Phase contrast imaging

Holography

Wave propagation

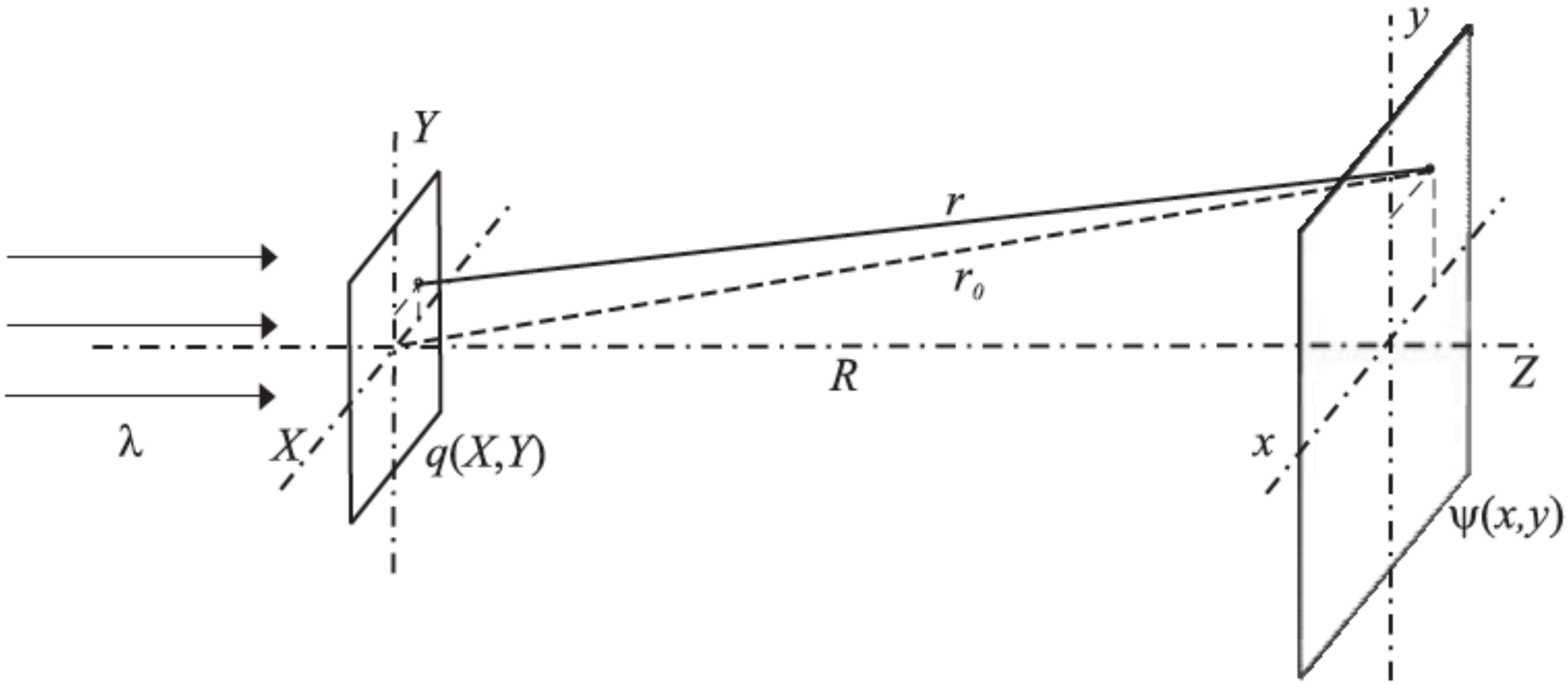
Interference phenomena

Martin Bech

Holography

Source: Star wars episode IV (1977)

Wave propagation



Huygens-Fresnels principle

Simplest form of Hologram

A wave front interfering with itself during propagation.

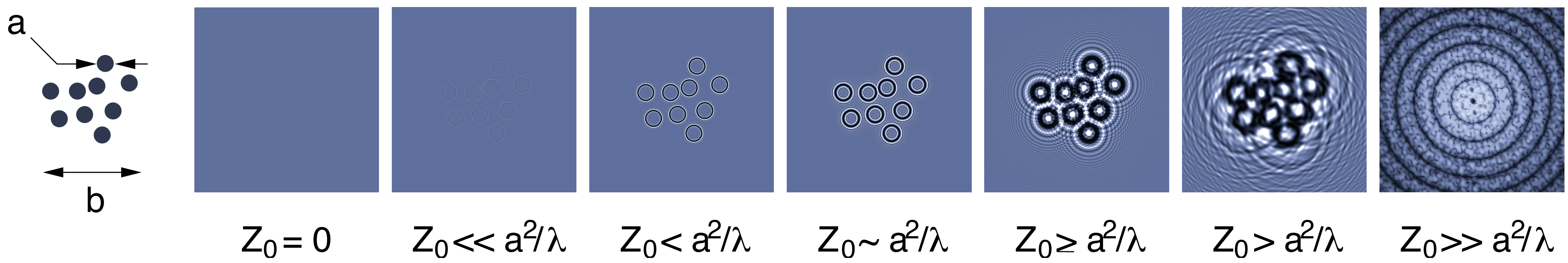
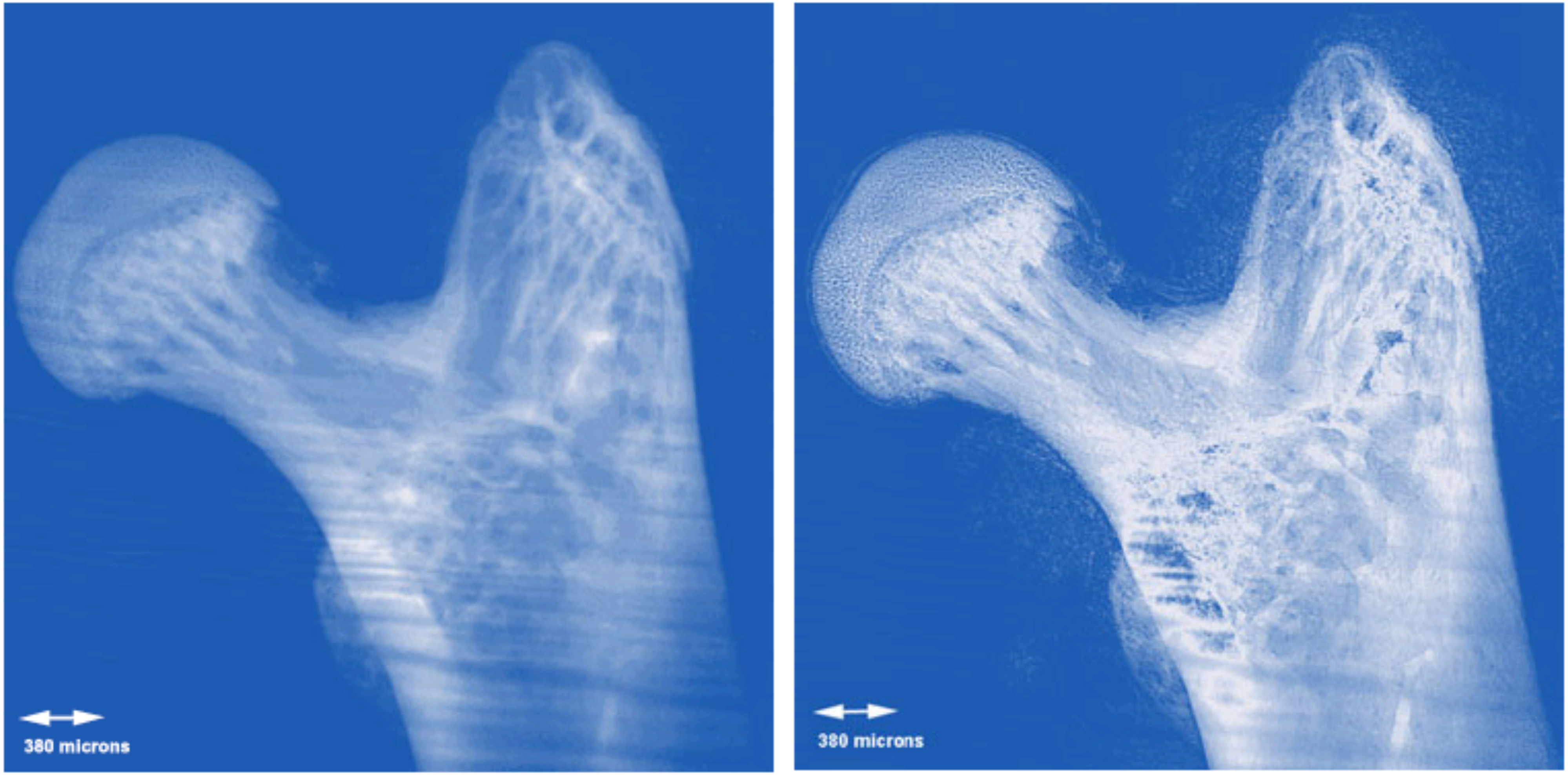


Figure 7.12 in "An introduction to Synchrotron Radiation", Philip Willmott, Wiley 2011

Propagation based phase contrast image

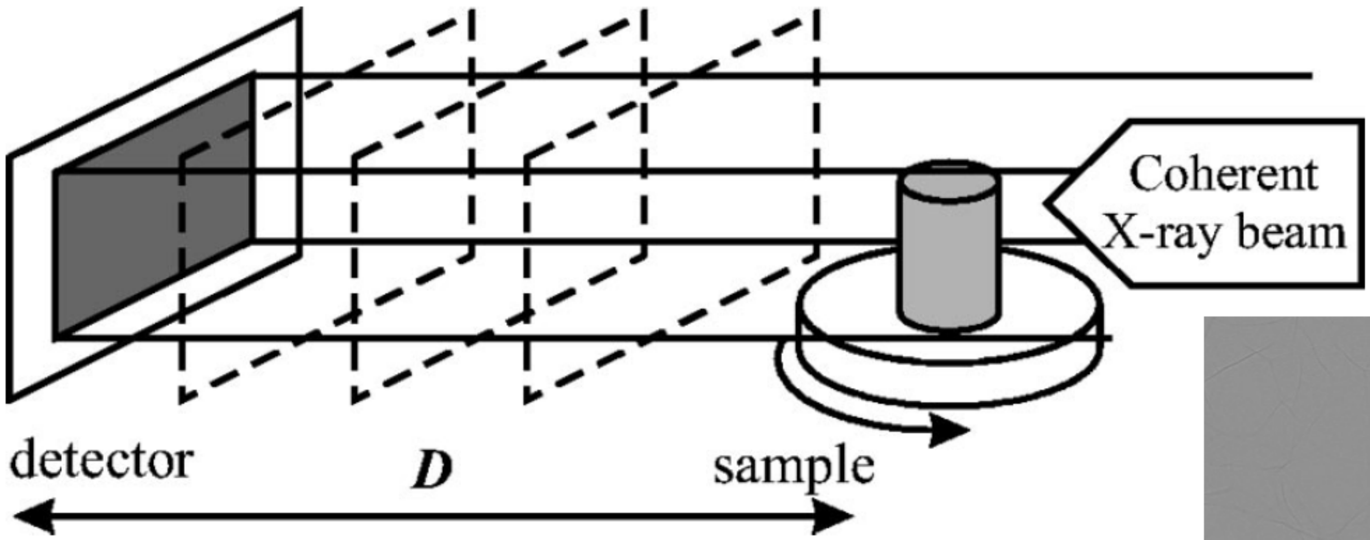
5010 F van der Veen and F Pfeiffer



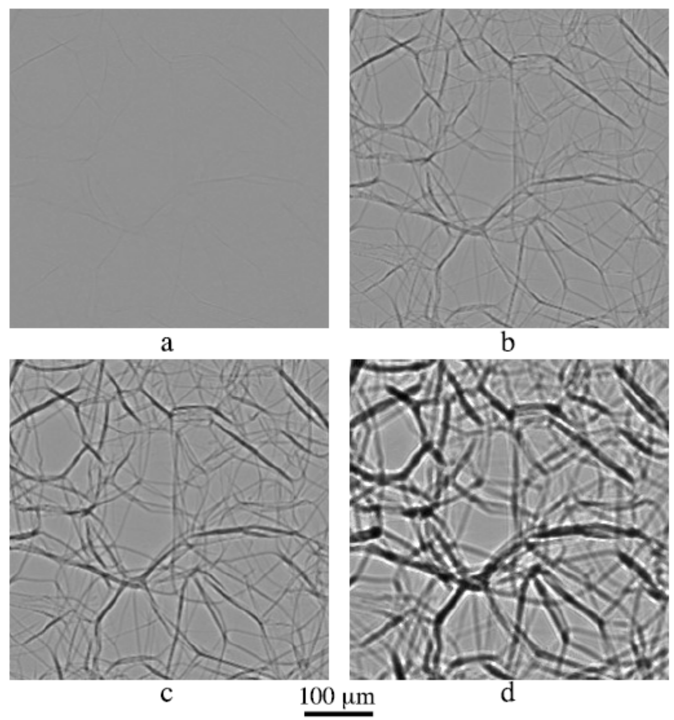
(a) distance: 0 mm (b) distance: 100 mm

Figure 5. A mouse femur head imaged at 15 keV at different sample–detector distances. From [26].

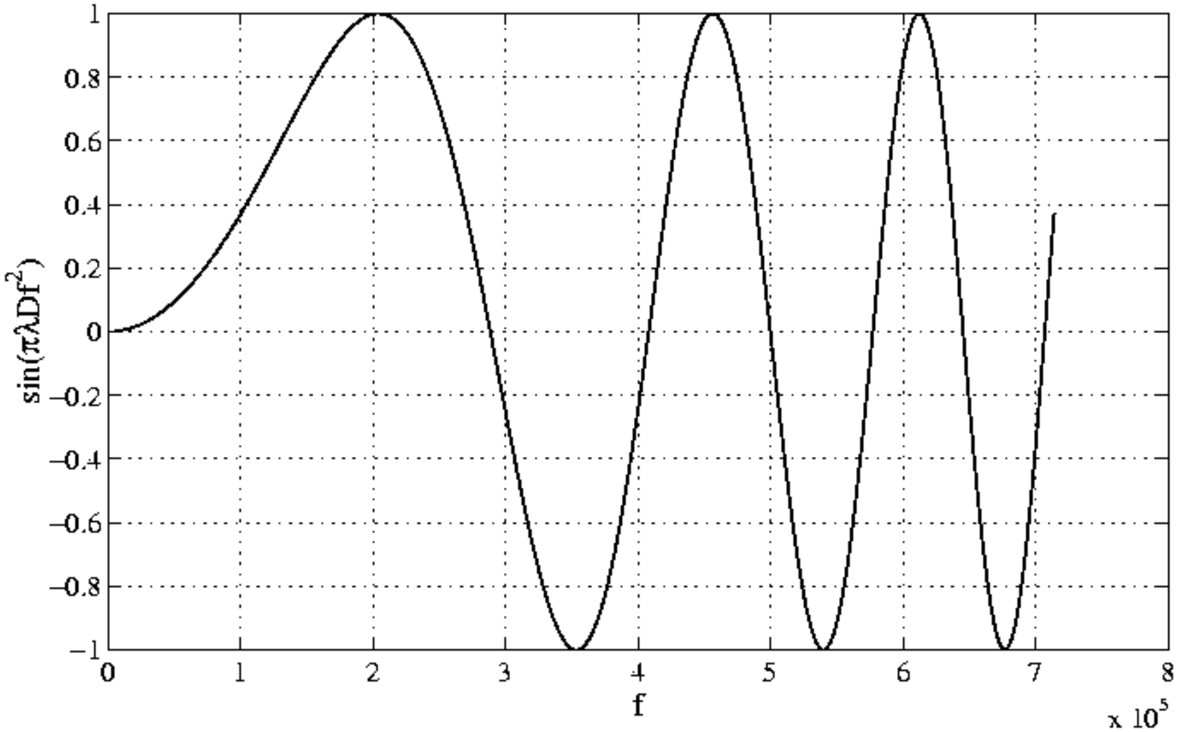
Holography / Holotomography



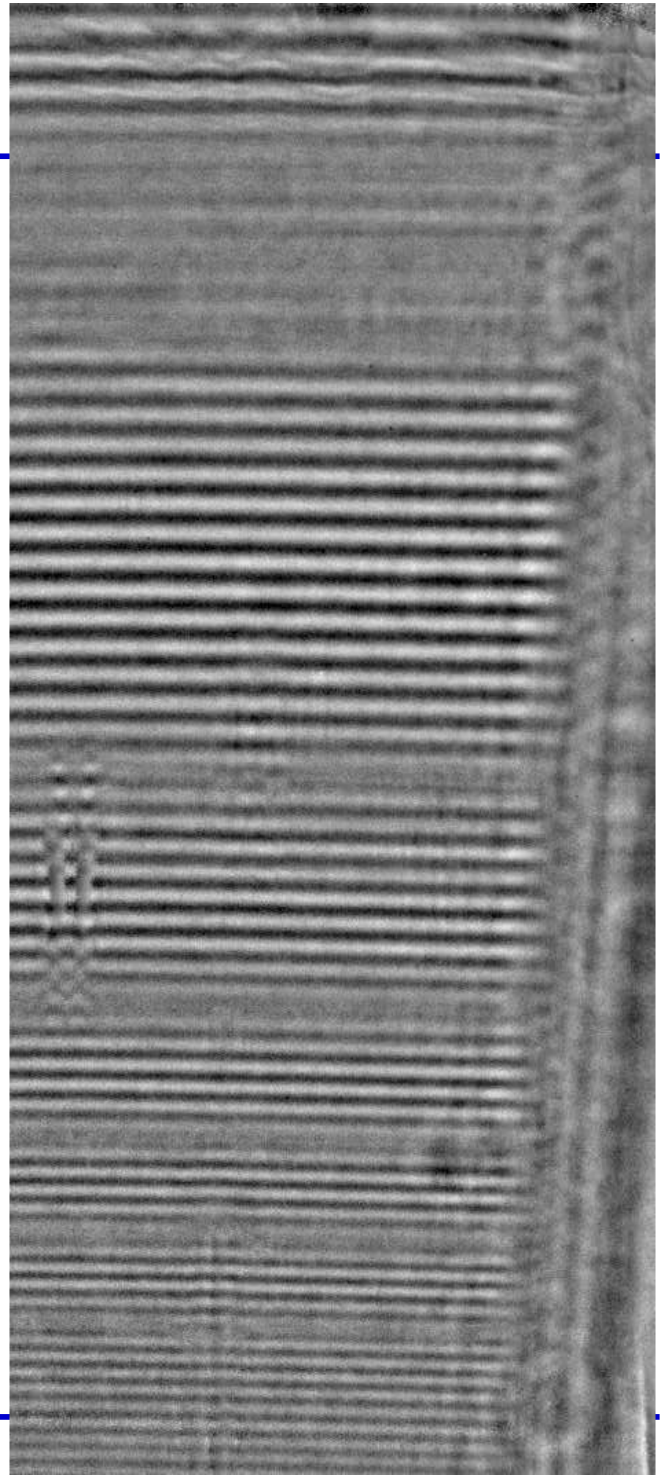
Polystyrene foam.
P. Cloetens 1999



Near-field imaging

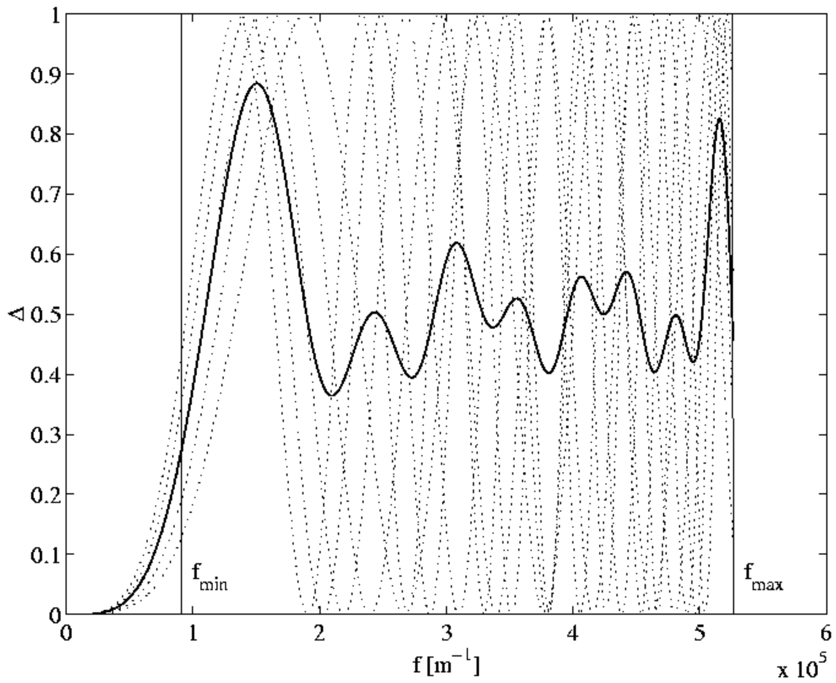


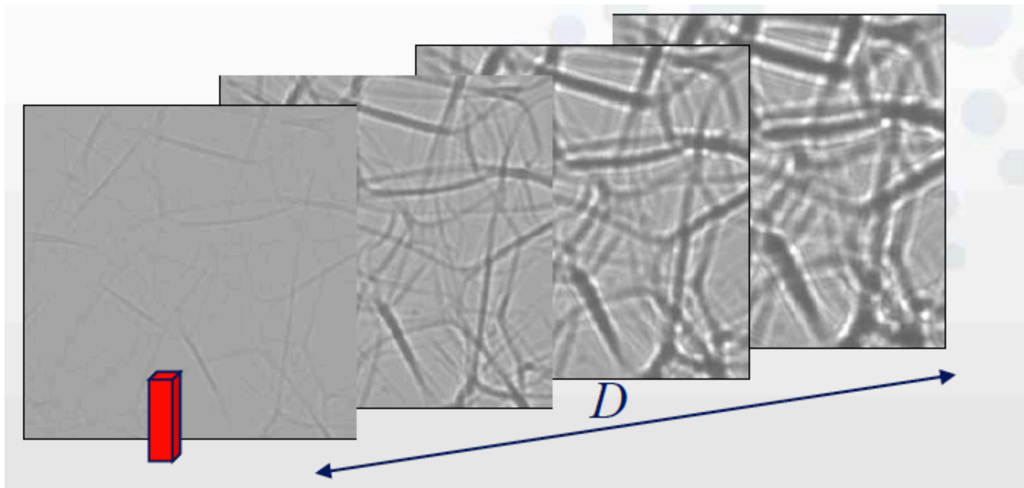
Frequency response is a function of propagation distance

