NUCLEAR ENGINEERING &
RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

Surrogate sample preparation with neutron irradiation

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Motivation

It is desirable to develop experimental benchmarks for DM and neutrino detection in minerals based on **neutron-induced nuclear recoils.**

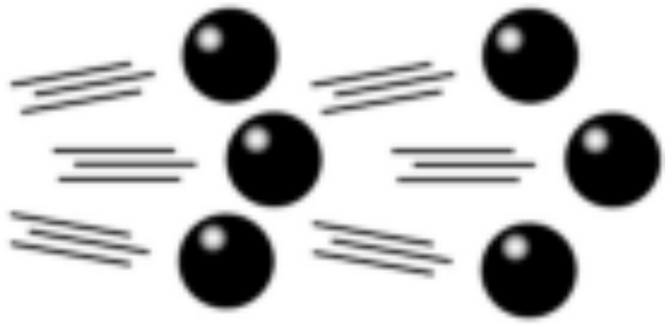
- well-understood energy scale (including spectrum) and spatial distribution of nuclear recoils
- known neutron fluence → known nuclear recoil population
- experimental conditions: temperature before/during/after irradiation

Mineral samples

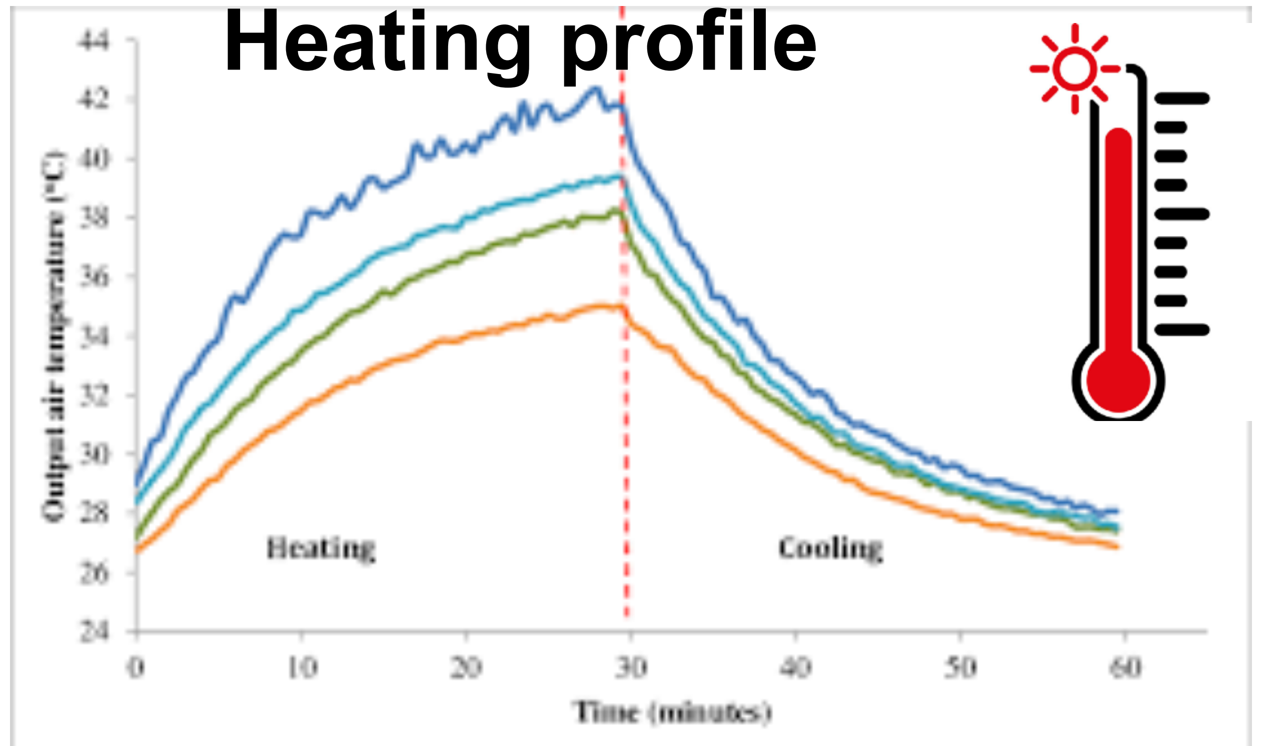
WIMP
ν

Material characterization + Modeling → Interpretation

Neutrons

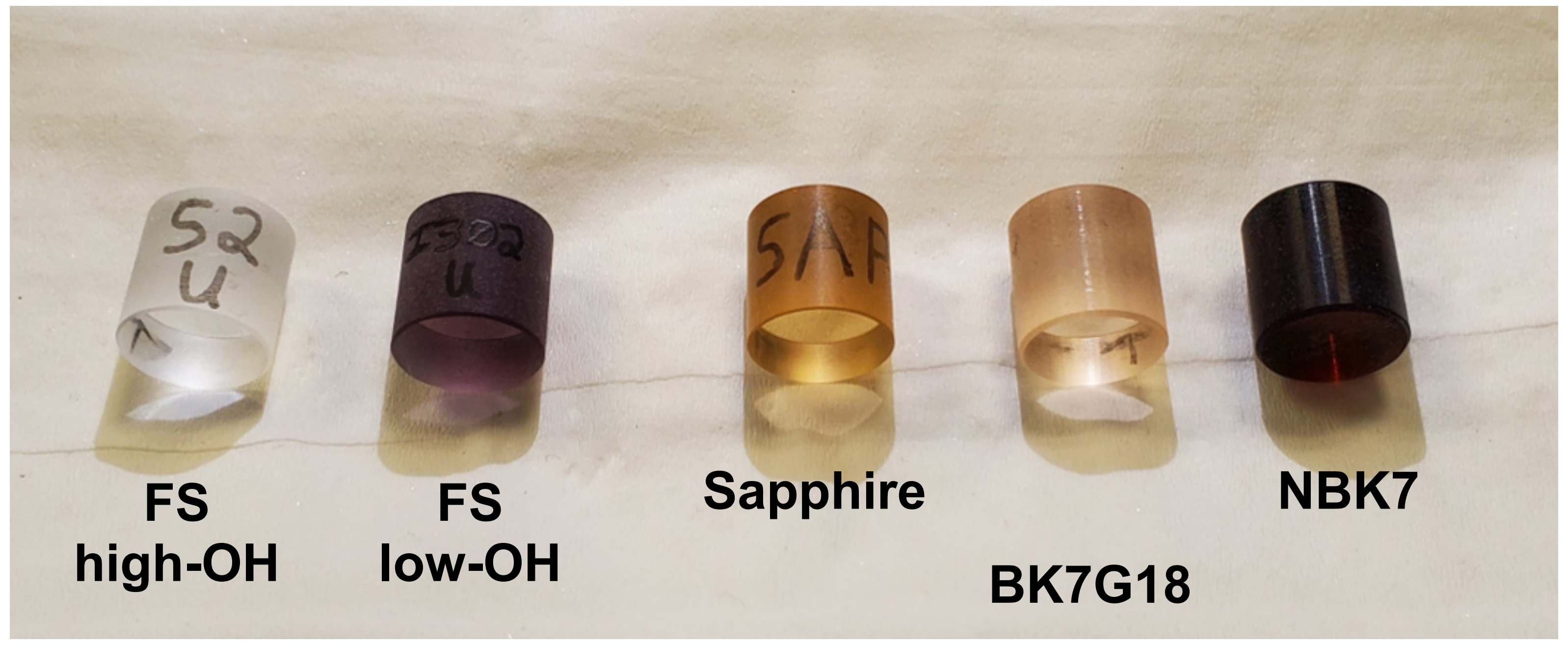


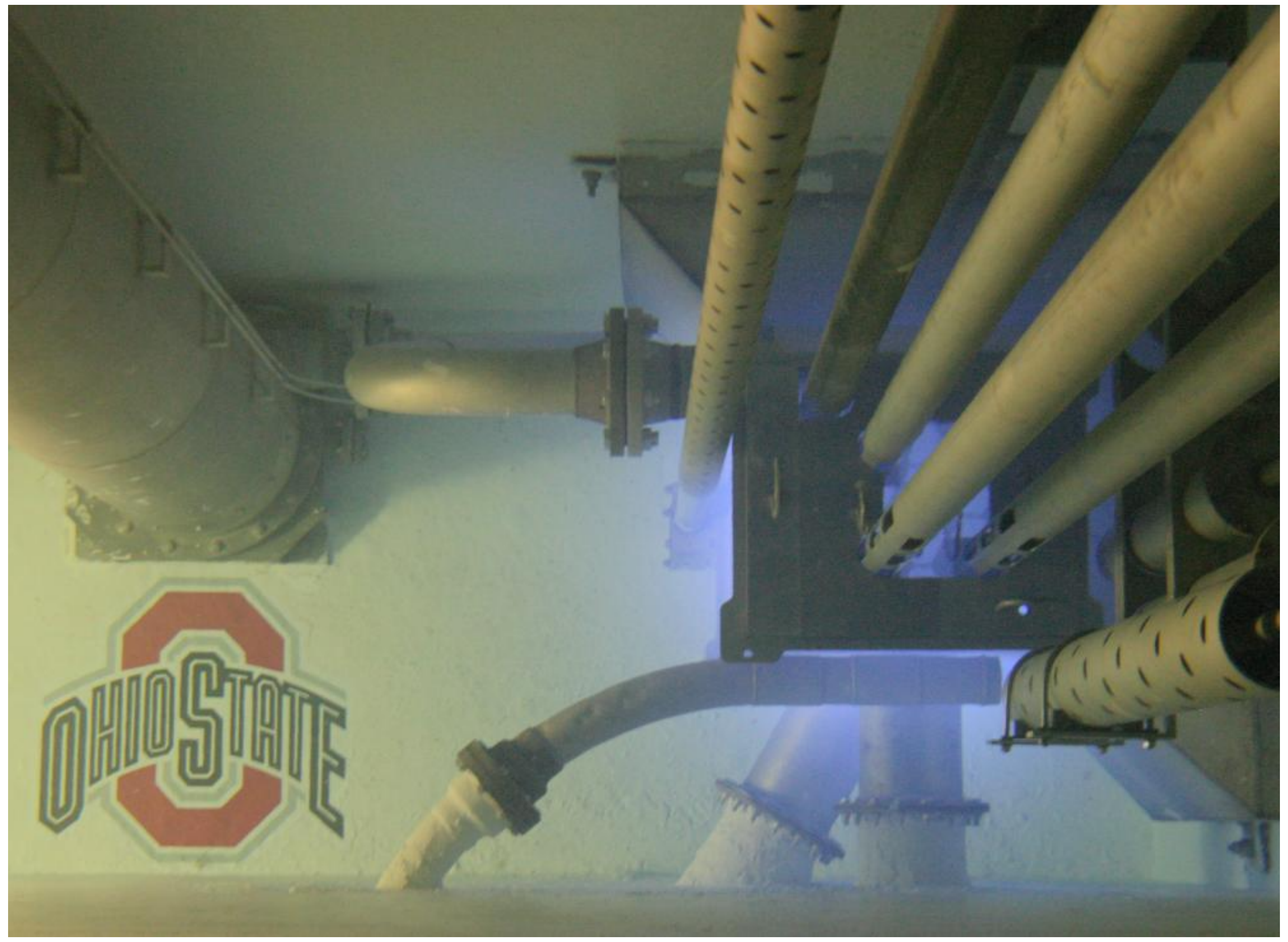
Synthetic samples



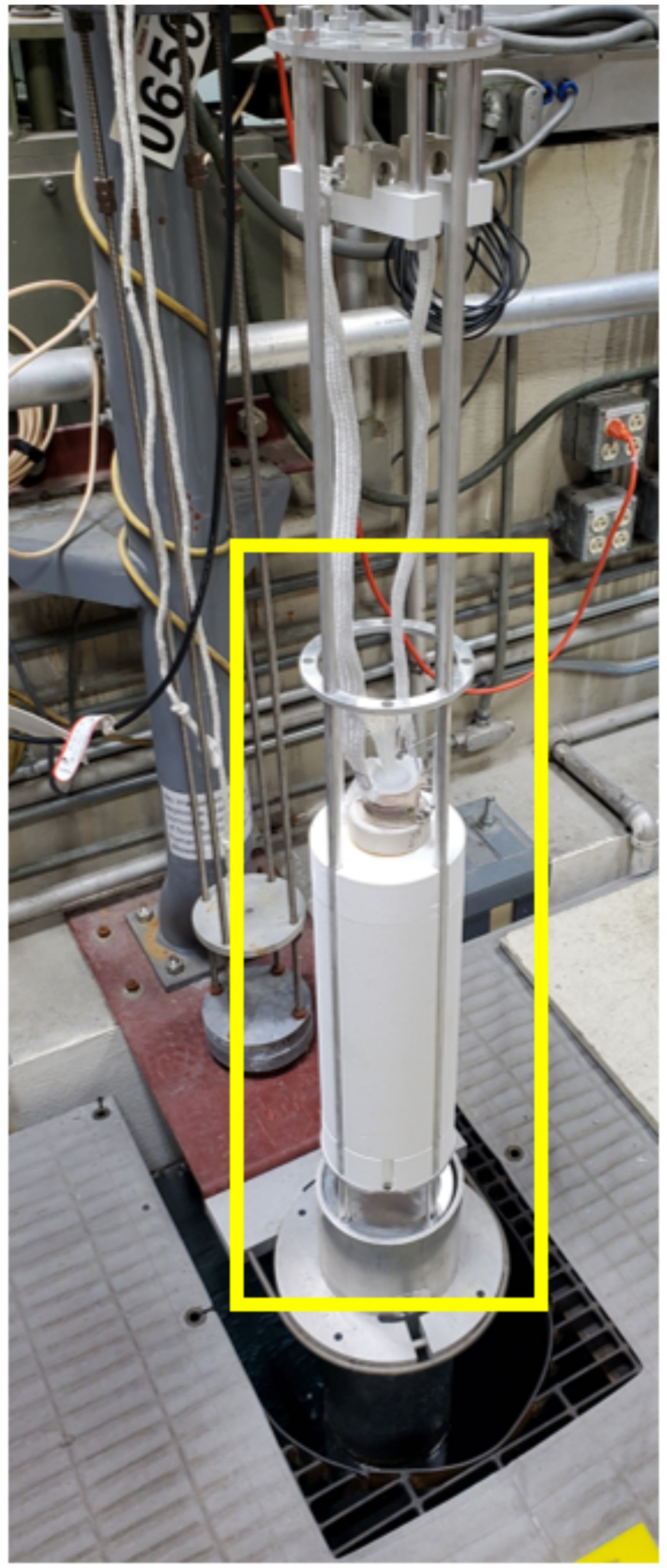
We have been irradiating glasses/crystals at <u>much</u> higher neutron/gamma fluences to study optical materials for use in nuclear instrumentation

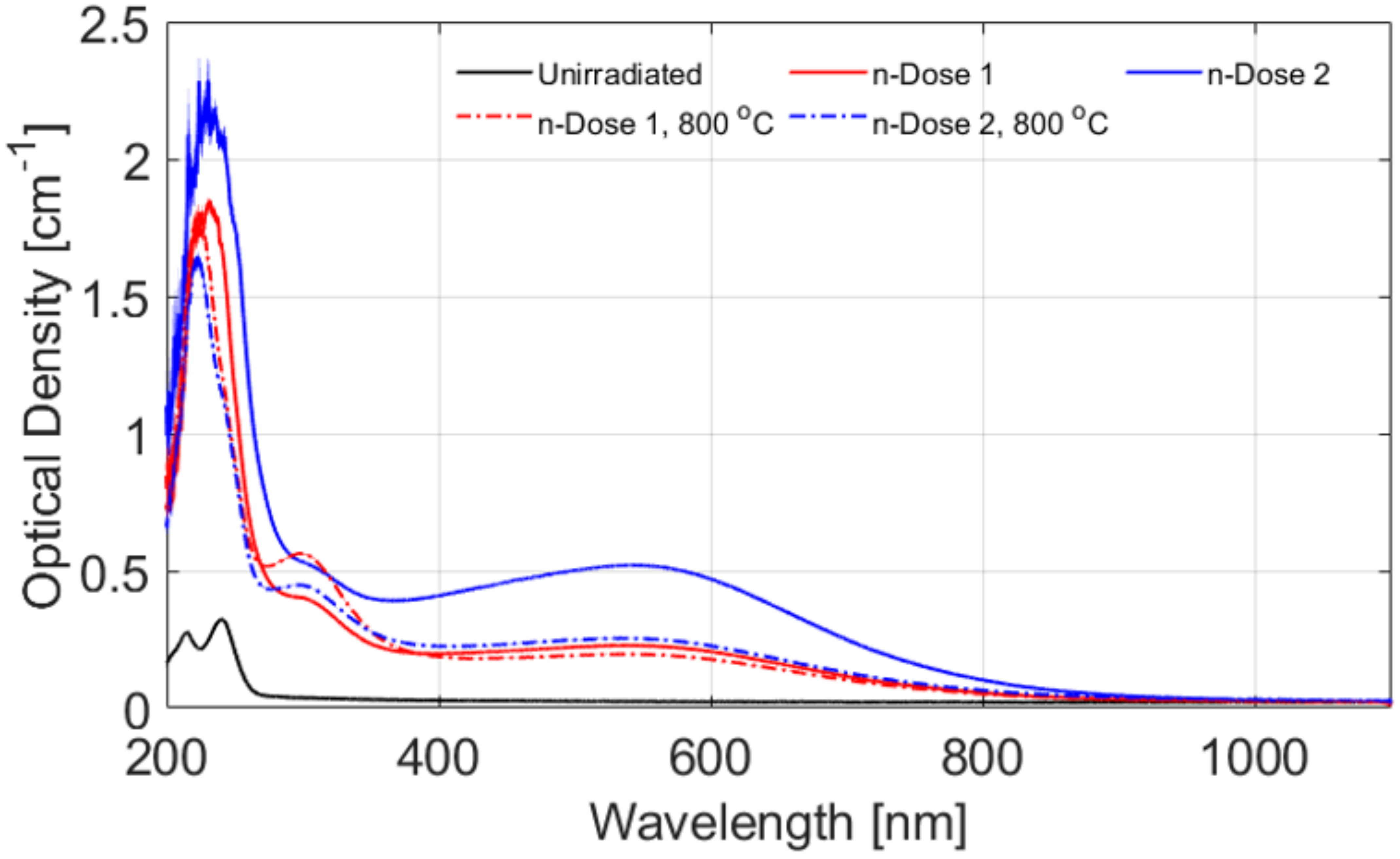
nsuf Nuclear Science User Facilities

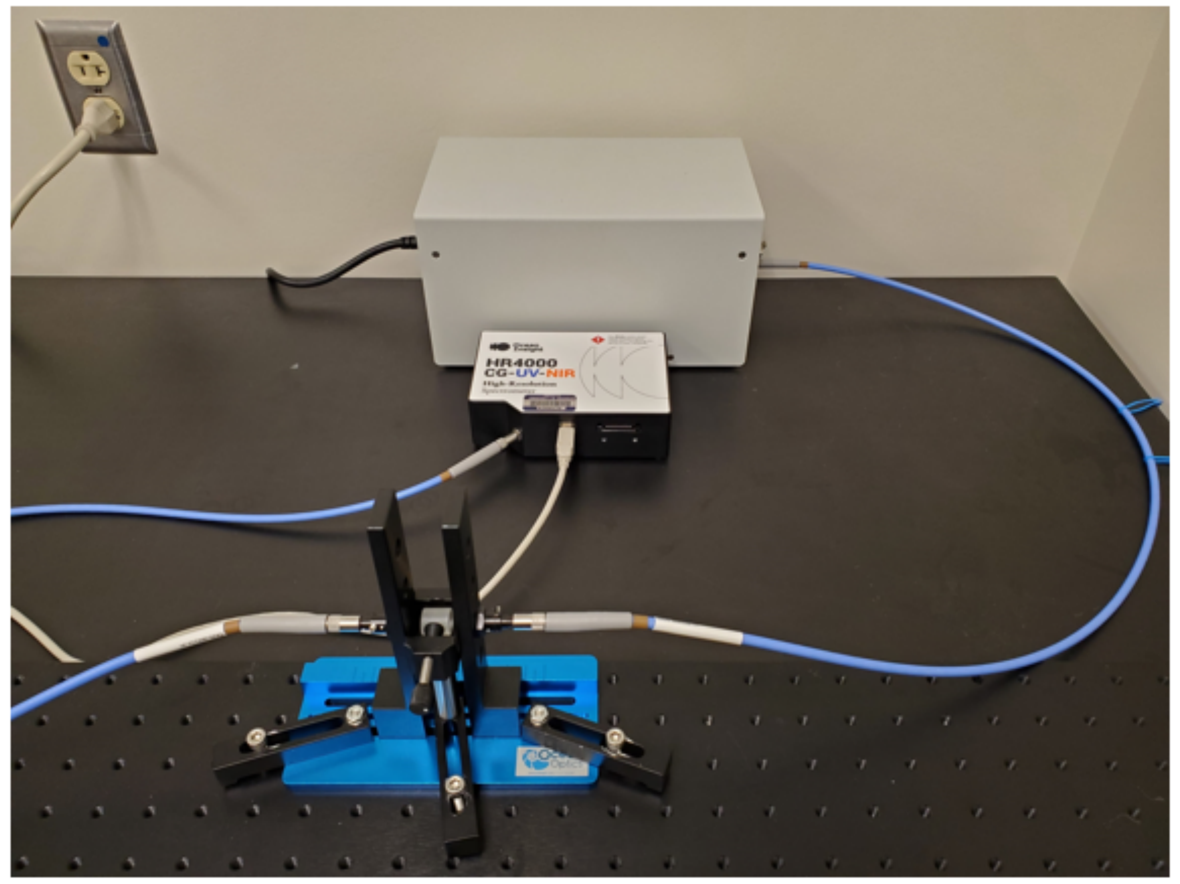




Furnace: in-situ irradiation and concurrent/post-heating

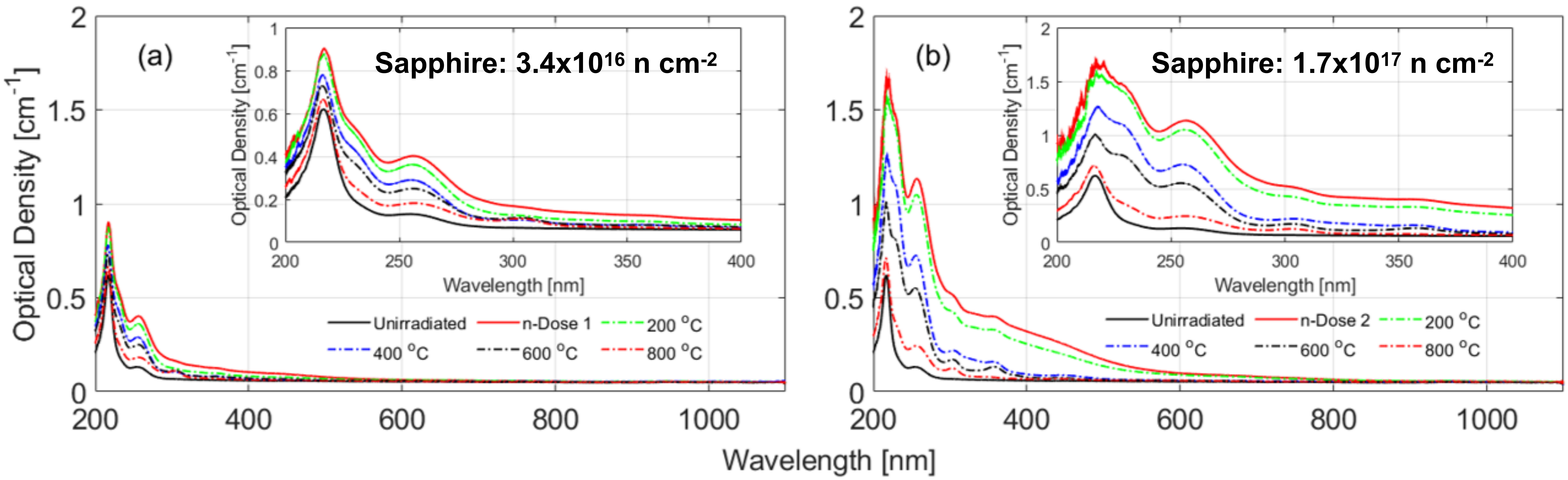


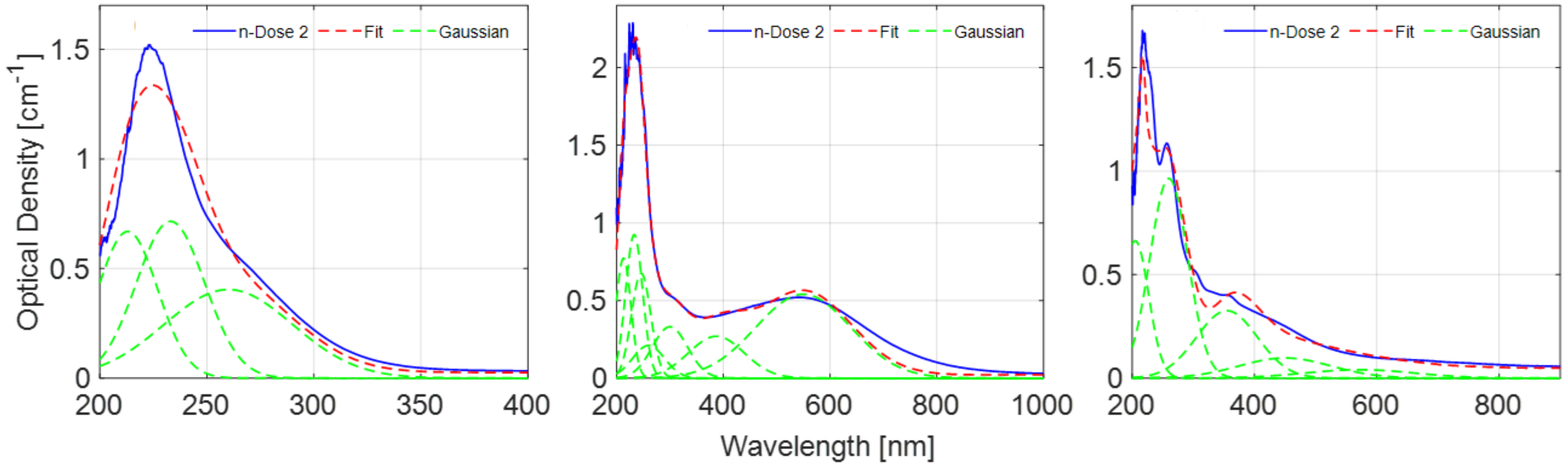




B. W. Morgan, M. P. Van Zile, C. M. Petrie, P. Sabharwall, M. Burger, and I. Jovanovic, J. Nucl. Mat. 570, 153945 (2022).

Example of irradiating crystals with concurrent/post-heating: sapphire

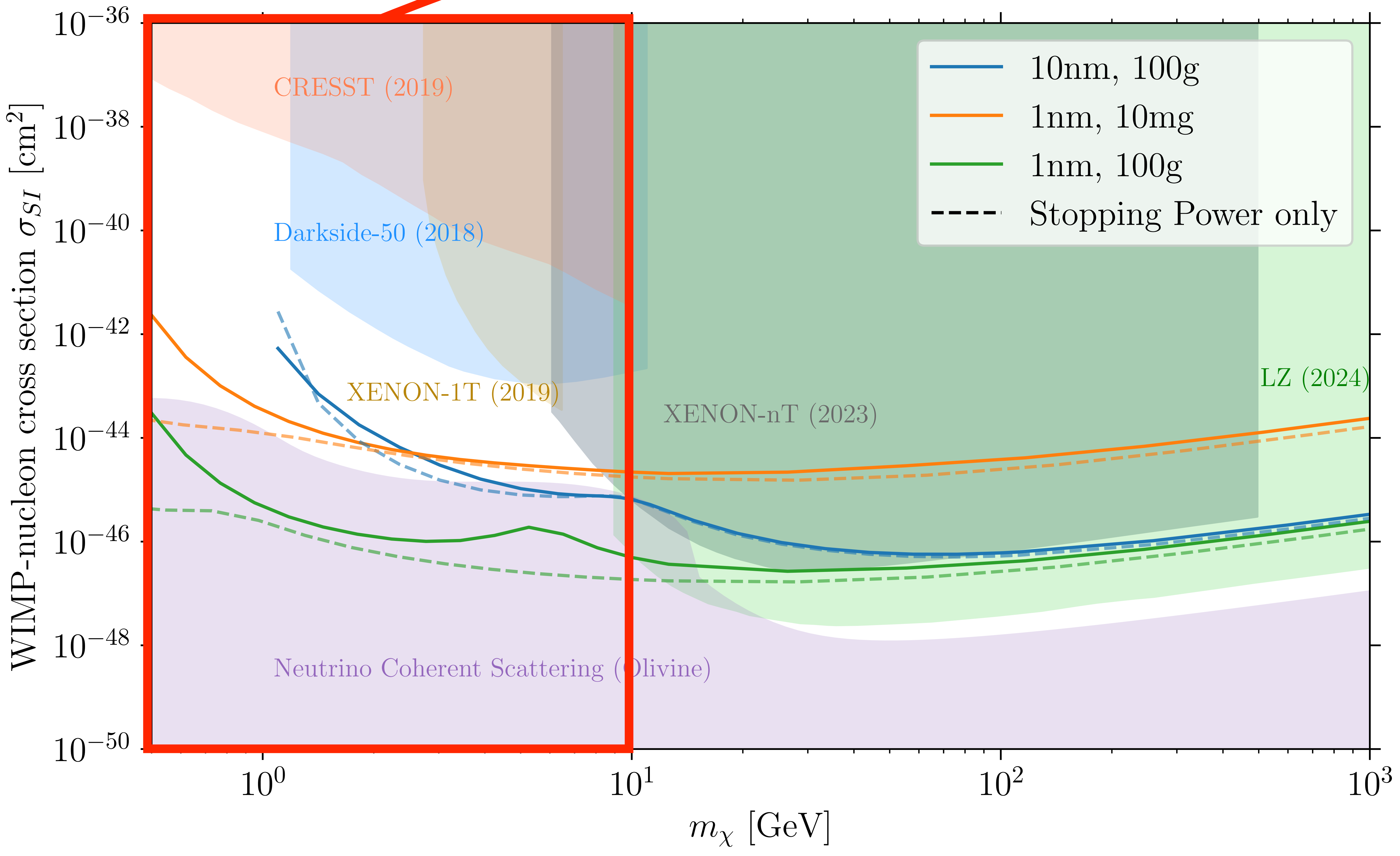




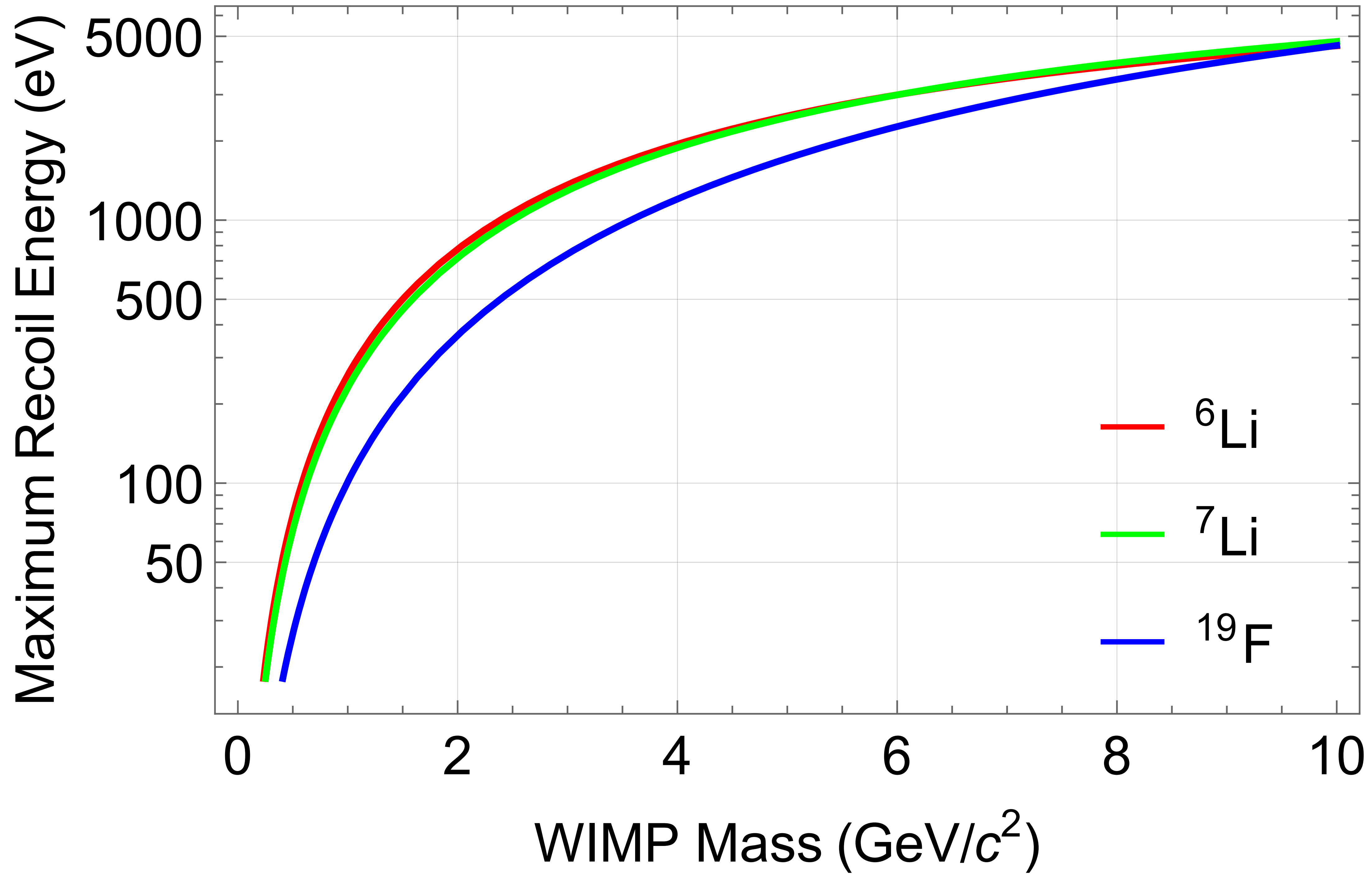
Fitting known absorption bands

- 205 nm F center
- 260 nm F^+ center
- 300 nm F_2 center
- 355 nm F_2^+ center
- 450 nm F_2^{2+} center
- 572 nm Al-OHC

