Mini-CLEAN and DEAP/CLEAN Detectors

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Dark Side of the Universe
University of Minnesota

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

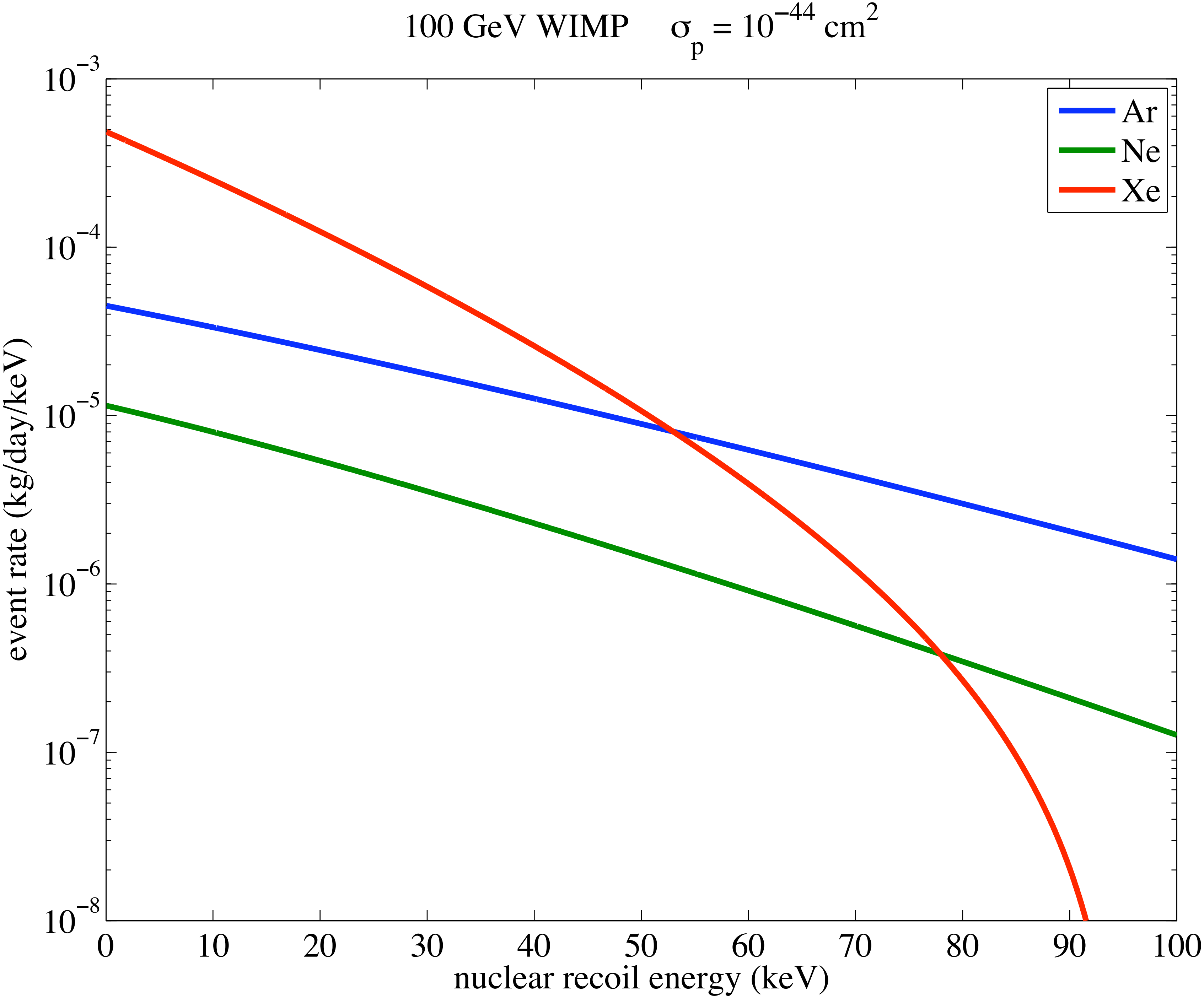
- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

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 σ_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)

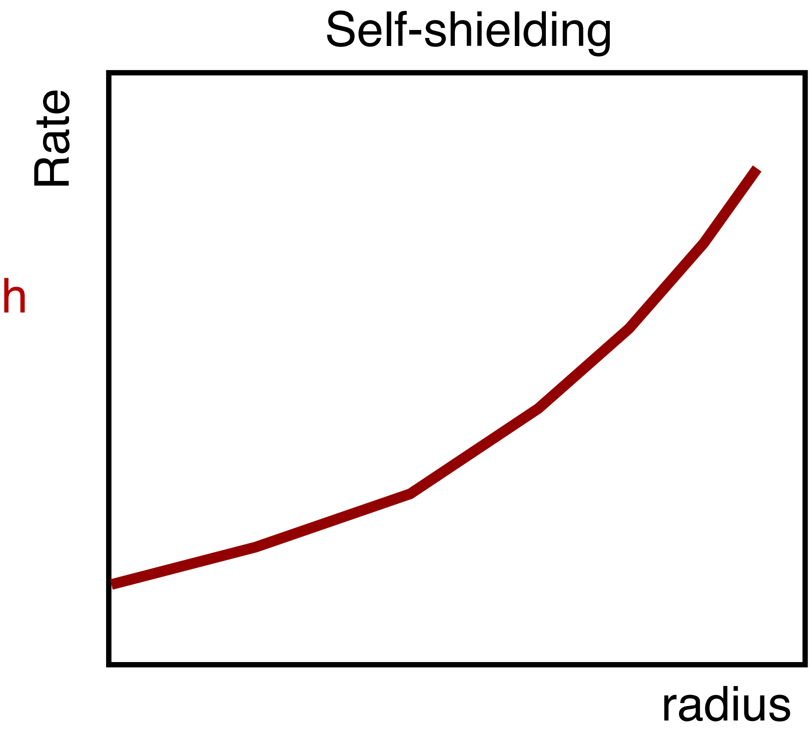
Strategies for Electronic Recoil Background Reduction in Scintillation Experiments

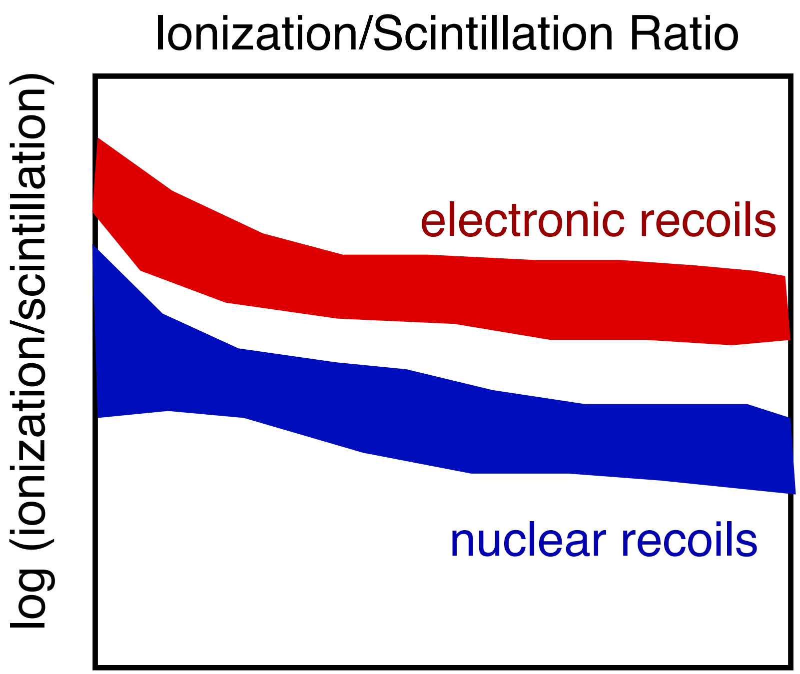
Require < 1 event in signal band during WIMP search

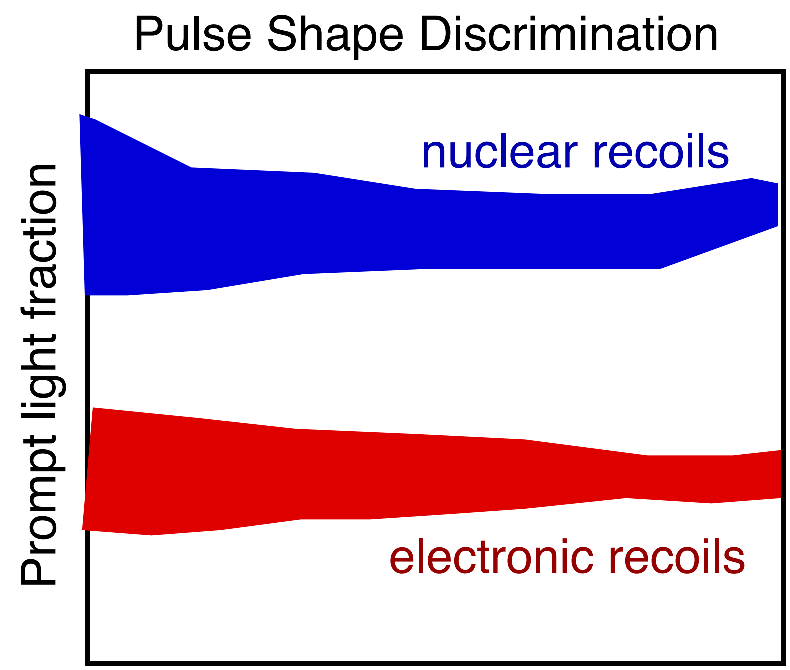
LXe: Self-shielding, Ionization/Scintillation ratio best

LAr: Pulse shape, Ionization/Scintillation ratio best

LNe: Pulse shape, Self-shielding best





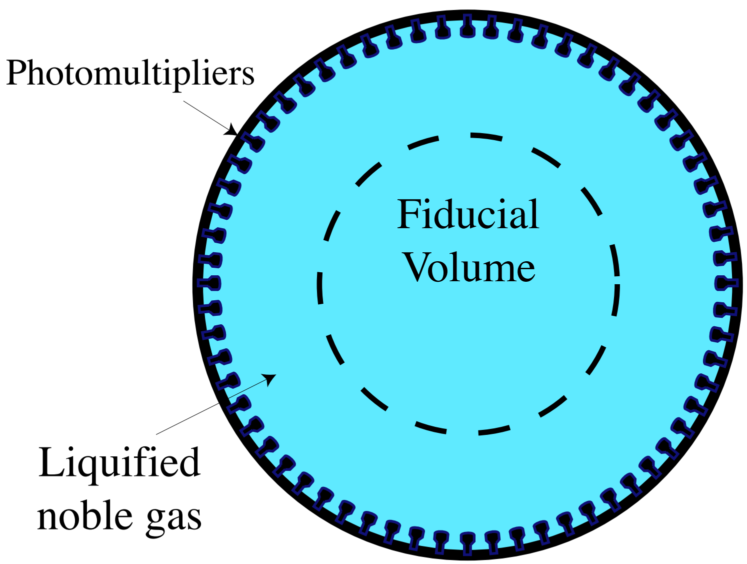


The Mini-CLEAN Approach

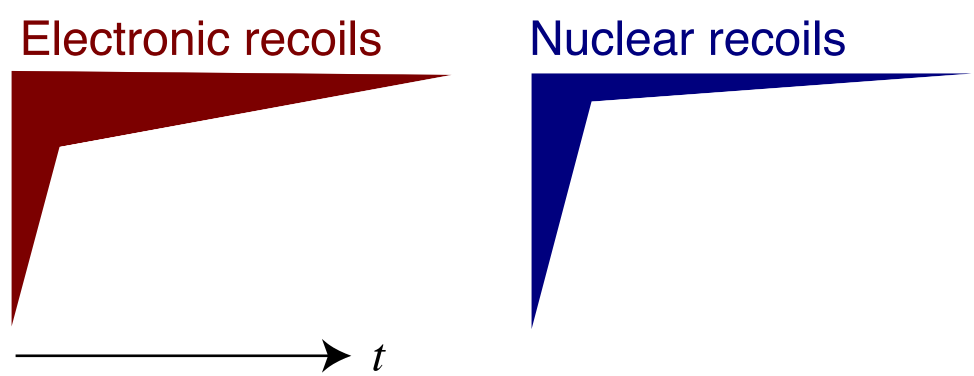
Scaleable technology based on detection of scintillation in liquified noble gases. No E field.
Ultraviolet scintillation light is converted to visible light with a wavelength-shifting film.

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 better characterization of radioactive backgrounds

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).

The CLEAN/DEAP family

A series of detectors based entirely on scintillation in LNe, LAr

No electric field!

This allows very efficient light collection with 4π photodetector coverage

✓ Pico-CLEAN: 200 g of LNe or LAr. Completed LNe scintillation R&D.

✓ Micro-CLEAN: 4 kg of LNe or LAr. LAr and LNe R&D underway.

DEAP-I: 7 kg LAr. DM search at SNOLAB. To go underground in 2007.

Mini-CLEAN: 100 fiducial kg of LNe or LAr. R&D, DM search. Begin 2007?

CLEAN/DEAP: 1 fiducial ton LAr/LNe. DM search. 2009 - ?

CLEAN: 10 fiducial tons LNe, maybe LAr. pp neutrinos, DM search. 2011 ?

