University of Heidelberg

HELMHOLTZ
ZENTRUM BERLIN
für Materialien und Energie

# Advances in neutron imaging

M. Strobl

# Content

**I. Neutron imaging**

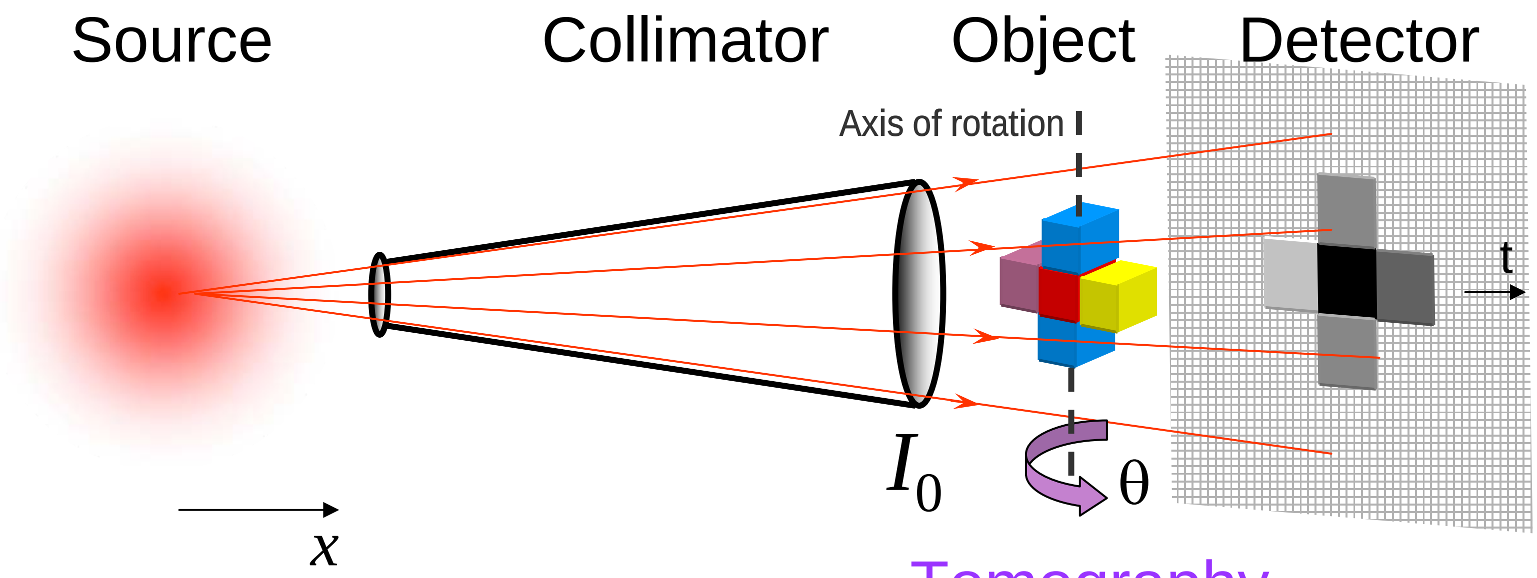
**II. Energy resolved neutron imaging**

**III. Dark field contrast imaging**

**IV. Polarised neutron imaging**

**VI. Outlook & Discussion**

# Neutron Imaging




Tomography

$$\sim I_0 e^{-\int \Sigma(x)dx}$$

Radon Transformation

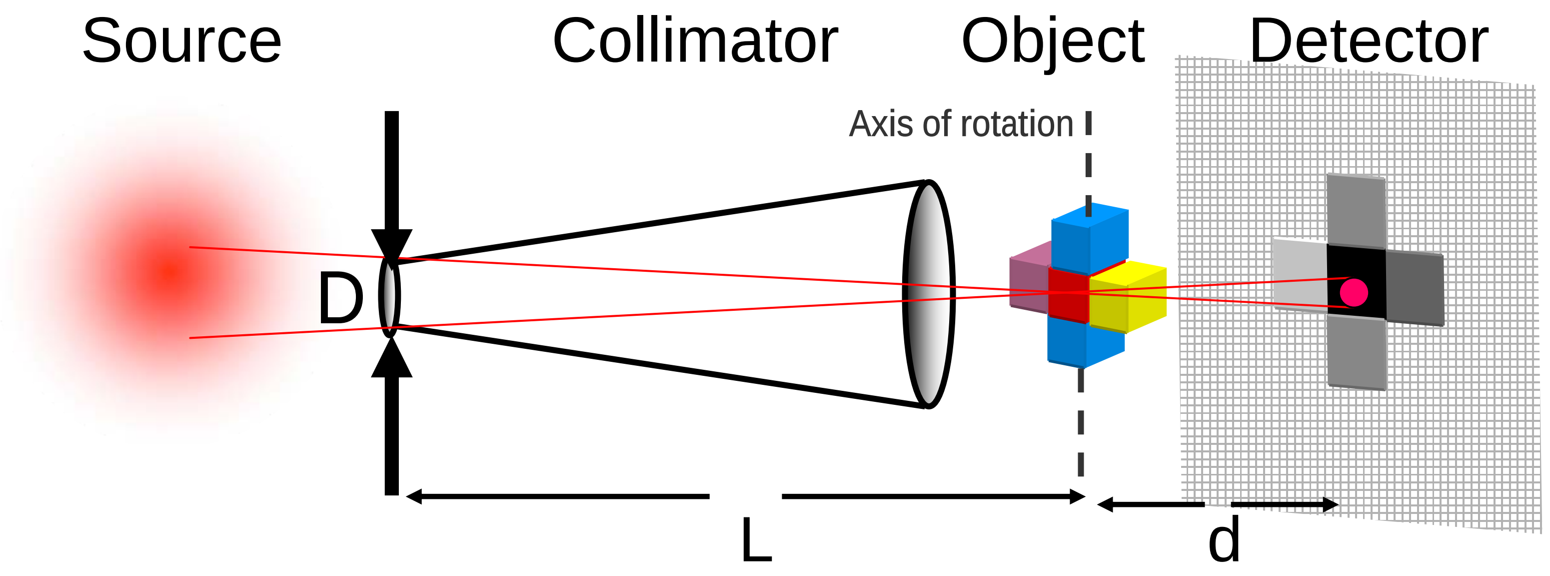
$$P_\theta(t) = \ln \frac{I(t,\theta)}{I_0} = \int_{path} \mu_\theta(x, y(x,t,\theta))ds$$

$I_0$ – primary beam

$\Sigma(x)$ – attenuation coefficient

$x$ – propagation direction

# Neutron Imaging



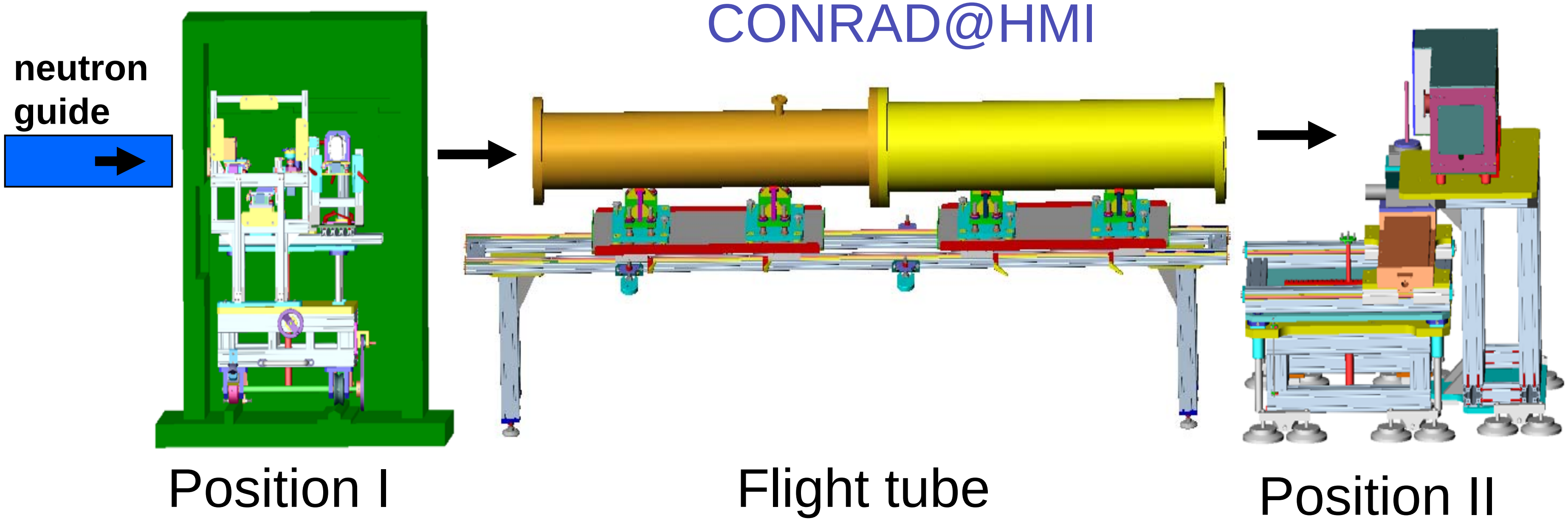

blur
collimation ratio

$$b = \frac{d}{L/D}$$

typical: several 100

# Neutron Imaging

CONRAD@HMI

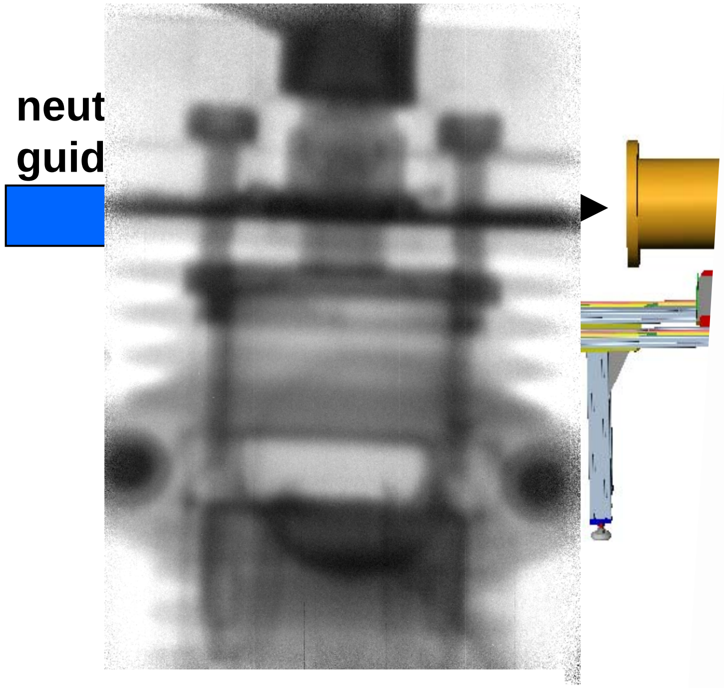


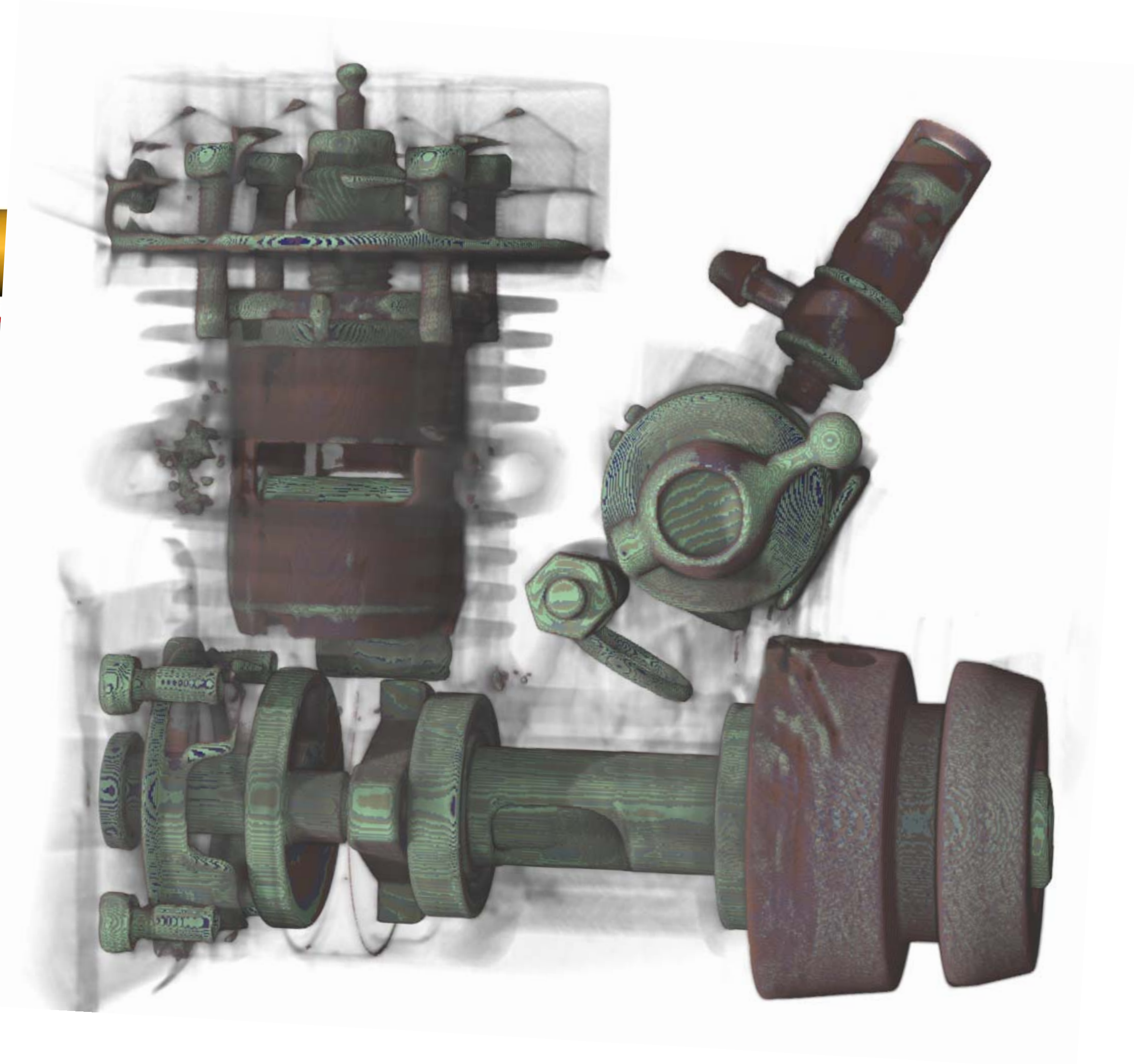

- ✓ Flux: 2.0x10$^8$ n/cm$^2$s
- ✓ Beam size: 5 x 3 cm$^2$
- ✓ L/D ~ 70

- ✓ Flux: 5.8x10$^6$ n/cm$^2$s (L/D 521)
- ✓ Beam size: 10 x 10 cm$^2$
- ✓ L/D: 521, 261, 174

