



EUROPEAN
SPALLATION
SOURCE

Advanced technology of neutron imaging

M. Strobl

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Prof. X-ray and Neutron Imaging Techniques (NBI, KU)

www.europeanspallationsource.se

Lund Imaging School, Oct. 2018,



Conventional (white beam) Imaging

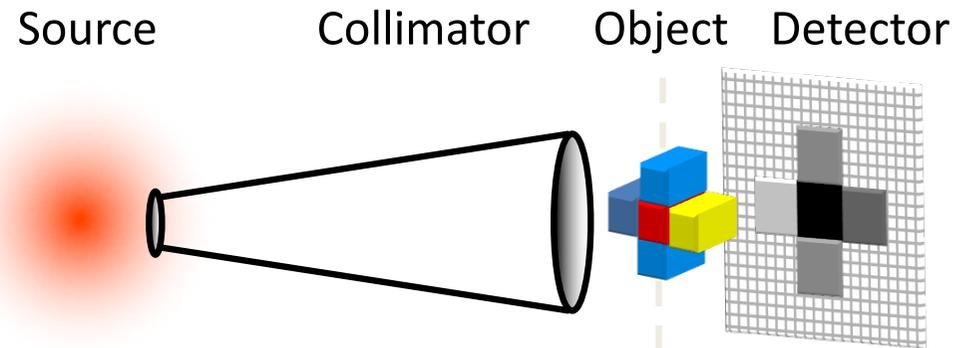
- White beam
 - Attenuation contrast

Advanced (wavelength resolved) Imaging

- Wavelength resolved imaging
 - Attenuation contrast
 - Dark-field contrast
 - Polarized neutron imaging
- White beam polarized neutron imaging
- White beam diffraction imaging

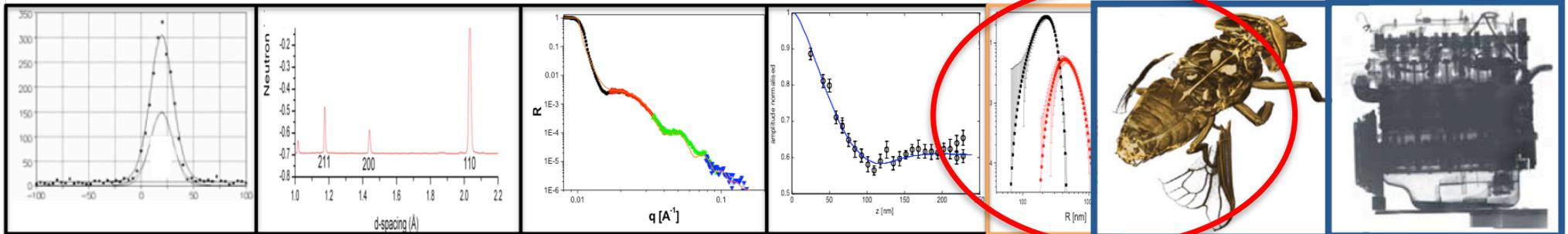
Conventional Neutron Imaging

- Requirements:
- high flux
 - large well defined FOV
 - spatial homogeneity
 - spectral homogeneity
 - large detector
 - fast detector
 - high resolution detector
 - save shielding



Diffraction regime

SANS regime



atomic and magnetic structures

organic molecules

surfaces and multilayers inhomogeneities

viruses

cracks and voids

Systems and components

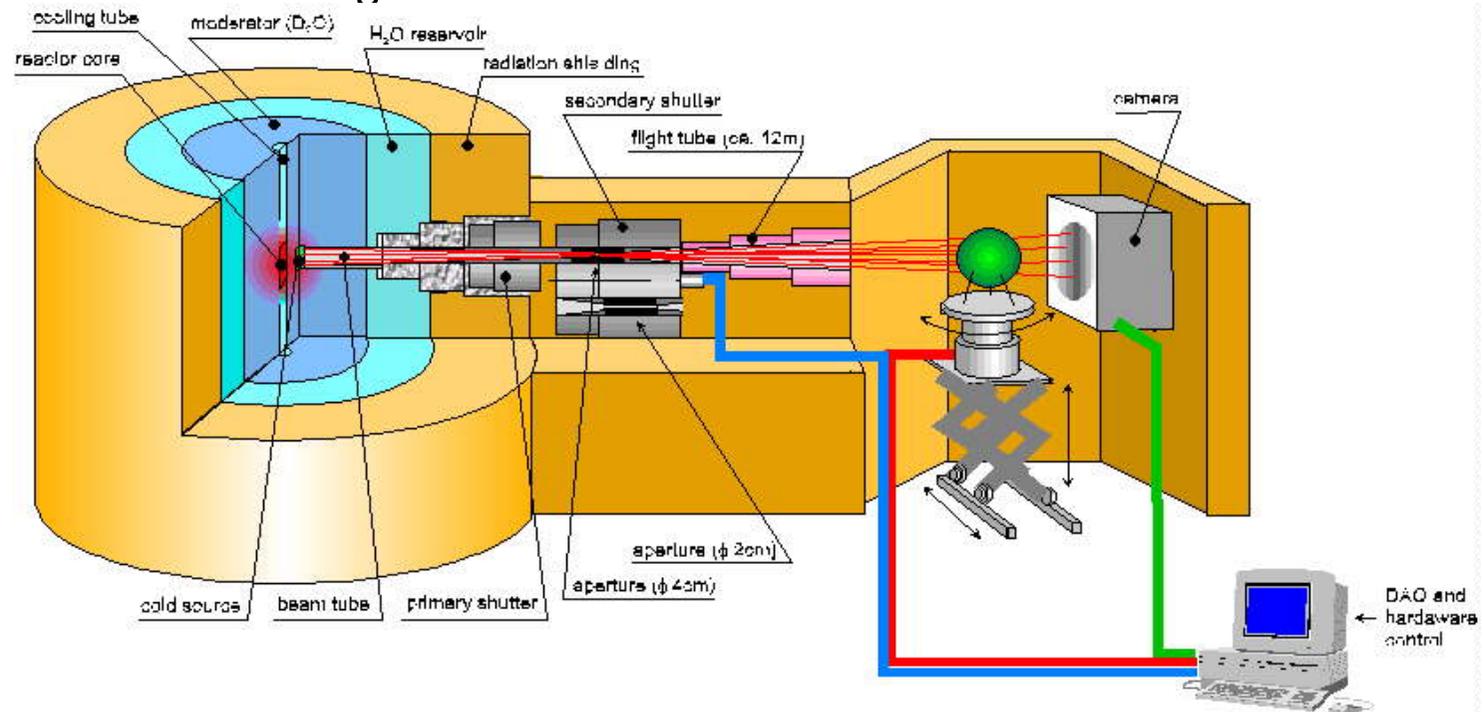
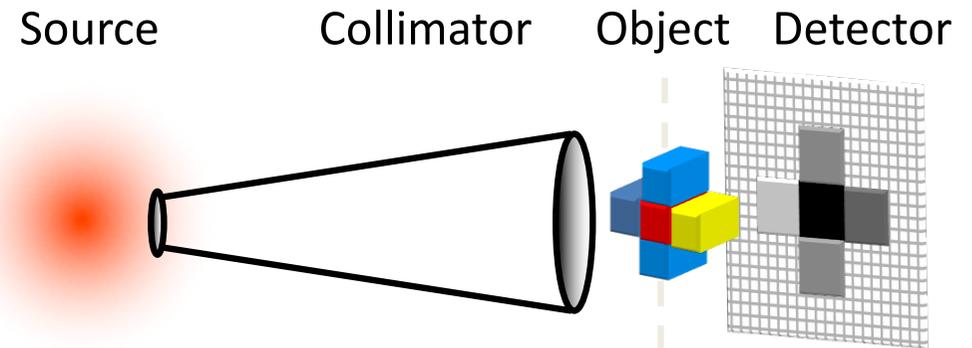
*magnetic defects
pharmaceuticals
supermolecules*

*micelles
proteins
polymers*

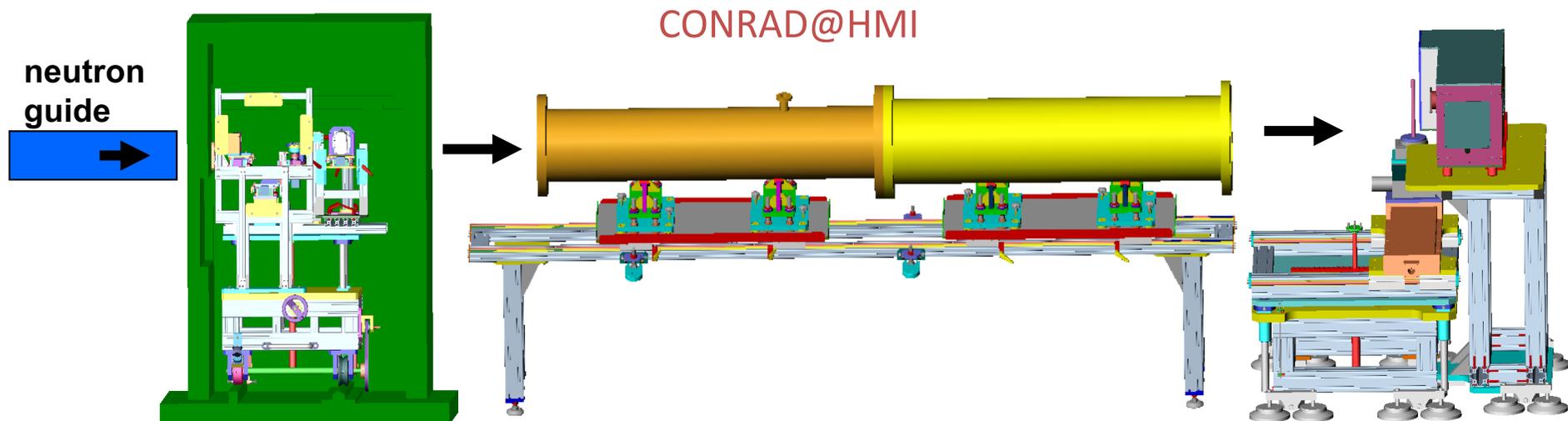
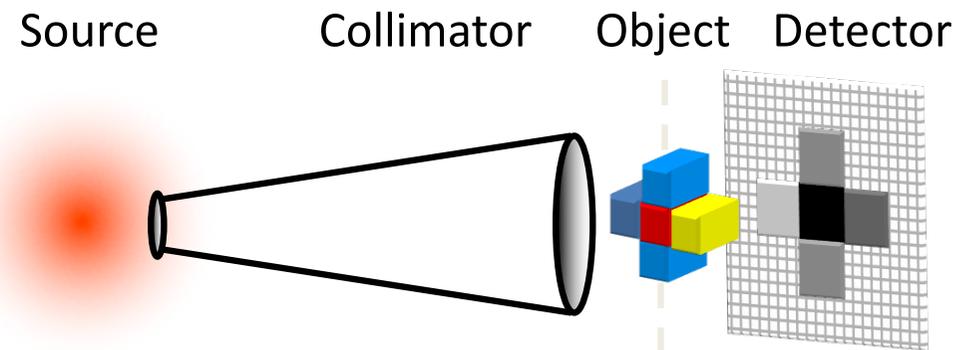
internal strain

Conventional Neutron Imaging

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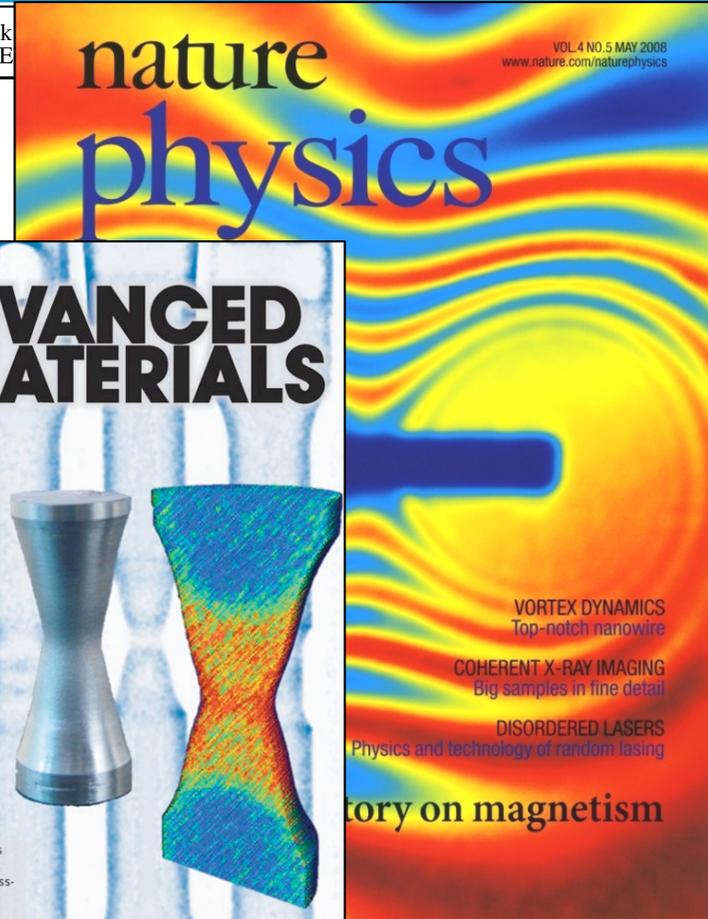


- Requirements:
- high flux
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 - spatial homogeneity
 - spectral homogeneity
 - large detector
 - fast detector
 - high resolution detector
 - save shielding



Neutron Dark-Field Tomography

M. Strobl,^{1,2} C. Grünzweig,³ A. Hilger,² I. Manke,² N. Kardjilov,² C. David,³ and F. Pfeiffer^{3,4}



ARTICLE

Received 23 Jun 2010 | Accepted 27 Oct 2010 | Published 23 Nov 2010

DOI: 10.1038/ncomms1125

Three-dimensional imaging of magnetic domains

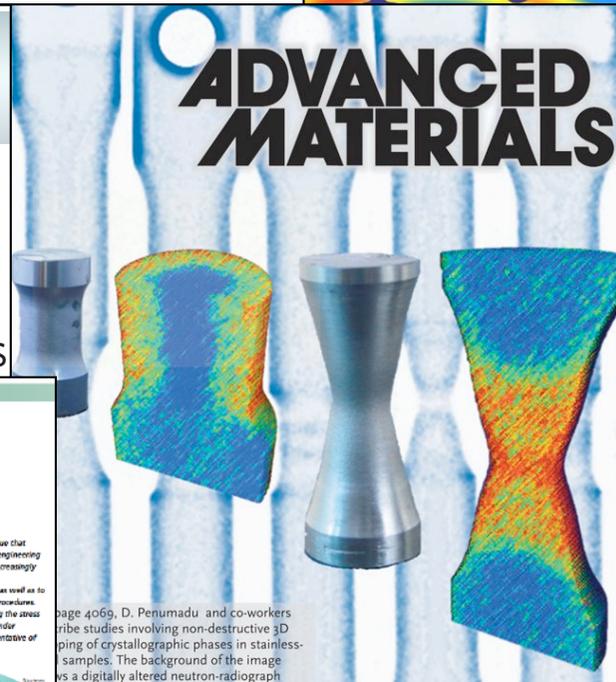
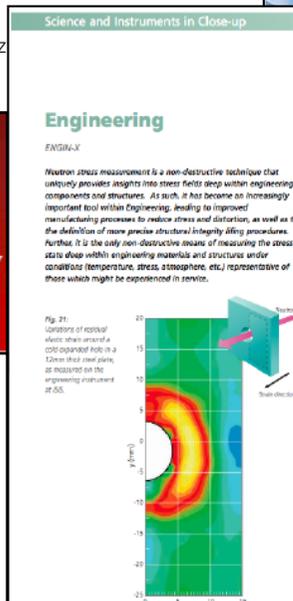
I. Manke¹, N. Kardjilov¹, R. Schäfer², A. Hilger¹, M. Strobl¹, M. Dawson^{1,3}, C. Grünzweig³, C. David⁴, A. Kupsch⁵, A. Lange⁵ & J. Banhart^{1,6}



Nature 408, 158-159 (9 November 2000) | doi:10.1038/35041626

Imaging: Phase radiography with neutrons

B. E. Allman¹, P. J. McMahon¹, K. A. Nugent¹, D. Paganin¹, D. L. Jacobson², M. Arif² & S. A. Werner³



page 4069, D. Penumadu and co-workers describe studies involving non-destructive 3D mapping of crystallographic phases in stainless-steel samples. The background of the image is a digitally altered neutron-radiograph

Neutron Phase Imaging and Tomography

F. Pfeiffer, C. Grünzweig, O. Bunk, G. Frei, E. Lehmann, and Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland (Received 6 April 2006; published 2 June 2006)

Neutron Imaging



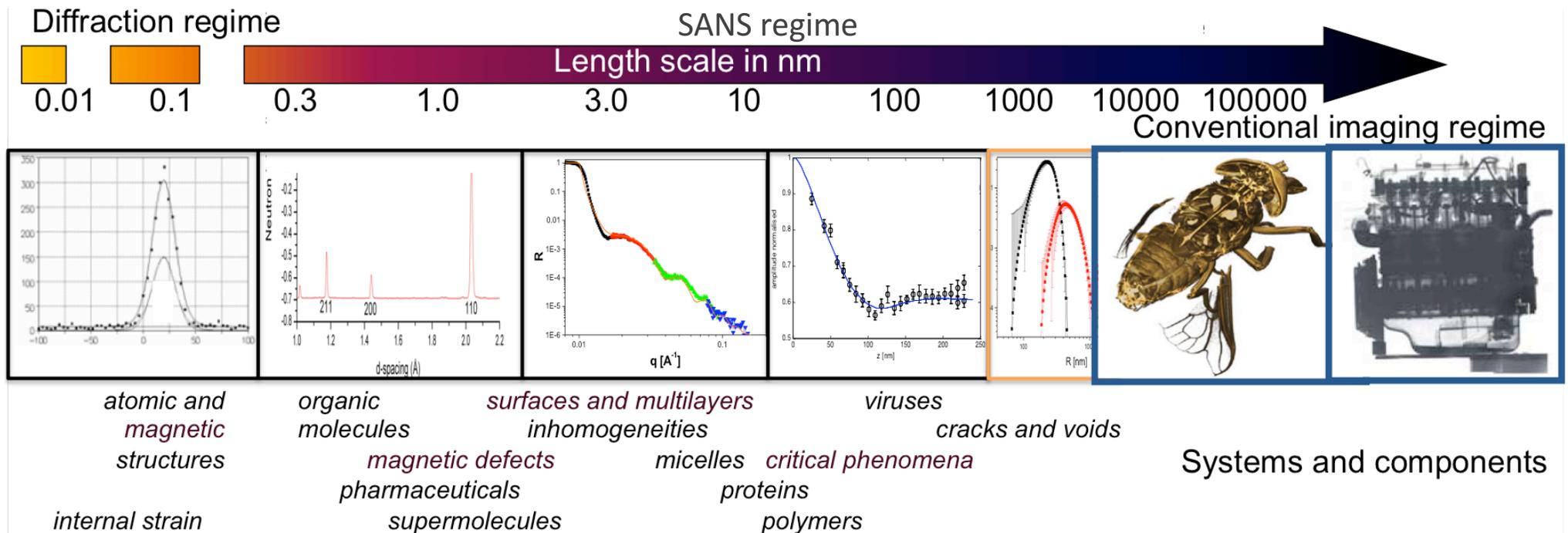
Conventional (white beam) Imaging

- White beam
 - Attenuation contrast

Advanced (wavelength resolved) Imaging

- Wavelength resolved imaging
 - Attenuation contrast
 - Dark-field contrast
 - Polarized neutron imaging
- White beam polarized neutron imaging
- White beam diffraction imaging

Advanced Neutron Imaging



- **Wavelength resolved imaging**
- **Wavelength resolved imaging**
 - Monochromatic
 - Energy selective
 - Attenuation contrast
 - Energy dispersive
 - Dark-field contrast
 - Polarized neutron imaging

Wavelength Resolved Imaging

Total neutron cross section

Most significant

Defines the Bragg edge position

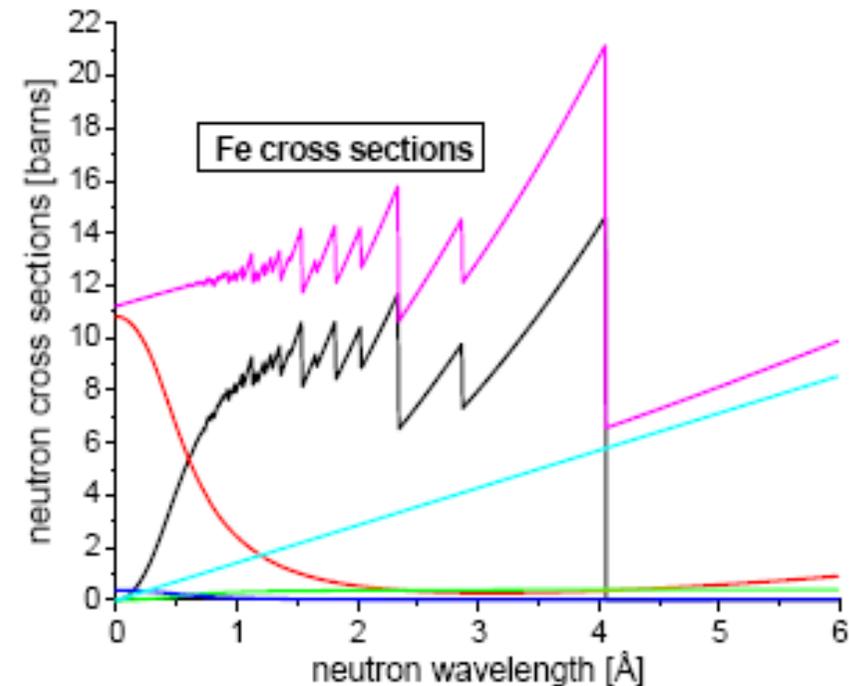
$$\sigma_{coh}^{el}(\lambda) = \frac{\lambda^2}{2V_0} \sum_{d_{hkl}=0}^{2d_{hkl} < \lambda} |F_{hkl}|^2 d_{hkl}$$

$$\sigma_{inc}^{el}(\lambda) = \bar{\sigma}_{inc} \sum_n \frac{\lambda^2}{2B_{iso,n}} (1 - e^{-\frac{2B_{iso,n}}{\lambda^2}})$$

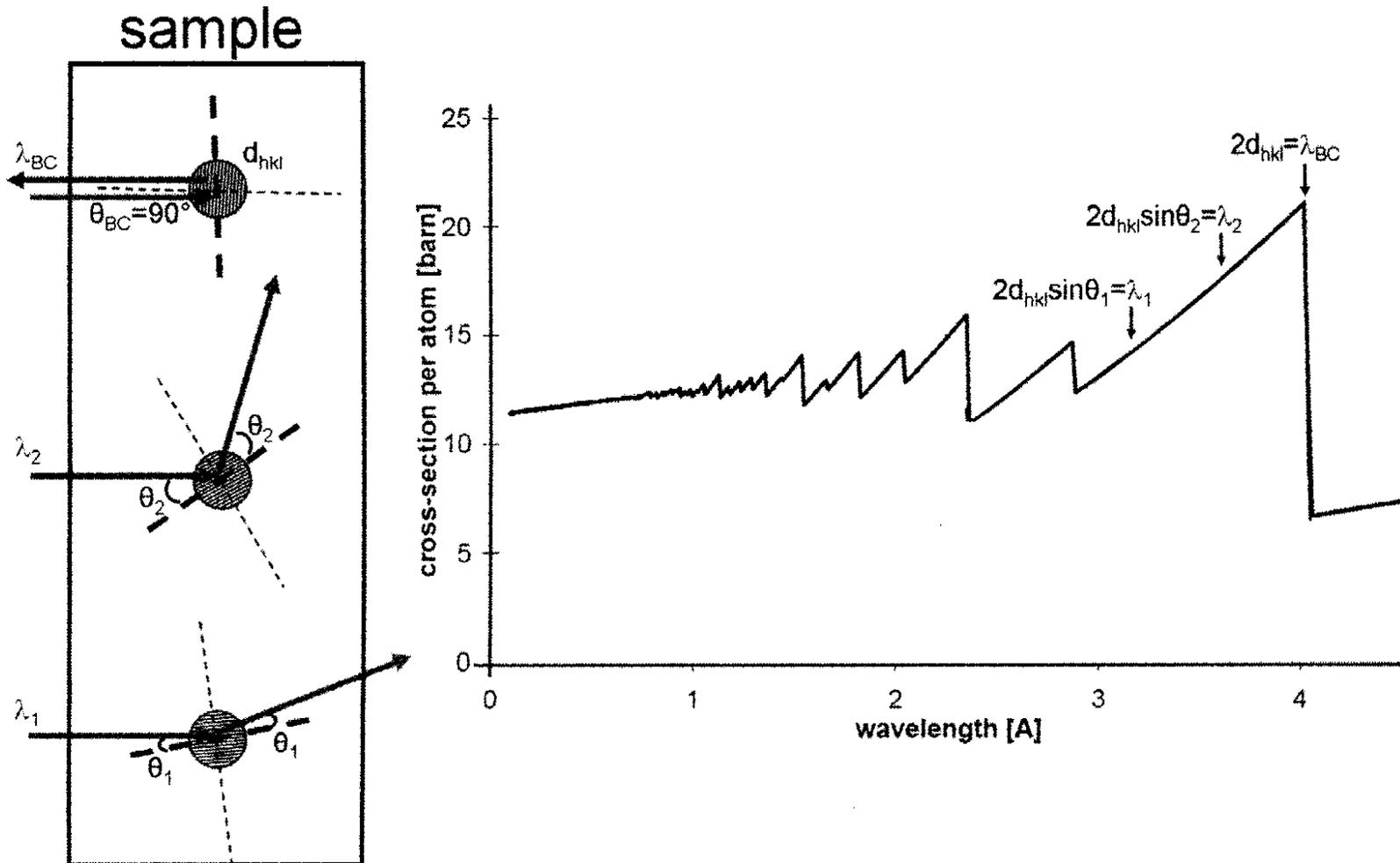
$$\sigma_{total}^{inel}(\lambda) = (\bar{\sigma}_{coh} + \bar{\sigma}_{inc}) \left(\frac{M/m}{M/m+1}\right)^2 \sum_n \left(1 + \frac{9\varphi_3(\theta)\varphi_3(\theta)\lambda^2}{2M^2/m^2 B_{iso}}\right) - \dots$$

$$\sigma_{abs}(\lambda) = B \cdot \frac{m\lambda}{h} = \frac{\sigma_{abs}^{2200m/s}}{1.798\text{\AA}} \cdot \lambda$$