CLEAN/DEAP Collaboration

Yale University: W. H. Lippincott, D. McKinsey, J. Nikkel

Boston University: D. Gastler, E. Kearns

Carleton University: K. Graham, K. McFarlane

Los Alamos National Laboratory: A. Hime, F. Lopez, J. Oertel, L. Rodriguez, K. Rielage, L. Stonehill, J. Wouters

National Institute for Standards and Technology: K. J. Coakley

Queen's University: M. Boulay, A. Hallin, J. Lidgard, R. Matthew, A. McDonald, P. Skensved

SNOLAB: F. Duncan, C. J. Jillings, I. Lawson

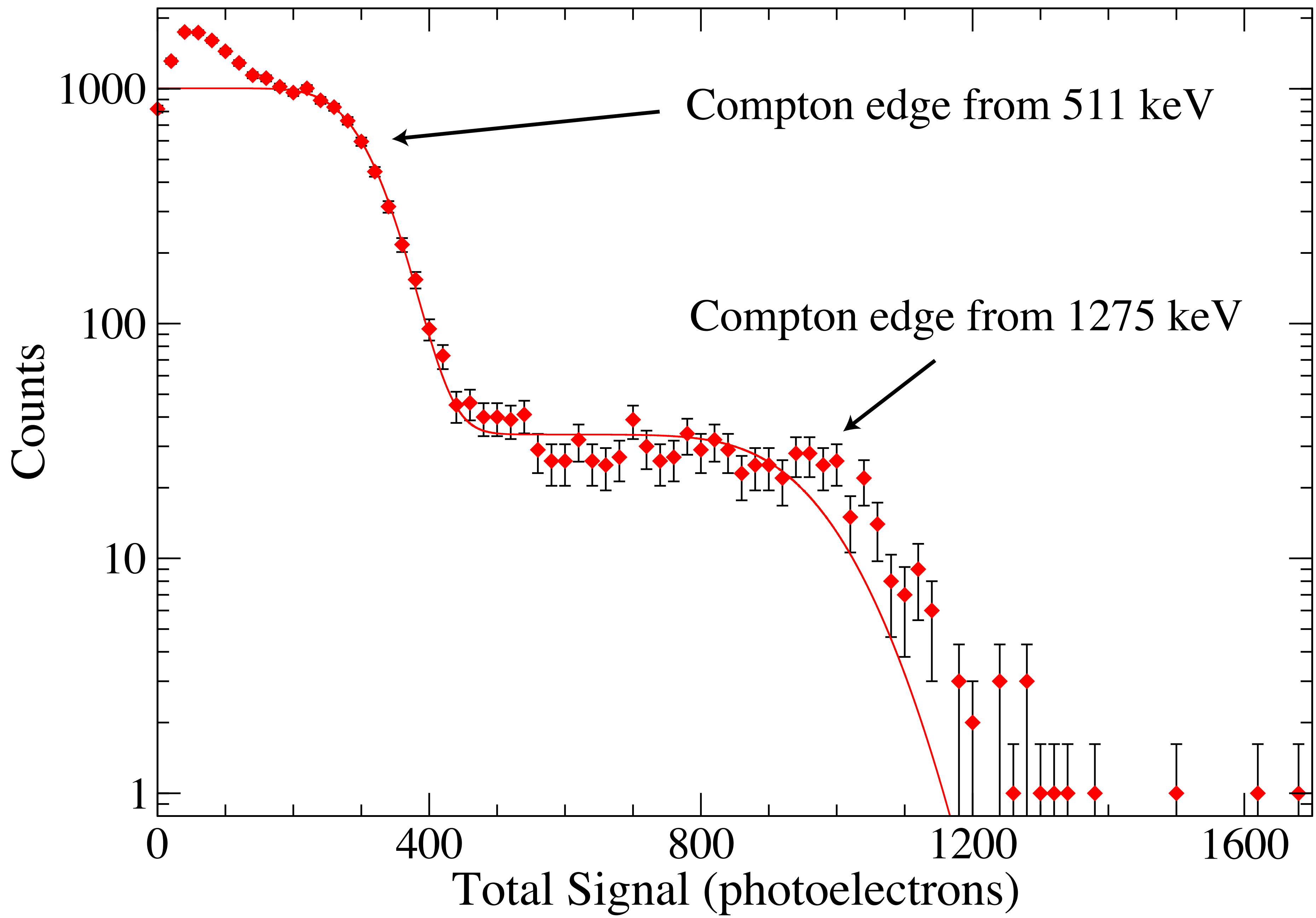
University of North Carolina: R. Henning

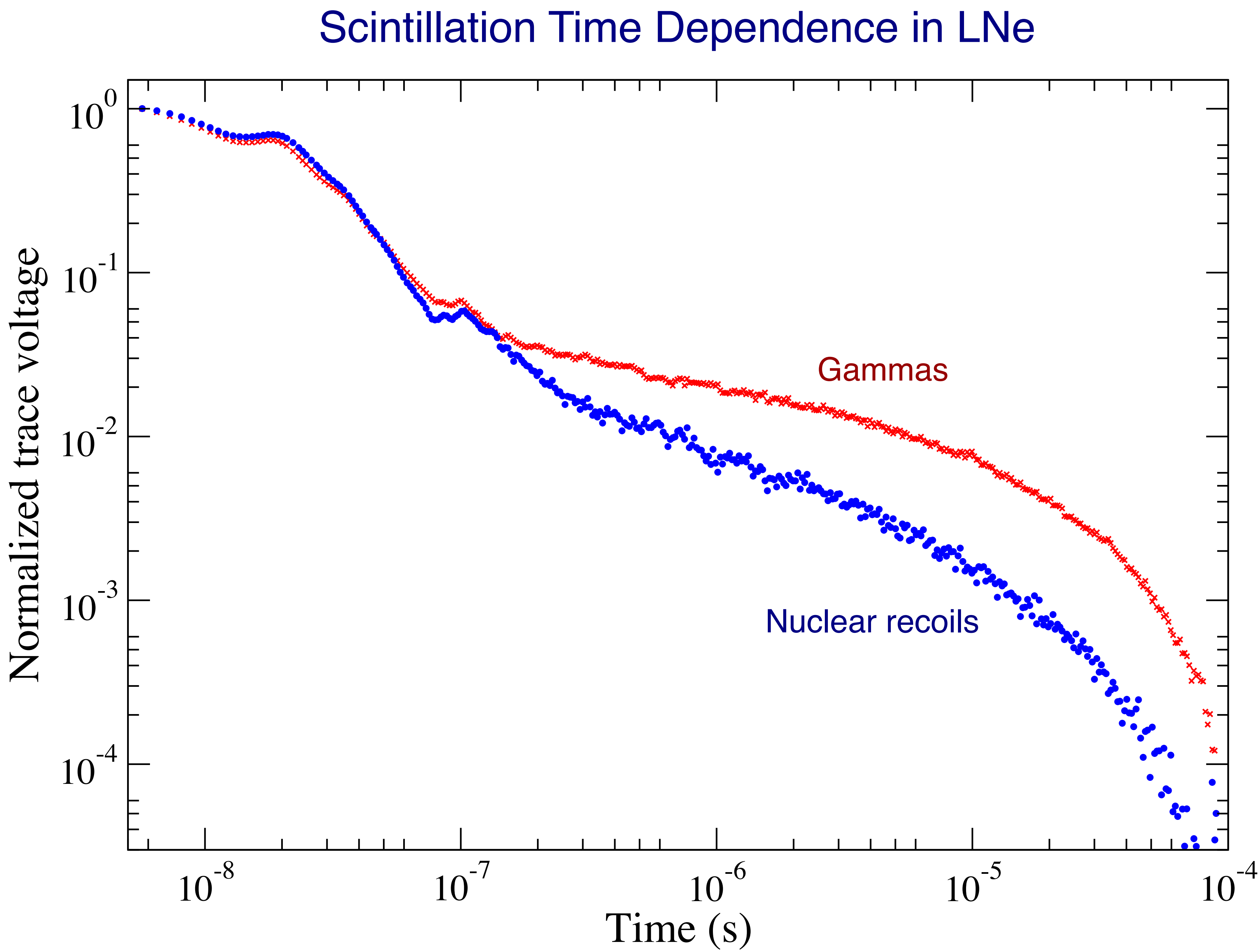
University of South Dakota: D. Mei

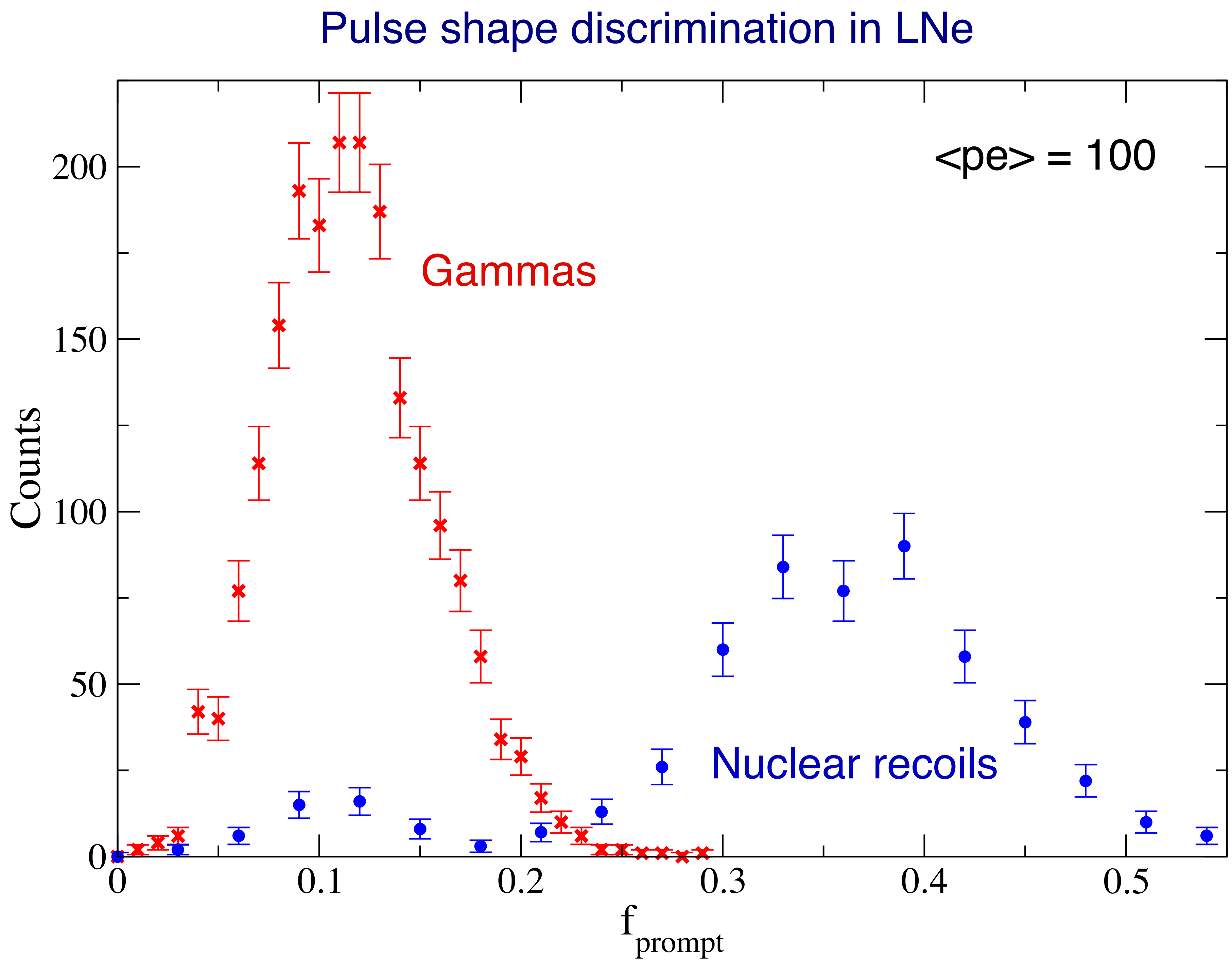
University of Texas: R. Hegde, J. Klein, S. Seibert

Liquid Neon calibration with Na-22 gamma rays gives 0.9 pe/keV

→ 30,000 photons/MeV

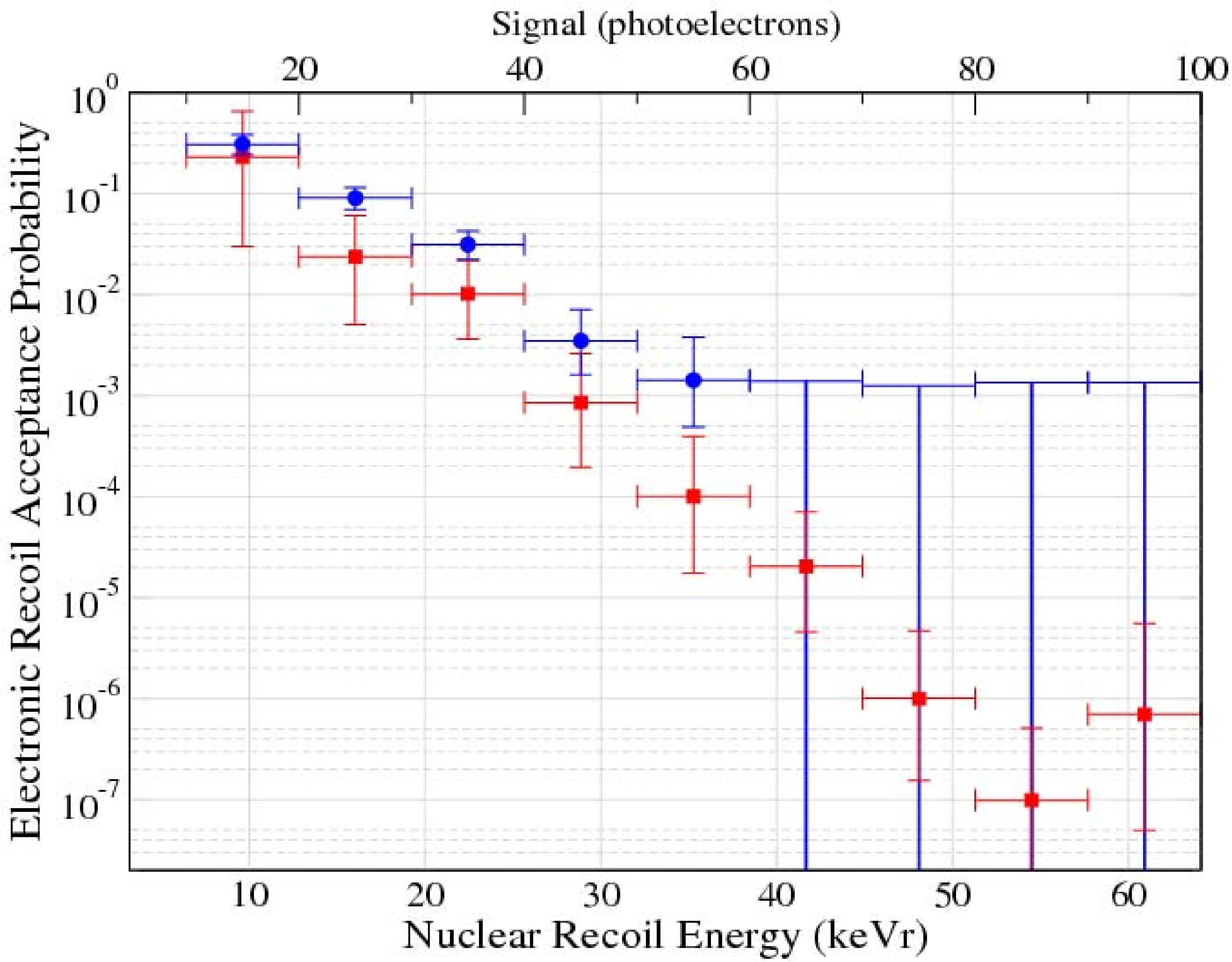



Scintillation Time Dependence in LNe
Normalized trace voltage
10^0
10^-1
10^-2
10^-3
10^-4
Gammas
Nuclear recoils
10^-8
10^-7
10^-6
10^-5
10^-4
Time (s)

