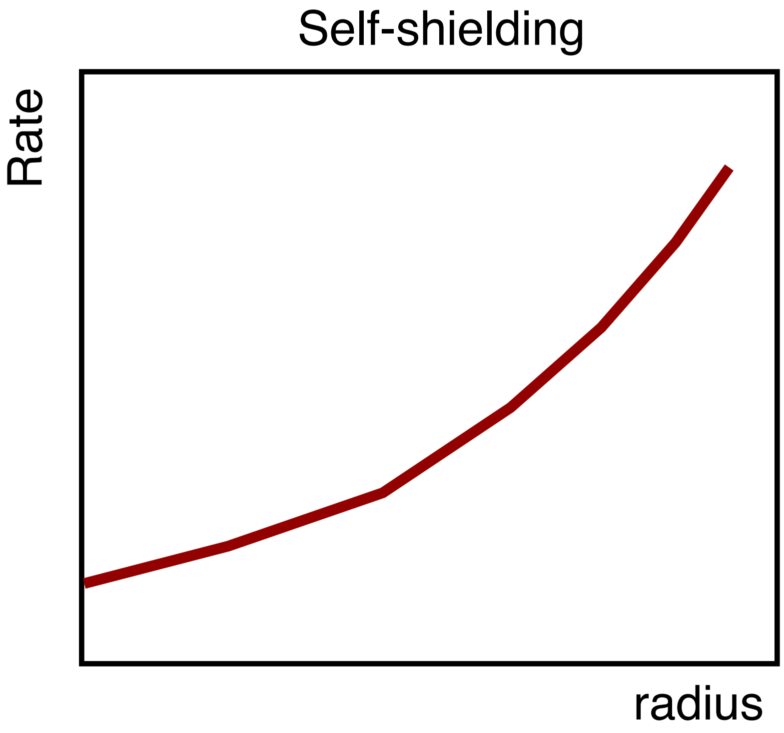
Strategies for Electronic Recoil Background Reduction in Scintillation Experiments

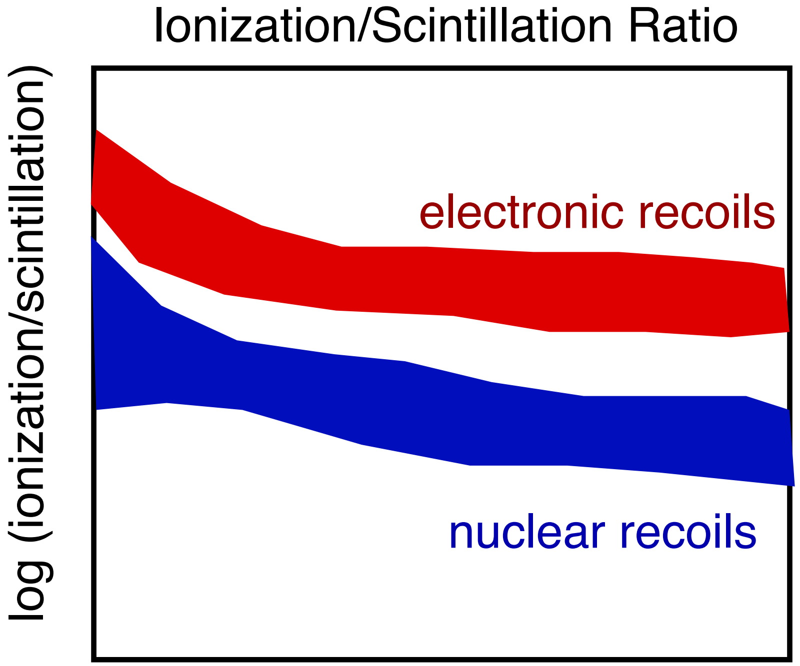
Require < 1 event in signal band during WIMP search

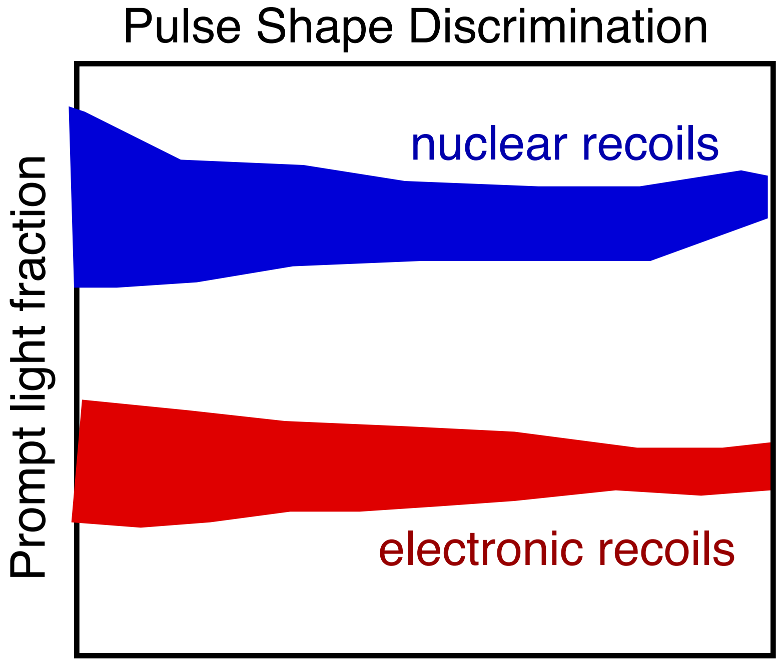
LXe: Self-shielding, Ionization/Scintillation ratio best

LAr: Pulse shape, Ionization/Scintillation ratio best

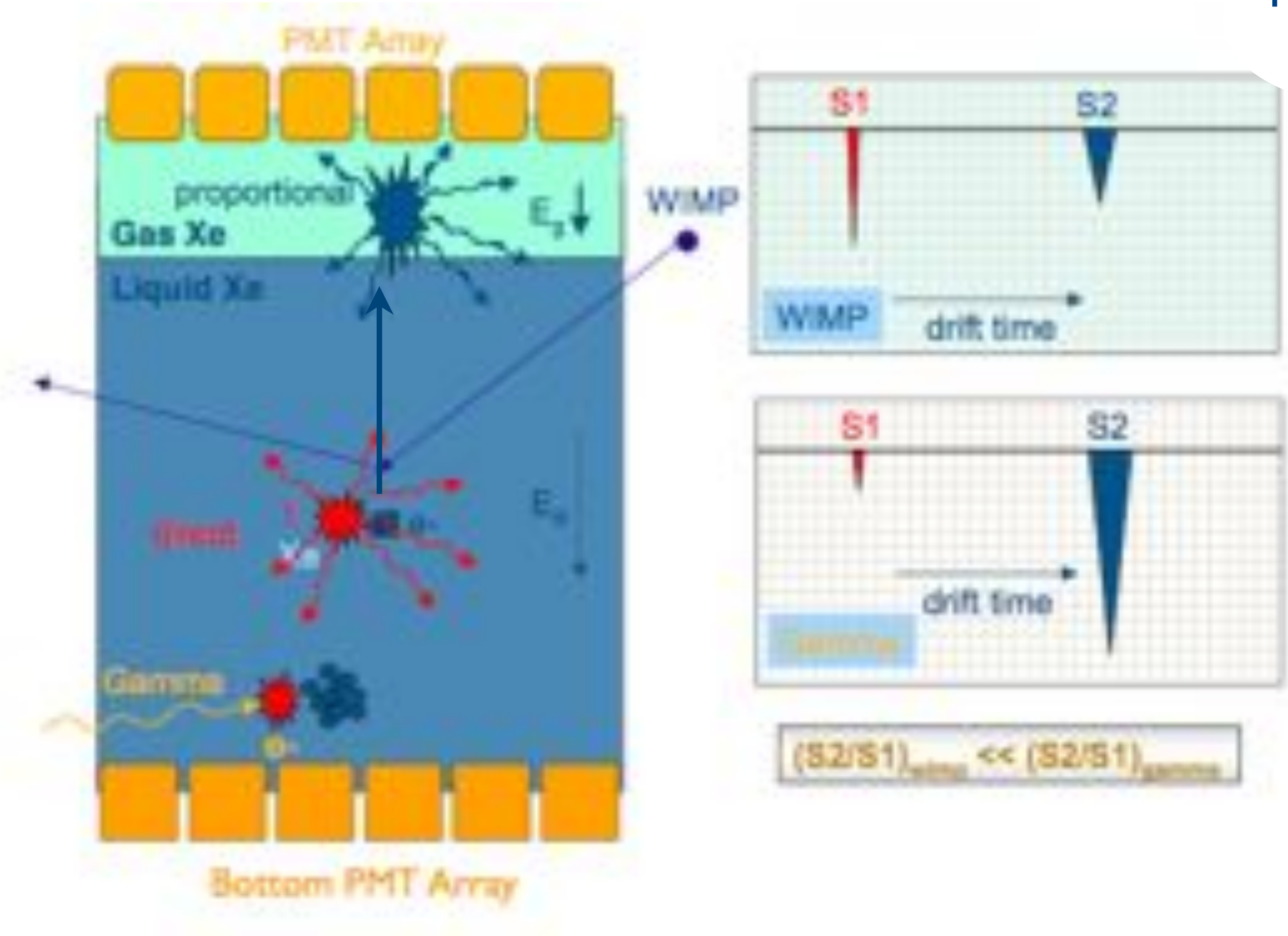
LNe: Pulse shape, Self-shielding best

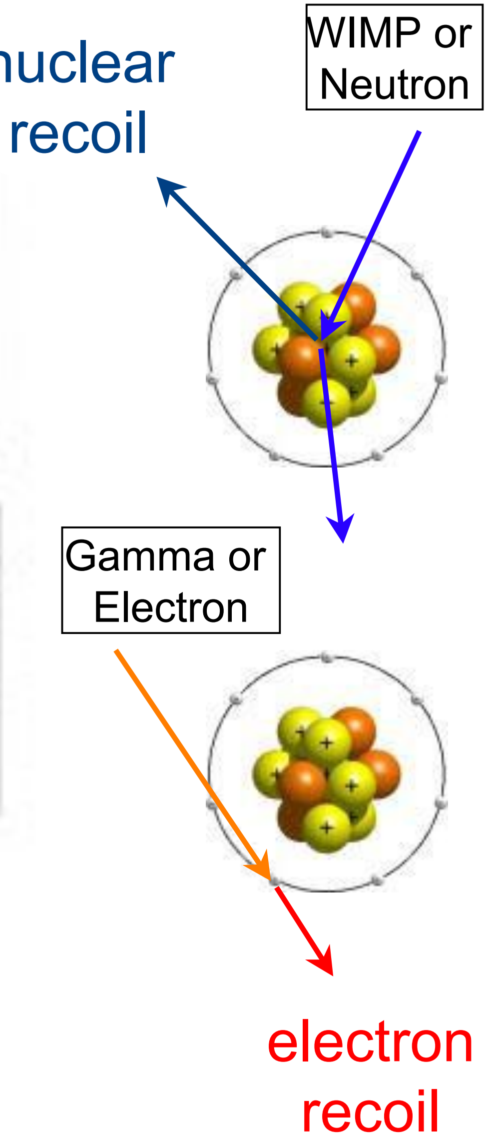

Self-shielding


Ionization/Scintillation Ratio


Pulse Shape Discrimination

Two-phase xenon detectors



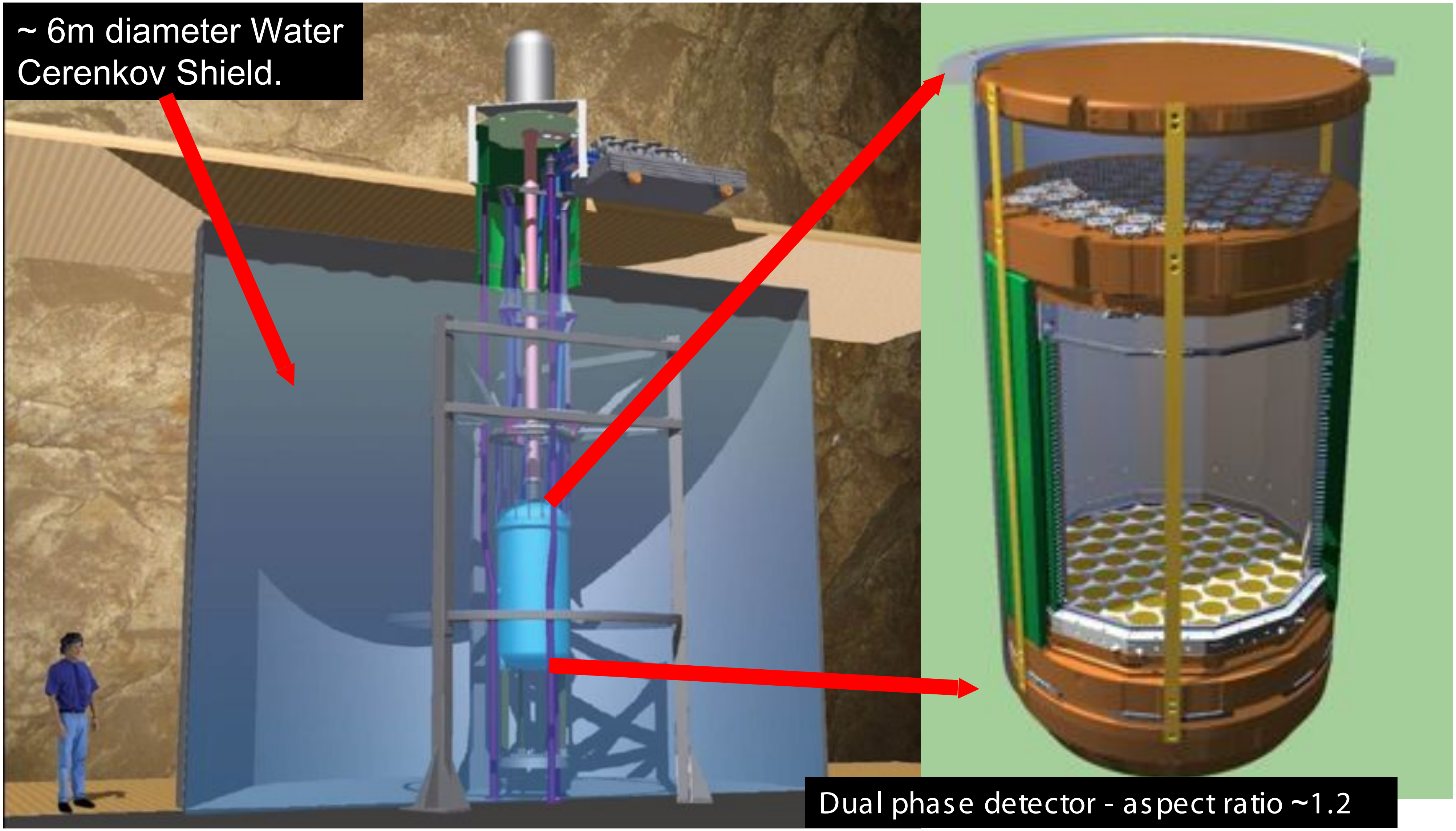

nuclear recoil

WIMP or Neutron

Gamma or Electron

electron recoil

The LUX Detector



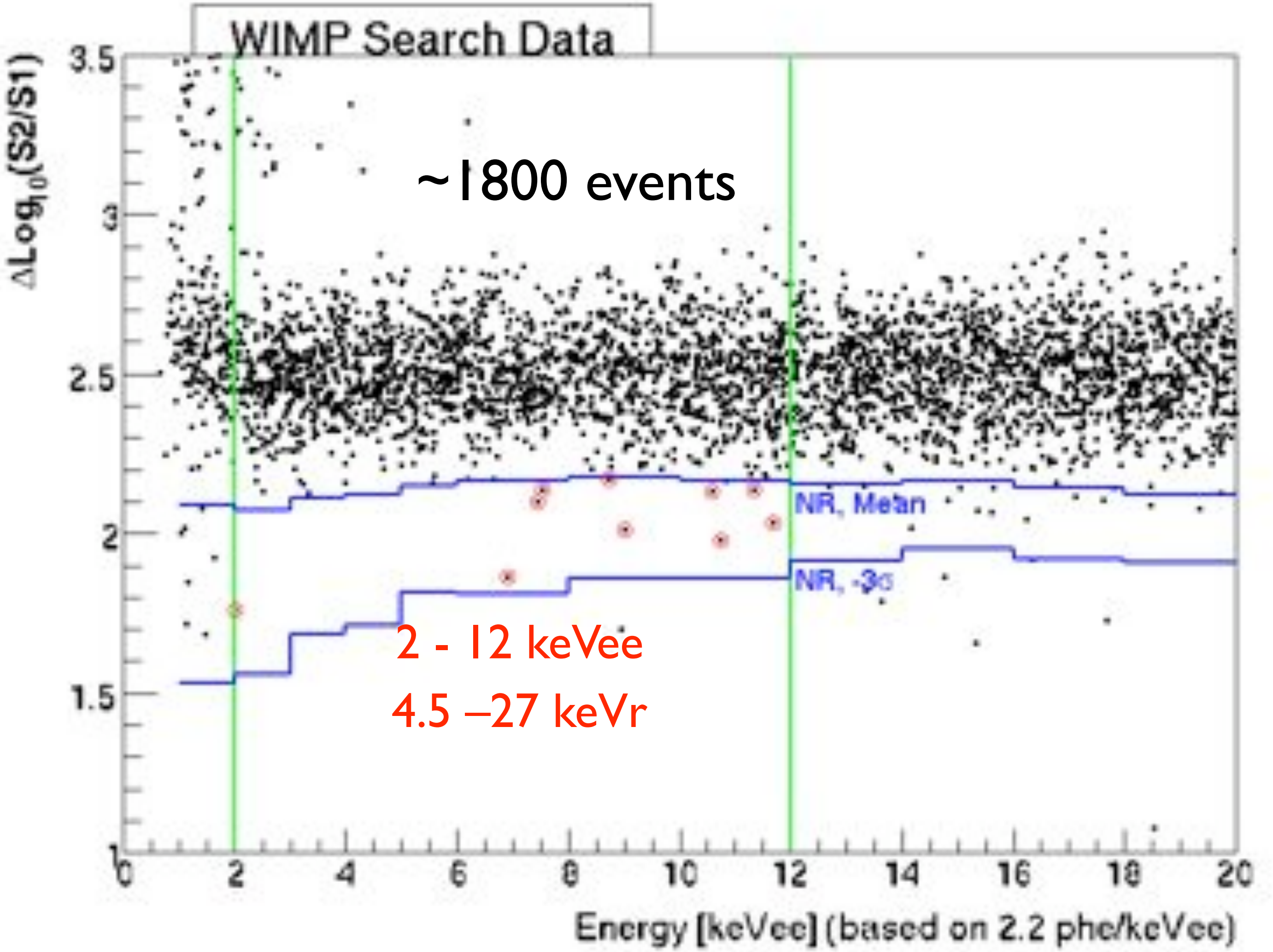
~ 6m diameter Water Cerenkov Shield.

Dual phase detector - aspect ratio ~1.2

350 kg Dual Phase Liquid Xenon Time Projection Chamber, fully funded by NSF and DOE
2 kV/cm drift field in liquid, 5 kV/cm for extraction, and 10 kV/cm in gas phase.
122 PMTs (Hamamatsu R8778) in two arrays
3D imaging via TPC eliminates surface events, defines 100 kg fiducial mass

XENON10 WIMP Search Data

136 kg-days Exposure= 58.6 live days x 5.4 kg x 0.86 (ε) x 0.50 (50% NR)



~1800 events

2 - 12 keVee

4.5 –27 keVr

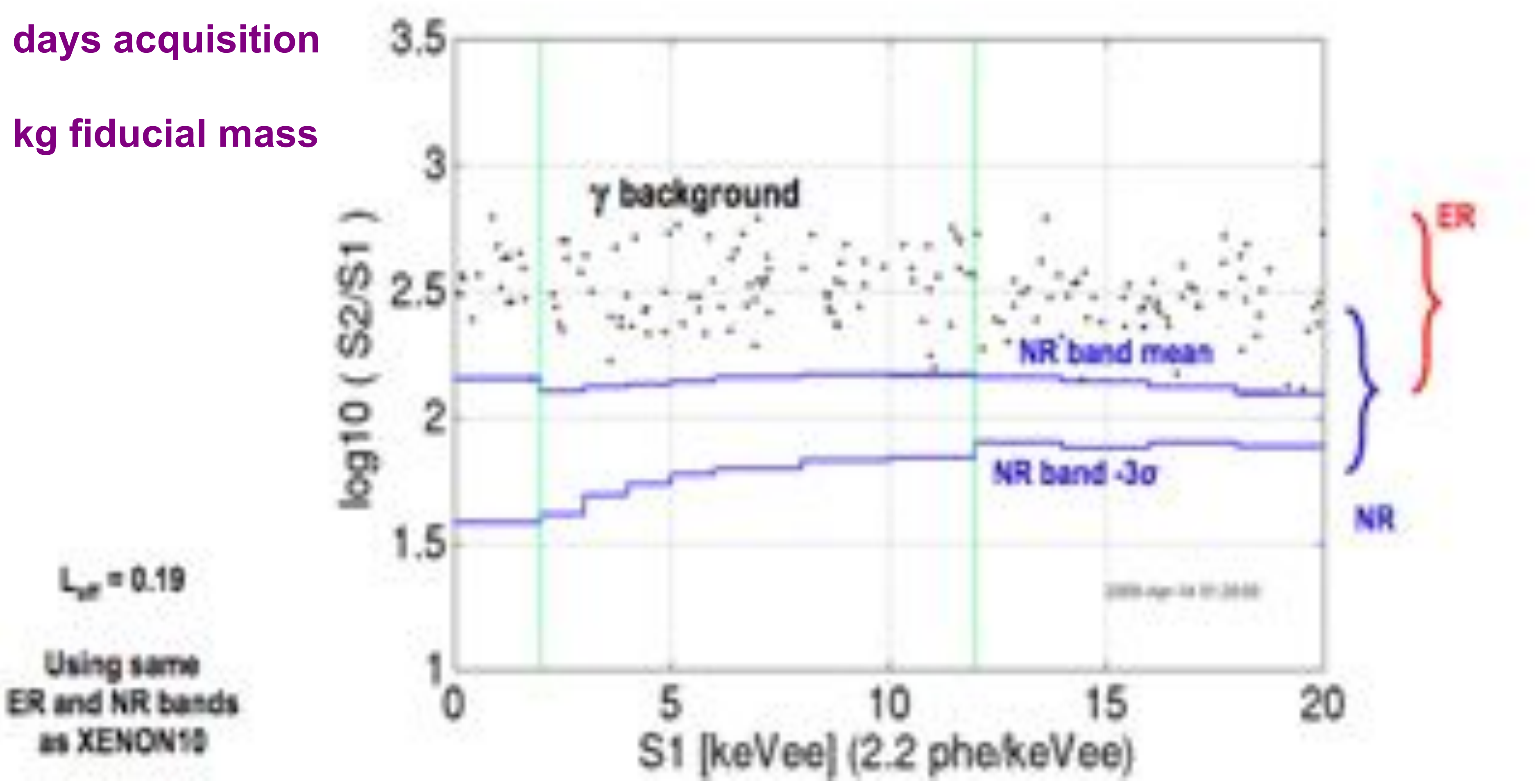
- WIMP “Box” defined at ~50% acceptance of Nuclear Recoils (blue lines): [Mean, -3σ]
- 10 events in the “box” after all cuts in Primary Analysis
- 6.9 statistical leakage events expected from ER band
- NR energy scale based on 19% constant QF

LUX-350 is a background-free experiment

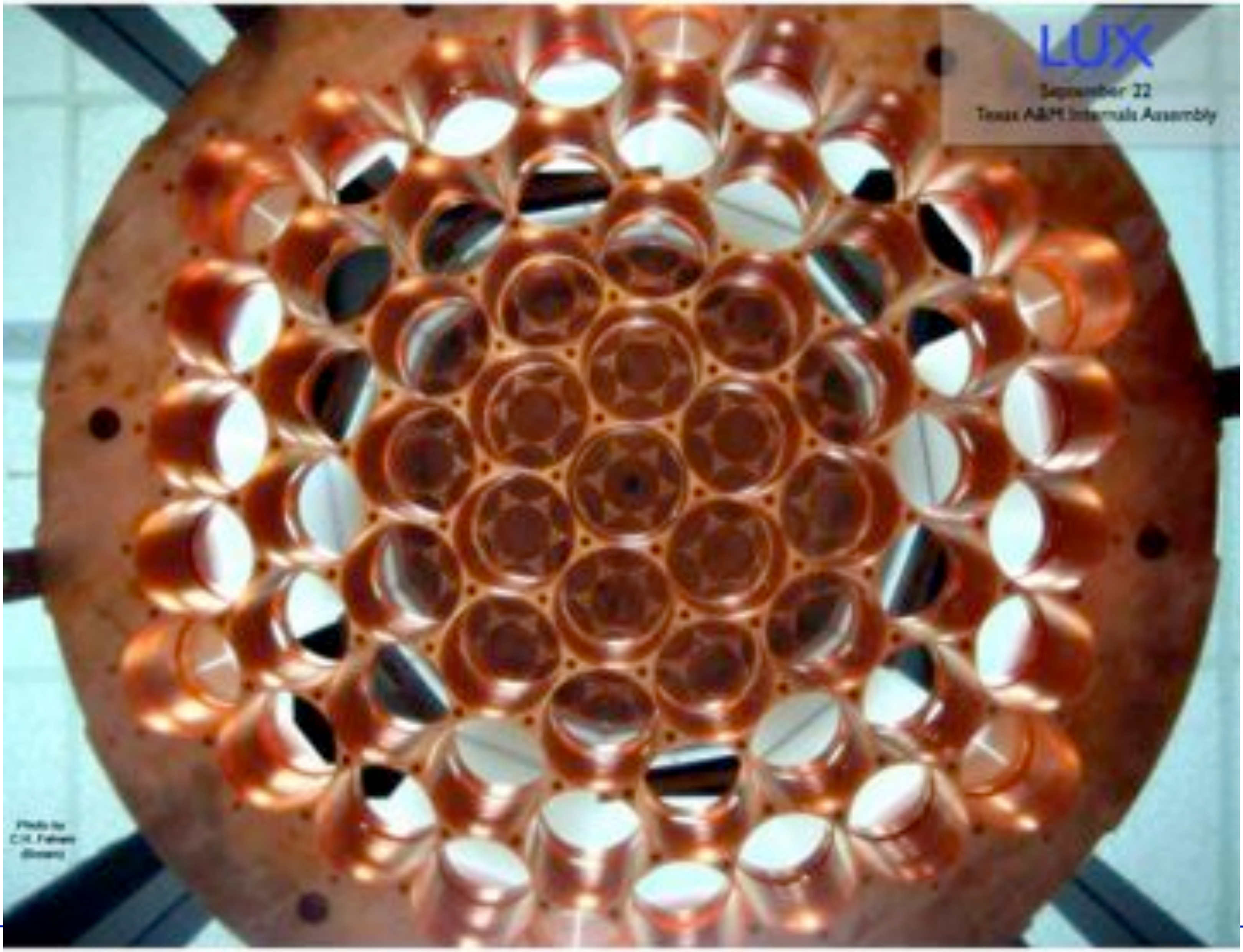
Self-shielding drastically reduces gamma-ray background in the fiducial volume
By defining a fiducial volume, gamma ray backgrounds drop enormously, scaling as exp[-L/Ls], where L is the size of the active volume, and Ls is the gamma ray scattering length. Electron recoil background ~2.6×10^{-4} events/keVee/kg/day (from simulations)

300 days acquisition

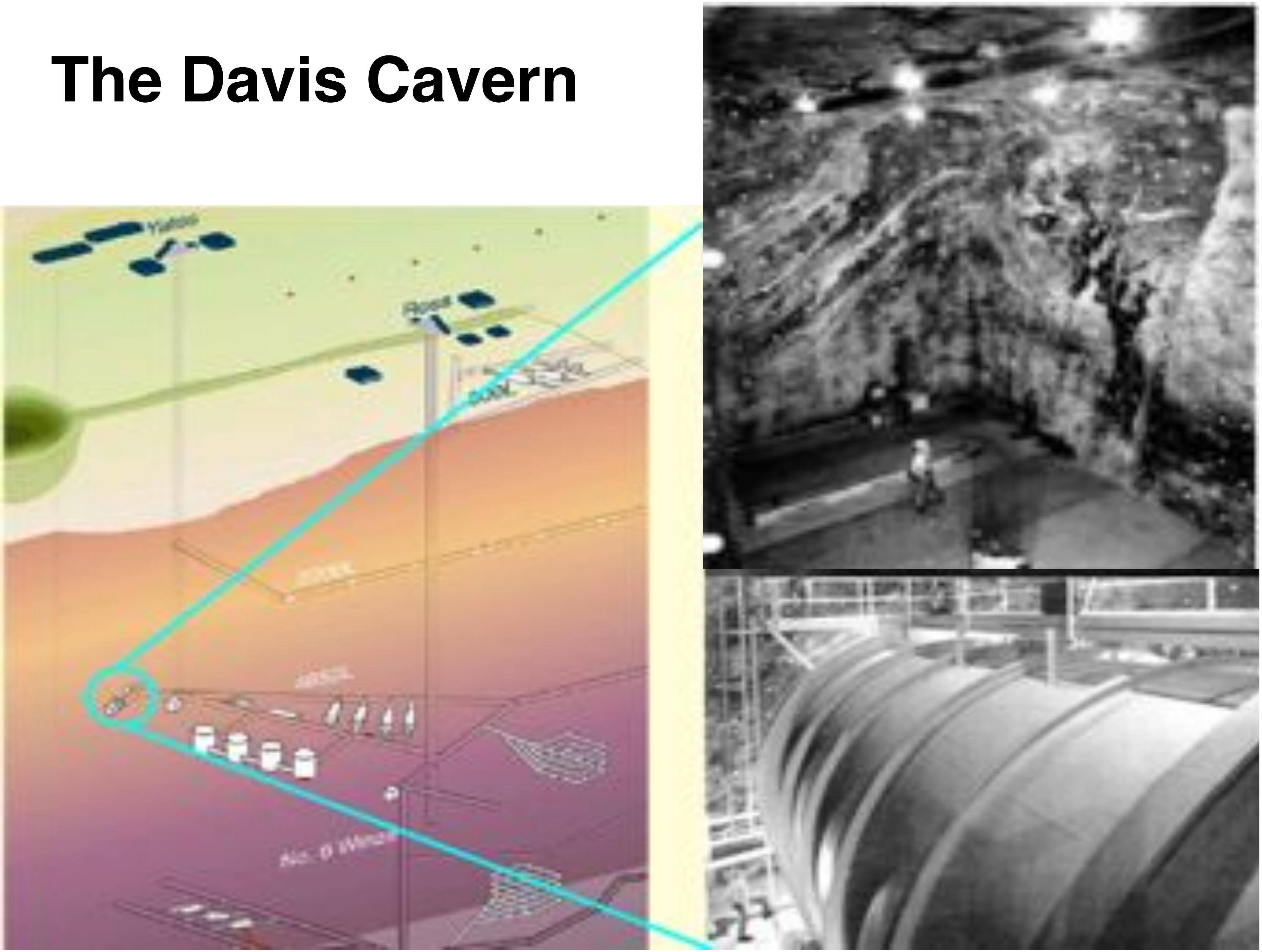
100 kg fiducial mass



LUX Internals Assembly


LUX
September 22
Texas A&M Internals Assembly
Photo by
C.H. Faham
(Brown)

The Davis Cavern



1964 / 2009 “They want to fill the cavern with what ?*?”

