nTOF facility, moderation and response function

Neutron Field Theory

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nTOF Winter School

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Outline

- Neutron Field theory
  - Neutron sources
  - Interaction Neutrons with Matter
  - Slowing down of neutrons
  - Neutron Diffusion
  - Flux – Fluence – Current
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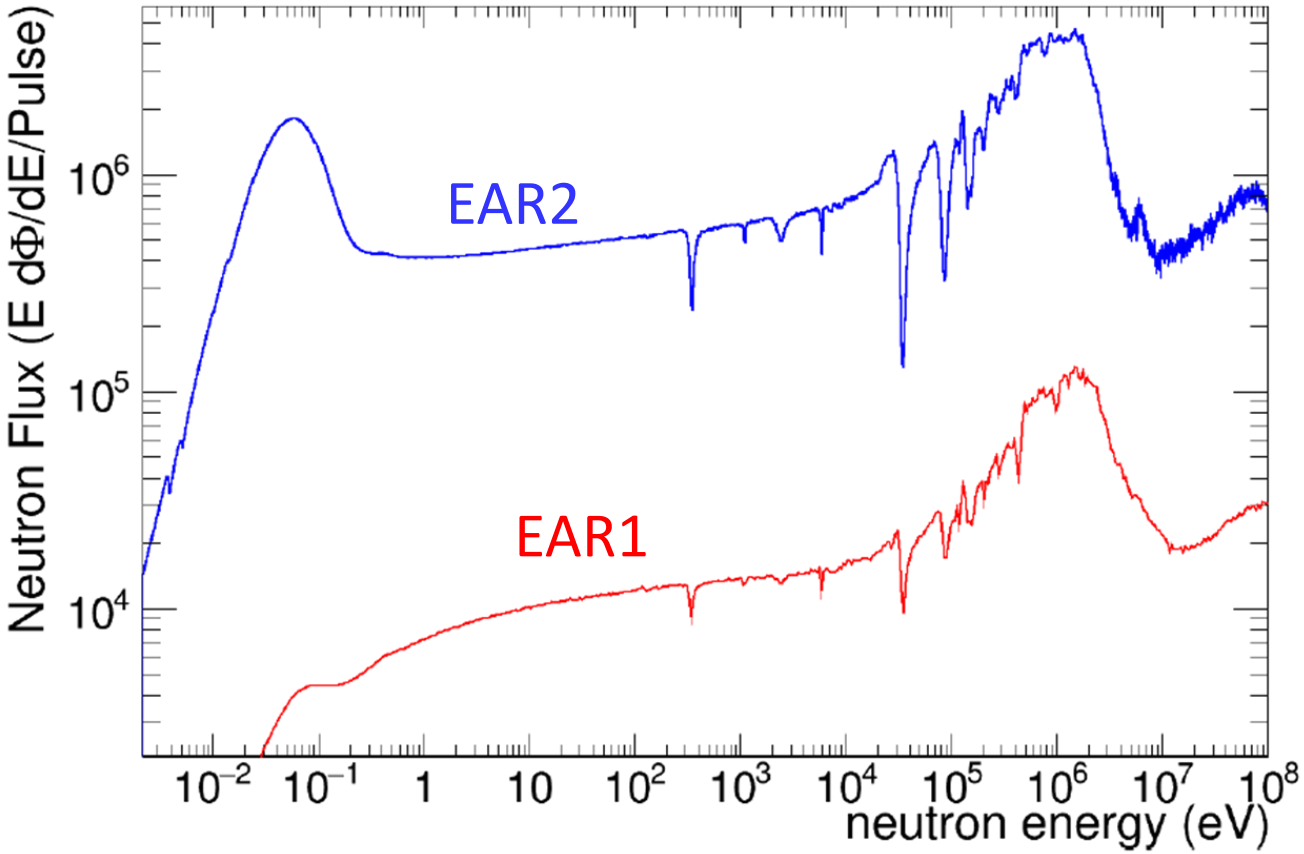
- Resolution function
  - Energy-Time relation
  - Effective Neutron path
- nTOF line
  - Particles' yield
  - Magnet
  - Collimation system
- Simulations
  - Transport code



Experimental neutron fluence per 7 $10^{12}p^{+}$

Neutron Sources

Through Reactions:

Binding energy of the last neutron:

- light nuclei: typically small apart from α-composed atoms
- intermediated: *7-10 MeV*
- heavy: *6-7 MeV*

→due to Coulomb barrier, light nuclei play the predominate rule (at low energies)

(α,n)

- Excitation energy *~10 MeV*, sometimes exothermic, or endothermic. → Continuous energy spectrum

(d,n)

- Due to small binding energy of the deuteron (*2.2 MeV*) and a very highly excited compound nucleus is almost always exothermic

(p,n)

- typically mono-energetic sources

(γ,n)

- nearly mono-energetic neutron production

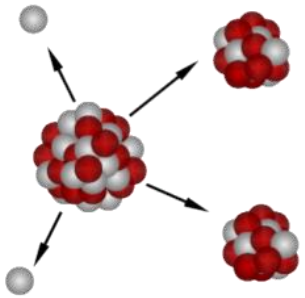
Nucleus	Binding Energy (Mev)	Nucleus	Binding Energy (Mev)
H^2	2.225	C^{12}	18.720
H^3	6.258	C^{13}	4.937
He^3	7.719	C^{14}	8.176
He^4	20.577	N^{13}	20.326
He^5	–0.956	N^{14}	10.553
Li^6	5.663	N^{15}	10.834
Li^7	7.253	N^{16}	2.500
Li^8	2.033	O^{15}	13.222
Be^8	18.896	O^{16}	15.669
Be^9	1.665	O^{17}	4.142
Be^{10}	6.814	O^{18}	8.047
B^9	18.575	F^{18}	9.141
B^{10}	8.440	F^{19}	10.442
B^{11}	11.456	F^{20}	6.599
C^{11}	13.092		

Binding energy of the last neutron in light nuclei

Neutron Sources

- Radioactive
  - (α,n): Ra-^{9}Be, Bi-Be, Pu-Be,...
  - (γ,n): ^{9}Be (*1.66 MeV*), ^{2}H(*2.2 MeV*) (almost mono-energetic)

- Fission:
  - On average 2.5 $\pm$ 0.1 neutrons



- Via Bremsstrahlung:
  - $E_{e-} \approx$ *50-100 MeV*
  - Heavy target → γ → (γ,n) or photo-fission

- Spallation

Hadron-Nucleus interactions: basics (simplified)

Fast stage (10^{-22} s)

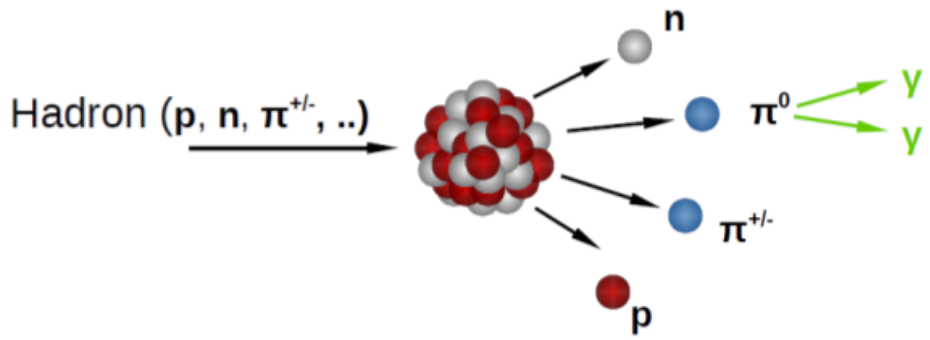
Hadron interacts with nucleons: particle production possible (mainly **π**)

Intra-nuclear cascade of p, n, π:

→ energetic particles can leave nucleus (→ forward directed)

→ others can deposit energy in nucleus (→ excited state)

e.g. nucleon-nucleon: π production opens at 290 MeV for a free nucleon (somewhat lower for nucleons in nucleus)



fast particle multiplicity ~ log(E)

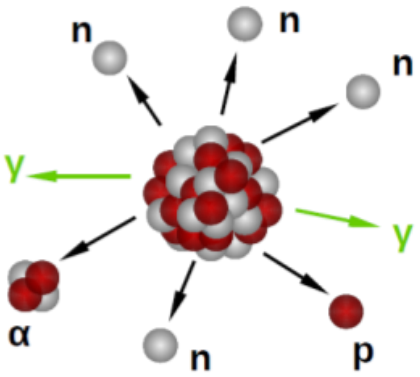
Hadronic + EM cascades

Slow stage (10^{-16} s)

Pre-compound

Equilibrium

Evaporation
(n, light fragments)
γ-deexcitation

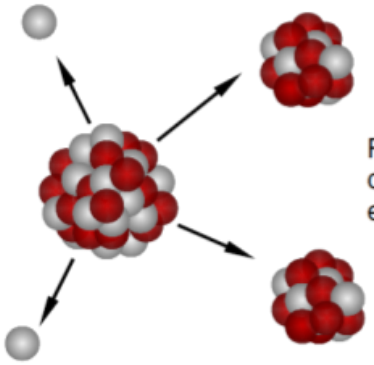


isotropic emission

few MeV

compete

Fission
(heavy elements)

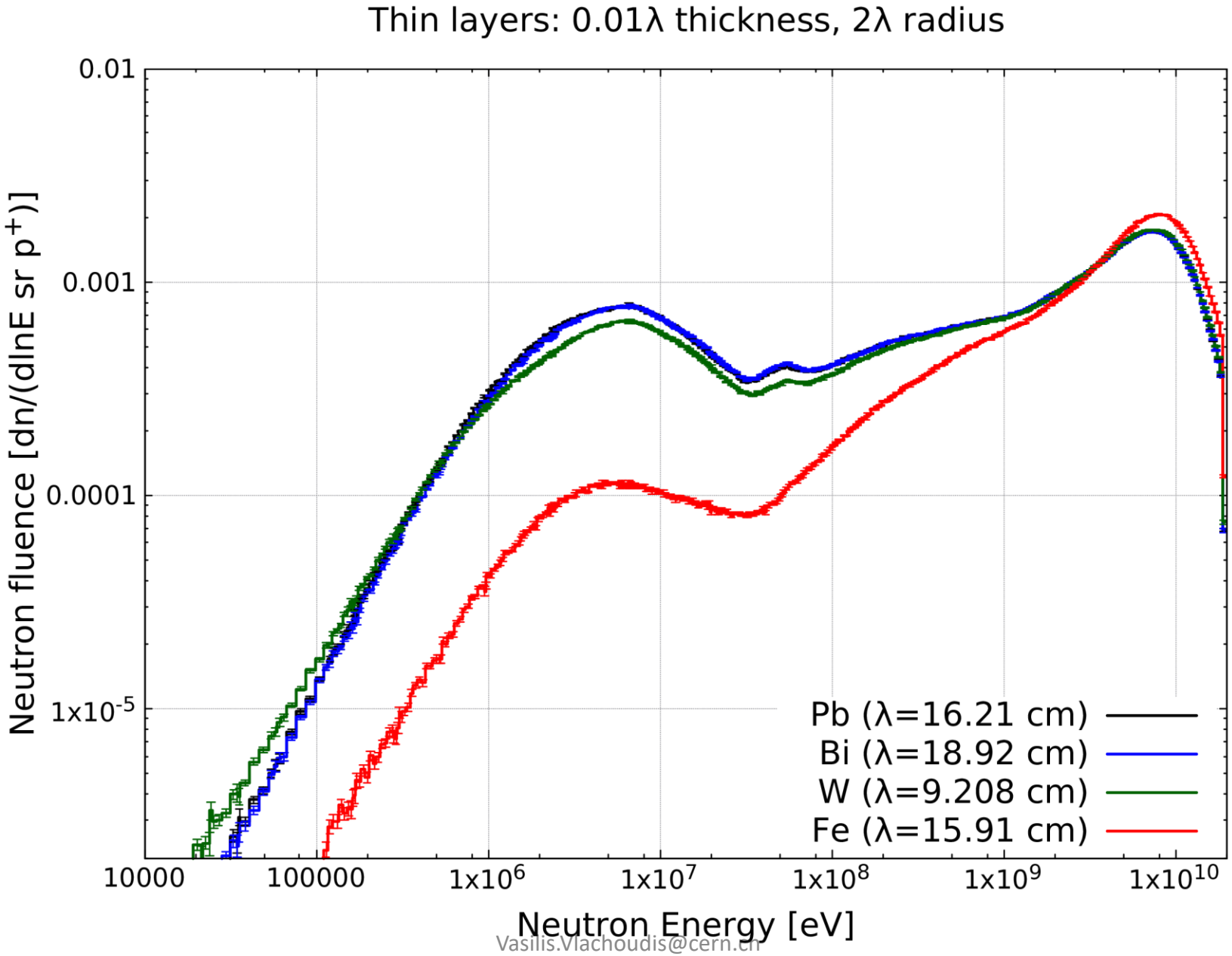


Fission products can also undergo evaporation

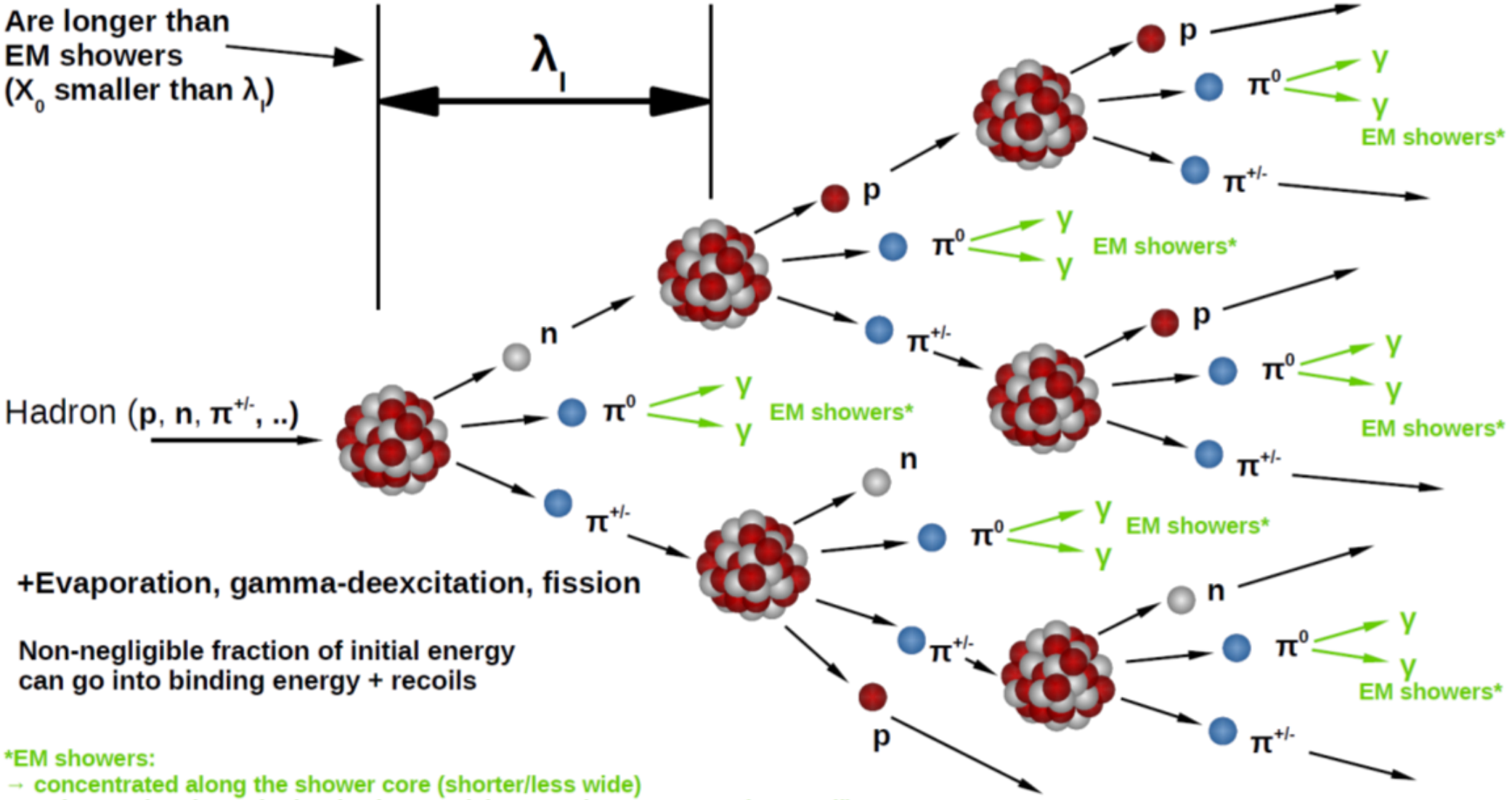
→ residuals can be radioactive

- At GeV energies there is no formation of compound nucleus

Hadron-Nucleus: Neutron yield



Hadronic shower: basics



Hadronic Showers: numbers

Average π^0 fraction:

$$\frac{\pi^0}{all} \approx 0.10 \log(E)$$

For *E=20 GeV*
0.3

Average ratio electromagnetic and hadronic particles:

$$\frac{e}{h} \approx 1.1 \ - 1.35$$

Shower maximum:

$$l_{\max} \approx [0.6 \log(E) - 0.2]\lambda$$

1.6 λ

Shower depth for 95% longitudinal containment:

$$l_{95\%} \approx l_{max} + 4E^{0.15}\lambda$$

7.9 λ

Shower radius for 95% radial containment:

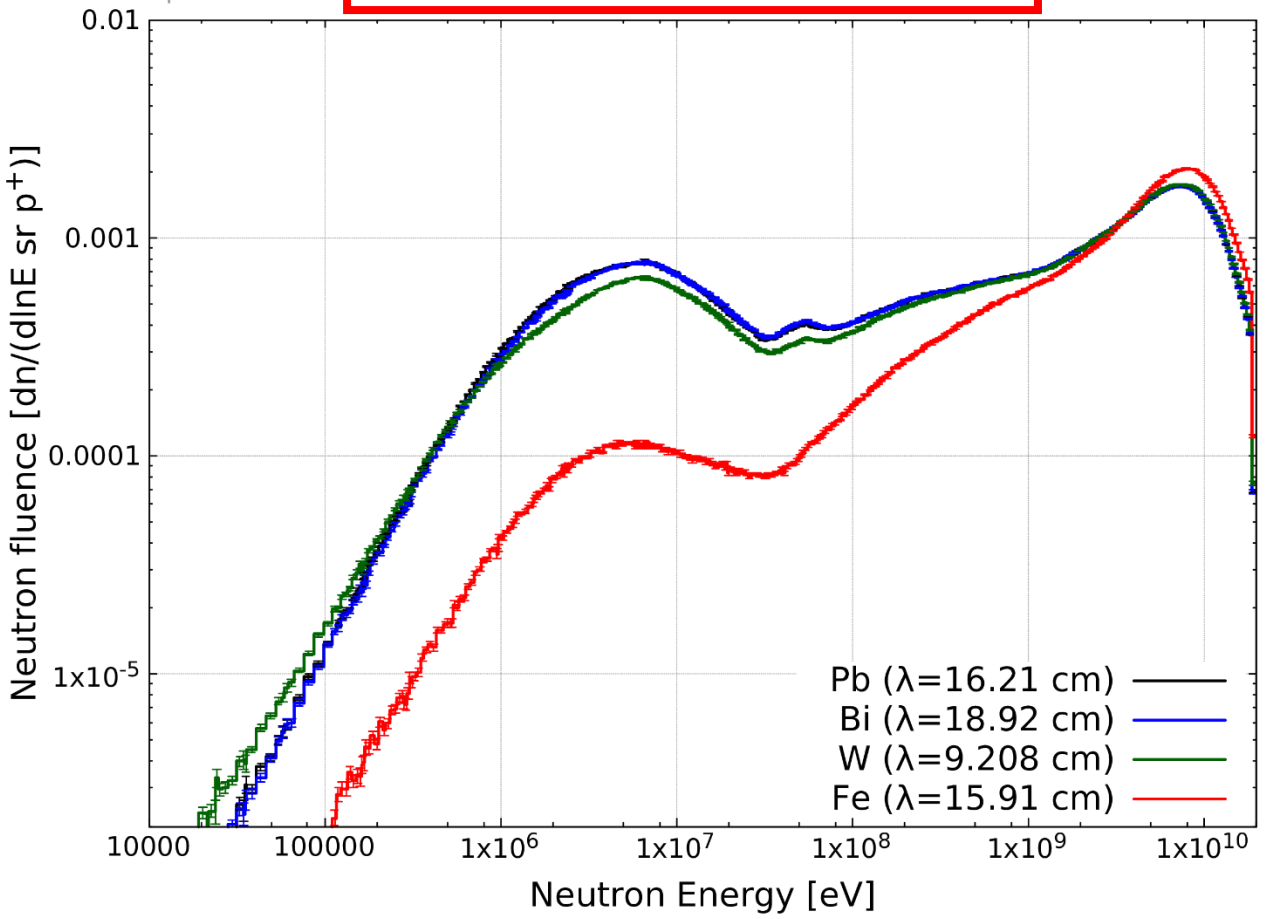
$$R_{95\%} \approx \lambda$$

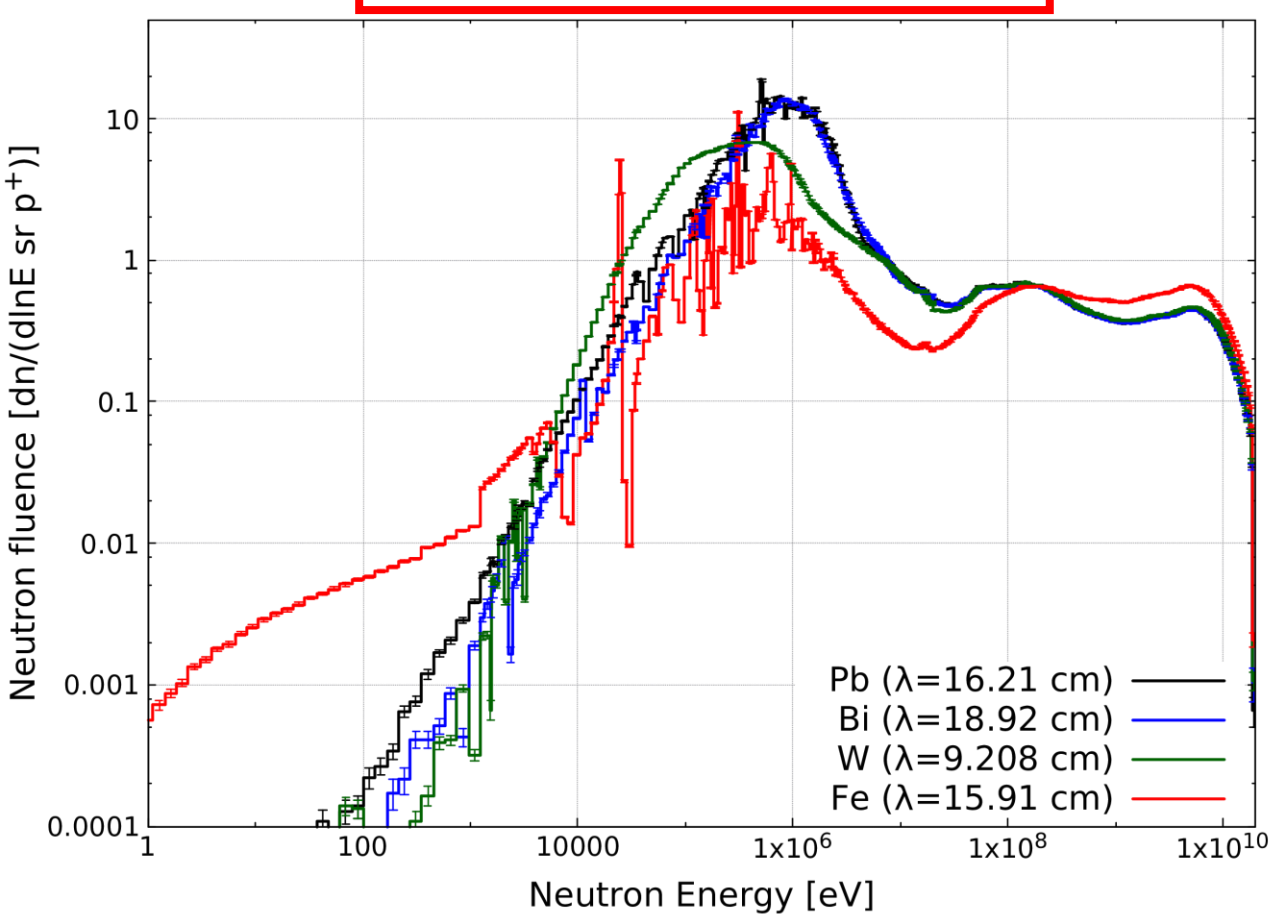
with: *E* in *GeV*

Hadronic shower: Neutron yield

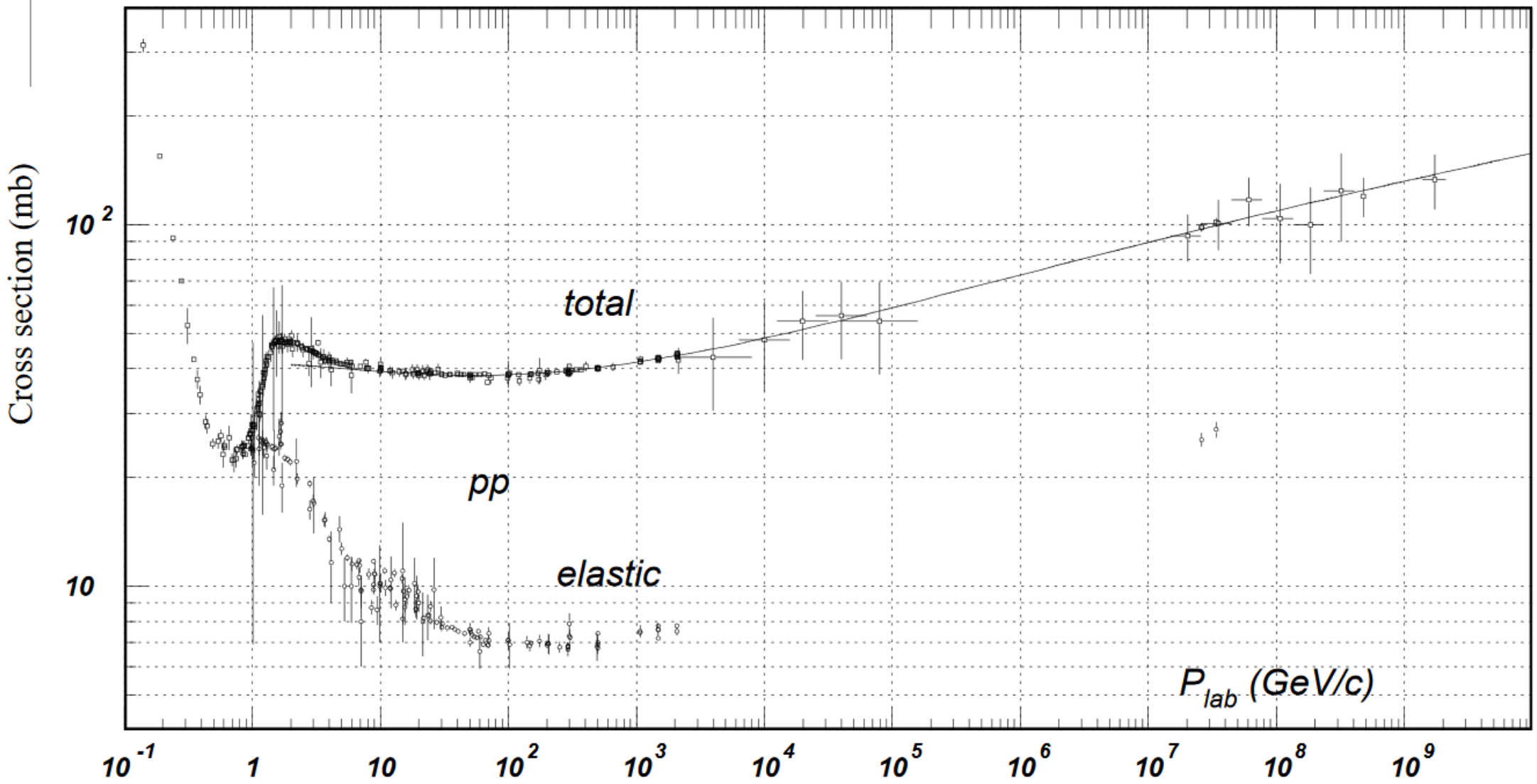
Thin layers: 0.01λ thickness, 2λ radius

Thick layers: 3λ thickness, 2λ radius





Hadron-hadron collision



Neutron production on thick targets

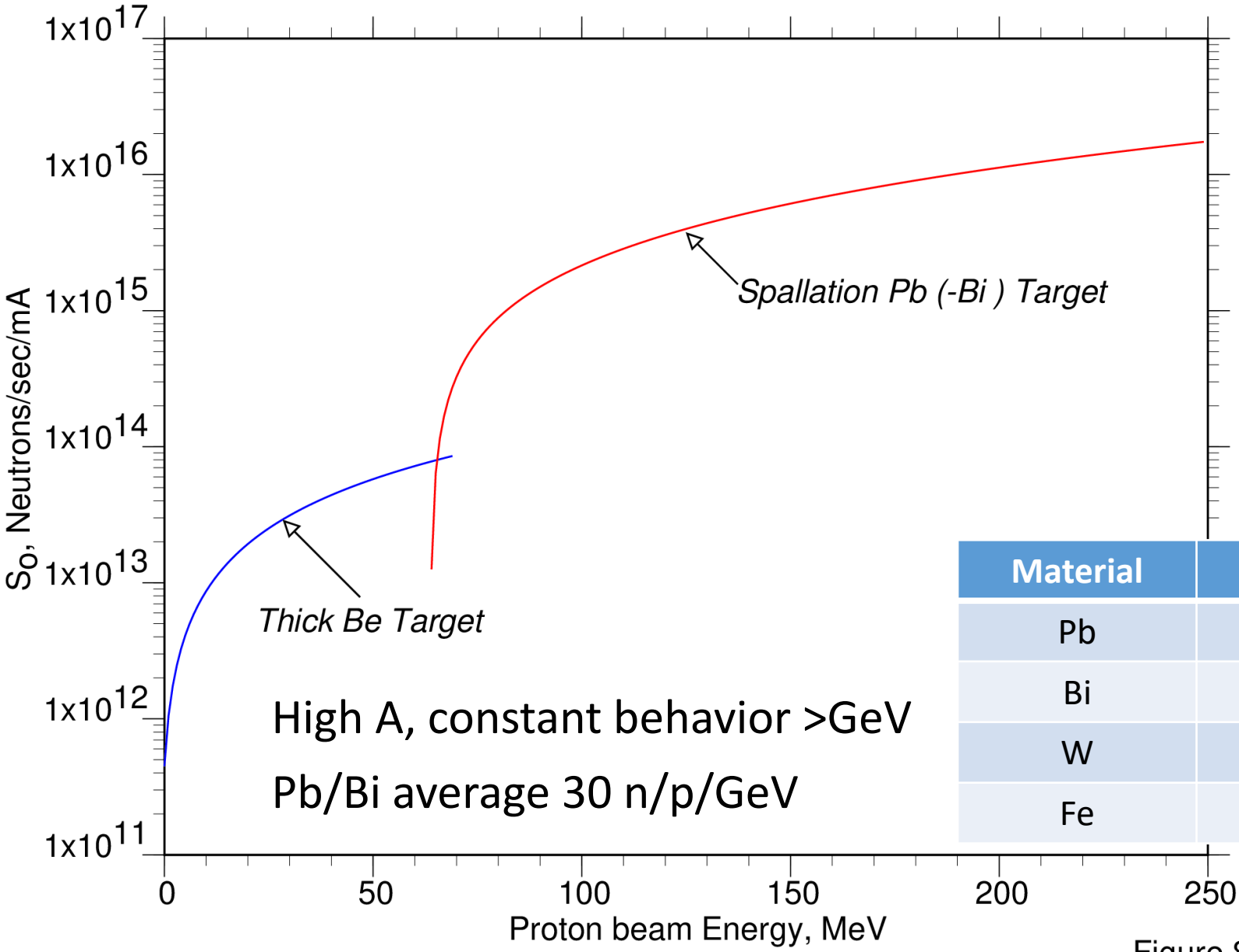


Figure 8

Why spallation Sources:

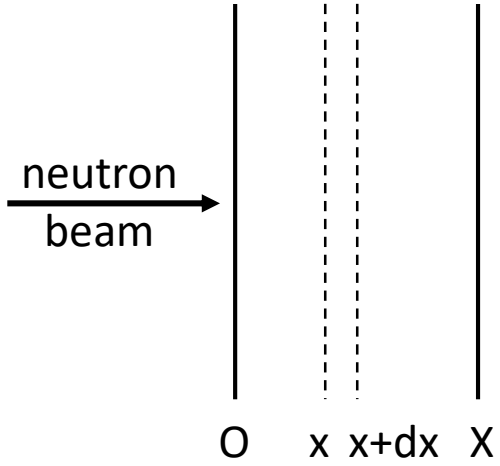
- Spallation x10 more neutrons per heat than fission
- Efficient spallation sources requires proton *E>0.5 GeV*
- Pulsed sources allows time-of flight

Material	1%×λ	3×λ	Infinite
Pb	1.6	19	29
Bi	1.6	19	28
W	1.4	17	18
Fe	0.35	6	10

Neutron yield /proton/GeV/(1-$e^{-x/\lambda}$)

Interaction with matter

- Neutron beam traversing a thickness of *dx* suffers a small diminution of dI (from dI to I-dI) in intensity



$$-\frac{dI}{I} = \frac{\sigma N S dx}{S}$$

where: S = surface [cm^2],

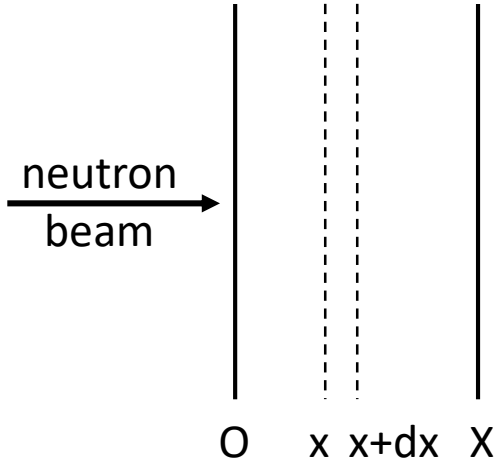
$N = N_A\rho/A$ = atom density [cm^{-3}],

σ = effective target area [$barn$=10^{-24} cm^2]

σ_t = total cross section [$barn$]

$\sigma_t = \sigma_\gamma + \sigma_f + \sigma_s + \ldots$

Interaction with matter



- Integrating gives: $I = I_o e^{-\sigma N X}$
- Probability of loss: $1 - \frac{I}{I_o} = 1 - e^{-\sigma_t N x}$
- Average penetration:

$$\bar{x} = \int_0^\infty x e^{-\sigma_t N_o x} \sigma_t N dx$$

$$= \frac{1}{\sigma_t N} = \frac{1}{\Sigma_t} = \lambda$$

λ = known as *mean free path* [*cm*]

$\Sigma_t = \sigma_t N$ = *macroscopic cross-section* [cm^{-1}]

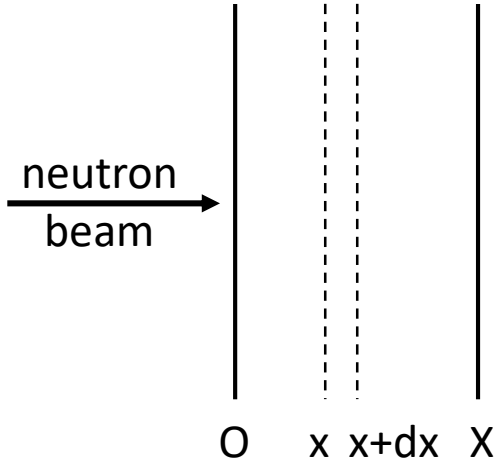
- σ, λ, Σ: are a function of particle type, material, and energy

Interaction with matter

- Both microscopic and macroscopic cross section are shown to have a similar physical meaning of:

"probability of interaction per unit length"

with length measured in different units. Thus, the number of interaction can be obtained from both by multiplying with the corresponding particle track-length.