A. Hilger, N. Kardjilov, M. Strobl et al., Phys. B (2006)

# Neutron Imaging



- ✓ **running engine at 6000 rpm**
- ✓ stroboscopic technique
  exposure time: 1 ms
- ✓ accumulation: 500 images

A. Hilger, N. Kardjilov, M. Strobl et al., Phys. B (2006)

# Neutron Imaging

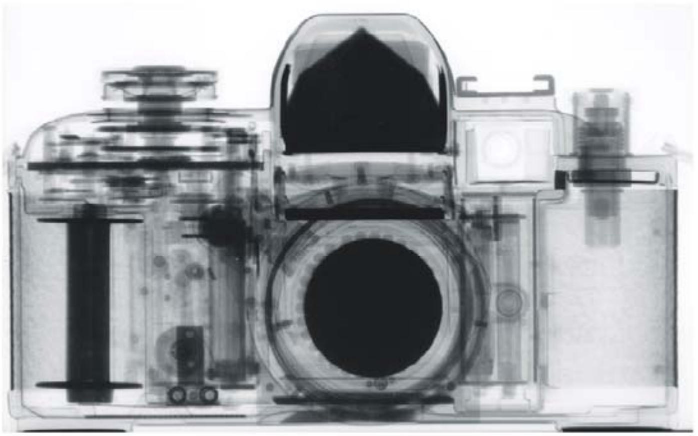
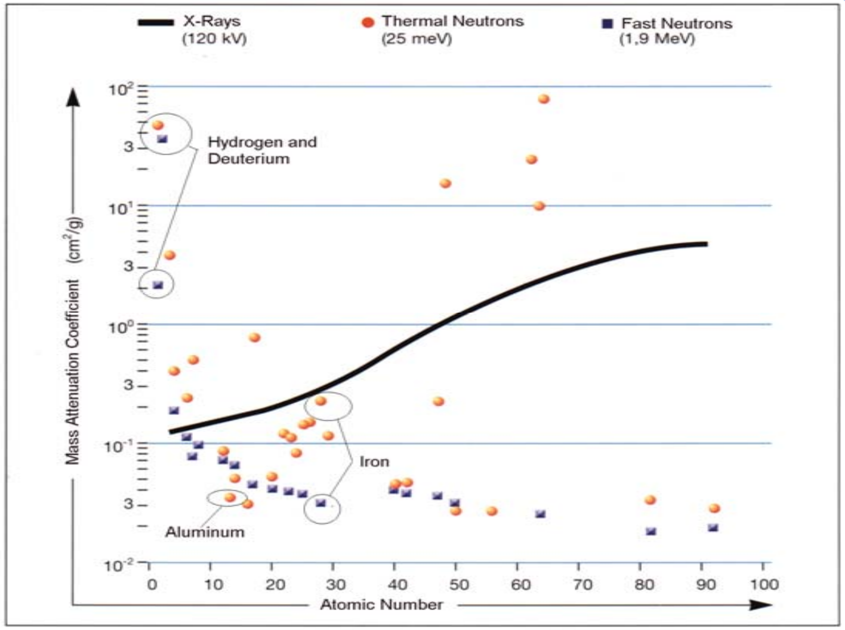


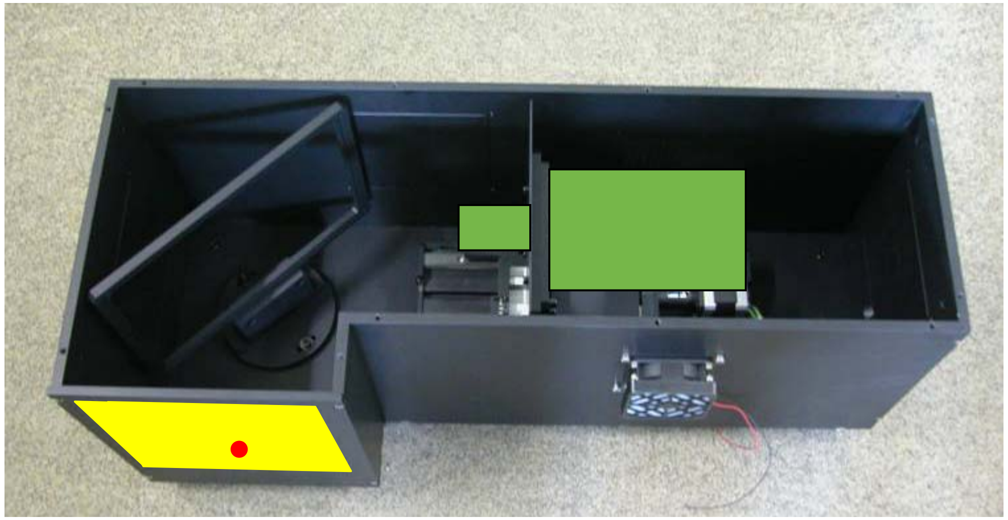
Fig. a: Neutron radiography of a camera

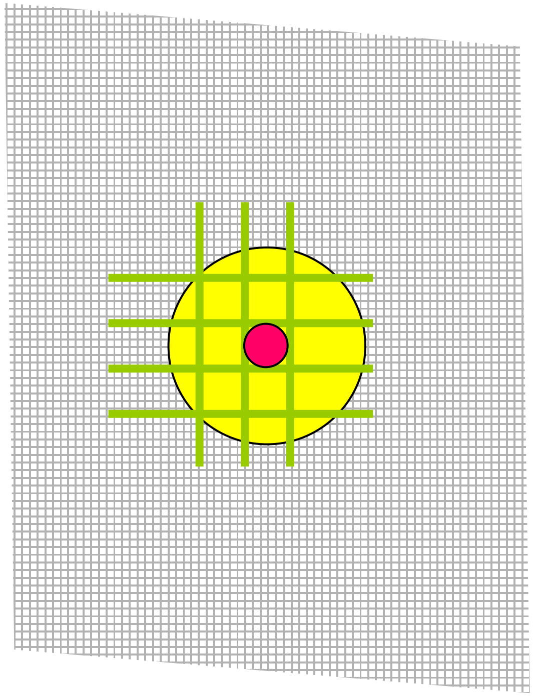
Fig. b: Radiographic image of a camera made X-rays



