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!

Neutron optics - subtopics

- Key properties of the neutron

- Transporting the beam
  - Neutron guides and how they work

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

The neutron - a reminder

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

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

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


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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Optical properties - slow neutrons vs. light

	light	neutrons
λ	< µm	< nm
E	> eV	> meV
n	$1 \rightarrow 4$	$0.9997 \rightarrow 1.0001$
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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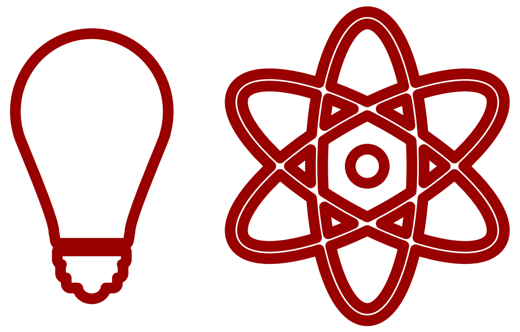
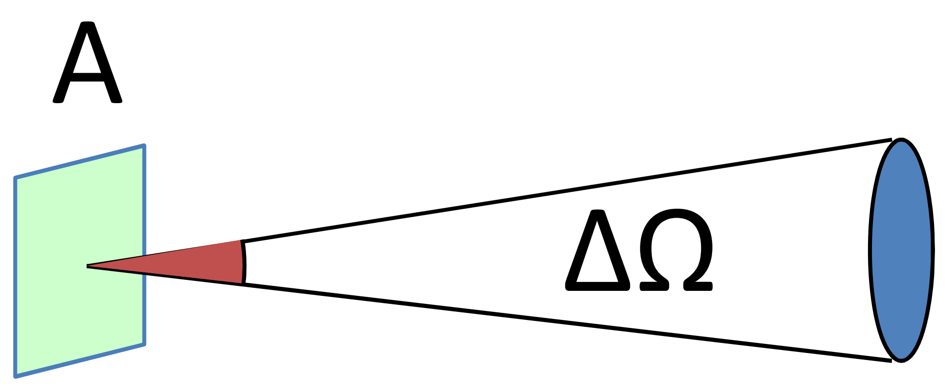
Corresponding to distances and excitations within condensed matter

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



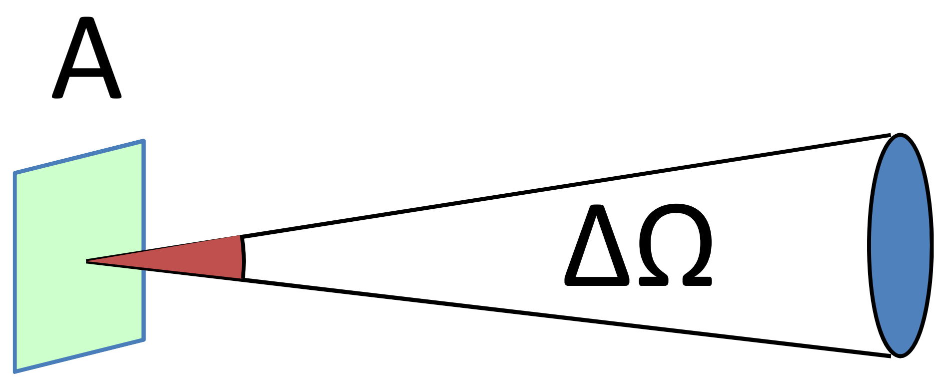
Neutron flux - and brilliance / brightness



B = N per time per A per ΔΩ

units = n/s/cm^2/sr

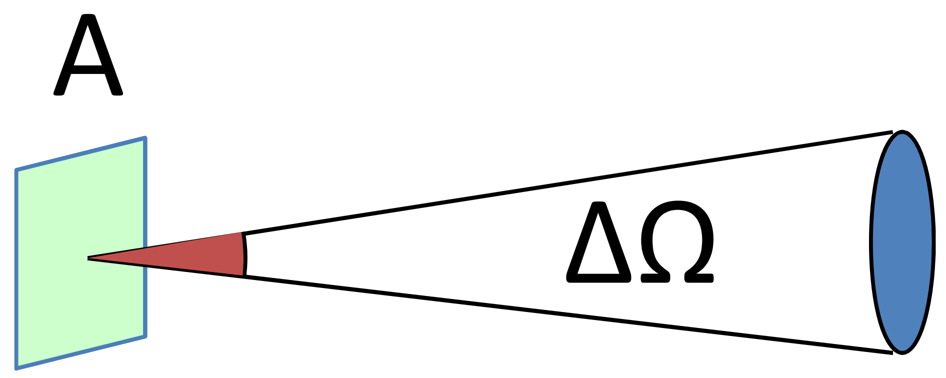
Neutron flux - and brilliance / brightness



B is independent of distance

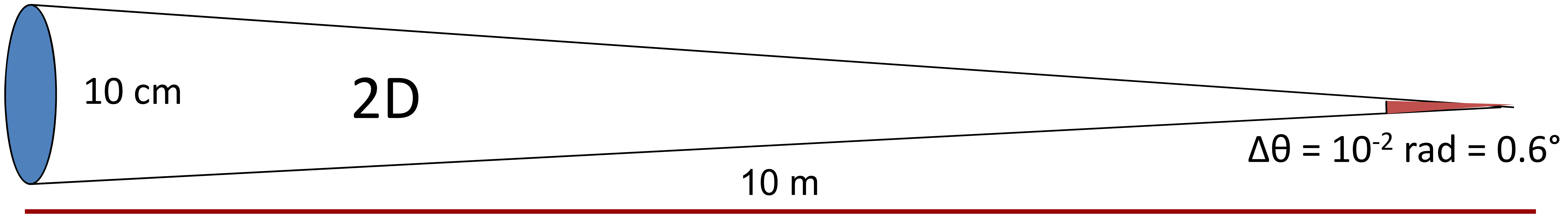
- property of the source

Neutron flux - and brilliance / brightness



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

Neutron flux - and brilliance / brightness



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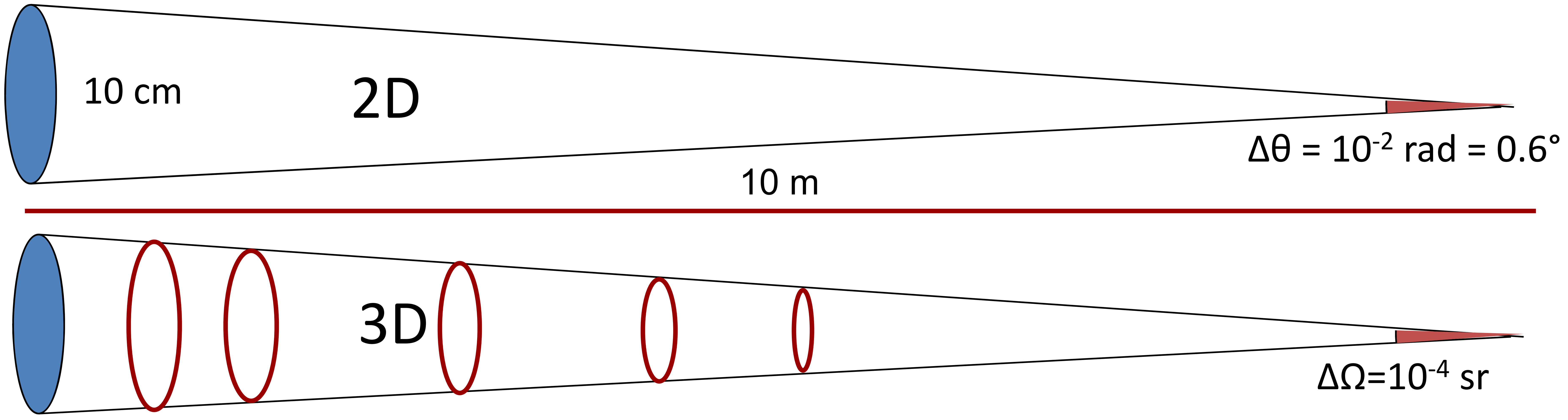

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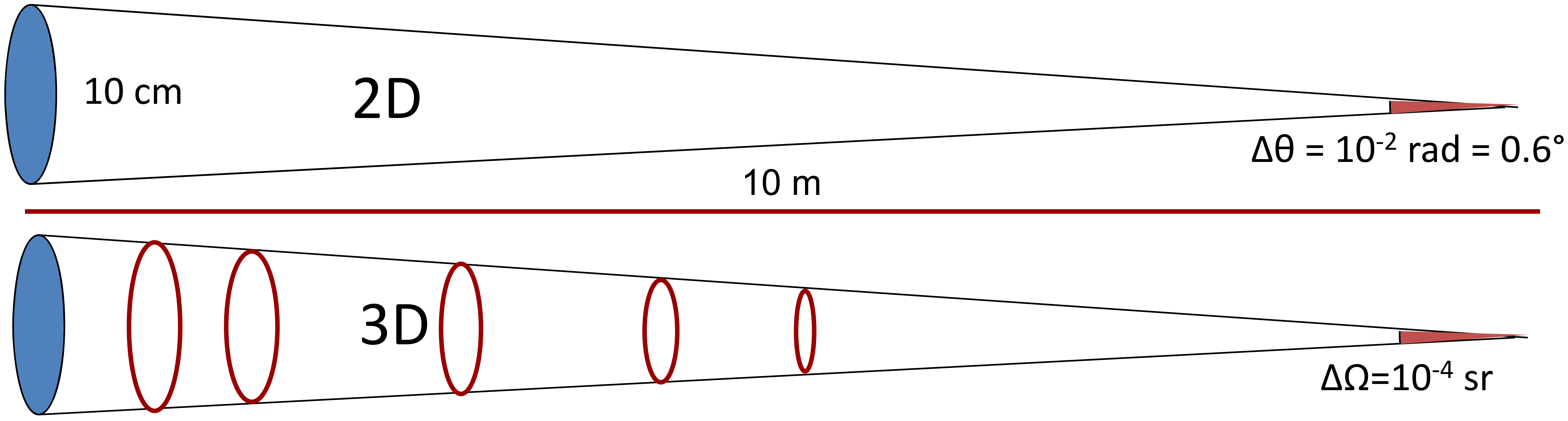
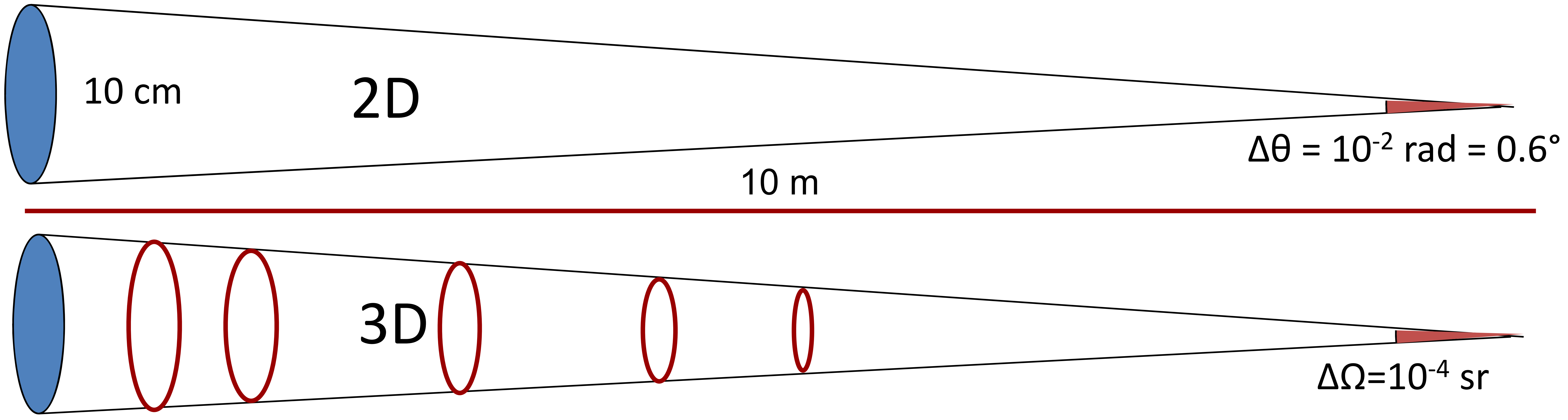


Flux = Source Brightness × Solid Angle

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

Neutron flux - and brilliance / brightness



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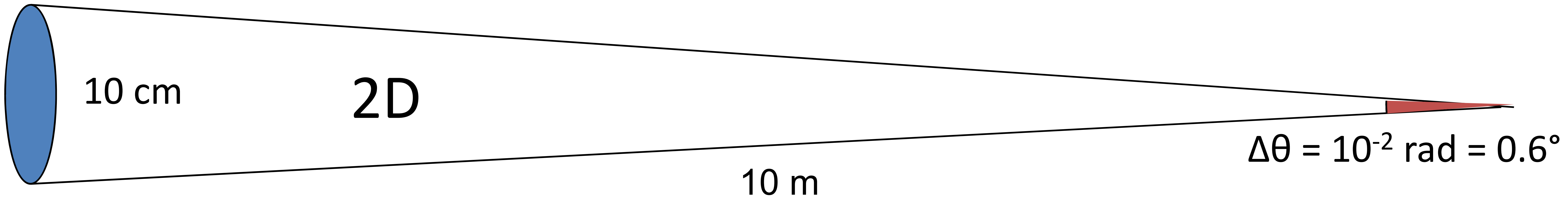

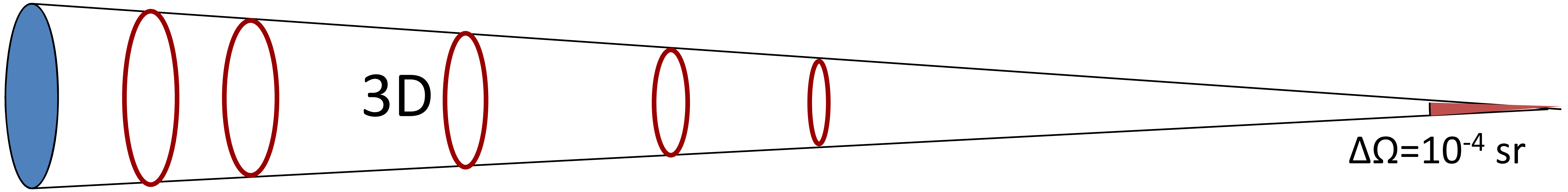

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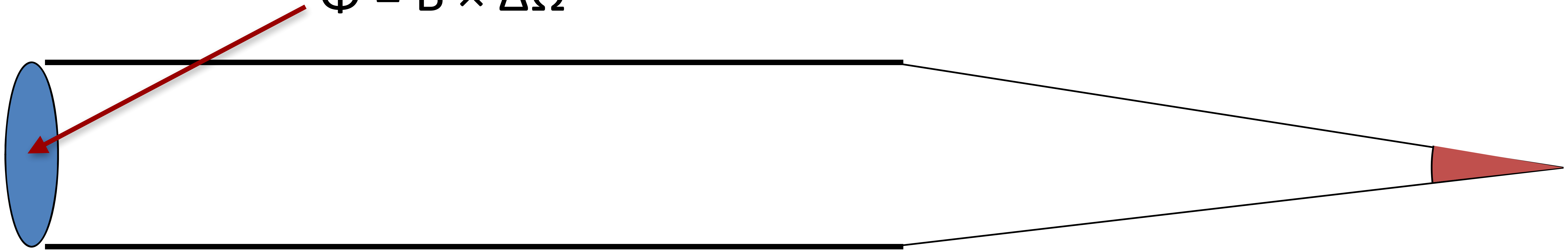
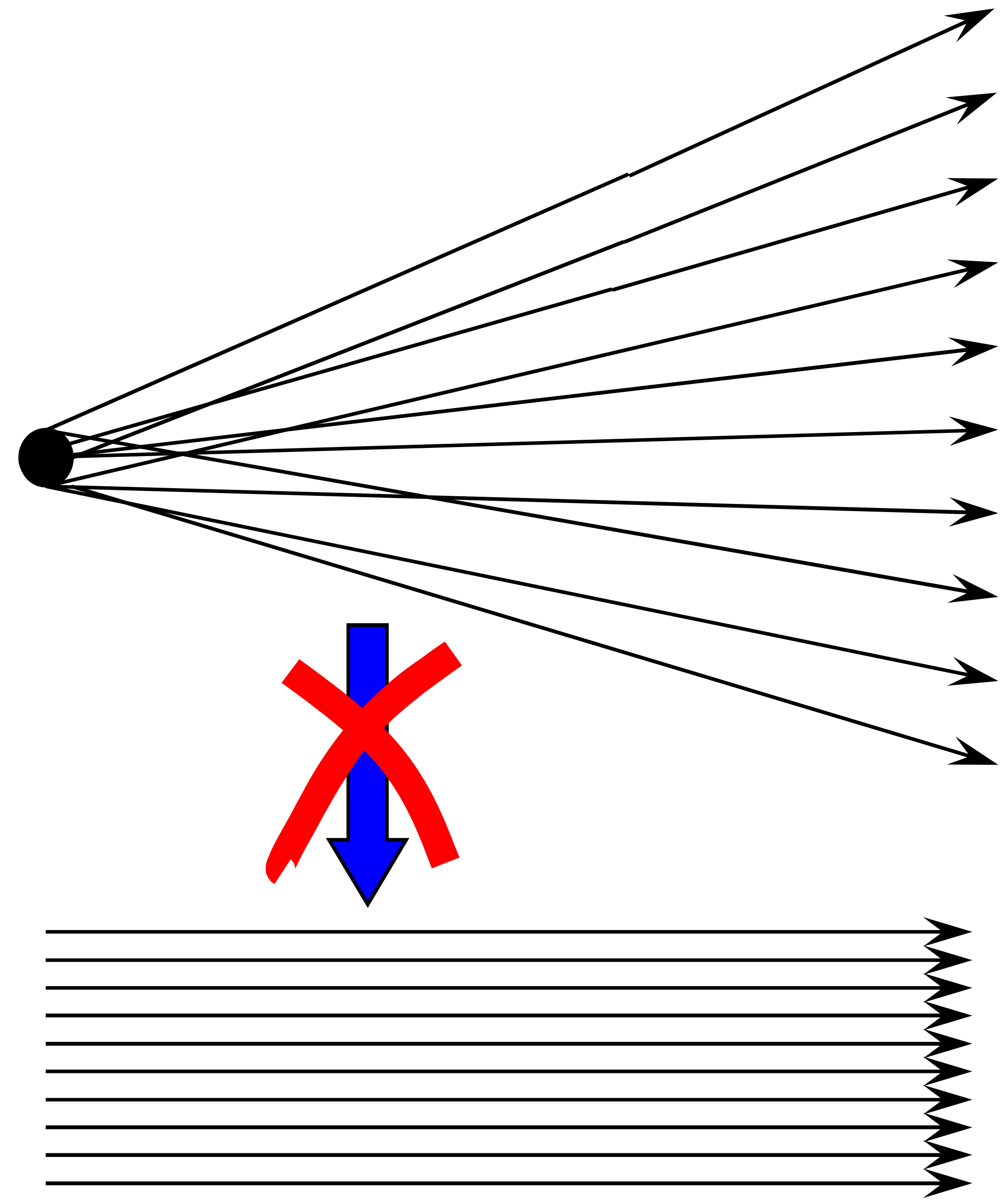
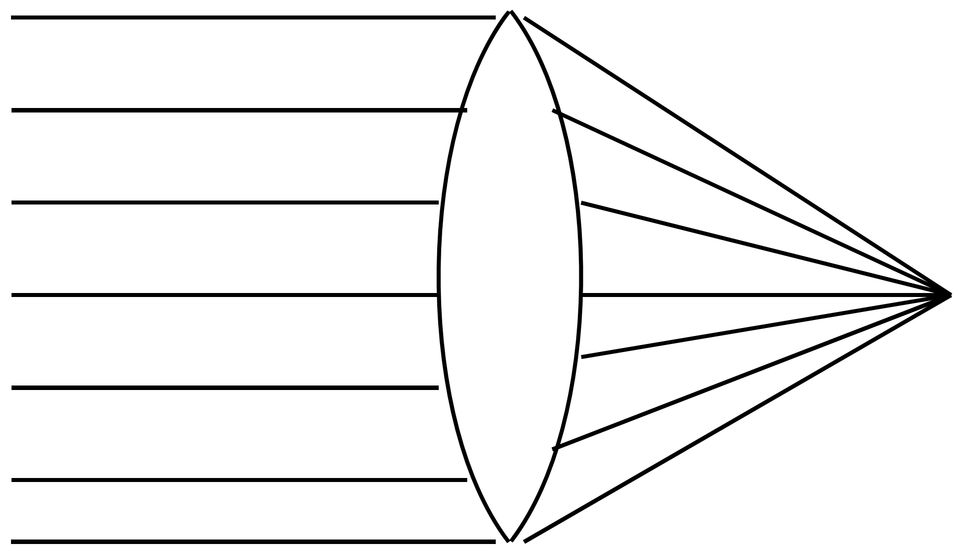


