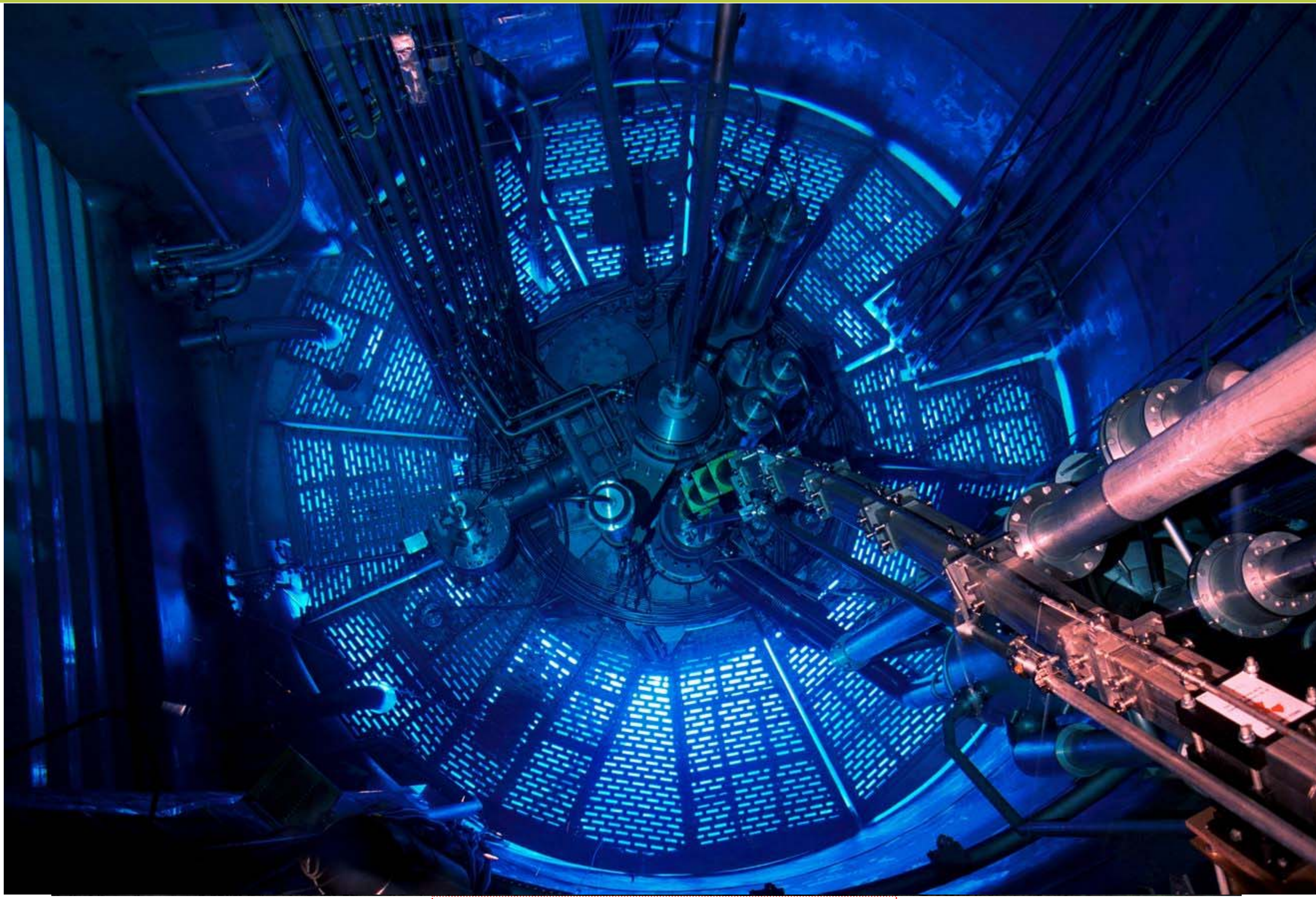
UCN – ultracold neutrons



Applications of UCN in fundamental particle physics:

- Search for non-zero neutron electric dipole moment,
- Measurement of the neutron lifetime,
- Experiments with the gravitationally bound quantum states of neutrons,
- Search for non-zero neutron electric charge,
- …

All these experiments are:

-Strongly limited by low UCN density (neutron electric dipole moment, neutron charge, gravitational states);

-Or, Systematical errors would be easier revealed if higher neutron density were available (neutron lifetime, neutron electric dipole moment).

UCN – ultracold neutrons

Possible approaches to increase UCN density:

-Solid deuterium neutron converter in vicinity of a cold-neutron (optimum ~5A) source – inside a reactor or a spallation source;

-Liquid helium super-thermal source at an external beam of cold neutron (optimum ~10A);

-Equilibrium cooling of very cold neutrons (optimum ~50A) at ultracold nanoparticles.

Nanoparticles as a possible moderator for an UCN source

G.Pignol, K.V.Protasov, V.V.N. – arXiv:nucl-th/0510021 6 Oct 2005

1. Model of free nanoparticles
2. Model of the infinite moderator
3. Realistic moderators

Motivations: 1) Nanoparticles at surface

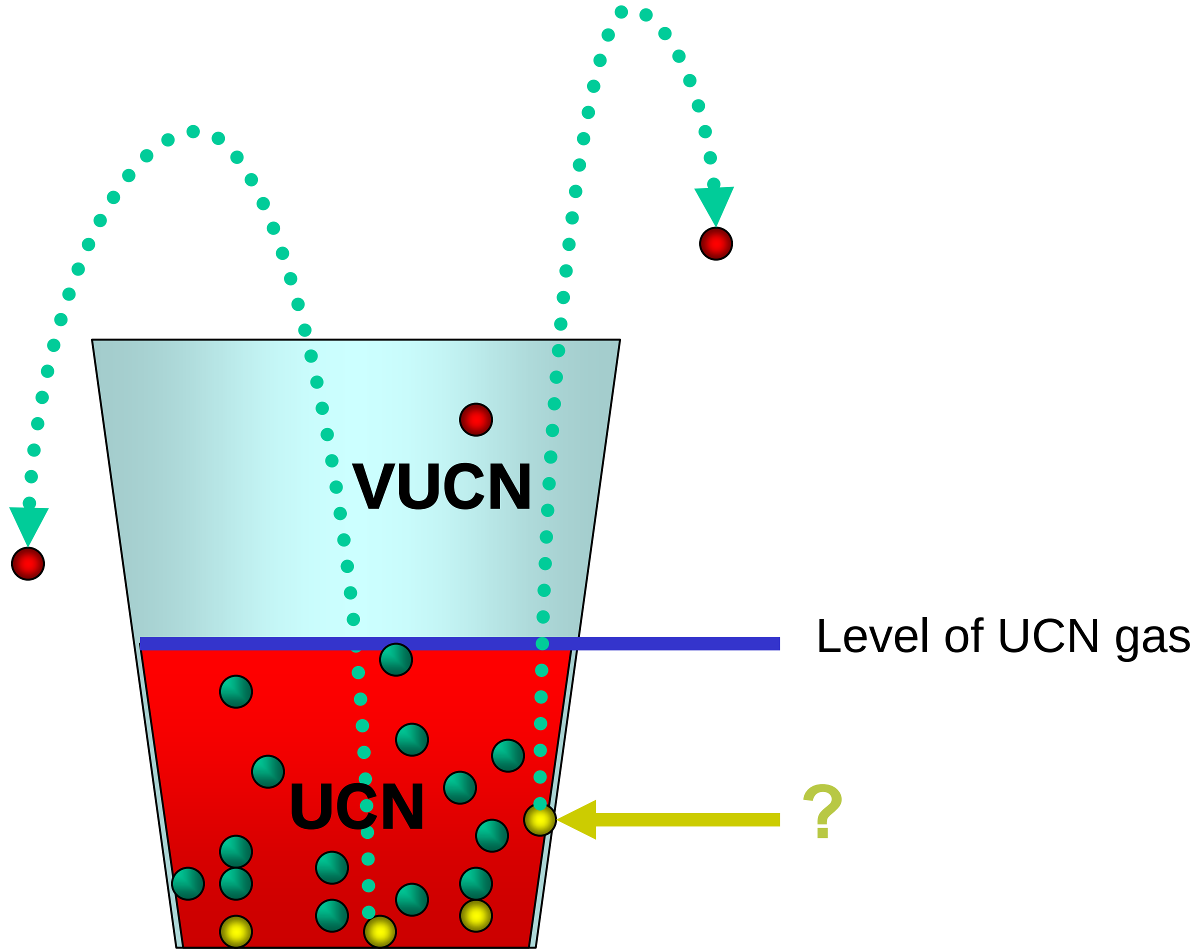
Systematics for neutron lifetime measurements ?