$\sigma_{total}(\lambda)$

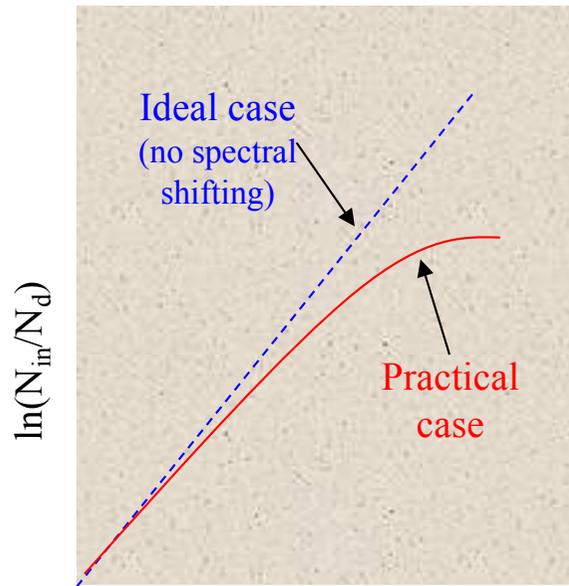


Energy resolved imaging

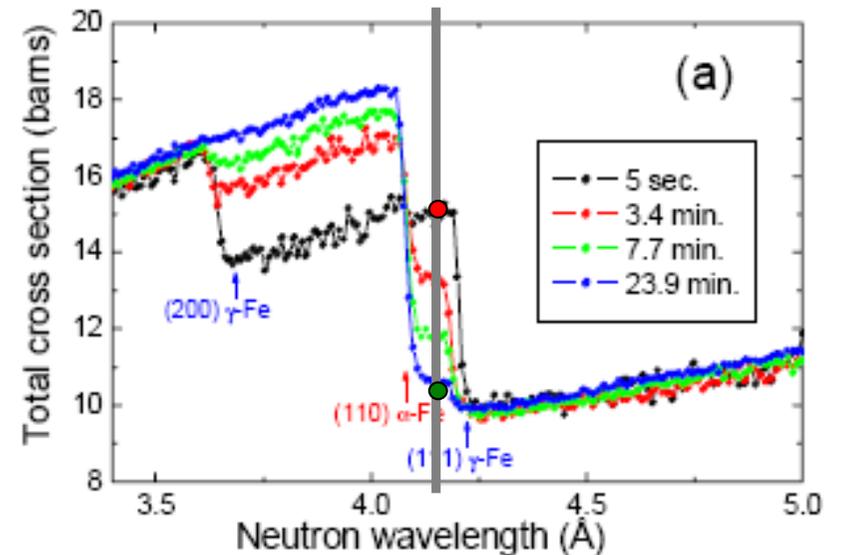
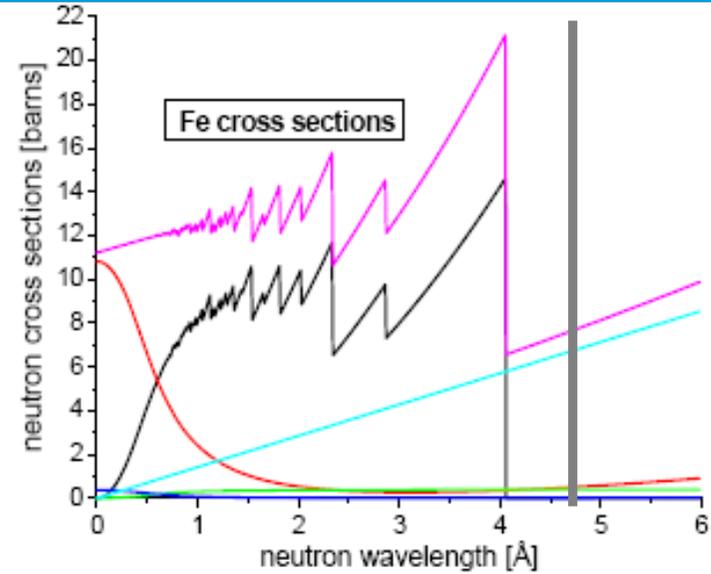
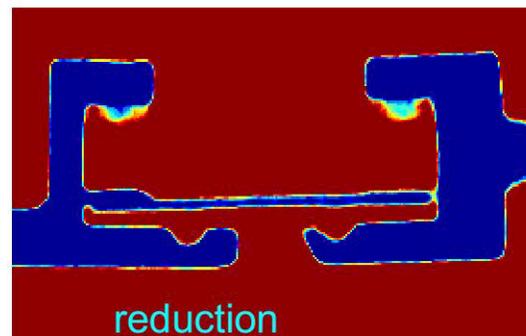
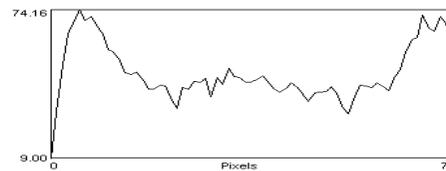
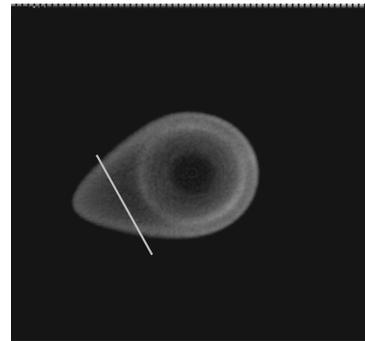


Monochromatic Imaging

- Wavelength resolved imaging
- Monochromatic



Thickness of a homogeneous absorber



Monochromatic Imaging

- Wavelength resolved imaging
- Monochromatic

And enabled:

- Grating Interferometry
- Spin-Echo modulation
- Polarized Neutron Imaging
- Phase Imaging
- Topography



$$\Delta\varphi = -Nb_c\lambda\Delta t$$



$$n = \sqrt{1 - \lambda^2 \frac{Nb}{2\pi} \pm \lambda^2 \mu B \frac{2m}{(2\pi\hbar)^2}}$$

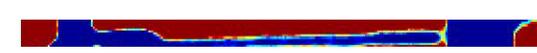


$$\varphi = \int_{path} \frac{\lambda m_n \gamma_n B}{h} ds$$

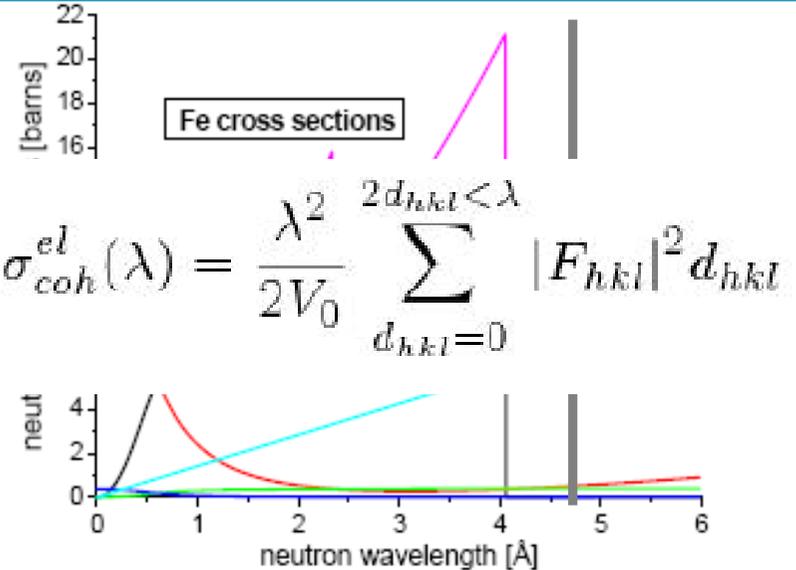
0 Pixels 71



$$\mathbf{q} = 2k \sin\theta = \frac{4\pi}{\lambda} \sin\theta$$



$$\frac{d\Sigma}{d\Omega}(\mathbf{q}) = \frac{N}{V} \frac{d\sigma}{d\Omega}(\mathbf{q}) = \frac{1}{V} \left| \int_V \rho(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} d\mathbf{r} \right|^2$$



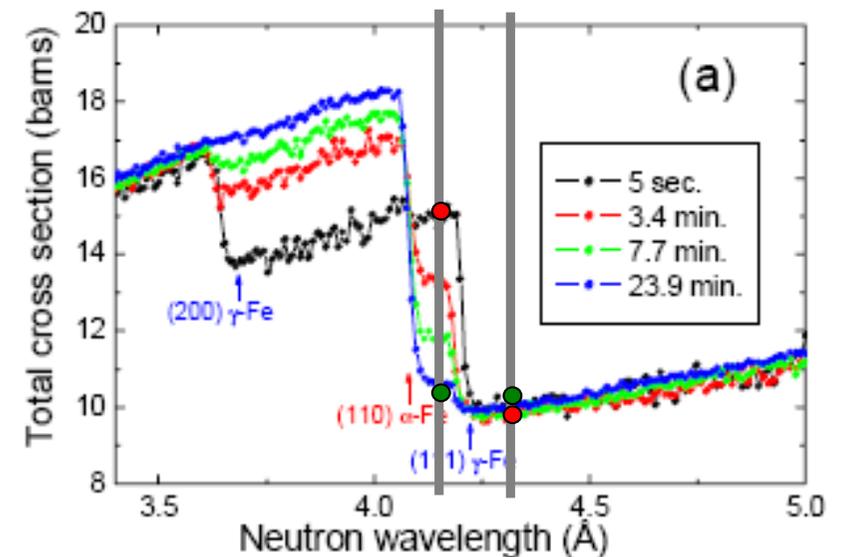
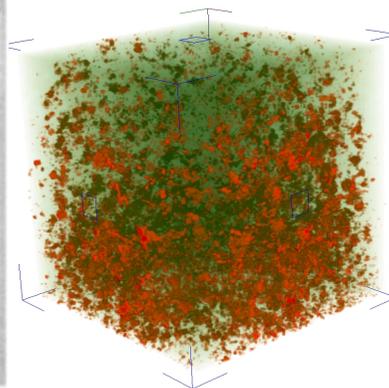
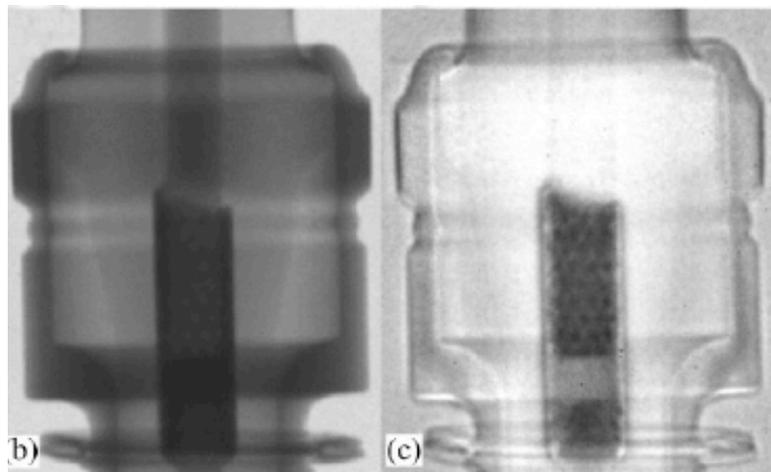
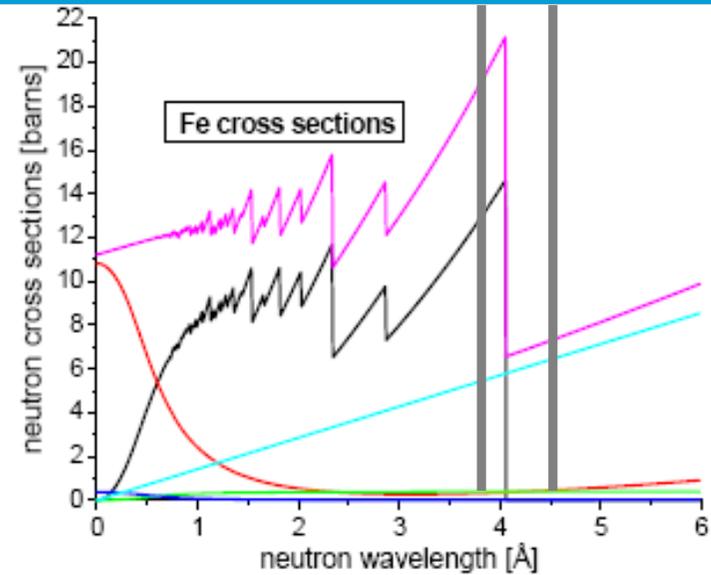
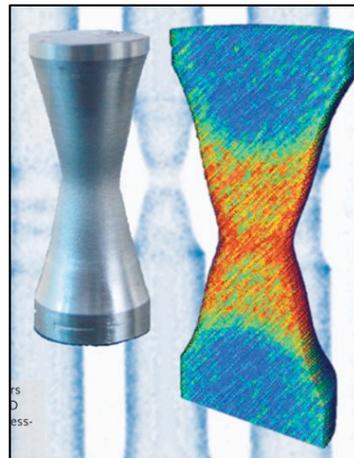
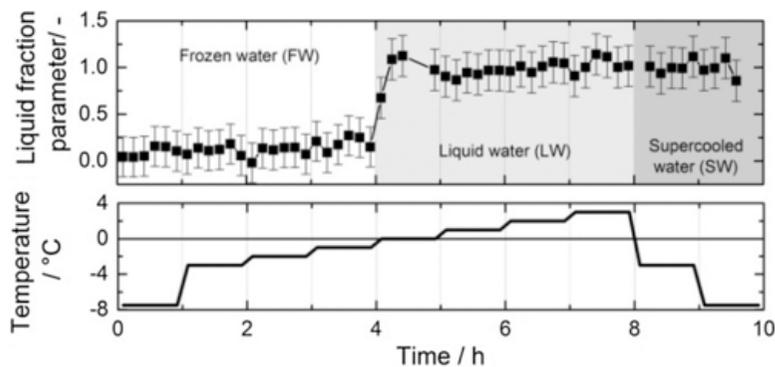
Because:

- Phase shift λ dependent
- Refractive index λ dependent
- Precession angle λ dependent
- Scattering vector λ dependent
- SANS λ dependent
- Bragg scattering λ dependent

Energy Selective

- Wavelength resolved imaging

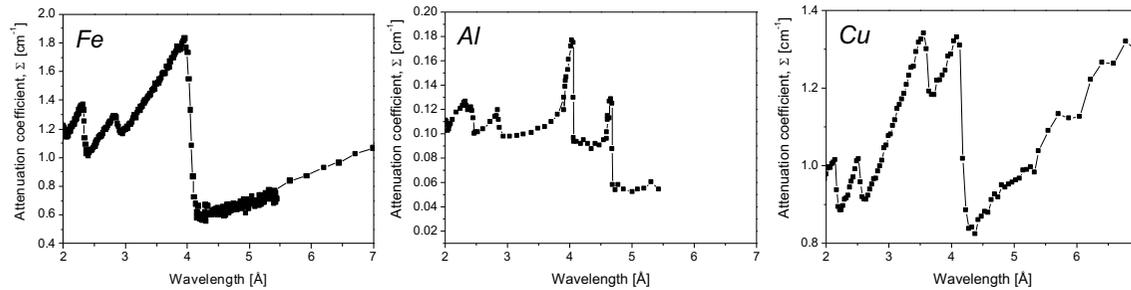
- Monochromatic
- Energy selective



Energy Dispersive

- Wavelength resolved imaging

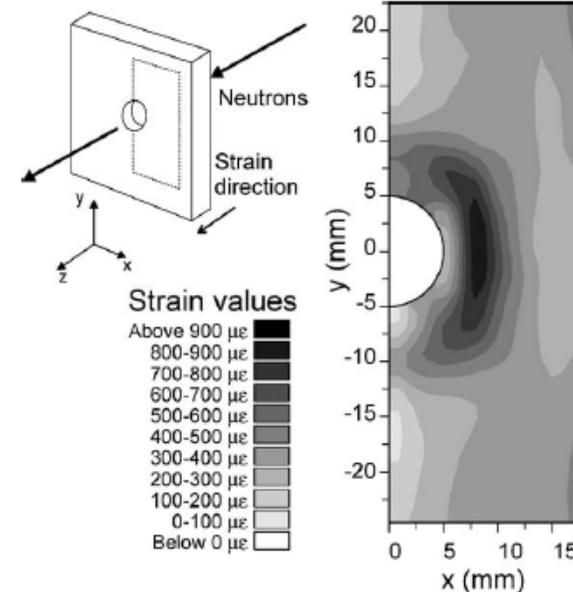
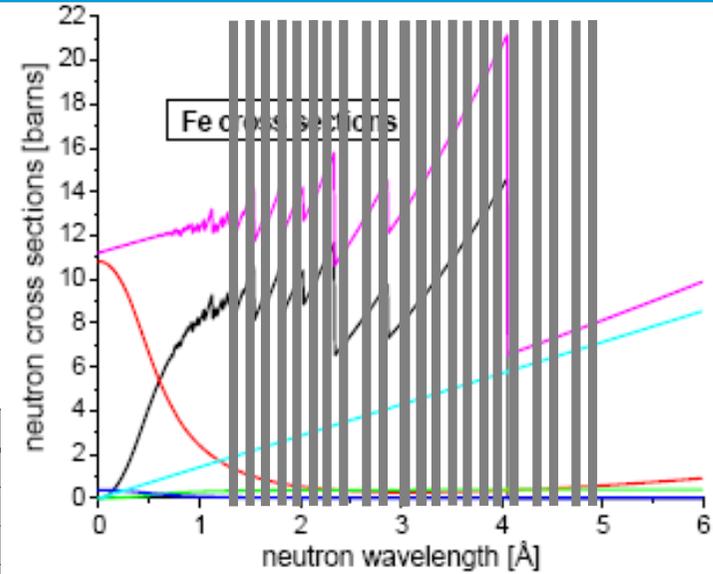
- Monochromatic
- Energy selective
- Energy dispersive



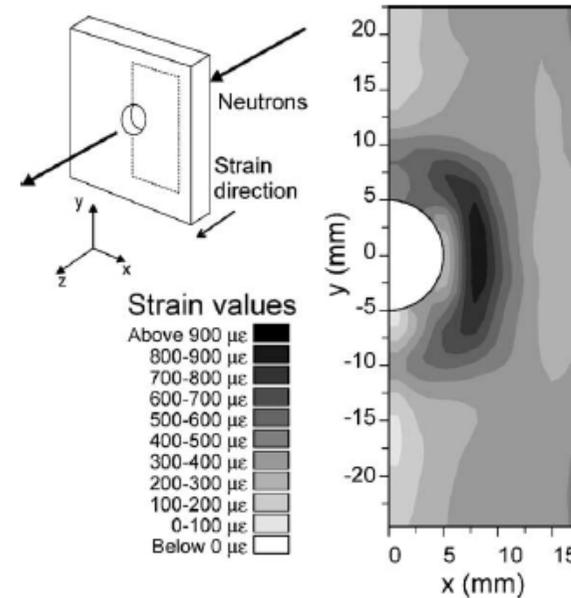
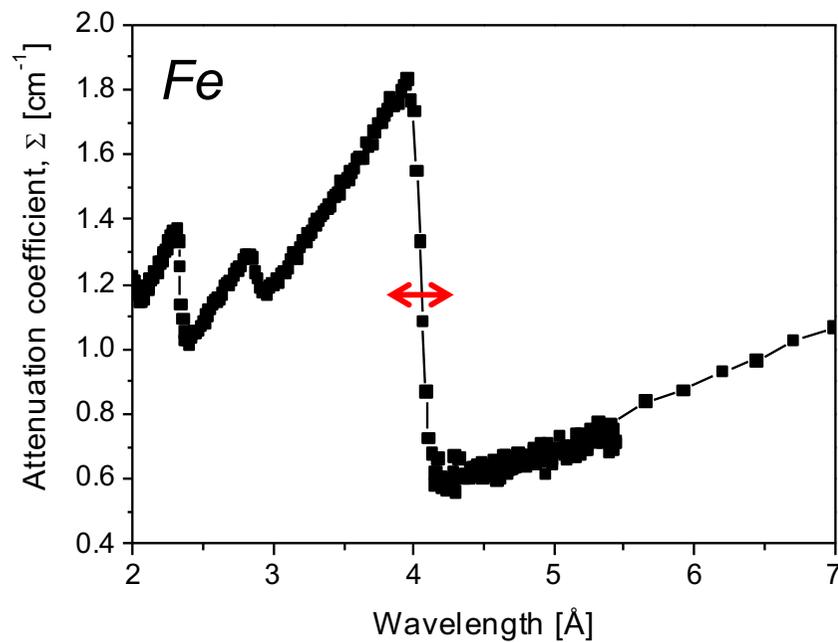
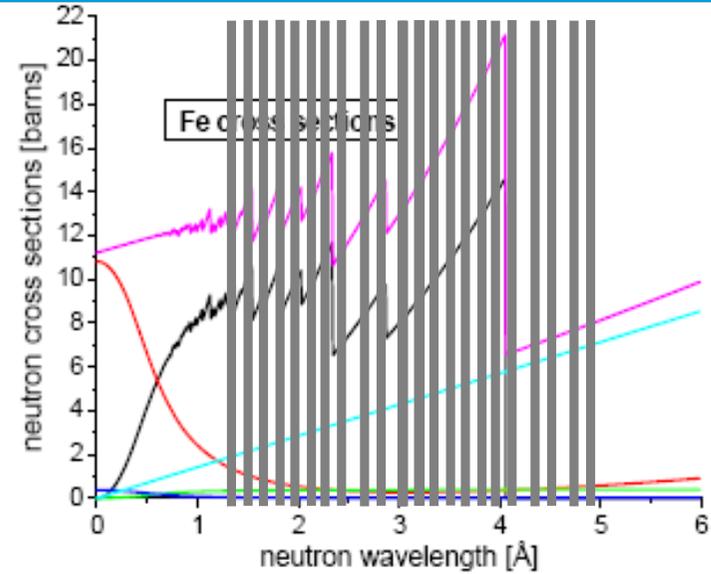
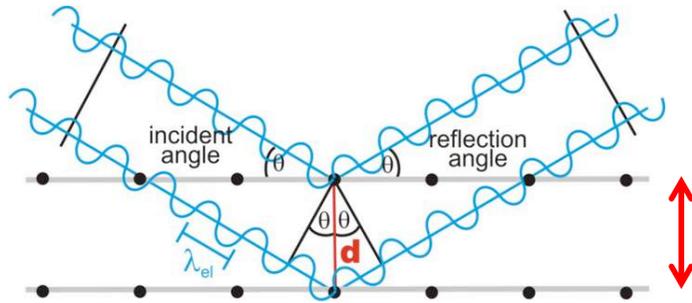
3.8 Å

4.0 Å

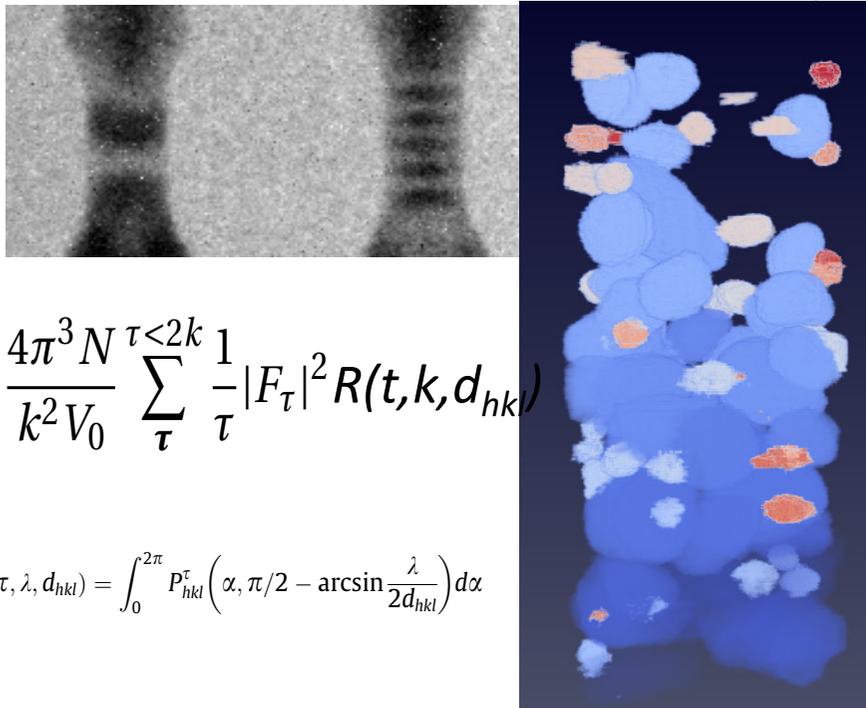
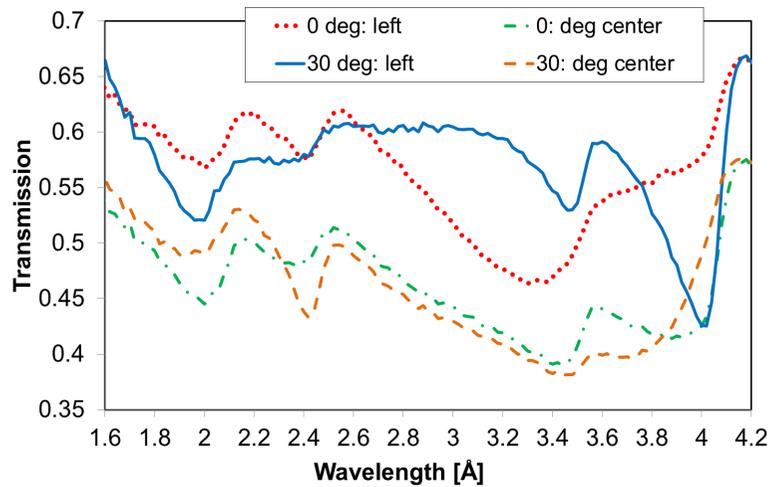
4.2 Å



Energy Dispersive

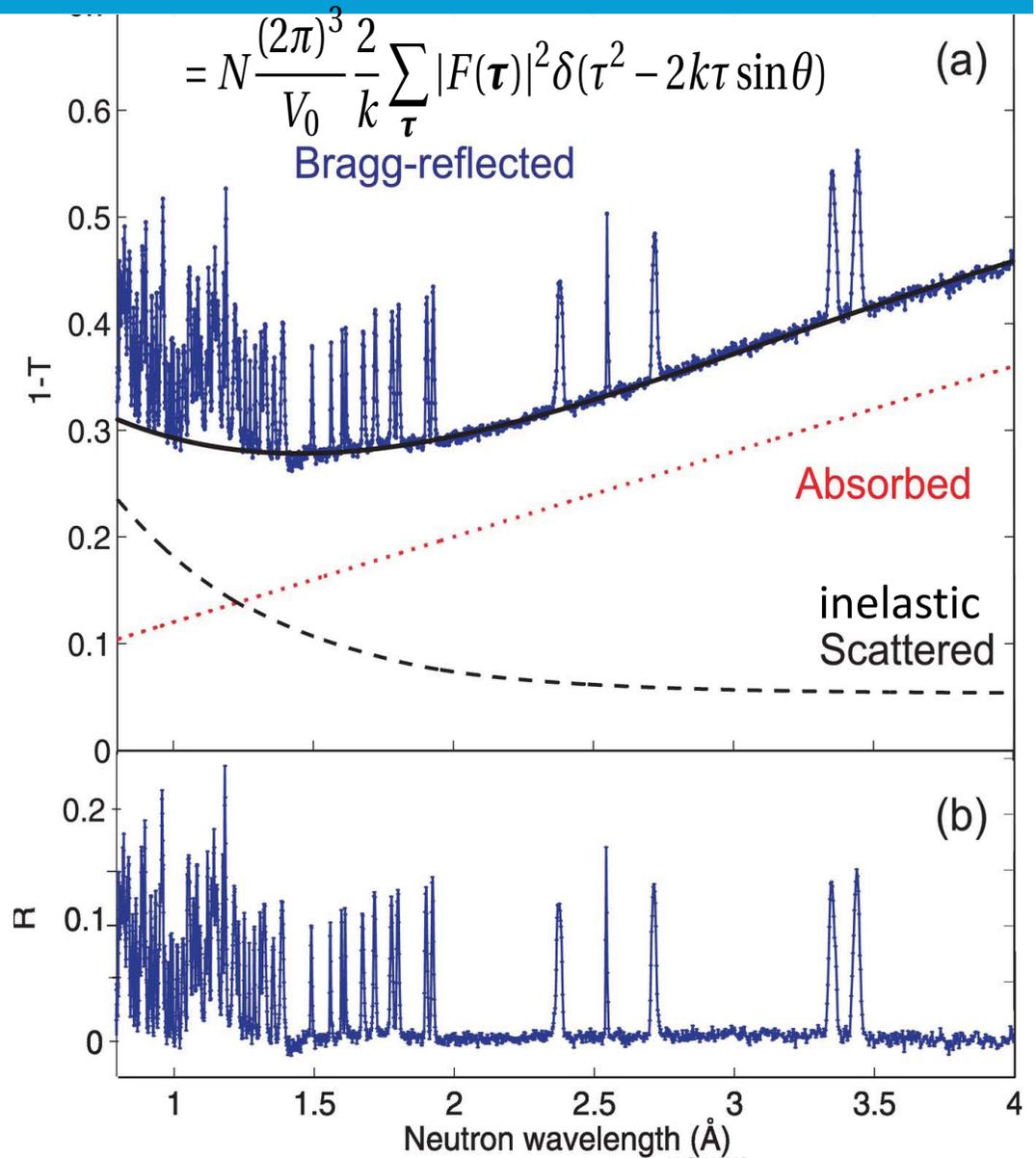


Energy Dispersive



$$= \frac{4\pi^3 N}{k^2 V_0} \sum_{\tau} \frac{\tau < 2k}{\tau} \frac{1}{\tau} |F_{\tau}|^2 R(t, k, d_{hkl})$$

$$R(\tau, \lambda, d_{hkl}) = \int_0^{2\pi} P_{hkl}^{\tau} \left(\alpha, \pi/2 - \arcsin \frac{\lambda}{2d_{hkl}} \right) d\alpha$$

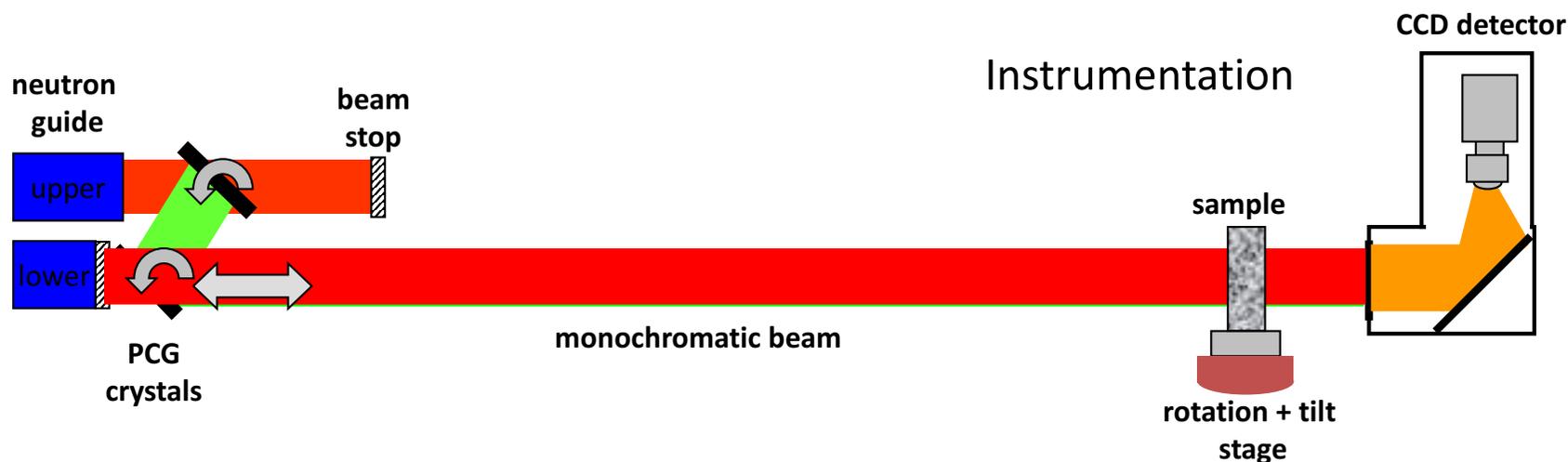


$$= N \frac{(2\pi)^3}{V_0} \frac{2}{k} \sum_{\tau} |F(\tau)|^2 \delta(\tau^2 - 2k\tau \sin\theta) \quad (a)$$

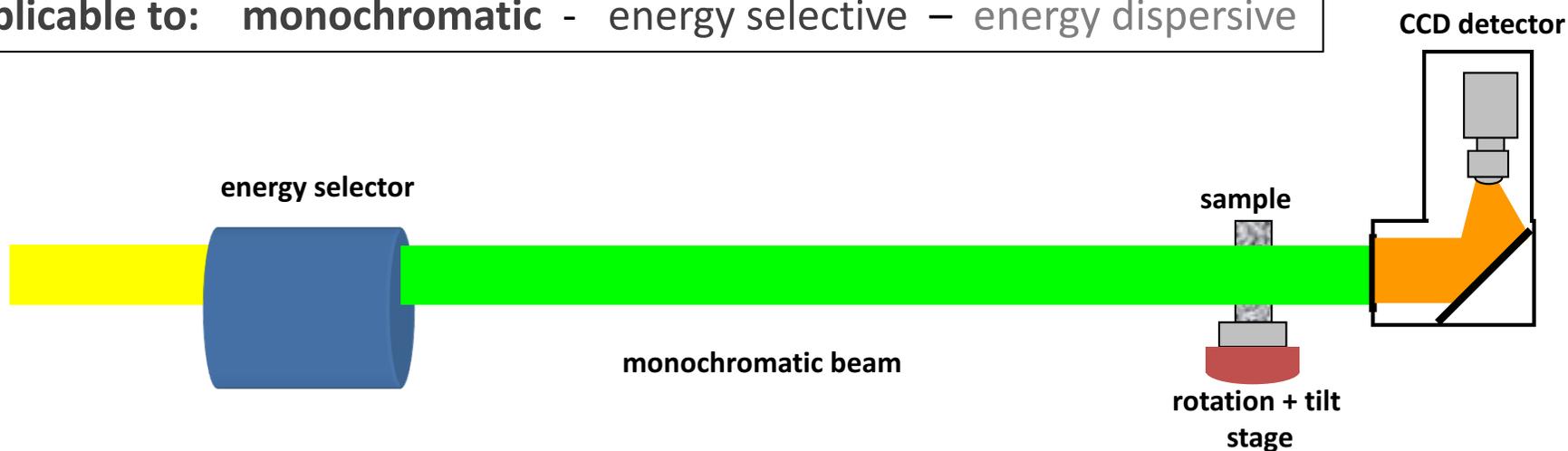
(b)

Advanced Imaging

- Wavelength resolved imaging → INSTRUMENTATION (cont.)

