Image Processing for Physicists

Prof. Pierre Thibault

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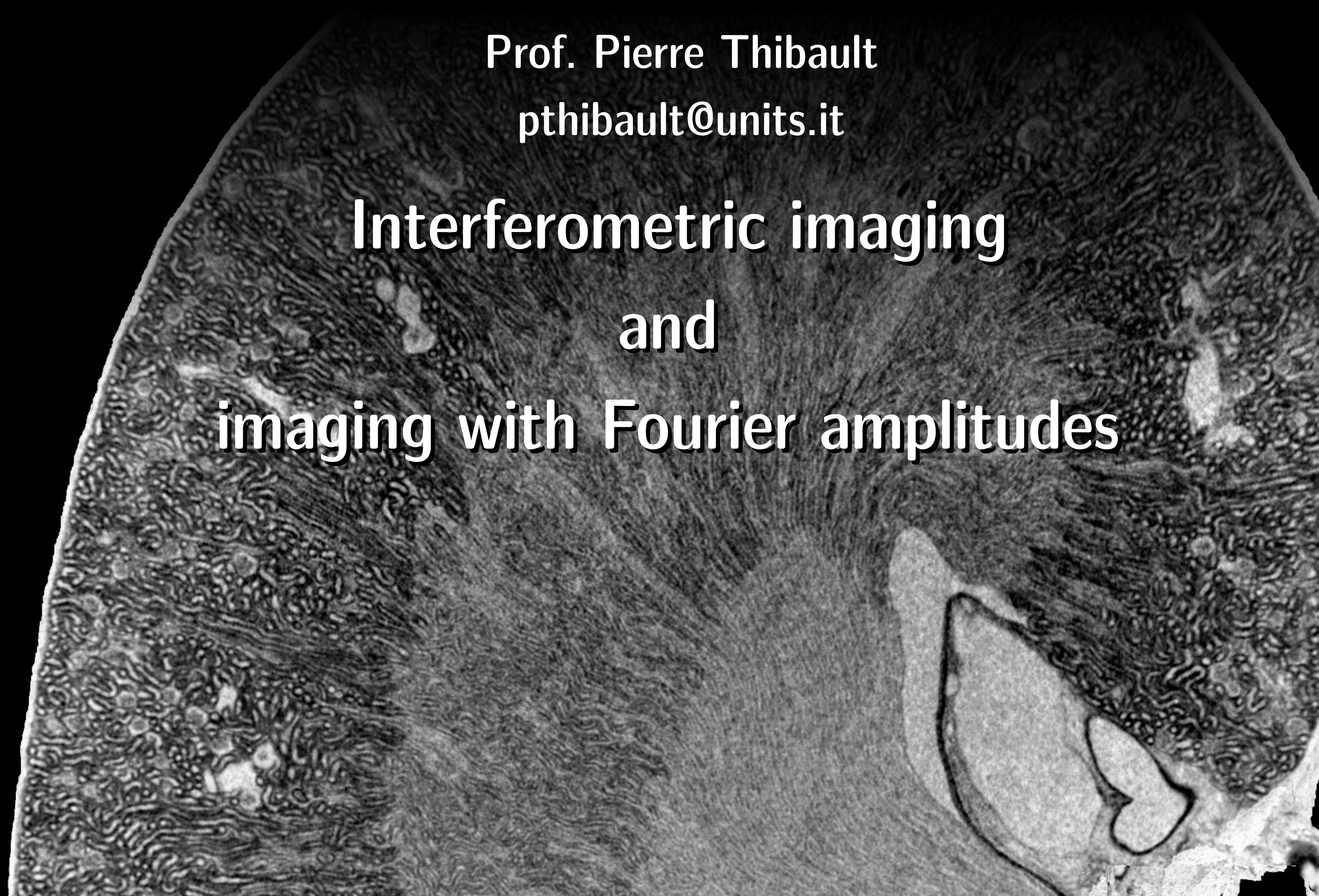
Interferometric imaging