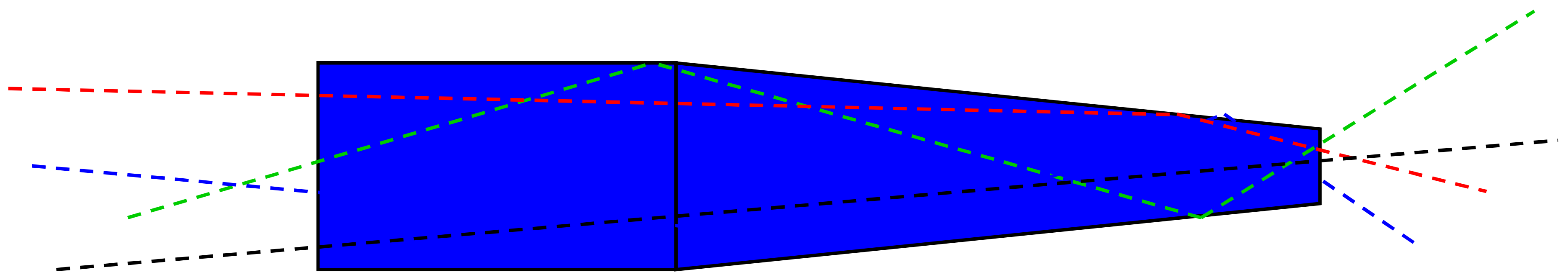
Liouville theorem
→ $\Delta x \Delta \phi$ = const

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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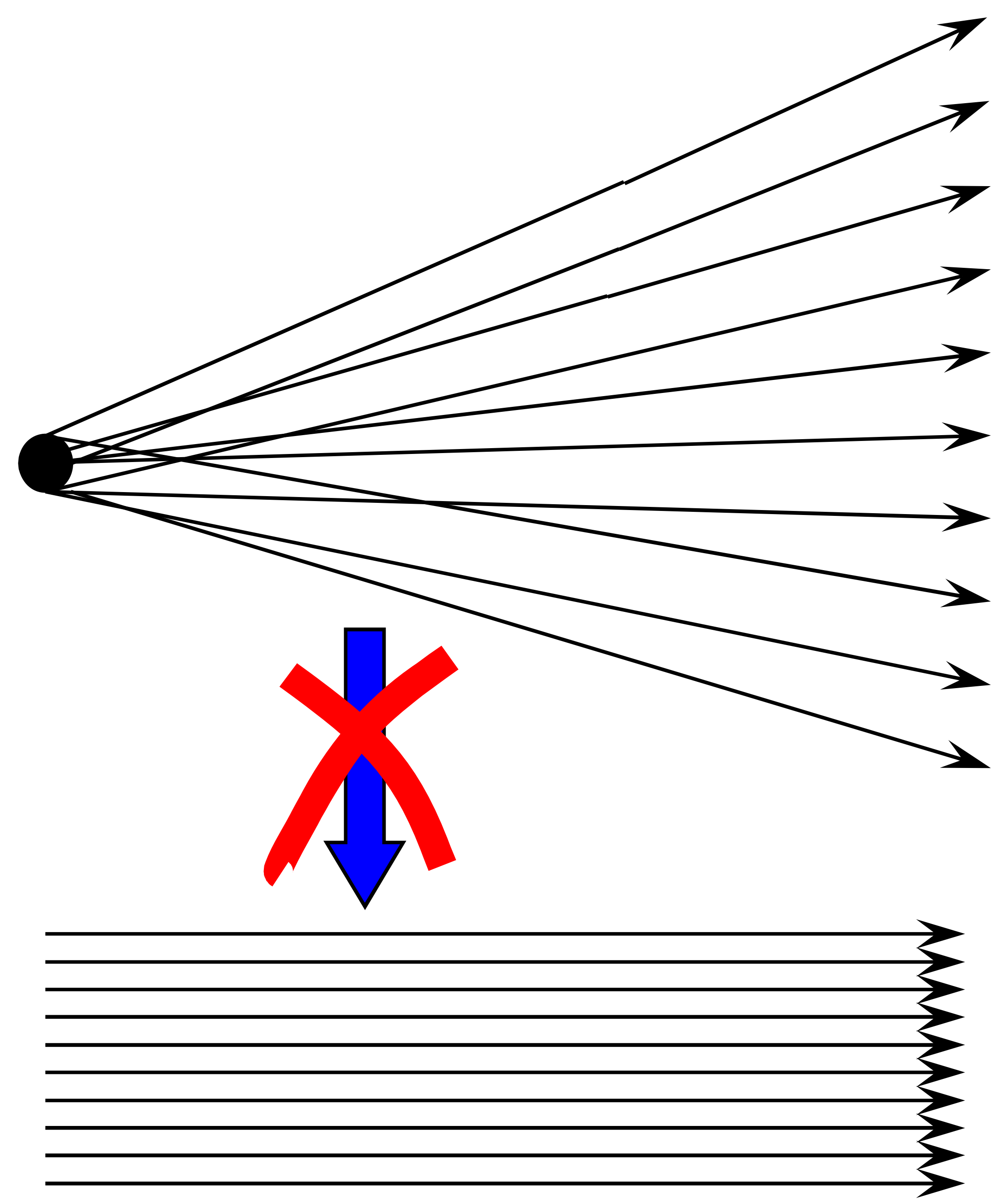
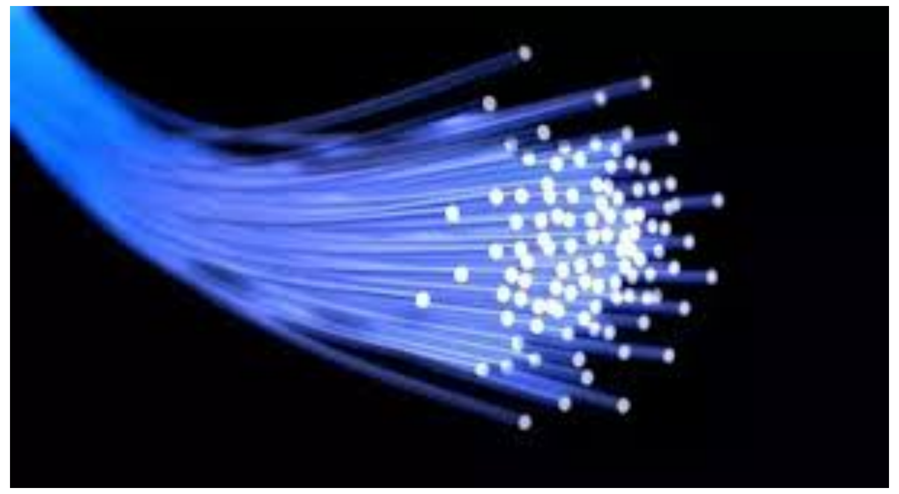


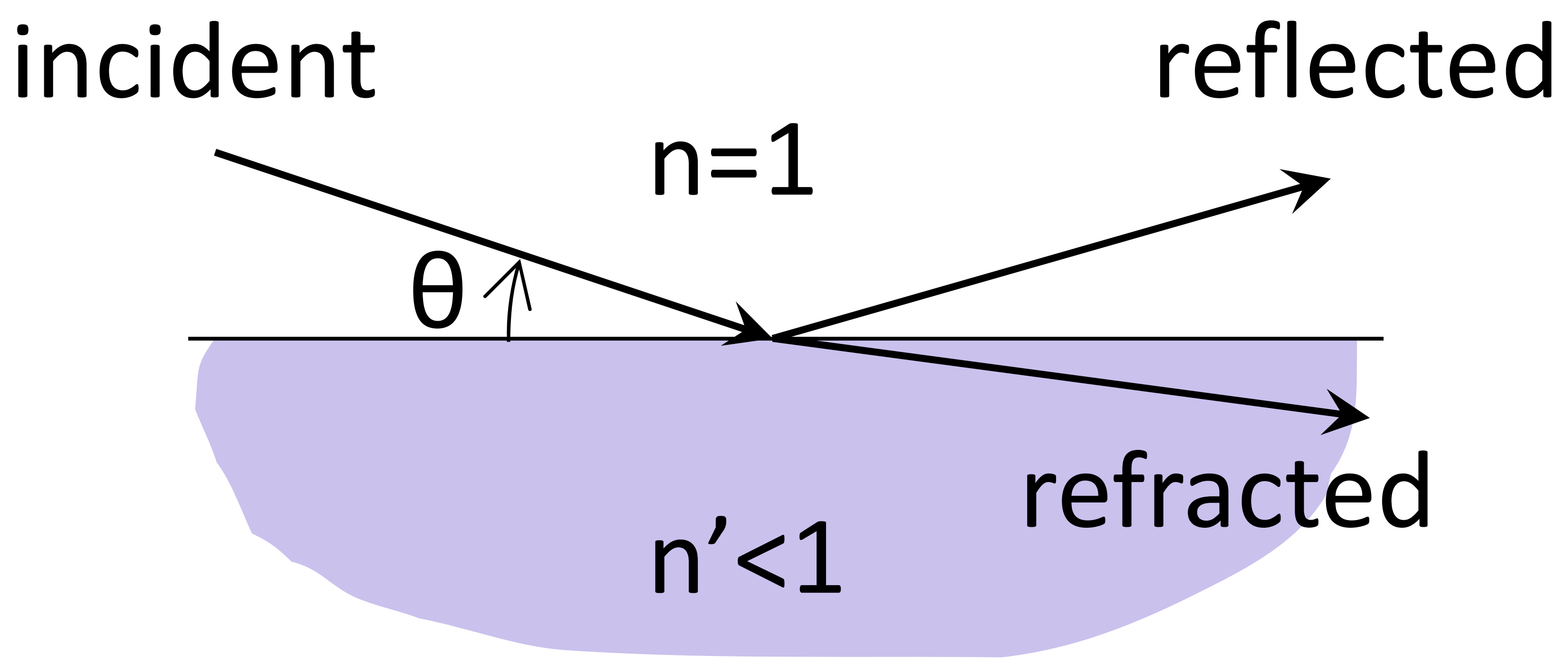
Integrated flux $\int \Psi \, dA \, d\Omega$ can never increase

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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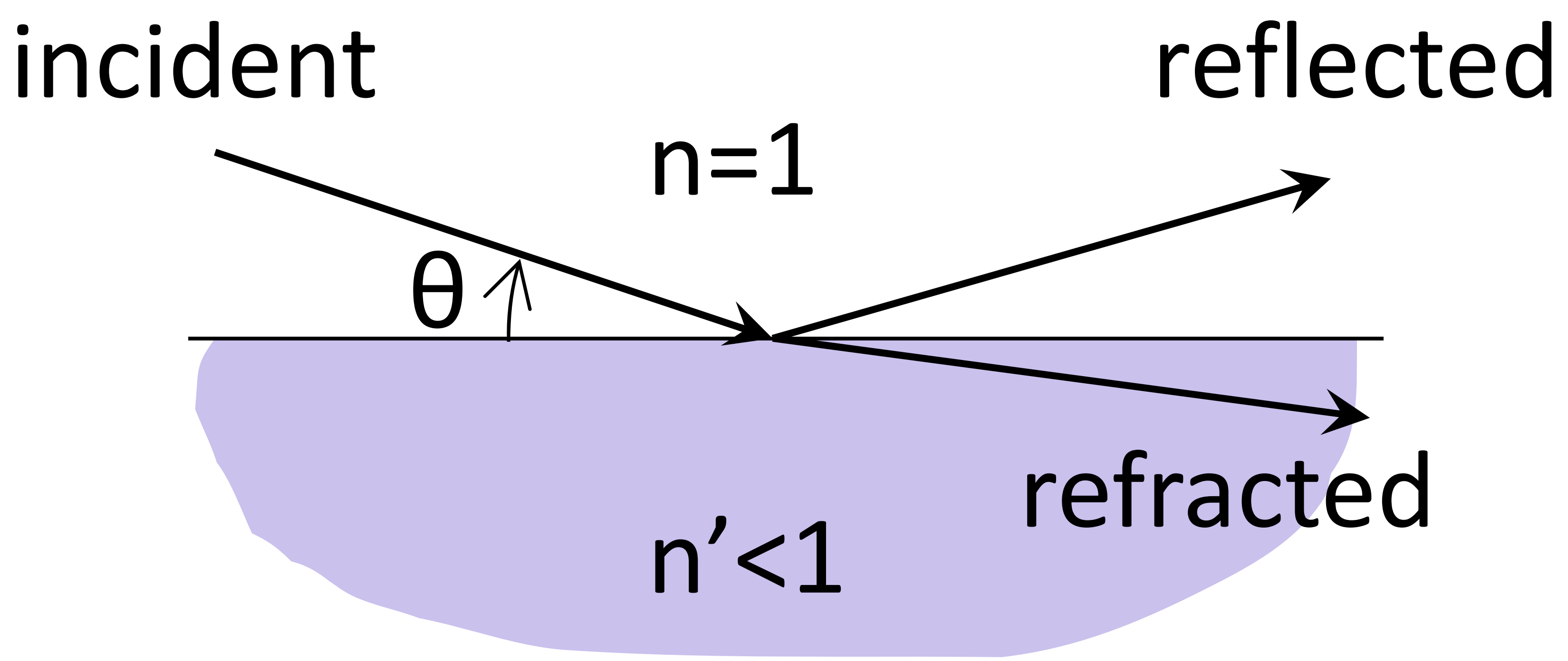

critical angle of total reflection θ_c

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

H. Maier-Leibnitz and T. Springer Reactor Science and Technology 1963. Vol. 17. pp. 217 to 225

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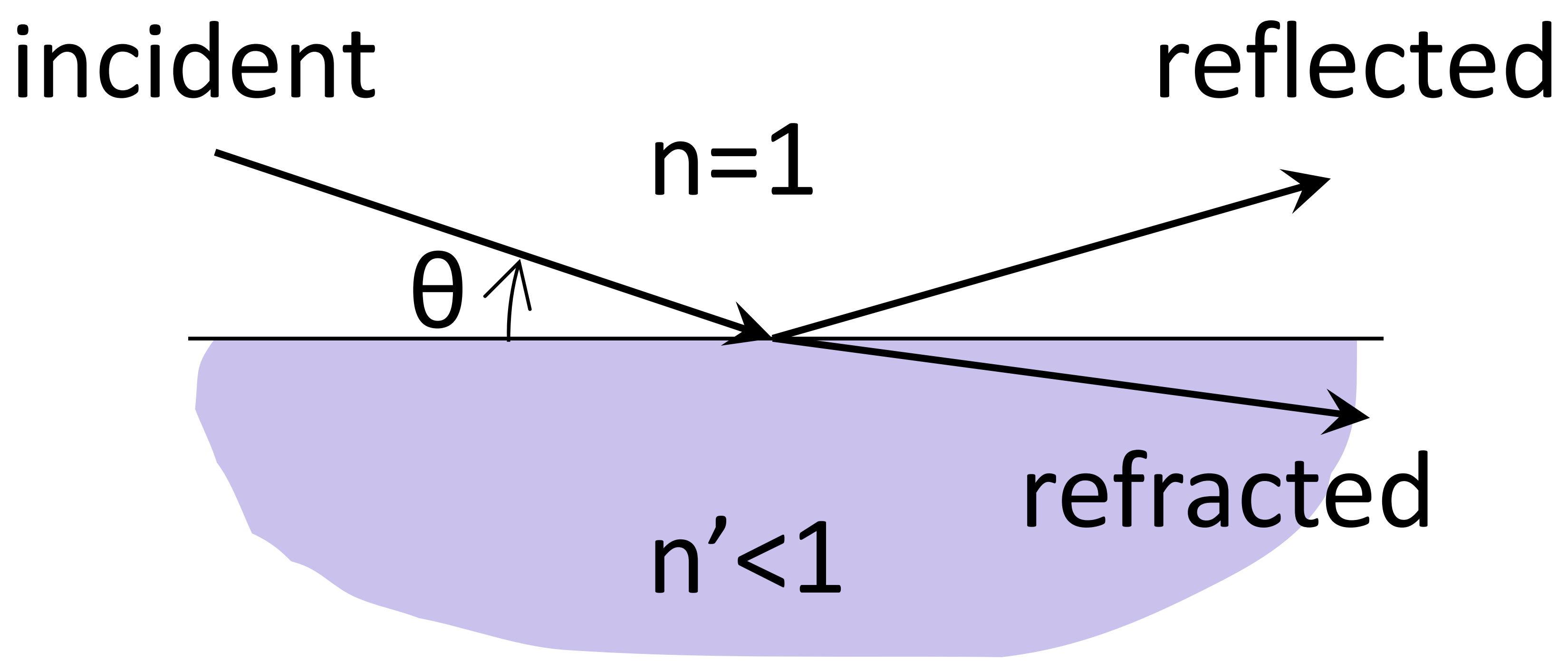

