Pushing Neutrons Calibrations to (even) Lower Energies

Scott Hertel
EXCESS2022 Workshop

Foundations

Goal:

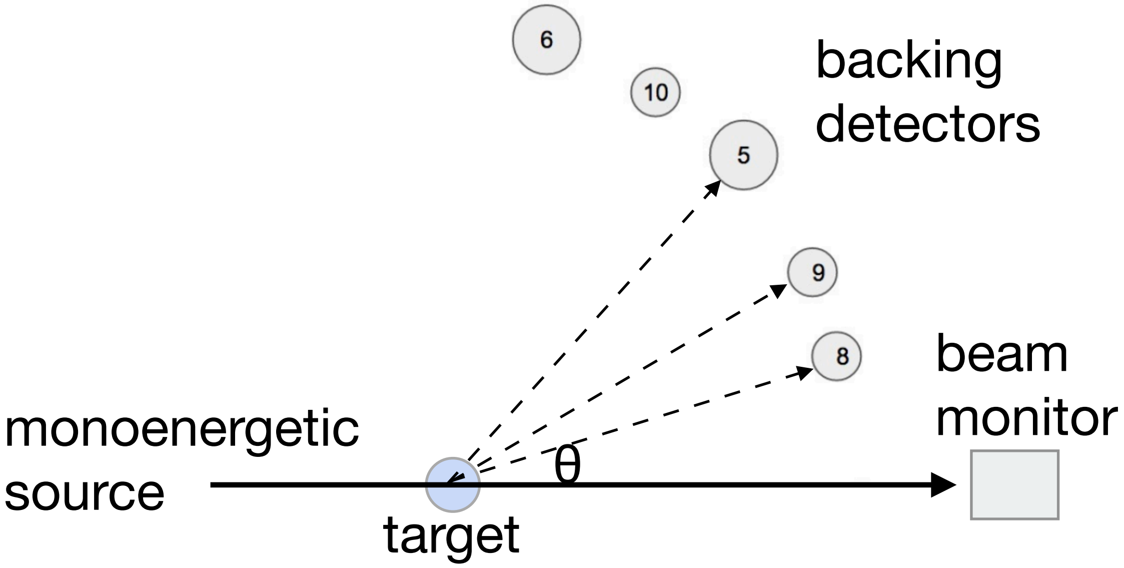
Produce a nuclear recoil of known energy.

Primary strategy:

Given a neutron of known energy, tag its scattering angle.

$$E_{\mathrm{nr},A} = \zeta E_n$$

$$\zeta = \frac{4 m_n m_A}{(m_n + m_A)^2} \frac{(1 - \cos\theta_{\mathrm{CM}})}{2}$$

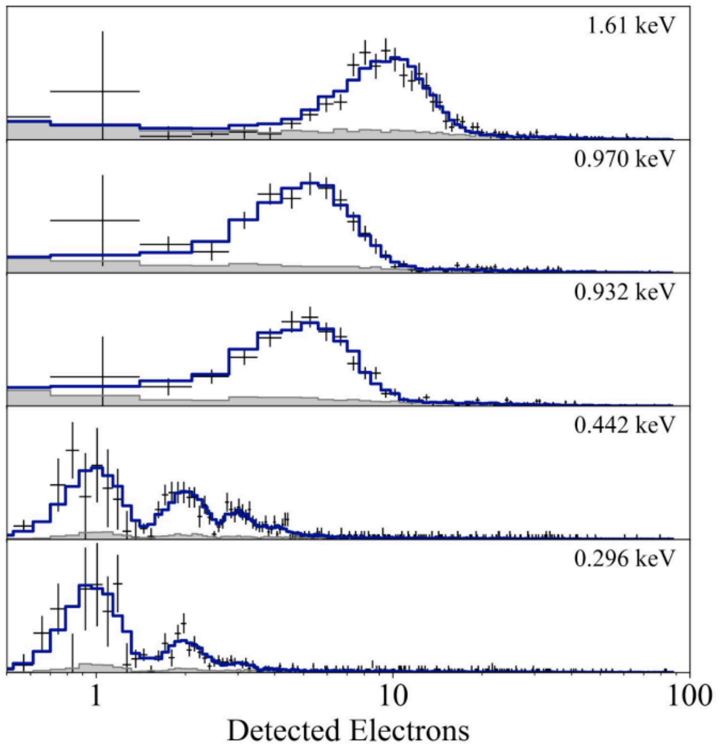


backing detectors

beam monitor

monoenergetic source

target



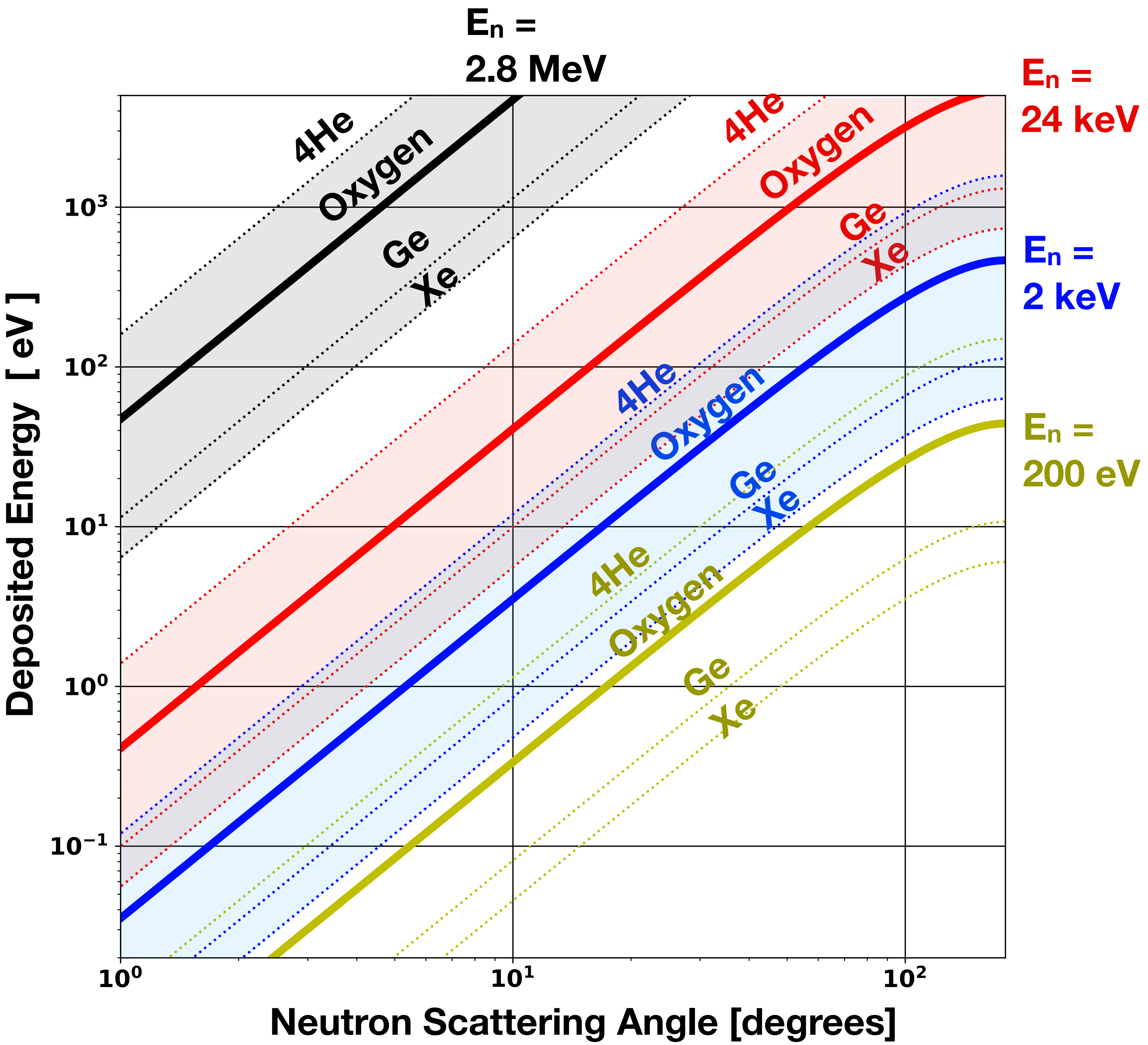
Foundations

The natural energy scale of neutron production is ~MeV.

MeV-scale neutrons have been pushed to their natural limit (by LUX and others)

few-degree
angular
precision
↔
few-hundred-
eV energies

To probe $E_{recoil} < 100\text{eV}$,
aim for $E_n < 10\text{keV}$



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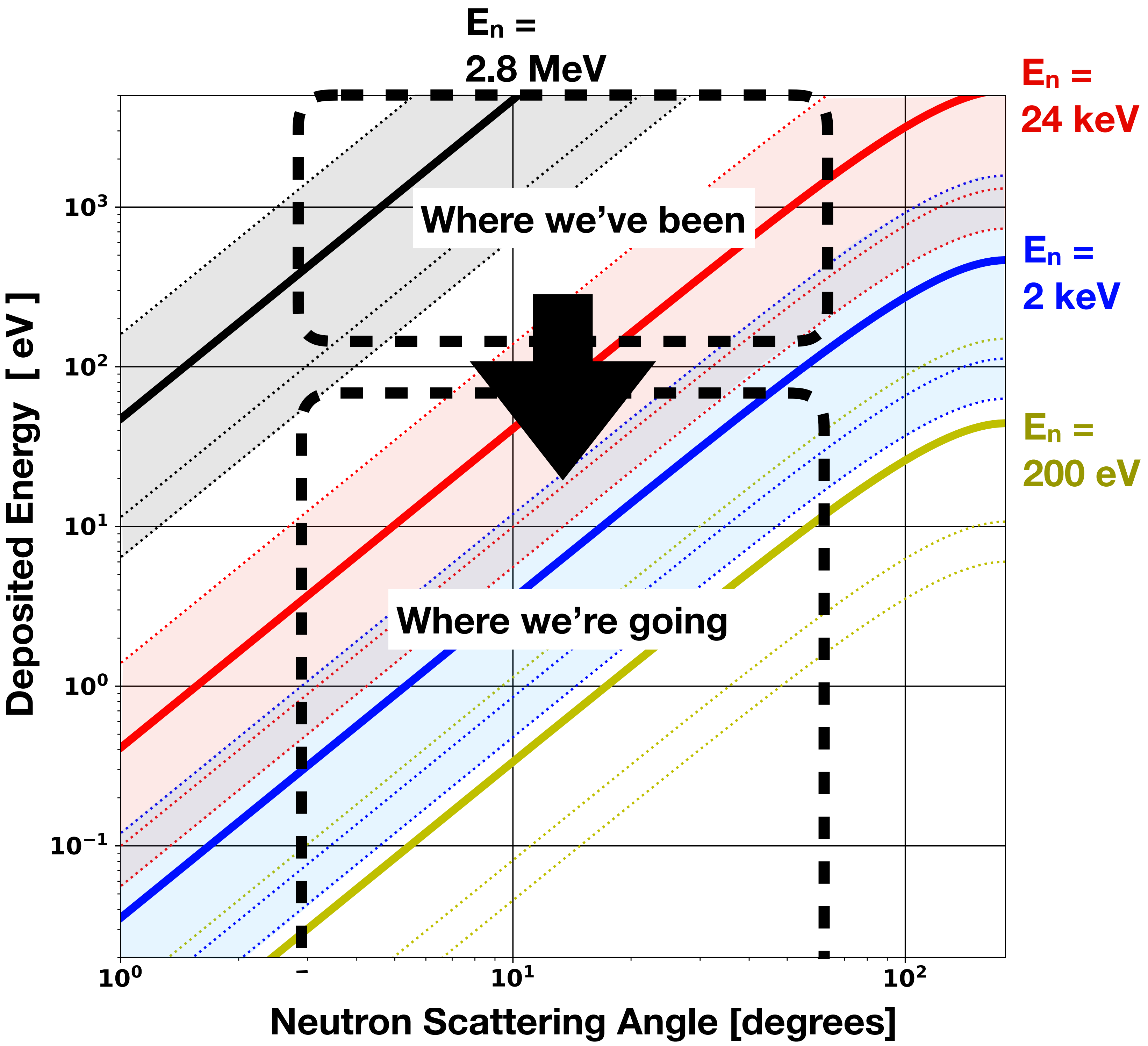
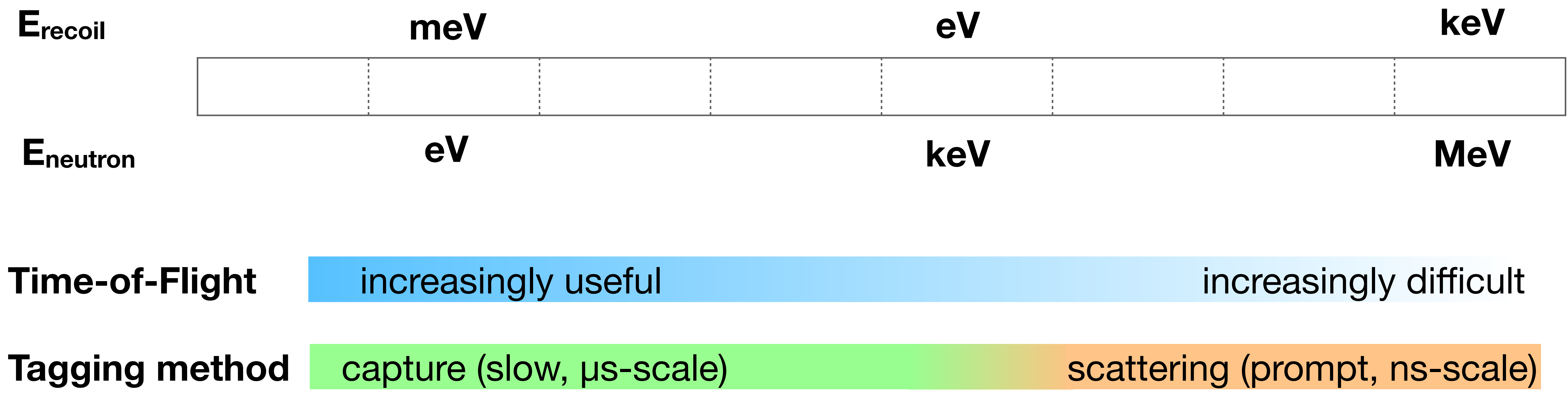
MeV-scale neutrons have been pushed to their natural limit (by LUX and others)

few-degree angular precision ⟷ few-hundred-eV energies



To probe $E_{recoil} < 100$eV,
aim for $E_n < 10$keV

Foundations



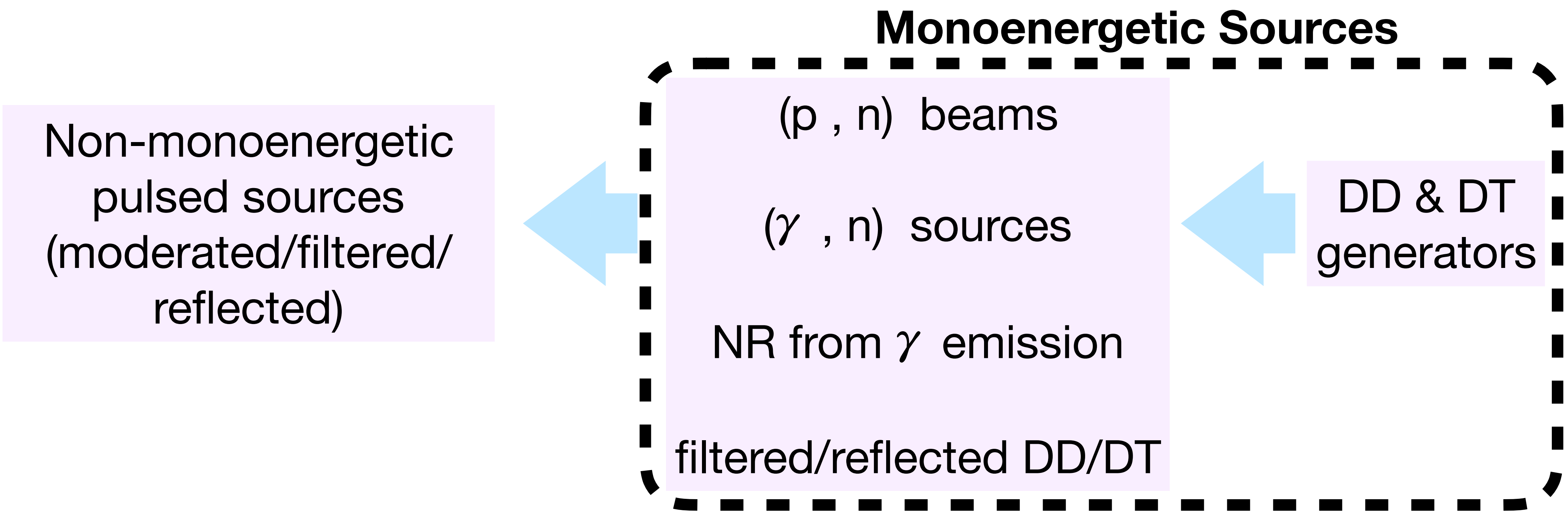
E_{recoil} meV eV keV

$E_{neutron}$ eV keV MeV

Time-of-Flight increasingly useful → increasingly difficult

Tagging method capture (slow, µs-scale) → scattering (prompt, ns-scale)

Talk Outline:



Non-monoenergetic pulsed sources (moderated/filtered/reflected)

Monoenergetic Sources

(p , n) beams

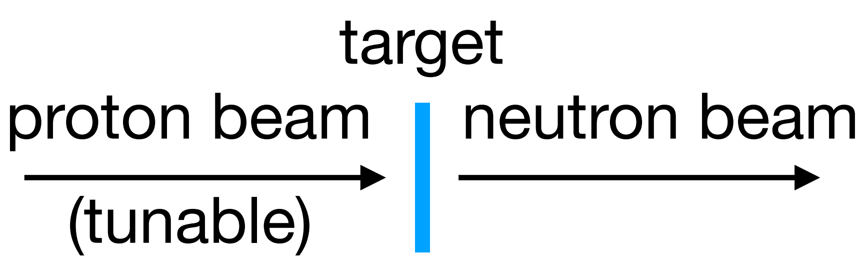
(γ , n) sources

NR from γ emission

filtered/reflected DD/DT

DD & DT generators

proton beams and (p,n) reactions

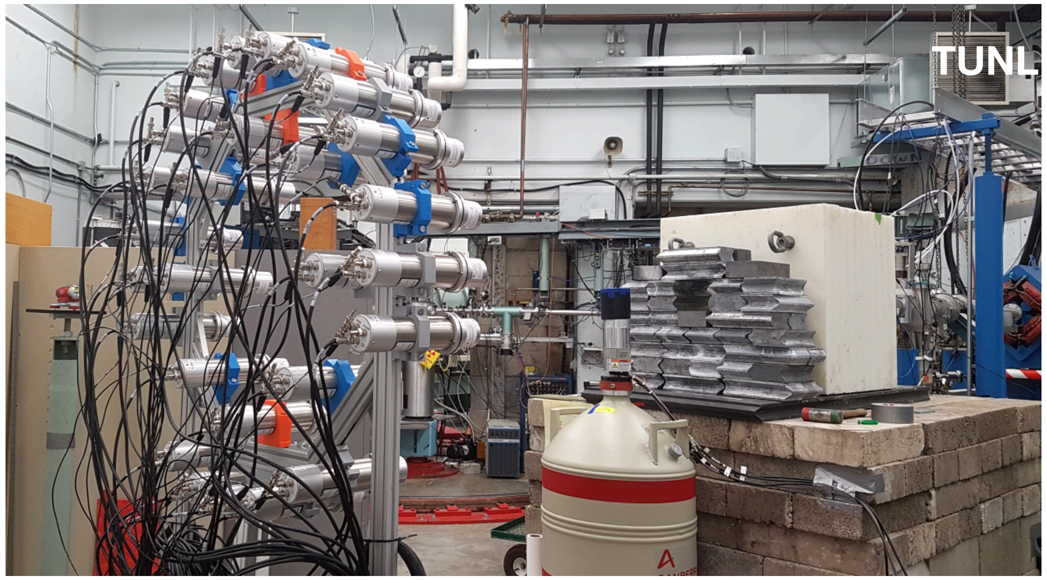


target

proton beam

(tunable)

neutron beam



Typically a tandem van der Graaff generator
onto a Lithium target: ^{7}Li(p,n)

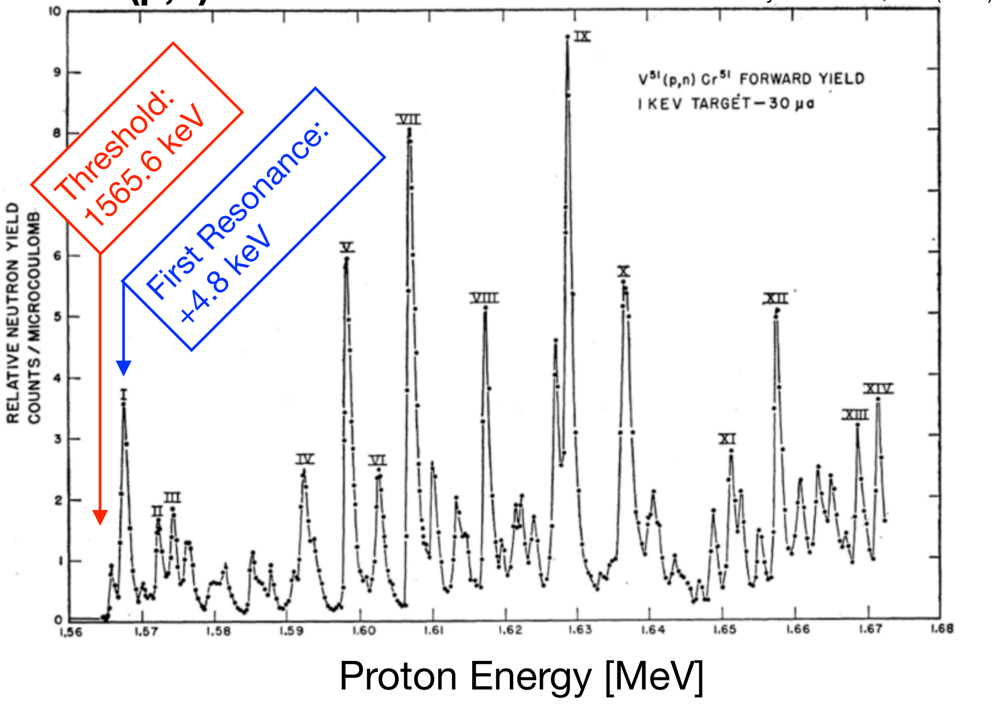
Well-demonstrated at TUNL, PTB, …
Long and growing literature of beautiful calibration results!