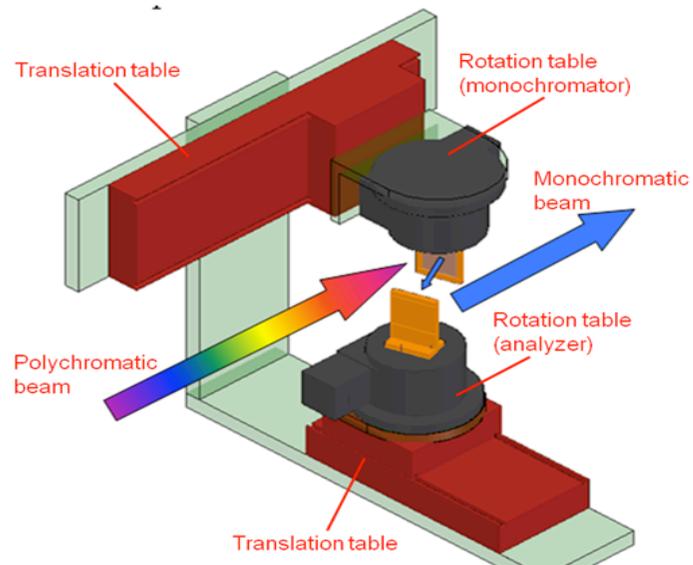
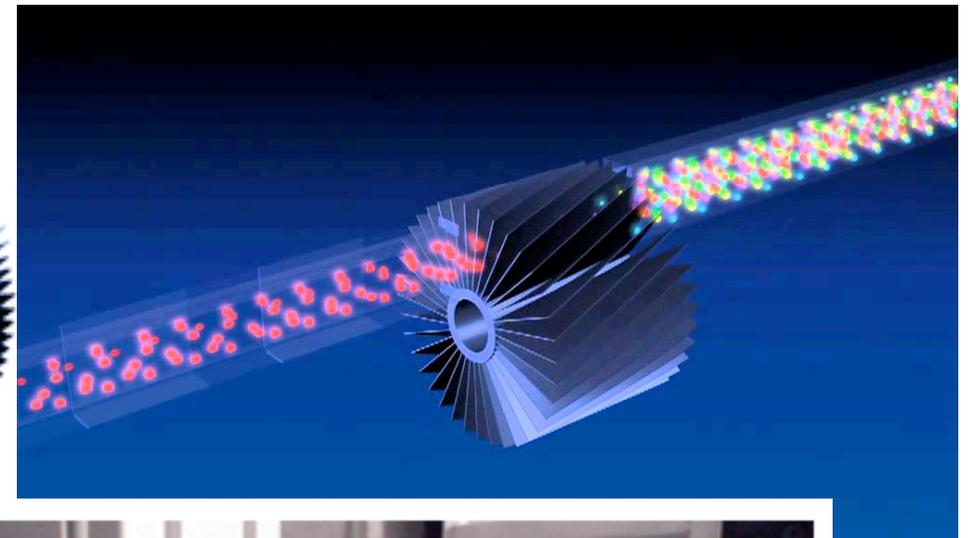
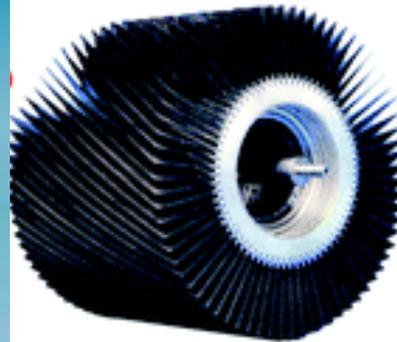
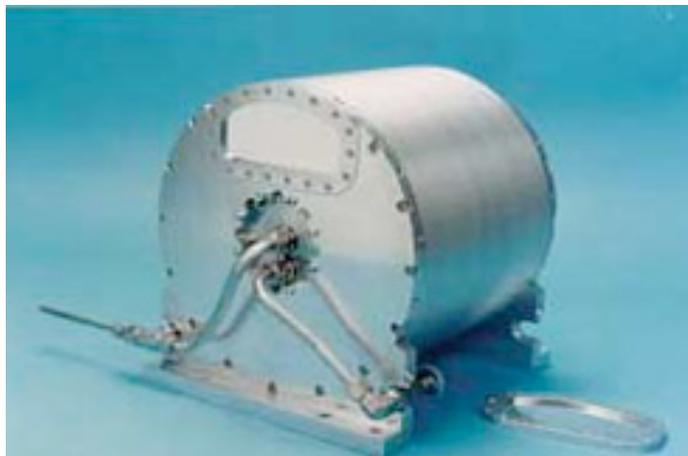


Applicable to: monochromatic - energy selective – energy dispersive

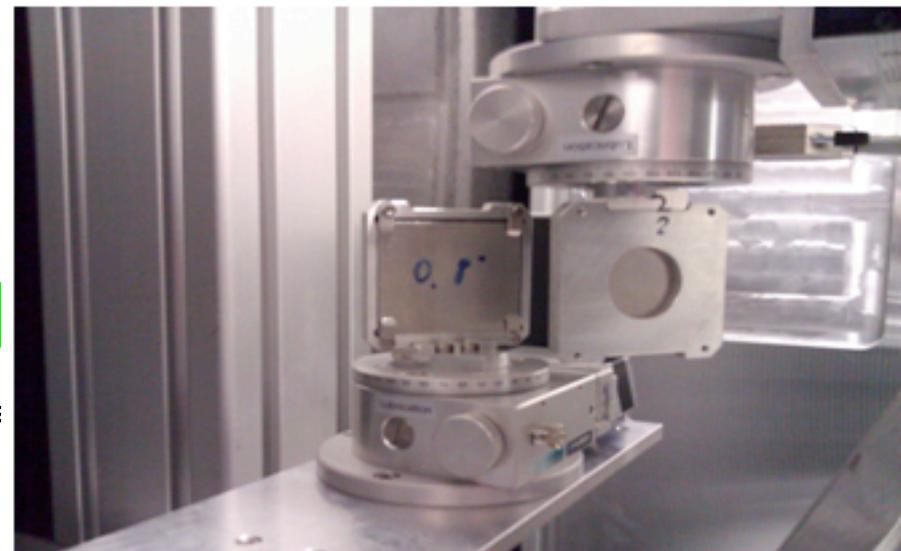


Advanced Imaging

- Wavelength resolved imaging → INSTRUMENTATION

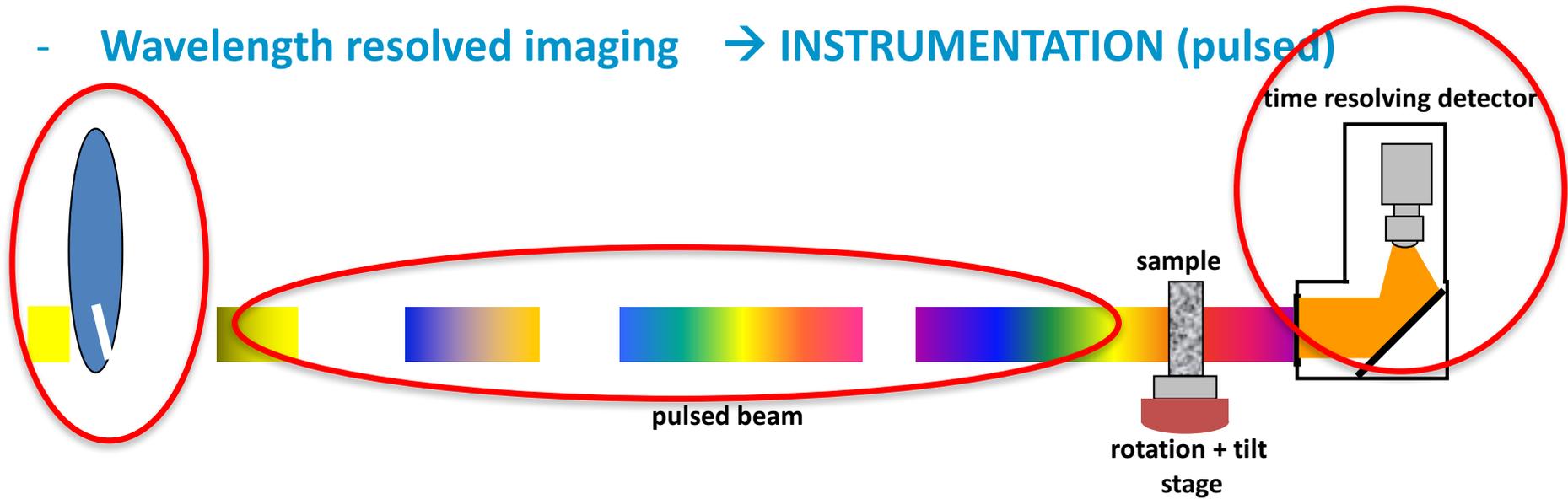


monochromator

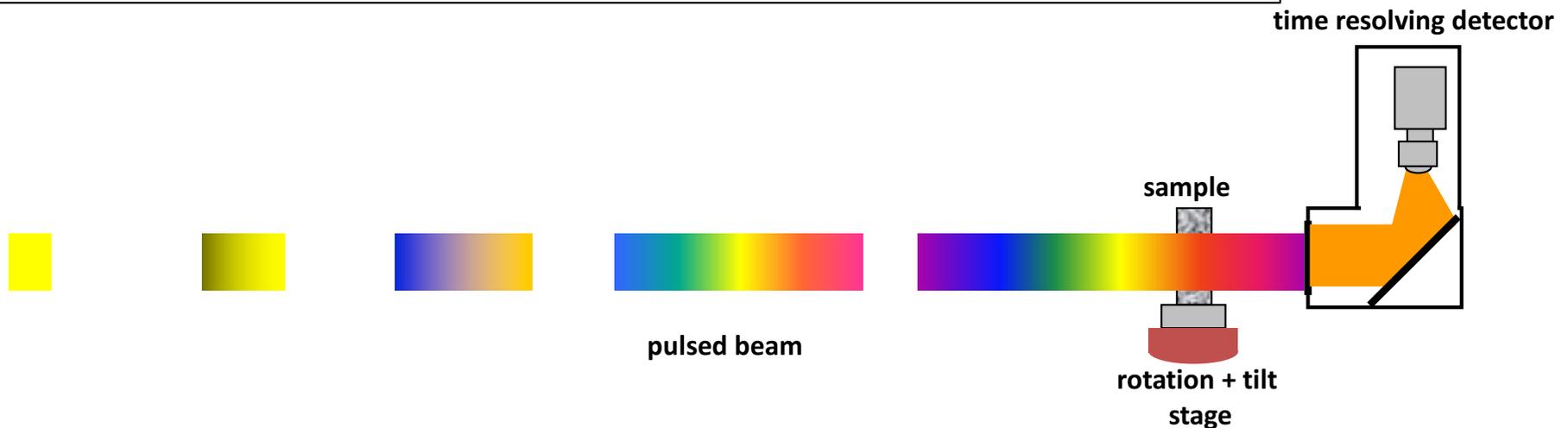


Advanced Imaging

- Wavelength resolved imaging → INSTRUMENTATION (pulsed)

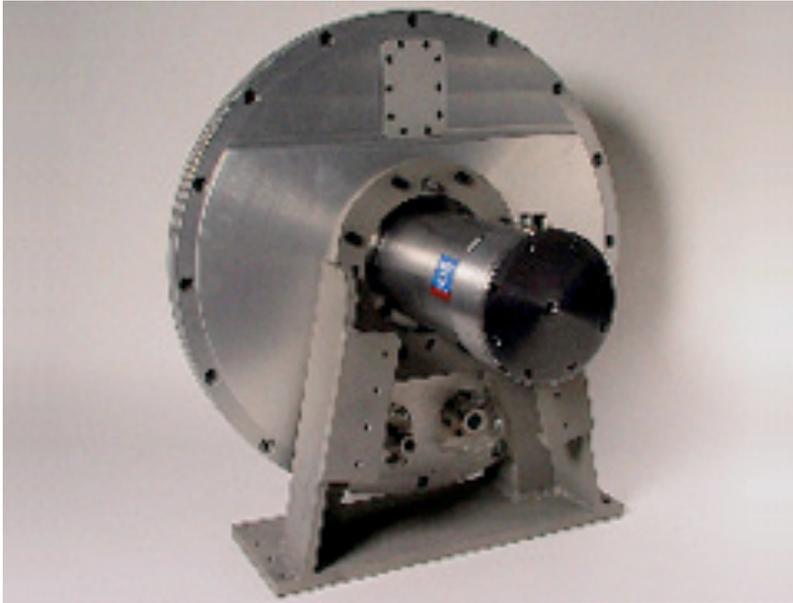


Applicable to: monochromatic - energy selective - energy dispersive

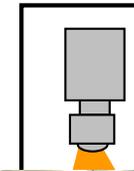


Advanced Imaging

- Wavelength resolved imaging → INSTRUMENTATION

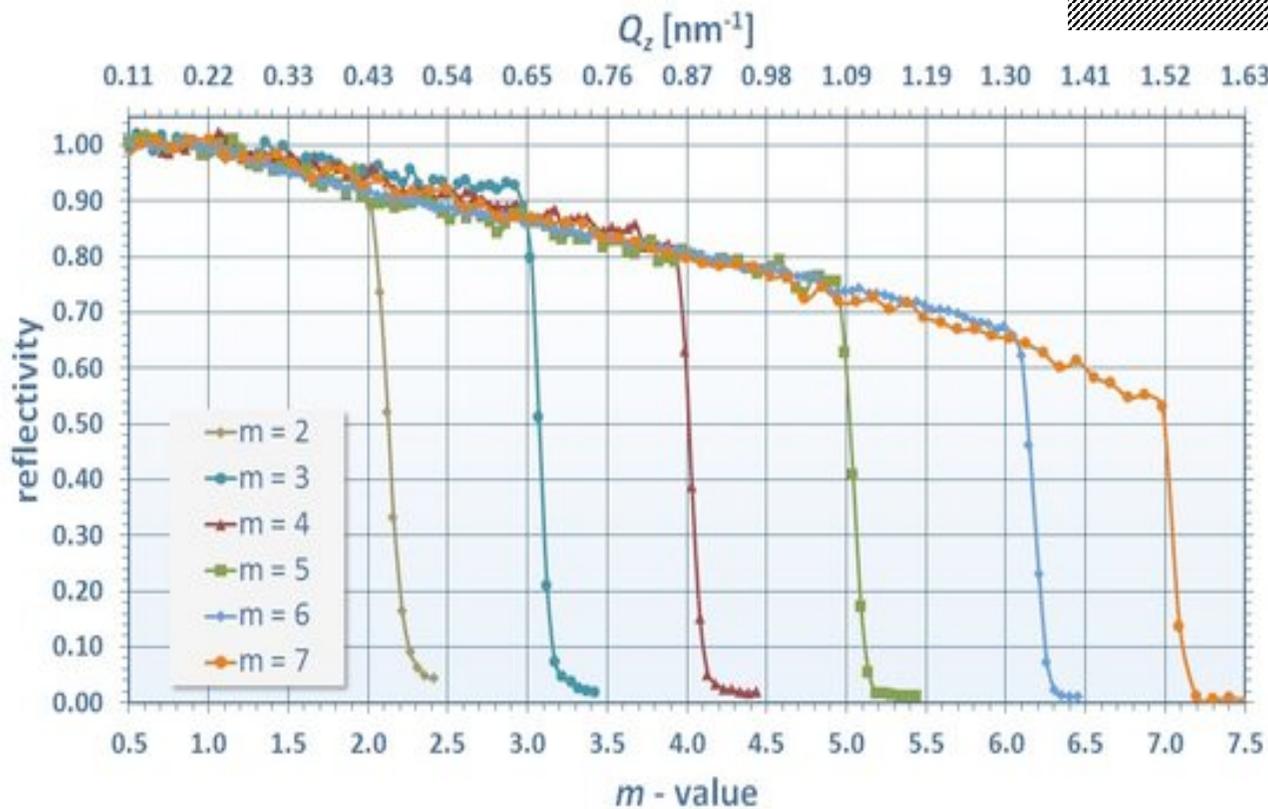
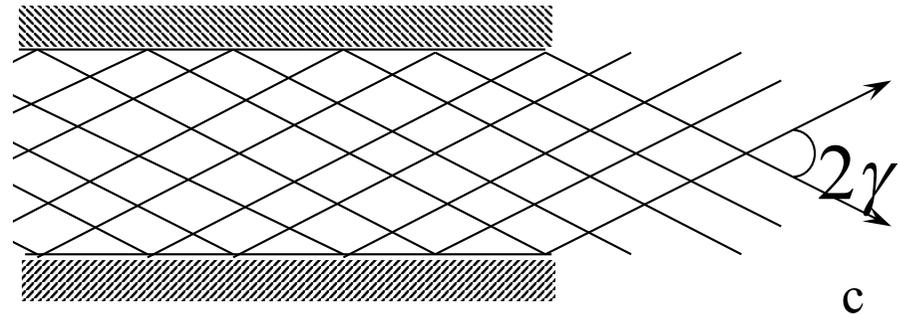


time resolving detector



Advanced Imaging

INSTRUMENTATION (pulsed)



Lower limit L/D

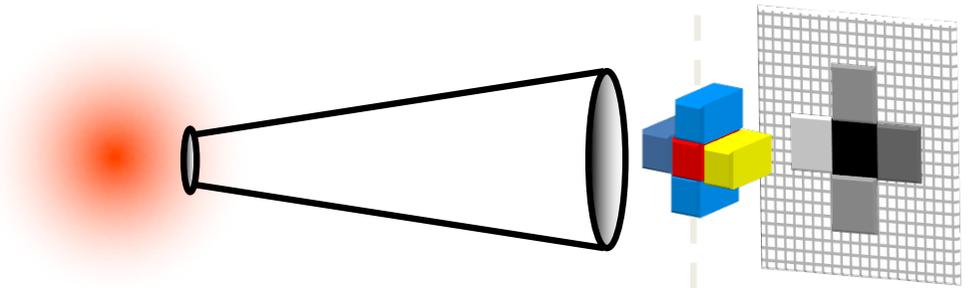
$$L/D = 1/\tan(2\gamma_c(\lambda)).$$

Advanced Imaging

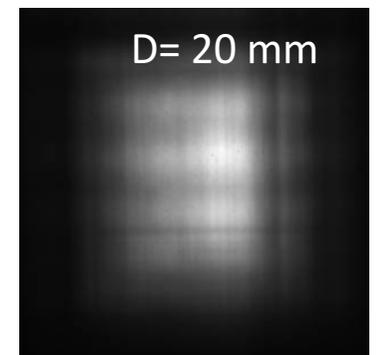
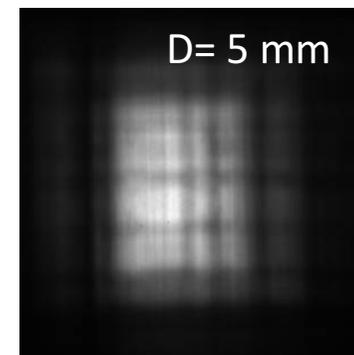
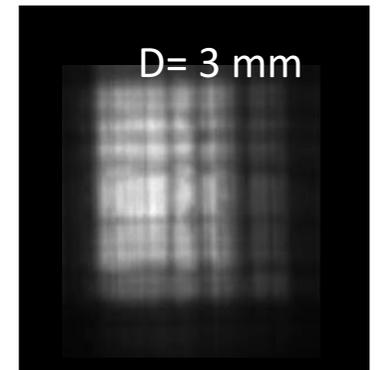
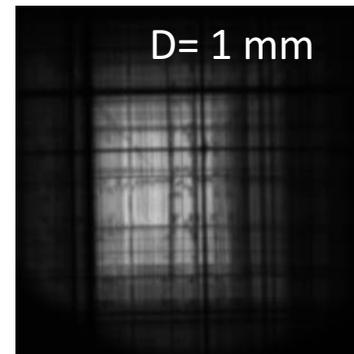
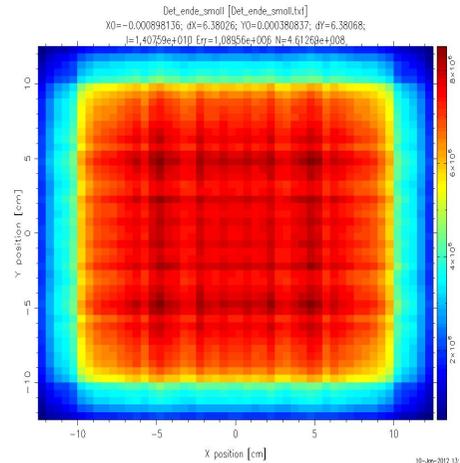
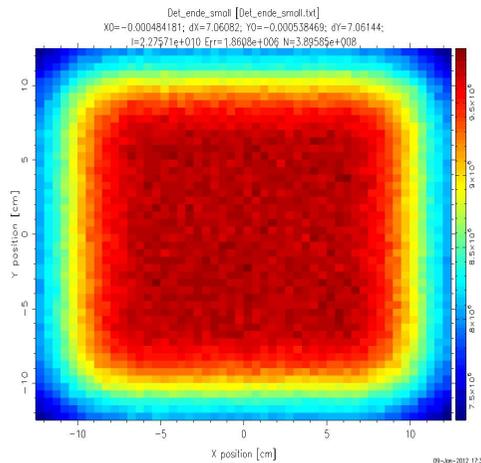
Guide



Source Collimator Object Detector

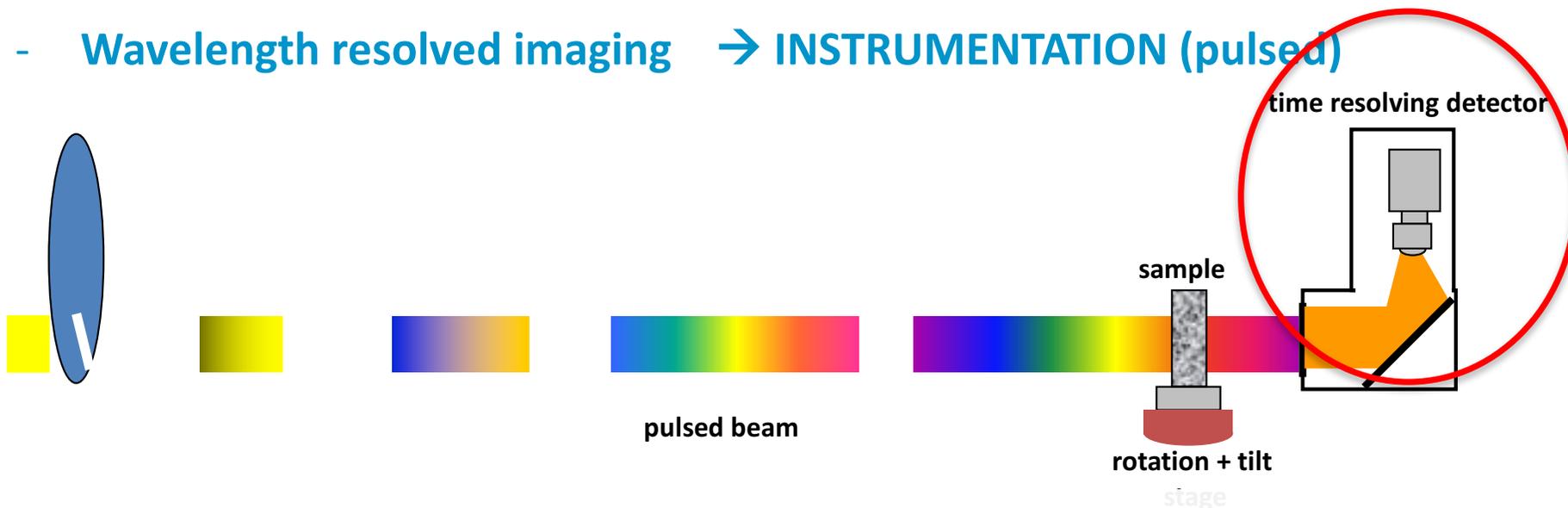


JSER

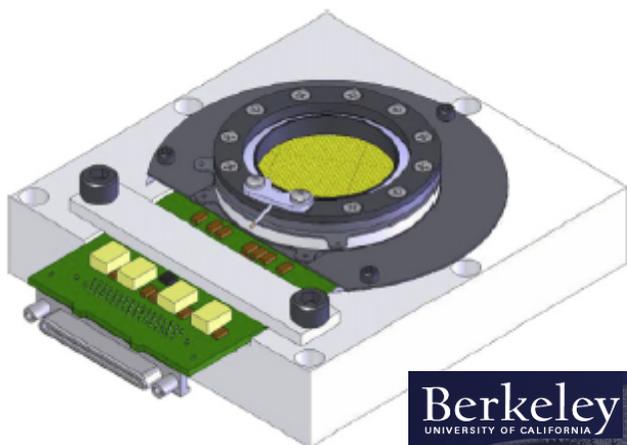


Advanced Imaging

- Wavelength resolved imaging → INSTRUMENTATION (pulsed)



