Development of a cryogenic neutron monitor and Dark Matter search with a Lithium-based target

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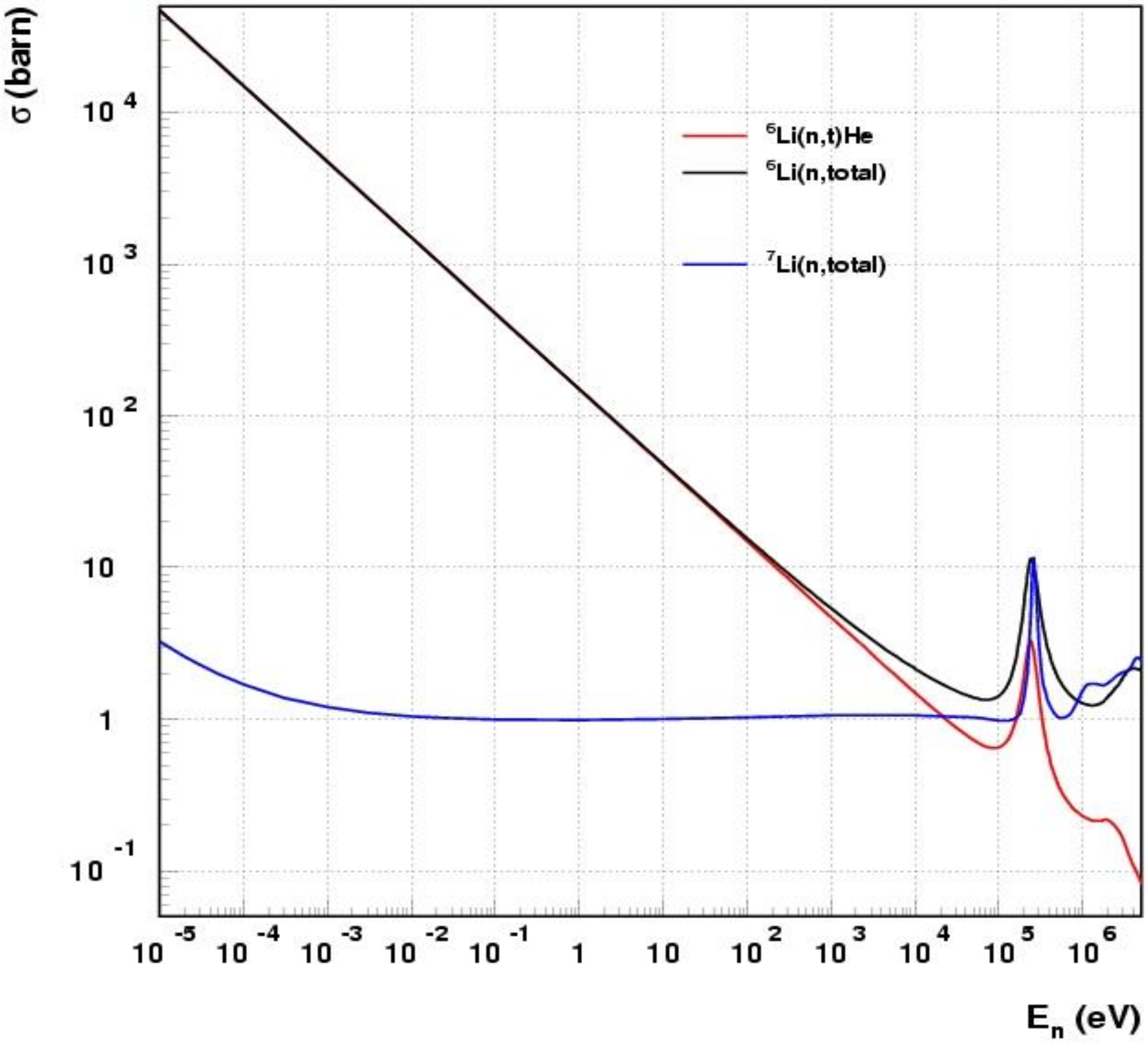
Why detecting neutrons?

- Dangerous background for direct dark matter search experiments (like CRESST). Neutrons cause Nuclear Recoils, as expected from dark matter particles

- Measuring the neutron spectrum inside the experimental setup would give us useful information for the development of a Background Model (input for Monte Carlo simulations)

How to detect neutrons?



- Crystals containing Lithium as a target, to take advantage of neutron capture:

^{6}Li(n, α)

$$^{6}\text{Li} + \text{n} \longrightarrow {}^{3}\text{H} + \alpha \qquad 4.78\ \text{MeV}$$

$$E_{3H} = 2.73\ \text{MeV},\ E_{\alpha} = 2.05\ \text{MeV}$$

- Detect phonons (heat) and photons (light) to achieve particle discrimination, operating the detector at cryogenic temperatures

Which crystal as a target?

One big advantage of CRESST is that we can easily change target inside our experimental setup.

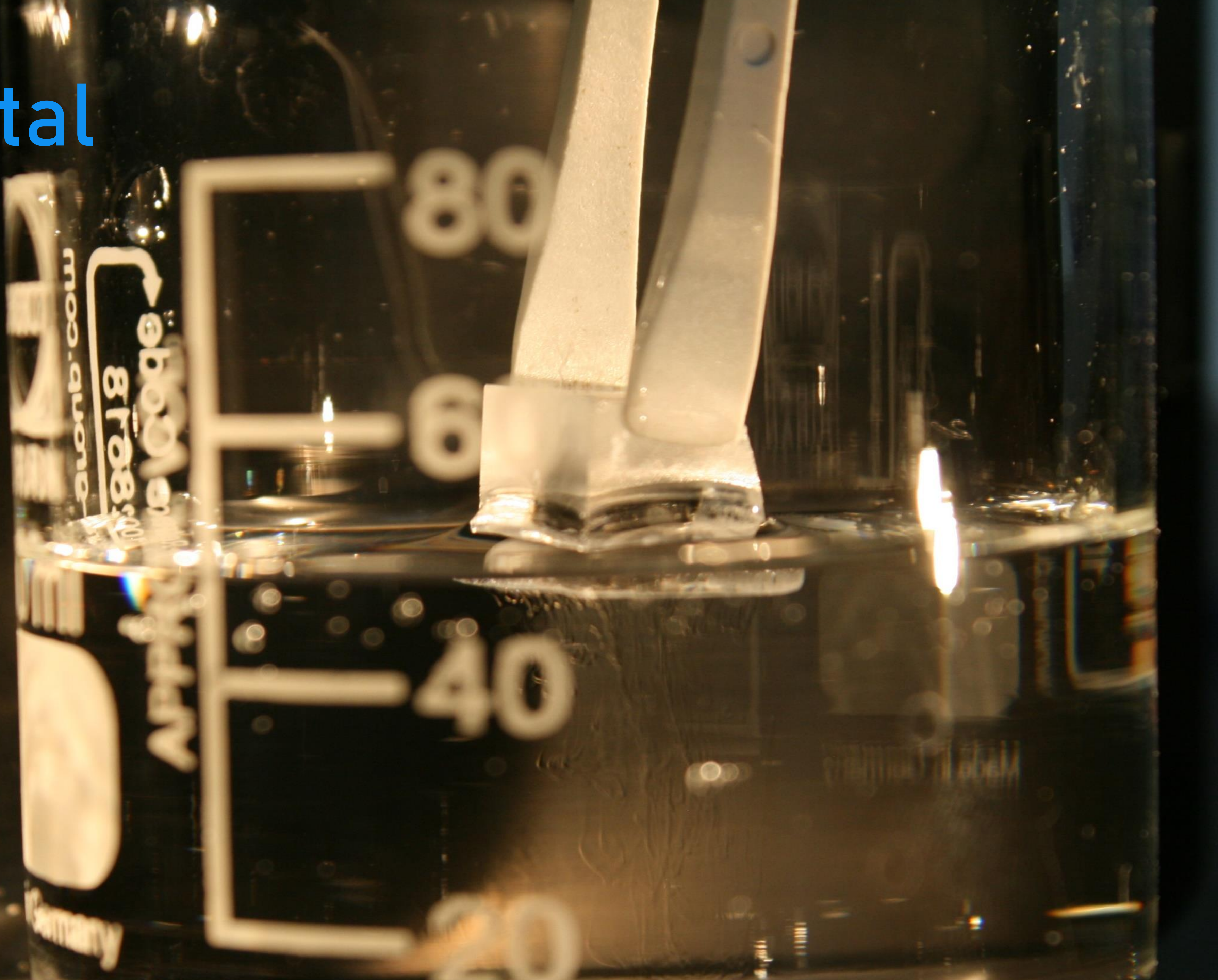
There are multiple crystals containing Lithium to choose from:

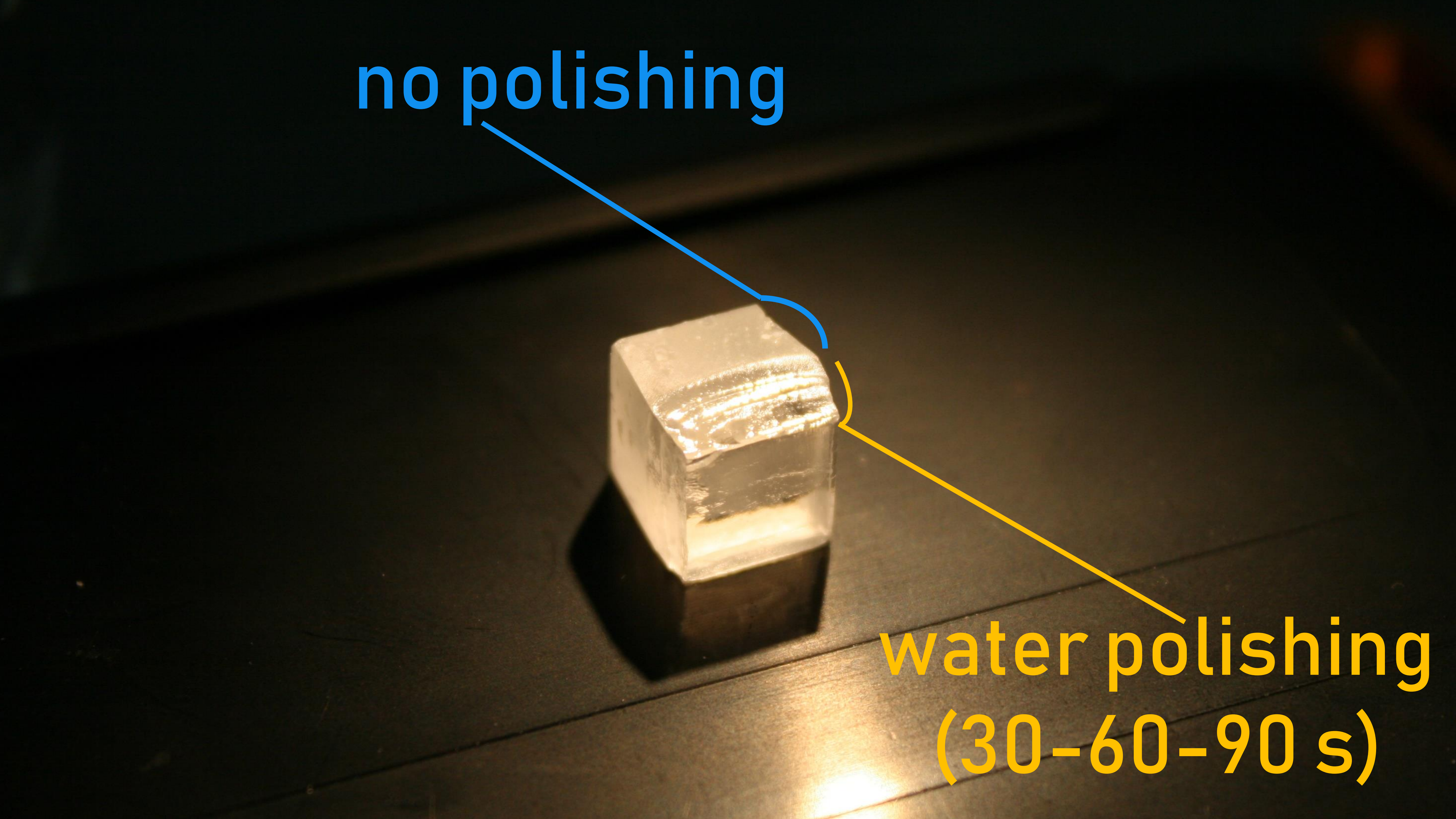
- Lithium Molybdate – Li_2MoO_4 (8.0% - 0.25 g/cm^3 Lithium)
- Lithium Fluoride – LiF (26.8% - 0.64 g/cm^3 Lithium)
- Lithium Aluminate – $LiAlO_2$ (10.5% - 0.27 g/cm^3 Lithium)
- Lithium Tantalate – $LiTaO_3$ (2.9% - 0.22 g/cm^3 Lithium)
- Lithium Niobate – $LiNbO_3$ (4.7% - 0.22 g/cm^3 Lithium)

