Neutron Guides

29th July 2015

Ken Andersen

Neutron Guides

29th July 2015

Disclaimer:
I will only speak about how guides work and are designed from a Neutron Optics viewpoint.
Nothing is said about engineering – how they can or should be built.

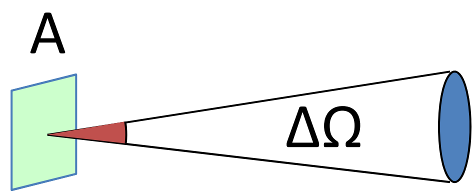
Agree Disagree

Ken Andersen

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

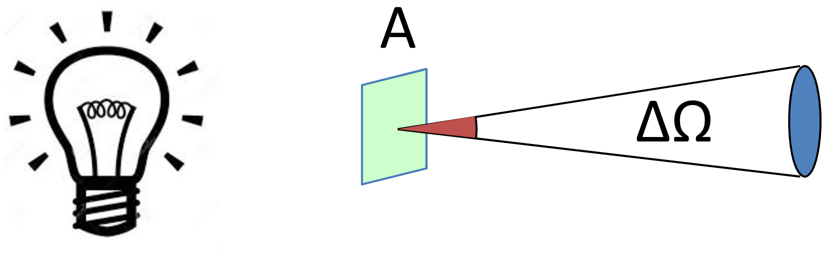
Neutron Flux



B = N per time per A per ΔΩ

units = $n/s/cm^2/sr$

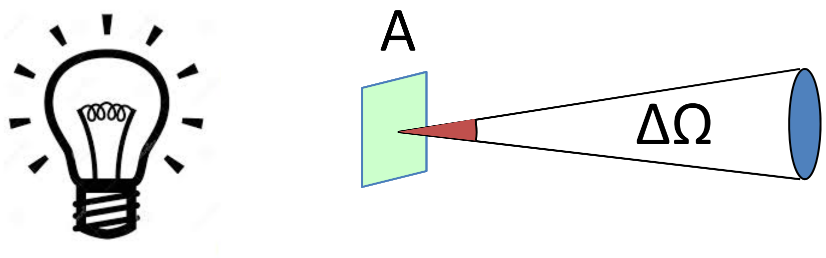
Neutron Flux



B is independent of distance

- property of the source

Neutron Flux



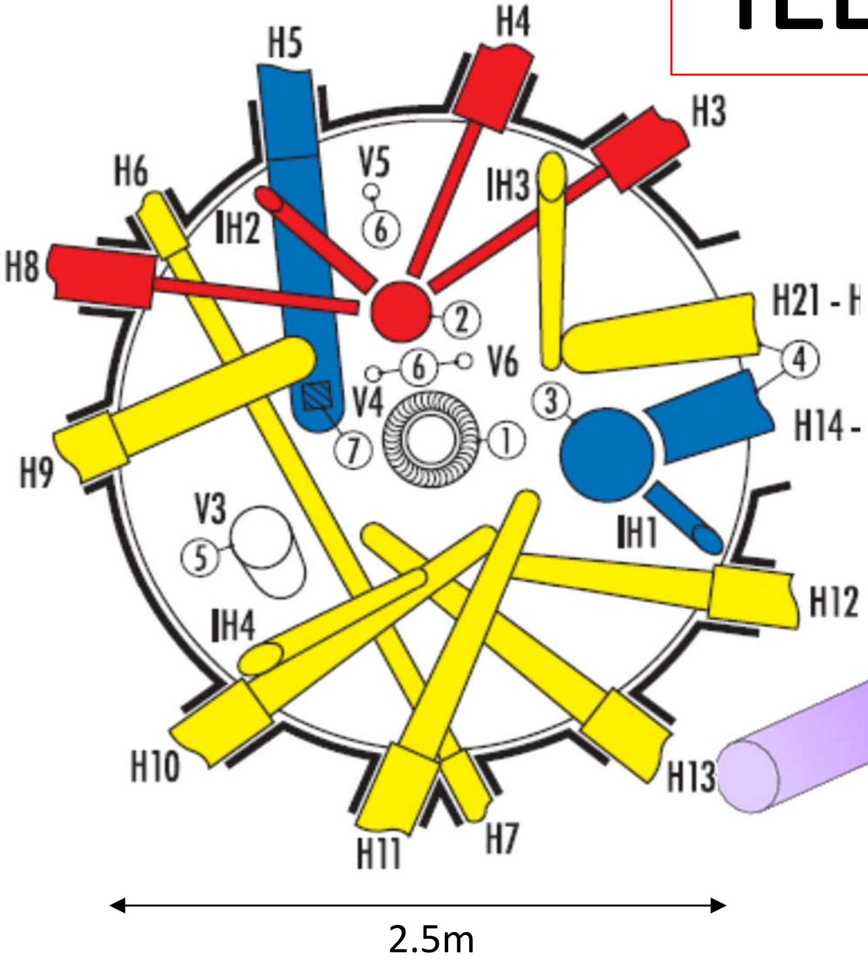
Brilliance/Brightness B $[n/s/cm^2/sr]$

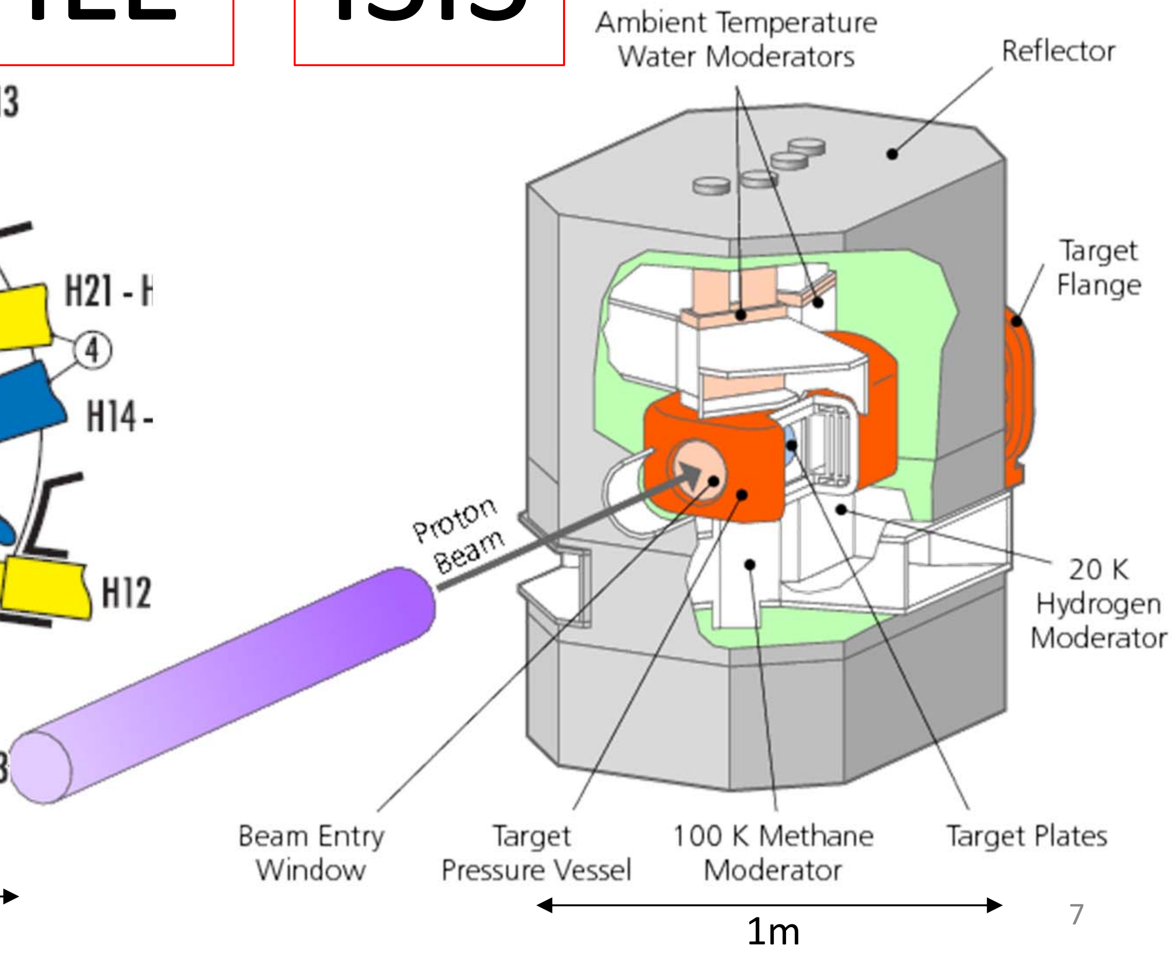
Flux Ψ $[n/s/cm^2]$

Neutron Sources

ILL

ISIS

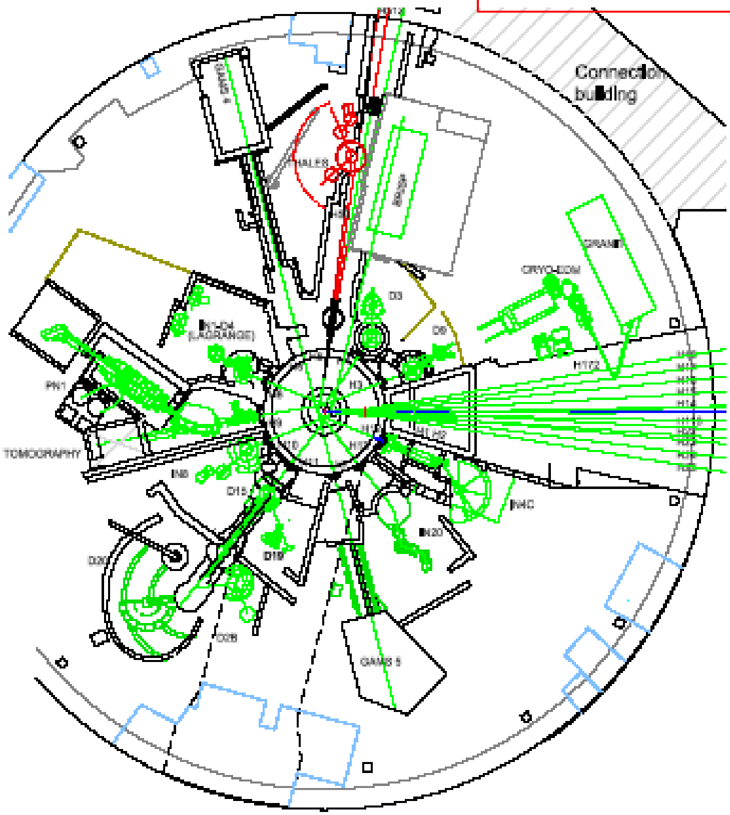




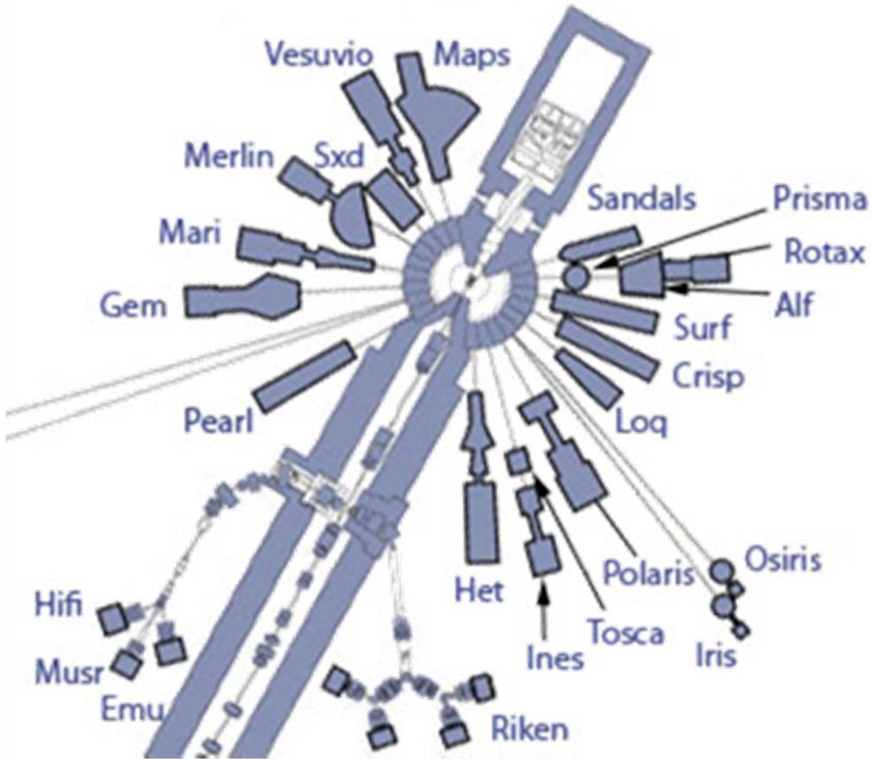
Neutron Sources

ILL

ISIS

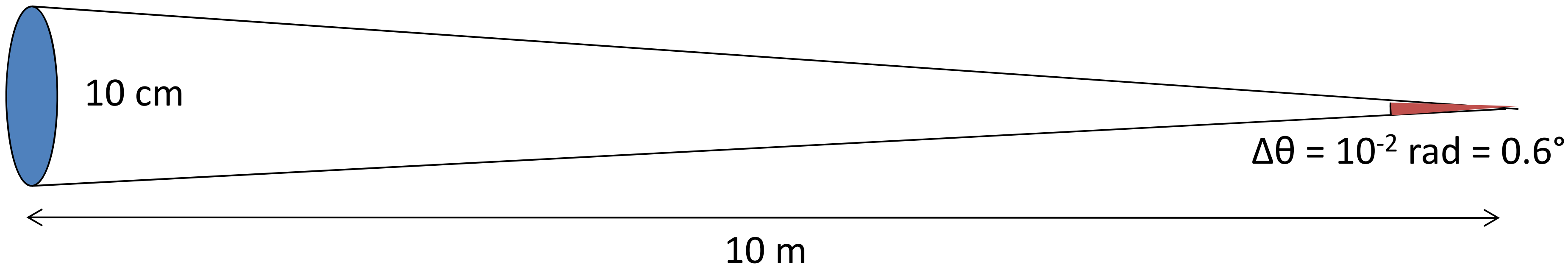


30m

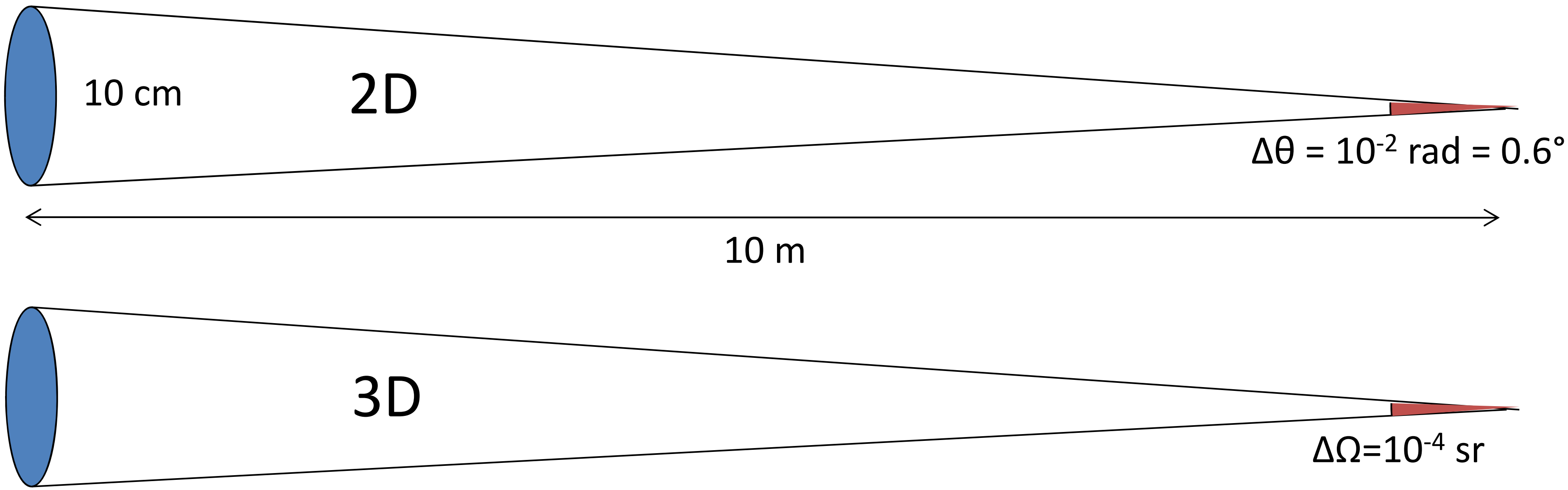


30m

Neutron Sources



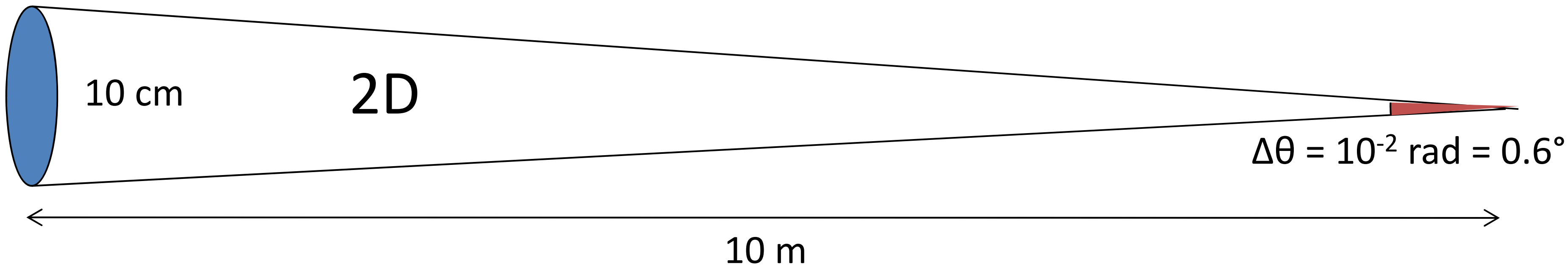
Neutron Sources

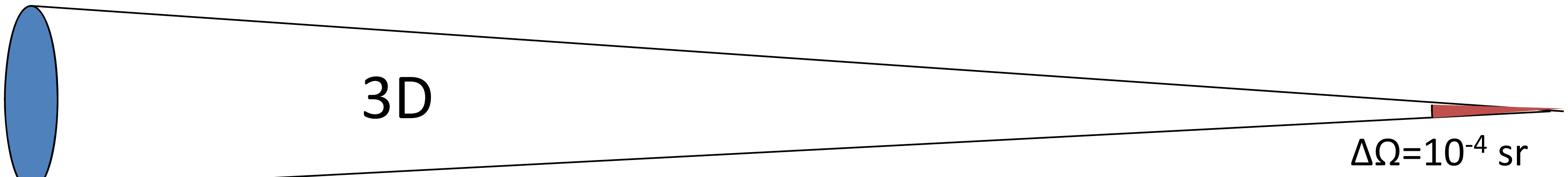


Flux = Source Brightness × Solid Angle

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

Neutron Sources

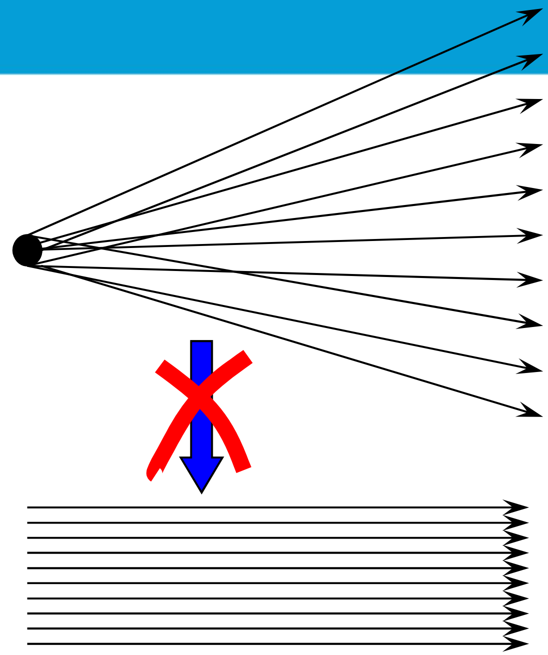




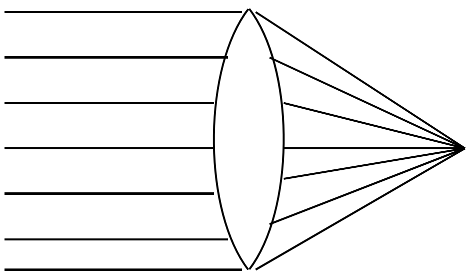
Flux = Source Brightness × Solid Angle

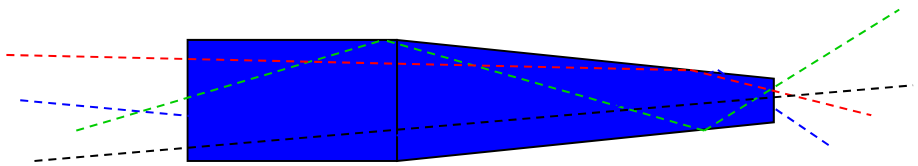
$\Phi = B \times \Delta\Omega$

Liouville's Theorem



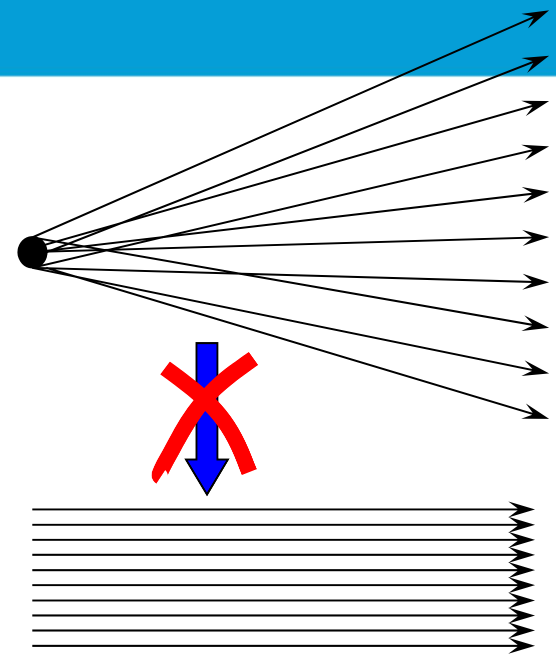
- Conservation laws:
  - neutrons can't be created from thin air
  - neither can "phase space density"
- There is no such thing as a free lunch
  - Beam manipulation transfers distribution between time, area, divergence, energy
- Most common application:
  - Focusing increases divergence
  - improve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





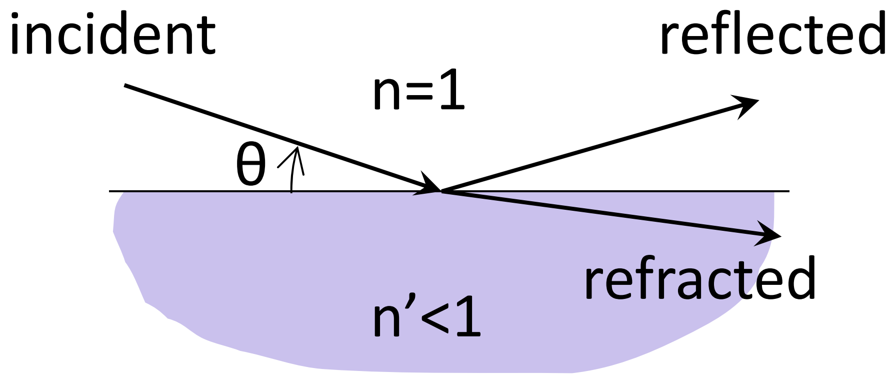
Liouville's Theorem

- 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



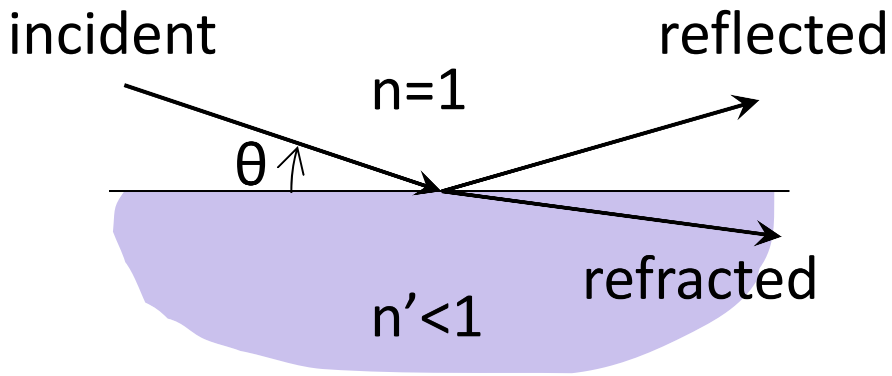
Integrated flux $\int \Psi \, dA \, d\Omega$ can never increase

Reflection: Snell's Law



critical angle of total reflection θ_c

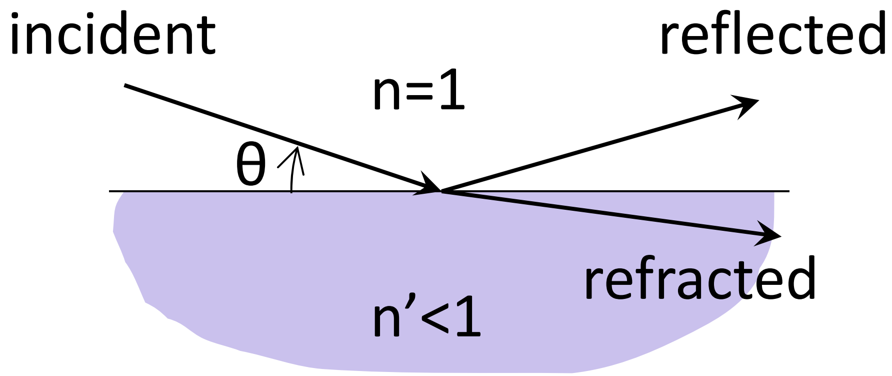
Reflection: Snell's Law



critical angle of total reflection θ_c

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

Reflection: Snell's Law



critical angle of total reflection θ_c

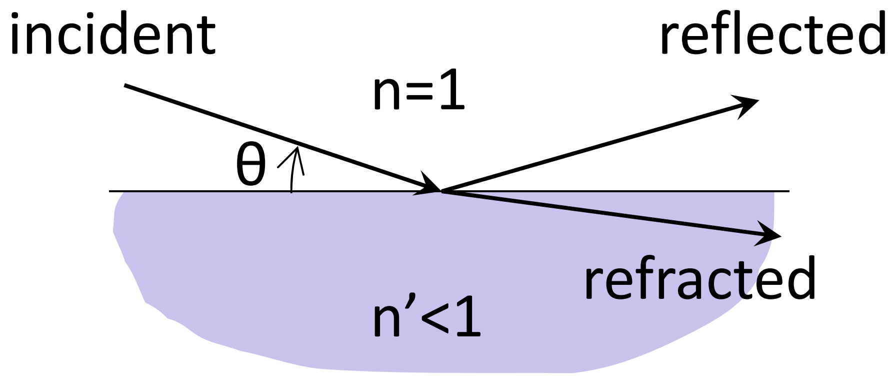
$$\left.\begin{aligned} \cos\theta_c &= n'/n = n' \\ n' &= 1 - \frac{N\lambda^2 b}{2\pi} \\ \cos\theta_c &\approx 1 - \theta_c^2/2 \end{aligned}\right\} \Rightarrow \theta_c = \lambda\sqrt{Nb/\pi}$$

for natural Ni,

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

$Q_c = 0.0218$ Å^{-1}

Reflection: Snell's Law



critical angle of total reflection θ_c

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

Definition:

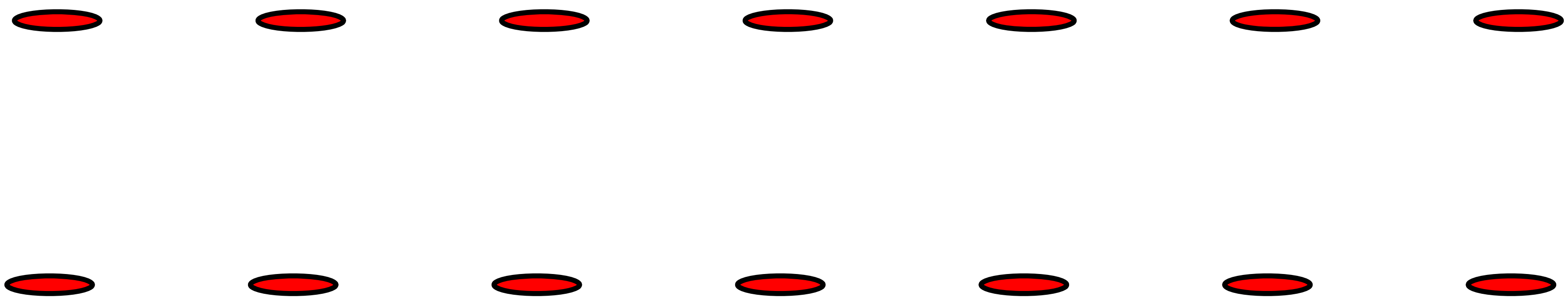
$$Q = 4\pi \sin\theta / \lambda$$

for natural Ni:

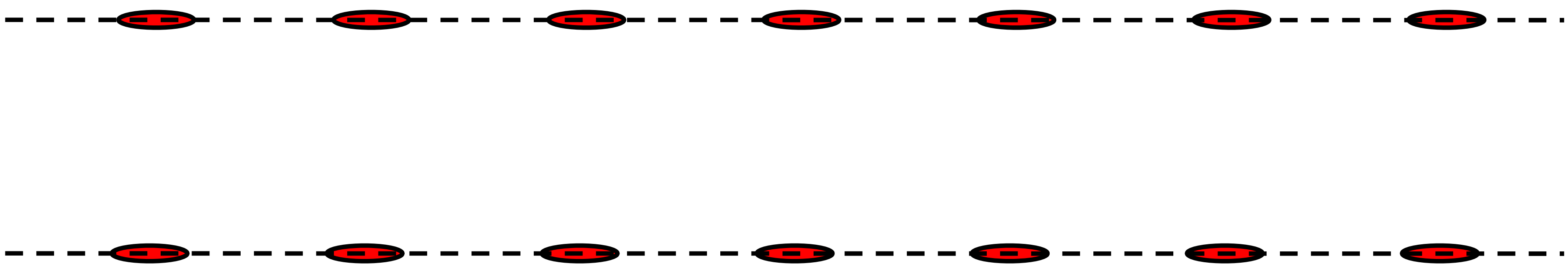
$\theta_c = \lambda[\text{Å}] \times 0.1°$

