EUROPEAN SPALLATION SOURCE

2019
1ST BILBAO NEUTRON SCHOOL
SCIENCE AND INSTRUMENTATION FOR COMPACT ACCELERATOR-DRIVEN NEUTRON SOURCES (CANS)
JUNE, 17, 18, 19
More information and registration:
www.BNS2019.org

Peter Willendrup, DTU Physics & ESS DMSC

Neutron optics

- And thanks to Ken Andersen ESS for letting me use a lot of his slides on guides!

McStas

Neutron optics - subtopics

- Key properties of the neutron

- Transporting the beam
  - Neutron guides and how they work

- Tailoring the beam
  - Spatially
  - Directionally
  - Temporally
  - Energetically

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The neutron - a reminder

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Life time:	$\tau_{1/2} = 890s$
Mass:	$m = 1.675 \times 10^{-27} kg$
Charge:	$Q = 0$
Spin:	$s = \hbar/2$
Magnetic moment:	$\mu/\mu_n = -1.913$

$$\boxed{E = \frac{1}{2}mv^2 = \frac{\hbar^2 k^2}{2m}, \qquad \lambda = 2\pi/k}$$

$$\boxed{E = 81.81 \cdot \lambda^{-2} = 2.07 \cdot k^2 = 5.23 \cdot v^2}$$


Mr. Neutron

	Energy	Wavelength	n-Wavevector	Velocity	Frequency
cold neutrons:	E = 1 meV	l = 9.0446 Å	k = 0.6947 1/Å	v = 437 m/s	v = 0.2418 THz
	E = 5 meV	l = 4.0449 Å	k = 1.5534 1/Å	v = 978 m/s	v = 1.2090 THz
thermal neutrons:	E = 25 meV	l = 1.8089 Å	k = 3.4734 1/Å	v = 2187 m/s	v = 6.045 THz
	E = 50 meV	l = 1.2791 Å	k = 4.9122 1/Å	v = 3093 m/s	v = 12.090 THz

Cross section: coherent + incoherent + absorption

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Cross section: coherent + incoherent + absorption

Optical properties - slow neutrons vs. light

	light	neutrons
λ	< µm	< nm
E	> eV	> meV
n	1→4	0.9997→1.0001
θ_c	90°	1°
B	10^{18} p/cm²/ster/s (60W lightbulb)	10^{14} n/cm²/ster/s (60MW reactor)
spin	1	½
interaction	electromagnetic	strong force, magnetic
charge	0	0

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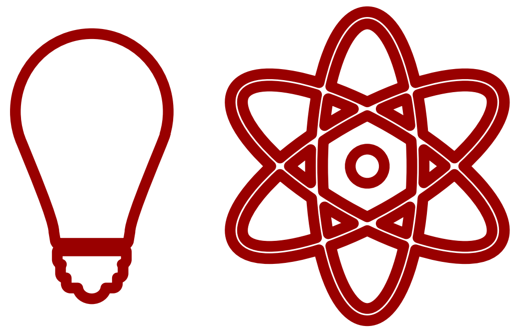
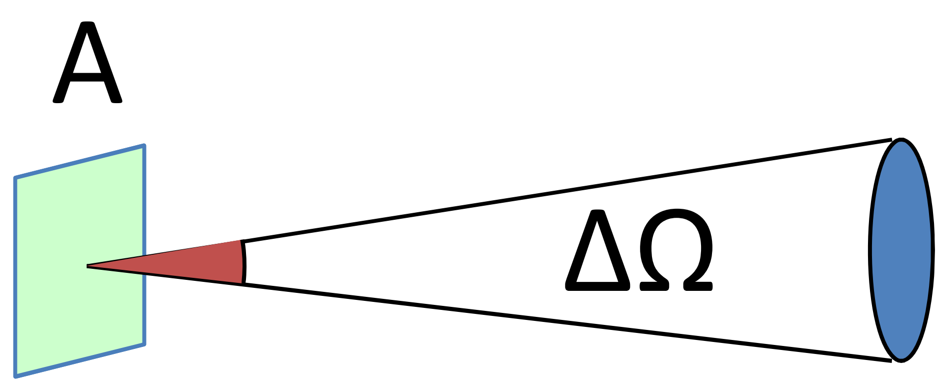
Corresponding to distances and excitations within condensed matter

Neutrons are scarce, but we have a chance to transport them



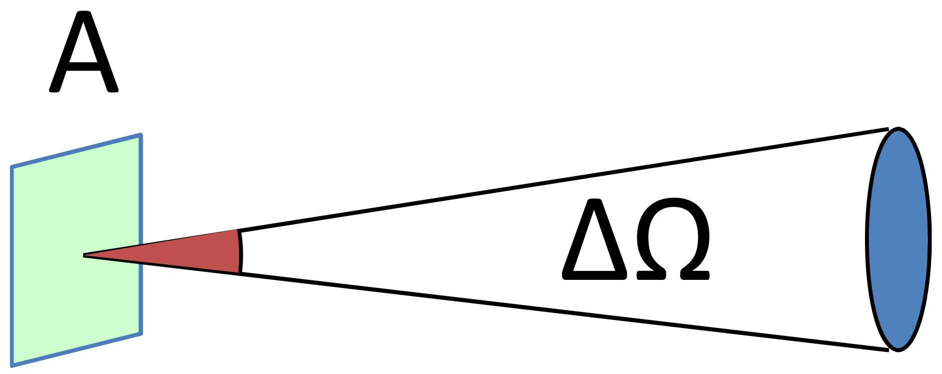
Neutron flux - and brilliance / brightness



B = N per time per A per ΔΩ

units = n/s/cm^2/sr

Neutron flux - and brilliance / brightness



B is independent of distance

- property of the source

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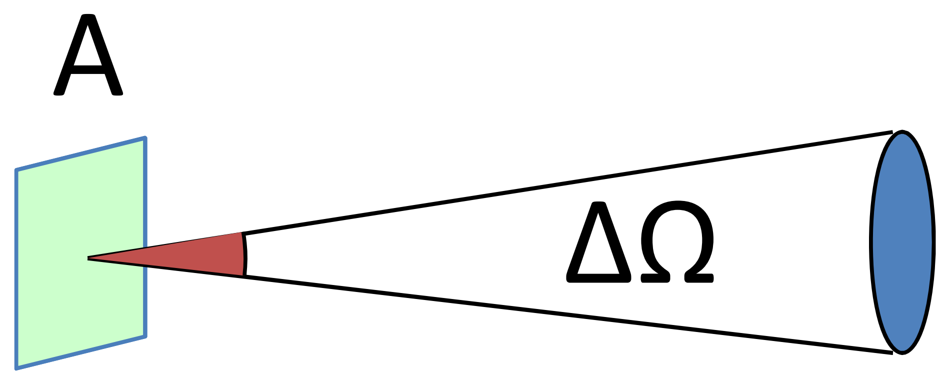
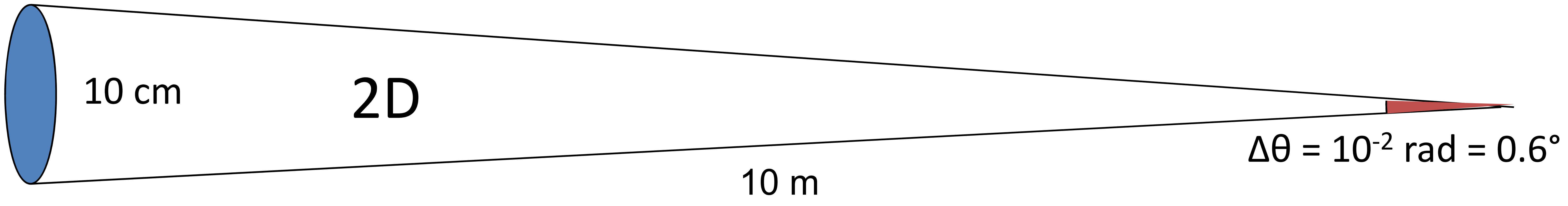


Brilliance/Brightness	B	[$n/s/cm^2/sr$]
Flux	Ψ	[$n/s/cm^2$]

Neutron flux - and brilliance / brightness



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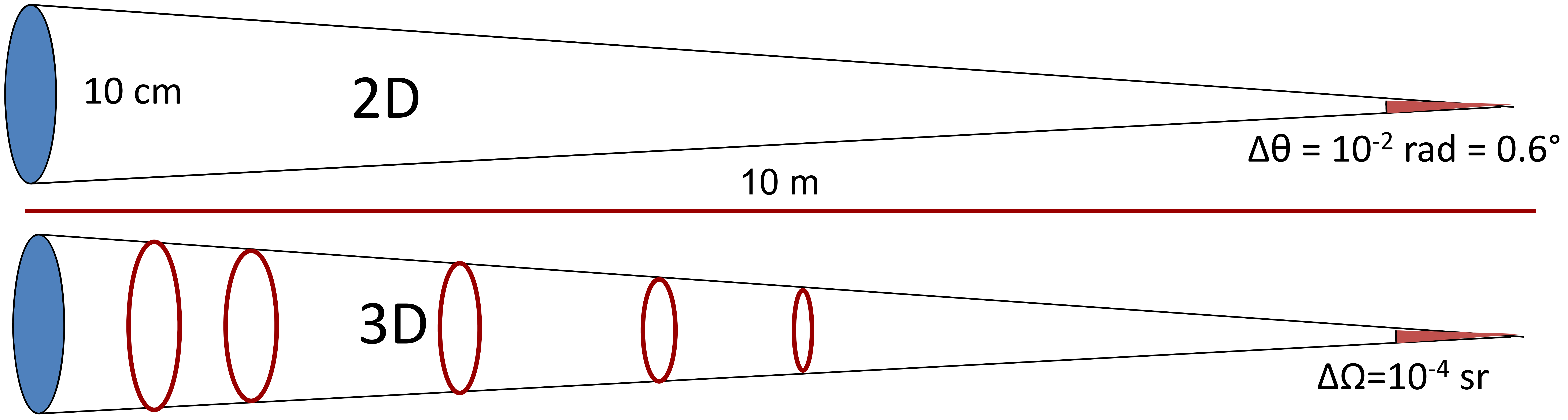