$VUCN$: ●

$\Delta E \sim 10^{-7} eV$

$\Delta V \sim 1 m/s$

$P_{VUCN} \sim 10^{-8} - 10^{-3}$



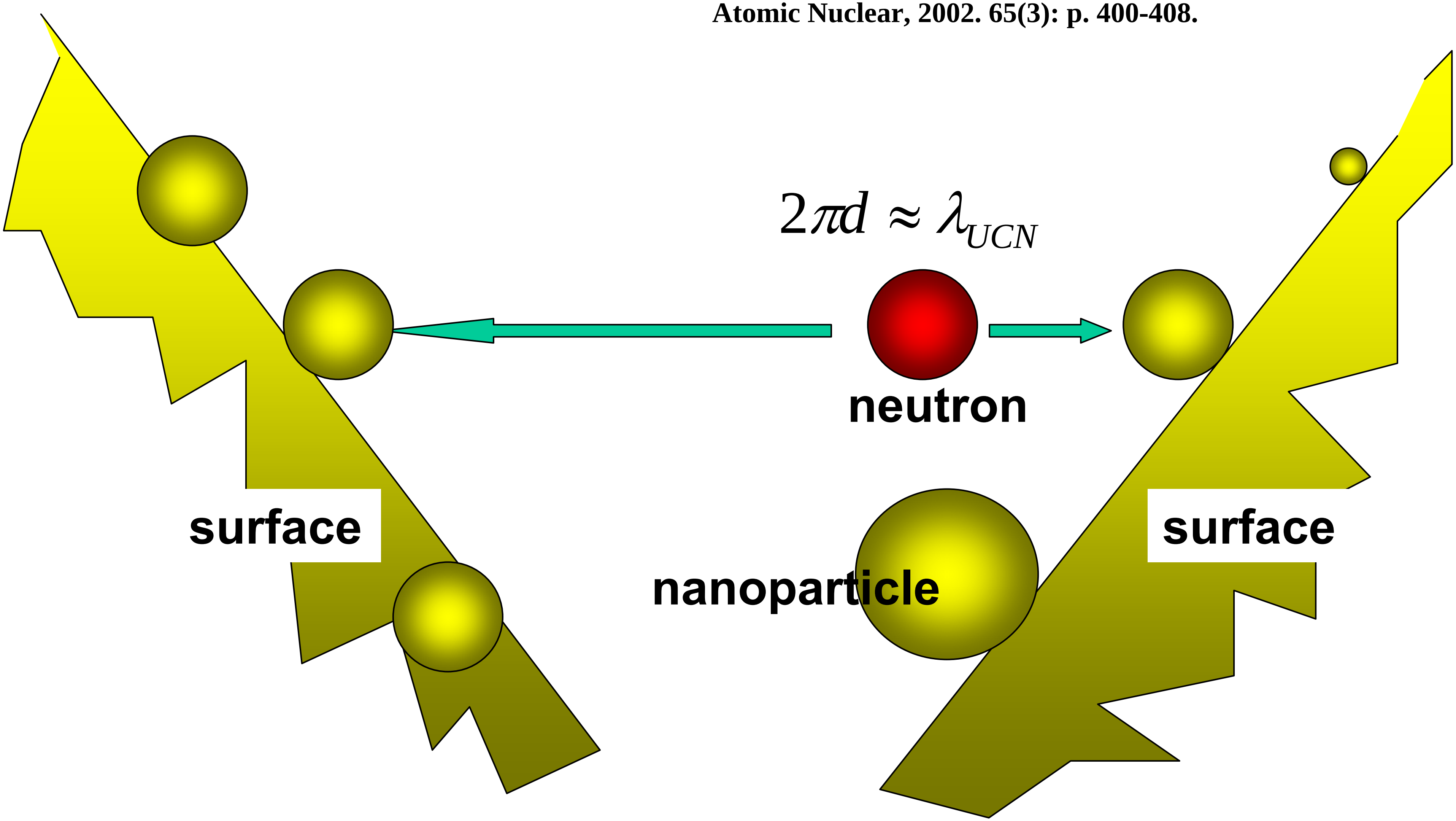
A.V.Strelkov et al, NIM 440A(3), 695-703 (2000)

D.G.Kartashov et al, Physics of Atomic Nuclei 65(11), 1-4 (2002)

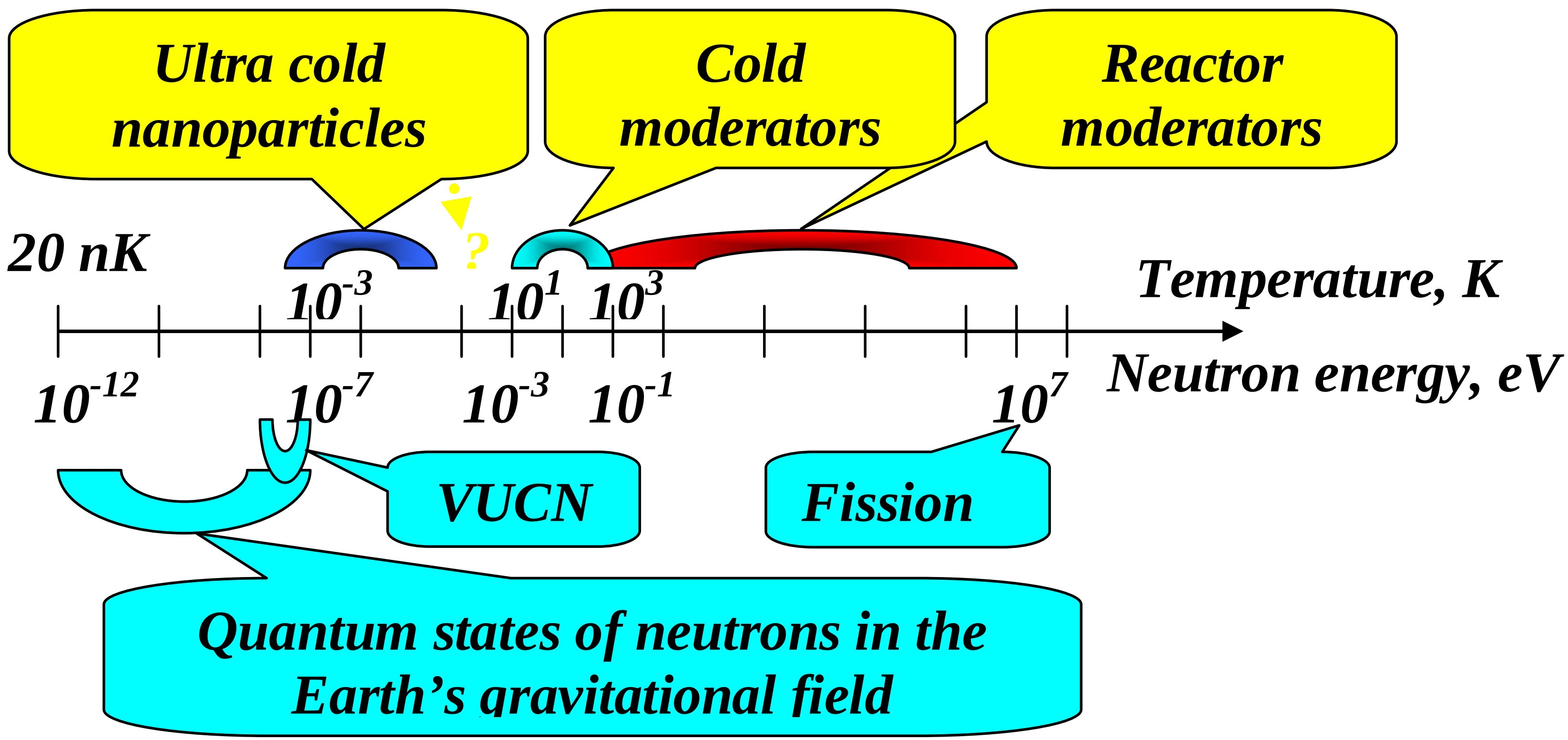
V.V.N., Physics of Atomic Nuclear 65(3), 400-408 (2002)

Motivations: 1) Nanoparticles at surface

V.V.N., Interaction of neutrons with nanoparticles. Physics of Atomic Nuclear, 2002. 65(3): p. 400-408.



Motivations: 2) Reactor moderators

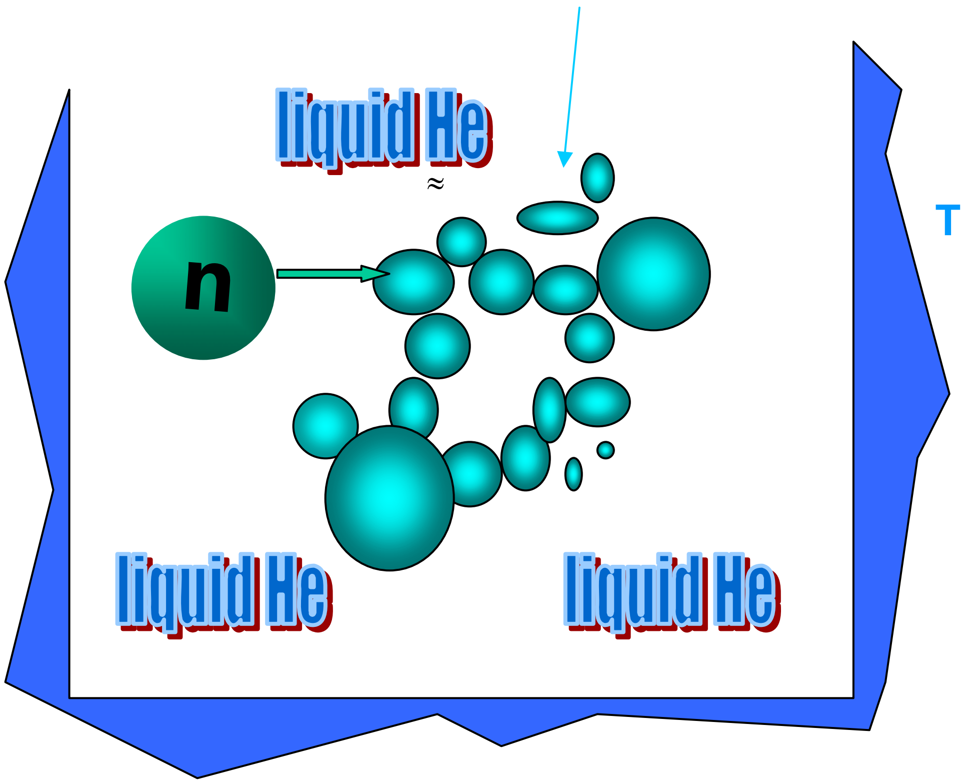


Nanoparticles as a possible moderator for an UCN source

Nanoparticles

D_2, D_2O, O_2, C ?

d ~ 5 nm ?