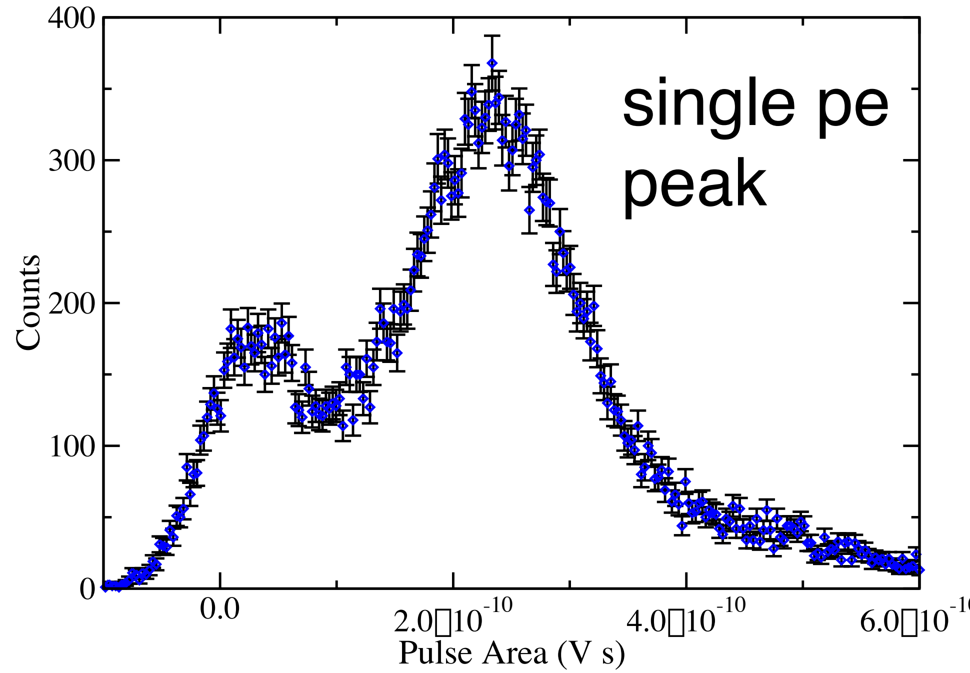


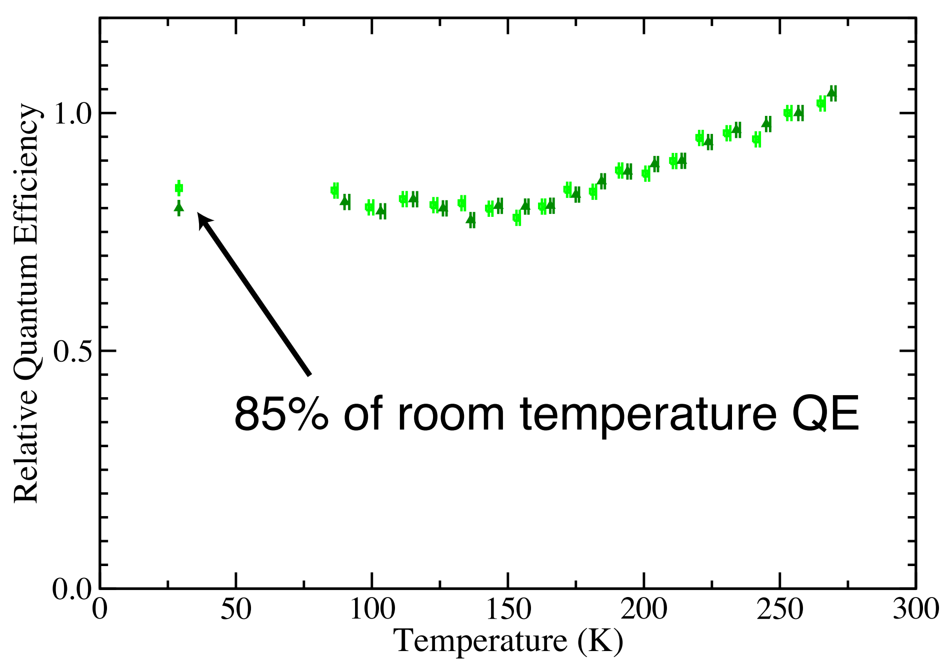
Pulse shape discrimination in LNe
<pe> = 100
Gammas
Nuclear recoils
Counts
f_{prompt}
0
50
100
150
200
0
0.1
0.2
0.3
0.4
0.5

Neon PSD from pico-CLEAN



PMT testing at 27 K





Micro-CLEAN

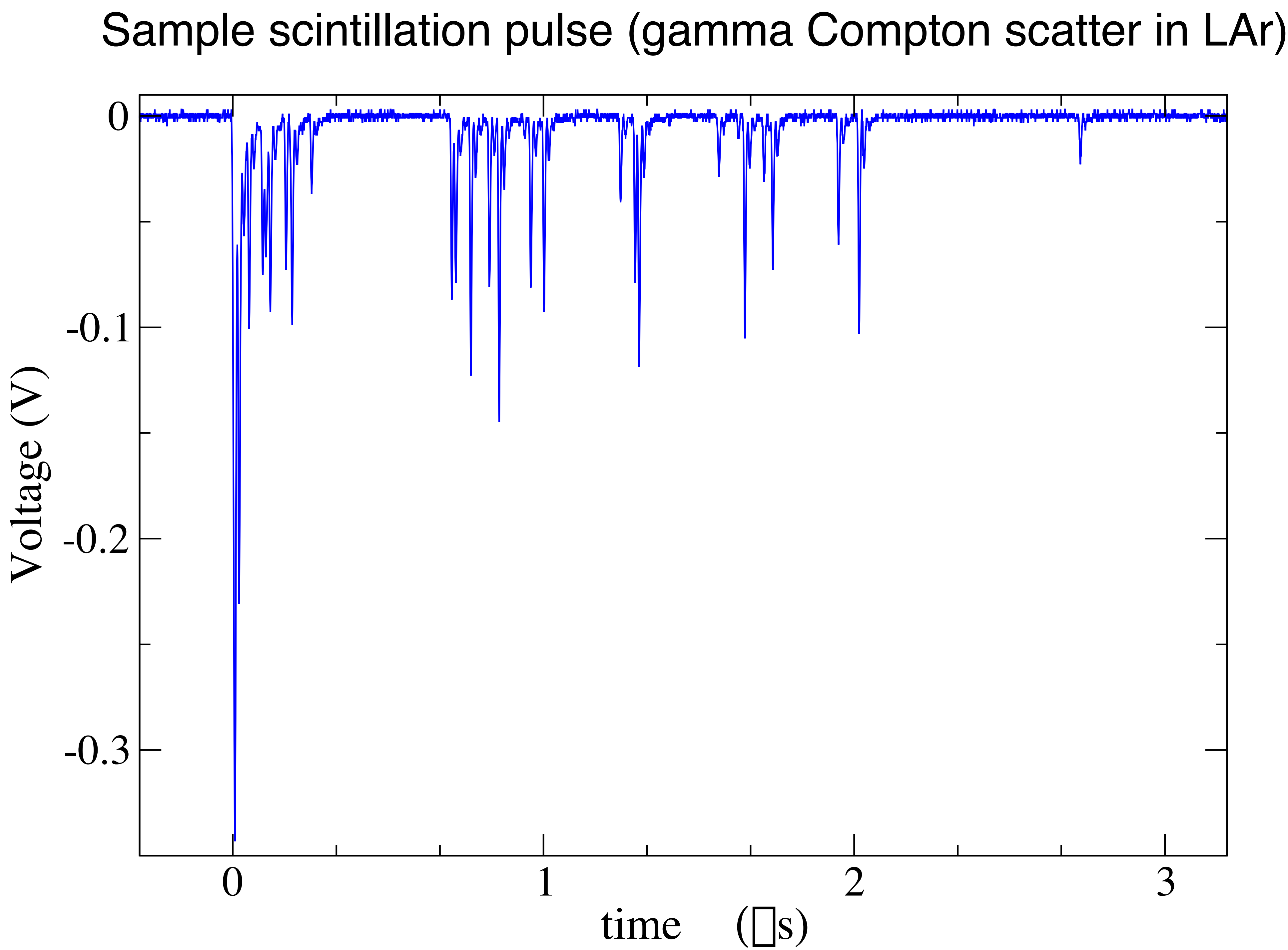
Currently in operation at Yale
Two 20-cm PMTs
4 kg active mass of LAr or LNe
PMTs are immersed in the liquid

Signal:
4.2 pe/keV for electronic recoils in 2006.

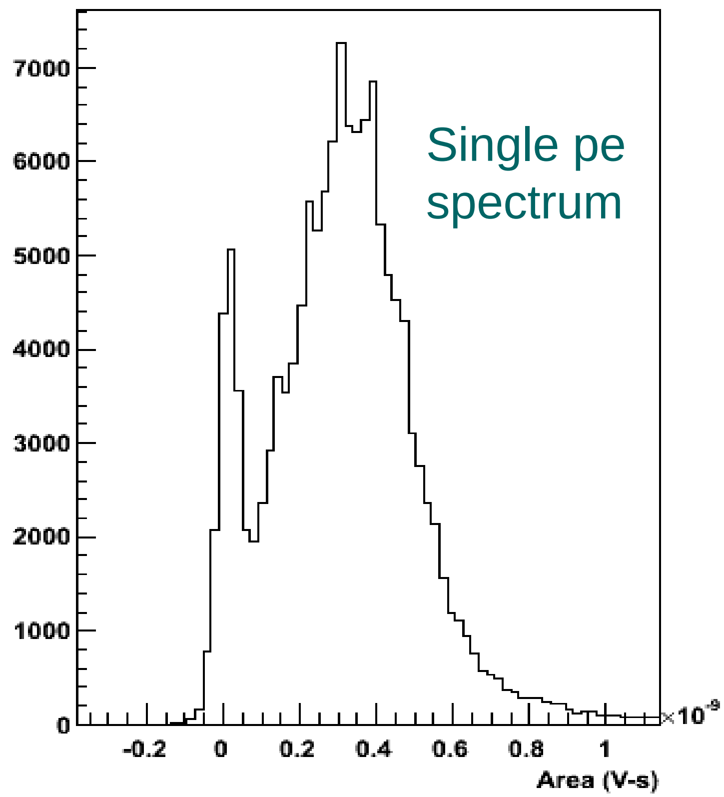
Jan-Feb 2007: improved WLS coating
added continuous purification

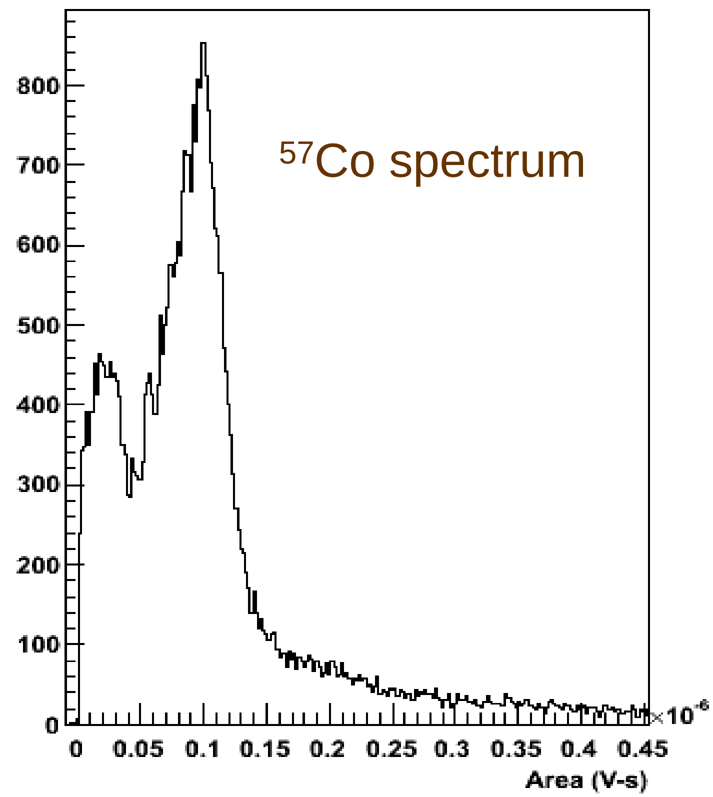
-----> 4.9 pe/keV right now

Goals:
1) Measure light yield for nuclear recoils
2) Test PMTs in LAr, LNe
3) Test digitization electronics
(from Boston U)
4) Test discrimination down to 10 keVr


