Neutron Instrumentation

Oxford School on Neutron Scattering

9th September 2015

Ken Andersen

Summary

- Neutron instrument concepts
  - time of flight
  - Bragg's law
  - Liouville's theorem
- Neutron Instrumentation
  - guides
  - detectors
  - choppers
- Neutron diffractometers
- Neutron spectrometers

De Broglie Relations

Particle	Wave
$p = mv$	$p = \hbar k = h/\lambda$
$E = \frac{1}{2}mv^2$	$E = \hbar\omega = hf$

$$\hbar = h/2\pi$$

$$h = 6.6 \times 10^{-34}\,\mathrm{J \cdot s}$$

$$m_n = 1.67 \times 10^{-27}\,\mathrm{kg}$$

$$\lambda = h / mv$$

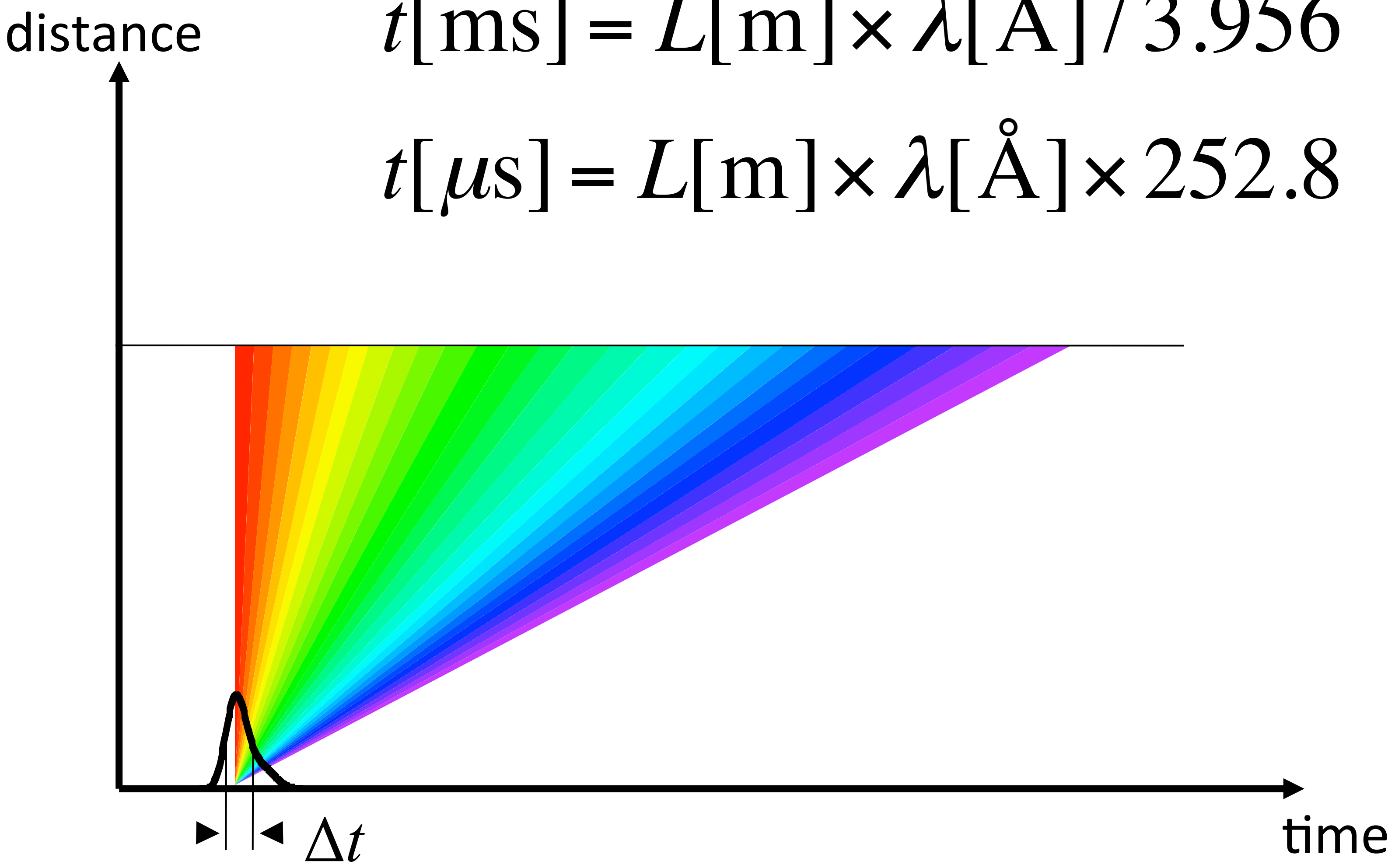
$$\lambda[\text{Å}] = 3.956 / v[\mathrm{m/ms}]$$

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

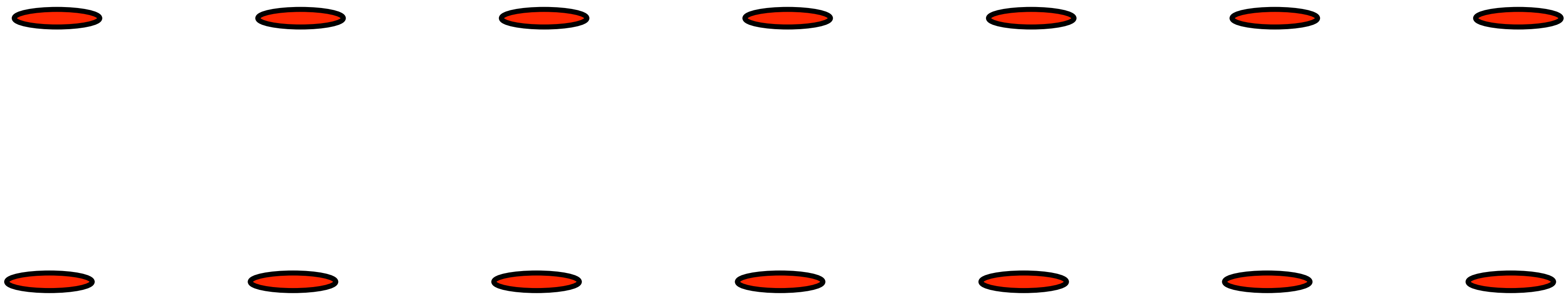
The time-of-flight (TOF) method

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

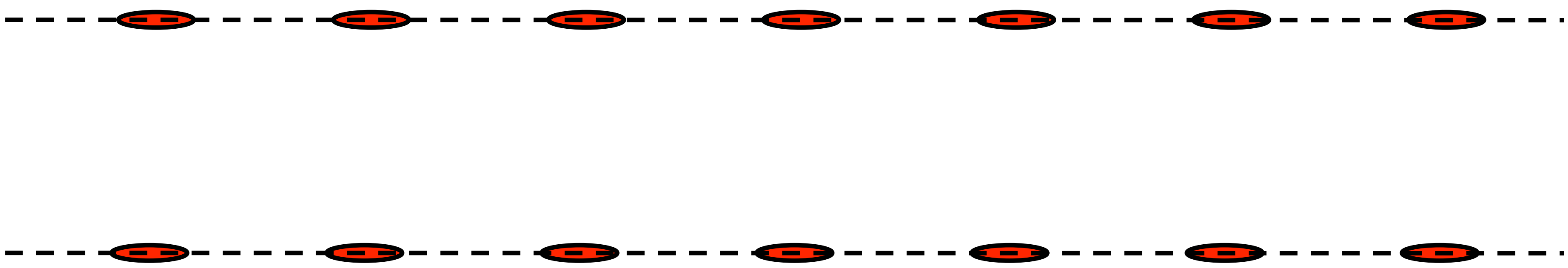
$$t[\mu\mathrm{s}] = L[\mathrm{m}] \times \lambda[\text{Å}] \times 252.8$$



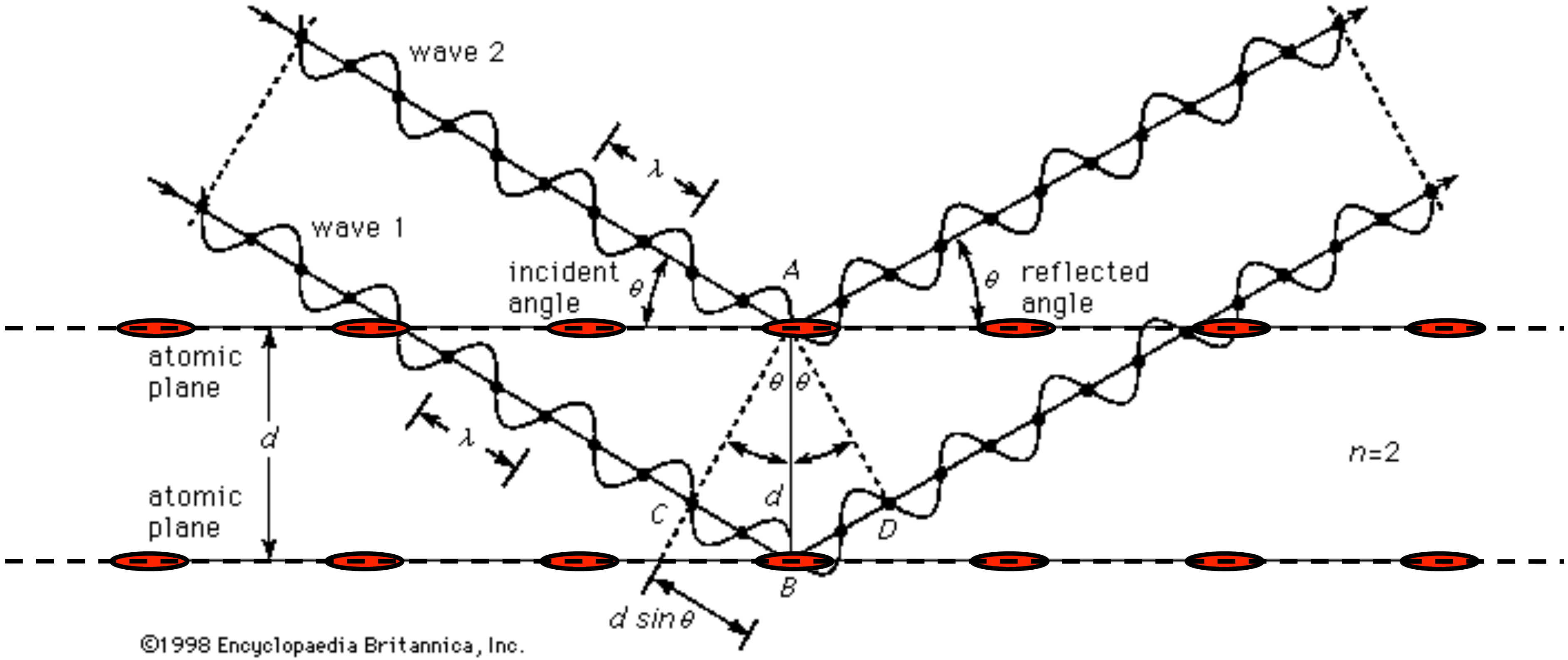
Diffraction: Bragg's Law



Diffraction: Bragg's Law

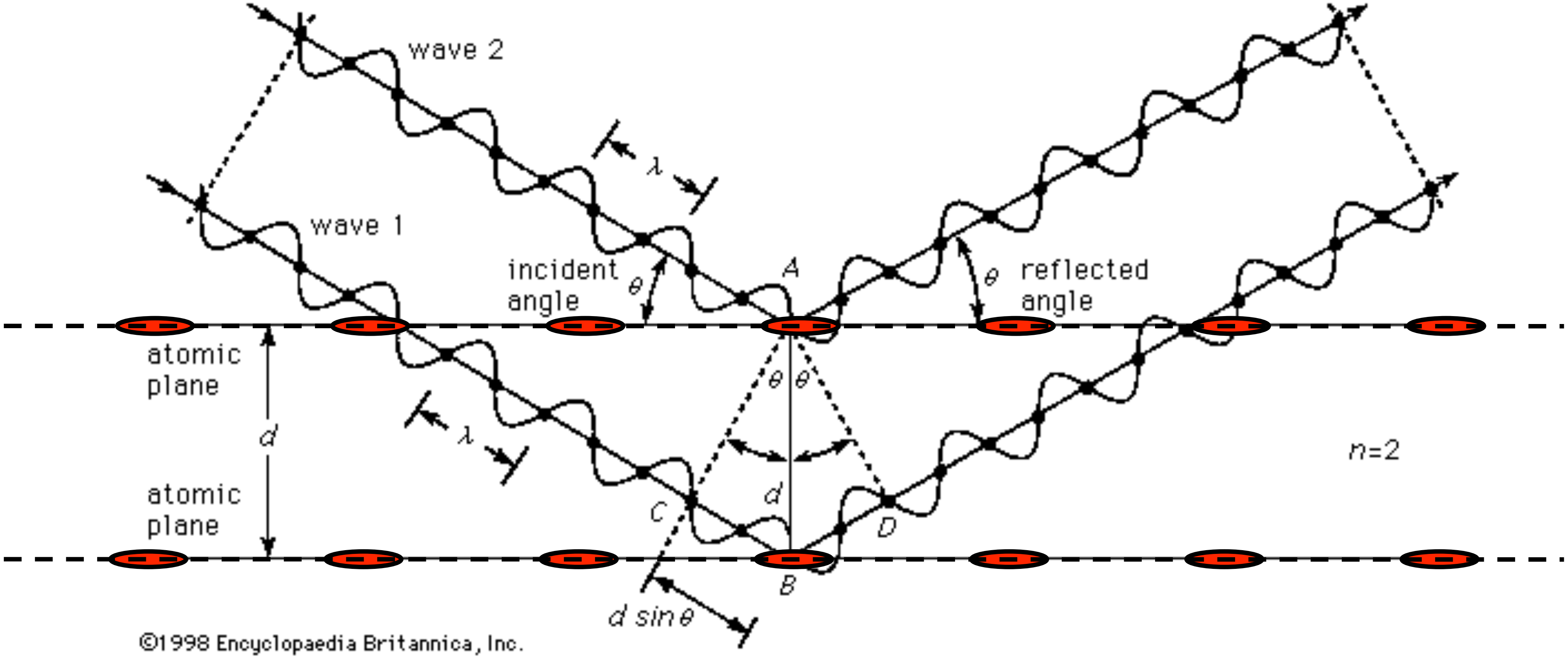


Diffraction: Bragg's Law



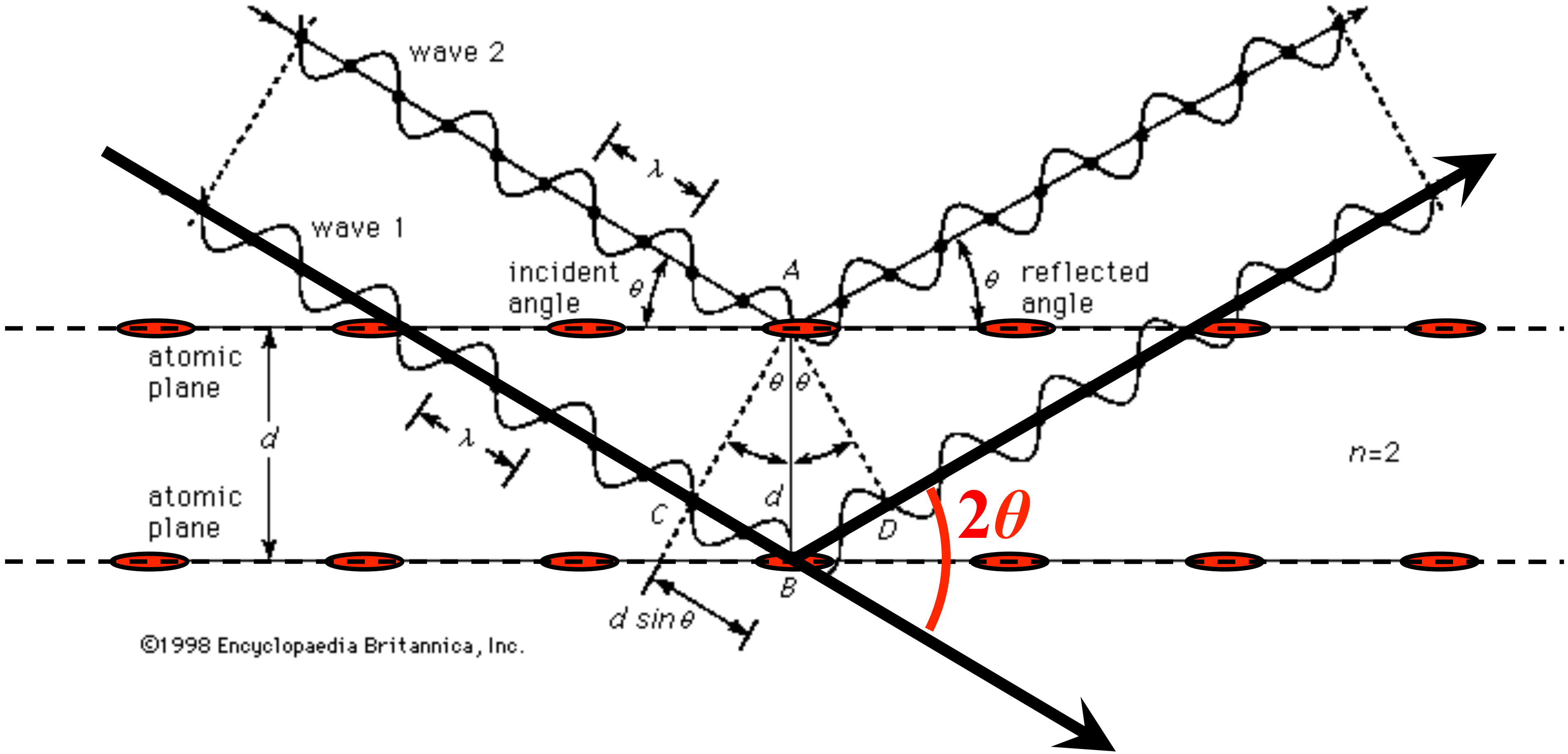
Diffraction: Bragg's Law

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



Diffraction: Bragg's Law

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

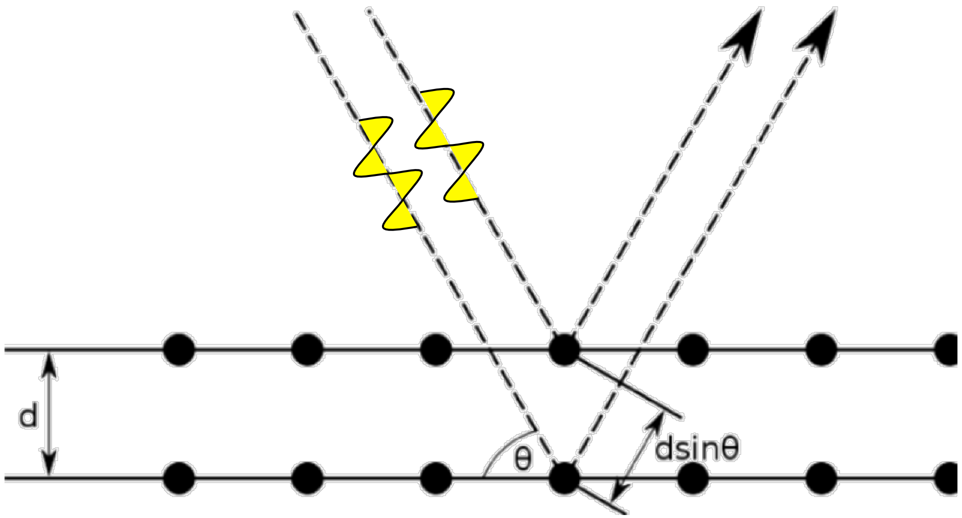


Diffraction: Bragg's Law

Wavevector:

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

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



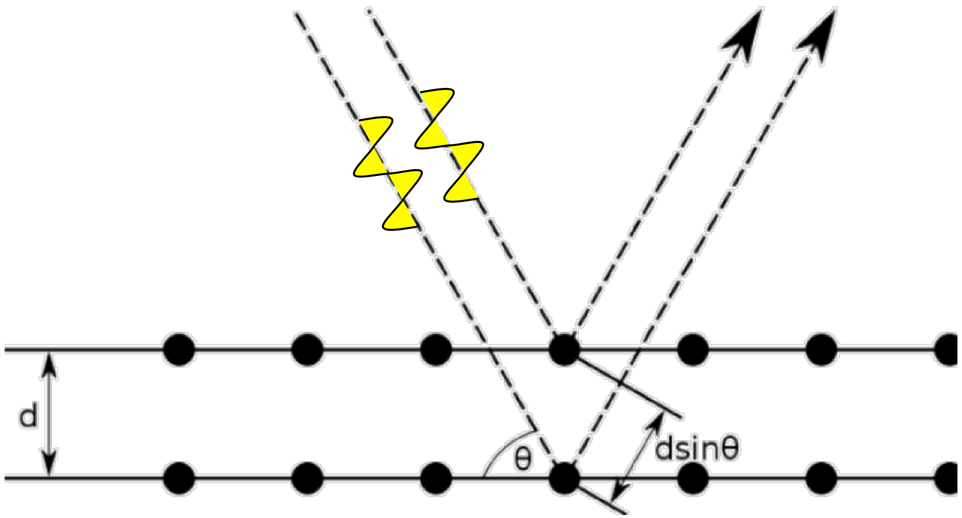
Diffraction: Bragg's Law

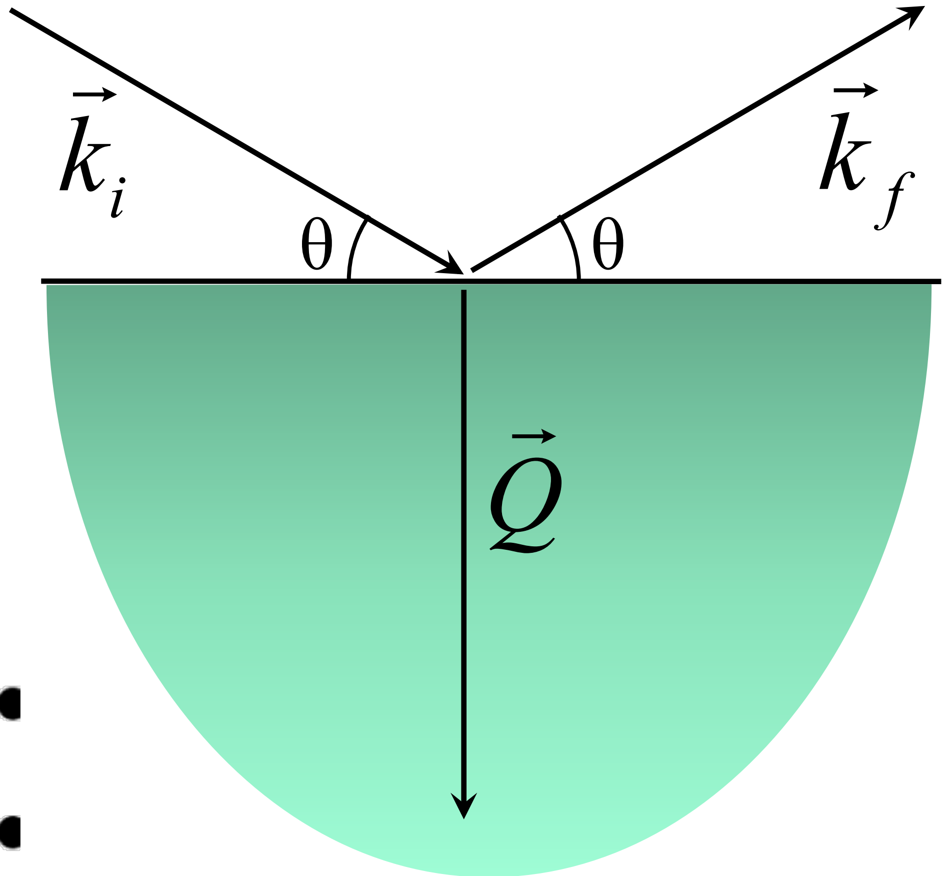
Wavevector:

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

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

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

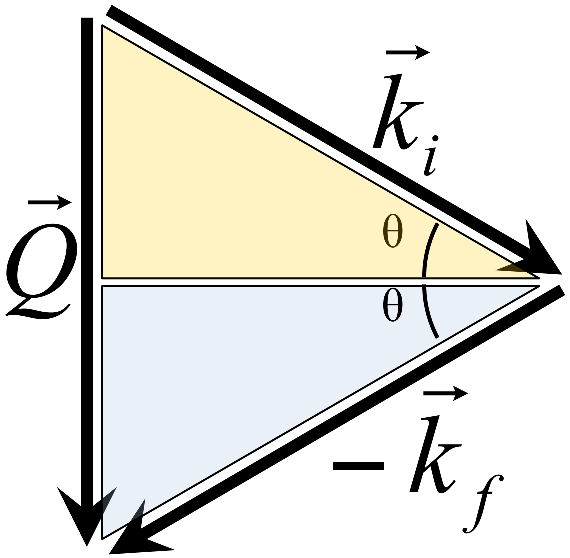


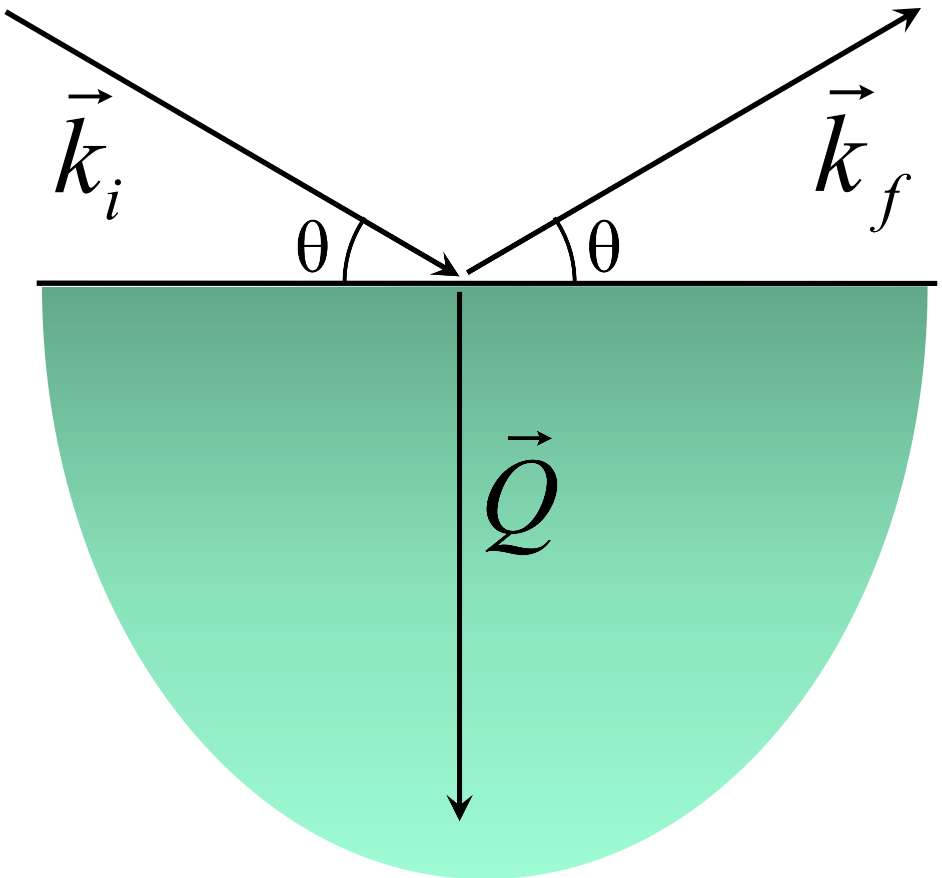


Diffraction: Bragg's Law

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

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

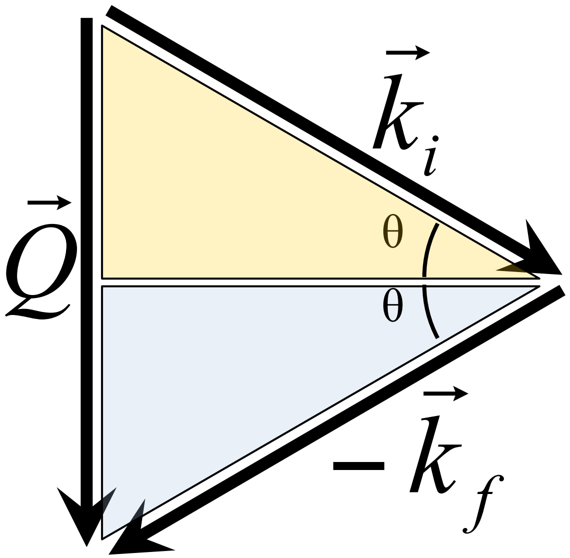




Diffraction: Bragg's Law

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

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



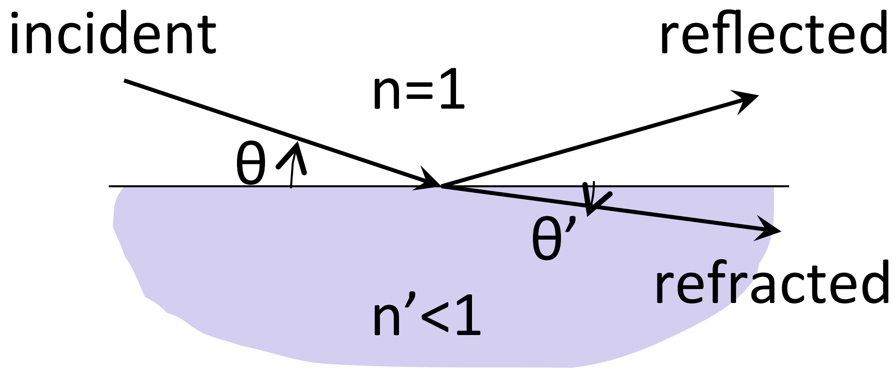
$$Q = 2k\sin\theta$$

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

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

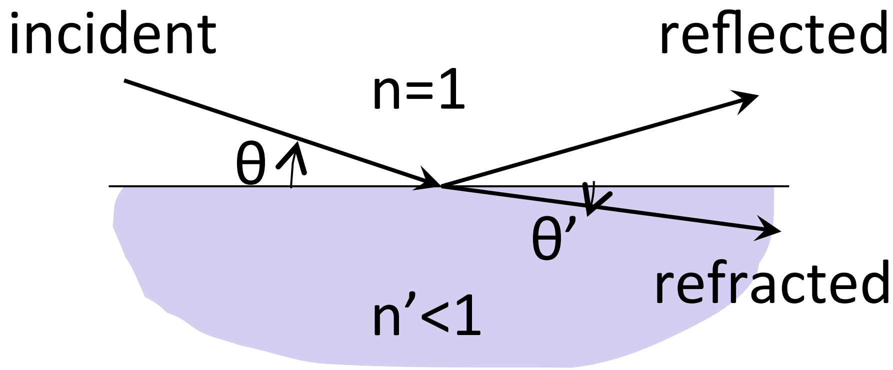
Bragg's Law: $\boxed{Q = \frac{2\pi}{d}}$

Reflection: Snell's Law



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

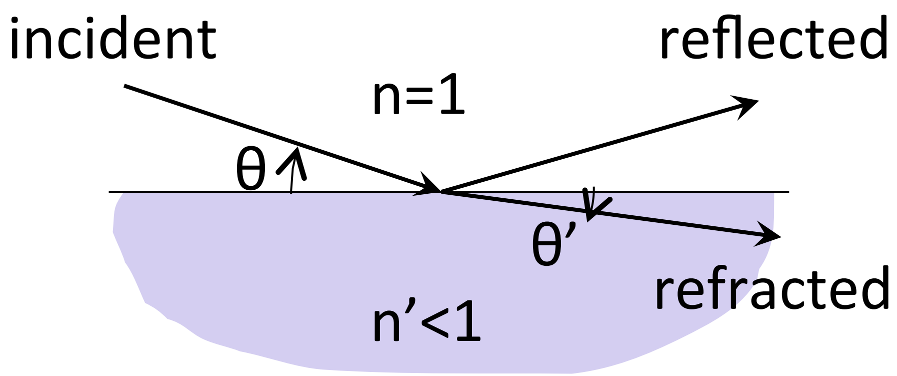
Reflection: Snell's Law



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

θ'=0: critical angle of total reflection θ_c

Reflection: Snell's Law

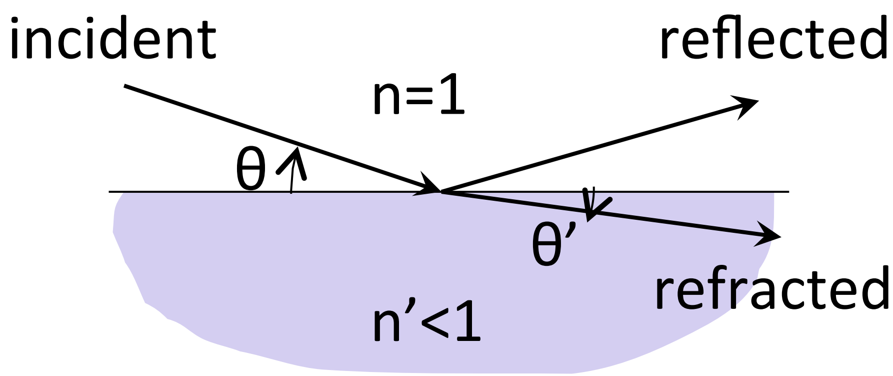


$$\frac{\cos\theta}{\cos\theta'} = \frac{v_1}{v_2} = \frac{n'}{n} = n'$$

θ'=0: 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



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

θ'=0: critical angle of total reflection θ_c

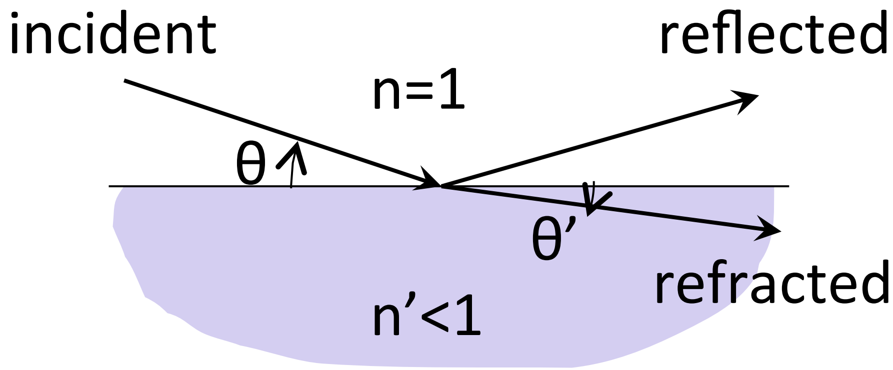
$$\left.\begin{aligned} \cos\theta_c &= n'/n = n' \\ n' &= 1 - \frac{N\lambda^2 b}{2\pi} \\ \cos\theta_c &\approx 1 - \theta_c^2/2 \end{aligned}\right\} \Rightarrow \theta_c = \lambda\sqrt{Nb/\pi}$$

for natural Ni,

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

$Q_c = 0.0218$ Å^{-1}

Reflection: Snell's Law



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

θ'=0: 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:

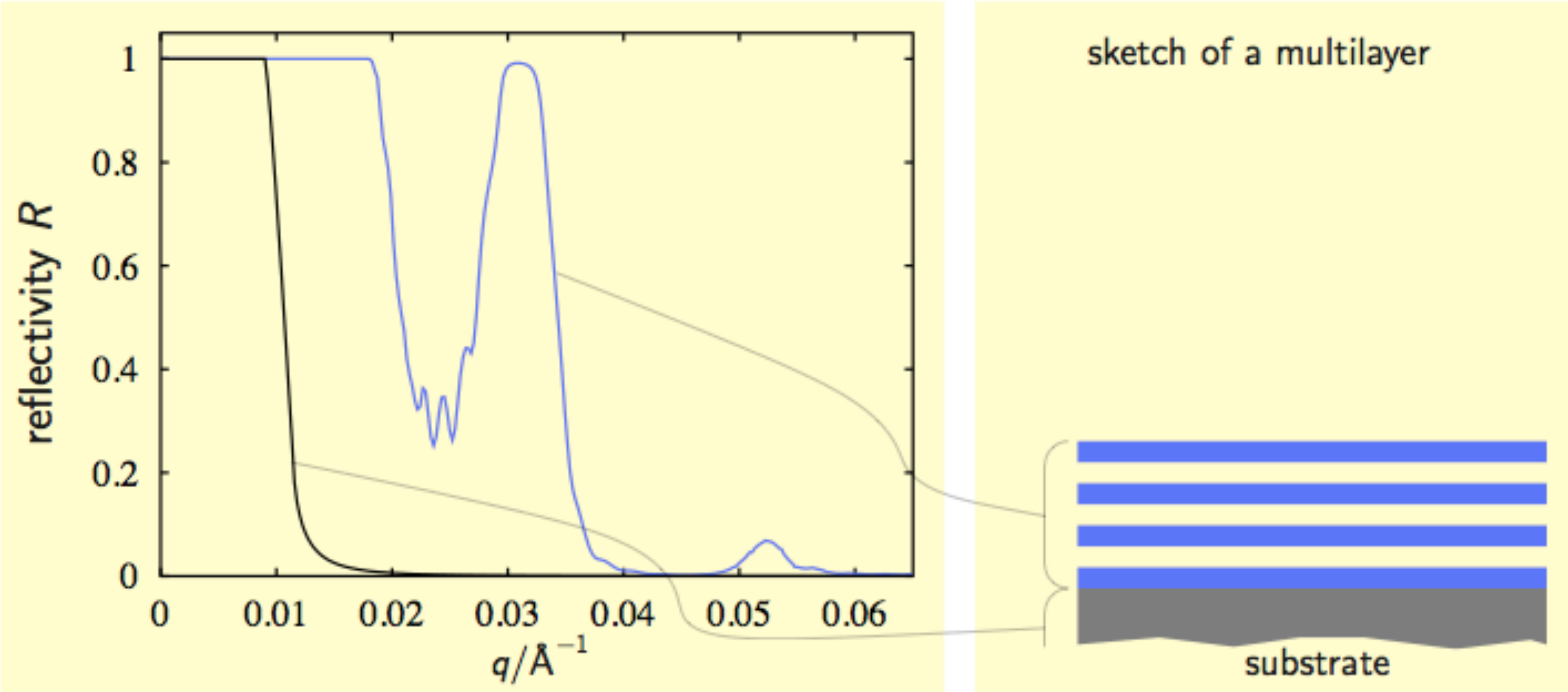
$$Q = 4\pi \sin\theta / \lambda$$

for natural Ni,

$\theta_c = \lambda[Å] \times 0.1°$

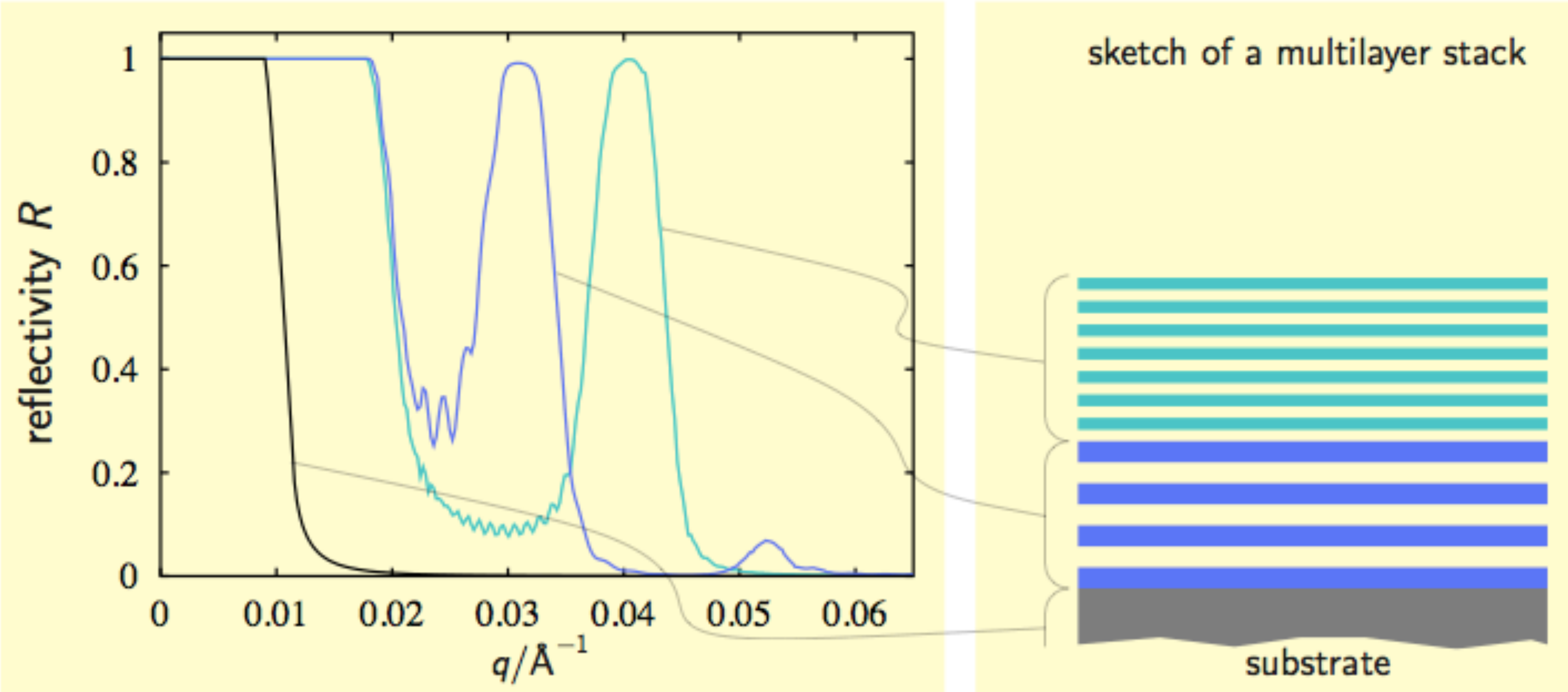
$Q_c = 0.0218$ $Å^{-1}$

Neutron Supermirrors



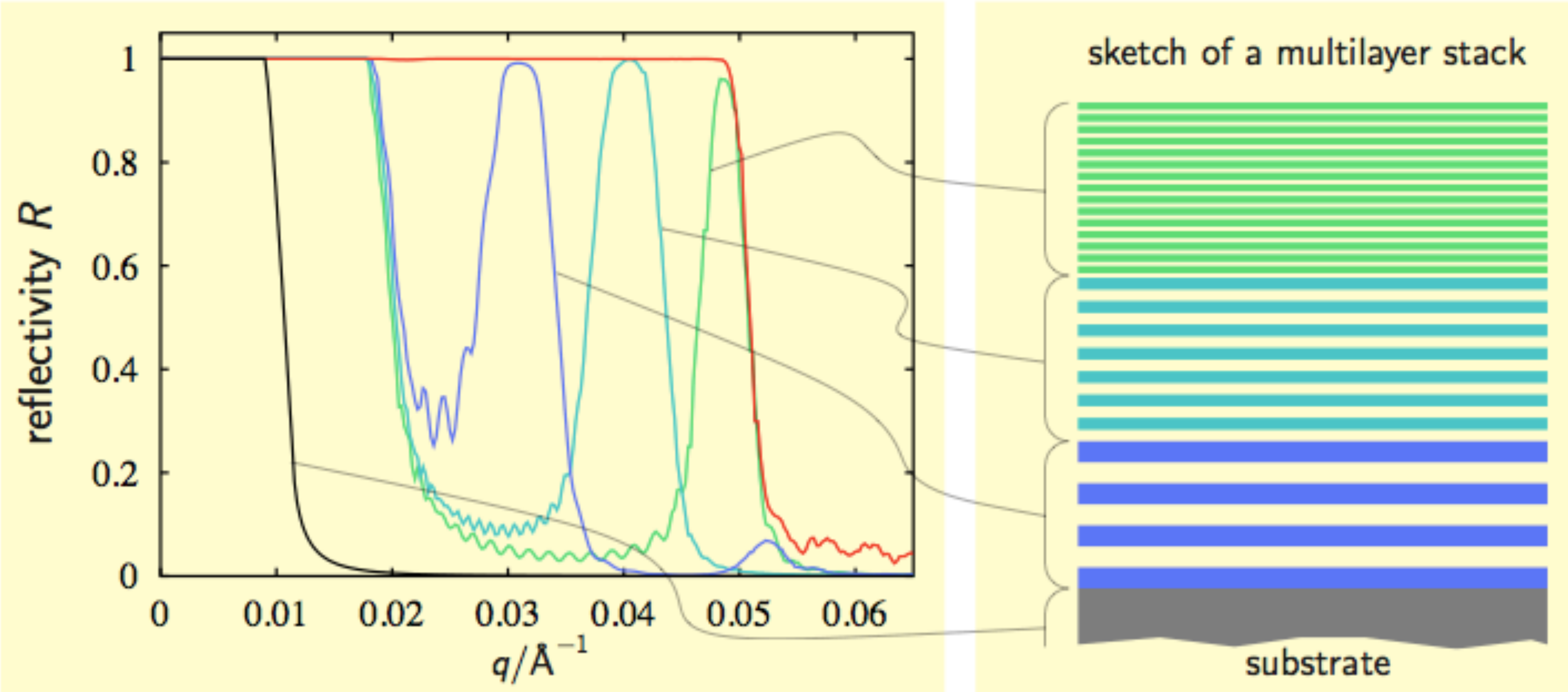
Courtesy of J. Stahn, PSI

Neutron Supermirrors



Courtesy of J. Stahn, PSI

Neutron Supermirrors

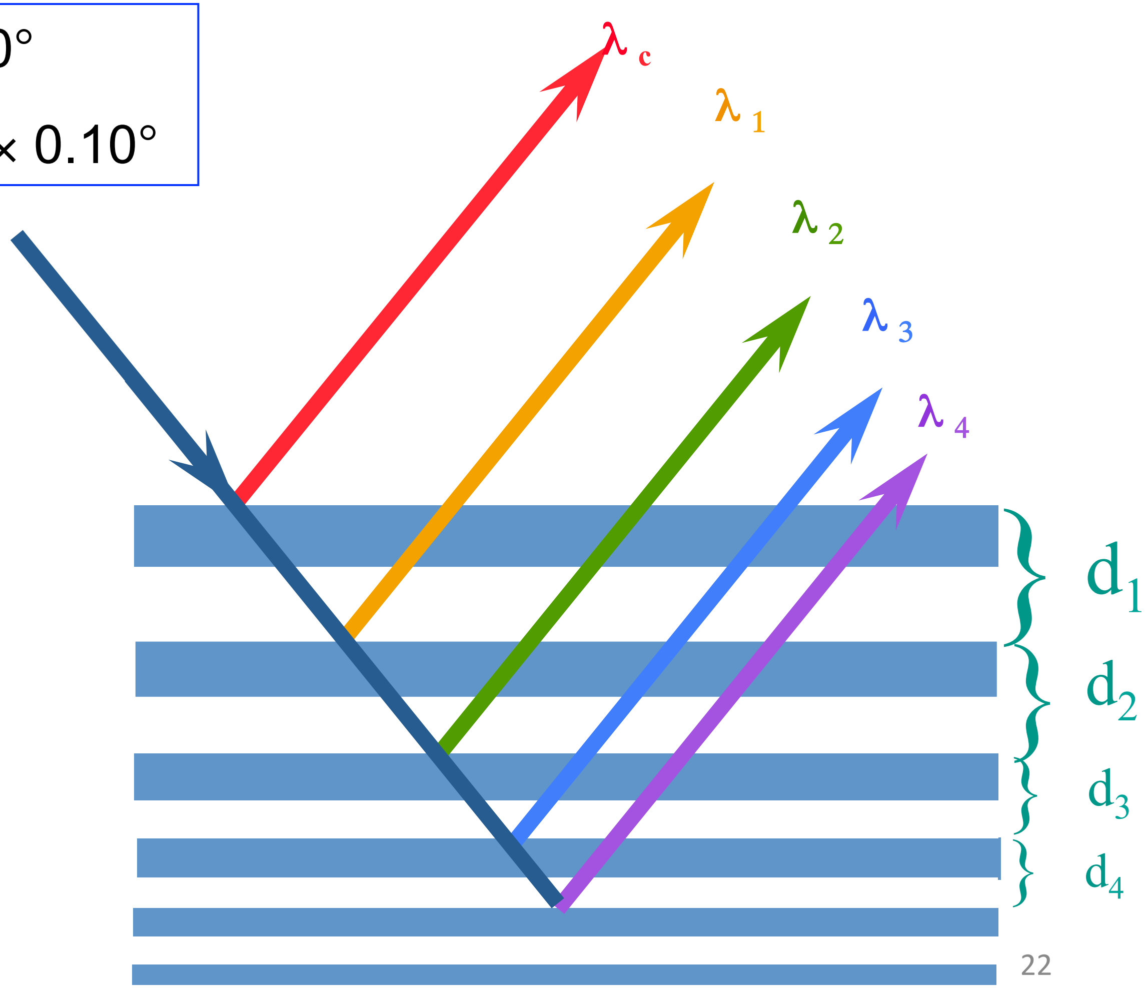


Courtesy of J. Stahn, PSI

Neutron Supermirrors

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

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

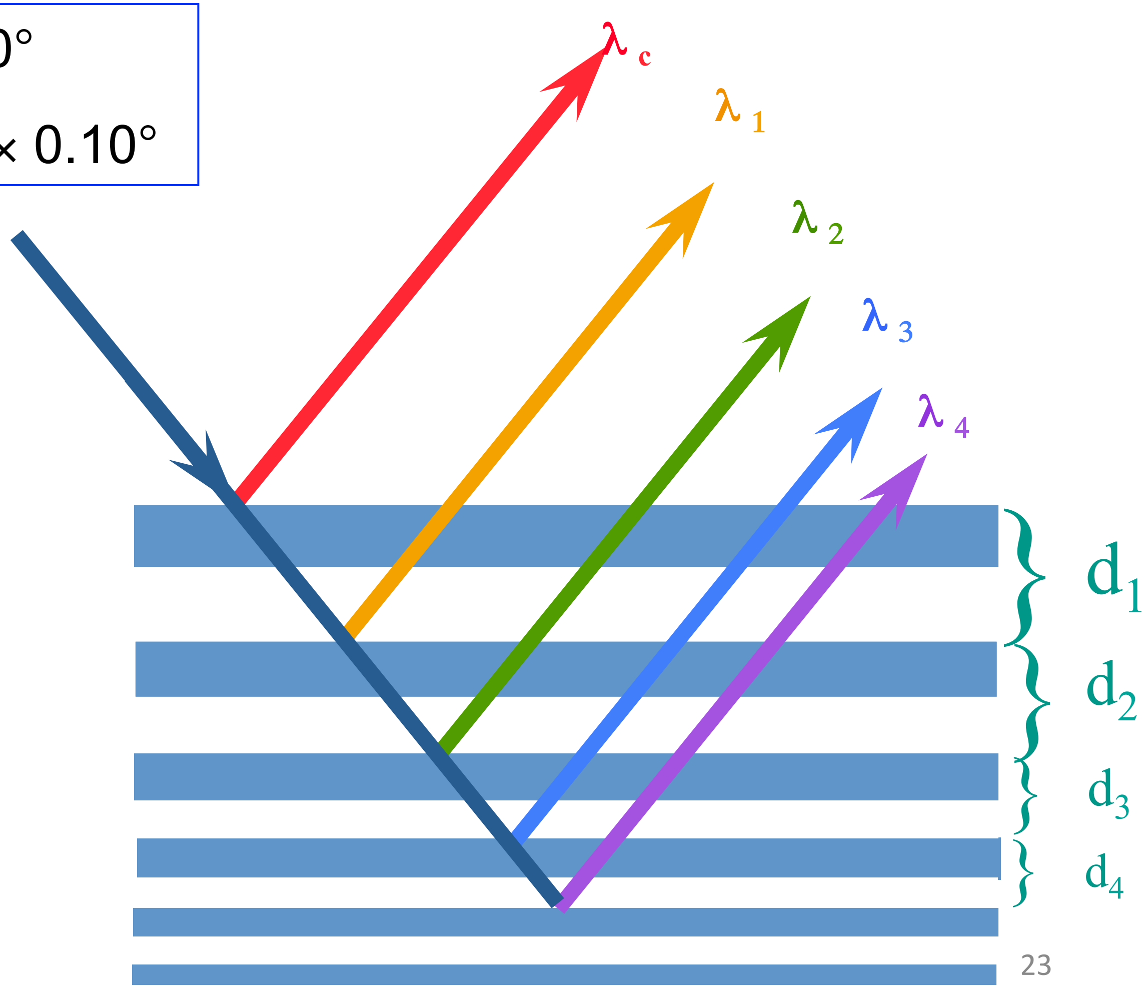


Neutron Supermirrors

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

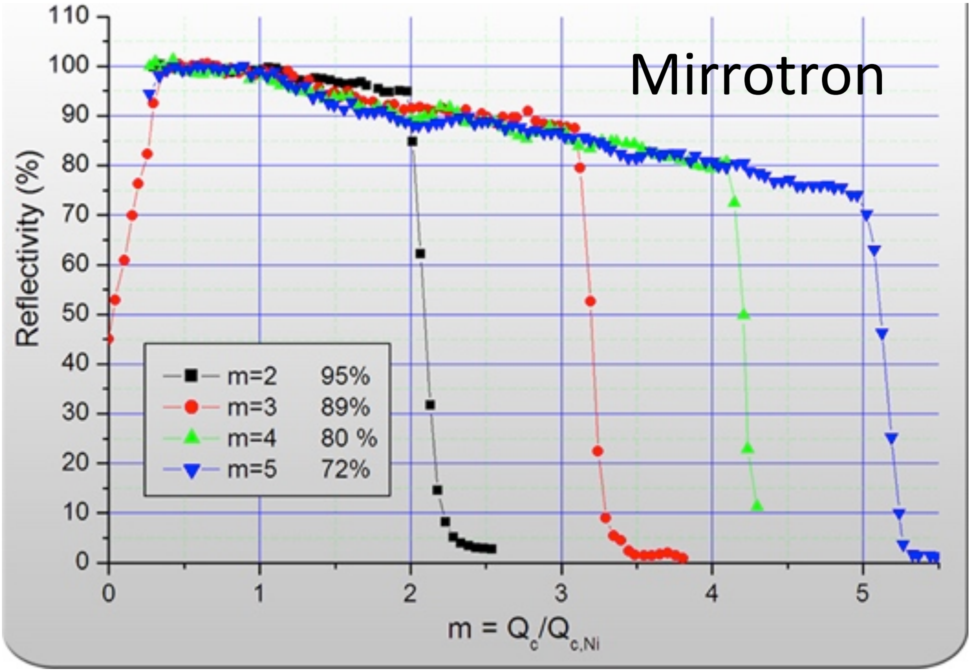
Multilayer: $\theta_c(\mathrm{SM}) = m \times \lambda[\text{Å}] \times 0.10°$