Applicable to: monochromatic - energy selective - energy dispersive



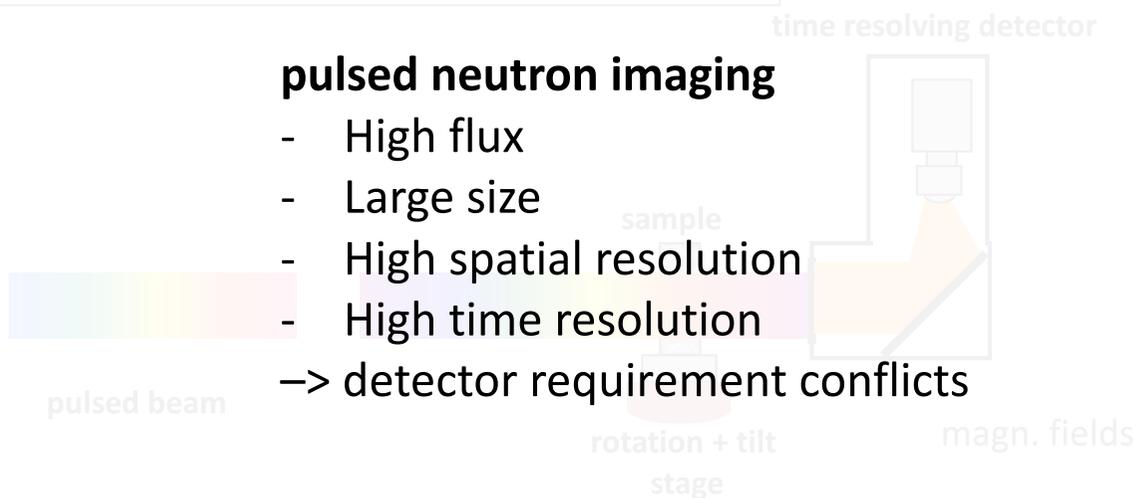
A. Tremsin et al.



pulsed neutron imaging

- High flux
- Large size
- High spatial resolution
- High time resolution

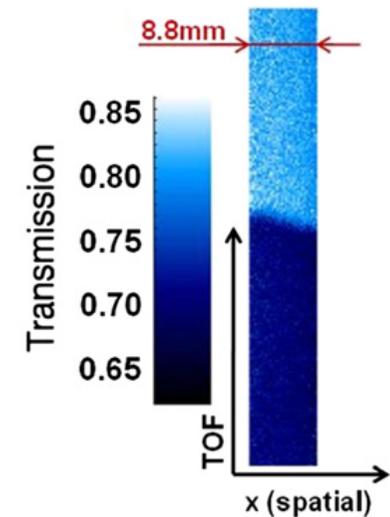
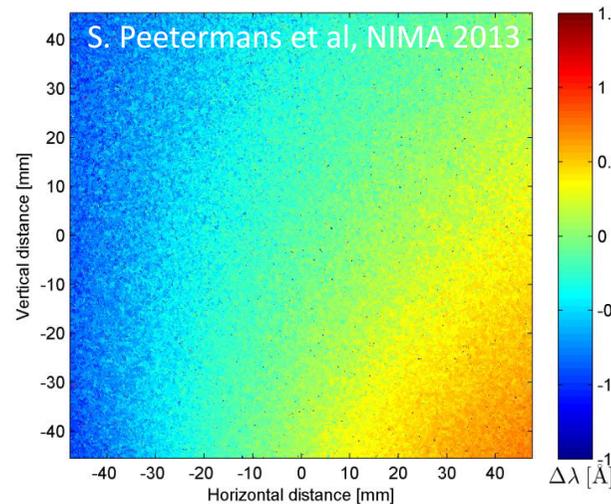
→ detector requirement conflicts



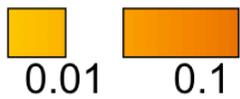
Advanced Imaging

Monochromators for Imaging:

- crystal monochromators
 - velocity selectors
 - choppers
- > homogeneity requirement conflicts



Diffraction regime



0.3

1.0

3.0

10

100

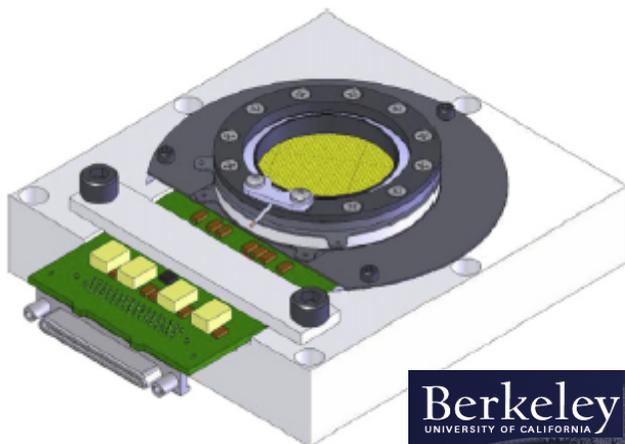
1000

10000

100000

Length scale in nm

Conventional imaging regime



A. Tremsin et al.



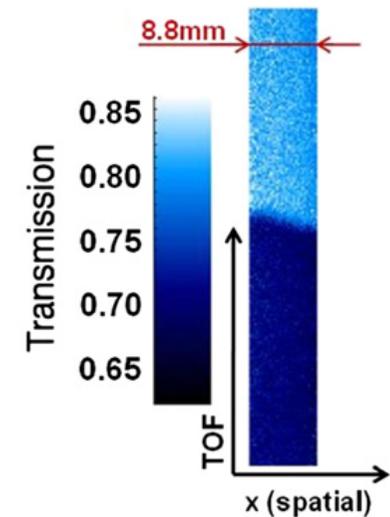
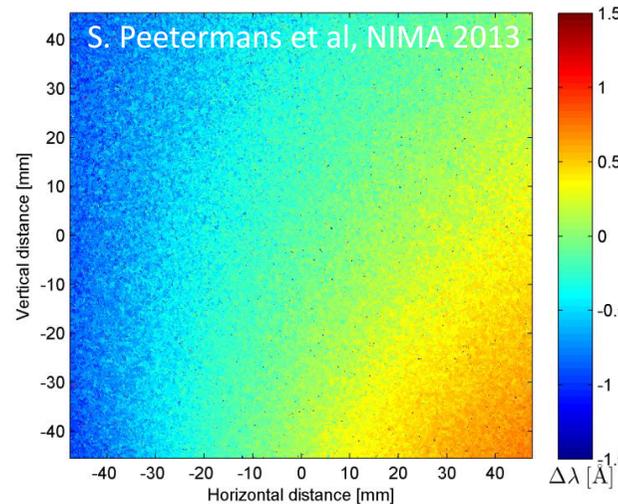
pulsed neutron imaging

- High flux
 - Large size
 - High spatial resolution
 - High time resolution
- > detector requirement conflicts

Advanced Imaging

Monochromators for Imaging:

- crystal monochromators
 - velocity selectors
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- > homogeneity requirement conflicts



Diffraction regime



0.3

1.0

3.0

10

100

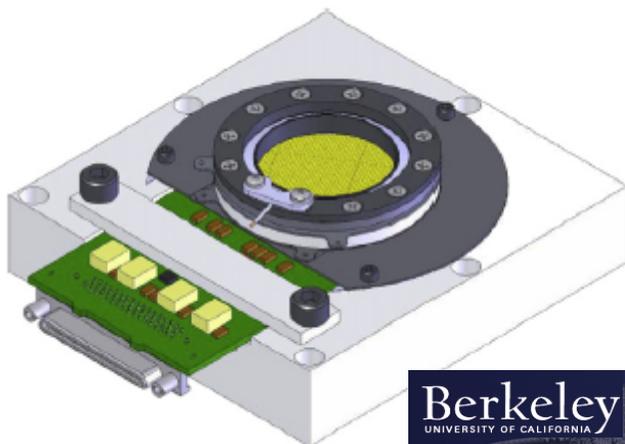
1000

10000

100000

Length scale in nm

Conventional imaging regime



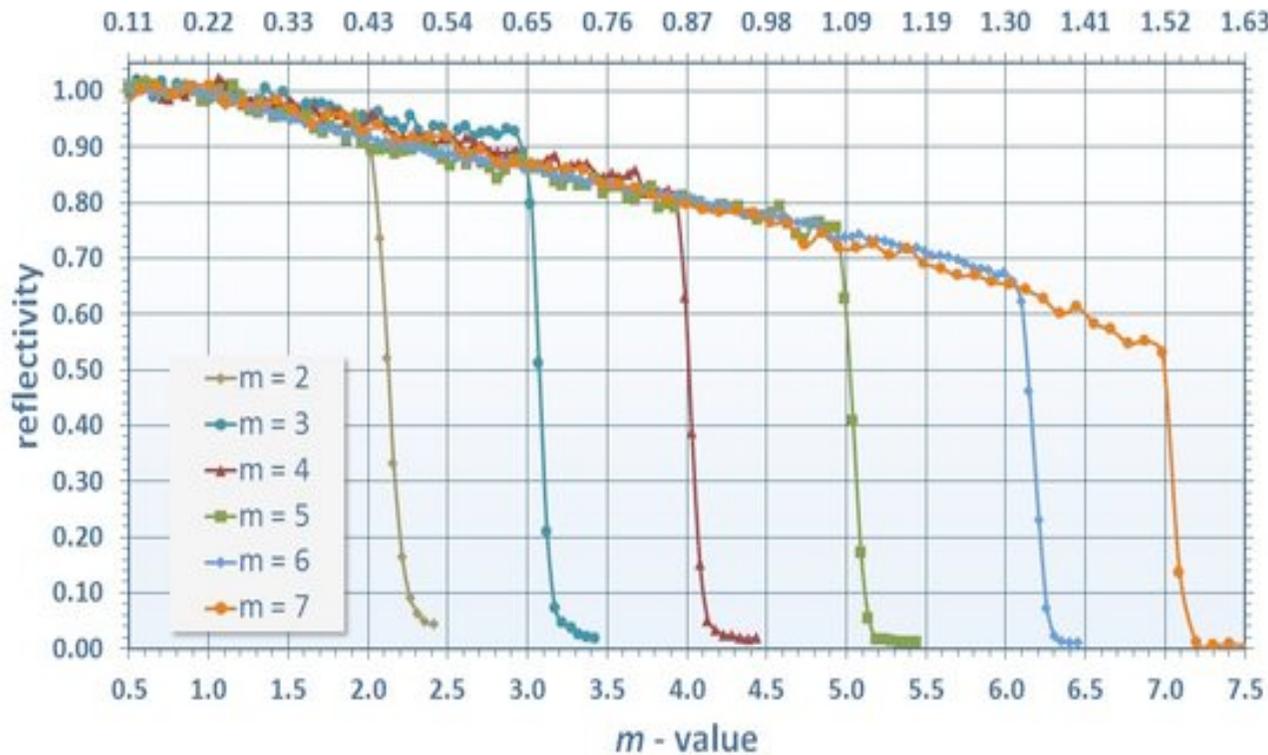
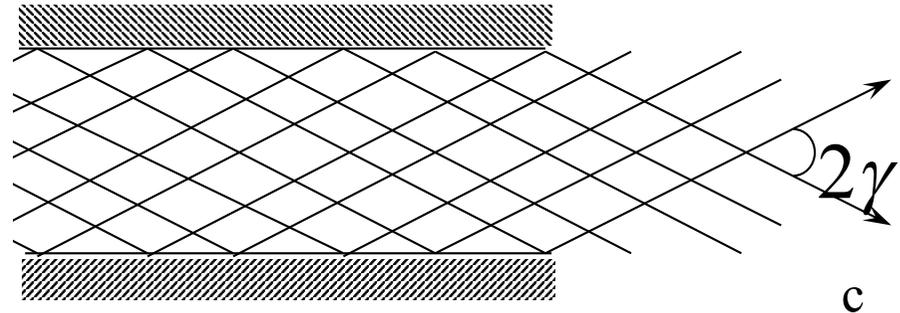
A. Tremsin et al.



pulsed neutron imaging

- High flux
 - Large size
 - High spatial resolution
 - High time resolution
- > detector requirement conflicts

Advanced Imaging

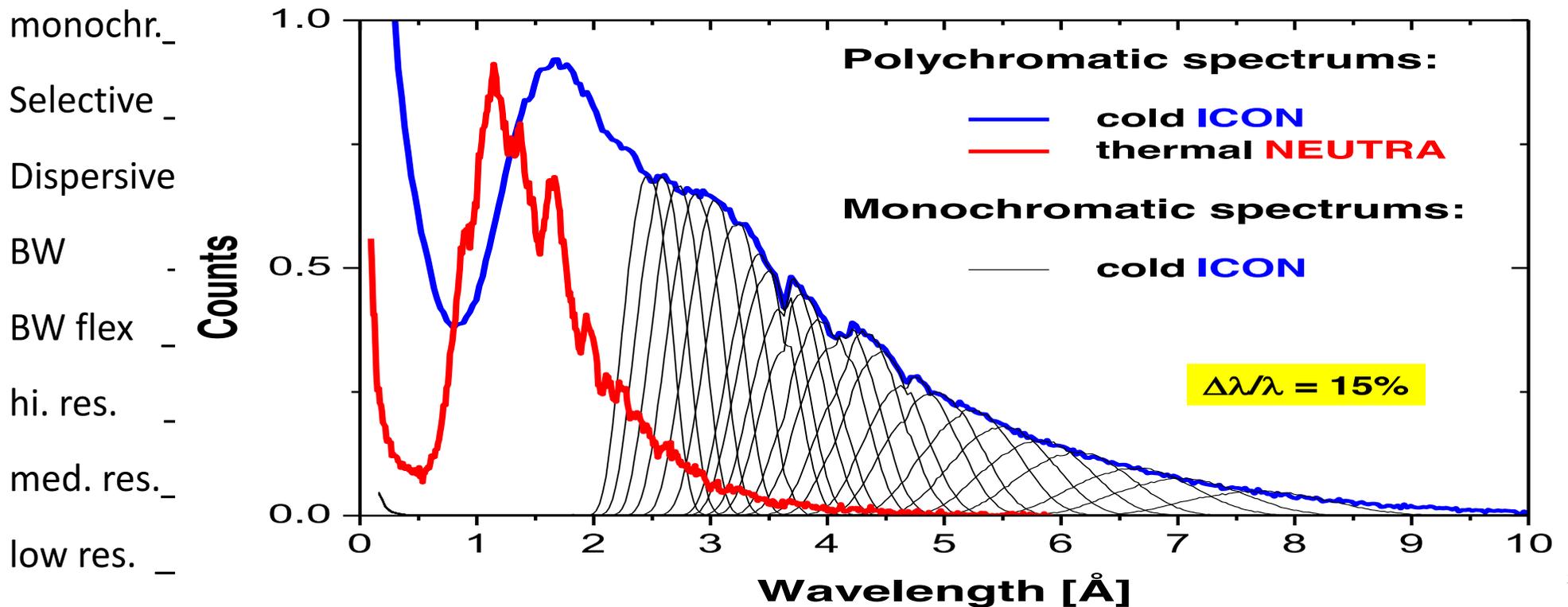


Lower limit L/D

$$L/D = 1/\tan(2\gamma_c(\lambda)).$$

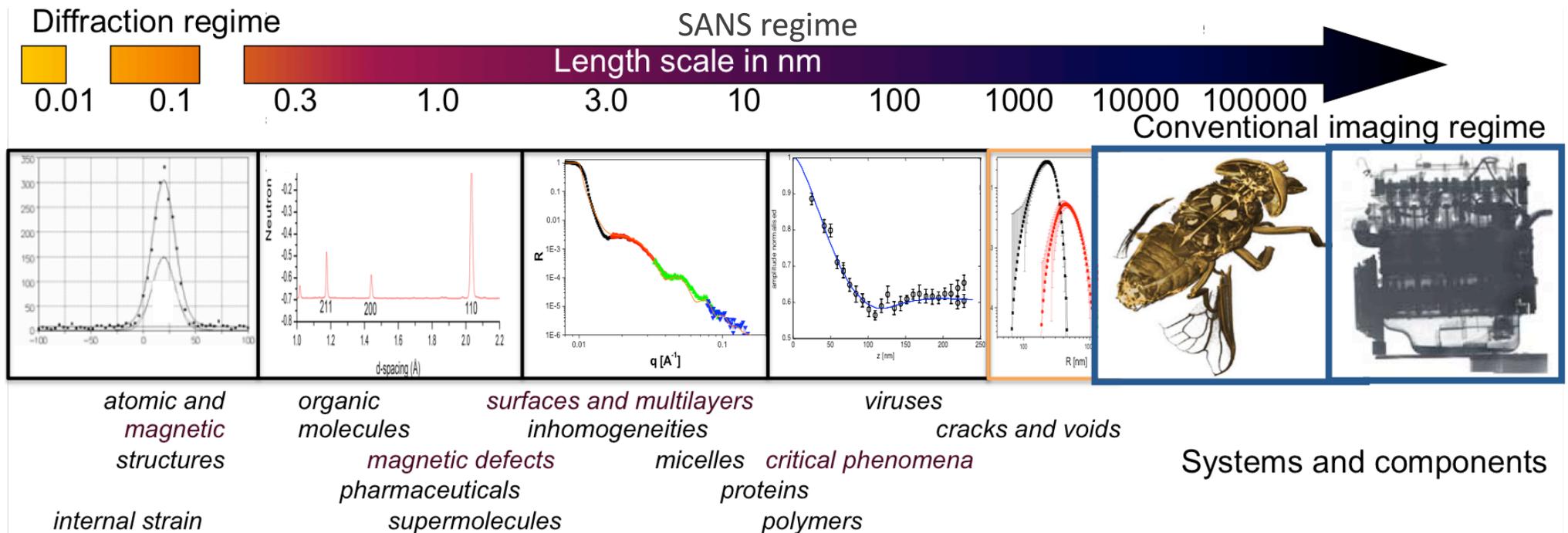
- **Wavelength resolved imaging** → INSTRUMENTATION

Velocity selector Crystal monochromator Choppers Pulsed Source
short- long pulse



monochr. _
Selective _
Dispersive _
BW _
BW flex _
hi. res. _
med. res. _
low res. _

Advanced Neutron Imaging

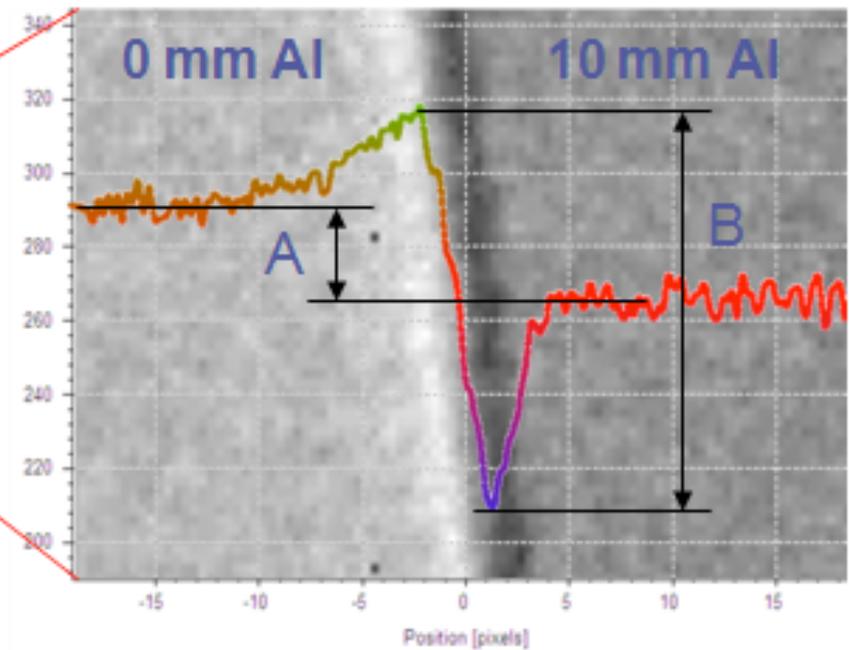
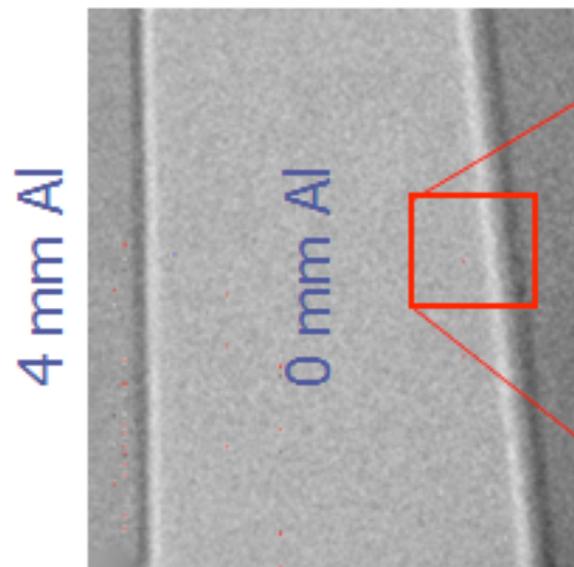
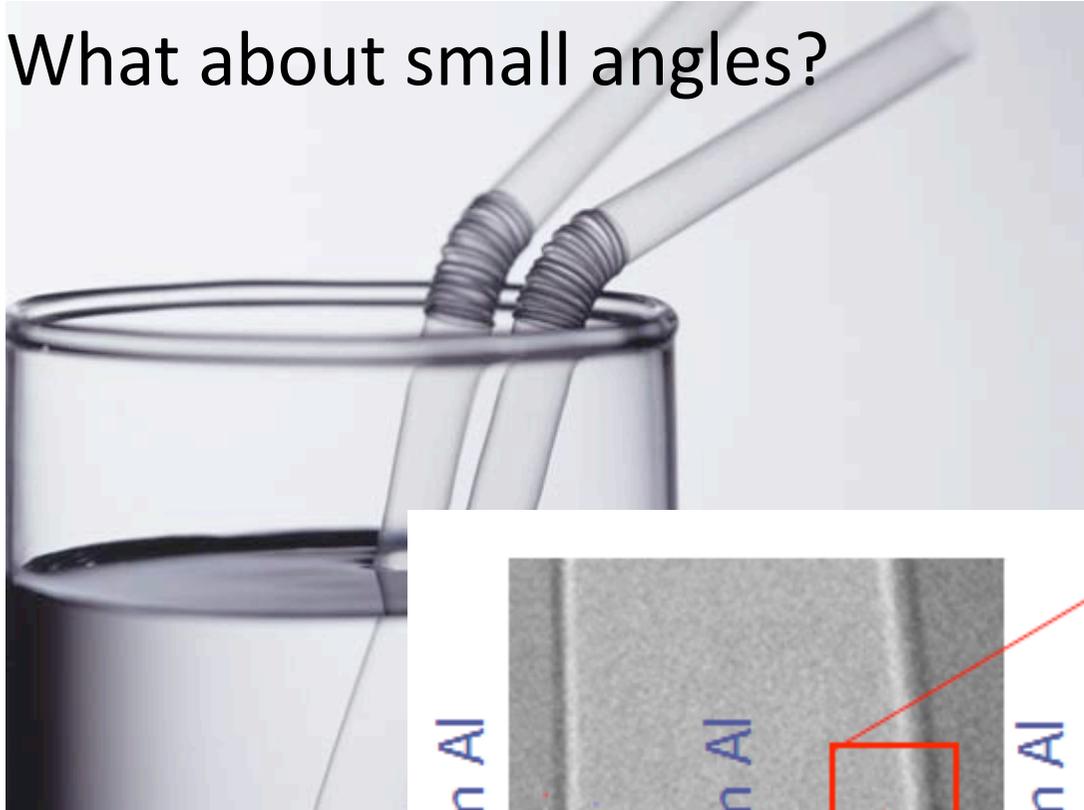


- **Wavelength resolved imaging**
 - Attenuation contrast
 - **Dark-field contrast**
 - Polarized neutron imaging

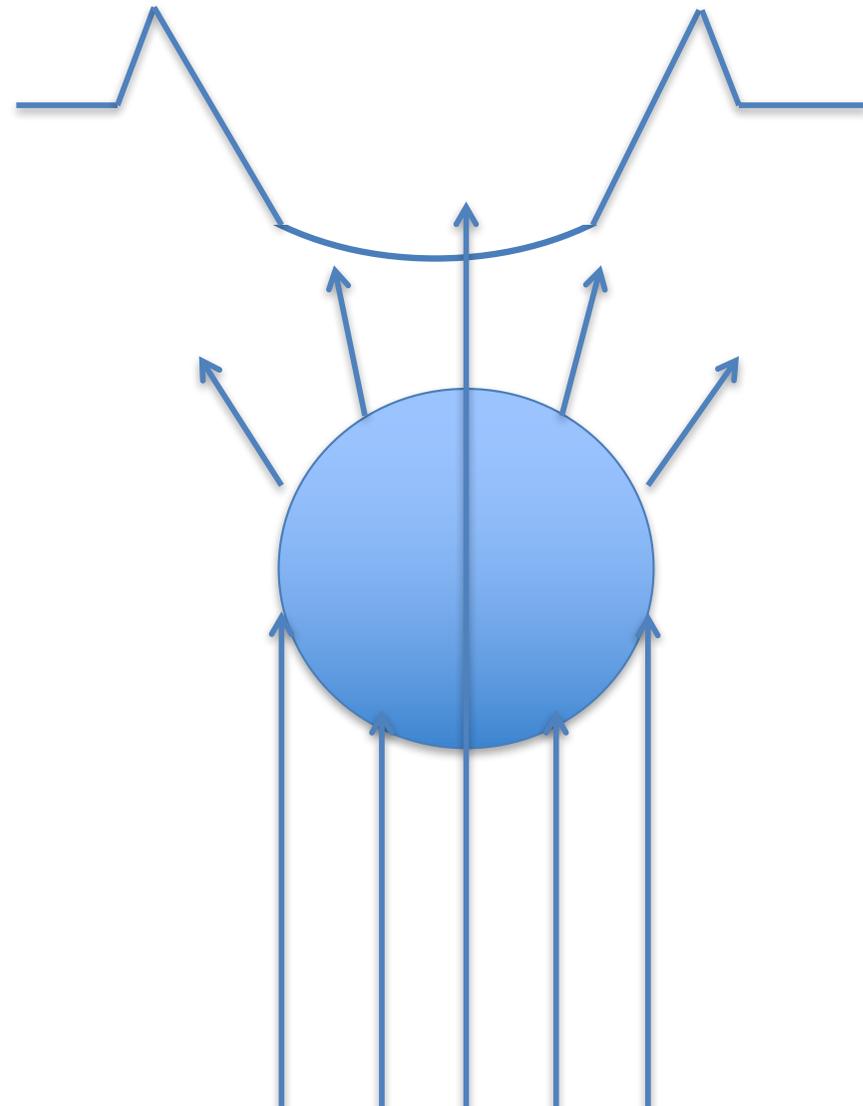
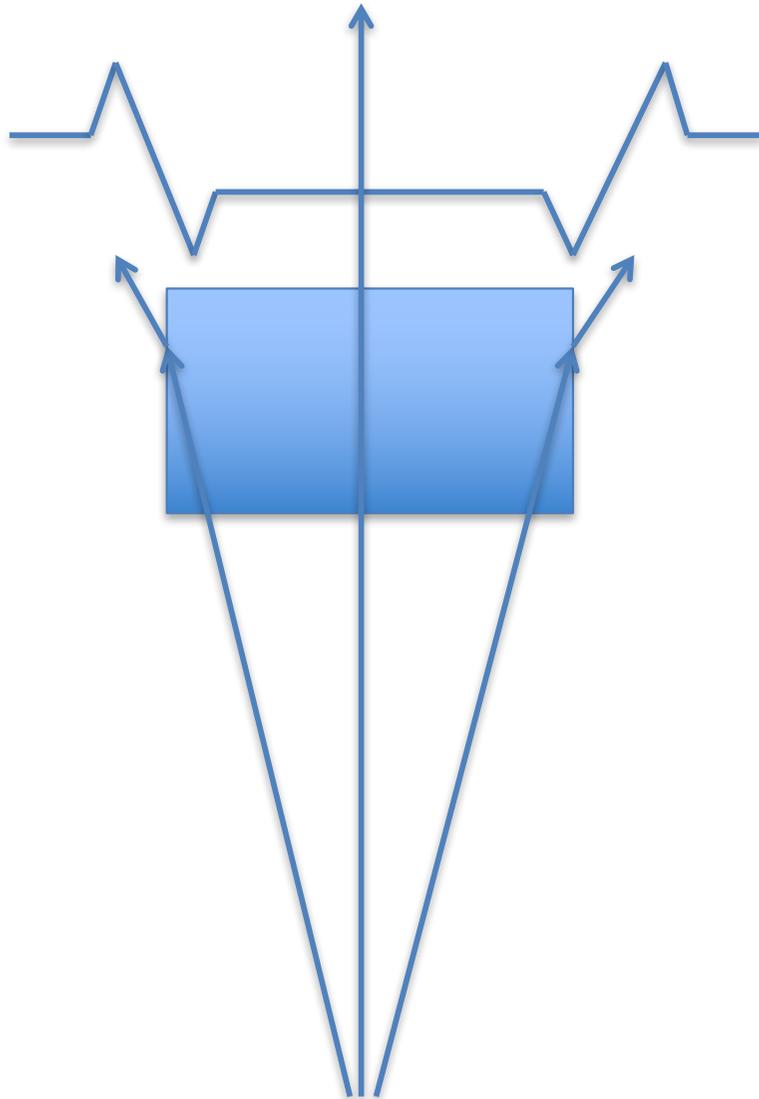
Advanced Imaging

What about small angles?

