Principles of neutron TOF cross section measurements

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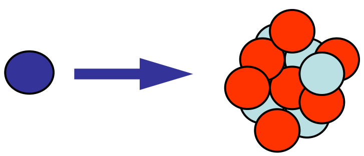
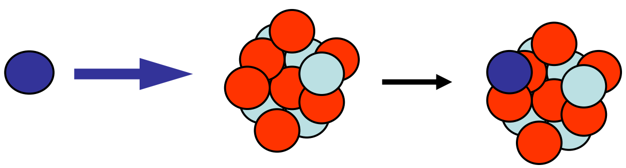
Neutron induced reactions

Neutron + ^{A}X

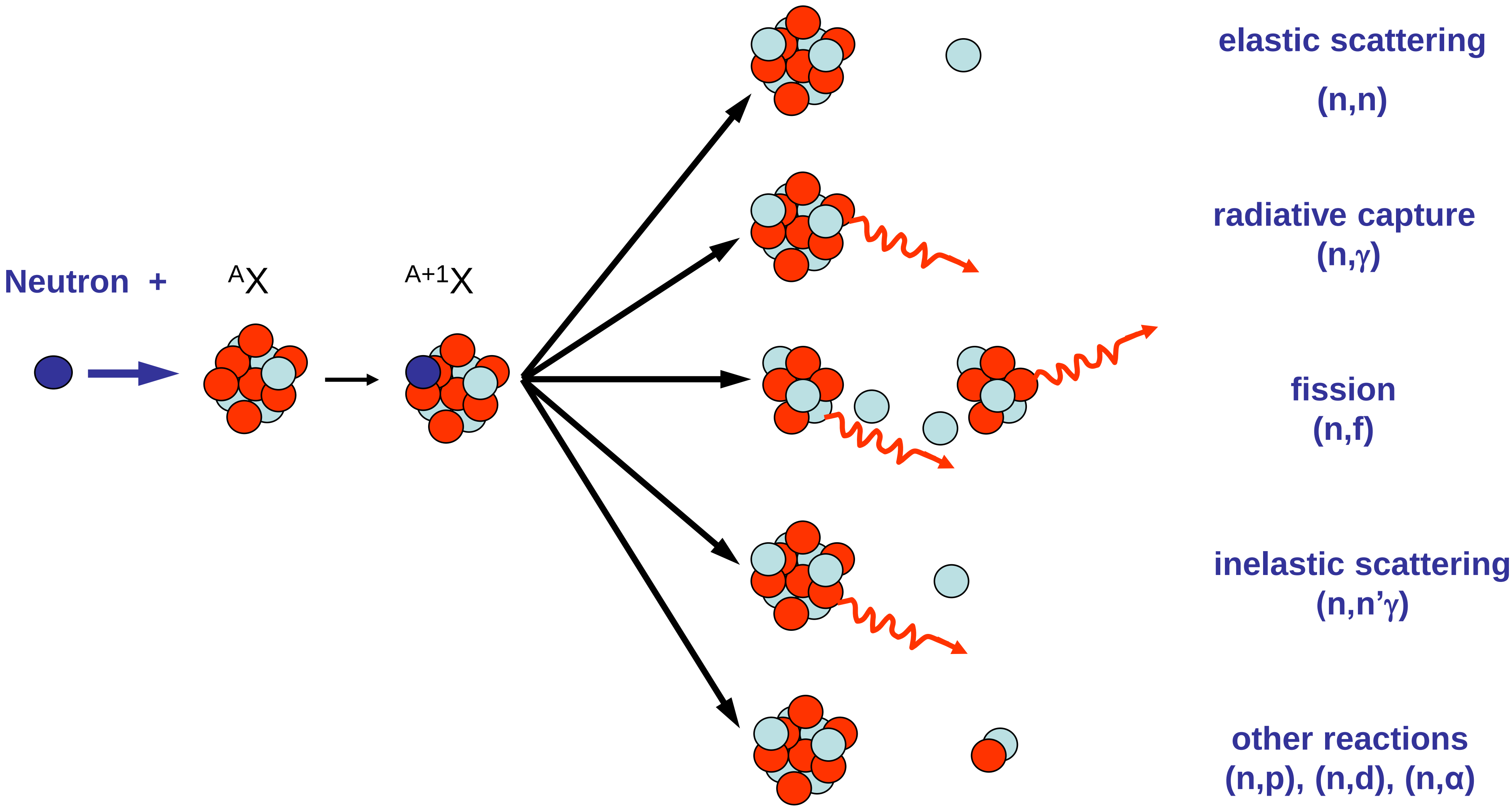


Neutron induced reactions

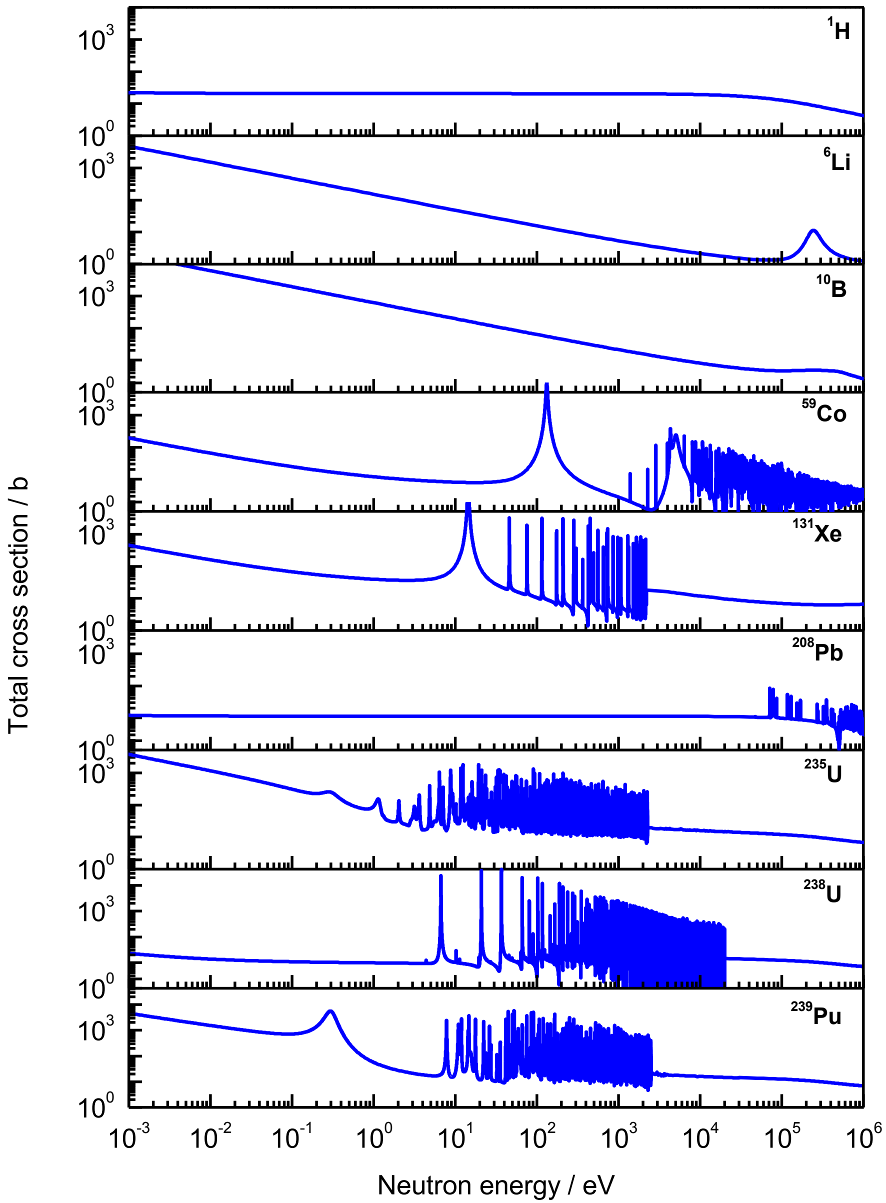
Neutron + ^{A}X ^{A+1}X



Neutron induced reactions

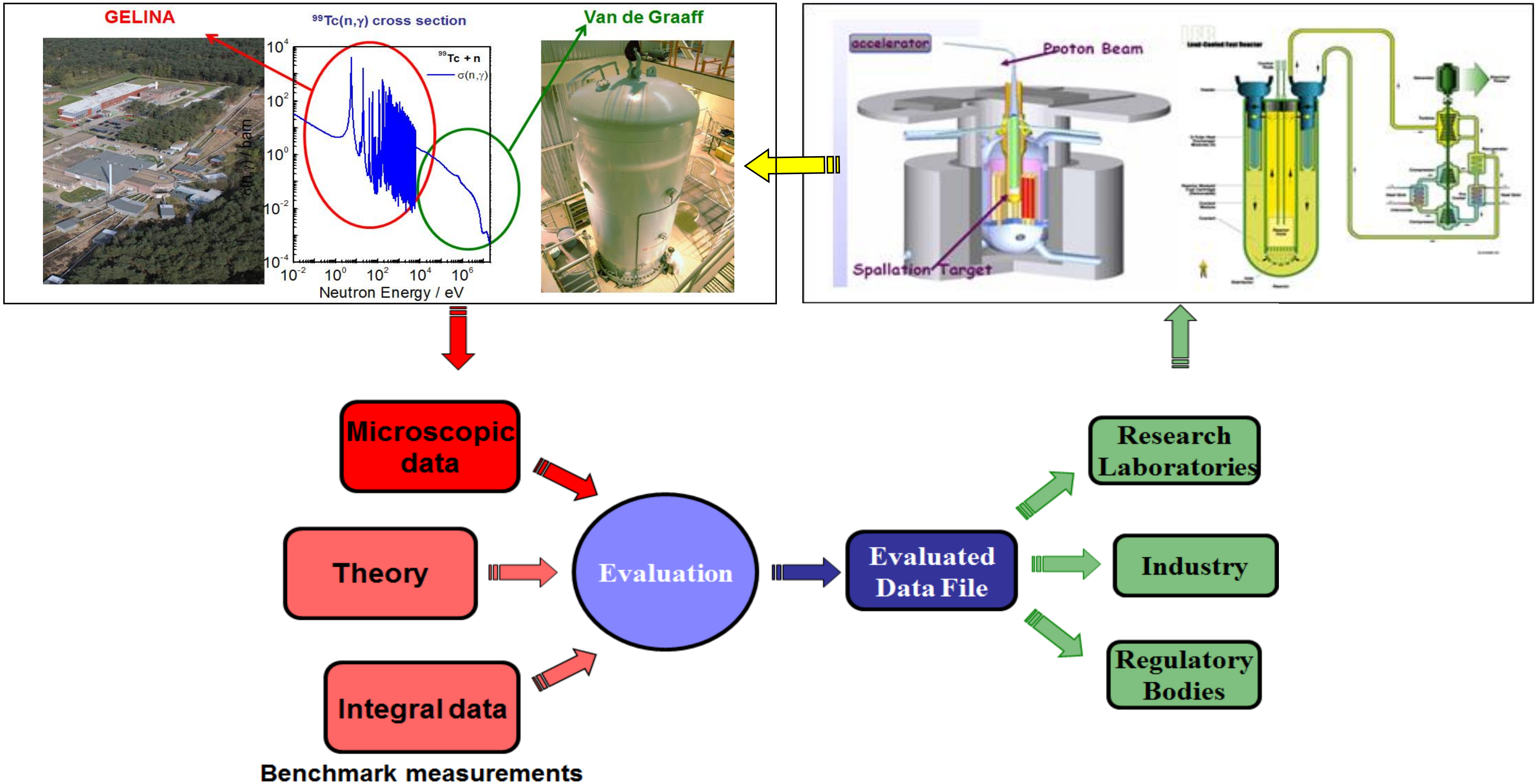


Neutron induced reaction cross section



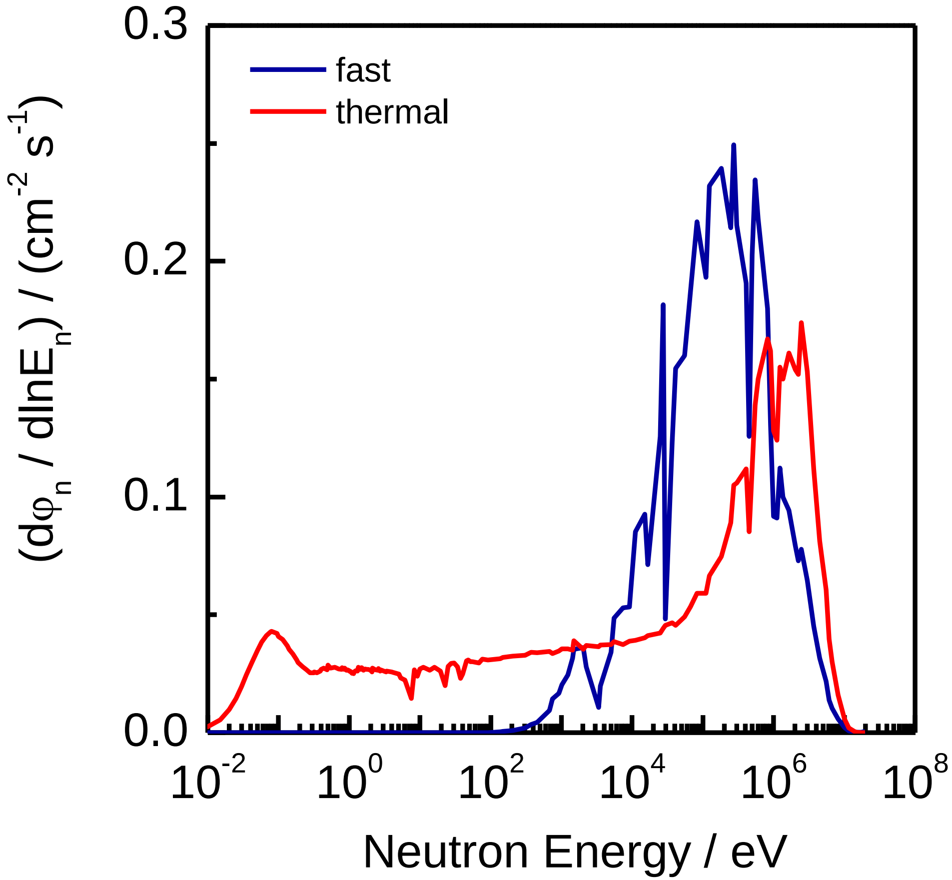
- Cross section is a measure for the interaction probability
- Cross sections strongly depend on:
  - target nucleus
  - incoming neutron energy
- Dedicated facilities required depending on energy region of interest
  - thermal energy
  - resonance region
  - continuum

Production and use of nuclear data

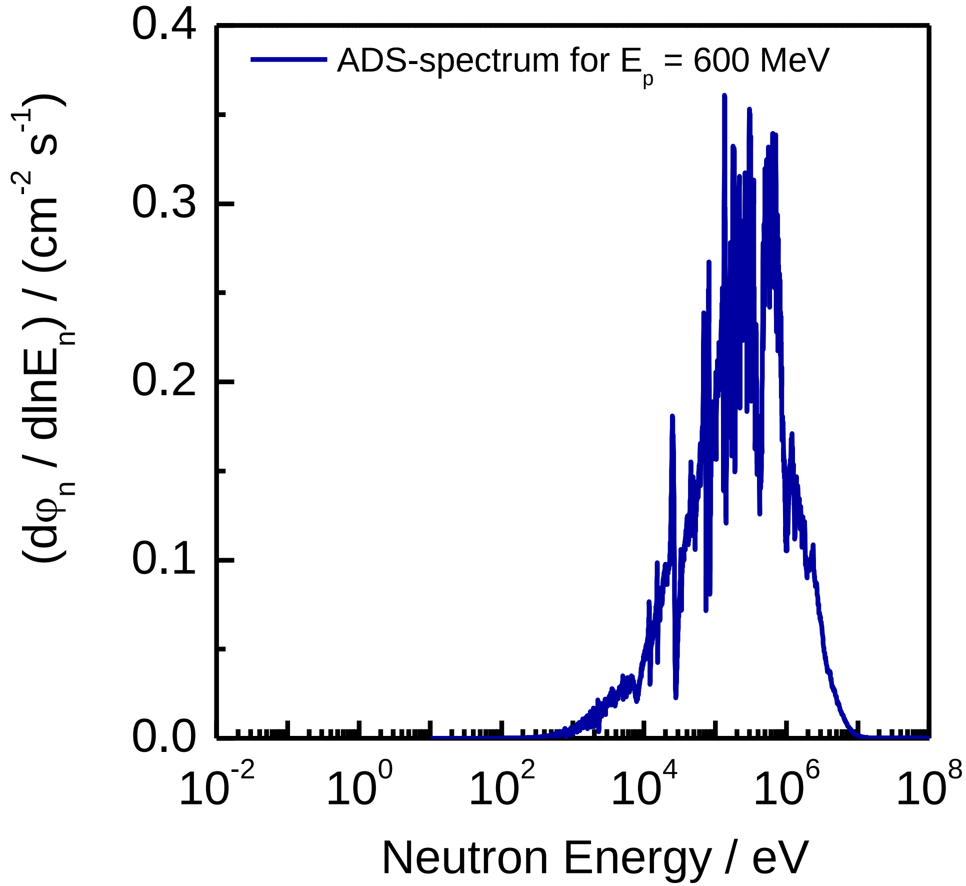


Neutron energy spectrum

Reactor
Neutron induced fission



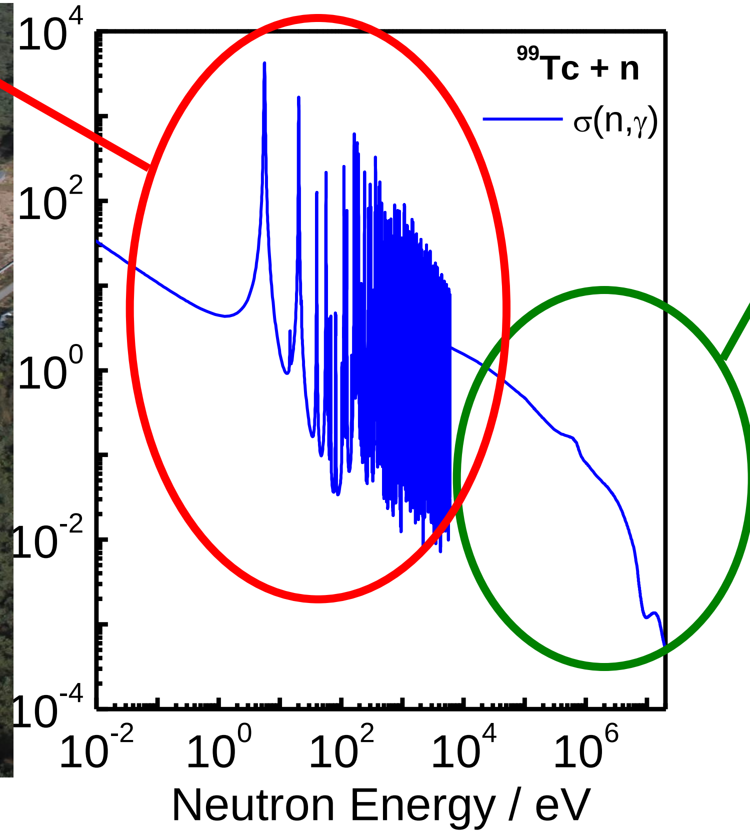
ADS : E_p = 600 MeV
Spallation reactions



Neutron facilities at JRC-IRMM

GELINA

$^{99}Tc(n,\gamma)$ cross section

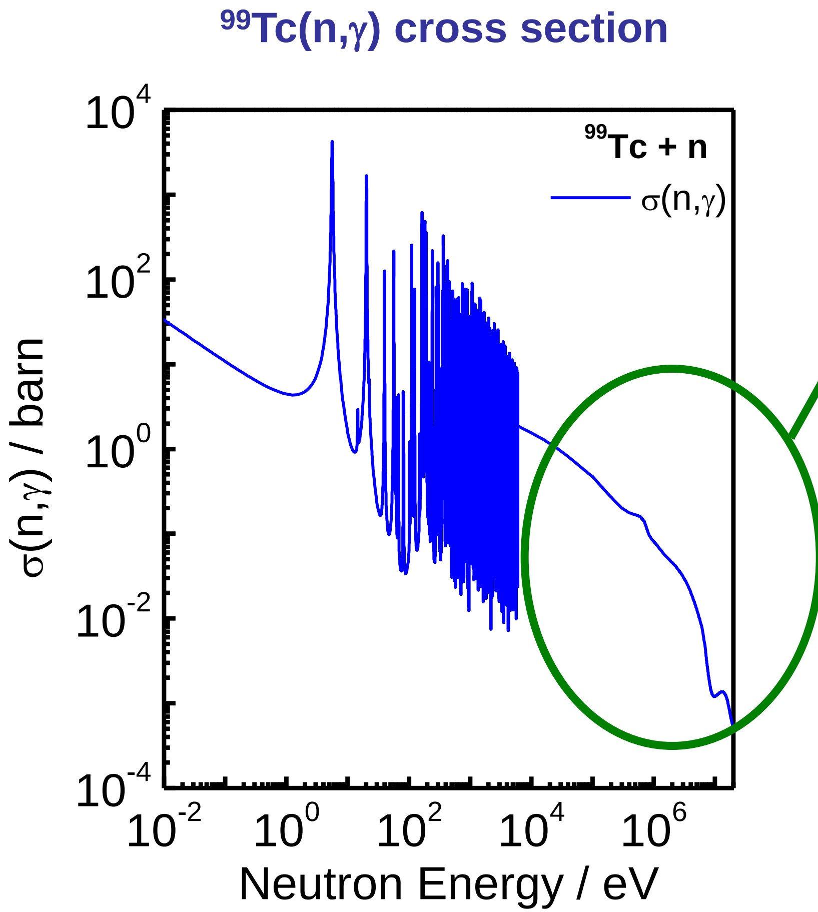


Van de Graaff

White neutron source
+
Time-of-flight (TOF)

Quasi mono-energetic neutrons through (cp,n) reactions

Neutron facilities at JRC-IRMM



Van de Graaff

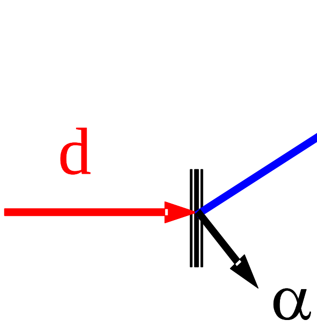
Quasi mono-energetic neutrons through (cp,n) reactions

Quasi mono-energetic neutron beams

Charged particle induced neutron reactions

quasi mono-energetic neutrons produced via charged particle induced nuclear reactions

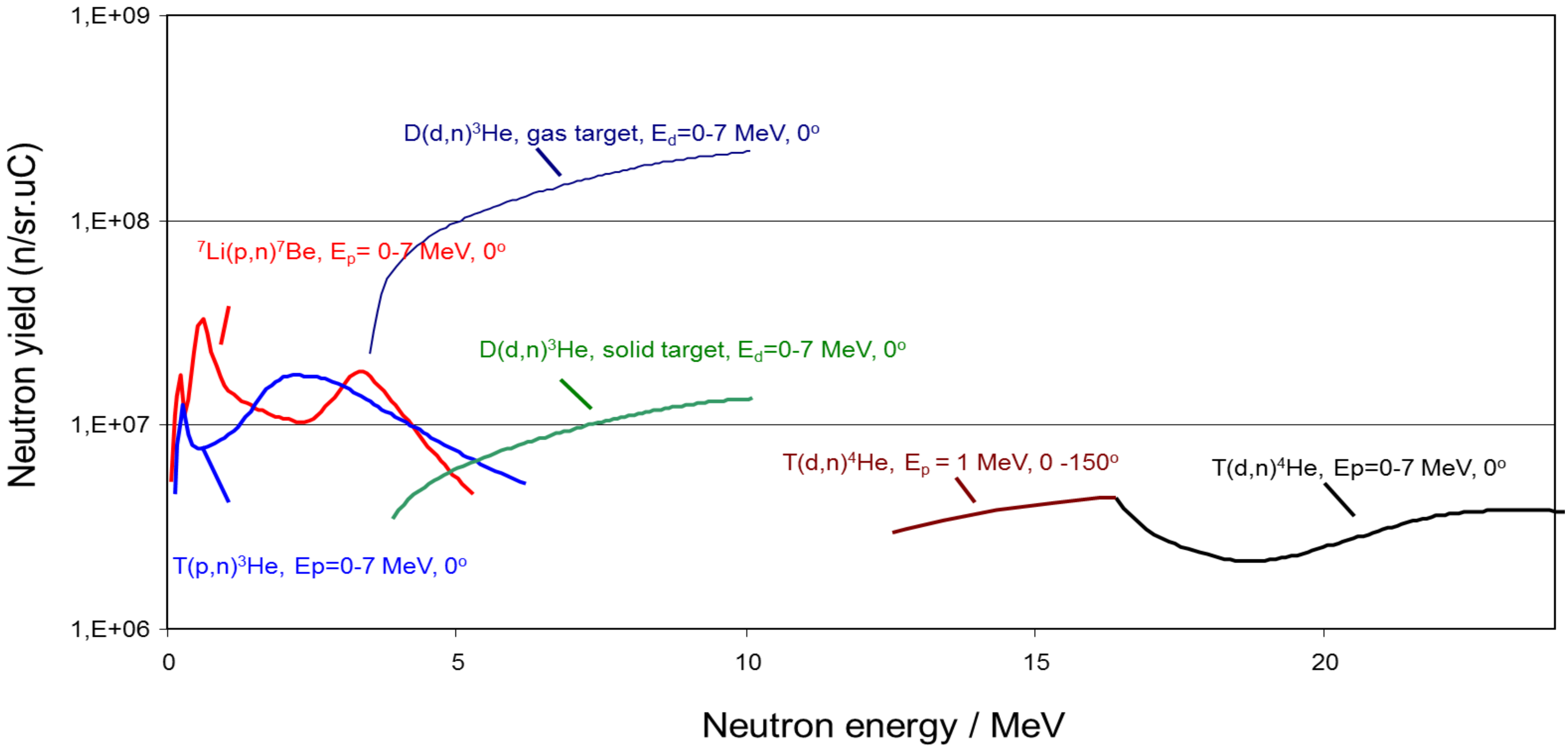
e.g. $T(d,n)^4He$



- 7 MV VDG - accelerator
  - DC ($I_{p,d} < 50\ \mu A$),
  - Pulsed beam available (1 – 2 ns)
- 6 beam lines
- fast rabbit systems ($T_{1/2} > 1s$) : activation

$^7Li(p,n)^7Be$	E_n: 0 - 5.3 MeV
$T(p,n)^3He$	E_n: 0 - 6.2 MeV
$D(d,n)^3He$	E_n: 1.8 - 10.1 MeV
$T(d,n)^4He$	E_n: 12.1 - 24.1 MeV

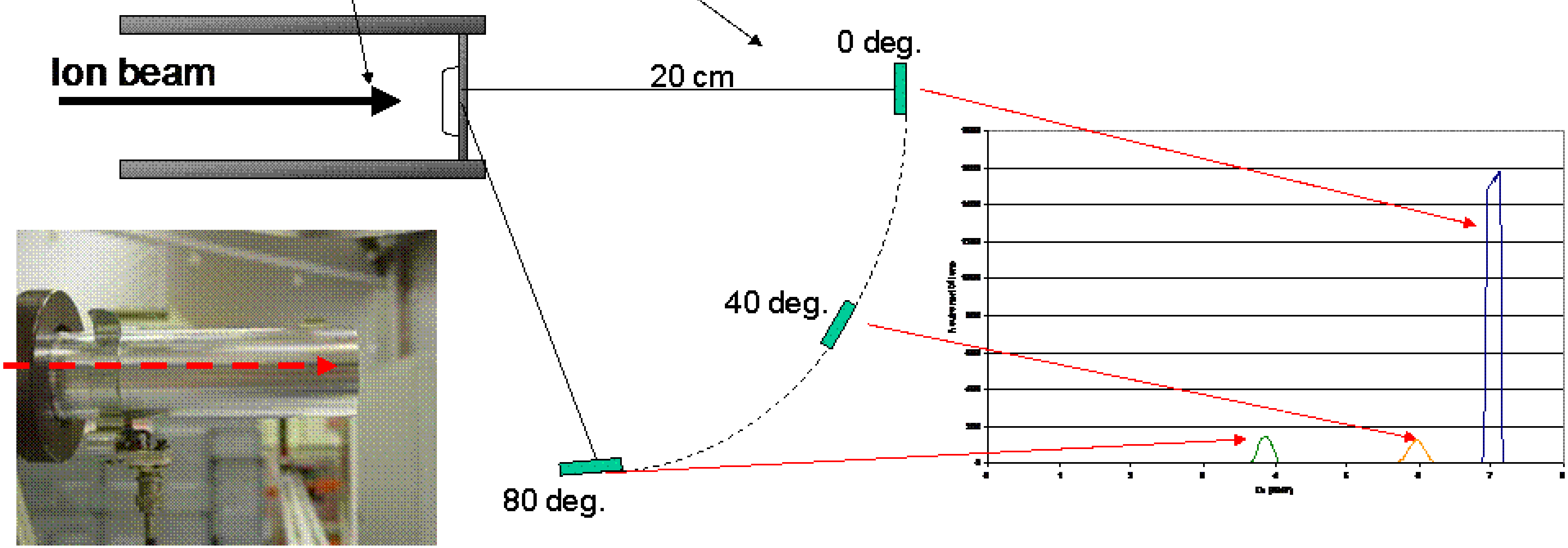
Charged particle induced neutron reactions



Charged particle induced neutron reactions

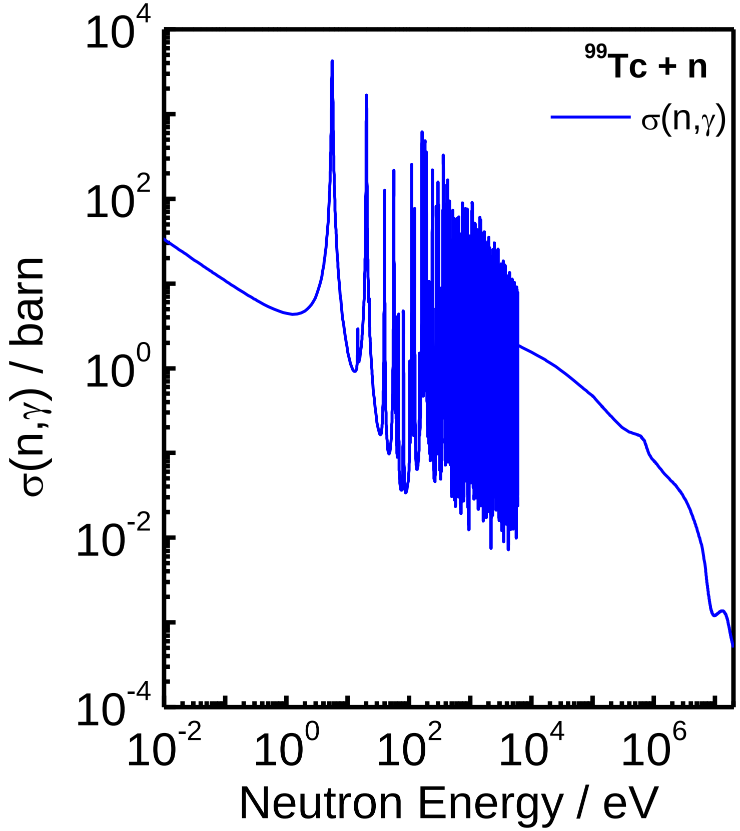
- nuclear reaction,
- neutron emission angle,
- ion energy.