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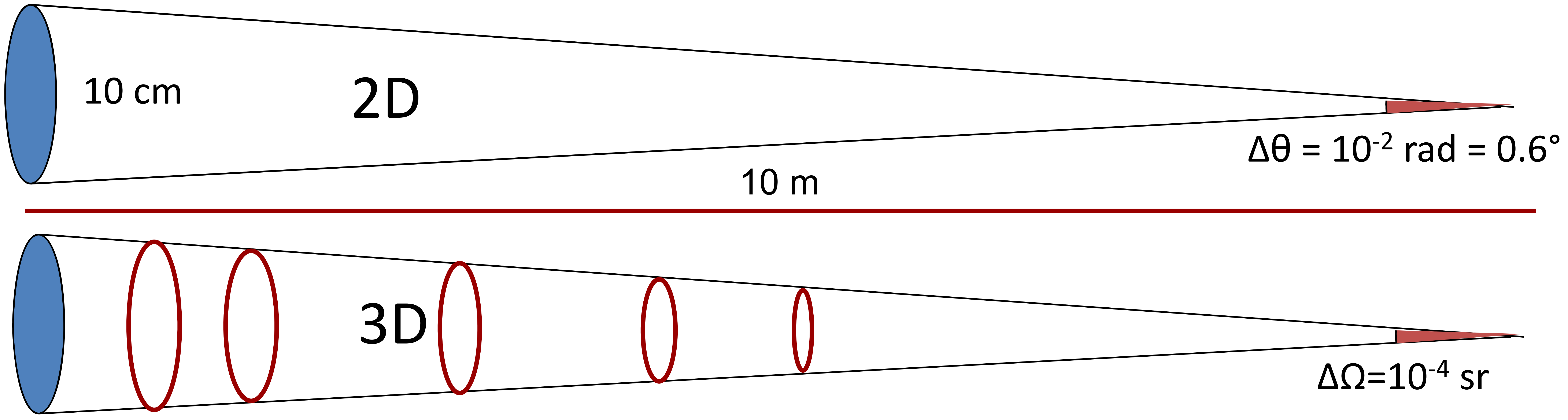
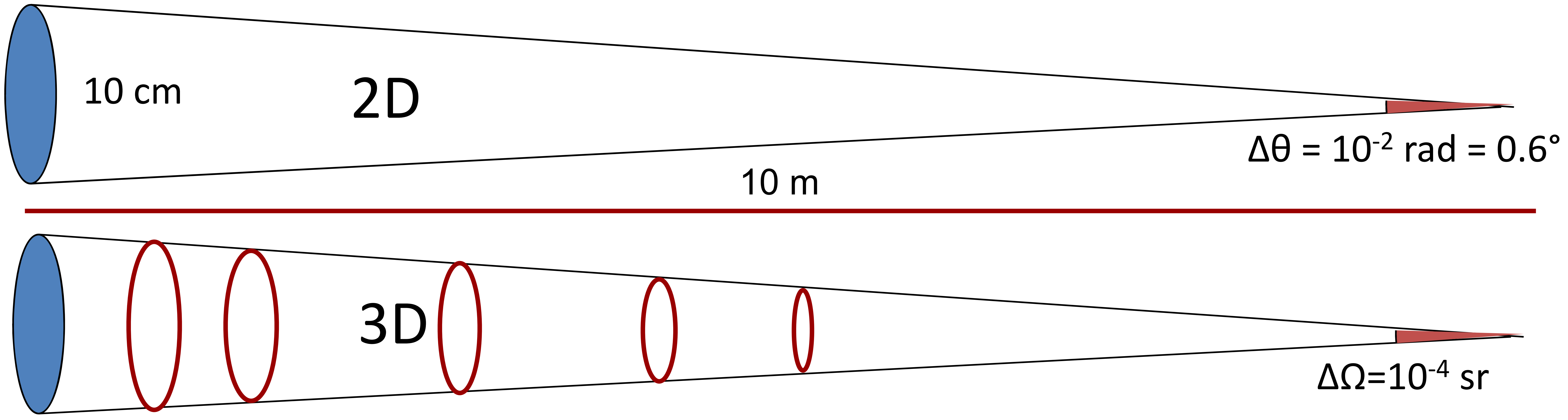


Flux = Source Brightness × Solid Angle

$\Phi = B \times \Delta\Omega$

Neutron flux - and brilliance / brightness



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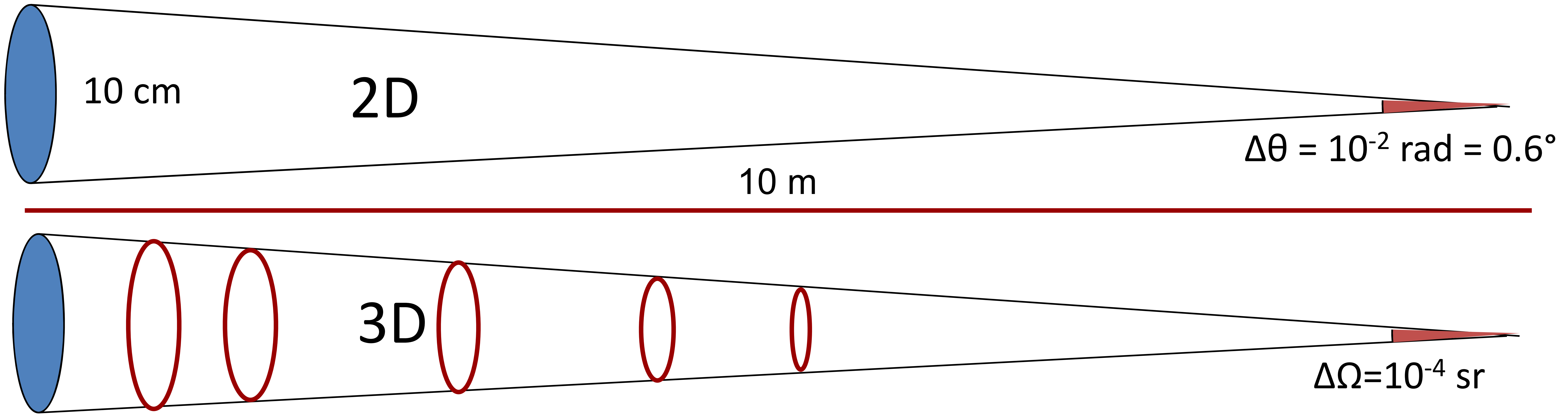

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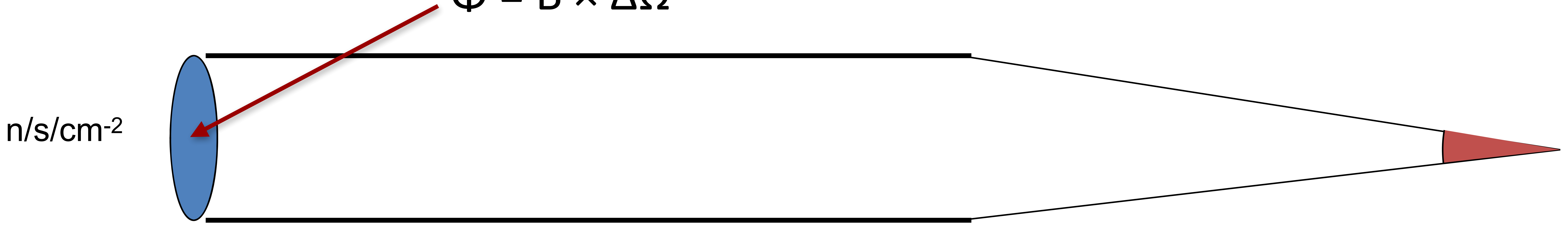

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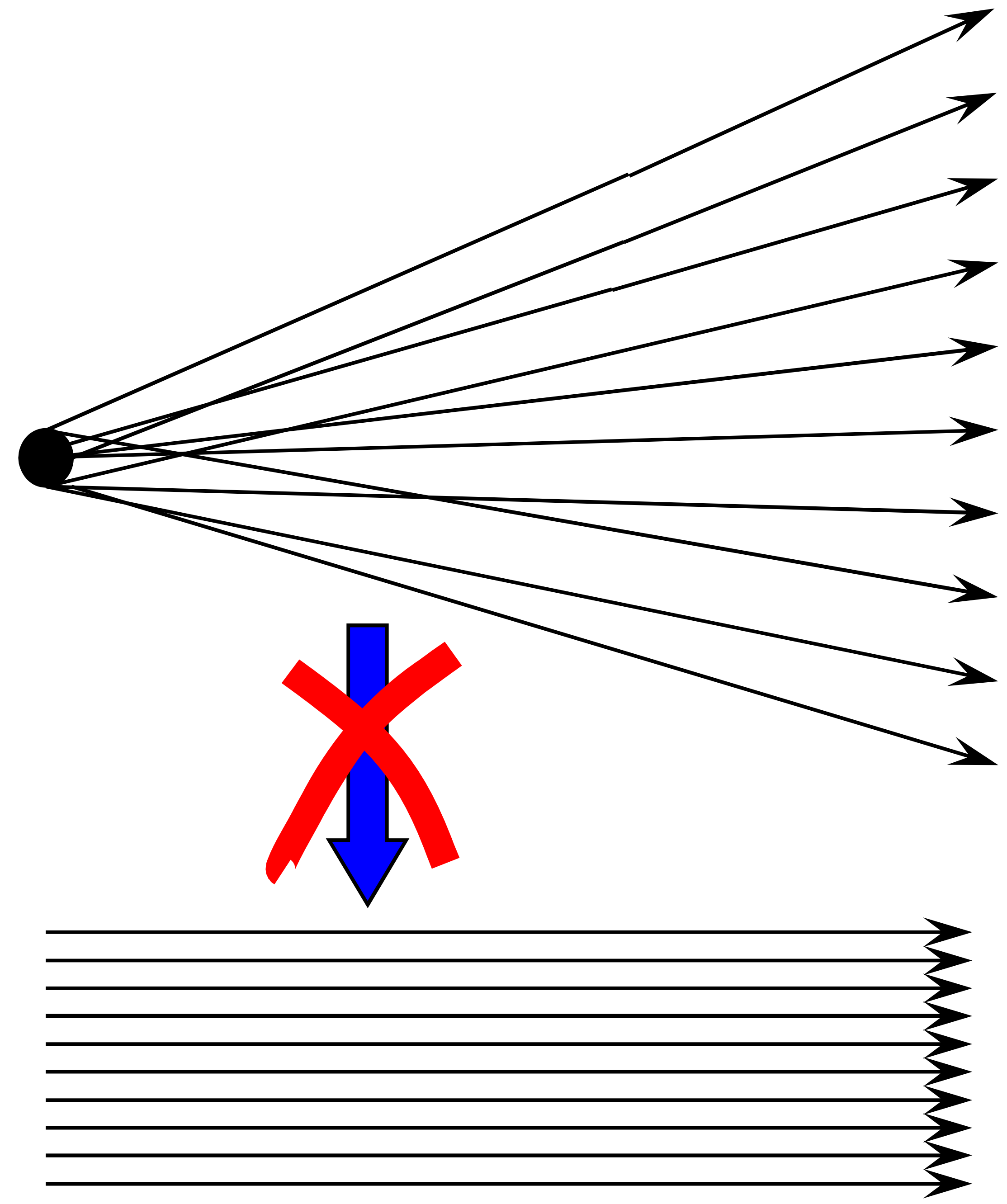
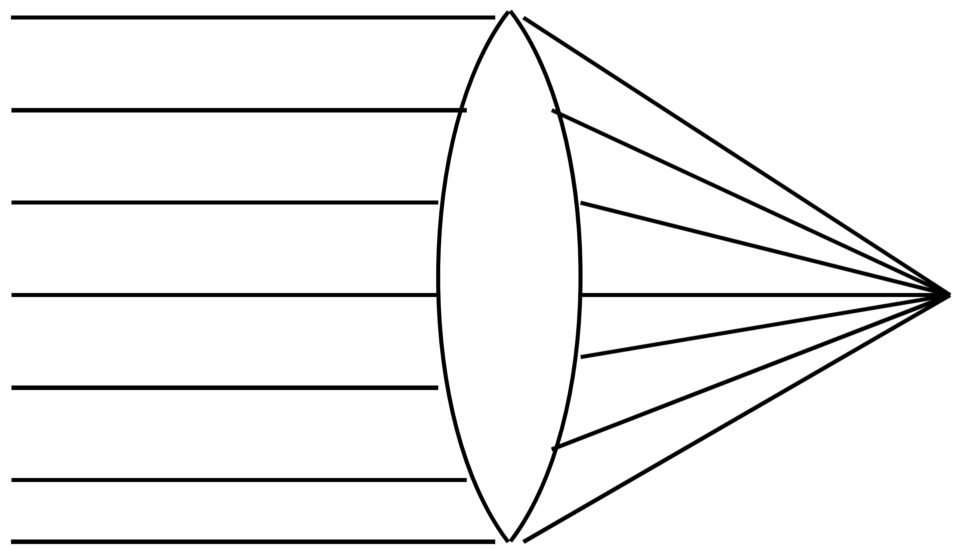
Liouville theorem

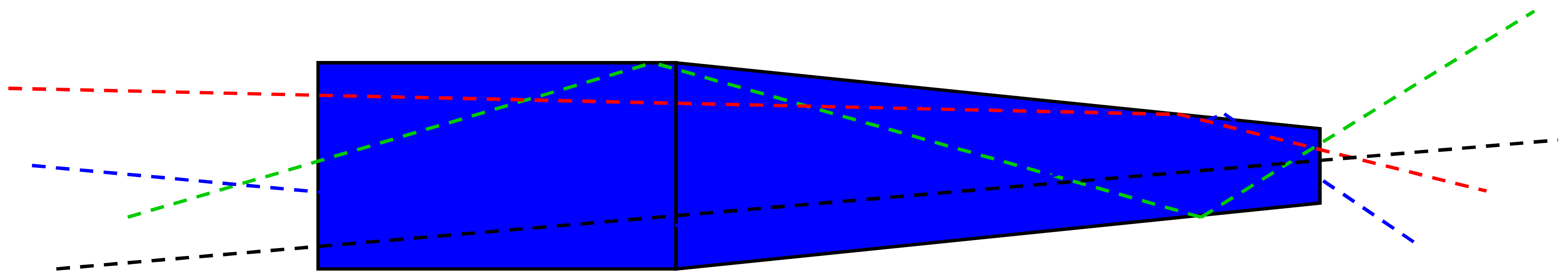
→ $\Delta x \Delta \phi$ = const

Liouvilles Theorem

- Conservation laws:
  - neutrons can't be created from thin air
  - neither can "phase space density"
- There is no such thing as a free lunch
  - Beam manipulation transfers distribution between time, area, divergence, energy
- Most common application:
  - Focusing increases divergence
  - improve flux, lose angular resolution