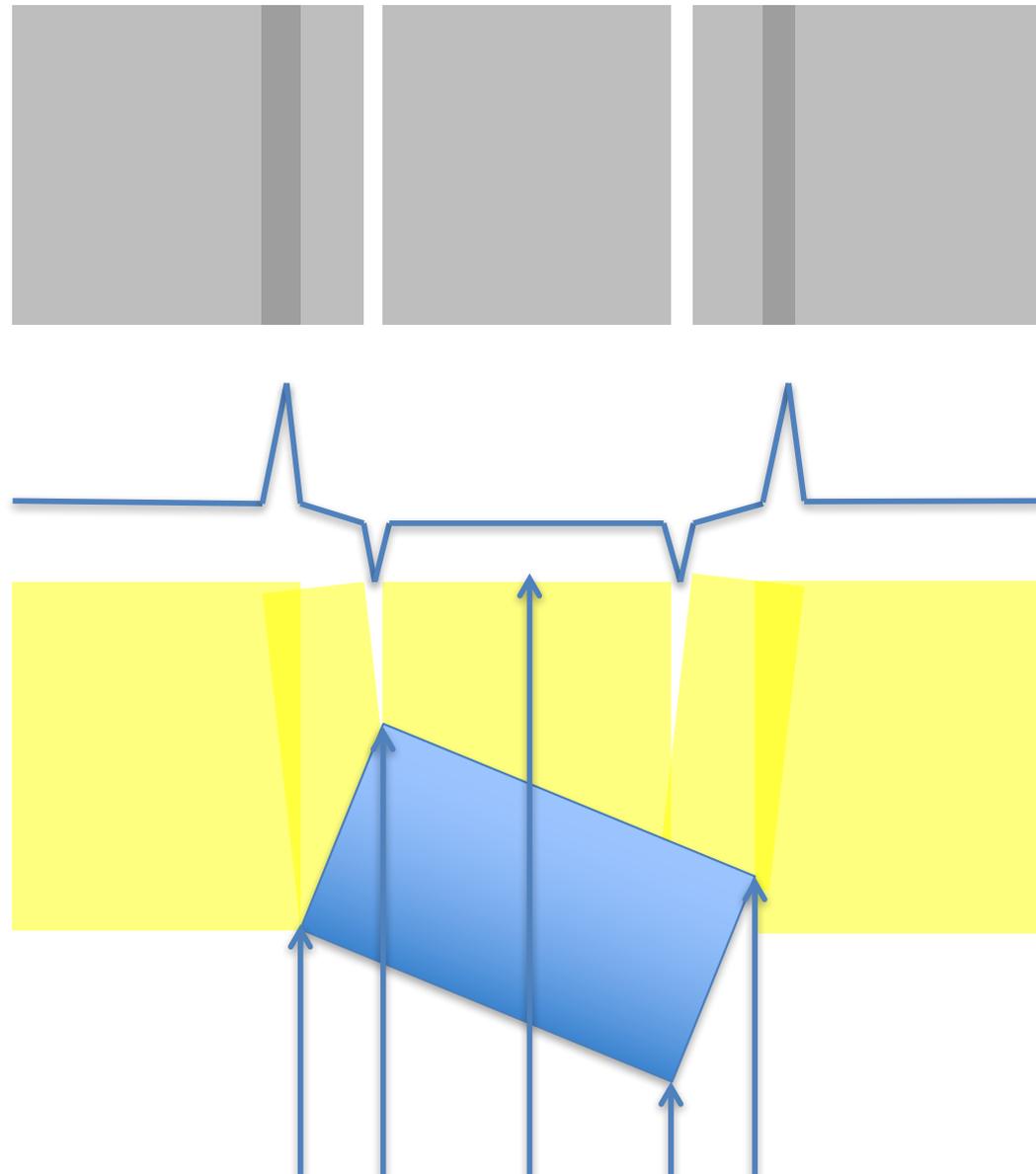
e.g. refraction



Advanced Imaging



Advanced Imaging



Advanced Imaging

Small angle scattering

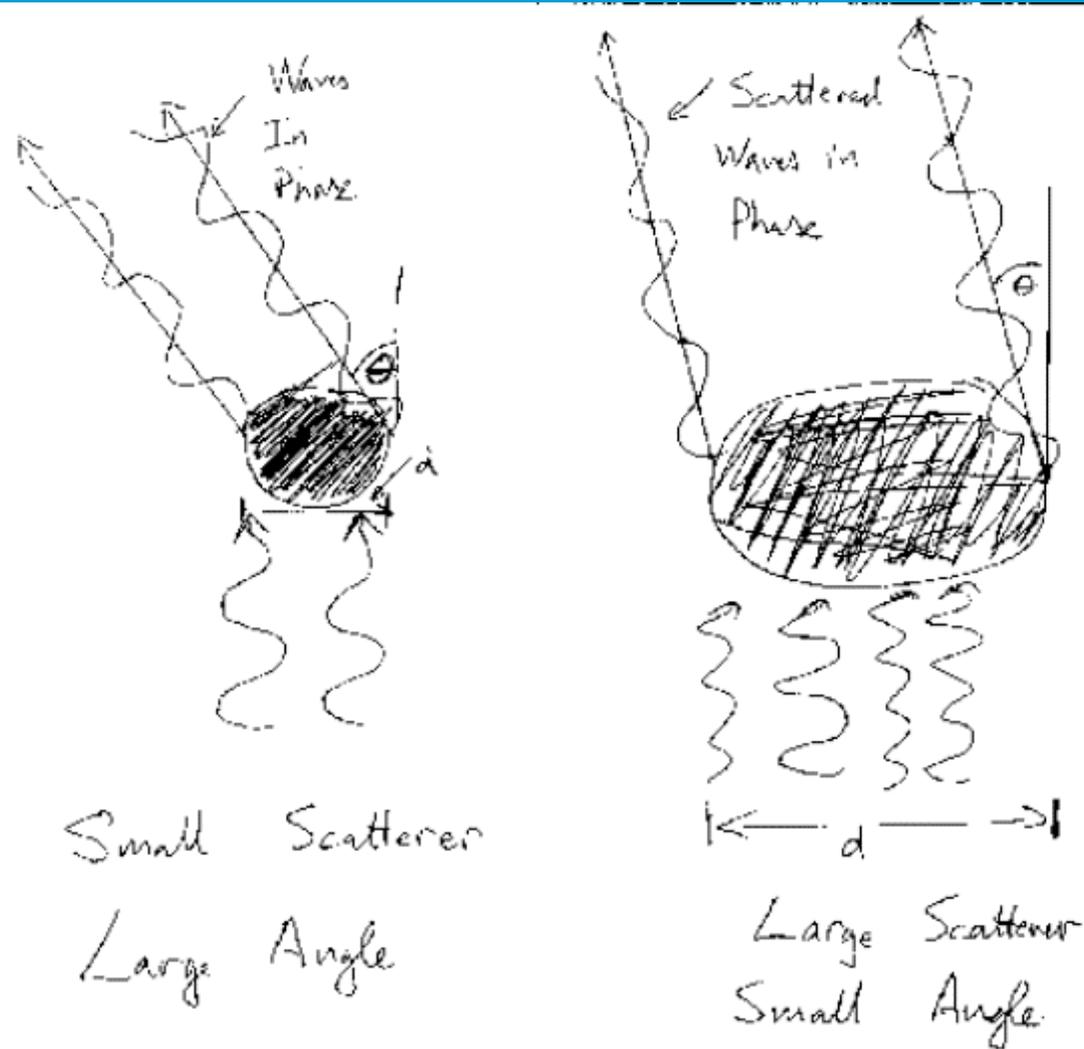
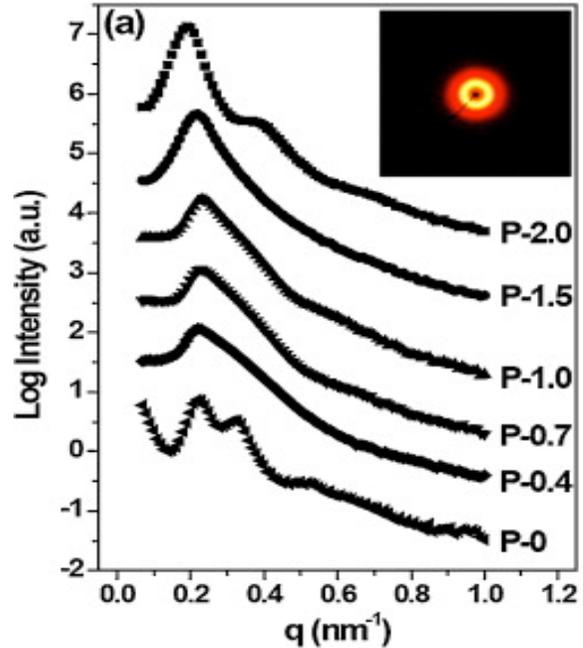
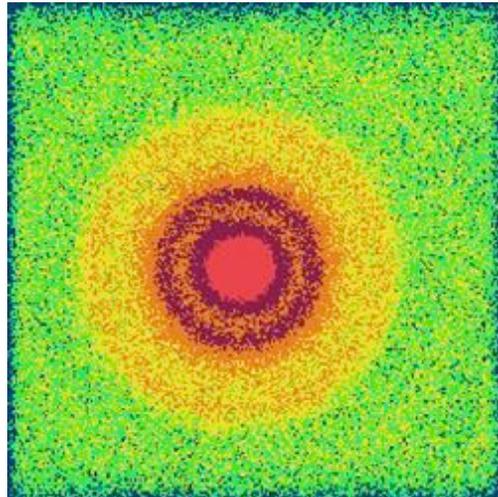
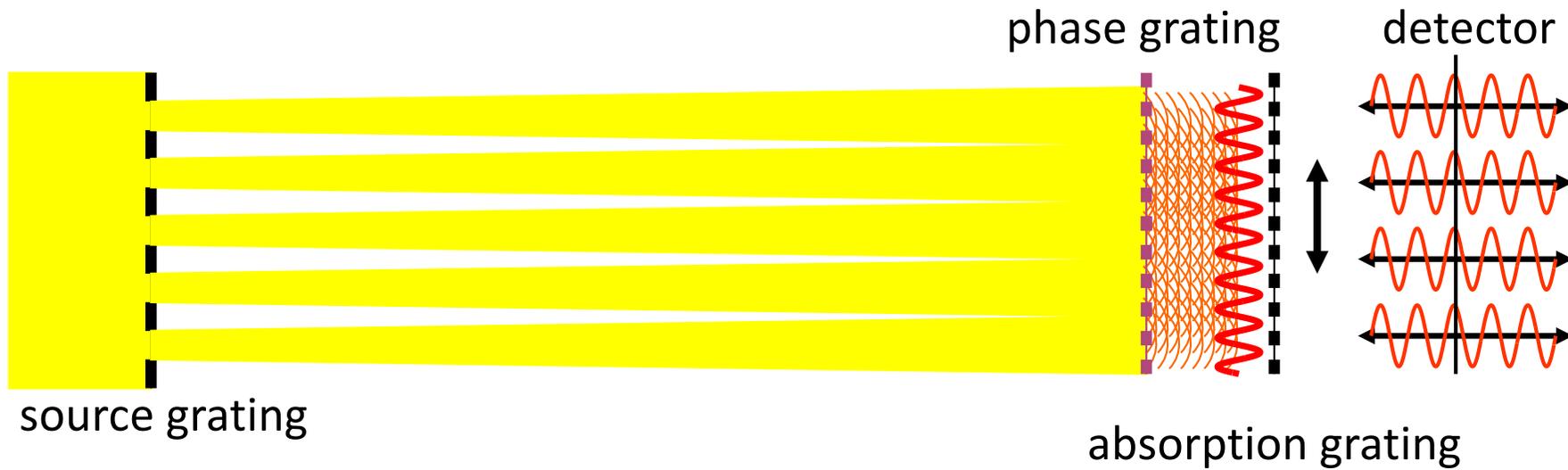


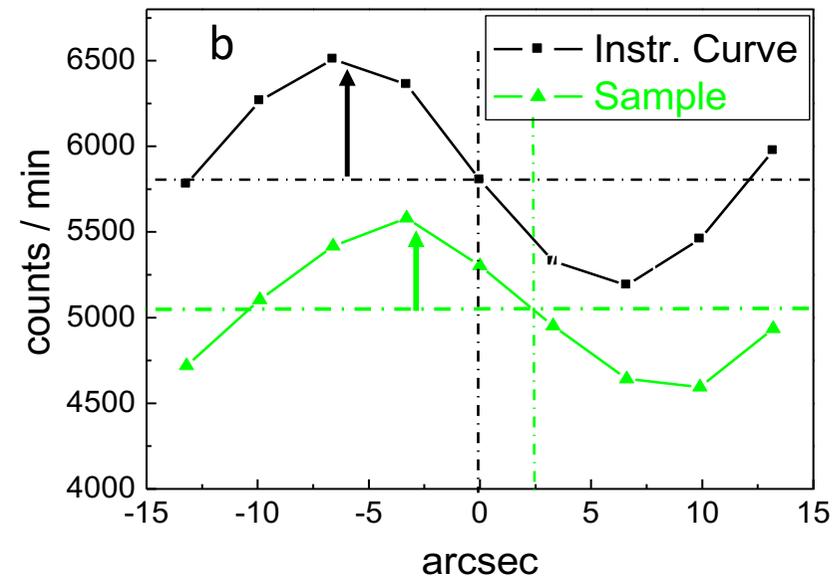
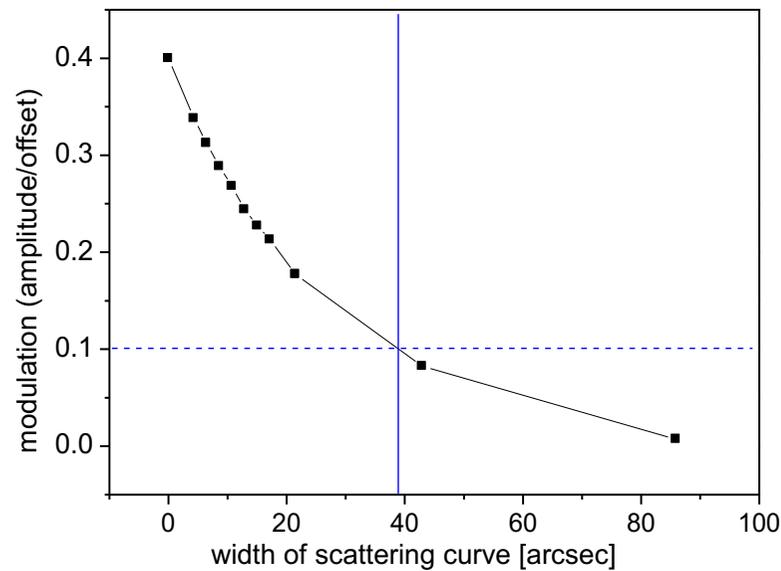
Fig 2: Scattering From Objects

$$\theta \propto \frac{1}{d}$$

Grating Interferometer **monochromatic**

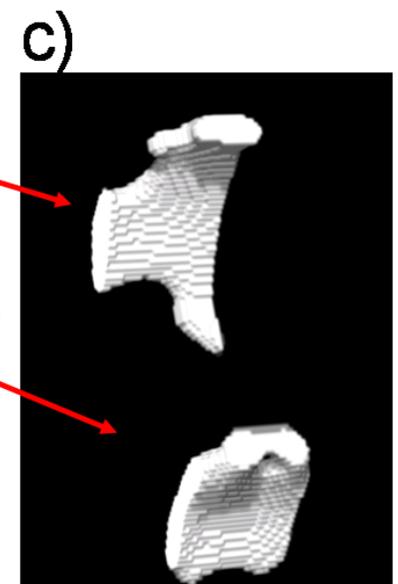
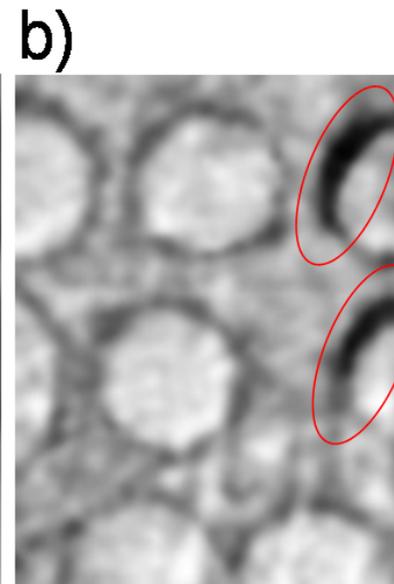
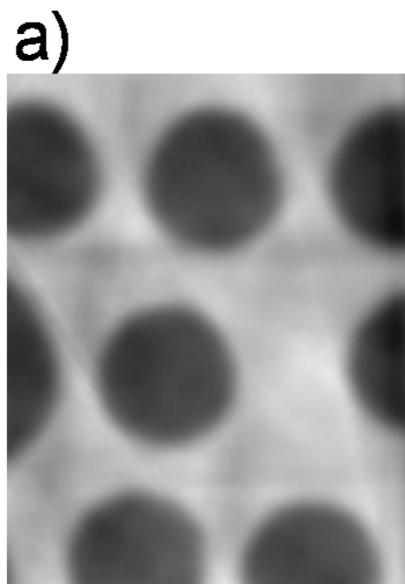
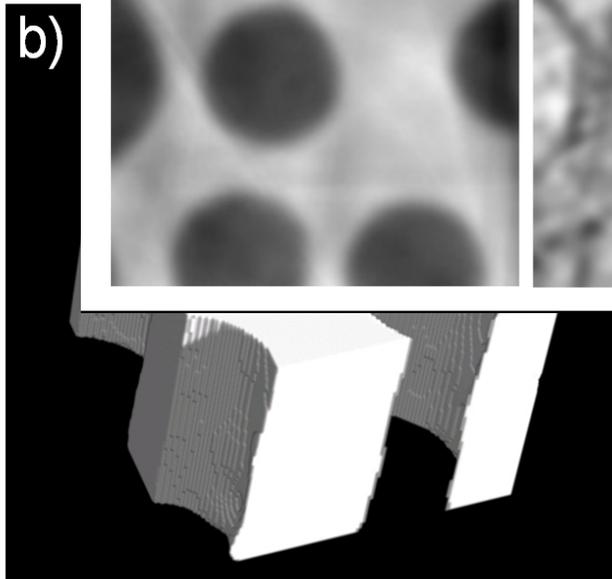
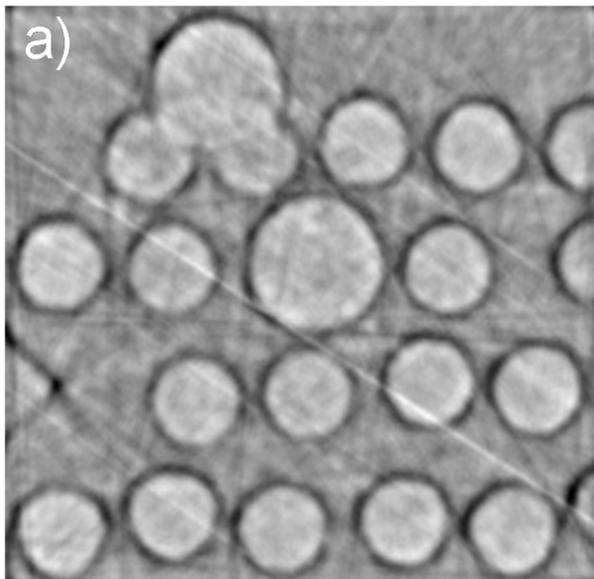
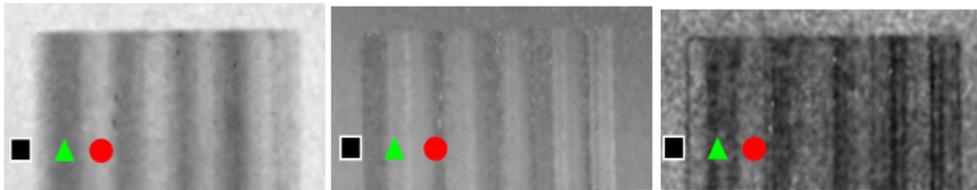


Dark field contrast

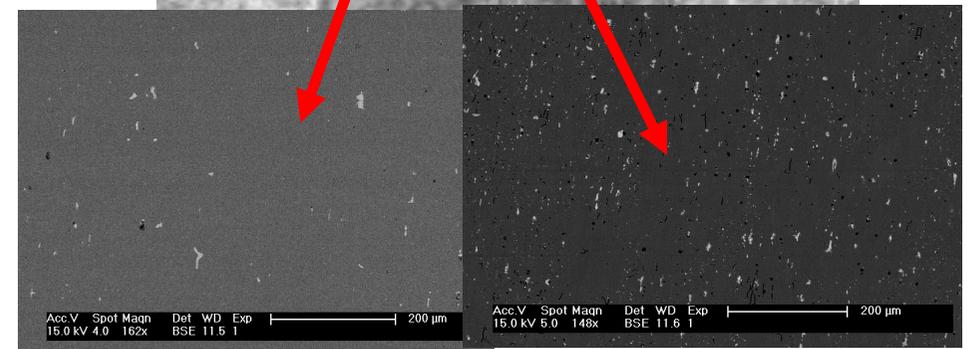
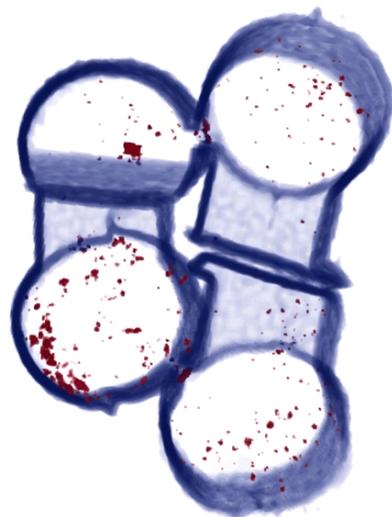
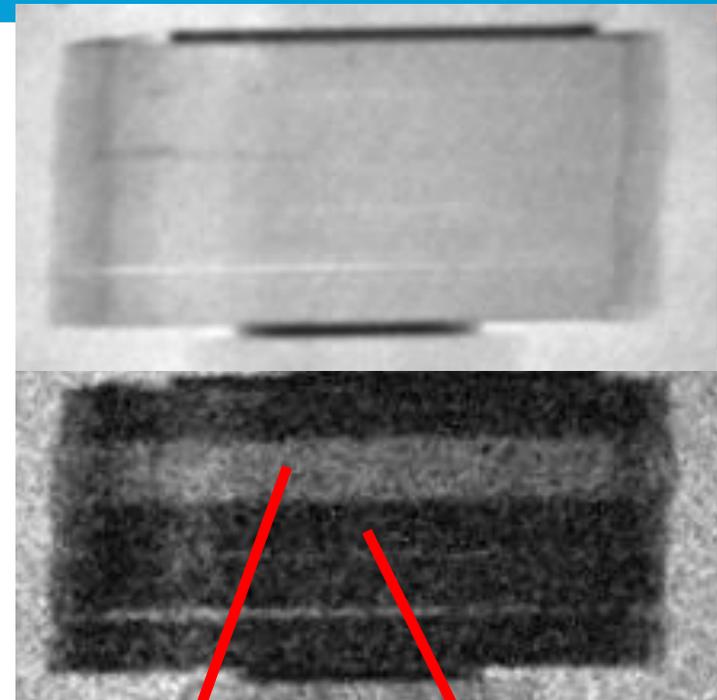
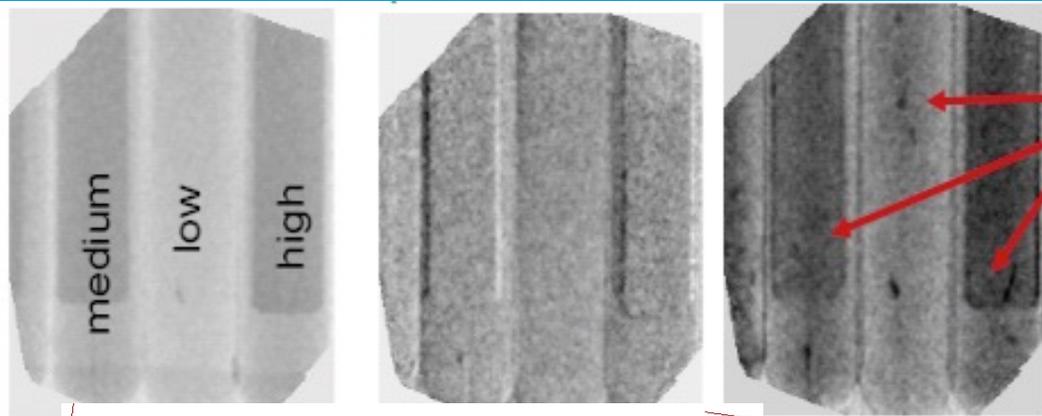


$$P_{\theta}(t) = w(\theta, t)^2 = \int_{path} \frac{\sigma(x, y)N(x, y)}{R^2(x, y)} \cdot ds$$

Dark field contrast



Dark field contrast

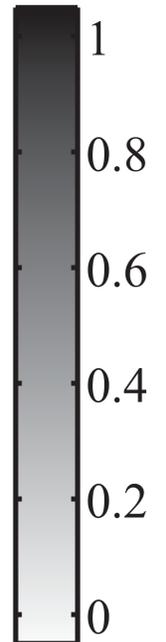
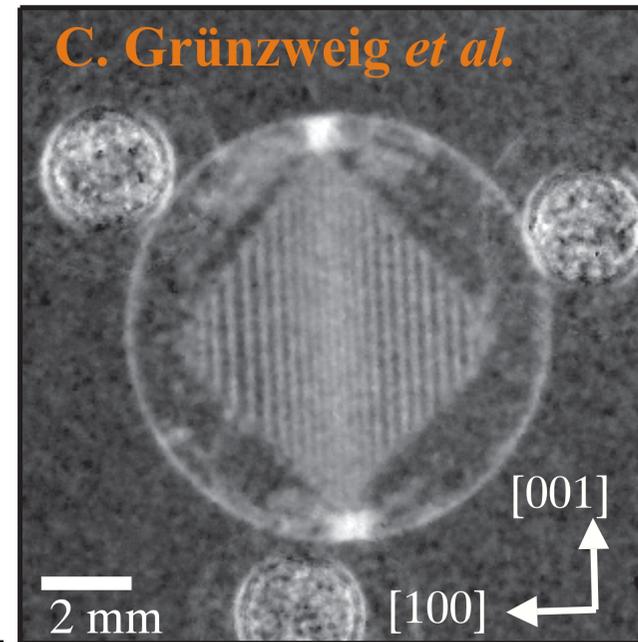
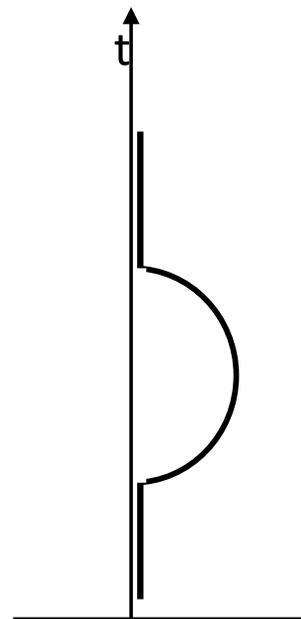
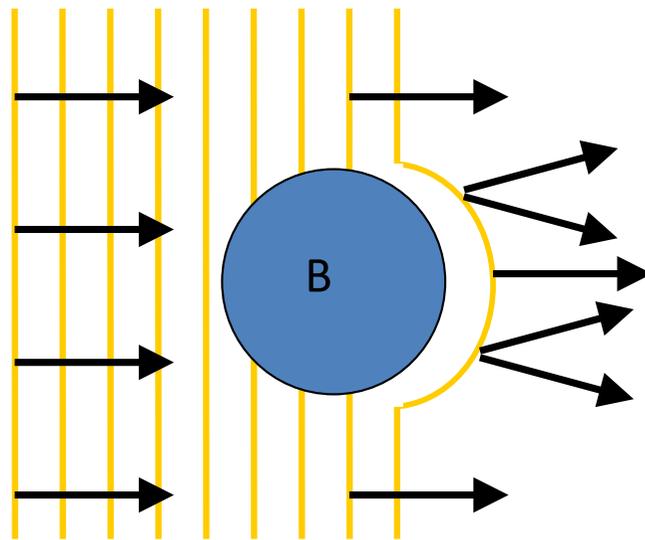


A. Hilger et al. JAP (2010)

Dark field contrast

Refractive index: **phase** **absorption** **magn. phase**

$$n(x, y, z, \lambda) = 1 - \delta(x, y, z, \lambda) - i\beta(x, y, z, \lambda) \pm \delta_B(x, y, z, \lambda, B)$$



