Neutron Optics Technologies

3rd April 2016

Ken Andersen

Announcements

EUROPEAN SPALLATION SOURCE

- Social Dinner Monday 4/4 at 20:30 at ULISSE
  - Couscous and other Sicilian specialities
- Excursion Tuesday 5/4 to SEGESTA
  - 13:00 Bus Departure
  - 13:45 Arrival at Segesta
  - 14:00 Lunch
  - 15:30 Visit to Archeological Site
  - 17:30 Bus Departure
- Join SoNS facebook group

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 Optics

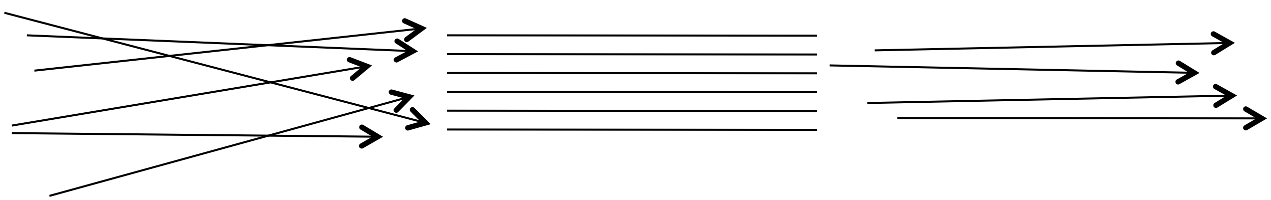
- Absorption
- Reflection
  - from surfaces: Snell's law
- Diffraction
  - from multilayers and crystals: Bragg's law
- Refraction
  - from materials and magnetic fields

Collimation

Reducing divergence

- improving resolution
- reducing background
- reducing flux

Soller collimator



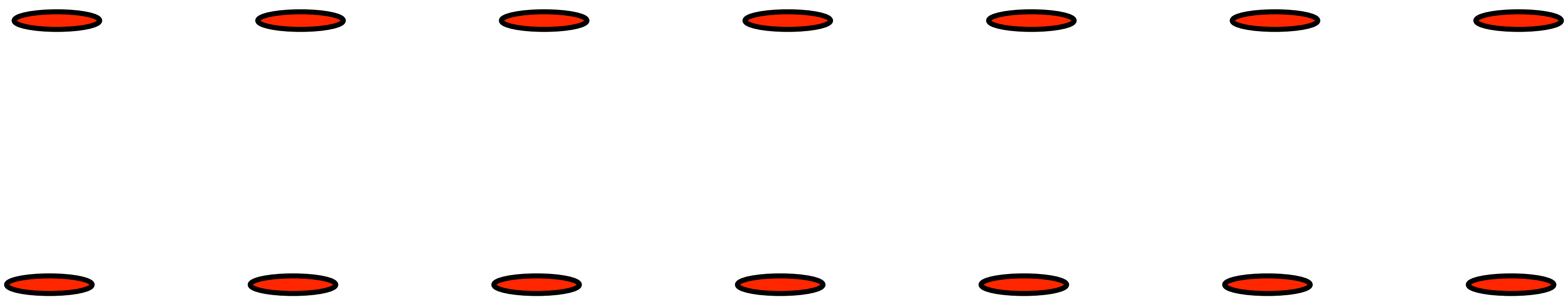
Pin-holes separated by distance

Neutron Optics

EUROPEAN SPALLATION SOURCE

- Absorption
- Reflection
  - from surfaces: Snell's law
- Diffraction
  - from multilayers and crystals: Bragg's law
- Refraction
  - from materials and magnetic fields

Diffraction: Bragg's Law



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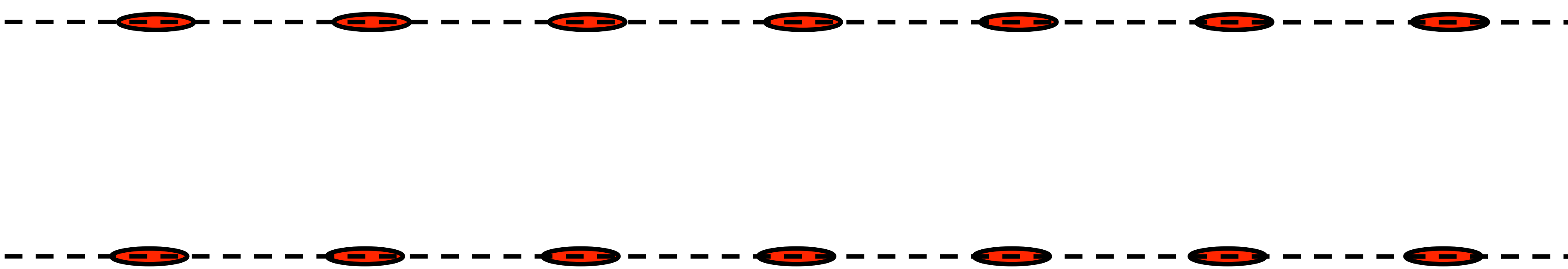

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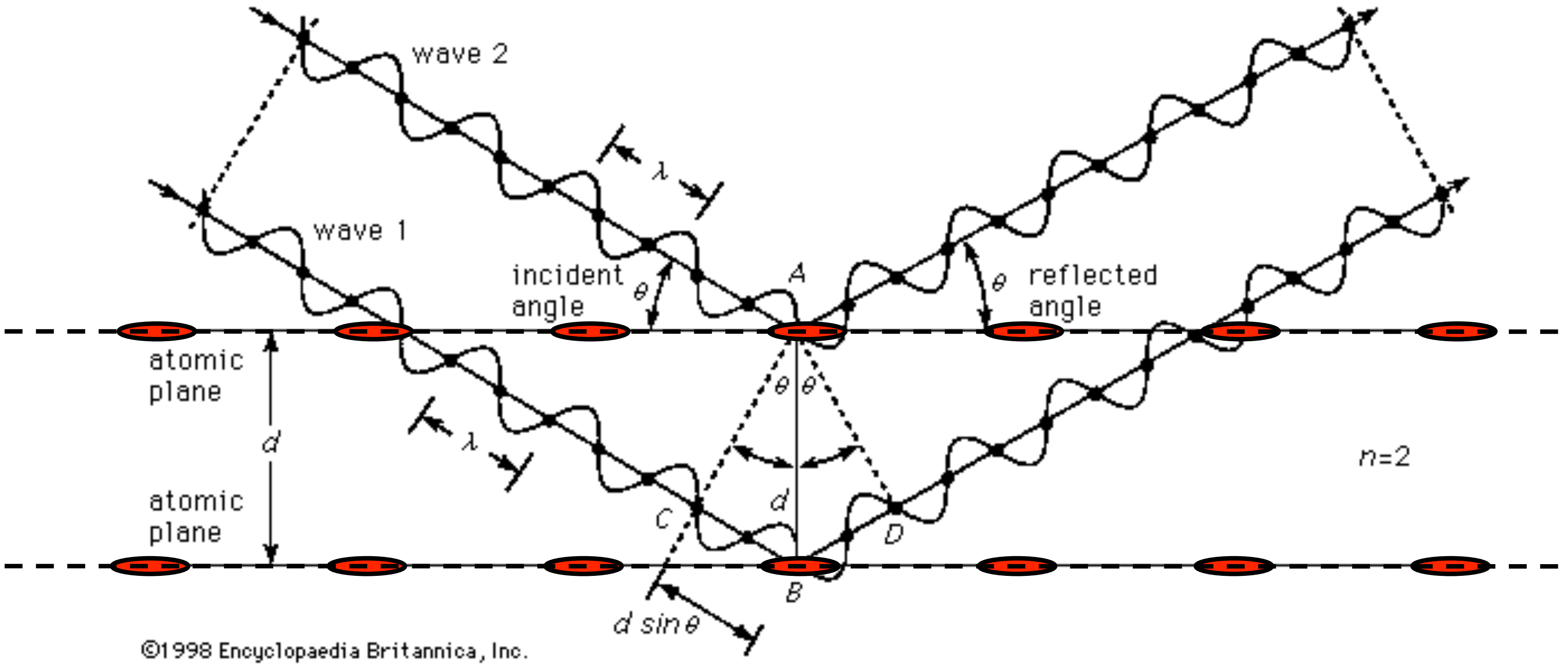
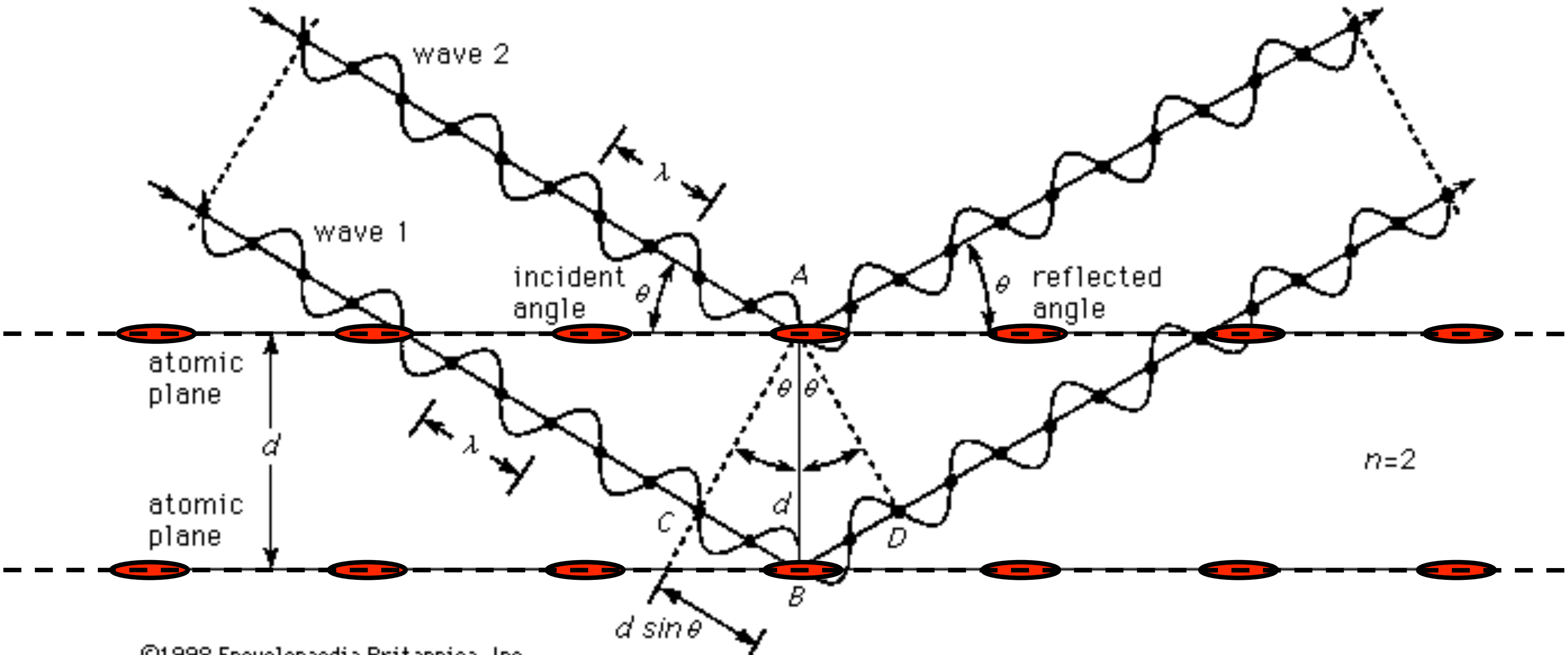


Diffraction: Bragg's Law

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



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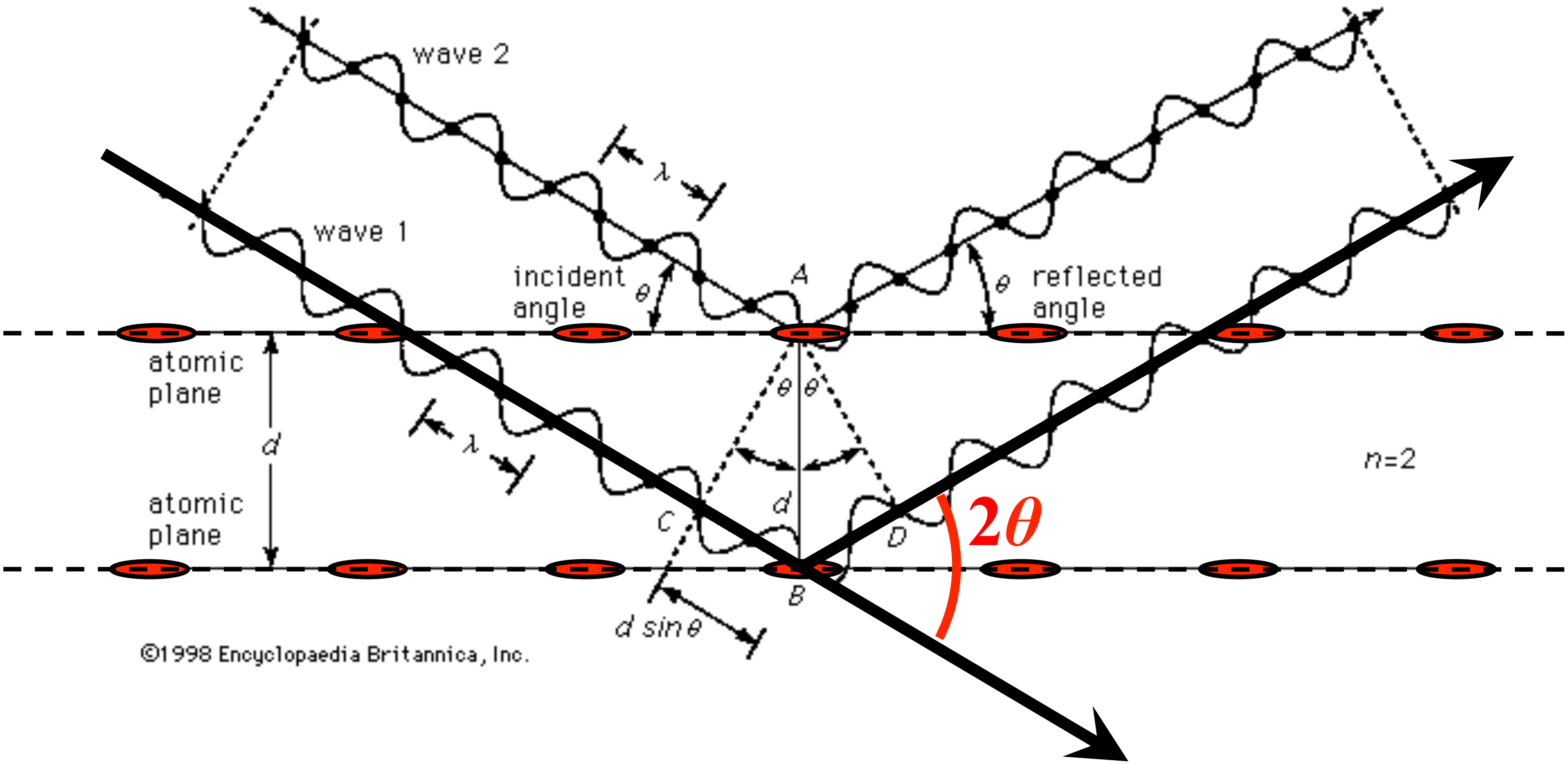
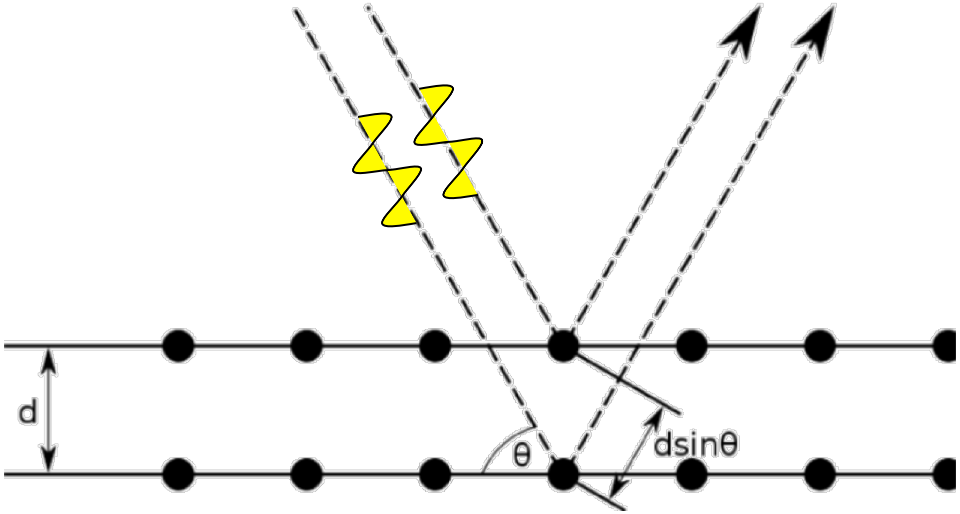


Diffraction: Bragg's Law

Wavevector:

$$k = \frac{2\pi}{\lambda} \qquad p = \hbar k$$

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



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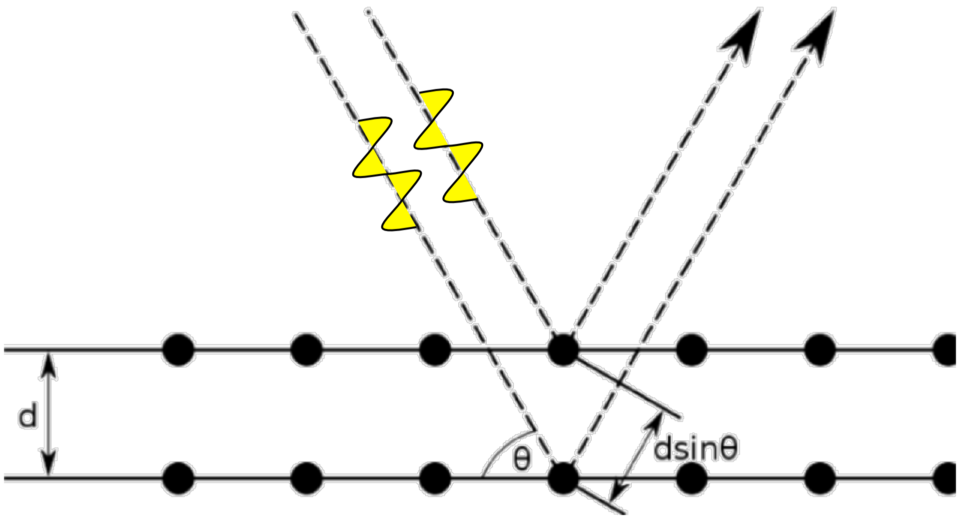
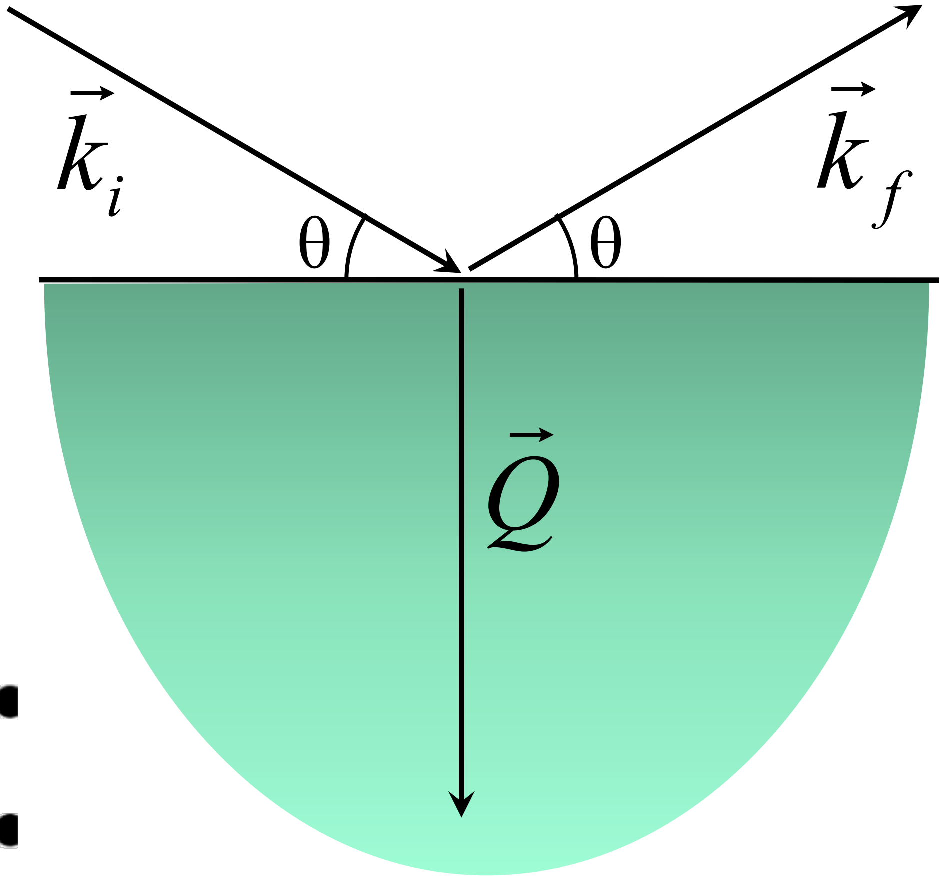


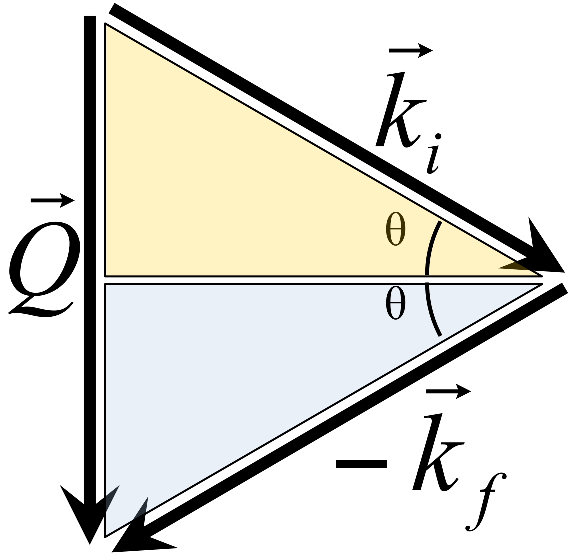
$$\left|\vec{k}_i\right| = \left|\vec{k}_f\right| = k$$



