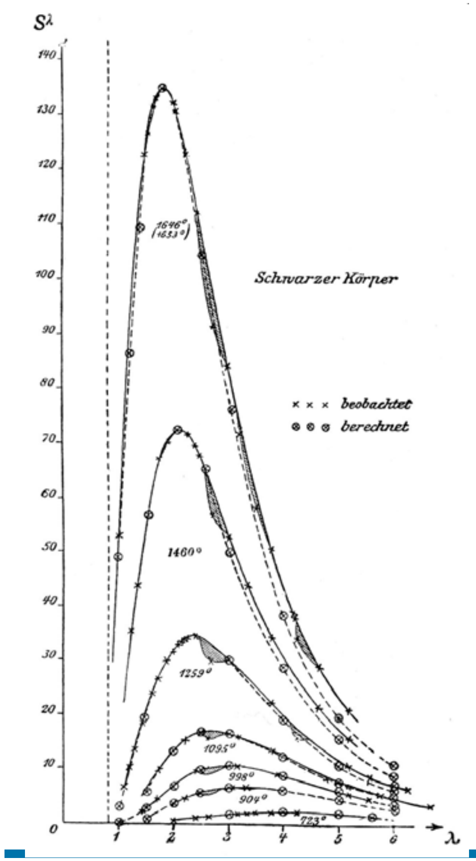
Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

XUV scatterometry and fluorescence for nano-structured surfaces

Frank Scholze, Anna Andrle , Analía Fernández Herrero, Anton Haase, Philipp Hönicke, Mika Pflüger, Quais Sadeeh. Victor Soltwisch

PTB, Department Radiometry with Synchrotron Radiation

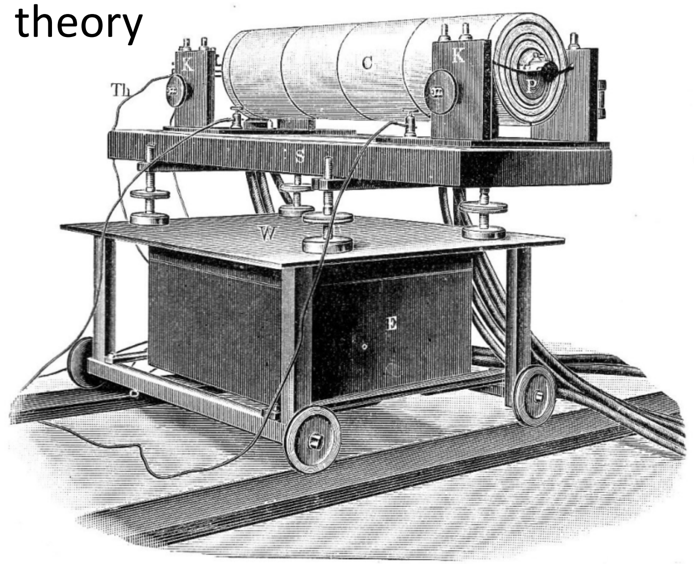
Metrology with SR: Motivation



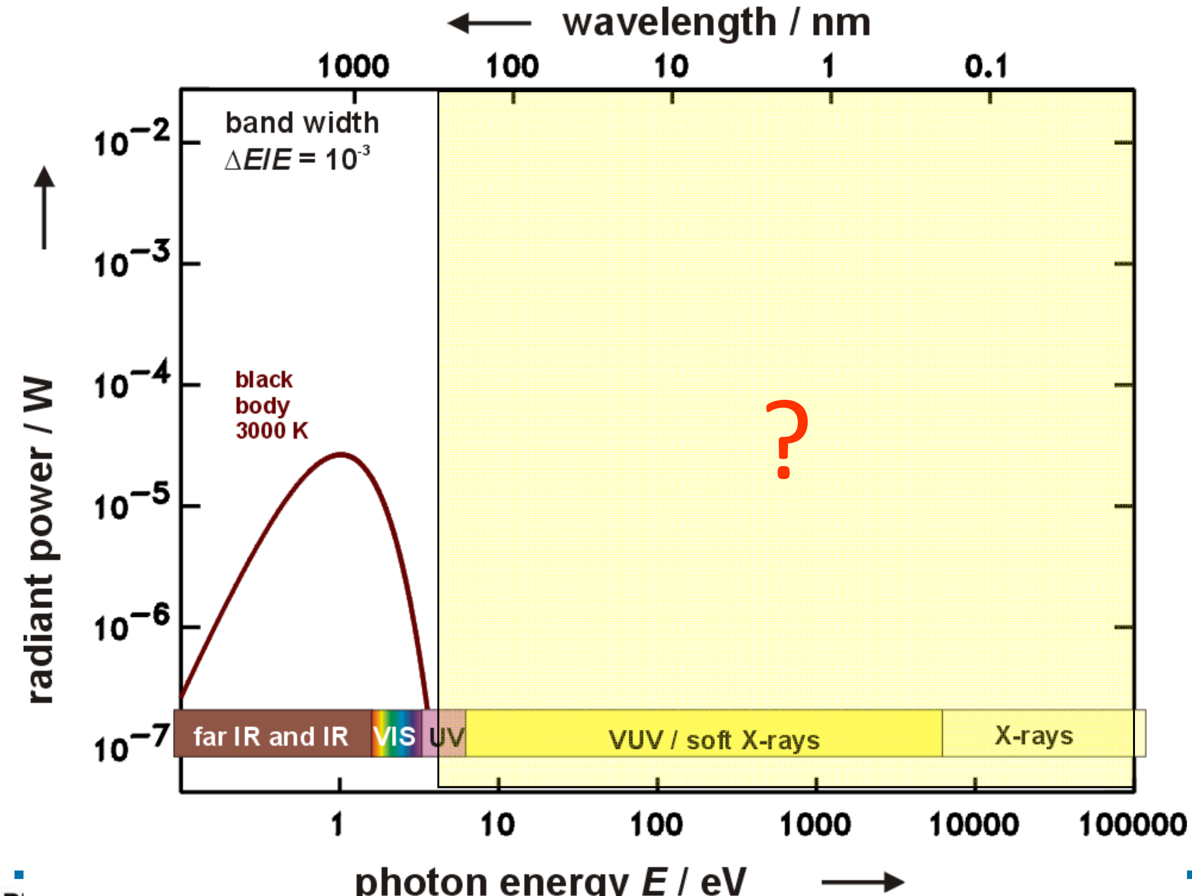
Early 1890‘s:
precision measurements of black body radiation at the PTR (Lummer, Wien, Kurlbaum, Pringsheim)

1900:
Planck‘s law – the birth of quantum theory

Black Body Radiator
is a standard source



Metrology with SR: Radiometry beyond UV



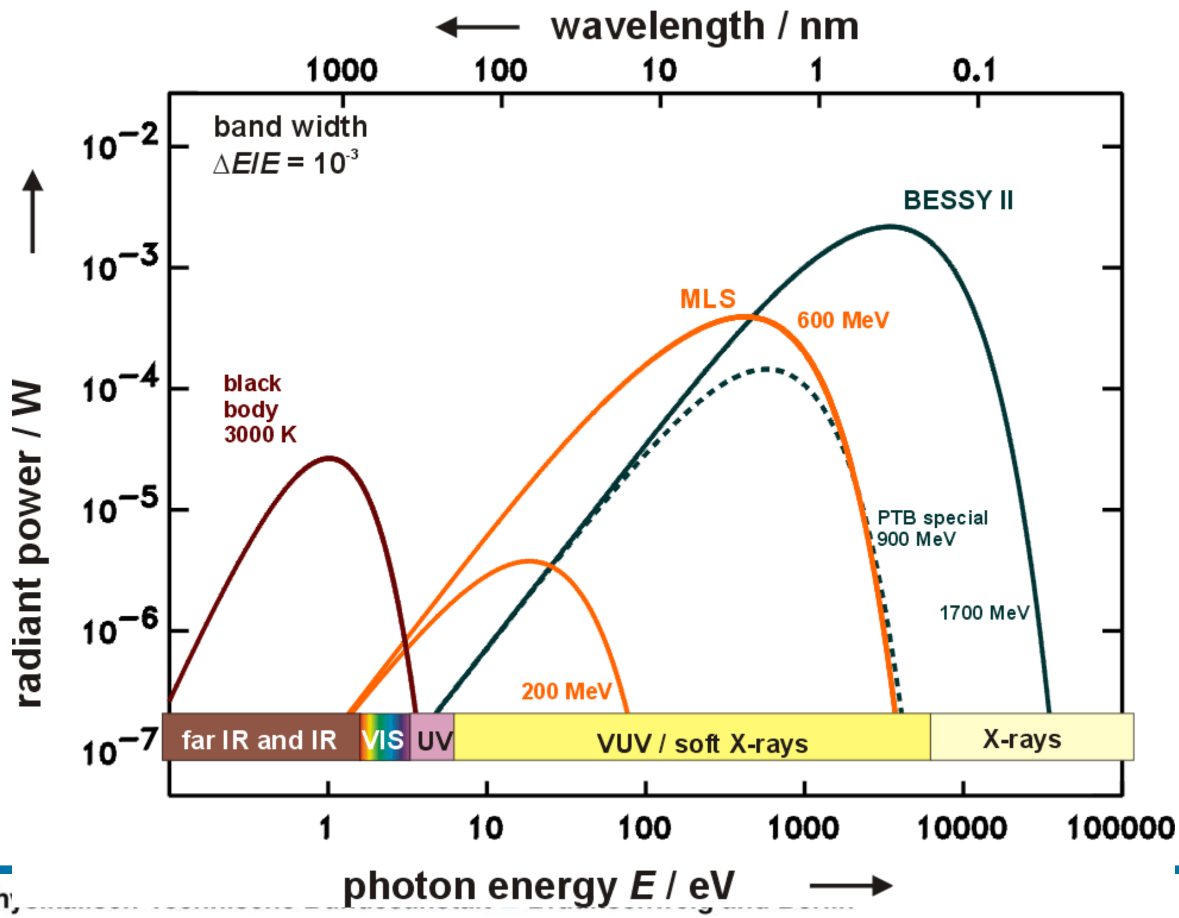
Black Body Radiatior

Thermodynamics
(Planck‘s Radiation Law)