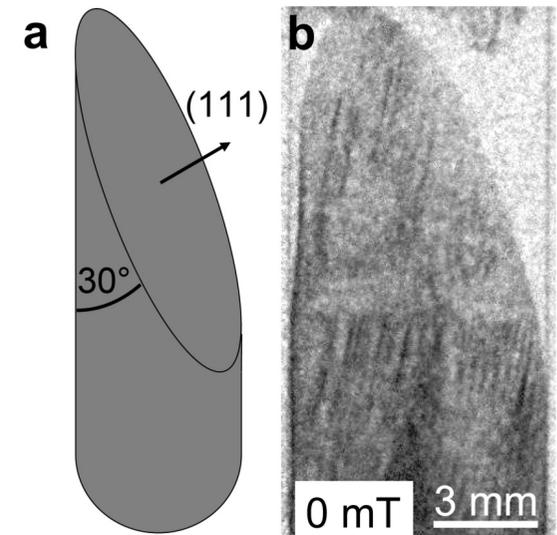
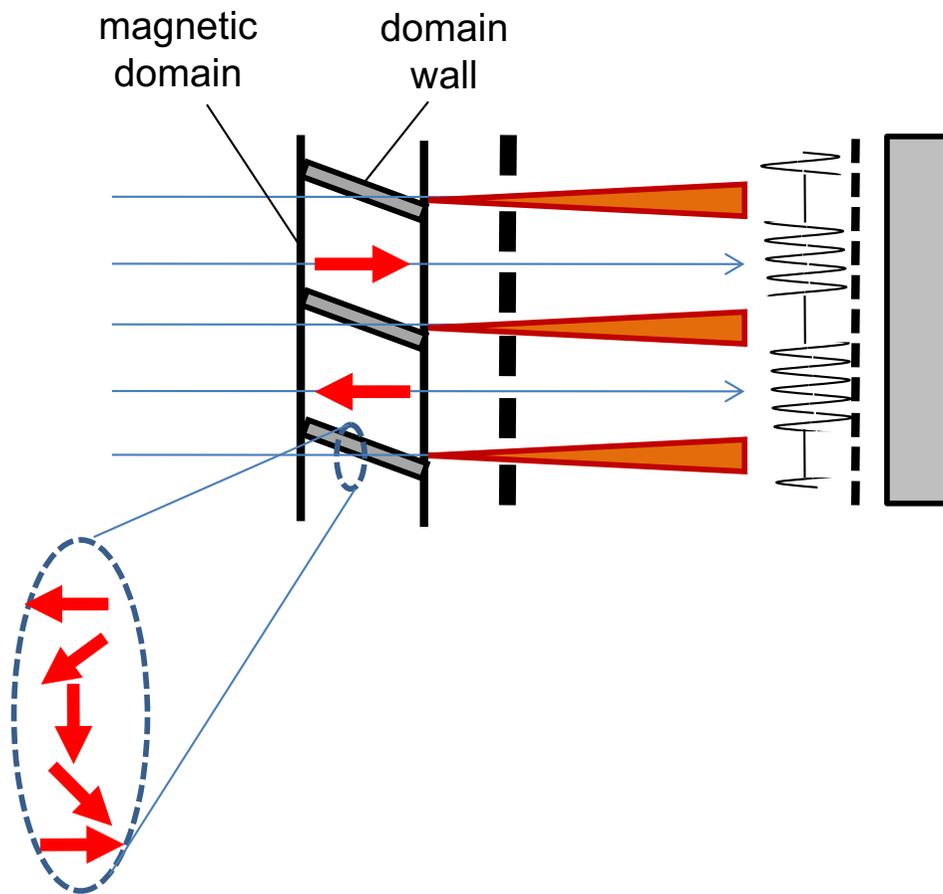
$$\varphi = -k \int_{-\infty}^z \delta(z') dz \quad \partial\varphi / \partial t$$

K.M. Podurets et al. Zh. Tekh. Fiz. 67 (1994)

M. Strobl et al., APL (2007)

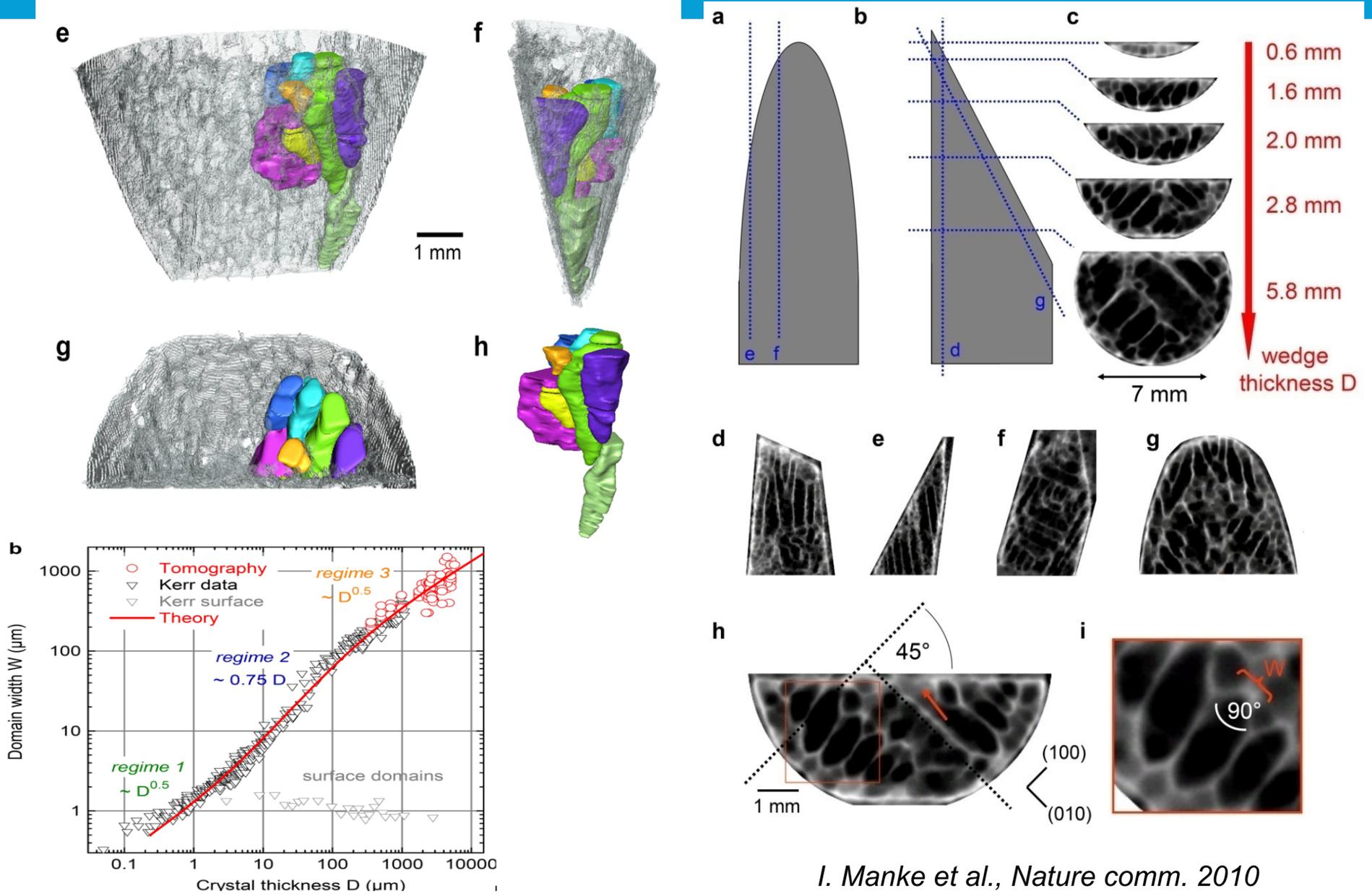
Ch. Gruenzweig et al. APL (2008)

Dark field contrast

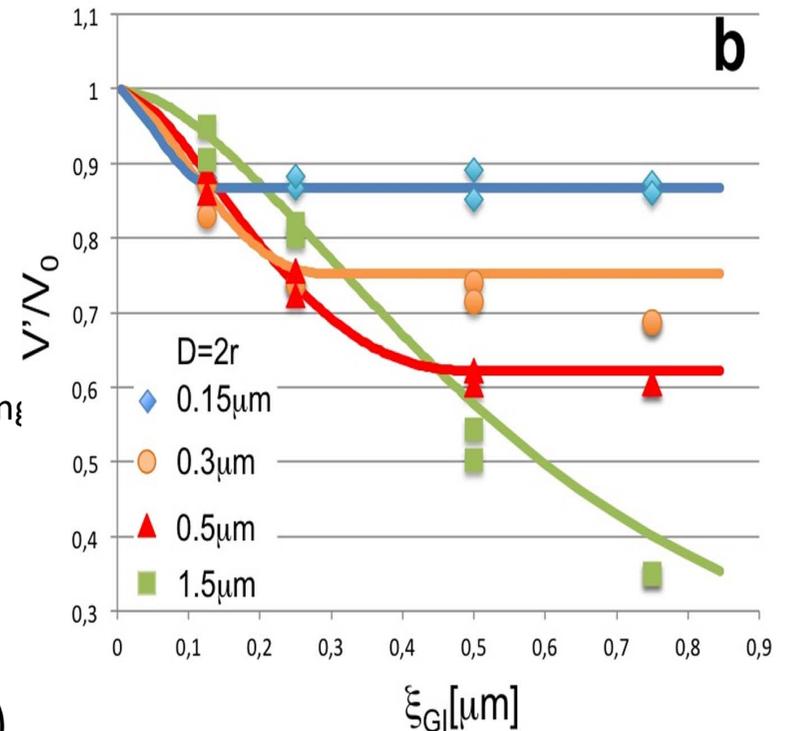
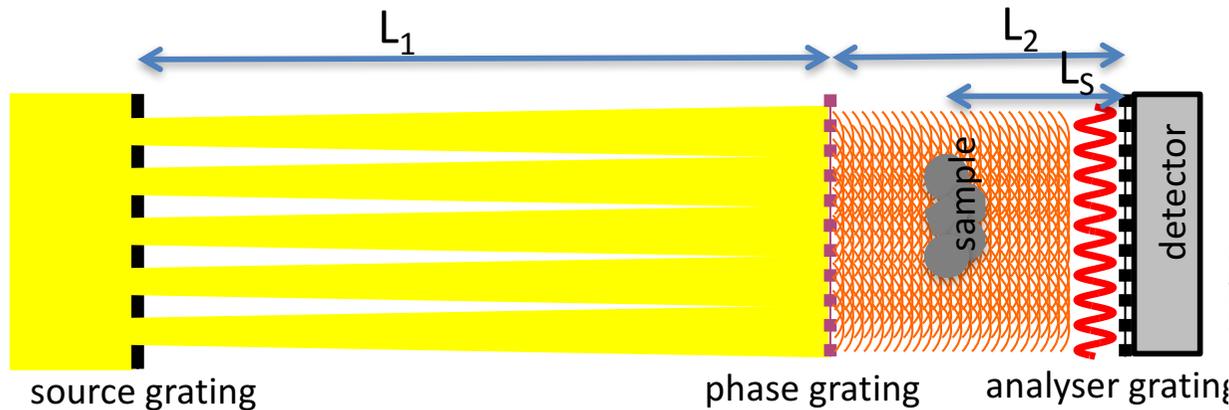


K. M. Podurets et al. Phys. B 1989
M. Strobl et al. APL 2007
Ch. Grünzweig et al. APL 2009

Dark field contrast



Dark field contrast – quantitative SANS



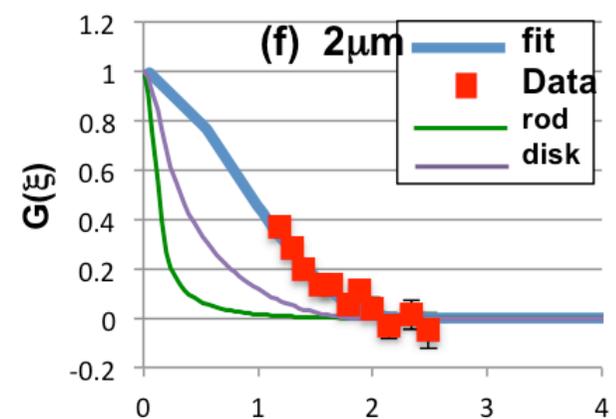
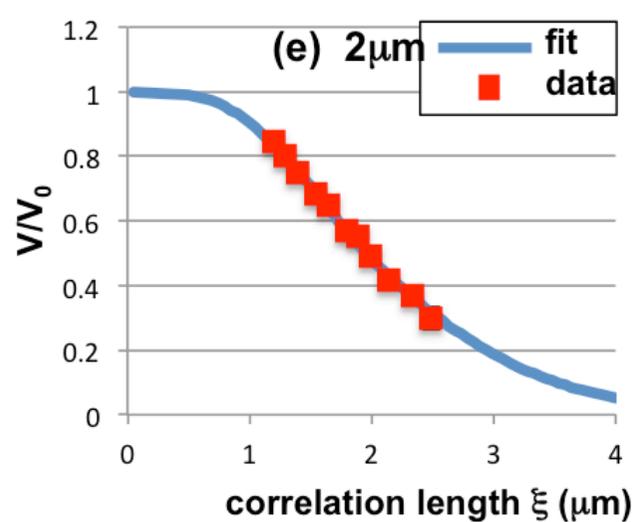
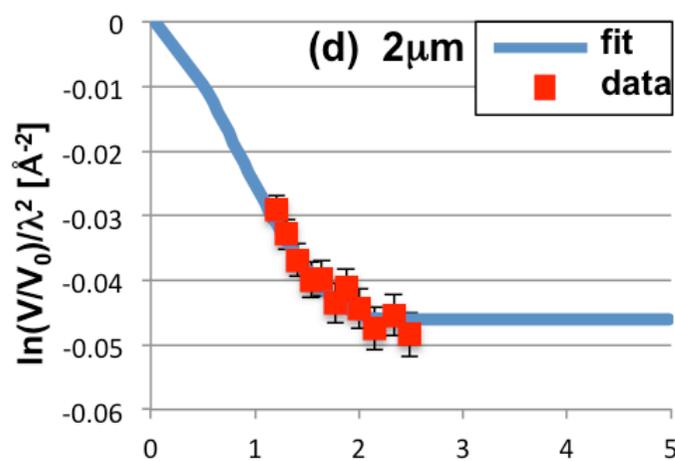
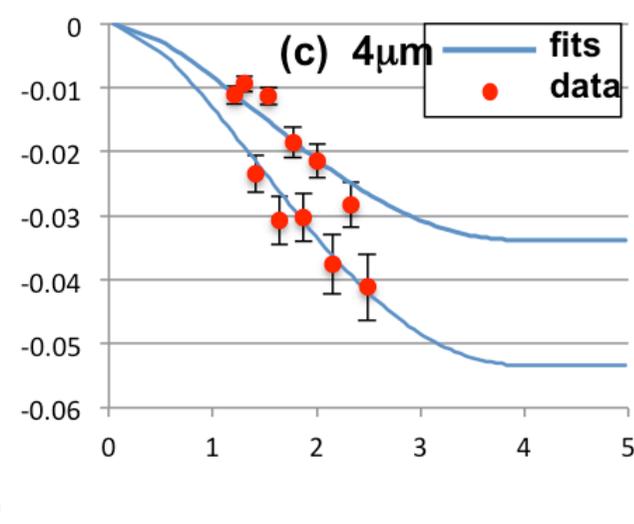
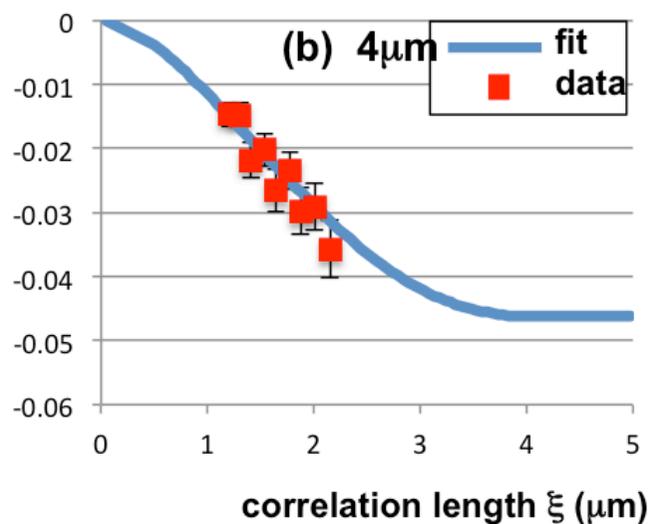
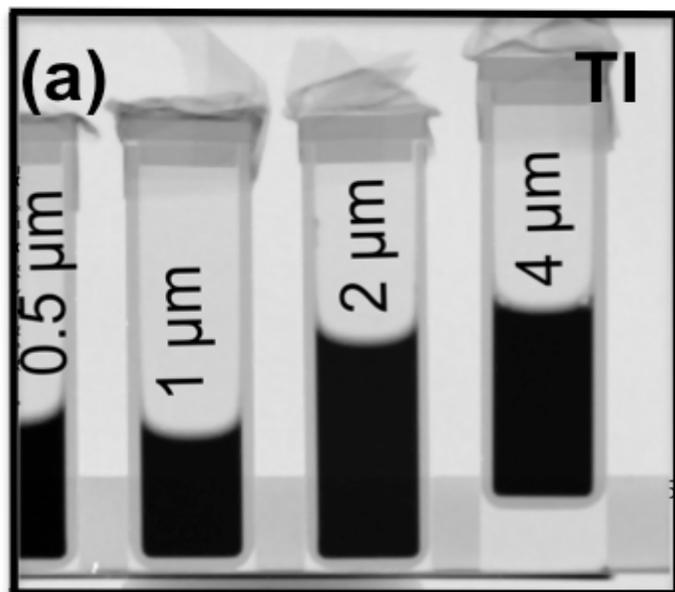
Visibility $V = (I_{\max} - I_{\min}) / (I_{\max} + I_{\min})$

$$V_s(\xi_{GI}, q) = V_0(\xi_{GI}) \int_{-\infty}^{\infty} dq S(q) \cos(\xi_{GI} q).$$

$$\xi_{GI} = \frac{\lambda L_s}{p}$$

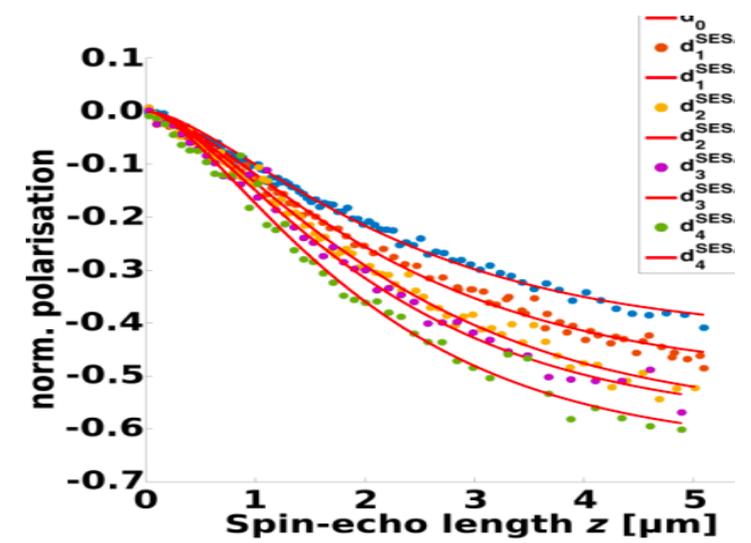
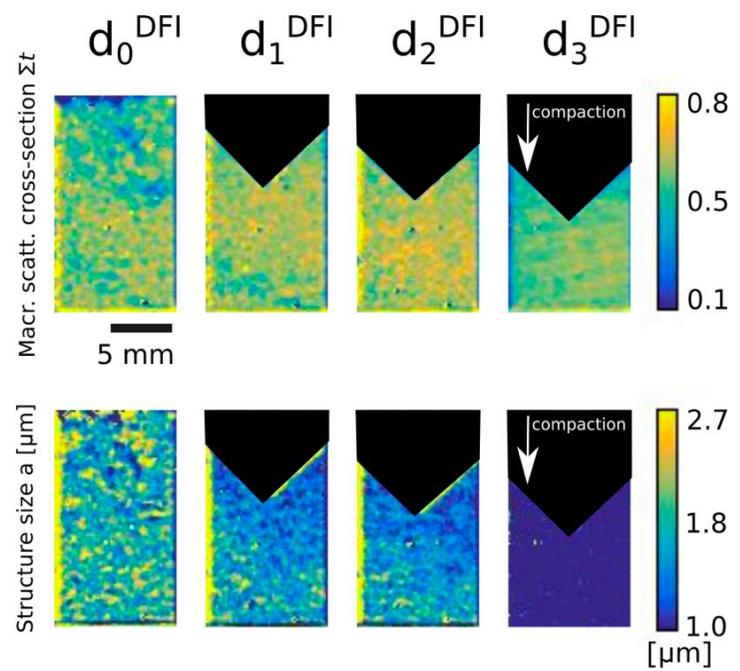
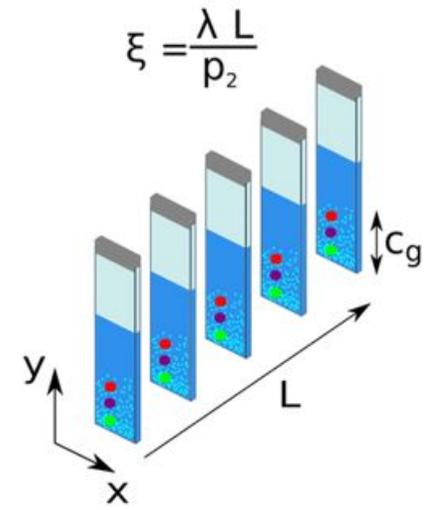
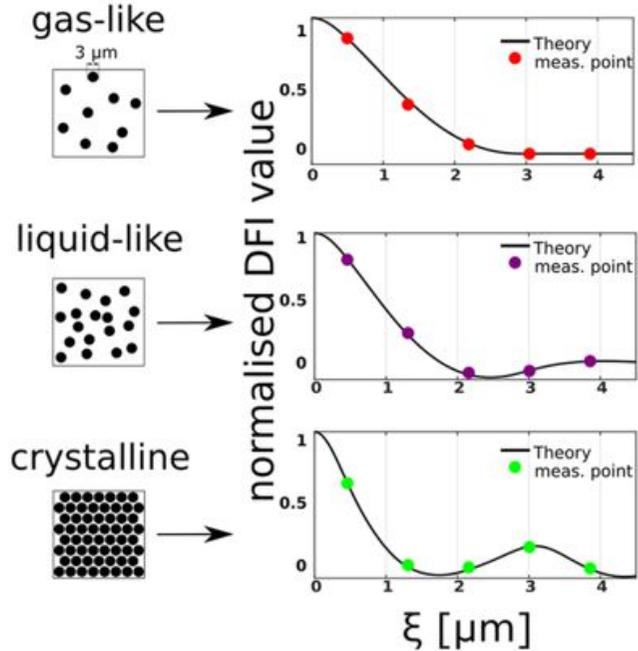
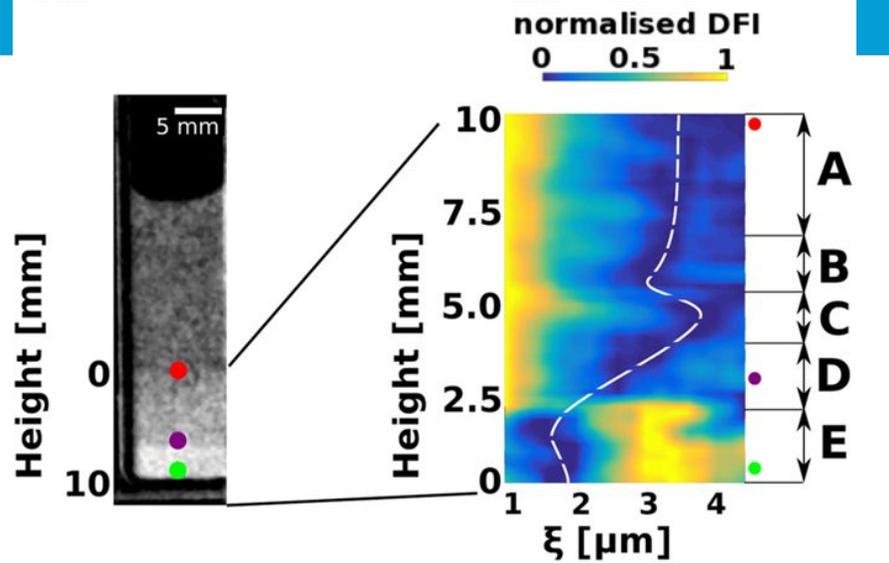
$$V_s(\xi_{GI}) / V_0(\xi_{GI}) = e^{\Sigma t (G(\xi_{GI}) - 1)}$$

Dark field contrast – quantitative SANS

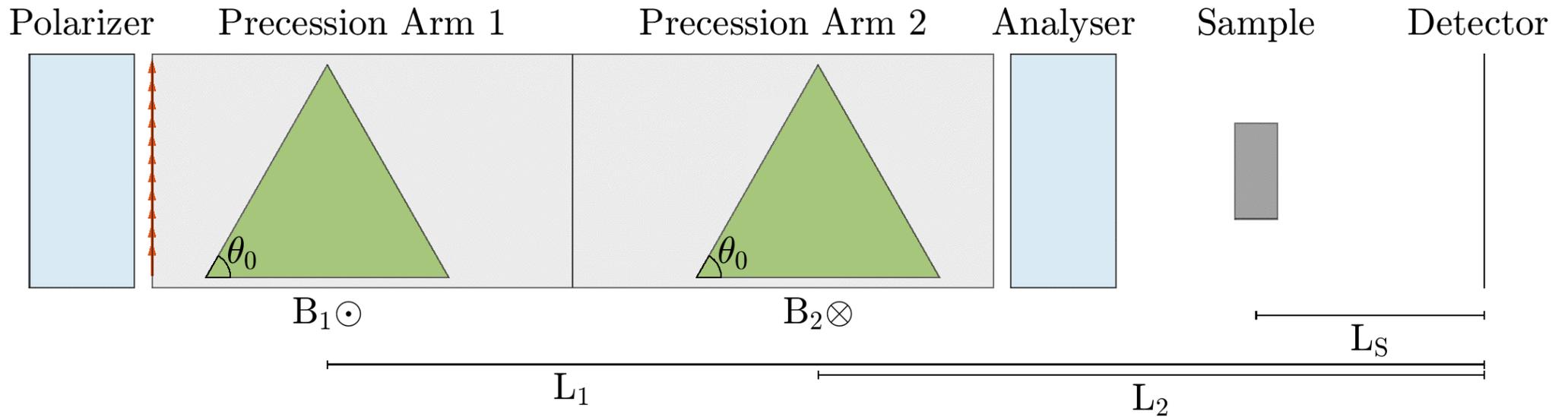


Energy dispersive

Dark field contrast – quantitative SANS



Dark-field contrast - Spin-Echo modulation



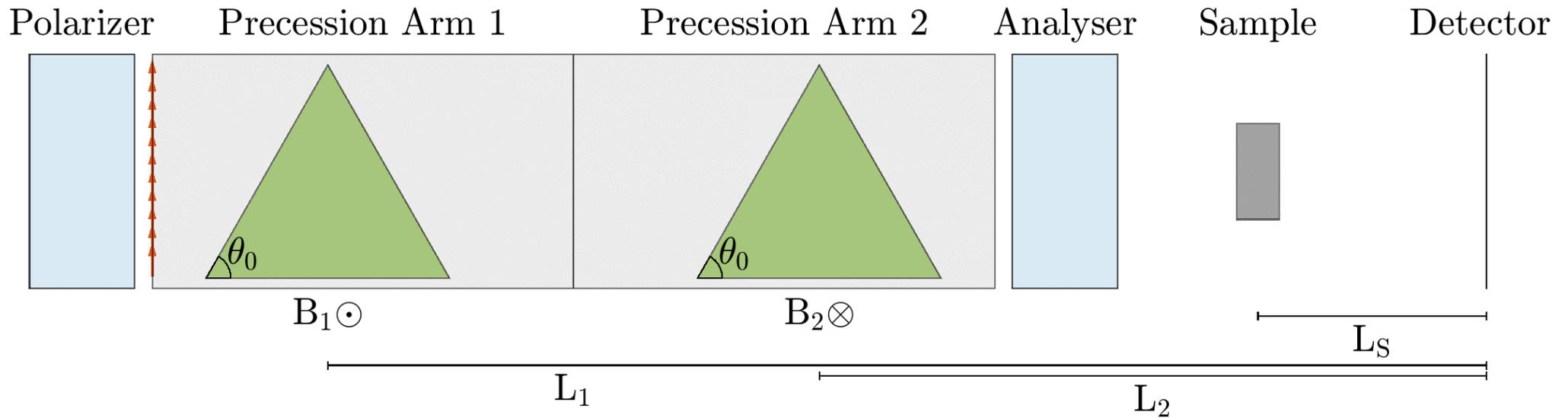
$$B_1 L_1 = B_2 L_2$$

$$p = \frac{\pi \tan \theta_0}{c\lambda(B_2 - B_1)}$$

R. Gähler @ PNCMI 2006

W. G. Bouwman et al. Phys. B (2009).

Dark-field contrast - Spin-Echo modulation



$$\delta^{SE} = \frac{c\lambda^2 L_S (B_2 - B_1)}{\pi \tan \theta_0} = \frac{\lambda L_S}{p}$$