"m-number"
Supermirror critical angle

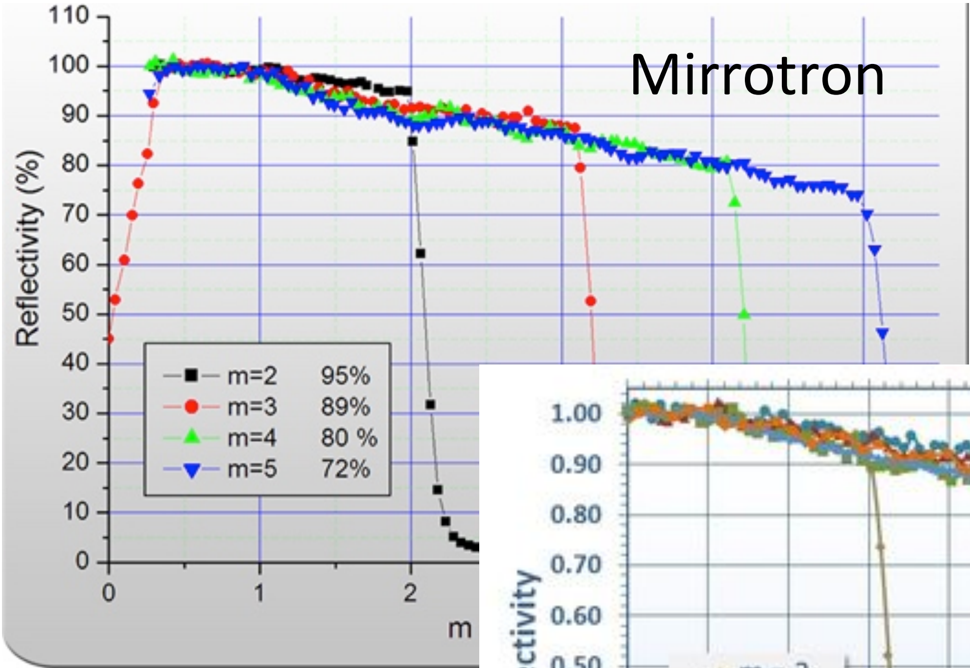


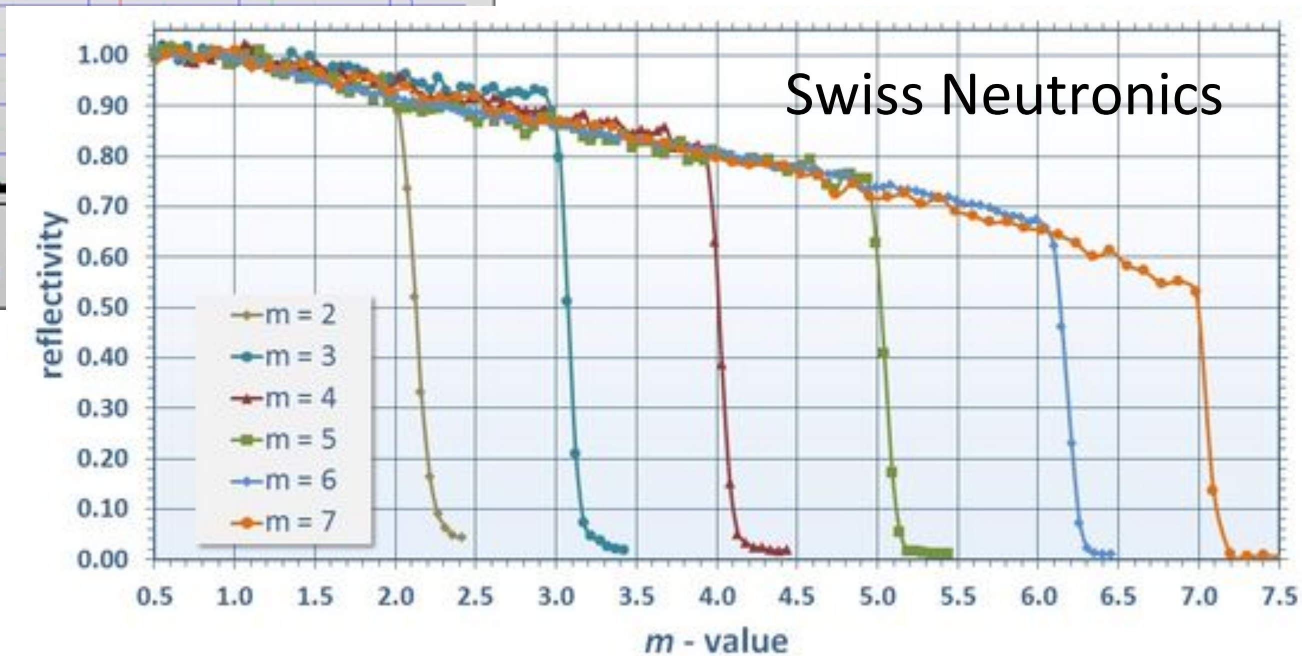
State-of-the-art Supermirrors

EUROPEAN SPALLATION SOURCE

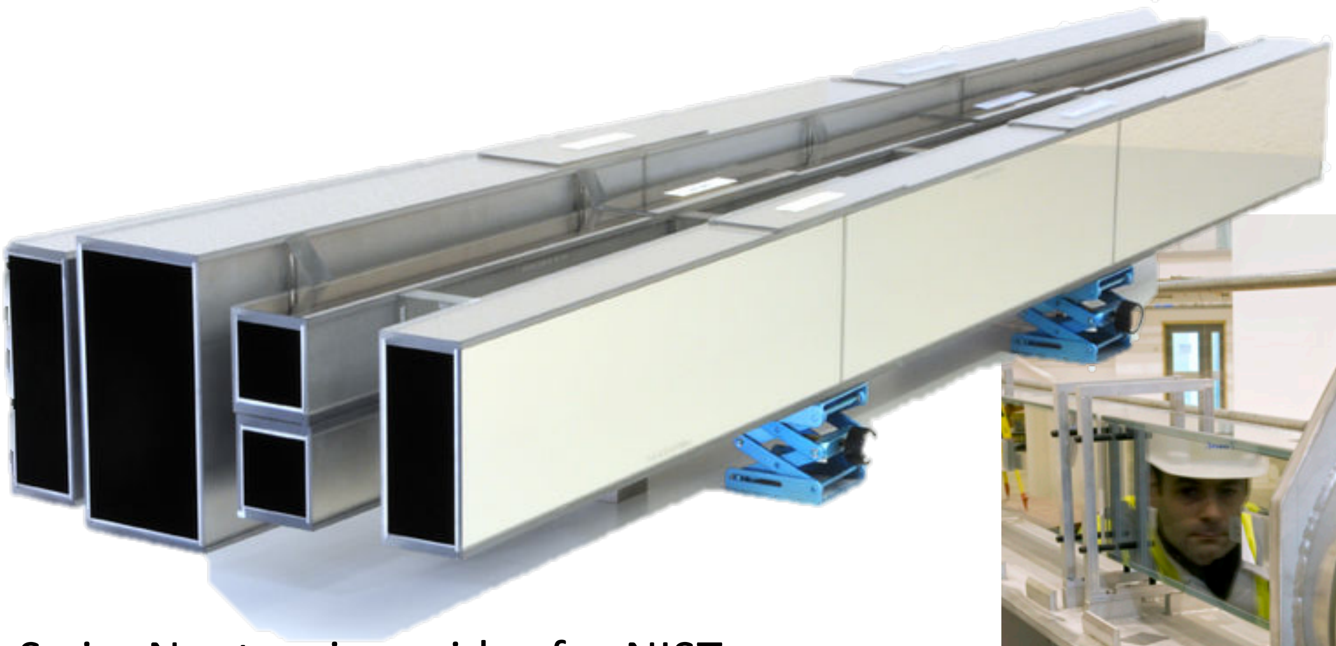


State-of-the-art Supermirrors





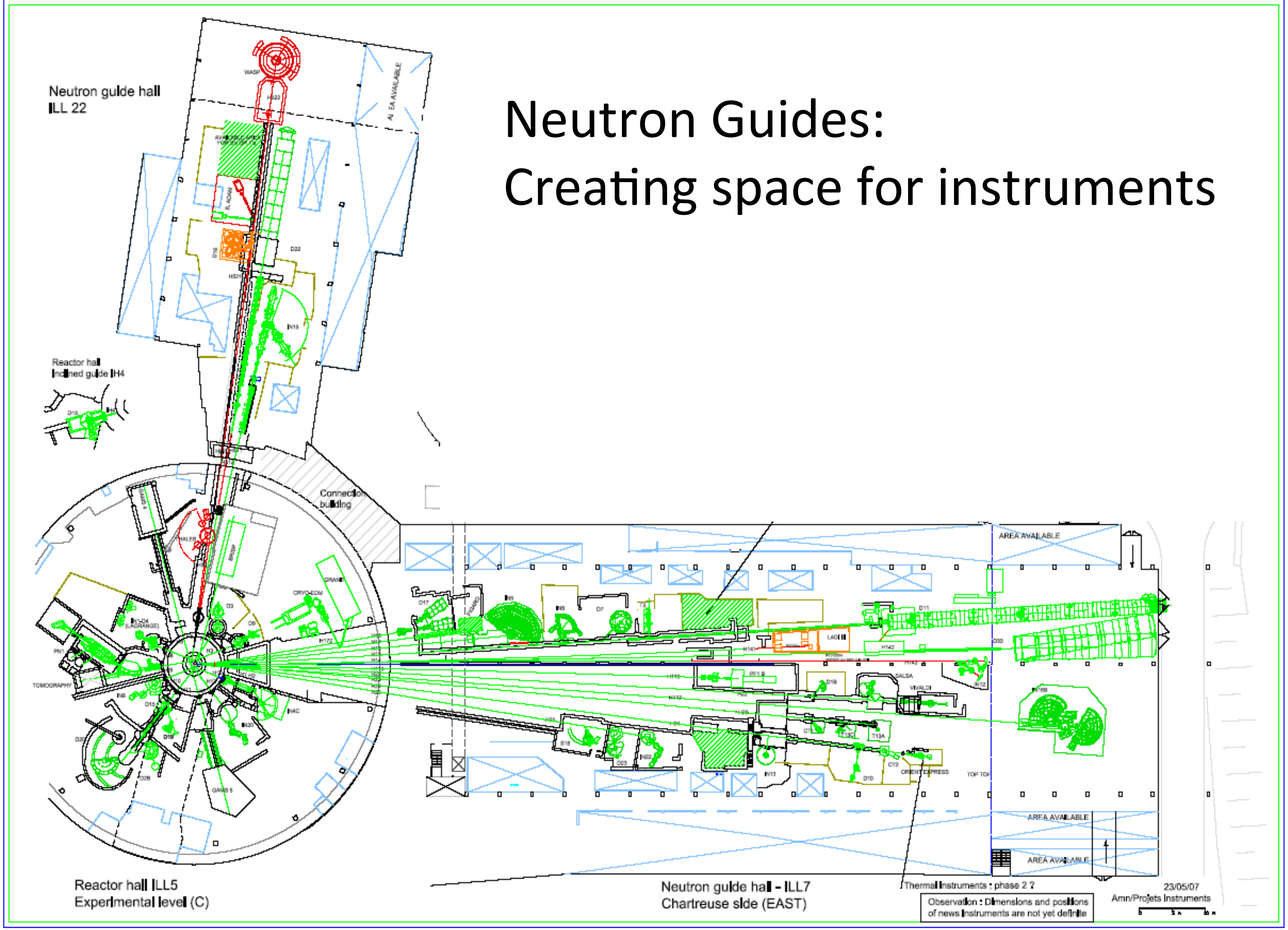
Neutron guides



Swiss Neutronics guides for NIST

WISH @ ISIS

Neutron Guides: Creating space for instruments



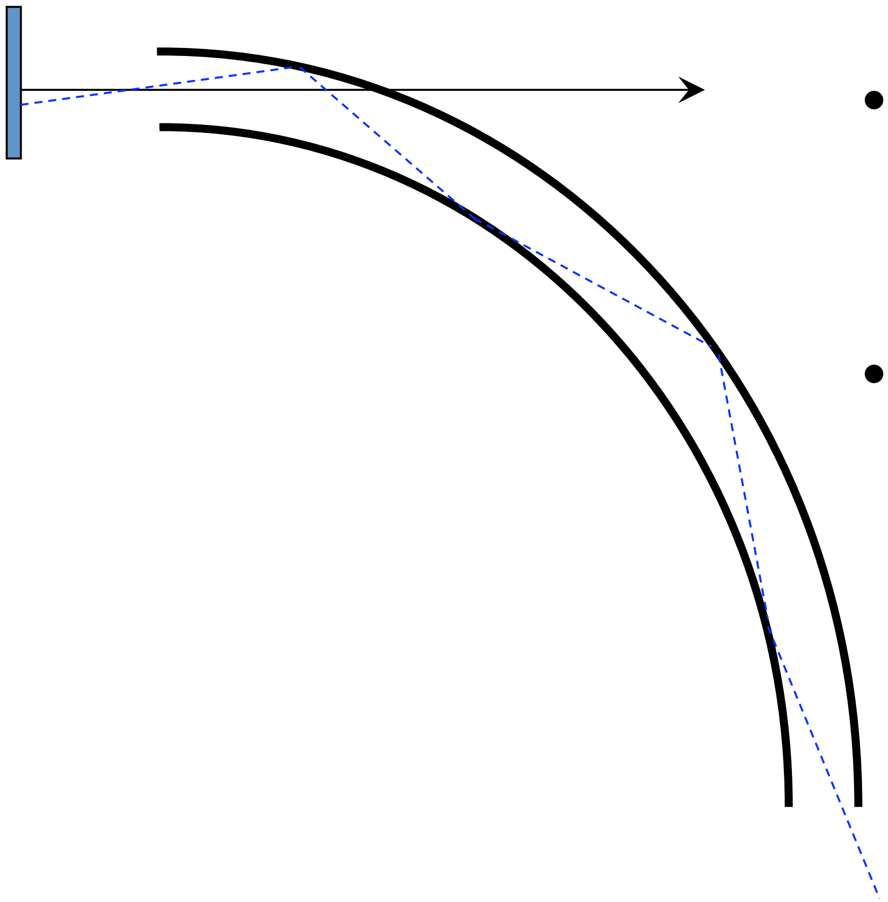
Background Reduction

Guides can be used to reduce background

- Distance:
  - move away from fast-neutron source ~ $1/R^2$

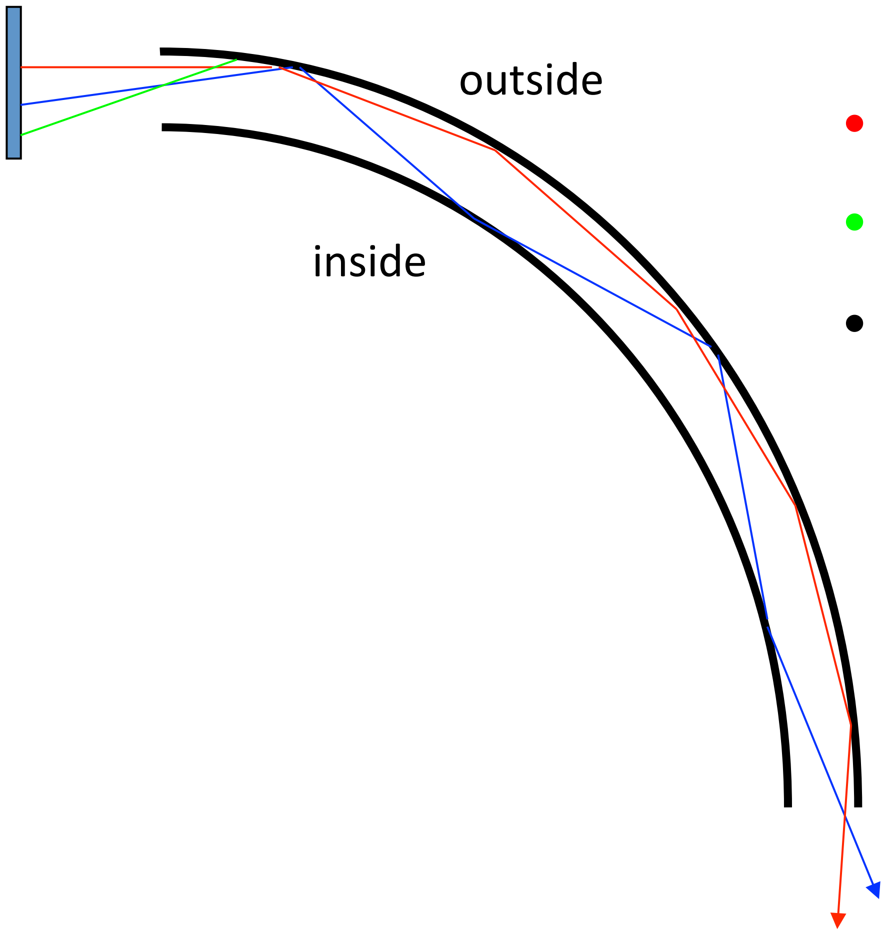
Background Reduction

Guides can be used to reduce background



- Distance:
  - move away from fast-neutron source ~ $1/R^2$
- Curved Guides:
  - avoid direct line-of-sight
  - avoid gammas
  - avoid fast neutrons

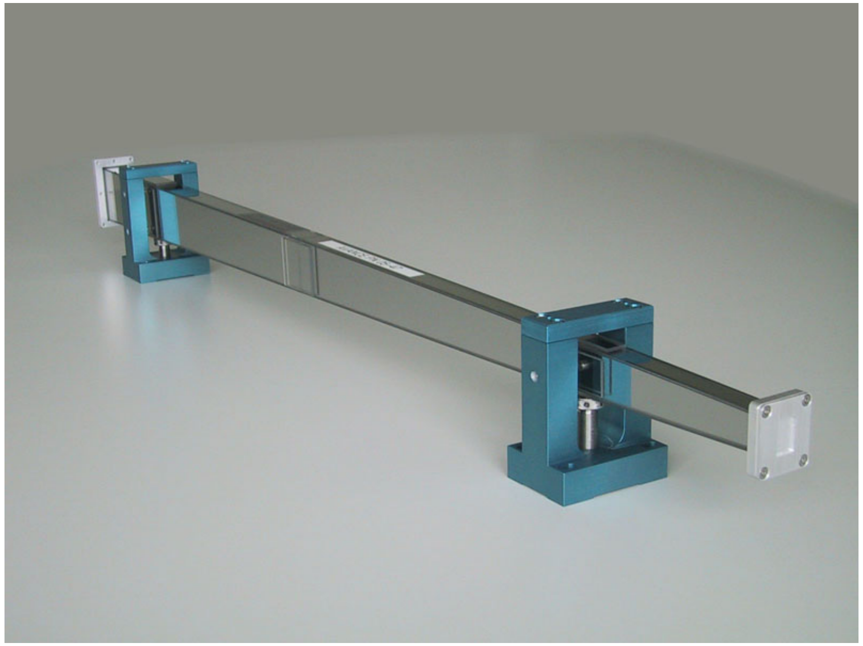
Curved Guides



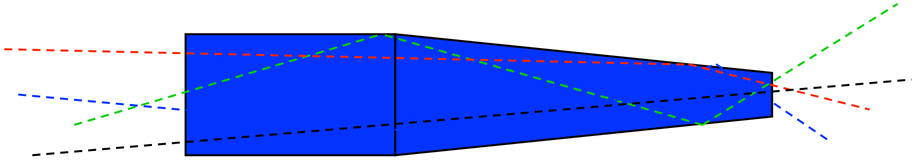
- Blue – reflecting from both sides
- Red – garland reflections
- Green – exceeds critical angle
- Fewer neutrons along inside face

Focusing

Guides can also be used to increase flux



Converging guide increases flux,
but increases divergence

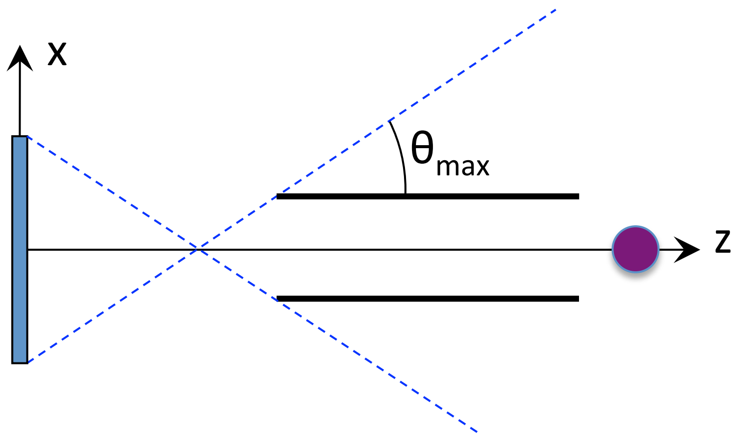


Liouville's Theorem

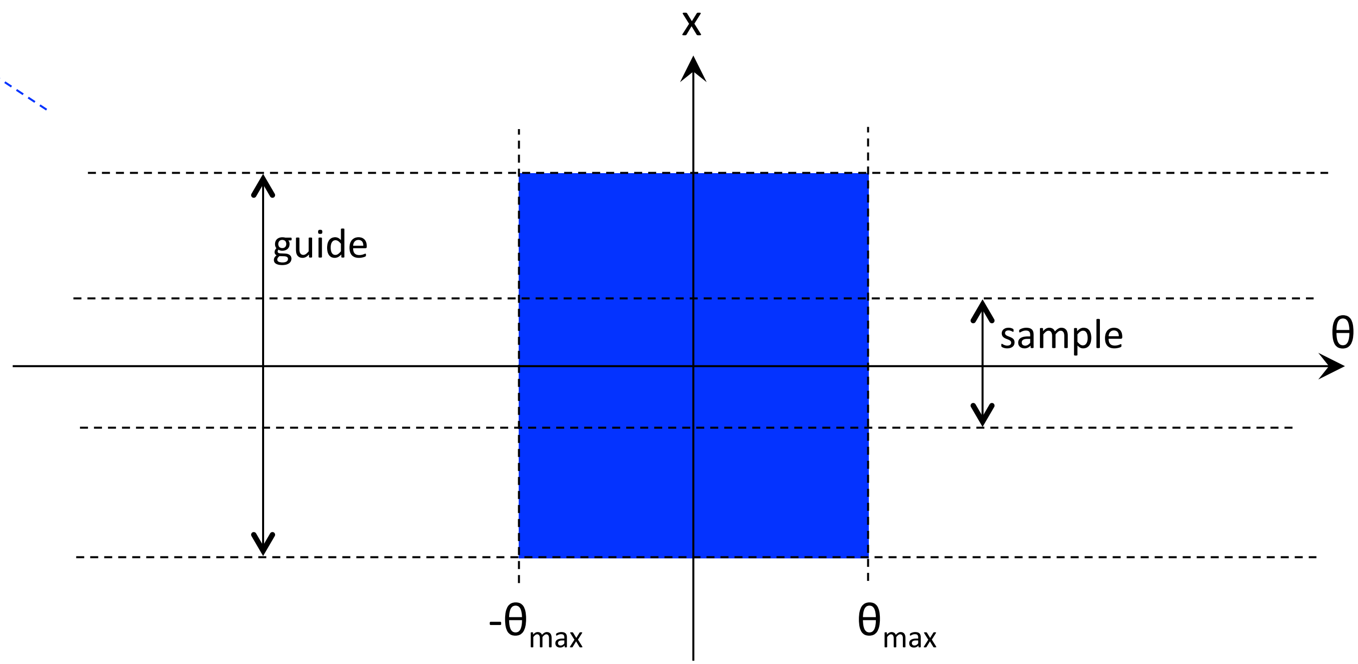
- Conservation laws:
  - neutrons can't be created from thin air
  - neither can phase space density

Intensity(position,angle,time,wavelength,...)

