Characterization of Neutron Beams

Zsolt Révay

Institute of Isotopes, Budapest

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Reminder: neutron sources

- Neutron generators
  - $D(d,n)^3He$ 2.4 MeV neutrons
  - $D(t,n)^4He$ 14 MeV neutrons
- Radioisotopic neutron sources
  - (α,n) reactions
    - α-decay from ^{239}Pu, ^{241}Am, ^{210}Po (~5MeV α-s)

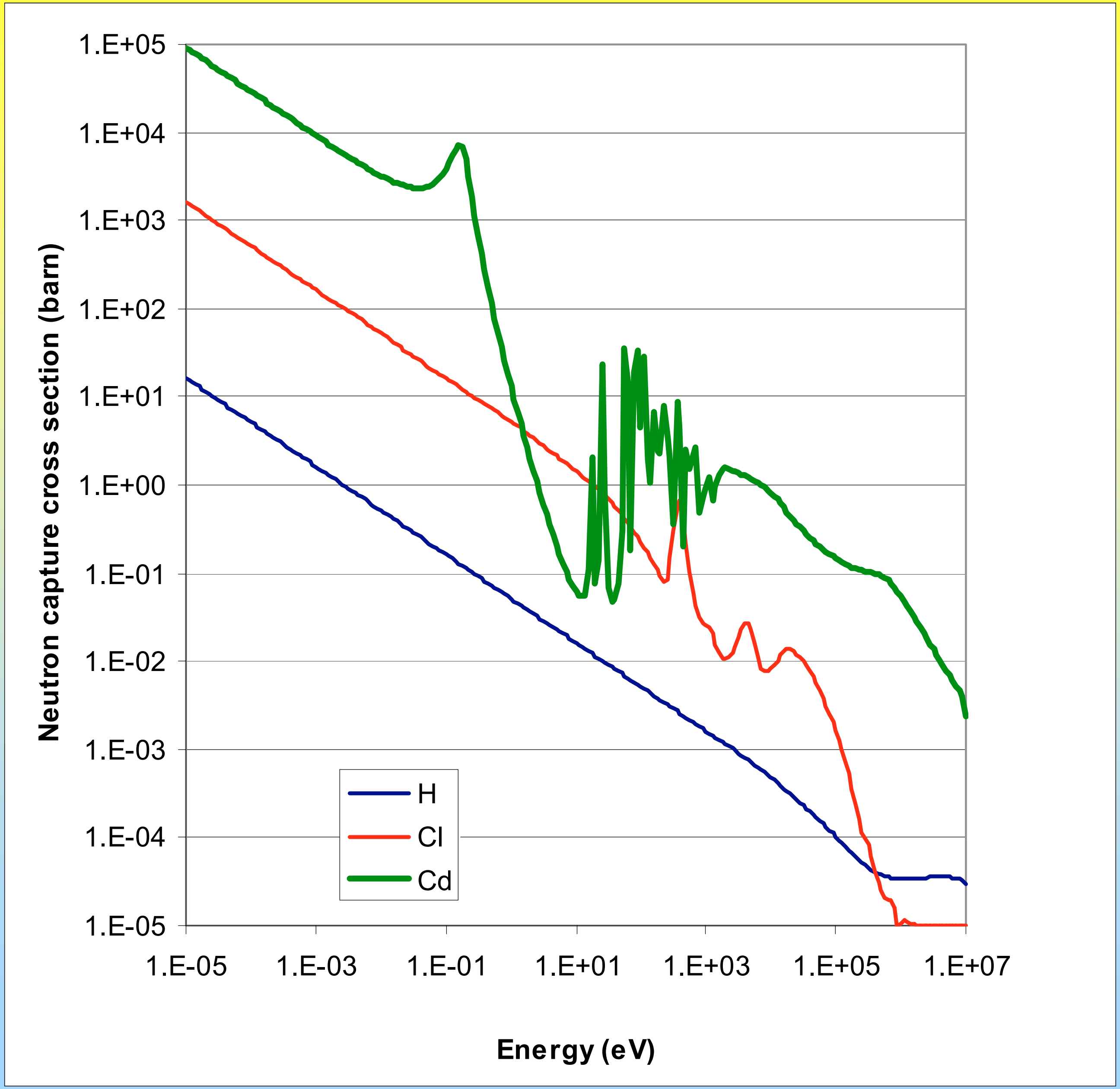
      then $^9Be(\alpha,n)^{12}C$, average n energy ~ 4—4.5 MeV
  - photoneutron sources
    - high-E_γ sources, ^{24}Na (2.76 MeV), ^{124}Sb (2.09 MeV)

      then $^9Be(\gamma,n)2\ ^4He$, few 100 keV n
  - spontaneous fission
    - ^{252}Cf, average E_n ~ 2 MeV

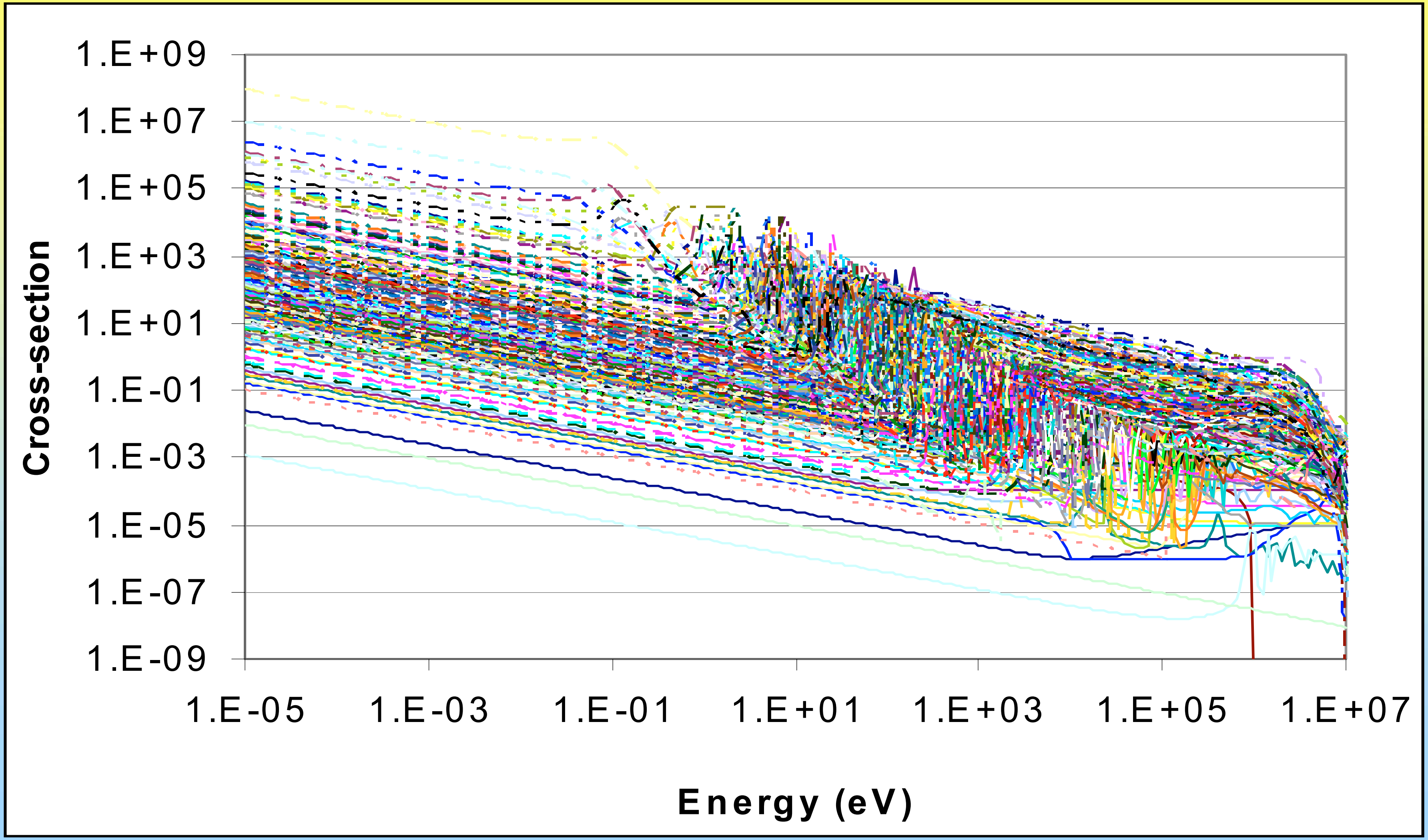
Reminder: neutron sources (2)

- spallation sources
  - few MeV n-s
- research reactors
  - few MeV n-s

Neutron capture cross-sections



Neutron capture cross-sections (2)



generated neutrons ~ MeV

neutron capture efficient below eV

⇩

To achieve high reaction rates, neutrons must be slowed down:
elastic scattering on light nuclei
= moderation

Reminder: moderators

- water (reactor moderator) (82 b, 18 collisions)
- heavy water (reactor moderator) (7.6 b, 25 coll.)
- graphite (reactor moderator) (4.8 b, 90 coll.)

- liquid hydrogen (cold source for beams)
- liquid deuterium (could source)

Reminder: research reactor

1 fast horizontal channel

2 thermal horiz. ch.

3 fast vertical channel

4 thermal vertical ch.