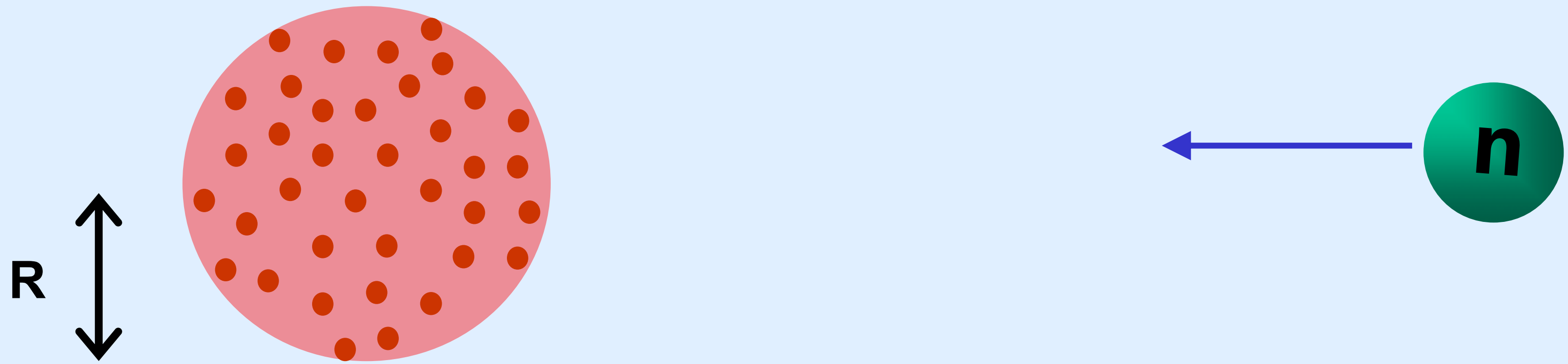


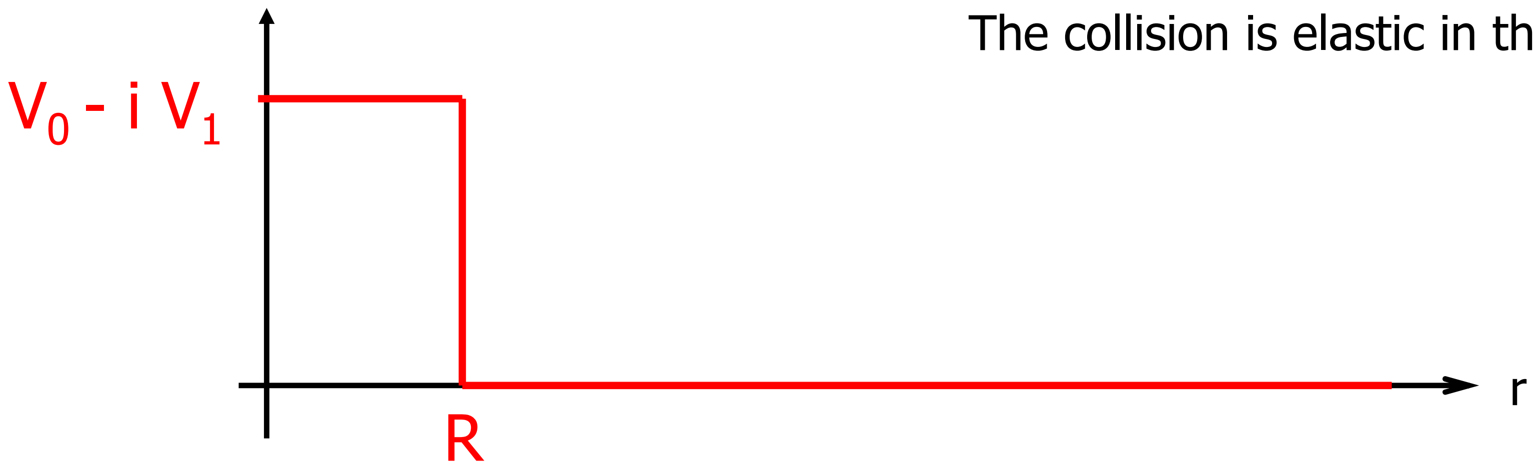
T < 10 mK

Neutrons can excite many degrees of freedom:

- Simple collision with a single nanoparticle
- Rotation
- Collective degrees of freedom (phonons, rotons)
- Breaking of inter-particle bonds

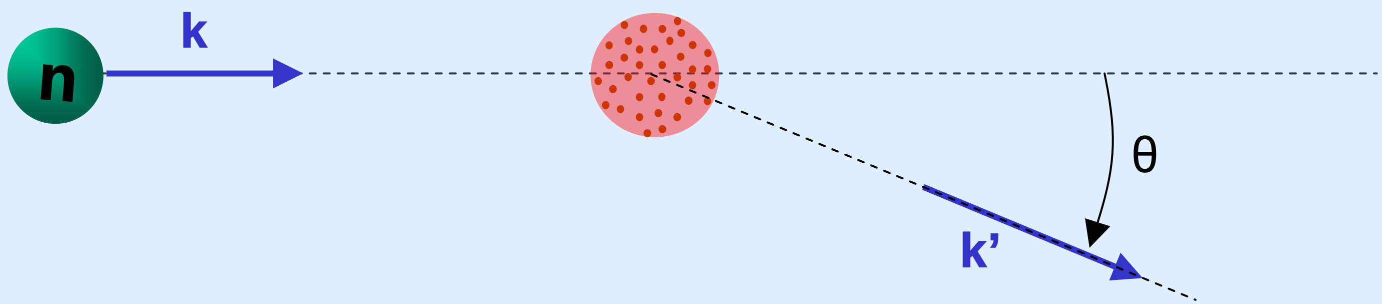
Model of free nanoparticles





The collision is elastic in the C.M. frame

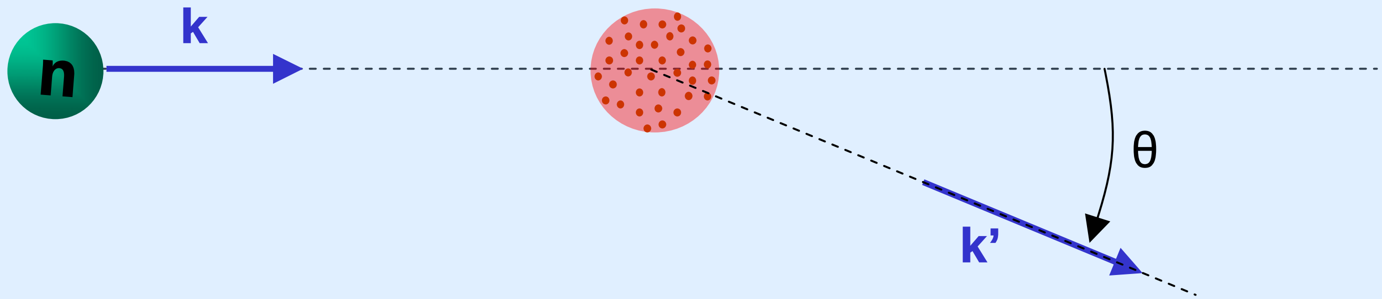
Cross sections: diffusion, absorption, energy change



Tree main quantities can be derived from the scattering amplitude f(θ) :

- The diffusion cross-section $$\sigma_s = \int |f|^2 \, d\Omega = 2\pi \int_0^{\pi} |f(\theta)|^2 \sin(\theta) d\theta$$
- The absorption cross-section $$Im(f(\theta = 0)) = \frac{k}{4\pi}\sigma_a$$
- The relative mean energy loss per collision $$\xi = \frac{\langle \Delta E \rangle}{E} = \frac{4}{A} \langle \sin^2(\theta/2) \rangle$$

Model of free nanoparticles and Born approximation



Calculations at the first order of the Born approximation

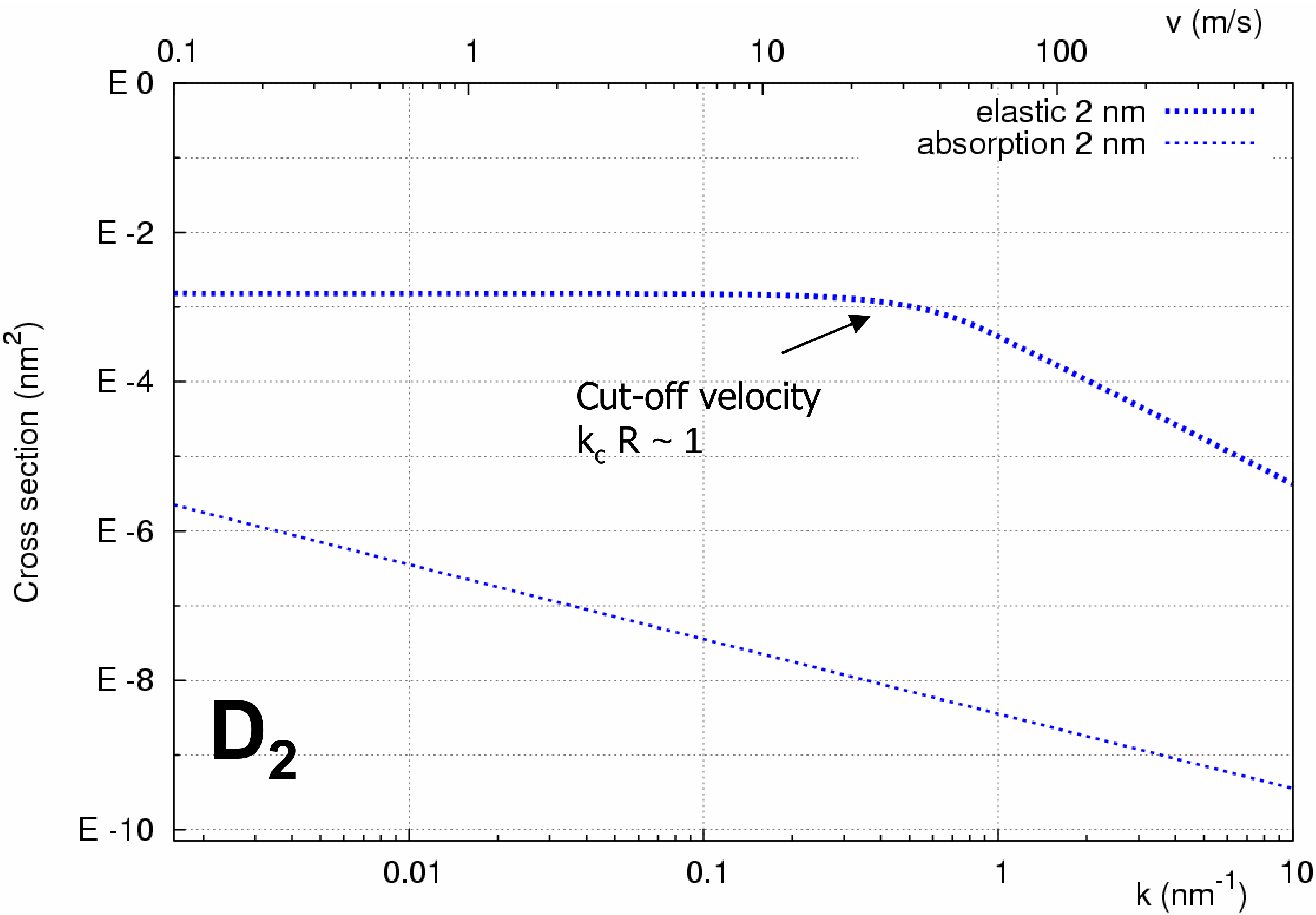
Validity : $V R^2 \ll \frac{\hbar^2}{2m}$