How low can we push E_n?
^{7}Li(p,n) cross section starts falling bellow ~70keV.

A possible future path: ^{51}V(p,n)
Advantage: emission resonance at 4.8keV.
Under investigation at U. Montreal
Resonances recently re-measured.

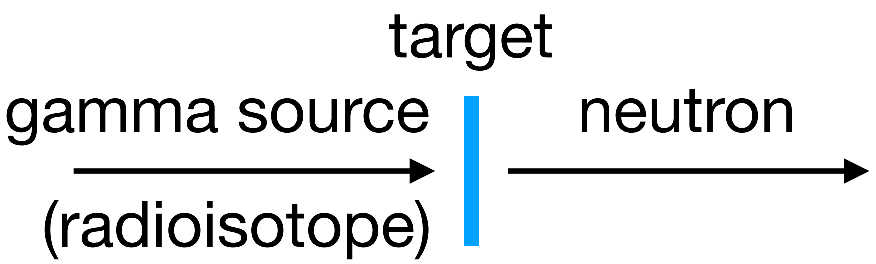
^{51}V(p,n) Cross section

J.H. Gibbons et al Phys. Rev. 100, 167 (1955)


Threshold: 1565.6 keV

First Resonance: +4.8 keV

Photo-neutron sources



target

gamma source

(radioisotope)

neutron

Typically a Be target: $^{9}Be(\gamma\ ,n)$

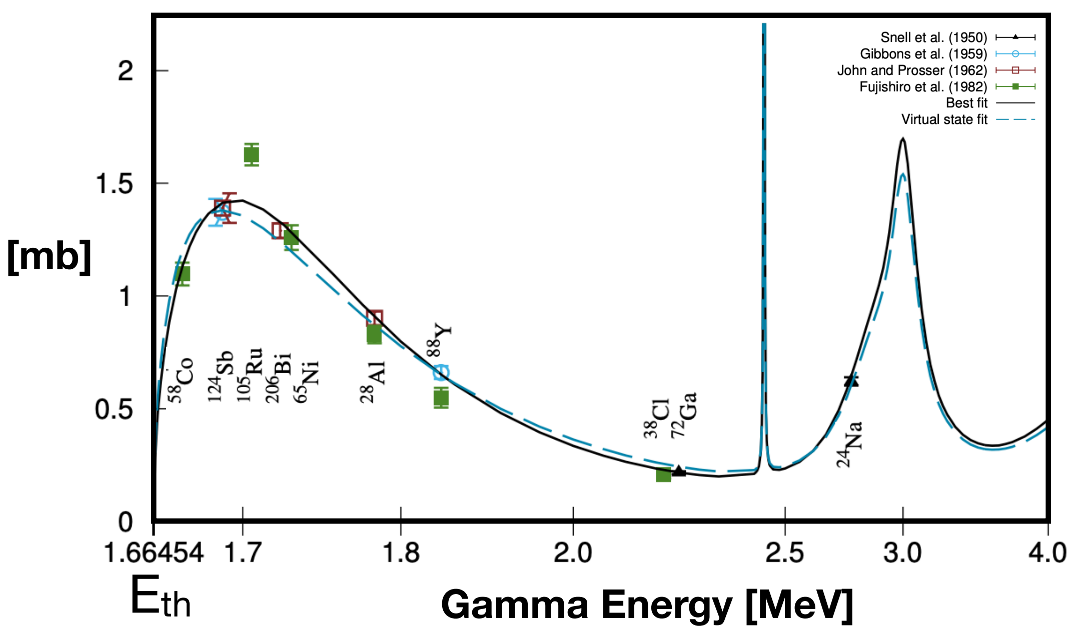
Also a long history of beautiful calibration results, including from yesterday!

How low can we push E_n?
Limited to list of available gamma sources…

^{124}Sb (E_{th} +23.5 keV) and ^{88}Y (E_{th} +152 keV) stick out as the lowest-energy *practical* sources.

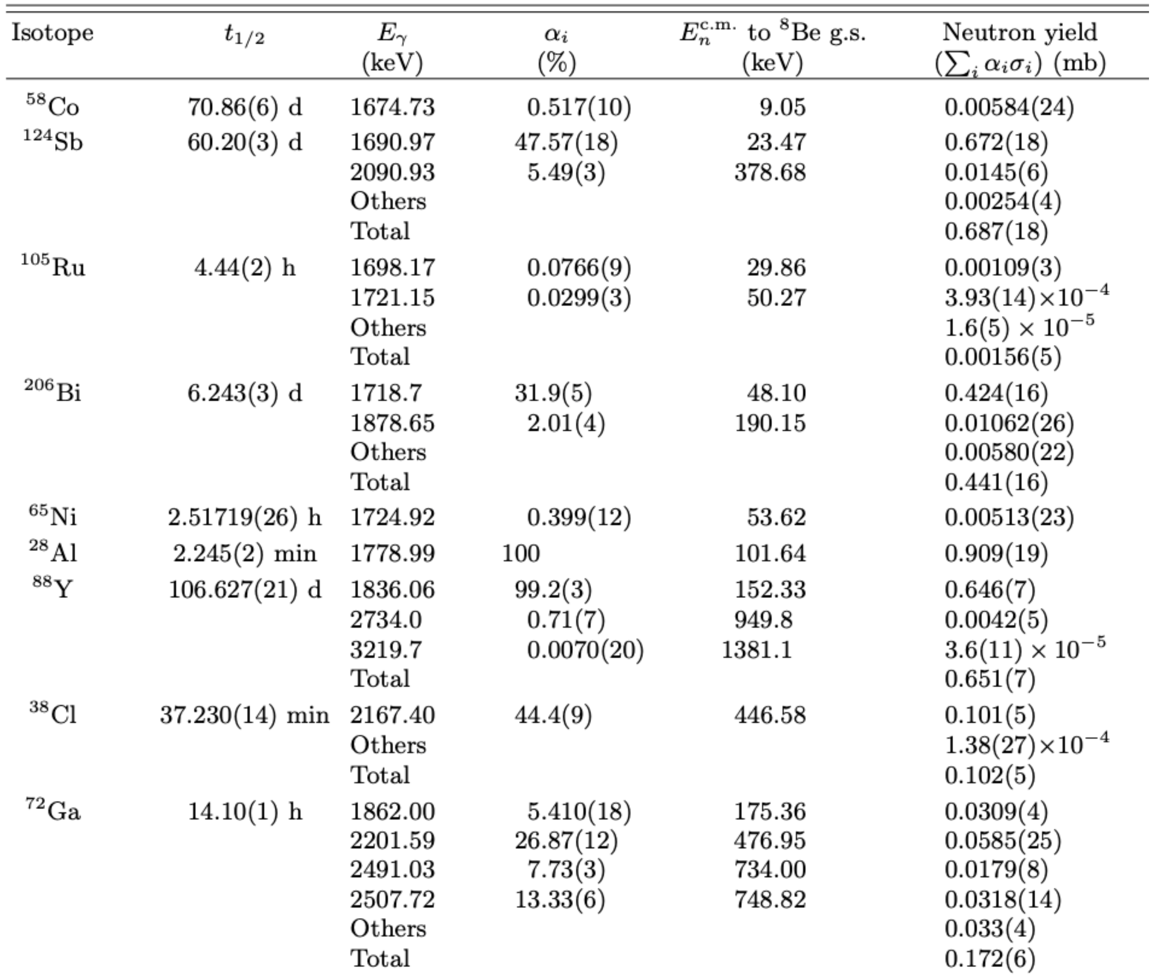
Main challenge: gamma backgrounds
The gamma source must be very ‘hot’ to achieve a useful neutron flux. Classic catch-22.

Gamma shielding introduces neutron moderation and simulation uncertainty.



$^{9}Be(\gamma\ ,n)\ ^{8}Be$ Cross-section

A. Robinson, arXiv:1602.05911



Isotope	$t_{1/2}$	E_γ (keV)	α_i (%)	$E_n^{c.m.}$ to ^{8}Be g.s. (keV)	Neutron yield ($\sum_i \alpha_i \sigma_i$) (mb)
^{58}Co	70.86(6) d	1674.73	0.517(10)	9.05	0.00584(24)
^{124}Sb	60.20(3) d	1690.97	47.57(18)	23.47	0.672(18)
		2090.93	5.49(3)	378.68	0.0145(6)
		Others			0.00254(4)
		Total			0.687(18)
^{105}Ru	4.44(2) h	1698.17	0.0766(9)	29.86	0.00109(3)
		1721.15	0.0299(3)	50.27	$3.93(14)\times10^{-4}$
		Others			$1.6(5) \times 10^{-5}$
		Total			0.00156(5)
^{206}Bi	6.243(3) d	1718.7	31.9(5)	48.10	0.424(16)
		1878.65	2.01(4)	190.15	0.01062(26)
		Others			0.00580(22)
		Total			0.441(16)
^{65}Ni	2.51719(26) h	1724.92	0.399(12)	53.62	0.00513(23)
^{28}Al	2.245(2) min	1778.99	100	101.64	0.909(19)
^{88}Y	106.627(21) d	1836.06	99.2(3)	152.33	0.646(7)
		2734.0	0.71(7)	949.8	0.0042(5)
		3219.7	0.0070(20)	1381.1	$3.6(11) \times 10^{-5}$
		Total			0.651(7)
^{38}Cl	37.230(14) min	2167.40	44.4(9)	446.58	0.101(5)
		Others			$1.38(27)\times10^{-4}$
		Total			0.102(5)
^{72}Ga	14.10(1) h	1862.00	5.410(18)	175.36	0.0309(4)
		2201.59	26.87(12)	476.95	0.0585(25)
		2491.03	7.73(3)	734.00	0.0179(8)
		2507.72	13.33(6)	748.82	0.0318(14)
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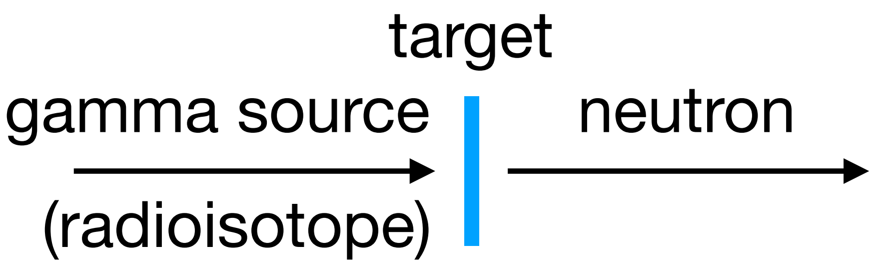

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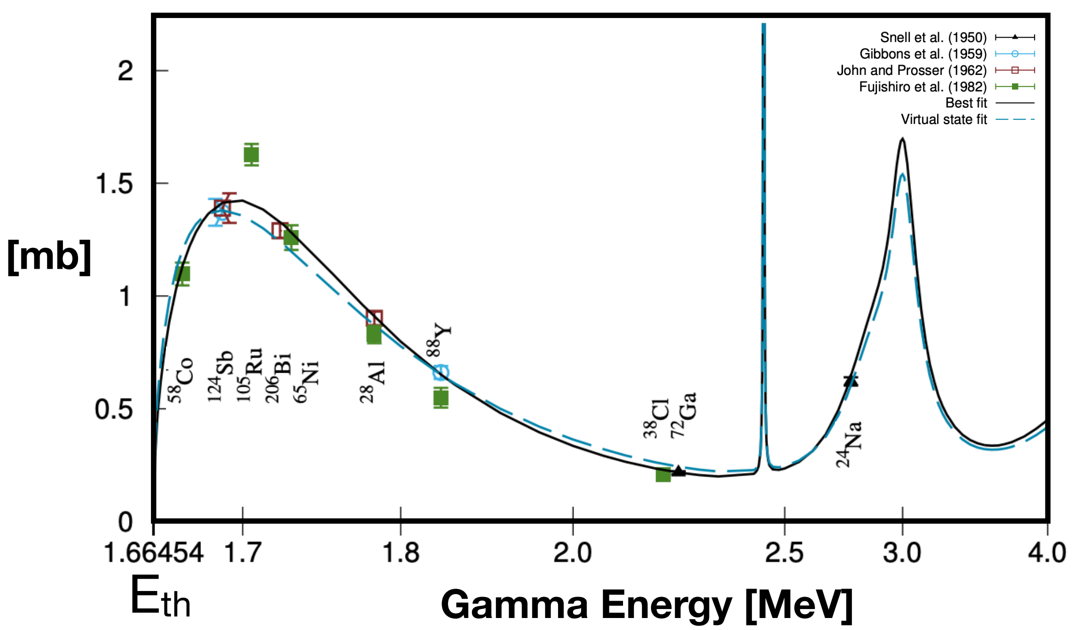

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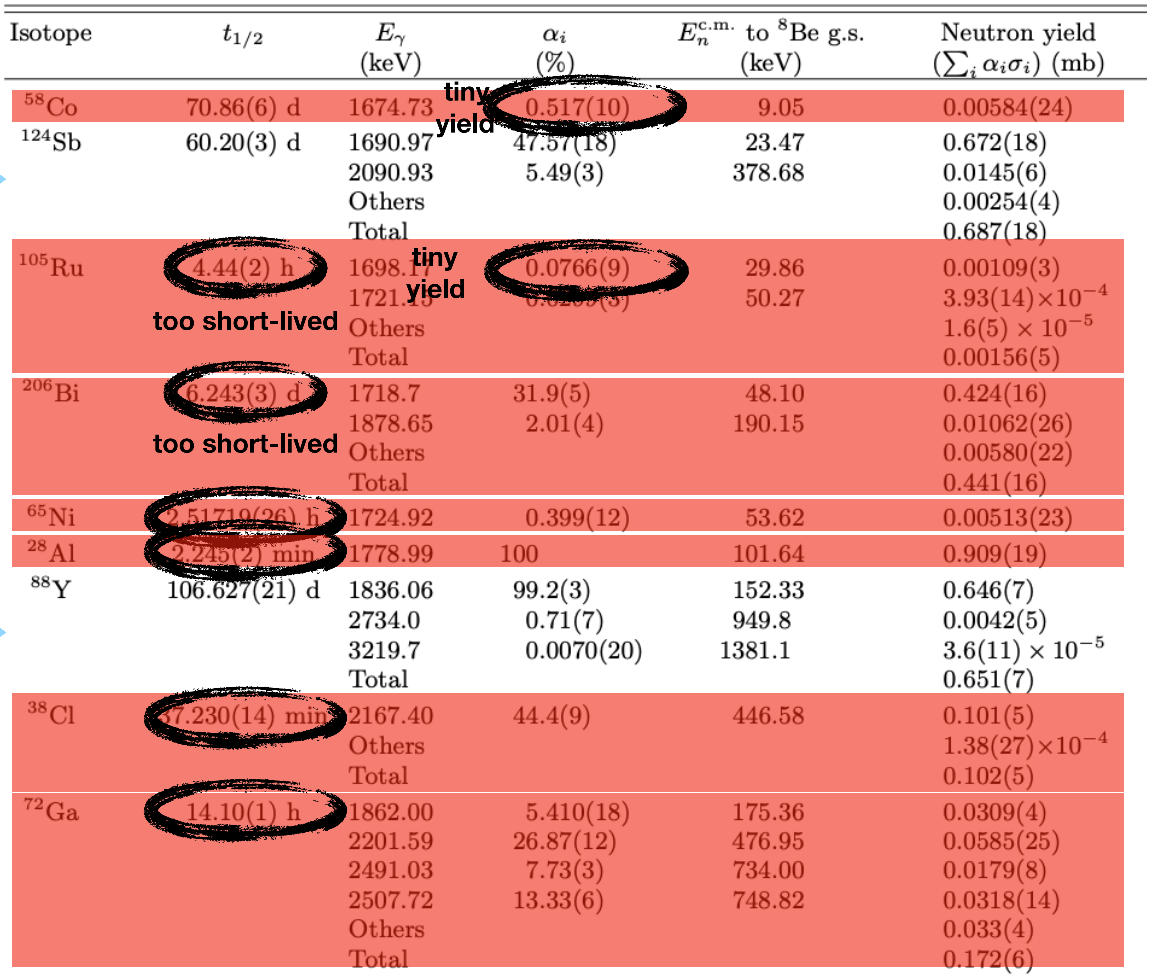