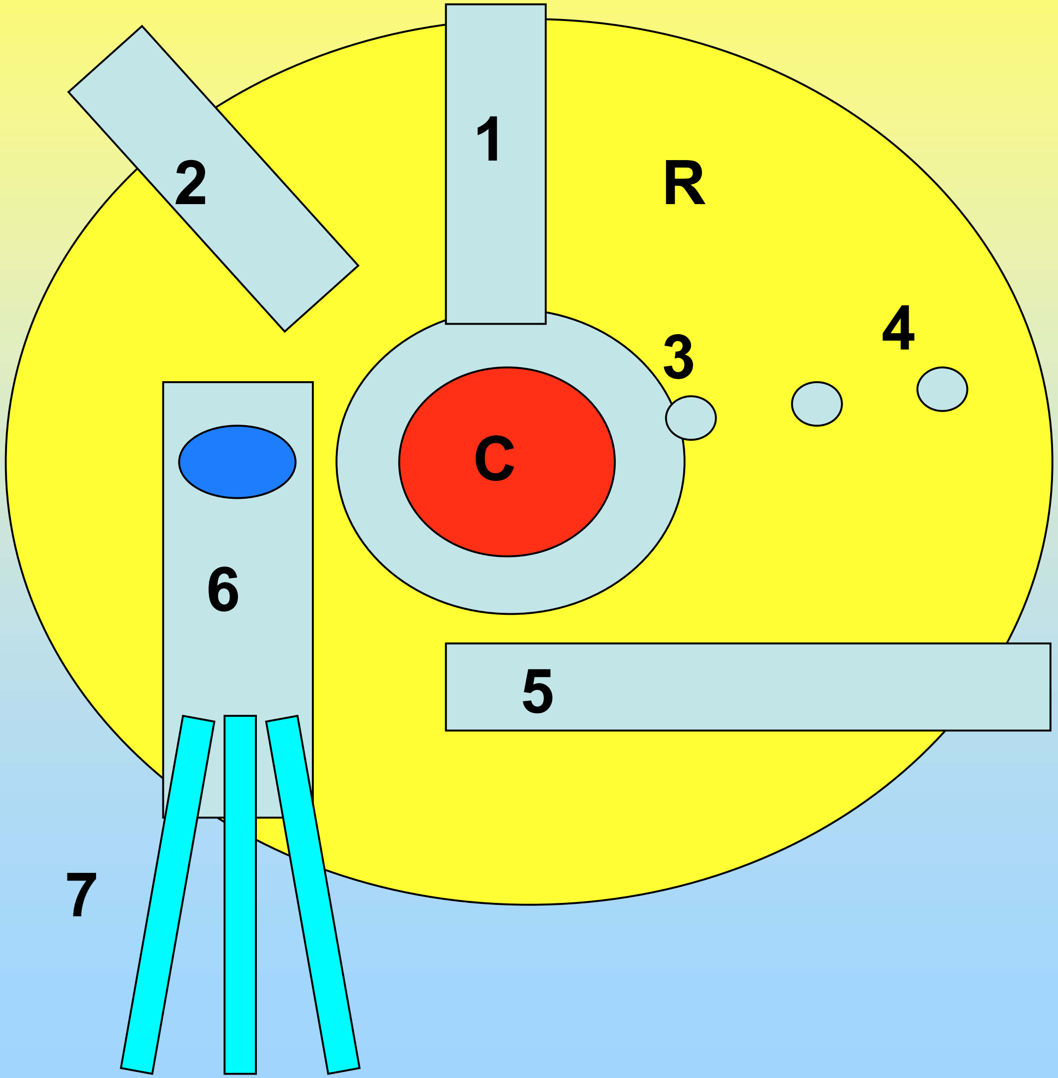
5 tangential channel

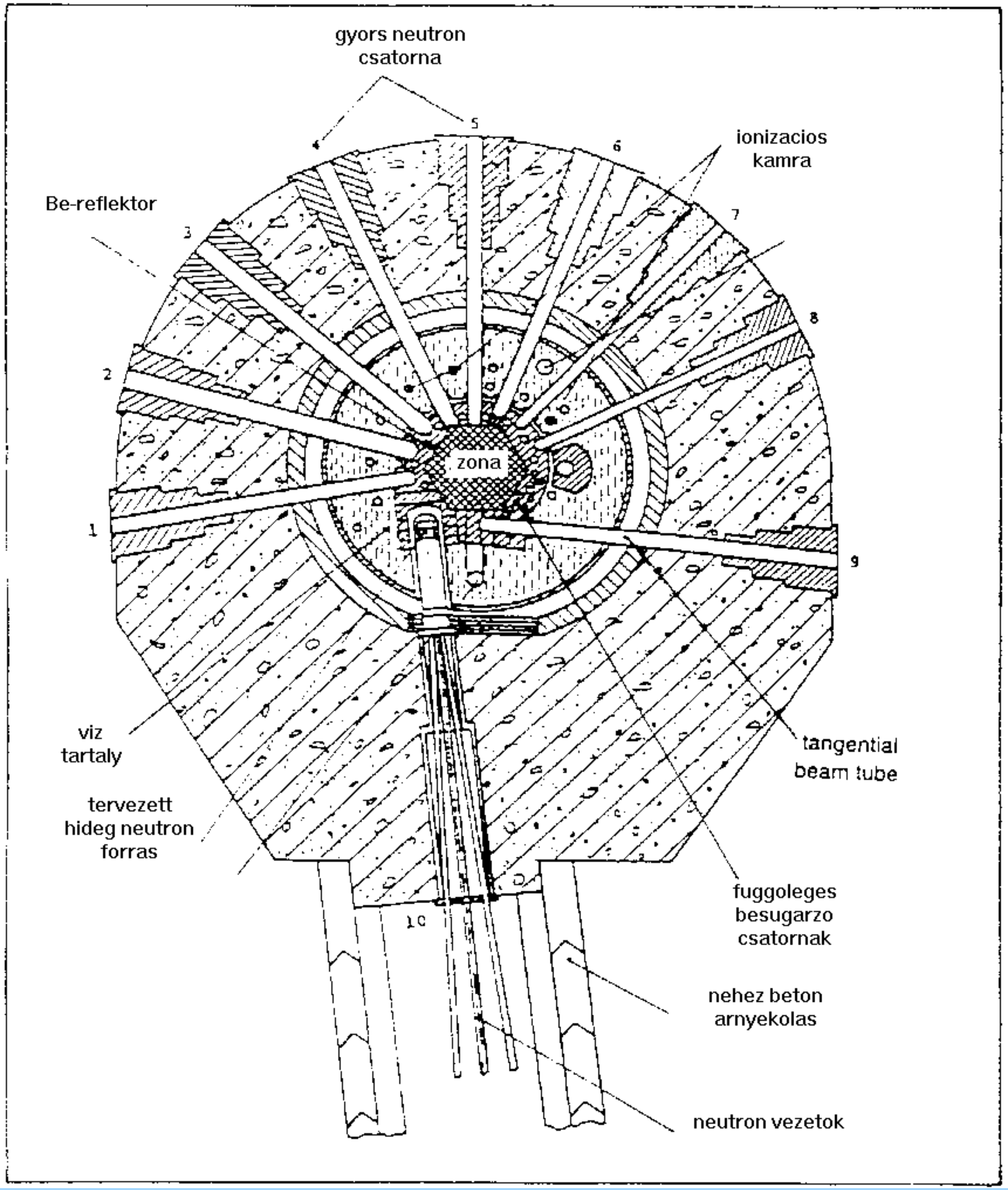
6 tangential channel with a cold source

7 neutron guides

R reflector

C core

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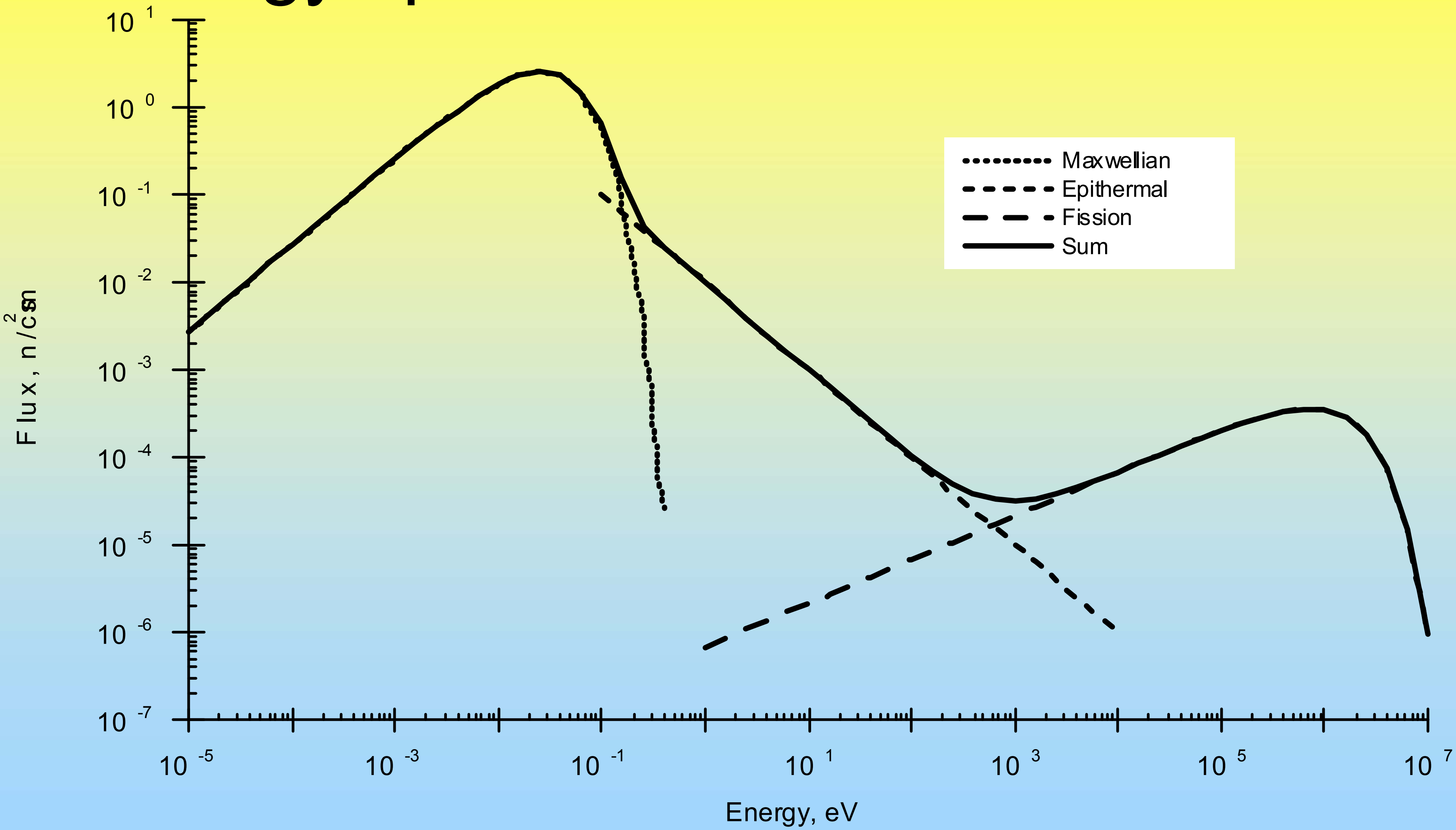
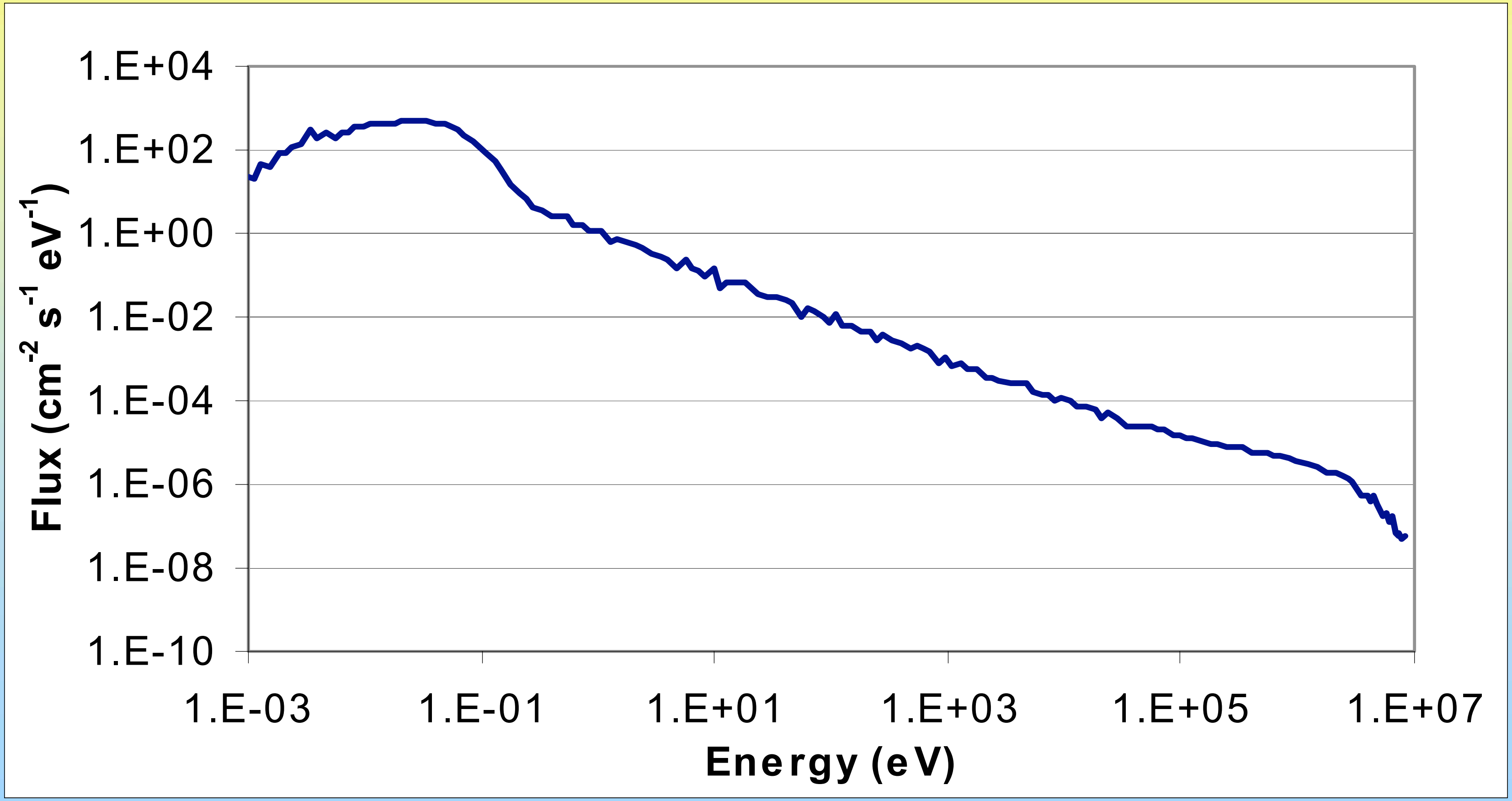
Energy spectrum of reactor neutrons

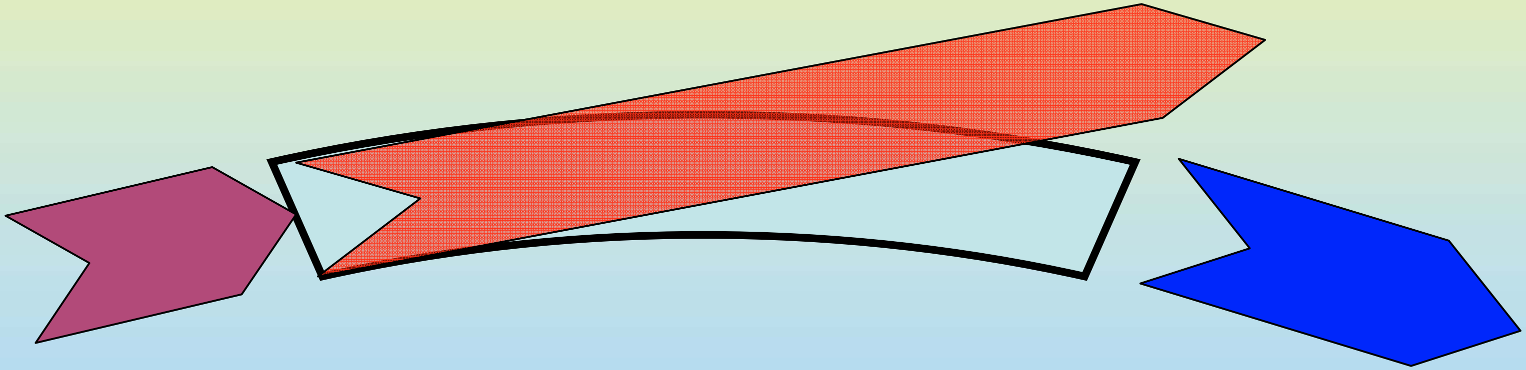


Example (TRIGA reactor) simulated energy spectrum (by A. Trkov)



Neutron guides

- continuation of a horizontal channel
  - thermal and cold neutrons transported
  - epithermal and fast neutron filtered out

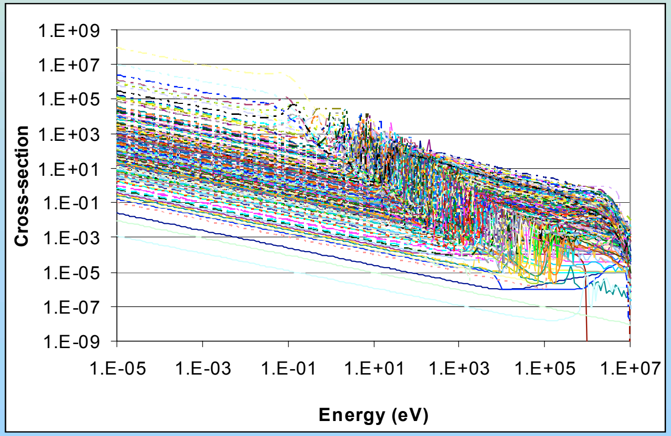


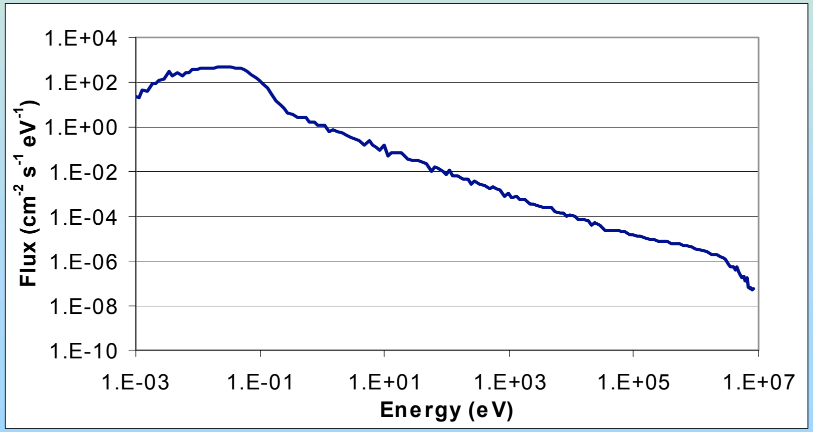
neutron guides distort the neutron spectrum!!!

Goal

Reaction rate for every nuclide

$$R = \int_{0}^{\infty} \sigma(E)\,\varphi(E)\,dE$$

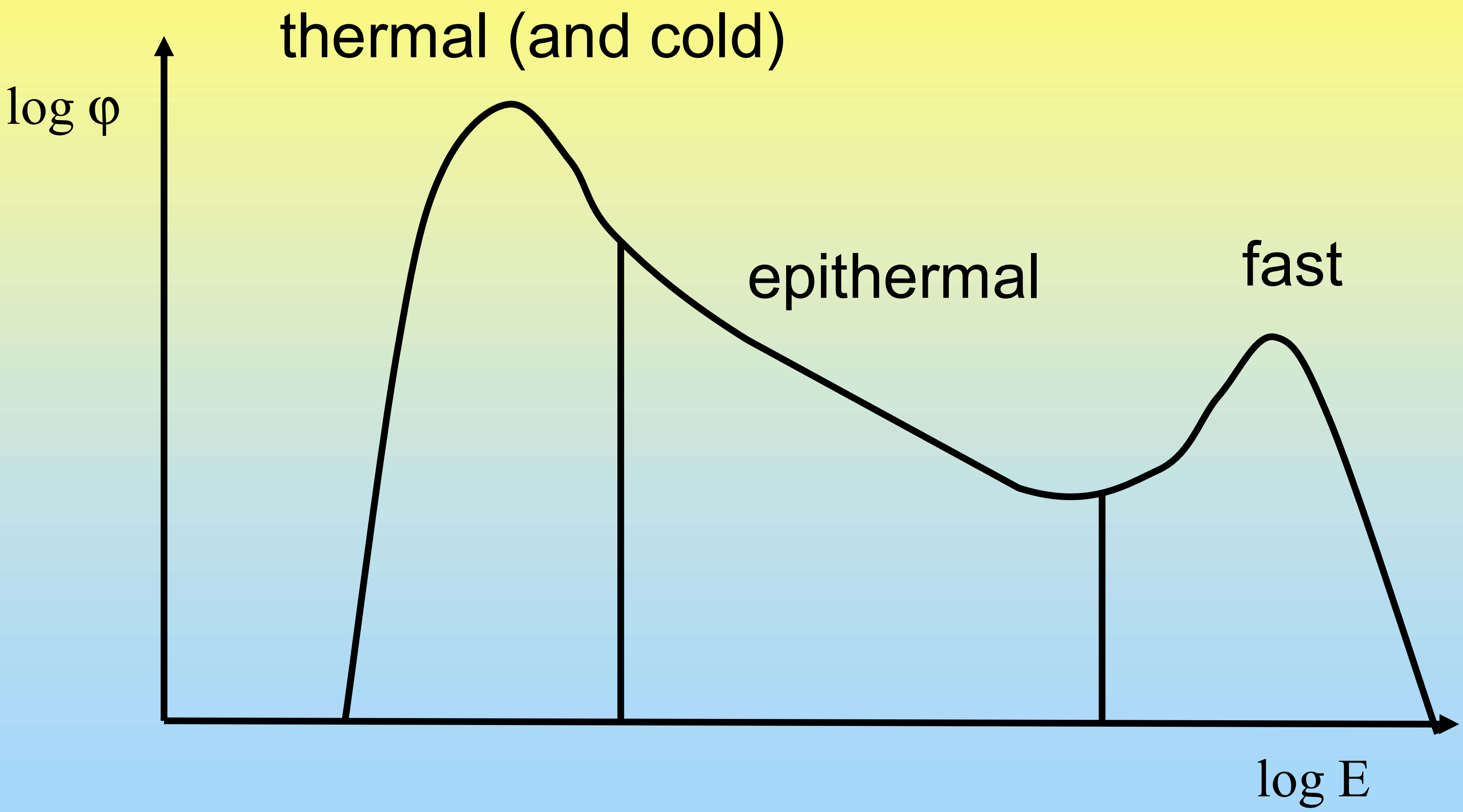




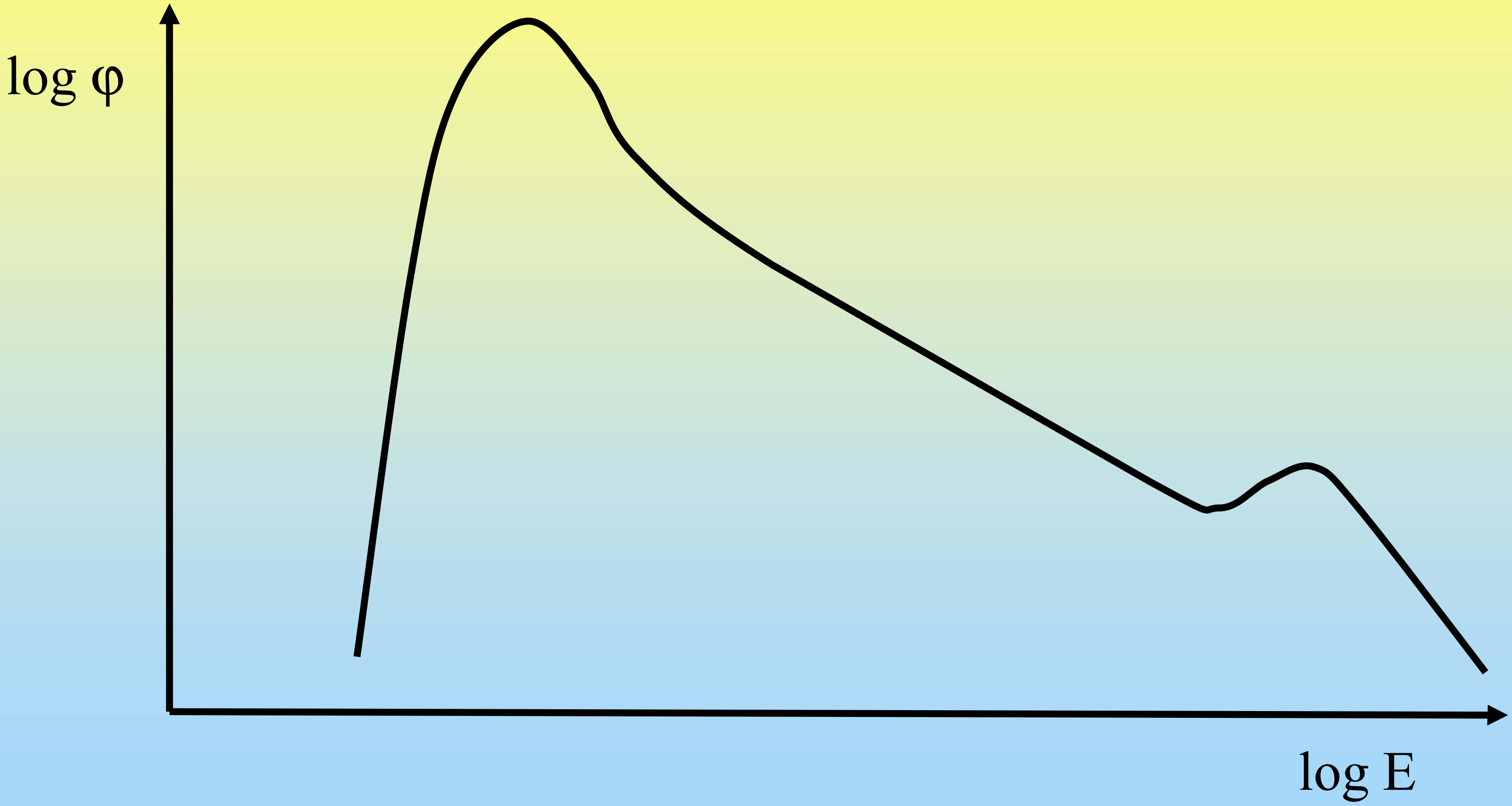
Approximation

- different ranges accounted for separately
  - thermal (and cold)
  - epithermal
  - fast