- Temperature

$$\Phi = \Phi\ (T)$$

Metrology with SR: Radiometry beyond UV



Electron Storage Ring

Electrodynamics
(Synchrotron radiation)

- electron energy
- magnetic induction
- stored current

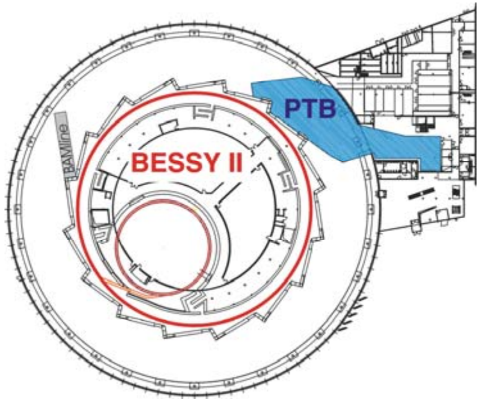
$$\Phi = \Phi\ (E, B, I)$$

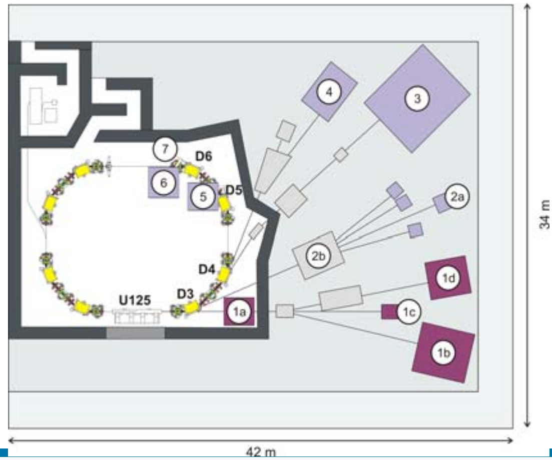
PTB laboratories @ BESSY I, II, MLS

1982 – 1999: BESSY I

since 1999: BESSY II

since 2008: MLS





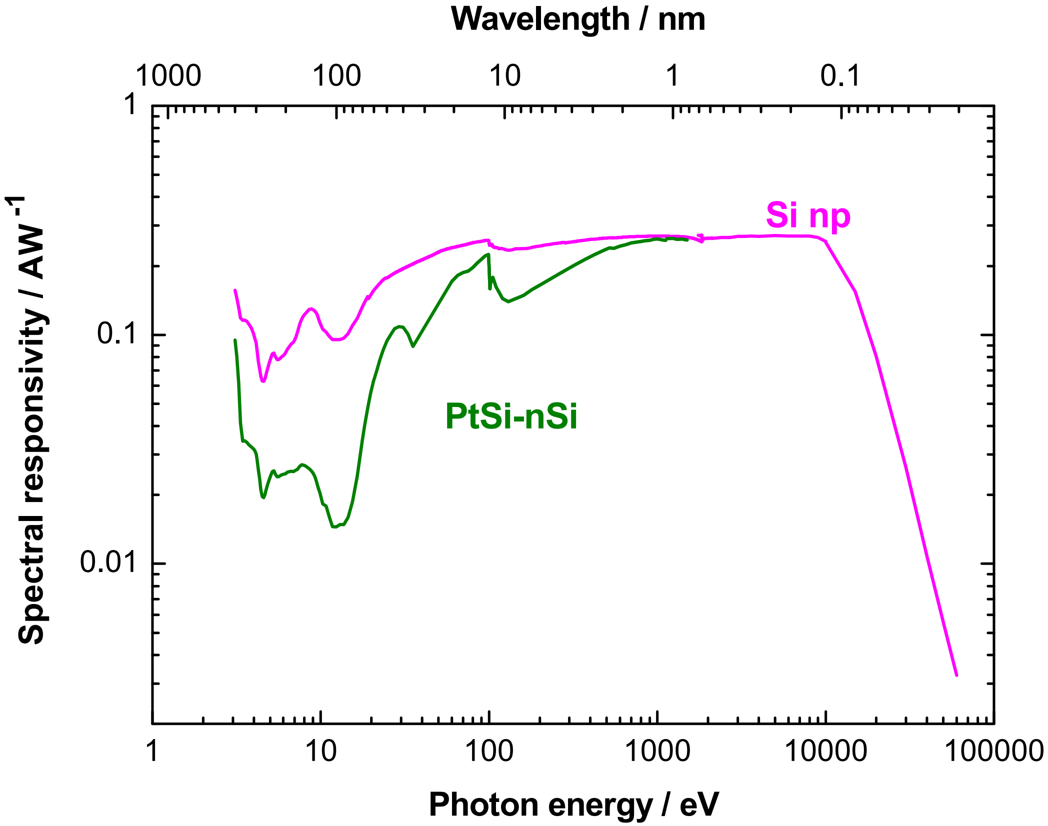
BESSY II:
circumference 250 m
electron energy 1.7 GeV

PTB:
10 beamline branches
from 400 nm (3 eV)
to 0.02 nm (60 keV)

Metrology Light Source MLS
circumference 48 m
electron energy 100 - 630 MeV

8 beamlines
from 8 mm
to 4 nm (300 eV)

Basic PTB capabilities: detector calibration



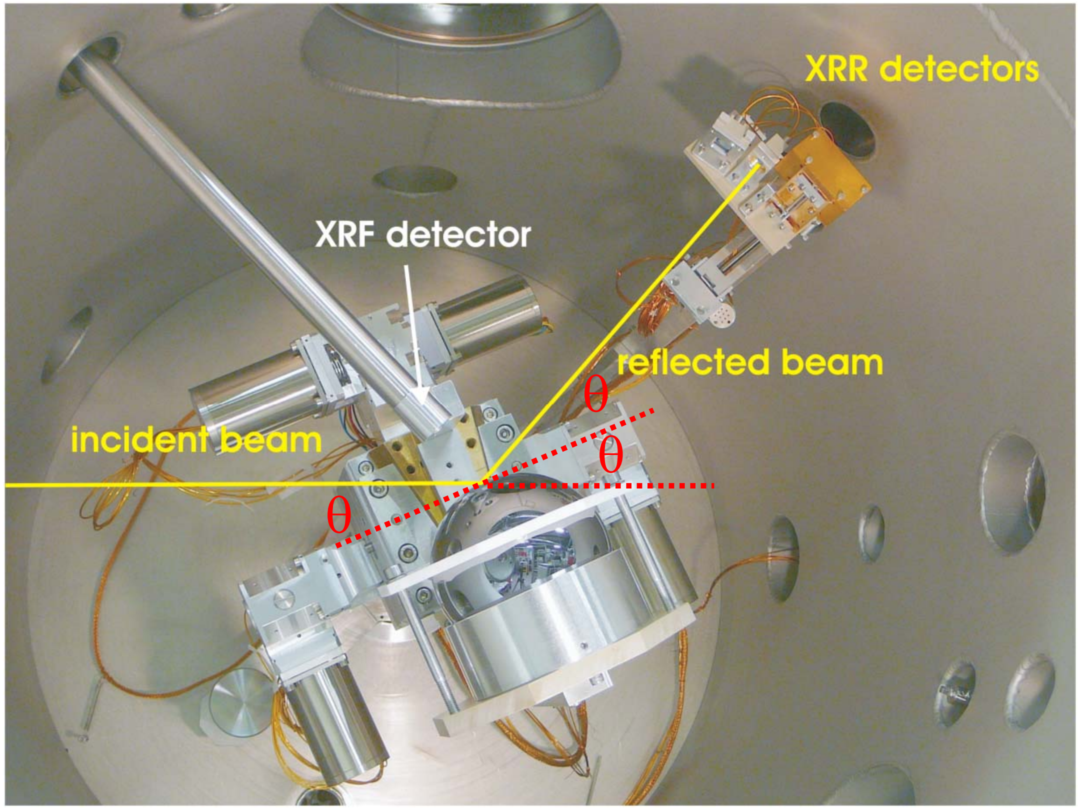
Calibration of photodetectors

example:
semiconductor photodiodes,
type depending from energy range due to

- stability
- linearity
- spatial uniformity

Relative standard uncertainty:
0.3 % ... 1.2 %

Basic PTB capabilities: XUV reflectometry

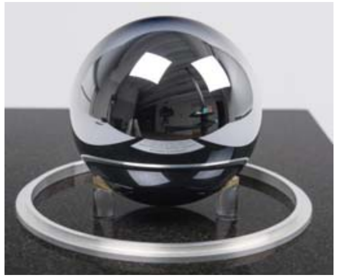


X-ray reflectometry (XRR):

Reflectance is measured as function of the incidence angle

Basic PTB capabilities: XUV reflectometry

PTB Avogadro project: redefinition of the kilogram



Avogadro constant: $$N_A = \frac{M\,V\,n}{m}$$

m : mass
M : molar mass
V : volume
n : atomic densitiy

Realization of a „perfect" Si crystal sphere
Determination of the number of atoms by measuring all other parameters thus determining the Avogadro constant.

