X-ray and Neutron Scattering from Crystalline Surfaces and Interfaces

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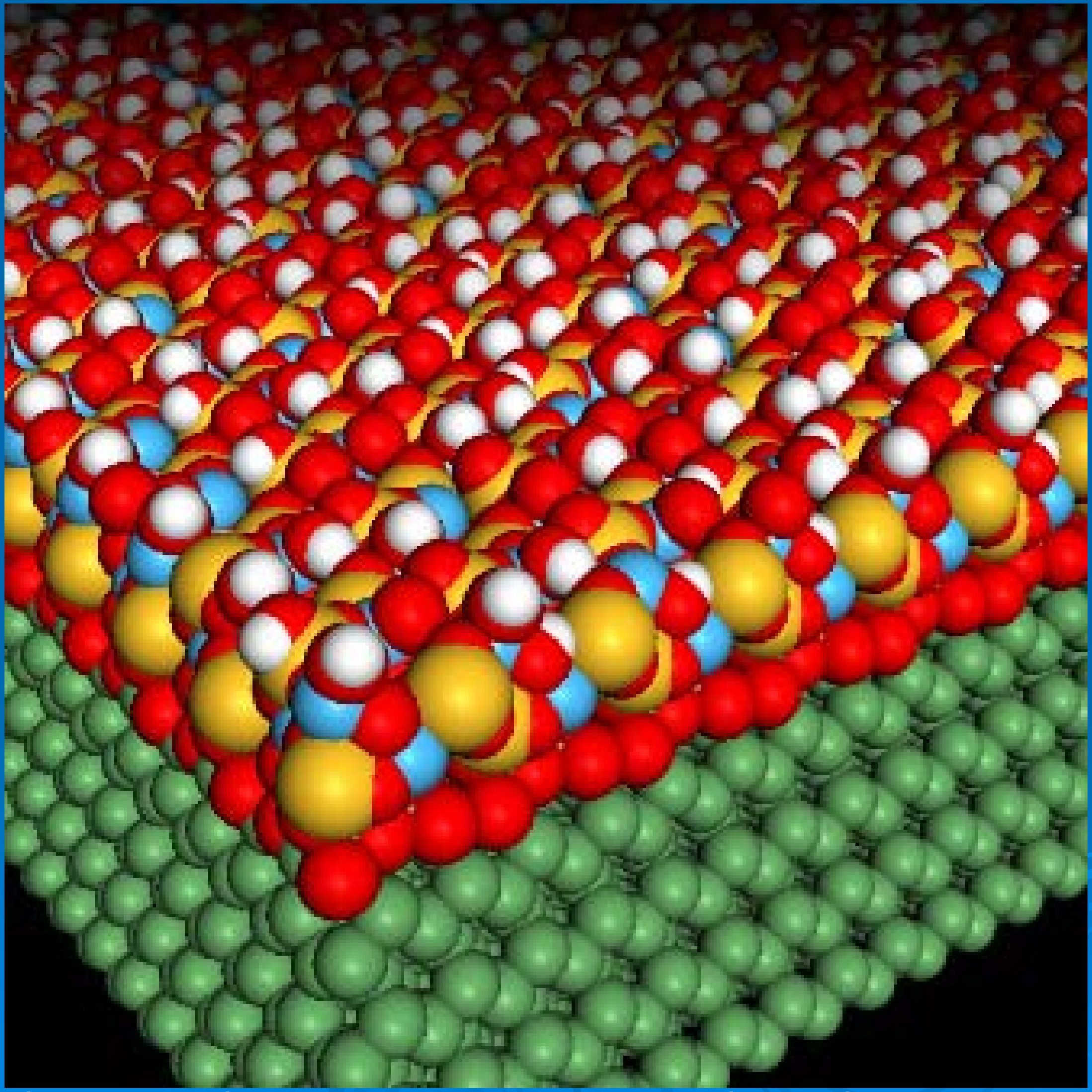
W. Elliott, C. Botez, S.W. Han, M. Gramlich, S. Hayden, Y. Chen, C. Kim, C. Jeffrey, E. H. Conrad, C.J. Palmstrøm, P.W. Stephens, M. Tringides; and to NSF and DOE for funding.

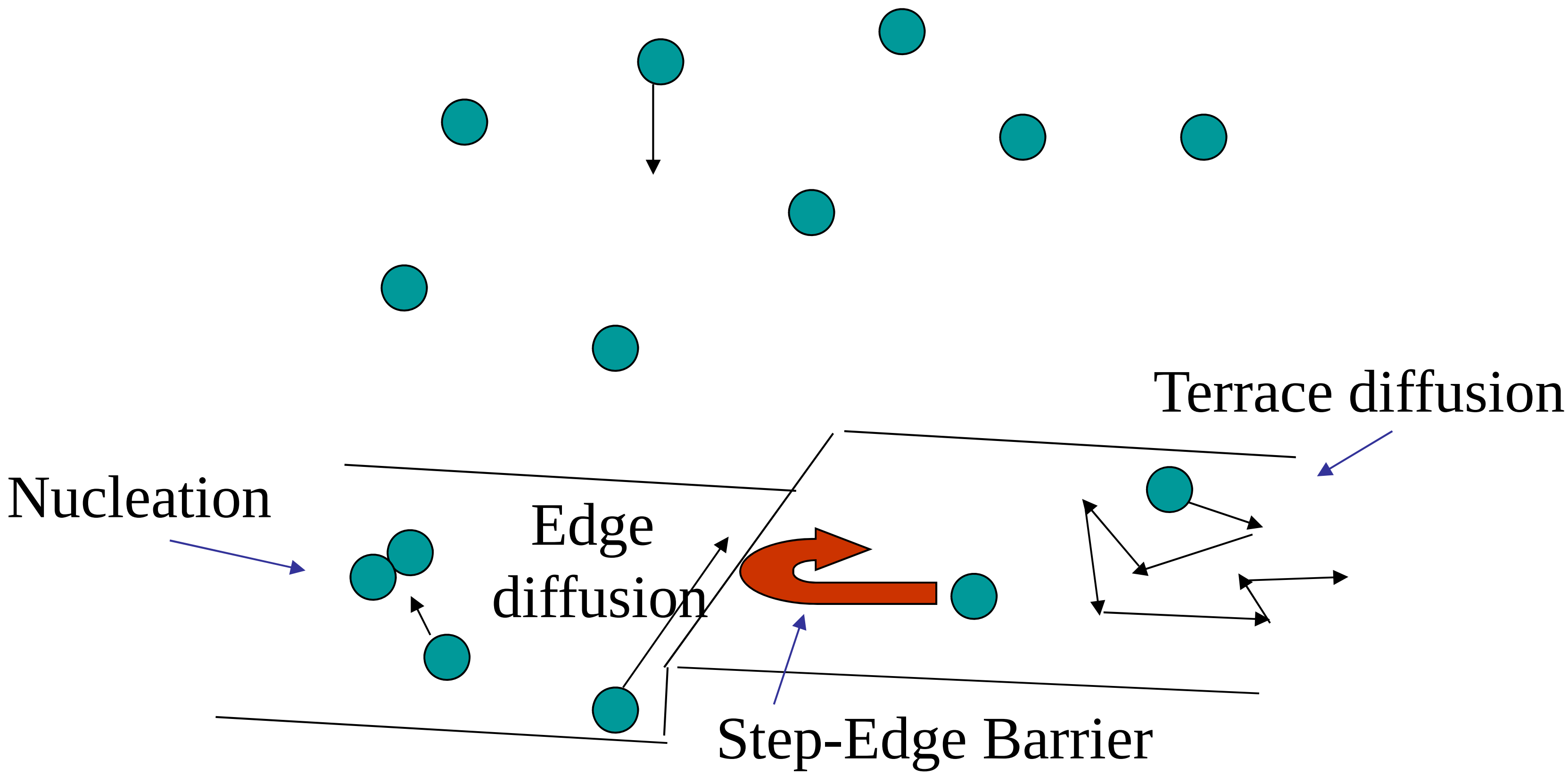
Buried Interface Structure

to understand the growth and function of materials

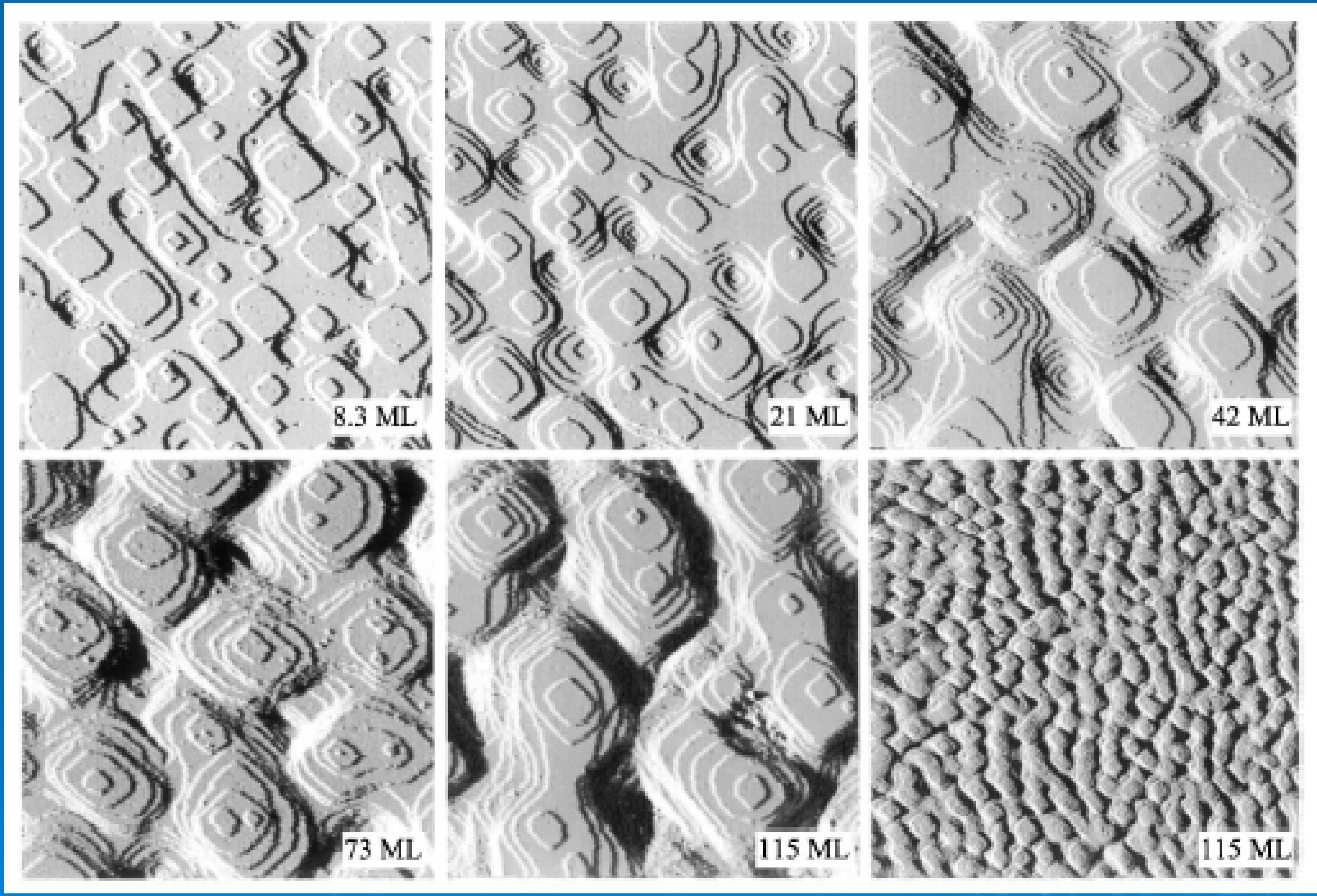


http://www.tyndall.ie/research/electronic-theory-group/thin_film_simulation.html

Crystal growth from a vapor



Morphology → atomic scale mechanisms



Cu/Cu(001)

Zuo & Wendelken

Interplay between two regimes of Length Scales

- Interatomic distances
  →Structure, physics, chemistry → Mechanisms

- "Mesoscale" – Nanoscale
  → Morphology → Mechanisms

Unique Advantages of X-ray Scattering:

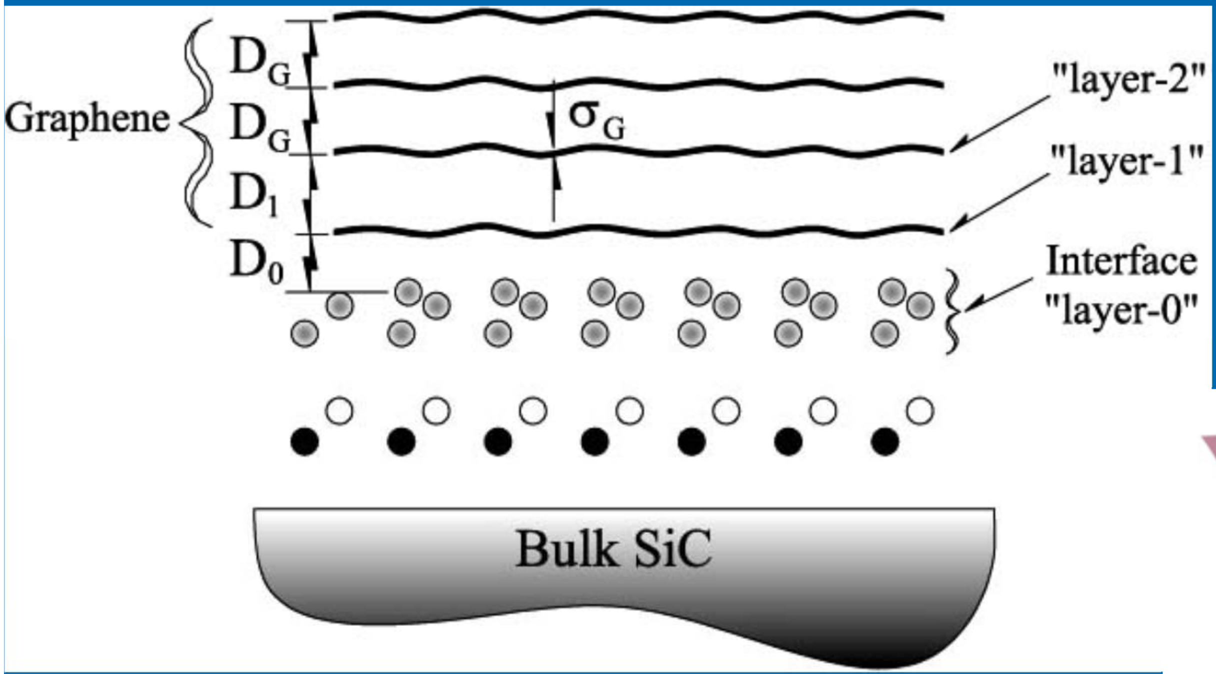
- Atomic-scale structure at a buried interface
- Morphological structure at buried interfaces
- Subsurface phenomena
  Strains and defects near a surface
- Accurate statistics of distributions
  (eg. Island size distributions)

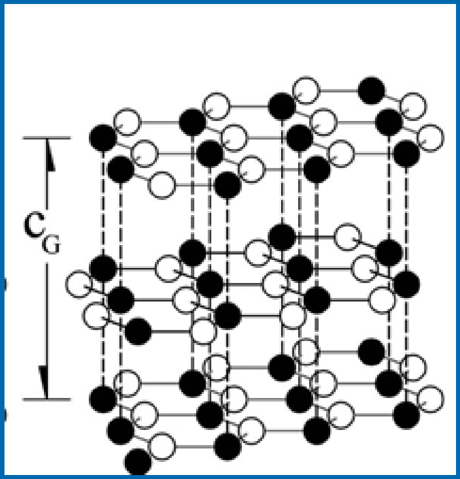
Neutrons: low intensity- limited to reflectivity

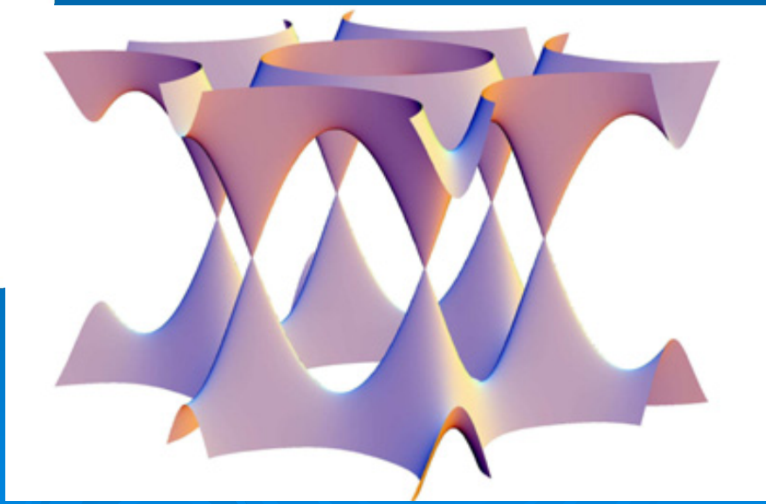
- Soft Matter and Bio materials; H_2O & D_2O
- Magnetic materials

Example:
Rotation of graphene planes affect electronic properties

Graphene made from SiC

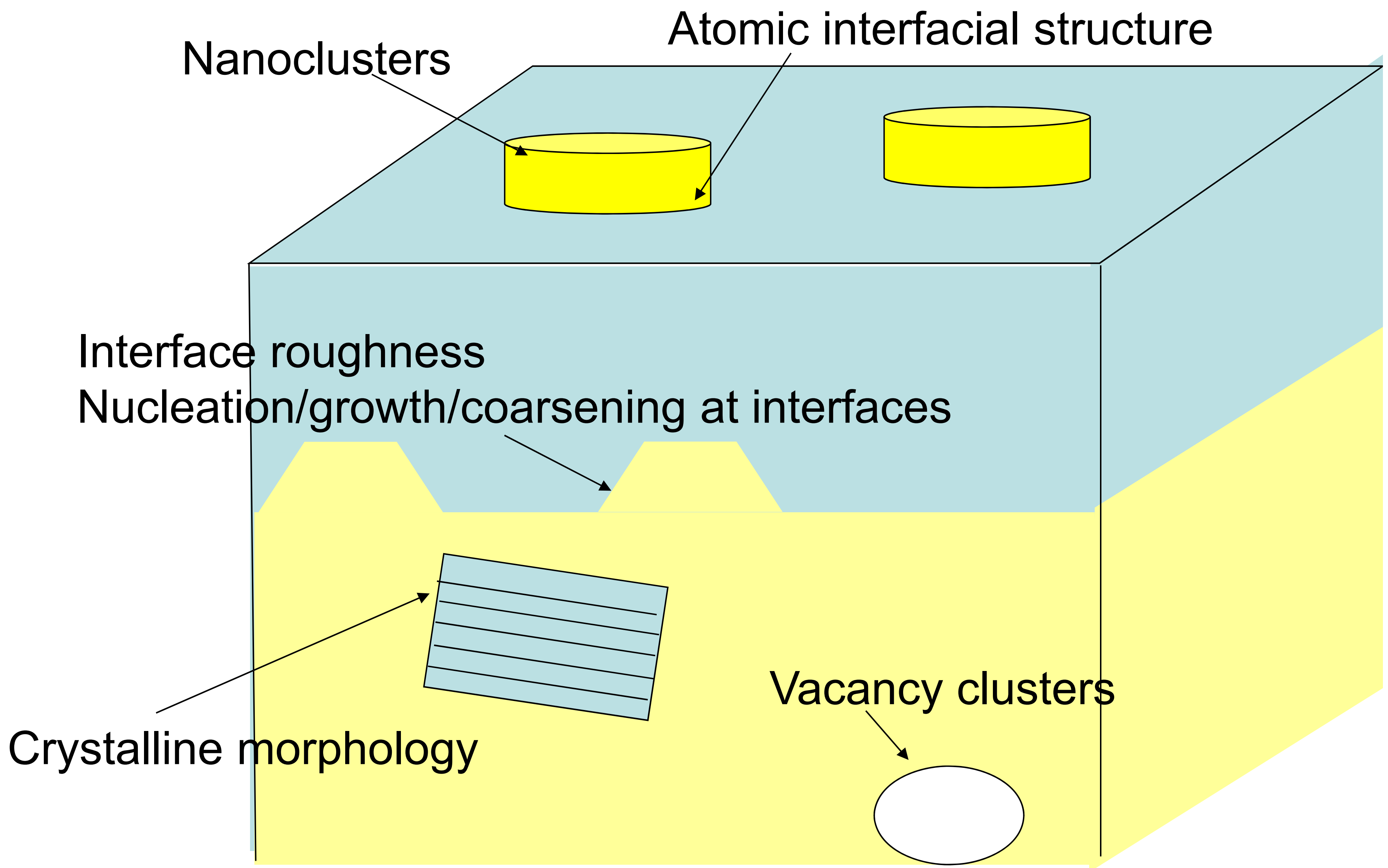






J. Phys.: Condens. Matter **20** (2008) 323202

Morphology → atomic scale mechanisms



Objective

- An introduction to surface scattering techniques
  Build a conceptual framework

- Reciprocal Space is a large place: where do we look?

Scattering of X-rays and Neutrons: Helmholtz Equation

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

X-rays

$$\nabla^2 \vec{E} + k^2 n^2(\vec{r})\vec{E} = 0$$

Neutrons

$$\nabla^2 \Psi + \frac{2m}{\hbar^2}\left[E - V(\vec{r})\right]\Psi = 0$$

n(r)=inhomogeneous refractive index

Refractive Index for neutron: $n(\vec{r}) = \sqrt{1 - \frac{2m}{\hbar^2 k^2} V(\vec{r})} = \sqrt{1 - \lambda^2 \rho_b(\vec{r})/\pi}$

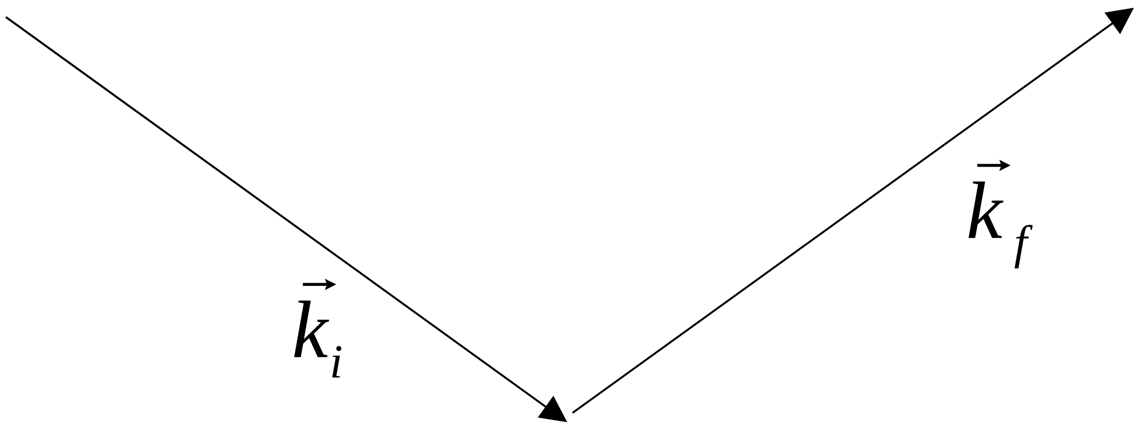
Scattering length density: $\rho_b(\vec{r}) \xrightarrow{monoatomic} \rho_N(\vec{r})\, b$

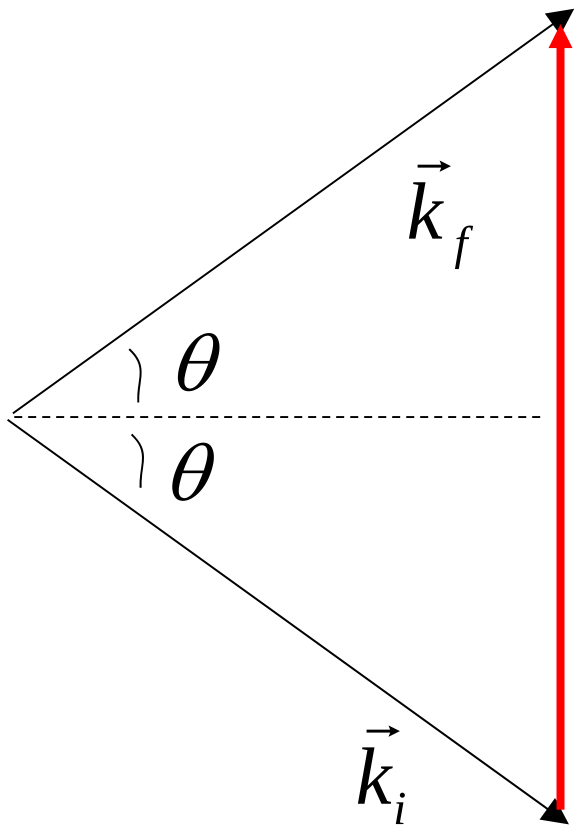
number density

scattering length:

$$b = \begin{cases} r_e f(Q) & x - rays \\ tabulated - neutrons \end{cases}$$

One language for both x-rays and neutrons





Wavevector Transfer:

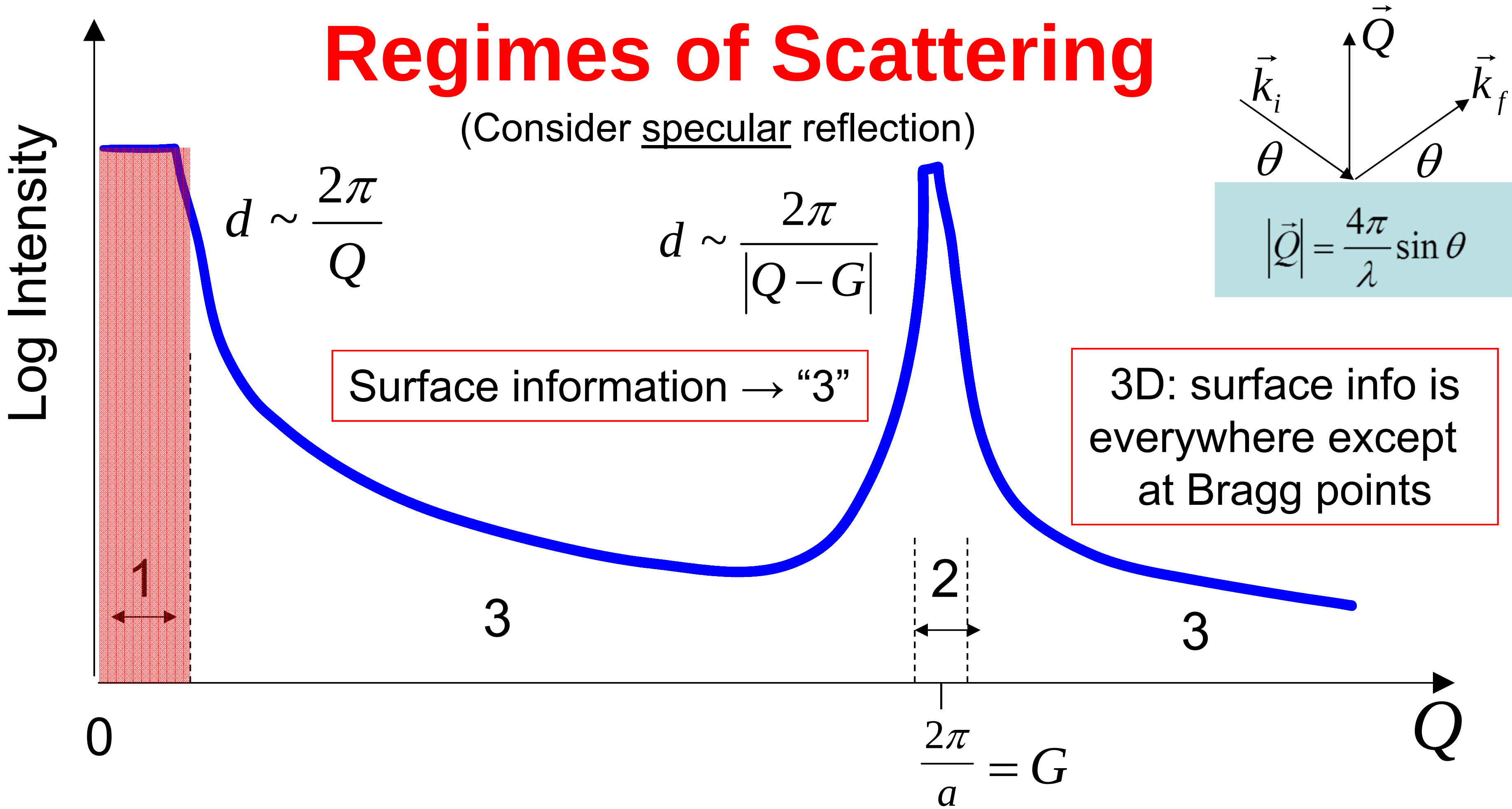
$$\vec{Q} = \vec{k}_f - \vec{k}_i$$

$$\left|\vec{Q}\right| = \frac{4\pi}{\lambda}\sin\theta \sim \frac{2\pi}{d}$$

Probing Length Scale

Regimes of Scattering

(Consider specular reflection)



1. Grazing angle reflectivity: strong scattering d>>interatomic distances
   Exact solution required. Neglect atomic positions: homogeneous medium

2. Bragg region: strong scattering; d~interatomic distances = a
   Exact solution required. Atomic positions needed. Similar to e^- band theory.