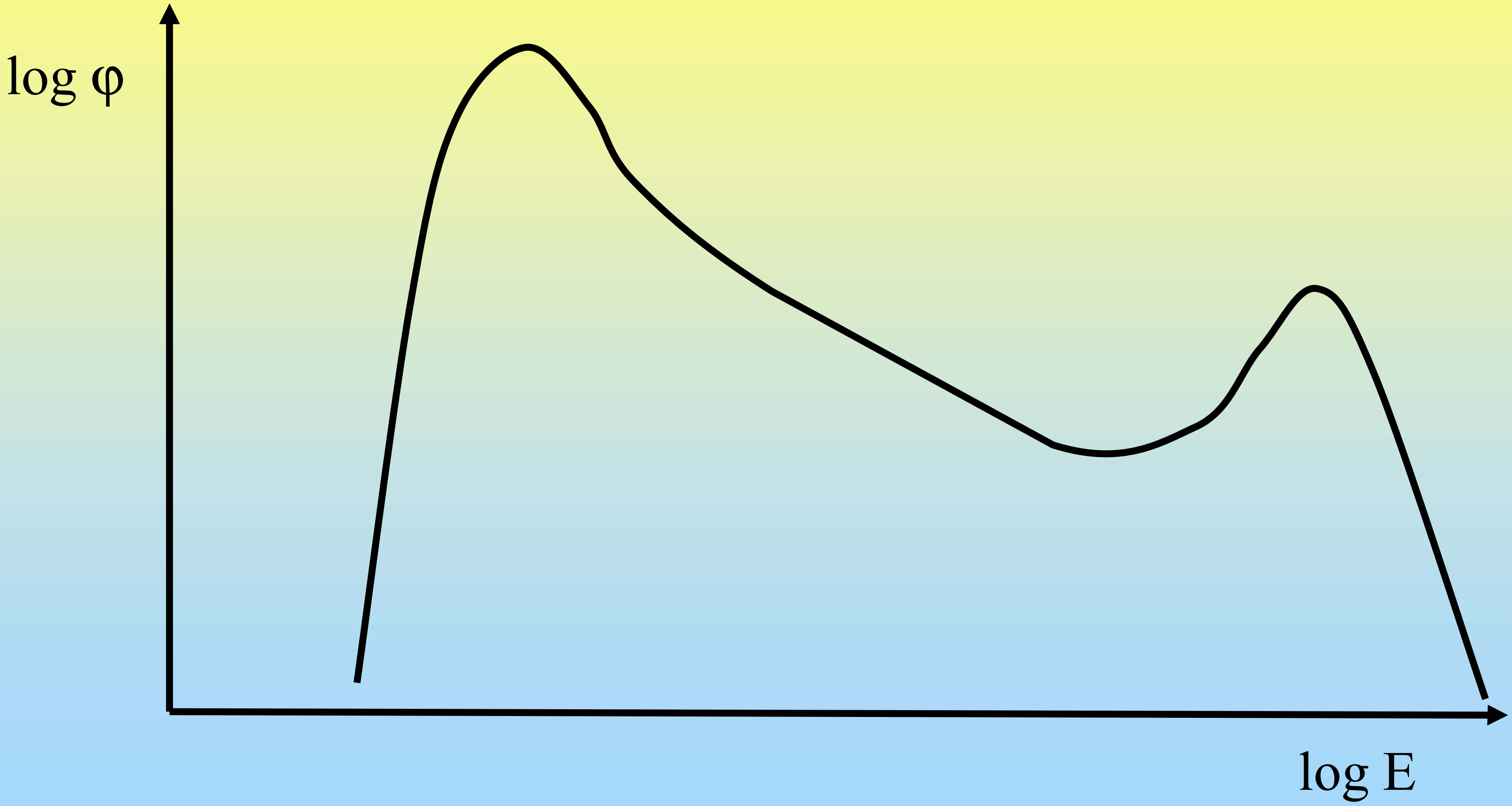
Flux components



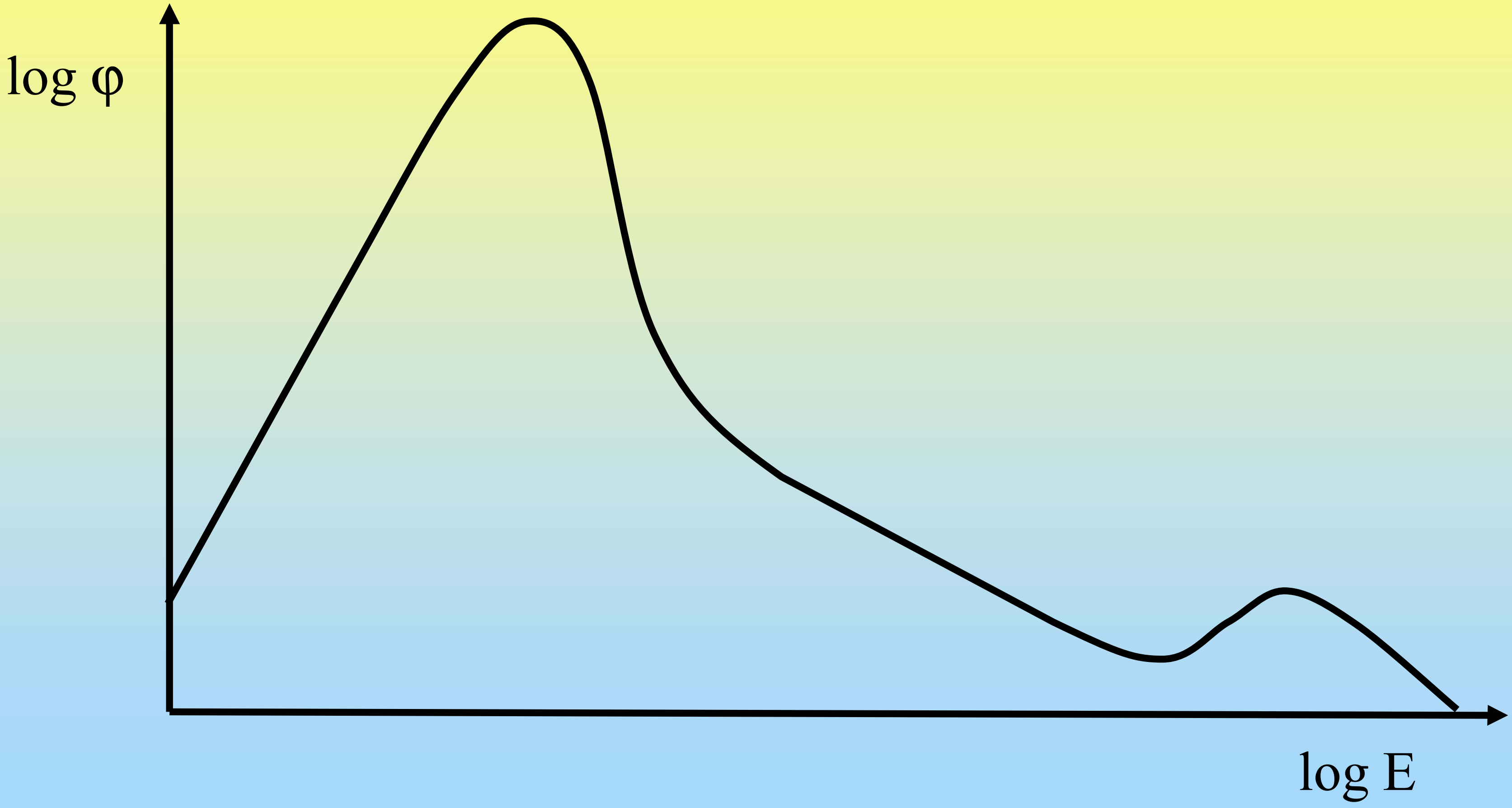
Thermal channel



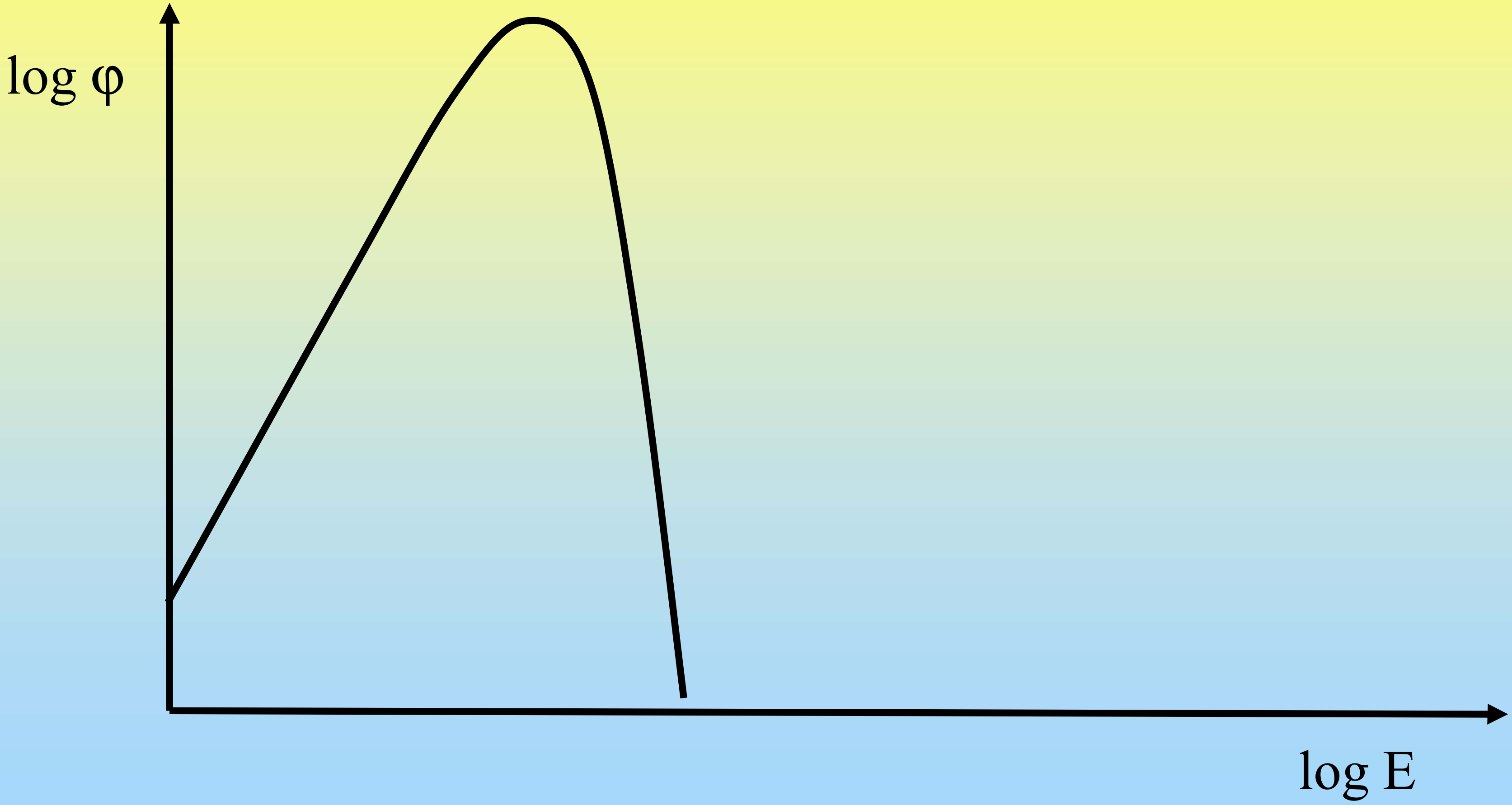
Fast channel



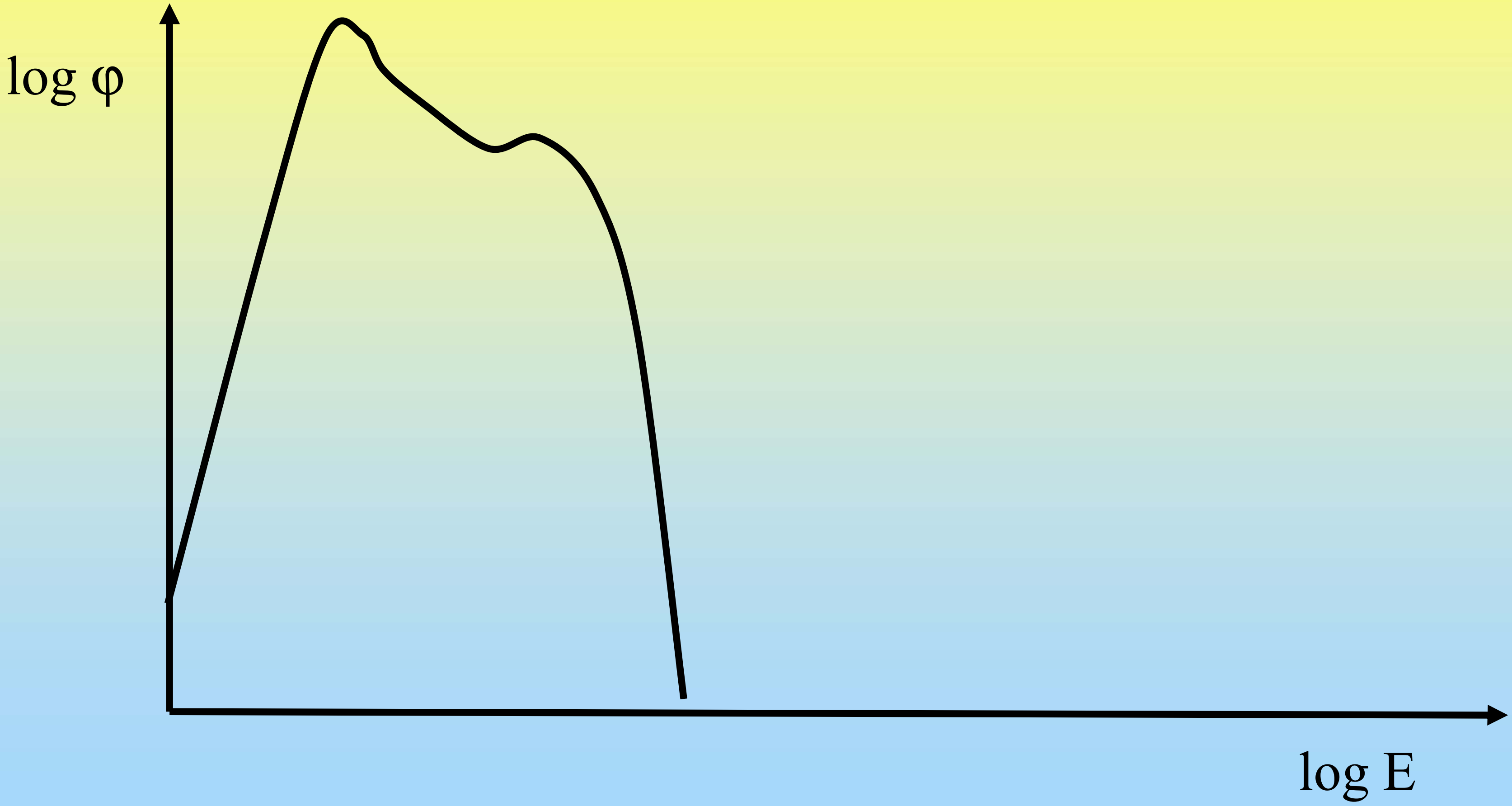
Thermal (tangential) guide



Curved thermal guide



Curved cold guide



Fluxes in different energy ranges

- fission neutrons, fast (~MeV)

$$\varphi(E) = \varphi_{\mathrm{f}} e^{-E} \cdot \sinh\sqrt{2E}$$

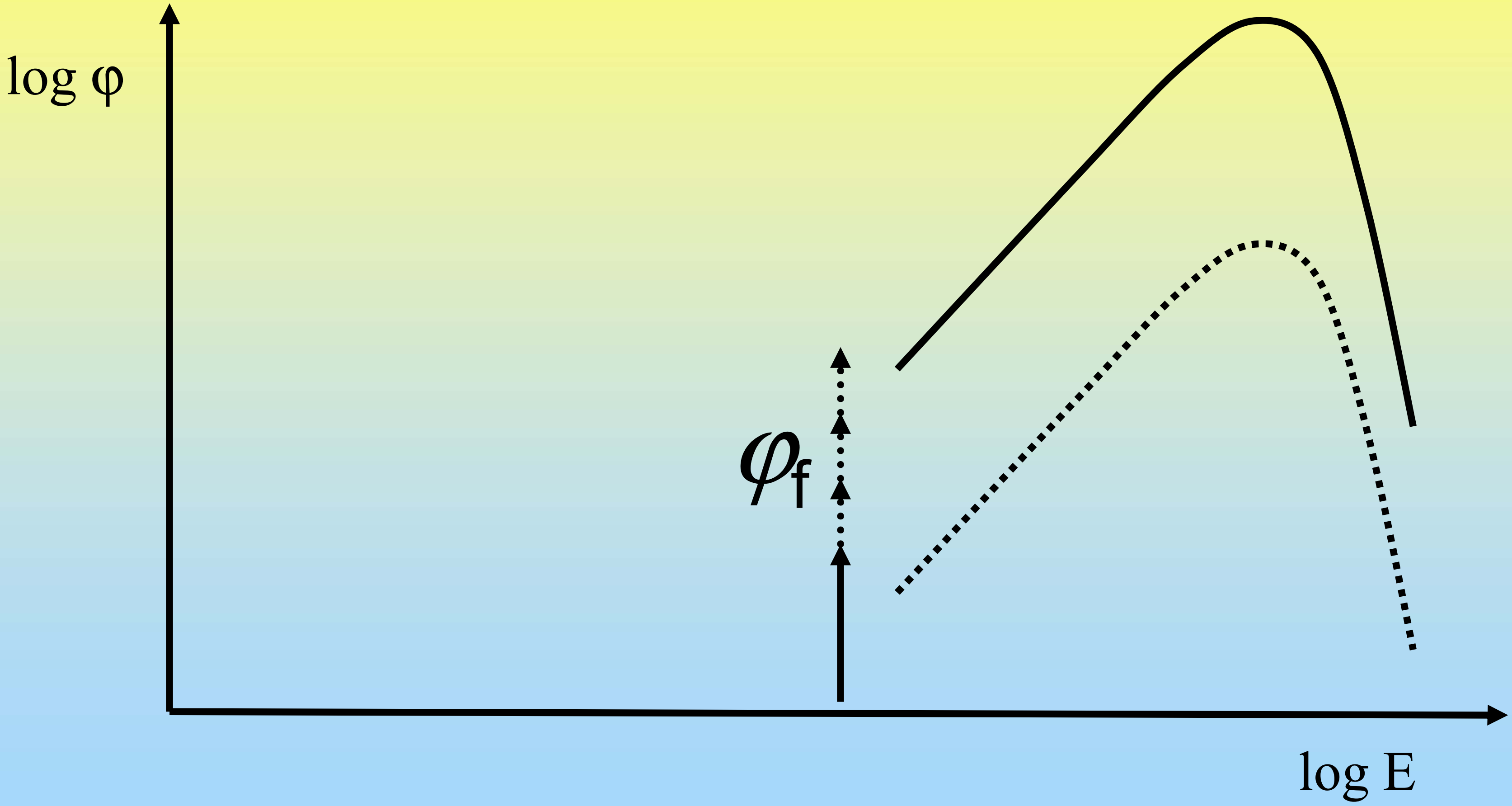
- transitional region, epithermal neutrons (eV—MeV)

$$\varphi(E) = \varphi_{\mathrm{e}} \frac{1}{E} \qquad \varphi(E) = \varphi_{\mathrm{e}} E^{-(1+\alpha)}$$