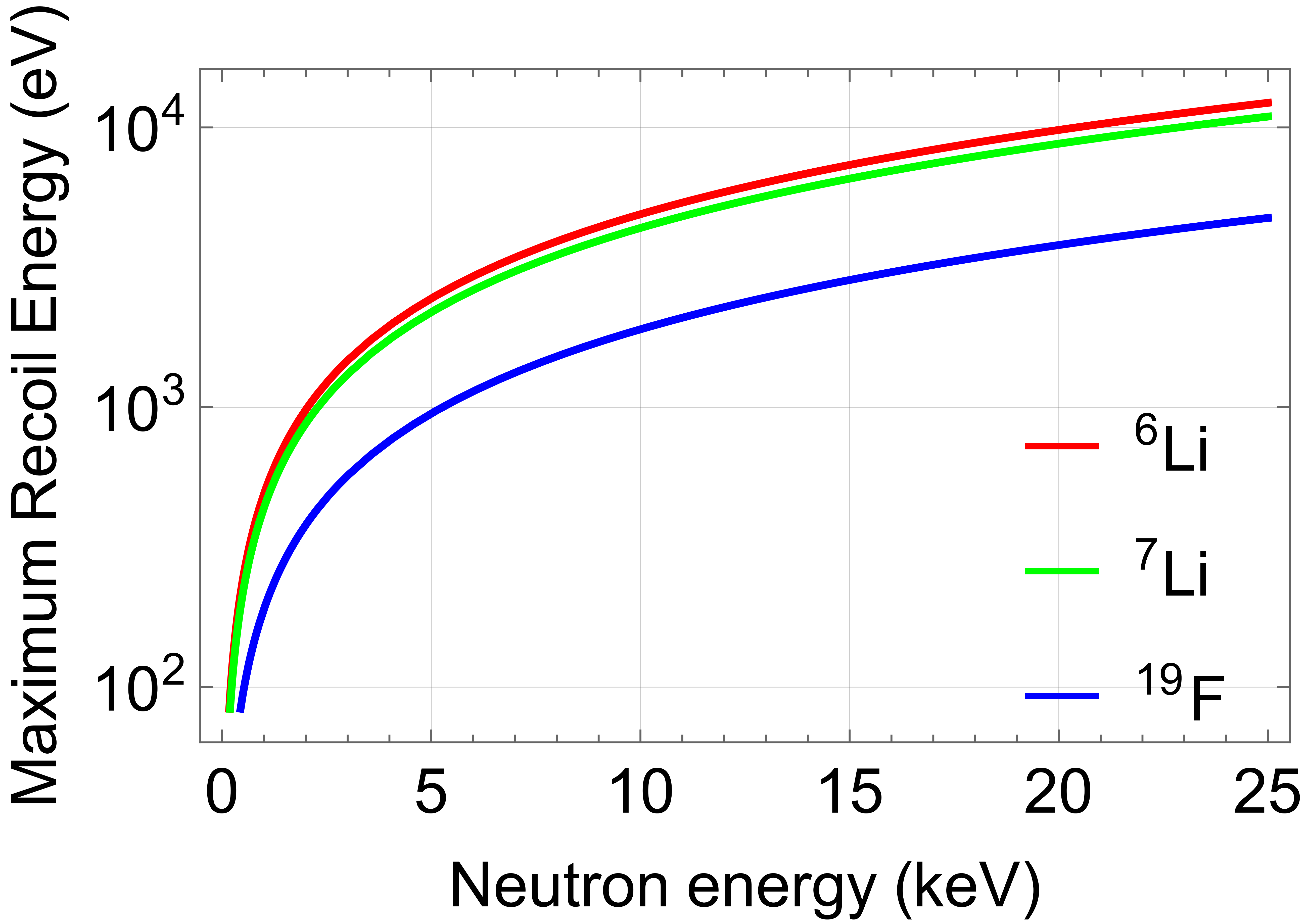
Low-energy DM nuclear recoil energy scale in LiF



[0,5 keV]

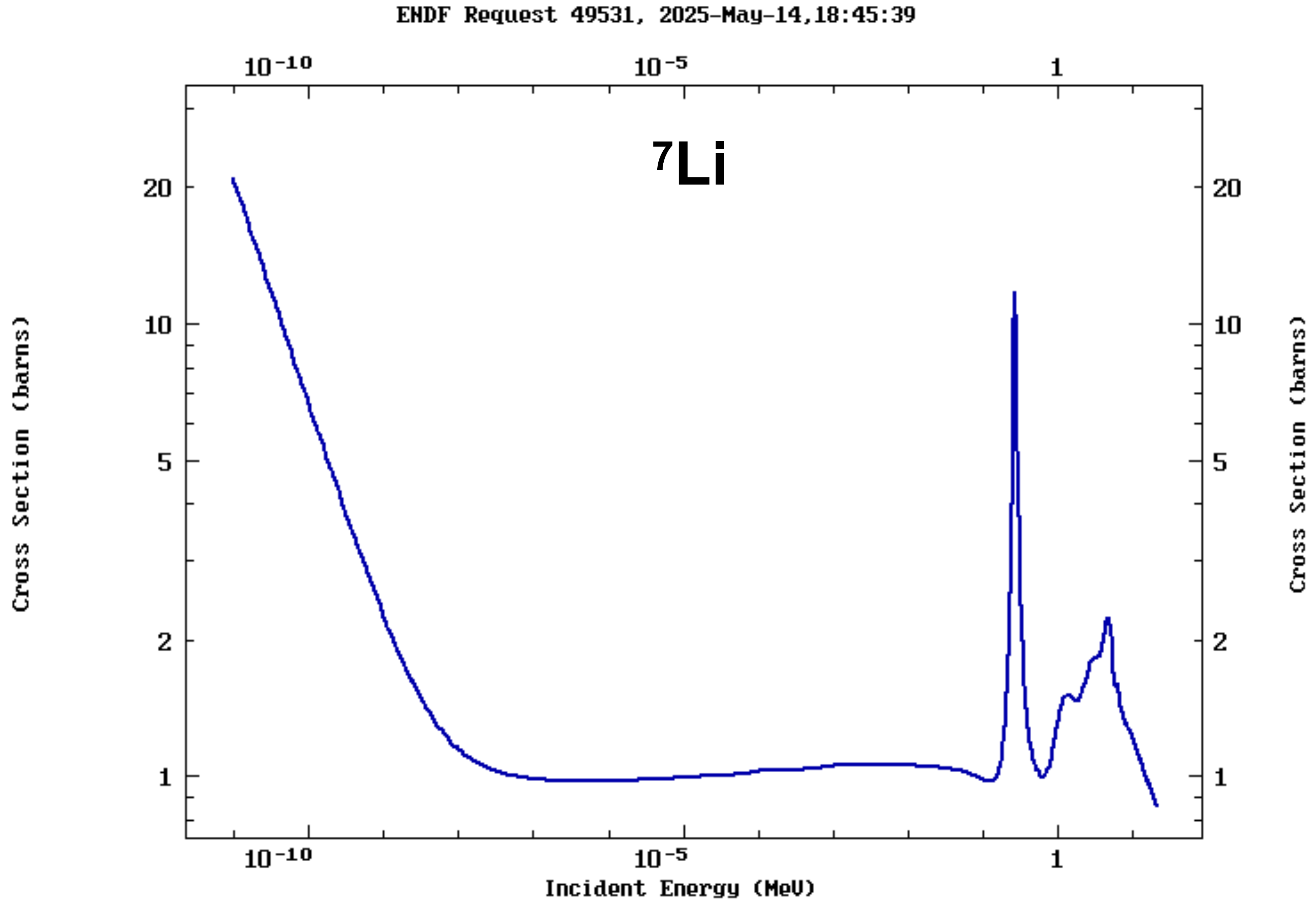


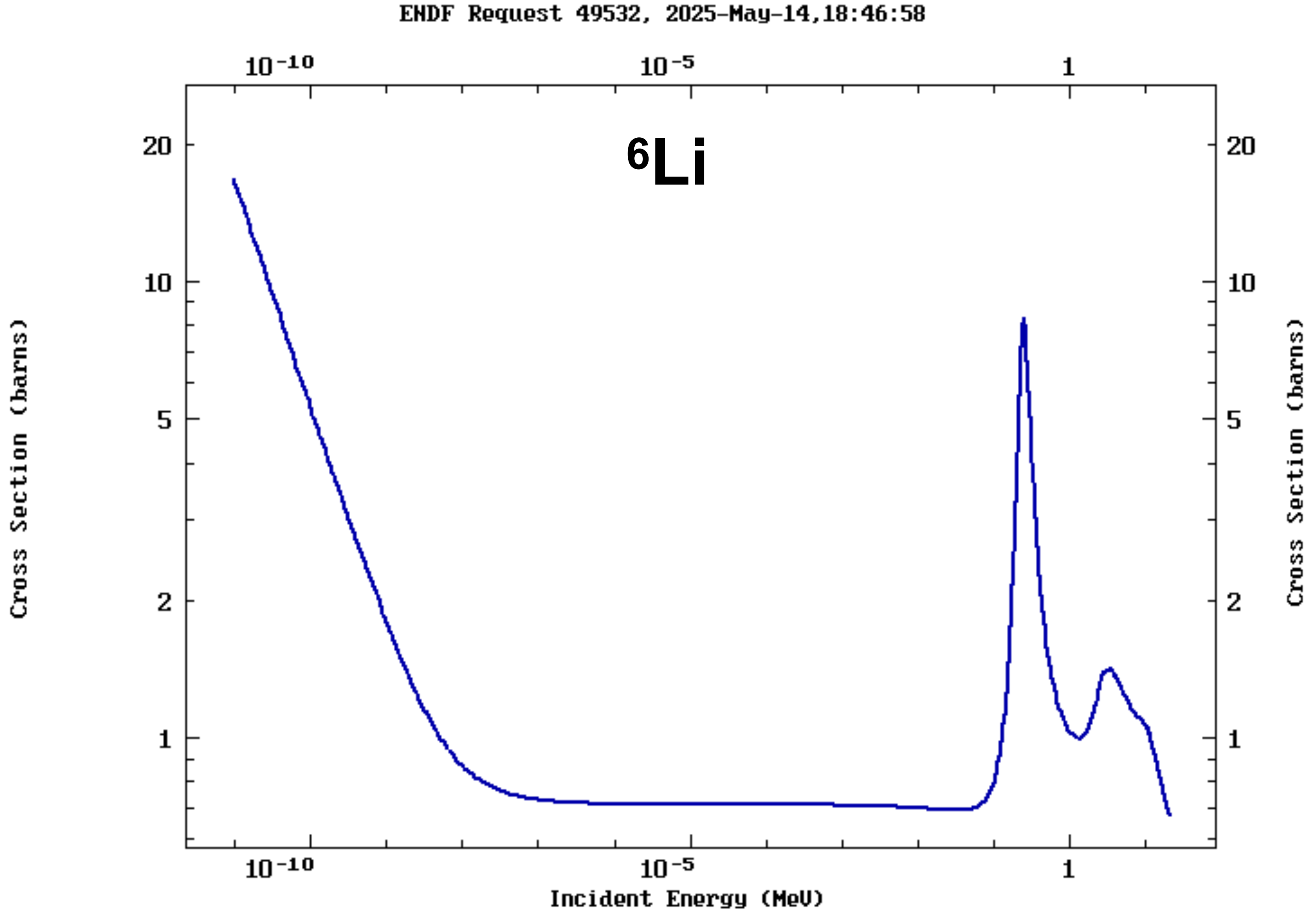
Equivalent neutron recoil energy



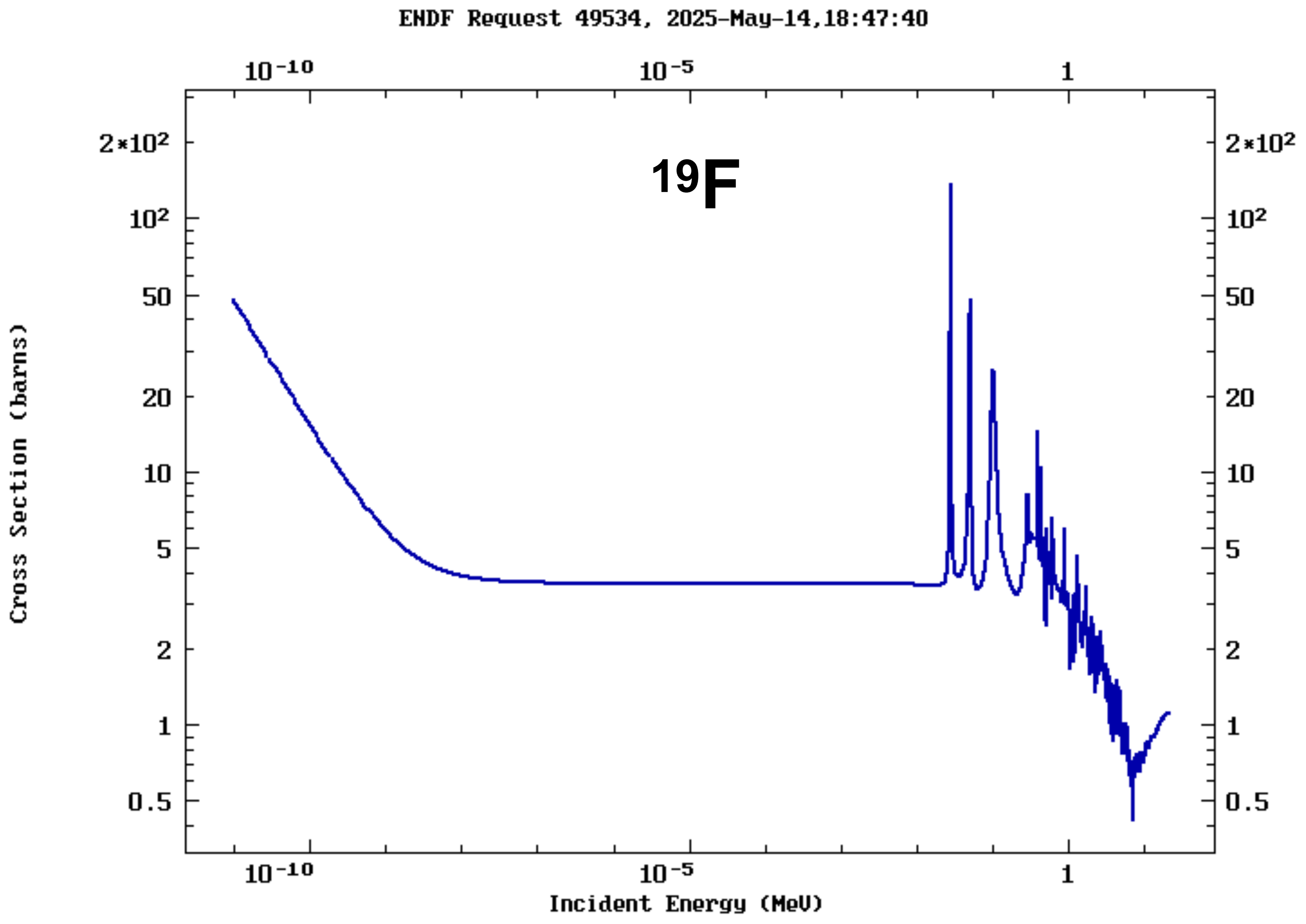
We are interested in accessing this energy scale for DM signal, but in a wider range of other energy scales for the background.

Elastic scattering cross-sections in LiF





7.5 a/o abundance in Li

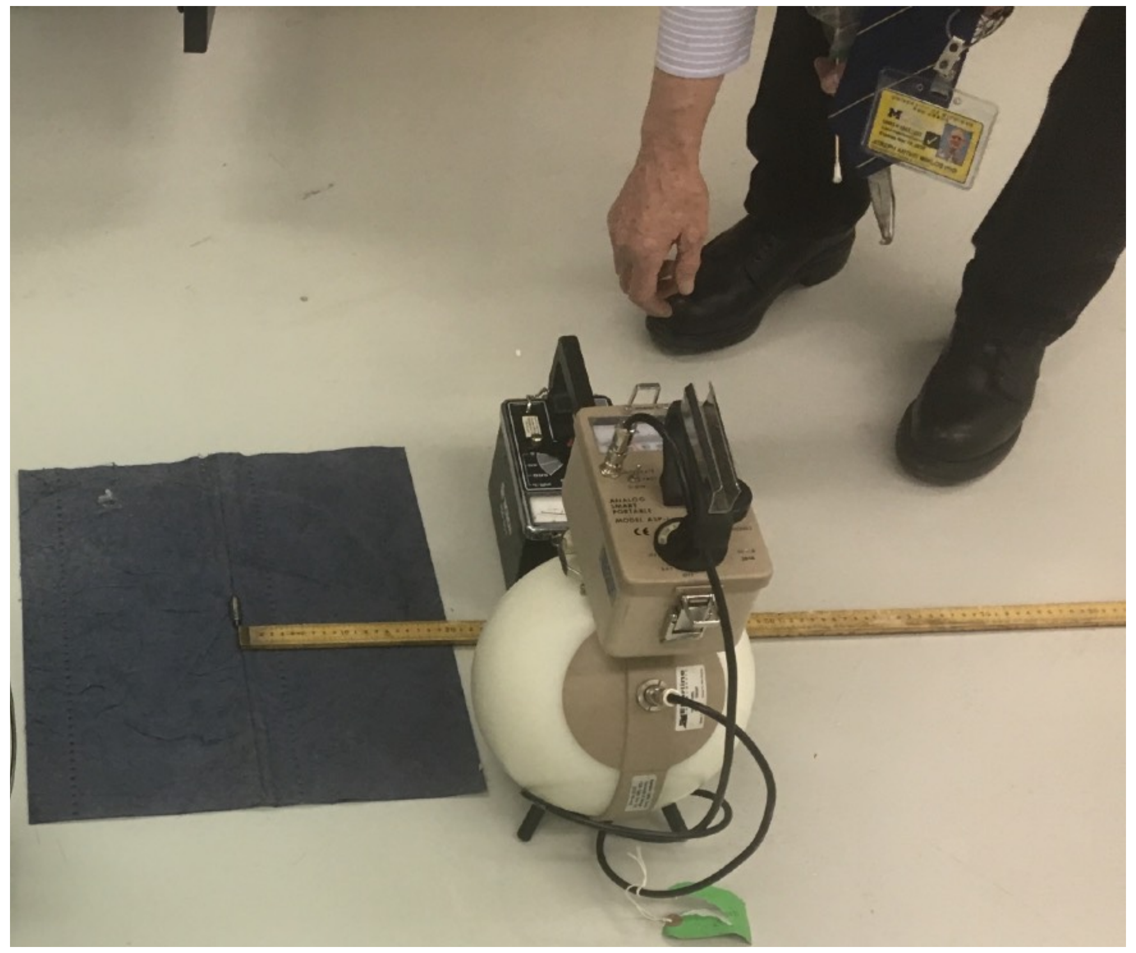


highest ES cross-section

Overview of available neutron sources

Radioisotopes

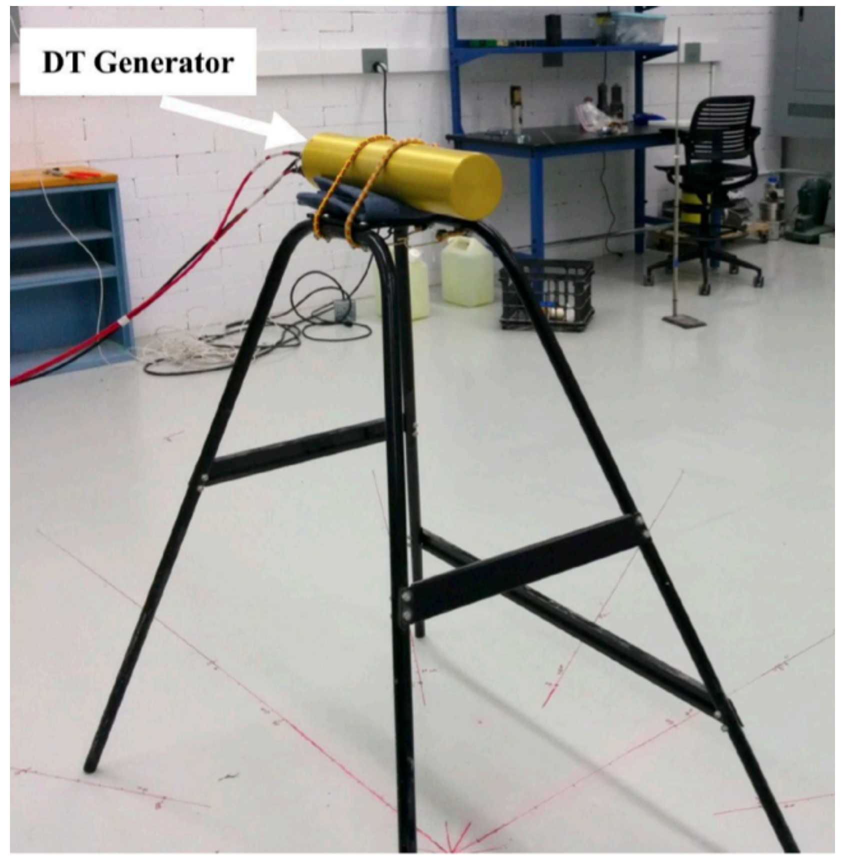
spontaneous fission
(alpha,n)



Neutron generators

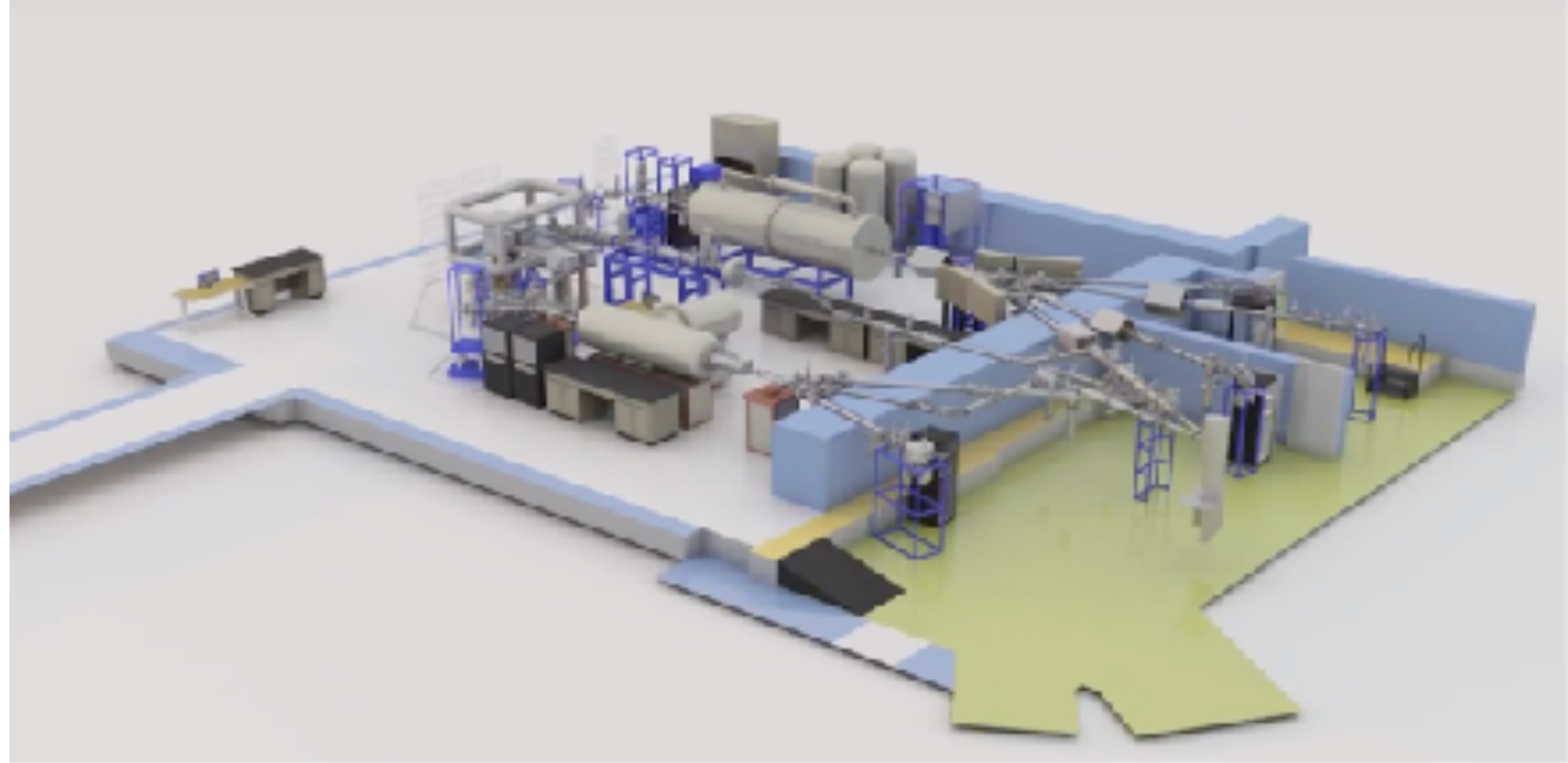
DD

DT



Nuclear reactors

Linacs



We estimate the nuclear recoil rates in LiF produced with practical sources

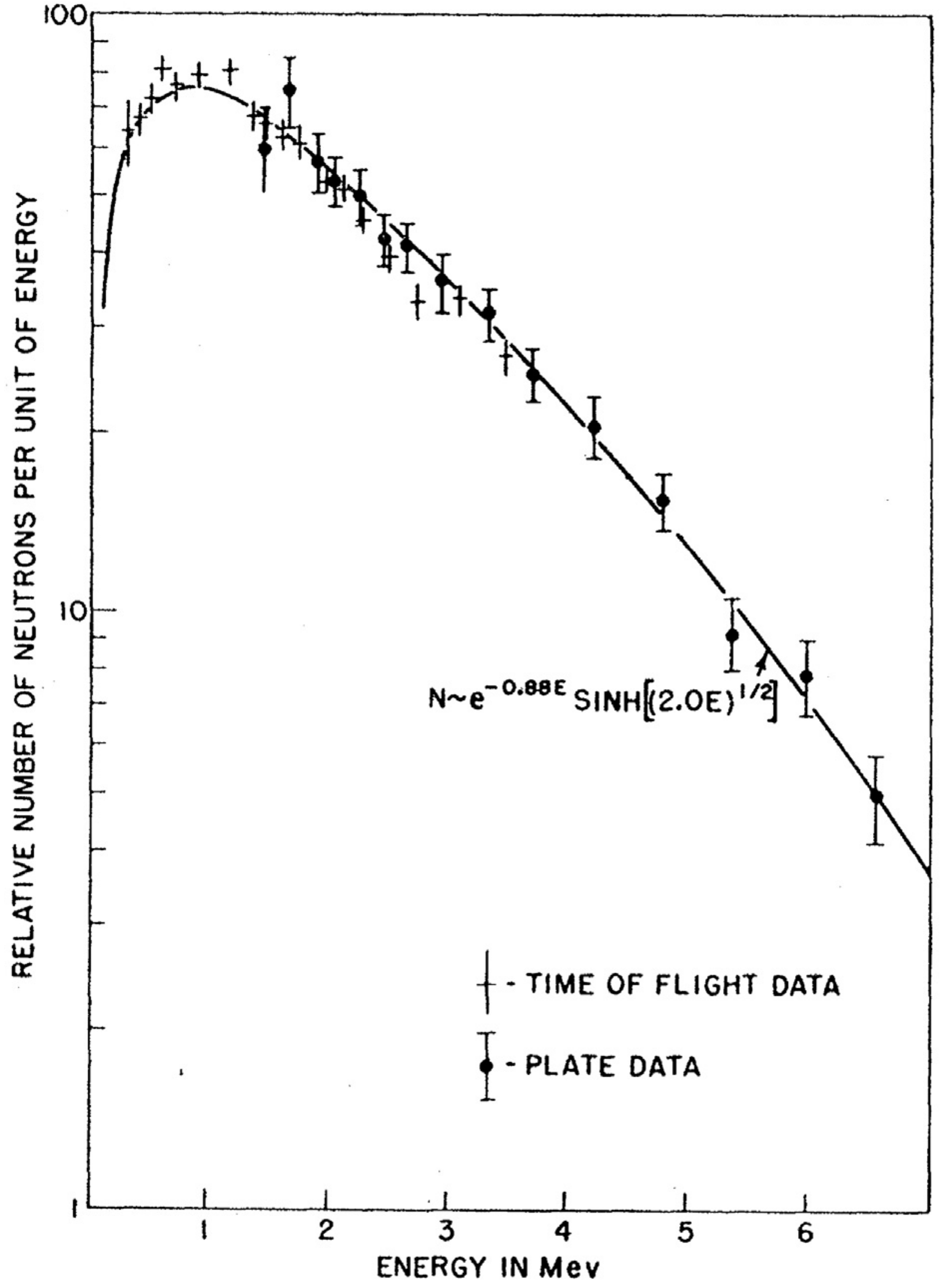
1 cm^3 of LiF(nat)

^{19}F, ^{6}Li (7.5 a/o of Li), ^{7}Li (92.5 a/o of Li)