Diffraction: Bragg's Law

$$\vec{k}_i = \vec{k}_f + \vec{Q}$$

$$\Rightarrow \vec{Q} = \vec{k}_i - \vec{k}_f$$



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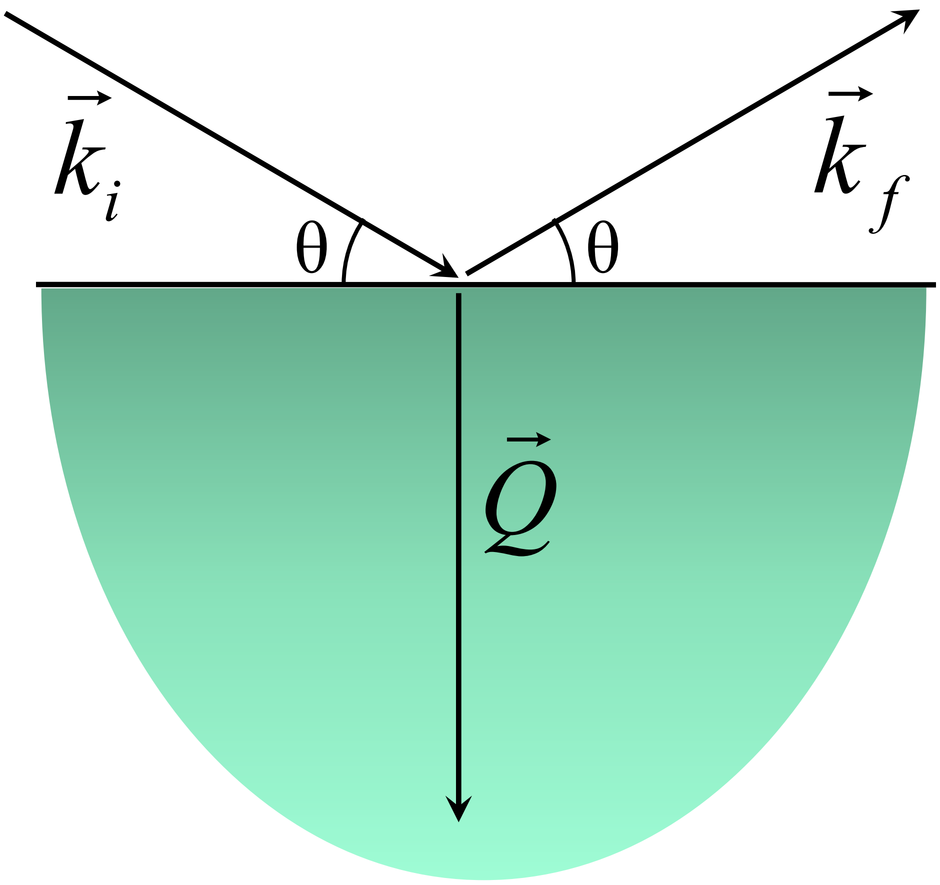

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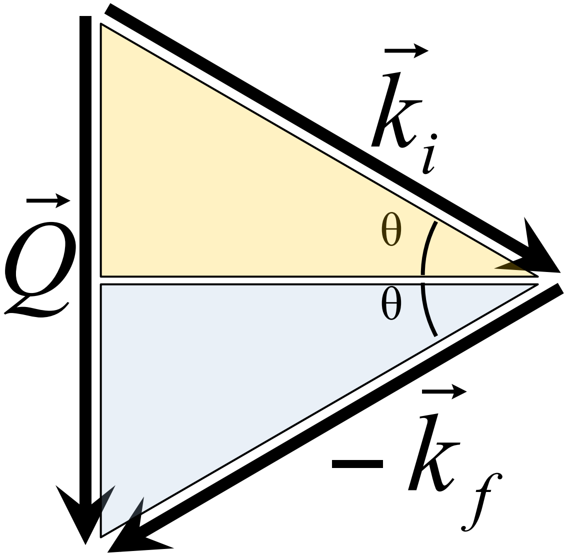

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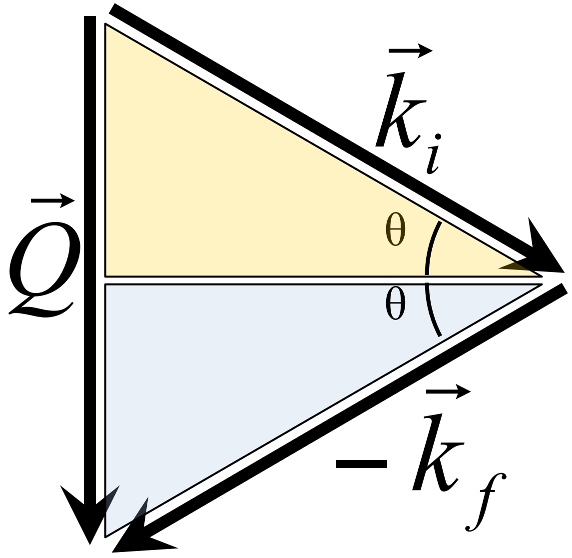

$$Q = 2k\sin\theta$$

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

$$k = \frac{2\pi}{\lambda}$$

Diffraction: Bragg's Law

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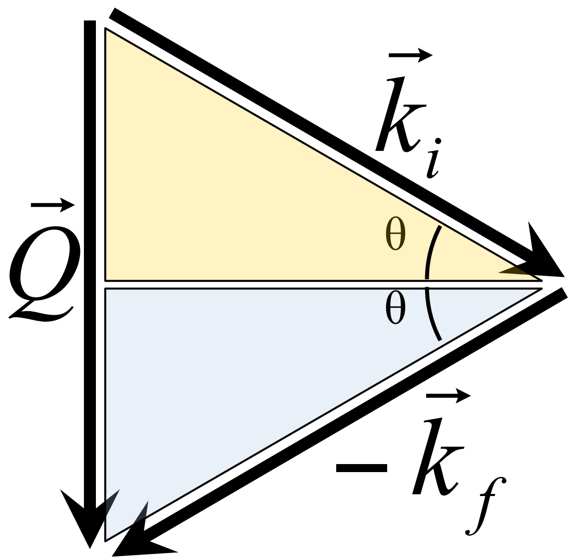

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Bragg's Law: $\boxed{Q = \frac{2\pi}{d}}$

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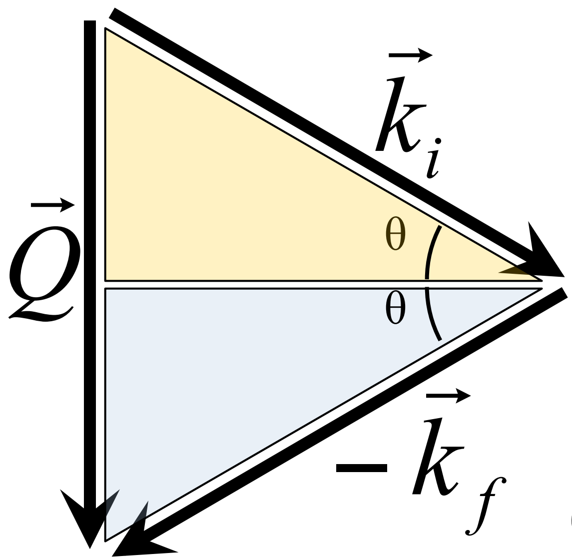


$$Q = 2k\sin\theta$$

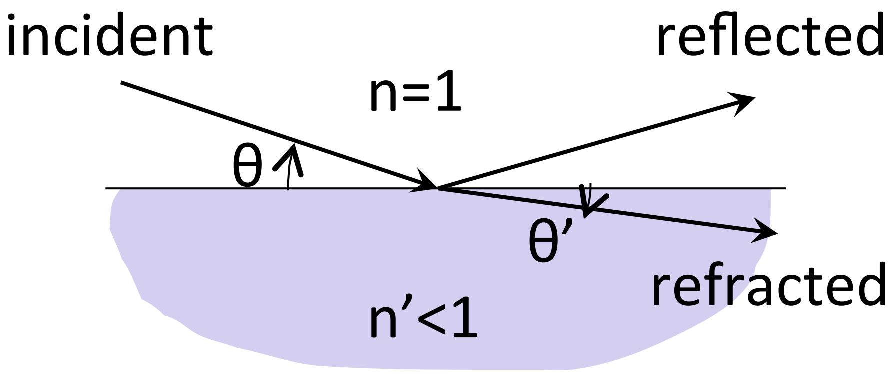
$$\lambda = 2d\sin\theta$$

$$k = \frac{2\pi}{\lambda}$$

Bragg's Law: $$\boxed{Q = \frac{2\pi}{d}}$$

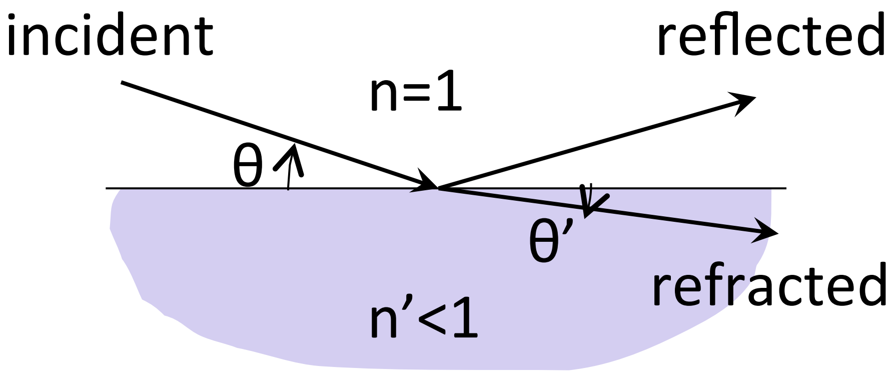
Conversion: $Q = 4\pi\sin\theta/\lambda$

Reflection: Snell's Law



$$\frac{\cos\theta}{\cos\theta'} = \frac{v_1}{v_2} = \frac{n'}{n} = n'$$

Reflection: Snell's Law



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θ'=0: critical angle of total reflection θ_c

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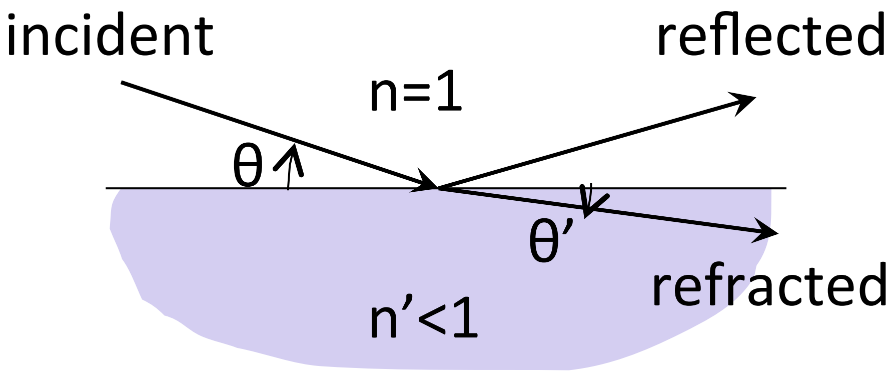

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$$\left.\begin{aligned} \cos\theta_c &= n'/n = n' \\ n' &= 1 - \frac{N\lambda^2 b}{2\pi} \\ \cos\theta_c &\approx 1 - \theta_c^2/2 \end{aligned}\right\} \Rightarrow \theta_c = \lambda\sqrt{Nb/\pi}$$

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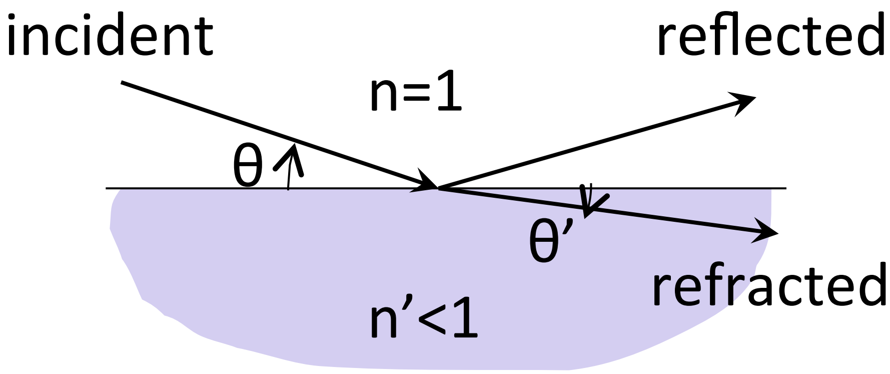

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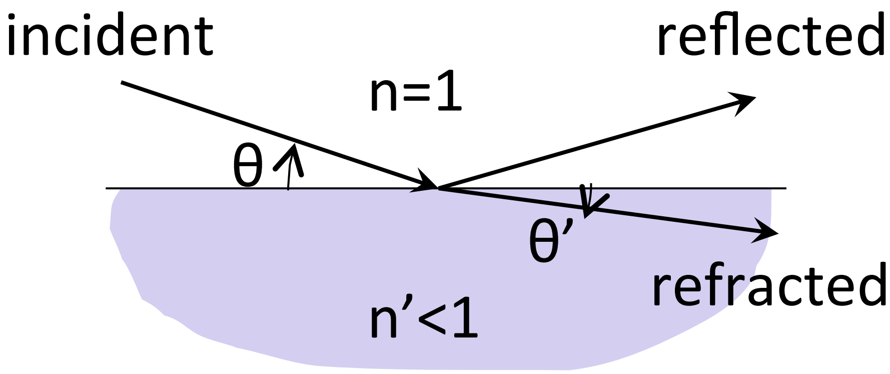
for natural Ni,

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

$Q_c = 0.0218$ Å^{-1}

Reflection: Snell's Law



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Definition:

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

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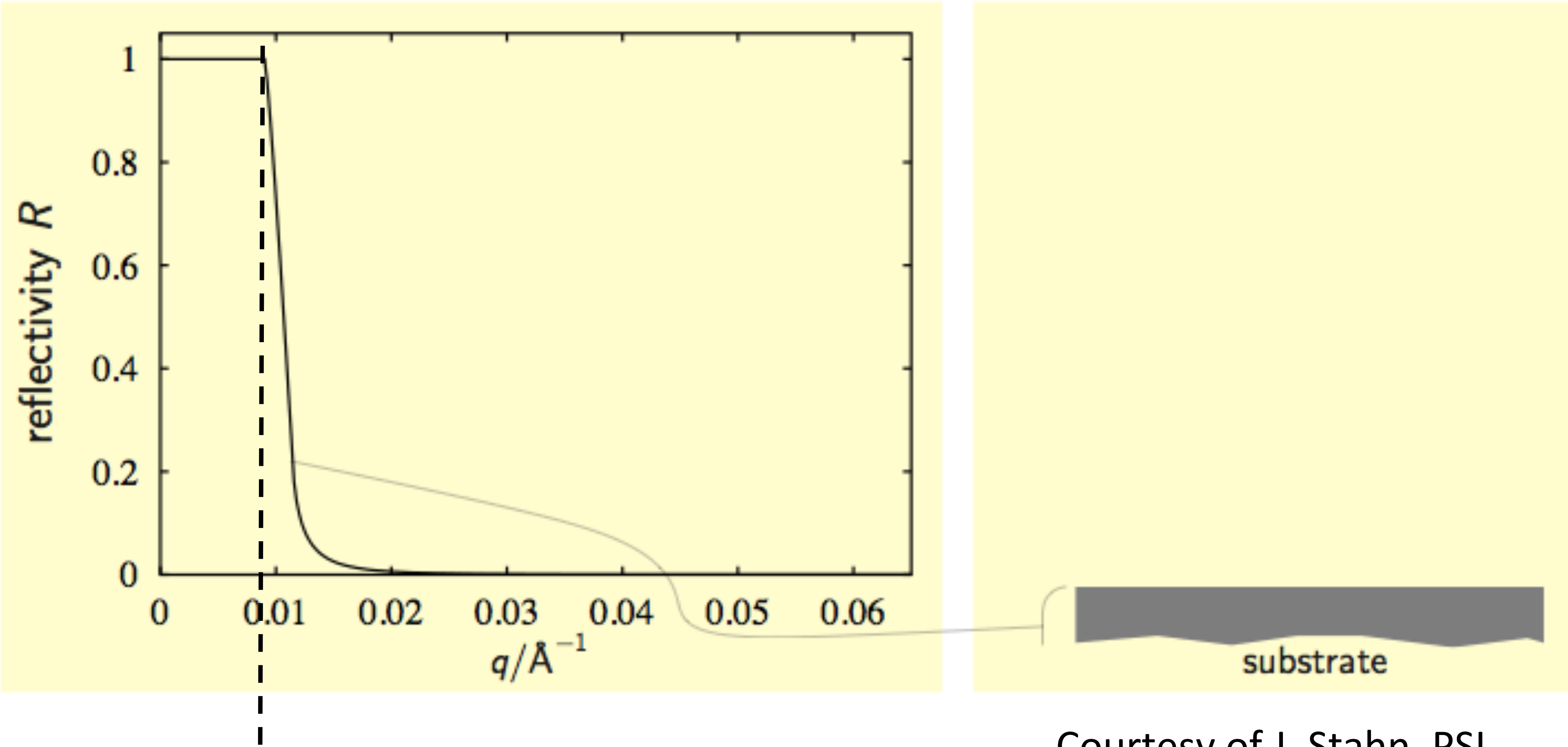
$\theta_c = \lambda[\text{Å}]\times 0.1°$

$Q_c = 0.0218$ Å^{-1}

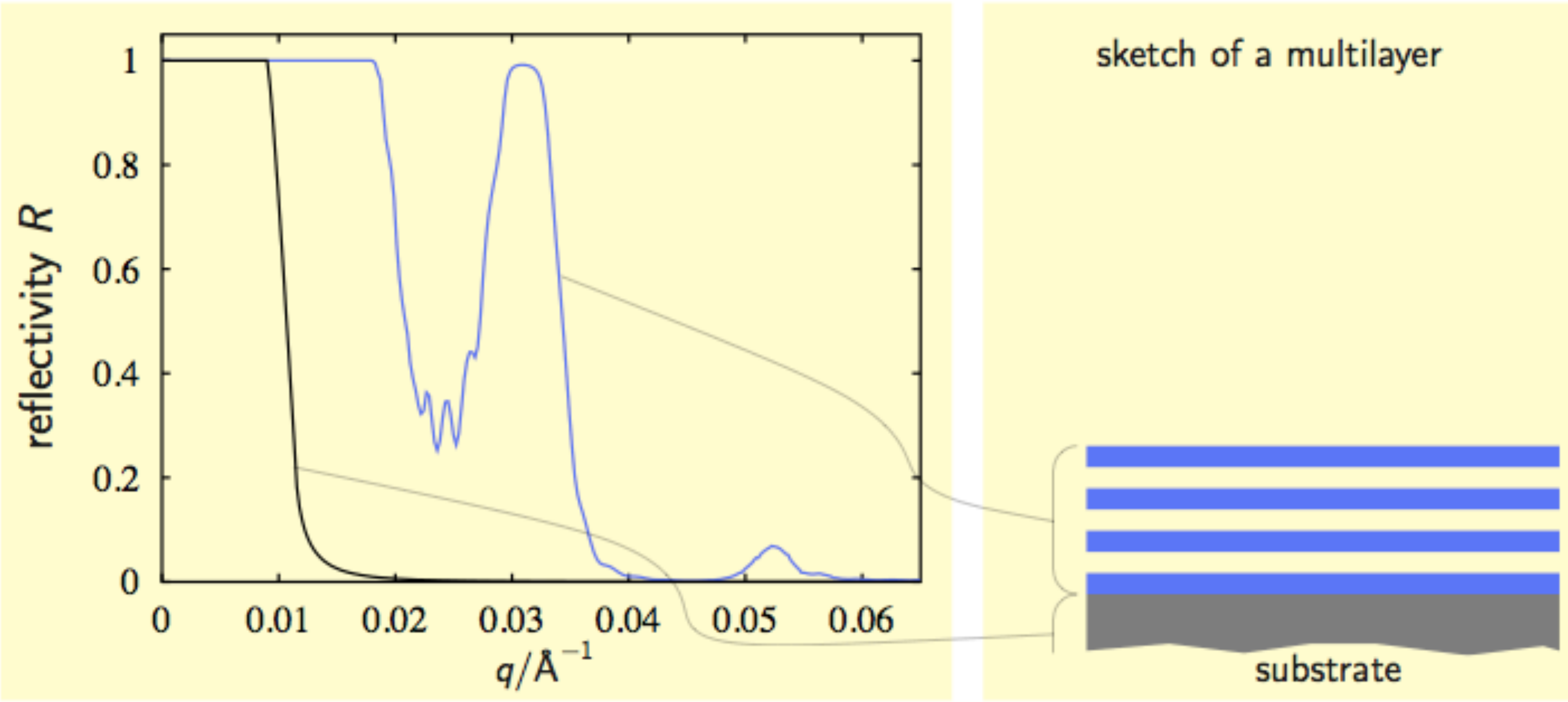
Neutron Supermirrors



Q_c as given by Snell's Law

Courtesy of J. Stahn, PSI

Neutron Supermirrors



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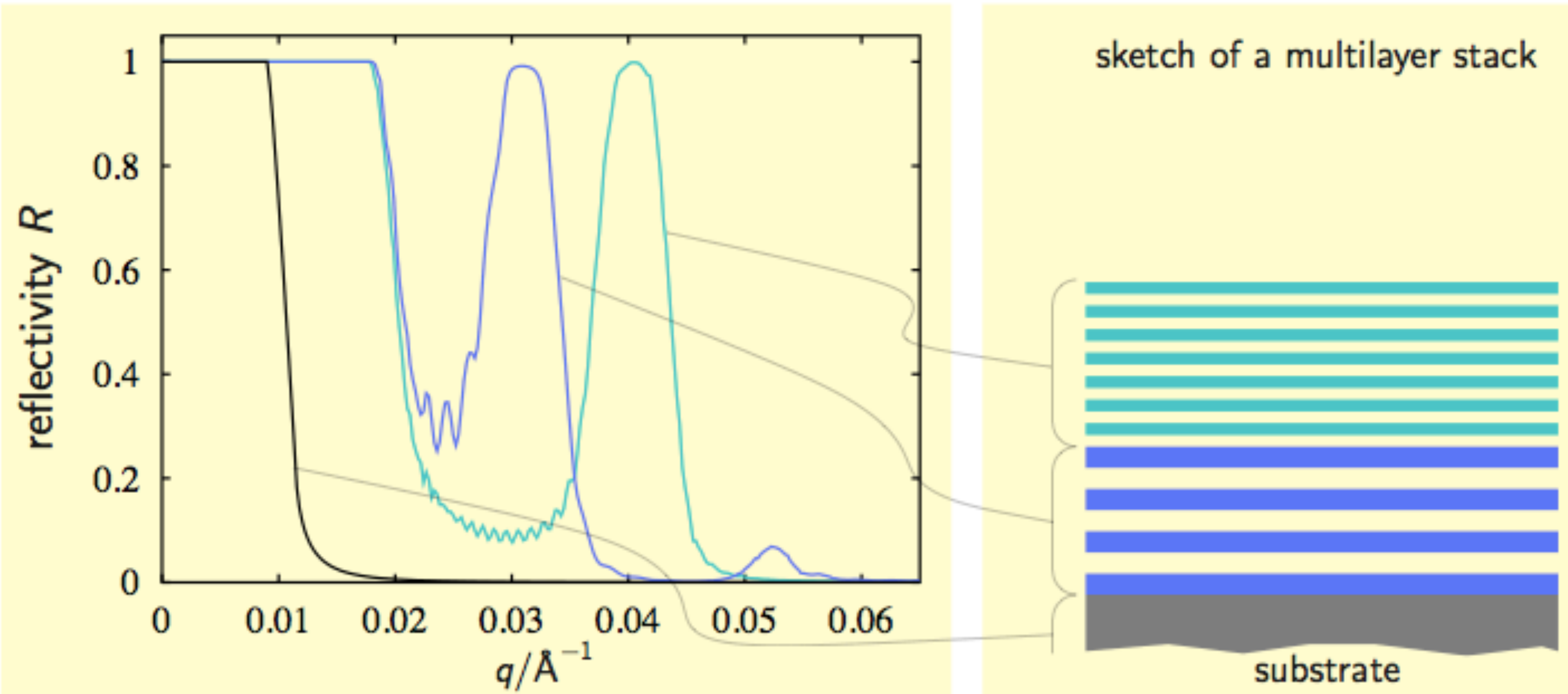