Sample scintillation pulse (gamma Compton scatter in LAr)
0
-0.1
-0.2
-0.3
Voltage (V)
0
1
2
3
time (μs)

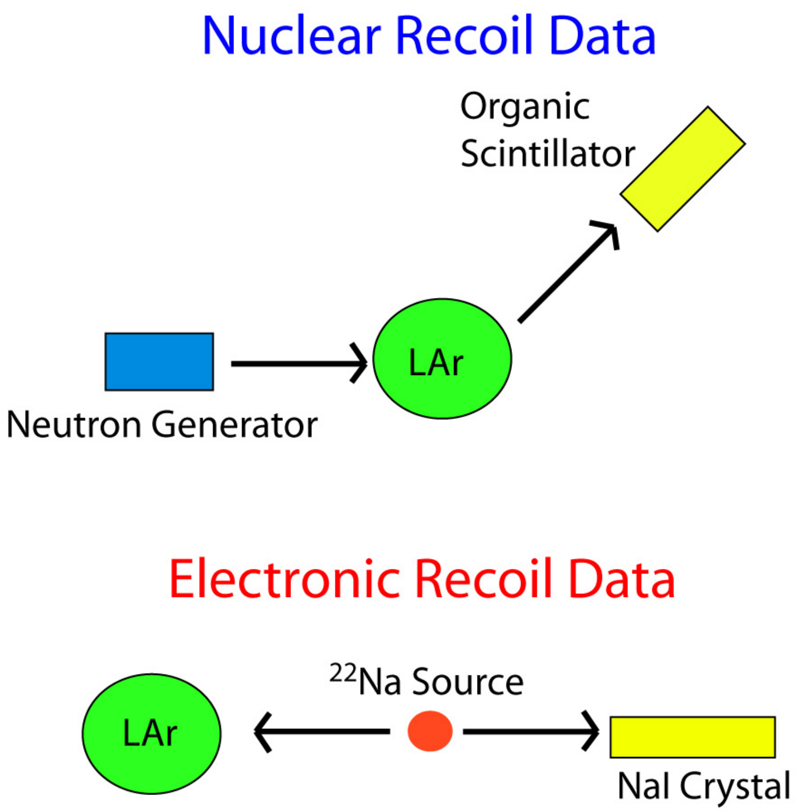
Light Yield





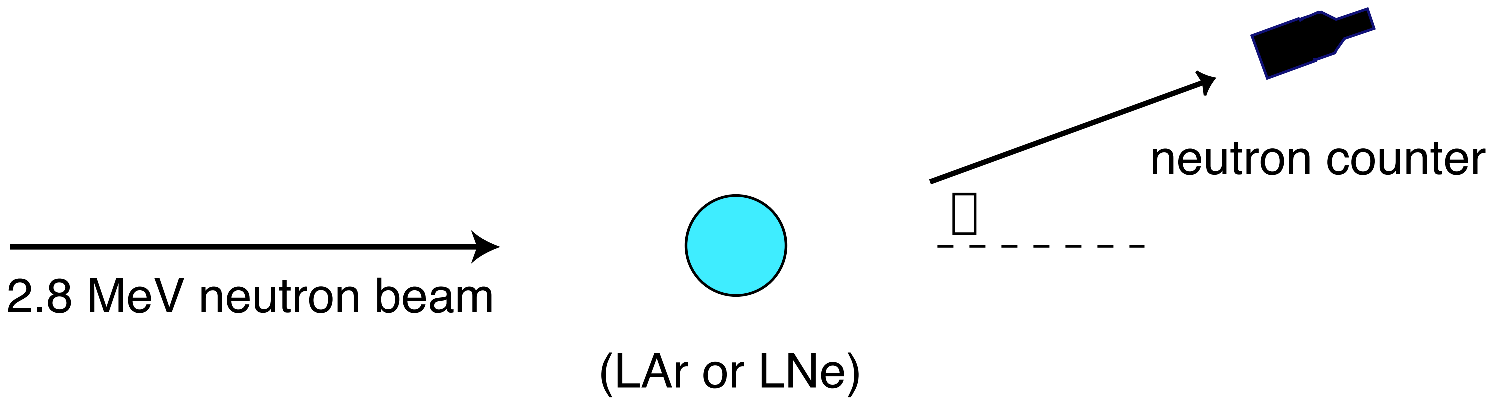
- Single photoelectron spectrum and cobalt peak for one of the PMTs
- Measure the light yield to be 4.9 pe/keVee

Data Tagging and Quality



- Require coincidence with external detector
- Time of Flight cut
- PSD cut in organic scintillator
- Energy cut in NaI crystal
- Asymmetry cut in the PMTs

Calibration of nuclear recoil-induced scintillation in LAr and LNe



Require delayed coincidence between cryogenic scintillator and neutron counter

$$E_A = E_n \frac{2M_n M_A}{(M_n + M_A)^2} (1 - \cos \theta)$$

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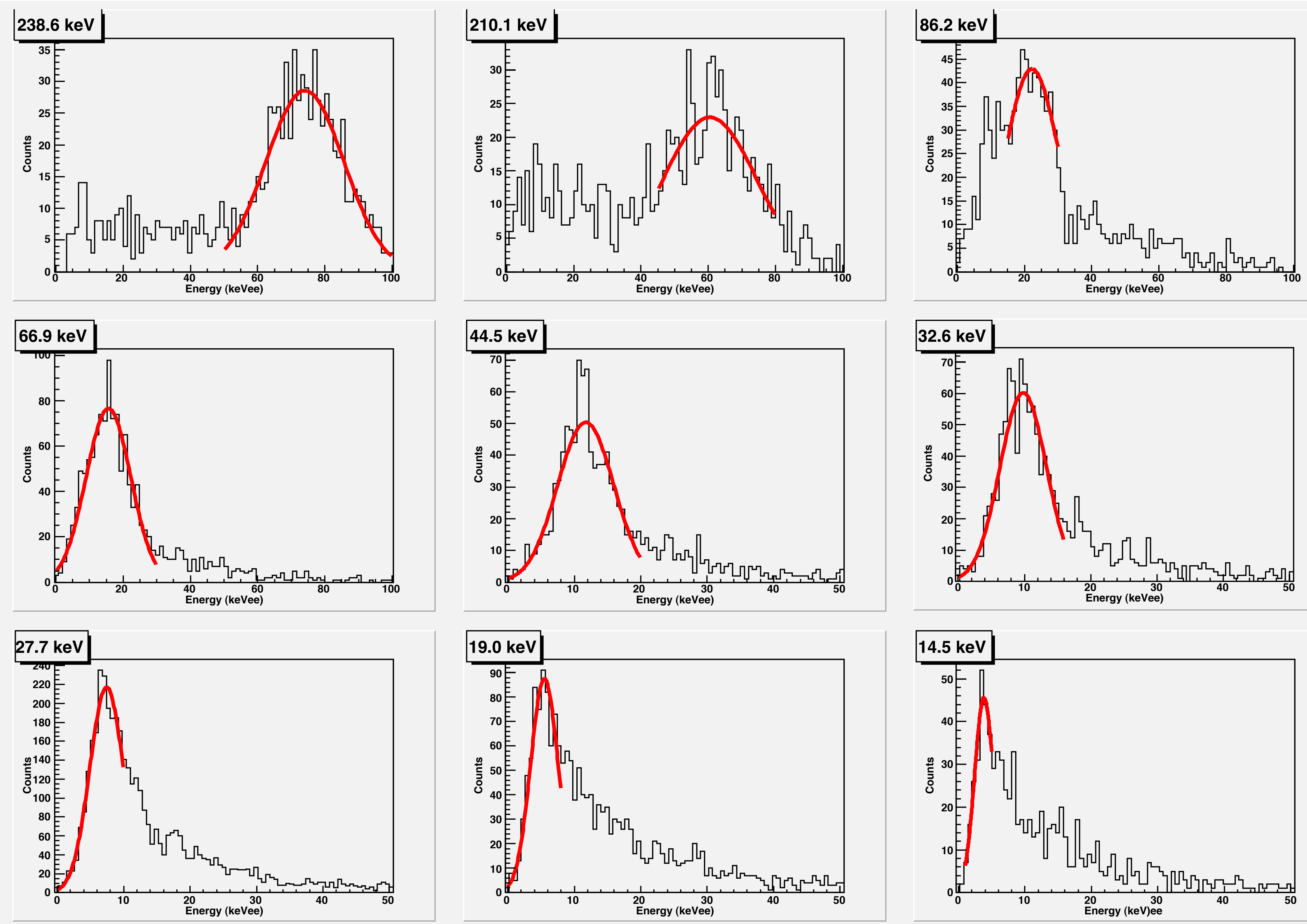
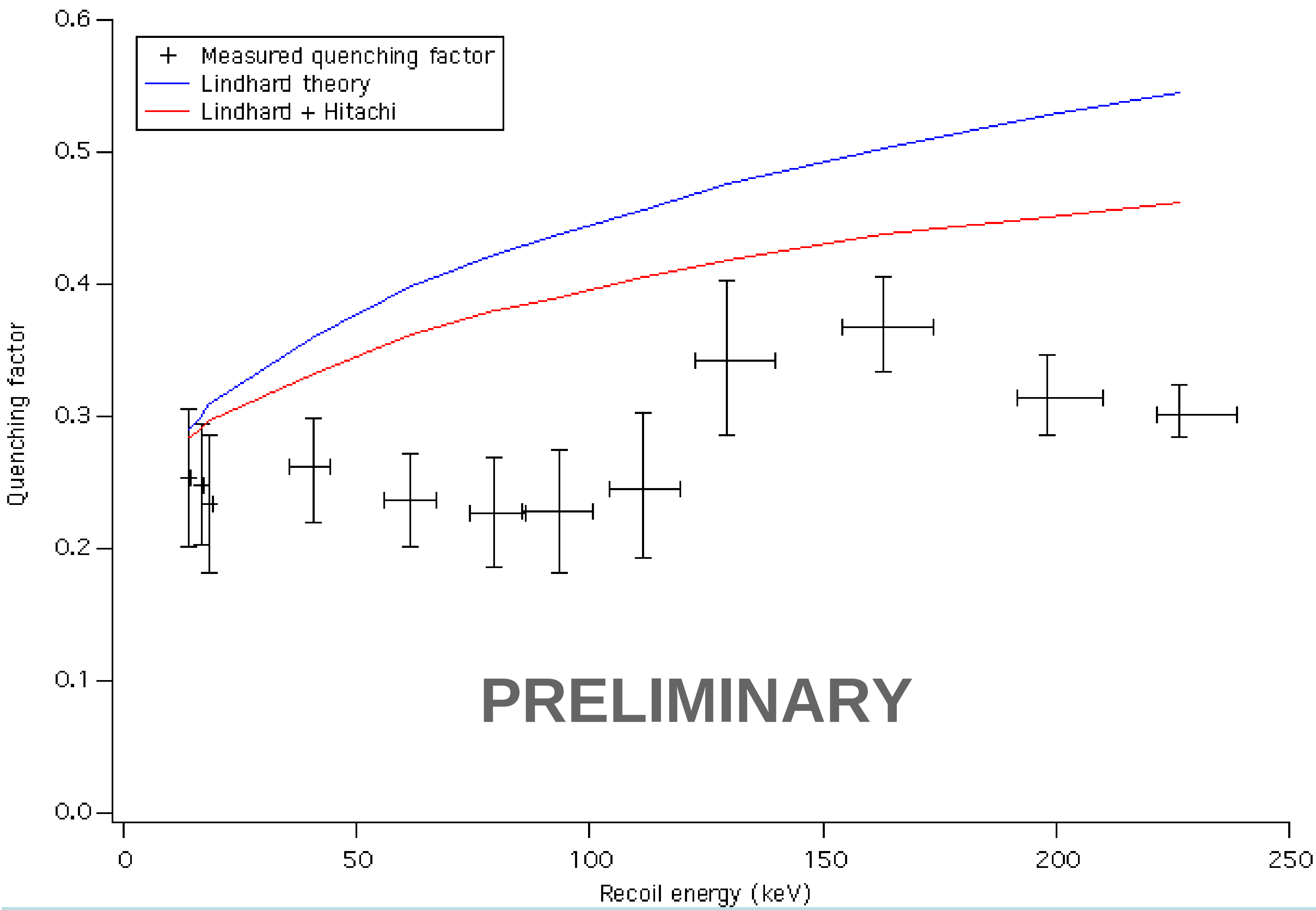
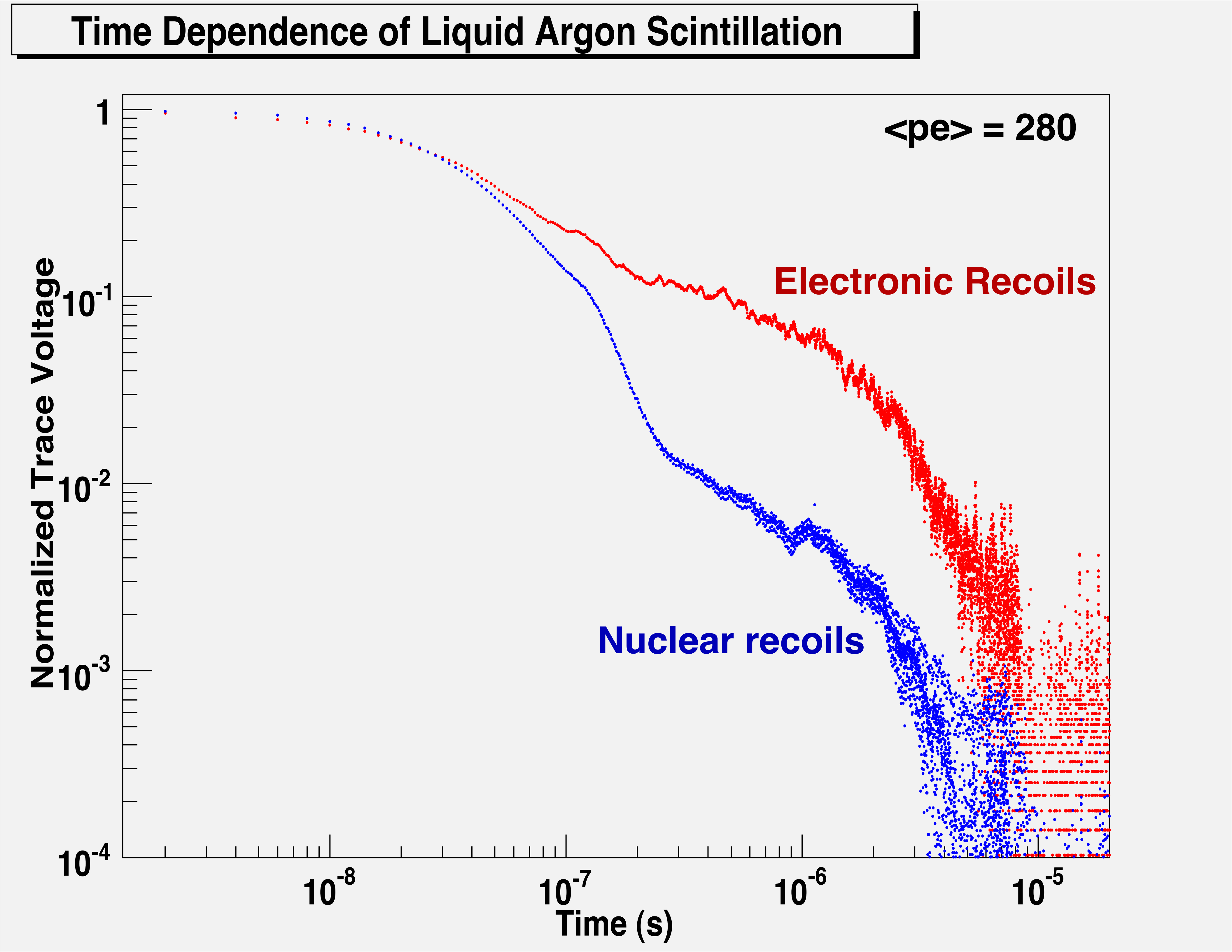
Neutron Peaks at a Variety of Scattering Angles in LAr