$^{7}Li(p,n)^{7}Be$ E_n: 0 - 5.3 MeV
$T(p,n)^{3}He$ E_n: 0 - 6.2 MeV
$D(d,n)^{3}He$ E_n: 1.8 - 10.1 MeV
$T(d,n)^{4}He$ E_n: 12.1 - 24.1 MeV



Neutron facilities at JRC-IRMM

^{99}Tc(n,γ) cross section



Neutron facilities at JRC-IRMM

GELINA

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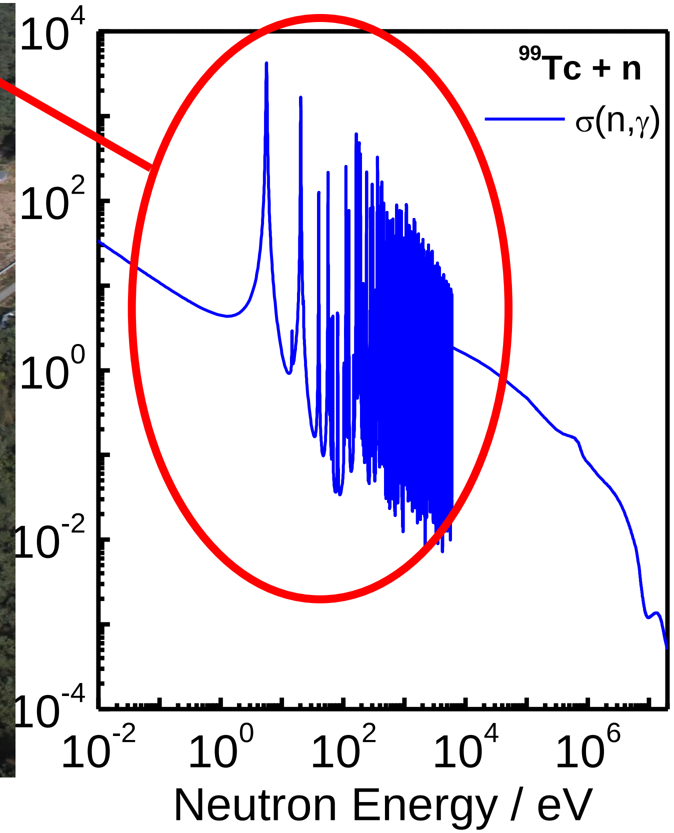


White neutron source
+
Time-of-flight (TOF)

TOF - Facility GELINA

GELINA (Geel Electron LINear Accelerator)

- Pulsed white neutron source

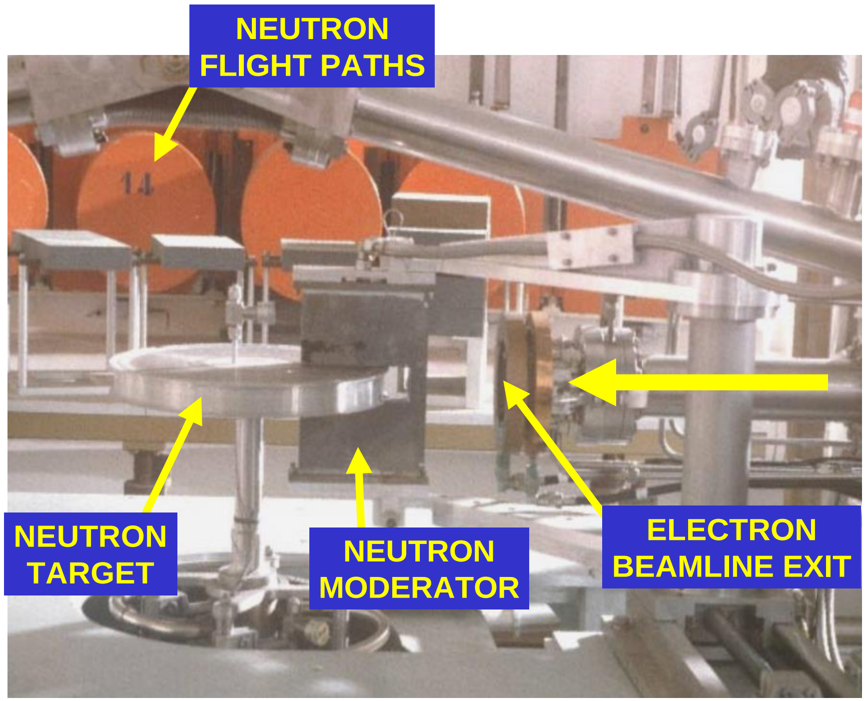
  $(10 \text{ meV} < E_n < 20 \text{ MeV})$

- Pulse frequency 50Hz – 800 Hz
- Neutron energy : time – of – flight (TOF)
- Multi-user facility: 10 flight paths

  (10 m - 400 m)

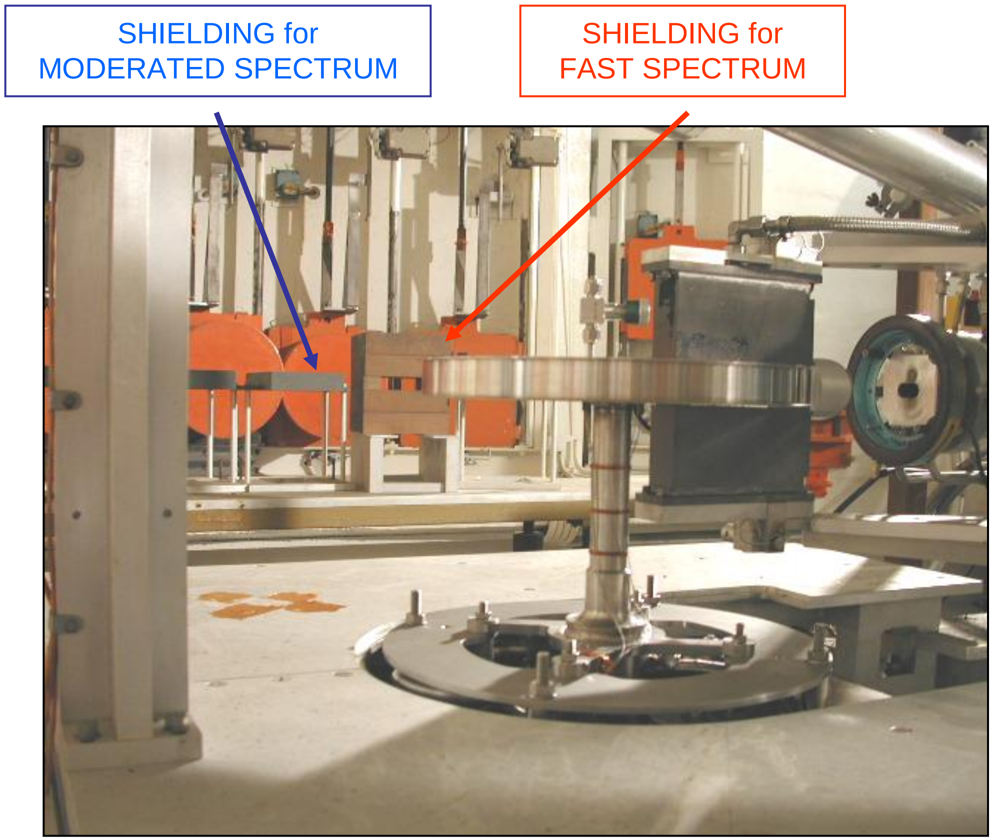
- Measurement stations with special equipment to perform:
  - Total cross section measurements
  - Partial cross section measurements

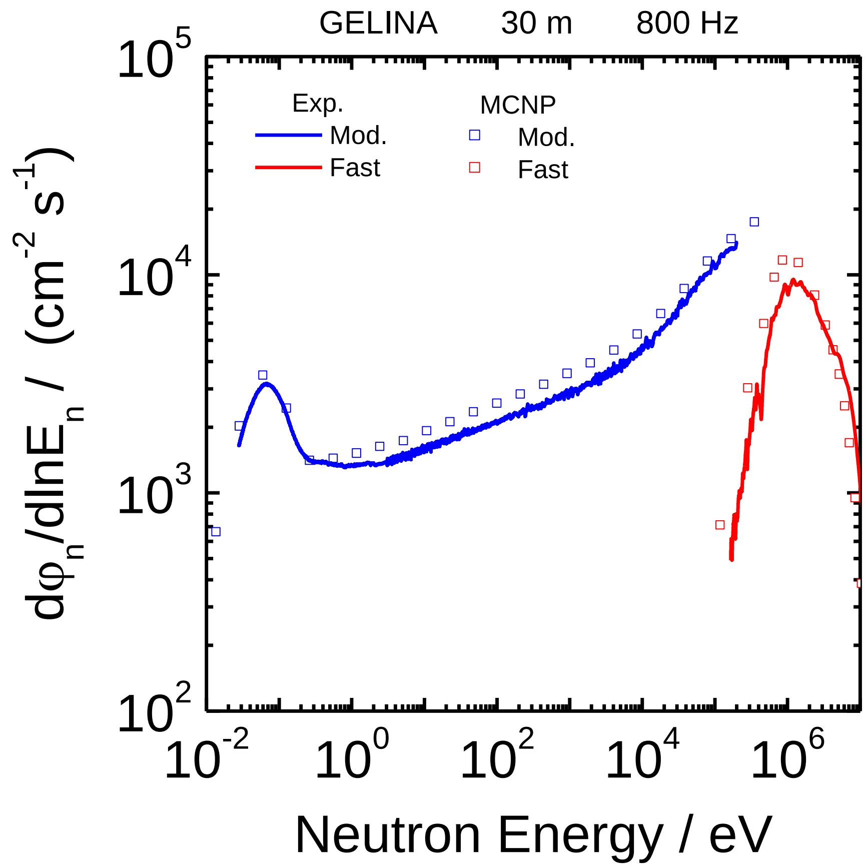
GELINA : neutron production



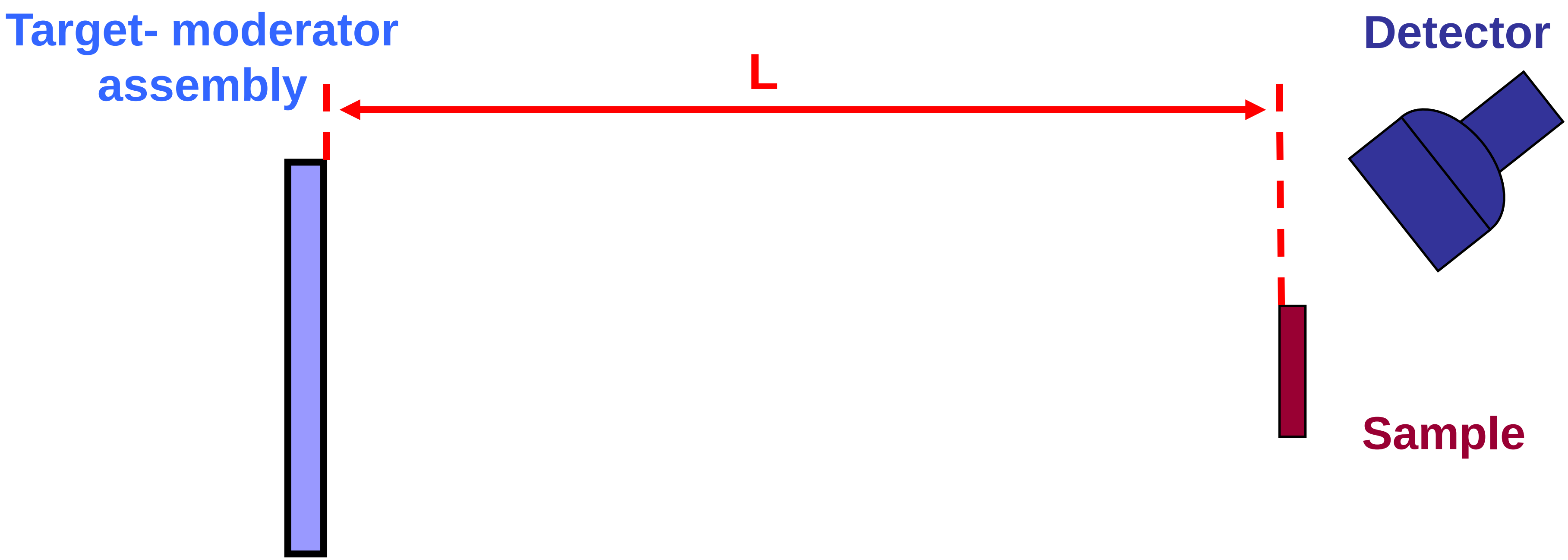
- e^- accelerated to $E_{e-,max} \approx 140$ MeV
- Bremsstrahlung in U-target
  (rotating & cooled with liquid Hg)
- (γ, n), (γ, f) in U-target
- Low energy neutrons by moderation
  (water moderator in Be-canning)

GELINA : neutron production





Time-of-flight technique



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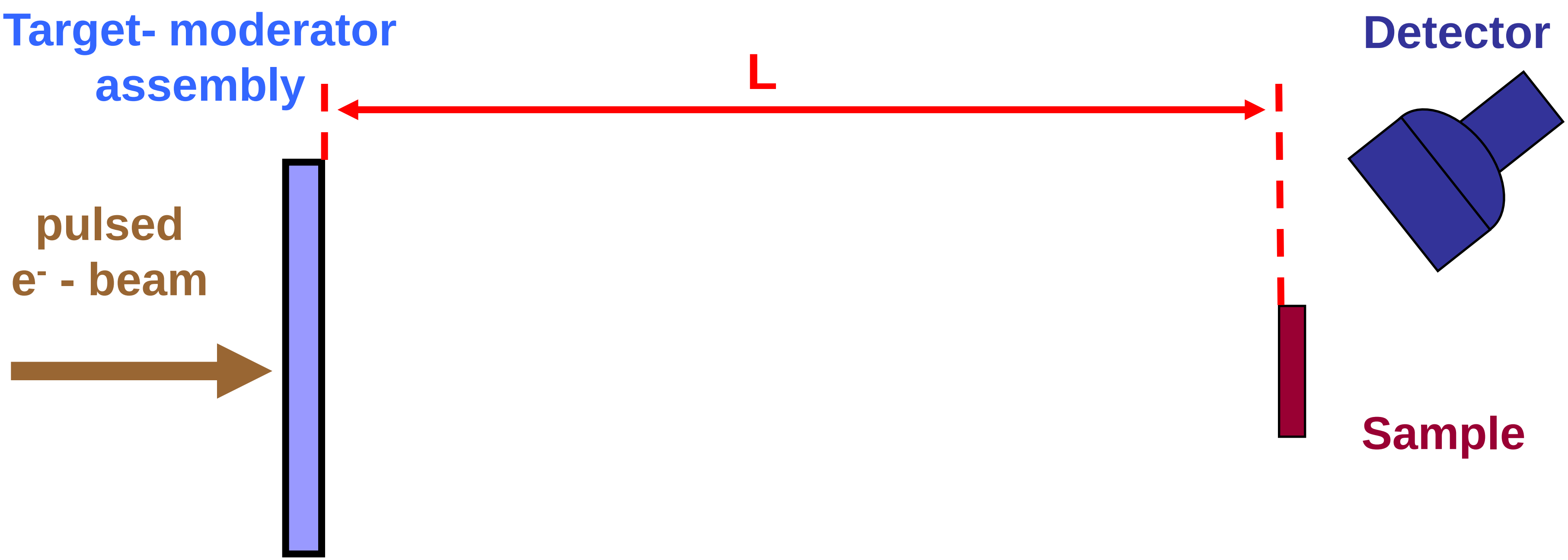

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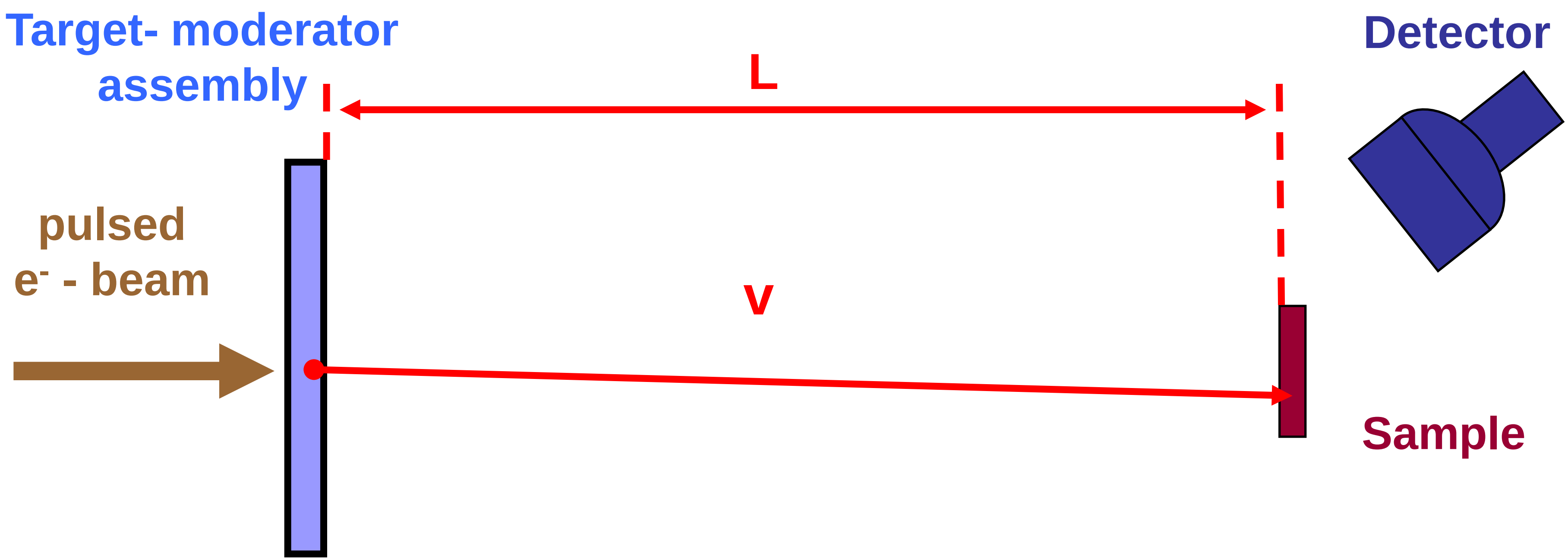

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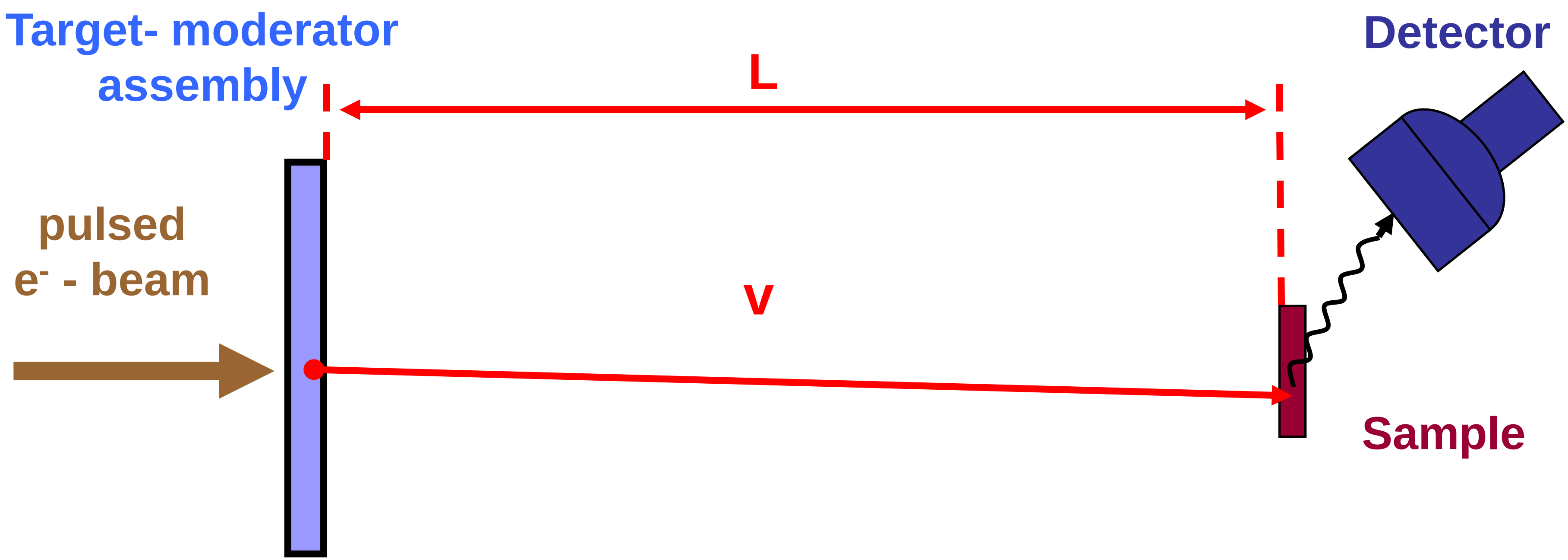

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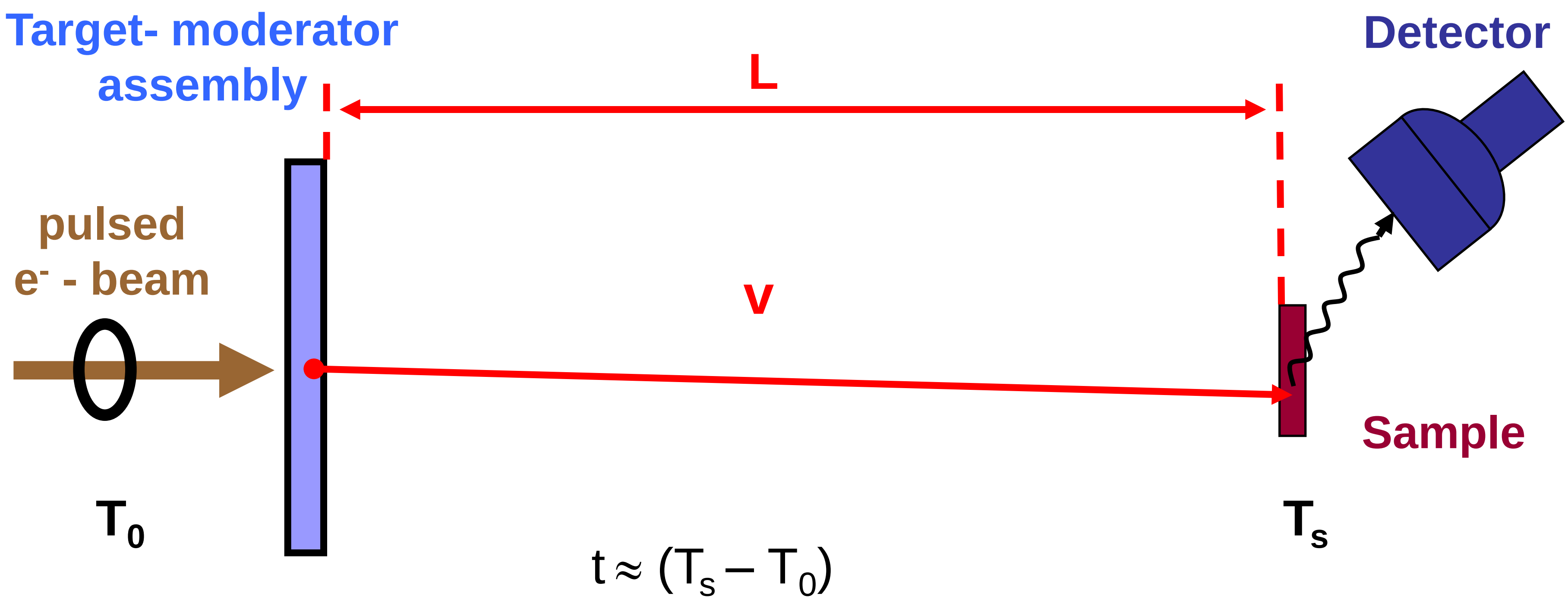
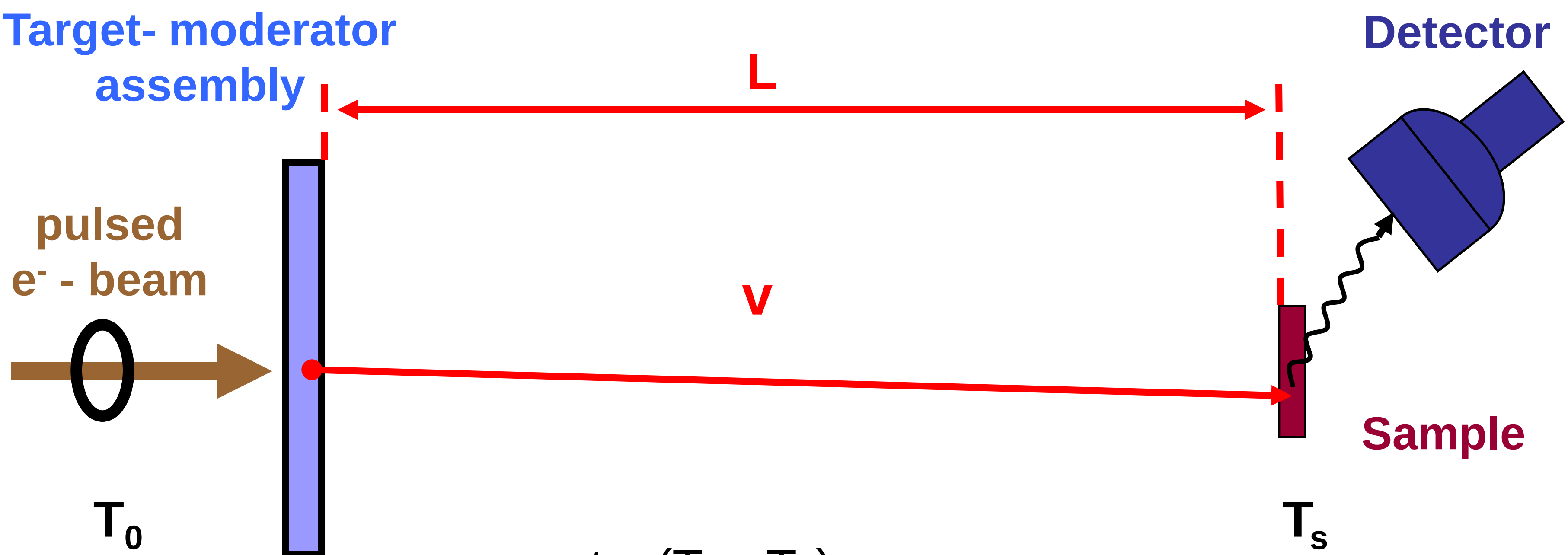