# Neutron imaging

Detector





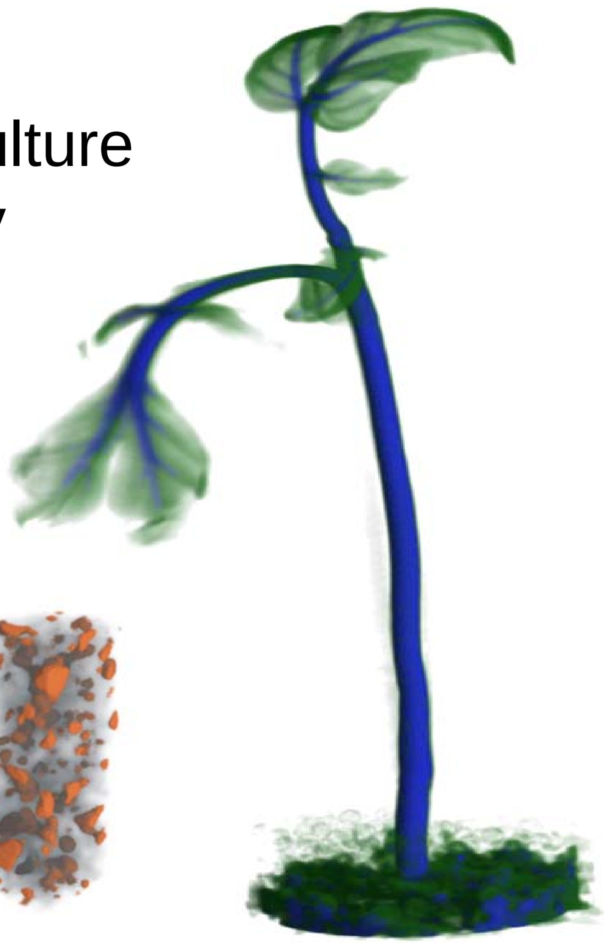
recent developments

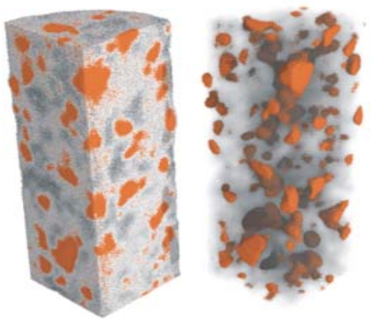
***HZB:*** **25 µm**

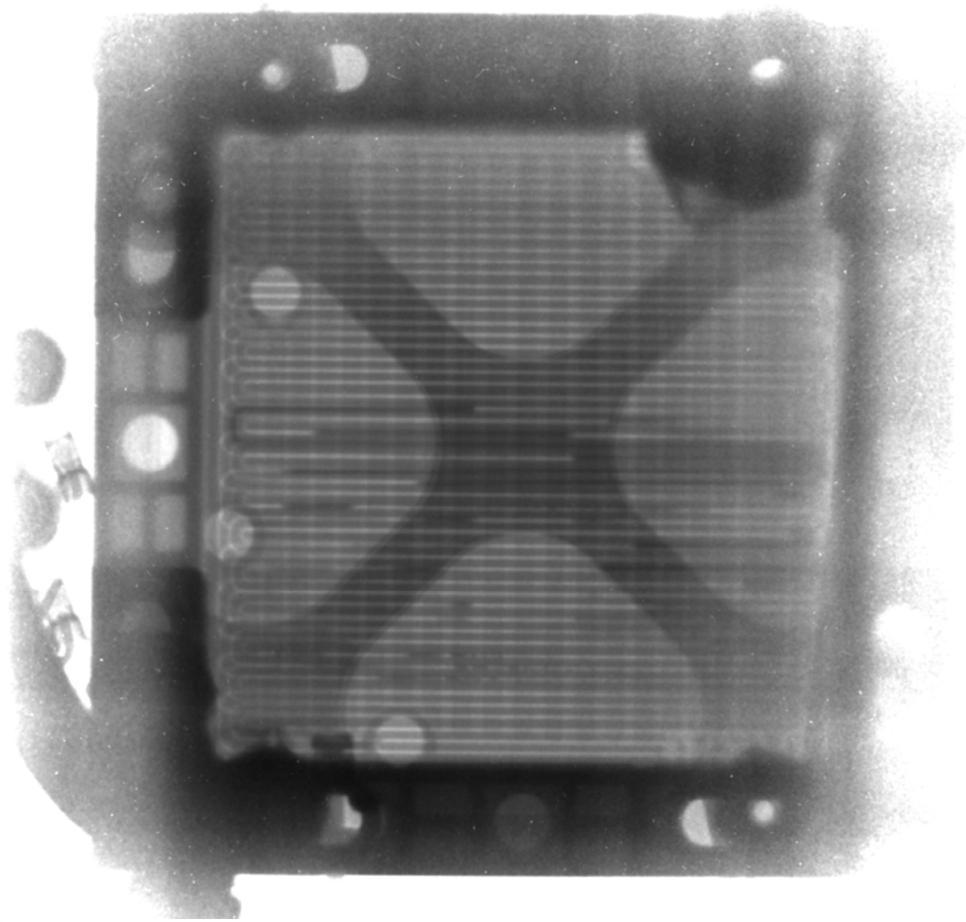
N. Kardjilov et al. to be submitted

# n Imaging Applications

R&D
Biology
& Agriculture
Geology

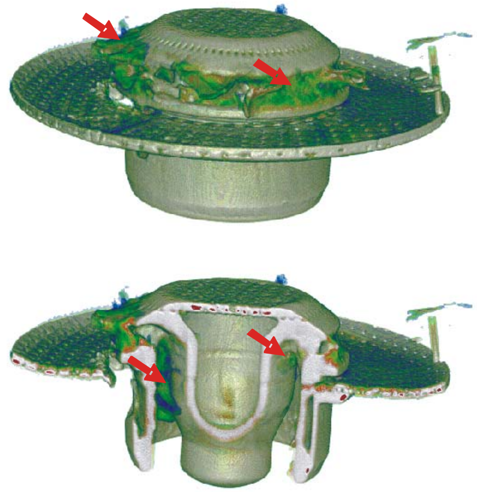


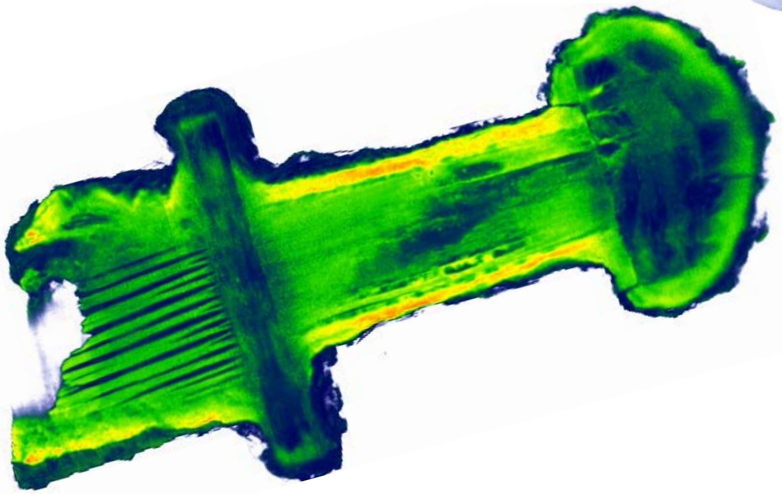


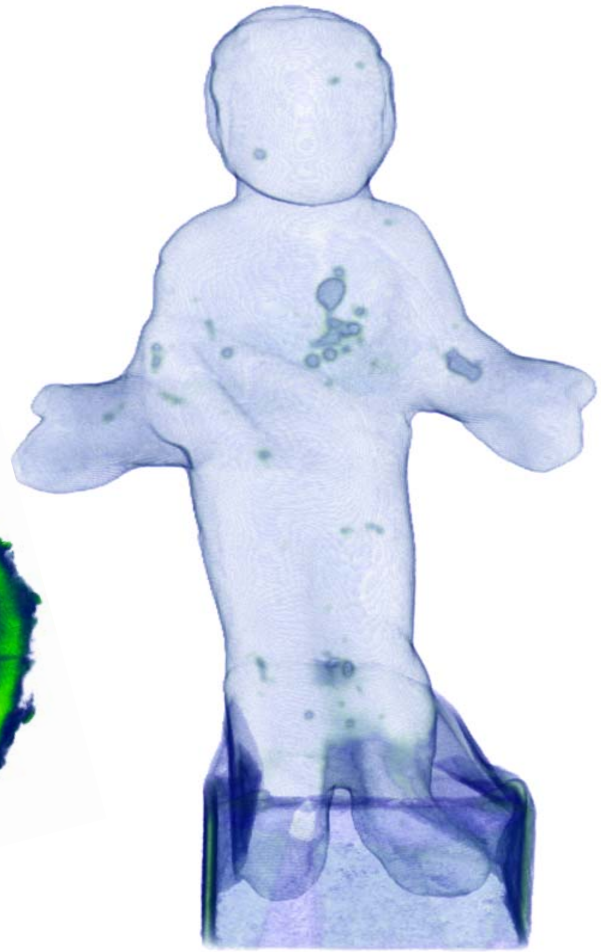


# n Imaging Applications

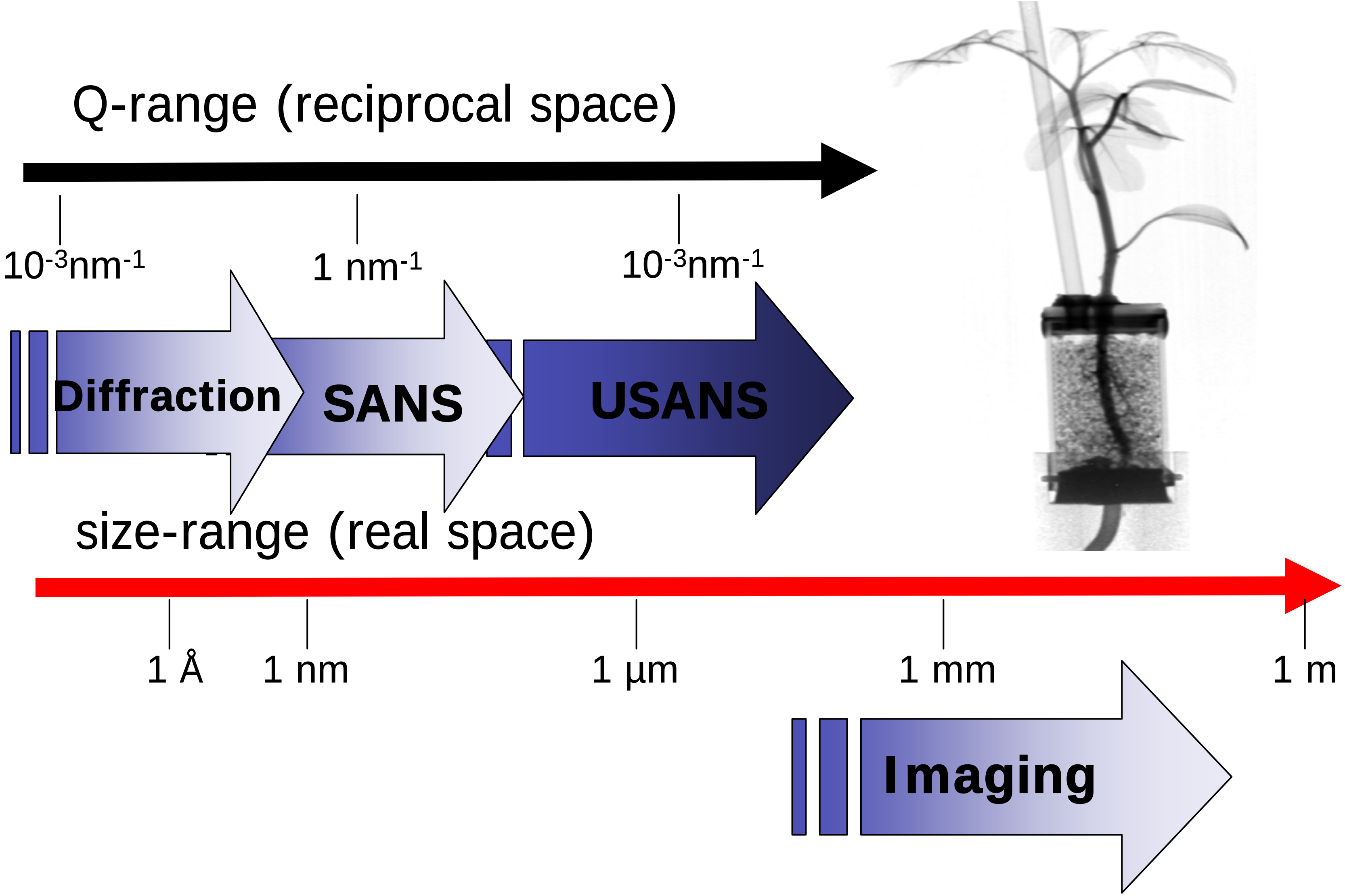
R&D
Biology
& Agriculture
Geology
Archeology
Paleontology
Art History
Material science
& Engineering
Industry
etc.







# Neutron imaging



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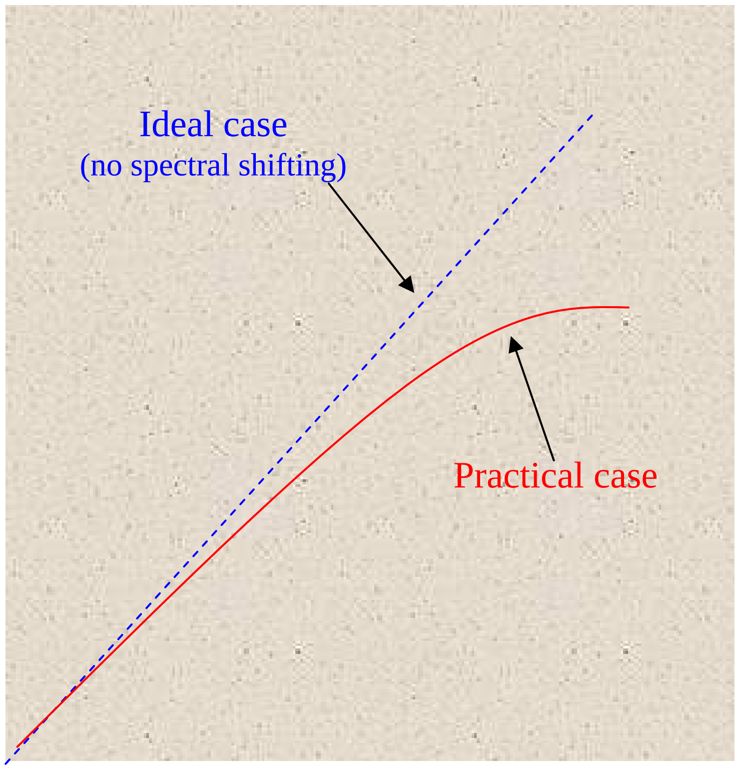
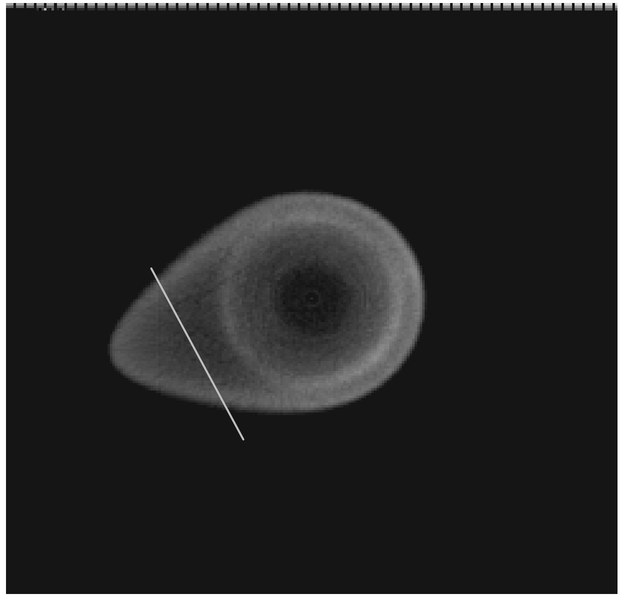
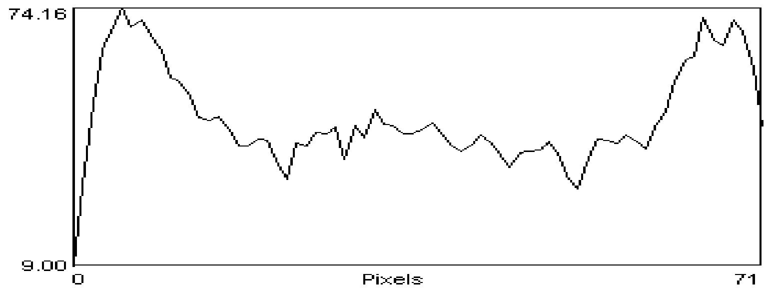
# Energy resolved imaging