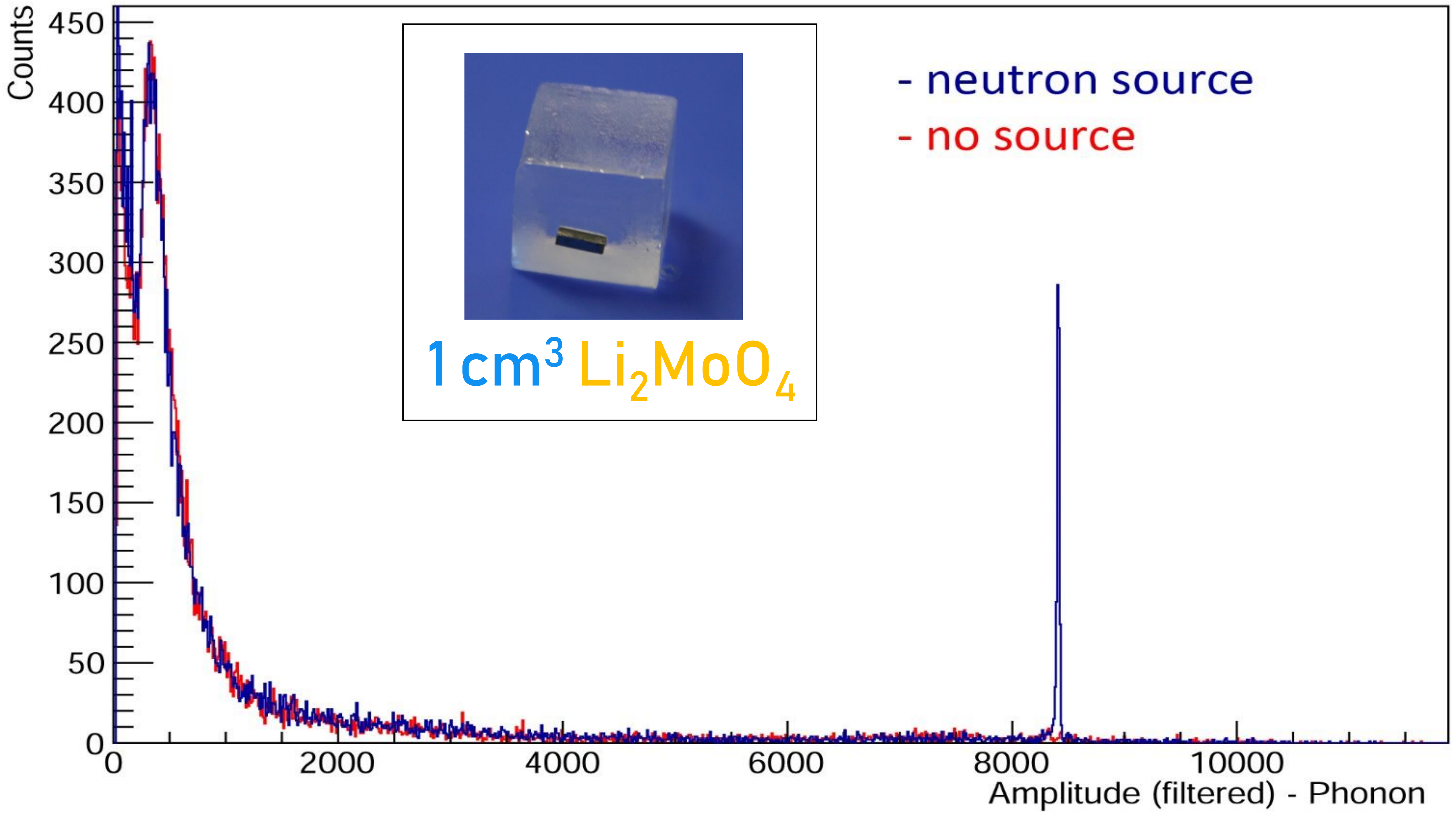
…

Li_2MoO_4 crystal

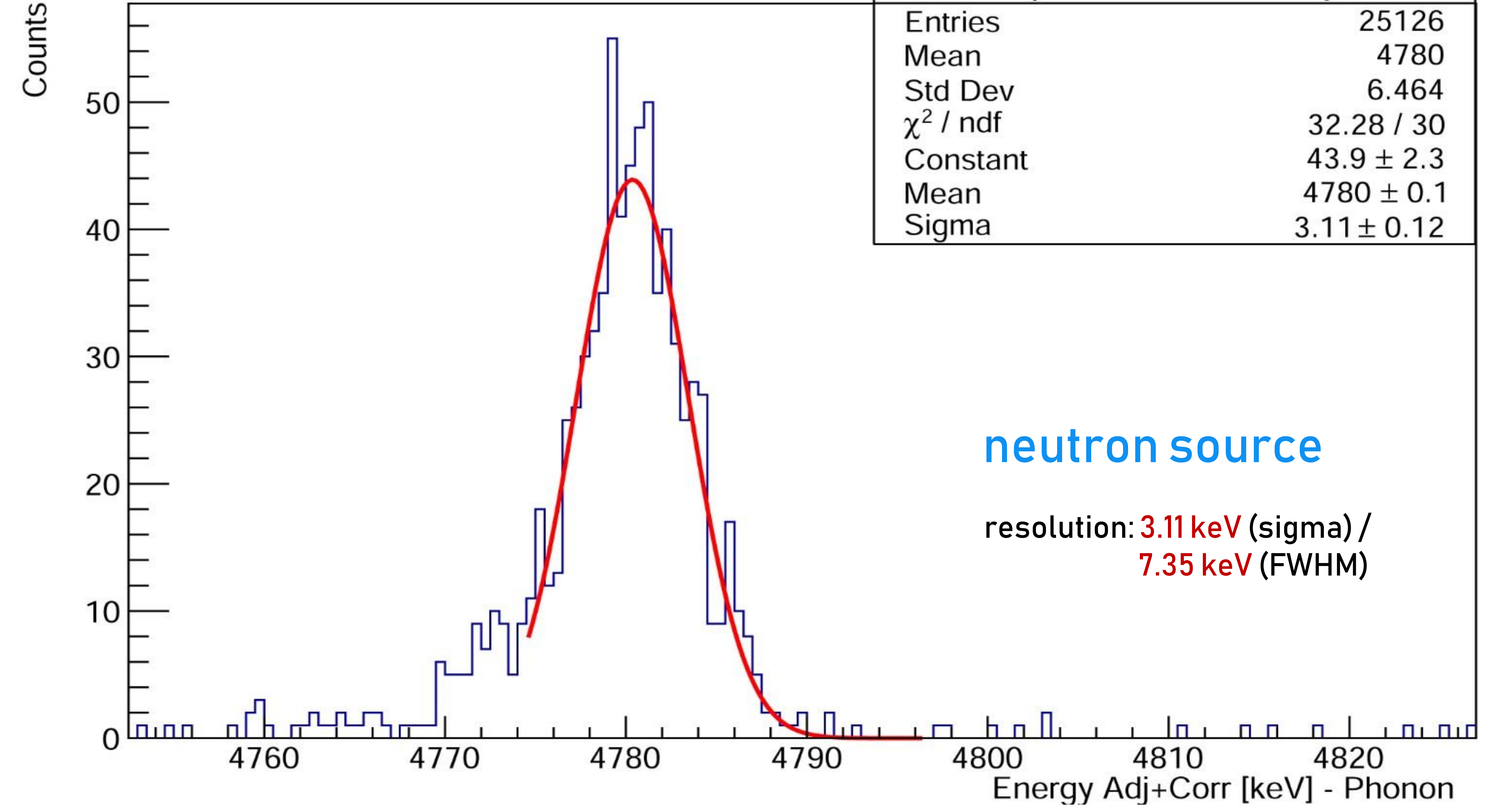
- High purity
- Soluble
- Scintillating
- Easy polishing




no polishing
water polishing
(30-60-90 s)

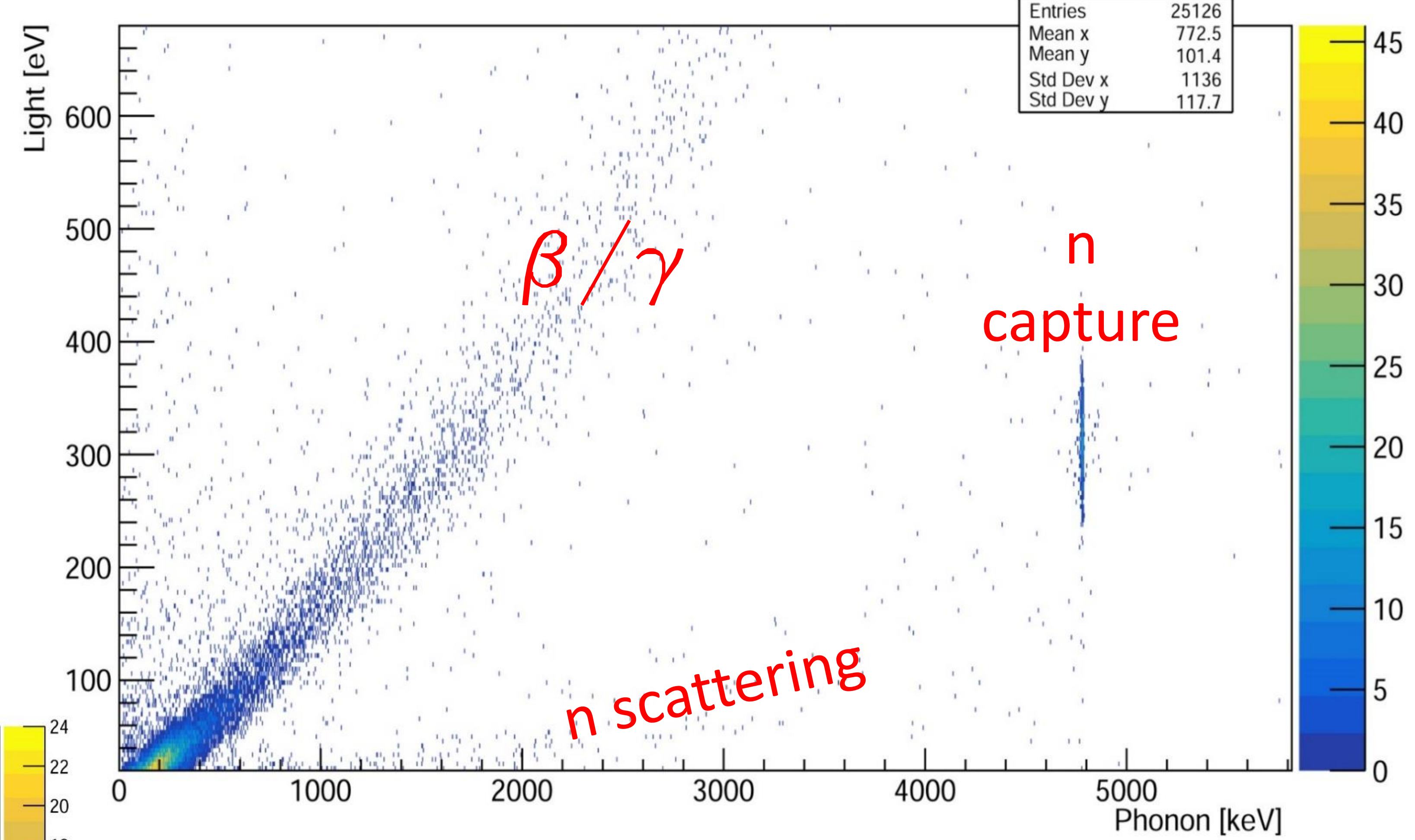


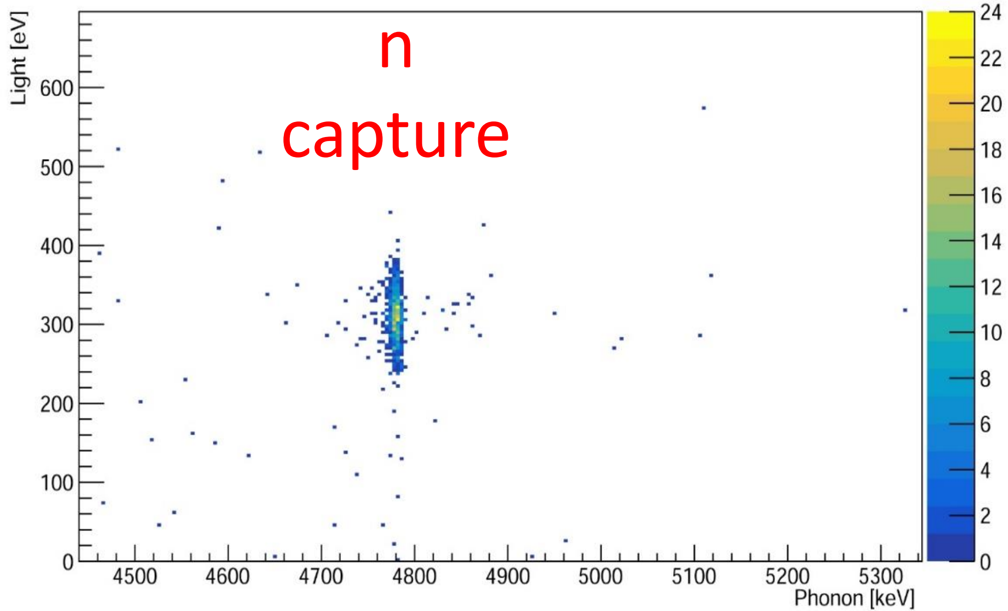
Counts
450
400
350
300
250
200
150
100
50
0
0
2000
4000
6000
8000
10000
Amplitude (filtered) - Phonon
1 cm3 Li2MoO4
- neutron source
- no source