Source

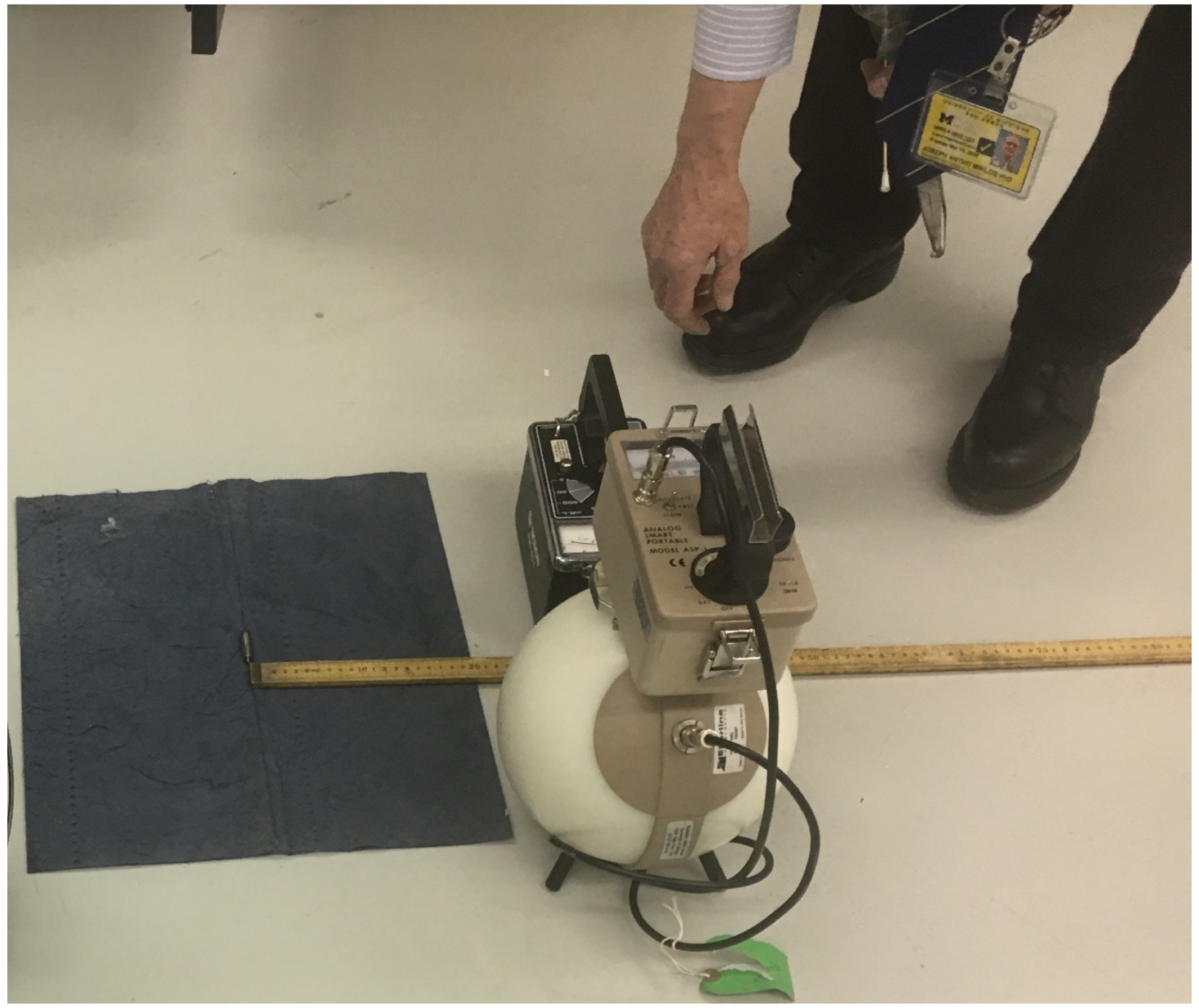
10 cm

Radioisotope sources at UM: ^{252}Cf

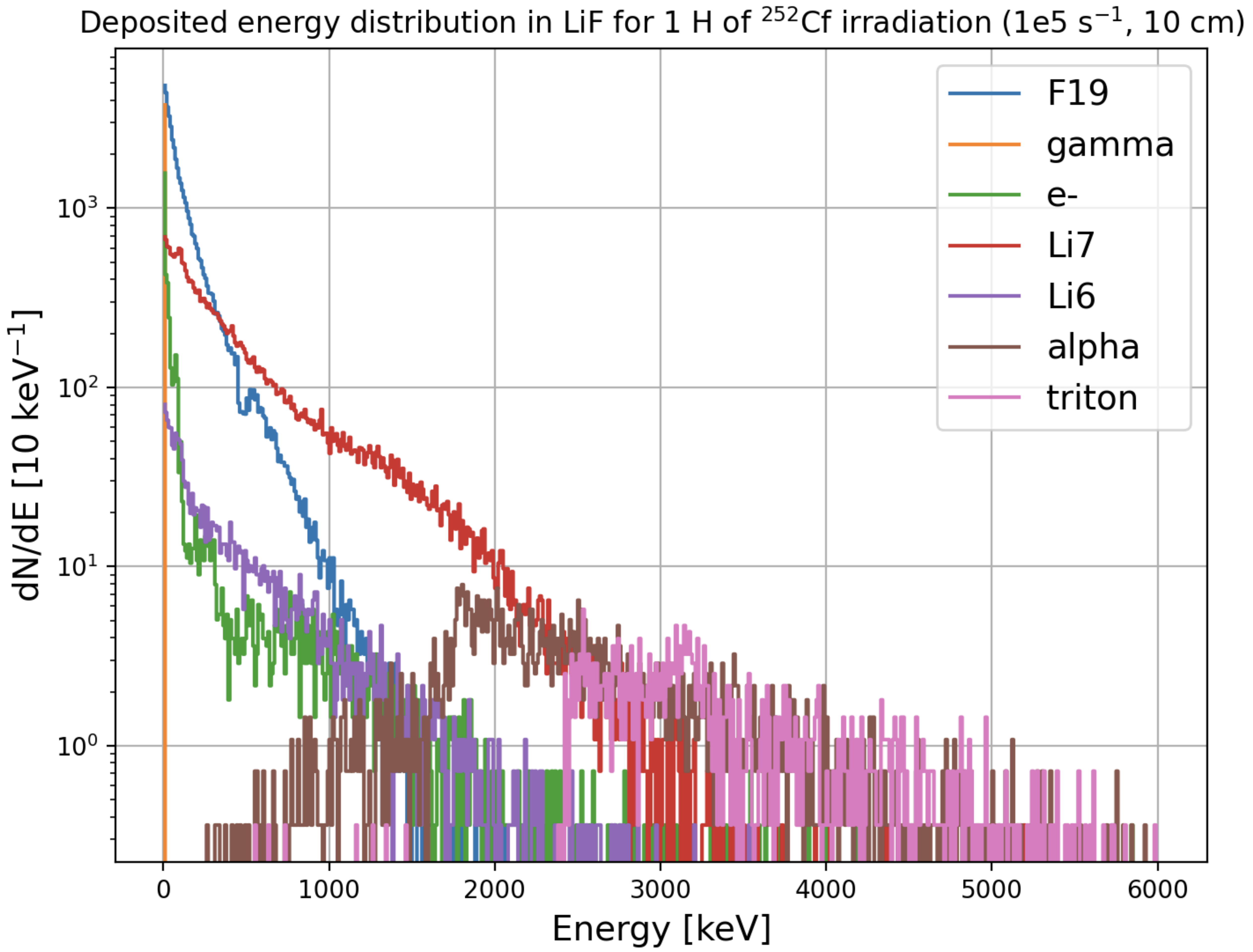


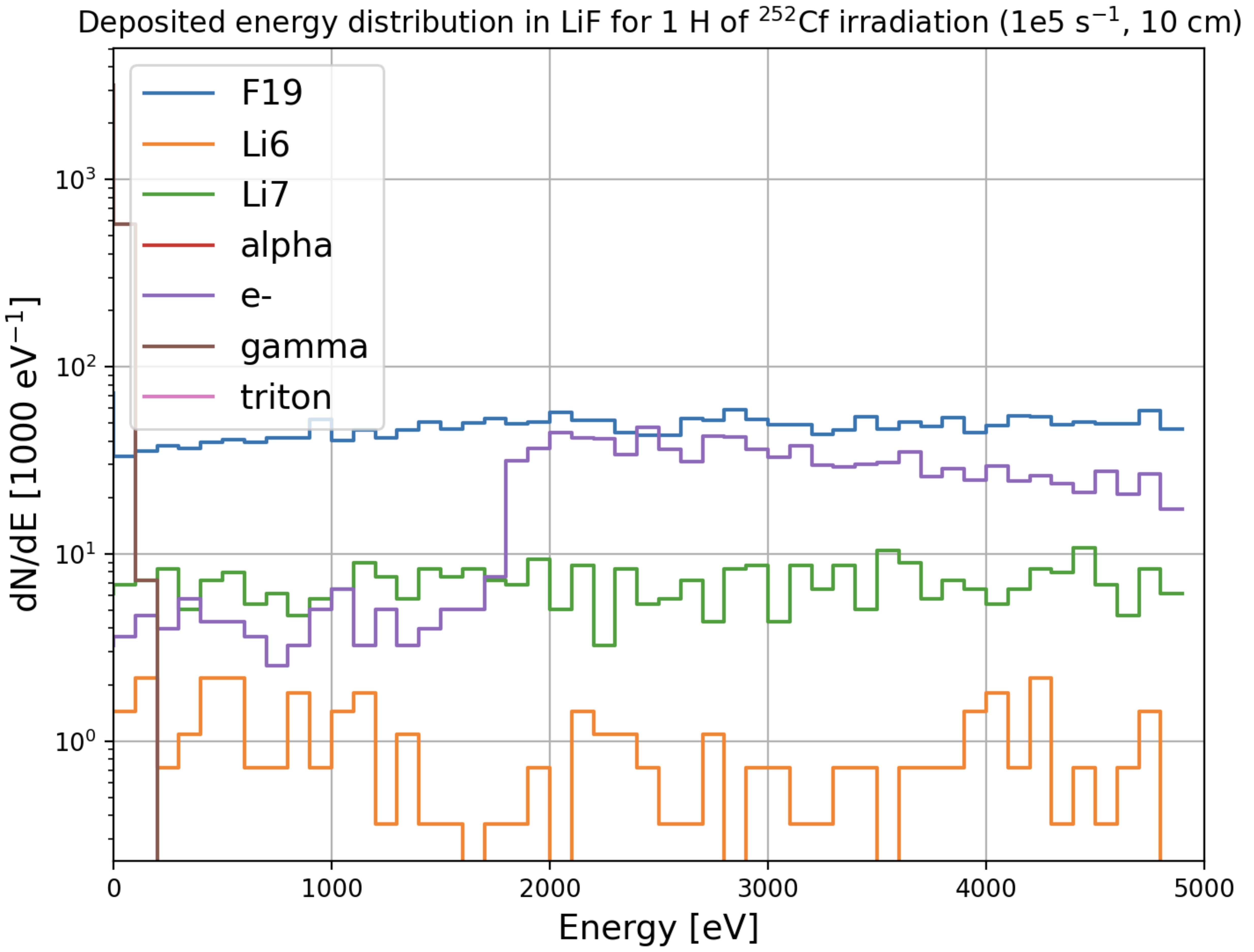
Current neutron emission rate: 5.1 x 10^4 n/s

- we can readily access another stronger source if needed: 1.75 x 10^6 n/s



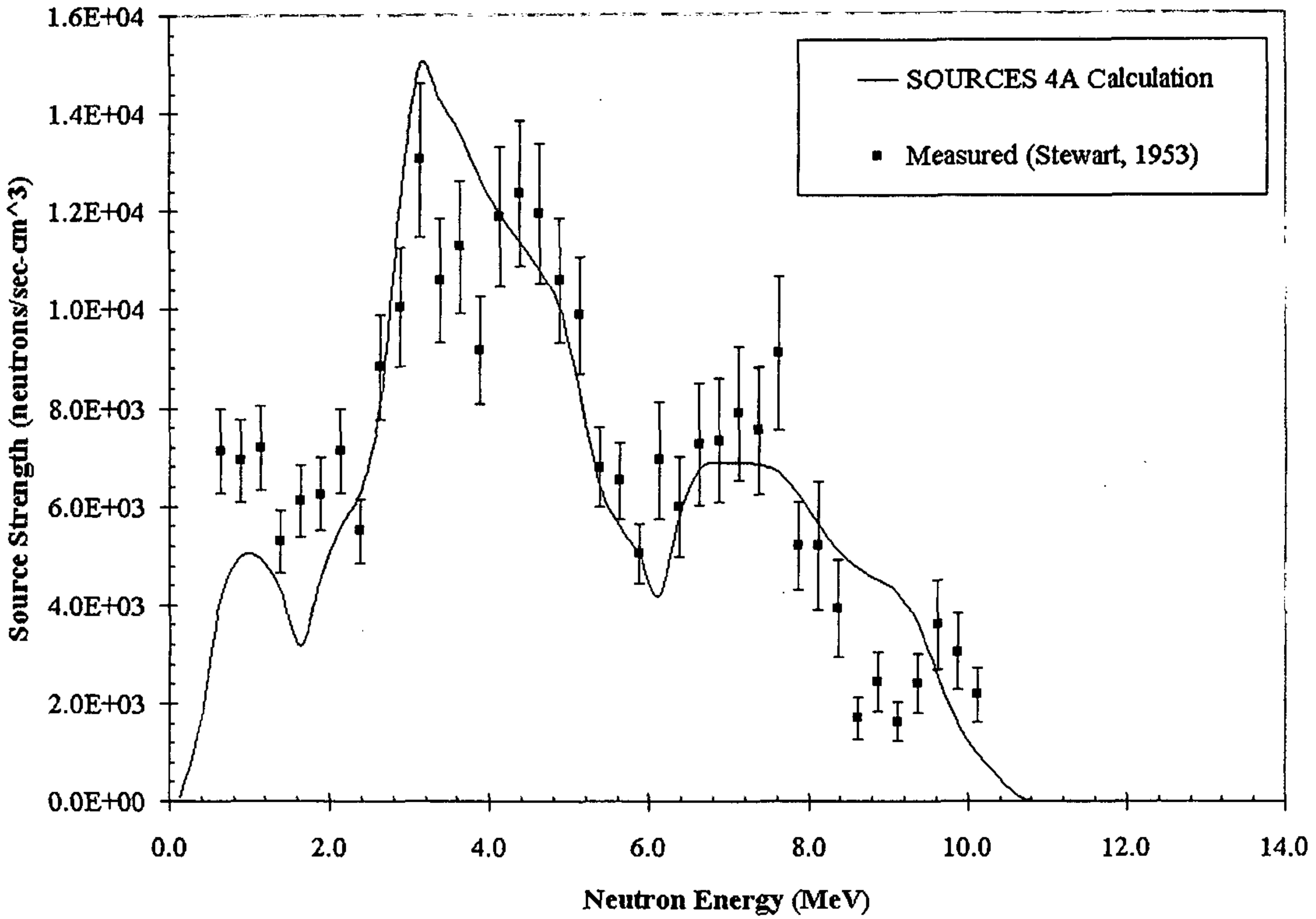
Estimated nuclear recoil rates in LiF: ^{252}Cf





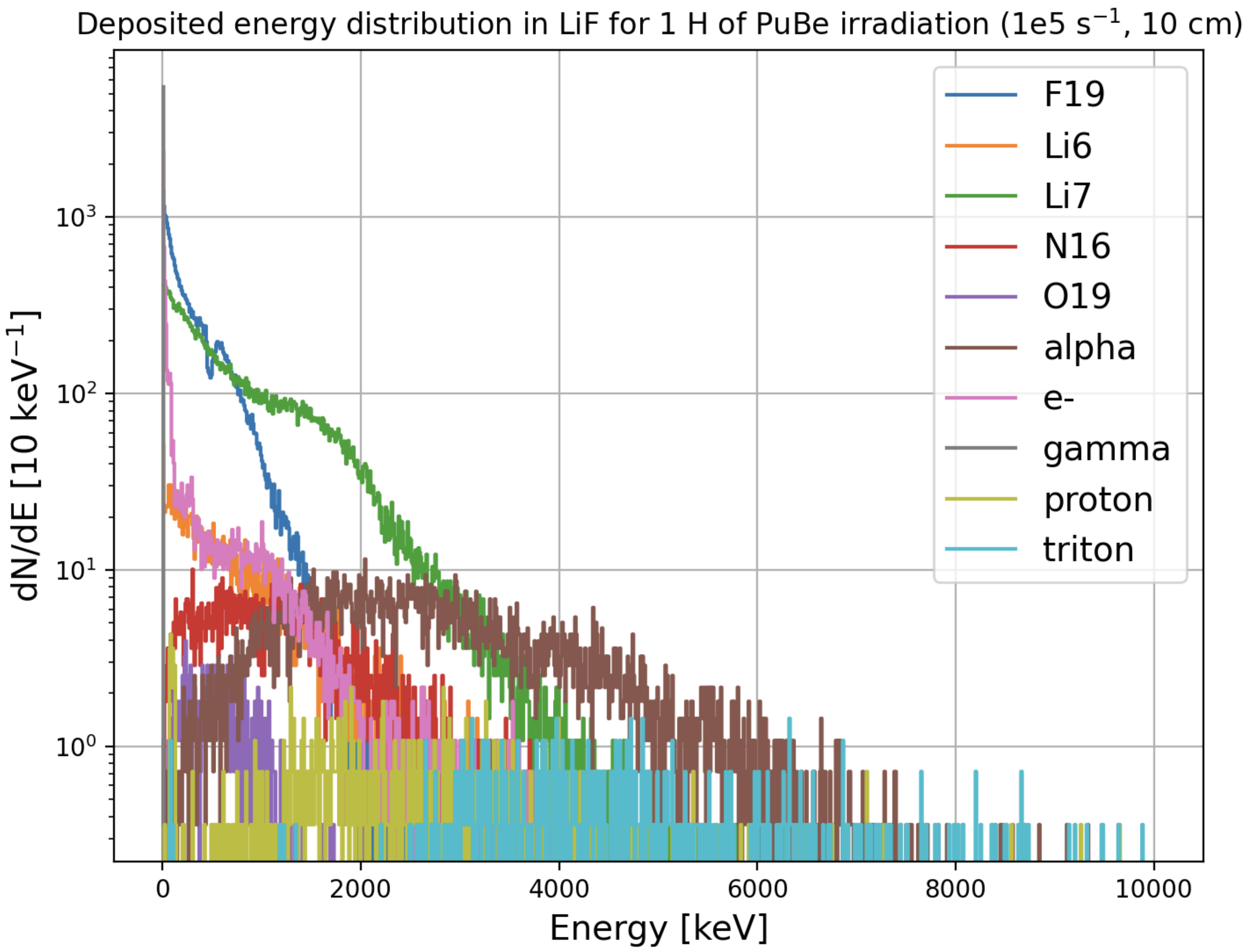
~ 20–30 recoils / h in [0,5 keV] for “old” Cf-252
~ 700–1000 recoils / h in [0,5 keV] for “new” Cf-252

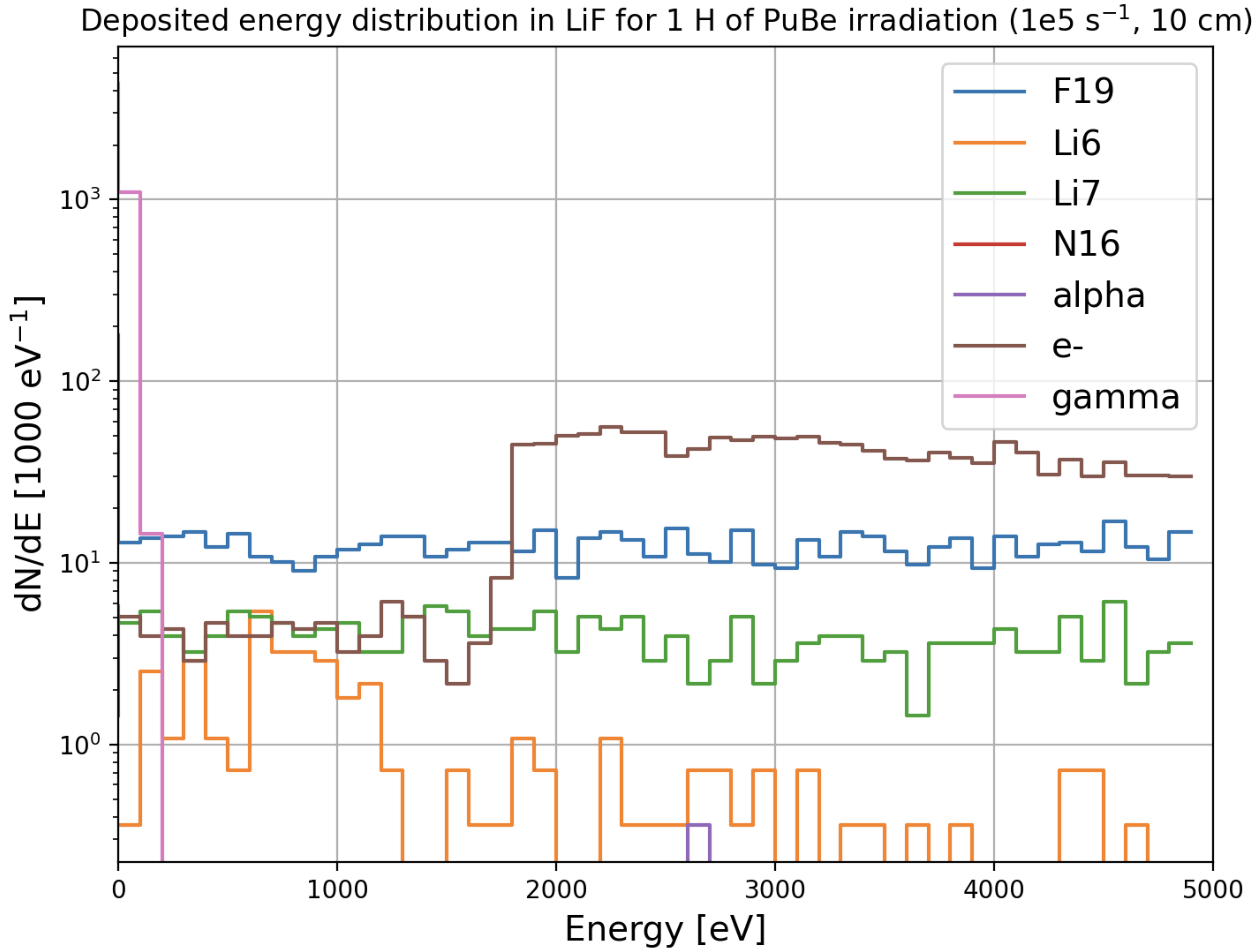
Radioisotope sources at UM: PuBe



Current activity: 1.5–2 x 10^6 n/s

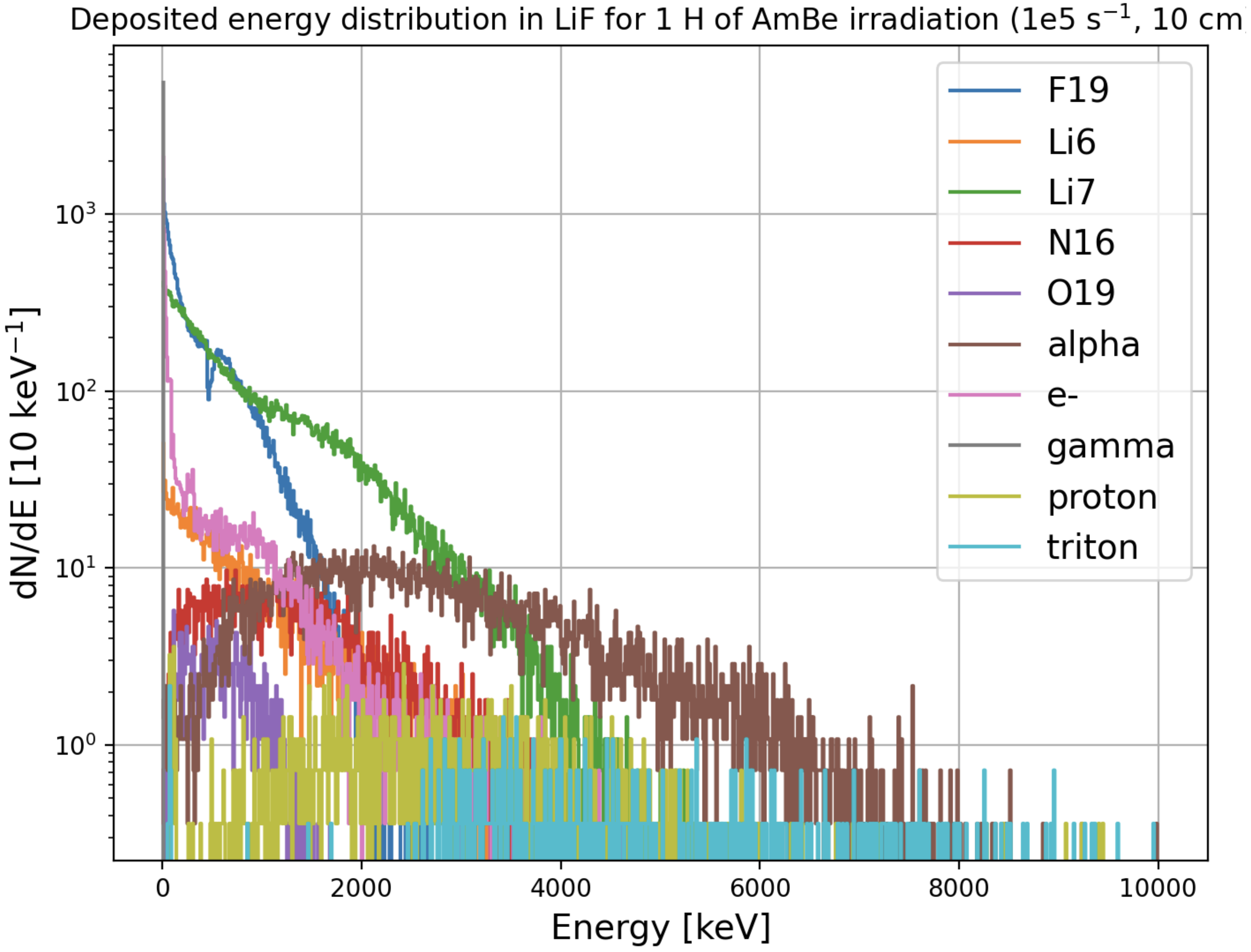
Estimated nuclear recoil rates in LiF: PuBe

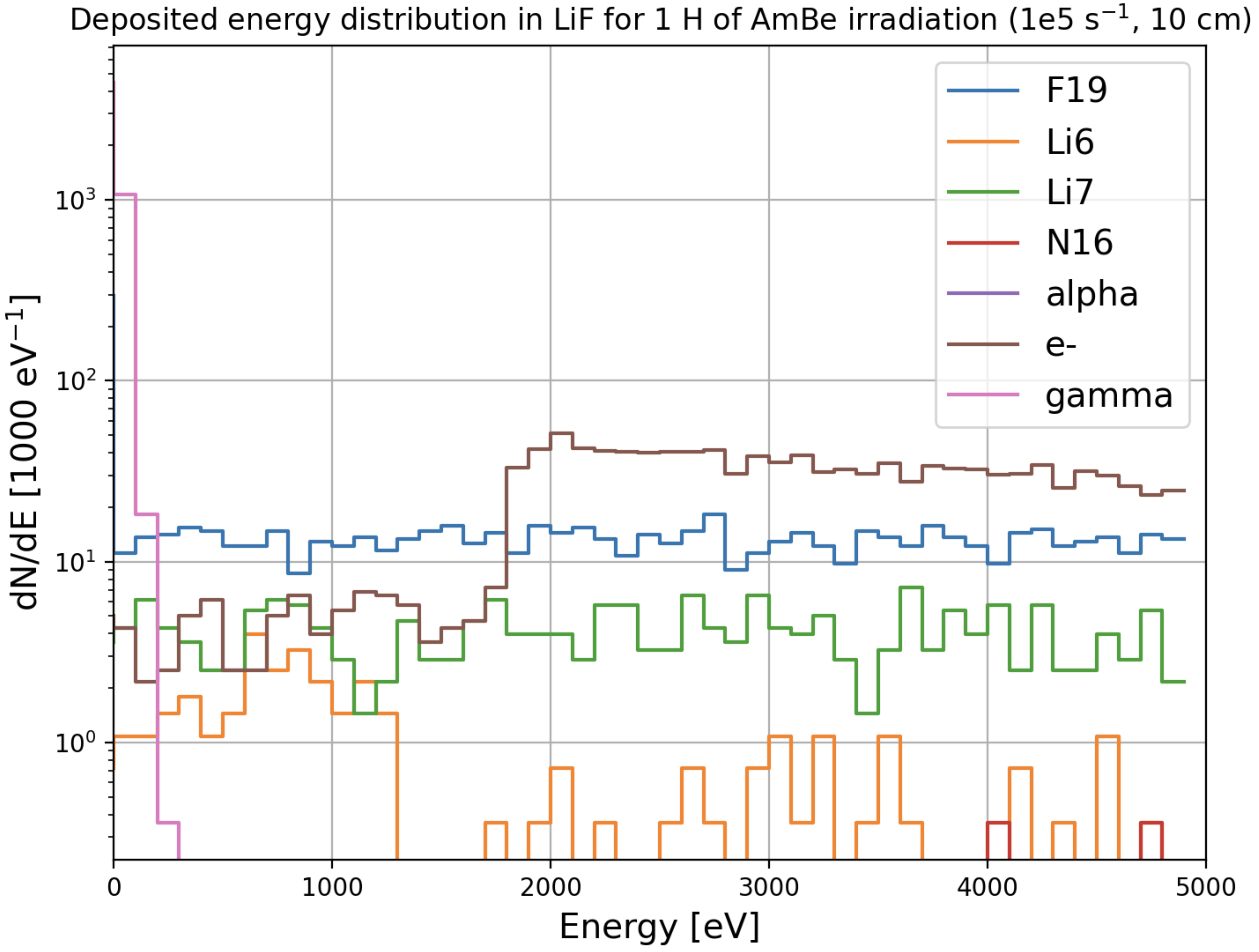




~ 750–1000 recoils / h in [0,5 keV]