By defining the value of this constant, the mass unit can be determined.

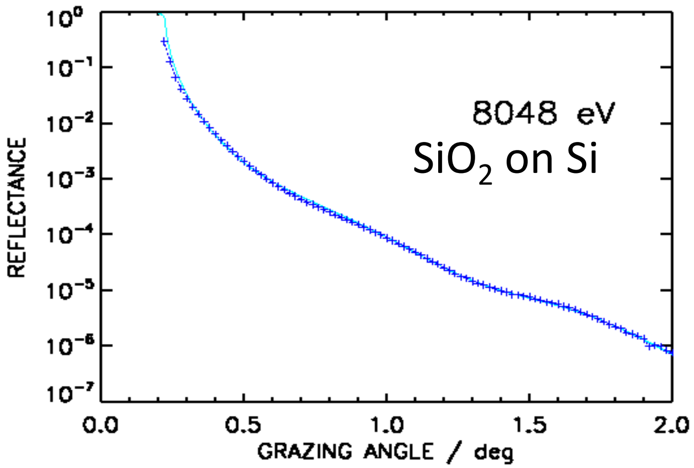
How perfect is „perfect" ? $Si + O_2 = SiO_2$!   uncertainty < 10^{-8} needed !

The mass (thickness) of the oxide Layer must be accurately determined

XUV reflectometry for dimensional metrology

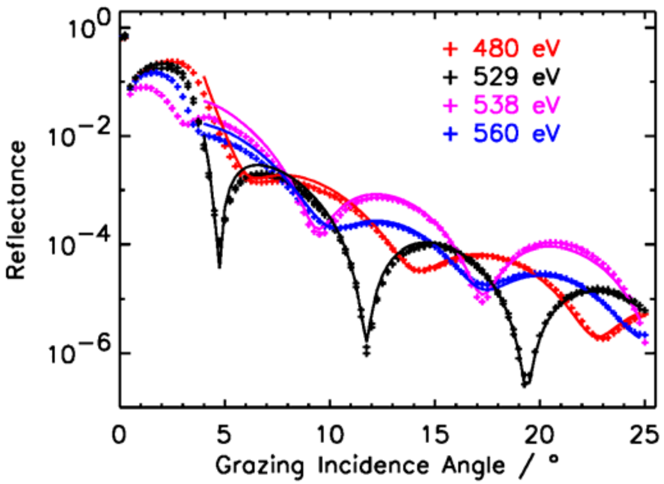
X-ray reflectometry: Thickness determination by interference patterns in reflectance

laboratory: Cu-K_α



Issues:
- contrast SiO_2 on Si too weak
- extremely grazing incidence

Monochromatized SR: tunable



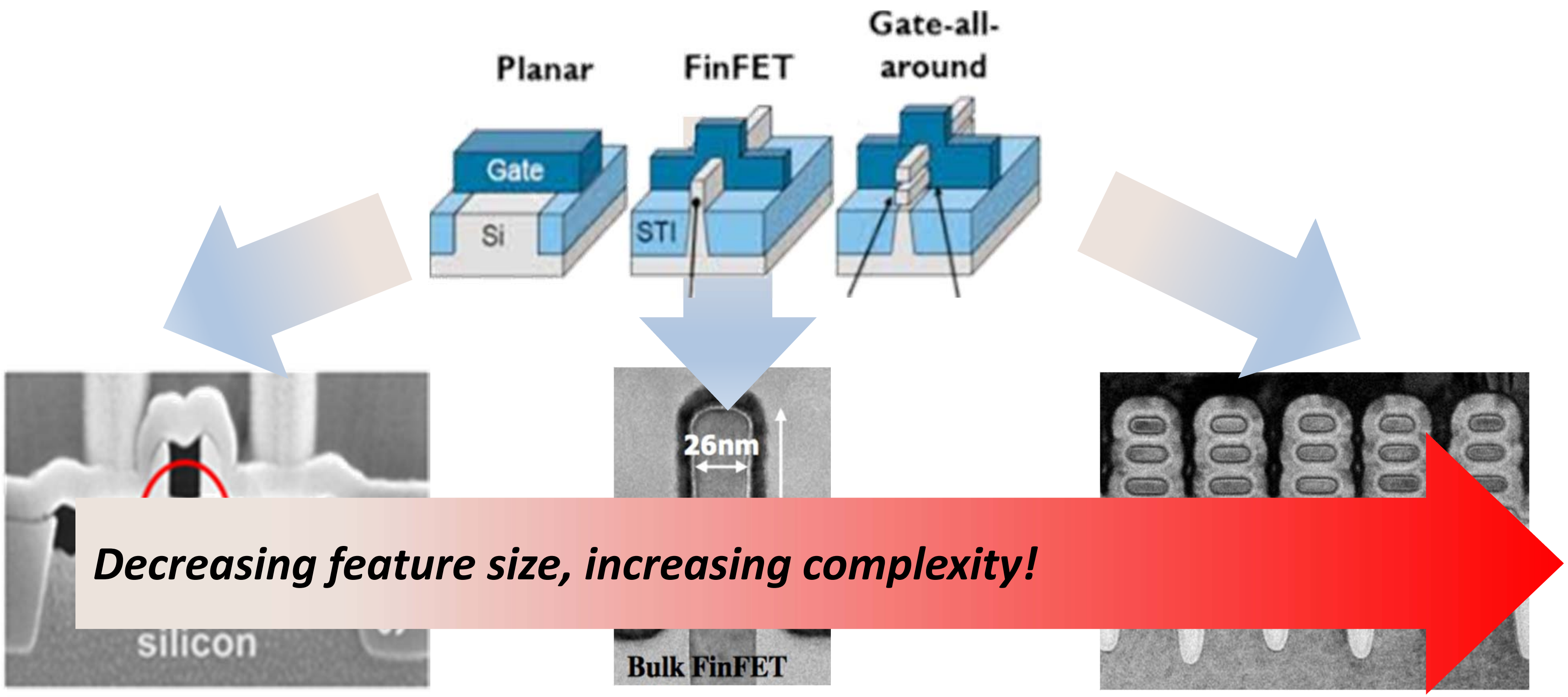
Low energy

→ steeper angles

→ curved surface can be investigated

8.29 nm thermal SiO_2 on Si-sphere, 111 orientation
0.67 nm C-contamination
=> **Unit of mass: the new kg**

New metrology challenges

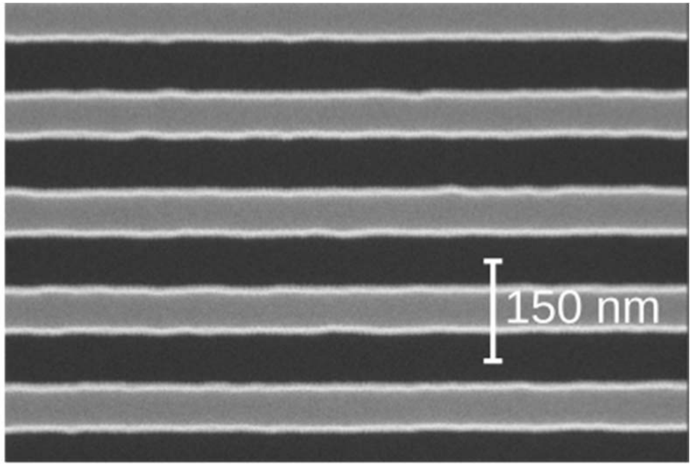


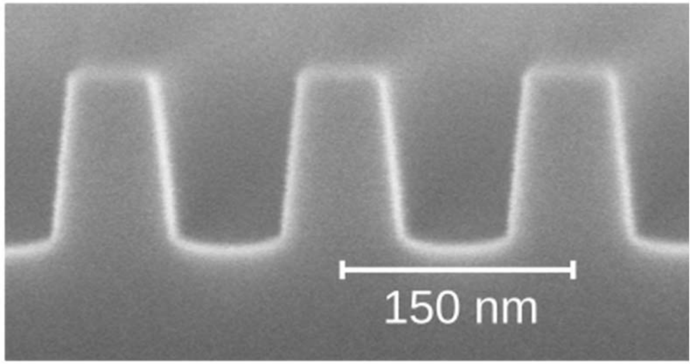
(Texas Instruments, 1997)

