Towards Characterization of sub-keV Nuclear Recoils in Liquid Argon

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SLAC - Advanced Instrumentation Seminars

Feb 20, 2013

LLNL-PRES-622432
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Outline

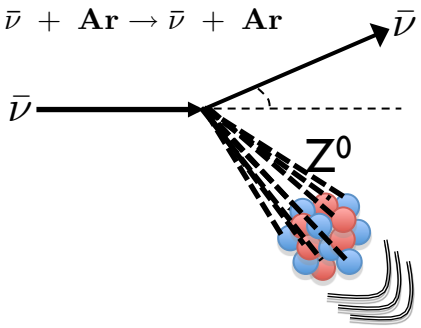
- Low-energy nuclear recoils: motivations and challenges
- The LLNL prototype and performances
- Inducing nuclear recoils in Ar with neutrons
- Conclusions

Low-energy nuclear recoils: why do we care? (1) Coherent Neutrino Nucleus Scattering

CNNS a neutral current process where an incoming neutrino elastically scatters on a nucleus

- undisputed prediction of the Standard Model
- enhanced cross-section:

$$\frac{d\sigma}{d(\cos\theta)} \approx \frac{G^2}{8\pi} N^2 E^2 (1+\cos\theta)$$



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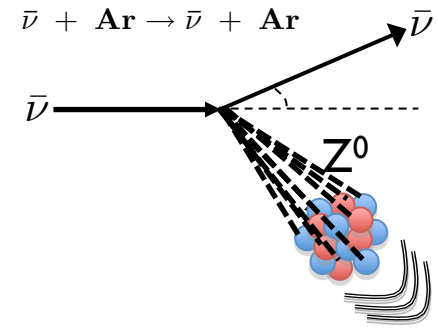


- undisputed prediction of the Standard Model
- enhanced cross-section:

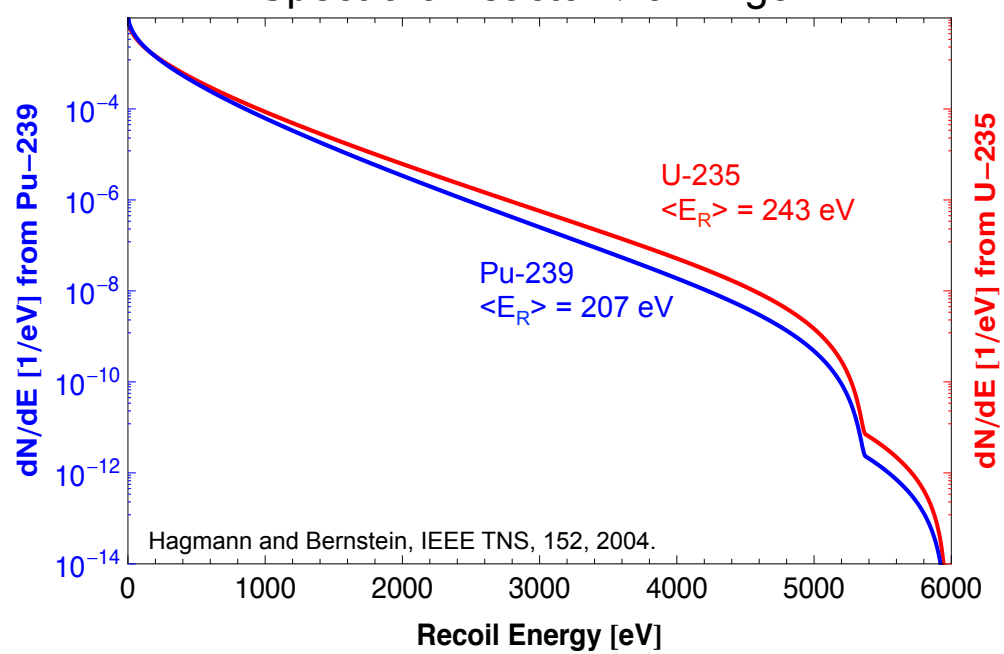
$$\frac{d\sigma}{d(\cos\theta)} \approx \frac{G^2}{8\pi} N^2 E^2 (1+\cos\theta)$$

- very low recoil energy

$$\langle E_r \rangle = 716\ \mathrm{eV}\ \frac{(E_\nu/\mathrm{MeV})^2}{A}$$

CNNS interests for:
- Test the SM
- Supernovae
- Reactor antineutrino monitoring
- …

Spectra of reactor ν on Argon

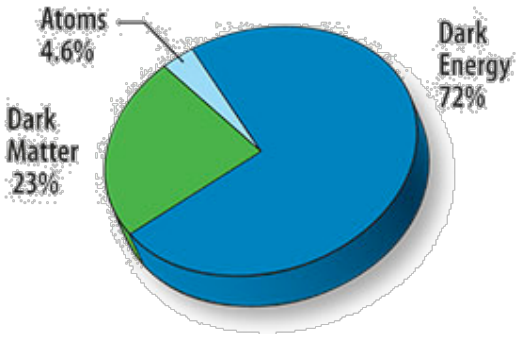


Need detector with to low energy threshold

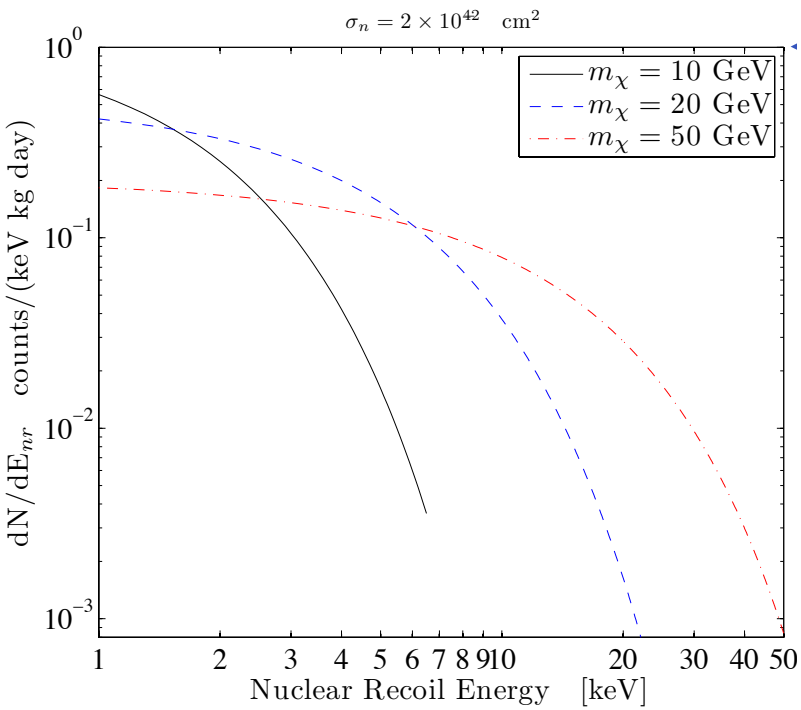
Low-energy nuclear recoils: why do we care? (2) Dark Matter

Detection of WIMPs hinges on nuclear recoils

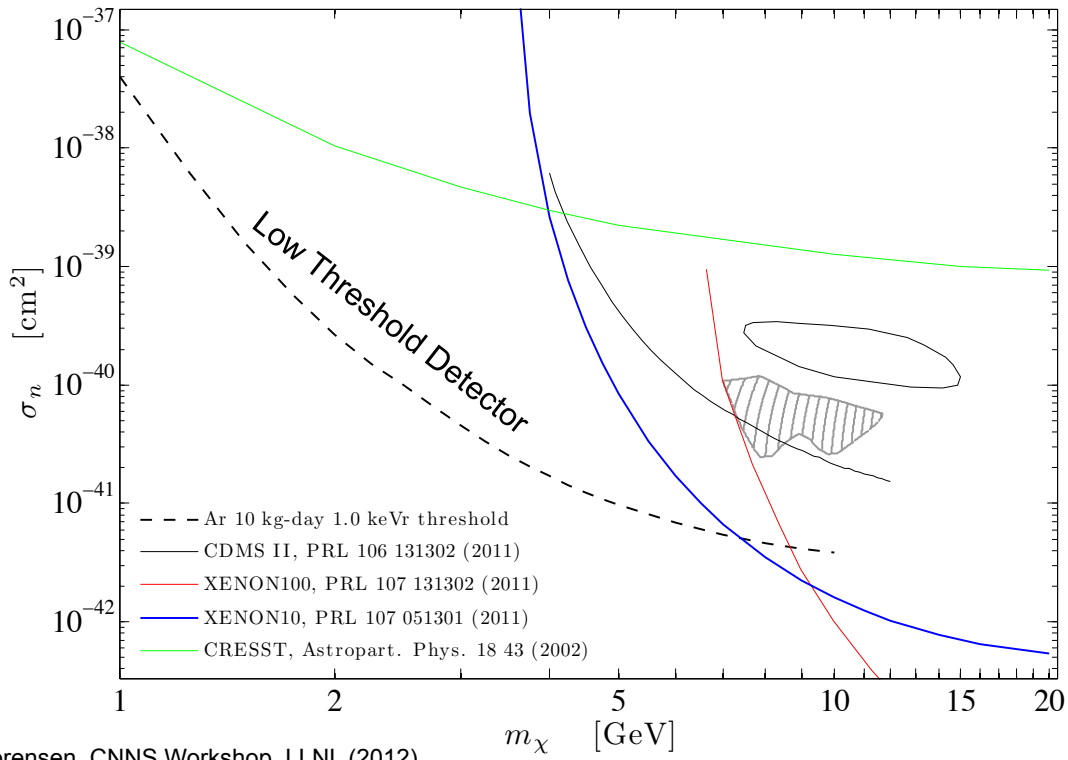
Low threshold allows to probe “light” WIMPs candidates



Dark Matter Elastic Scatter on Xe



Setting Dark Matter Mass Limits



Plots from P. Sorensen, CNNS Workshop, LLNL (2012)

Need detector with to low energy threshold

Nuclear recoils: how to detect?

Bolometers
CUORE

Superheated liquids

COUPP

PHONONS
~10 meV/ph

Scintillating bolometers
CRESST

Hybrid bolometers
CDMS
EDELWEISS

SCINTILLATION
~1 keV/γ

IONIZATION
~10 eV/e$^-$

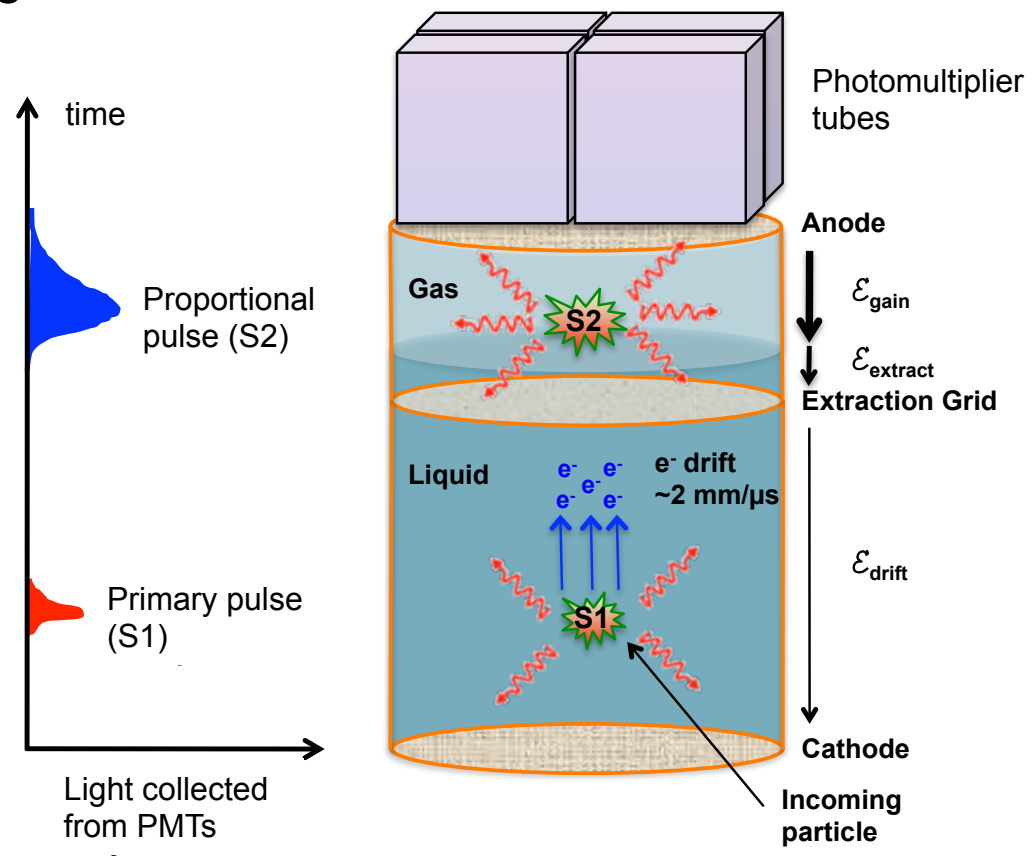
Solid Scintillators
DAMA
Single-phase noble liquids
DEAP
CLEAN

Dual-phase noble liquids
LUX
XENON
ZEPLIN
DARKSIDE

Ionization detectors
CoGeNT
Dual-phase noble liquids

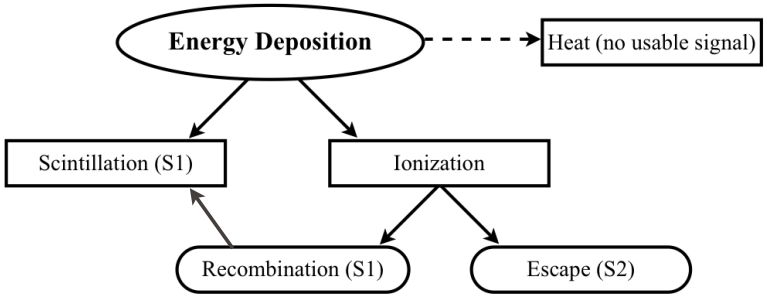
Noble-gas dual-phase detectors

- Well known technology, extensively used in Dark Matter experiments
- Good electron drift properties
- Large mass
- Low thresholds
- Scalability

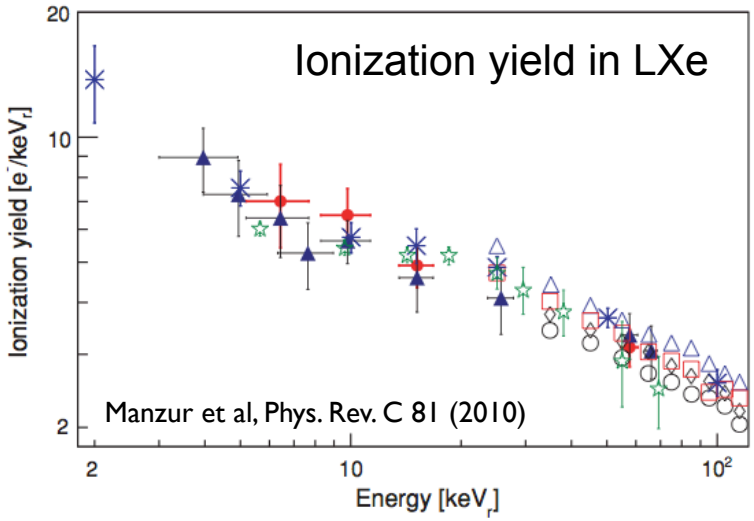


Low-energy nuclear recoils: what do we know?

- The energy loss mechanism in noble liquids depends on particle type and energy



- Experimental data for LXe for nuclear recoils down to 4 keV.