3. Everywhere else: weak scattering
   Born approximation →simplification. Atomic positions required.

Grazing Angles: Refraction and Total Reflection

d>>a: consider homogenous medium

Use average refractive index:

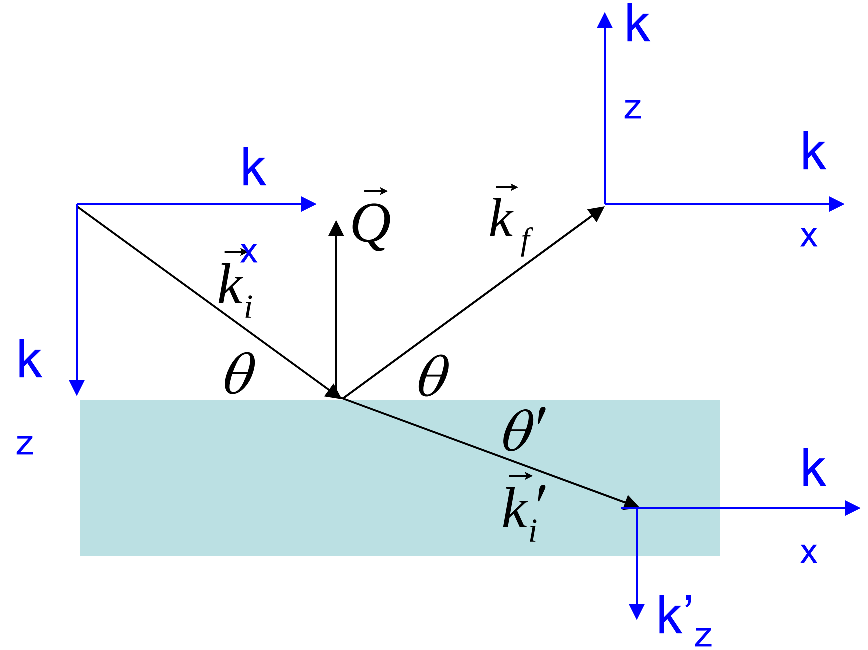
$$n = \sqrt{1-\lambda^2\rho_b/\pi} \equiv 1-\delta \qquad \delta = \frac{\lambda^2\rho_b}{2\pi} << 1 \quad (\sim 10^{-5})$$

With absorption: $n = 1-\delta - i\beta$

Snell's Law:

$$\sin^2\theta' = \sin^2\theta - 2\delta$$

Critical Angle for Total Reflection: $\theta_c = \sqrt{2\delta}$



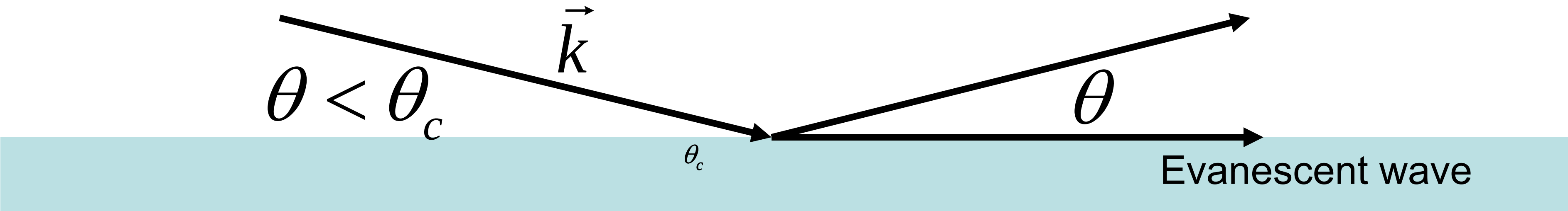
Wavevector transfer:

$$Q'^2 = Q^2 - Q_c^2$$

Only k_z component is affected by the surface. k_x is unchanged.

$$Q_c^2 = 16\pi\rho_b$$

Total Reflection



$$\sin^2(\theta') = 0 = \sin^2(\theta_c) - 2\delta$$

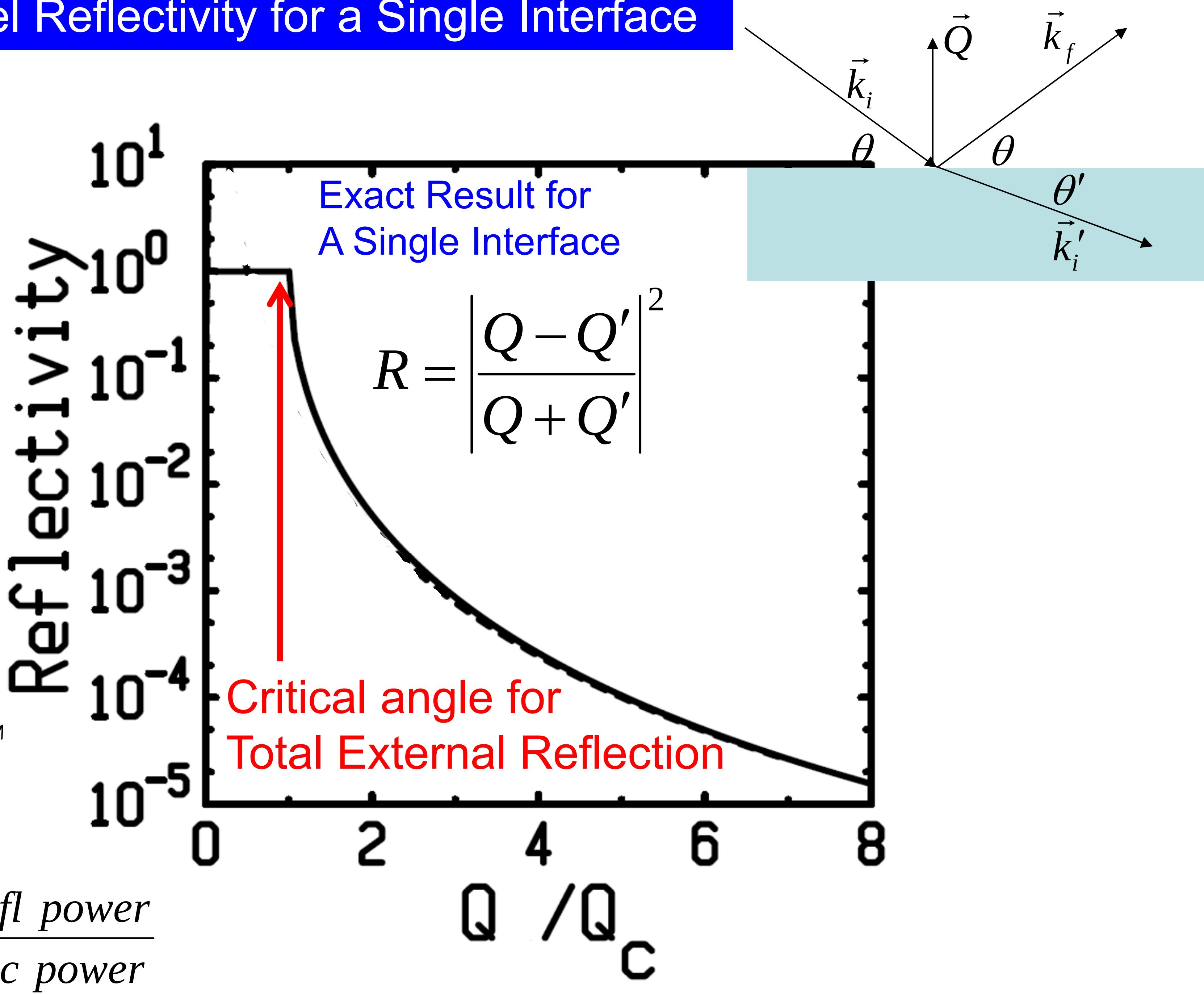
Critical Angle for Total External Reflection:

$$\theta_c = \sqrt{2\delta}$$

$$Q_c = \frac{4\pi}{\lambda}\theta_c$$

Beam does not transmit below θ_c

Frenel Reflectivity for a Single Interface

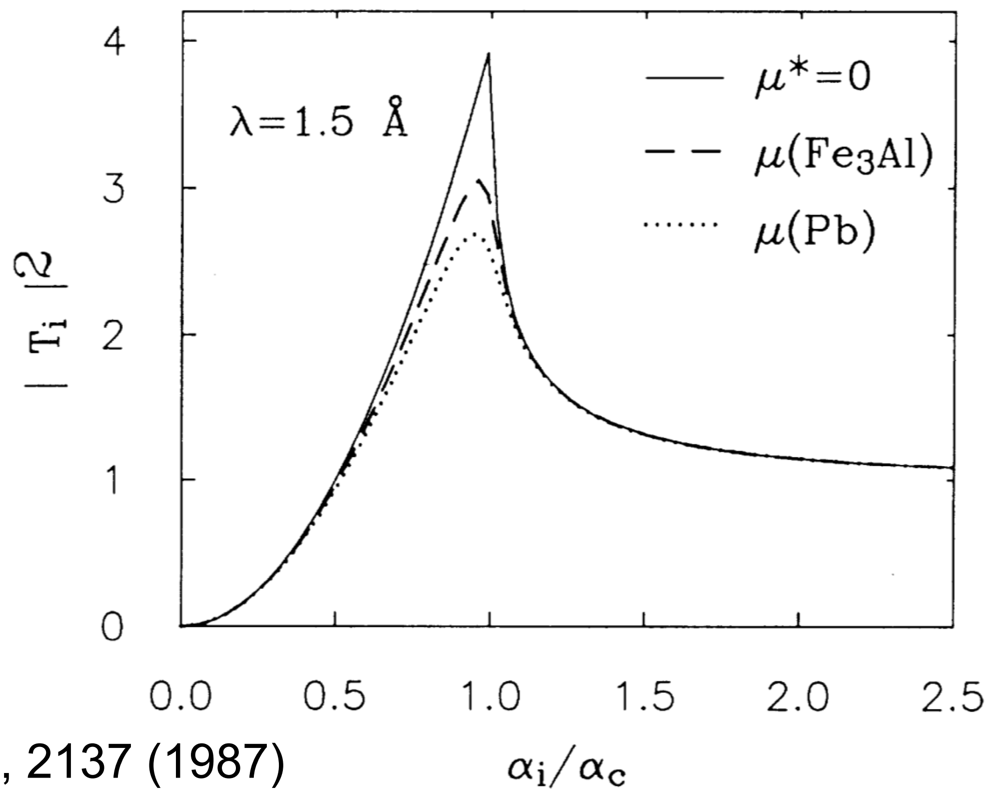


$$R = \left| \frac{Q - Q'}{Q + Q'} \right|^2$$

$$R = \frac{refl\ power}{inc\ power}$$

Transmission Amplitude

$$T_i = \frac{2\sin\alpha_i}{\sin\alpha_i + (\sin^2\alpha_i - 2\delta)^{1/2}}$$



H. Dosch, PRB **35**, 2137 (1987)

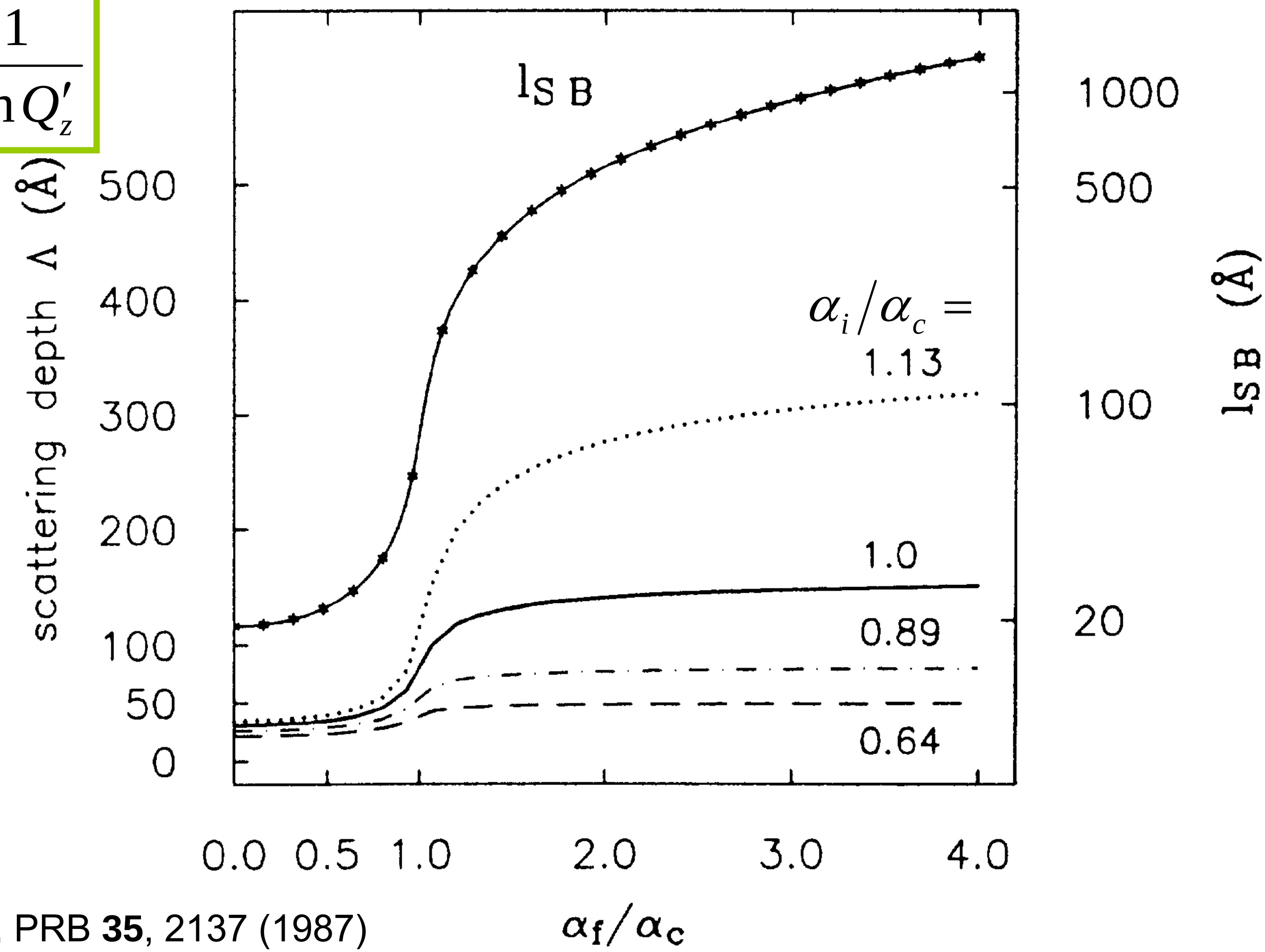
FIG. 1. Fresnel transmissivity $|T_i|^2$ as a function of α_i/α_c for a transparent medium and the real systems Fe_3Al and Pb.

$$\Lambda = \lambda / [2\pi(l_i + l_f)]$$

Penetration Length

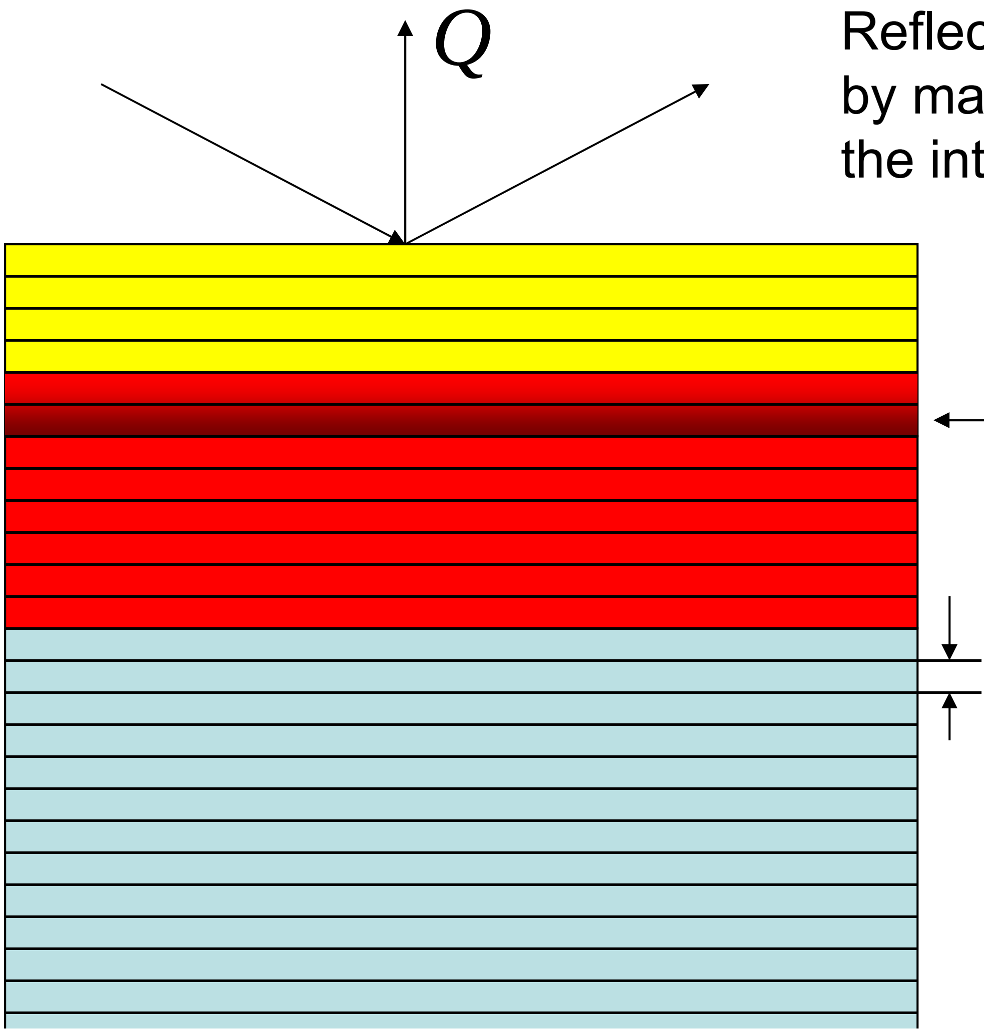
$$l_{i,f} = \frac{1}{2}\sqrt{2}\{(2\delta - \sin^2\alpha_{i,f}) + [(\sin^2\alpha_{i,f} - 2\delta)^2 + (2\beta)^2]^{1/2}\}^{1/2}$$

$$\Lambda = \frac{1}{\mathrm{Im}\, Q_z'}$$



H. Dosch, PRB **35**, 2137 (1987)

Calculation of reflectivity



Reflectivity, R, can be calculated, exacty, by matching boundary conditions at the interfaces.

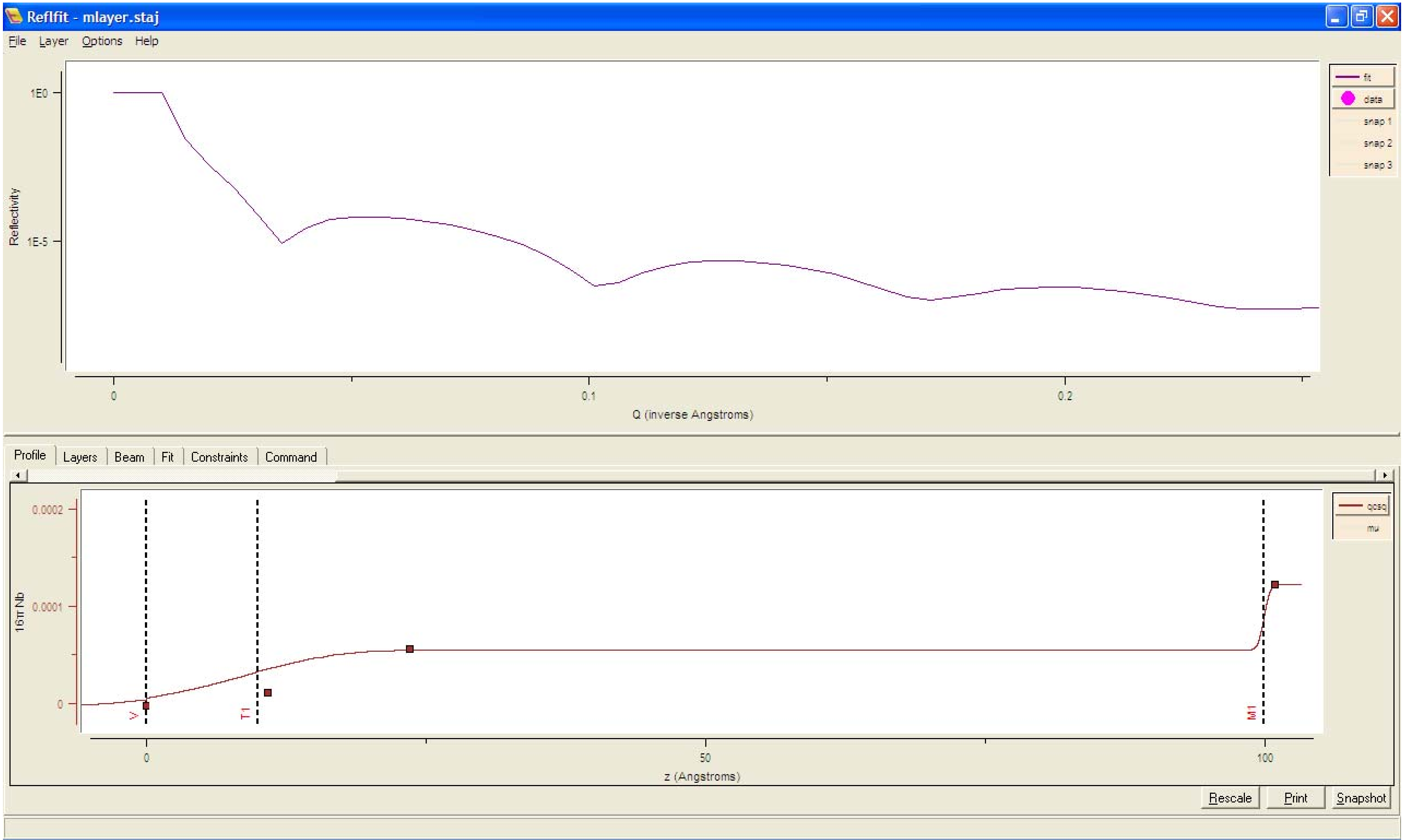
Include an interfacial transition

Multi-slice method:
Numerical simulations

L.G. Parratt, Phys Rev 95, 359 (1954)

M-layer

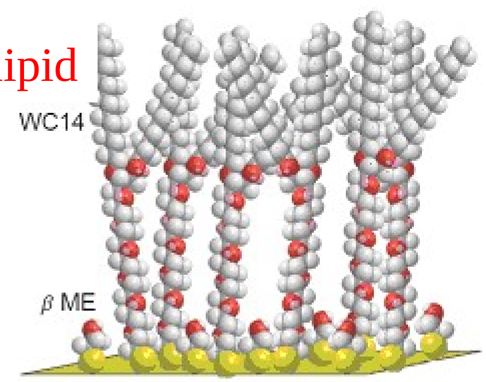
http://www.ncnr.nist.gov/reflpak/

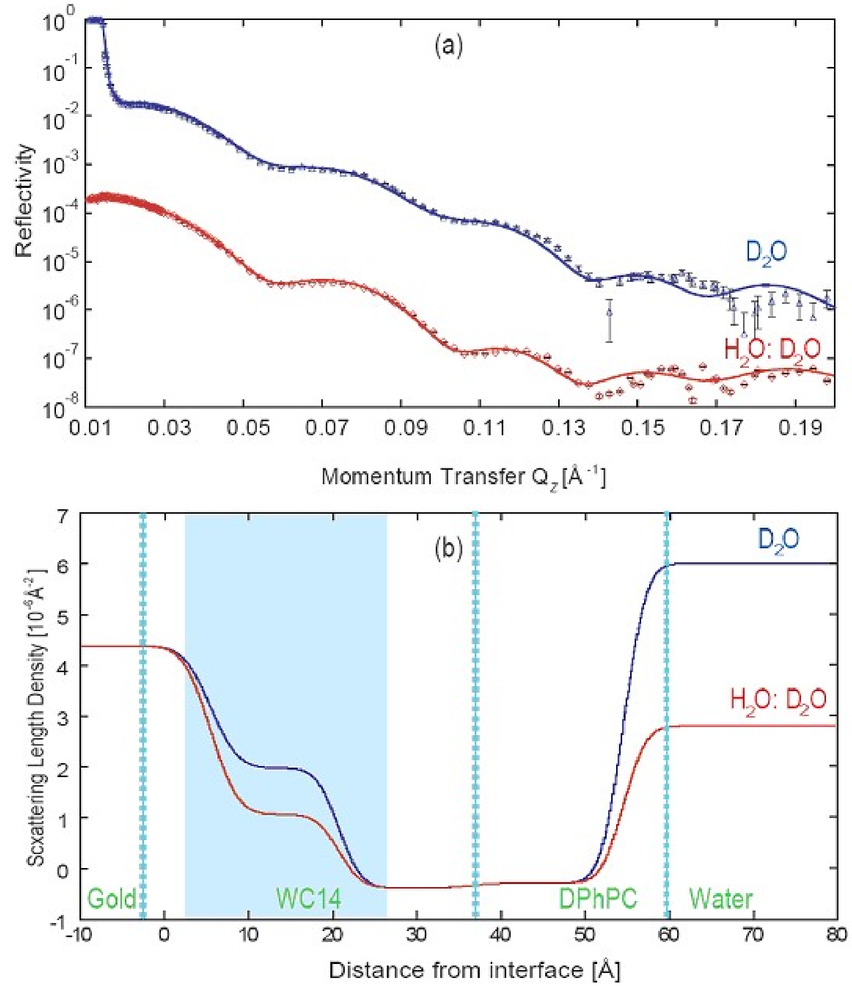


Soft Matter: Neutron Reflectivity

- Thin film interfaces
  - Light elements
  - Isotopic substitutions
  - Polymers

lipid





D. J. McGillivray and M. Lösche
D. J. Vanderah and J. J. Kasianowicz
G. Valincius

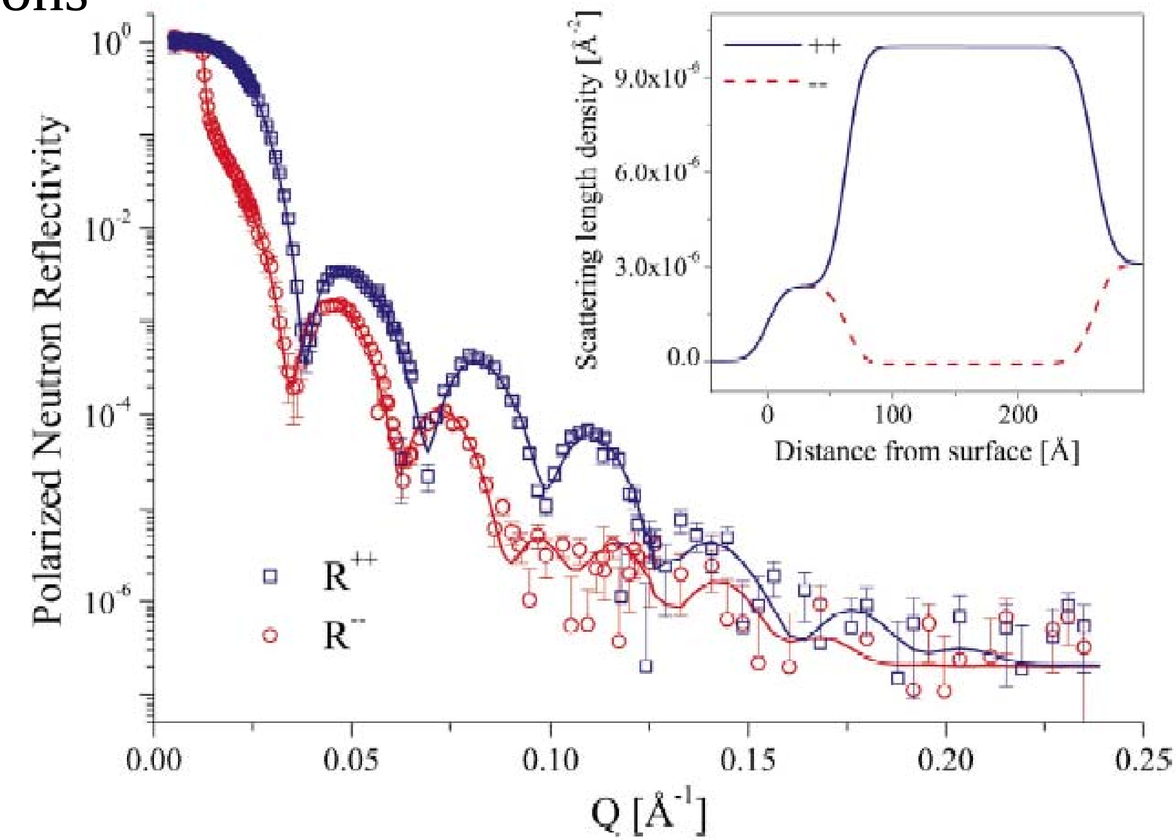
Biophysical Journal Volume 95 November 2008 4845–4861

Magnetic Films: Neutron Reflectivity

- Magnetic thin films

  Spin-polarized neutrons

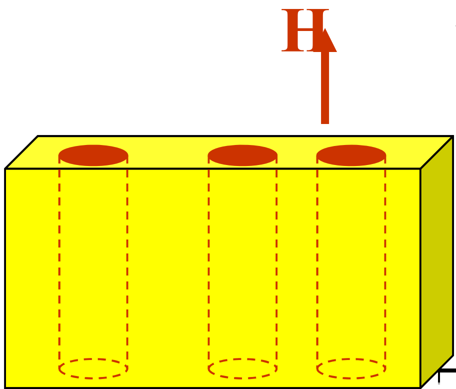
FeCo/GaAs



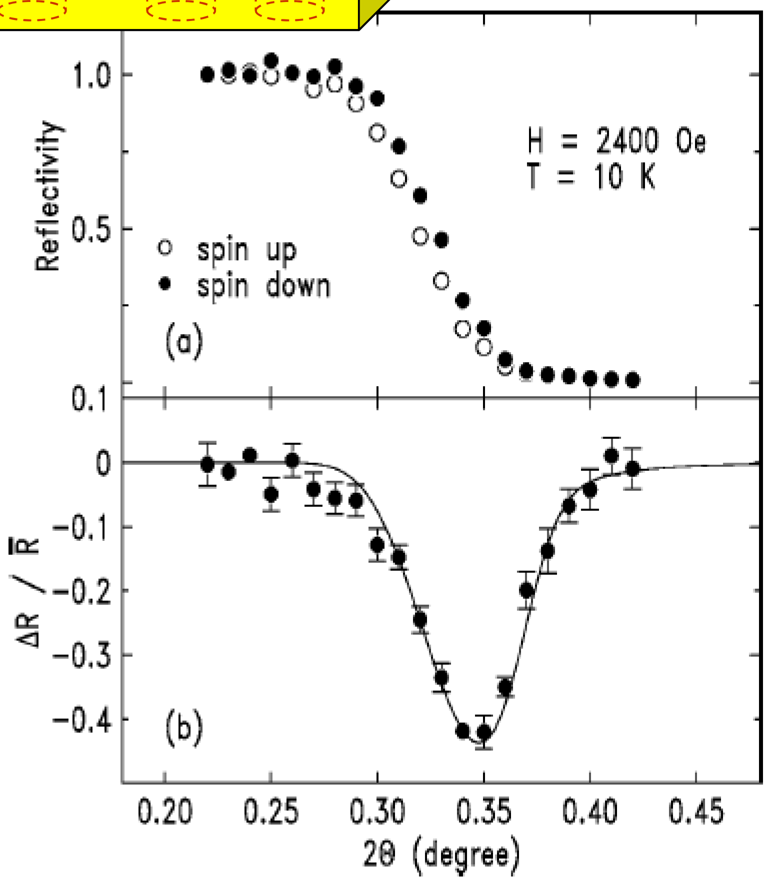
S. Park, M. R. Fitzsimmons, X. Y. Dong,
B. D. Schultz, and C. J. Palmstrøm, Phys Rev B 70 104406 (2004)