$ln(N_{in}/N_d)$



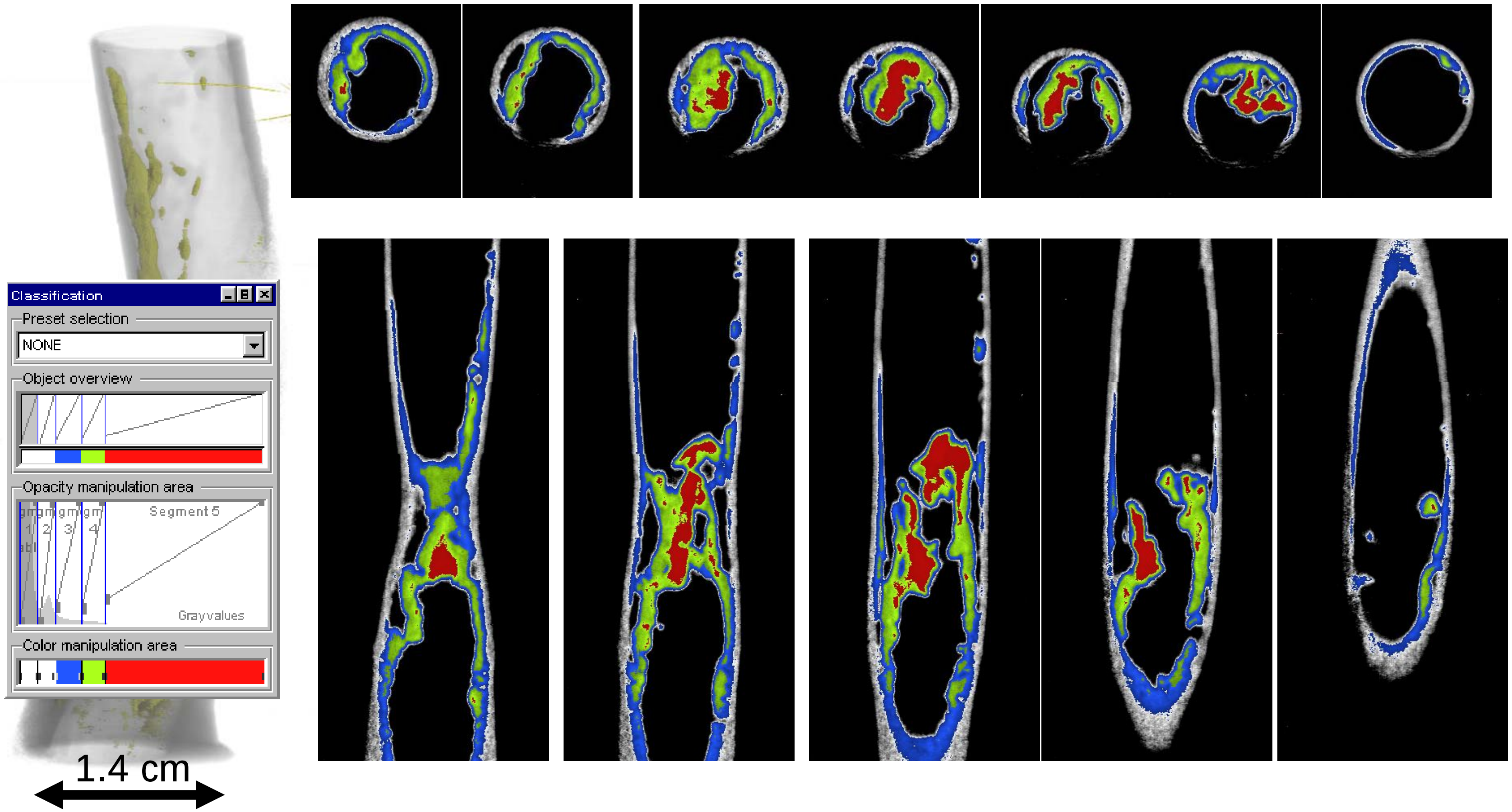

Thickness of a homogeneous absorber





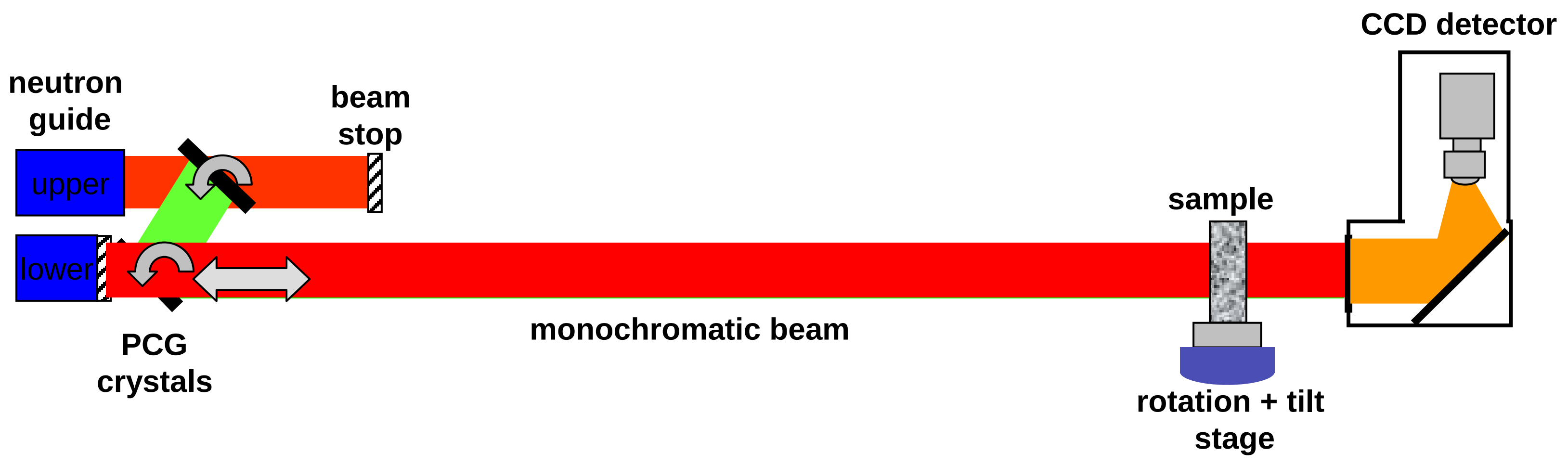
# Monochromatic imaging

## vent tube



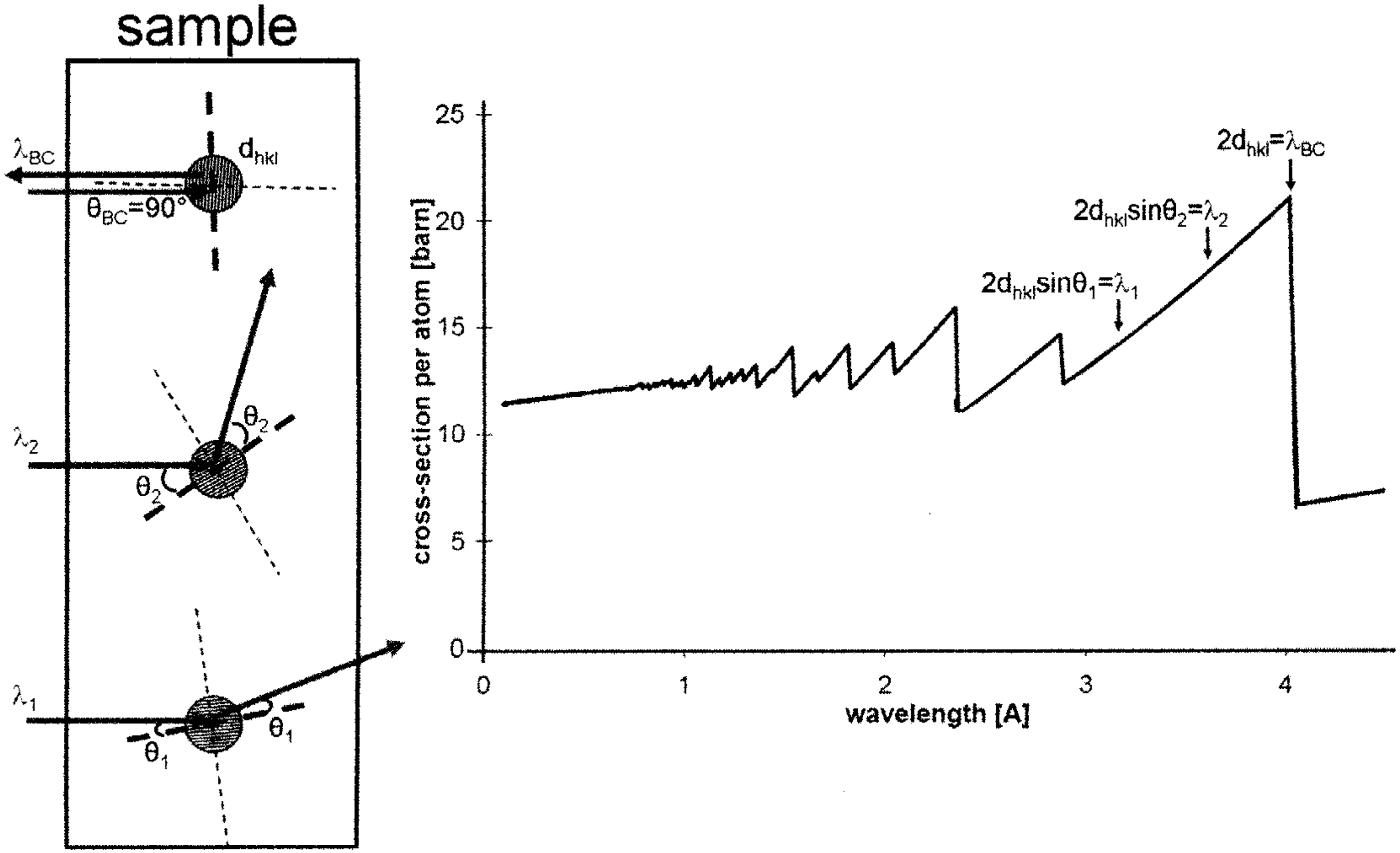

M. Strobl et al. J. Appl. Cryst. (2007) **40**

# Energy resolved imaging

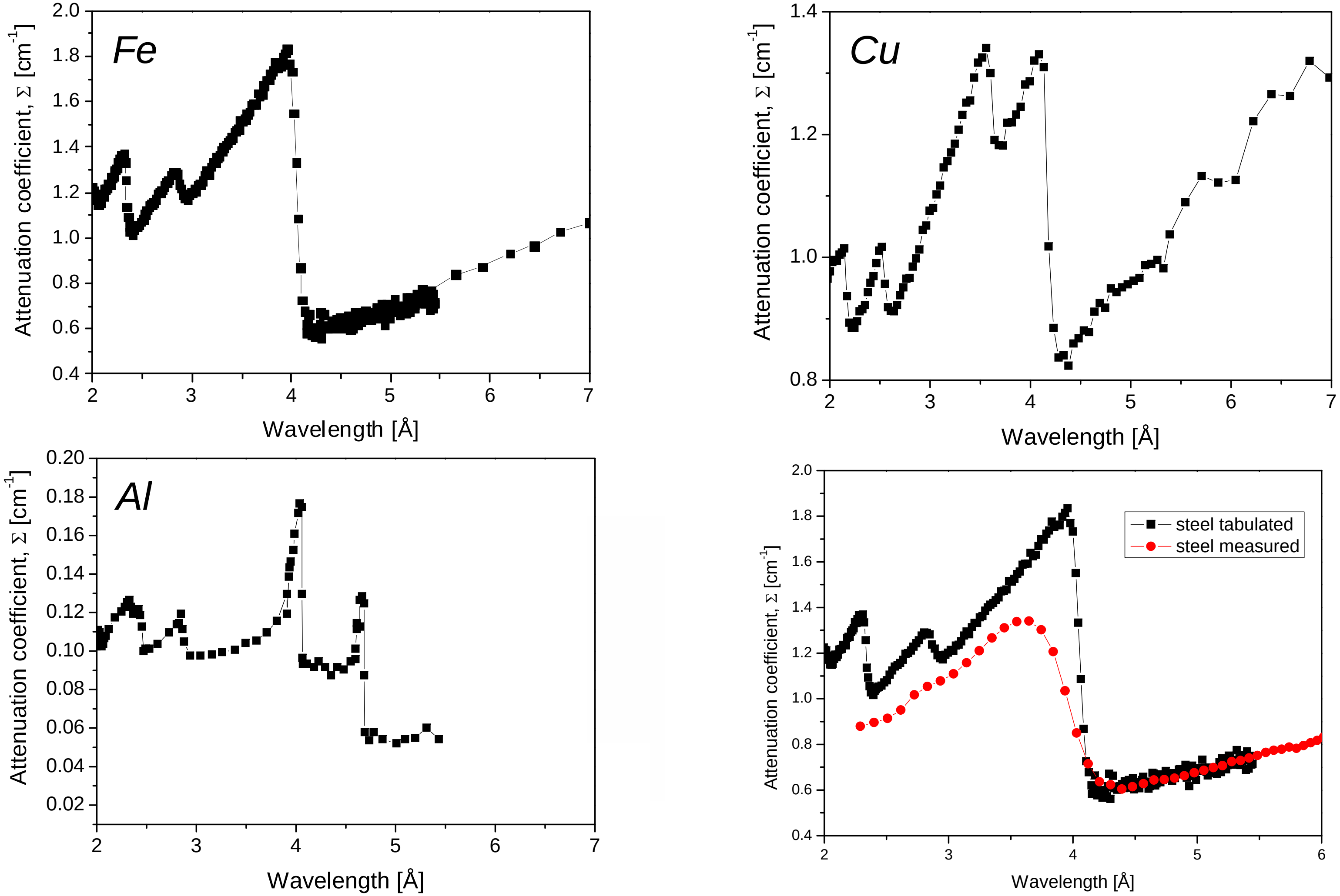



*W.T., M. Strobl et al. APL (2006)*

# Energy resolved imaging

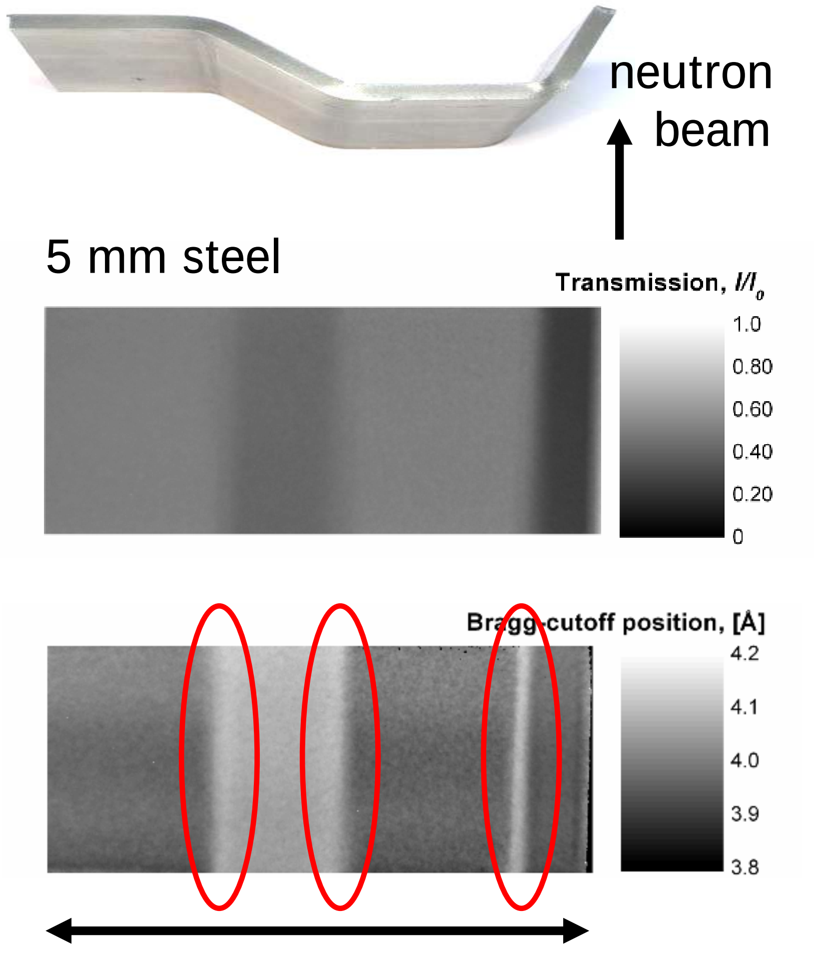


# Energy resolved imaging




N. Kardjilov et al., NIM A 501 (2003) 536

# Energy resolved imaging



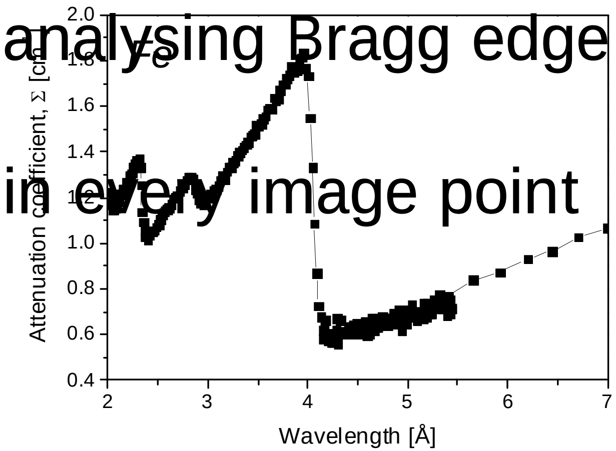