LUX

Sanford
Lab

$$L_{eff} = \frac{\text{scintillation per unit energy for nuclear recoils}}{\text{scintillation per unit energy for electron recoils}}$$

In practice, we define the denominator based on
122 keV photoabsorption events from Co-57

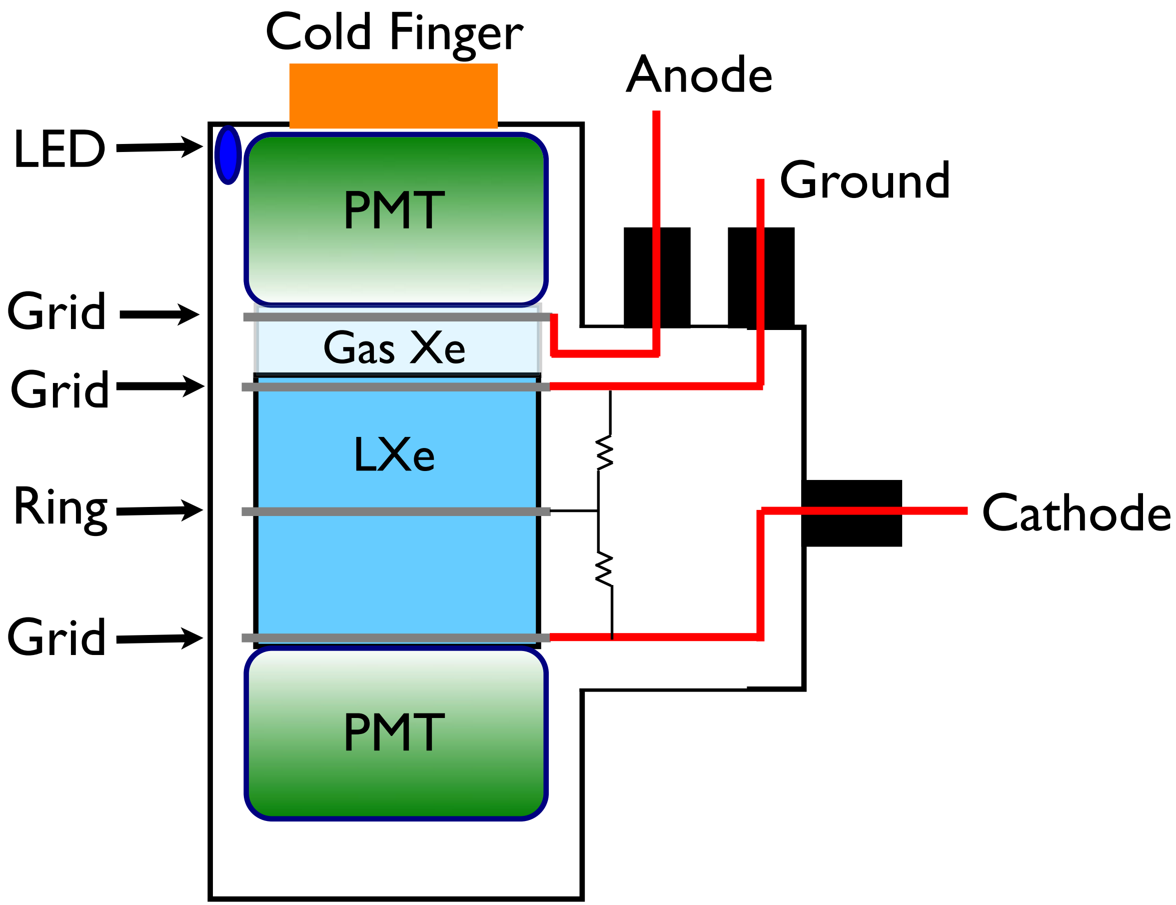
In the XENON10 analysis, we assumed an energy-independent Leff of 0.19
for the WIMP search analysis, and for determining our cross-section limits.

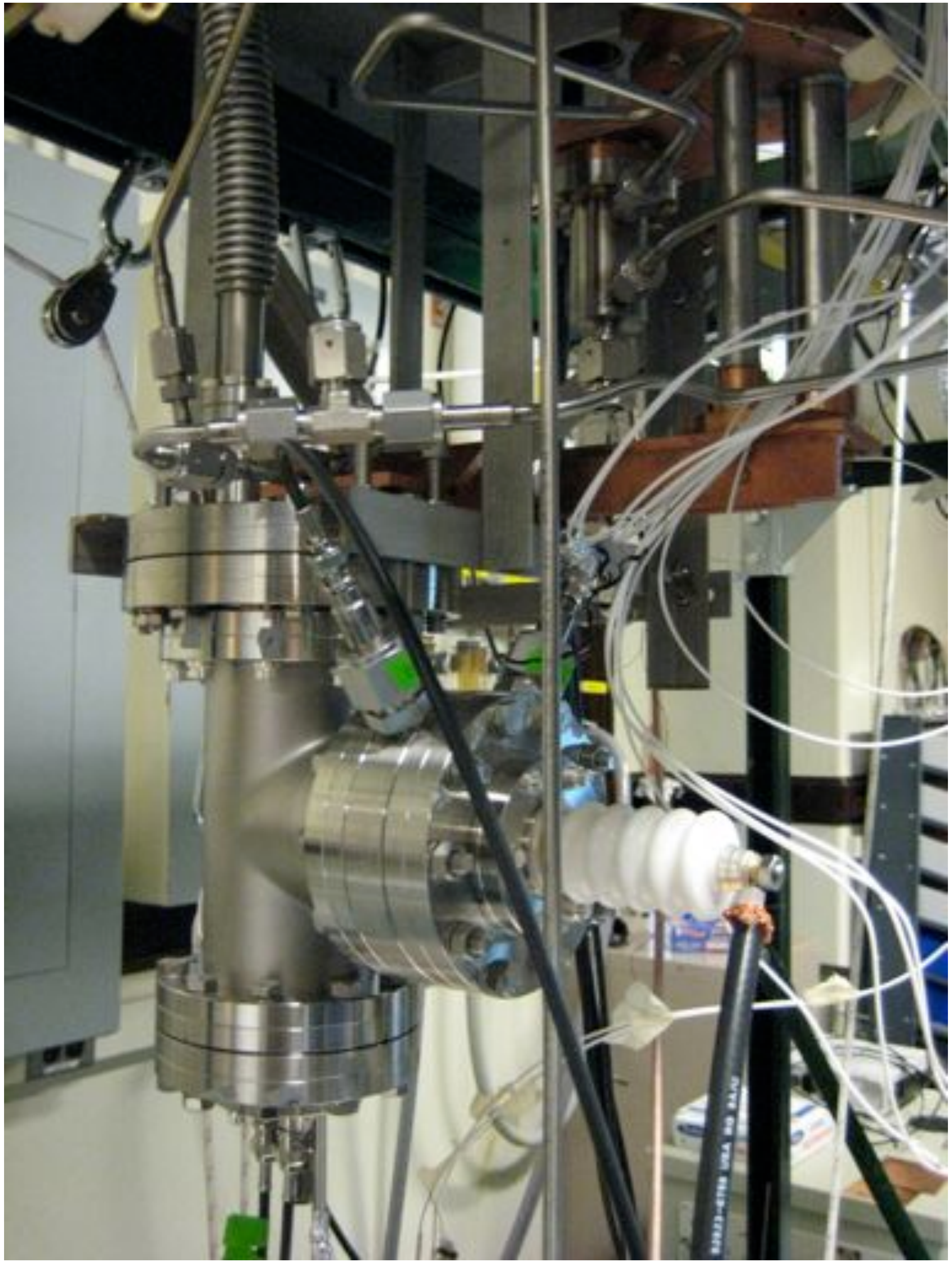
Uncertainty in Leff was the main source of systematic uncertainty
in determining the cross-section limits.

New measurement of Leff: A. Manzur et al., Phys. Rev. C 81, 025808 (2010).

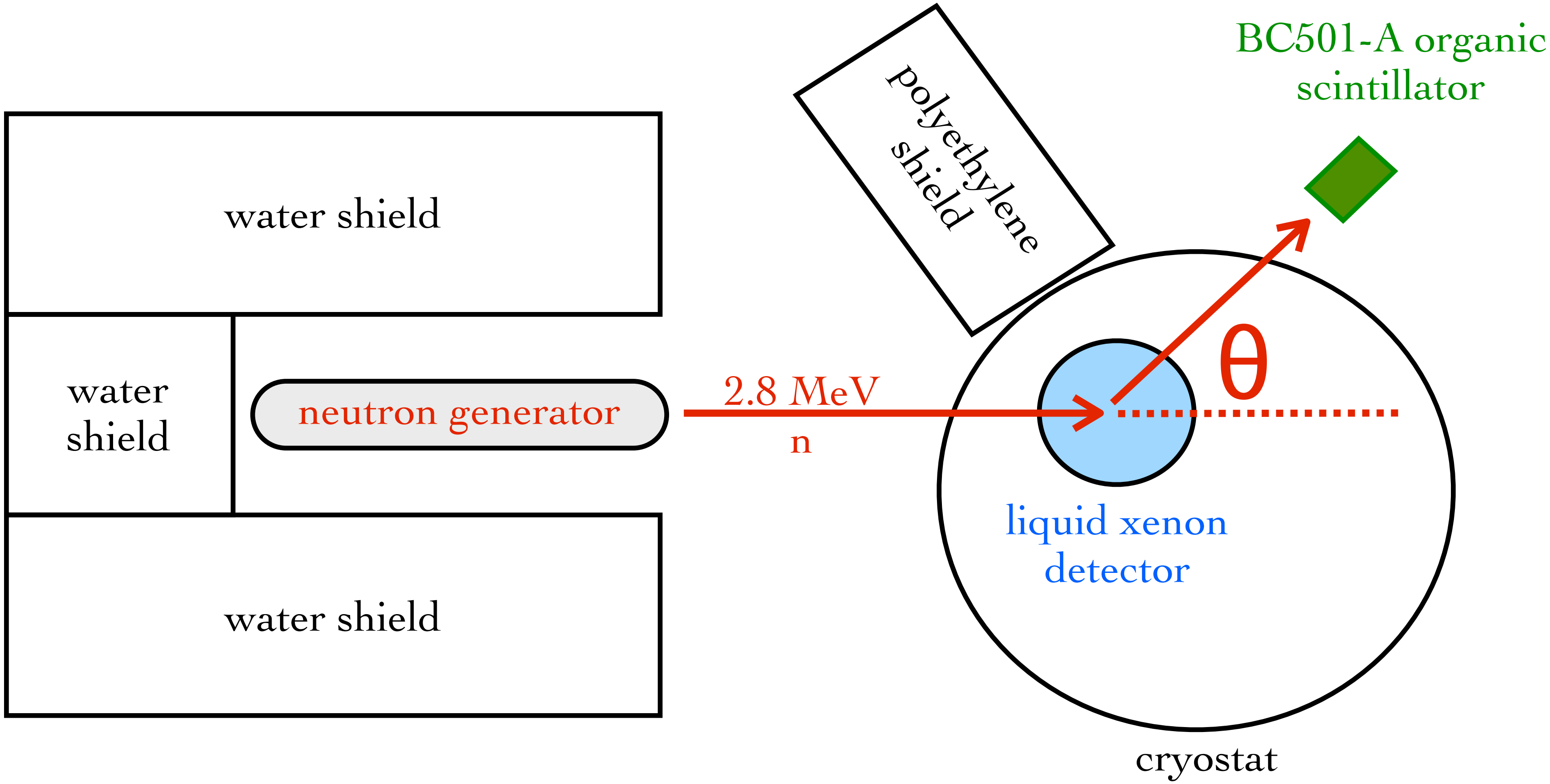
Two-phase LXe detector at Yale (MAXe)

Variable drift field (1-4 kV/cm)
Variable extraction & proportional scintillation field (6-10 kV/cm)
11 pe/keV at zero field
PMTs have ~35% quantum efficiency





Experimental setup

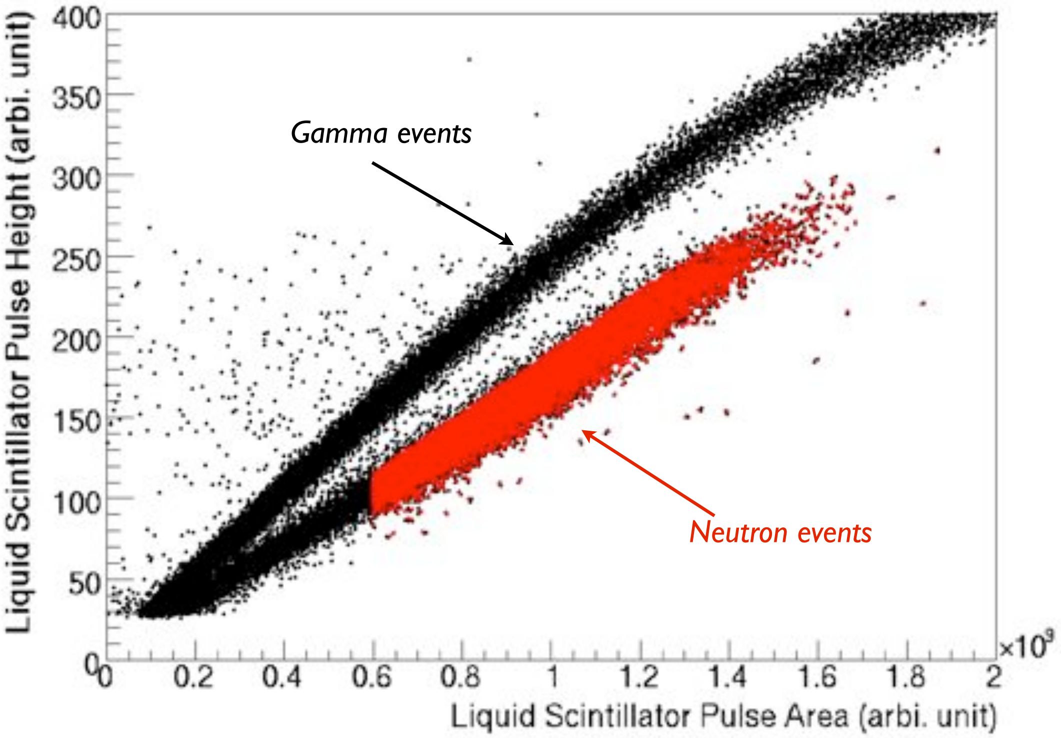


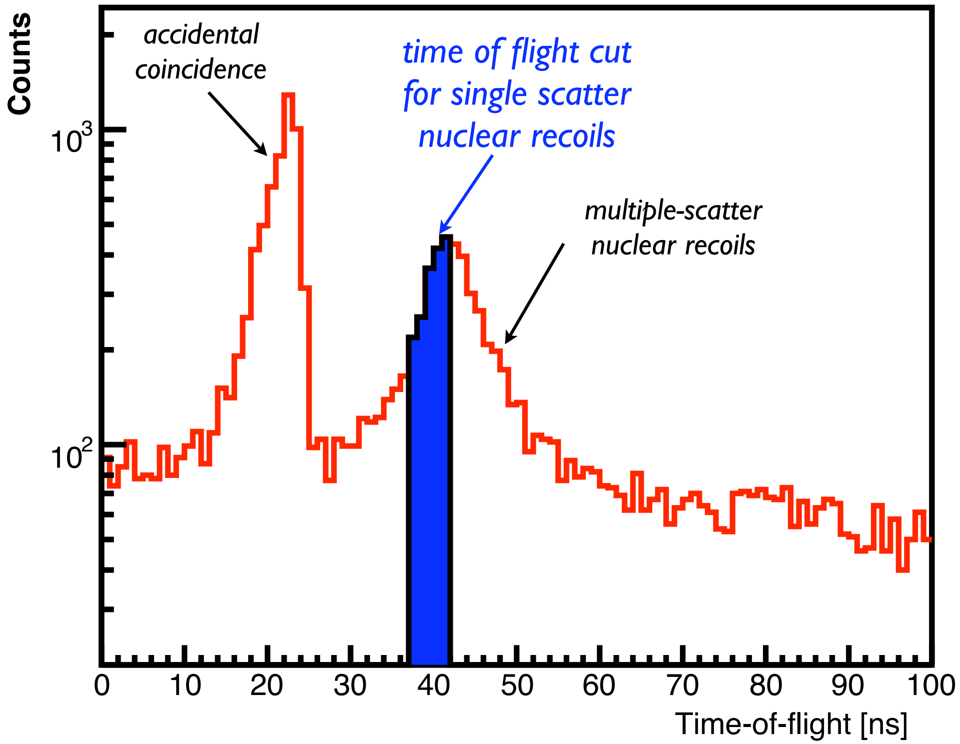
$$E_R = E_n \frac{2 m_n M_{Xe}}{(m_n + M_{Xe})^2} (1 - \cos\theta)$$

Energies: 4 - 66 keVr

Selecting single nuclear recoils

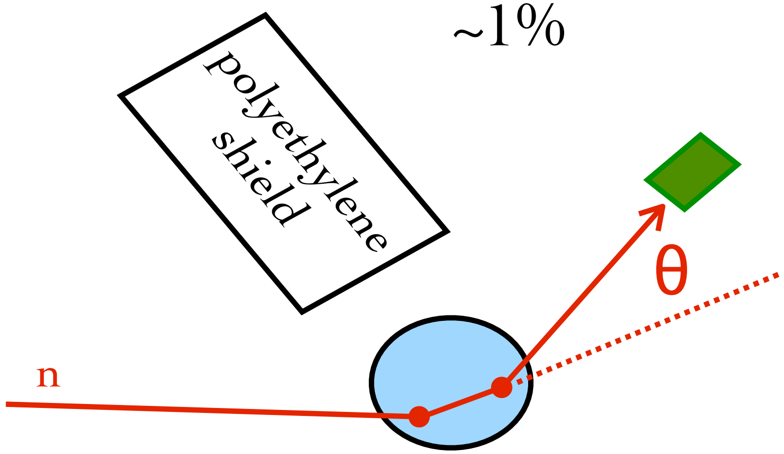
- Quality cuts Q0: remove noise event, high energy events, S1 asymmetry
- Select neutrons using PSD and time of flight (TOF)



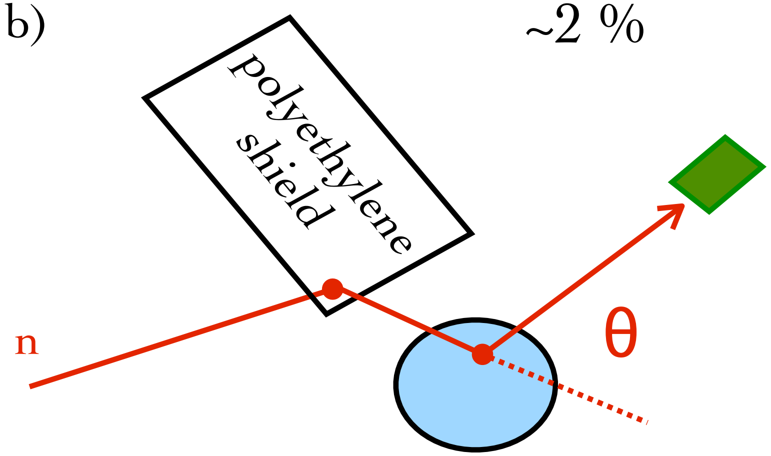


Systematic error

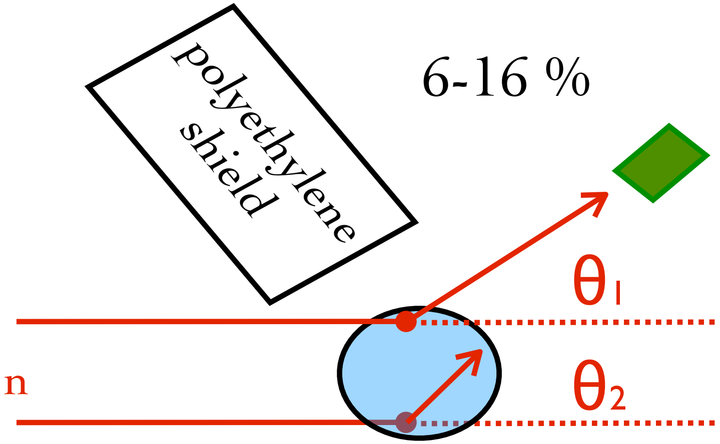
a)



b)



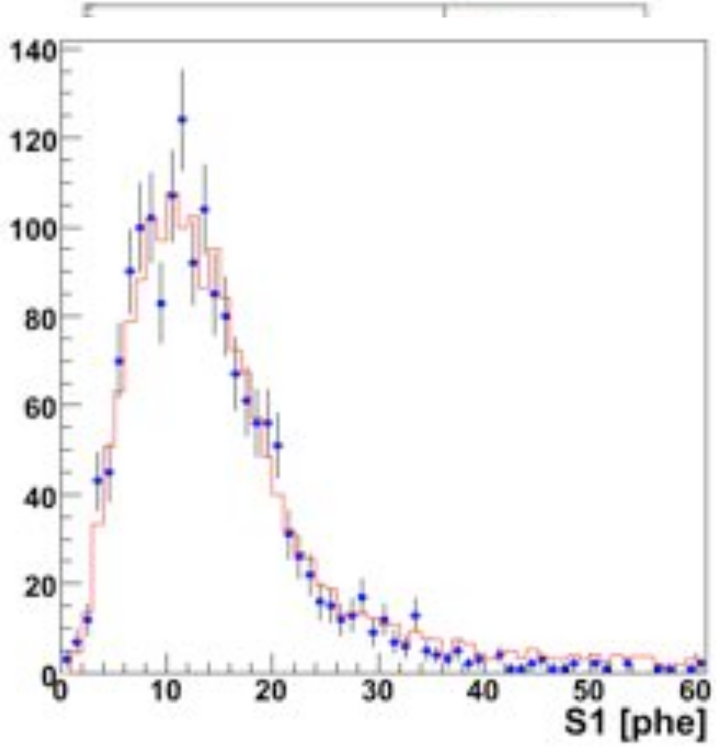
c)

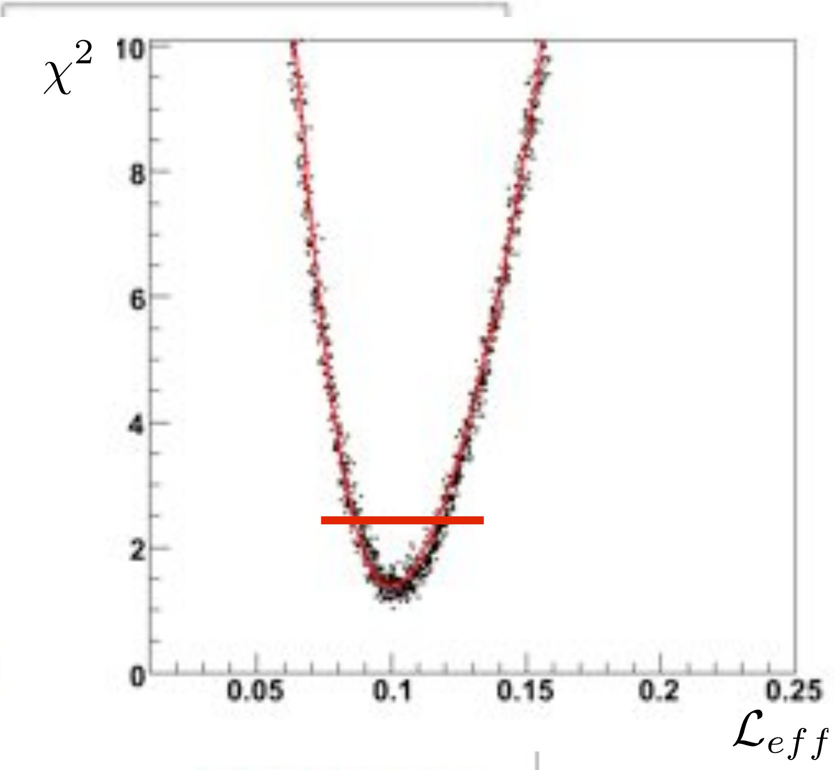


- a) Multiple elastic scatters
- b) Outside scatters
- c) Size and position
- d) Cross-section database ~2 - 4%

Comparing data & Monte Carlo

$E_R = 10 \text{ keV}_r$



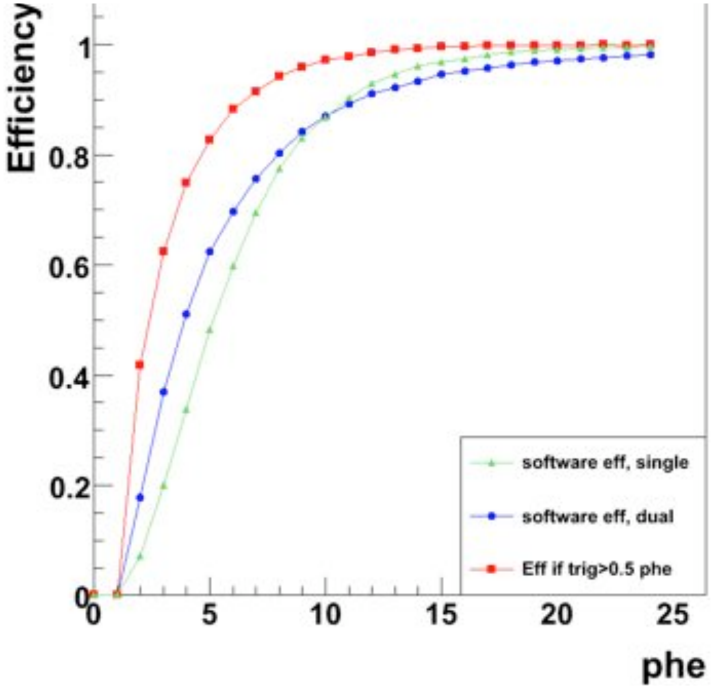


To compare MC & data:

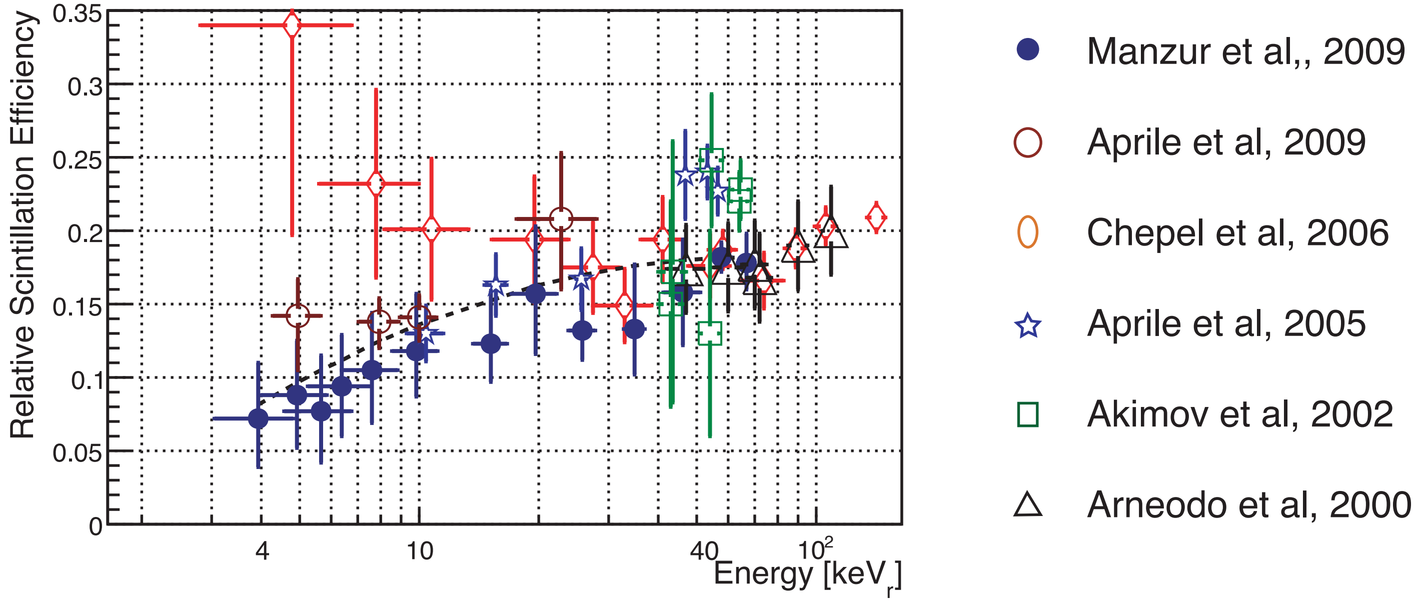
1 $E_R \rightarrow E_e$

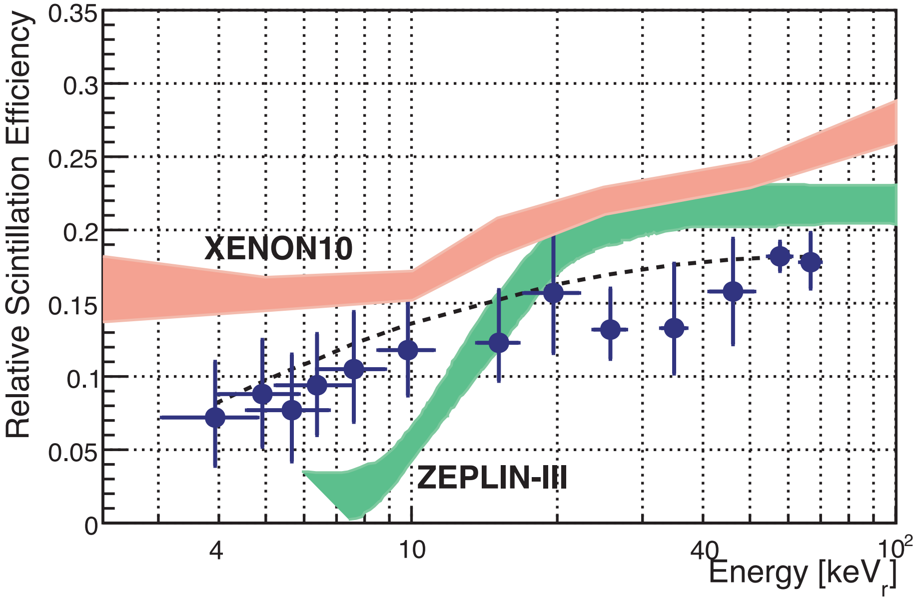
2 $\sigma = 3.2\sqrt{N_{phe}}$

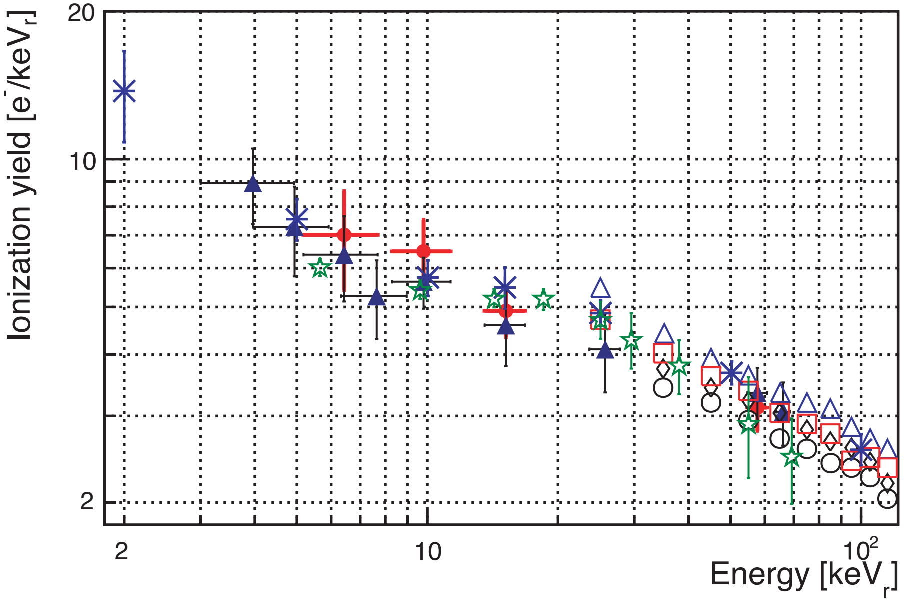
3 software + trigger efficiency



Leff results







$\mathcal{L}_{eff}$ model

$$\mathcal{L}_{eff} = q_{ncl} \times q_{el} \times q_{esc}$$

- q_{ncl} nuclear quenching (Lindhard factor), energy goes into heat.

- q_{el} electronic quenching. Bi-excitonic collisions

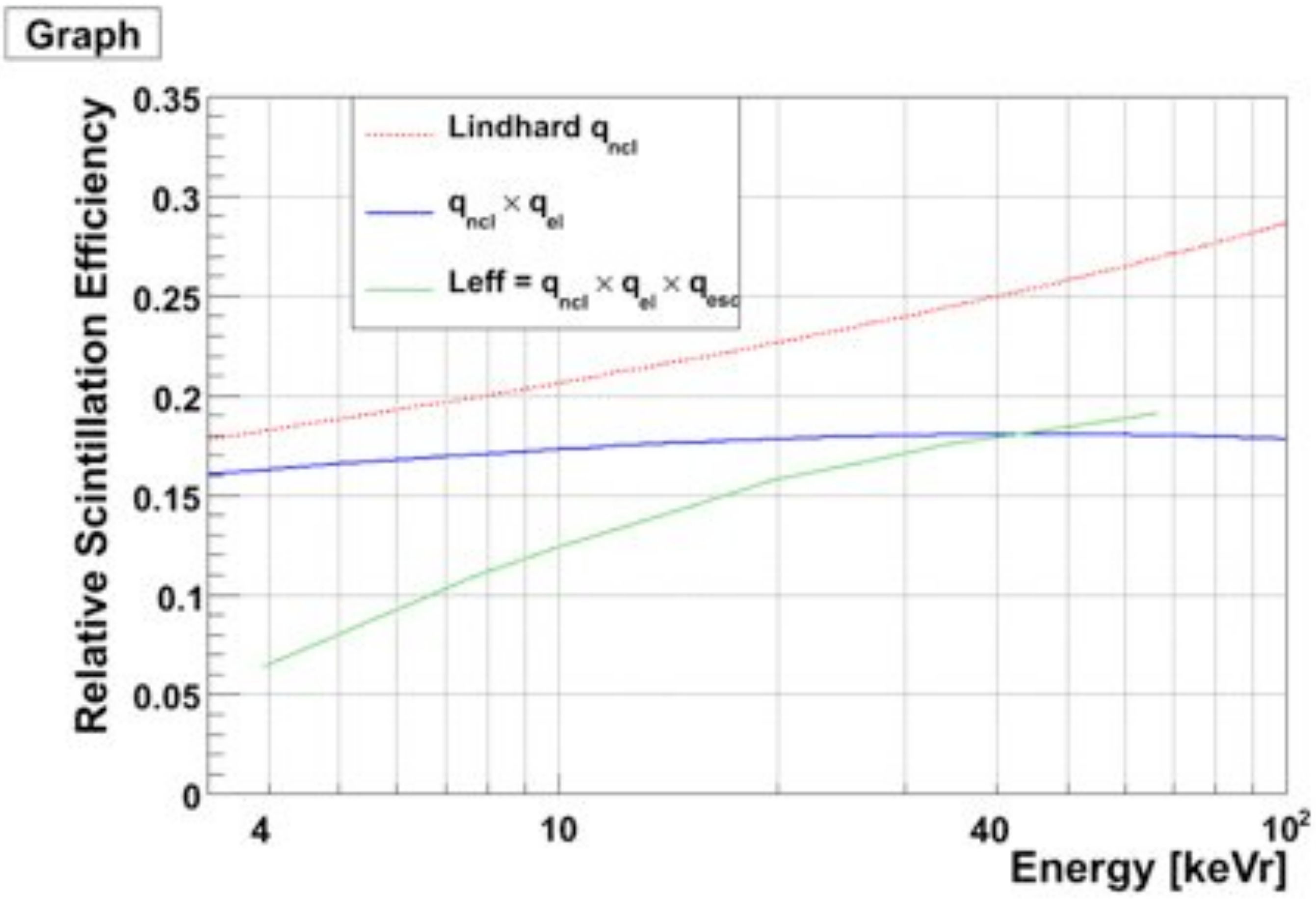
$$\mathrm{Xe}^* + \mathrm{Xe}^* \rightarrow \mathrm{Xe} + \mathrm{Xe}^+ + e^-$$

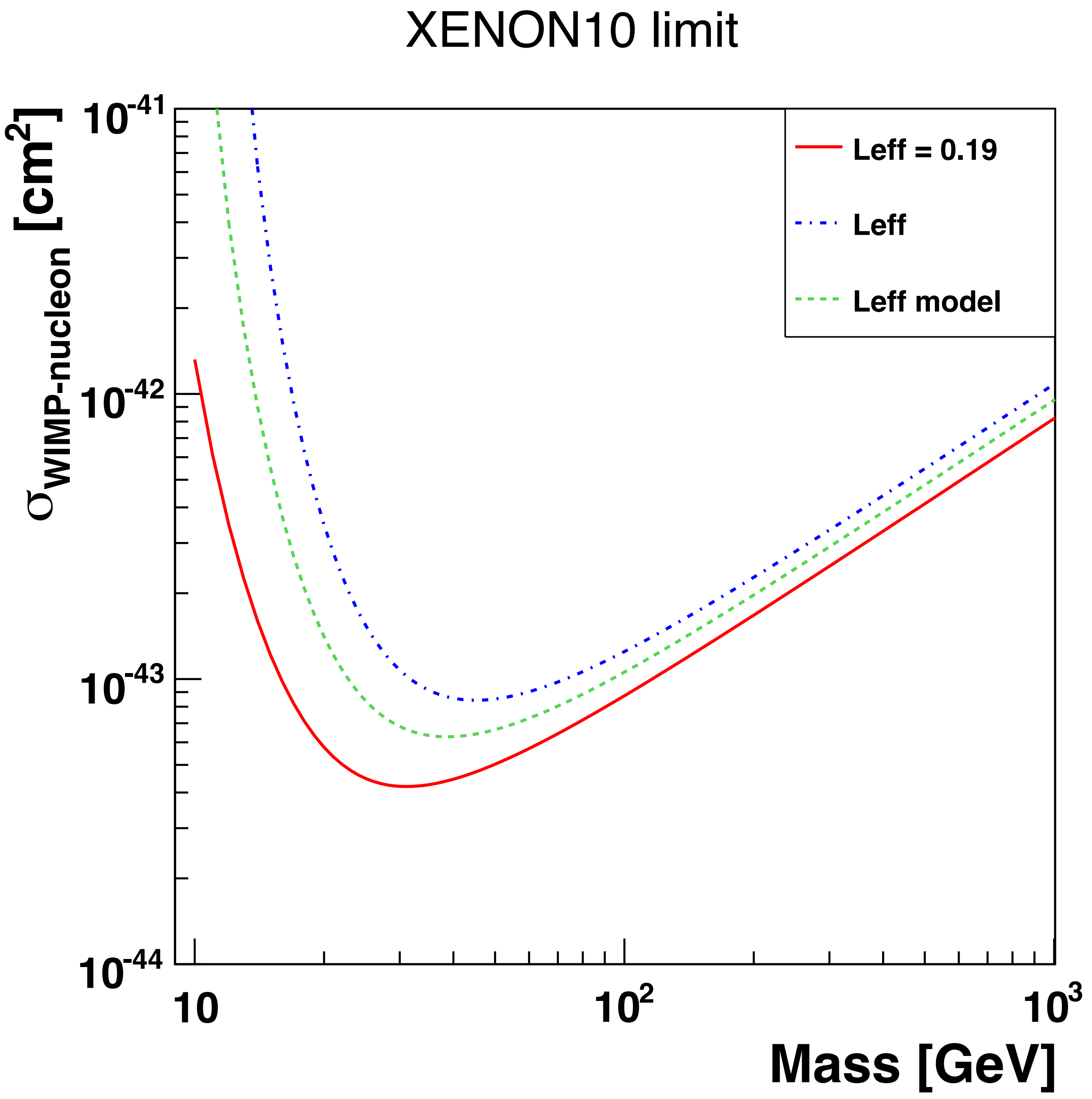
$$q_{el} = \frac{1}{1 + k\frac{dE}{dx}}$$

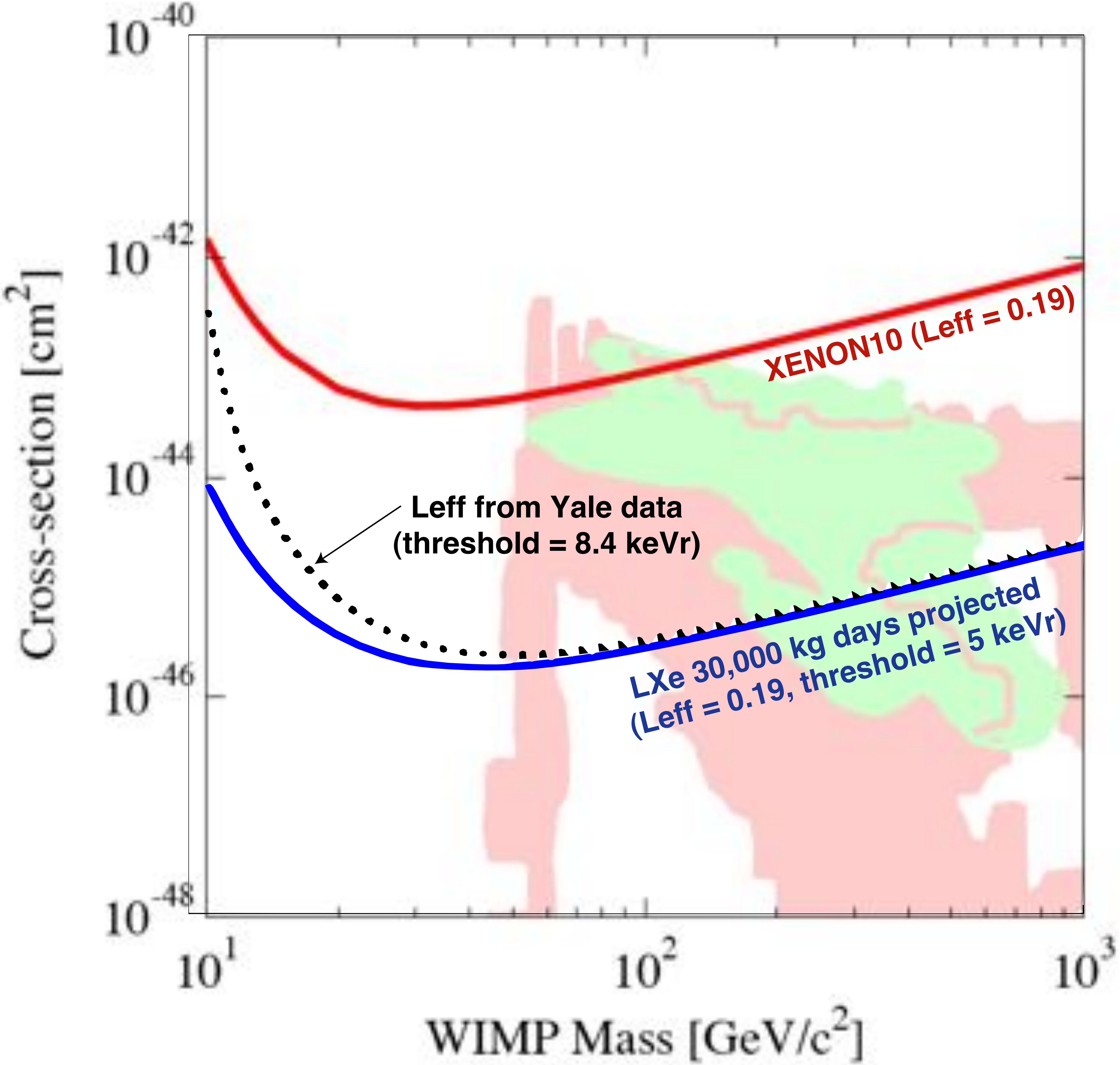
- Escape electrons

$$q_{esc} = \frac{N_{ex} + N_i - N_{esc}}{N_{ex}^{122} + N_i^{122} - N_{esc}^{122}} = \frac{\alpha + 1 - \beta}{\alpha + 1 - \beta^{122}}$$

$\mathcal{L}_{eff}$ model




XENON10 limit
Leff = 0.19
Leff
Leff model
$\sigma_{\mathrm{WIMP\text{-}nucleon}}$ [cm^2]
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10
10^2
10^3
Mass [GeV]

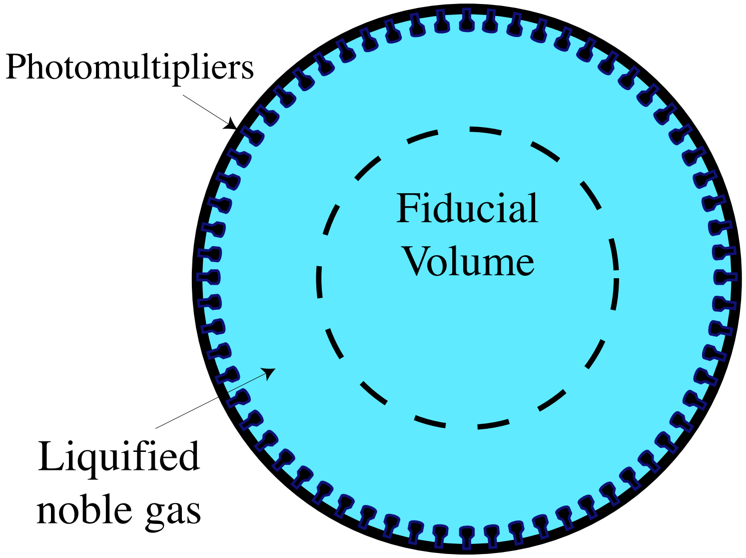

10^-40
10^-42
10^-44
10^-46
10^-48
Cross-section [cm^2]
10^1
10^2
10^3
WIMP Mass [GeV/c^2]
XENON10 (Leff = 0.19)
Leff from Yale data
(threshold = 8.4 keVr)
LXe 30,000 kg days projected
(Leff = 0.19, threshold = 5 keVr)

The Mini-CLEAN Approach

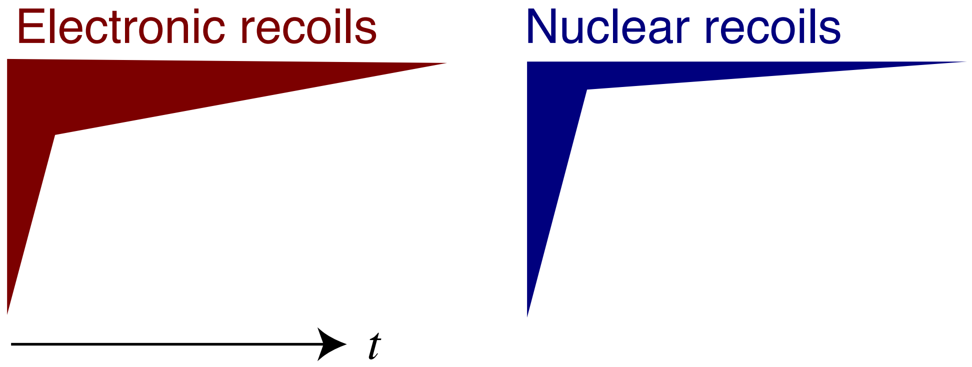
Scaleable technology based on detection of scintillation in liquified noble gases. No E field.
Ultraviolet scintillation light is converted to visible light with a wavelength-shifting film.

Liquid neon and liquid argon are bright scintillators (30,000 - 40,000 photons/MeV).
Do not absorb their own scintillation.
Are inexpensive (Ar: \$2k/ton, Ne: \$60k/ton).
Are easily purified underground.
Exhibit effective pulse shape discrimination.
Exchange of targets allows direct testing of A^2 dependence of WIMP scattering rate

Self-shielding



Pulse-shape discrimination



Fast component: < 10 ns
Slow component: 1.6 μs (LAr), 15 μs (LNe)
Discriminate based on fraction of light in first 100 ns (Fprompt)

D. N. McKinsey and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000).
D. N. McKinsey and K. J. Coakley, Astropart. Phys. 22, 355 (2005).
M. Boulay, J. Lidgard, and A. Hime, nucl-ex/0410025
M. Boulay and A. Hime, Astropart. Phys. 25, 179 (2006).

Why single-phase?

Ar-39 background (1 Bq/kg in natural argon) drives design.

Pile-up is a significant issue for two-phase, because of the high Ar-39 rate and the ~ms drift time for a tonne-scale instrument. In a blind analysis, how to match up S1 and S2 signals to achieve good S2/S1 discrimination and position resolution? Depleted Ar therefore needed in two-phase.

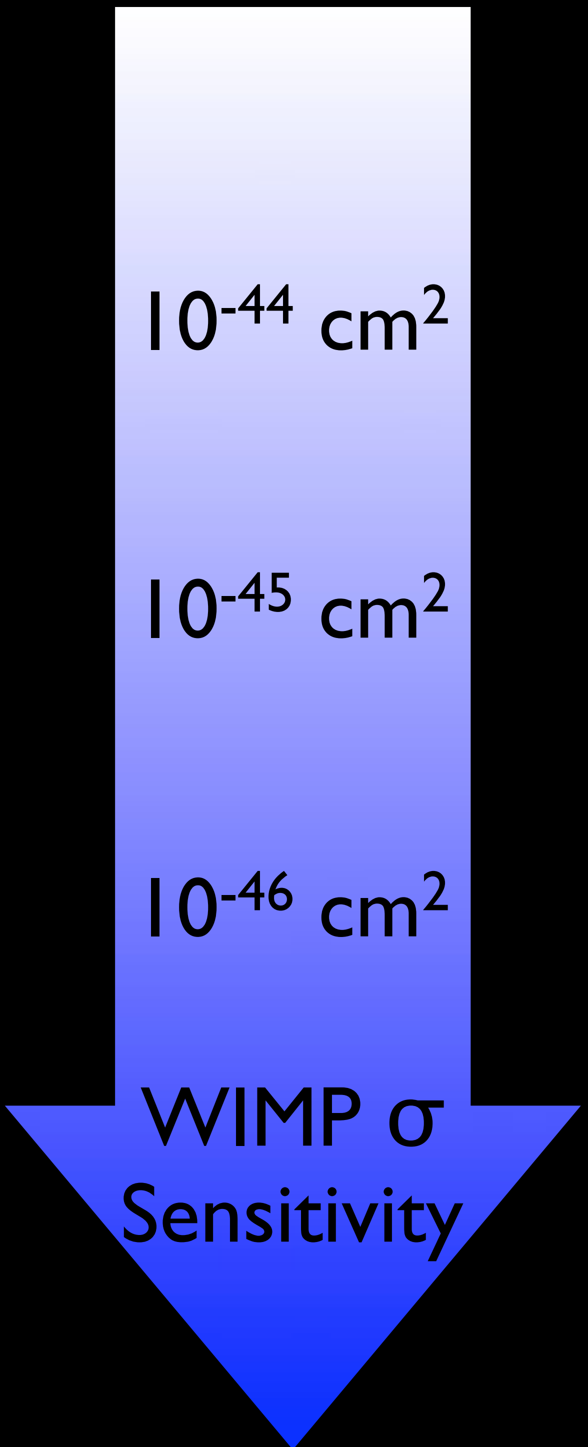
In single-phase, event lifetime is set by triplet molecule lifetime of 1.5 μs, allowing detectors with tens of tons of inexpensive readily available natural argon (CLEAN). Depleted argon not needed in single-phase.

Pulse-shape discrimination is the most effective means of rejecting Ar-39 beta-decay background in LAr. At a given energy threshold, PSD efficiency depends exponentially on scintillation signal yield.

In microCLEAN, we see 6 photoelectrons/keVee (see James Nikkel's talk). Based on MicroCLEAN data and detailed optical Monte Carlo data, we project 6-7 photoelectrons/keVee in MiniCLEAN. This will allow superb Ar-39 background rejection at a reasonable energy threshold (~50 keVr)

No need for very high cathode voltages - simplifies design.