Vortices in Thin-Film Superconductors Studied by Spin-Polarized Neutron Reflectivity (SPNR)

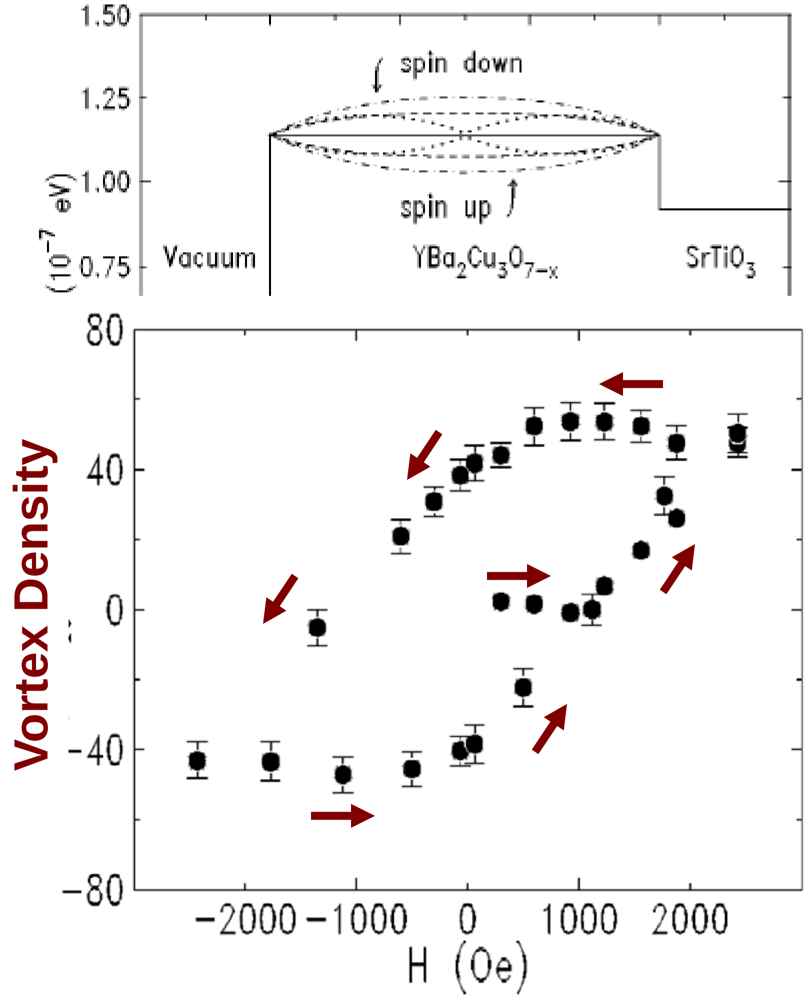
S-W. Han, J.F. Ankner, H.Kaiser, P.F.Miceli,
E.Paraoanu, L.H.Greene, PRB **59**, 14692 (1999)



Field parallel
to film surface

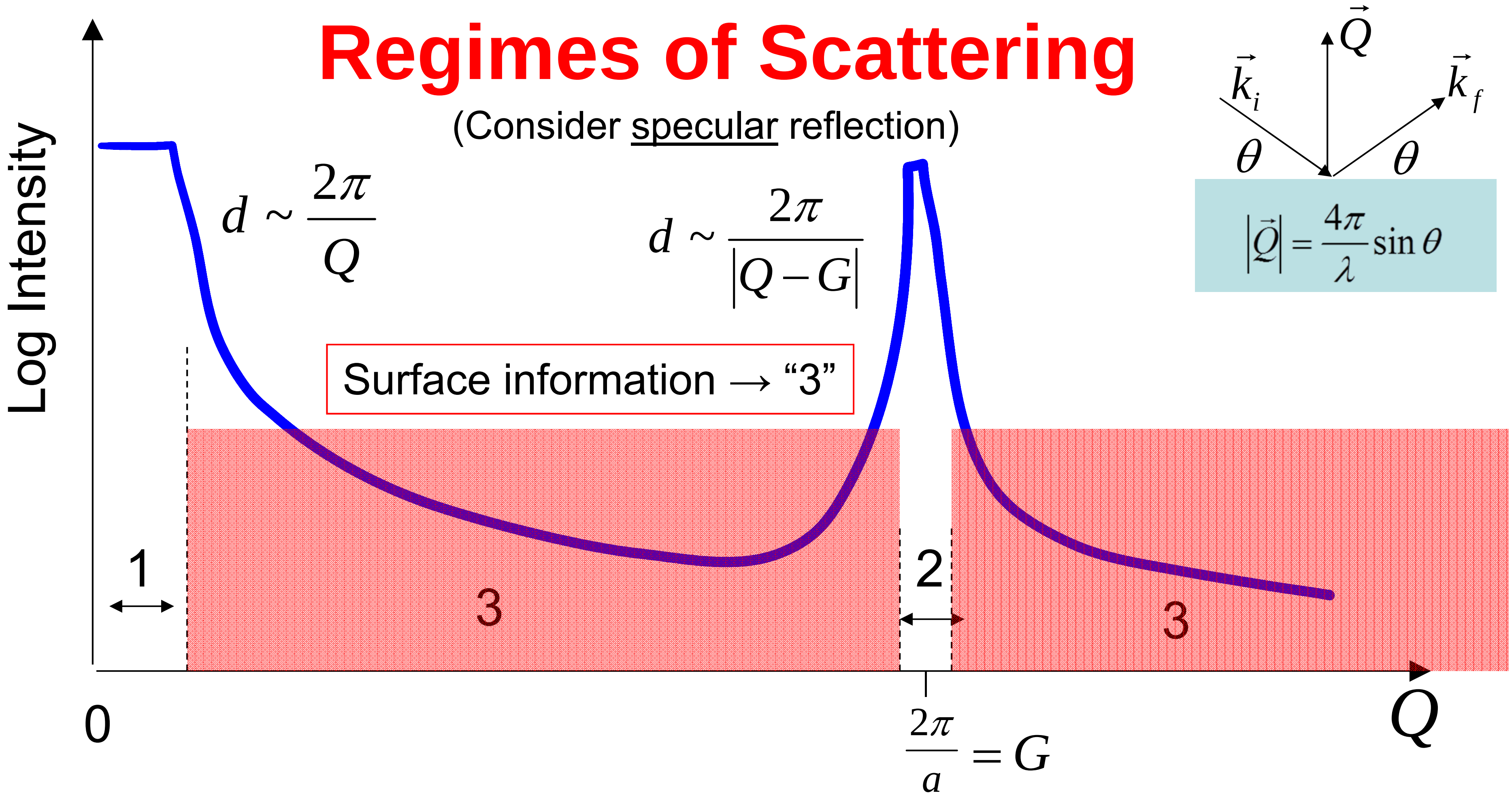


YBCO 600 nm Superconducting Film



Regimes of Scattering

(Consider specular reflection)



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Differential Scattering Cross Section

Weak Scattering

“Born Approximation” or “Kinematic Approximation”

$$\frac{d\sigma}{d\Omega} = P\,S\left(\vec{Q}\right) = P\left|A\left(\vec{Q}\right)\right|^2$$

P is the polarization factor (x-ray case)

S(Q) is the structure factor

A(Q) is the scattering amplitude

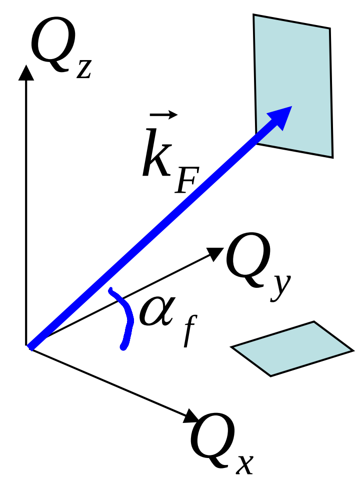
f(Q) is the atomic form factor

ρ_b is the scattering length density

Reflectivity:

$$R = \frac{1}{A_{inc}} \int d\Omega \frac{d\sigma}{d\Omega}$$

$$d\Omega = \frac{d^2\vec{Q}_p}{k^2 \sin\left(\alpha_f\right)}$$



Born Approximation: simple sum over atomic positions

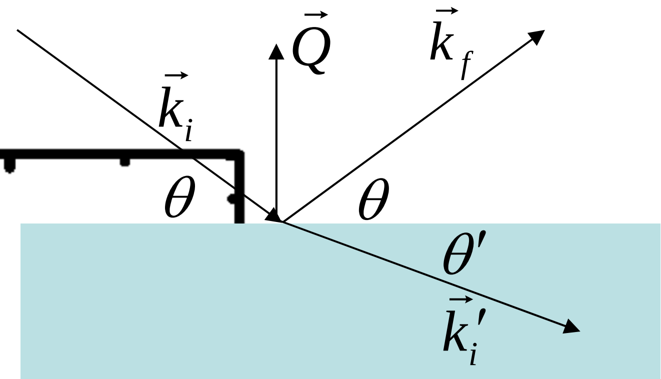
Sum over all atomic positions

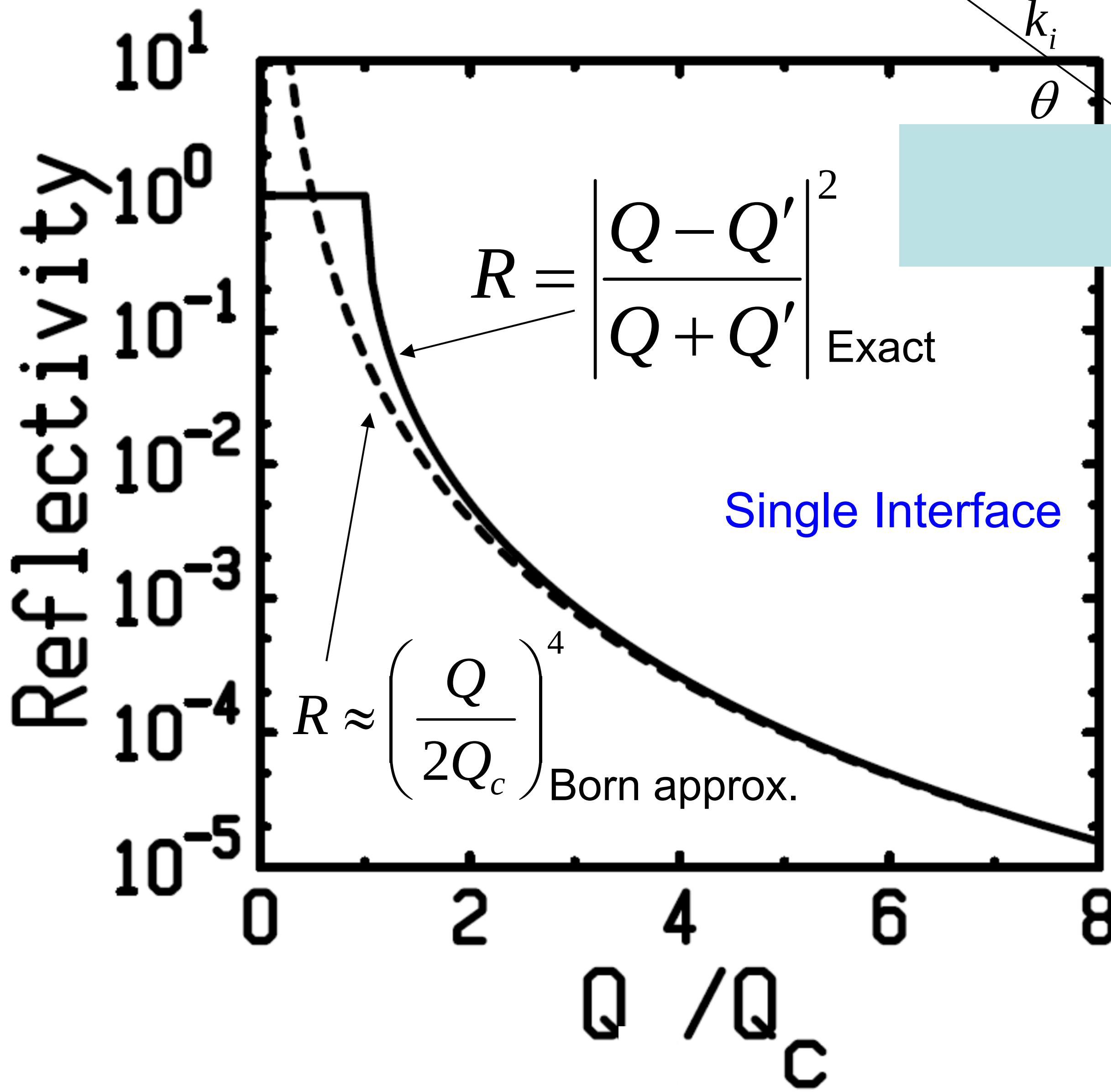
$$A\left(\vec{Q}\right) = \int d^3\vec{r}\, \rho_b\left(\vec{r}\right) e^{i\vec{Q}\cdot\vec{r}} = \sum_{\vec{r}} b_{\vec{r}}\, e^{i\vec{Q}\cdot\vec{r}}$$

$b = r_e f\left(Q\right)$ for x-rays or tabulated for neutrons

Born Approximation works if the reflectivity is not too large.

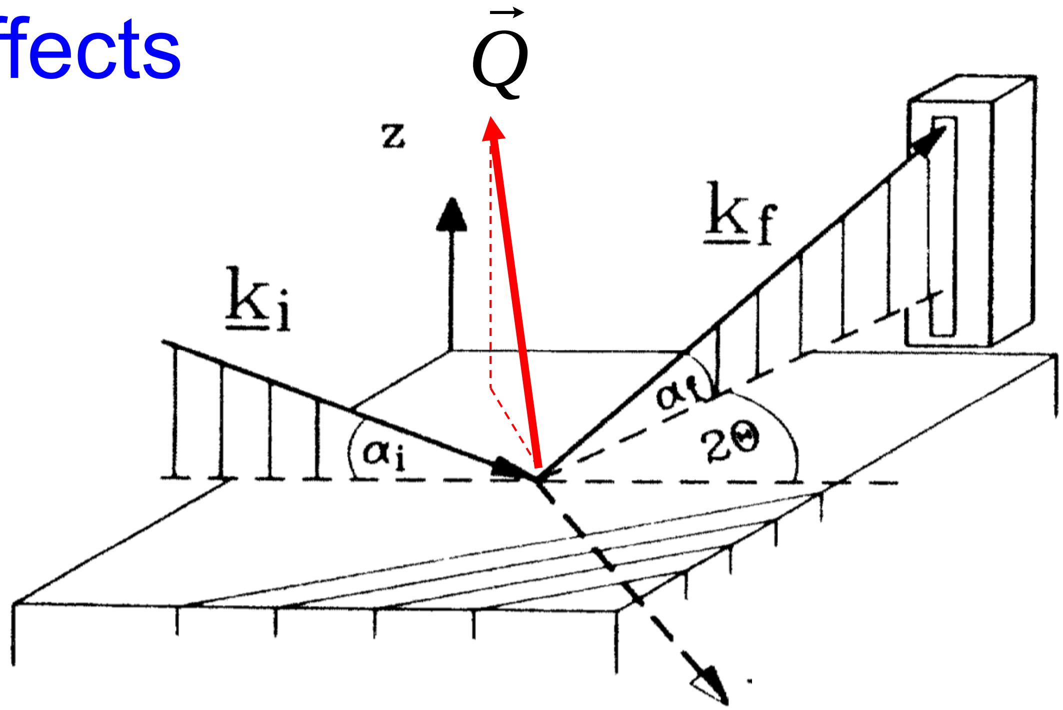
Specular Reflection





General Case: non-specular scattering

Grazing Incidence Effects



3D Scattering

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

If $\vec{k}_i$ or $\vec{k}_f$ are near grazing:

- refraction of both beams
  internal wavevector transfer: $\vec{Q}'$

- transmission of both beams: $T_i\ , T_f$

Perpendicular to Surface: internal **Q'** and external **Q** are different

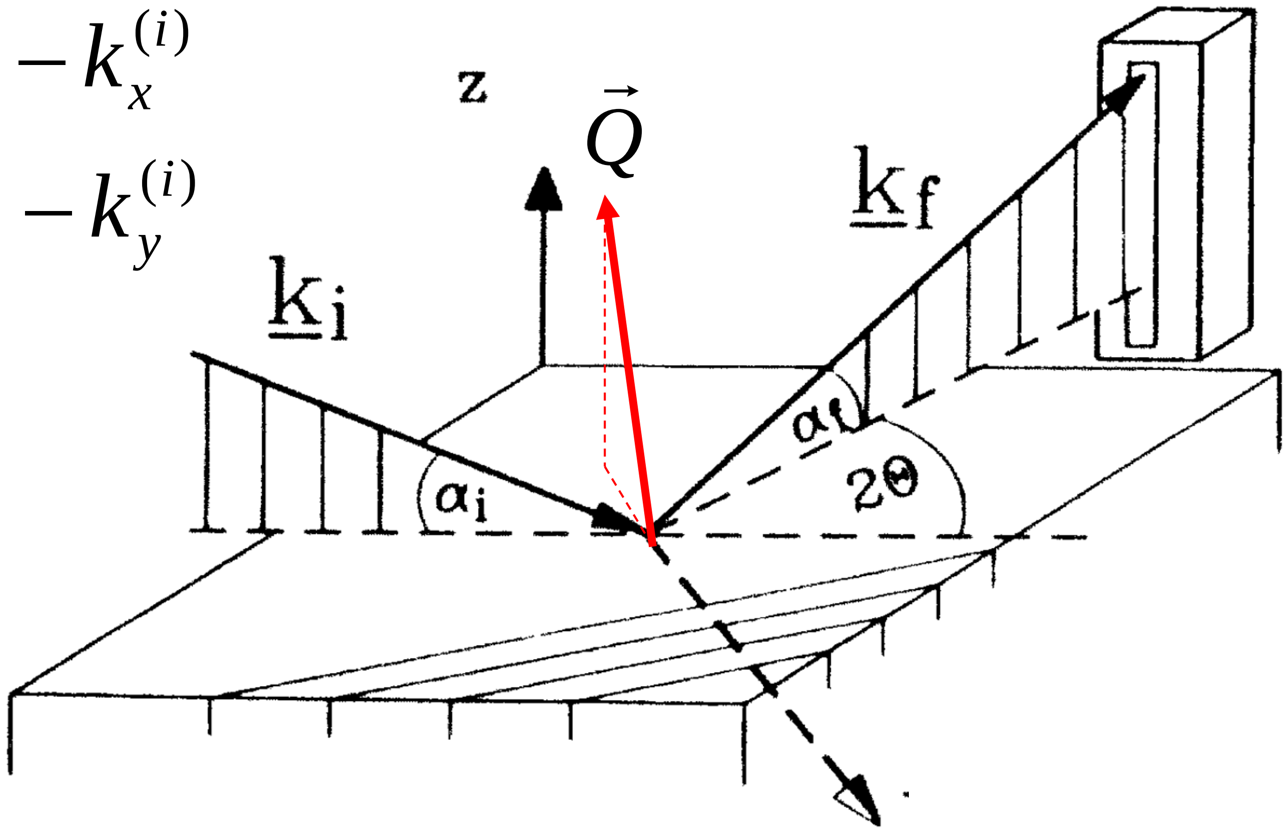
$$Q_z = k_z^{(f)} - k_z^{(i)} = (2\pi/\lambda)[\sin\alpha_f + \sin\alpha_i].$$

$$Q_z' = k_z^{(f)\prime} - k_z^{(i)\prime} = (2\pi/\lambda)[(\sin^2\alpha_f - 2\delta - 2i\beta)^{1/2} + (\sin^2\alpha_i - 2\delta - 2i\beta)^{1/2}].$$

Parallel to Surface: internal **Q'** and external **Q** are same

$$Q_x' = Q_x = k_x^{(f)} - k_x^{(i)}$$

$$Q_y' = Q_y = k_y^{(f)} - k_y^{(i)}$$



H. Dosch, B.W. Batterman and D. C. Wack, PRL **56**, 1144 (1986)

$$\Lambda = \lambda / [2\pi(l_i + l_f)]$$

Penetration Length

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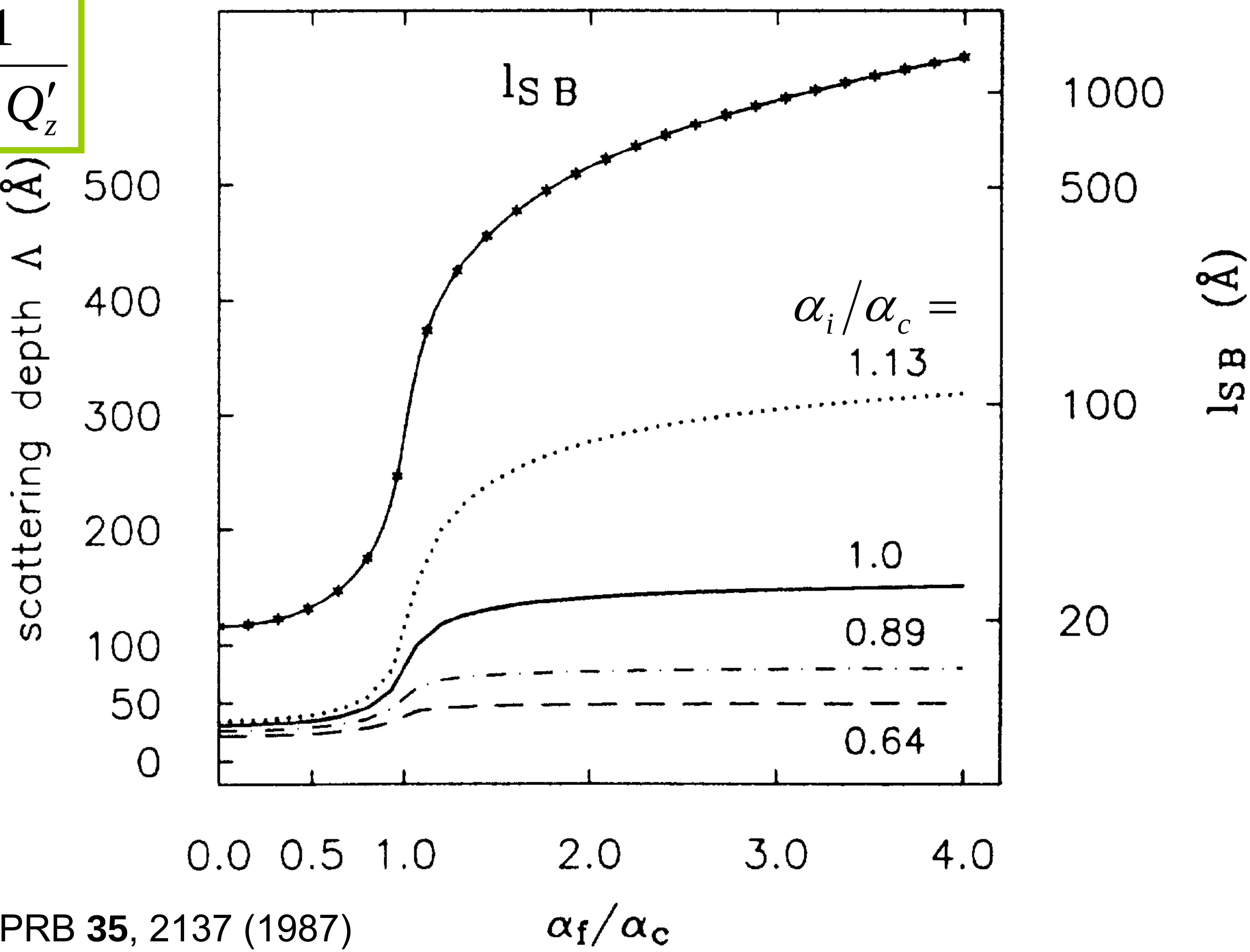
$$\Lambda = \frac{1}{\operatorname{Im} Q_z'}$$



H. Dosch, PRB **35**, 2137 (1987)

Fe_3Al

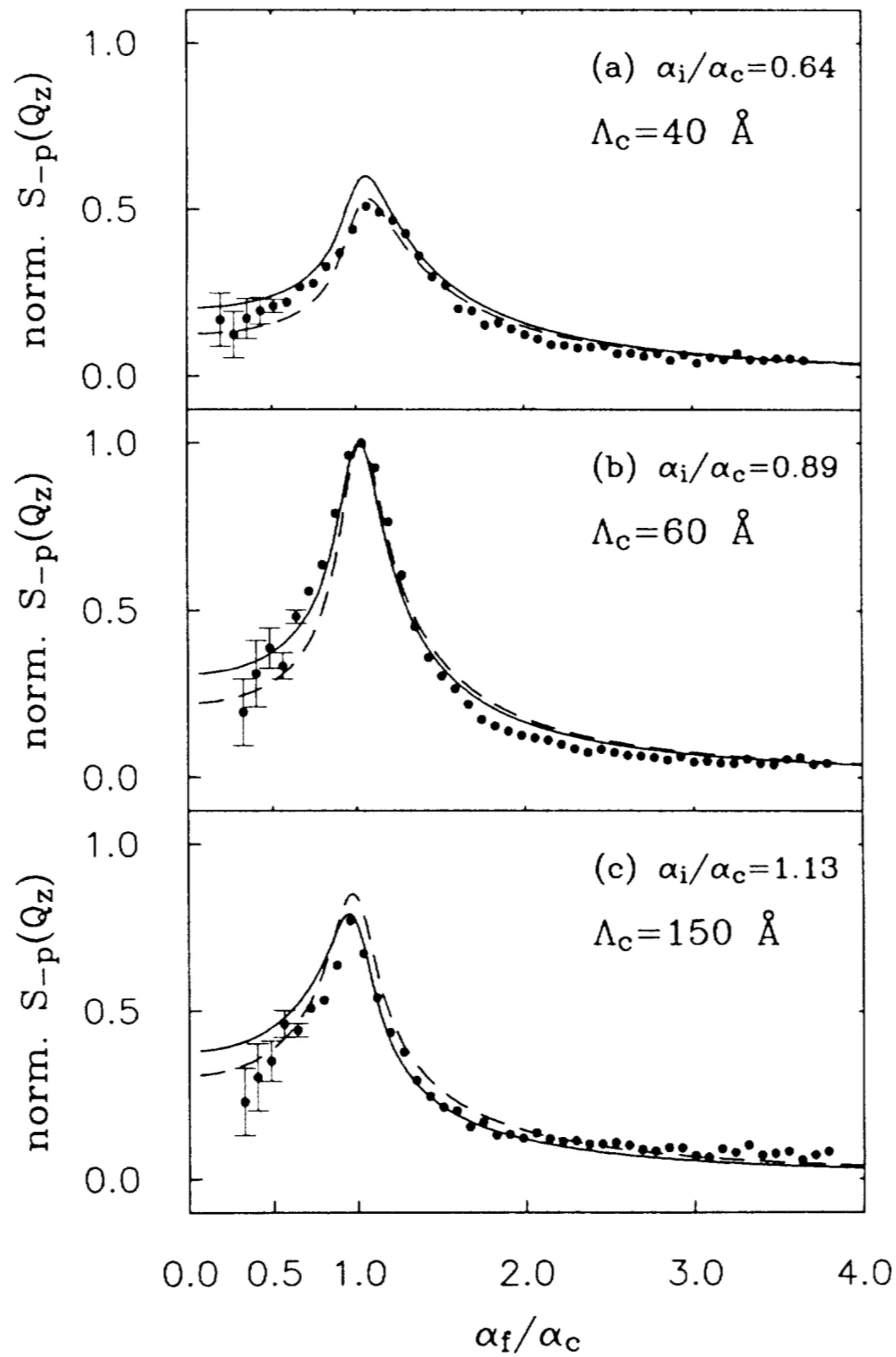
H. Dosch, PRB **35**, 2137 (1987)