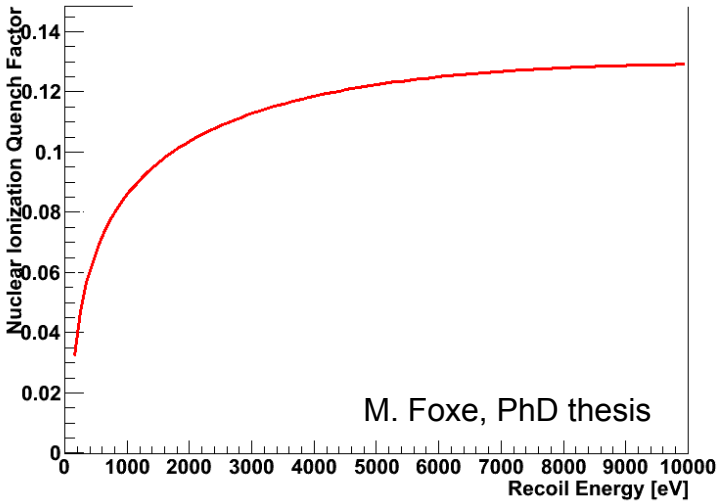


- Nuclear recoils are less effective than electron recoils in producing ionization

nuclear ionization quench factor

$$q(E_r) = \frac{N_{ion}(E_r, \text{nucleus})}{N_{ion}(E_r, \text{electron})}$$

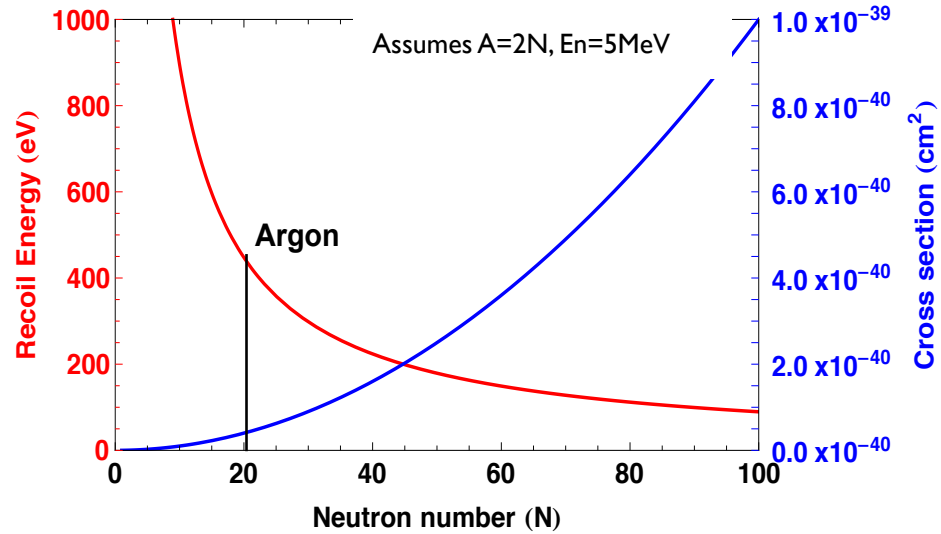
- No data at low energy in Ar
- Lindhard theory
- LLNL in-house MonteCarlo based on atomic collision in Ar



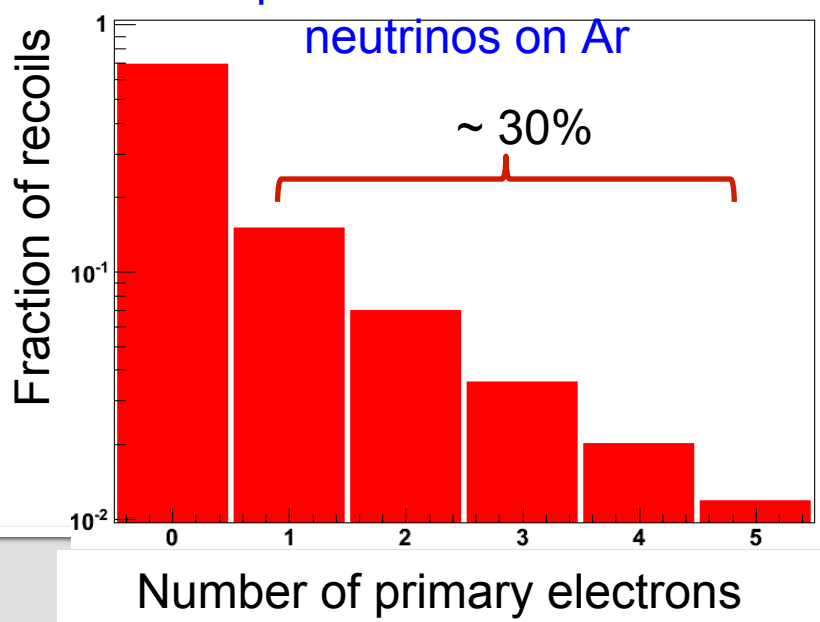
Need to measure the ionization yield of nuclear recoils at < keVr

Choice of Argon driven by CNNS application

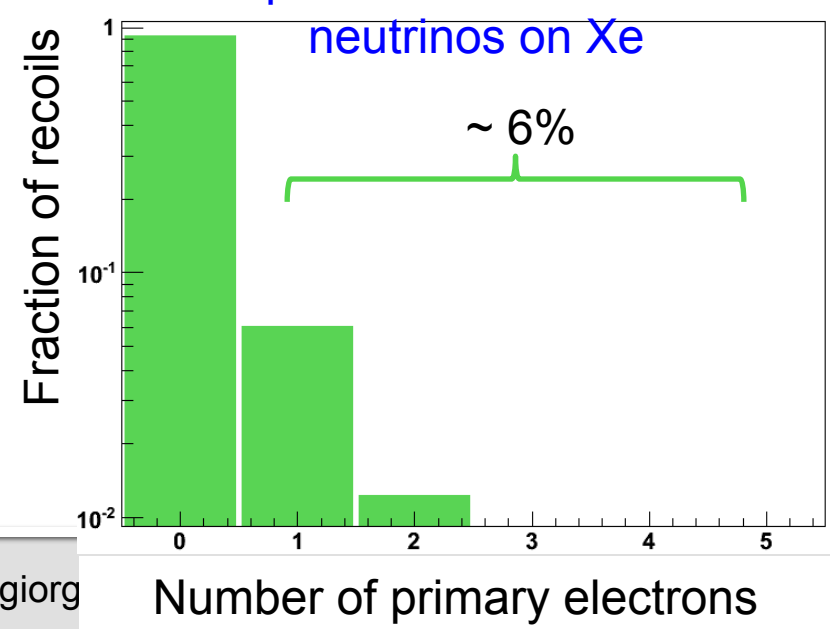
	Ar	Xe
Atomic number	18	54
Boiling point [K]	87	165
Liquid phase density [g/cm^3]	1.4	3.06
Radioactive isotopes	^{39}Ar	^{136}Xe ?
Price [\$/ft^3]	\$	\$\$\$
Scintillation light [nm]	128	178



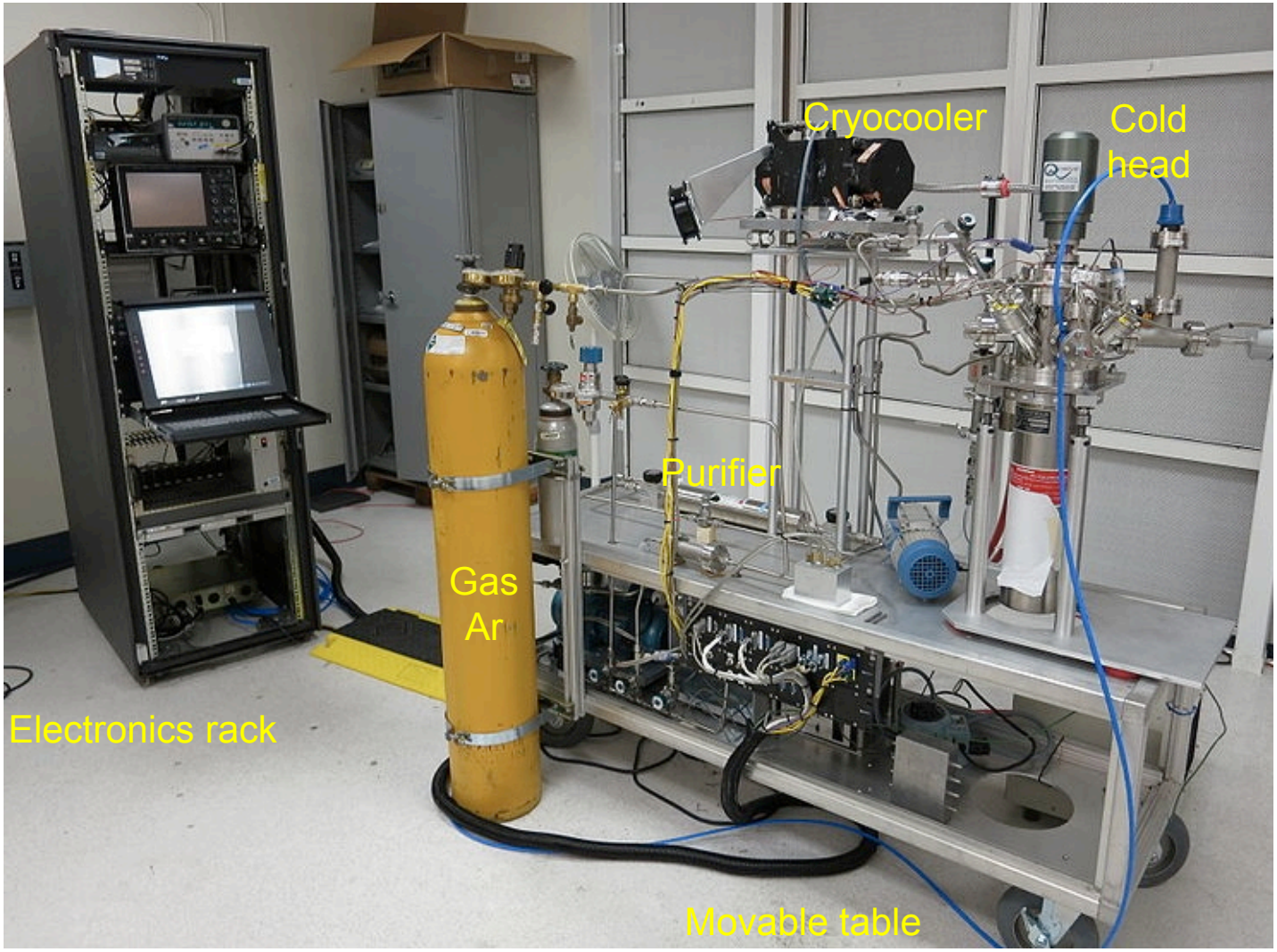
Simulated ionization spectrum from reactor neutrinos on Ar



Simulated ionization spectrum from reactor neutrinos on Xe

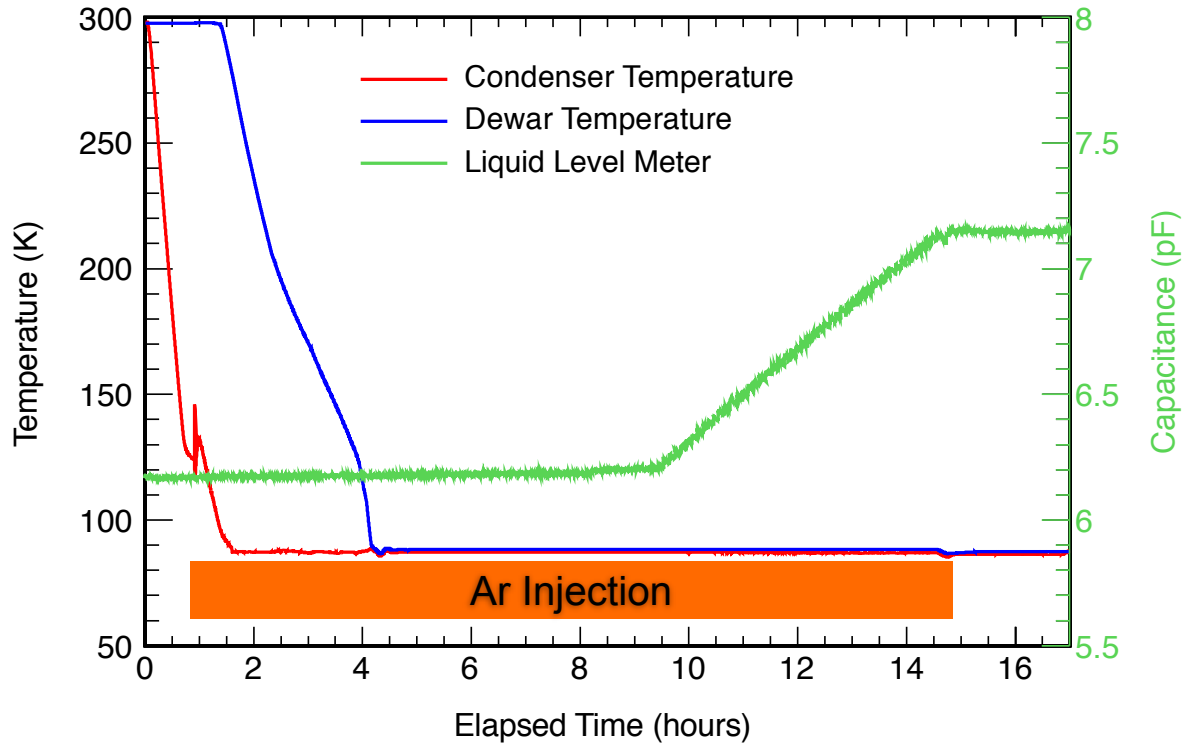


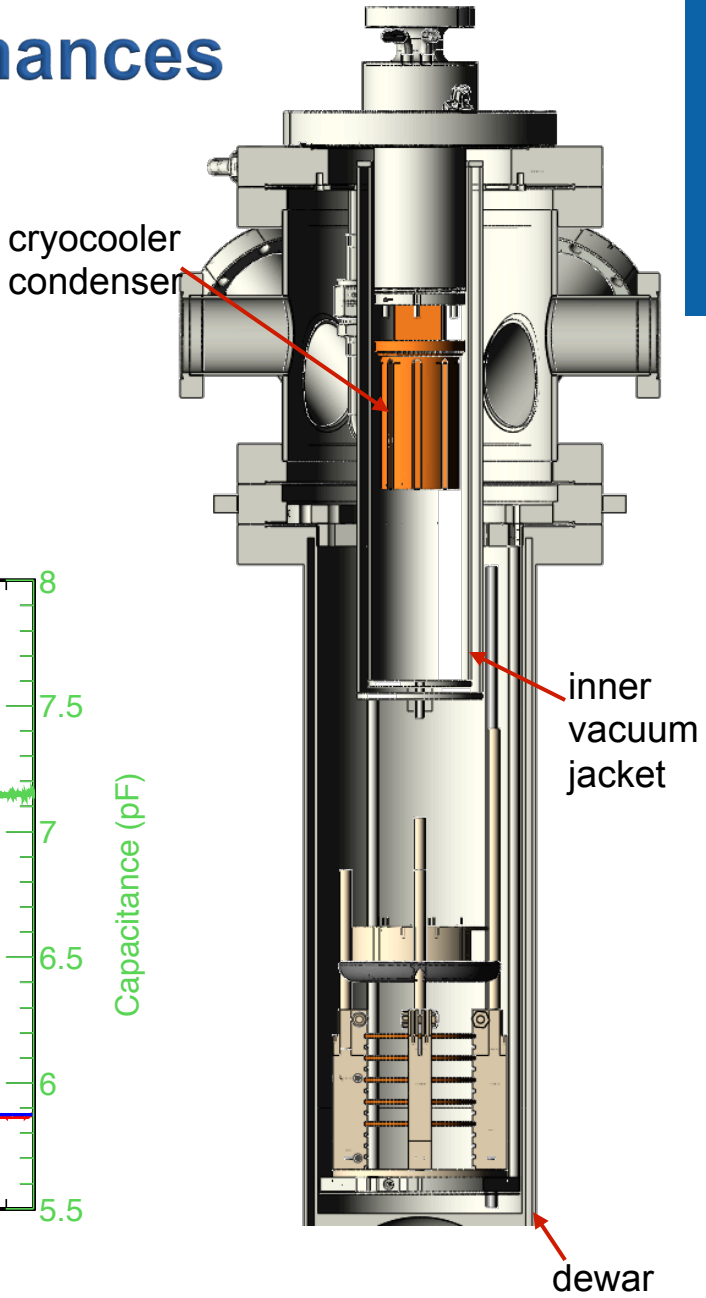
The Dual-Phase LAr Setup



Cryogenic Operation & Performances

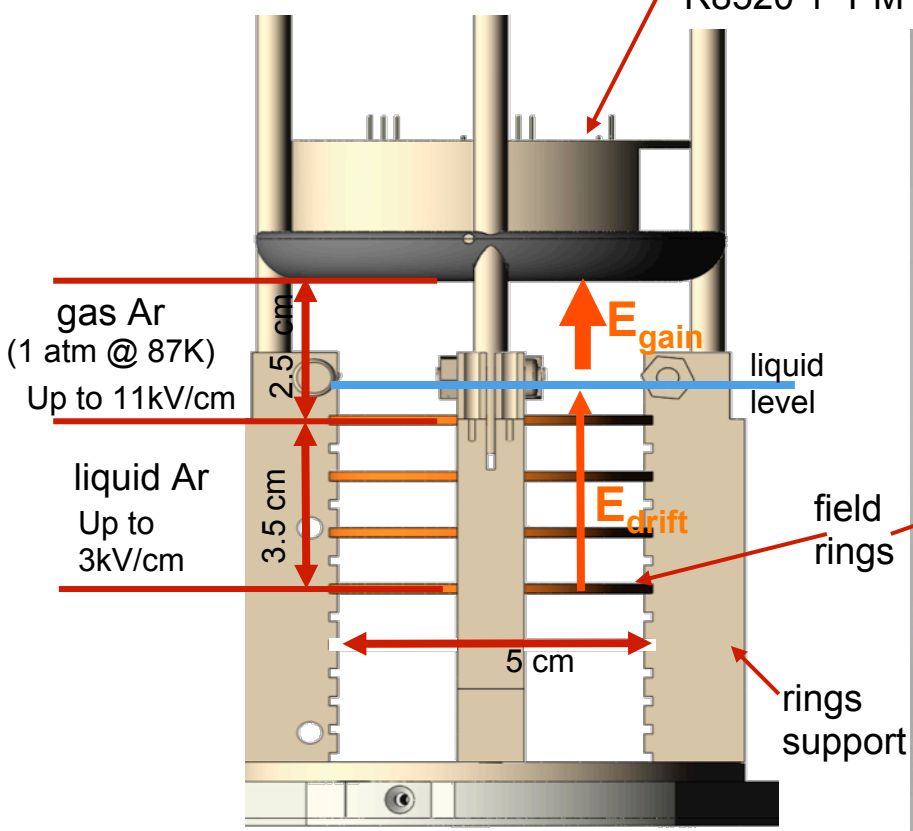
- In-situ production of LAr w/ cryocooler
- Automated cooldown and liquefaction in ~14h
- Temperature stability ± 0.05 K
- Total ~1 liter of Argon can be circulated 3-4 times per day