- Some numbers:

C:	σ_s(1keV) = 4.7 *b*	λ_s = 2.1 *cm*
Al:	σ_s(1keV) = 1.42 *b*	λ_s = 11.7 *cm*
Pb:	σ_s(1keV) = 10.7 *b*	λ_s = 2.8 cm
H_2O:	σ_{sH}(1keV) = 20.3 *b*, σ_{sO}(1keV) = 3.85 *b*,	λ_s = 0.67 cm

Flux

- The number of interactions (*reaction rate*) [$cm^{-2}\ s^{-1}$] with a sample in a beam:

$$\frac{n(\boldsymbol{r})\ dx\ \sigma N}{dt} = n(\boldsymbol{r})\frac{dx}{dt}\Sigma = n(\boldsymbol{r})v\Sigma = \frac{n(\boldsymbol{r})v}{\lambda}$$

where: $n(\boldsymbol{r})$ = neutron density [cm^3], having velocity v [cm/s]

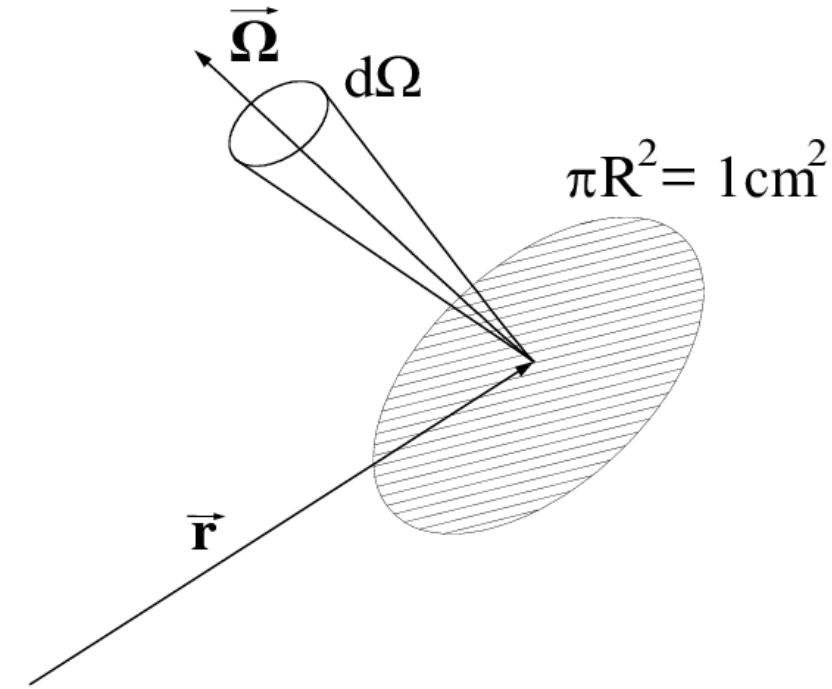
- The quantity $\Phi(E, \boldsymbol{r}, \boldsymbol{\Omega}, t) = n(\boldsymbol{r}, \boldsymbol{\Omega})v$ is known as *differential neutron flux*
- Integrating over all solid angles

$$\Phi(E, \boldsymbol{r}, t) = \int_{4\pi} \Phi(E, \boldsymbol{r}, \boldsymbol{\Omega}, t) d\boldsymbol{\Omega} = n(E, \boldsymbol{r})v$$

- we get the *fluence rate* or *flux density*

Flux / Fluence

- with dimensions:
  $[cm^{-3}\ cm\ s^{-1}]=[cm^{-2}\ s^{-1}]$.
- The time integral of the flux density $\Phi(E,\mathbf{r})$ is the fluence $[cm^{-2}]$
- Fluence is measured in *particles per* cm^2 but in reality it describes the ***density of particle tracks!***
- The number of reactions inside a volume V is given by the formula: (where the product $\Sigma\,\Phi\,V$ is integrated over energy or velocity)



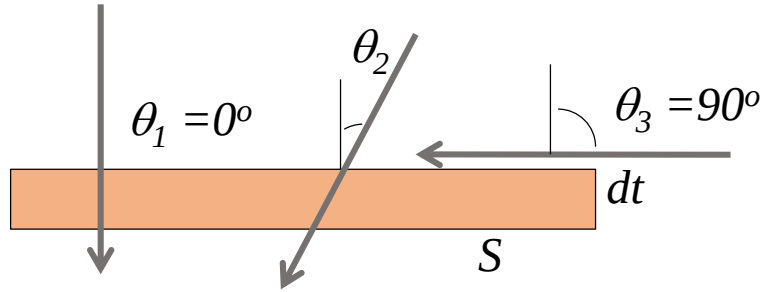
Fluence is equivalent to the particles crossing a surface of $1cm^2$ always perpendicular to the particle direction. Or a sphere with cross section of $1cm^2$

Properties: Isotropic vs Uniform?

Current vs Fluence

Surface crossing

- Imagine a surface having an infinitesimal thickness dt. A particle incident with an angle θ with respect to the normal of the surface S will travel a segment $dt/cos\theta$.



- Therefore, we can calculate an average surface fluence by adding $dt/cos\ \theta$ for each particle crossing the surface, and dividing by the volume $S\ dt$:

$$\Phi = \lim_{dt \to 0} \frac{\sum_i \frac{dt}{\cos\theta_i}}{Sdt}$$

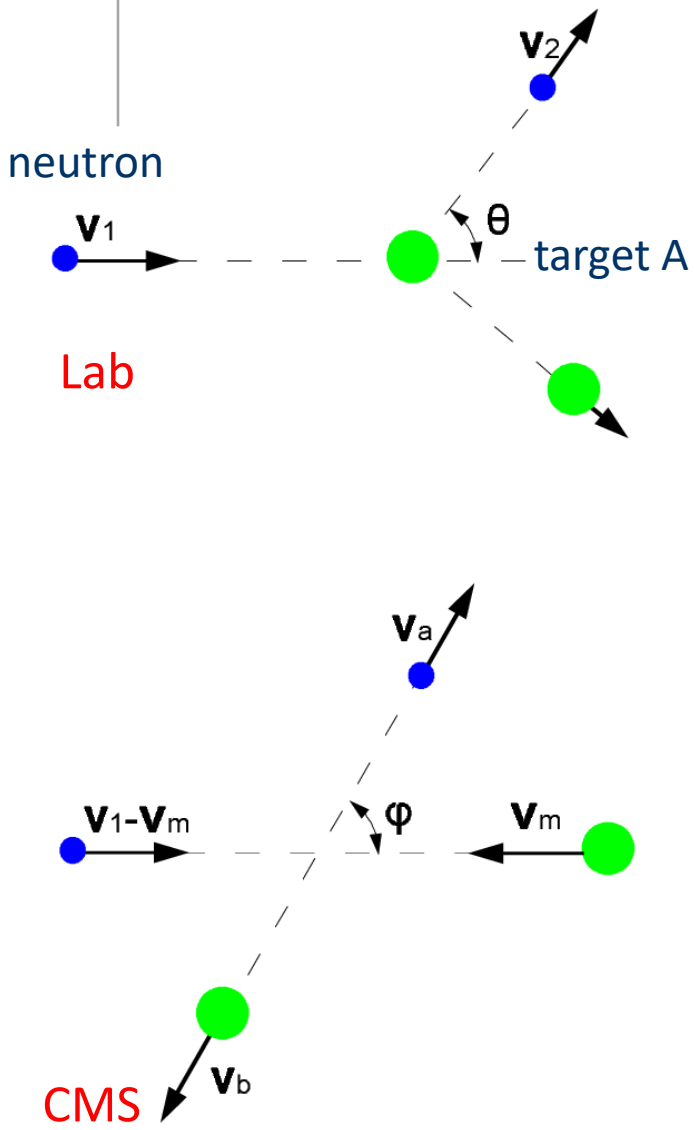
- While the current J counts the number of particles crossing the surface divided by the surface:

$$J = dN/dS$$

The fluence is independent from the orientation of surface S, while the current is NOT!

Q: In an isotropic field can be easily seen that on a flat surface $J = \Phi/2$

Slowing down of neutrons



The Center of Mass System CMS is moving with

$$v_m = \frac{v_1}{A+1}$$

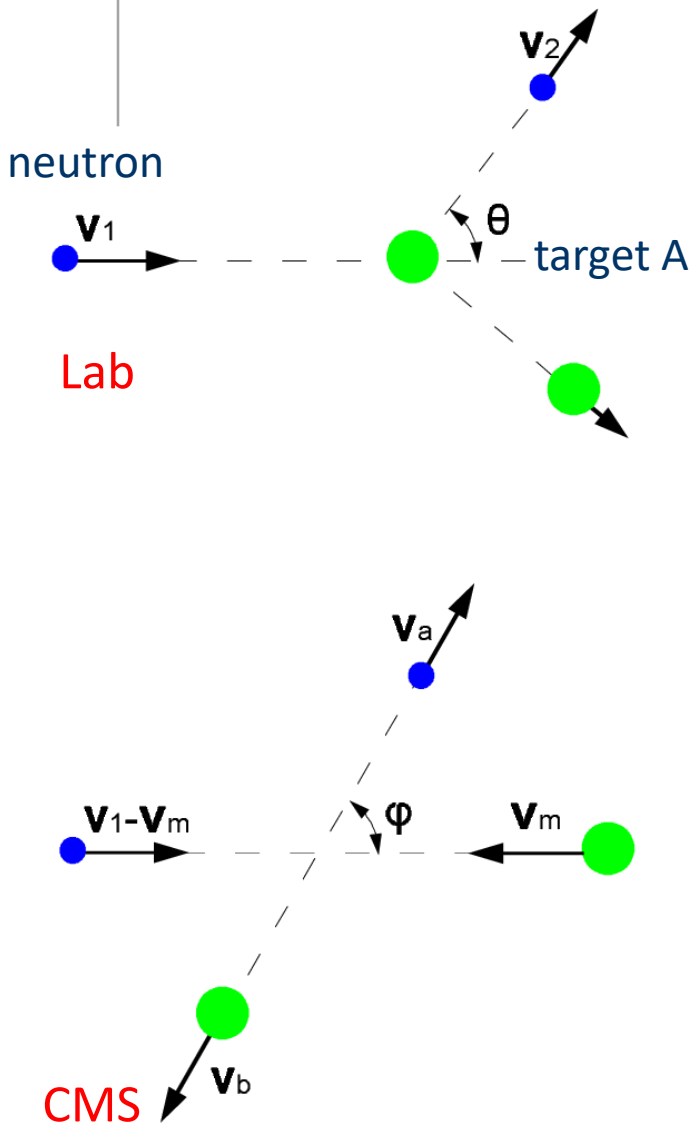
From conservation energy & momentum we have

$$|v_a| = |v_1 - v_m| \text{ and } |v_m| = |v_b|$$

Transforming back to the lab

$$\frac{E_2}{E_1} = \frac{v_2^2}{v_1^2} = \frac{A^2 + 2A\cos\phi + 1}{(A+1)^2}$$

Slowing down of neutrons



For low energies <*MeV* angle ϕ is isotropic
→ flat distribution in $cos\phi$
→ anisotropic in the θ LAB

$$b = \overline{cos\theta} = \frac{2}{3A}$$

The scattering probability to have a final energy in the interval (*E,E+dE*) is

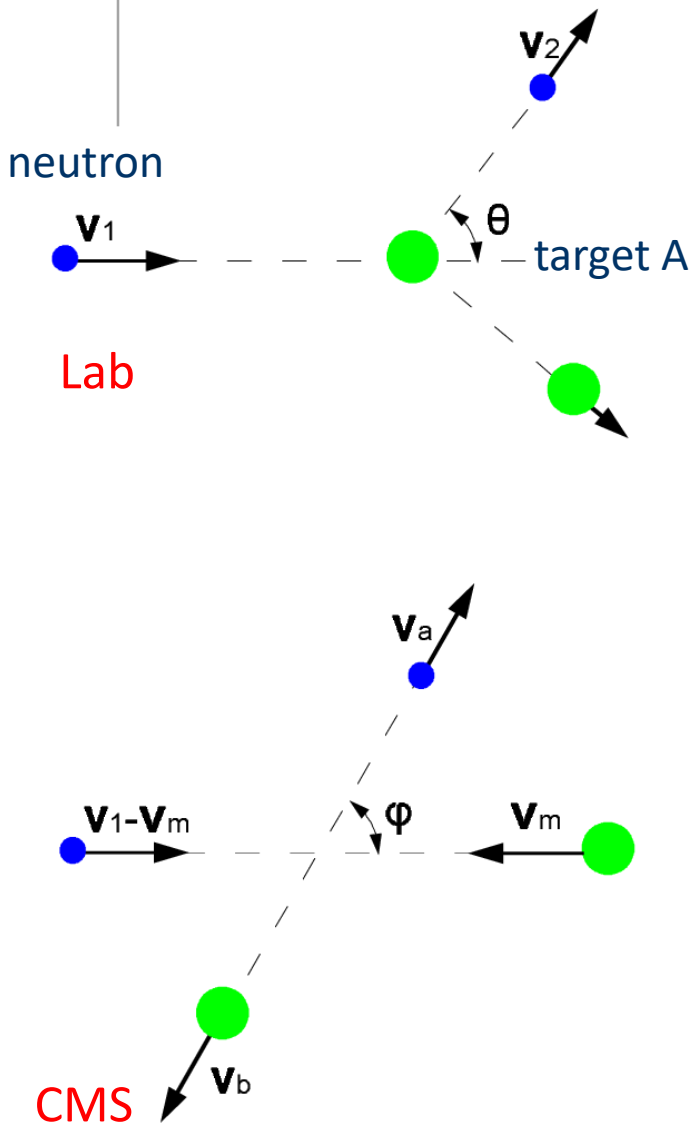
$$F(E)dE = \frac{2\pi\, sin\phi\, d\phi}{4\pi} = -\frac{d(cos\phi)}{2}$$

Integrating the *F(E)dE* we get that

$$\frac{\overline{\Delta E}}{E} = \frac{1-a}{2}$$

with $a = \left(\frac{A-1}{A+1}\right)^2$

Slowing down of neutrons



The quantity $ln(E_1/E_2)_{avg}$ is called *lethargy* and represents the *average logarithmic energy* loss per collision:

$$\xi = \overline{ln\frac{E_1}{E_2}} = 1 + \frac{a}{1+a} lna$$

Taylor approximation gives us (for A>1):

$$\xi \approx \frac{2}{A + {}^{2}/_{3}}$$

- For A≥10 is a good approximation.
- For A=2 the error of the approximation is 3%

For mixtures:

$$\bar{\xi} = \frac{\sum_i N_i \sigma_s^i \xi_i}{\sum_i N_i \sigma_s^i}$$

Slowing down of neutrons

- lethargy can be used to estimate the number of collisions to moderate from the initial energy E_i to E_f

$$n\xi = ln\frac{E_i}{E_f}$$

- Giving a neutron fluence

$$\Phi(E) = \frac{C}{\bar{\xi}\Sigma_s E}$$

Slowing down power: $\bar{\xi}\Sigma_s$ → Moderation ratio: $\xi\Sigma_s/\Sigma_a$

- larger ξ → faster slow down; larger Σ_s → more often collisions

	H	D	He	Li	Be	C	O	Pb	U
A	1	2	4	7	8	12	16	207	238
a	0	0.111	0.360	0.562	0.640	0.716	0.778	0.981	0.983
ξ	1.0	0.725	0.425	0.268	0.209	0.158	0.120	0.00963	0.00838
n	18	25	43	67	86	114	150	1888	2172

Slow down parameters from 2MeV → 0.025 eV (thermal)

Thermal Neutrons

The velocities of thermal motion of the moderator atoms are distributed with a Maxwellian distribution

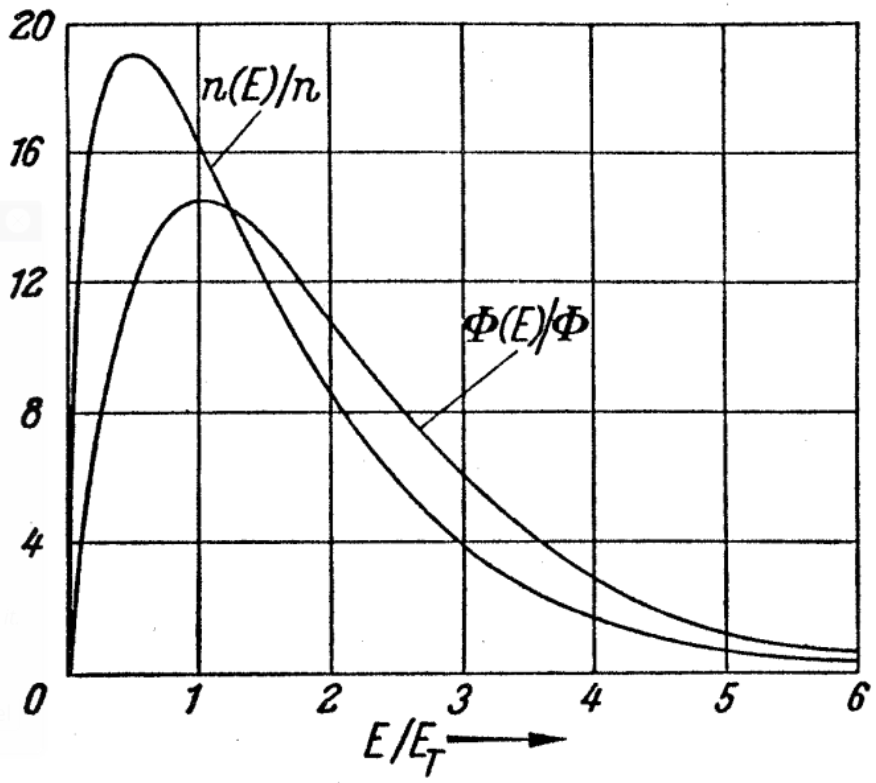
$$n(E)dE = \frac{2\pi n}{(\pi kT)^{3/2}} e^{-E/kT} \sqrt{E} dE$$

where $n(E)dE$ is the number of neutrons per cm^3 with energies $[E,E+dE)$, n is the total density

The average energy is $\bar{E} = \frac{3}{2} kT$

The most probable energy is $E_T = kT$

At T=20°C=293°K, $kT = 0.0253eV$, $v=2200m/s$



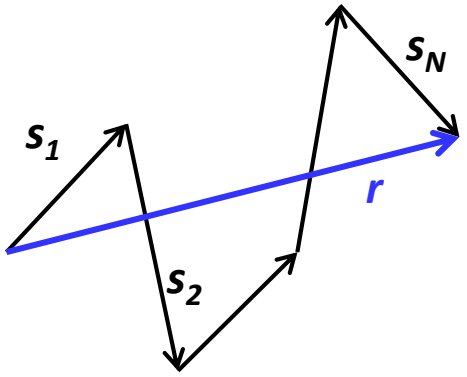
Neutron flux is given

$$\frac{\Phi(E)dE}{\Phi} = e^{-E/E_T} \frac{E}{E_T} \frac{dE}{E_T}$$

Neutron diffusion

Total vector of travel during moderation

$$\boldsymbol{r} = \sum_{i=1}^{N} \boldsymbol{s}_i$$



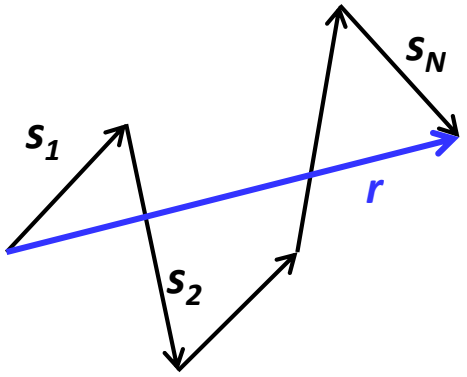
Thus

$$\boldsymbol{r} \cdot \boldsymbol{r} = \boldsymbol{r}^2 = \sum_{i=1}^{N} \sum_{j=1}^{N} \boldsymbol{s}_i \, \boldsymbol{s}_j = \sum_{i=1}^{N} \boldsymbol{s}_i^2 + \sum \sum_{i \neq j}^{N} \boldsymbol{s}_i \, \boldsymbol{s}_j$$

If we make the assumption we are isotropic in LAB (normally it is not, it is in CMS for low energies) → the second term will average to zero

$$\overline{\boldsymbol{r}^2} \cong N \overline{\boldsymbol{s}^2}$$

Neutron diffusion



Combining the probability of a neutron traversing a distance *s* without making interaction and then making a collision in *ds* we have

$$e^{-\frac{s}{\lambda_s}}\frac{ds}{\lambda_s}$$

Assuming that $\Sigma_s \gg \Sigma_a$

$$\overline{\boldsymbol{s^2}} = \int_0^\infty s^2 e^{-\frac{s}{\lambda_s}}\frac{ds}{\lambda_s} = 2\lambda_s^2$$

Finally

$$\overline{\boldsymbol{r^2}} = 2N\lambda_s^2$$

Including the mean cosine *b* per scattering

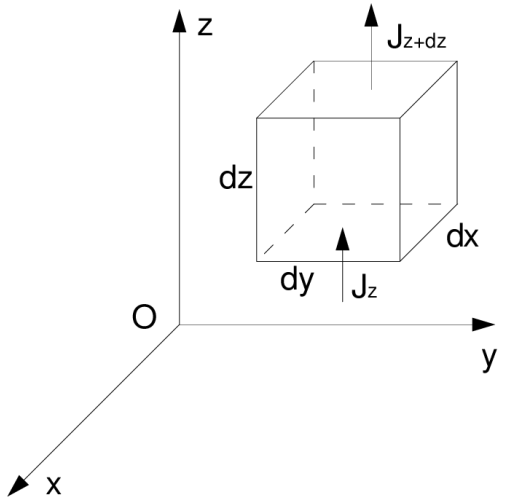
$$\overline{\boldsymbol{r^2}} = \frac{2N\lambda_s^2}{1-b}$$

Neutron diffusion

Outflow in z direction in a small volume *dV=dxdydz*

$$(J_{z+dz} - J_z)dxdy = -D\left[\left(\frac{\partial\Phi}{\partial z}\right)_{z+dz} - \left(\frac{\partial\Phi}{\partial z}\right)_z\right]dxdy$$

$$= -D\frac{\partial^2\Phi}{\partial z^2}dxdydz$$



where $D = \lambda_s/3(1 - \overline{cos\vartheta})$ diffusion length coefficient

The balance of neutrons per unit volume
→ diffusion equation

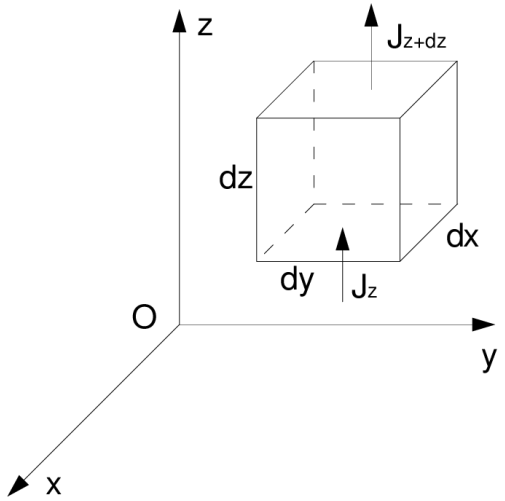
$$\frac{\partial\Phi(\boldsymbol{r})}{\partial t} = S(\boldsymbol{r}) + D\nabla^2\Phi(\boldsymbol{r}) - \Sigma_a\Phi(\boldsymbol{r})$$

production rate | outflow rate | absorption rate

Neutron diffusion

For a point like source in the center (Ficks'law)

$$\frac{S(\boldsymbol{r})}{D} + \nabla^2\Phi(\boldsymbol{r}) - \frac{\Sigma_a}{D}\Phi(\boldsymbol{r}) = 0$$



where $L = \sqrt{D/\Sigma_a} \approx \sqrt{\frac{\lambda_a \lambda_s}{3}}$ = *Diffusion length* [*cm*]

→ specifies the average distance between the place where a neutron is born and the place where it is absorbed.

Notes:

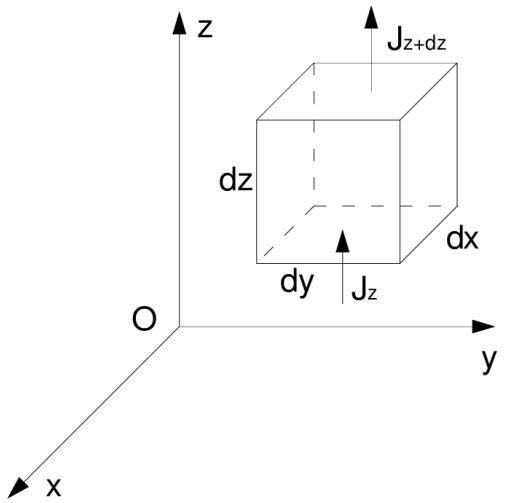
- A neutron reflector should be of the order of a diffusion length
- Infinite medium should be at least one diffusion length

Some numbers:

Carbon: L ≈ 48 *cm*

Lead: L ≈ 100 – 150 *cm*

Neutron diffusion



- For an infinite medium the solution (Green's function)

$$\Phi(\boldsymbol{r}) \approx So\,\frac{e^{-\kappa r}}{4\pi D r}$$

where S_o=neutron source rate [*n/s*] and $\kappa \approx \sqrt{3\Sigma_a\Sigma_t}$ [*m*]

- Flux Enhancement with the use of a moderator:

For a region close to the source $\kappa r << 1$

$$\Phi(r) \approx S_o/4\pi D r$$

Considerably higher wrt to absence of moderator

$$\Phi_o(r) \approx S_o/4\pi r^2$$

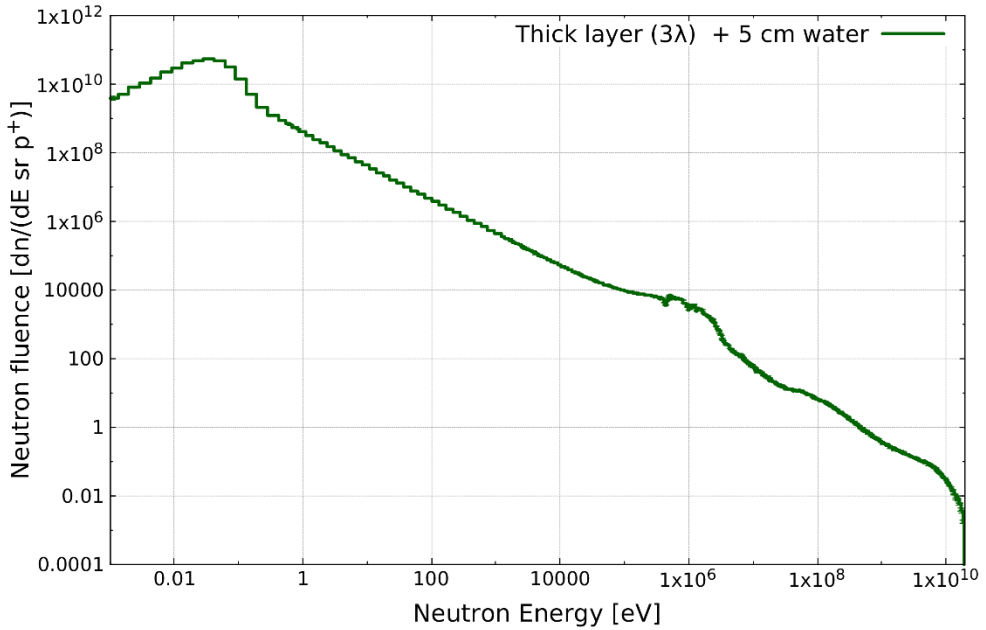
Enhancement $F = \frac{\Phi(r)}{\Phi_o(r)} = r/D$

Carbon: @30cm, F=30/(2.1/3) = 42.8

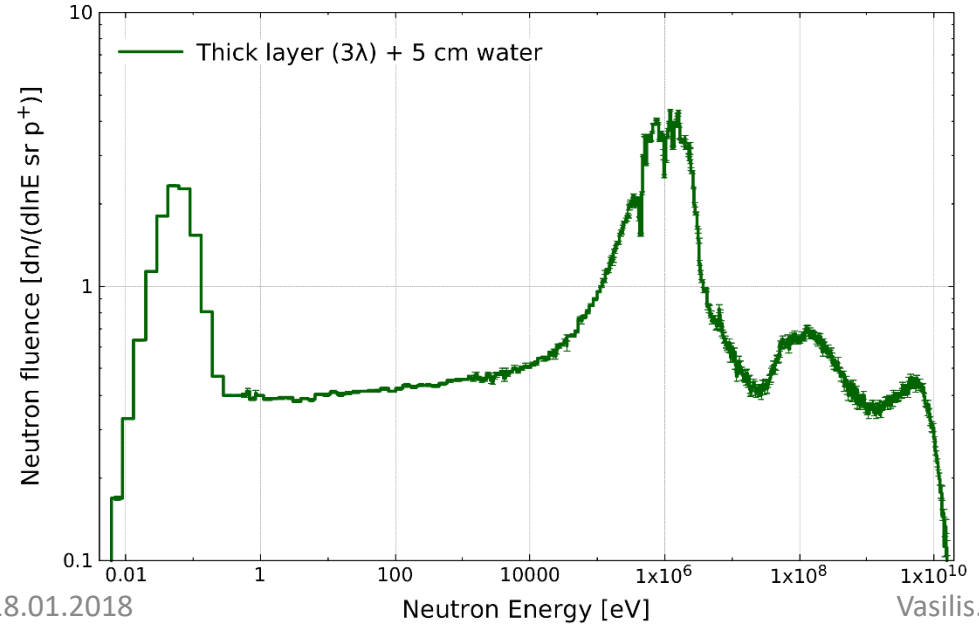
Lead: @30cm, F=30/(2.8/3) = 32.1

Flux/Fluence – Isolethargic

dn/dE



dn/dlnE



- Textbook representation of fluence as $\Phi(E) = dn/dE$ is spanning over several orders of magnitude
  → hides a lot of information
- For energies above thermal the flux is almost: $\Phi(E) \approx \frac{C}{\bar{\xi}\Sigma_s E}$

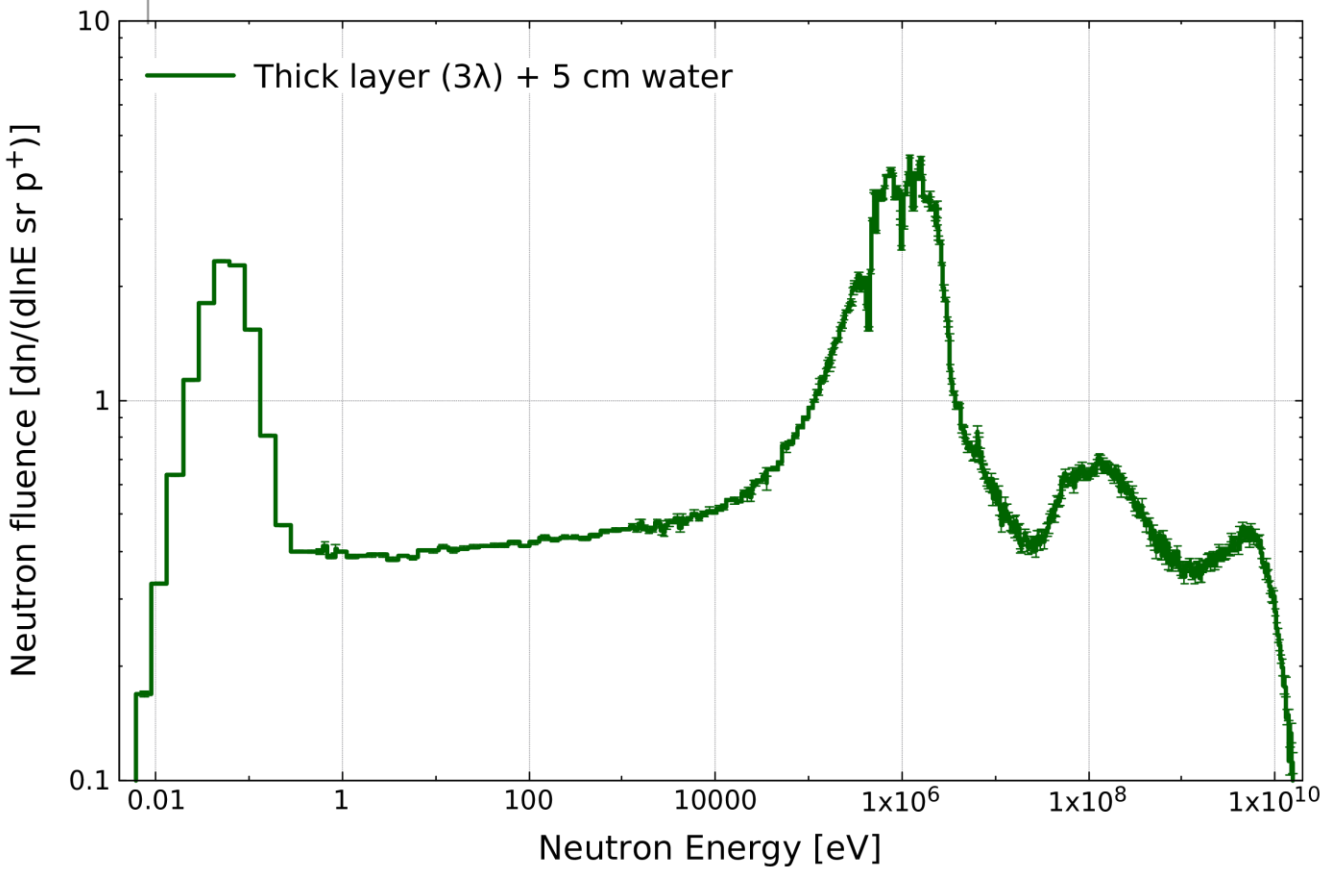
  which can be converted to

$$E\ \Phi(E) = E\frac{dn}{dE} \approx C/\bar{\xi}\Sigma_s$$

$$\Leftrightarrow \frac{dn}{dlnE} \approx C/\bar{\xi}\Sigma_s = const$$

- Resulting to a histogram "*flat*" in log space in the epithermal region

Isolethargic



Advantages:

- Structures are more visible
- The Y scale is in-depended on the X unit
  since $\mathrm{d}lnE = \mathrm{d}E/E$= unit less
- When X in log, the areas represent the integral of neutrons

How to read:

- It gives the amount of neutrons at energy *E* for an energy interval $\Delta E = E$

Converting histogram to Isolethargic

Logarithmic Histogram:

- Defined as: $X_{min}=log_{10}(E_{min})$, $X_{max}=log_{10}(E_{max})$, N_{bins}
- Log step: $s = (X_{max}-X_{min})/N_{bins}$
- Lower Energy of each bin: $E_i = 10^{X_{min}+i\cdot s}$
- Width of each bin: $\Delta E_i = 10^{X_{min}+(i+1)\cdot s} - 10^{X_{min}+i\cdot s}$
- Geometric Mean of the each bin: $\bar{E}_i = \sqrt{E_i \cdot E_{i+1}} = 10^{X_{min}+(i+\frac{1}{2})\cdot s}$
- To convert to isolethargic can be done by multiplying with:

$$f = \frac{\bar{E}}{\Delta E} = \frac{10^{X_{min}+(i+\frac{1}{2})\cdot s}}{10^{X_{min}+(i+1)\cdot s} - 10^{X_{min}+i\cdot s}} = \frac{\sqrt{10^s}}{10^s - 1}$$

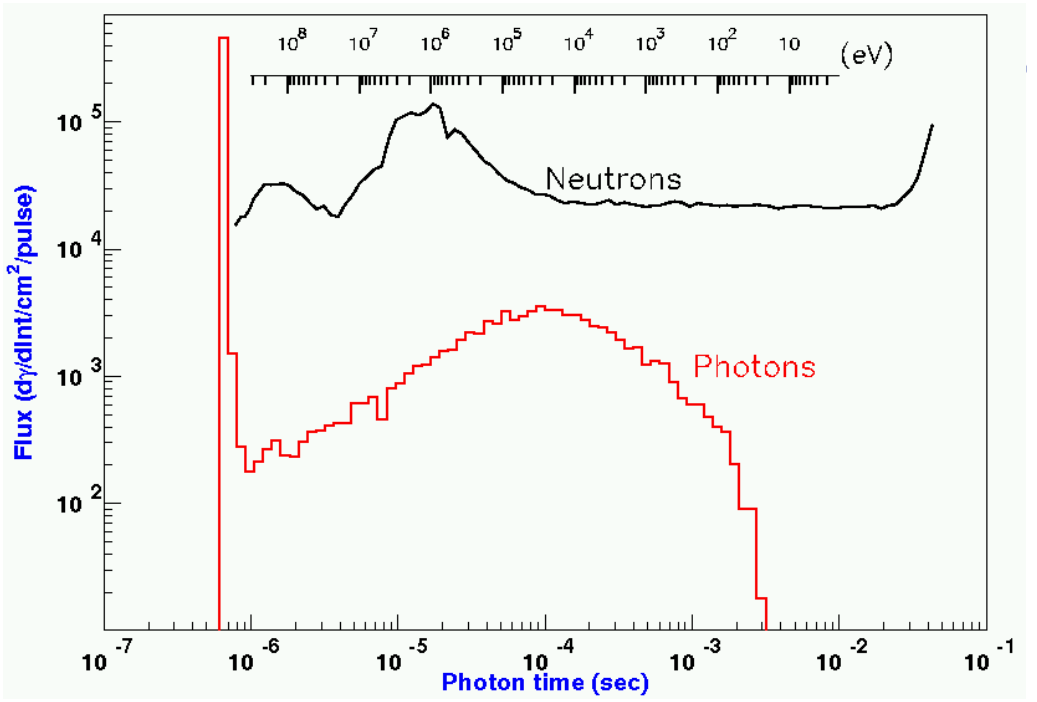
Q: difference of geometric mean vs mean for 20 bins per decay?

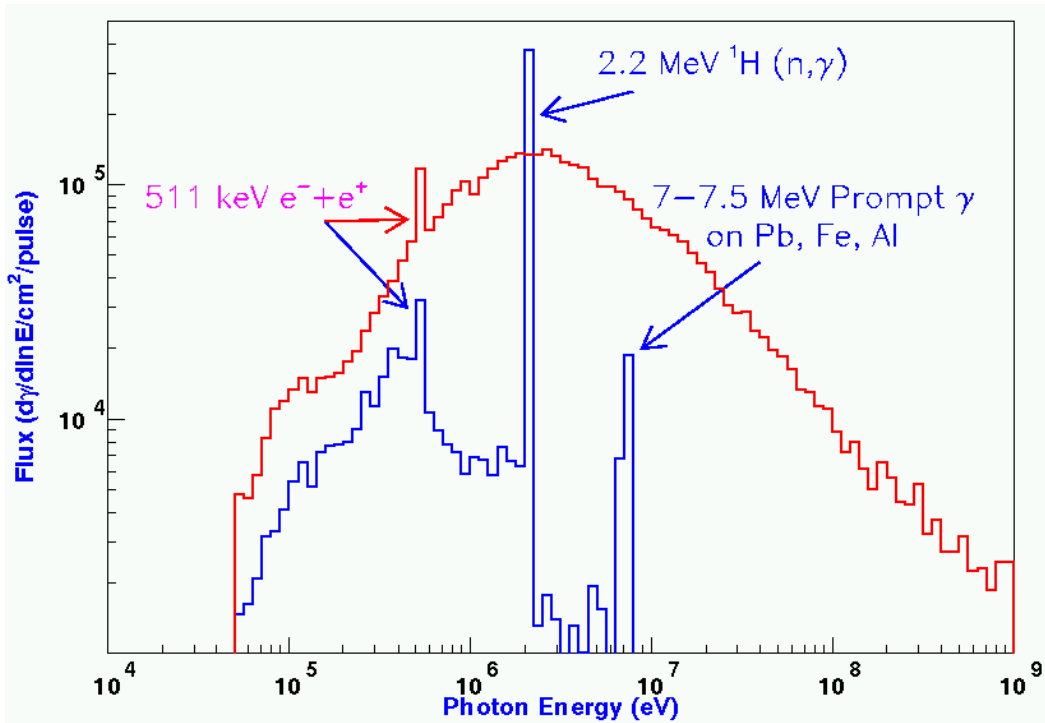
Delayed Gammas

"Delayed" gammas comes mostly from thermal neutrons radiative capture on ^{1}H

$$ {}_{1}^{1}H + {}_{0}^{1}n \rightarrow {}_{1}^{2}D + \gamma(2.2MeV) $$

Arrives to the experimental area EAR1 at times from $\mu s \ldots ms$, together with the $keV \ldots 100keV$ neutrons.