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for natural Ni:

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

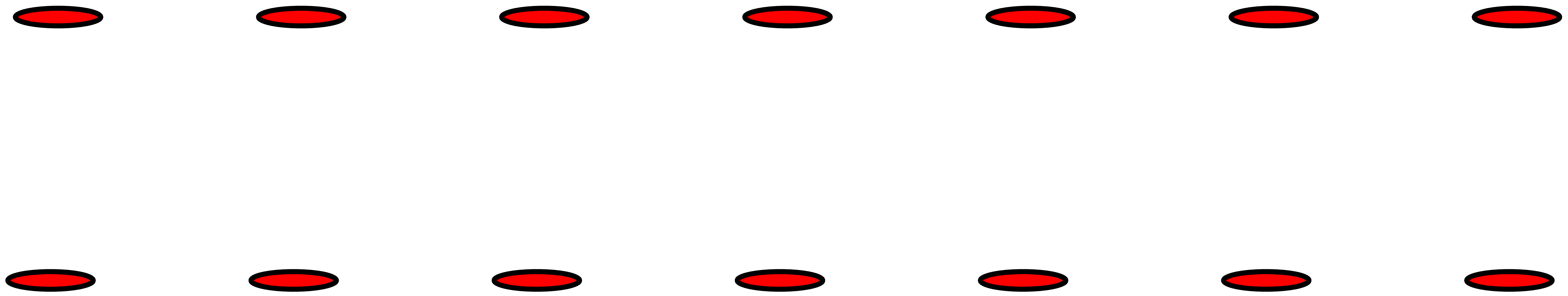
$Q_c = 0.0218\ \text{Å}^{-1}$

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

Idea:

“Expand reflectivity by means of Bragg scattering?

Diffraction: Bragg’s Law



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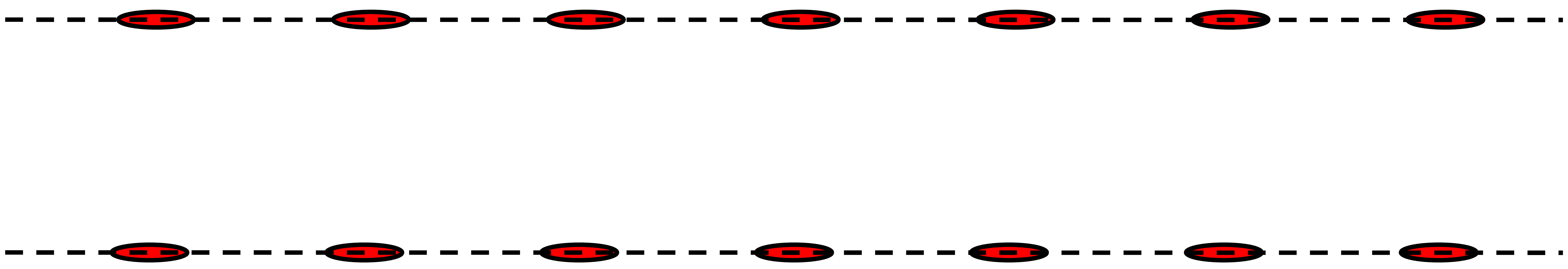

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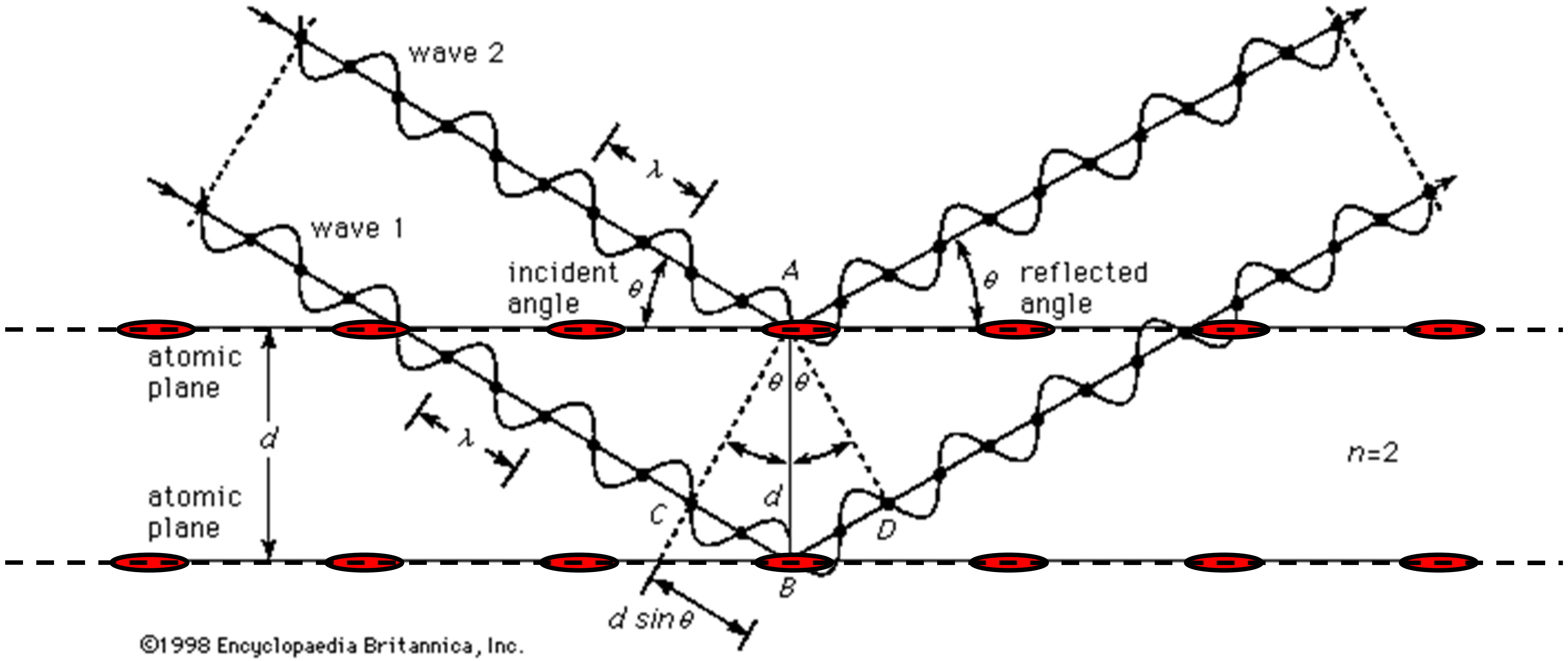

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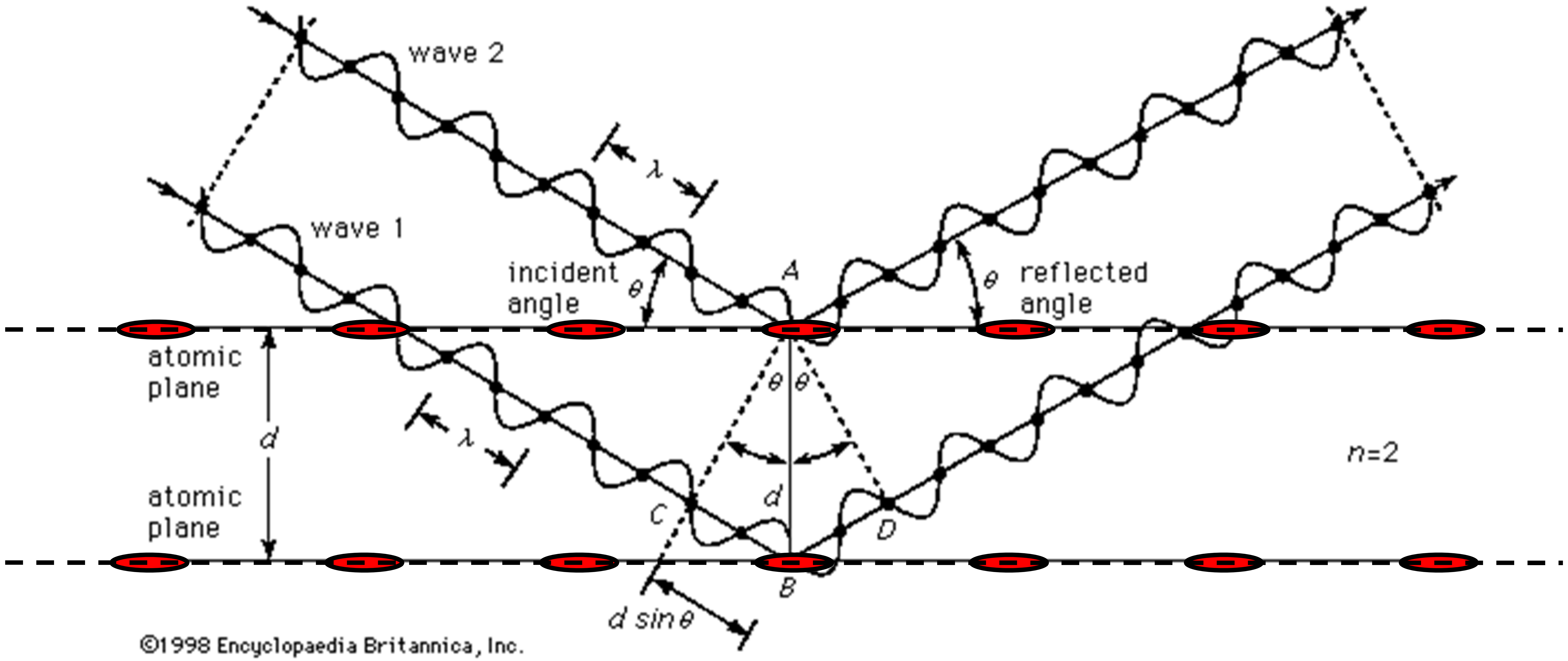
$$\lambda = 2d\sin\theta$$



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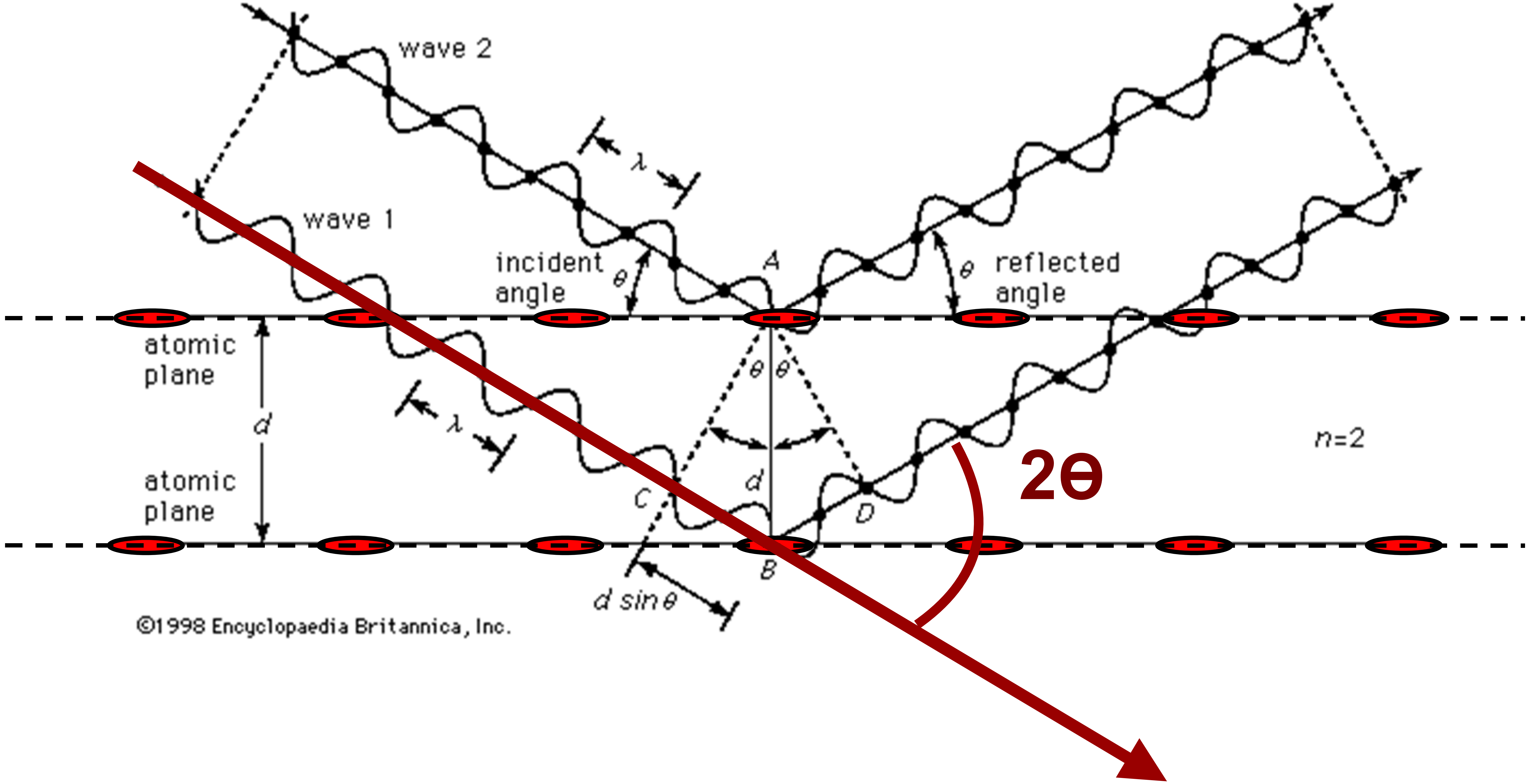
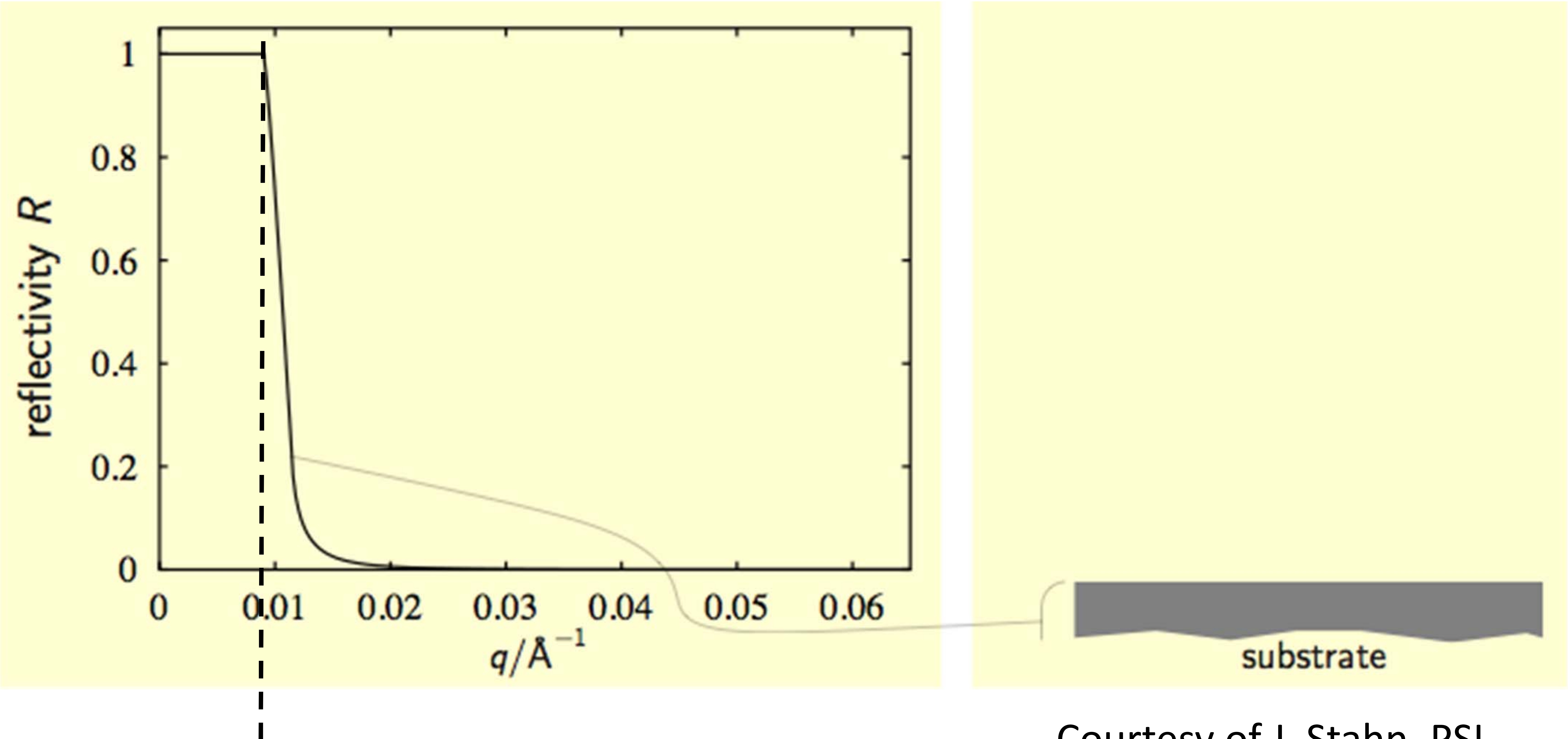