Distorted Wave Born Approximation

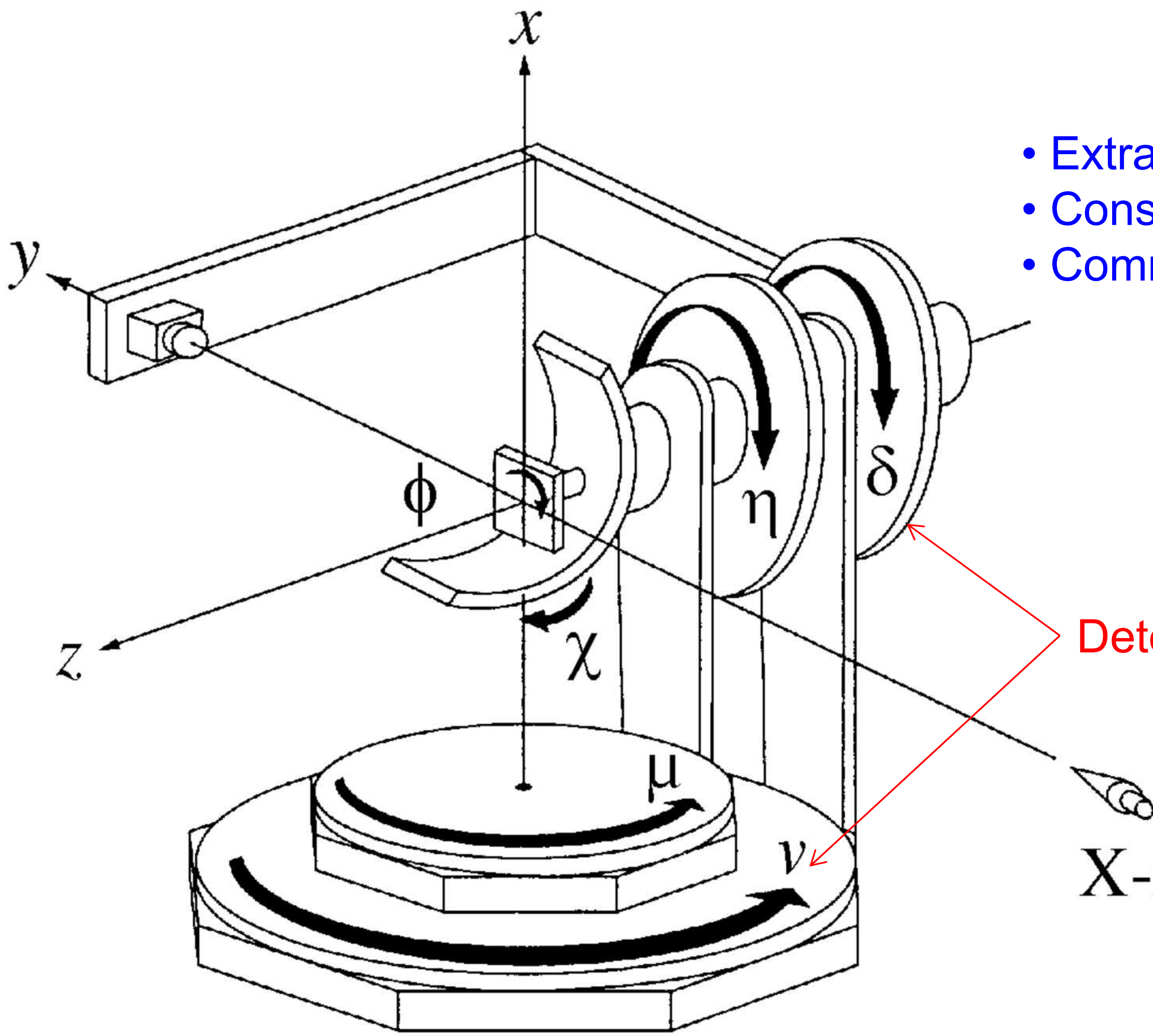
$$I_{GID}(Q') \propto |T_i|^2 S(Q') |T_f|^2$$

- refraction
- transmission

$S(\vec{Q}')$ is the structure factor using the internal wavevector transfer



A Six-Circle Diffractometer



- Extra Angles give flexibility
- Constraints are needed
- Common working modes:

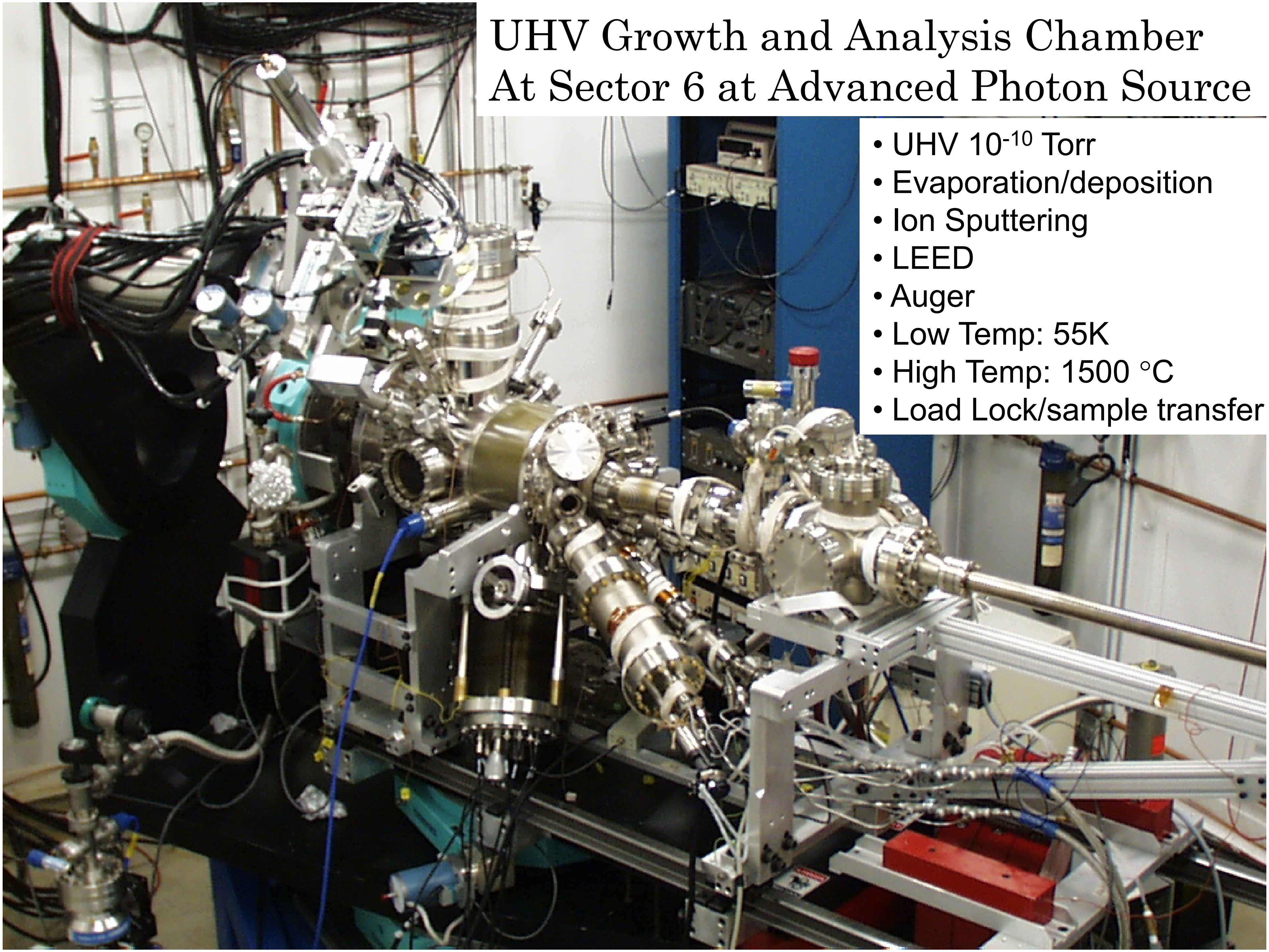
$$\alpha_i = fixed$$

$$\alpha_f = fixed$$

$$\alpha_i = \alpha_f$$

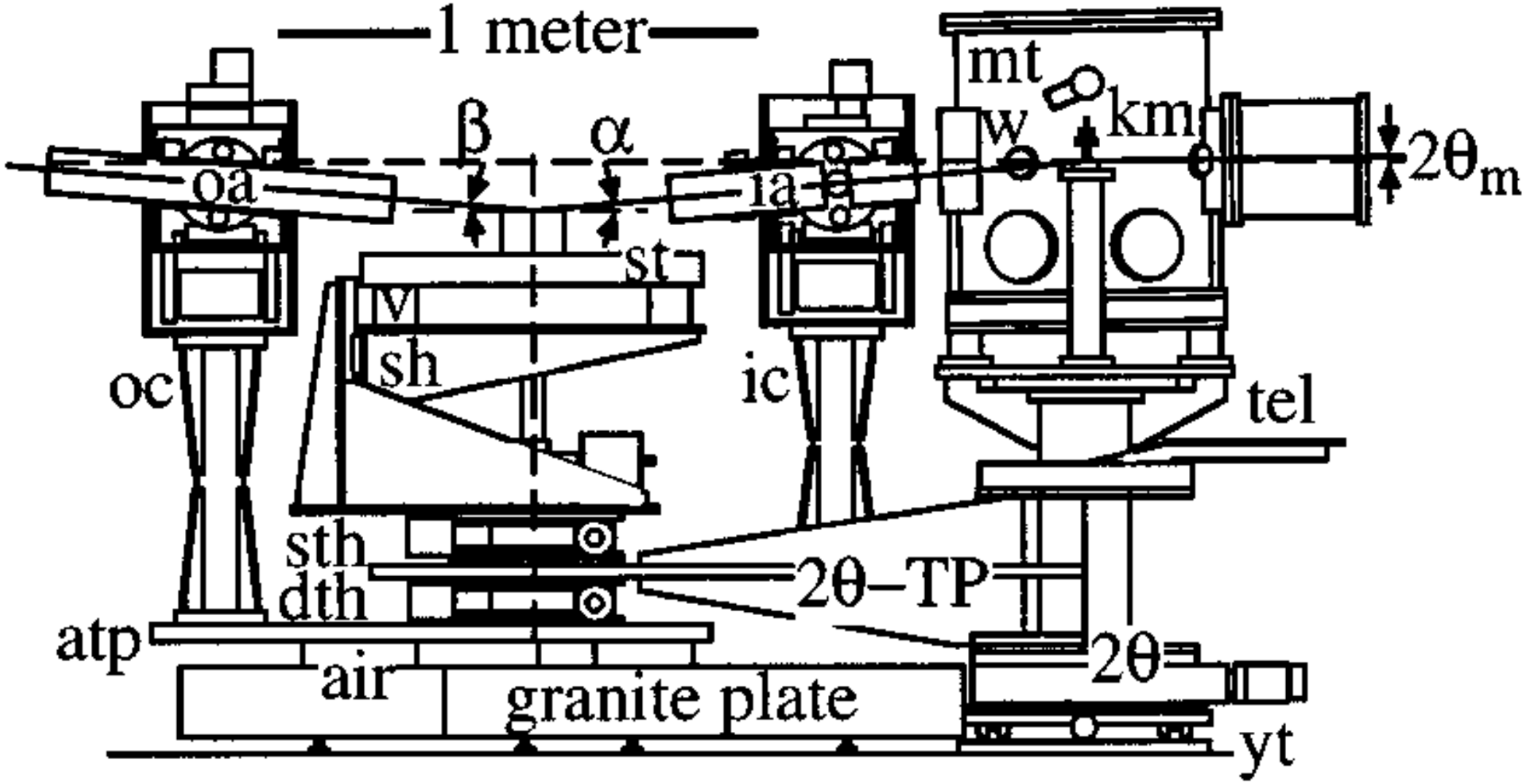
H. You, *J. Appl. Cryst*. **32**, 614-623 (1999)

UHV Growth and Analysis Chamber At Sector 6 at Advanced Photon Source

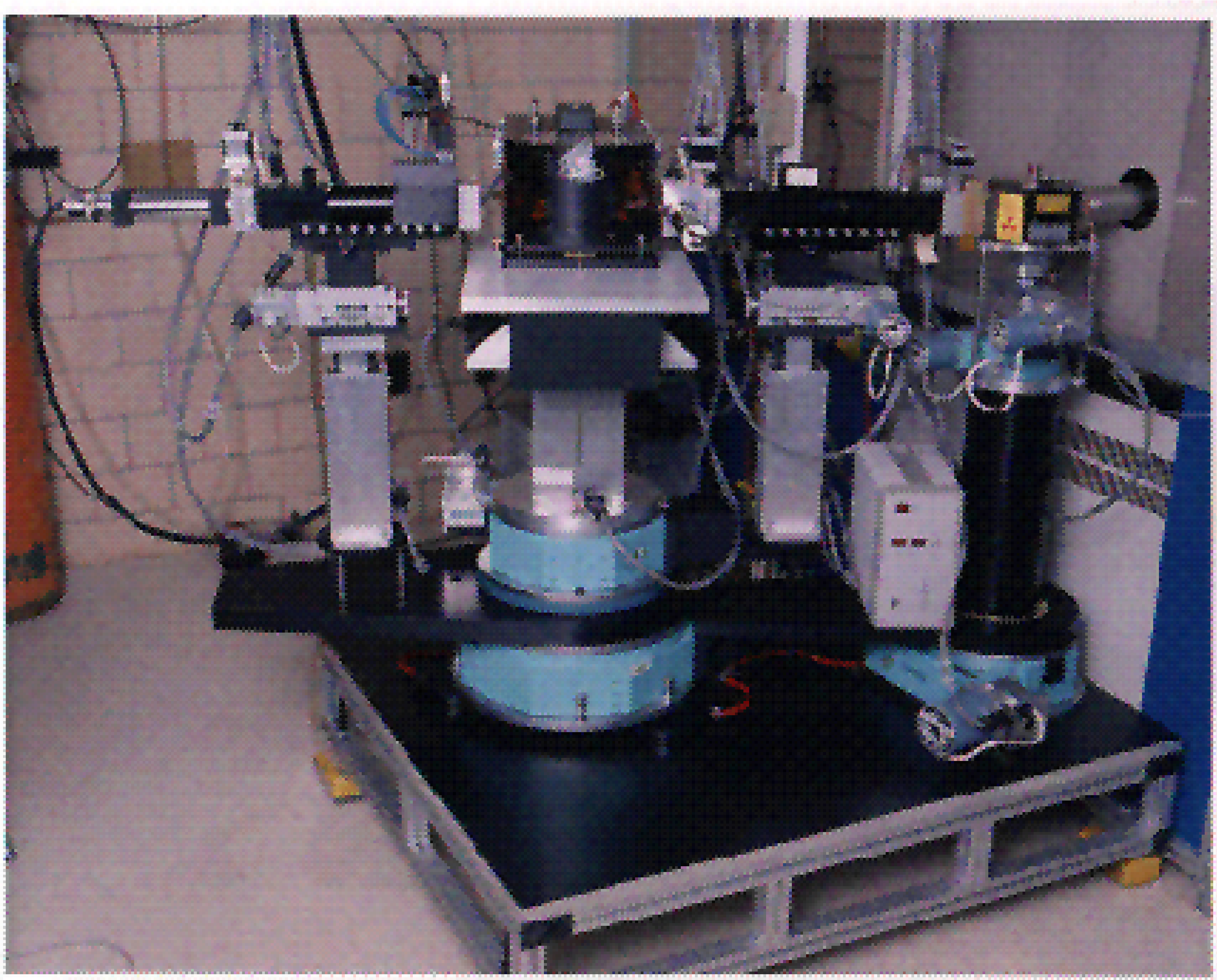


- UHV 10^{-10} Torr
- Evaporation/deposition
- Ion Sputtering
- LEED
- Auger
- Low Temp: 55K
- High Temp: 1500 °C
- Load Lock/sample transfer

Liquid Surface Diffractometer



M. Schlossman et. al., Rev. Sci. Inst. **68**, 4372 (1997)



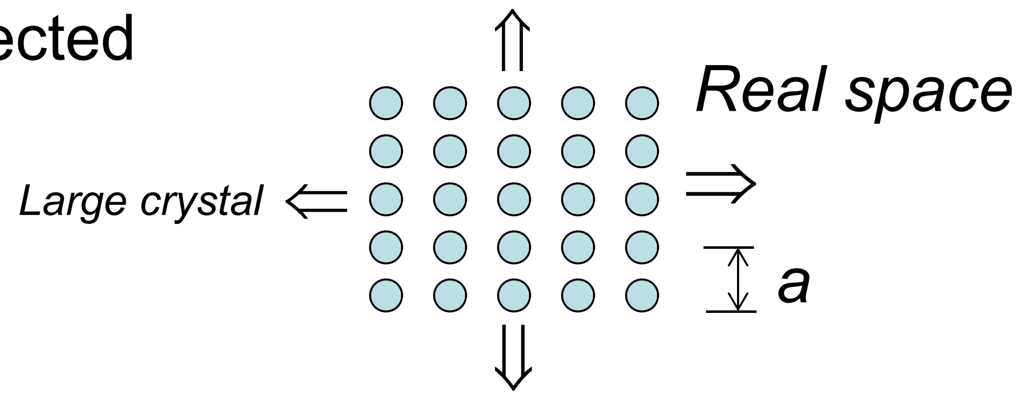
David Vaknin, Ames Lab

The Effect of a Crystalline Boundary

What is a crystal truncation rod?

<u>First consider:</u>

- Large crystals; rough and irregular boundaries
- Boundaries neglected

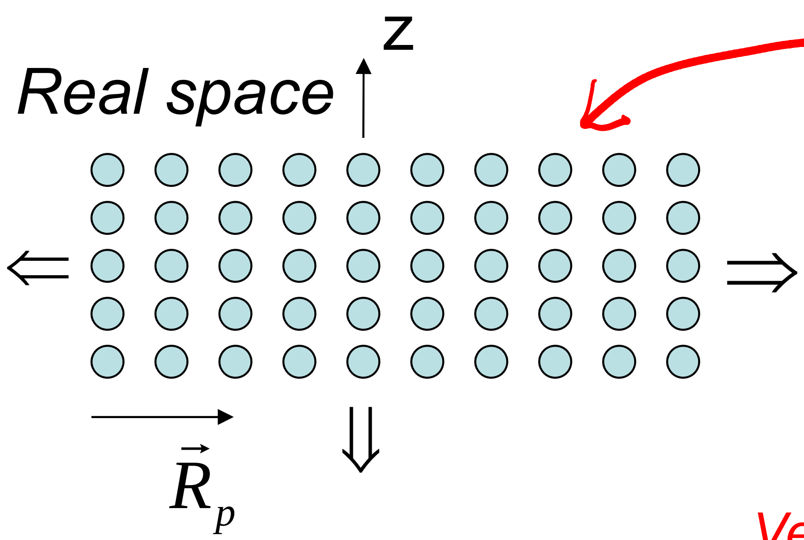


$$S(\vec{Q}) = \left| \sum_{n_x=0}^{N-1} e^{iQ_x a n_x} \sum_{n_y=0}^{N-1} e^{iQ_y b n_y} \sum_{n_z=0}^{N-1} e^{iQ_z c n_z} \right|^2 = \frac{\sin^2\left(\frac{NQ_x a}{2}\right)}{\sin^2\left(\frac{Q_x a}{2}\right)} \frac{\sin^2\left(\frac{NQ_y b}{2}\right)}{\sin^2\left(\frac{Q_y b}{2}\right)} \frac{\sin^2\left(\frac{NQ_z c}{2}\right)}{\sin^2\left(\frac{Q_z c}{2}\right)}$$

$$\propto \sum_{\vec{G}} \delta\left(\vec{Q} - \vec{G}\right)$$

$\vec{G}$ is a reciprocal lattice vector

Now consider a crystal with one atomically flat boundary…



- Large crystal; flat boundary $z=0$
- Neglect boundary at $z=-\infty$

Very small attenuation $\varepsilon <\sim 1$

$$S(\vec{Q}) = b^2 \left| \sum_{n_z=0}^{N-1} \varepsilon^{n_z} e^{-iQ_z c n_z} \right|^2 \sum_{\vec{R}_p} \sum_{\vec{R}'_p} e^{i\vec{Q}_p \bullet (\vec{R}_p - \vec{R}'_p)}$$

Reflected wave vanishes

Crystal Truncation Rod Factor

$$\lim_{\varepsilon\to 1} \lim_{N\to\infty} \left| \frac{1-\varepsilon^N e^{-iQ_z cN}}{1-e^{-iQ_z c}} \right|^2 = \frac{1}{4\sin^2\left(\frac{Q_z c}{2}\right)} \approx \frac{1}{c^2 (Q_z - G_z)^2}$$

By neglecting the lateral boundaries:

$$\sum_{\vec{R}_p}\sum_{\vec{R}'_p} e^{i\vec{Q}_p \bullet \left(\vec{R}_p - \vec{R}'_p\right)} = N_{irr}\sum_{\vec{R}_p} e^{i\vec{Q}_p \bullet \vec{R}_p}$$

and

$$\sum_{\vec{R}_p} e^{i\vec{Q}_p \bullet \vec{R}_p} = \frac{(2\pi)^2}{s_c}\sum_{\vec{G}_p}\delta\left(\vec{Q}_p - \vec{G}_p\right)$$

N_{irr} = the number of irradiated atoms at the surface

s_c = area per surface atom

$\vec{G}_p$ = an in-plane reciprocal lattice vector

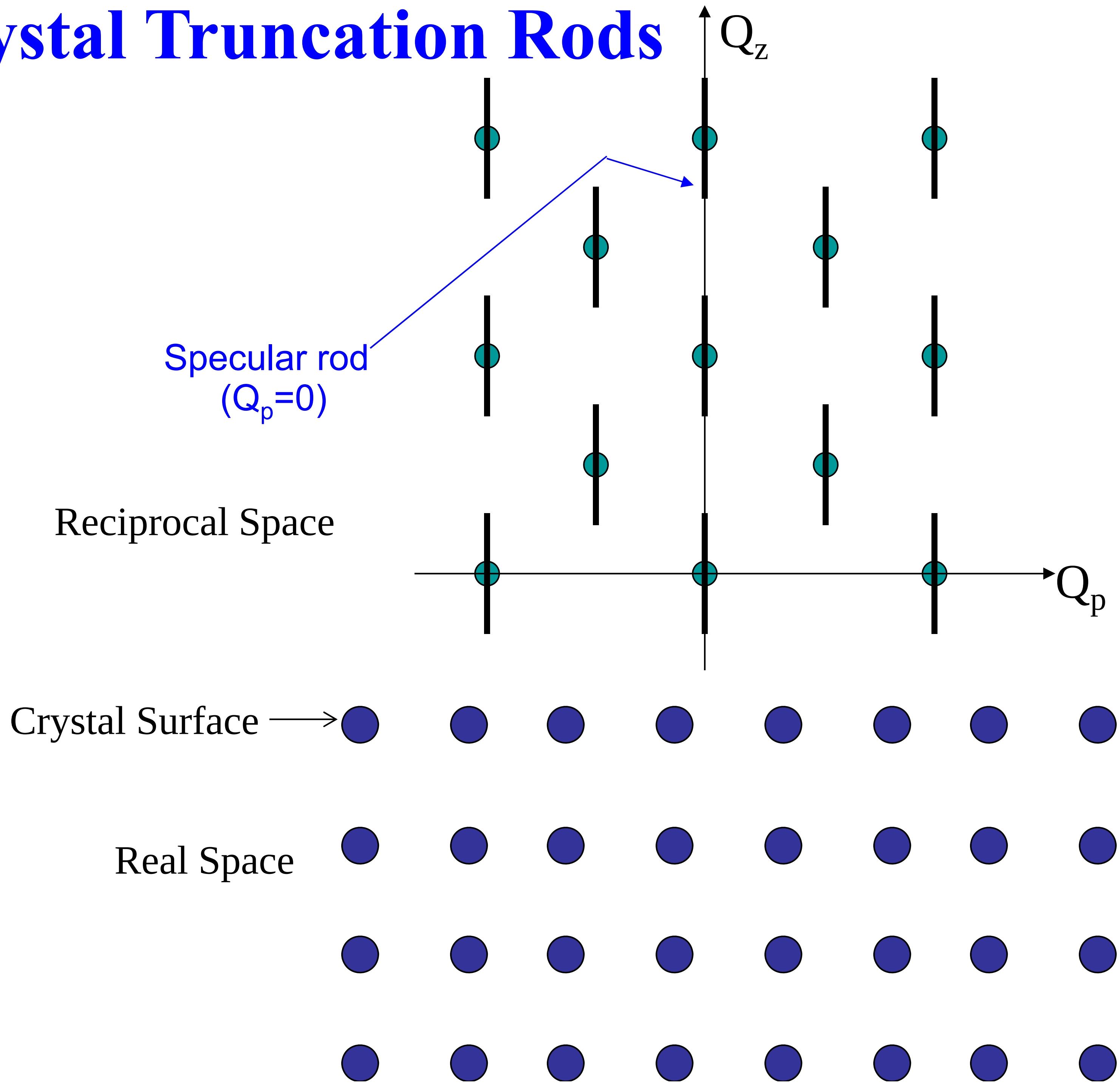
$$S\left(\vec{Q}\right) = \frac{(2\pi)^2 N_{irr} b^2}{s_c}\,\frac{1}{4\sin^2\left(\frac{Q_z c}{2}\right)}\sum_{\vec{G}_p}\delta\left(\vec{Q}_p - \vec{G}_p\right)$$

CTR

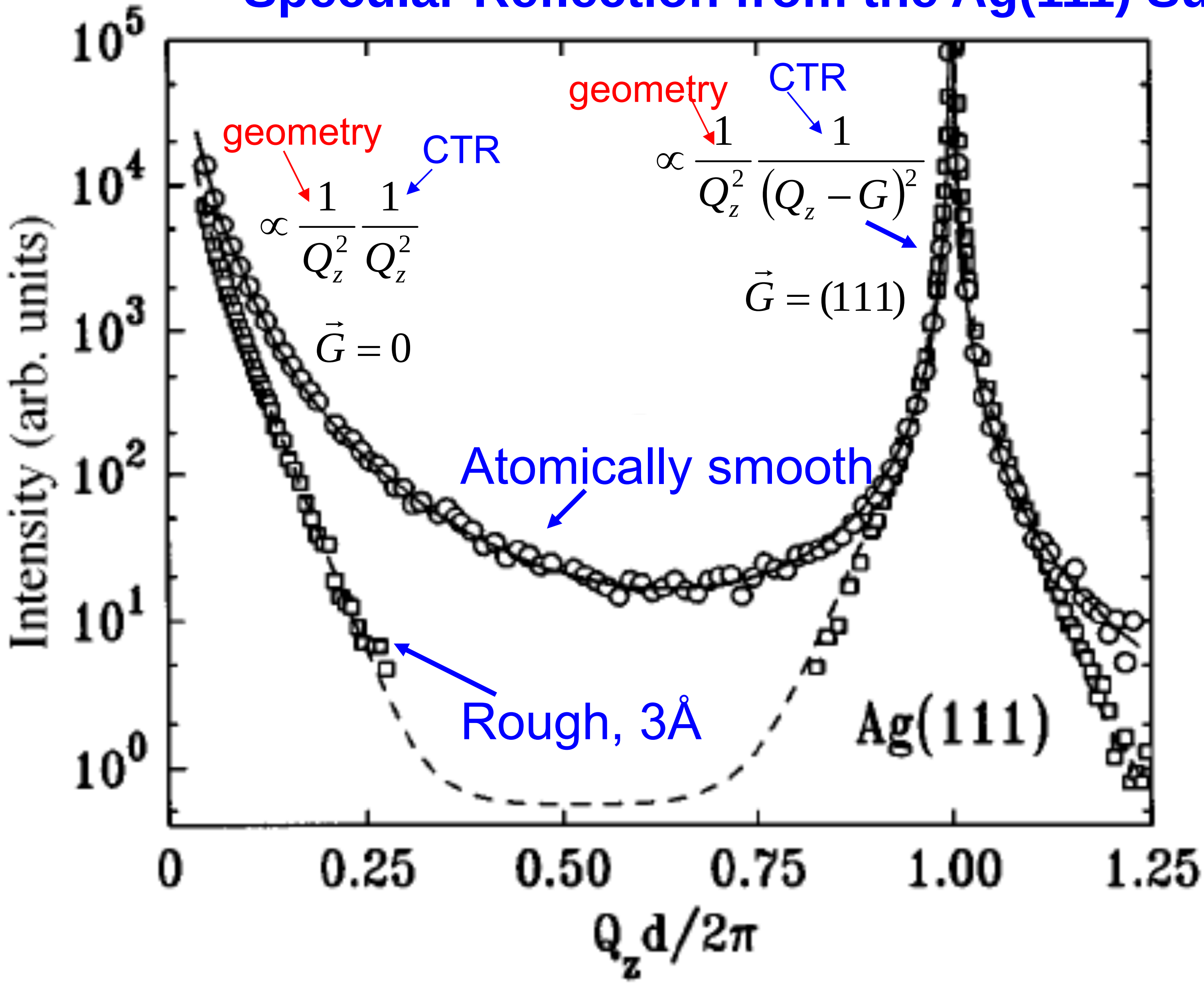
Intensity falls slowly

Narrow reflection in-plane

Crystal Truncation Rods

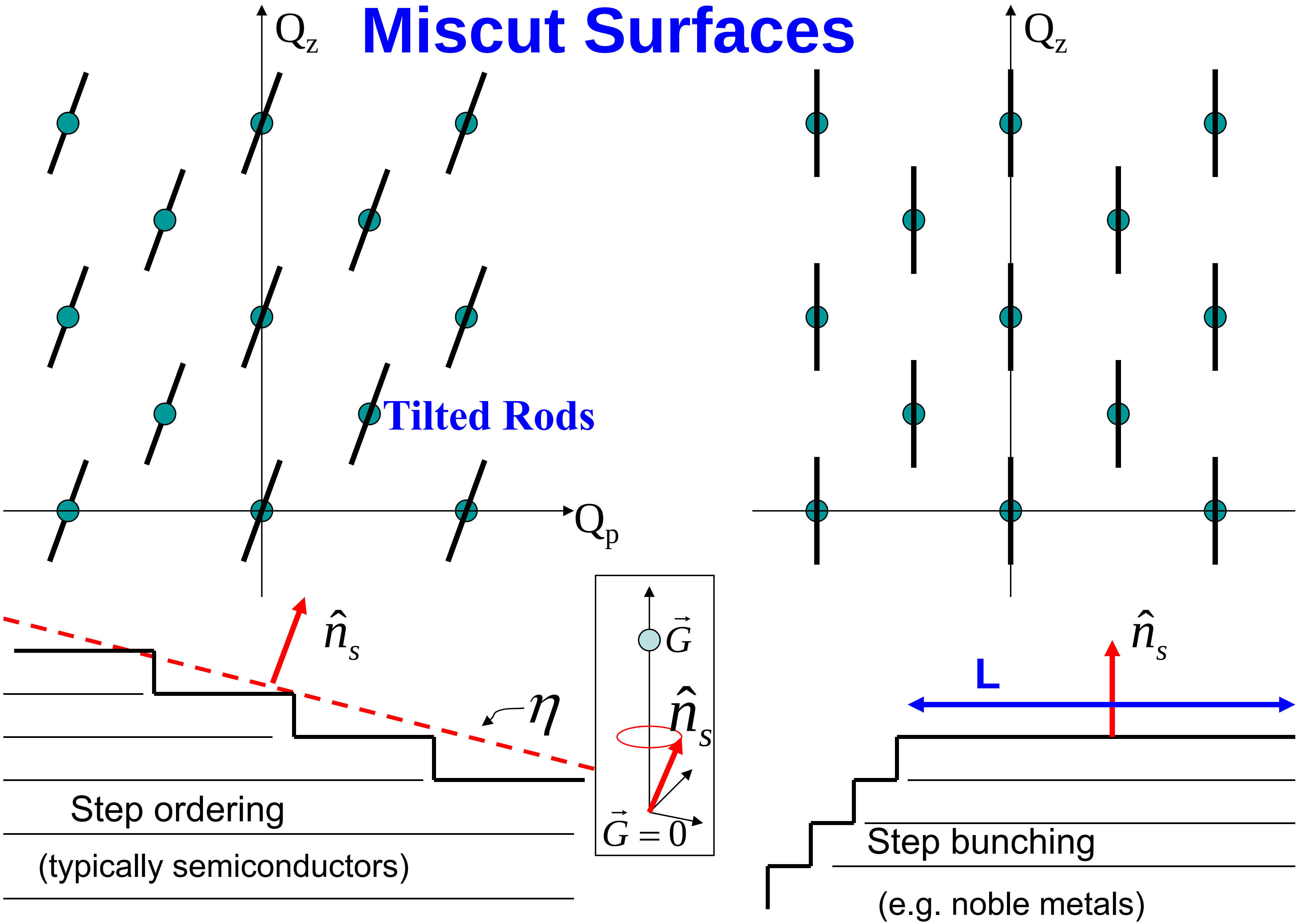


Crystal Truncation Rod Scattering for Specular Reflection from the Ag(111) Surface