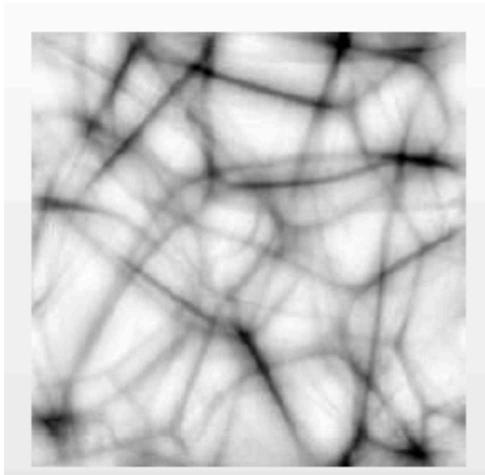


Images P. Cloetens

Near-field imaging

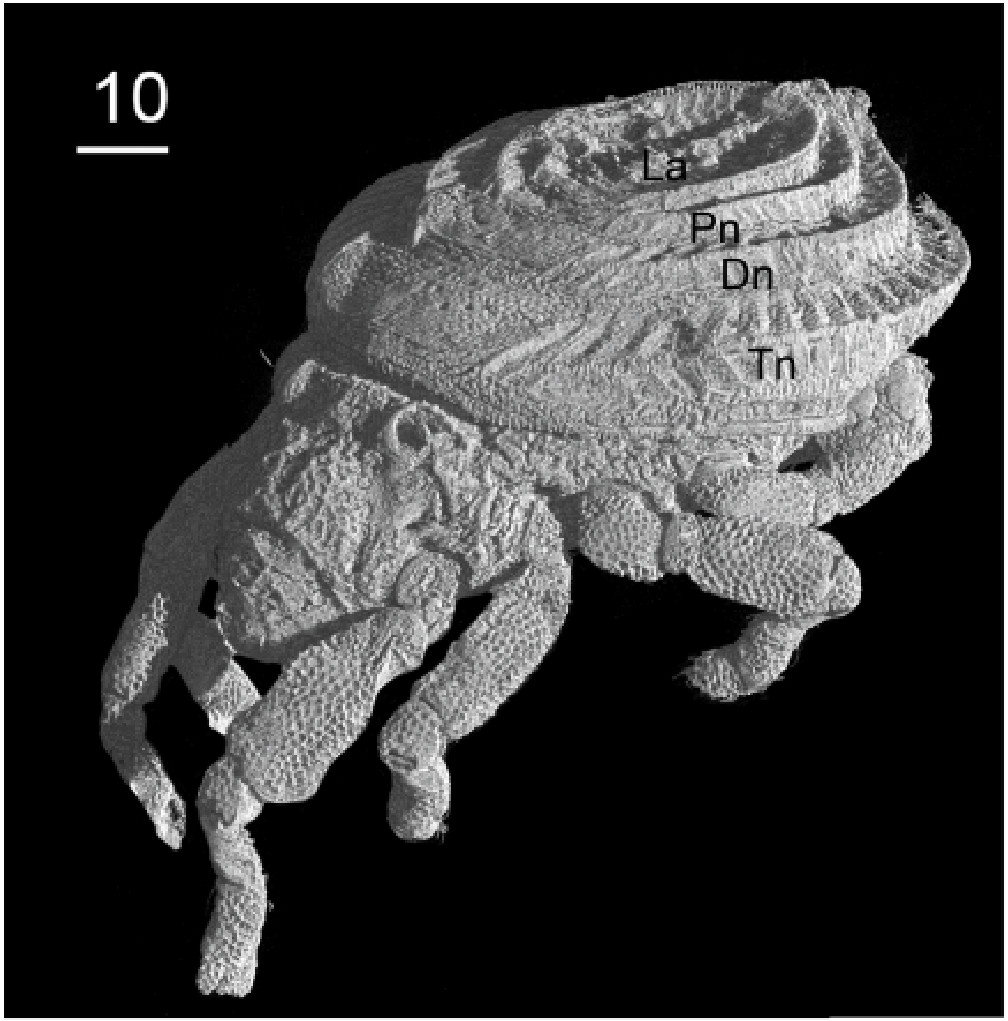






Polystyrene foam.
P. Cloetens 1999

In-line Holotomography



Source: M. Heethoff *et al.* J. Paleont., **83** 153-159 (2009)

Off-axis holography

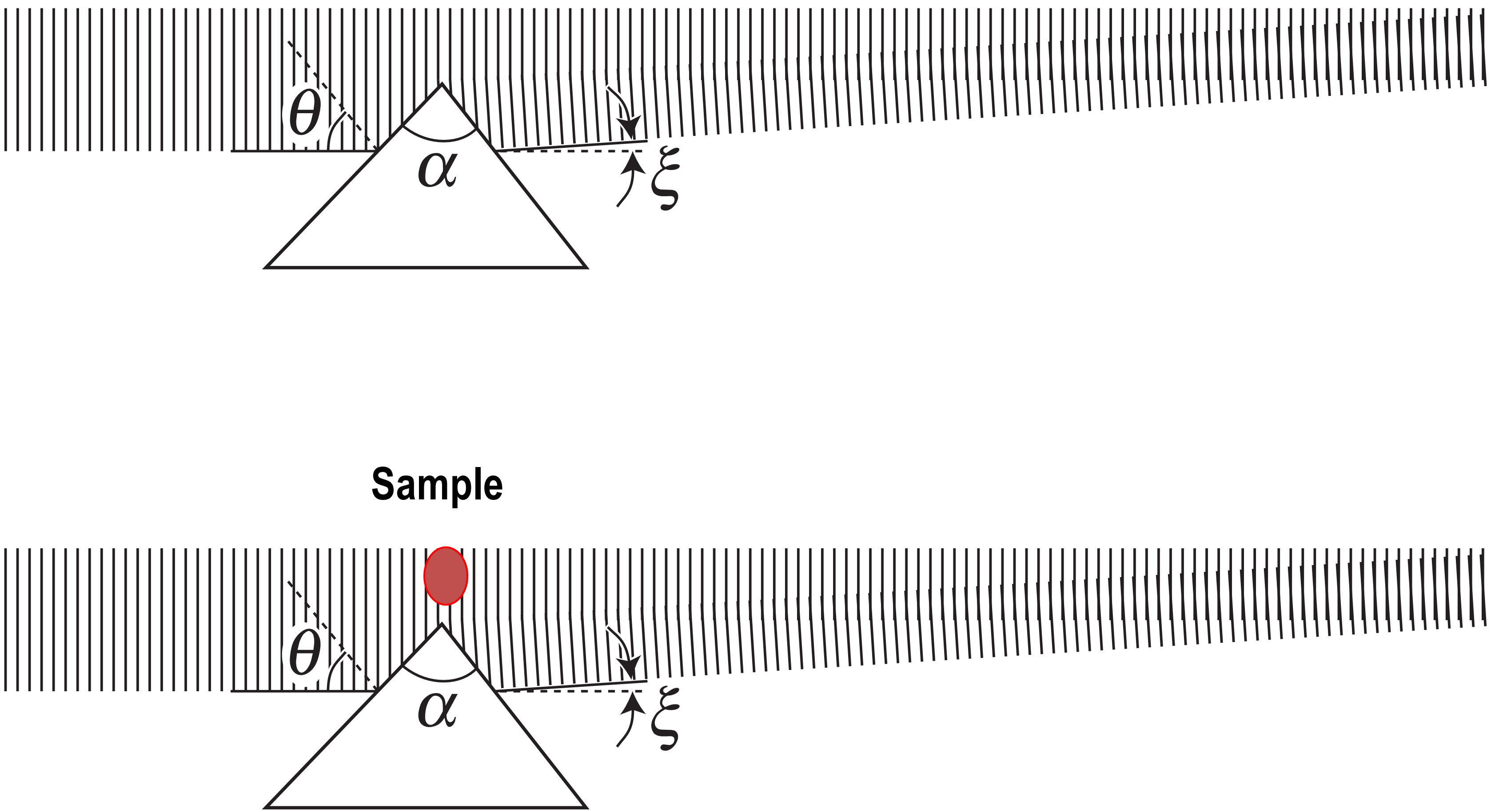


Fig. 10. Interference caused by an X-ray prism.

Momose et al. *Jpn. J. Appl. Phys.* **44** 6355 (2009)

Crystal Interferometer (Bonse & Hart 1965)

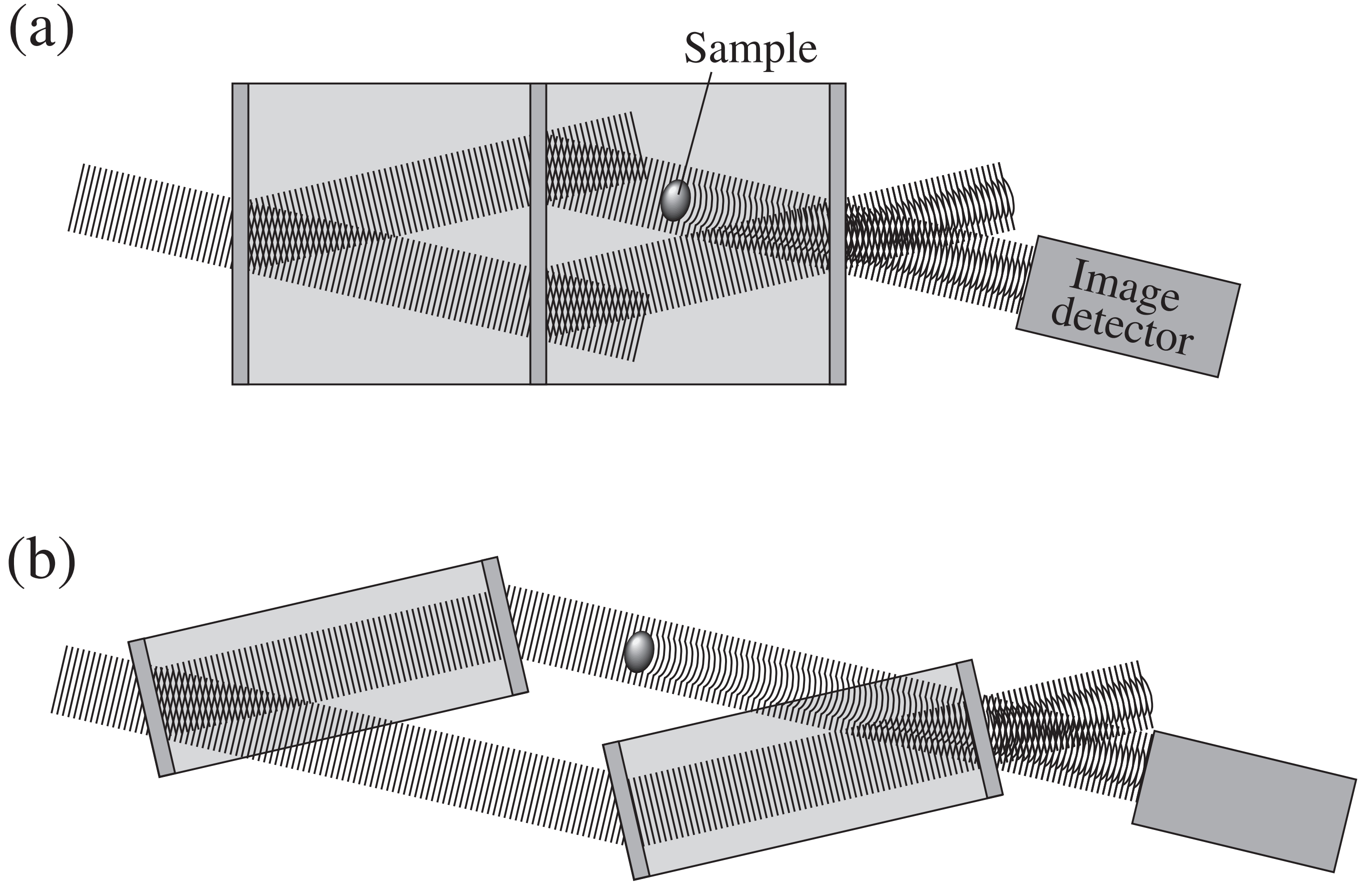
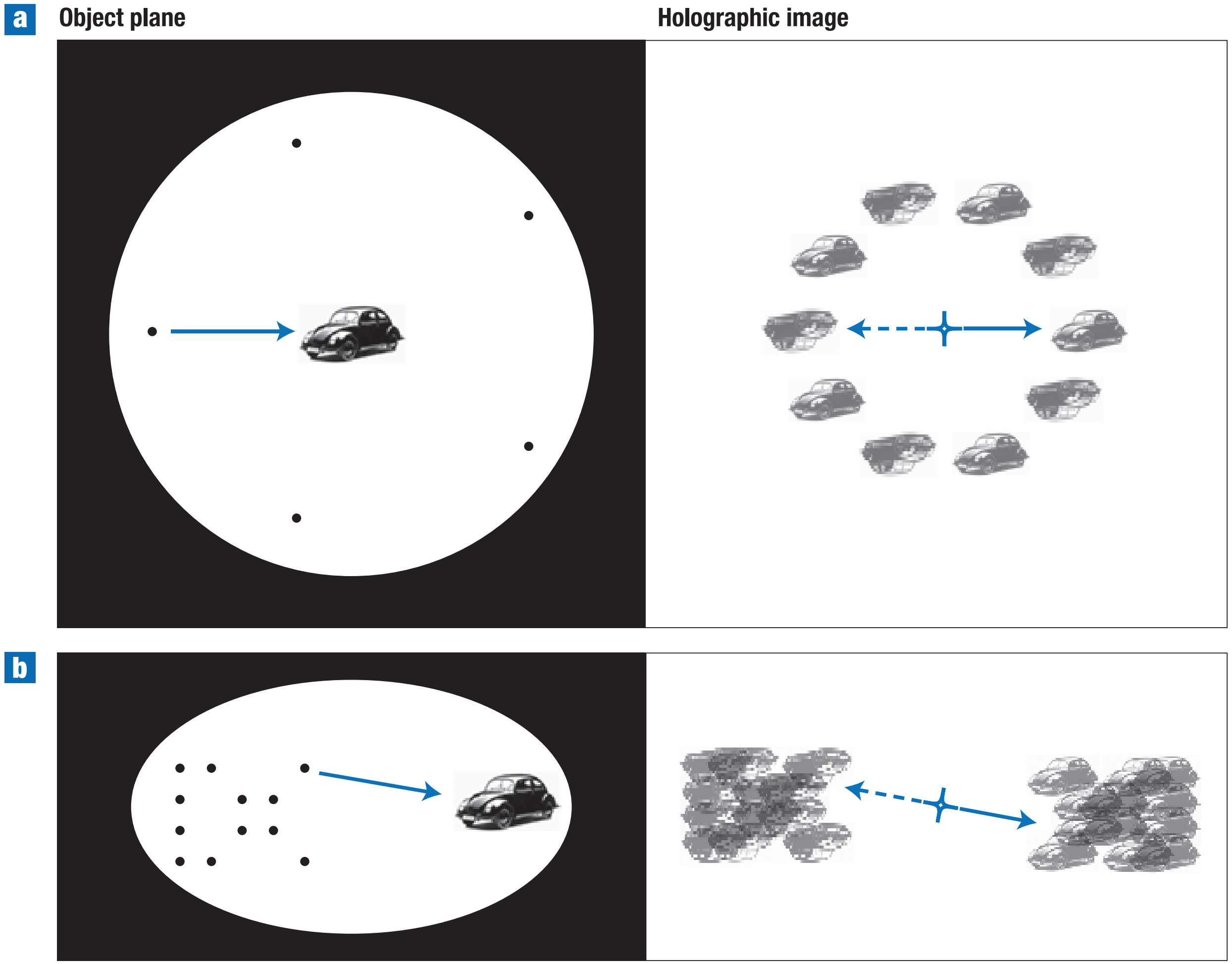


Fig. 5. Crystal X-ray interferometers of a monolithic type (a) and a non-monolithic type (b), which was developed to expand its field of view.