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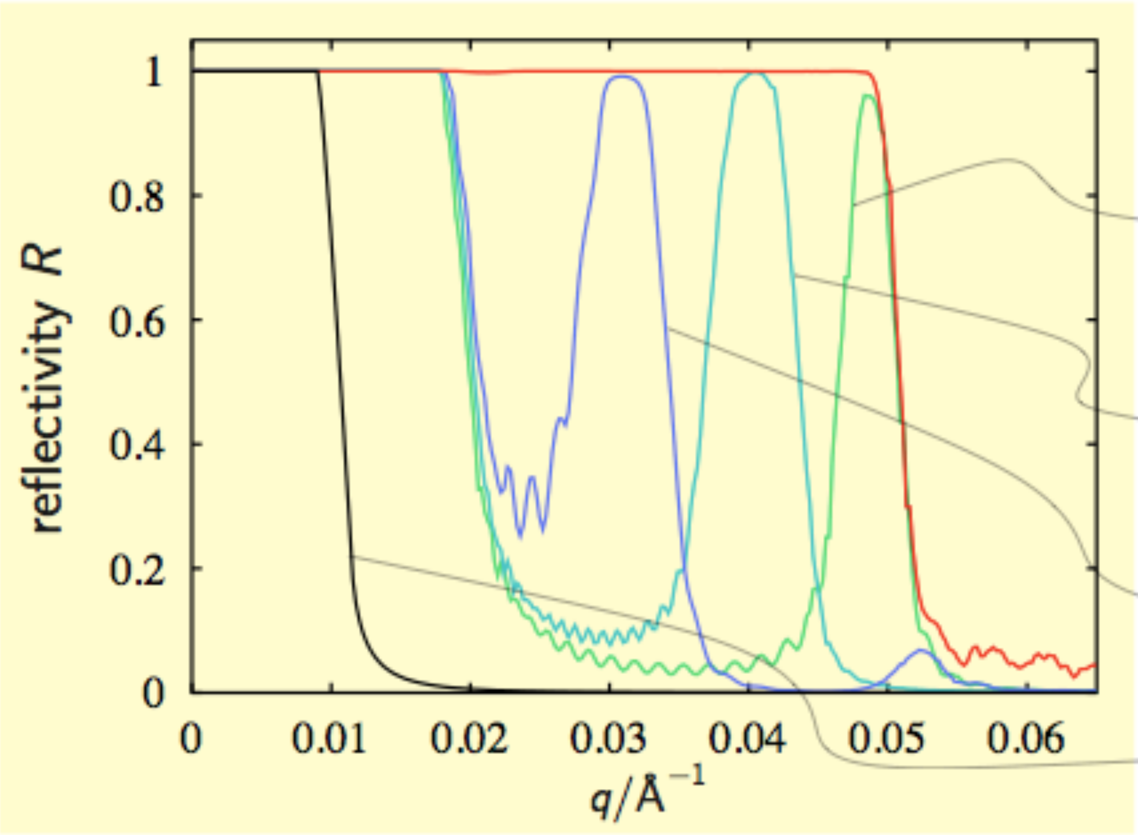
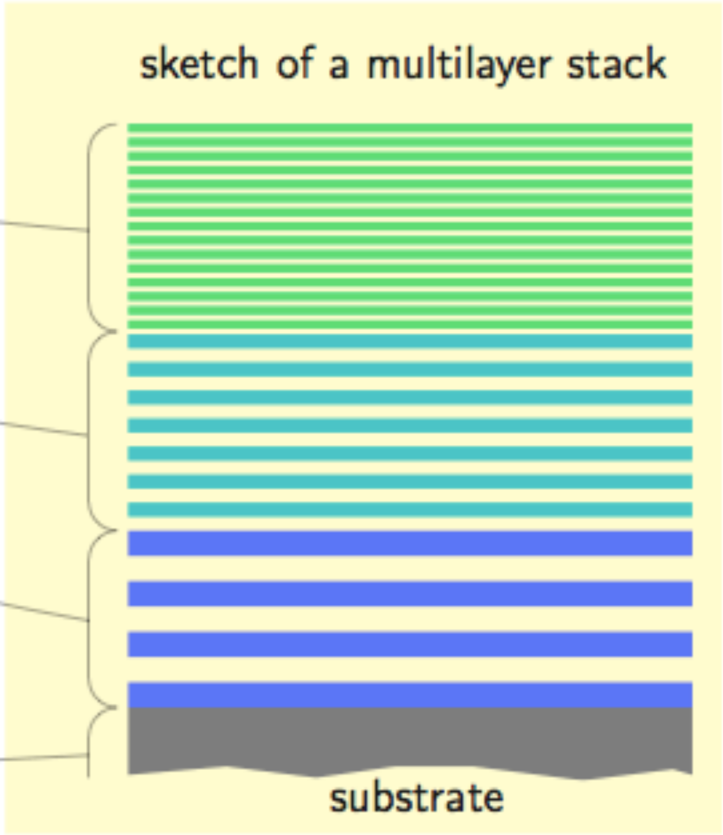


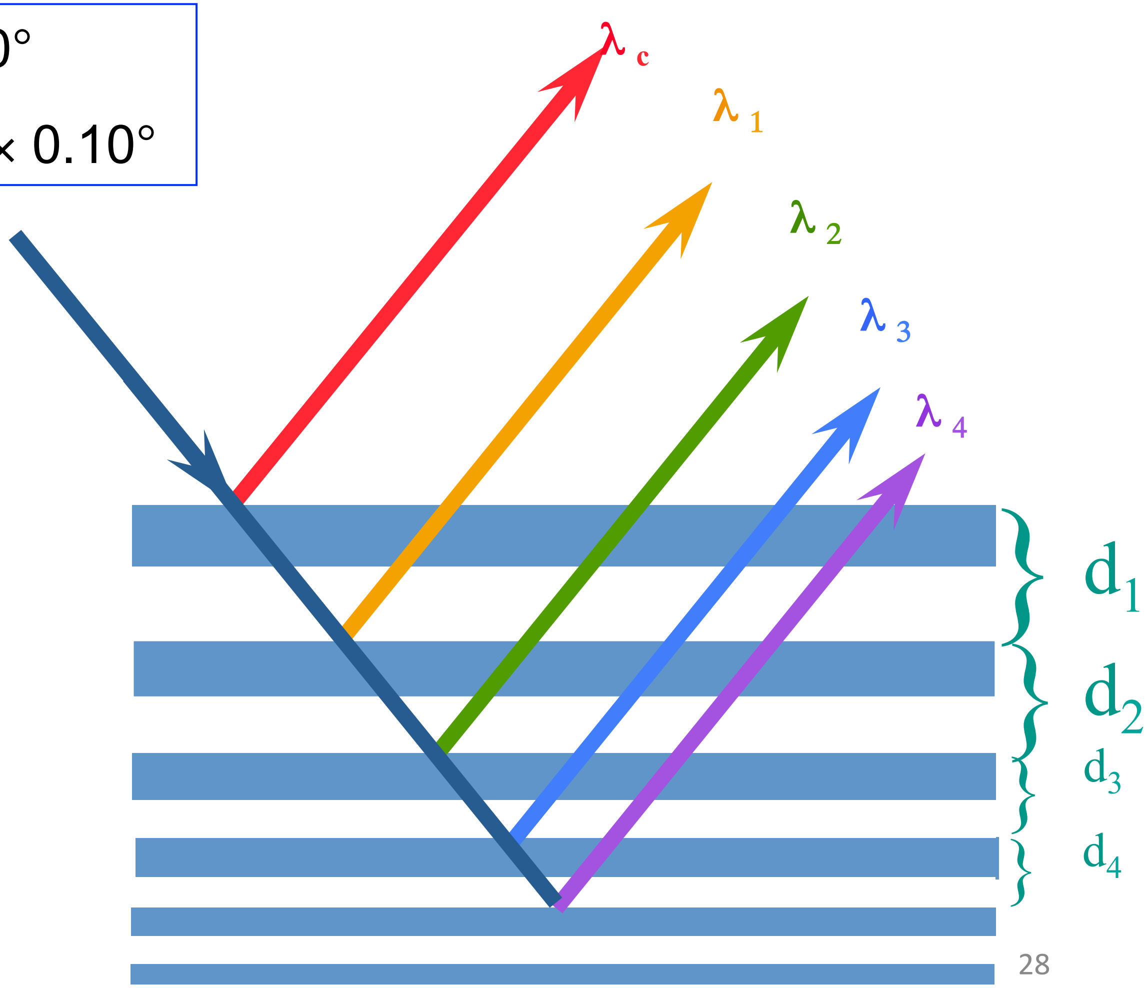


Courtesy of J. Stahn, PSI

Neutron Supermirrors

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

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



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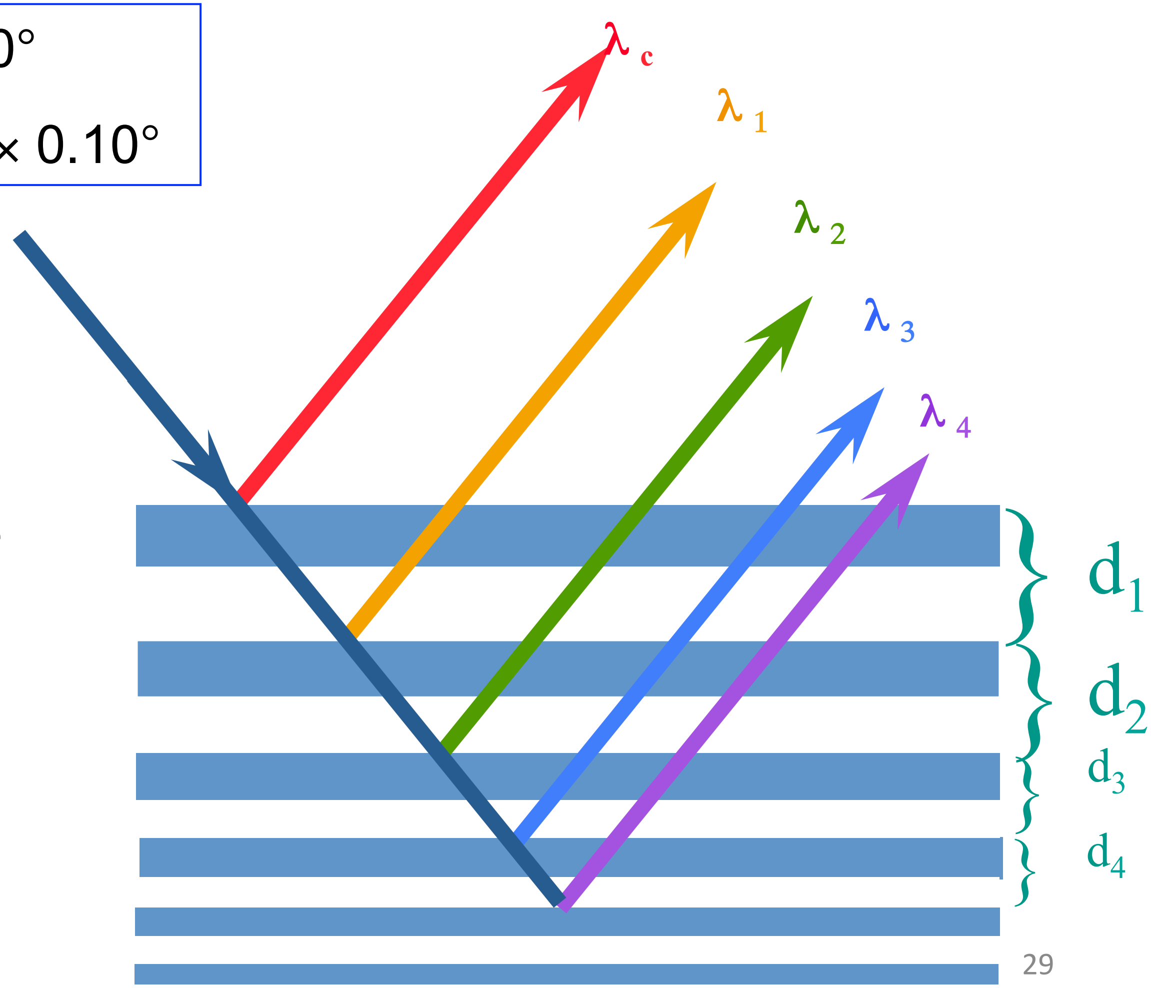
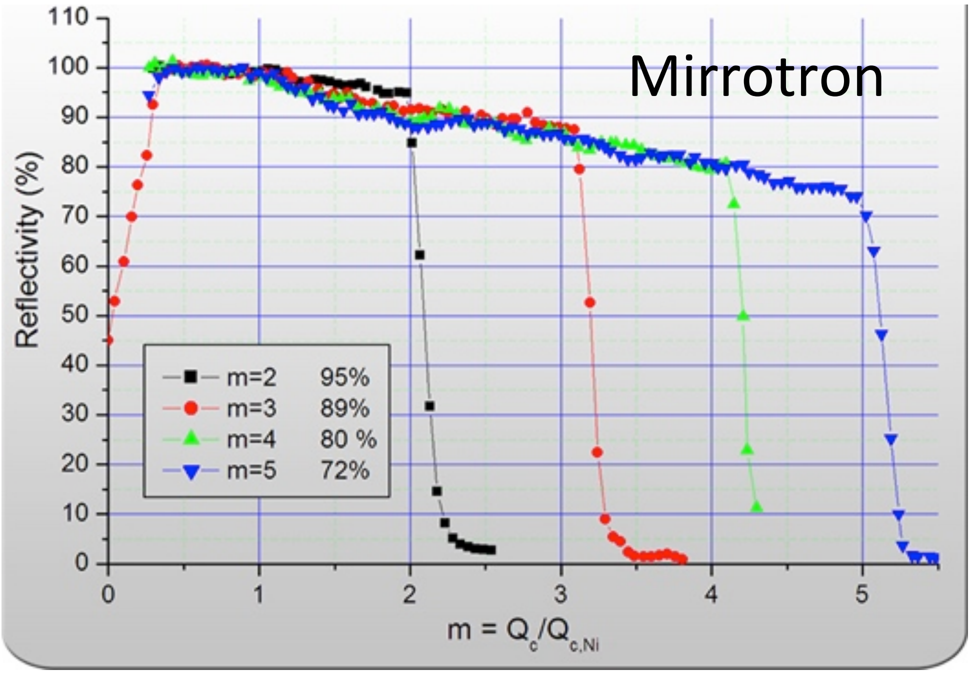
"m-number"
Supermirror critical angle



State-of-the-art Supermirrors



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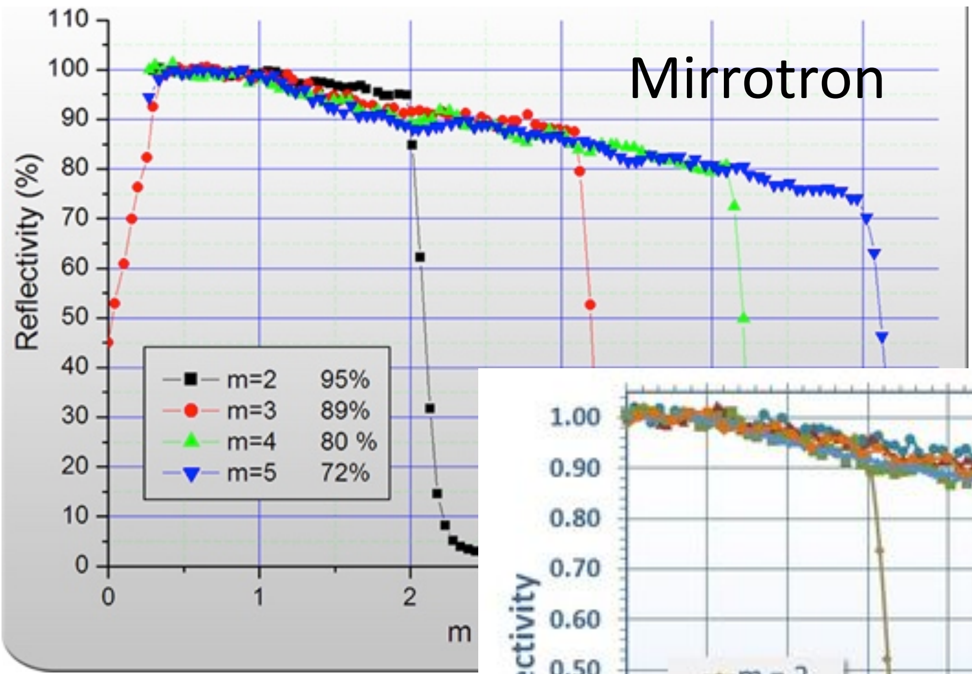
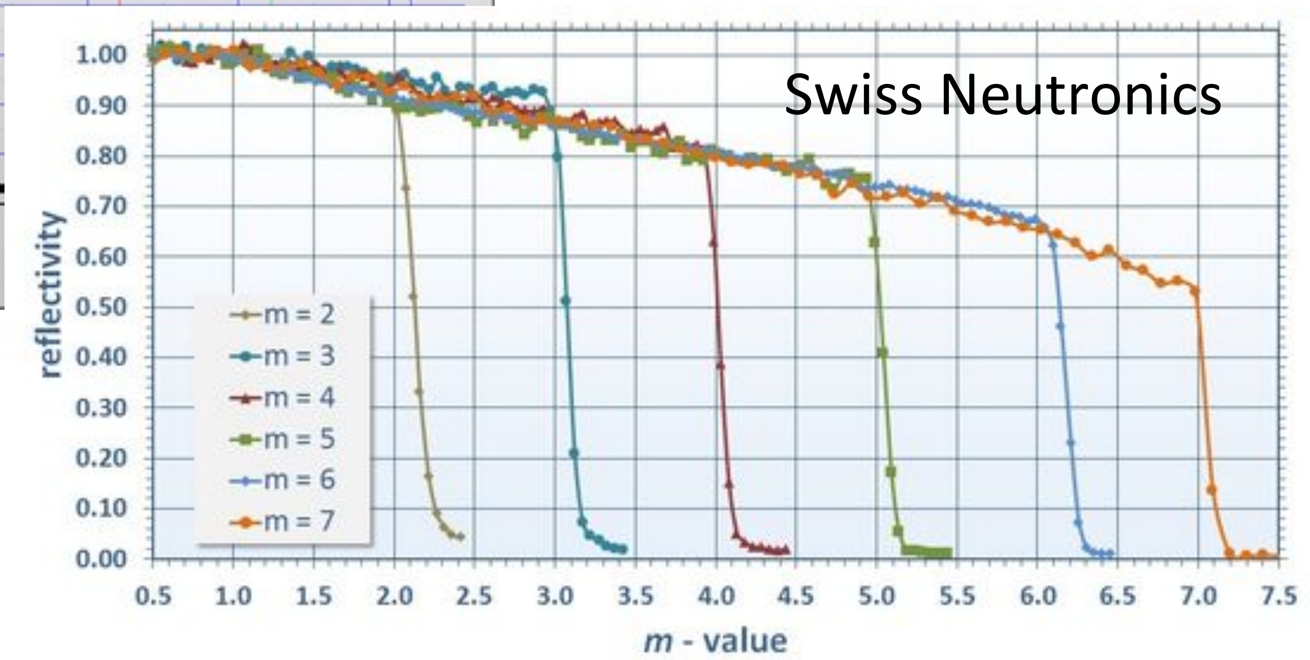
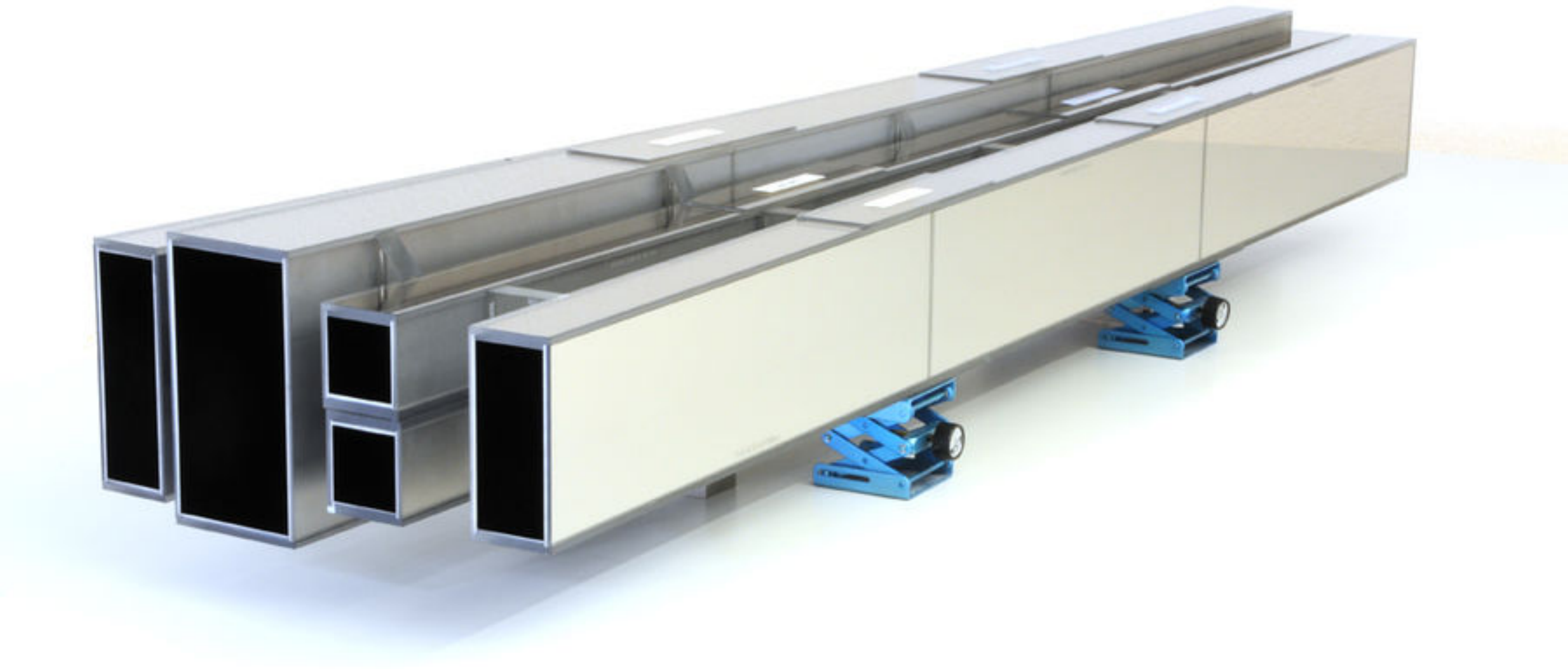