and

imaging with Fourier amplitudes

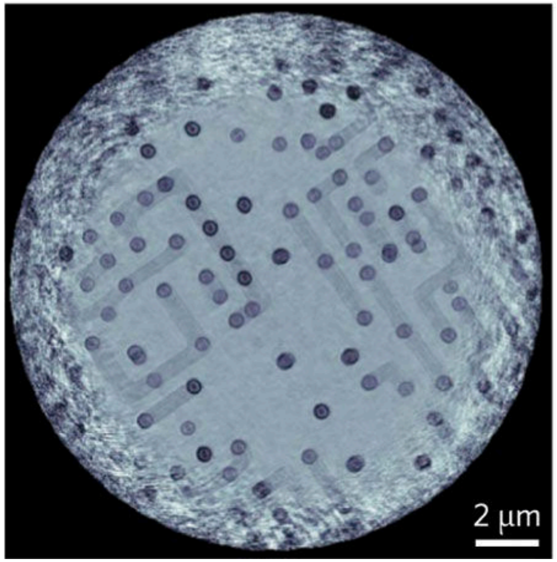


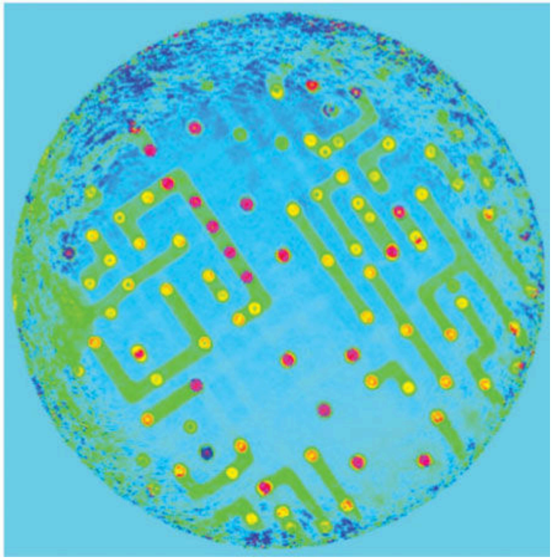
Overview

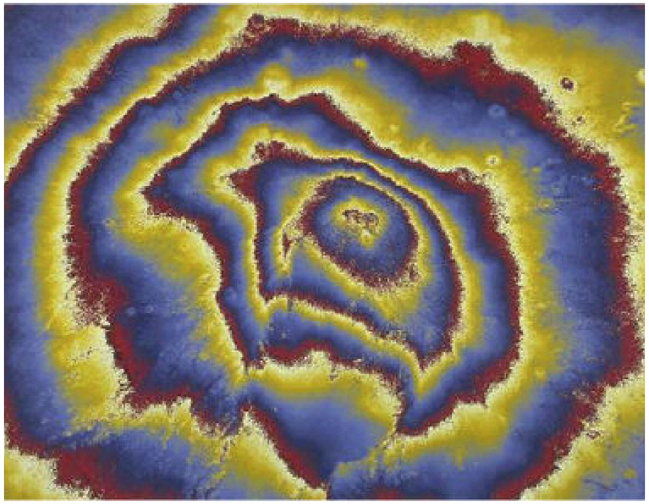
- The phase problem
- Holography: on/off-axis
- Grating interferometric imaging
- Imaging using far-field amplitude measurements
  - Fourier transform holography
  - Coherent diffraction imaging
  - Ptychography