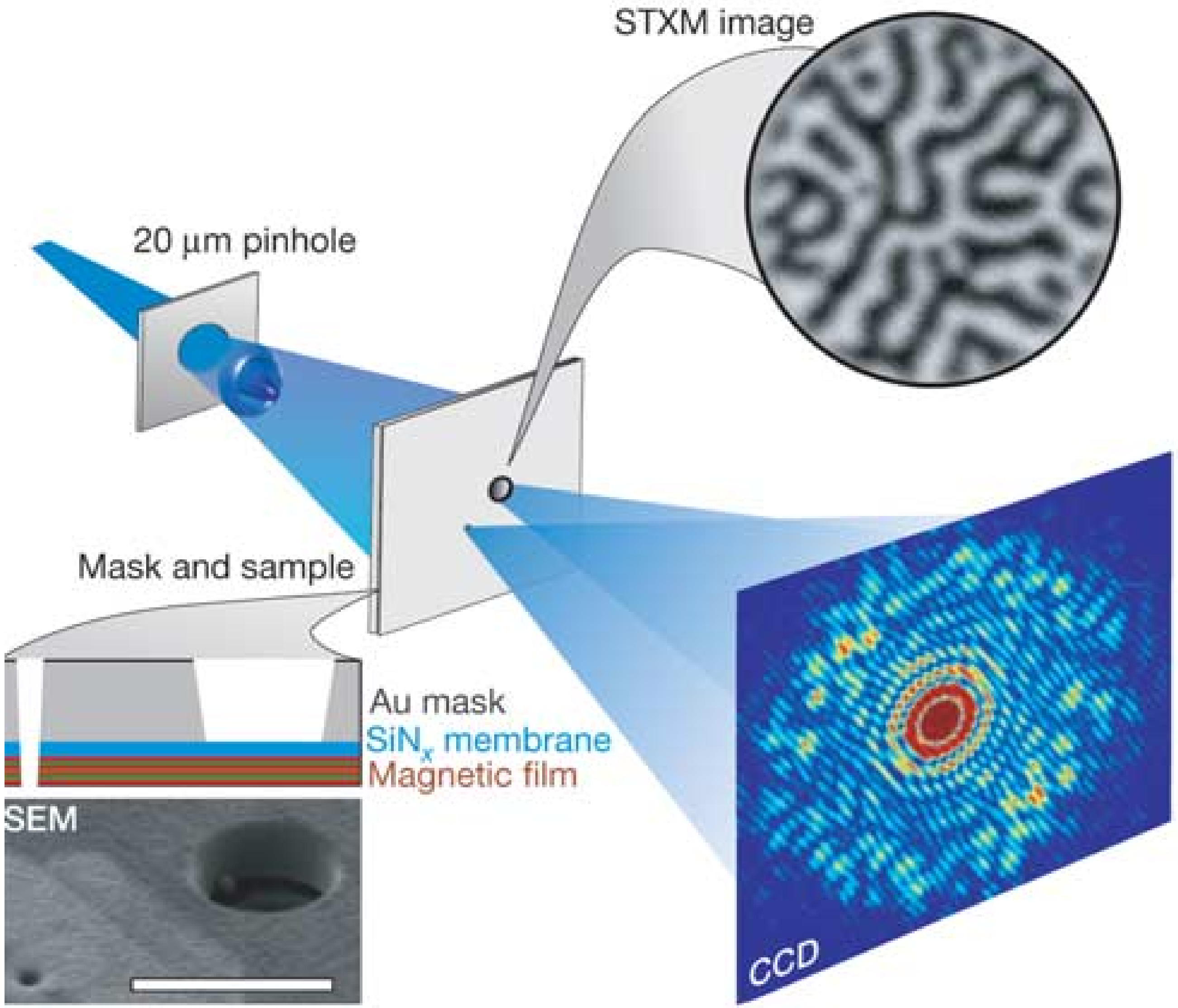
Momose et al. *Jpn. J. Appl. Phys.* **44** 6355 (2009)

Fourier Transform Holography



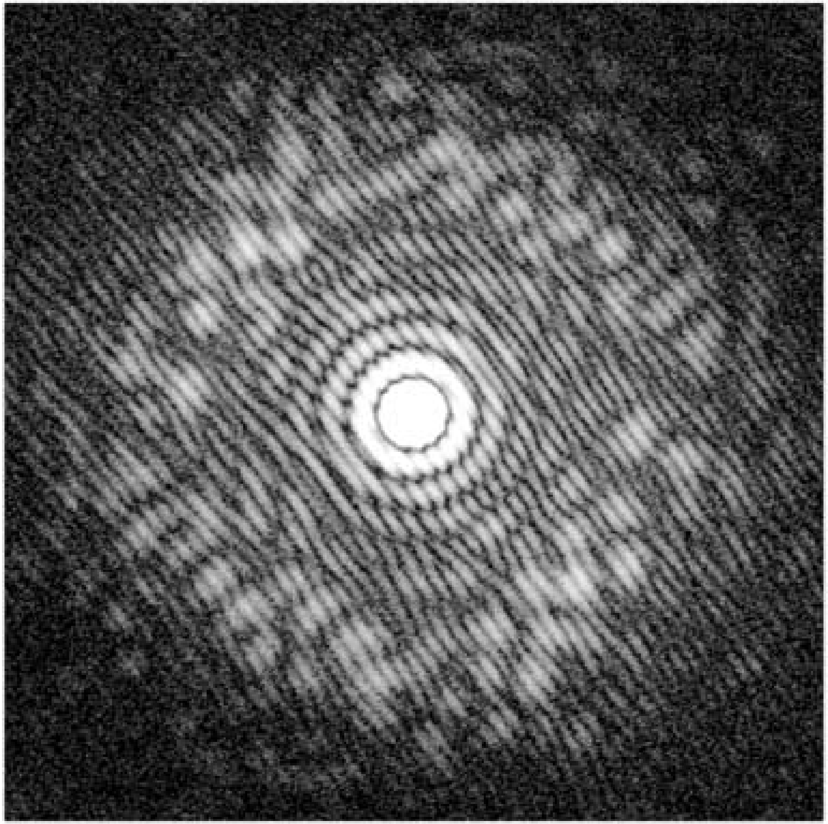
Eisebitt *Nature Photonics* (2008)

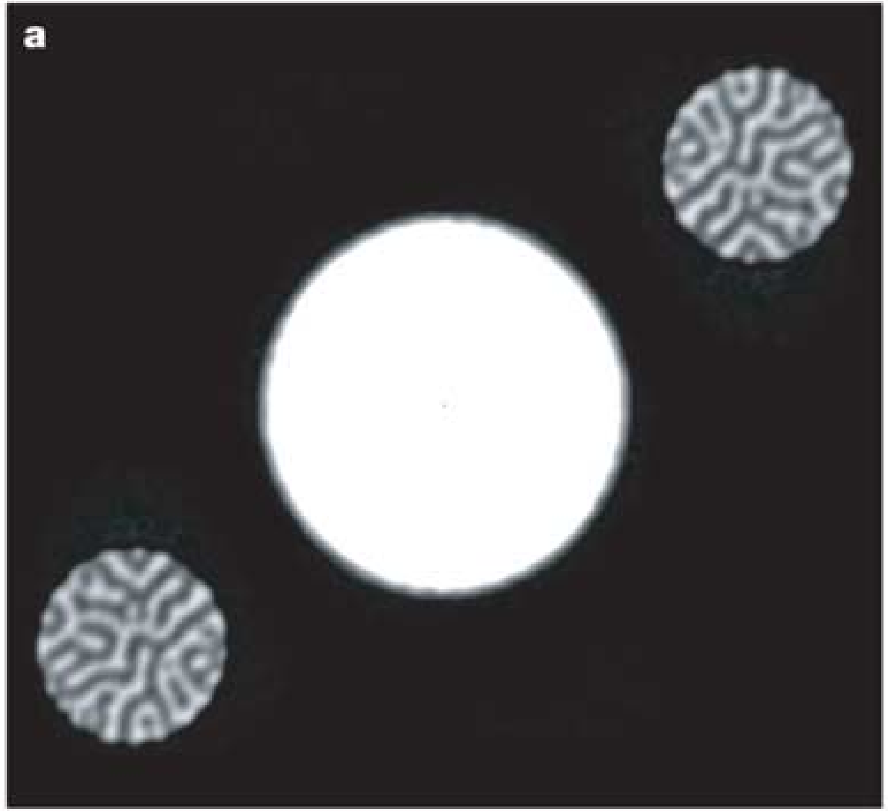
Fourier Transform Holography



Eisebitt et al. *Nature* (2004)

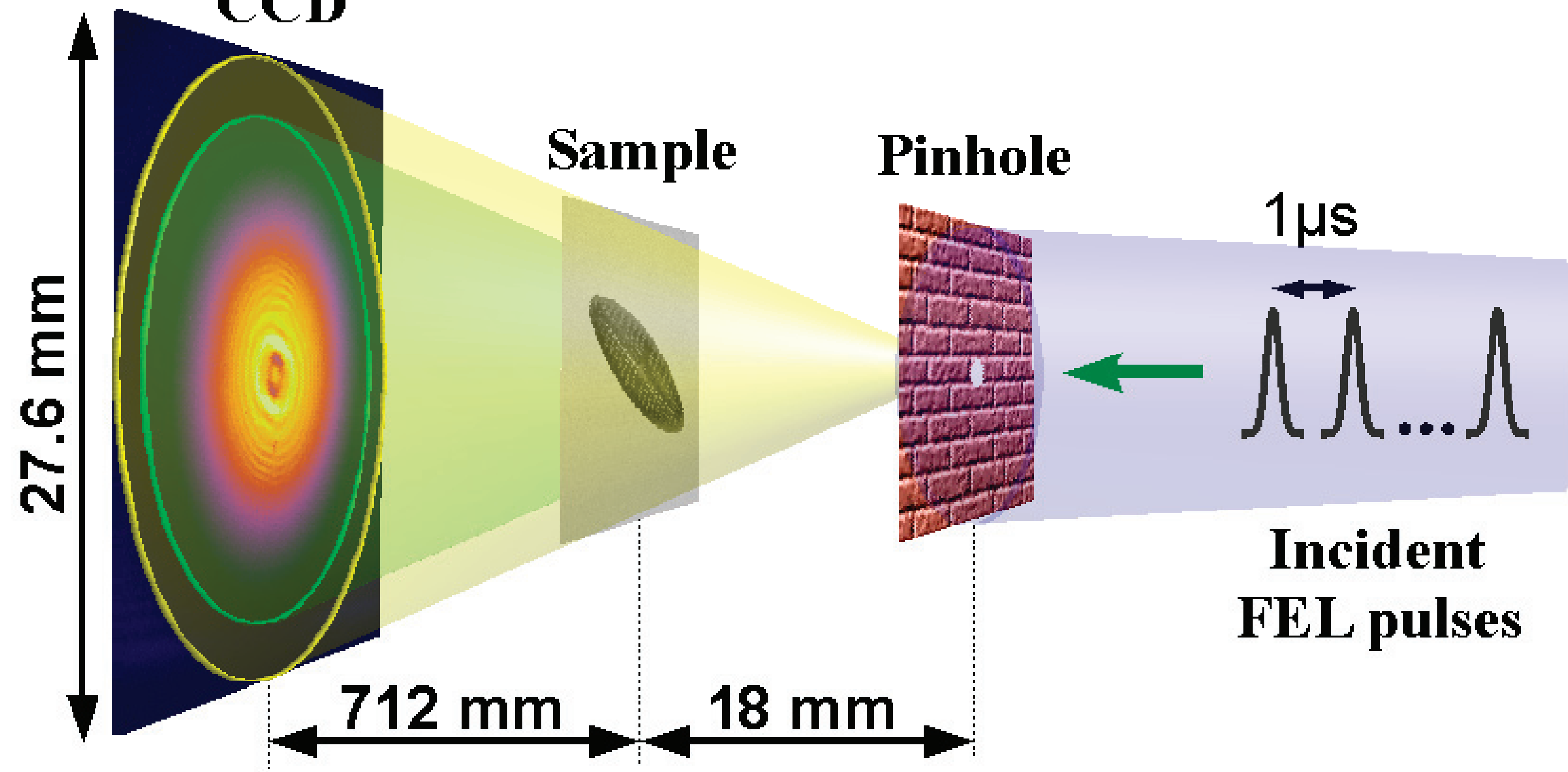
Recorded hologram and Fourier transform





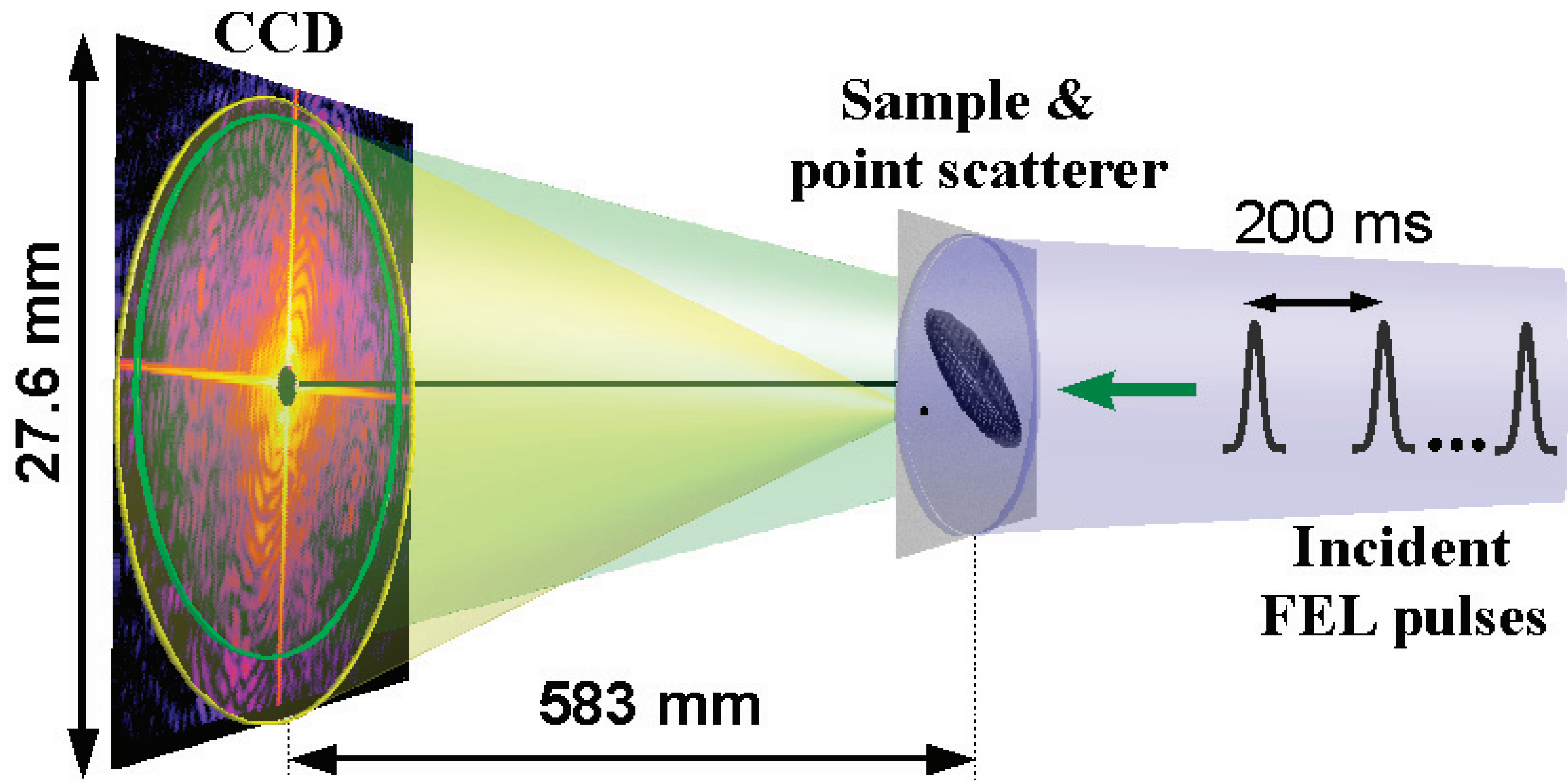
Eisebitt et al. *Nature* (2004)

In-line Holography



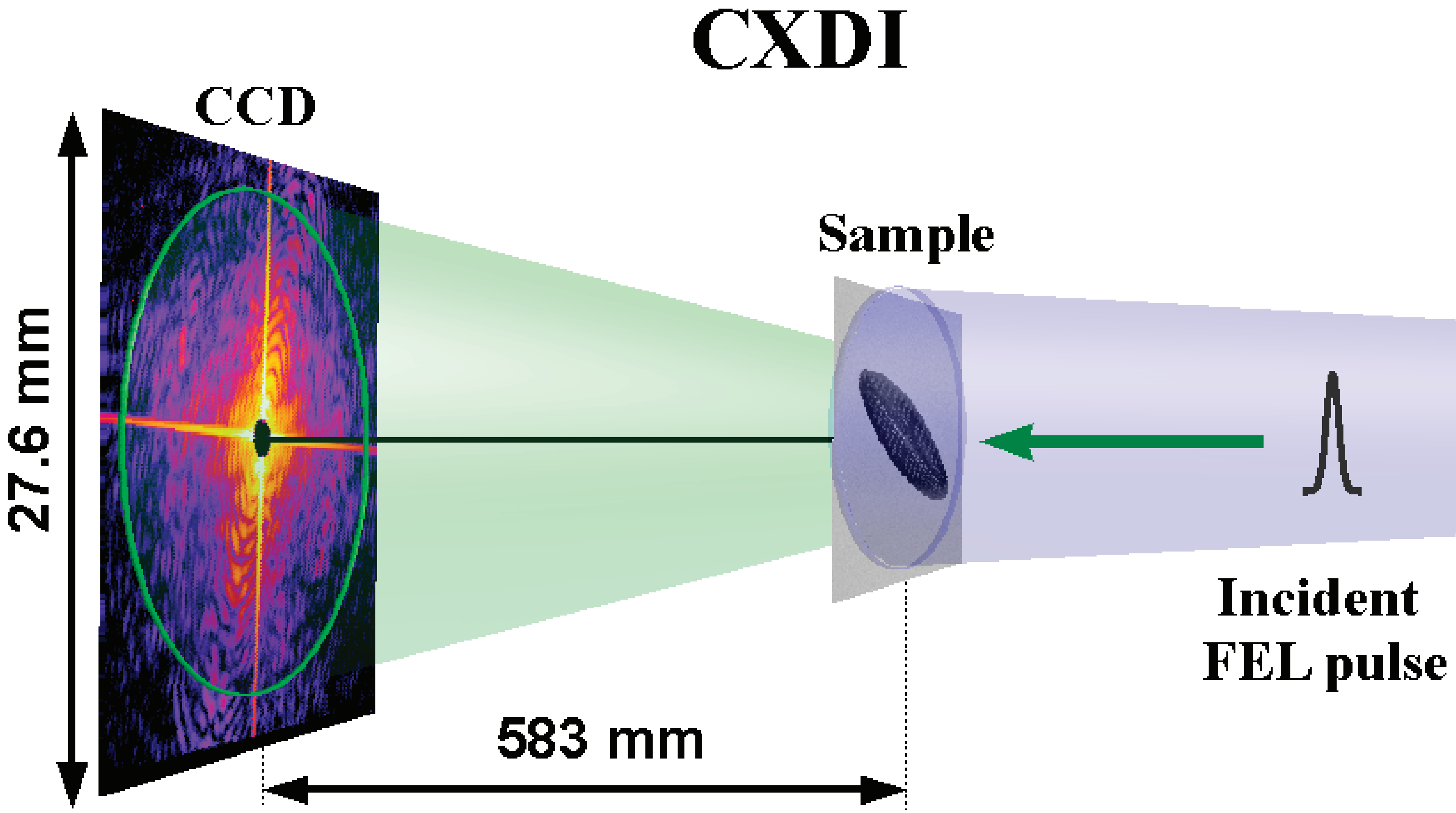
Mancuso et al. *New. J. Phys.* **12** (2010)

Fourier Transform Holography



Mancuso et al. *New. J. Phys.* **12** (2010)