Estimated nuclear recoil rates in LiF: AmBe



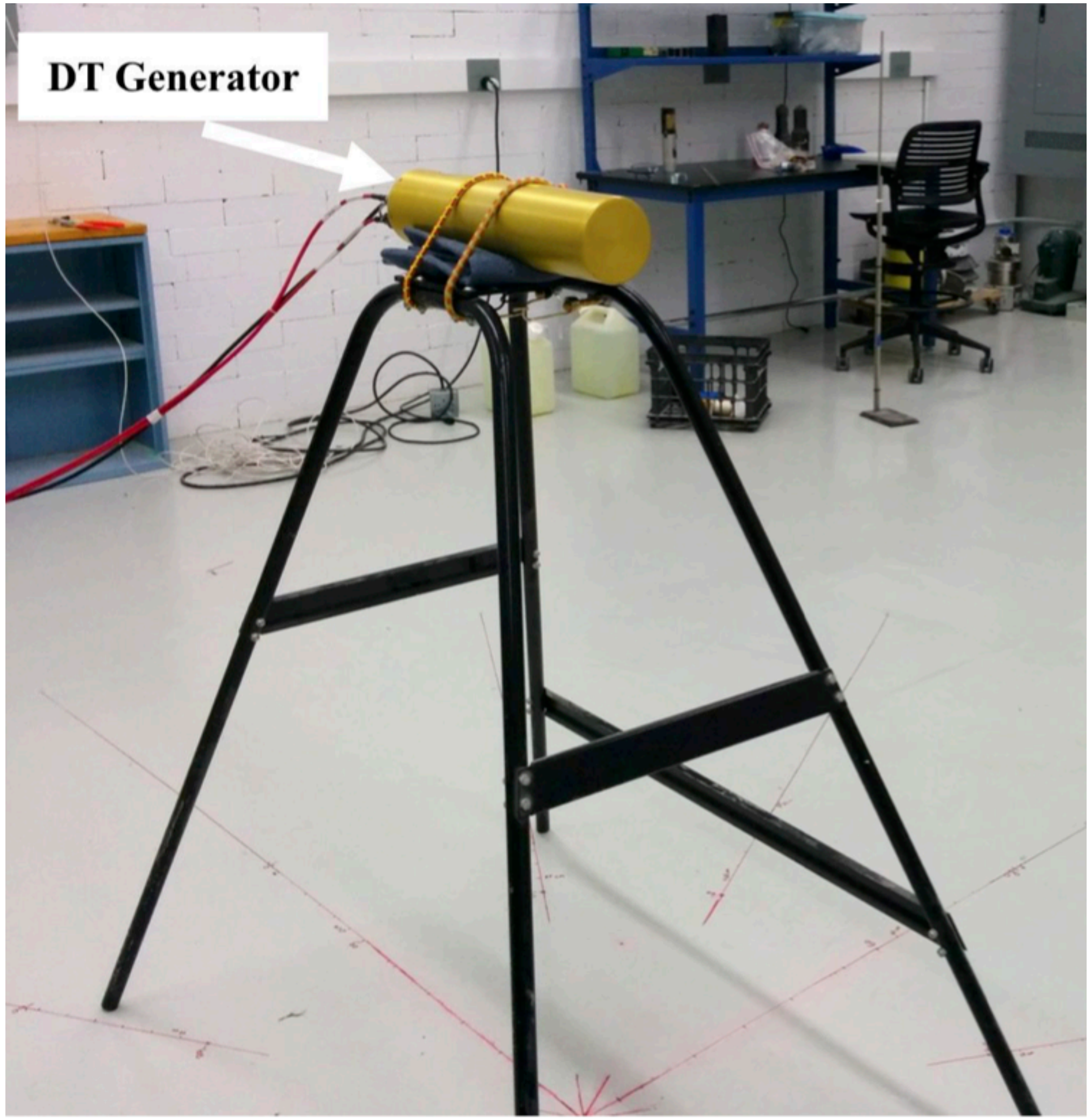


Similar to PuBe

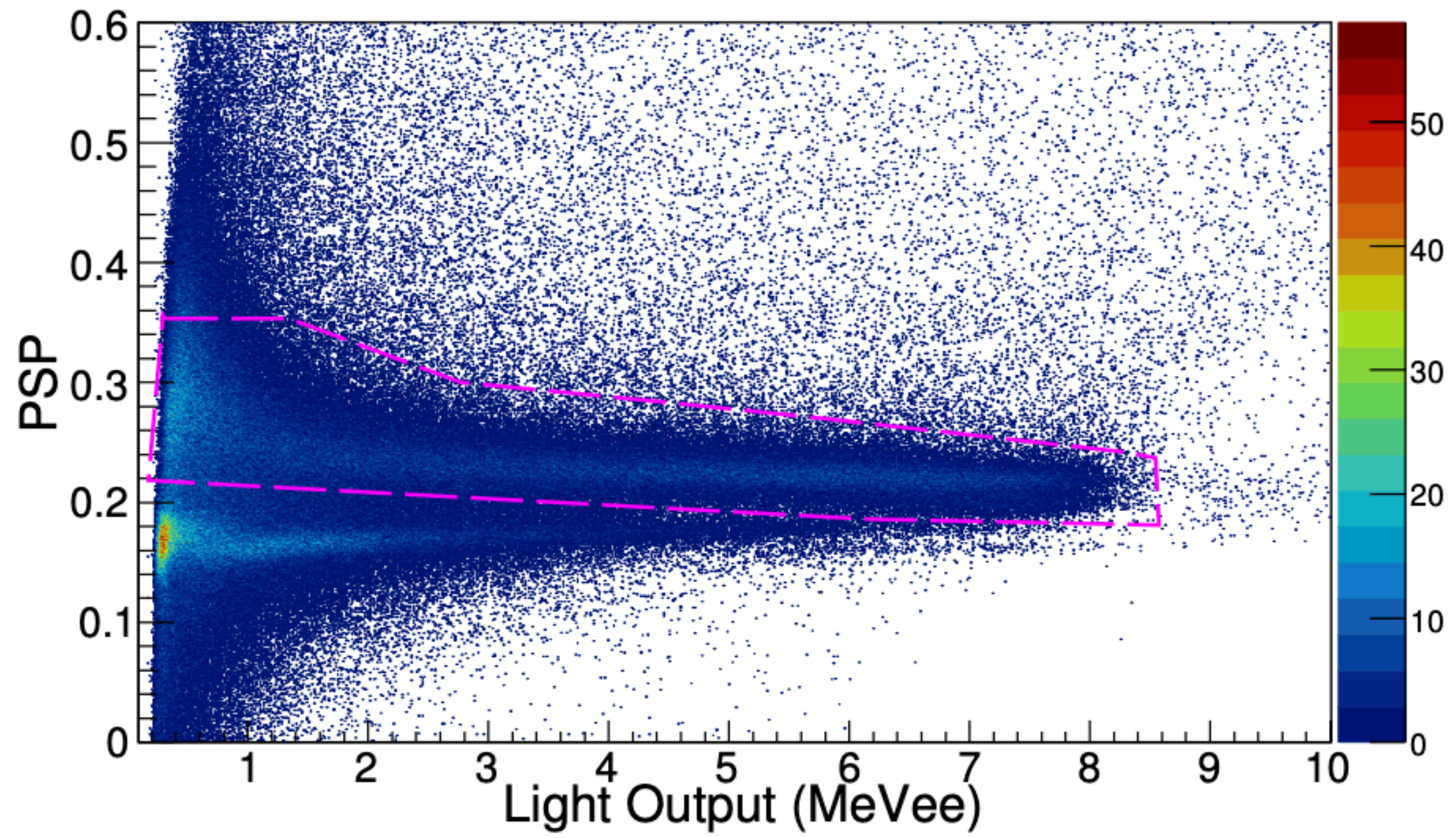
Neutron generators at UM

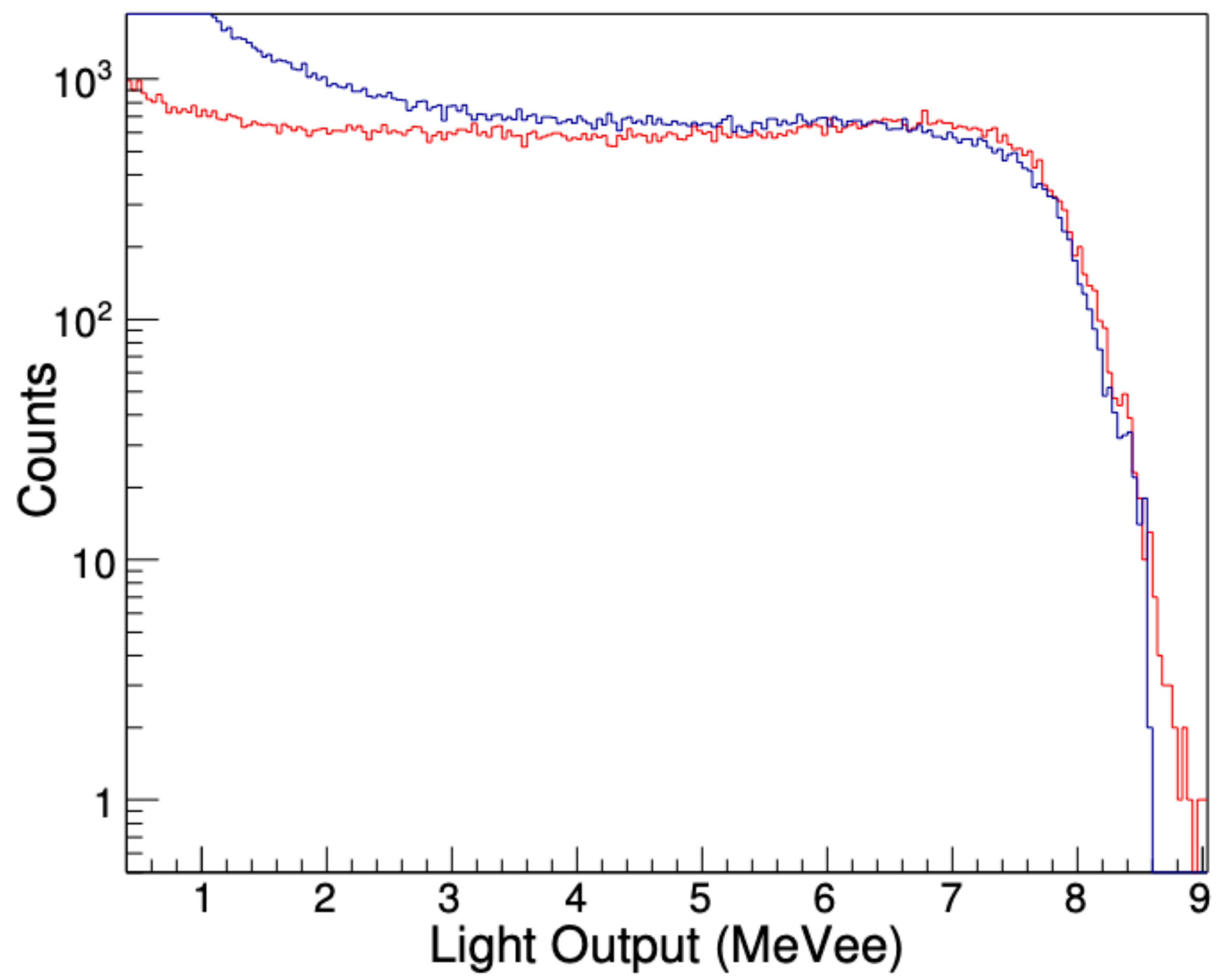
DD: 10^6 n/s

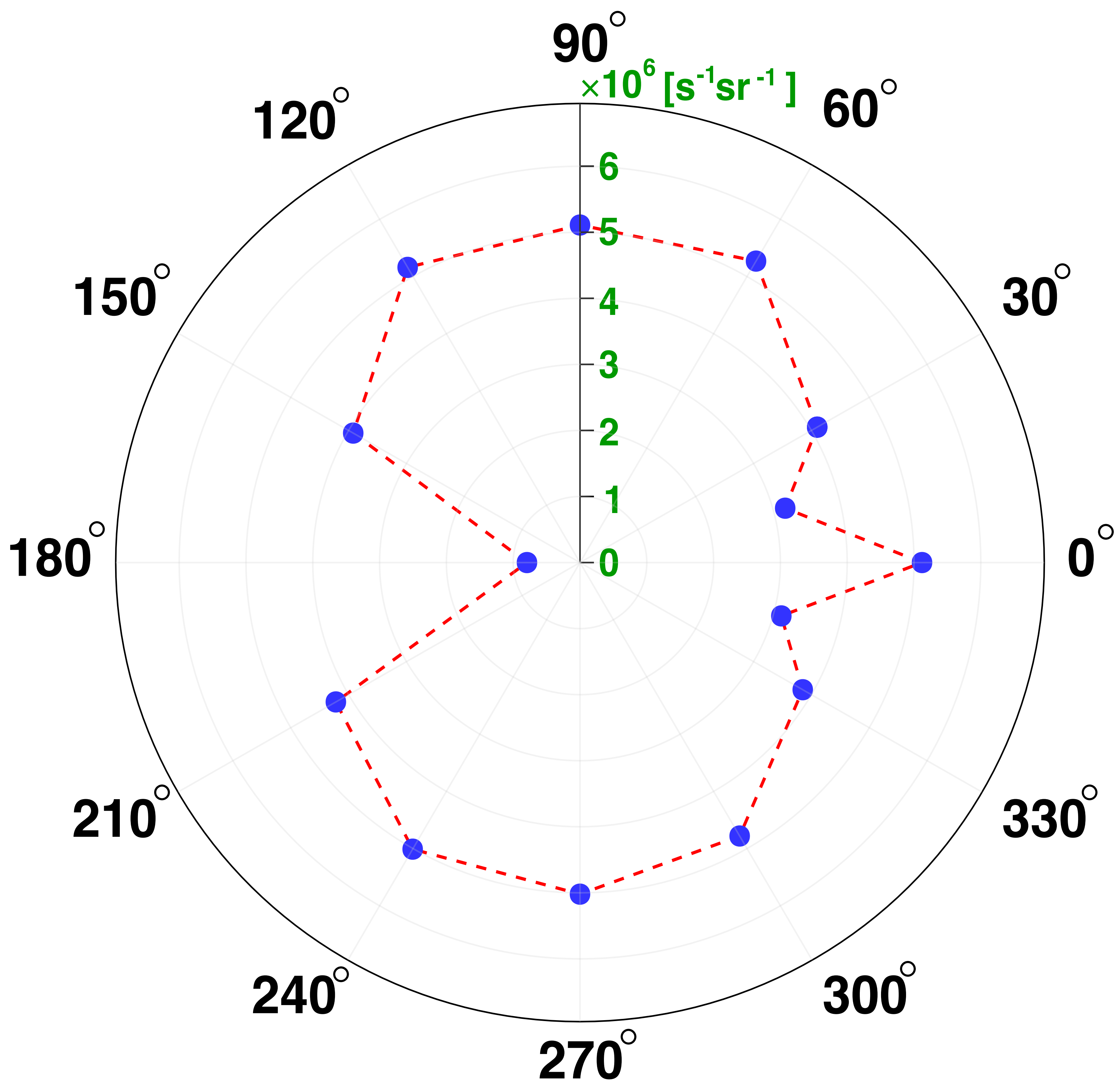
DT: 5.5×10^7 n/s



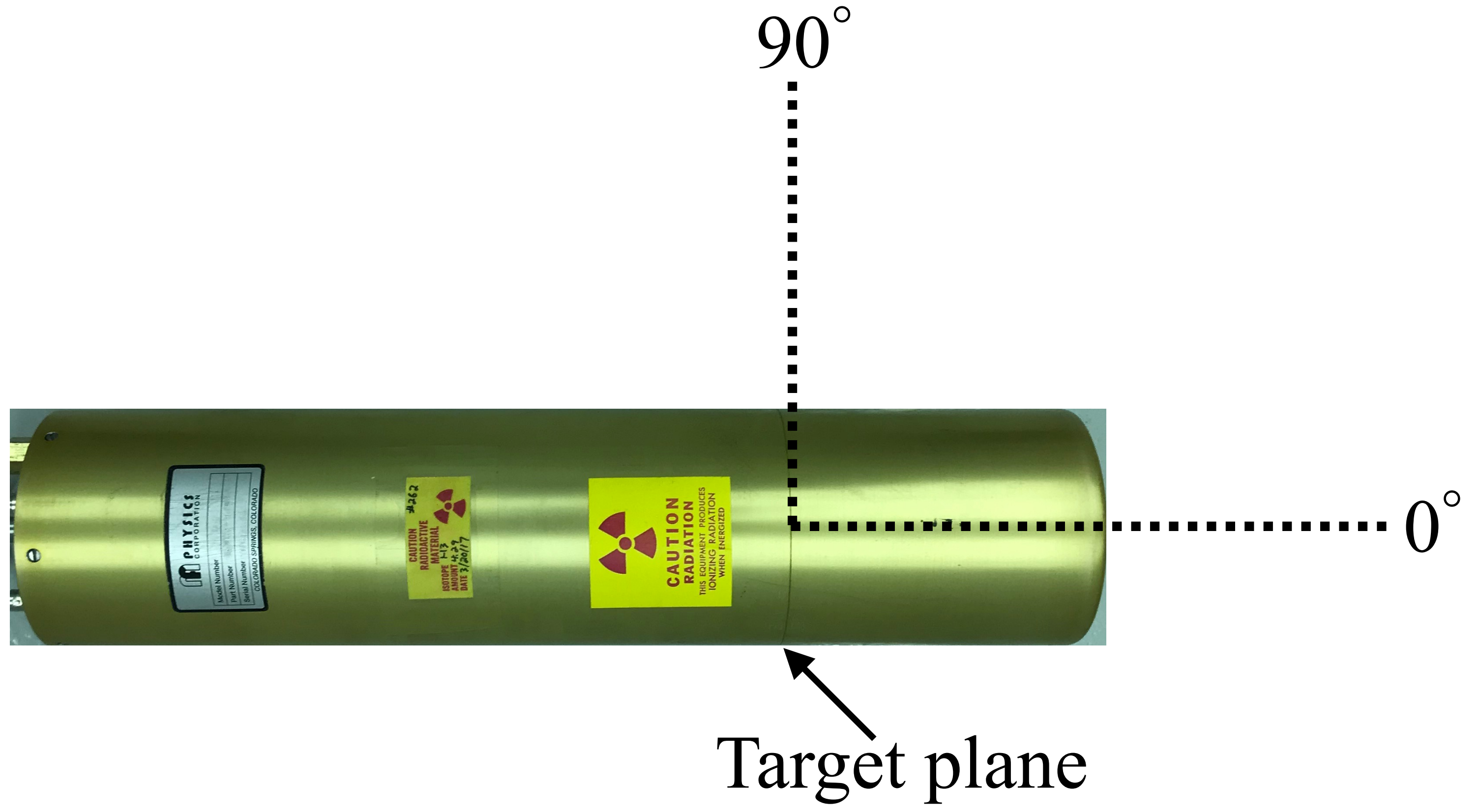
DT generator angular distribution



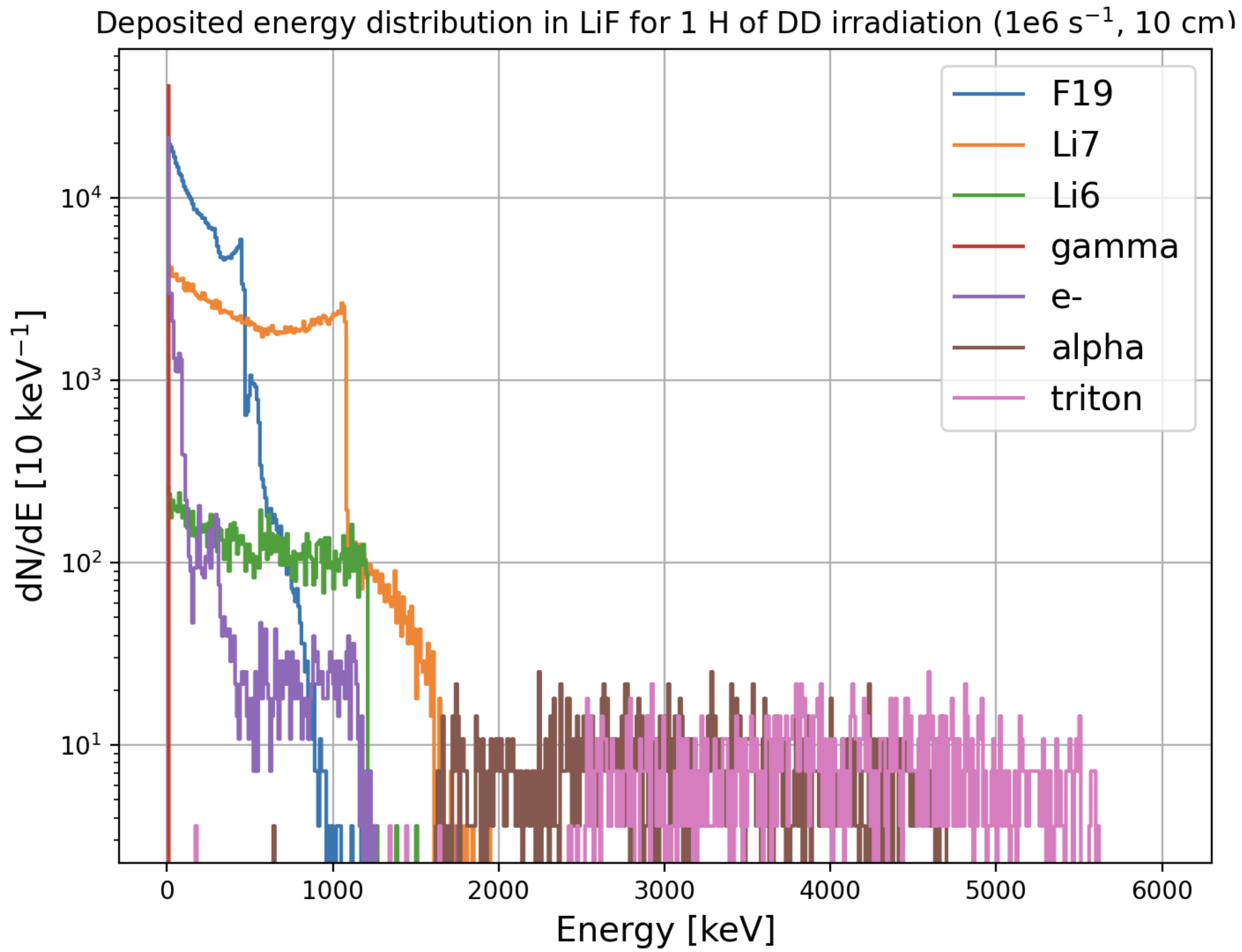


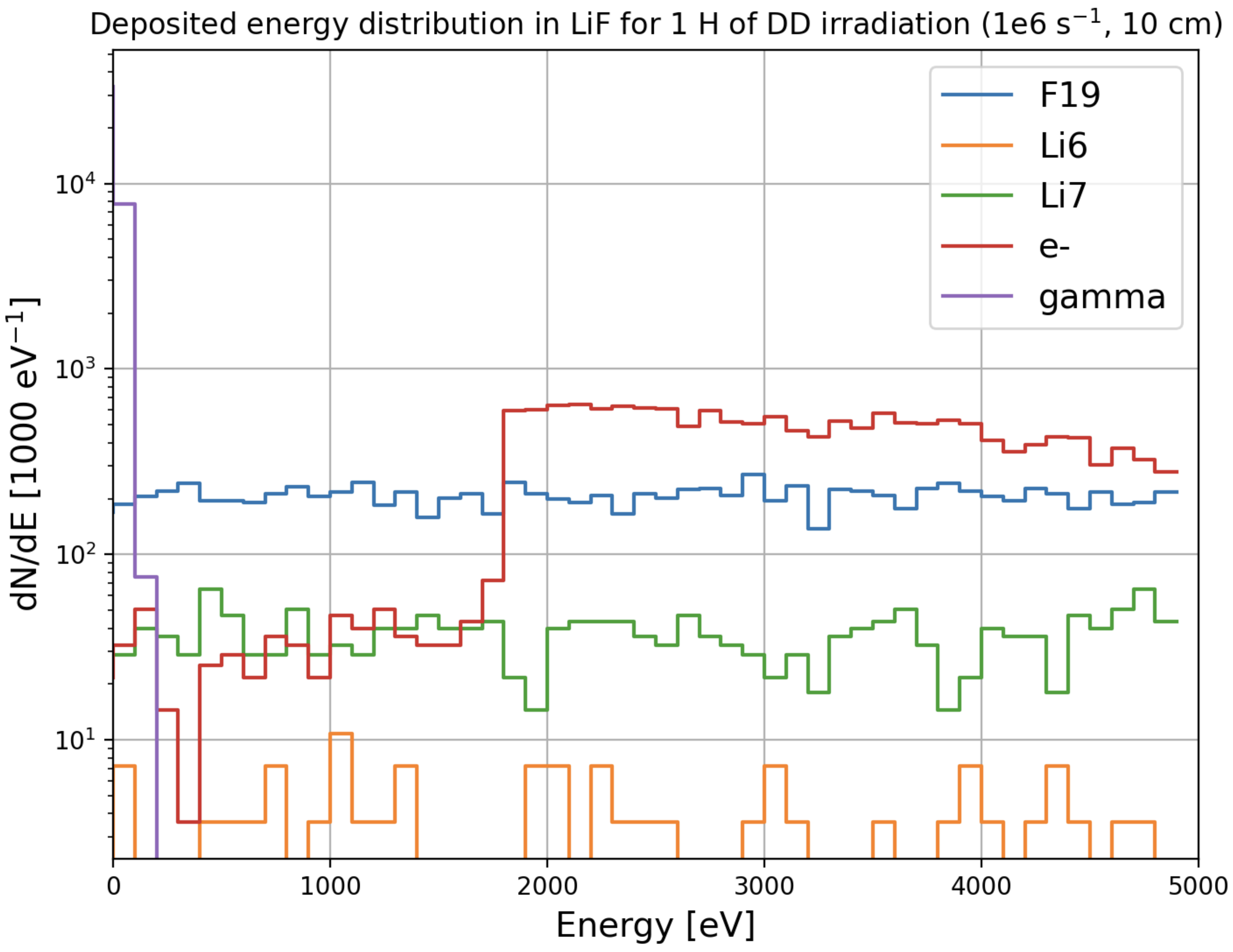


M. K. Sharma, J. Nattress, and I. Jovanovic, NIMA 911, 37–44 (2018)



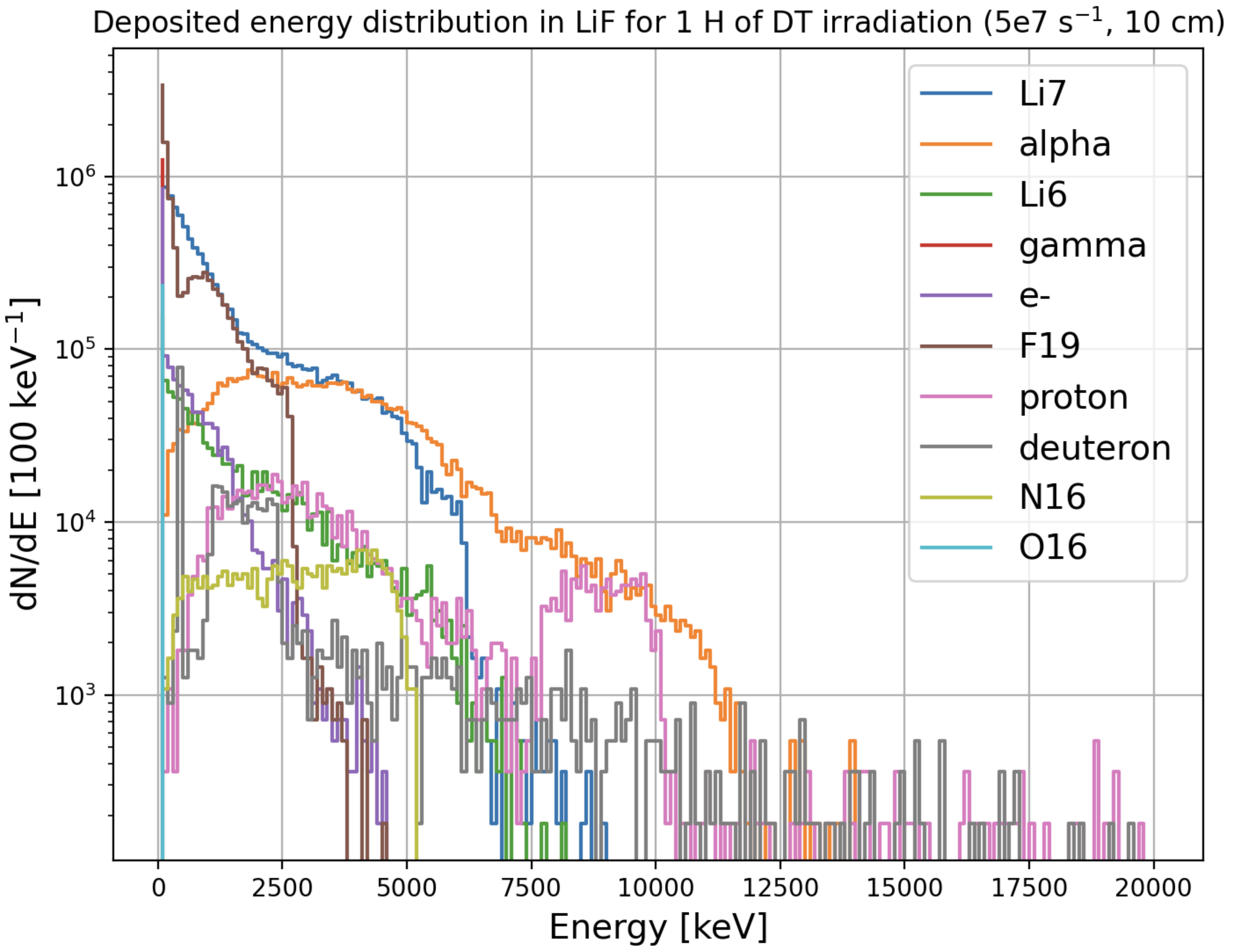
Estimated nuclear recoil rates in LiF: DD

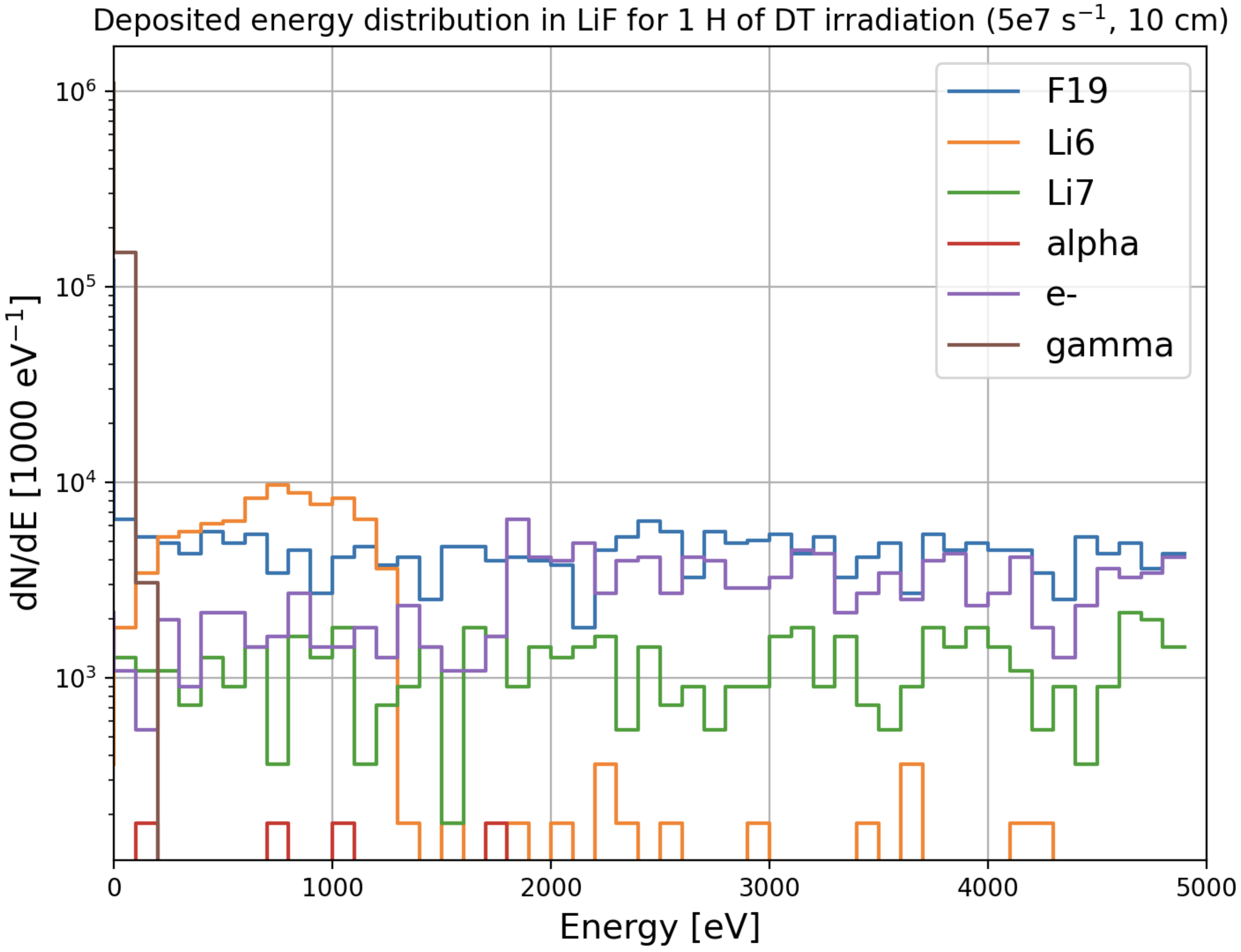




~ 1000 recoils / h in [0,5 keV]

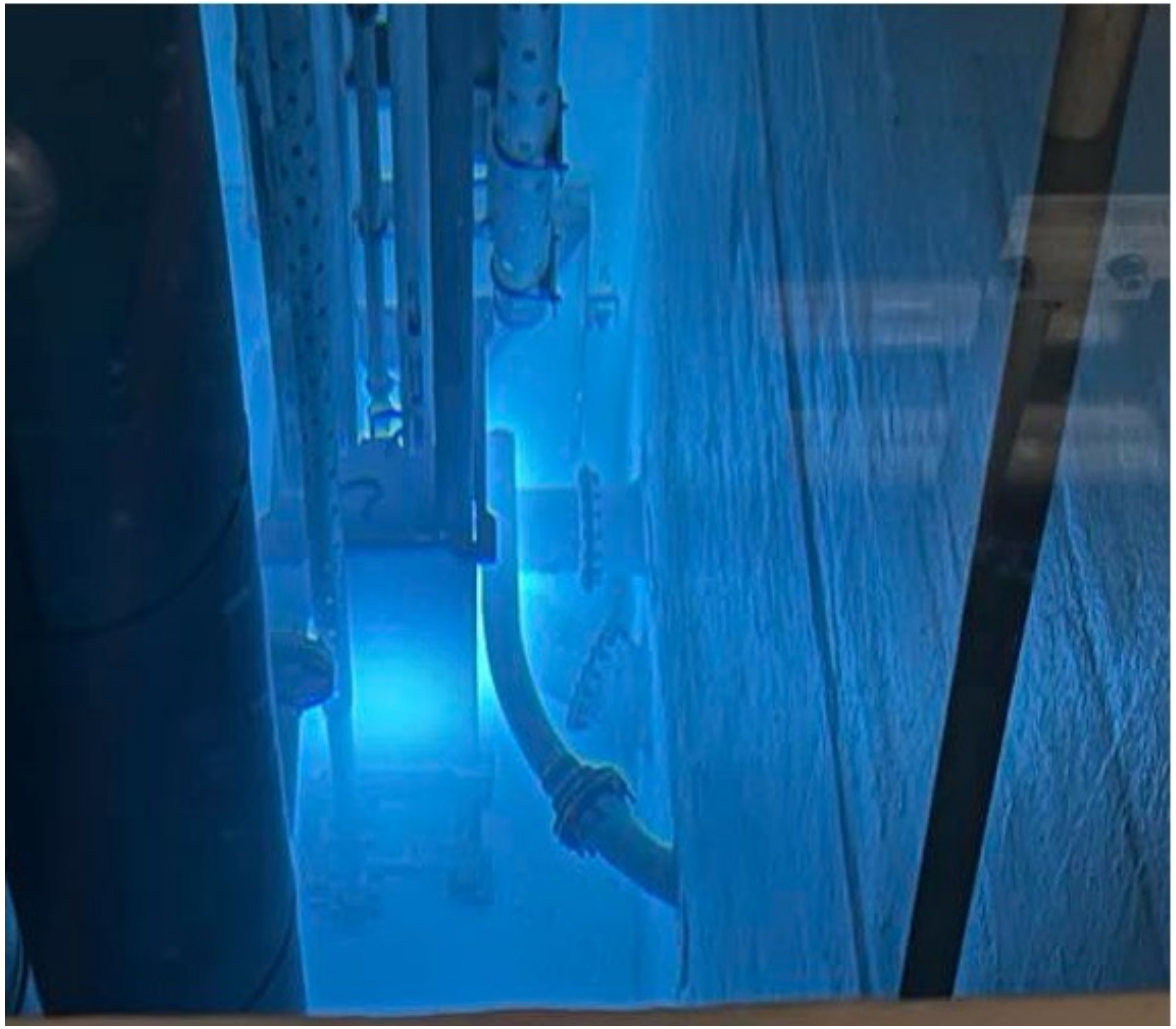
Estimated nuclear recoil rates in LiF: DT

