Calibration and Modeling of Nuclear and Electron Recoils in Liquid Argon

Workshop on Calibration of
Low Energy Particle Detectors

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Lawrence Livermore National Laboratory

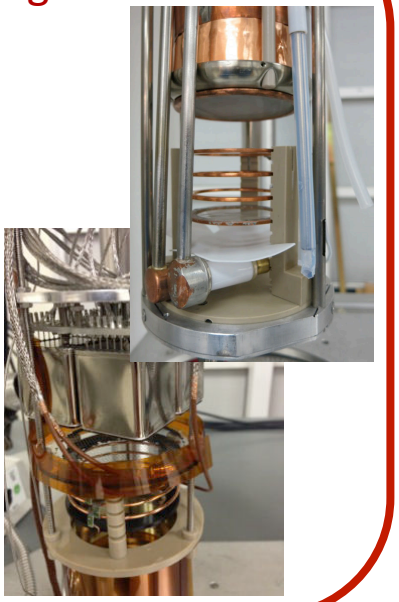
LLNL's Noble Liquid R&D Program

Physics Motivations

- Dark Matter
- Coherent Elastic Neutrino-Nucleus Scattering

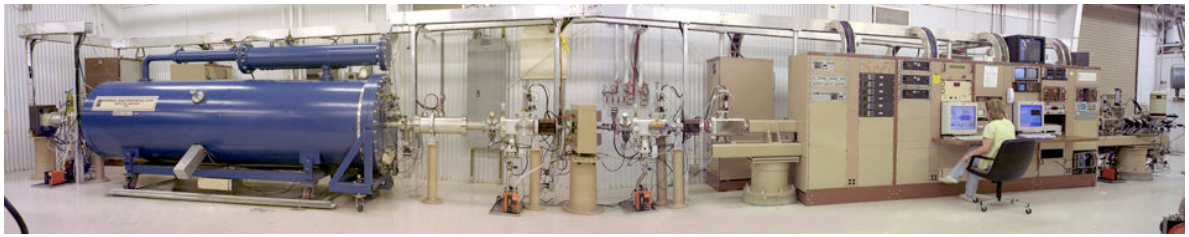
Liquid Xenon and Argon Detectors

- Two small dual-phase detectors
- Measure electron and nuclear recoils < few keV
- Understand and control low-energy backgrounds
- HV stability in noble liquids



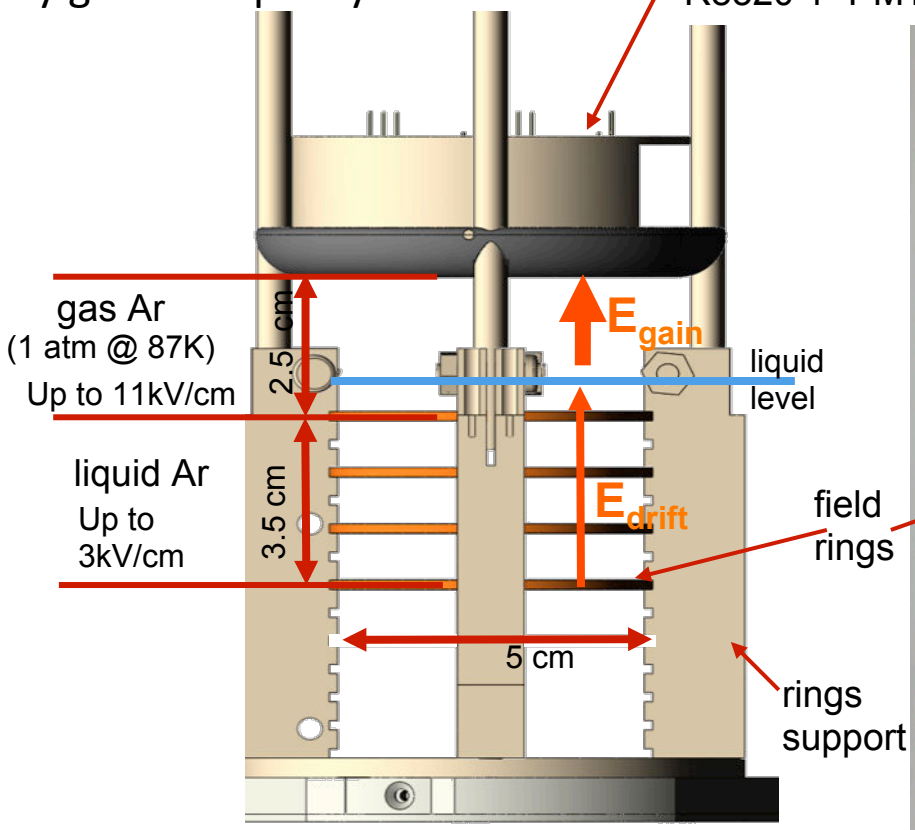
Dedicate low-energy neutron beam

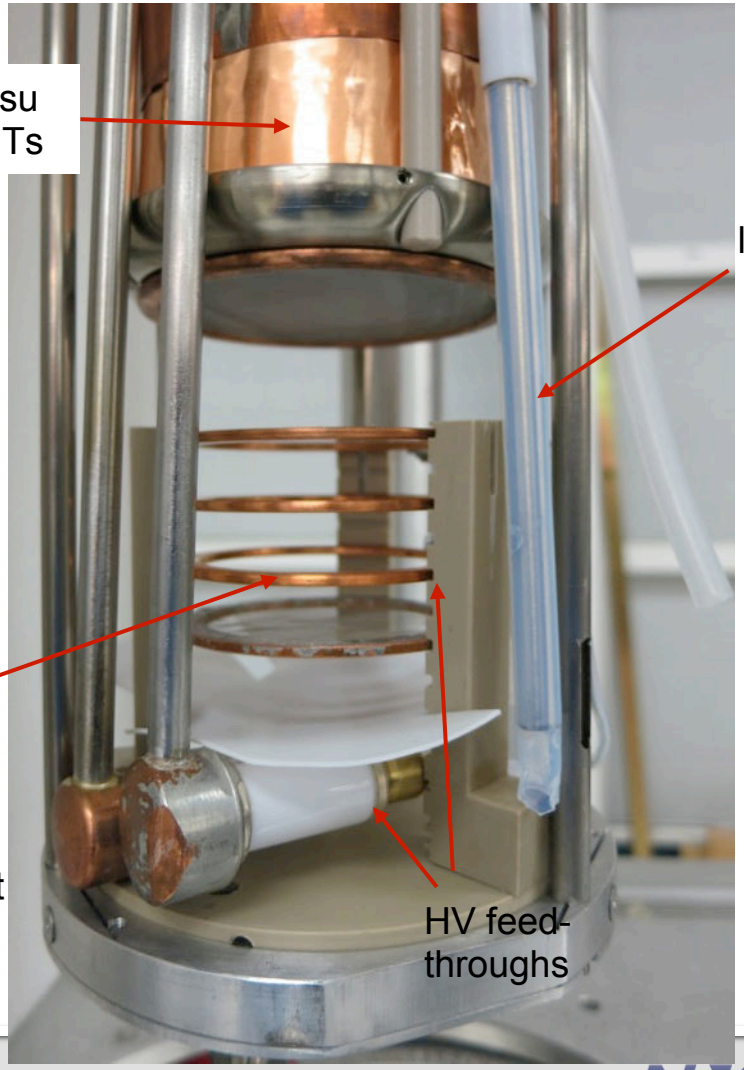
- On-site at LLNL
- Quasi-monoenergetic filtered neutron beam



LLNL Dual-Phase LAr Detector

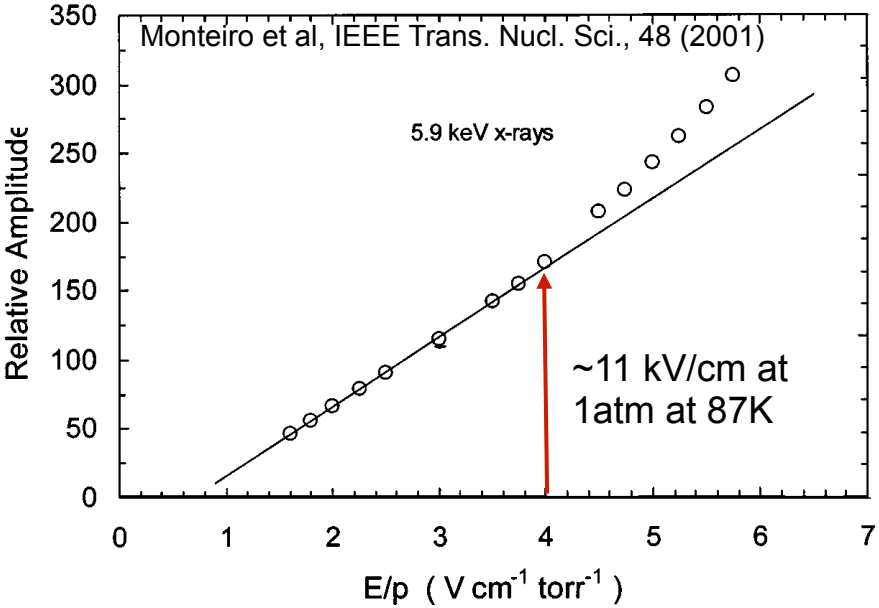
- Active volume: ~ 100 g Lar
- TPB as wavelength shifter
- Home-built HV feed-throughs
- Very good LAr purity

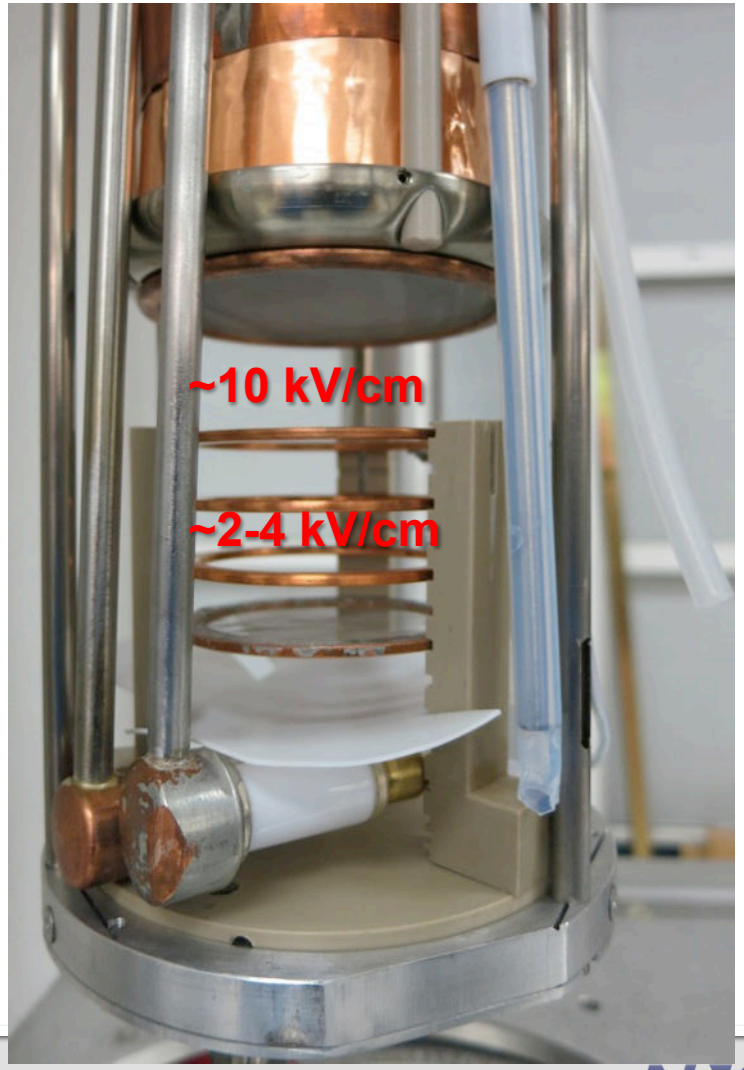




High Gain Detection of Ionization Signal

- Interest in the lowest energy possible
- Emphasis on detection of ionization by means of S2 only
- Operate close to electron multiplication in gas