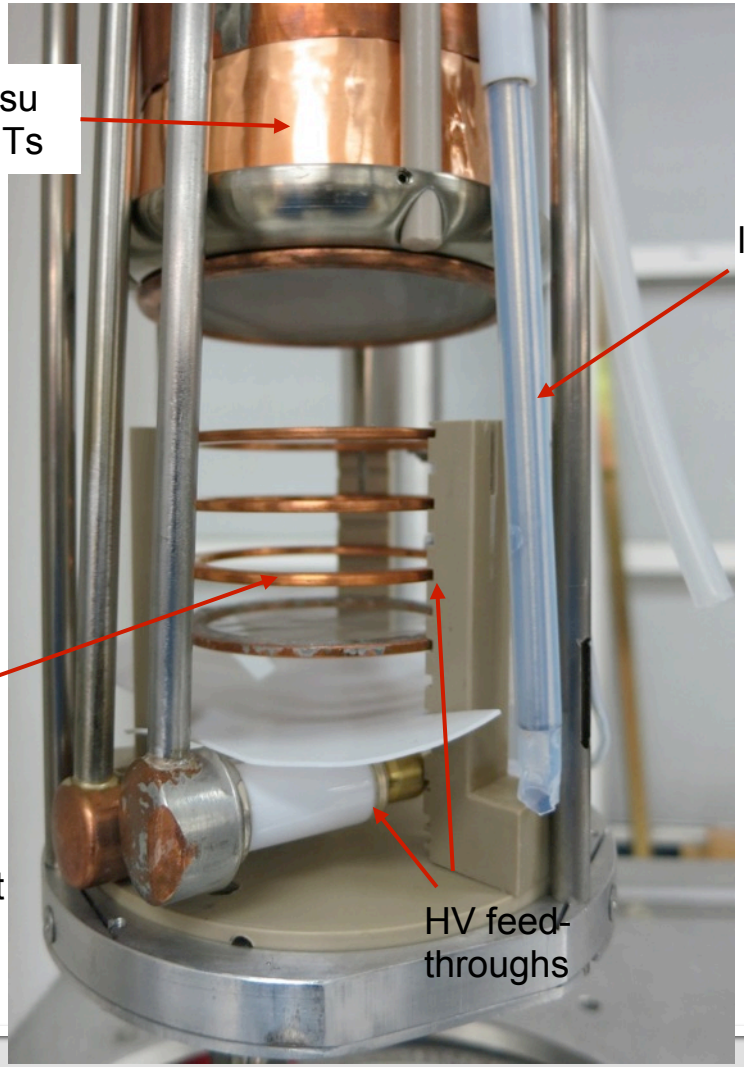




LLNL Dual-phase Ar Prototype Detector

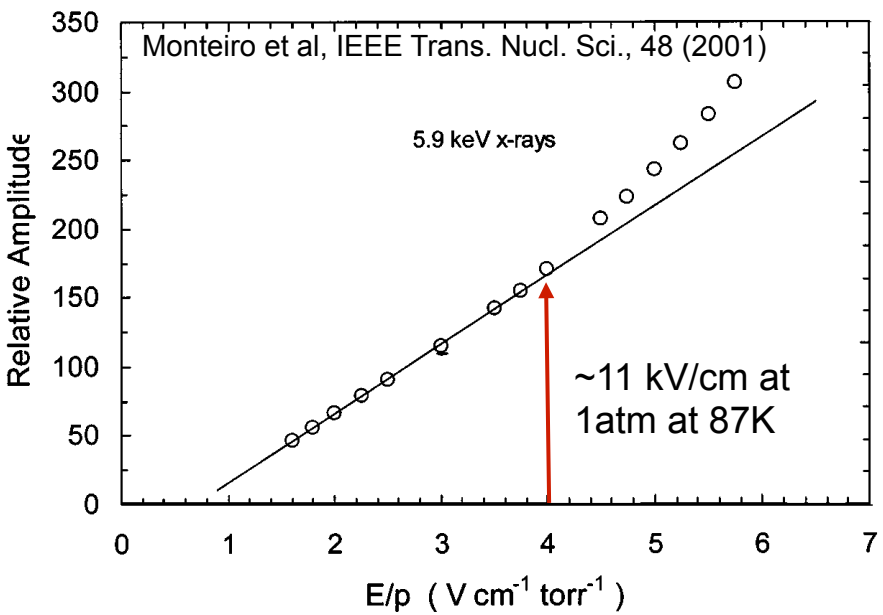
- Active volume: ~ 100 g LAr
- Materials selected for low outgassing
- TPB as wavelength shifter
- Home-built HV feedthroughs

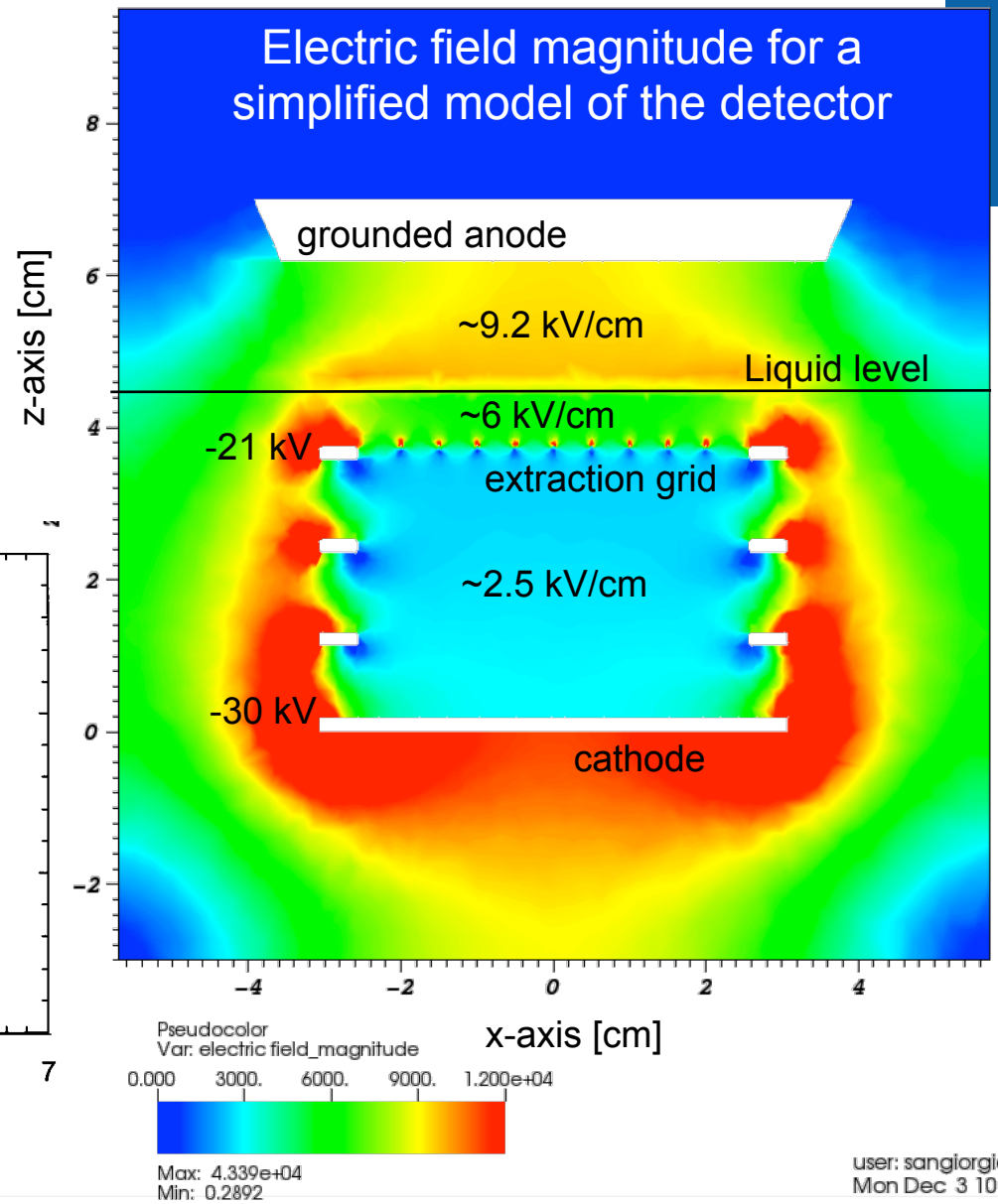




High Gain Detection of Ionization Signal

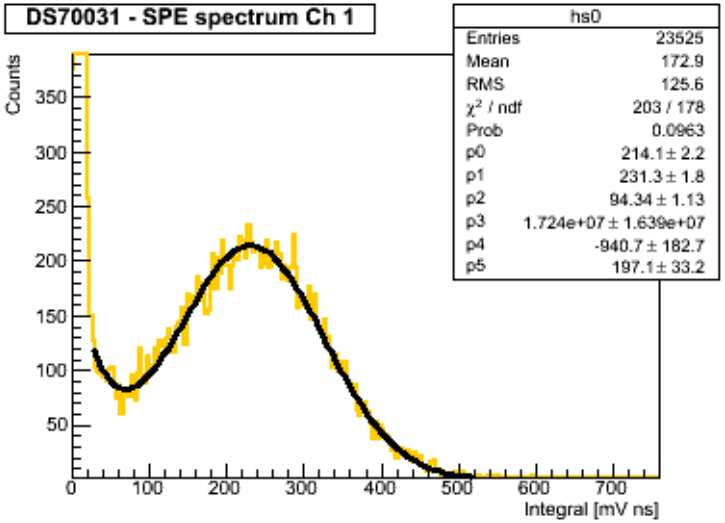
- Emphasis on detection of ionization by means of S2 only
- Operate close to electron multiplication in gas

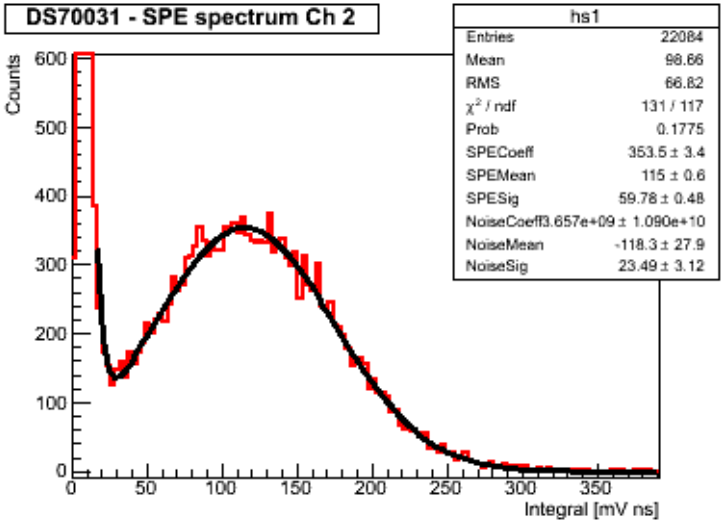


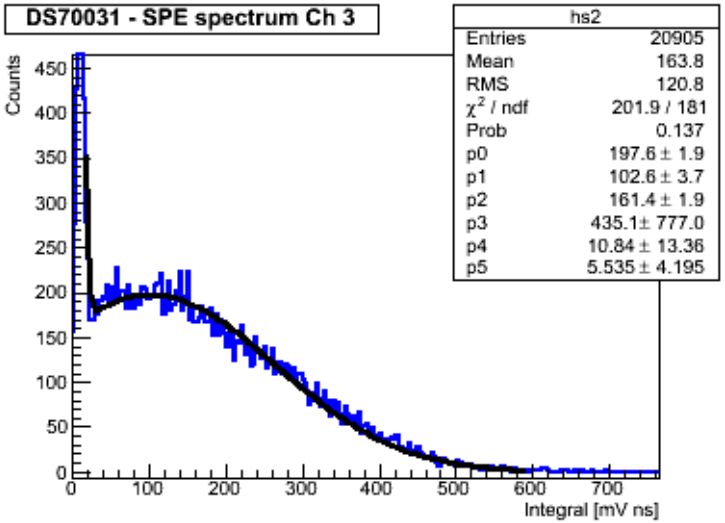


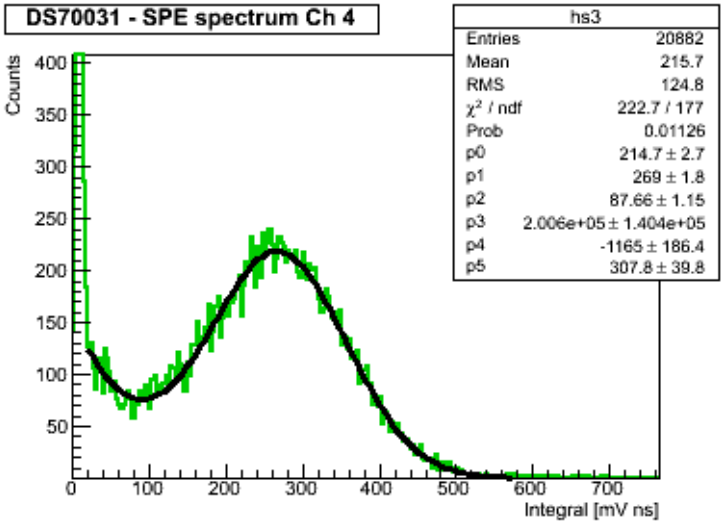
PMTs S.P.E. Response

Hamamatsu R8520 1” PMTs for cryogenic operation



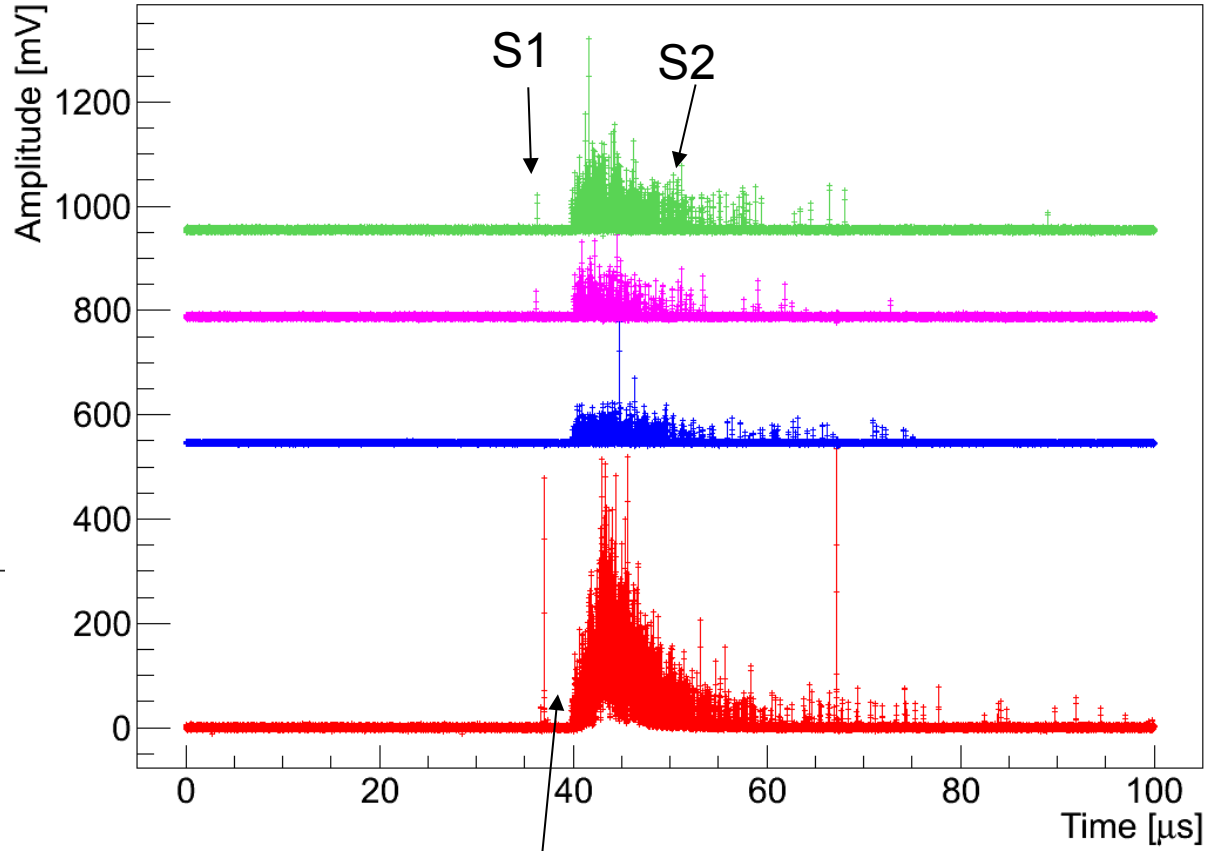




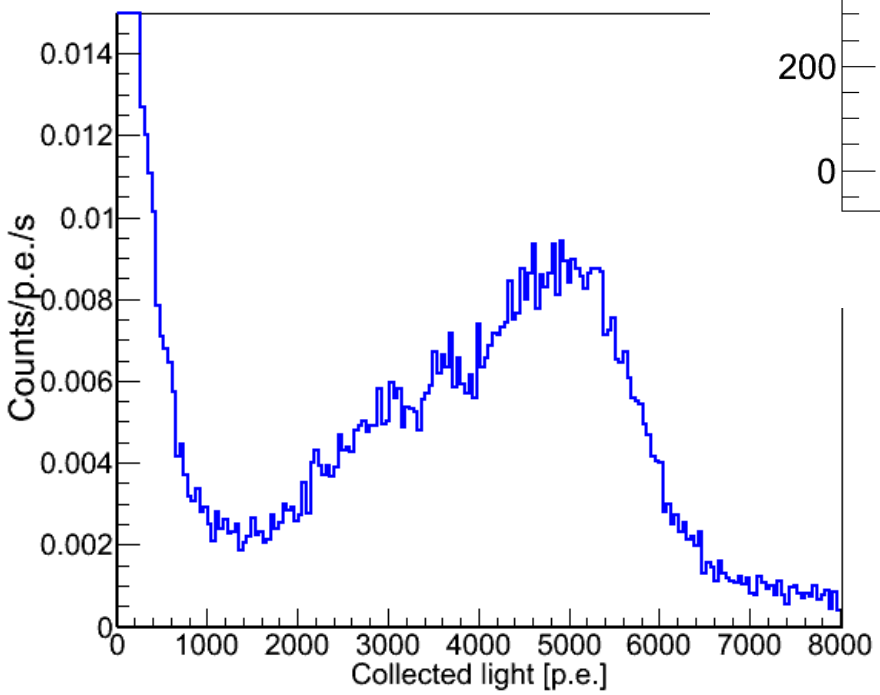


Detector Response

Sample event from a 60 keV photoelectric interaction in the detector as seen by the 4-PMT array