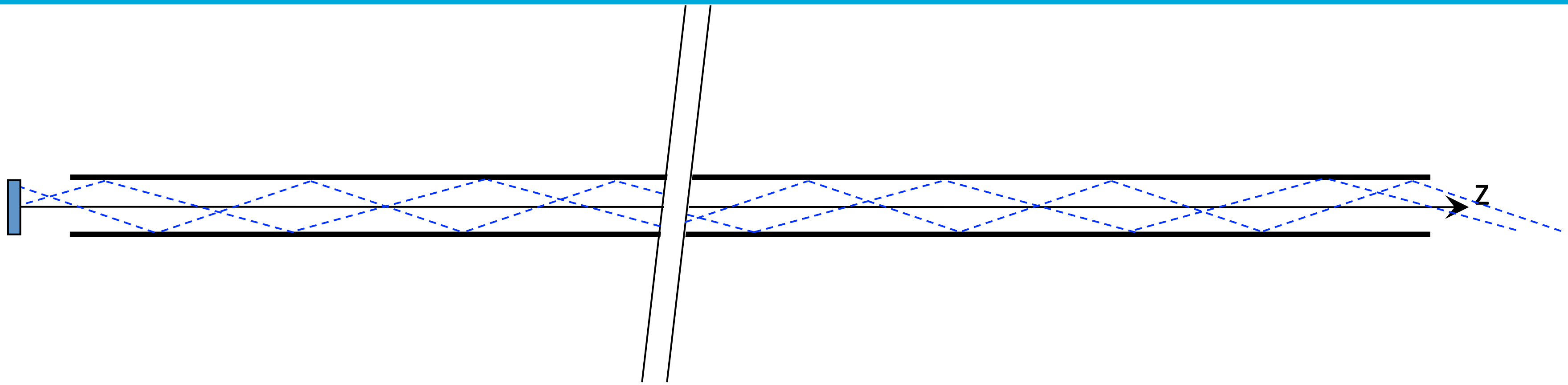
Neutron Guides

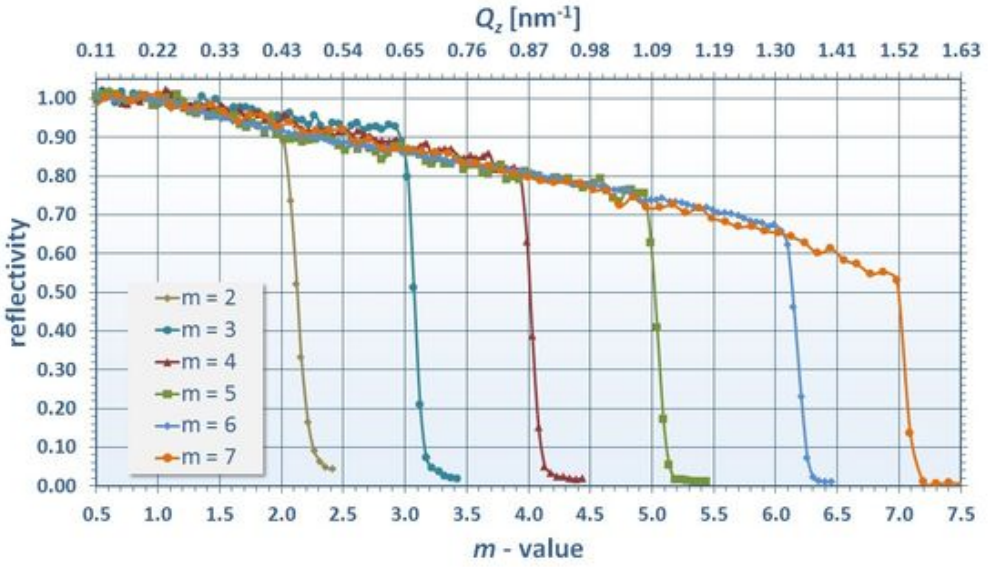


What are guides used for?

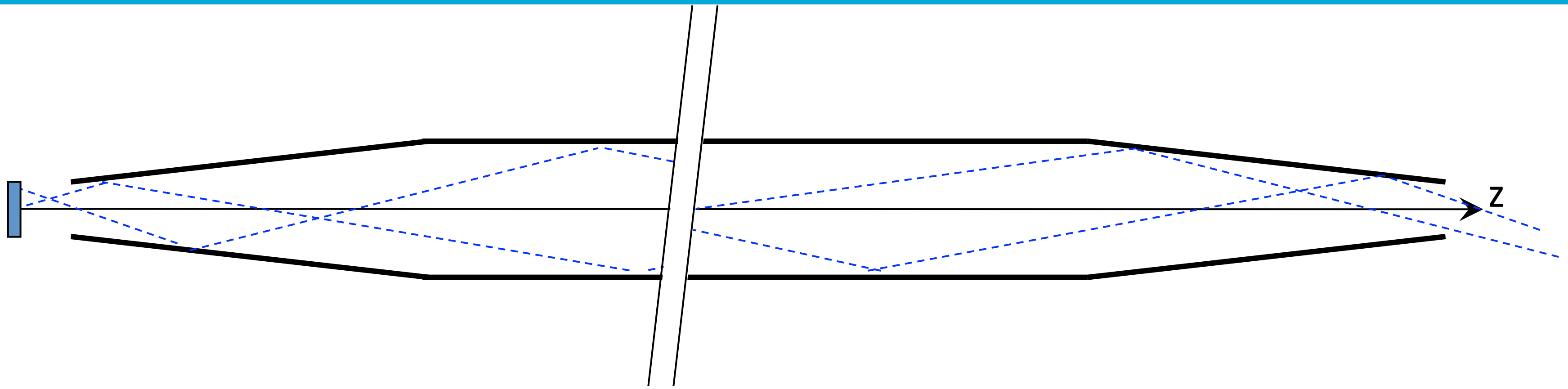
- Transport divergence
  – large m-numbers needed for short wavelengths
  – ballistic geometry required for supermirror guides
- Create space
  – build instruments far from neutron source
- Improve TOF resolution
- Reduce background
  – transport only “good” neutrons
- Focusing
  – increased divergence: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

Ballistic guides



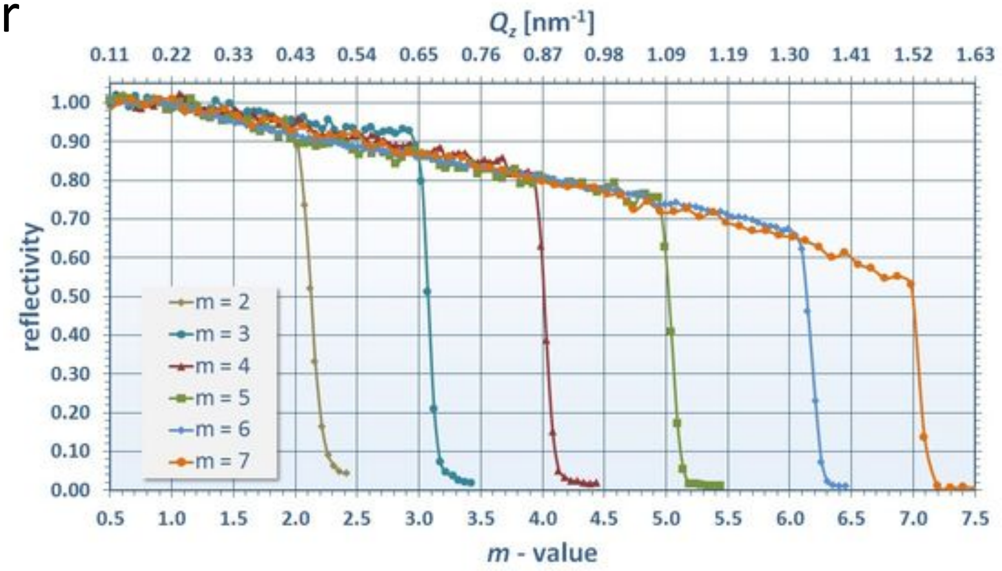


Ballistic guides



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

  adiabaticity - reversible



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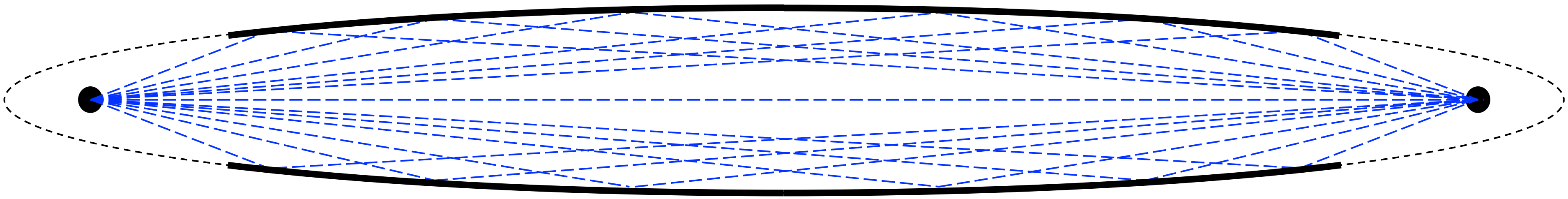

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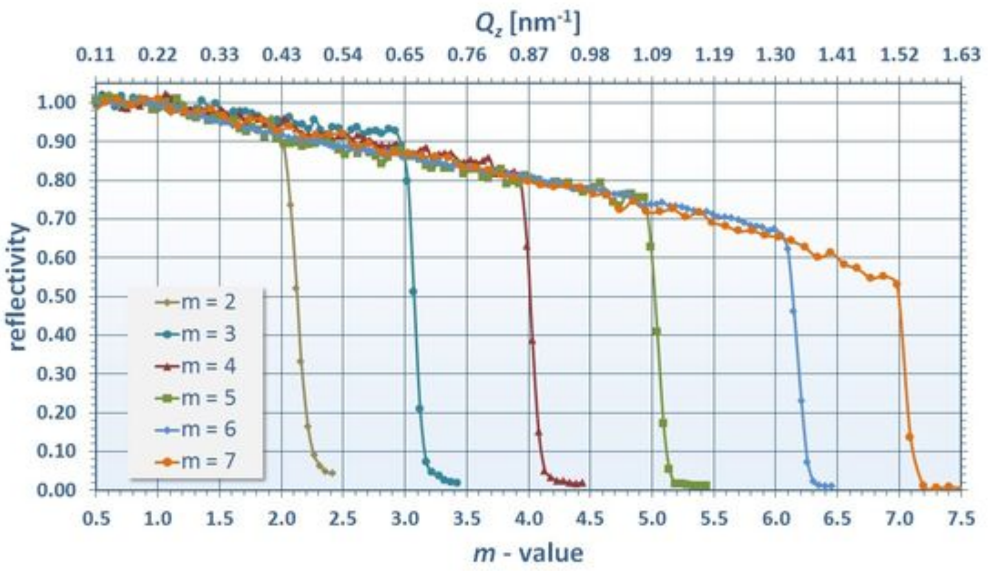
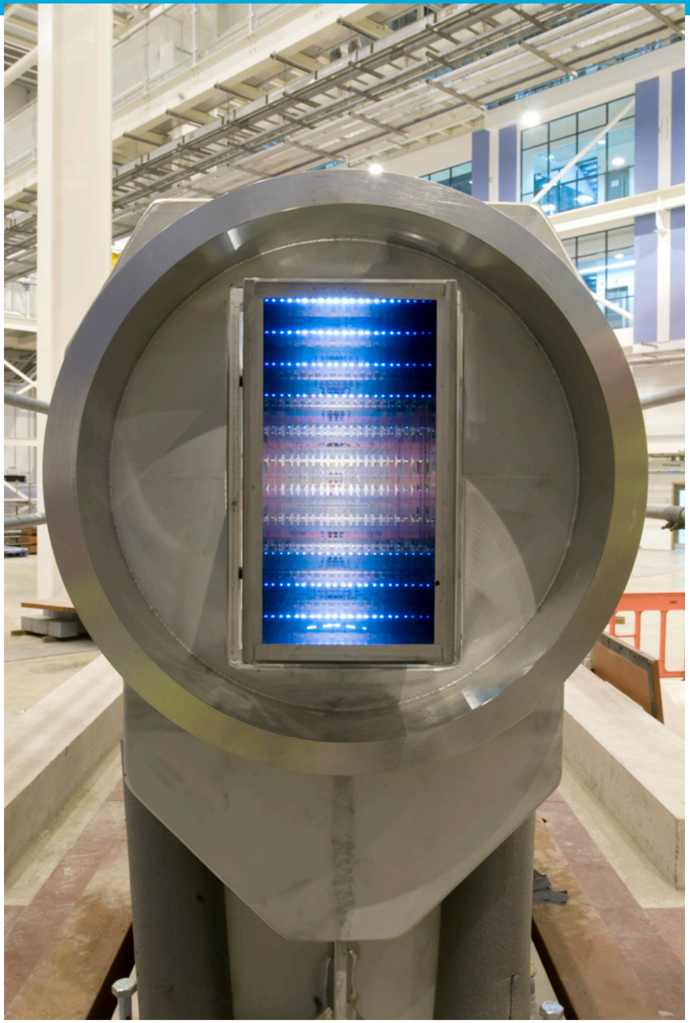
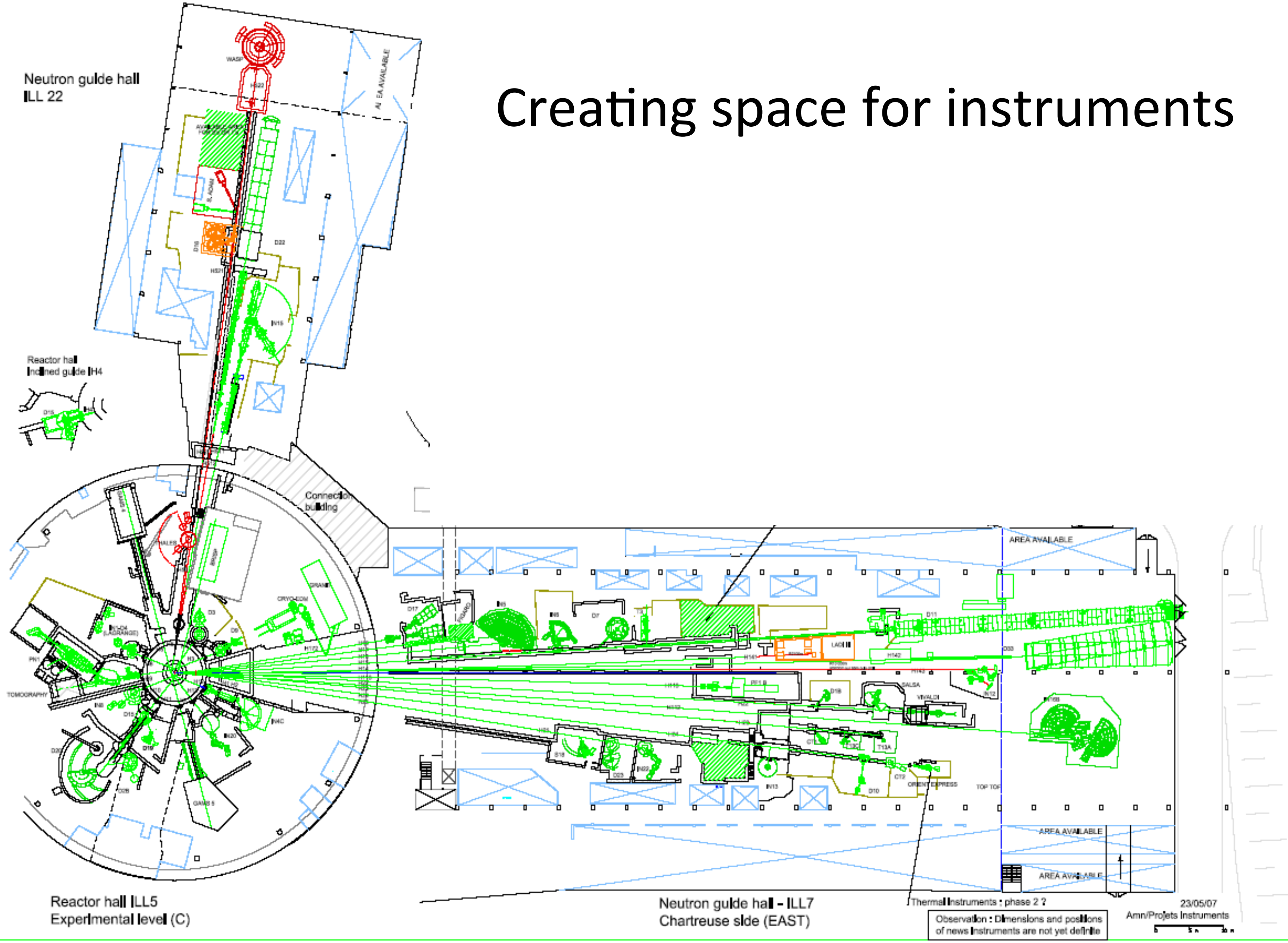