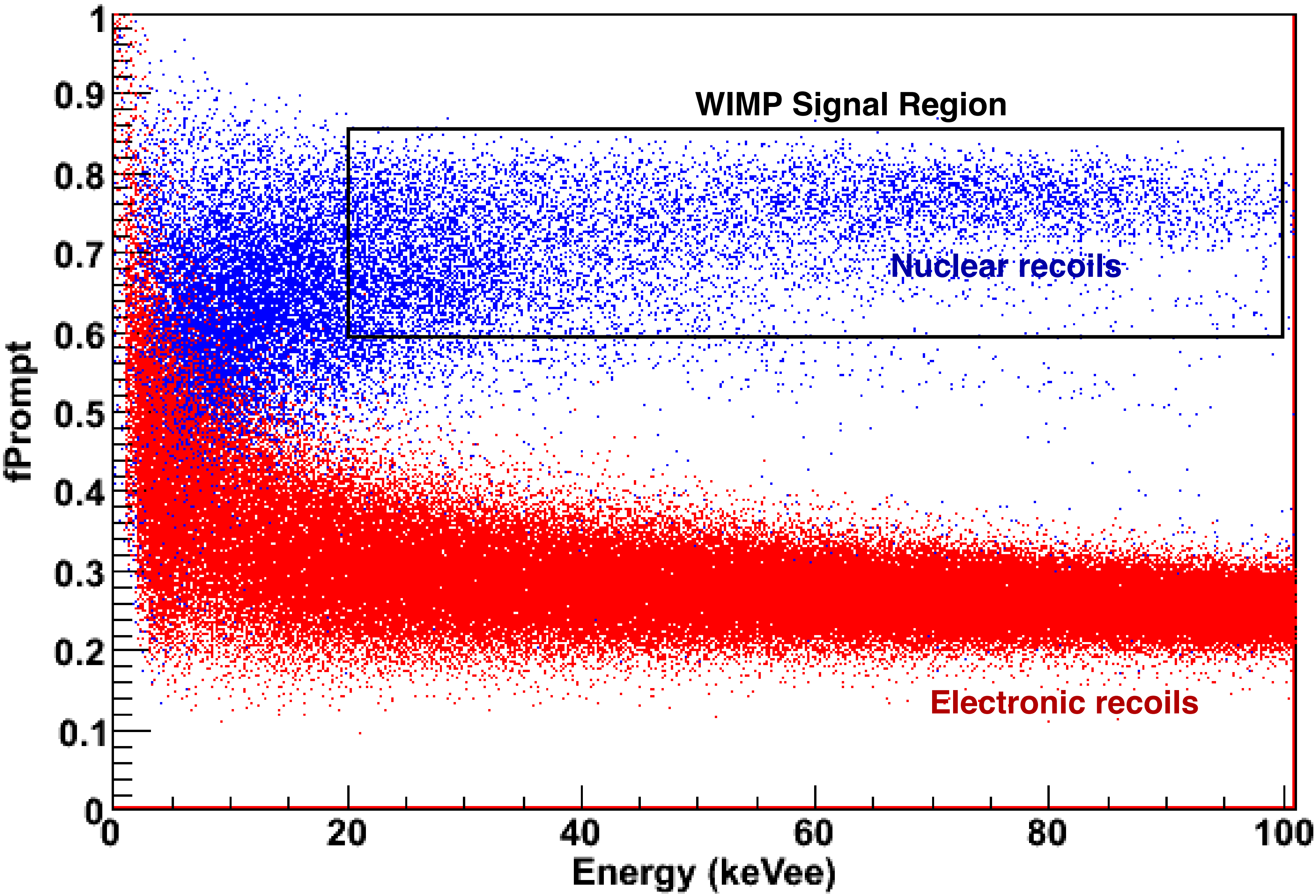


LAr Quenching Measurements





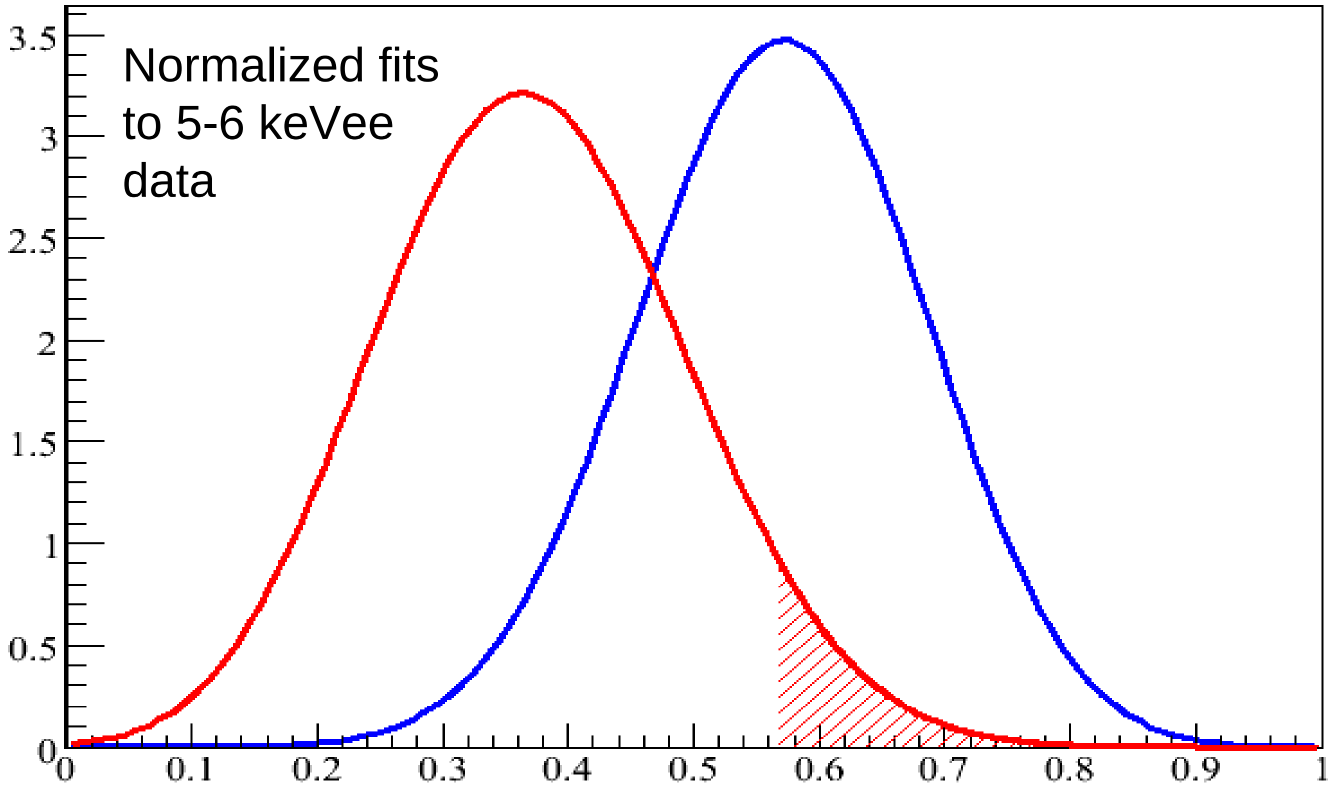
Time Dependence of Liquid Argon Scintillation
<pe> = 280
Electronic Recoils
Nuclear recoils
Normalized Trace Voltage
1
10-1
10-2
10-3
10-4
10-8
10-7
10-6
10-5
Time (s)



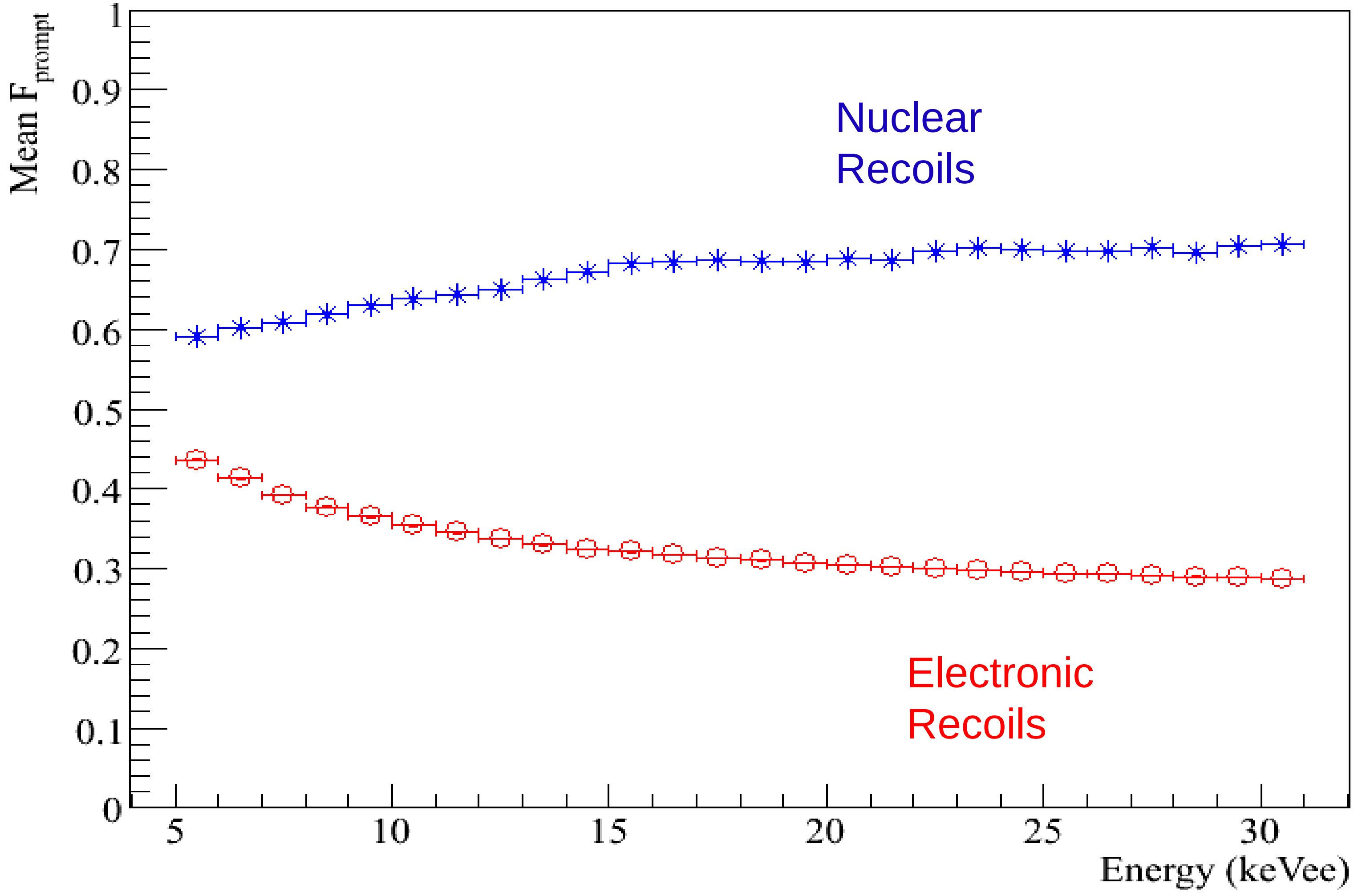
WIMP Signal Region
Nuclear recoils
Electronic recoils
fPrompt
Energy (keVee)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100