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tiny yield

tiny yield

too short-lived

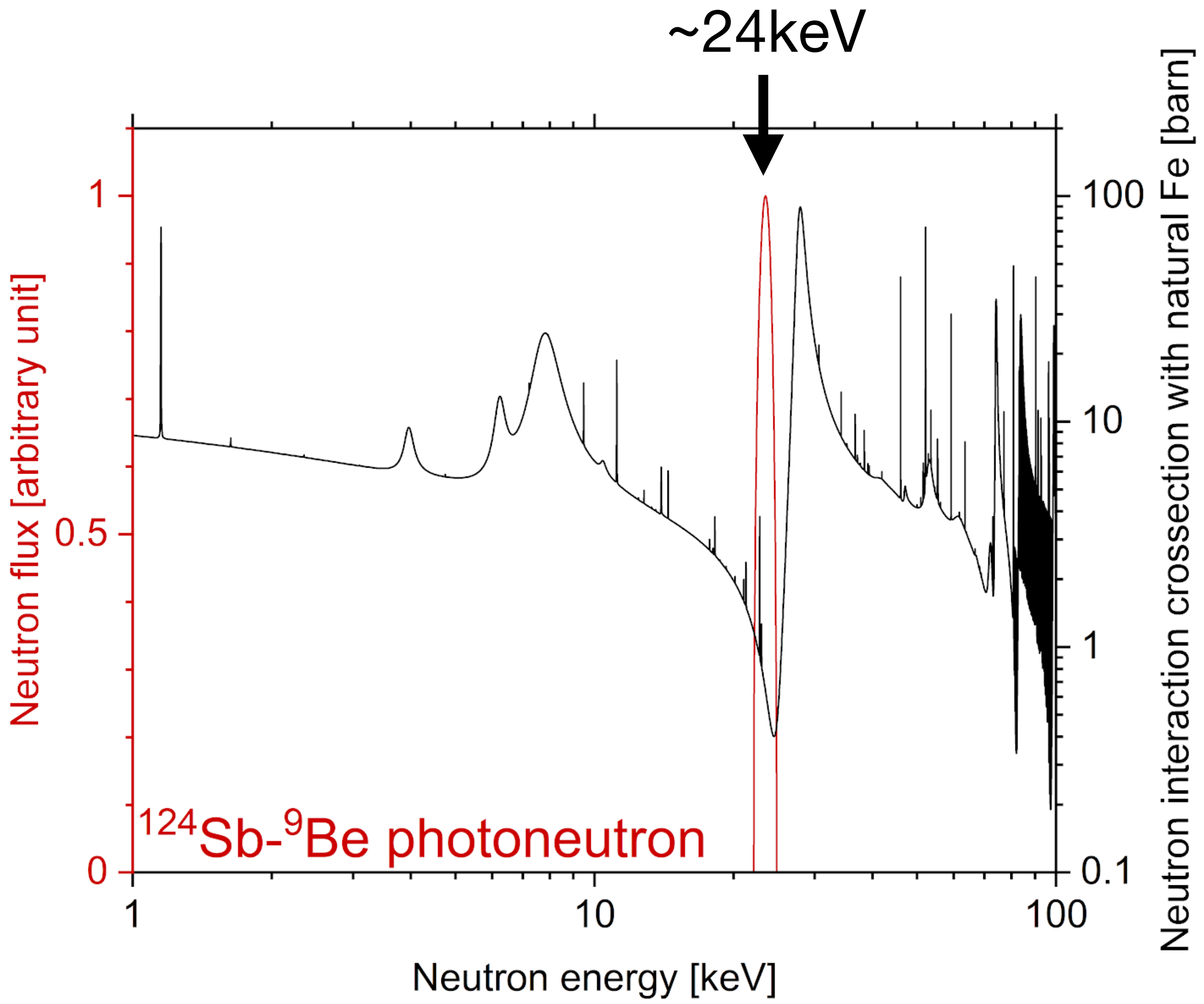
too short-lived

^{124}SbBe photoneutron + Fe shield

A remarkable coincidence

^{124}SbBe neutron energy : 23.47 keV

Fe n-transmission resonance : 24.54 keV



^{124}SbBe photoneutron + Fe shield

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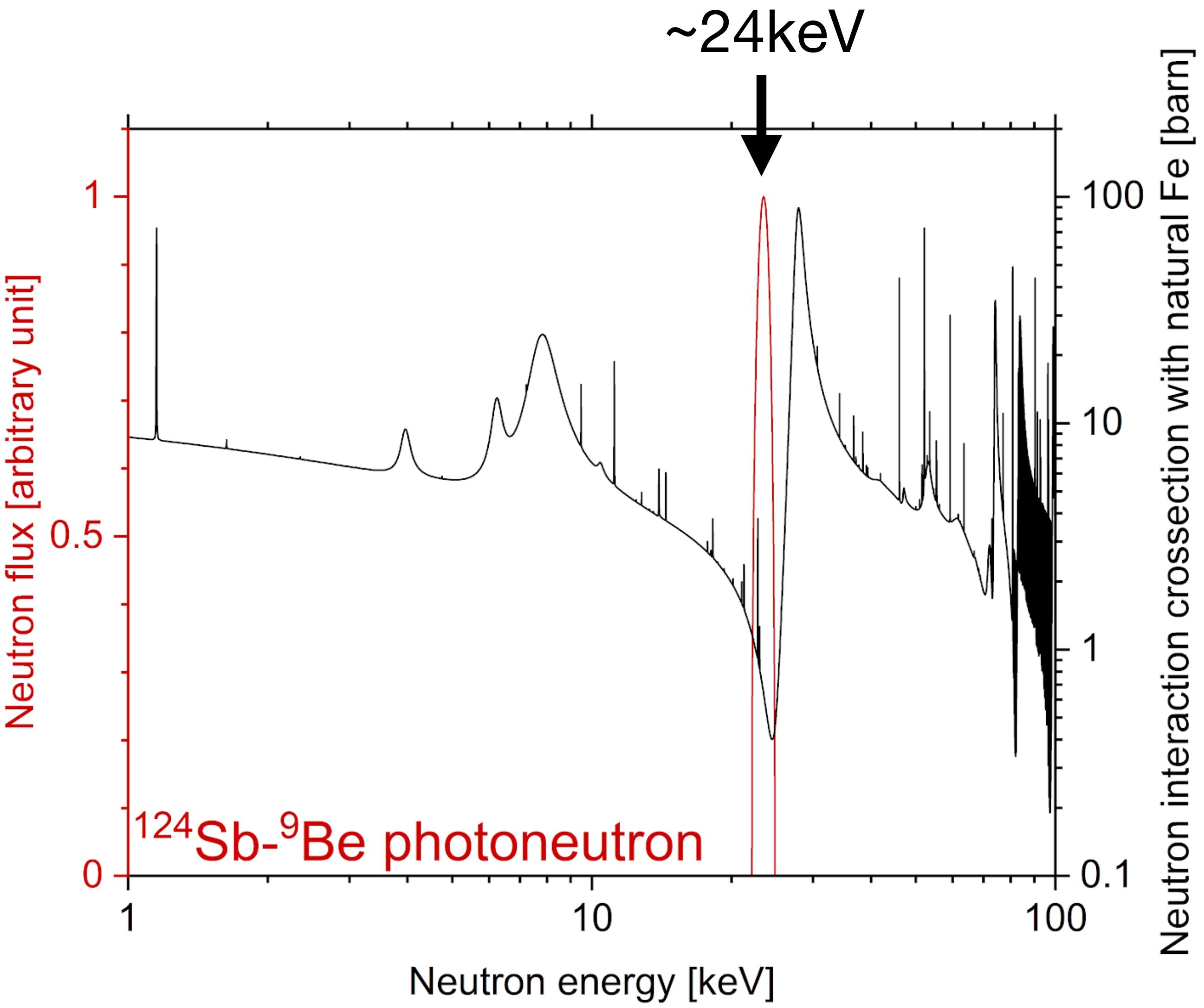
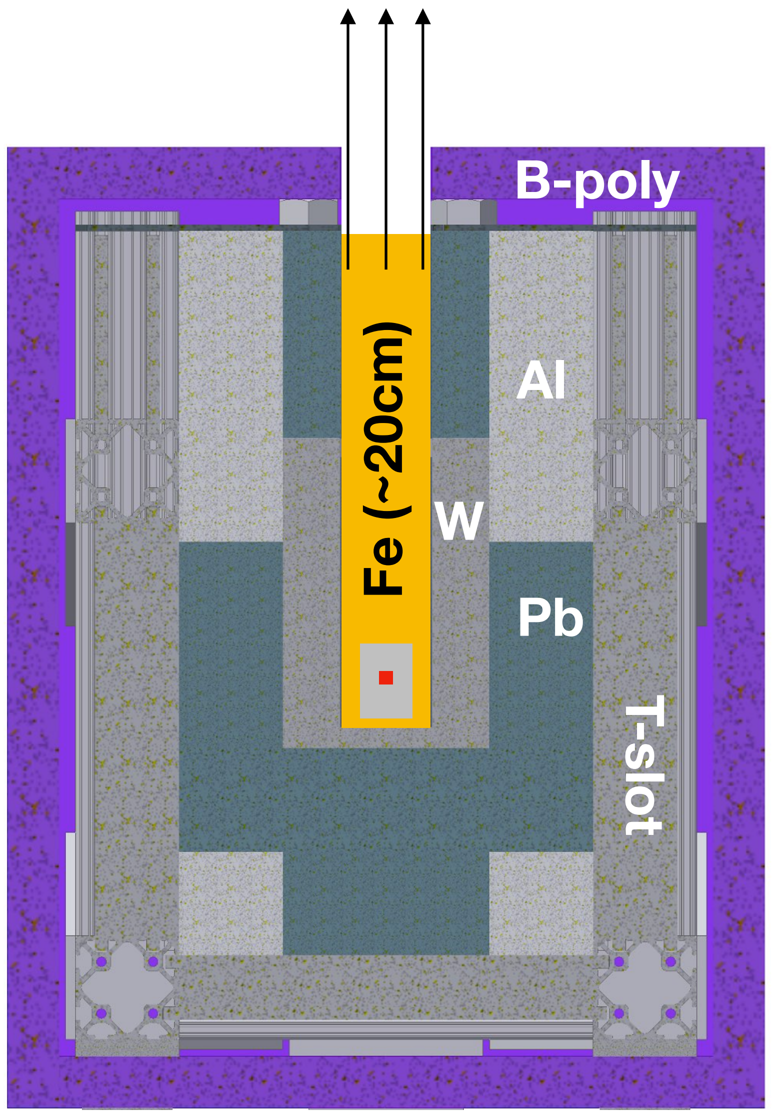
Concept:

~20cm Fe, similar to the neutron mean free path

Fe provides efficient gamma shielding (^{124}Sb: 1.7 & 2.1MeV)

Fe transparent enough to neutrons to serve as collimator



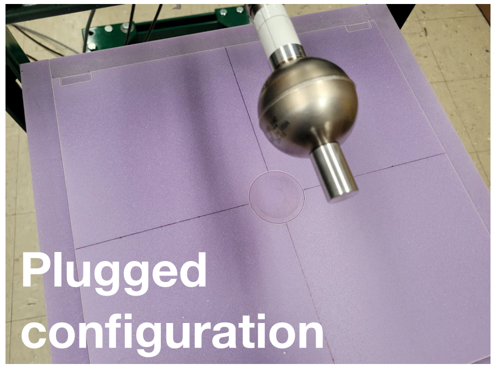


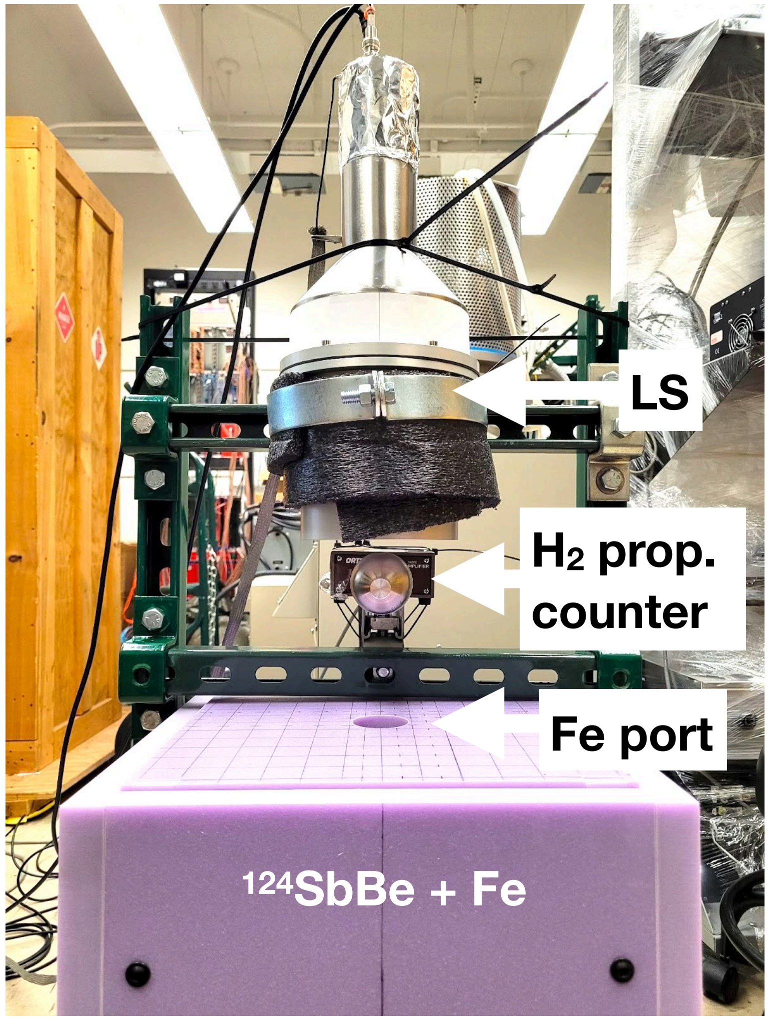
^{124}SbBe photoneutron + Fe shield

Designed, assembled, and …. working! (at McKinsey group, UCB)

^{124}Sb activated at Davis reactor to ~1GBq

Ongoing multi-pronged characterization (NaI, 3He, H_2 prop. counter, LS…)





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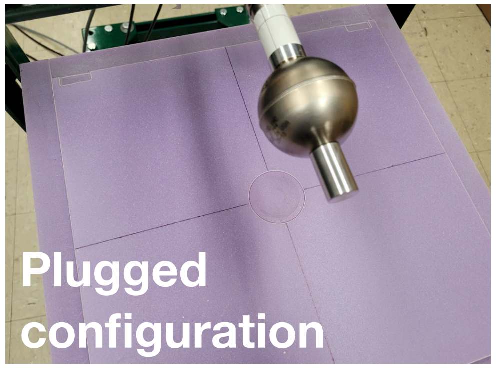
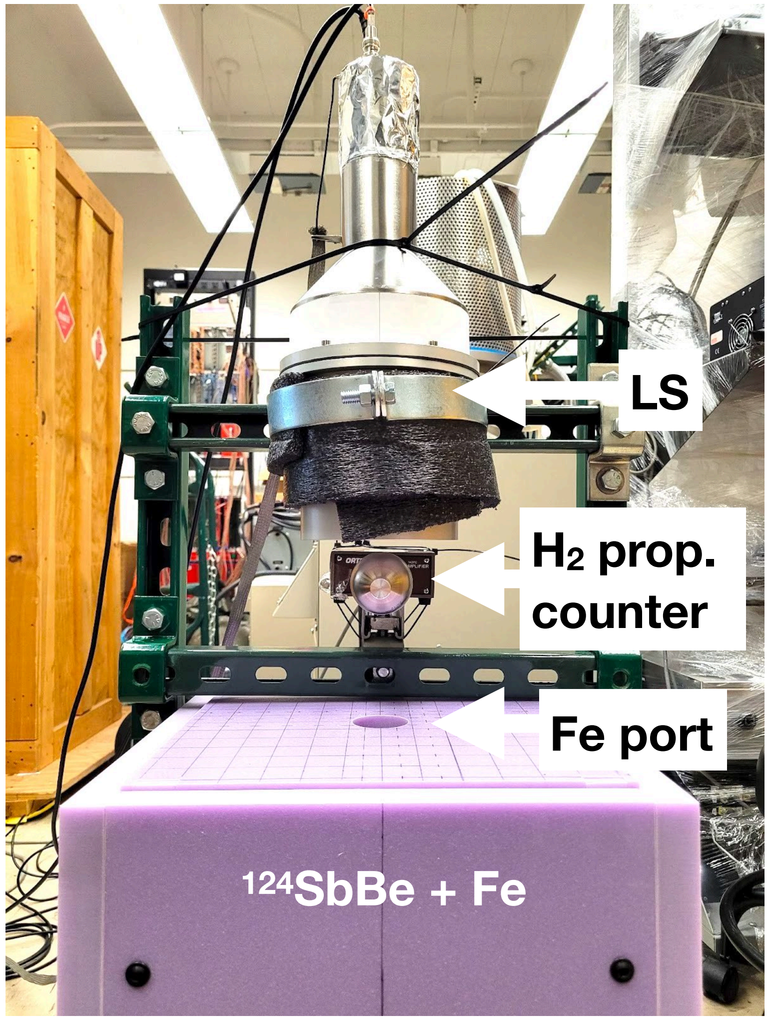
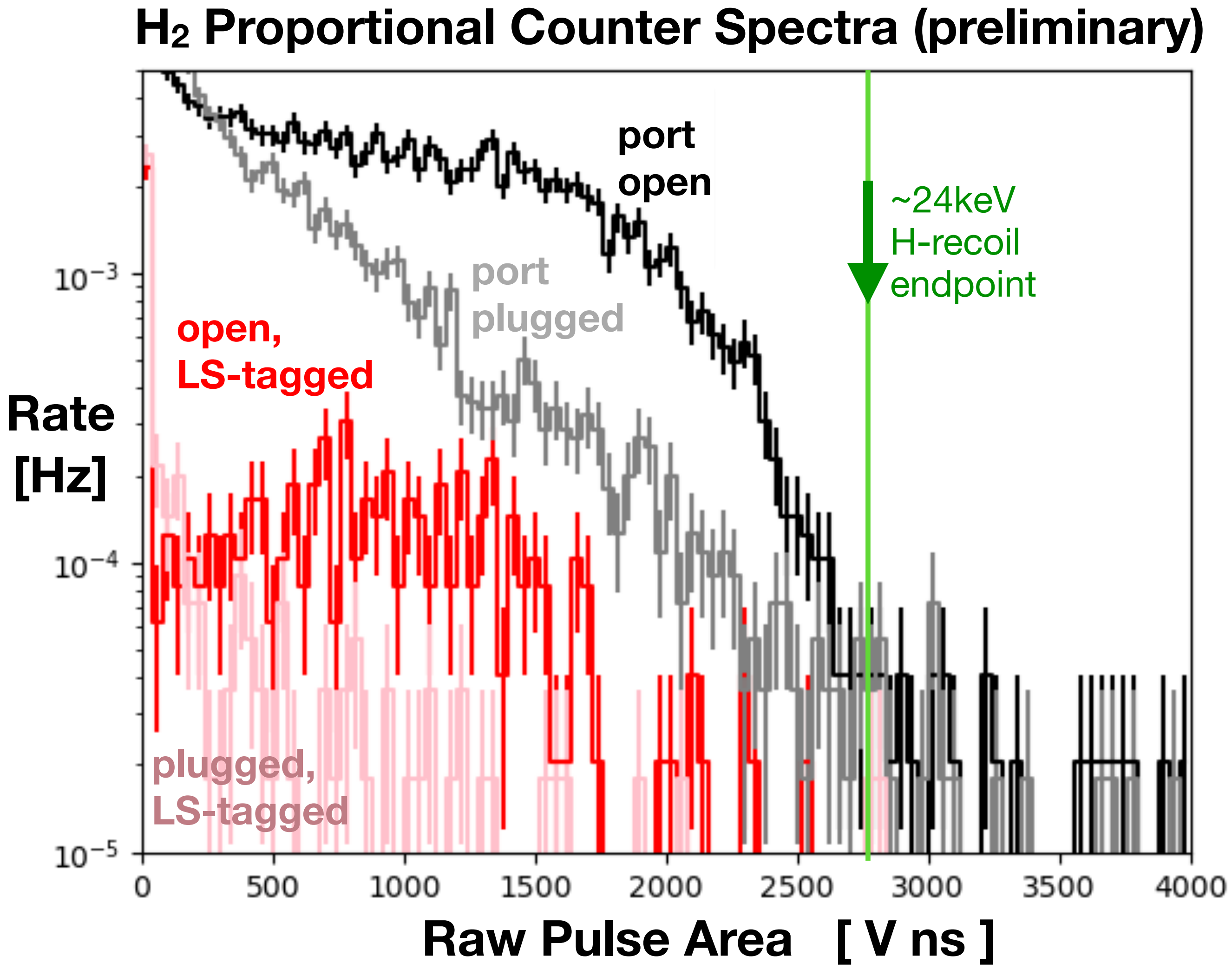


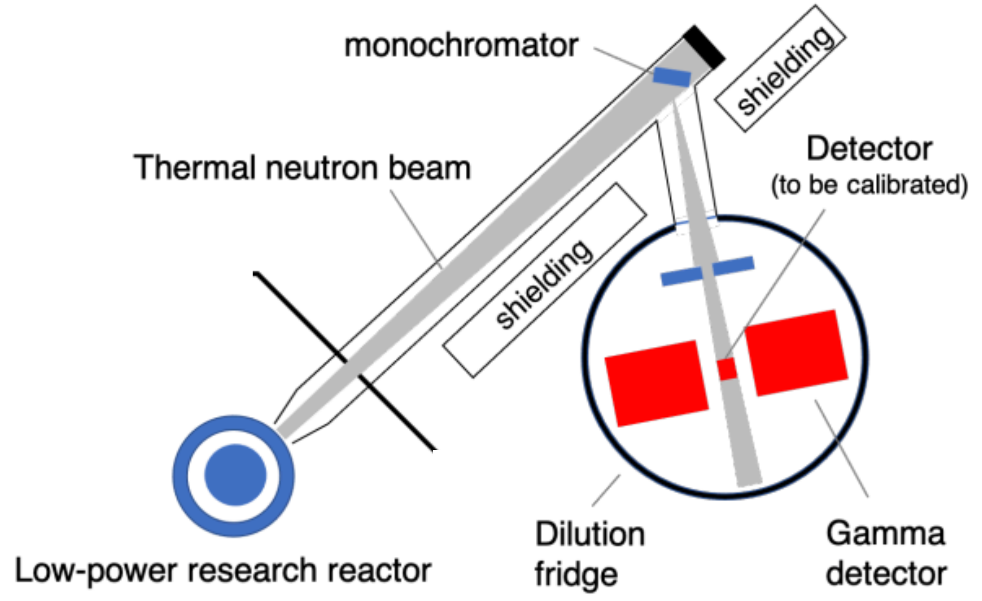




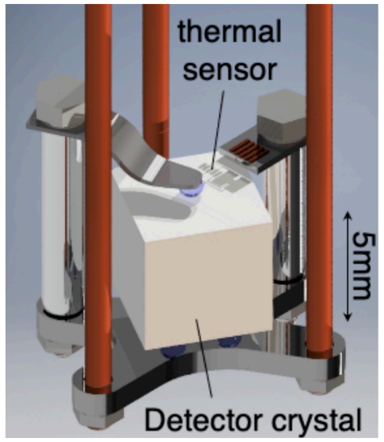
CRAB calibration effort

Setup

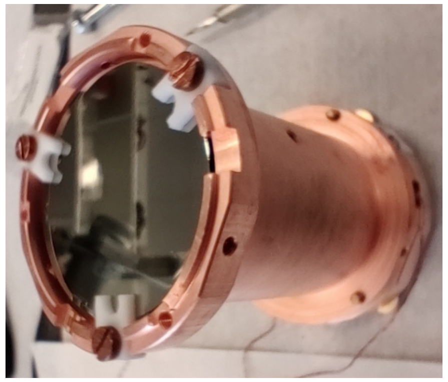
1. Well-collimated beam of thermal neutrons (TRIGA reactor in Vienna)



2. Detector holder with minimized Cu etc. (passive materials which can also activate and produce gammas)



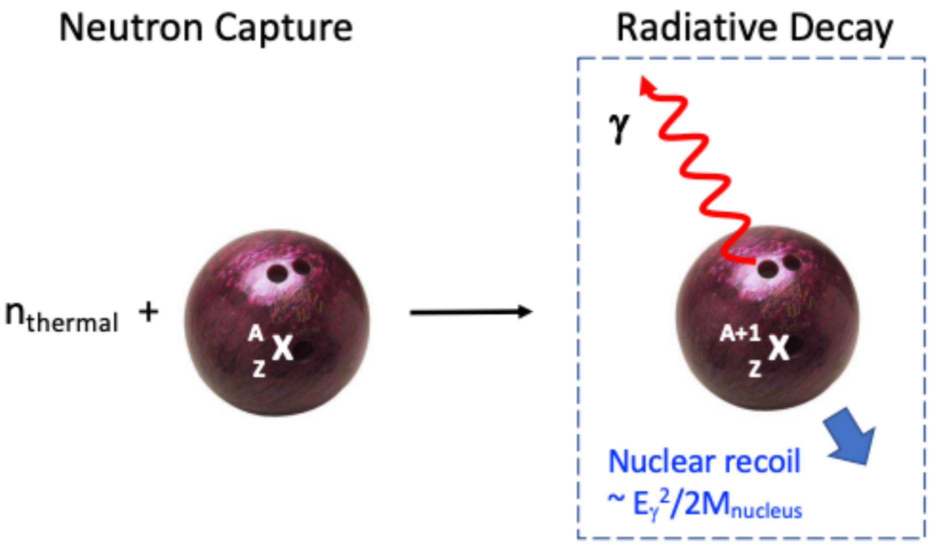
3. Gamma tagging of specific activation decays (large solid angle BGO within cryostat)



Result

Neutron capture of target material, with decays gamma-tagged.

Gamma emission results in low-energy monoenergetic NR.