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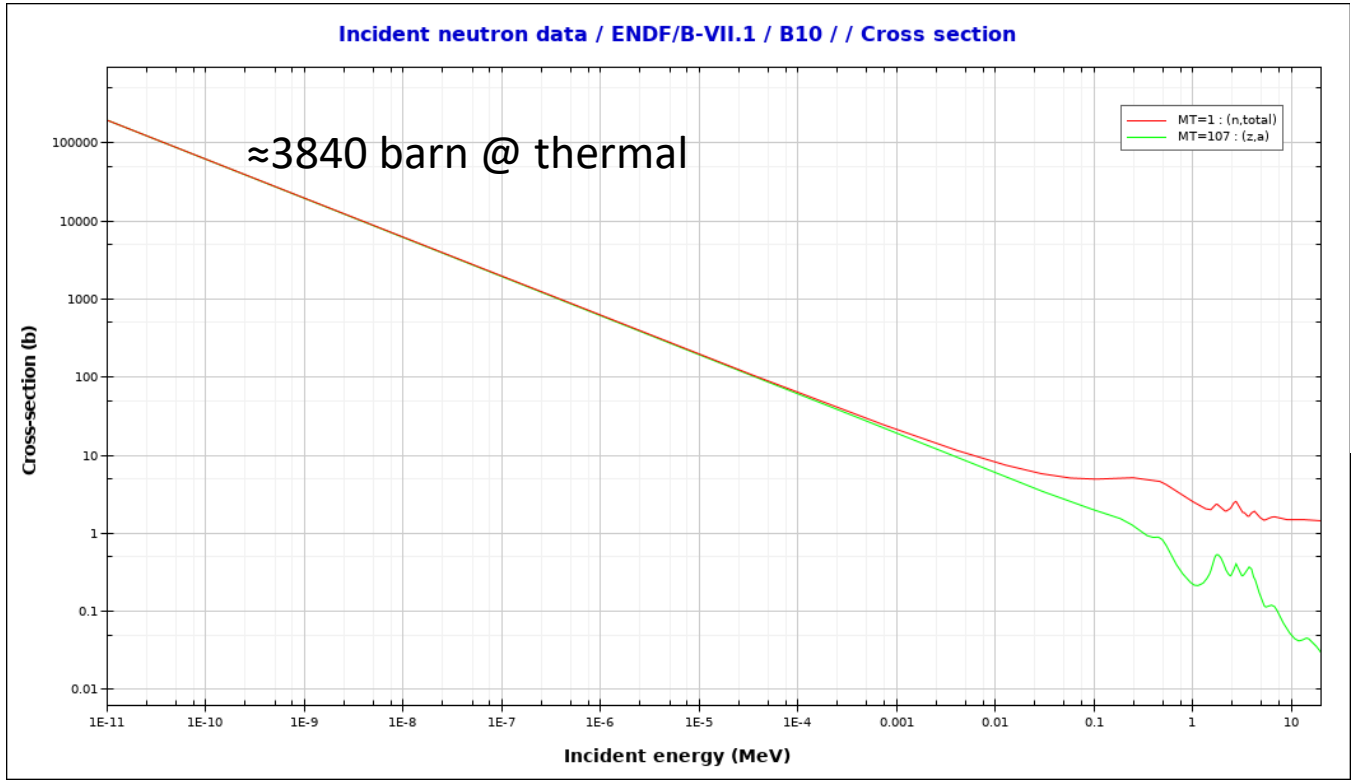
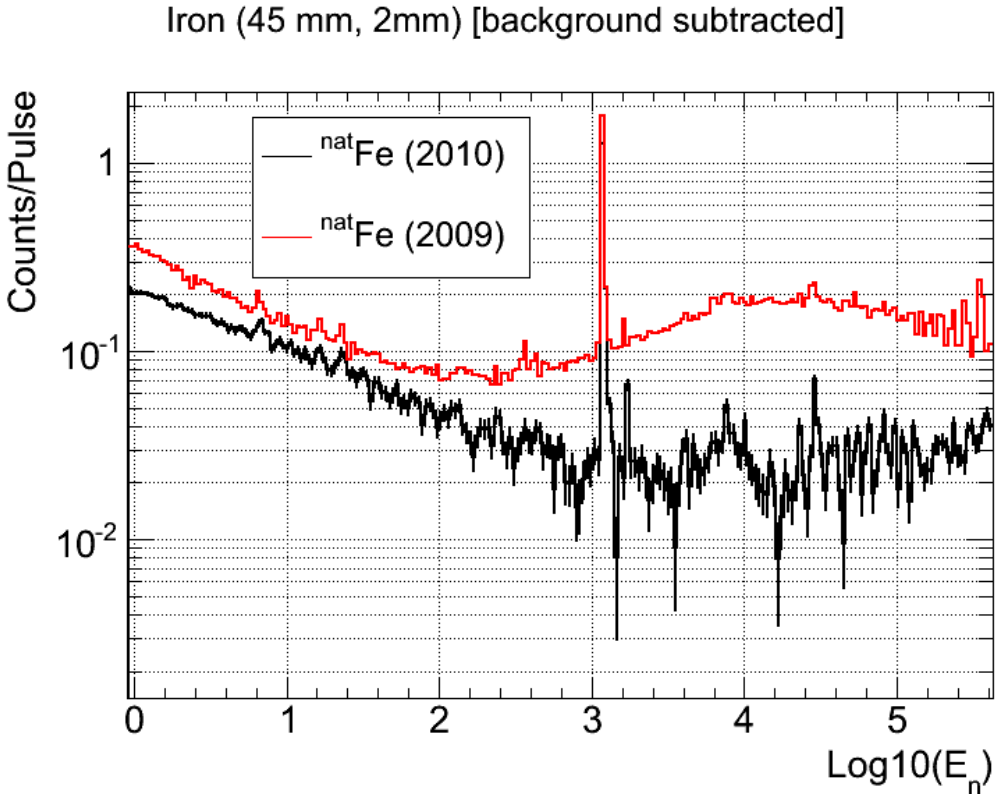
Borated Water effect

One option to suppress this background, was the addition of Boric Acid in the moderator circuit.

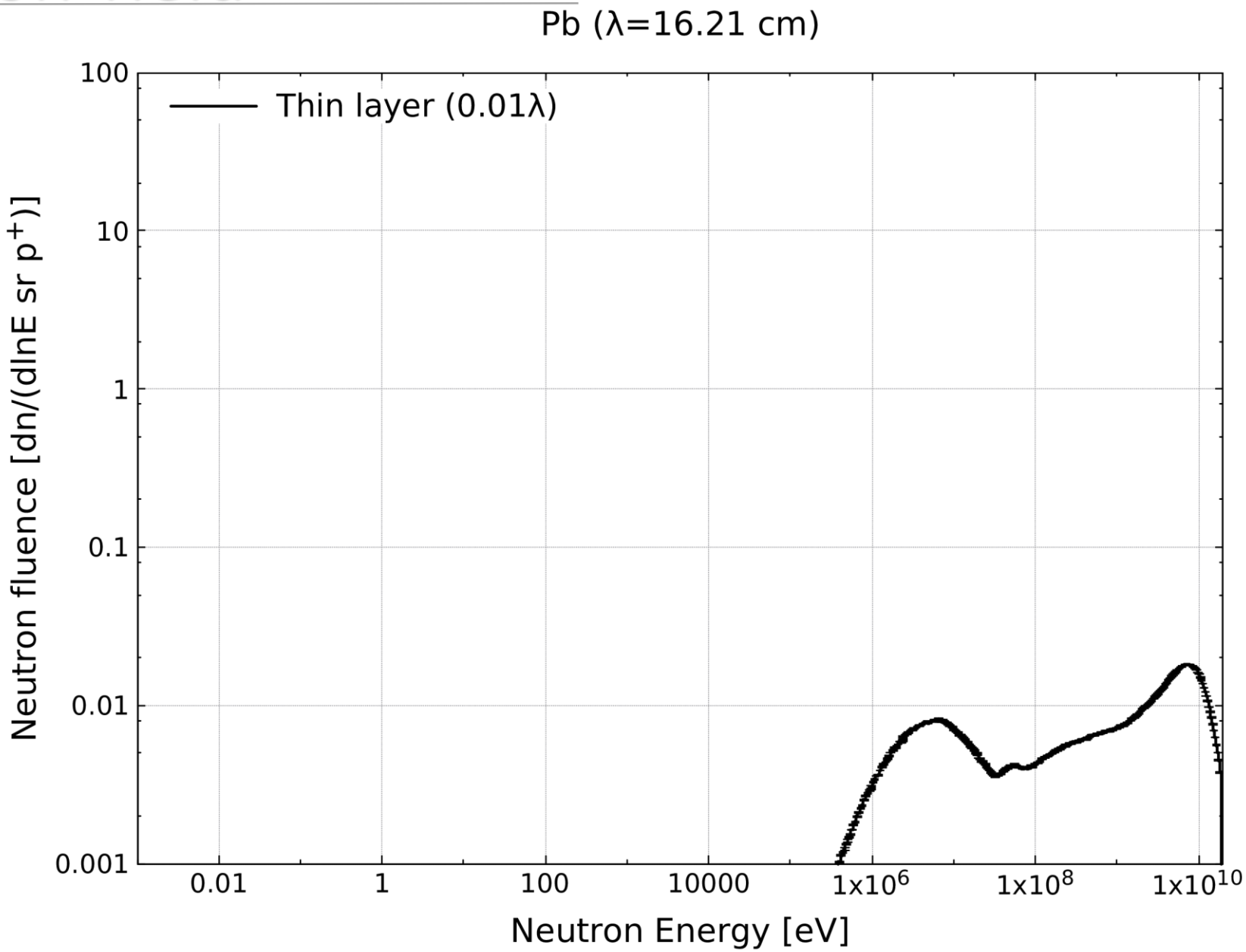
Boric acid: Saturated at 1.28 % enriched with 95% ^{10}B



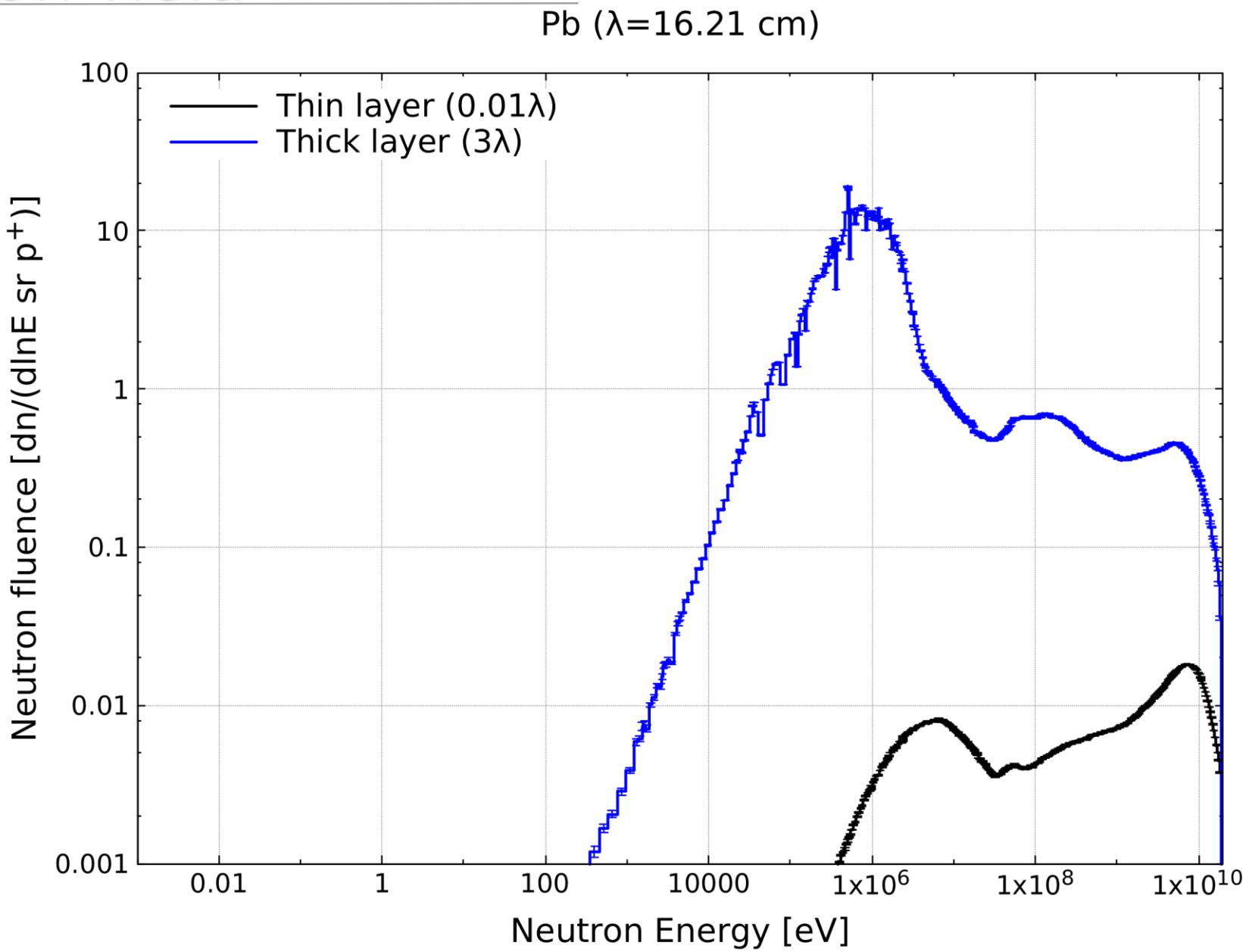


The 2.2 MeV γ is replaced by a *484 keV* (94%) from the ^{10}B(n,α)
6% gives *2.79 MeV*

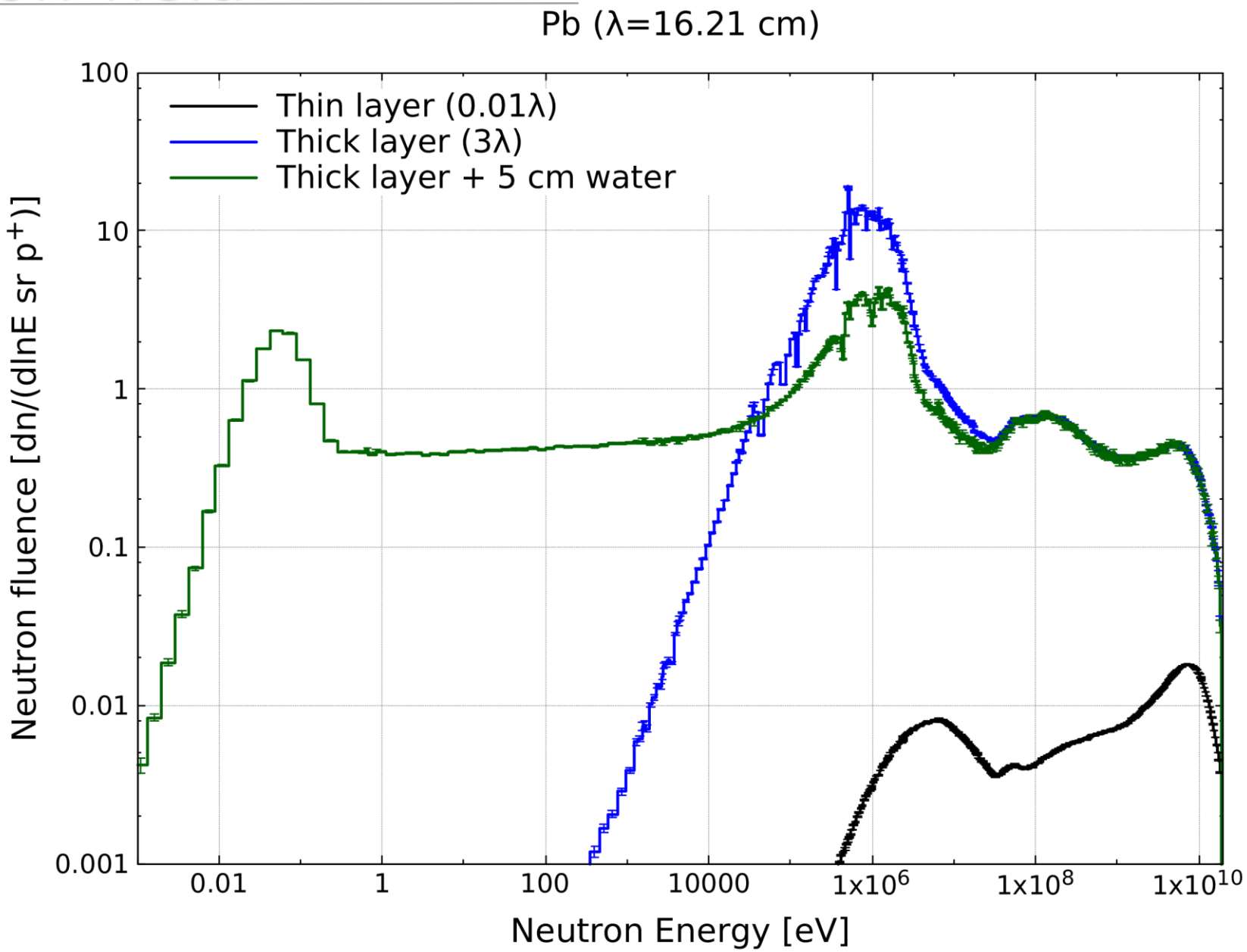
Neutron Yield



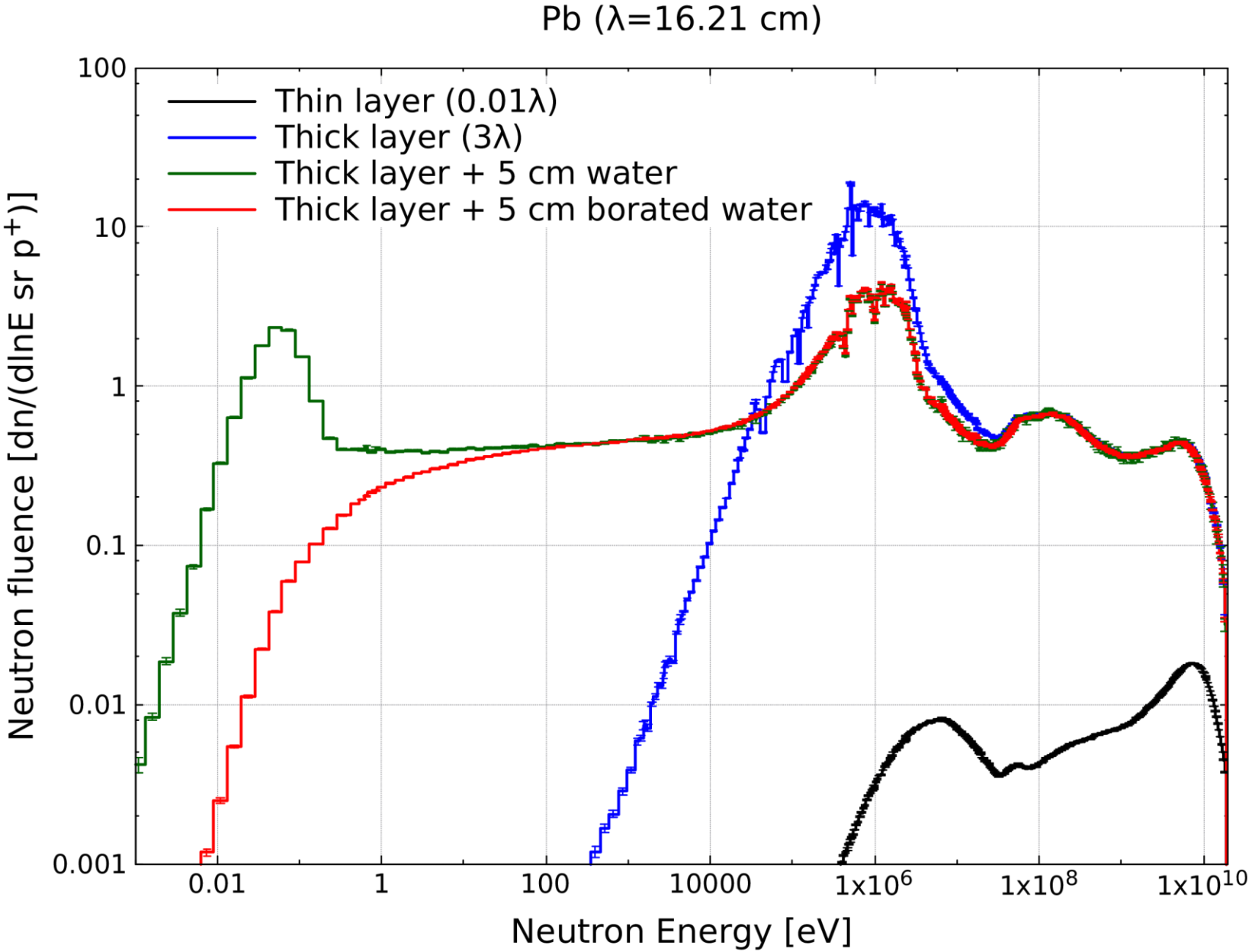
Neutron Yield



Neutron Yield



Neutron Yield



Energy Time relation

The average increase in lethargy $u=n\xi$ during moderation is

$$\frac{du}{dt} = \xi\Sigma_s \frac{dx}{dt} = \xi\Sigma_s v$$

From the lethargy $\mathrm{u} = n\xi = \ln(\frac{E_i}{E_f})$ we have $v_f = v_i e^{-\frac{u}{2}}$

Therefore: $$\frac{dv}{dt} = -\frac{\xi\Sigma_s}{2} v^2$$

Integrating: $$t = \frac{2}{\xi\Sigma_s}\int_v^{v_o} \frac{dv}{v} = \frac{2}{\xi\Sigma_s}\left(\frac{1}{v_f} - \frac{1}{v_i}\right)$$

Converting to energy: $$E = \frac{2m_n}{(\xi\Sigma_s t)^2} v(t)$$

Energy-Time relation

for A=1 $$\overline{E(t)} = \frac{3m_n}{(\Sigma_s t)^2} = \frac{1.8 eV\mu s^2}{t^2}$$

for A>>1 $$\overline{E(t)} = \frac{m_n}{2}\frac{A(A+2)}{(\Sigma_s t)^2} \approx \frac{A^2}{(\Sigma_s t)^2} 0.522\ eV\mu s^2 cm^{-2}$$

more accurately* $$\overline{E(t)} = \frac{K}{(t+t_o)^2}$$

where $K = \frac{m_n \lambda_s^2 (1-a)^2}{2a^2}$ and $t_o = (1-a)\frac{\lambda_s}{a}\sqrt{\frac{m_n}{2E_o}}$

* R.E.Slovacek et al, Nucl. Sci. and Eng. 62:445-462,1977

Energy-Time relation

Moderation:

$$\overline{E(t)} = \frac{K}{(t + t_o)^2}$$

Flight:

$$E = \frac{m_n L^2}{2\, t^2}$$

Relativistically:

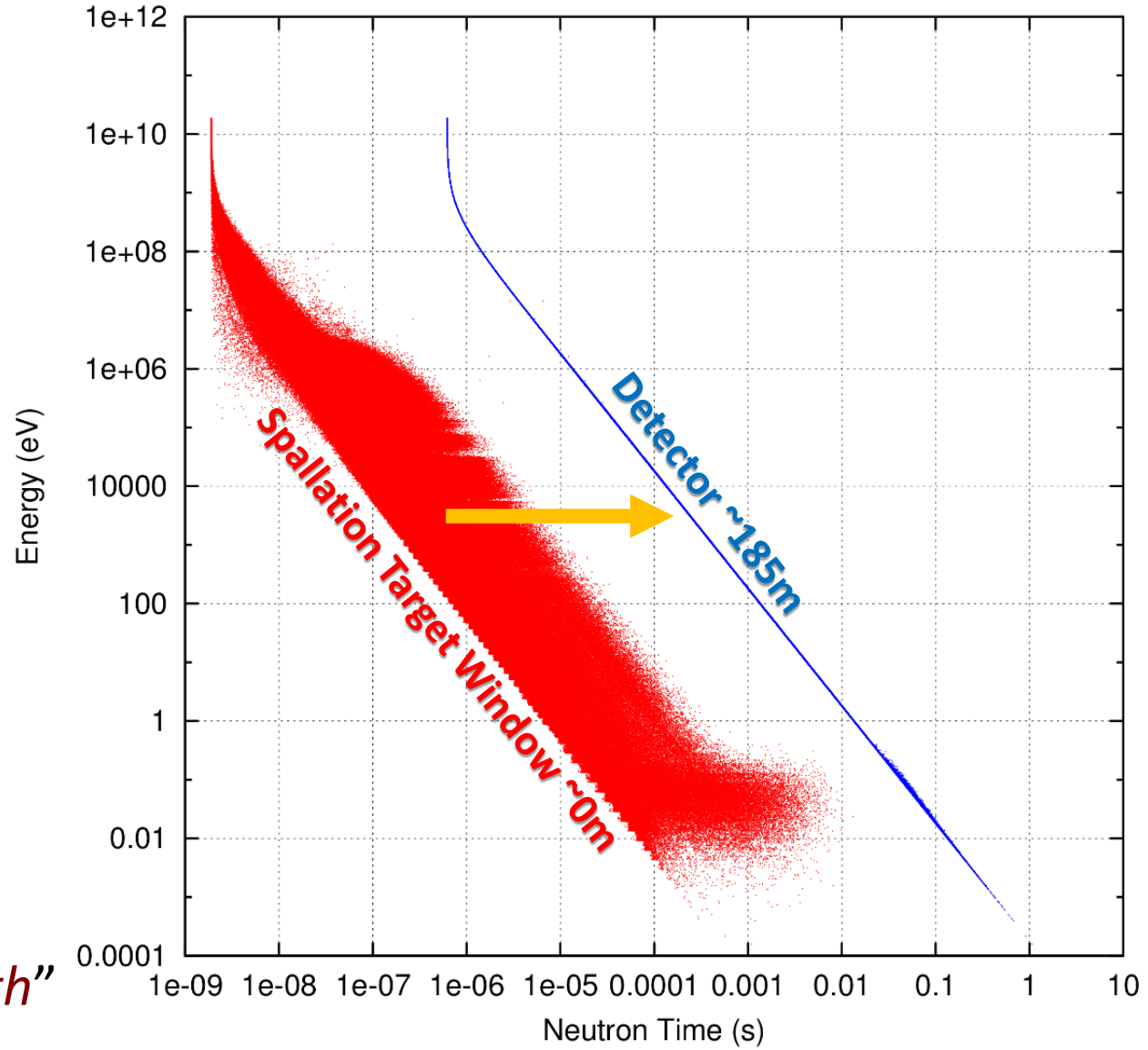
$$\gamma = 1/\sqrt{1 - \left(\frac{L}{tc}\right)^2}$$

$$E_{kin} = (\gamma - 1)\, m_n$$

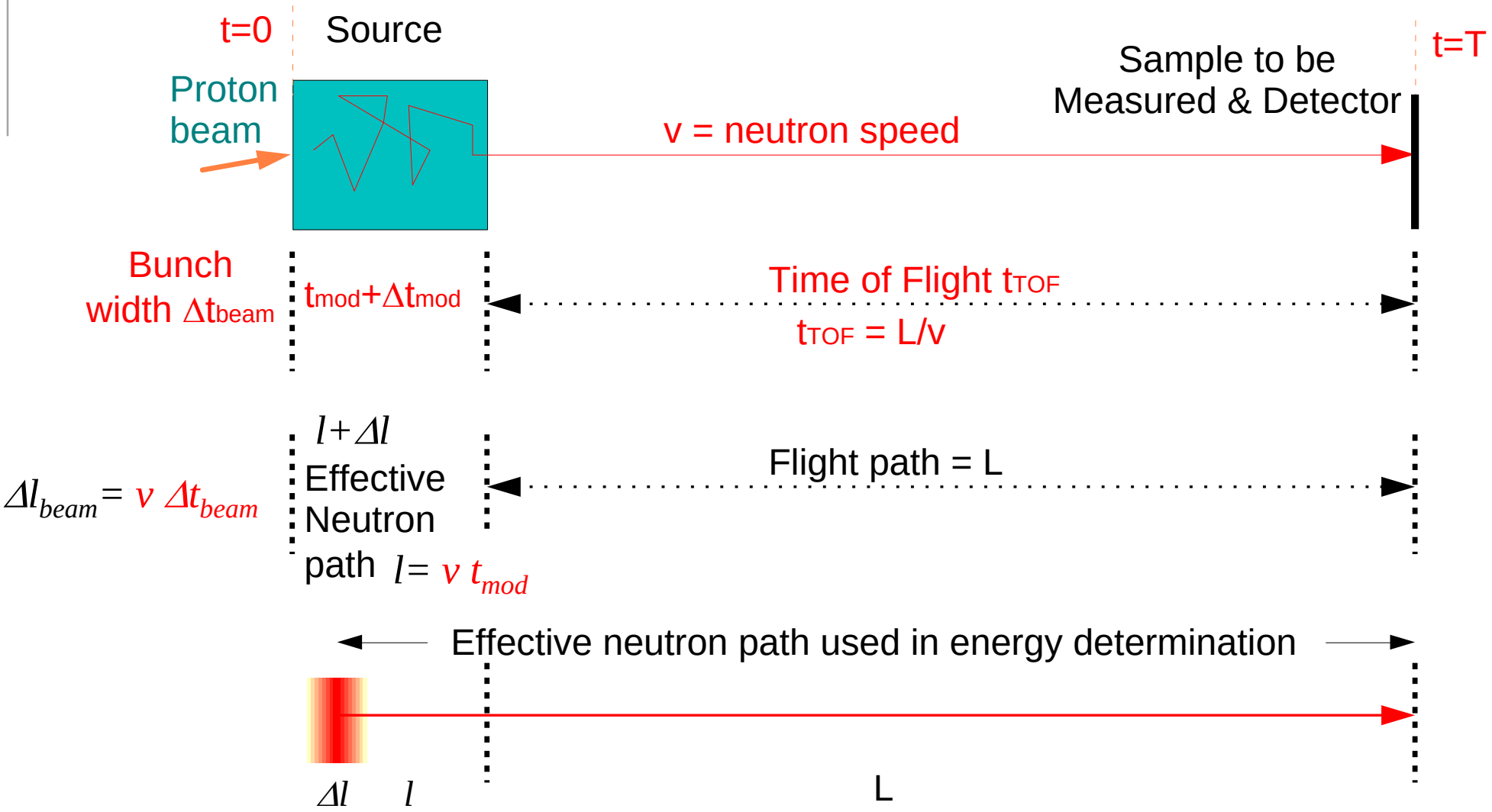
Differentiating we get the uncertainty:

$$\frac{\Delta E}{E} = -2\frac{\Delta t}{t} = 2\frac{\Delta l}{L + l}$$

l = virtual quantity "*effective neutron path*"



Effective Neutron Path *l*

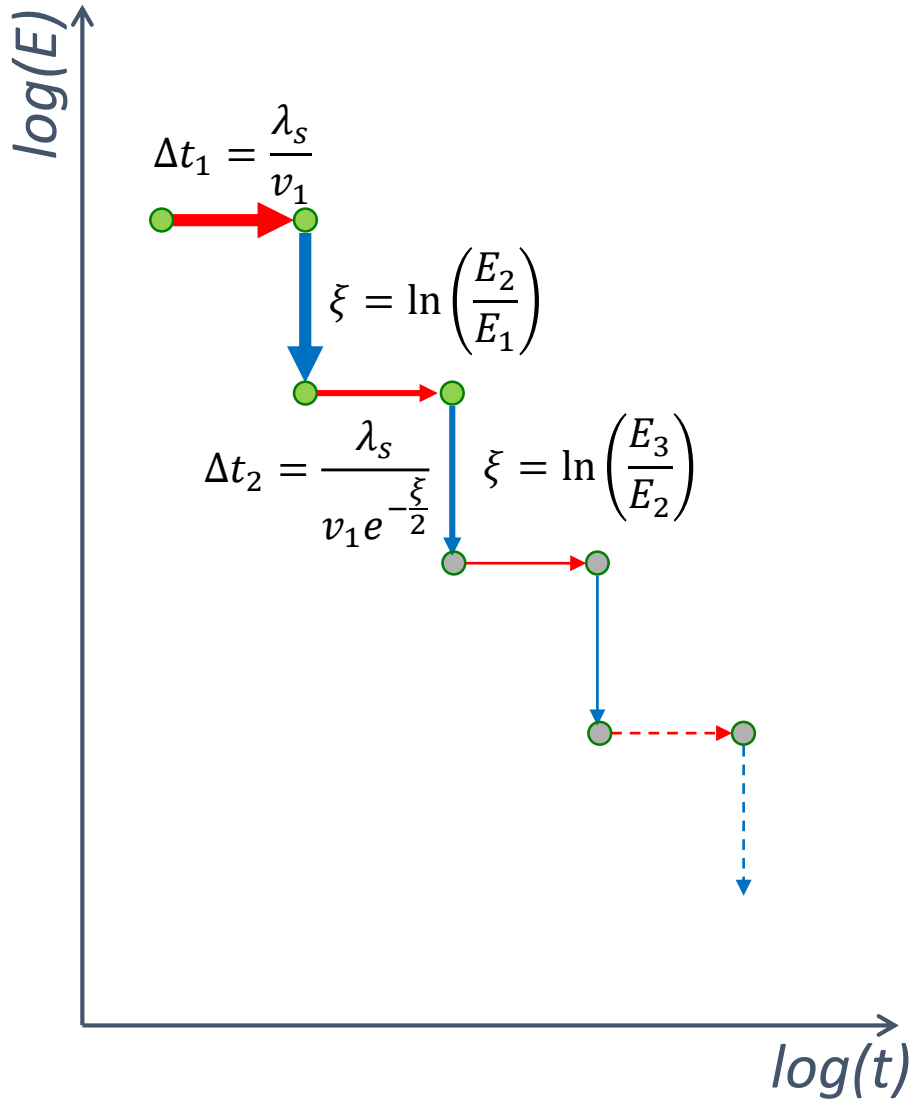


The neutron velocity v is derived from the "effective neutron path"
$v=(L+l)/t$ with an uncertainty $\Delta v = \Delta l/t$

WARNING:

Moderation path ≠ effective neutron path

Neutron Moderation



Mean free path

$$\lambda_s = \frac{1}{\Sigma_s} = \frac{1}{\sigma_s \frac{N_A}{A} \rho} \approx const$$

Average energy loss in collision

$$\xi = \ln\left(\frac{E_2}{E_1}\right) \approx \frac{2}{A + 2/3}$$

Velocity after *n* collisions

$$v_n = v_1 \cdot e^{-\frac{n-1}{2}\xi}$$

Time after *n* collisions

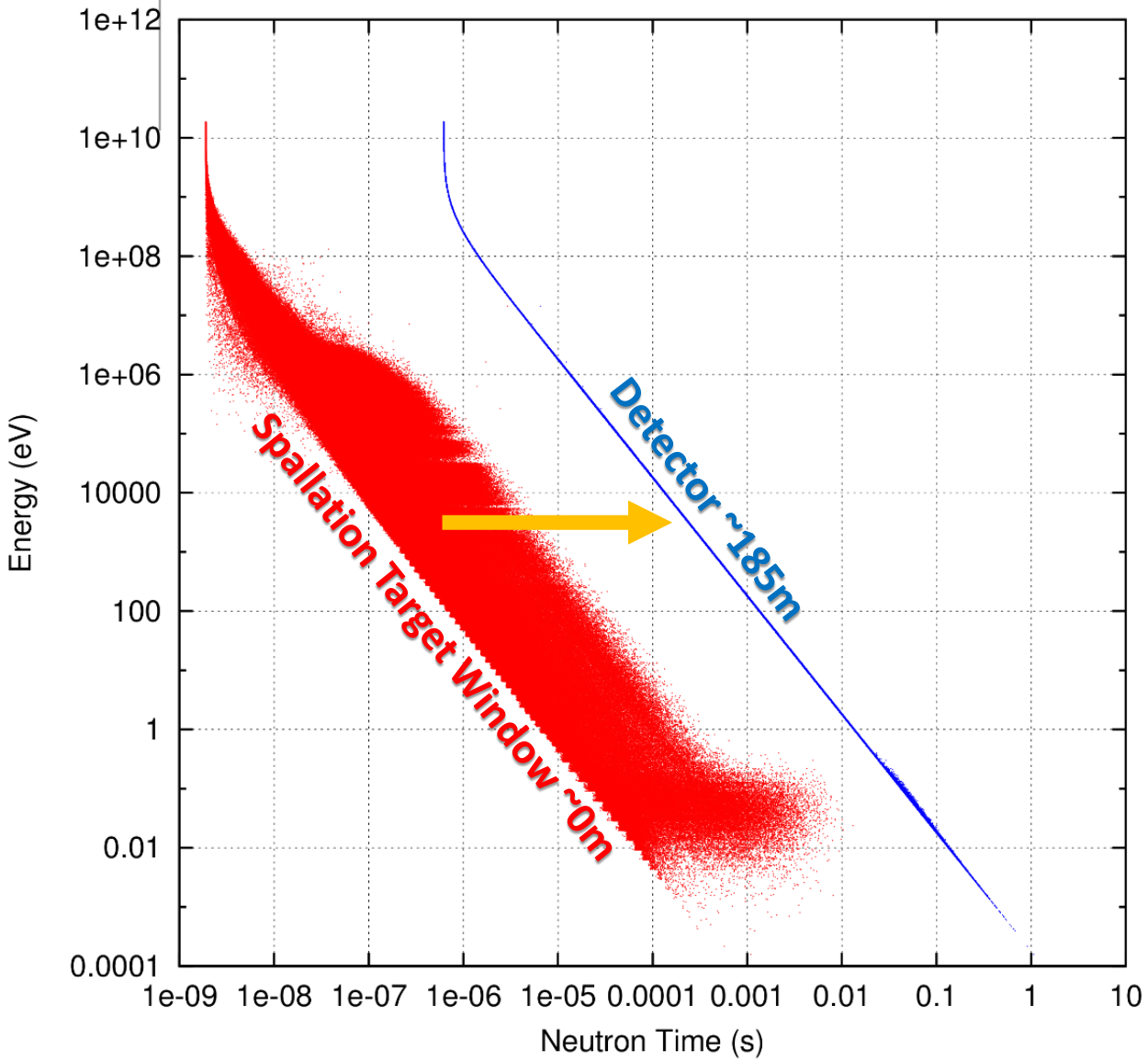
$$t_n = \frac{\lambda_s}{v_1} \sum_{i=1}^{n} e^{\frac{i-1}{2}\xi}$$