Wave propagation

Complex-valued images



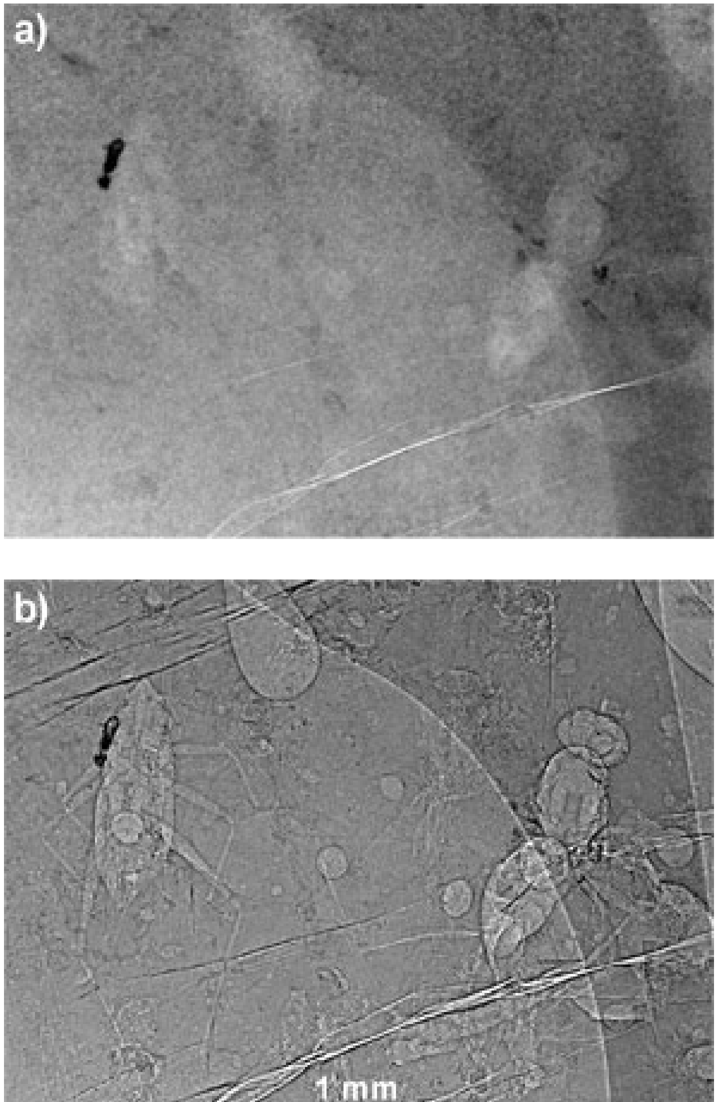




Imaging with