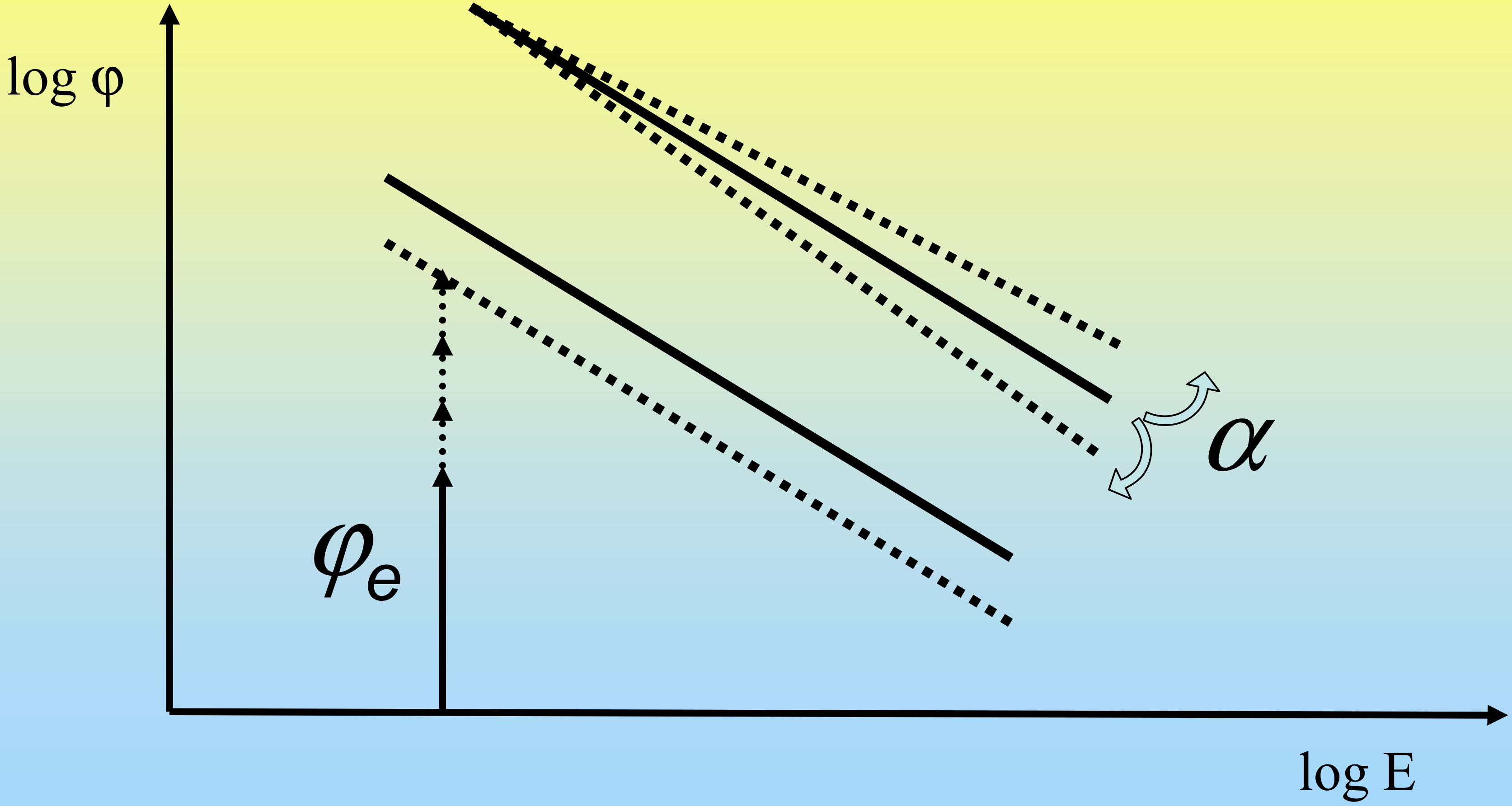
- thermal neutrons (below ~eV)

$$\varphi(E) = \varphi_{\mathrm{t}} E \cdot e^{-E/kT}$$

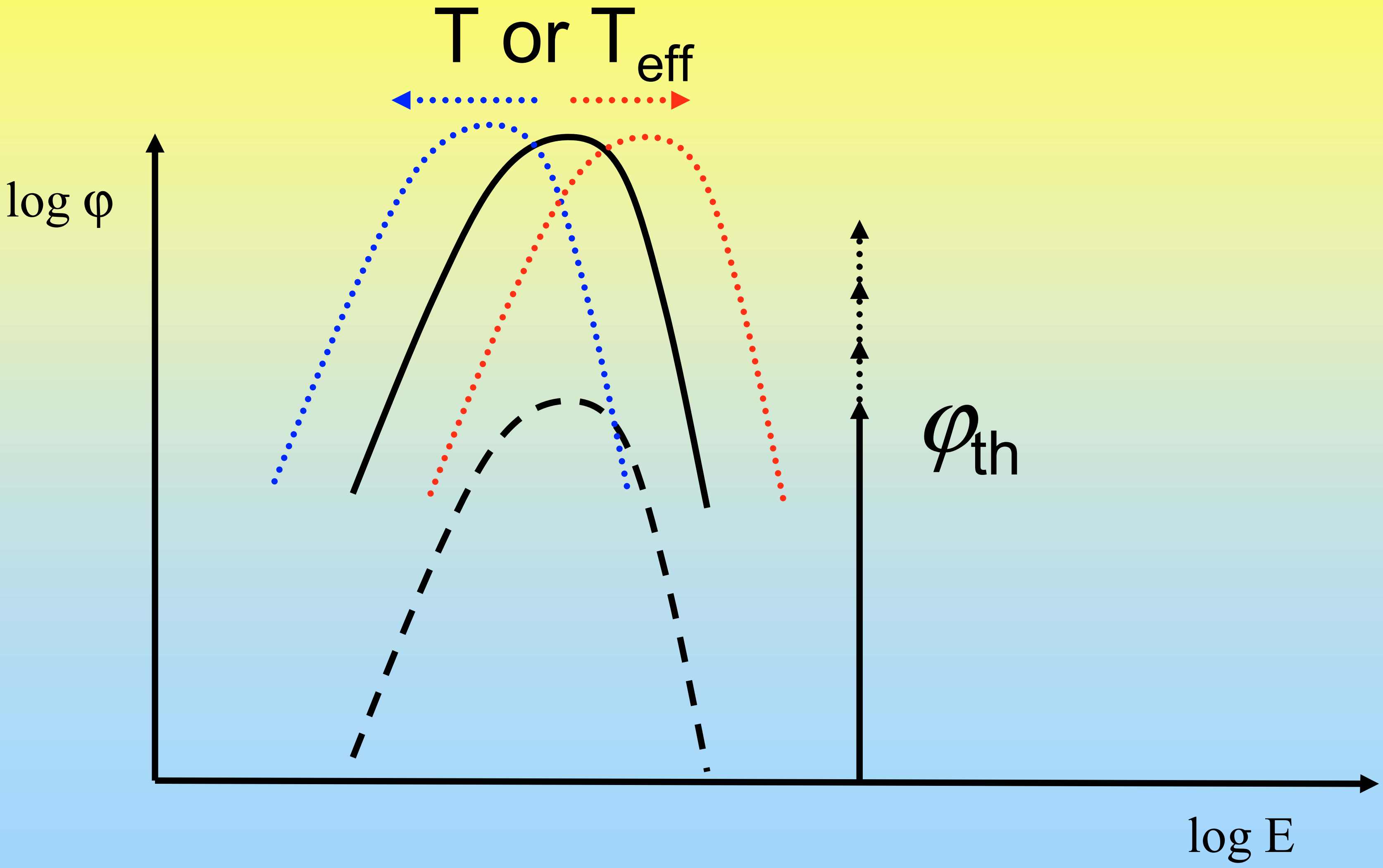
Parameters (fast component)



Parameters (epithermal component)



Parameters (thermal component)



Parameters

- thermal range
  - thermal flux
  - (effective) temperature
- epithermal range
  - epithermal flux, $f = \Phi_{th} / \Phi_e$ ($= \Phi_s / \Phi_e$)
  - α factor (discrepancy from $1/E$ dependence)
- fast range
  - fast flux

Neutron capture induced by different components

- fast neutron   negligible
  - disturbing reactions may occur: (n,p), (n,2n),...
- epithermal   must be corrected for
- thermal   preferable

Reaction rate:

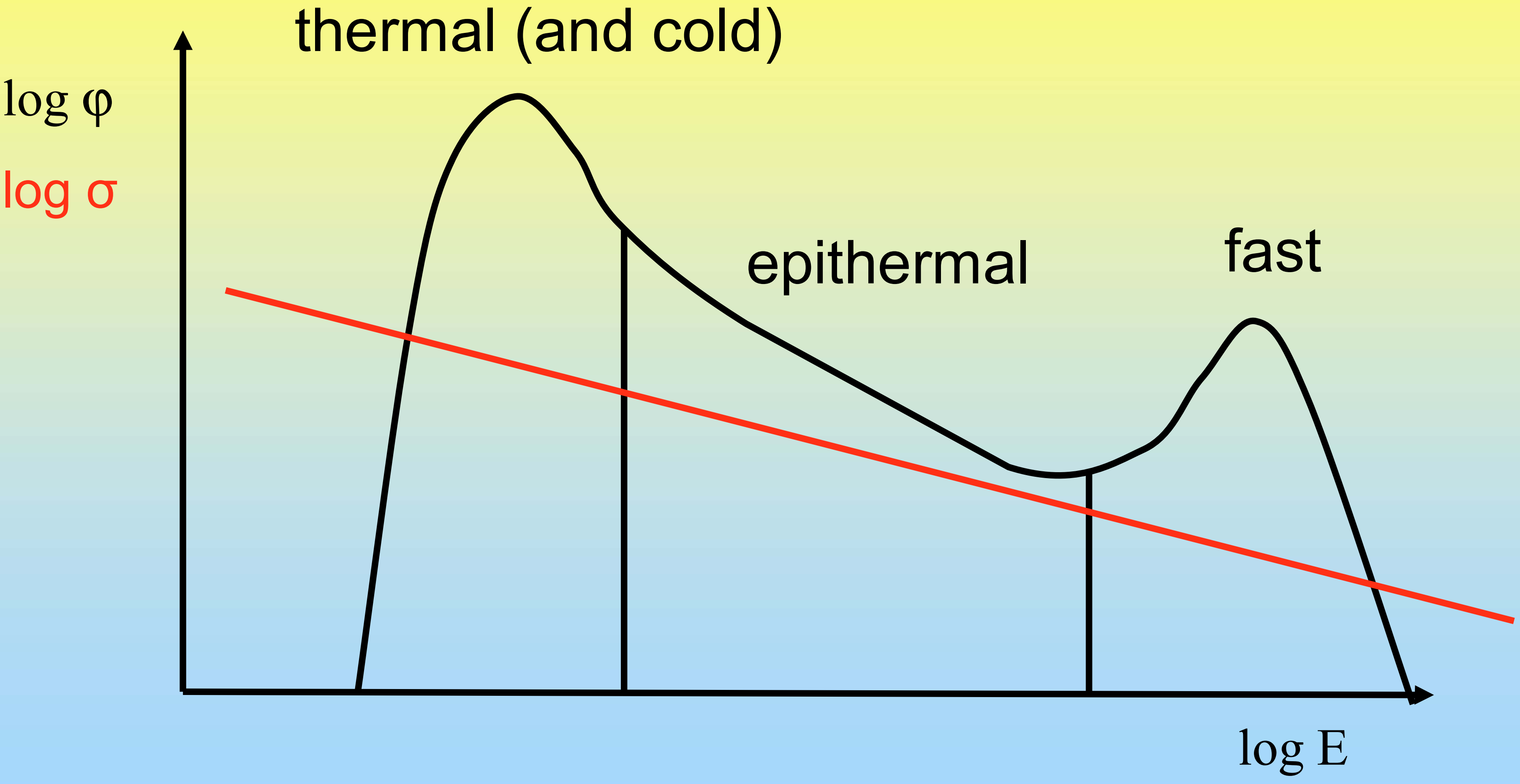
$$R = \int_0^\infty \sigma(E)\,\varphi(E)\,dE =$$

$$= \int_{\text{thermal}} \sigma(E)\,\varphi(E)\,dE + \int_{\text{epithermal}} \sigma(E)\,\varphi(E)\,dE$$

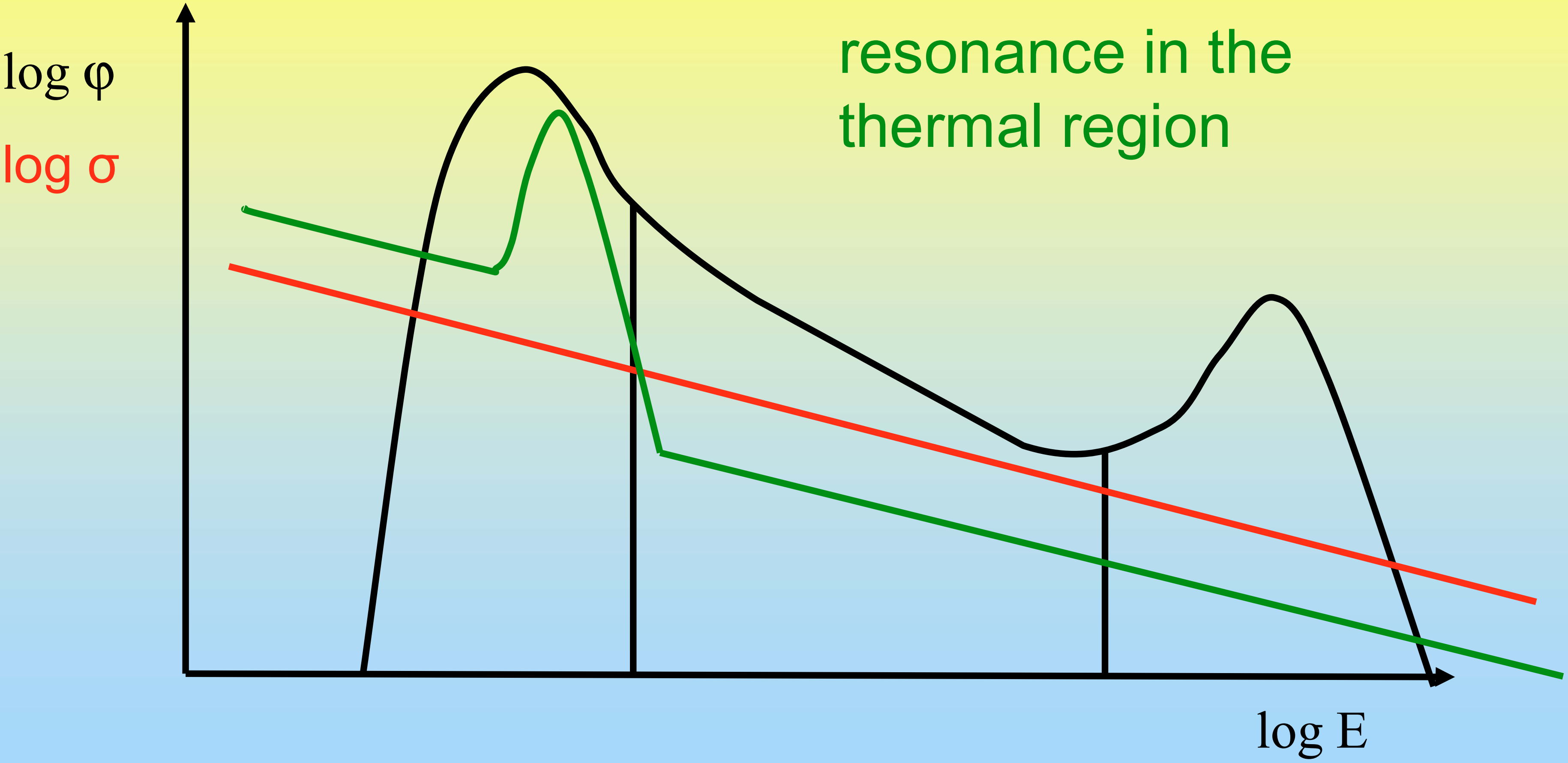
Components used

- thermal (and cold)
  - flux
  - shape
    - Maxwellian / guided Maxwellian
      - temperature
- epithermal
  - flux
  - shape
    - 1/E
    - $1/E^{(1+\alpha)}$
- (fast – disturbing reactions)

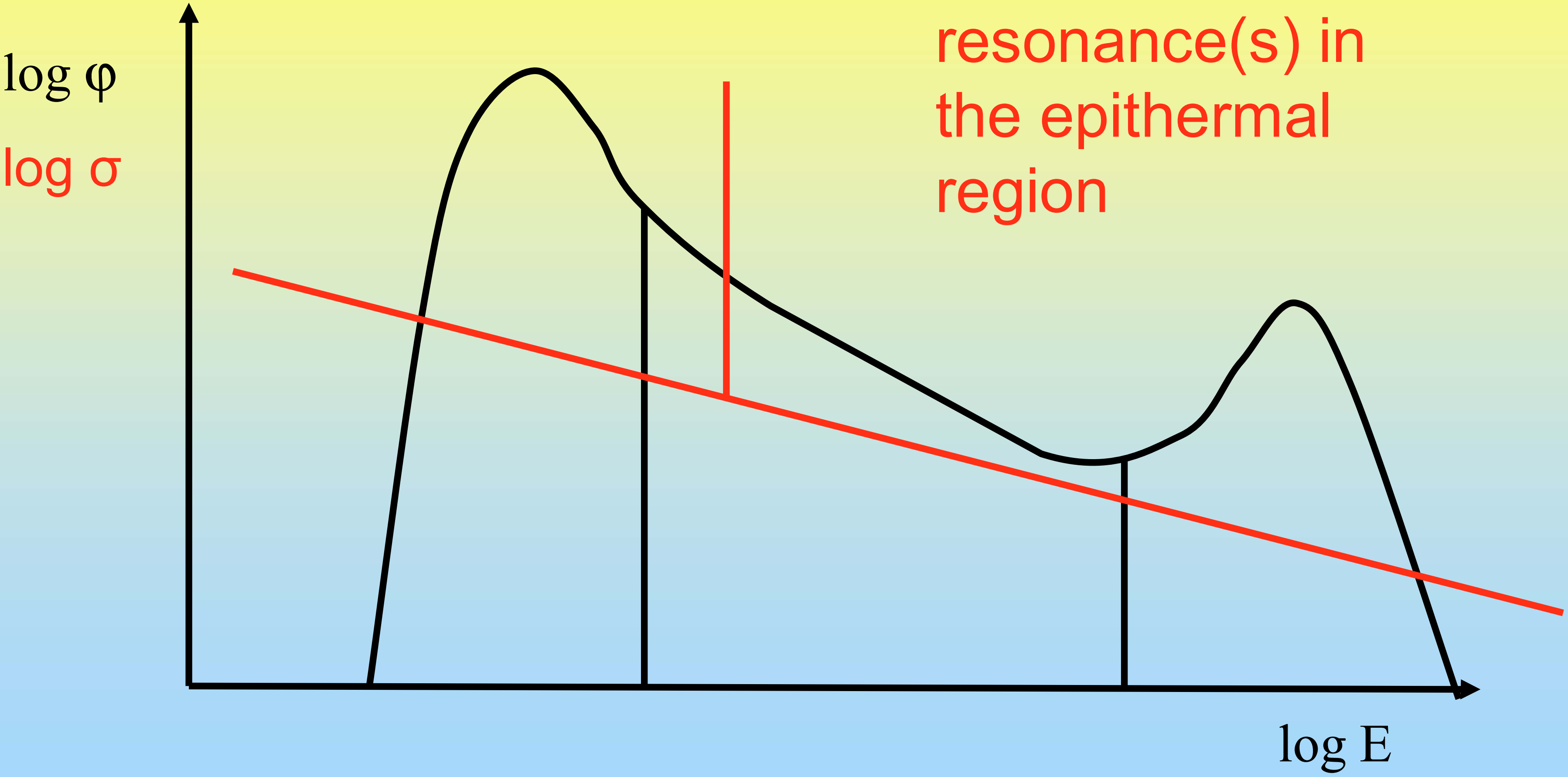
Thermal flux monitor



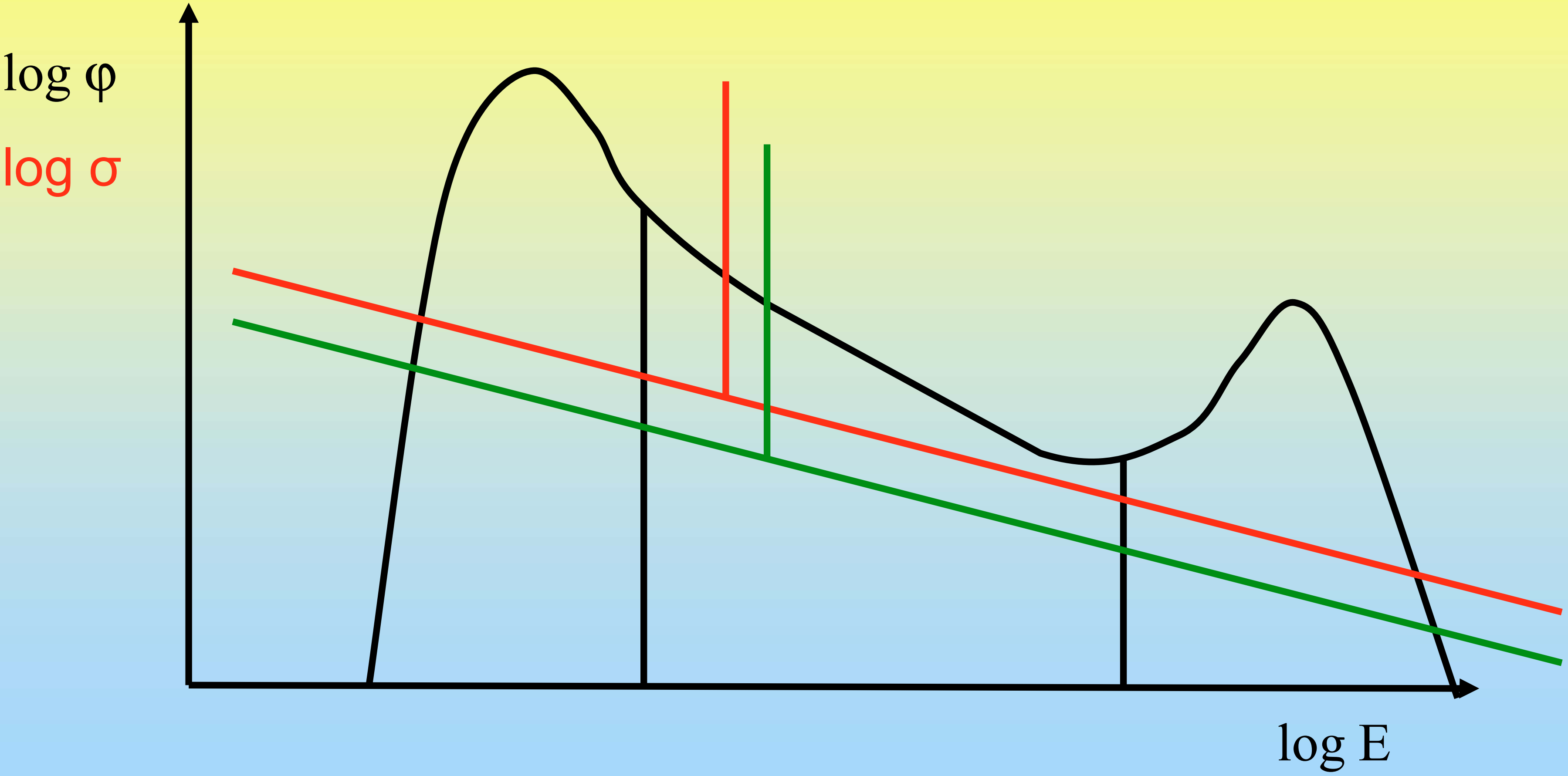
Temperature monitoring in thermal region