Ballistic guides

WISH @ ISIS: ballistic (elliptical) guide

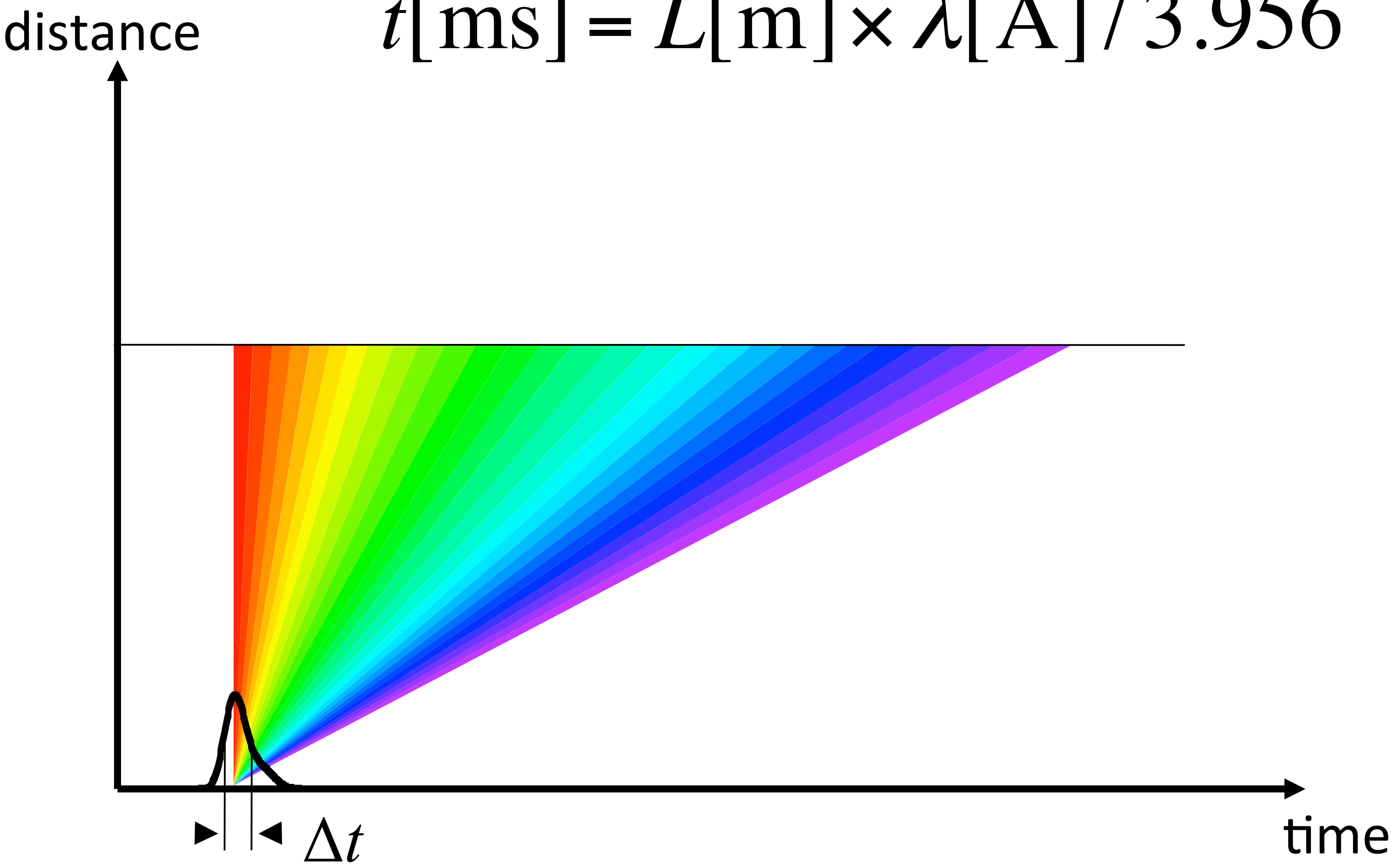


Creating space for instruments



Time-of-flight (TOF) resolution

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



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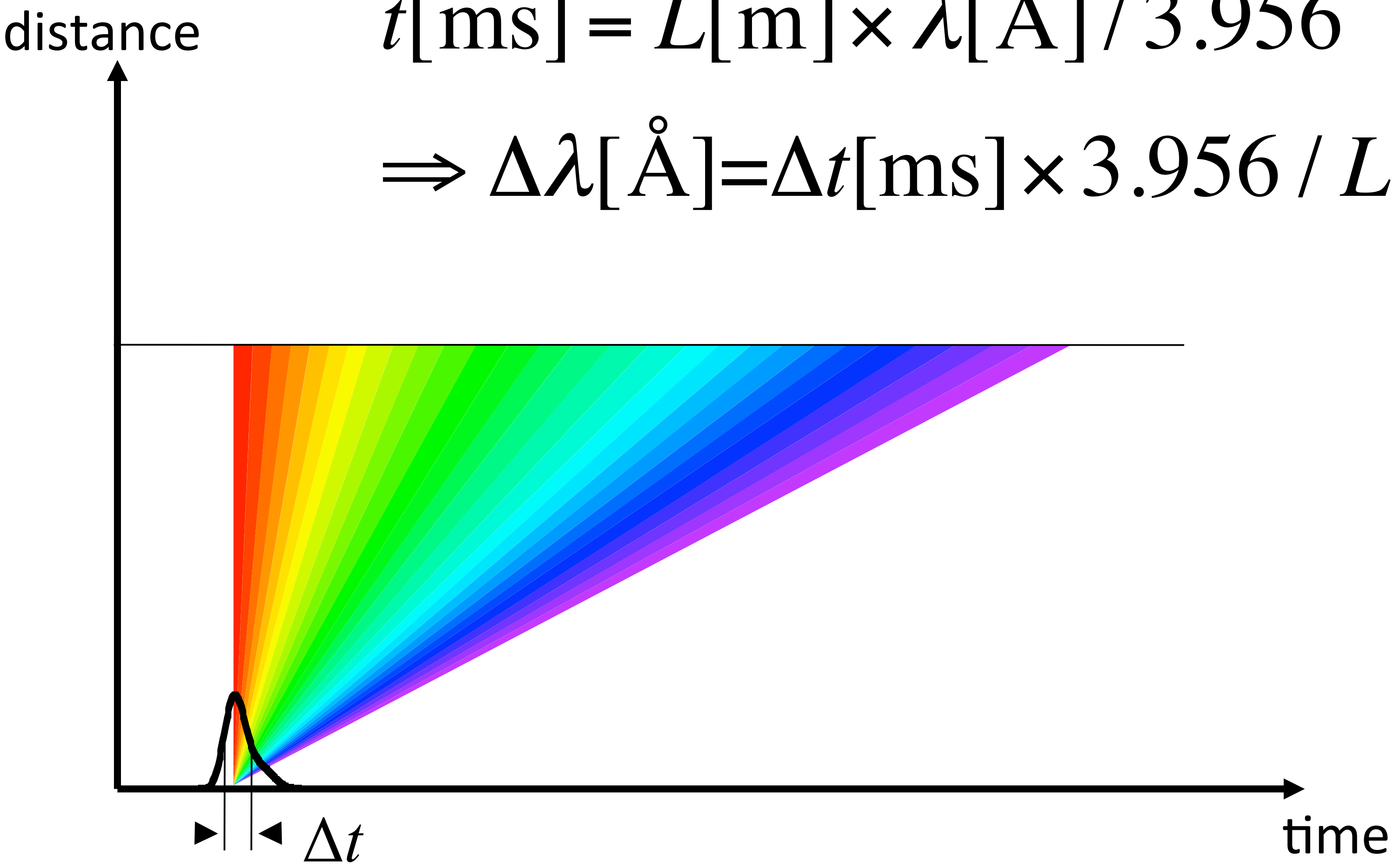
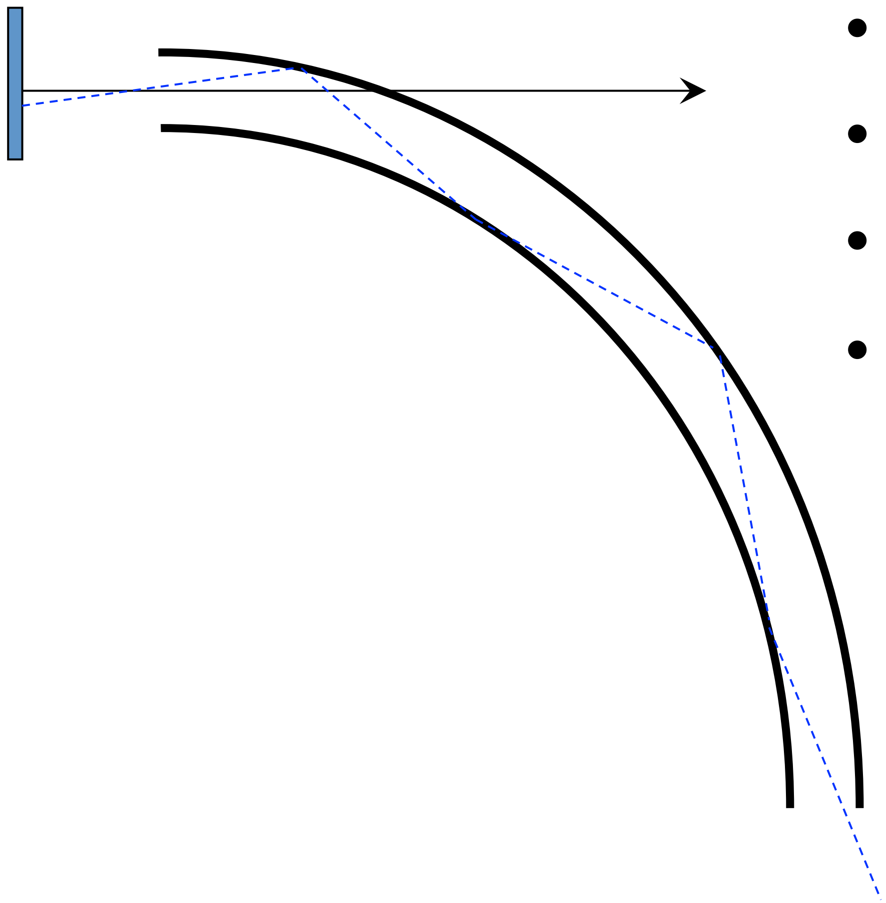
$$\Rightarrow \Delta\lambda[\text{Å}] = \Delta t[\text{ms}] \times 3.956 / L[\text{m}]$$

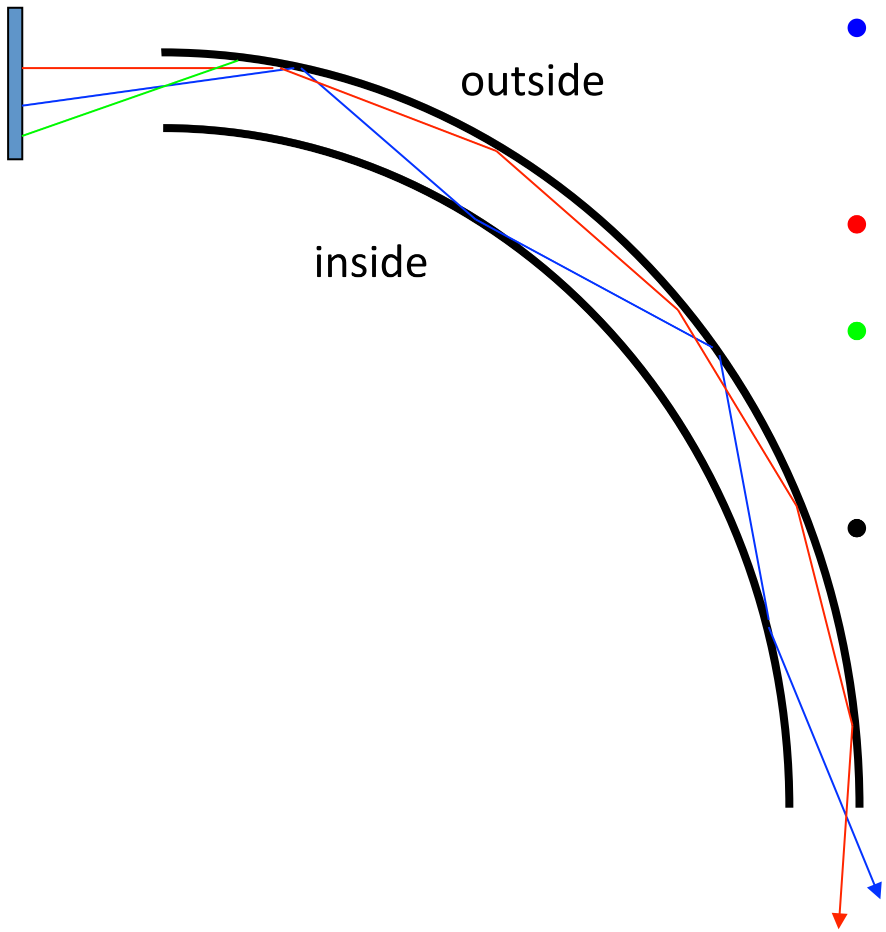


Curved Guides



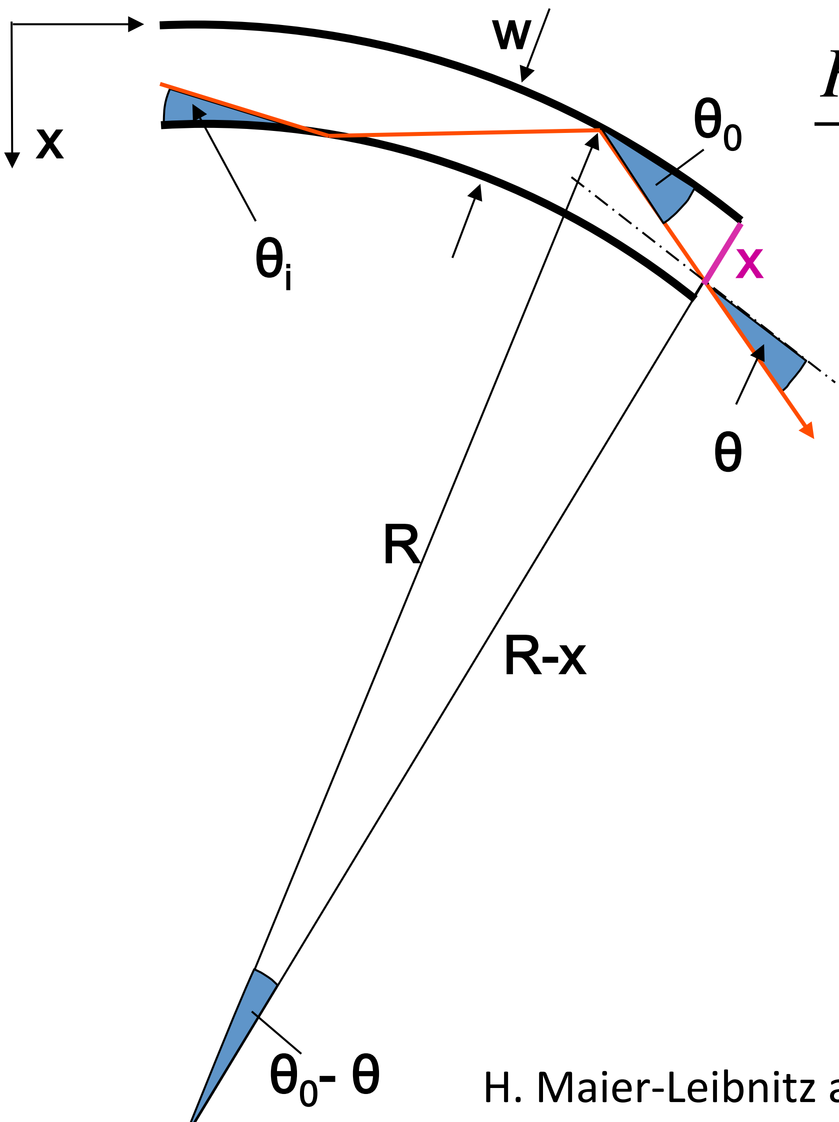
- Avoid direct line-of-sight
- Avoid gammas
- Avoid fast neutrons
- Reduce background

Curved Guides



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

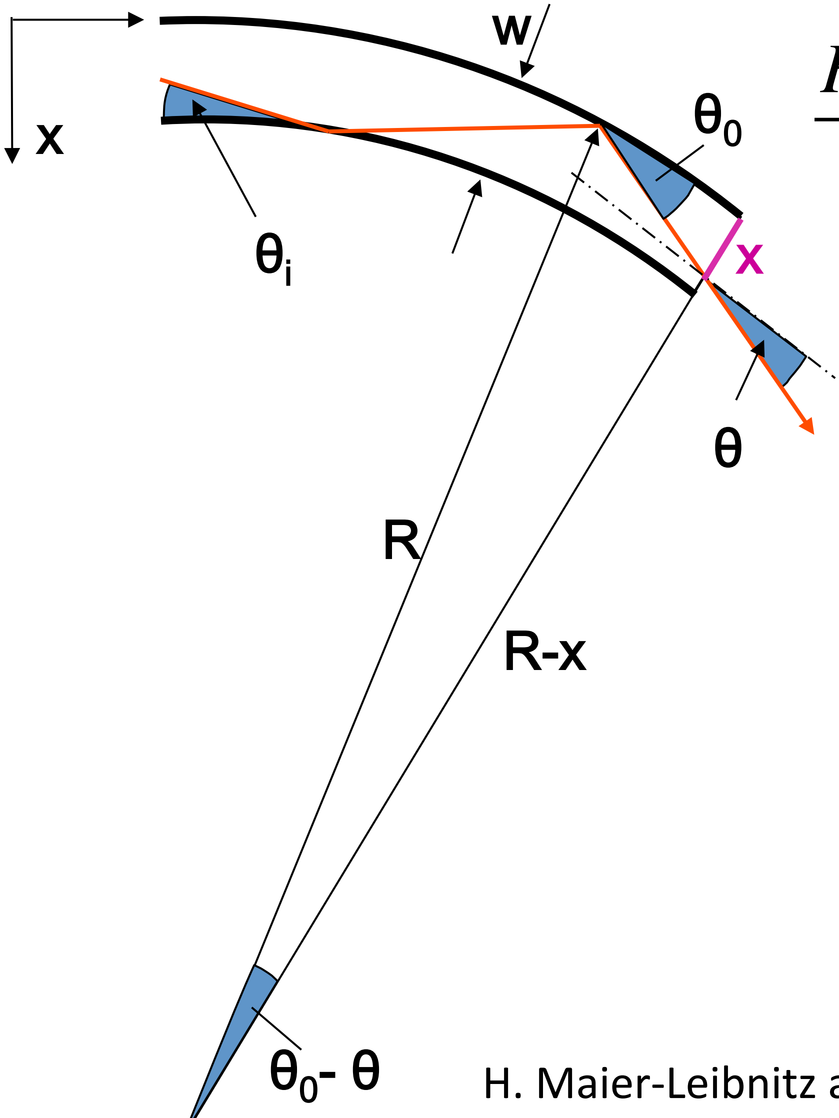
Curved Guides



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

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

Curved Guides



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

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

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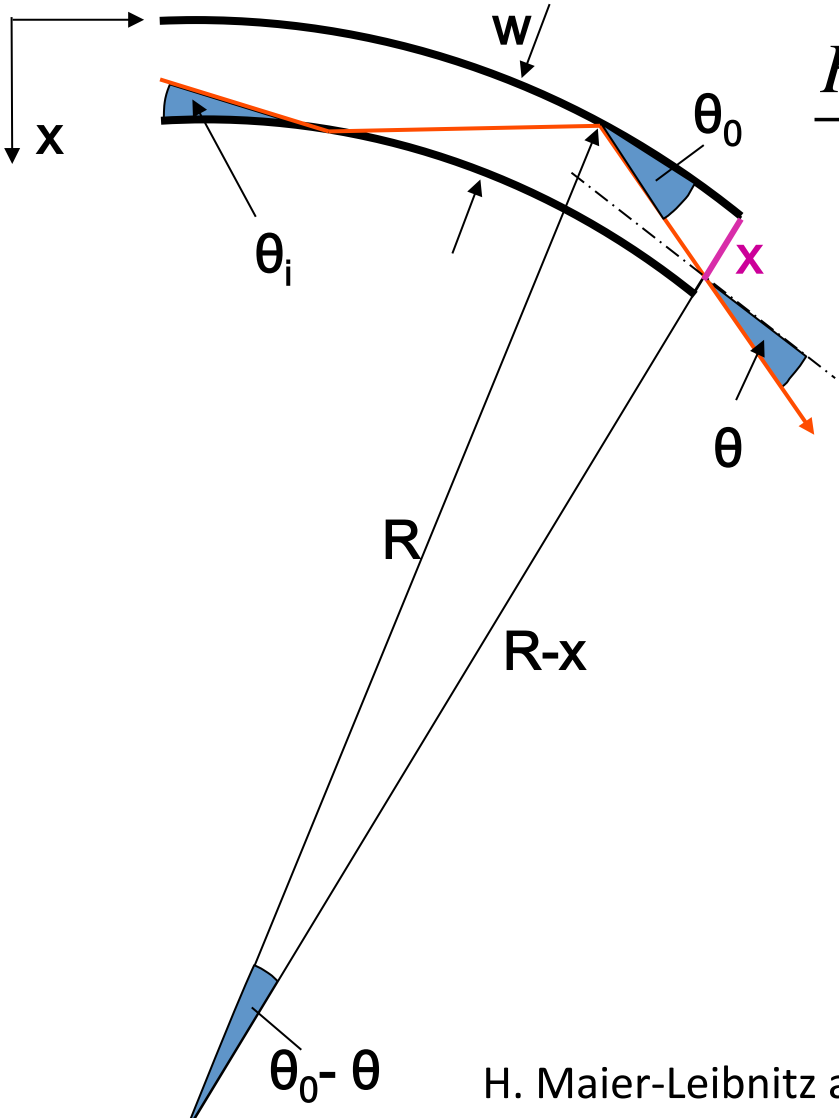
Curved Guides



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neutrons "just" reach inside face

when θ = 0 for x = w :