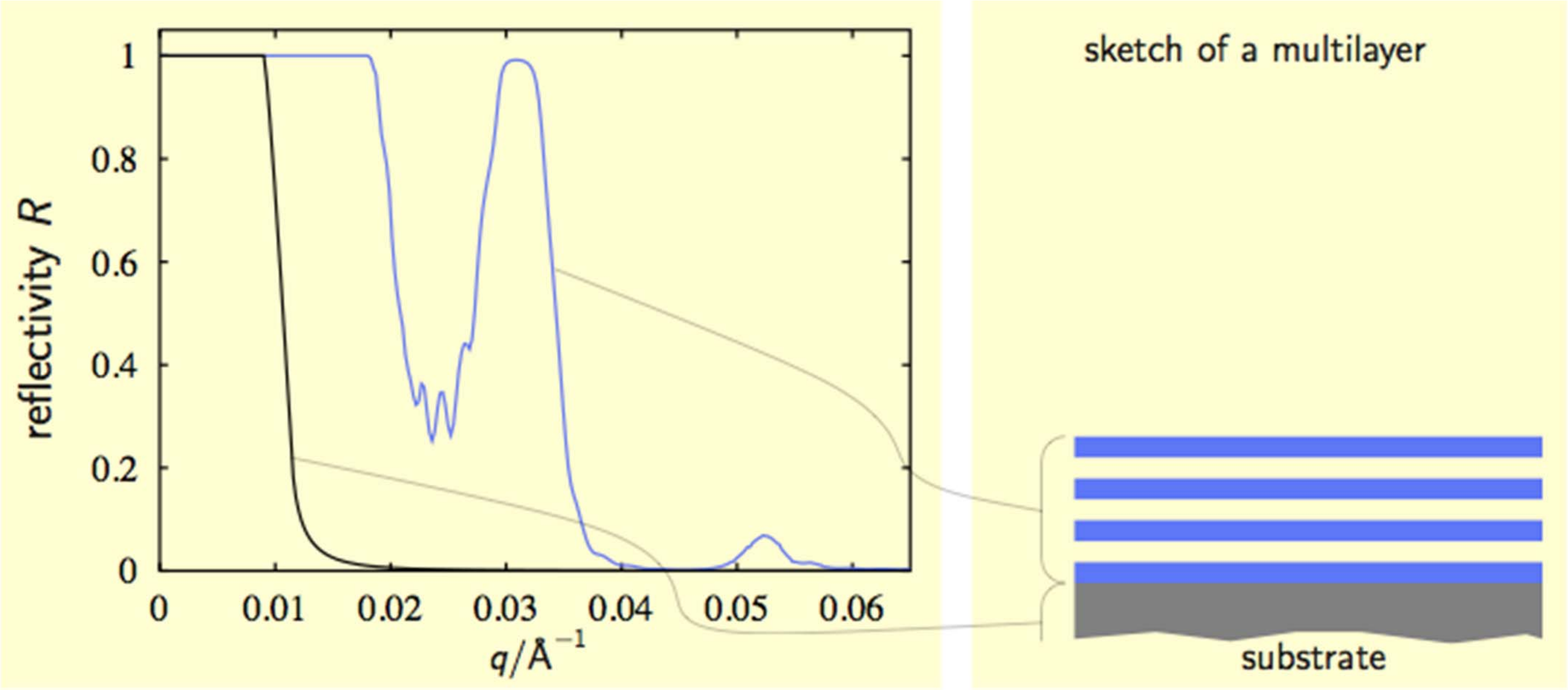
Neutron Supermirrors



Q_c as given by Snell's Law

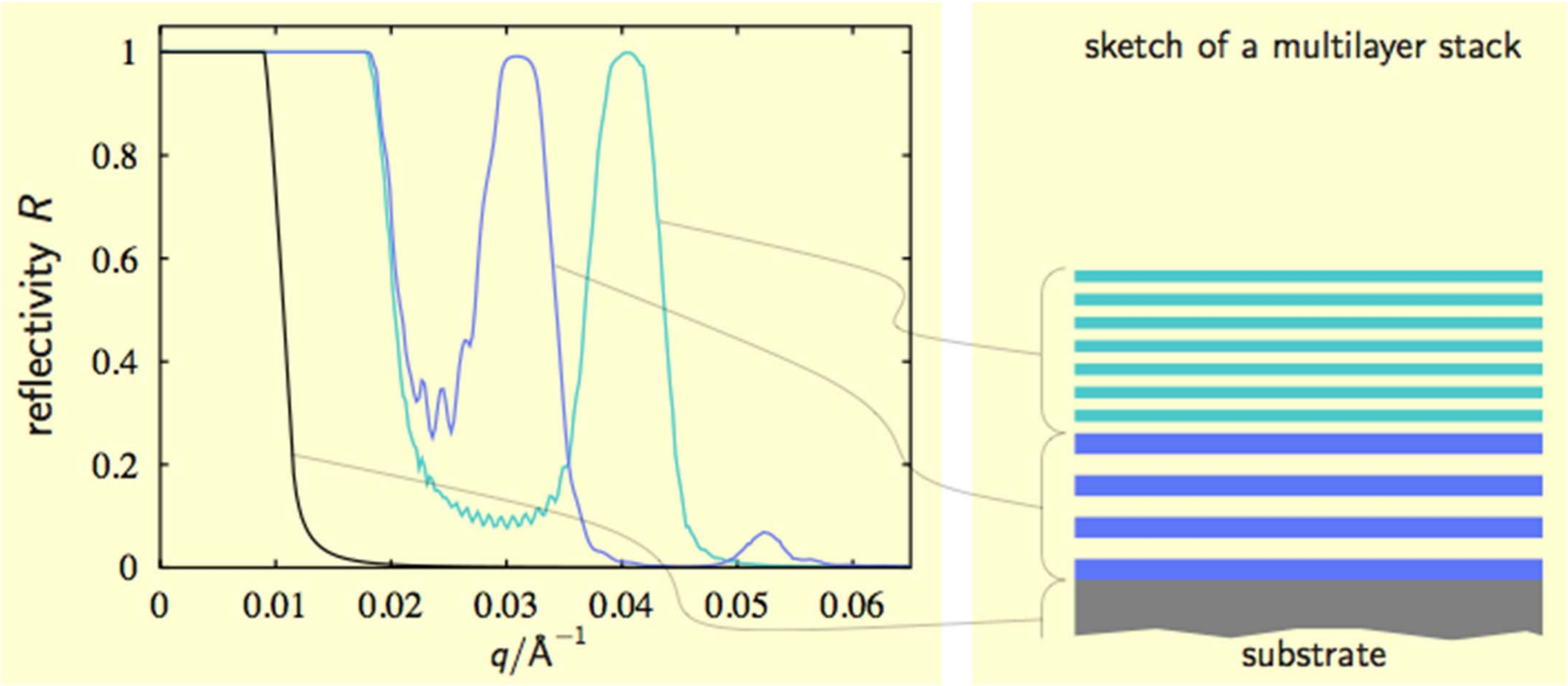
Courtesy of J. Stahn, PSI

Neutron Supermirrors



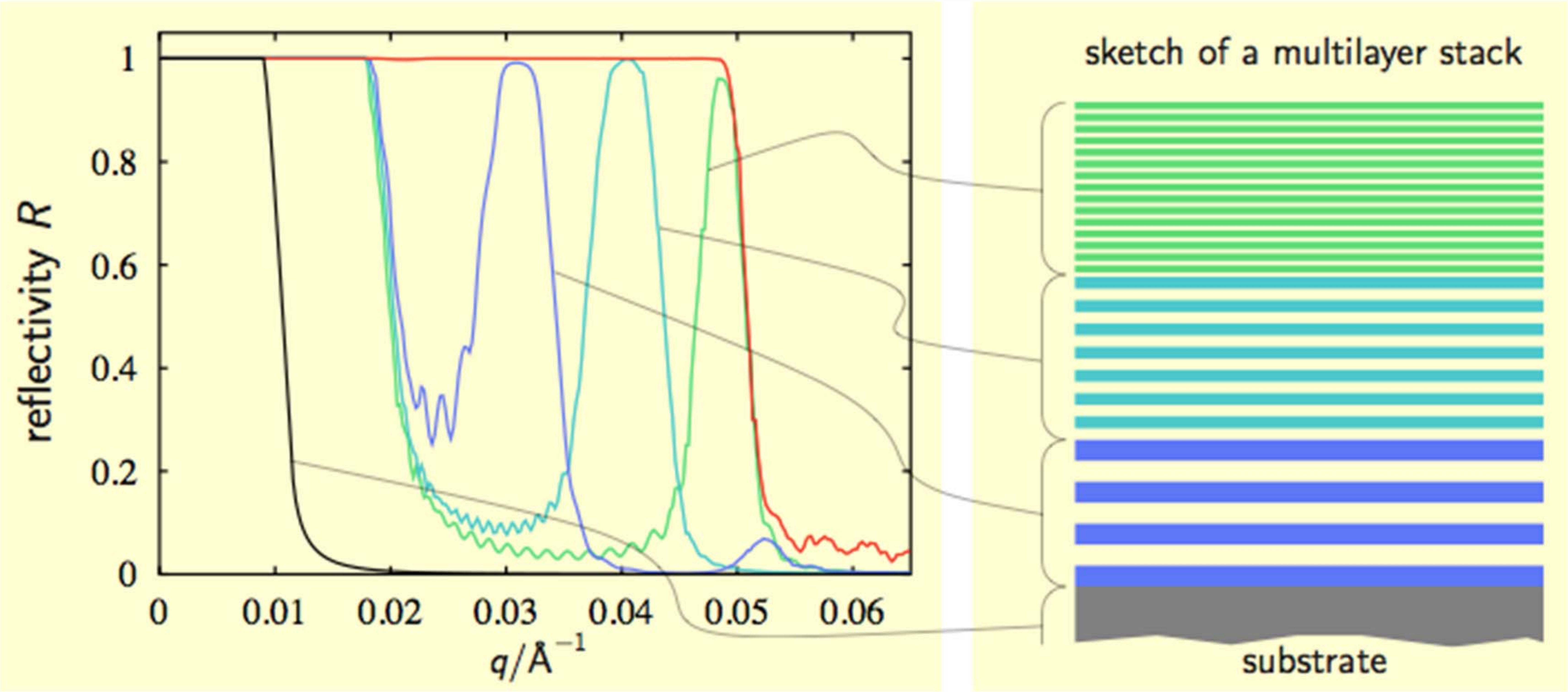
Courtesy of J. Stahn, PSI

Neutron Supermirrors



Courtesy of J. Stahn, PSI

Neutron Supermirrors

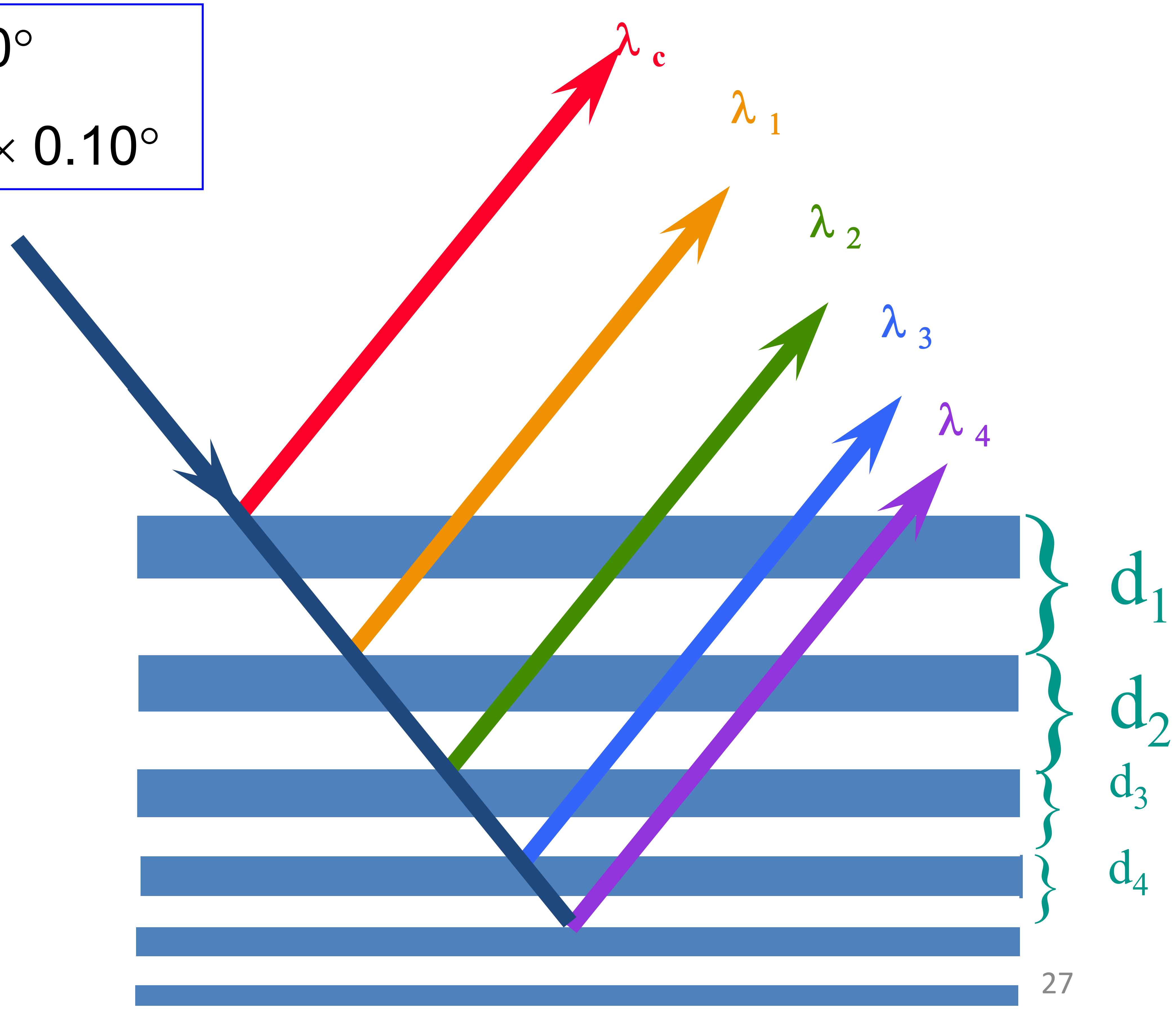


Courtesy of J. Stahn, PSI