Coherent Diffractive X-ray Imaging



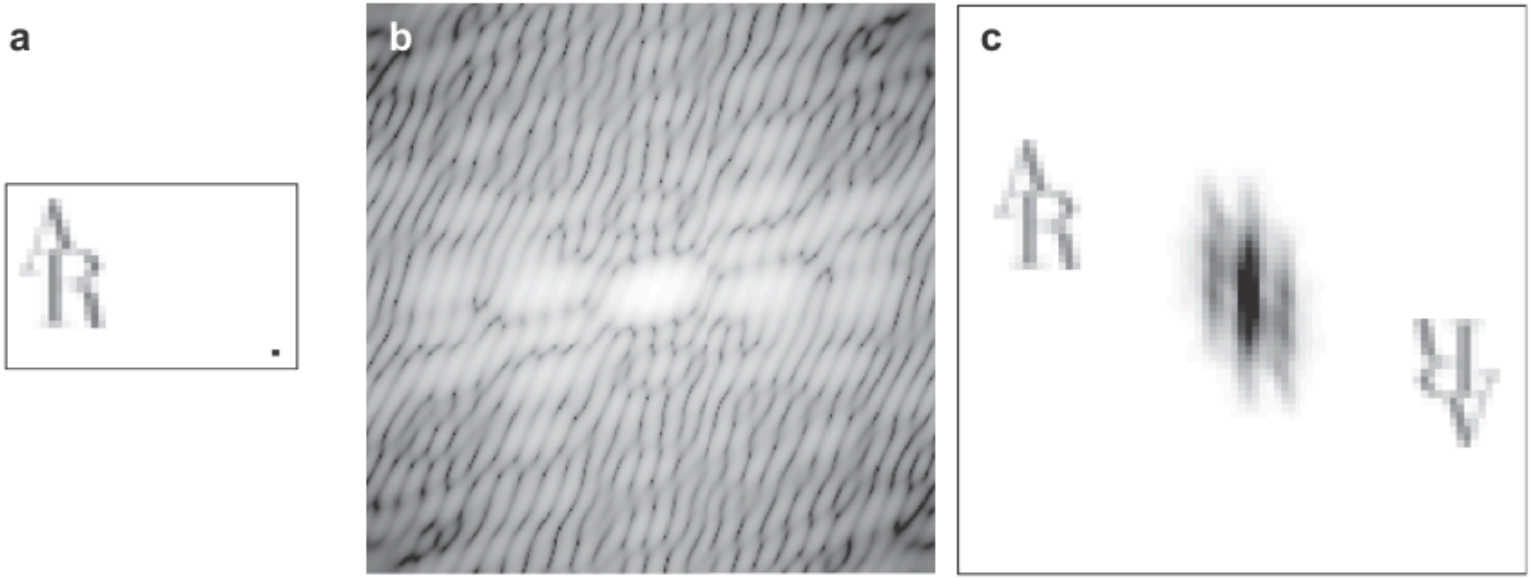
Mancuso et al. *New. J. Phys.* **12** (2010)

Coherent imaging

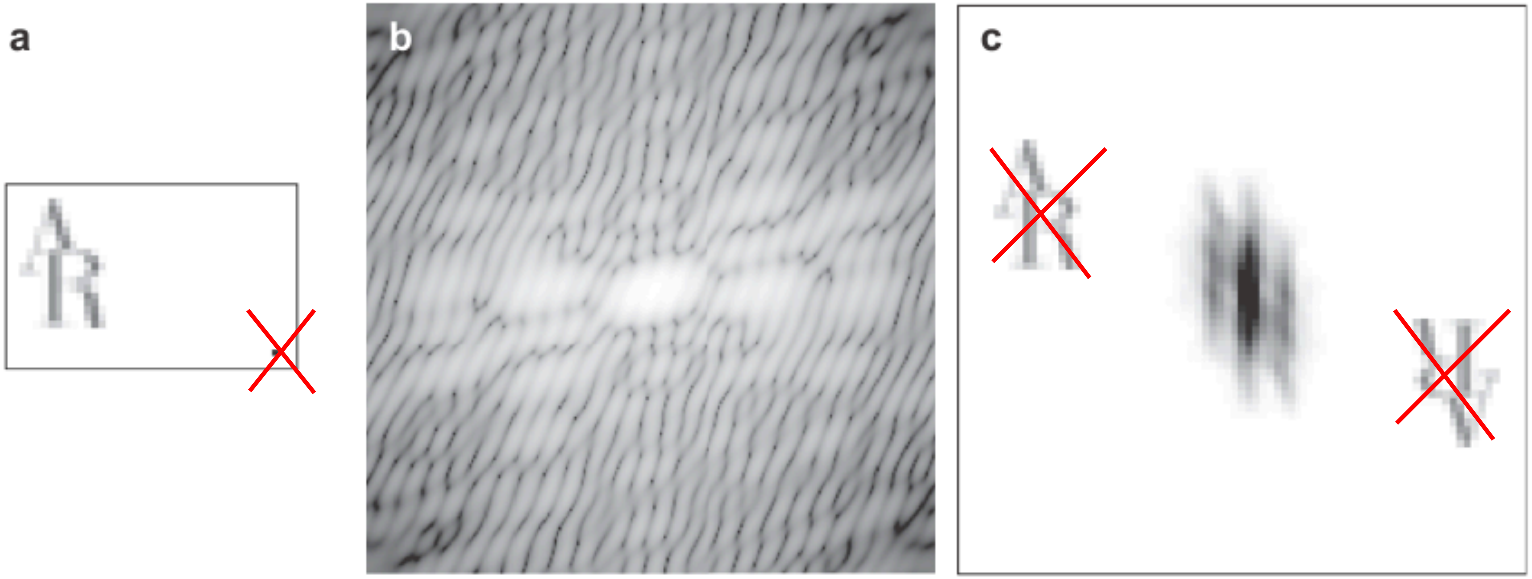
Coherent diffractive imaging (CDI)

Ptychography

With reference wave

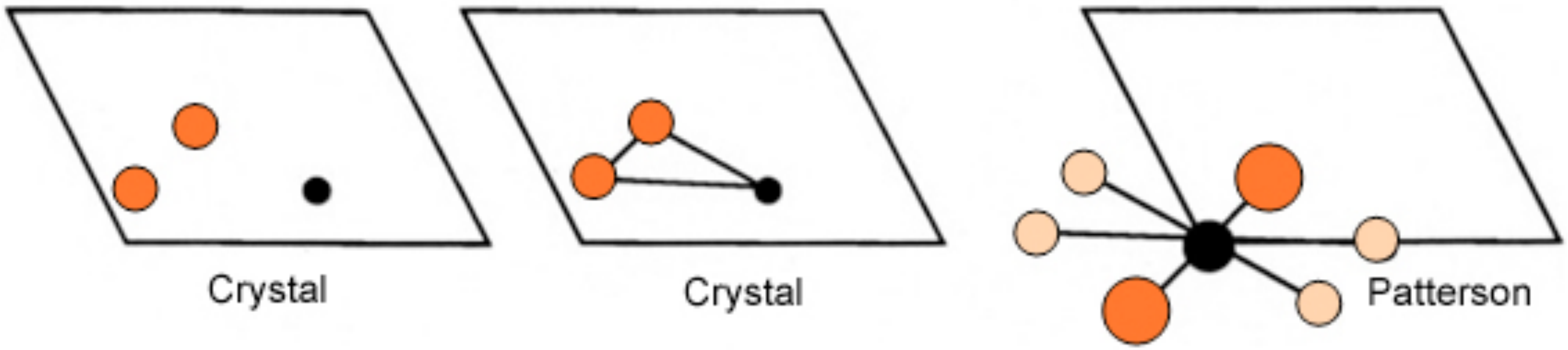


Without reference wave



Imaging of molecules / Crystallography

Patterson function: Autocorrelation function of density distribution

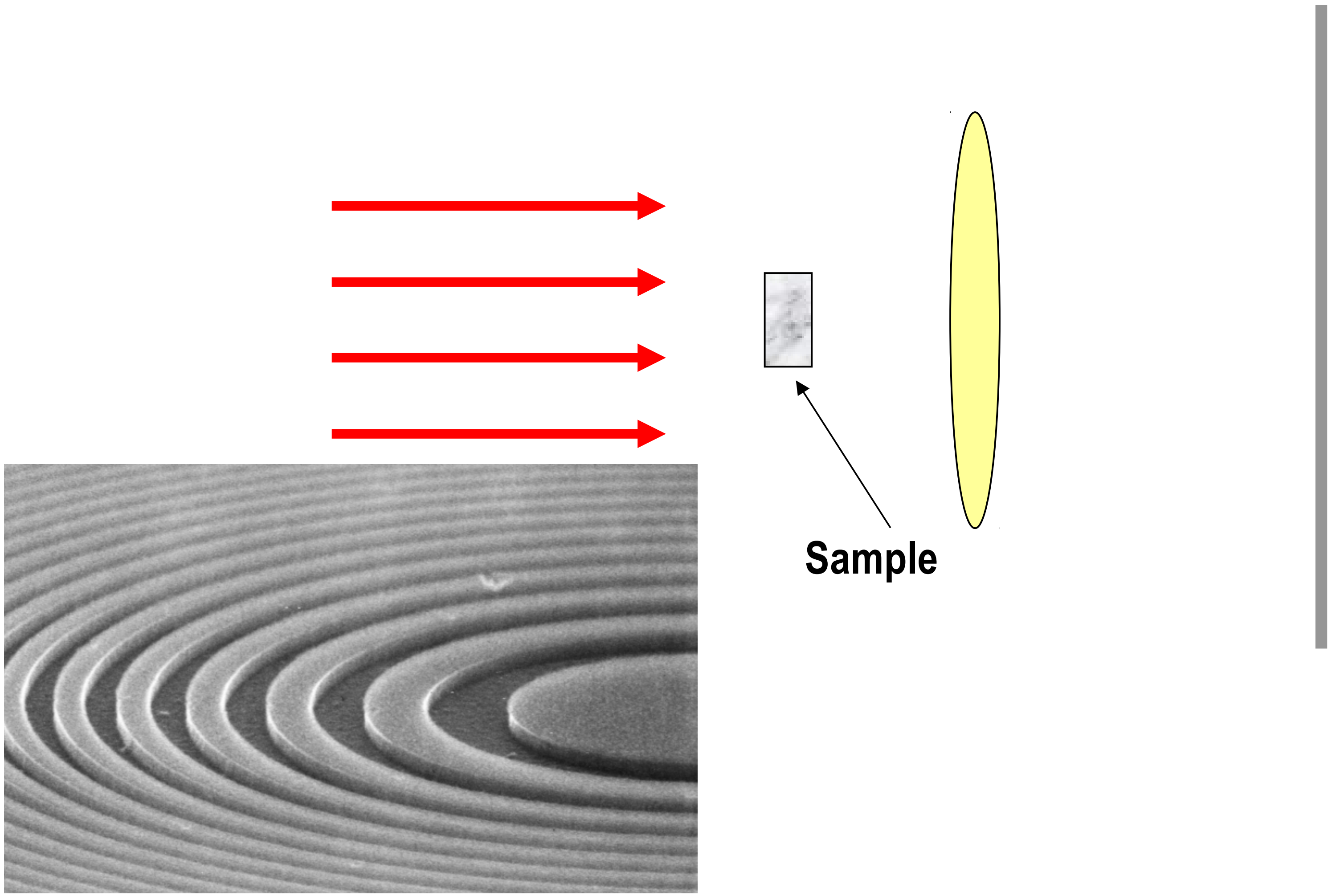


Inverse Fourier transform of measured intensity pattern.

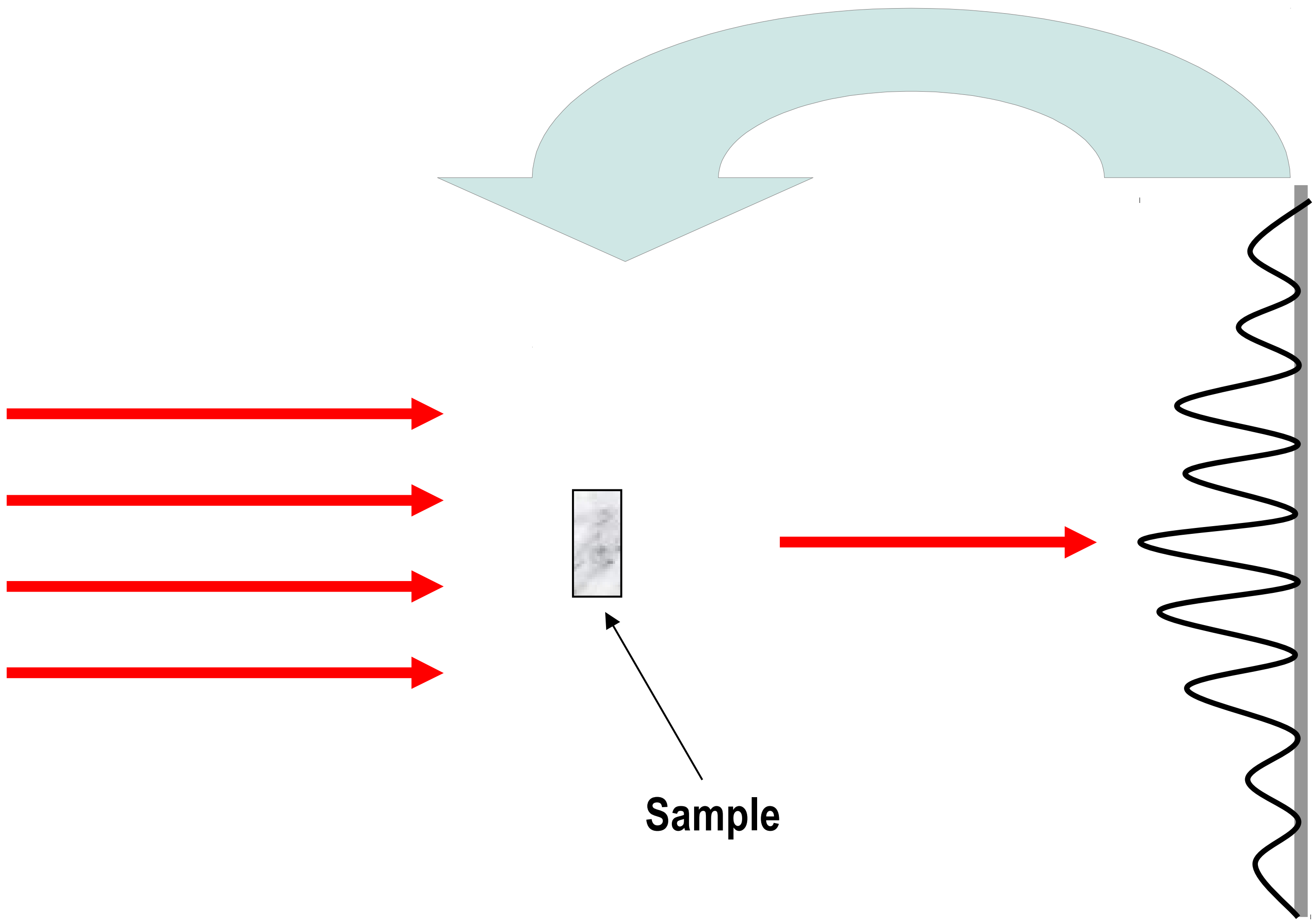
$$P = FT^{-1}(|\Phi|^2)$$

Known as "the phase problem"

From lens based microscopy …



… to lens less imaging / Coherent diffractive imaging



Lens less diffraction microscopy

Visible light example

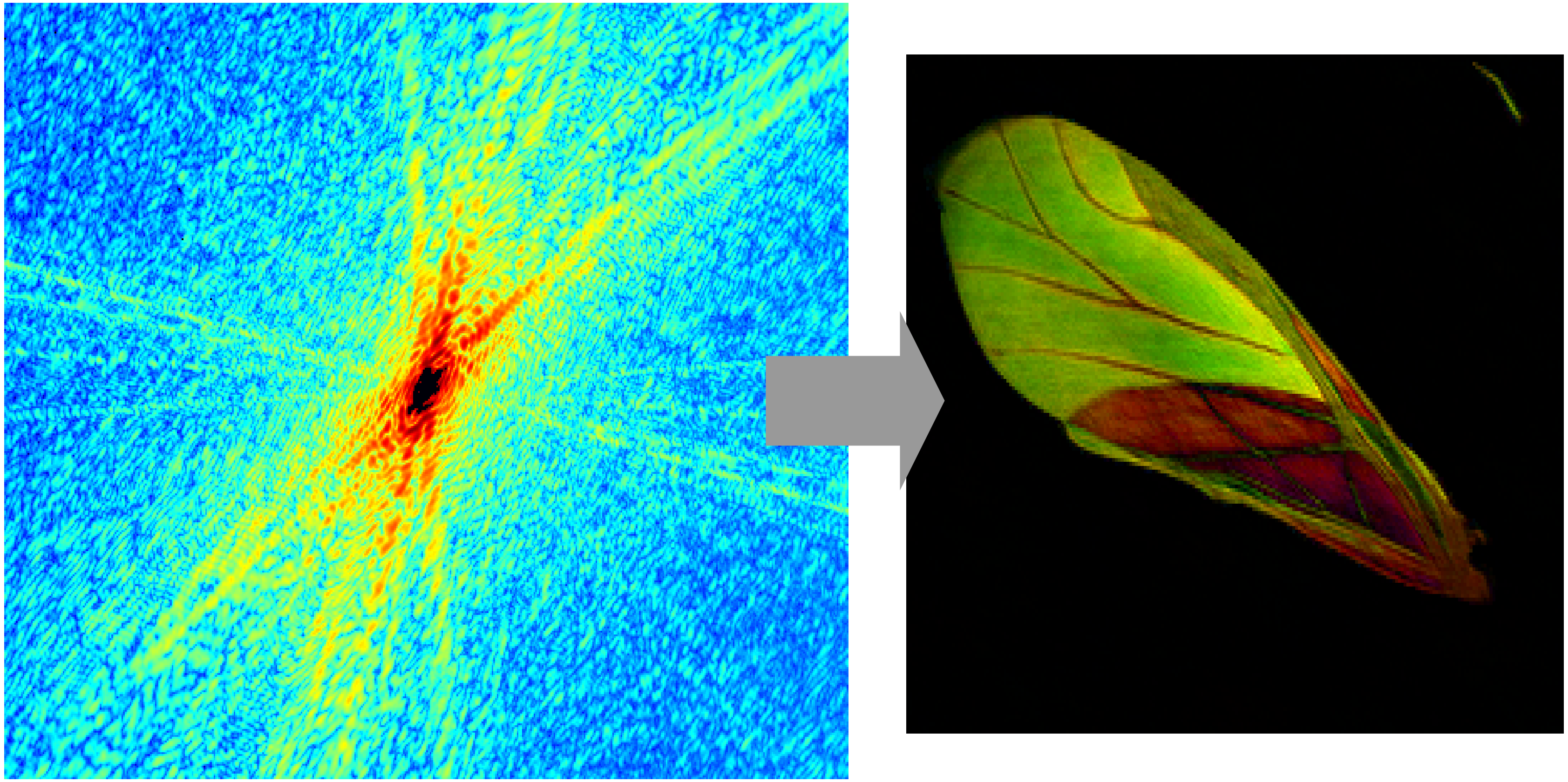
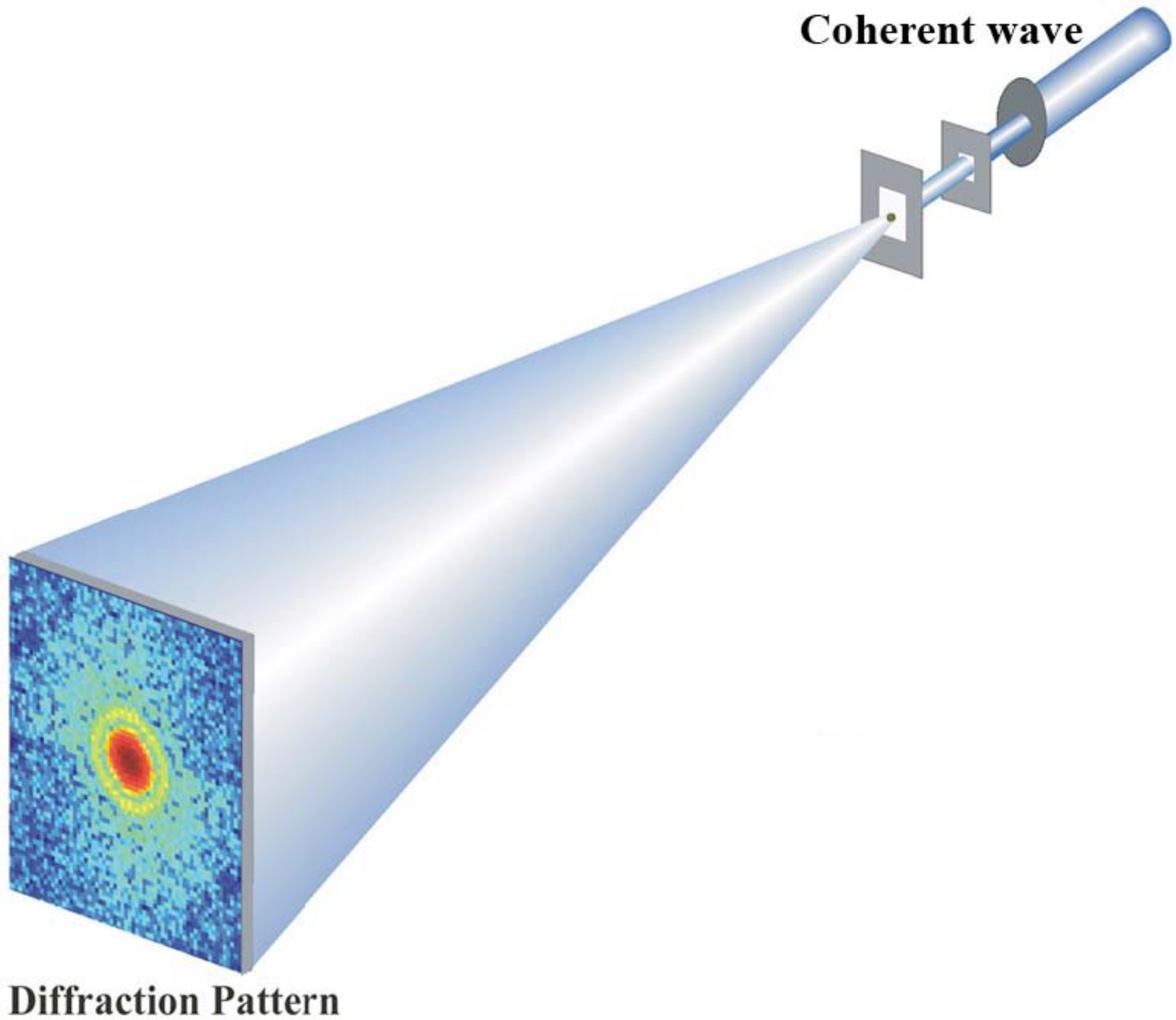