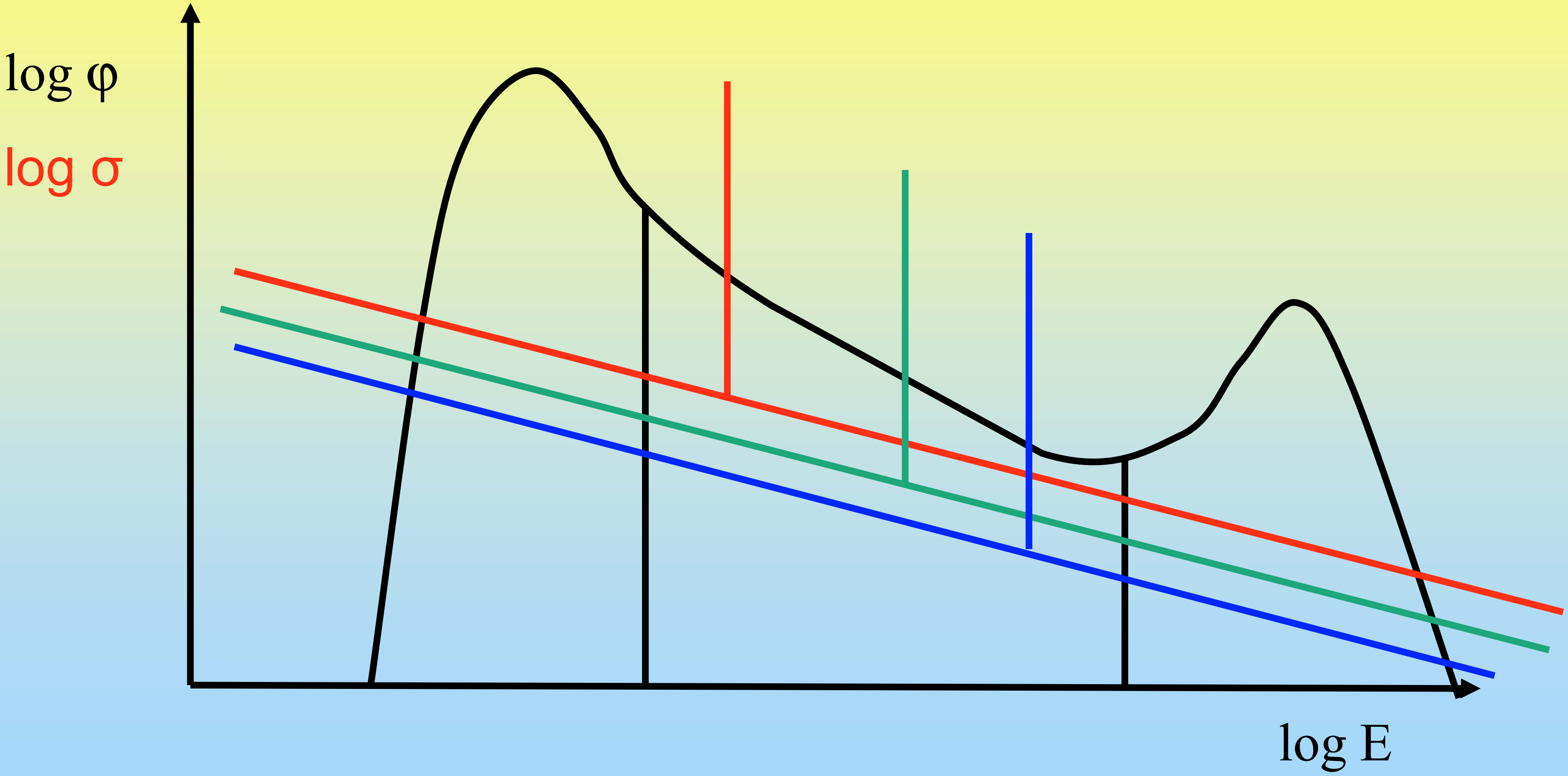
Epithermal flux monitor



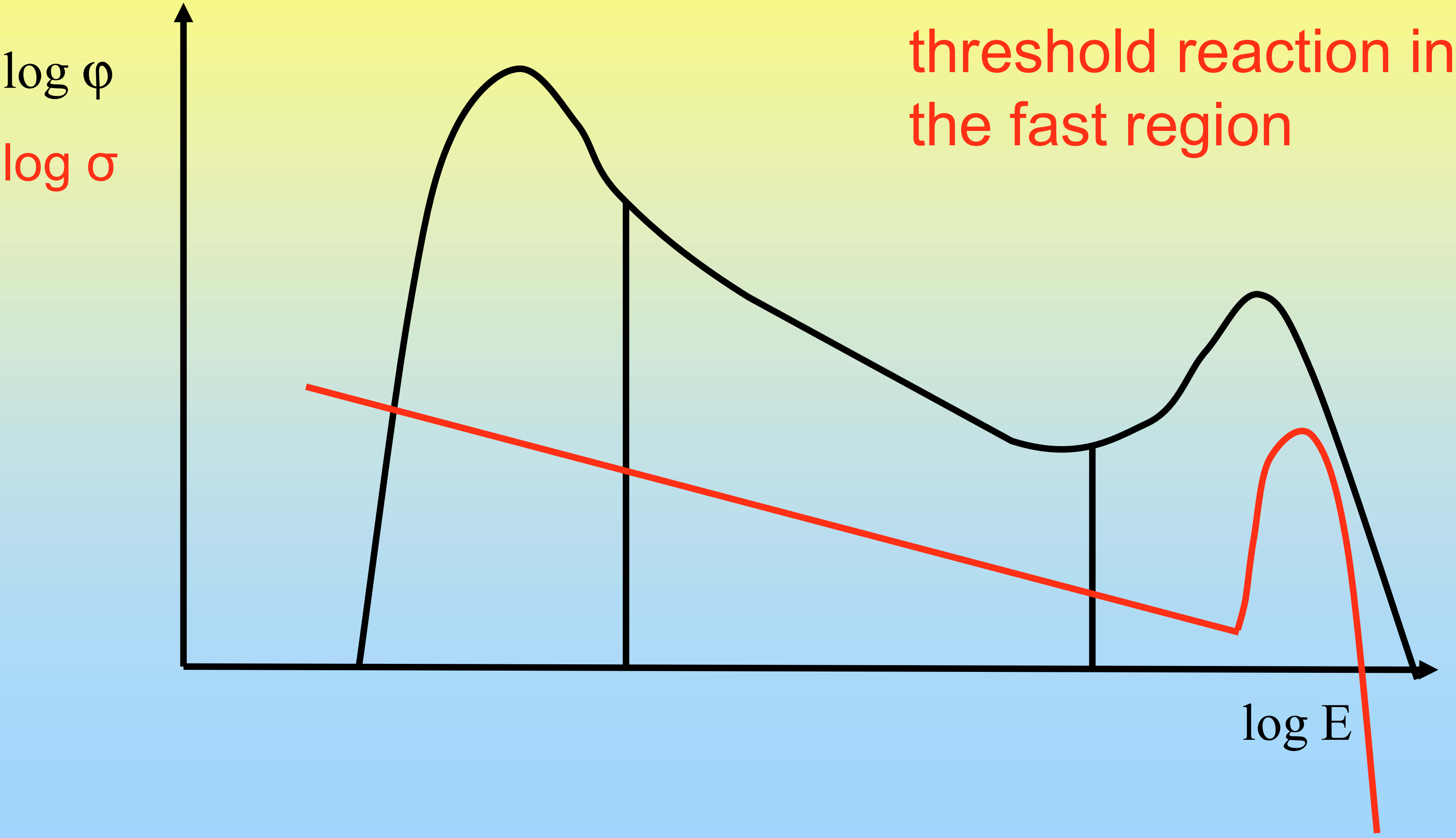
(Thermal/epithermal (*f*) monitor)



α monitoring



Fast flux monitor



Determination of flux parameters (1)

- **1 → Φ_e: for closely Maxwellian**
  - "foil activation" → thermal equivalent neutron flux
    - irradiation with beam:
      - ^{197}Au(n,γ), or prompt gamma emission (e.g. Ti)
    - for long irradiation in reactor:
      - ^{197}Au (**98 barn !!!,** 2.69 day)
        [burn-up of ^{198}Au (26 000b)!!!]
      - ^{59}Co (20 b, 5.27 year)
      - ^{109}Ag (4.7 b, 250 day)
    - for short irradiation in reactor:
      - ^{68}Zn (0.08 b, 14 h)
      - ^{55}Mn (**13 b !!!**, 2.6 h)
      - ^{98}Mo (0.2 b, 66 h)

Determination of flux parameters (2)

- **2 → Φ_s, Φ_e or Φ_s, *f* : for closely ideal reactor spectrum (Maxwellian+1/E)**
  - **"cadmium ratio" method (foil bare + in Cd):**
    - for long irradiation in reactor:
      - ^{197}Au (**98 + 1550barn !!!,** 2.69 day) [burn-up !!!]
      - ^{59}Co (20 + 39 b, 5.27 year)
      - ^{109}Ag (4.7 + 73 b, 250 day)
      - ^{58}Fe (1.3 b, 45 day)
    - for short irradiation in reactor:
      - ^{98}Mo (0.2 + 3.8 b, 66 h)

Determination of flux parameters (3)

- **3 → Φ_s, Φ_e, α or Φ_s, *f*, α :**

for non-ideal n-spectrum (Maxwellian+1/$E^{1+\alpha}$)

  - thermal flux – Fe, or Au
  - *f* and α – ^{197}Au, ^{96}Zr, ^{94}Zr (see later)

Determination of flux parameters (4-5)

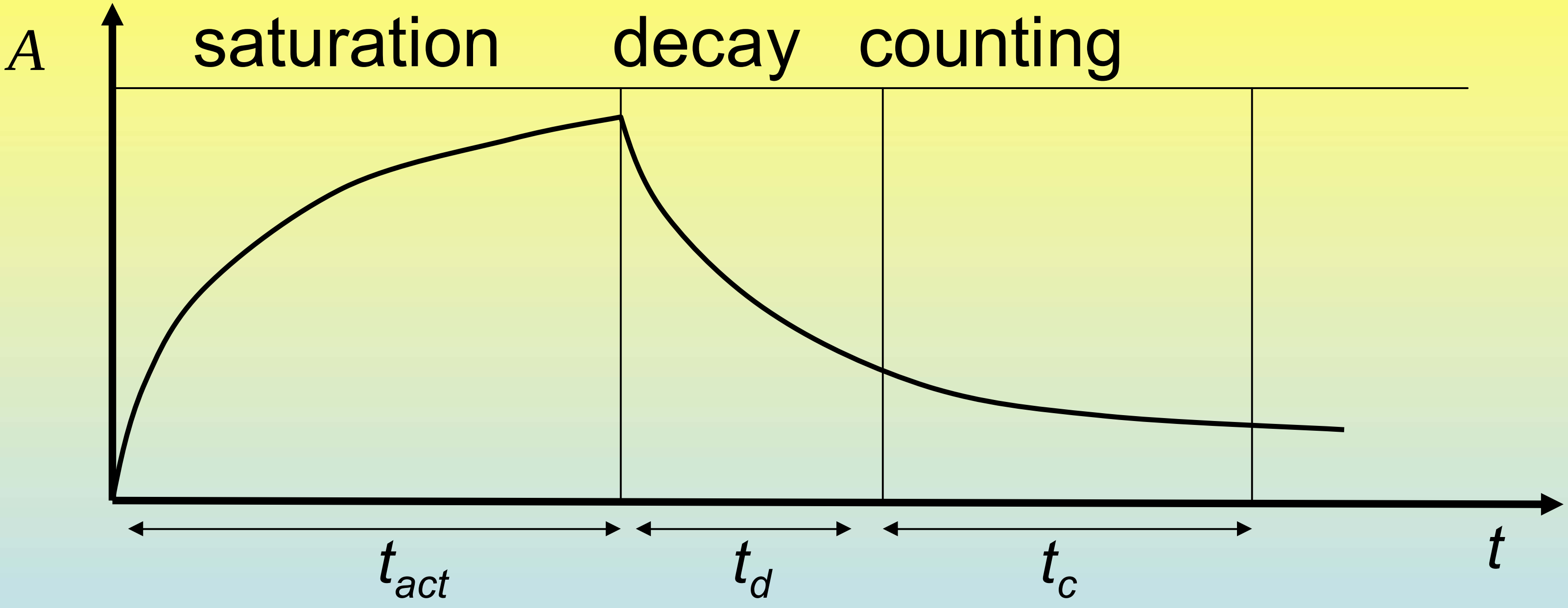
- **4 → + *T* : temperature, for non-ideal n-spectrum (Maxwellian(*T*)+1/E$^{1+\alpha}$)**
  - ^{176}Lu/^{175}Lu or **^{176}Lu**/^{197}Au (2.6+2090 b, 6.7 day)
- **5 → + Φ_f: for fast flux**
  - ^{103}Rh(n,n')^{103m}Rh (0.15 MeV, 720 mbarn)
  - ^{115}In(n,n')^{115m}In (0.6 MeV, 188 mb)
  - ^{58}Ni(n,p)^{58}Co (1 MeV, 113 mb)
  - ^{27}Al(n,p)^{27}Mg (1.9 MeV, 3.5 mb)
  - ^{56}Fe(n,p)^{56}Mn (3.7 MeV, 1 mb)
  - ^{58}Ni(n,2n)^{57}Ni (13 MeV, 13 mb)

Reminder: activation

- reaction rate per atom: $R = \Phi\,\sigma$
- number reactions in t seconds: $N = n\,R\,t = \frac{m}{M} N_A\,R\,t$
- number of emitted gammas (of a given E): $N_\gamma = N\,P_\gamma$
- peak area: $a = \varepsilon\,N_\gamma$
- in case of radioactive decay: $A = a\,S\,D\,C$
- specific count rate: $A_{\mathrm{sp}} = A\,/(m\,t)$

m – mass, M – atomic weight, N_A – Avogadro number
P_γ – emission probability
ε – counting efficiency
$S\,D\,C$ – saturation, decay and counting factors

Reminder: S D C factors



$$S = 1 - e^{-\lambda t_{act}} \qquad D = e^{-\lambda t_d} \qquad C = \frac{1 - e^{-\lambda t_c}}{\lambda t_c}$$

Conventions

reaction rate from

- thermal and
- epithermal neutrons

- Westcott (1955)
  - discrepancy from 1/*v*-law
- Høgdahl (1962) – most popular
  - Cadmium filter method

Westcott convention

- for perfect 1/*v* isotopes (no resonances):

$$R = \Phi_0 \ \sigma_0$$

- for non-1/*v* isotopes in the thermal region

$$R = \Phi_0 \ \sigma_0 \ g(T)$$

where $g(T)$ is the Westcott g factor, describing the non-1/*v* behavior of the nuclide

Westcott convention (2)

- for non-1/*v* isotopes in the epithermal region:

$$R = \Phi_0 \sigma_0 \left(g(T) + r\, s(T) \right)$$

where *R* is the reaction rate / atom

r is the ratio of the epithermal neutrons

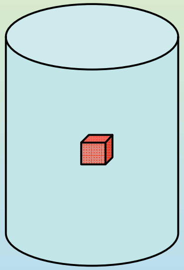
s(*T*) shows the non-1/*v* behavior in the epithermal region

Used for ...