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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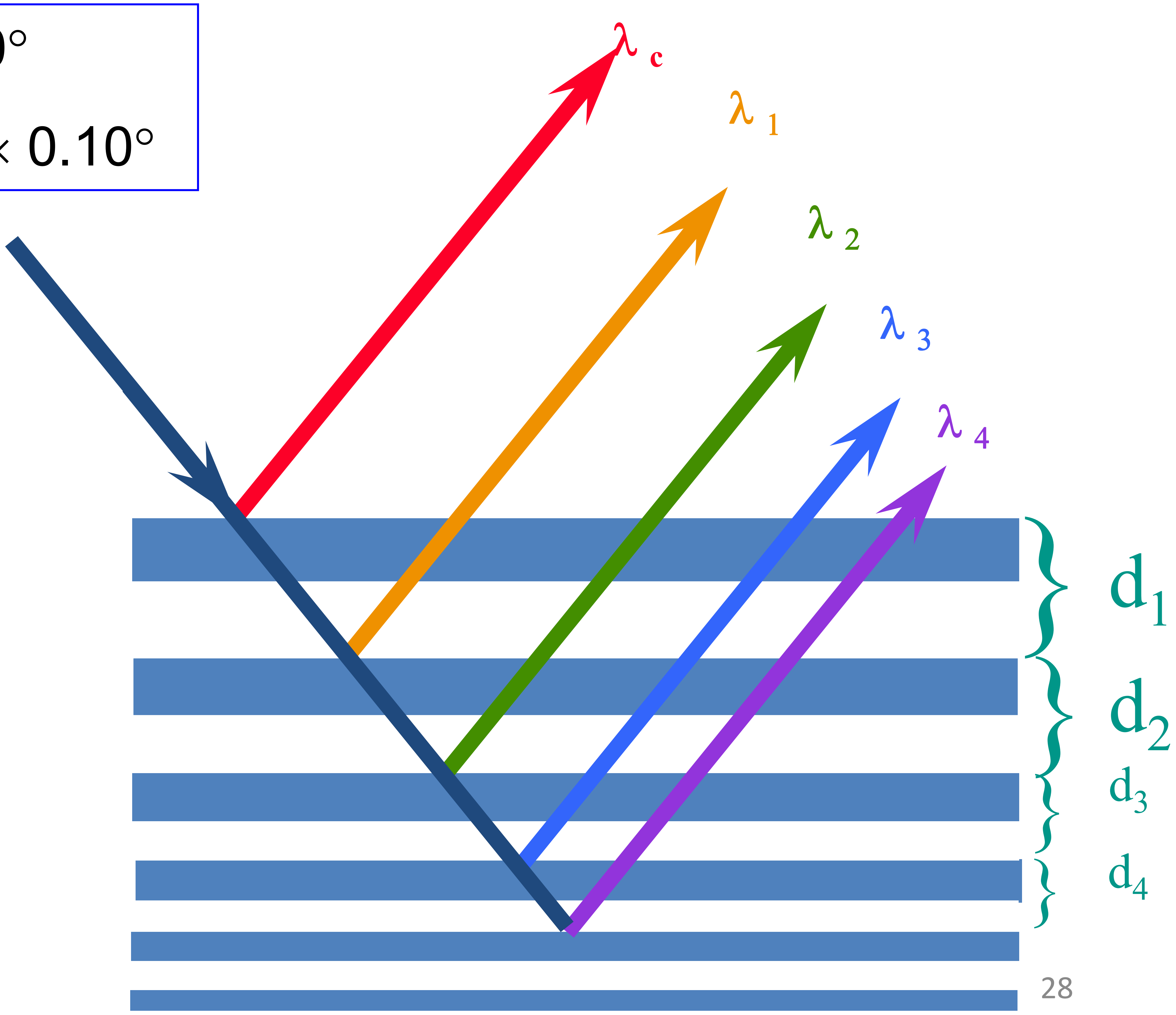
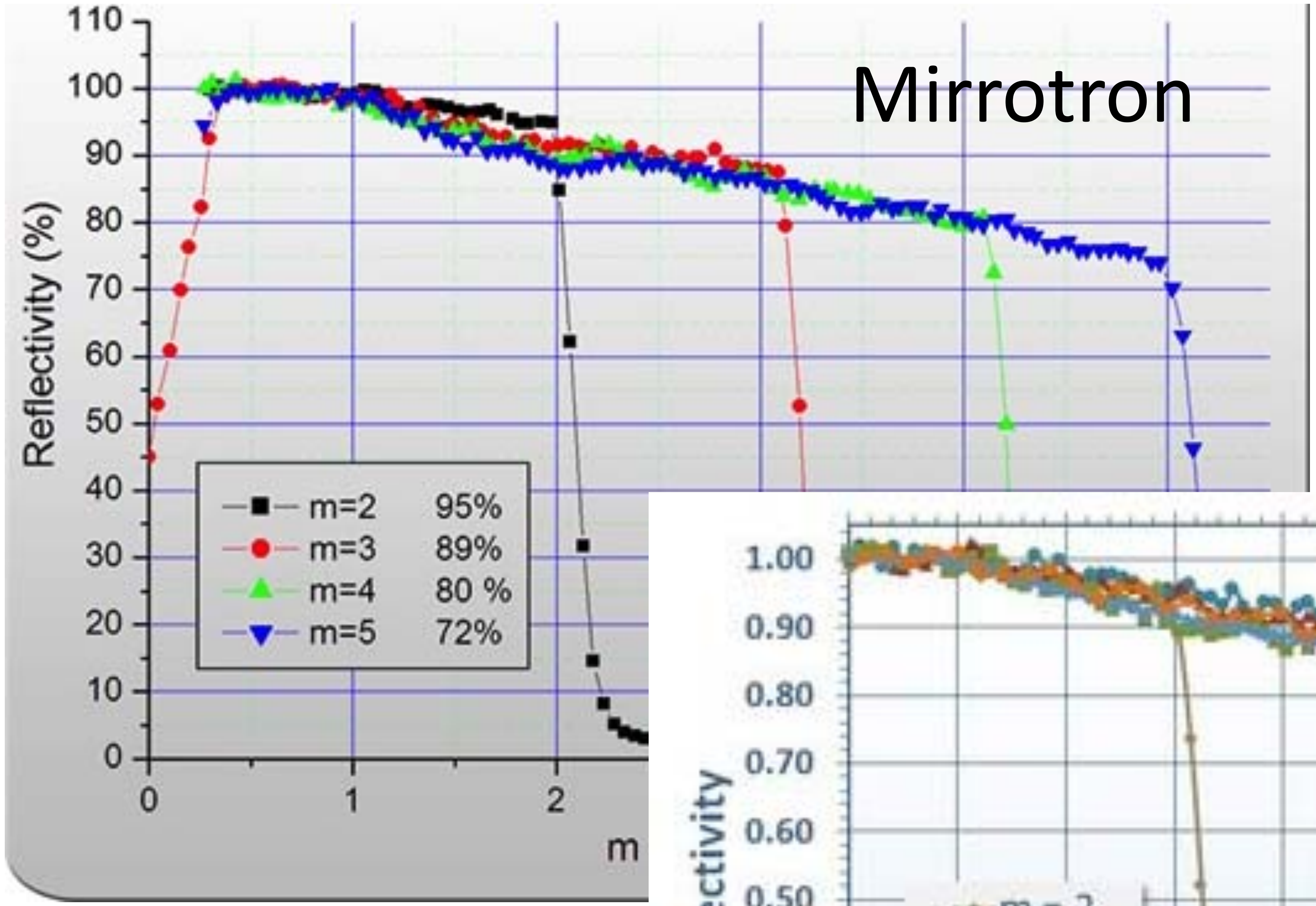
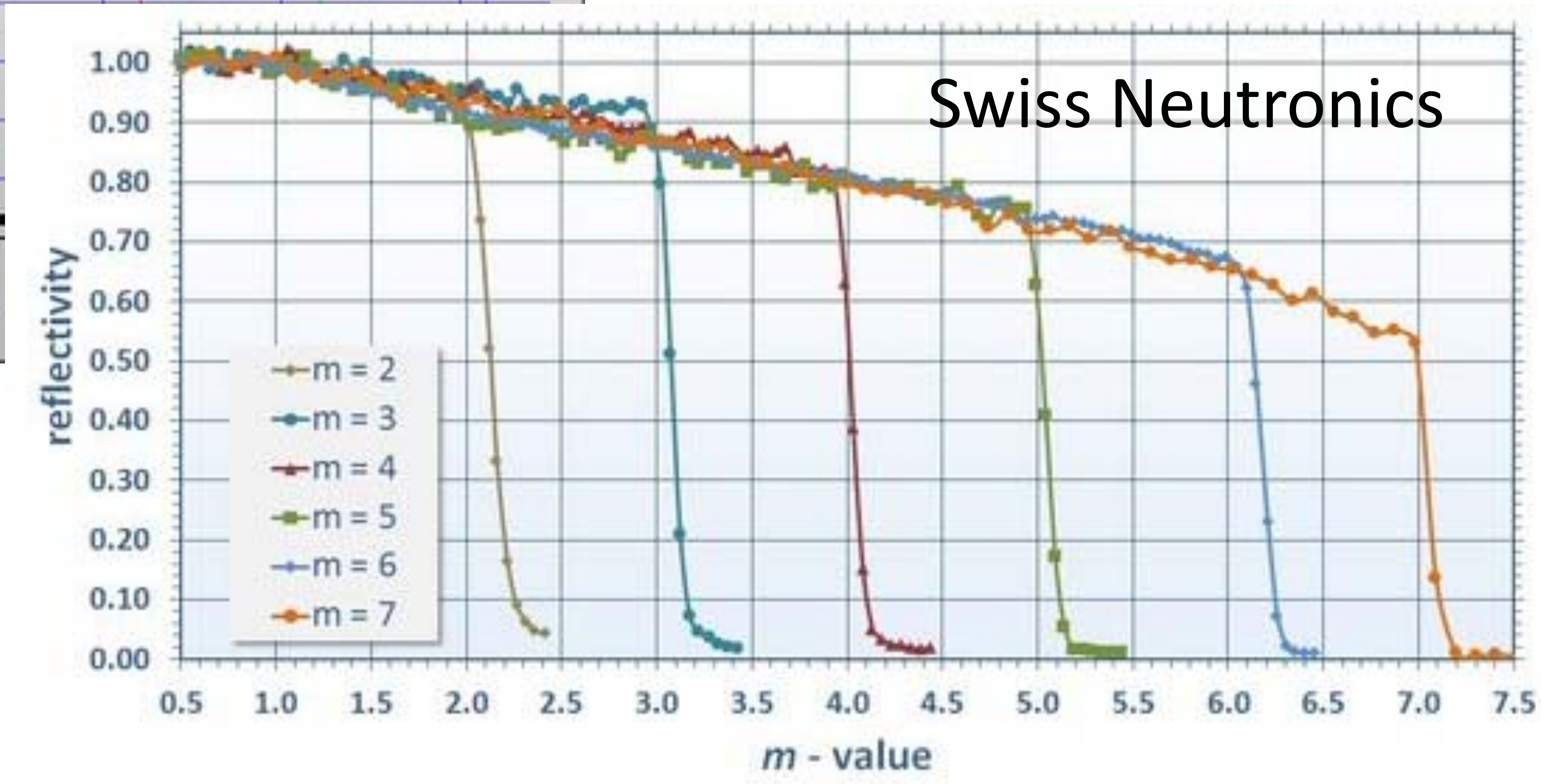
"m-number"
Supermirror critical angle

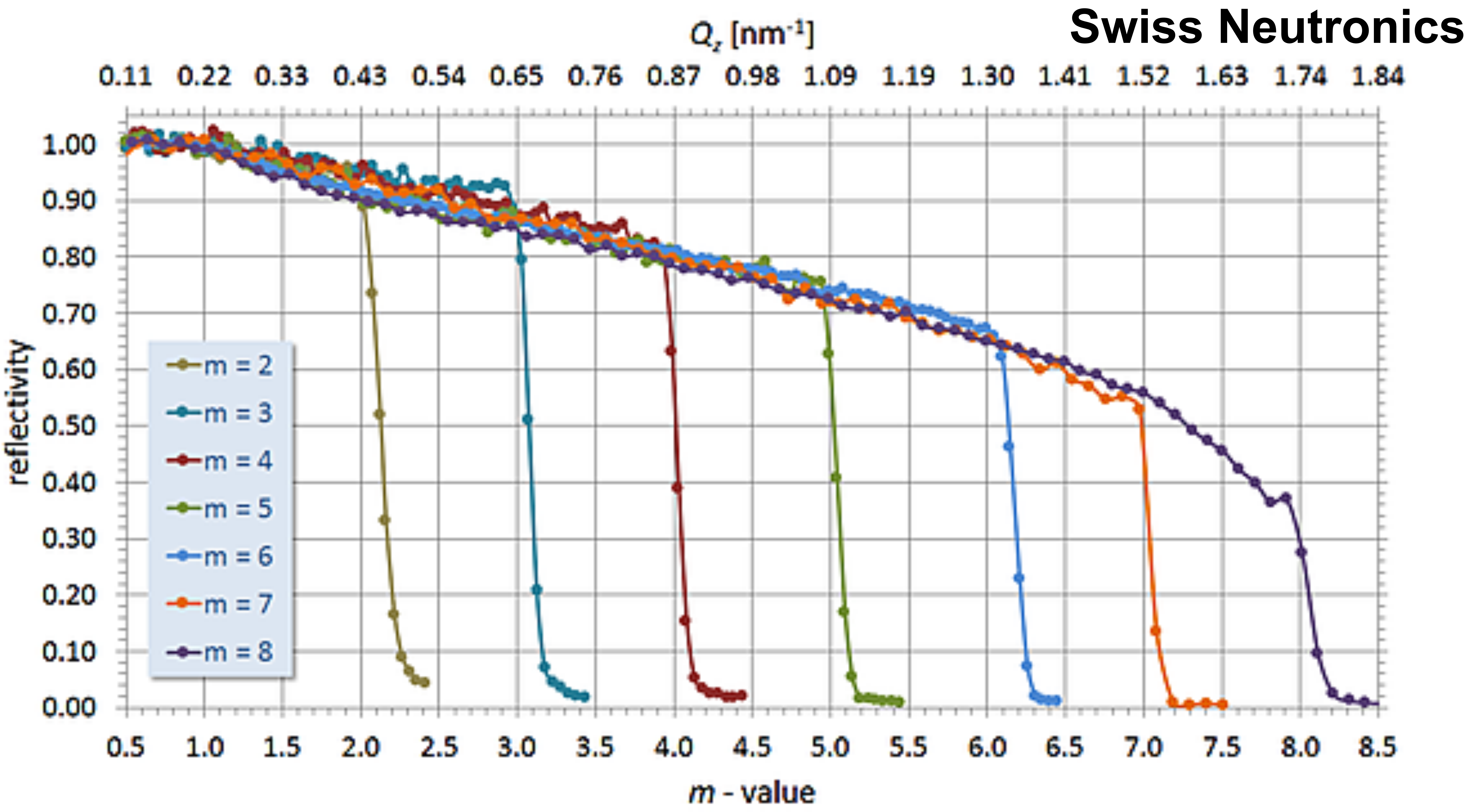


State-of-the-art Supermirrors (2015?)



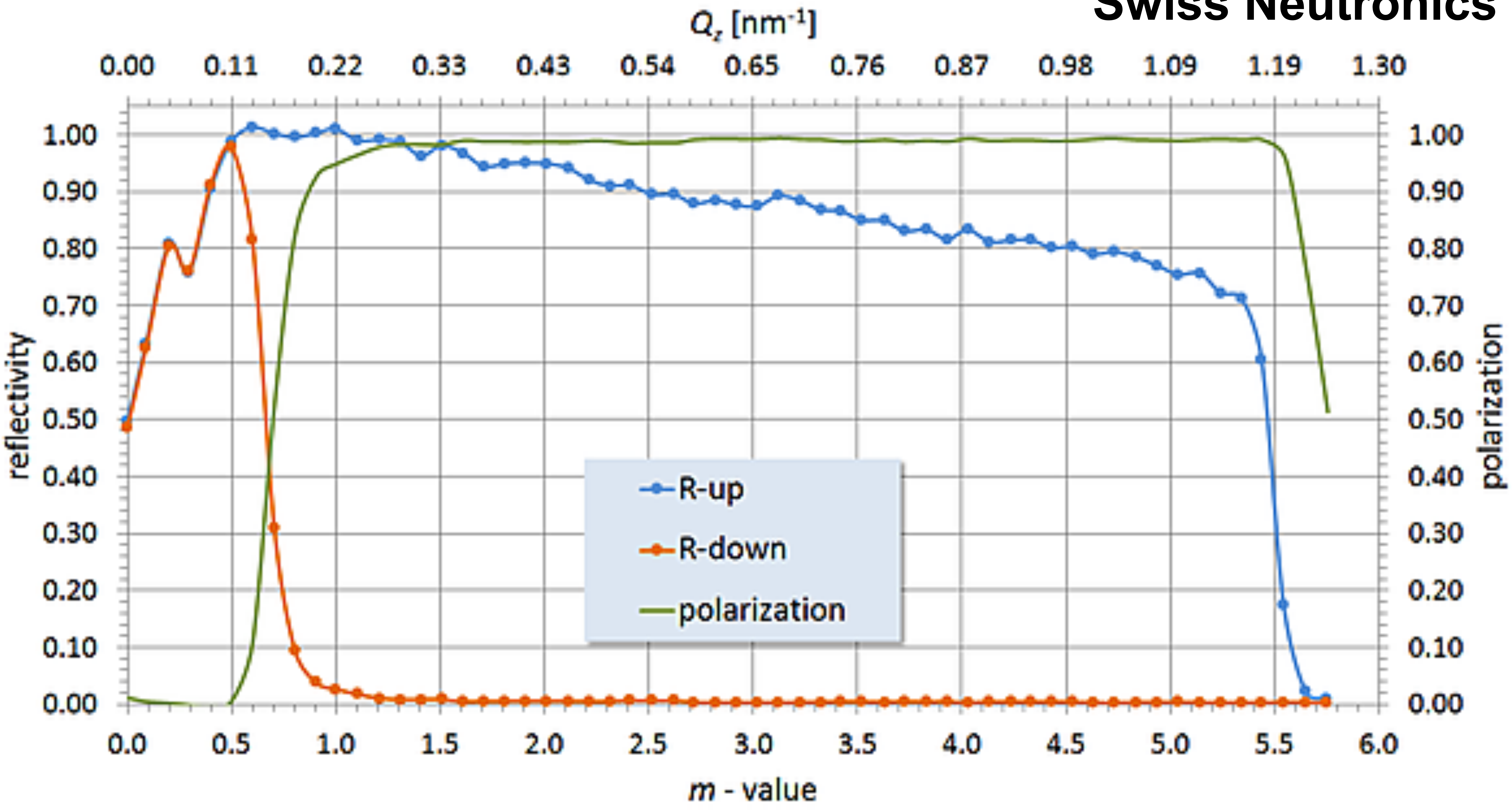


State-of-the-art Supermirrors (2019)