Figure: Pierre Thibault

Far-field (lensless) imaging



Adapted from http://www.physics.ucla.edu/

Diffraction microscopy
Coherent Diffractive Imaging (CDI)

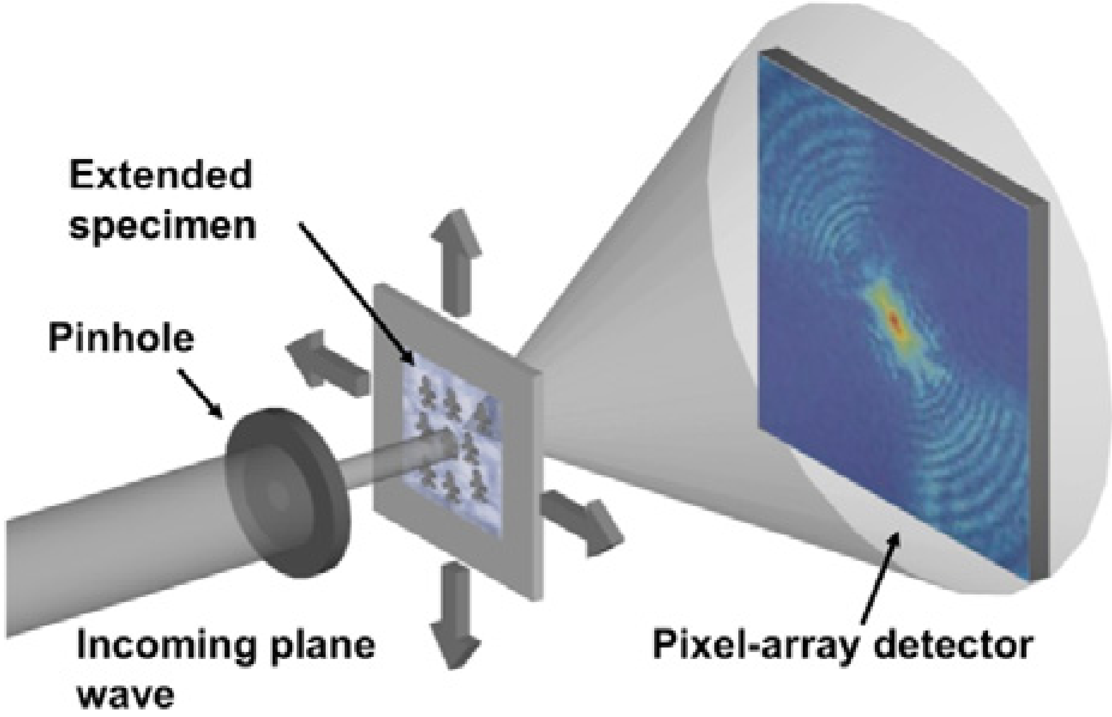
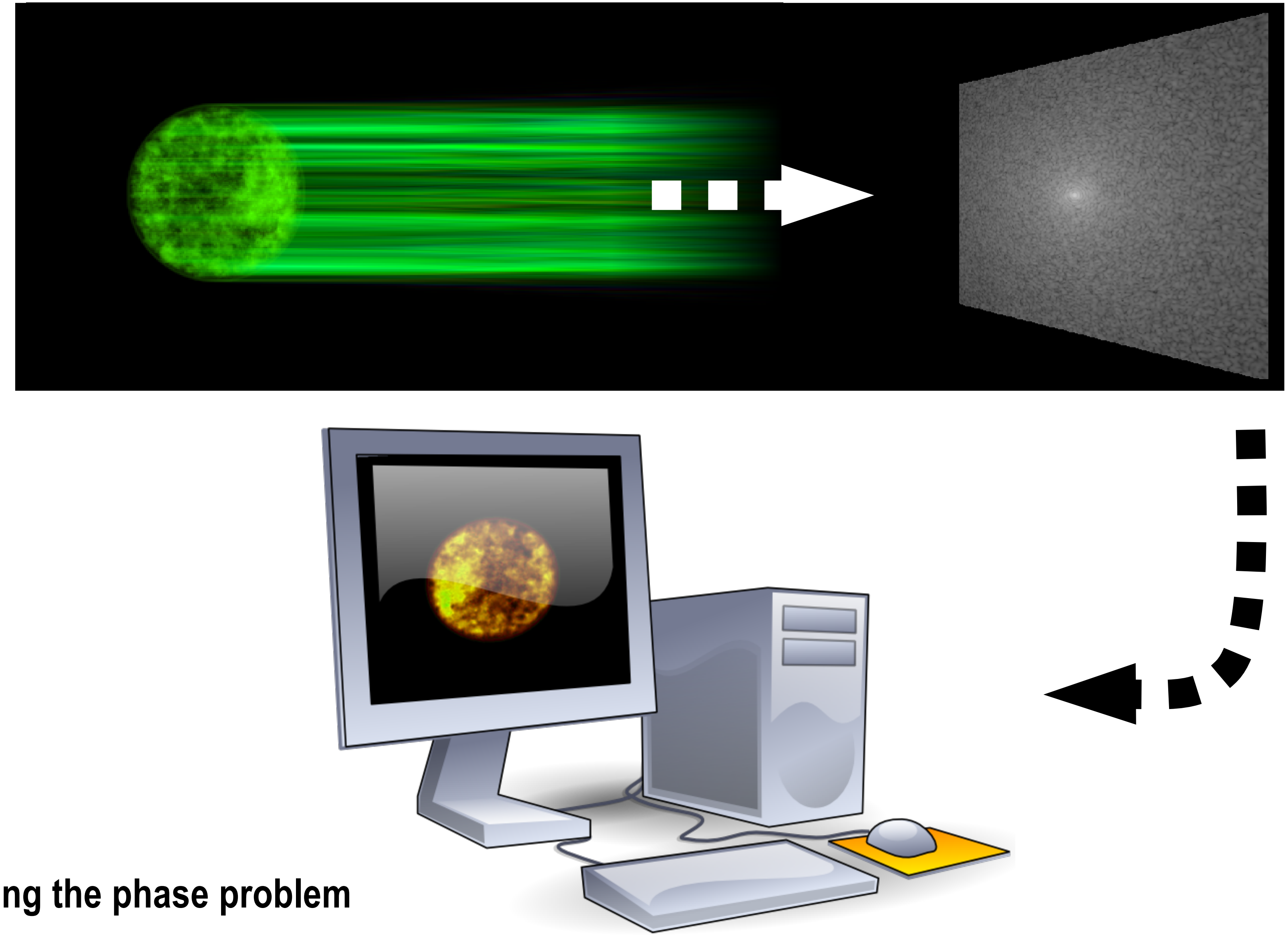


Figure 5.1. Schematic of a diffraction microscopy experimental setup. An incoming plane wave illuminates an isolated specimen. The diffraction pattern from the specimen is recorded on a pixel-array detector.

Source: Kaulich et al. *J. Phys.: Condens. Matter* **23** (2011) 083002

Lens less diffraction microscopy



Solving the phase problem

Figure: Pierre Thibault

CDI

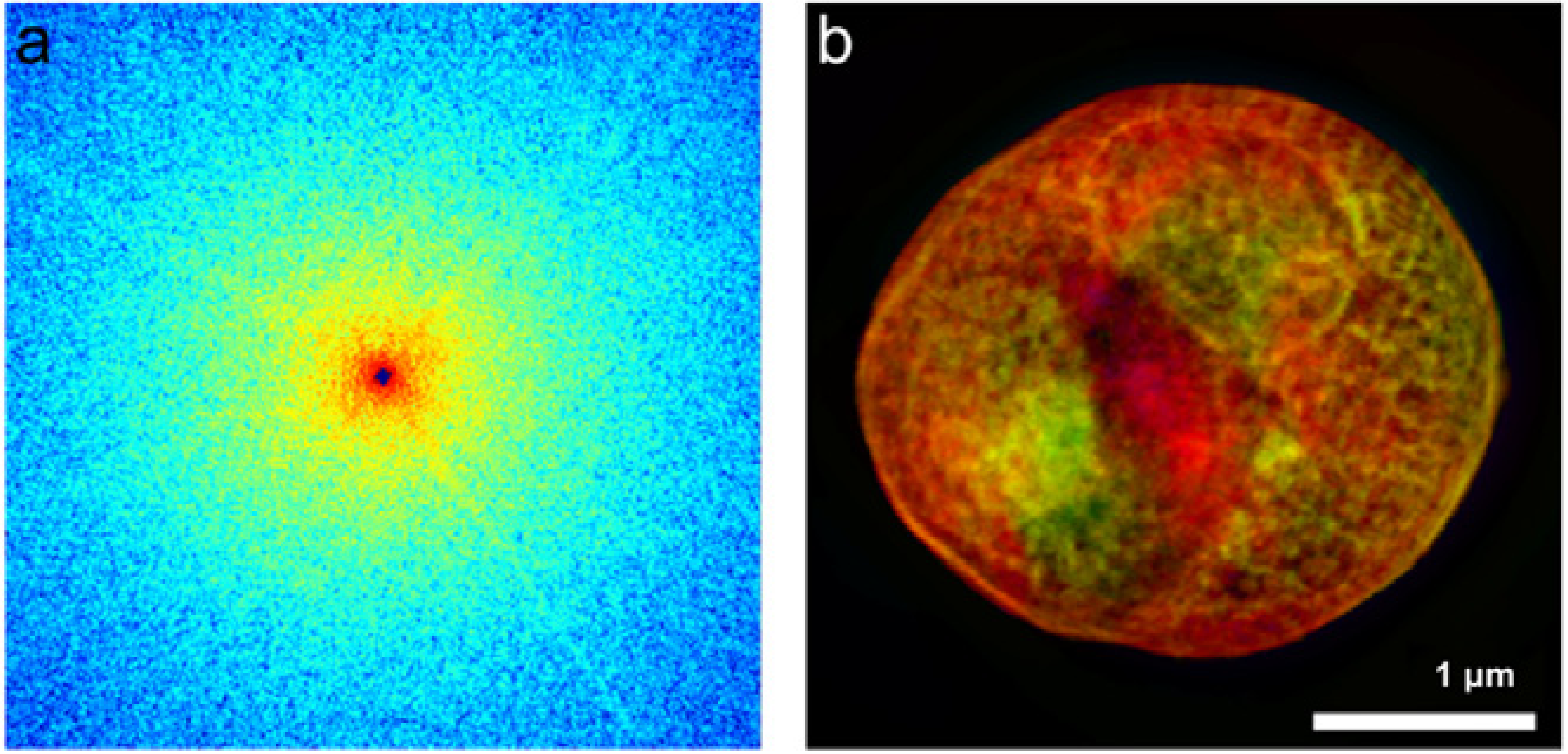
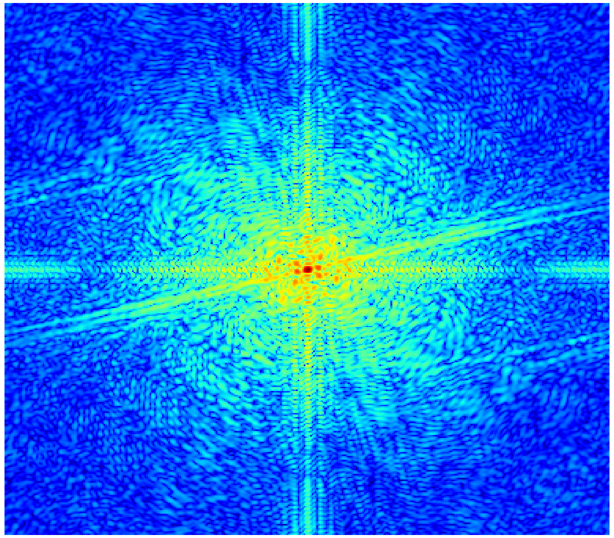
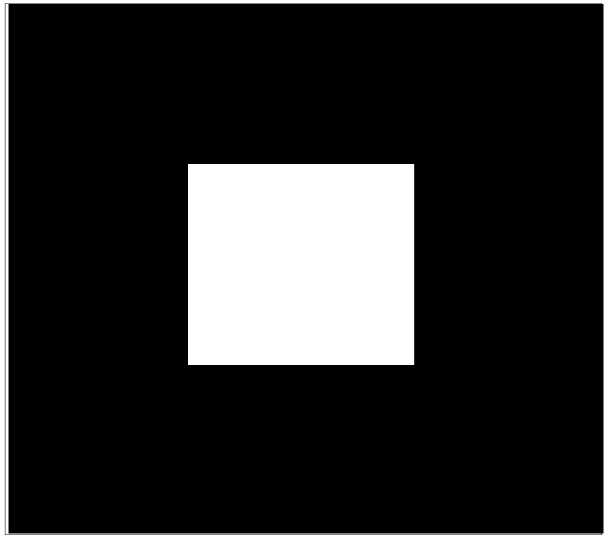


Figure 5.2. (a) Diffraction pattern of a yeast cell; (b) x-ray micrograph reconstructed from the diffraction pattern in (a). Figure adapted from Shapiro *et al* (2005).

Source: Kaulich et al. *J. Phys.: Condens. Matter* **23** (2011) 083002

Diffraction microscopy



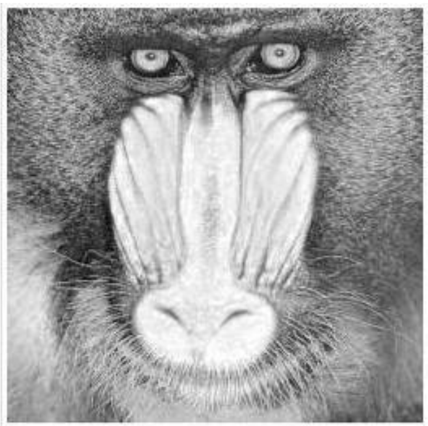


Constraint set formalism

- **Fourier space constraint**
  - **The squared magnitudes of the Fourier transform are equal to the measured intensities.**
- **Support constraint**
  - **The reconstructed image is non-zero only inside the support**

The phase problem

Object to be reconstructed



Measured data

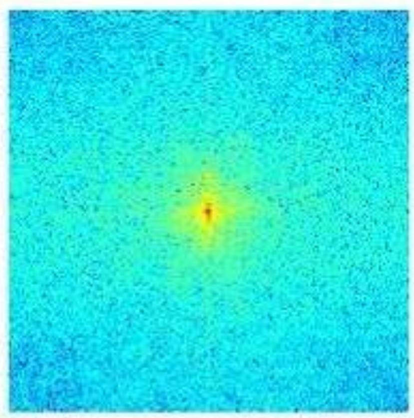
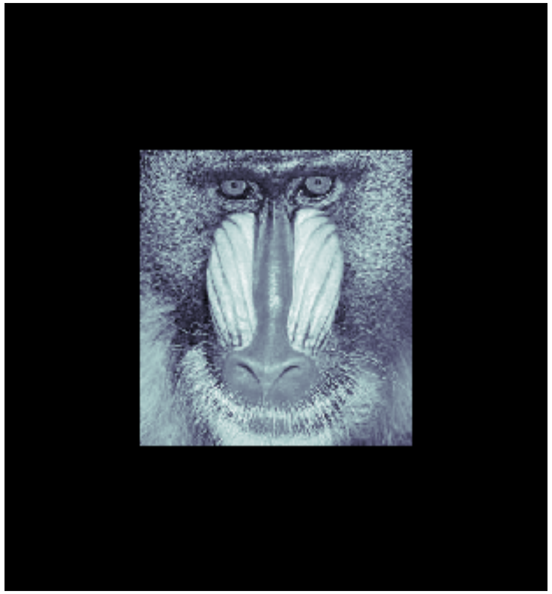