Dark-field contrast - Spin-Echo modulation

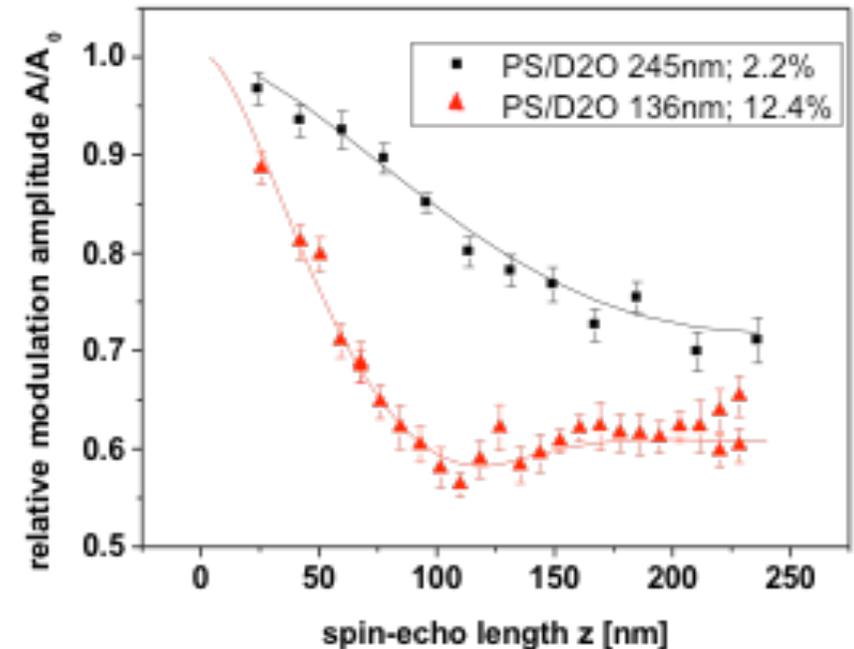
Visibility $V = (I_{\max} - I_{\min}) / (I_{\max} + I_{\min})$

$M = (I^+ - I^-) / (I^+ + I^-)$

$V_s / V_0 = M_s / M_0$

$$V_s(\xi_{GI}) / V_0(\xi_{GI}) = e^{\Sigma t(G(\xi_{GI}) - 1)}$$

M. Strobl Scientific Reports 4 7243 (2014)

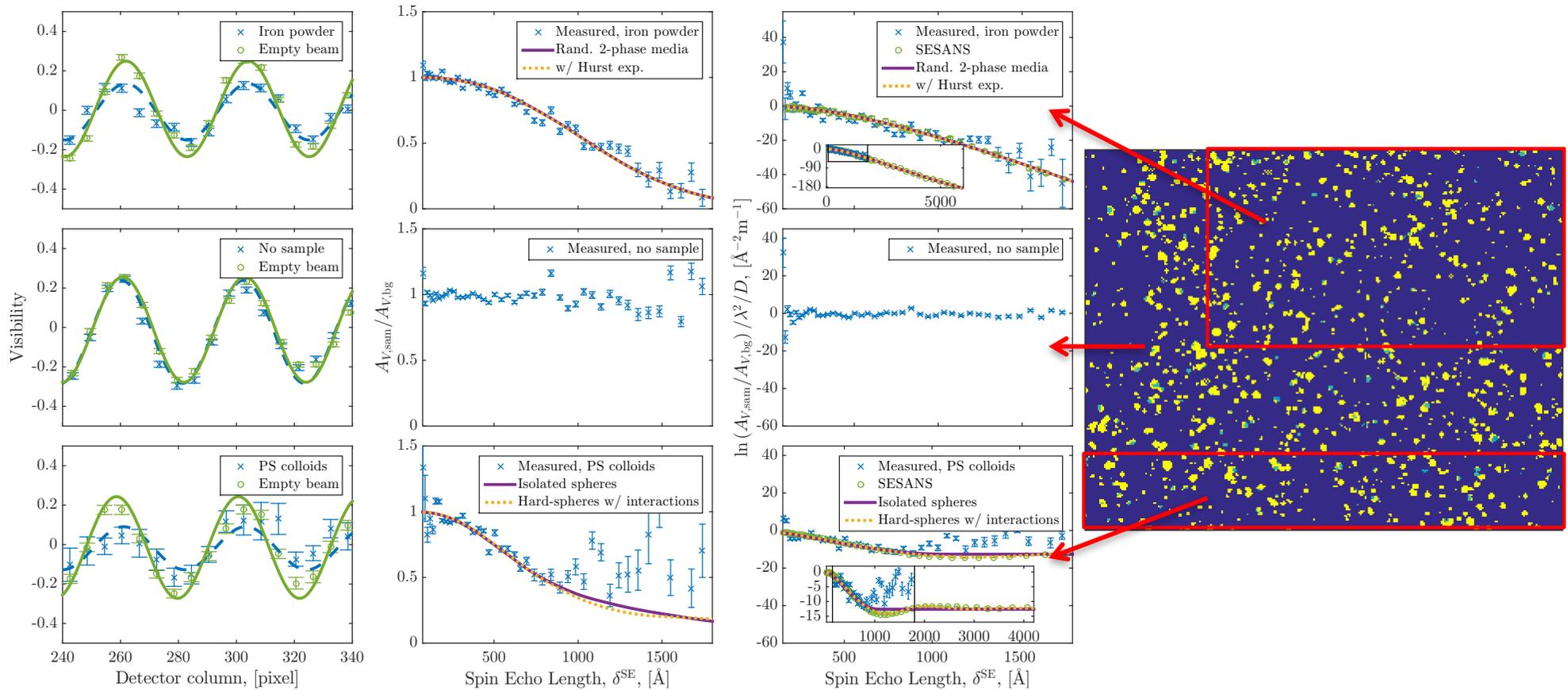


$$\xi_{GI} = \frac{\lambda L_s}{p}$$

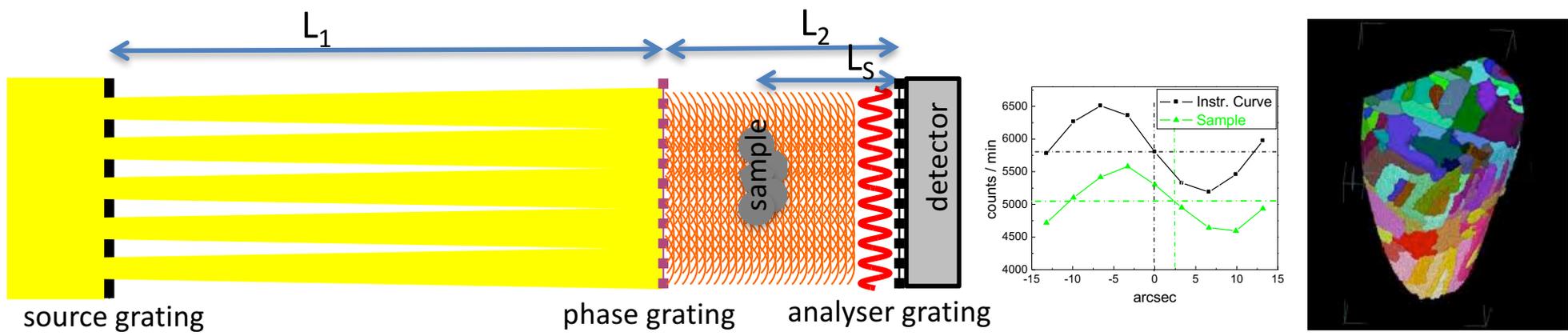
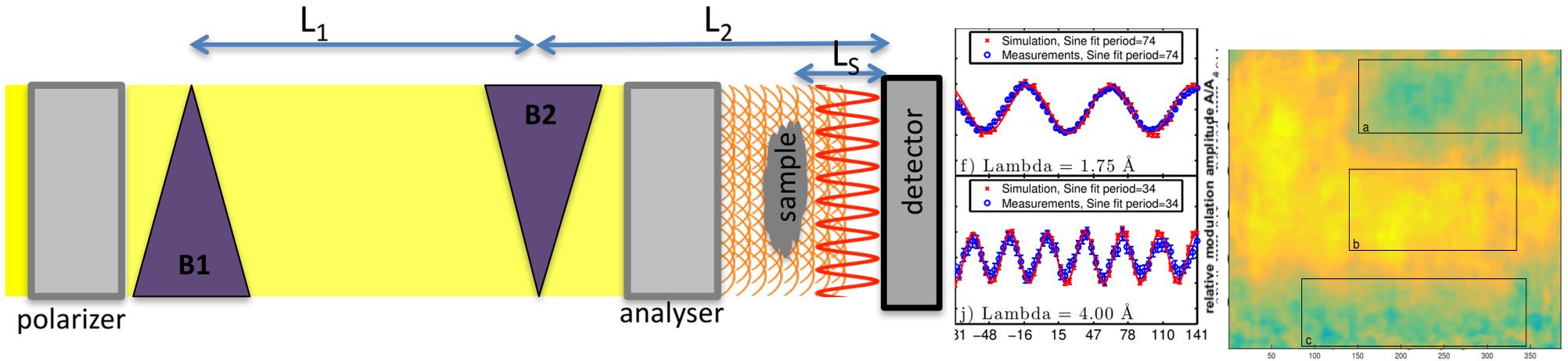
equivalent

$$\delta^{SE} = \frac{c\lambda^2 L_s (B_2 - B_1)}{\pi \tan \theta_0} = \frac{\lambda L_s}{p}$$

Dark-field contrast - Spin-Echo modulation

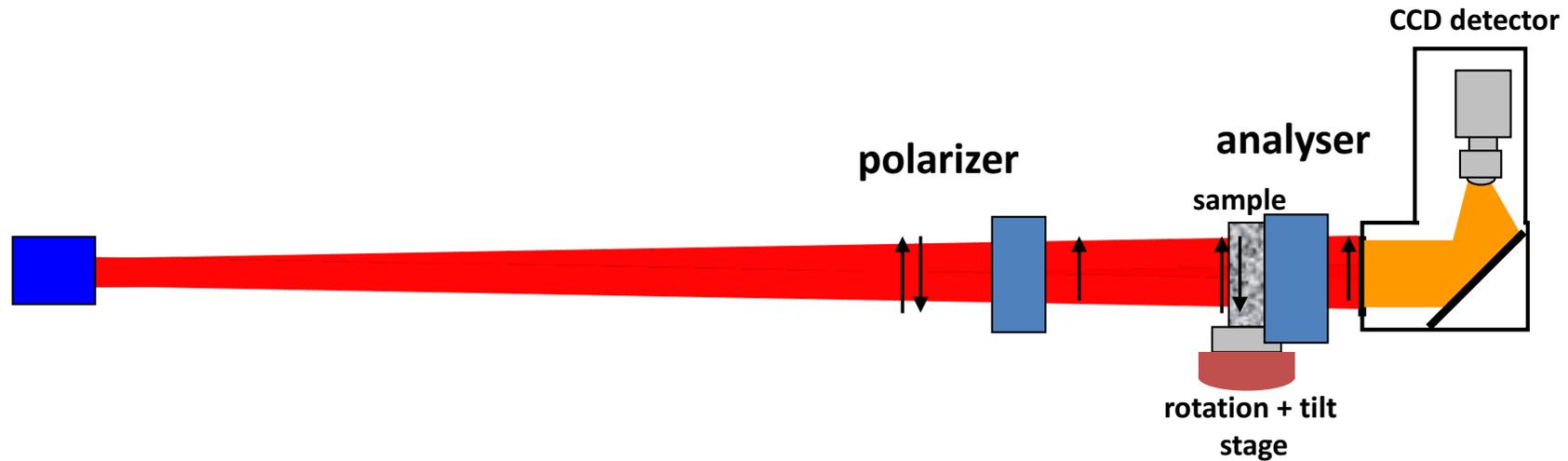


Dark-field contrast - Beam modulation



- **Wavelength resolved imaging**
 - Attenuation contrast
 - Dark-field contrast
 - **Polarized neutron imaging**

Imaging with polarized neutrons



$$I(x, y) = I_0(x, y) \cdot \exp\left(- \int_{\text{path}} \sigma \cdot ds\right)$$

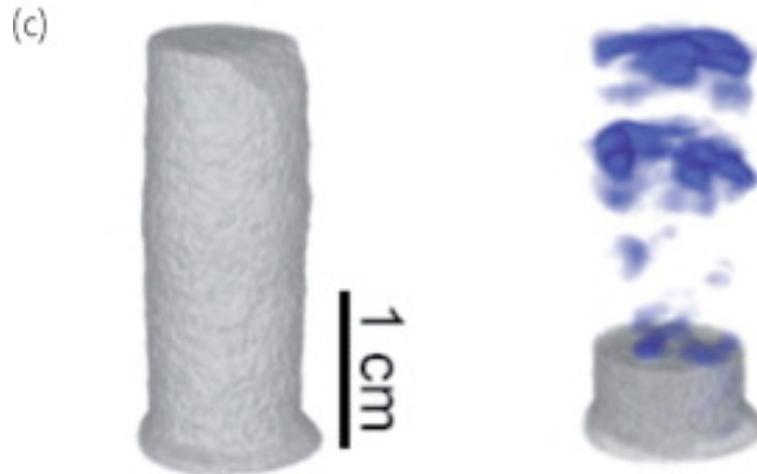
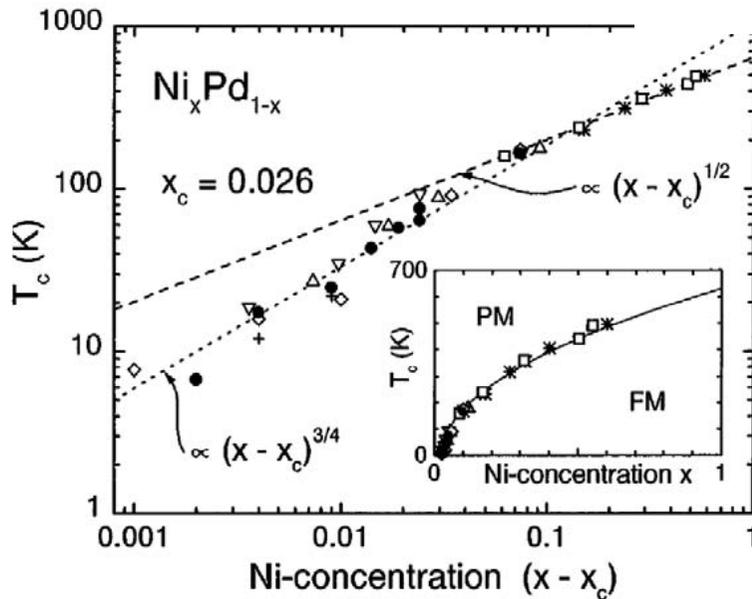
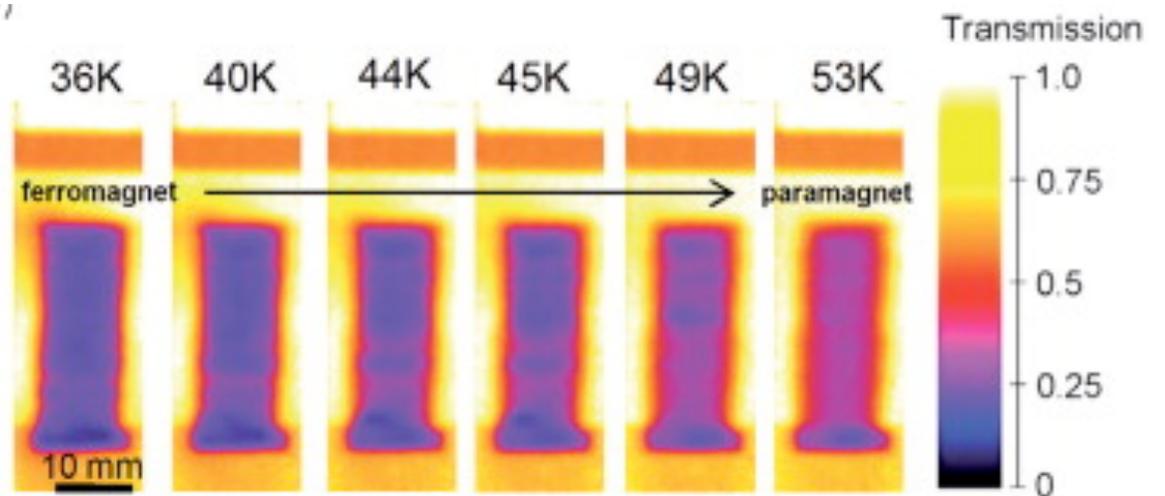
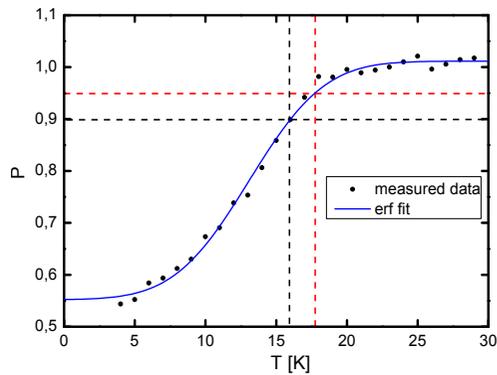
$$\varphi = \int_{\text{path}} \frac{\lambda m_n \gamma_n B}{h} ds$$

$$|P| \approx 1 \rightarrow |P| \approx 1$$

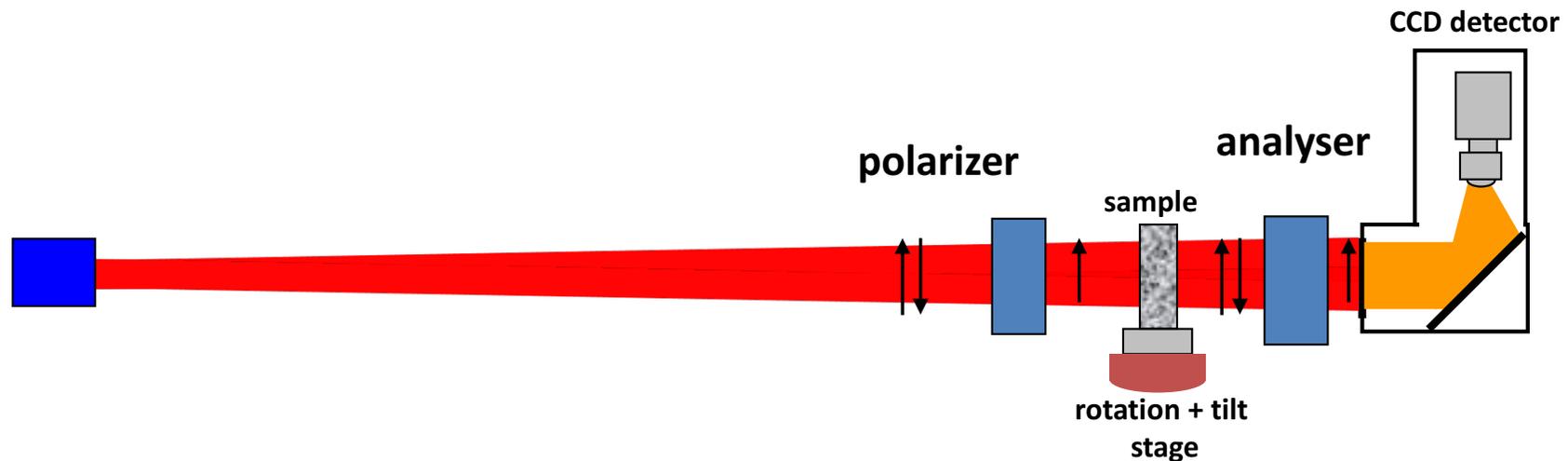
or

$$|P| \approx 1 \rightarrow |P| \approx 0$$

Imaging with polarized neutrons



Imaging with polarized neutrons



$$I(x, y) = I_0(x, y) \cdot \exp\left(- \int_{\text{path}} \sigma \cdot ds\right)$$

$$\varphi = \int_{\text{path}} \frac{\lambda m_n \gamma_n B}{h} ds$$

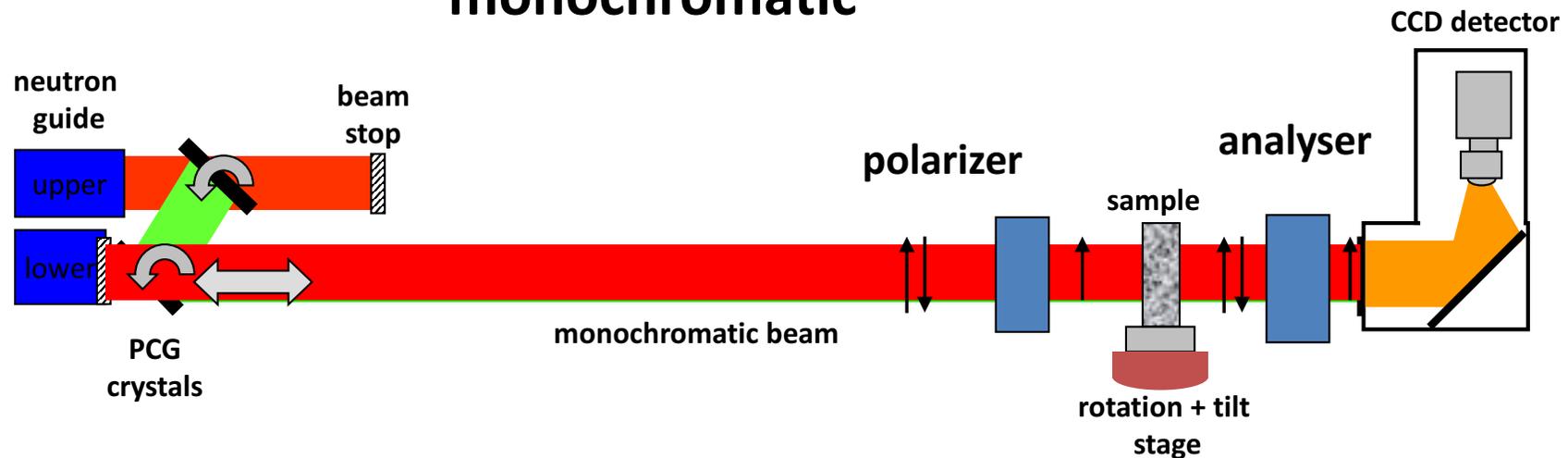
$$|P| \approx 1 \rightarrow |P| \approx 1$$

or

$$|P| \approx 1 \rightarrow |P| \approx 0$$

Imaging with polarized neutrons

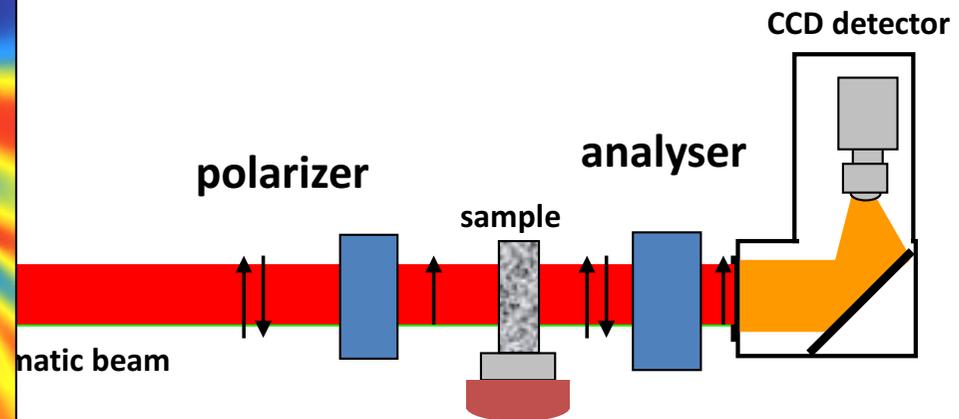
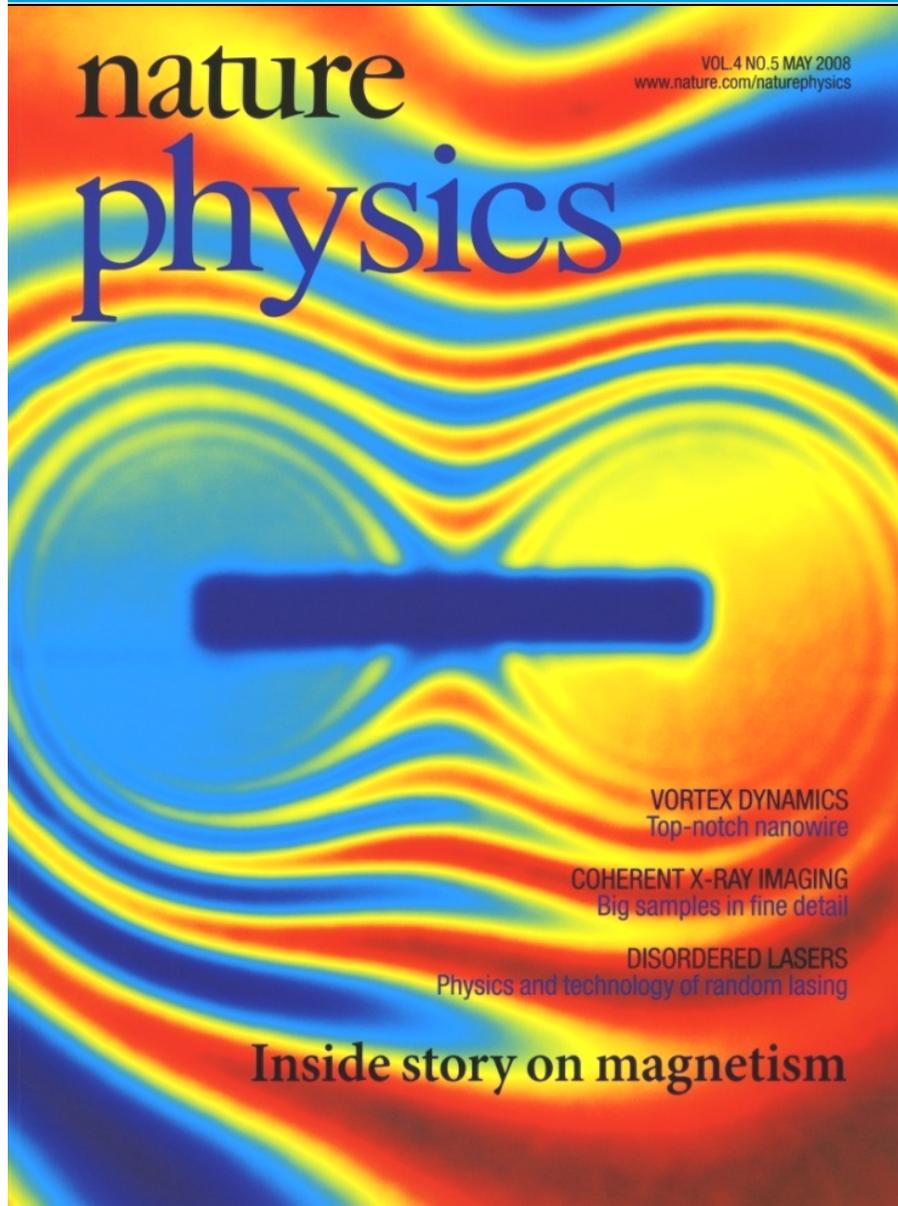
monochromatic