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

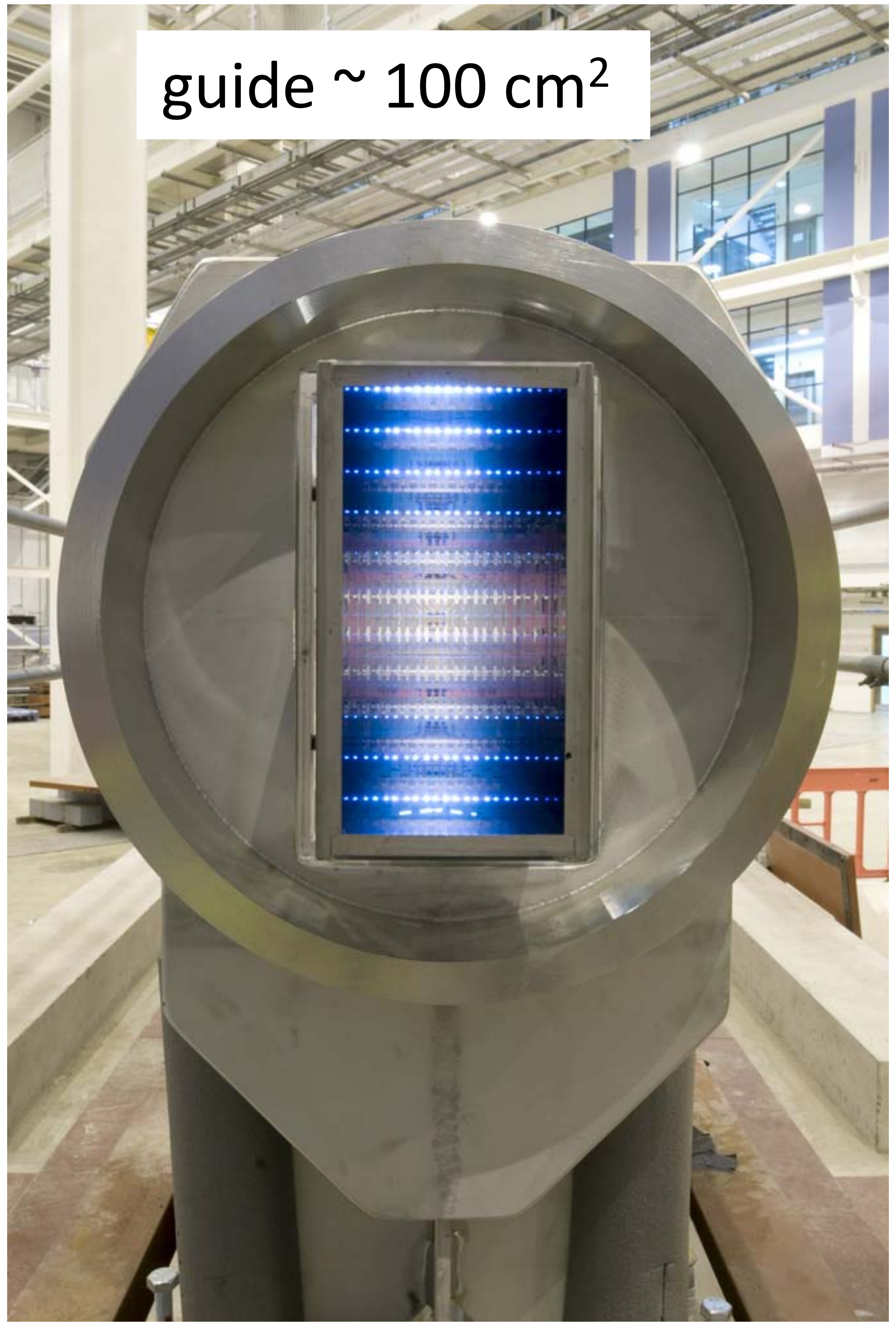
Swiss Neutronics



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

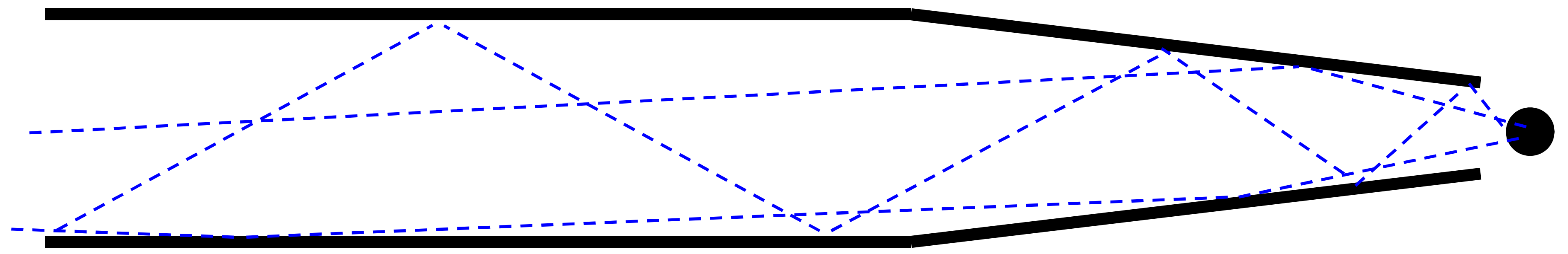
Focusing



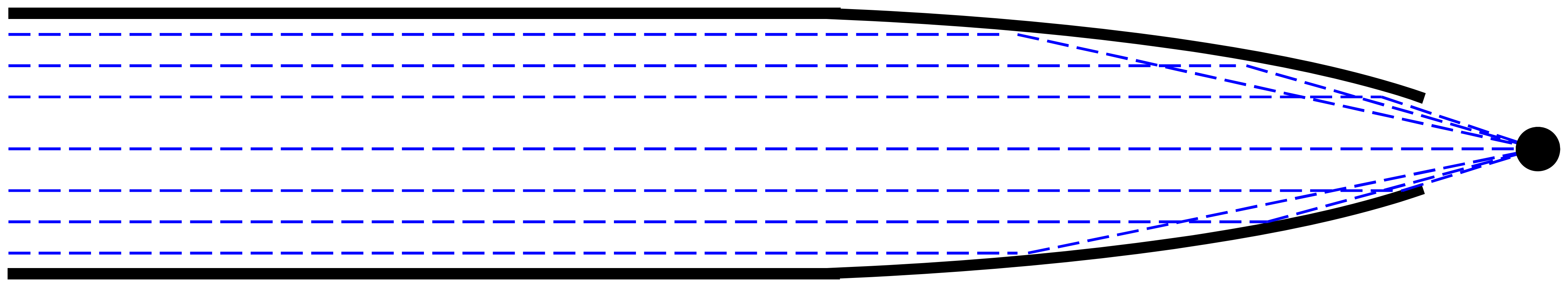
samples < 1 cm^2

Focusing

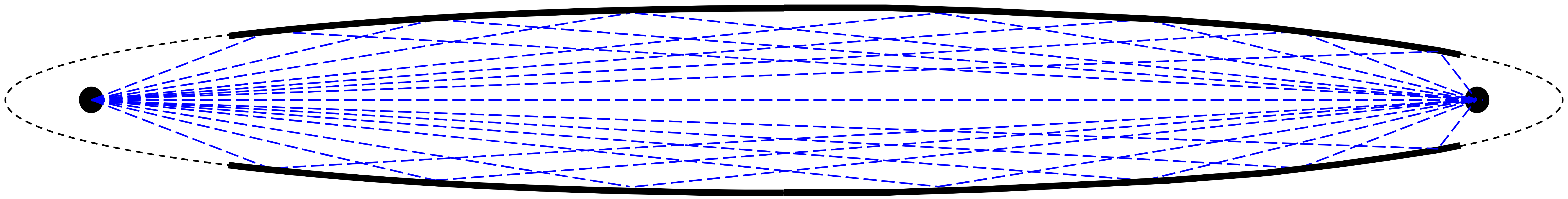
Linear tapering



Parabolic



Elliptic



Focusing

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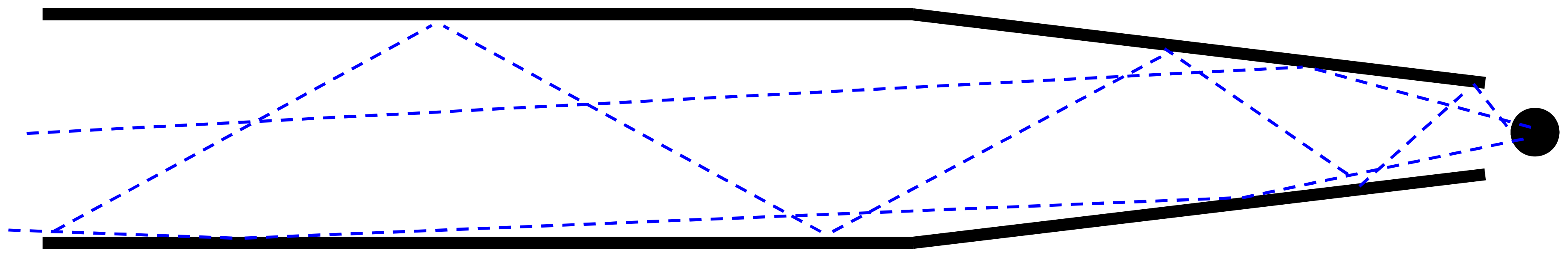

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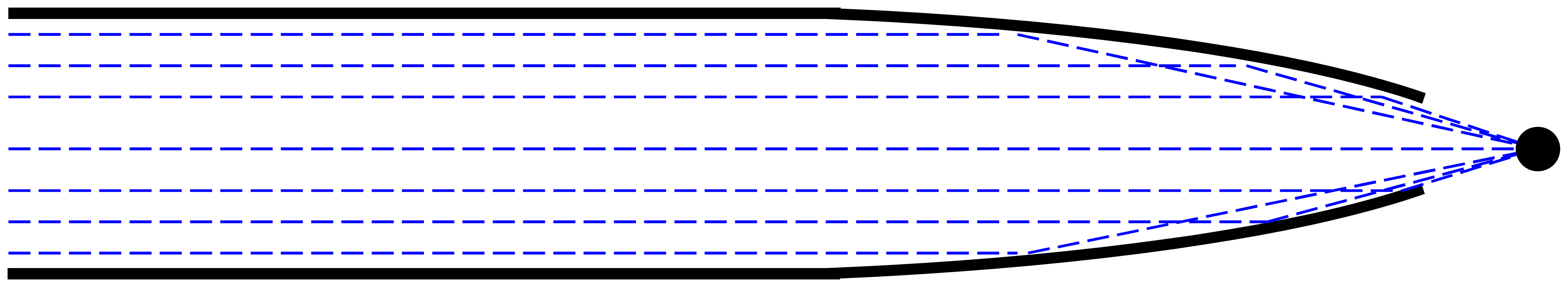

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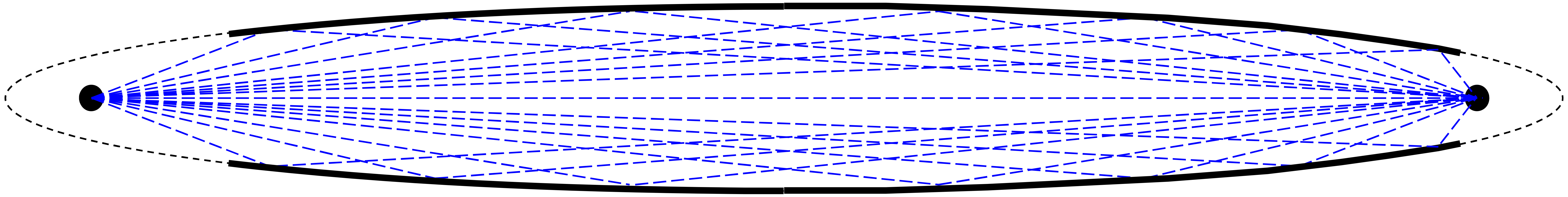
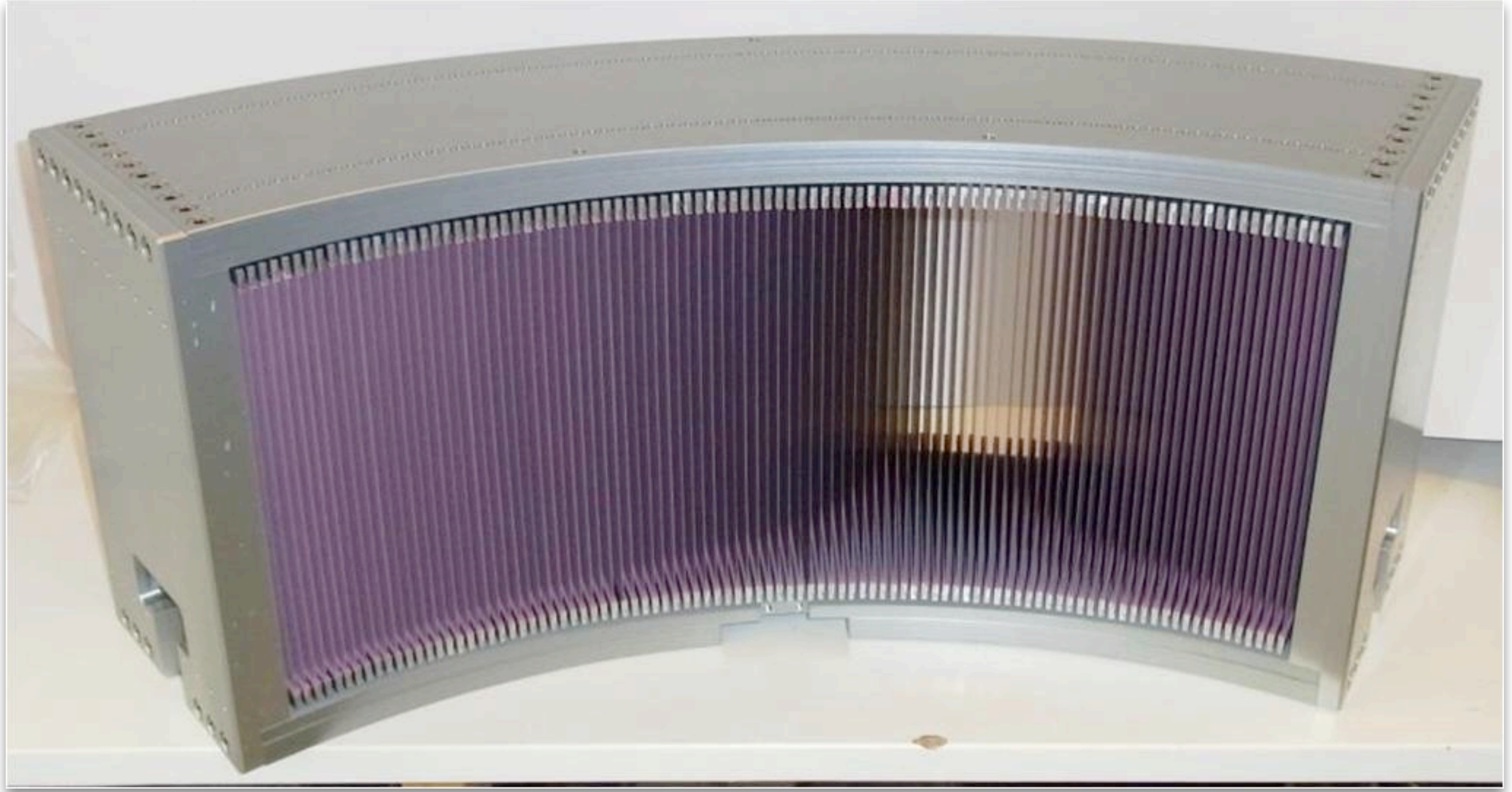