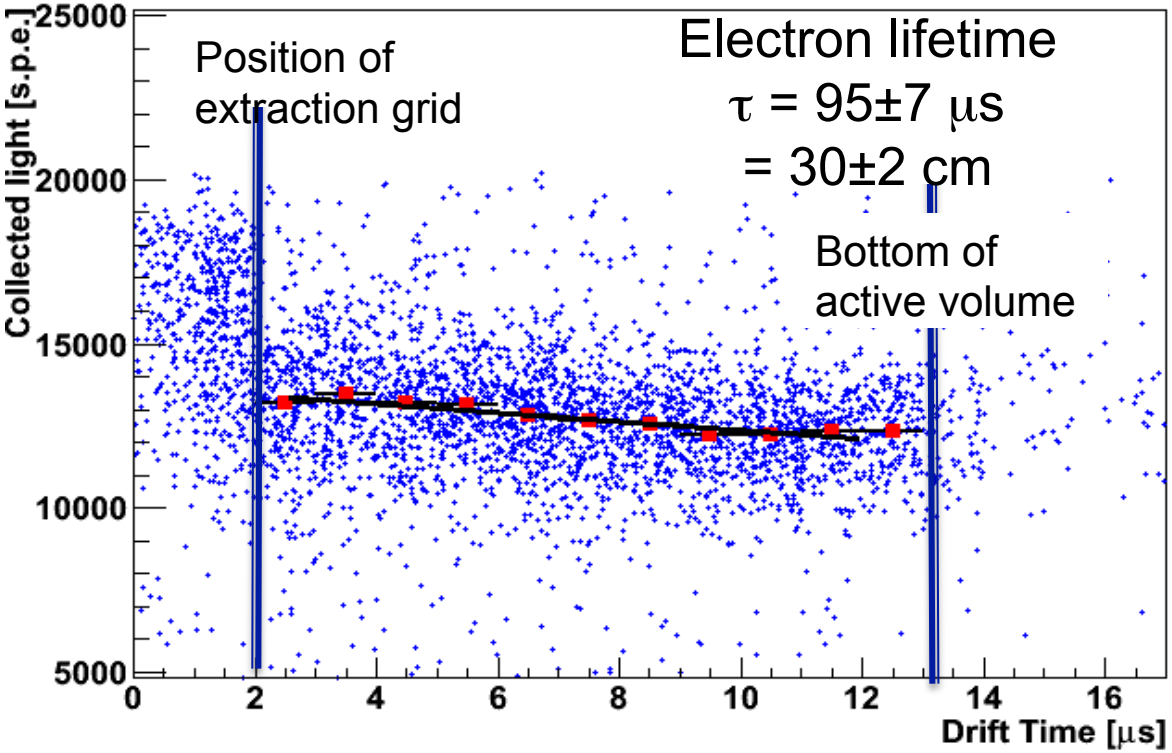


^{241}Am raw spectrum



Time between S1 and S2 gives depth of the interaction

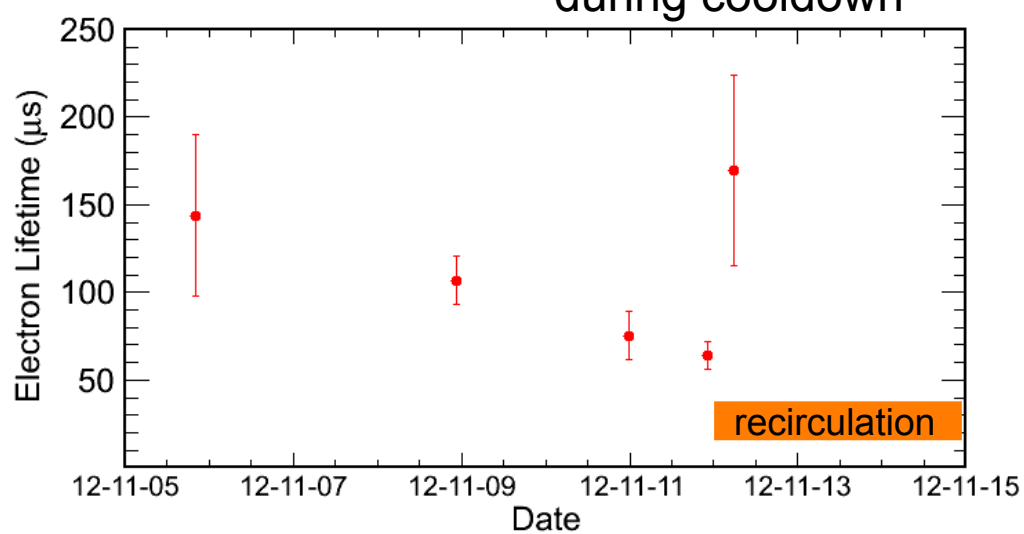
Long-lasting Argon Purity



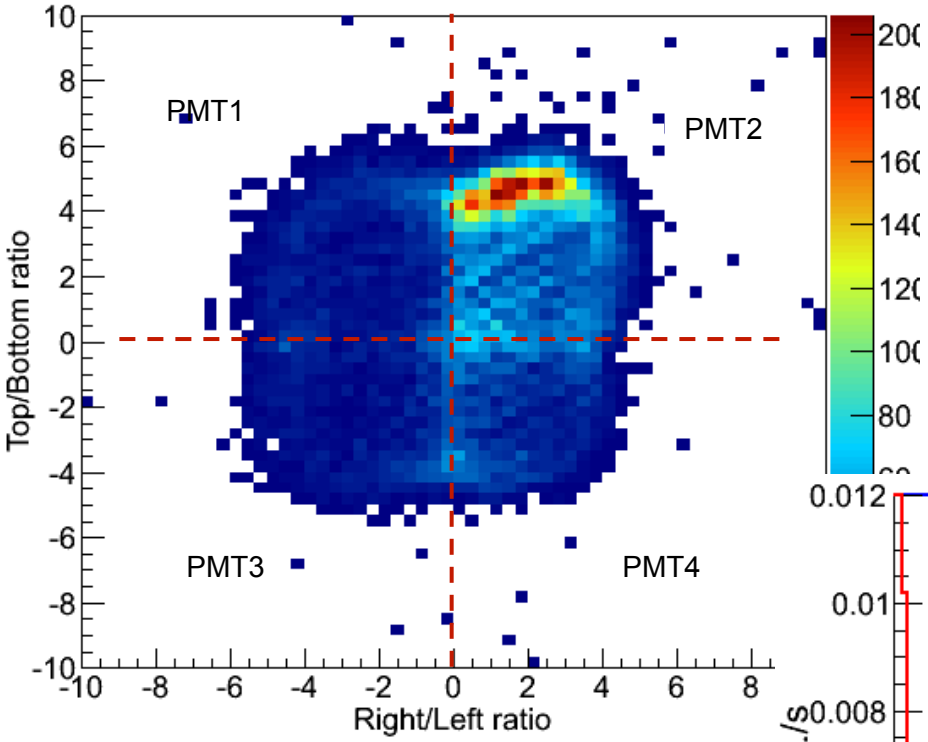
Plot of S2 amplitude in ^{241}Am photopeak as a function of depth extracted from S1-S2 time

Electron lifetime during cooldown

Recirculation needed only after ~6.5 days



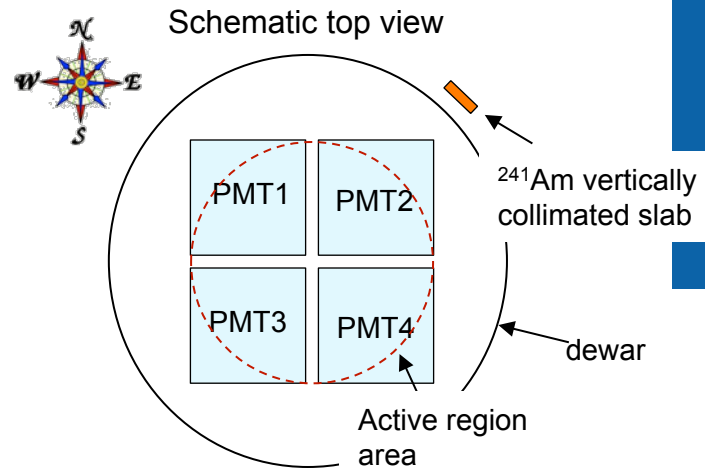
Event Localization



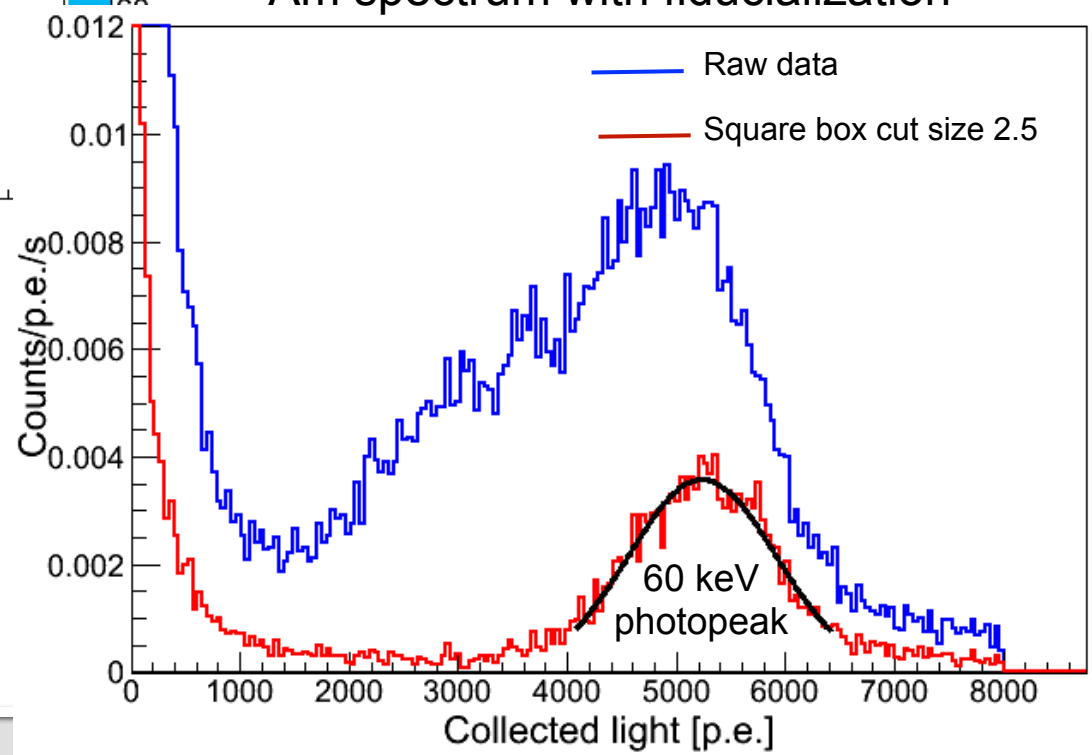
^{241}Am peak fiducial plot

(PMT1+PMT2) / (PMT3+PMT4)

(PMT1+PMT3) / (PMT2+PMT4)

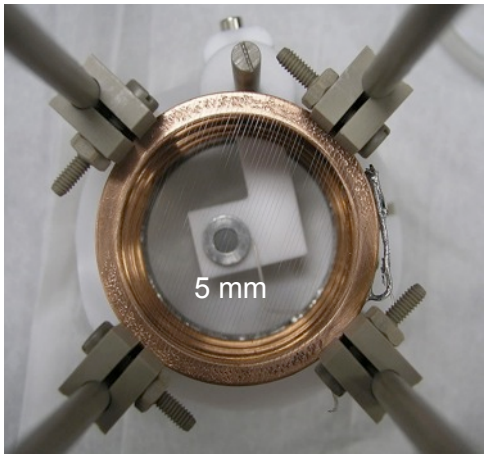


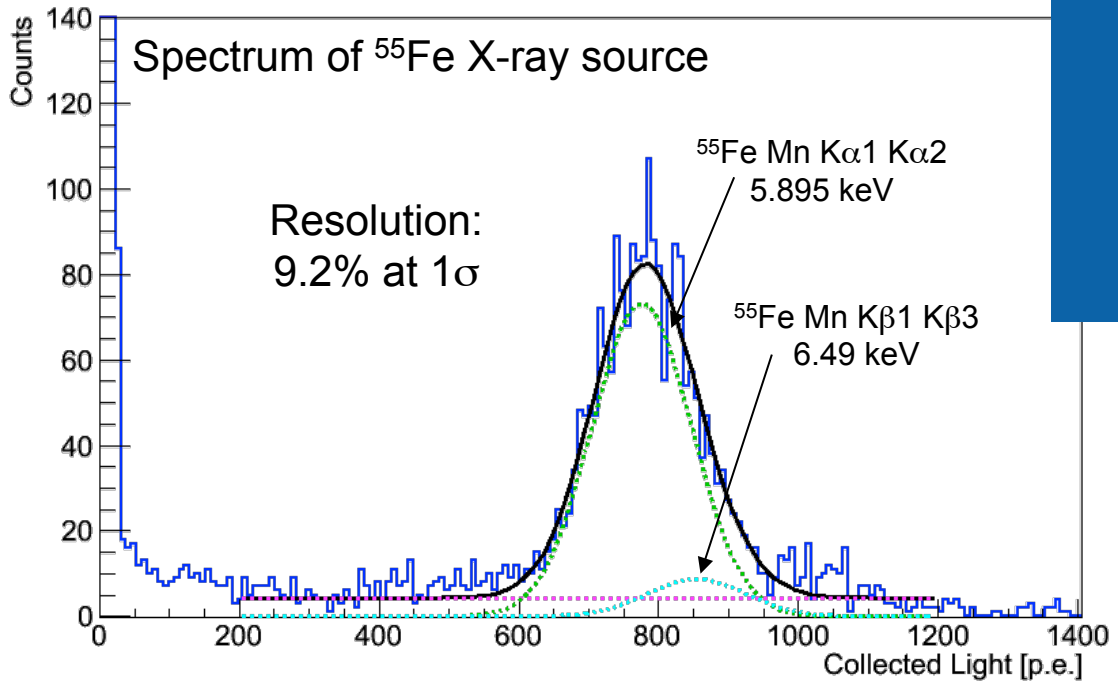
^{241}Am spectrum with fiducialization



^{55}Fe Calibration

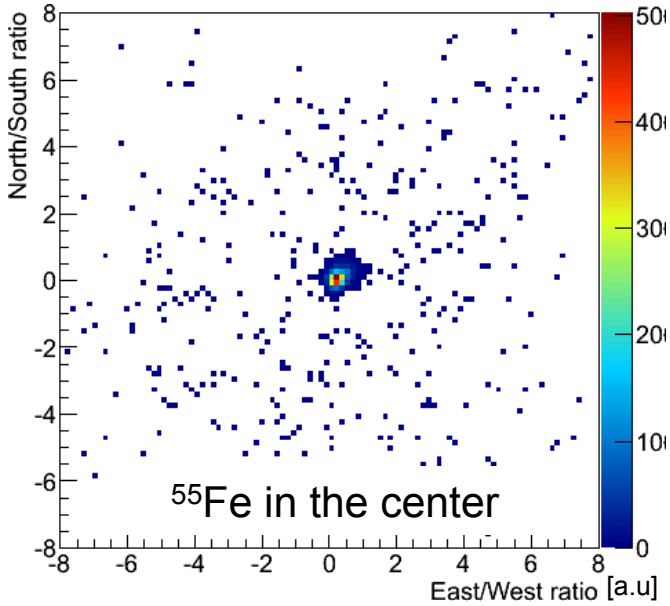
Electroplated ~100Bq
^{55}Fe on a movable arm

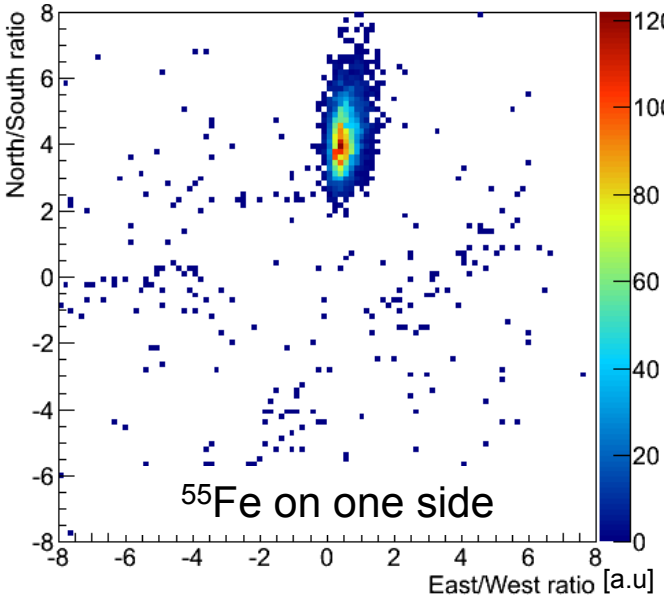




Under study:

- Mapping of fiducialization parameter space
- Position systematics





Novel Approach for Calibration: ^{37}Ar

Provides low-energy uniform calibration throughout the whole detector volume

Isotope production

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

Decay scheme

100% electron capture

$t_{1/2}$ = 35.04 d

Q(gs) = 813.5 keV

Decay radiation

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

L- capture 0.27 keV (8.9%)

M- capture 0.02 keV (0.9%)

^{nat}Ar isotopes

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

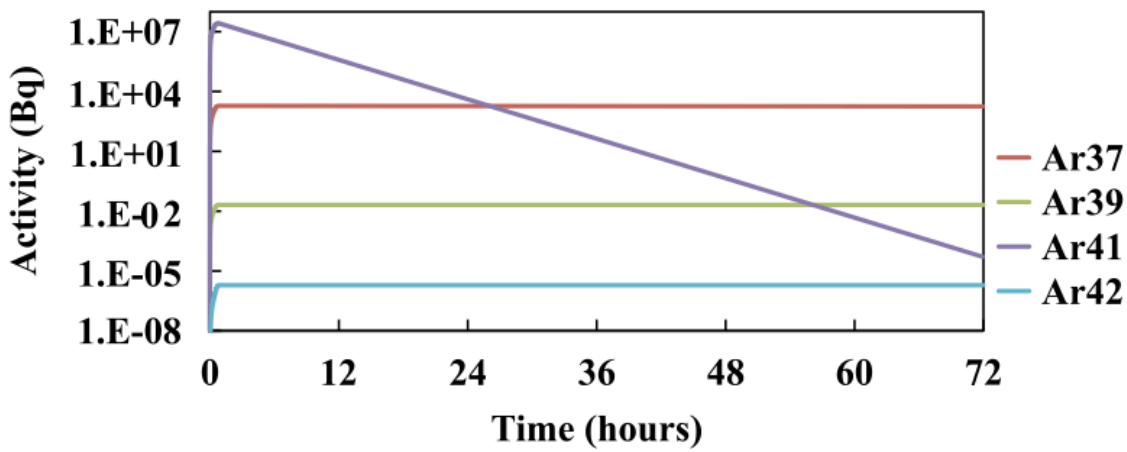


Fig. 1. Calculated activity of radioargon isotopes from 1 h, in-core neutron irradiation of 1 cm^3 of natural argon gas.