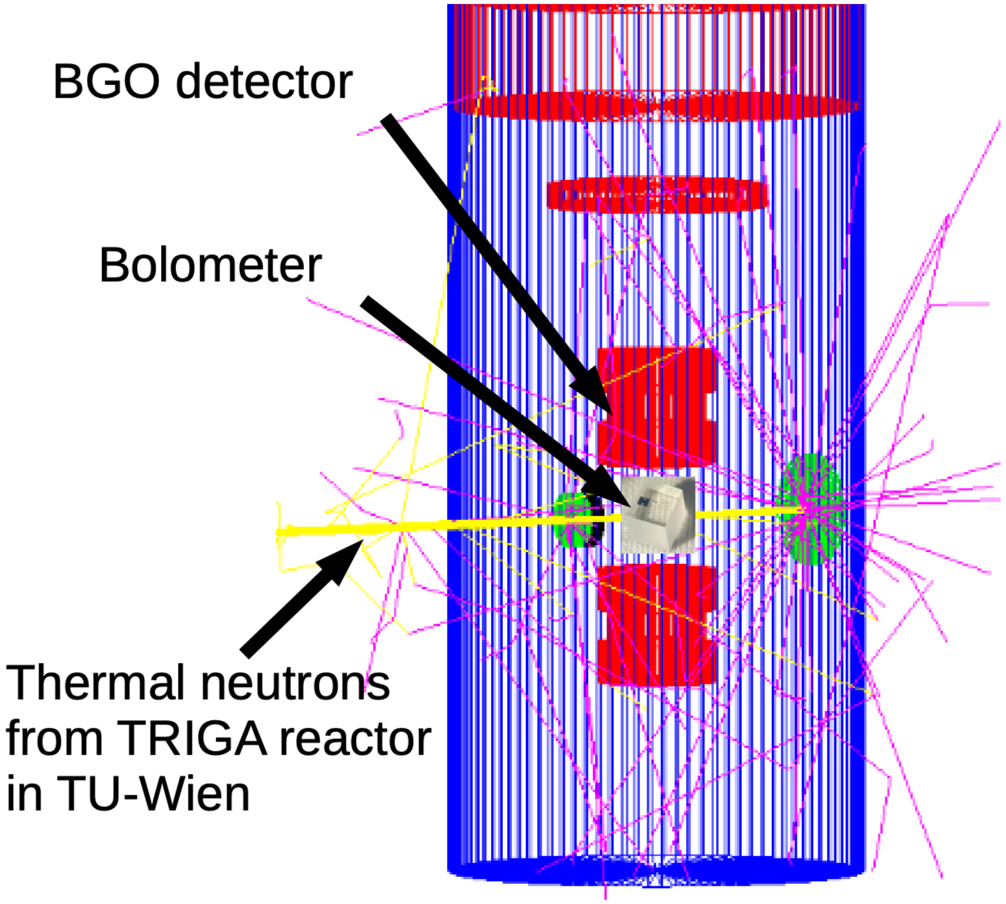
link

CRAB calibration effort

Clean tagging of monoenergetic recoils at interesting energies

examples:

^{182}W :	112.5 eV	(6.2 MeV gamma)
^{186}W :	85.8 eV	(5.8 MeV gamma)
^{70}Ge :	416.2 eV	(7.4 MeV gamma)
^{74}Ge :	303.2 eV	(6.5 MeV gamma)



BGO detector

Bolometer

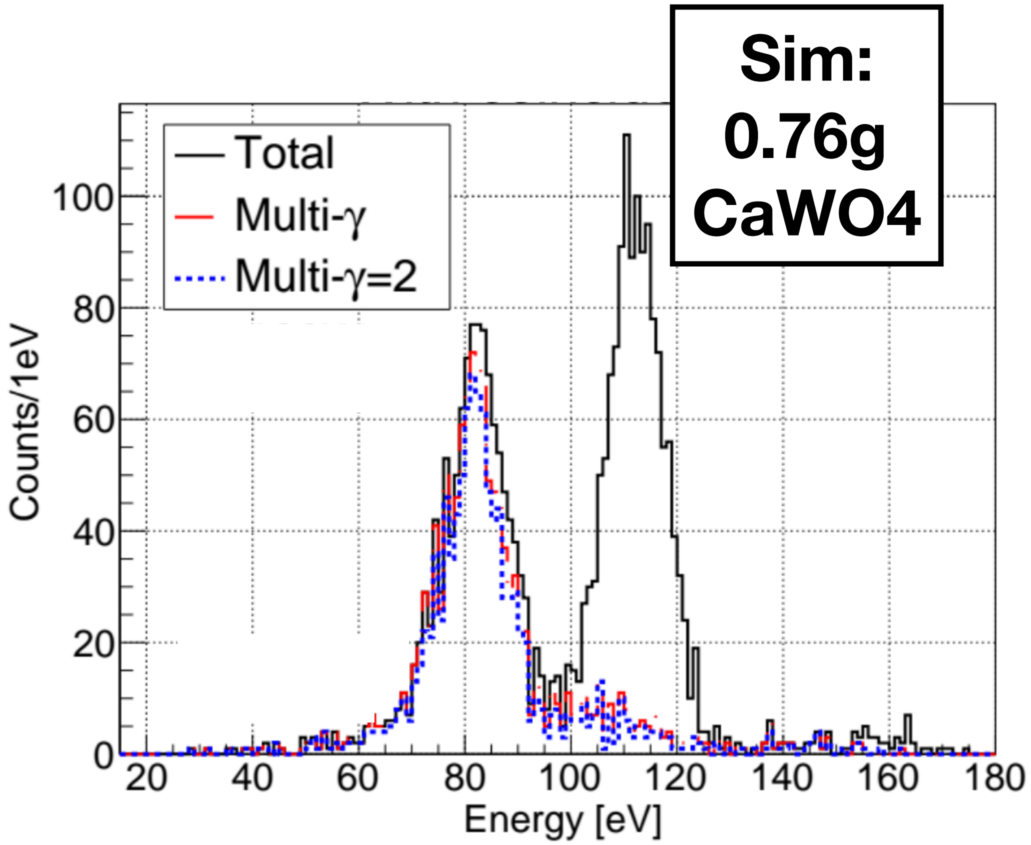
Thermal neutrons from TRIGA reactor in TU-Wien

Tantalizing possibilities:

-still sorting through all possible peaks in detector materials

-additional useful peaks via triple coincidence (two gammas)

-gamma records *direction* of NR…



Sim: 0.76g CaWO4

CRAB planning for first measurement in 2023

Also: Si effort from Villano *et al.*

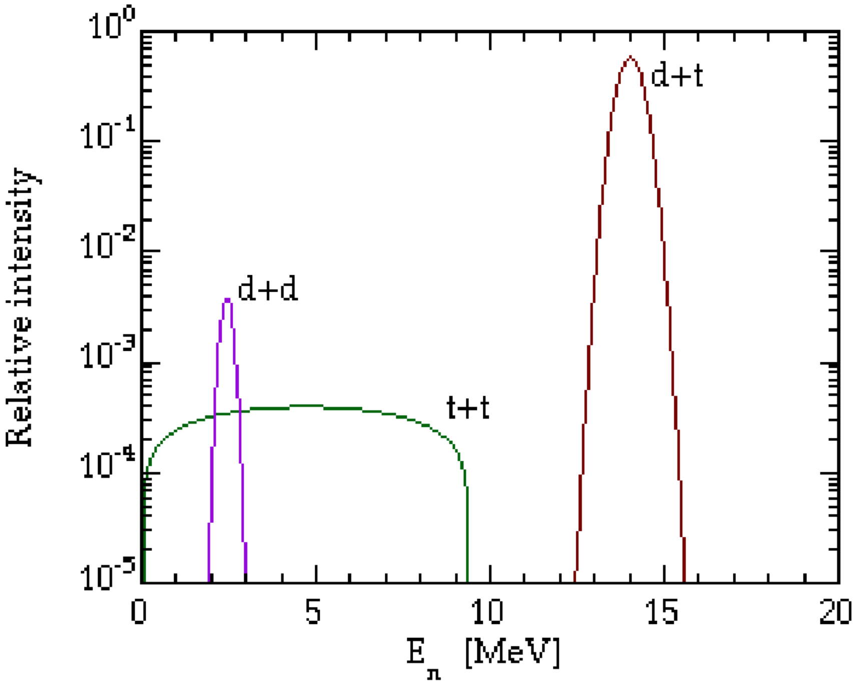
(real data, but waiting gamma-tagging)

arXiv:2110.02751

link

DD/DT generators

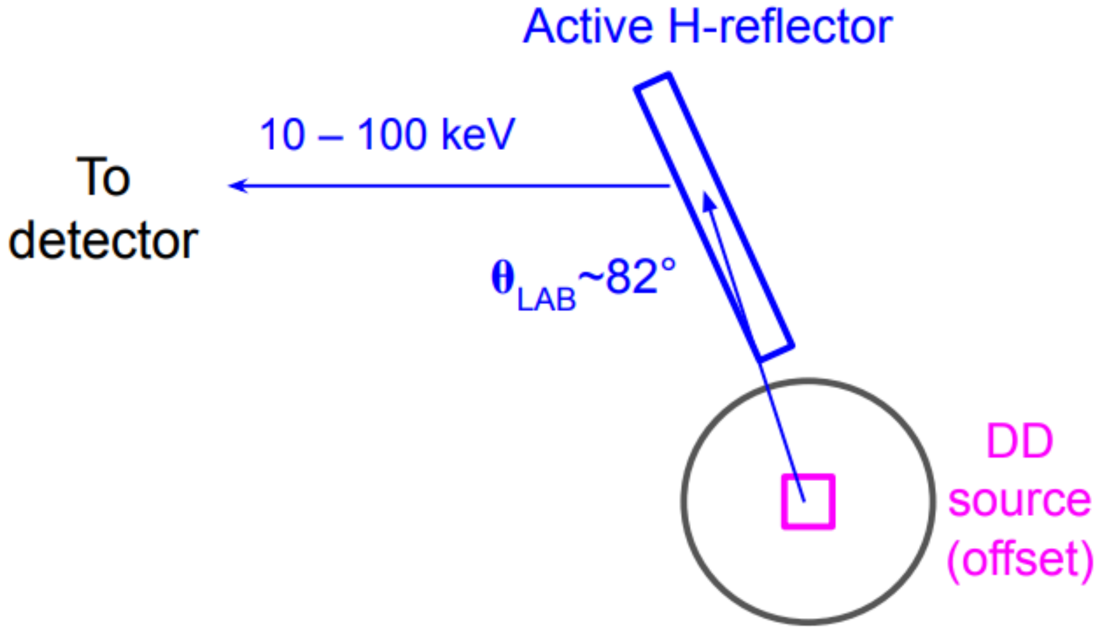
A beautiful MeV-scale technology:
- -monoenergetic
- -pulsable (~1μs)
- -portable
- -affordable

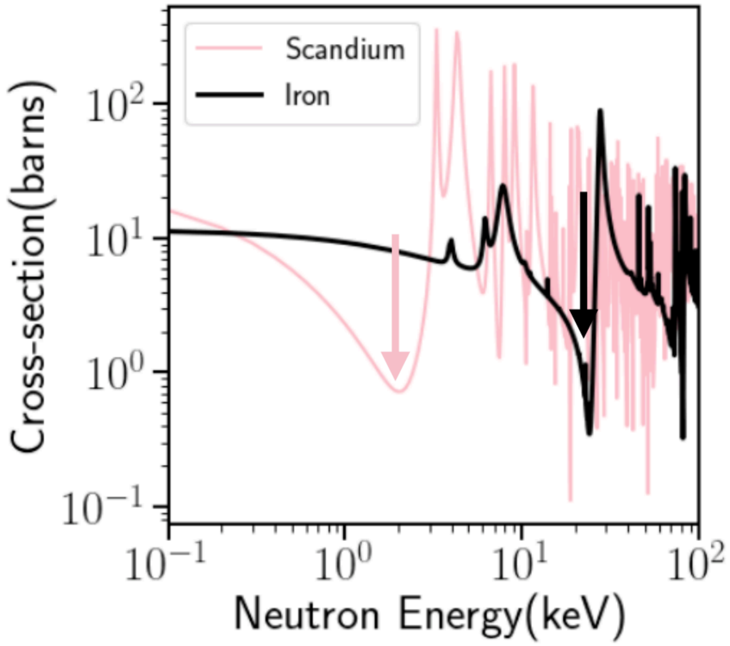


Two ways to bring the energy down, while retaining the pulsed monoenergetic nature:

1) Scatter off known nucleus at known angle

2) Moderate, then filter





Reflected DD neutrons

Championed by Gaitskell Group at Brown.

(for LZ context, but of general utility.)

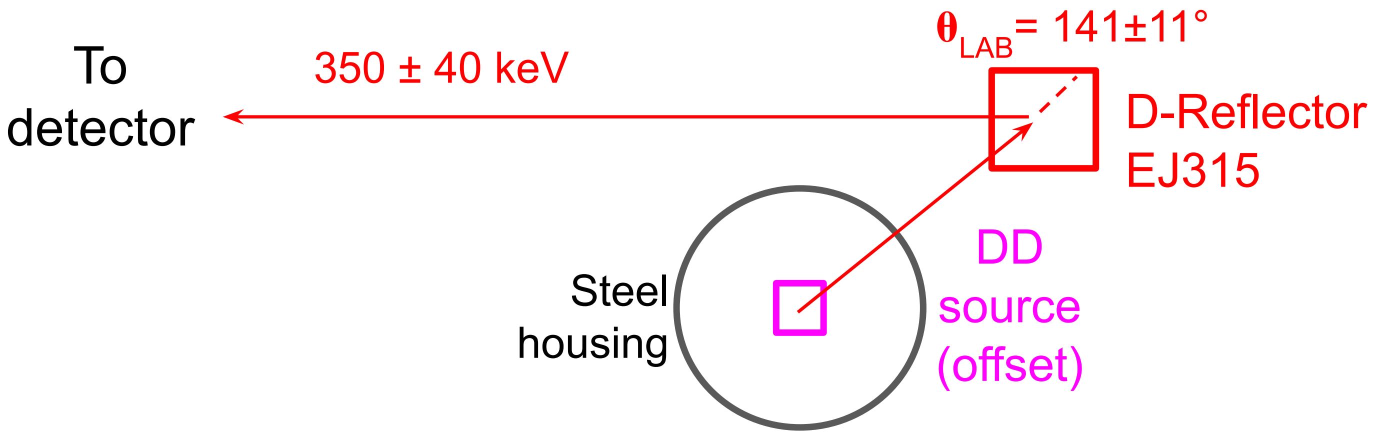
A single scatter at a known angle ‘downshifts’ monoenergetic DD neutrons to a tunable lower energy.

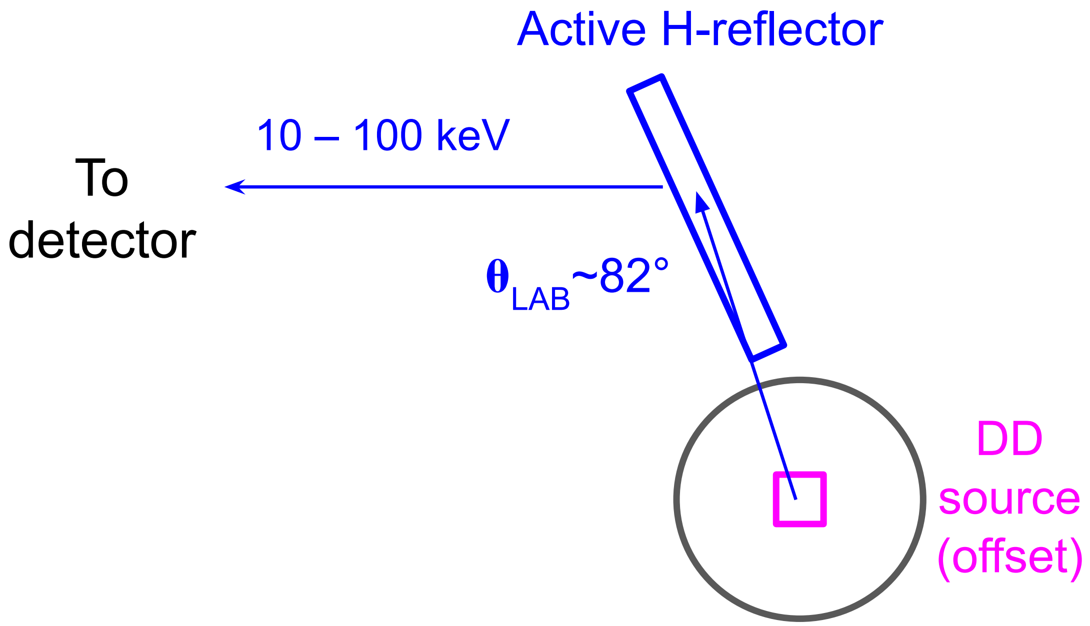
Developed two reflectors for different energy regimes:

- Deuteron-reflector for ~350 keV
- H-reflector for for <100 keV

Reflector material can be active scintillator, tagging the reflection event and starting a ToF clock.

Requires significant shielding to avoid direct path.





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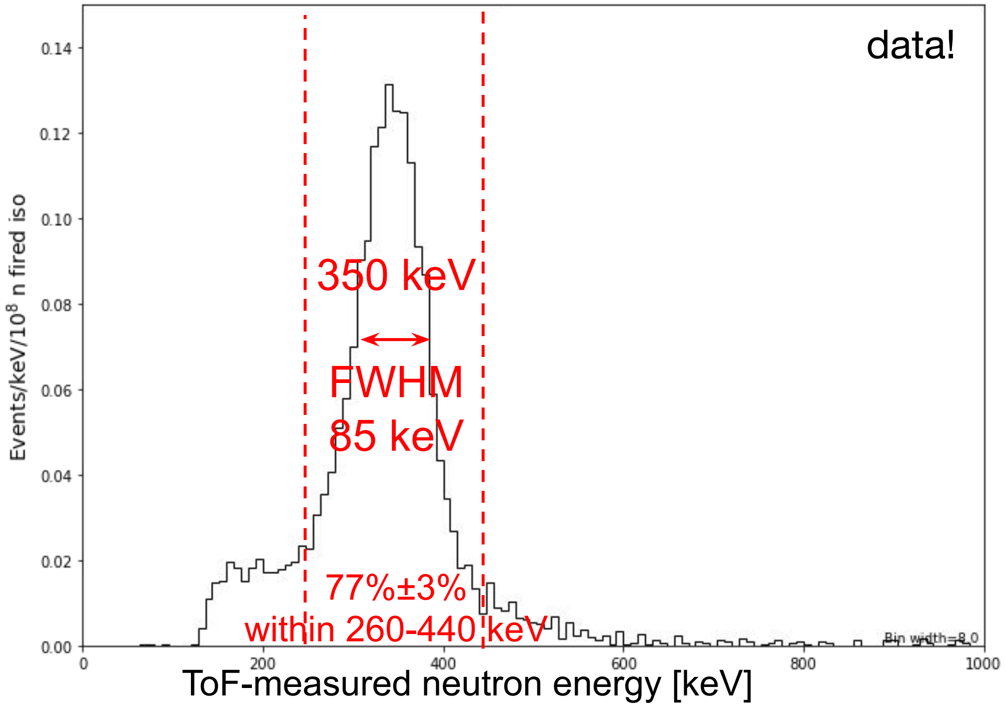
Reflected DD neutrons

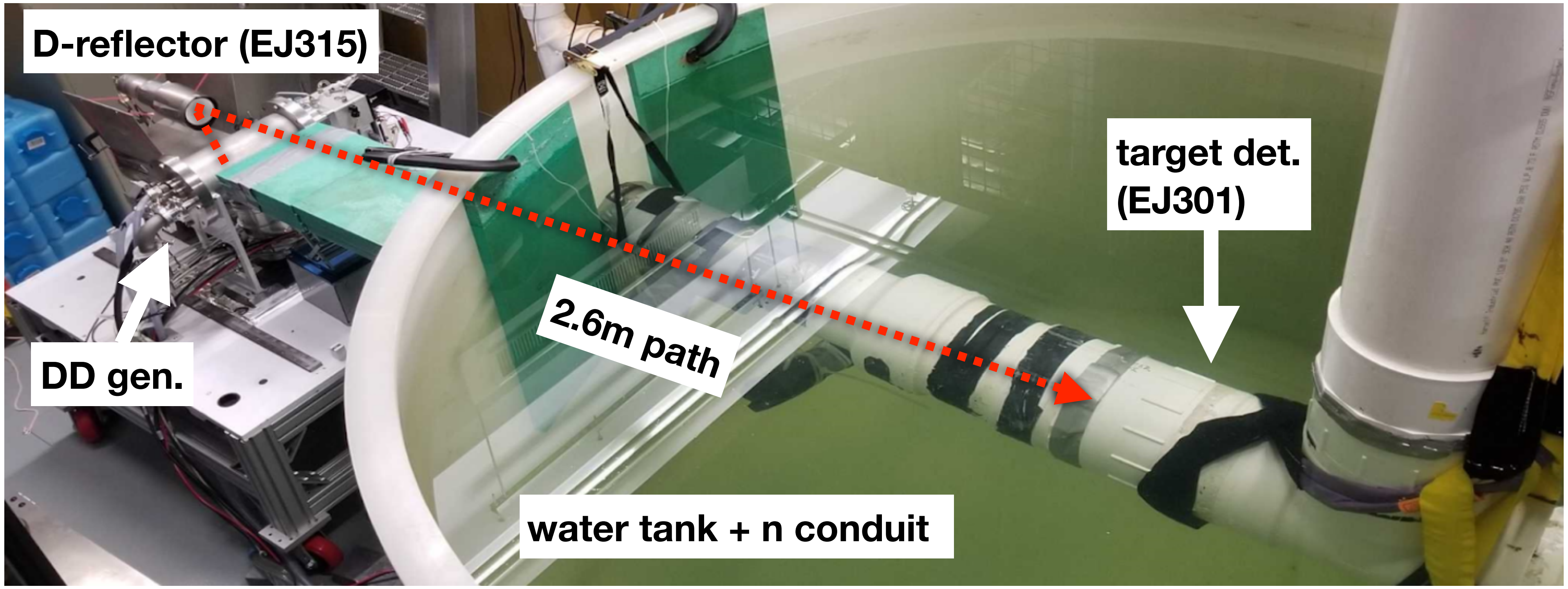
D-reflector demonstration at Brown:

Reflector is D-loaded EJ315 (instrumented)
  Fast (4ns) scatter timing resolution

Time of flight measurements permit per-neutron energy reconstruction (assuming fast target detector)

4E7 n/s total DD flux becomes 5 n/s in 350keV peak at target detector (2.6m path)





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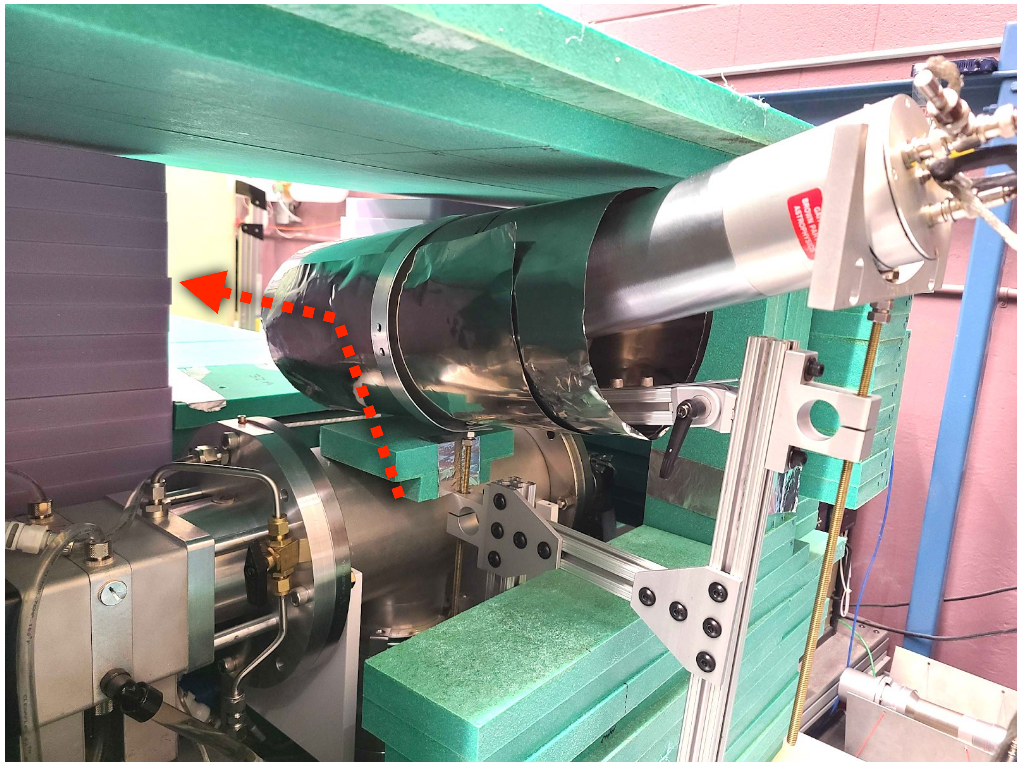
Reflected DD neutrons

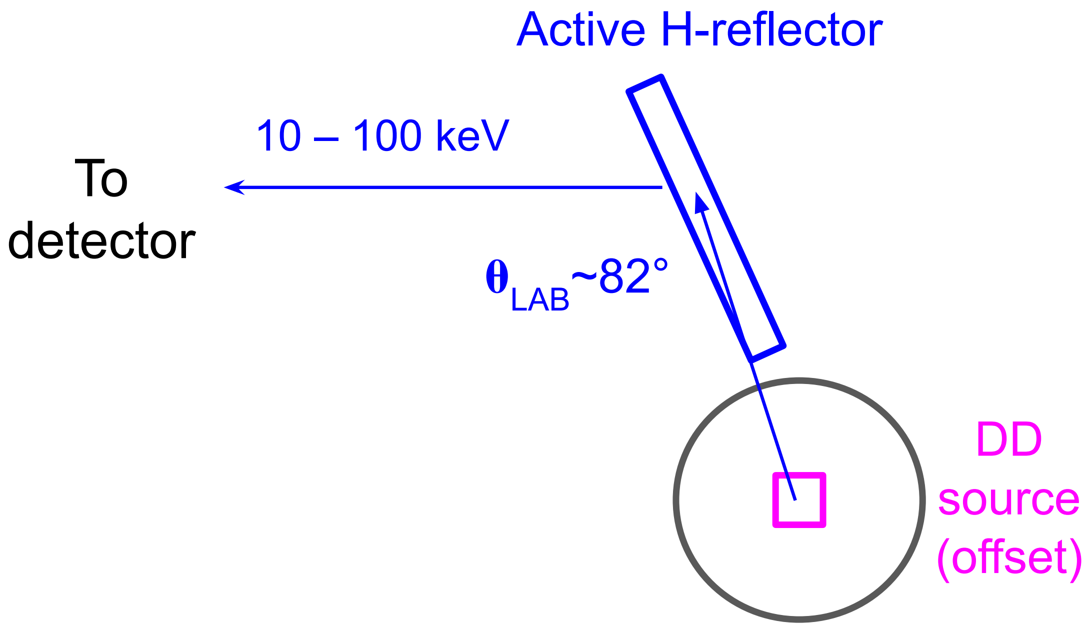


H-reflector demonstration at Brown:

Forward scatter produces <100kev neutrons.