Liouville’s theorem: more intensity => more divergence

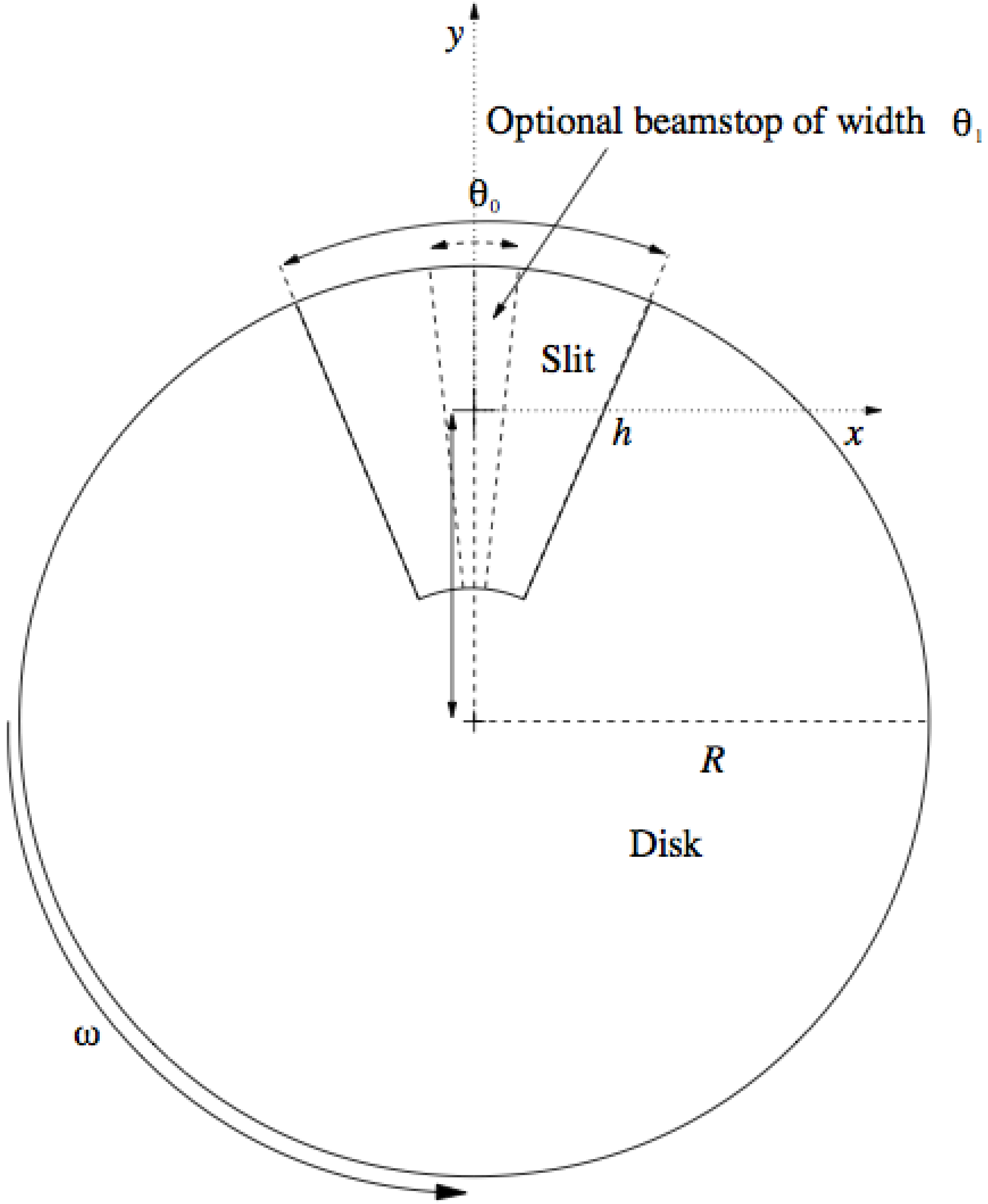
Spatial, directional beam tailoring

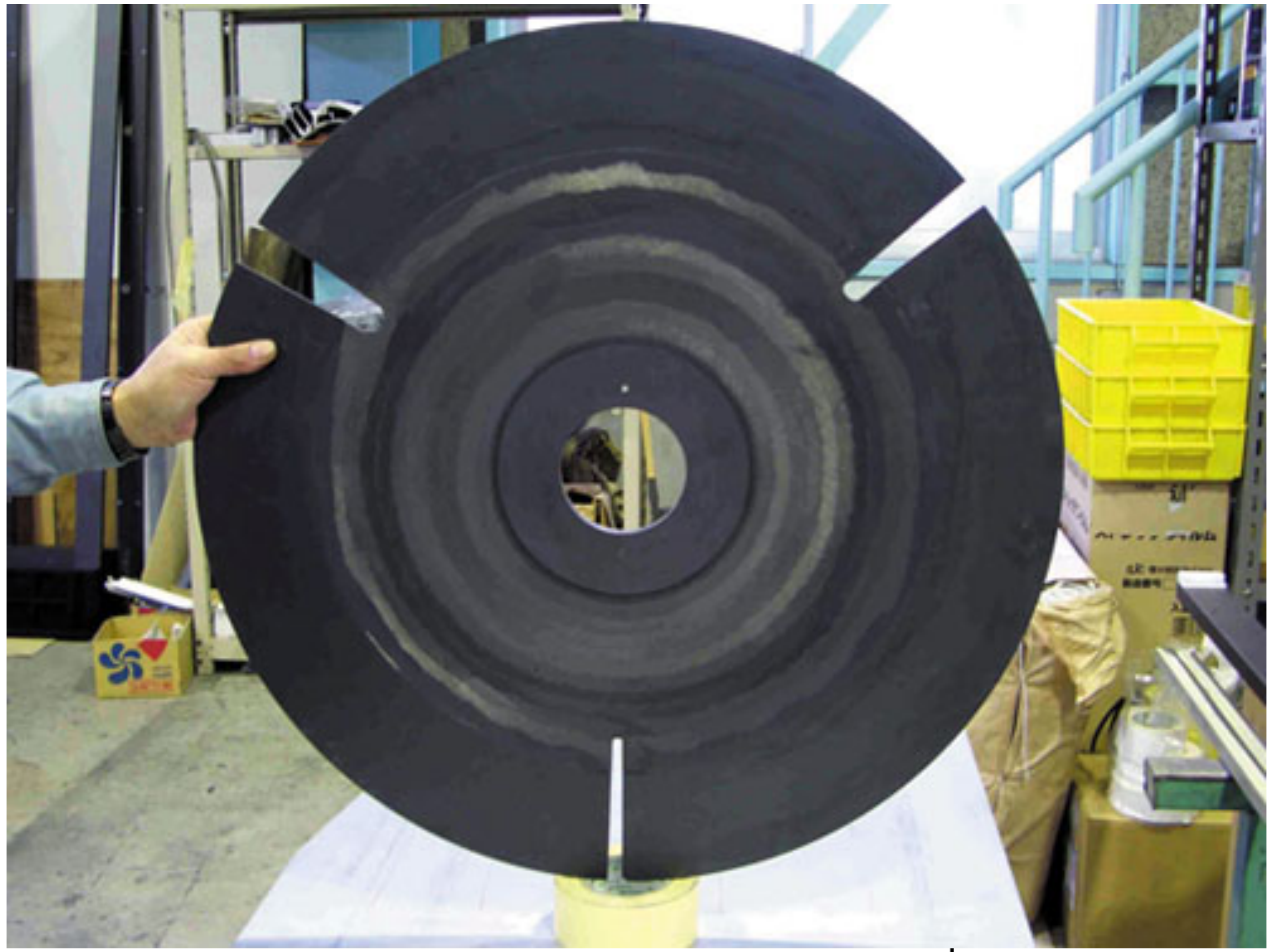
Slit: (configurable) opening in absorbing material

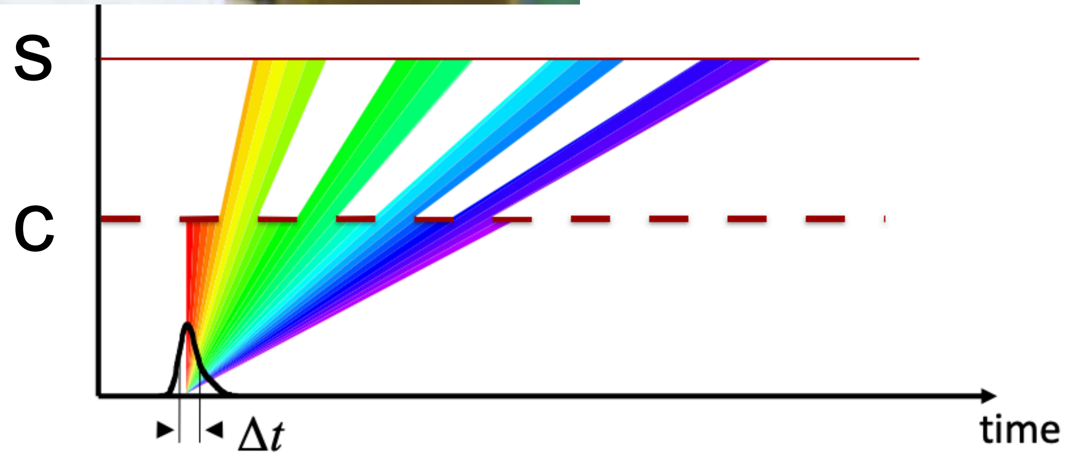


Collimators: Limiting divergence by sheets of absorbing material

Disk Chopper - a “rotating slit”





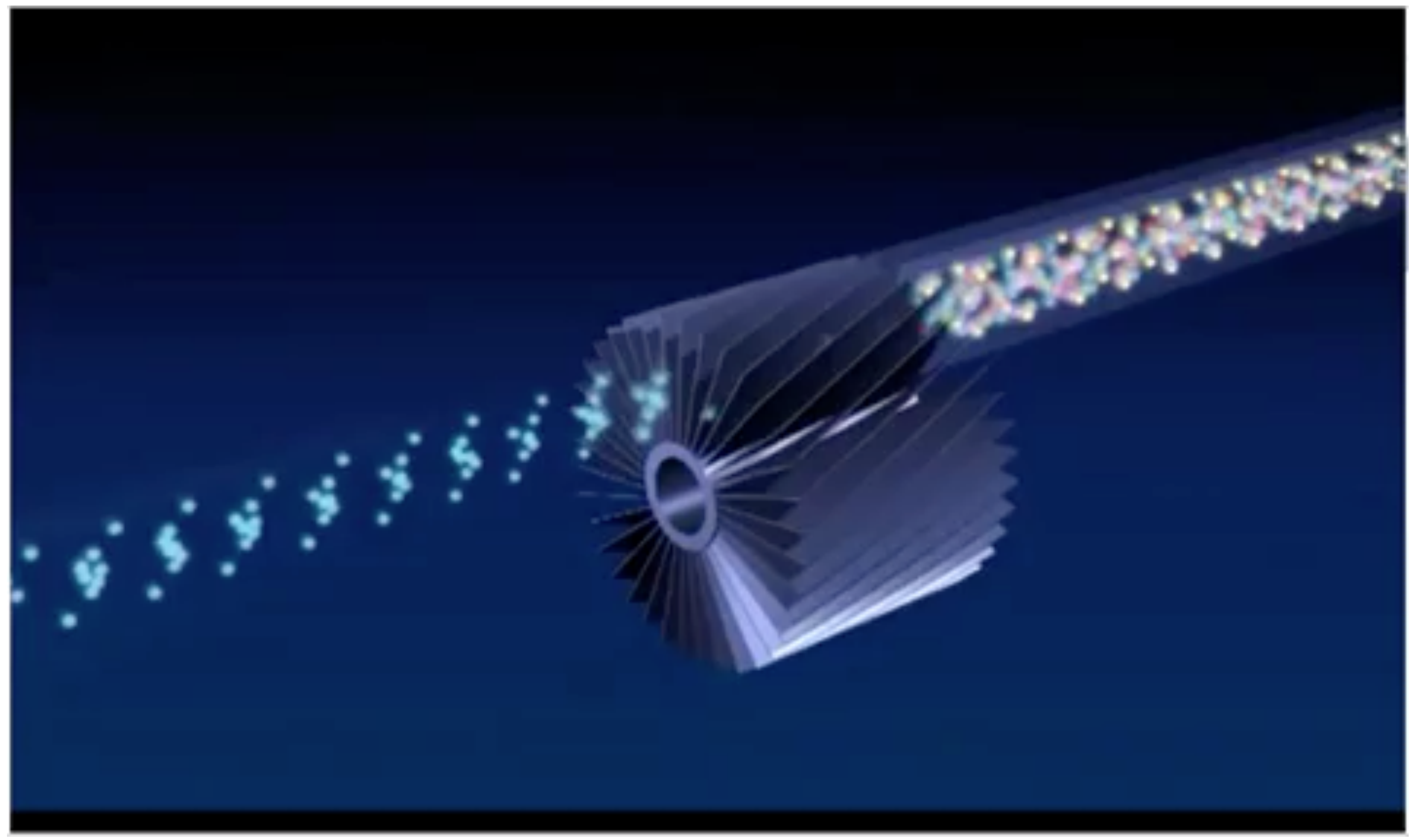


- Spatio-temporal tailoring of the beam
- A cascade of these will introduce spectral filtering

Velocity selector

- A sort of “rotating collimator”

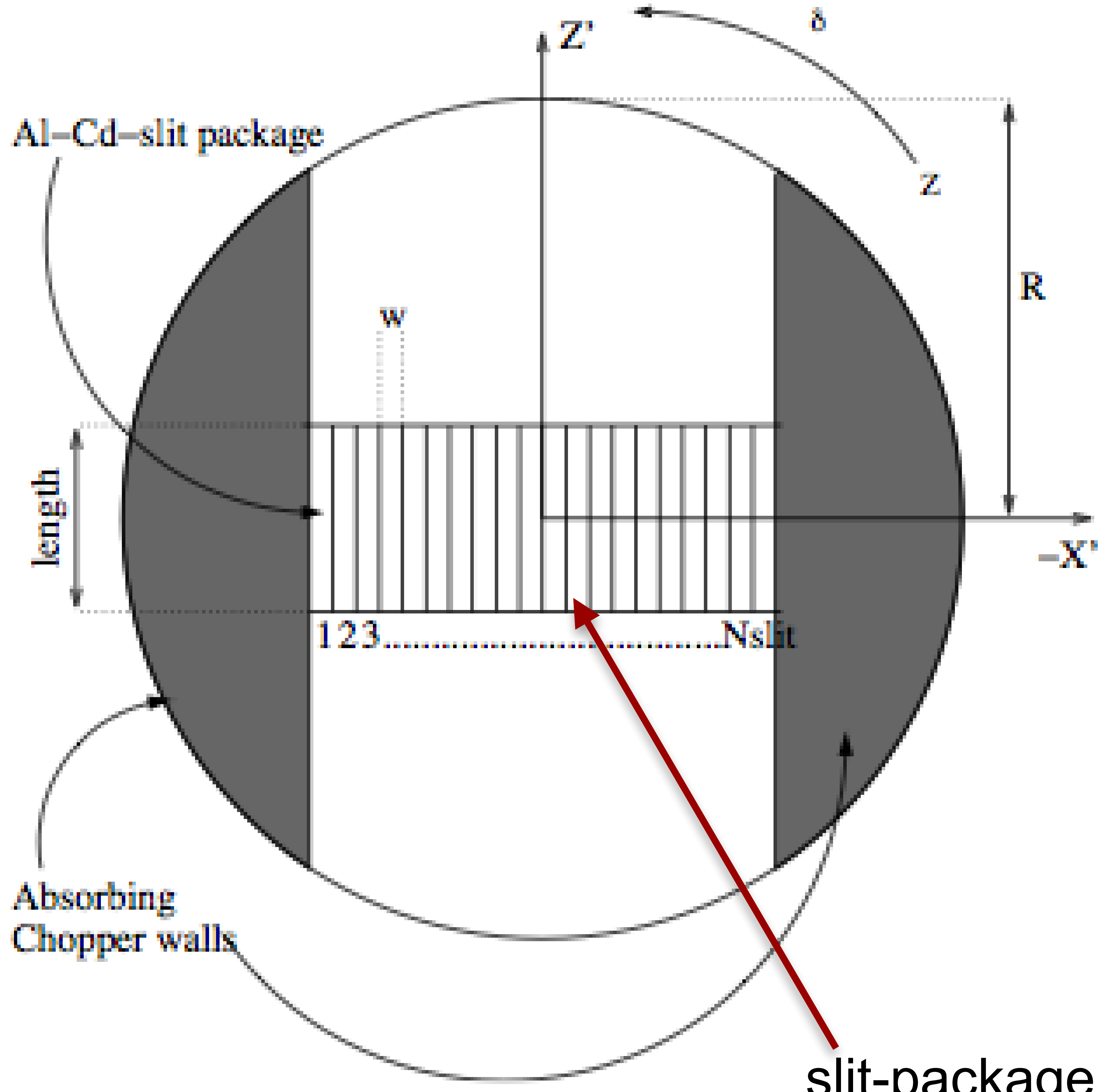
ILL - SANS instrument D11: a "microscope" for exploring the nanoworld (YouTube)