Image courtesy: Martin Dierolf

The phase problem – additional constraints

Object to be reconstructed



Measured data

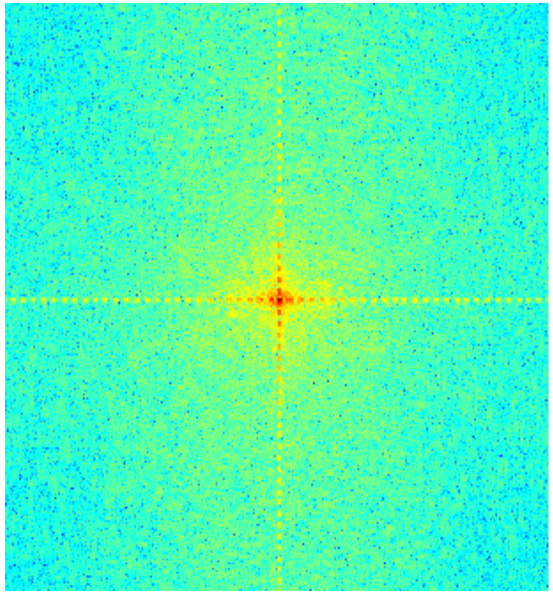


Image courtesy: Martin Dierolf

Coherent Diffractive Imaging

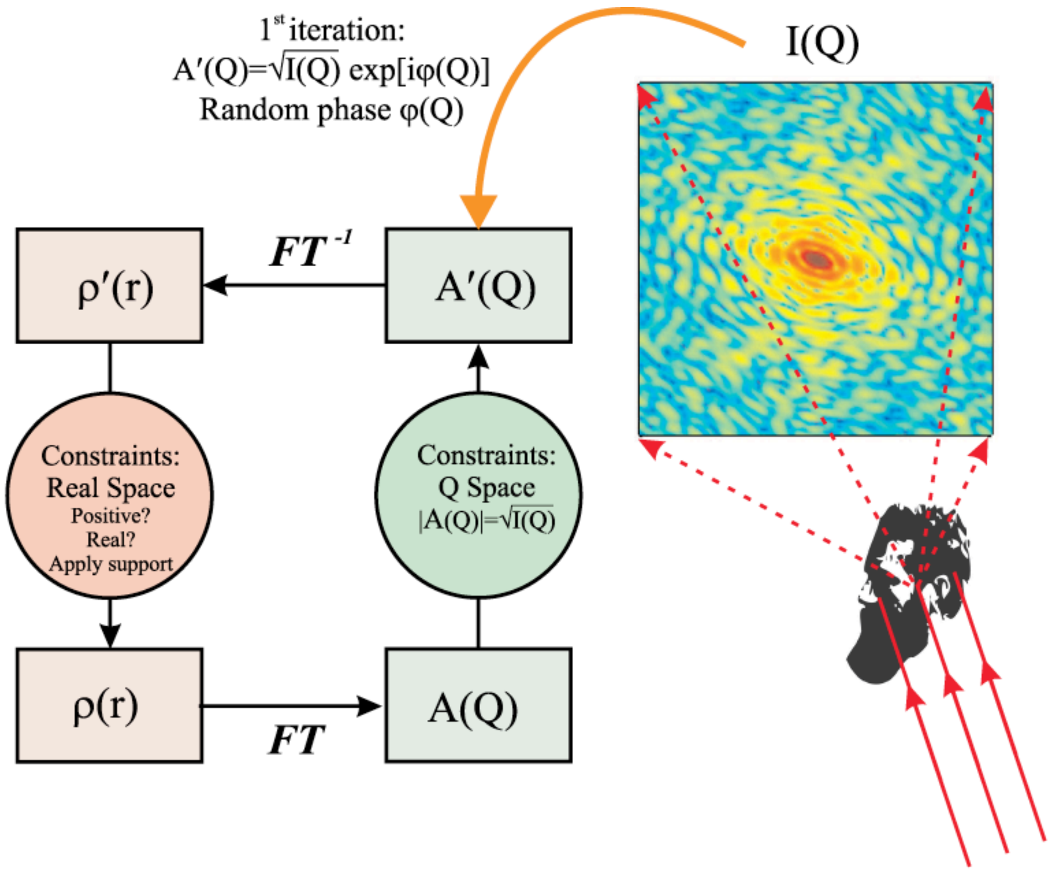


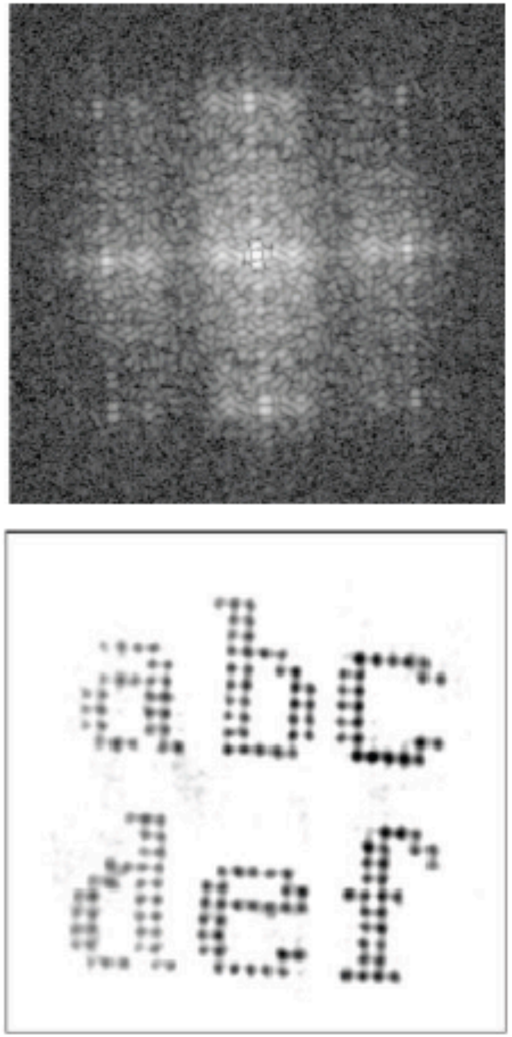
Fig. 9.21 Schematic of the iterative, phase retrieval algorithm used to reconstruct real space images from coherent X-ray diffraction images. In the right hand panel a test object is illuminated by a coherent X-ray beam and the diffracted intensity, $I(\mathbf{Q})$, is recorded on a position sensitive area detector placed in the far-field. The diffraction pattern in this case is that of a portrait of W.C. Röntgen.

Diffraction microscopy

Extending the methodology of X-ray crystallography to allow imaging of micrometre-sized non-crystalline specimens

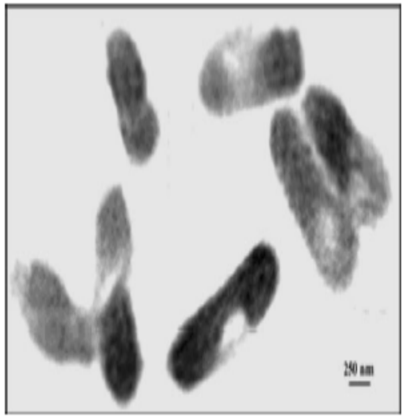
Jianwei Miao*, Pambos Charalambous†, Janos Kirz*
& David Sayre*‡

NATURE | VOL 400 | 22 JULY 1999 | www.nature.com

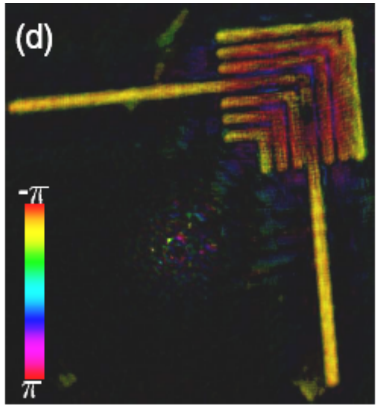


Successful demonstrations of coherent diffractive imaging

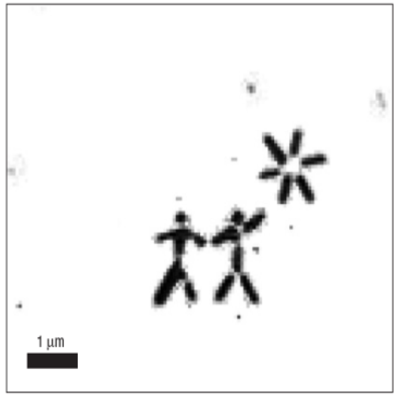
J. Miao et al.,
Nature 400 , 342 (1999)



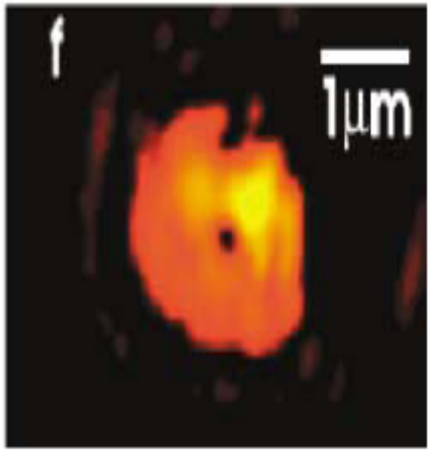
J. Miao et al.,
PNAS 100 , 110 (2003)



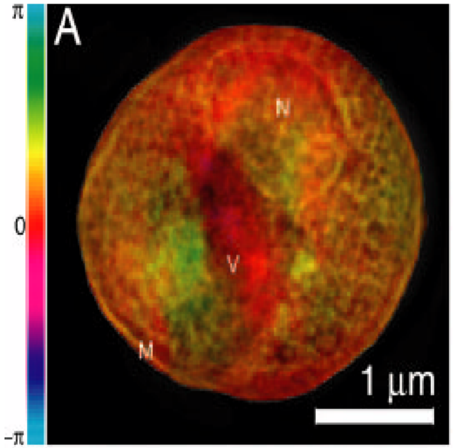
G. Williams et al.,
PRL 97 , 025506 (2006)



H. Chapman et al.,
Nat. Phys. 2 , 839 (2006)

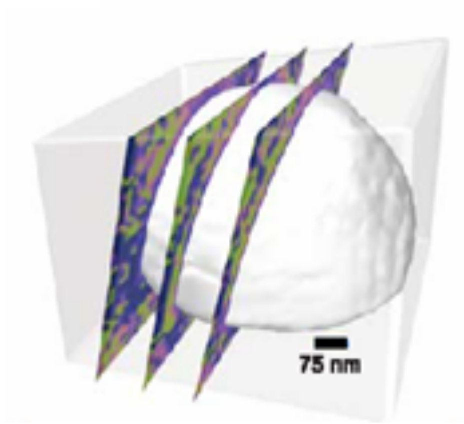


I. Robinson et al.,
PRL 90 , 195505 (2001)



D. Shapiro et al.,
PNAS 102 , 15343 (2005)

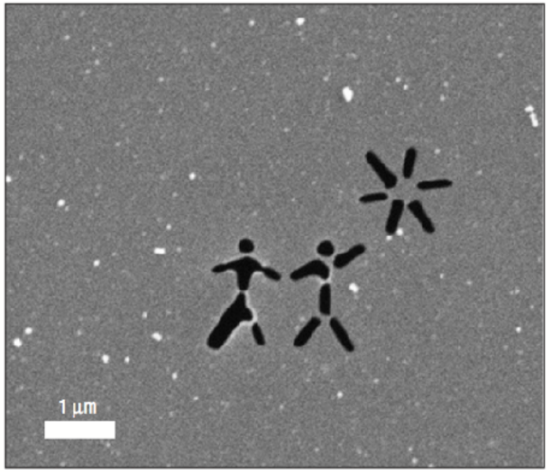
H. Chapman et al.,
JOSA 23 , 1179 (2006)

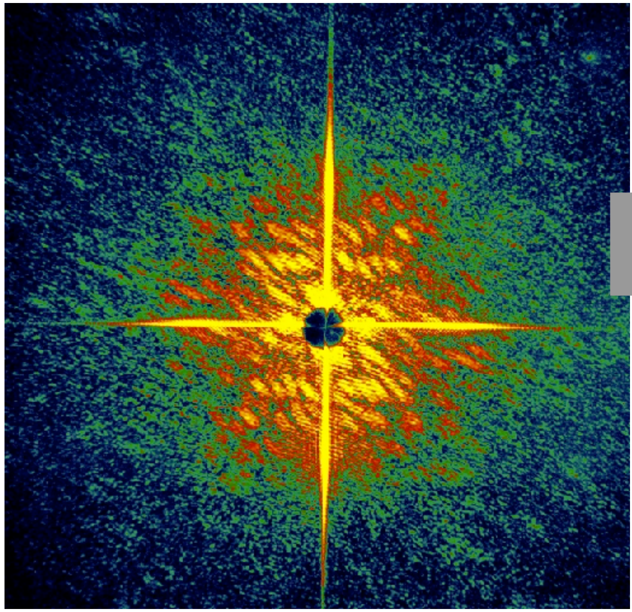


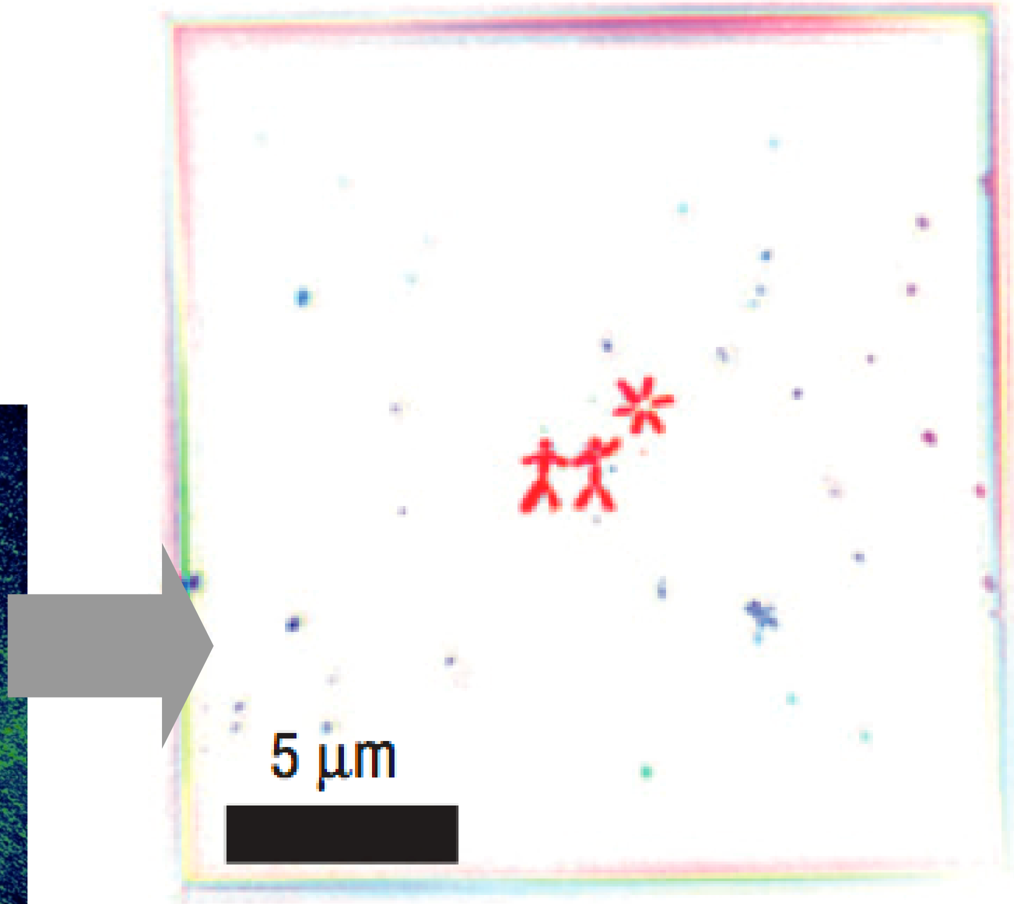
M. Pfeifer et al.,
Nature 442 , 63 (2006)

Examples

@ XFEL

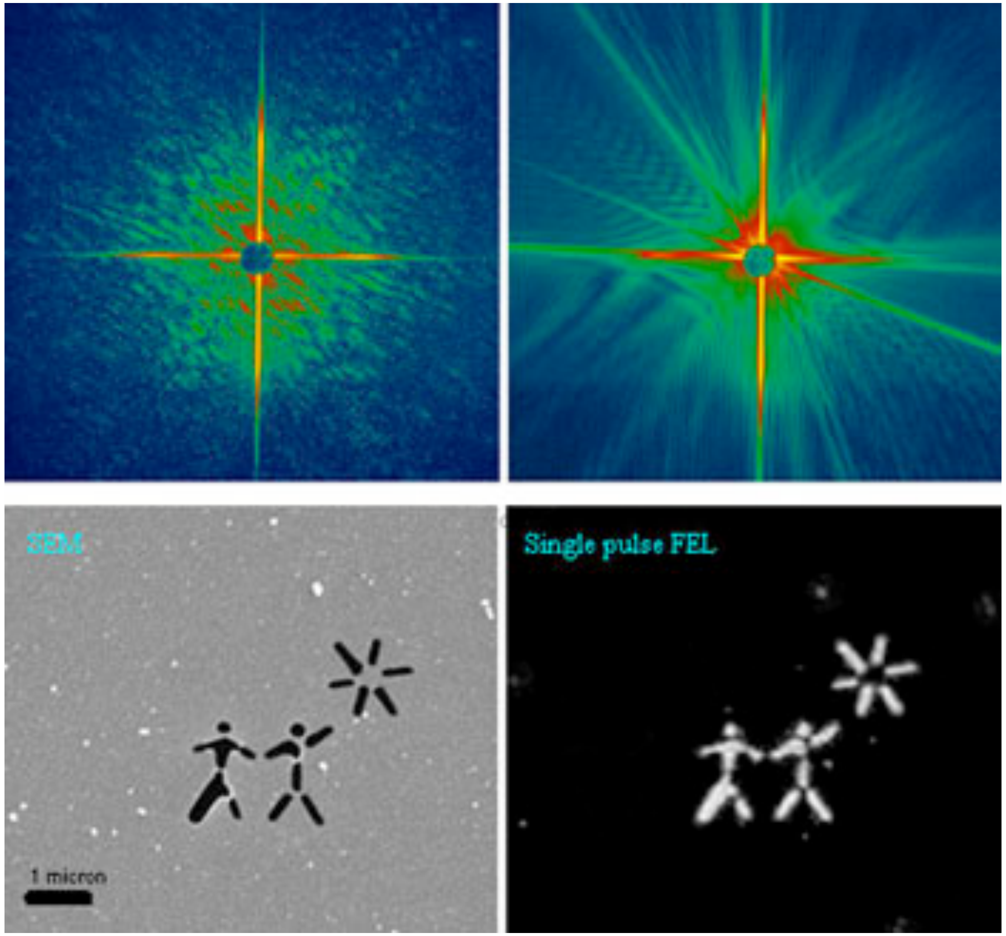






Source: H. N. Chapman *et al*, Nat. Phys. **2**, 839 (2006)

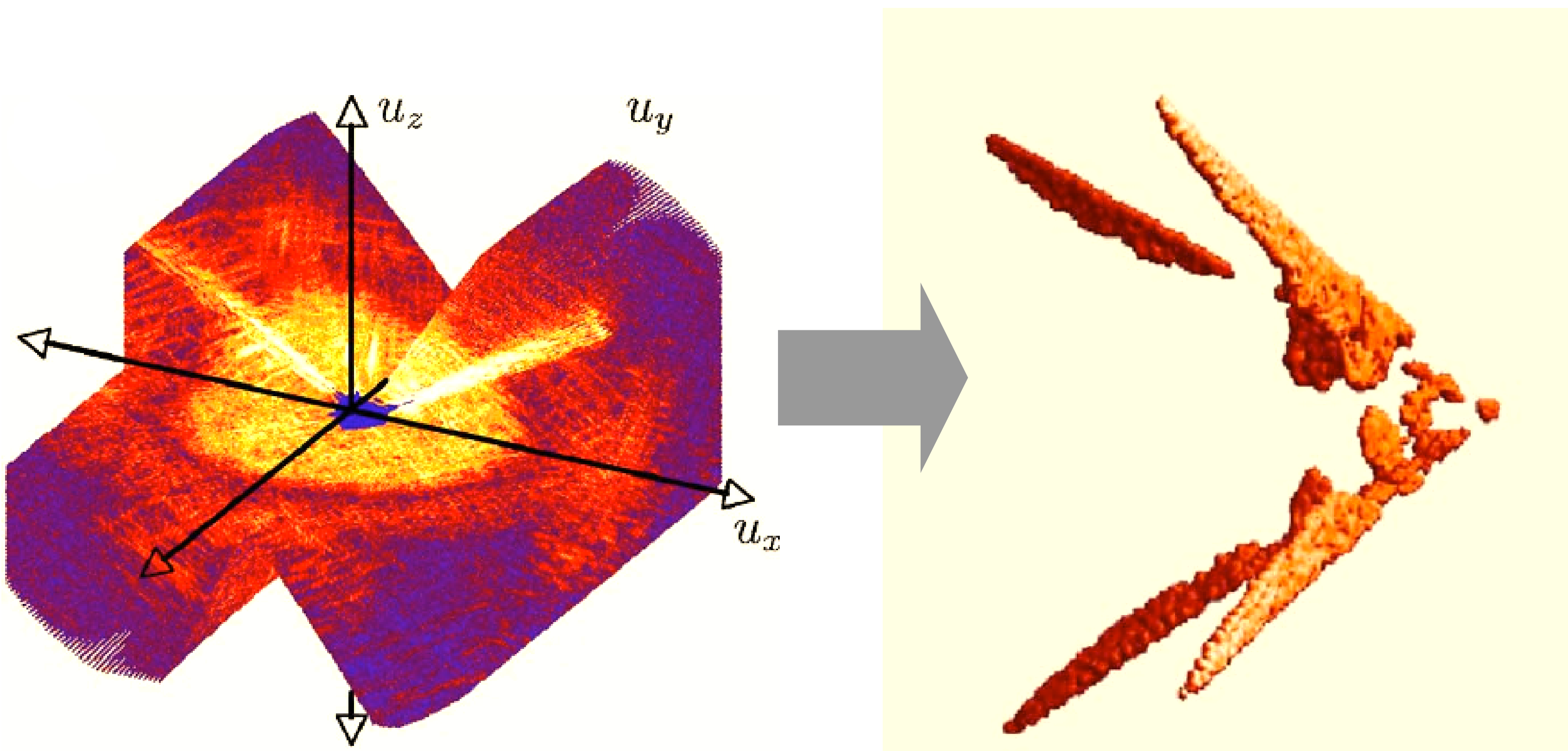
Examples



Source: H. N. Chapman *et al*, Nat. Phys. **2**, 839 (2006)