Again an actively-instrumented reflector, and again ToF permits per-neutron energy reconstruction (assuming fast target detector)

(No public data yet.)


Active H-reflector

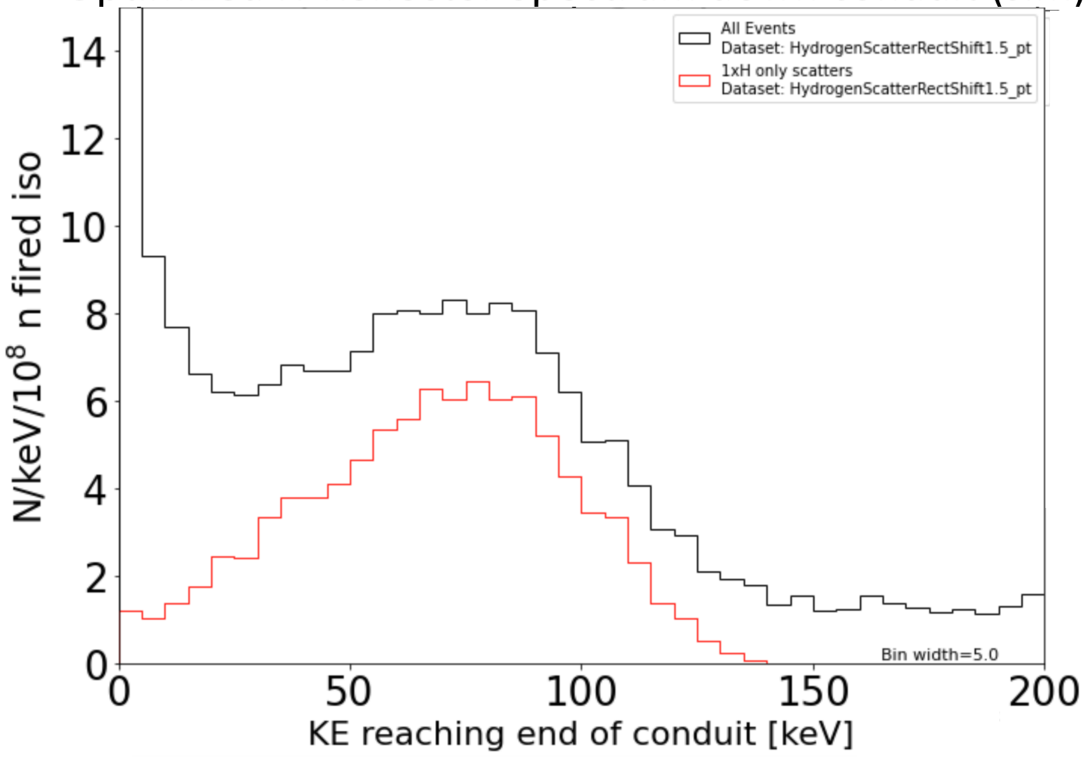
10 – 100 keV

To detector

θ_{LAB}~82°

DD source (offset)

Optimized H-Reflector Spectrum down conduit (sim)



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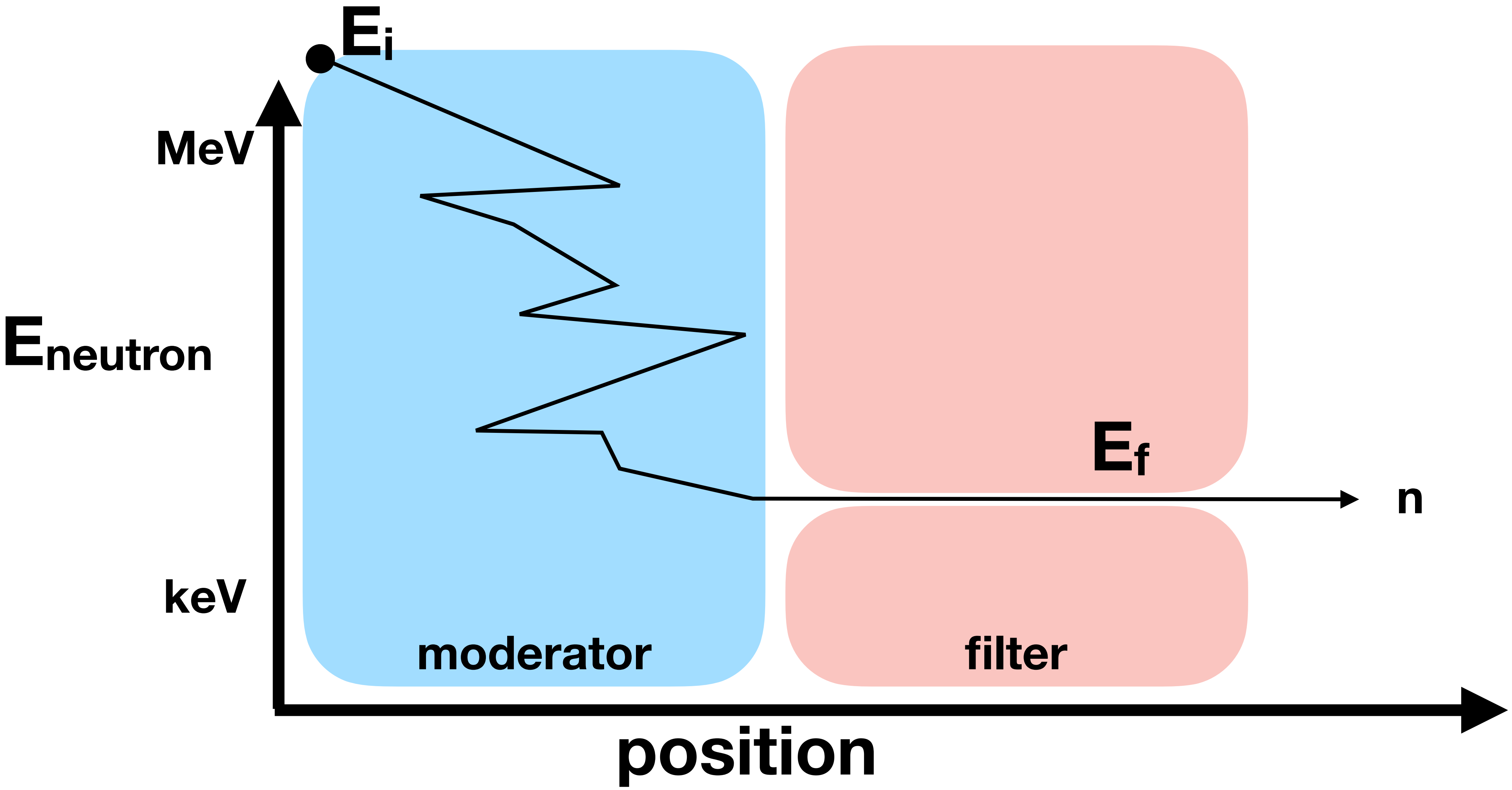
Moderated/Filtered DT neutrons

Championed by Hertel Group at UMass.
(Rest of talk largely work of my student Pratyush Patel)

In SPICE/HeRALD context, but is of general utility.

1. *Many* scatters moderate neutrons to the keV scale

2. Materials with special neutron transmission energies filter the moderated flux.

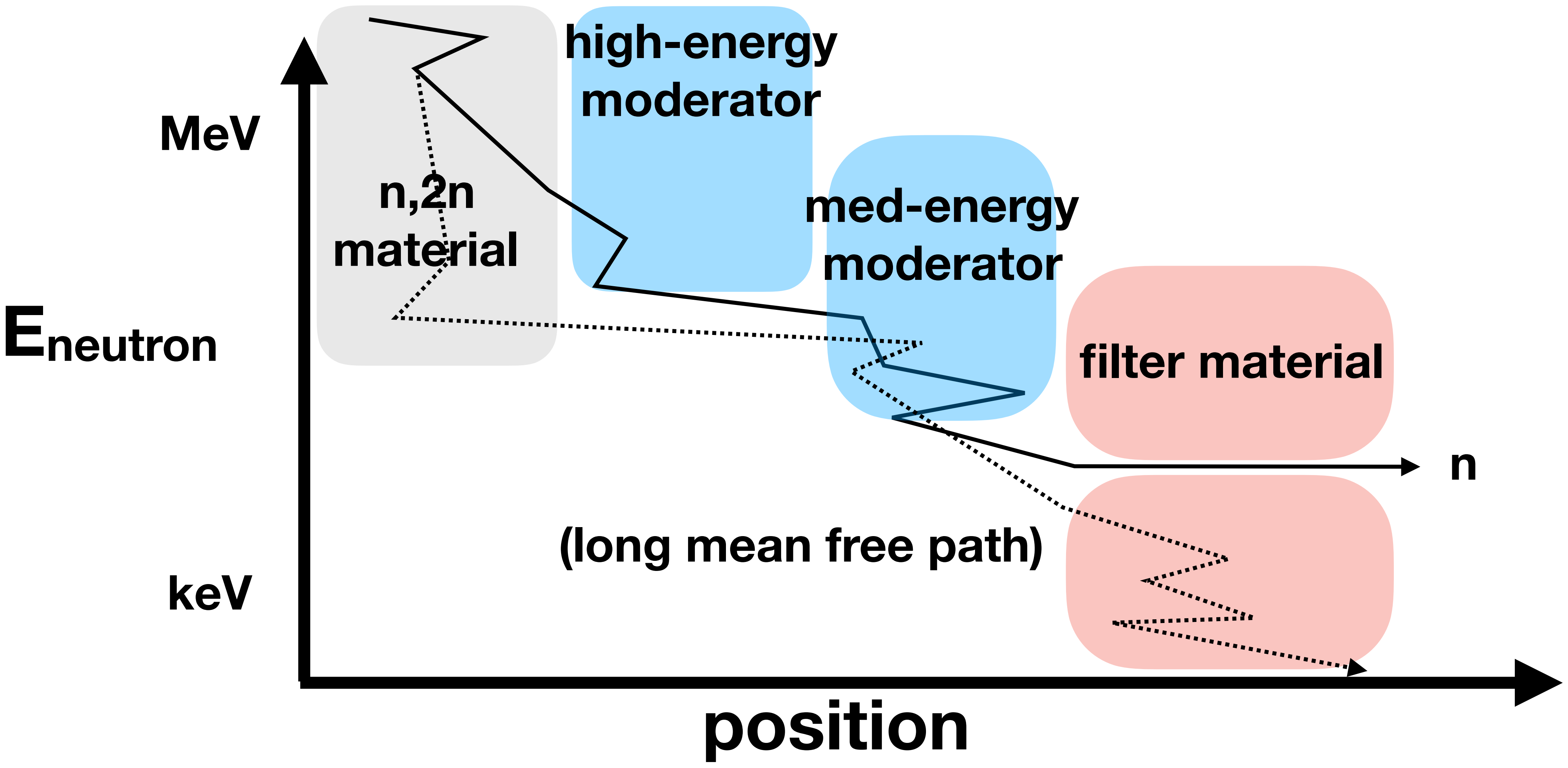


Moderated/Filtered DT neutrons

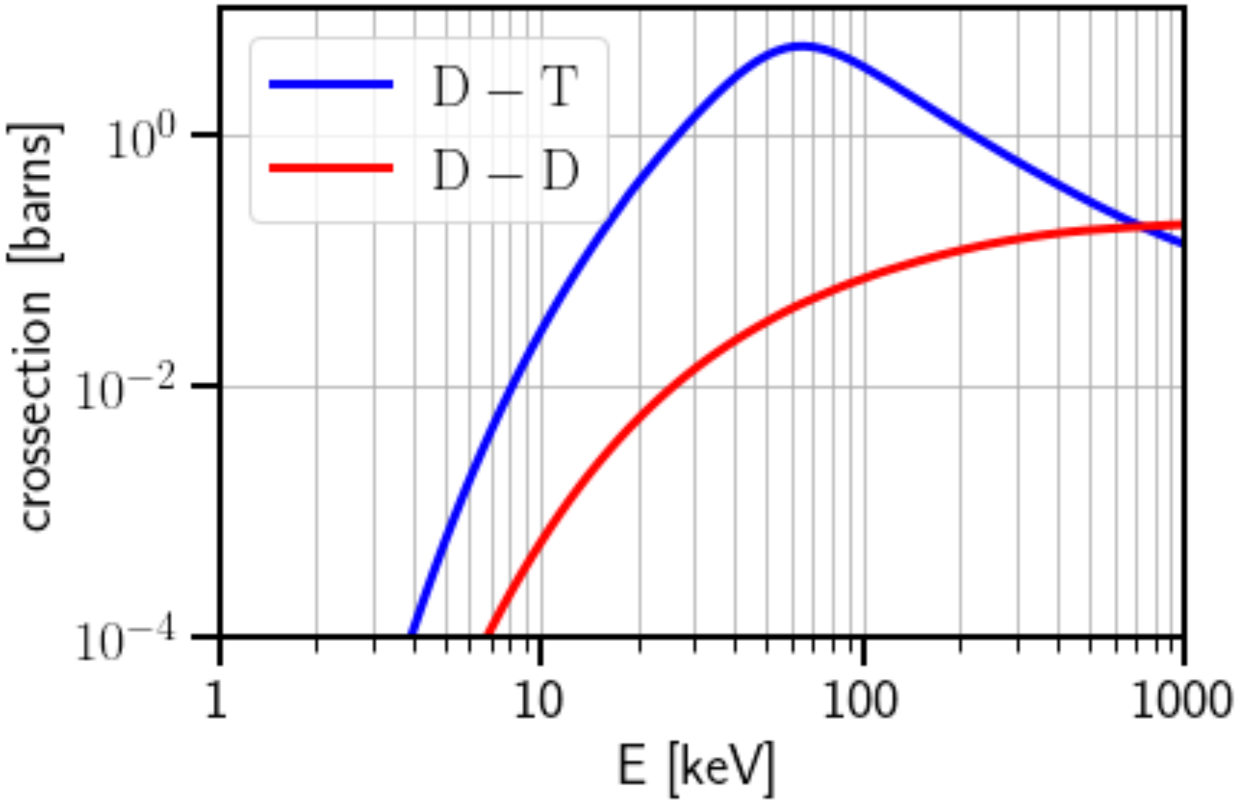
Can be made more efficient by…

1. Starting with DT at 14MeV, which allows initial moderation via n,2n

2. Using an ordered sequence of tuned moderators with tuned low-energy cut-offs

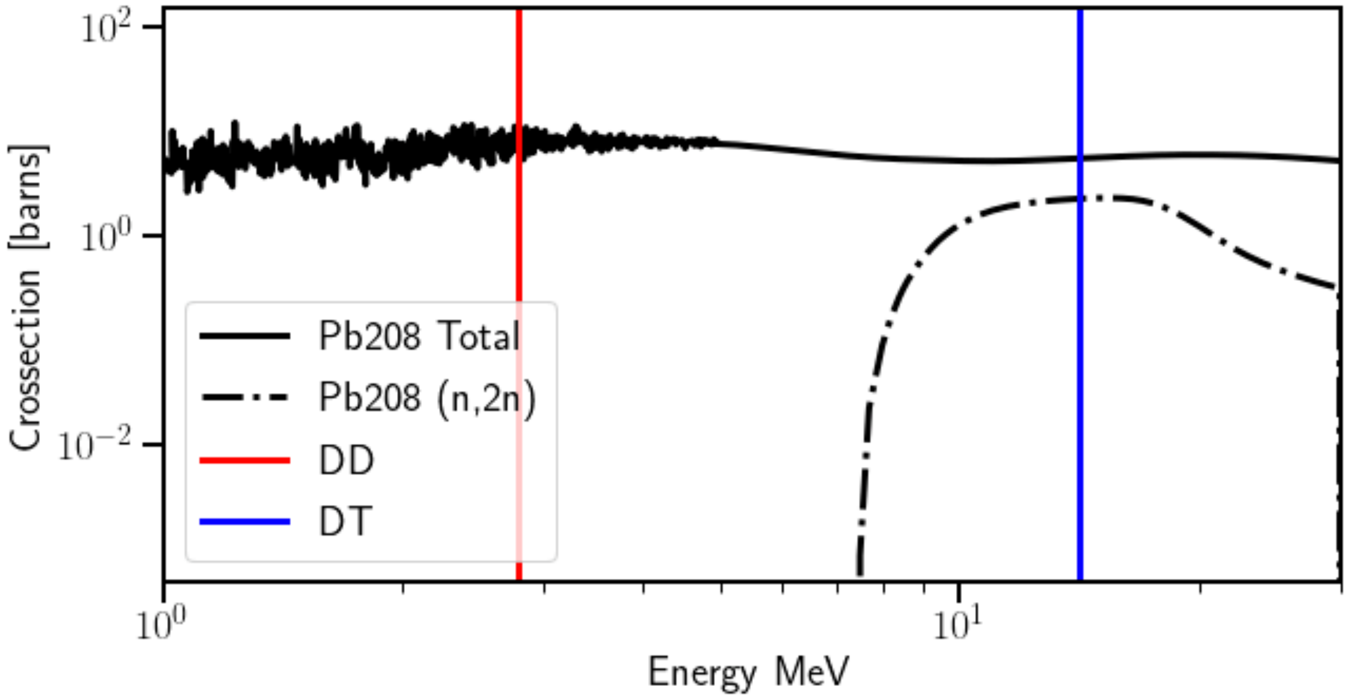


Moderator/Filter… step 1



DT reaction cross section much higher than DD

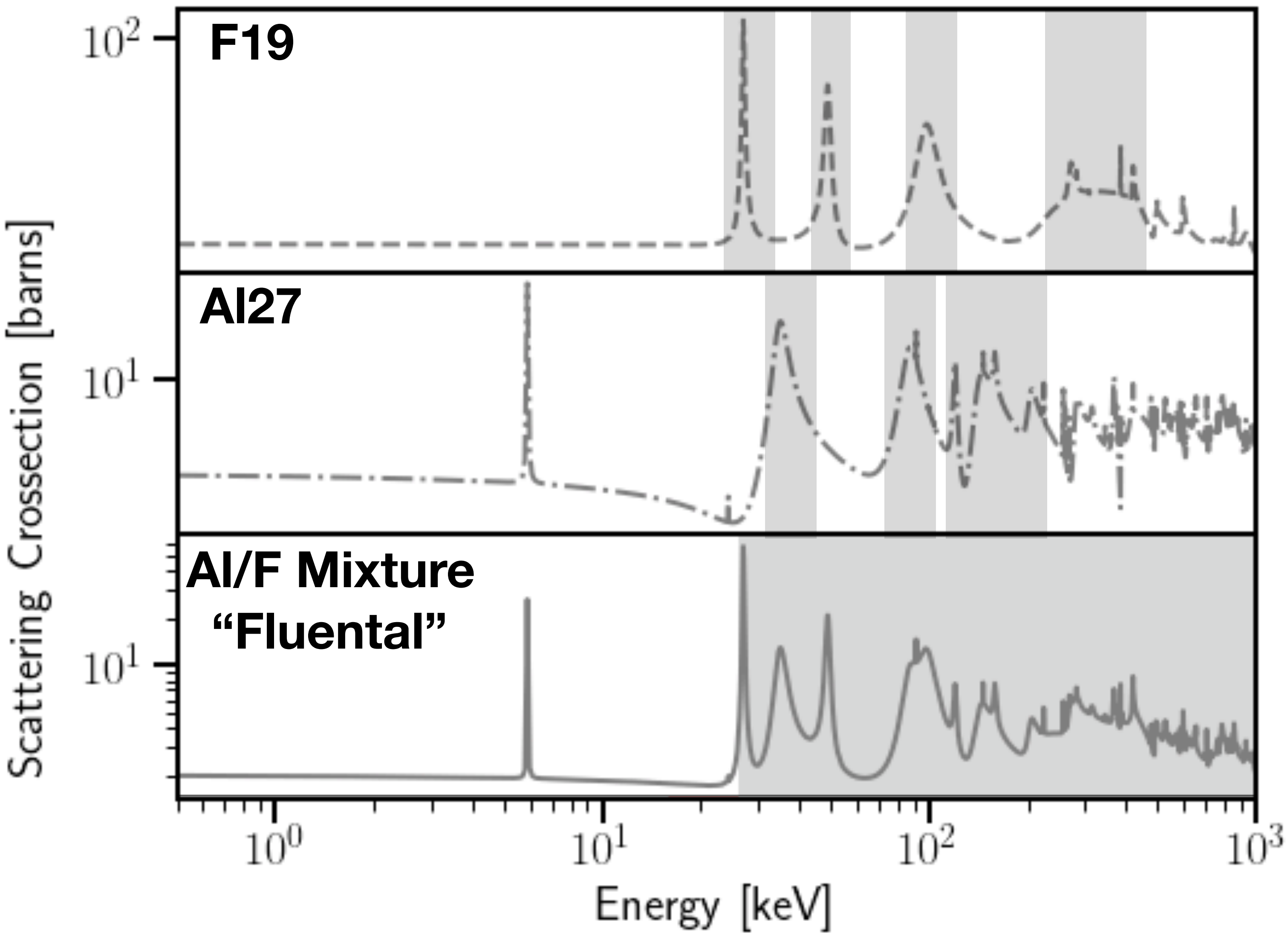
(more neutrons per pulse)