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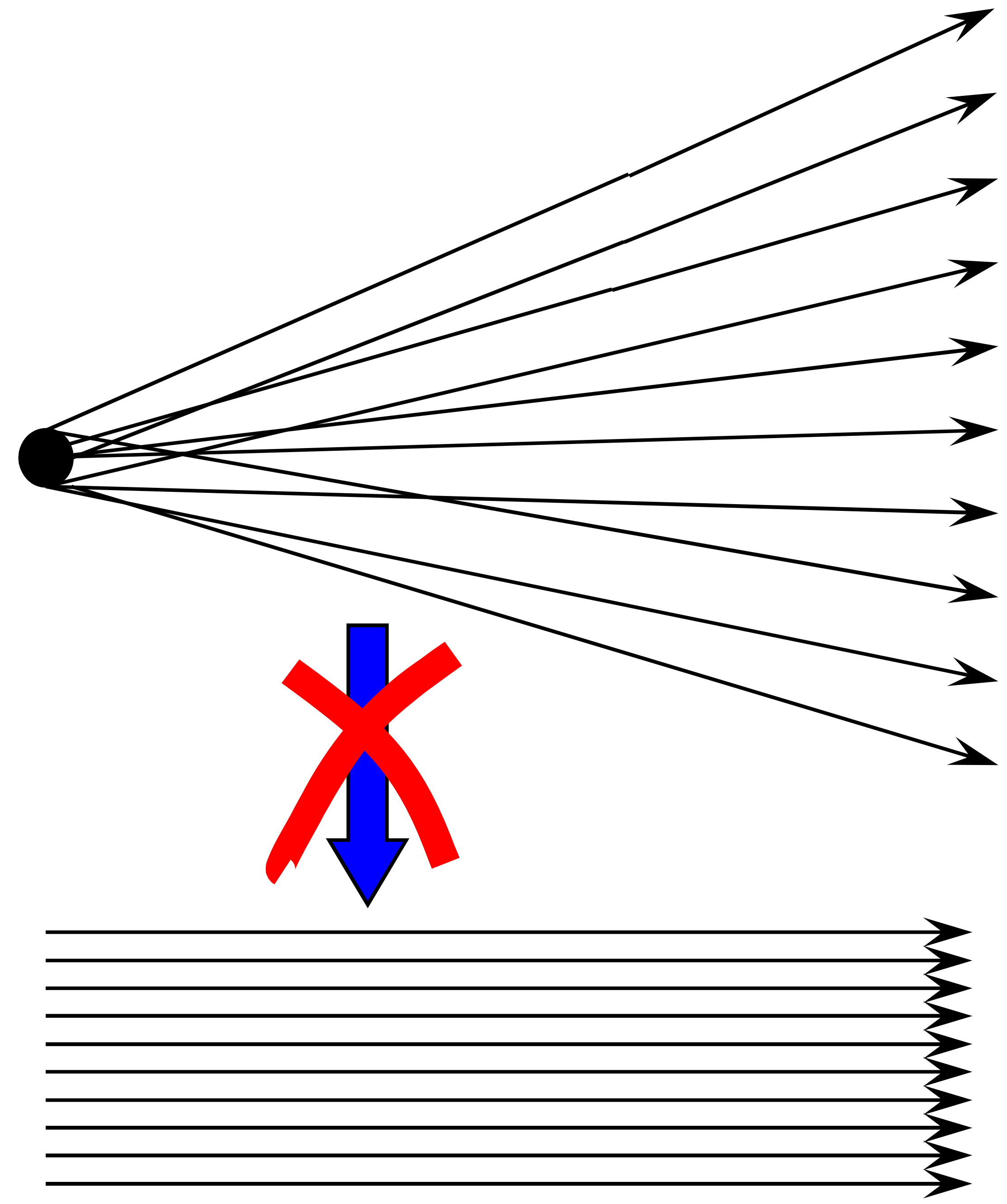

Integrated flux $\int \Psi \, dA \, d\Omega$ can never increase

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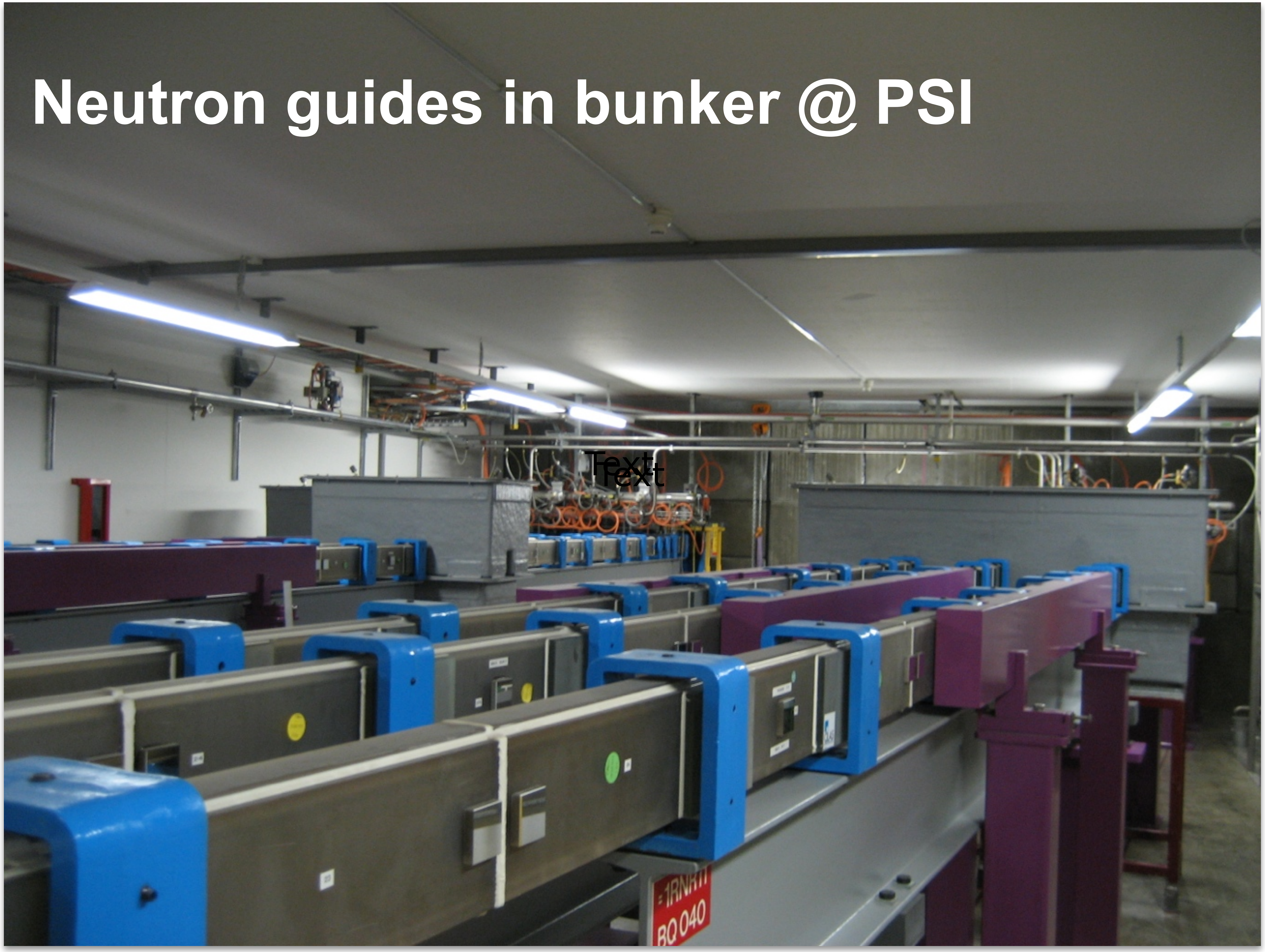
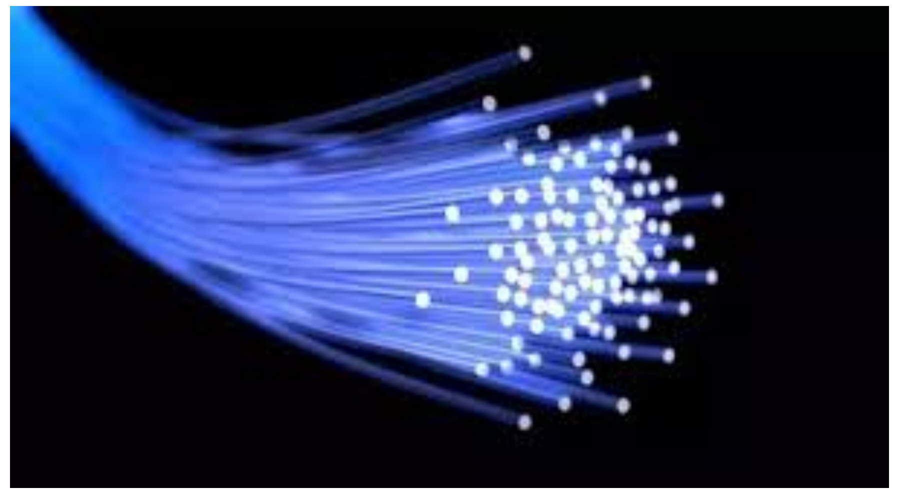
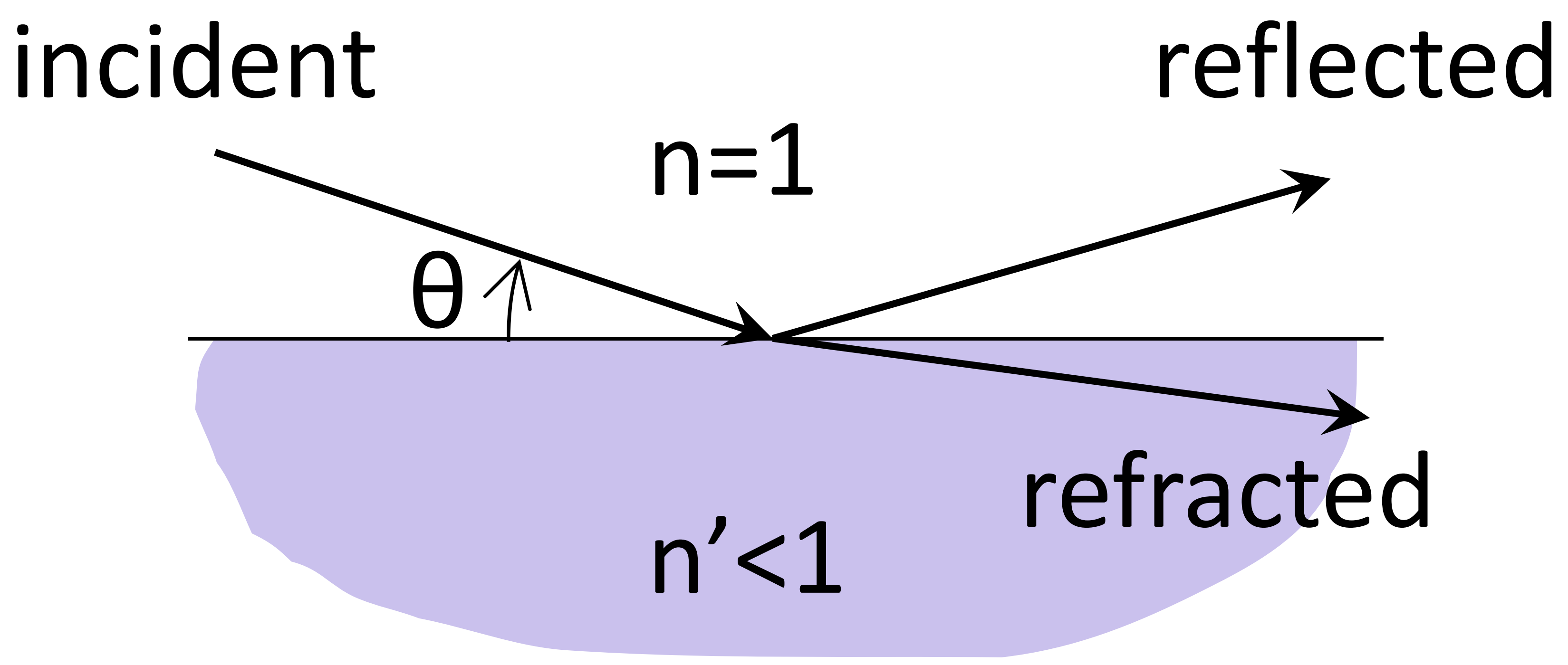
Neutron guides in bunker @ PSI