$Q_c = 0.0218\ \text{Å}^{-1}$

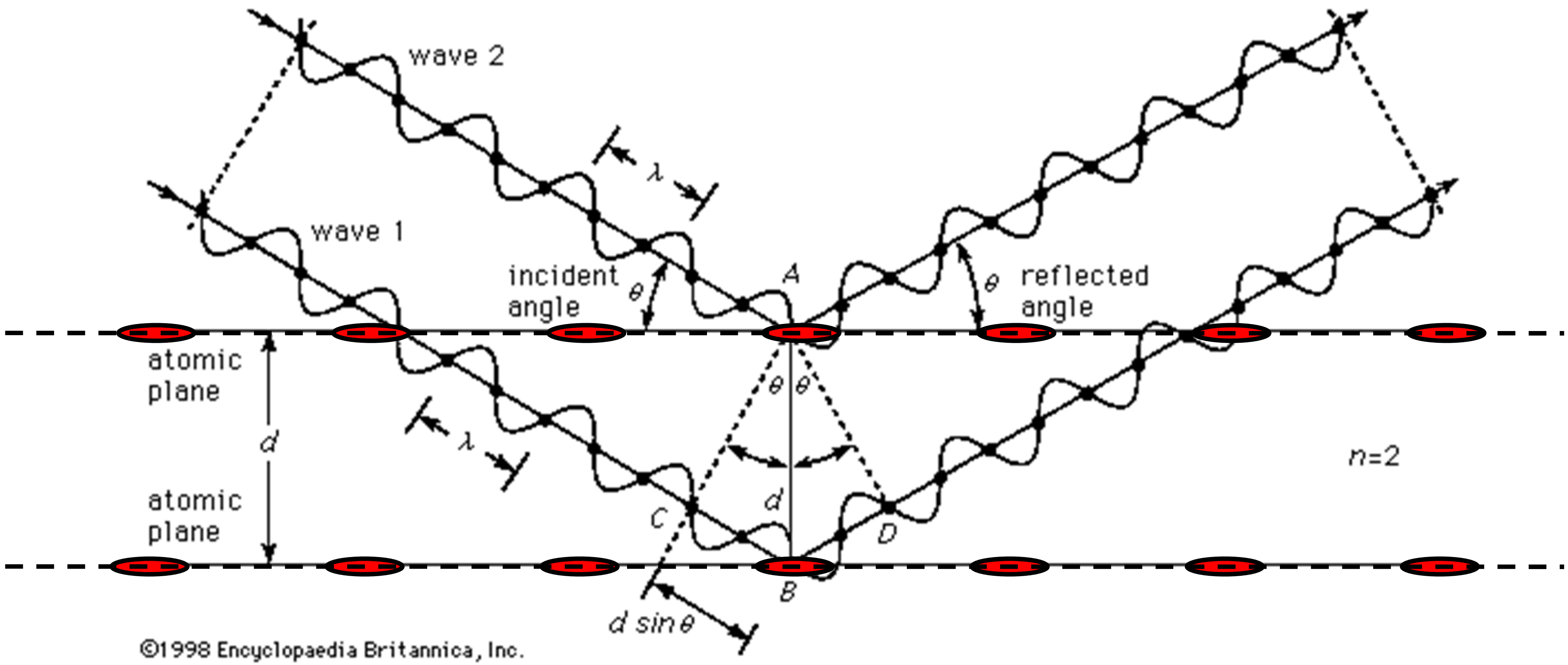
Diffraction: Bragg’s Law



Diffraction: Bragg's Law

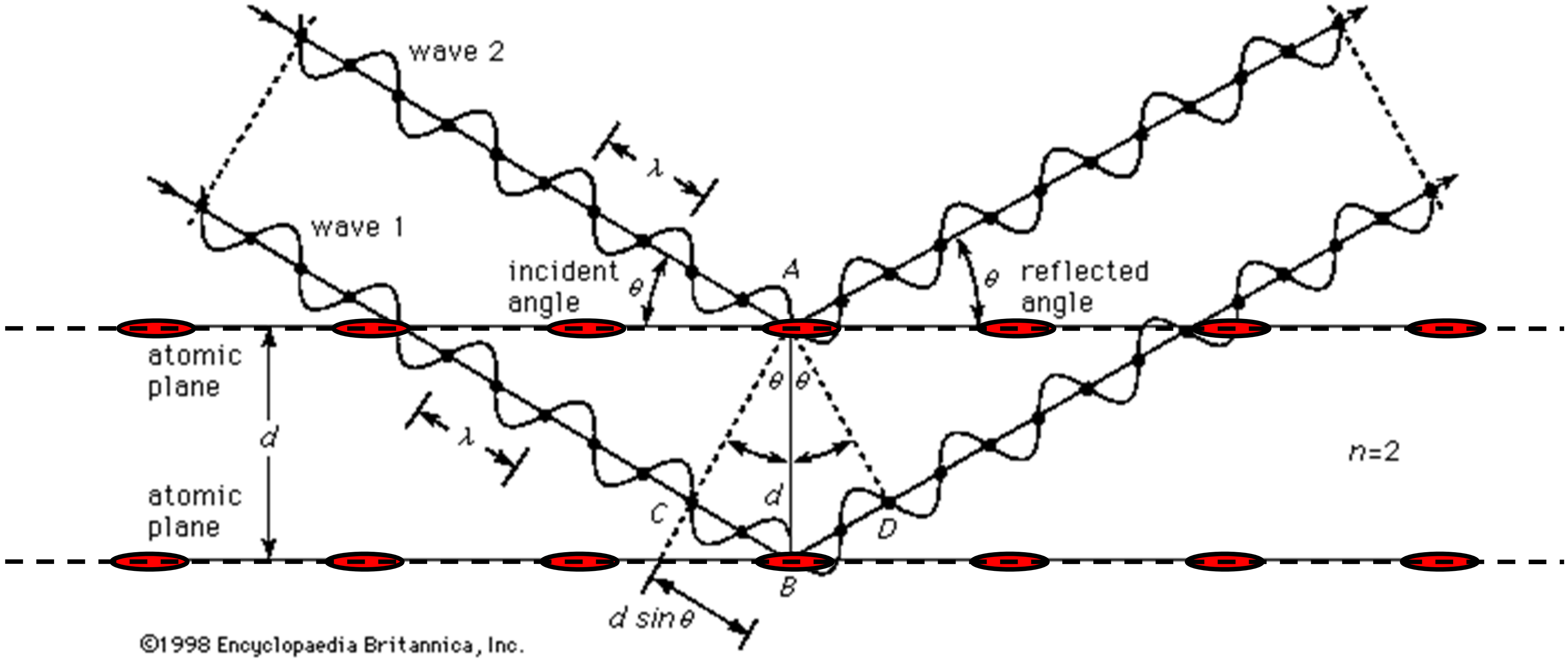


Diffraction: Bragg's Law



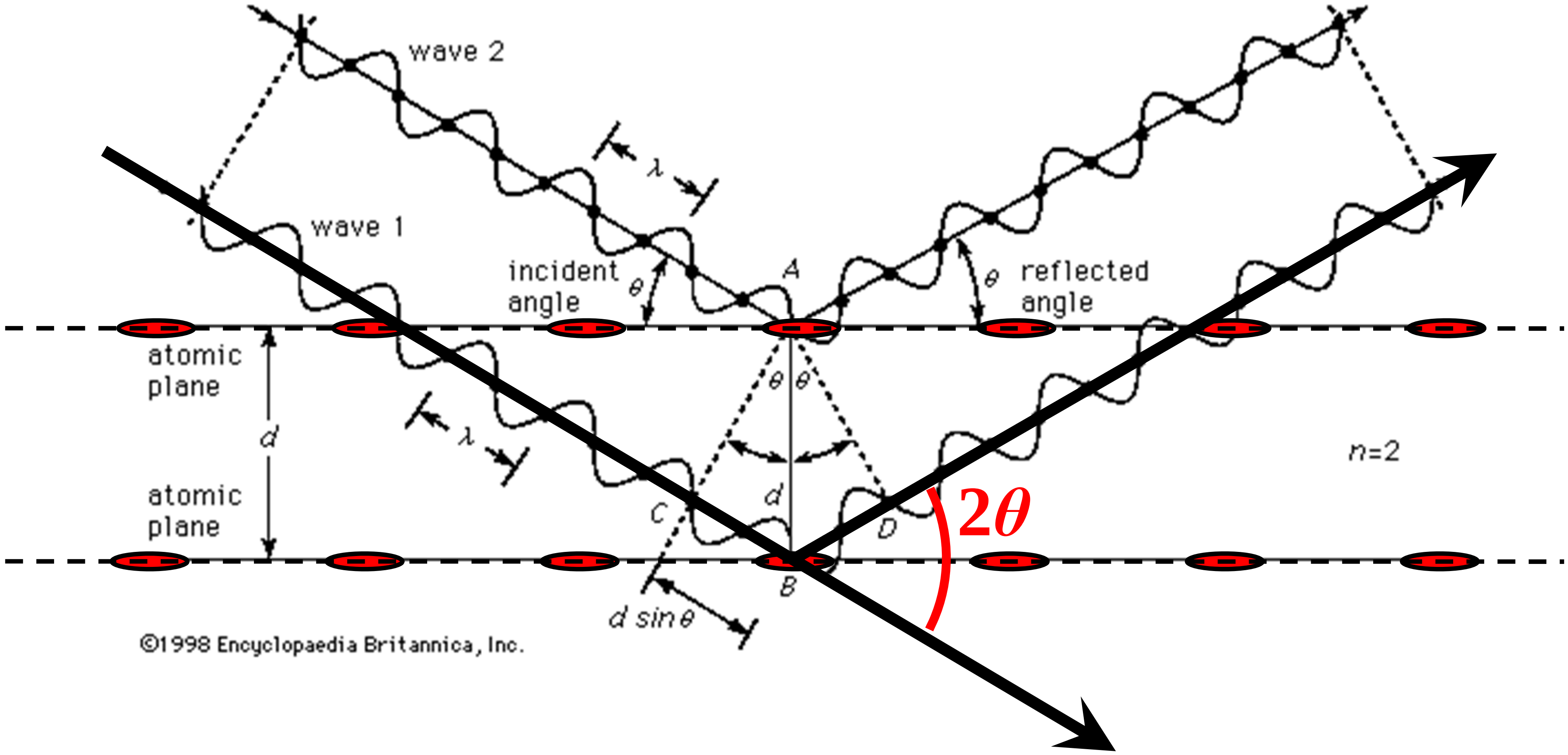
Diffraction: Bragg's Law

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

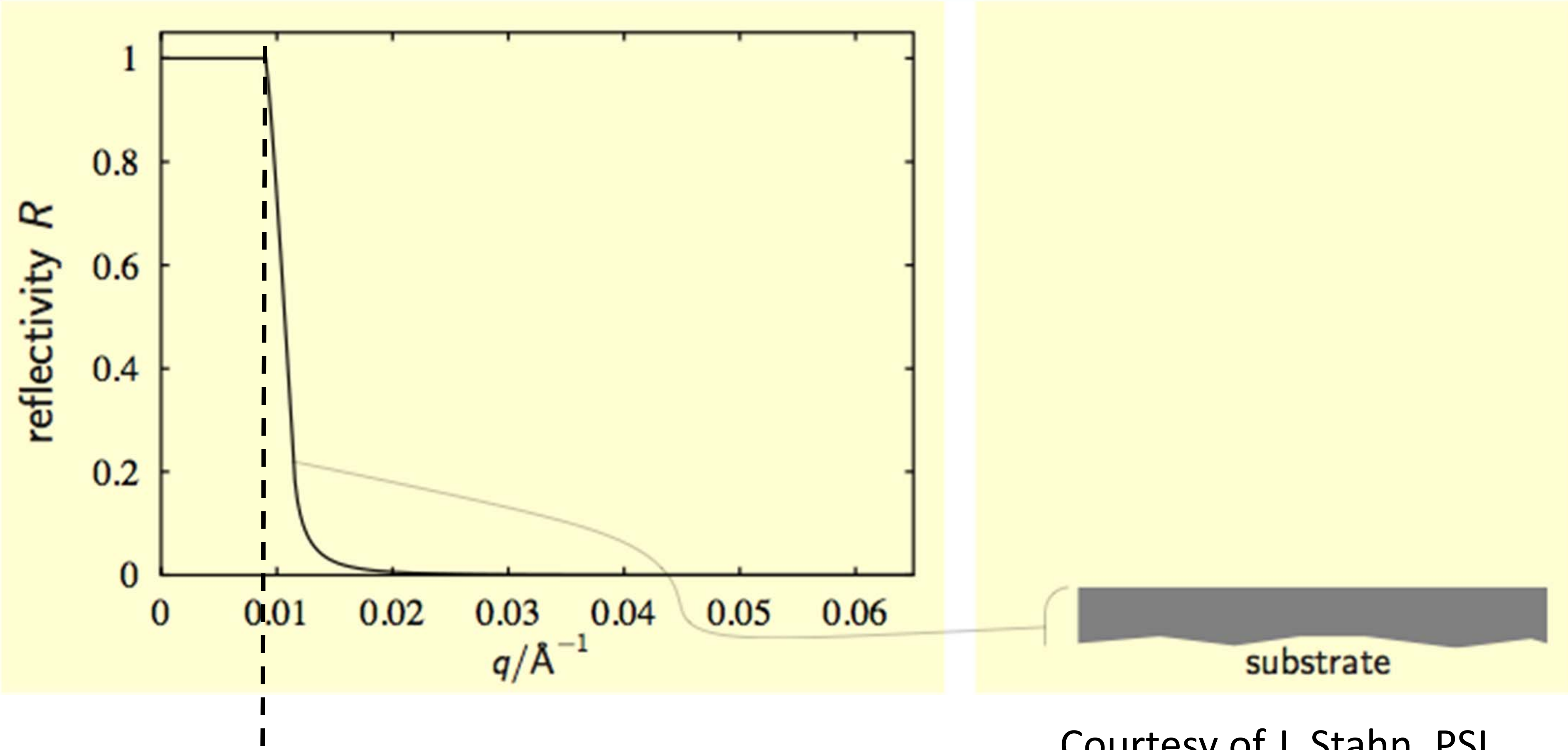


Diffraction: Bragg's Law

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



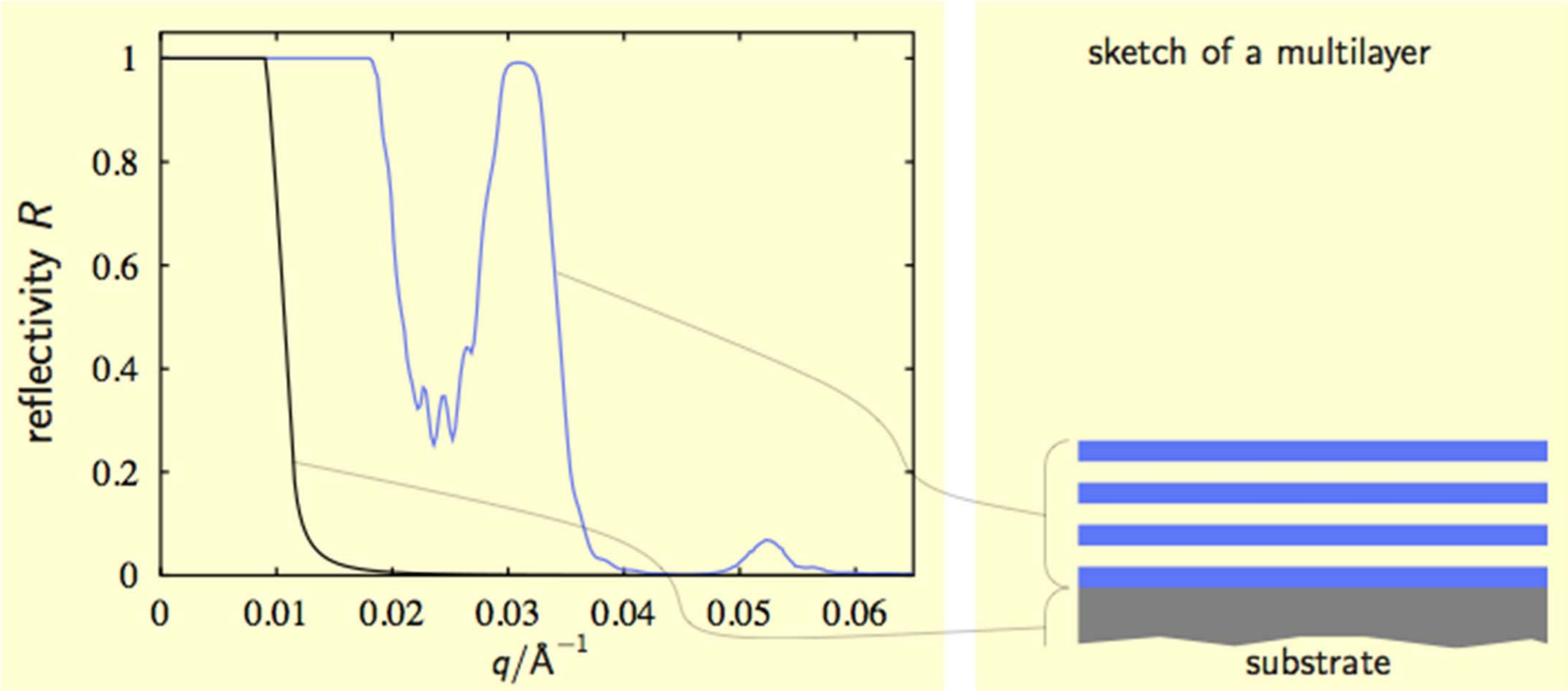
Neutron Supermirrors



Q_c as given by Snell's Law

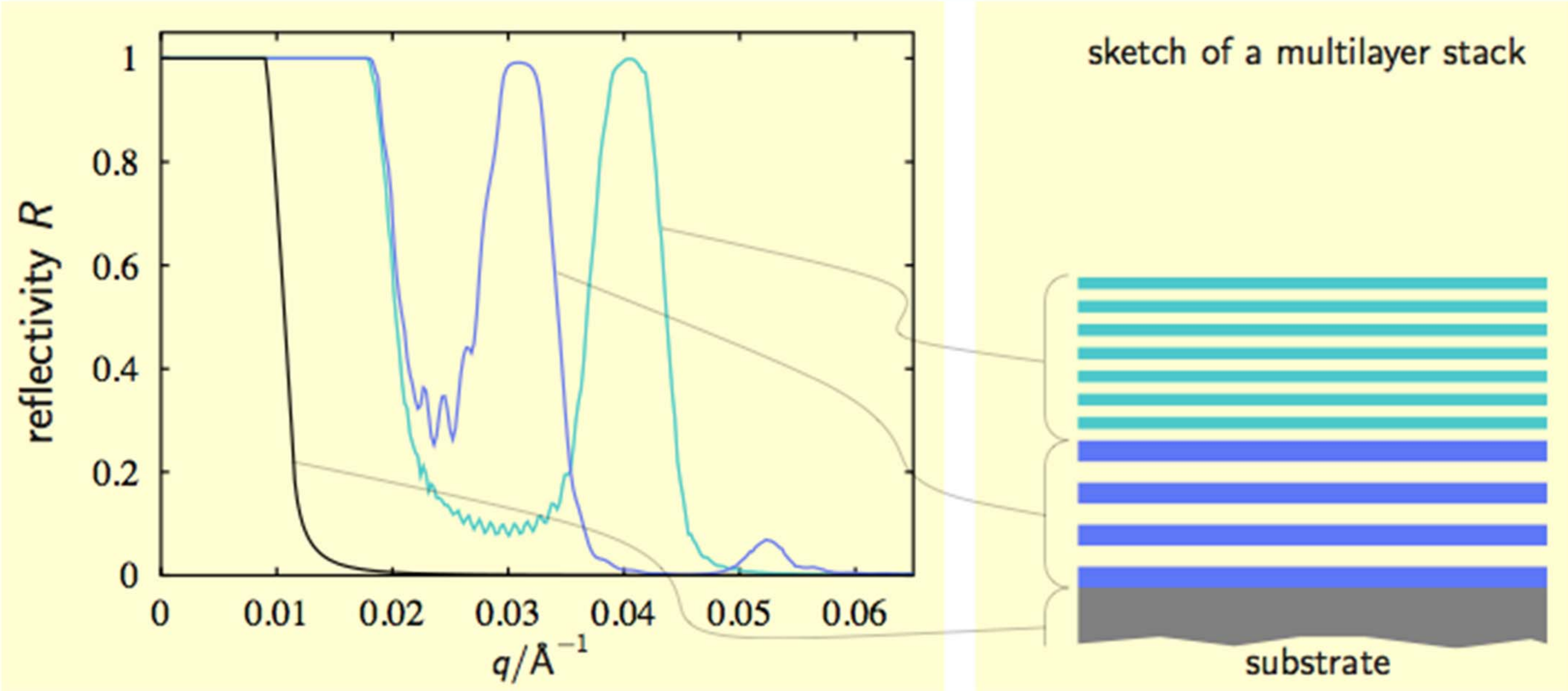
Courtesy of J. Stahn, PSI

Neutron Supermirrors



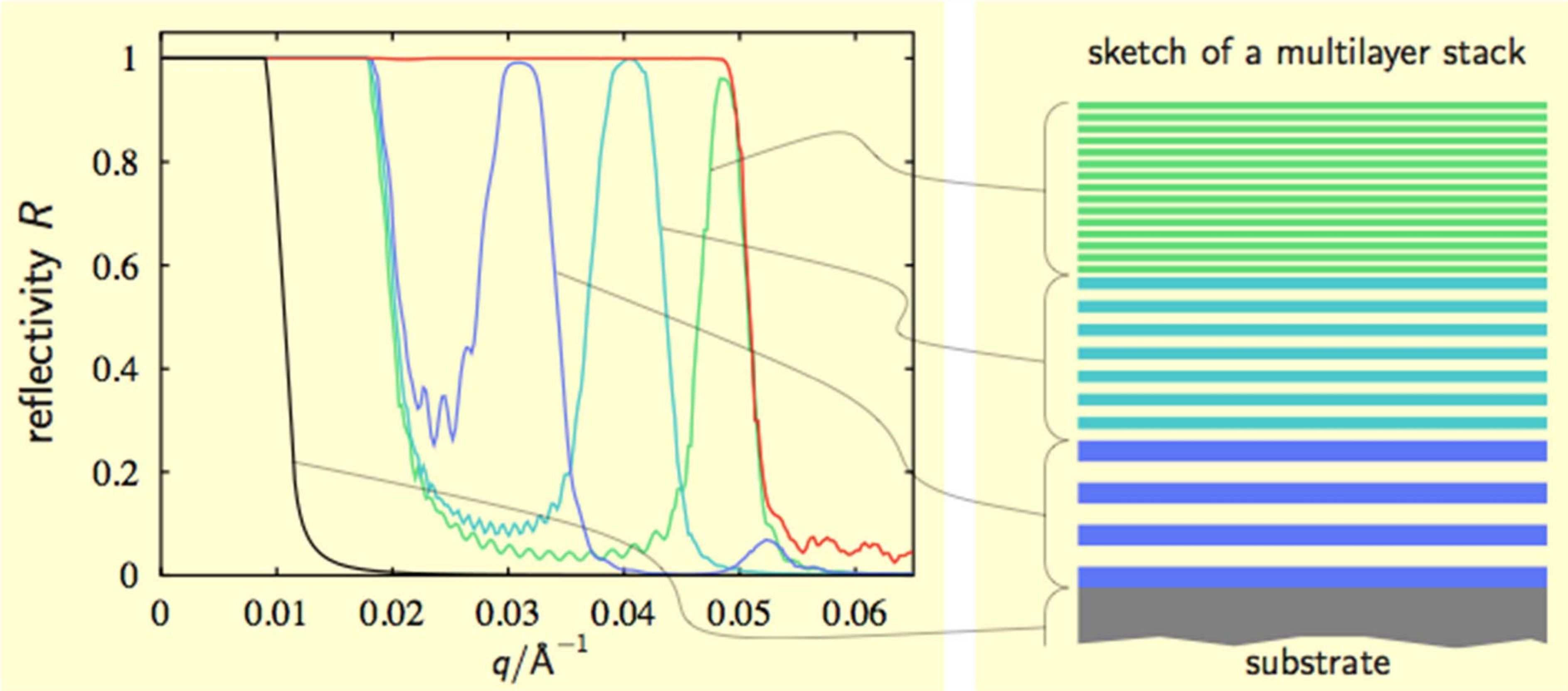
Courtesy of J. Stahn, PSI