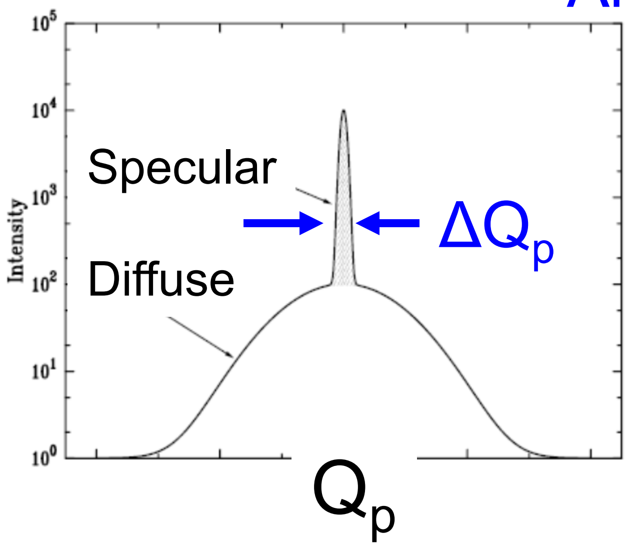


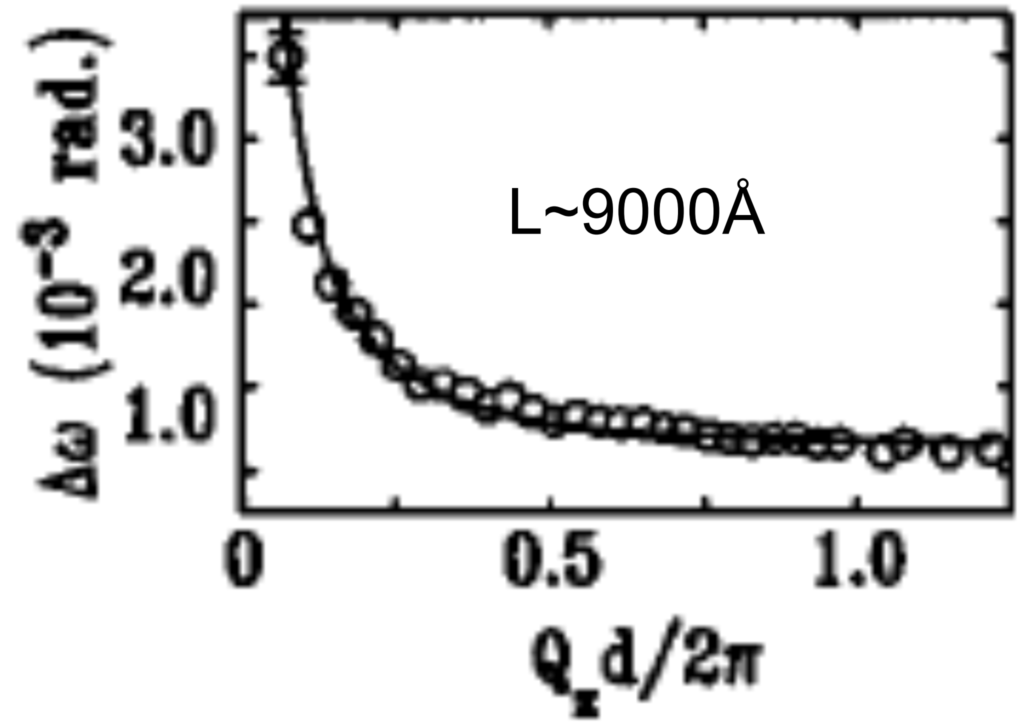
Elliott et. al. PRB **54**, 17938 (1996)

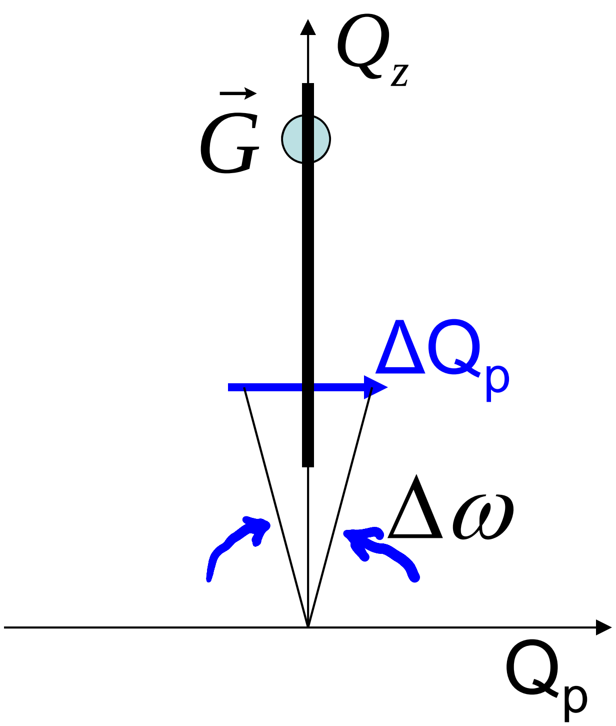
Miscut Surfaces



Angular Width of Specular Decreases with Q_z







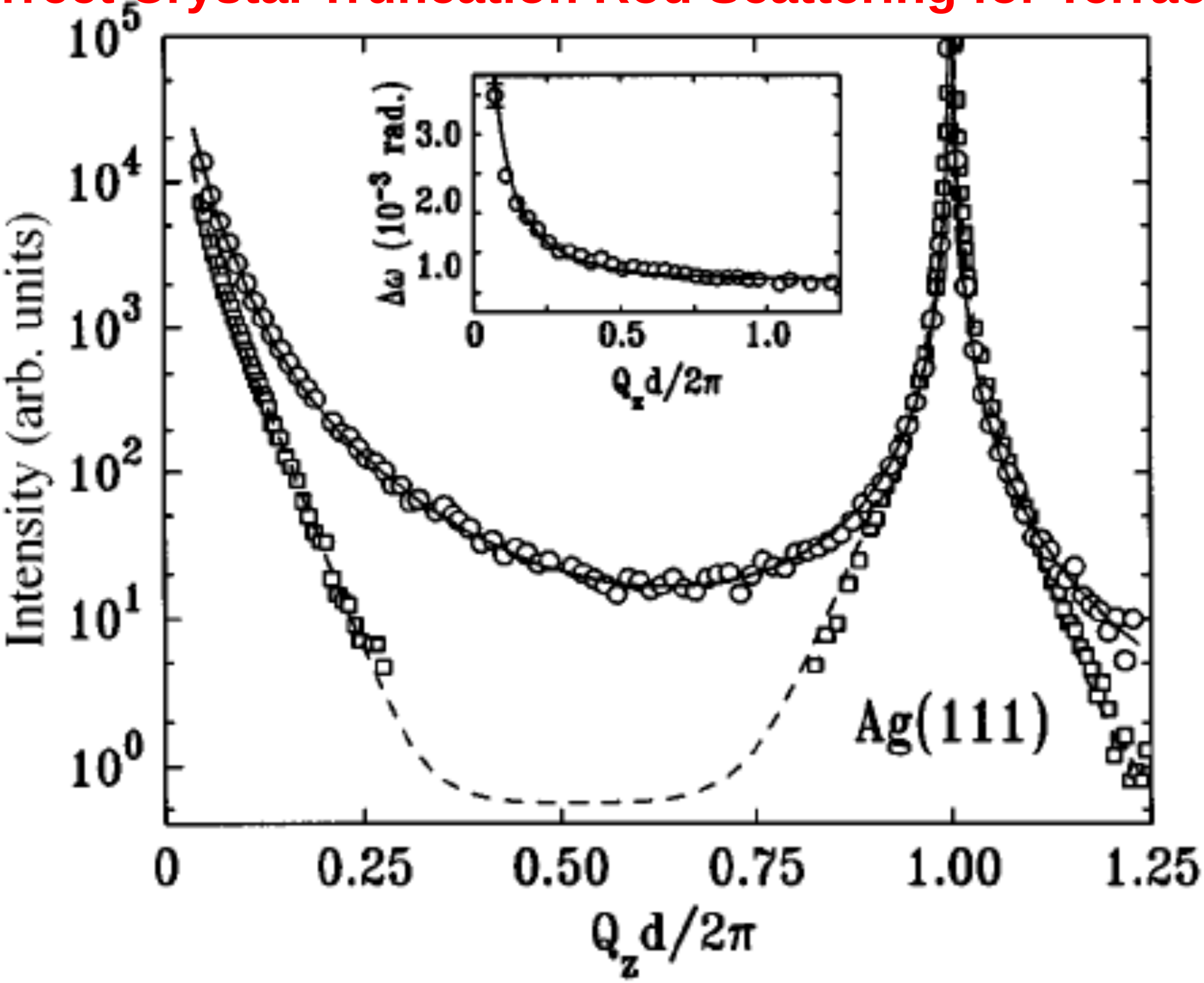
$$\Delta\omega = \frac{\Delta Q_p}{Q_z}$$

Can determine terrace size, L

$$\Delta Q_p = \frac{2\pi}{L}$$

Specular Reflection from the Ag(111) Surface

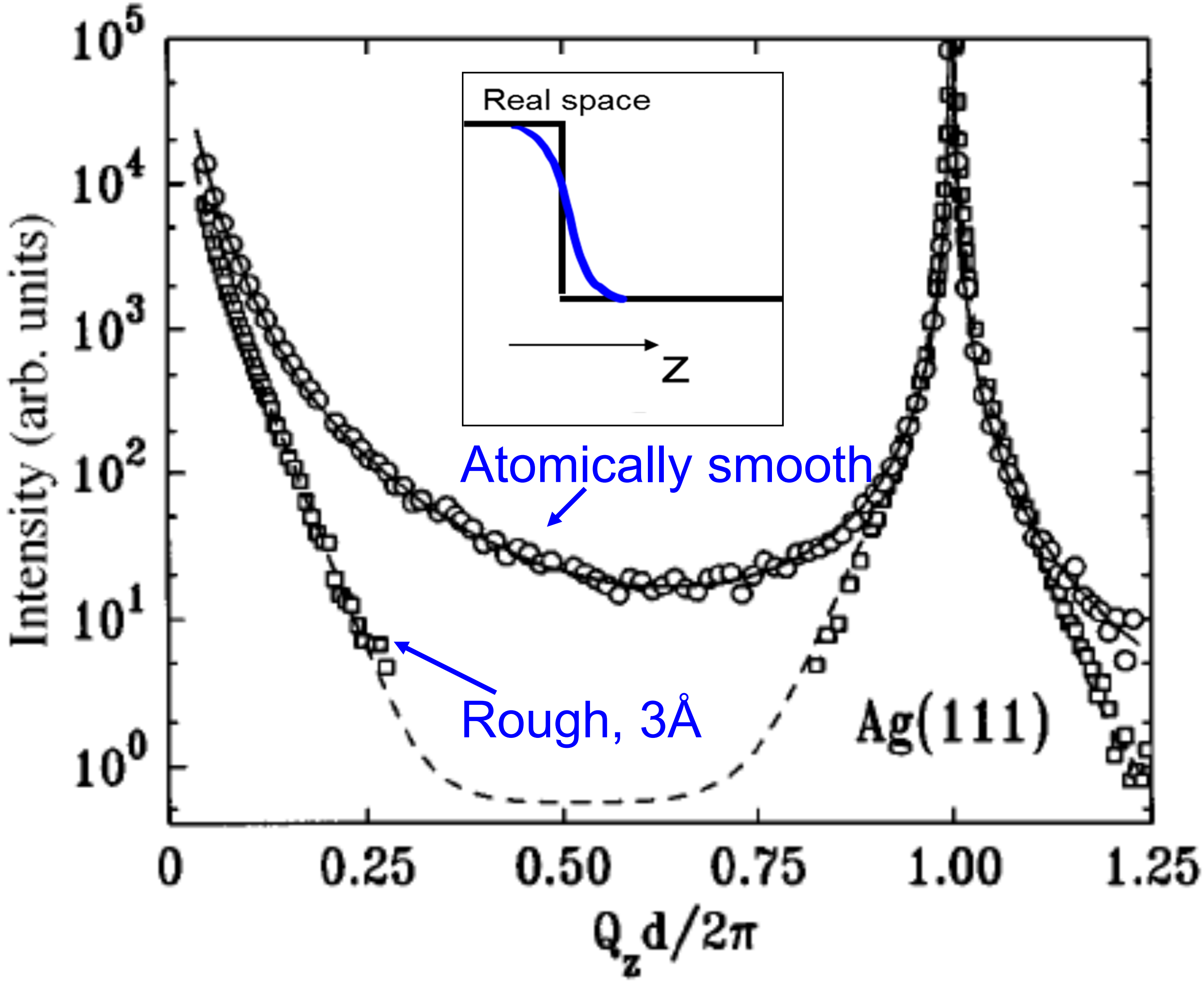
Correct Crystal Truncation Rod Scattering for Terrace Size



Elliott et. al. PRB **54**, 17938 (1996)

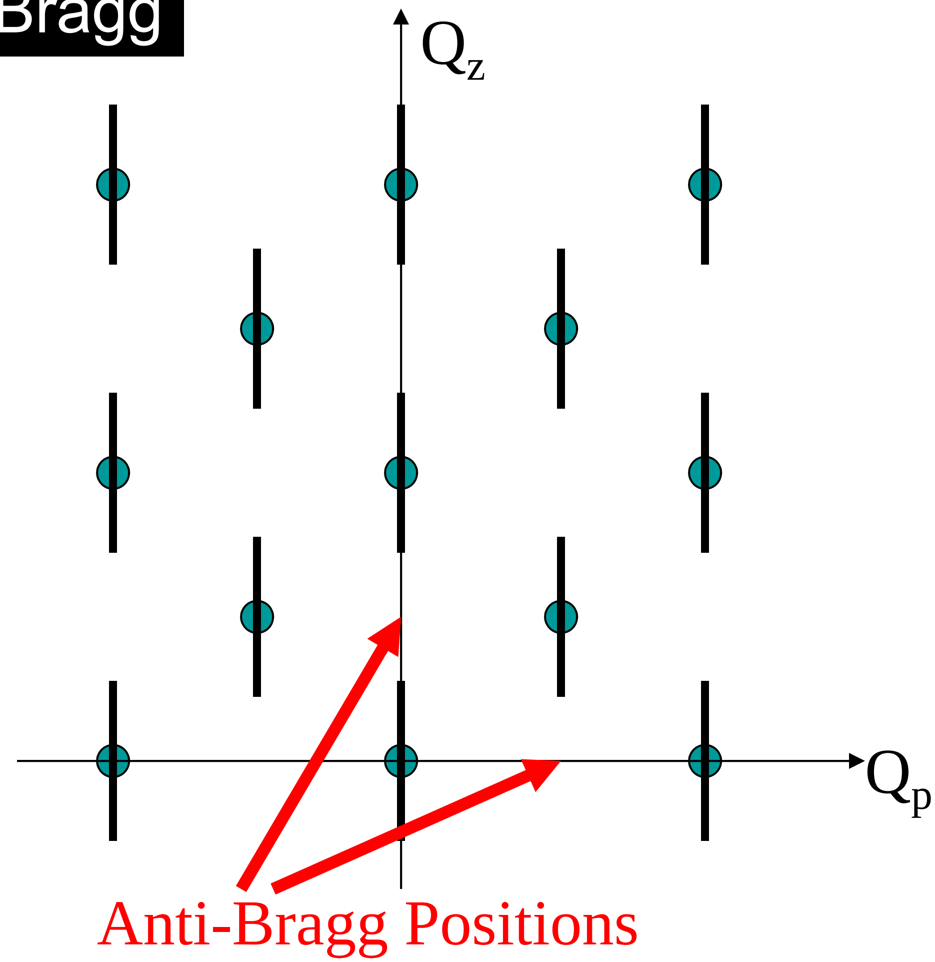
The Effect of a Rough Surface

Sharper interface (real space) gives "broader" scattering



Elliott et. al. PRB **54**, 17938 (1996)

Special location along CTR: anti-Bragg



Bragg Position:

$$Q_z c = 2\pi m$$

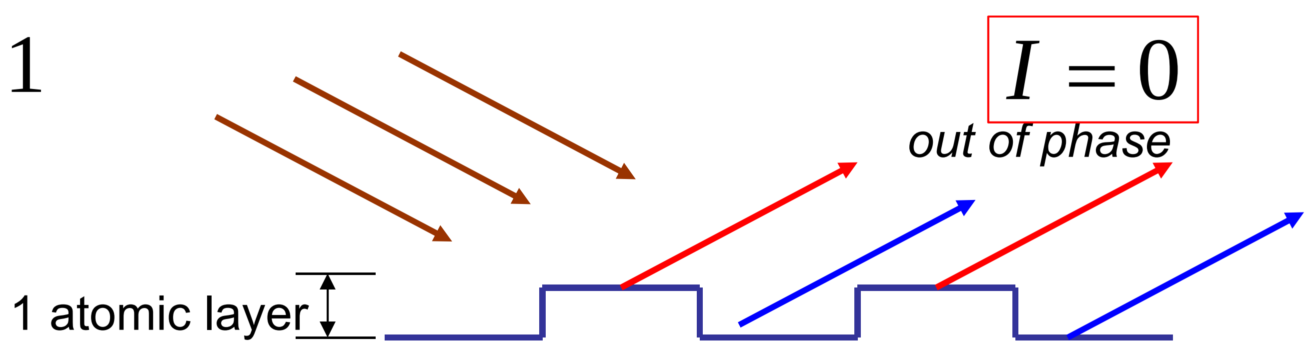
$$I = \left| \sum_{n_z=0}^{N-1} e^{-i2\pi n_z} \right|^2 \rightarrow N^2$$

Anti-Bragg Position:

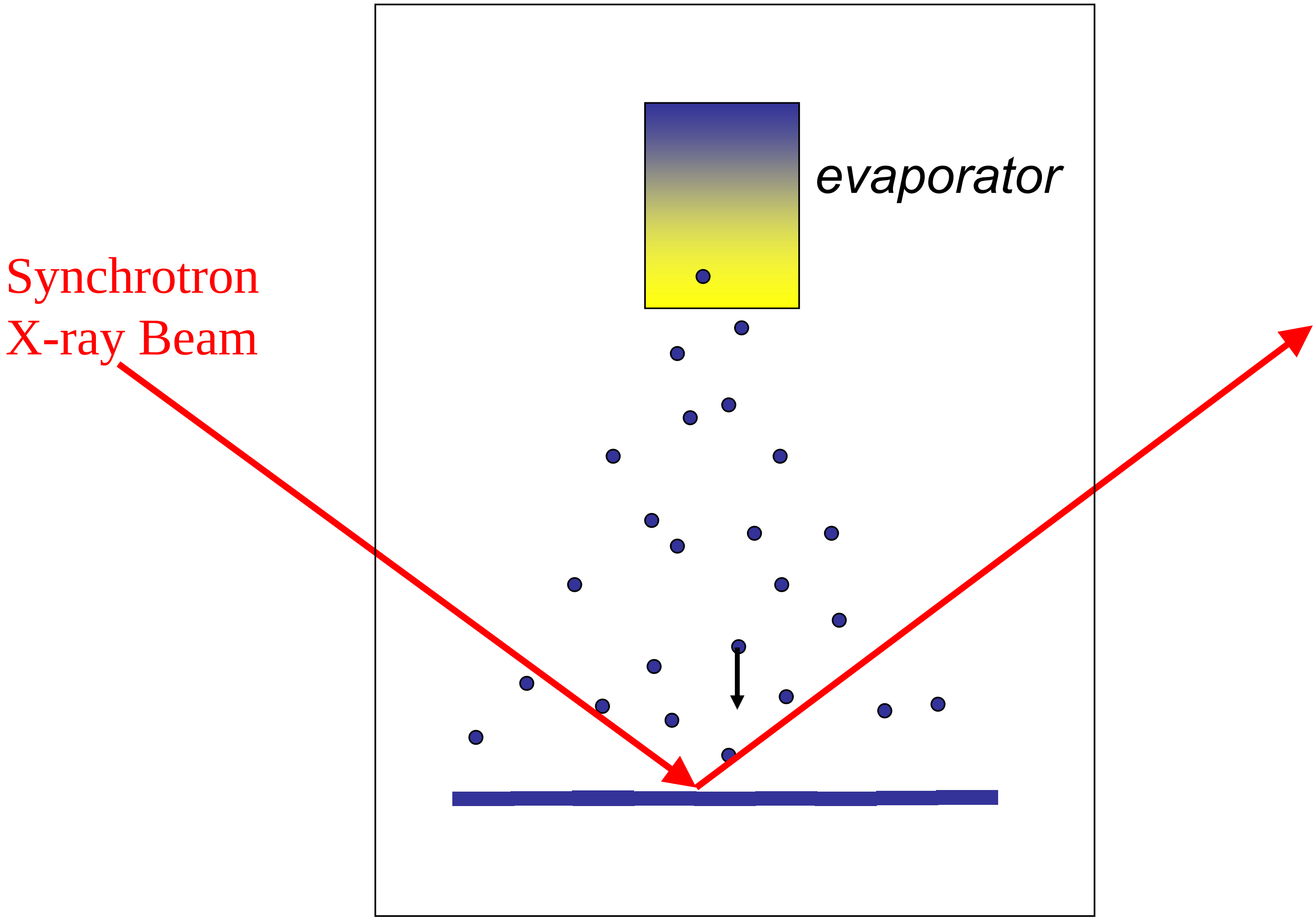
$$Q_z c = \pi m \quad (m \text{ odd})$$

$$I = \left| \sum_{n_z=0}^{N-1} e^{-i\pi n_z} \right|^2 \rightarrow 1$$

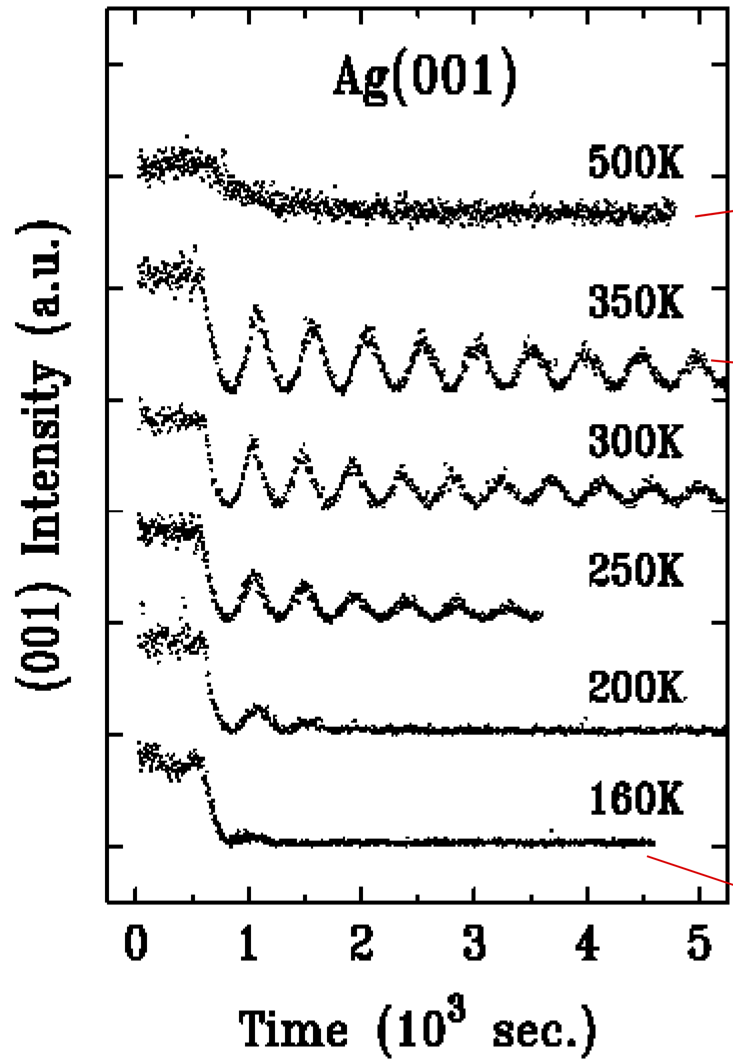
For a smooth surface

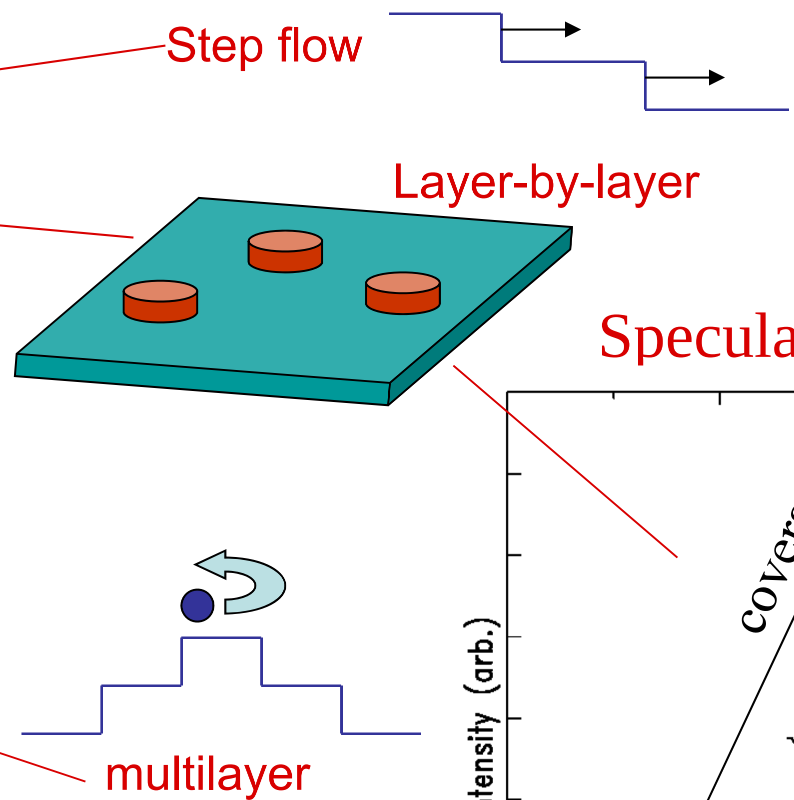


In situ vapor deposition in UHV

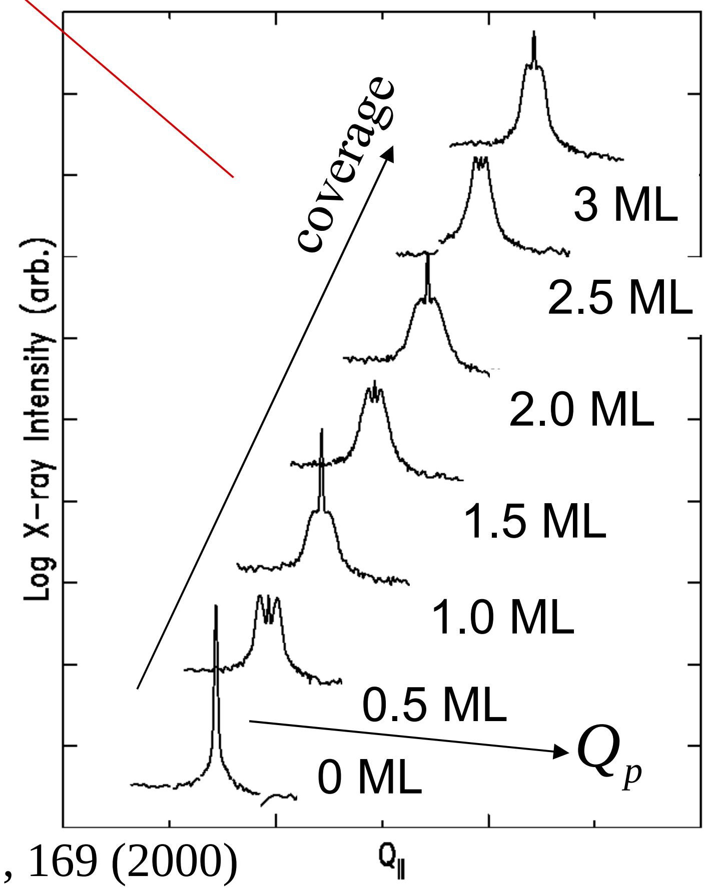


Nucleation and Growth





Specular and Diffuse



Specular Anti-Bragg Intensity

Elliott et. al. PRB **54**, 17938 (1996)

Adv. X-ray Anal. **43**, 169 (2000)