Ar-37 as a Diffuse Low-E Calibration Source

Decay scheme

100% electron capture

$t_{1/2}$ = 35.04 d

Decay radiation

K- capture **2.82 keV** (90.2%)

L- capture **0.27 keV** (8.9%)

M- capture 0.02 keV (0.9%)

Isotope production

Produced by neutron irradiation of ^{nat}Ar at a nuclear reactor

^{nat}Ar isotopes

Mass number	Natural Abundance
40	99.6%
36	0.34%
38	0.06%

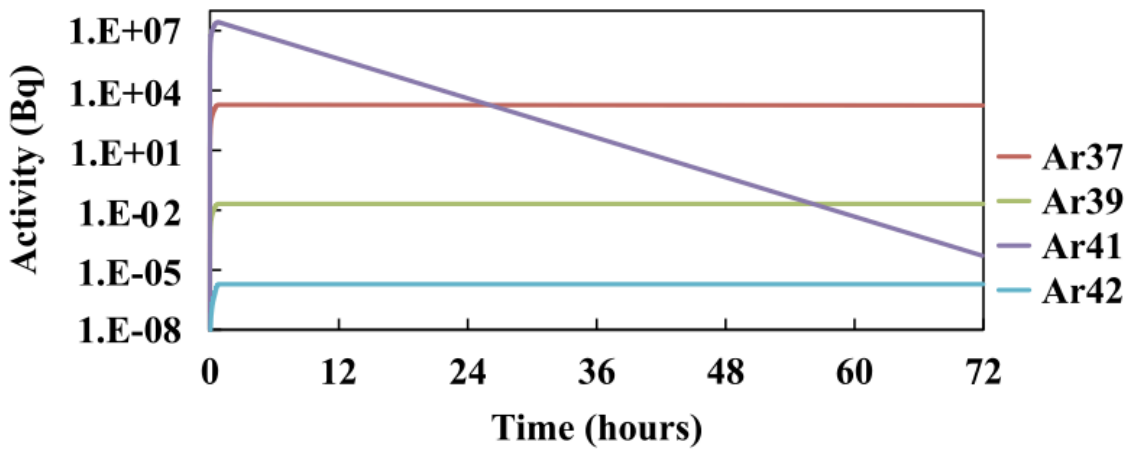
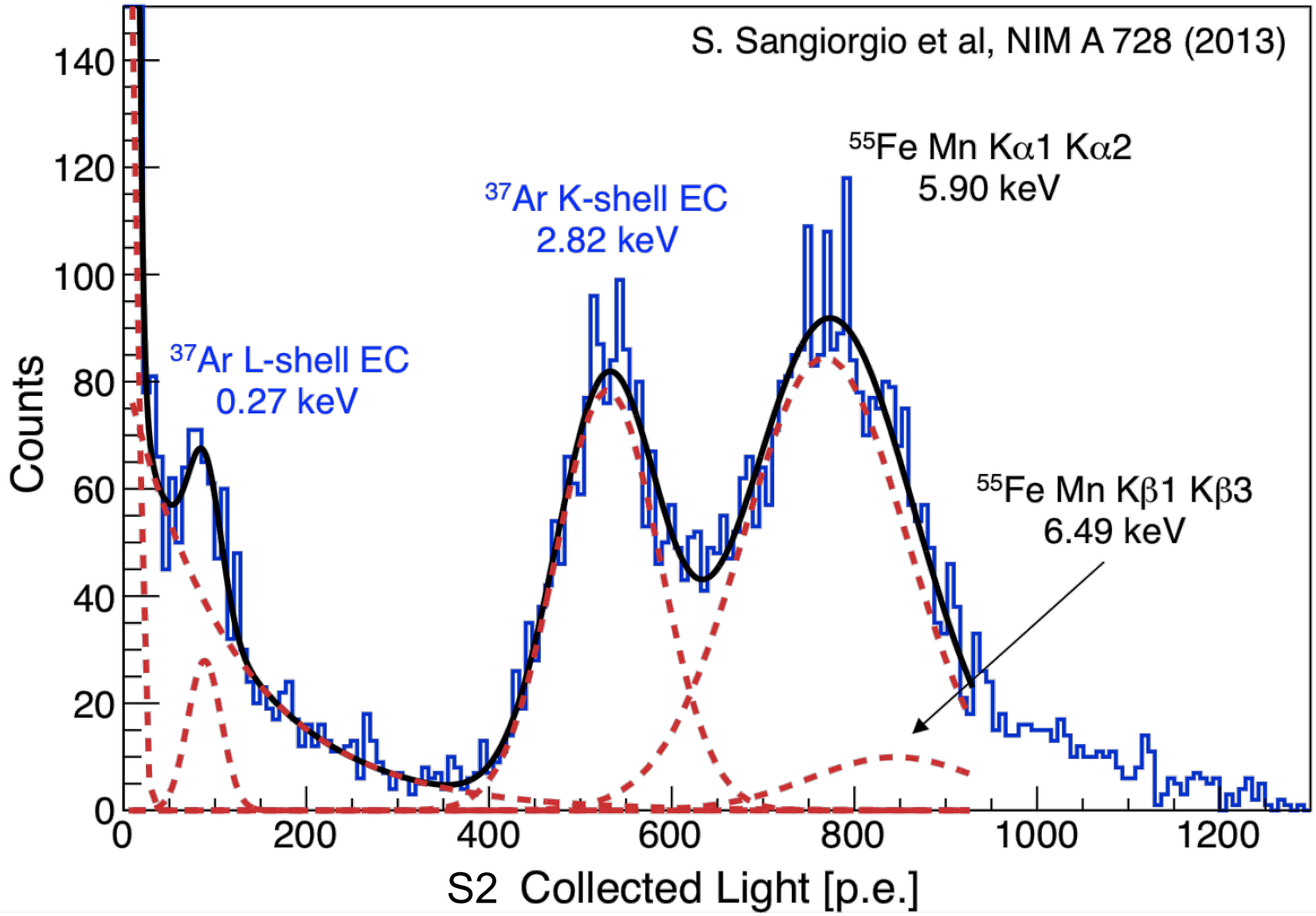


Fig. 1. Calculated activity of radioargon isotopes from 1 h, in-core neutron irradiation of 1 cm^3 of natural argon gas.

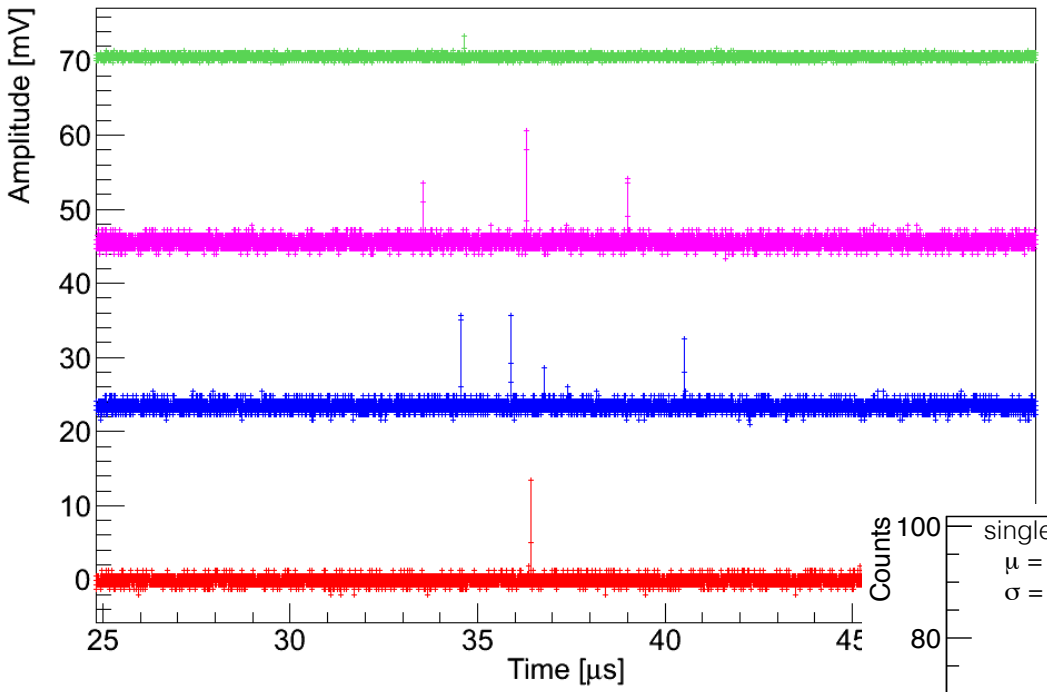
Aalseth, C. E. *et al. NIM A* **652**, 58–61 (2011).

Barsanov, V. I. *et al. Phys. Atomic Nucl* ***70*** (2007).