$V R^2_{\mathrm{Born}} = \frac{1}{10}\frac{\hbar^2}{2m}$

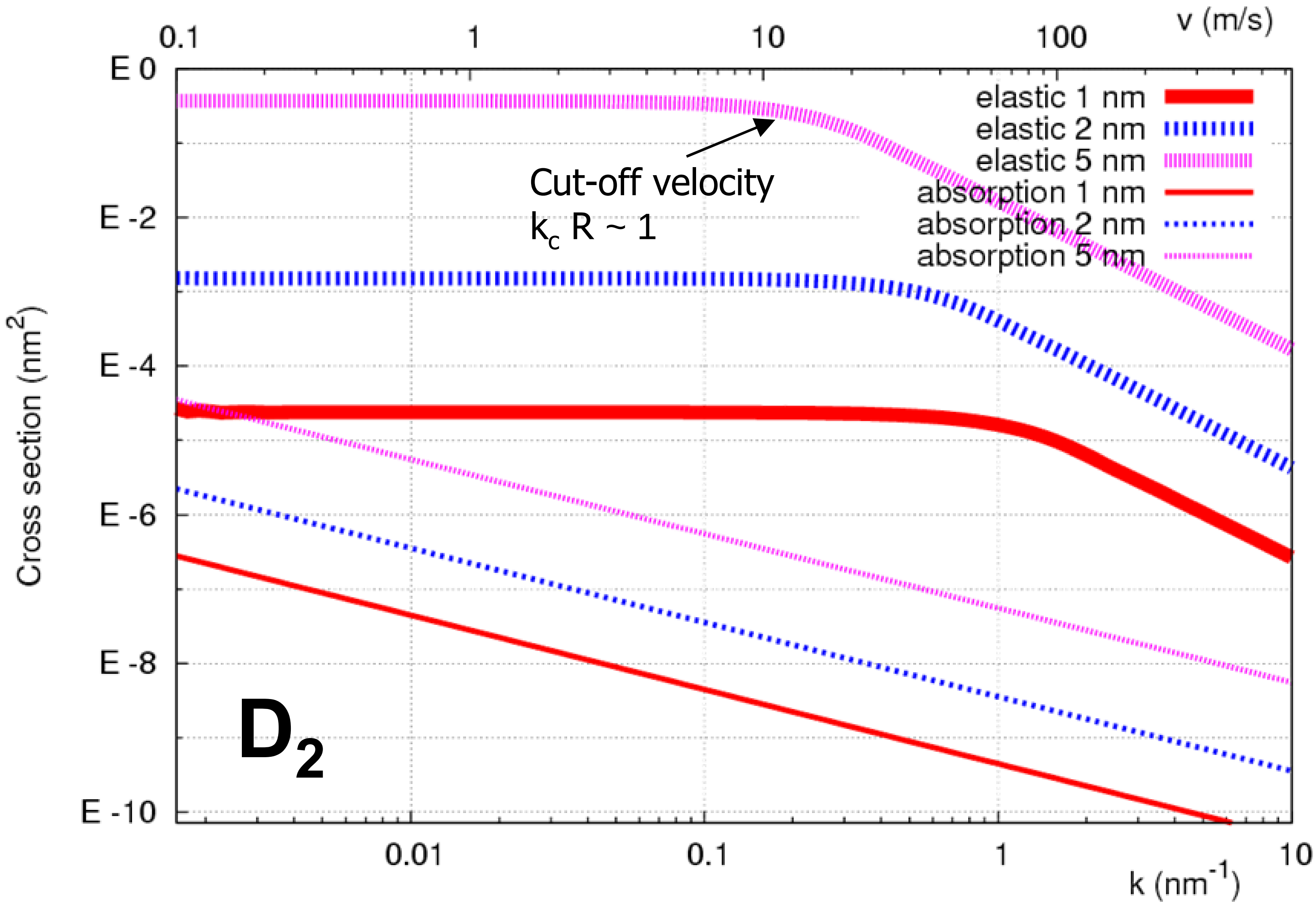
nanoparticle	D_2	D_2O	O_2	CO_2	C (Diamond)	Be
R_{Born} (nm)	4.5	3.7	5.4	4.5	2.6	2.9

Result : $f(\theta) = -\frac{1}{4\pi}\frac{2m}{\hbar^2}\int e^{i(\mathbf{k}-\mathbf{k}')\cdot\mathbf{r}} V(\mathbf{r}) d\mathbf{r}$

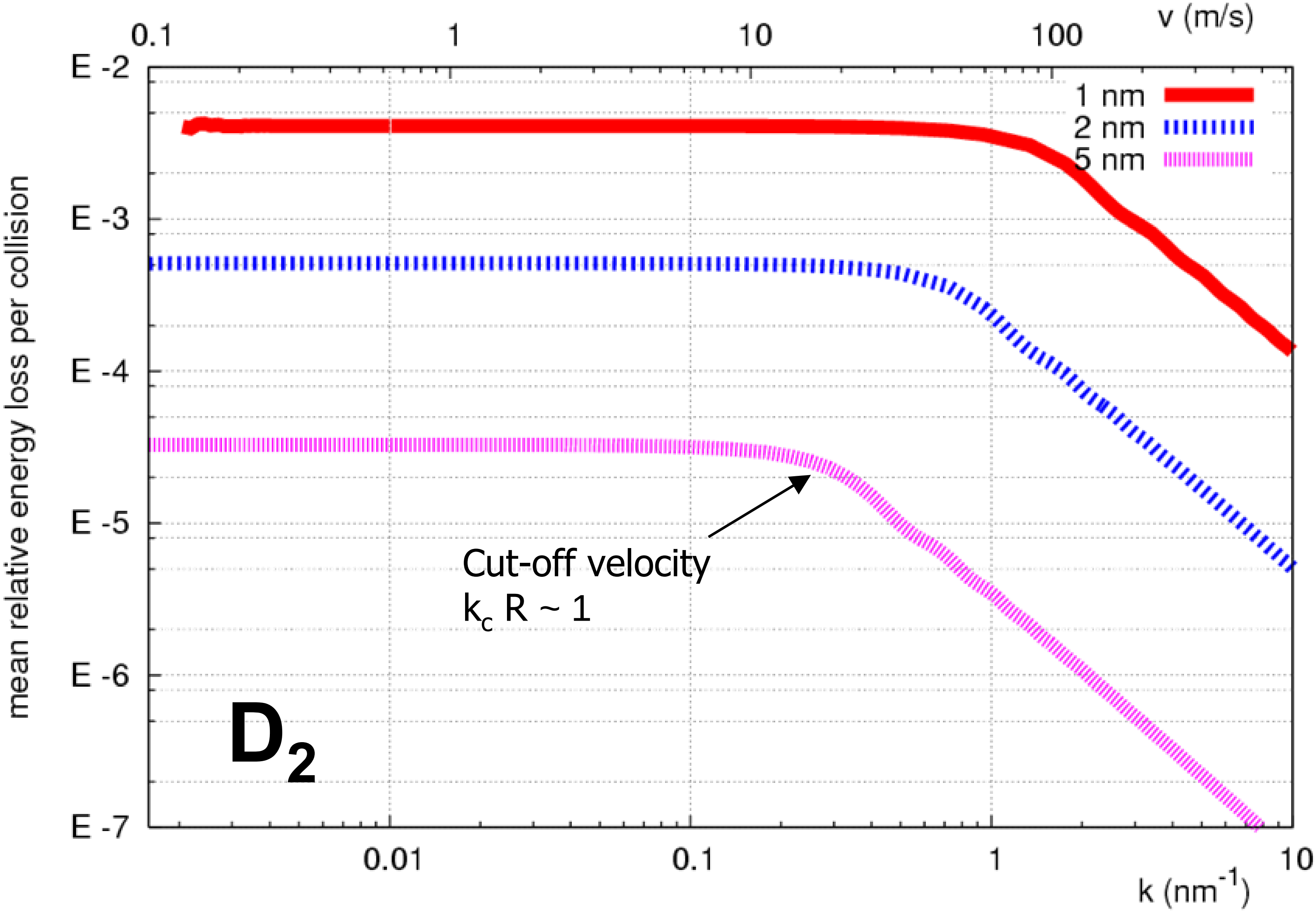
Model of free nanoparticles: scattering/absorption



Dependence on radius

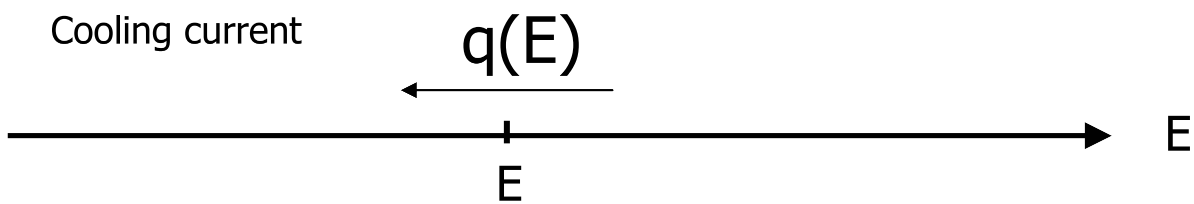


Energy loss


v (m/s)
0.1
1
10
100
E -2
E -3
E -4
E -5
E -6
E -7
mean relative energy loss per collision
1 nm
2 nm
5 nm
Cut-off velocity
$k_c R \sim 1$
D_2
0.01
0.1
1
10
k (nm^{-1})

Model of the infinite moderator

- Realistic model $n(\mathbf{r}, \mathbf{v}, t)$ solution of the (too complicated) Boltzmann equation
- Infinite Moderator $n(E, t)$



Equation of conservation for the number of neutrons

$$\frac{\partial n}{\partial t} - \frac{\partial q}{\partial E} + \text{Absorption} - \text{Source} = 0$$

Model of the infinite moderator

Conservation equation

$$\frac{\partial n}{\partial t} - \frac{\partial q}{\partial E} + \text{Absorption} - \text{Source} = 0$$