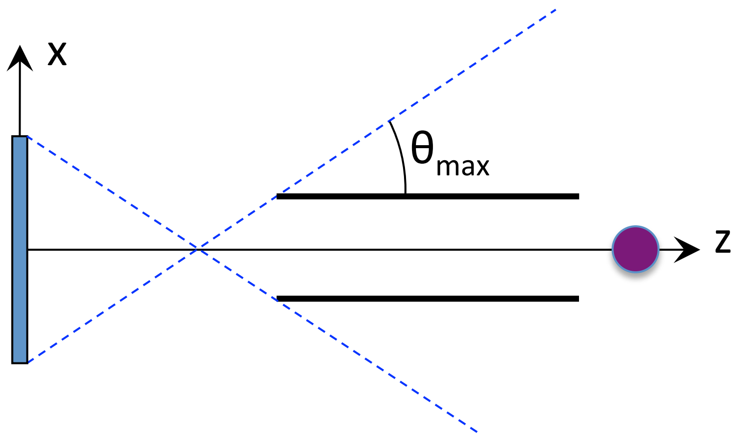
Liouville's Theorem



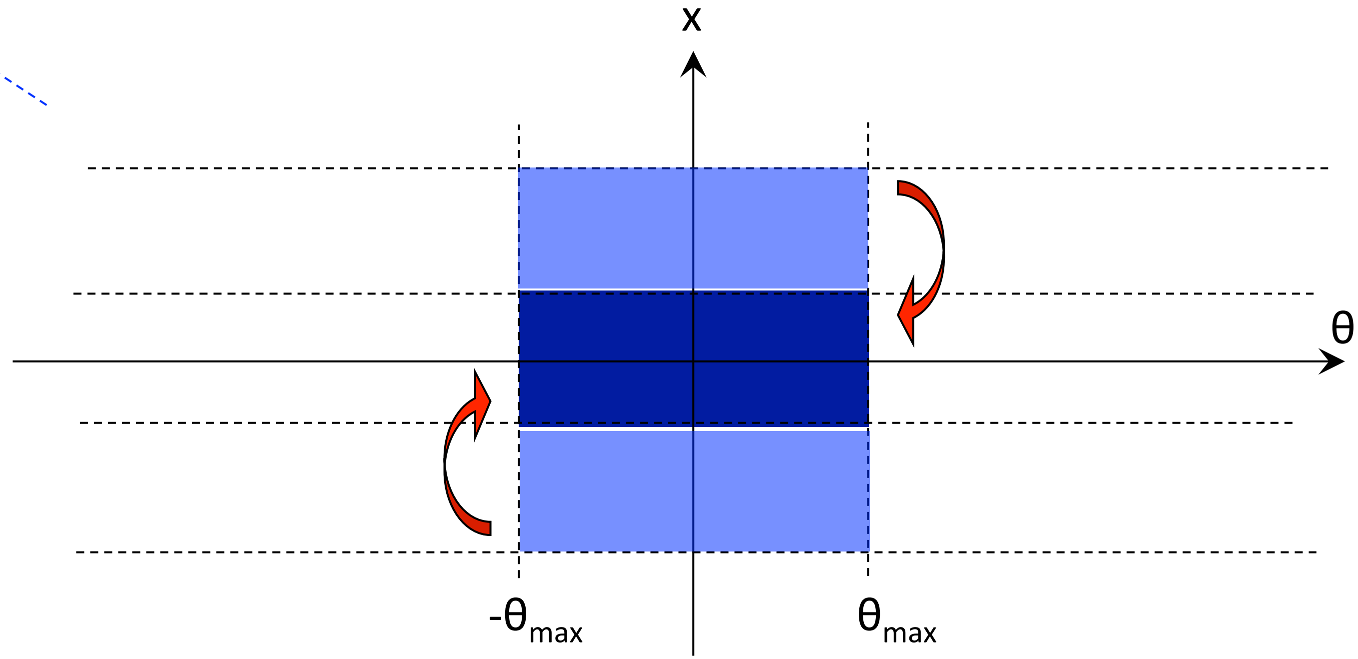
Acceptance Diagram



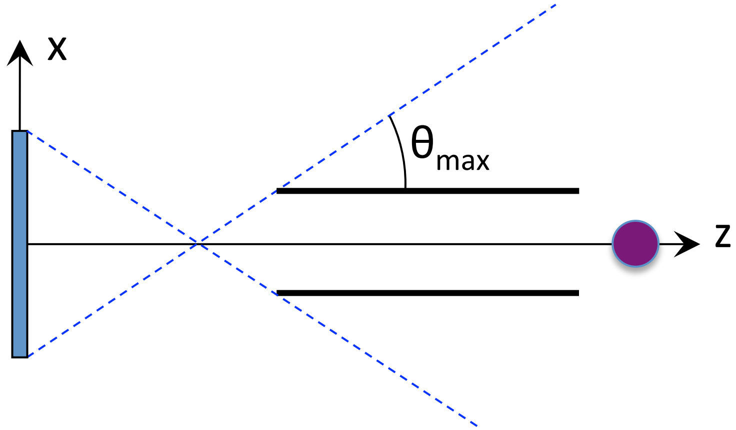
Liouville's Theorem



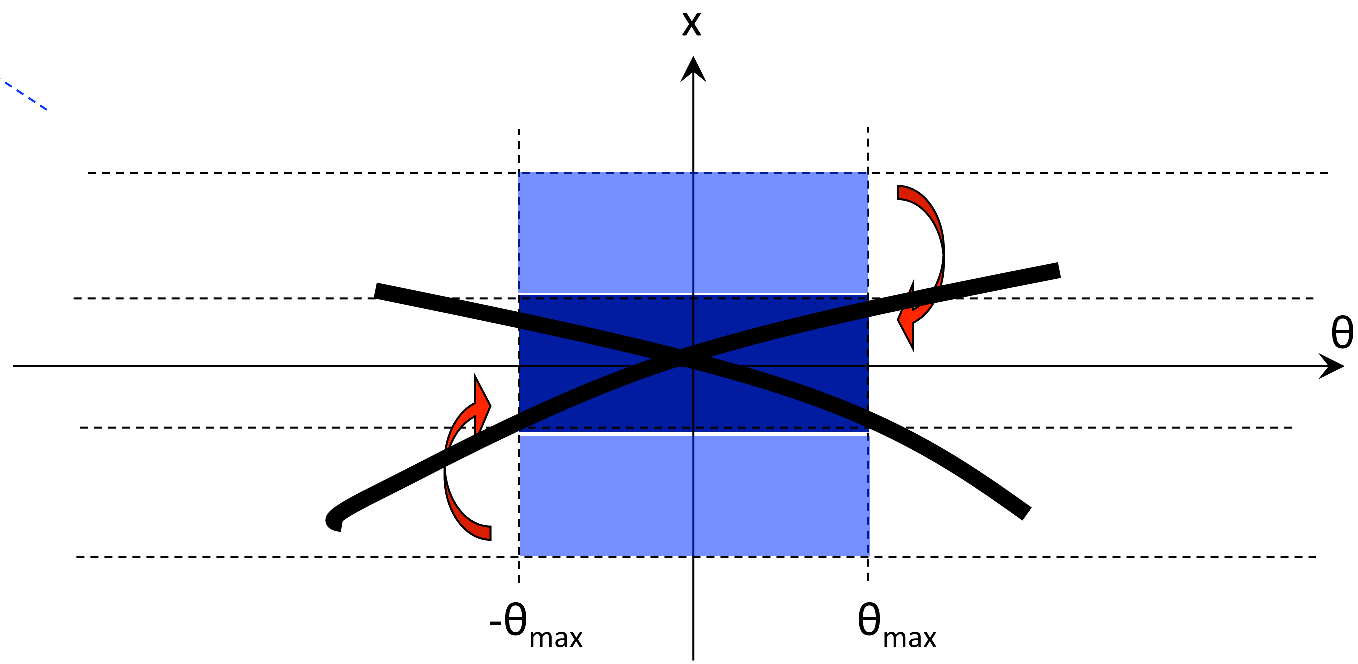
Acceptance Diagram



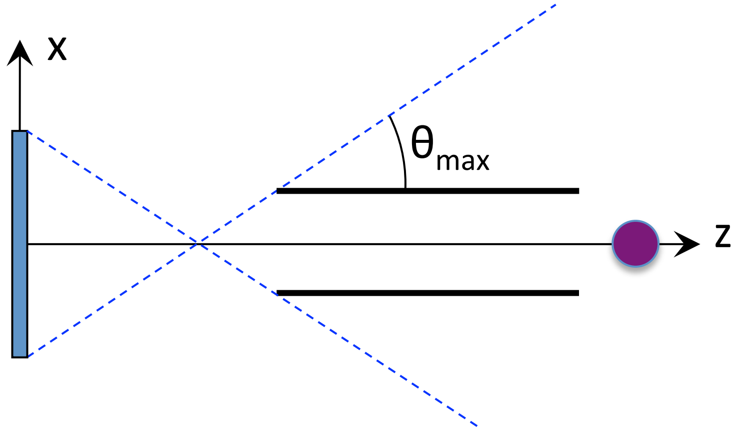
Liouville's Theorem



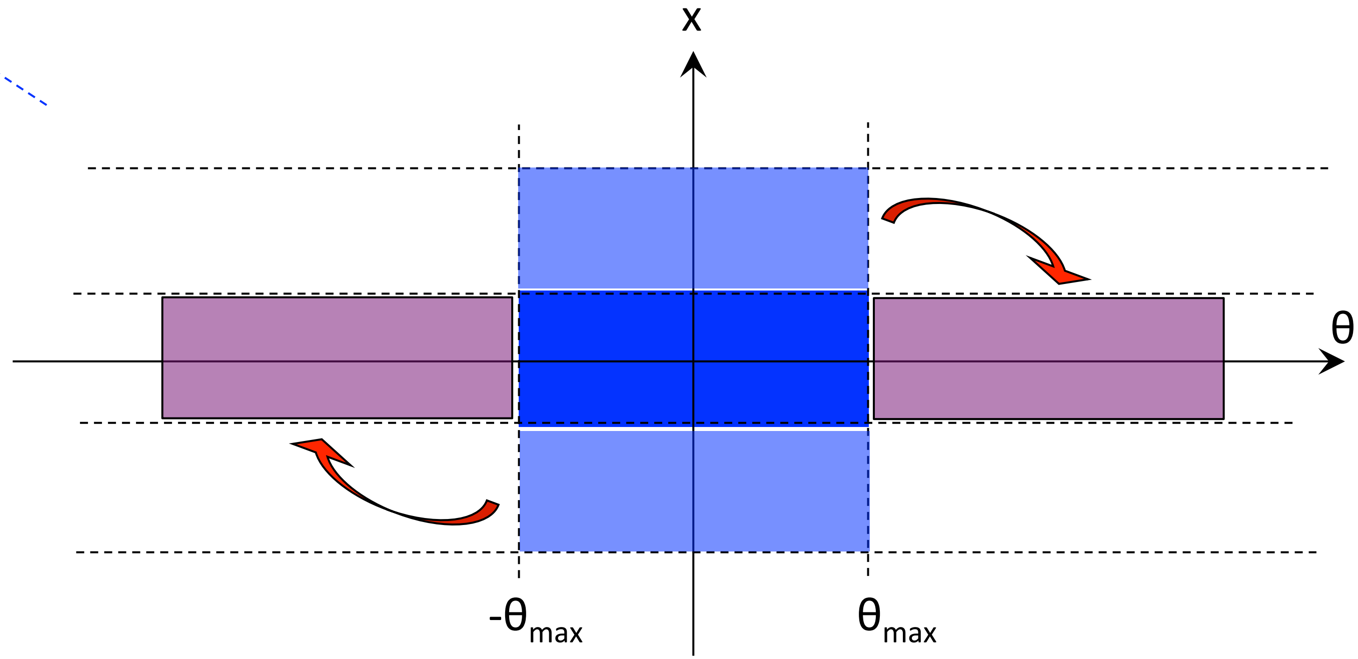
Acceptance Diagram



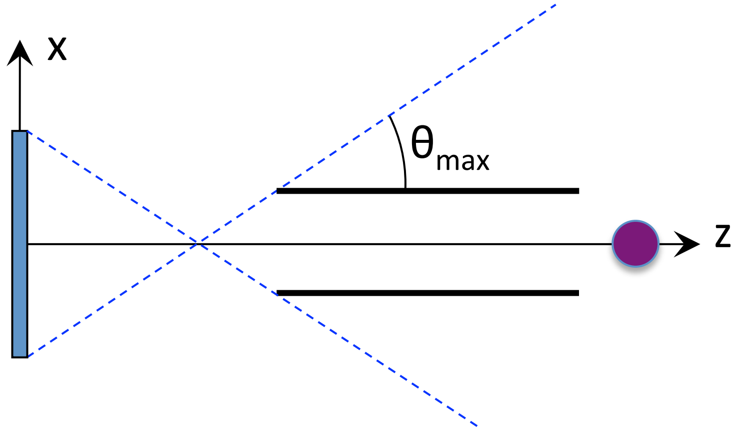
Liouville's Theorem



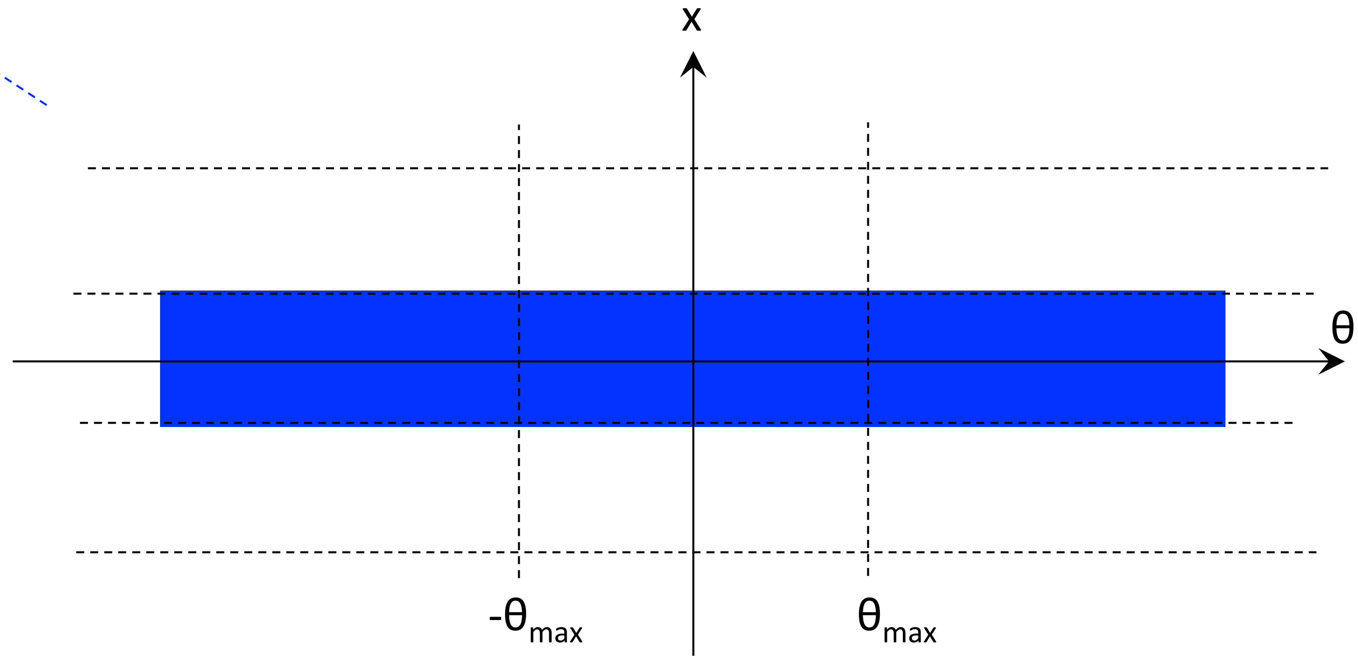
Acceptance Diagram



Liouville's Theorem



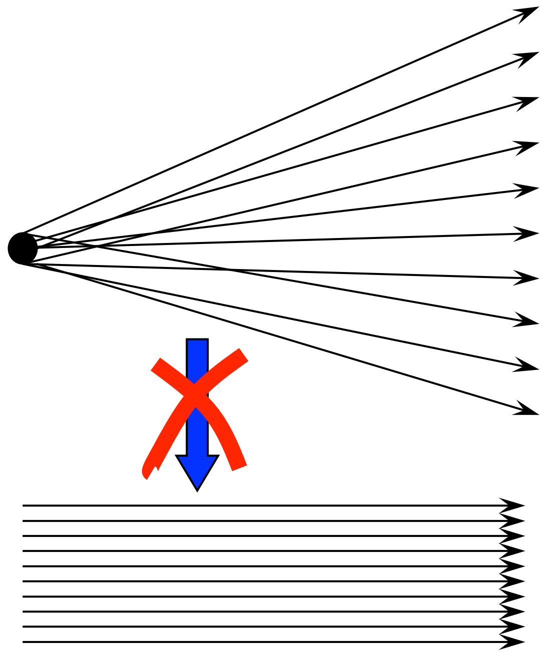
Acceptance Diagram

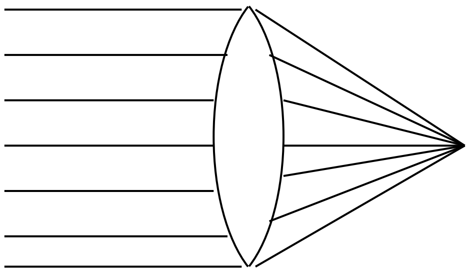


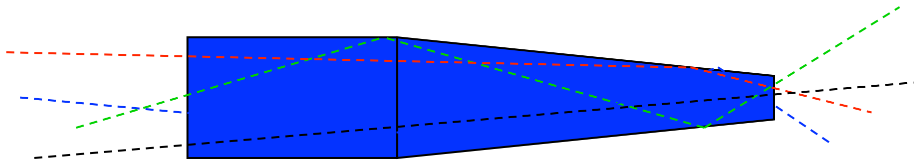
Liouville's Theorem

EUROPEAN SPALLATION SOURCE

- 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 area, divergence, time, energy
- Most common application:
  - Focusing increases divergence
  - improve flux, lose angular resolution





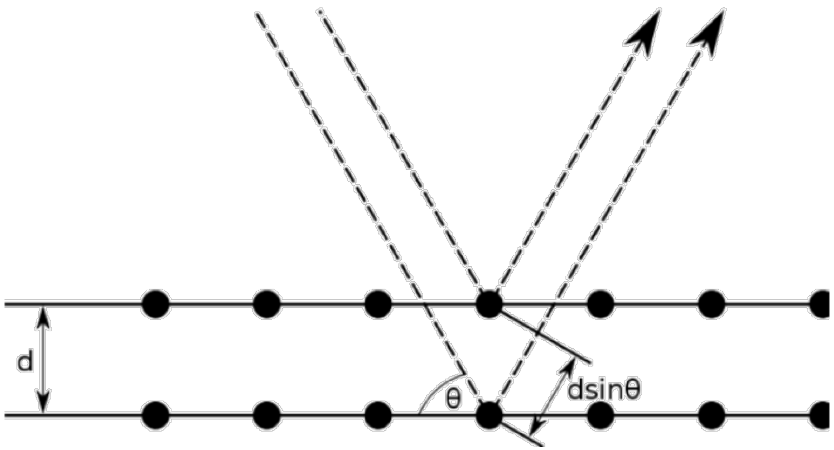


Diffractometers

- Measure structure (d-spacings)
- Assume $k_i = k_f$
- Measure k_i or k_f :
  - Bragg diffraction
  - Time-of-flight
- Samples :
  - Crystals
  - Powders
  - Liquids
  - Large molecules or structures
  - Surfaces

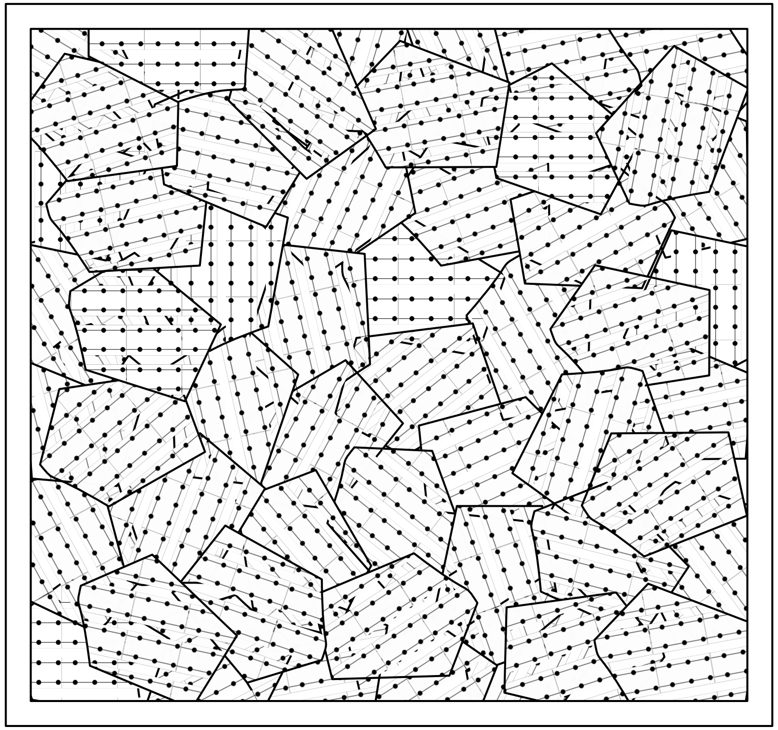
Powder diffractometers

- Measure crystal structure using Bragg's Law
- Large single crystals are rarely available