interferometry and far-field

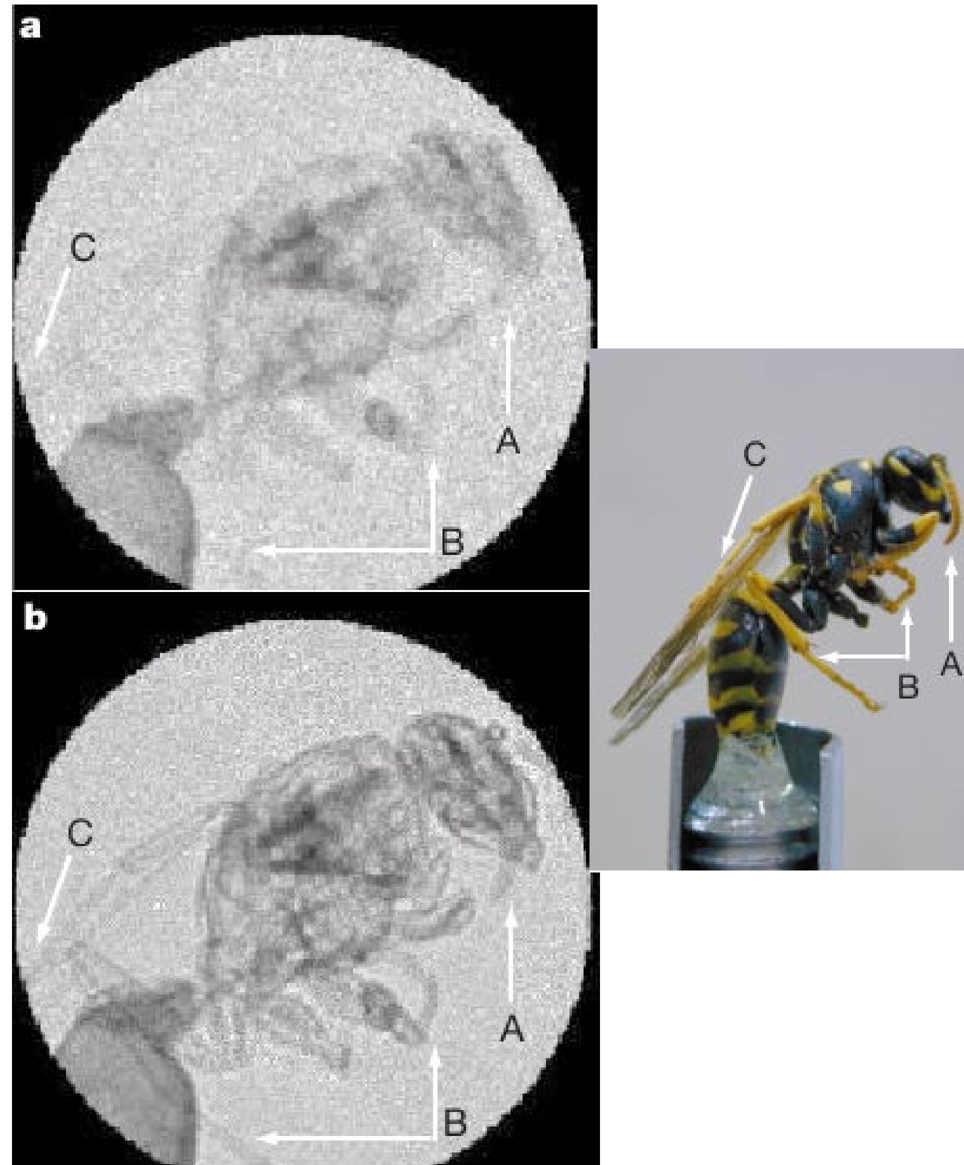
Phase-contrast

Hard X-ray propagation-based