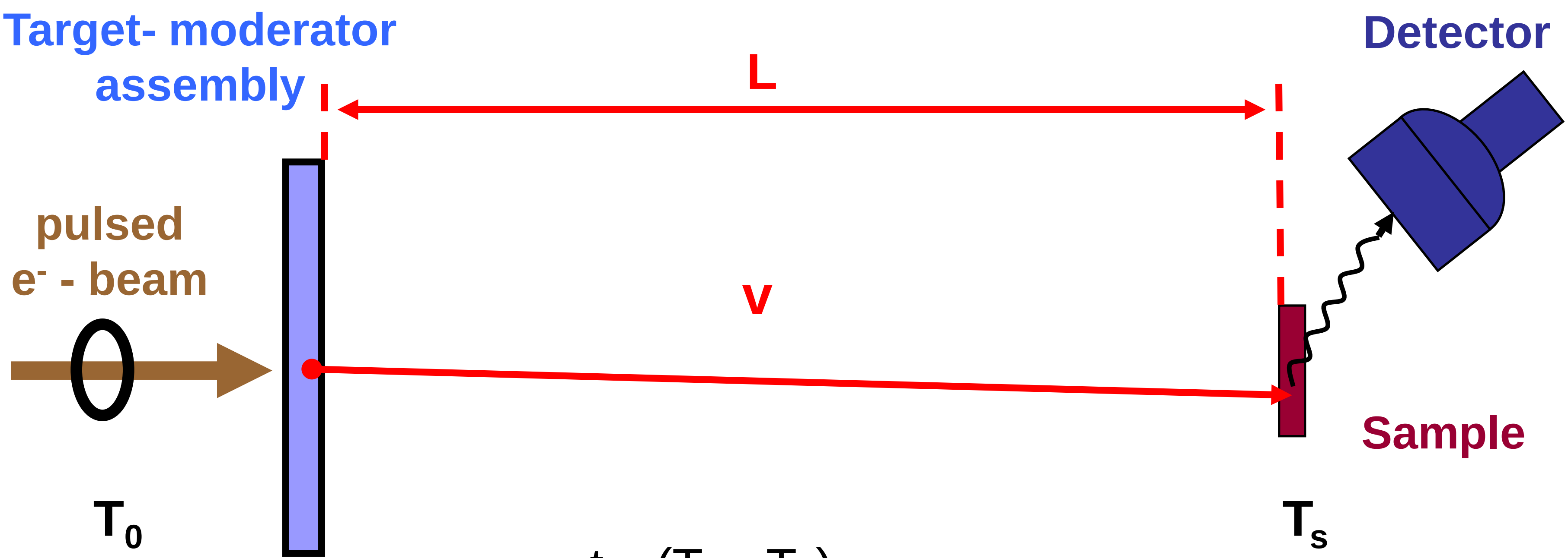
Time-of-flight technique



$$t \approx (T_s - T_0)$$

$$v = \frac{L}{t}$$

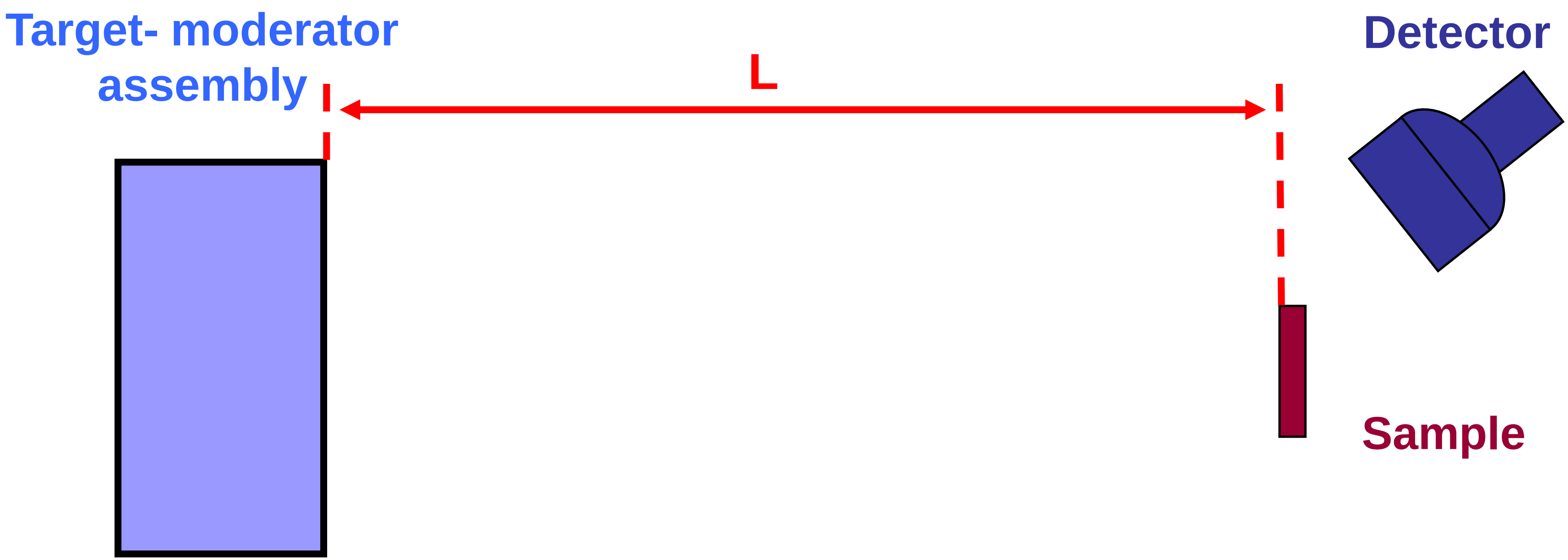
Time-of-flight technique



$$t \approx (T_s - T_0)$$

$$v = \frac{L}{t} \quad \Rightarrow \quad E = mc^2(\gamma - 1) \cong \frac{1}{2}mv^2$$

Time-of-flight technique



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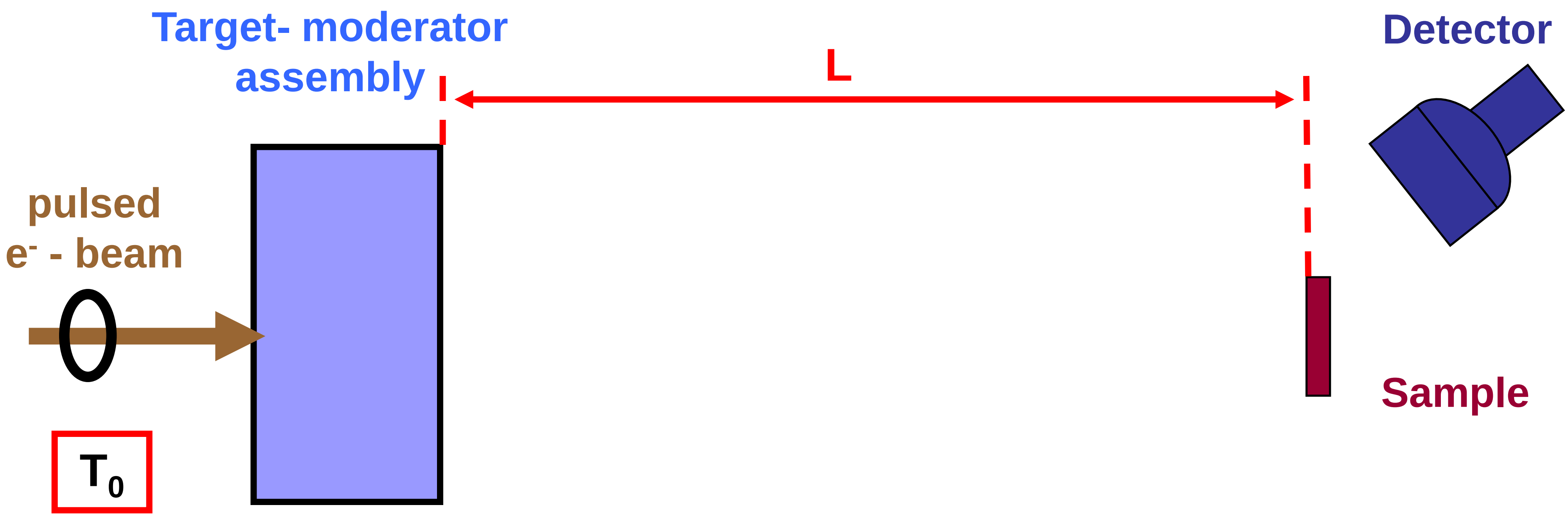

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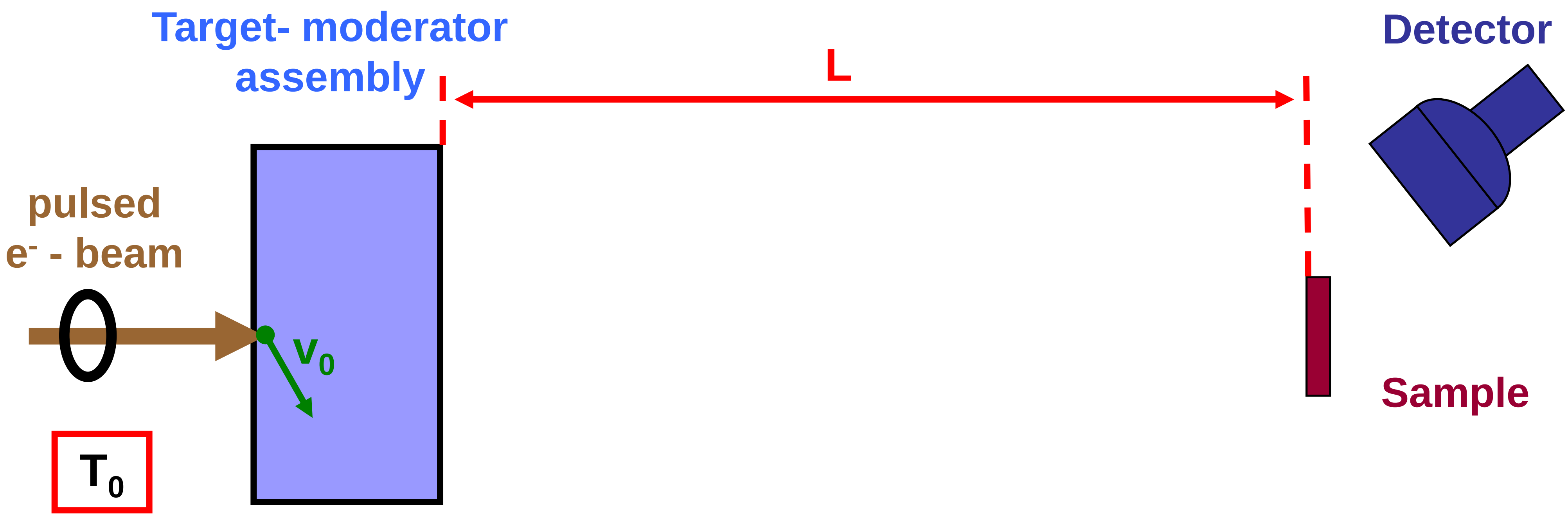
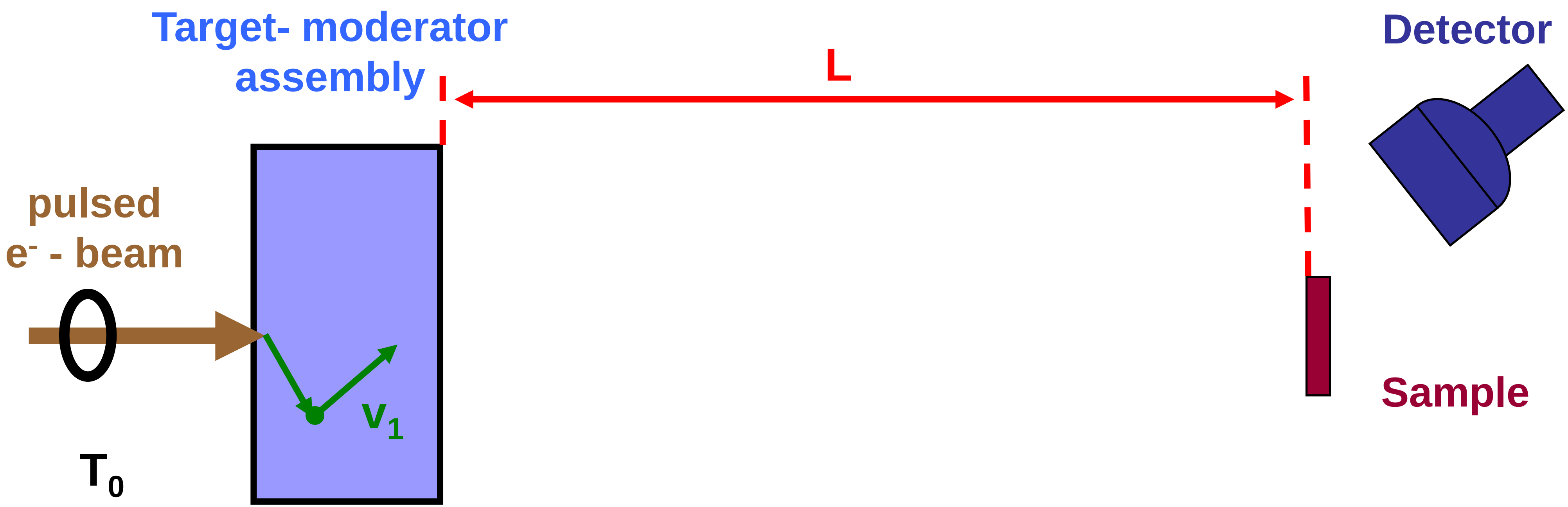


Time-of-flight technique



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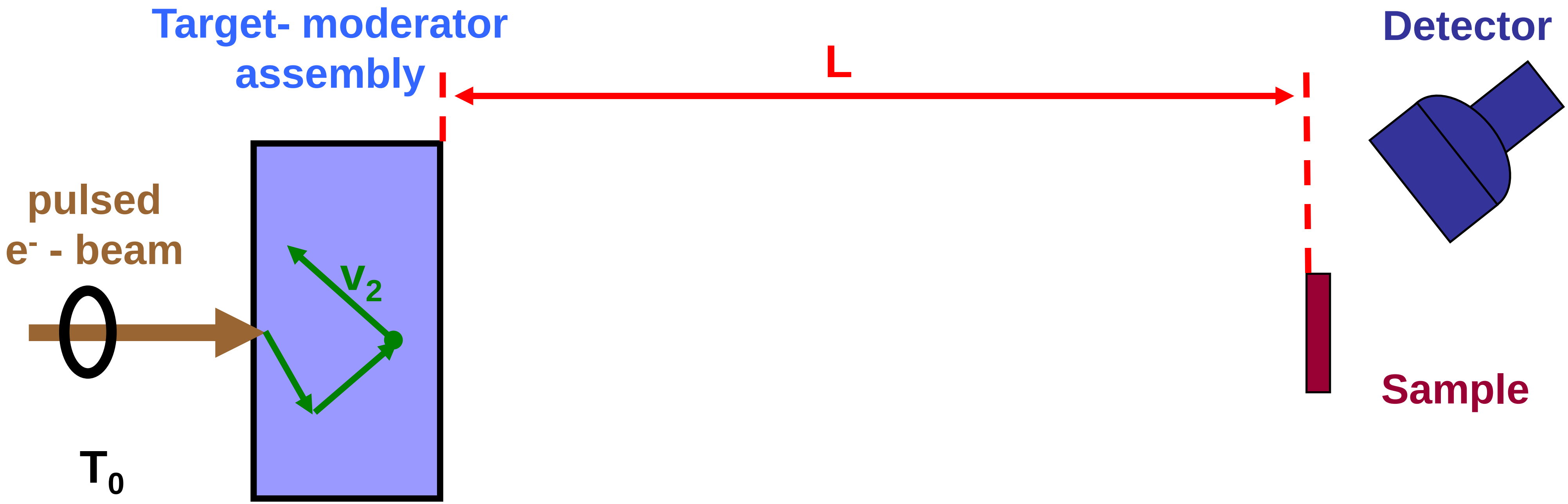

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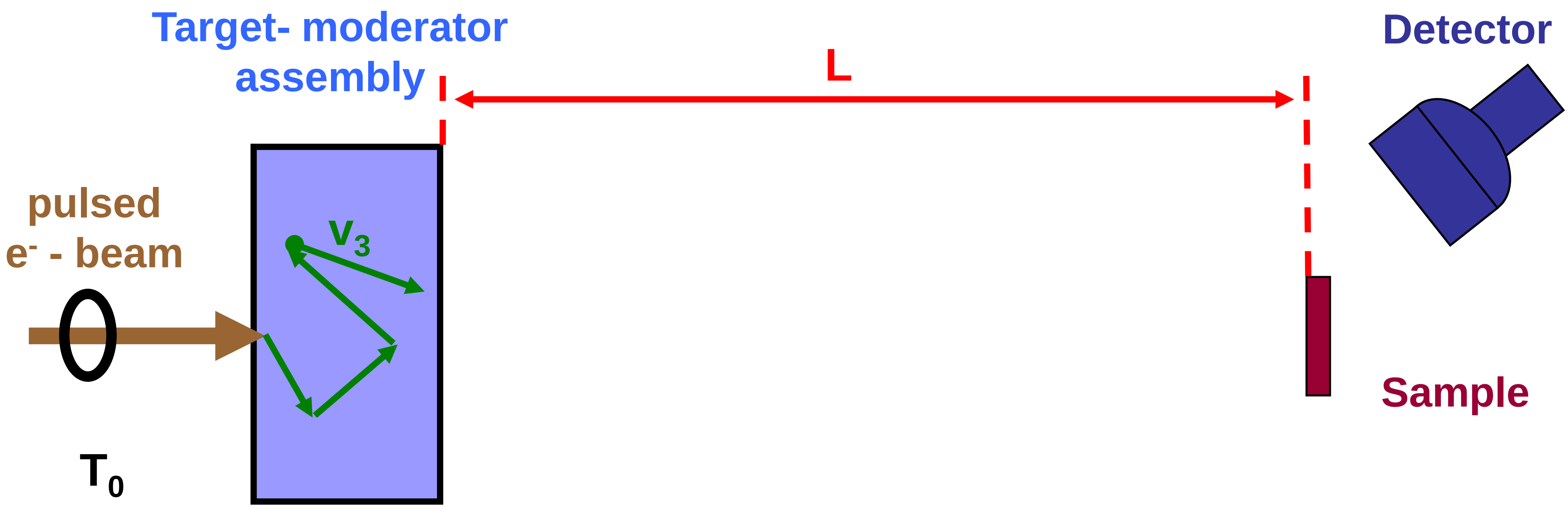

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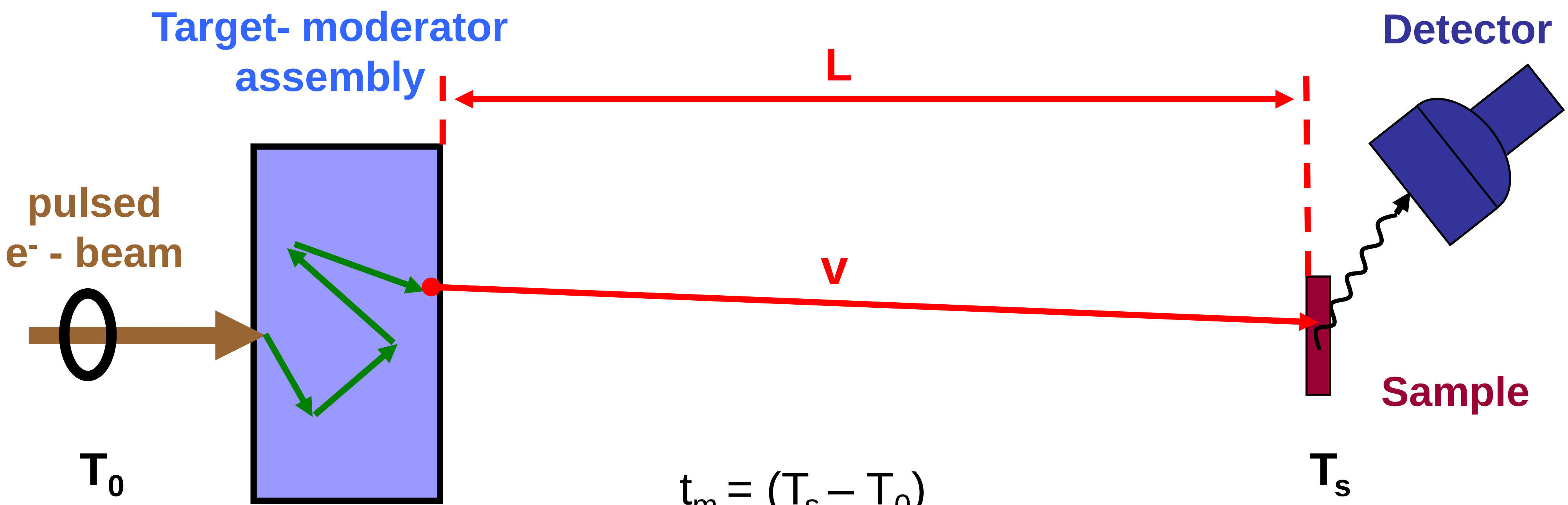
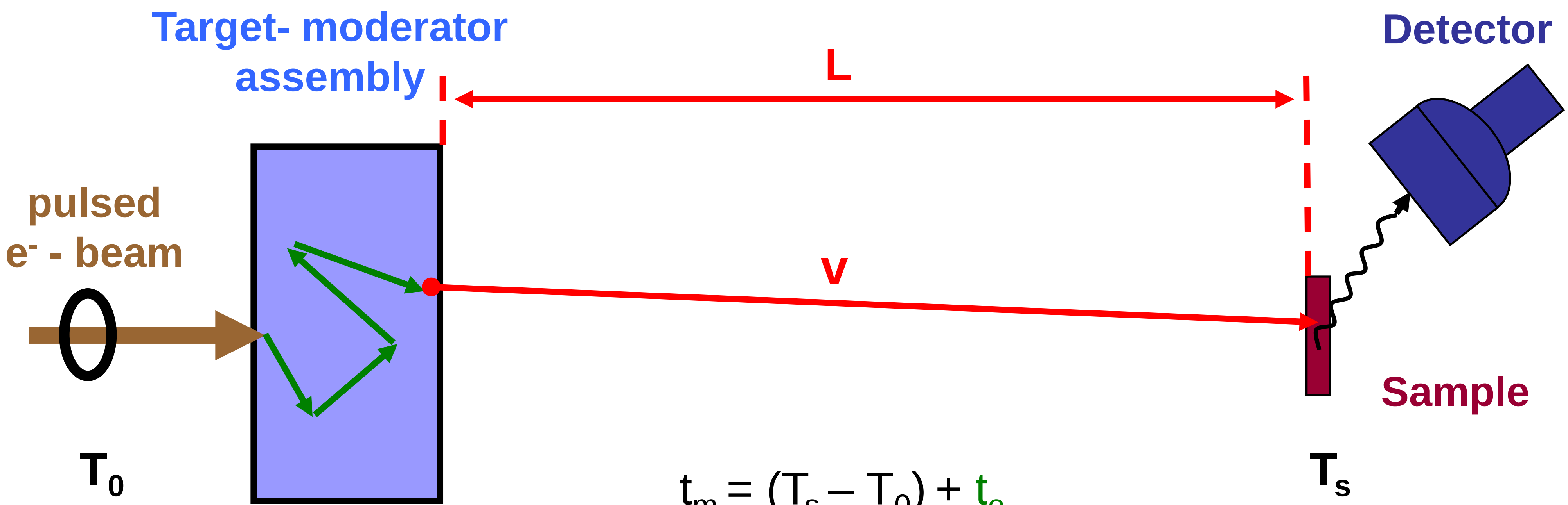