Neutron flux

$$\phi(E) = v\ n(E) = \sqrt{\frac{2E}{m}} n(E)$$

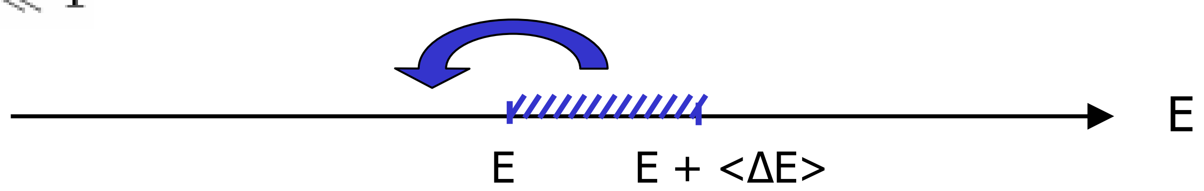
Absorption term

$$dN_a = \Sigma_a\ \phi(E) dE\ dt$$

Cooling current

$$q(E) = E\xi(E)\ \Sigma_s(E)\ \phi(E)$$

$$\xi \ll 1$$



Model of the infinite moderator

Conservation equation

$$\frac{\partial n}{\partial t} - \frac{\partial q}{\partial E} + \text{Absorption} - \text{Source} = 0$$

With flux variable

$$\sqrt{\frac{m}{2E}}\frac{\partial \phi}{\partial t} - \frac{\partial q}{\partial E} + \Sigma_a \phi = \text{Source}$$

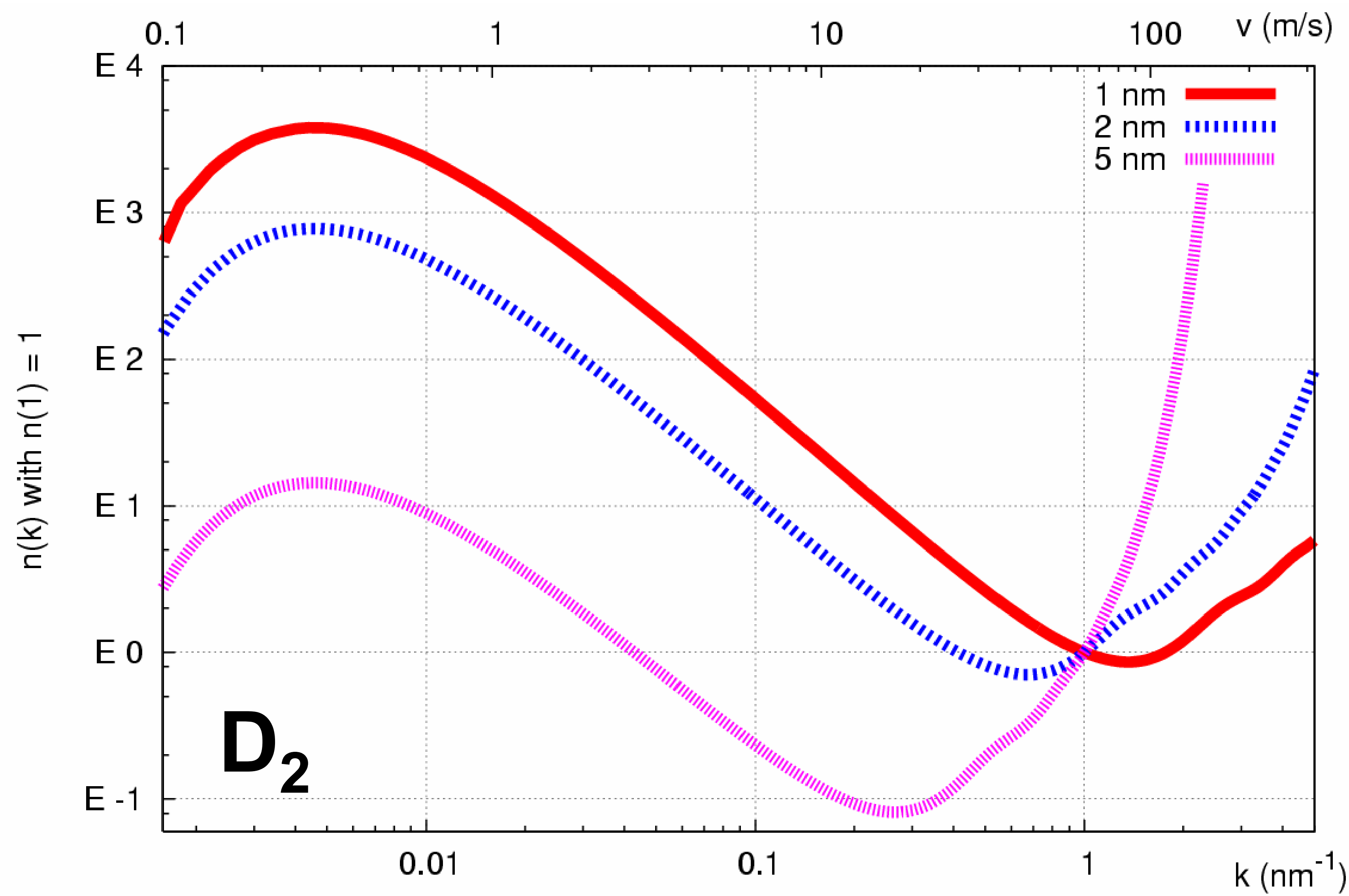
In stationary regime, with a mono-energetic source at energy E_0

$$-\frac{\mathrm{d}}{\mathrm{d}E}\left(\xi \Sigma_s E \phi\right) + \Sigma_a \phi = 0$$

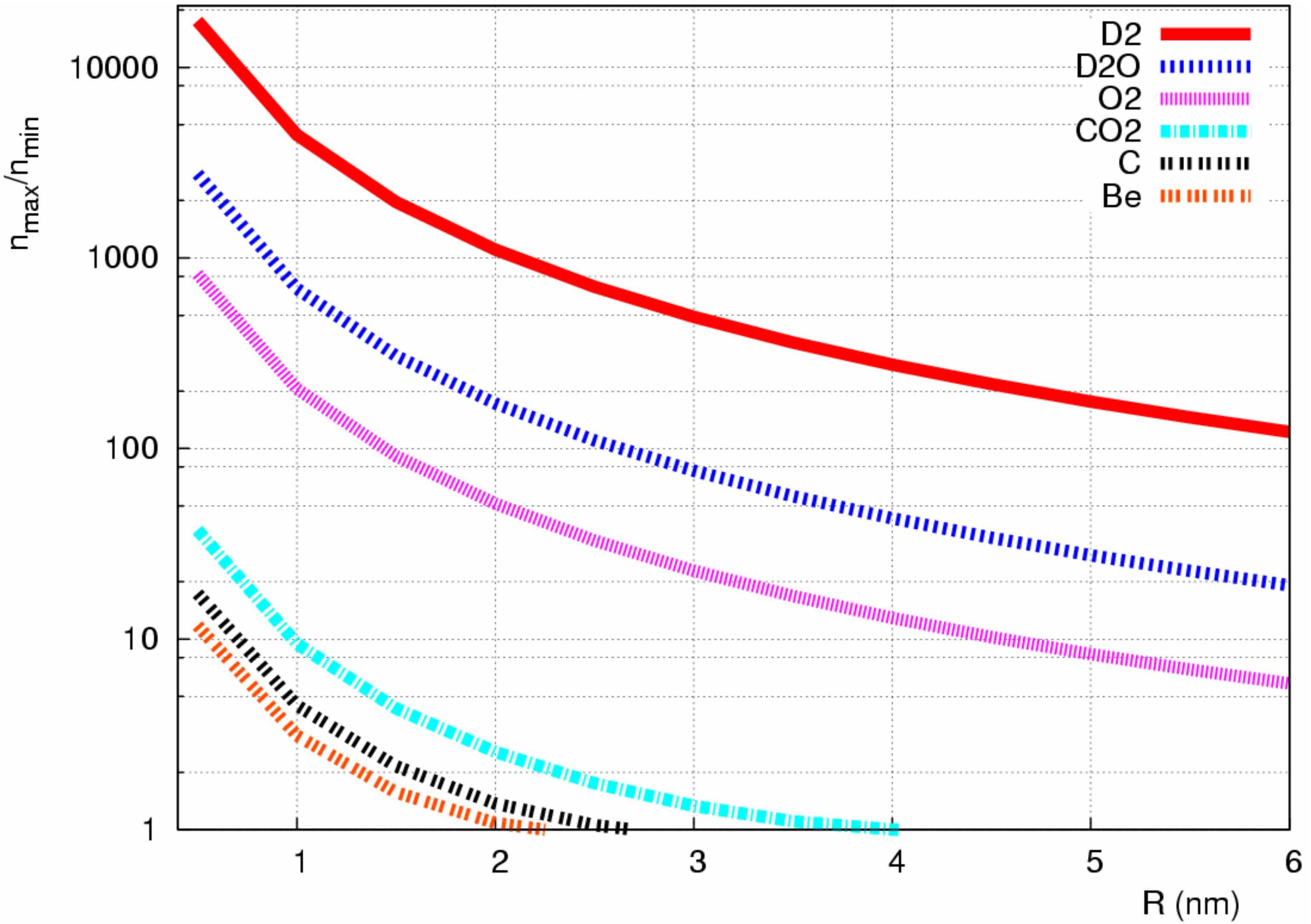
Solution:

$$n_{stat}(E) = n_{stat}(E_0)\left(\frac{E_0}{E}\right)^{3/2} \frac{\xi(E_0)\Sigma_s(E_0)}{\xi(E)\Sigma_s(E)} \exp\left(-\int_E^{E_0} \frac{\Sigma_a}{\xi \Sigma_s}\frac{d\epsilon}{\epsilon}\right)$$