R. Colin Johnson, *EETimes, 7/2/2015*

R. Colin Johnson, *EETimes, 6/5/2017*

Reconstruction of Silicon nanostructures



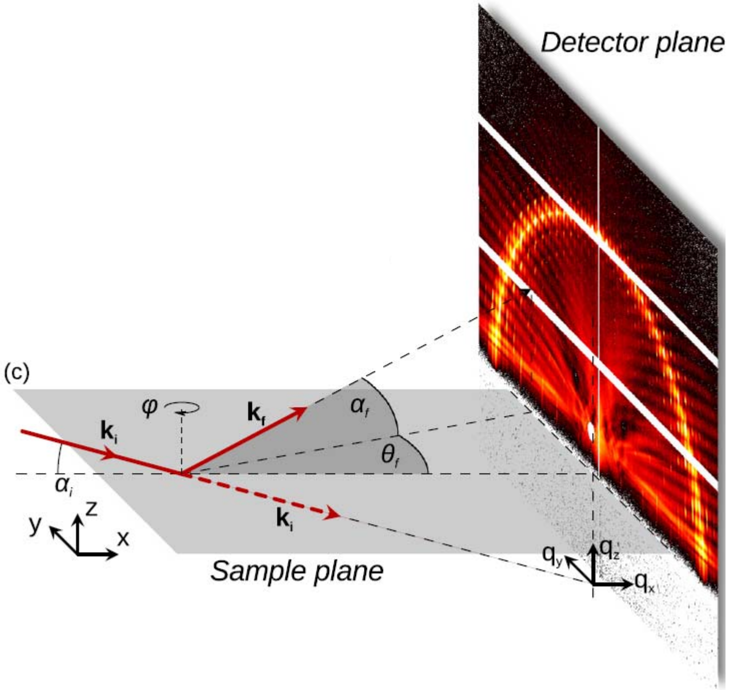


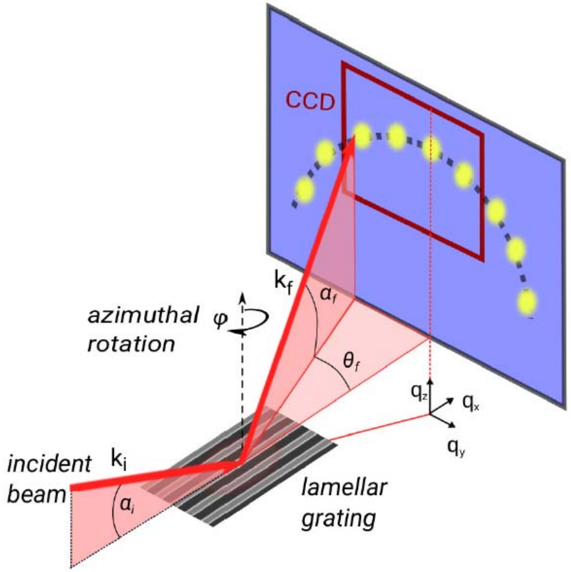
prototype samples:

lamellar gratings fabricated
with E-beam lithography

Pitch 50 -150 nm
Linewidth 25 – 65 nm
Height 25 -100 nm
(etched into Si, Si3N4)

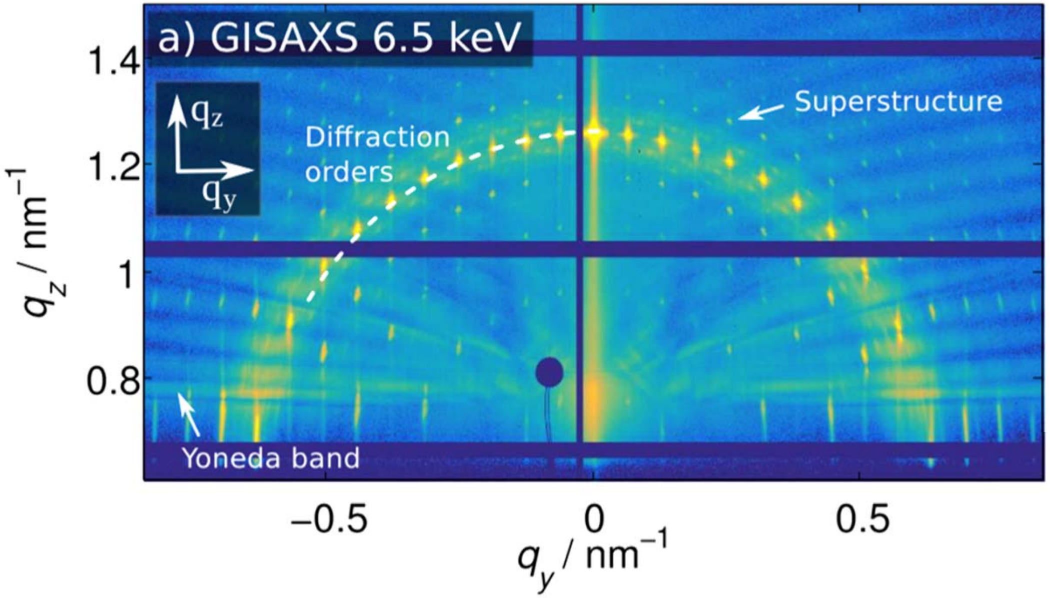
GISAXS and XUV-Scatterometry

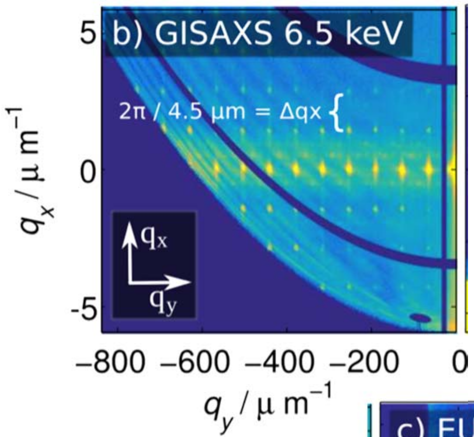




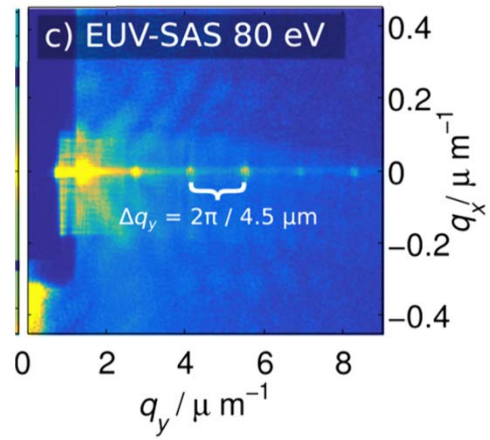
Idea: transfer the GISAXS approach to lower photon energy (XUV) & work at steeper angle to reduce the footprint