Neutron Supermirrors



Courtesy of J. Stahn, PSI

Neutron Supermirrors

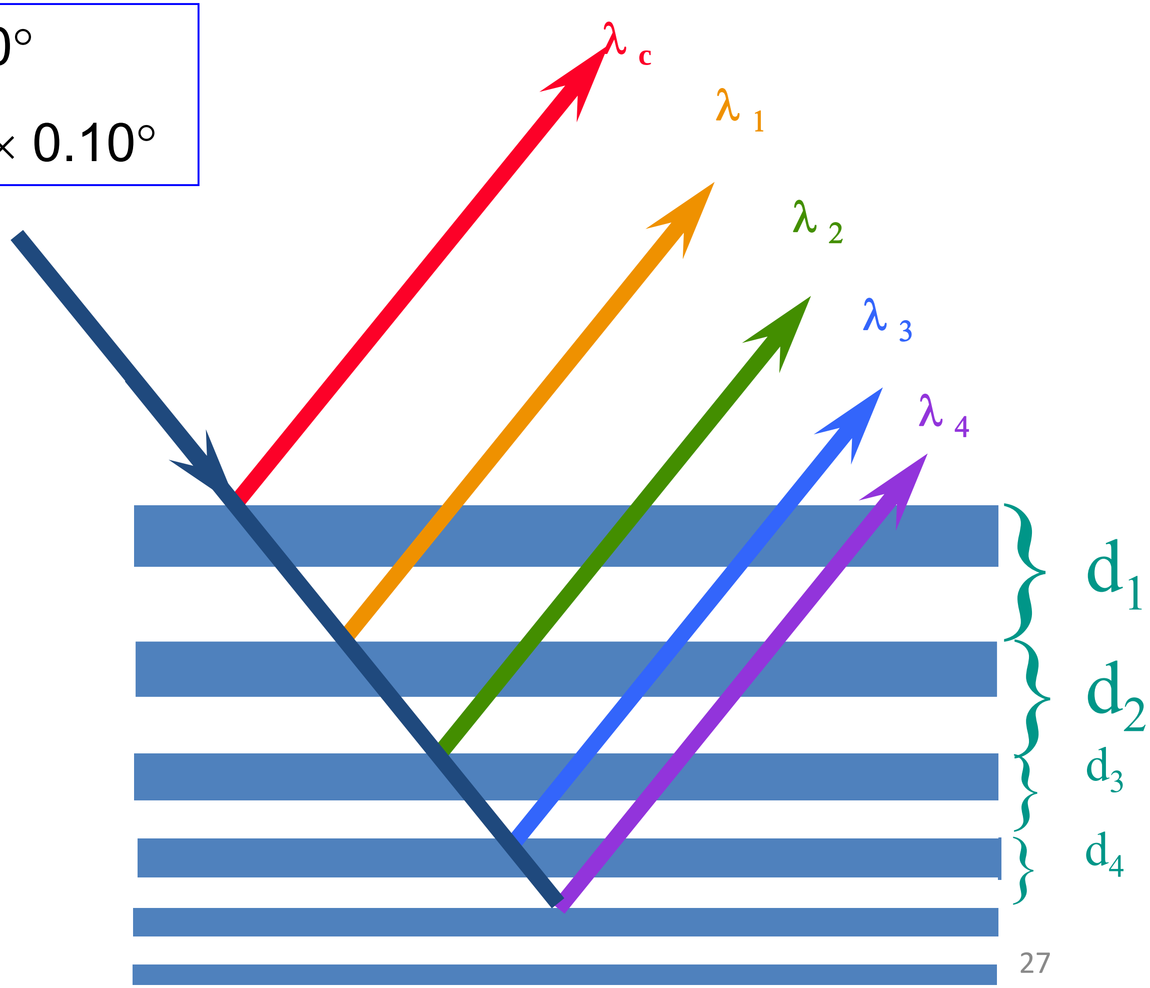


Courtesy of J. Stahn, PSI

Neutron Supermirrors

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

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

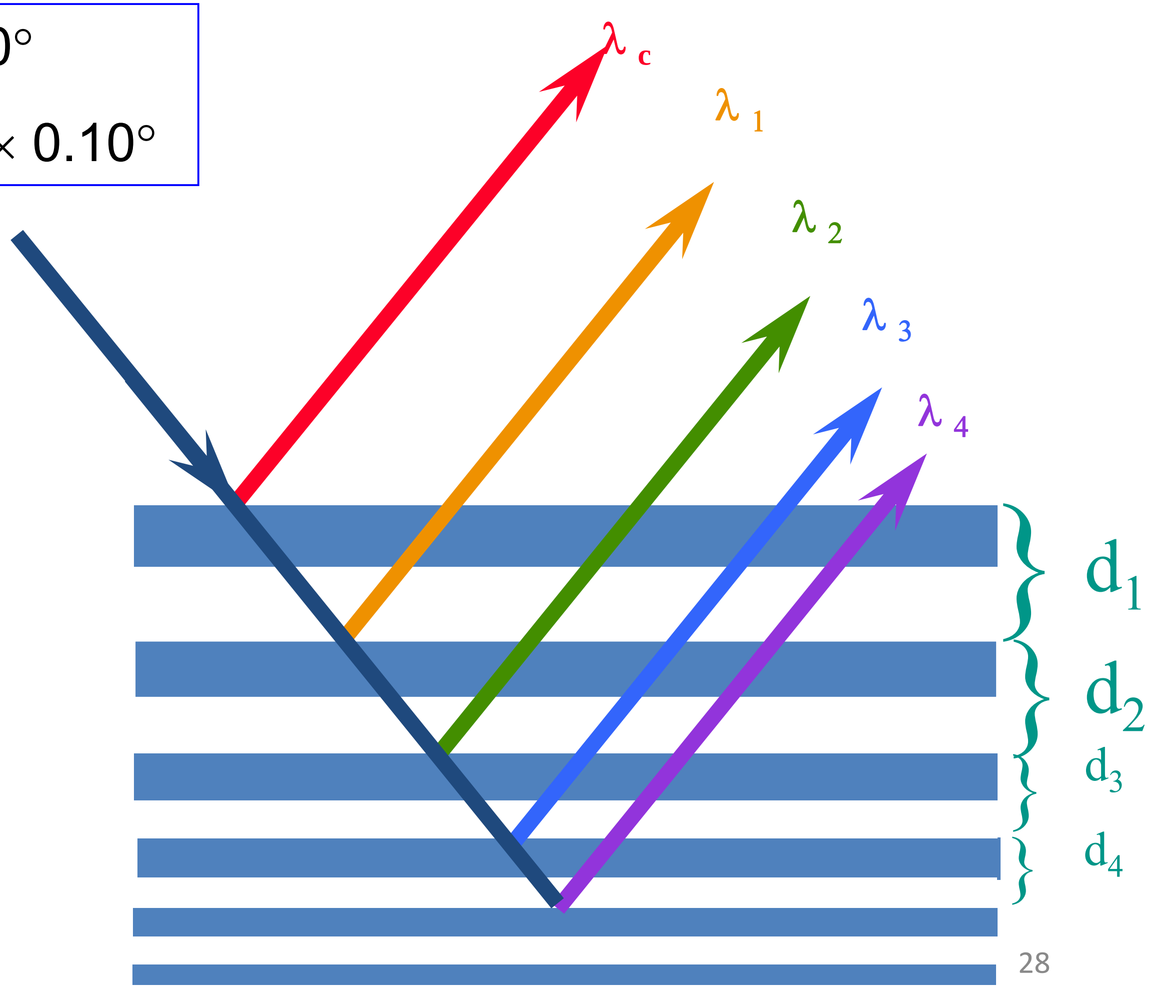


Neutron Supermirrors

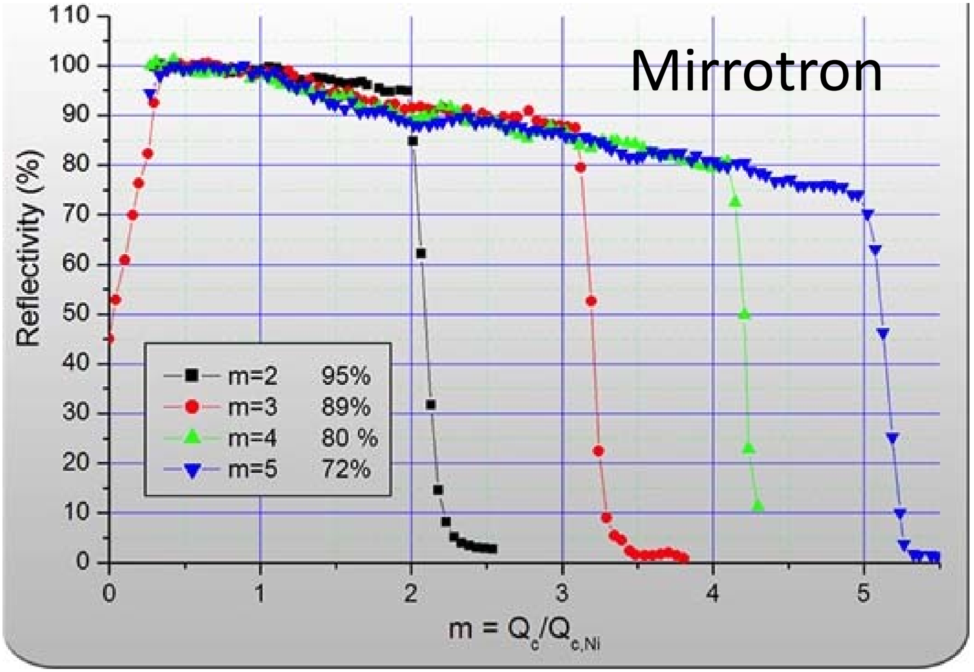
Reflection: $\theta_c(Ni) = \lambda[Å] \times 0.10°$

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

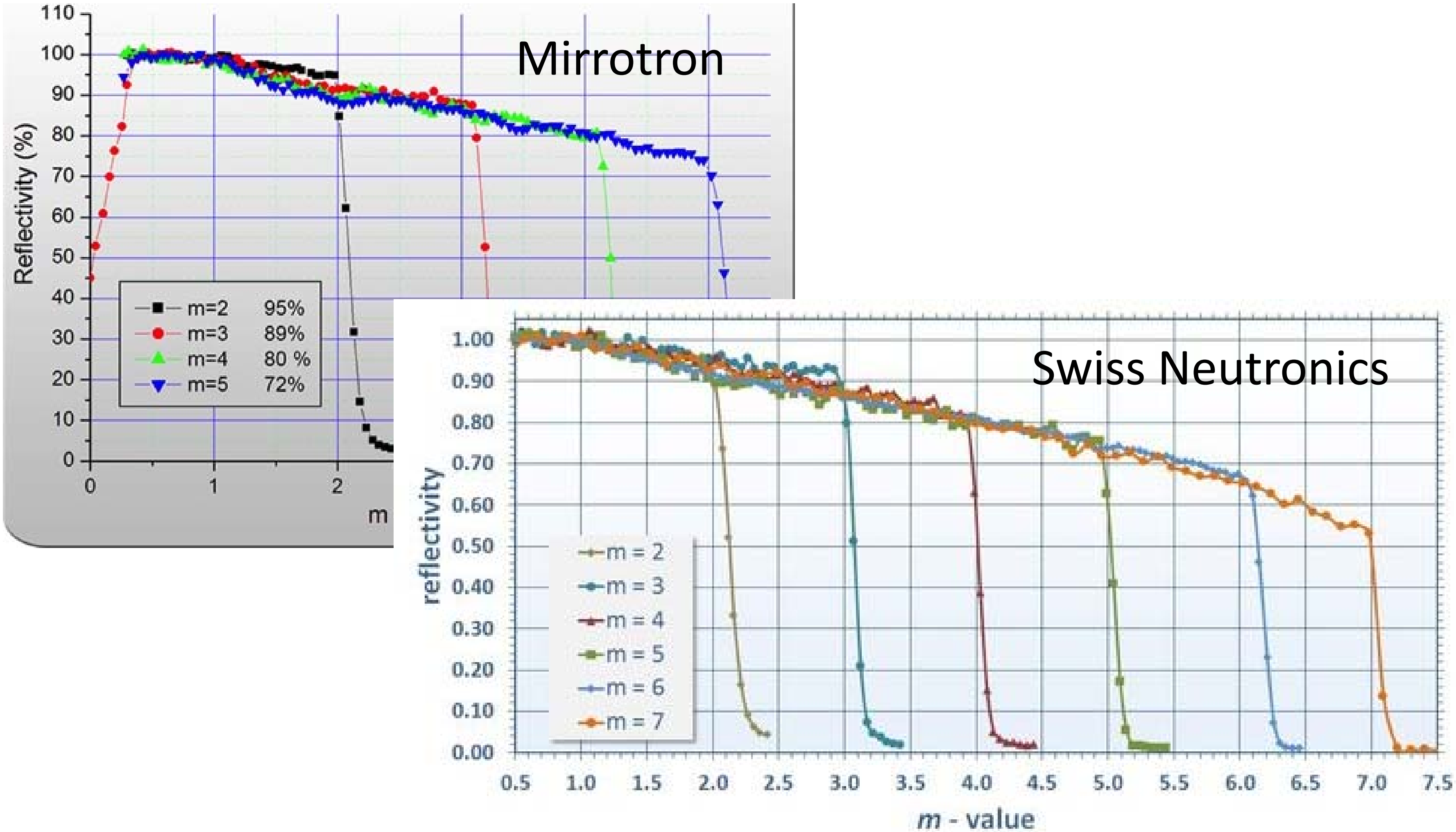
"m-number"
Supermirror critical angle



State-of-the-art Supermirrors



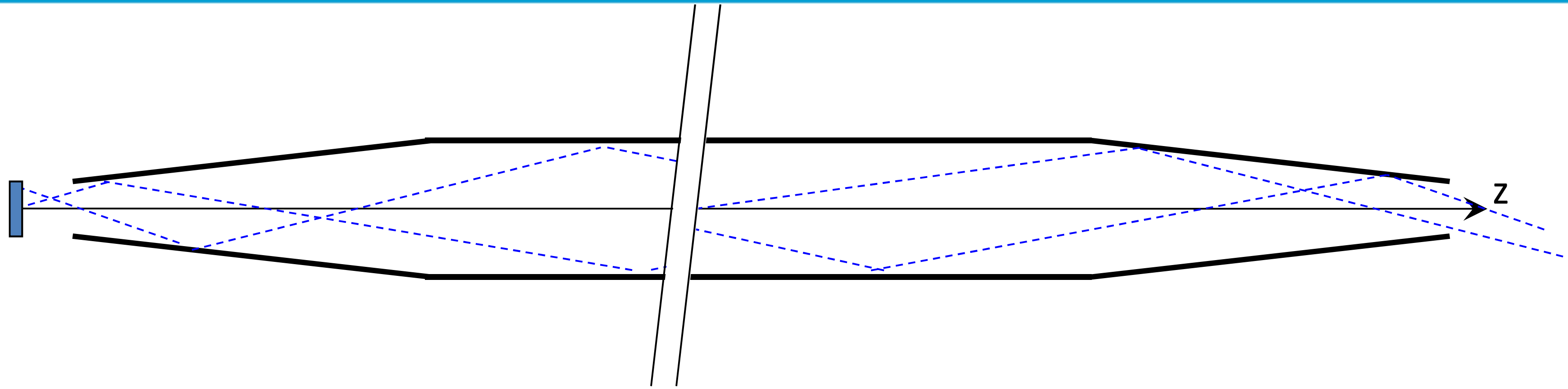
State-of-the-art Supermirrors



What are guides used for?