The DEAP and CLEAN Family of Detectors



10^{-44} cm^2

10^{-45} cm^2

10^{-46} cm^2

WIMP σ Sensitivity

DEAP-0:

Initial R&D detector

DEAP-1:

7 kg LAr
2 warm PMTs
At SNOLab 2008

DEAP-3600:

3600 kg LAr (1000 kg fiducial mass)
266 cold PMTs
At SNOLAB 2011

picoCLEAN:

Initial R&D detector

microCLEAN:

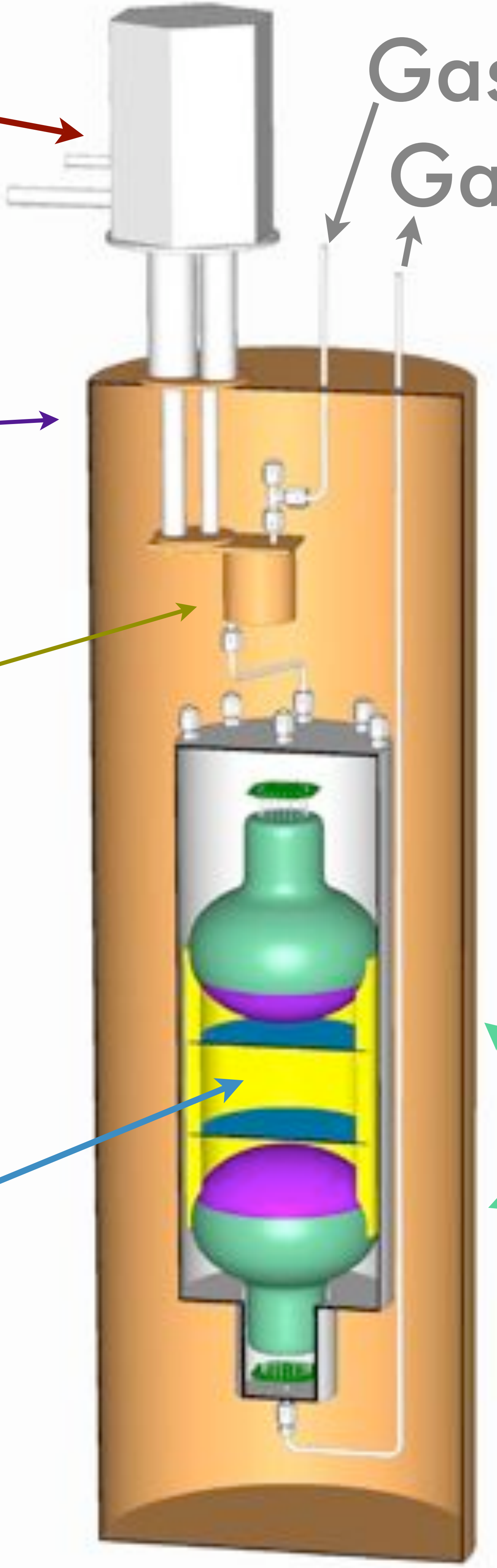
4 kg LAr or LNe
2 cold PMTs
surface tests at Yale

MiniCLEAN:

500 kg LAr or LNe (150 kg fiducial mass)
91 cold PMTs
At SNOLAB mid-2010

50-tonne LNe/LAr Detector:

pp-solar ν, supernova ν, dark matter <10^{-46} cm^2
At DUSEL ~2015?



PT805 Pulse
Tube
Refrigerator

Gas in

Gas out

Heat Shield
on
1st Stage

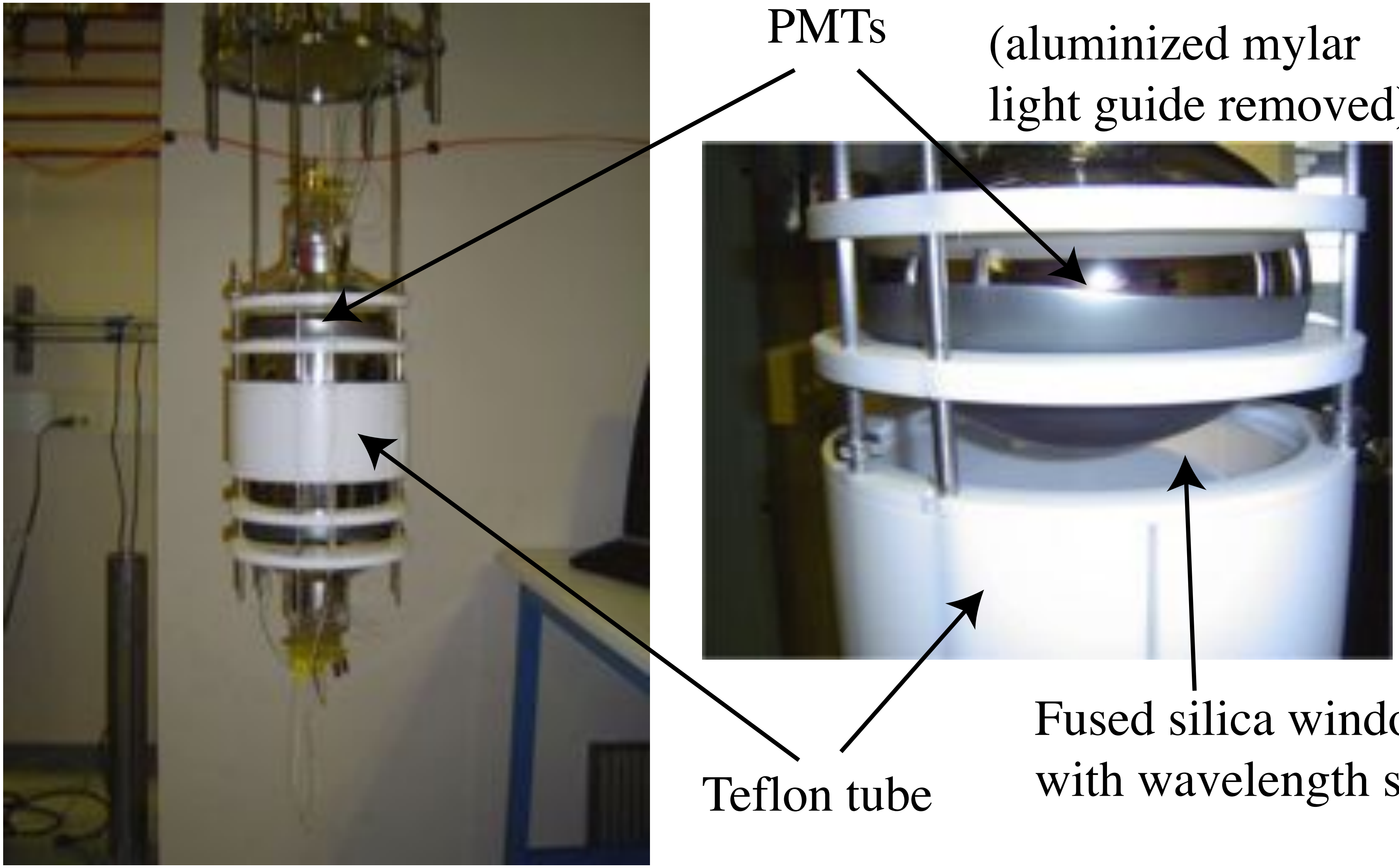
Liquefier
on
2nd Stage

Start with ultra-high purity gas, run through a getter before introducing to central volume. Circulate at ∼2 l/min through getter.

Central volume:
20 cm diameter
10 cm high
3.1 litres

Hamamatsu
R5912-02-MOD
20 cm
PMTs

Close-up shots of micro-CLEAN



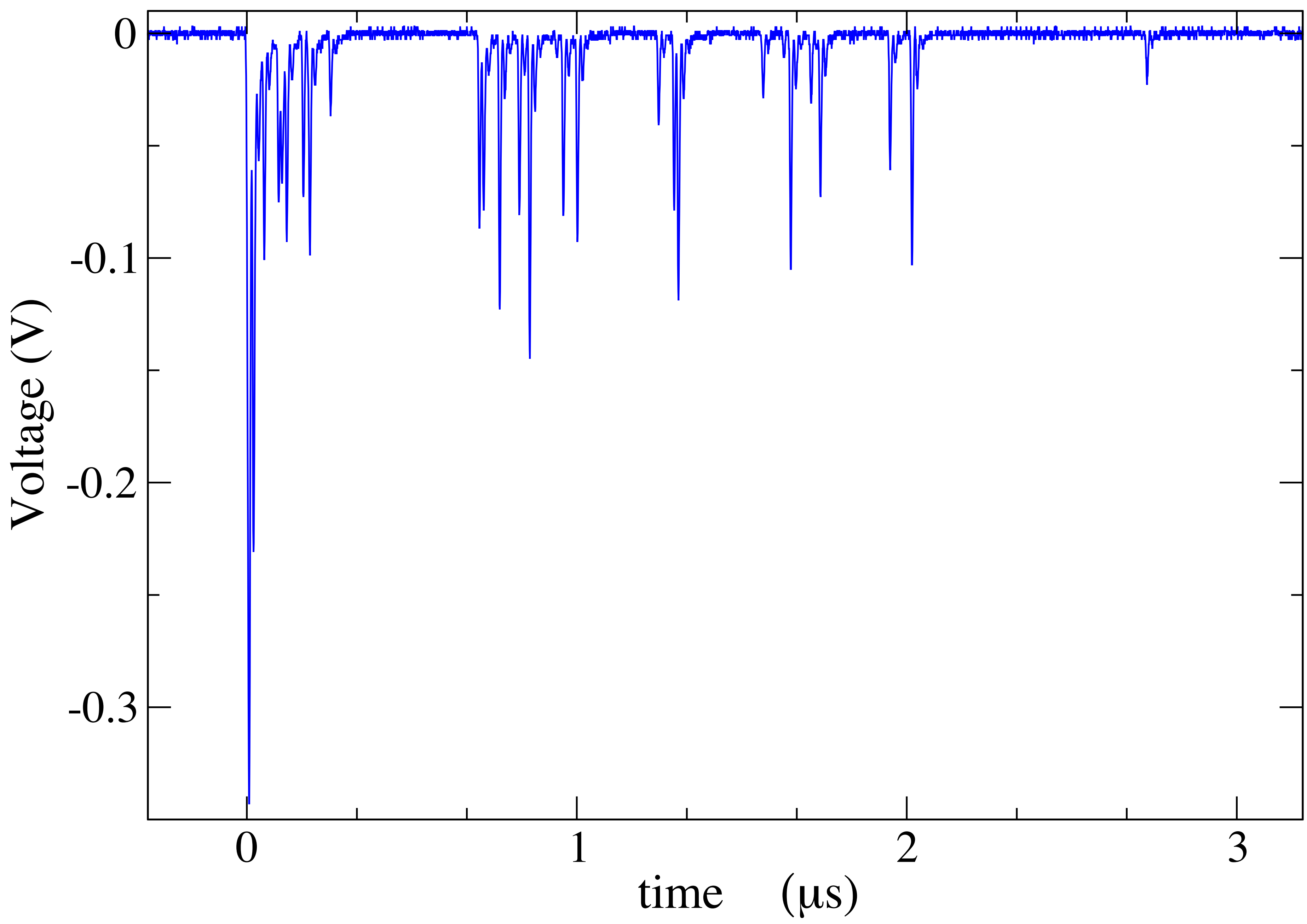
PMTs

(aluminized mylar light guide removed)

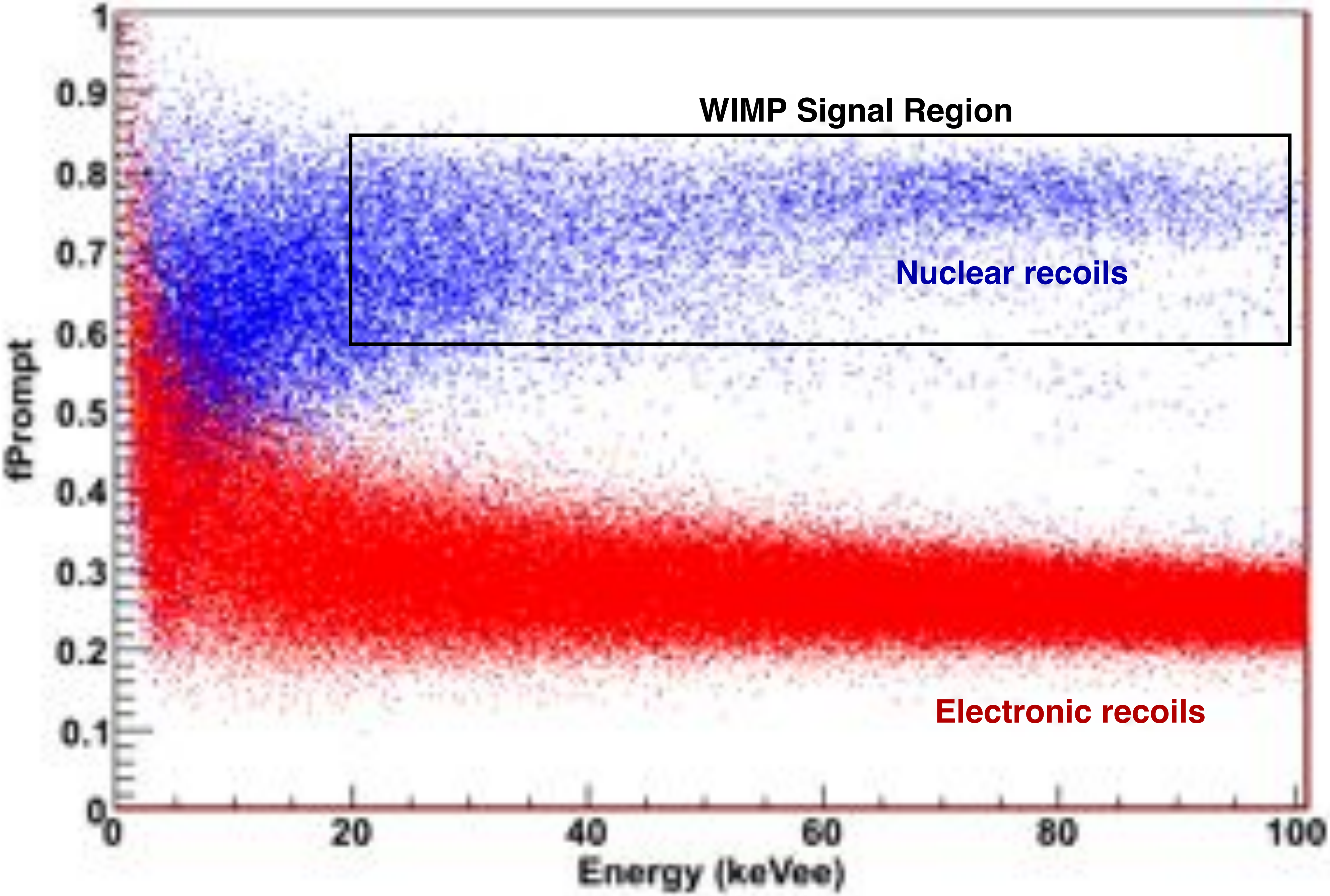
Teflon tube

Fused silica window with wavelength shifter

Sample scintillation pulse (gamma Compton scatter in LAr)

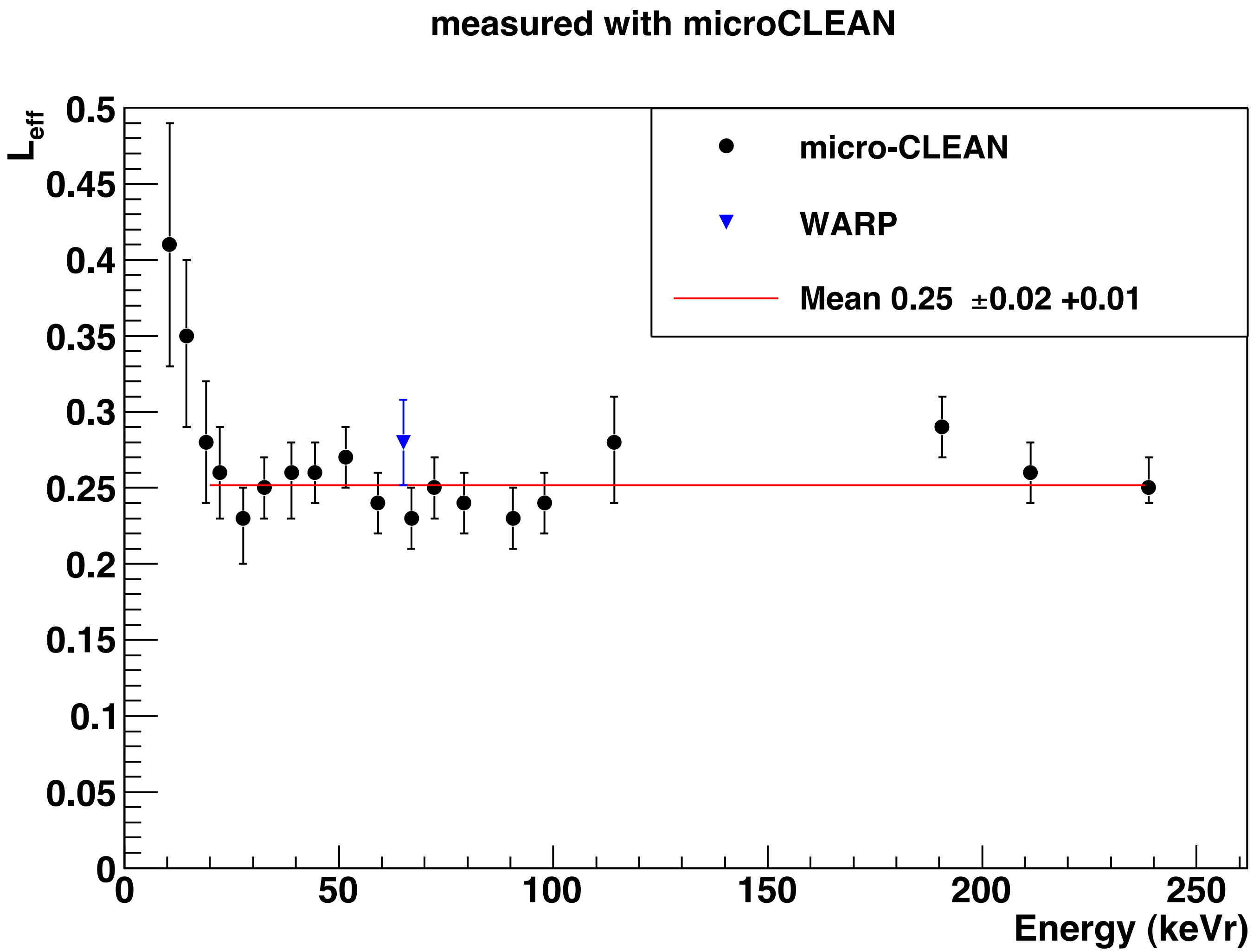


We measure an electron recoil contamination of 7.6 x 10^{-7} above 52 keVr



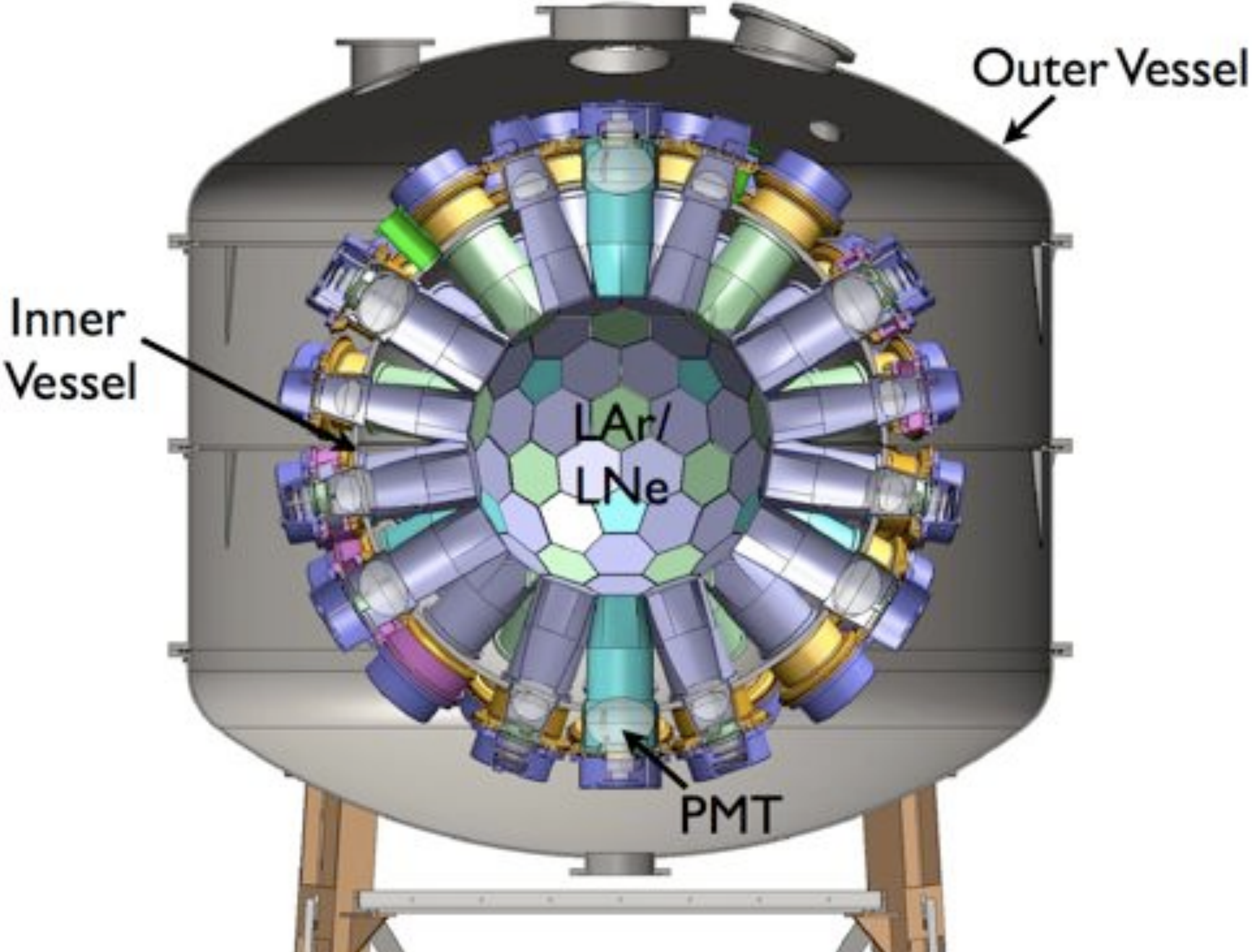
Lippincott et al., Phys. Rev. C 78, 035801 (2008).

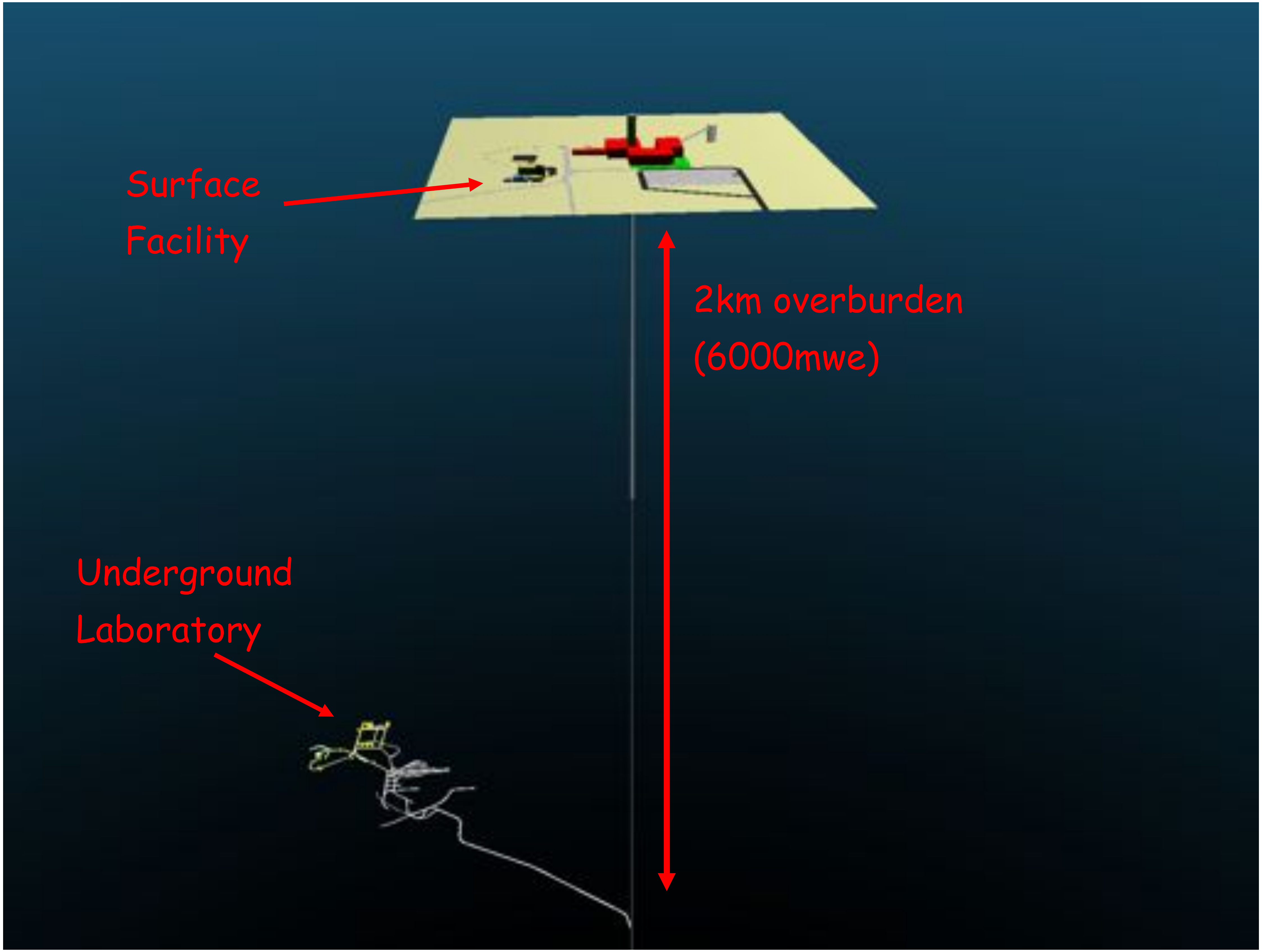
Nuclear Recoil Scintillation Yield in LAr