Efficiency ranges



Density increase

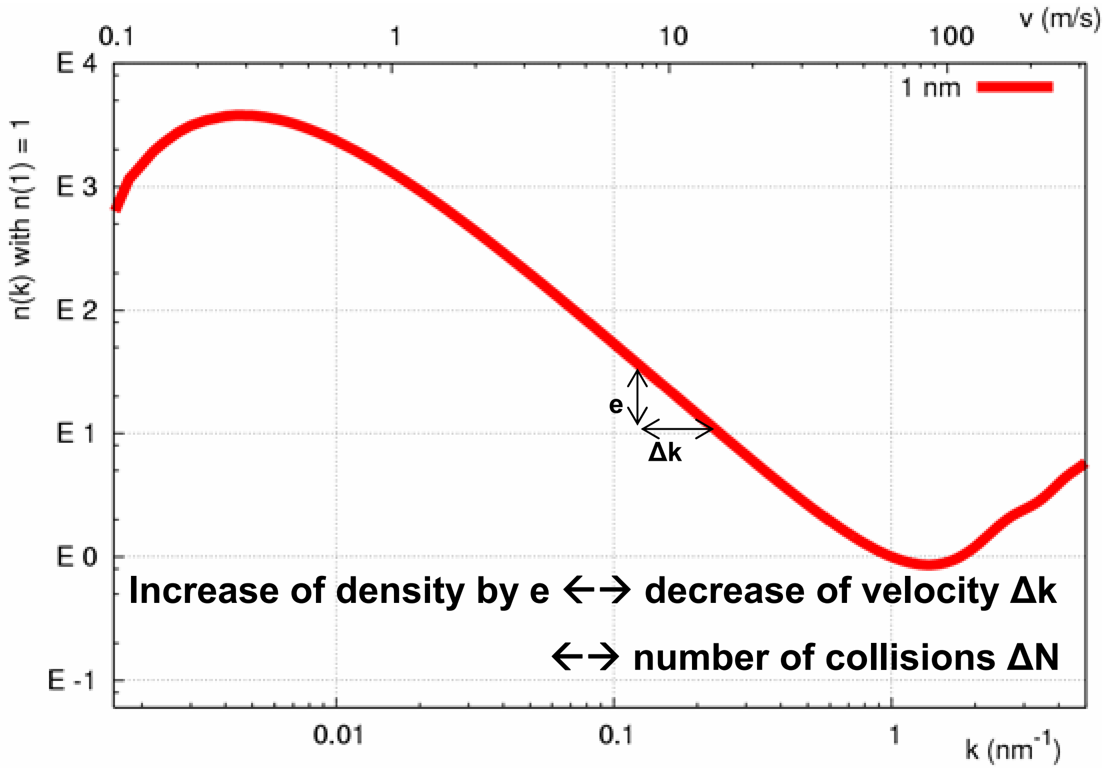


Maximum increase of density in the phase space for different materials.

Moderator: time versus size

Two important quantities to consider for a more realistic moderator

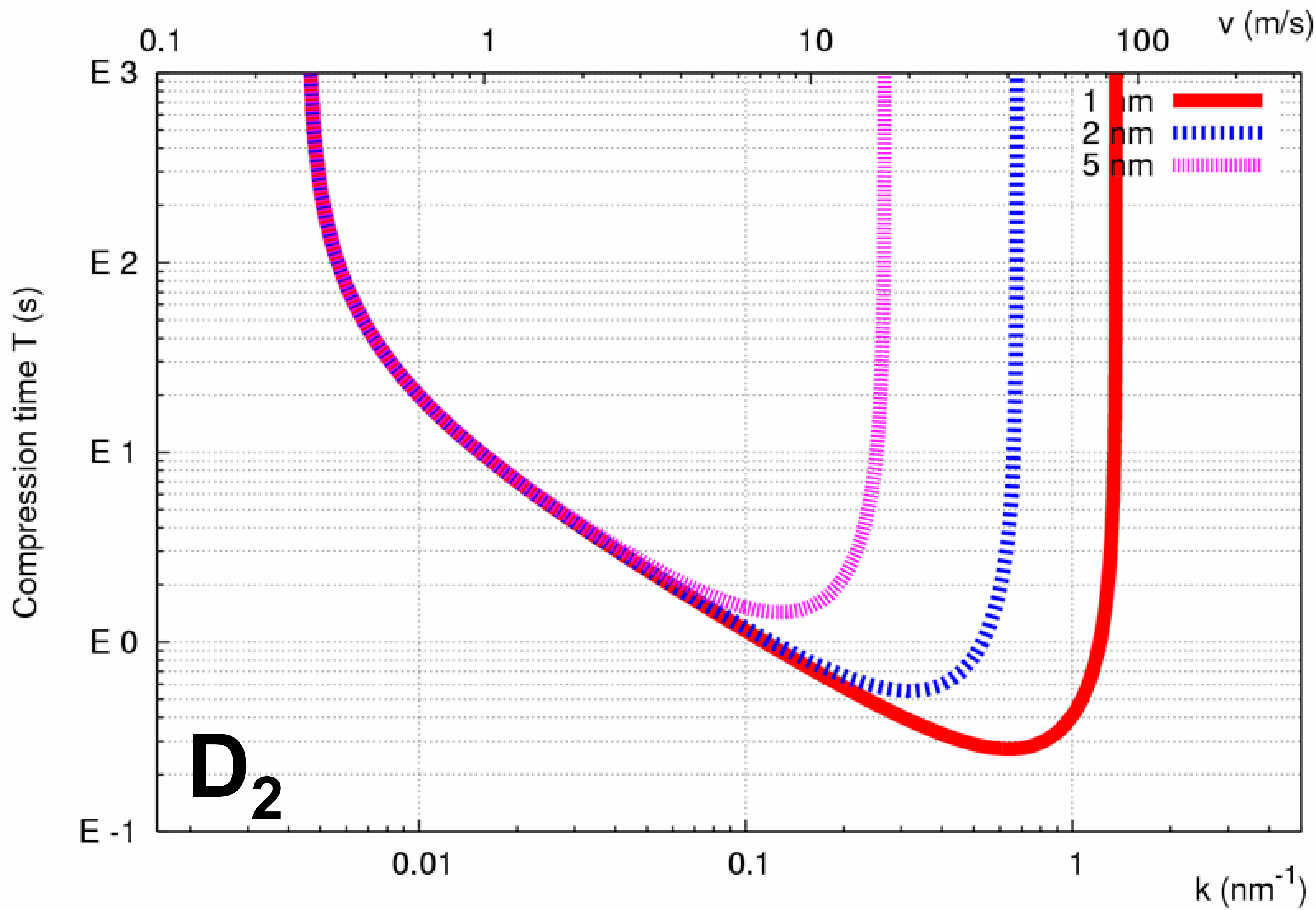
1. **The Size of the moderator**
2. **The thermalization time**



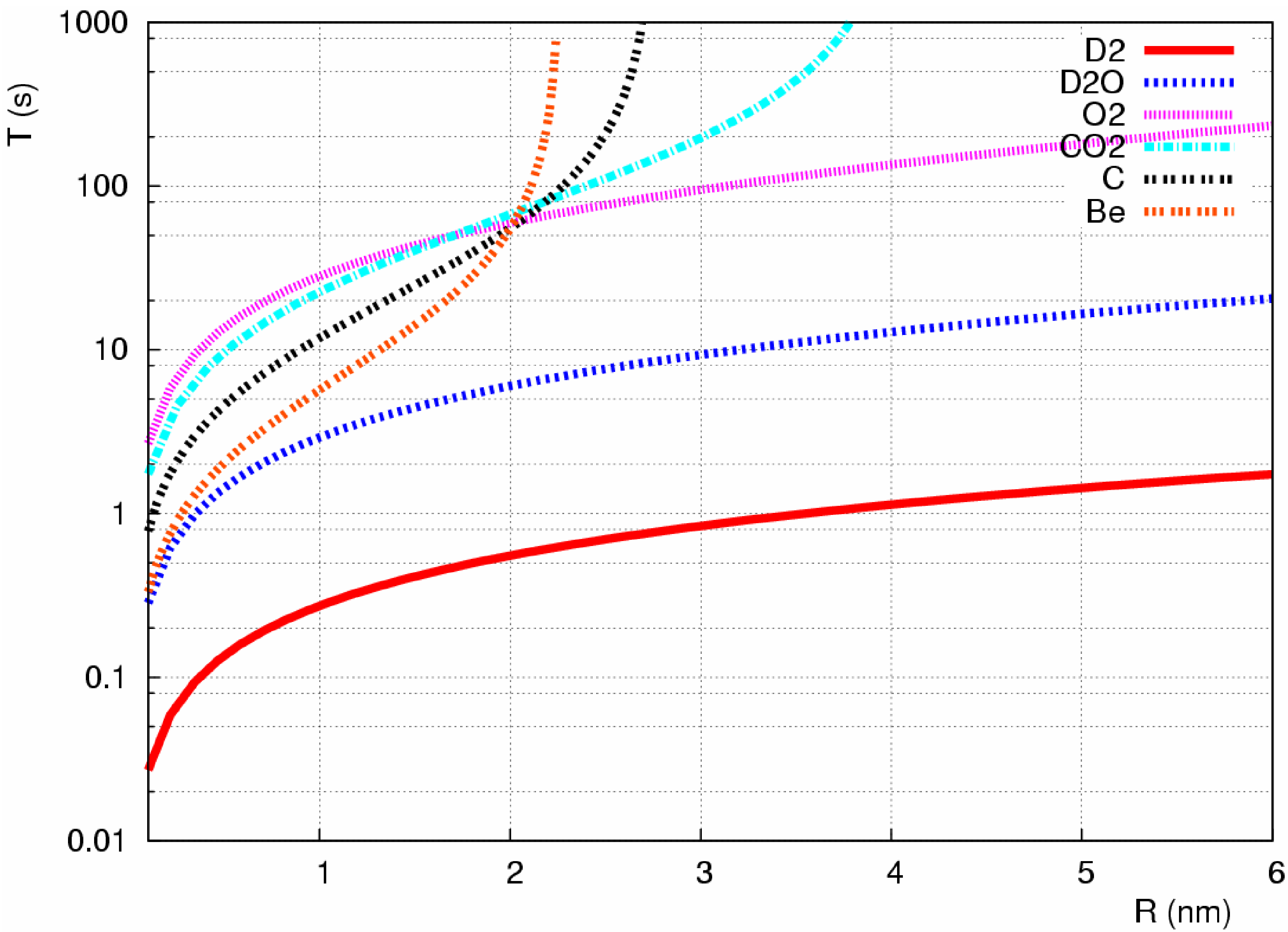
We can estimate, for ΔN collisions:

1. **The square mean root of the distance traveled L(k)**
2. **The mean time it lasted T(k)**