Effective length l_n after *n* collisions

$$l_n = v_n \cdot t_n = v_1 \cdot e^{-\frac{n-1}{2}\xi} \cdot \frac{\lambda_s}{v_1} \sum_{i=1}^{n} e^{\frac{i-1}{2}\xi}$$

$$l_n \approx 2\frac{\lambda_s}{\xi}$$

Neutron Moderation



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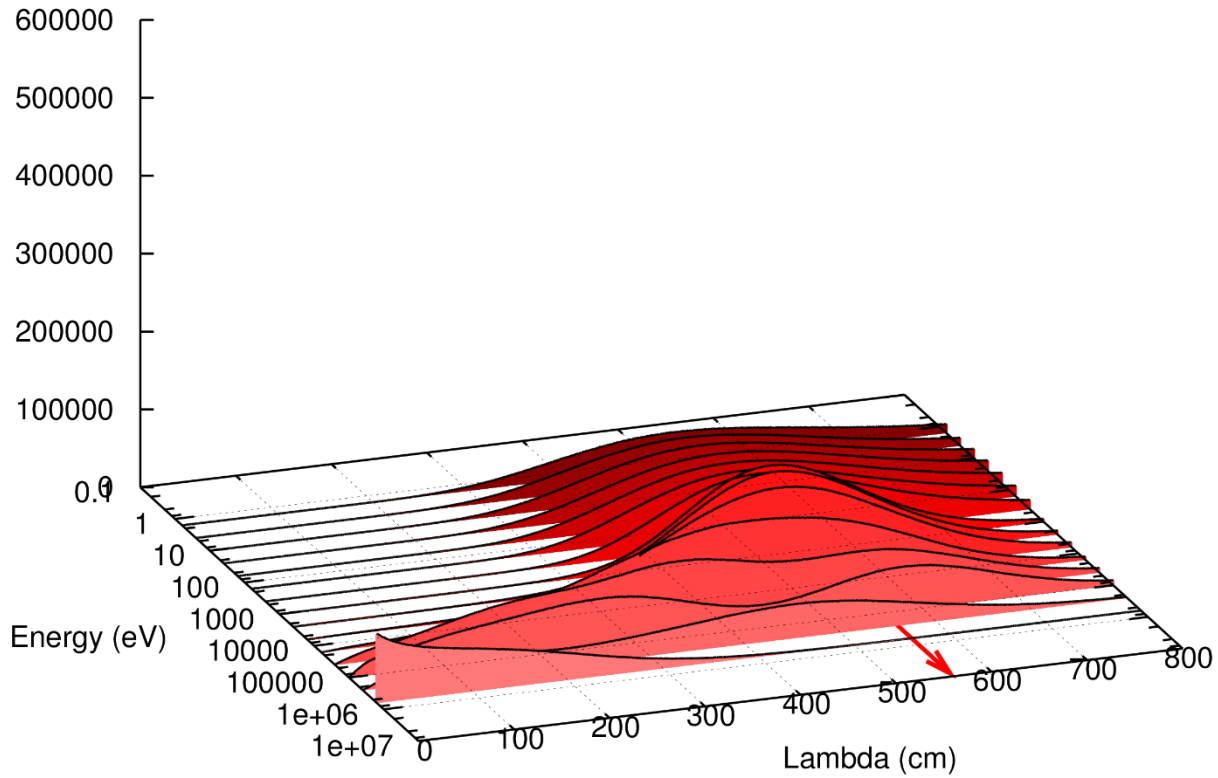
$$l_n \approx 2\frac{\lambda_s}{\xi}$$

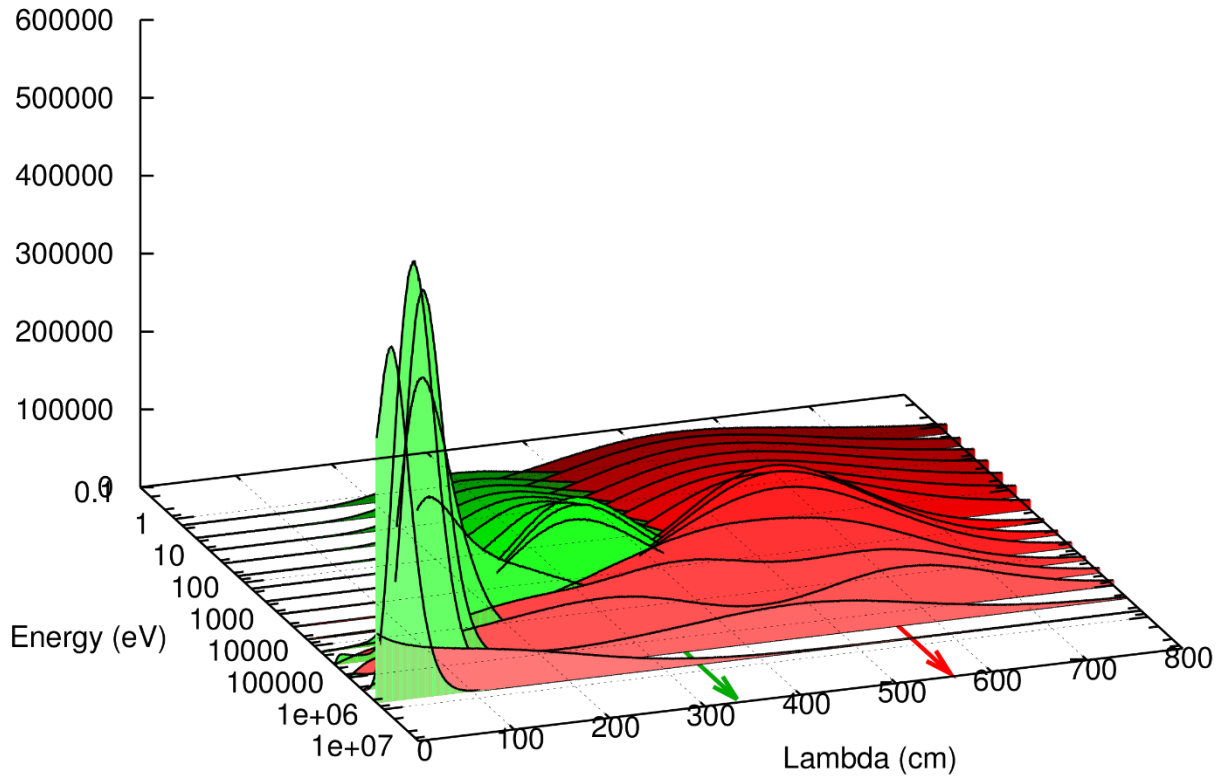
Effective Neutron Path

- **Lead:**
  σ_s(1keV) = 11.35 b
  λ_s = 2.7 cm
  $\xi = 9.6\times10^{-3}$
  $l \approx 560$ cm



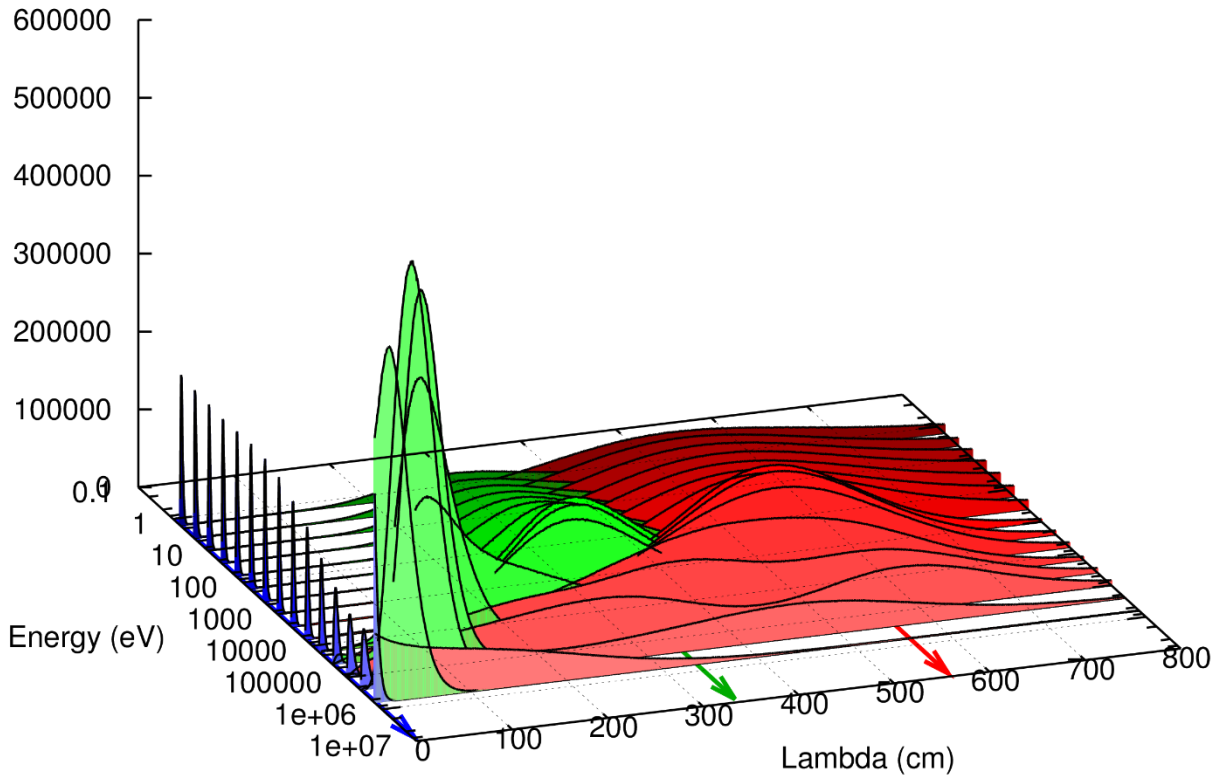
Effective Neutron Path

- **Lead:**
  σ_s(1keV) = 11.35 b
  λ_s = 2.7 cm
  $\xi = 9.6\times10^{-3}$
  $l \approx$ 560 cm
- **Aluminum:**
  σ_s(1keV) = 1.42 b
  λ_s = 11.7 cm
  $\xi = 7.2\times10^{-2}$
  $l \approx$ 320cm



Effective Neutron Path

- **Lead:**
  σ_s(1keV) = 11.35 b
  λ_s = 2.7 cm
  $\xi = 9.6\times10^{-3}$
  l ≈ 560 cm
- **Aluminum:**
  σ_s(1keV) = 1.42 b
  λ_s = 11.7 cm
  $\xi = 7.2\times10^{-2}$
  l ≈ 320cm
- **Water:**
  σH_s(1keV) = 20.3 b
  σO_s(1keV) = 3.85 b
  λ_s = 0.67 cm
  $\xi_H = 1, \xi_O = 0.12$
  l_H ≈ 1.5 cm



Effective Neutron Path Spread

Lambda spread determined by the energy loss after the collision

Maximum (θ=0°)

$$E_{2max} = E_1$$

Minimum (θ=180°)

$$E_{2\min} = \left[\frac{A-1}{A+1}\right]^2 E_1$$

and a mean scattering angle

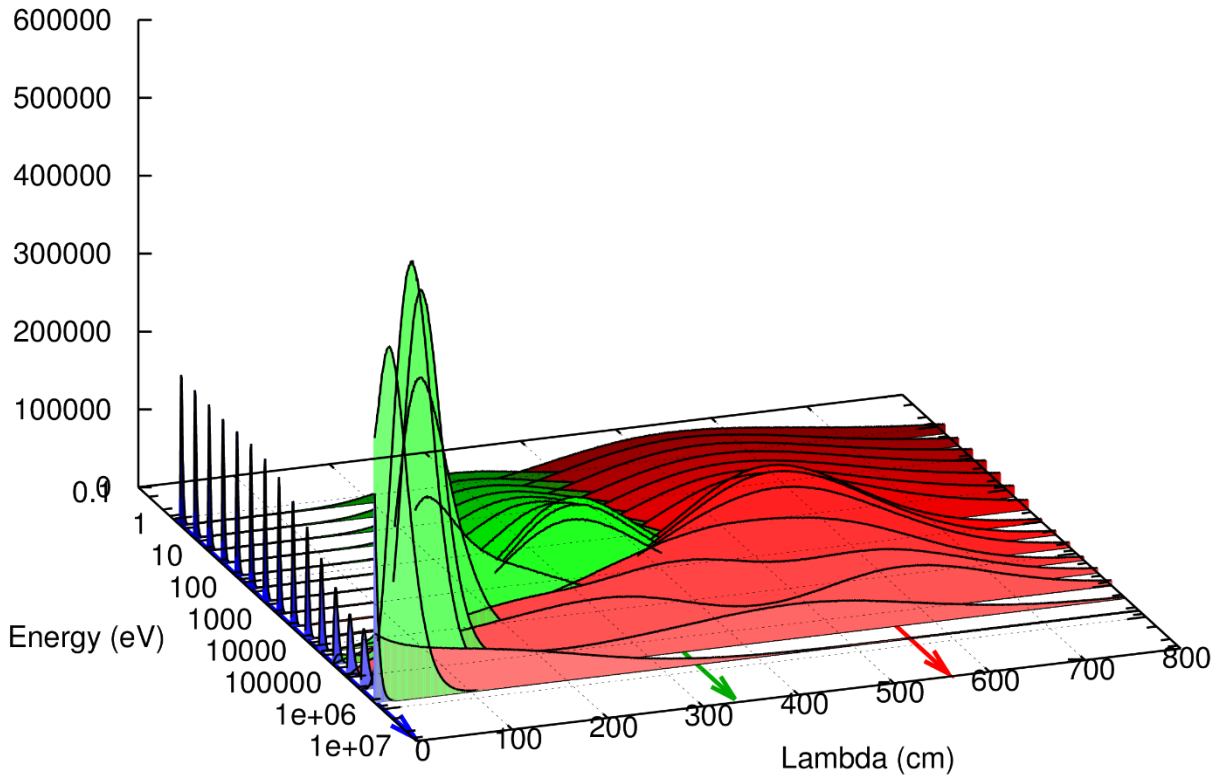
$$b = \overline{cos\theta} = \frac{2}{3A}$$

and solving for the sum (A>>1)

$$\left(\frac{\Delta E}{E}\right)^2 \approx \frac{8}{3A}$$

For H (A=1)

$$\overline{\left(\frac{\Delta E}{E}\right)^2} = \frac{7}{3}$$



Effective Neutron Path Spread

- **Lead:**

$$\sqrt{(\Delta E/E)^2} = 11.4\%$$

$$\Delta l \approx 32\text{cm}$$

- **Aluminum:**

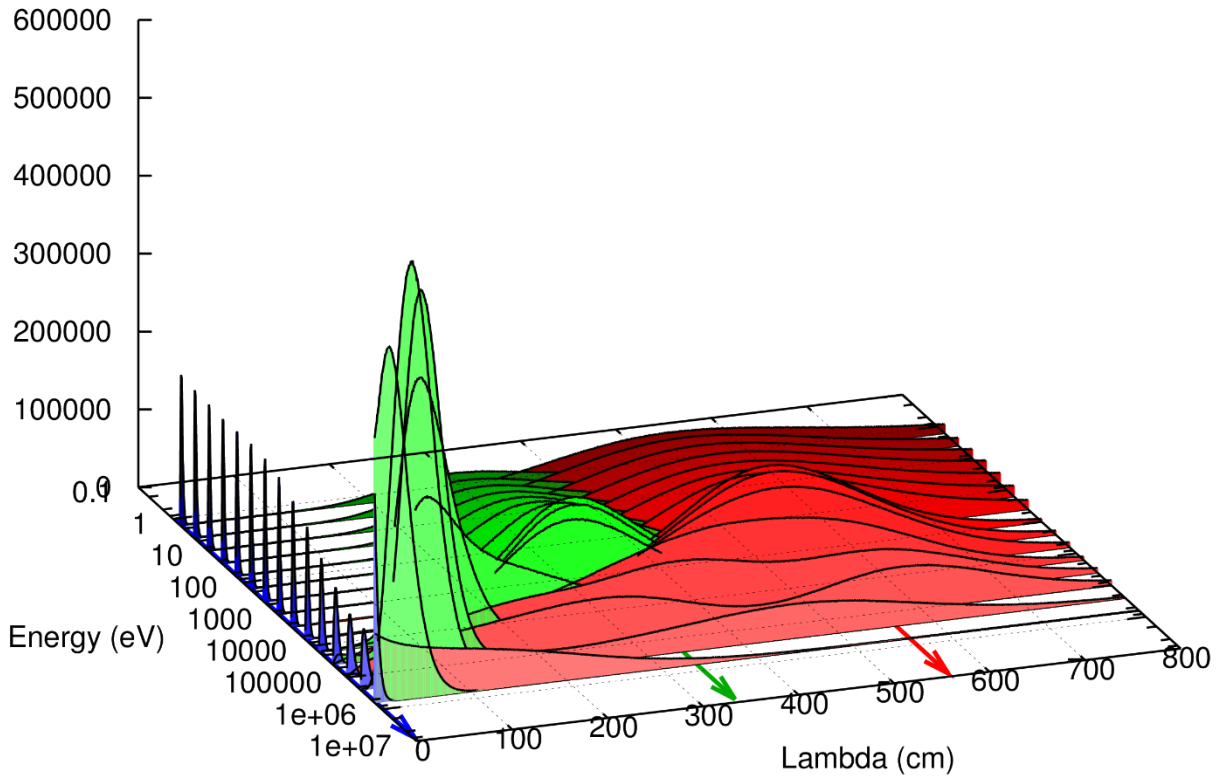
$$\sqrt{(\Delta E/E)^2} = 31.4\%$$

$$\Delta l \approx 53\text{cm}$$

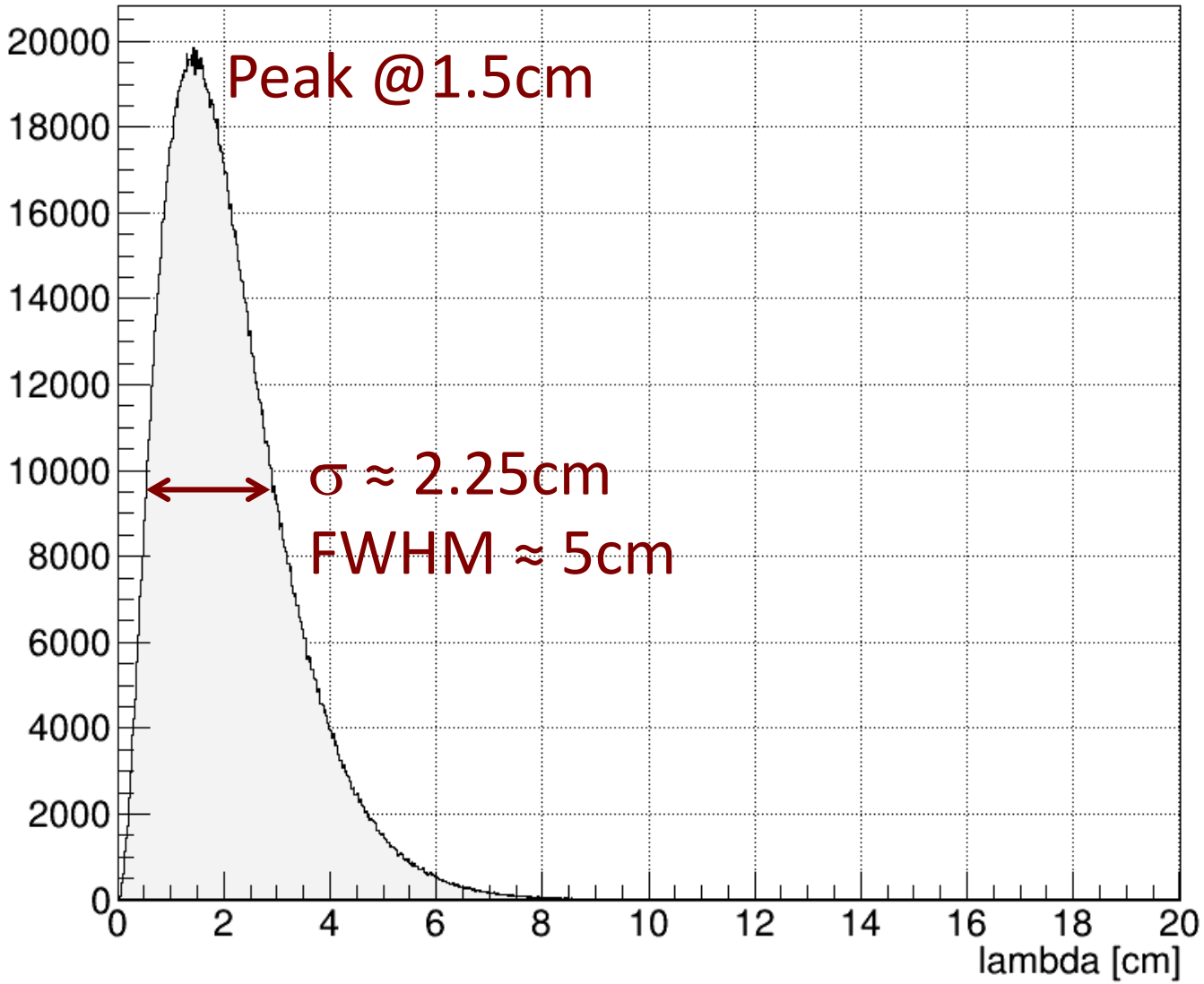
- **Water:**

$$\sqrt{(\Delta E/E)^2} = 150\%$$

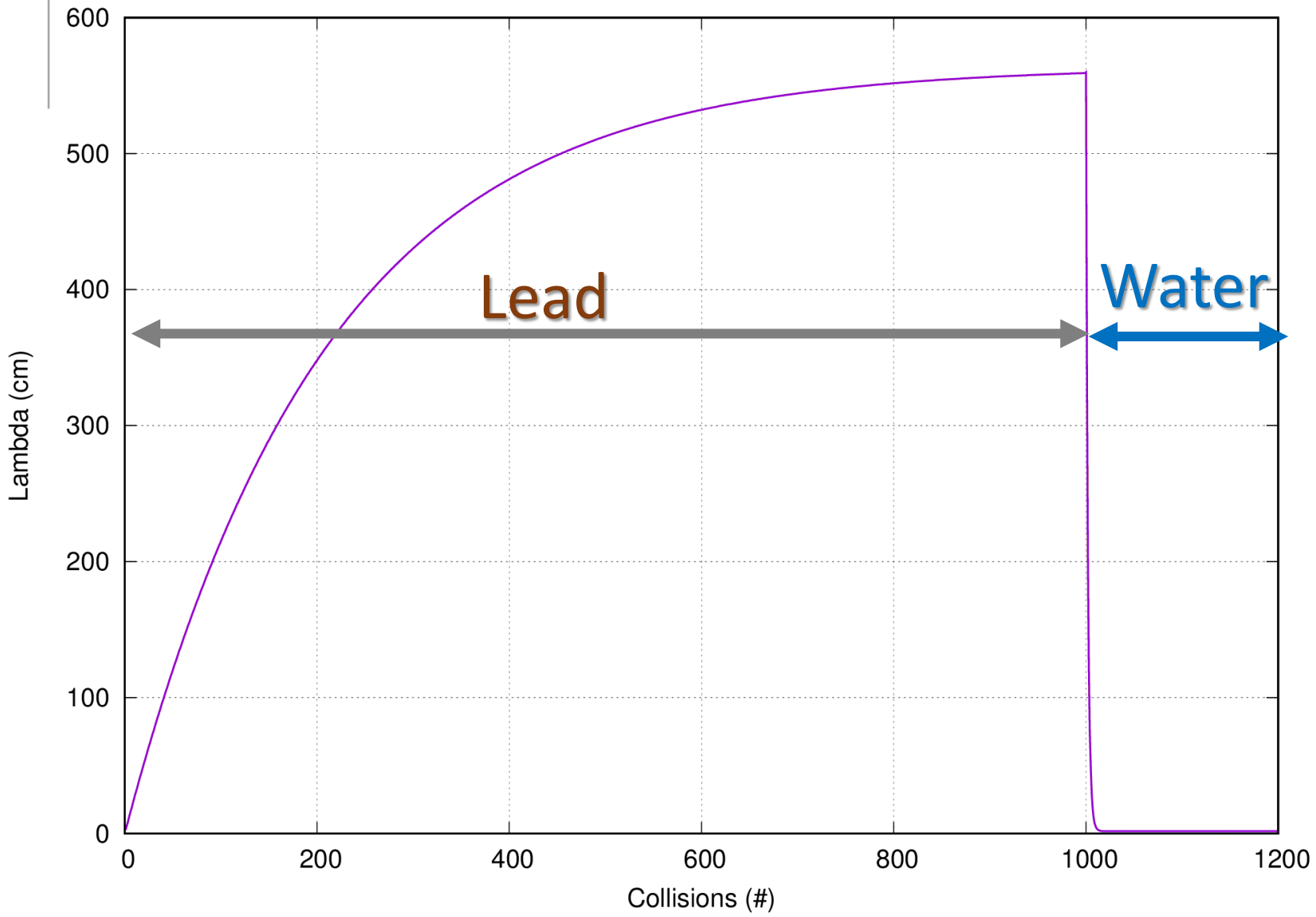
$$\Delta l \approx 2.25\text{cm}$$



Hydrogen Energy resolution @1eV



Lambda vs # neutron collisions

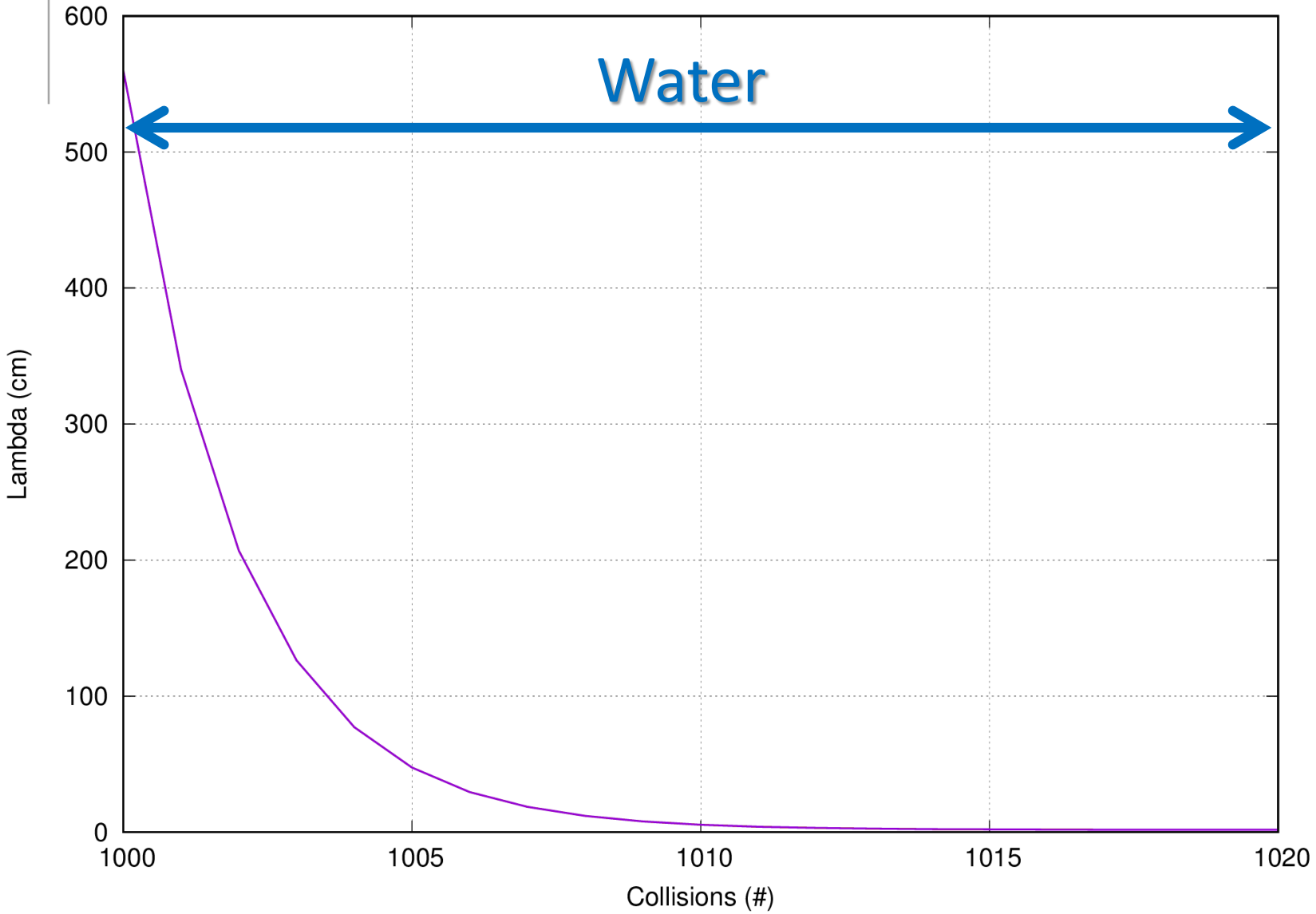


Note:

- to thermalize 2MeV in Pb we need ~1900 collisions
- 1000 col ≈ keV energies
- Average distance traveled

$$r = \sqrt{2N\lambda_s^2}$$
$$\approx \sqrt{2 \cdot 1000 \cdot 2.5^2}$$
$$= 111\ cm$$

Lambda vs # collisions

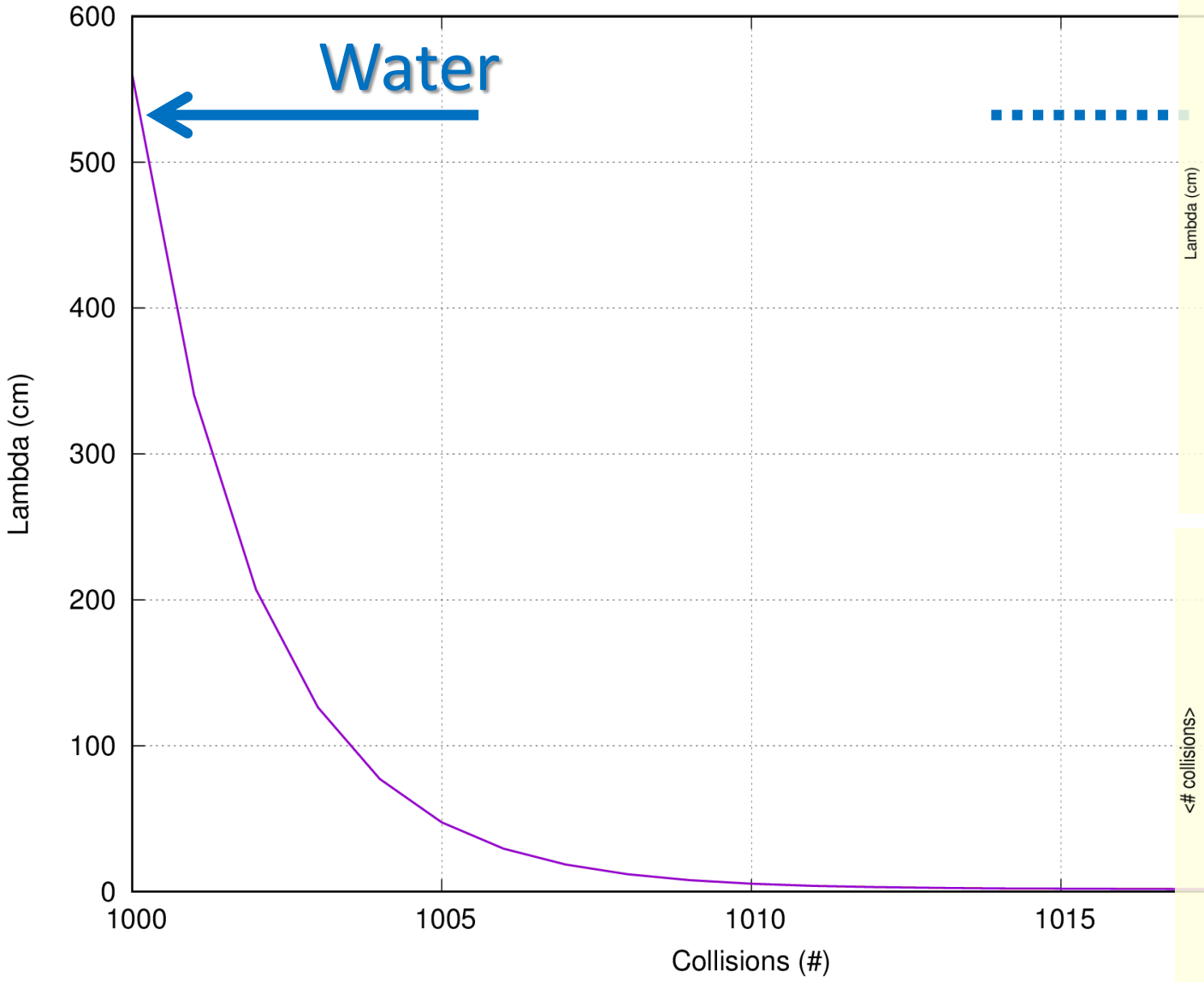


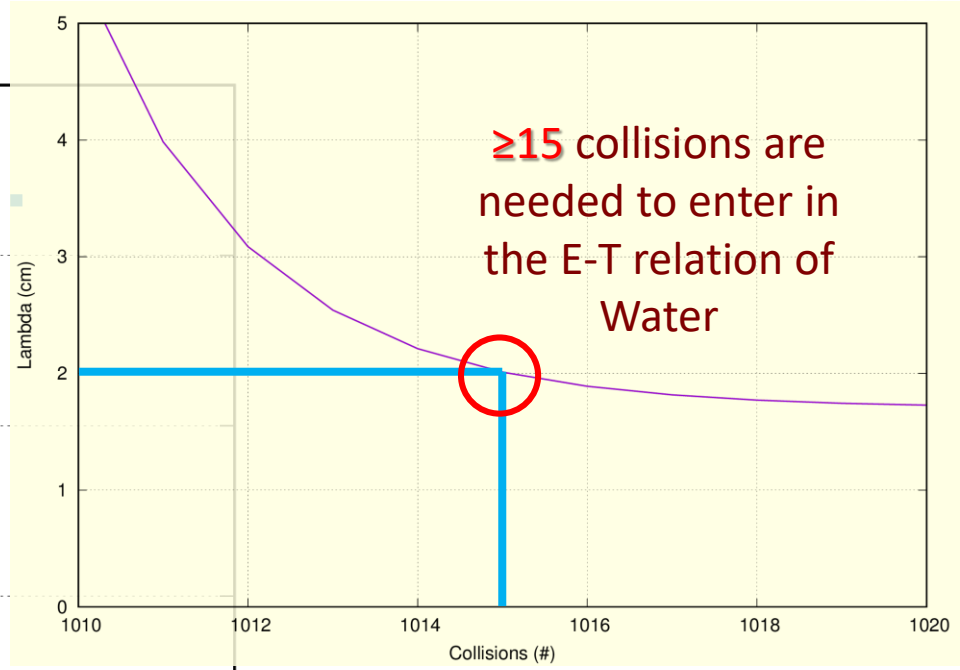
Note:

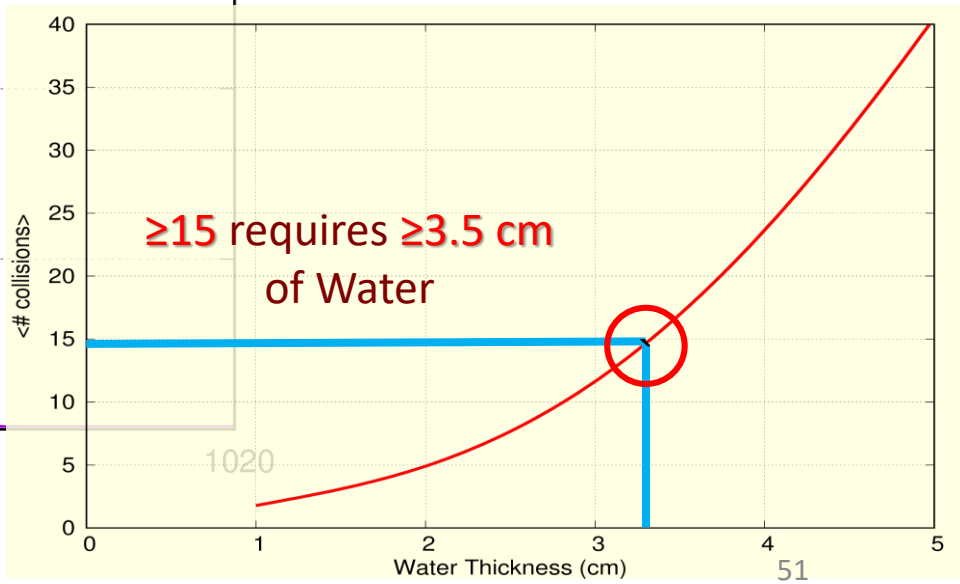
- to thermalize 2MeV in H we need ~18 collisions
- 10 col ≈ keV energies
- Average distance traveled

$$r = \sqrt{2N\lambda_s^2}$$
$$\approx \sqrt{2 \cdot 20 \cdot 0.67^2}$$
$$= 4.2\ cm$$