D. Gastler et al, arXiv:1004.0373

MiniCLEAN detector




Surface
Facility
2km overburden
(6000mwe)
Underground
Laboratory

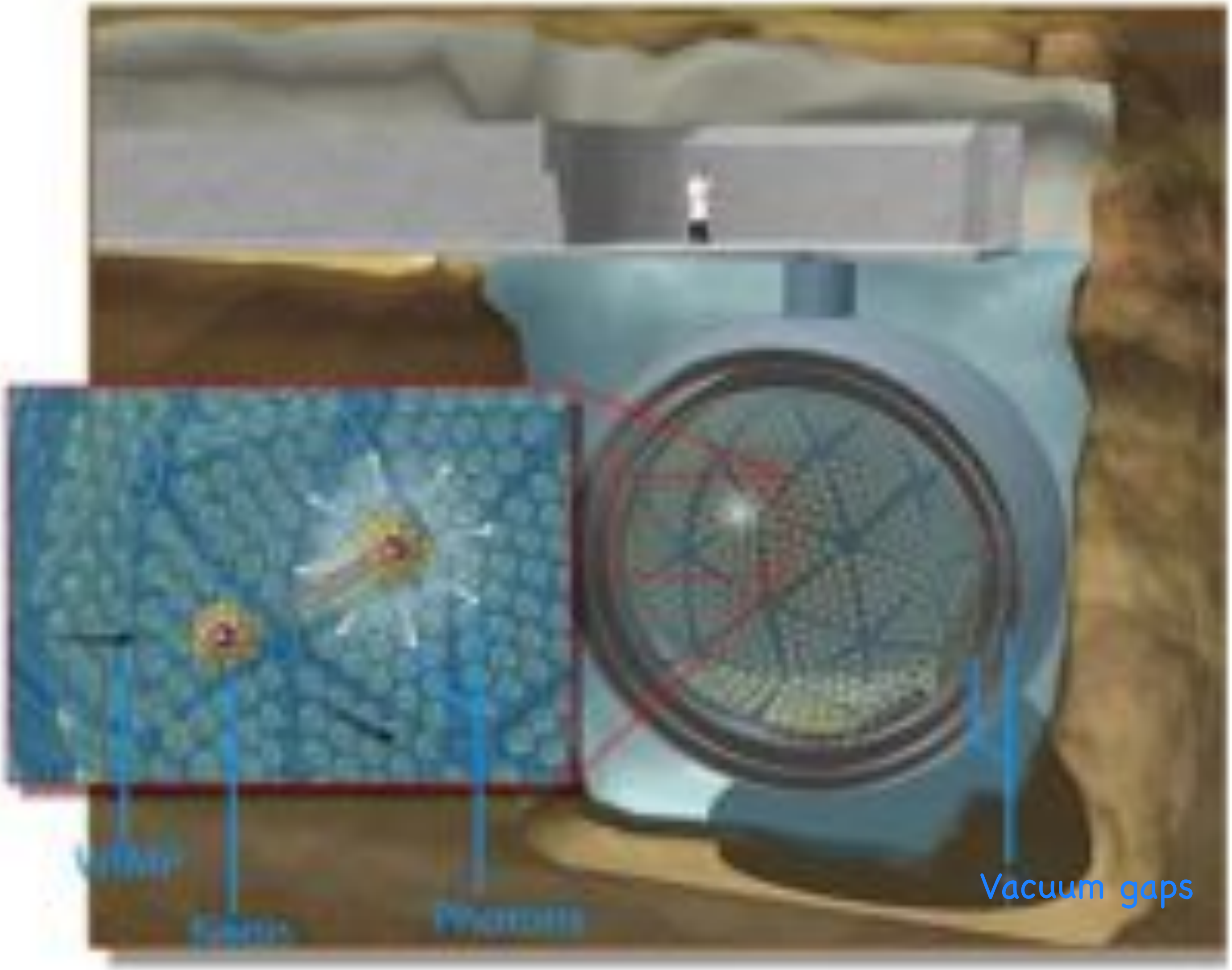
SNOLAB


2009-12-17 11:53:46

Inner Vessel Progress

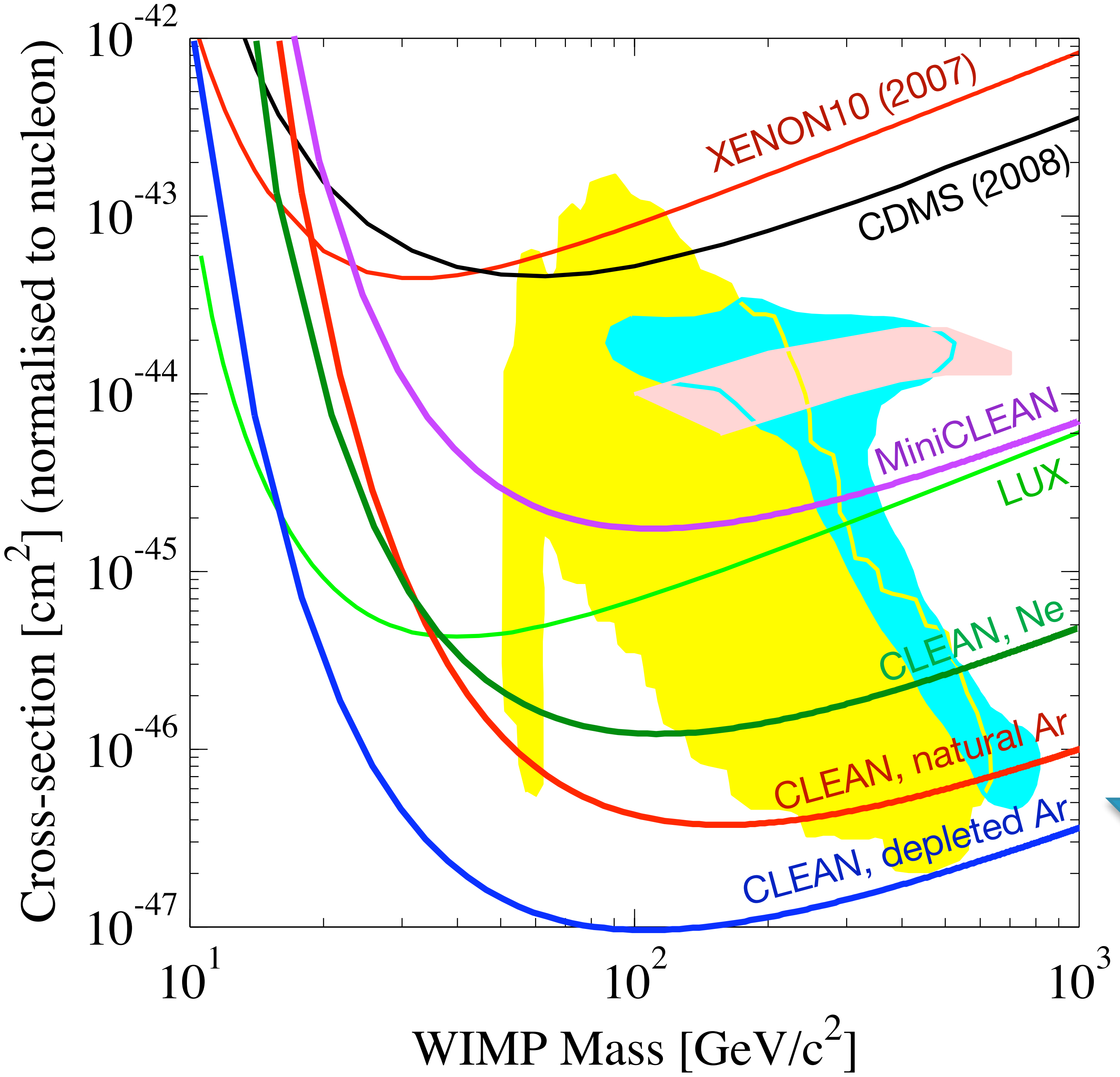
- Stainless steel hemispheres made by Trinity Heads, Inc in Texas
- Will go for machining next

50 ton CLEAN detector, filled with LAr, then LNe



Science: WIMP dark matter, pp neutrinos, supernova neutrinos

Sensitivity



Events / 10 kg / yr

Events / 100 kg / yr

Events / 1000 kg / yr

CLEAN Projected Sensitivity to Light DM

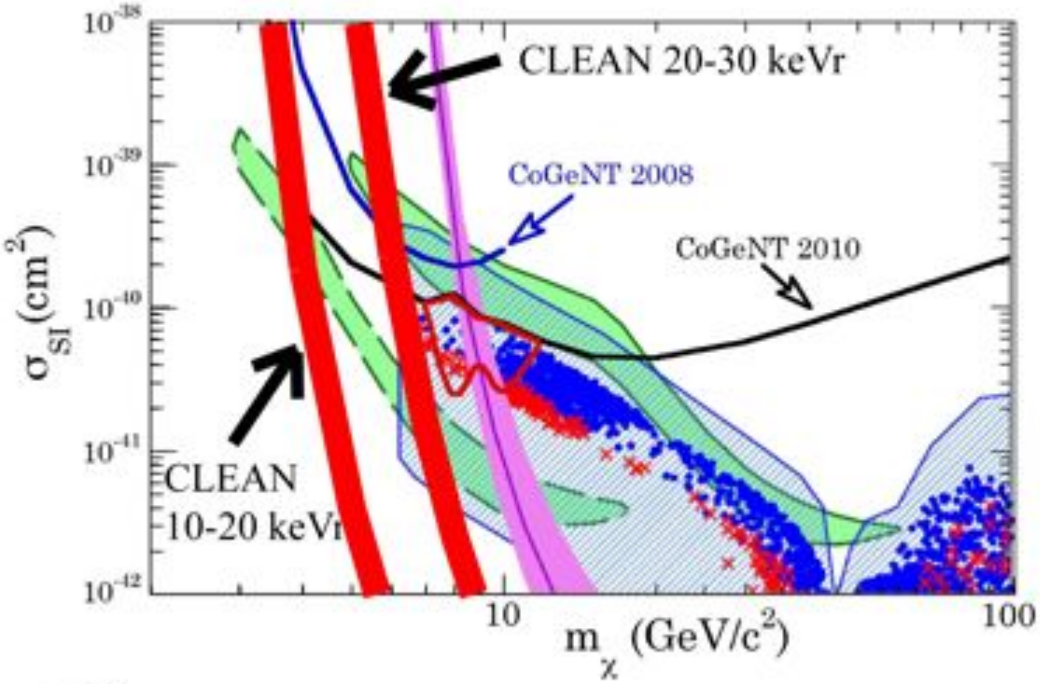
Strategy: Don't use pulse shape discrimination, just accept electron recoil events as background.

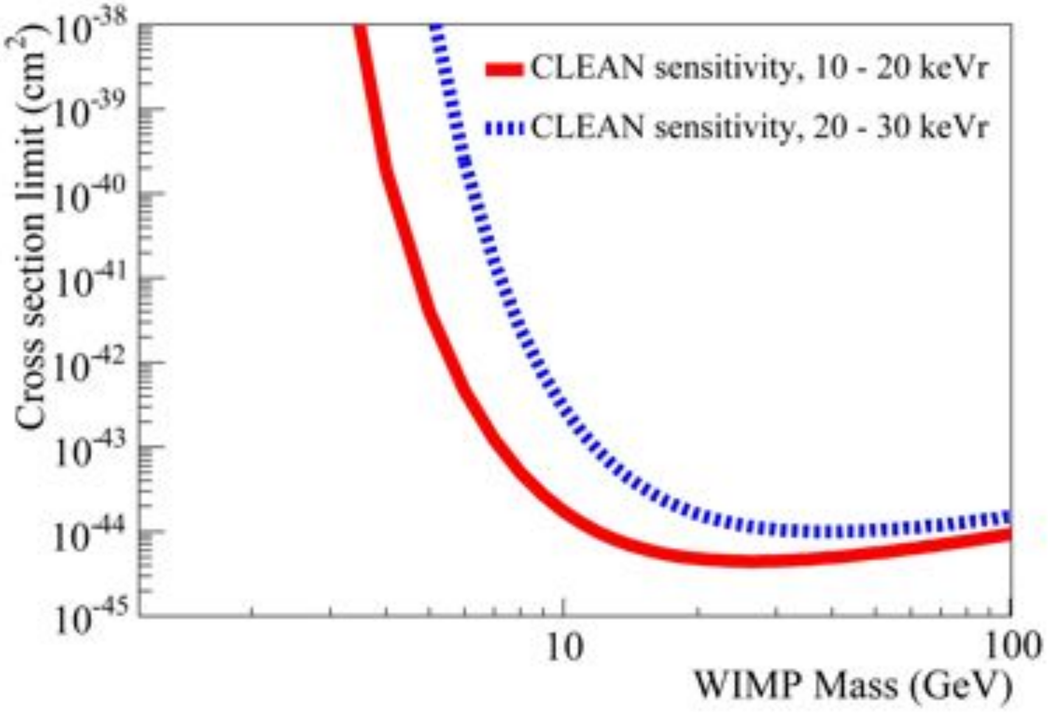
This allows a lower energy threshold.

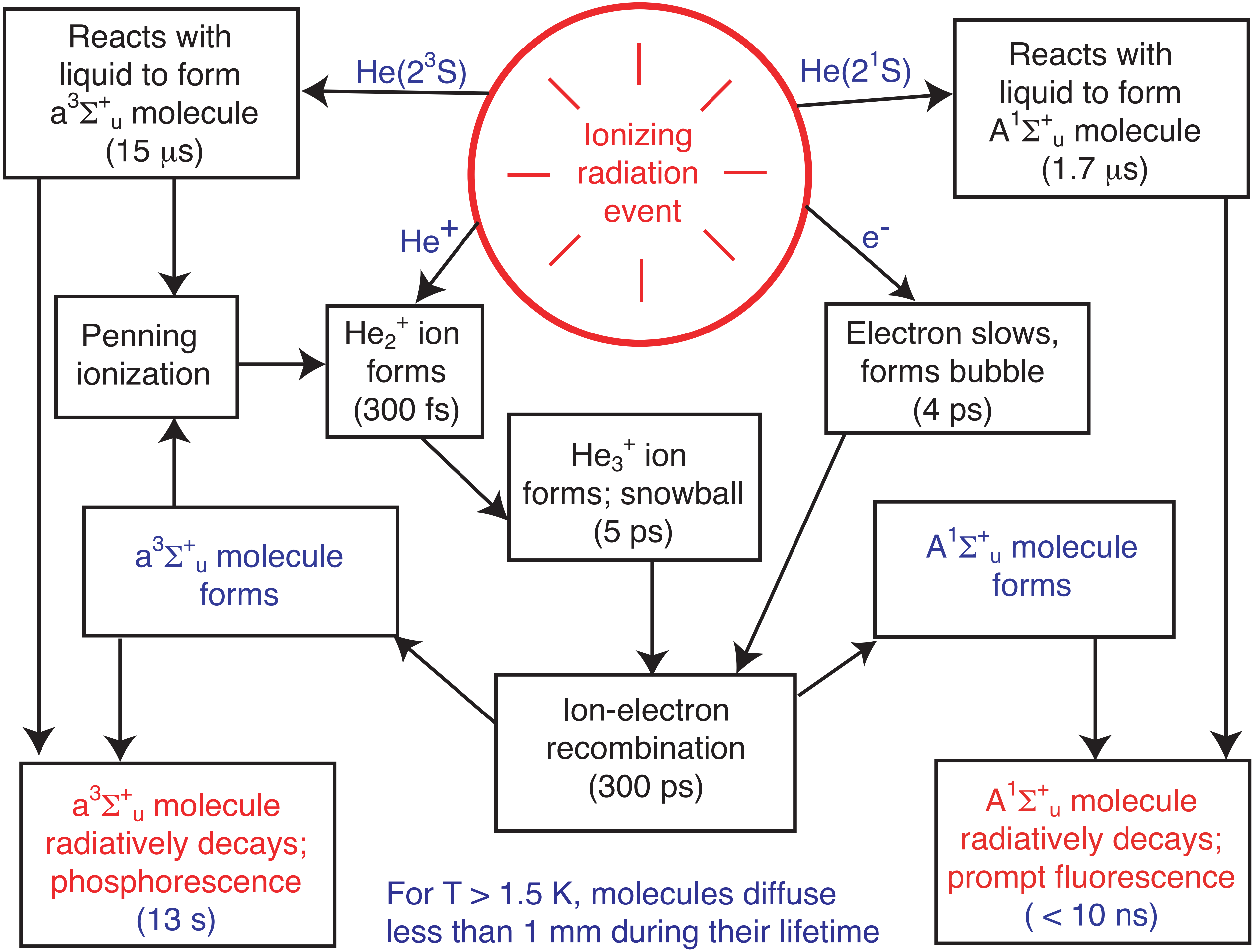
Main background is pp solar neutrino scattering from electrons in the fiducial volume.

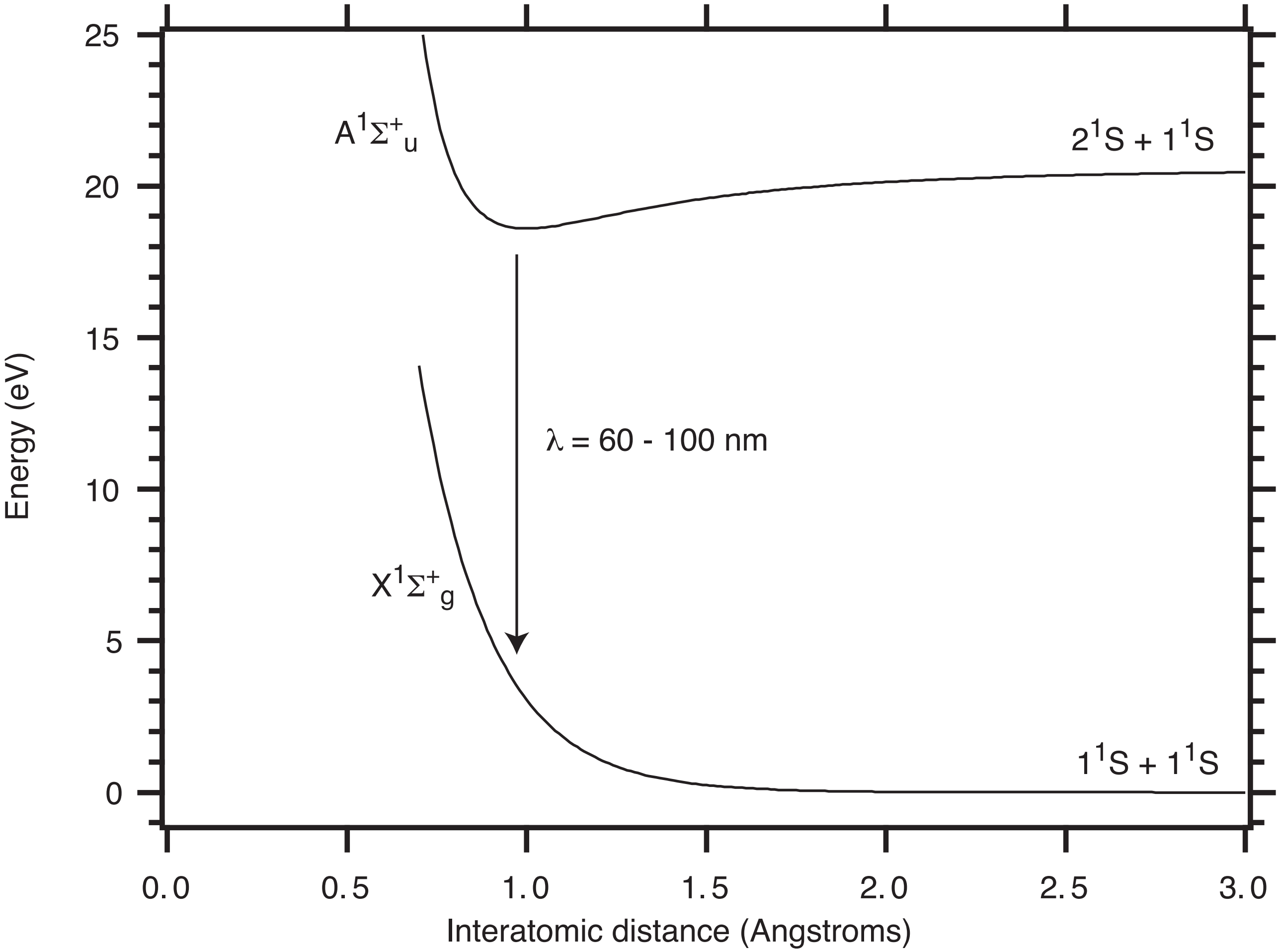
Energy threshold limited by need to eliminate gamma ray backgrounds through self-shielding, position resolution.

Analysis does not yet take into account improvements in position resolution based on PMT timing information.






Ionizing radiation event
He(2^{3}S)
He(2^{1}S)
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)
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)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Interatomic distance (Angstroms)
$A^1\Sigma^+_u$
$2^1S + 1^1S$
λ = 60 - 100 nm
$X^1\Sigma^+_g$
$1^1S + 1^1S$

PHYSICAL REVIEW A VOLUME 59, NUMBER 1 JANUARY 1999

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

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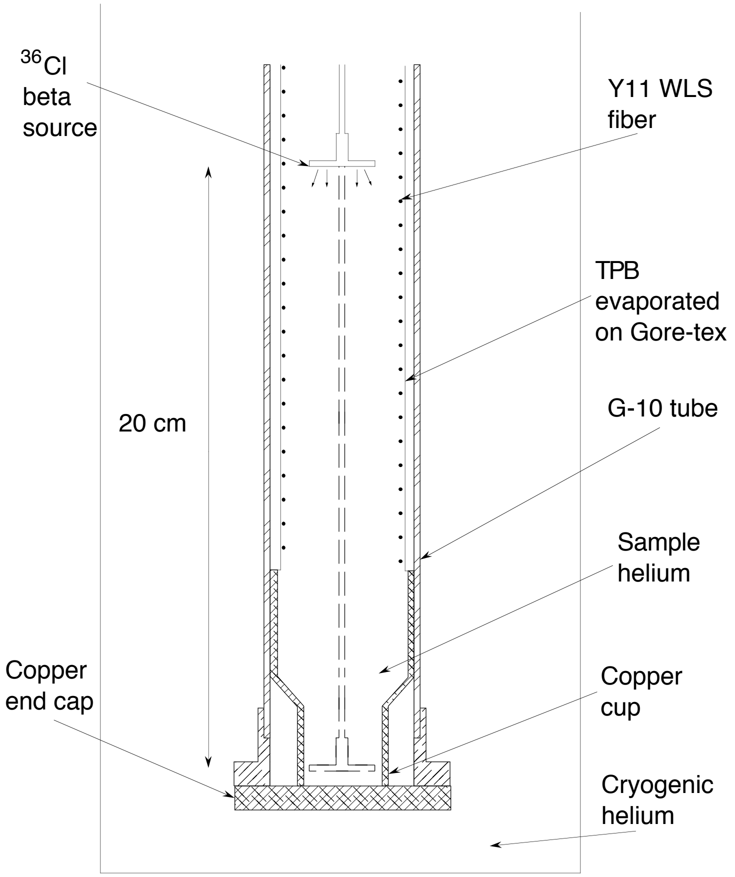
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

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

(Received 27 July 1998)



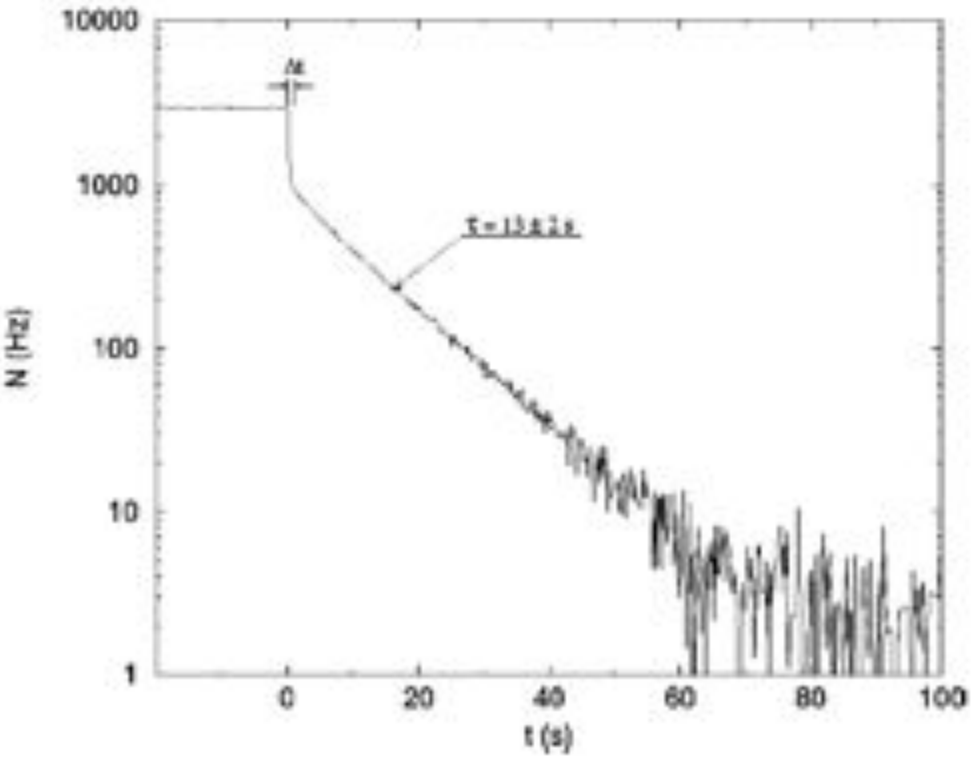
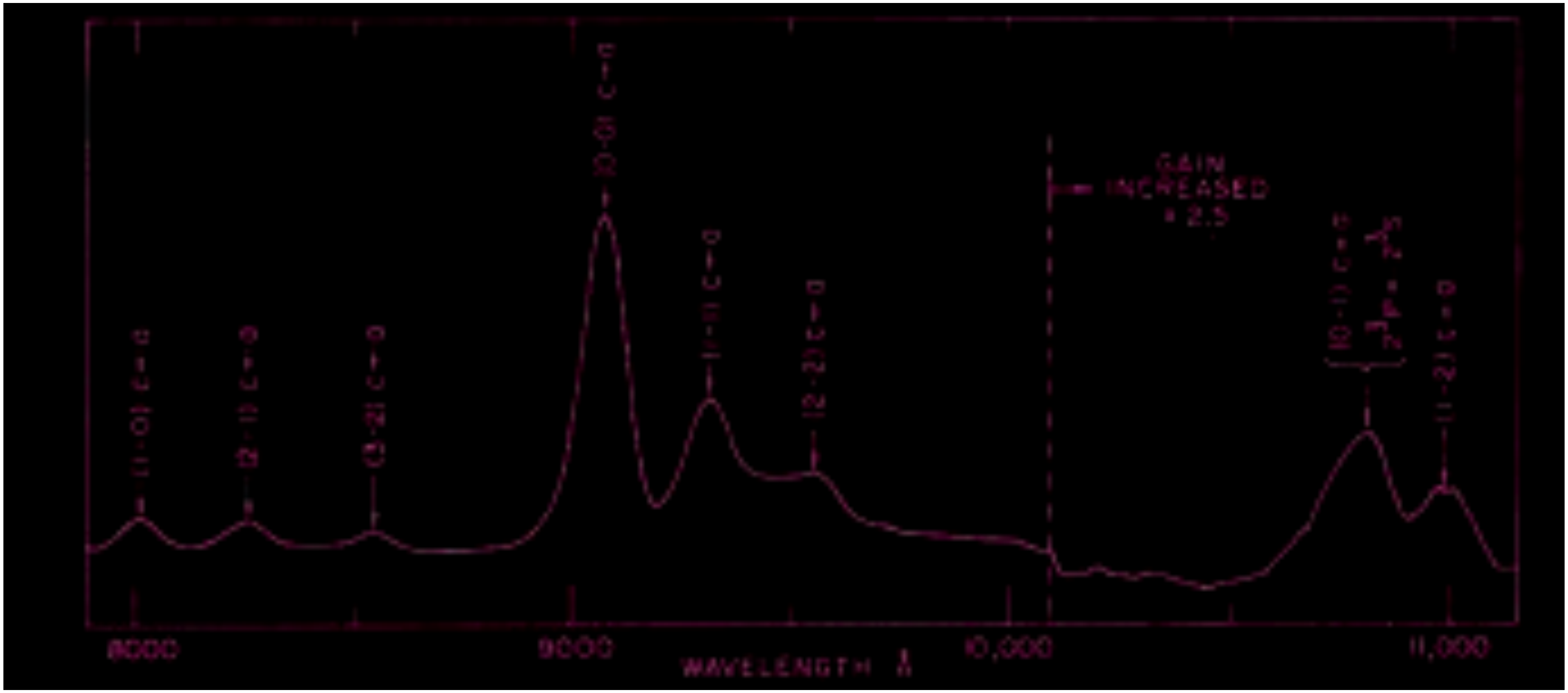


FIG. 2. Count rate N of detected $He_2(a\,^3\Sigma_u^+)$ decays versus time. A ^{36}Cl β source is placed in the center of the detection region and then removed in a time $\Delta t < 1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate τ of 13 ± 2 s.

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).