## Bragg scattering analyses

recording radiographies

scanning the spectrum

analysing Bragg edge

in every image point

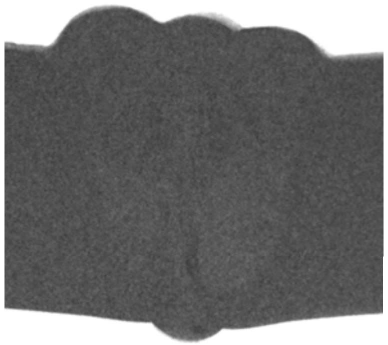



*W.T., M. Strobl et al. APL (2006)*

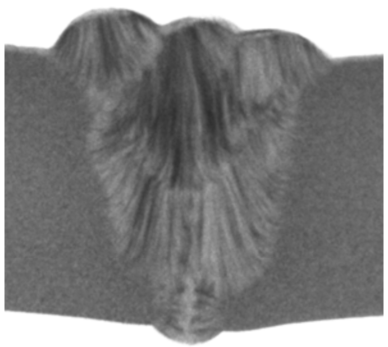
# Energy resolved imaging

## Investigation on steel weld

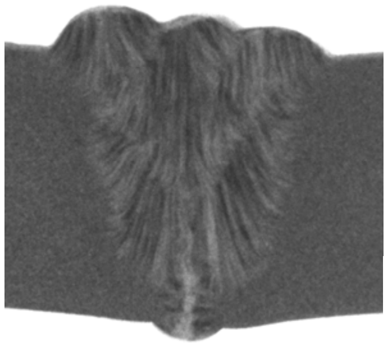
photo



4.2 Å



4.0 Å

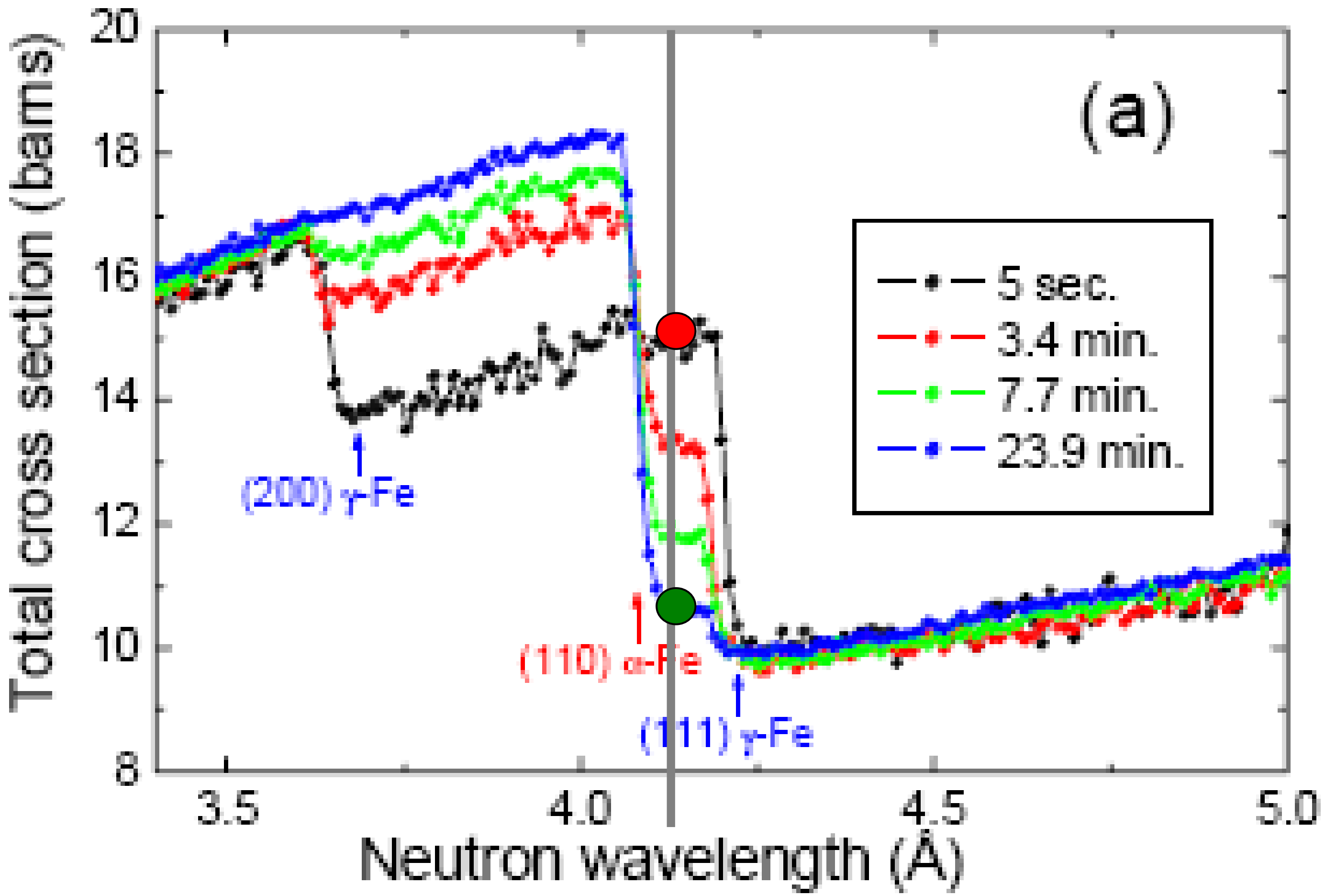


3.8 Å

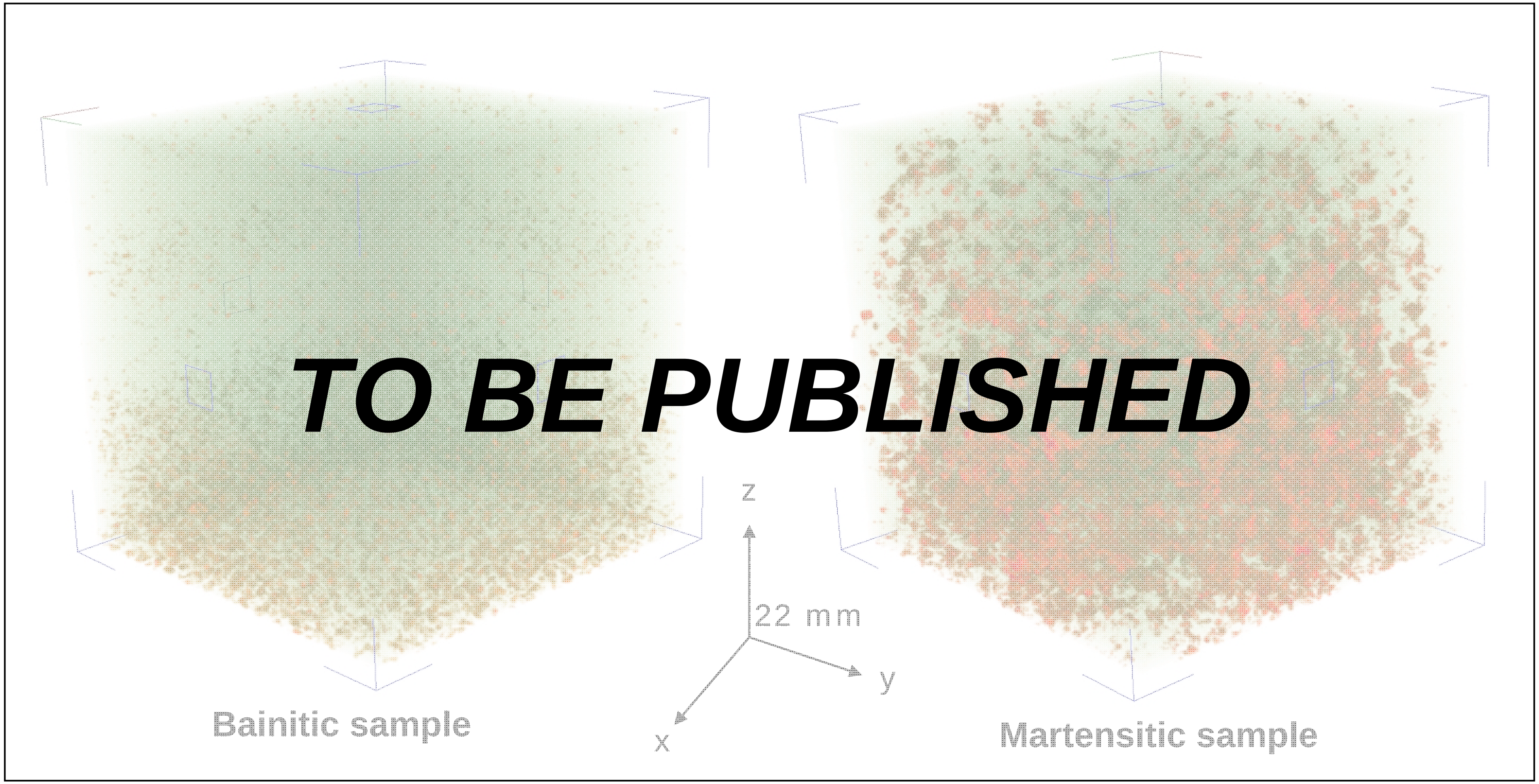
resolution: 50 µm

preliminary results in cooperation with G. Kühne & G. Frei (PSI)