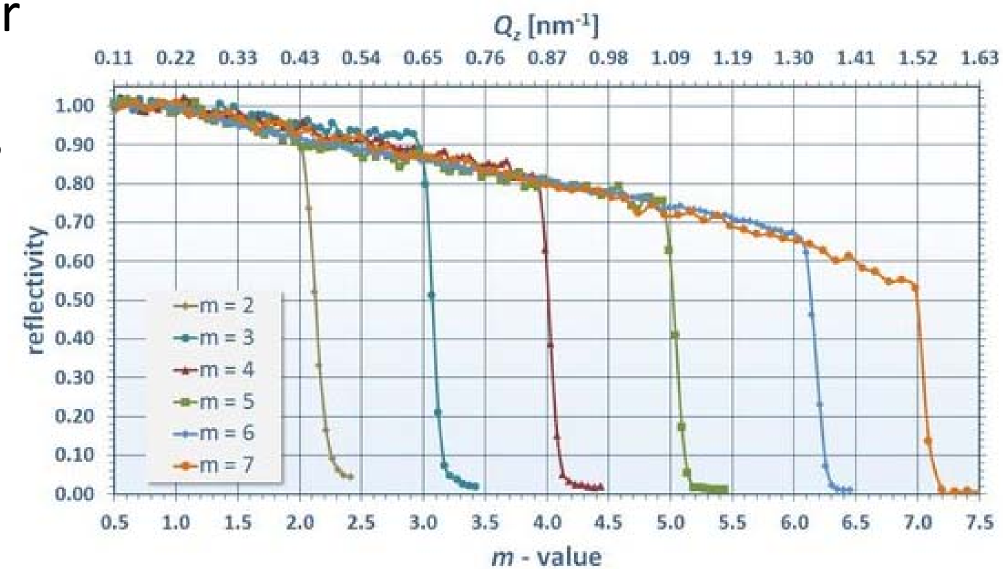
- Transport divergence
  - large m-numbers needed for short wavelengths
  - ballistic geometry required for supermirror guides
- Create space
  - build instruments far from neutron source
- Improve TOF resolution
- Reduce background
  - transport only “good” neutrons
- Focusing
  - increased divergence: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

Ballistic guides

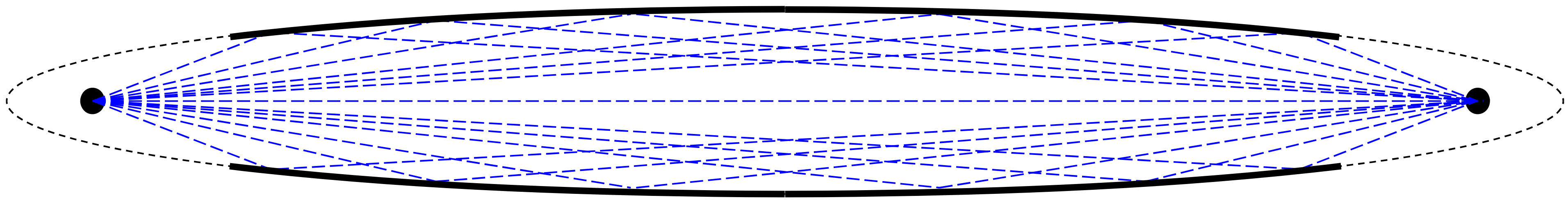


- Used to transport neutrons over long distances
- Minimise number of reflections
- Minimise reflection angles
- Increase width slowly to decrease divergence

  adiabaticity - reversible

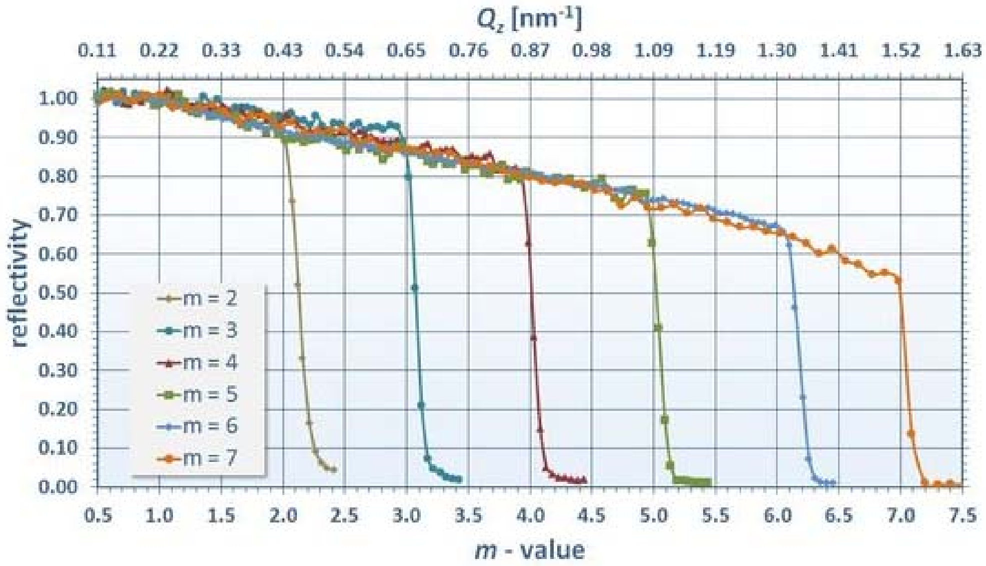


Ballistic guides



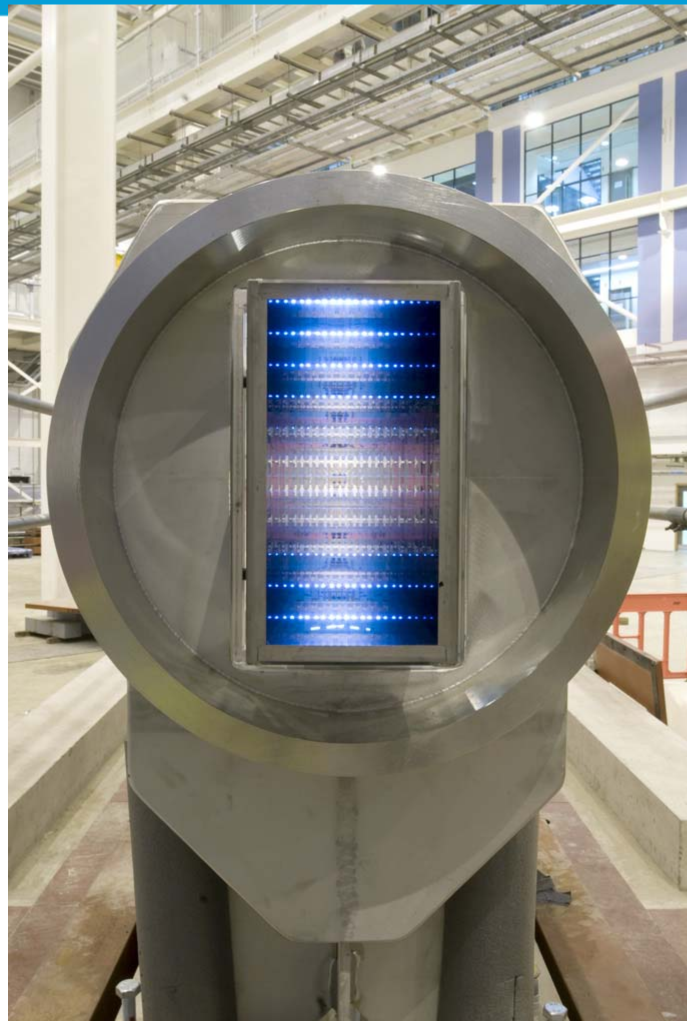
- Used to transport neutrons over long distances
- Minimise number of reflections
- Minimise reflection angles
- Increase width slowly to decrease divergence

adiabaticity - reversible

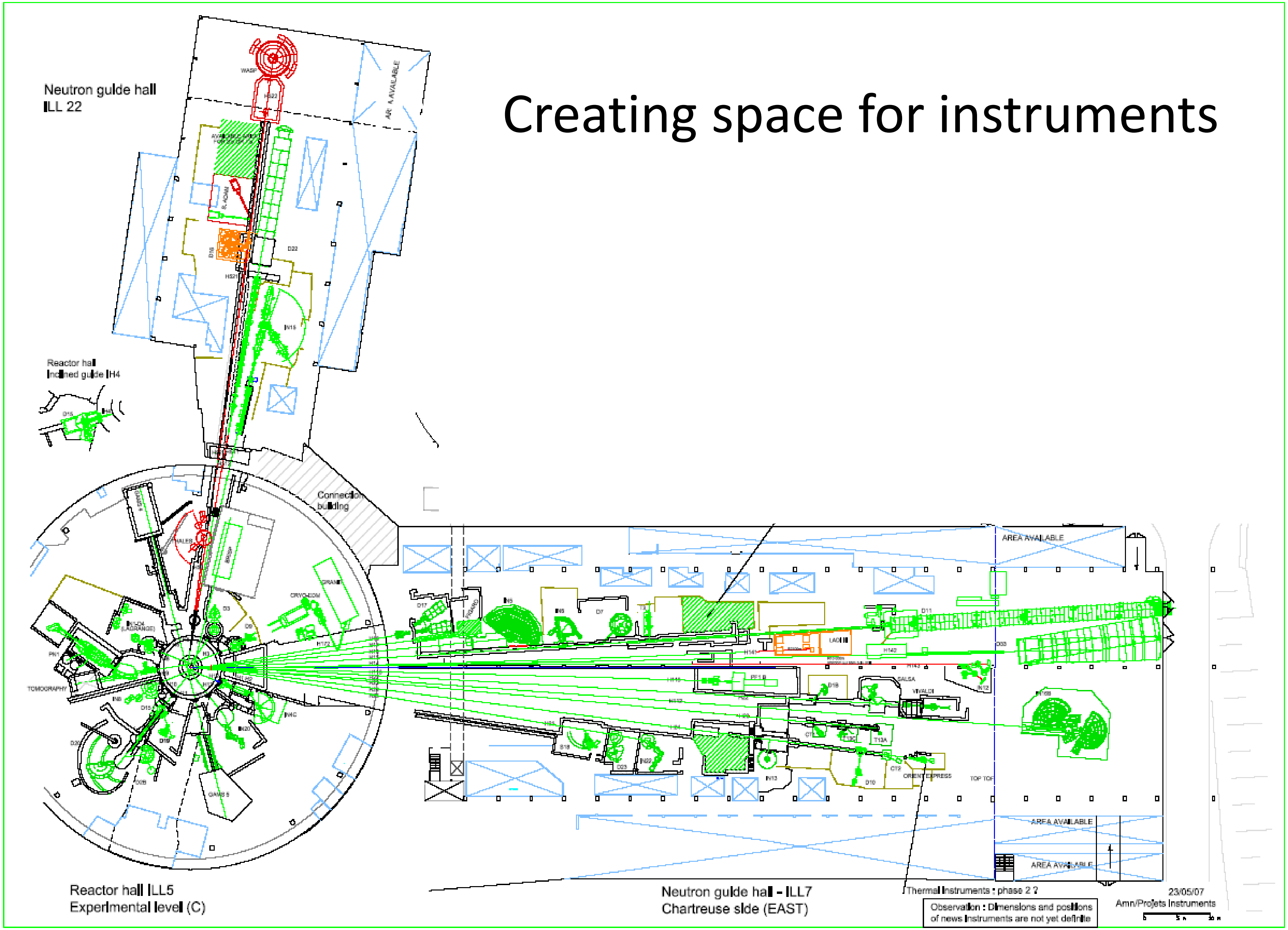


Ballistic guides

HRPD @ ISIS: ballistic (elliptical) guide

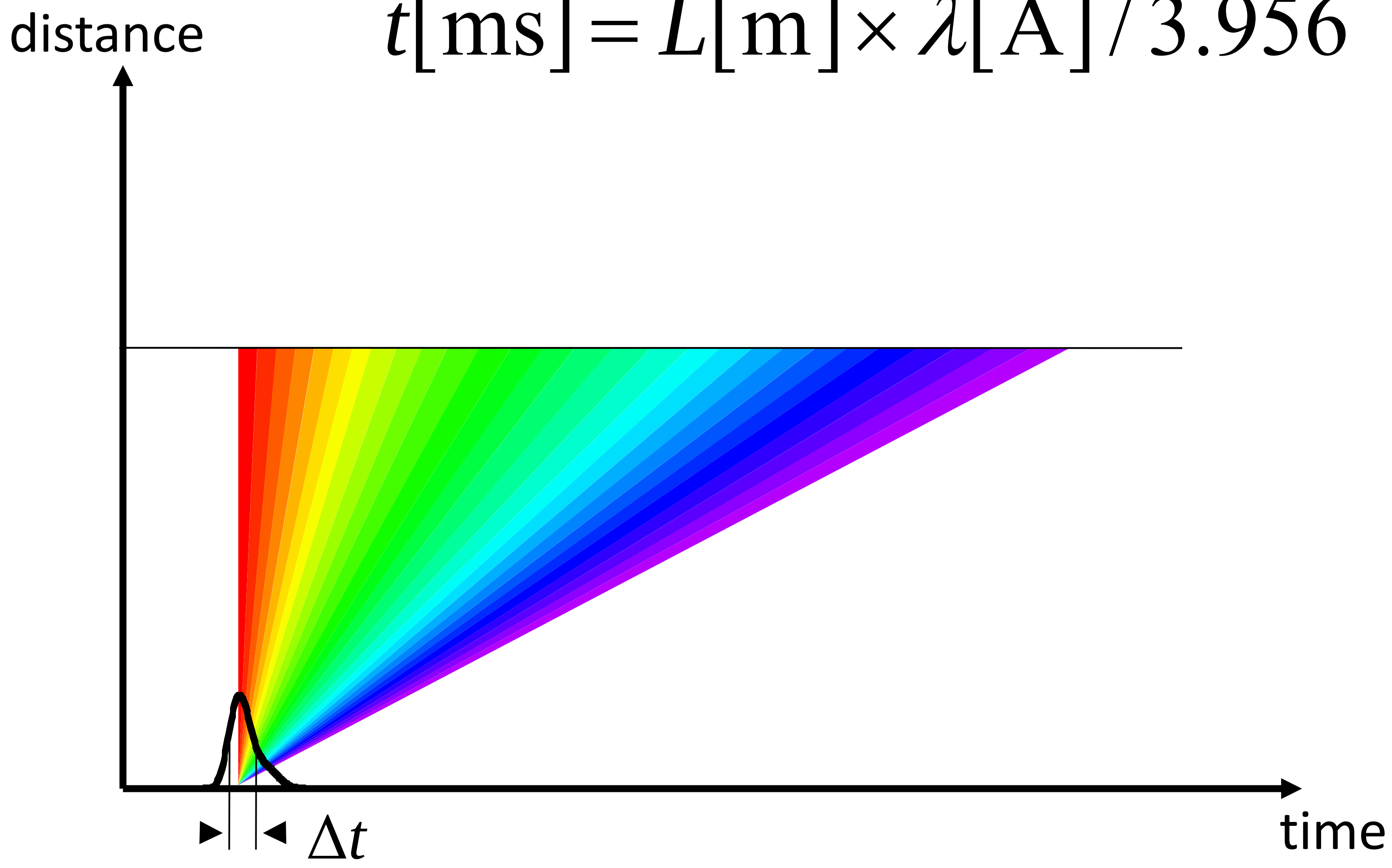


Creating space for instruments



Time-of-flight (TOF) resolution

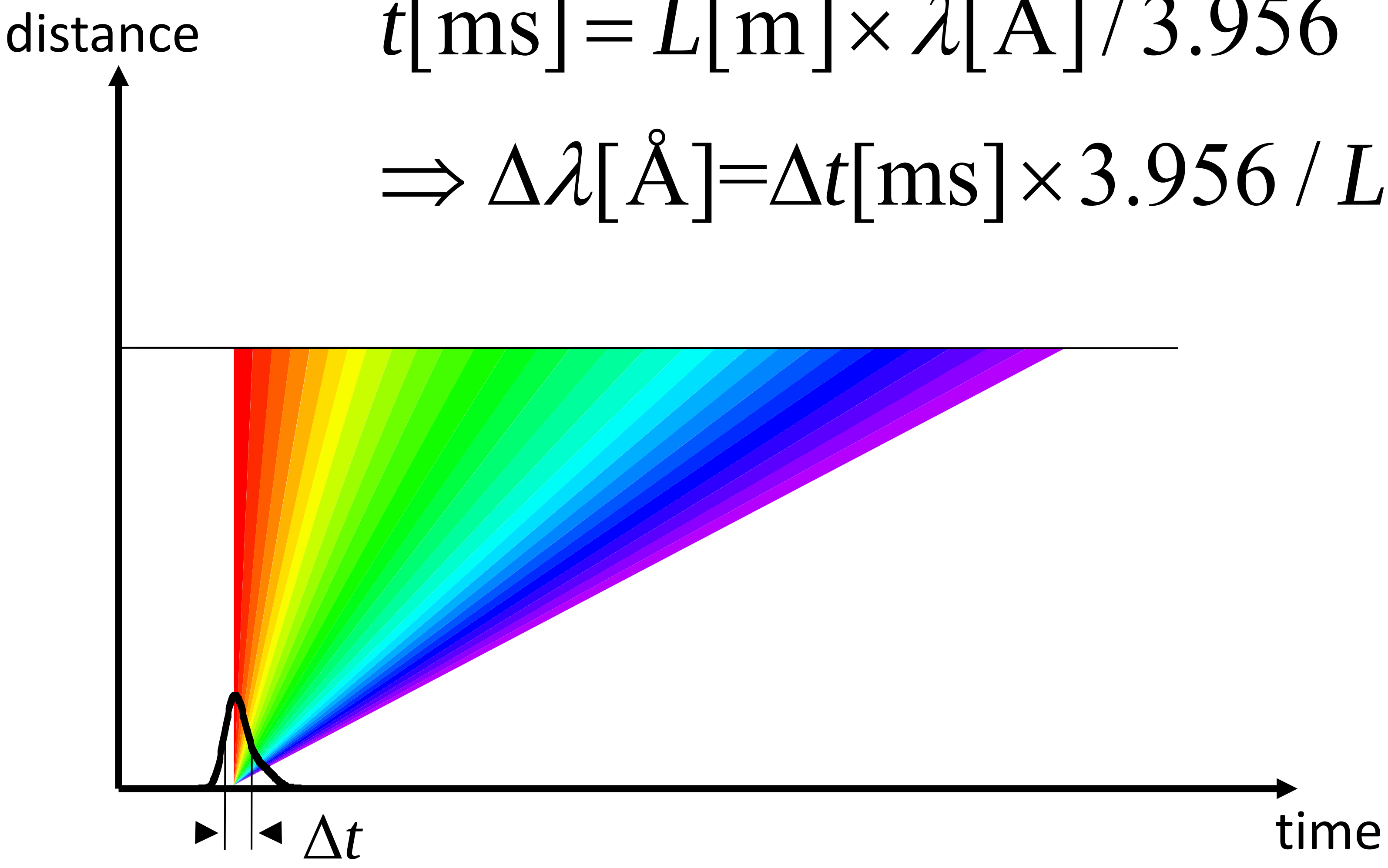
$$t[\text{ms}] = L[\text{m}] \times \lambda[\text{Å}] / 3.956$$