Sub-keV Calibration for Electron Recoils



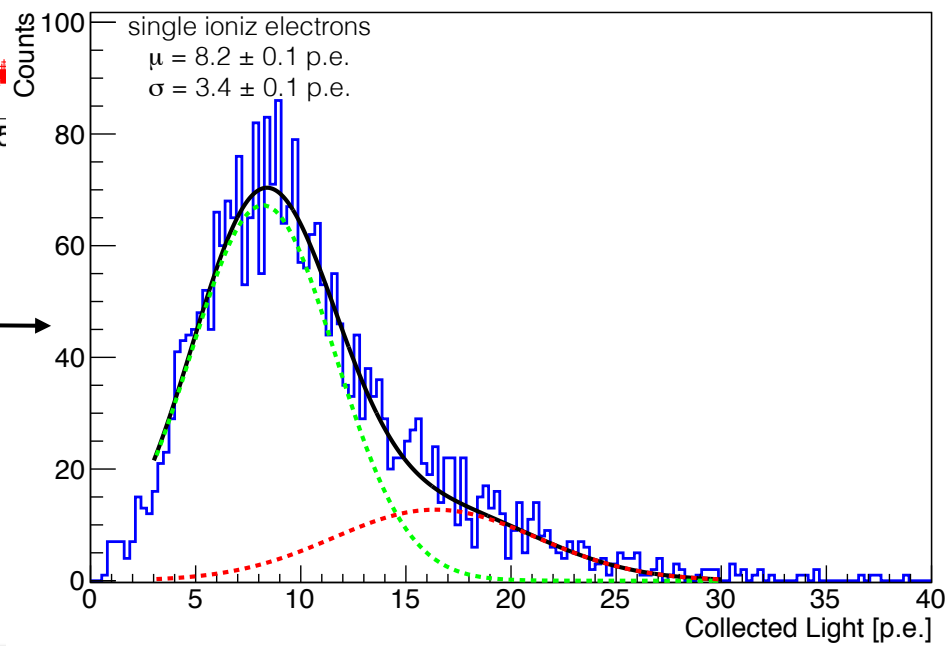
Single Electrons



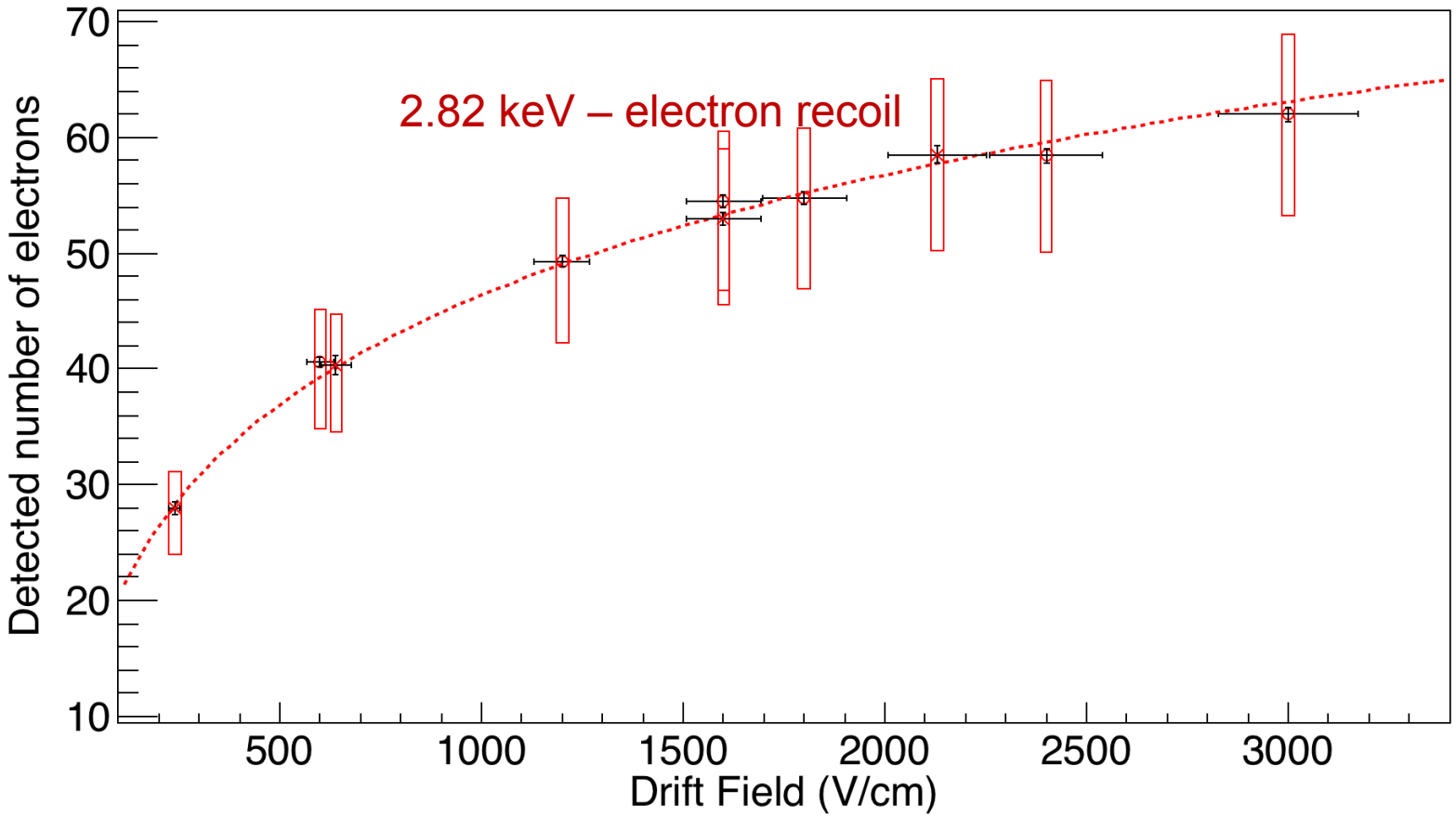
- Typical S.E. event as seen on the scope

- Experimental spectrum of single and double ionization electrons

- Provides absolute calibration of the number of detected electrons



^{37}Ar Electron Recoils vs Electric Field



- Electric field reduces recombination of electron with ions
- Measurements of the 0.27 keV peak vs E field are ongoing
  - Need to deal with low-energy background

Recombination in LAr

Consider electron recoils first

$$S2 \propto n_e = rN_{\rm i}$$

$$N_{\rm i} + N_{\rm ex} = \frac{E}{W} \cdot q(E)$$

Thomas-Imel parameterization of recombination

$$r = \ln(1+\xi)/\xi$$

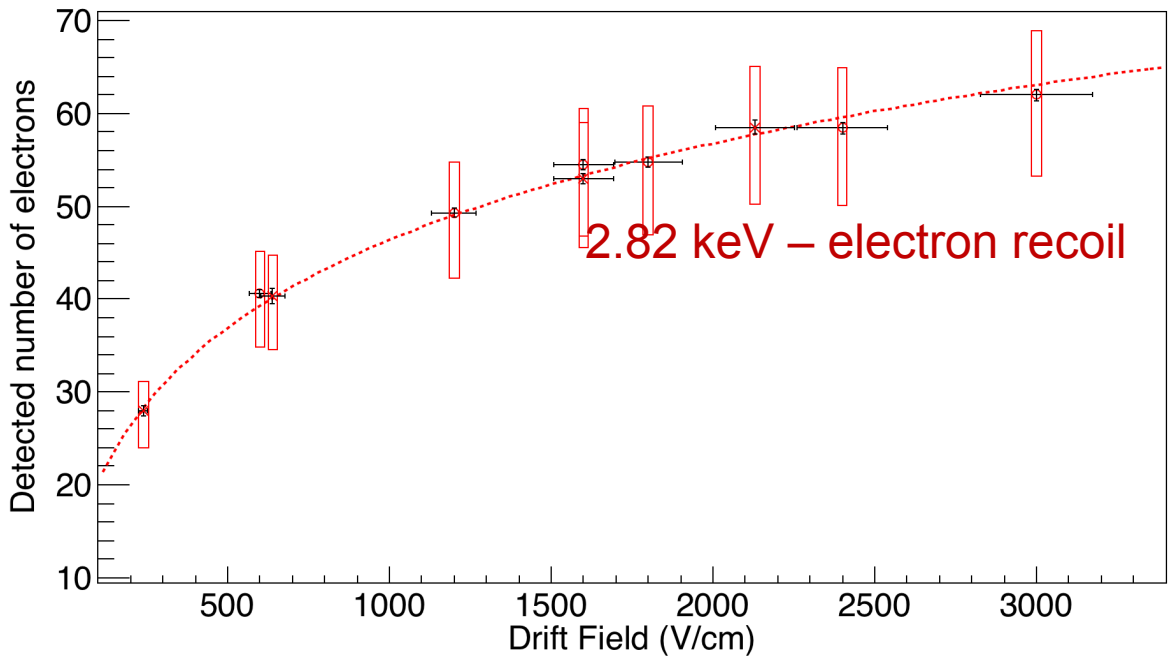
Introduce phenomenological scaling for field dependence:

$$\xi = CN_{\rm i} \cdot \mathcal{E}^{-b}$$

Extract field dependence parameter C, b from fit

For electron recoils the amount of initial ionization N_i is calculable:

- N_{ex} / N_i = 0.21
- E = 2.82 keV for 37Ar K-shell
- W = 19.5 eV
- q(E) = 1



Cfr. Sorensen, P. and Dahl, C. E., *Phys. Rev. D.* **83** (2011)

Modeling recombination in Liquid Argon

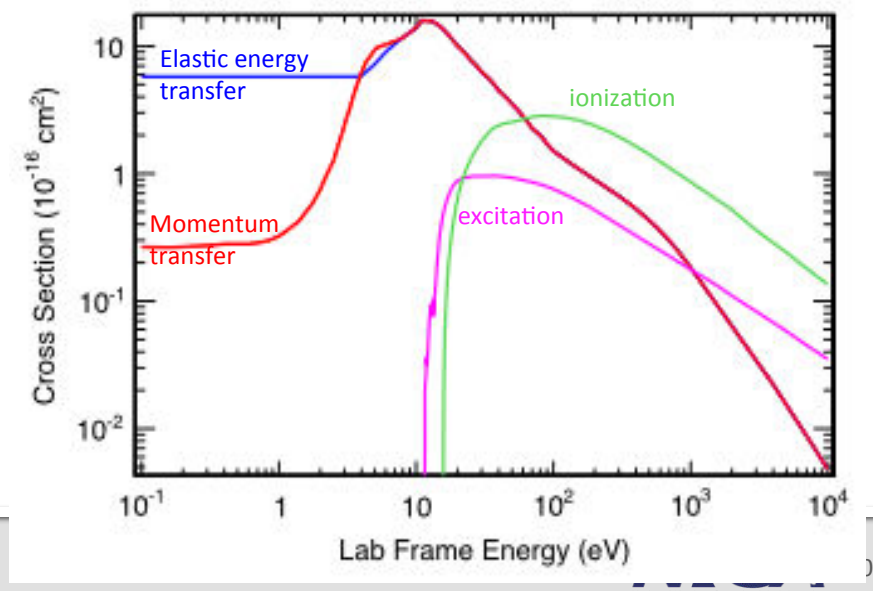
At low energy, empirical Thomas-Imel box model seems successful but

- Empirical field dependence
- All electron-ion pairs recombine for zero electric field
- Little insight on physical processes involved

M. Foxe, C. Hagmann, et al, NIM A 771 (2015)

Simulation Approach

1. Initial interaction
   - Simulate initial emission of photoelectrons and/or auger electrons
2. Follow electrons using electron transport algorithm
   - based on prior work by Wojcik et al for thermal electrons
   - Solves equation of motion for electrons under external fields and ions field
   - Positions and velocity of electrons are forward propagated
3. Compute interactions as electrons slow down
   - electrons-induced excitation, ionization and elastic scattering
   - secondary electron generated and followed as well
   - Thermal model validated against measurements (drift velocity, escape probability,…)
4. Recombination criteria:
   - Electron energy < 1 eV
   - Electron-ion distance < 1.3 nm



No tunable parameter!