Lambda vs # collisions







Optimization: Figure of Merit

Distance dependence

- Neutron Fluence:

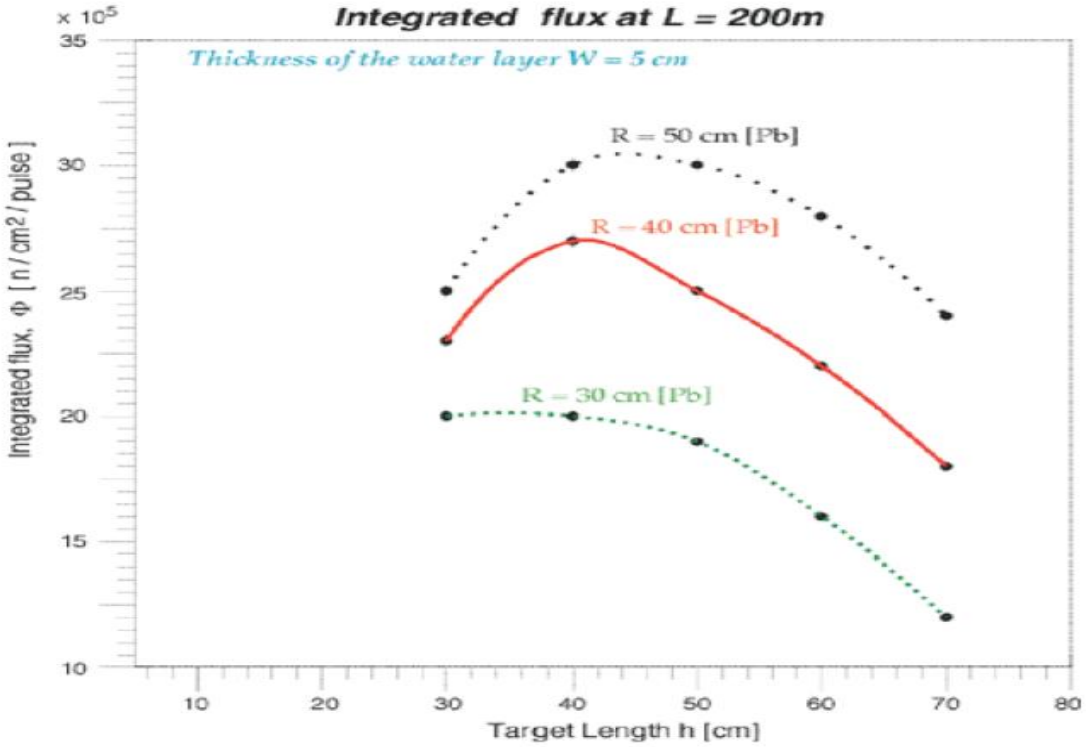
$$\Phi = \frac{\Phi_o}{L^2}$$

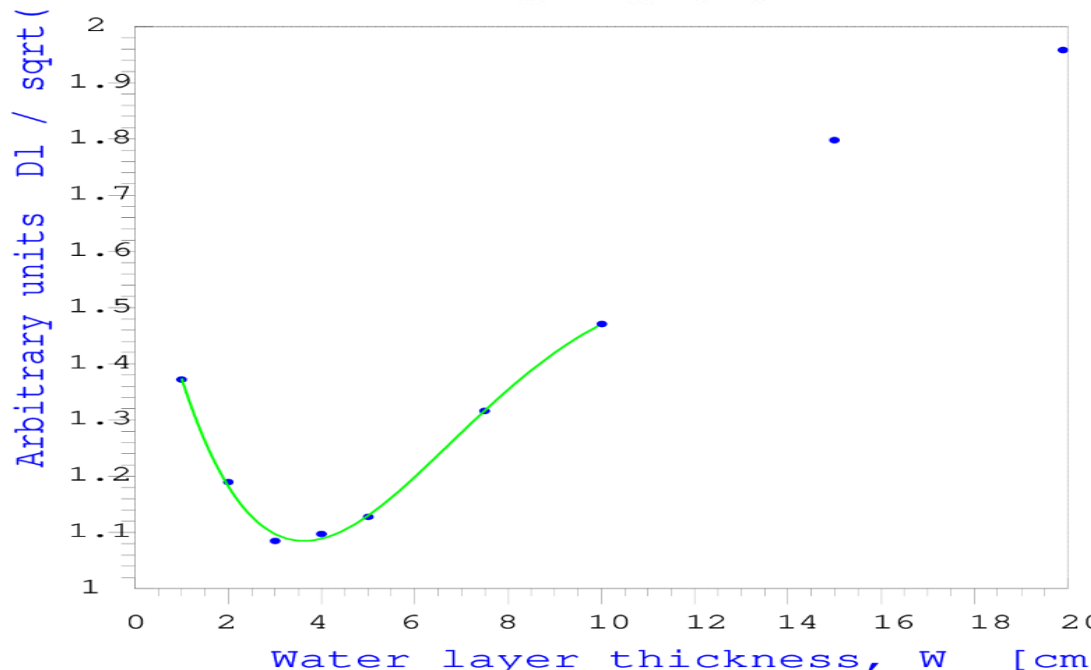
- Resolution:

$$\frac{\Delta E}{E} = 2\frac{\Delta l}{L+l} \approx 2\frac{\Delta l}{L}$$

- Figure of Merit

$$\frac{\Delta E/E}{\sqrt{\Phi}} \approx \frac{2\Delta l}{\sqrt{\Phi_o}}$$





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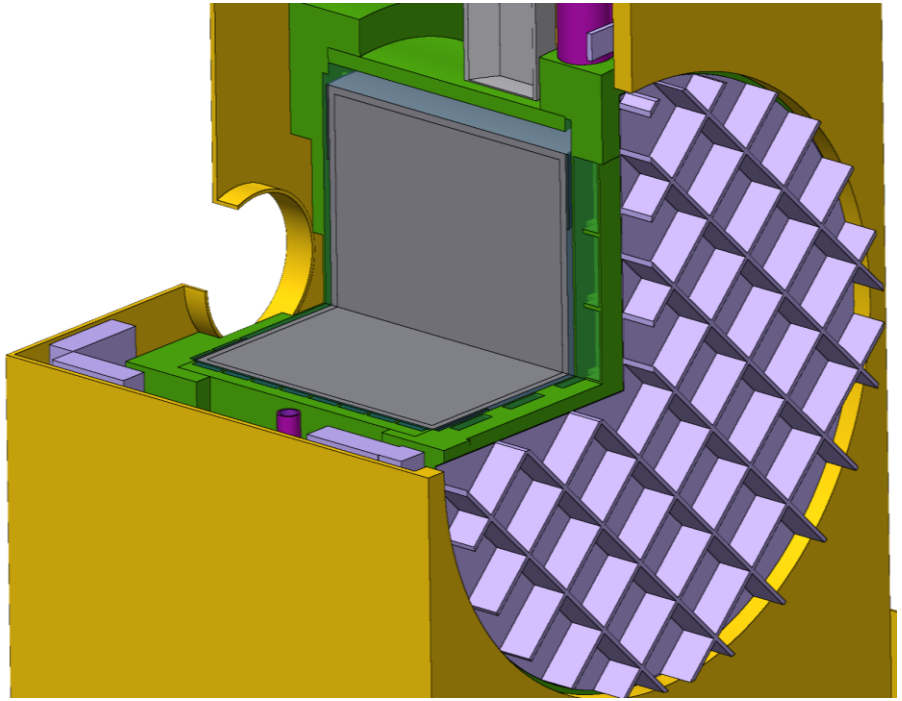
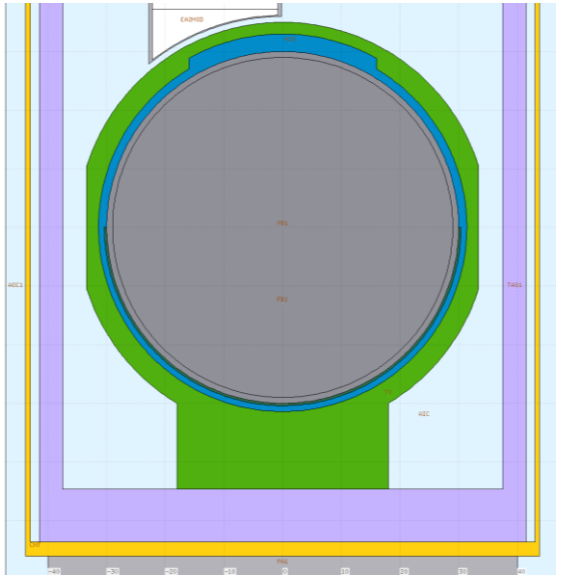
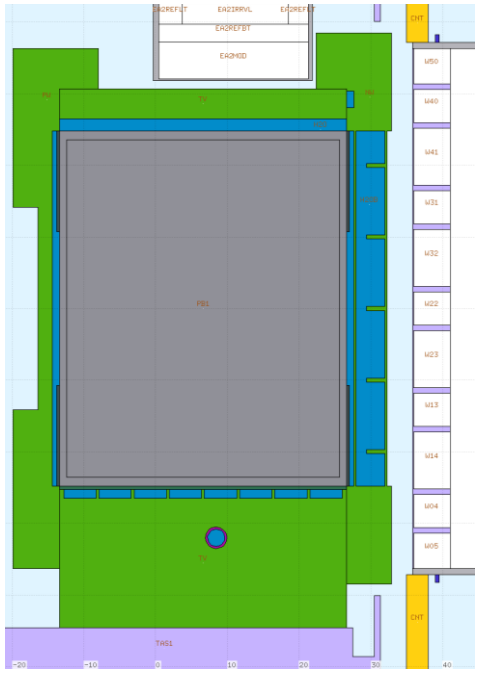
nTOF Present Target #2

- Spallation Target:
  - Pb cylinder L=40cm, ∅60cm
- Moderator composed:
  - Cooling water 10mm
  - Borated water 4cm
  - Enclosed in Al container 3mm thick

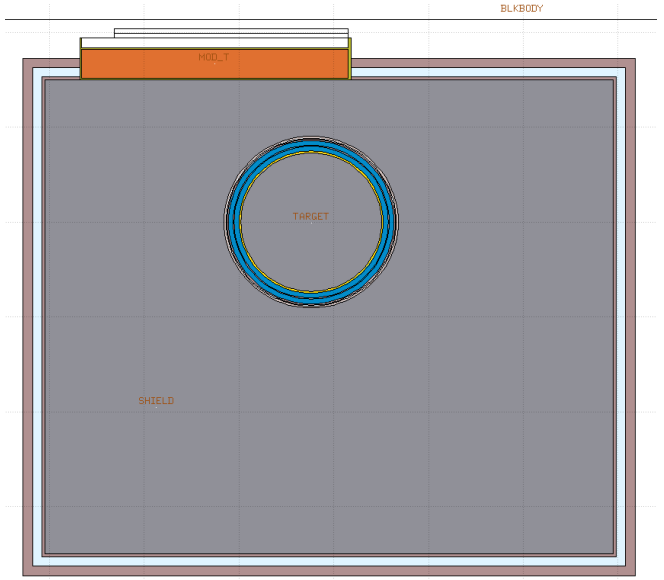


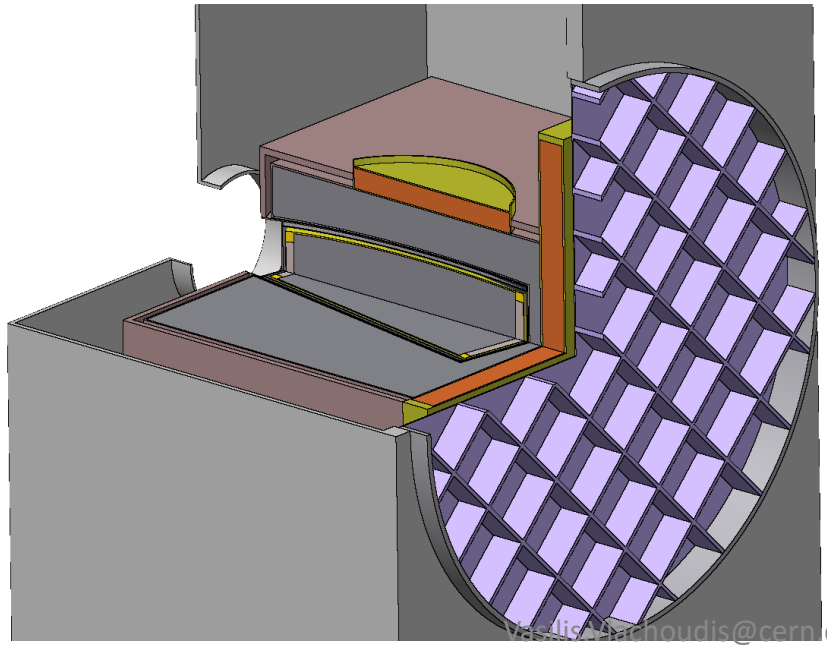


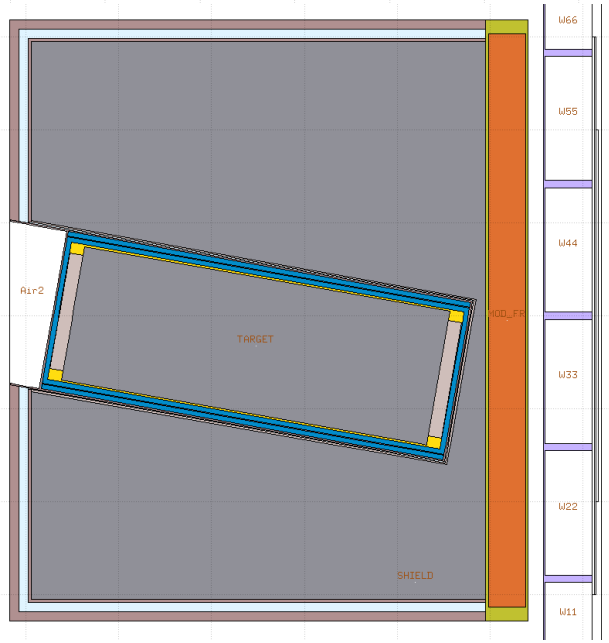


Solution #4 (Pb + core)

- Spallation Target
  - Pb-core cylinder L=40cm, ∅15cm enclosed in Ti_4Al_6V cladding 2mm
  - Beryllium end caps 1.5cm thick
  - Cooling water 1cm thick around core, 5mm downstream
  - Enclosed in Stainless Steel container 2mm (Possibility to use Al >3mm
  - Surrounded by Pb mass
- Moderator: Borated water enclosed in Al container 3mm







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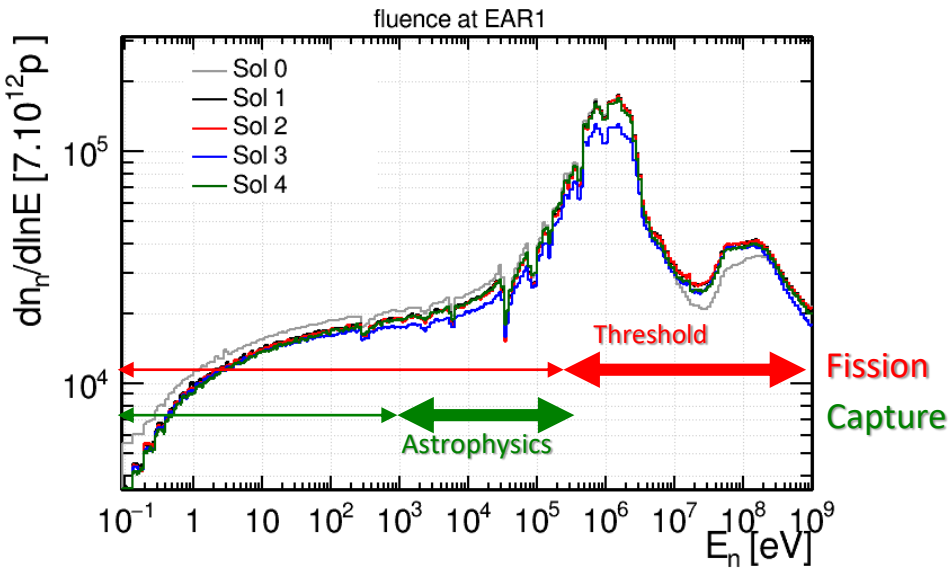
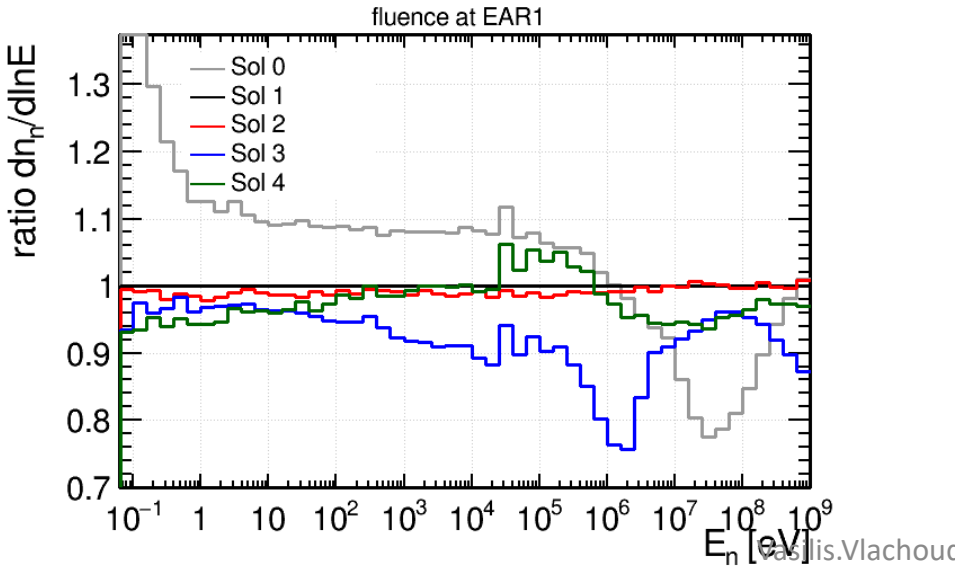
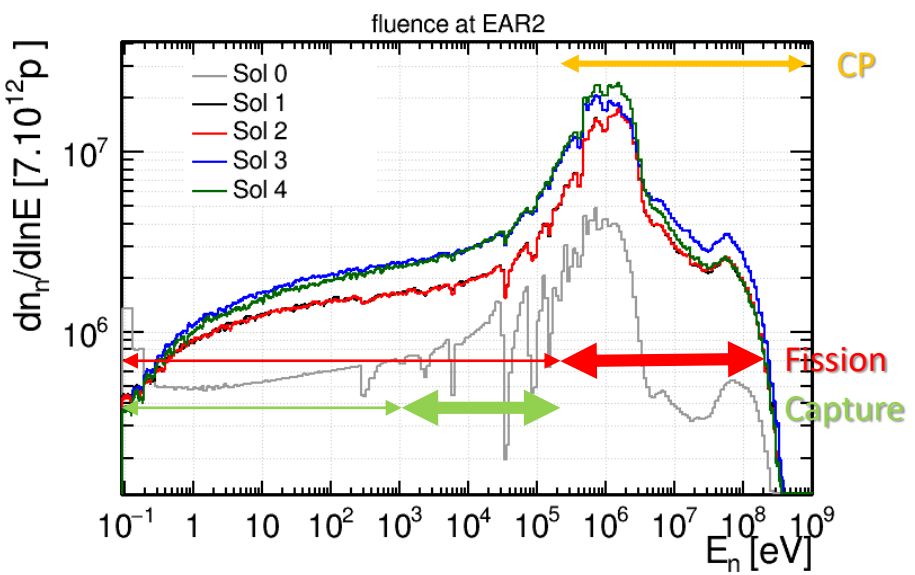
Neutron Fluence

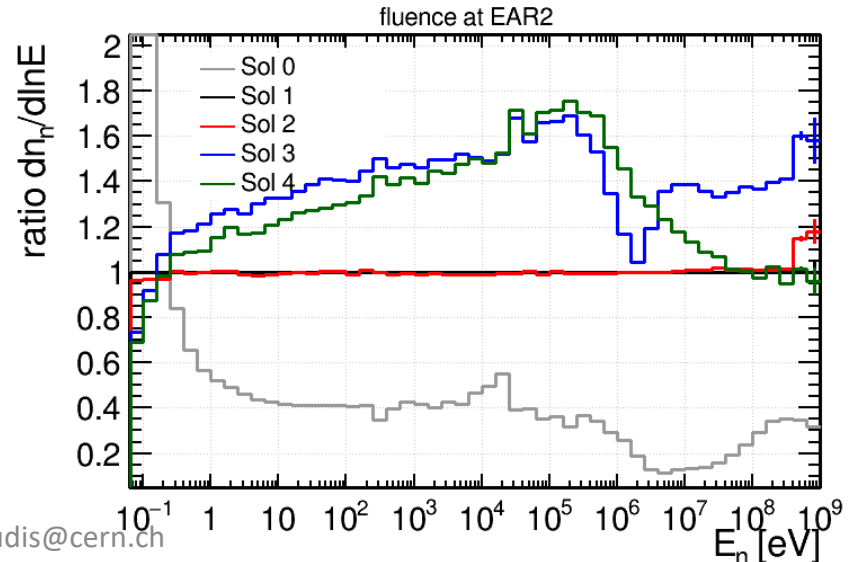
EAR1



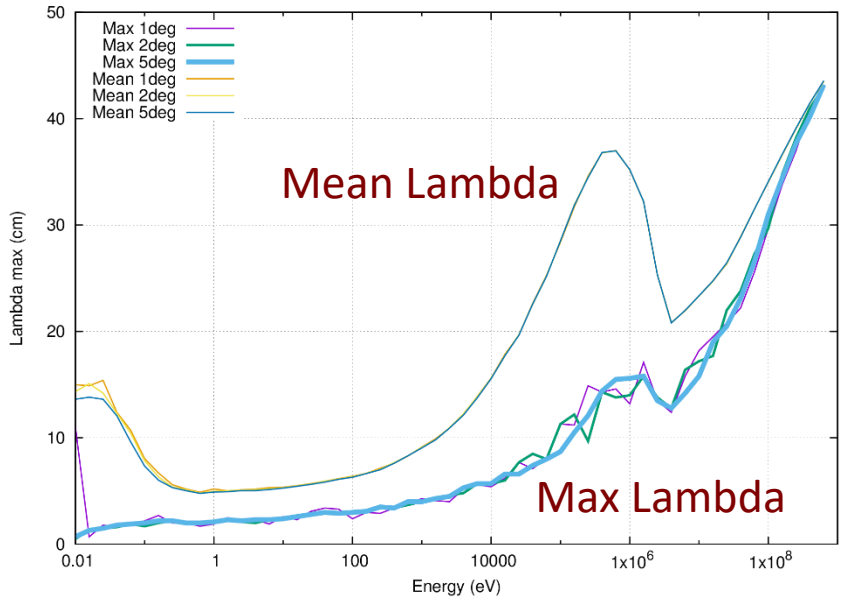


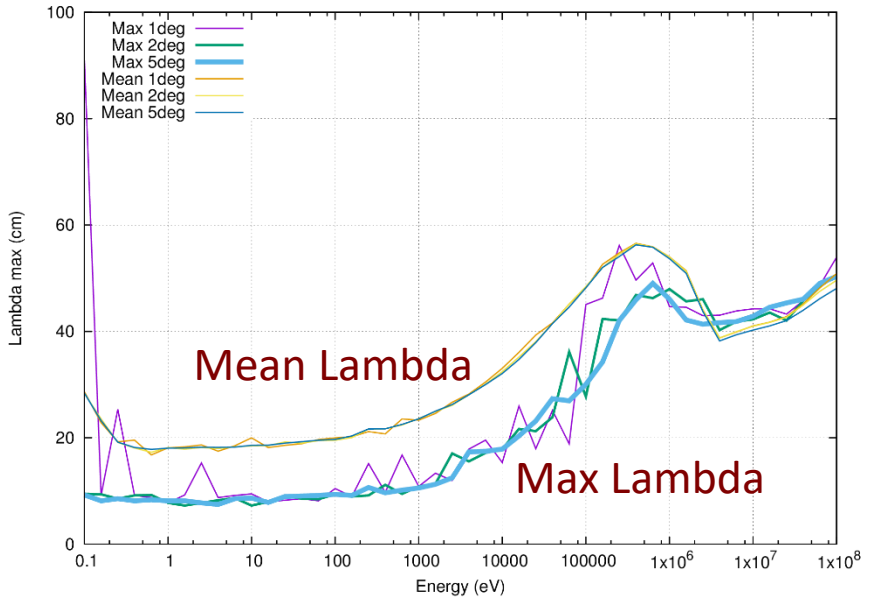
EAR2

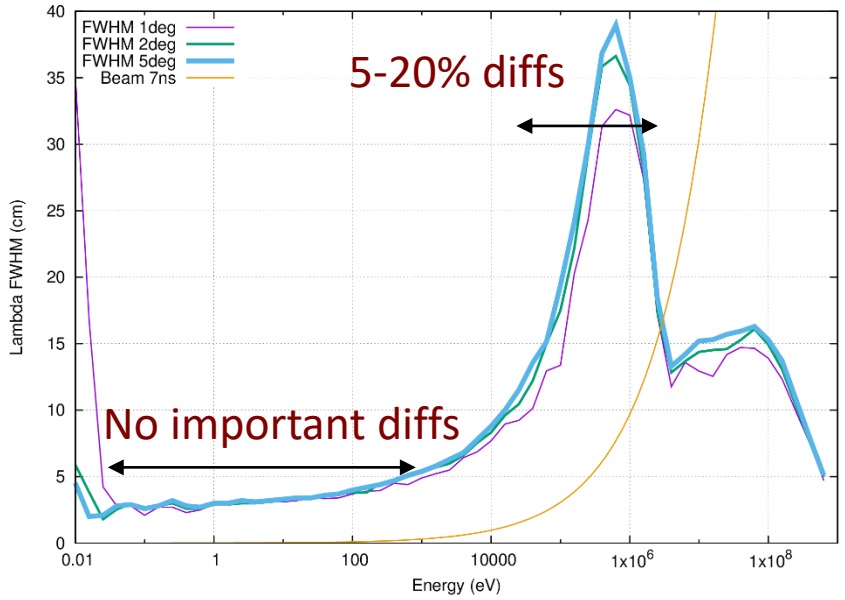


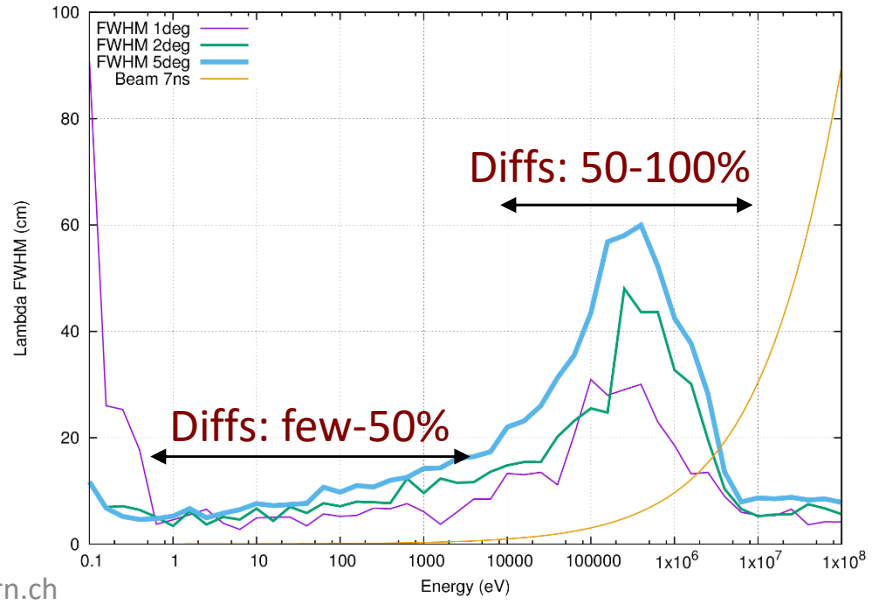


Lambda and resolution

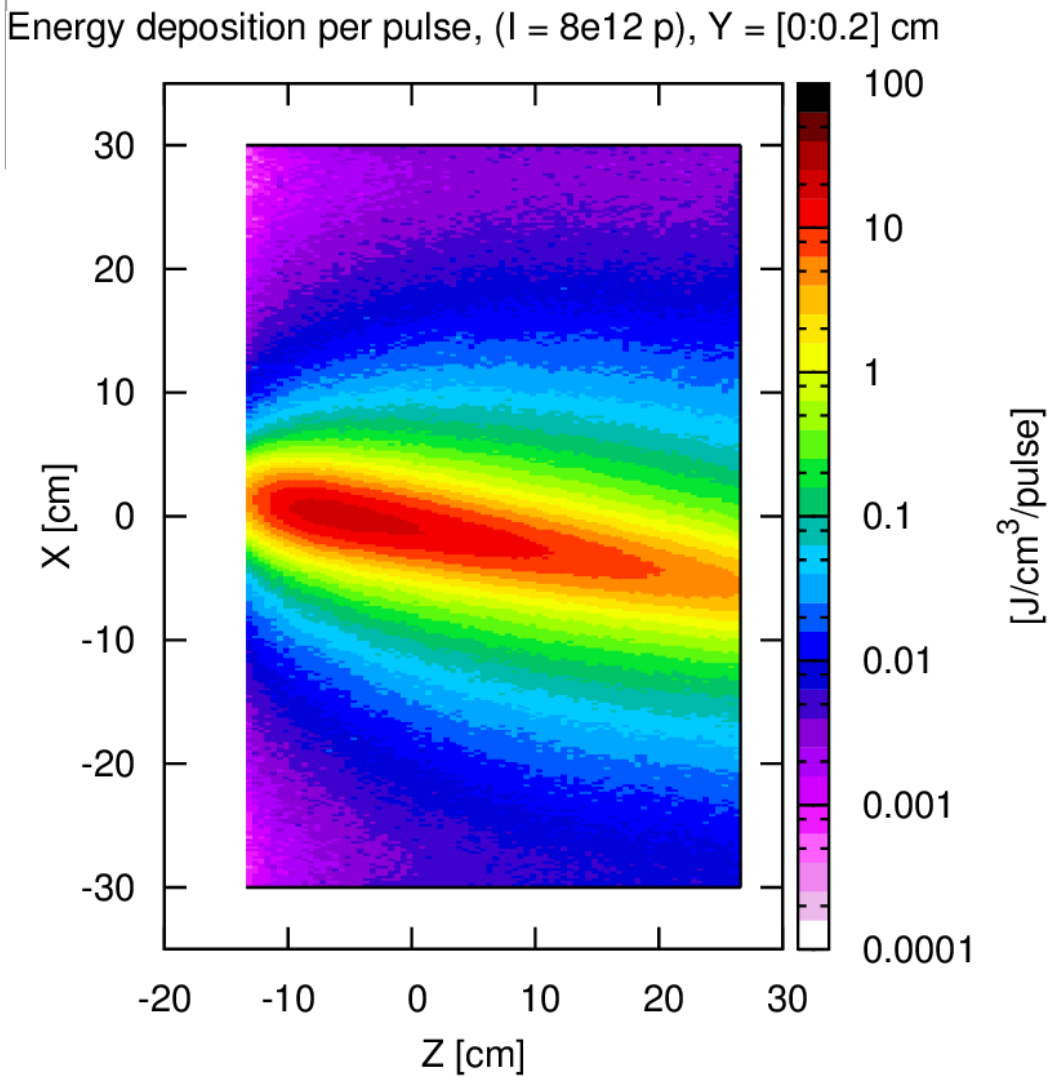


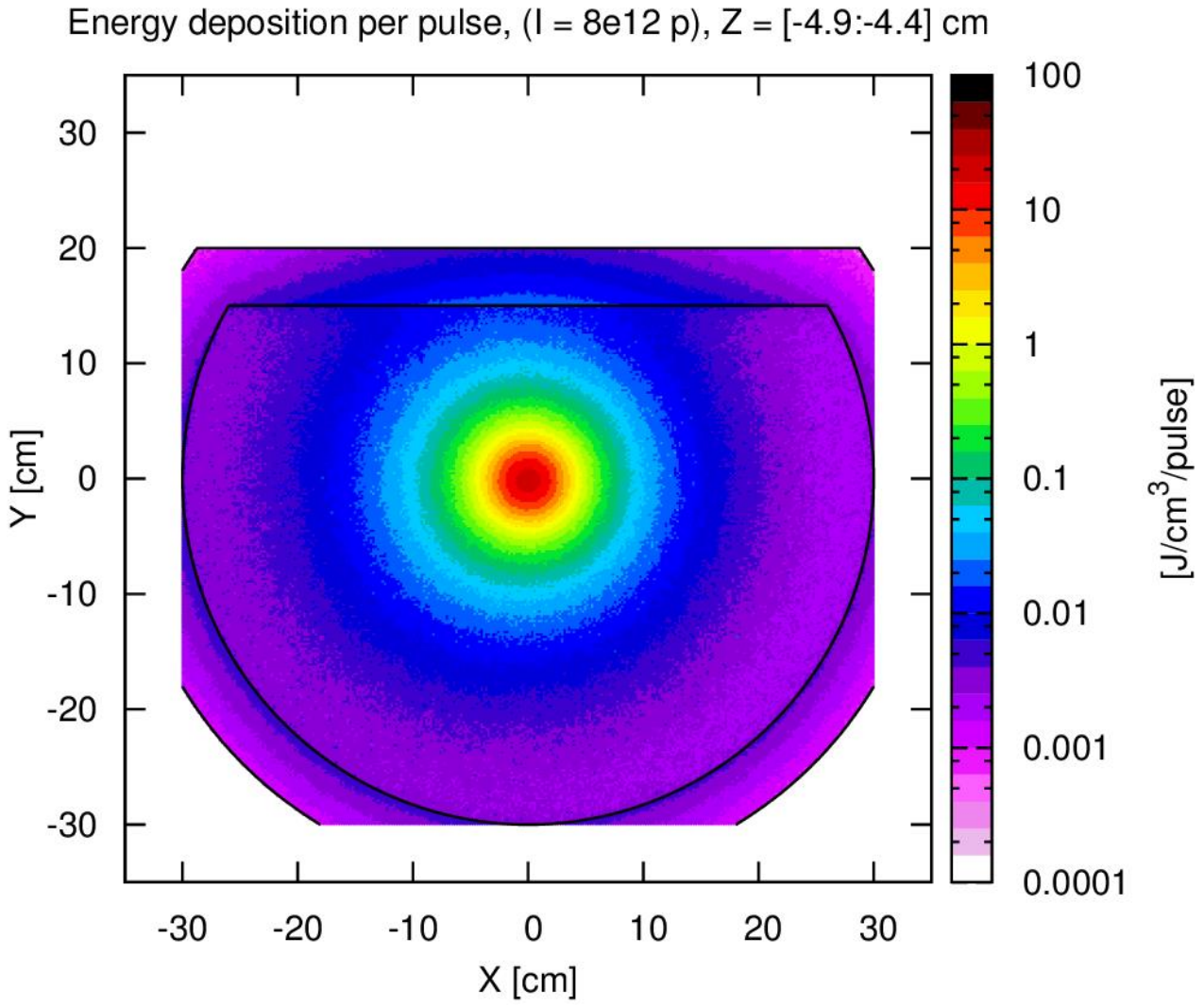






Energy deposition

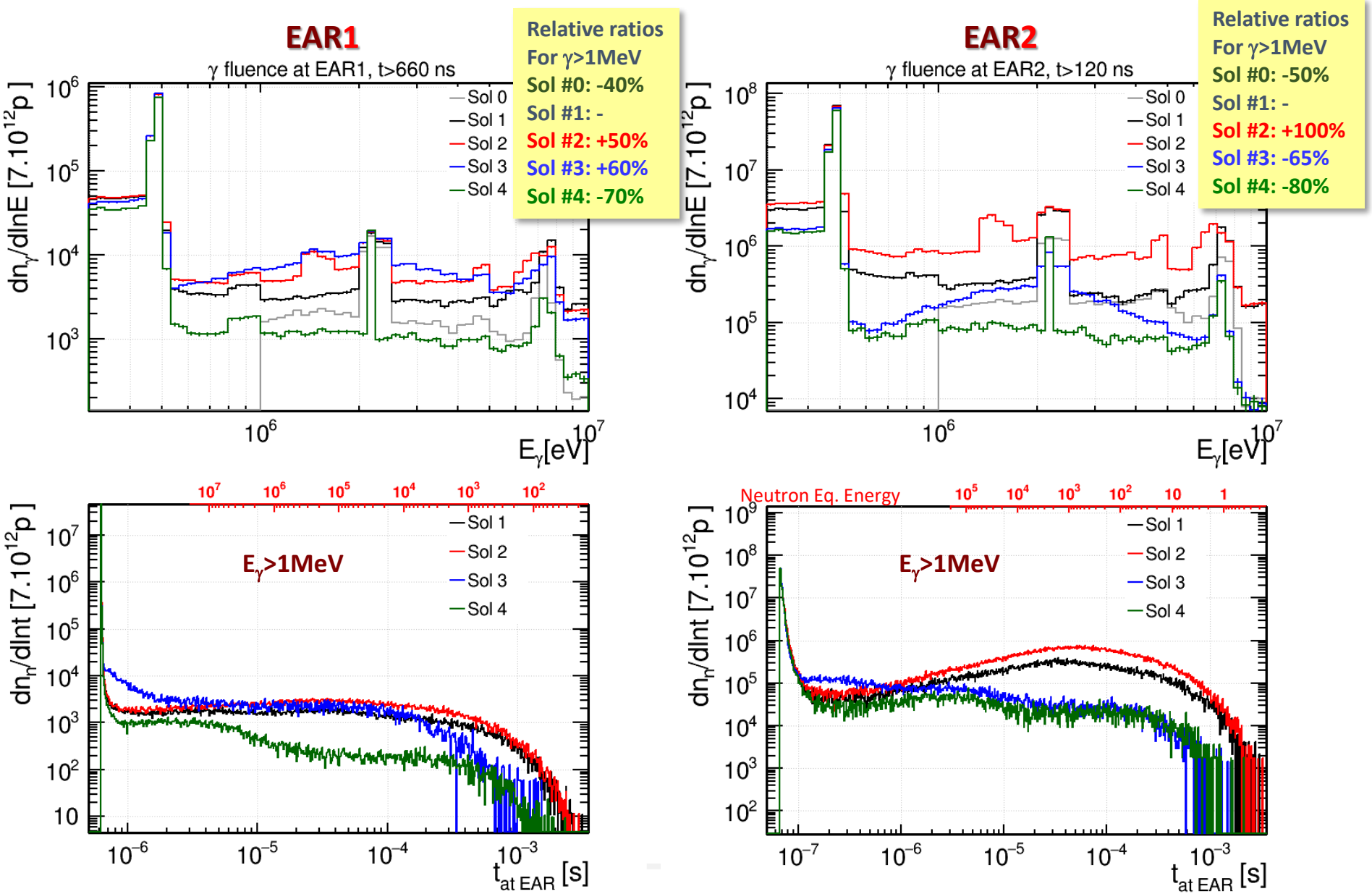




Total Beam Energy = 20 GeV 7 10^{12} p^+ = 22.4 kJ

Energy escaping 35%

Photons at EARx



Background: Charged Particles

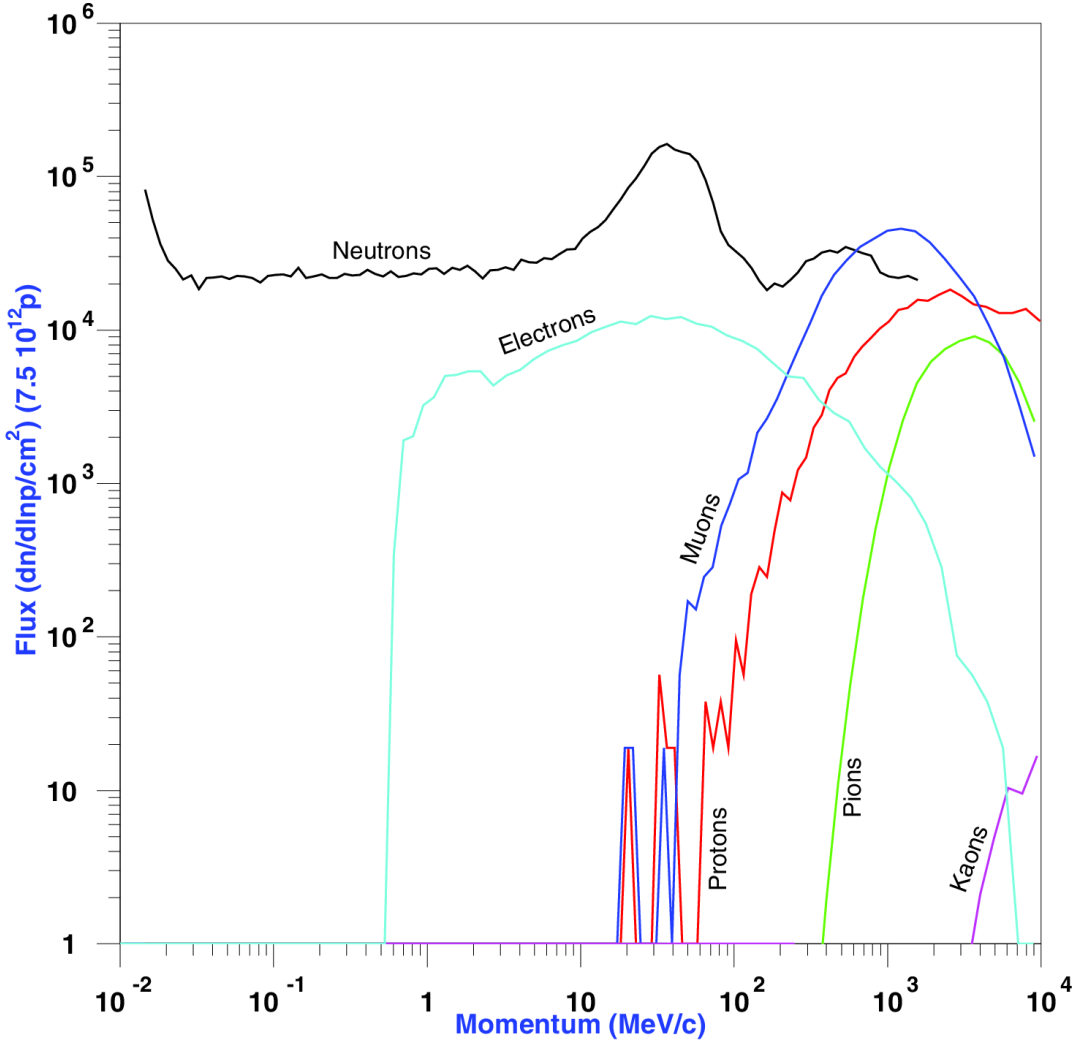
- Spallation reactions produces a lot of CP (π^{+-}, K^{+-}) which decay in flight to μ^{+-}
- Maximum momentum towards EAR1 *p<20GeV/c*
  while for EAR2 *p<300MeV/c*