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

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

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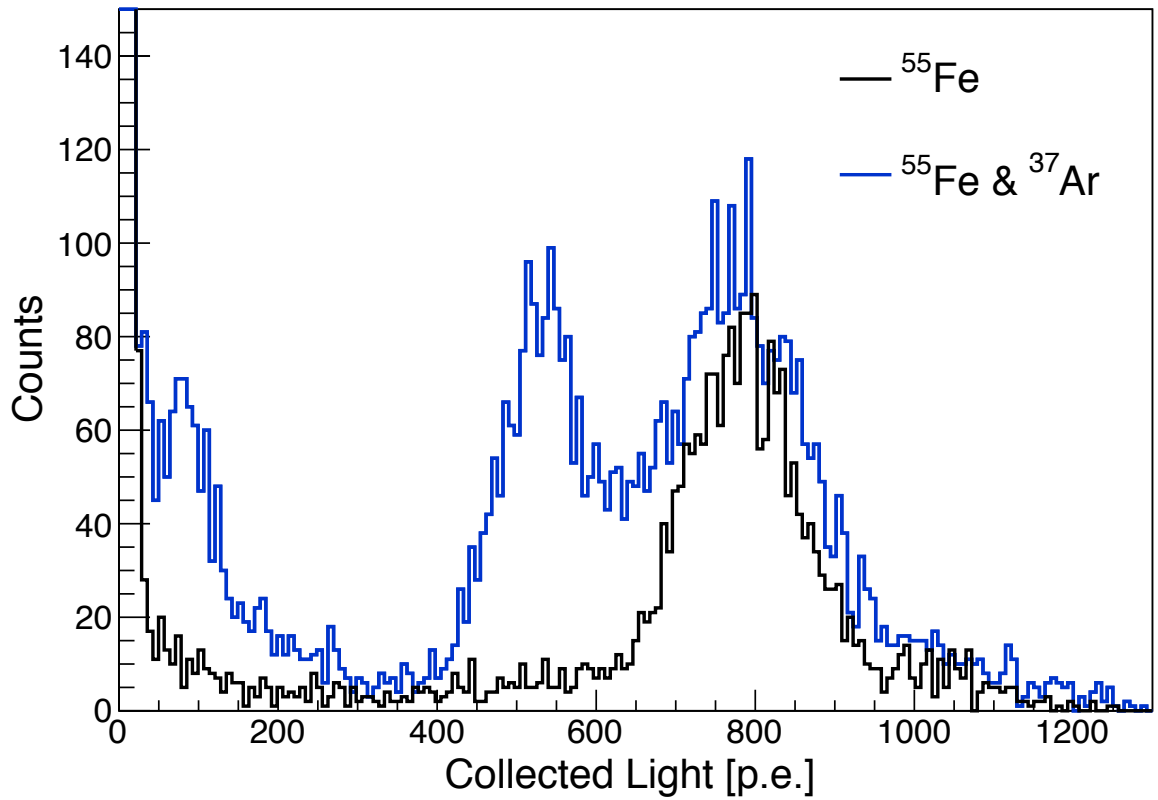
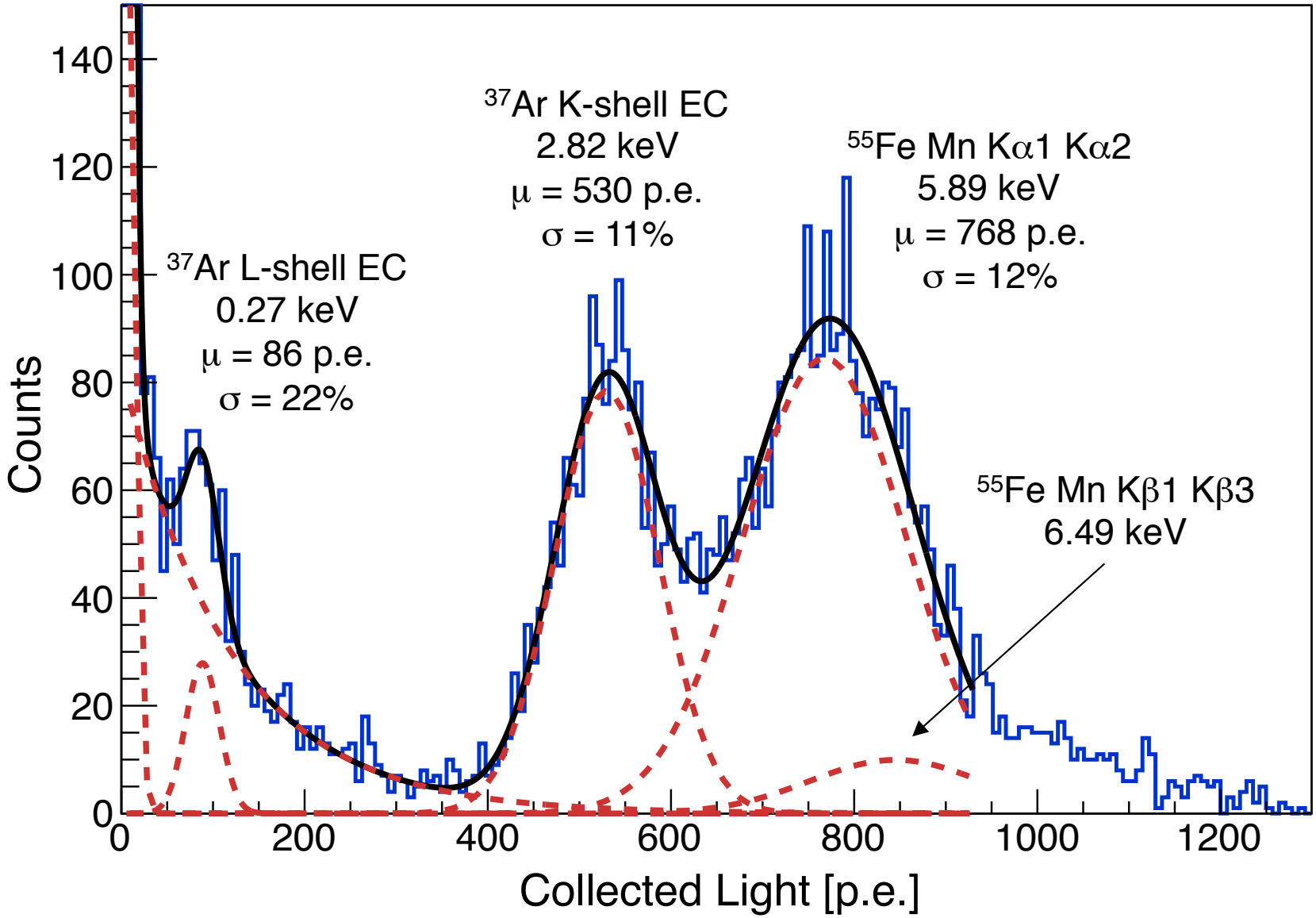
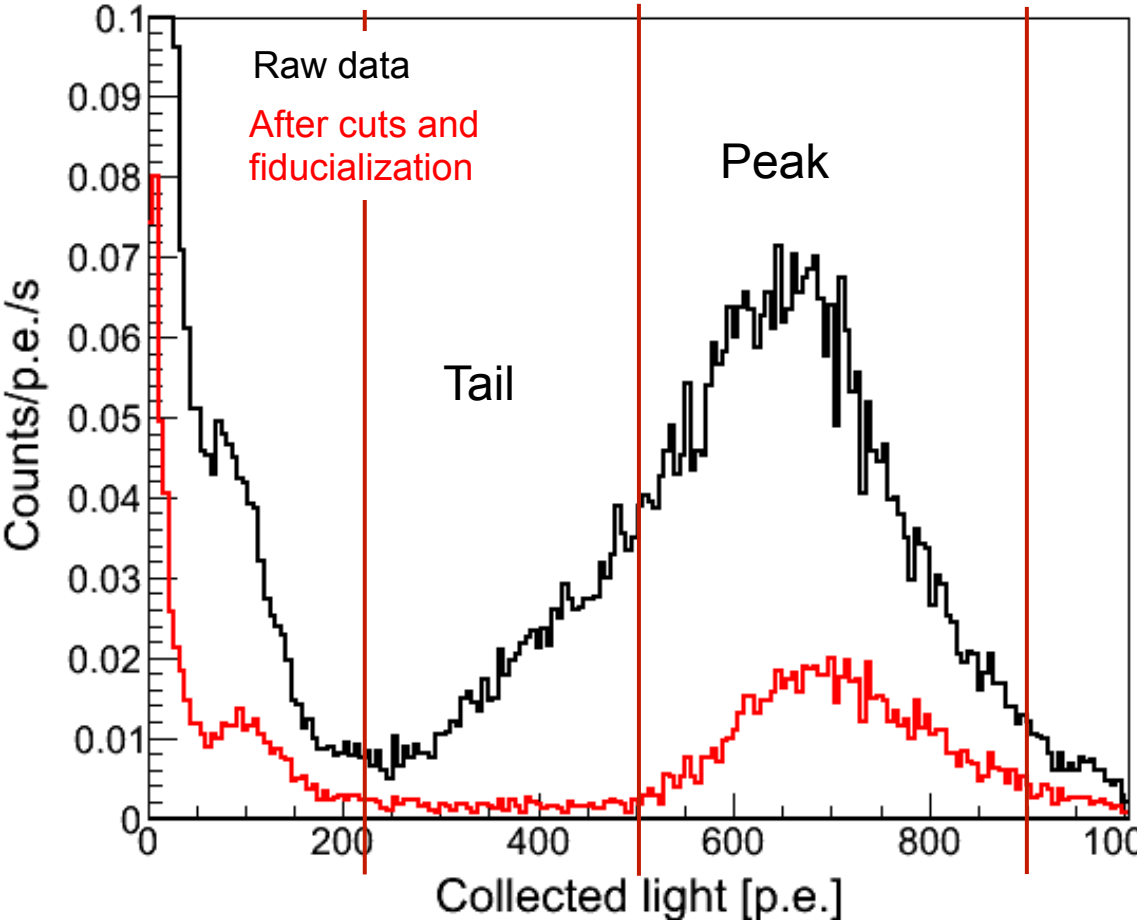


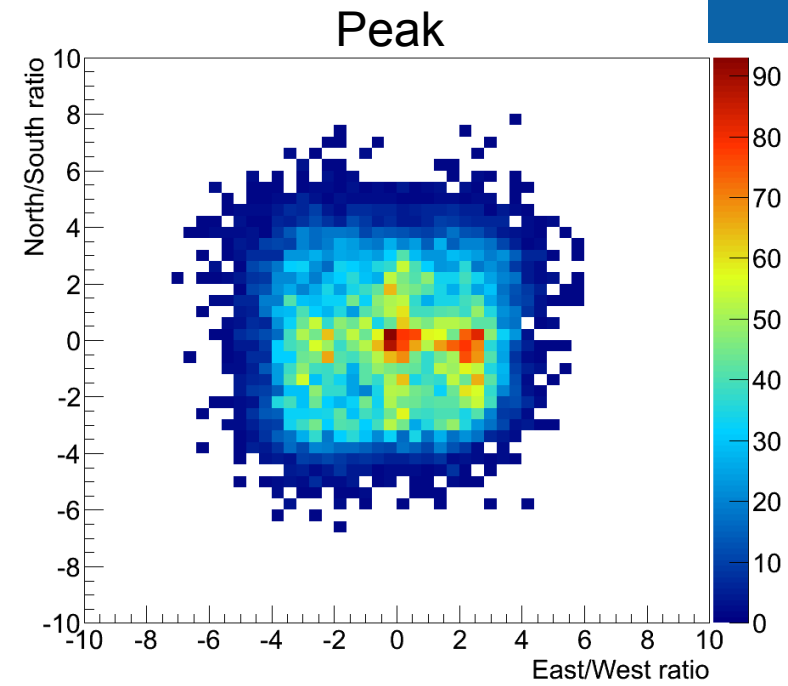
Sub-keV Sensitivity for Electron Recoils

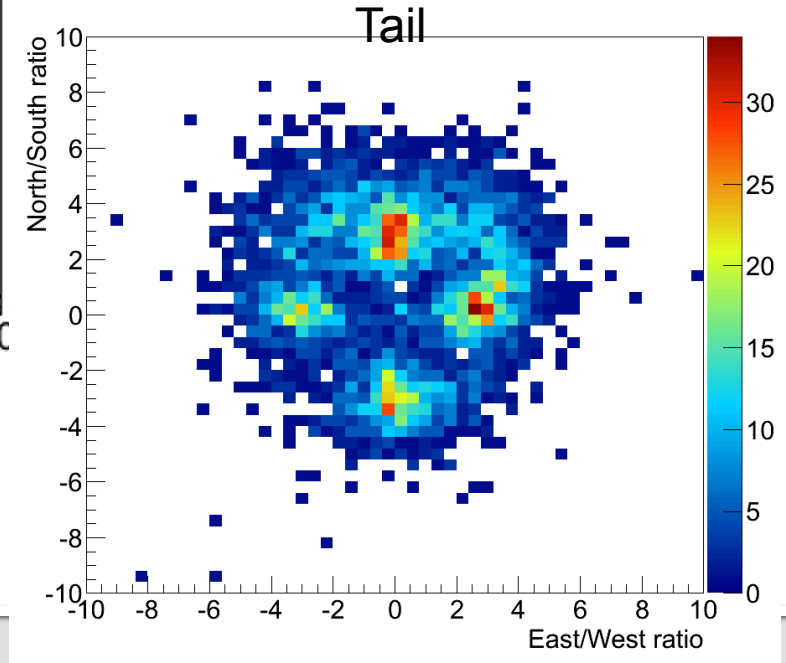


S. Sangiorgio, et al. arXiv:1301.4290

Ar-37 Fiducialization

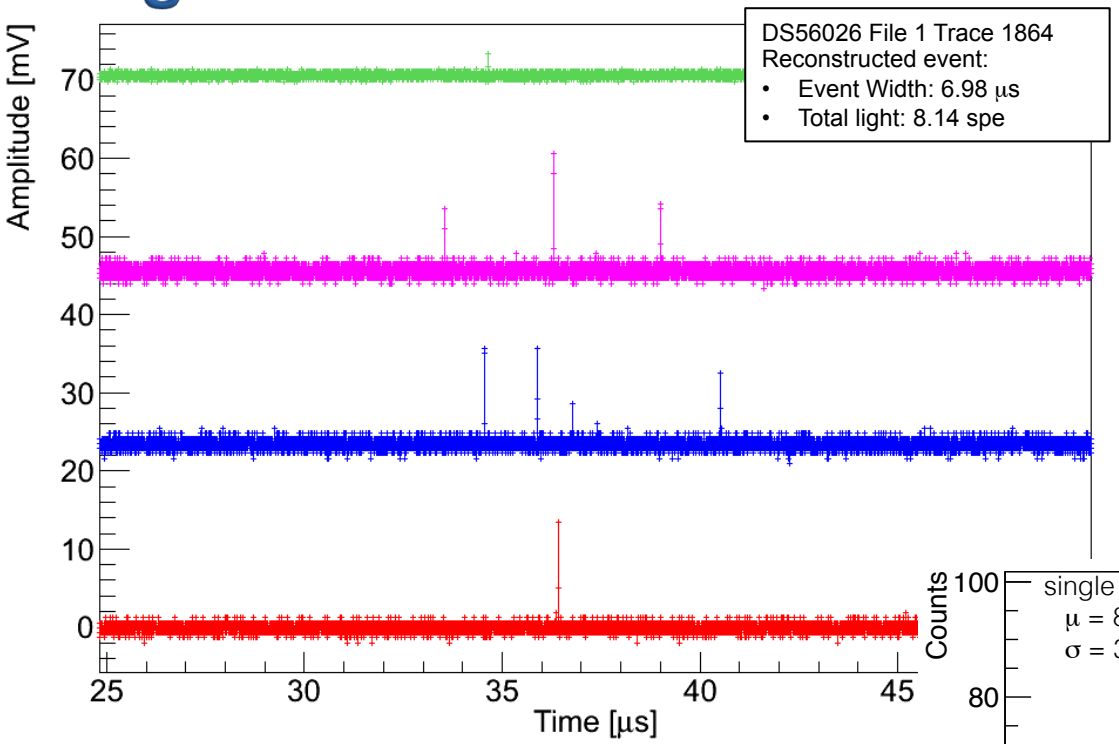






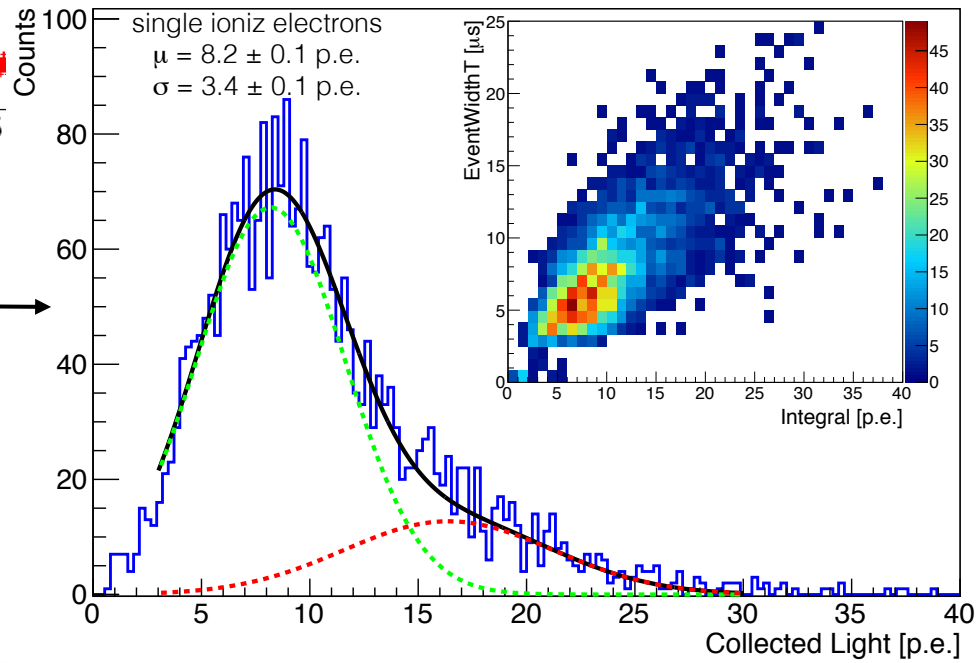
Events in the tail mostly due to lower geometric light collection efficiency