$$t_m = (T_s - T_0)$$

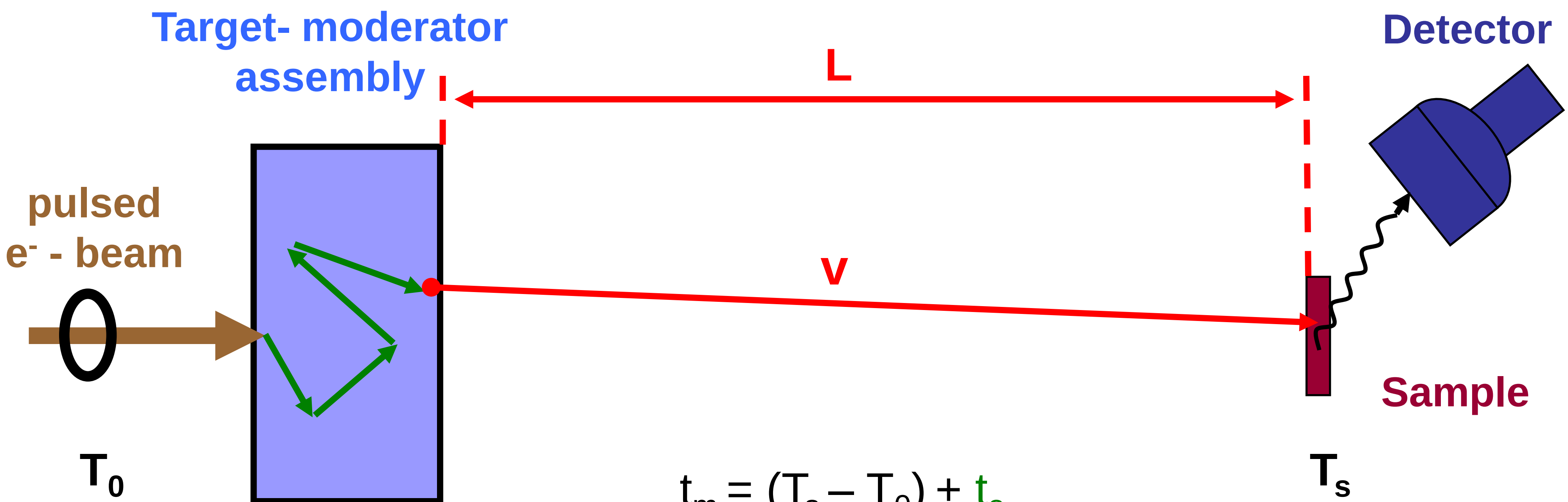
Time-of-flight technique



$$t_m = (T_s - T_0) + t_o$$

t_0 : time-offset

Time-of-flight technique



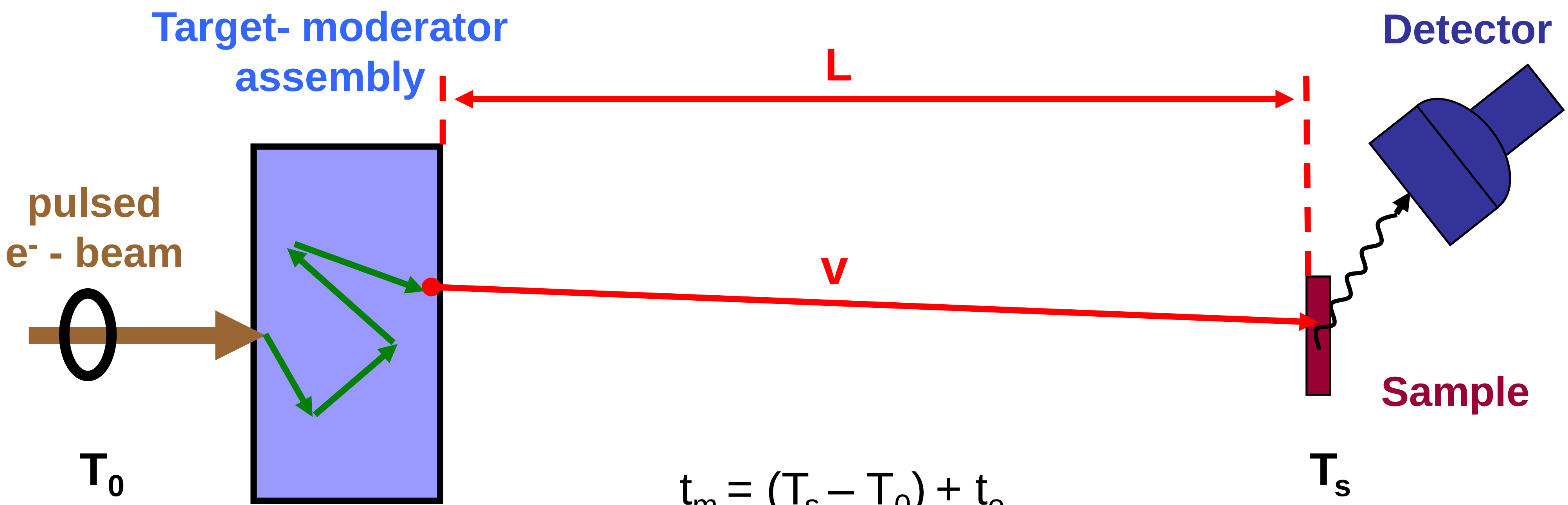
$$t_m = (T_s - T_0) + t_o$$

t_0 : time-offset

determined by γ-flash

$$\frac{L}{c} = (T_s - T_0) + t_0$$

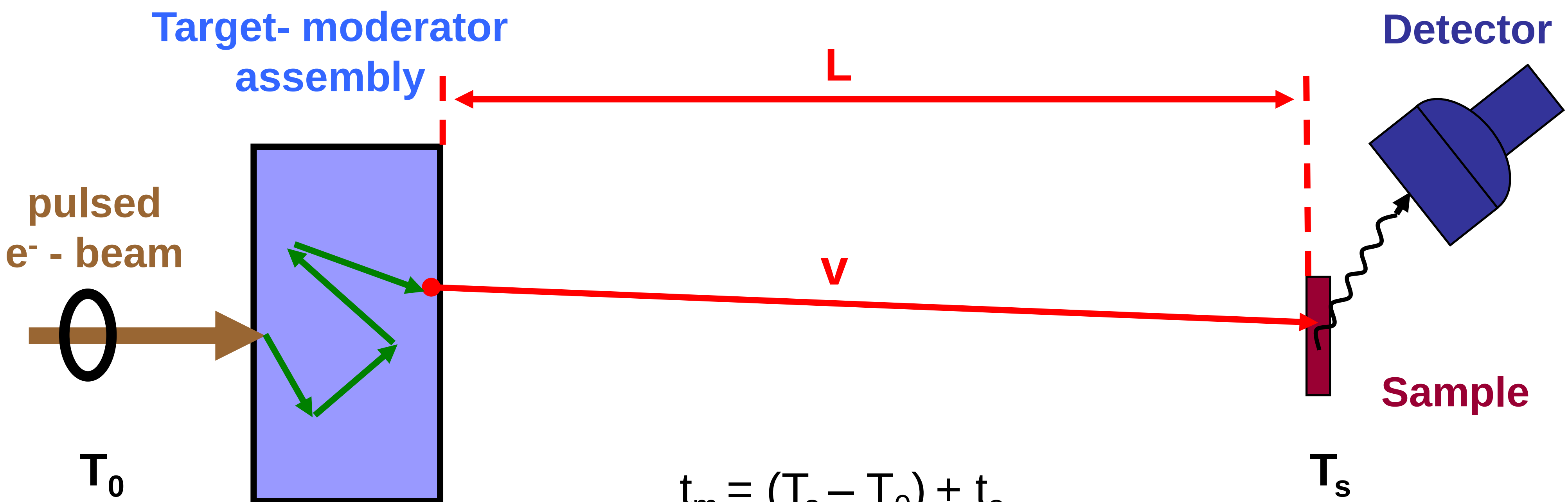
Time-of-flight technique



$$t_m = (T_s - T_0) + t_o$$

$$\boxed{v = \frac{L}{t}}$$

Time-of-flight technique

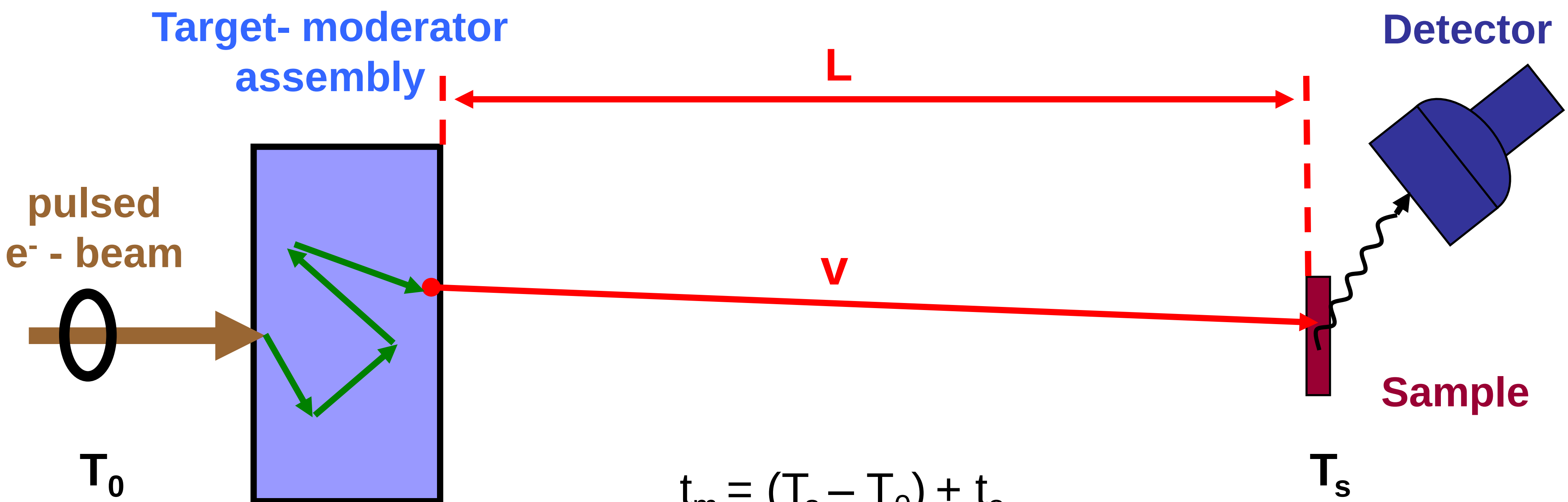


$$t_m = (T_s - T_0) + t_o$$

$$\boxed{t = t_m - (t_t + t_d)}$$

$$\boxed{v = \frac{L}{t}}$$

Time-of-flight technique



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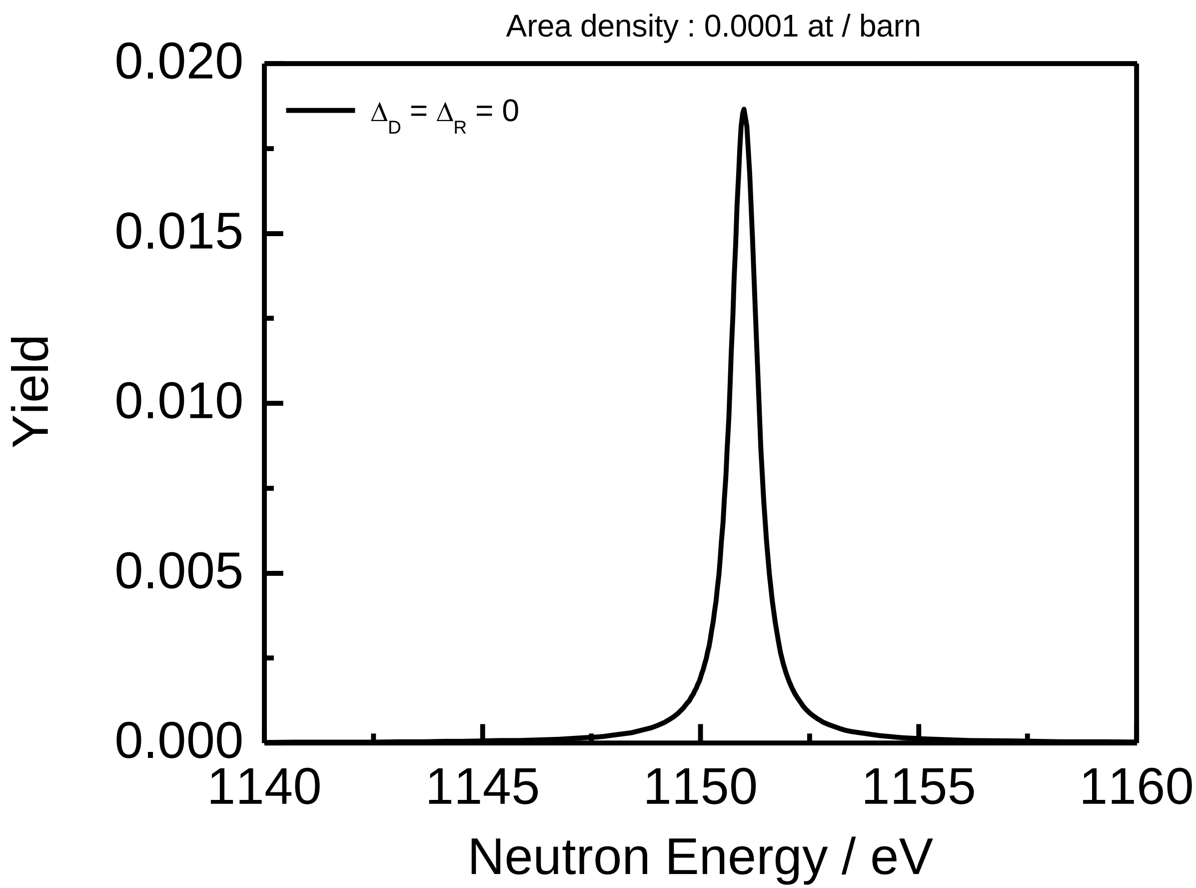
$$\boxed{v = \frac{L}{t}} \quad \Rightarrow \quad E = mc^2(\gamma - 1) \cong \frac{1}{2}mv^2$$

Theoretical capture yield

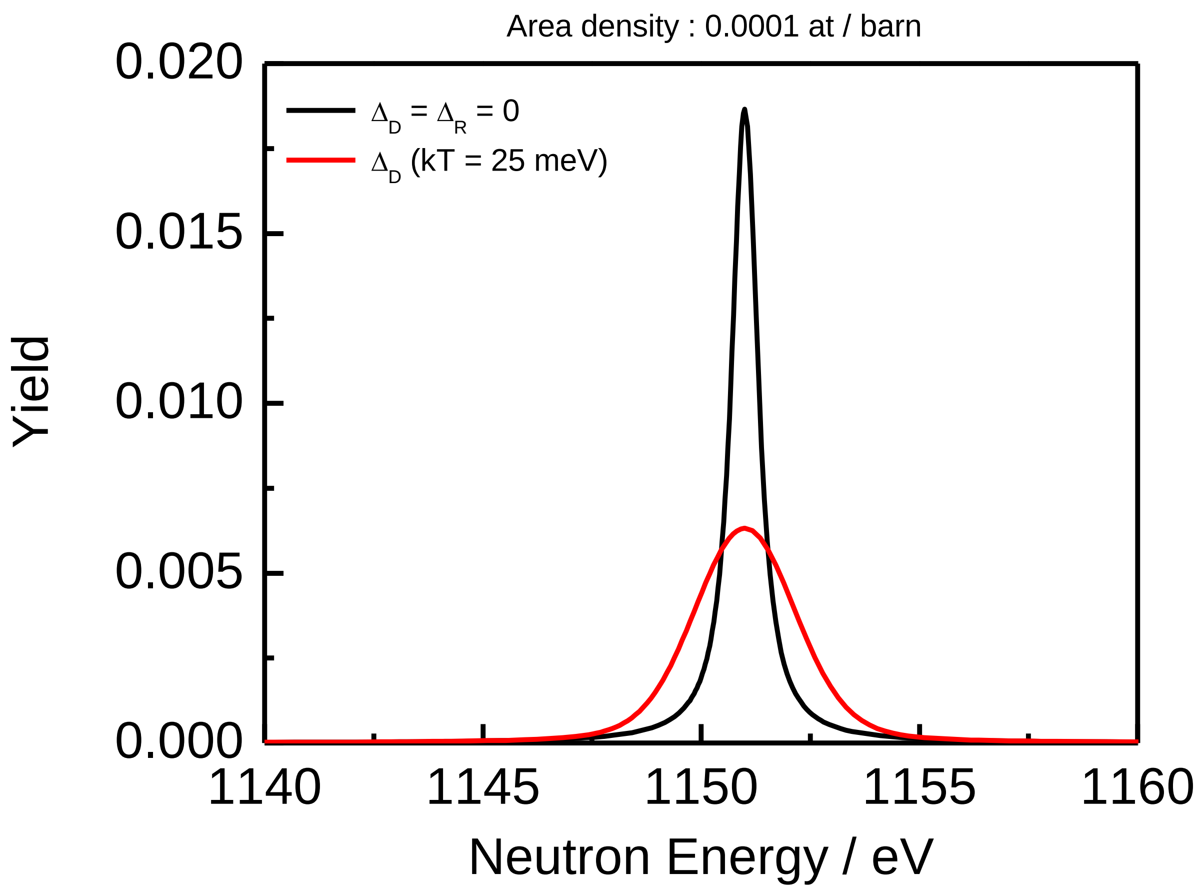
^{65}Fe 1.15 keV resonance

$$Y_\gamma \cong \frac{\sigma_\gamma}{\sigma_{tot}}(1-e^{-n\sigma_{tot}})+\dots$$



+ Doppler

^{65}Fe 1.15 keV resonance



$$Y_\gamma \cong \frac{\bar{\sigma}_\gamma}{\bar{\sigma}_{tot}}\left(1 - e^{-n\bar{\sigma}_{tot}}\right) + \ldots$$

$$\boxed{\bar{\sigma}(E) = \int dE'\, S(E')\, \sigma(E - E')}$$

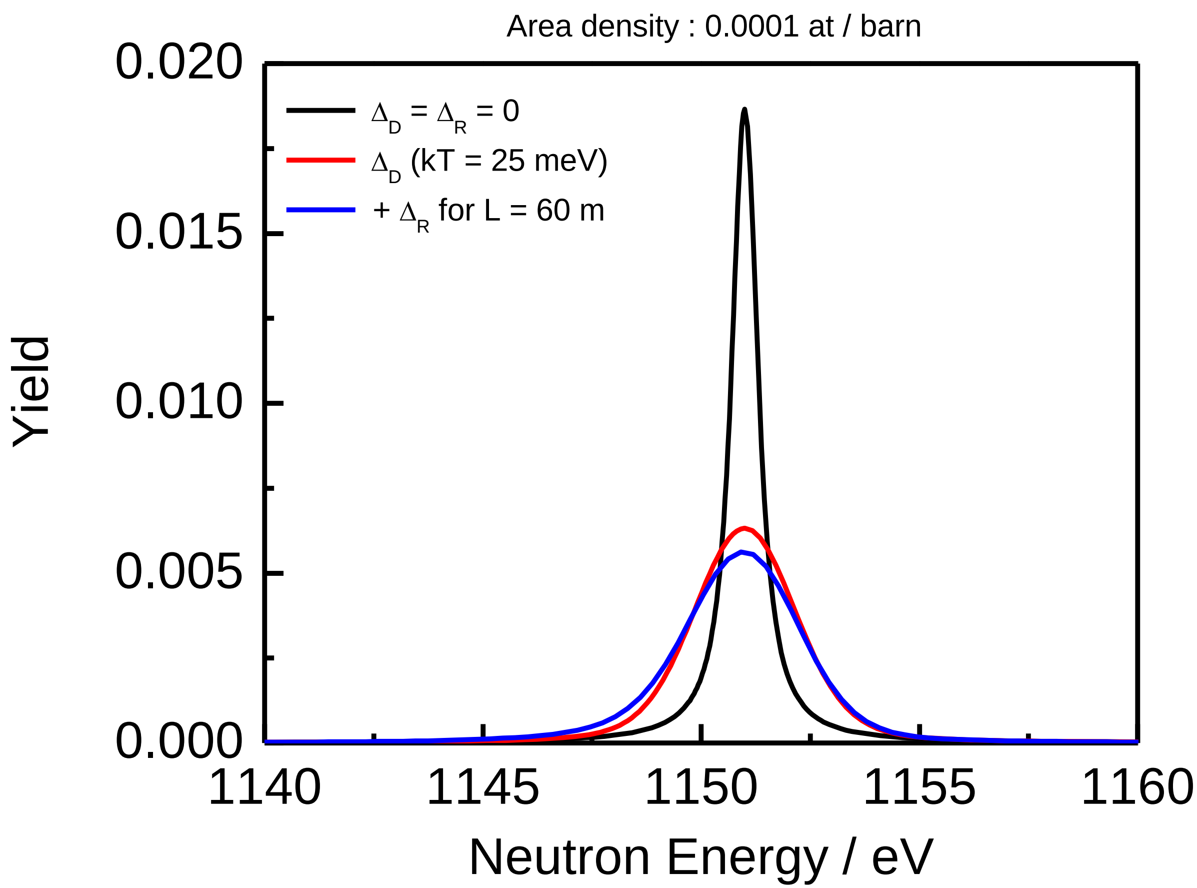
$$\bar{\sigma}(E) \cong \frac{1}{\Delta_D \sqrt{\pi}} \int dE'\, e^{-\left(\frac{E'-E}{\Delta_D}\right)^2} \sqrt{\frac{E'}{E}}\, \sigma(E')$$

$$\Delta_D = \sqrt{\frac{4\, E\, k_B T}{m_X / m_n}}$$

$$\mathrm{FWHM} = 2\sqrt{\ln 2}\, \Delta_D$$

+ Doppler + Response

^{65}Fe 1.15 keV resonance



$$Y_\gamma \cong \frac{\bar{\sigma}_\gamma}{\bar{\sigma}_{tot}}\left(1 - e^{-n\bar{\sigma}_{tot}}\right) + \ldots$$

$$\boxed{\bar{\sigma}(E) = \int dE'\, S(E')\, \sigma(E - E')}$$

$$\boxed{Y_{exp} = \frac{\int R(t,E) Y_\gamma(E) dE}{\int R(t,E) dE}}$$

L = 60 m

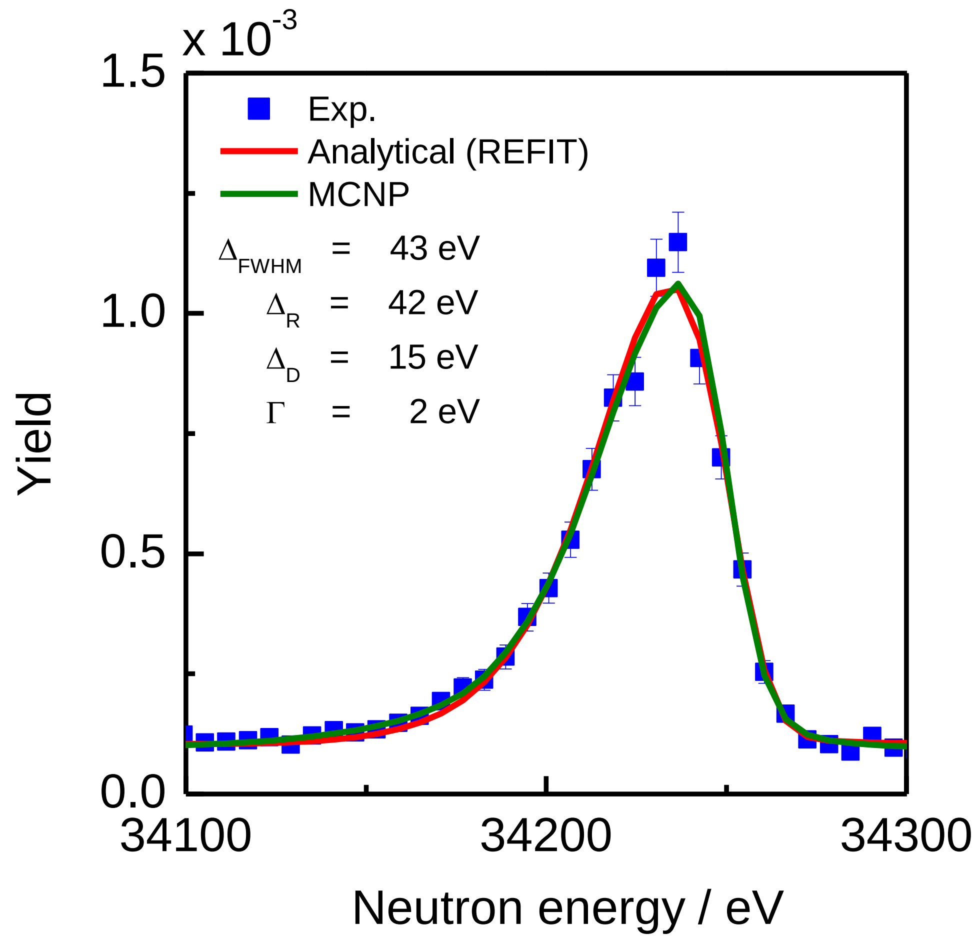
$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

Experimental observable

$$\Delta_{FWHM} = \sqrt{\Gamma^2 + \Delta_D{}^2 + \Delta_R{}^2}$$

with

- Γ **Total resonance width**
- Δ_R **Experimental resolution**
- Δ_D **Doppler broadening**



Experimental observable

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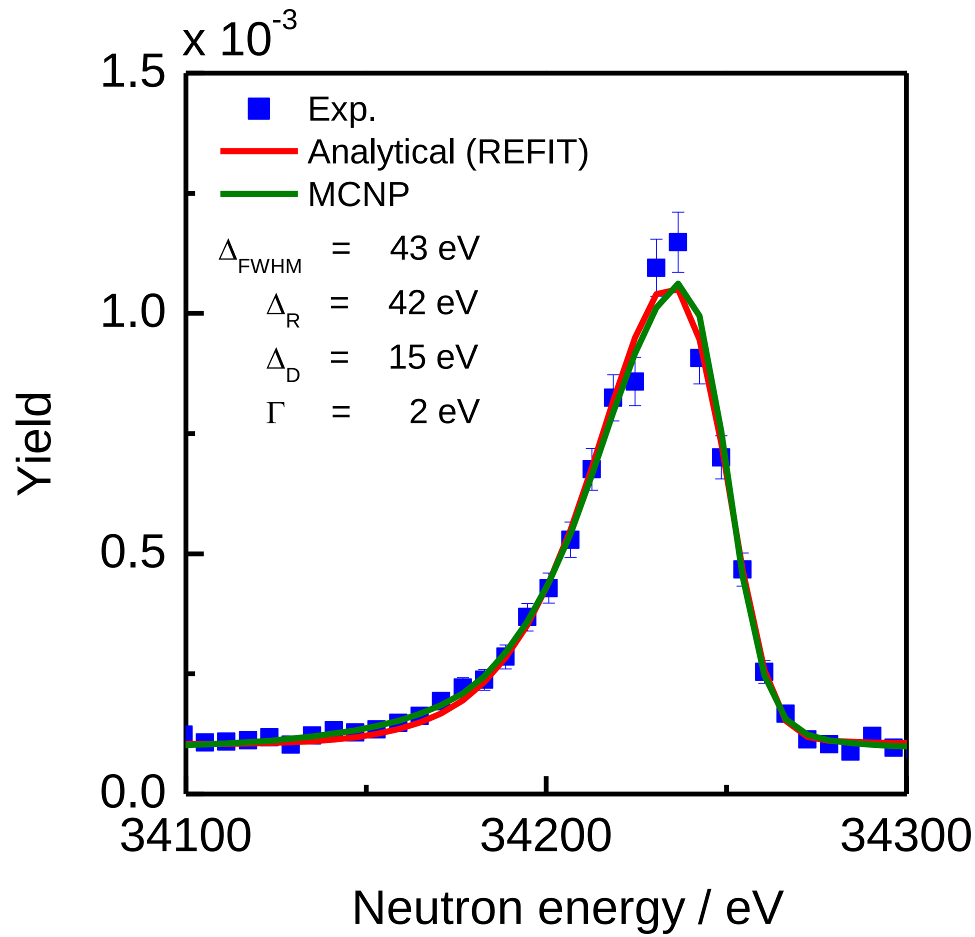
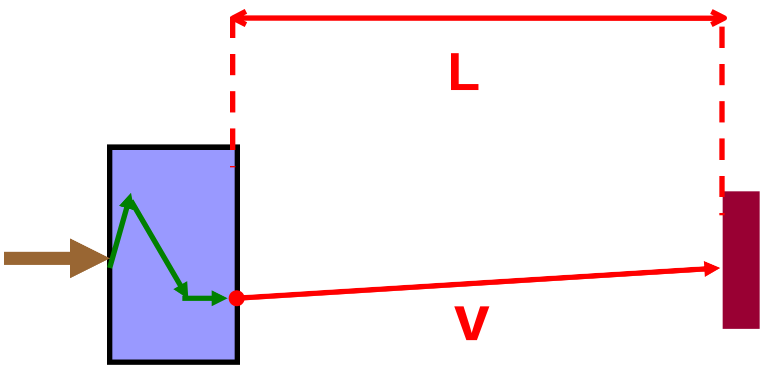


Time-of-flight technique: experimental resolution

$$v = \frac{L}{t}$$

$$t = (T_s - T_0) + t_o - (t_t + t_d)$$



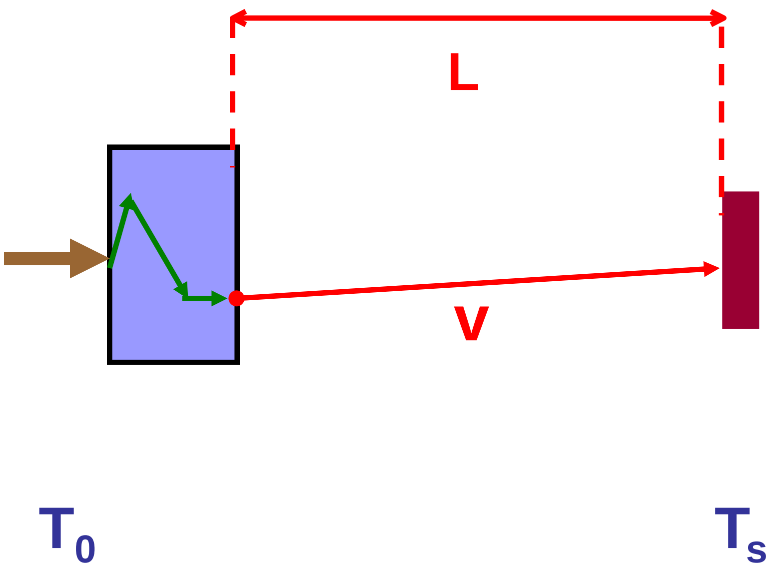
T_0 T_s

Time-of-flight technique: experimental resolution

$$v = \frac{L}{t}$$

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}}$$

$$t = (T_s - T_0) + t_o - (t_t + t_d)$$



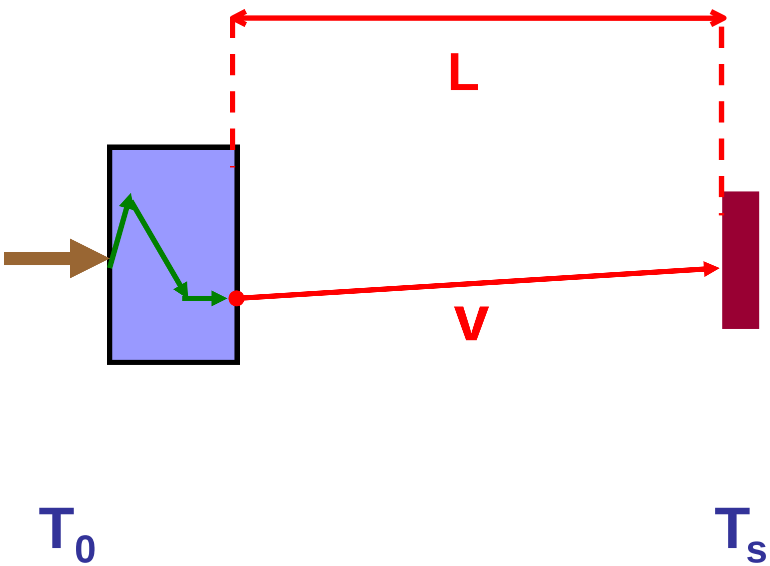
Time-of-flight technique: experimental resolution

$$v = \frac{L}{t} \quad \Rightarrow \quad E = mc^2(\gamma - 1) \quad \cong \frac{1}{2}mv^2$$

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}}$$

$$\frac{\Delta E}{E} = (1+\gamma)\gamma\frac{\Delta v}{v} \cong 2\frac{\Delta v}{v}$$

$$\color{red}{t} = (T_s - T_0) + t_o - (\, t_t + t_d\,)$$



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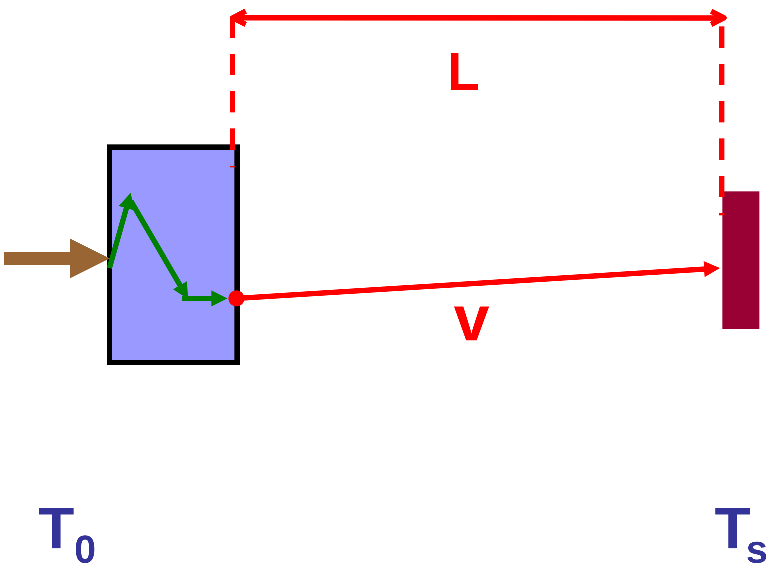

Time-of-flight technique: experimental resolution

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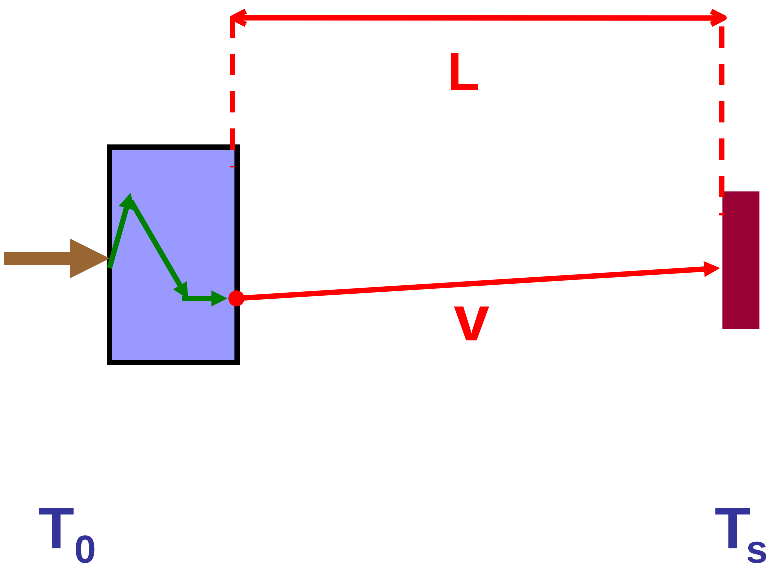

- **ΔL (~1 mm)**
- **Δt**
  - **Initial burst** ΔT_0
  - **Time resolution detector & electronics** ΔT_s
  - **Neutron transport in target - moderator** Δt_t
  - **Neutron transport in detector** Δt_d

Time-of-flight technique: experimental resolution

$$t = (T_s - T_0) + t_o - (t_t + t_d)$$

- Δt
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Time-of-flight technique: experimental resolution

$$t = (T_s - T_0) + t_o - (t_t + t_d)$$

- Δt
  - Initial burst ΔT_0
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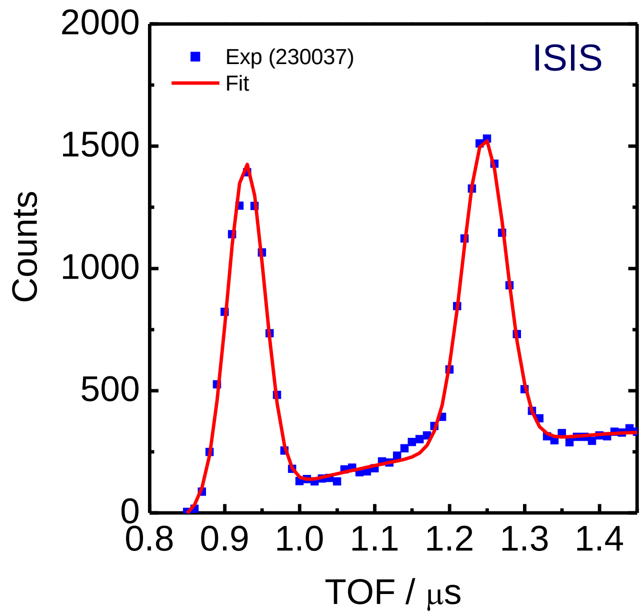
  - Neutron transport in target - moderator Δt_t
  - Neutron transport in detector Δt_d

Resolution: initial burst (T_0)

- **Single burst : mostly normal (Gaussian) distribution**
  - **GELINA : ΔT_0 = 2 ns (FWHM)**
  - **ORELA : ΔT_0 = 4 ns (FWHM)**
  - **nTOF : ΔT_0 = 8 ns (FWHM)**

- **Double pulse structure :**
  - **ISIS**
  - **J-PARC**



Gaussian response

- $P_2 - P_1$ = 318 ns
- FWHM = 60 n

Time-of-flight technique: experimental resolution

$$t = (T_s - T_0) + t_o - (t_t + t_d)$$

- Δt
  - Initial burst ΔT_0
  - Time resolution detector & electronics ΔT_s
  - Neutron transport in target - moderator Δt_t
  - Neutron transport in detector Δt_d

Resolution: detector & electronics (T_s)

- **Mostly supposed to be normal (Gaussian) distributed**
  Strongly depends on detector type

  e.g.