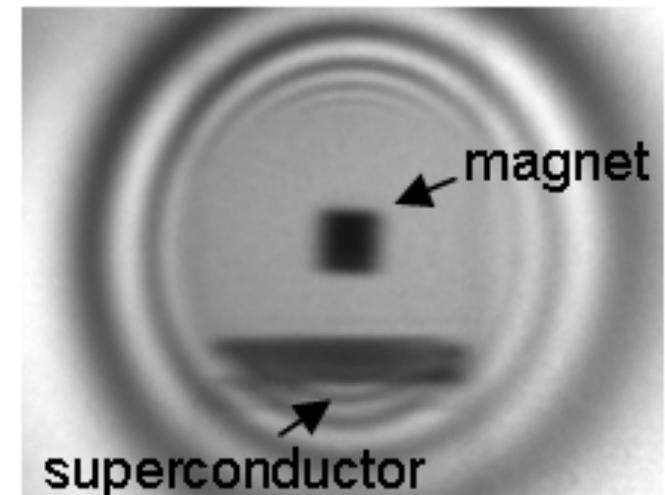
$$I(x, y) = I_0(x, y) \cdot \exp\left(-\int_{\text{path}} \sigma \cdot ds\right) \cdot \frac{1}{2} (1 + \cos \varphi(x, y)) \quad |P| \approx 1 \quad \rightarrow \quad 0 \leq |P| \leq 1$$

$$\varphi = \int_{\text{path}} \frac{\lambda m_n \gamma_n B}{h} ds$$

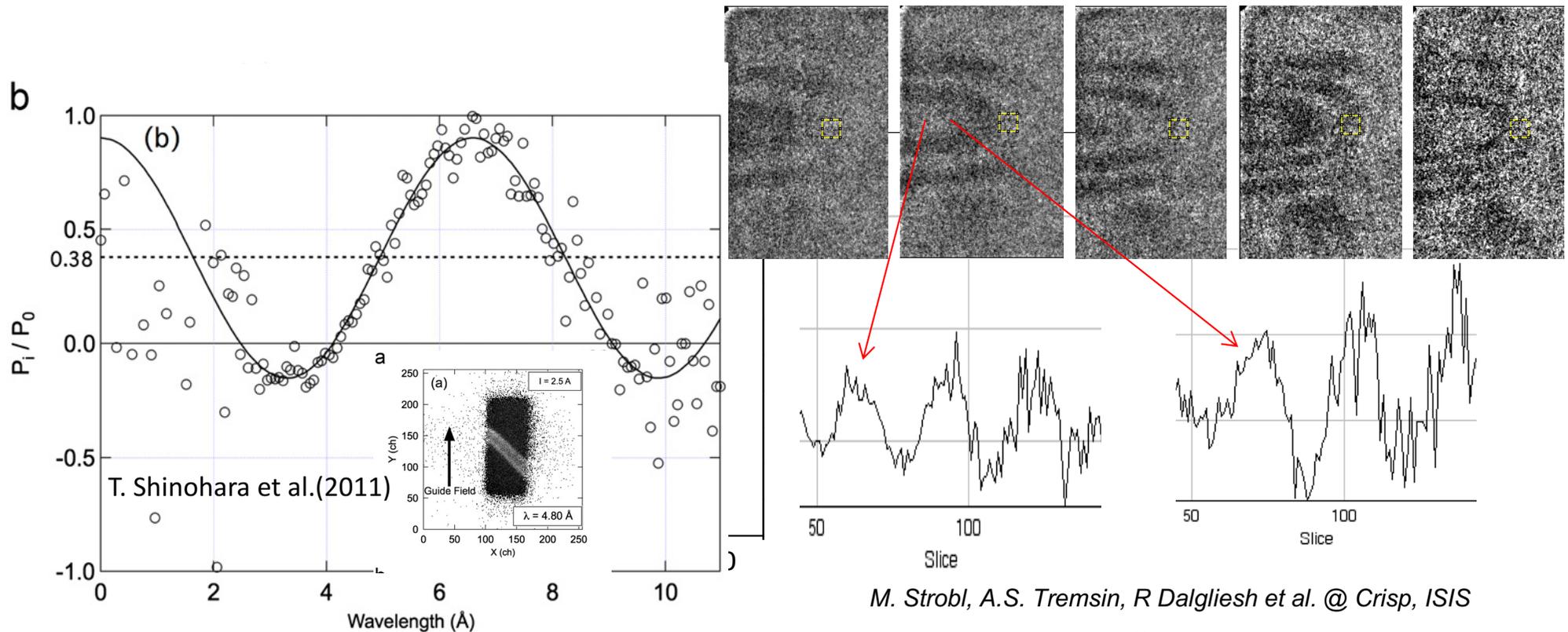
Imaging with polarized neutrons



$$(1 + \cos \varphi(x, y))$$



Imaging with polarized neutrons

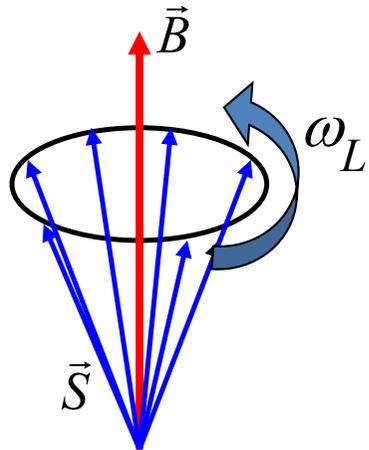


$$I(x, y) = I_0(x, y) \cdot \exp\left(-\int_{\text{path}} \sigma \cdot ds\right) \cdot \frac{1}{2} (1 + \cos \varphi(x, y))$$

$$\varphi = \int_{\text{path}} \frac{\lambda n_n \gamma_n B}{h} ds$$

Quantification requires/possible through **energy dispersive imaging**

Imaging with polarized neutrons

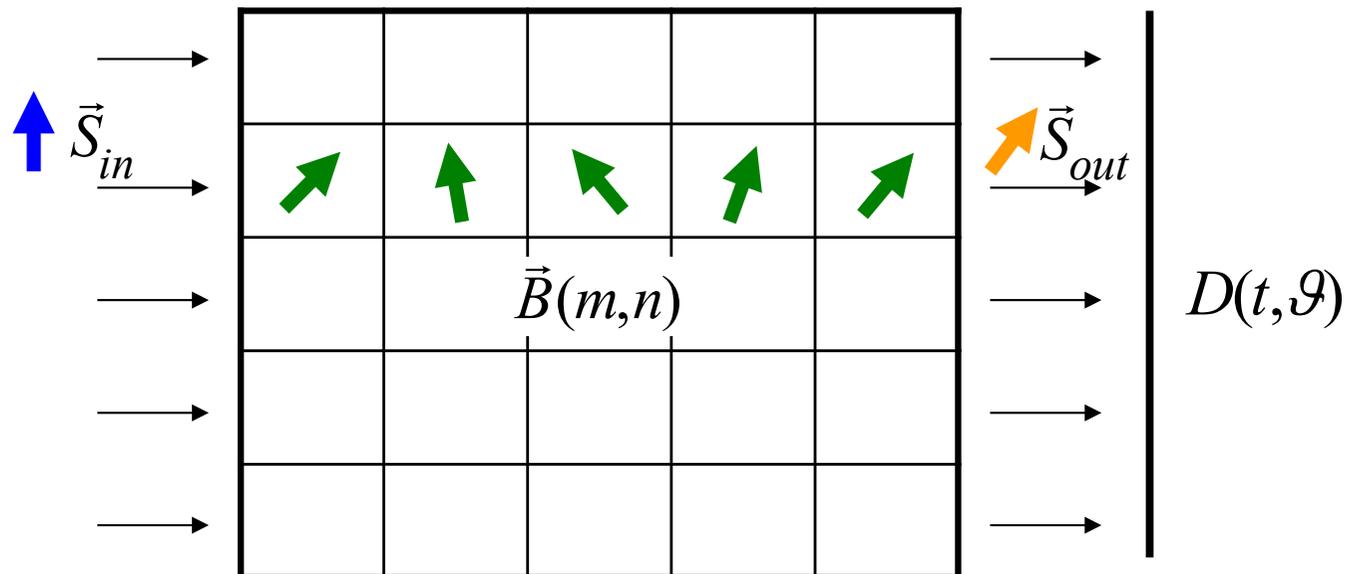


Larmor frequency:

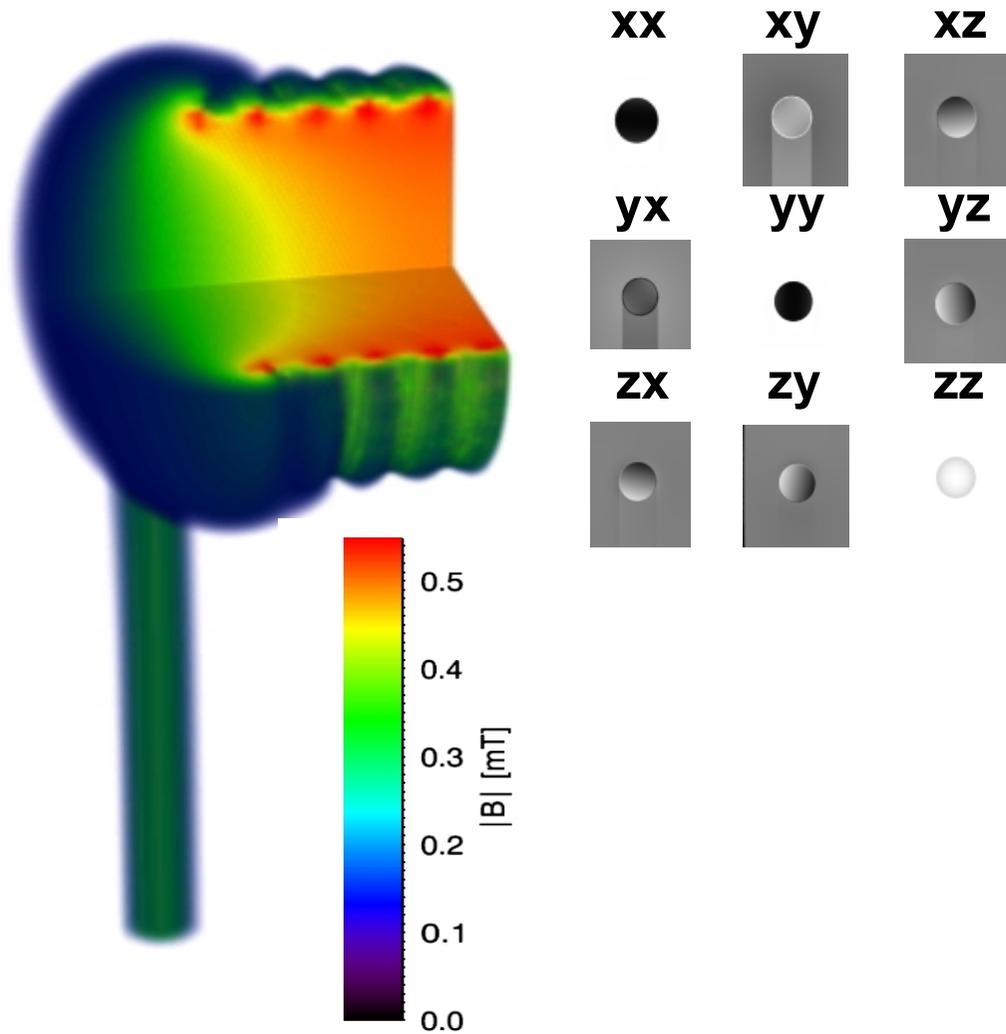
$$\omega_L = \gamma B$$

Gyromagnetic ratio:

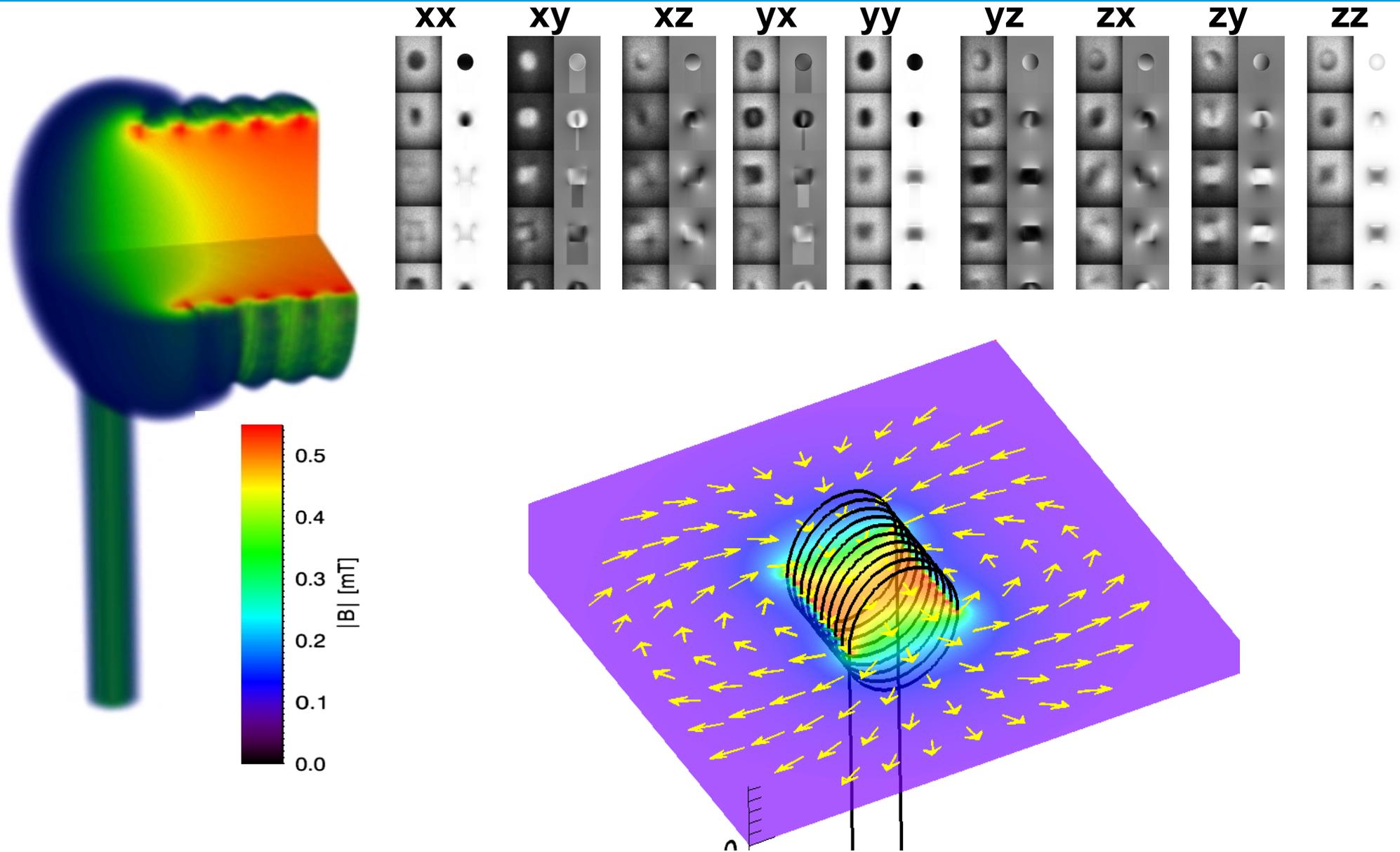
$$\gamma = 1.83 \cdot 10^8 \frac{\text{rad}}{\text{s} \cdot \text{T}}$$

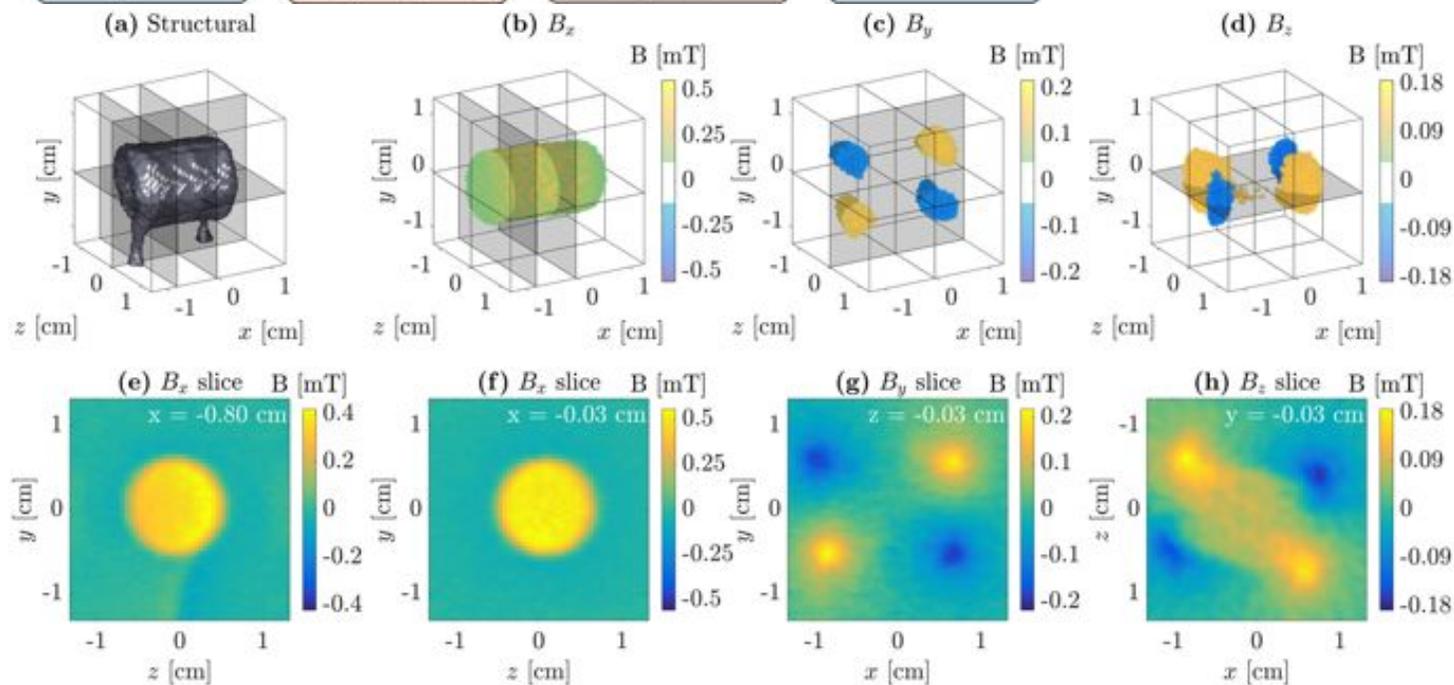
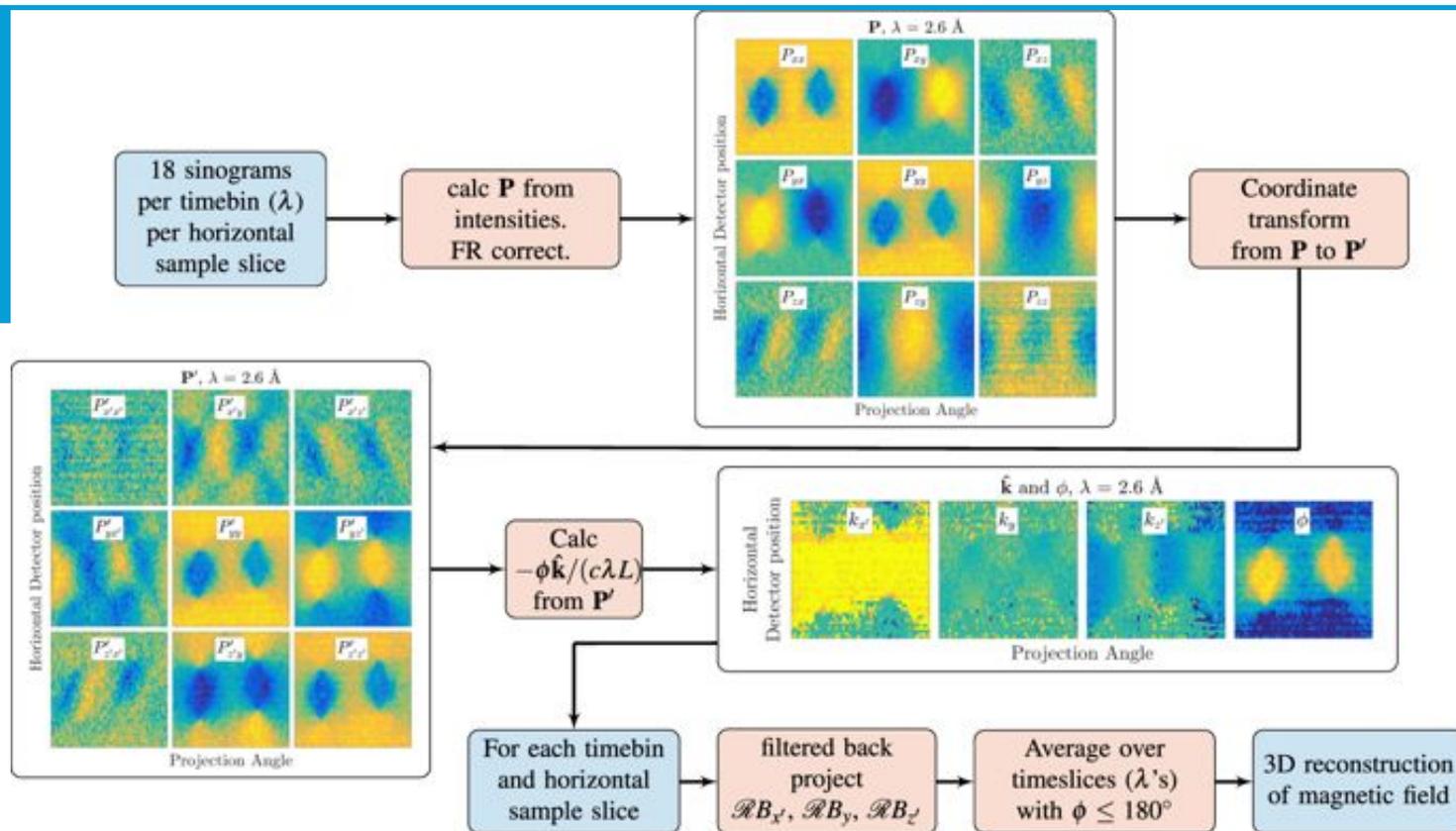


Imaging with polarized neutrons



Imaging with polarized neutrons





Conventional (white beam) Imaging

- White beam
 - Attenuation contrast

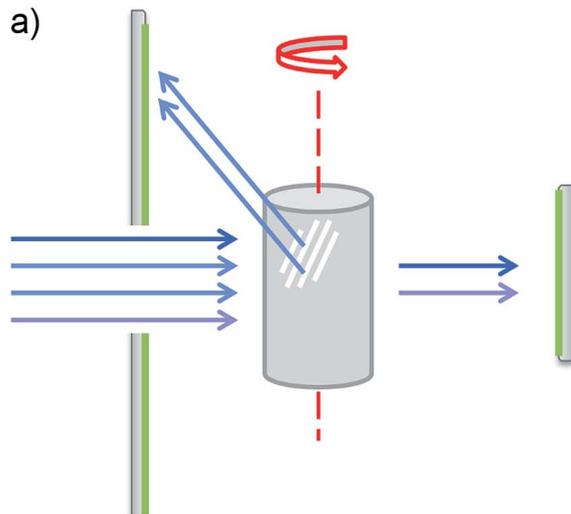
Advanced (wavelength resolved) Imaging

- Wavelength resolved imaging
 - Attenuation contrast
 - Dark-field contrast
 - Polarized neutron imaging
- White beam polarized neutron imaging
- **White beam diffraction imaging**

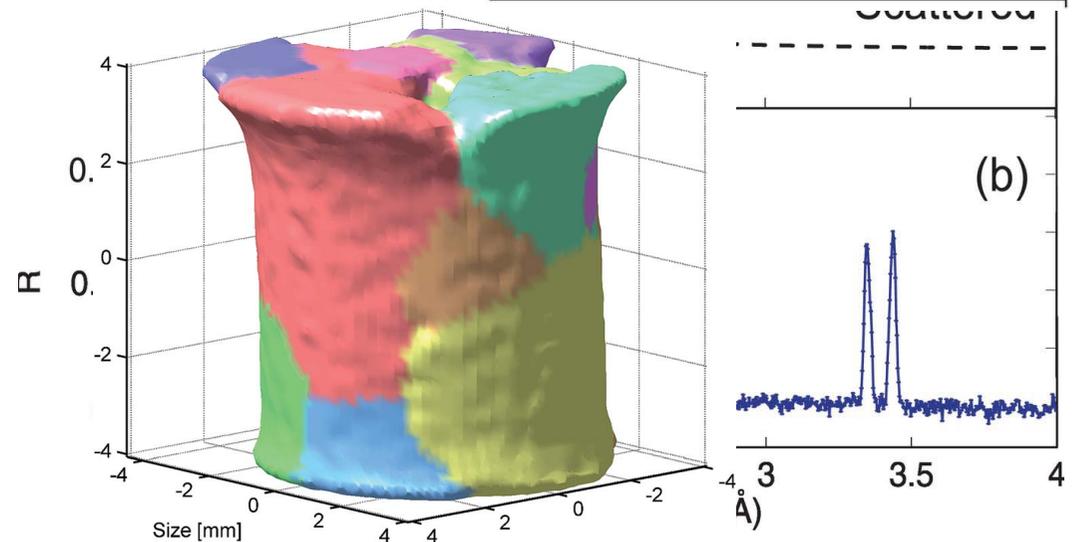
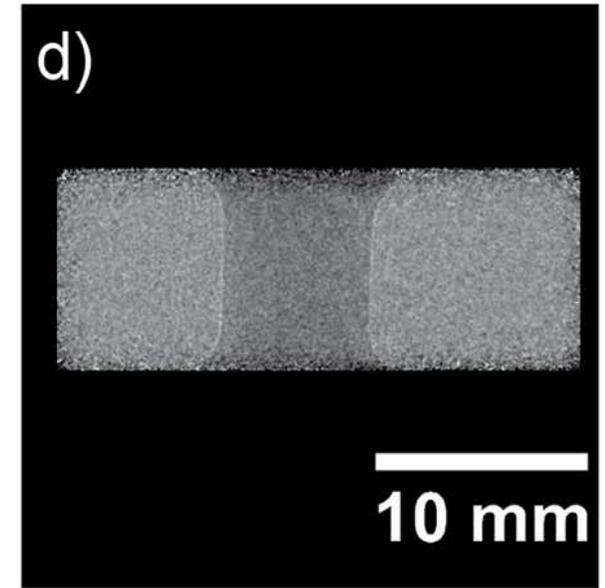
Advanced Imaging

White beam diffraction imaging

S. Peetermans et al., The Analyst (2014)



No grain info in transmission
Requires imaging detectors in diffraction geometry
-> limited number of grains accessible



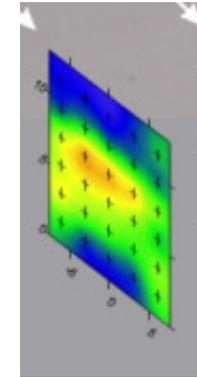
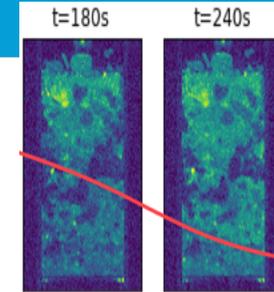
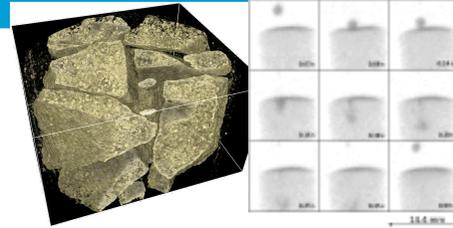
Imaging

2D

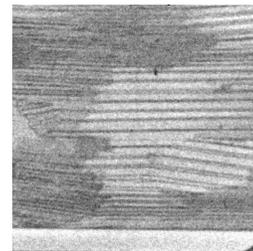
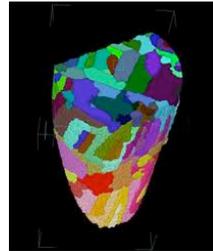
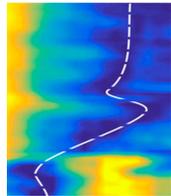
3D

4D...

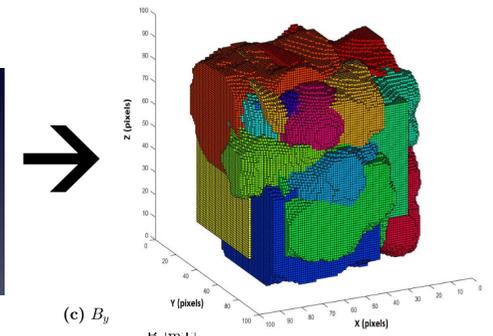
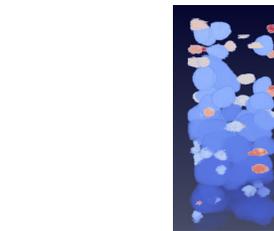
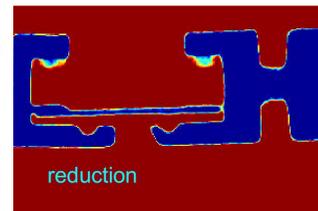
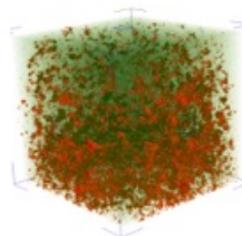
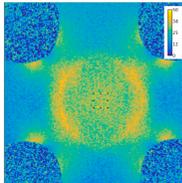
White beam
attenuation



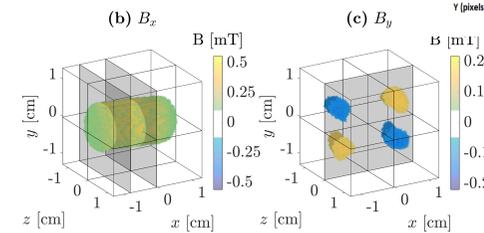
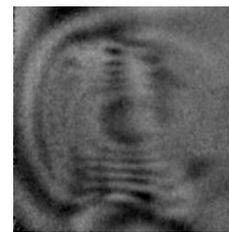
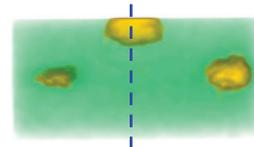
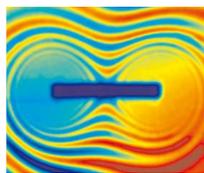
-Phase & Dark-field



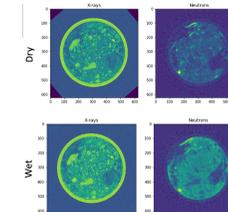
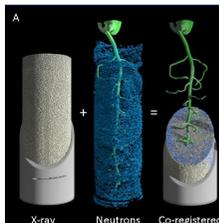
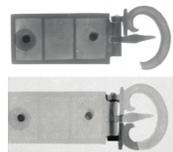
-Diffraction Contrast



-Polarisation Contrast



-Bi-modal





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www.europeanspallationsource.se

Lund Imaging School, Oct. 2018