# Energy resolved imaging

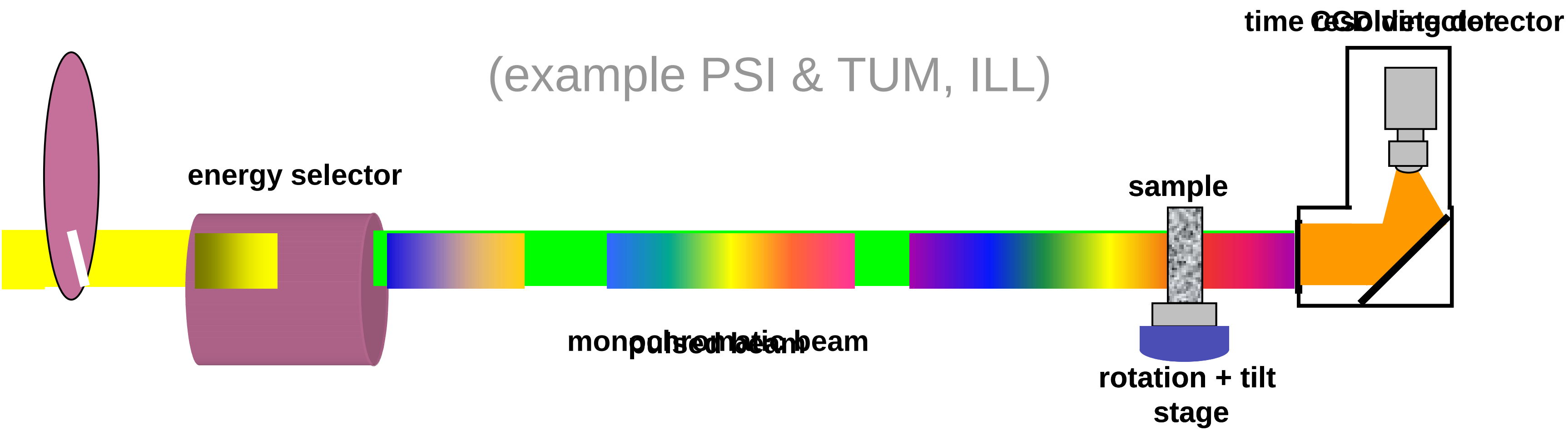


# Energy selective imaging

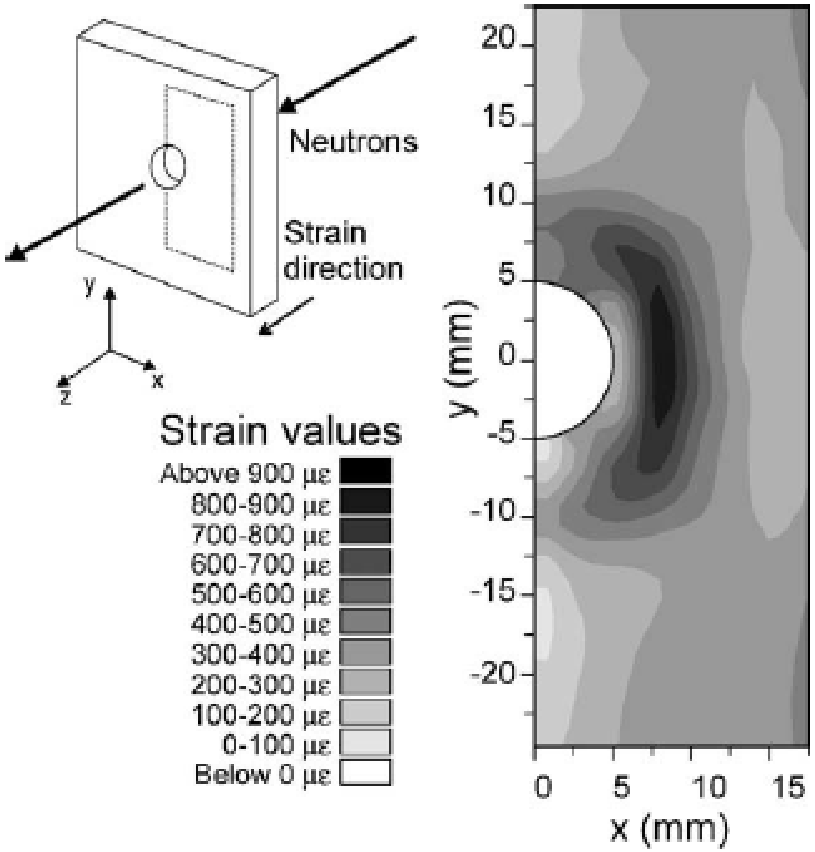



*T. Kandemur, master thesis 2008*

# Energy resolved imaging




# Energy resolved imaging




J.R. Santisteban et al. NIM A 481 (2002) 765–768

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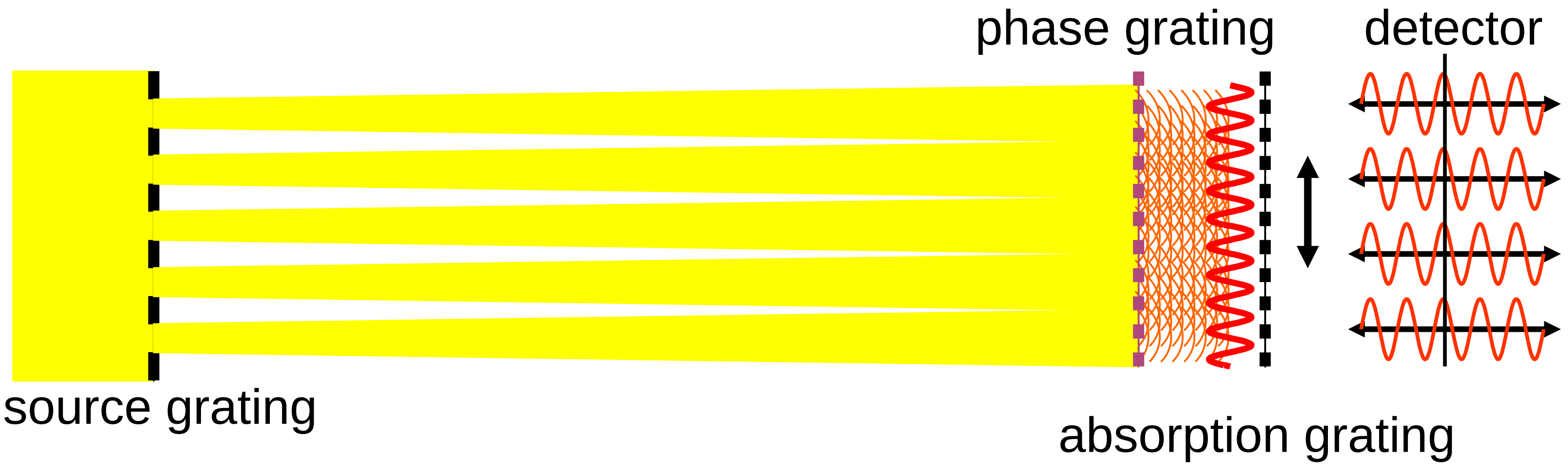
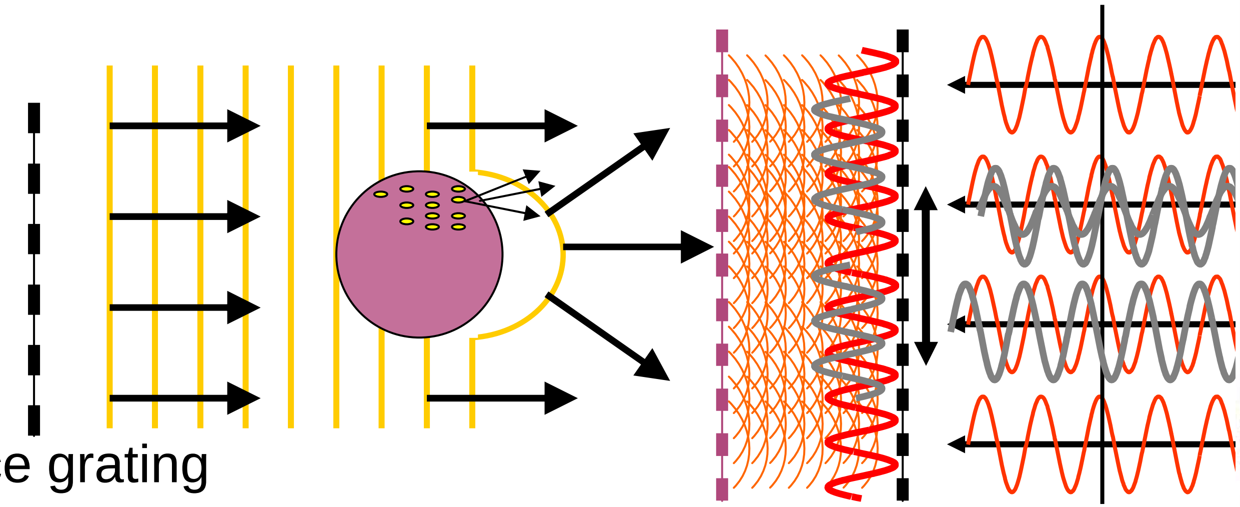
# Phase contrast

## Grating Interferometer




*F. Pfeiffer et al. Phys. Rev.Lett. 96, 215505 (2006)*

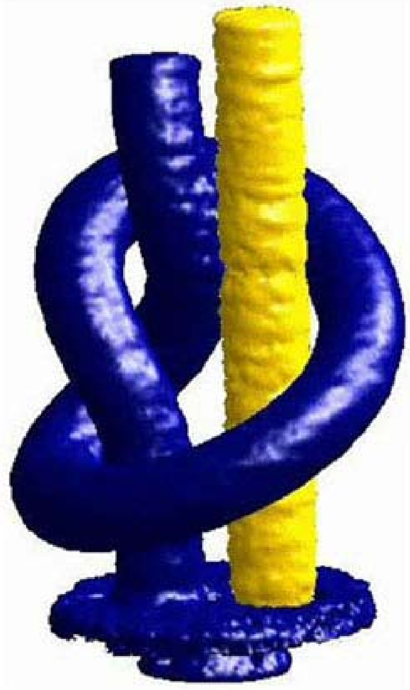
# Dark field contrast



source grating

grating interferometer

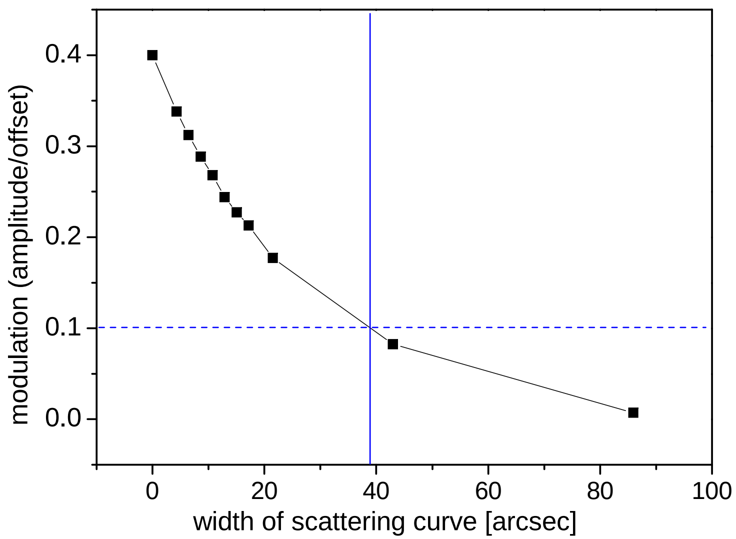
δ(x,y)

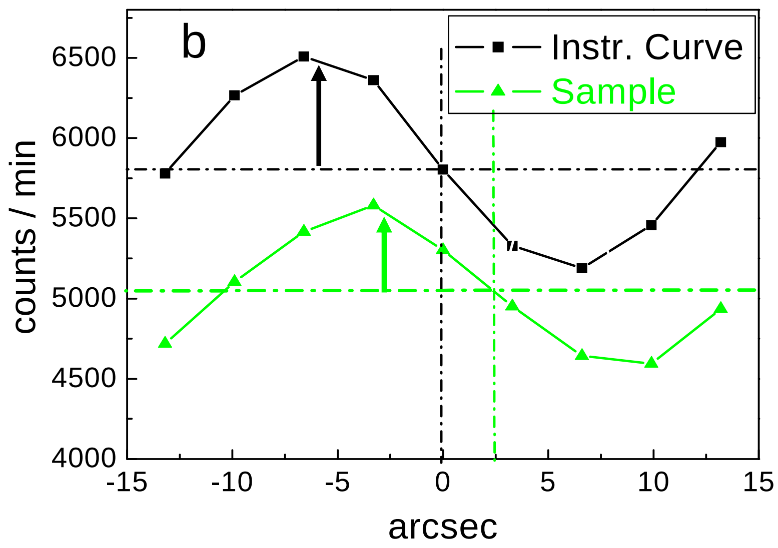


$$P_{\theta}(t) = w(\theta, t)^2 = \int_{path} \frac{\sigma(x,y) N(x,y)}{R^2(x,y)} \cdot ds$$

*M. Strobl et al. PRL (2008)*

# Dark field contrast

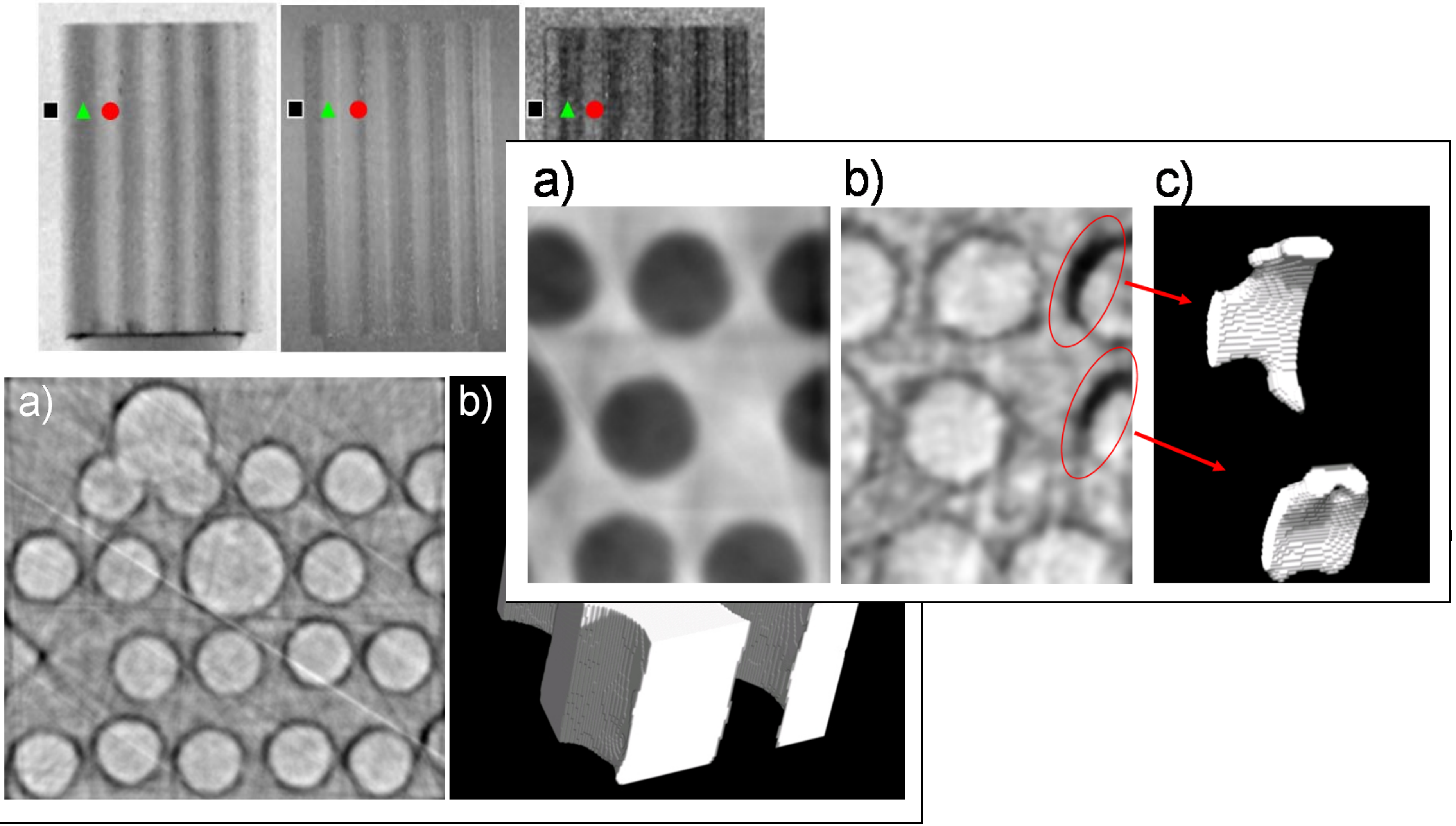



$$P_{\theta}(t) = w(\theta, t)^2 = \int_{path} \frac{\sigma(x,y)N(x,y)}{R^2(x,y)} \cdot ds$$