  •C_6D_6 liquid scintillator < 1 ns

  •Li-glass scintillator < 1ns

  •Frisch-grid ionisation chamber ~ 20 ns

  •Ge-detector (with RTP) ~ 10 ns

- **Mostly response of (T_s - T_0) lumped in one normal distribution**

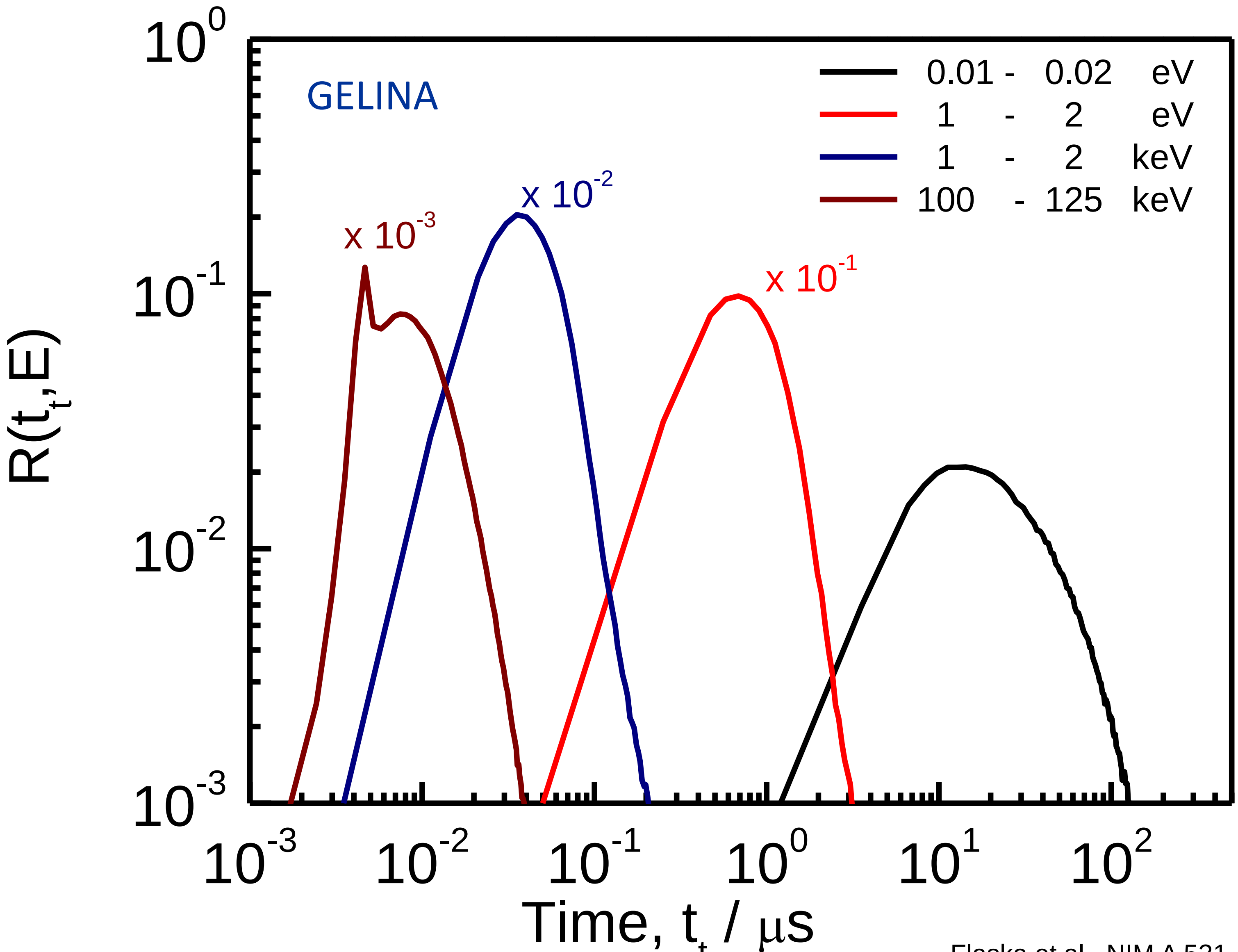
Time-of-flight technique: experimental resolution

$$t = (T_s - T_0) + t_o - (t_t + t_d)$$

- Δt
  - Initial burst ΔT_0
  - Time resolution detector & electronics ΔT_s
  - Neutron transport in target - moderator Δt_t
  - Neutron transport in detector Δt_d

Resolution: Probability distribution of t_t

Response function



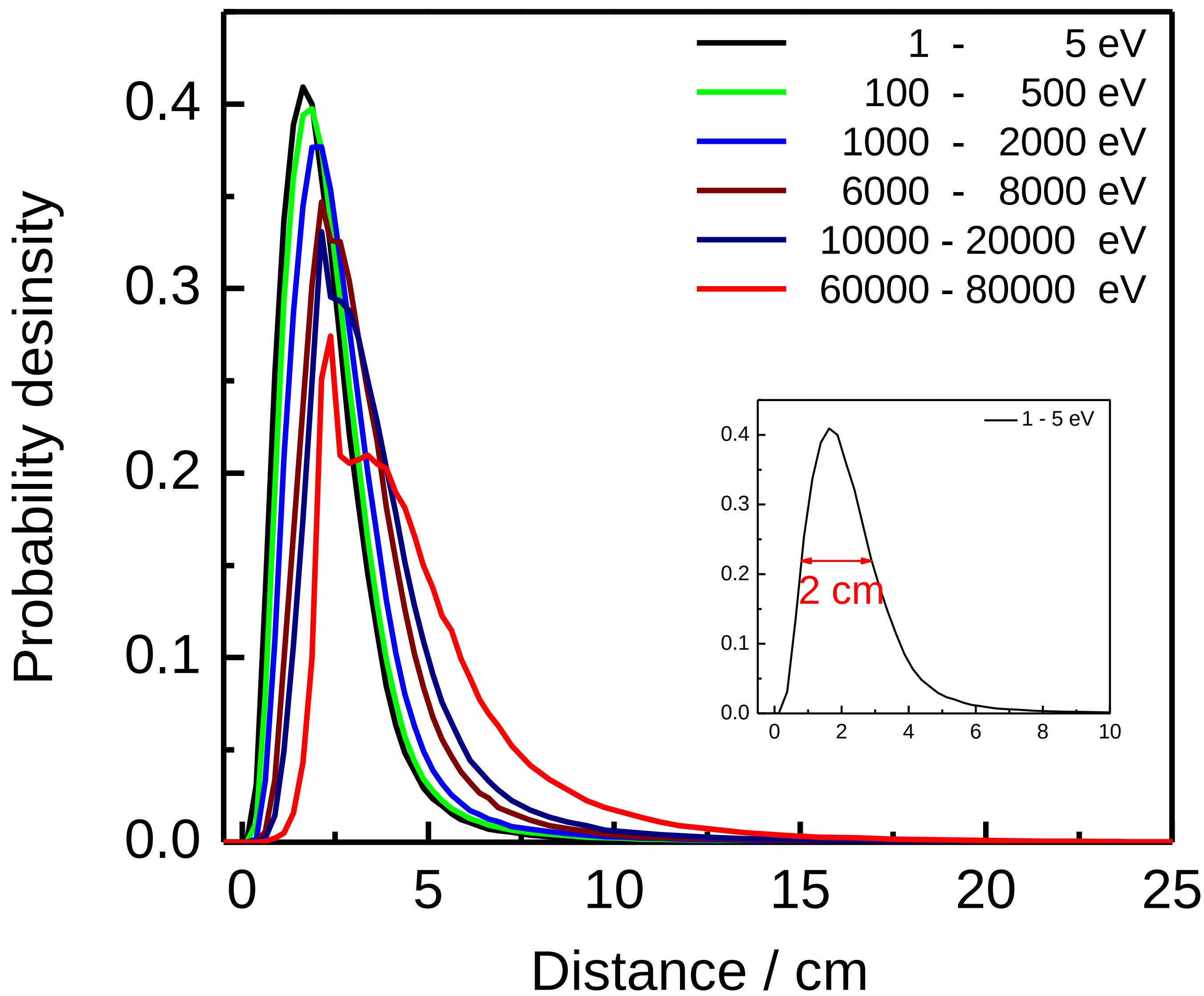
Flaska et al., NIM A 531, 394 (2004)

Equivalent distance : $L_t = v\, t_t$

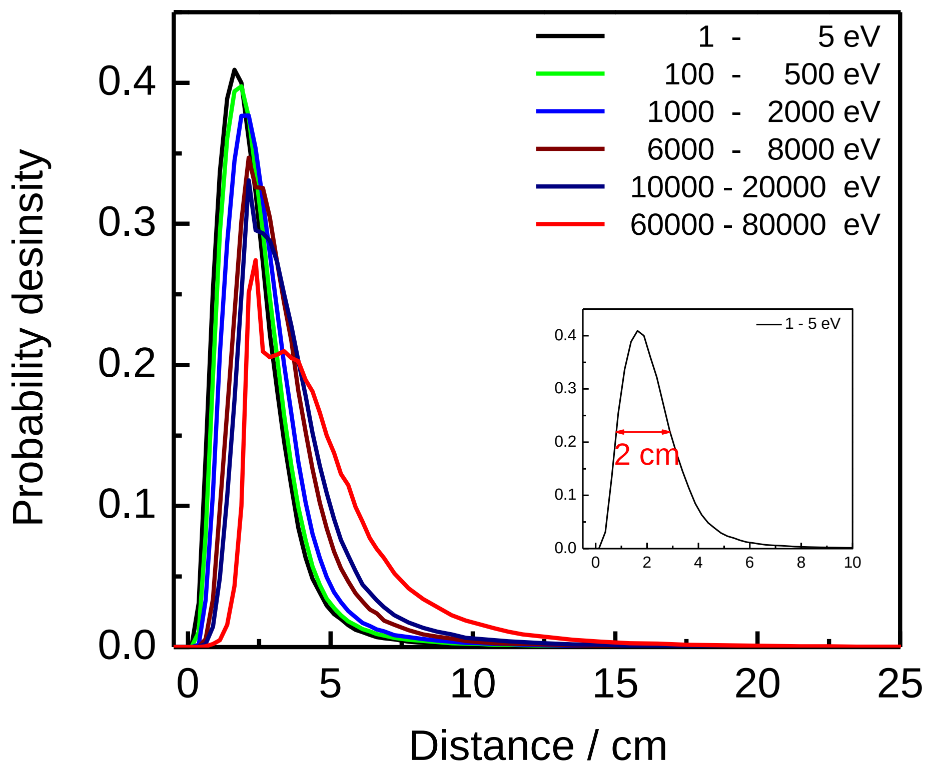
$$\boxed{P(t_t, E_n) = P'(L_t(t_t), E_n)\left|\frac{dL_t}{dt_t}\right|}$$

Equivalent distance : $L_t = v\, t_t$

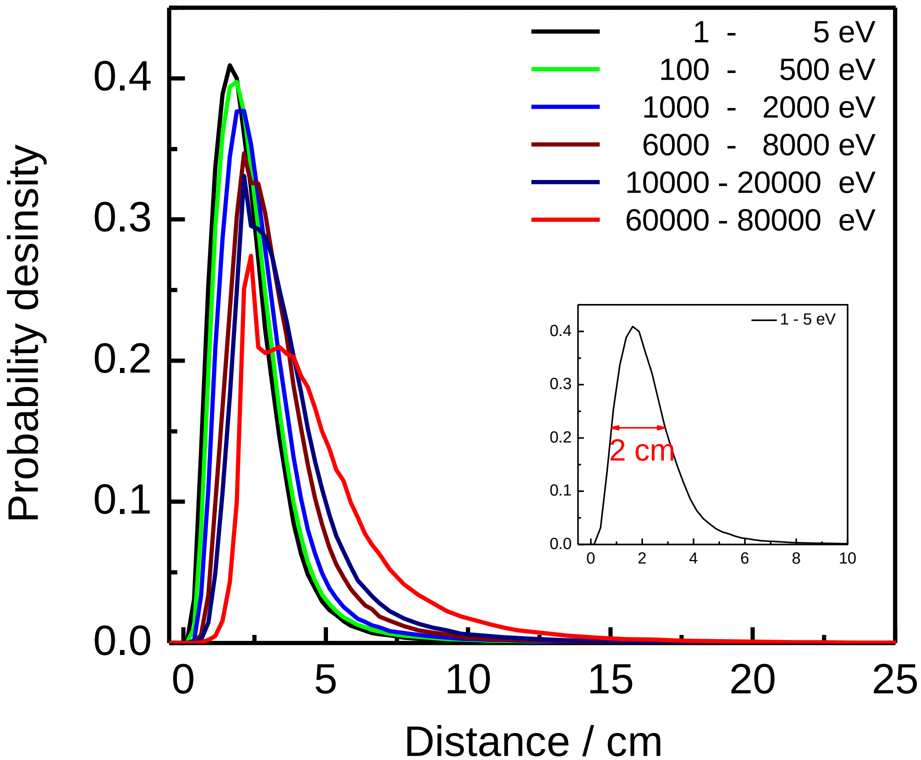
$$P(t_t, E_n) = P'(L_t(t_t), E_n)\left|\frac{dL_t}{dt_t}\right|$$

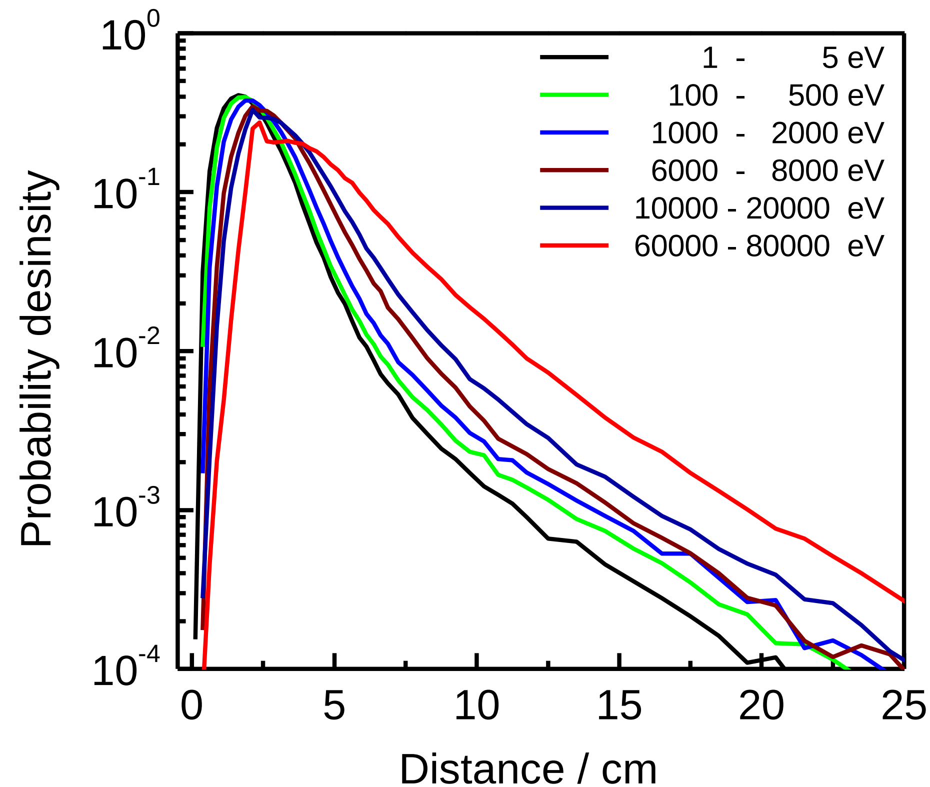


TOF response function $R(L_t,E_n)$



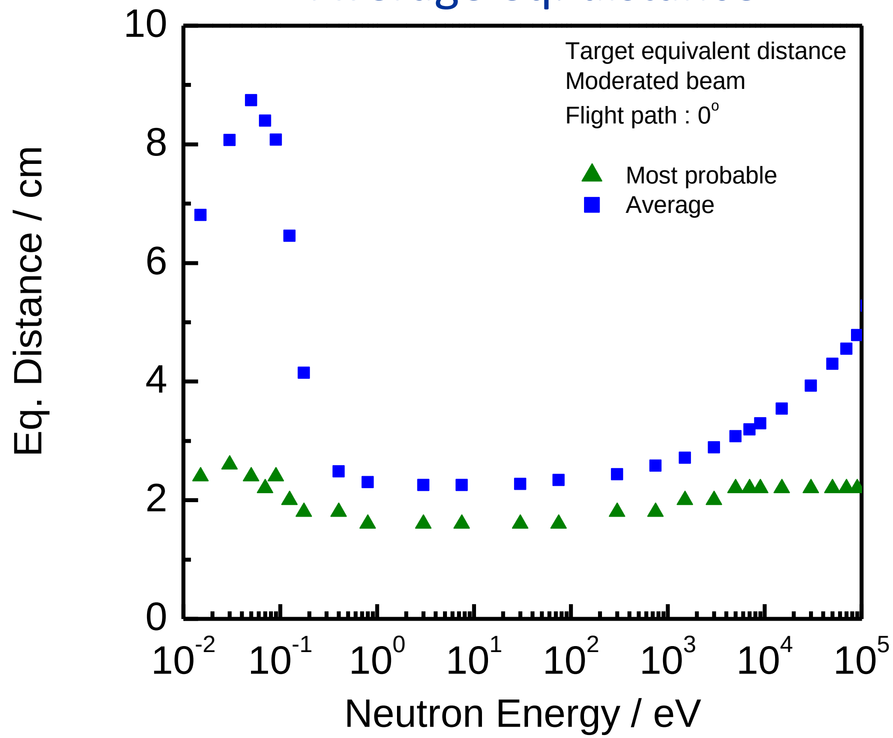
TOF response function $R(L_t,E_n)$



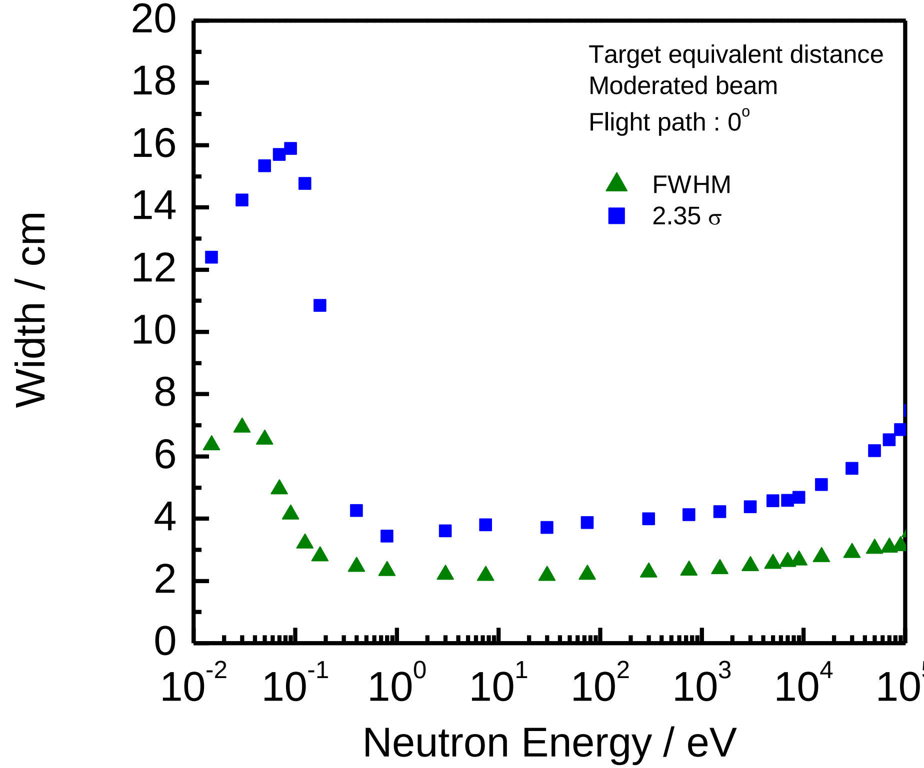


TOF response function: characteristics

Average eq. distance



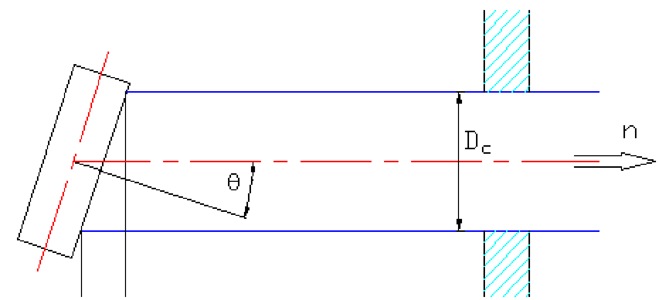
Resolution function



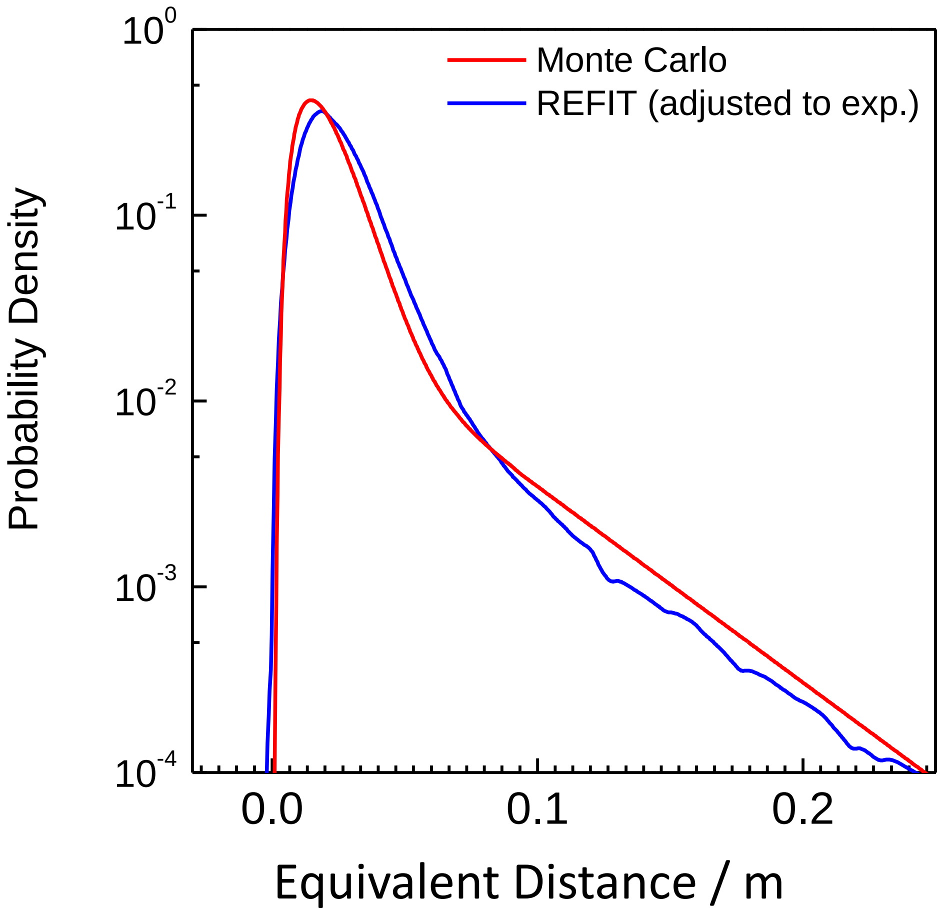
Neutron production & transport: analytical

Different components (analytical approach)

- Neutron production
  - Exponential decay
- Neutron moderation
  - χ^2 - distribution + Storage term (Ikeda & Carpenter)
  - Cole and Windsor function (applied at JPARC)
- Neutron emission : direction flight path with respect to moderator



Neutron production & transport: analytical

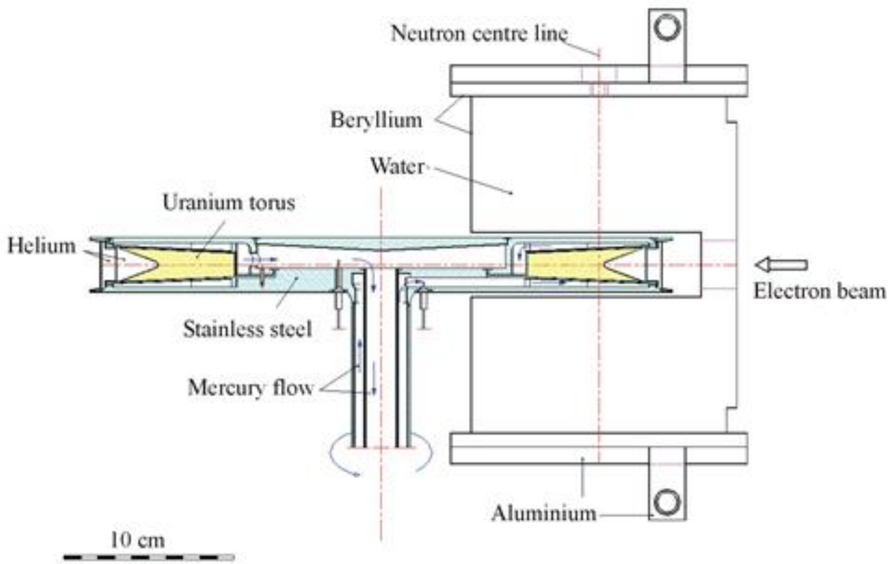


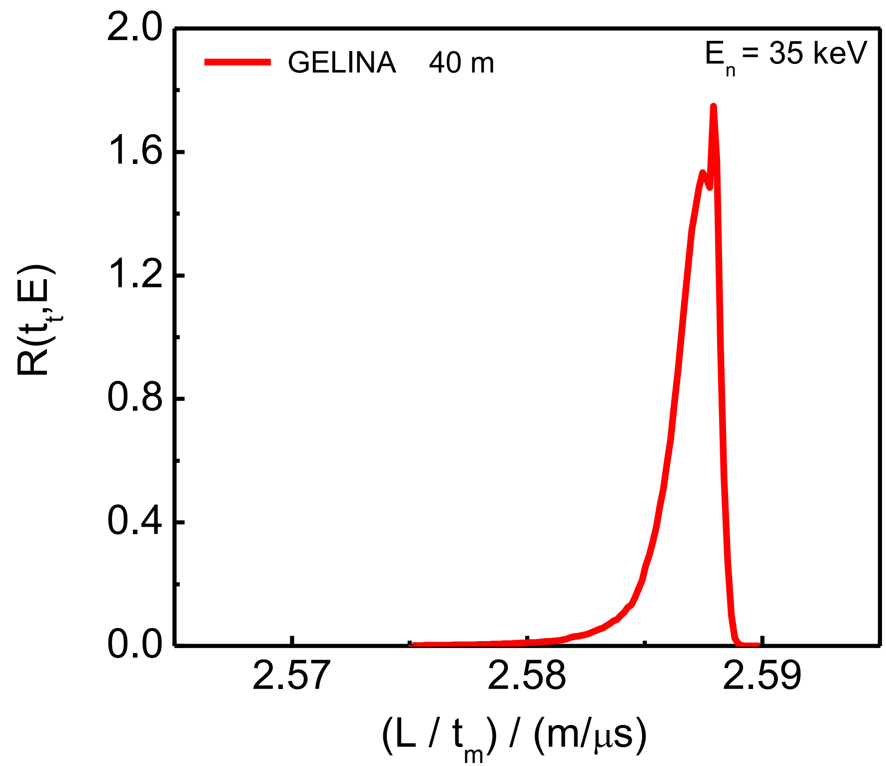
Analytical approximation

- Below 0.5 eV : χ^2 + storage
- Between 0.5 eV and 1000 eV:

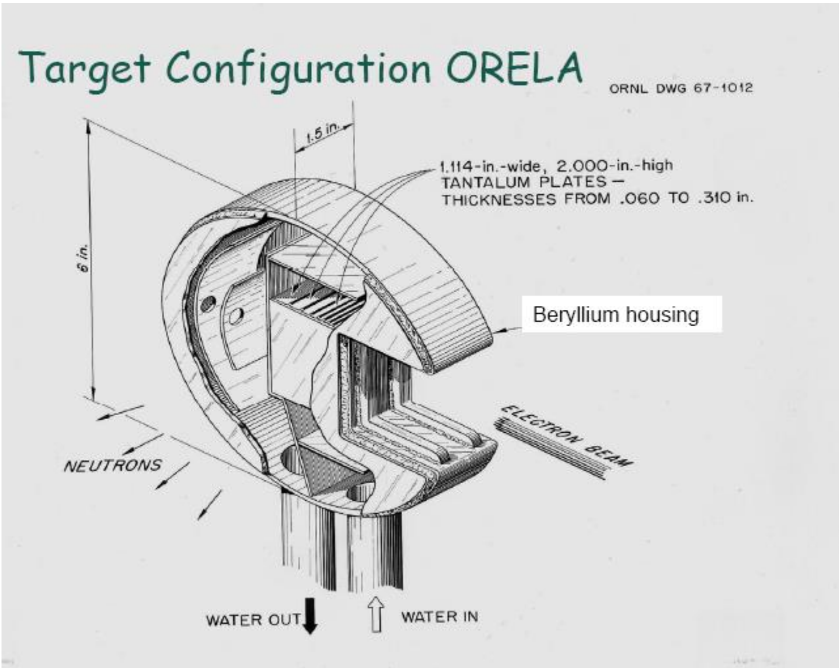
  dominated by χ^2 due to moderation process and almost independent of E_n
- Above 1000 keV : more complex