phase contrast



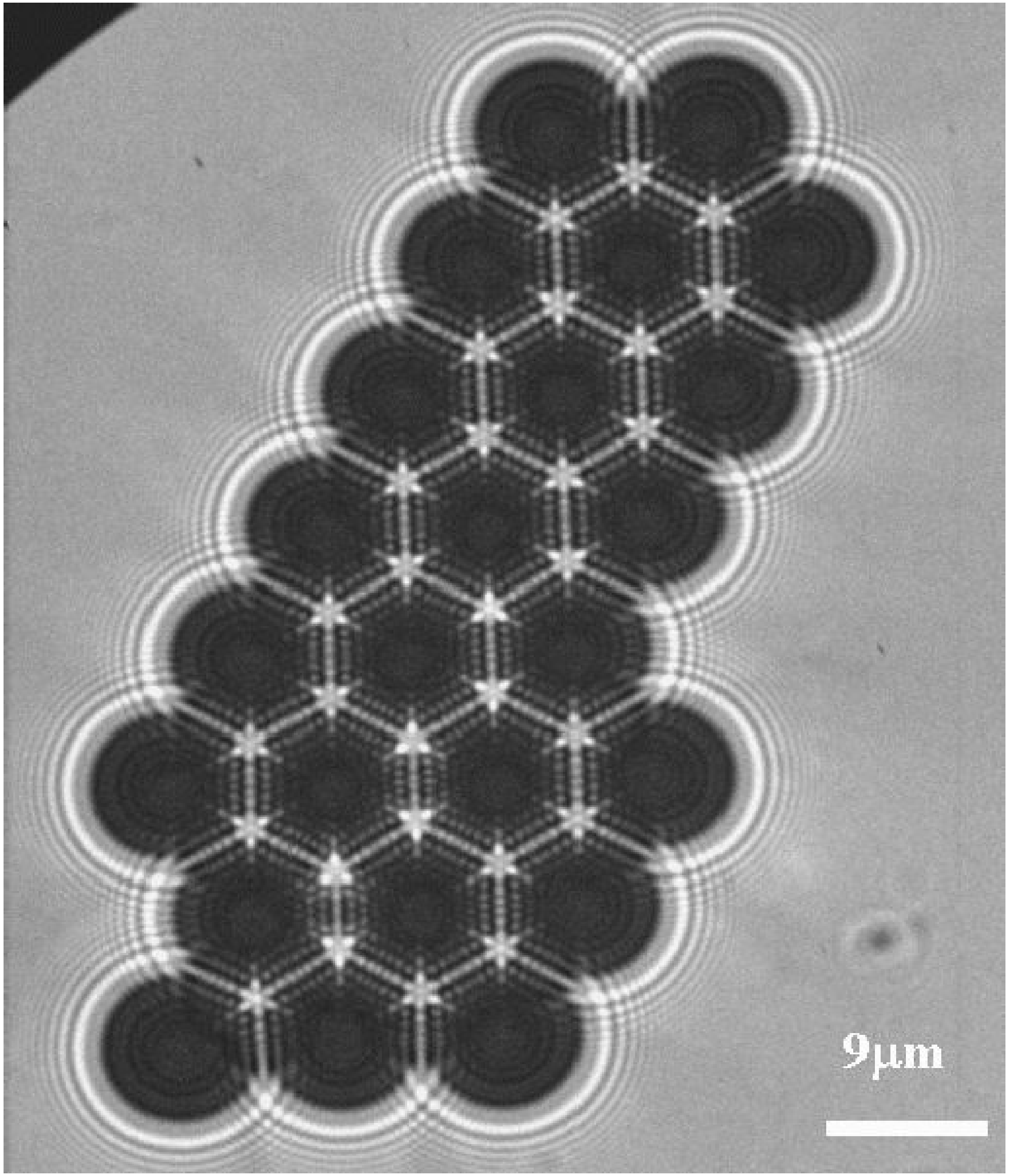
Source: www.esrf.eu/news/general/amber/amber/