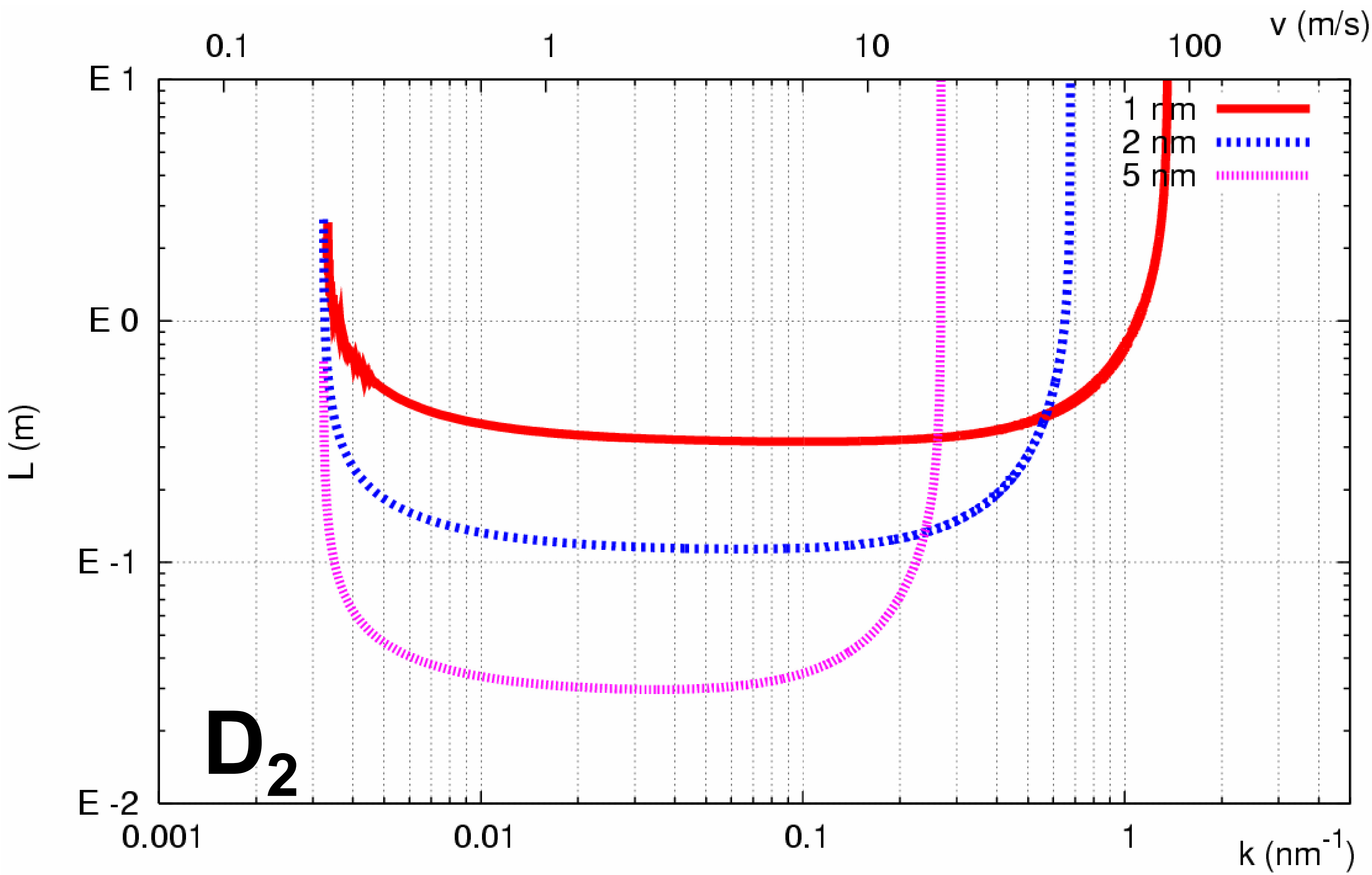
Compression time for different radius



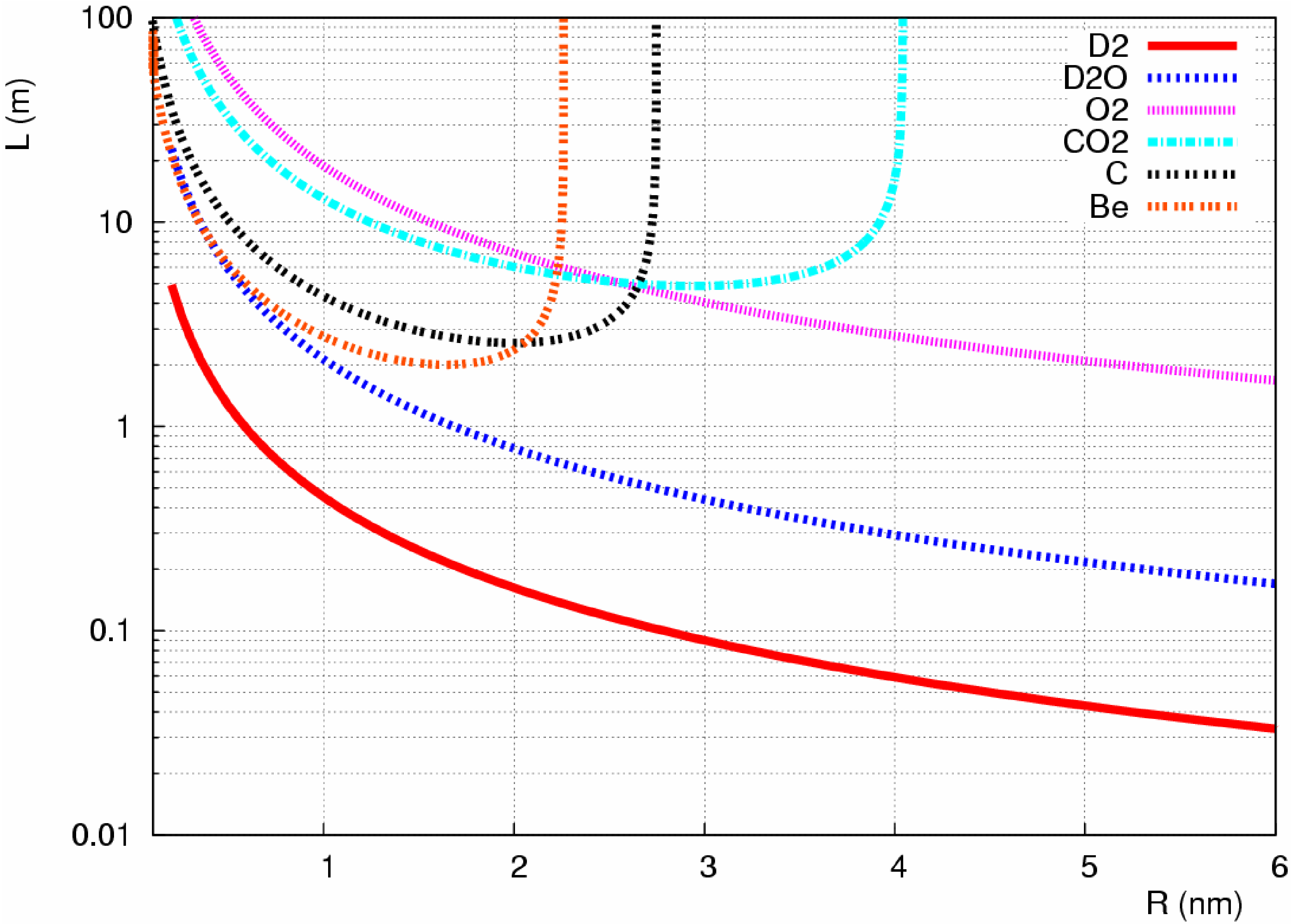
Compression time for different materials



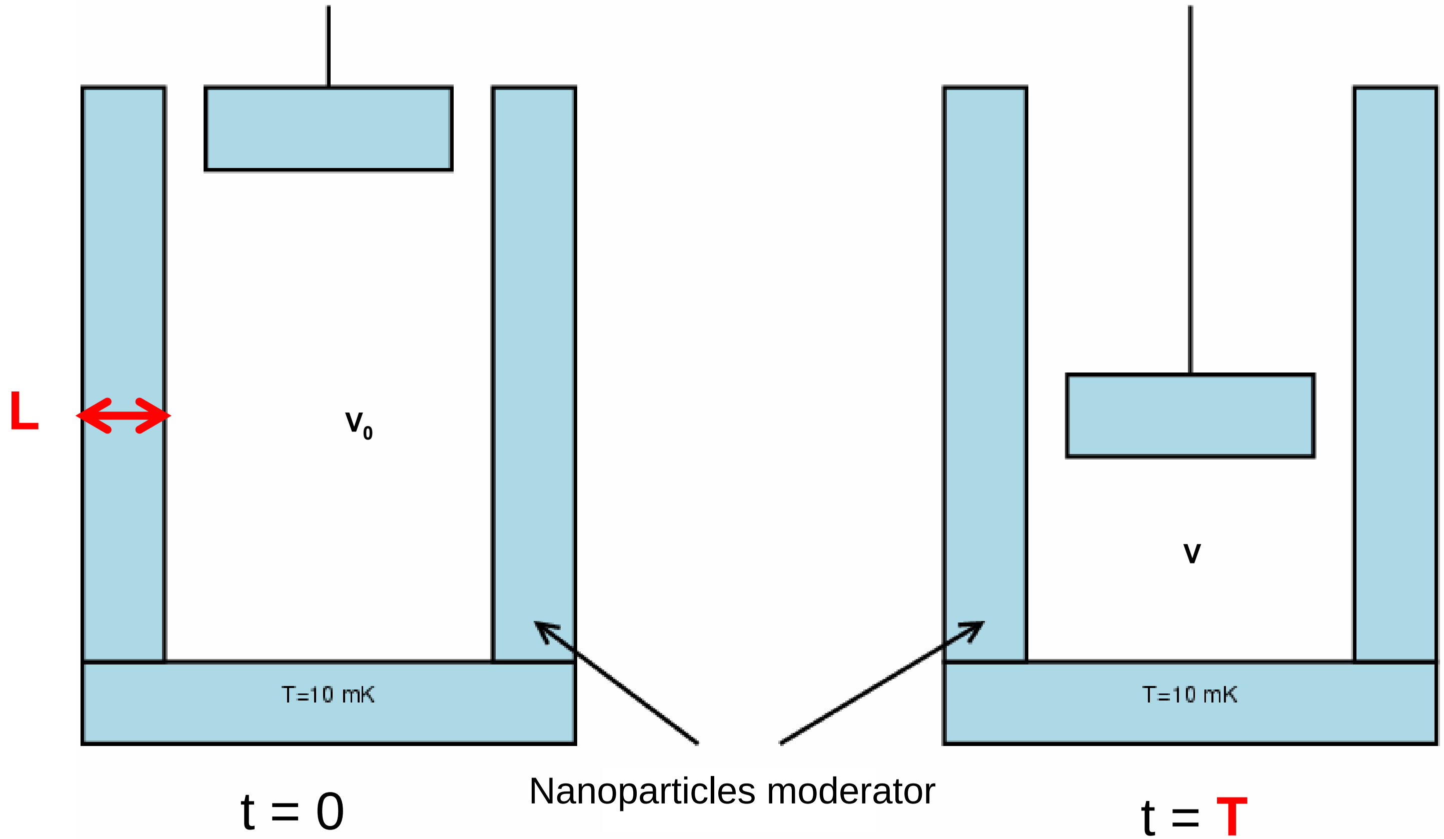
Moderator size for different nanoparticle materials