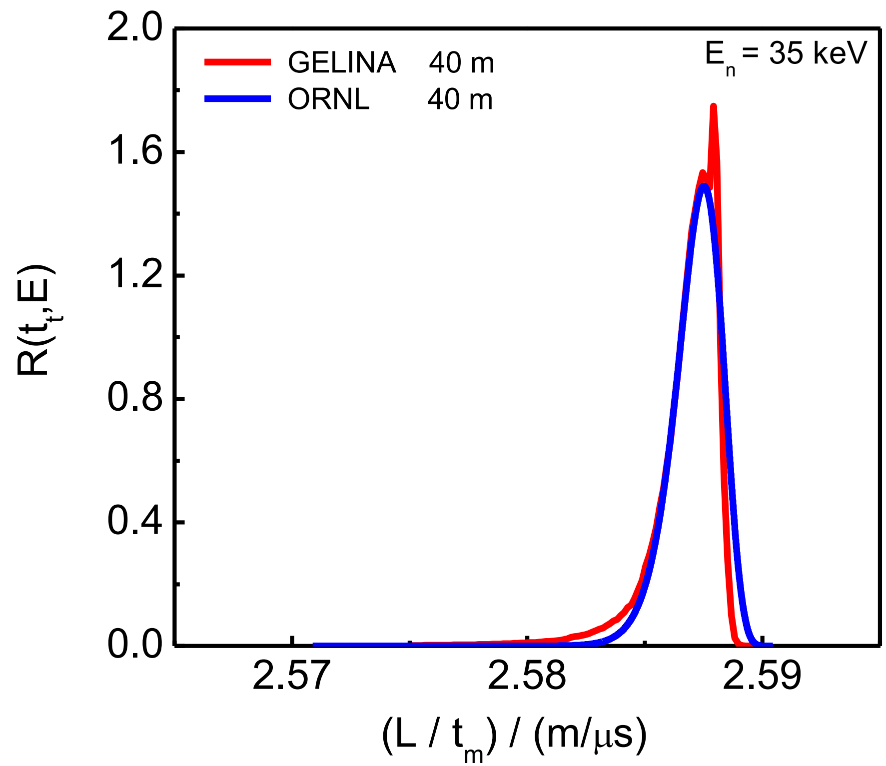
$P(t_t, E)$: photonuclear



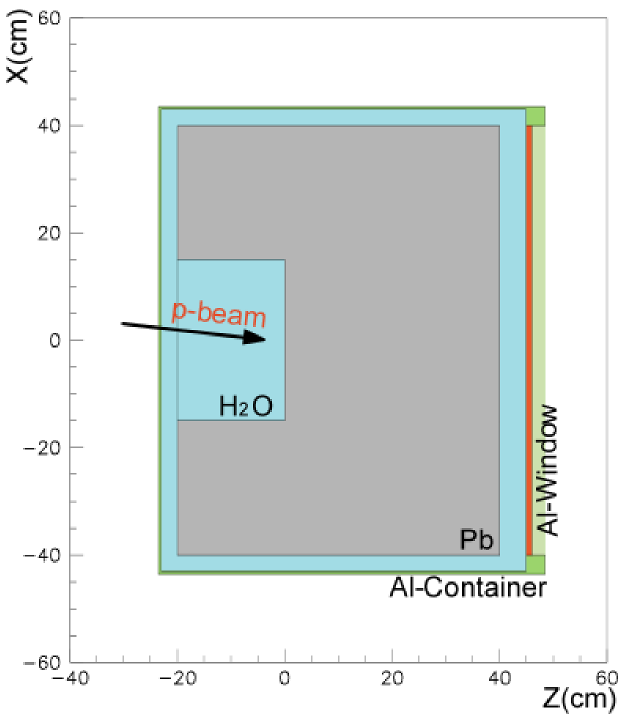


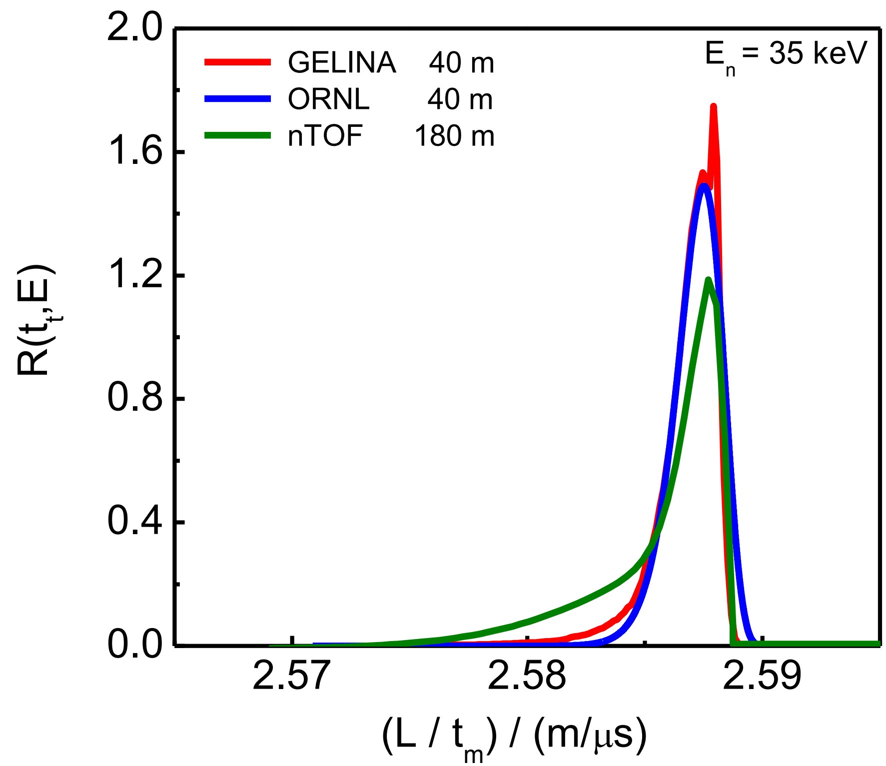
P(t_t, E) : photonuclear





$P(t_t, E)$: photonuclear ⇔ spallation reactions

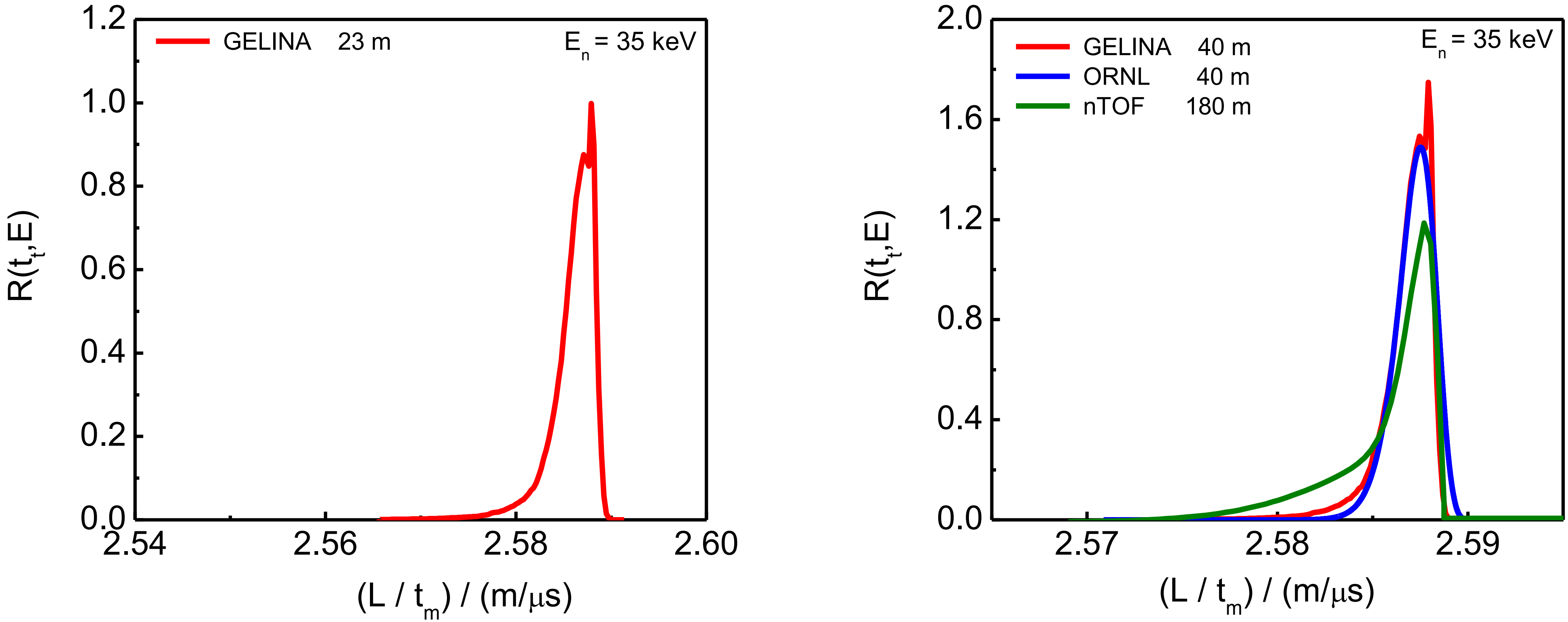




Dimensions	: 80 × 80 × 60 cm^3
Pure Lead	: 4 t
H_2O moderator	: 5 cm
Al-window	: 1.6 mm
Al-container	: 140 l

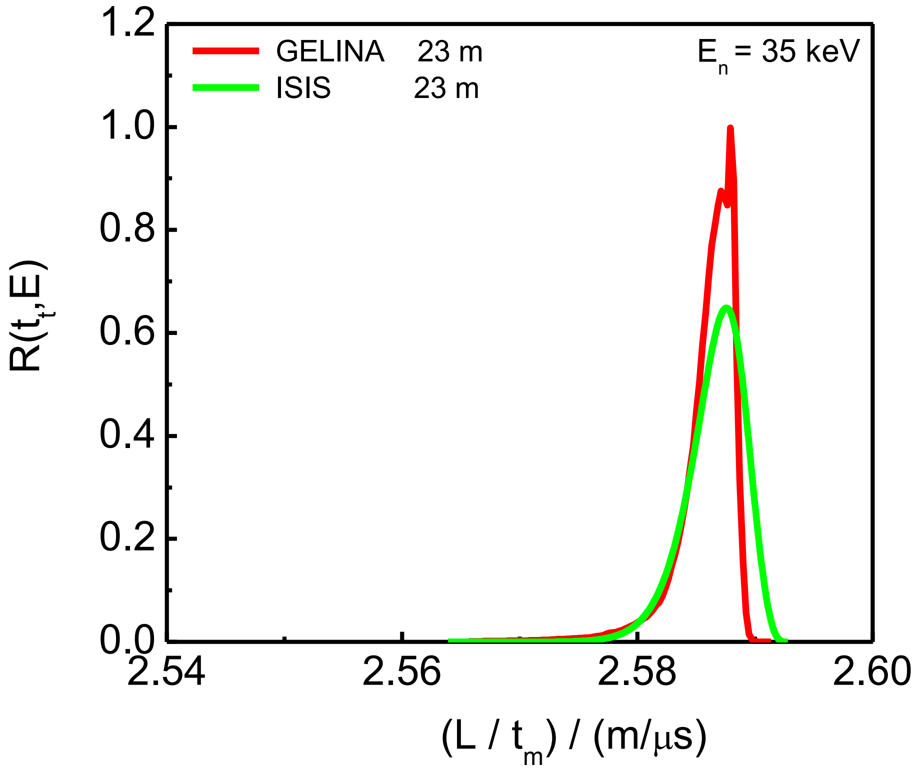
Resolution	: ΔL
GELINA	: 2 cm
ORELA	: 2 cm
nTOF	: 12 cm

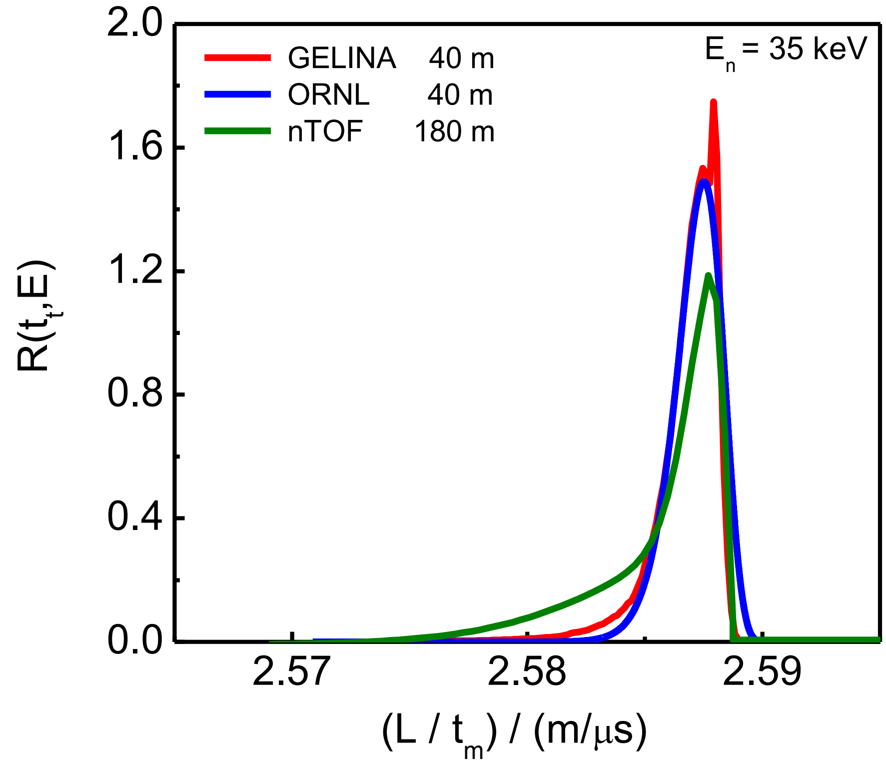
$P(t_t, E)$: photonuclear ⇔ spallation reactions



Resolution	: ΔL
GELINA	: 2 cm
ORELA	: 2 cm
nTOF	: 12 cm

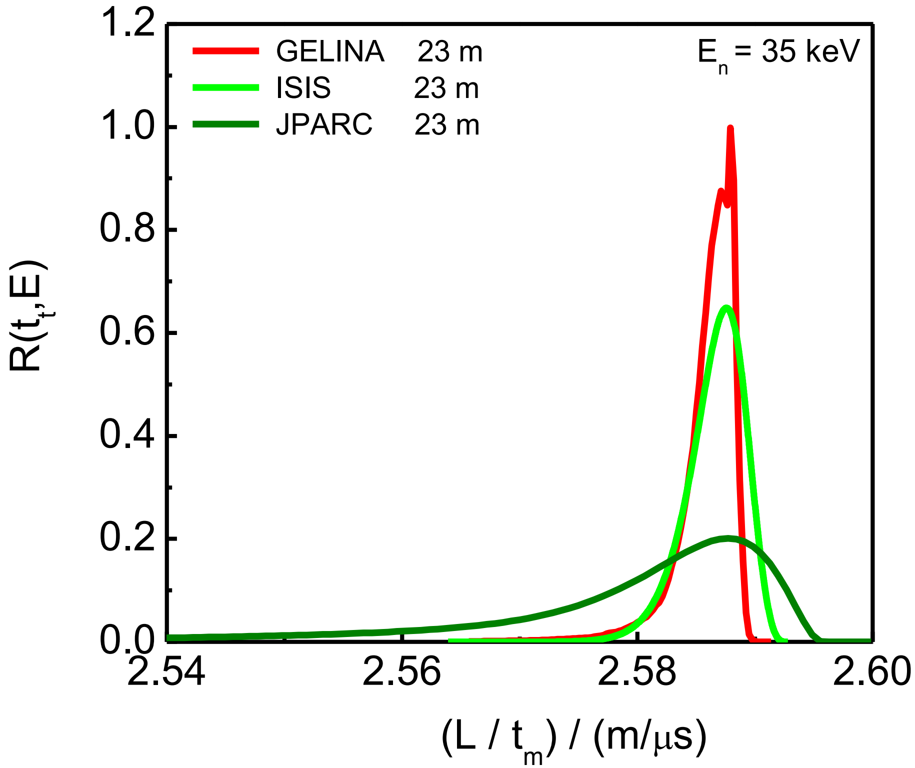
$P(t_t, E)$: photonuclear ⇔ spallation reactions

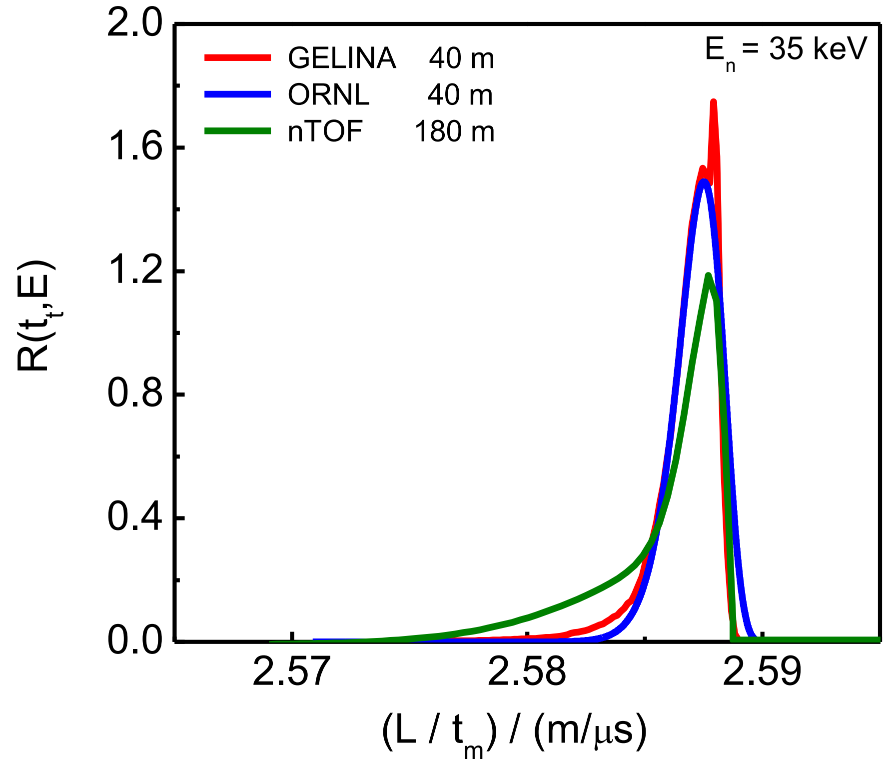




Resolution	:	ΔL
GELINA	:	2 cm
ORELA	:	2 cm
nTOF	:	12 cm

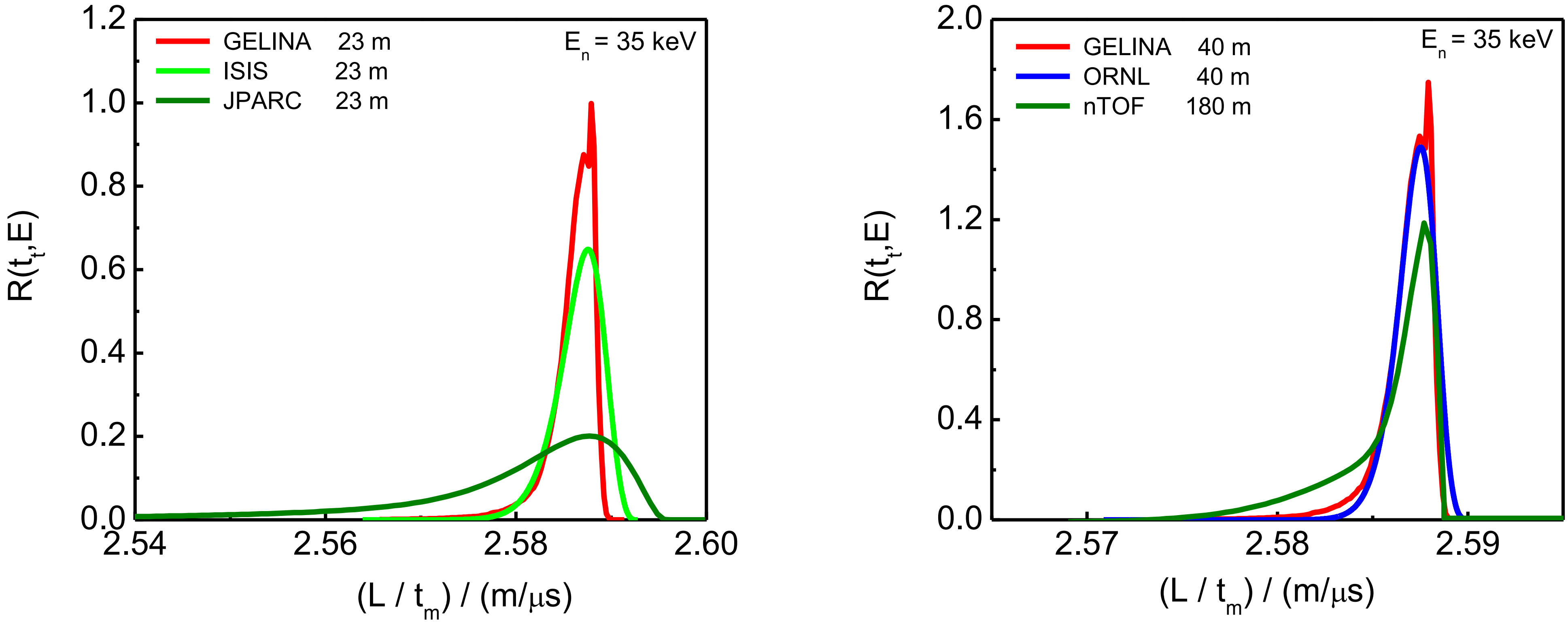
$P(t_t, E)$: photonuclear ⇔ spallation reactions





Resolution	:	ΔL
GELINA	:	2 cm
ORELA	:	2 cm
nTOF	:	12 cm

$P(t_t, E)$: photonuclear ⇔ spallation reactions

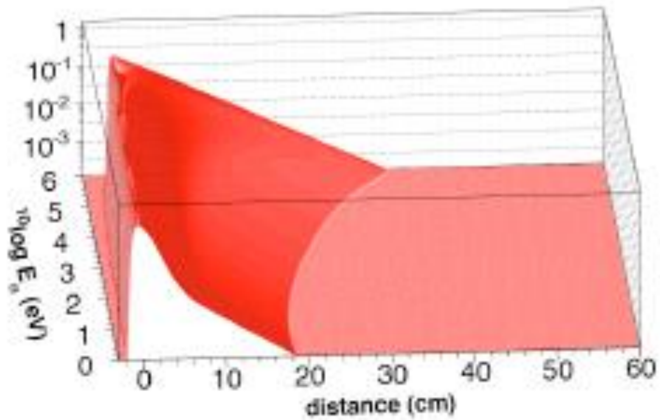


Resolution	:	ΔL
ISIS (INES)	:	5 cm
J-PARC (MLF/ANNRI)	:	13 cm

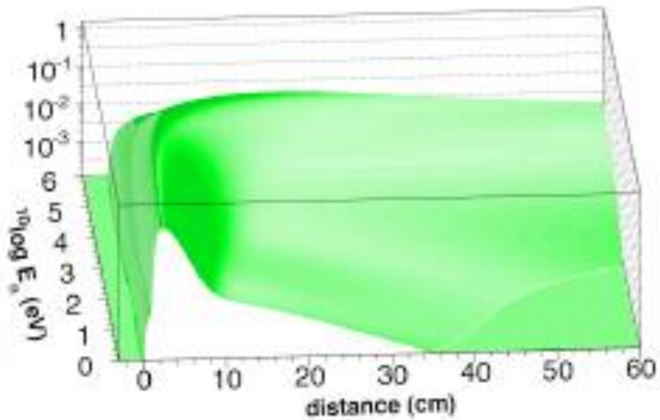
Strongly depend on target/moderator configuration (coupled/decoupled)

Resolution	:	ΔL
GELINA	:	2 cm
ORELA	:	2 cm
nTOF	:	12 cm

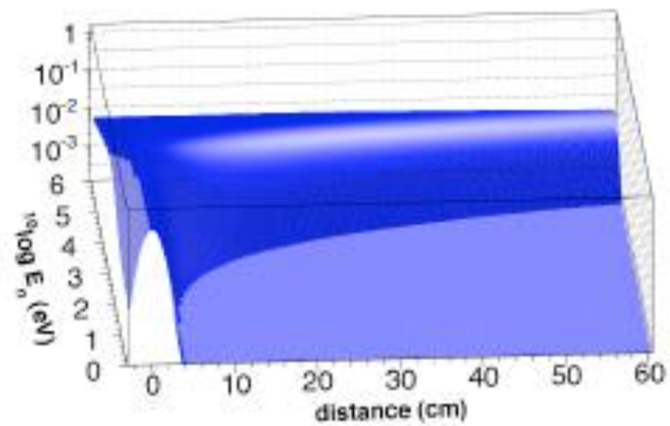
TOF – response matrix



GELINA



n_TOF



LANSCE-MLNSC
(simplified)

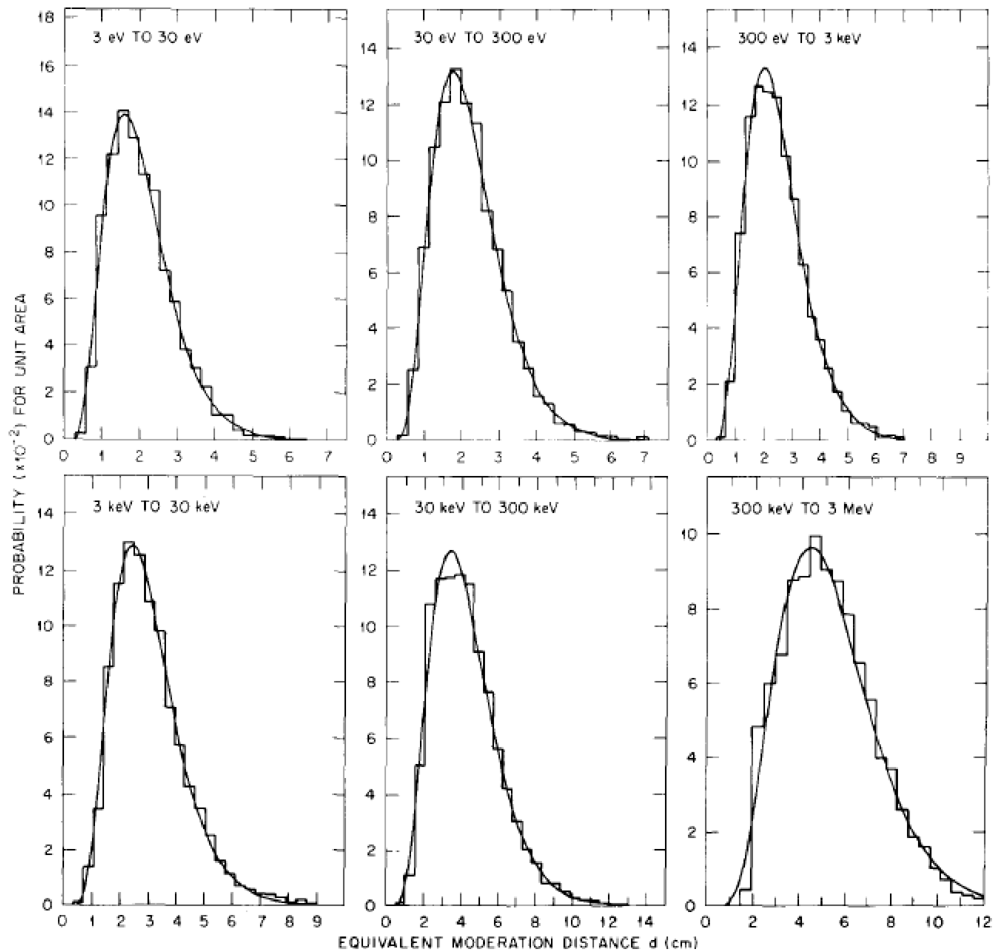
Neutron production & transport

Photonuclear

- GELINA
  - Flaska et al. NIMA 531 (2004) 394
  - Ene et al., NIM A 618, 54 (2010)
- ORELA
  - Coceva et al., NIM 221, 459 (1983)
- RPI
  - Overberg et al., NIM A 438, 253 (1999)

Spallation source

- nTOF
  - Gunsing et al., NIM B 261, 925 (2007)
- J-PARC
  - Hasemi et al., NIM A 773 (2015) 137