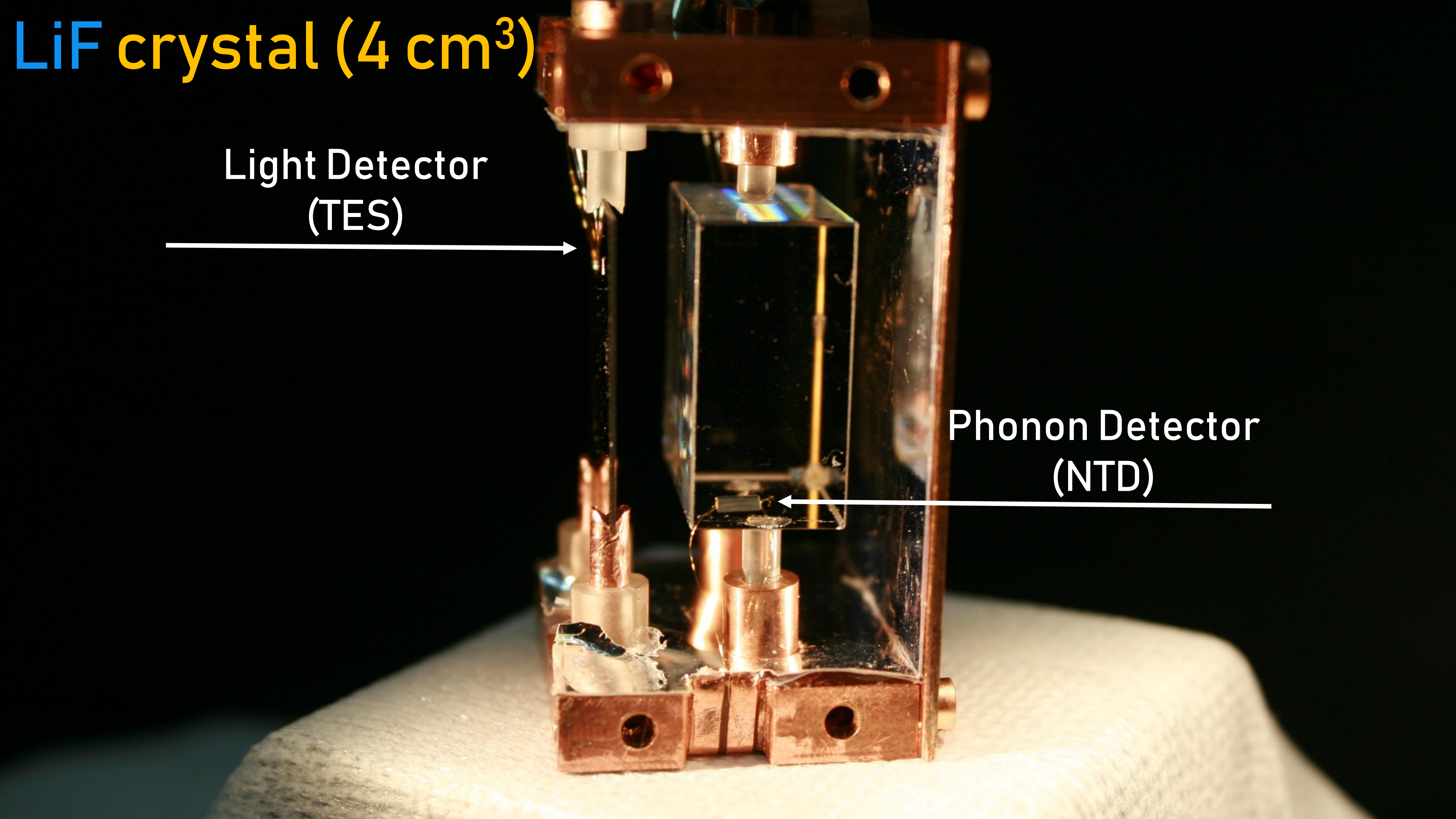
Counts
Entries 25126
Mean 4780
Std Dev 6.464
χ2 / ndf 32.28 / 30
Constant 43.9 ± 2.3
Mean 4780 ± 0.1
Sigma 3.11 ± 0.12
Energy Adj+Corr [keV] - Phonon
neutron source
resolution: 3.11 keV (sigma) /
7.35 keV (FWHM)