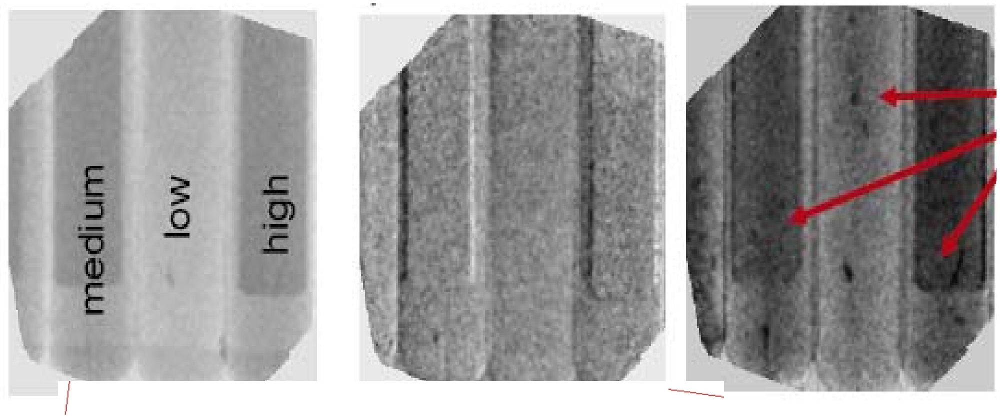
*M. Strobl et al. PRL (2008)*

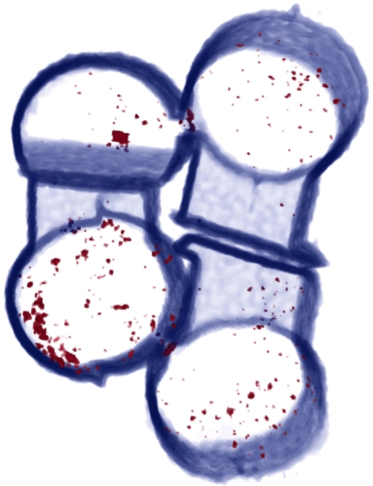
# Dark field contrast



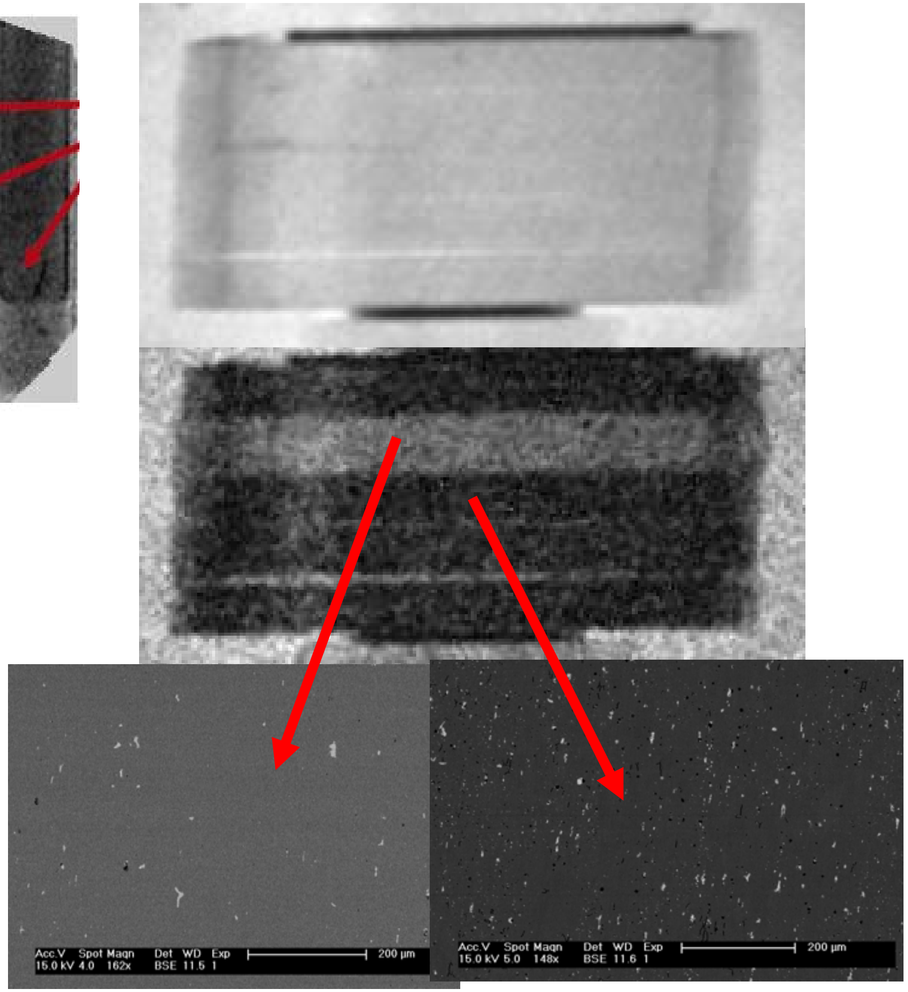

*M. Strobl et al. PRL (2008)*

# Dark field contrast



A. Hilger et al. JAP (2010)

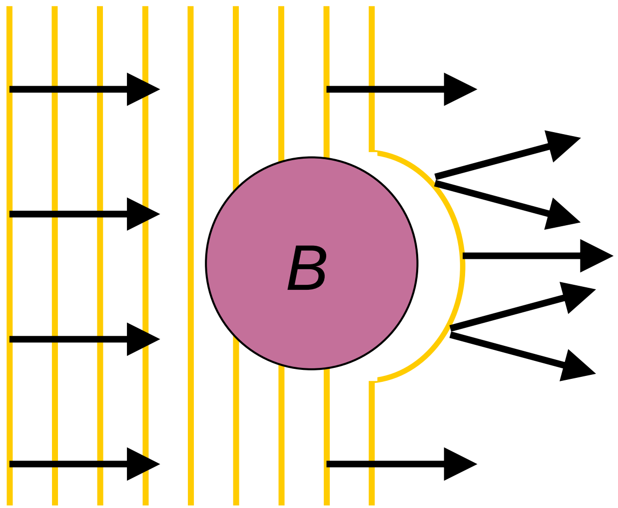


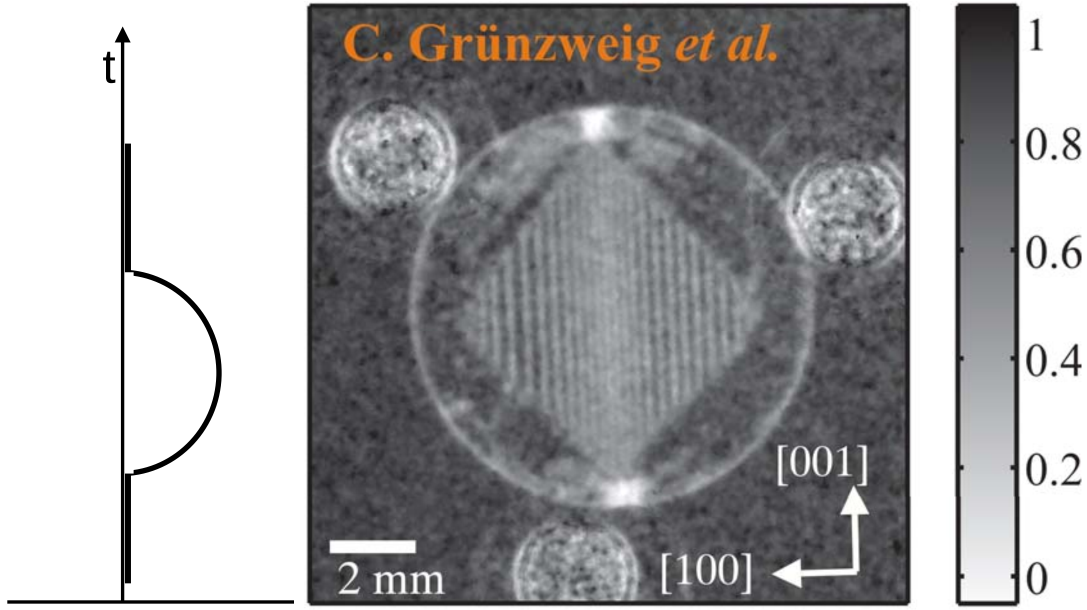
Collaboration Uni Tennessee, D. Penumadu

# Phase and dark field contrast

Refractive index: phase absorption magn. phase

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




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

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

*M. Strobl et al., APL (2007)*

*Ch. Gruenzweig et al. APL (2008)*

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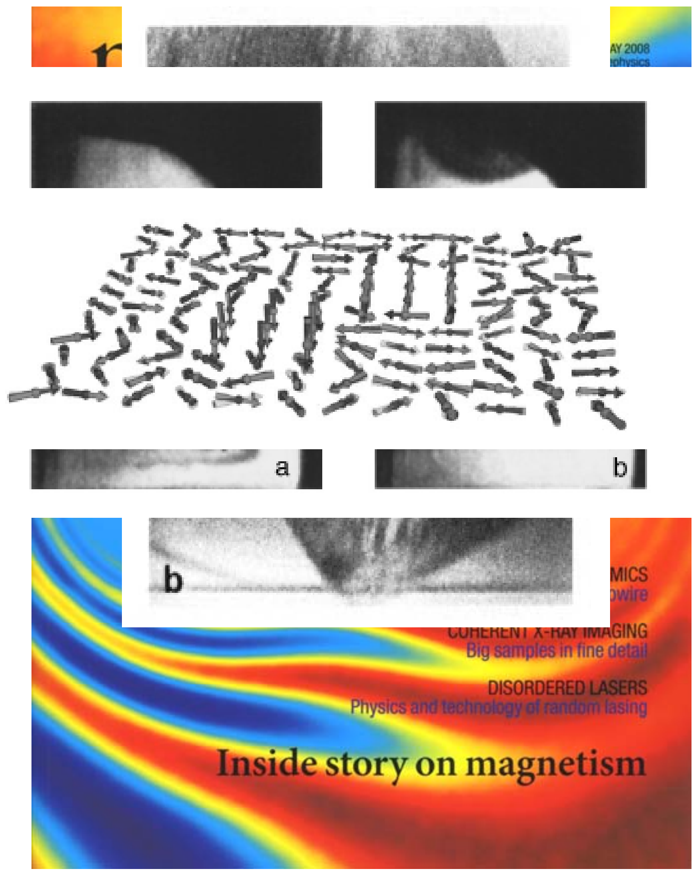
# Polarised neutron imaging

M. Schlenker, W. Bauspiess, W. Graeff, U. Bonse, H. Rauch
Journ. of Magn. & Magn. Mat. 15-8 (1980) 1507-1509

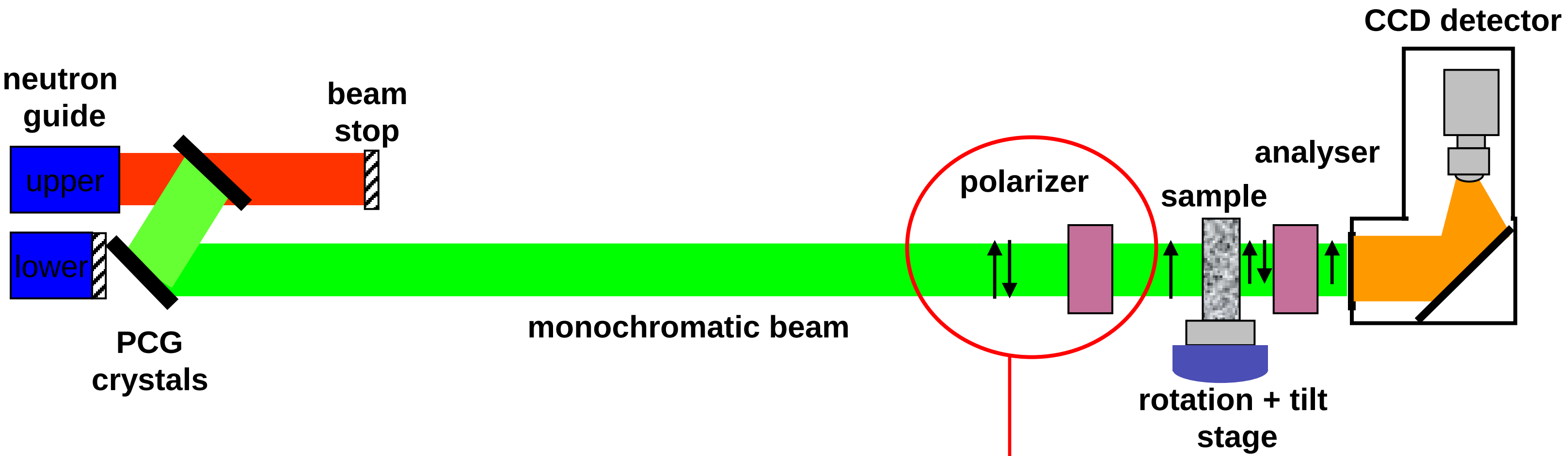
*K.M. Podurets, R.R. Chistyakov and S.Sh. Shil'shtein*
*Zh. Tekh. Fiz. 67 (1994)  134-136*