- thermal beams
  - characterization
  - activation
- reactor channels
  - for the correction of non 1/*v* nuclides

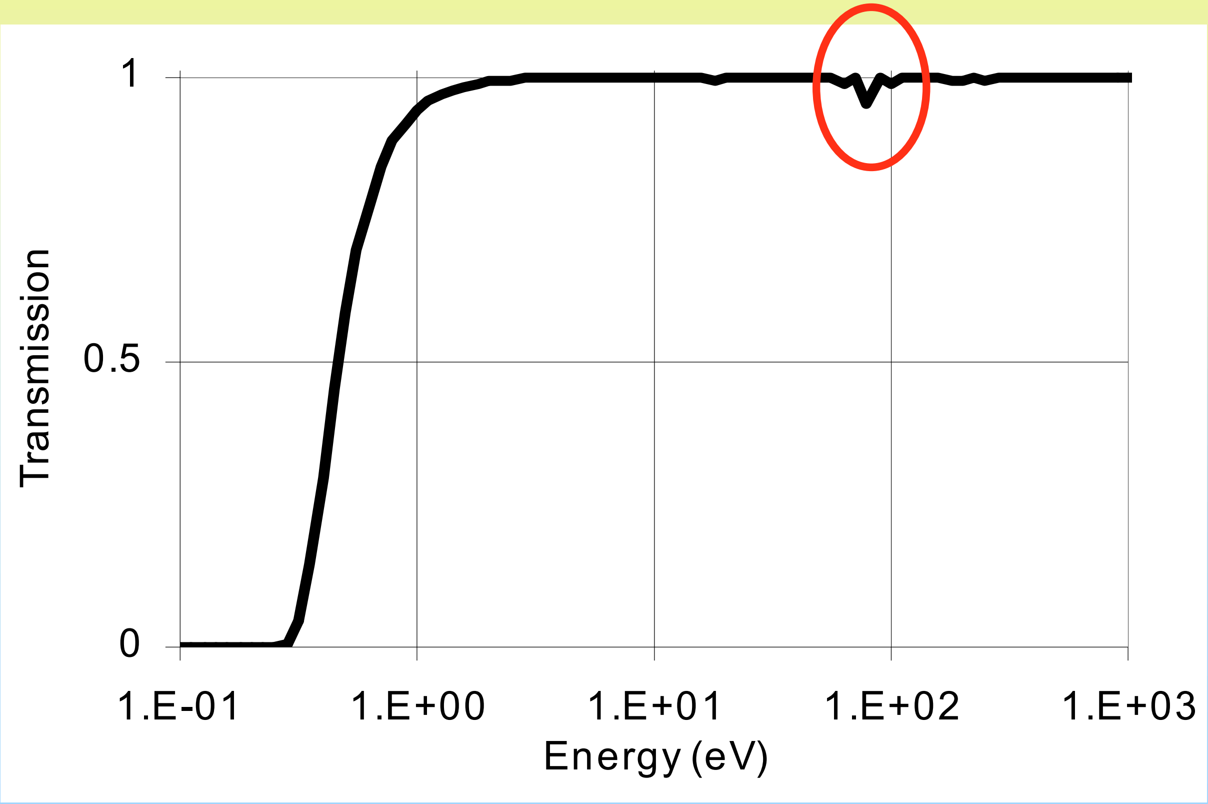
Høgdahl convention

- uses cadmium to separate the thermal and the epithermal component
  - standard Cd shielding:
    - 1 mm thick
    - cylindrical
    - height/diameter = 2
    - sample in the middle
    - epithermal n-spectrum follows 1/*E*



Cadmium cut-off

Transmission through 1 mm Cd



in some cases (e.g. Au and W) the transmission of epithermal neutrons through Cd must be corrected for:

$$R_e \, F_{Cd}$$

Høgdahl convention (2)

$$R = \Phi_s \sigma_0 + \Phi_e I_0 = \Phi_s \sigma_0 (1 + Q_0 / f)$$

Φ_s flux below E_{Cd}

Φ_e flux above E_{Cd}

$$f = \Phi_s / \Phi_e$$

σ_0 thermal cross-section

I_0 resonance integral (above E_{Cd})

$$Q_0 = I_0 / \sigma_0$$

$E_{Cd} = 0.55$ eV

Høgdahl convention (3)
for non-ideal case

$$R = \Phi_s \sigma_0 + \Phi_e I_0(\alpha) = \Phi_s \sigma_0 (1 + f Q_0)$$

I_0 modified resonance integral for $1/E^{1+\alpha}$ neutron spectrum (above E_{Cd})

Used for ...

- reactor channels
  - –characterization
  - –INAA
    - k_0 method

Reminder: k_0

$$k_0 = \frac{A_{sp} - (A_{sp})_{Cd}}{A_{sp}^* - (A_{sp}^*)_{Cd}} \frac{\varepsilon^*}{\varepsilon} = \frac{A_{sp}}{A_{sp}^*} \frac{f + Q_0^*}{f + Q_0} \frac{\varepsilon^*}{\varepsilon} =$$

$$= \frac{M^* \theta P_\gamma \sigma_0}{M \theta^* P_\gamma^* \sigma_0^*}$$

Determination of thermal flux in case of no epithermal component

- ^{197}Au ($\theta=1$) is a 1/*v* nuclide in the thermal region,
  - thermal cross-section: σ_0 = 98.65±0.09 barn
  - emission probability of 411 keV: $P\gamma = 0.9556$
- if the thickness is < 25µm, then the absorption is < 1%.

$$\frac{A_{\mathrm{Au}}}{\varepsilon} = \frac{m}{M} N_A \cdot \Phi_0 \cdot \theta P_\gamma \sigma_0 \cdot t_c \; S \; D \; C$$

A – peak area, ε – counting efficiency, m – mass, $N_A=6.022\times10^{23}$, t_c – counting time, *S D C* – saturation, decay and counting factors.

Determination of epithermal + thermal fluxes

- ^{197}Au has a large resonance at 4.91 eV
  - resonance integral: I_0 = 1550±28 barn
- two foils
- bare Au (same as previous) A_{Au}
- Au in 1-mm thick Cd foil must be thinner $A_{Au(Cd)}$

$$\frac{A_{\mathrm{Au(Cd)}}}{\varepsilon} = \frac{m}{M} N_A \cdot \Phi_e \cdot I_0 P_\gamma \cdot t_c \; S \; D \; C$$

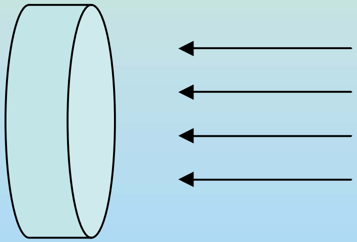
$$\frac{A_{\mathrm{Au}}}{\varepsilon} = \frac{m}{M} N_A \cdot (\Phi_s \sigma_0 + \Phi_e I_0) P_\gamma \cdot t_c \; S \; D \; C$$

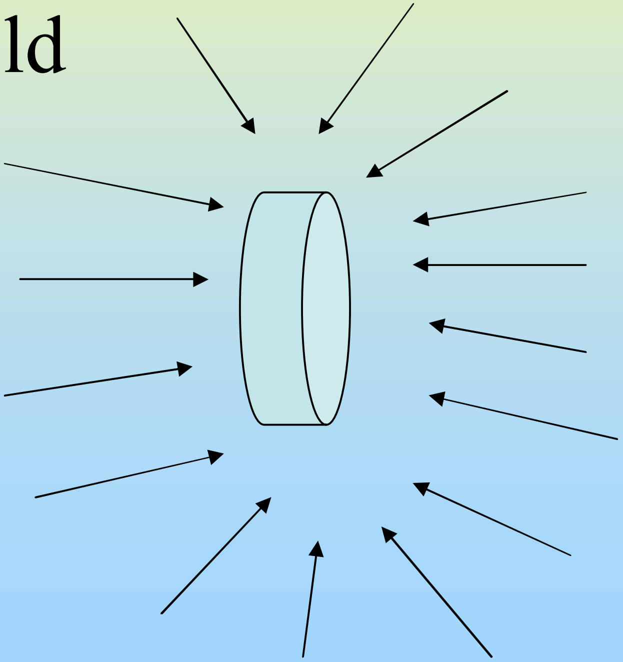
Self-shielding

- in case of self-shielding flux values must be corrected for:

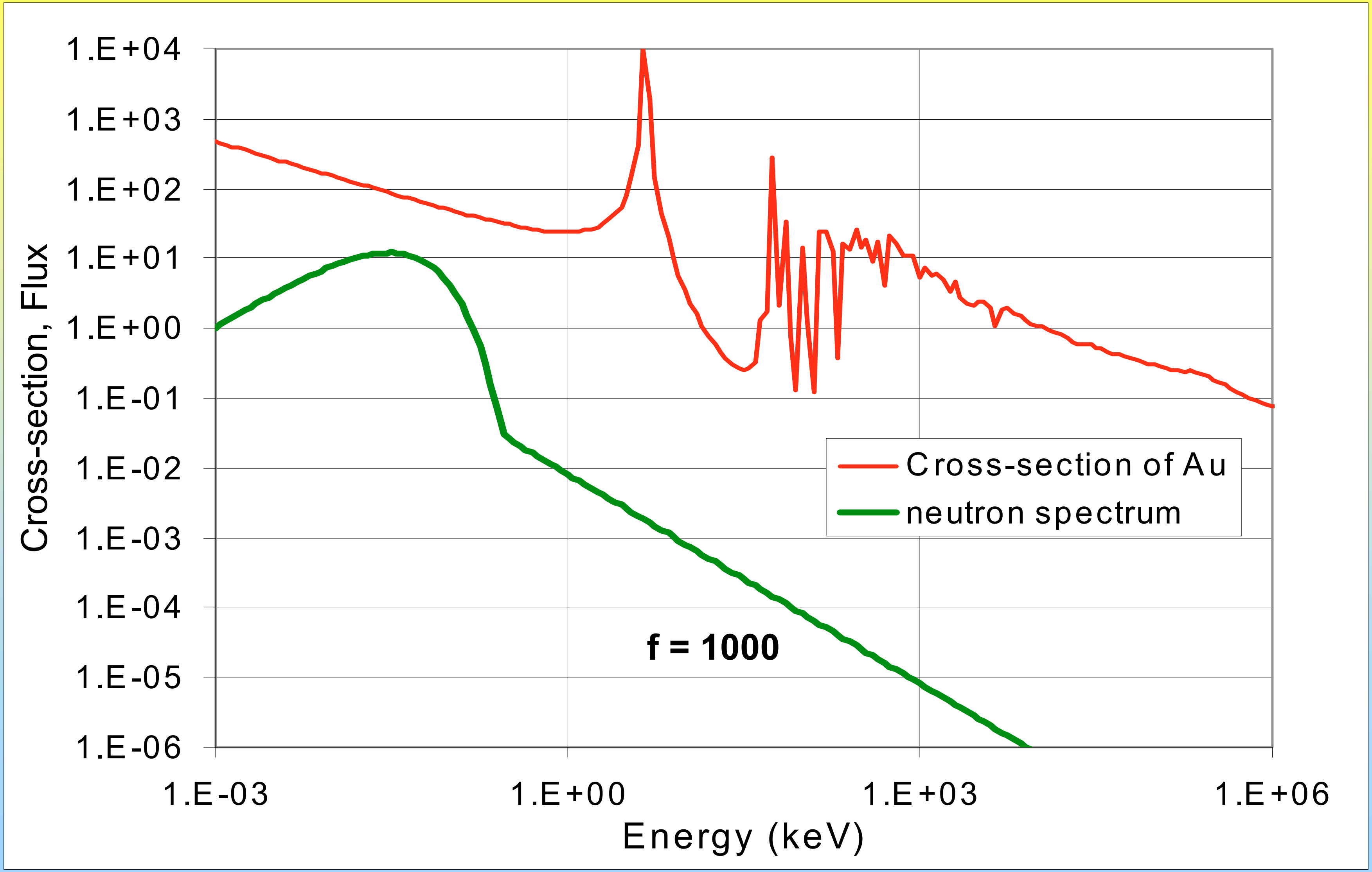
$$G_{th}\,\Phi_s \qquad\qquad G_e\,\Phi_e$$

- beam ↔ isotropic neutron field

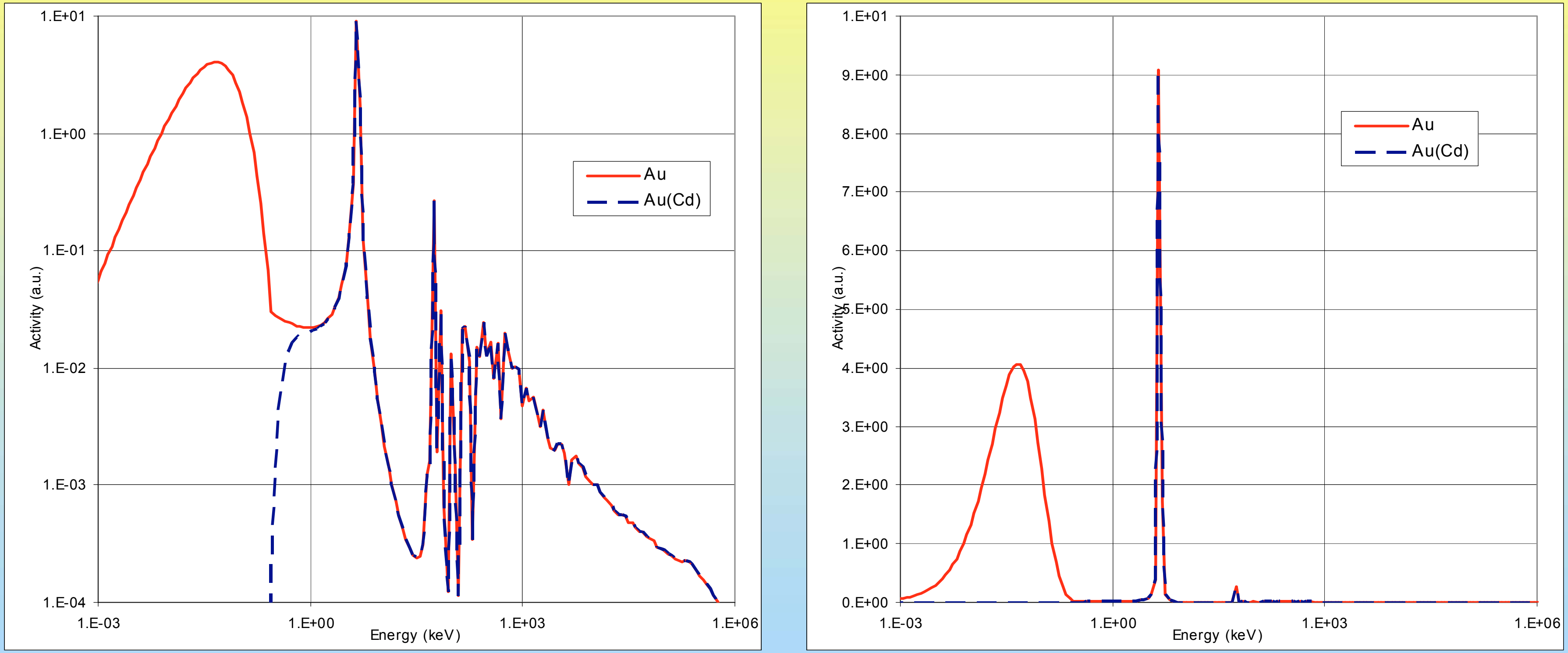




Activation of Au



Activation of Au (2)
Au foil with and without Cd



logarithmic *f* = 1000 linear

When Cd cannot be used...

- Cd melts at 321°C
  - when the channel is too hot
- Cd suppresses the flux in its vicinity

→ **“bare multimonitor” methods must be used**

Determination of *f* with bare multimonitor method

- $R = \Phi_s\, \sigma_0\, (1 + Q_0 / f\,)$ for nuclides 1 and 2

$$f = \frac{R_1 \sigma_{0,2} - R_2 \sigma_{0,1}}{Q_{0,1}\, R_2 \sigma_{0,1} - Q_{0,2}\, R_1 \sigma_{0,2}}$$

$$\left(f = \frac{G_{e,1} \dfrac{k_{0,1}}{k_{0,2}} \dfrac{\varepsilon_1}{\varepsilon_2} Q_{0,1} - G_{e,2} \dfrac{A_{sp,1}}{A_{sp,2}} Q_{0,2}}{G_{th,2} \dfrac{A_{sp,1}}{A_{sp,2}} - G_{th,1} \dfrac{k_{0,1}}{k_{0,2}} \dfrac{\varepsilon_1}{\varepsilon_2}} \right)$$

If epithermal flux is not ideal...

- *f* will be different calculated for different nuclide pairs

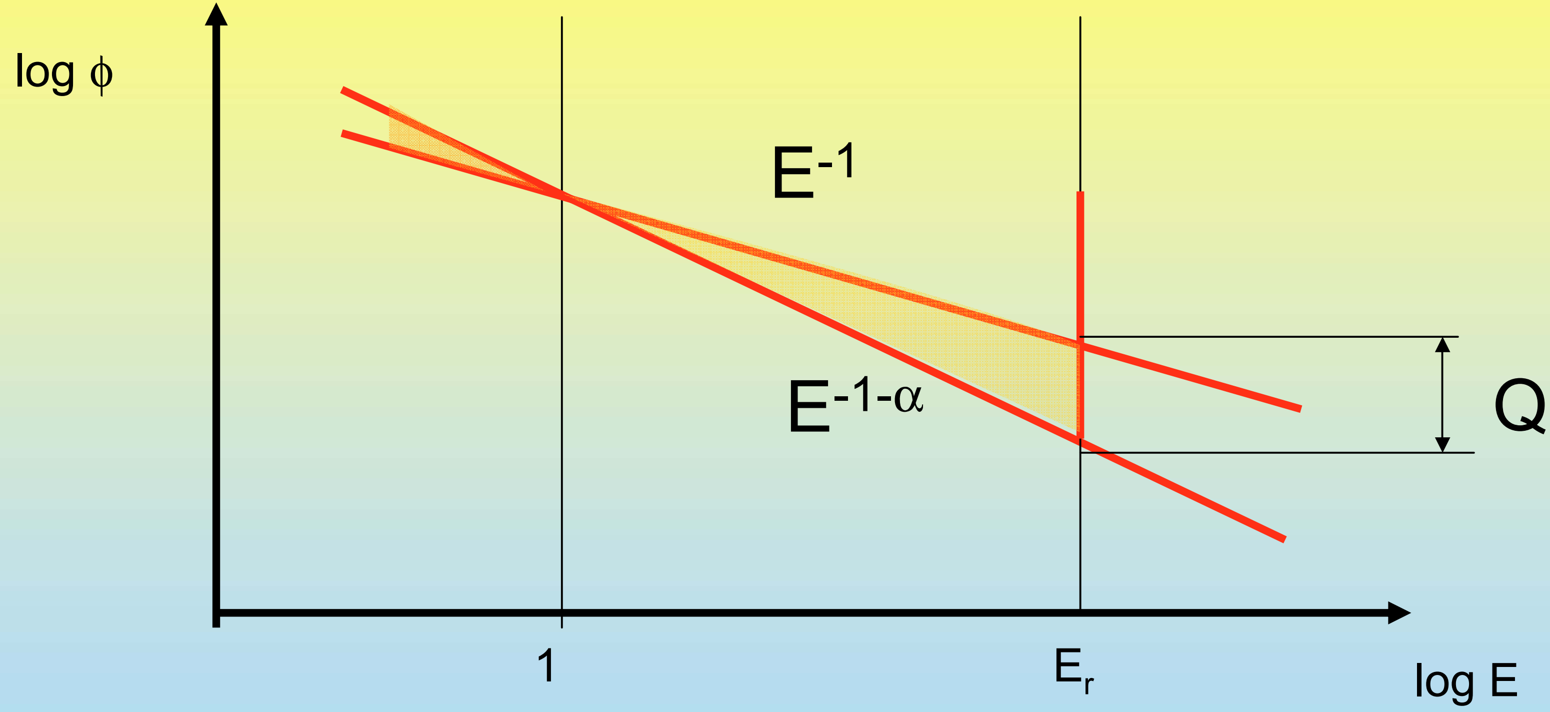
Introduction of α helps in most cases

$$\varphi(E) = \varphi_{\mathrm{e}} E^{-(1+\alpha)}$$

- $\alpha < 0$: H_2O moderated reactors, close to core, poorly moderated channels
- $\alpha > 0$: in graphite and D_2O reactors

$Q_0 \rightarrow Q_0(\alpha)$ (1)

when the nuclide has one (significant) resonance at E_r



$$Q_0(\alpha) = \frac{Q_0 - 0.429}{E_r^{\alpha}} + \frac{0.429}{(2\alpha+1)\,0.55^{\alpha}}$$

$Q_0 \rightarrow Q_0(\alpha)$ (2)

when the nuclide has several resonances

$$Q_0(\alpha) = \frac{Q_0 - 0.429}{\bar{E}_r^{\alpha}} + \frac{0.429}{(2\alpha + 1)\, 0.55^{\alpha}}$$

$\bar{E}_r$ effective resonance energy

can be determined in different channels having different α-s

Determination of α

- determination of *f* from two pairs (at least 3 nuclides)

$$f = \frac{R_1 \sigma_{0,2} - R_2 \sigma_{0,1}}{Q_{0,1}(\alpha)\, R_2 \sigma_{0,1} - Q_{0,2}(\alpha)\, R_1 \sigma_{0,2}}$$

- iterate α until $f_1 = f_2$.