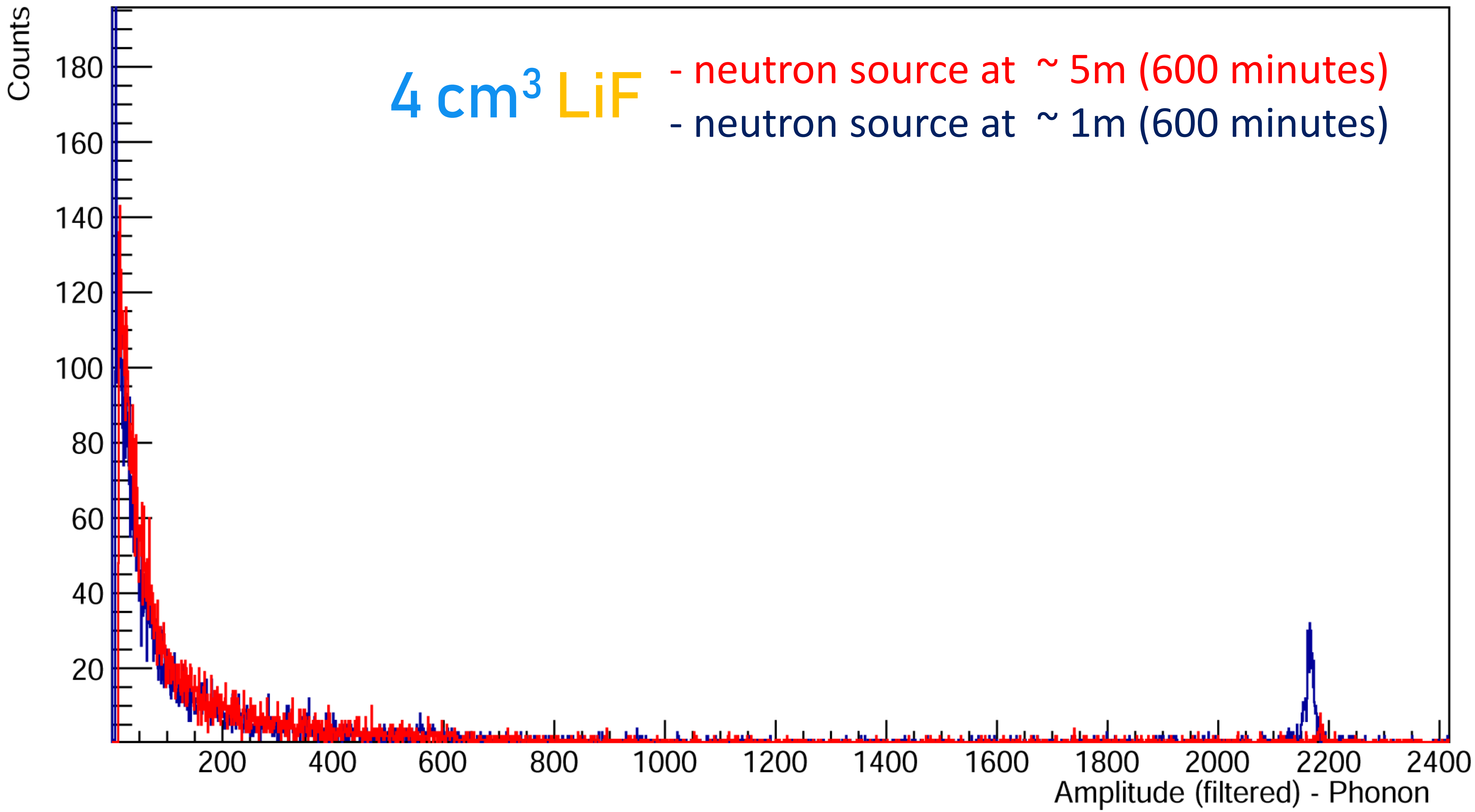
neutron source

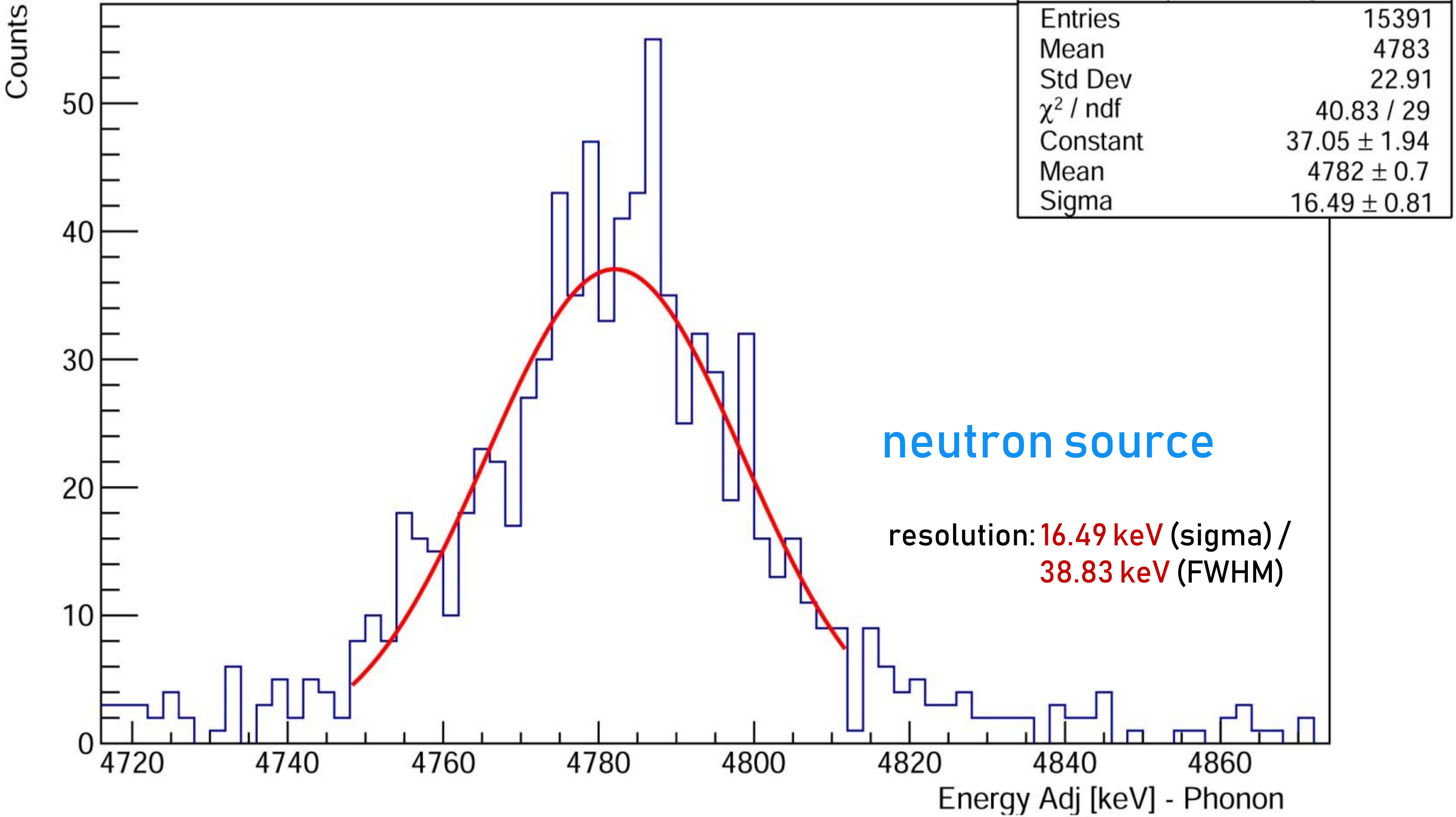


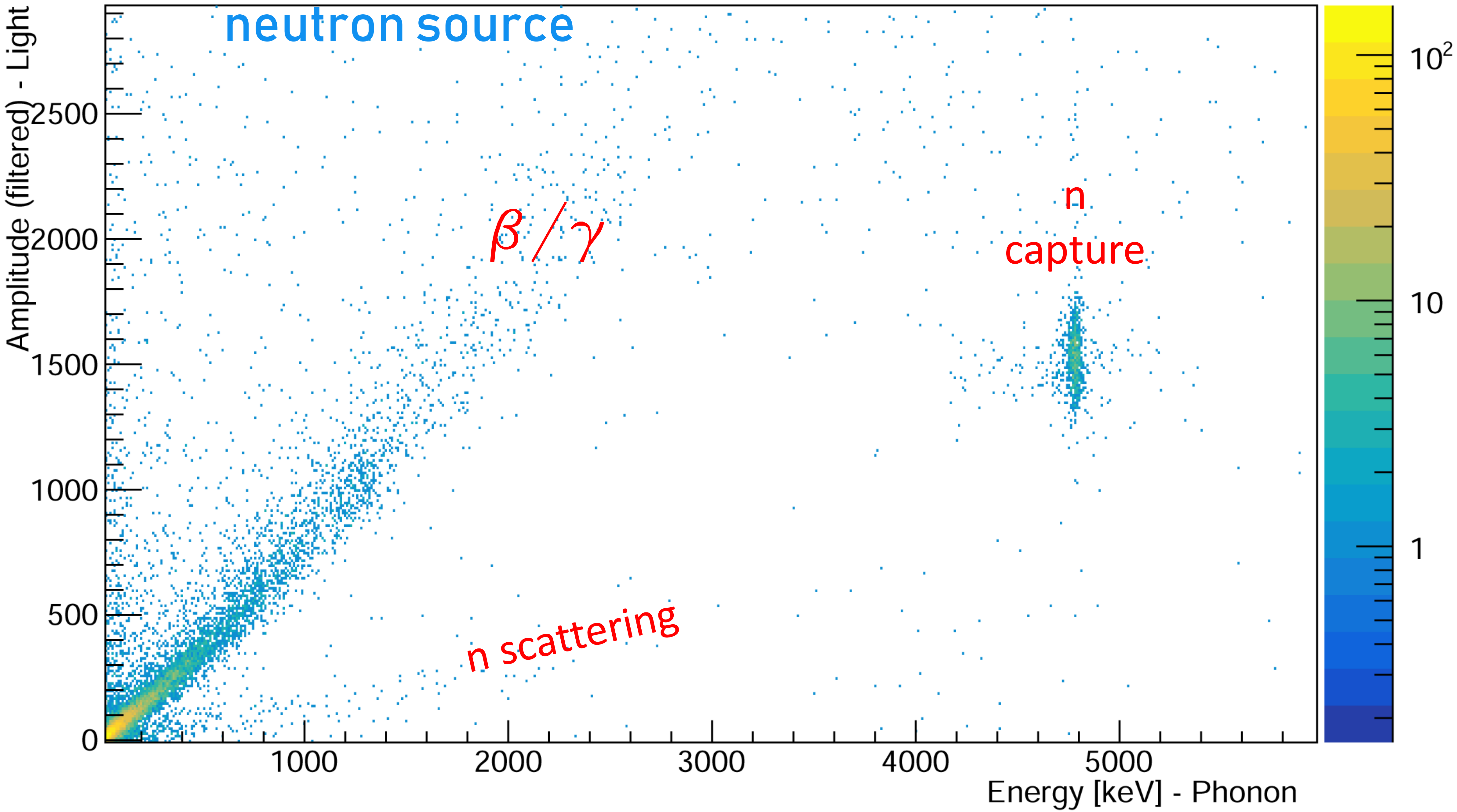


LiF crystal (4 cm^3)