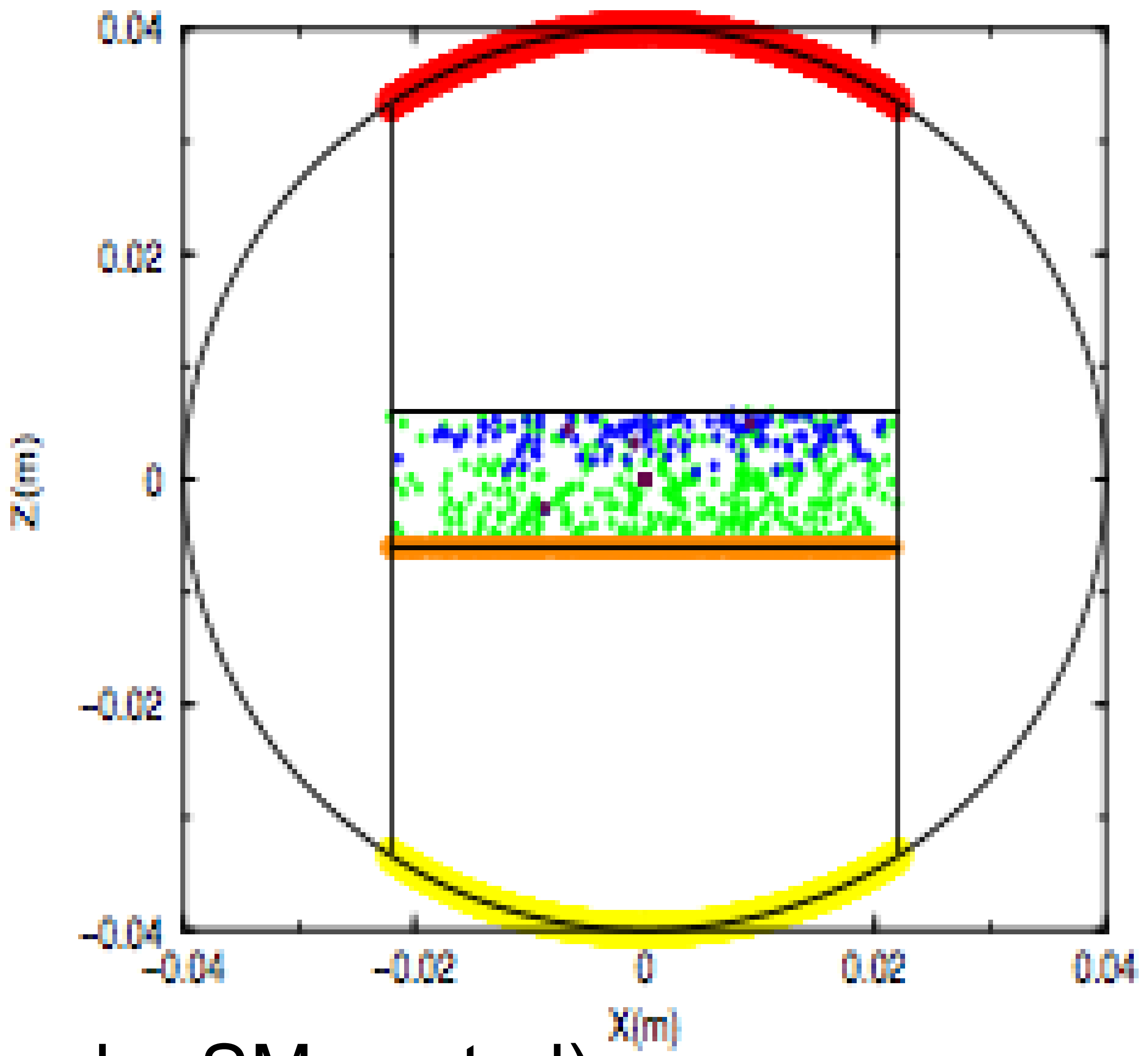


- Spectral tailoring of the beam

$$\frac{\delta\lambda}{\lambda} \approx 10\%$$

Fermi Choppers

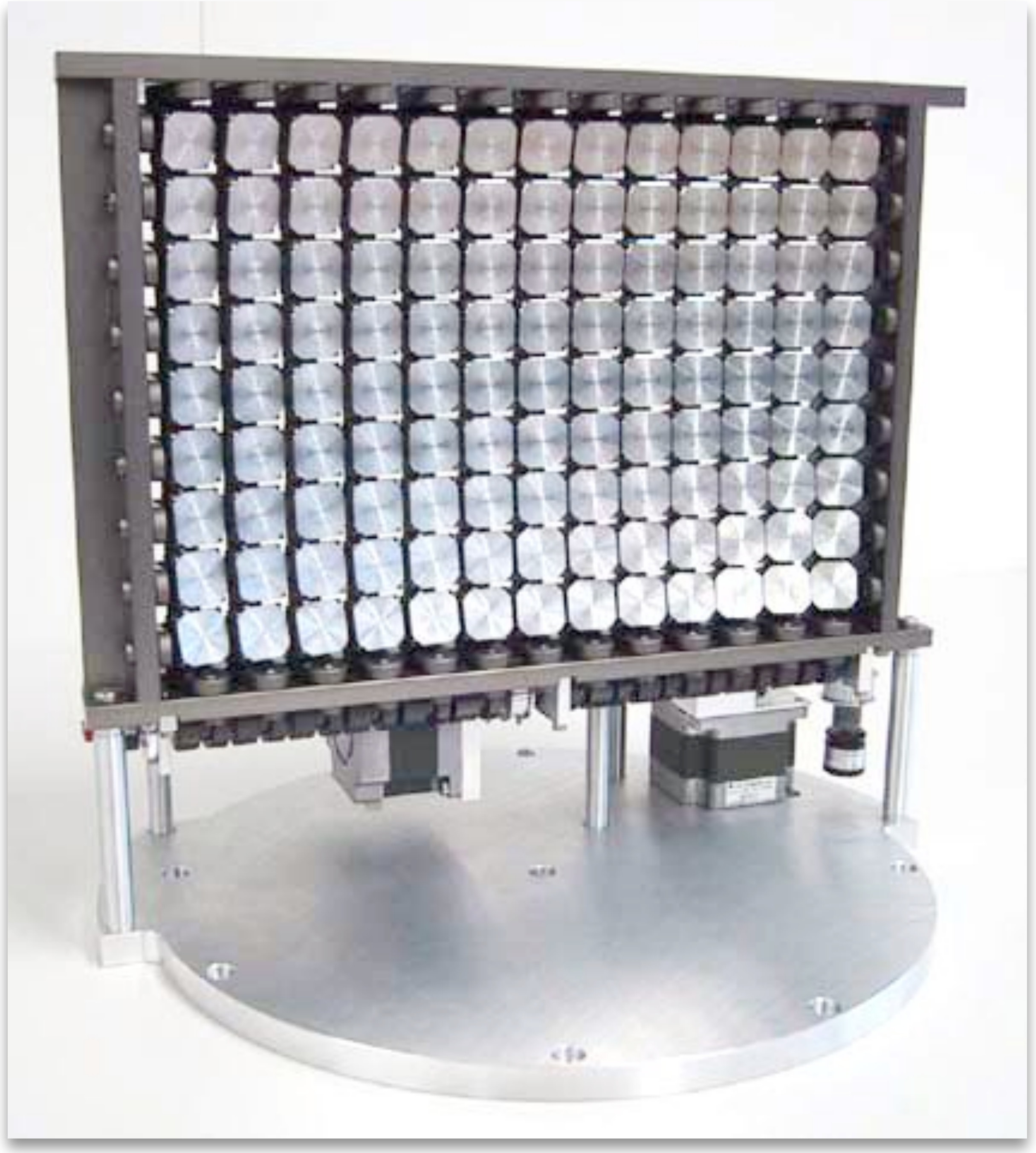


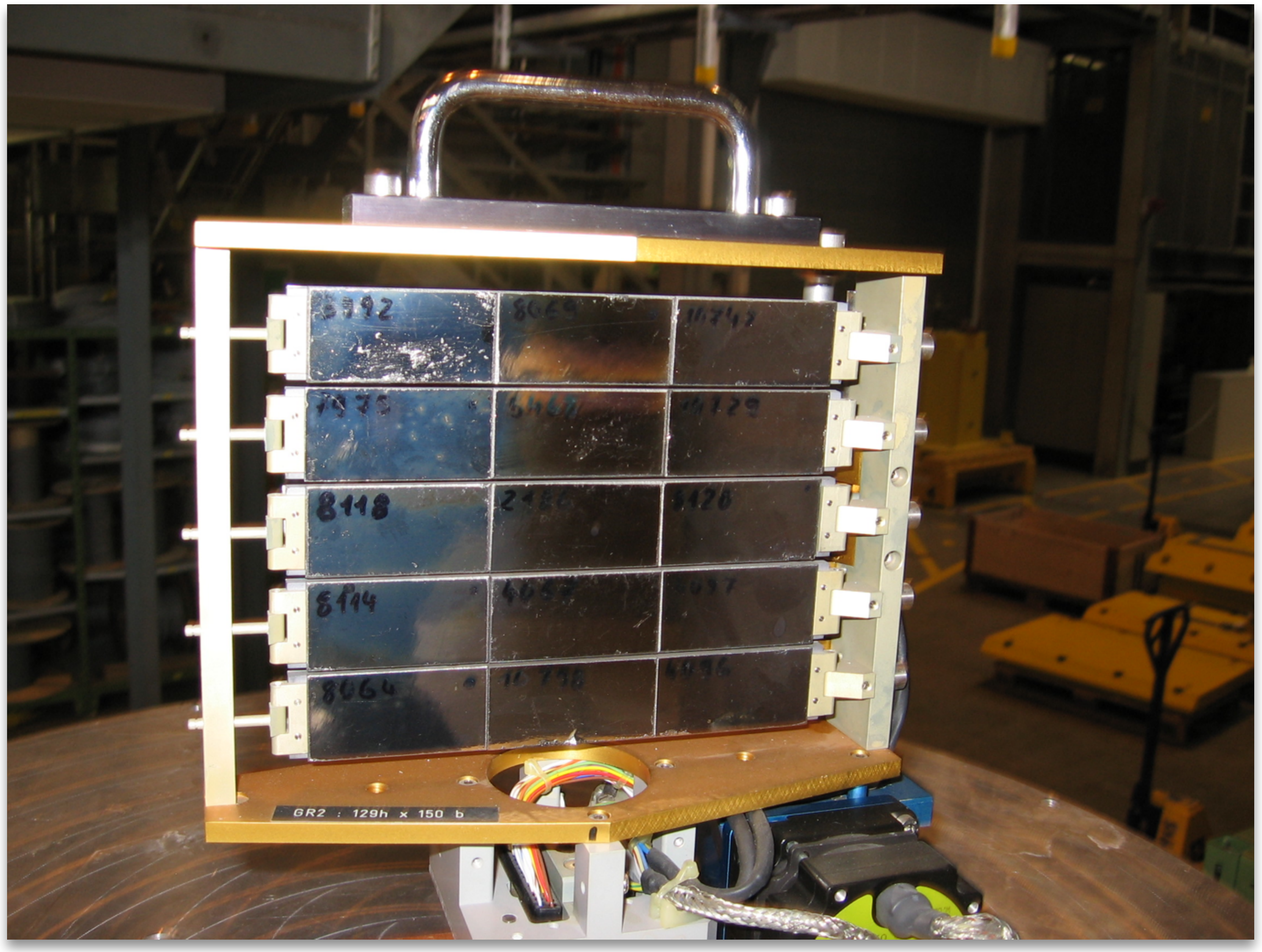


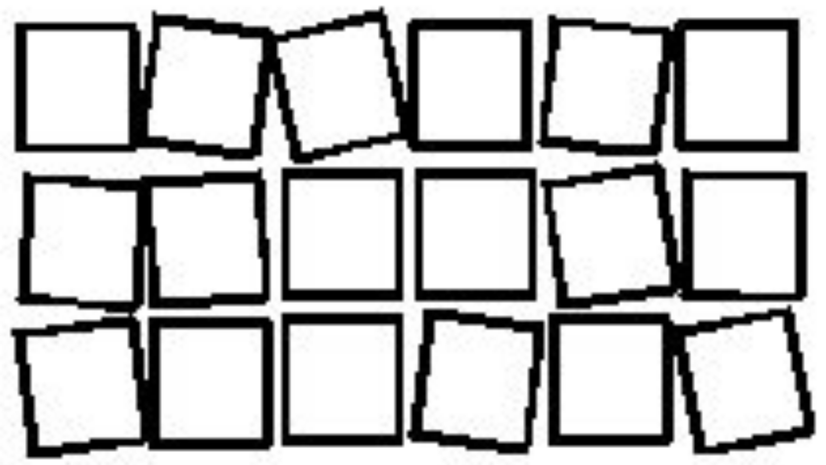
slit-package (can be SM-coated)

- Spectro-temporal tailoring of the beam, quite monochromatic $\frac{\delta\lambda}{\lambda} \approx 1\,\%$

Crystal monochromators (and analyzers)







Often far from being perfect single crystals

Various means of increasing crystal **mosaicity** are used

→ impacts divergence

→ focusing geometries

→ • Spectral tailoring via Bragg's law $\boxed{n}\lambda = 2d\sin(\theta)$

PG

$$\frac{\delta\lambda}{\lambda} \approx 3\%$$

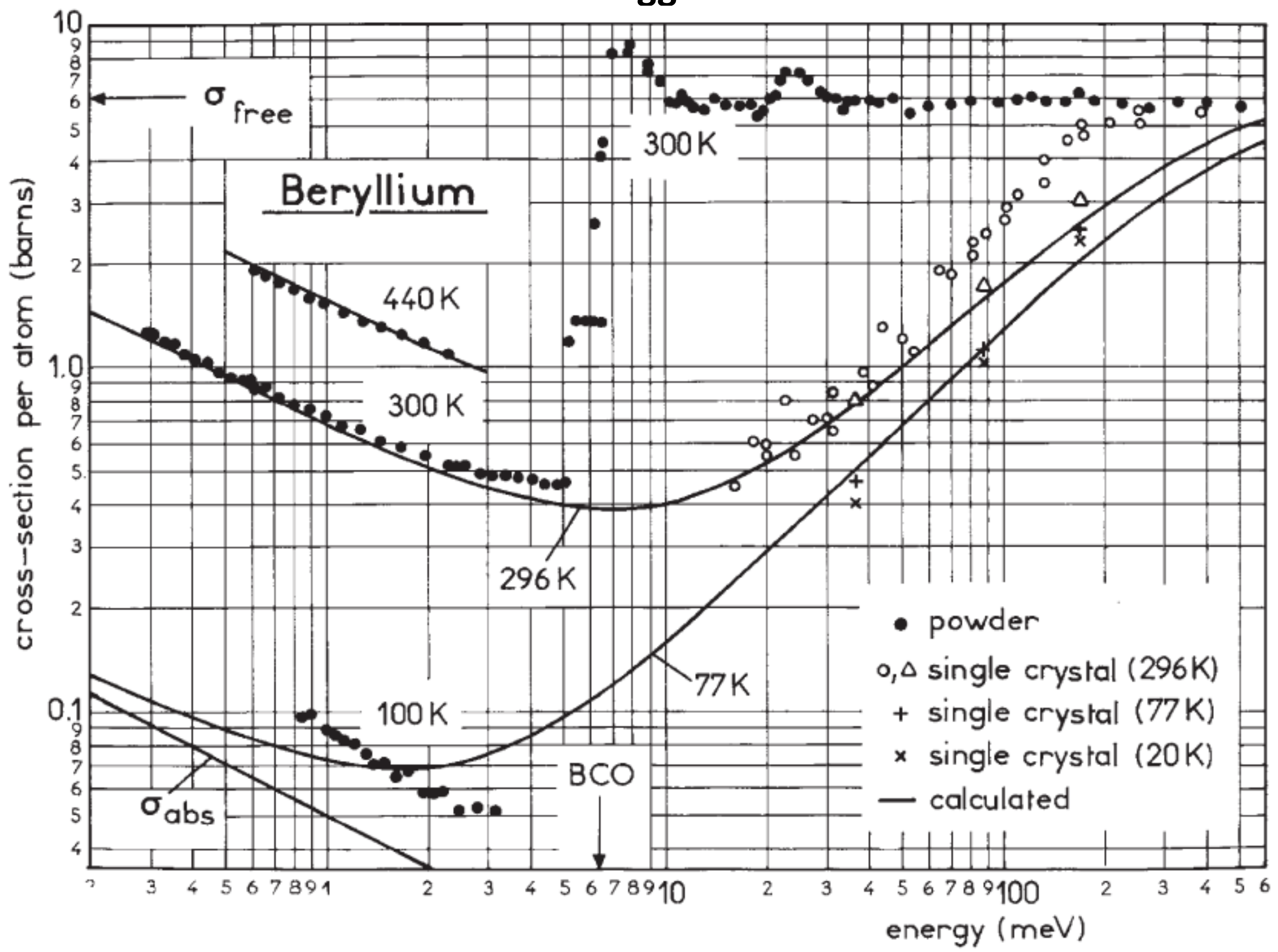
Filters…

- Removal of **fast neutrons or gammas**
- Suppression of **higher-order contributions λ/n** of monochromator

$\boldsymbol{\sigma = \sigma_{abs} + \sigma_{tds} + \sigma_{bragg}}$

Freund, NIM 213 495 (1983)

σ_{abs}	Absorption cross section ($1/v$ at low energy)
σ_{tds}	Thermal diffusive cross section (single phonon at low, multi phonon at high energy)
σ_{bragg}	Bragg scattering in single or polycrystals
	$\boldsymbol{\sigma_{bragg} = 0}$ for $\boldsymbol{\lambda > 2d_{max}}$



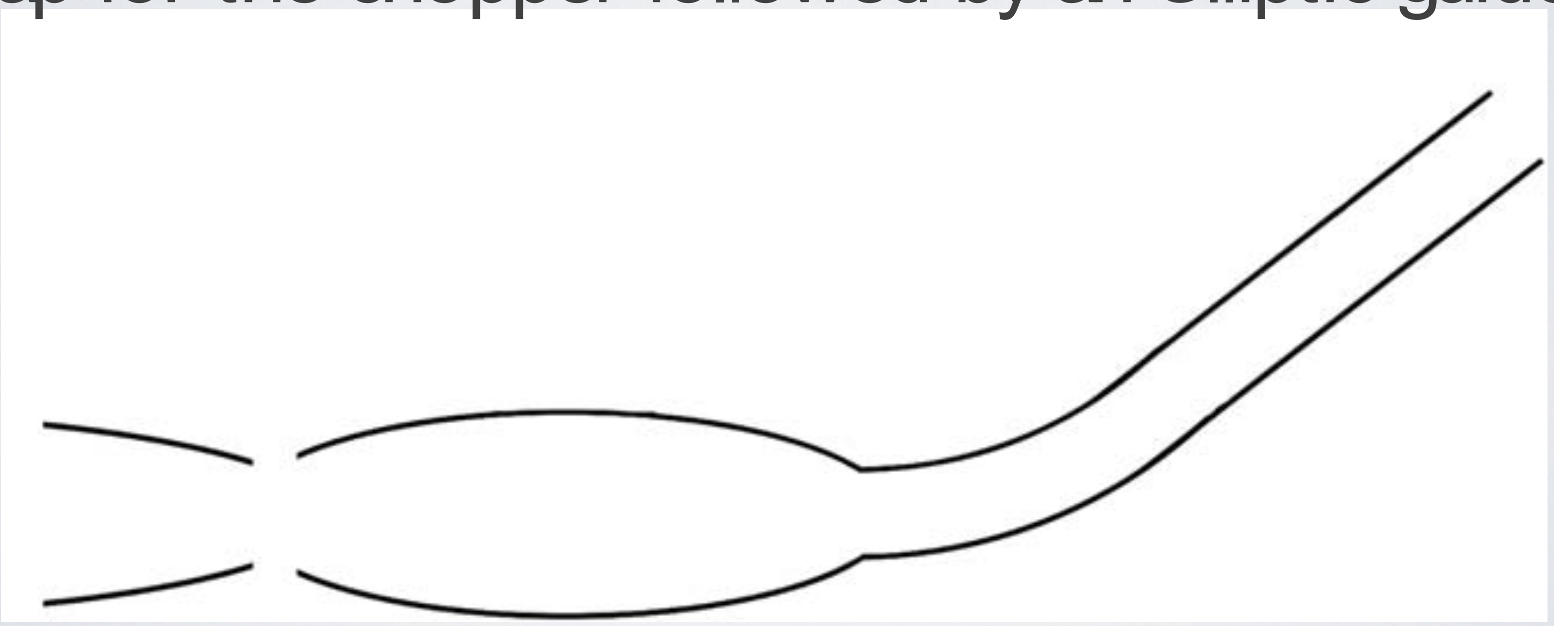
Techniques for neutron-optical design

- Back of the envelope
- Acceptance diagrams
- Monte Carlo (ray-tracing) simulations
  - McStas
  - Vitess
  - SimRes
- Always apply sanity checks
  - Liouville's theorem
  - check Brilliance Transfer: variation of calculated flux: $\int \Psi \, dA \, d\Omega$
  - check divergence and beam profiles
- Optimisation package
  - Guide_bot

McStas

Guide_bot McStas Optimisation

"I want a feeder system consisting of a **p**arabola and a **g**ap for the chopper followed by an **e**lliptic guide"



Mads Bertelsen, Copenhagen Univ.

https://github.com/mads-bertelsen/guide_bot

CAMEA

PGESKSE

```
P
G(start=6.5,length=0.1)
E(maxStartWidth=0.030)
S(minlength=1)
K(minstart=66,maxstart=96,maxlength=2.5)
S(minlength=1,maxlength=12)
E
```

Demands

Sample size H	15mm
Sample size V	15mm
Divergence H	±0.75°
Divergence V	±1.00°
Wavelength	1.65 - 6.40Å
Length	170m
Sample - guide	60cm

Literature

- G. L. Squires: Introduction to the Theory of Thermal Neutron Scattering, Cambridge
  Great all-round resource for understanding neutron-matter interaction

- V. F. Sears: Neutron Optics, Oxford University Press 1989
  Theoretically rigorous, not so many applications

- M Utsuro & V. K. Ignatovich, Handbook of Neutron Optics, Wiley-VCH 2010
  Very complete with many applications

- R. Golub et al, Ultra-Cold Neutrons, IOP Publishing 1991
  Introduction interactions neutrons – matter

- A.-J. Dianoux & G. Lander (eds.), Neutron Data Booklet, Institut Laue Langevin 2003
  Compact overview and formulas
  Download:
  https://www.ill.eu/fileadmin/user_upload/ILL/1_About_ILL/Documentation/NeutronDataBooklet.pdf

Thank you!

- Questions?
- McStas talk and demo after the coffee break…