Moderator size for different nanoparticle materials



Options for realistic moderators



There is no theoretical limitations on the increase of density

Limitations of our model

- **This model neglects any other degrees of freedom of nanoparticles in gels → further theoretical work is needed**

- **Use of the Born approximation → not a problem**

- **Limitation at high energy → not a problem**

- **Limitation at low energy → is there a problem ?**

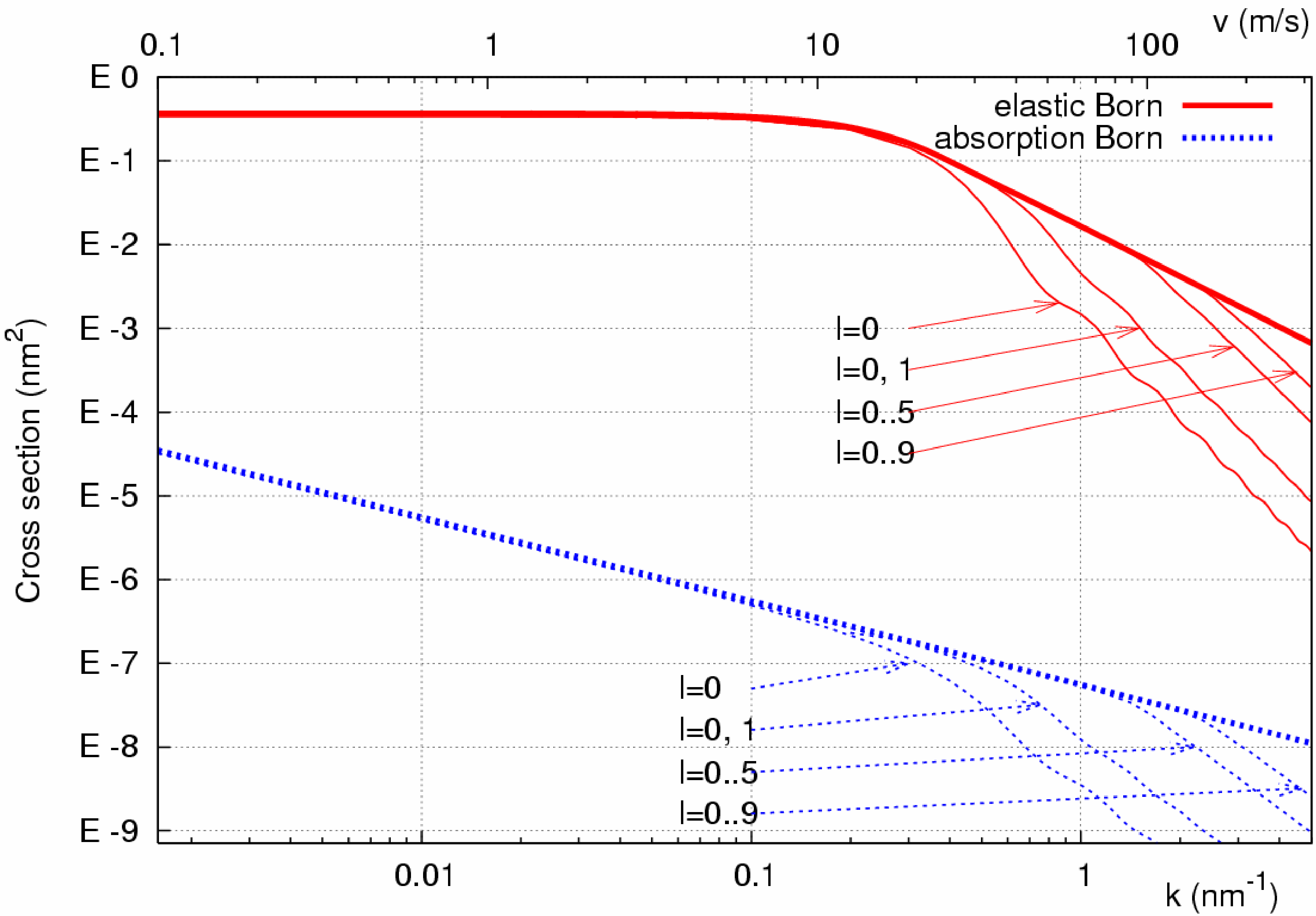
Conclusions

- The best nanoparticle material is Deuterium.
- The range of efficient moderation is ~1-100 m/s

Very cold neutrons

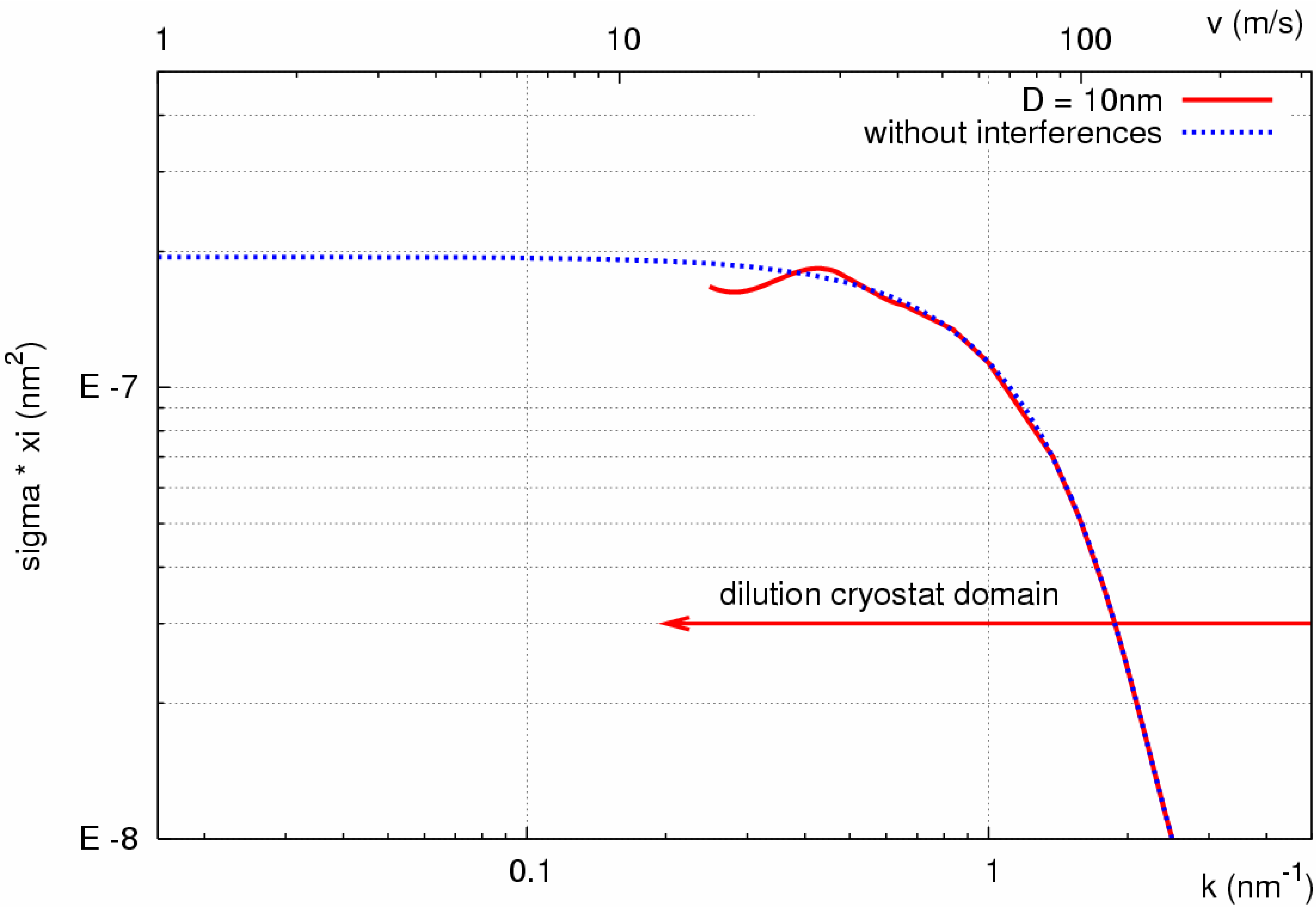
- The optimal size of the nanoparticles is about R=2 nm
- With the thermalisation time of a few seconds and the moderator size of a few times 10 cm, a principle realization of the presented cooling mechanism is feasible

Back slides



v (m/s)
0.1
1
10
100
E 0
E -1
E -2
E -3
E -4
E -5
E -6
E -7
E -8
E -9
Cross section (nm2)
elastic Born
absorption Born
l=0
l=0, 1
l=0..5
l=0..9
l=0
l=0, 1
l=0..5
l=0..9
0.01
0.1
1
k (nm-1)

Back slides



v (m/s)
1
10
100
D = 10nm
without interferences
sigma * xi (nm²)
E -7
E -8
dilution cryostat domain
0.1
1
k (nm⁻¹)