Data needed

- k_0 or $\sigma_\gamma = \sigma_0 P_\gamma \theta$
- Q_0
- E_r
  - can be found e.g. at http://iriaxp.iri.tudelft.nl/~rc/fmr/k0www3/mainframes3.htm
  - (F_{Cd}-s are also given here)
- determine α and f
- calculate $Q_0(\alpha)$

Neutron beams

- horizontal channels
- neutron guides

- low epithermal flux
- thermal flux and temperature may be important
- especially important in PGAA

Wescott *g* factor

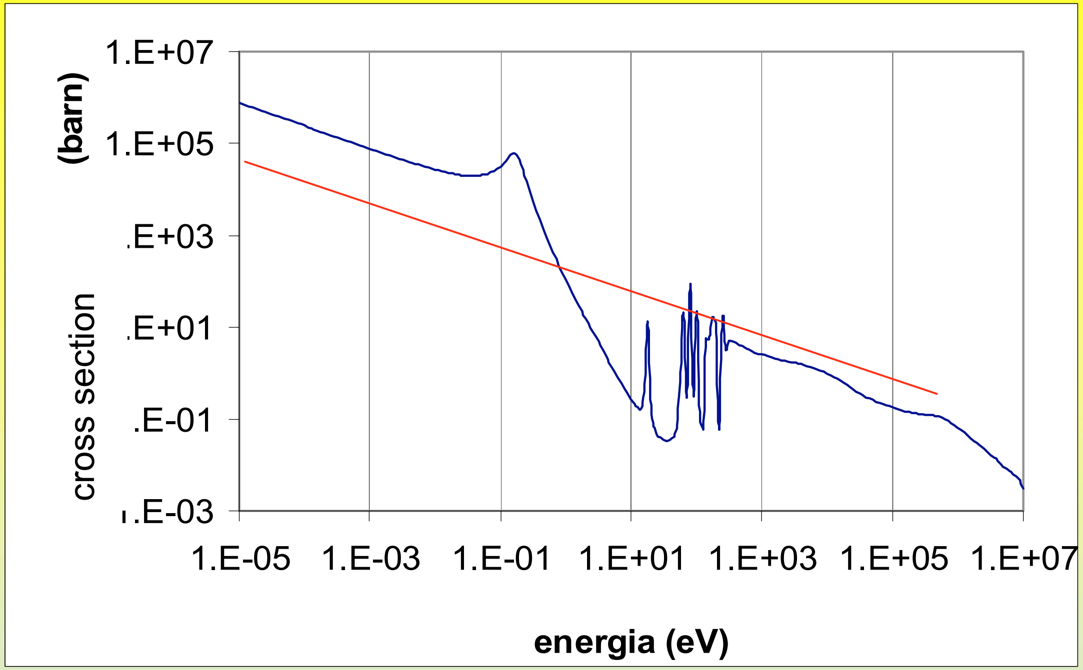
- depends on temperature

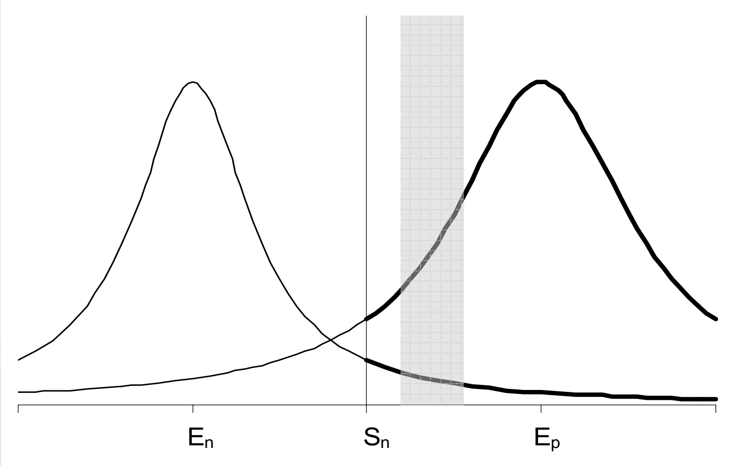
$$g(T)=\frac{\int_0^\infty \sigma(v)\,v\,p_T(v)\,dv}{\sigma_0 v_0}=\int_0^\infty \delta_0(v)\,p_T(v)\,dv$$

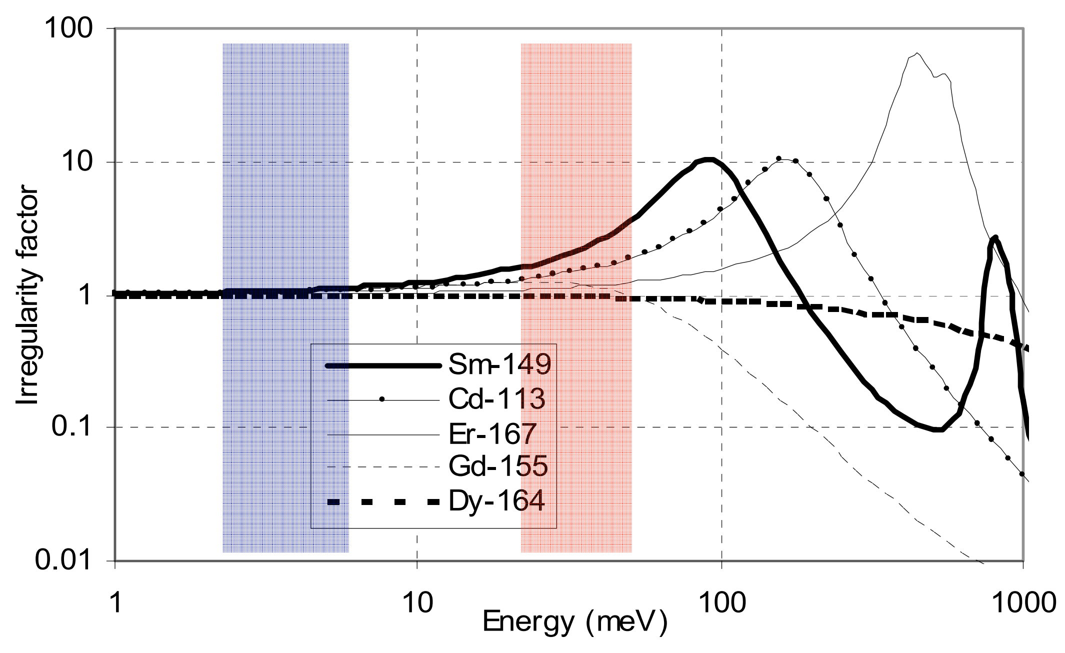
- $\delta_0(v)$ – irregularity factor
- $p_T(v)$ – neutron spectrum

Discrepancy from 1/v law

low-E resonances







non-1/*v* nuclides

- INAA (radioactive after activation)
  - ^{103}Rh (*g* =1.023)
  - ^{113,115}In (1.012, 1.019)
  - ^{175,176}Lu (0.976,1.752)
  - ^{193}Ir (1.017)
  - ^{235}U (0.985)
- PGAA (not radioactive after activation)
  - ^{113}Cd (*g* = 1.337)
  - ^{149}Sm (1.718)
  - ^{155,157}Gd (0.843, 0.852)
  - ^{167}Er (1.069)
  - ^{180}Ta (1.358)
  - ^{187}Re (0.982)
  - ^{187}Os (0.983)

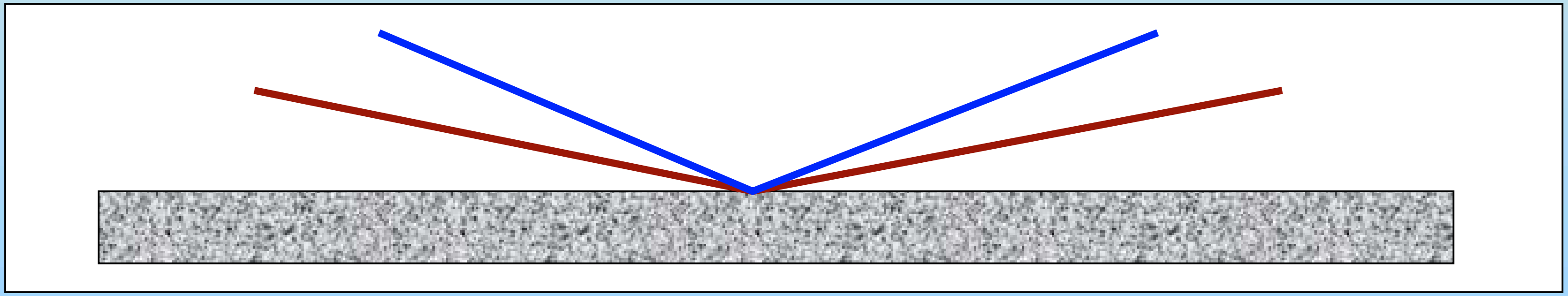
Neutron mirrors (in guides)

total reflection

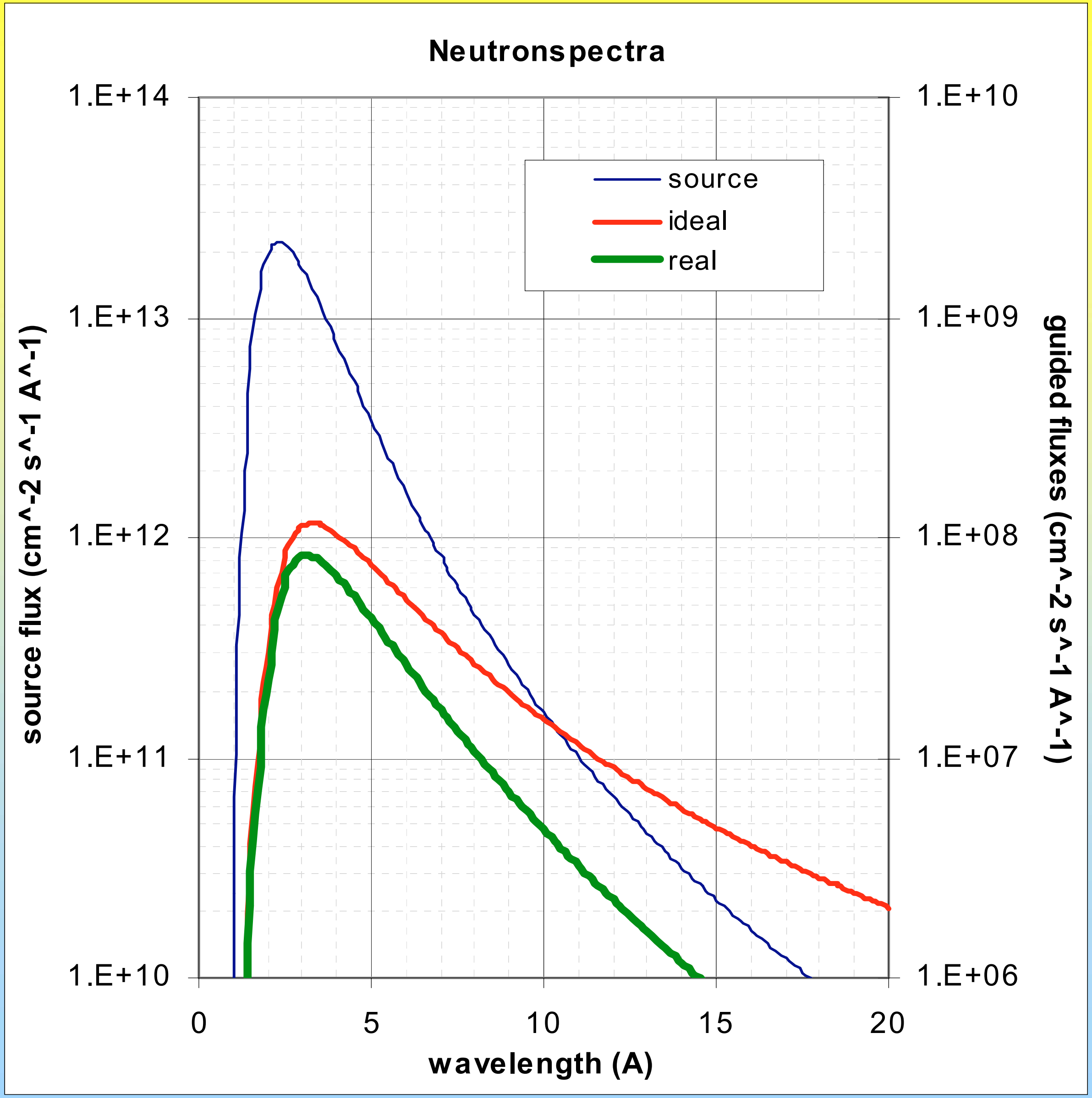
critical wavelength ~ λ, $1/v$, $1/E^{0,5}$

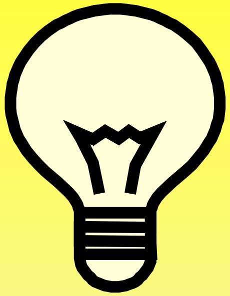
- natural Ni: $\theta_c/\lambda = 0.099$ °/Å
- ^{58}Ni: $\theta_c/\lambda = 0.117$ °/Å
- supermirror: $\theta_c/\lambda = m \times 0.099$ °/Å,

  m = 1.5, 2, 3, ...



Wavelength spectrum of guided beams

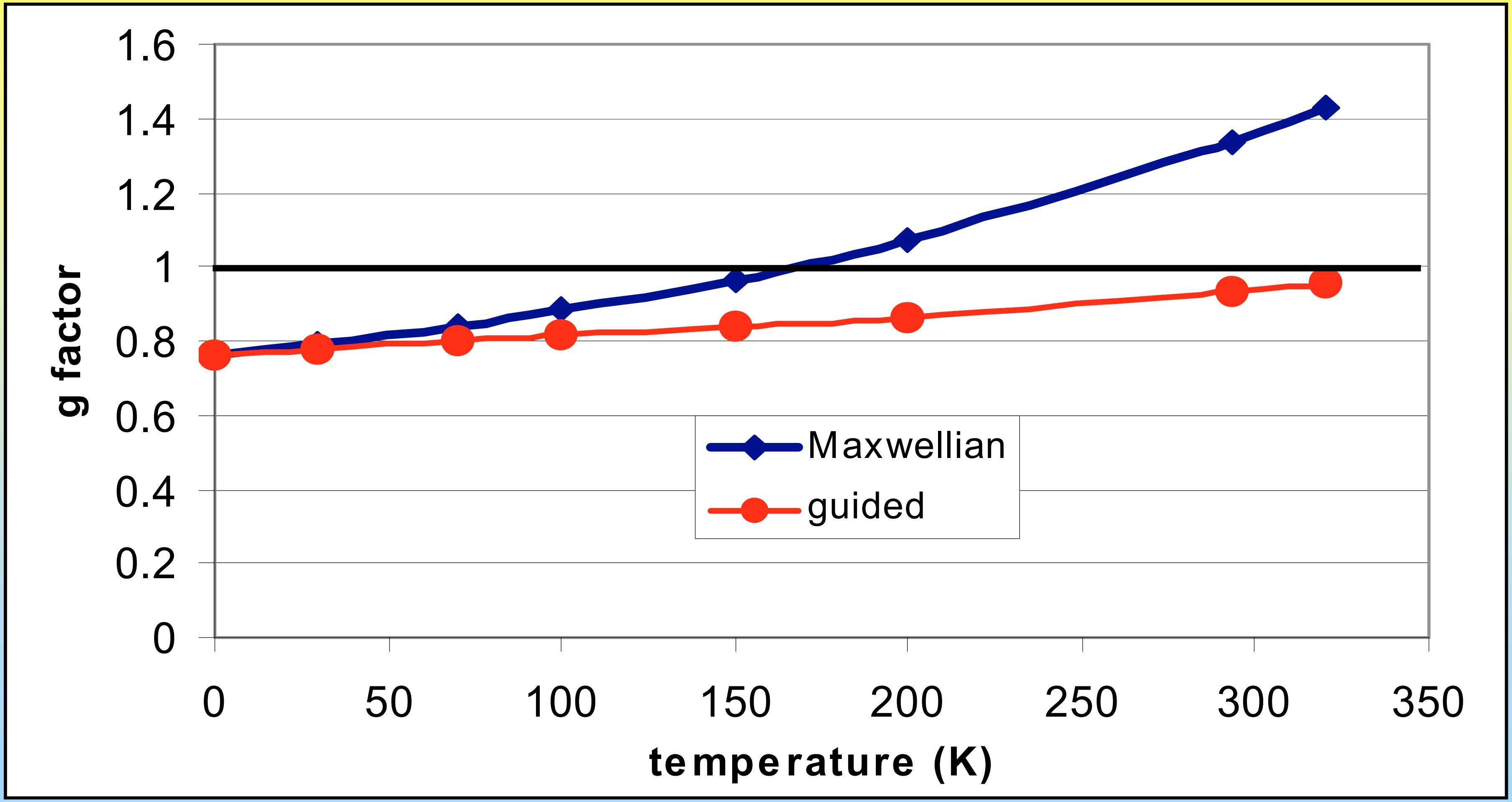




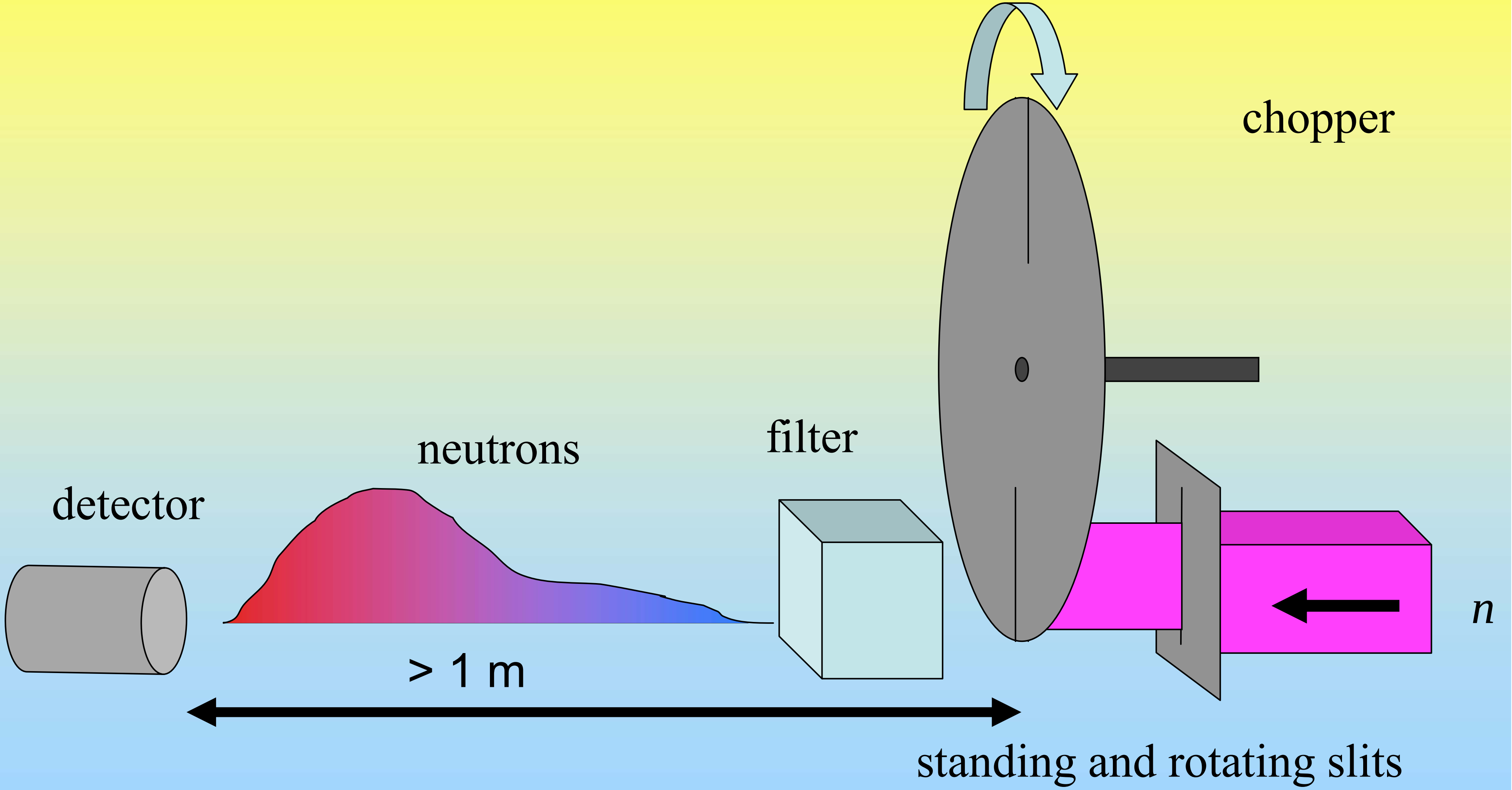
spectrum of guided beam =
Maxwellian × λ^2