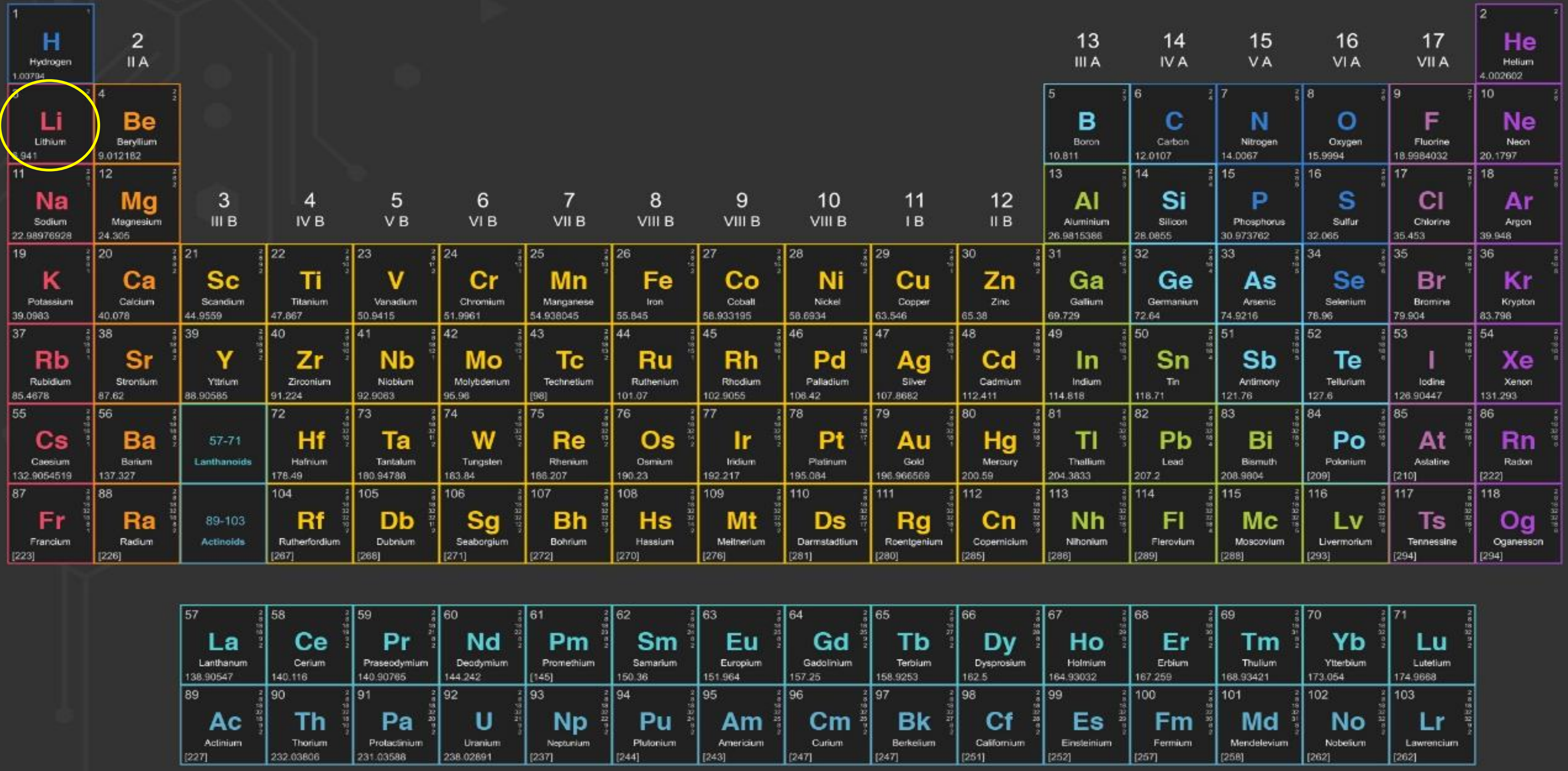

4 cm3 LiF
- neutron source at ~ 5m (600 minutes)
- neutron source at ~ 1m (600 minutes)
Counts
180
160
140
120
100
80
60
40
20
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Amplitude (filtered) - Phonon


Counts
Energy Adj [keV] - Phonon
Entries 15391
Mean 4783
Std Dev 22.91
χ² / ndf 40.83 / 29
Constant 37.05 ± 1.94
Mean 4782 ± 0.7
Sigma 16.49 ± 0.81
neutron source
resolution: 16.49 keV (sigma) /
38.83 keV (FWHM)



neutron source
β / γ
n
capture
n scattering
Amplitude (filtered) - Light
Energy [keV] - Phonon
0
500
1000
1500
2000
2500
3000
4000
5000
10²
10
1

Direct Dark Matter Search with Lithium



Expected Rate – Spin Independent

$$\frac{dR}{dE}\left[\frac{1}{keV \cdot kg \cdot day}\right] = \varphi' \cdot \frac{m_T}{A\, m_\chi \mu_p^2} \cdot A^2 \cdot F^2(E_r) \cdot I_{halo} \cdot \sigma^{SI}$$

Expected Rate – Spin Dependent

$$\frac{dR}{dE}\left[\frac{1}{keV \cdot kg \cdot day}\right] = \varphi \cdot \frac{m_T}{A\, m_\chi \mu_{p/n}^2} \frac{J}{(J+1)} \cdot < S_{p/n} >^2 \cdot F^2(E_r) \cdot I_{halo} \cdot \sigma_{p/n}{}^{SD}$$

$$I_{halo} = \frac{\rho_0}{k} \int_{v_{min}}^{v_{max}} \frac{f(\boldsymbol{v}, \boldsymbol{v_E})}{v}\, d^3\boldsymbol{v}$$

$$v_{min} = \sqrt{\frac{m_T E_{th}}{2\mu_T^2}}$$

Spin Dependent interaction requires targets with odd-numbered nuclei

Lithium
3
Li
6.941

^{6}Li – 7.59%
^{7}Li – 92.41%

Calcium Tungstate

CRESST TARGETS

Sapphire

Calcium
20
Ca
40.078

^{40}Ca – 96.941%
^{42}Ca – 0.647%
^{43}Ca – 0.135%
^{44}Ca – 2.086%
^{46}Ca – 0.004%
^{48}Ca – 0.187%