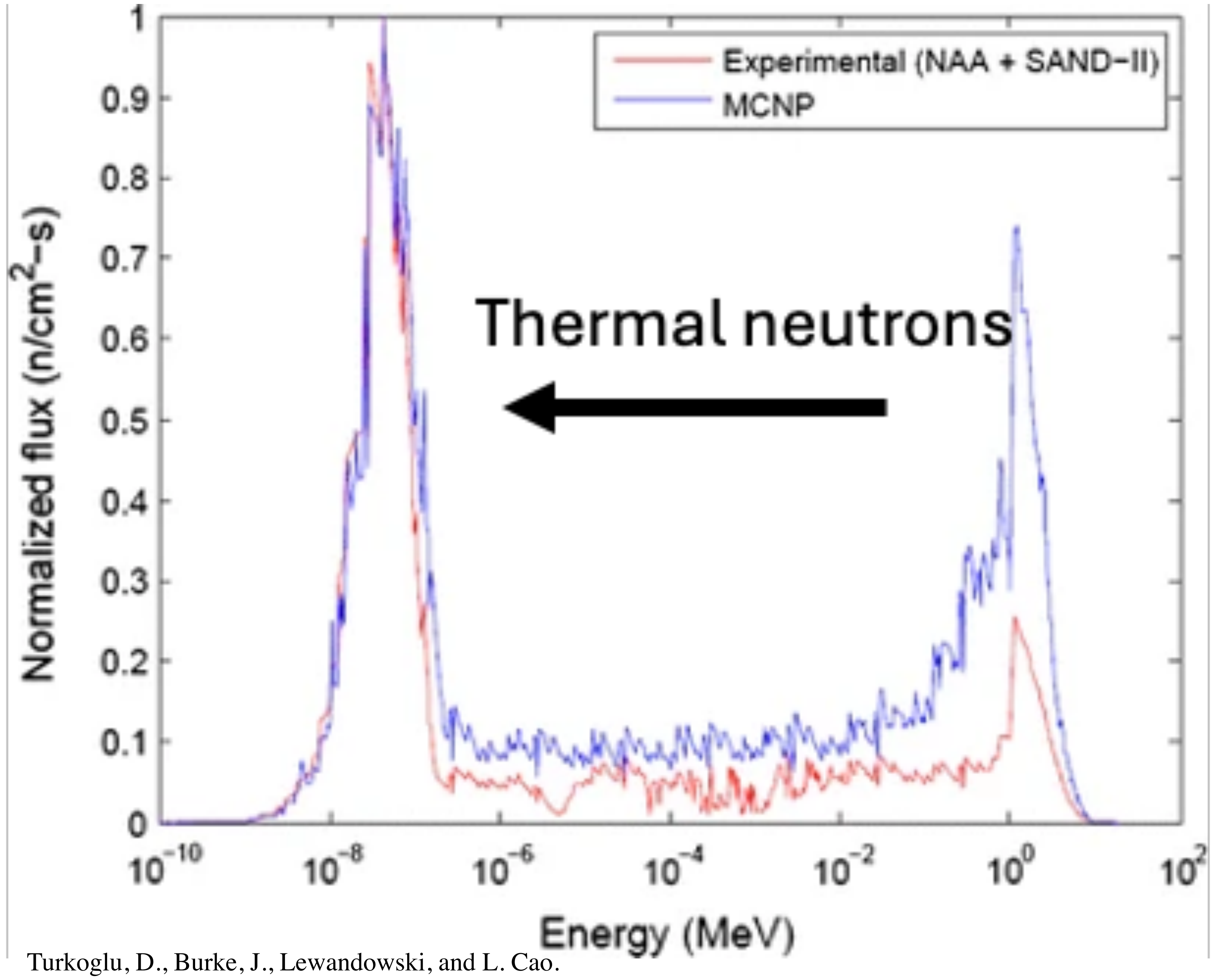




~ 30,000 recoils / h in [0,5 keV]

Irradiations using nuclear reactor

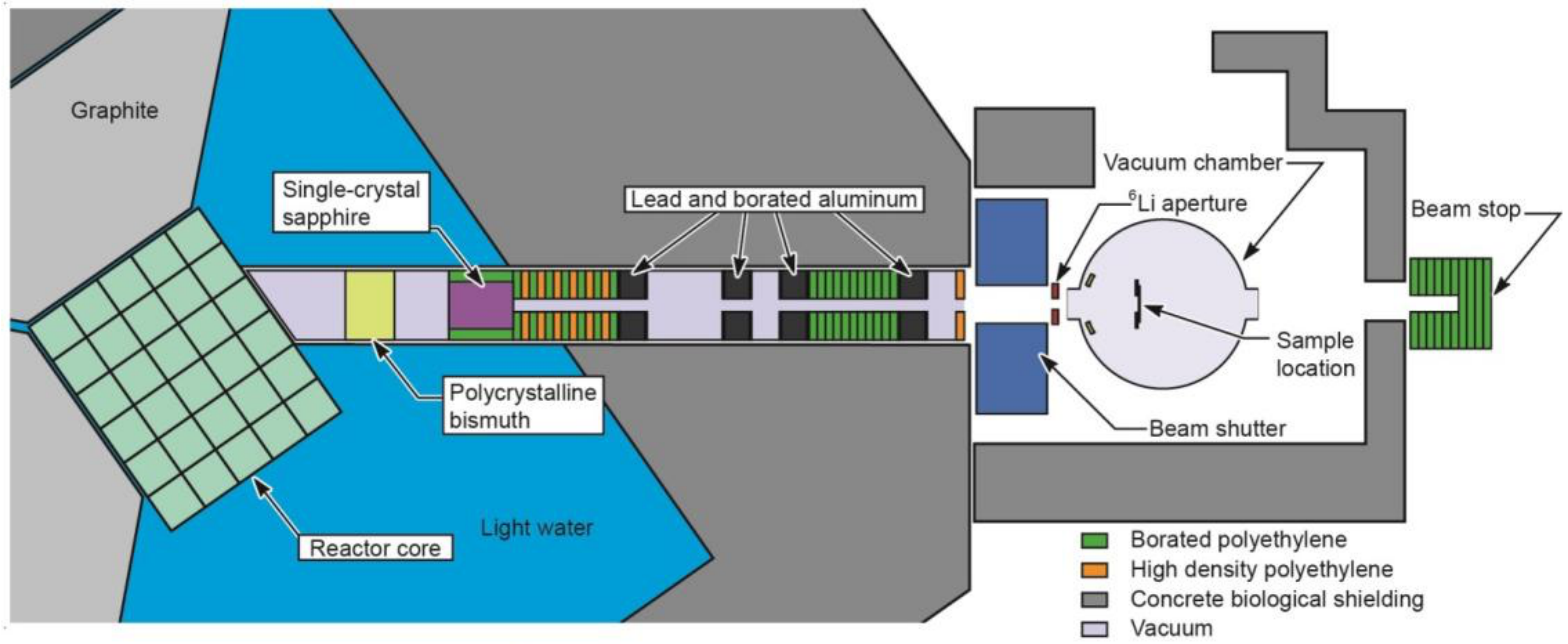




Turkoglu, D., Burke, J., Lewandowski, and L. Cao.
J. *Radioanal Nucl Chem* **291**, 321–327 (2012). https://doi.org/10.1007/s10967-011-1289-2

~4 x 10^6 n cm^{-2} s
30 mm beam
Cd ratio: 160

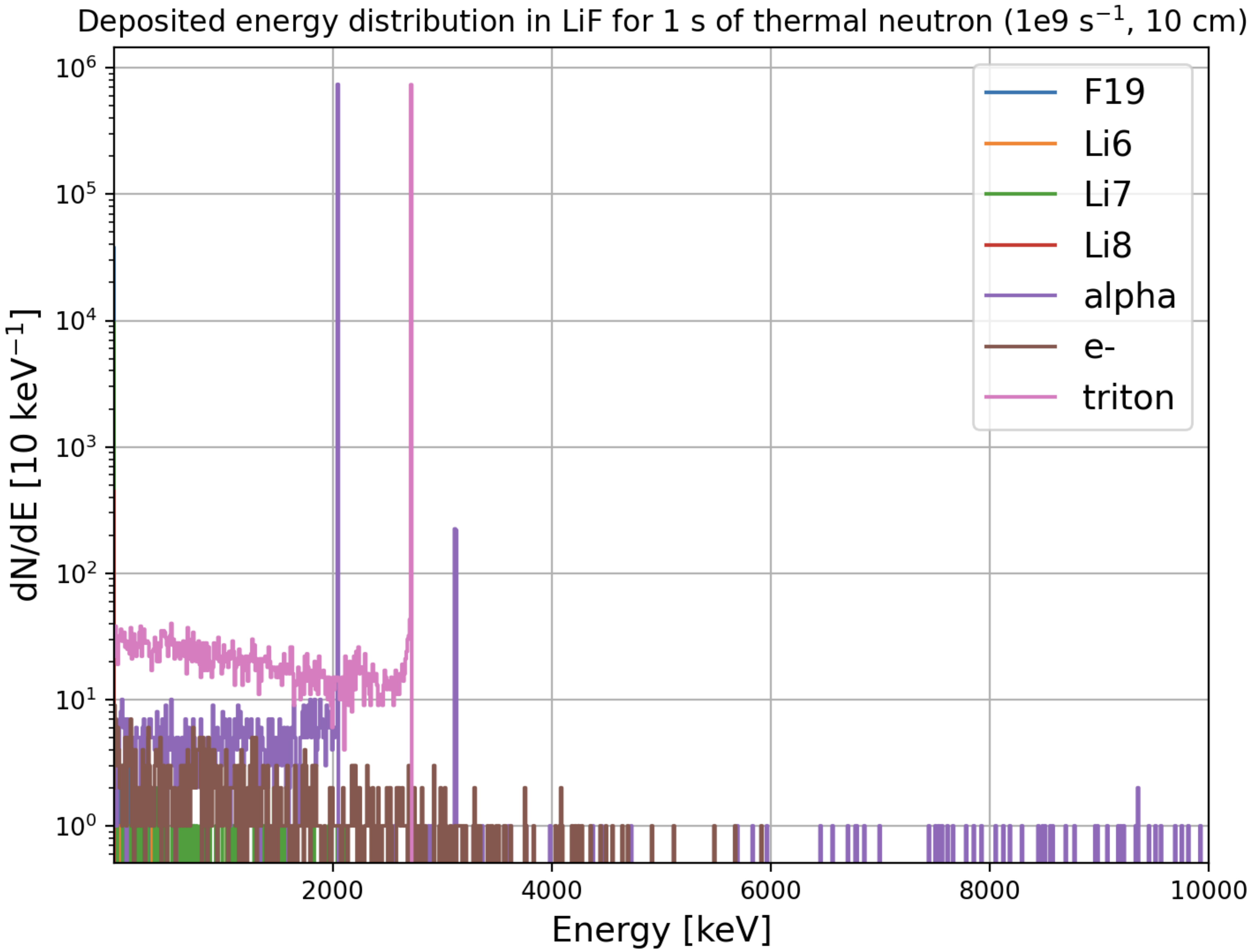
OSU nuclear reactor: thermal neutron beam generation

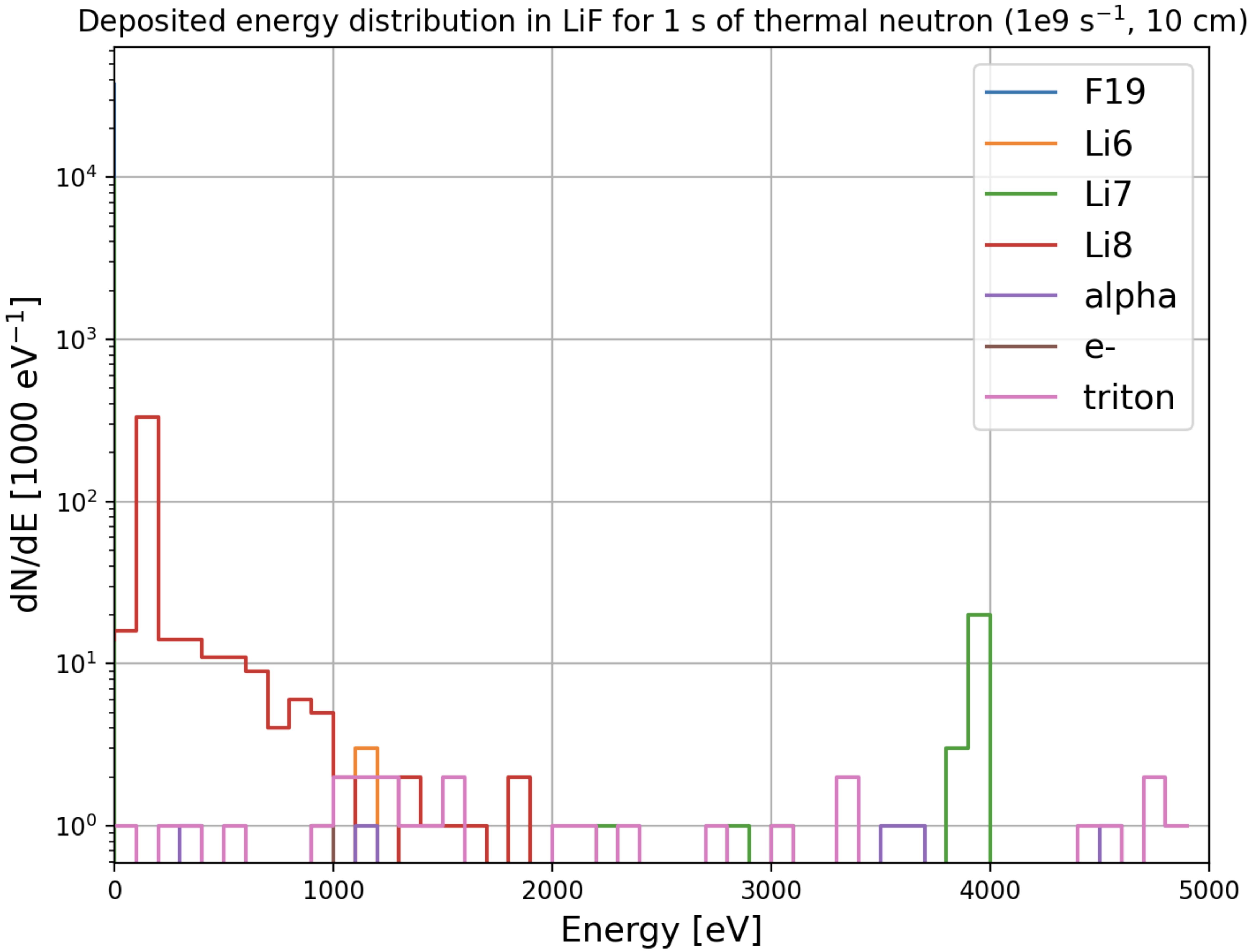


P.L. Mulligan, L.R. Cao, D. Turkoglu, Rev. Sci. Instrum. **83**, 073303 (2012).

- Sample position approximately 3.2 m from edge of reactor core
- Flux at sample location is ≈ 2.5×10^6 n/cm^2-s

Estimated nuclear recoil rates in LiF: reactor thermal beam





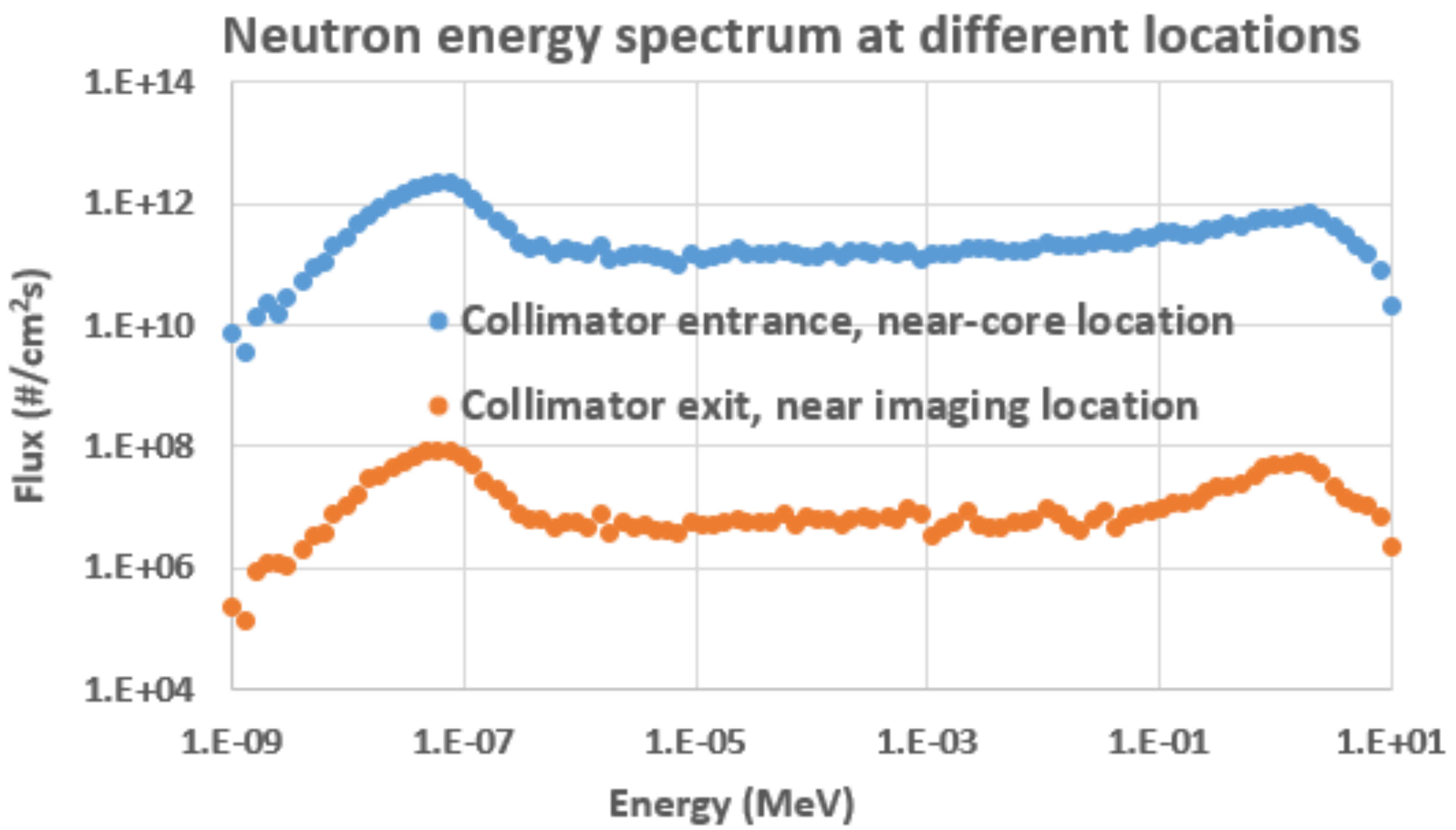
~ 500 ^{8}Li recoils / h in [0,1 keV]

Fast neutron irradiation on OSU nuclear reactor

~ 10^7 recoils/h in [0,5 keV] based on scaling from ^{252}Cf simulations

Reactor-spectrum neutron beam diameter of 1.25” (32 mm)
~ 2×10^7 n cm^{-2} s^{-1}

36% thermal neutrons (E_n<0.5 eV, 0.8 x 10^7 n cm^{-2} s^{-1})
64% epi-cadmium neutrons (E_n>0.5 eV, 1.5 x 10^7 n cm^{-2} s^{-1})

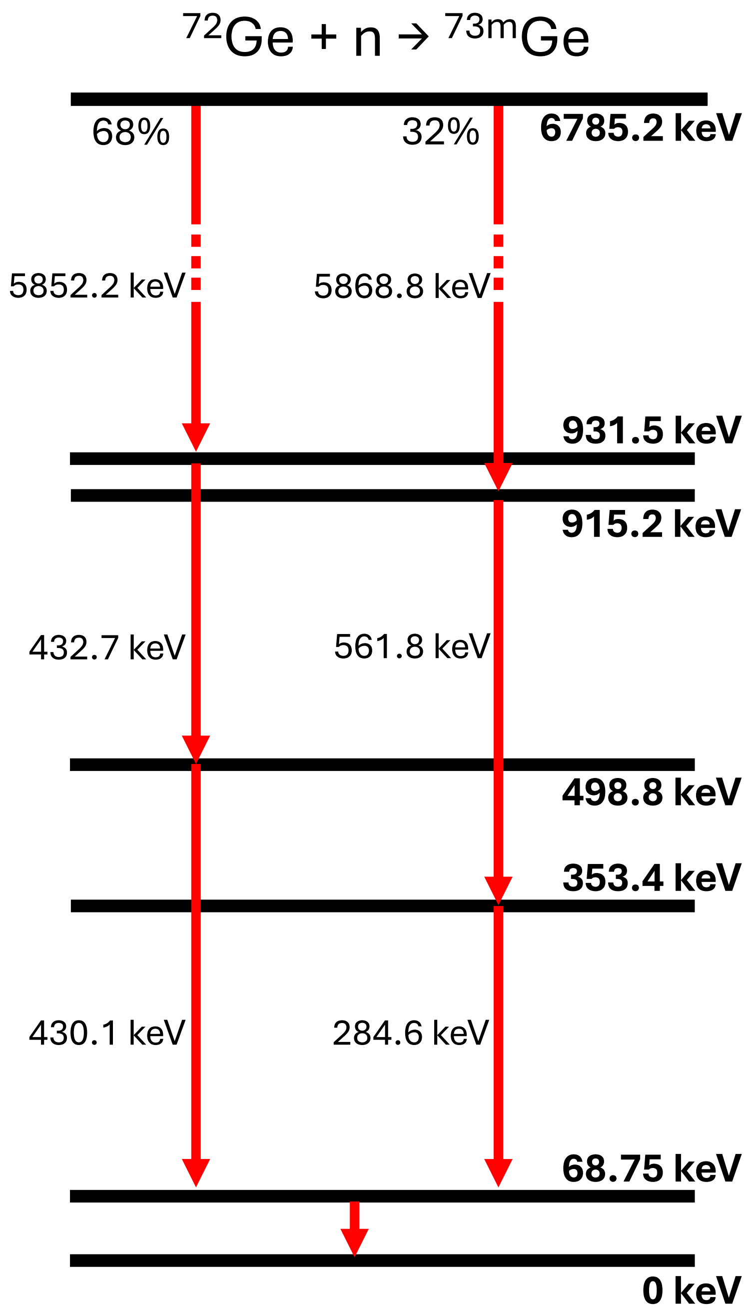


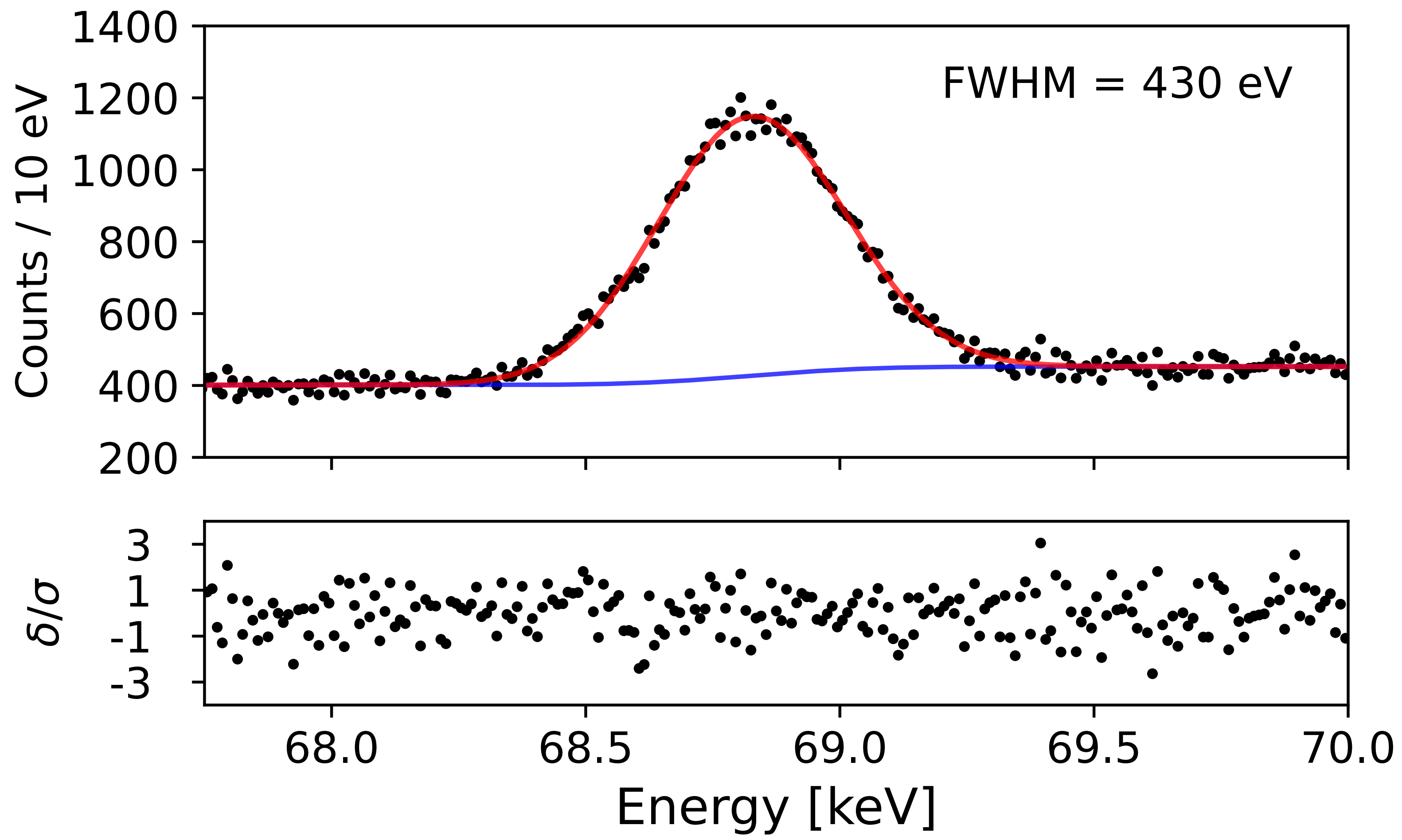
In-core irradiation at the OSU nuclear reactor

~2 x 10^{13} n cm^{-2} s^{-1}

We will probably not be interested in this due to strong gamma flux.

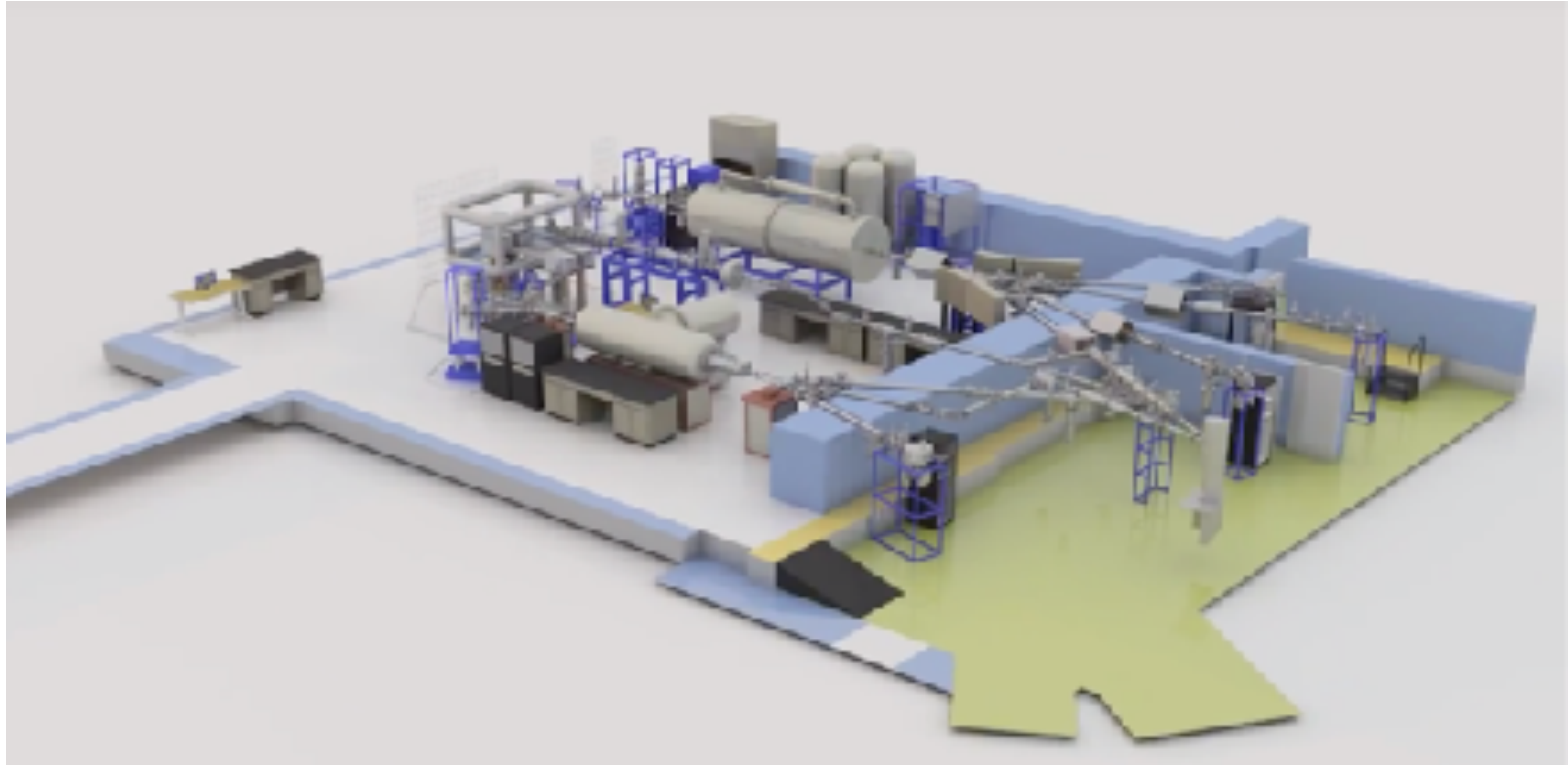
Example experiment with thermal neutron beam at OSU nuclear reactor





A.R.L. Kavner and I. Jovanovic, Phys. Rev. D 110, 083043 (2024)