Single Ionization Electrons



- Typical S.E. event as seen on the scope
- Full trace is 100μs long and has no s.p.e. other than those shown

- Experimental spectrum of single and double ionization electrons
- Not compatible with primary scintillation signal (S1) because:
  - Event width of 5-8 μs is too long
  - Light distribution not compatible with LAr S1 characteristics
  - Dependence on gain field



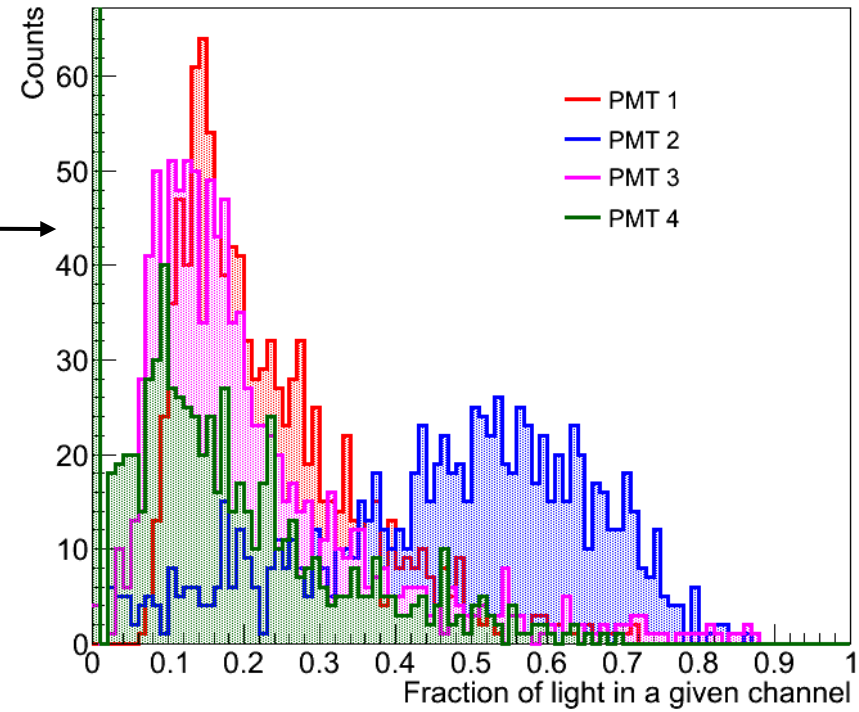
Single Electron Investigation in Progress

- S.E.s appearance has been seen in the aftermath of electrical discharges from the HV system, with rate decreasing with time

Different from observations in Xe by RED collaboration

- Indications of S.E. production from a specific point in the detector from the light content per PMT

Light content per PMT in S.E. events



- Single Electrons:
  - Absolute detector calibration
  - Source of background
  - Need to understand origin
  - Controlled production?

Model of Ionization in Liquid Argon

Initial ionization from energy partitioning between ionization and excitation:

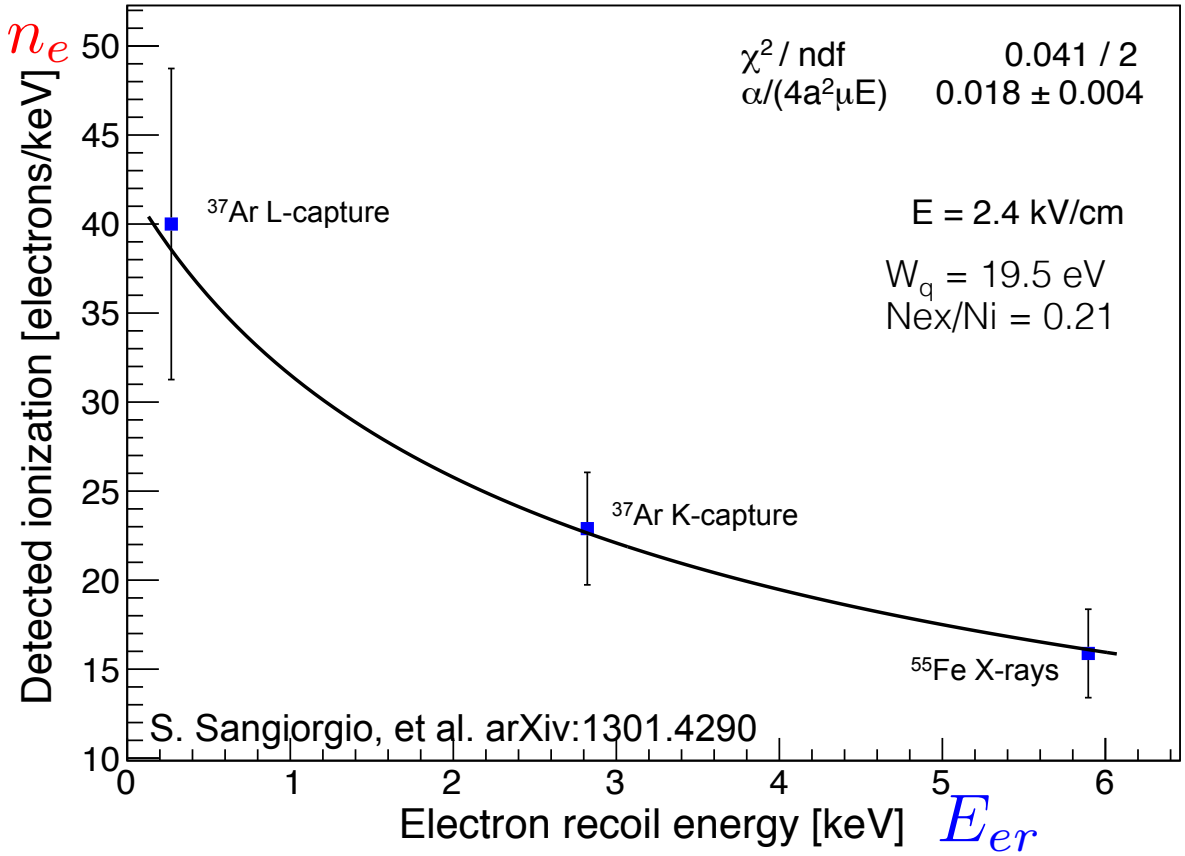
$$N_i = \frac{E_{er}}{w_q} \frac{1}{(1 + N_{\rm ex}/N_i)}$$

Assume Thomas-Imel box model of recombination:

$$\frac{n_e}{N_i} = \frac{1}{\xi} \ln(1 + \xi)$$

$$\xi = \frac{N_i \alpha}{4a^2 u E}$$

constant single fit parameter



Can this be extended to nuclear recoils?
- See NEST [M. Szydagis, arxiV:1106.1613

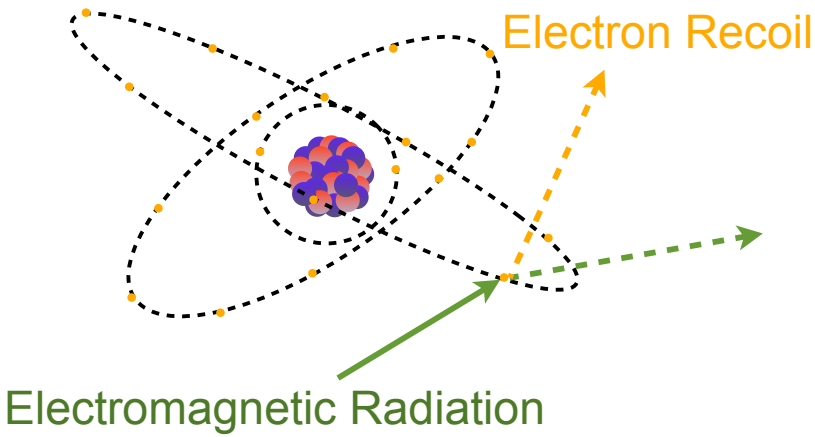
Cfr. Sorensen, P. and Dahl, C. E., *Phys. Rev. D.* **83** (2011)

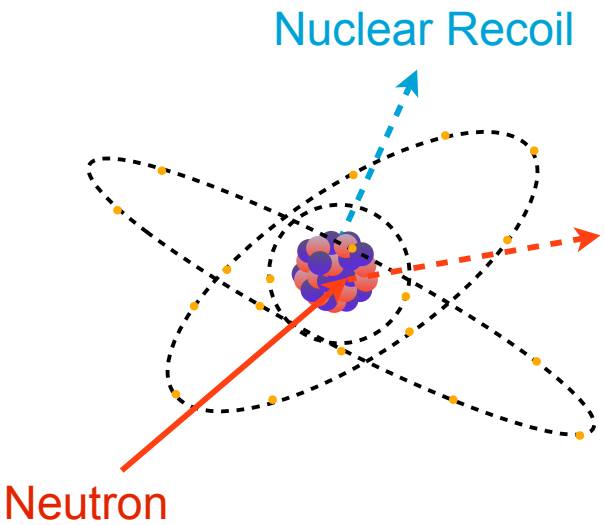
Half-time recap

- LLNL prototype
  - Novel calibration approach with 37Ar
  - Sub-keV spectroscopy
  - Single electron sensitivity

Demonstrated low-energy threshold in LAr

- Inducing nuclear recoils with neutrons





Use neutrons to mimic neutrino-induced recoils

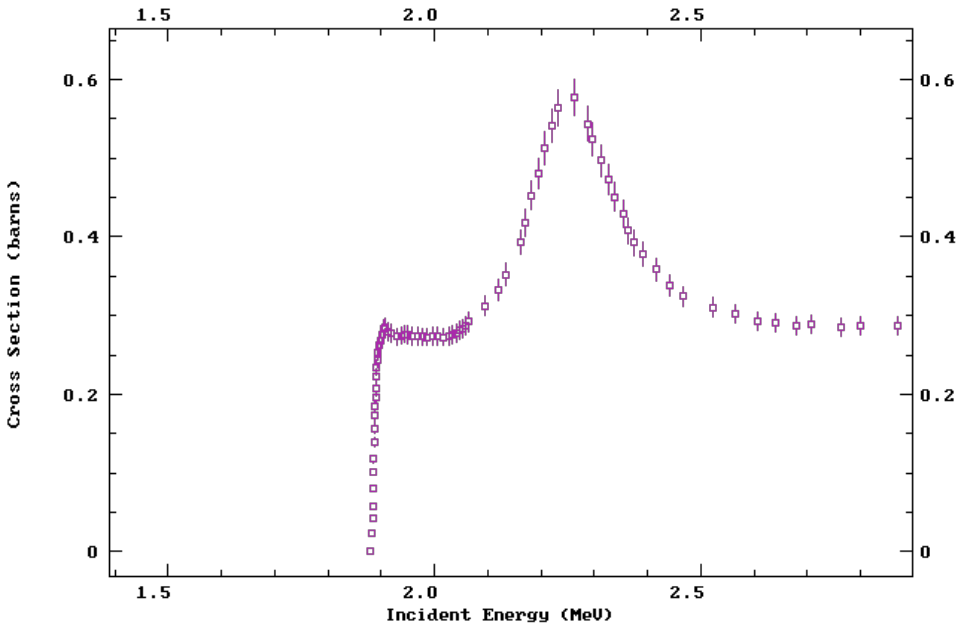
Elastic scattering of neutrons on argon

- End-point measurement

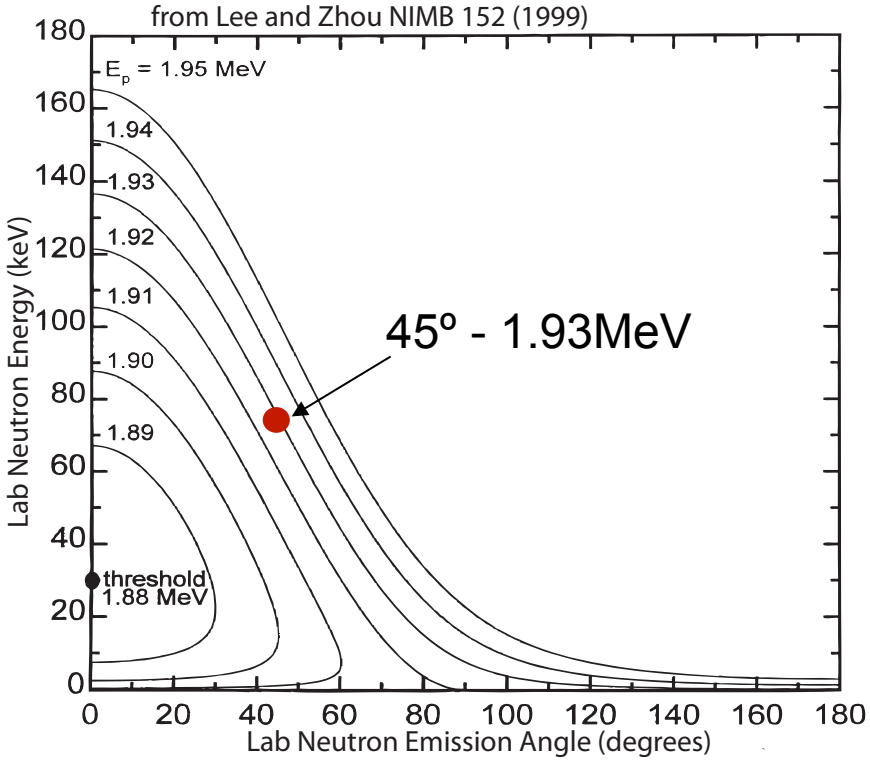
$$T_{\mathrm{Ar}}^{\mathrm{MAX}} = \frac{4mM}{(m+M)^2} E_n$$

Using near-threshold kinematics we can control maximum neutron energy

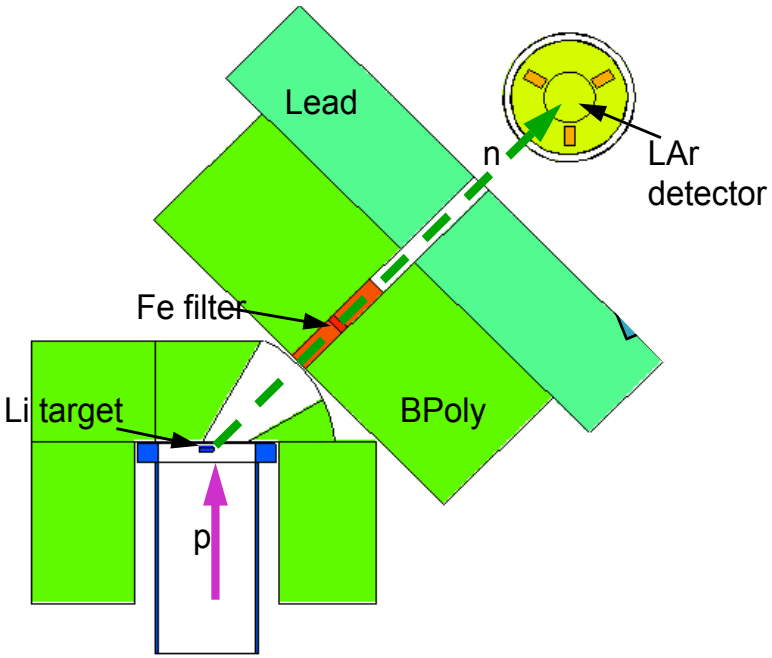
^{7}Li(p,n)^{7}Be

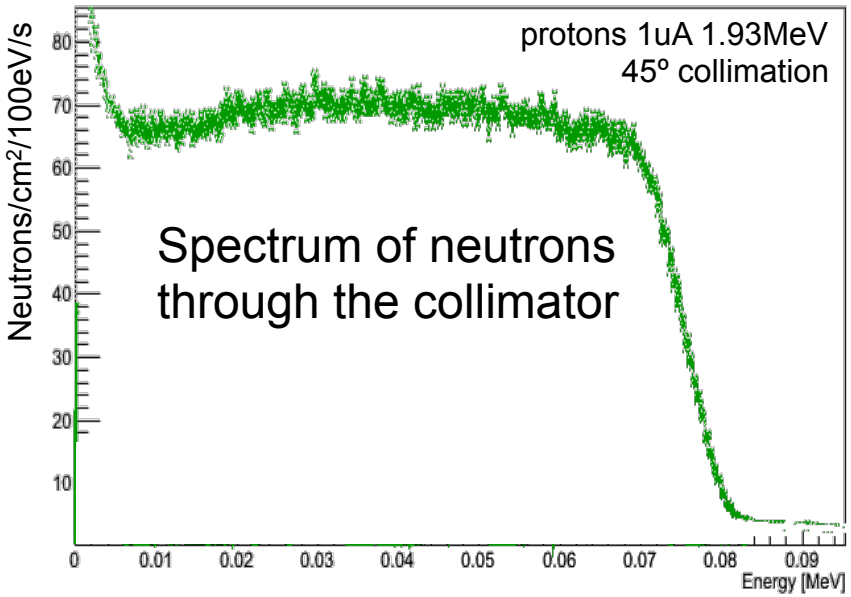


Proton Energy Countours for a Thick Lithium Target from Lee and Zhou NIMB 152 (1999)