Neutron phase contrast



Source: Allman et al. Nature **408** (2000).

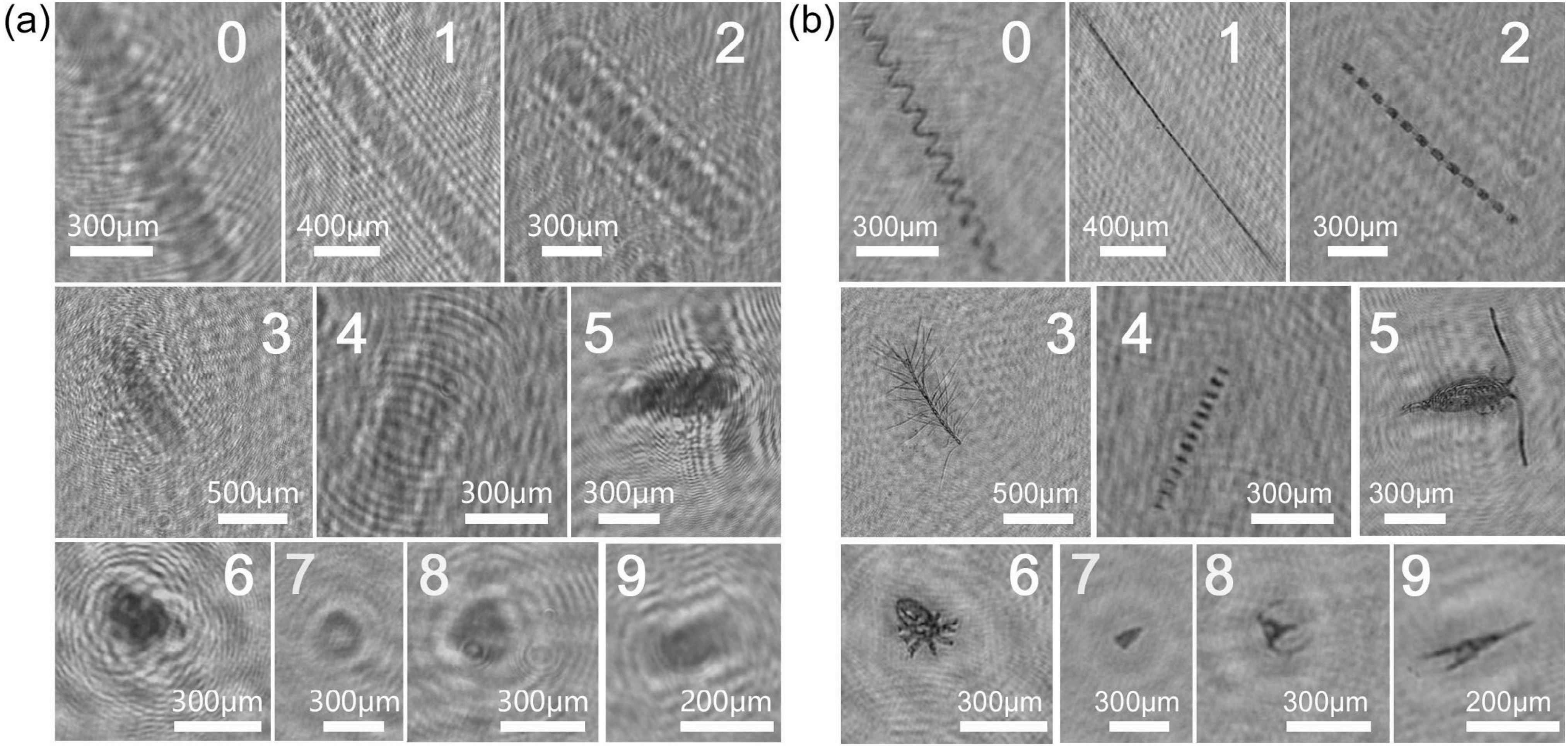
Inline holography



Source: Mayo et al. Opt Express **11** (2003).