GISAXS scattering pattern





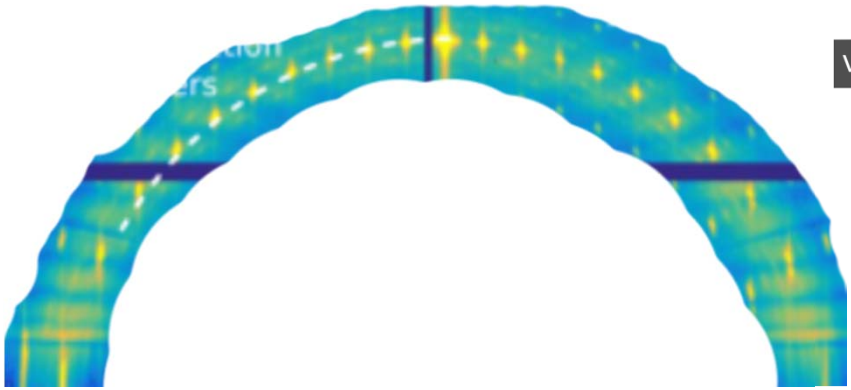
XUV-angle resolved scatter



GISAXS:
similar range for q_y and q_z
different range for q_x and q_y

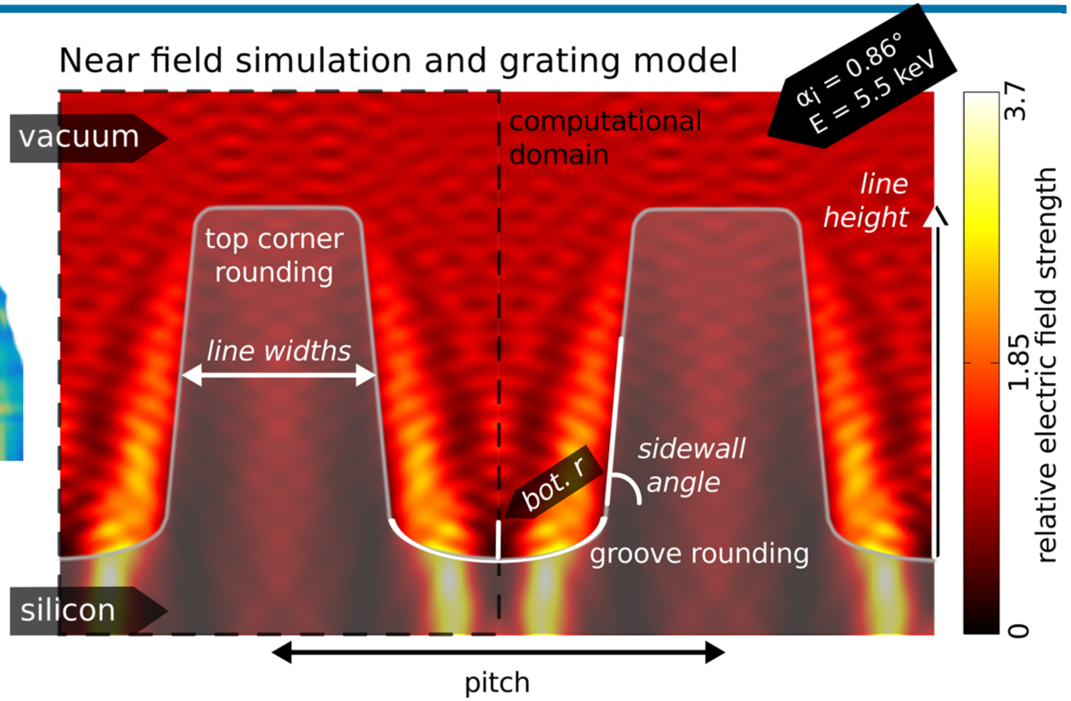
similar range for q_x and q_y

Reconstruction of 2D nanostructures



Using the diffraction intensities for line shape reconstruction

Solving the inverse problem by forward calculation (JCMwave)



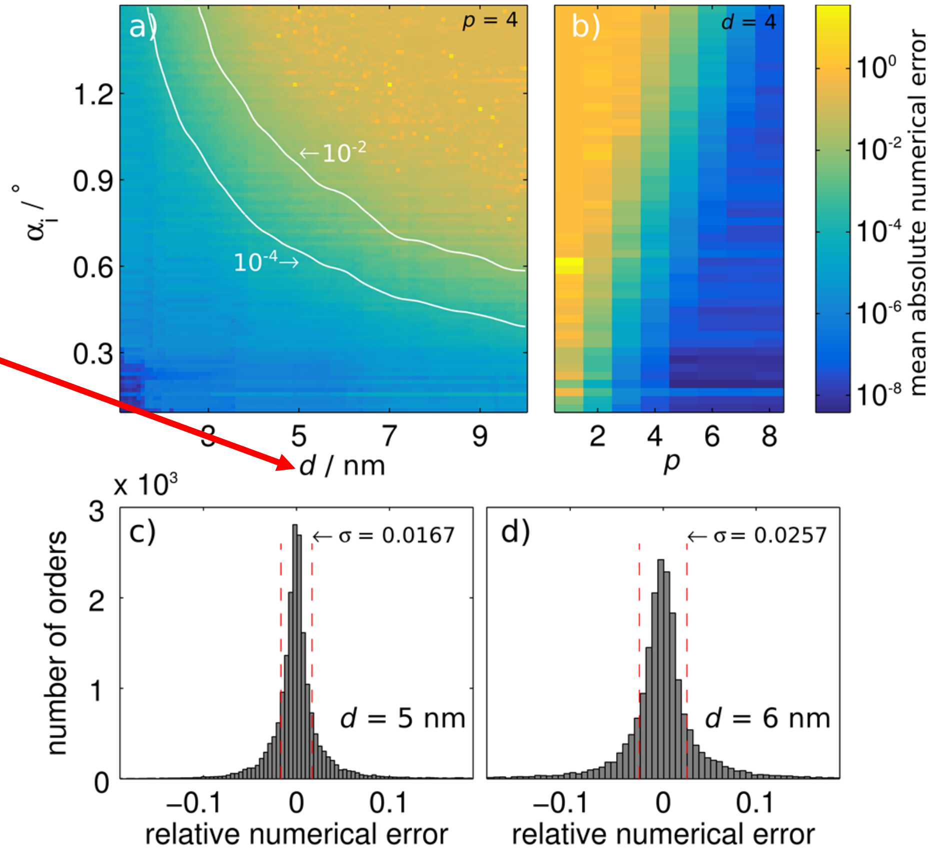
FEM approach for X-rays is challenging:
λ: ≈ 0.2 nm
Computational domain: ≈ $(200\ \text{nm})^2$

Numerical precision depends on incident angle

For GI, the finite-element size may be much larger then the incident wavelength!

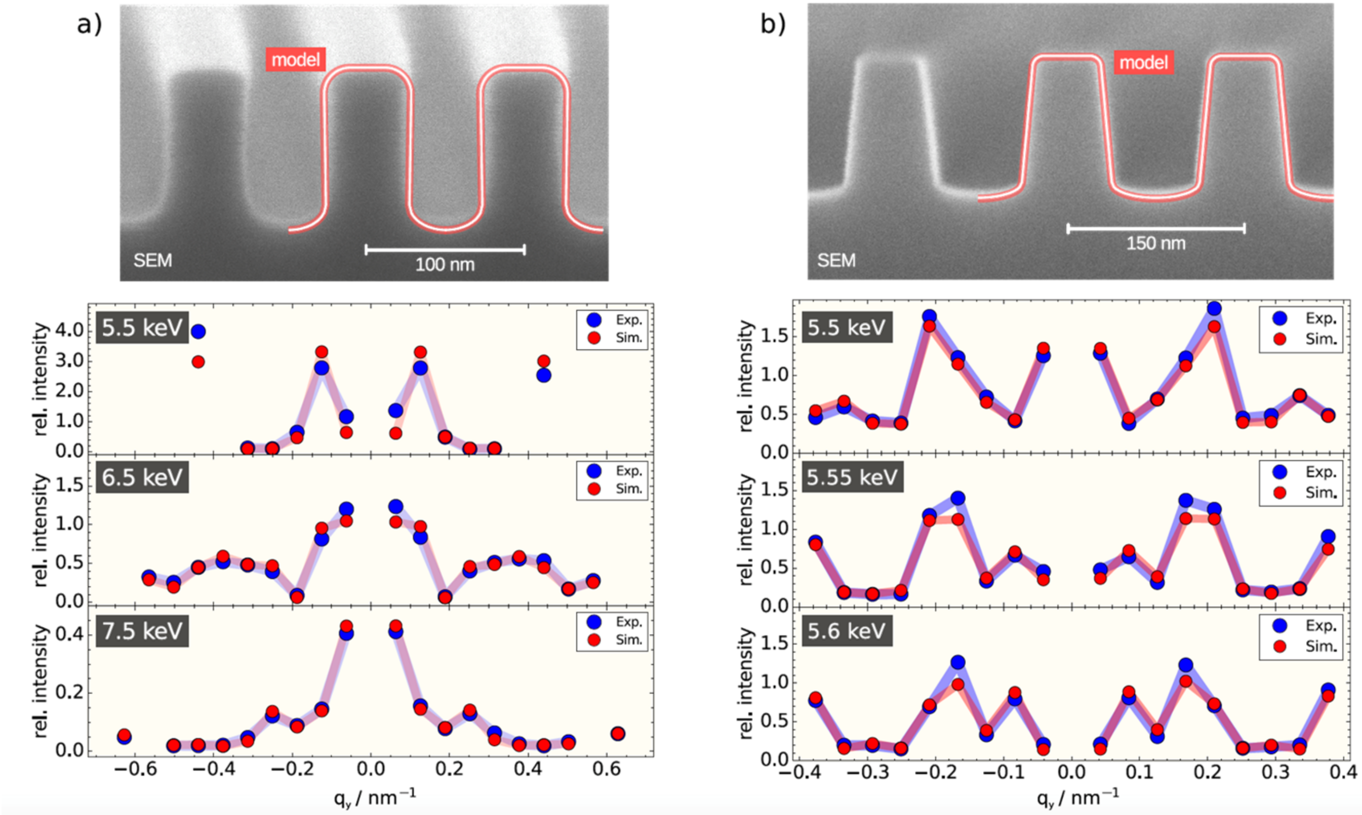
single forward calculation:
< 1 s / core @ 10^{-2} numerical precision