Pb first stage

Above 7MeV, allows efficient moderation and flux-enhancment via (n,2n) reactions

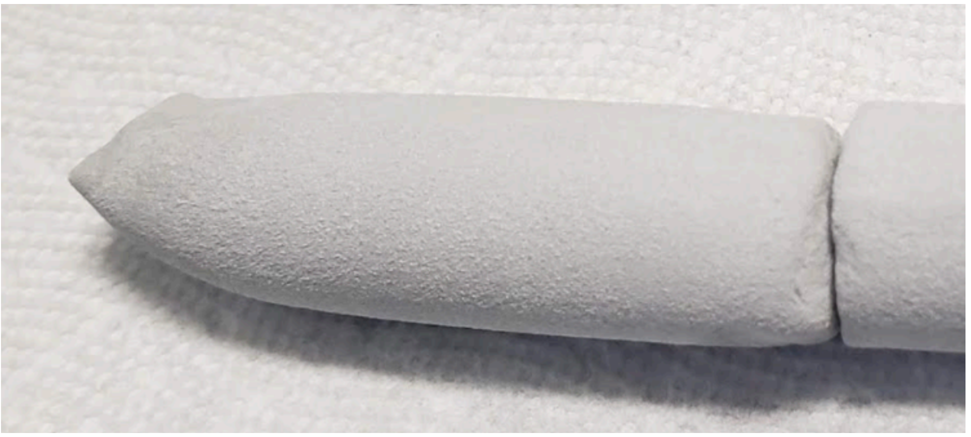
Moderator/Filter… step 2: tuned moderators



Al and F: Complementary resonances

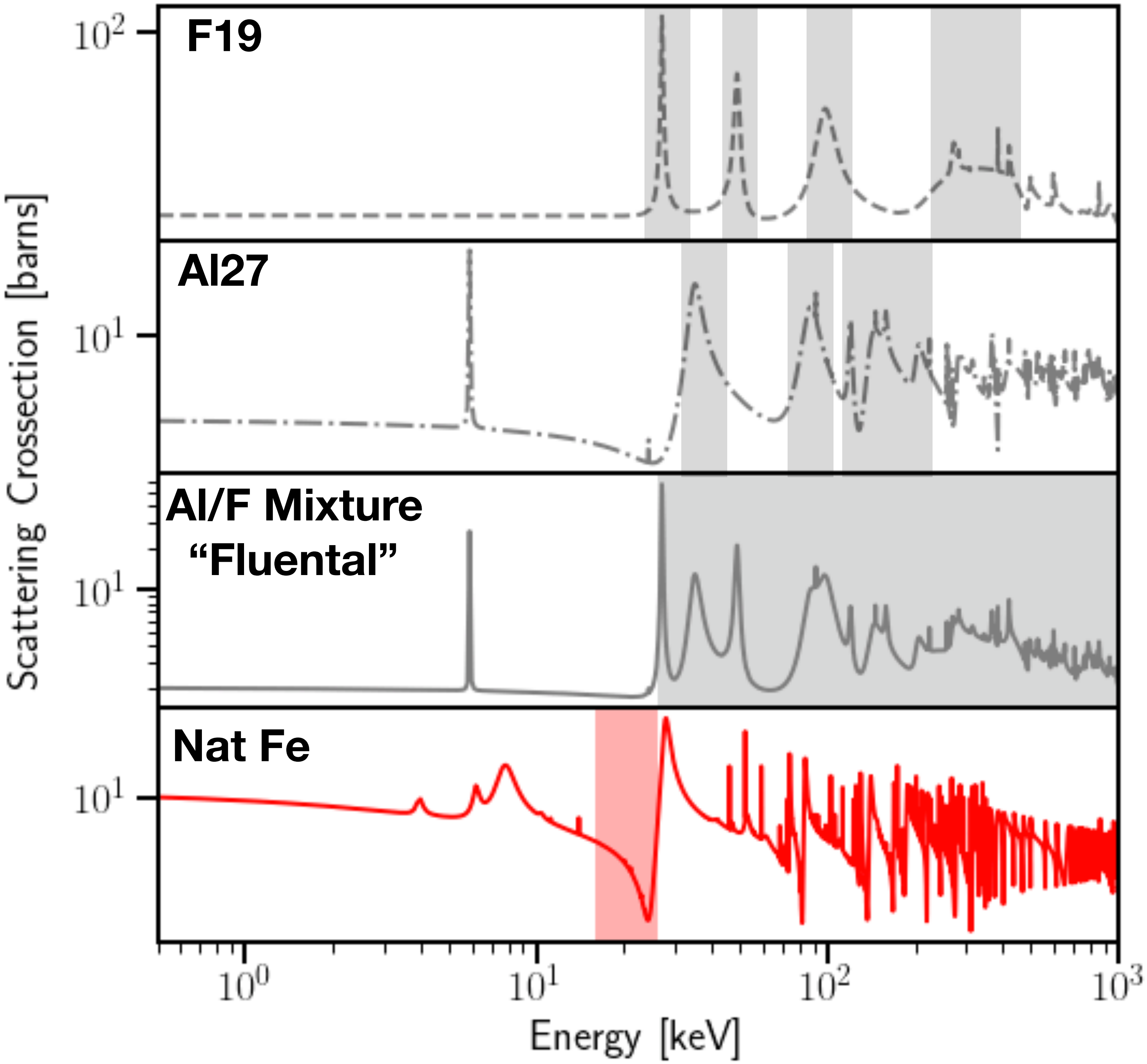
Together:
>30keV : neutrons scatter and moderate
<30keV : neutrons have long mfp

We are working with hot isostatic press (HIP) companies to form the Al/F.



Fluental link

Moderator/Filter… step 3: filtering



Al and F: Complementary resonances

Mixed together:
>30keV neutrons scatter and moderate
<30keV neutrons have long mfp

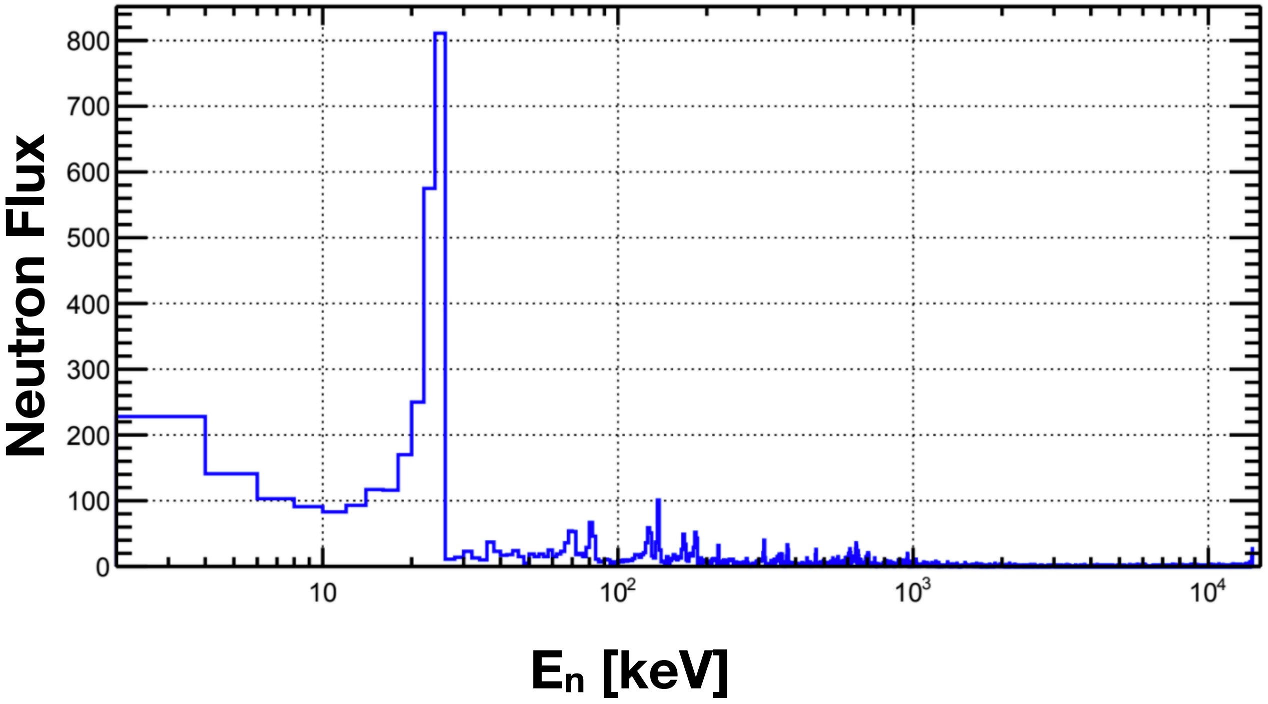
"dump" neutron flux at the 24 keV transmission resonance of Fe

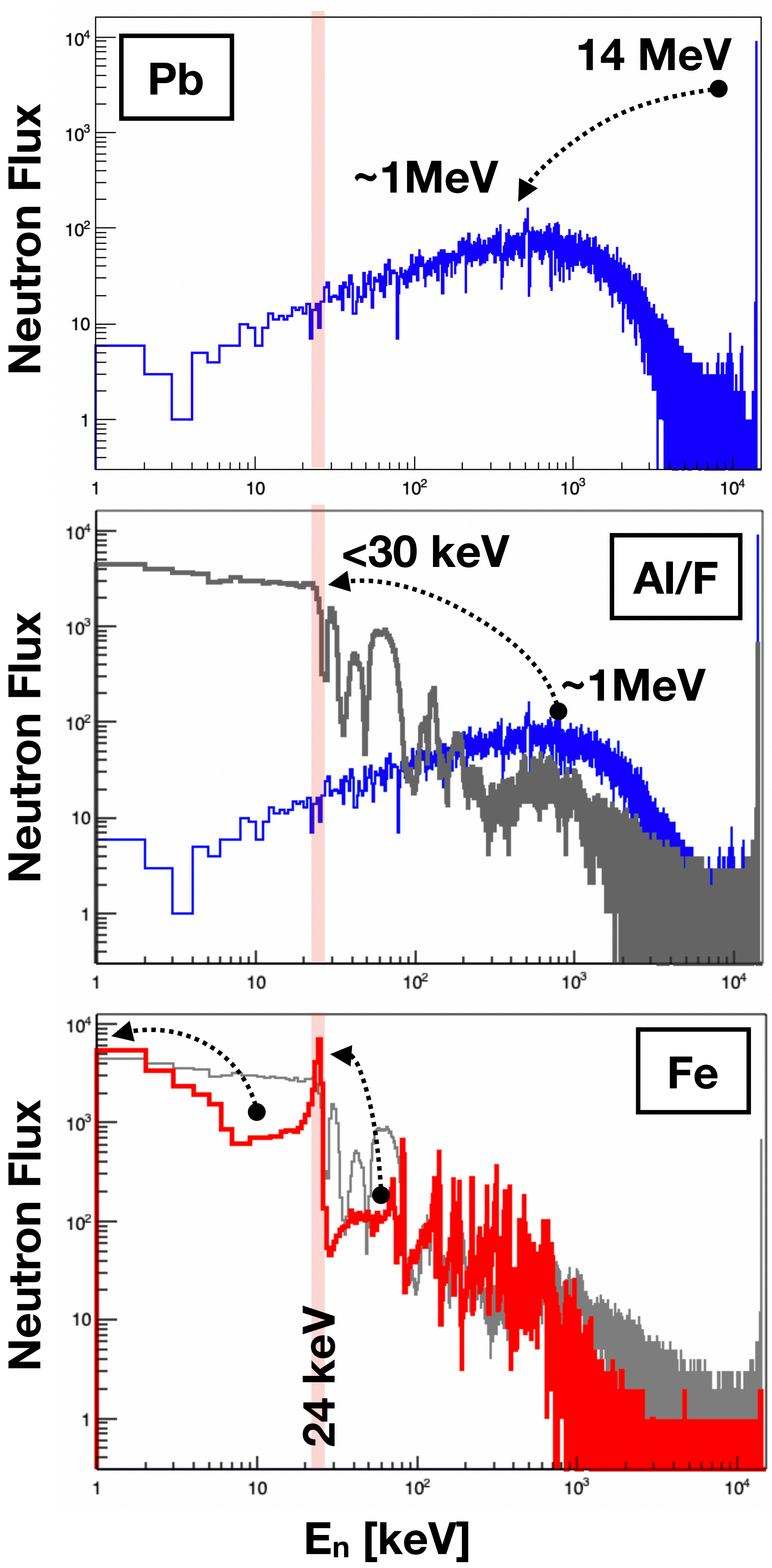
Fluental link

Putting the pieces together:

Simulations show each step performing its role.

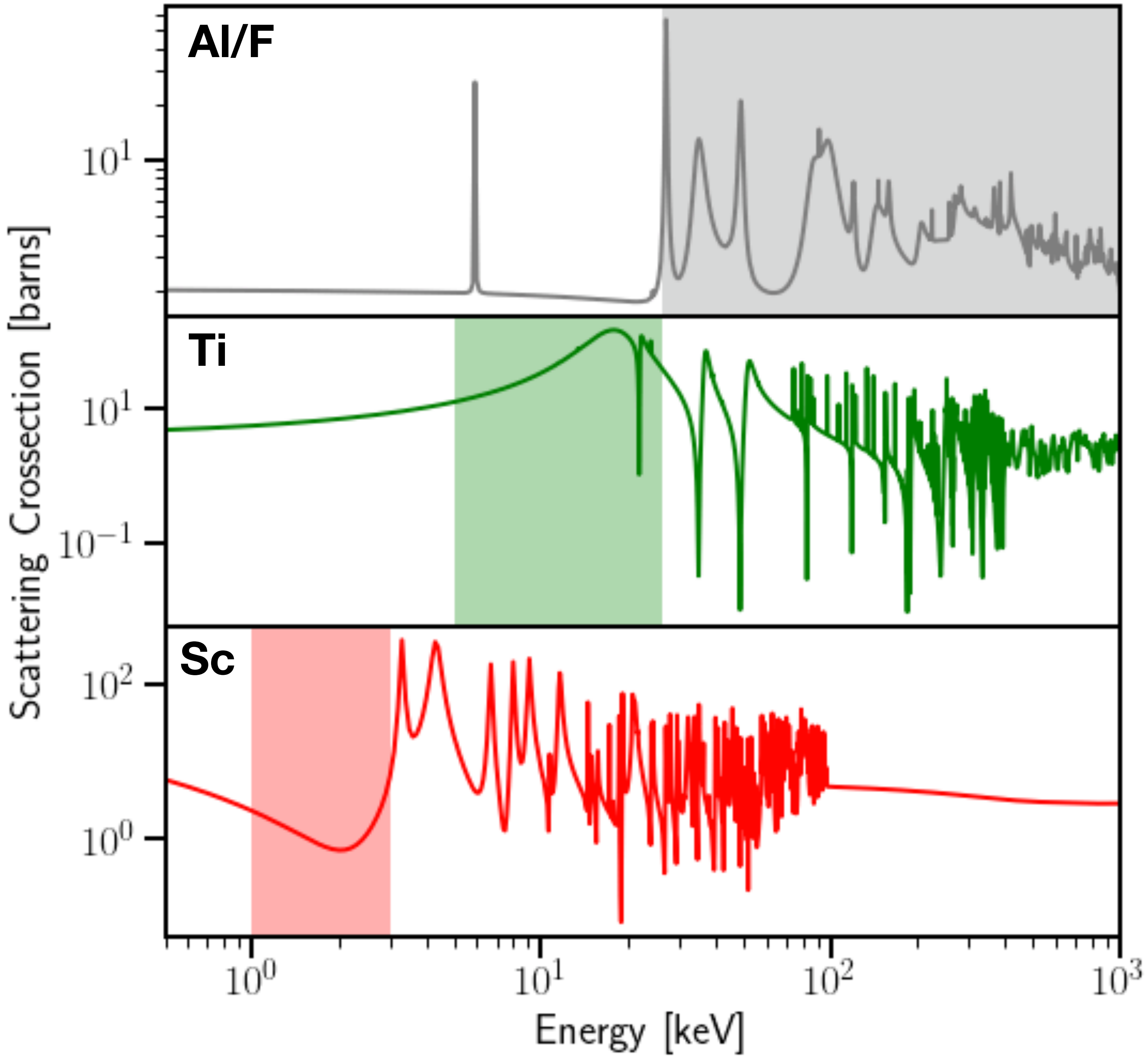
Sufficient flux and excellent resolution.





Sc filter (2 keV)

The scandium filter benefits from an additional stage of tuned-moderation.



Al/F mixture
(complementary resonances above 30keV)

Titanium
(large scattering cross-section near 20 keV)

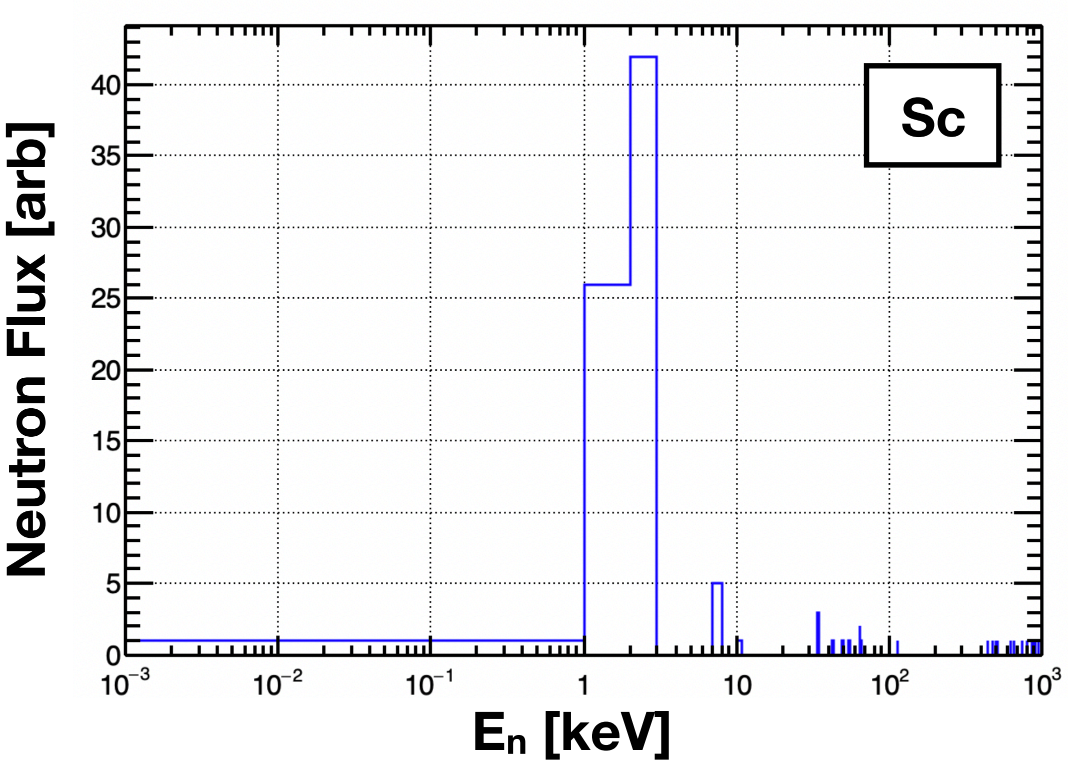
Scandium
(narrow anti-resonance feature at 2keV)

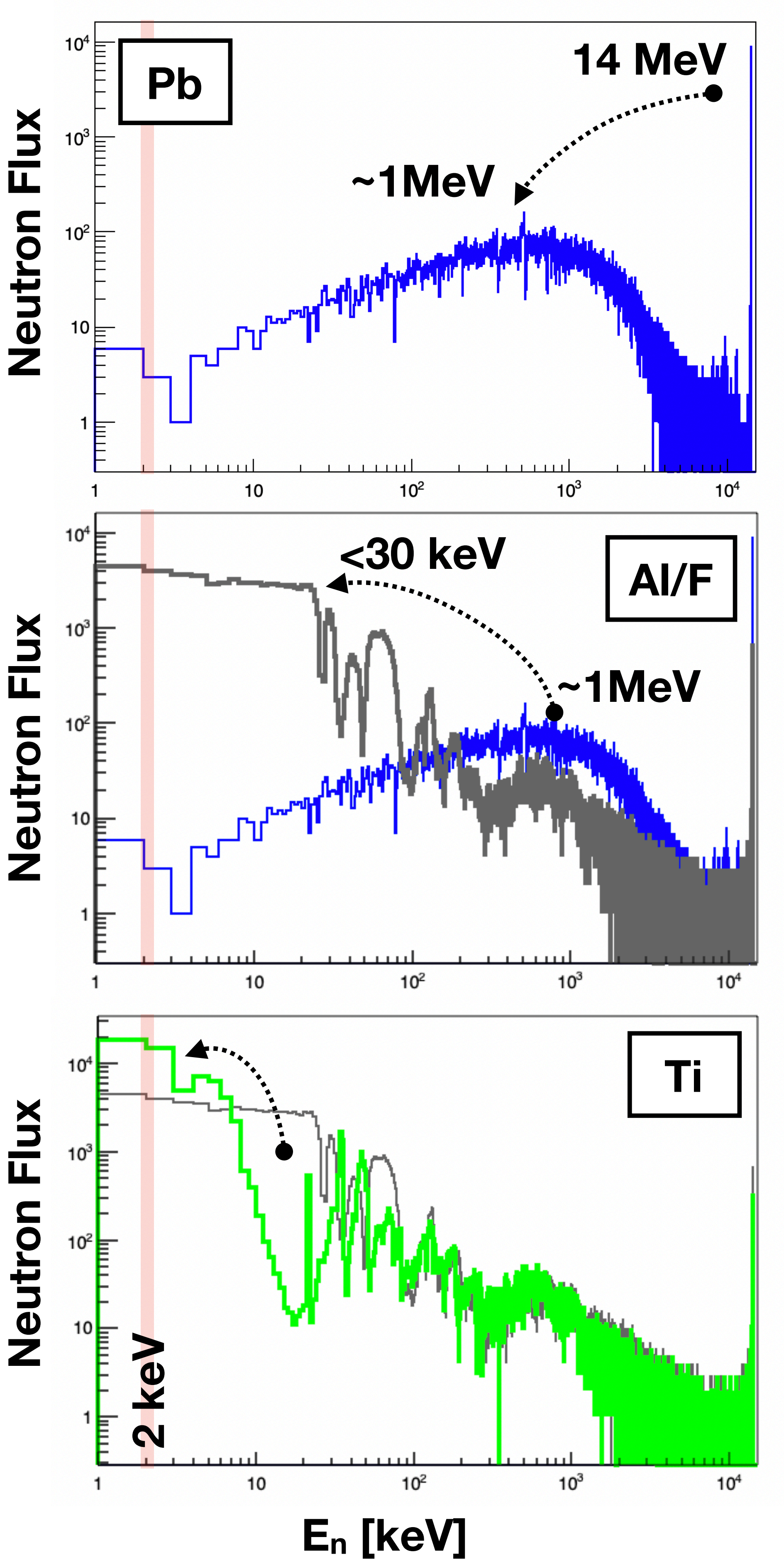
Sc filter (2 keV)

Simulations again show each step performing its role.