$^7Li(p,n)^7Be$ for keV neutron production



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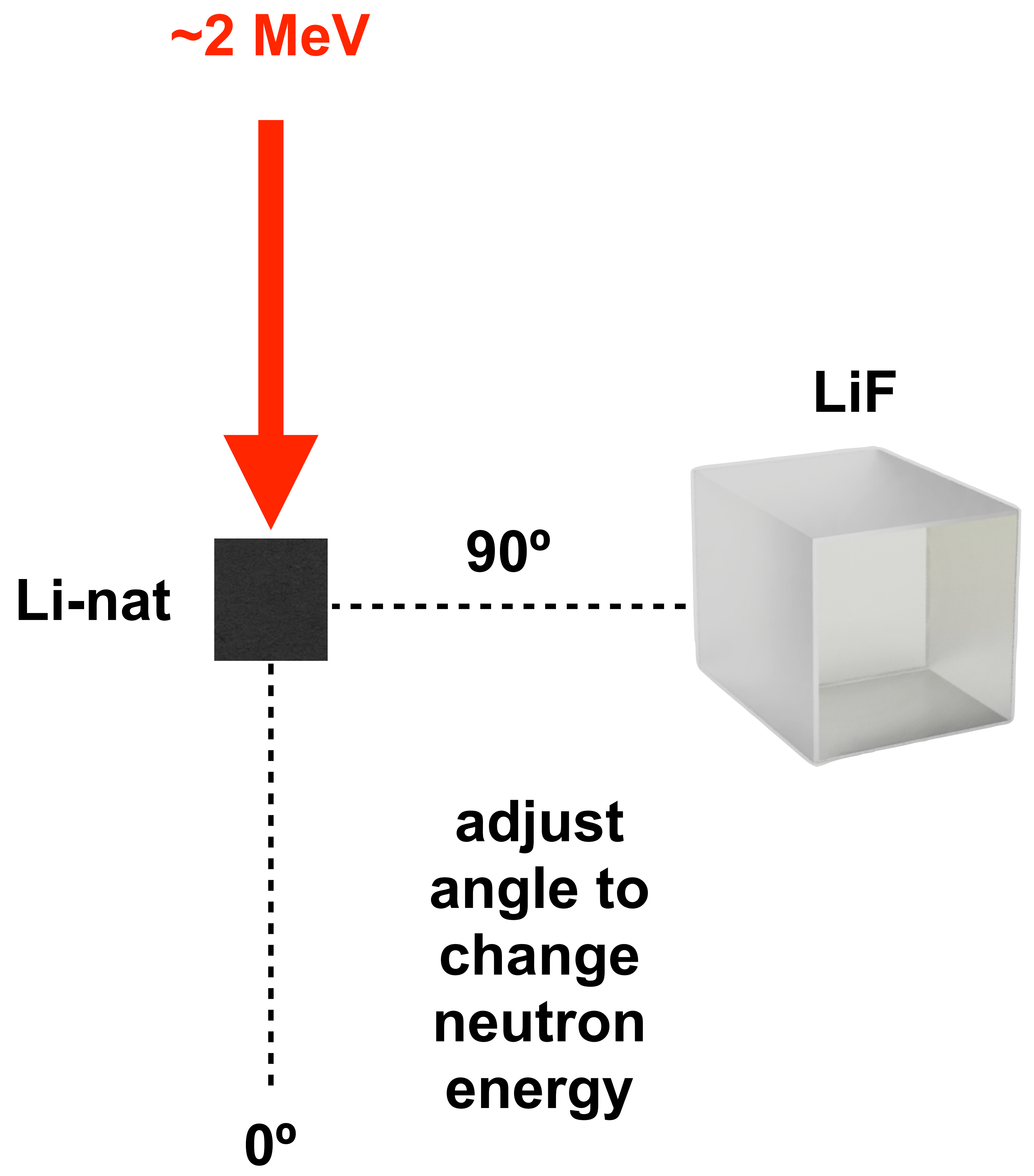
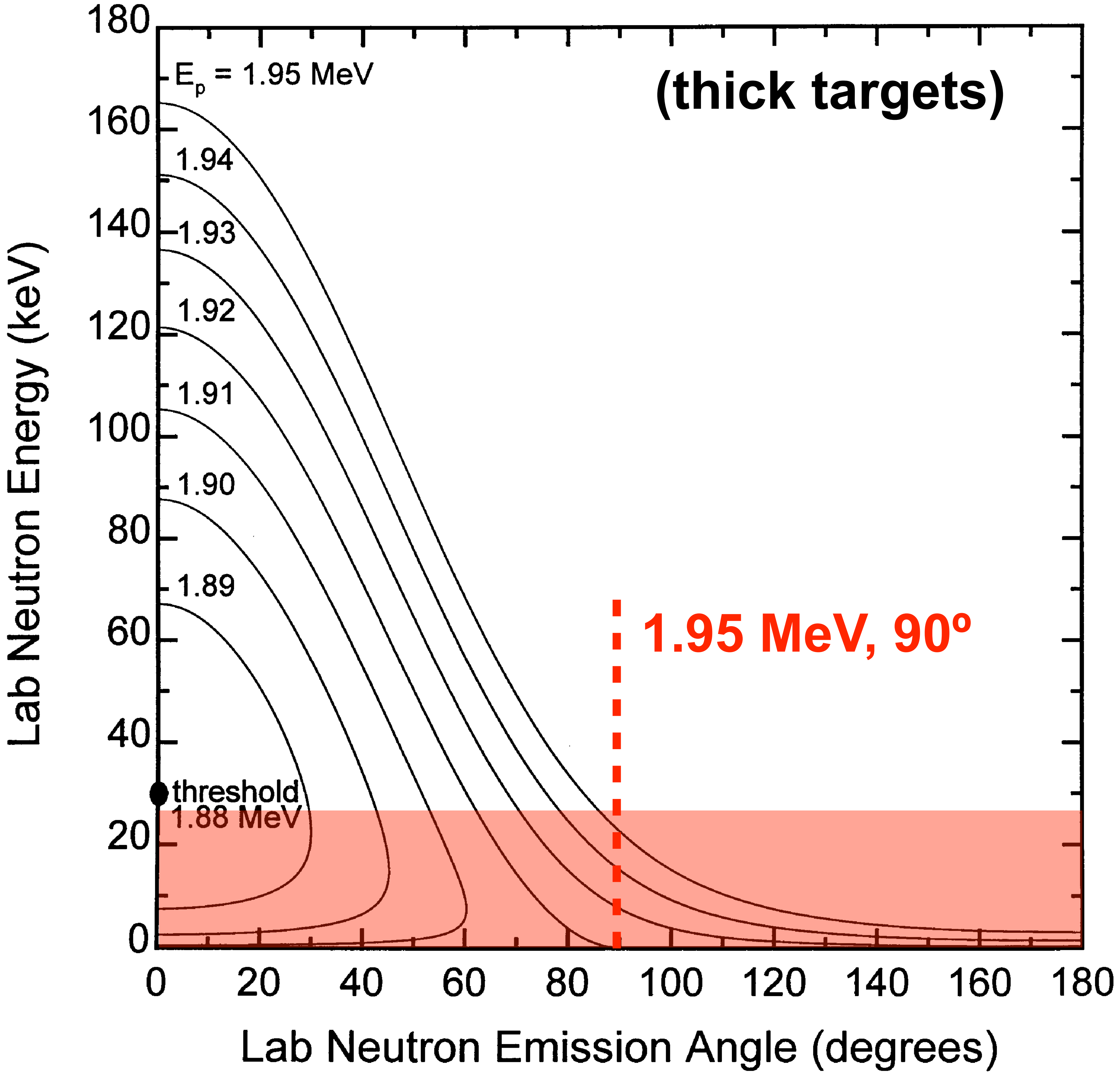
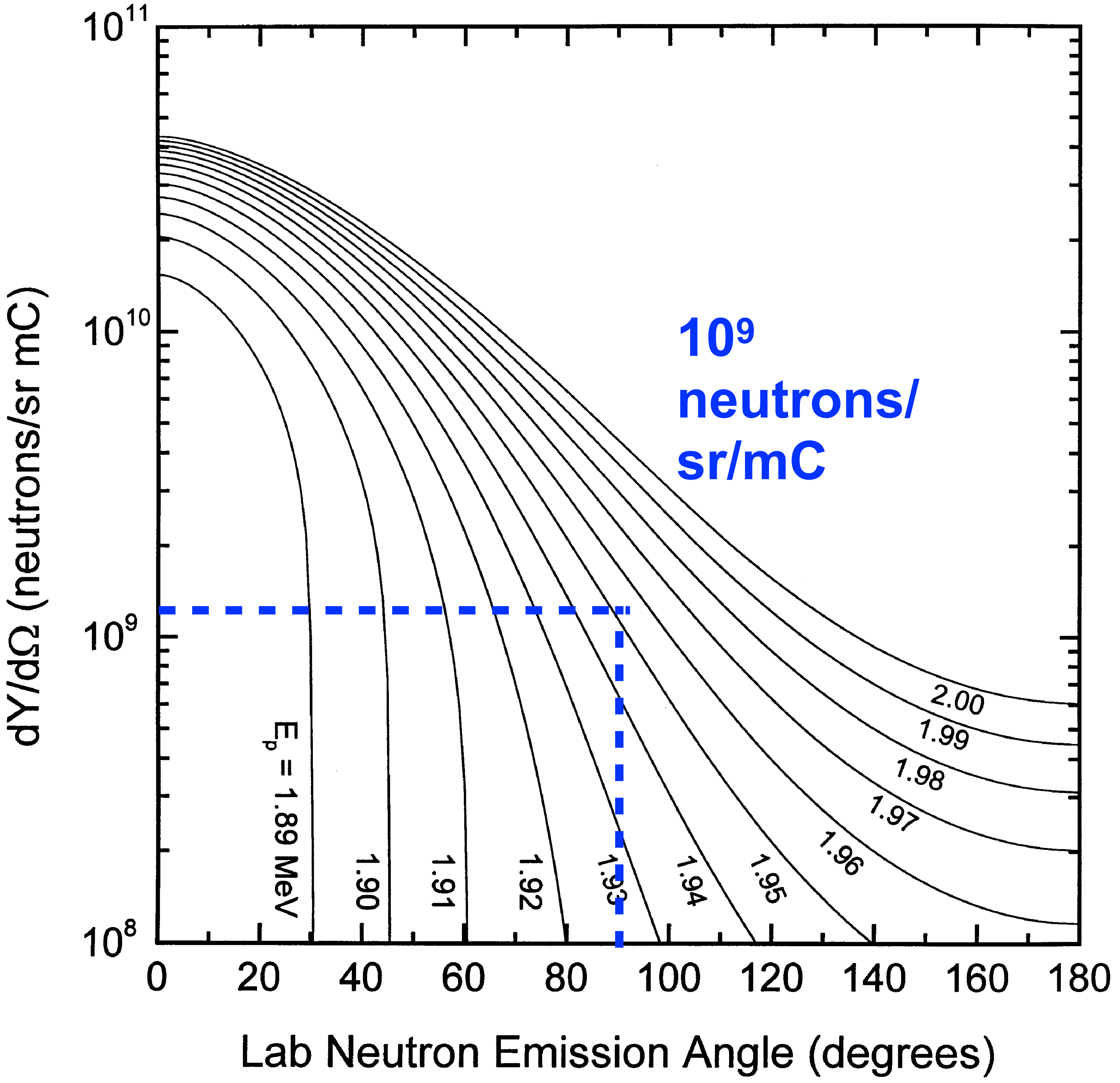
protons 1–6 MeV
up to 50 μA



$^7Li(p,n)^7Be$ for keV neutron production





1 cm^3 LiF at 10 cm: ~0.001 sr
10^6 neutrons/mC

MIBL protons up to 50 μA

~10^8 neutrons/h in [0,25 keV]

~7x10^6 nuclear recoils / h in [0,5 keV]

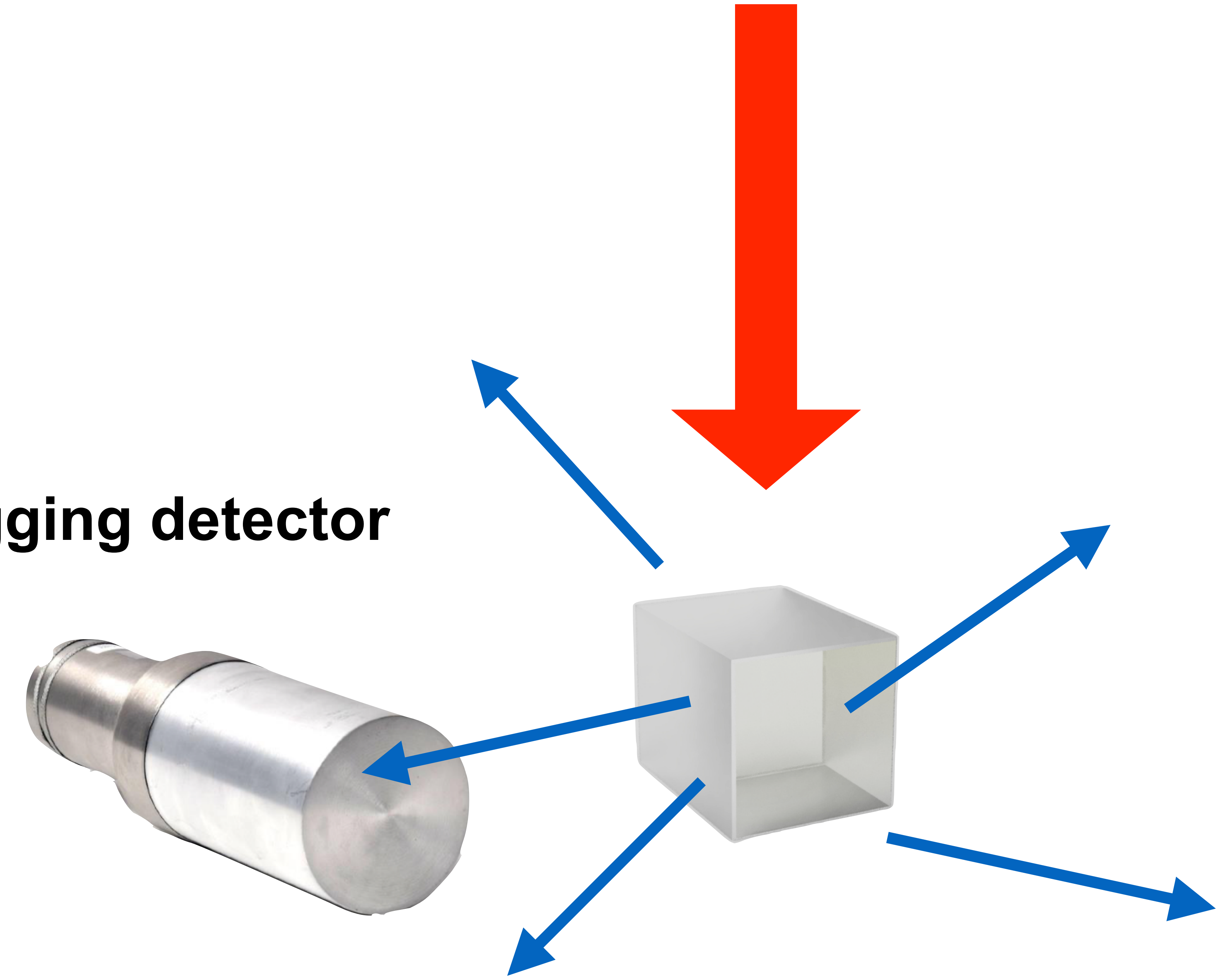
C. L. Lee & X.-L. Zhou, NIM B 152, 1-11 (1999)

Summary of approximate recoil rates in [0,5 keV]

in 1 cm^3 of LiF at 10 cm distance
including ^{6}Li, ^{7}Li, and ^{19}F

Source	Spectrum	Rate / h	Recoil density in 1 day (cm^{-3})
^{252}Cf	Watt	20–30 / 700–1000	500–700 / 1.7–2.4 x 10^4
PuBe	continuous	750–1000	1.8–2.4 x 10^4
DD	2.45 MeV	1000	2.4 x 10^4
DT	14.1 MeV	3 x 10^4	7.2 x 10^5
MIBL $^{7}Li(p,n)$	10-30 keV	7 x 10^6	1.7 x 10^8
OSU-NRL	thermal	500	1.2 x 10^4
OSU-NRL	fast	10^7	2.4 x 10^8

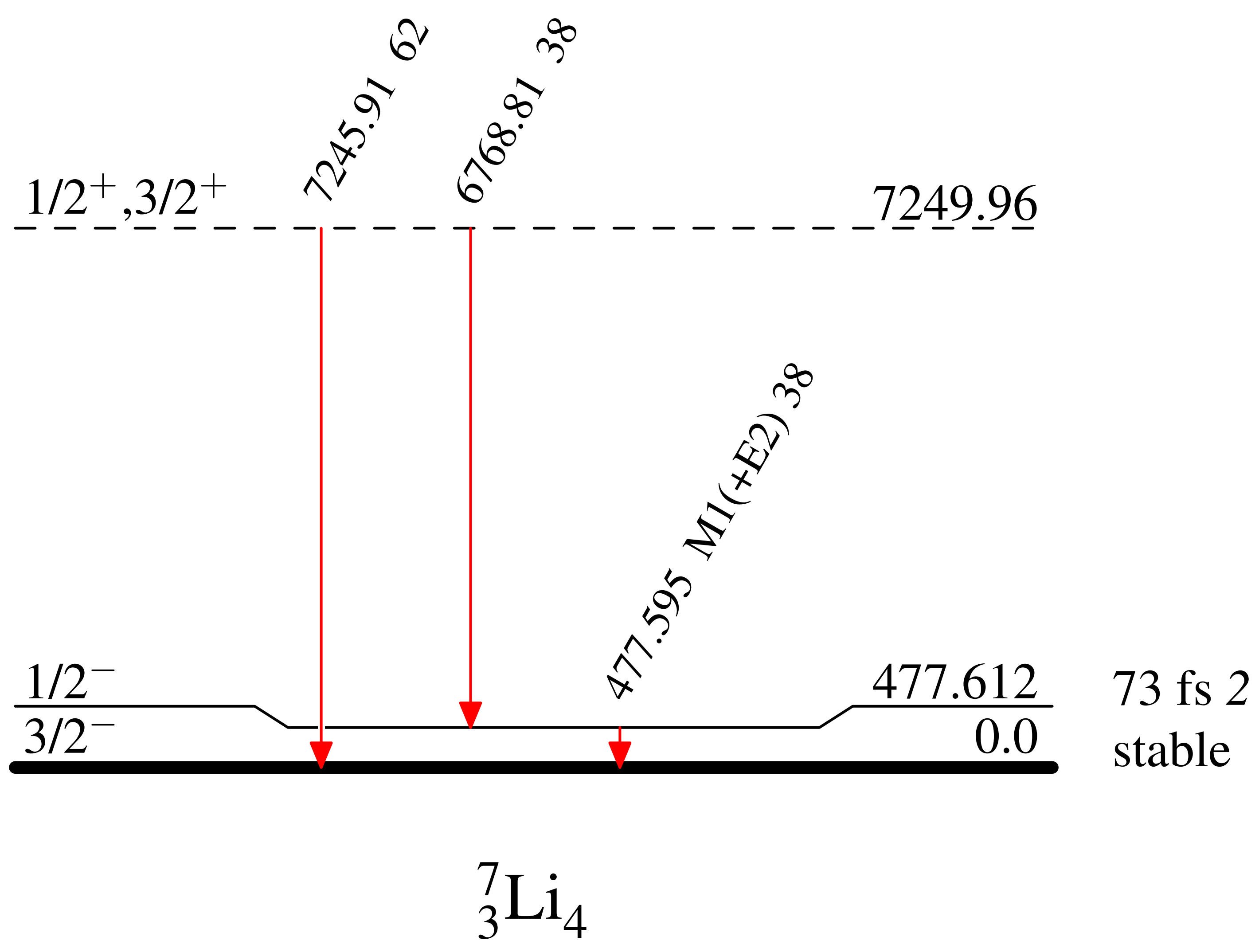
CRAB: Calibration by Recoils for Accurate Bolometry



- Detector efficiency obtained by simulation and validated using calibration sources
- Use single or multiple isolated gammas to determine the number of captures/recoils

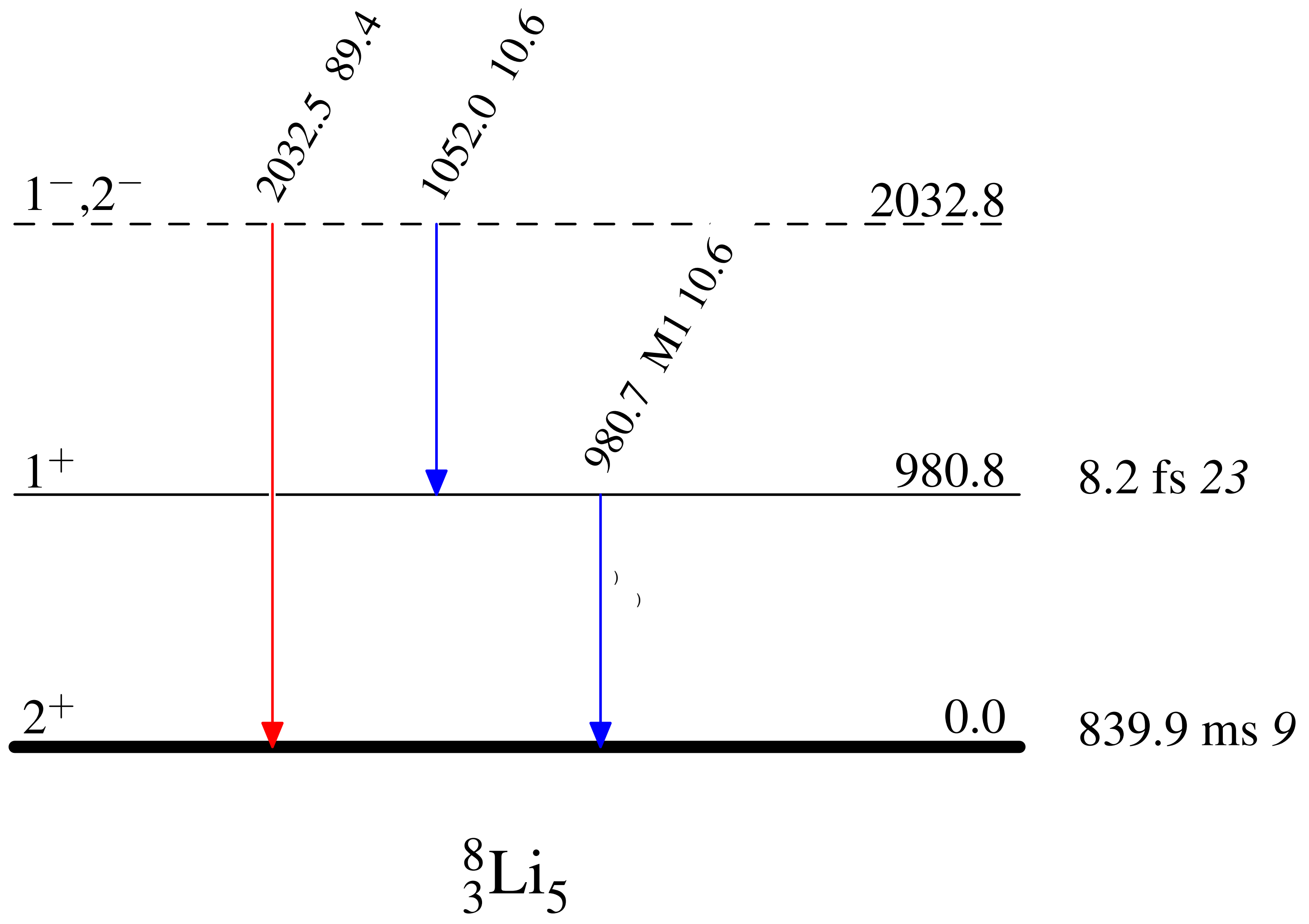
CRAB in LiF

^{6}Li(n,g) 0.039 b



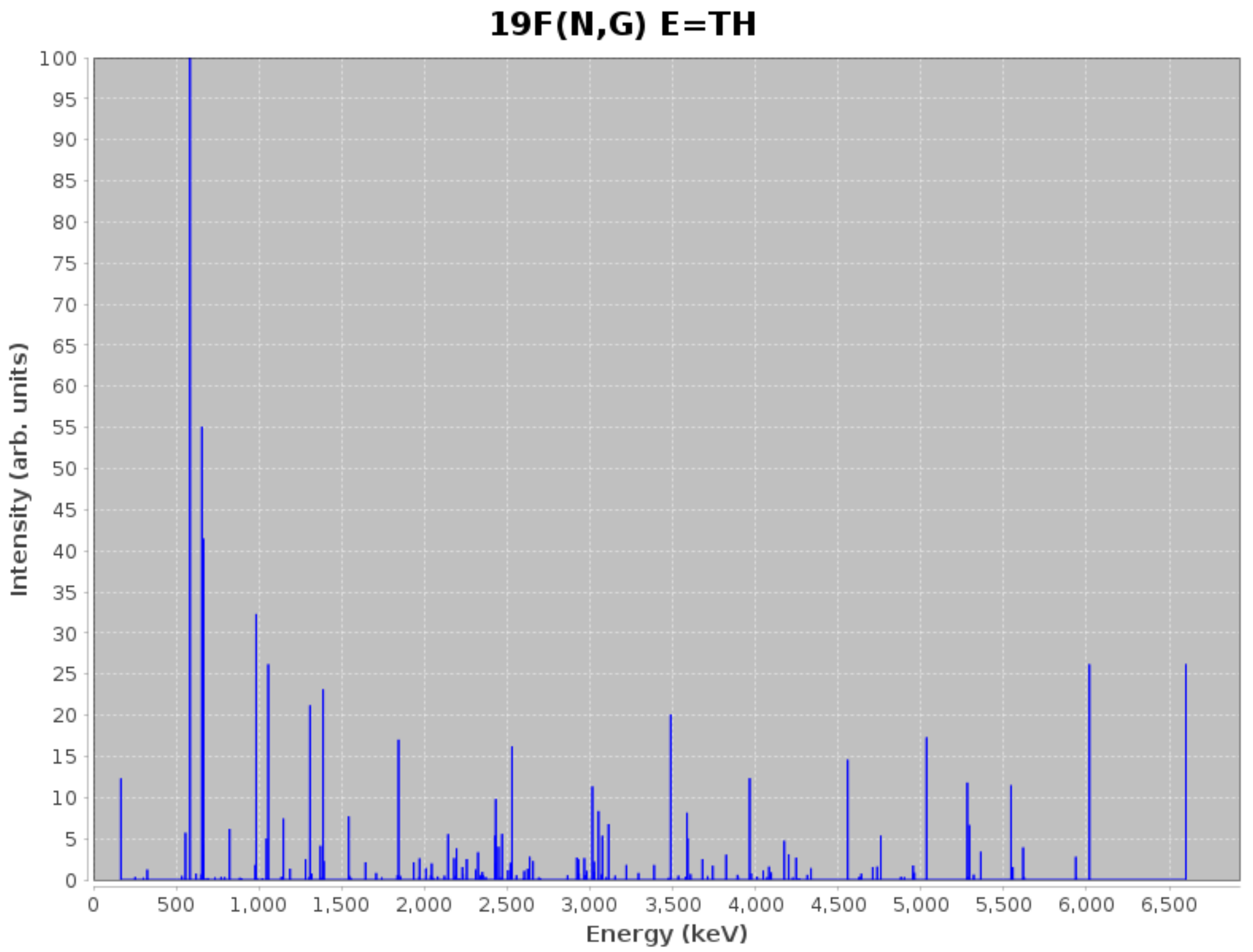
0.477 MeV (38%)
6.8 MeV (38%)
7.2 MeV (62%)

^{7}Li(n,g) 0.045 b



0.981 MeV (10.6%)
1.1 MeV (10.6%)
2.0 MeV (89.4%)

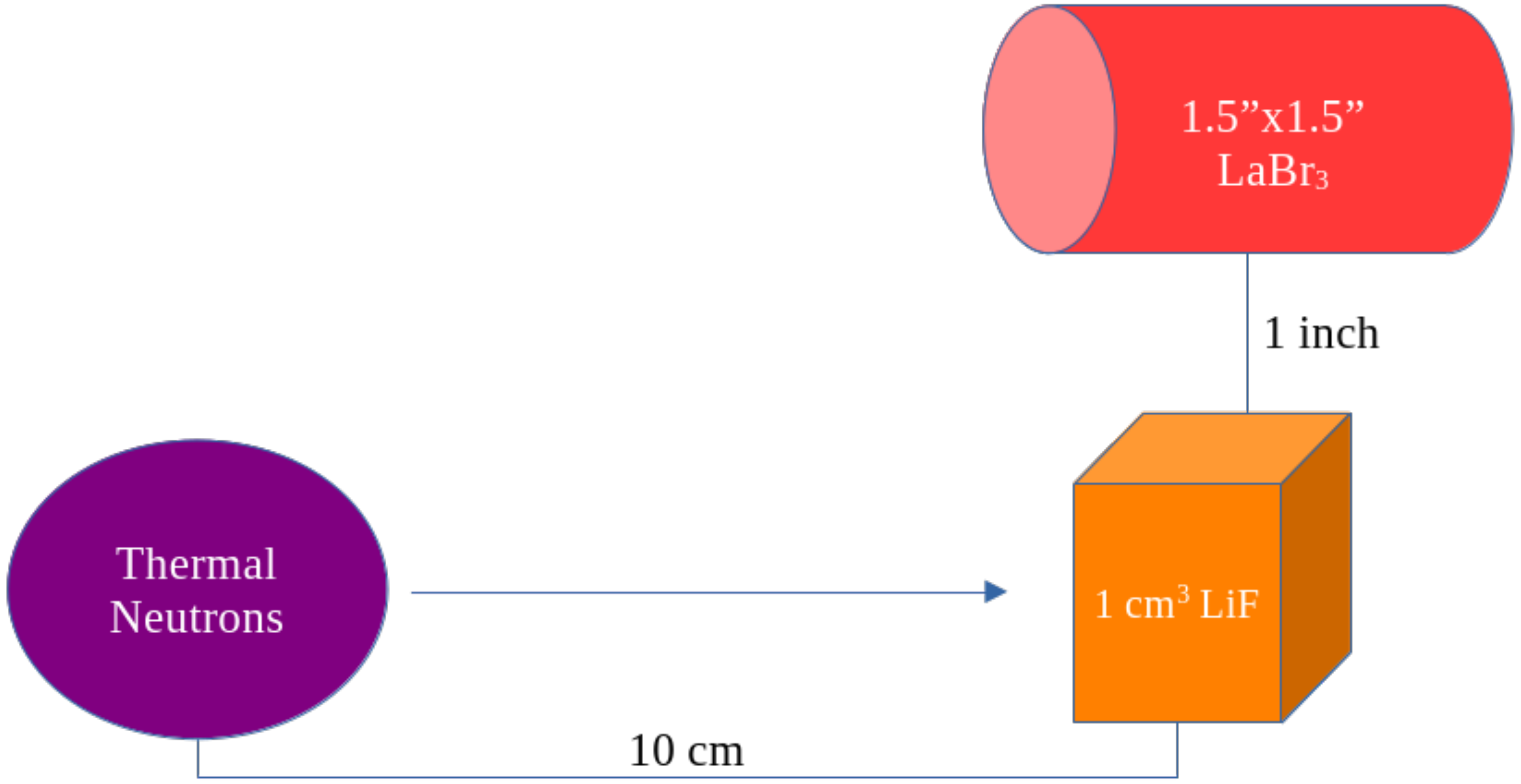
^{19}F(n,g) 0.00951 b



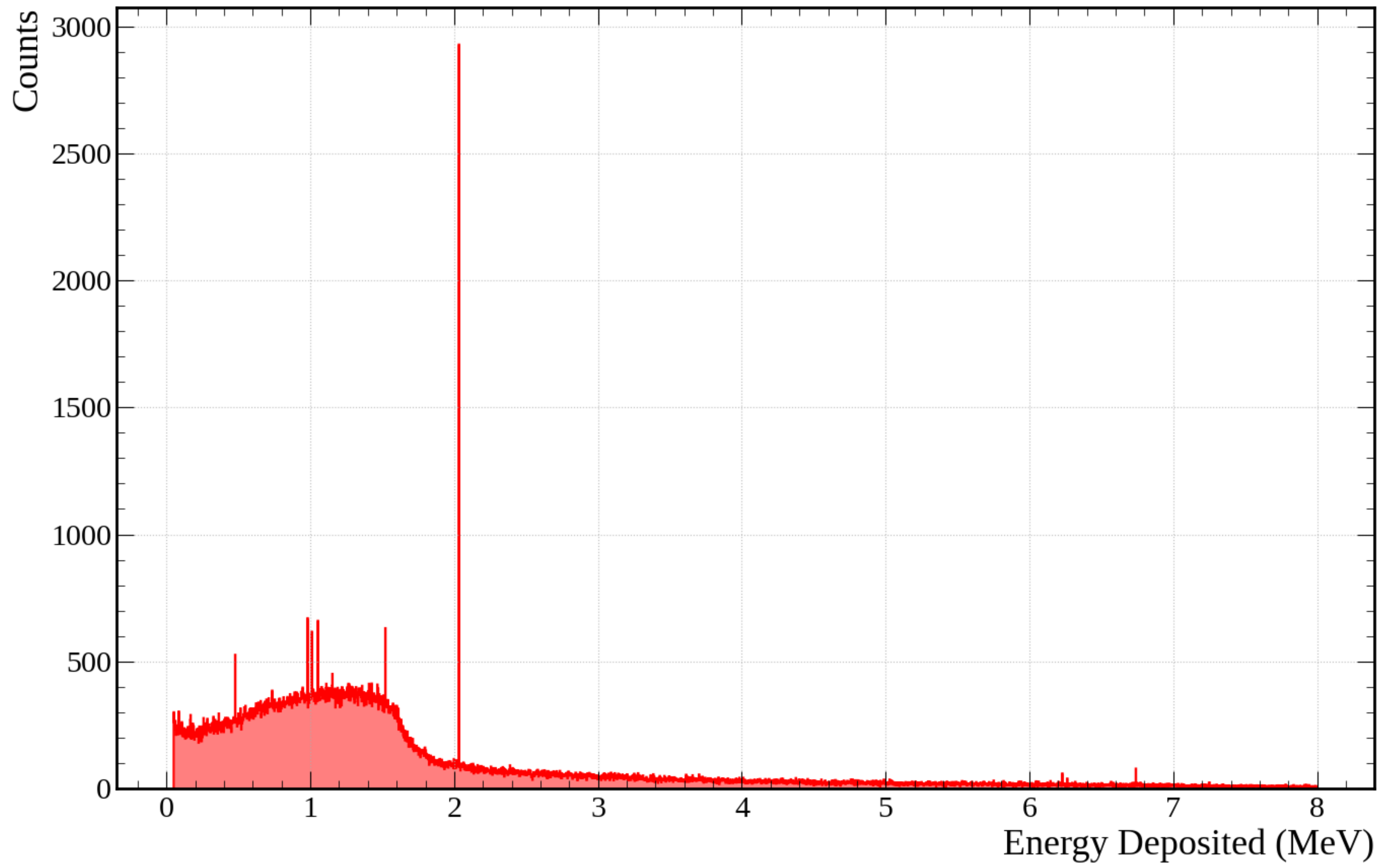
0.58 MeV (3.6%)
0.656 MeV (1.98%)
2.0 MeV (0.047%)

Likely easiest to capture-tag: decent cross-section, abundance, and emission probabilities