Modeling ^{37}Ar Decays

Average ionization track length << electron thermalization length (2.6 μm)

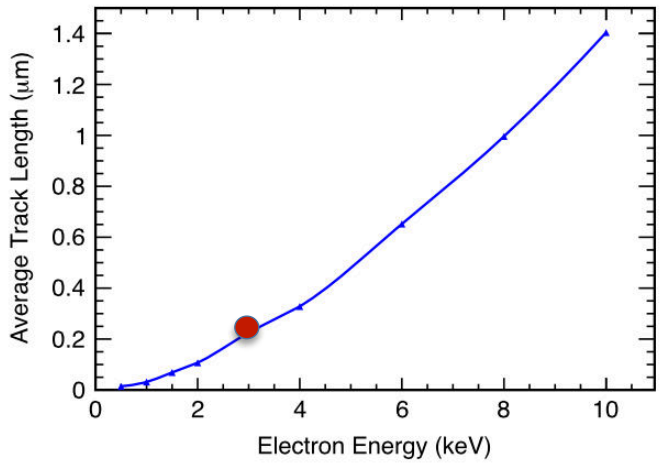
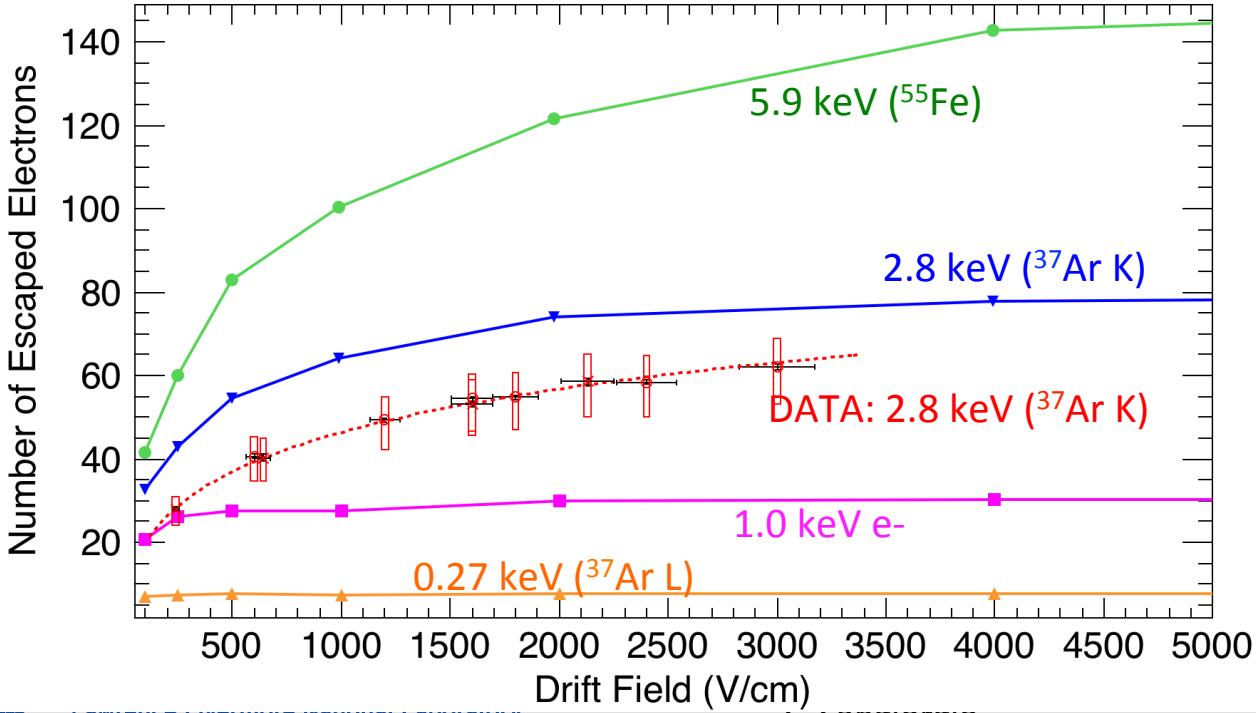


Table 3
The electron transport code calculates the total number of electrons and photons created during the thermalization process of the initial high energy electrons for ^{37}Ar and ^{55}Fe. Errors given correspond to a 1-sigma variation, based on 1000 simulations.

Isotope	Ionizations	Excitations	N_{exc}/N_{ion}
^{37}Ar L-shell	7.6 ± 1.2	4.3 ± 1.8	0.57 ± 0.25
^{37}Ar K-shell	89.9 ± 4.2	41.8 ± 5.7	0.47 ± 0.07
^{55}Fe	193.9 ± 6.6	87.2 ± 8.0	0.45 ± 0.04

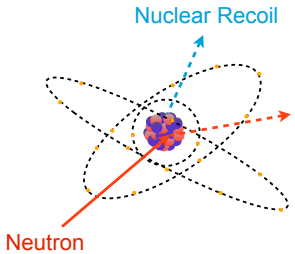
Compare with 0.21 from Doke from ^{217}Bi conversion electrons



Model limitations:

- Ionization cross-section uses binding energies of gas

Neutron-induced Nuclear Recoils in LAr



- Elastic neutron scattering
- Two complementary approaches:

SCENE

SCintillation (and ionization)
Efficiency **N**oble **E**lements

- Recoils from tagged neutron scatter
- Energy 11 – 57 keV → DarkMatter
- Scintillation & Ionization

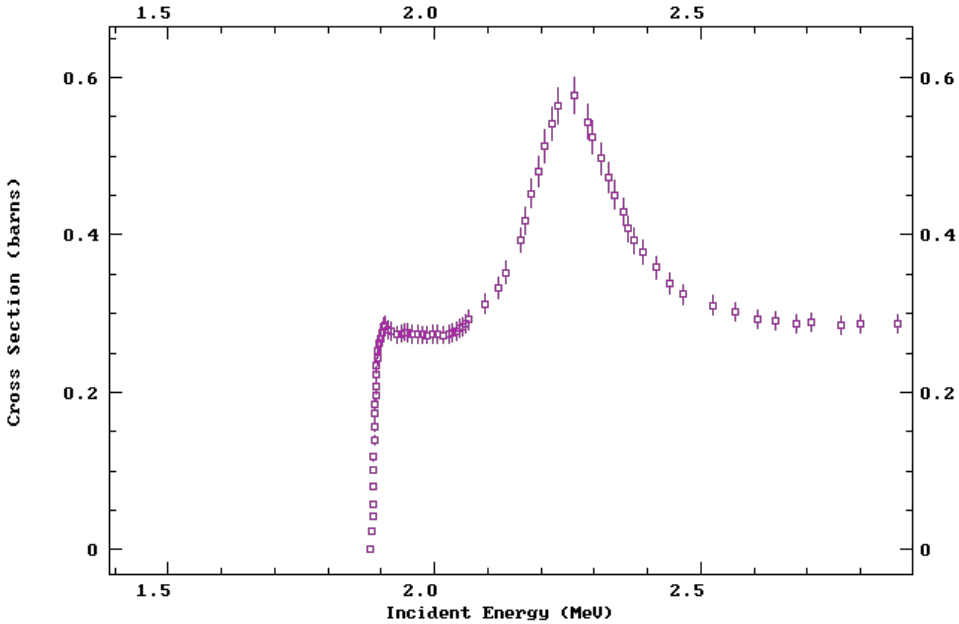
NARRLI

Neutron **A**rgon **R**ecoils **R**esulting in **L**iquid **I**onization

- End-point measurement
- Low energy < 10 keV → CENNS
- Ionization signal only

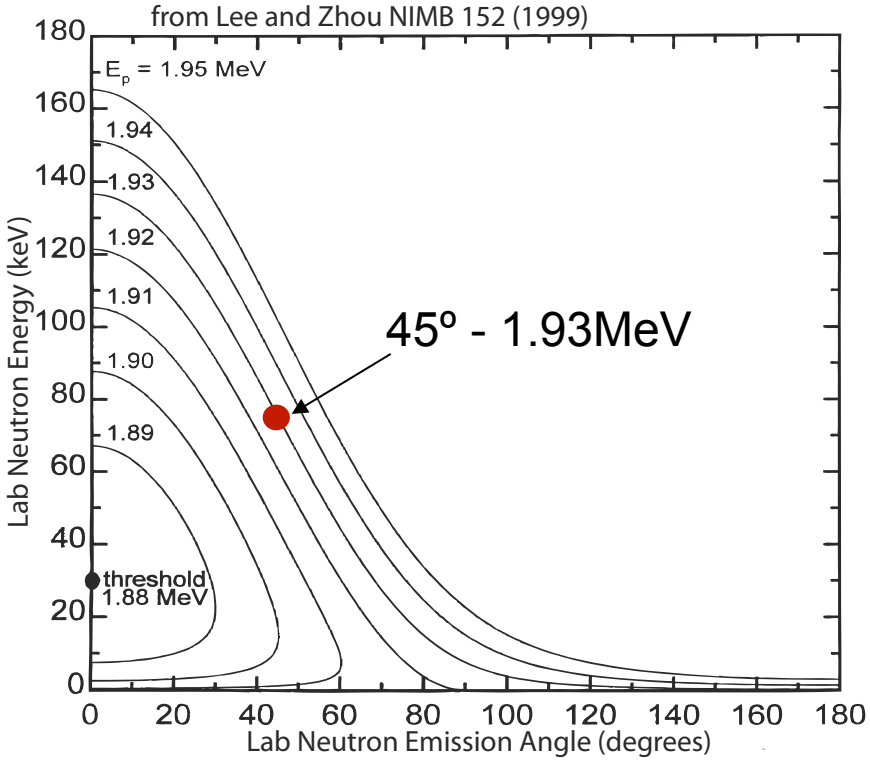
Creating a low-E neutron beam

$^{7}Li(p,n)^{7}Be$



Near-threshold kinematics of $^{7}Li(p,n)$ allow control of maximum neutron energy

Proton Energy Countours for a Thick Lithium Target from Lee and Zhou NIMB 152 (1999)



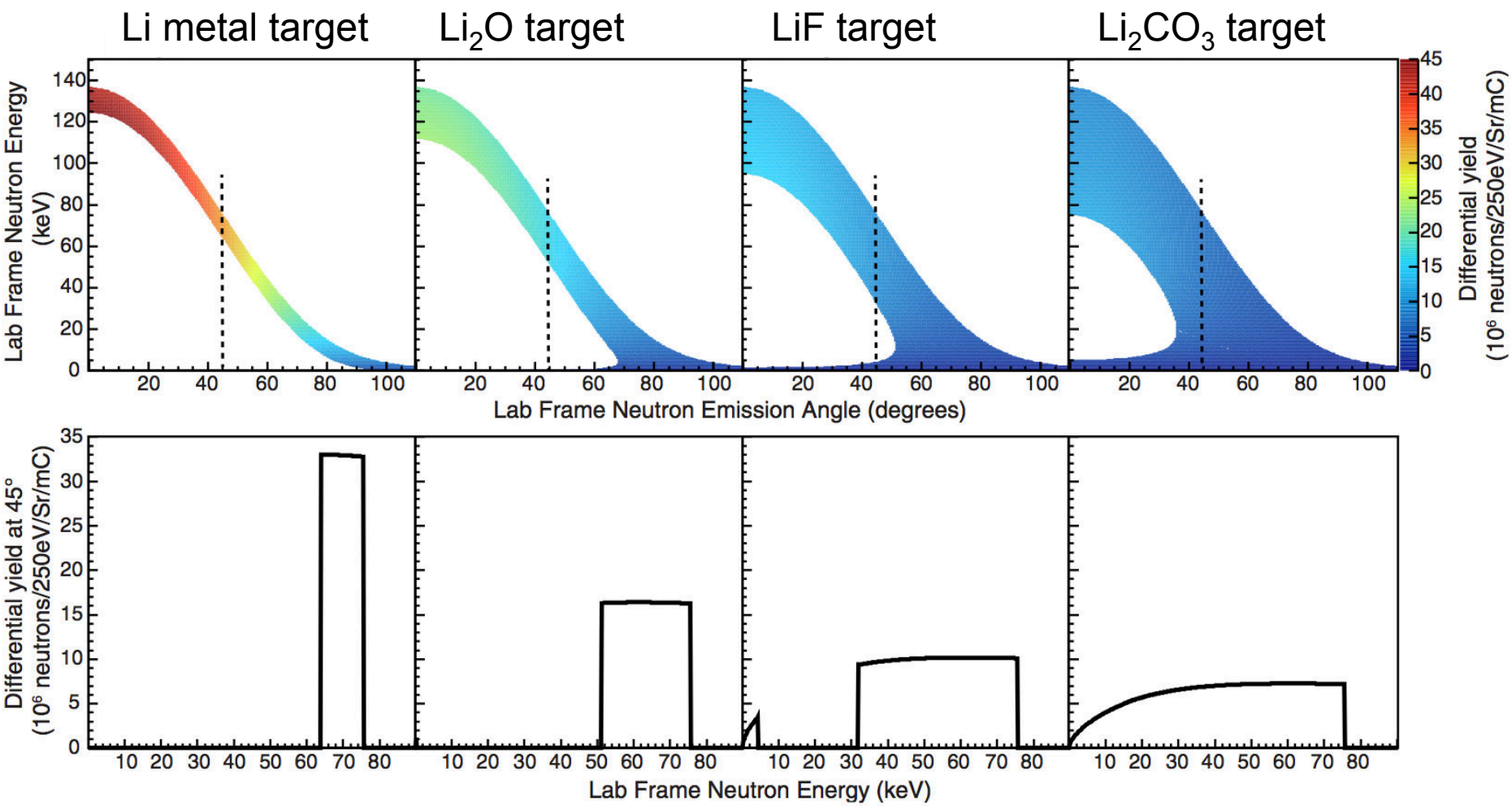
Requirements:

- Continuous p beam
- No ToF in detector (no S1)

The Li target

Ep = 1.93 MeV

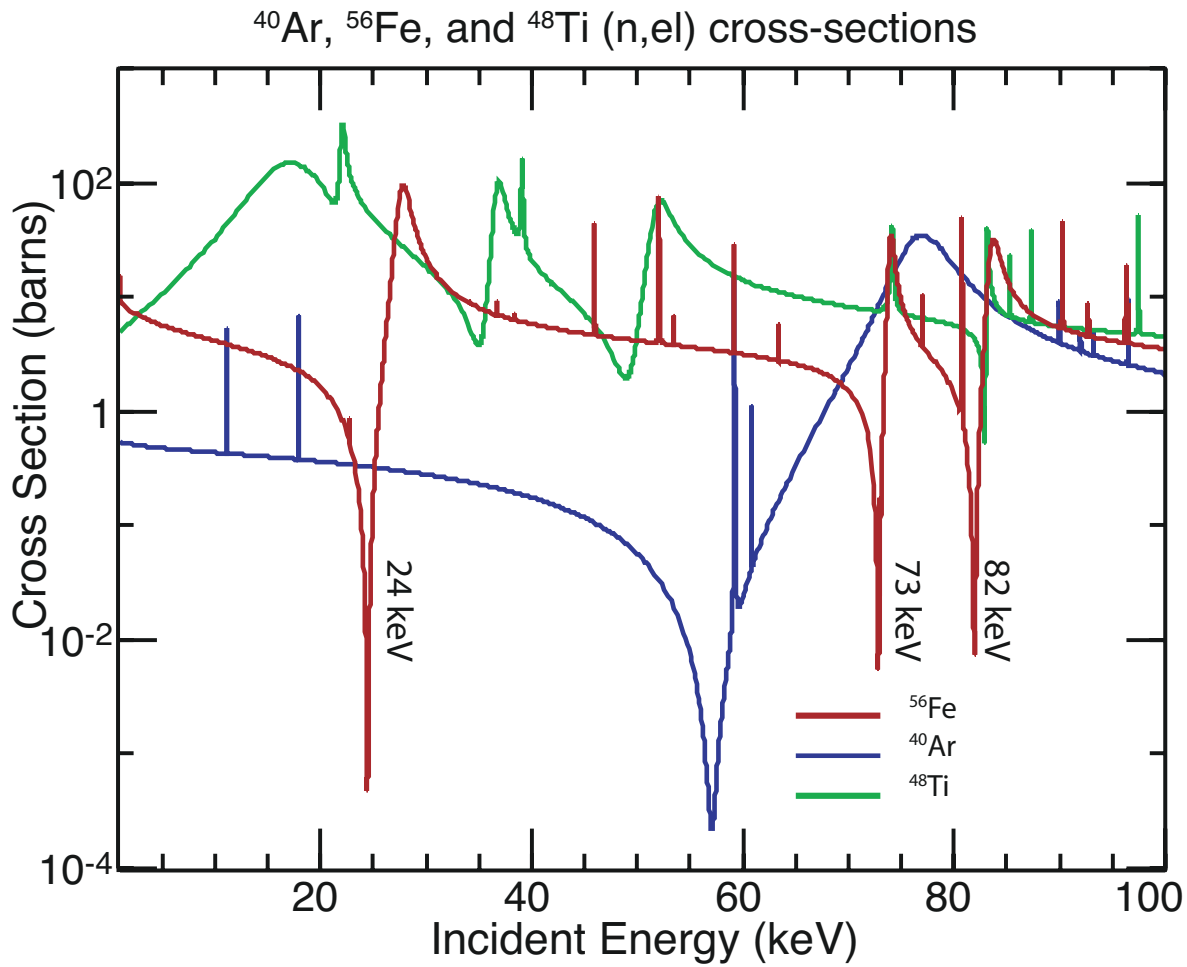
Same total Li content



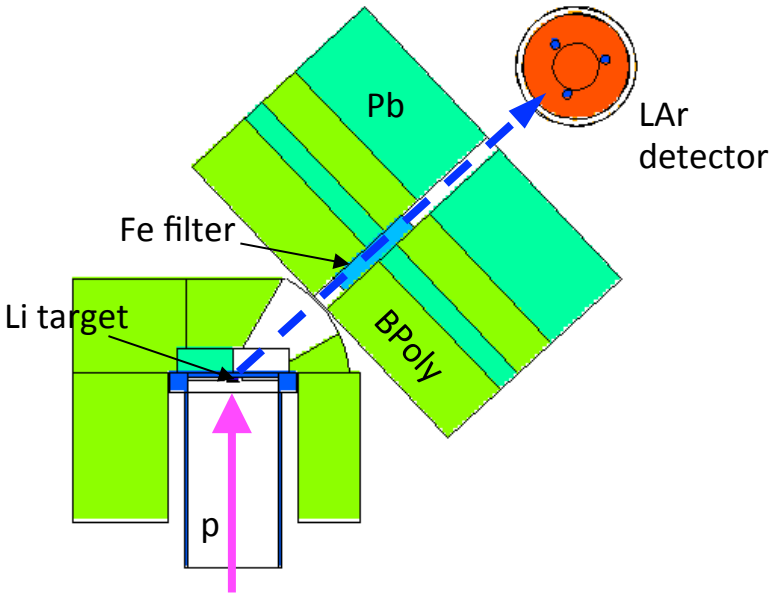
Neutron Filtering

T. Joshi, S. Sangiorgio, et al, NIM B 333 (2014)
P. Barbeau et al, NIM A (2007)

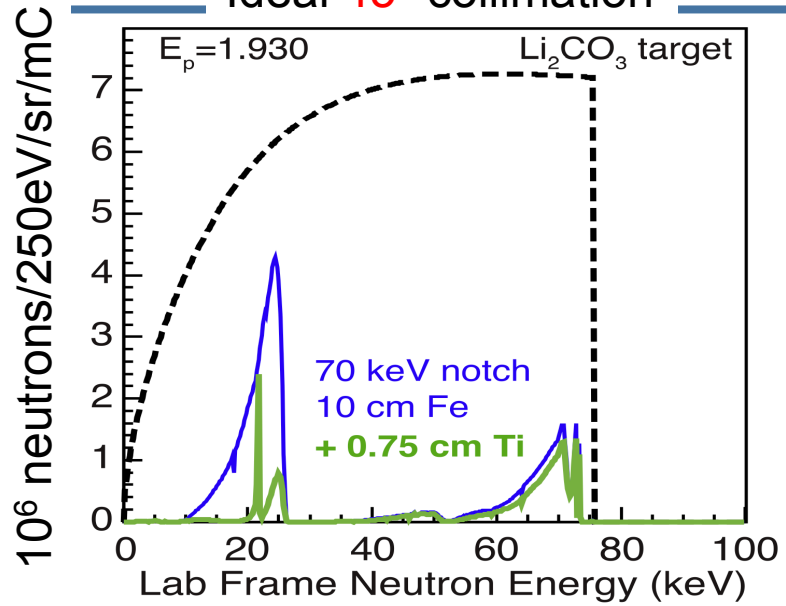
- Take advantage of nuclear physics to selectively transmit neutrons through interference dips in scattering x-sections



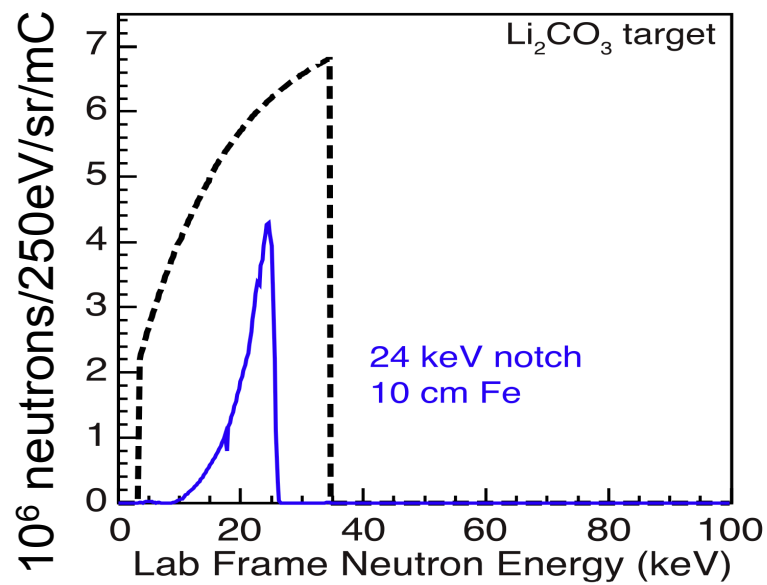
Creating a low-E neutron beam



Ideal 45° collimation



Ideal 55° collimation



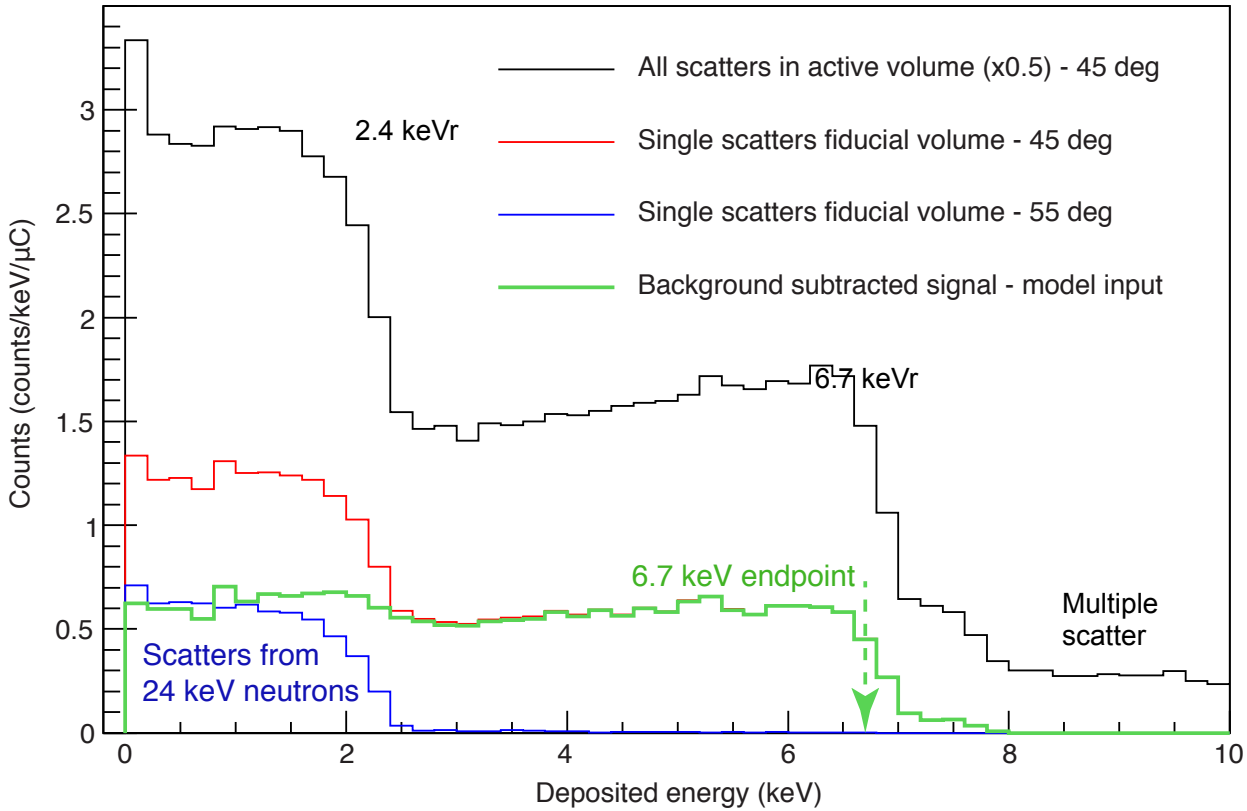
Backgrounds:

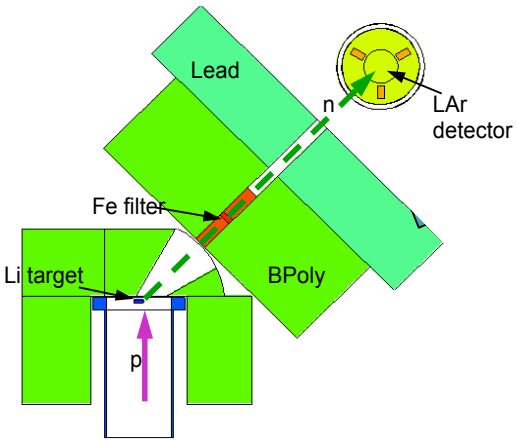
- gammas from ^{7}Li(p,p')
- neutron-capture gammas in shield
- 24 keV neutrons through the filter

→ Measure at different collimation angle, normalize and subtract

Expected Recoil Spectrum in LAr

MCNP calculation of neutron transport and interaction using detailed geometry



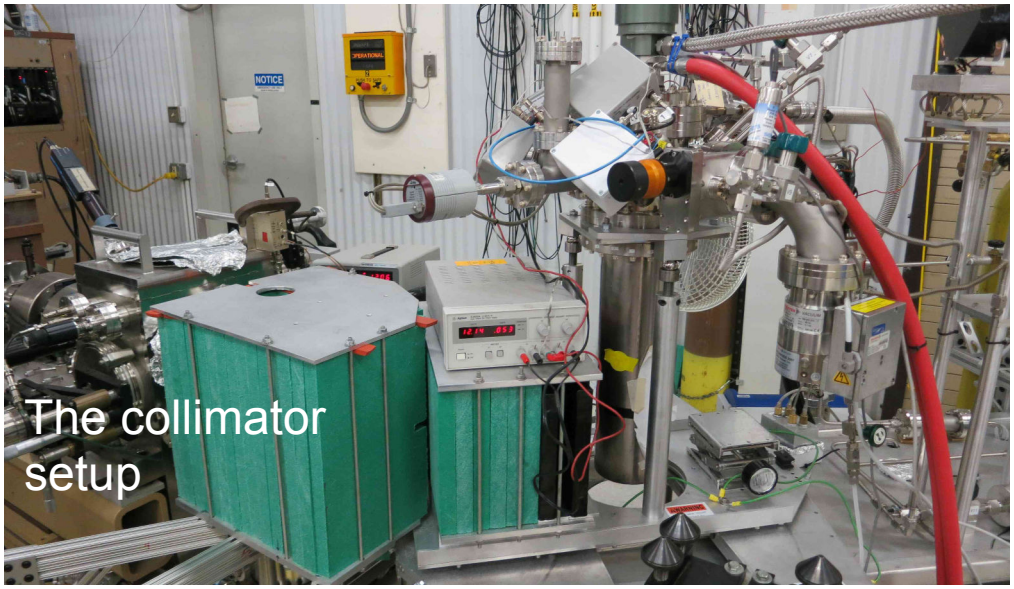


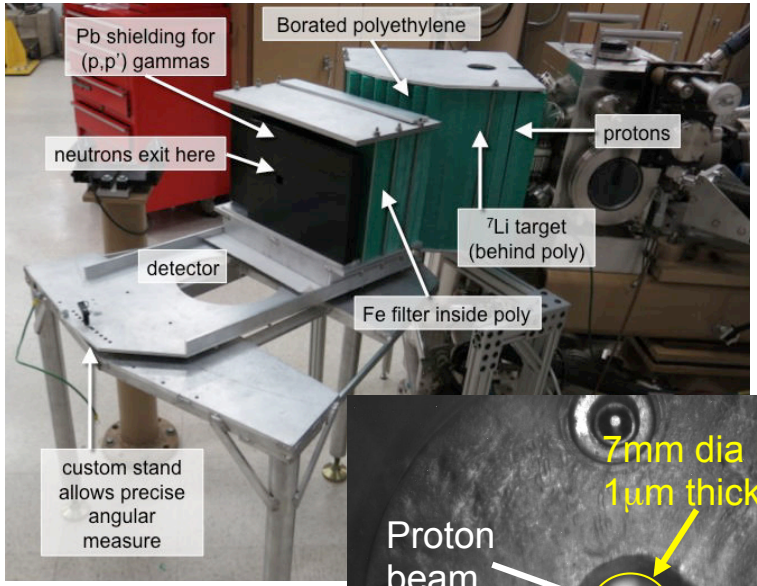
Endpoint Measurement

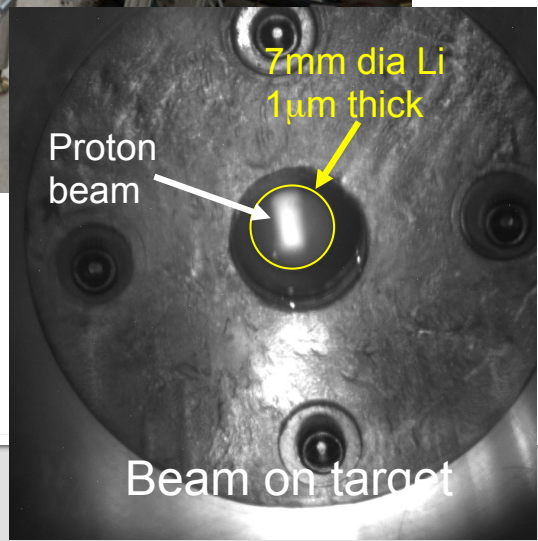
$$T_{\mathrm{Ar}}^{\mathrm{MAX}} = \frac{4mM}{(m+M)^2} E_n$$

Endpoint measurement at 6.7 keV nuclear recoils

LLNL's on-site dedicated neutron beam

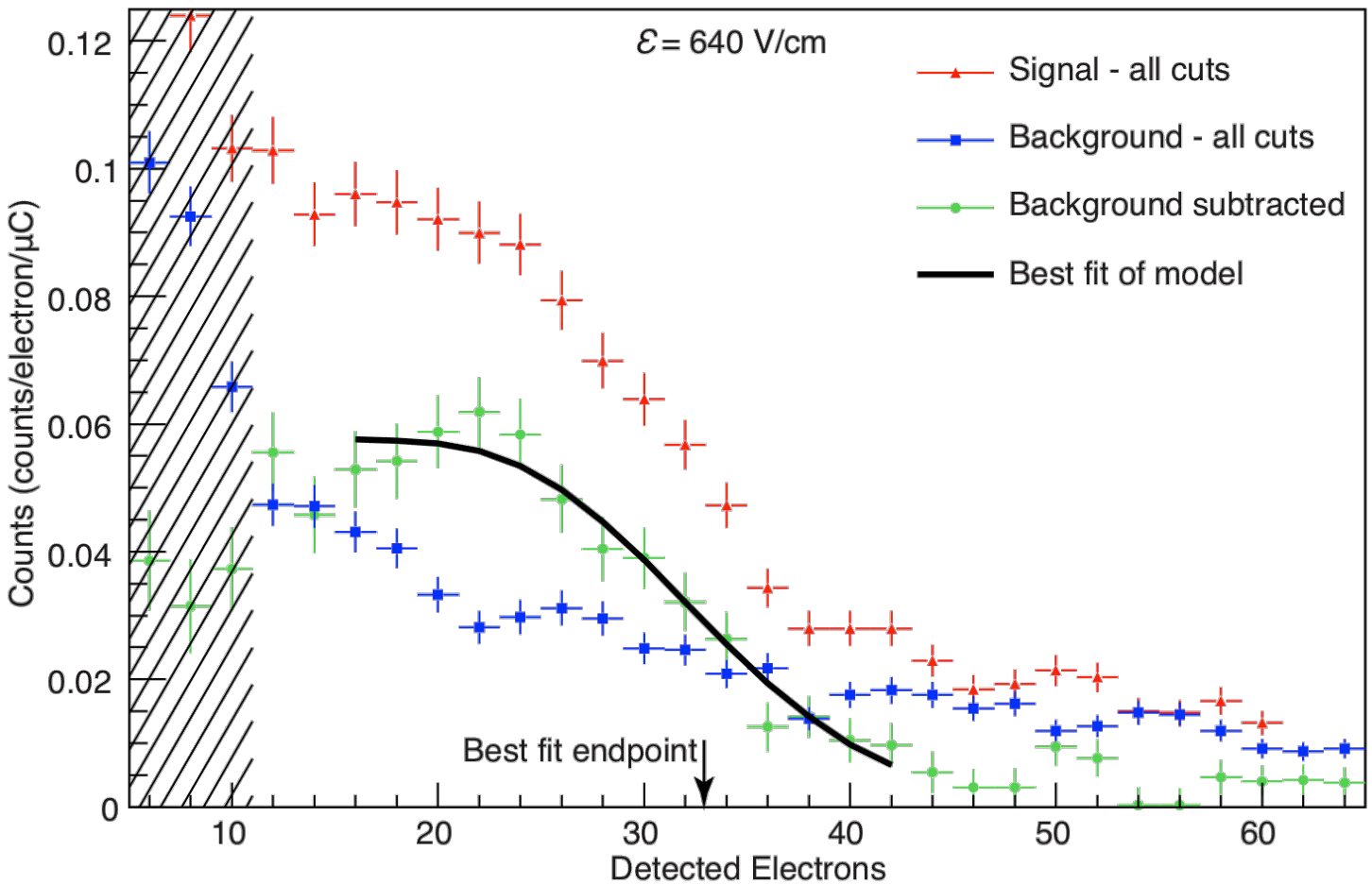






Unique neutron facility for detector calibration to low-energy neutrons (< 150 keV)

Ionization Yield at 6.7 keVr



Fit using the MCNP spectrum convolved with measured detector resolution and three free parameters:

- fixed ionization yield,
- rate normalization,
- fano factor

$$\rightarrow Q_y = 4.9^{+0.1}_{-0.2}\,(\mathrm{stat})\,^{+0.7}_{-0.9}\,(\mathrm{syst})\,e^-/\mathrm{keV}$$

at 640V/cm

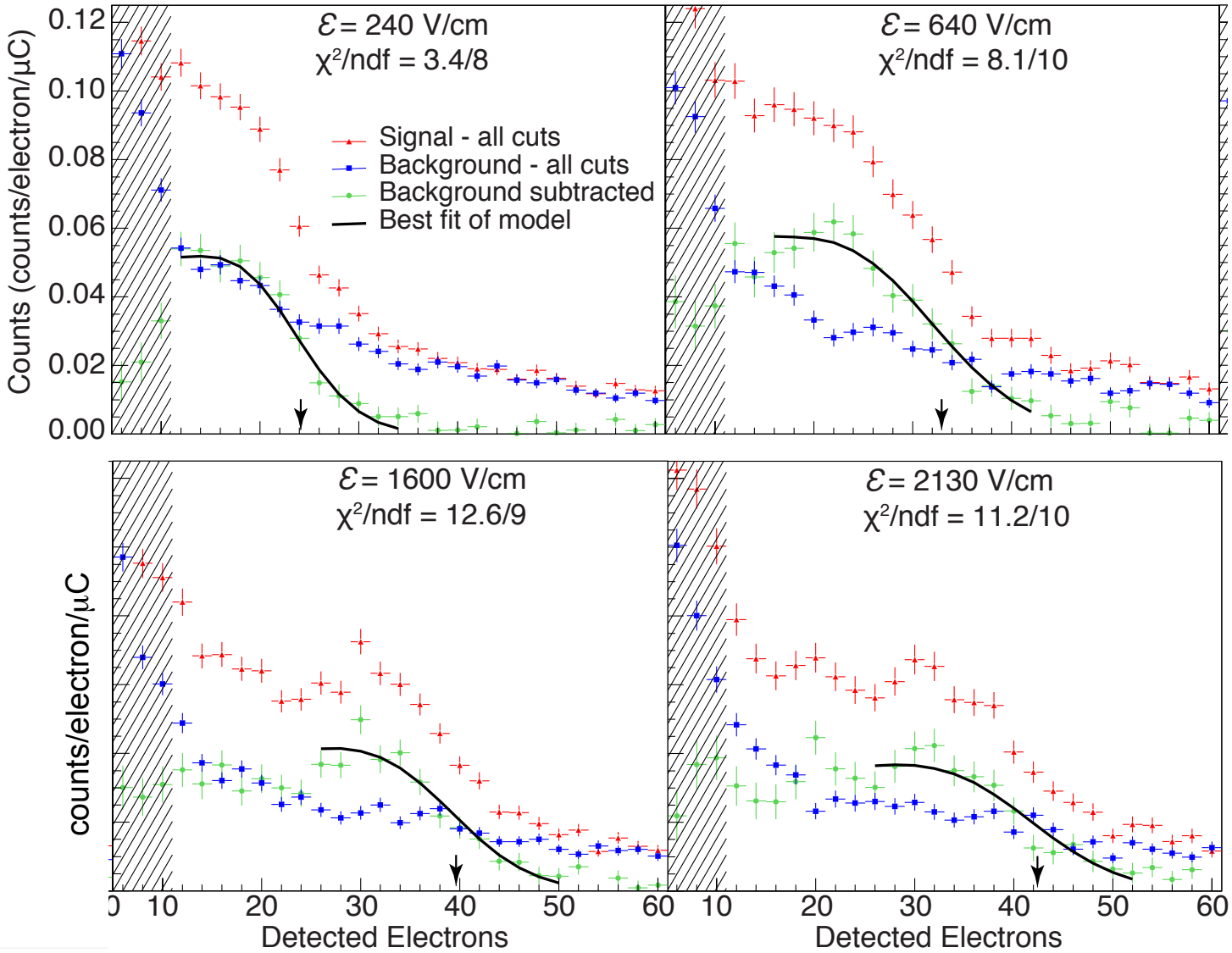
T. Joshi, S. Sangiorgio, et al, PRL 112 (2014)

Uncertainty Estimation

Component	Statistical (%)	Systematic (%)
Single electron peak	2–10	10
Single electron calibration	2	10
χ^2 analysis	3–5	...
Input spectrum	...	5
Background subtraction	...	1–3
Slope of Q_y in model 240 V/cm	...	$^{+5}_{-25}$
" 640 V/cm	...	$^{+2}_{-18}$
" 1600 V/cm	...	$^{+0}_{-19}$
" 2130 V/cm	...	$^{+0}_{-21}$
Liquid argon purity	...	5
Drift field ($\mathcal{E}$)	...	6

Electric Field Dependence of Ionization Yield

Nuclear recoils at 6.7 keVr at varying electric field



Field Dependence

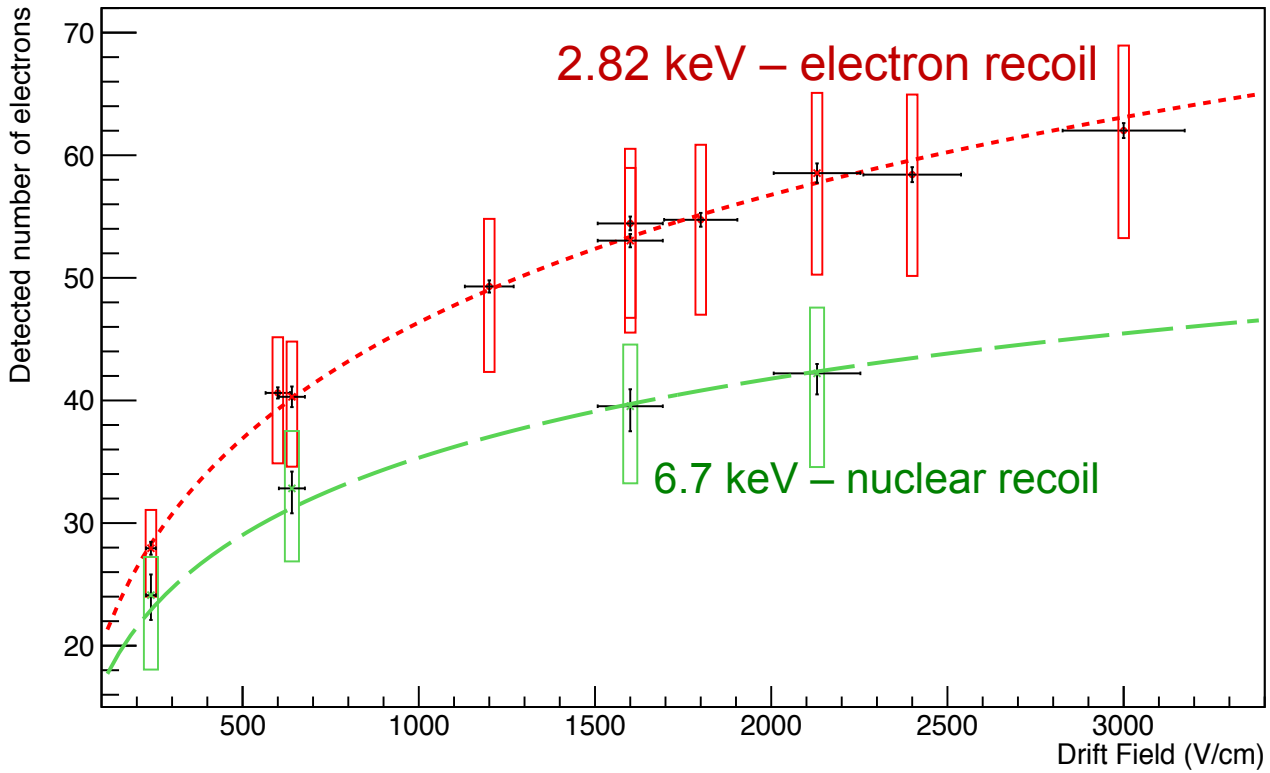
For nuclear recoils

$$S2 \propto n_e = rN_{\mathrm{i}}$$

$$N_{\mathrm{i}} + N_{\mathrm{ex}} = \frac{E}{W} \cdot q(E)$$

Use modified Thomas-Imel to account for recombination using parameters obtained from 2.82 keV electron recoils

Fit with N_i as only free parameter



For nuclear recoils the amount of initial ionization N_i is unknown:

- N_{ex} / N_i = ??
- E = 6.7 keV
- W = 19.5 eV
- q(E) = ??

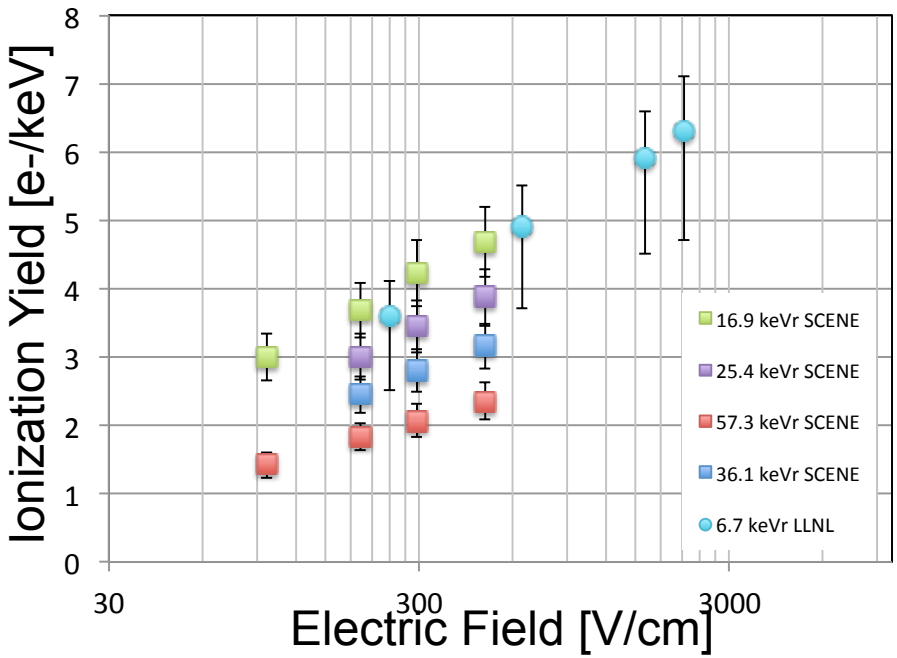
Same phenomenological model of recombination holds in both cases

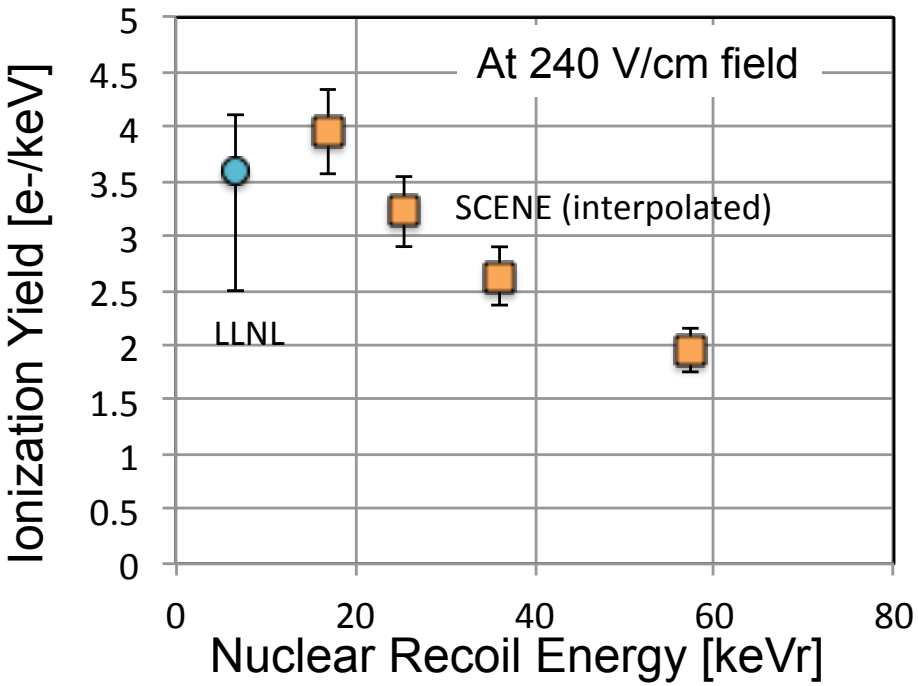
↓

Similarities in spatial distributions of ions and electrons

Comparison with SCENE Measurements

- Different energies and electric field range. Very complementary but hard to cross-check directly
- Agreement on recombination: same fit result for the electric field parameter 'b' in the modified Thomas-Imel (b = 0.61)
- Combined ionization yield data:

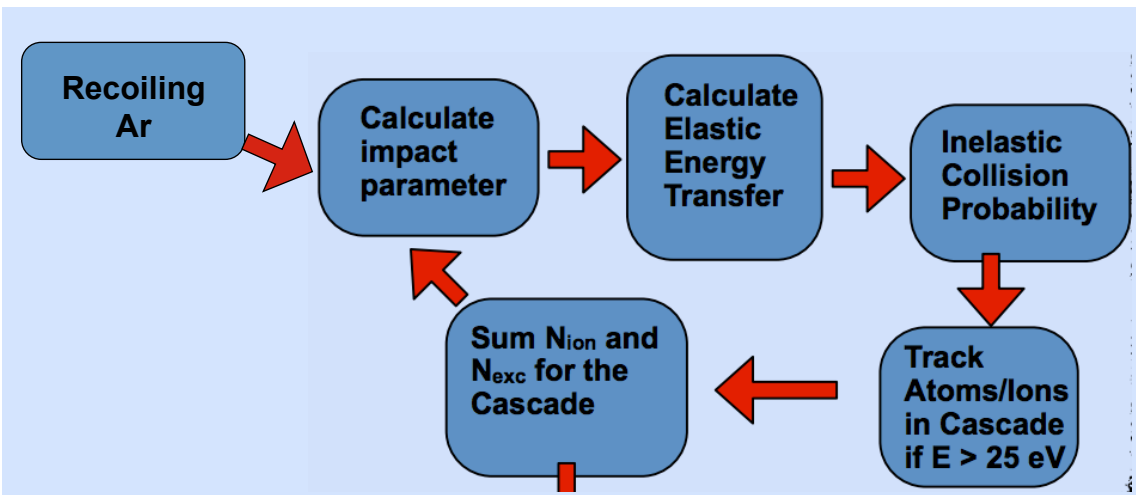




Modeling Low-E Nuclear Recoils in Liquid Argon

TRIM-based binary collision Monte Carlo Model

- Elastic Coulomb collisions
- Inelastic collisions producing excitation and ionization

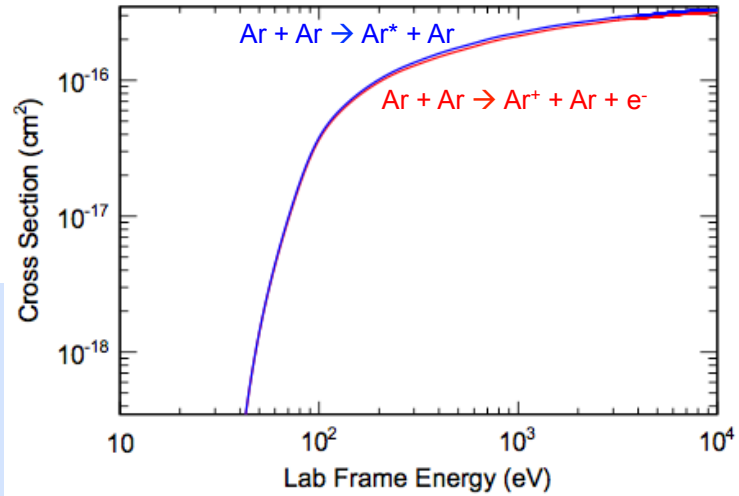


Notes:

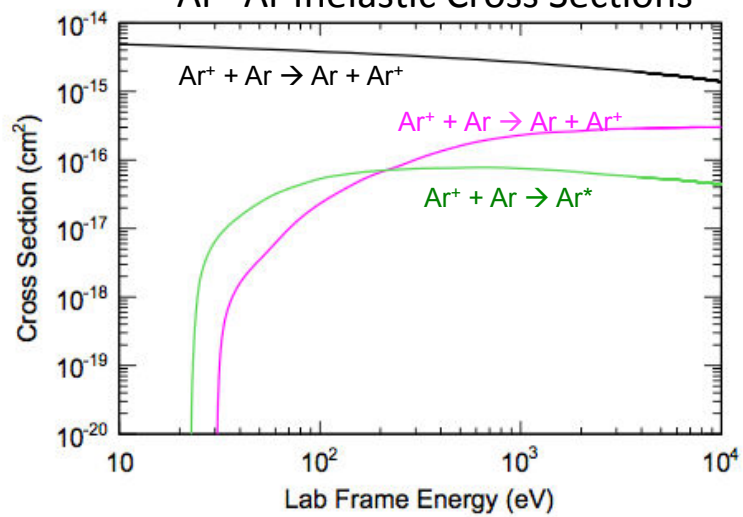
- Ionization energy spectrum is not well known and depends on collision energy → use 3 and 10 eV
- Three-body collisions are neglected
- Bi-excitonic quenching mechanism not included

M. Foxe, C. Hagmann, et al, Astroparticle Physics 69 (2015)

Ar-Ar Inelastic Cross Sections

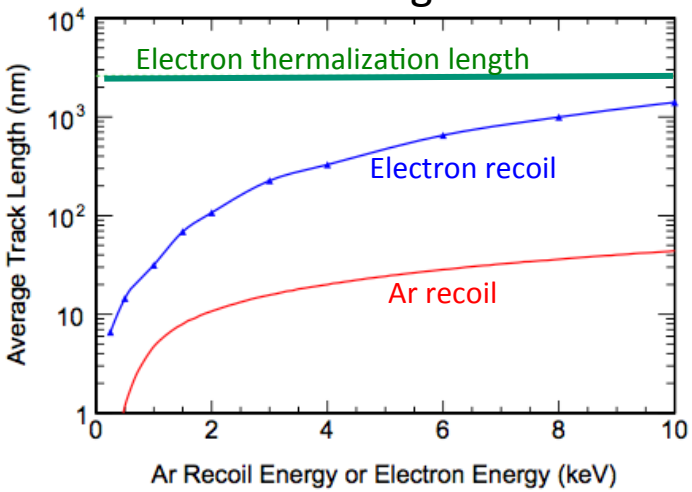


Ar^+-Ar Inelastic Cross Sections

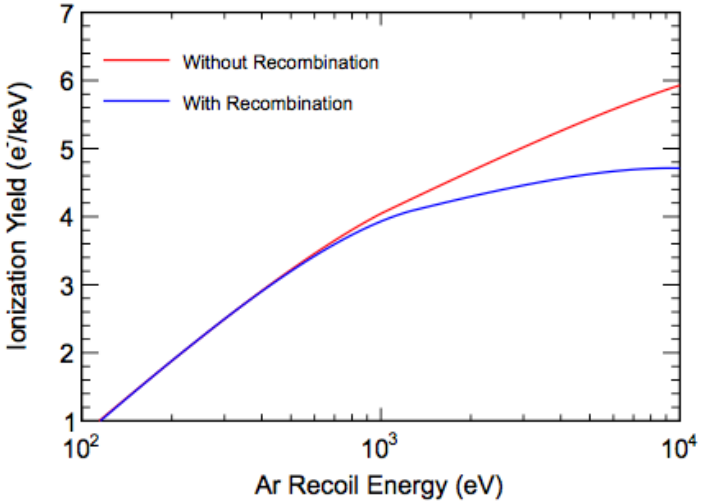


Modeling Results

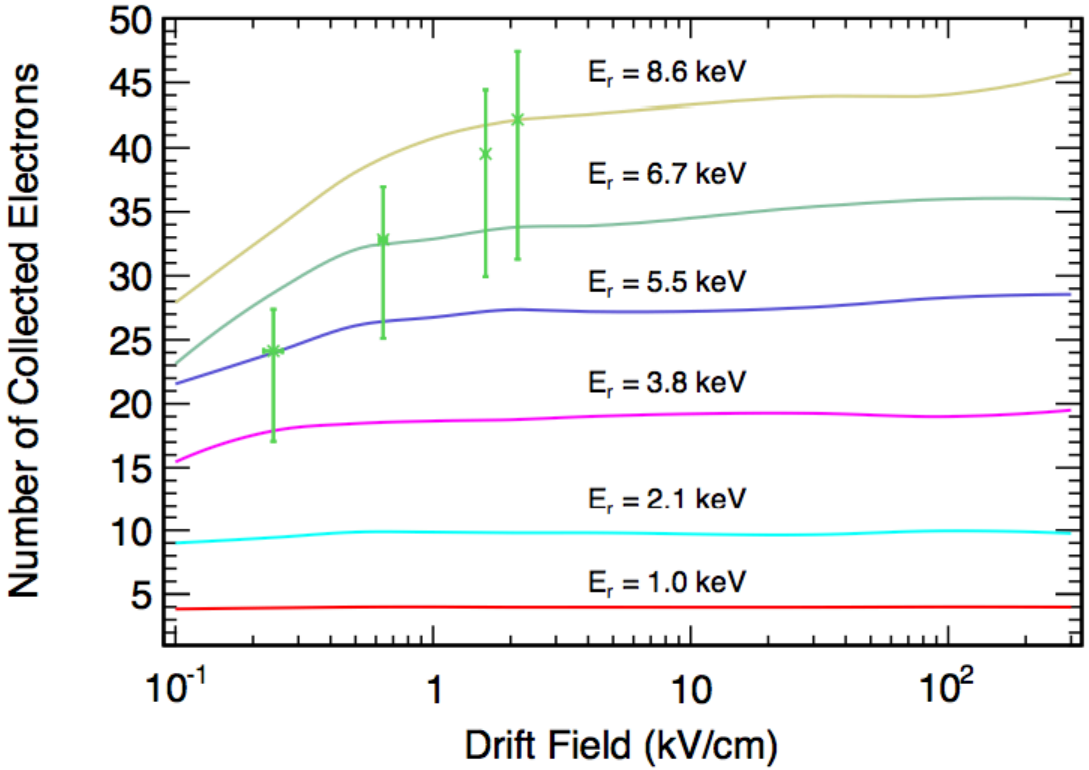
Track Length



Ionization Yield at 1 kV/cm



Ionization Yield vs E Field



Conclusions and outlook

- Demonstrated use of ^{37}Ar to calibrate down to sub-keV energies
- Measured the ionization yield at 6.7 keVr in liquid argon as a function of electric field
- Developed atomic collision simulation for low-energy (< 10 keV) interactions in liquid argon
  - Appreciably good agreement
  - Would be interesting to extend it to xenon

- Nuclear recoil measurements:
  - Refurbishment of Li target for higher neutron efficiency
  - Access lower recoil energy using different filters
  - Xe target

Neutron energy (keV)	Max recoil energy (keV)		
	Xe	Ar	Ge
17	0.5	1.6	0.9
24	0.7	2.3	1.3
47	1.4	4.5	2.5
59	1.8	5.7	3.2
70	2.1	6.7	3.8
82	2.5	7.9	4.4

- **Things to consider:**
  - Liquid Argon vs Liquid Xenon
  - Few-electrons backgrounds
  - Single electron calibration

Acknowledgements

- A. Bernstein, C. Hagmann, K. Kazkaz, V. Mozin, S. Pereverzev, F. Rebassoo, S. Sangiorgio
- T. Joshi
- P. Sorensen
- I. Jovanovic
- M. Foxe

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