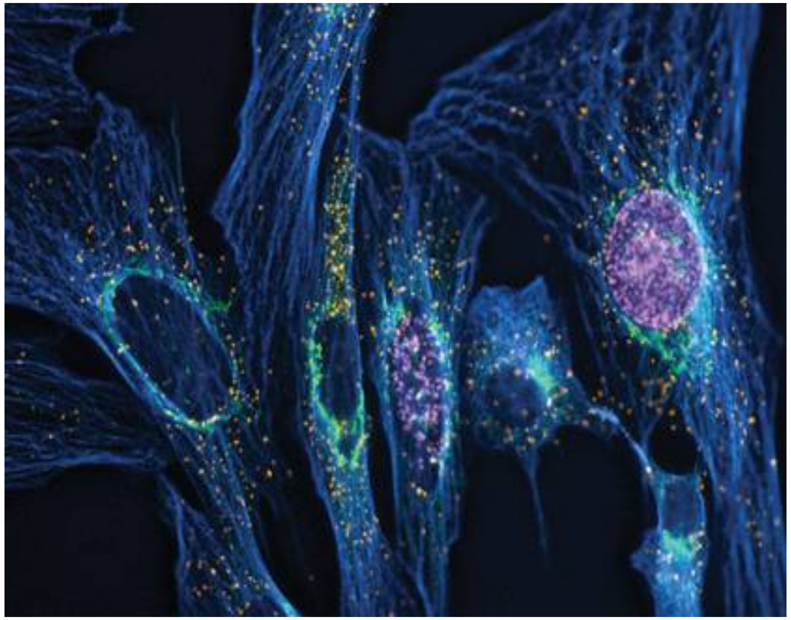
Examples

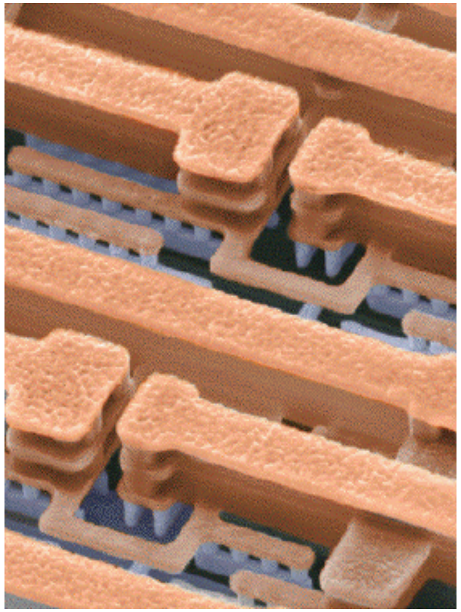
3D reconstruction (analogous to crystallography)

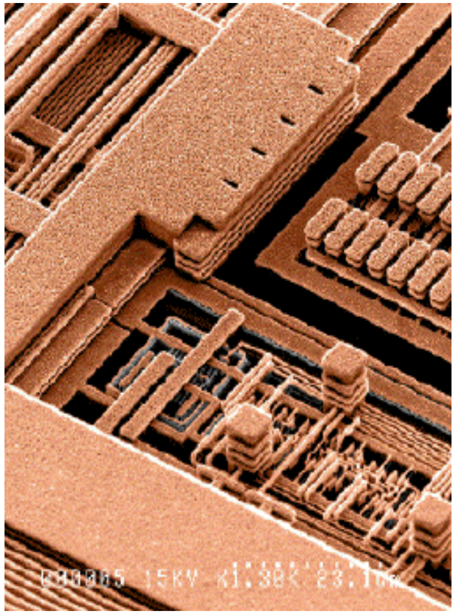


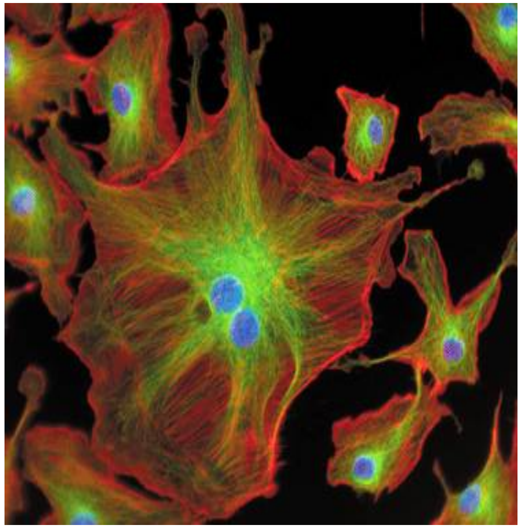
Source: H. N. Chapman *et al.* J. Opt. Soc. Am. A **23**, 1179–1200 (2006).

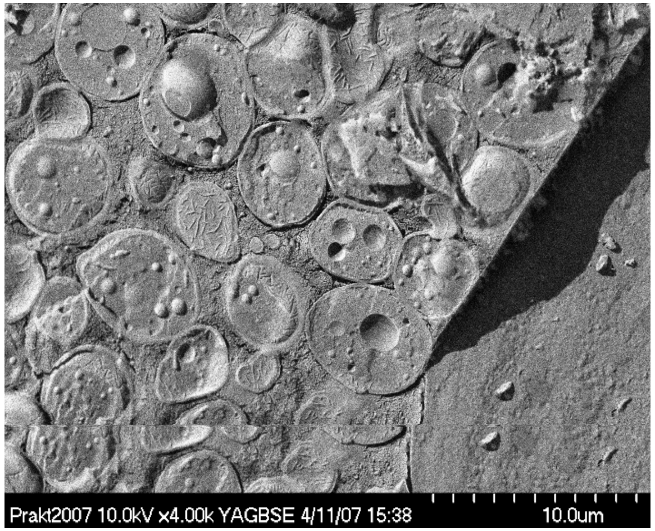
What about extended objects?

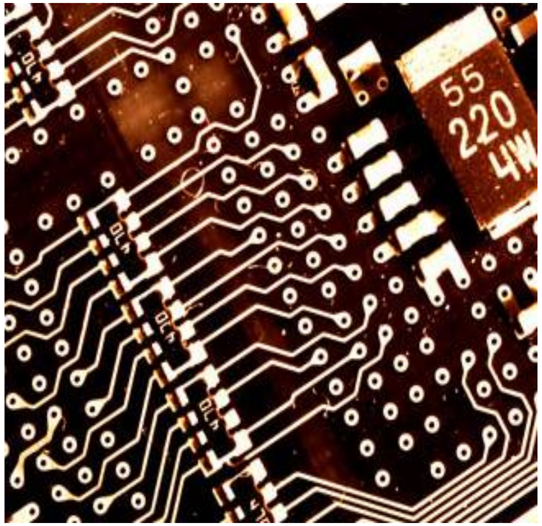












Ptychography

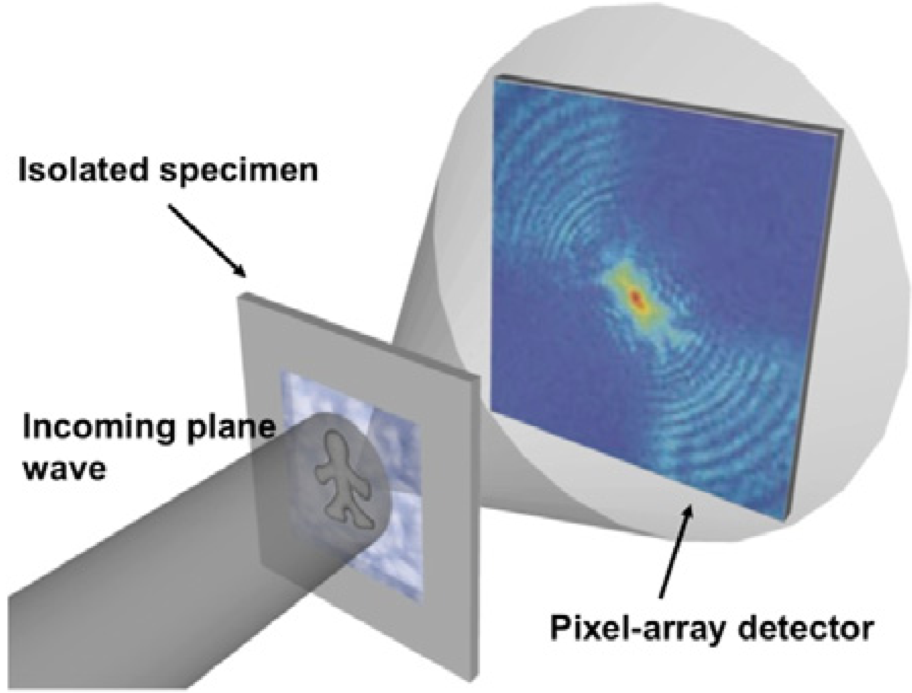


Figure 5.3. Schematic illustration of a ptychography experimental setup. A compact coherent illumination is produced with a small pinhole (or a lens). Far-field diffraction patterns are measured for each position of the sample as it is scanned in the beam. The overlap of the illuminated areas of neighboring scan points creates redundancy in the data that is exploited to reconstruct the sample's image and the illumination profile.

Source: Kaulich et al. *J. Phys.: Condens. Matter* **23** (2011) 083002

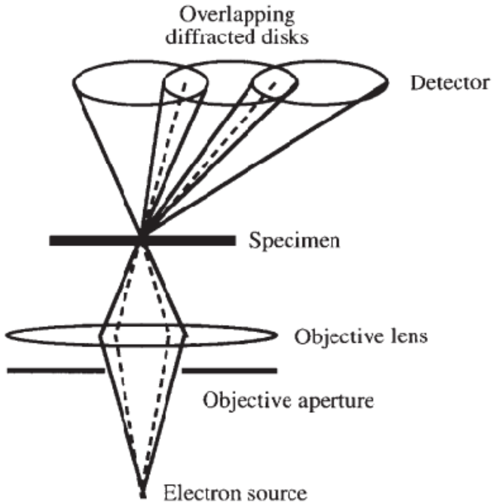
Ptychography

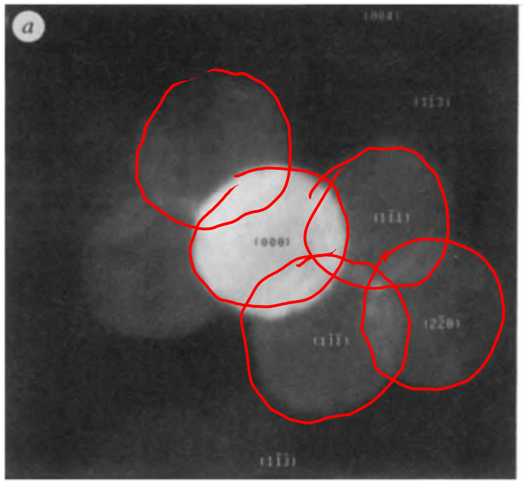
Dynamische Theorie der Kristallstrukturanalyse durch Elektronenbeugung im inhomogenen Primärstrahlwellenfeld

1970

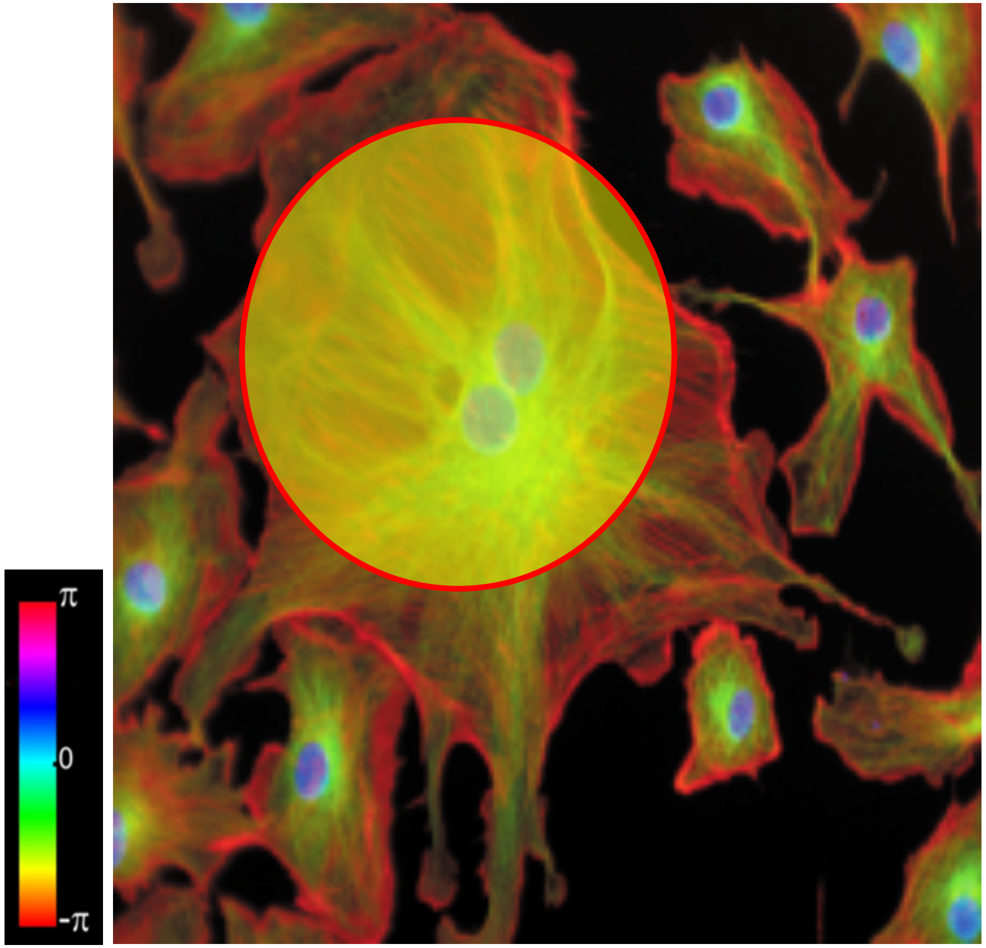
Von R. Hegerl und W. Hoppe

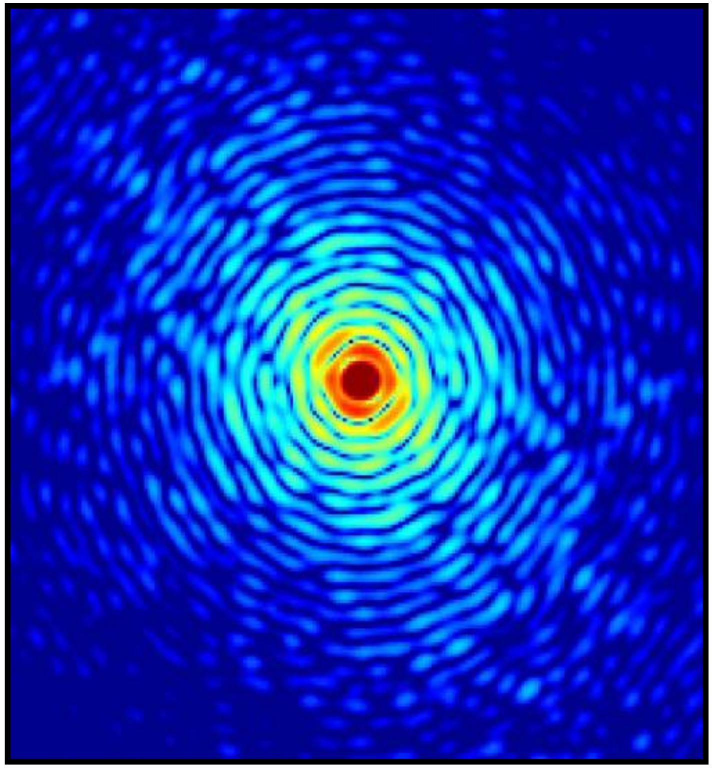
Some time ago a new principle was proposed for the registration of the complete information (amplitudes and phases) in a diffraction diagram, which does not – as does Holography – require the interference of the scattered waves with a single reference wave. The basis of the principle lies in the interference of neighbouring scattered waves which result when the object function $\varrho(x, y)$ is multiplied by a generalized primary wave function $p(x, y)$ in Fourier space (diffraction diagram) this is a convolution of the Fourier transforms of these functions. The above mentioned interferences necessary for the phase determination can be obtained by suitable choice of the shape of $p(x, y)$. To distinguish it from holography this procedure is designated "ptychography" ($\pi\tau\upsilon\xi$ = fold). The procedure is applicable to periodic and aperiodic structures. The relationships are simplest for plane lattices. In this paper the theory is extended to space lattices both with and without consideration of the dynamic theory. The resulting effects are demonstrated using a practical example.