Flux is more of a challenge, but sufficient.

Sc roughly $30,000 /kg, and roughly 1kg needed.





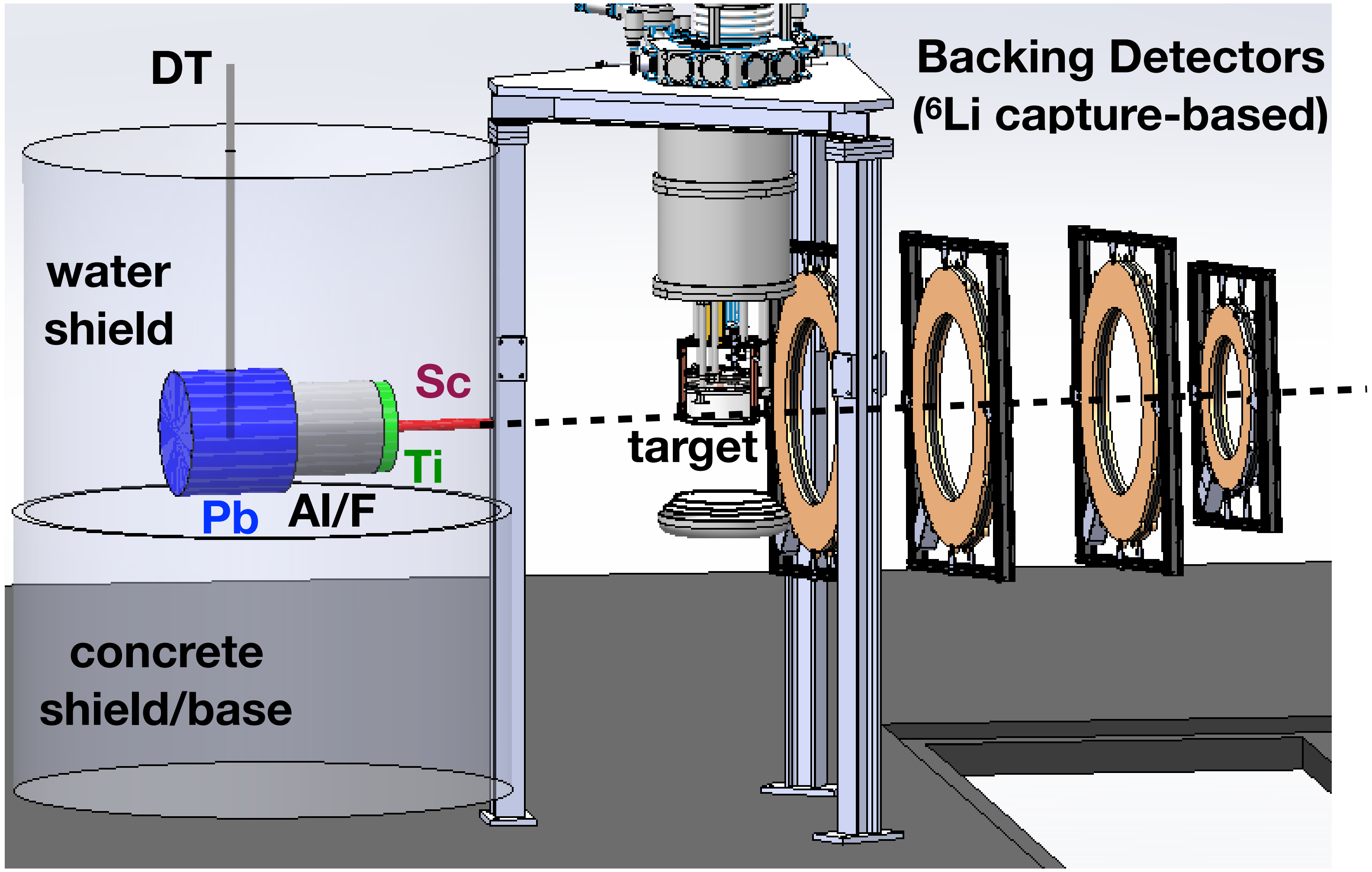
Sc filter : shielding and backing detectors

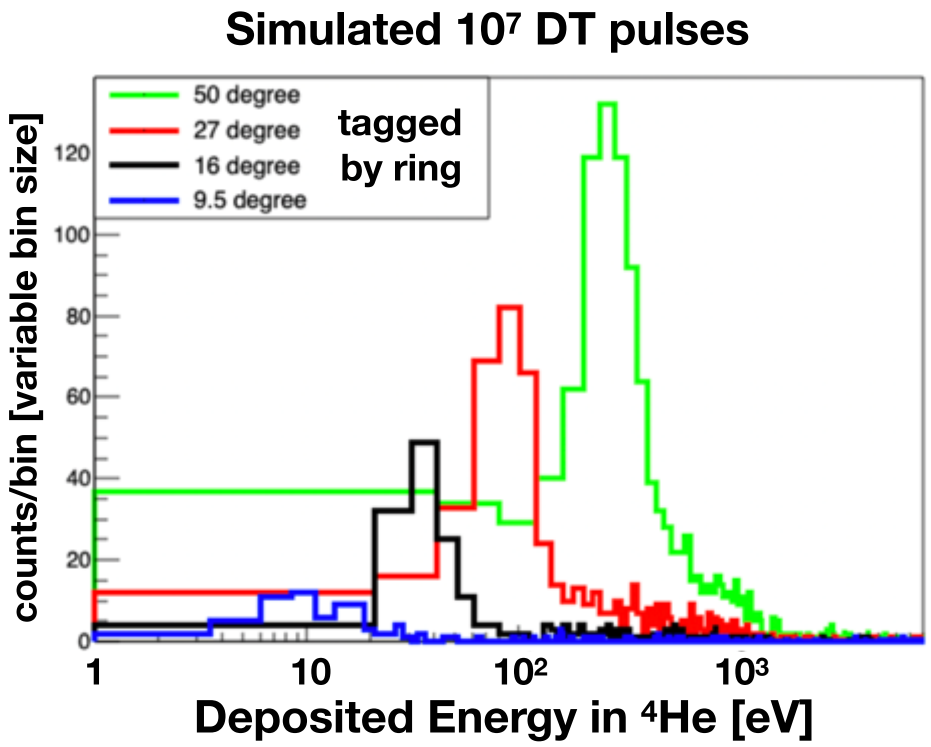
DT/moderator/filter assembly requires bulky shielding

(options: poly, water, concrete)

Simulations of entire calibration process (in 4He)

- -clean peaks at 10s to 100s of eV
- -sufficient flux/stats





Transitioning from monoenergetic sources to time-of-flight

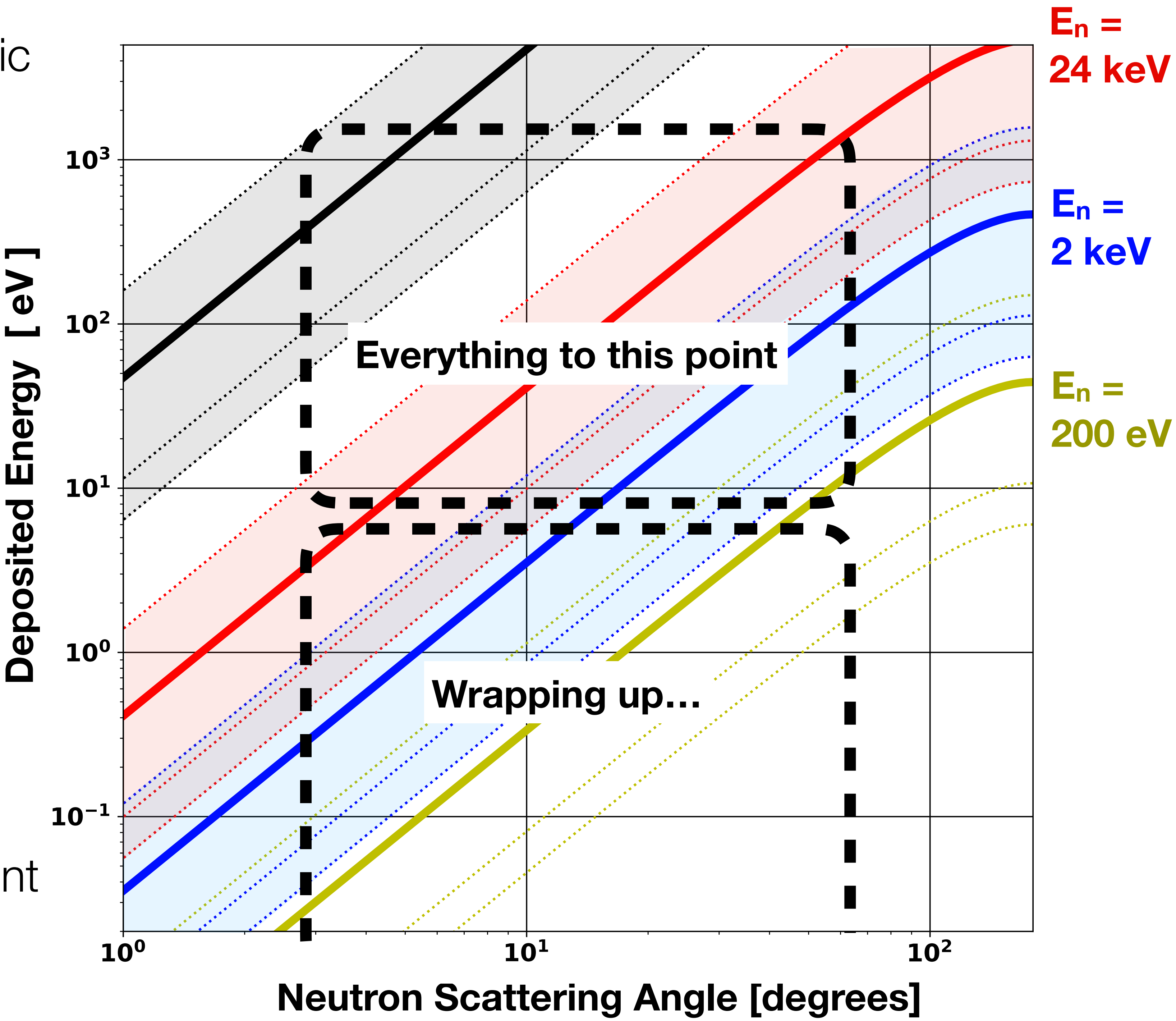
We have hit the end of mono-energetic neutron techniques.
(till we get to wave-like neutrons…)

But don't despair!

Things get EASIER for E_n<1keV, thanks to TOF:

-Neutrons are slow
  (energies are distinct)

- Capture-based det. fast and efficient



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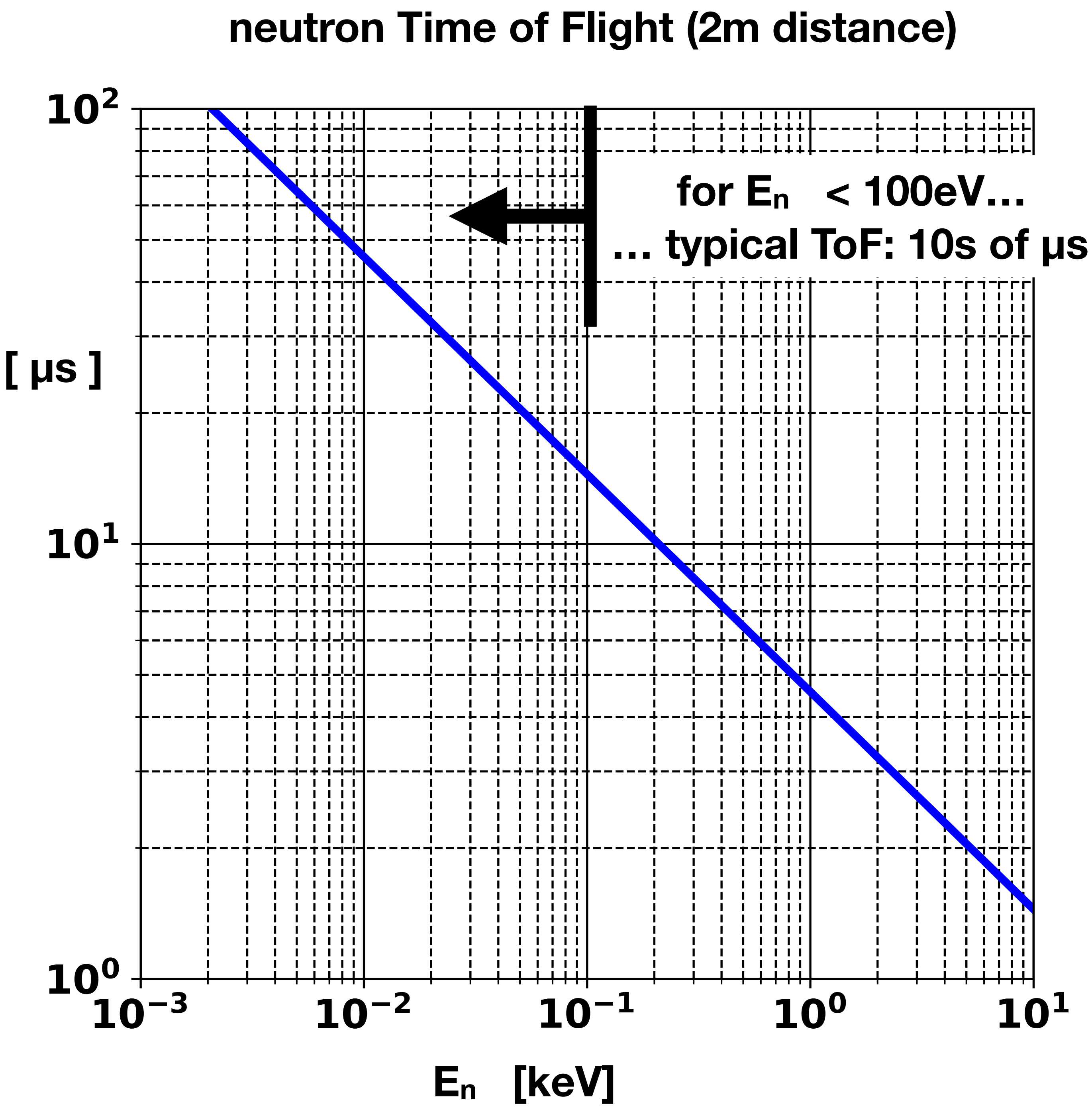


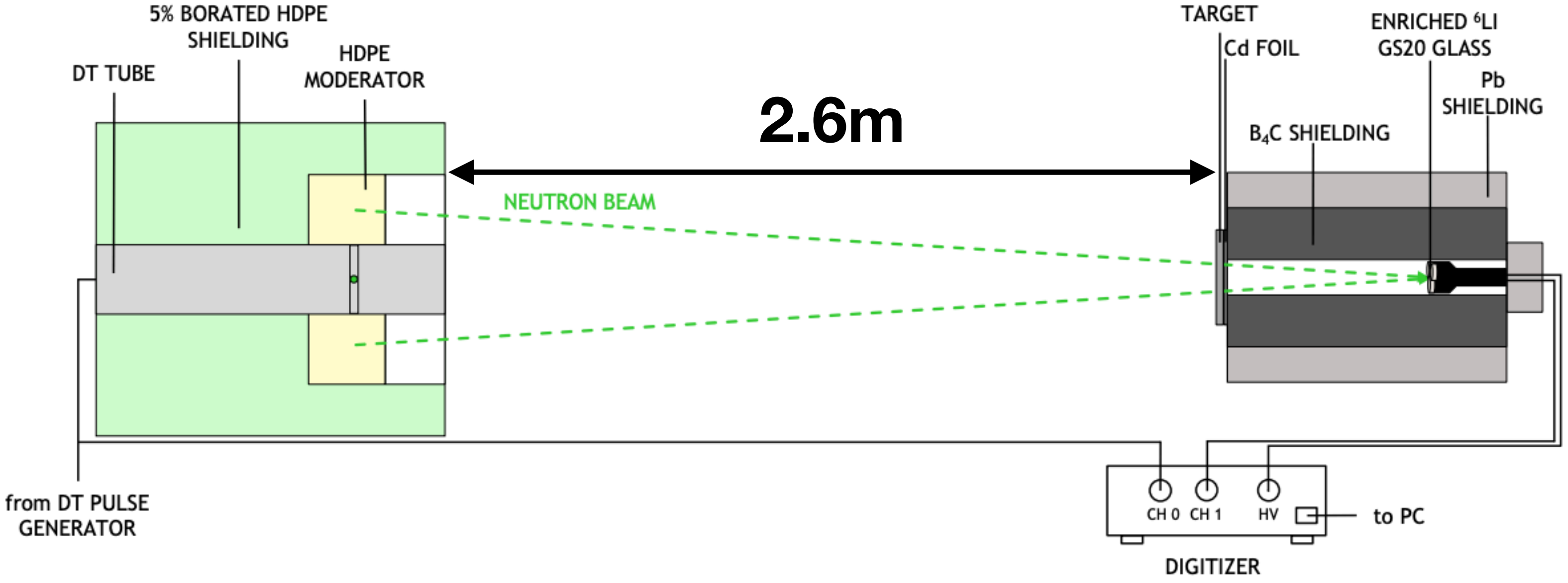
An encouragingly simple ToF measurement

Klein et al 2021 **arXiv:2012.03937**

DT Generator

Moderated by HDPE (several cm)