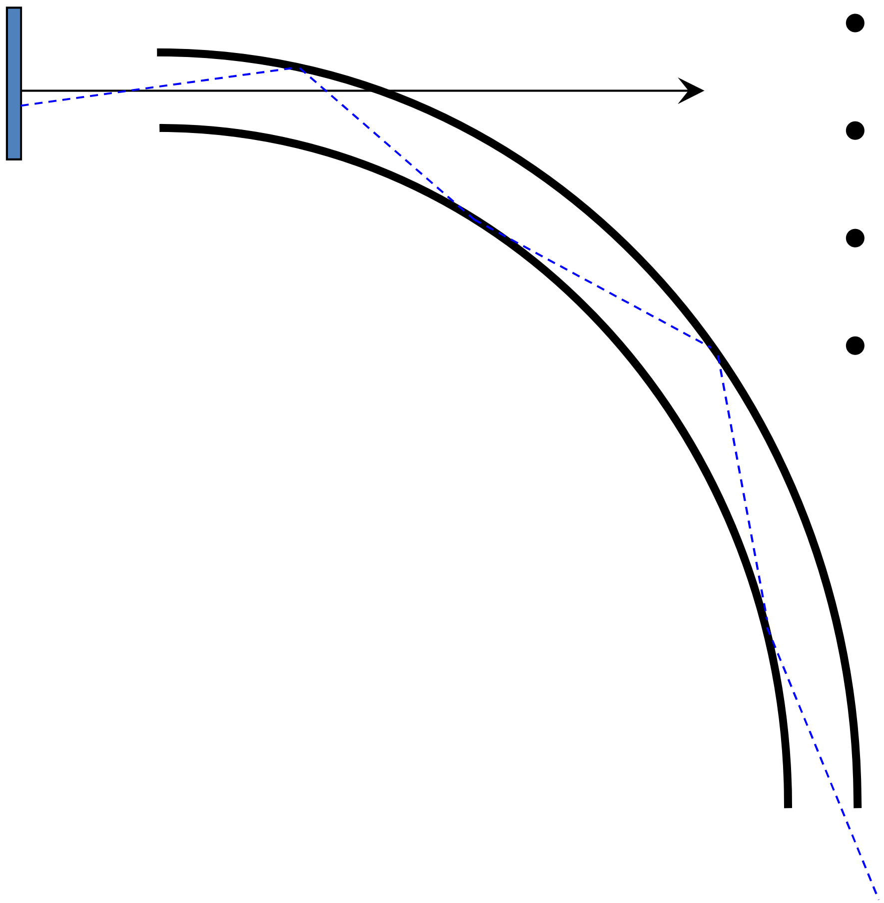
Time-of-flight (TOF) resolution

$$t[\mathrm{ms}] = L[\mathrm{m}] \times \lambda[\text{Å}] / 3.956$$

$$\Rightarrow \Delta\lambda[\text{Å}] = \Delta t[\mathrm{ms}] \times 3.956 / L[\mathrm{m}]$$

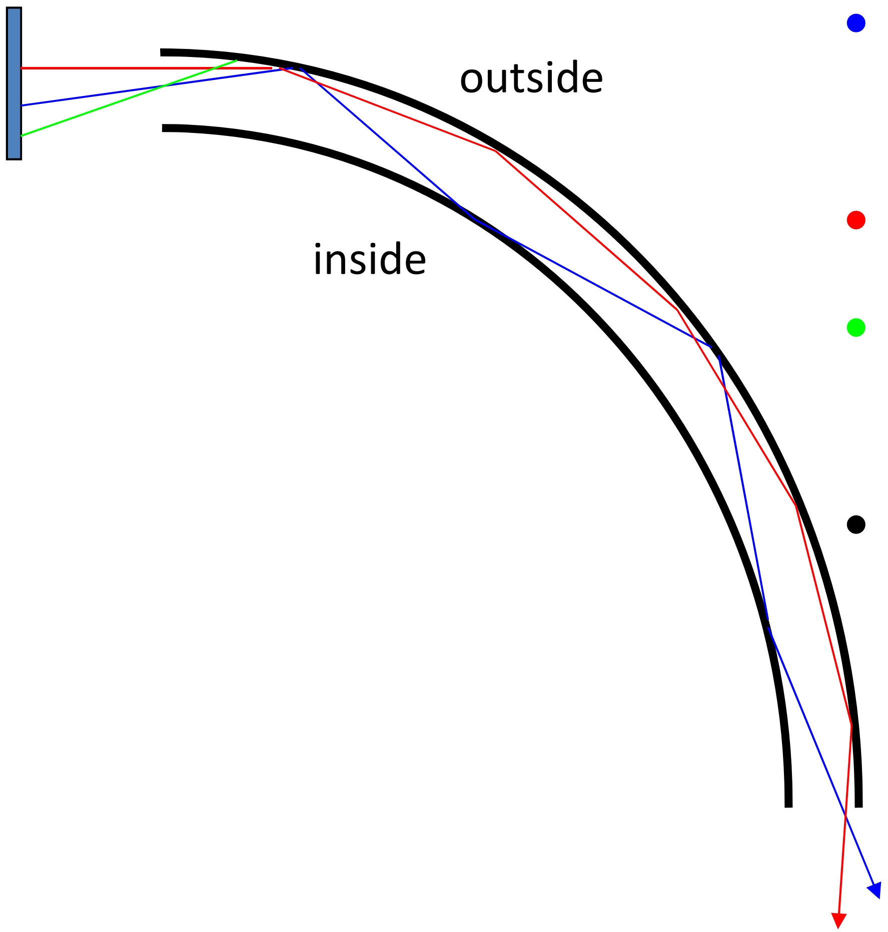


Curved Guides



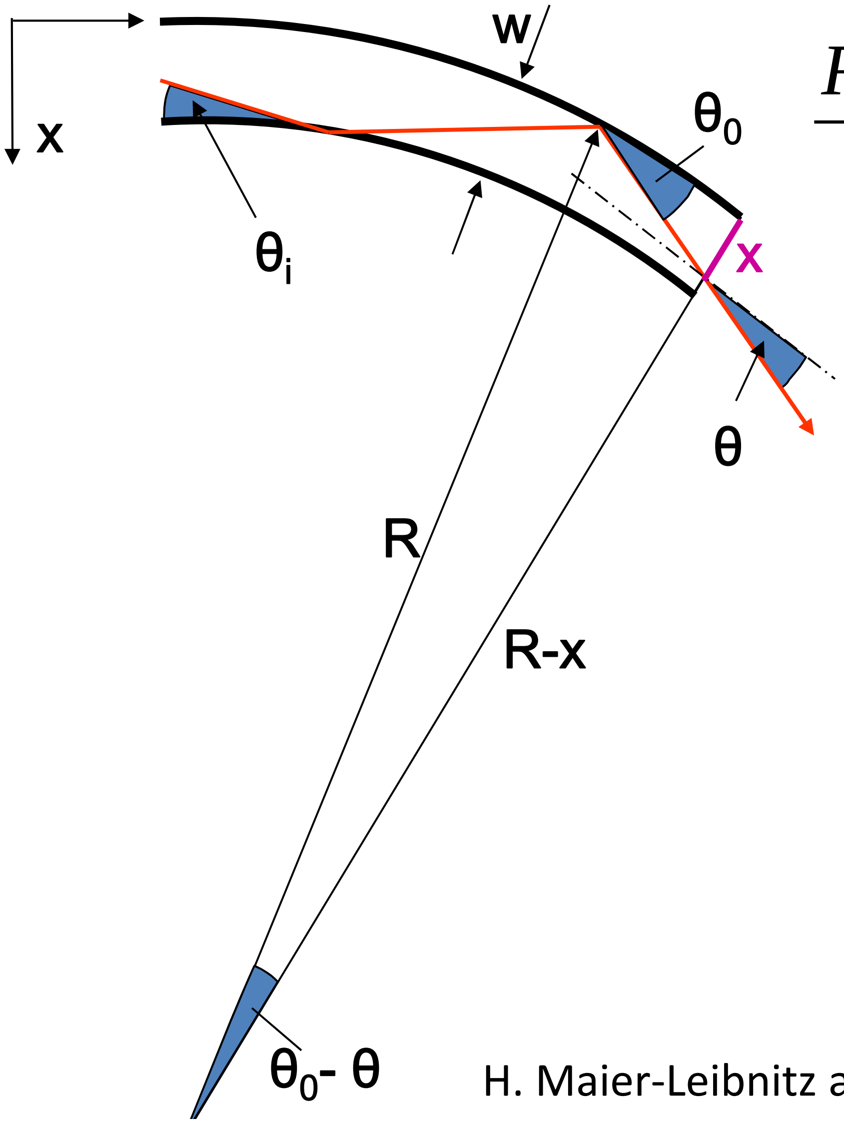
- Avoid direct line-of-sight
- Avoid gammas
- Avoid fast neutrons
- Reduce background

Curved Guides



- Blue – reflecting from both sides
- Red – garland reflections
- Green – exceeds critical angle
- Fewer neutrons along inside face - quantify

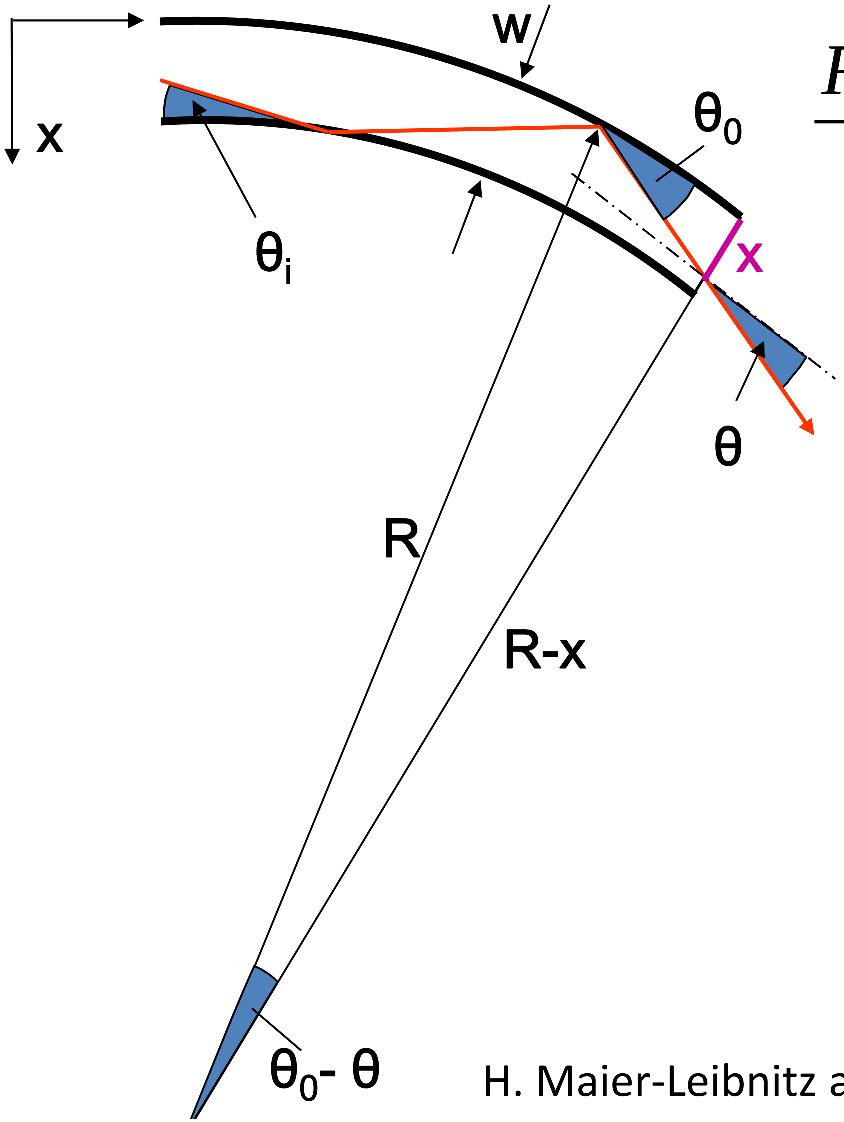
Curved Guides



$$\frac{R-x}{R} = \frac{\cos\theta_0}{\cos\theta}$$

H. Maier-Leibnitz and T. Springer, React. Sci. Technol. 17, 217 (1963)

Curved Guides



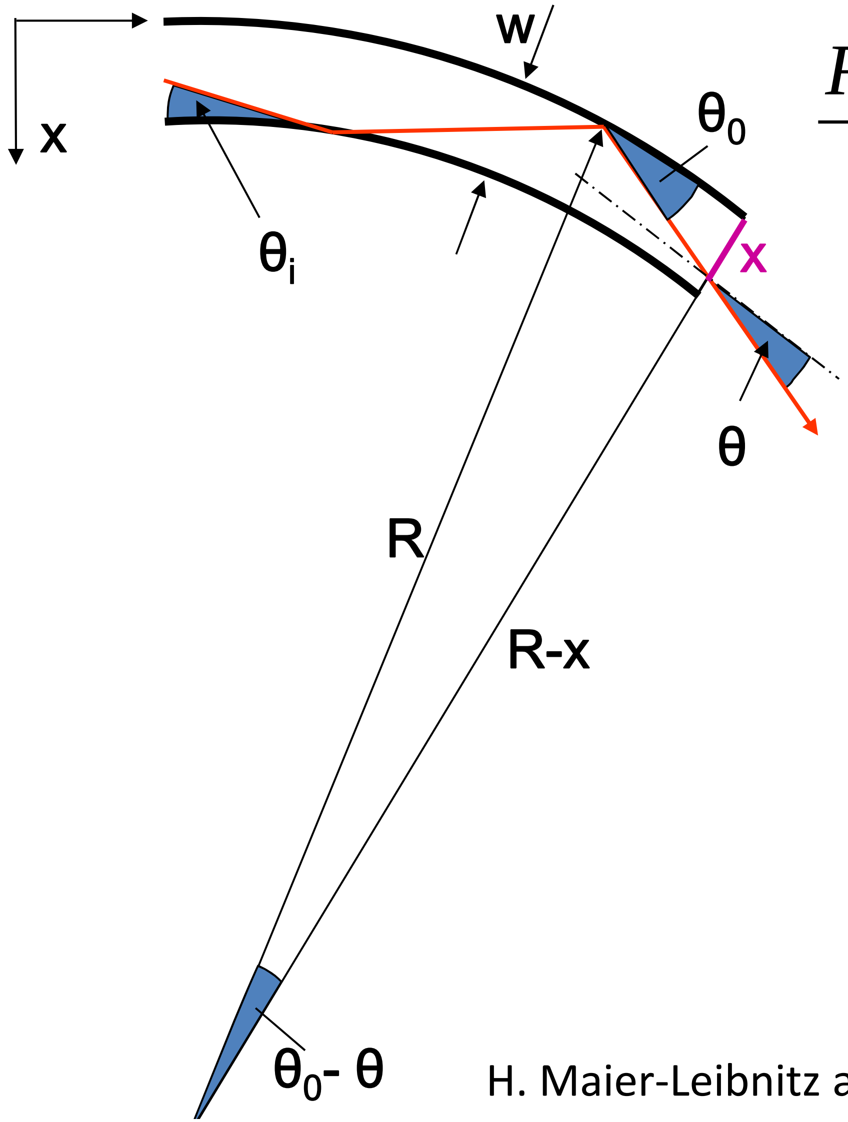
$$\frac{R - x}{R} = \frac{\cos\theta_0}{\cos\theta}$$