$$B\rho\ (Tm) = 3.3356\ p\ (\frac{GeV}{c})$$

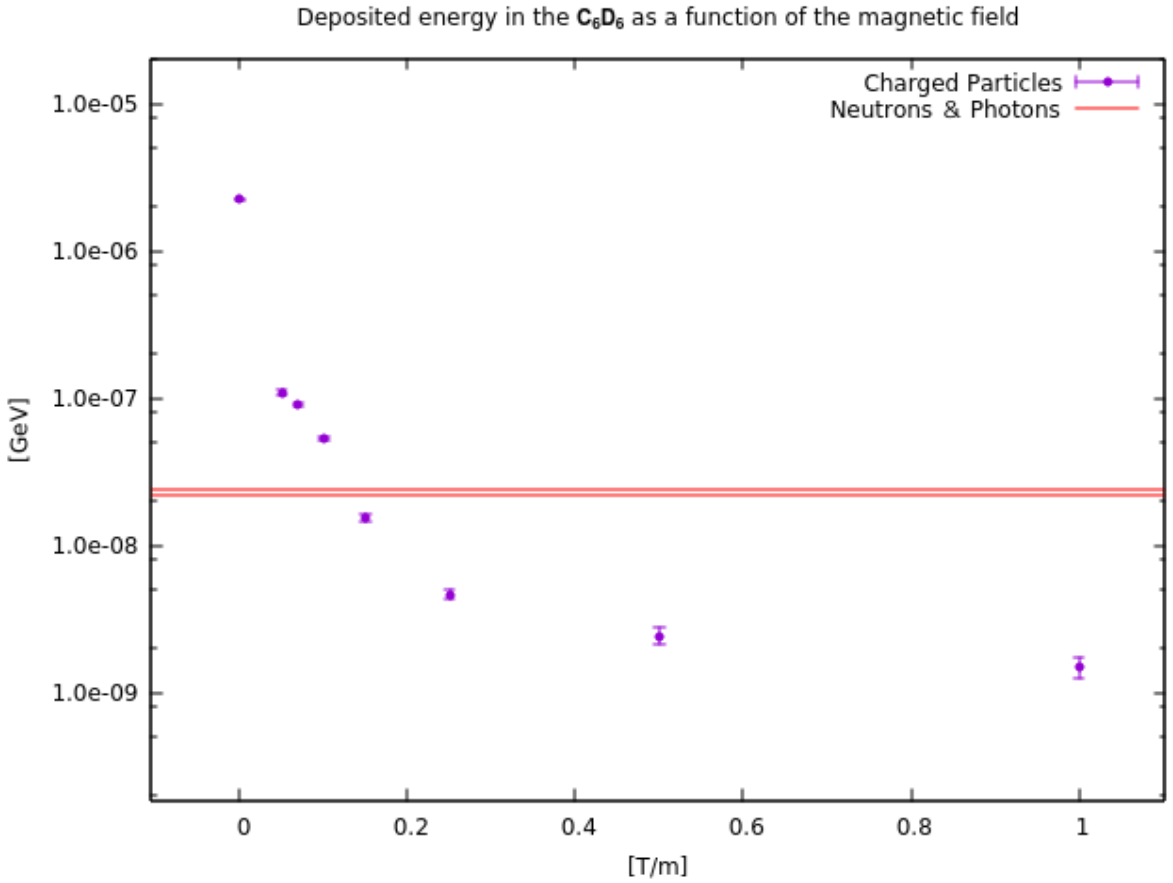
Magnetic field needed to deviate the most energetic particle

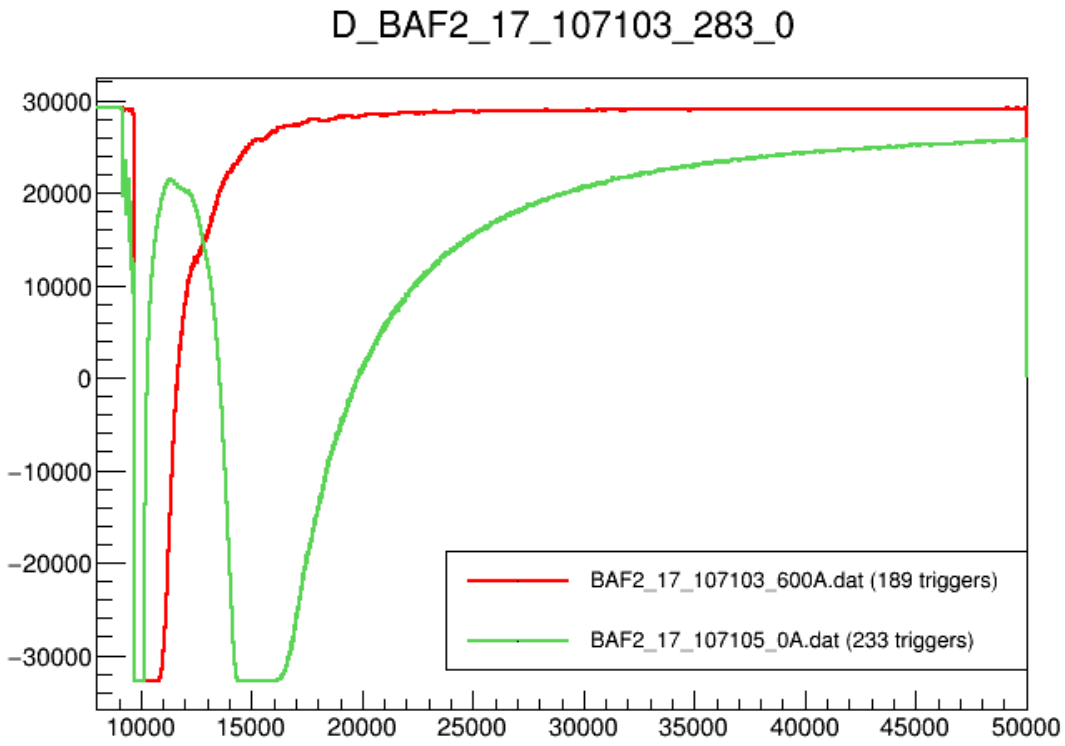
EAR1: 0.6 *Tm @ 145m*

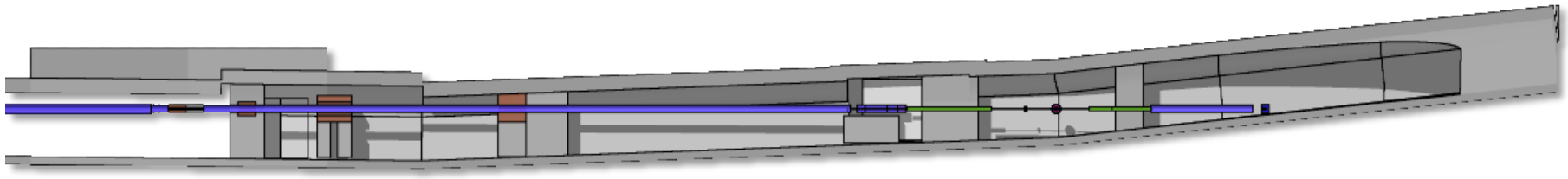
EAR2: 0.2 *Tm @ 10m*



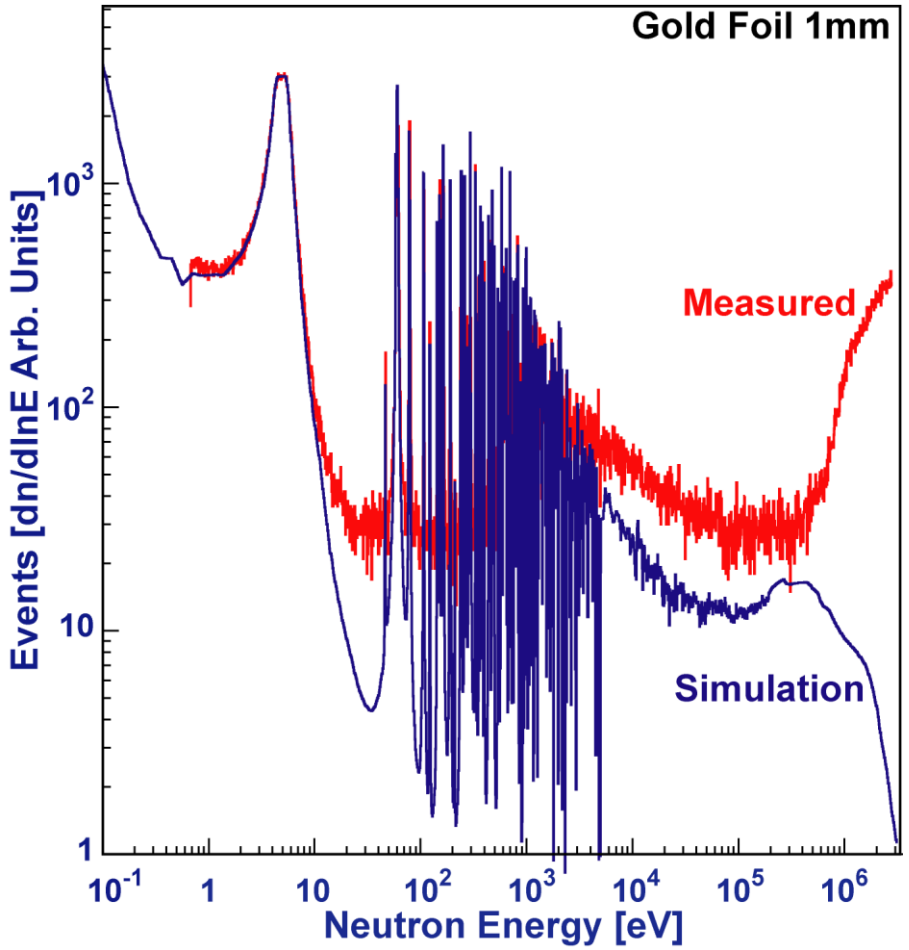
Magnet Simulations





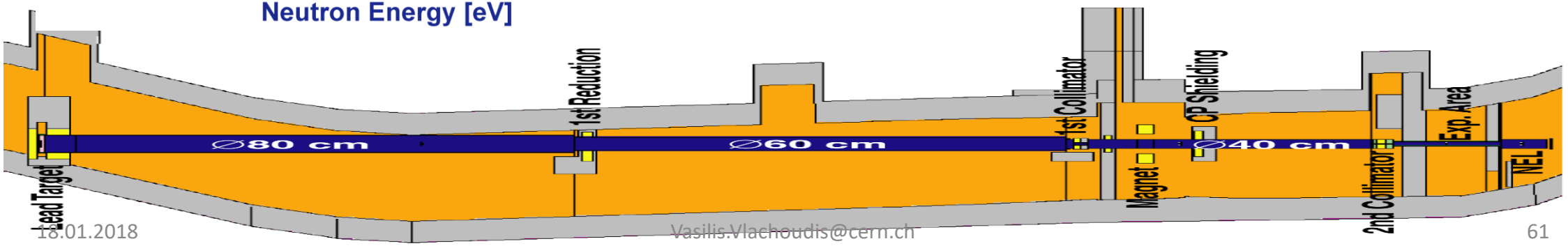


Muon background

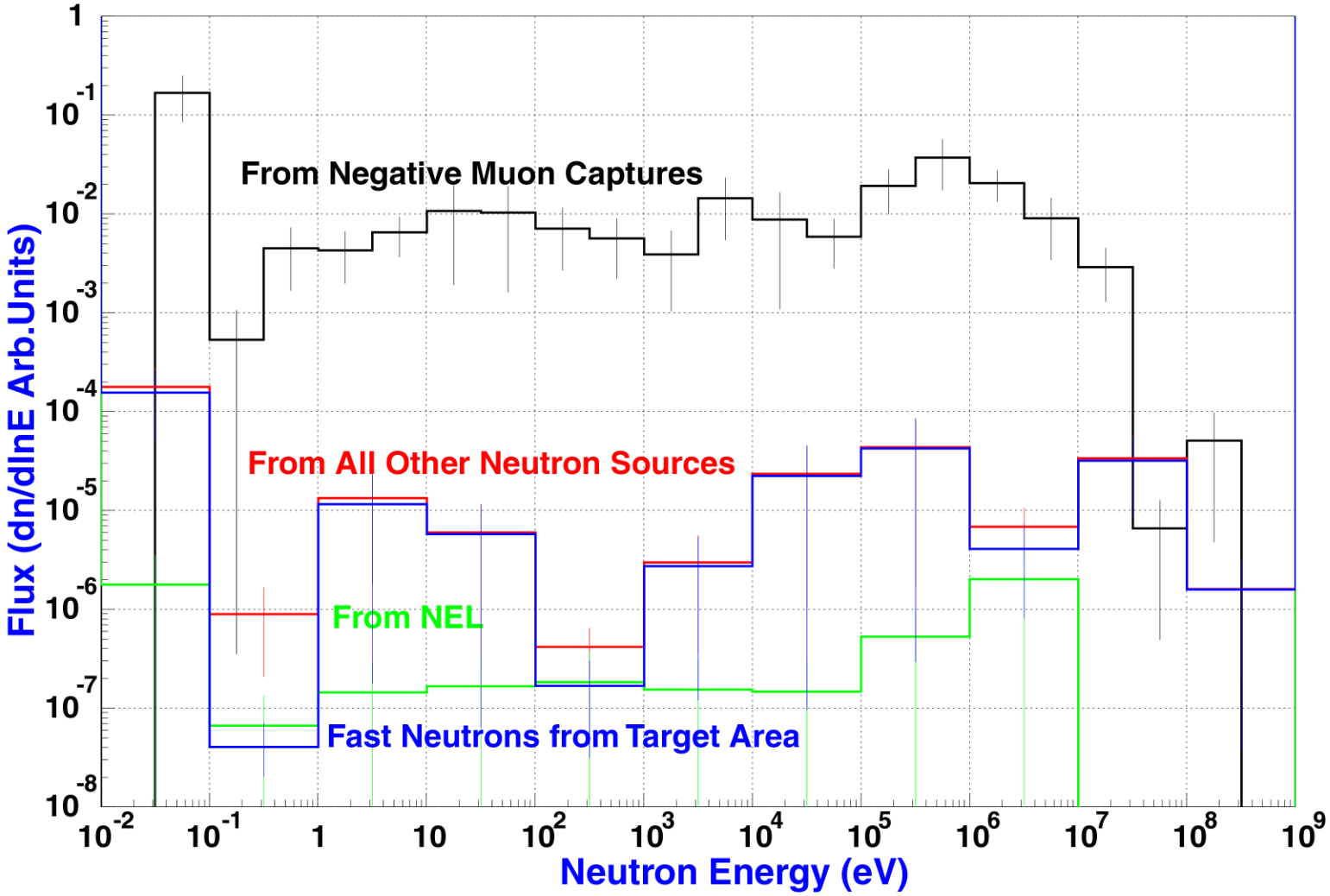


Background Features

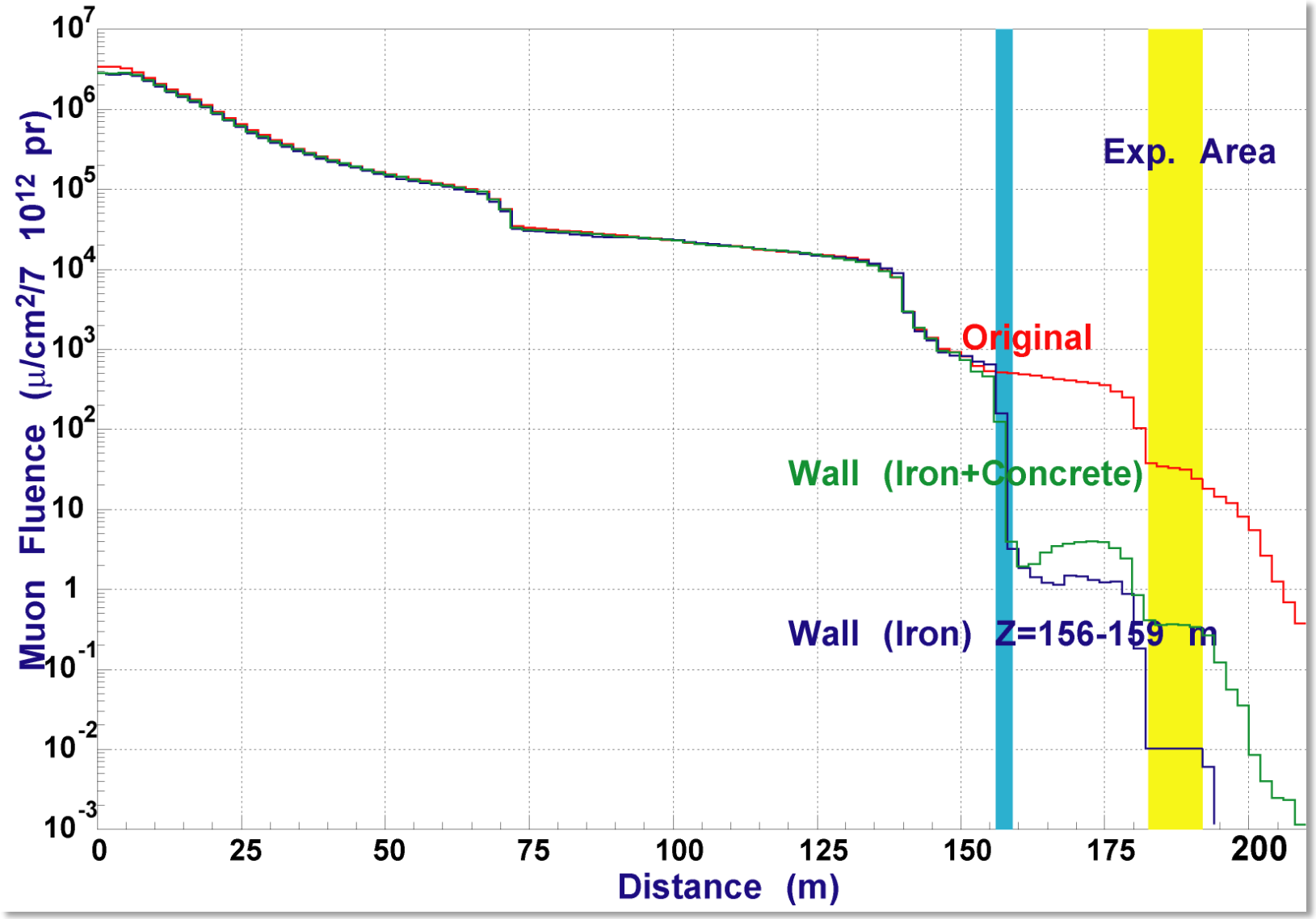
- ×50 larger than simulations
- Three time components
  - 400 ns “flash”
  - 20 μs – fast neutrons
  - > 16 ms – thermal neutrons
- Position depended
- Strong Left-Right asymmetry
- Strong ionization signal
- Not sample related



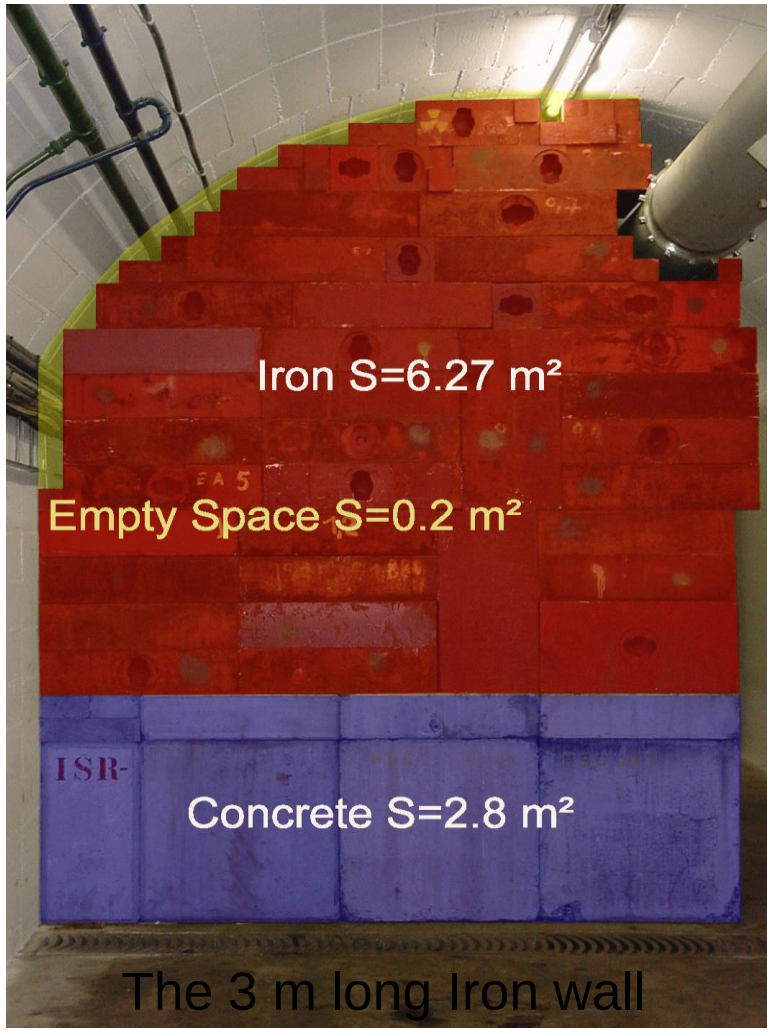
Muon Background: Possible sources

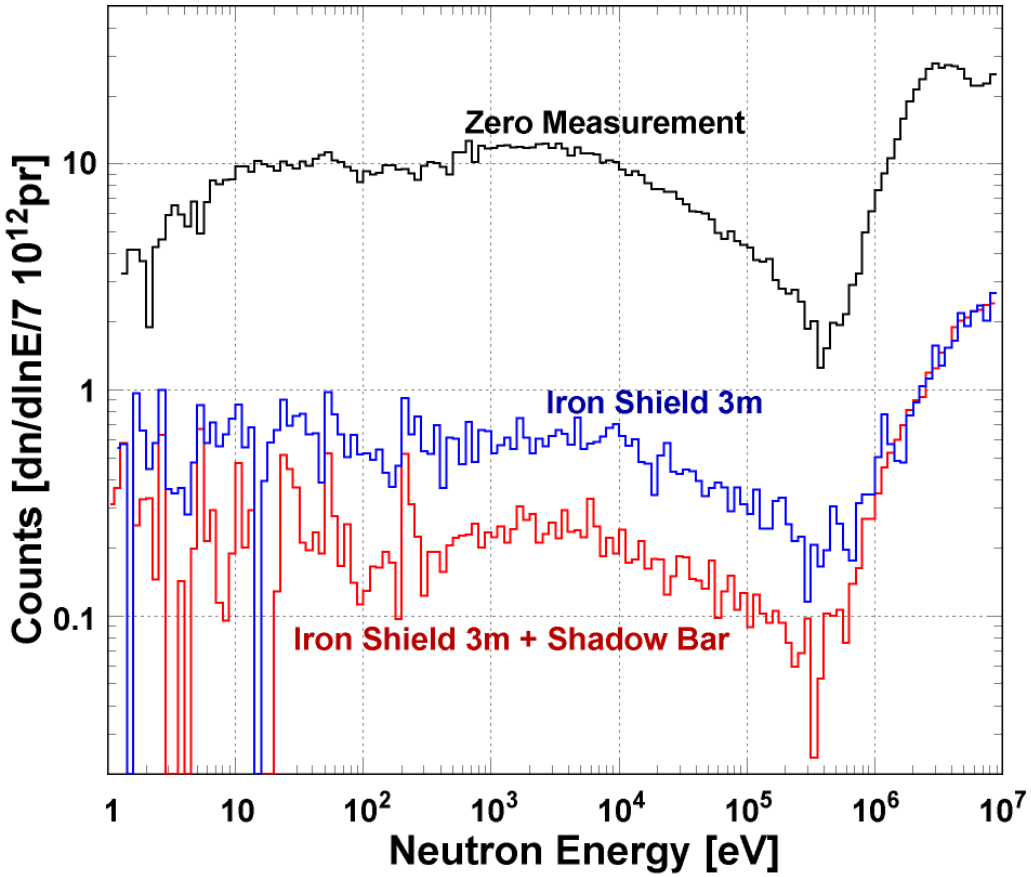


Muon background: wall effectiveness



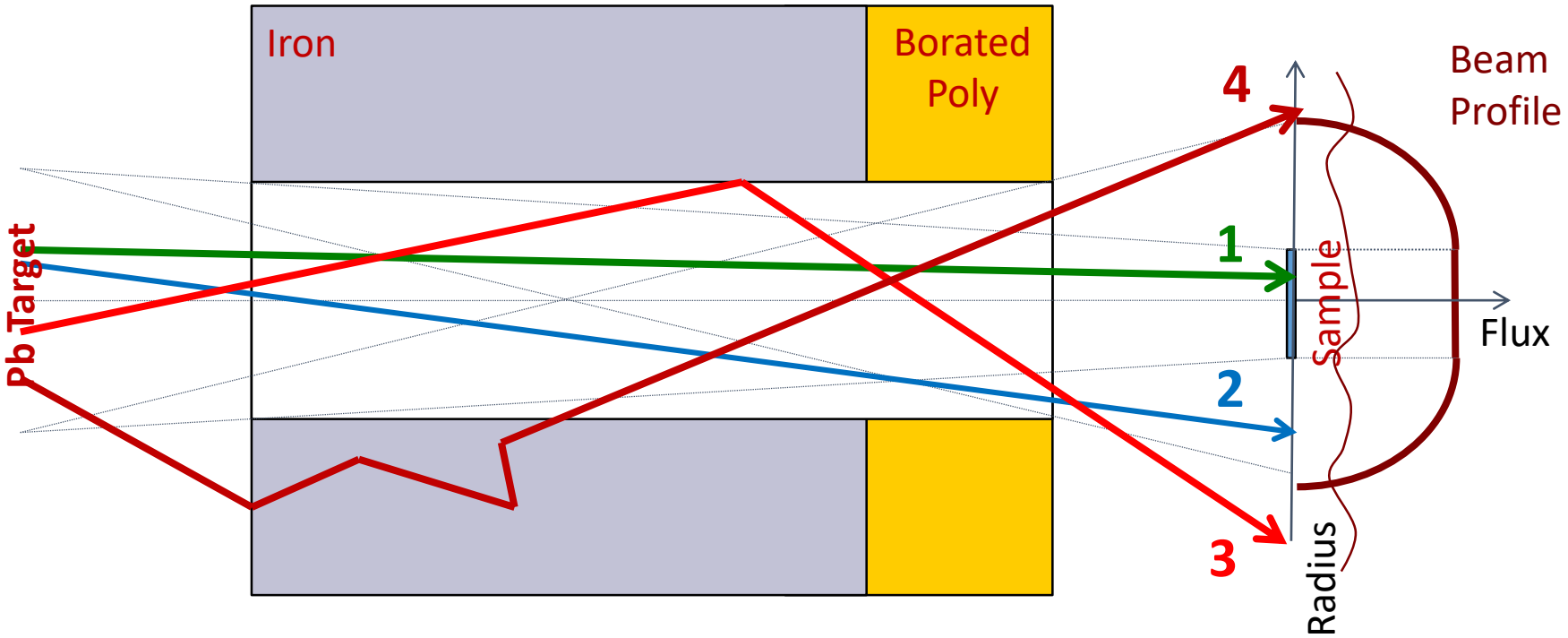
Muon background: Summary results





C_6D_6 raw data with various setups

Collimator



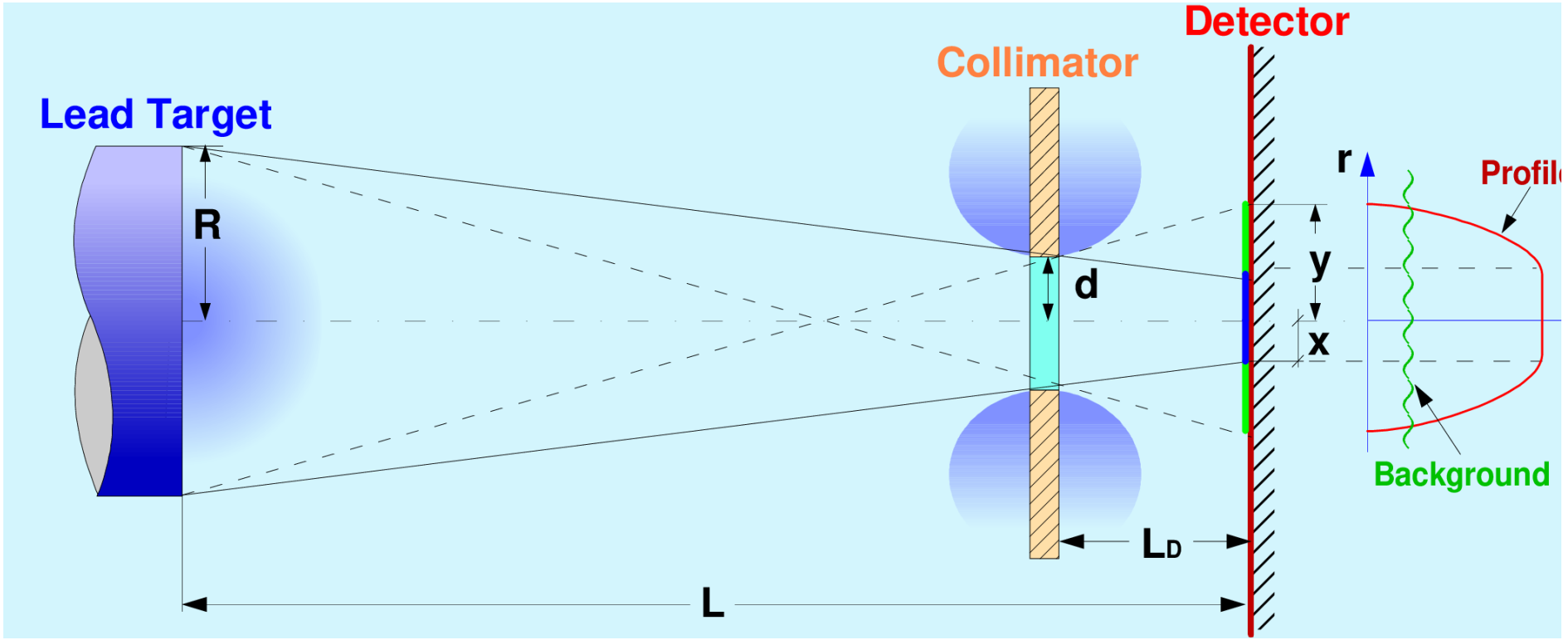
1. Direct – Full View → Contributes to the Plateau/Flat
2. Direct – Partial View → Contributes to Halo
3. Indirect Hitting collimator gap → Major contribution to Background
4. Indirect Hitting front face of collimator → Minor contribution to Background

Collimator

- Constant flux radius: $x = \frac{L \cdot d - L_D R}{L - L_D}$
- Halo radius: $y = \frac{L \cdot d + L_D R}{L - L_D}$