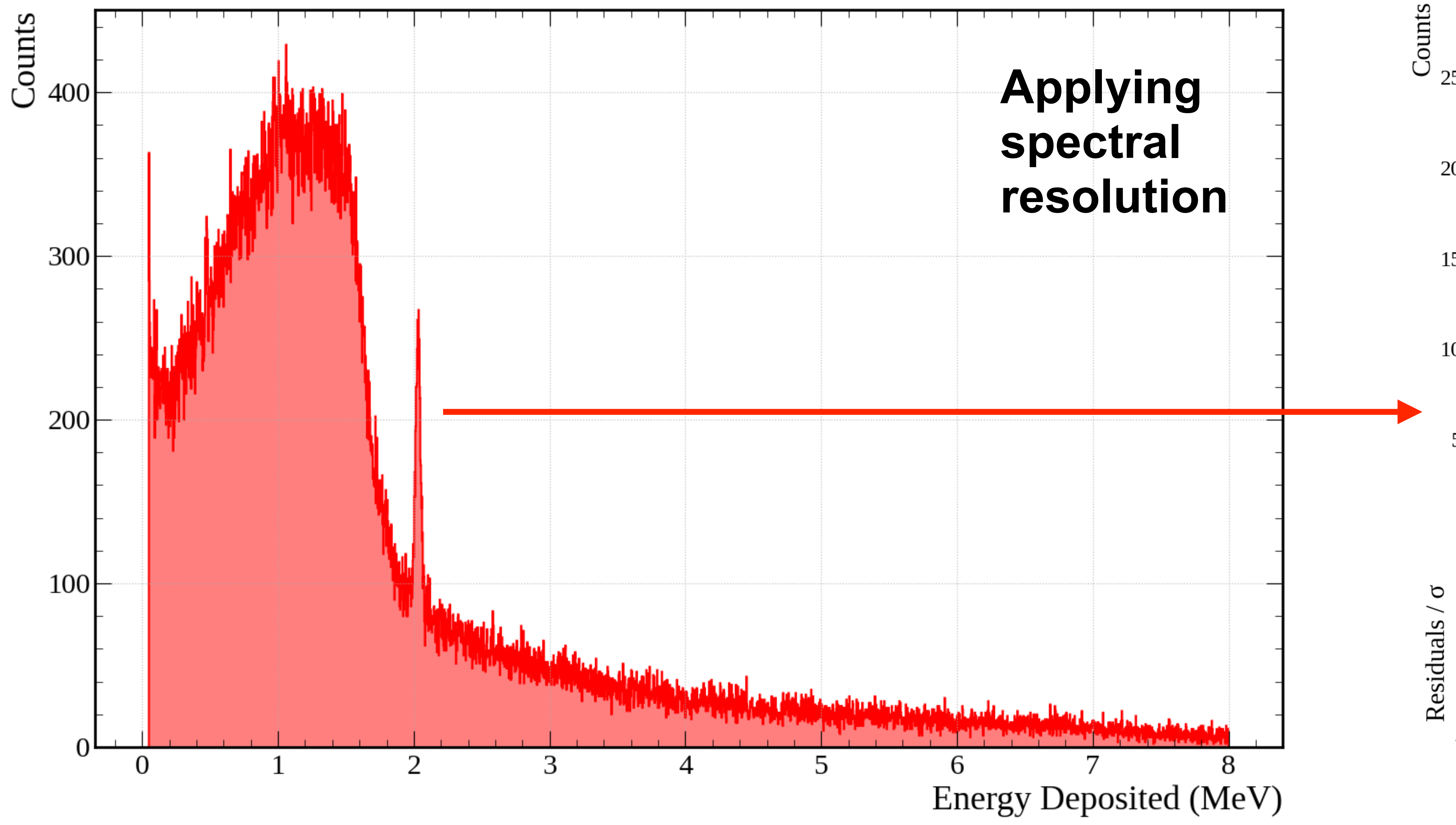
CRAB in LiF: initial simulations

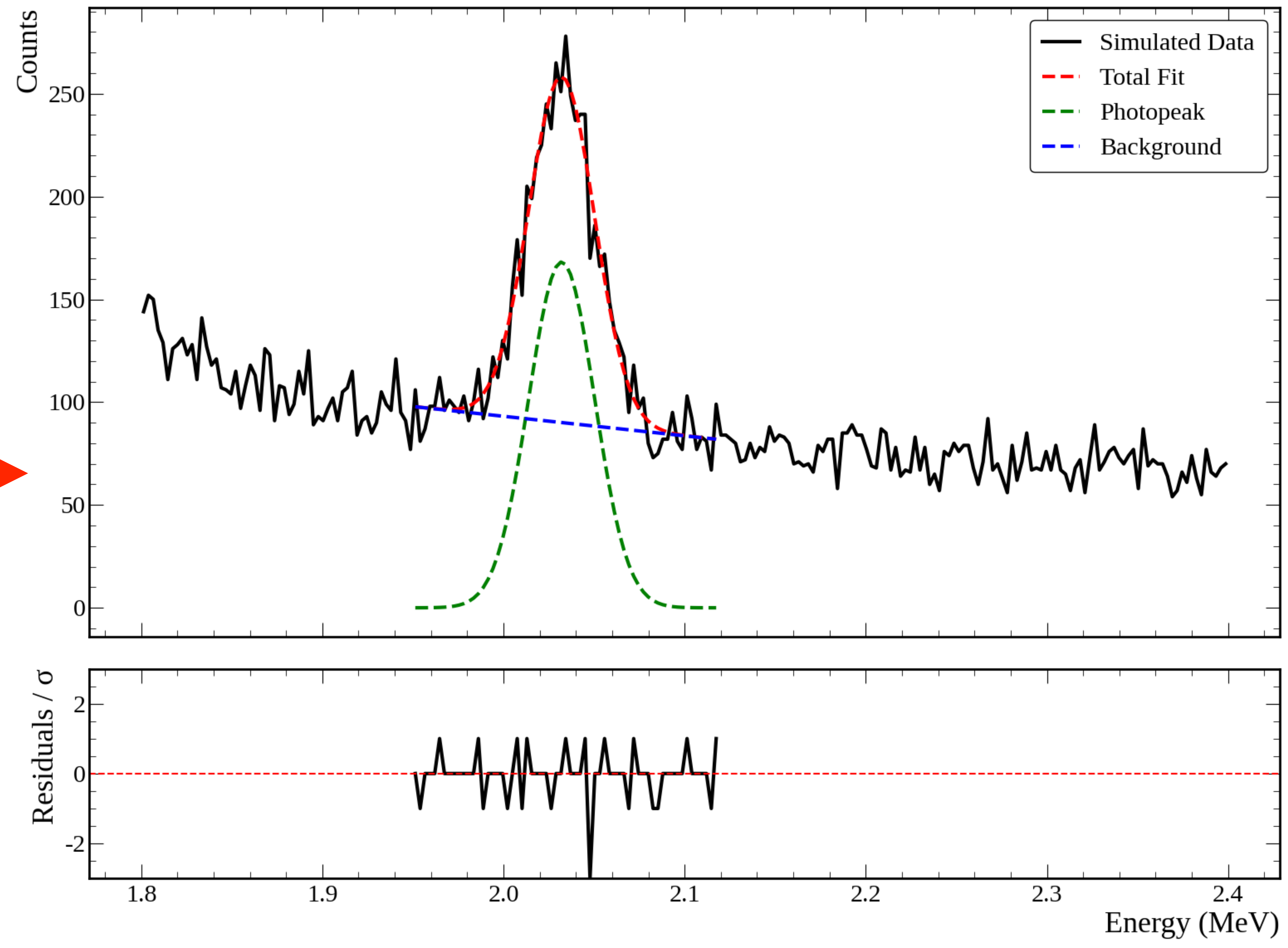


Deposited energy in $LaBr_3$



CRAB in LiF: initial simulations

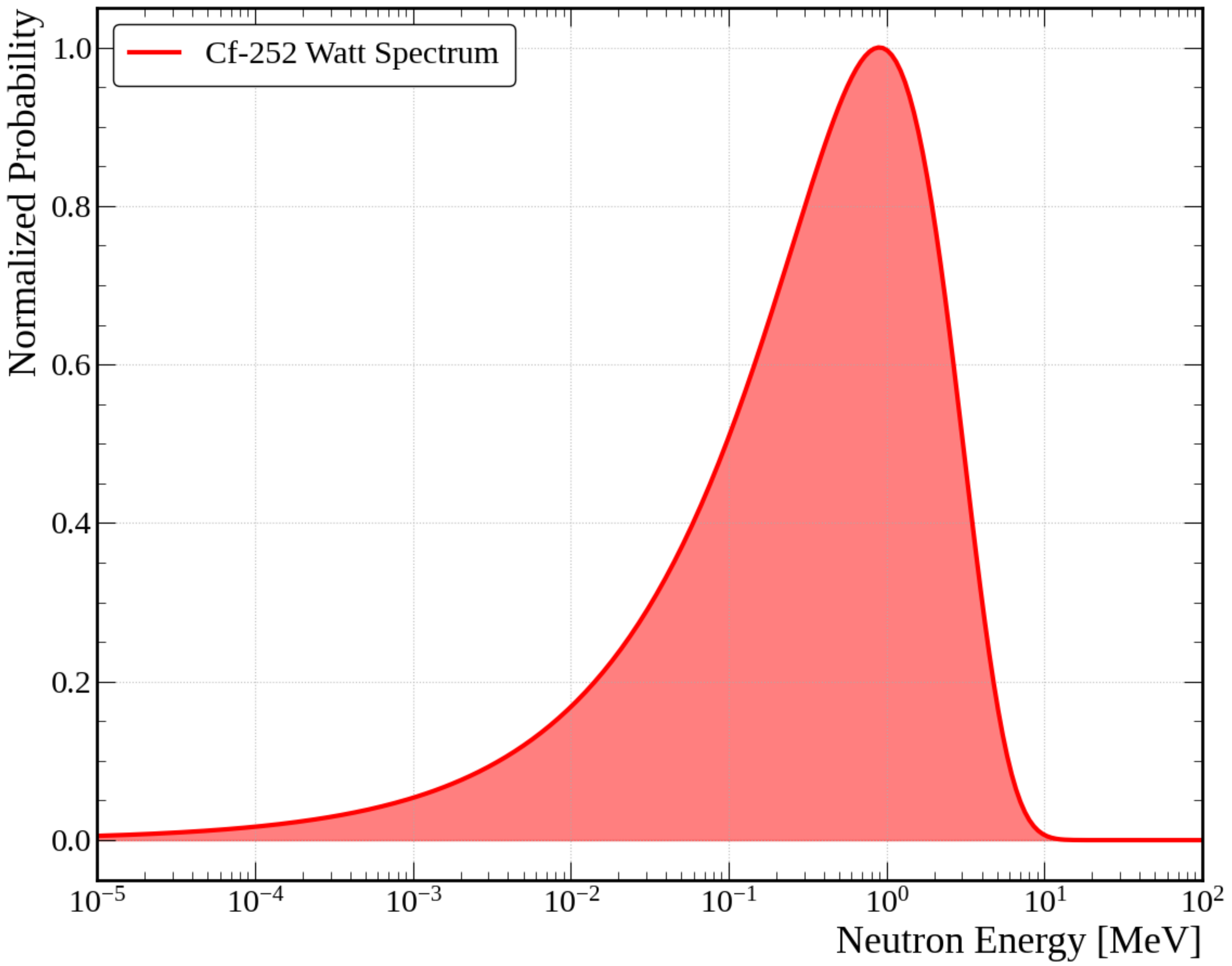


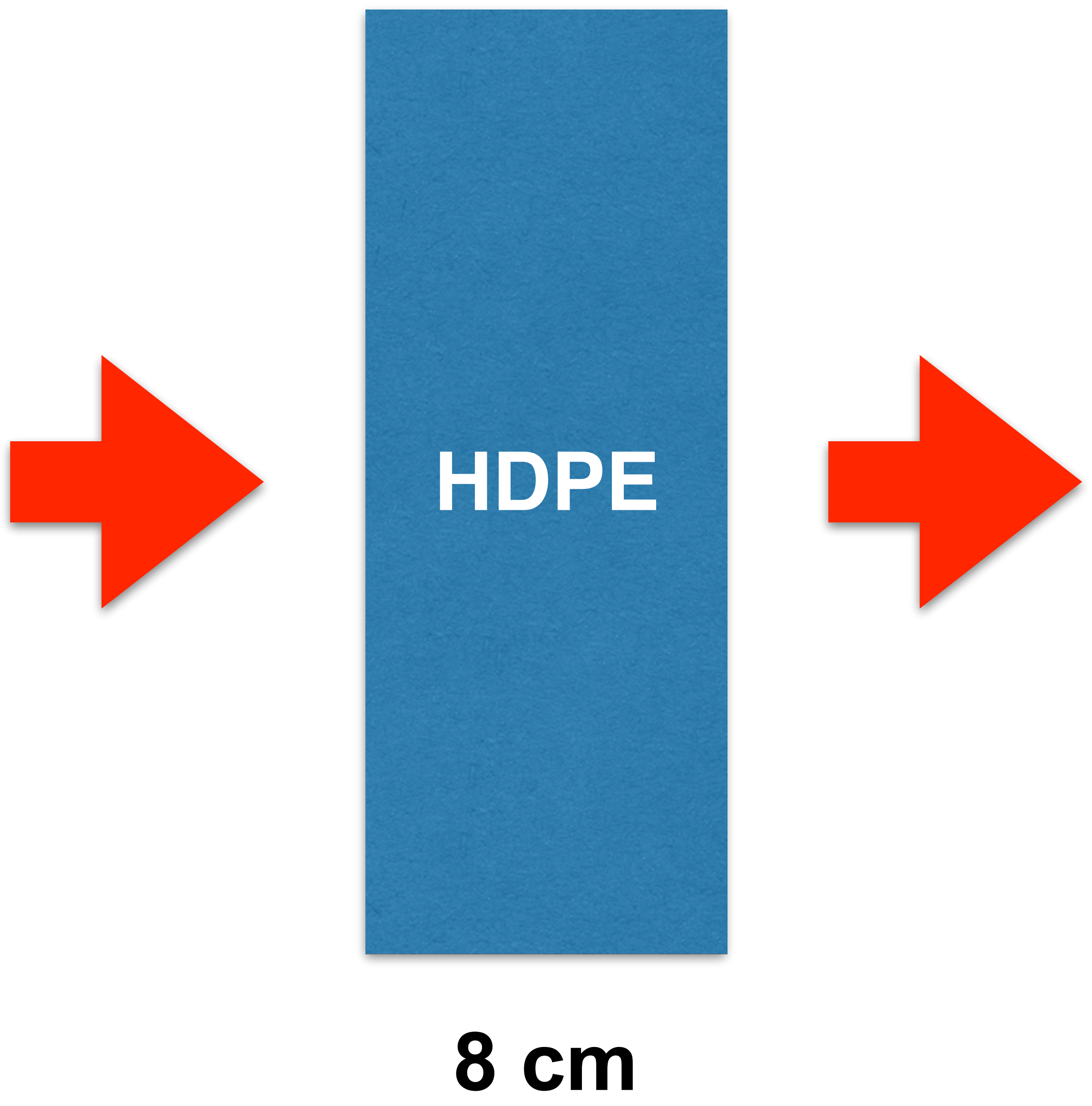


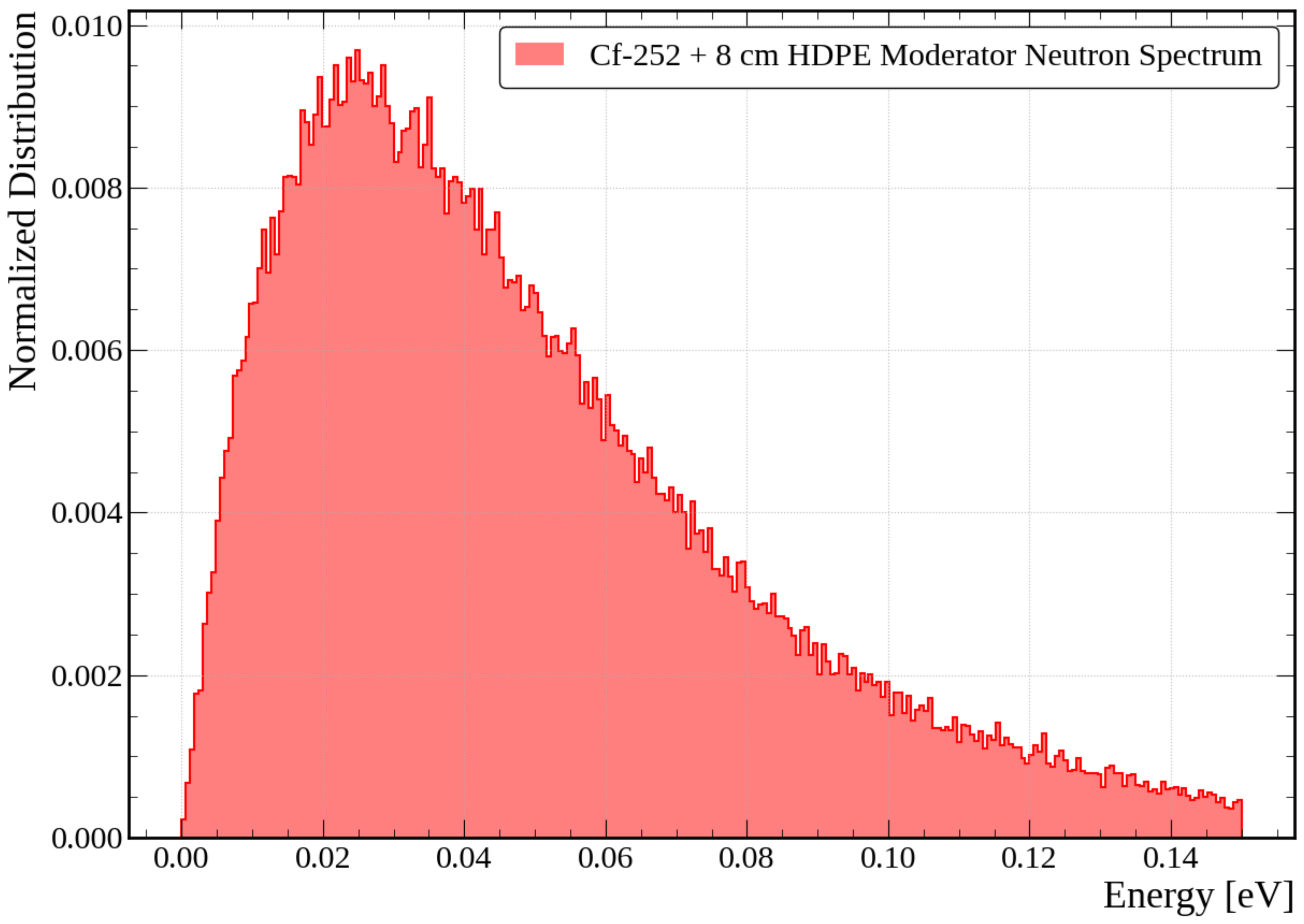
Hypothetical OSU reactor experiment
10^7 n/s in 32 mm diameter beam
10^6 n/s incident onto 1 cm^3 LiF

~3 counts/s in 2 MeV peak in $LaBr_3$

CRAB with fast neutron source moderated by HDPE



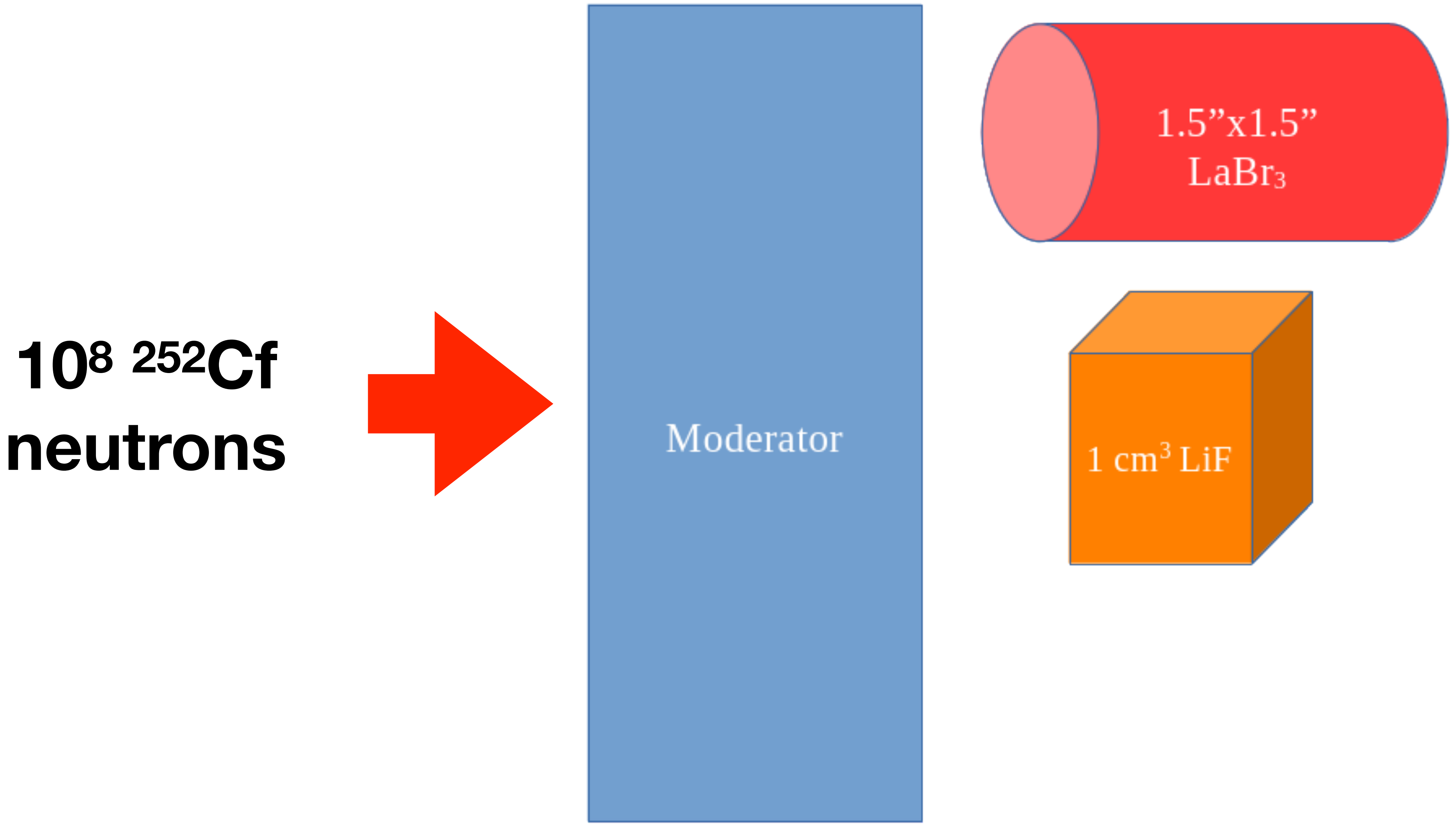


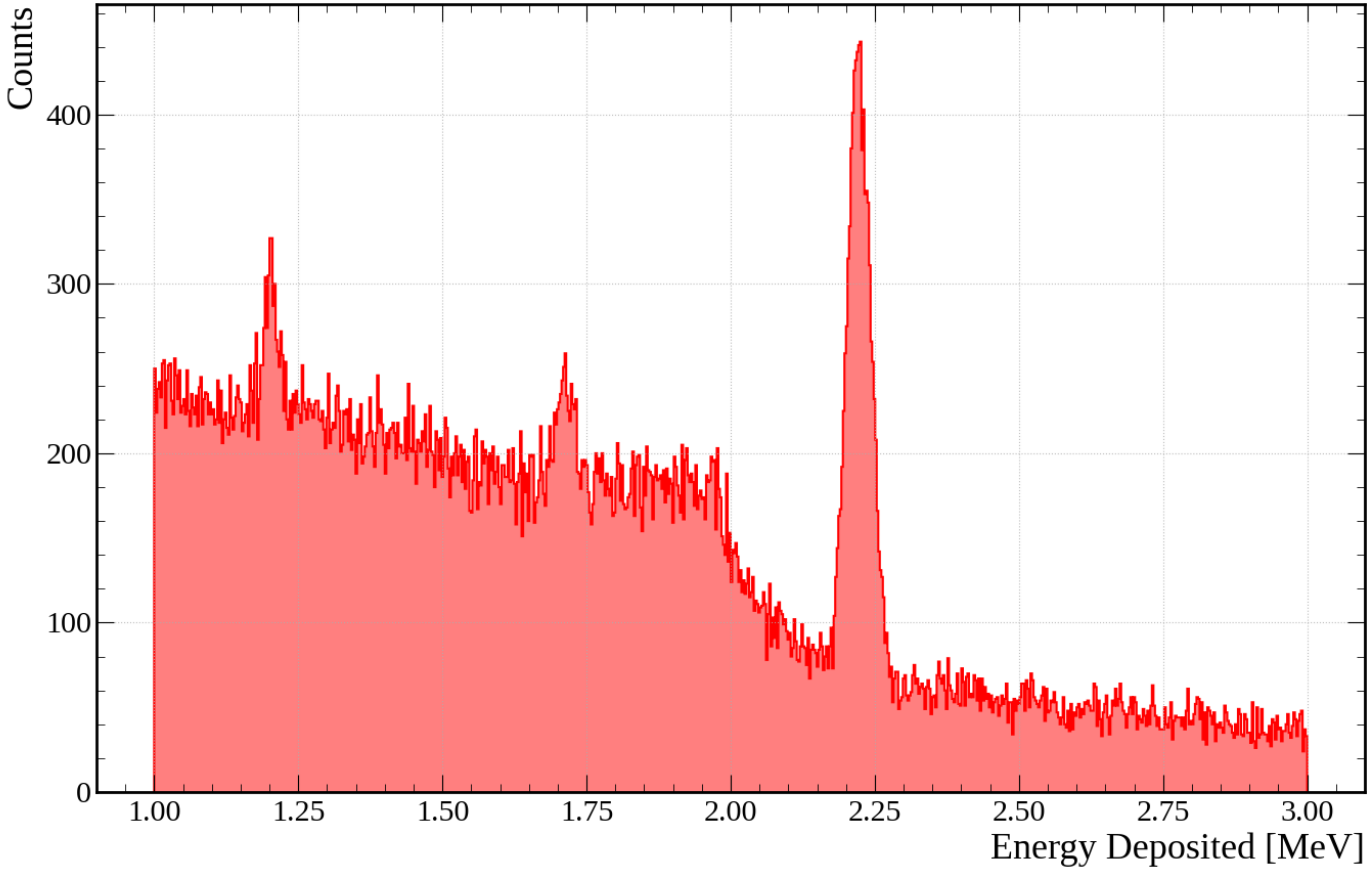


Moderated neutron source

Efficiency is much worse in the presence of a moderator due to increased background: 2.2 MeV gamma from hydrogen, 4.4 MeV gamma from carbon.

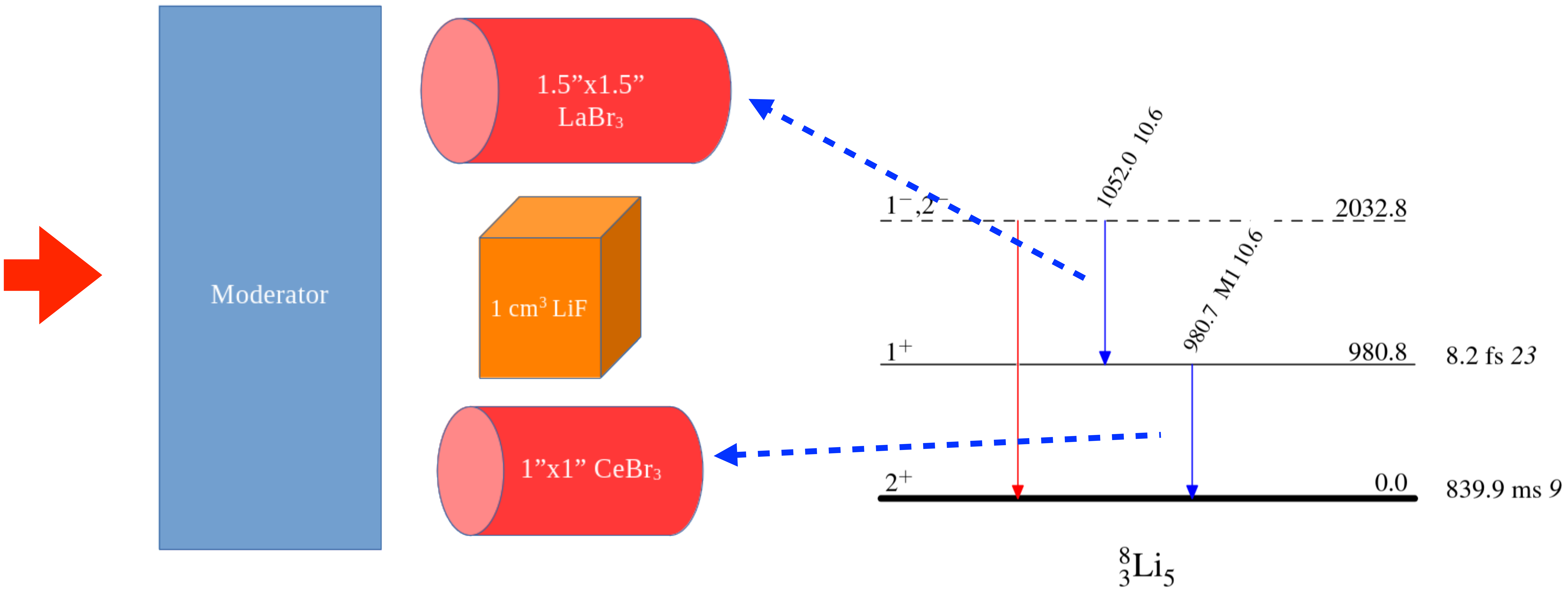
Need a better shielding configuration.