- think optical fiber, however not total internal, rather total external reflection



Reflection: Snell's Law



critical angle of total reflection θ_c

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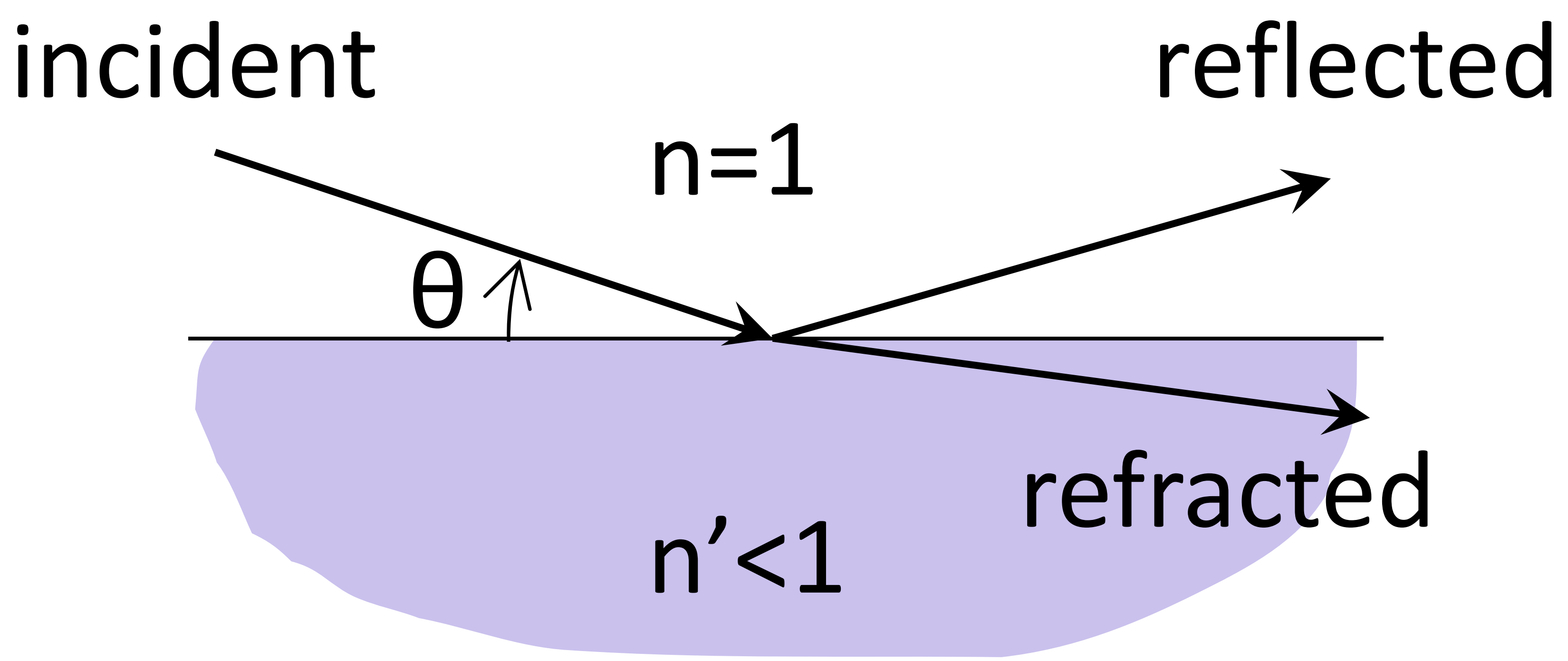

critical angle of total reflection θ_c

$$\left.\begin{aligned} \cos\theta_c &= n'/n = n' \\ n' &= 1 - \frac{N\lambda^2 b}{2\pi} \\ \cos\theta_c &\approx 1 - \theta_c^2/2 \end{aligned}\right\} \Rightarrow \theta_c = \lambda\sqrt{Nb/\pi}$$

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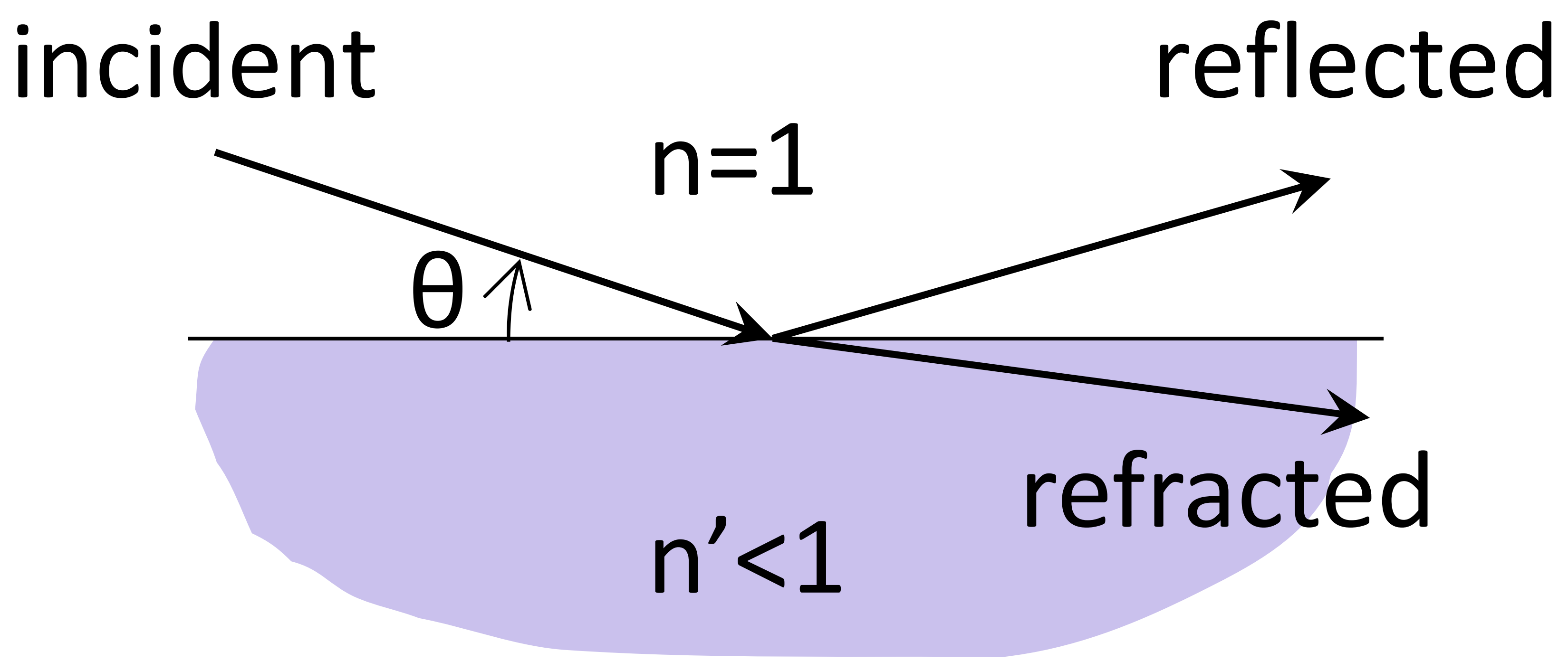

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for natural Ni:

$\theta_c = \lambda[\text{Å}]\times 0.1°$

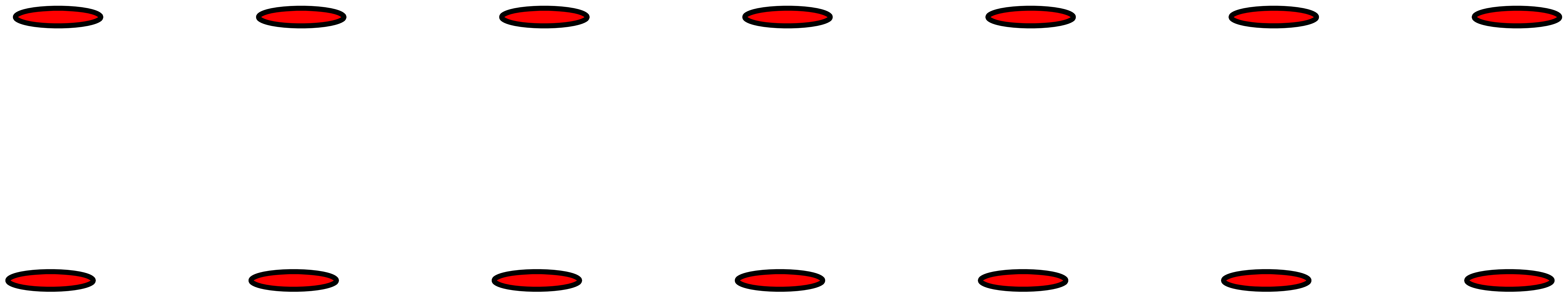
$Q_c = 0.0218\ \text{Å}^{-1}$

Definition:
$Q = 4\pi \sin\theta / \lambda$

Idea:

“Expand reflectivity by means of Bragg scattering?

Diffraction: Bragg’s Law



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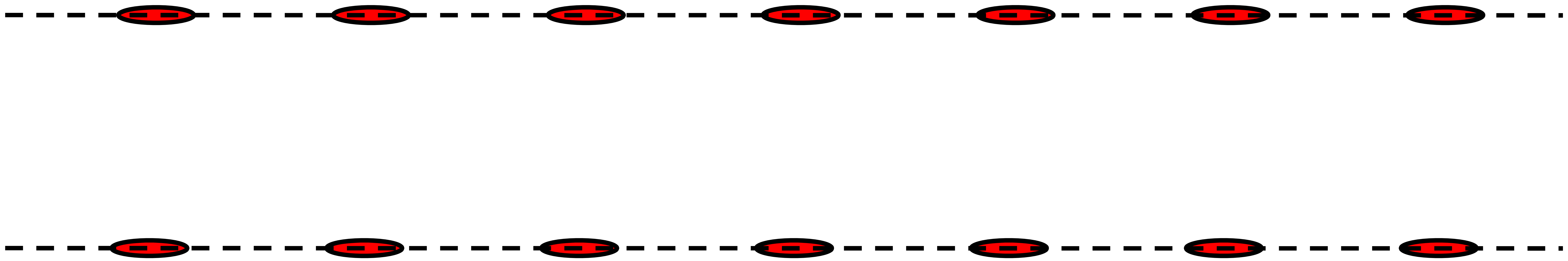