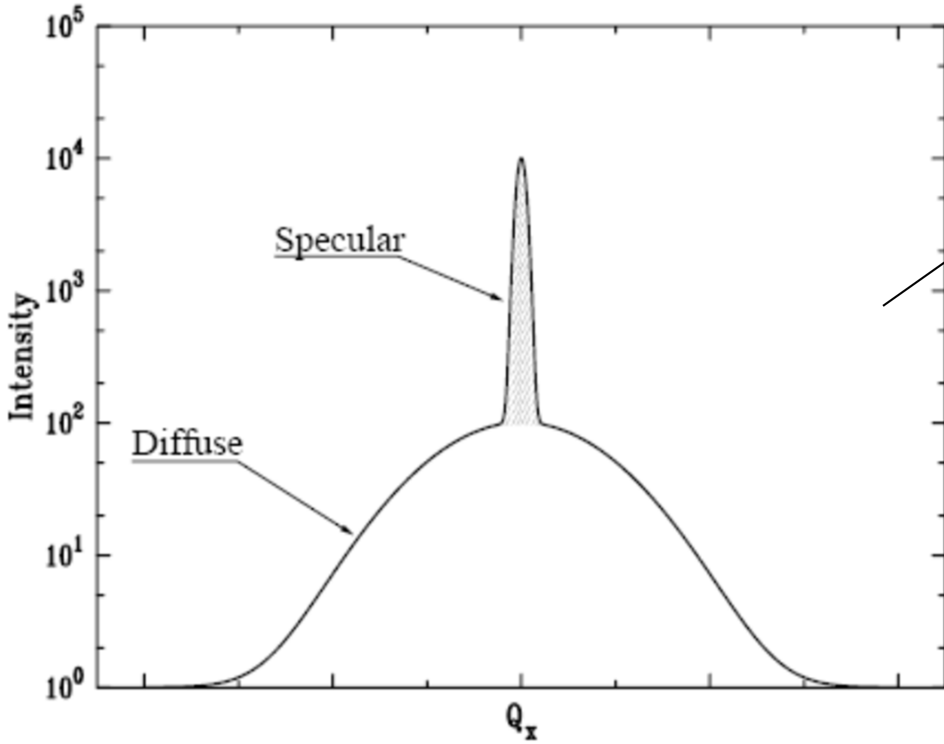
Diffuse Scattering

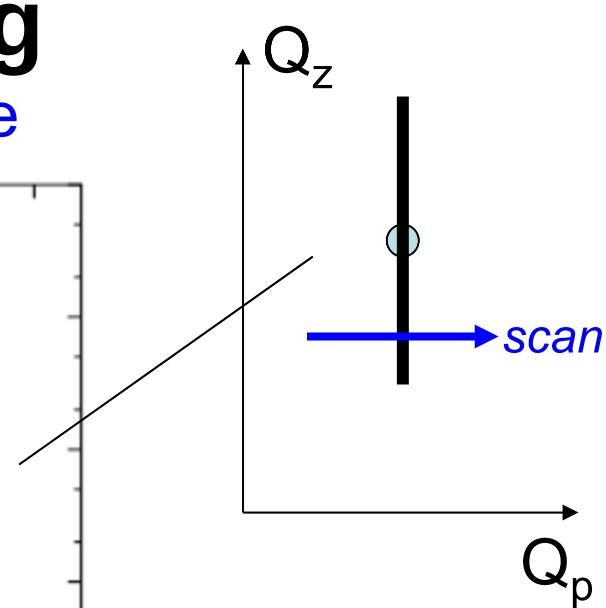
Caused by lateral structure

$$\left|A(\vec{Q})\right|^2 =$$

$$= |b|^2 \sum_{\vec{R}_p} \sum_{\vec{R}'_p}$$

$$= \frac{N_{irr}|b|^2}{\left|1 - e^{iQ_z c}\right.}$$





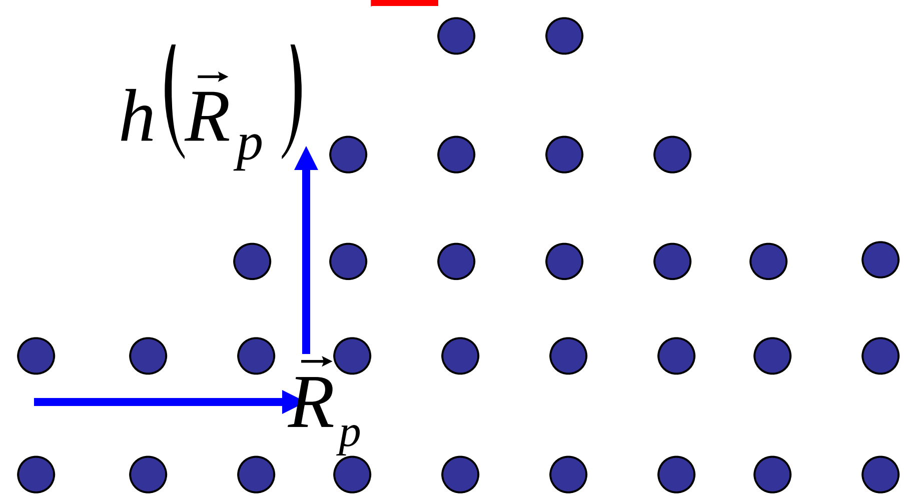
$\vec{R}'_p$

Q_p dependence

$=S_T(Q_p)$

CTR factor

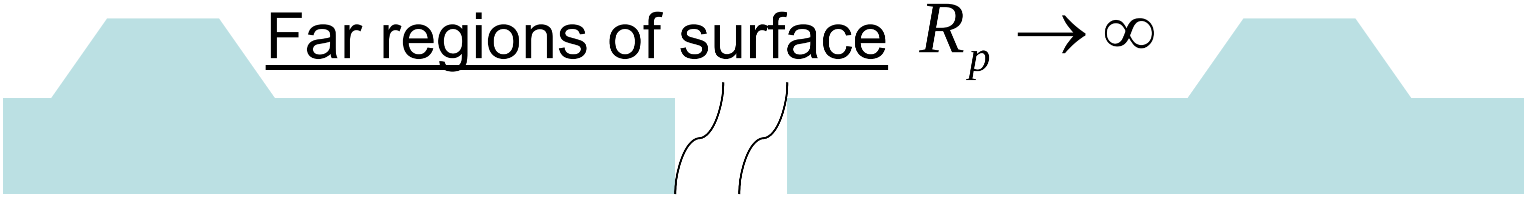
FT of average phase difference due to lateral height-differences



- Neglect lateral boundaries

Transverse Lineshape

Far regions of surface $R_p \rightarrow \infty$



Uncorrelated heights

$$\left\langle e^{iQ_z\left(h\left(\vec{R}_p+\vec{R}'_p\right)-h\left(\vec{R}'_p\right)\right)}\right\rangle_{\vec{R}'_p} \rightarrow \left|\left\langle e^{iQ_z h}\right\rangle\right|^2$$

Uncorrelated Roughness @ Large Distance Gives Bragg:

$$S_T^{Bragg}\left(\vec{Q}_p\right)=\frac{(2\pi)^2}{s_c}\delta\left(\vec{Q}_p-\vec{G}_p\right)\left|\left\langle e^{iQ_z h}\right\rangle\right|^2$$

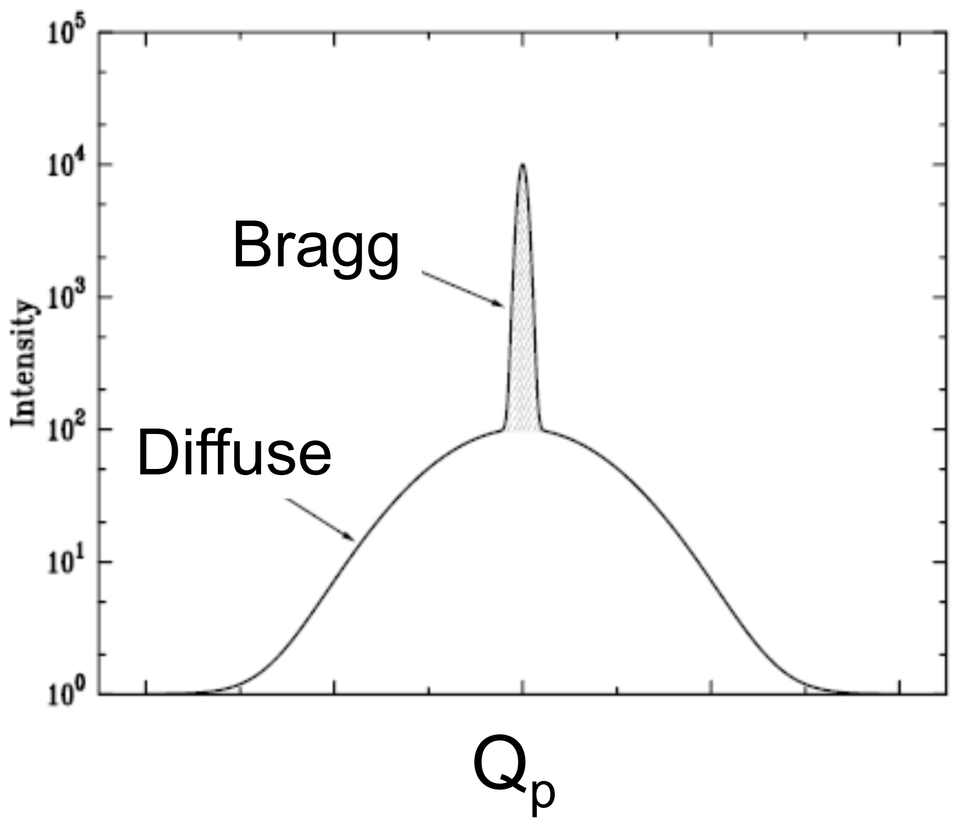
Short-Range Correlations Give Diffuse Scattering:

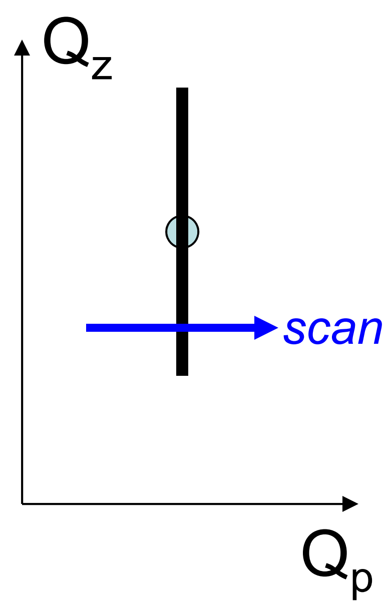
$$S_T^{Diffuse}\left(\vec{Q}_p\right)=\sum_{\vec{R}_p} e^{i\vec{Q}_p\bullet\vec{R}_p}\left\{\left\langle e^{iQ_z\left(h\left(\vec{R}_p+\vec{R}'_p\right)-h\left(\vec{R}'_p\right)\right)}\right\rangle_{\vec{R}'_p}-\left|\left\langle e^{iQ_z h}\right\rangle\right|^2\right\}$$

Two Component Line Shape: Bragg + Diffuse

$$S_T\left(\vec{Q}_p\right) = S_T^{Bragg}\left(\vec{Q}_p\right) + S_T^{Diffuse}\left(\vec{Q}_p\right)$$

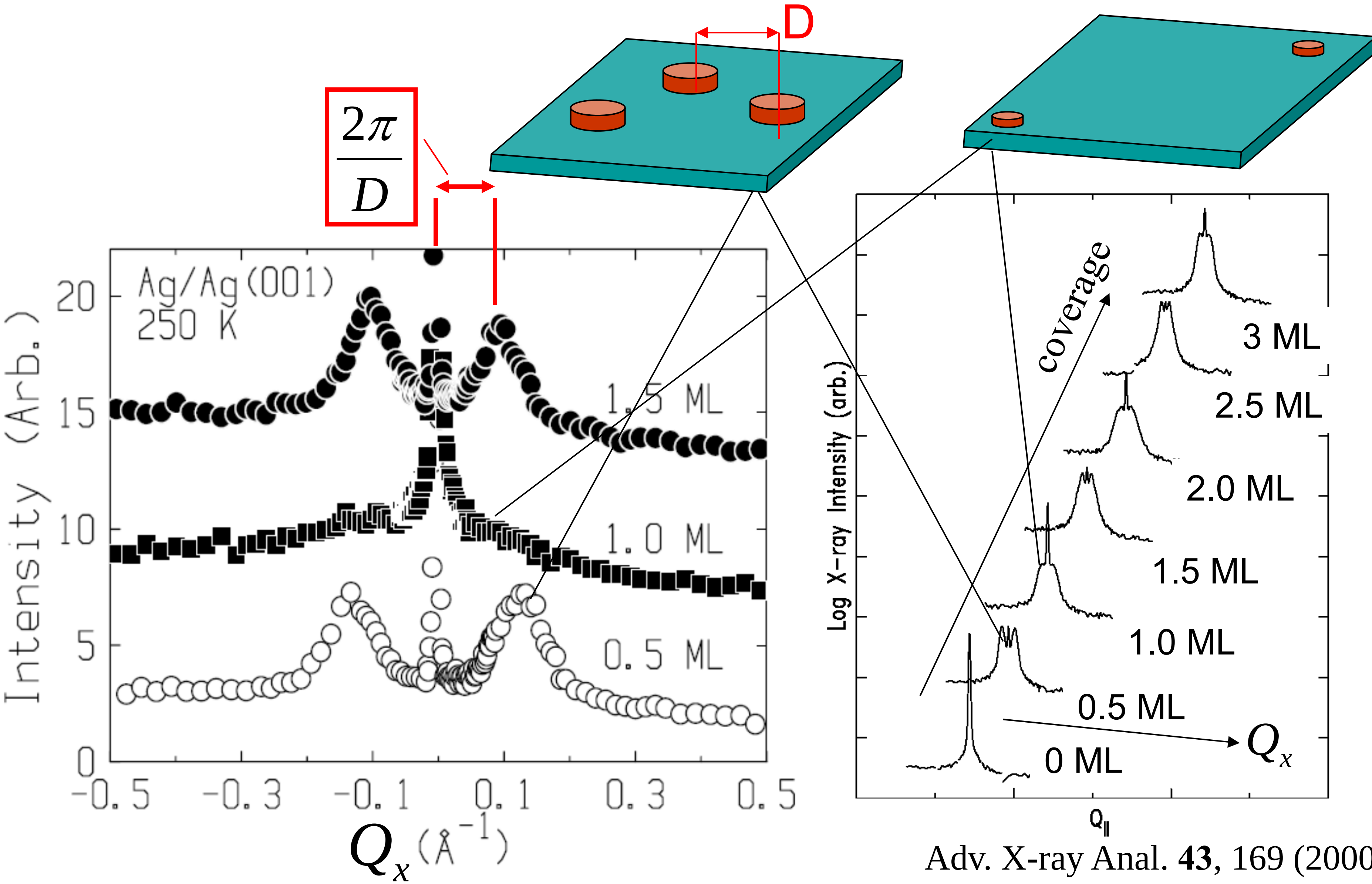
- Bragg due to laterally uncorrelated disorder at long distances
- Diffuse due to short-range correlations





Layer-by-layer growth

- Specular Bragg Rod: intensity changes with roughness
- Strong inter-island correlations seen in the diffuse

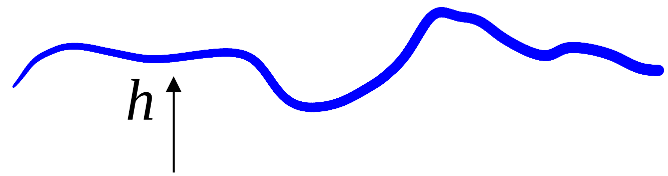


Adv. X-ray Anal. **43**, 169 (2000)

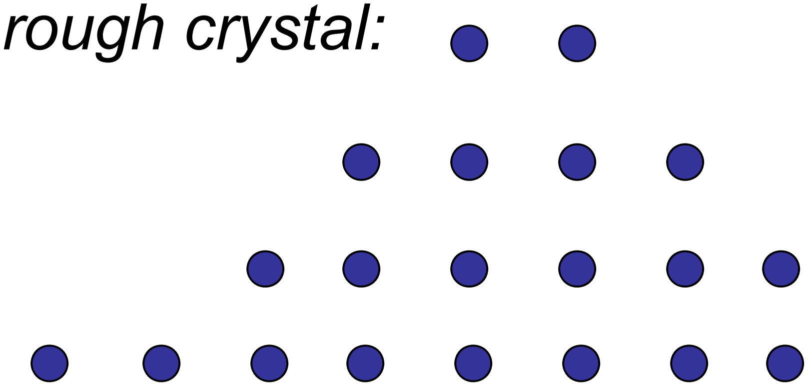
Attenuation of the Bragg Rod and Surface Roughness

If height fluctuations are Gaussian: σ is rms roughness

$$\left|\left\langle e^{iQ_z h}\right\rangle\right|^2 \rightarrow e^{-Q_z^2\sigma^2}$$



But crystal heights are <u>discrete</u> for a rough crystal:

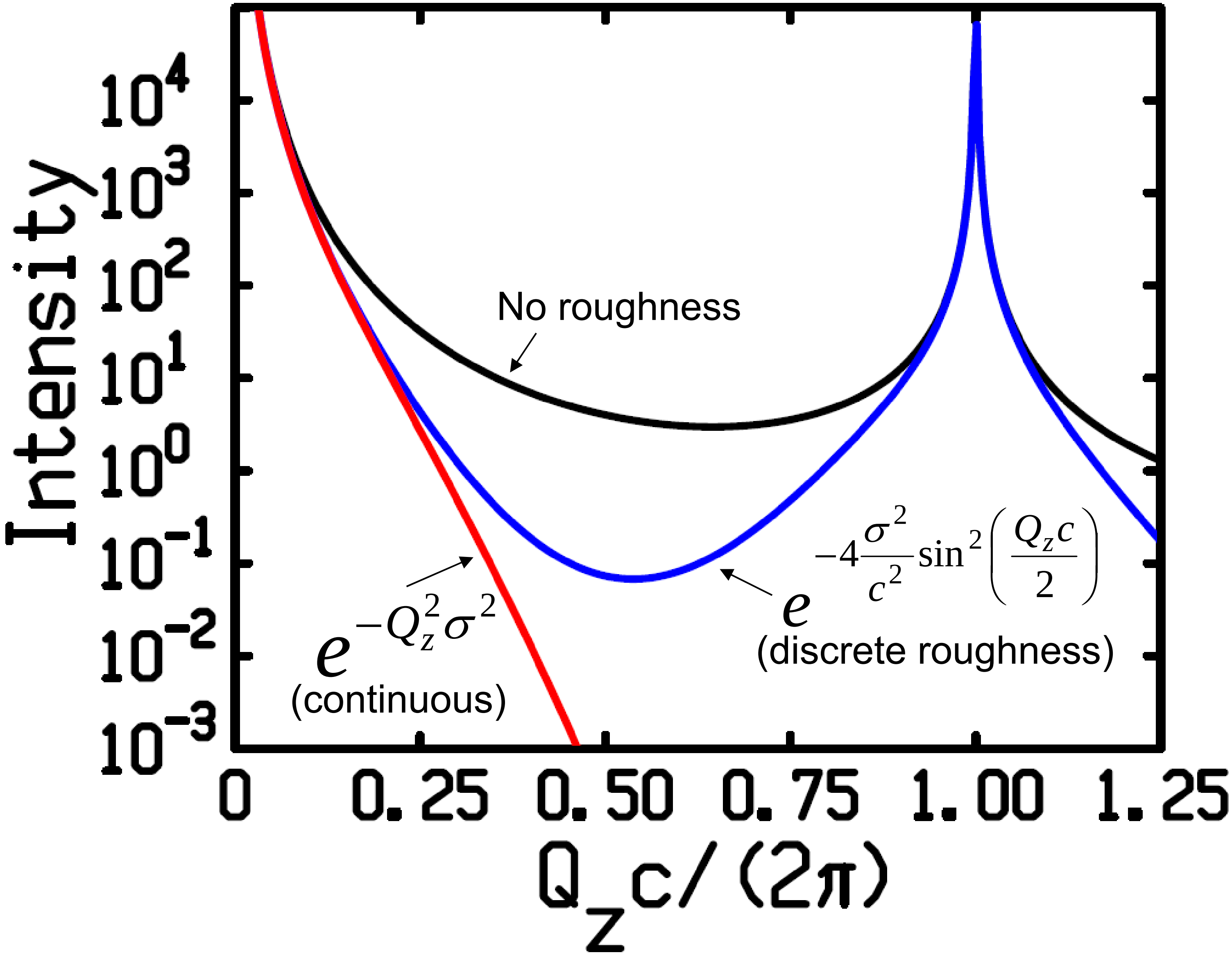


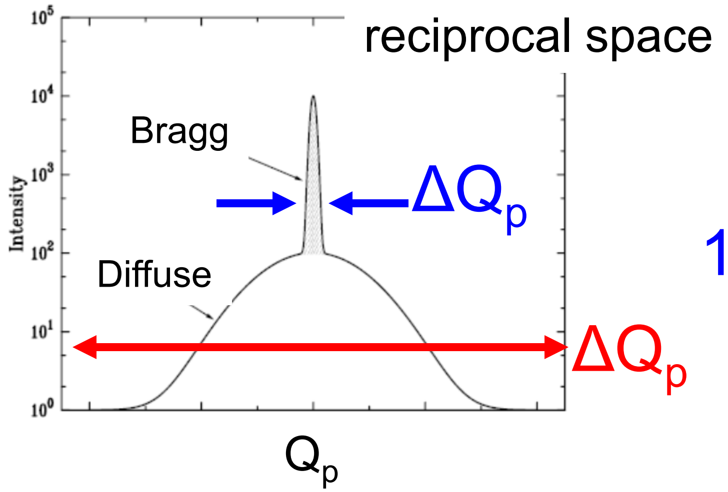
$$\left|\left\langle e^{iQ_z h}\right\rangle\right|^2 \rightarrow e^{-4\frac{\sigma^2}{c^2}\sin^2\left(\frac{Q_z c}{2}\right)}$$

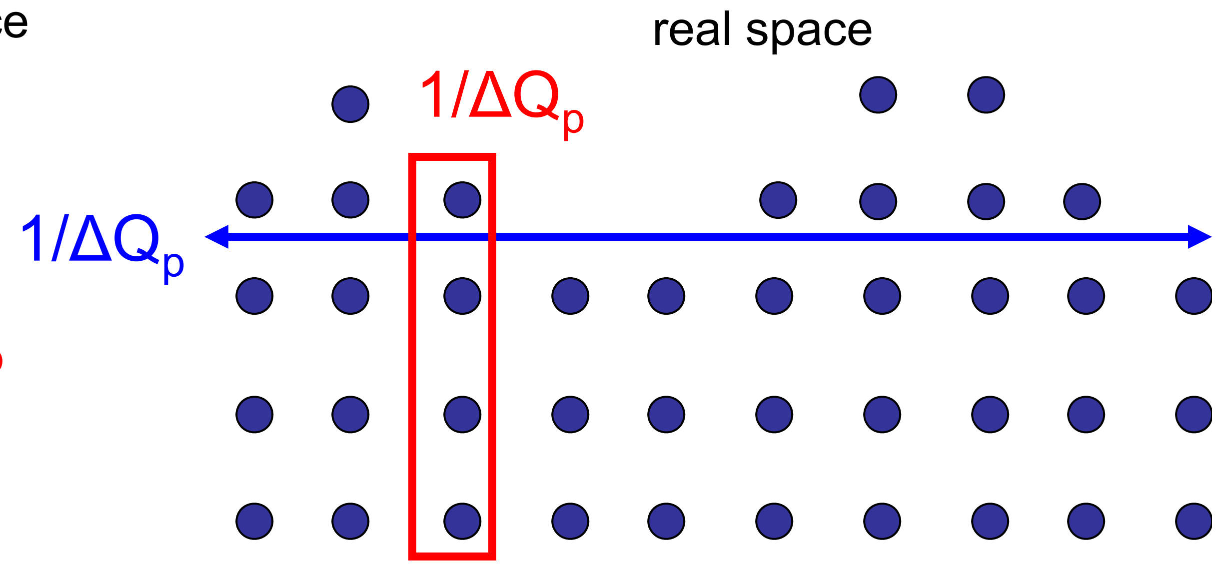
- Binomial distribution (limits to a Gaussian for large roughness)
- Preserves translational symmetry in the roughness

Physica B **221**, 65 (1996)

- Sharper interface (real space) gives broader scattering
- Gaussian roughness does not give translational symmetry







Bragg is narrow:

it samples laterally uncorrelated roughness at long distances

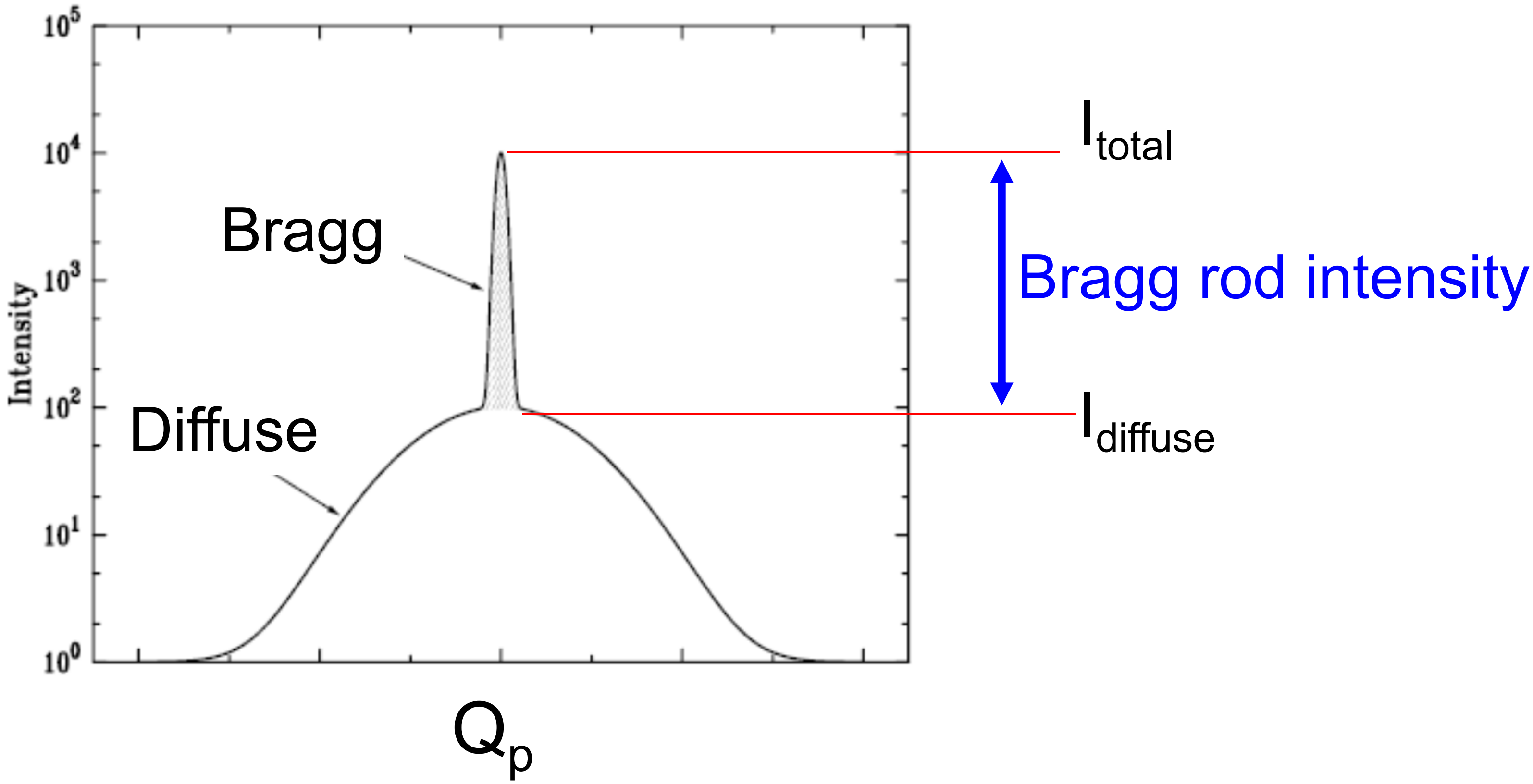
$$S^{Bragg}\left(\vec{Q}\right) \propto \frac{\left|b\right|^2}{\left|1-e^{iQ_z c}\right|^2} e^{-4\frac{\sigma^2}{c^2}\sin^2\left(\frac{Q_z c}{2}\right)}$$

Transversely-integrated scattering shows no effect of roughness:

(for 1 interface)

$$\iint d^2Q_p\, S\left(\vec{Q}\right) \propto \frac{\left|b\right|^2}{\left|1-e^{iQ_z c}\right|^2}$$

In practice, at every Q_z the diffuse must be subtracted from the total intensity to get the Bragg rod intensity:

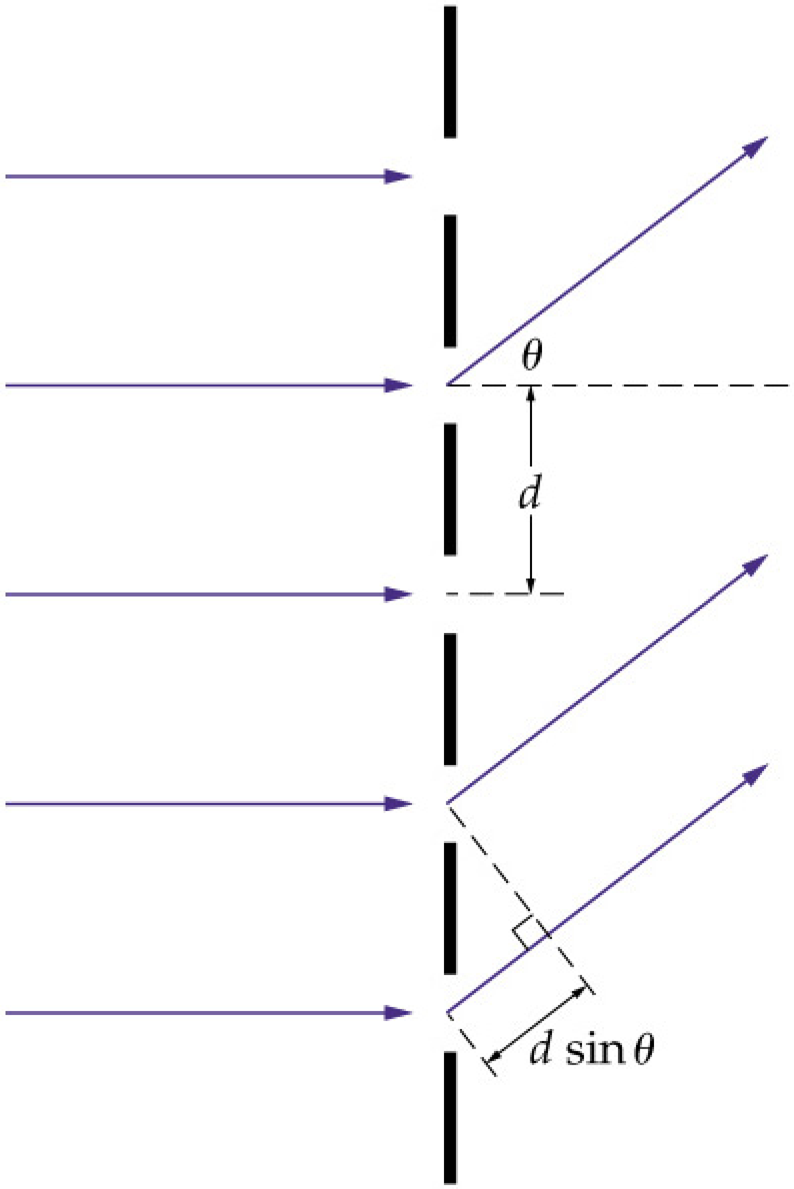


What do we expect from a **<u>Thin Film</u>**?