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

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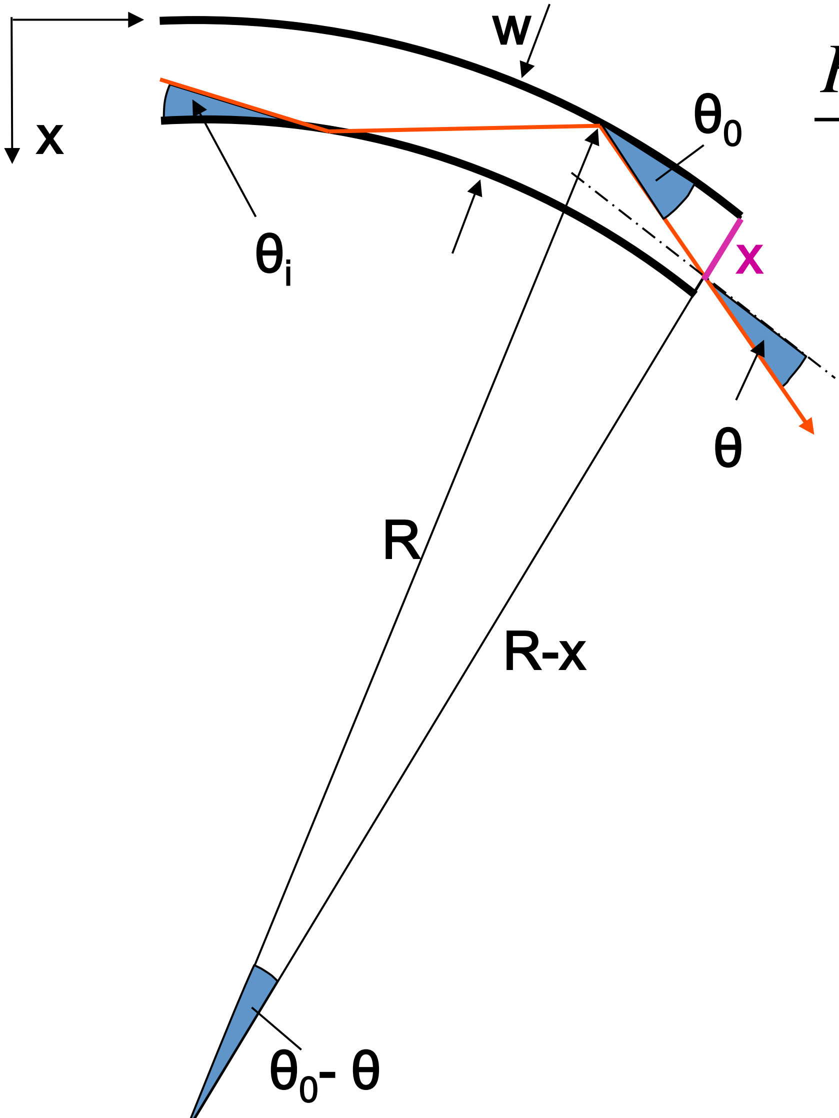
Curved Guides



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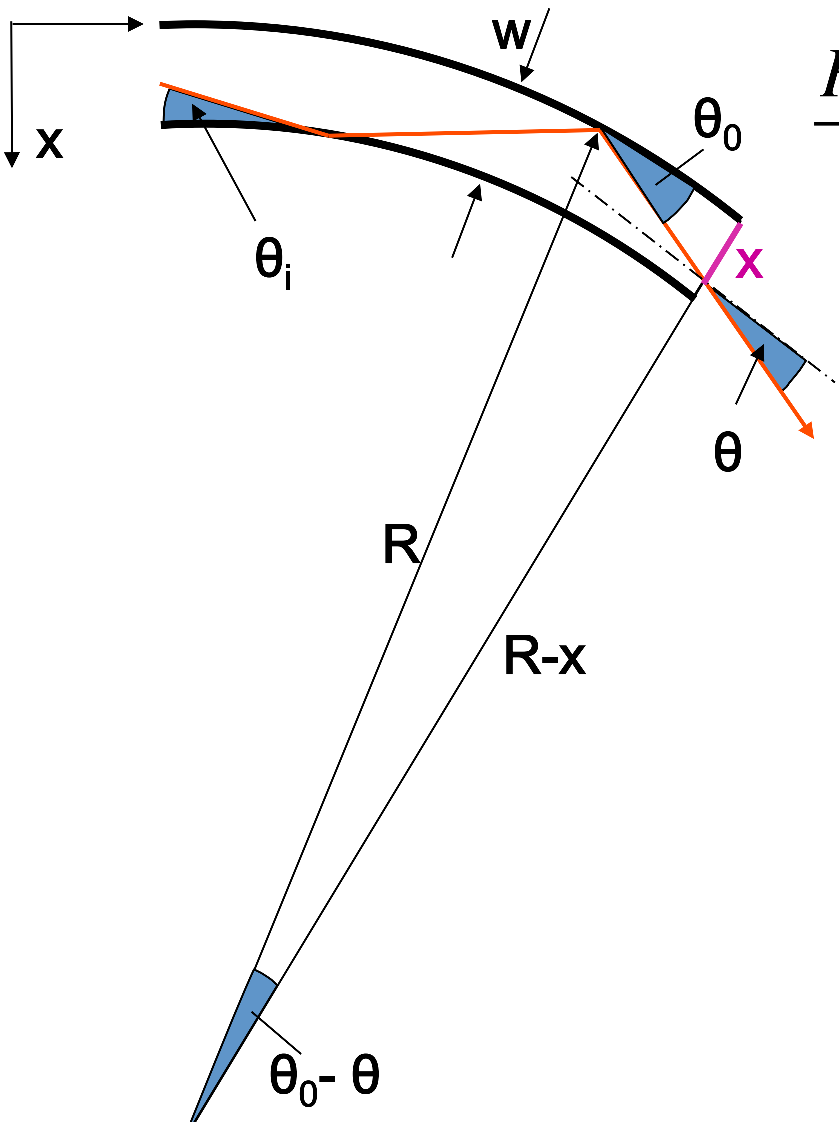
Curved Guides



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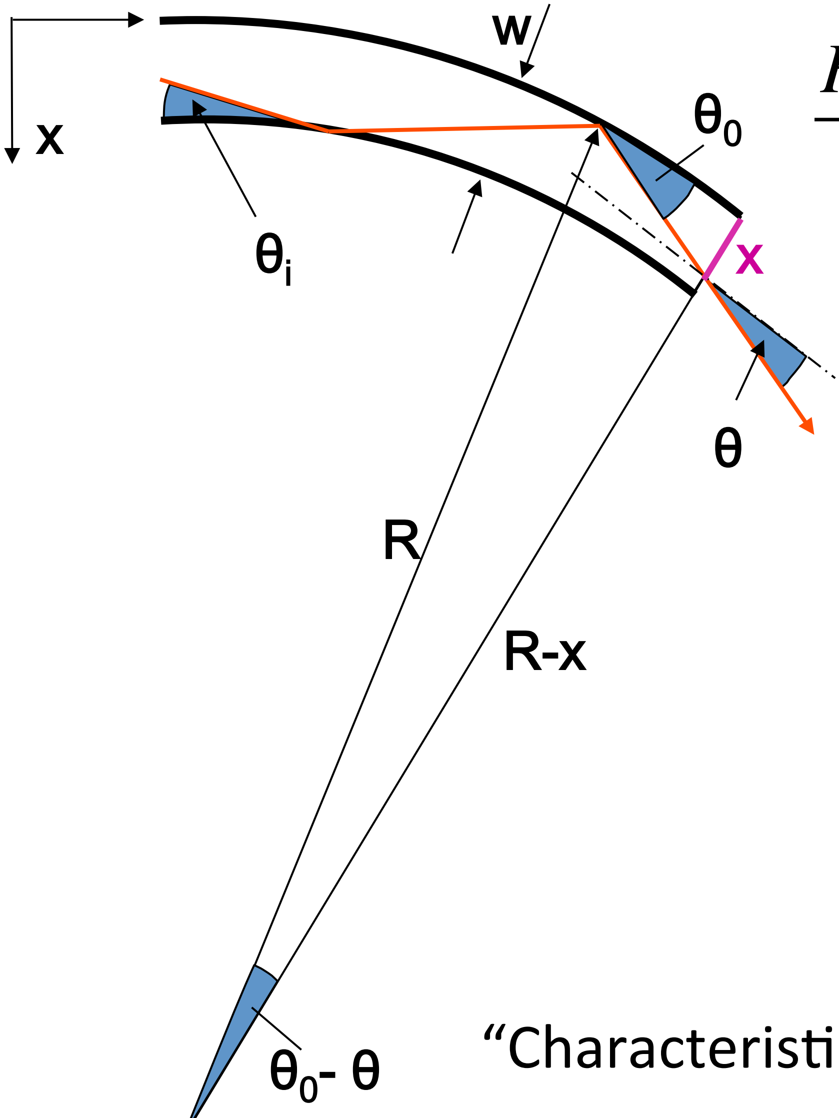
$$\theta_c = \theta_0^* \Rightarrow \lambda^* = \frac{575}{m}\sqrt{2w/R}$$

Curved Guides



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

$$x = -R(\theta^2 - \theta_0^2)$$

neutrons "just" reach inside face

when θ = 0 for x = w :

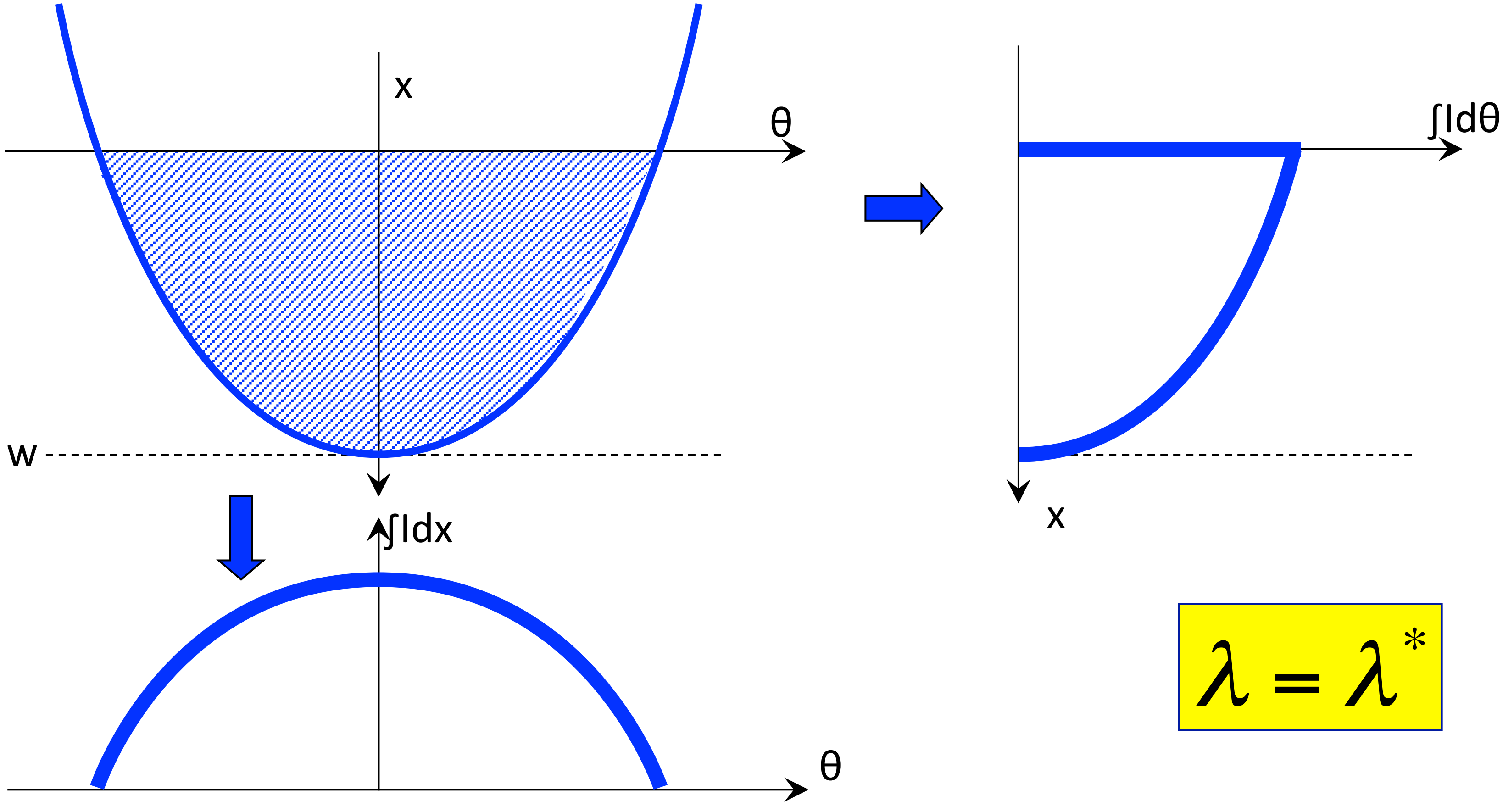
$$\theta_0^* = \sqrt{2w/R}$$

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

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

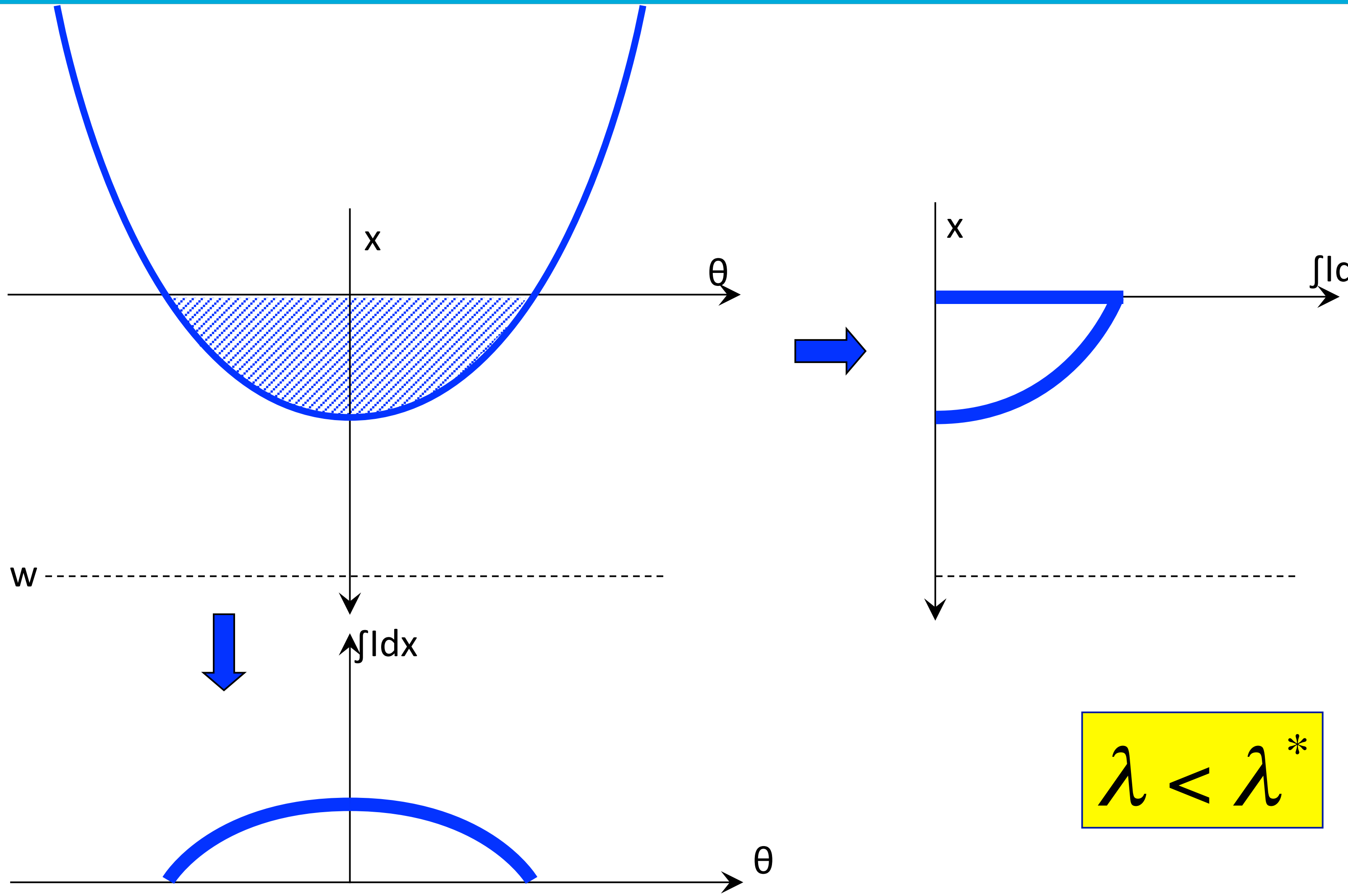
"Characteristic wavelength"