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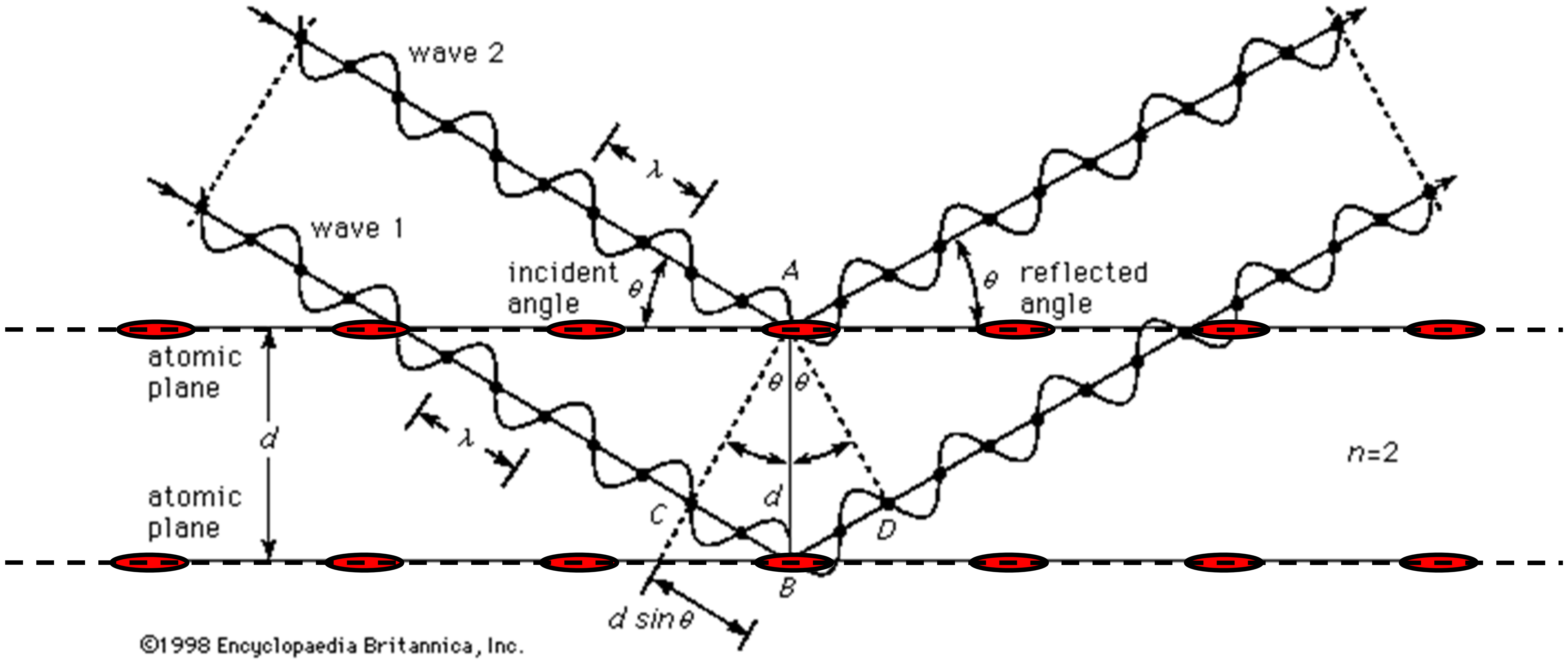

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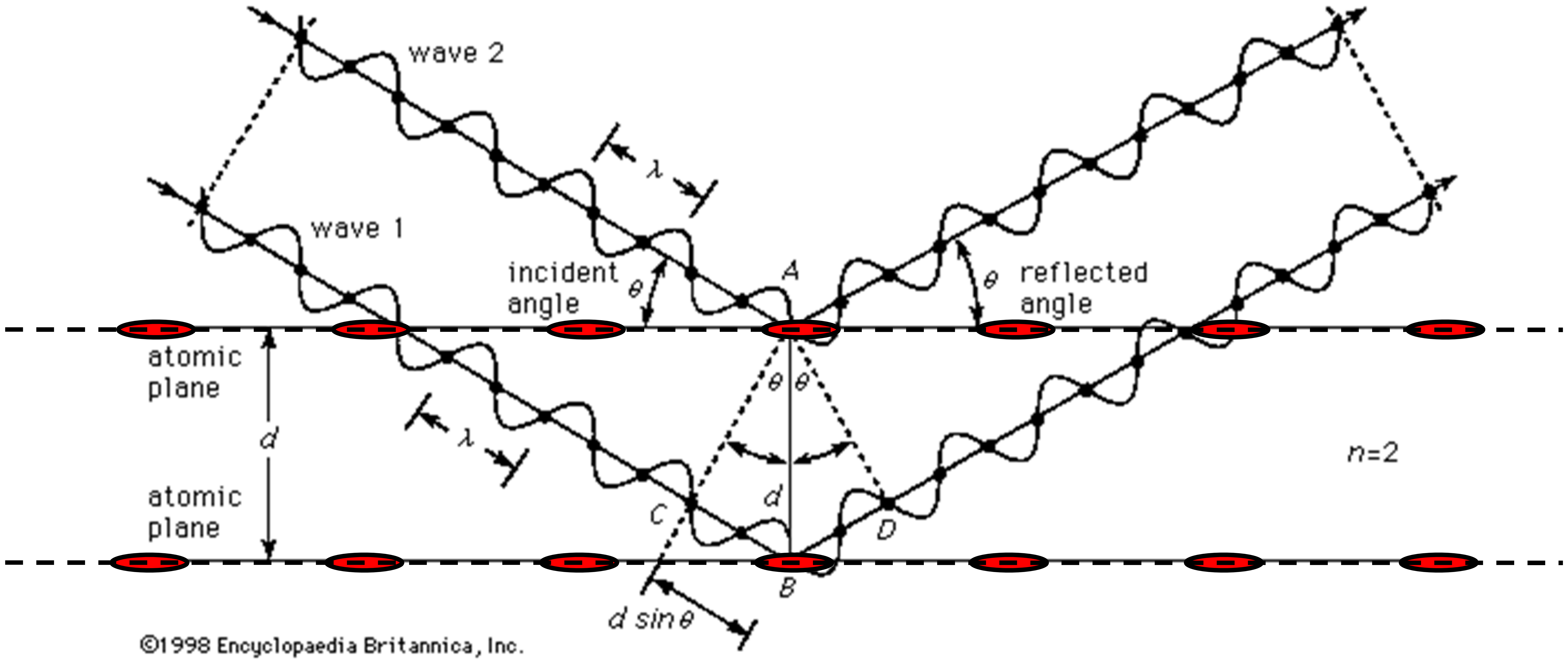

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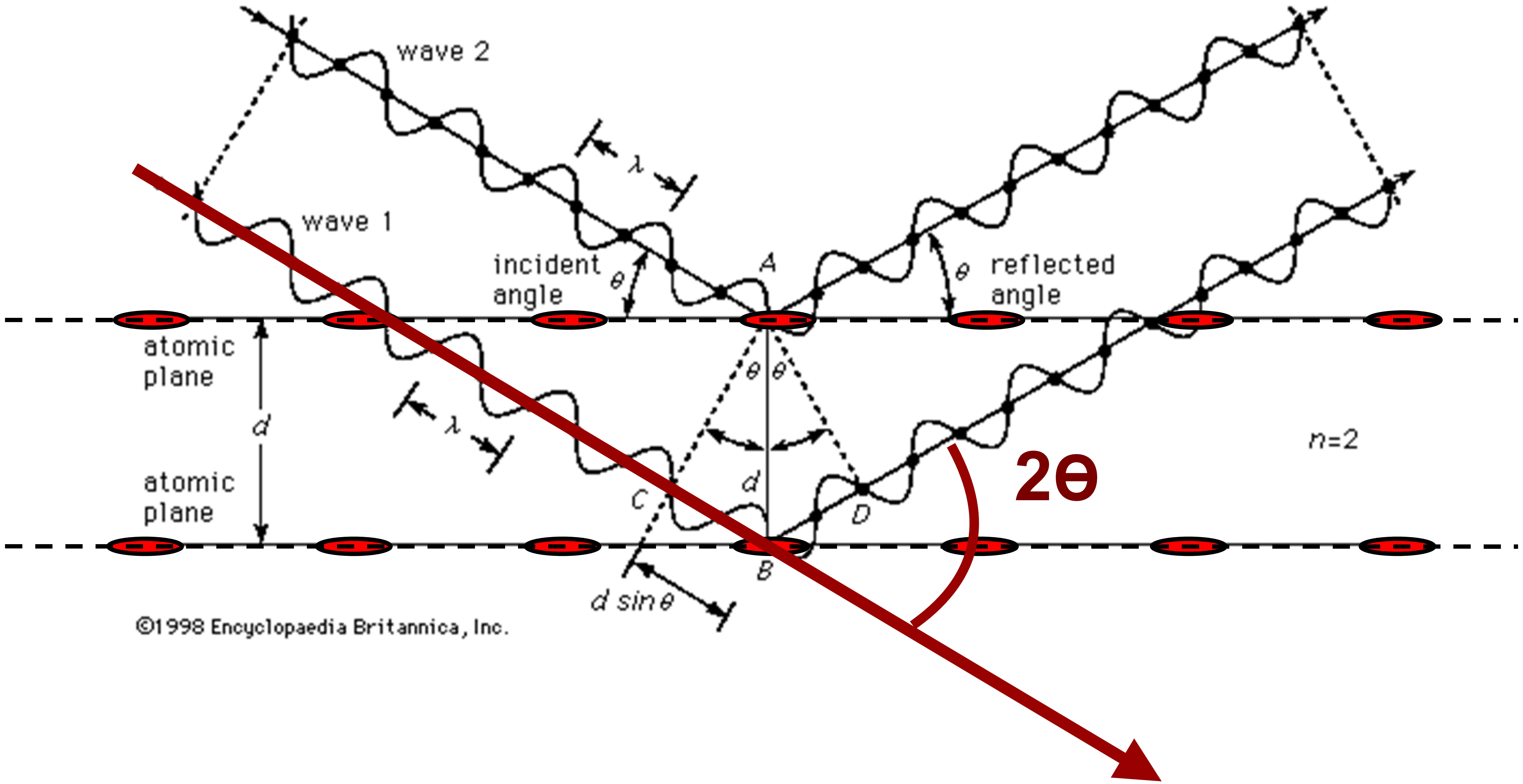

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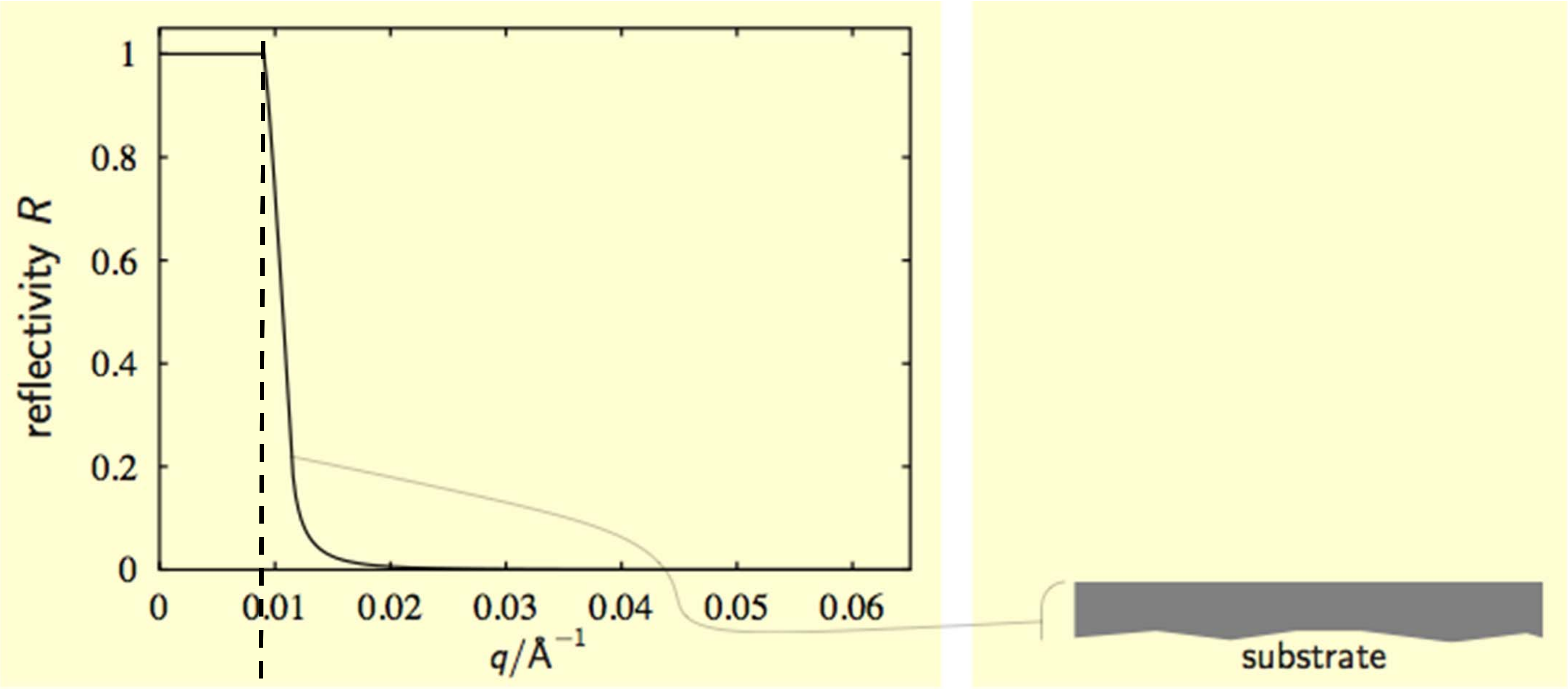
Neutron Supermirrors