Halo ring: $|y - x| = 2\frac{L_D}{L - L_D} R$

Focal length: $f = d\,\frac{L - L_D}{R - d}$

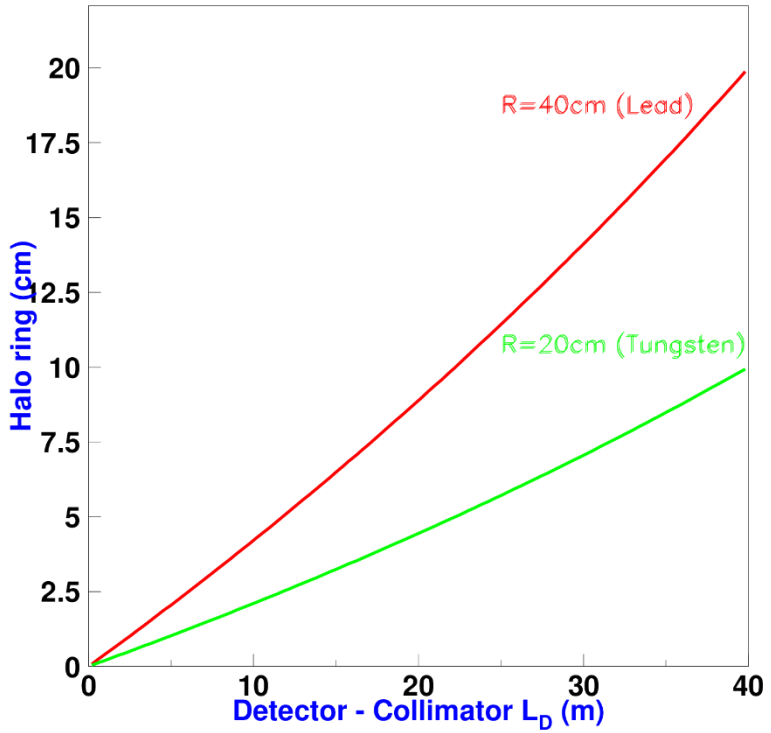


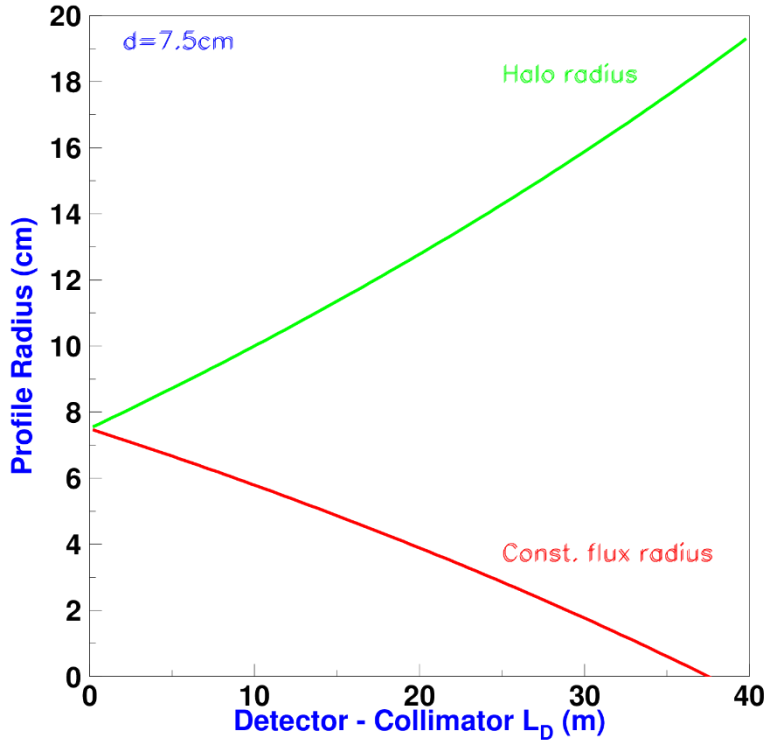
Collimator: Const.Flux & Halo

The neutron halo depends on the

- collimator distance L_D
- target radius R

L_D	Background	Const. Flux Radius	Halo |y-x|
↑	↓	↓	↑
↓	↑	↑	↓





Collimator: Neutron profile

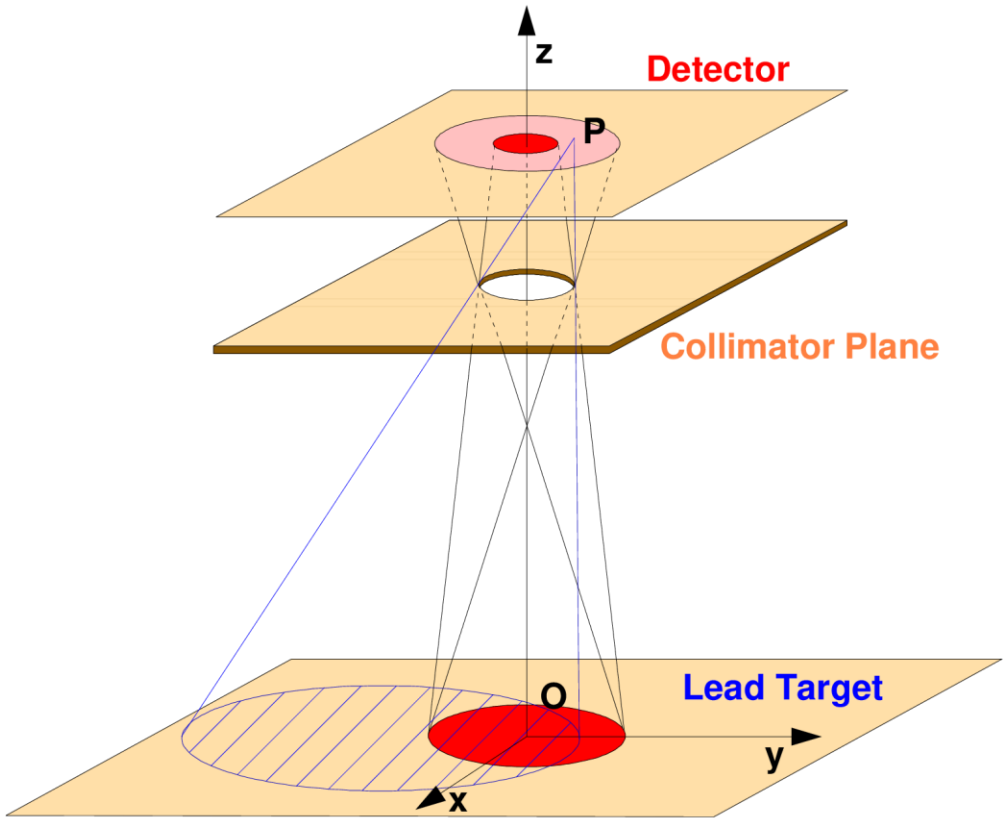
- The beam intensity @ distance r_d from the beam axis is determined by the intersection of the neutron source and projection of the collimator

Projection radius: $r = d \cdot \frac{L}{L_D}$

Projection center: $y_c = r_d \frac{L - L_D}{L_D}$

Intersection point:

$$x_o = \pm \sqrt{r^2 - \left(\frac{R^2 - r^2 - d^2}{2d}\right)^2}$$



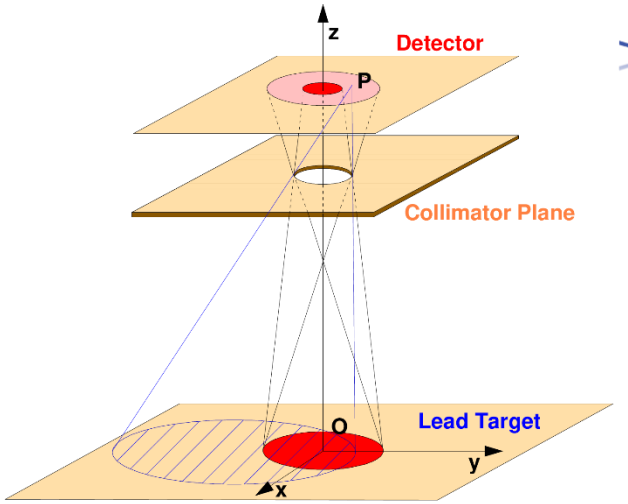
Collimator: Neutron profile

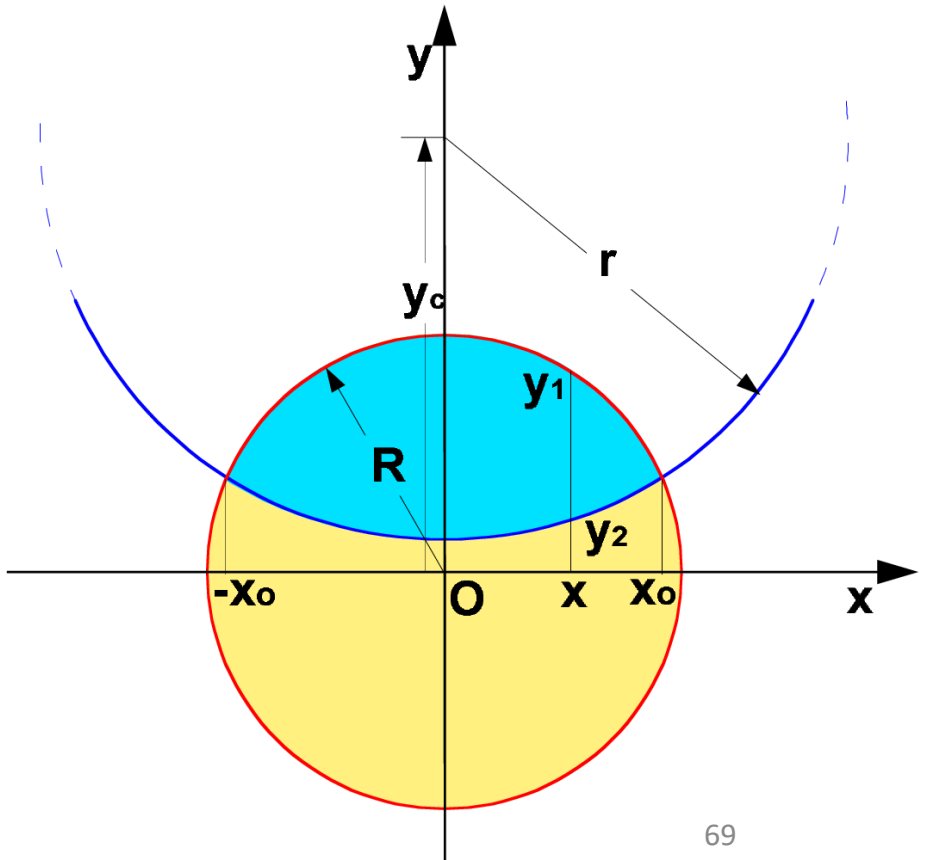
Intersection point:

$$x_o = \pm\sqrt{r^2 - \left(\frac{R^2 - r^2 - d^2}{2d}\right)^2}$$

Area (∝flux):

$$I = \int_{-x_o}^{x_o} \left[\sqrt{r^2 - x^2} + y_c - \sqrt{R^2 - x^2}\right] dx$$





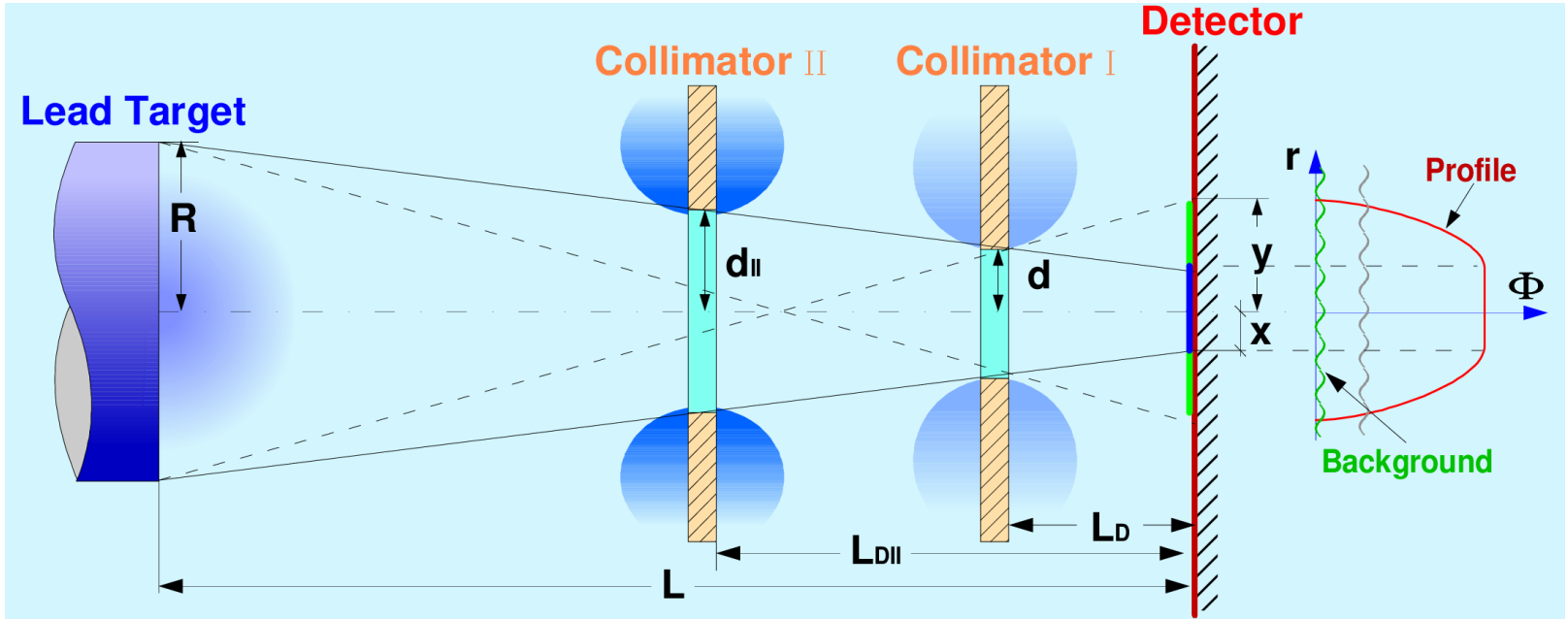
Two Collimators

By placing a second collimator at a larger distance with an opening such as to have the same or greater area of constant flux (within the focal distance)

→ The neutron background is reduced

→ First collimator is shaping the beam

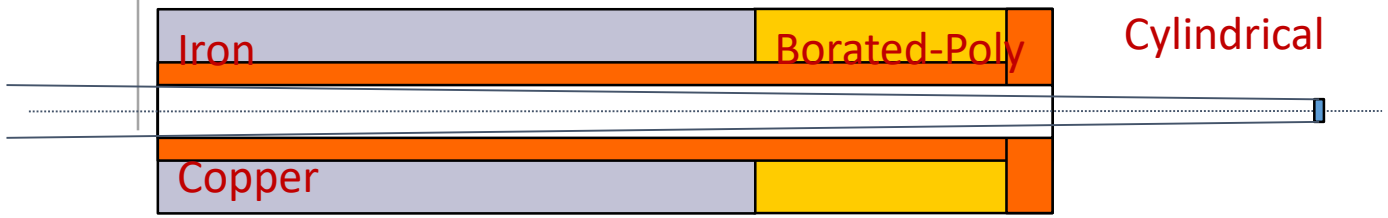
→ The beam profile is determined by the last collimator



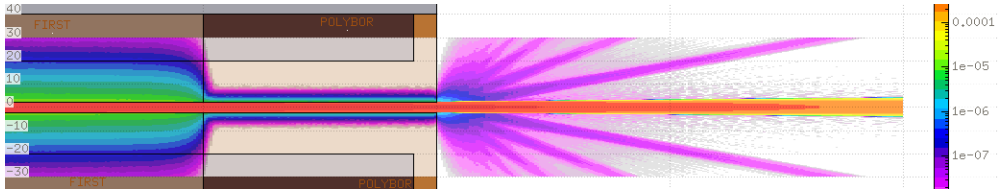
nTOF collimators

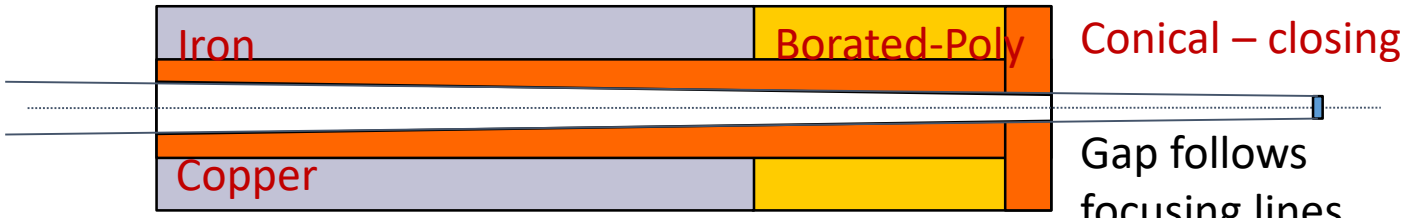
Area	Setup	R_t [cm]	L_1 [m]	R_1 [cm]	L_2 [m]	R_2 [cm]	Lf_1 [m]	Lf_2 [m]	L [m]	R_{flat} [cm]	R_{halo} [cm]
EAR1	capture	30	137.6	5.5	177.55	0.9	168.5	185.4	185	0.04	2.20
	-//- (>MeV)	15	137.6	5.5	177.55	0.9	217.3	185.4	185	0.04	1.57
	fission	30	137.6	5.5	177.55	4.0	168.5	284.1	185	3.72	5.43
	-//- (>MeV)	15	137.6	5.5	177.55	4.0	217.3	284.1	185	3.72	4.80
EAR2	small	15	8.4	10	18.3	1.09	25.2	19.5	19.8	-0.26	2.41
	big	15	8.4	10	18.3	4.0	25.2	24.9	19.8	3.09	5.56

Collimator shapes



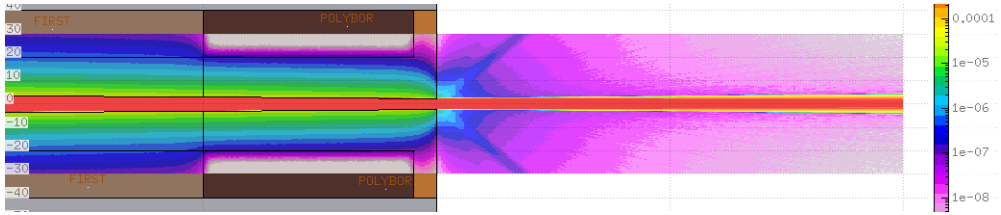
Cylindrical

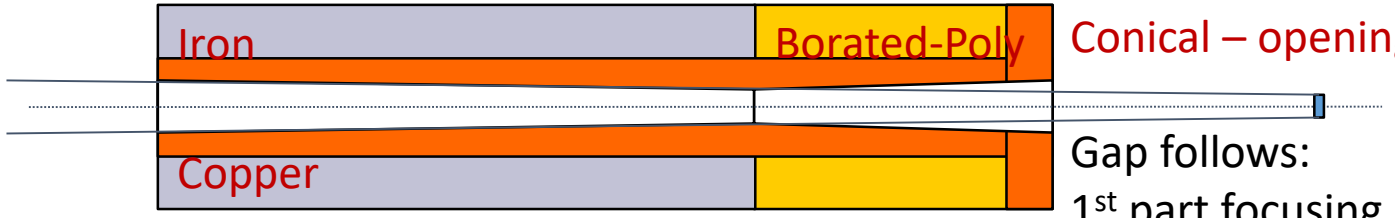




Conical – closing

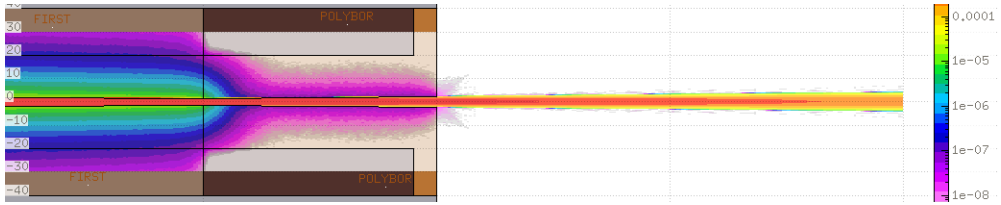
Gap follows
focusing lines



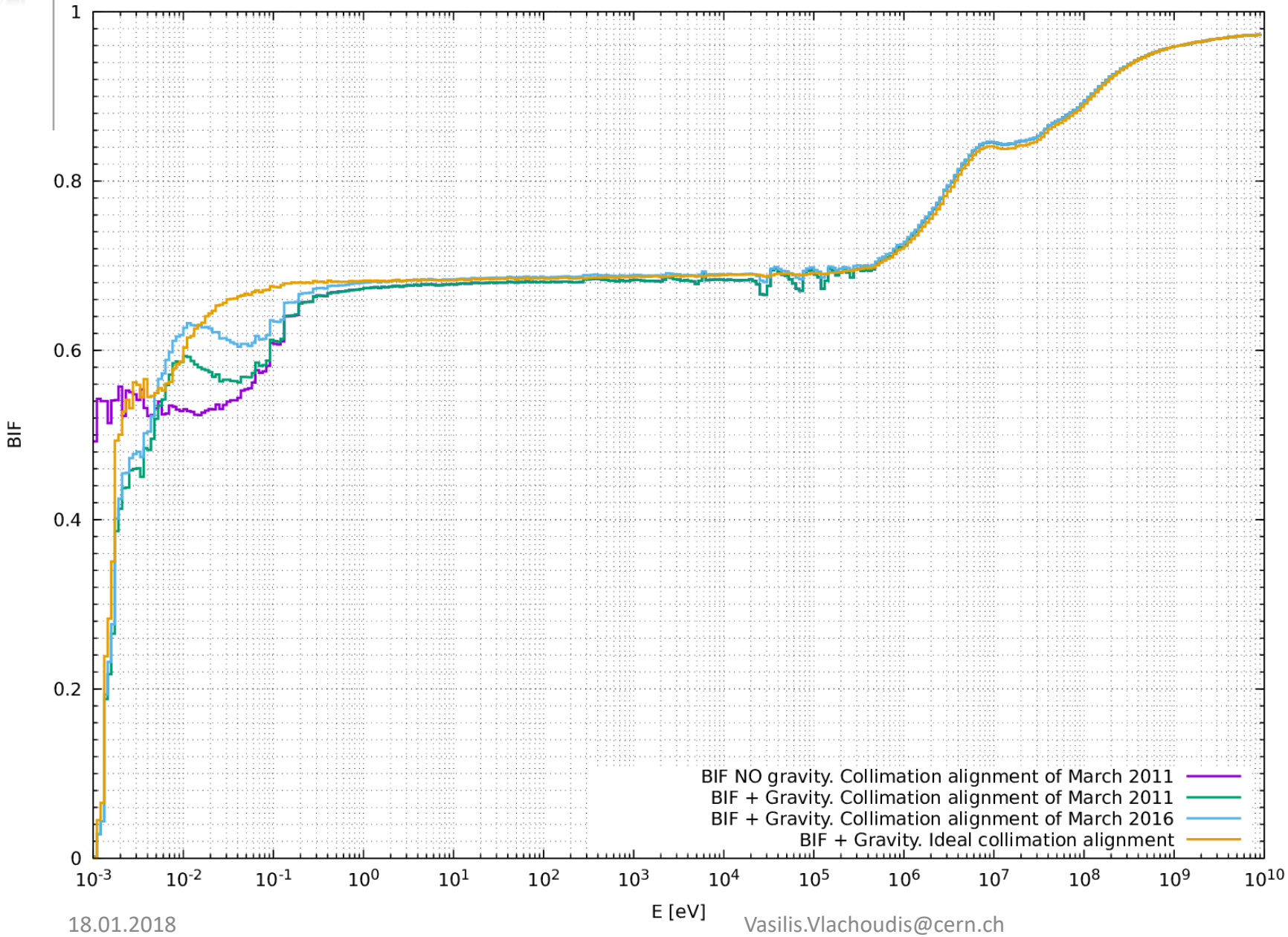


Conical – opening

Gap follows:
1st part focusing lines
2nd part defocusing



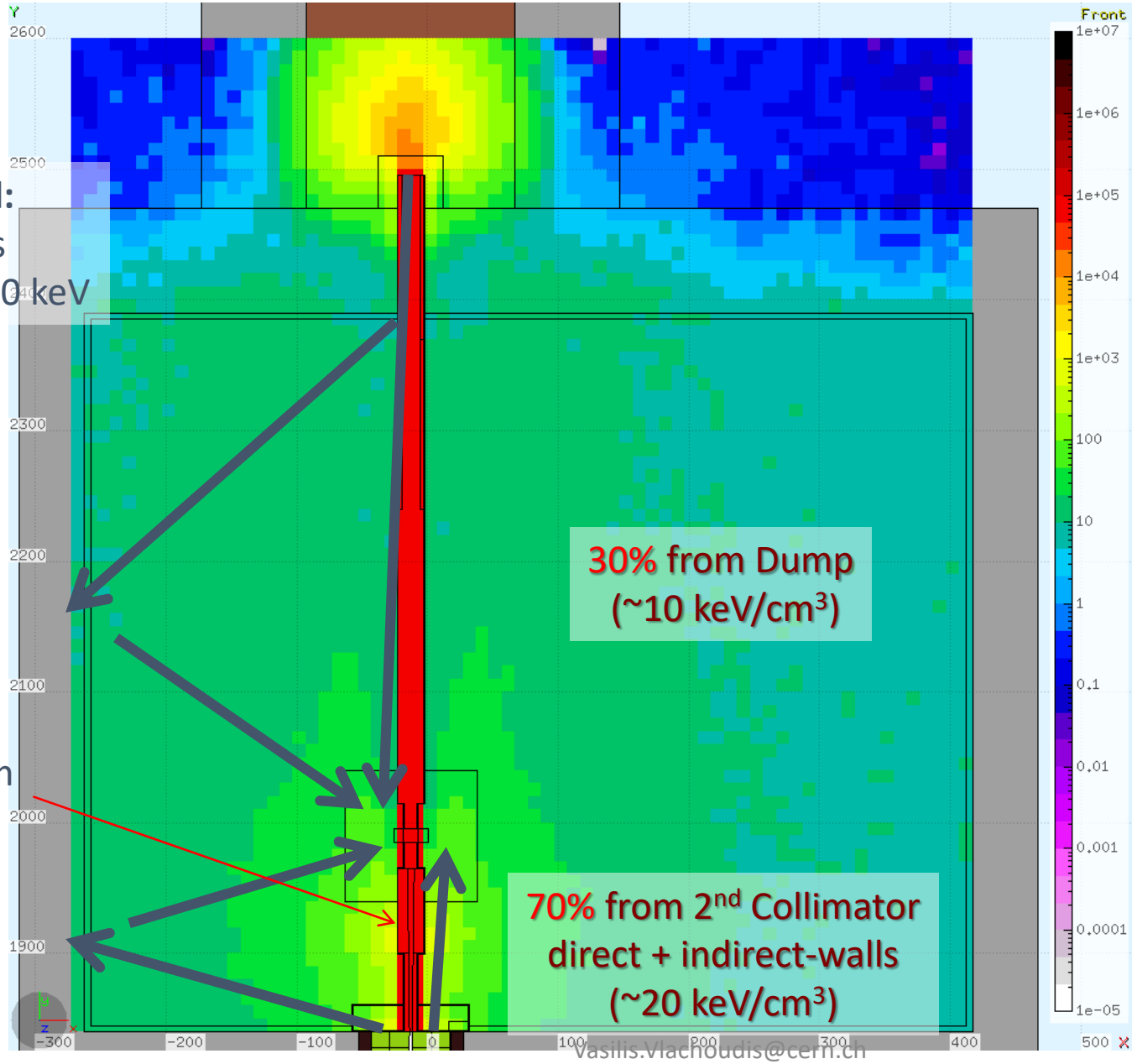
Collimator Alignment & Gravity



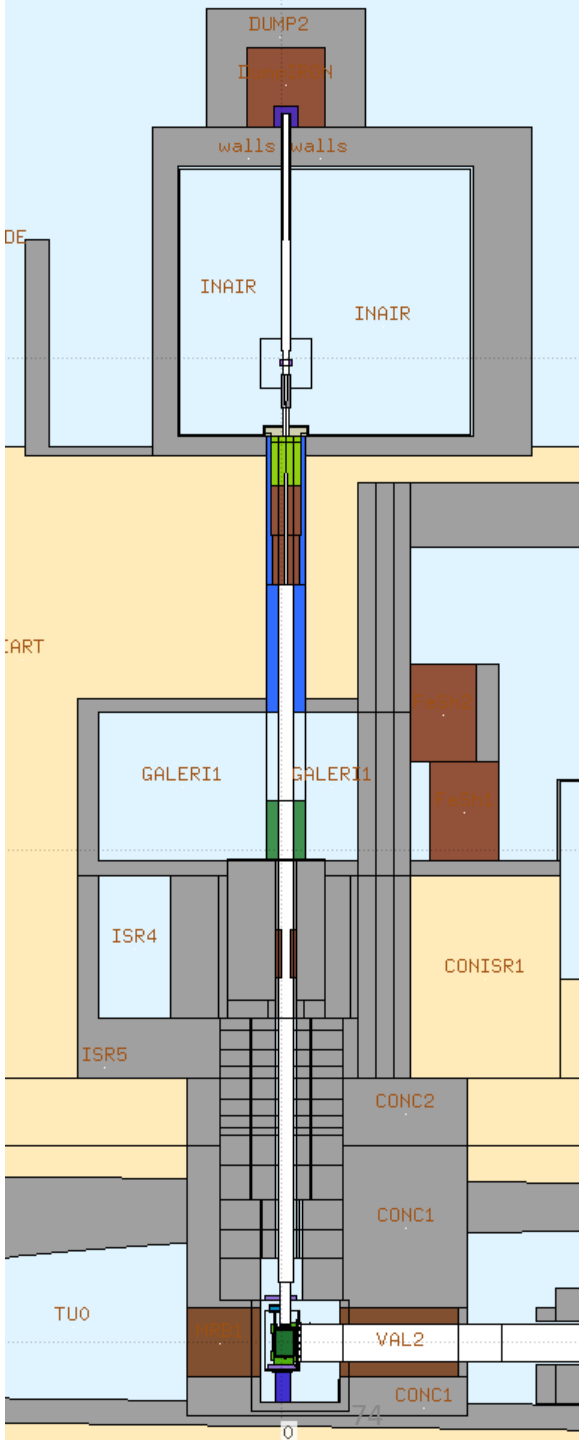
Beam Interception Factor (BIF) for a sample @ EAR1 R=1cm @ 184m versus various mis-alignments of the collimators

Origin of background (Energy deposition)

Time interval:
t: 10 .. 100µs
E_n: 200eV .. 20 keV

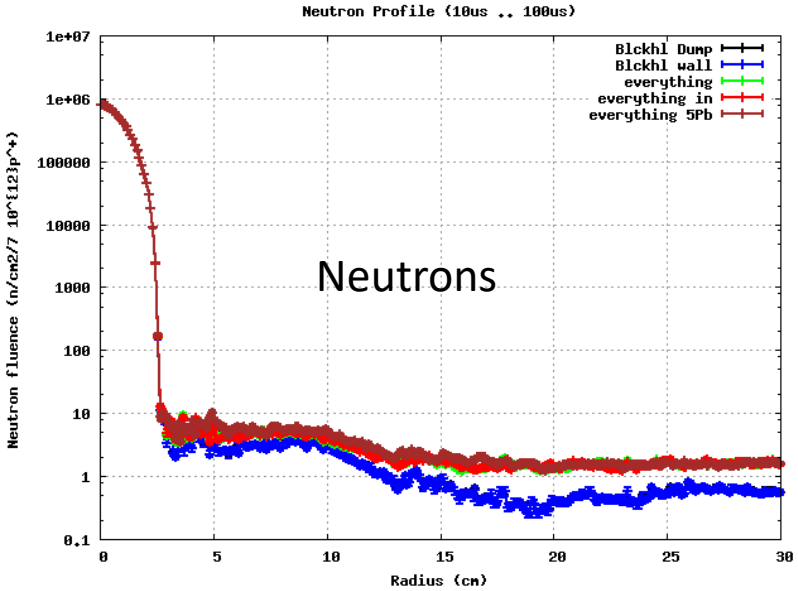


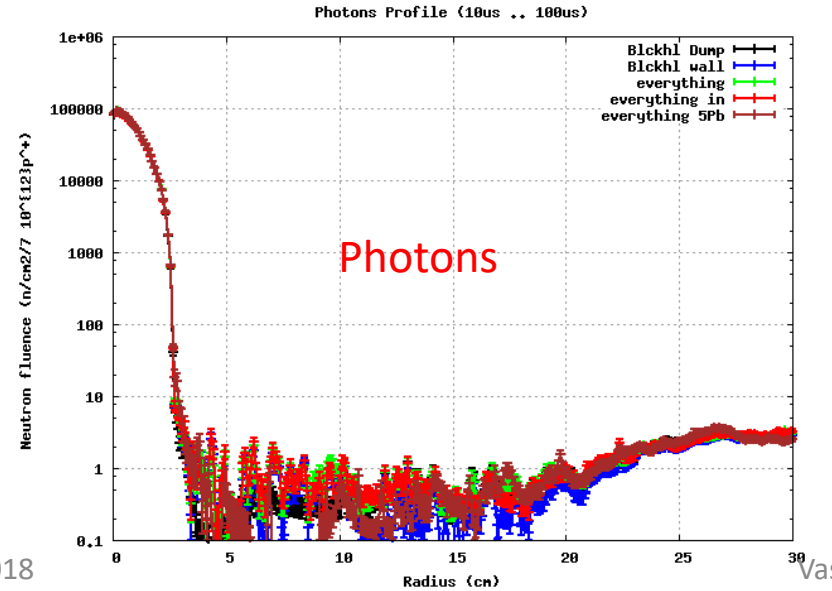
Including 60cm
Pb shielding



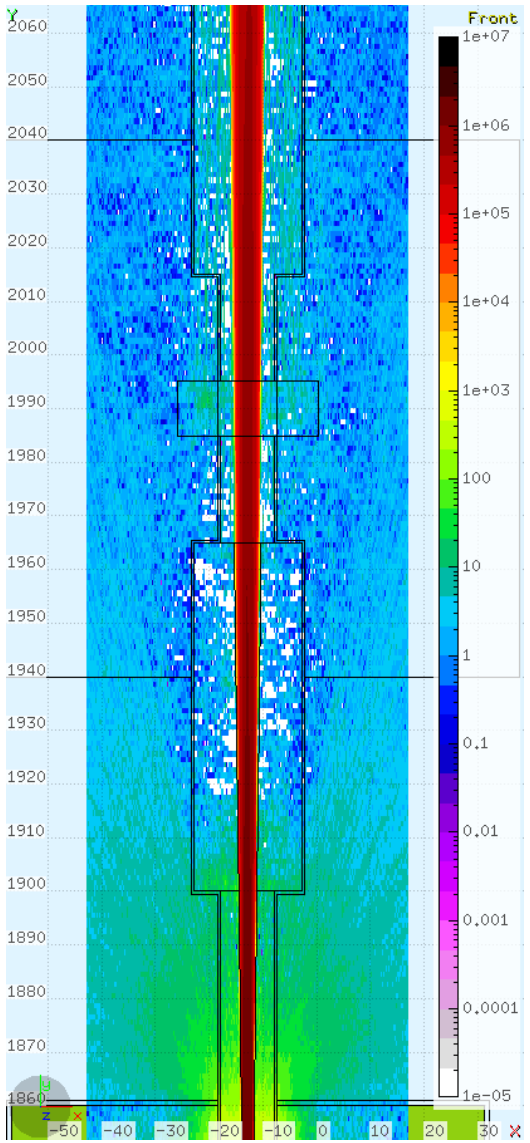
Vasilis.Vlachoudis@cern.ch

EAR2 Neutron & Photon: 200eV< E_n < 20keV

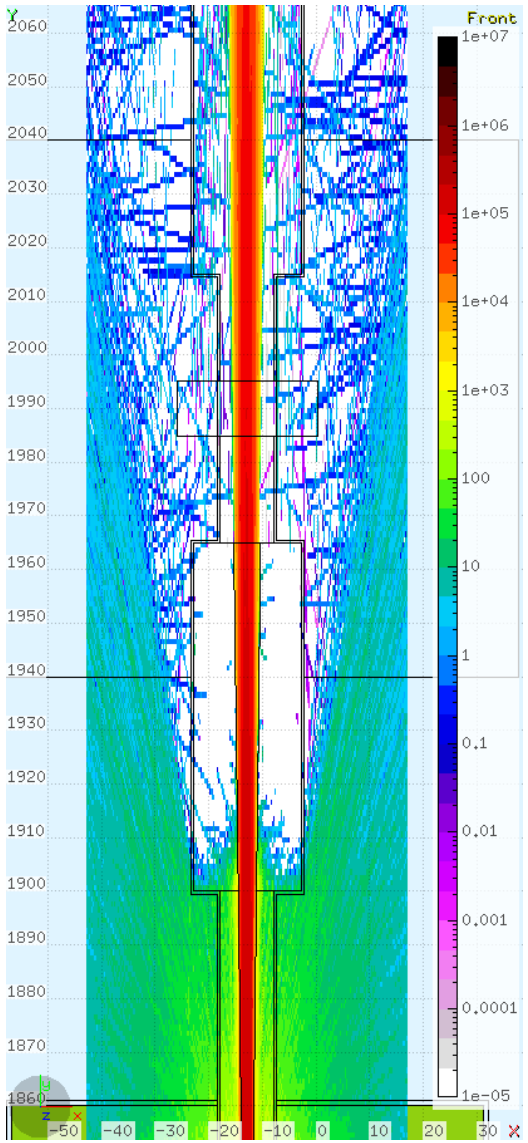




Neutrons

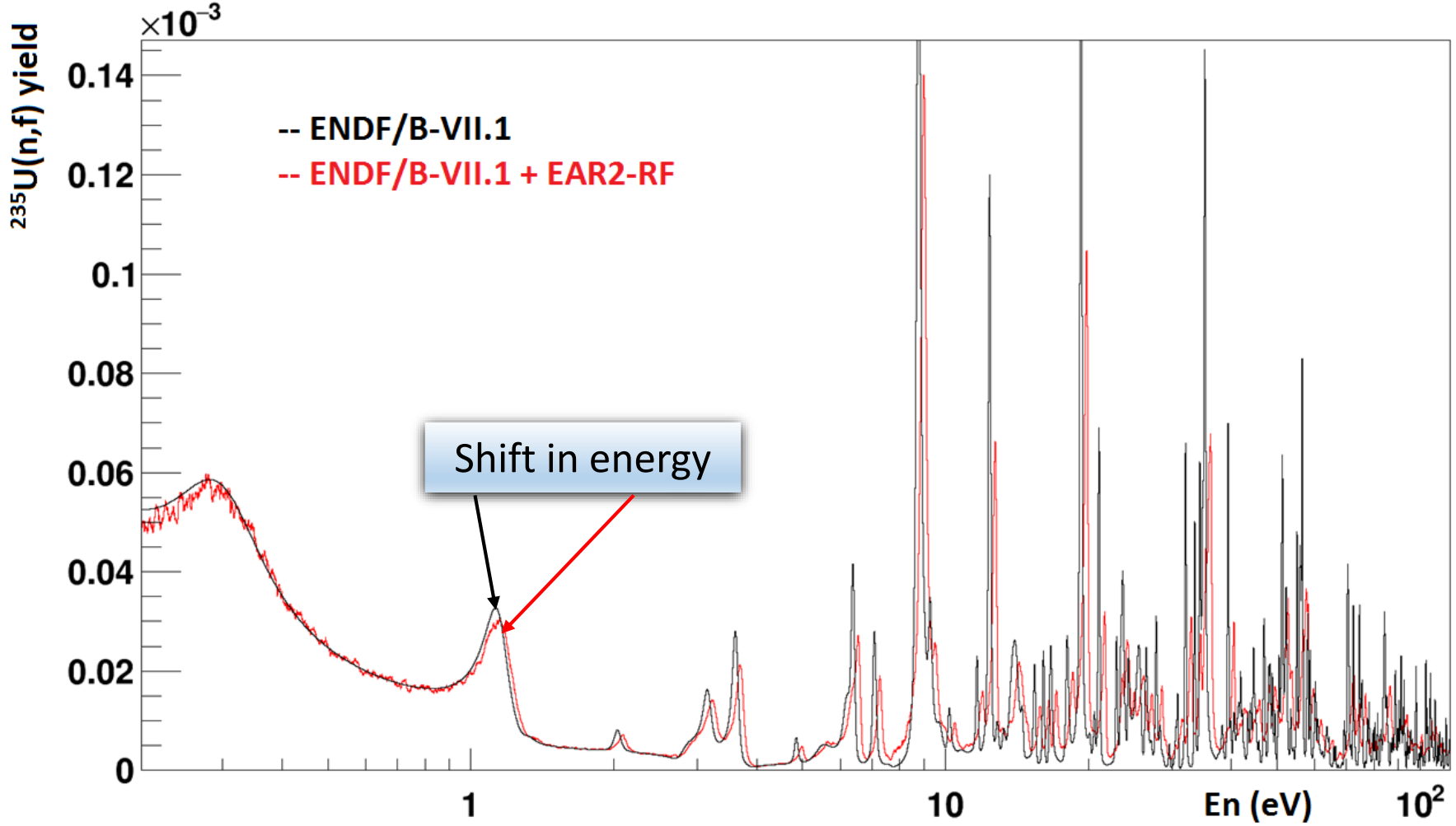


Photons



Resolution effect

- The flight path of EAR2 (19.5 m) is rather small → the effect of the RF cannot be neglected even at few eV