Ptychographic coherent diffractive imaging

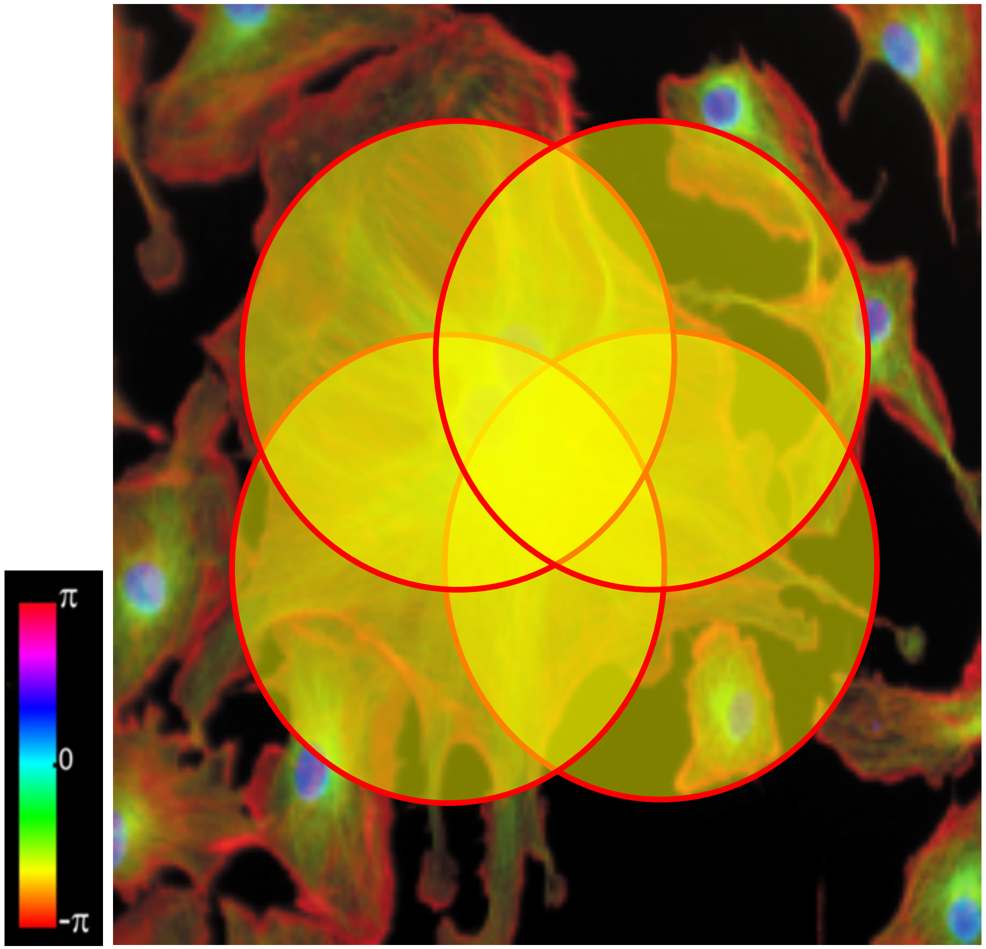


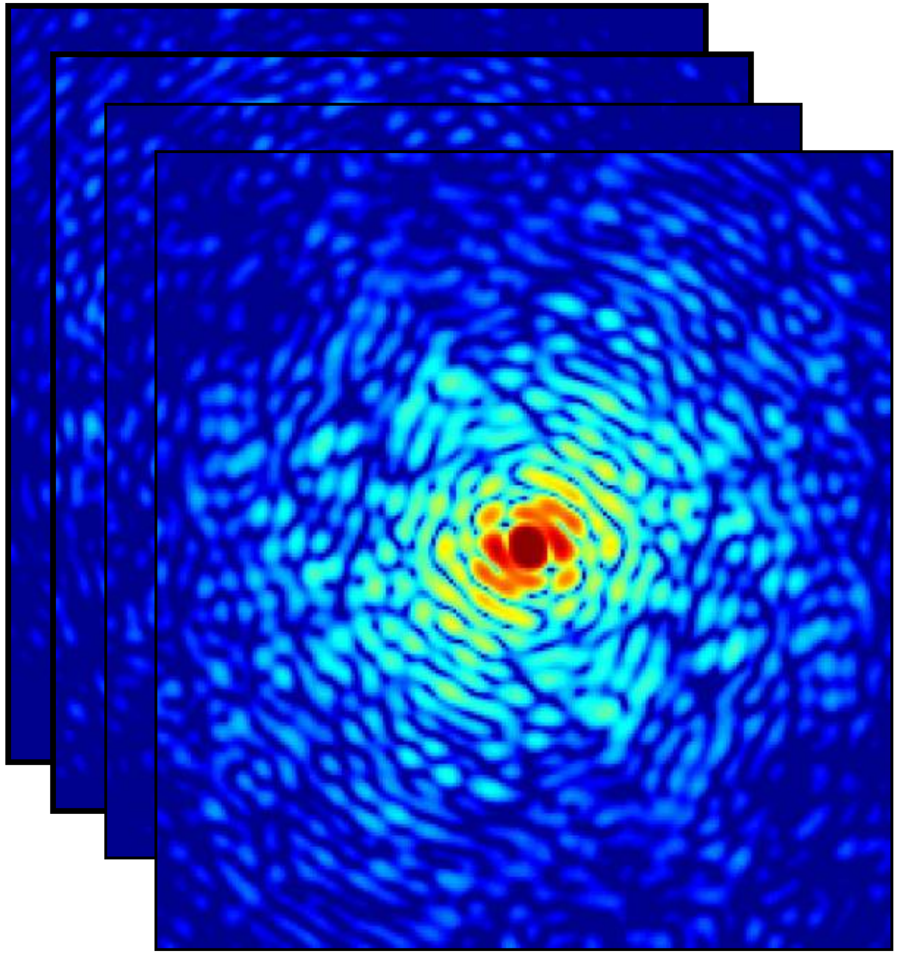


brightness => amplitude

hue => phase

Ptychographic coherent diffractive imaging





brightness => amplitude

hue => phase

Overlapping illumination!

Ptychography

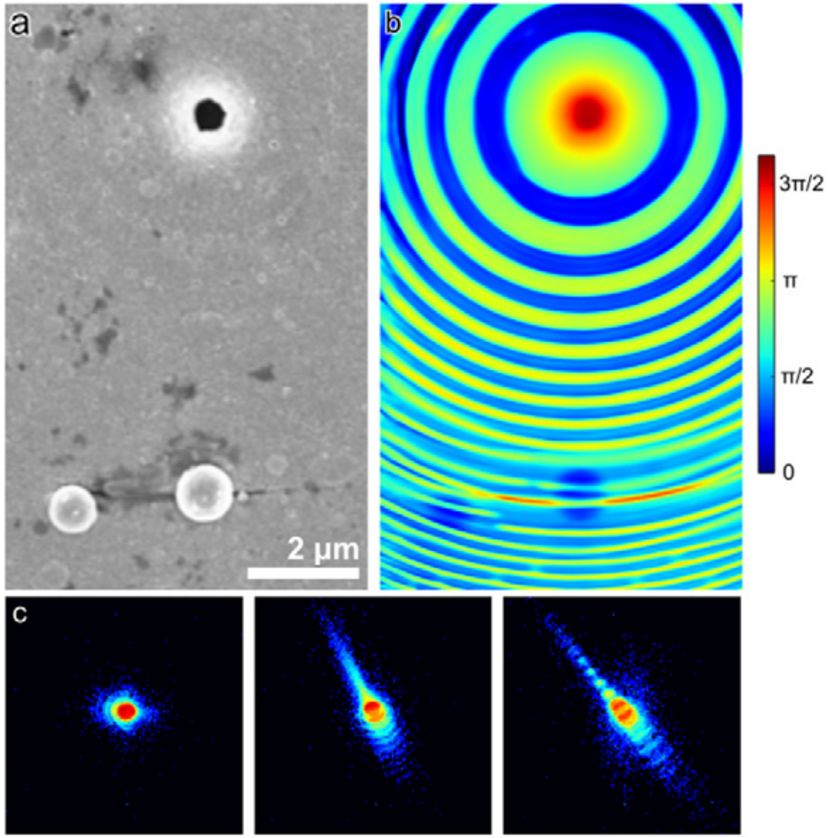
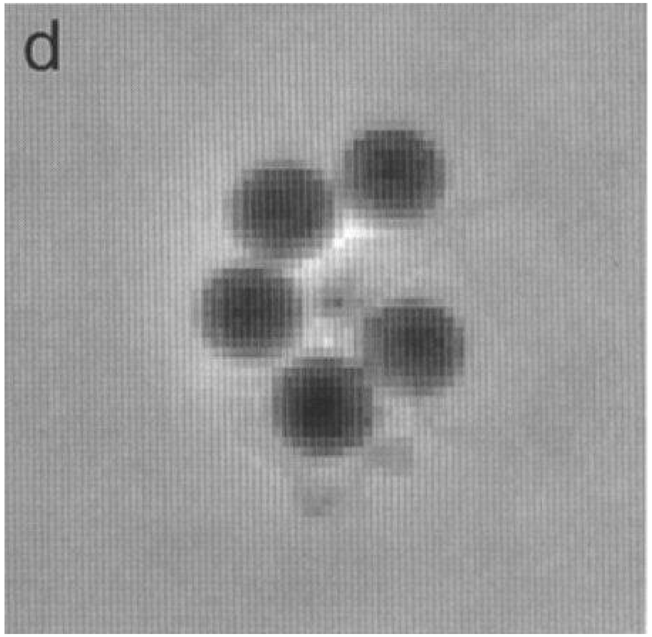


Figure 5.4. Hard x-ray ptychography on a zone plate test specimen. (a) Scanning electron microscopy (SEM) image of a nanofabricated sample covered with gold. (b) Phase part of the transmission function obtained by ptychographic reconstruction. The color scale indicates the phase shift introduced by the sample on the incoming wave, and is proportional to the integrated thickness of the object. (c) Selection of individual diffraction patterns collected for this reconstruction. Figure adapted from Thibault *et al* (2008).

Source: Kaulich et al. *J. Phys.: Condens. Matter* **23** (2011) 083002

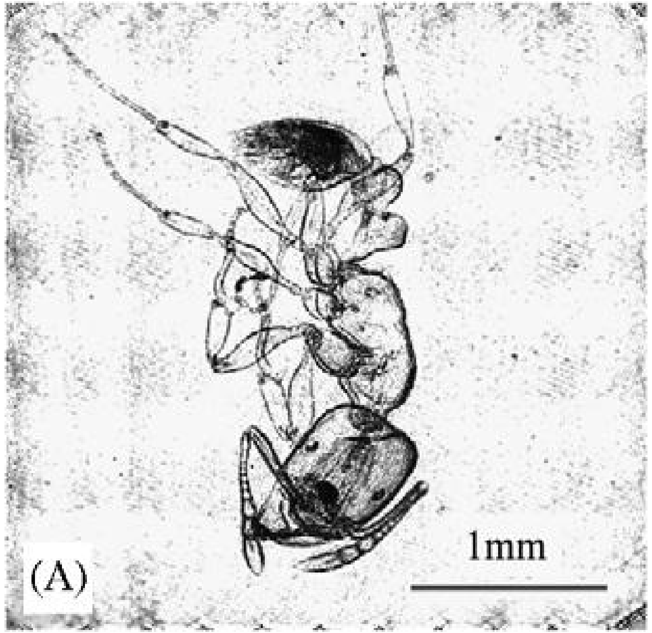
Ptychography

Soft X-rays



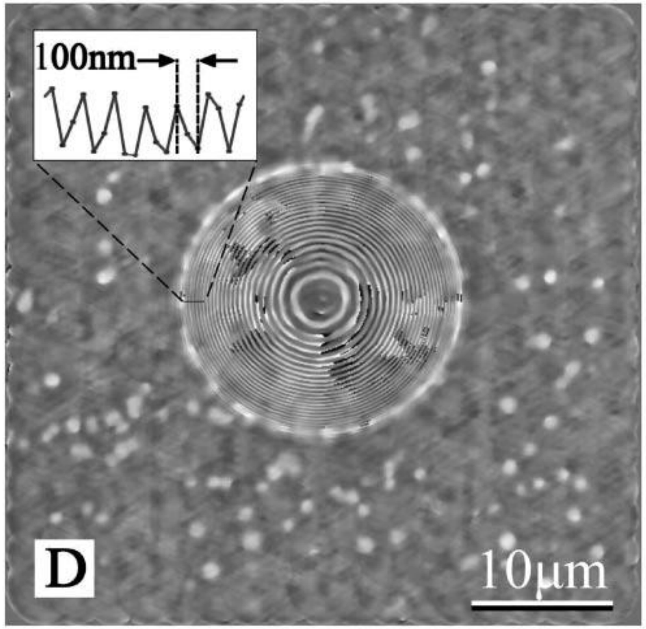
H.N. Chapman *,*
Ultramicroscopy, **56** , 153-172 (1996)

Visible light



J.M. Rodenburg *et al.*
Ultramicroscopy **107** , 227-231 (2007)

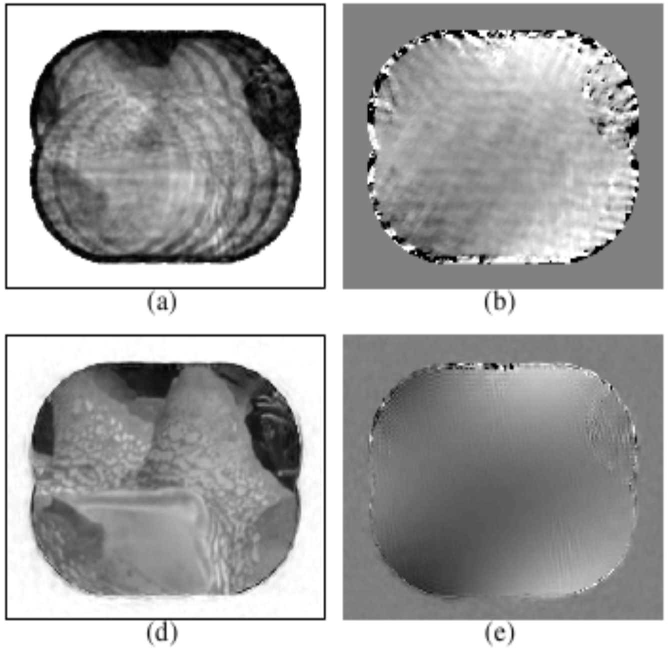
Hard X-rays



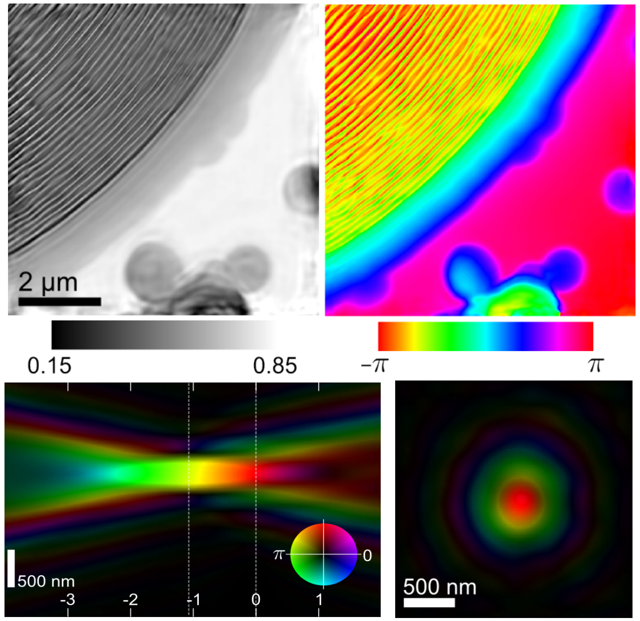
J.M. Rodenburg *et al.*
Phys. Rev. Lett. , **98** , 034801 (2007)

Problem: Probe may not be well behaved

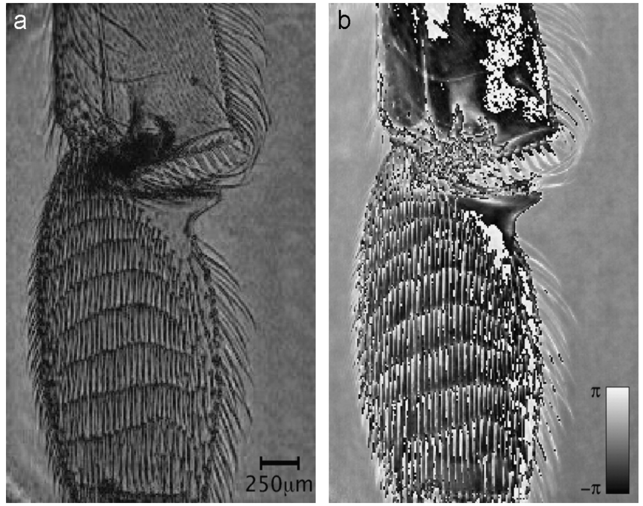
Solution: Reconstruct object and illumination



M. Guizar-Sicairos , J.R. Fienup,
Opt. Express 16 , 7264 (2008).

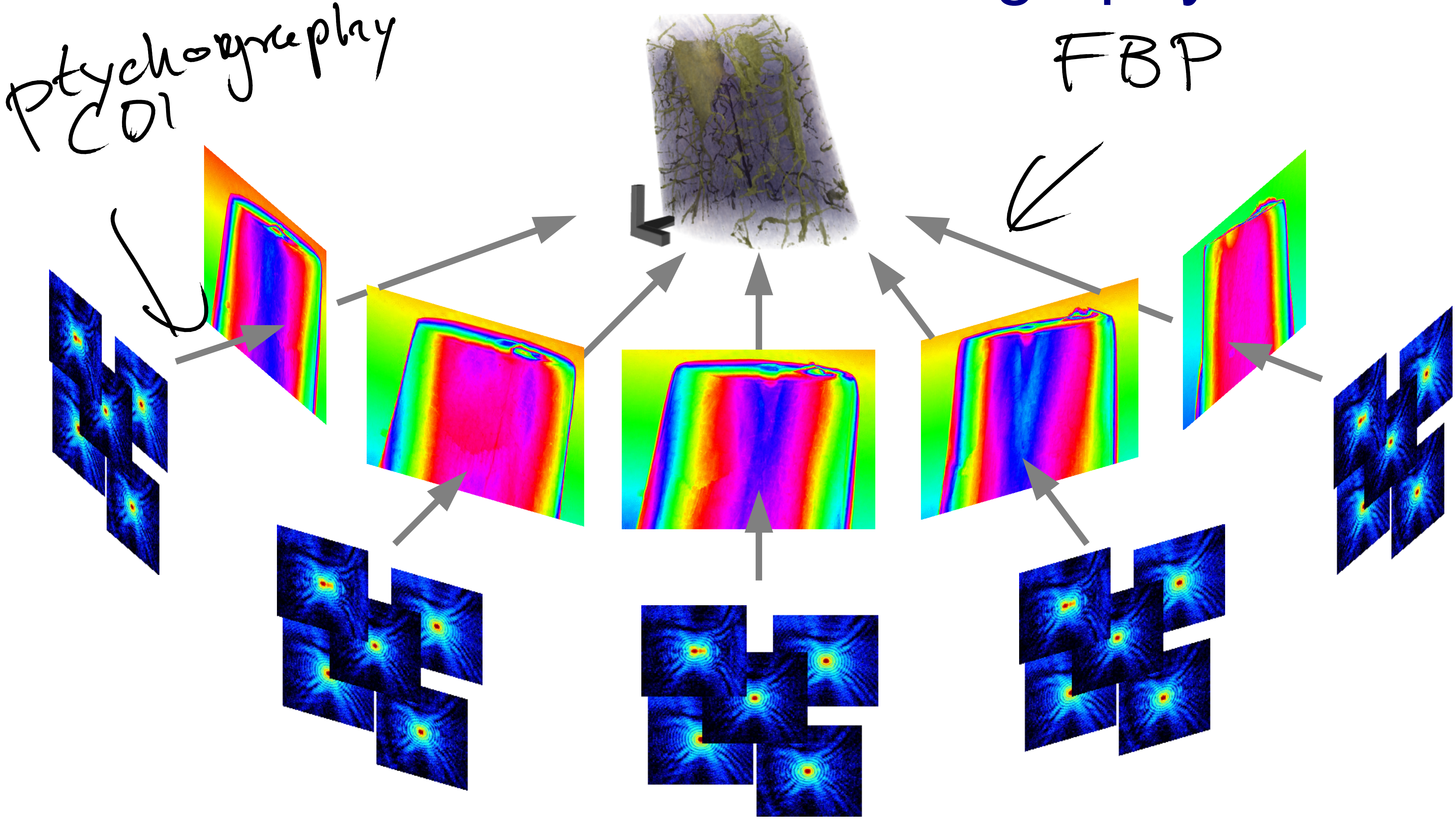


P. Thibault, M. Dierolf et al.,
Science 321 , 379-382 (2008).



A.M. Maiden, J.M. Rodenburg ,
Ultramicroscopy 109 , 1256 (2009).

Combination with tomography



M. Dierolf, A. Menzel, P. Thibault *et al.,* Nature 467, 436 (2010)