Q_c as given by Snell's Law

Courtesy of J. Stahn, PSI

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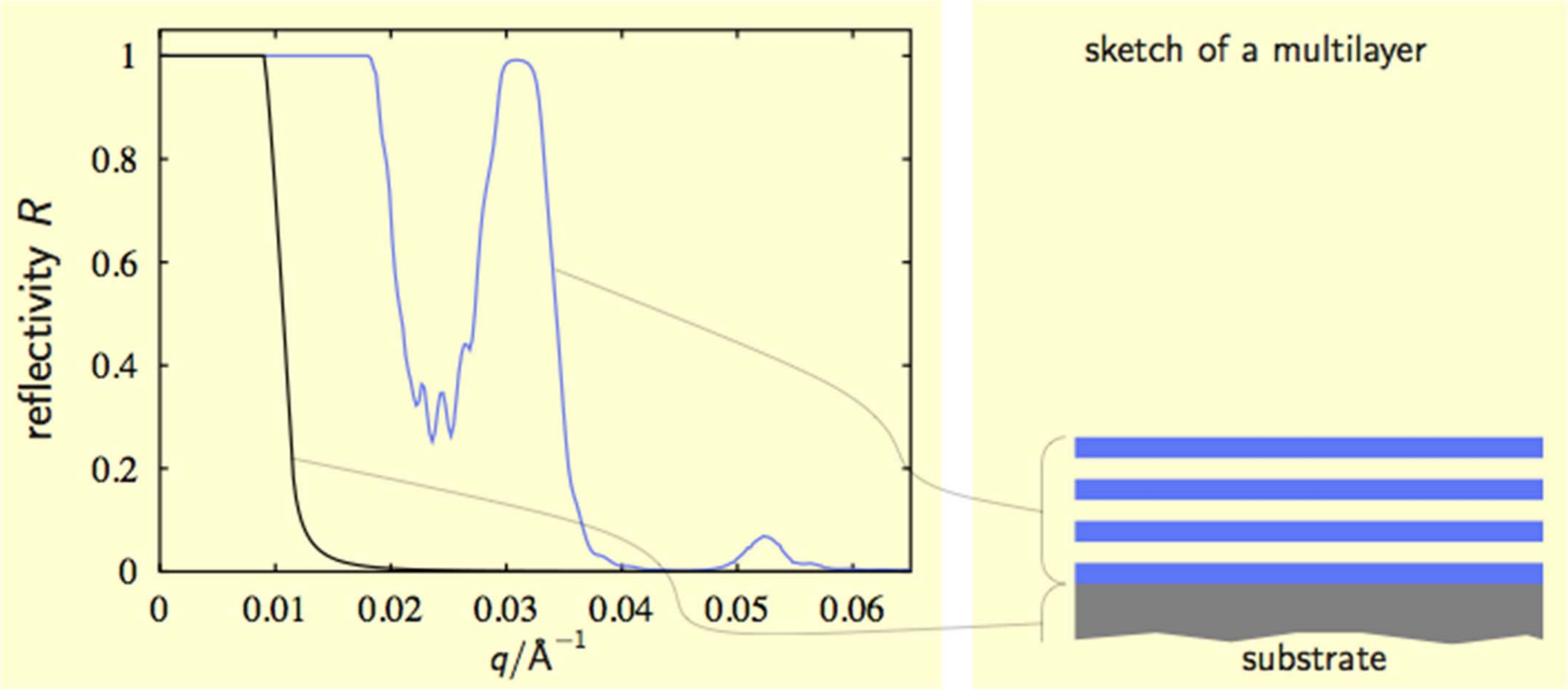

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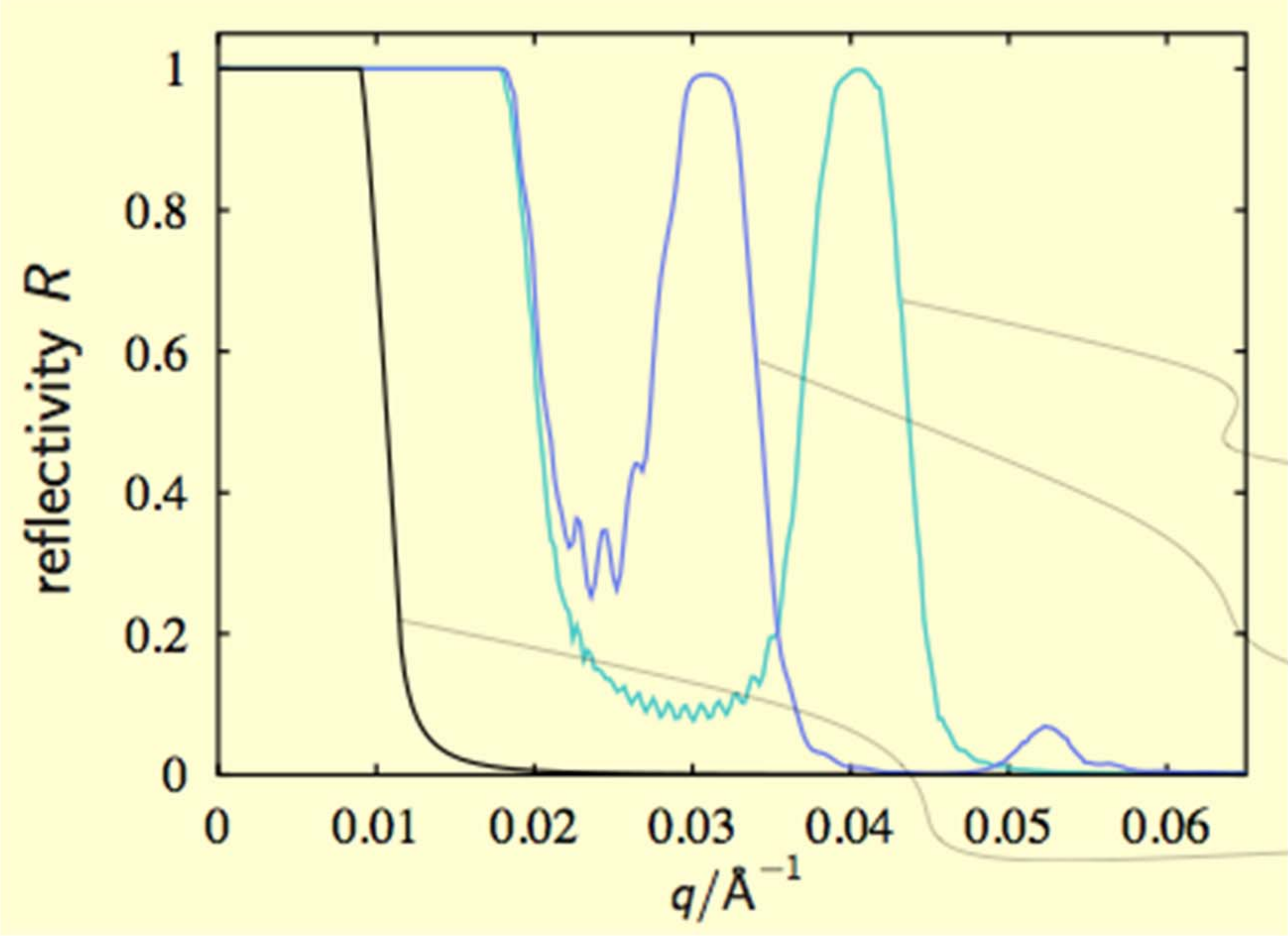