1st let’s recall Young’s slit interference…

Recall…

N-Slit Interference and Diffraction Gratings



Principle maxima

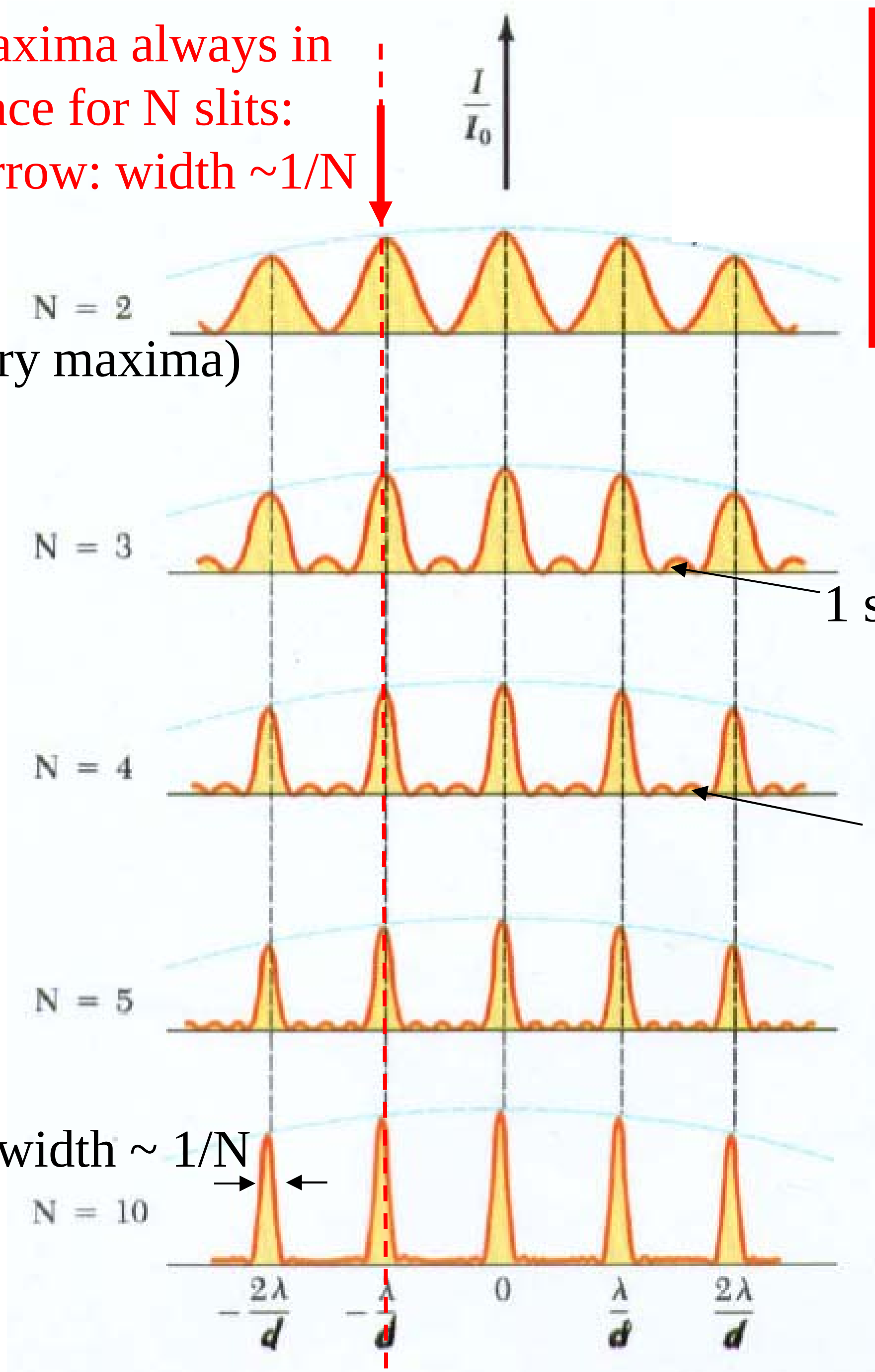
$$d \sin \theta = m\lambda$$

Principle maxima always in the same place for N slits:
But they narrow: width ~1/N

Principle maxima
$d \sin \theta = m\lambda$

(N-2 subsidiary maxima)

Double Slit
(no subsidiary maxima)



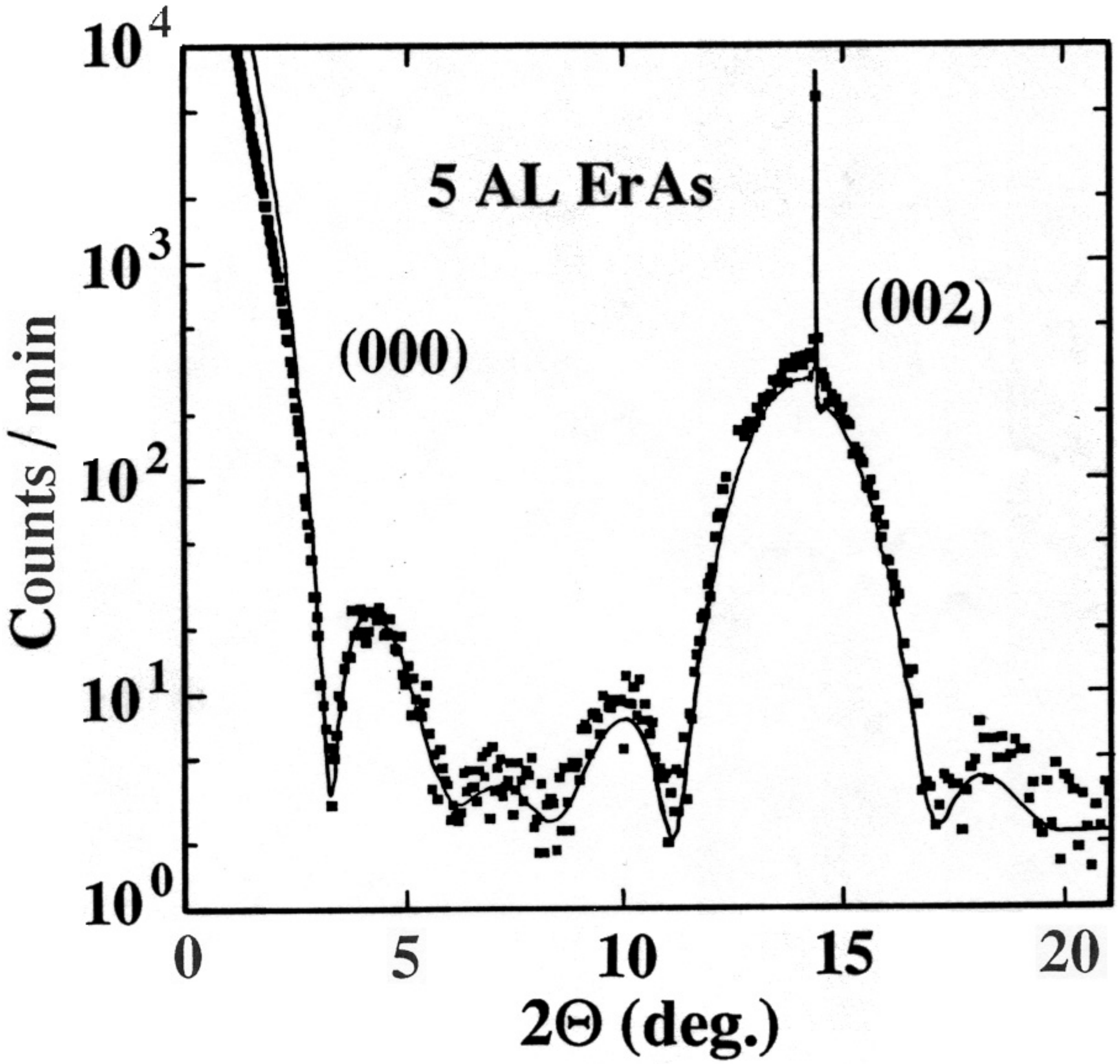
1 subsidiary maximum

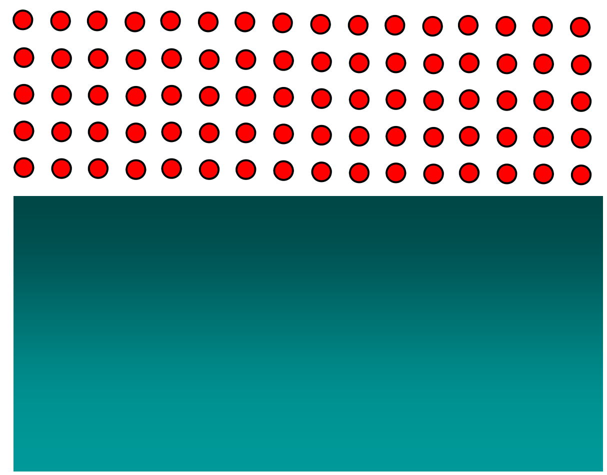
2 subsidiary maximum

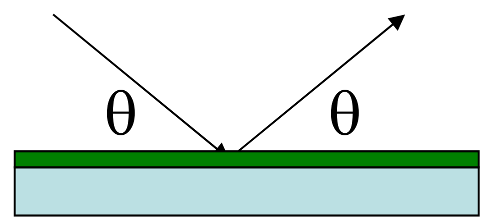
width ~ 1/N

N large:
- Weak subsidiary maxima
- Sharp principle maxima

“5-slit” interference of x-rays from 5 layers of atoms

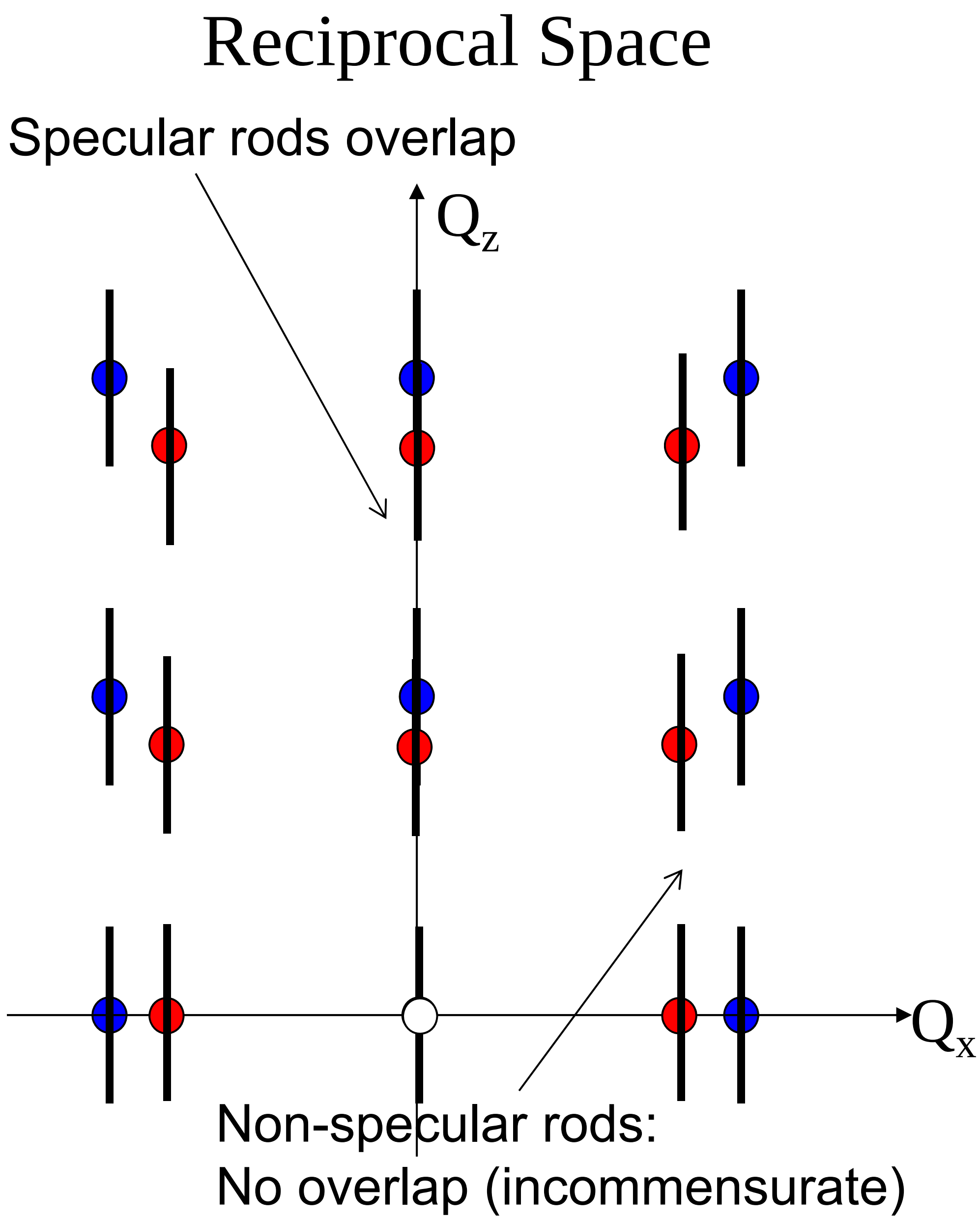


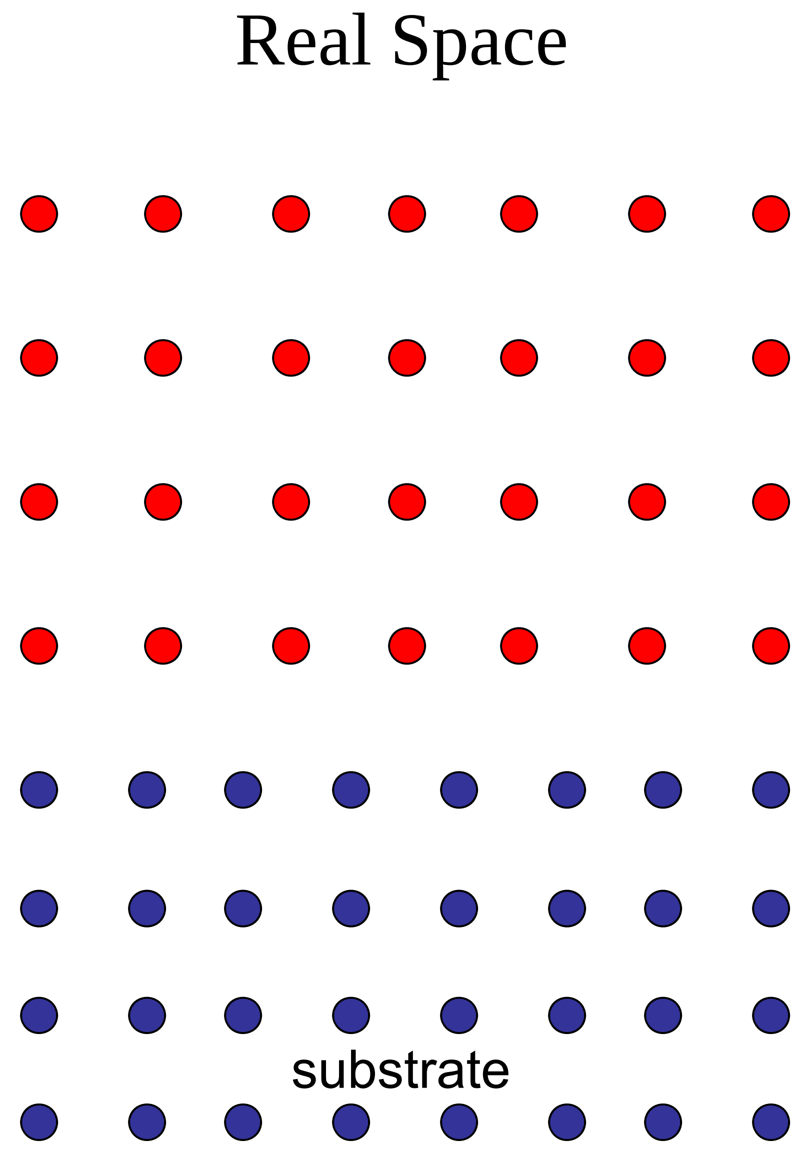




Miceli et al., Appl. Phys. Lett. **62**, 2060 (1992)

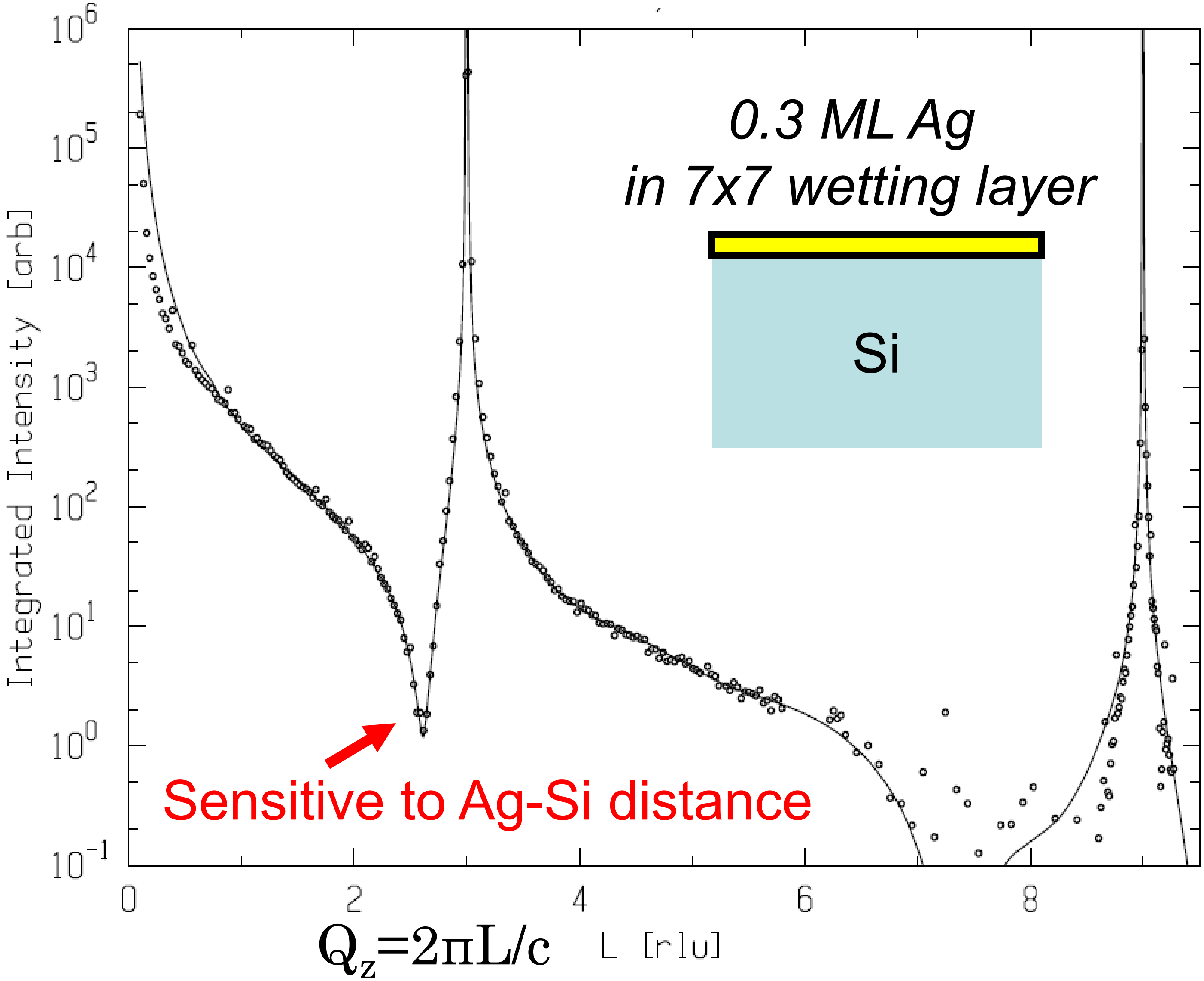
Thin Films

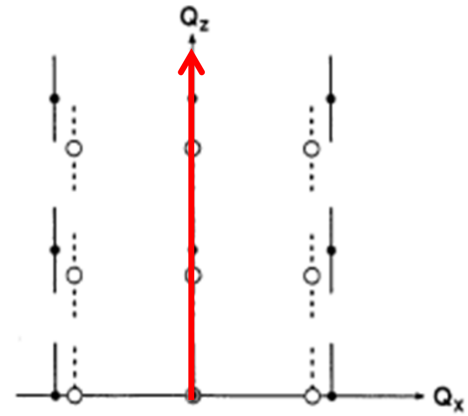

Reciprocal Space
Specular rods overlap
Q_z
Q_x
Non-specular rods:
No overlap (incommensurate)


Real Space
substrate

Ag/Si(111)7x7

Specular Reflectivity: 0.3ML Ag/Si(111)7x7

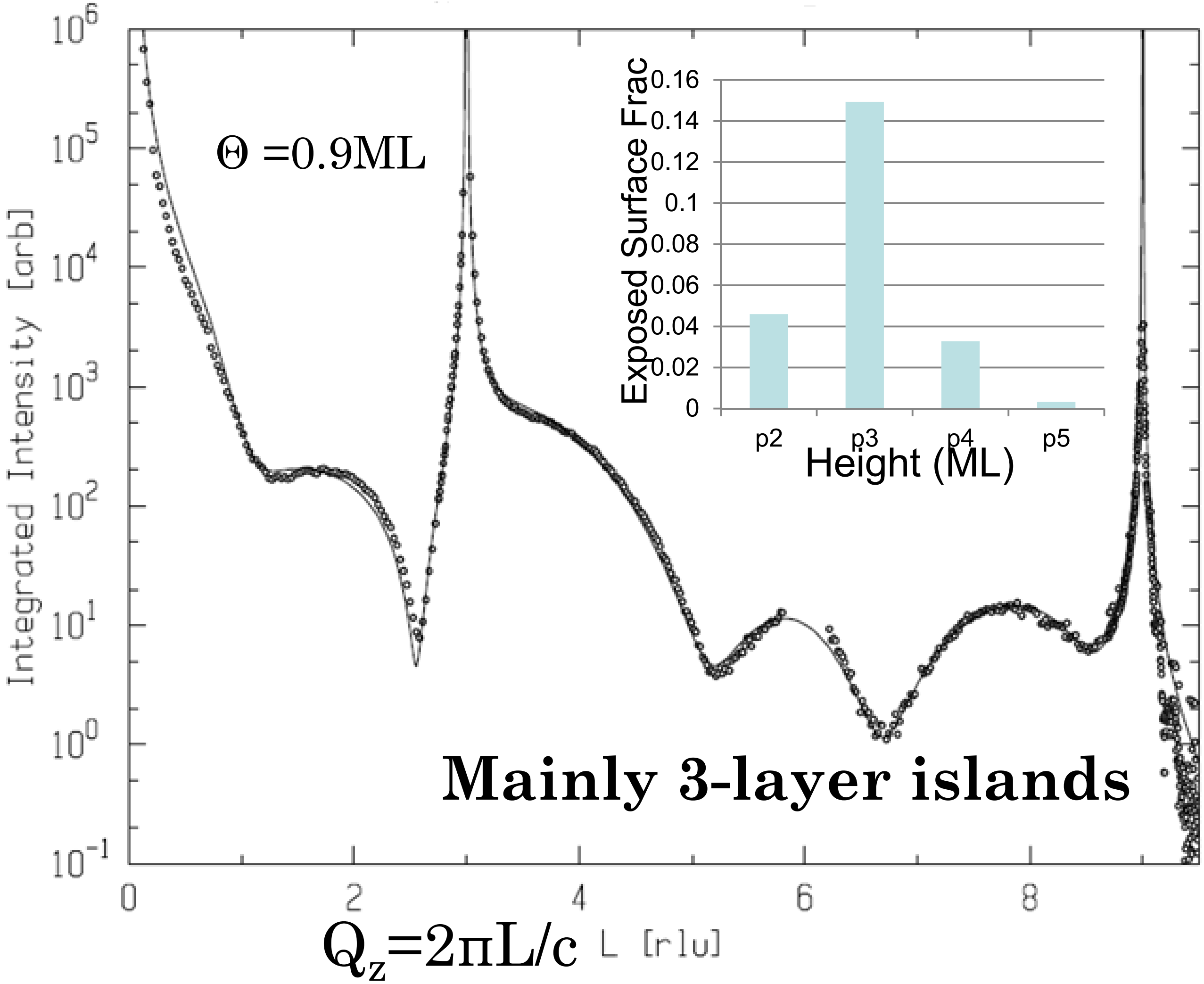


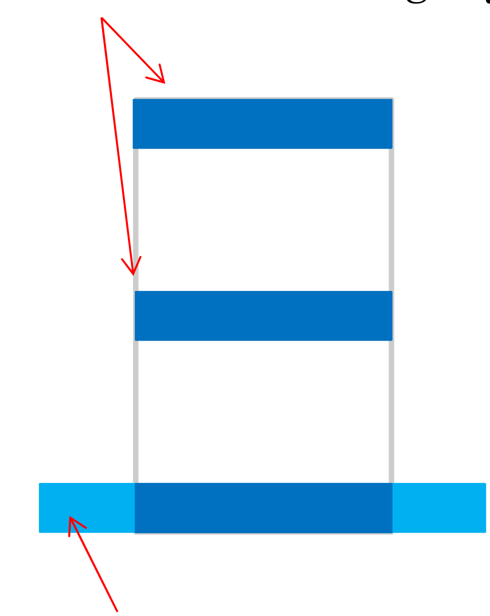


Yiyao Chen et al.

Ag/Si(111)7x7

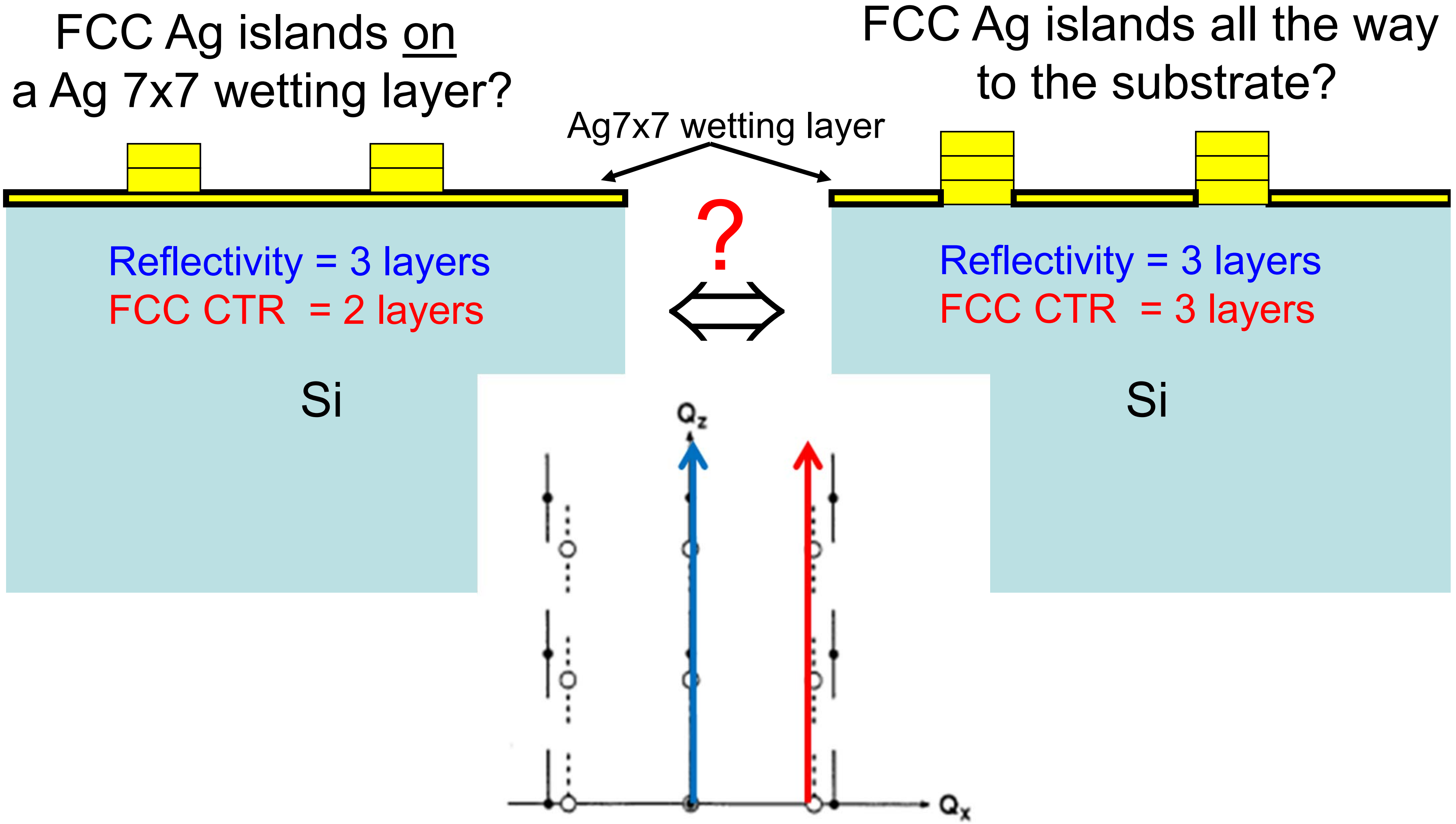
Specular Reflectivity: 0.9ML Ag/Si(111)7x7





Yiyao Chen et al.