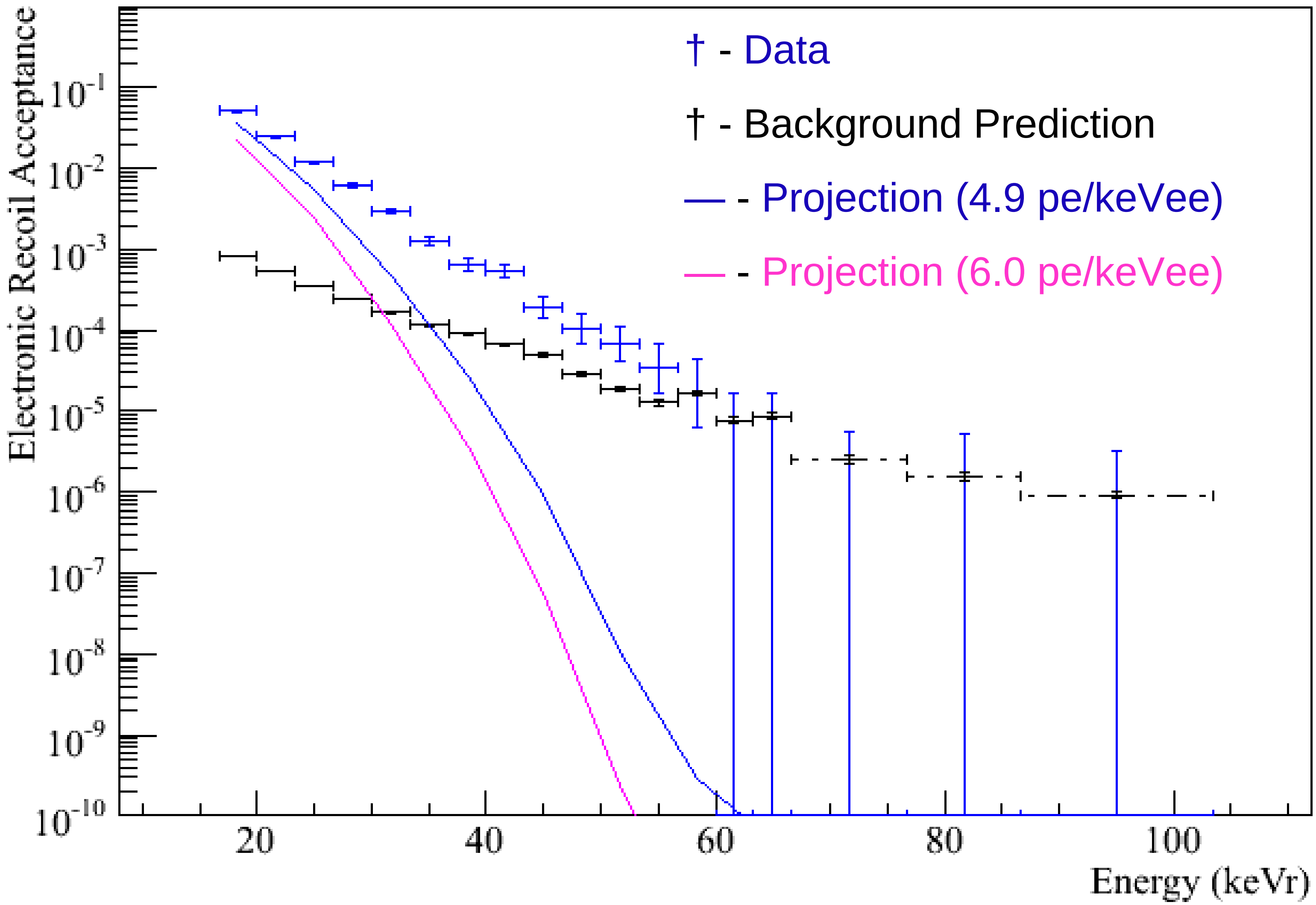
Analytic Projections

- Analytically integrate area underneath electronic recoil curve above 50% nuclear recoil acceptance level
- Scale fitted binomial widths linearly with light yield, relative to 4.9 pe/keV in microCLEAN



Mean F_{prompt} v. Energy





- Binning set to have relatively equal counts in the high energy background bins
- From 60-103 keVr, we have 0 “nuclear recoil events” – better than 1.25 x 10^{-6} rejection

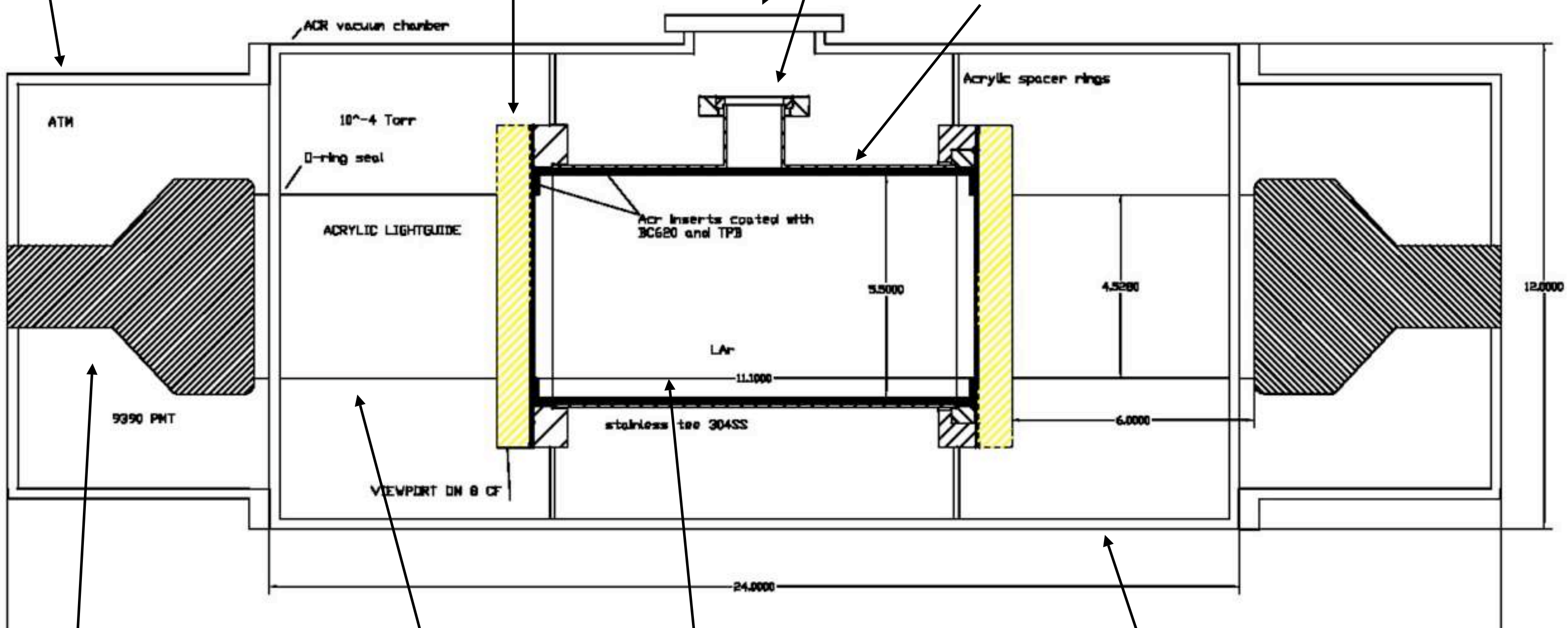
DEAP-1 design

Neck connects to vacuum and
Gas/liquid lines

Quartz windows

11” x 6” (8” CF) tee

poly PMT supports



6” acrylic guide

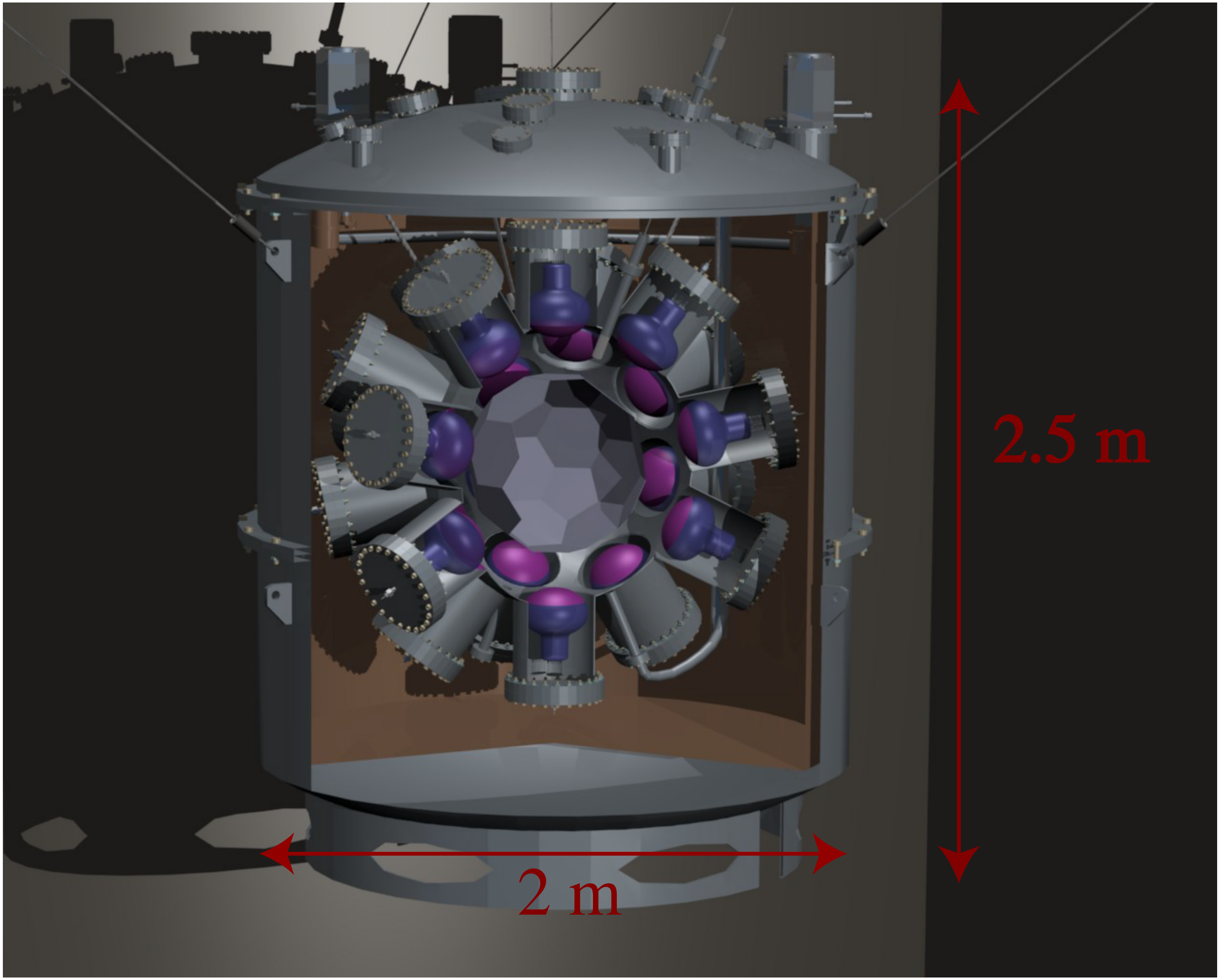
Acrylic vacuum chamber

ET 9390 PMT 5”

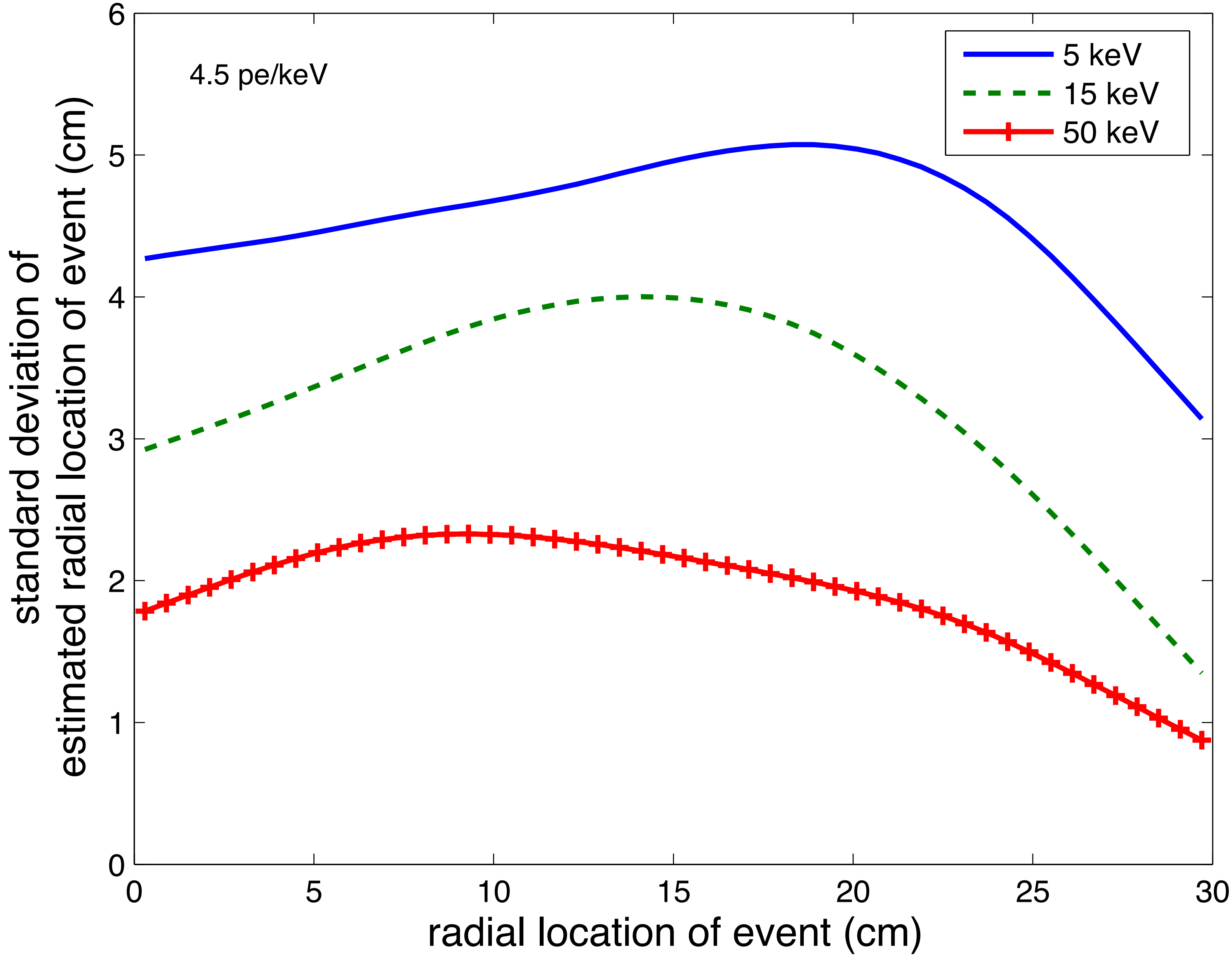
inner surface 97% diffuse reflector,
Covered with TPB wavelength shifter