Tungsten
74
W
183.84

^{180}W – 0.12%
^{182}W – 26.50%
^{183}W – 14.31%
^{184}W – 30.64%
^{186}W – 28.43%

Oxygen
8
O
15.999

^{16}O – 99.76%
^{17}O – 0.04%
^{18}O – 0.20%

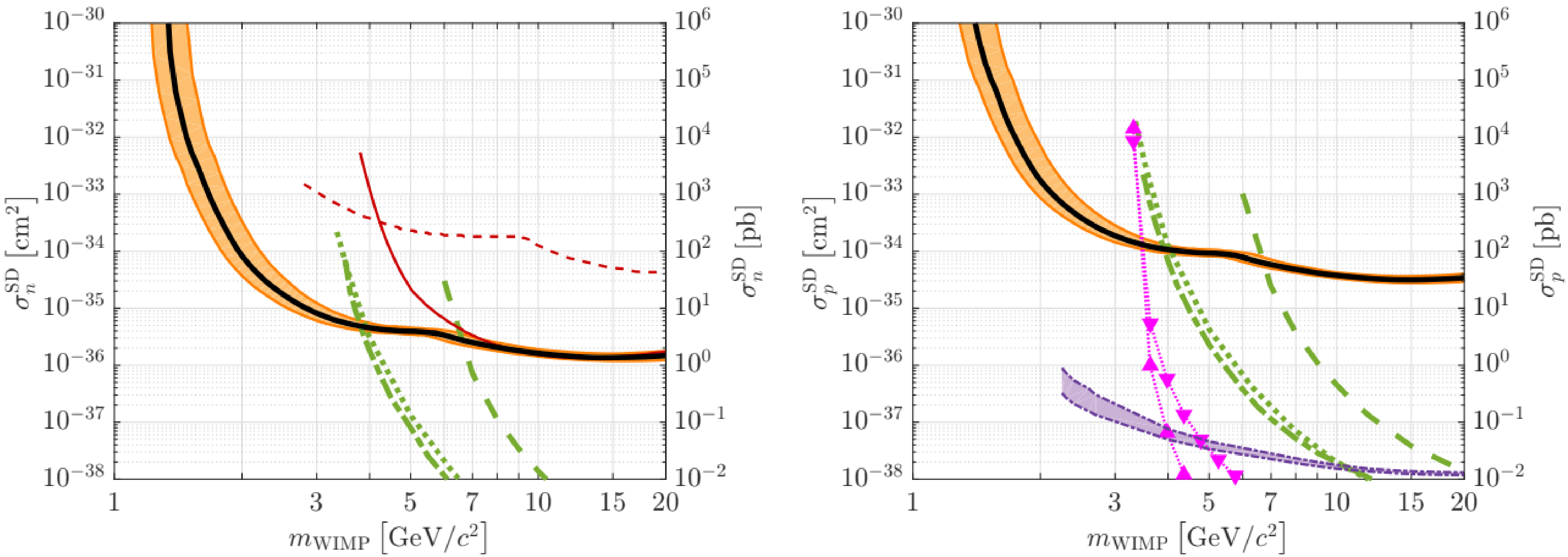
Aluminium
13
Al
26.982

^{27}Al – 100.00%

Oxygen
8
O
15.999

^{16}O – 99.76%
^{17}O – 0.04%
^{18}O – 0.20%

Spin Dependent Search – State of the Art

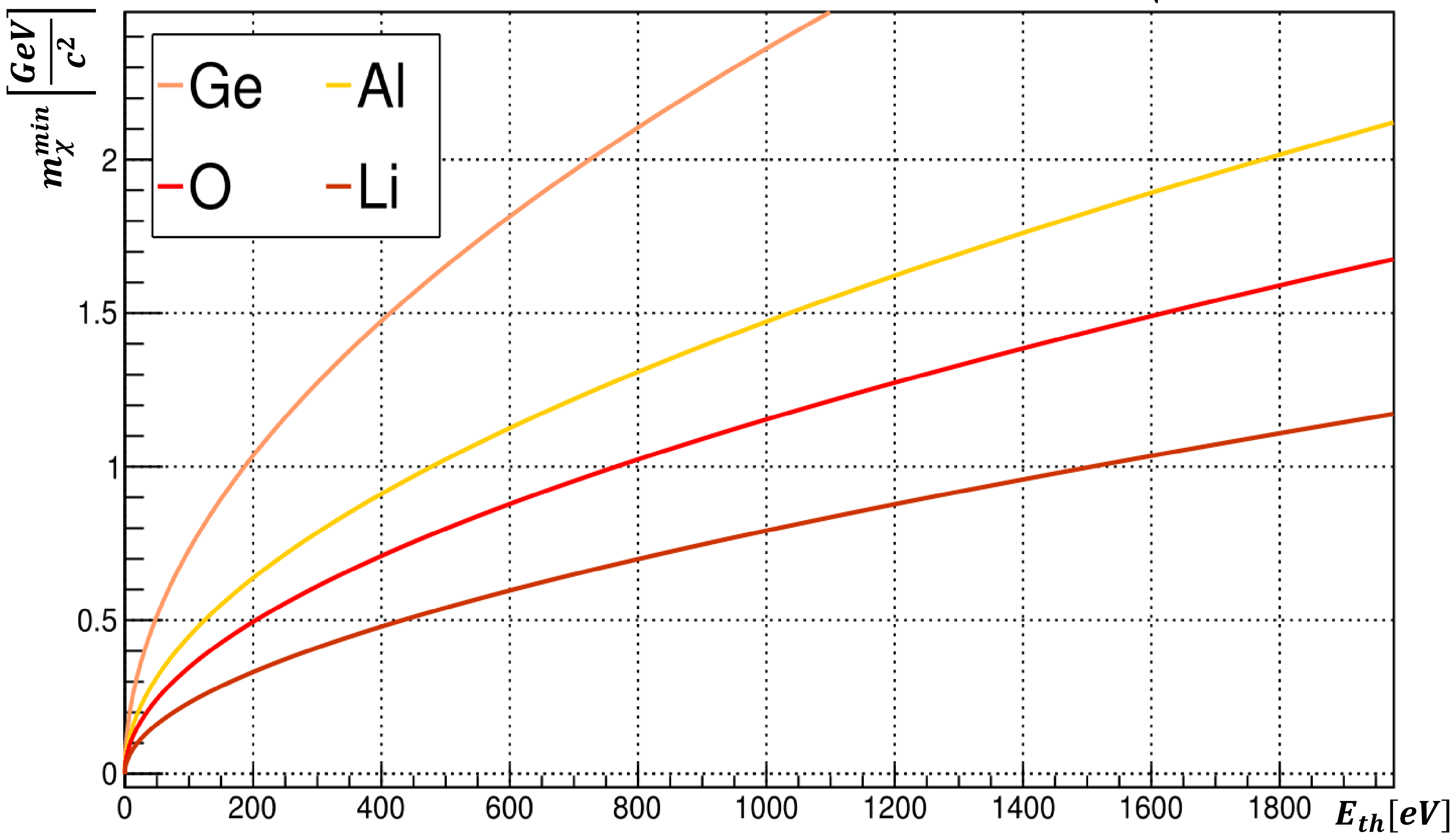


* Figure 32. Upper limits on the spin-dependent free neutron σ_n^{SD} (left) and free proton σ_p^{SD} (right) WIMP scattering cross sections in the proton- and neutron-only models, respectively. For both, the median (90 % C.L) (thick black solid curve) upper limit from CDMSlite Run 2 is compared to other selected direct-detection limits from PANDAX-II (thick-green dotted curve) [61], LUX (thick-green dot-dashed curve) [62], XENON100 (thick-green dashed curve) [63], PICO-60 (magenta upward triangles) [64], PICO-2L (magenta downward triangles) [65], PICASSO (purple dot-dashed band) [66], CDEX-0 (thin-red dashed curve) [67, 68], and CDEX-1 (thin-red solid curve) [68]. The orange band surrounding the Run 2 result is the 95 % uncertainty interval on the upper limit. The Run 2 limits are the most sensitive for $m_{\rm WIMP} \lesssim 4$ and $\lesssim 2$ GeV/c^2 for the neutron- and proton-only models, respectively.

(* *Low-mass dark matter search with CDMSlite*, SuperCDMS Collaboration, 2017)

Probing Power:

$$v_{min} = \sqrt{\frac{m_T E_{th}}{2\mu_T^2}} \longrightarrow m_\chi^{min} = \frac{m_T}{\sqrt{\frac{2 m_T v_{max}^2}{E_{th}} - 1}}$$



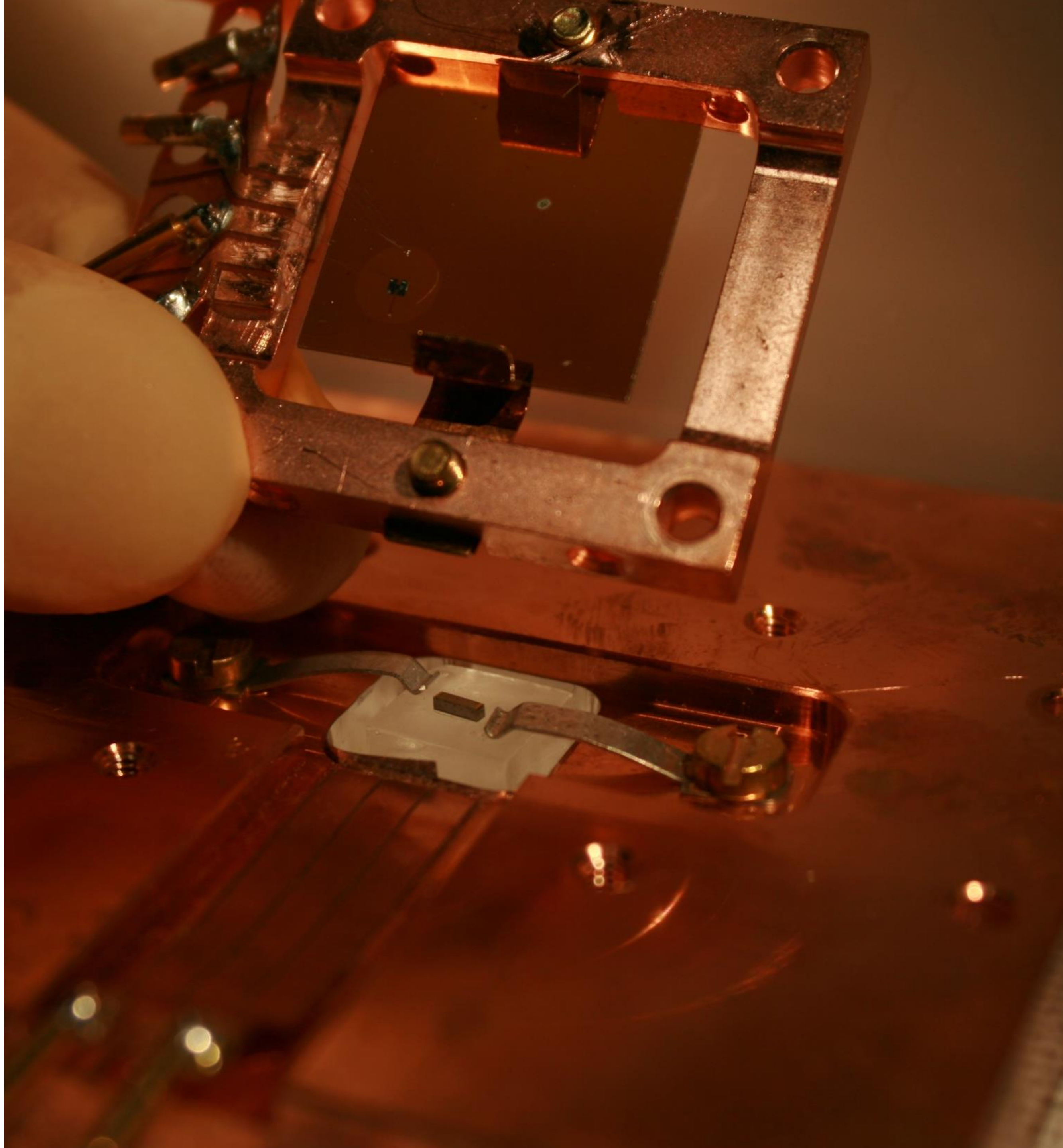
SUMMARY

- **R&D** to find a suitable crystal (Li_2MoO_4) to build a cryogenic neutron monitor for CRESST experiment

- **Motivation** to use Lithium-based crystals for Dark Matter search

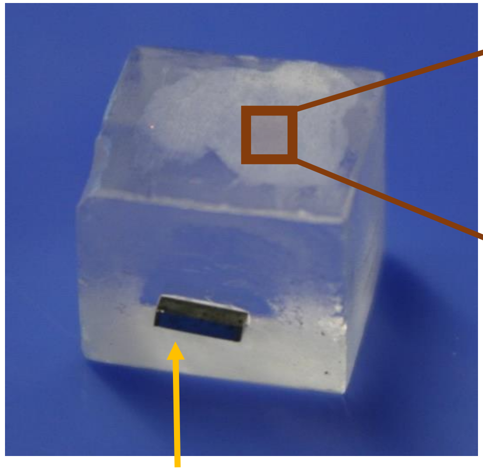
- **First results** for Spin-Dependent DM search with Lithium are coming soon