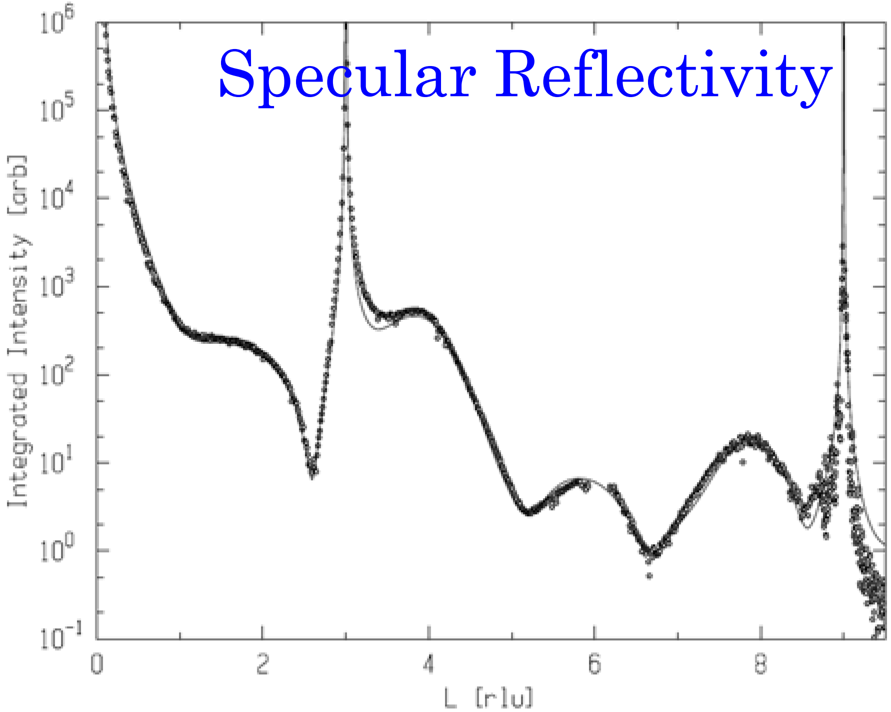
Specular reflectivity cannot easily distinguish between these two cases:

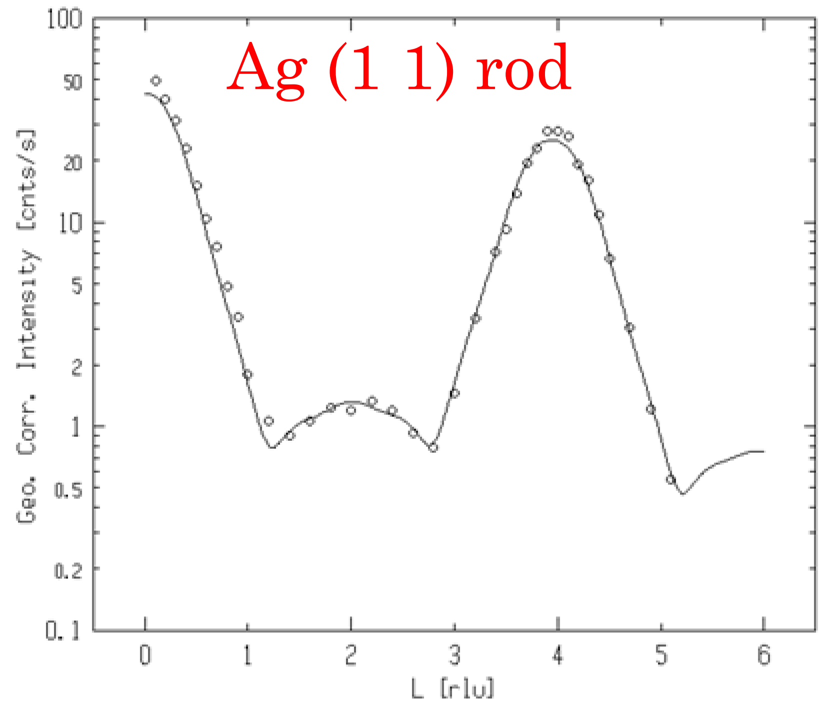


Specular reflectivity and rod give same thickness:

Island is FCC Ag all the way to the substrate

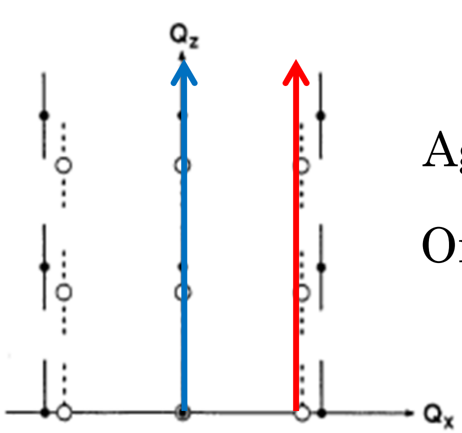
Islands *remove* the wetting layer!





Specular Reflectivity

Probes Si substrate, Ag wetting layer and Ag island



Ag truncation rod

Only probes FCC Ag

Yiyao Chen et al.

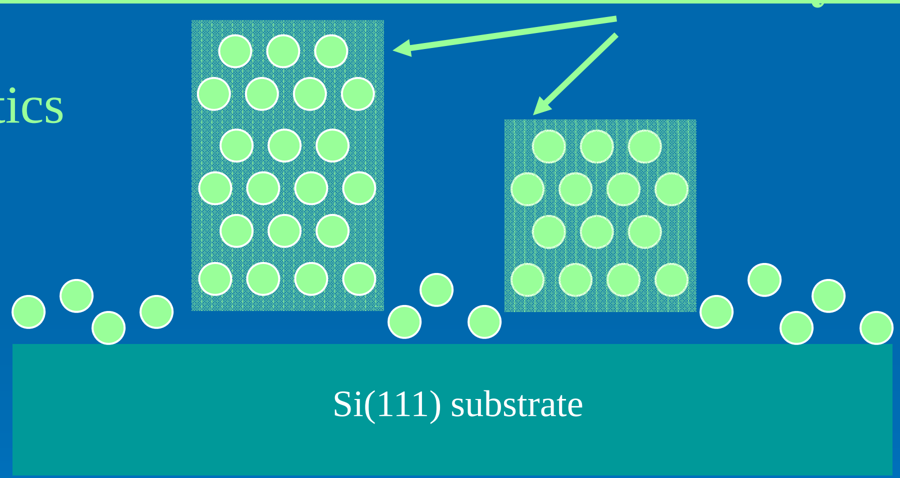
Quantum-Size-Effects: Pb Nanocyrstals on Si(111)7x7

Height Selection: "Magic" crystal heights

Quantum Mechanics Influences Nanocrystal Growth

Discoveries:

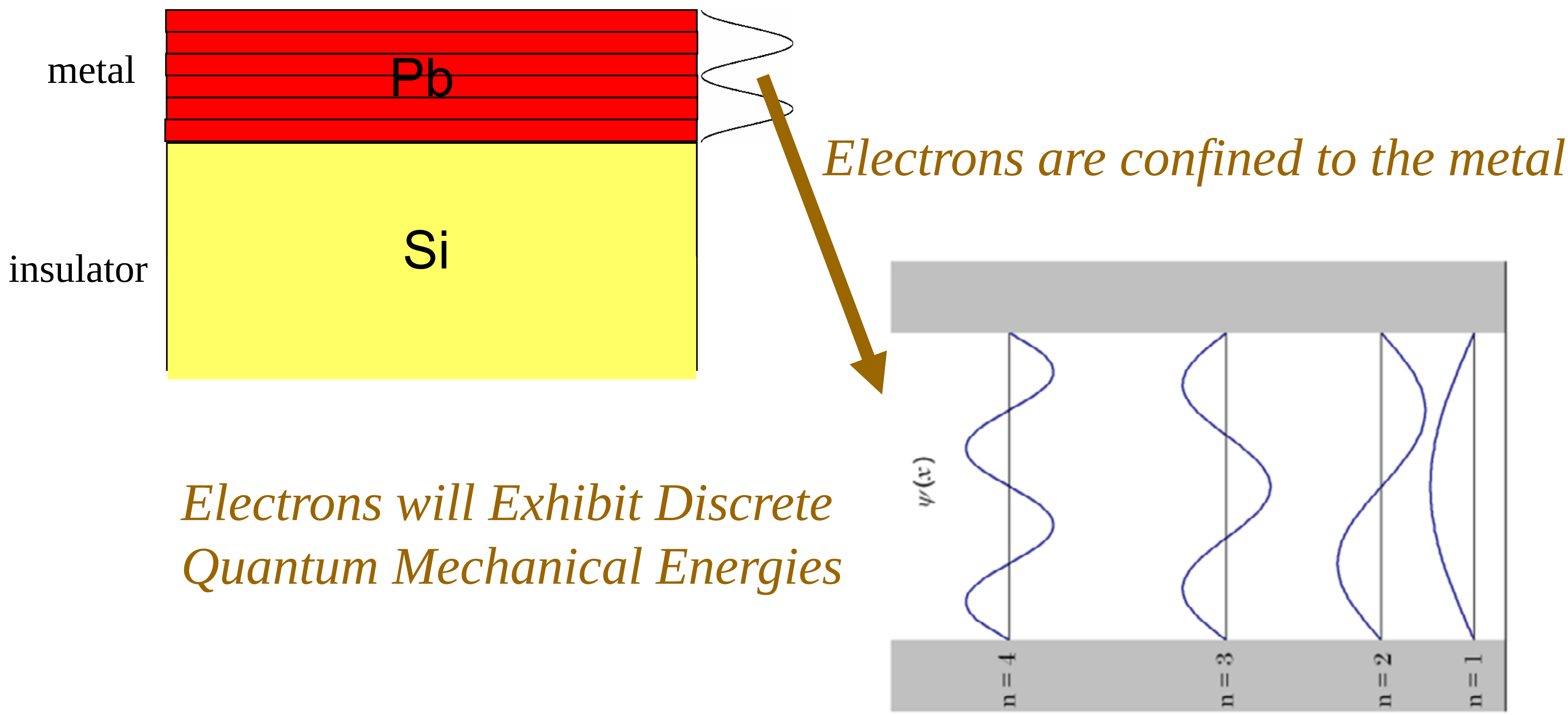
- anomalously (10^4) fast kinetics
- Non-classical coarsening
- Unusual behavior: fast growth => most stable structures



Disordered Pb wetting layer

C. A. Jeffrey et al., PRL **96**, 106105 (2006)

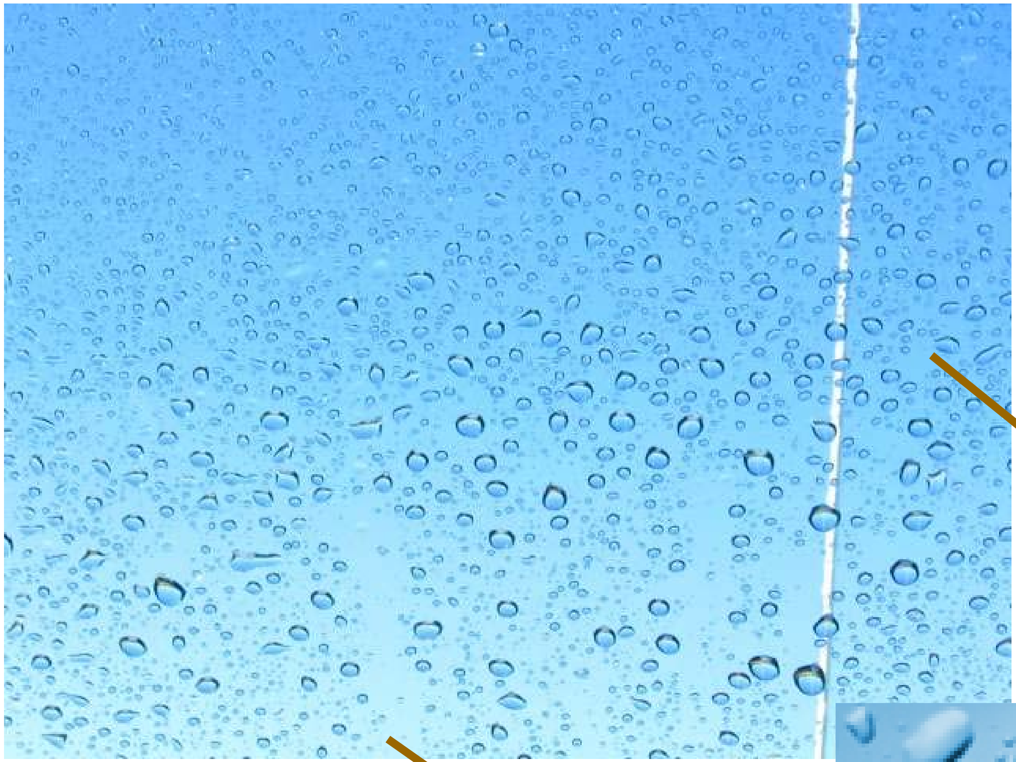
Electrons in a "box"



Electrons will Exhibit Discrete Quantum Mechanical Energies

F. K. Schulte, Surf. Sci. **55**, 427 (1976)
P. J. Feibelman, PRB **27**, 1991 (1983)

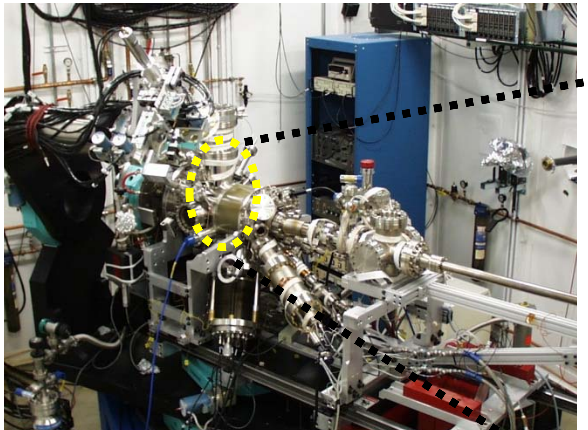
Rain Drops On Your Winshield



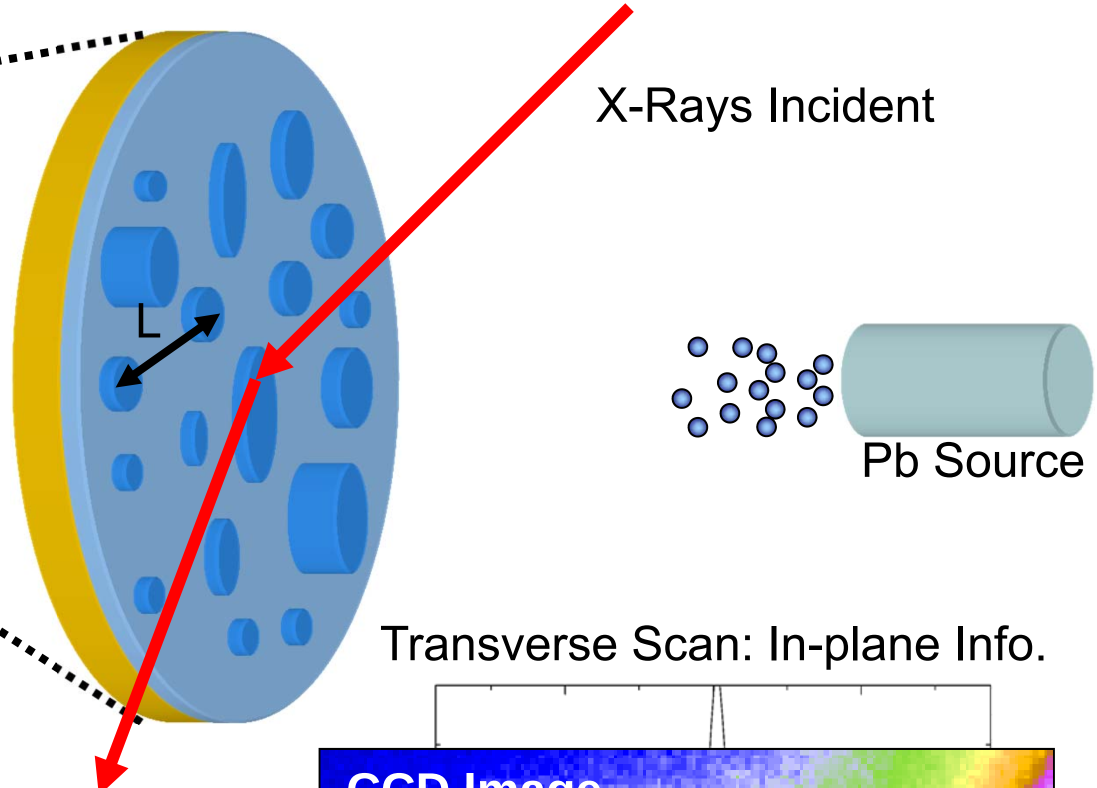
Coarsening

laist.com
greeneurope.org

Kinetics: In Situ Surface X-ray Scattering



Surface Chamber
Advanced Photon Source



Mean island separation, <L>:

$$\Delta\kappa = \frac{2\pi}{\langle L \rangle}$$

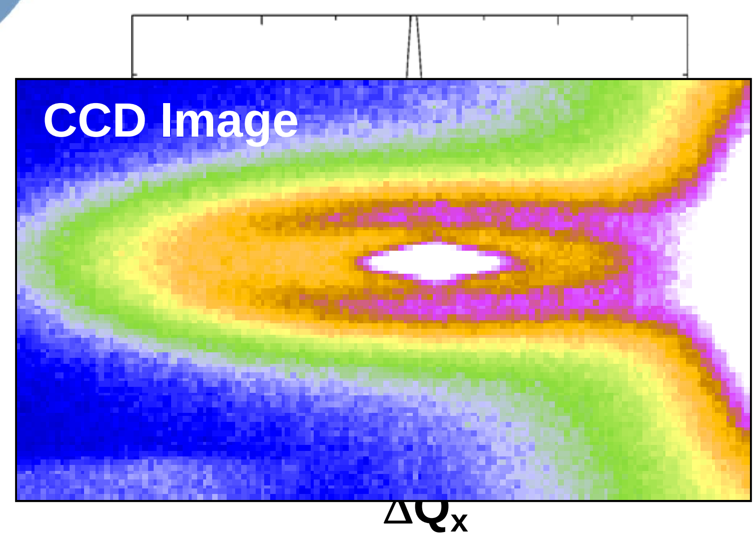
Island Density:

$$n \propto \frac{1}{\langle L \rangle^2}$$

Experiment:

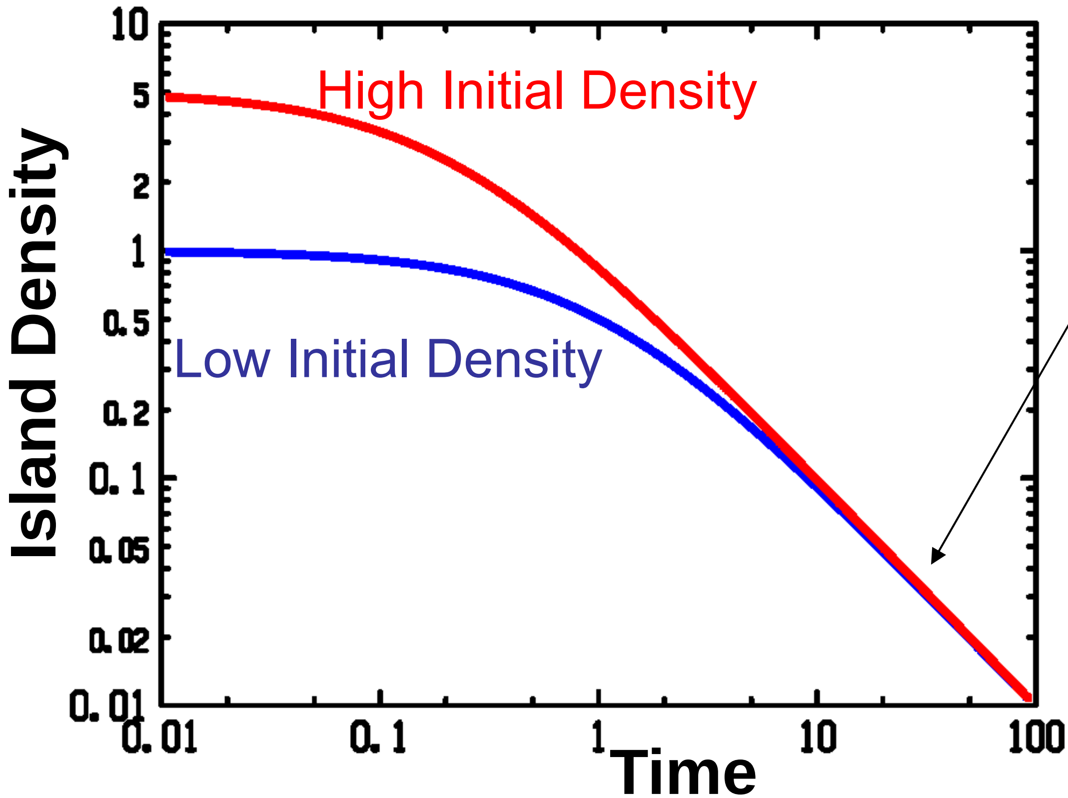
- Deposit Pb (1.2 to 2 ml) at 208K
- Measure the island density vs time (flux off)

Transverse Scan: In-plane Info.



Classical Coarsening: Ostwald Ripening

$$n(t) = n_0 \left(1 + \frac{t}{\tau}\right)^{-\beta} \qquad \beta = \frac{2}{(m+2)},\ m = 0,1,2$$



Long time: independent of initial conditions

$$n(t) \Rightarrow \left(n_0 \tau^{\beta}\right) t^{-\beta}$$

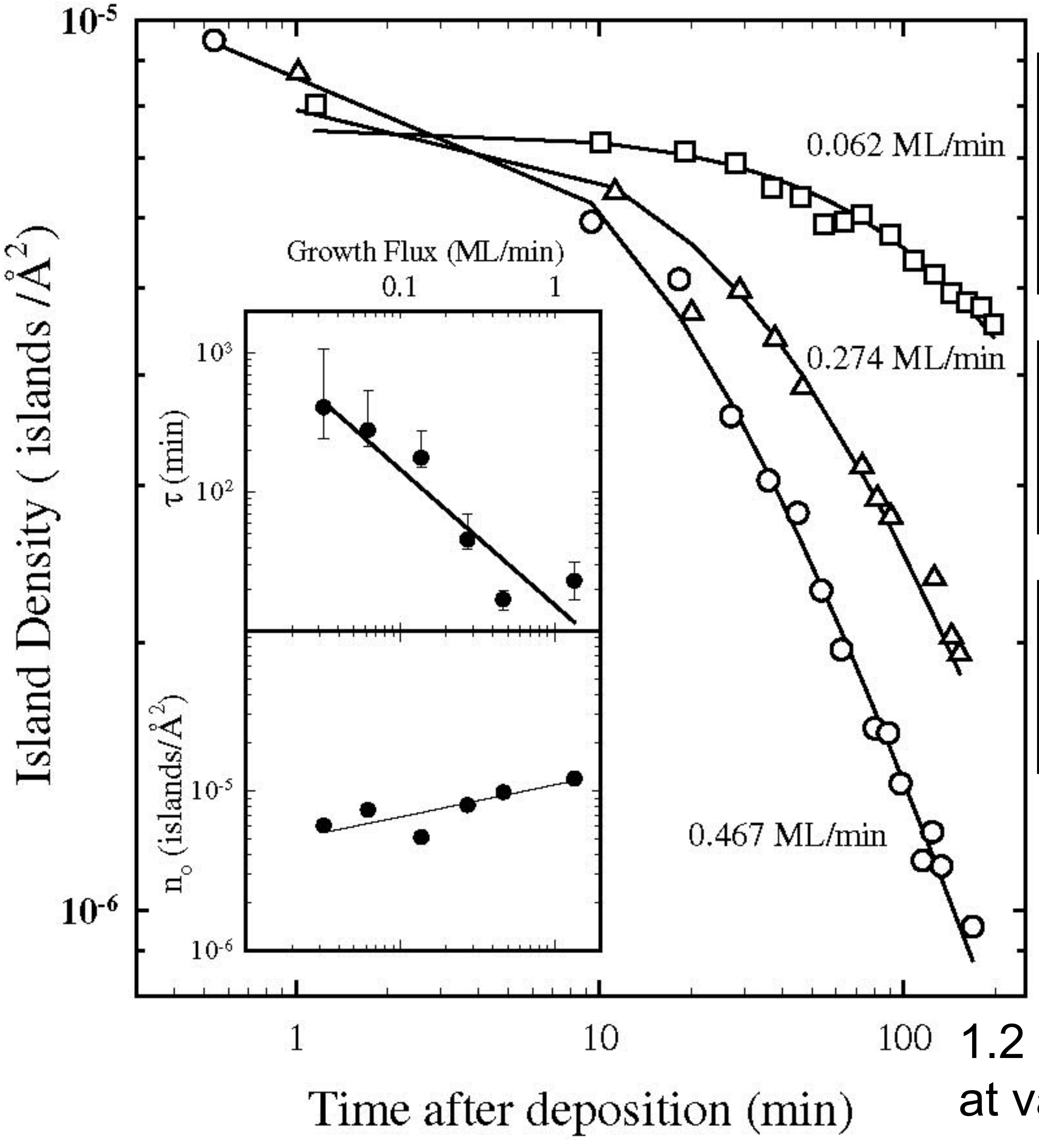
$$\tau \propto n_0^{-\frac{1}{\beta}}$$

Relaxation time depends <u>only</u> on the initial density

Pb Nanocrystal Coarsening

…does ***not*** conform to the classical picture!

C. A. Jeffrey et al., PRL **96**, 106105 (2006)



1.2 ML of Pb at 208K
at various flux rates

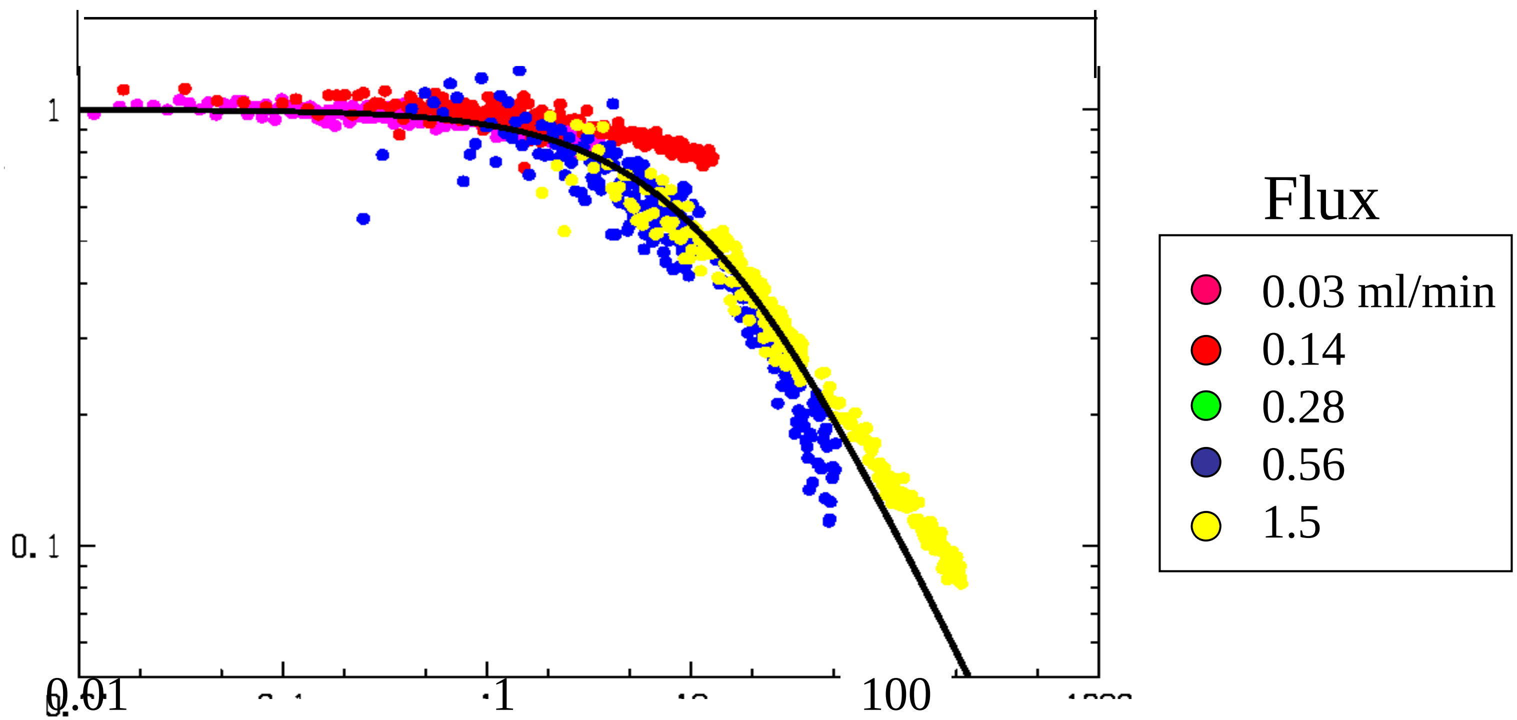
- Island densities do not approach each other at long times:
  QSE ⇒ Non-Oswald
  Breakdown of Classical Coarsening

- Time constant τ **~ 1/Flux**
  Strong flux dependence!
  Unexpected!

- Anomalously fast relaxation
  ~1000x faster than expected!
  ⇒allows equilibrium!

$$n(t) = \frac{n_0}{\left(1 + \frac{t}{\tau}\right)}$$

Reciprocal Space is Superb for Obtaining Good Statistics of Distributions



Equivalent ML Time = t*F

Summary

- Materials research problems require information on a broad range of length scales, from atomic to mesoscale

- Scattering from surfaces involves many different types of measurements:
  - Reflectivity, Rods, Grazing Incidence Diffraction, Diffuse Scattering

- Unique ability of x-rays: surface and subsurface structure simultaneously