Time-of-flight technique: experimental resolution

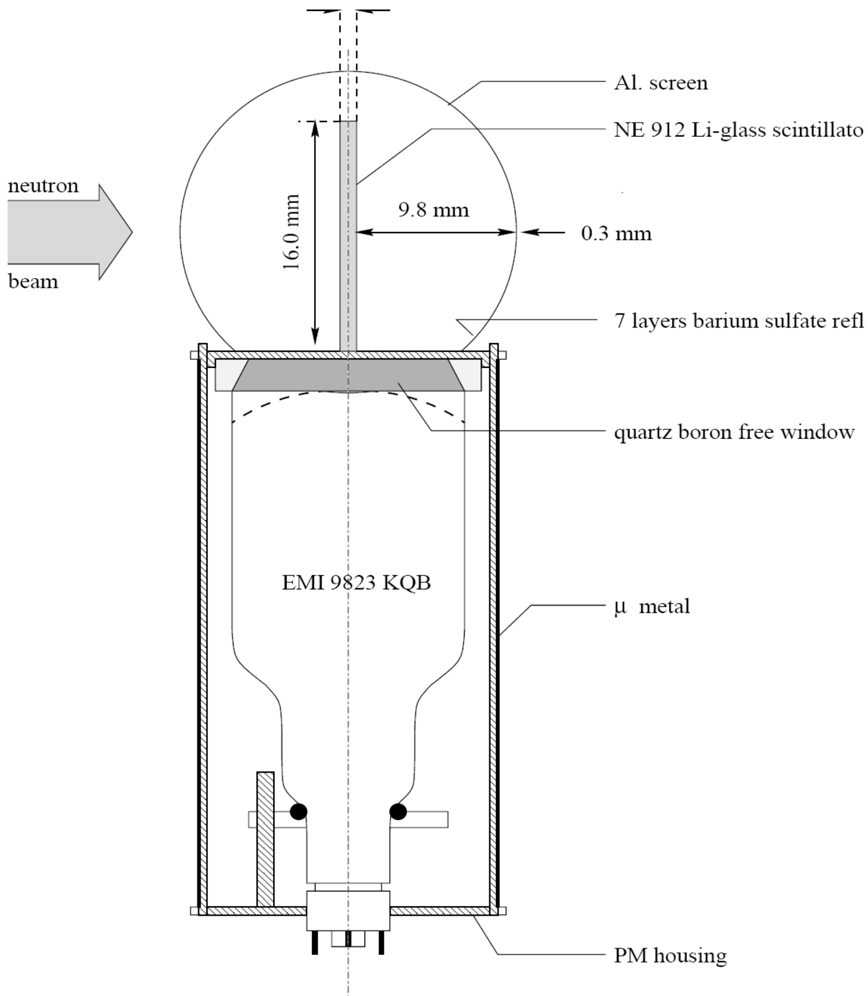
$$t = (T_s - T_0) + t_o - (t_t + t_d)$$

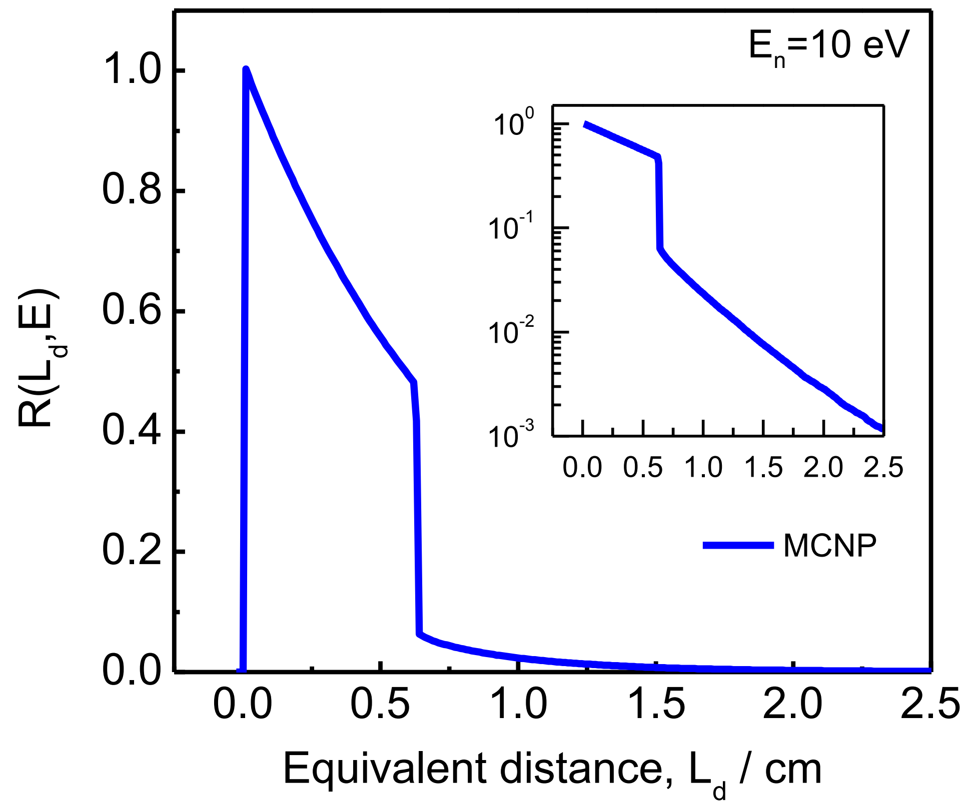
- Δt
  - Initial burst ΔT_0
  - Time resolution detector & electronics ΔT_s
  - Neutron transport in target - moderator Δt_t
  - Neutron transport in detector Δt_d

Li-glass scintillator : response function

$^{6}Li(n,t)\alpha$

Scintillator + PMT

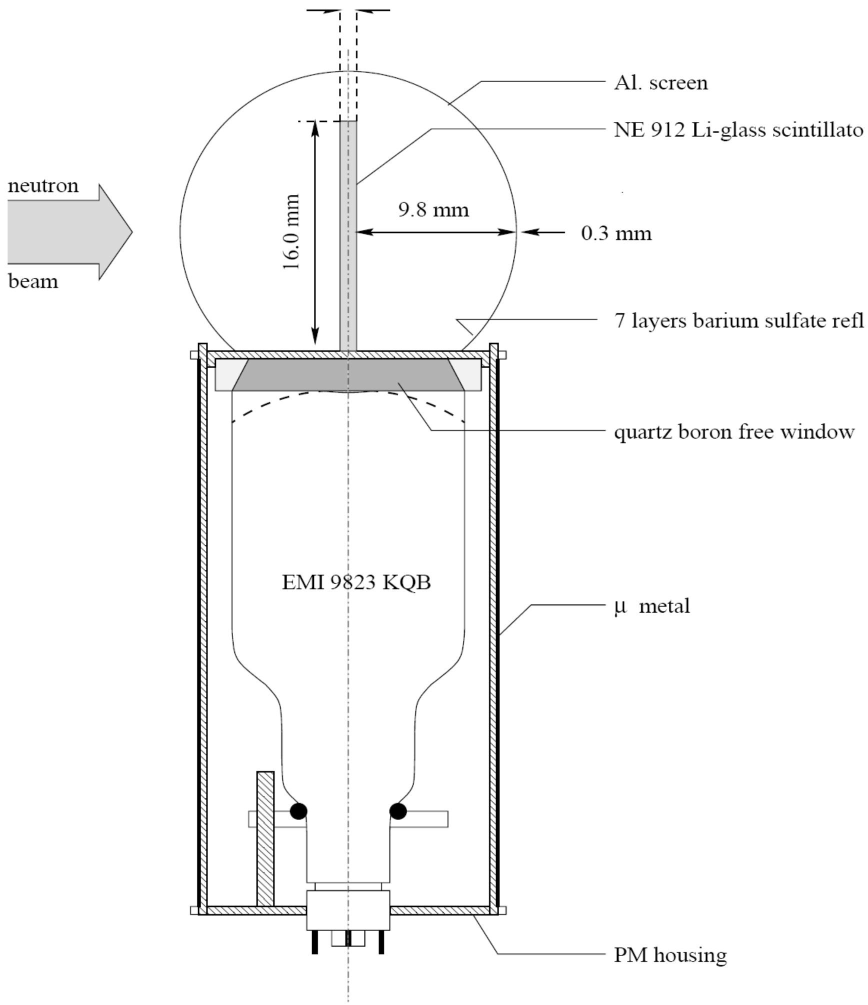


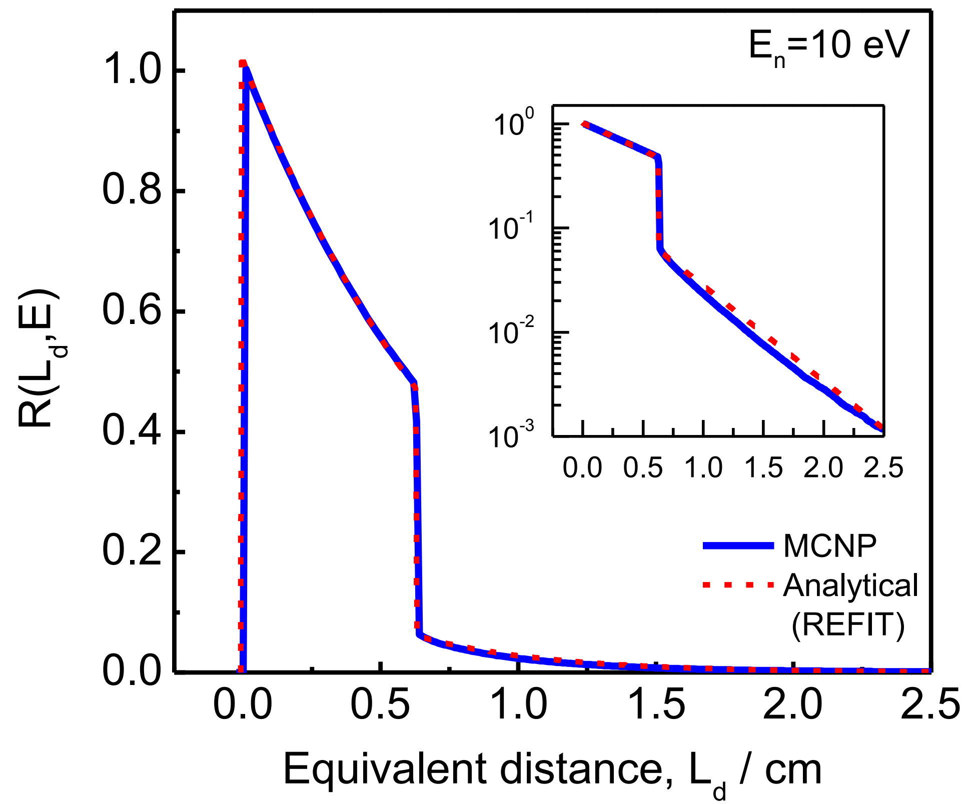


Li-glass scintillator : response function

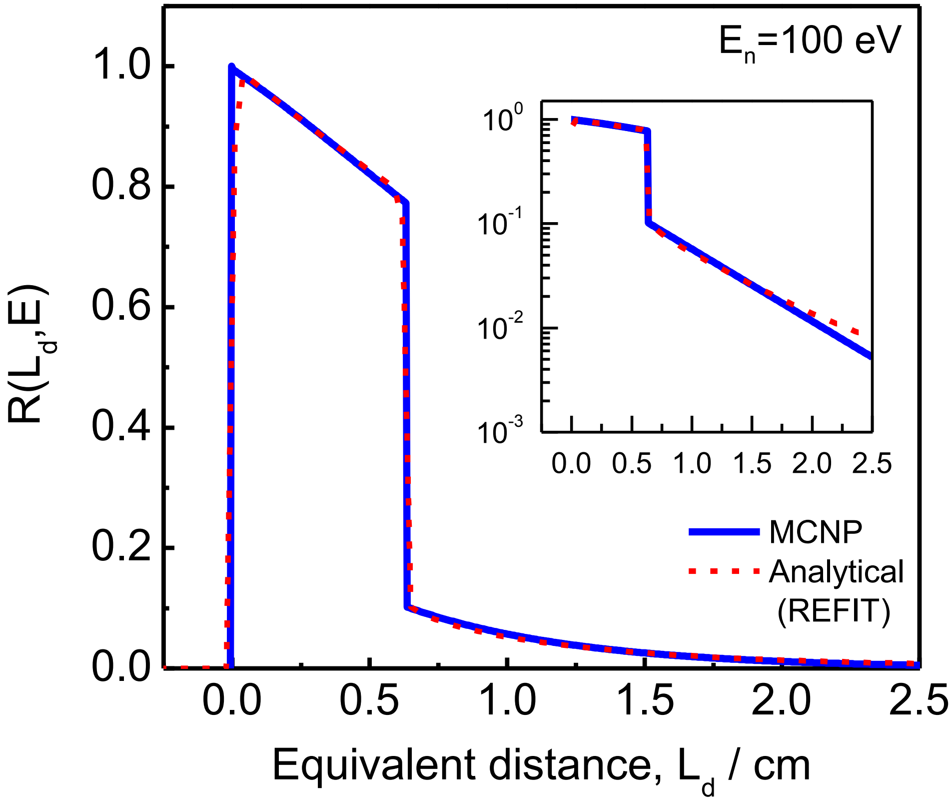
$^{6}Li(n,t)\alpha$

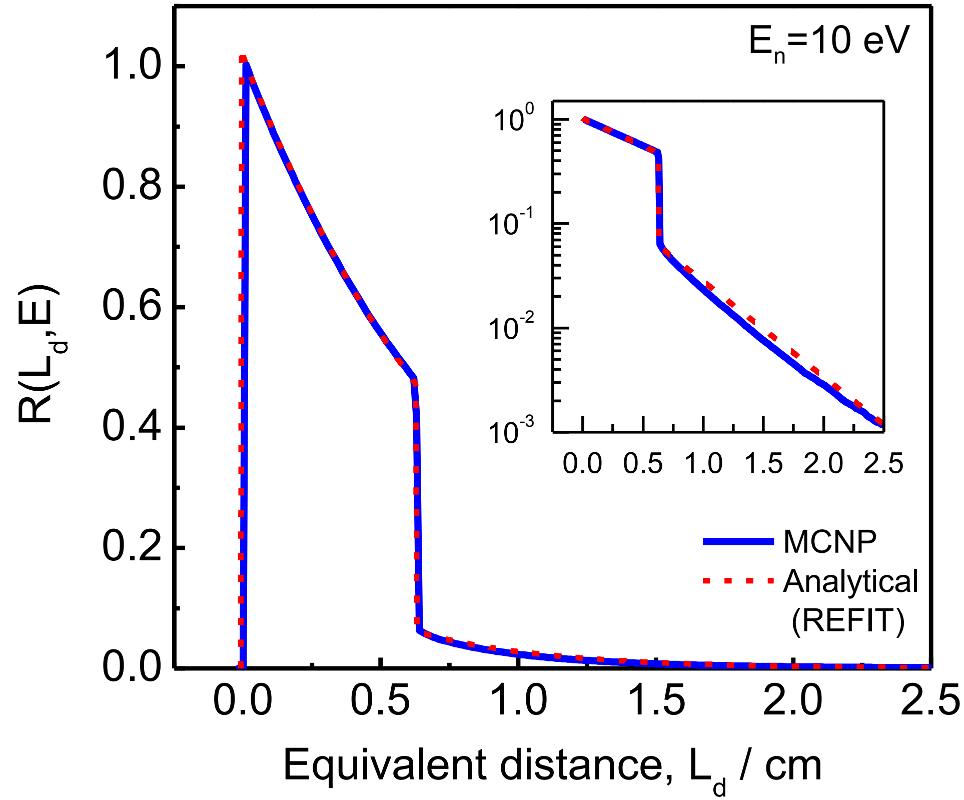
Scintillator + PMT





Li-glass scintillator : response function





Time-of-flight technique

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}}$$

$$\frac{\Delta E}{E} = (1+\gamma)\gamma\frac{\Delta v}{v}$$

Time-of-flight technique

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}} = \frac{1}{L}\sqrt{(v\Delta t)^2 + \Delta L^2}$$

$$\frac{\Delta E}{E} = (1+\gamma)\gamma \frac{\Delta v}{v}$$

Time-of-flight technique

Components:

- Initial burst ΔT_0
- Time resolution detector & electronics ΔT_s
- Neutron transport in target - moderator $\Delta t_t \Rightarrow \Delta L_t$ (equivalent length = v Δt_t)
- Neutron transport in detector $\Delta t_d \Rightarrow \Delta L_d$ (equivalent length = v Δt_d)

with (ΔT_0, ΔT_s , ΔL_t, ΔL_d) almost independent of neutron energy (velocity)

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}} = \frac{1}{L}\sqrt{(v\Delta t)^2 + \Delta L^2}$$

$$\frac{\Delta E}{E} = (1+\gamma)\gamma\frac{\Delta v}{v}$$

$$\boxed{= \frac{1}{L}\sqrt{(v\,\Delta T_0)^2 + (v\,\Delta T_s)^2 + \Delta L_t^2 + \Delta L_d^2 + \cancel{\Delta L^2}}}$$

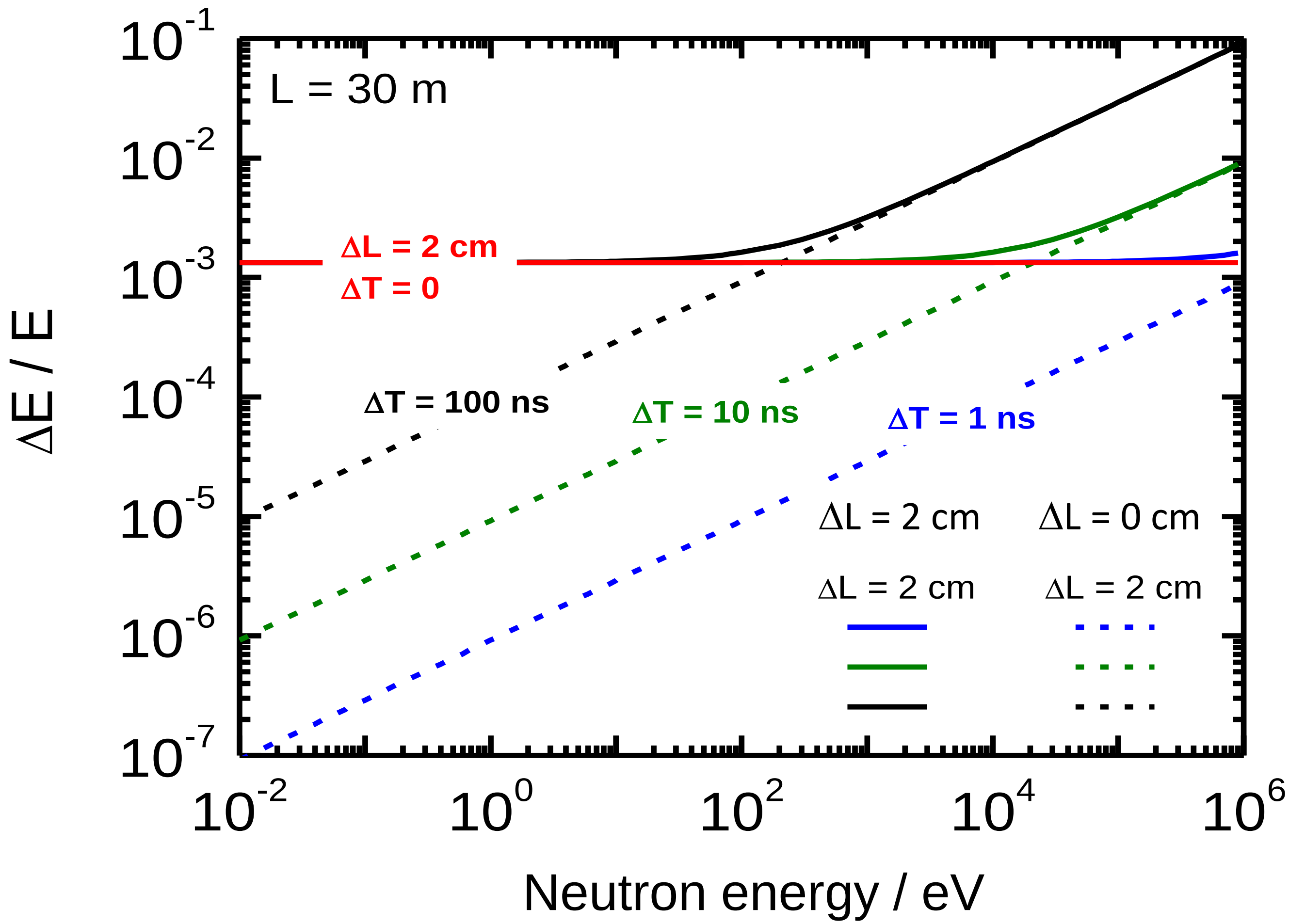
neglibible

REFIT: numerical and analytical response functions + combination

TOF-resolution : different components

$$\frac{\Delta v}{v} = \frac{1}{L}\sqrt{(v\,\Delta T_0)^2 + (v\,\Delta T_s)^2 + \underbrace{\Delta L_t^2 + \Delta L_d^2}_{\text{" }\Delta L^2\text{ "}}}$$

$$\frac{\Delta E}{E} = (1+\gamma)\gamma\frac{\Delta v}{v}$$

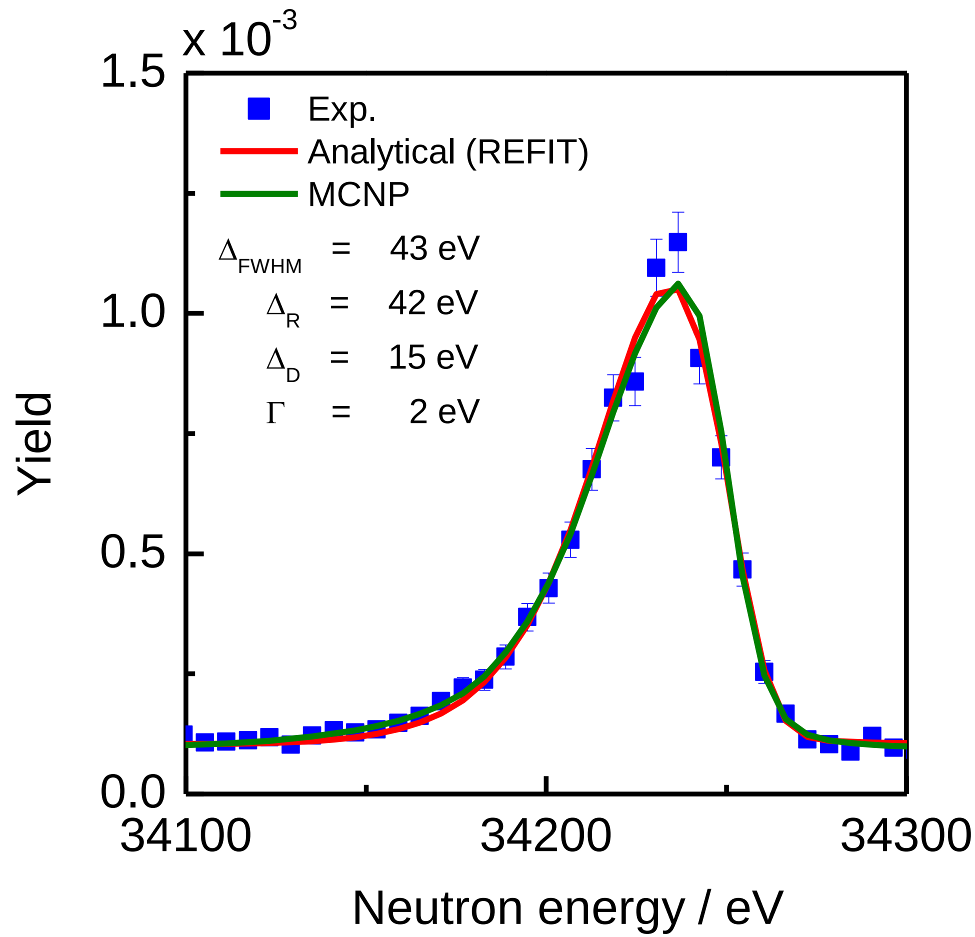


Experimental observable

$$\Delta_{FWHM} = \sqrt{\Gamma^2 + \Delta_D{}^2 + \Delta_R{}^2}$$

with

- **Γ Total resonance width**
- **Δ_R Experimental resolution**
- **Δ_D Doppler broadening**



Doppler broadening

$$\bar{\sigma}(T,v) = \frac{1}{v}\int |\vec{v}-\vec{V}|\,\sigma(|\vec{v}-\vec{V}|)\,P(V)dV$$

$\vec{v}$: **neutron velocity**

$\vec{V}$: **target velocity**

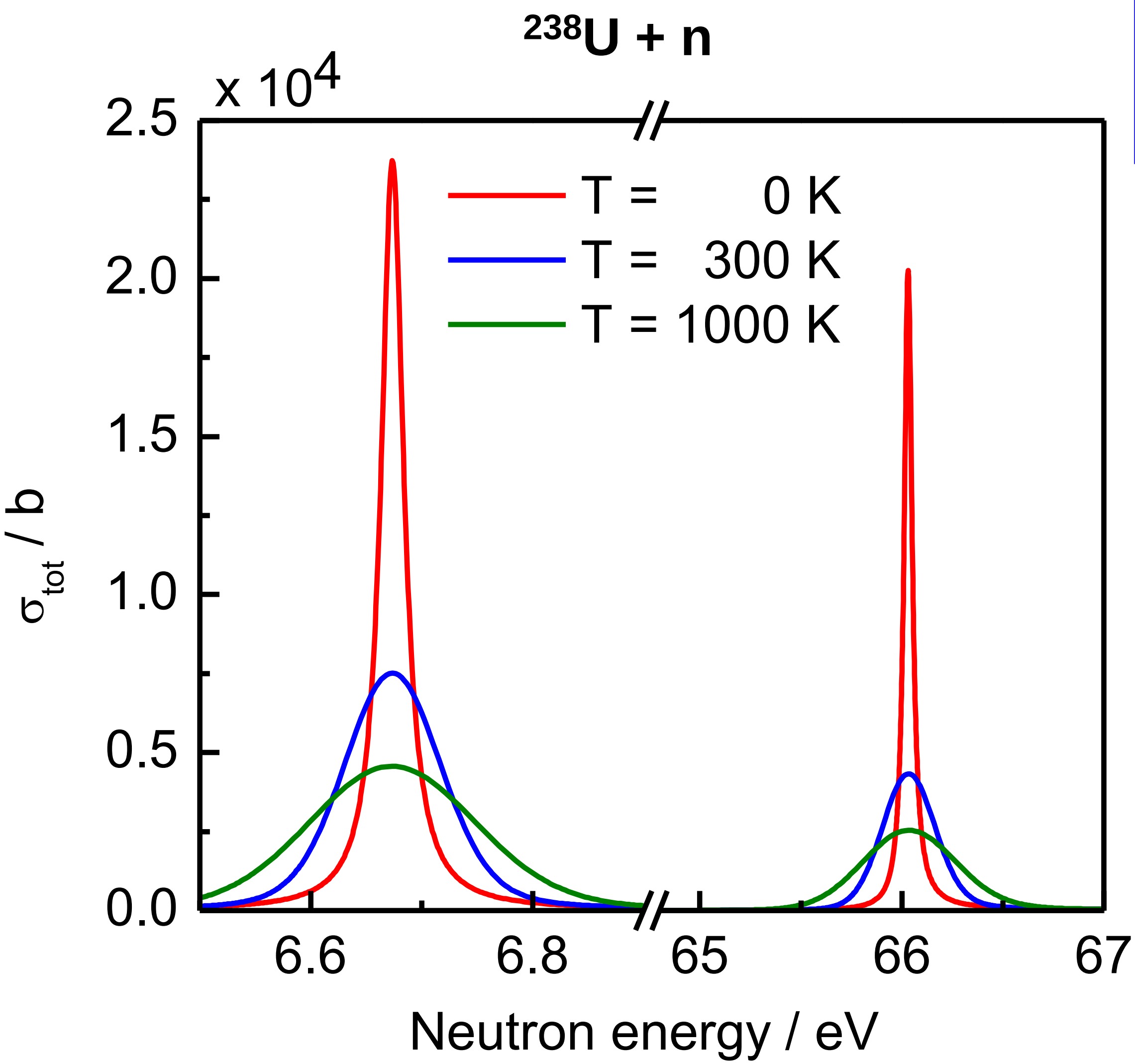
$P(V)$: **target velocity distribution**

σ : **nuclear (microscopic) cross section**

$\bar{\sigma}$: **Doppler broadened (microscopic) cross section**

T : **effective target temperature**

Doppler broadened cross sections



$$\boxed{\bar{\sigma}(T,v) = \frac{1}{v}\int |\vec{v}-\vec{V}|\,\sigma(|\vec{v}-\vec{V}|)\,P(V)\,dV}$$

$$\bar{\sigma}(E) = \int dE'\,S(E,E')\,\sigma(E')$$

$$\bar{\sigma}(E) = \frac{1}{\Delta_D\sqrt{\pi}}\int dE'\,e^{-\left(\frac{E'-E}{\Delta_D}\right)^2}\sqrt{\frac{E'}{E}}\,\sigma(E')$$