Mini-CLEAN

Fiducial (total) mass: □ 100 (~ 500) kg of LAr or LNe.   Expected signal yield > 6 pe/keV



Projected position resolution in mini-CLEAN
(Monte Carlo + Maximum Likelihood)



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Neutron Background Study for LAr-Mini-CLEAN

Mei & Hime

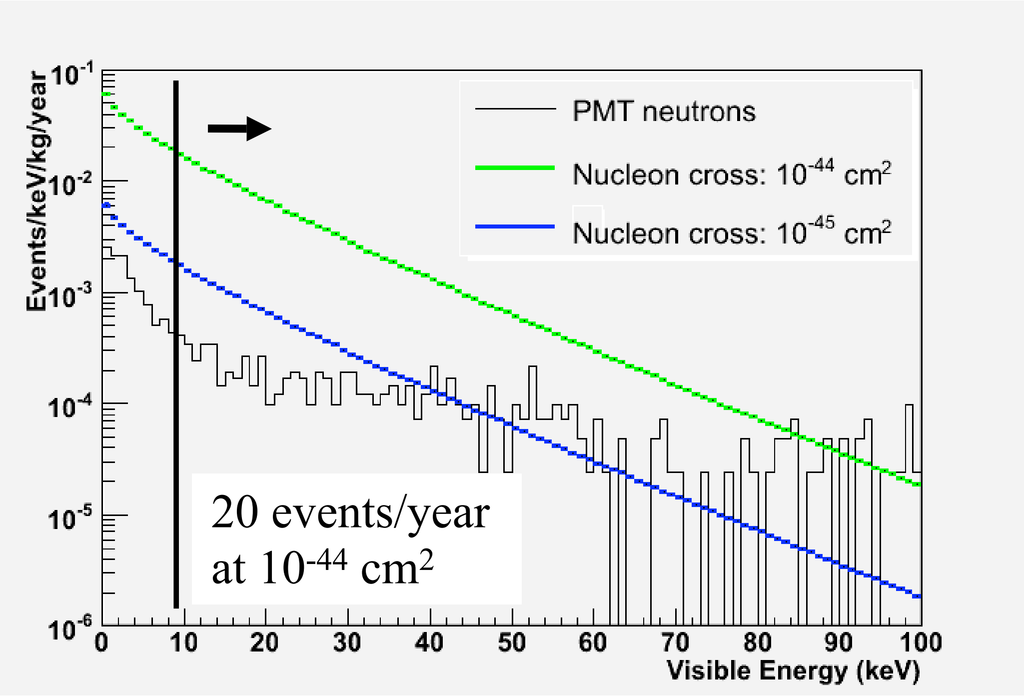
Component	Material	U/Th	Yield (n / yr)	Yield in Target (n / kg /yr)	Yield in ROI (n / kg /yr)	Yield in ROI* (n / kg /yr)
Fiducial Sphere	15 kg Quartz	3 ppb	19	0.090	0.047	0.0042
	5 kg SS	3 ppb	4	0.021	0.005	0.0006
PMT Sphere	20 kg SiO_2	30 ppb	256	0.020	0.011	0.0023
	4 kg B_2O_3	30 ppb	2304	0.340	0.100	0.0238
	85 kg SS	3 ppb	68	0.010	0.003	0.0006
Outer Cryostat	125 kg SS	3 ppb	100	0.020	0.003	0.0008
Total			2751	0.510	0.169	0.032

$R_f \sim 26$ cm for $M_f \sim 100$ kg

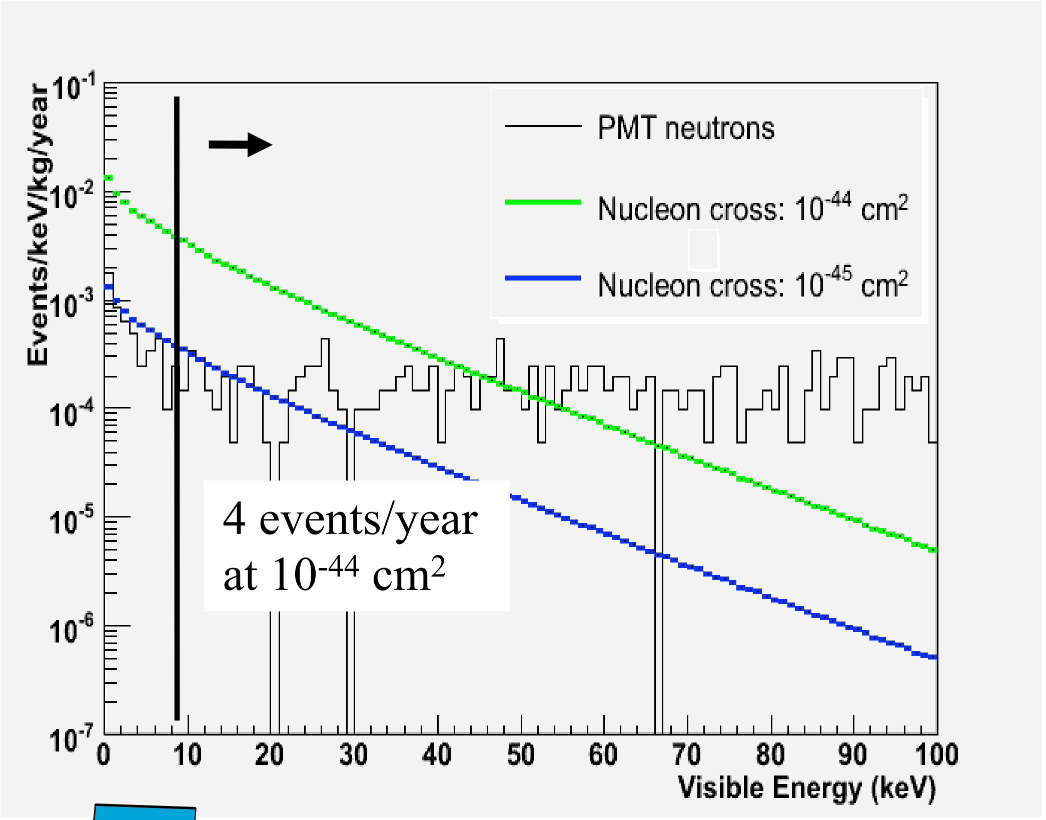
$R_{PMT} \sim 38$ cm

$R_C \sim 46$ cm

100kg Mini-CLEAN-LAr



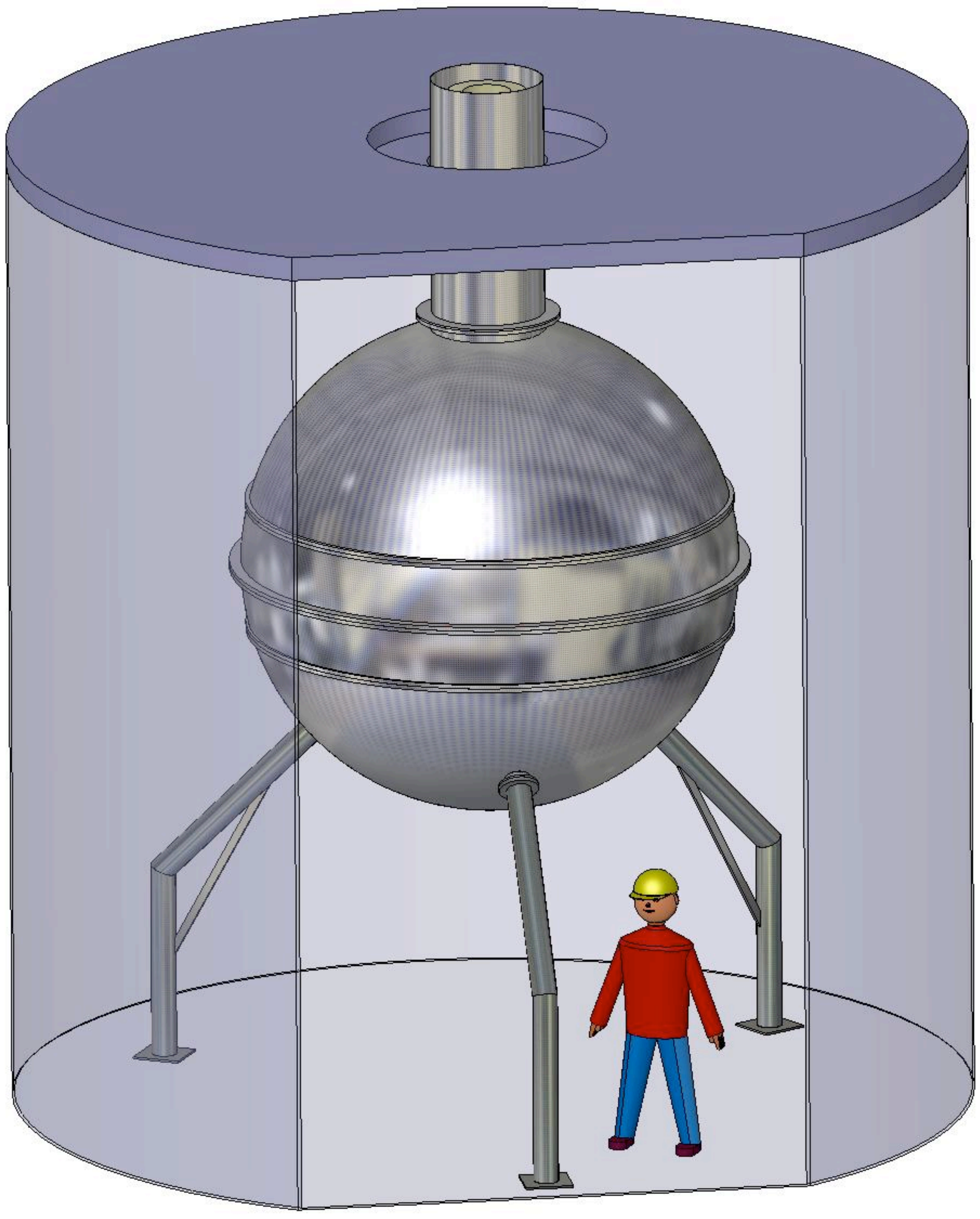
100kg Mini-CLEAN-LNe



Exchange Target in Identical Detector to “Exercise” Signal v.s. BGND

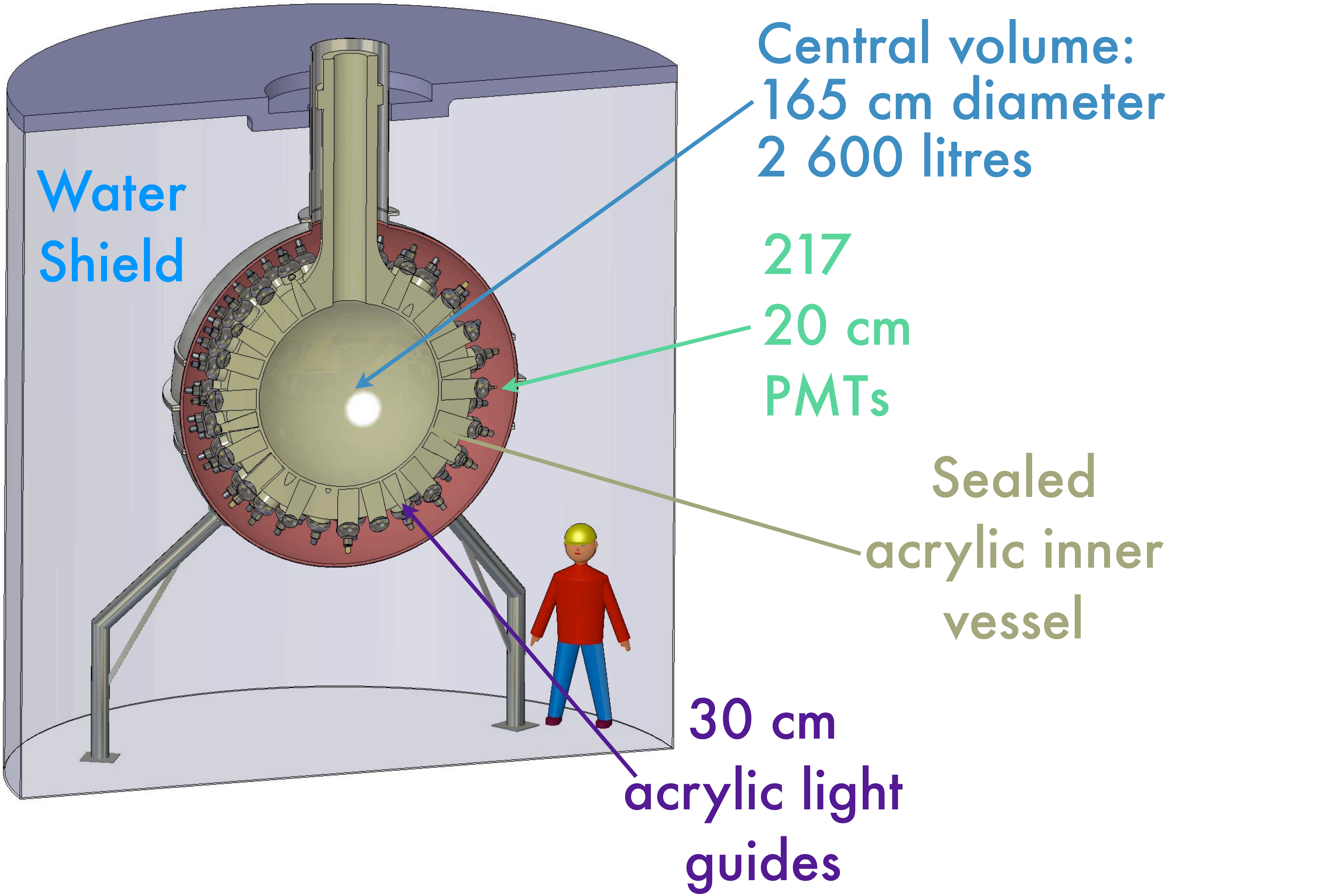
assuming a 100 GeV WIMP $\left\{ \begin{array}{c} S_{Ar} \sim 5 \text{ x } S_{Ne} \\ B_{Ar} \sim B_{Ne} \end{array} \right\}$ **& similar energy threshold**