2.6m distance from target

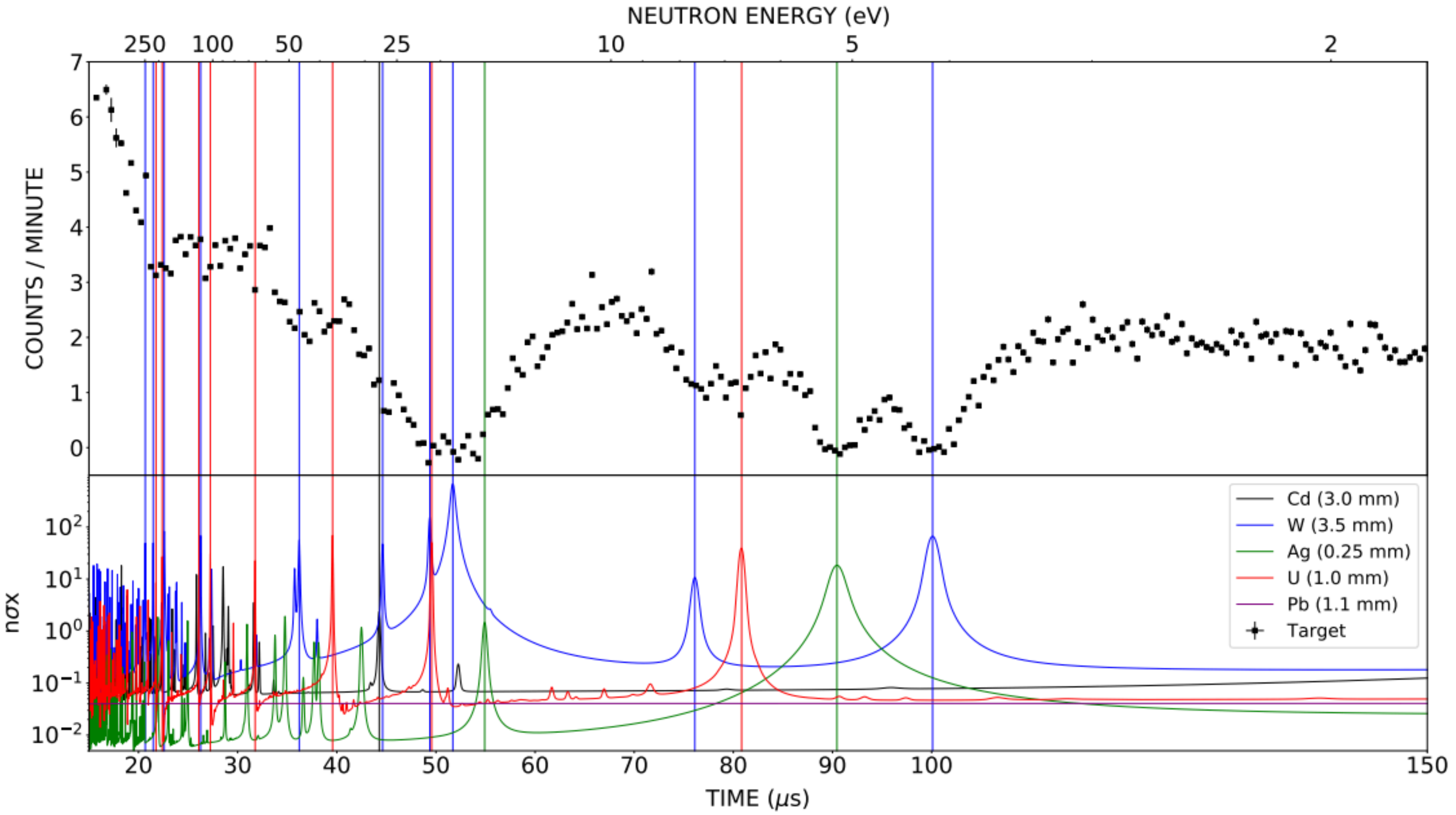


Moderated neutrons passes through sample, capture rate recorded in 6Li-glass

rate vs ToF data becomes…

… transmissibility vs E_n

E_n well-resolved in “our” energy window

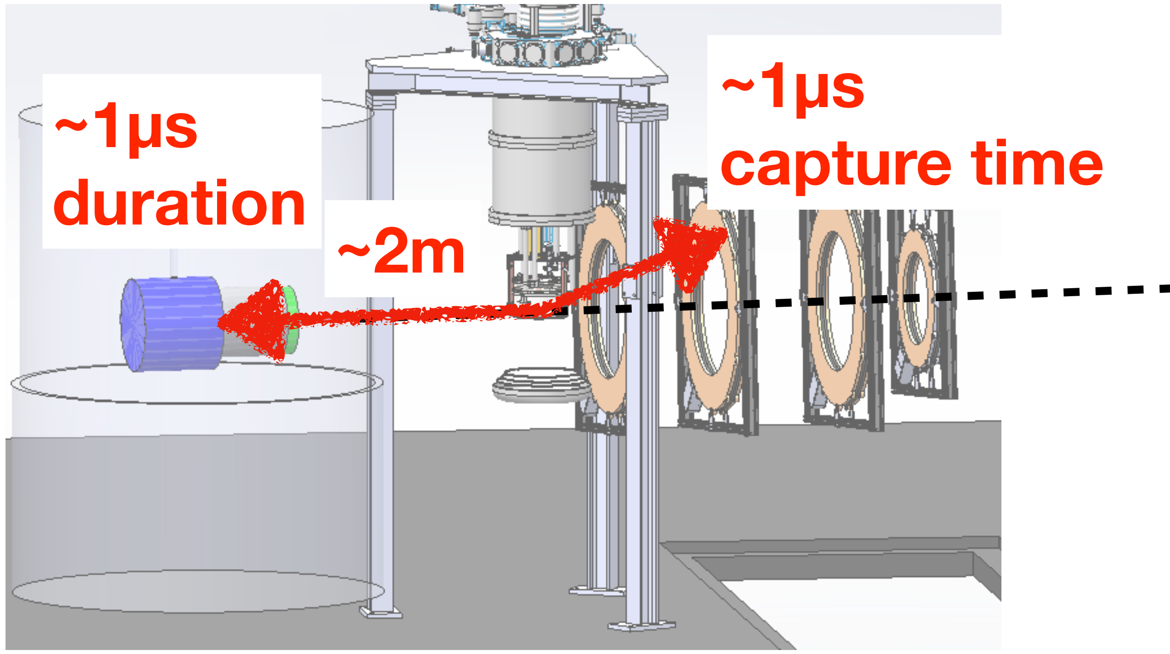


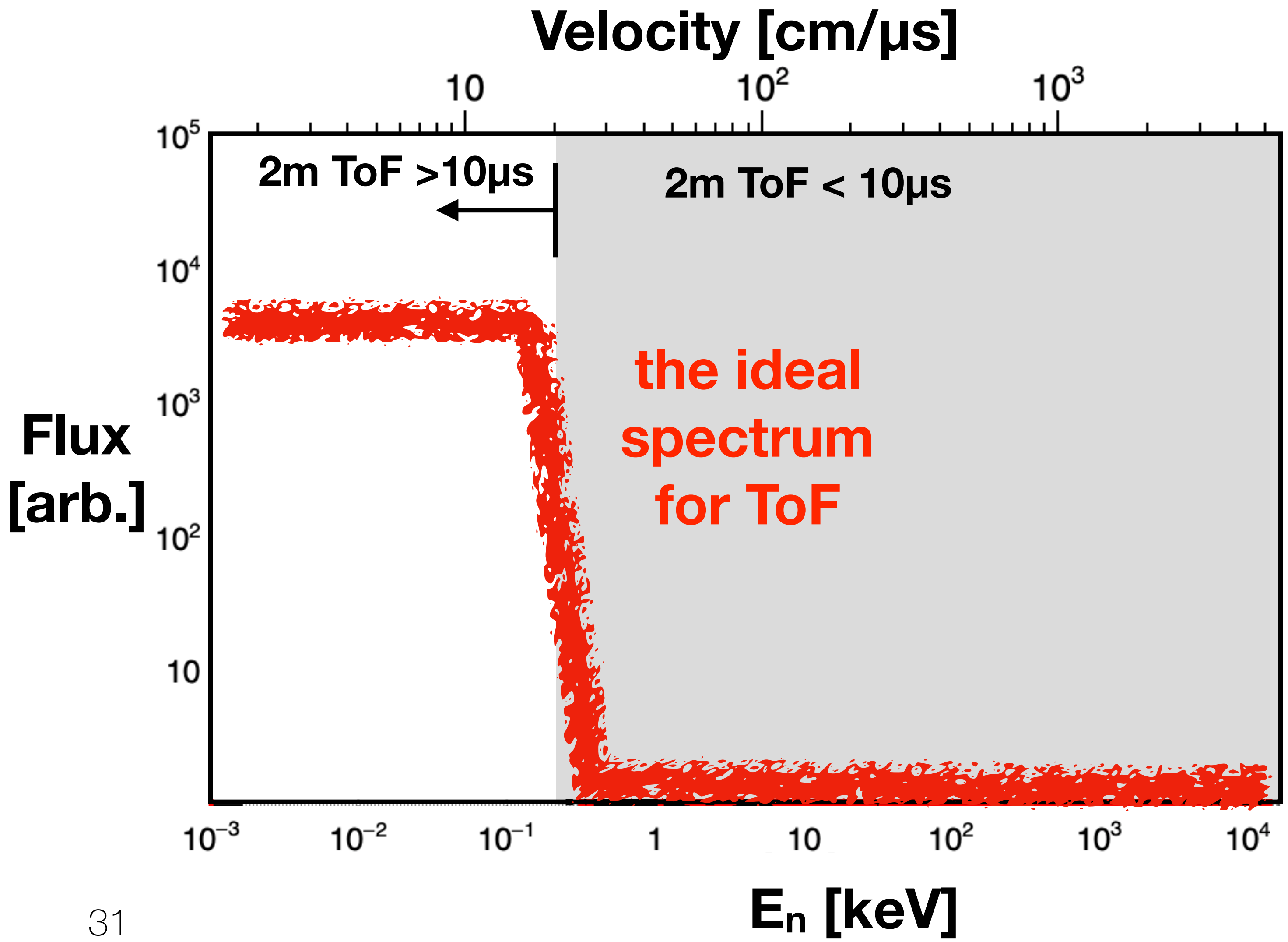
Optimizing our DT moderator for ToF

The only complexity in our case:
we need to *tune* the moderation.
(We can not accept >1 target scatter per DT pulse, so each neutron must 'count')

For a ~2m distance and ~1μs timing resolution…

…Our goal would be to push nearly all neutrons to a <100 eV window.





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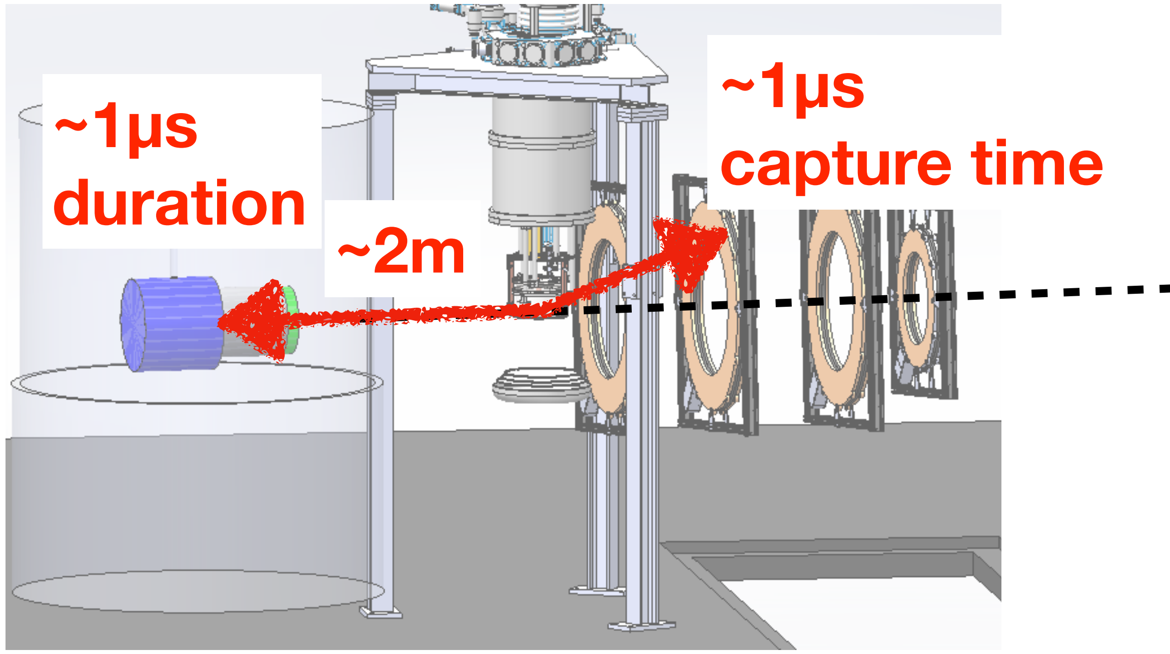
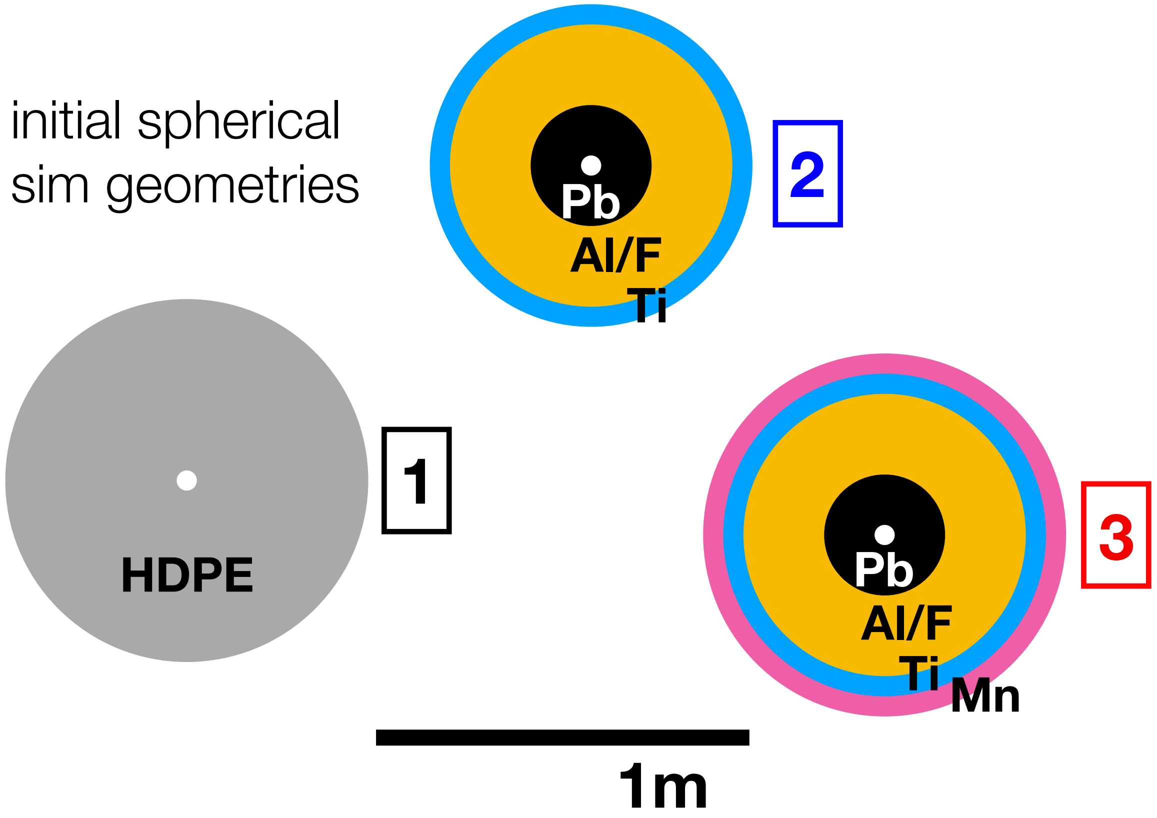
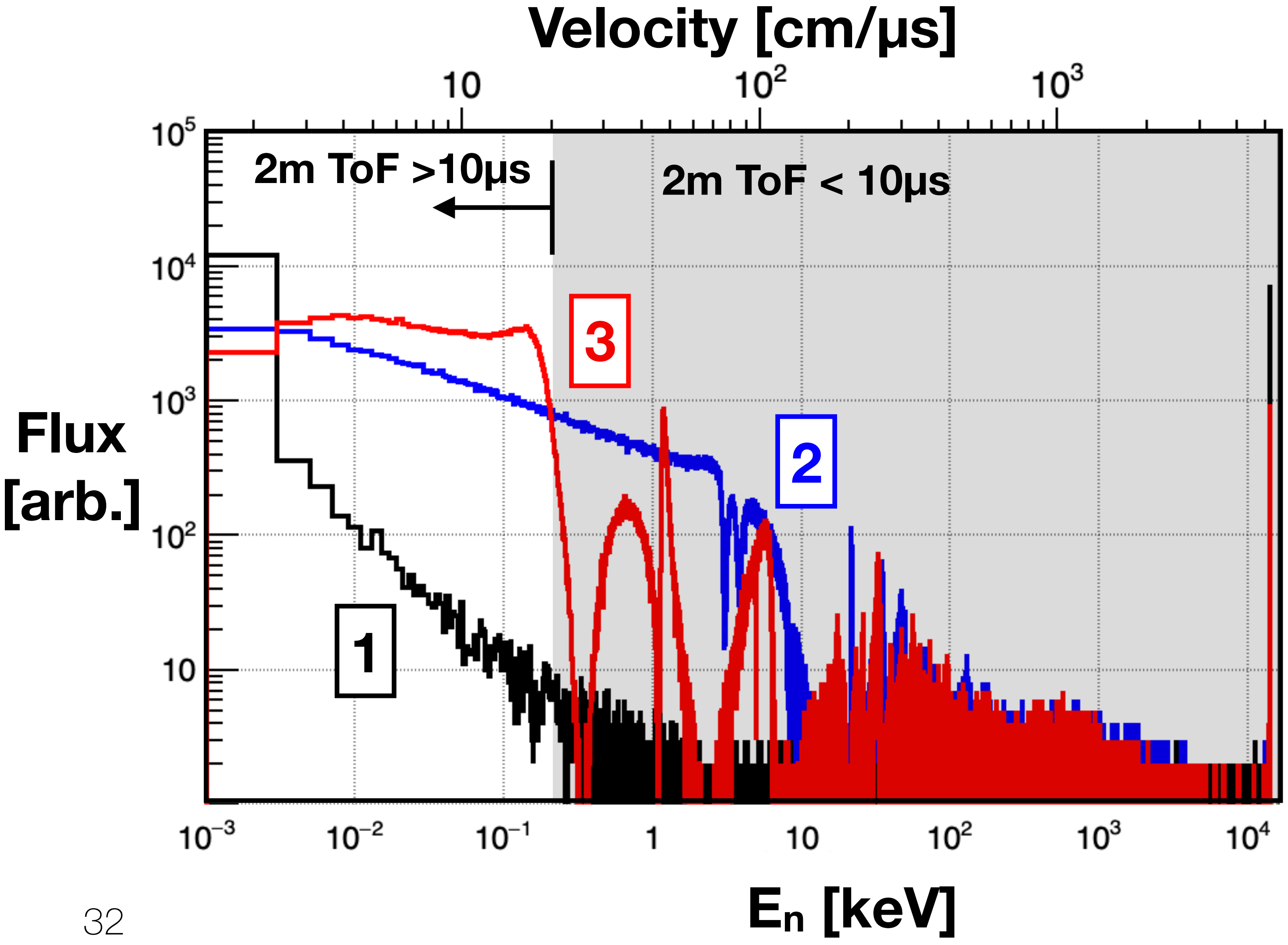
…Our goal would be to push nearly all neutrons to a <100 eV window.

Appears doable.



initial spherical sim geometries





Summary

DM and ce**ν**ns detectors fast progressing; neutron technologies need to keep pace.

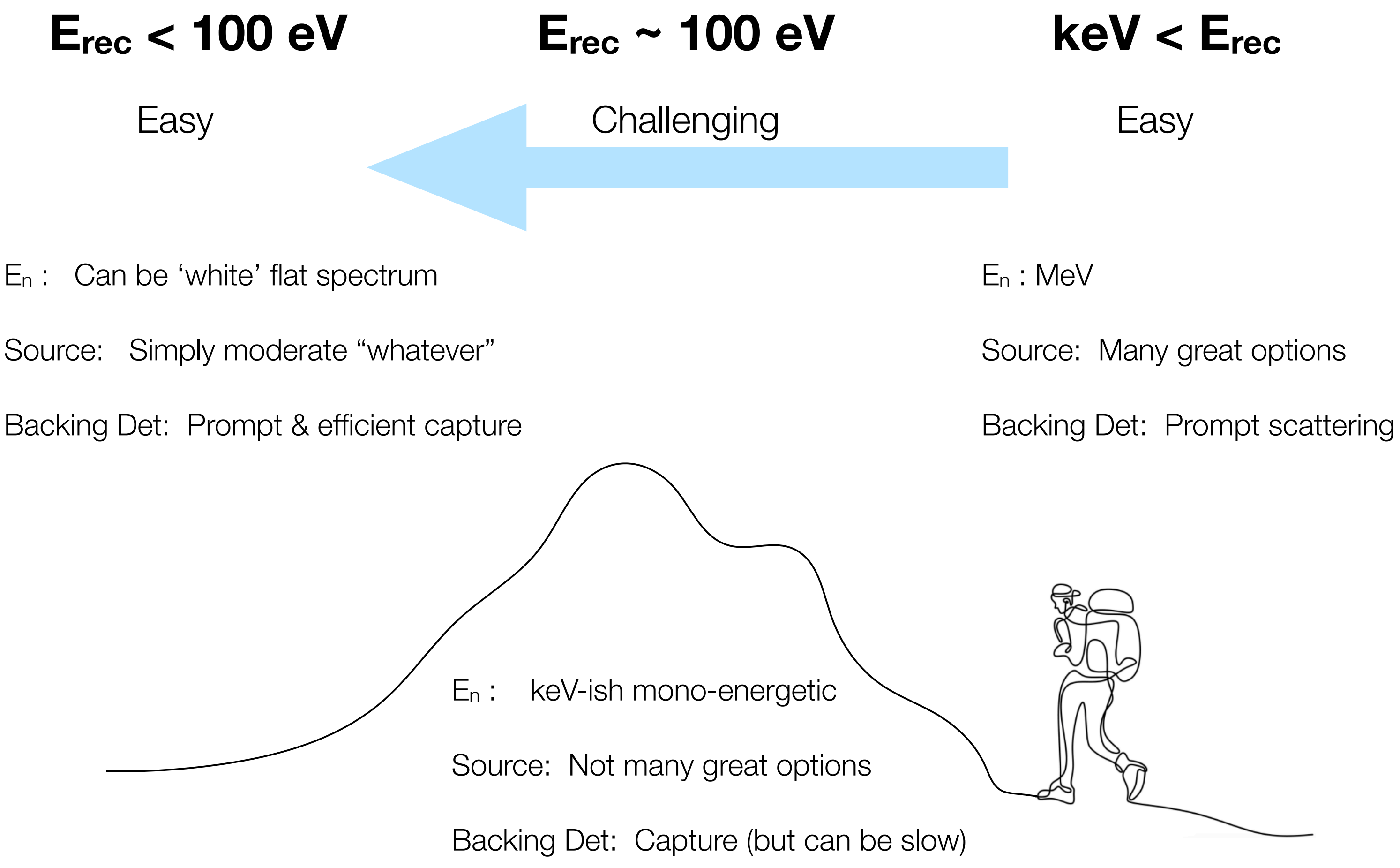
Entering “awkward window” between high-energy and low-energy.

Many creative ideas, not clear the winners and losers yet.

Possibility of pairing reflectors/moderators/filters with any source:

- Filtered (p,n) source ?
- H-reflected 124SbBe source ?
- Sc-filtered H-reflector DD source ?
- etc etc

I’m *sure* there are many great ideas not yet thought up.



E_{rec} < 100 eV

Easy

E_n : Can be ‘white’ flat spectrum

Source: Simply moderate “whatever”

Backing Det: Prompt & efficient capture

E_{rec} ~ 100 eV

Challenging

E_n : keV-ish mono-energetic

Source: Not many great options

Backing Det: Capture (but can be slow)

keV < E_{rec}

Easy

E_n : MeV

Source: Many great options

Backing Det: Prompt scattering