Curved Guides



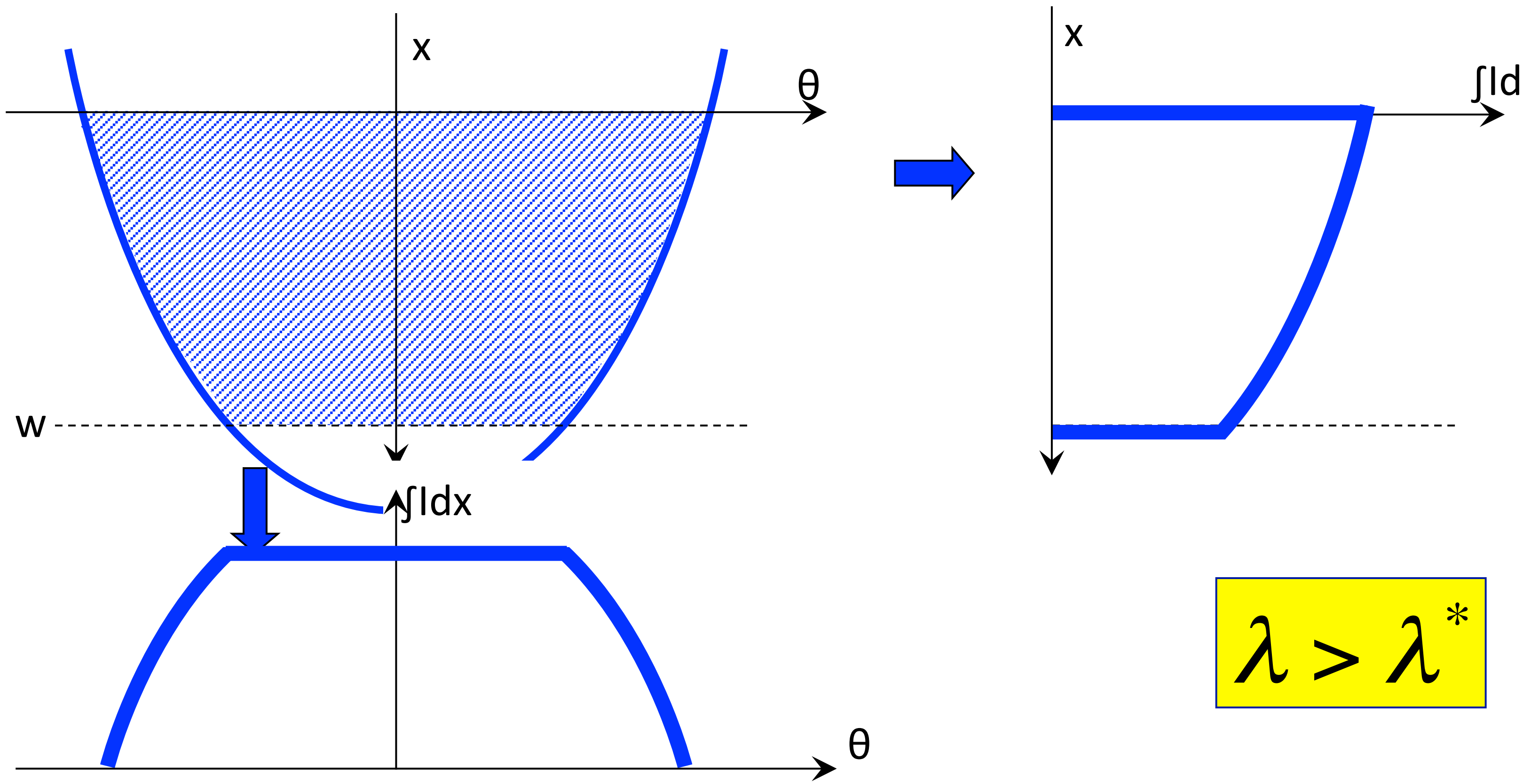
$$\lambda = \lambda^*$$

Curved Guides



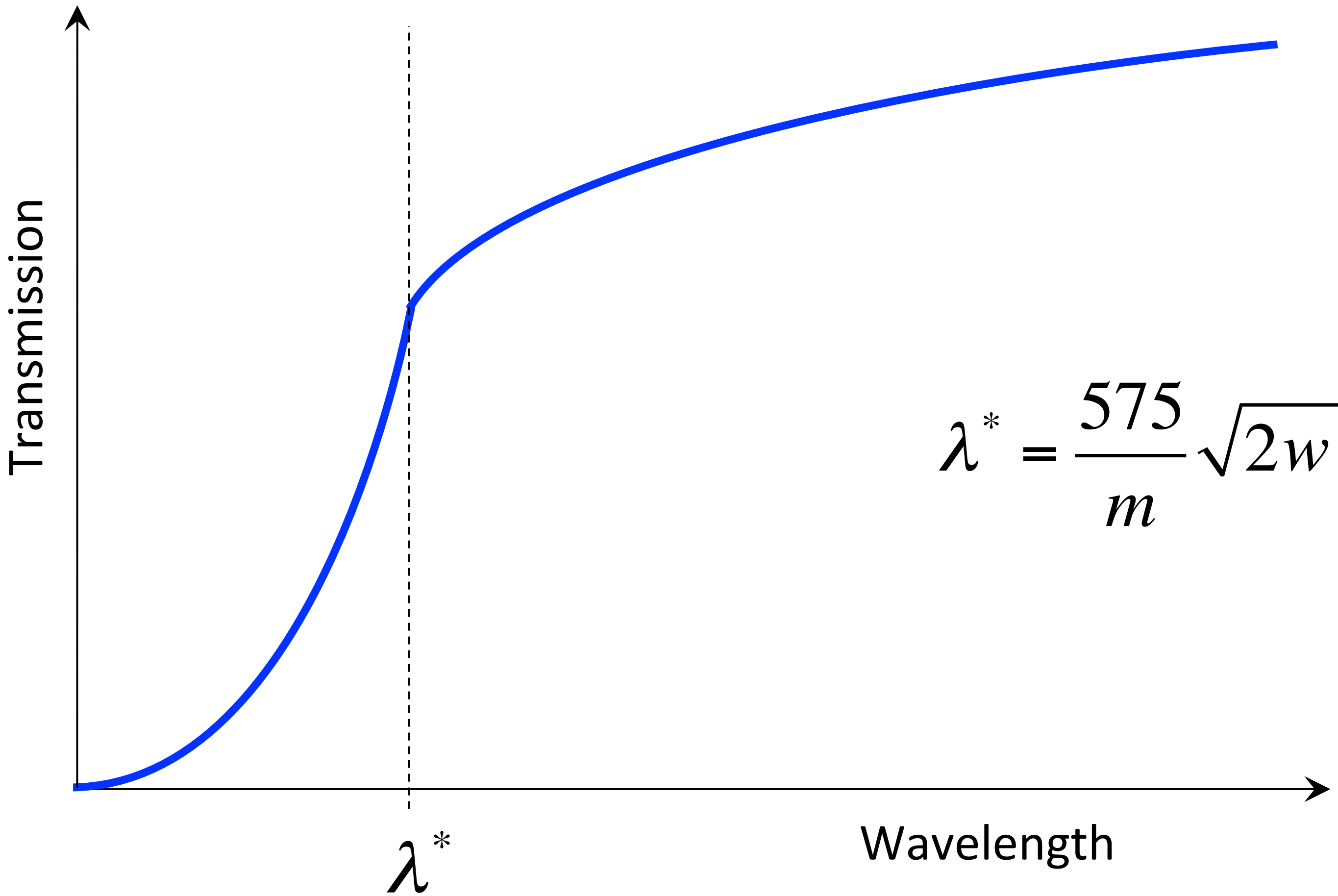
$$\lambda < \lambda^*$$

Curved Guides



$\lambda > \lambda^*$

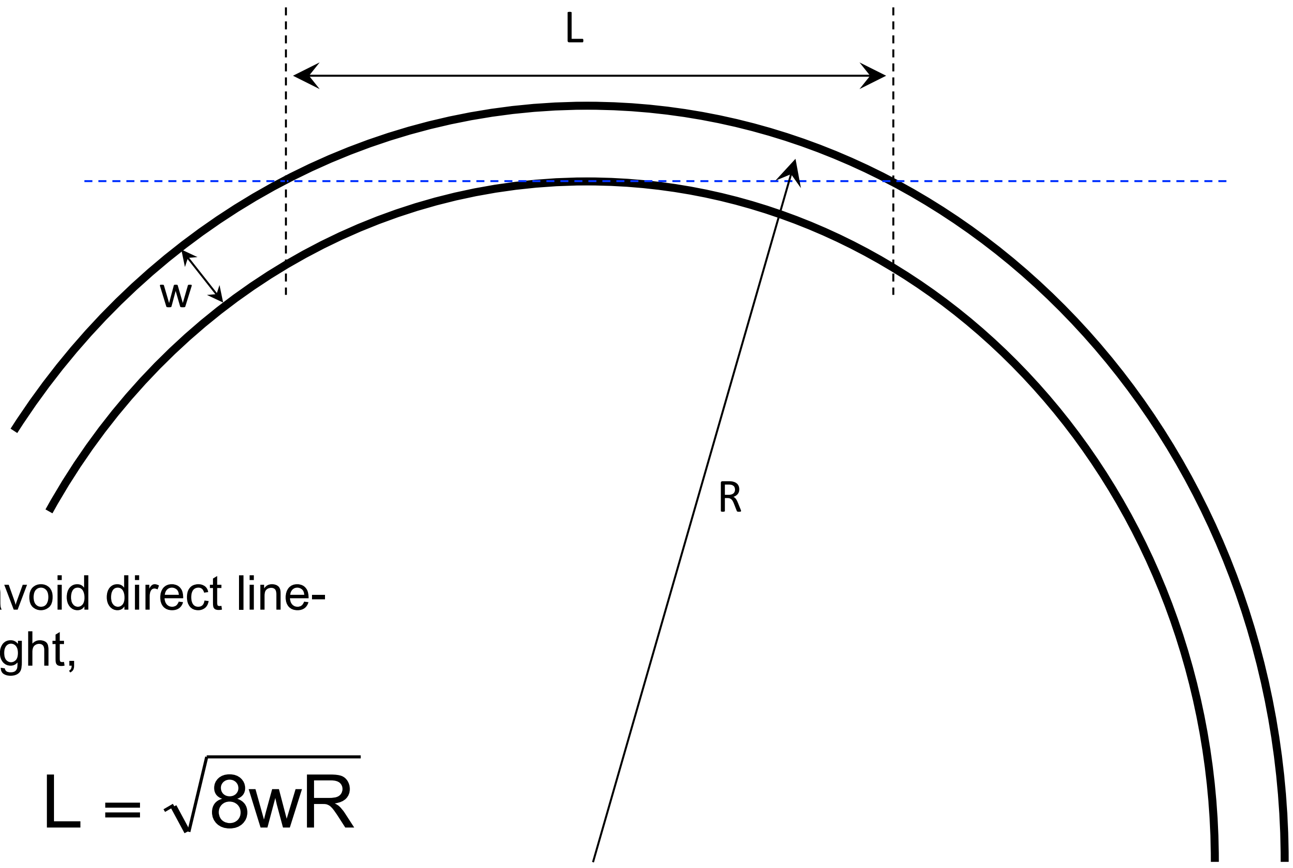
Curved Guides



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

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

Curved Guides

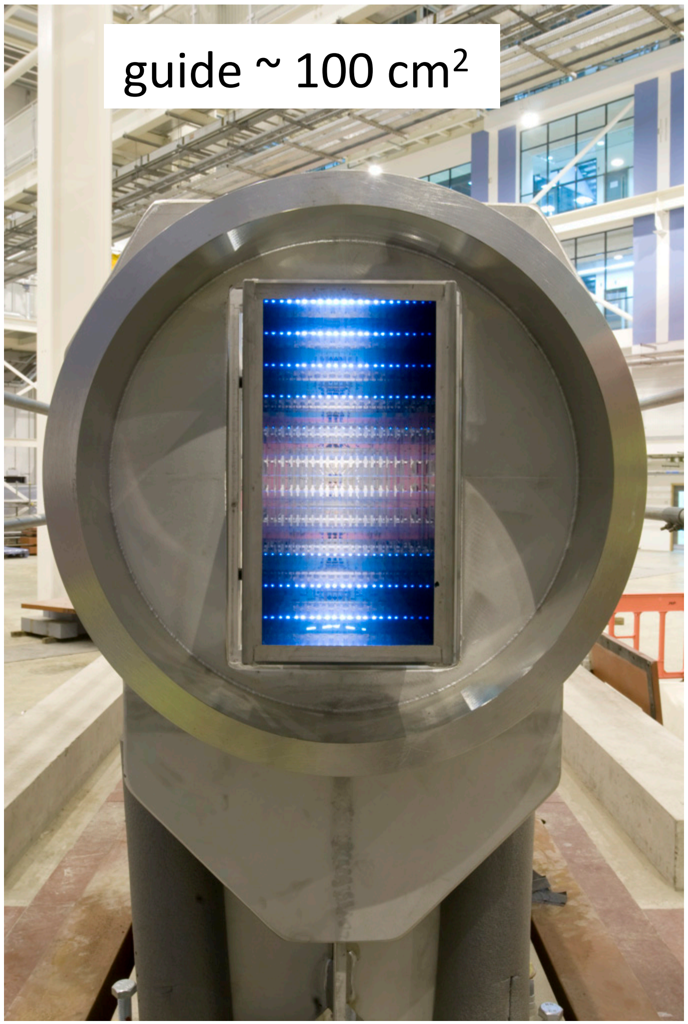


To avoid direct line-of-sight,

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

Focusing

guide ~ 100 cm^2



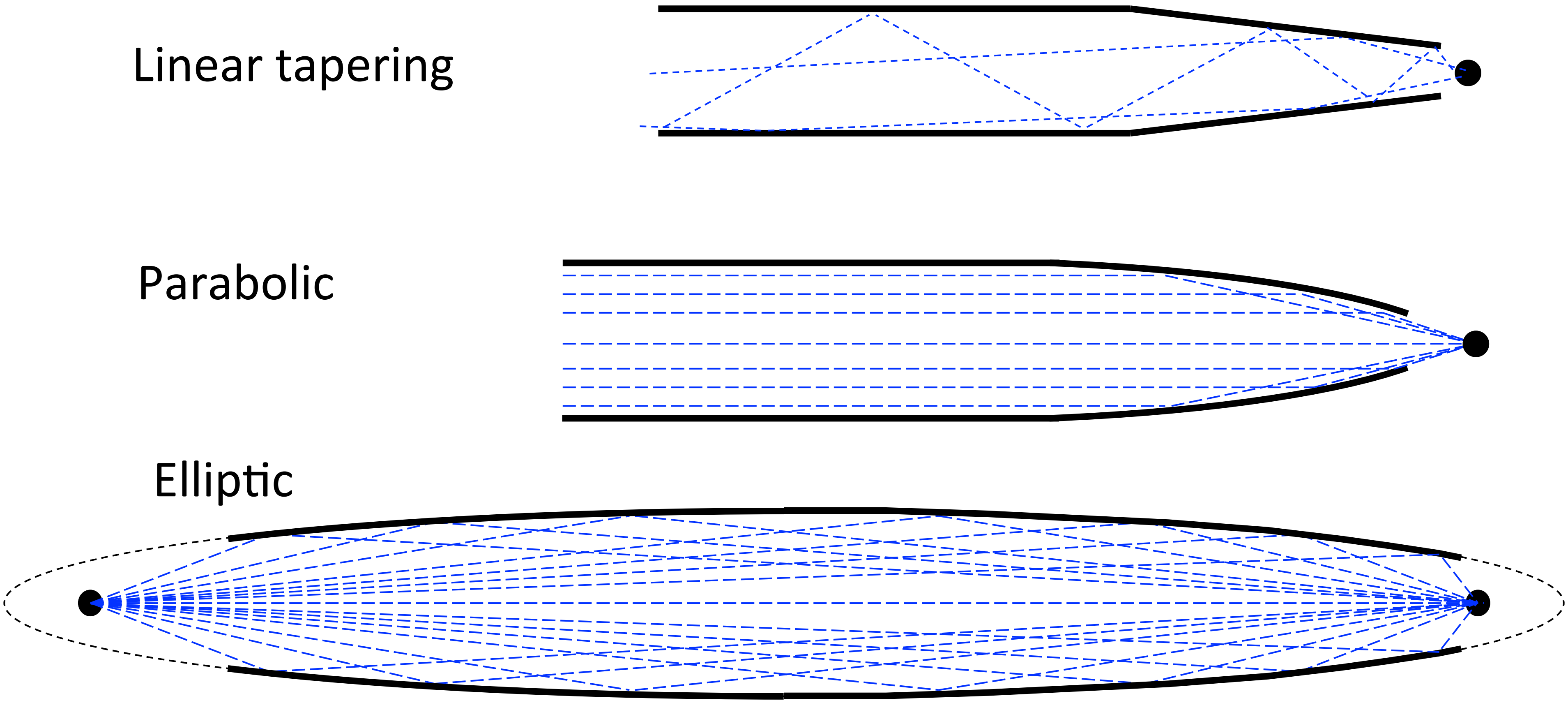
samples < 1 cm^2

Focusing

Linear tapering

Parabolic

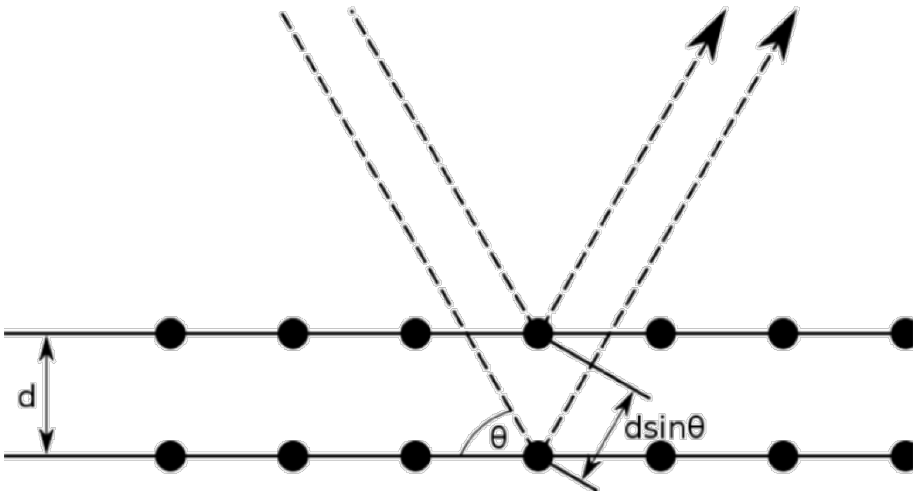
Elliptic



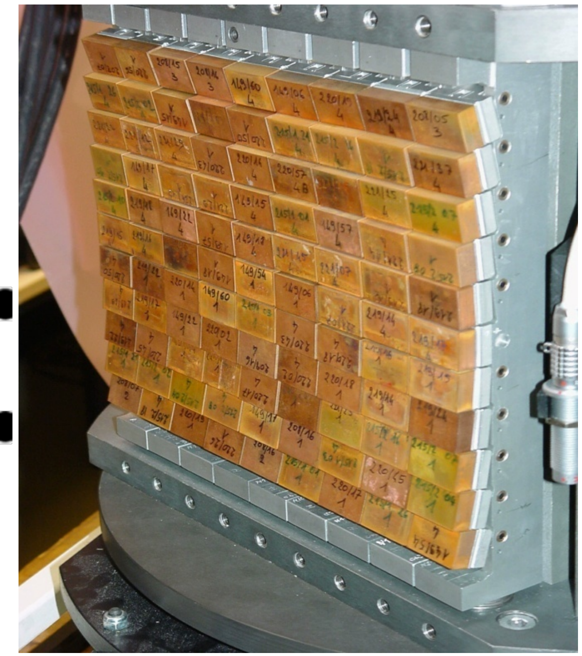
Crystal Monochromators

EUROPEAN SPALLATION SOURCE

Graphite 002



Copper 200



	d-spacing
Germanium 333	1.089 Å
Copper 200	1.807 Å
Silicon 111	3.135 Å
Graphite 002	3.355 Å

Crystal Monochromators

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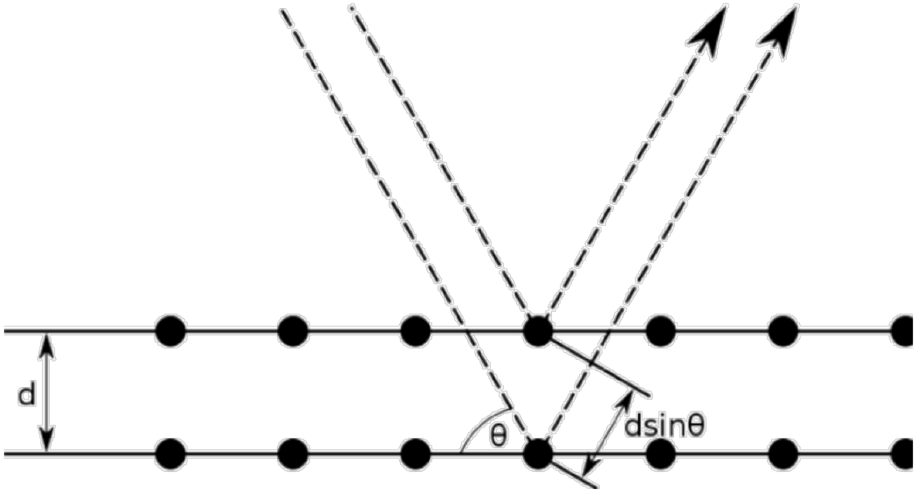
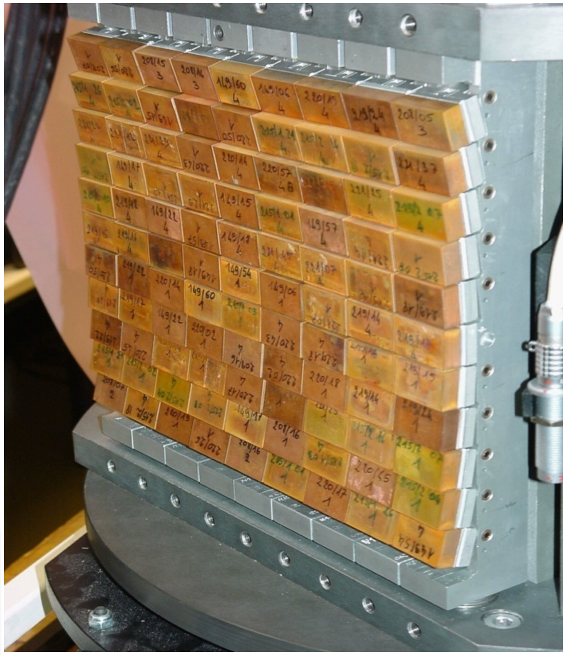
Graphite 002



Copper 200



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

$$\Rightarrow \Delta\lambda/\lambda = \Delta d/d + \cot\theta\Delta\theta$$

$$\Delta\lambda = \frac{\partial\lambda}{\partial d}\Delta d + \frac{\partial\lambda}{\partial\theta}\Delta\theta$$

Crystal Monochromators

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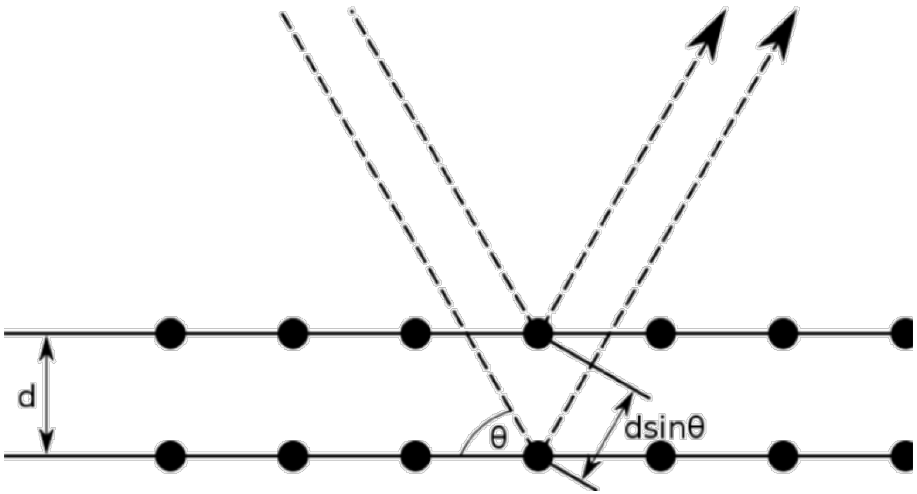
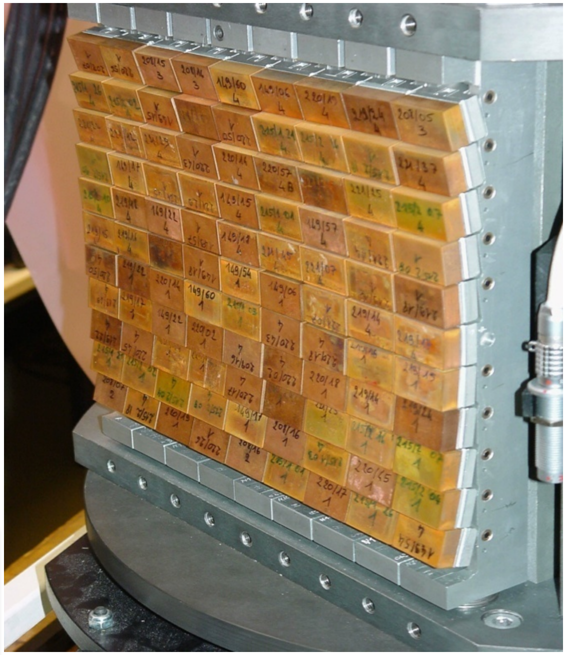
Graphite 002



Copper 200



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

$$\Rightarrow \Delta\lambda/\lambda = \cancel{\Delta d/d} + \cot\theta\Delta\theta$$

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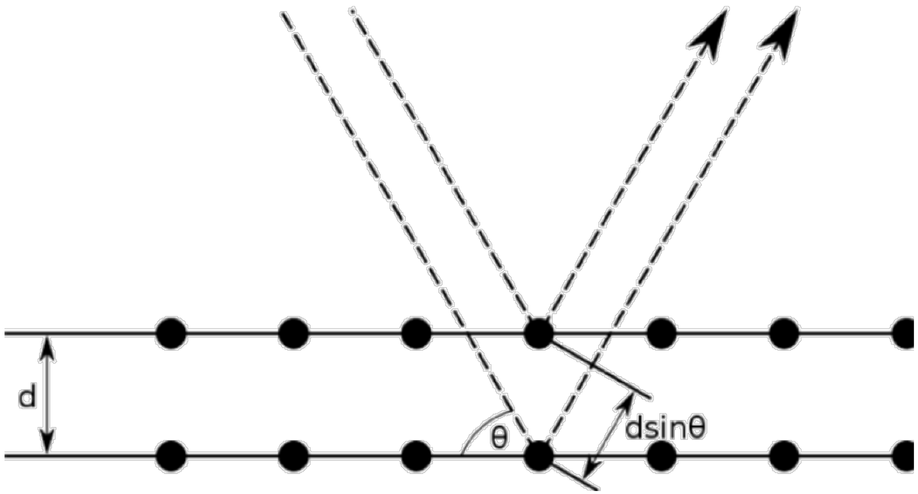
Crystal Monochromators

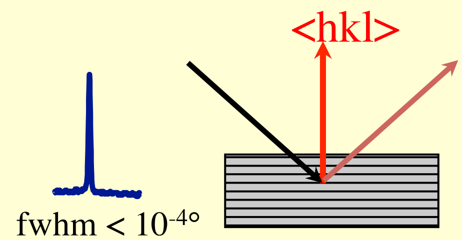
Graphite 002



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

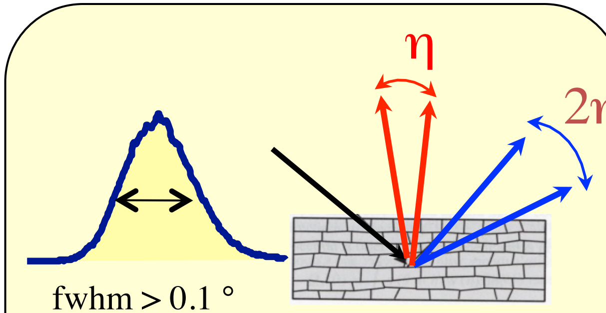
$$\Rightarrow \Delta\lambda/\lambda = \Delta d/d + \cot\theta\Delta\theta$$

$$\Delta\lambda = \frac{\partial\lambda}{\partial d}\Delta d + \frac{\partial\lambda}{\partial\theta}\Delta\theta$$



$\Delta\lambda/\lambda \rightarrow 0$!