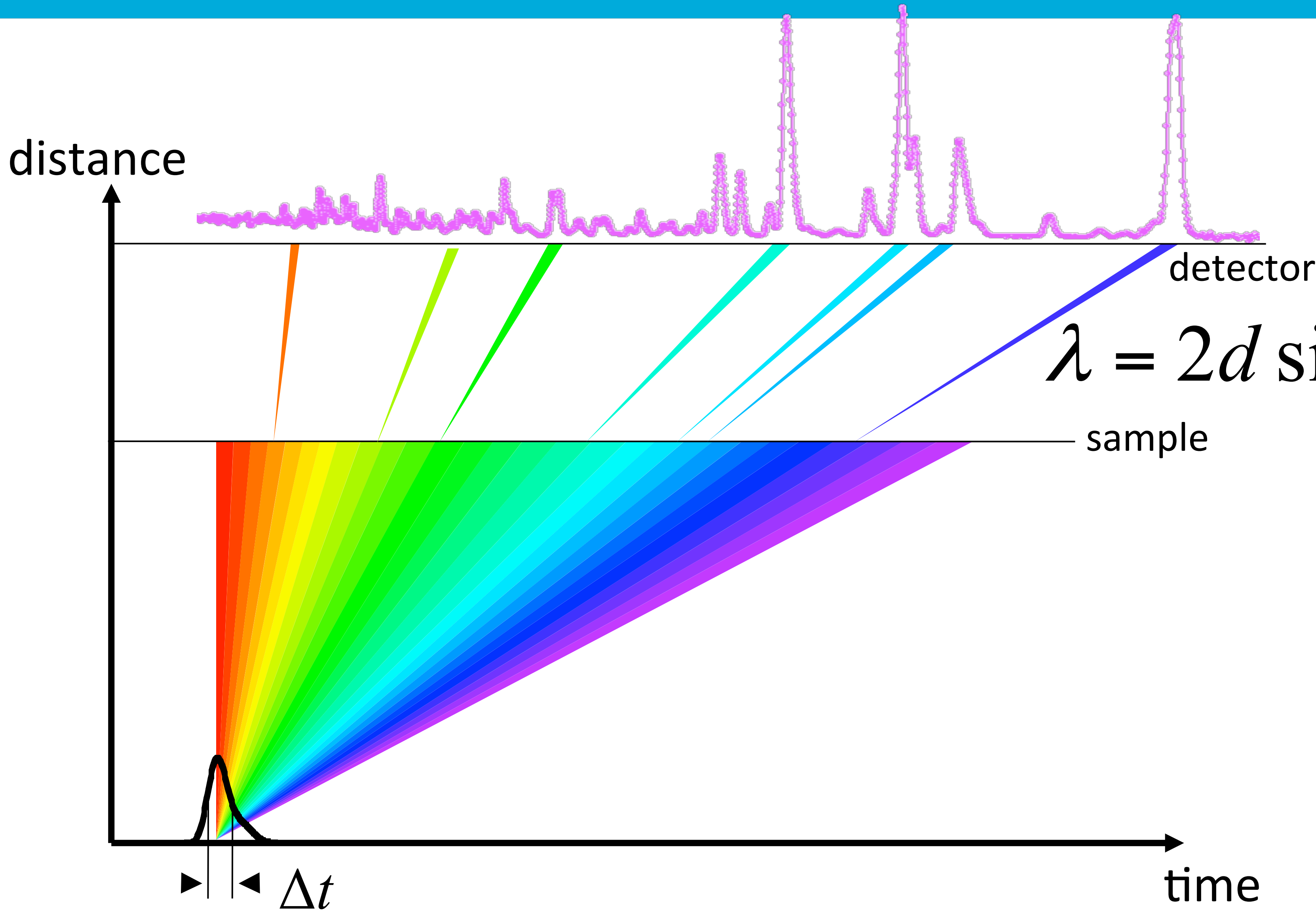


$$Q = \frac{2\pi}{d} \qquad \lambda = 2d\sin\theta$$

Polycrystal



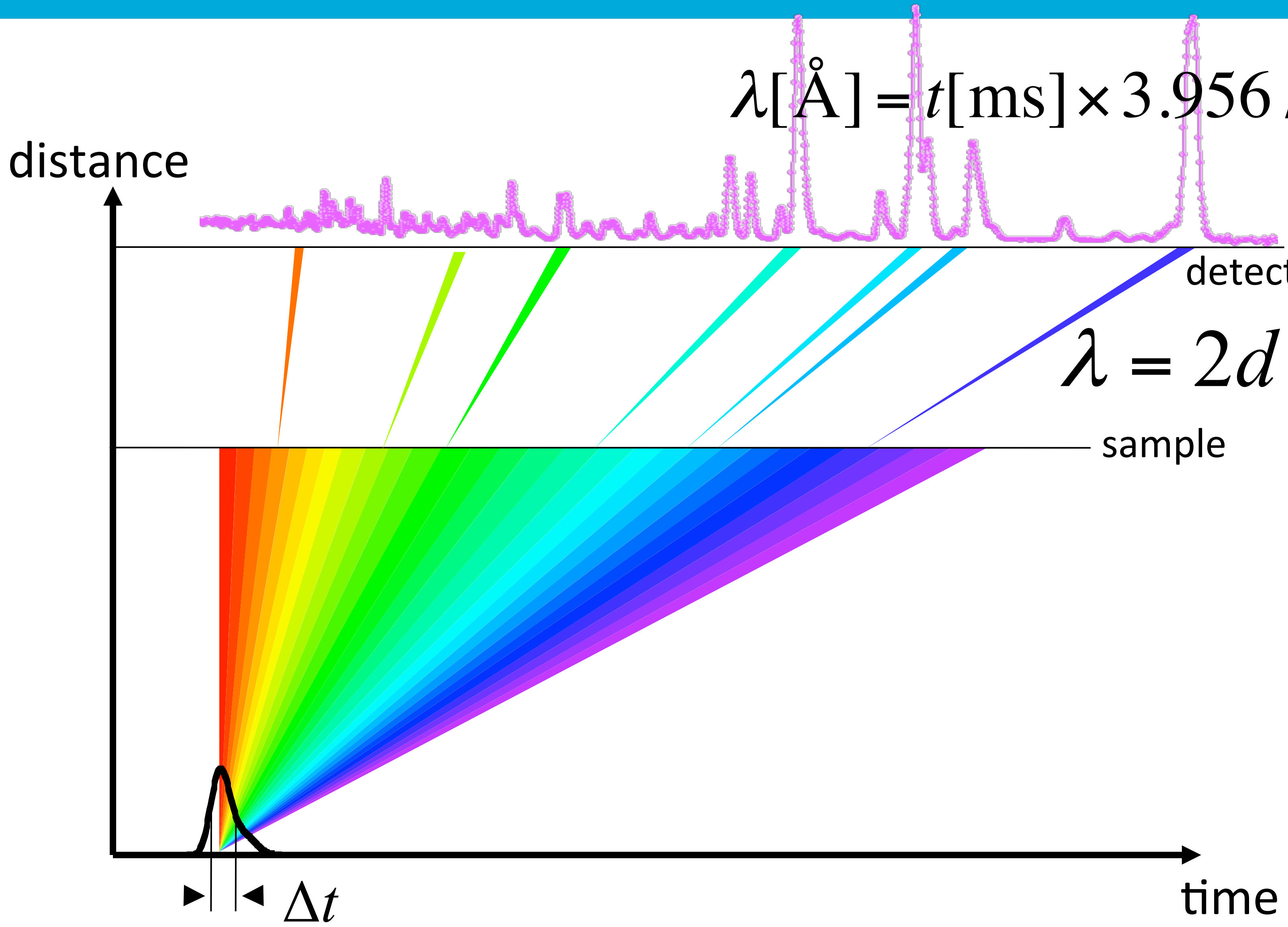
Time-of-flight (TOF) Method



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

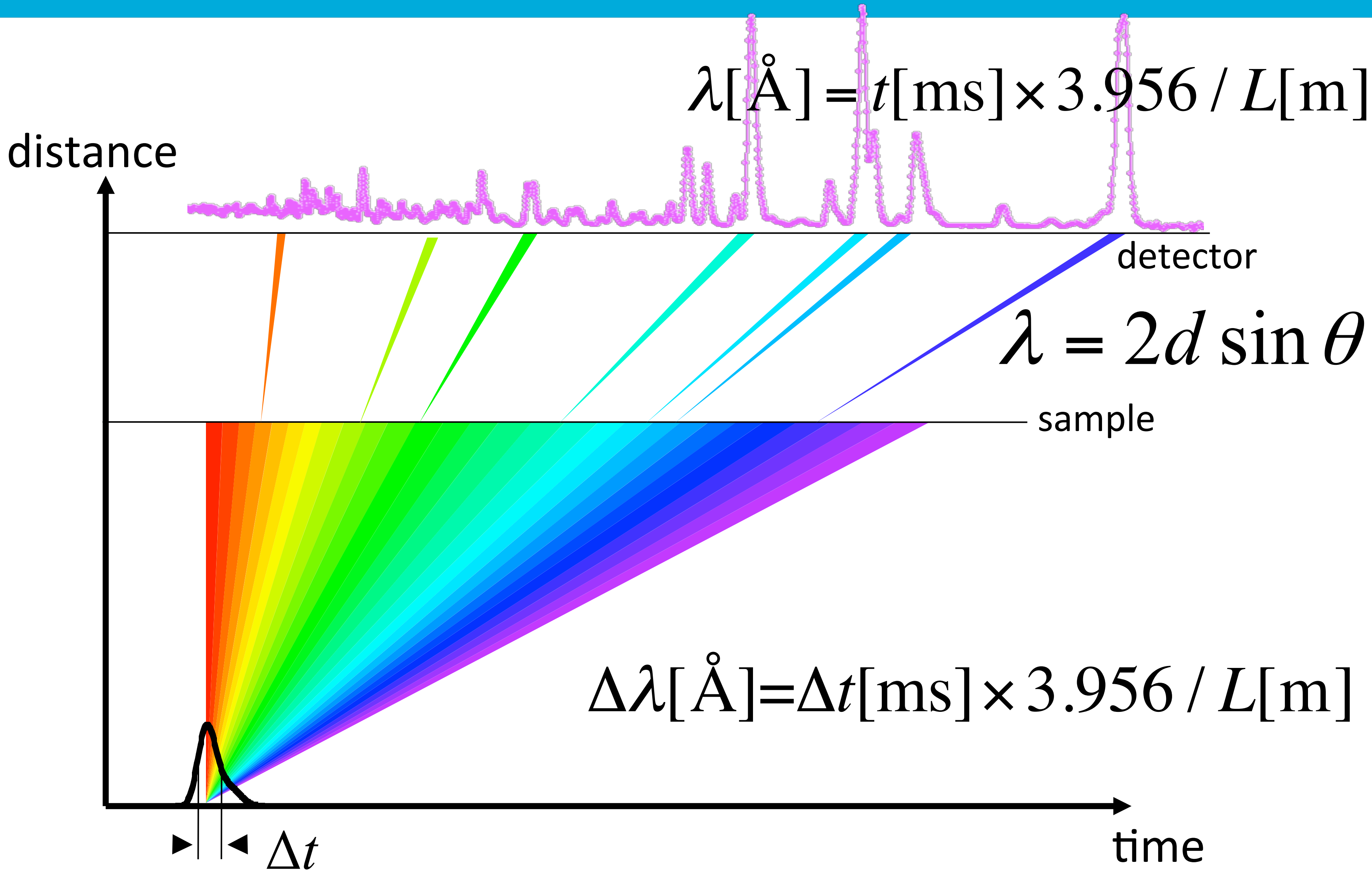
Time-of-flight (TOF) Method

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

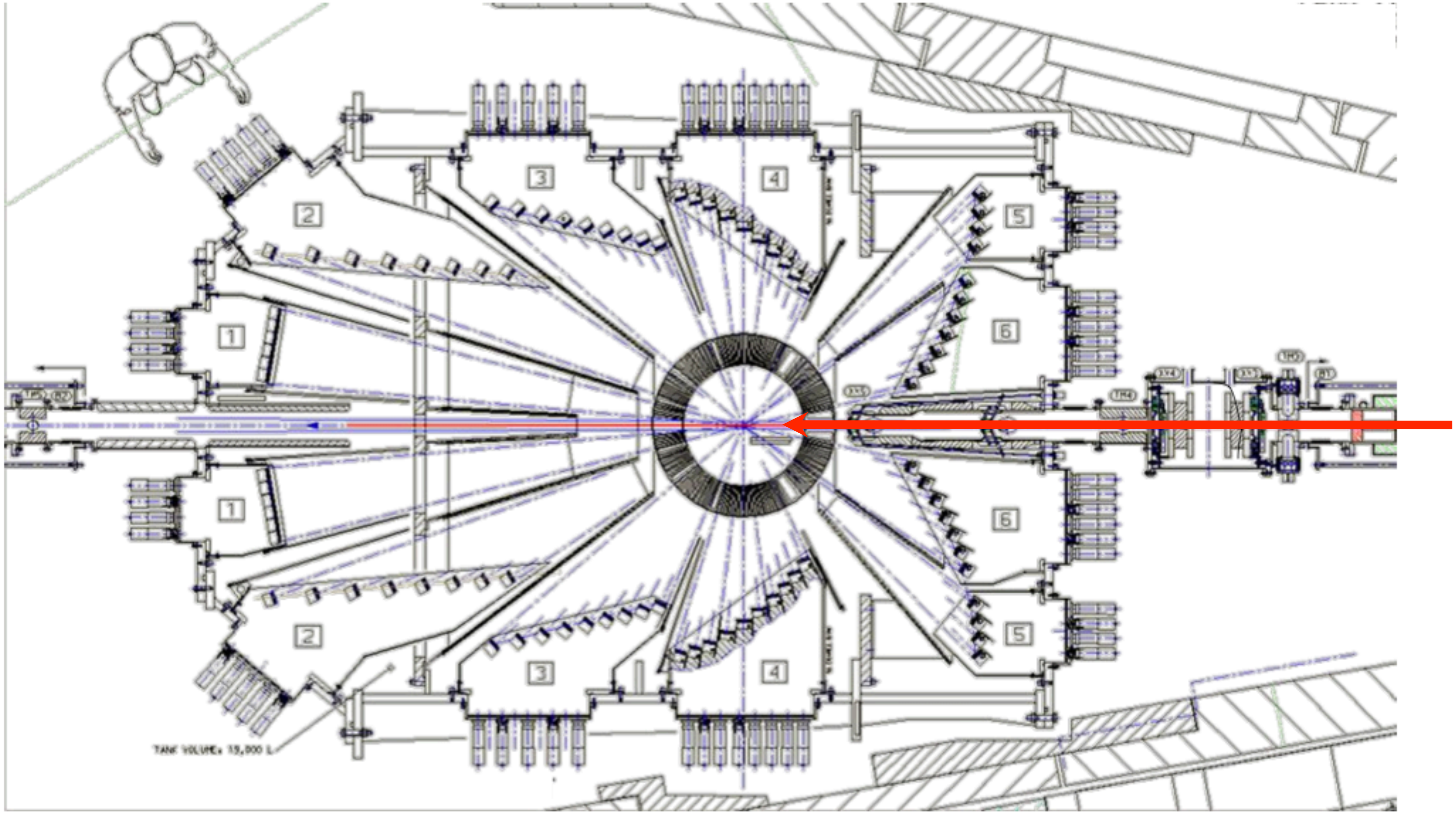


$$\lambda = 2d \sin\theta$$

Time-of-flight (TOF) Method



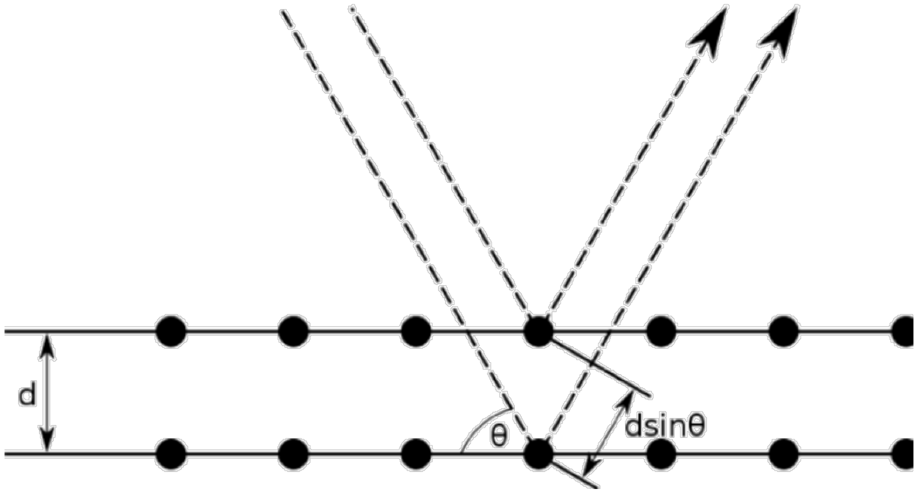
Time-of-flight (TOF) Method



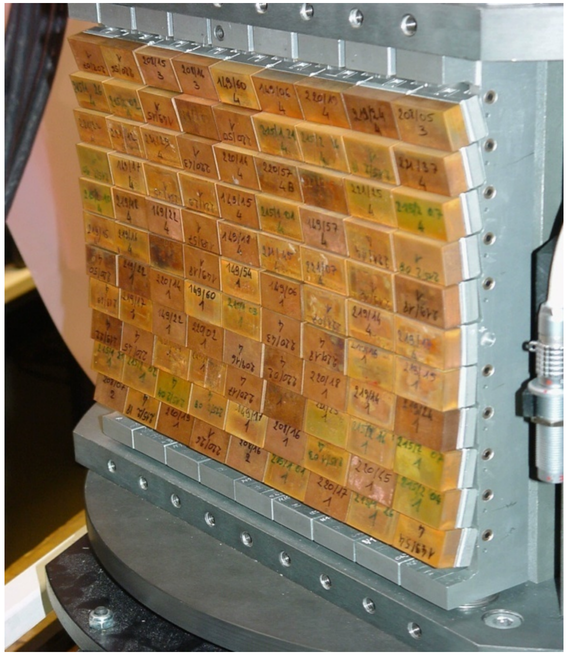
POLARIS @ ISIS TS1

Crystal Monochromators

Graphite 002



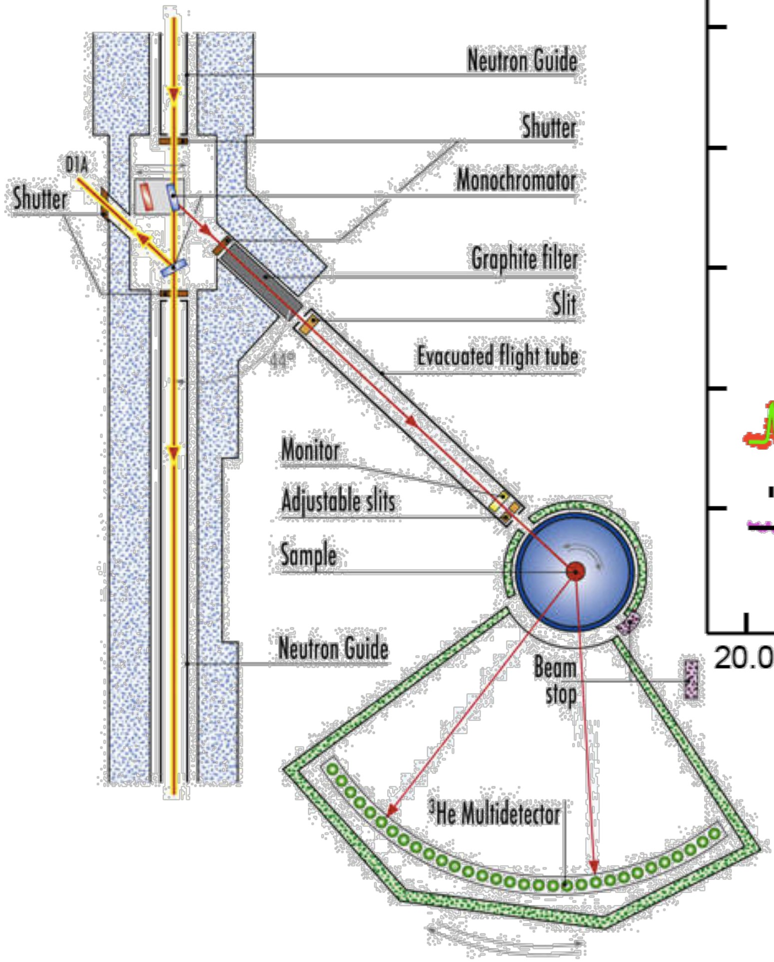
Copper 200

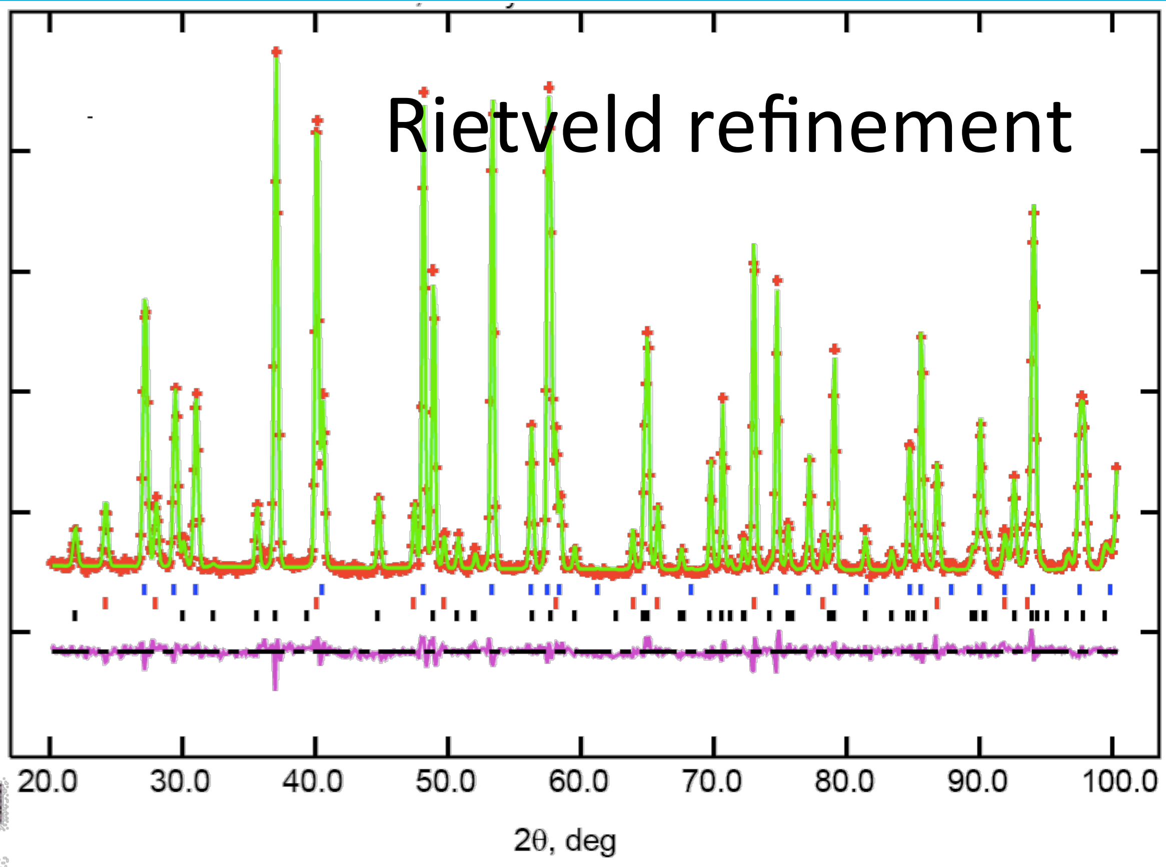


	d-spacing
Germanium 333	1.089 Å
Copper 200	1.807 Å
Silicon 111	3.135 Å
Graphite 002	3.355 Å

Constant-Wavelength Diffraction

D1B @ ILL

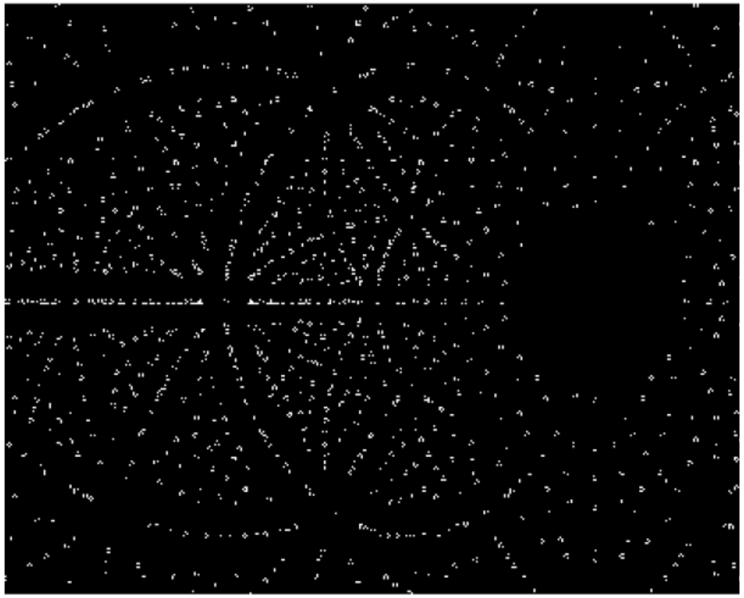


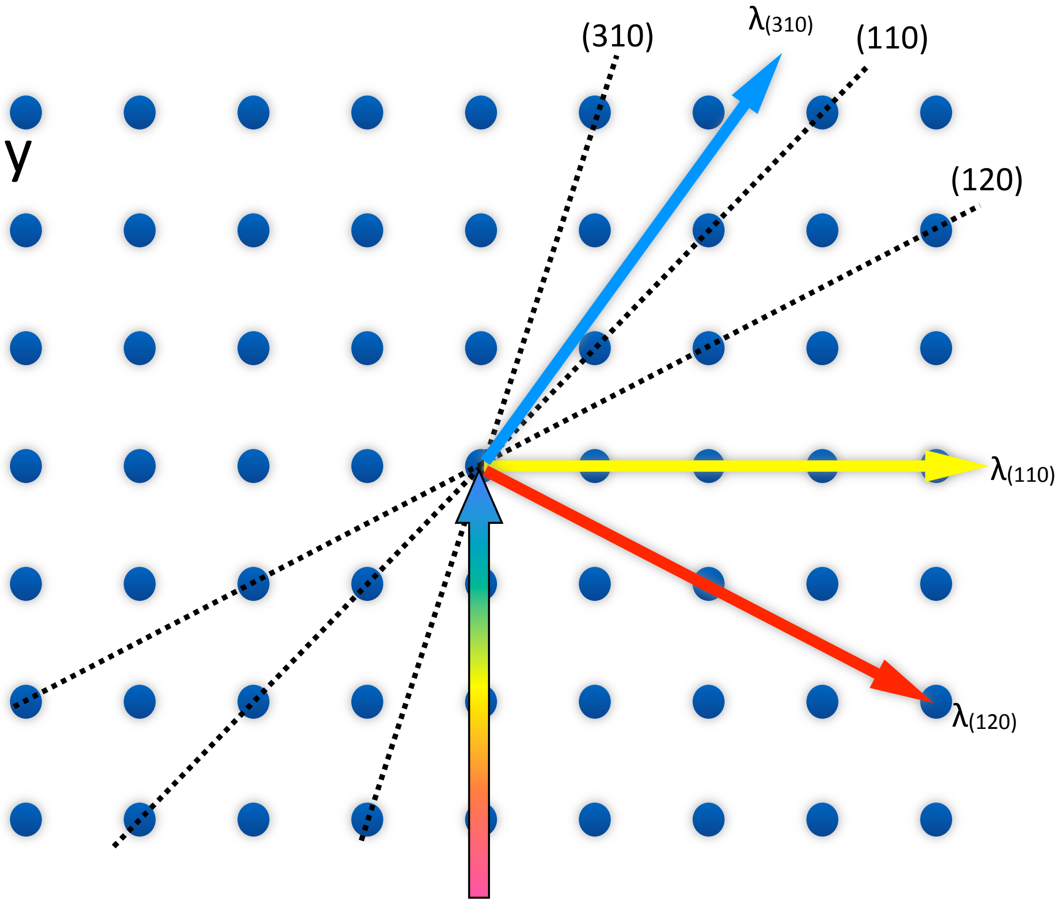


$$Q = 4\pi \sin\theta / \lambda$$

Single Crystal Diffraction

- Complex structures
- Large unit cells
  - Protein crystallography
- Laue method
  - white beam



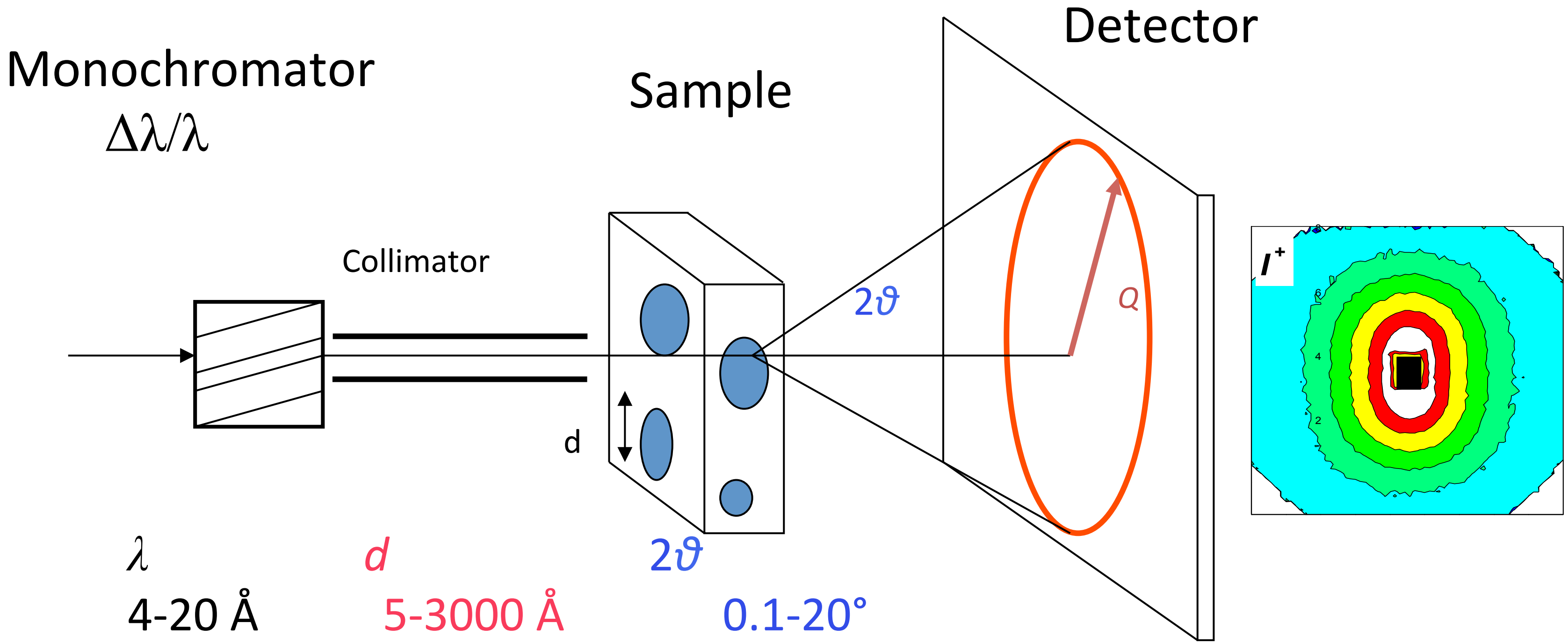


Small-Angle Neutron Scattering

Probing the longest length scales available to neutrons

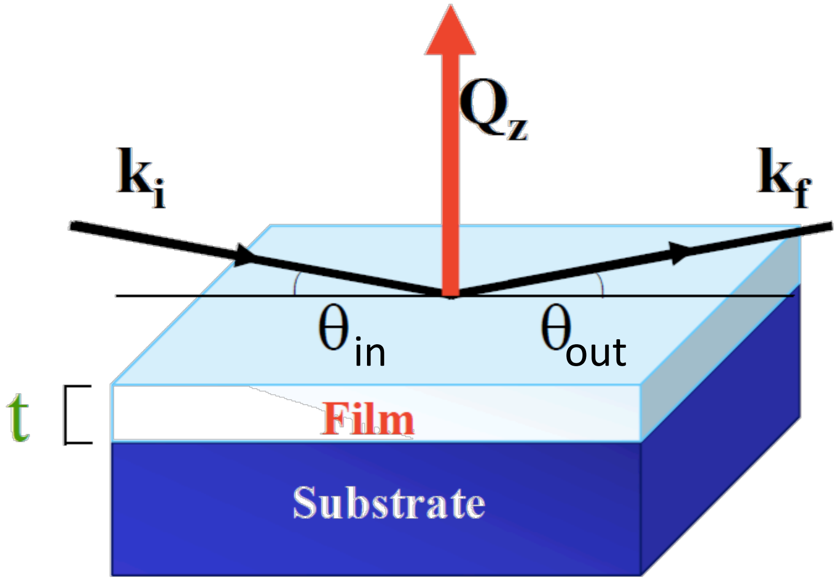
$$\lambda = 2d \sin\theta$$

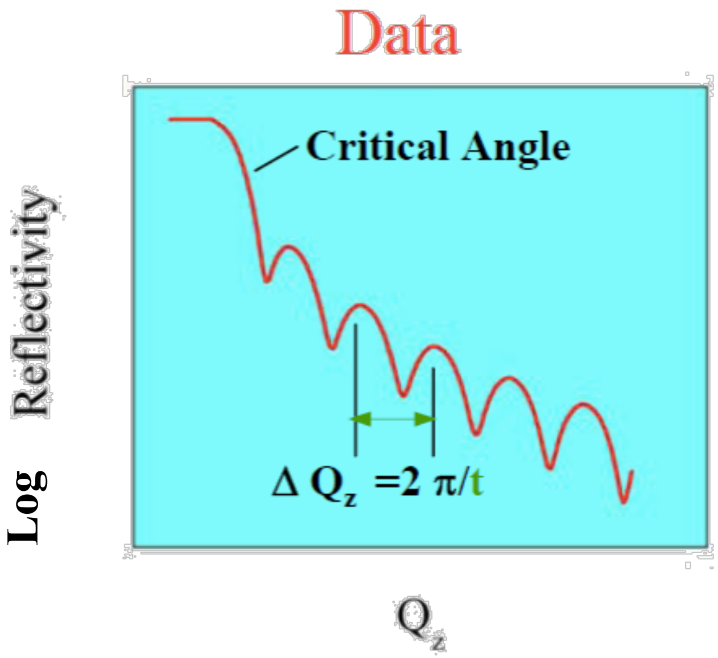
$$\Rightarrow d = \frac{\lambda}{2\sin\theta}$$