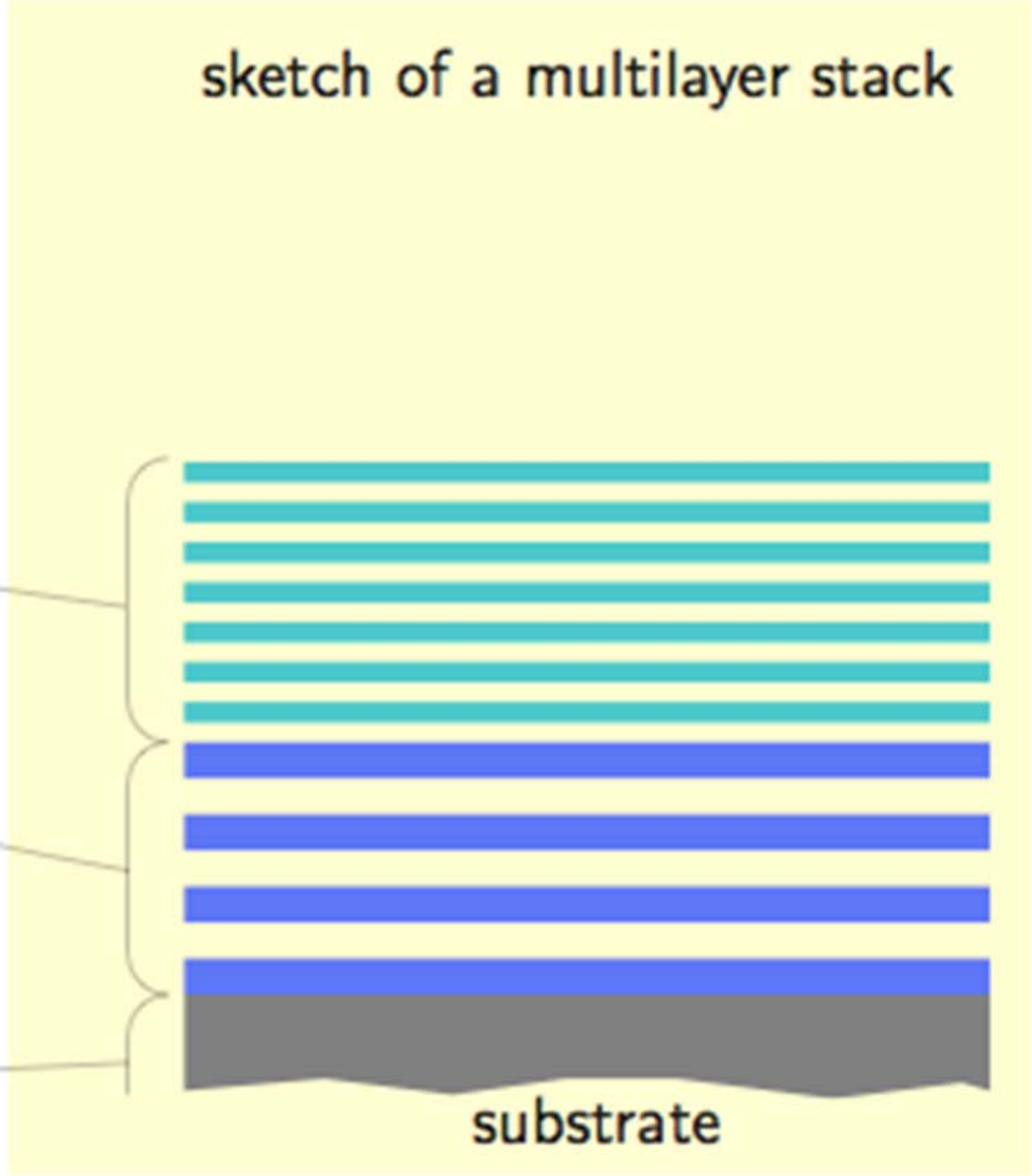

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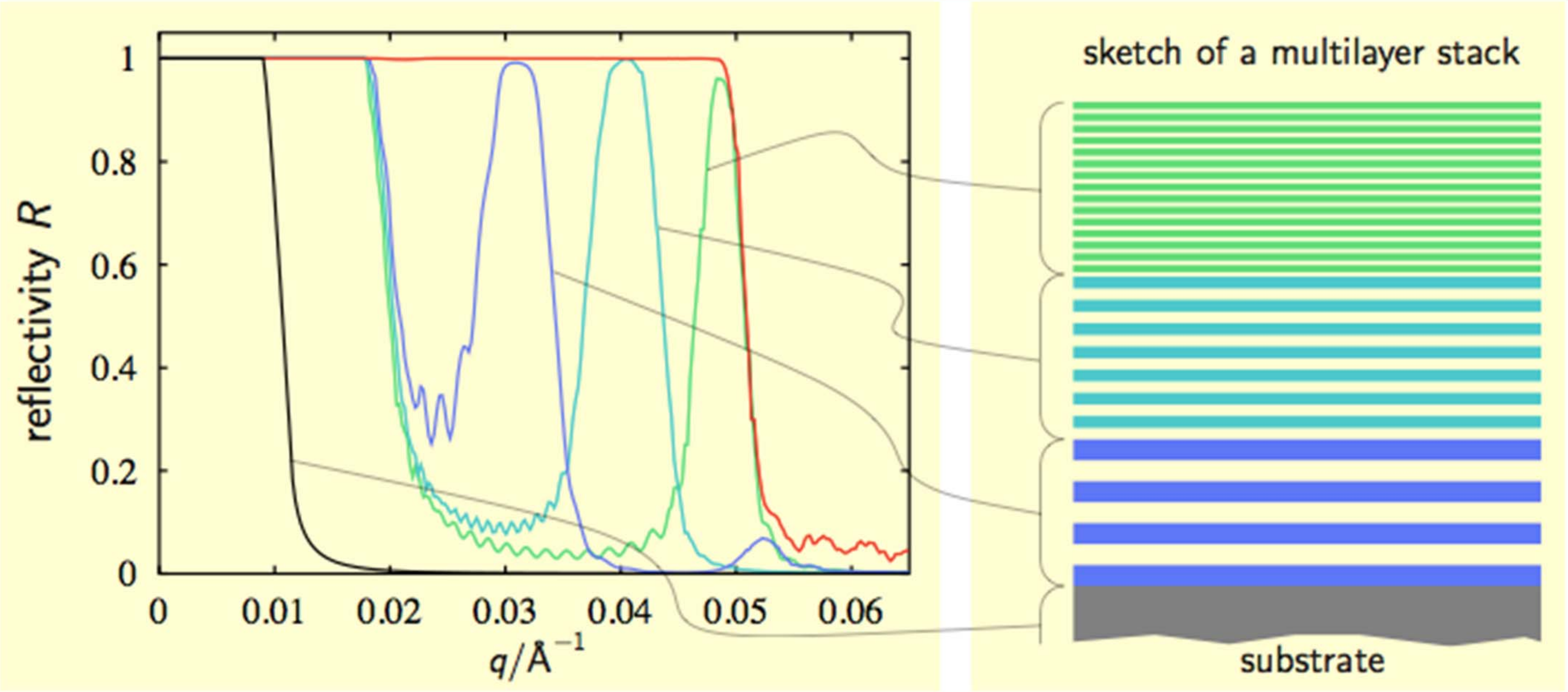
Neutron Supermirrors

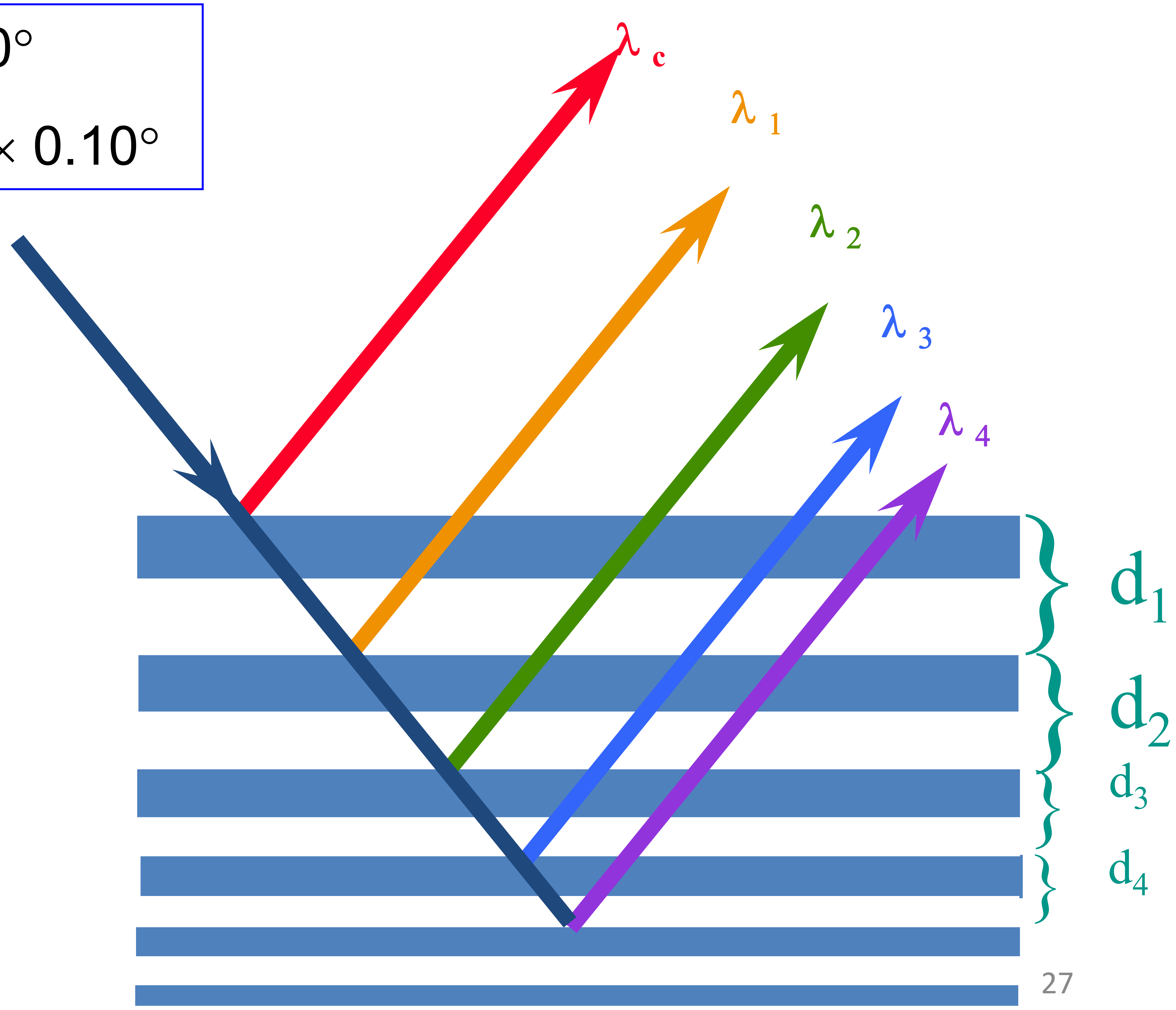


Courtesy of J. Stahn, PSI

Neutron Supermirrors

Reflection: $\theta_c(\mathrm{Ni}) = \lambda[\text{Å}] \times 0.10°$

Multilayer: $\theta_c(\mathrm{SM}) = m \times \lambda[\text{Å}] \times 0.10°$



Mezei, F.; Communications on Physics 1976, Volume 1, Issue 3, pp. 81-85
Mezei, F.; Dagleish, P. A. Communications on Physics 1977, Volume 2, Issue 2, pp. 41-3