=> FEM approach is feasible



Reconstruction of 2D nanostructures

reconstruction examples for differently shaped laminar lines using GISAXS



Reconstruction of 2D nanostructures

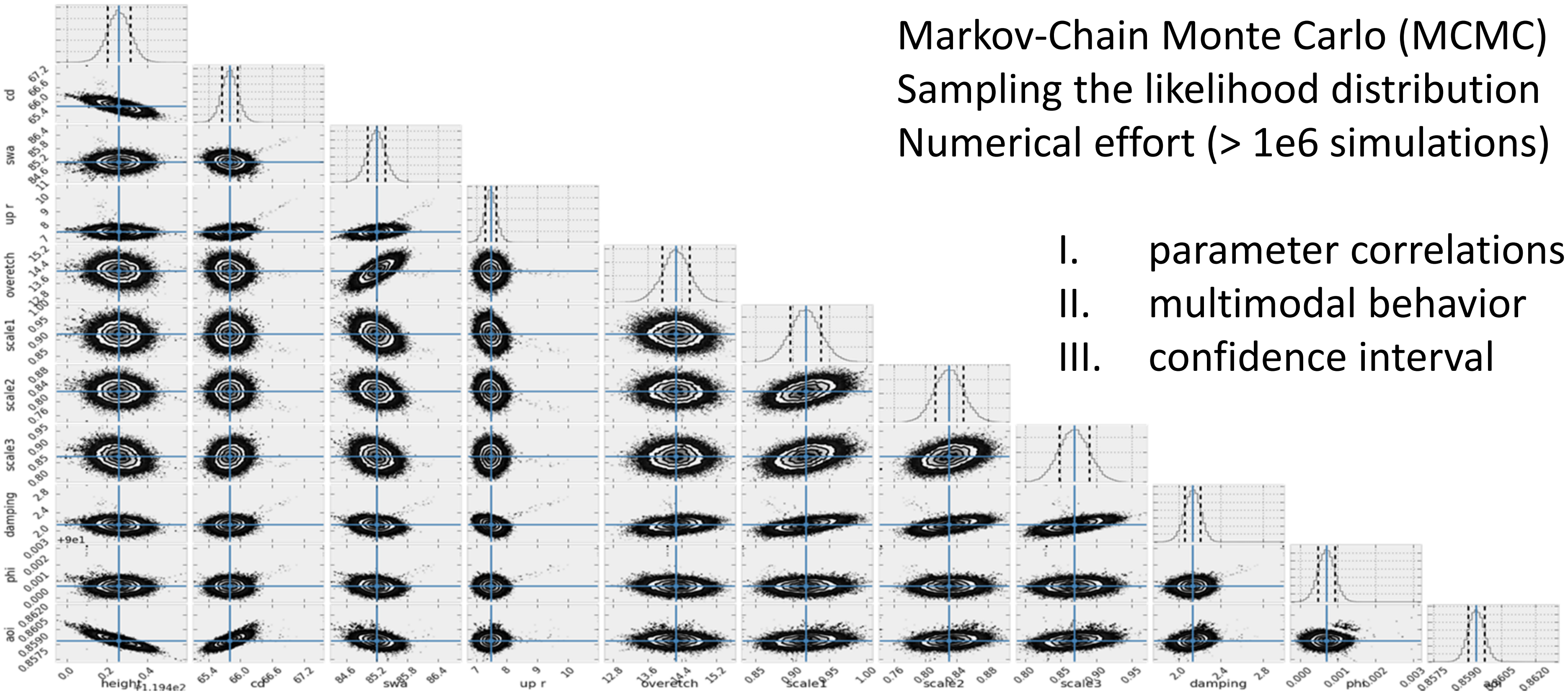
Objective function, uncertainty budget

$$\tilde{\chi}^2(E) = \sum_m \frac{\left(I_m^{\text{model}}(E) - I_m^{\text{meas}}(E)\right)^2}{\sigma^2(E)}.$$

include variation of uncertainties (maximize likelihood):

$$\log\left(\frac{1}{\sqrt{2\Pi\sigma^2}}\right) - \frac{(I_m - I_s)^2}{2\sigma^2}$$ with (e.g.) $\sigma^2 = (ax)^2 + b^2$

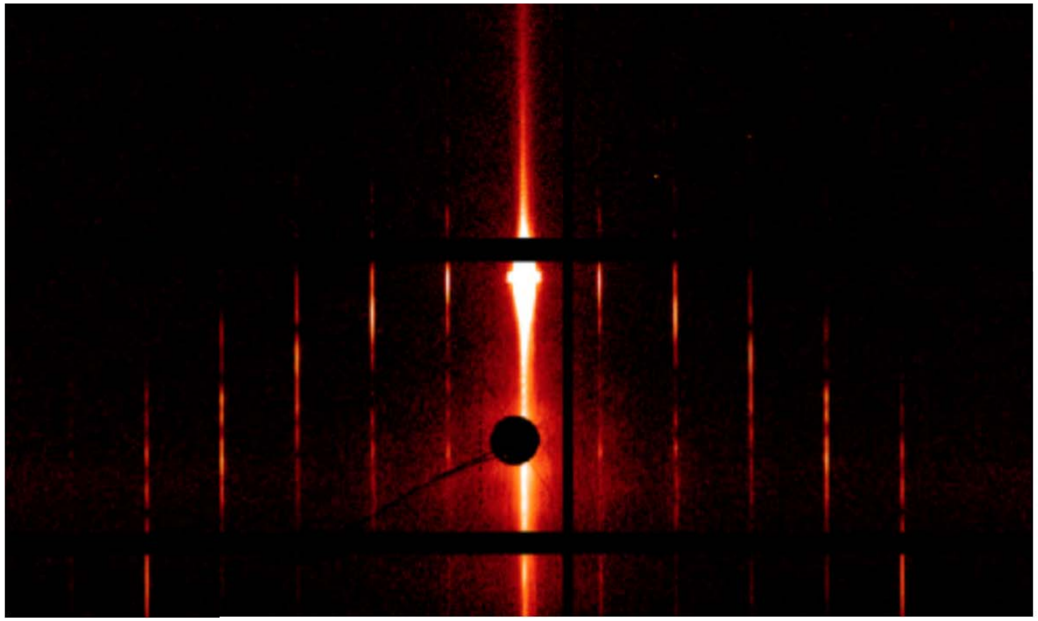
Reconstruction of 2D nanostructures



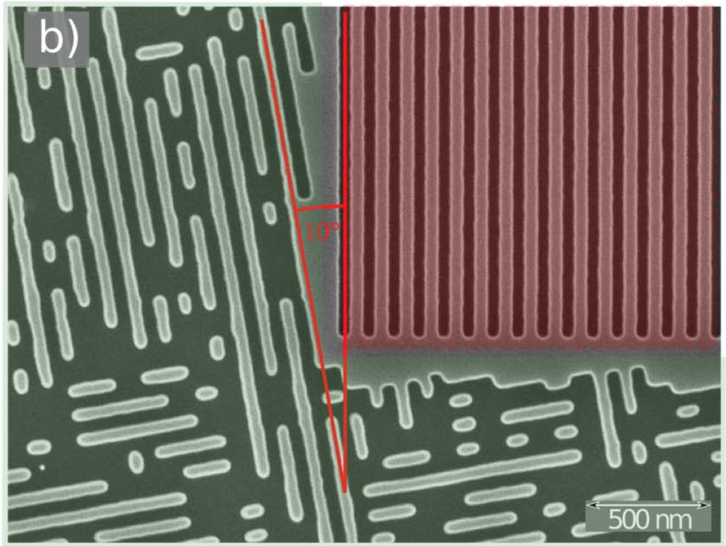
Markov-Chain Monte Carlo (MCMC)
Sampling the likelihood distribution
Numerical effort (> 1e6 simulations)

I. parameter correlations
II. multimodal behavior
III. confidence interval

GISAXS for small areas



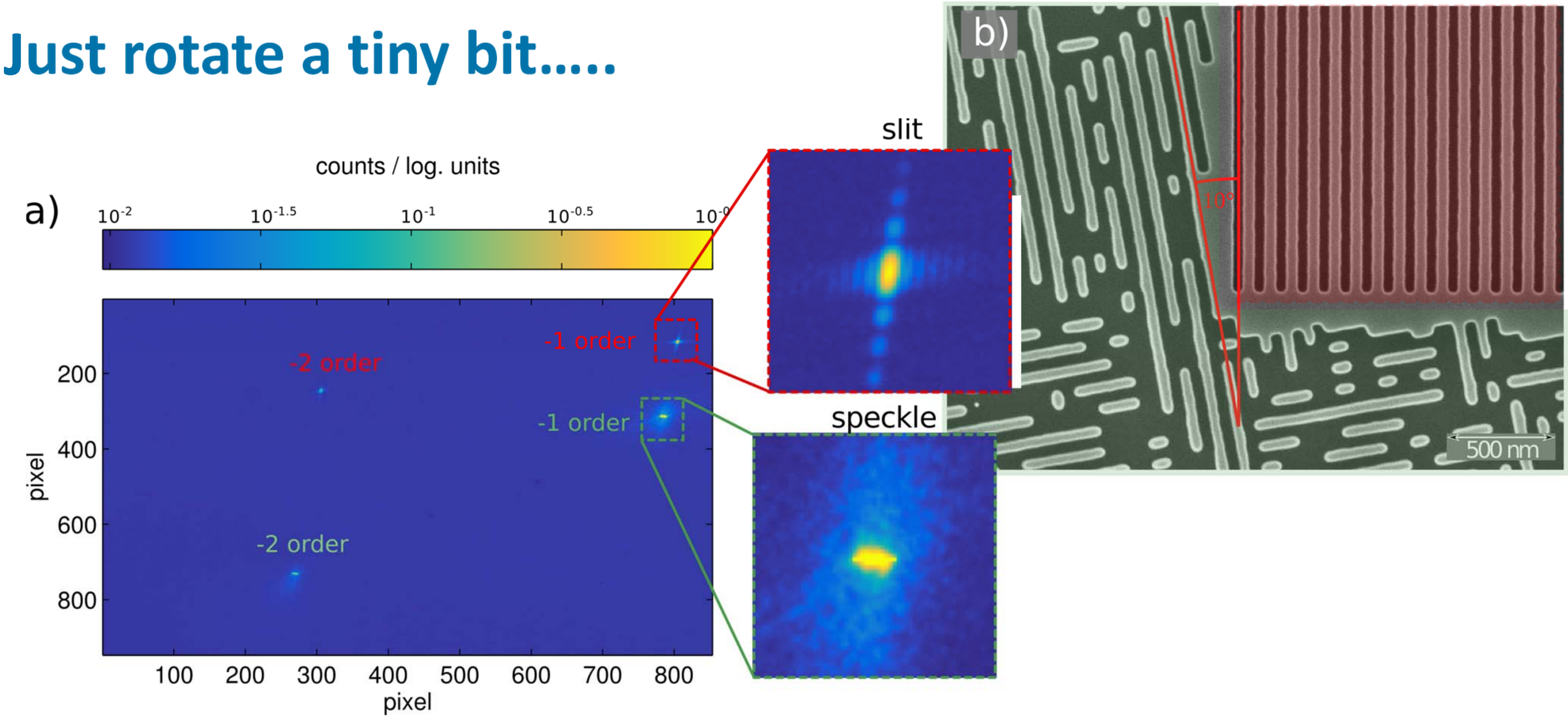
GISAXS: 4µm x 4 µm target
40 lines @ 100 nm pitch