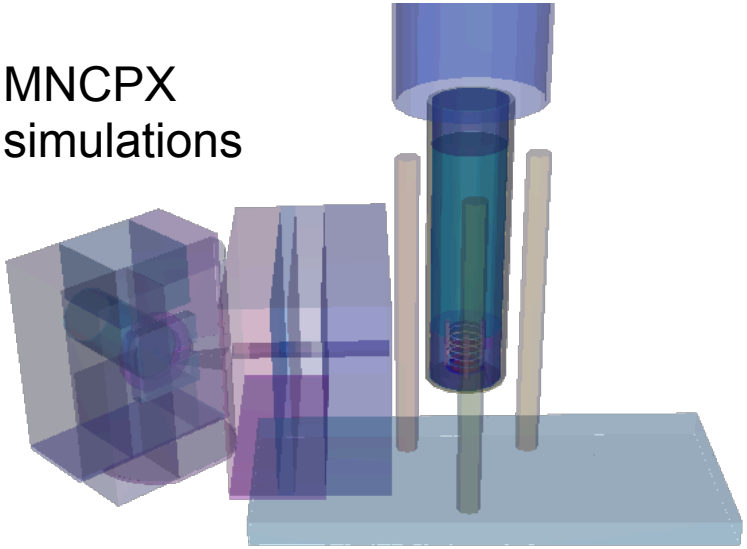


A collimated neutron source



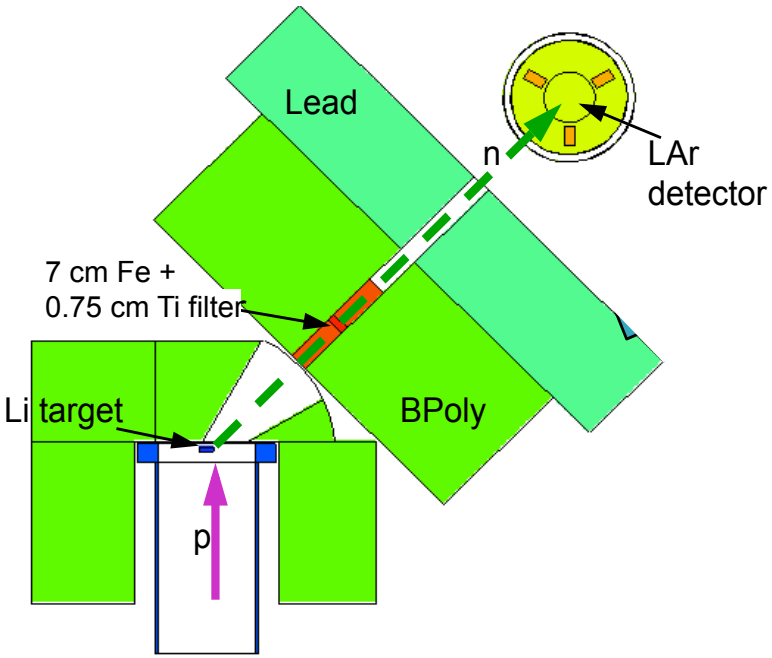


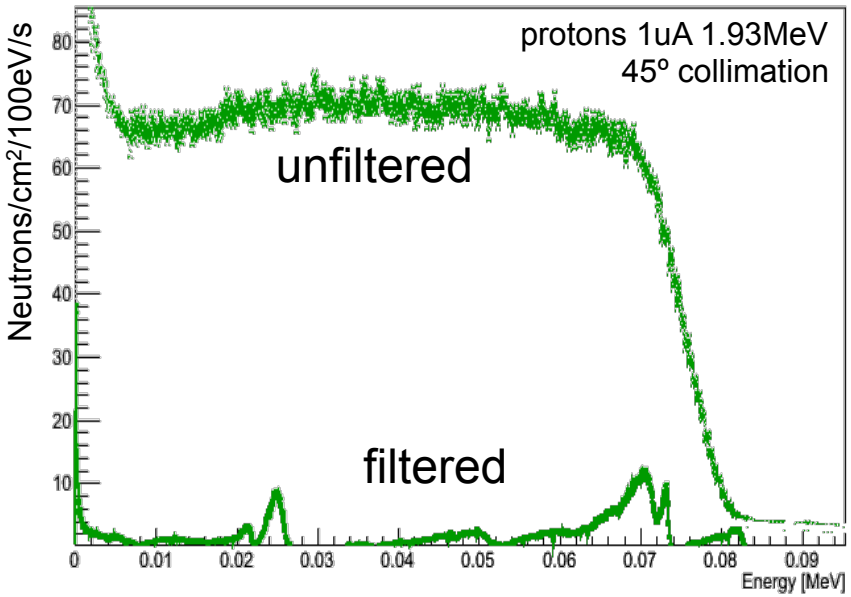
MNCPX
simulations

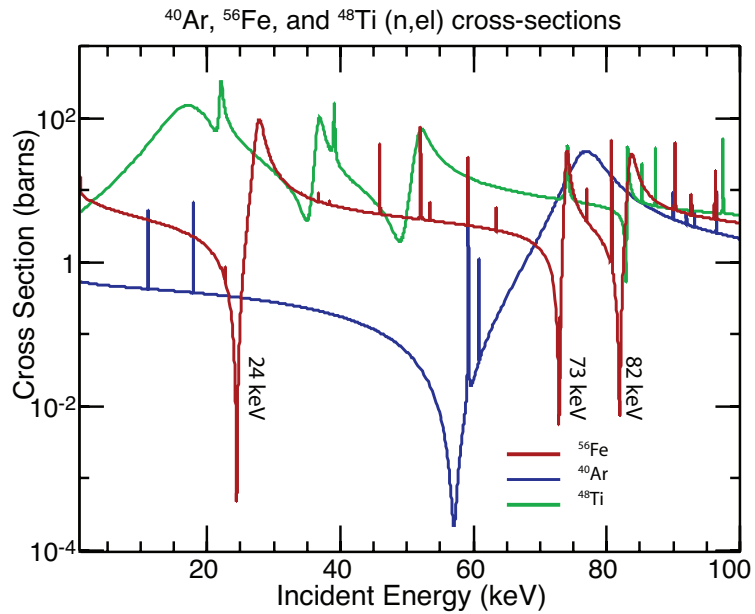


Backgrounds from
- (p,p') in Li → 478 keV γ
- 478 keV γ from n capture in BPoly

A filtered and collimated neutron source

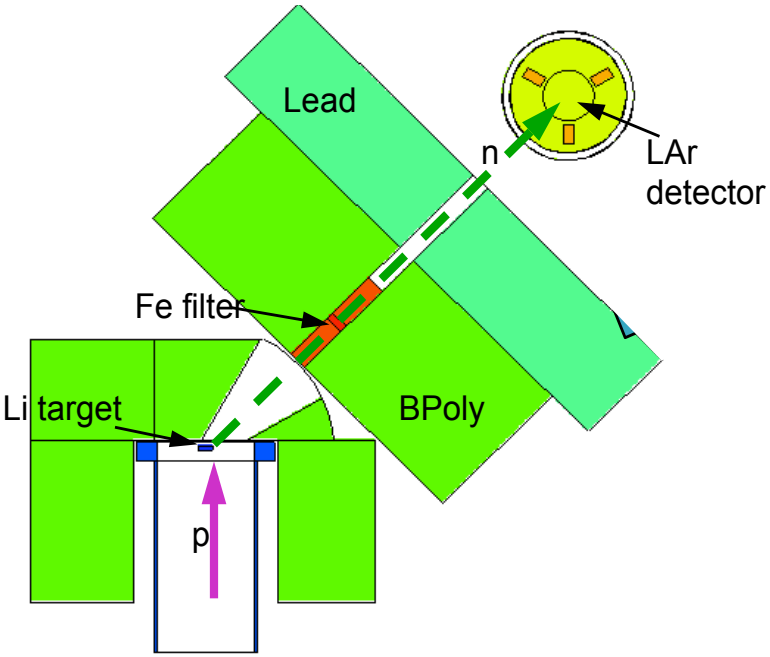


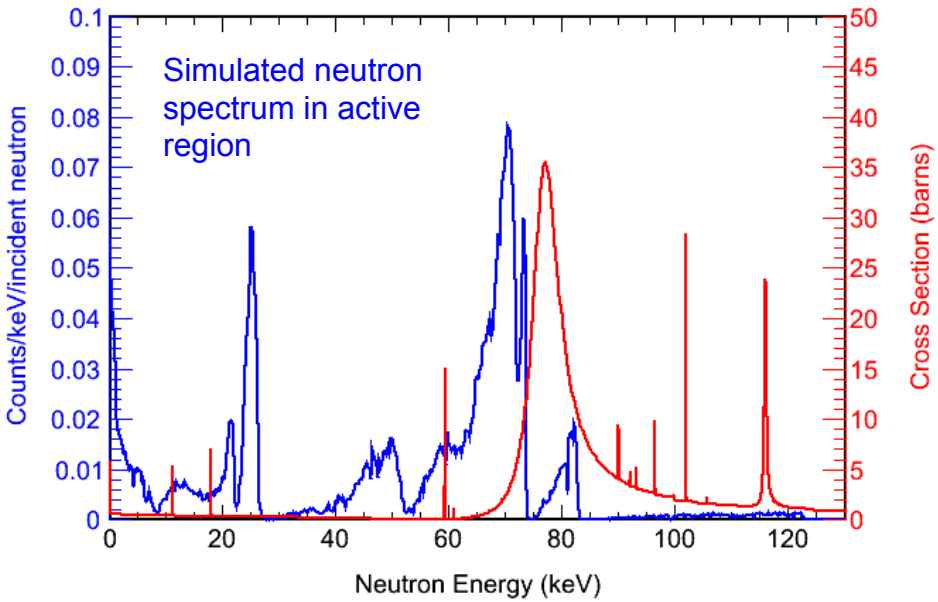


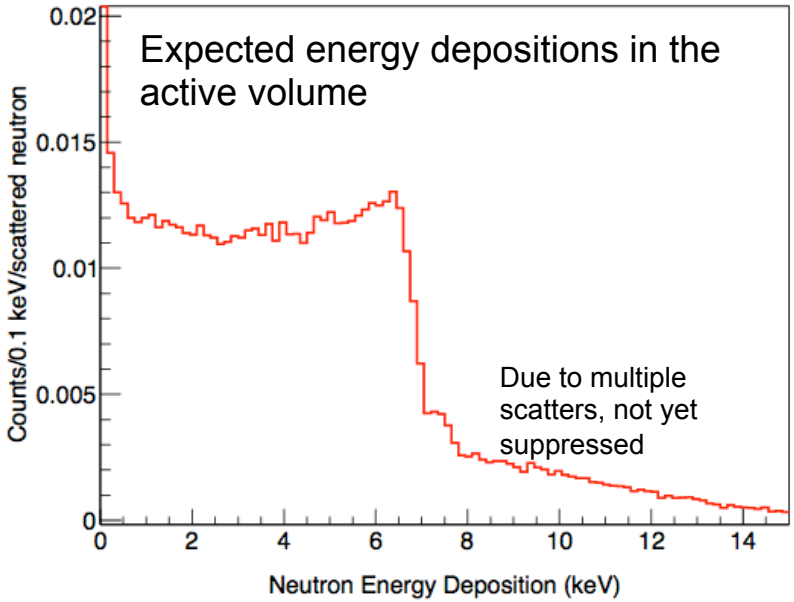


- Take advantage of nuclear data to selectively transmit neutrons through interference dips in scattering x-sections [see P. Barbeau et al, NIM A (2007)]
- Quasi-monoenergetic beam ~73 keV match Ar(n,el) resonance

Measurement of ionization yield at 7.3 keVr







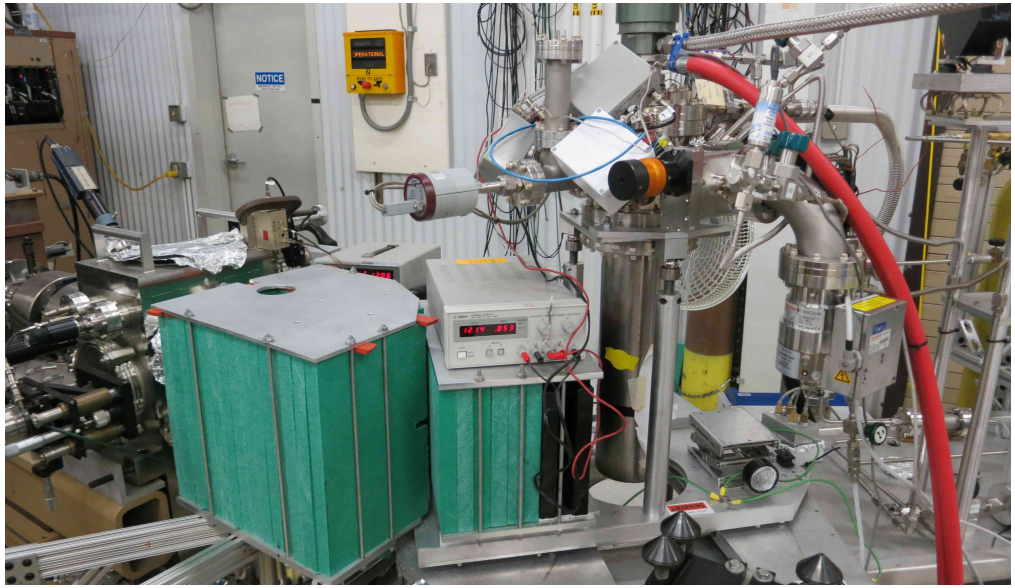
Look for paper on the neutron beam design in the near future

The setup at the accelerator

1.7 MeV Tandem accelerator at LLNL Center for Accelerator Mass Spectroscopy

The move. Garage sale?