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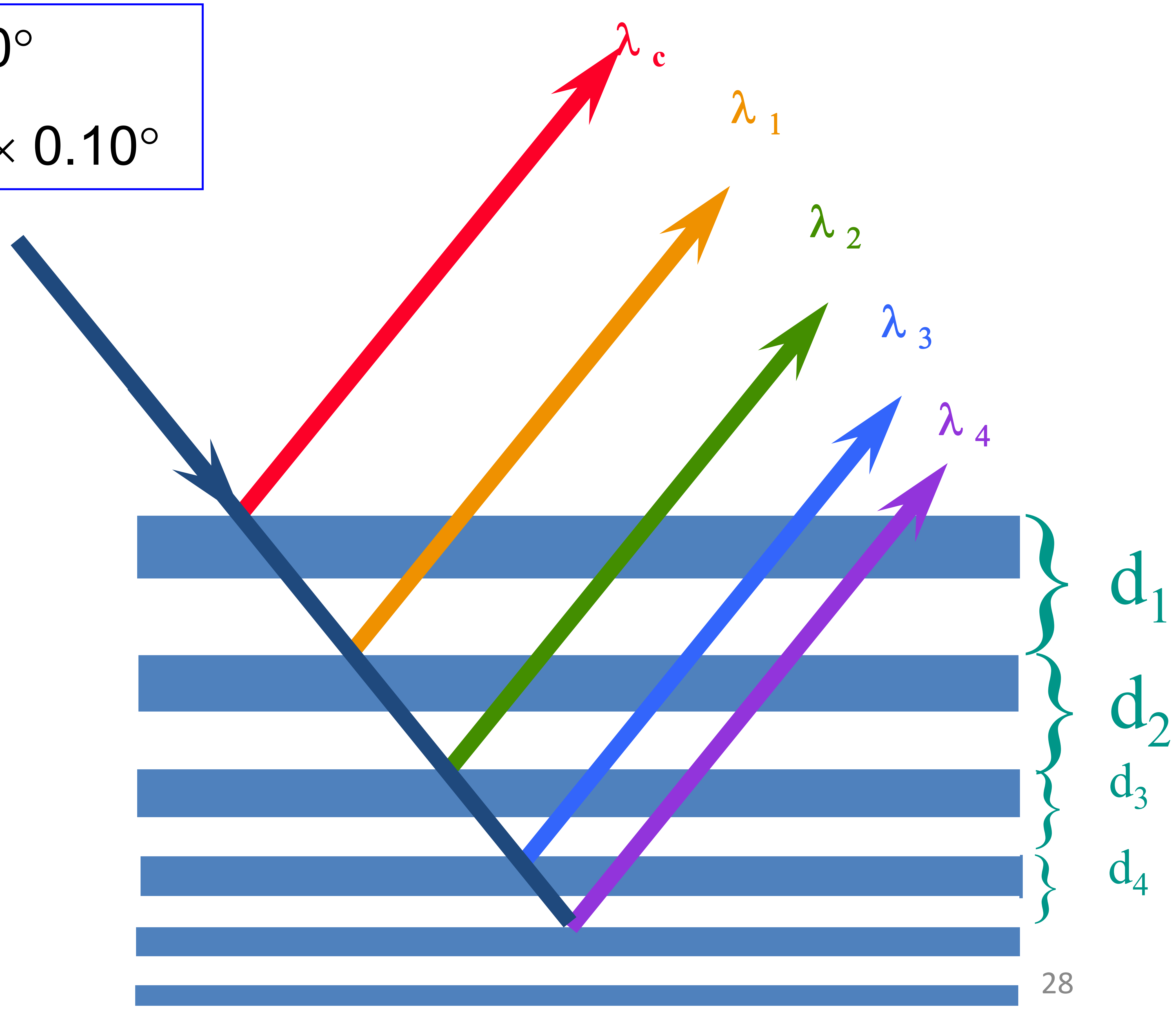
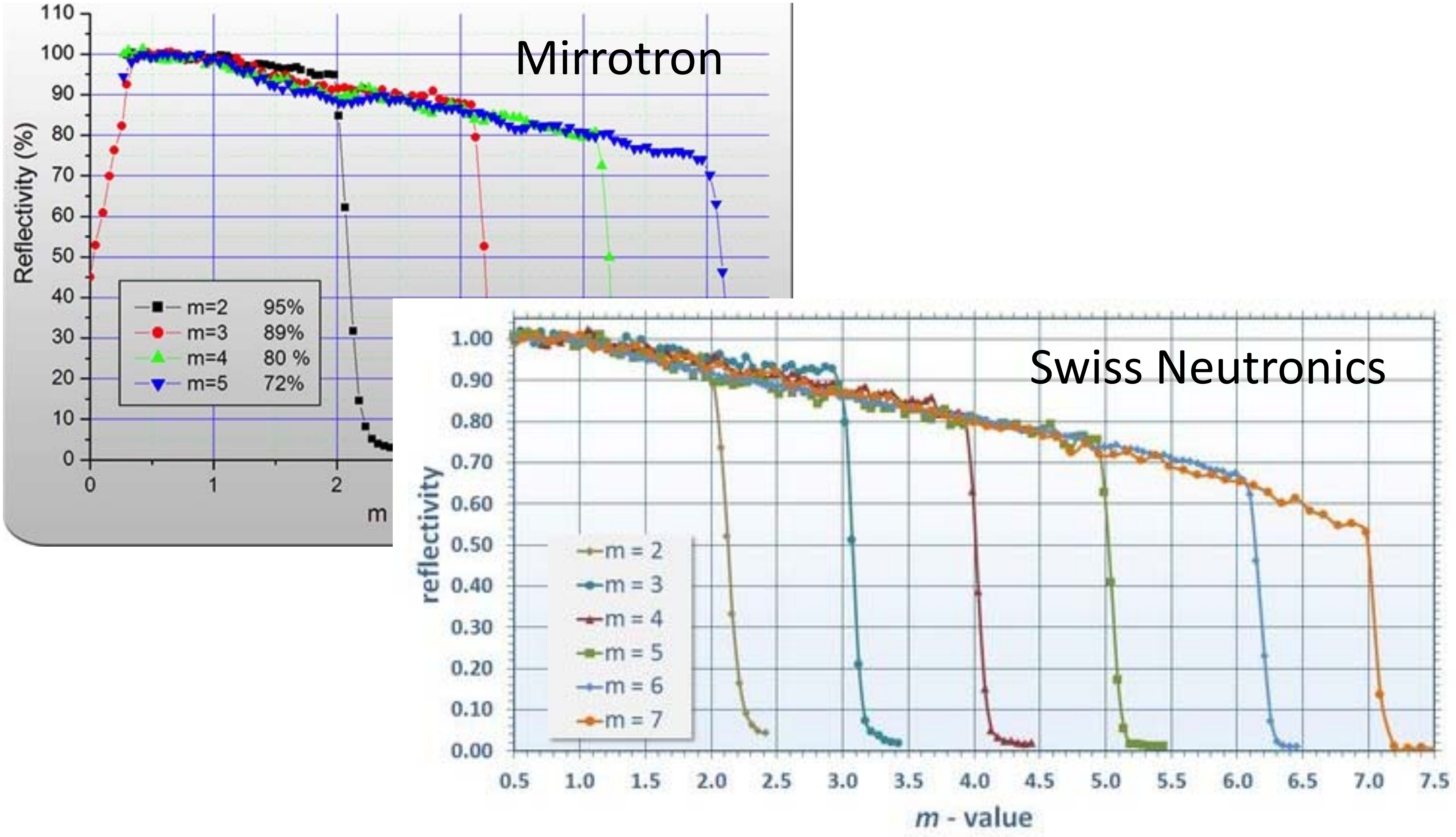
"m-number"
Supermirror critical angle



State-of-the-art Supermirrors (2015?)



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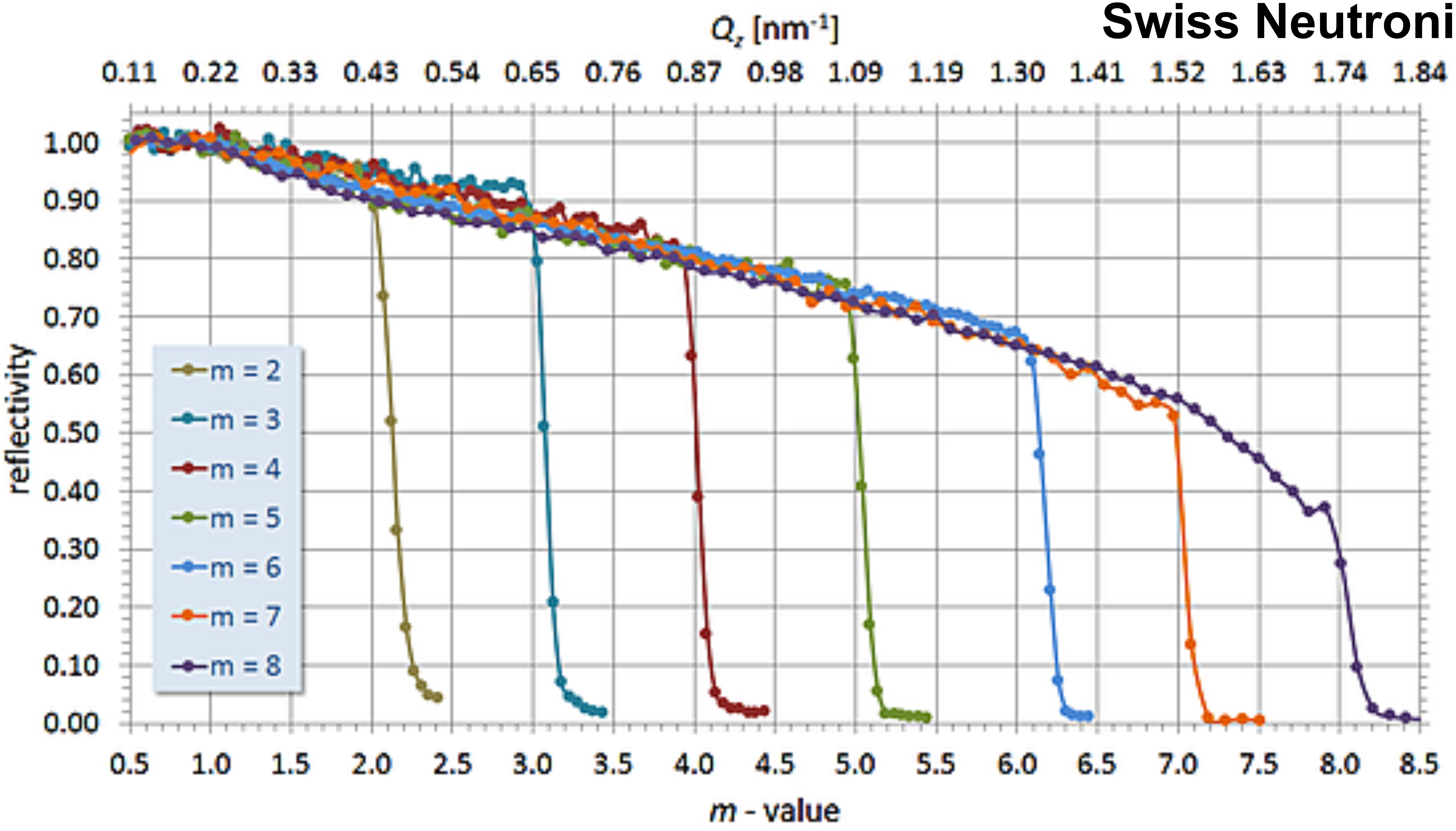
State-of-the-art Supermirrors (2019)

Swiss Neutronics



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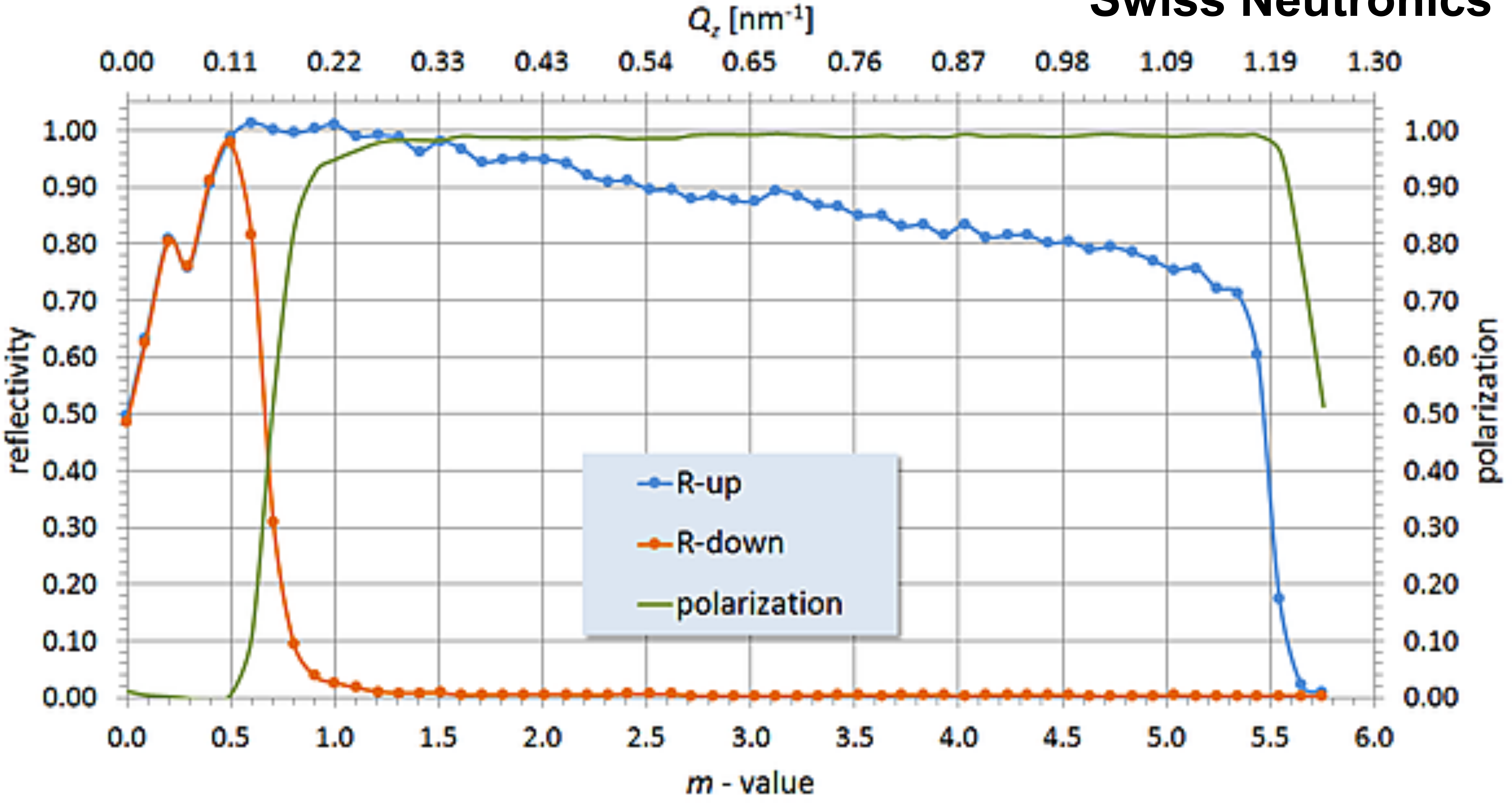
State-of-the-art Polarising Supermirrors (2019)

Swiss Neutronics



What are guides used for?

- Transport divergence
  - large m-numbers needed for short wavelengths
  - ballistic geometry required for supermirror guides
- Create space
  - build instruments far from neutron source
- Improve TOF resolution
- Reduce background
  - transport only "good" neutrons
- Focusing
  - increased divergence: increased flux