Reflectometry

Reflection from surfaces and interfaces





Specular: $\theta_{in}=\theta_{out}$
Off-specular: $\theta_{in}\neq\theta_{out}$

→ Depth profile of the scattering-length density

Neutron Spectroscopy

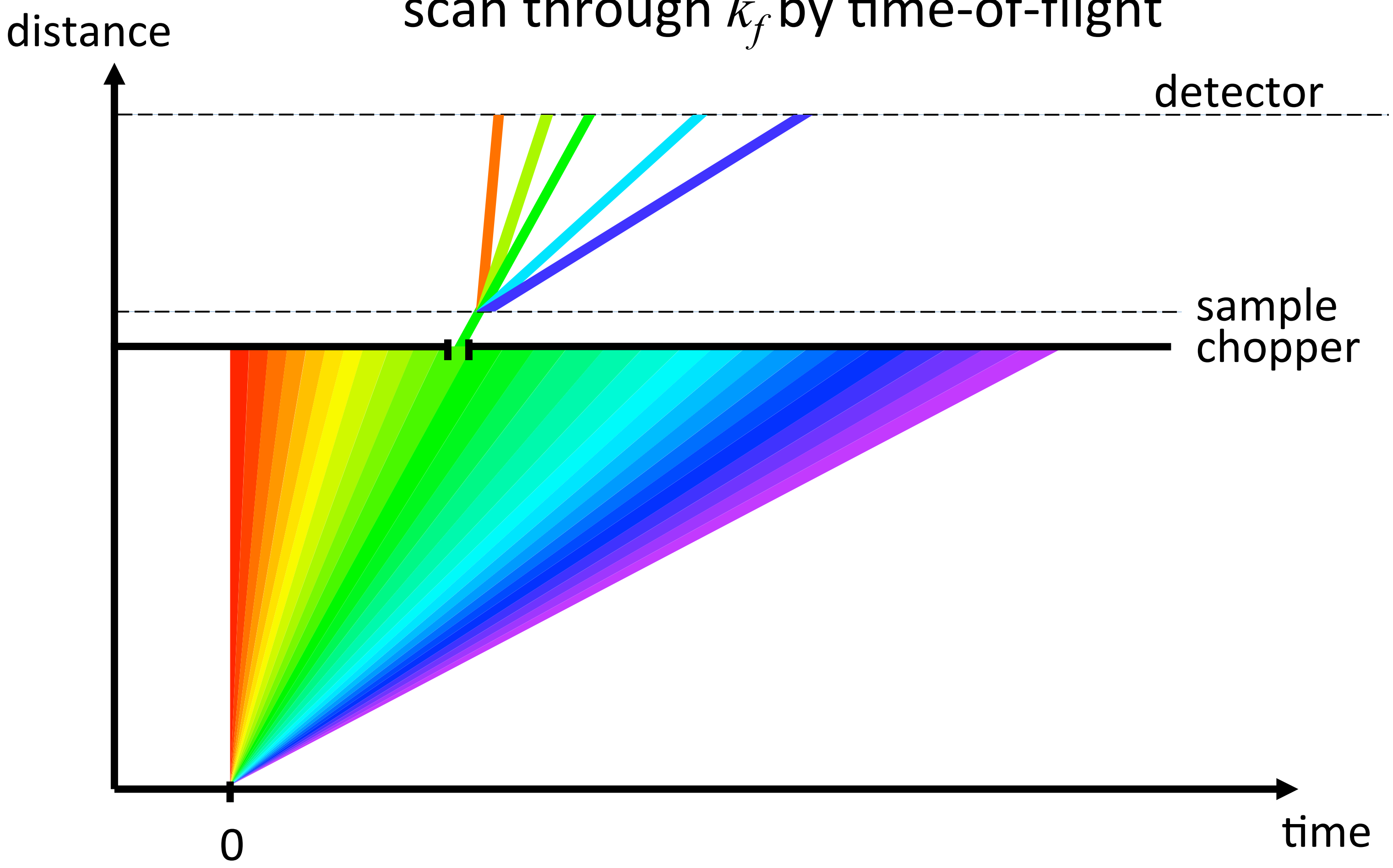
- Excitations: vibrations and other movements
- Structural knowledge is usually prerequisite
  - Measure diffraction first
- $k_i \neq k_f$
- Measure k_i and k_f:
  - Bragg Diffraction
  - Time-of-flight
  - Larmor precession
- Methods:
  - Fix k_i and scan k_f – ”direct geometry”
  - Fix k_f and scan k_i – ”indirect geometry”
- Energy scales: < µeV → > eV

Chopper Spectrometers

Direct geometry:

fix k_i by chopper phasing

scan through k_f by time-of-flight

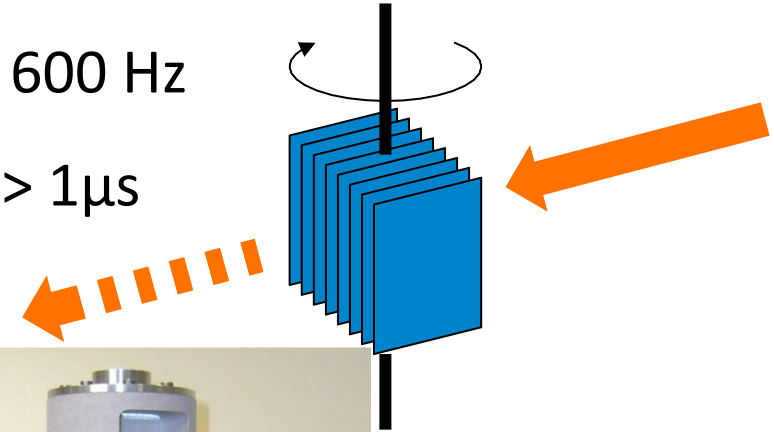


Neutron Choppers

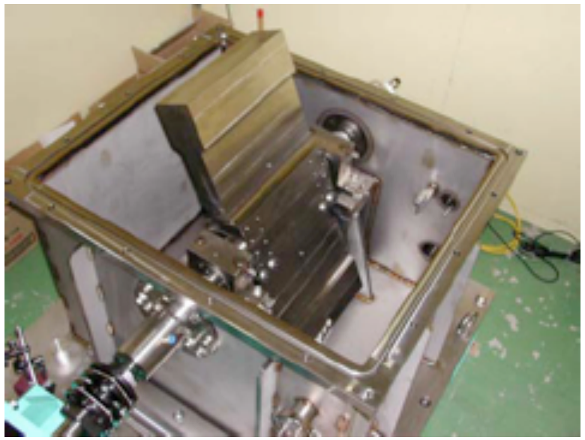
Fermi choppers

$f < 600$ Hz

$\Delta t > 1\mu s$



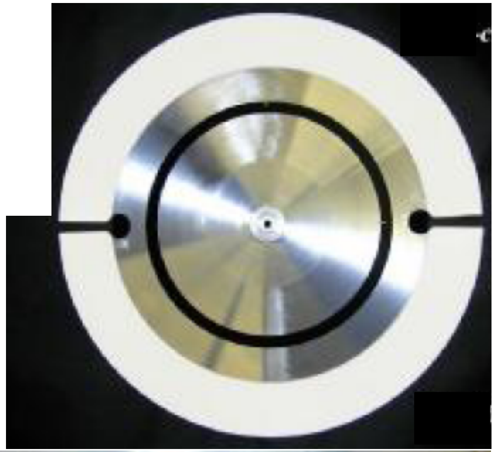
T_0 choppers



Disk choppers

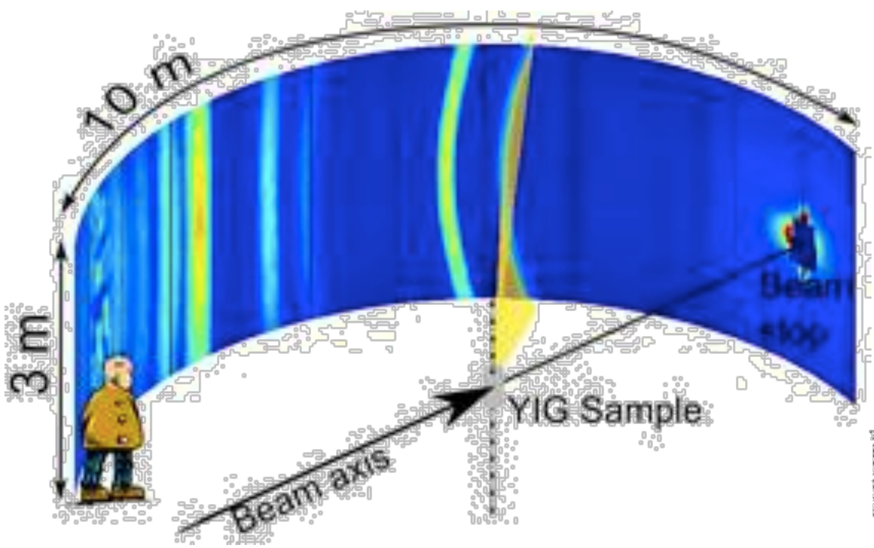
$f < 300$ Hz

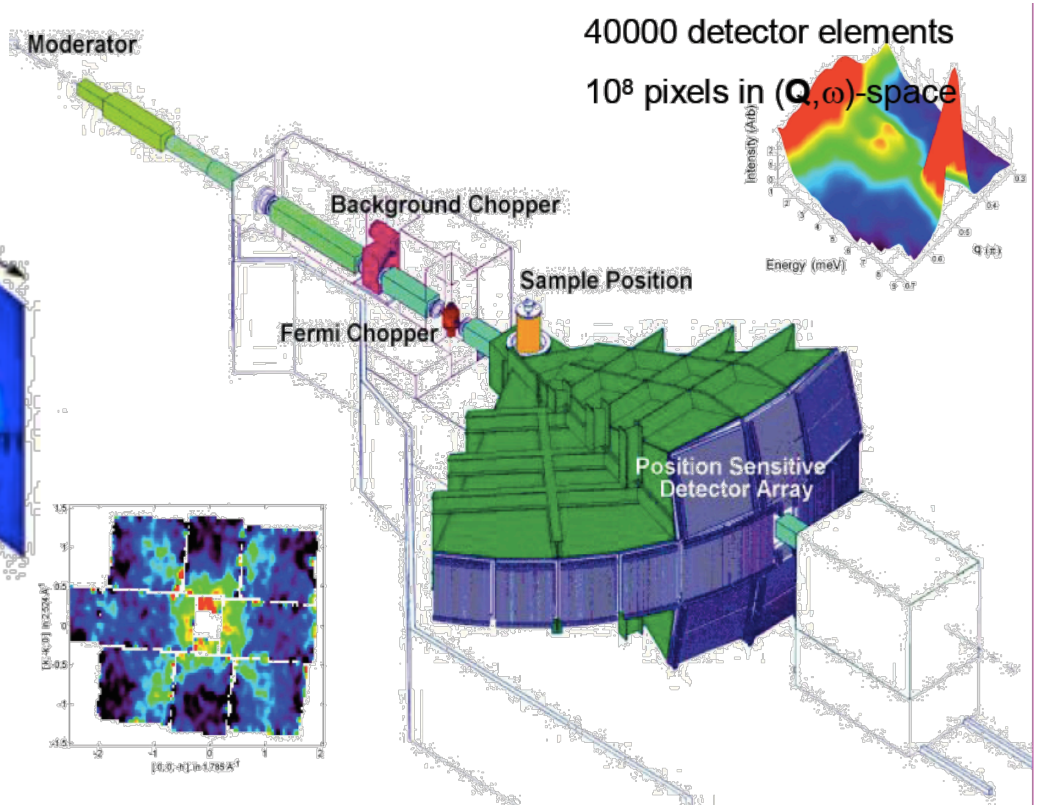
$\Delta t > 10\mu s$



Chopper Spectrometers

- General-Purpose Spectrometers
  - Incident energy ranges from 1meV to 1eV
- Huge position-sensitive detector arrays
  - Single-crystal samples





Detectors

^{3}He gas tubes

n + ^{3}He → ^{3}H + ^{1}H + 0.764 MeV

>1mm resolution

High efficiency

Low gamma-sensitivity

^{3}He supply problem

Scintillators

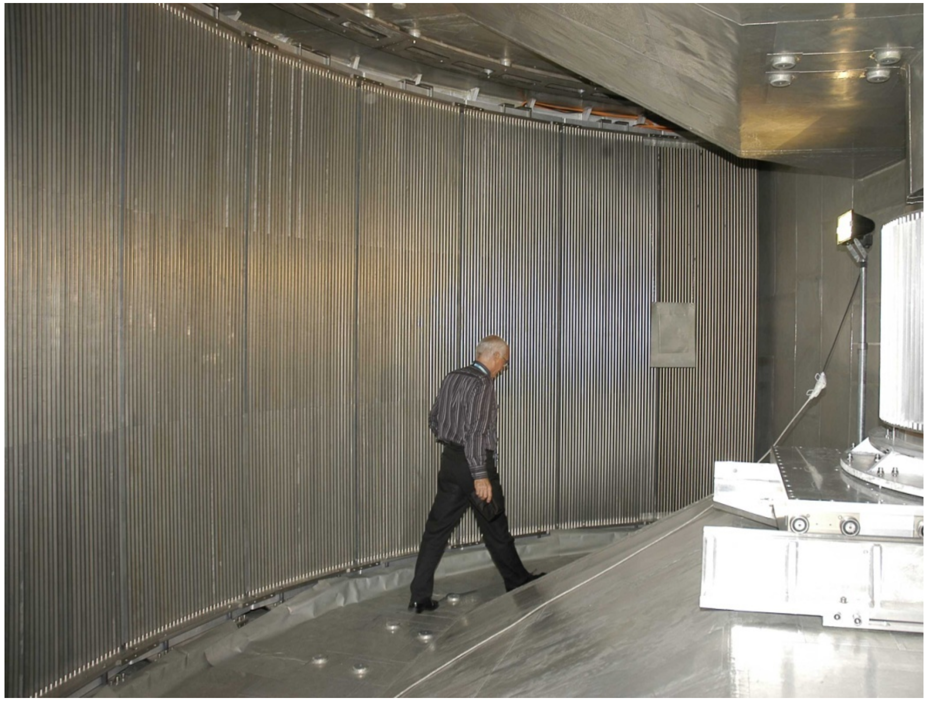
n + ^{6}Li → ^{4}He + ^{3}H + 4.79 MeV

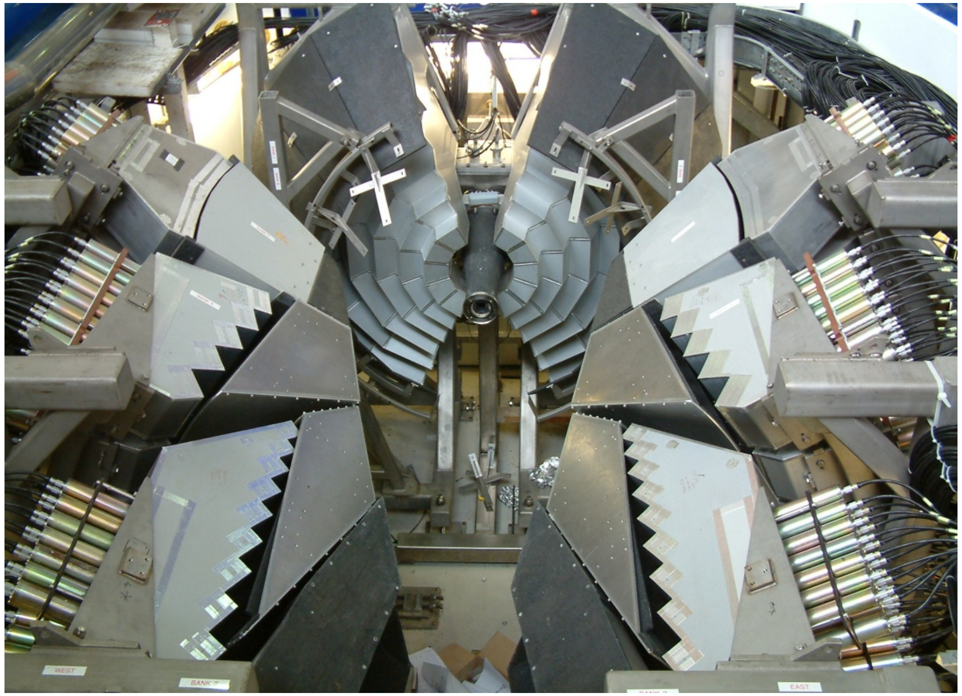
<1mm resolution

Medium efficiency

Some gamma-sensitivity

Magnetic-field sensitivity





Detectors

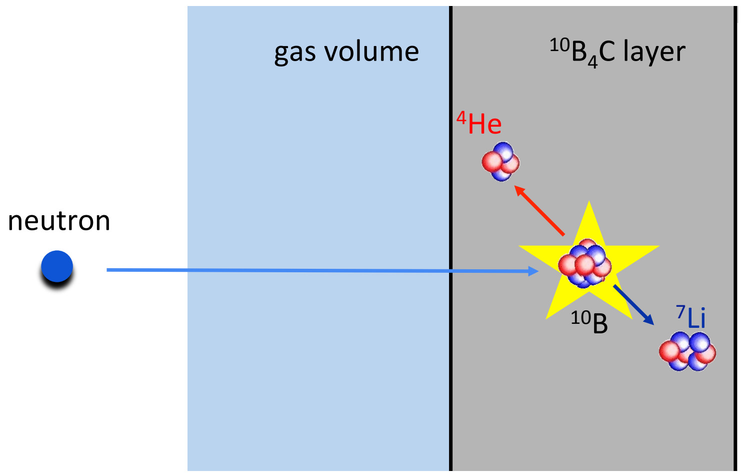
<u>^{10}B detectors</u>

n + ^{10}B → ^{7}Li + ^{4}He + 0.48 MeV

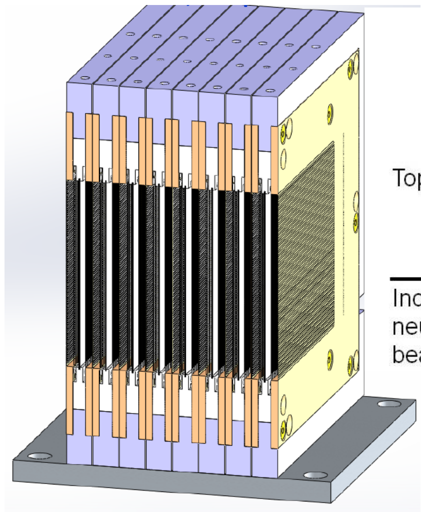
massive development programme

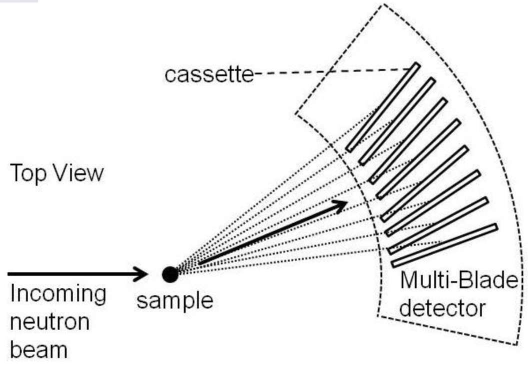
none yet in operation

many different types

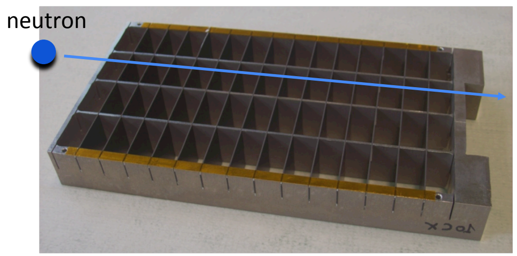


boron layer thickness limited to ~ 1 µm
=> ~ 5% efficiency

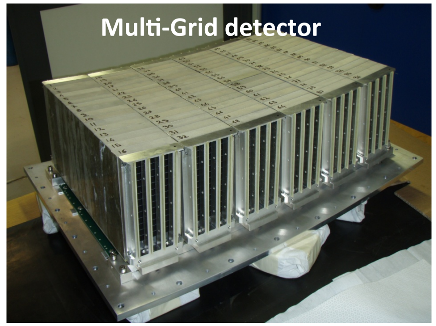




inclined blades



perpendicular blades

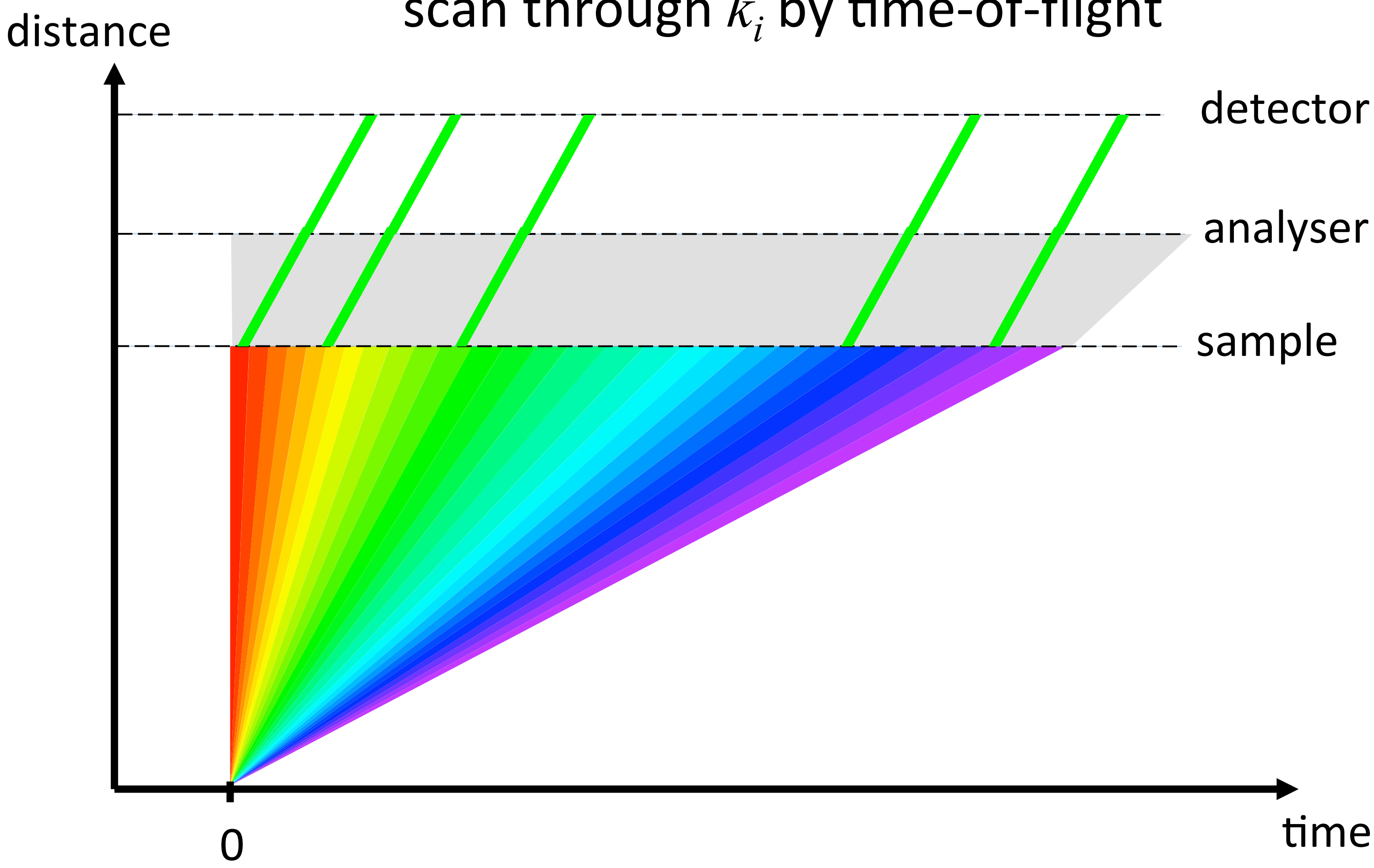


Alternative to Direct Geometry

Indirect geometry:

fix k_f – usually by analyser crystals

scan through k_i by time-of-flight



High Resolution 1: Backscattering

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

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

$$\theta \to \frac{\pi}{2}$$

$$\cot\theta = \frac{\cos\theta}{\sin\theta} \to 0$$

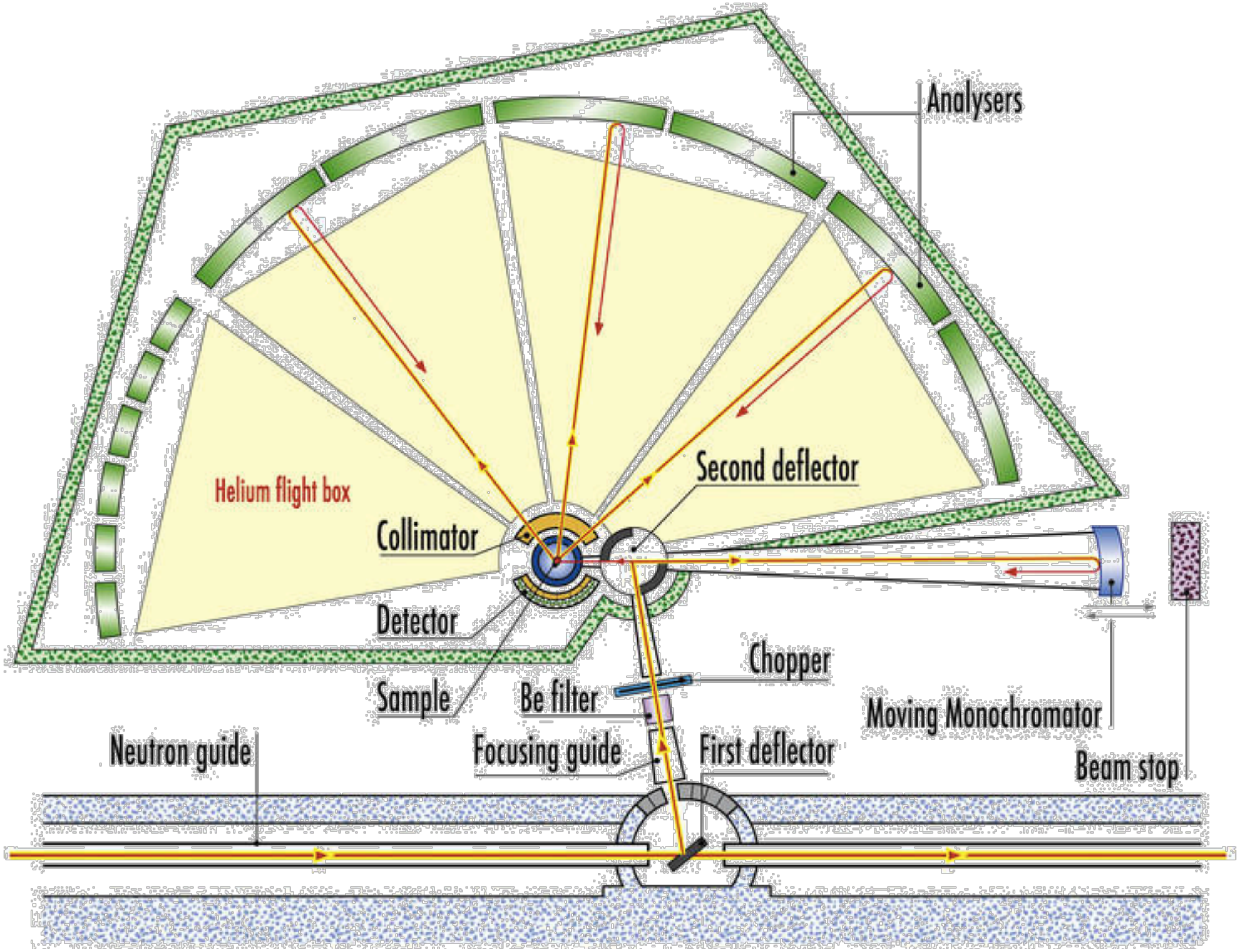
Use single crystals in as close to backscattering as possible to define k_f.
Scan through k_i with as good energy resolution.

Backscattering

BASIS@SNS Si111 3μeV

OSIRIS@ISIS PG002 25μeV

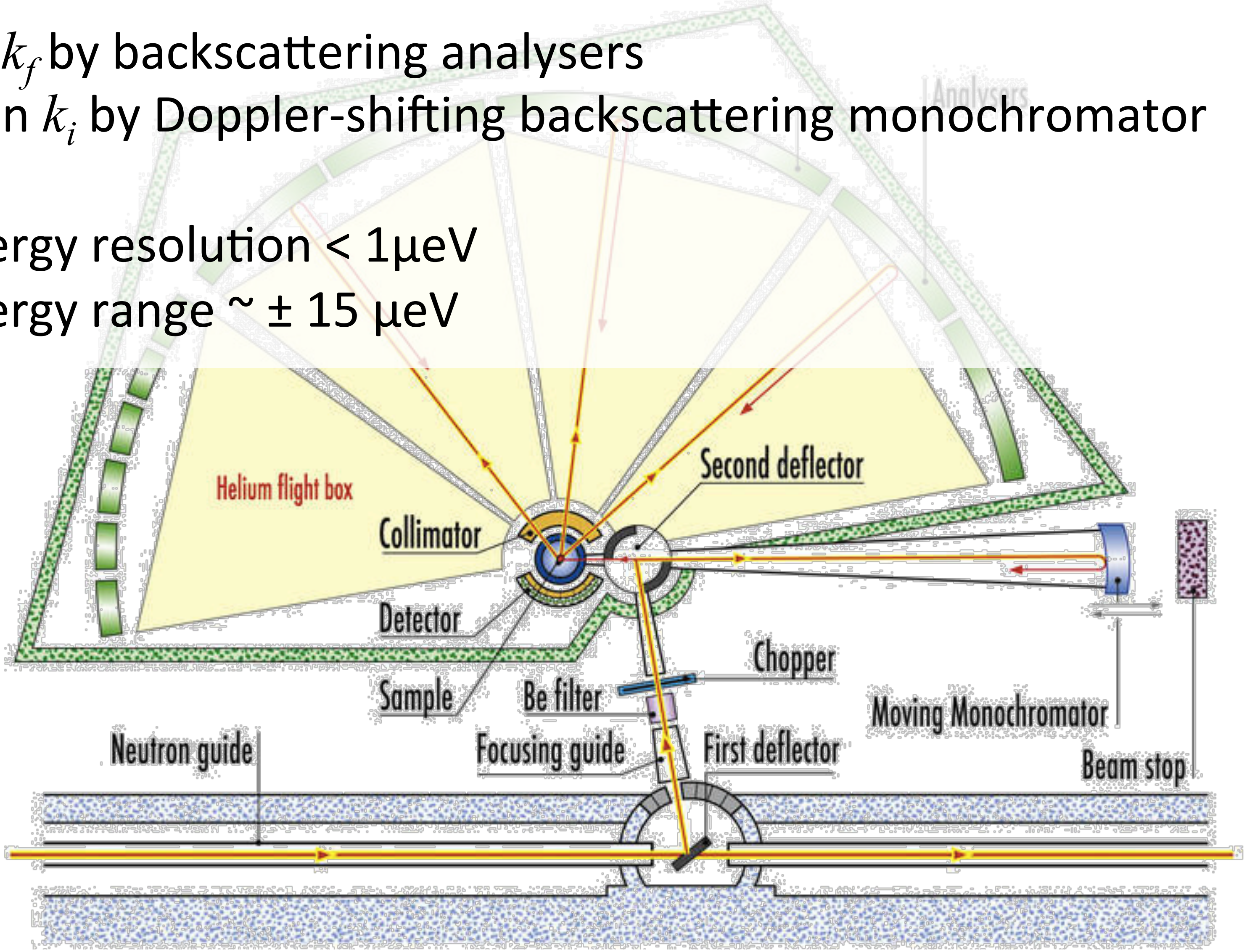
Continuous-Source Backscattering



Continuous-Source Backscattering

Fix k_f by backscattering analysers
Scan k_i by Doppler-shifting backscattering monochromator

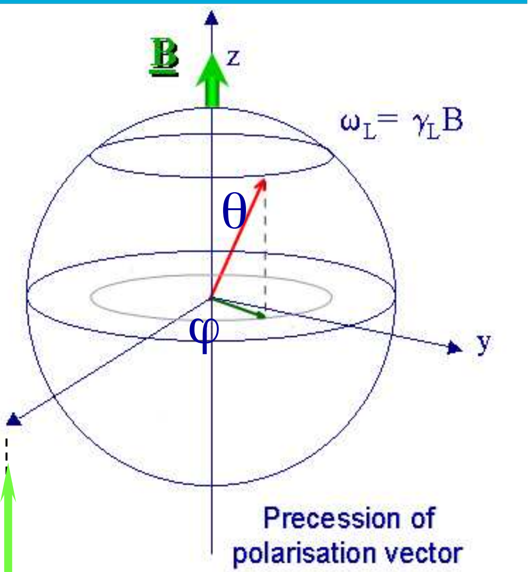
Energy resolution < 1μeV
Energy range ~ ± 15 μeV

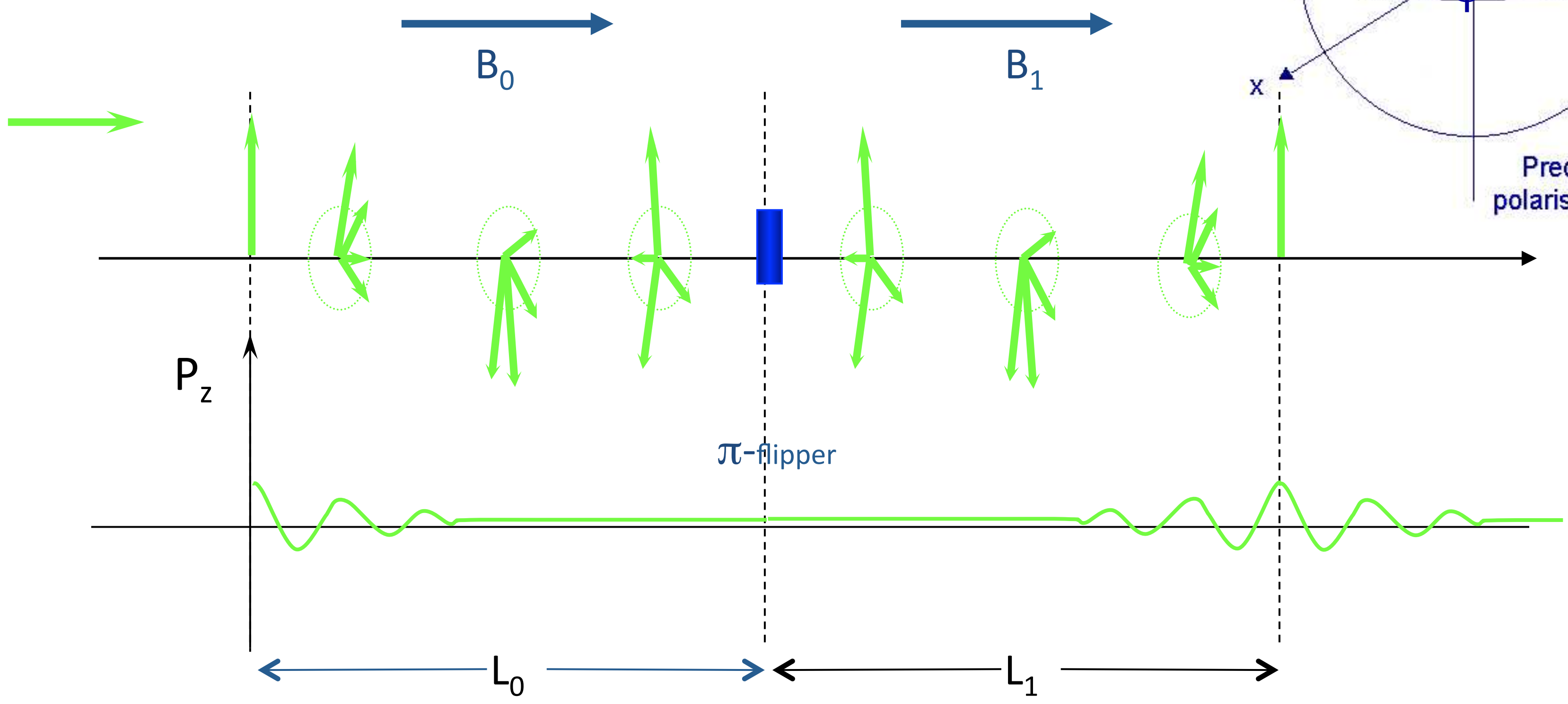


High Resolution 2: Neutron Spin Echo

High energy resolution < 1 μeV

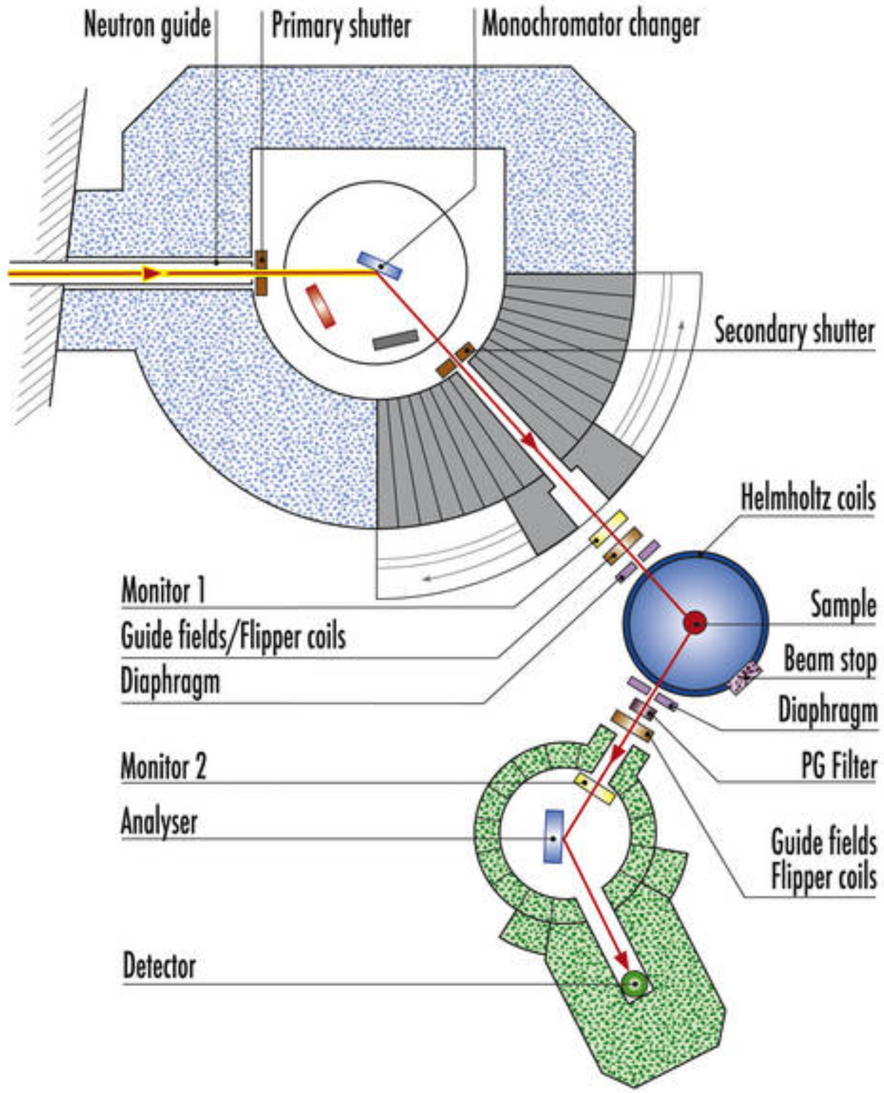
Larmor precessions encode energy transfer





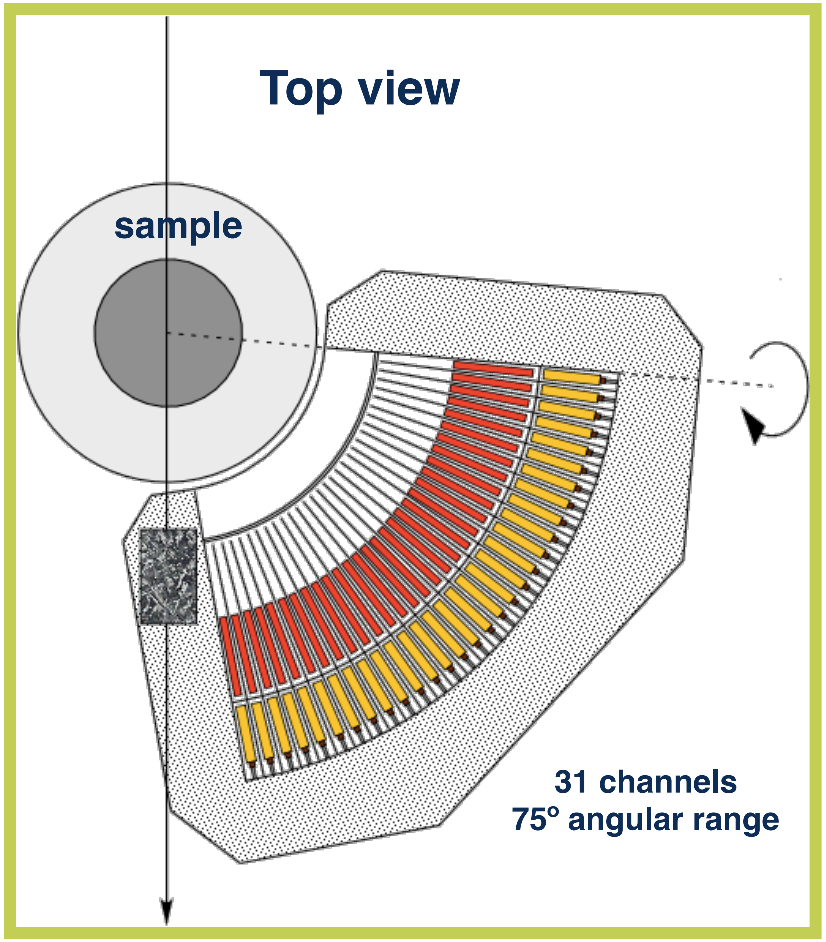
Triple-Axis Spectrometers

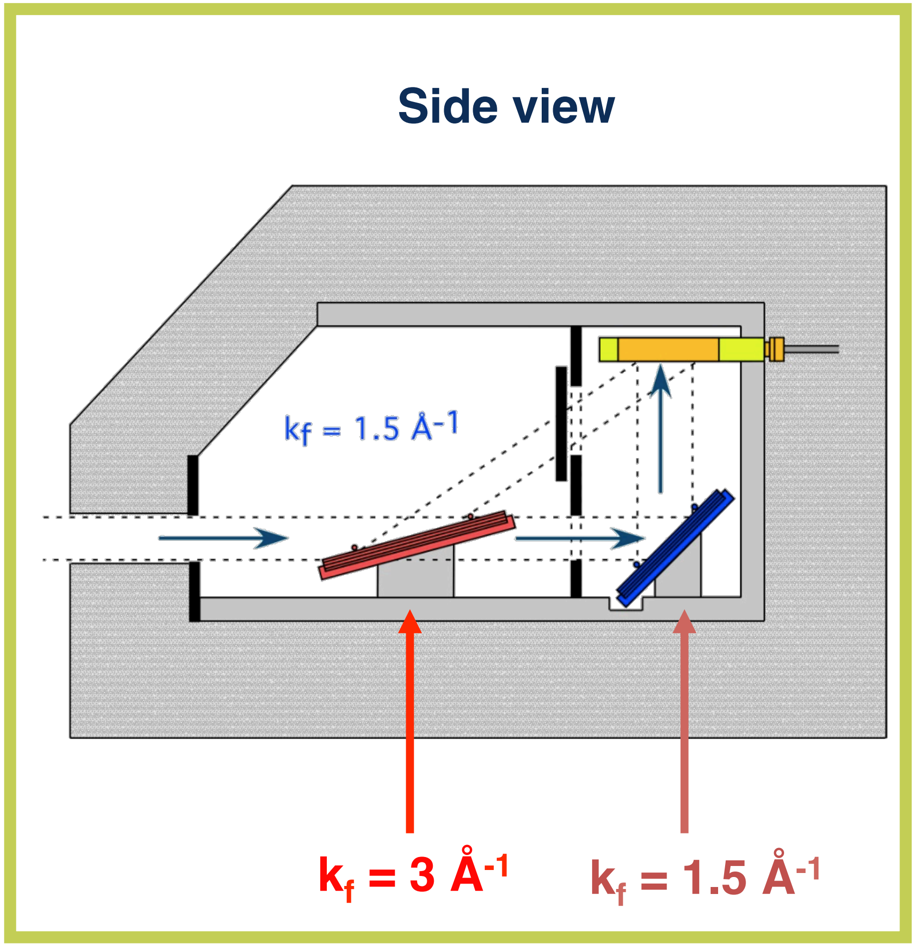
- Single-crystal excitations
- Very flexible
- Measures a single point in $\vec{Q}$ -E space at a time
- Scans:
  - Constant $\vec{Q}$: Scan E at constant $\mathbf{k_i}$ or $\mathbf{k_f}$
  - Constant E: Scan $\vec{Q}$ in any direction



TAS with multiplexing

IN20 flat-cone multi-analyser





Thank you!