For $\theta_0, \theta << 1$,

$$x = -\tfrac{1}{2} R(\theta^2 - \theta_0^2)$$

H. Maier-Leibnitz and T. Springer, React. Sci. Technol. 17, 217 (1963)

Curved Guides



$$\frac{R-x}{R} = \frac{\cos\theta_0}{\cos\theta}$$

For $\theta_0, \theta << 1,$

$$x = -\tfrac{1}{2} R(\theta^2 - \theta_0^2)$$

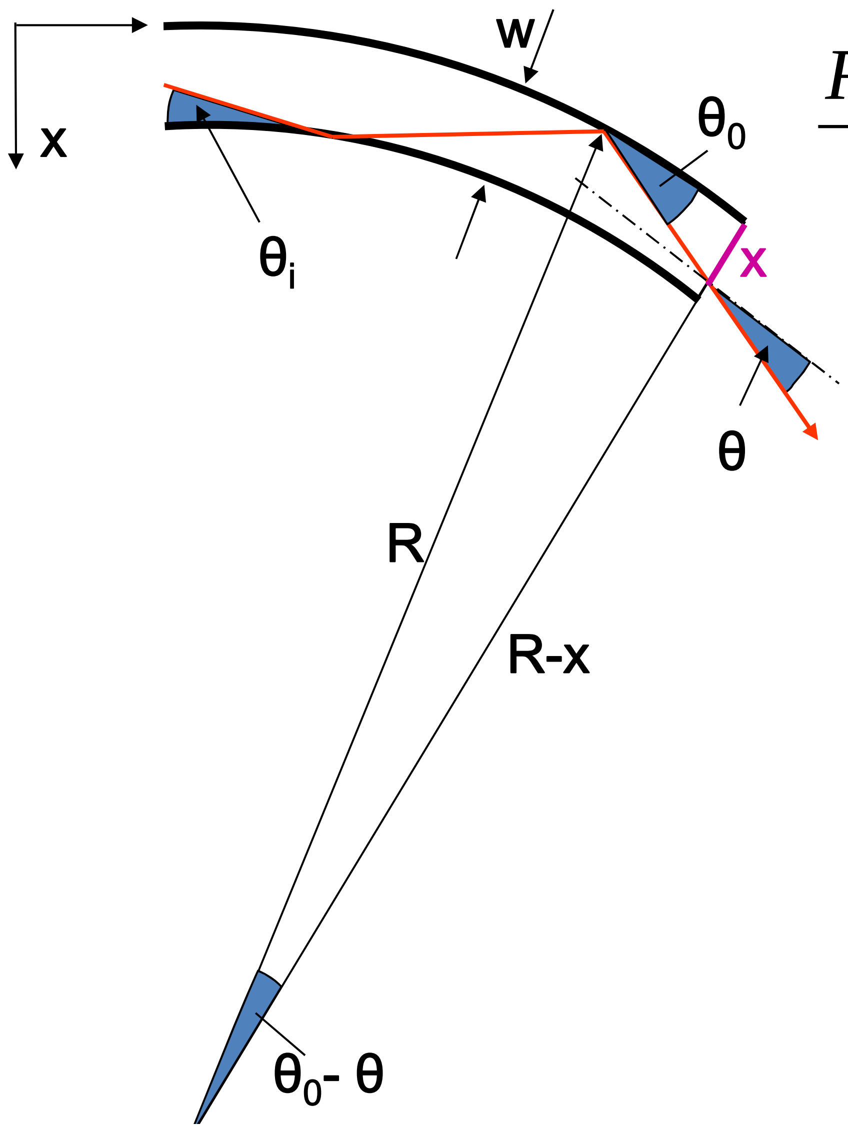
neutrons “just” reach inside face

when θ = 0 for x = w :

$$\theta_0^* = \sqrt{2w/R}$$

H. Maier-Leibnitz and T. Springer, React. Sci. Technol. 17, 217 (1963)

Curved Guides



$$\frac{R-x}{R} = \frac{\cos\theta_0}{\cos\theta}$$

For $\theta_0, \theta << 1$,

$$x = -\tfrac{1}{2}R(\theta^2 - \theta_0^2)$$

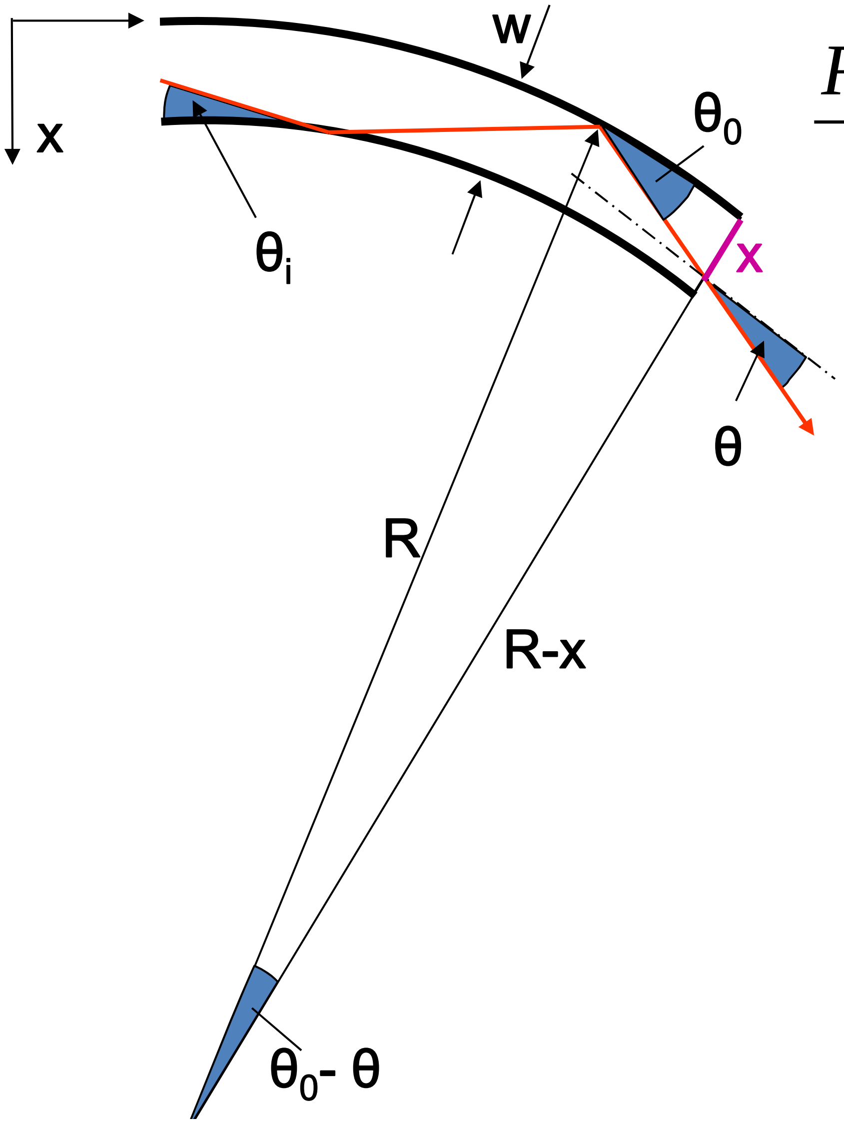
neutrons "just" reach inside face

when θ = 0 for x = w :

$$\theta_0^* = \sqrt{2w/R}$$

$$\theta_c = m \times \lambda[\text{Å}] \times 0.1^\circ$$

Curved Guides



$$\frac{R-x}{R} = \frac{\cos\theta_0}{\cos\theta}$$

For $\theta_0, \theta << 1,$

$$x = -\tfrac{1}{2} R(\theta^2 - \theta_0^2)$$

neutrons "just" reach inside face

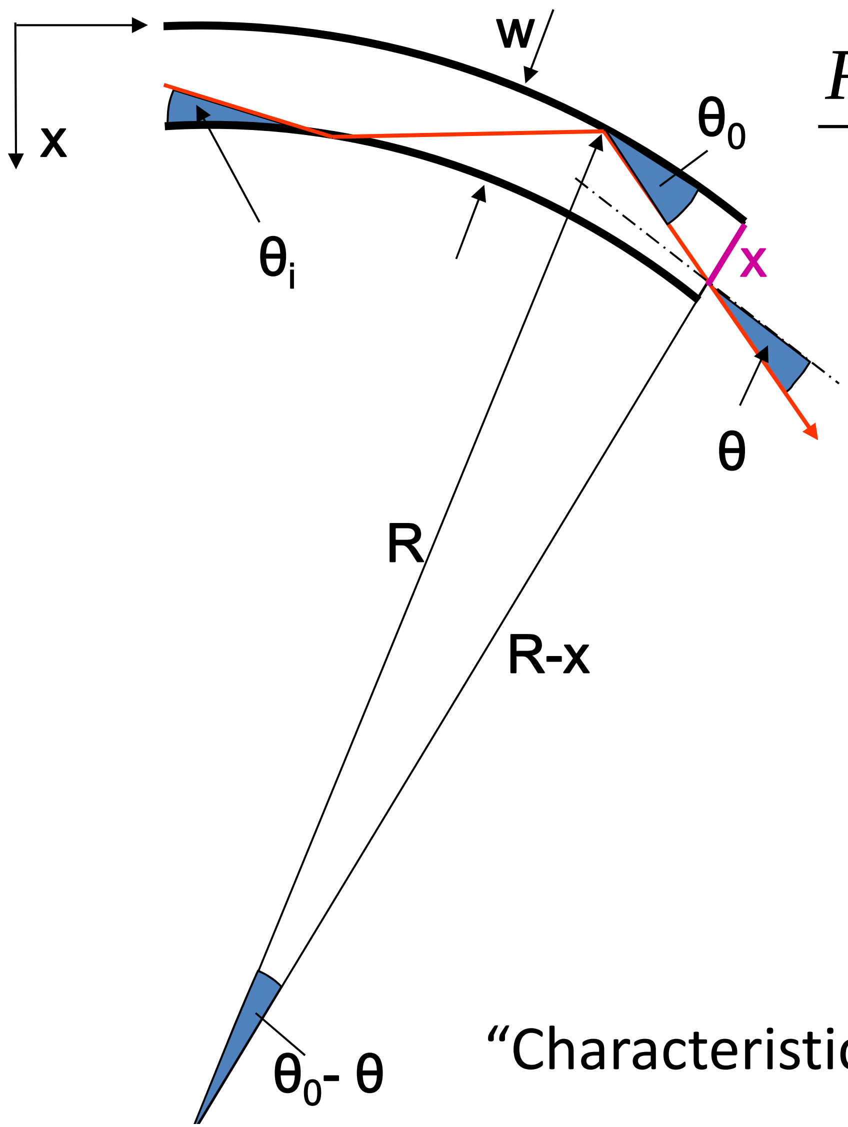
when θ = 0 for x = w :

$$\theta_0^* = \sqrt{2w/R}$$

$$\theta_c = m \times \lambda[\text{Å}] \times 0.1^\circ$$

$$\theta_c = \theta_0^* \Rightarrow \lambda^* = \frac{575}{m}\sqrt{2w/R}$$

Curved Guides



$$\frac{R-x}{R} = \frac{\cos\theta_0}{\cos\theta}$$

For $\theta_0, \theta << 1$,

$$x = -\tfrac{1}{2}R(\theta^2 - \theta_0^2)$$

neutrons “just” reach inside face

when θ = 0 for x = w :

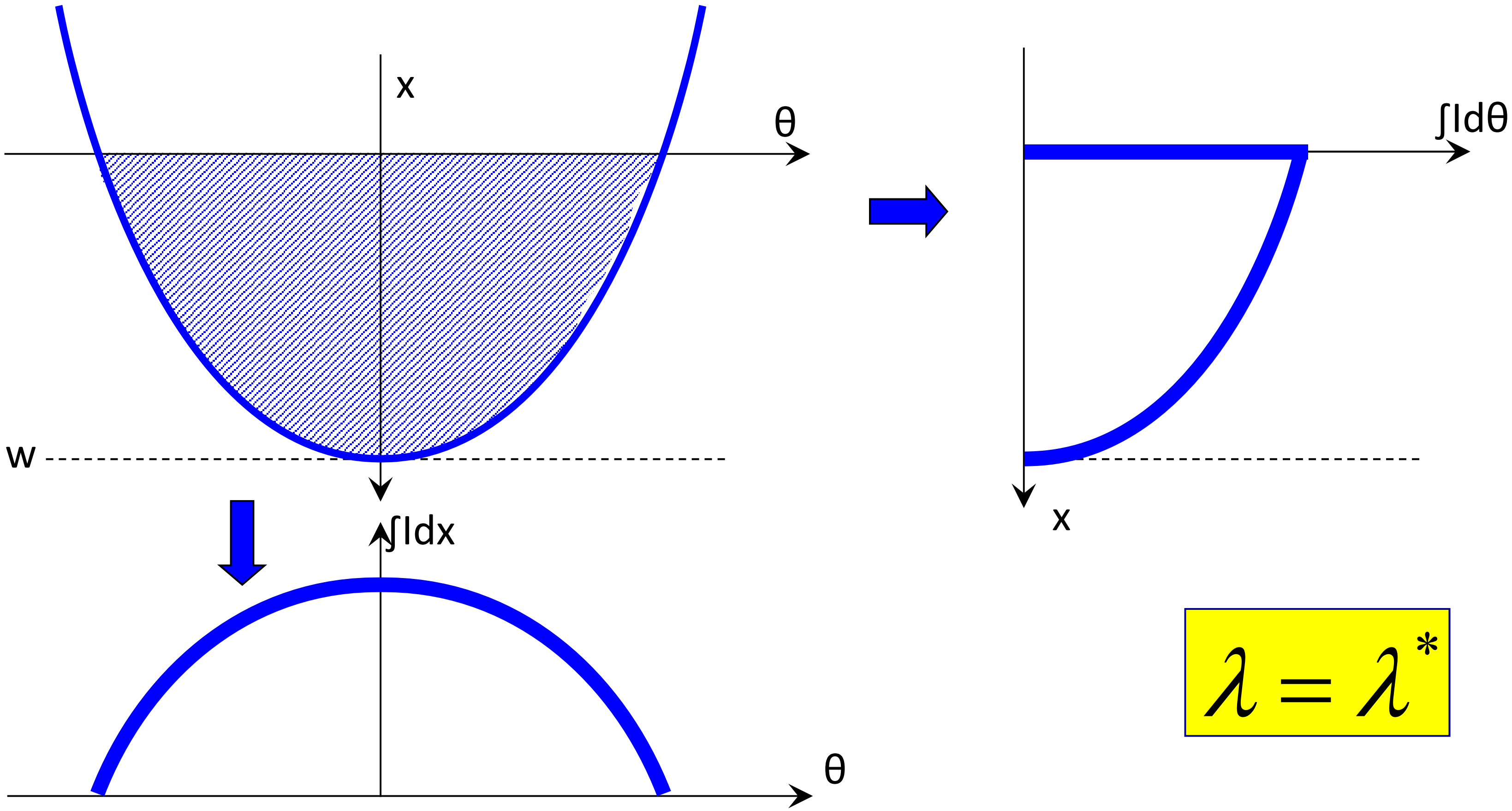
$$\theta_0^* = \sqrt{2w/R}$$

$$\theta_c = m \times \lambda[\text{Å}] \times 0.1^\circ$$

$$\theta_c = \theta_0^* \Rightarrow \lambda^* = \frac{575}{m}\sqrt{2w/R}$$

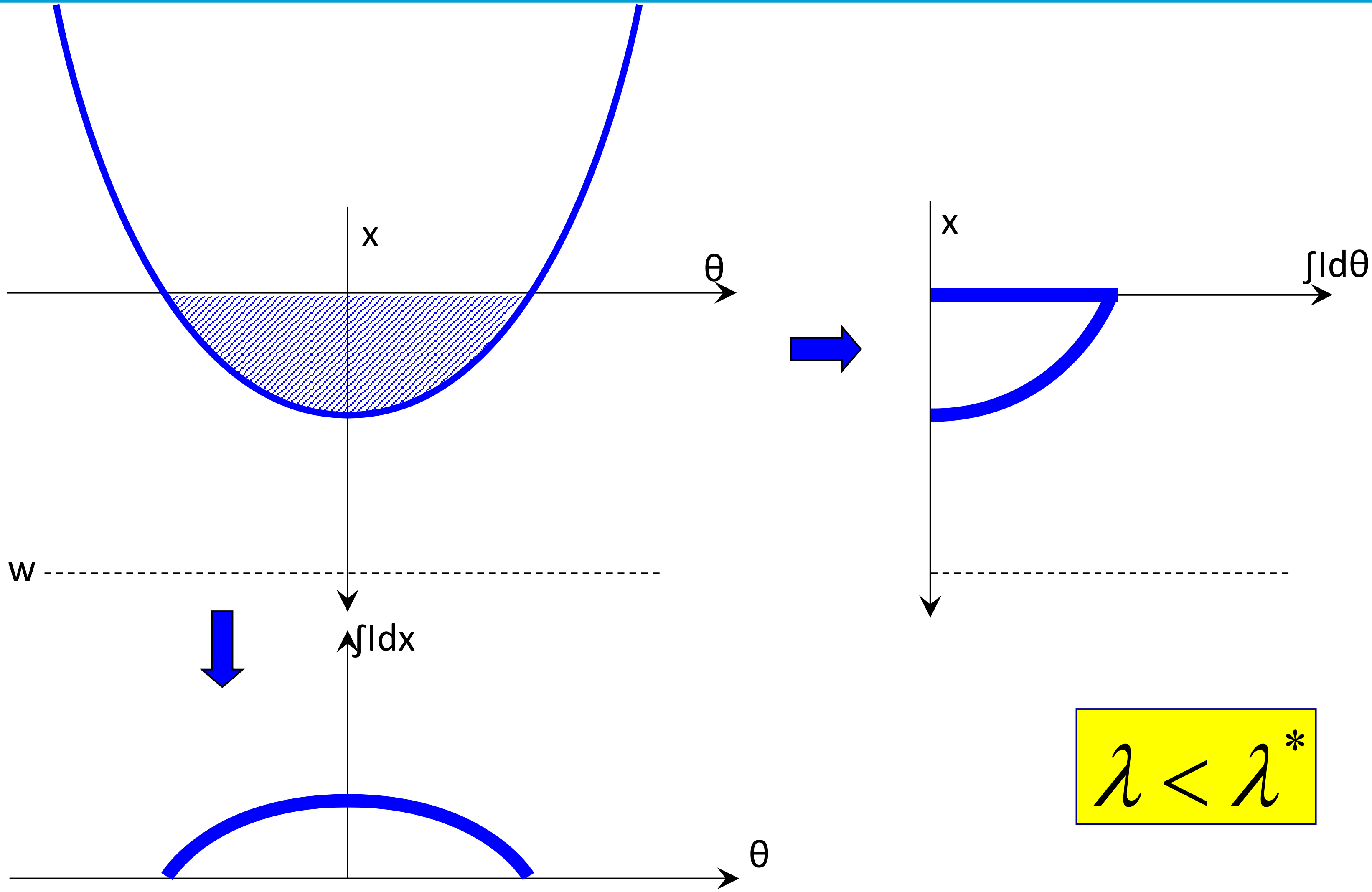
“Characteristic wavelength”