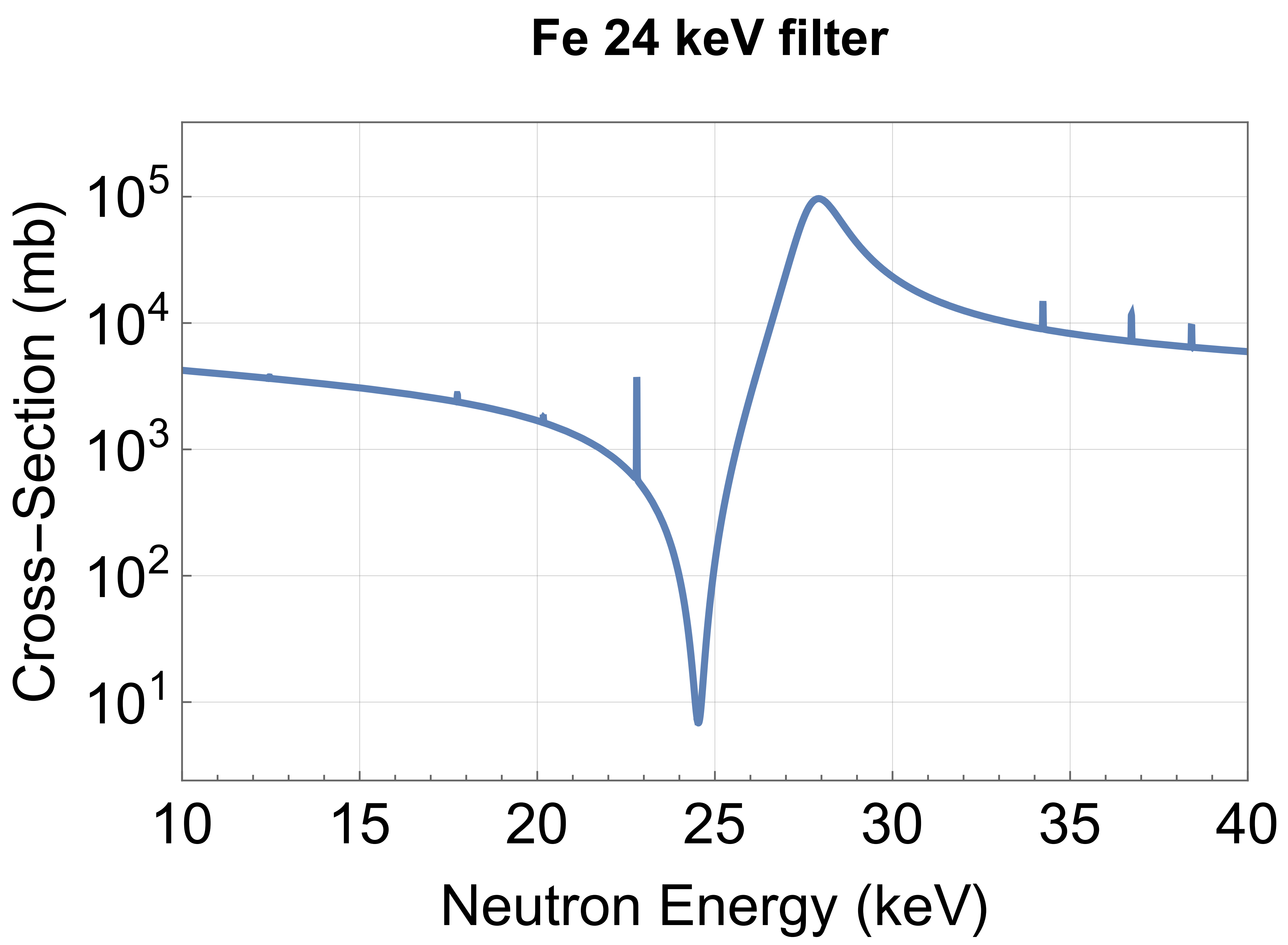


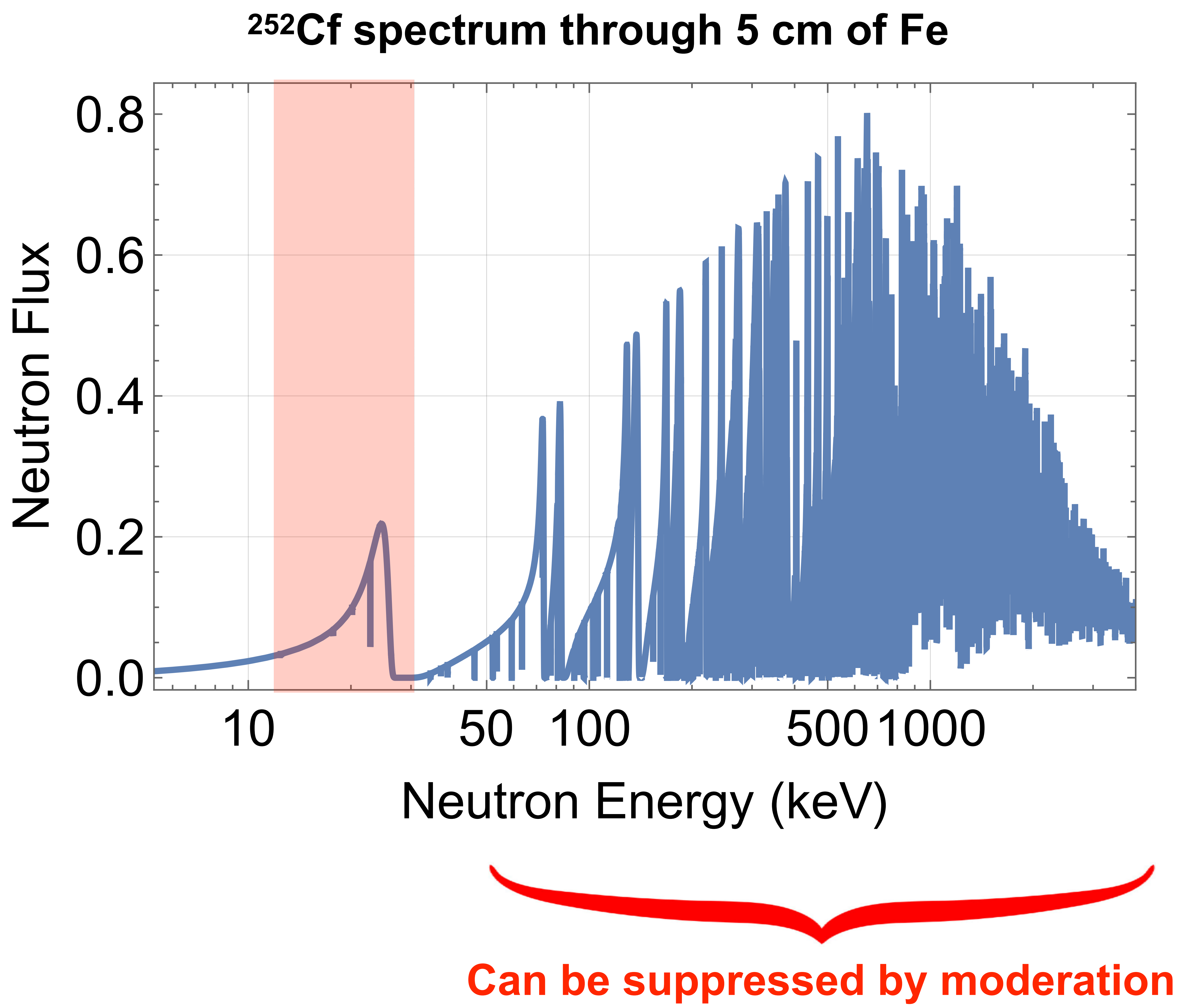
Coincidence tagging may reduce the background

^{252}Cf neutrons

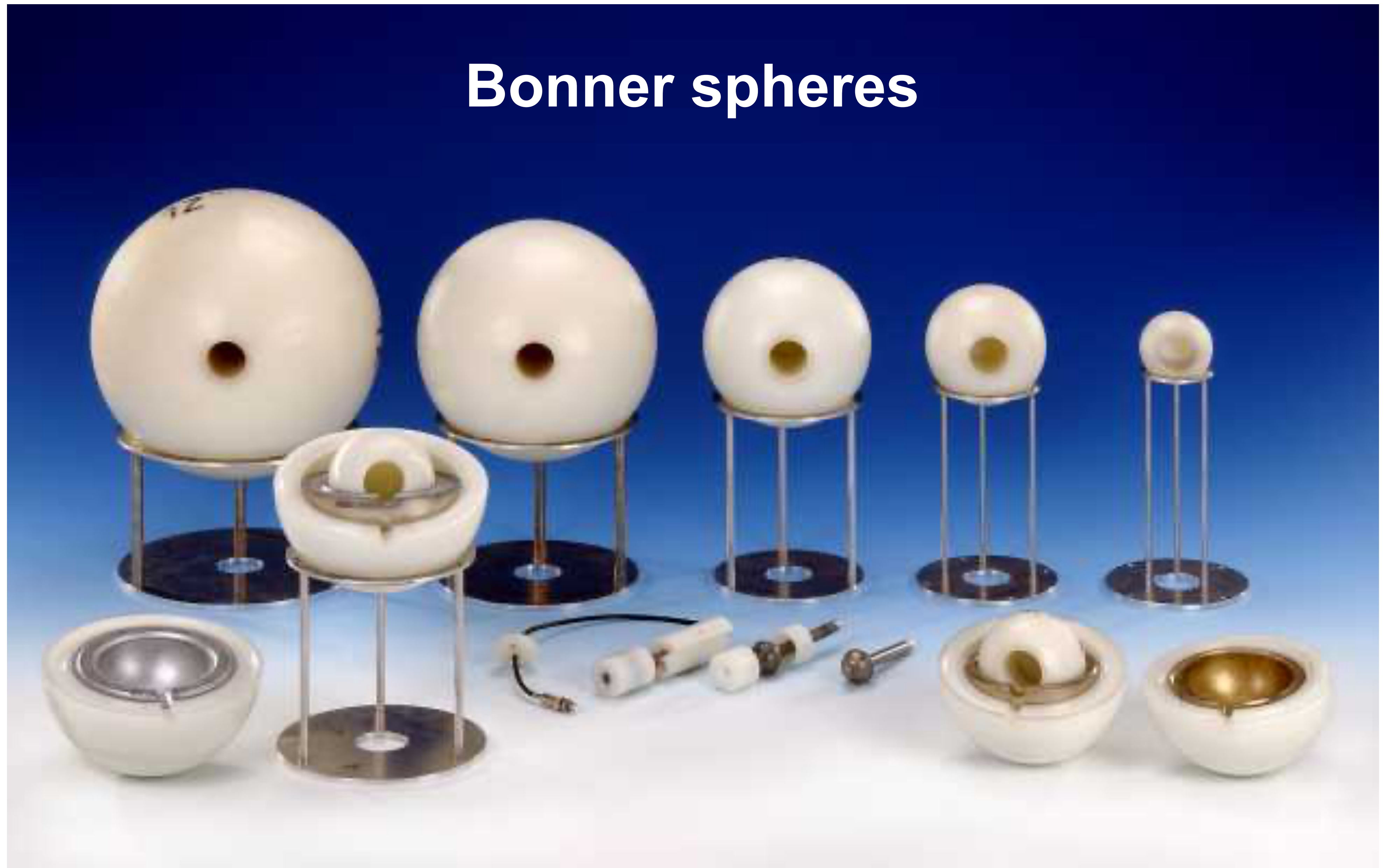


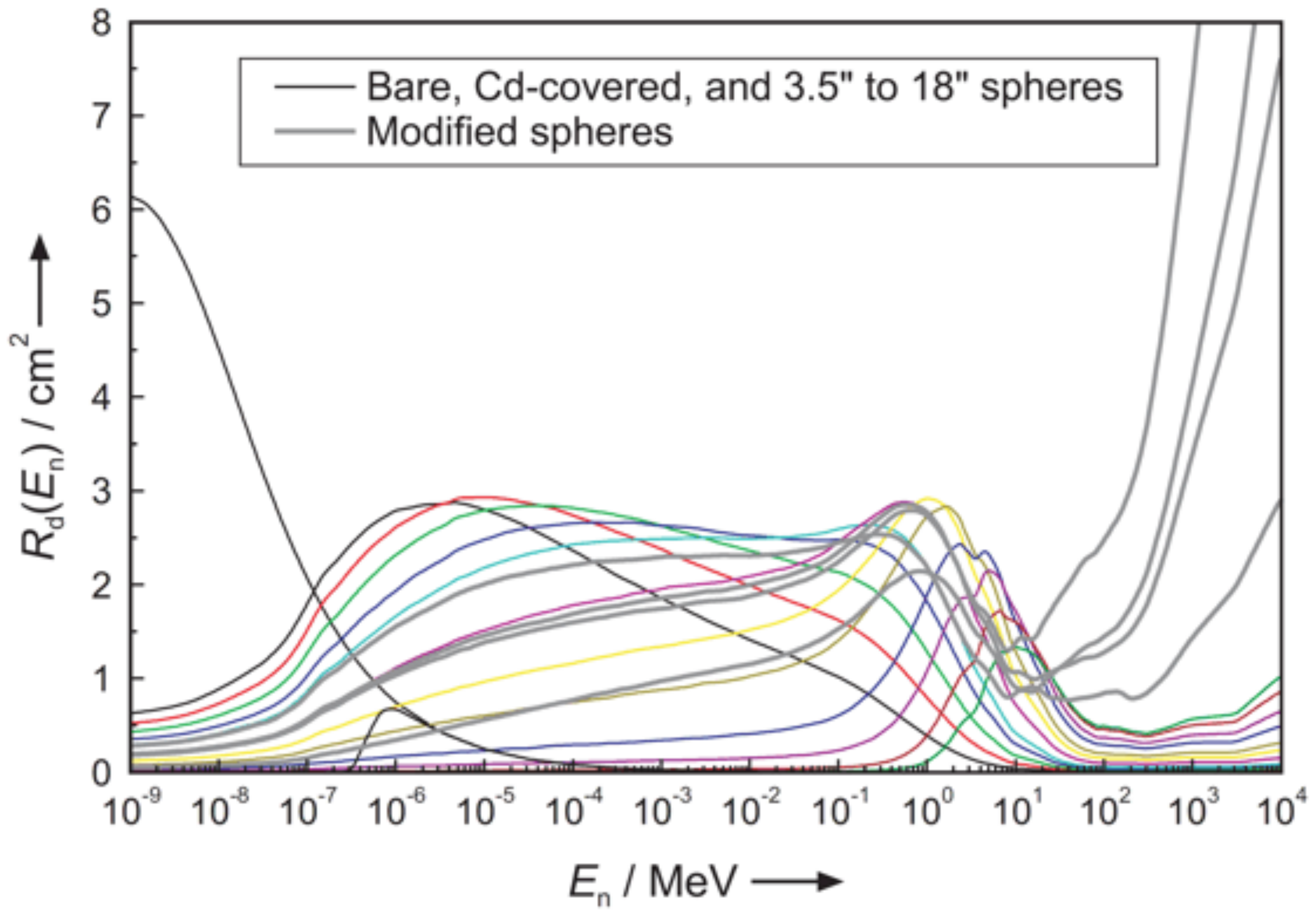
Filtering neutron spectrum





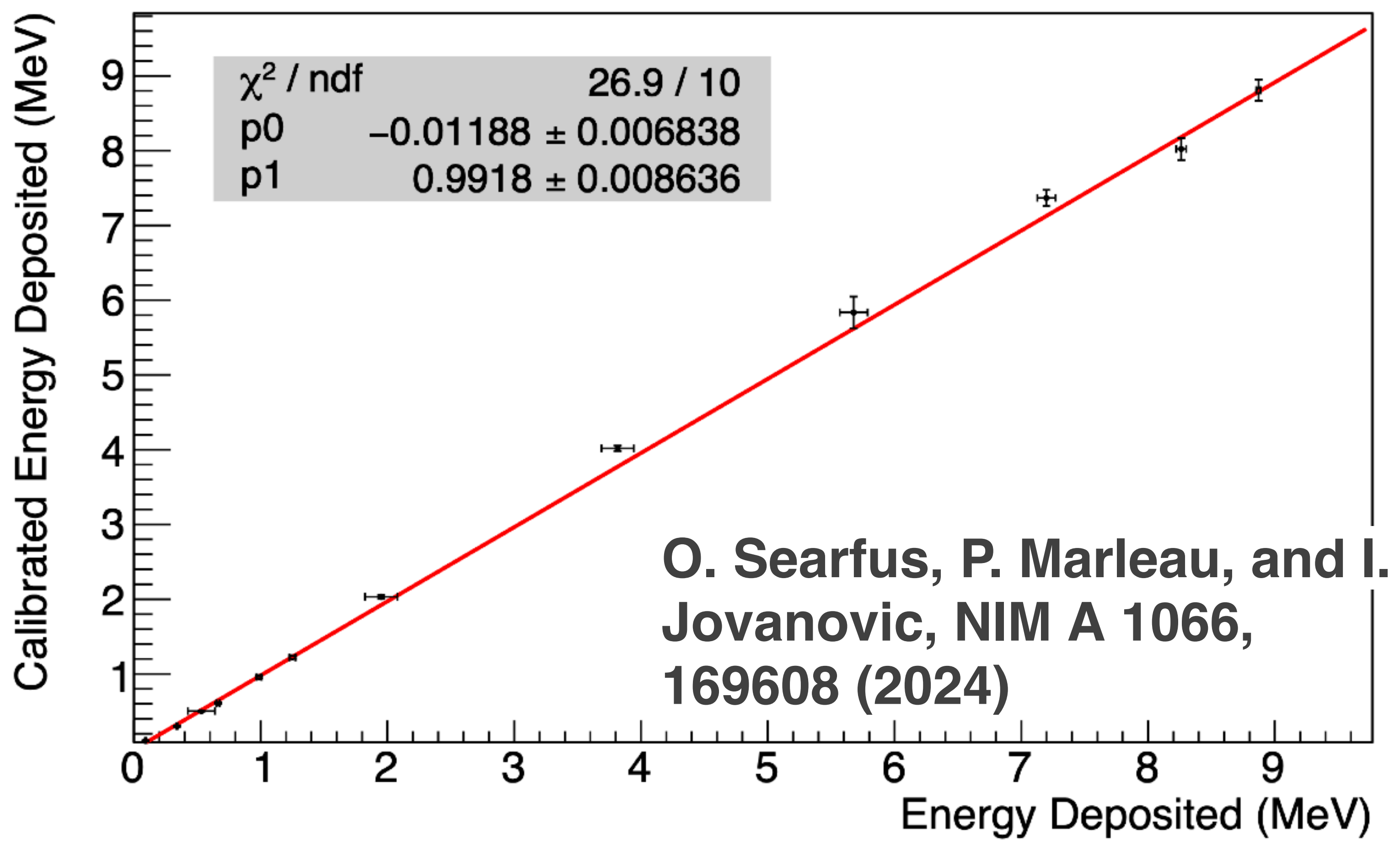
Measuring neutron spectra

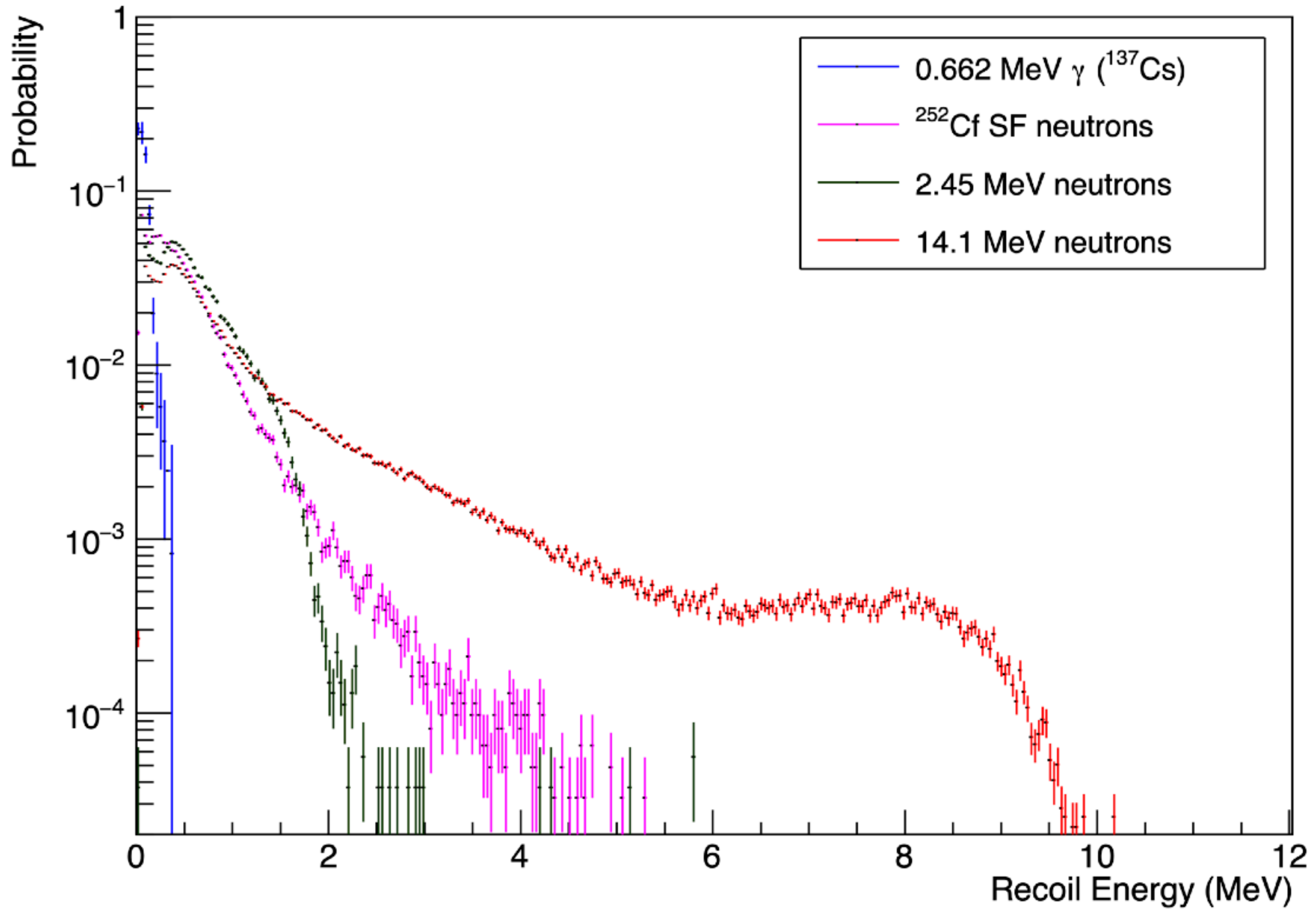


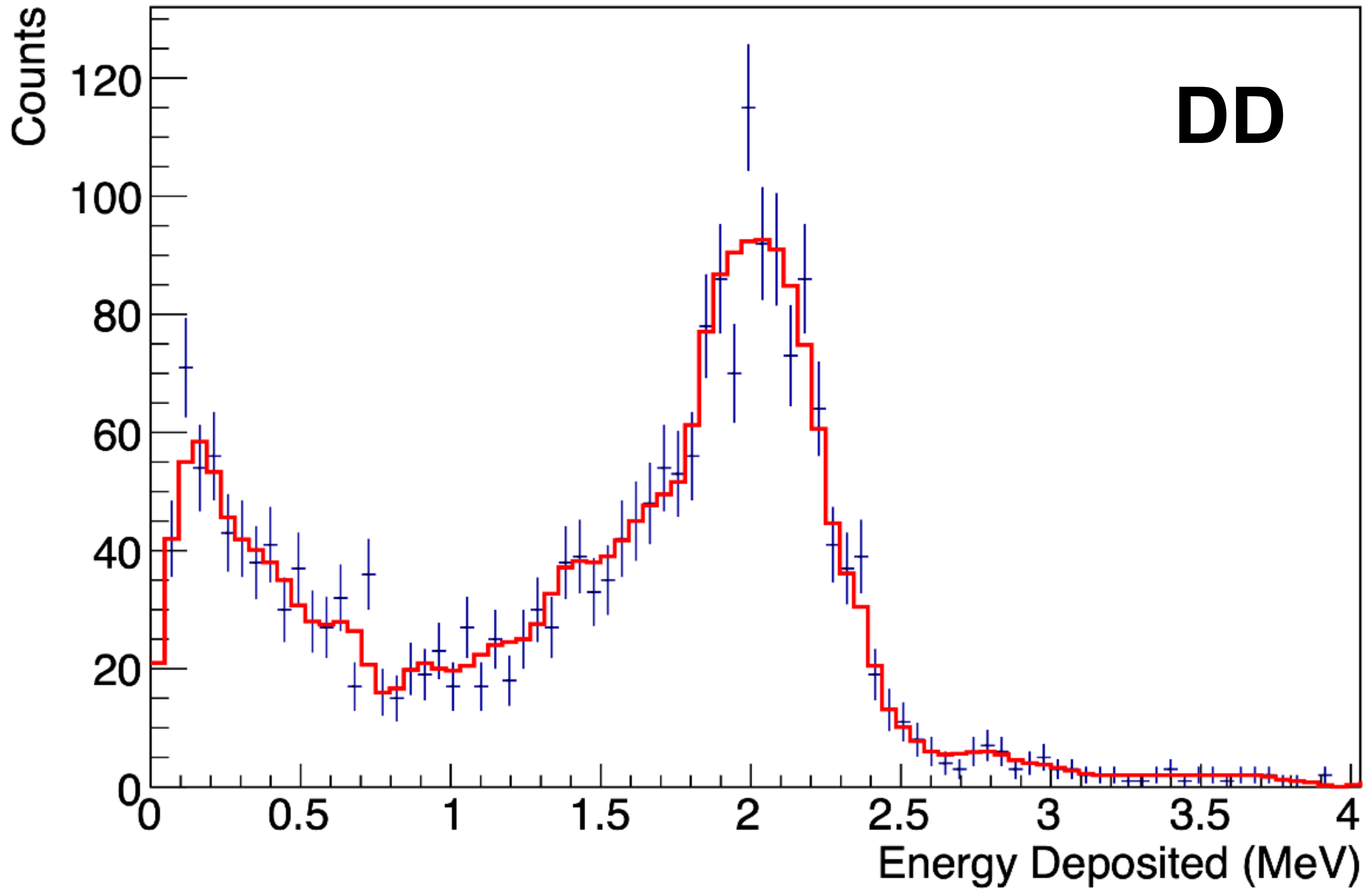


Inverse problem

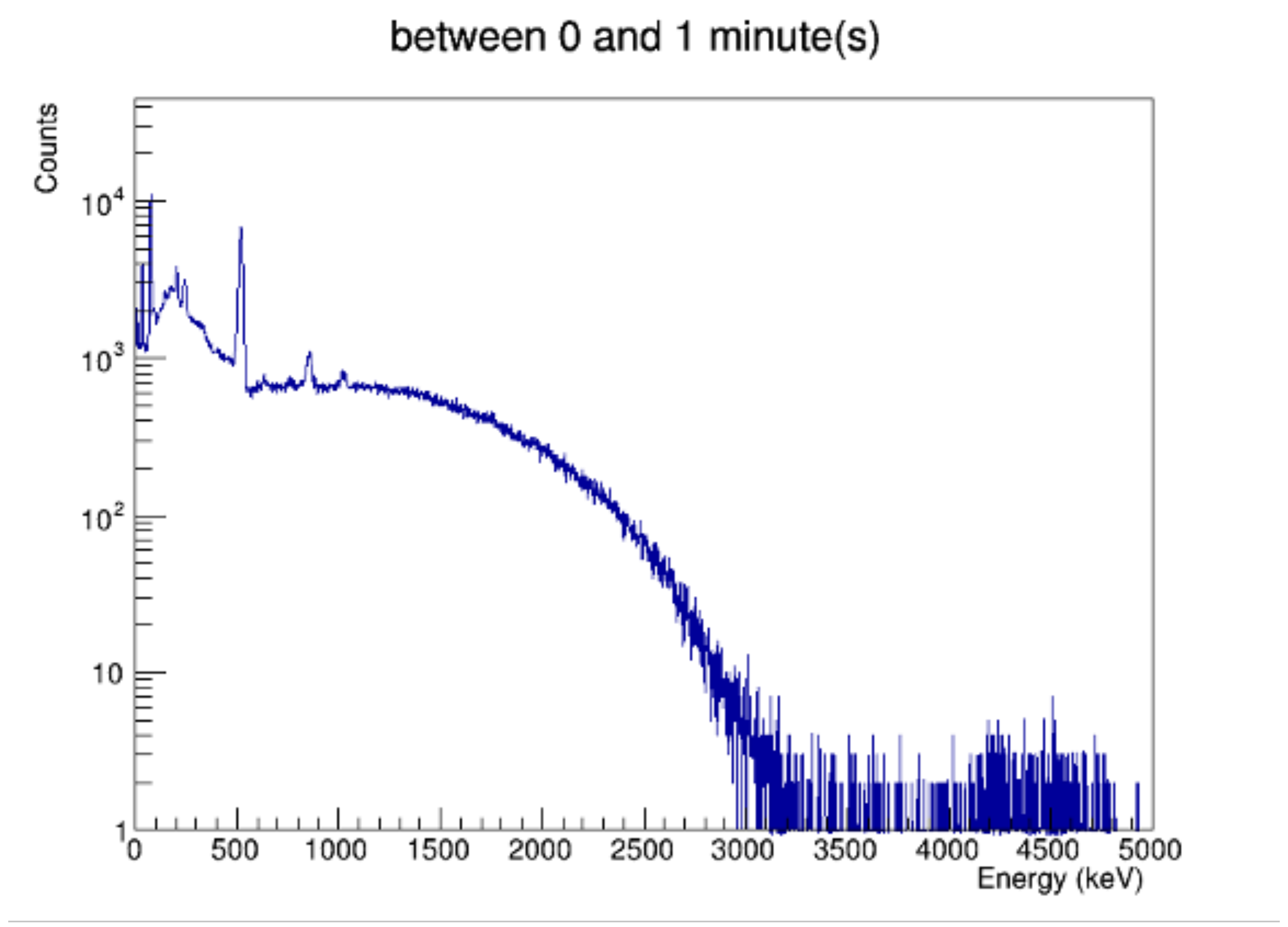
^{4}He
Arktis S670

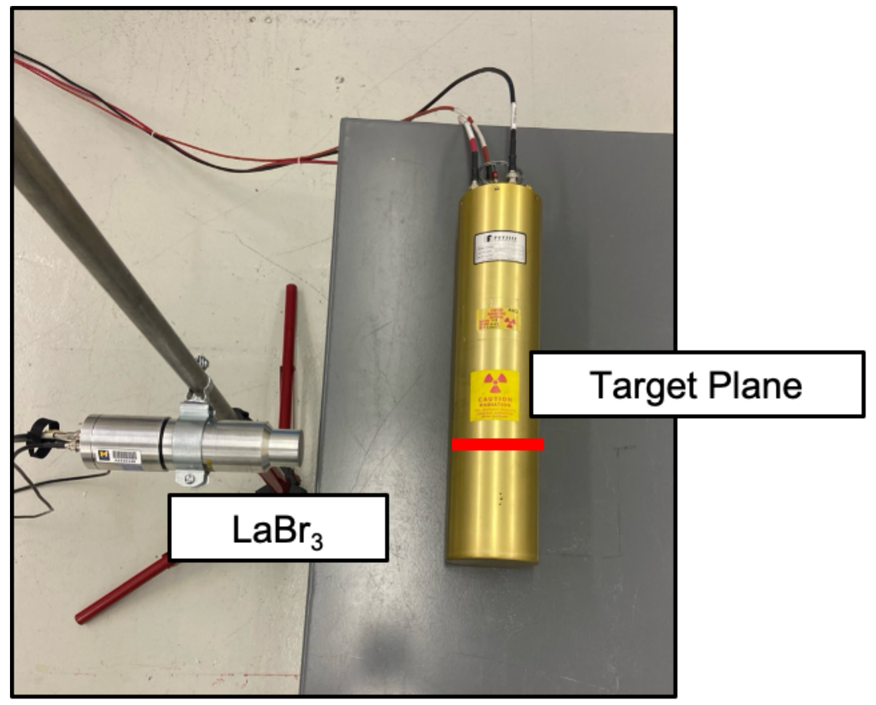


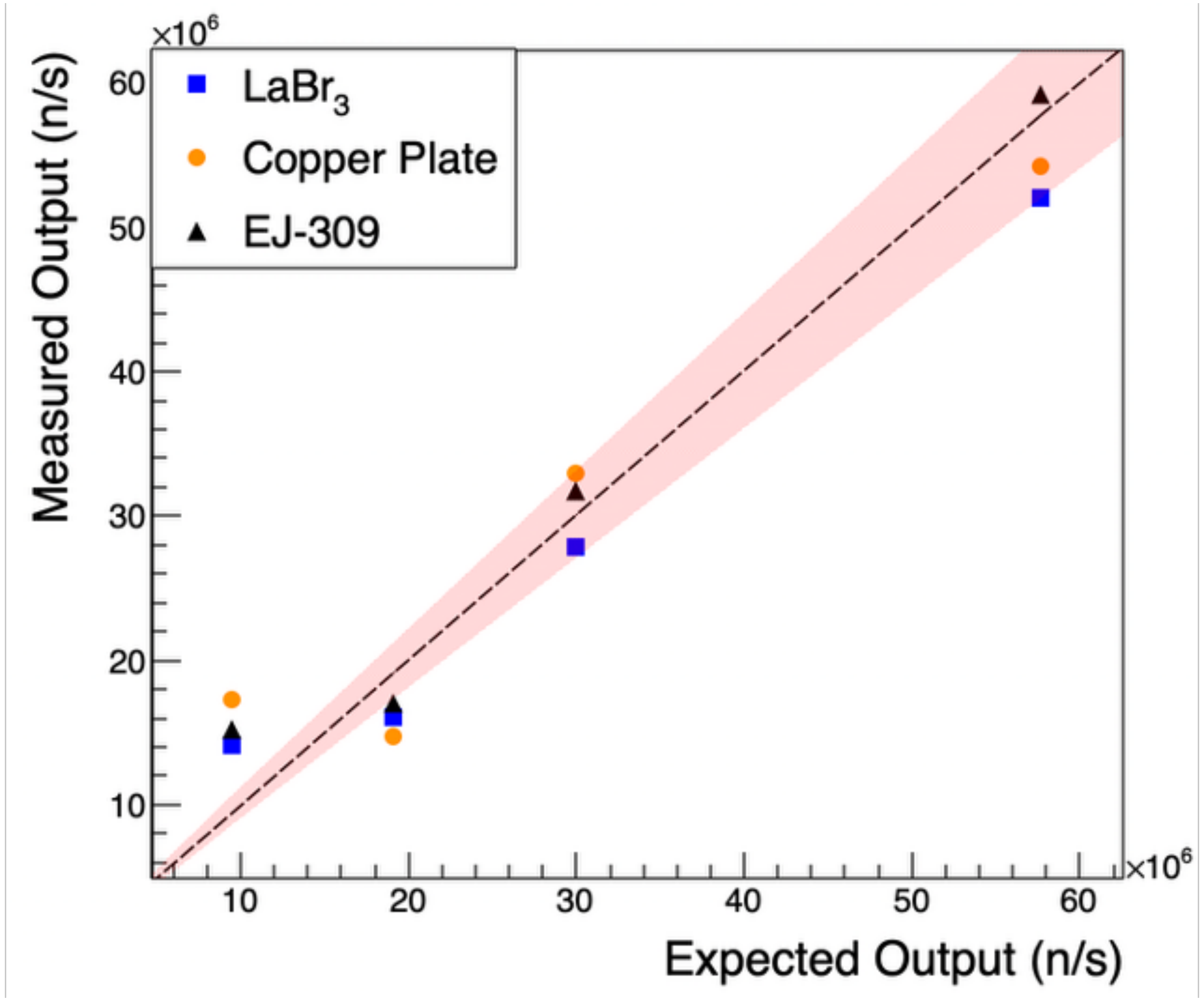




Measuring neutron flux: nuclear recoil, activation, and self-activation







Fast Reactions	Q (MeV)	Cross Section (b)	Half-life
^{79}Br(n,2n)^{78}Br	-10.6	0.9	6.5 min
^{81}Br(n,2n)^{80}Br	-10.1	1.02	17.7 min
^{81}Br(n,p)^{81}Se	-0.8	0.02	18.5 min
^{139}La(n,p)^{139}Ba	-1.5	0.003	83.0 min

Summary

- Preparation of surrogate samples is an important step for understanding DM and neutrino signals and backgrounds in mineral detection
- Nuclear recoils induced by fast neutrons and radiative neutron capture provide useful energy and efficiency scales, and are the closest analogue to bulk interactions of DM and neutrinos
- We can provide well-characterized neutron irradiations with a wide range of sources to collaborators (PALEOCCENE and others), anchored to detailed simulations
- Irradiation with concurrent heating may yield better understanding of real-world conditions for real mineral samples

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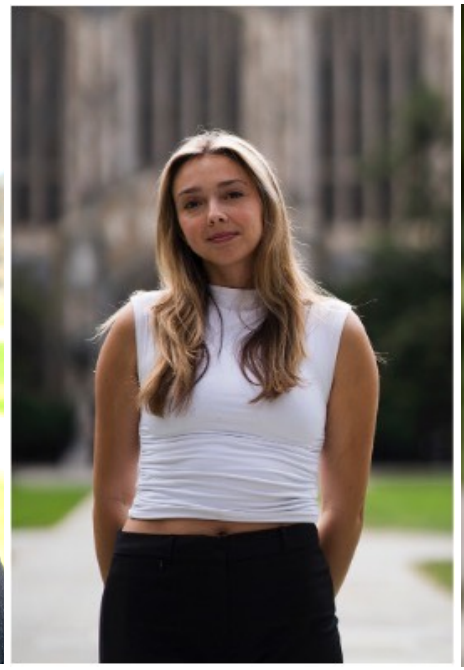
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