Badurek, G., Hochhold, M. & Leeb, H.
*Physica B* 234–236 (1997) 1171–1173

*N. Kardjilov, I. Manke, M. Strobl,*
*A. Hilger et al.*
*Nat. Phys. 4 (2008)*

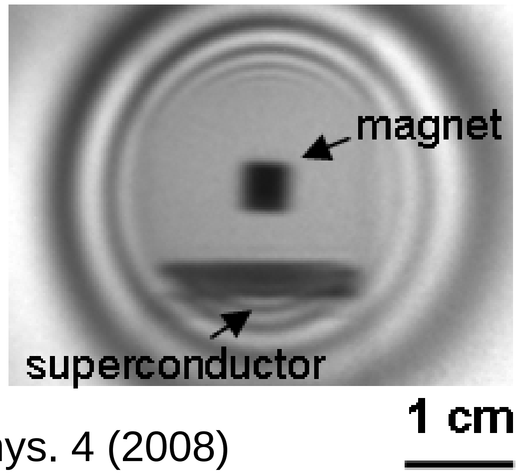


# Polarised neutron imaging



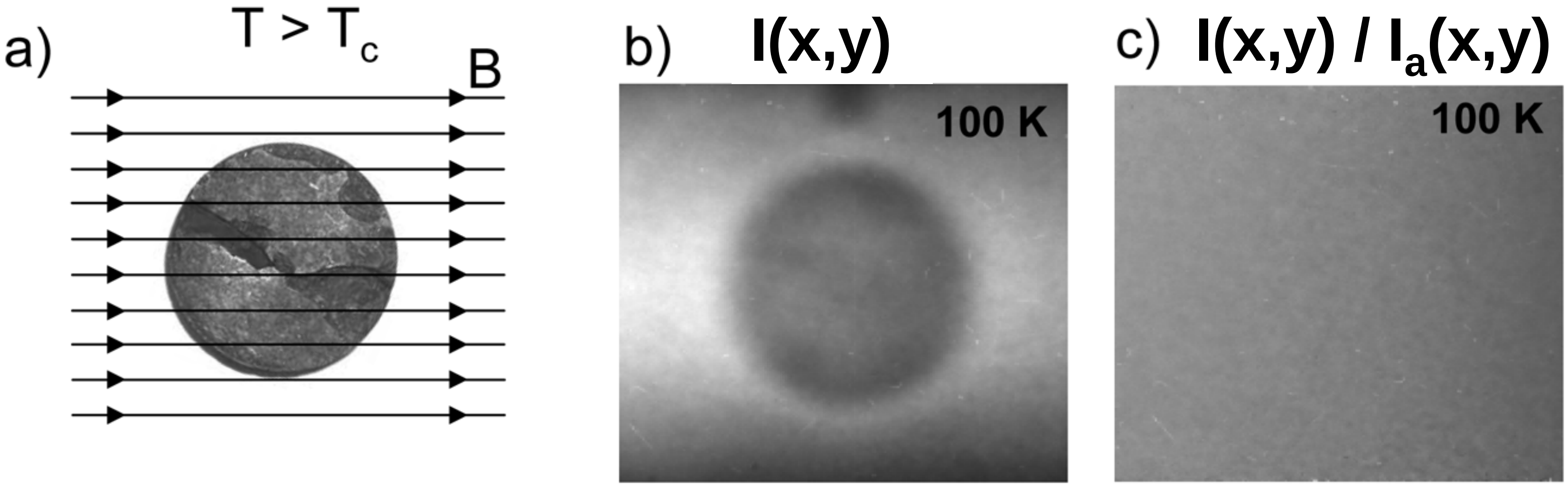

$$I(x,y) = I_0(x,y)\cdot \exp\left(-\int_{\text{path}} \sigma \cdot ds\right)\cdot \frac{1}{2}\left(1+\cos\varphi(x,y)\right)$$

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




N. Kardjilov, I. Manke, M. Strobl, A. Hilger et al. Nature Phys. 4 (2008)

# Polarised neutron imaging

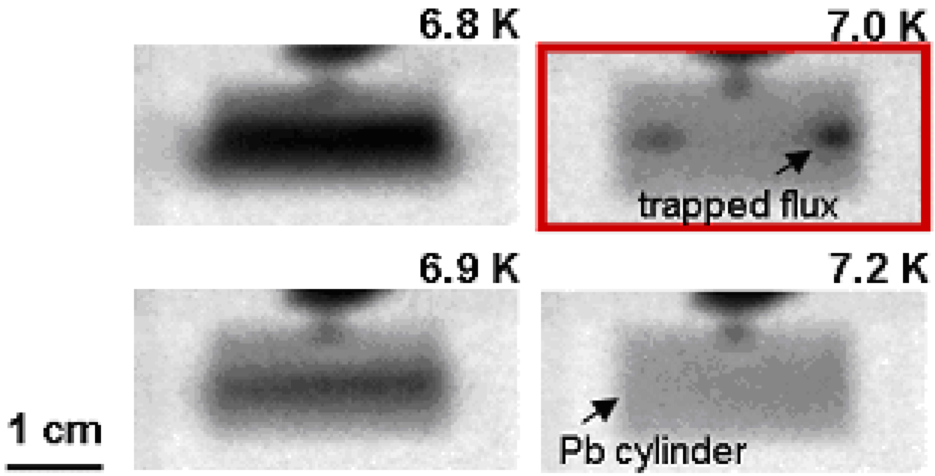


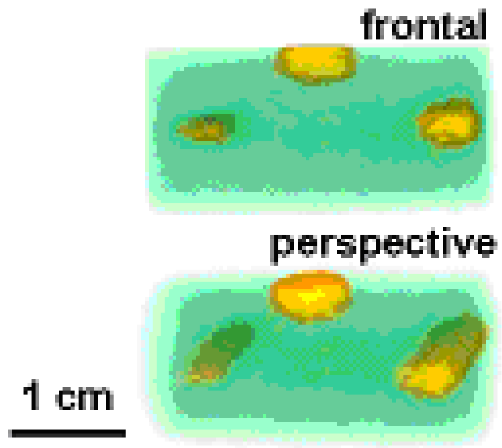

$$I(x,y) = \underbrace{I_0(x,y)\cdot\exp\left(-\int_{\text{path}}\sigma\cdot ds\right)}_{I_a(x,y)}\cdot\frac{1}{2}\left(1+\cos\varphi(x,y)\right)$$

**YBCO**

# Polarised neutron imaging

## Flux pinning in polycrystalline Pb superconductor

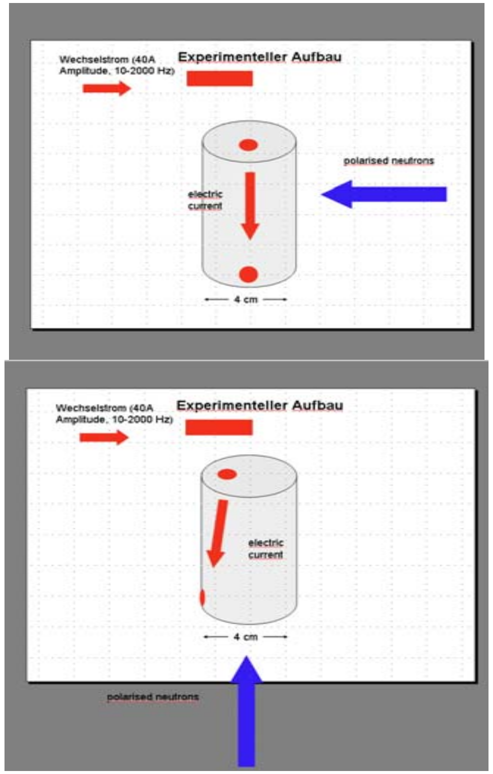


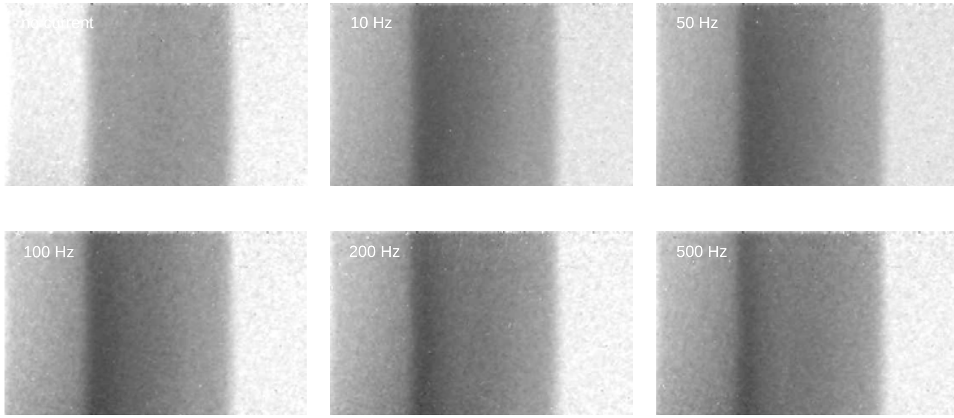



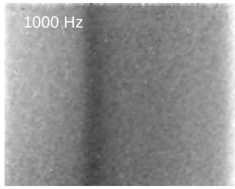

1.0(2) mT

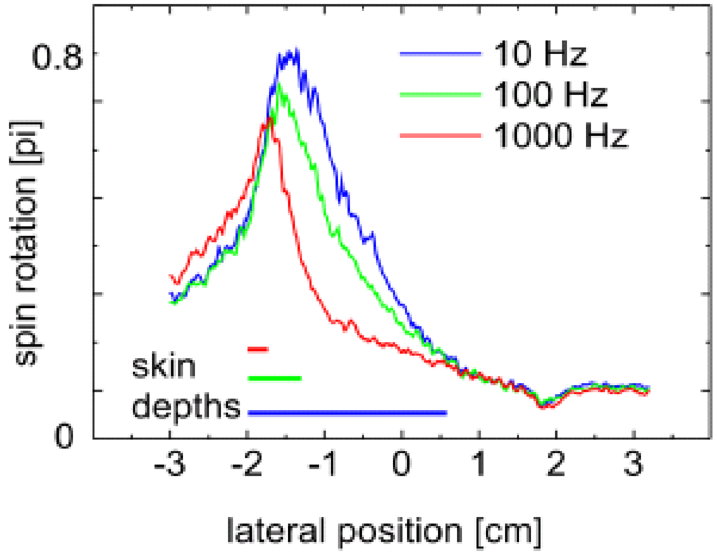
N. Kardjilov, I. Manke, M. Strobl, A. Hilger et al. Nature Phys. 4 (2008)

# Polarised neutron imaging




Electric currents: Skin effect

I. Manke, N. Kardjilov, M. Strobl et al., JAP (2008)

# Acknowledgement

**N. Kardjilov**

**I. Manke**

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**J. Banhart**

ATOMINSTITUT

**E. Jericha, G. Badurek**

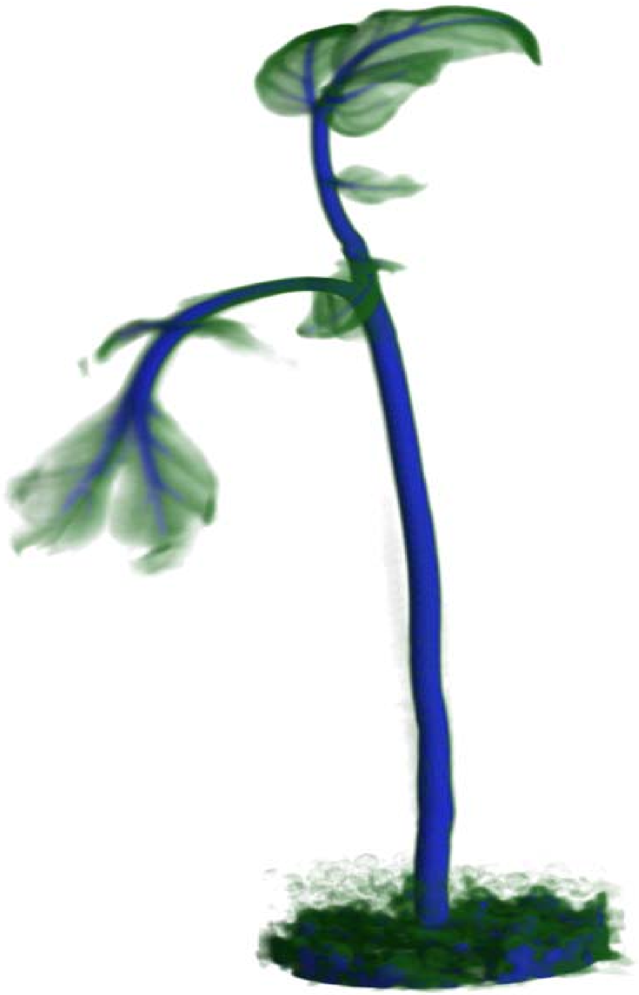
PAUL SCHERRER INSTITUT PSI

**Ch. Grünzweig, F. Pfeiffer**

**P. Böni, M. Schulz**

**F. Bordenave, D. Jullien**

# Finally…



Thank you !