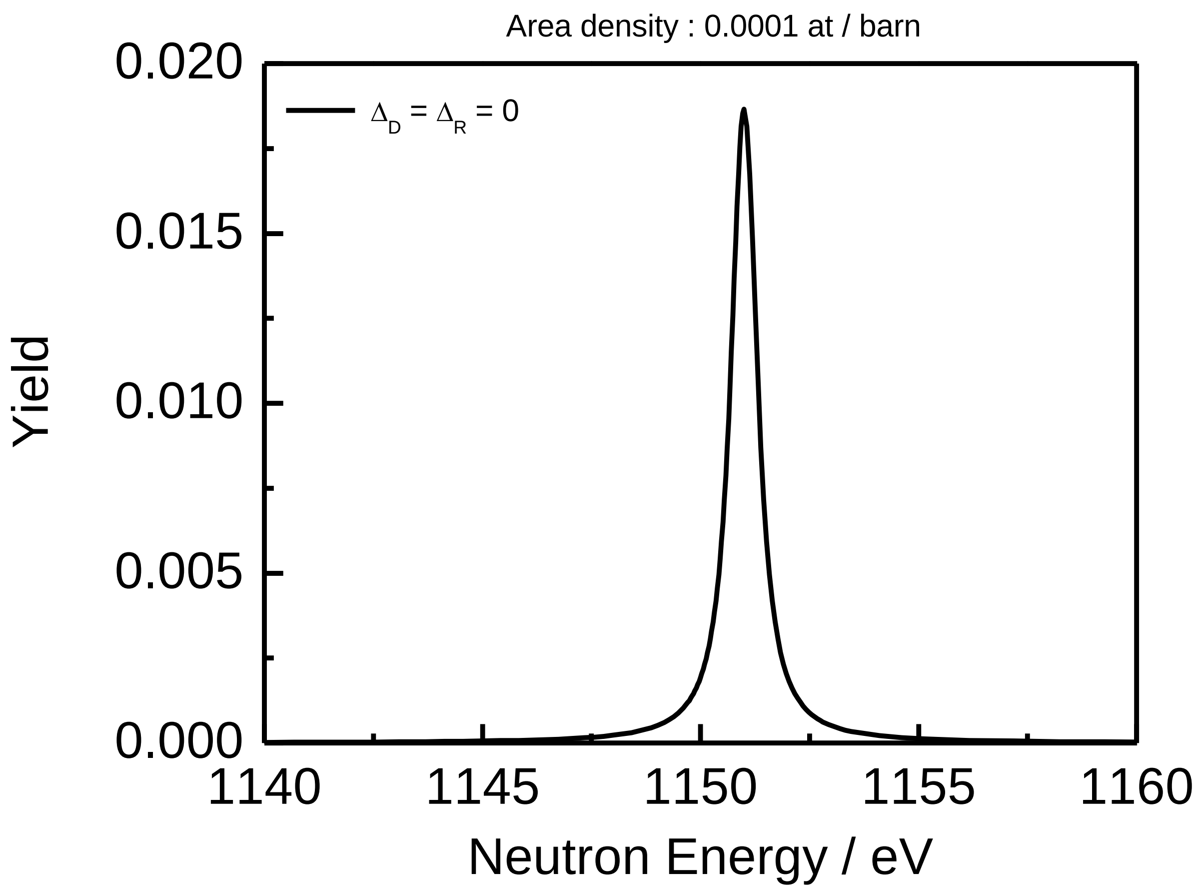
$$\Delta_D = \sqrt{\frac{4\,E\,k_B T}{m_X / m_n}}$$

$$\mathrm{FWHM} = 2\sqrt{\ln 2}\,\Delta_D$$

Theoretical capture yield

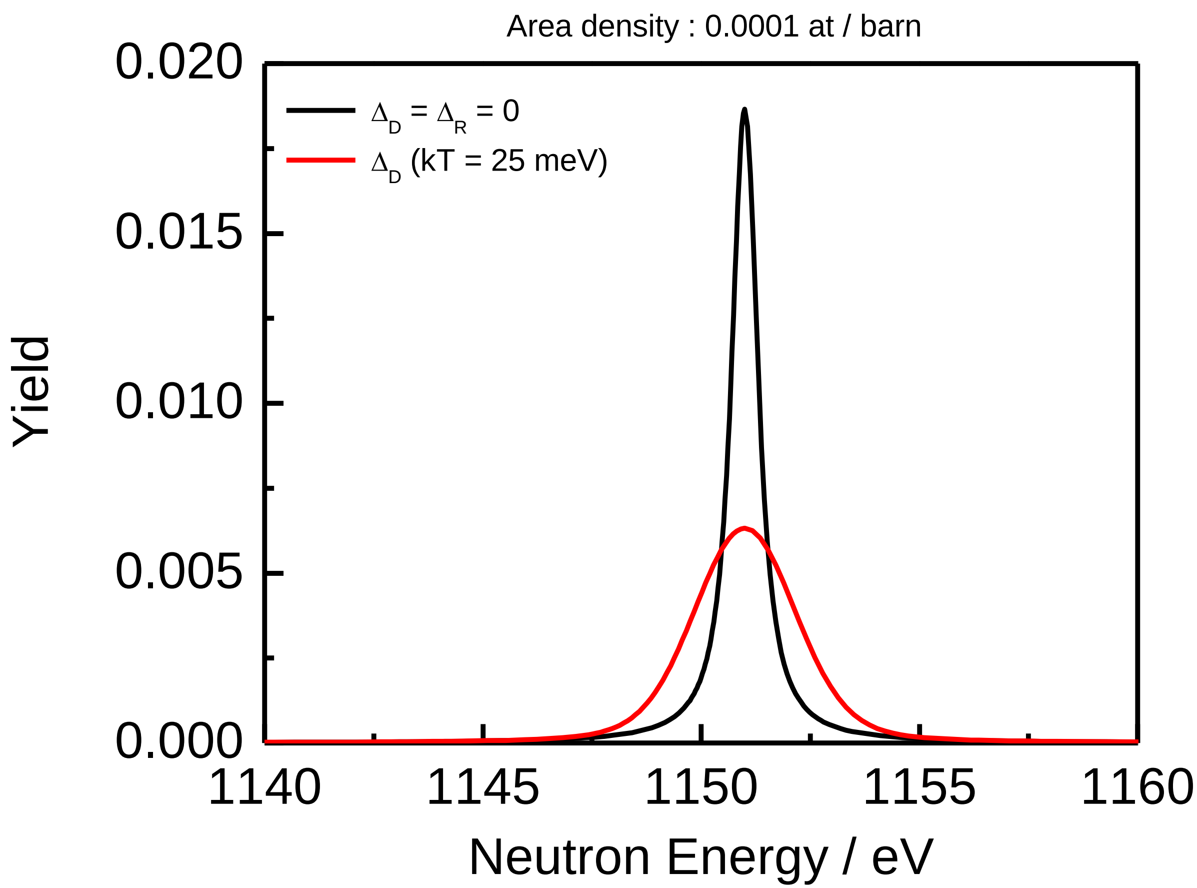
^{65}Fe 1.15 keV resonance

$$Y_\gamma \cong \frac{\sigma_\gamma}{\sigma_{tot}}\left(1-e^{-n\sigma_{tot}}\right)+\ldots$$



+ Doppler

^{65}Fe 1.15 keV resonance



$$Y_\gamma \cong \frac{\bar{\sigma}_\gamma}{\bar{\sigma}_{tot}}\left(1 - e^{-n\bar{\sigma}_{tot}}\right) + \dots$$

$$\boxed{\bar{\sigma}(E) = \int dE'\, S(E')\, \sigma(E - E')}$$

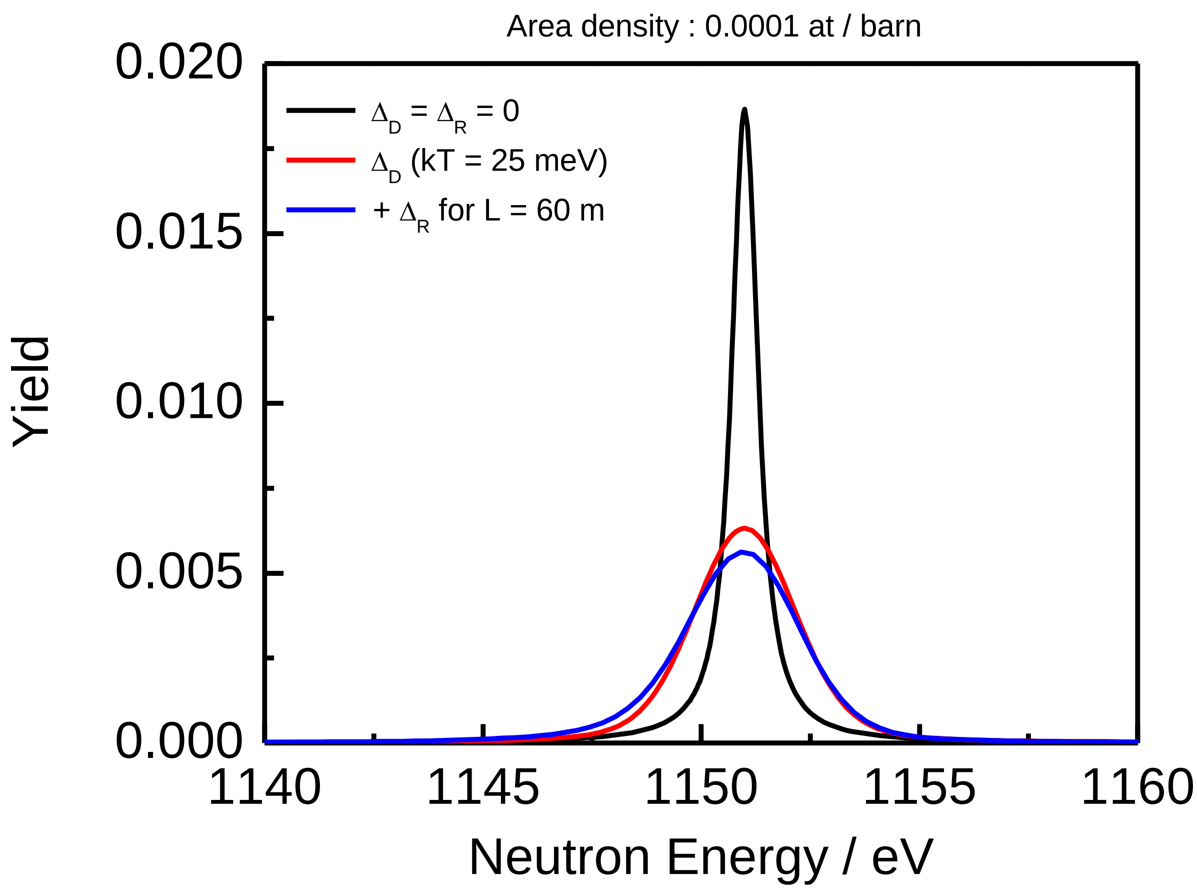
$$\bar{\sigma}(E) \cong \frac{1}{\Delta_D \sqrt{\pi}} \int dE'\, e^{-\left(\frac{E'-E}{\Delta_D}\right)^2} \sqrt{\frac{E'}{E}}\, \sigma(E')$$

$$\Delta_D = \sqrt{\frac{4 E k_B T}{m_X / m_n}}$$

$$\mathrm{FWHM} = 2\sqrt{\ln 2}\, \Delta_D$$

+ Doppler + Response

^{65}Fe 1.15 keV resonance



$$Y_\gamma \cong \frac{\bar{\sigma}_\gamma}{\bar{\sigma}_{tot}}\left(1 - e^{-n\bar{\sigma}_{tot}}\right) + \dots$$

$$\boxed{\bar{\sigma}(E) = \int dE'\, S(E')\, \sigma(E - E')}$$

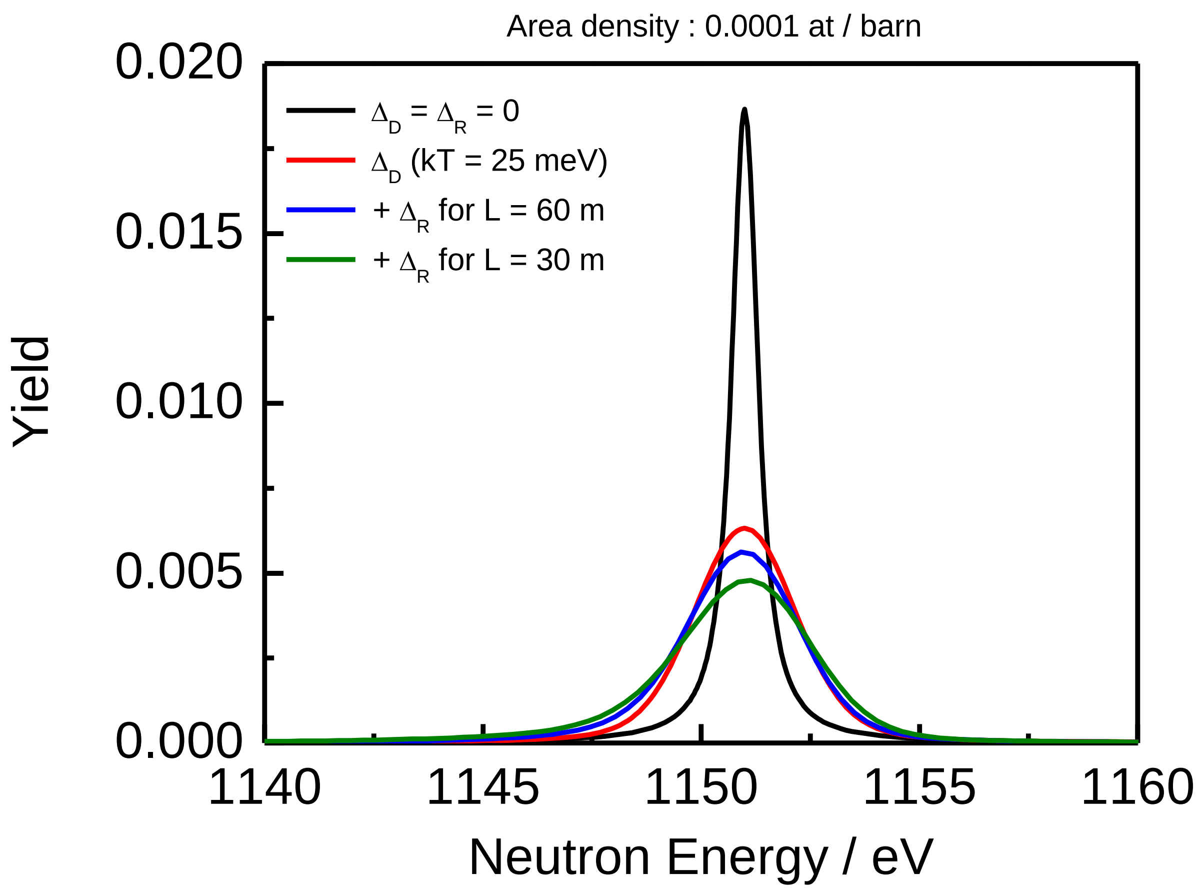
$$\boxed{Y_{exp} = \frac{\int R(t,E) Y_\gamma(E) dE}{\int R(t,E) dE}}$$

L = 60 m

$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

+ Doppler + Response

^{65}Fe 1.15 keV resonance



$$Y_\gamma \cong \frac{\bar{\sigma}_\gamma}{\bar{\sigma}_{tot}}\left(1 - e^{-n\bar{\sigma}_{tot}}\right) + \ldots$$

$$\boxed{\bar{\sigma}(E) = \int dE'\, S(E')\, \sigma(E - E')}$$

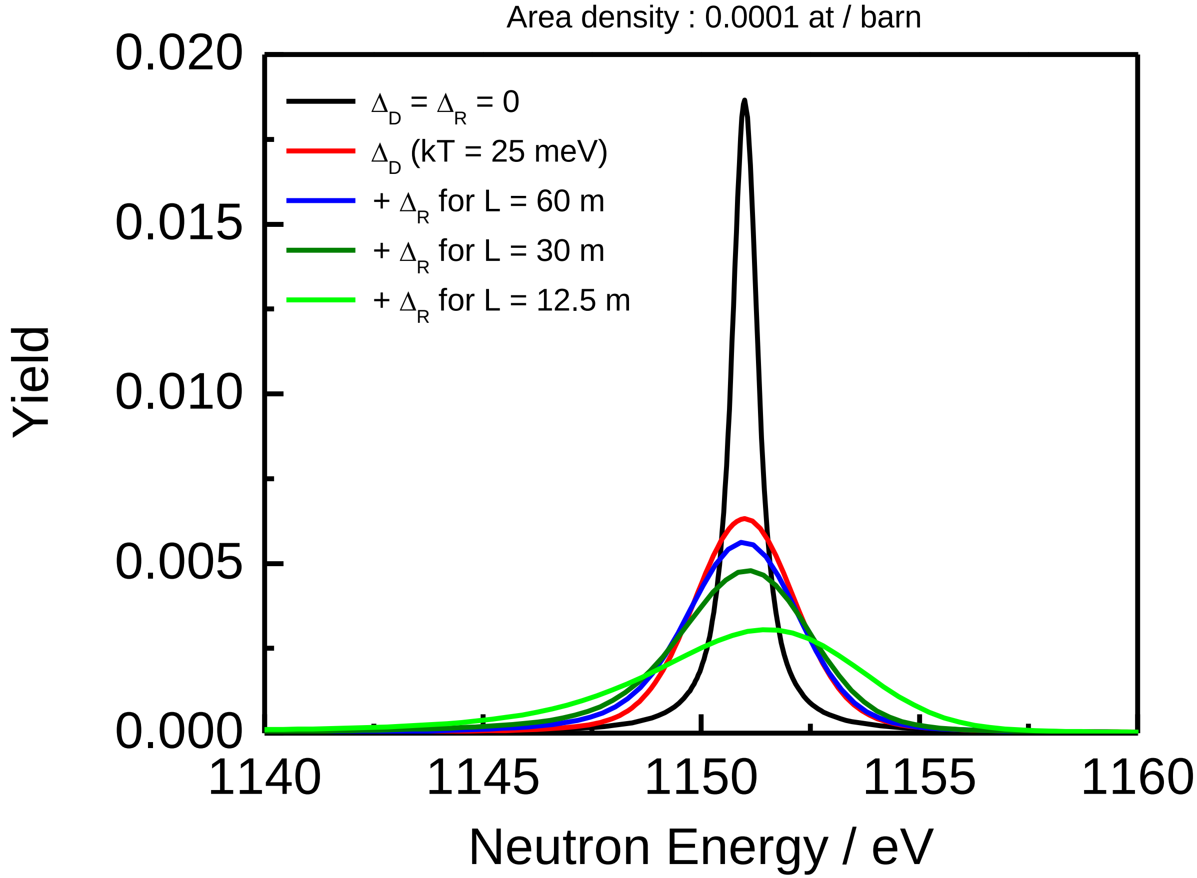
$$\boxed{Y_{exp} = \frac{\int R(t,E) Y_\gamma(E) dE}{\int R(t,E) dE}}$$

L = 60 m
L = 30 m

$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

+ Doppler + Response

^{65}Fe 1.15 keV resonance



$$Y_\gamma \cong \frac{\bar{\sigma}_\gamma}{\bar{\sigma}_{tot}}\left(1 - e^{-n\bar{\sigma}_{tot}}\right) + \ldots$$

$$\boxed{\bar{\sigma}(E) = \int dE'\, S(E')\, \sigma(E - E')}$$

$$\boxed{Y_{exp} = \frac{\int R(t,E) Y_\gamma(E) dE}{\int R(t,E) dE}}$$

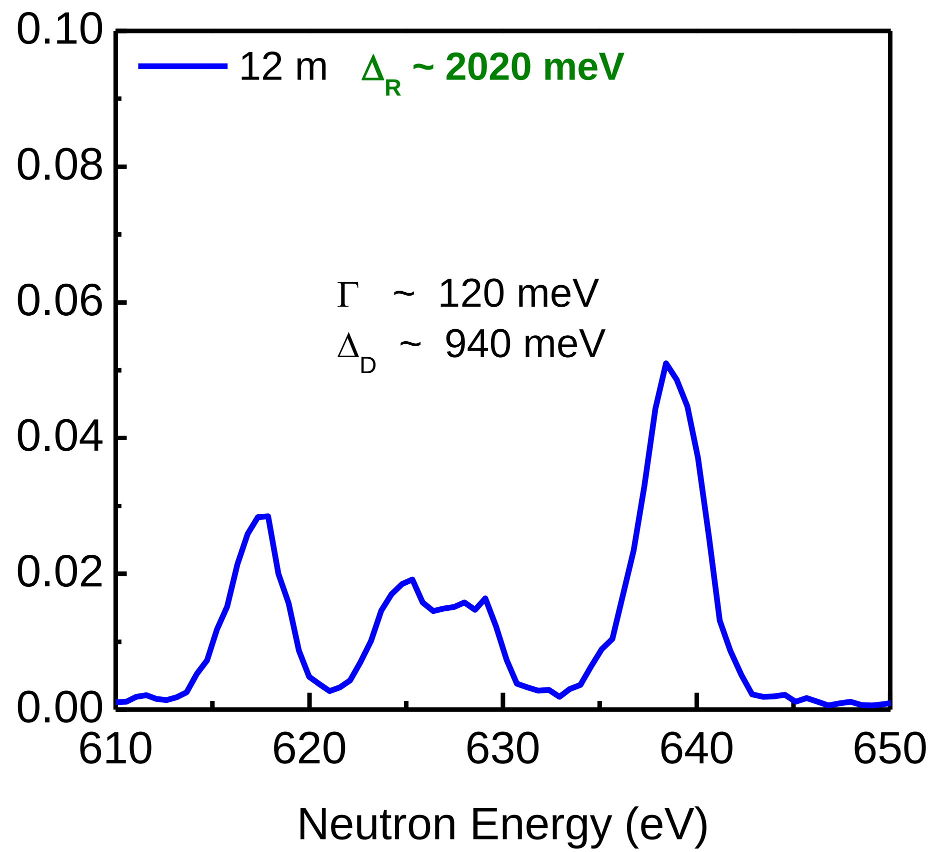
L = 60 m
L = 30 m
L = 12.5 m

$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

^{197}Au(n,γ) at L = 12 m

$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

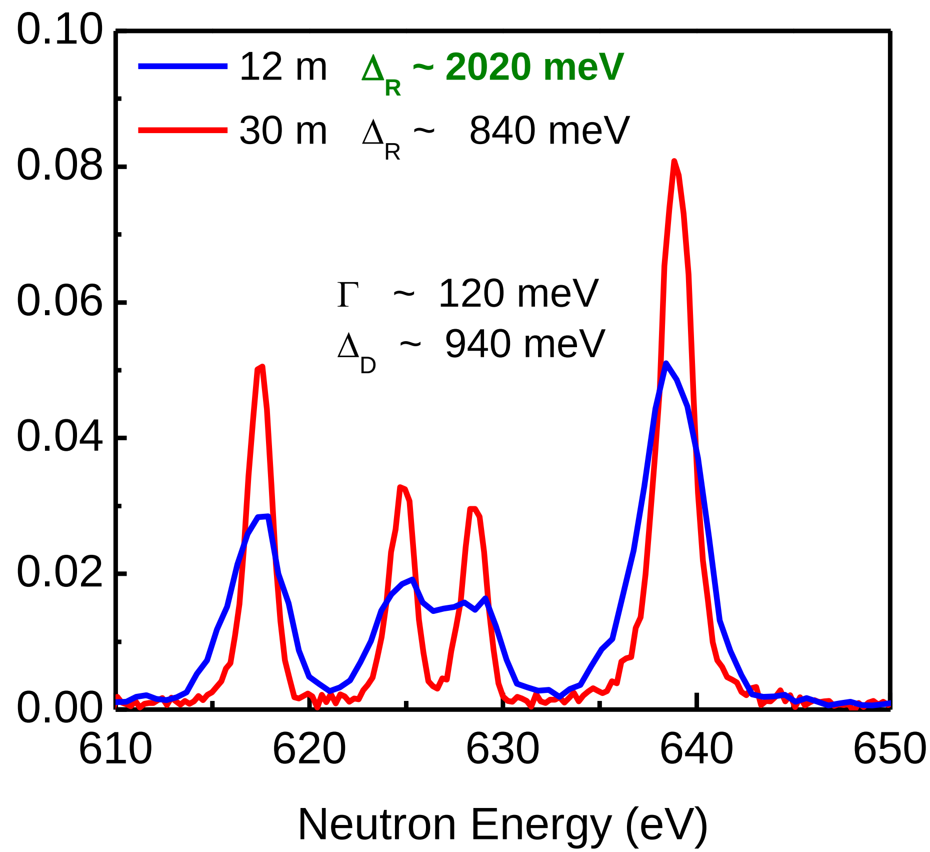
$$\Delta_D = \sqrt{\frac{4 E k_B T}{m_X / m_n}} \qquad \mathrm{FWHM} = 2\sqrt{\ln 2}\,\Delta_D$$



^{197}Au(n,γ) at L = 12 m and 30 m

$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

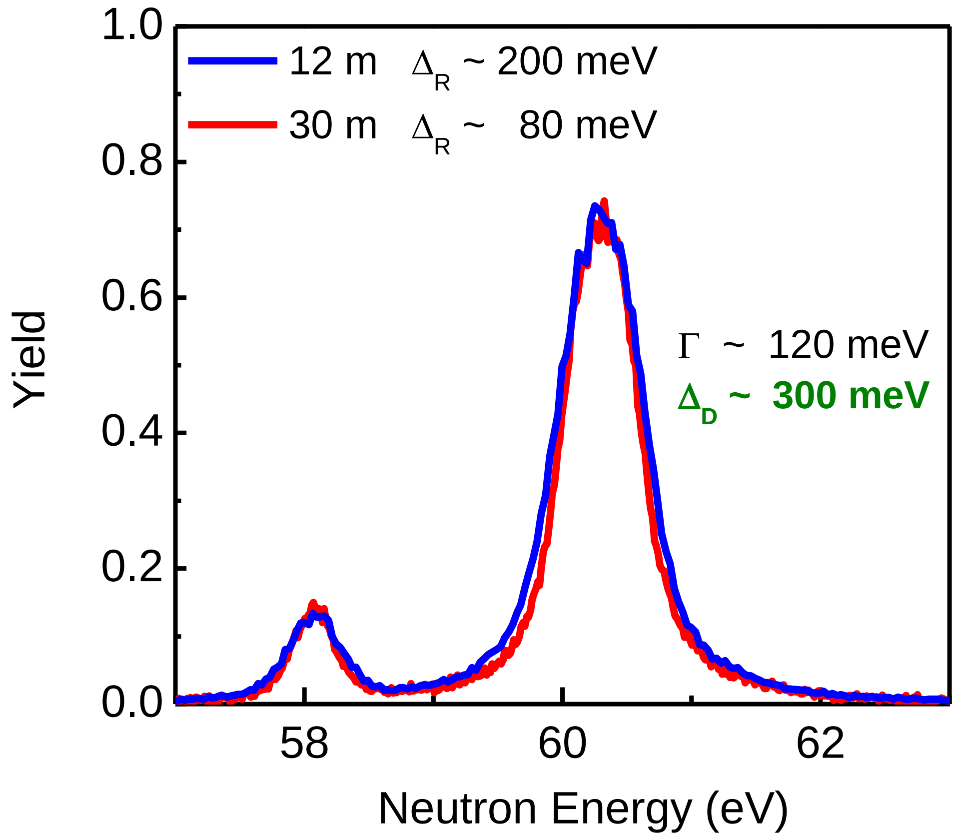
$$\Delta_D = \sqrt{\frac{4 E k_B T}{m_X / m_n}} \qquad FWHM = 2\sqrt{\ln 2}\,\Delta_D$$

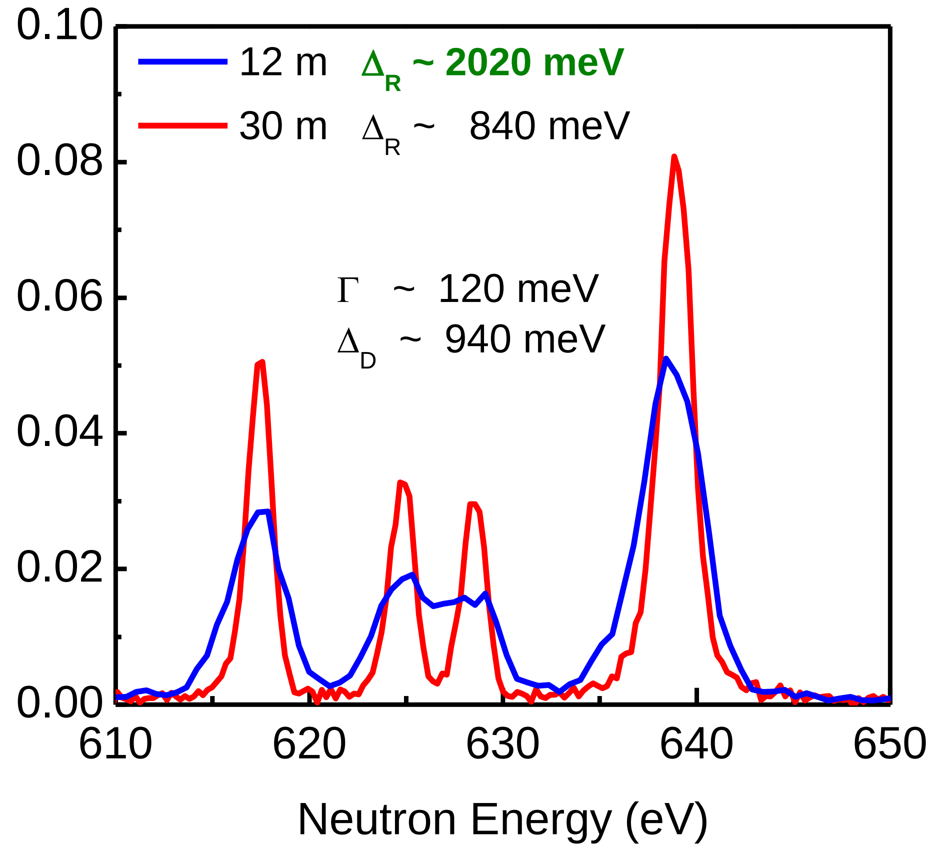


^{197}Au(n,γ) at L = 12 m and 30 m

$$\frac{\Delta E}{E} = 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

$$\Delta_D = \sqrt{\frac{4\,E\,k_B T}{m_X / m_n}} \qquad \mathrm{FWHM} = 2\sqrt{\ln 2}\,\Delta_D$$





Experimental observable when $\Gamma < \Delta_R$ or Δ_D

$$\Delta_{FWHM} = \sqrt{\Gamma^2 + \Delta_D{}^2 + \Delta_R{}^2}$$

Ofter dominated by Δ_R or Δ_D with

- **Γ Total resonance width**
- **Δ_R Experimental resolution**
- **Δ_D Doppler broadening**

$\Rightarrow$ effective experimental observable is resonance area