DEAP/CLEAN 3600



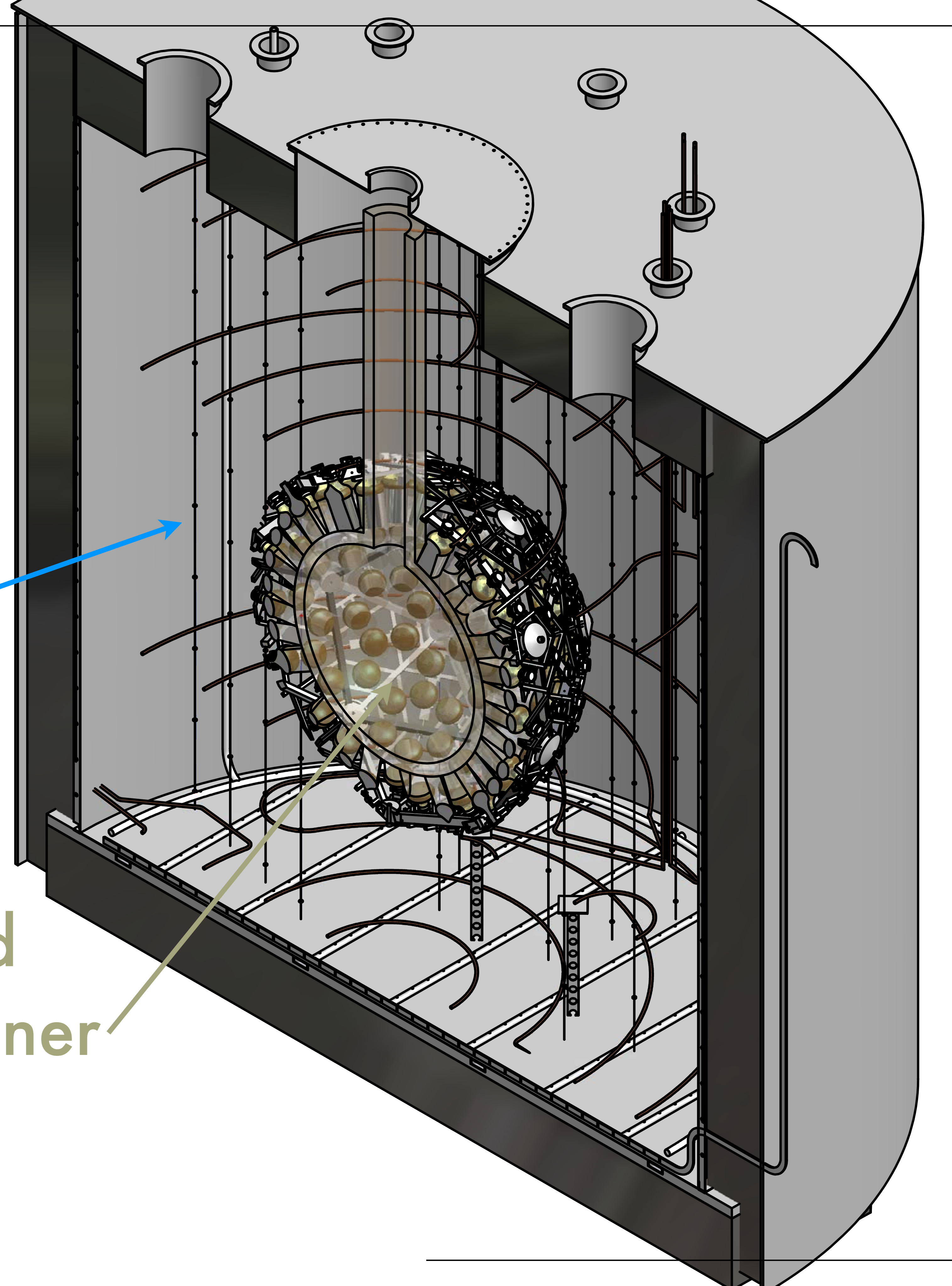
- Dark matter detector with a sensitivity of 3×10^{-46} cm^2 at 100 GeV
- Liquid neon and liquid argon capable
  - 3.1 tonne LNe
  - 3.6 tonne LAr

Cryostat option



Ice option

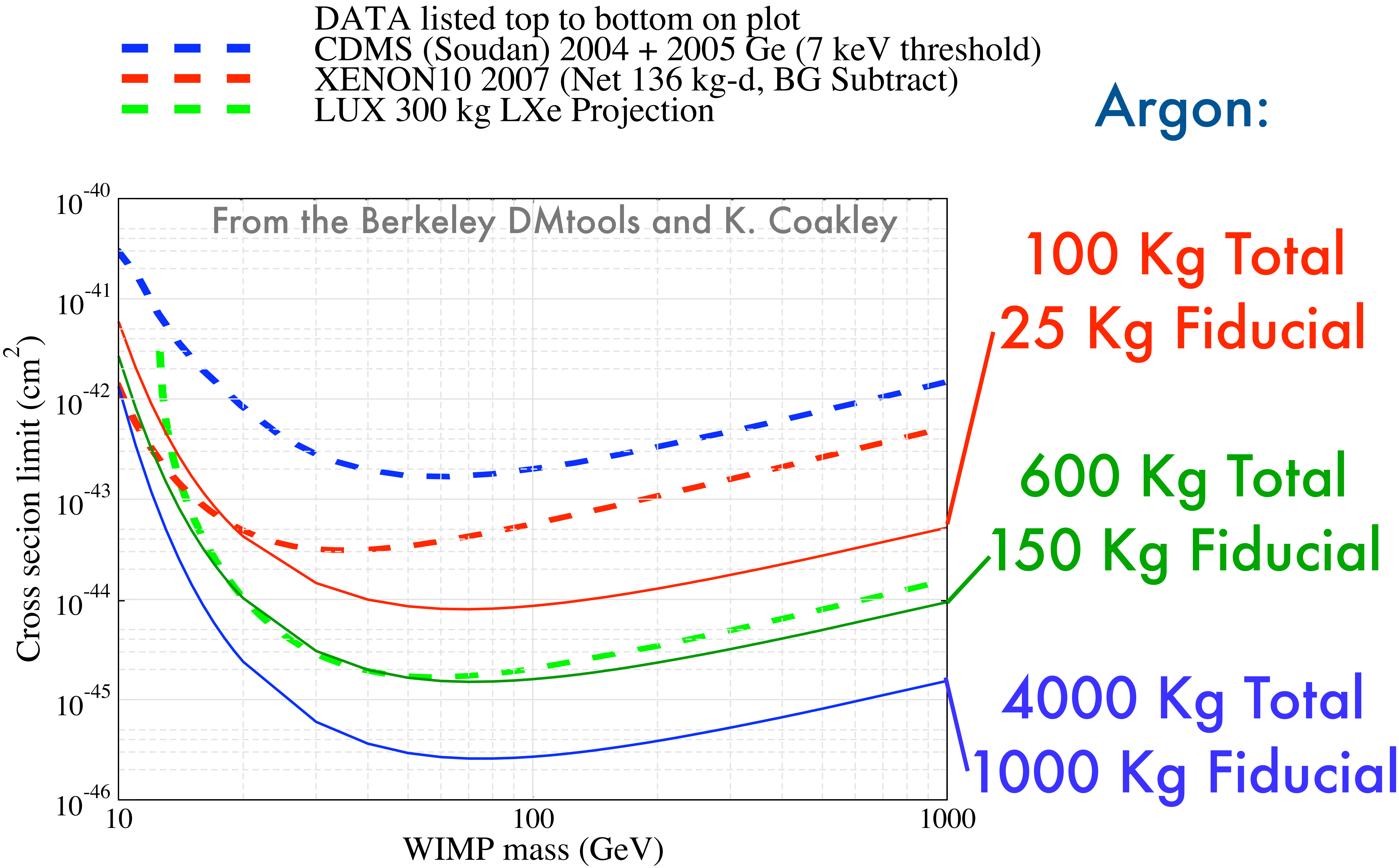
Central volume:
165 cm diameter
2 600 litres



Ice with no cryostat

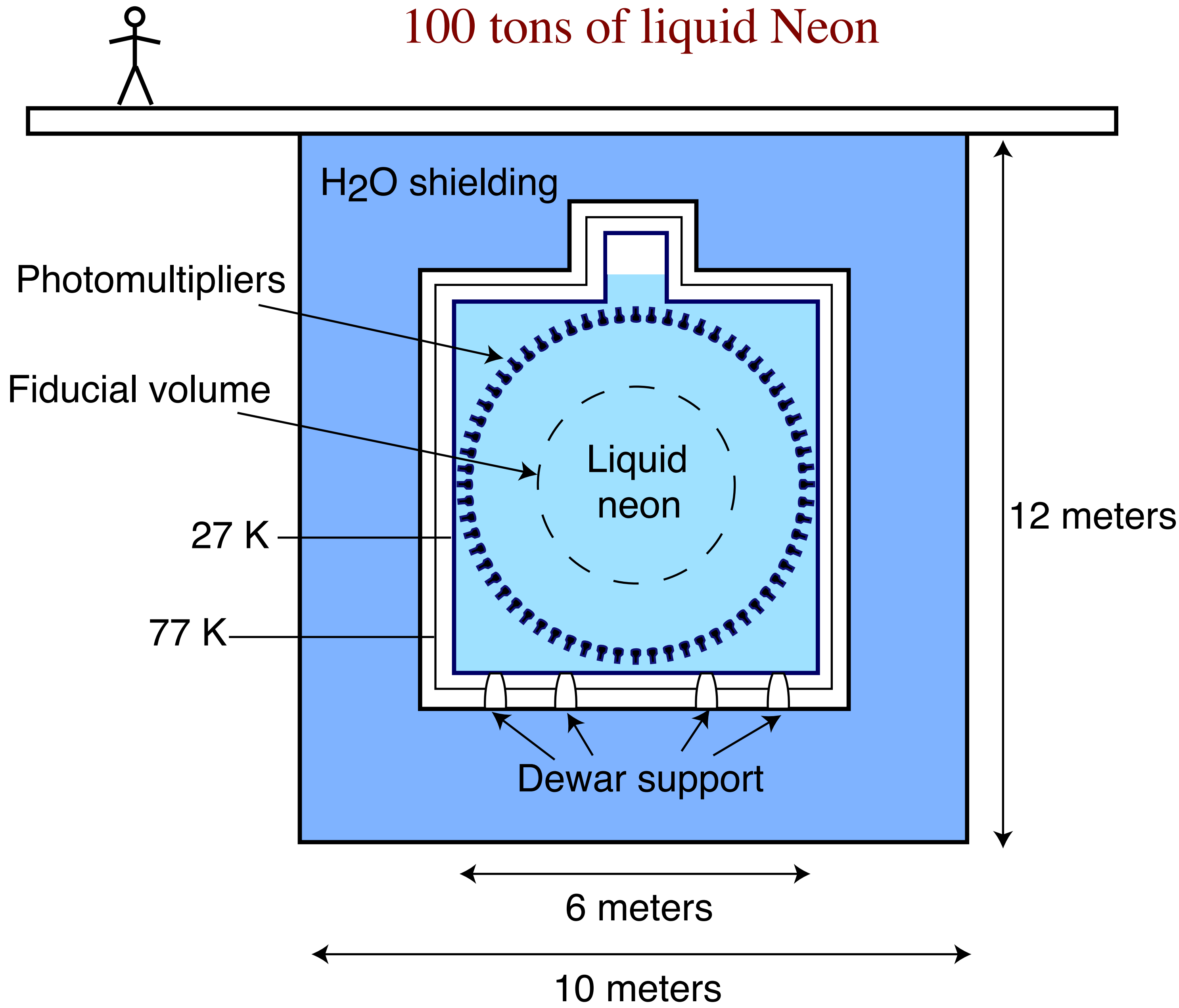
Sealed acrylic inner vessel

Reduced background by eliminating steel cryostat


DATA listed top to bottom on plot
CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
XENON10 2007 (Net 136 kg-d, BG Subtract)
LUX 300 kg LXe Projection
Argon:
From the Berkeley DMtools and K. Coakley
100 Kg Total
25 Kg Fiducial
600 Kg Total
150 Kg Fiducial
4000 Kg Total
1000 Kg Fiducial
Cross secion limit (cm^2)
WIMP mass (GeV)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10
100
1000

CLEAN

100 tons of liquid Neon



Requires > 6000 m.w.e.

DM and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000)
DM and K. J. Coakley, Astropart. Phys. 22, 355 (2005)

Monte Carlo simulation: M. Boulay, A. Hime, J. Lidgard, nucl-ex/0410025

Simulations performed with GEANT4
15,000 photons/MeV
60 cm Rayleigh scattering length
75% PMT coverage, 15% QE
100% photon-to-photon wavelength shifter efficiency
Background dominated by (commercially available) PMT glass: 30 ppb U/Th, 60 ppm K