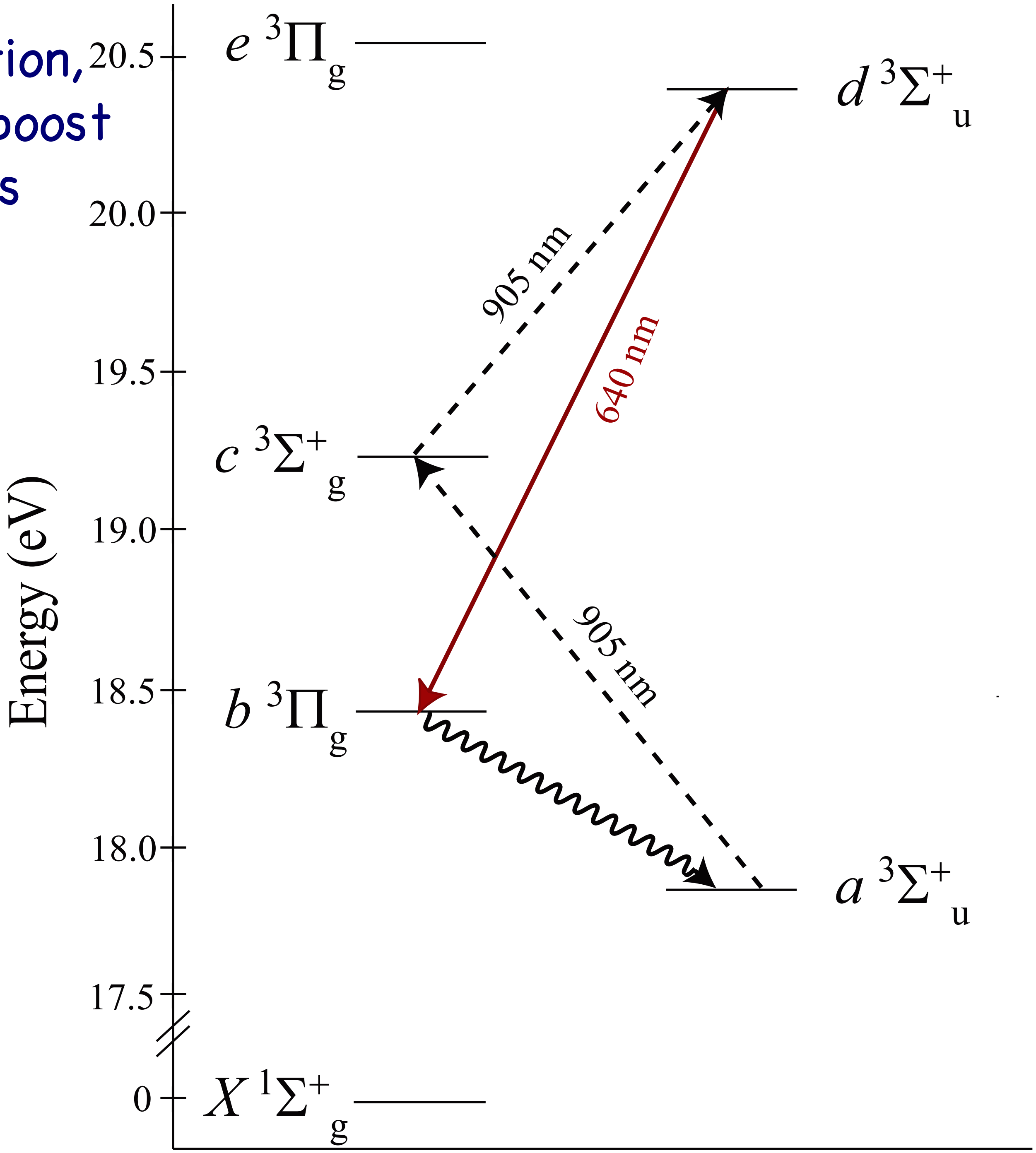
Strong absorption at 910 nm: c-a transition, 0-0 vibrational
Other vibrational transitions visible.
The triplet He_2 molecule exists as a bubble in liquid helium, with radius 0.7 nm.
Density is limited by Penning ionization, with rate constant 2E-10 to 4E-10 cm^3/s

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

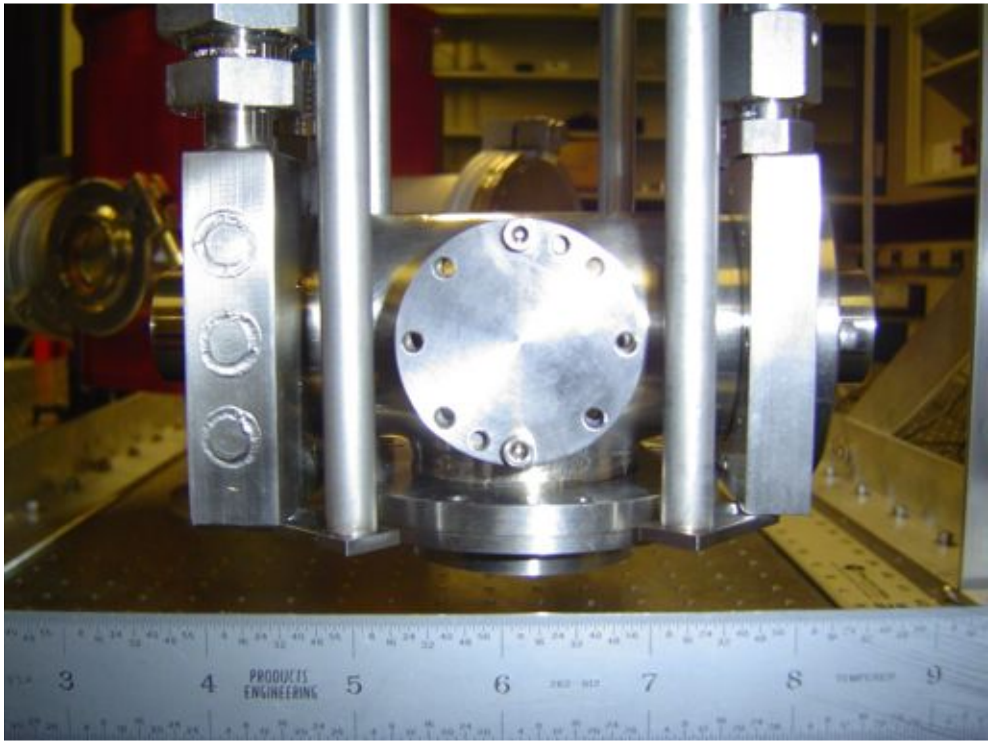
Uses:

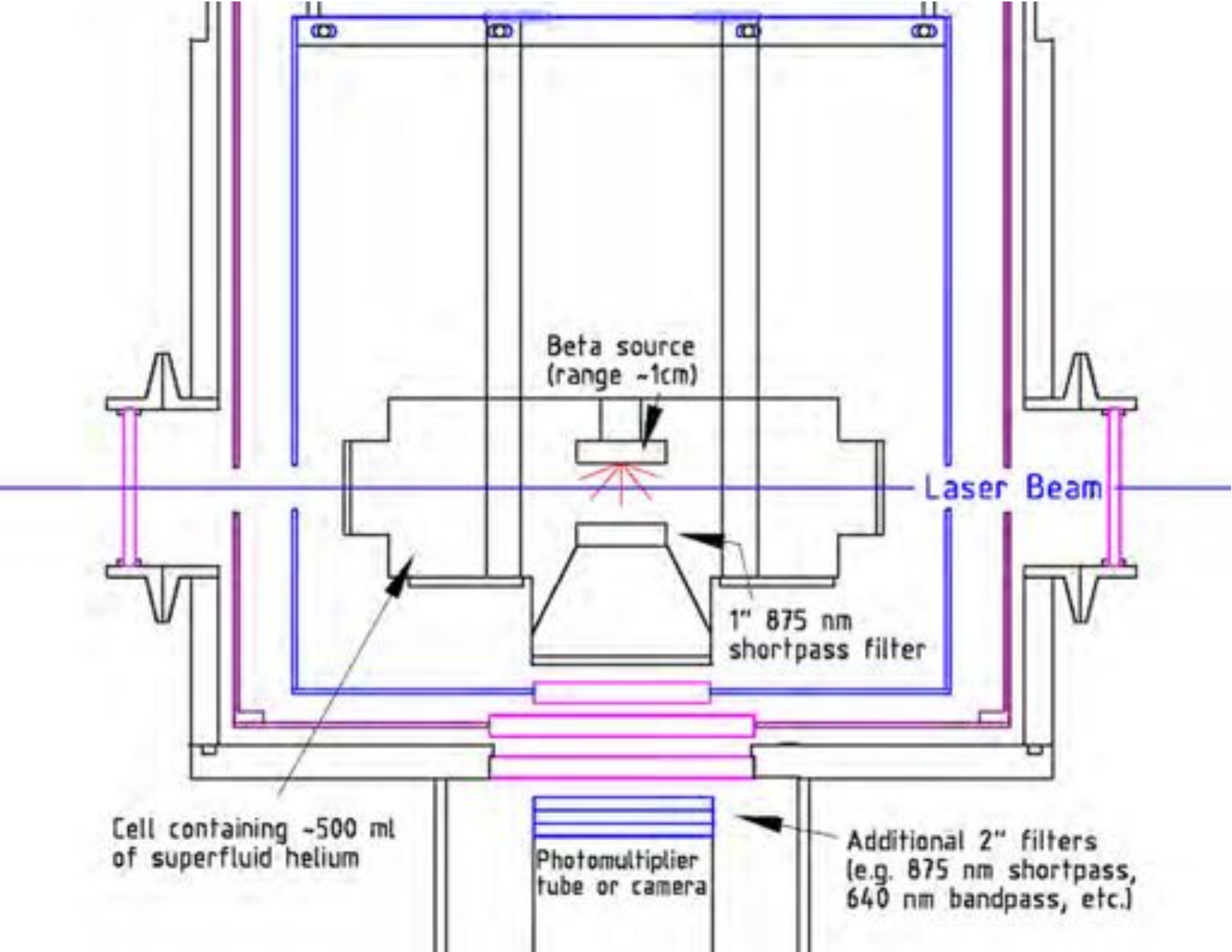
- WIMP detection
- ultracold neutrons
- gamma ray imaging
- Turbulence visualization

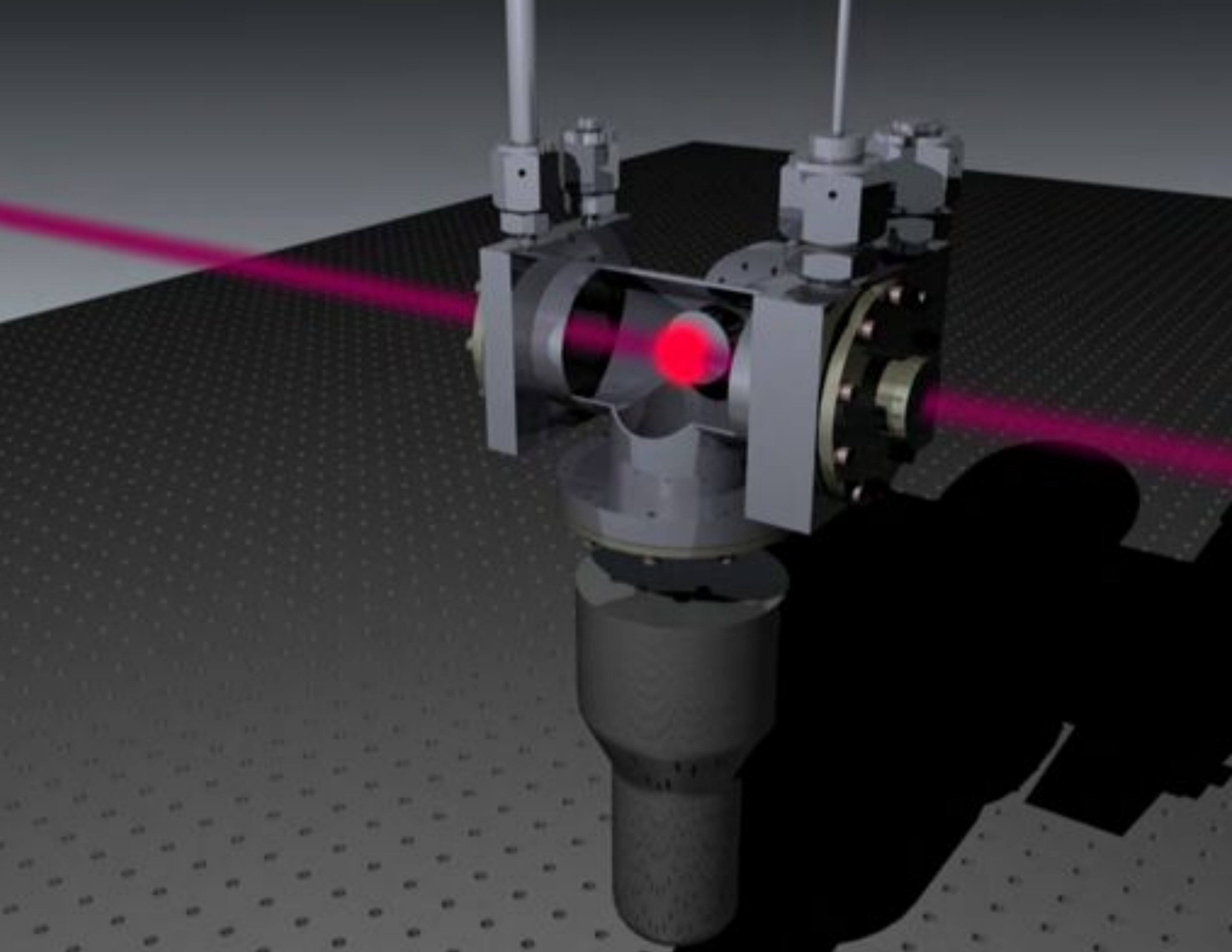
Recent support:
Packard foundation, DTRA

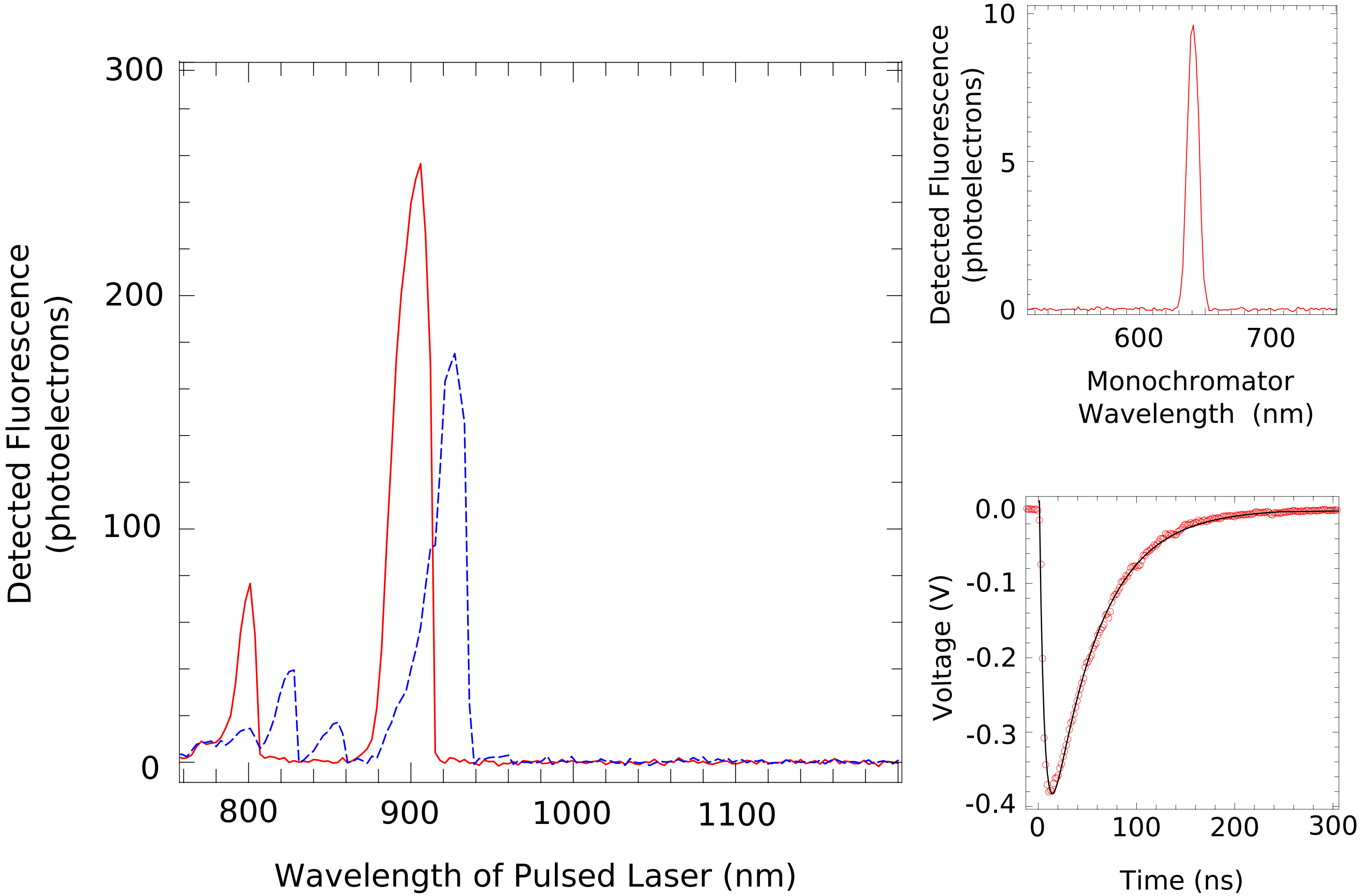


Pumped He-4 system at Yale, with optical access

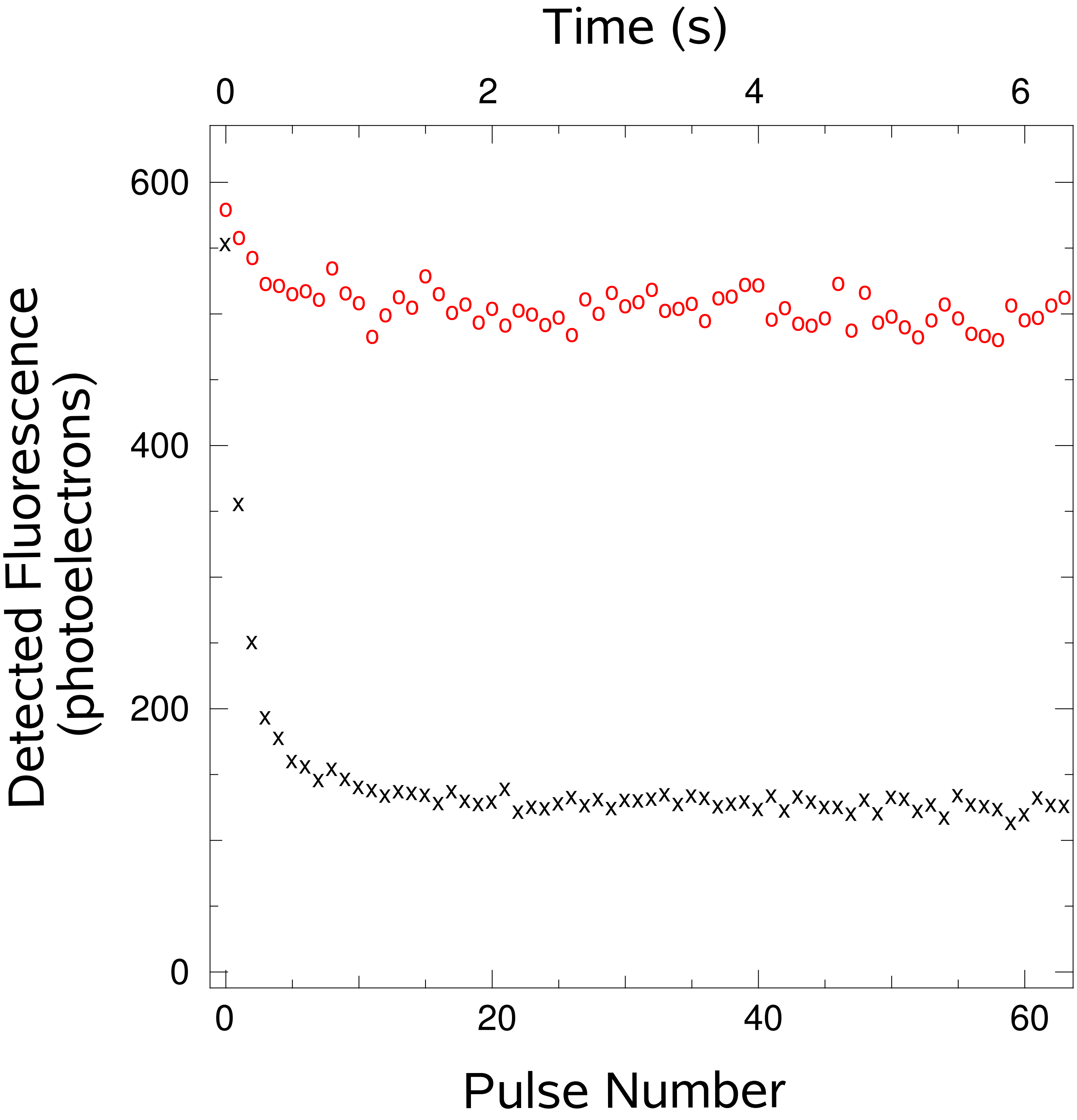



Beta source
(range ~1cm)
Laser Beam
1" 875 nm
shortpass filter
Cell containing ~500 ml
of superfluid helium
Photomultiplier
tube or camera
Additional 2" filters
(e.g. 875 nm shortpass,
640 nm bandpass, etc.)

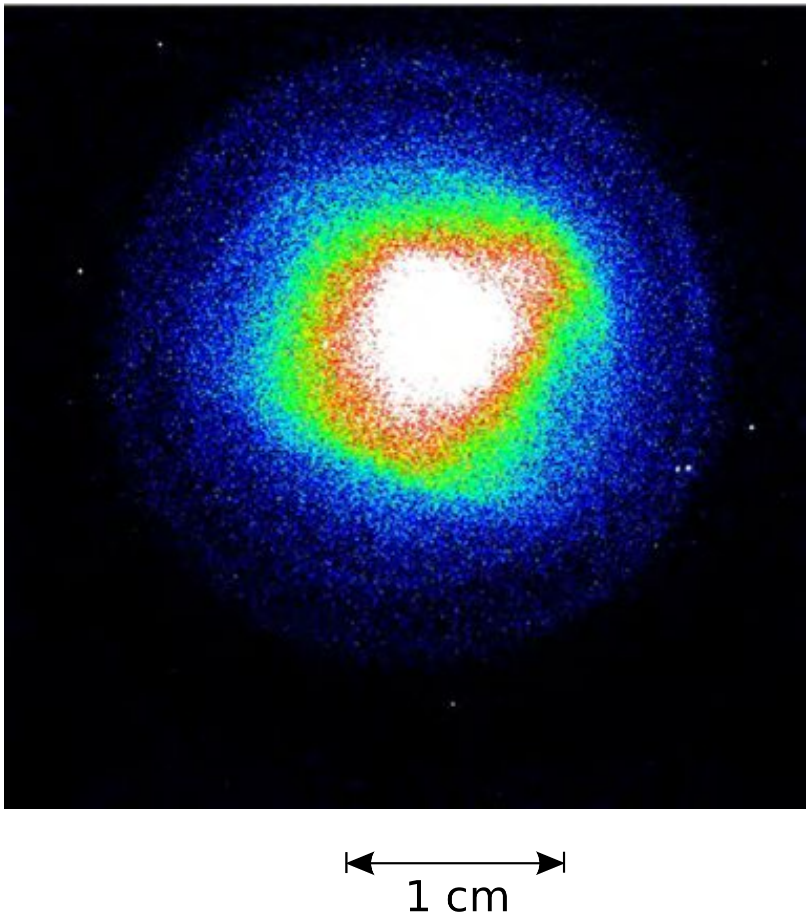


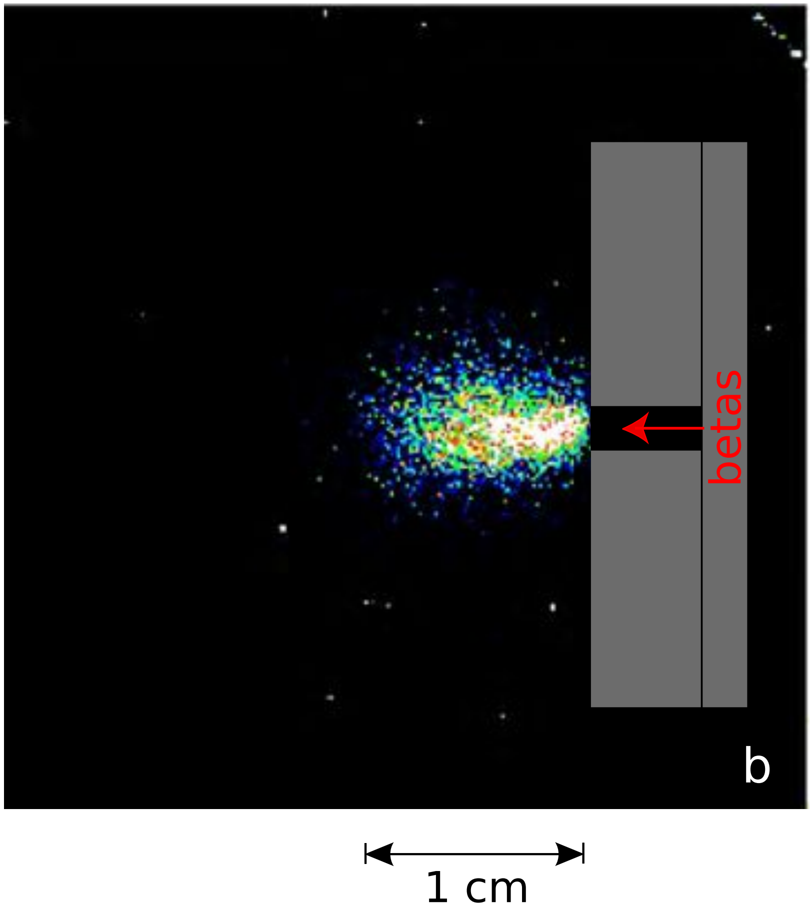


W. G. Rellergert *et al*, Phys. Rev. Lett. **100**, 025301 (2008).

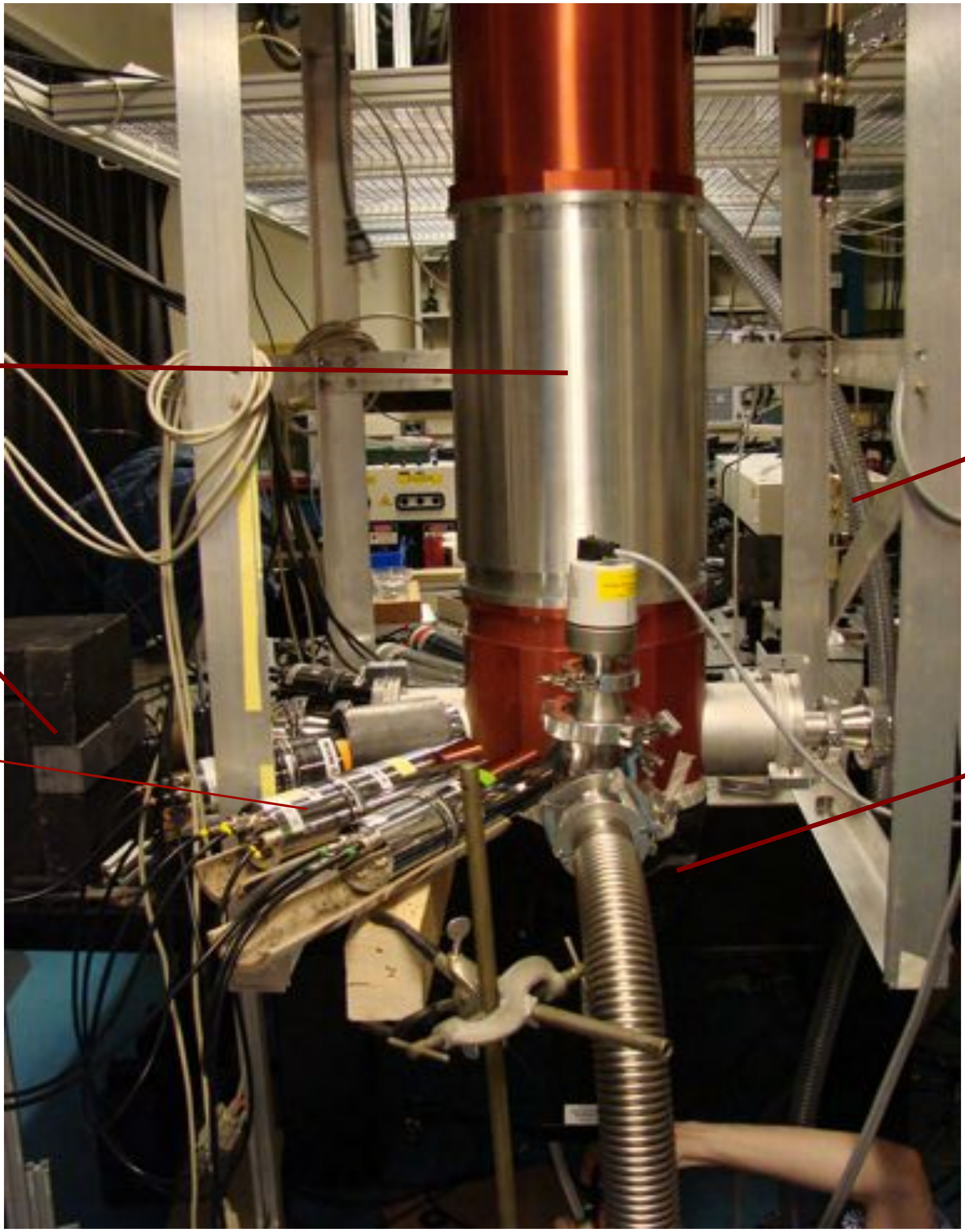

Time (s)
0
2
4
6
600
400
200
0
Detected Fluorescence (photoelectrons)
0
20
40
60
Pulse Number