Curved Guides



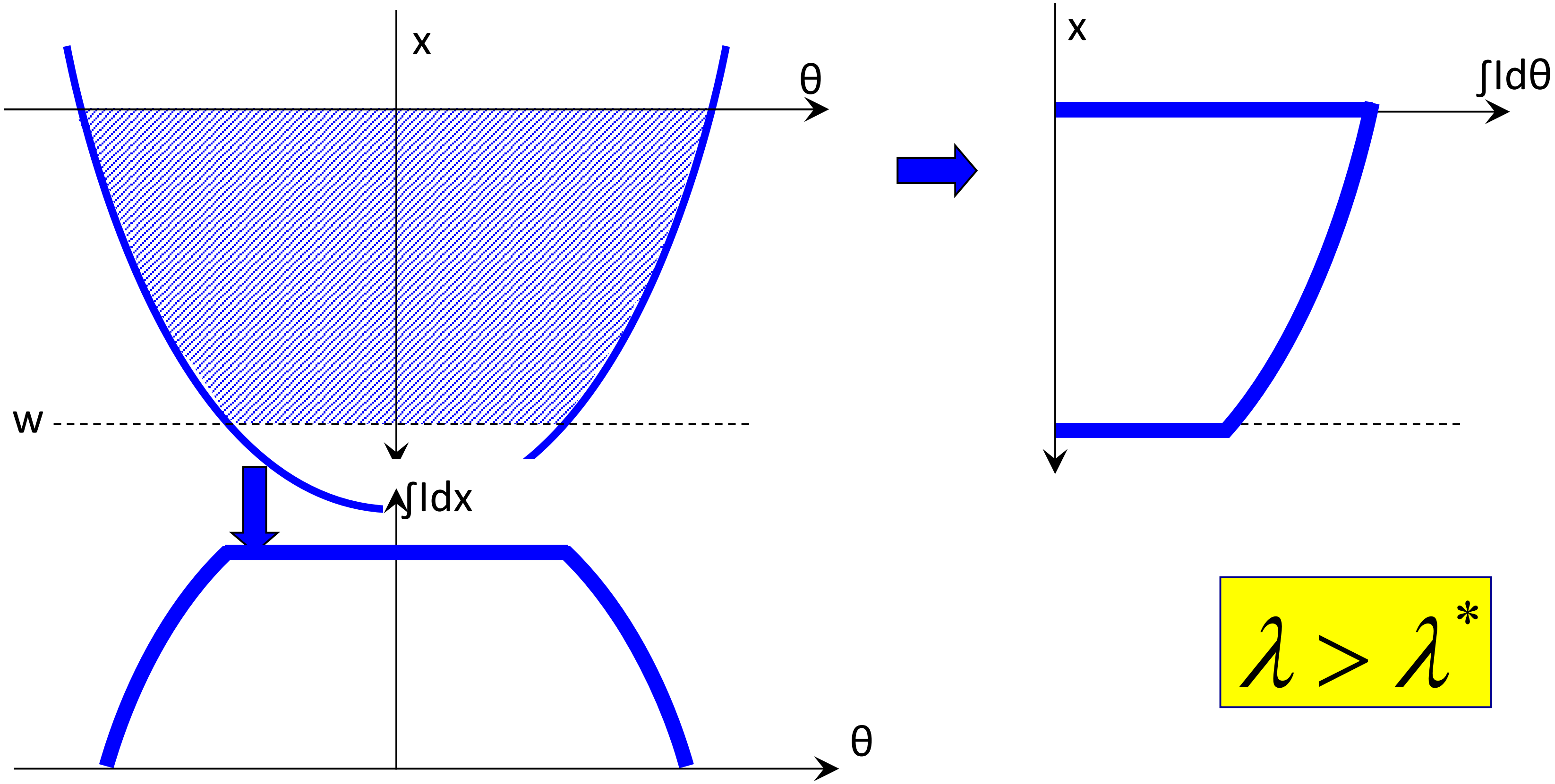
$$\lambda = \lambda^*$$

Curved Guides



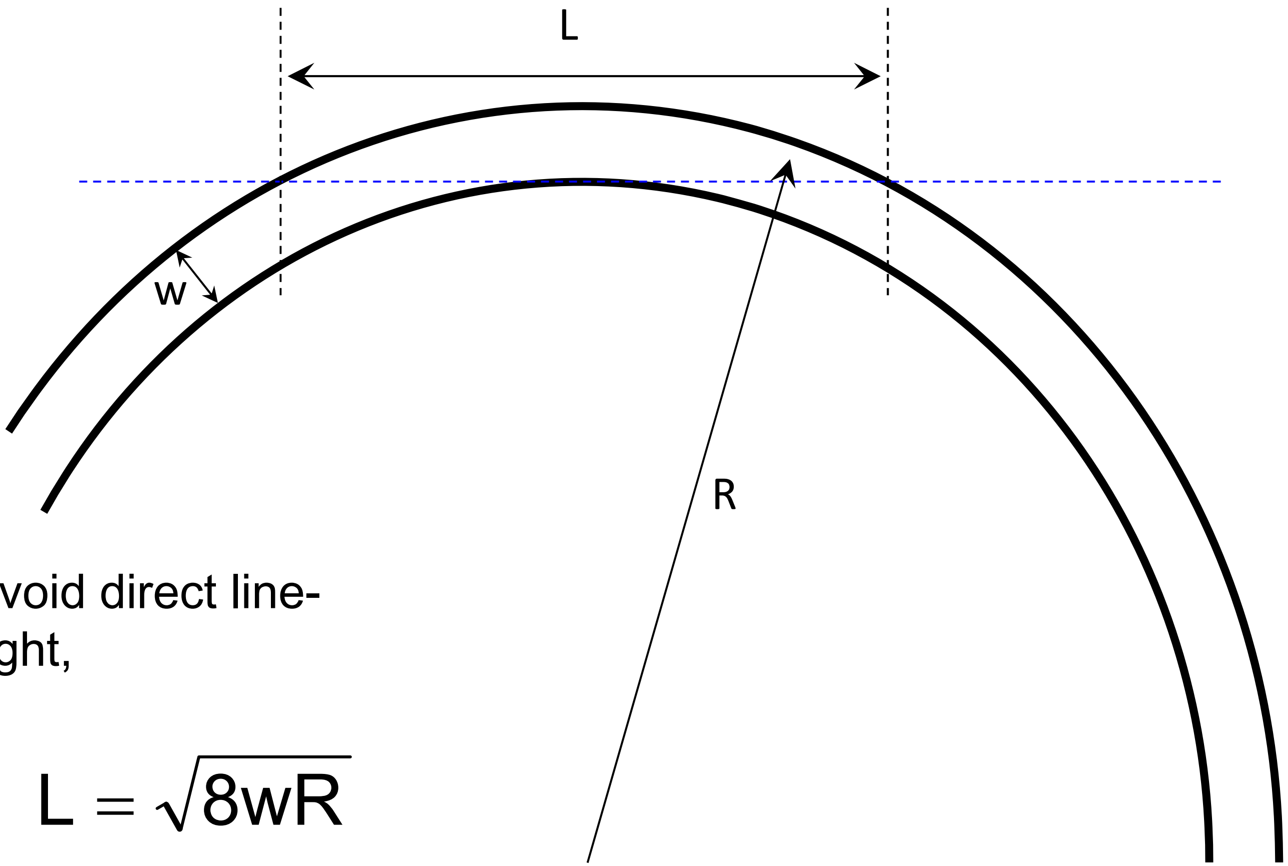
$$\lambda < \lambda^*$$

Curved Guides



$$\lambda > \lambda^*$$

Curved Guides

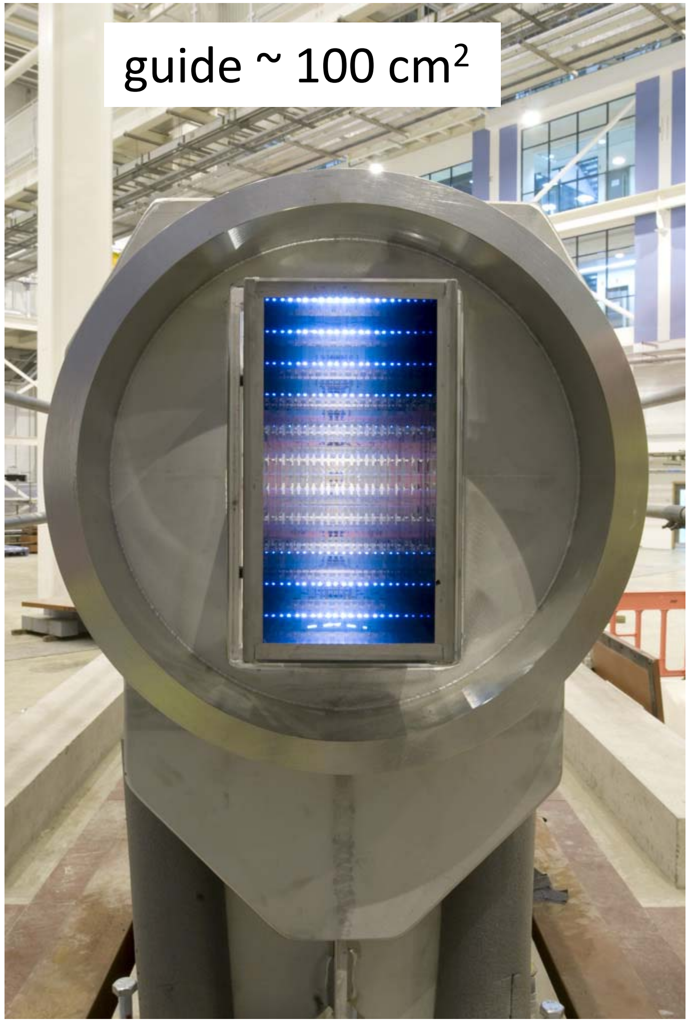


To avoid direct line-of-sight,

$$L = \sqrt{8wR}$$

Focusing

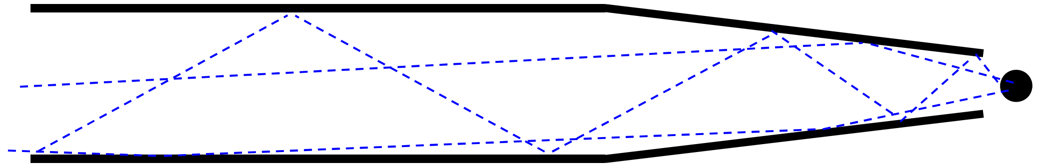
guide ~ 100 cm^2



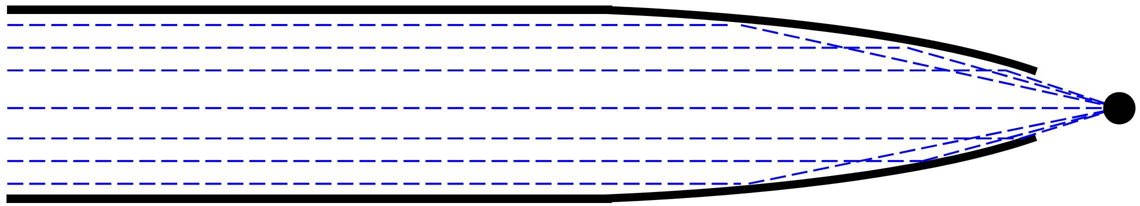
samples < 1 cm^2

Focusing

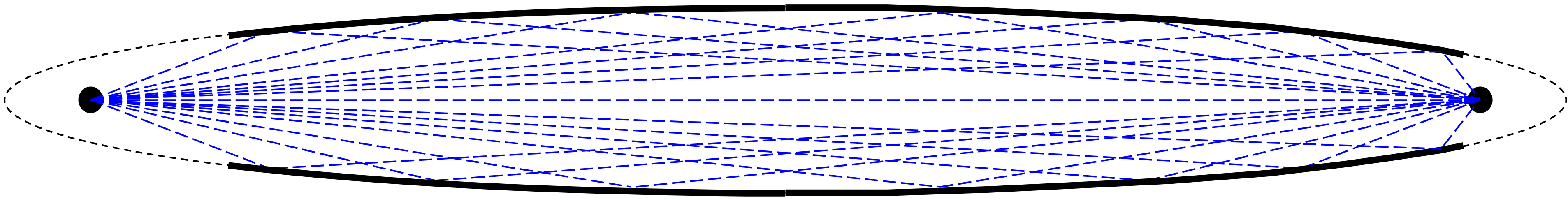
Linear tapering



Parabolic

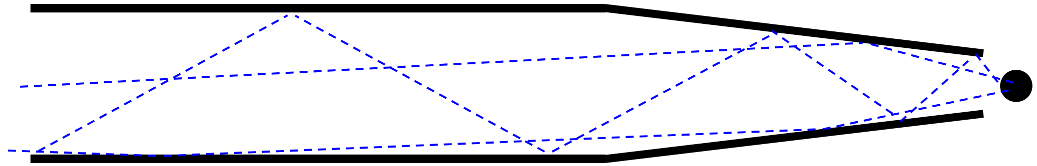


Elliptic

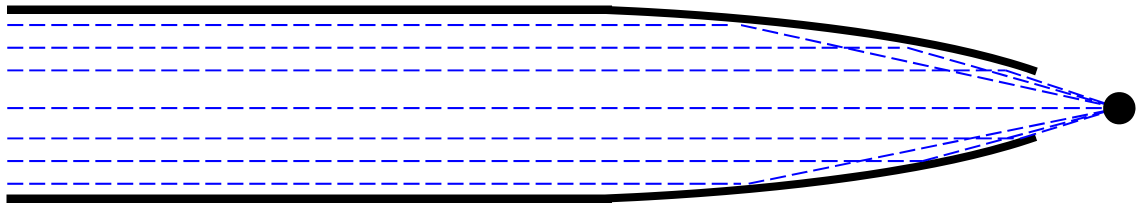


Focusing

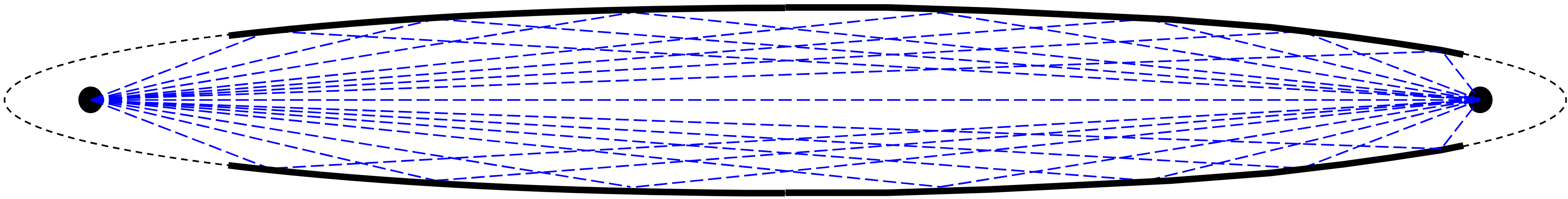
Linear tapering



Parabolic



Elliptic



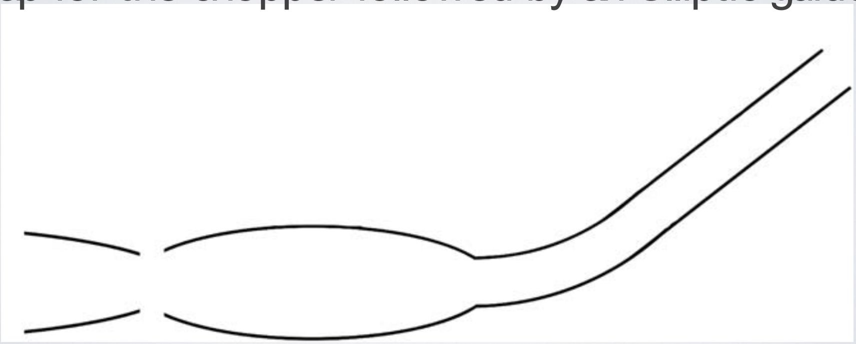
Liouville's theorem: more intensity => more divergence

Techniques for Guide 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

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.

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

Guide_Bot McStas Optimisation

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

Thank you!