guiding cools the beam

Westcott g factors of ^{113}Cd



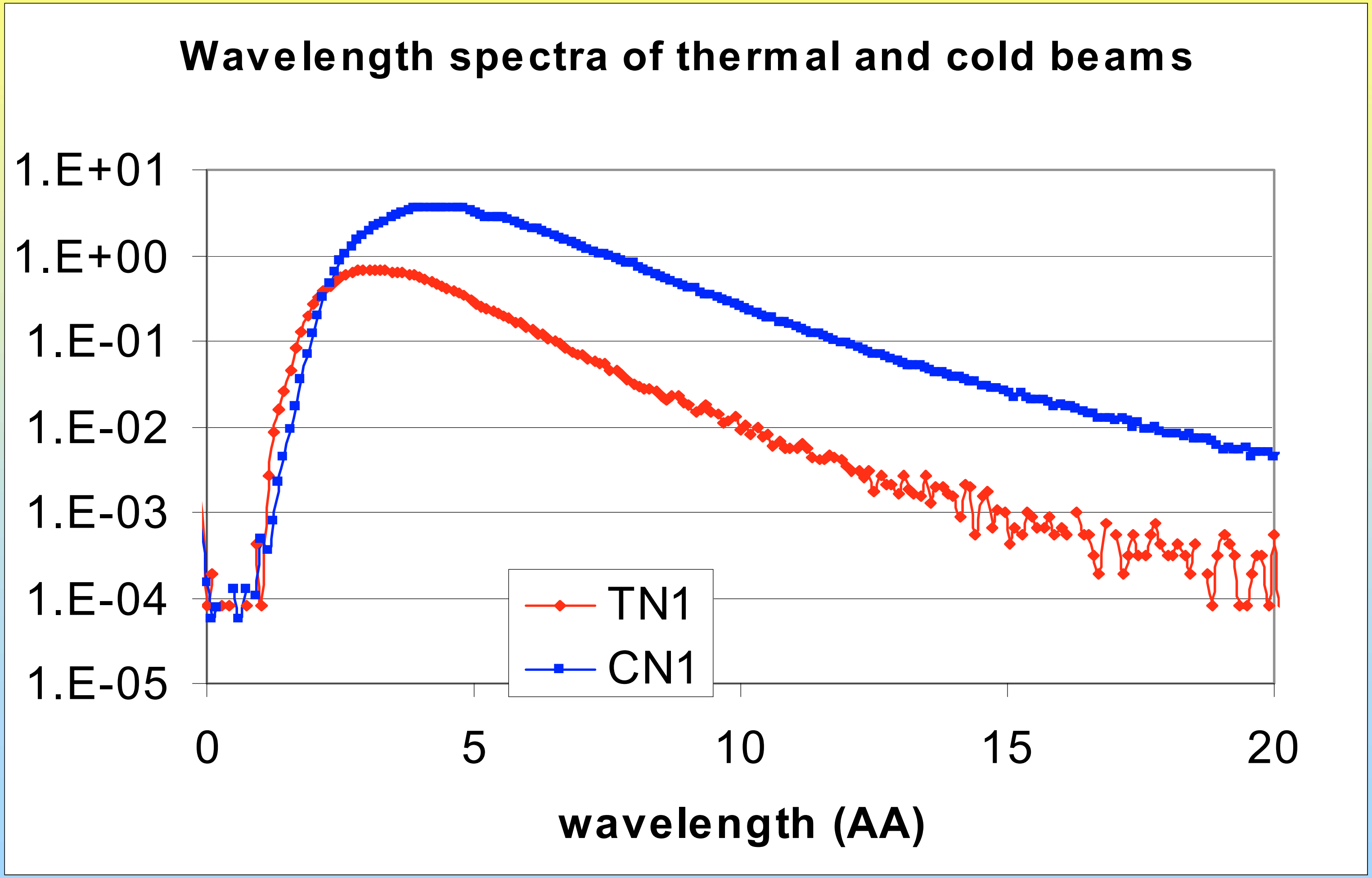
Time of flight measurement



Chopper measurements at Budapest cold and thermal beams

slit size	0.5 mm
frequency of chopper	50 Hz
diameter of chopper	16 cm
baseline	43 cm / 120 cm
time resolution	10 μs
detector	7 bar ^{3}He counter

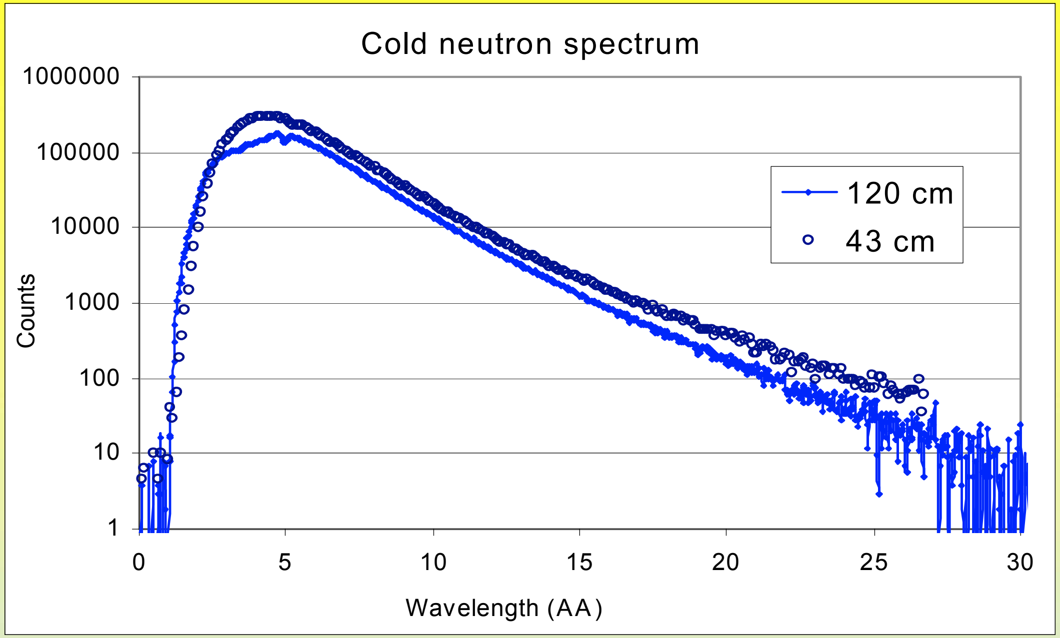
Neutron spectra of cold and thermal beams as measured with TOF (43 cm)

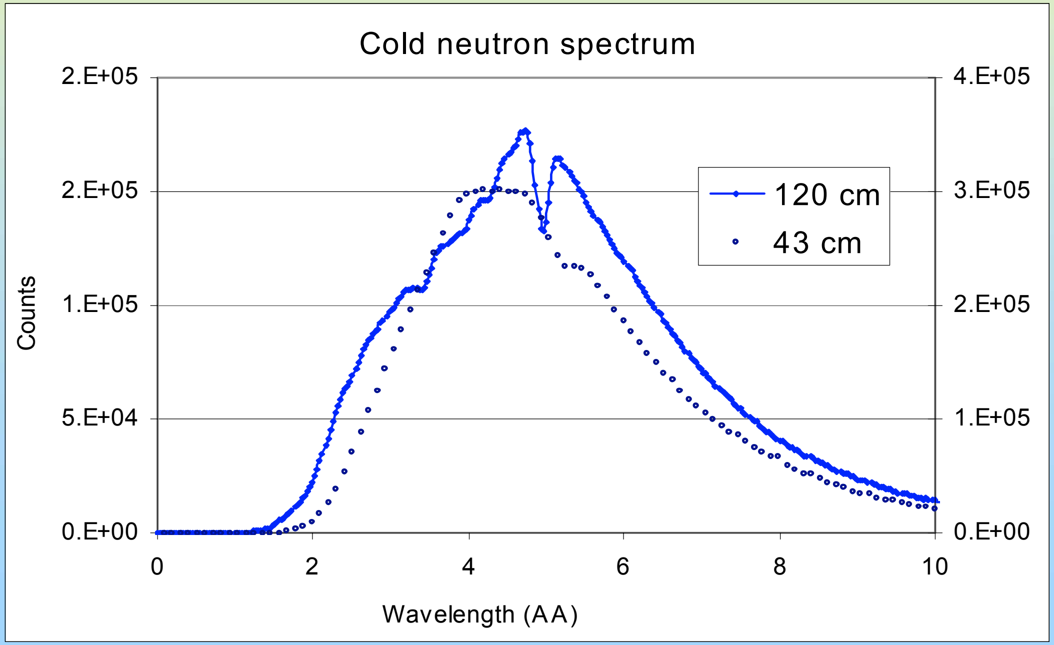


Greater distance

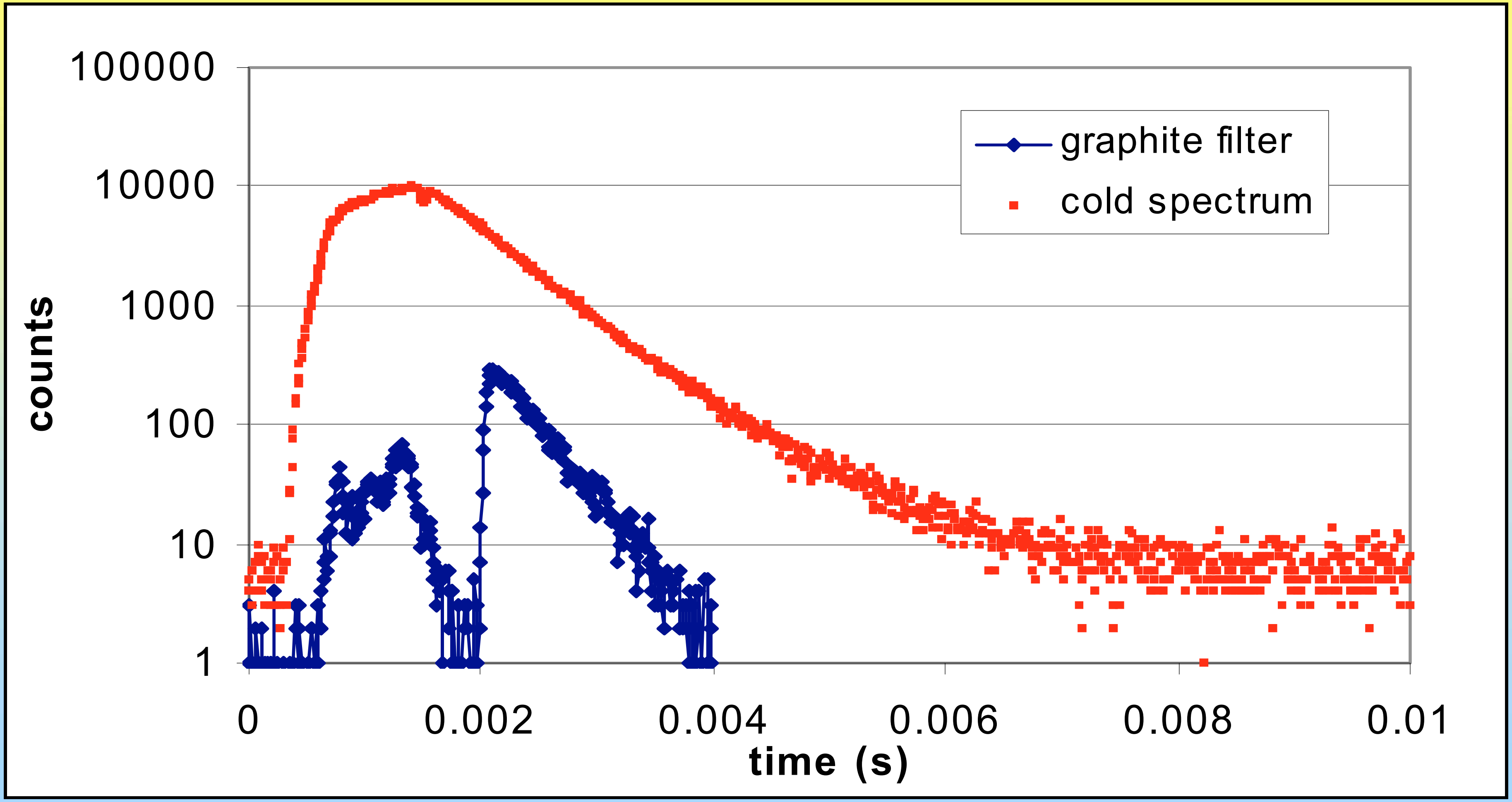
–

better resolution

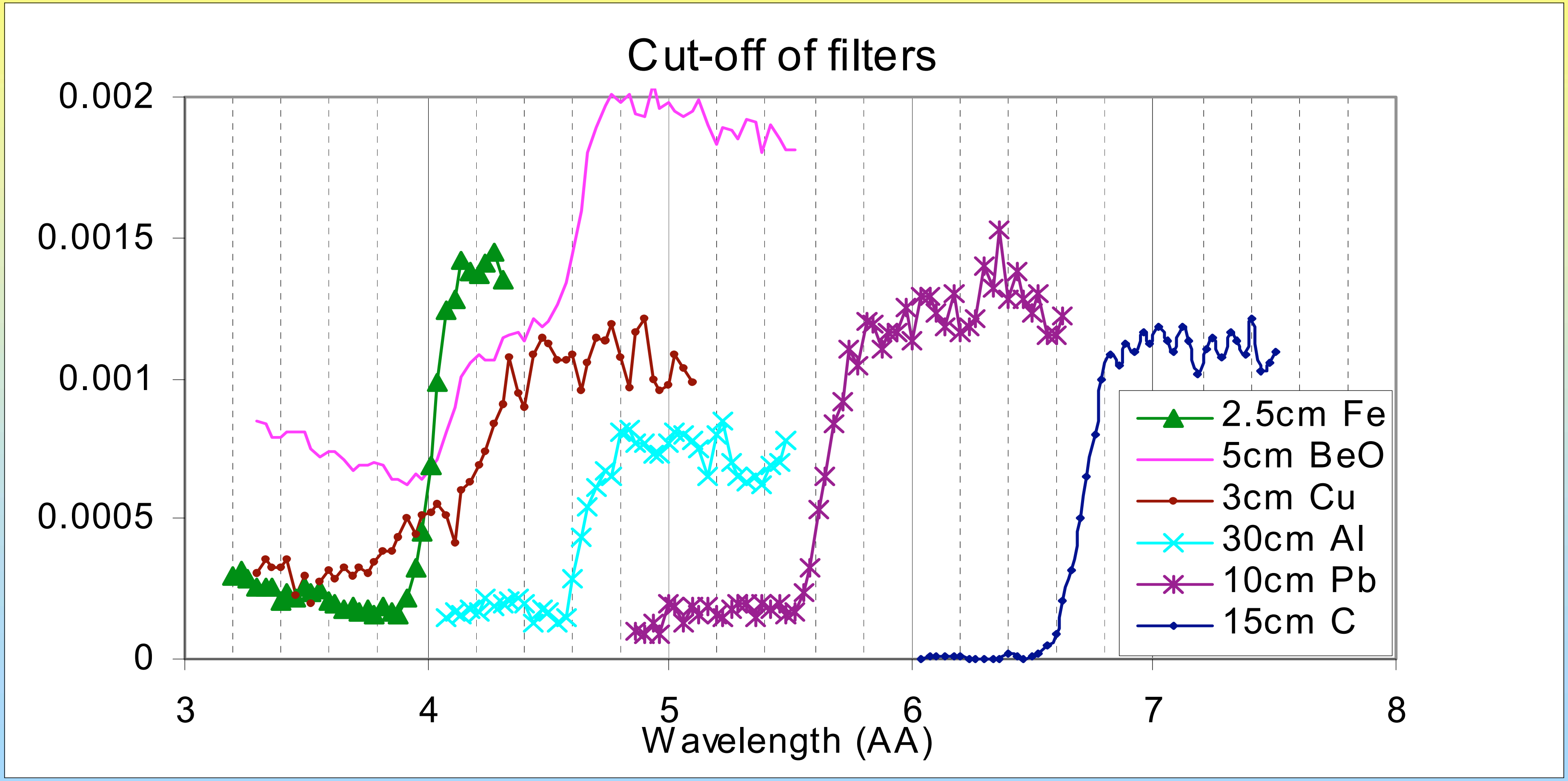




The effect of graphite filter



Cut-off of different filters



Cut-off wavelengths

Material	Cut-off wavelength (Å)	Thickness for attenuation by a factor 10 (cm)
Be	4.00	
BeO	4.67	15
C (graphite)	6.69	7
Al	4.67	60
Fe	4.04	3
Cu	4.16	6
Pb	5.7	15