The collimator setup

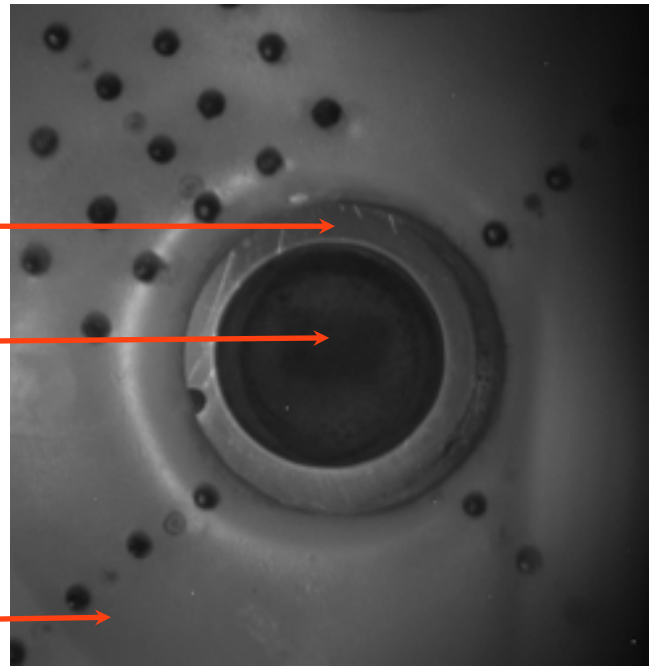


Protons on target

Ag Target Backing
- proton sink

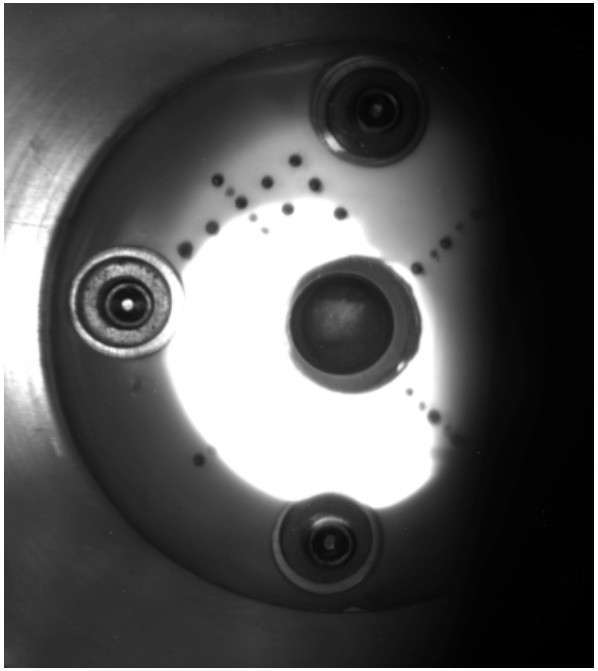
Li target
-8mm diameter
-10μm thick

Target holder



Protons on Target

- 3mm x 3mm square beam spot
- halo extends out ~15 mm



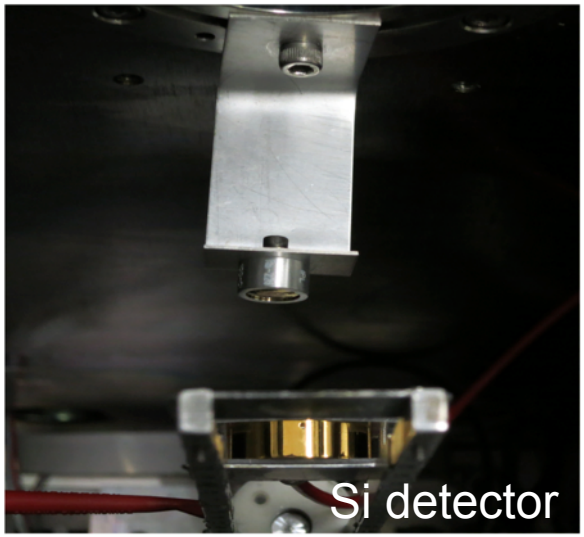
First attempt

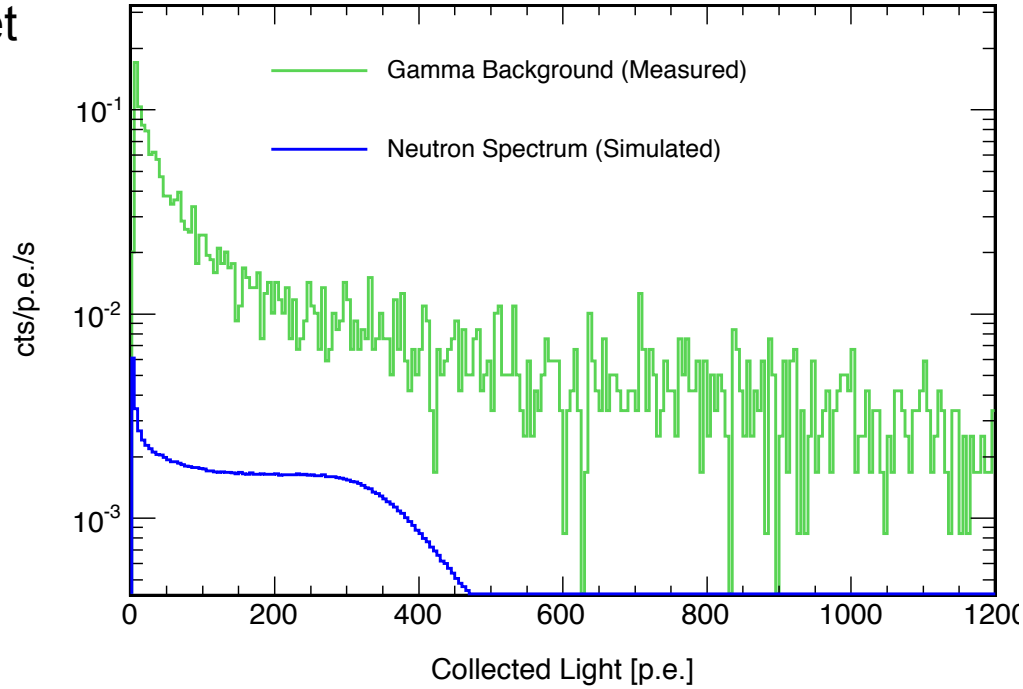
Goals:

- Integrate our setup with accelerator ☺
- Verify accelerator performances ☺
- Validate neutron signal and gamma background using He3 and NaI detectors ☹

Problems:

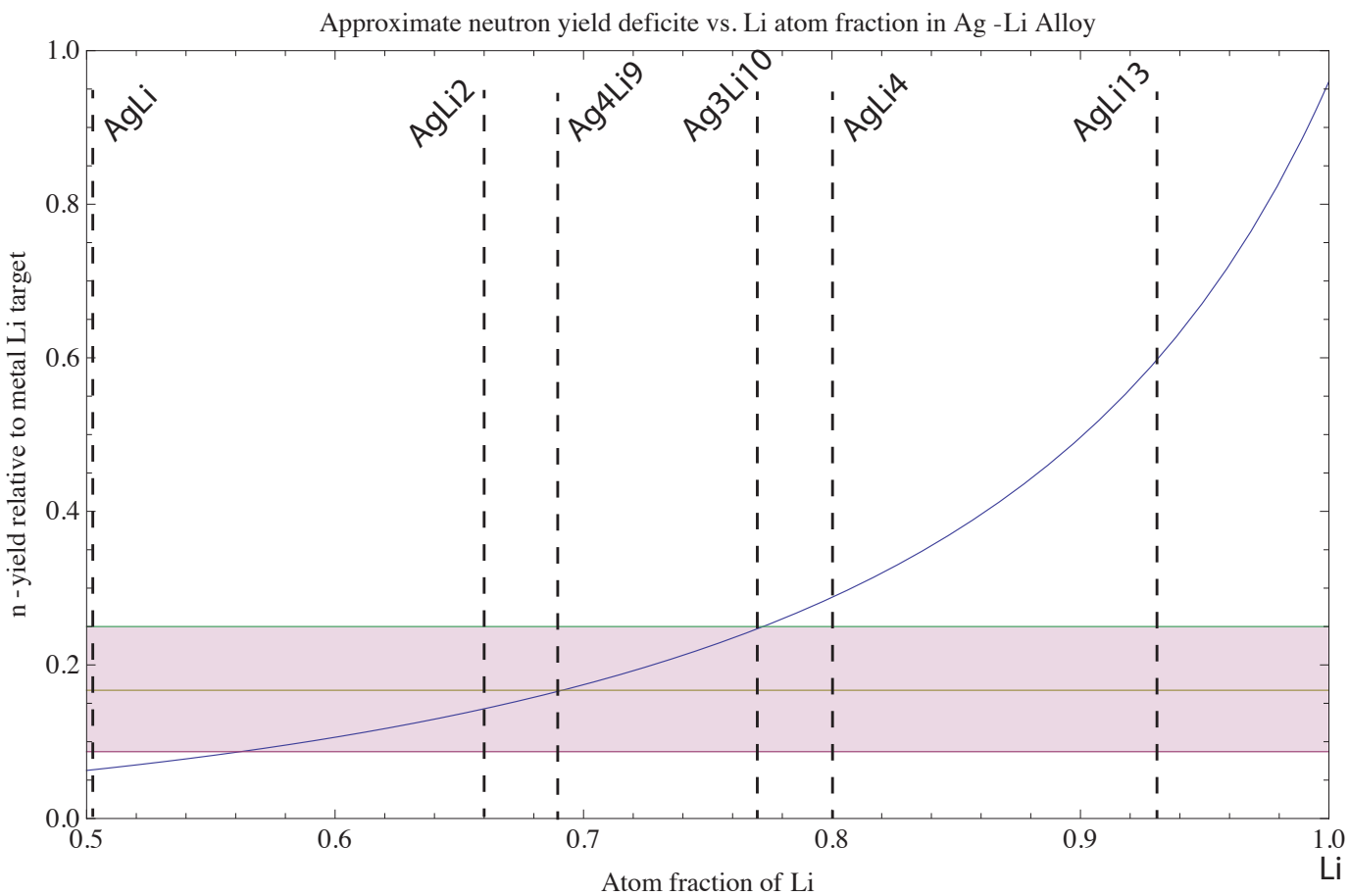
- Gamma shielding was found to be insufficient
- Deficit of neutrons from the target





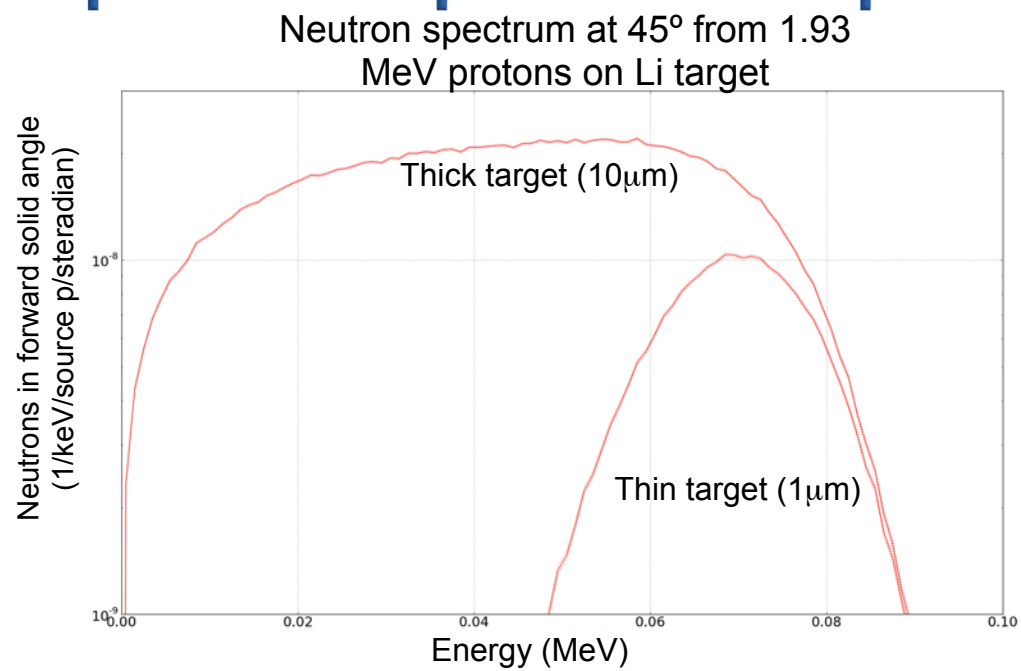
The issue with the Li target
i.e. how I learnt to beware of free stuff

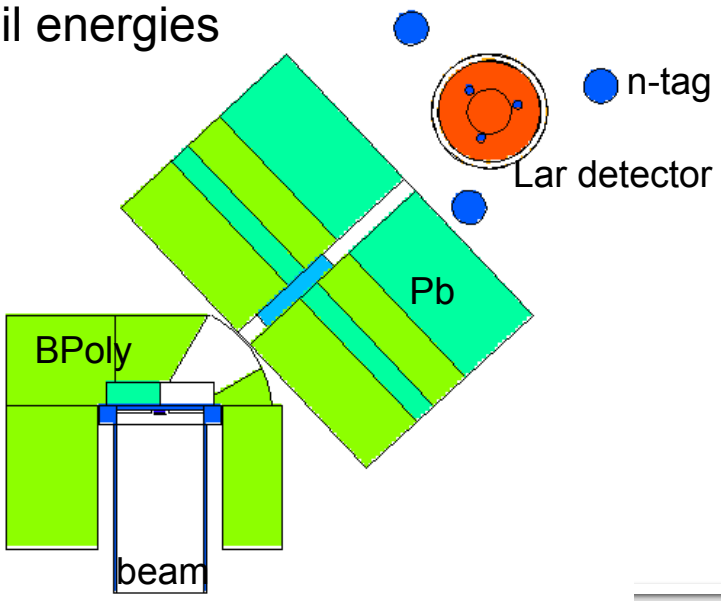
- Li target was produced in 2006
- Li was evaporated on Ag puck
- Lower neutron yield due to diffusion of Ag in Li

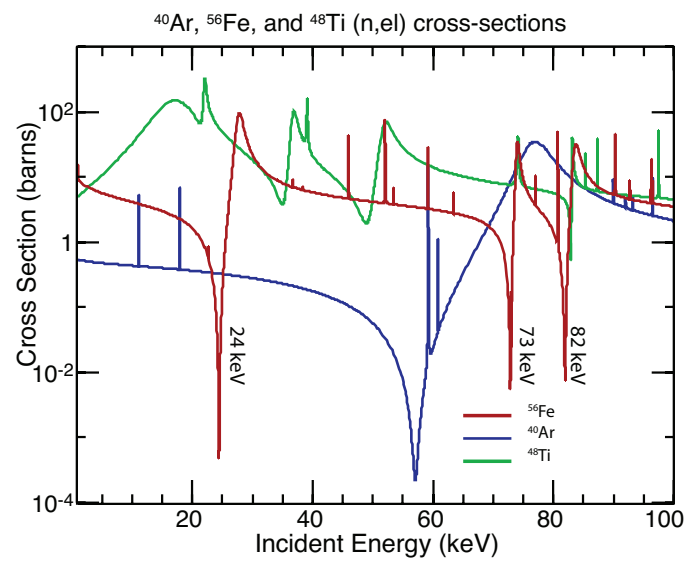


Preparing for 2nd attempt with improved setup

- Thin (1μm) Lithium procured
  - No low-energy neutrons
  - Remove Ti filter
  - Lower gamma background
- Optimized shielding
- Endpoint measurement with neutron beams at 73 keV and 24 keV
- Tag neutrons to access lower recoil energies

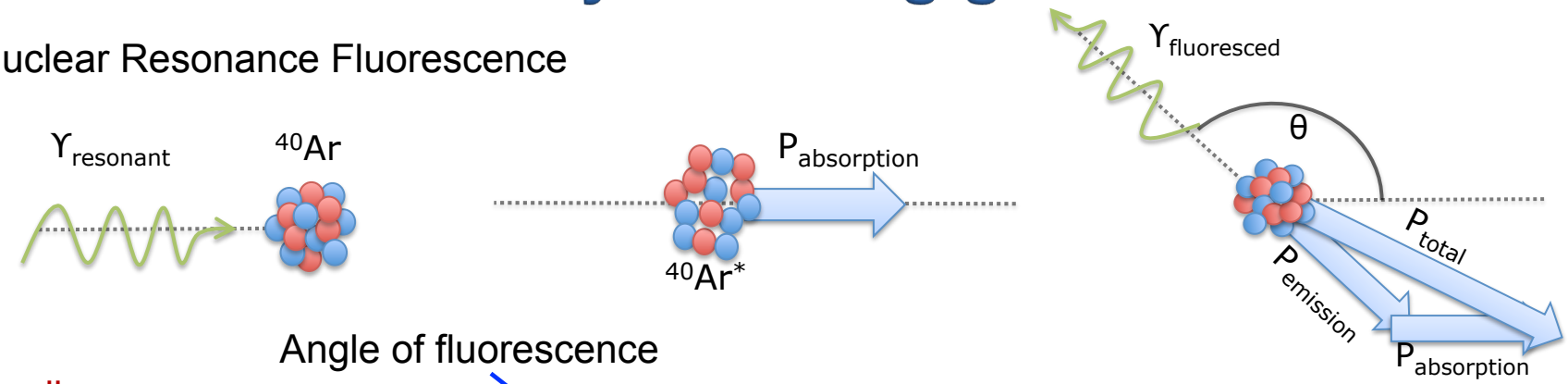






Nuclear Ionization yield using gammas

Nuclear Resonance Fluorescence



Angle of fluorescence

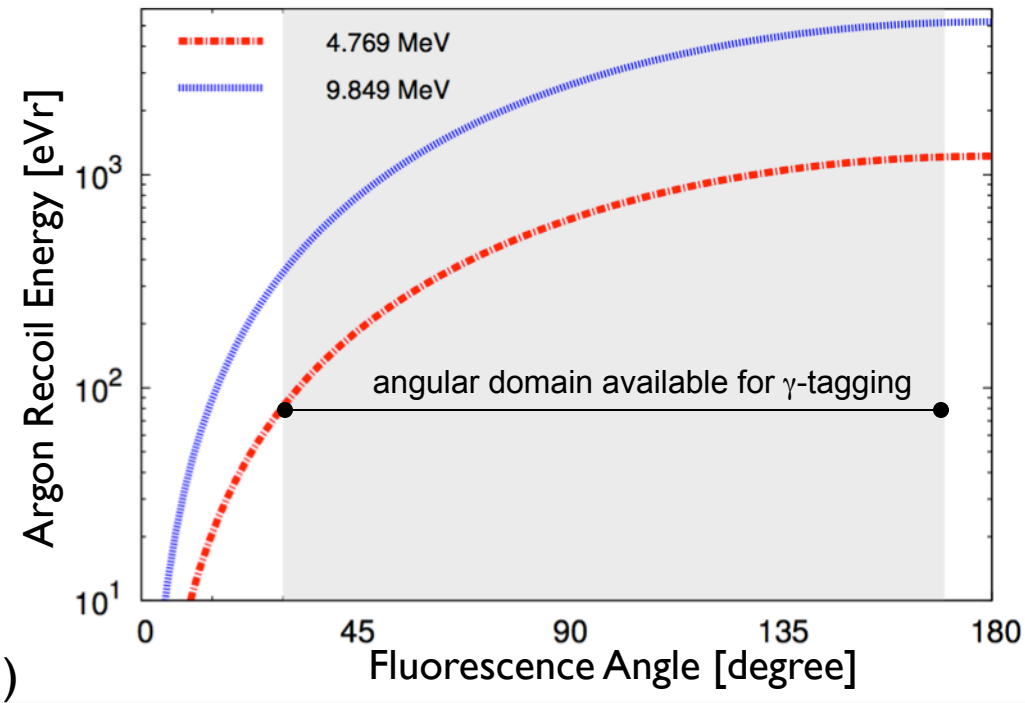
Recoil energy

$$E_{\mathrm{NR}} = \frac{2(E_r \sin(\theta/2))^2}{Mc^2}$$

Resonance energy
(for Ar: 4.8 MeV & 9.8 MeV)

Argon mass

- Possible gamma source: HIγS
- Experimentally challenging
- Could probe sub-keV recoils



T. Joshi, NIM A 656 (2011)

Future and ongoing activites

- Detector has capabilities to observe nuclear recoils > 2keVr for reasonable quenching values (> 0.1).
- Planned measurement at LLNL in the next few months.
- Detector improvements are being considered to extend sensitivity to even lower energies
- Improve understanding of detector response and backgrounds at low energy
- Complete detector simulation

Conclusions

- LLNL LAr detector:
  - Single electrons: achieved lowest detector sensitivity
  - Demonstrated sub-keV spectroscopy with LAr

- Ready to measure low energy nuclear recoils in LAr
  - determine ionization yield
  - key parameter to assess feasibility of Coherent Neutrino-Nucleus Scatter and extend range of accessible Dark Matter WIMPs mass

Lawrence Livermore
National Laboratory