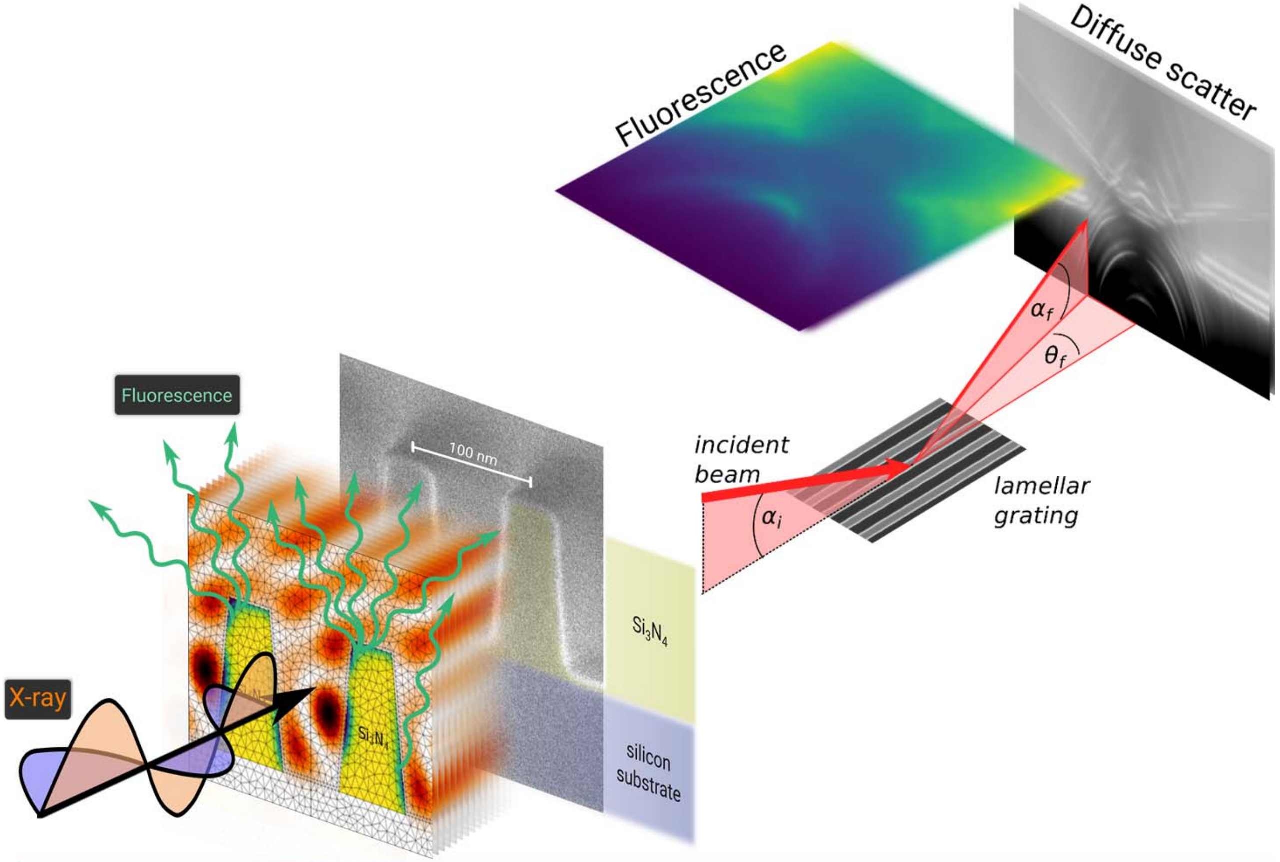
What about dense structures ?

GISAXS for small areas

Just rotate a tiny bit.....



Combined GISAXS & GIXRF

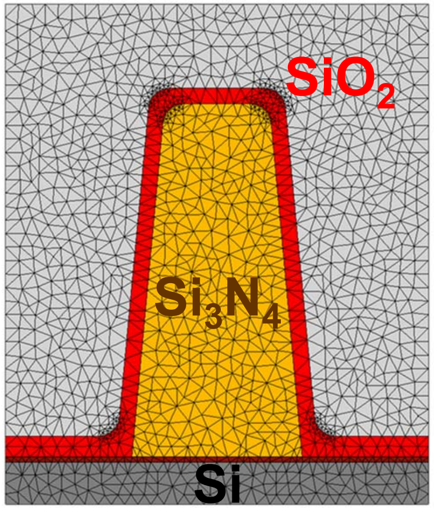


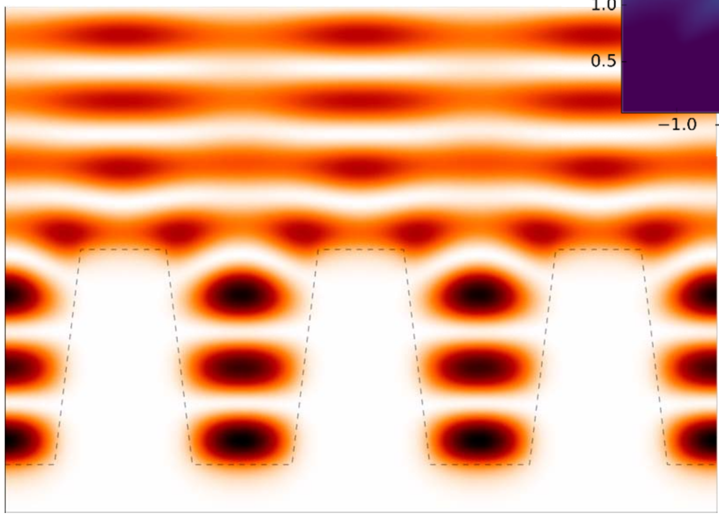
Idea:
combine GISAXS and GIXRF in XUV spectral range

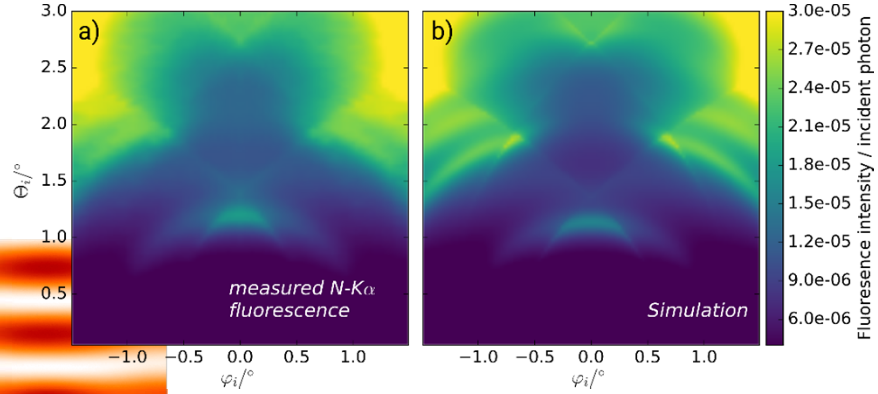
- footprint reduction
- light elements accessible
- elemental sensitive spatial distribution