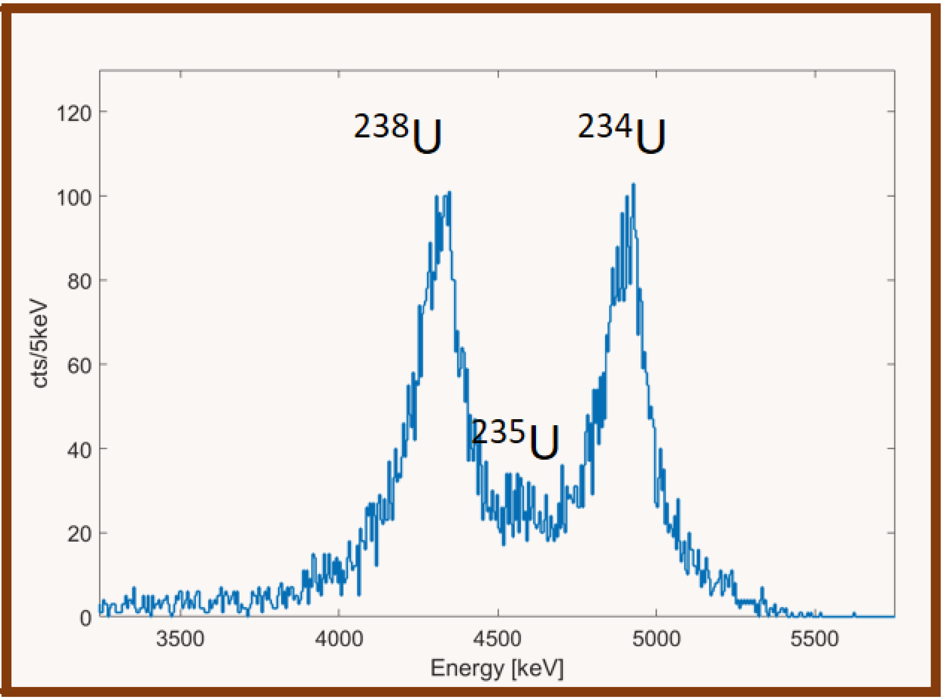
- **R&D** on crystals containing Lithium ($LiAlO_2$, $LiTaO_3$, and $LiNbO_3$) to be done



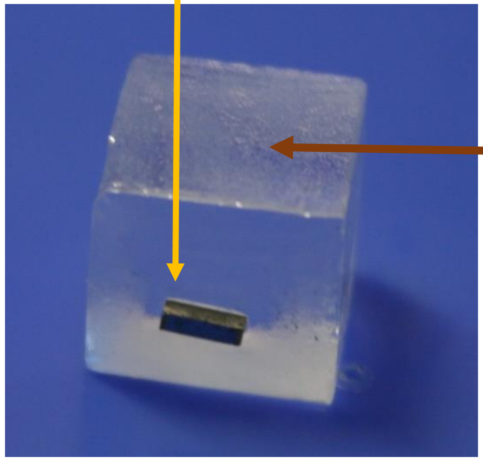
"I can't tell you what's in the dark matter sandwich. No one knows what's in the dark matter sandwich."

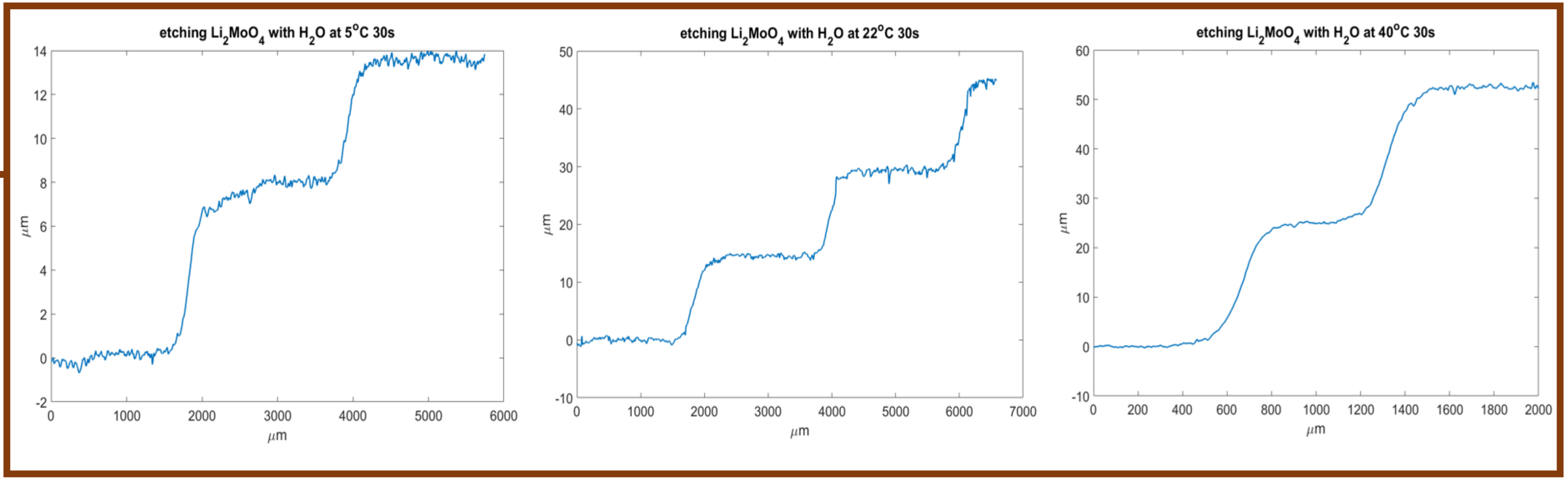
THANK YOU



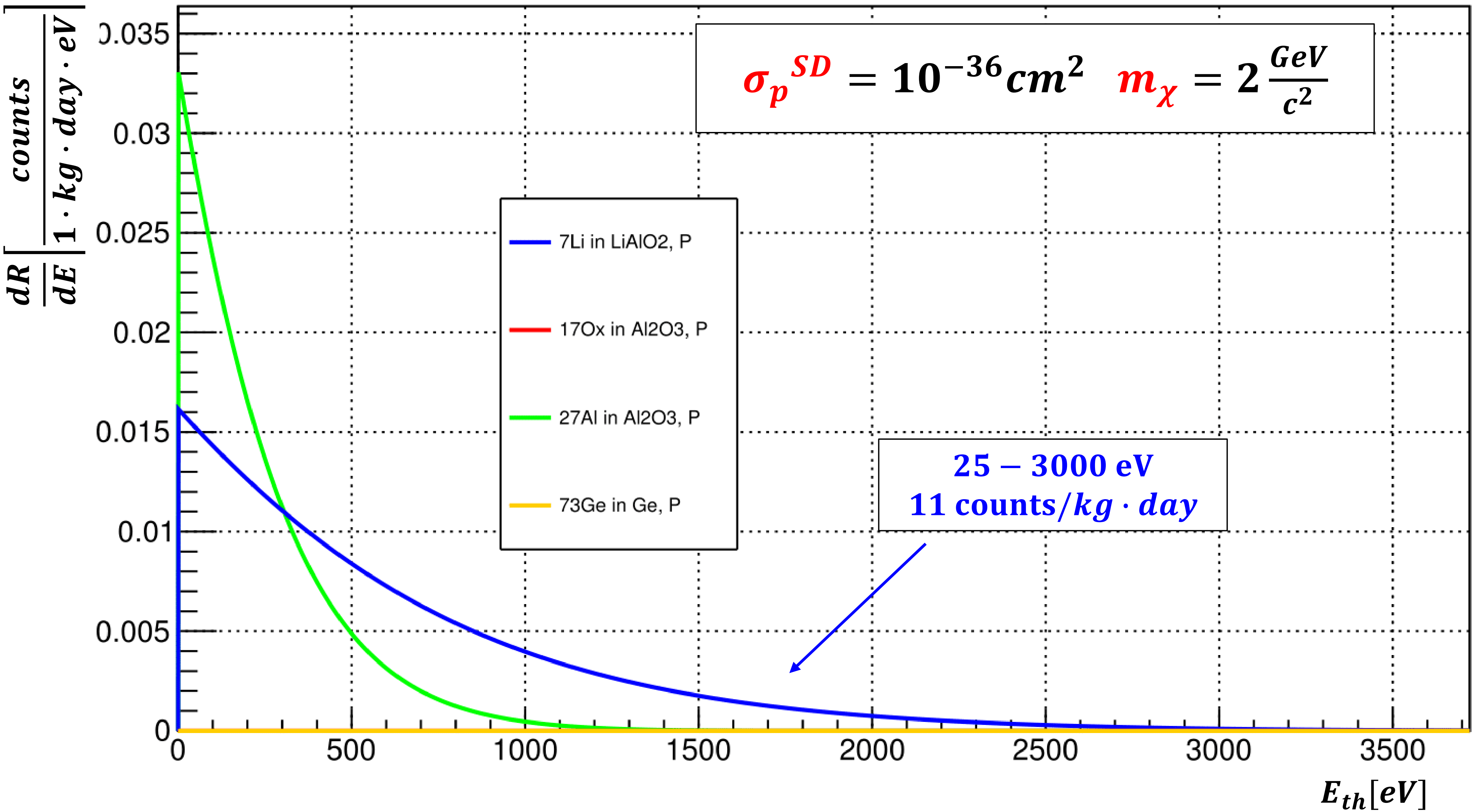


NTD - Neutron Transmutation Doped Ge
(Phonon Detector)





water polishing



$\frac{dR}{dE}\left[\frac{counts}{1 \cdot kg \cdot day \cdot eV}\right]$
$\sigma_p^{SD} = 10^{-36} cm^2 \quad m_\chi = 2 \frac{GeV}{c^2}$
7Li in LiAlO2, P
17Ox in Al2O3, P
27Al in Al2O3, P
73Ge in Ge, P
25 – 3000 eV
11 counts/$kg \cdot day$
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
500
1000
1500
2000
2500
3000
3500
$E_{th}[eV]$