Perfect crystal

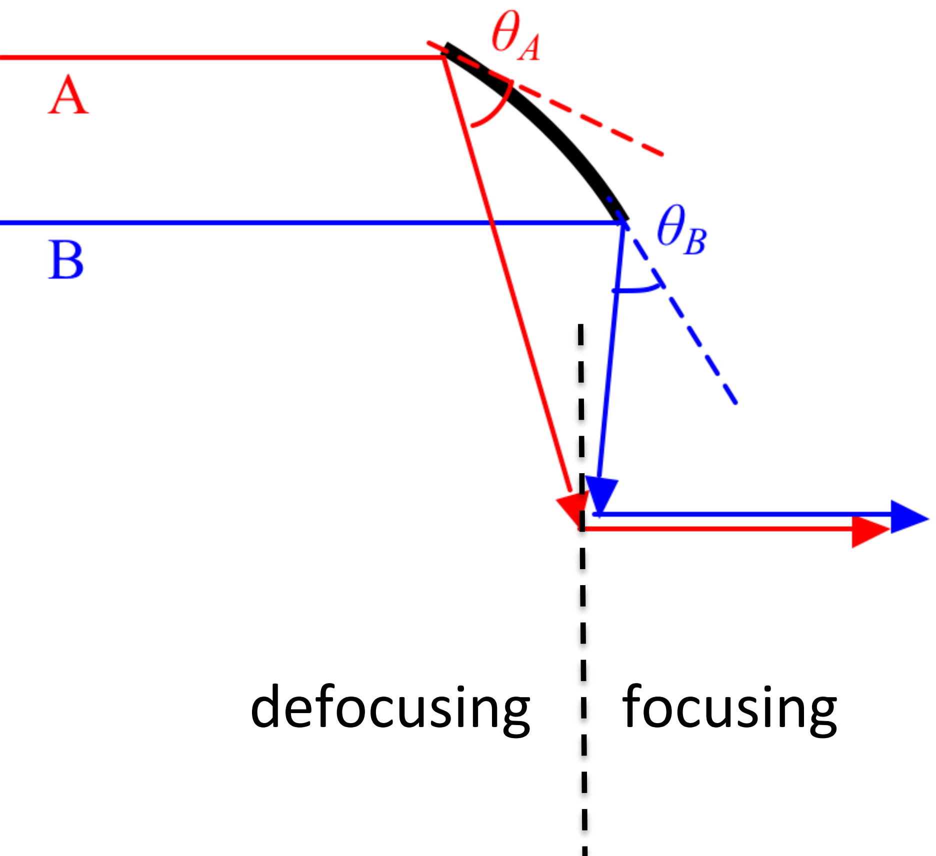


$\Delta\lambda/\lambda = \cot\theta_B\,\Delta\theta$

Mosaic crystal

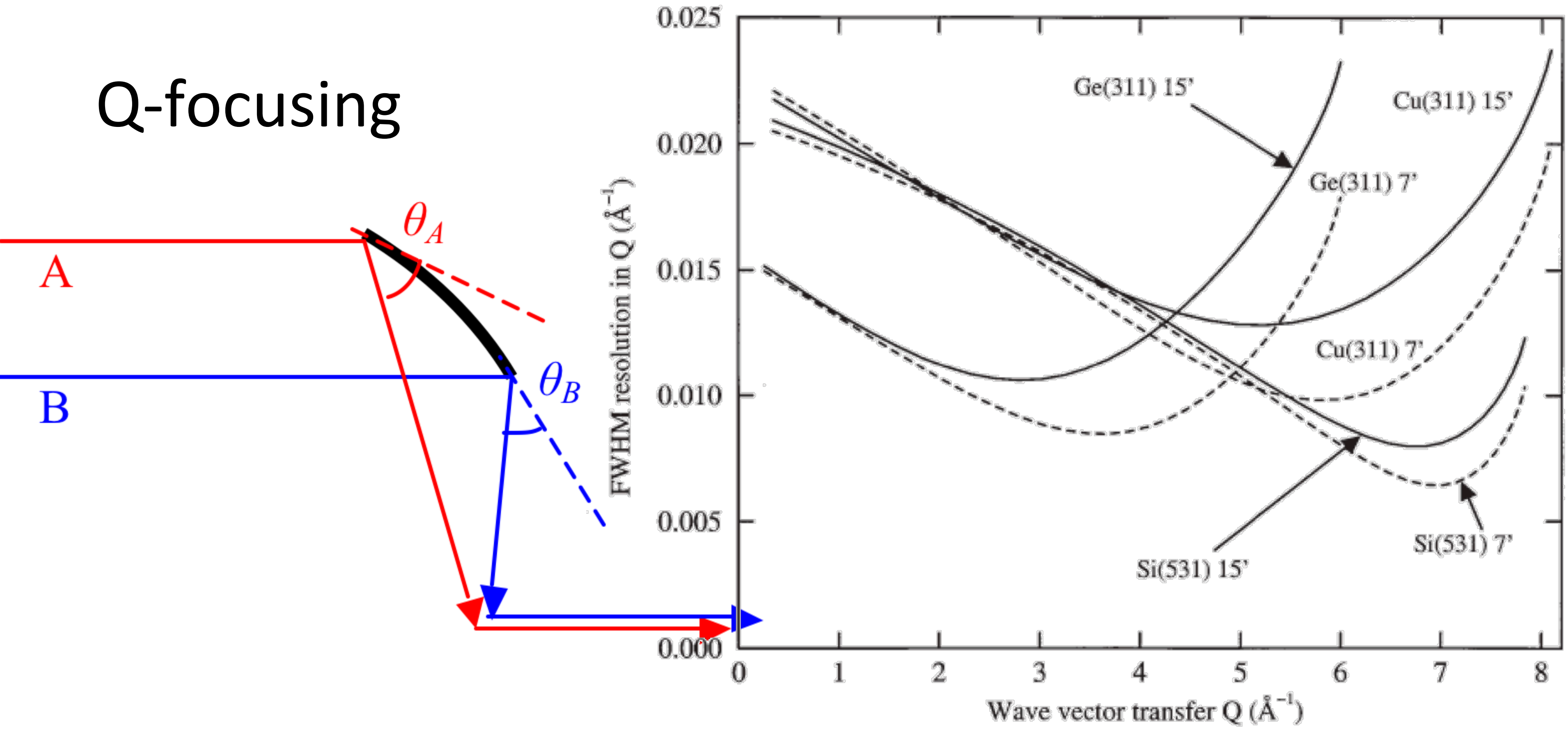
Focusing Monochromators

Q-focusing



Focusing Monochromators

Q-focusing



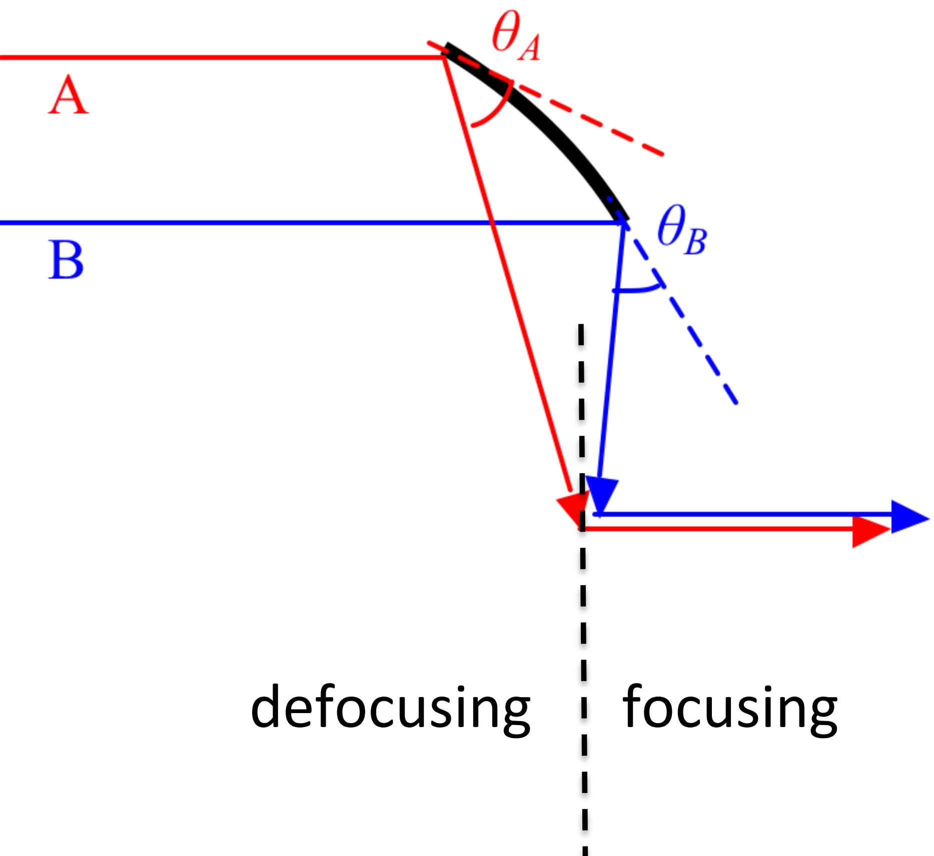
Powder Diffractometer Optimization:

G. Caglioti, A. Paoletti, F.P. Ricci, Nucl. Instr. Meth 3, 223 (1958)

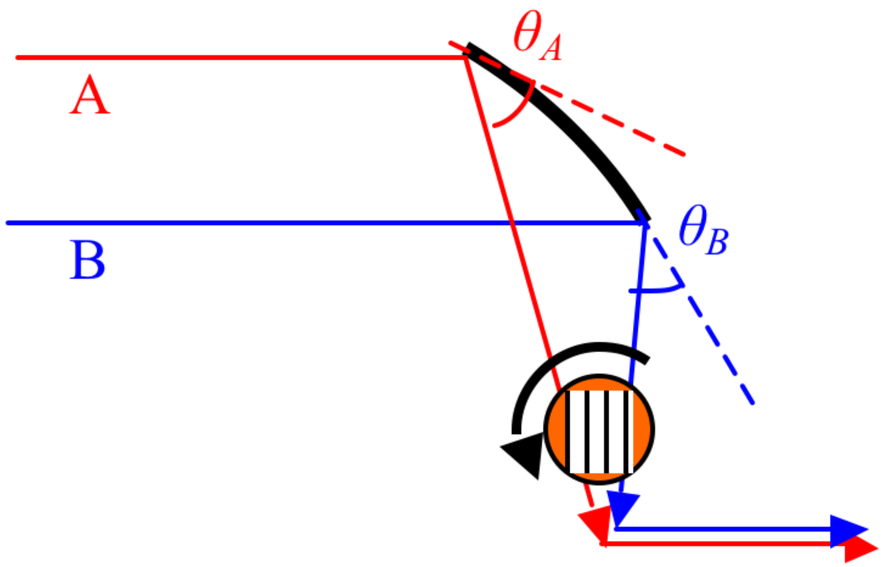
A.W. Hewat, Nucl. Instr. Meth. 127, 361 (1975)

Focusing Monochromators

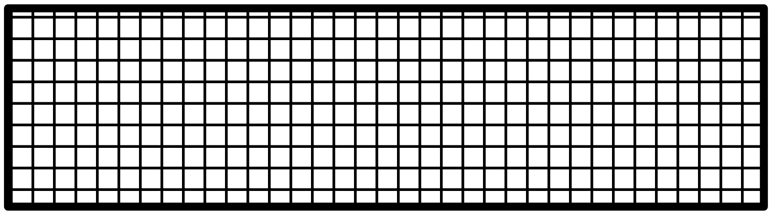
Q-focusing



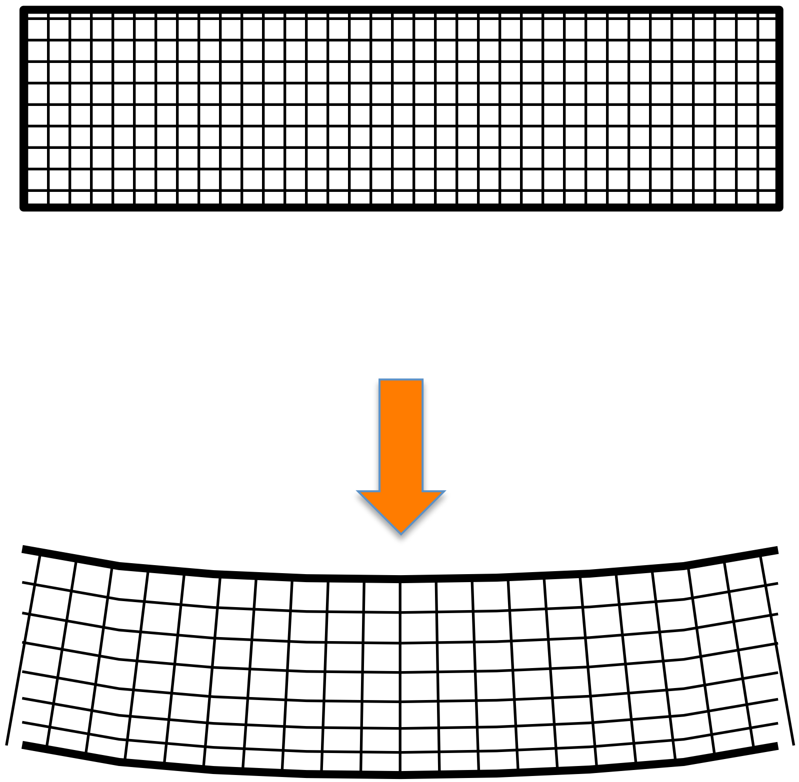
Time-focusing



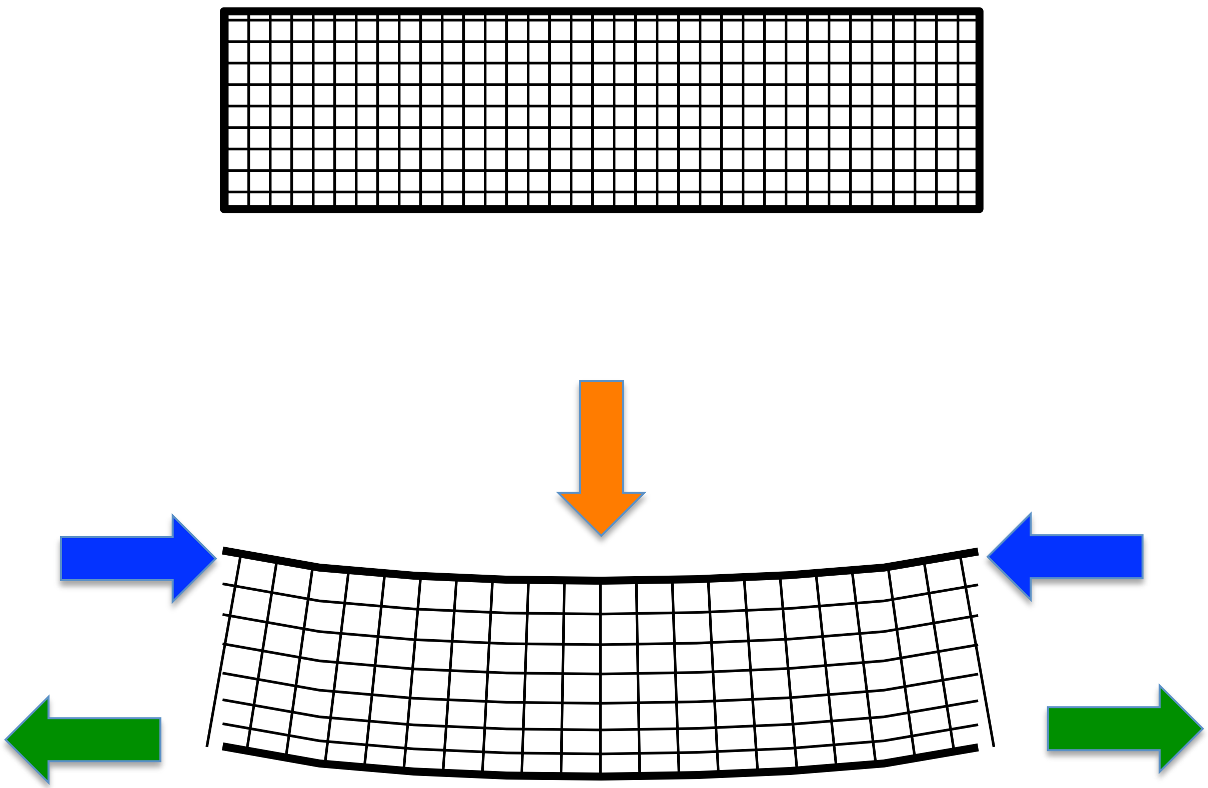
Bent Perfect Crystal Monochromators



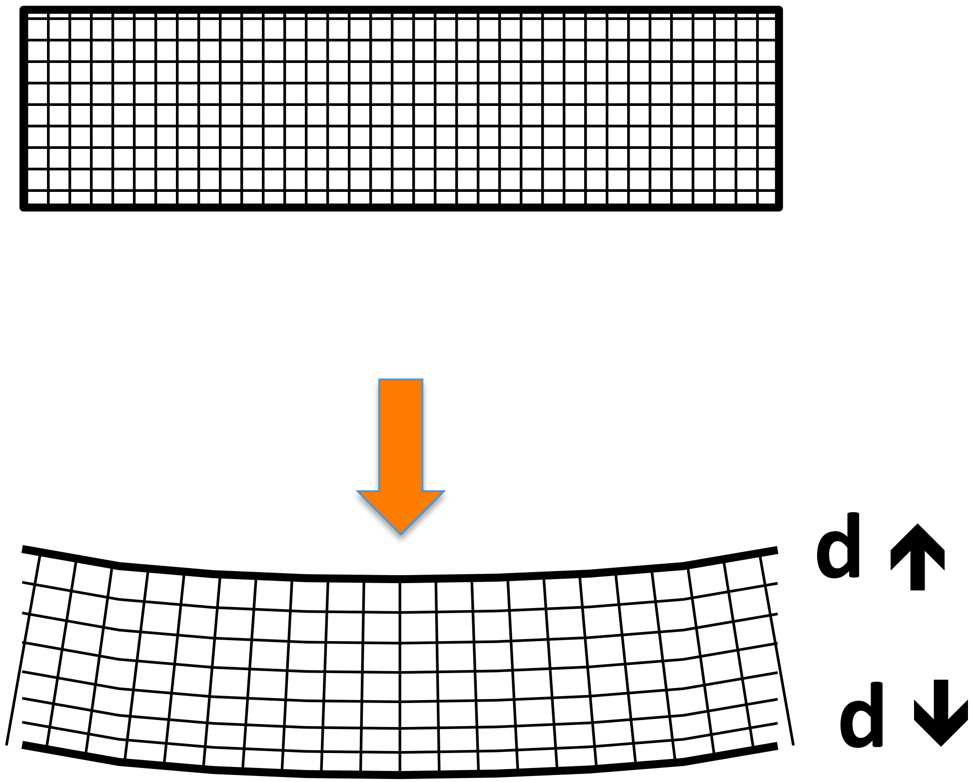
Bent Perfect Crystal Monochromators



Bent Perfect Crystal Monochromators

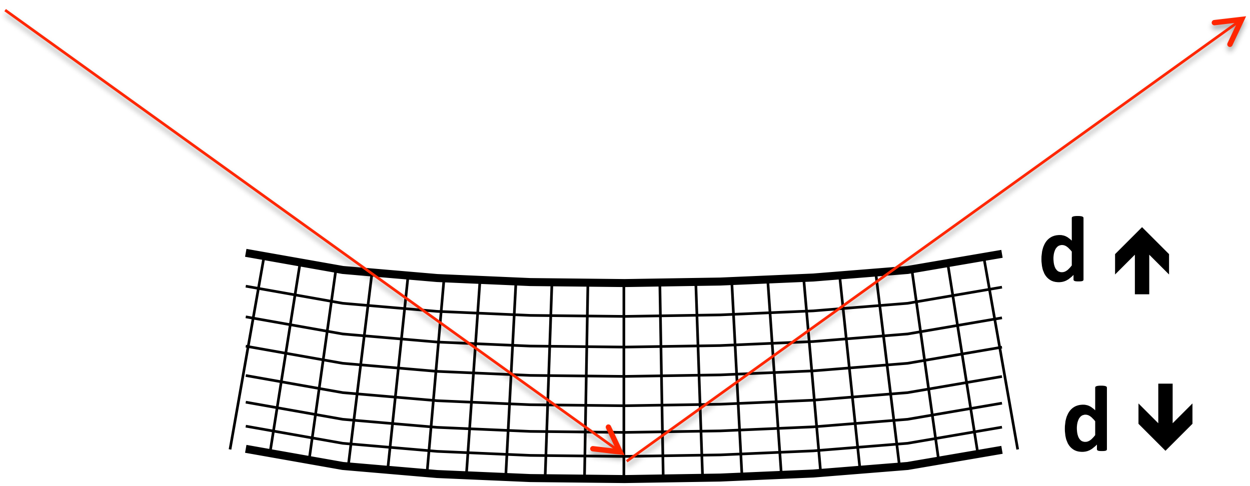


Bent Perfect Crystal Monochromators



Bent Perfect Crystal Monochromators

1. d-spacing varies with depth
2. orientation varies with depth



Summary

- Bragg's Law
- Neutron Guides
  - how they work
  - what they do
- Crystal Monochromators
- tools for calculating how they work …

Thank you!

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