Images of Helium Molecules





Scattering gamma rays in liquid helium



Cryostat

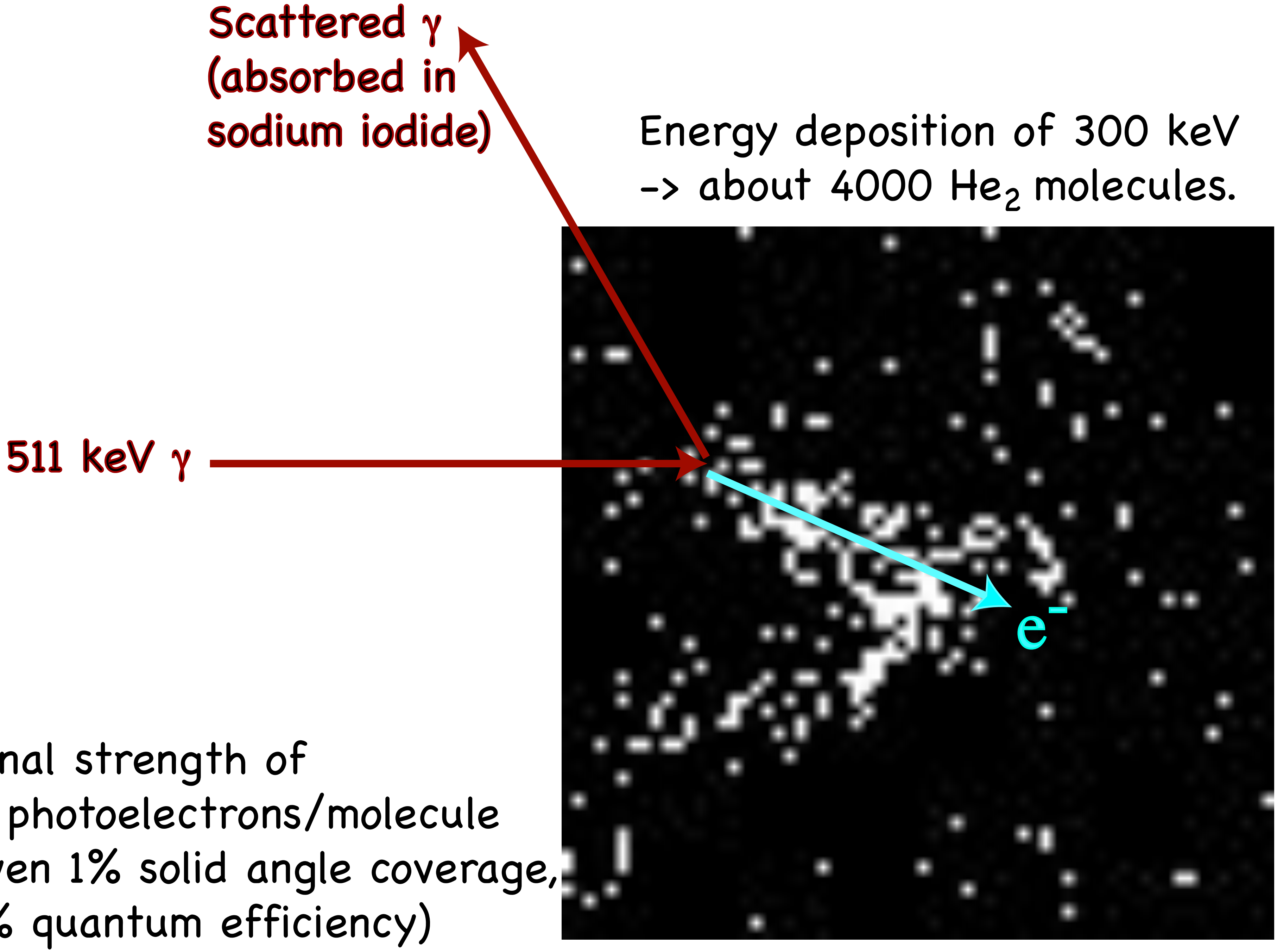
Laser

511 keV
gamma source

Sodium iodide
detectors

Camera

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

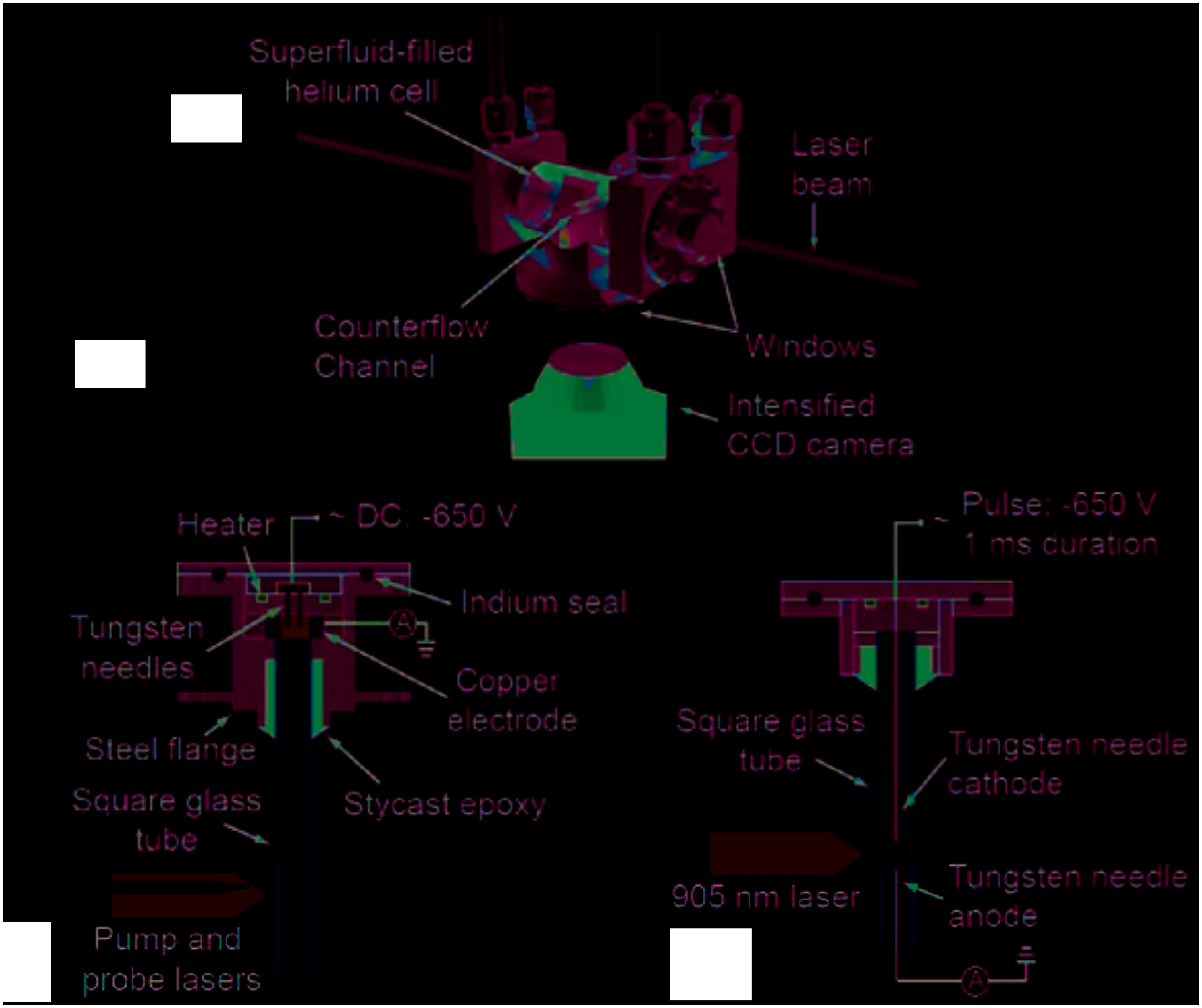


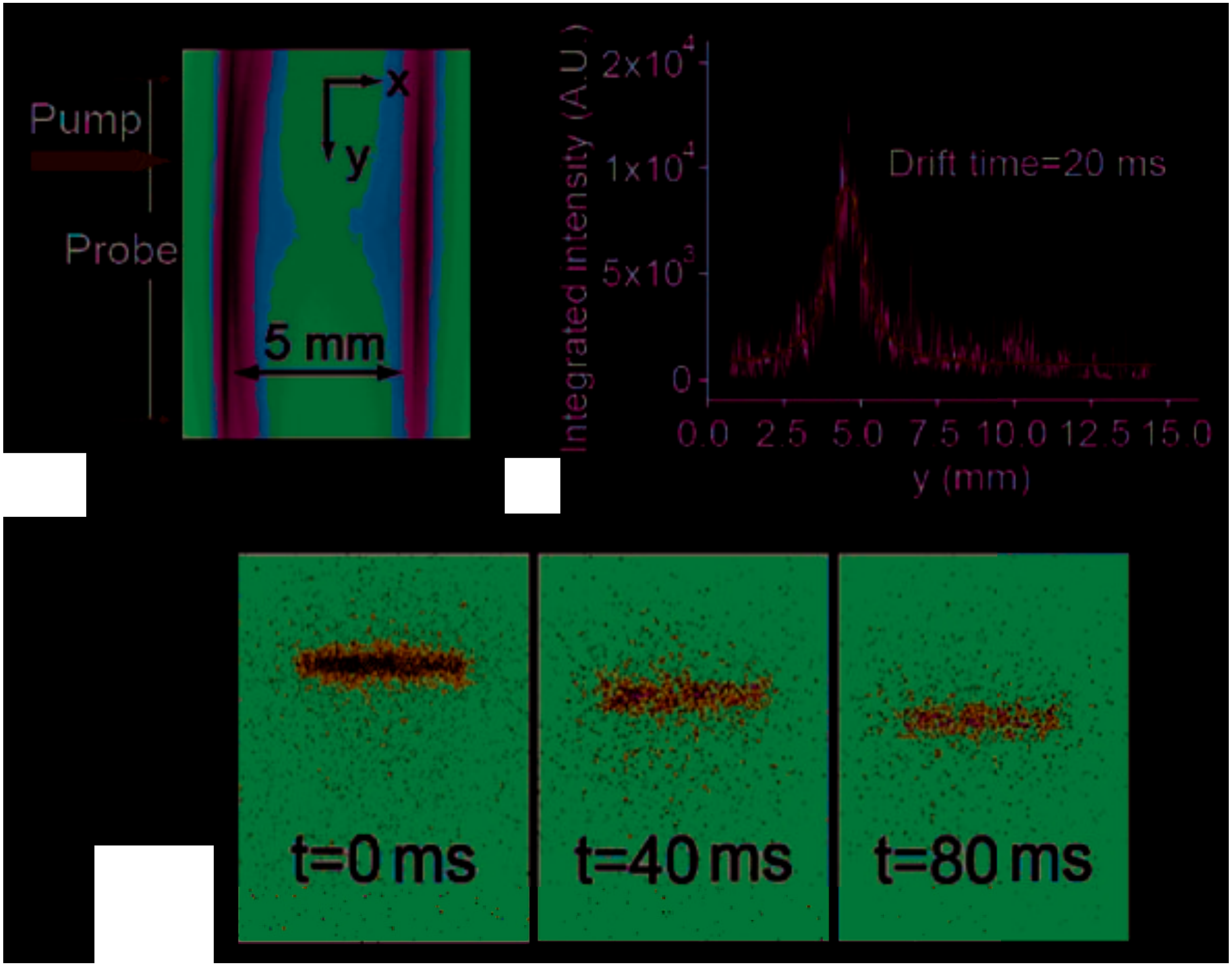
Scattered γ (absorbed in sodium iodide)

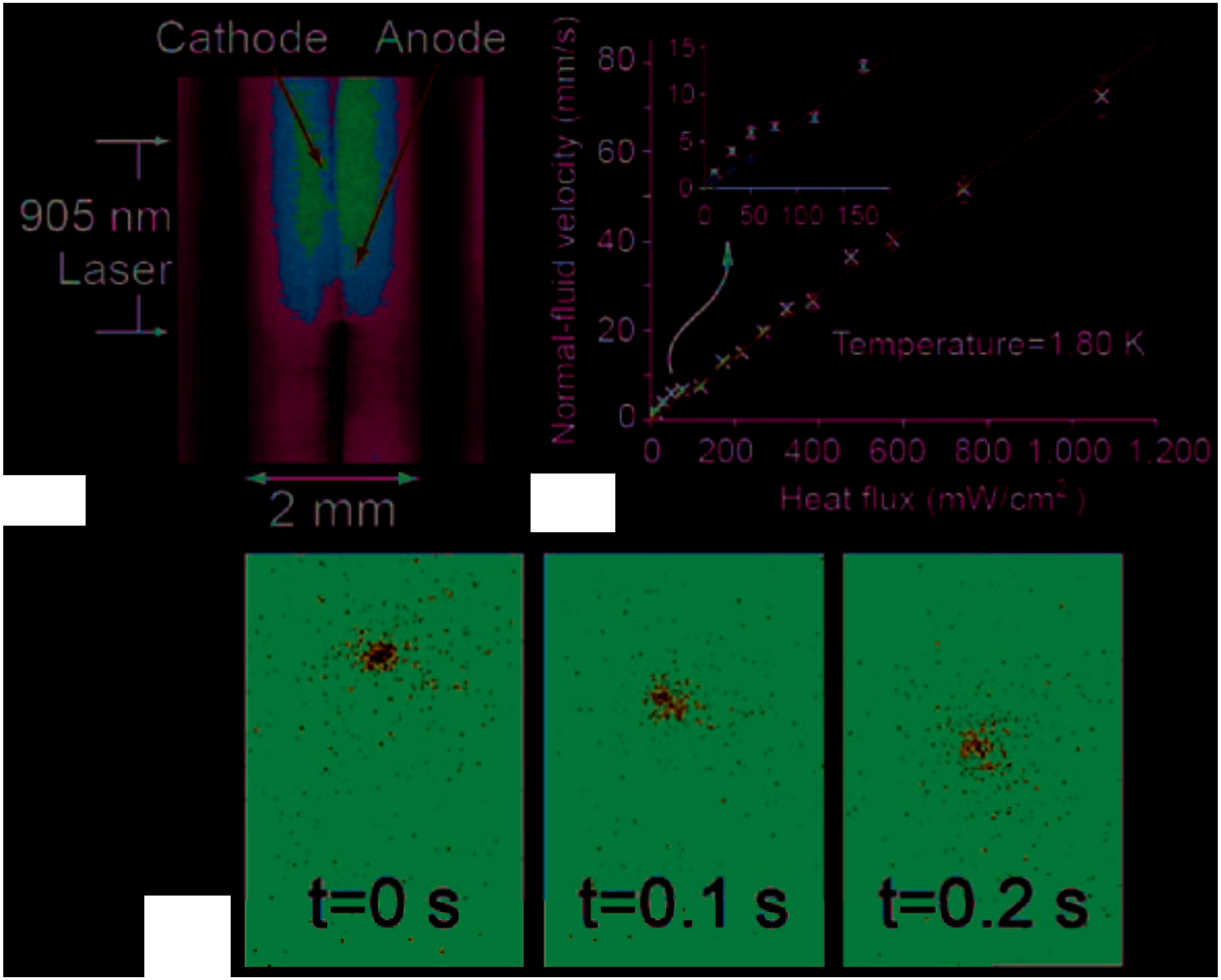
511 keV γ

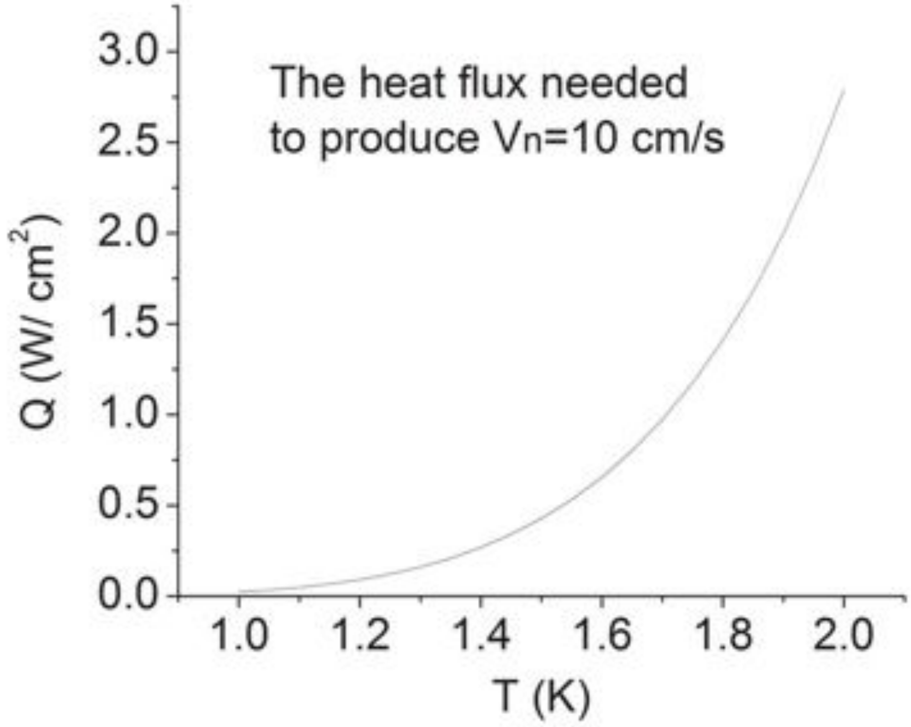
Signal strength of
0.1 photoelectrons/molecule
(given 1% solid angle coverage,
10% quantum efficiency)

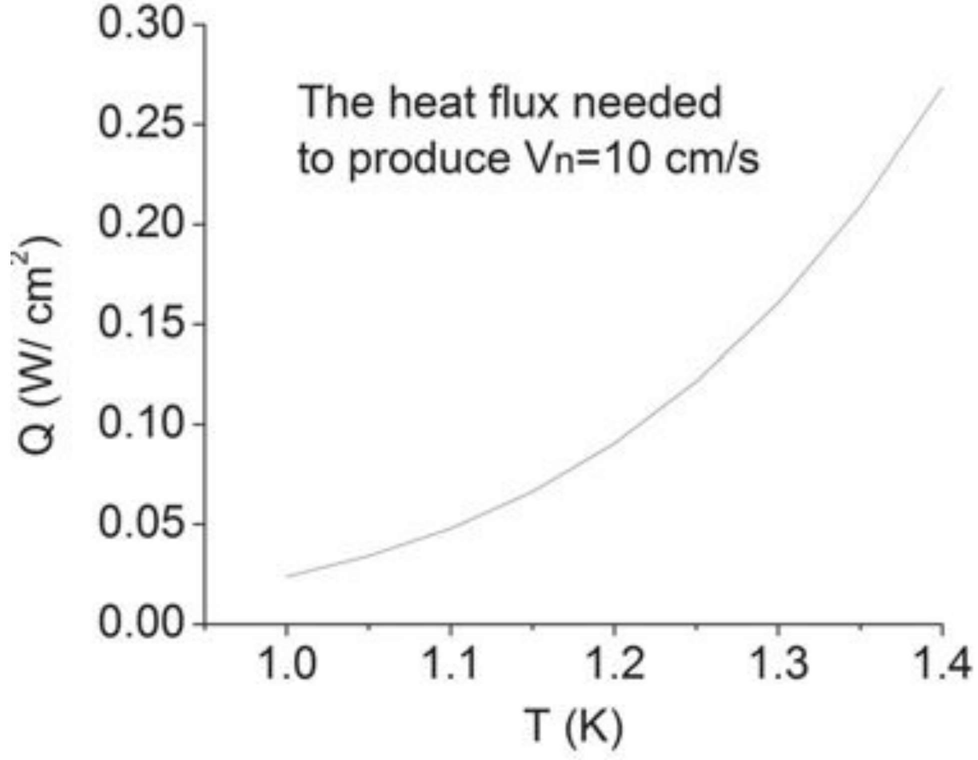
Helium molecule tracking experiments (Guo et al, arXiv:1004.2545)




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


Cathode
Anode
905 nm
Laser
2 mm
Normal-fluid velocity (mm/s)
80
60
40
20
0
0
200
400
600
800
1.000
1.200
Heat flux (mW/cm^2)
15
10
5
0
0
50
100
150
Temperature=1.80 K
t=0 s
t=0.1 s
t=0.2 s


The heat flux needed
to produce Vn=10 cm/s
Q (W/ cm^2)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1.0
1.2
1.4
1.6
1.8
2.0
T (K)


The heat flux needed
to produce Vn=10 cm/s
Q (W/ cm^2)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
1.0
1.1
1.2
1.3
1.4
T (K)

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.

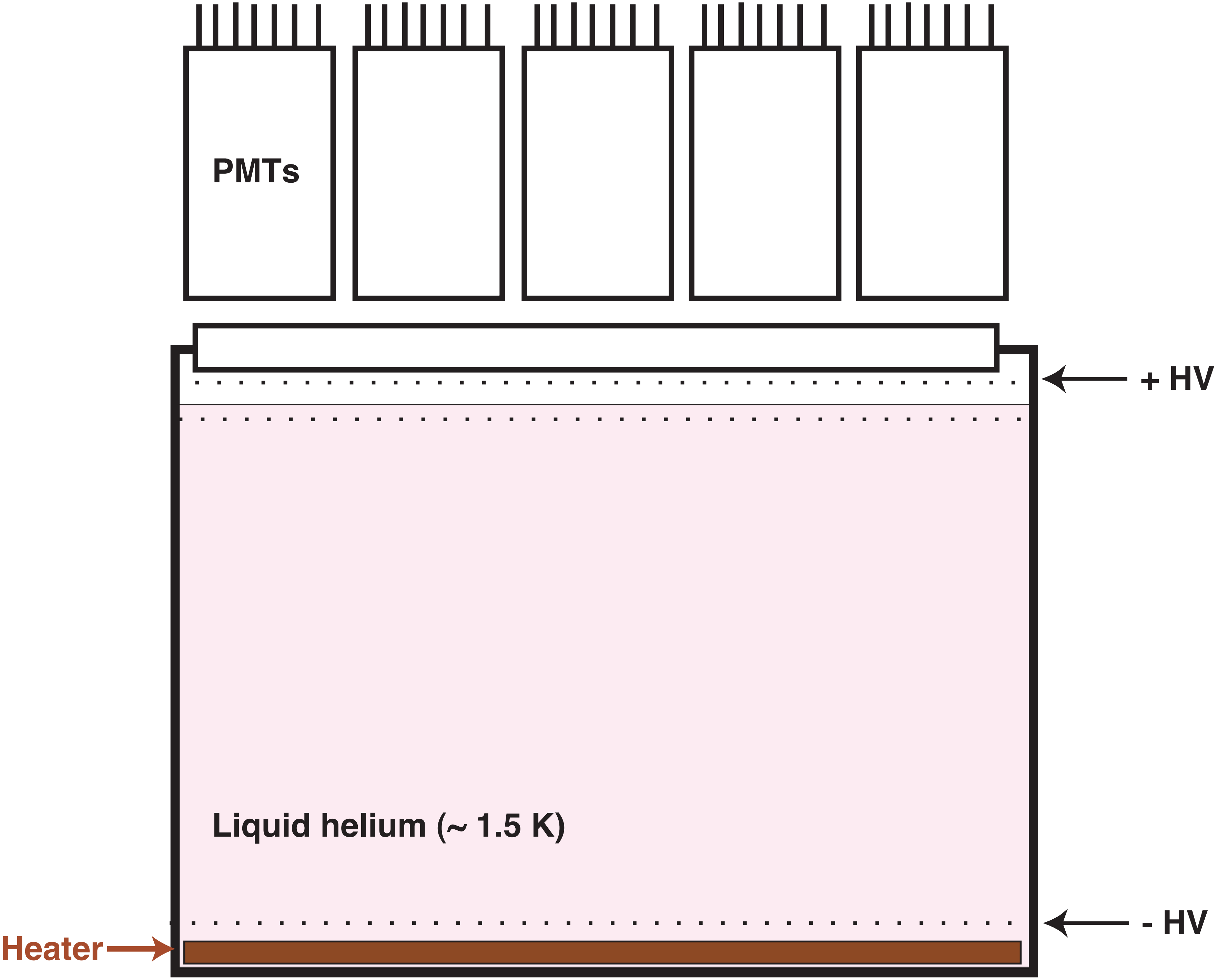
Signals:
Prompt light (S1)
Proportional scintillation from drifted electrons (S2)
Proportional scintillation from drifted triplet helium molecules (S3)

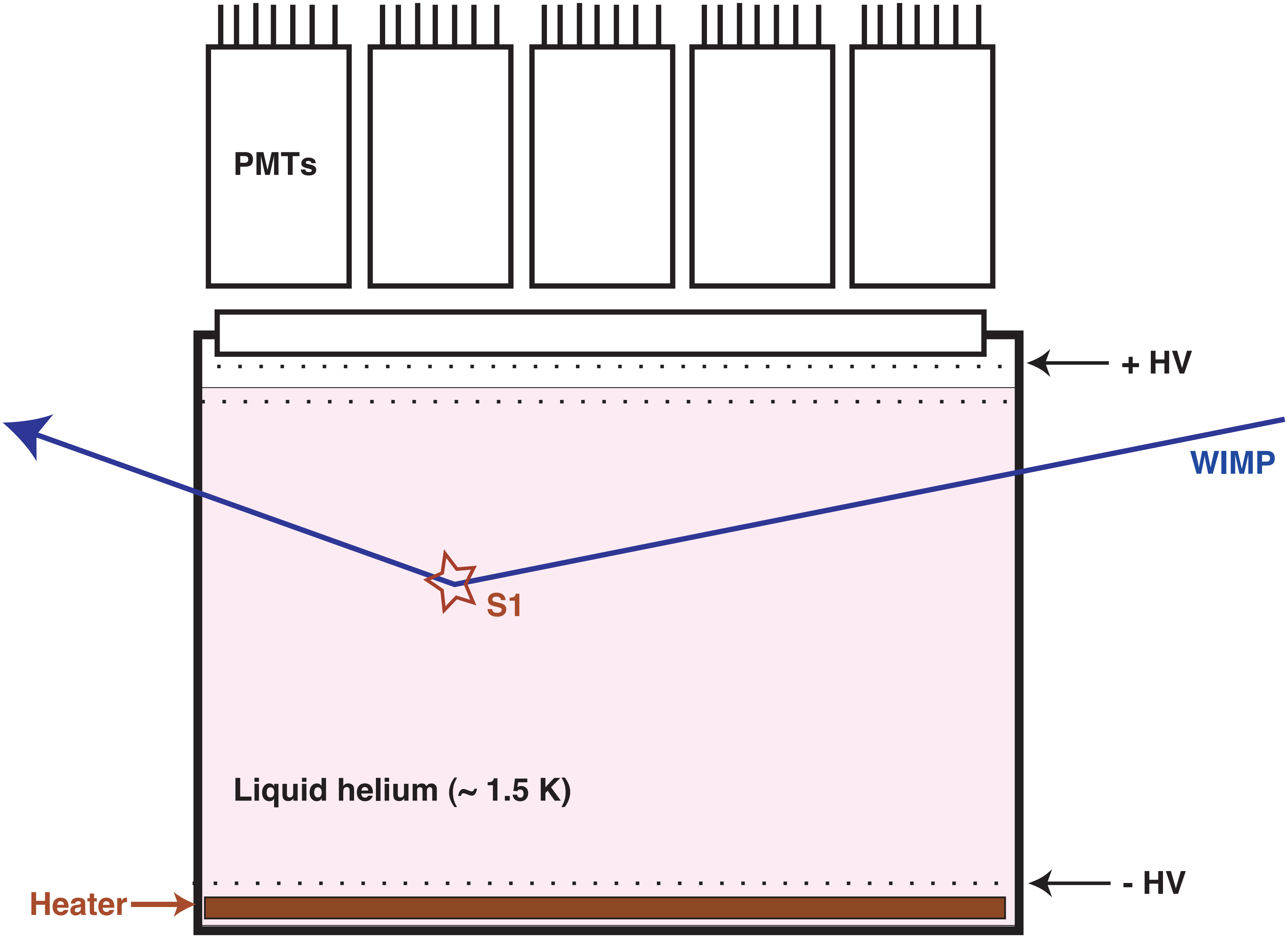
S2/S1 should give electron recoil/nuclear recoil discrimination, as in LXe

S2/S3 may give discrimination down to very low energy

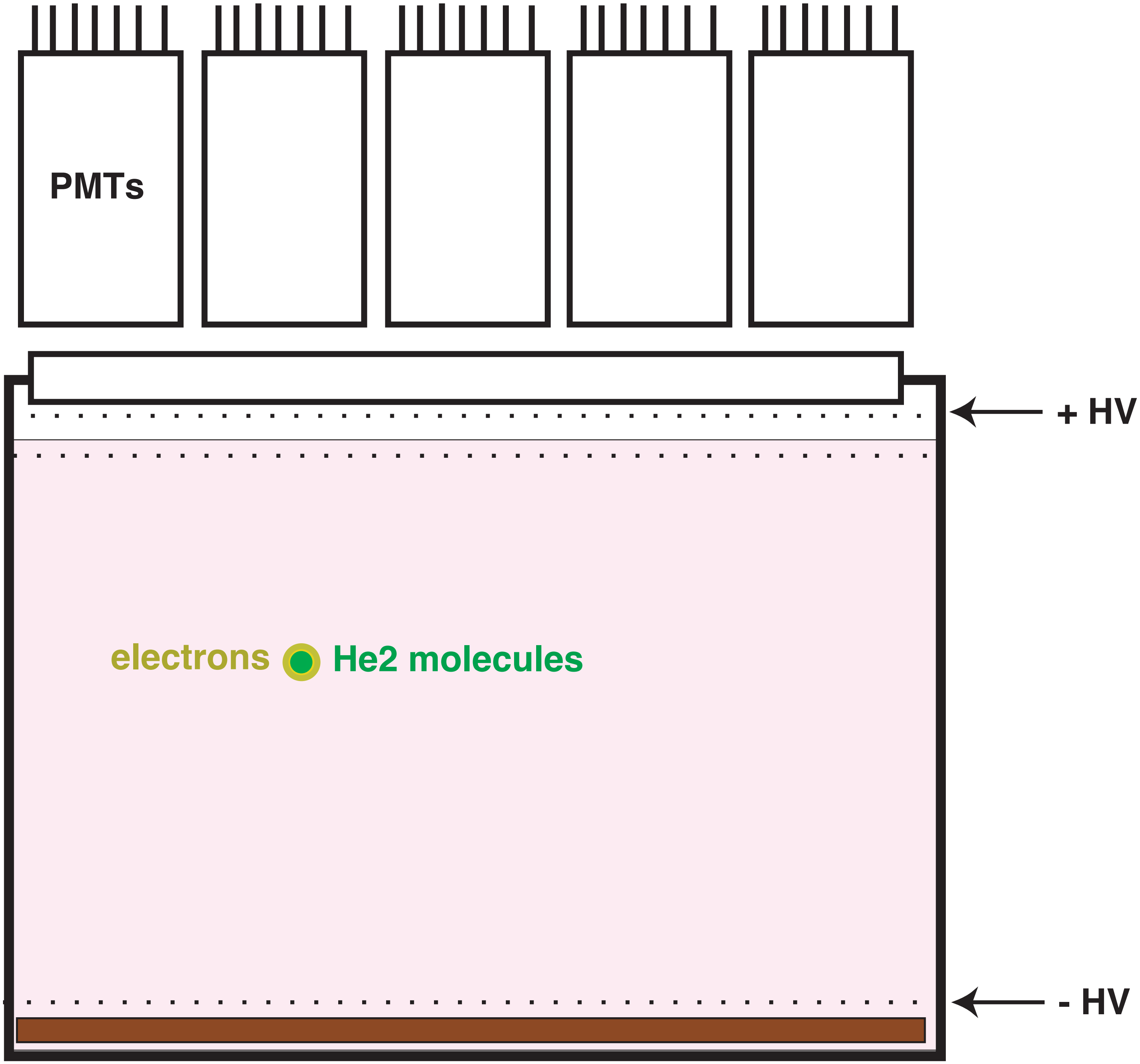
This is not a mature detector technology!