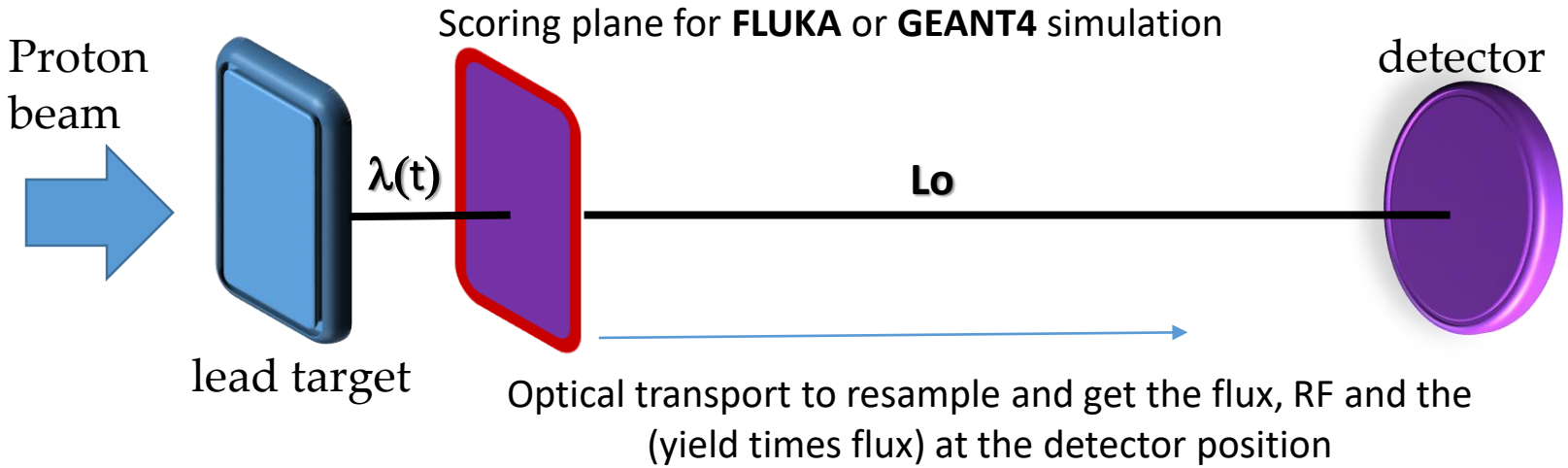


from: Marta Sabate

Transport code

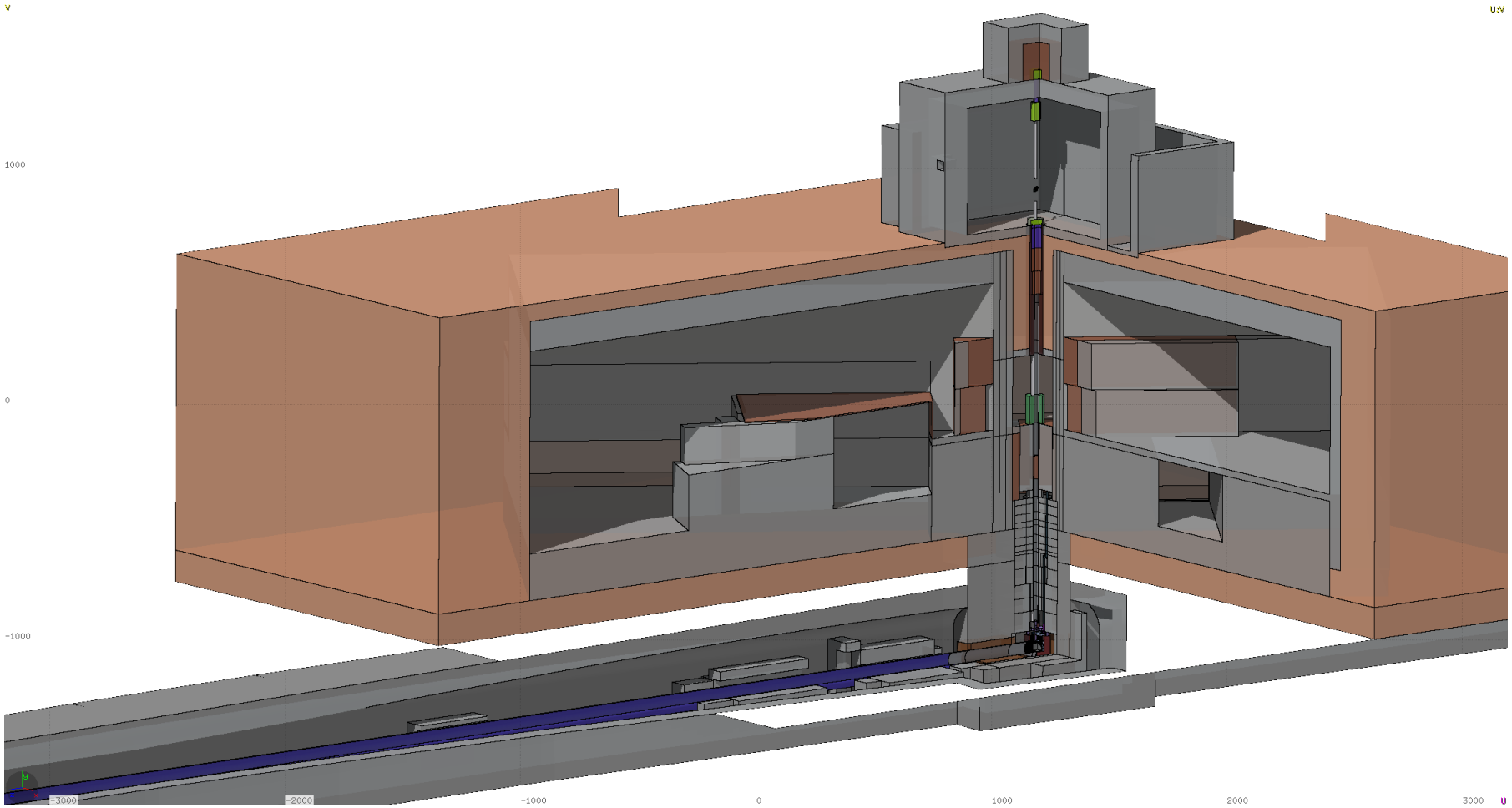
An alternative method to convolute the RF with the tabulated cross section. This method tries to replicate the experimental results with the use of simulations:

1. The spallation process is simulated with FLUKA/GEANT4 and the neutrons produced are scored in a plane located at a given distance from the center of the target.
2. Projection of each trajectory simulated from the scoring plane to the detector position: resampling.
3. An initial flight path must be defined: it could come from the adjustment of the ^{235}U resonances.
4. The detector efficiency, the transmission function and the total/reaction cross section from an evaluation as function of the neutron energy are taken as input

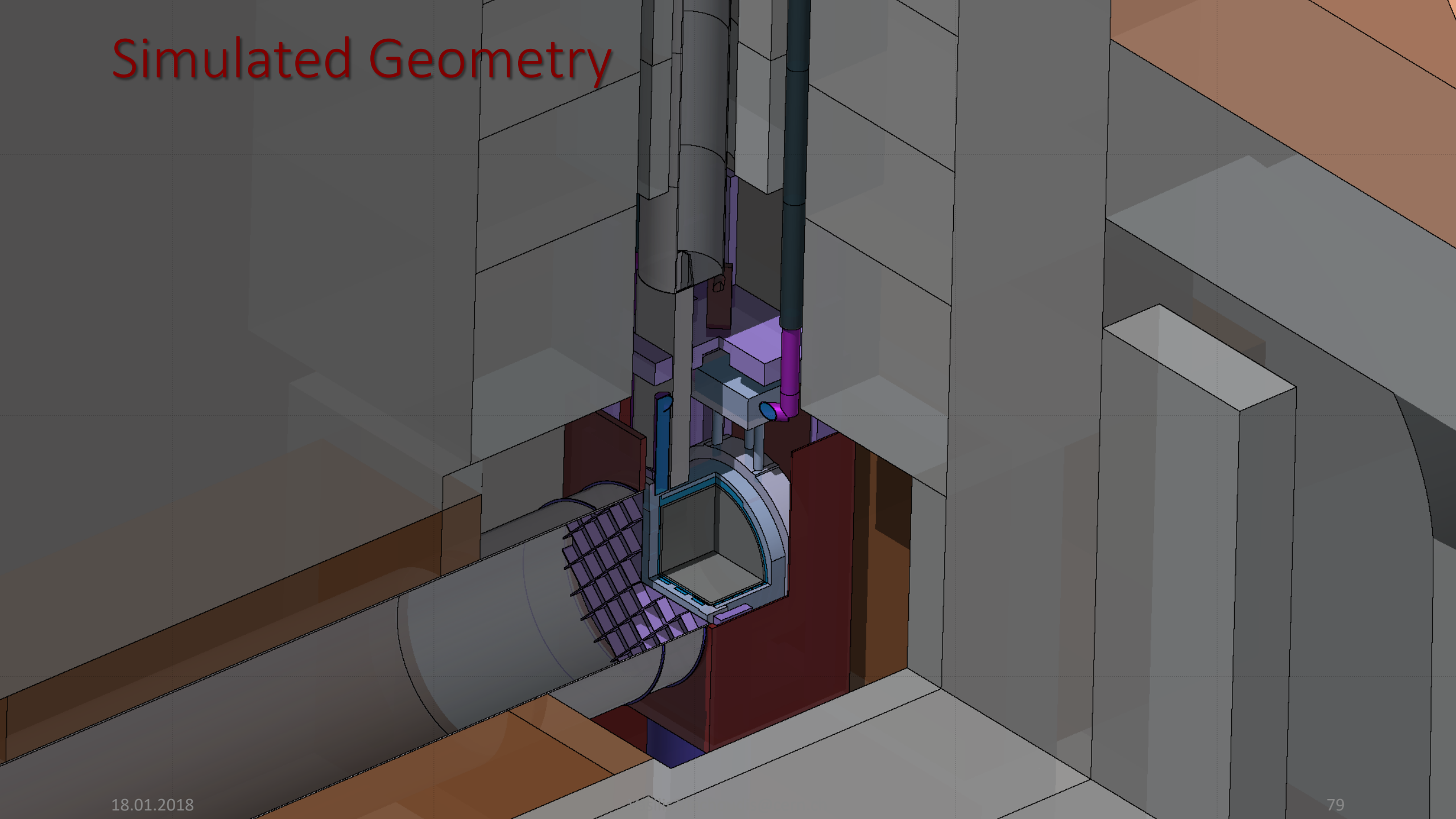


from: Marta Sabate

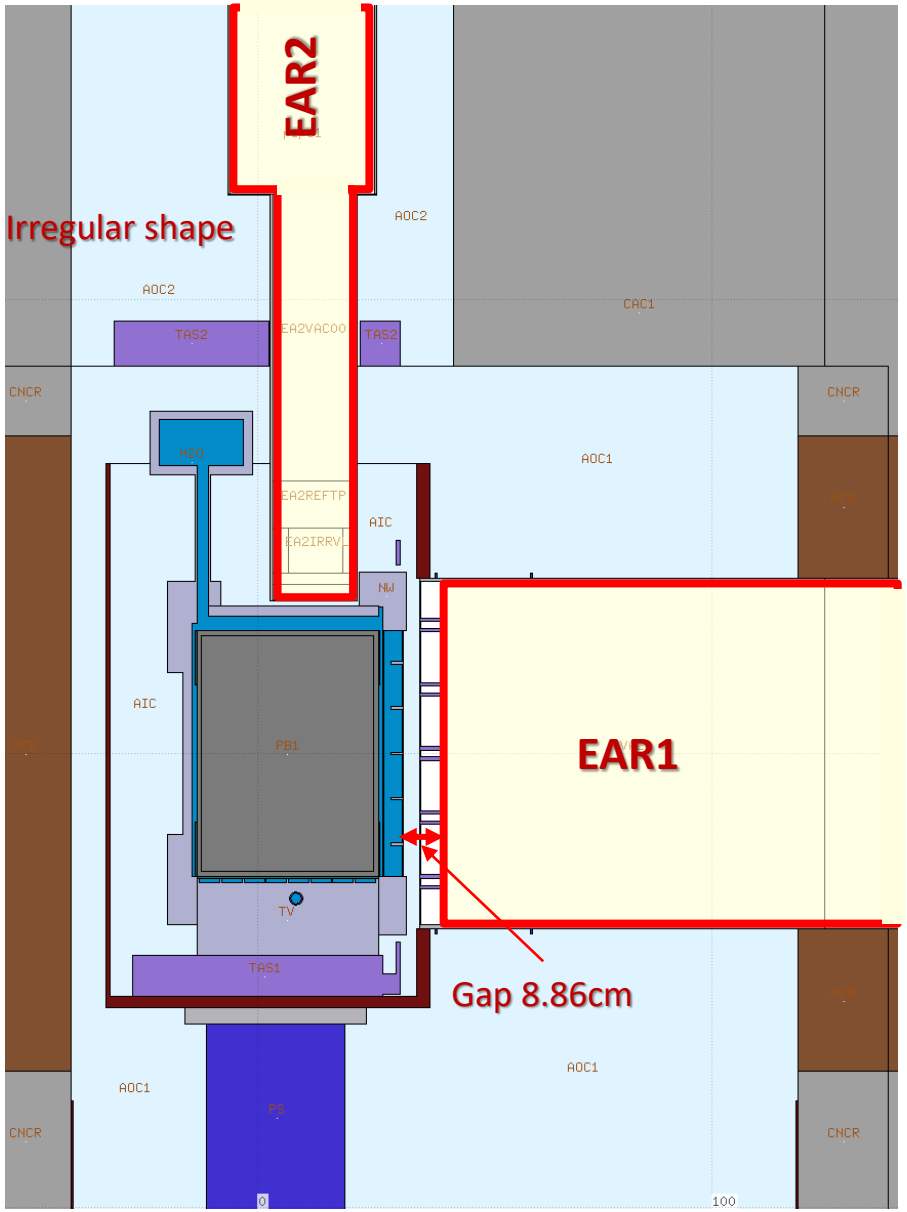
Simulated Geometry



Simulated Geometry



Simulations & Transport Code



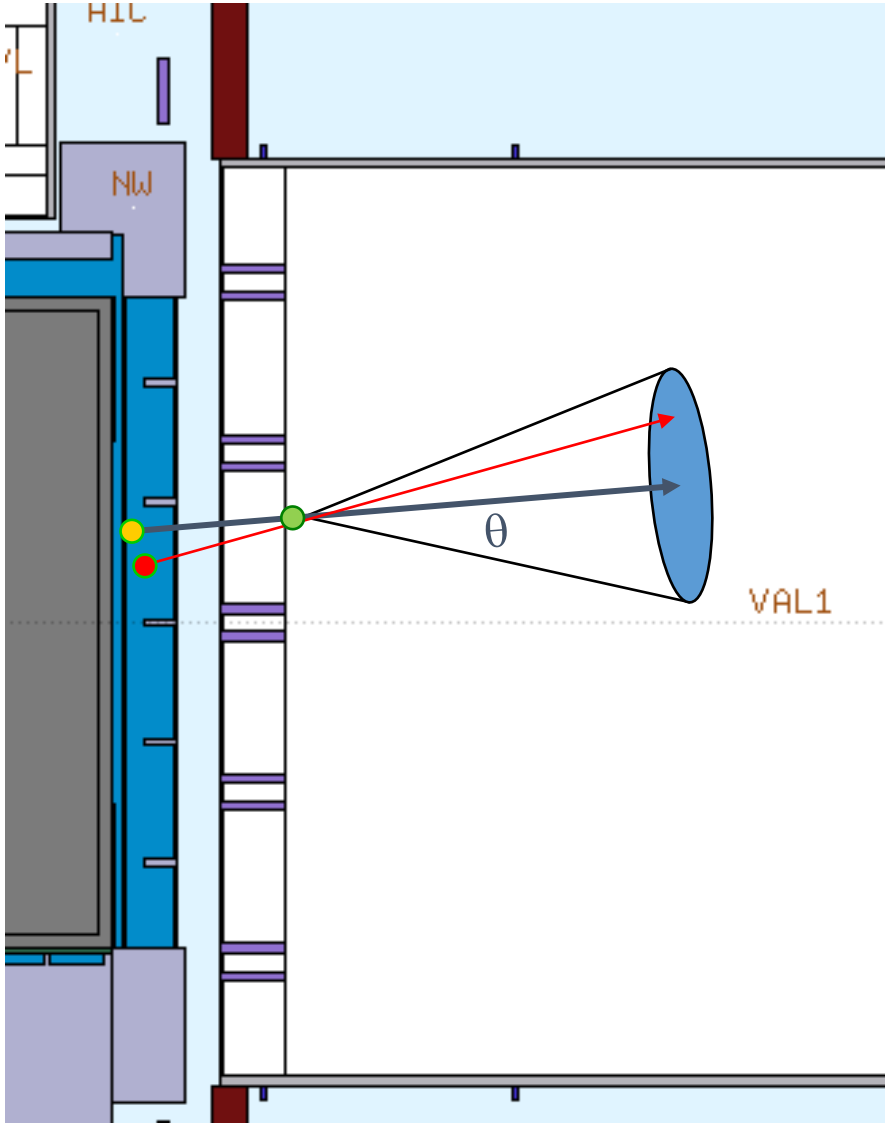
Scoring:
All particles crossing the scorer region with an angular acceptance

EAR1: acos(**tz**) ≤ **10º**
- z = 41.06 cm from lead Center
- gap 8.86cm additional between 1st window and scorer plane

EAR2: acos(**ty**) ≤ **10º**
- y > 37.2cm from lead Center
- Irregular shape

Resampling:
Smoothing direction within a cone of 1º,2º,5º ~~or 10º~~

Resampling Artefacts [1]



Resampling:

Neutrons within a certain angular acceptance are sampled isotopically within a cone

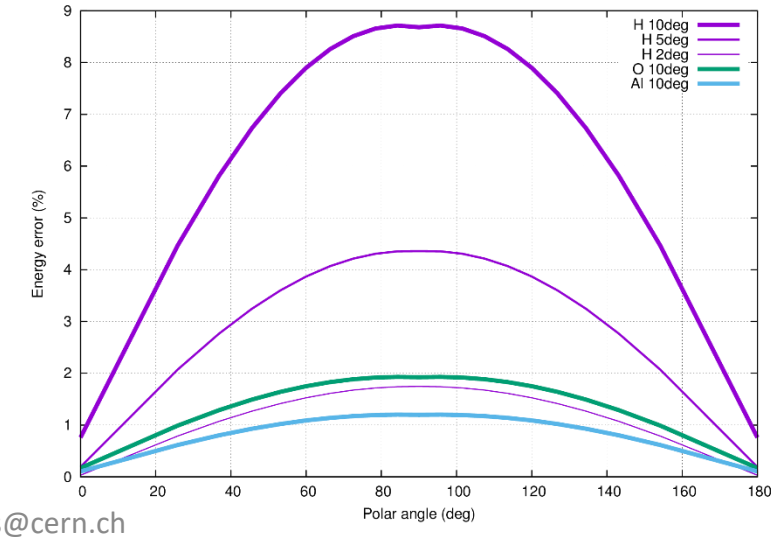
$$\Omega = 2\pi(1-\cos\theta)$$

Artefact #1:

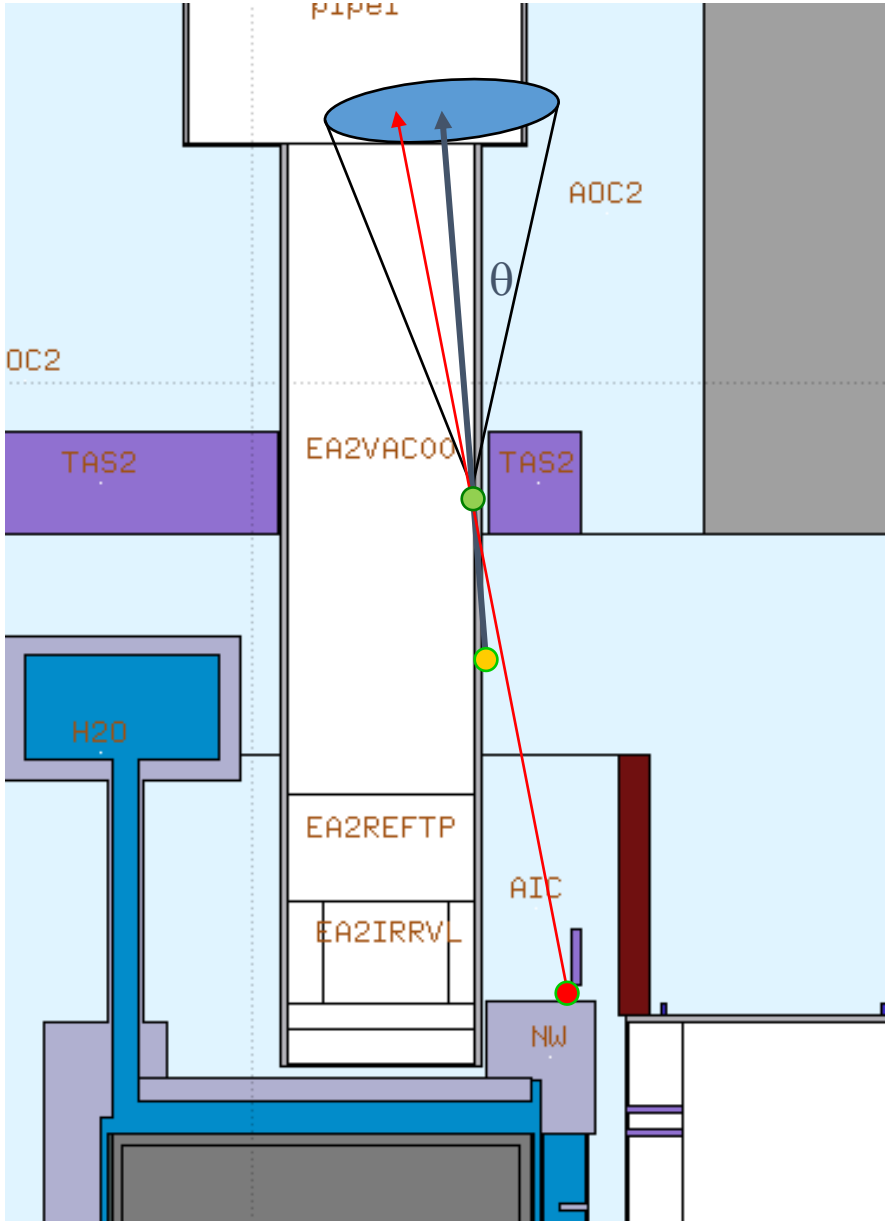
- Changing the angle should change the E_{out} from the last elastic collision

$$\frac{E_{out}}{E_{in}} = \frac{A^2 + 2A\cos\theta + 1}{(A+1)^2}$$

Max. Energy Error %



Resampling Artefacts [2]



Resampling:

Neutrons within a certain angular acceptance are sampled isotopically within a cone

$$\Omega = 2\pi(1-\cos\theta)$$

Artefact #2:

- Positioning error
  Not important for EAR1
  but important for EAR2

Simulation output

- Directory: **/eos/experiment/ntof/simul/data**
  - **1.3 10^{10}** pot where simulated with FLUKA
  - Scoring for both areas
    - EAR1: up to 2^{o}
    - EAR2: up to 10^{o}
- Folder Organization
  - 00___
    - 0001
      - ntofB001_EAR1, ntofB001_EAR2 // ASCII files with scored events
      - EAR1.bin, EAR2.bin // Binary files with scored events
      - ntofB001.out // FLUKA output file
      - … // various other files
    - 0002

      …
    - 0999
  - 01___

    …
  - 16___

ASCII Events files

*** Event nn**

xx yy zz tx ty tz E t wgt ij k g

...

nn	primary proton simulated
xx,yy,zz	position of particle
tx,ty,tz	direction cosines of particle (Z→EAR1, Y→EAR2)
E	energy (GeV)
t	time (s)
wgt	particle weight (should be used for scoring)
ij	particle type (8=neutron, 7=photon, http://www.fluka.org/fluka.php?id=man_onl&sub=7)
k	1=exact neutron energy, 0=average energy within the group
g	neutron group if any

WARNING: All files don't correspond to the same number of primaries. Majority is for 10^6 while some are for 5×10^5. Check the ntofB001.out for

"Total number of primaries run: xxxxx for a weight of: yyyyy"

Transport program

- Optical transport particles from the target to the experimental area(s).
- Directory: **/eos/experiment/ntof/simul/transport**
- Repository: **https://gitlab.cern.ch/ntof/transport.git**
- Input:
  - Collimation system (in subdirectory **input**)
  - Event files, can read either the binary or asci
  - Aperture smoothing angle
  - Integration step
  - Cross sections of support material and target
  - …
- Output:
  - 1D histograms of counts, or reaction rates, versus, energy, time, spatial distribution or lambda. True energy of neutrons or calculated from time
  - 2D histograms of any of the above
  - One file per cycle/run
- Average:
  - Average histograms to produce the mean value + error

transport Options

syntax: ./transport [options]:

-?, --help This help page
-a, --angle Anglular cut [degrees]
-b, --bmin Minimum 2D histogram y-value [eV,s,cm]
-B, --bmax Maximum 2D histogram y-value [eV,s,cm]
-c, --tmin minimum time cut at measuring station to score [s]
-C, --tmax maximum time cut at measuring station to score [s]
-d, --data Data file with particle distributions
-D, --dir Direction to propagate [XYZ]
-e, --emin minimum energy cutoff [eV]
-E, --emax maximum energy cutoff [eV]
-h, --hmin Minimum histogram x-value [eV,s,cm]
-H, --hmax Maximum histogram x-value [eV,s,cm]
-i, --input Input file with collimation information
-L, --length Scoring distance [m]
-m, --mbins Histogram number of bins of 2D
-n, --nbins Histogram number of bins
-p, --particle Particle type (def=8)
-P, --primaries Number of primaries (def=1)
-r, --rmin Minimum radius [cm]
-R, --rmax Maximum radius [cm]
-s, --rstep Scanning step size[cm]
-S, --sigma Sigma of Gaussian smoothing on time [s]
-t, --target Spallation target radius [cm]
-T, --type Histogram type ([e]nergy, [t]ime, profile[xyr2], [l]ambda)
-x, --x0 X-offset to subtract from data [cm]
-y, --y0 Y-offset to subtract from data [cm]
-z, --z0 Z-offset to subtract from data [cm]
-0, --t0 t0-offset to subtract from time [ns]

--xs <file> Sample cross section file with energy[eV] cross section[barn] of the reaction
--xstotal <file> Total cross section file with energy[eV] cross section[barn]
--atob # Sample atomic density [atoms/barn]
--Sxs <file> Support material cross section file
--Satob # Support material atomic density [atoms/barn]
--eff <file> Two column file with efficiency as a function of energy (eV)

Transport code: flux and yield estimations

- Output of the transport code:
  1. Flux (Φ), resolution function (λ) and the product of the flux times the expected yield ($Yield*\Phi$).
  2. The last value is comparable with the experimental count rate.
- The influence of the simulation is removed once the simulated yield is divided by the simulated flux, obtaining the experimental flux:

$$\Phi_{exp}(t) = \frac{(Yield \cdot \Phi)_{exp}(t)}{\frac{\int Yield_{MC}(t,E) \cdot \Phi_{MC}(t,E) \cdot dE}{\int (\Phi_{MC}(t,E) \cdot dE)}}$$

Rate from experimental data

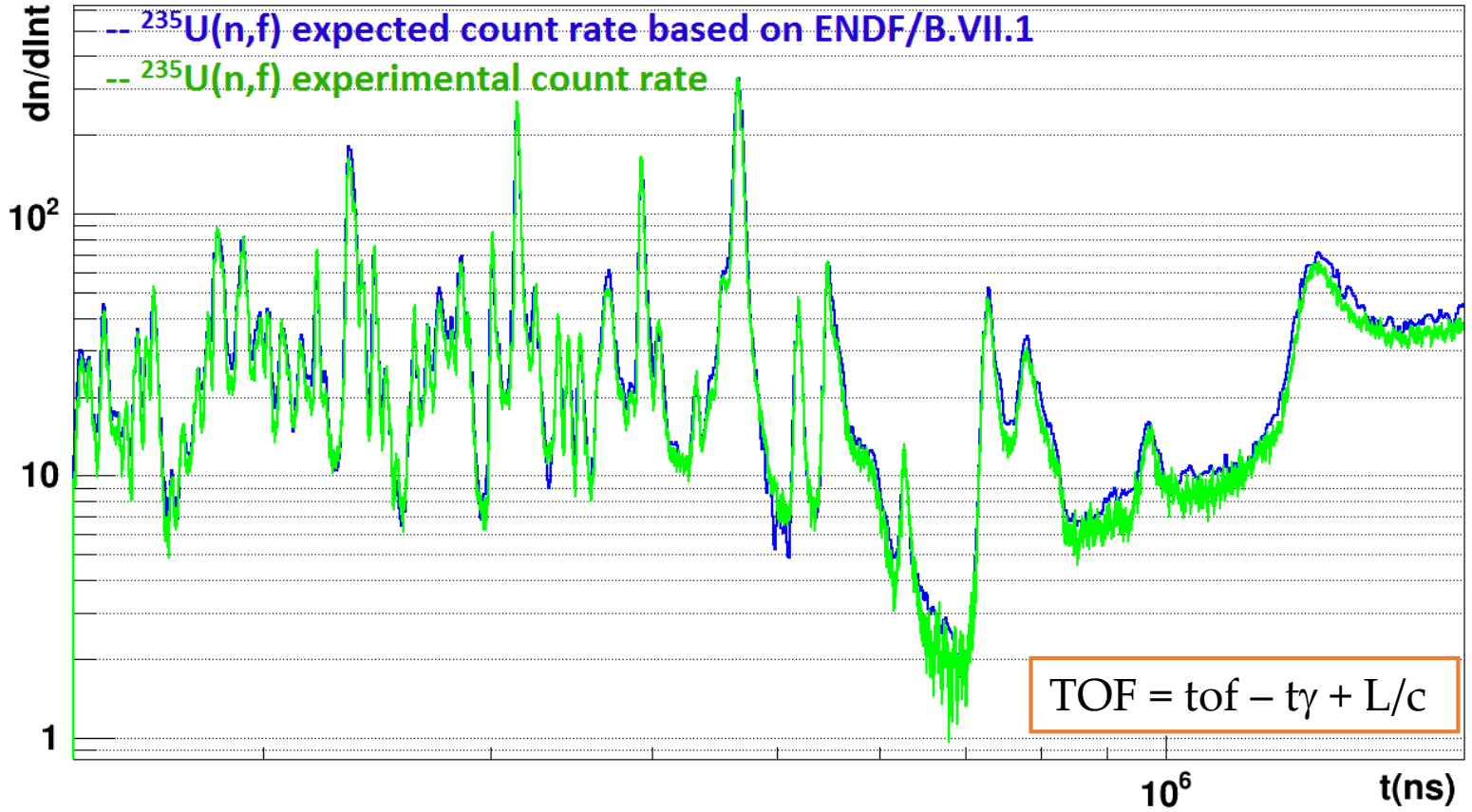
From simulations

Equivalent

$$\Phi_{exp}(t) = \frac{(C-B)_{exp}(t)}{\varepsilon \cdot \Pi T \cdot (1 - e^{-n \cdot \sigma_t}) \cdot \frac{\sigma_{reac}}{\sigma_t}}$$

from: Marta Sabate

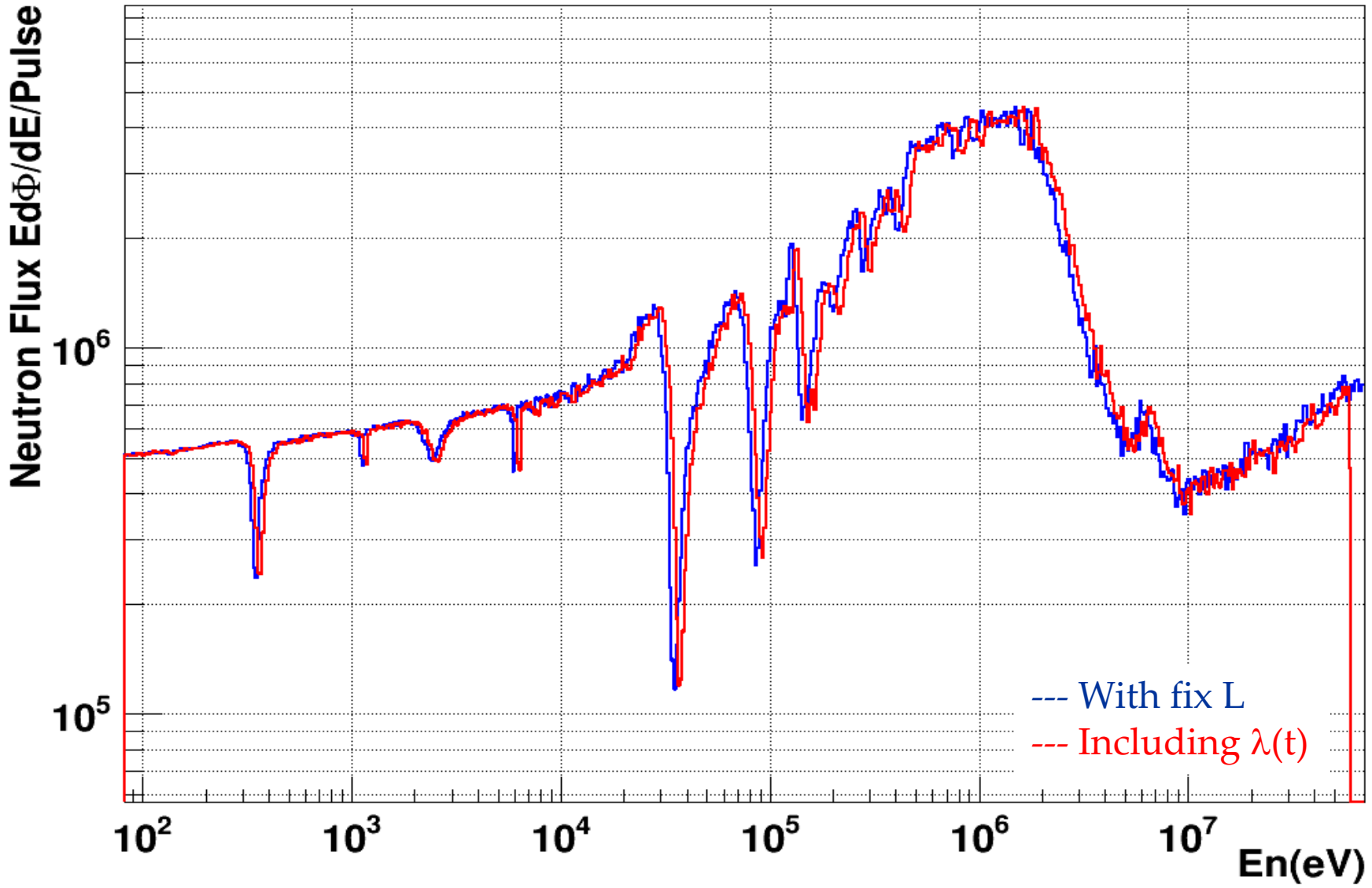
TOF Flight path determination



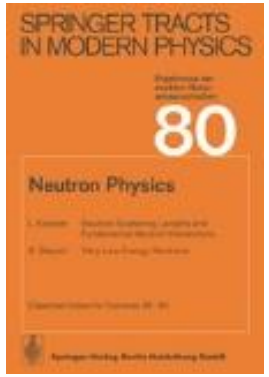
The flight path is extracted comparing the expected position of the resonances and the experimental ones in TOF

from: Marta Sabate

Evaluated flux n_TOF-EAR2 (2014-15)



from: Marta Sabate

Bibliography

- "*Neutron Physics*"
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  Springer-Verlag, 1964
  http://www.springer.com/de/book/9783642876165