Combined GISAXS & GIXRF

FEM model (JCMwave) => **standing wave field**



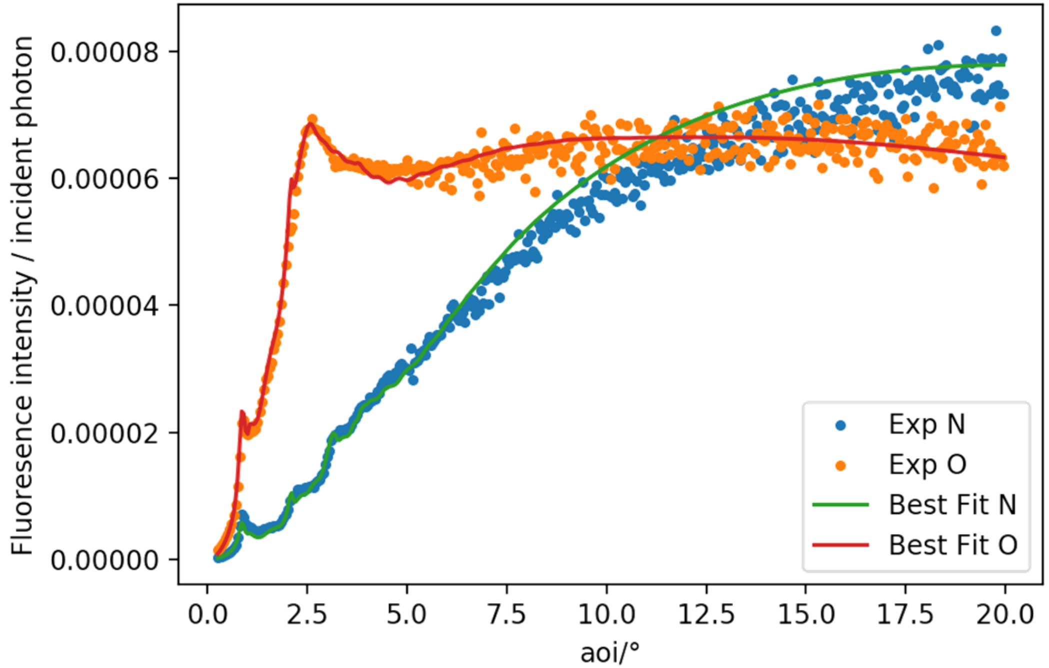




Combined GISAXS & GIXRF

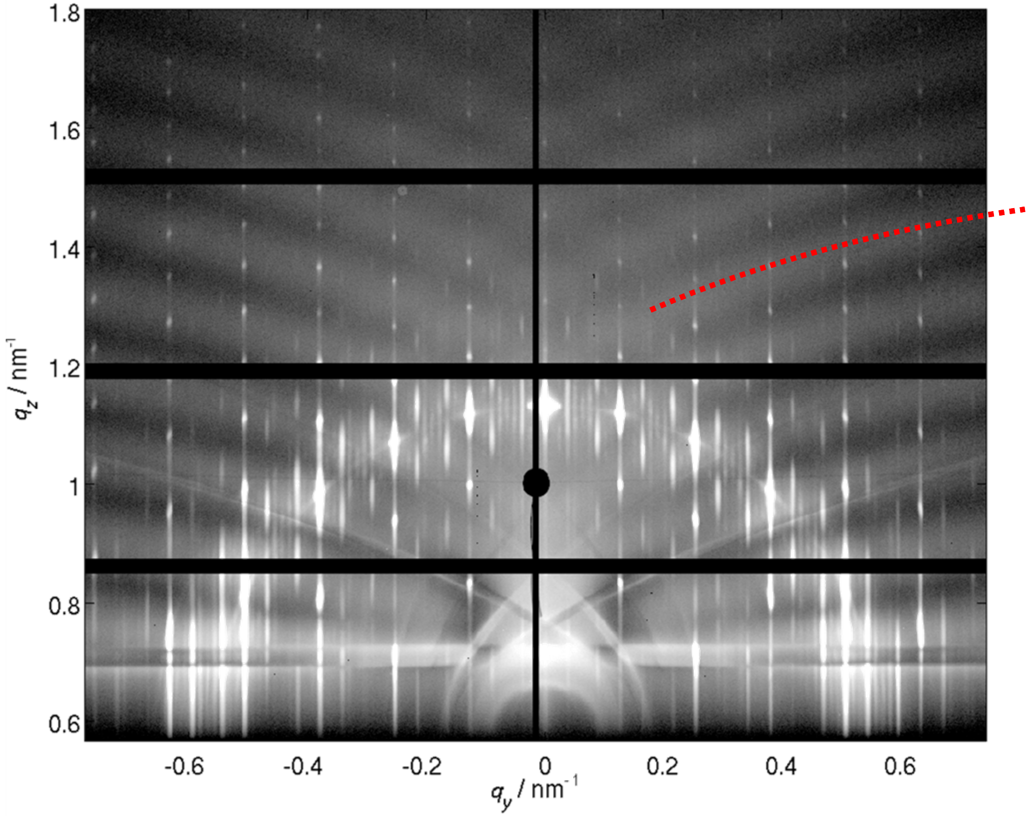
Element composition sensitivity

680 eV excitation
O-K and
N-K Fluorescence



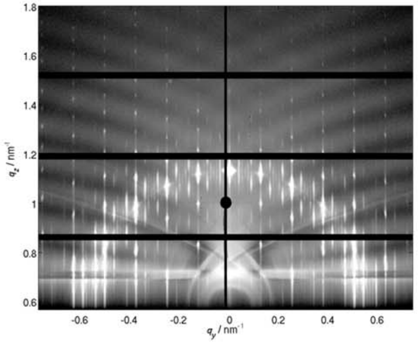
Intensity variation with AoI => position sensitivity via standing wave field

There is more.....



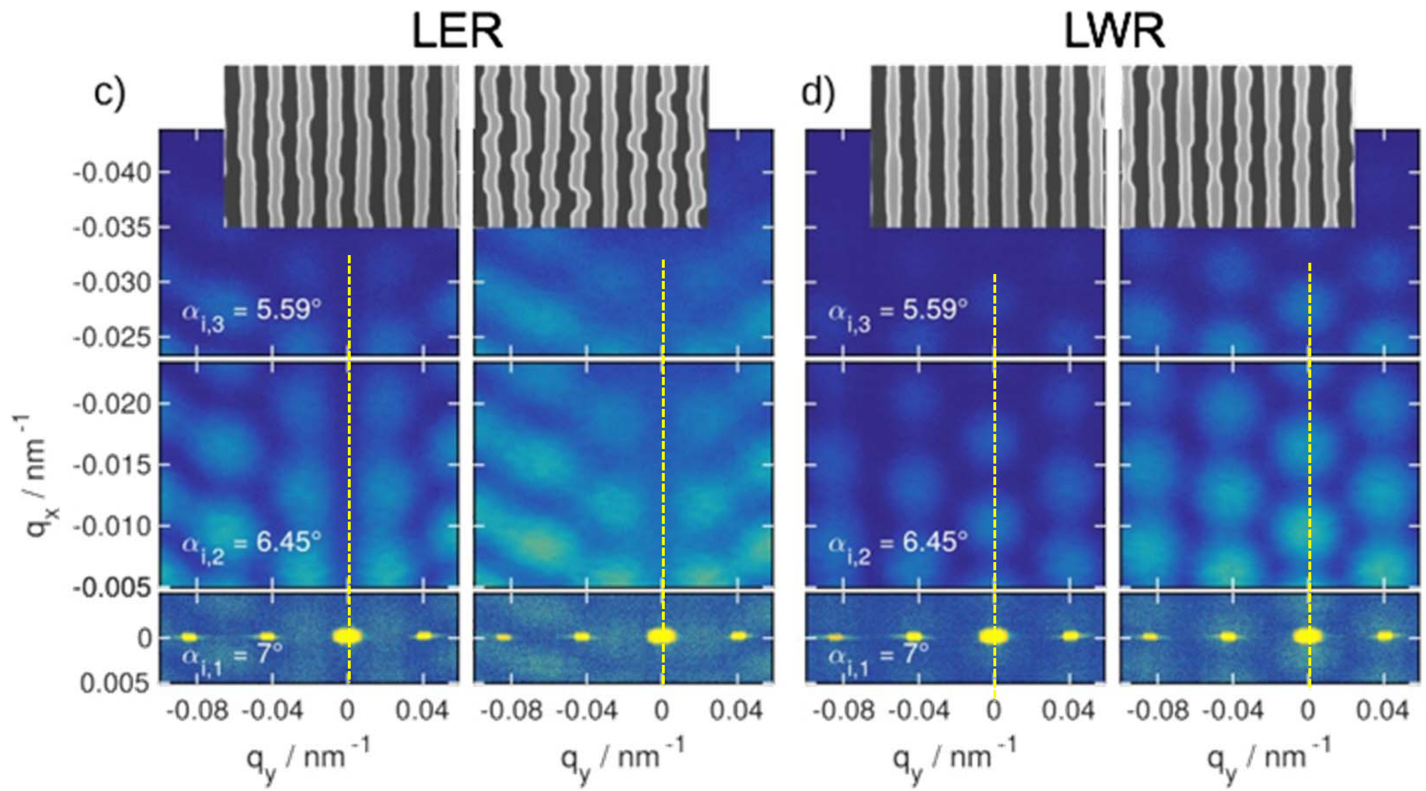
Resonant diffuse scatter

Resonant diffuse scatter



samples with
designed roughness:

Line edge vs.
line width roughness



Diffuse scatter provides information on structure => mathematics need to be developed

Thank you for your attention

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