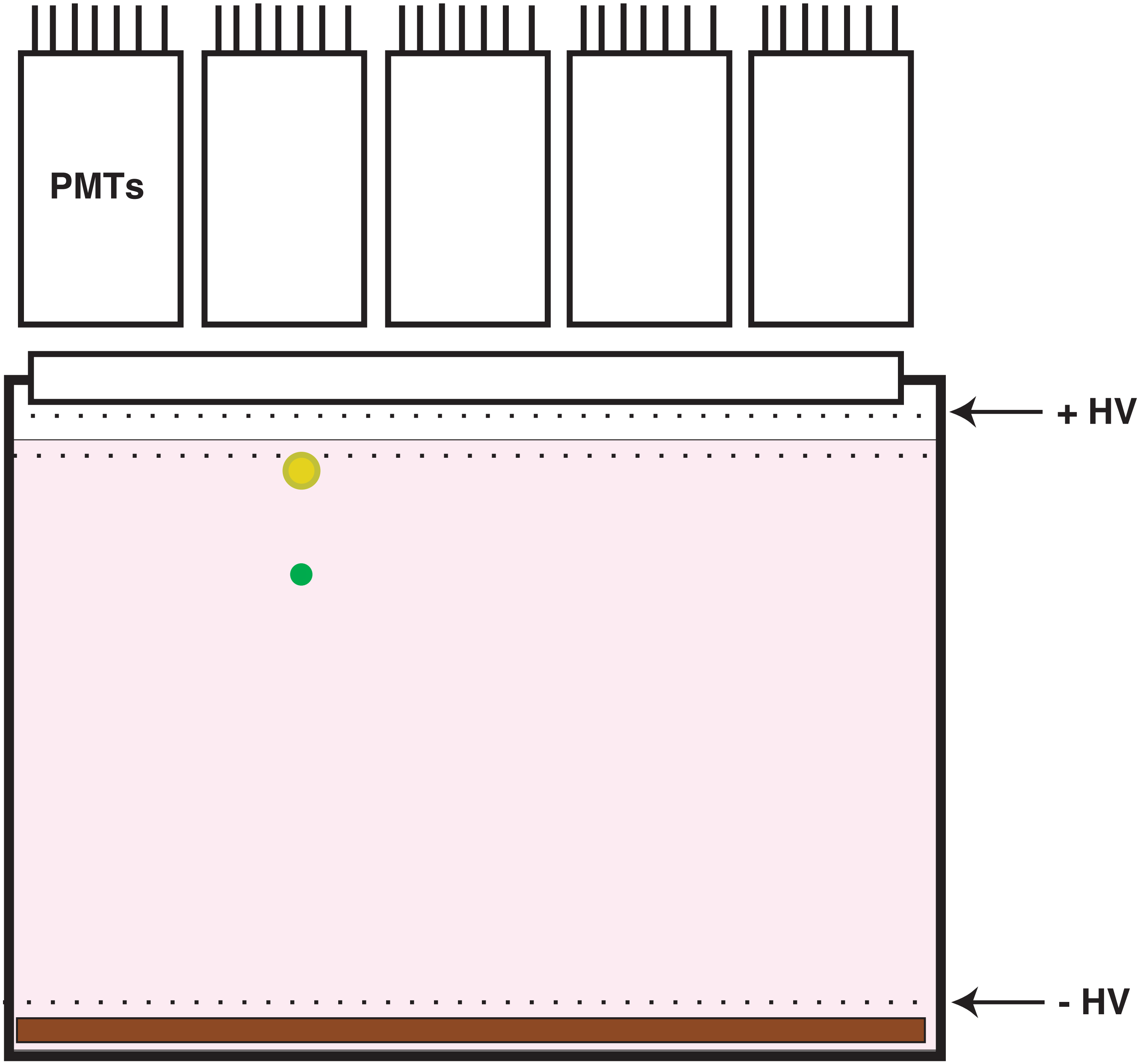
Research and development needed on determining the strength of S1, S2, S3 for electron recoils and nuclear recoils

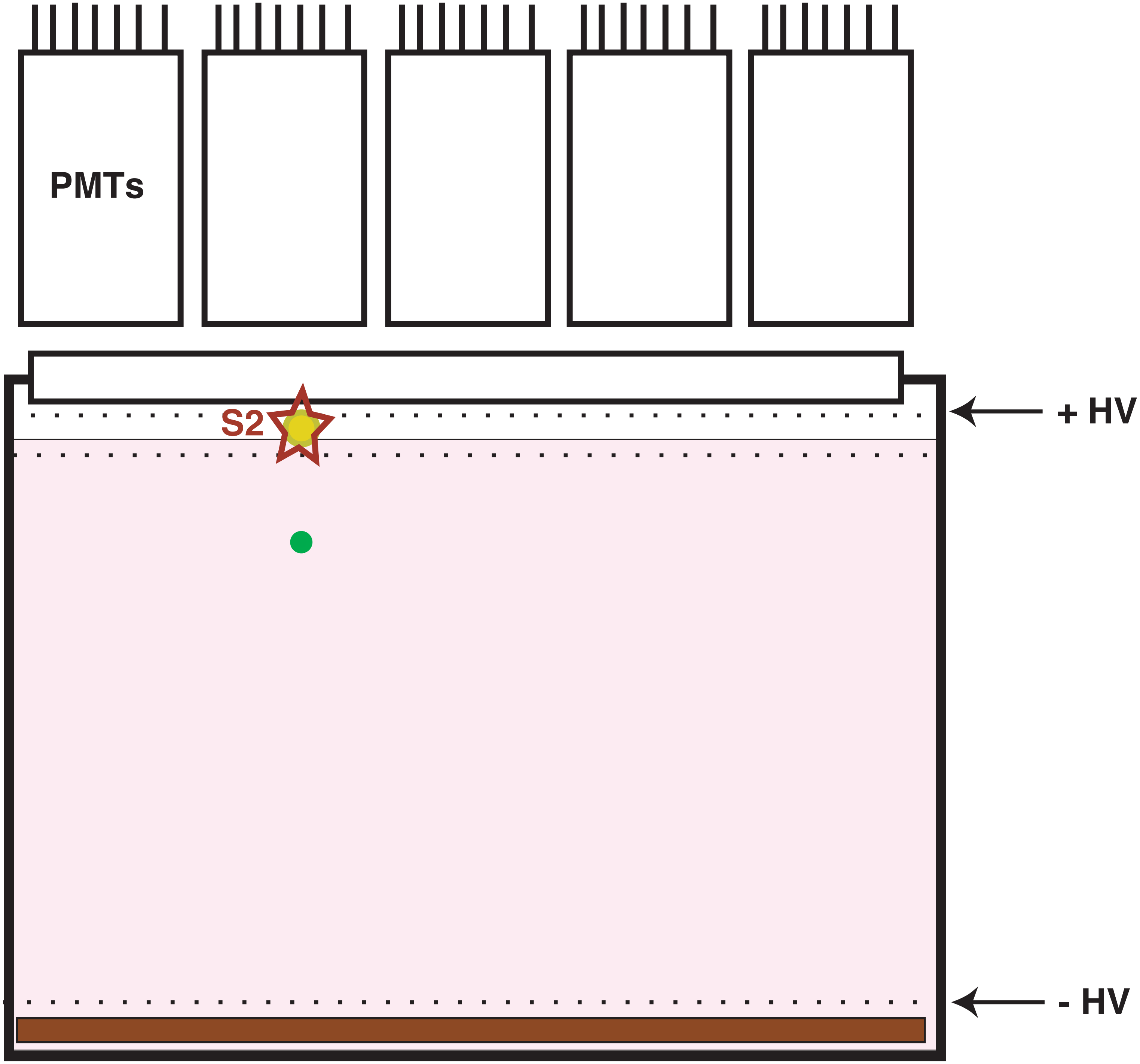

PMTs
+ HV
Liquid helium (~ 1.5 K)
- HV
Heater



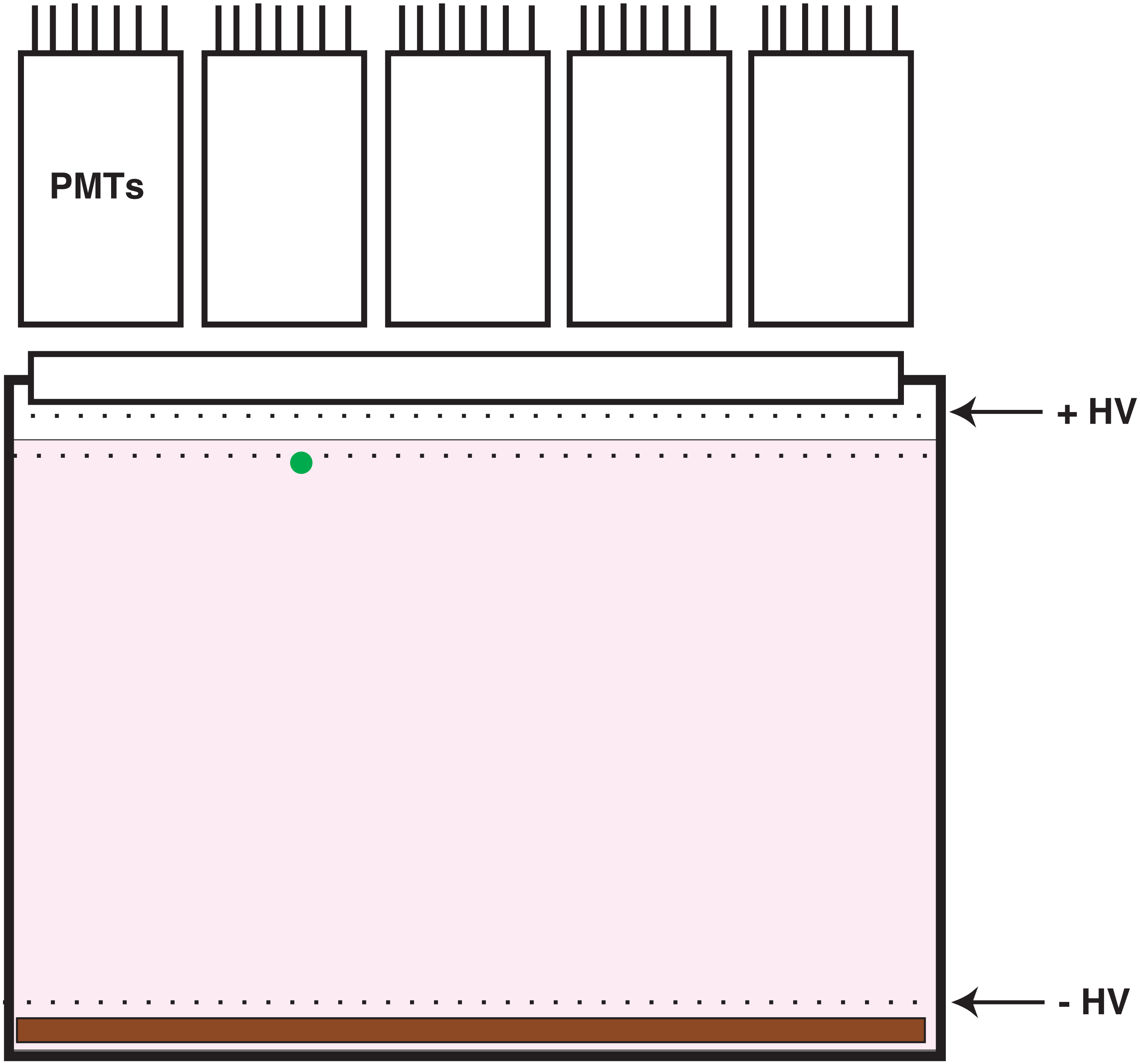
S1 detected by PMTs


PMTs
+ HV
electrons
He2 molecules
- HV

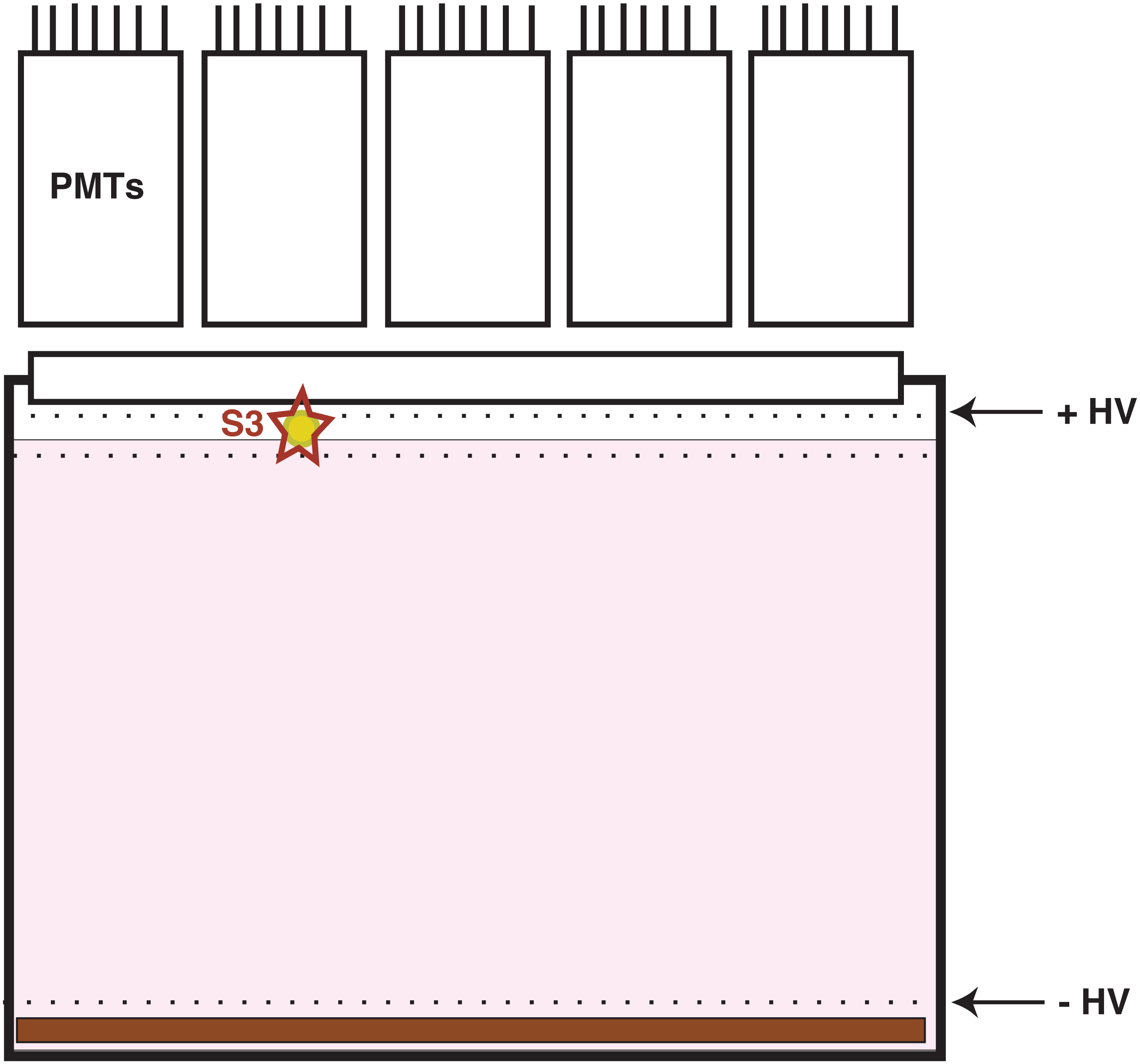

PMTs
+ HV
- HV



S2 detected by PMTs



Helium molecules attracted to wires by field gradient, quench and produce electrons



S3 detected by PMTs. S2/S3 gives discrimination. t3-t2 gives event depth

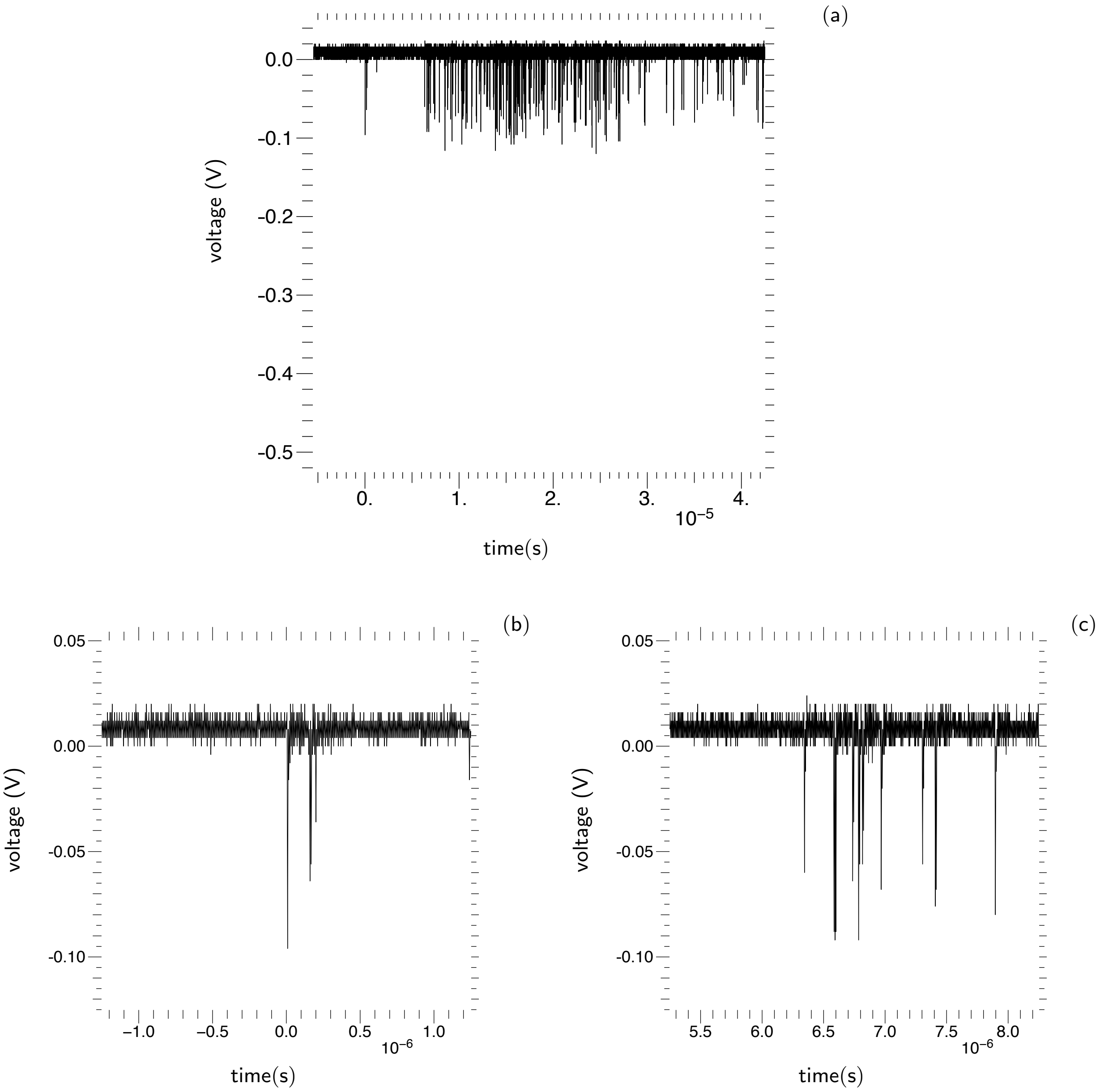


Figure 3: Oscilloscope trace of S1 and S2 in gaseous helium with $F_{\rm ps}$=+1800 V/cm, $V_{\rm drift}$=-25 V/cm, p=760 torr. Part (a) shows a global view. Parts (b) and (c) show closer views of S1 and S2 from the trace in part (a) on the indicated time scales.

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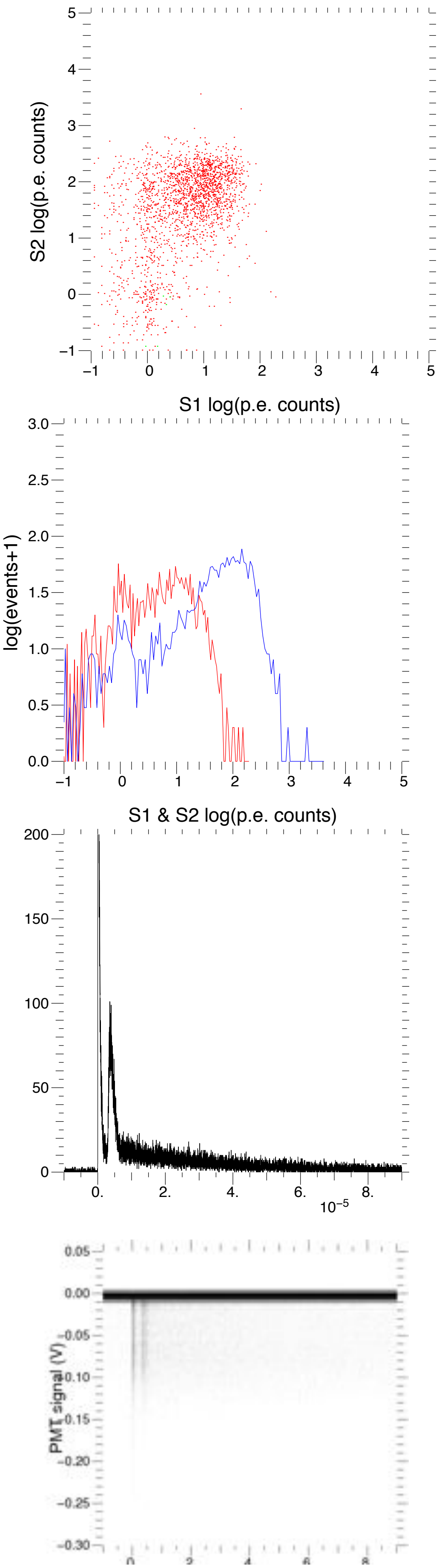

fig 1: $p = 1400$ torr $Va = 1490$, $Vc = -400$

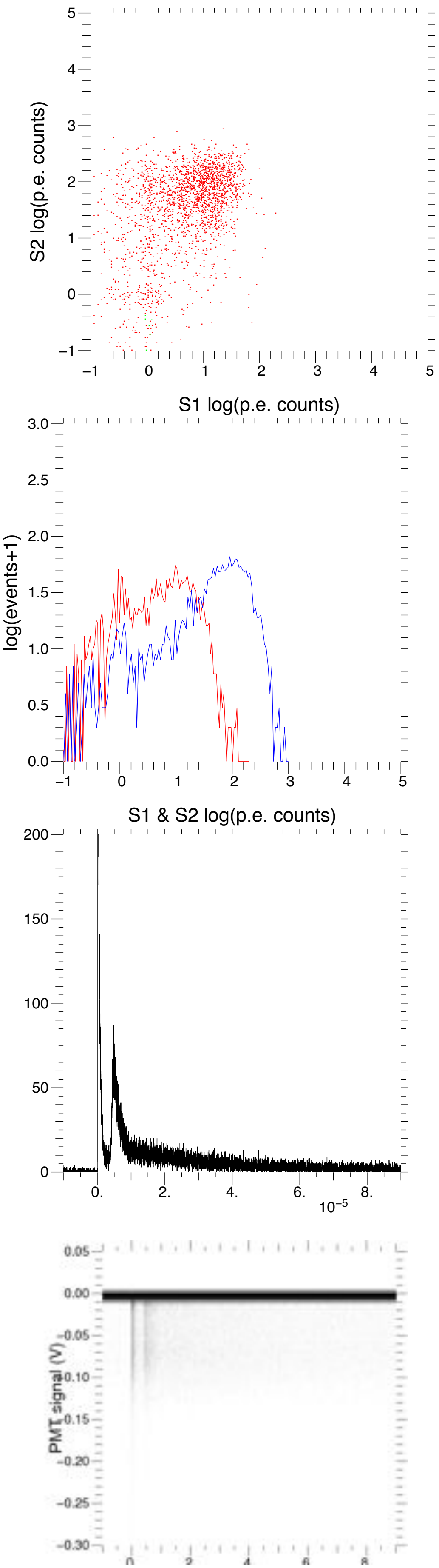

fig 2: $p = 1400$ torr $Va = 1490$, $Vc = -200$

Summary of noble liquids for light WIMP detection

LXe is now a mature technology, with a number of exciting experiments underway worldwide. However, low Leff at low energies and large nuclear mass limit sensitivity for low WIMP masses.

LAr is promising for large WIMP masses, however the need to reject Ar-39 radioactivity limits pulse shape discrimination at low energies, and raises the analysis energy threshold.

LNe is limited in energy threshold by the need to define a fiducial volume. However, very large LNe detectors (CLEAN) should have interesting sensitivity for light WIMPs.

LHe requires more development. A LHe-TPC, drifting both charge and He_2 molecules, might be an ideal light WIMP detection technology, with low internal backgrounds, discrimination, and position resolution.