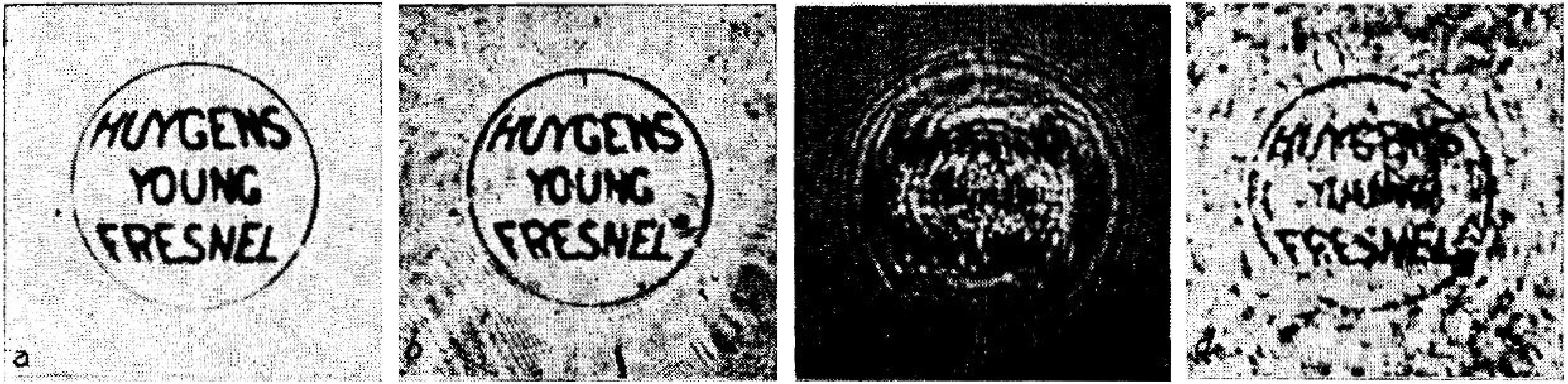
Inline holography

Digital inline holography



The phase problem

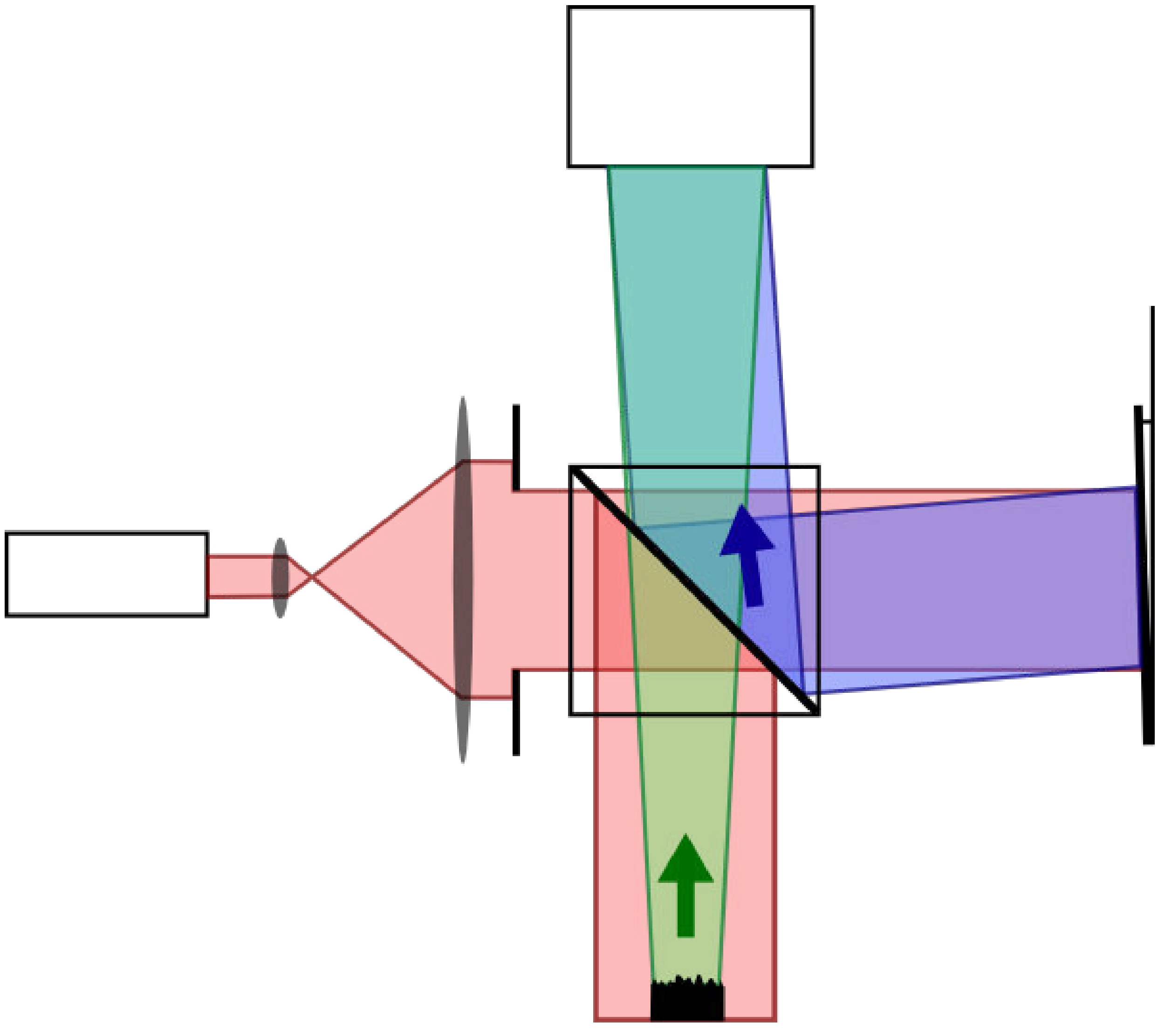
In-line holography



D. Gabor, Nature **161**, 777-778 (1948).

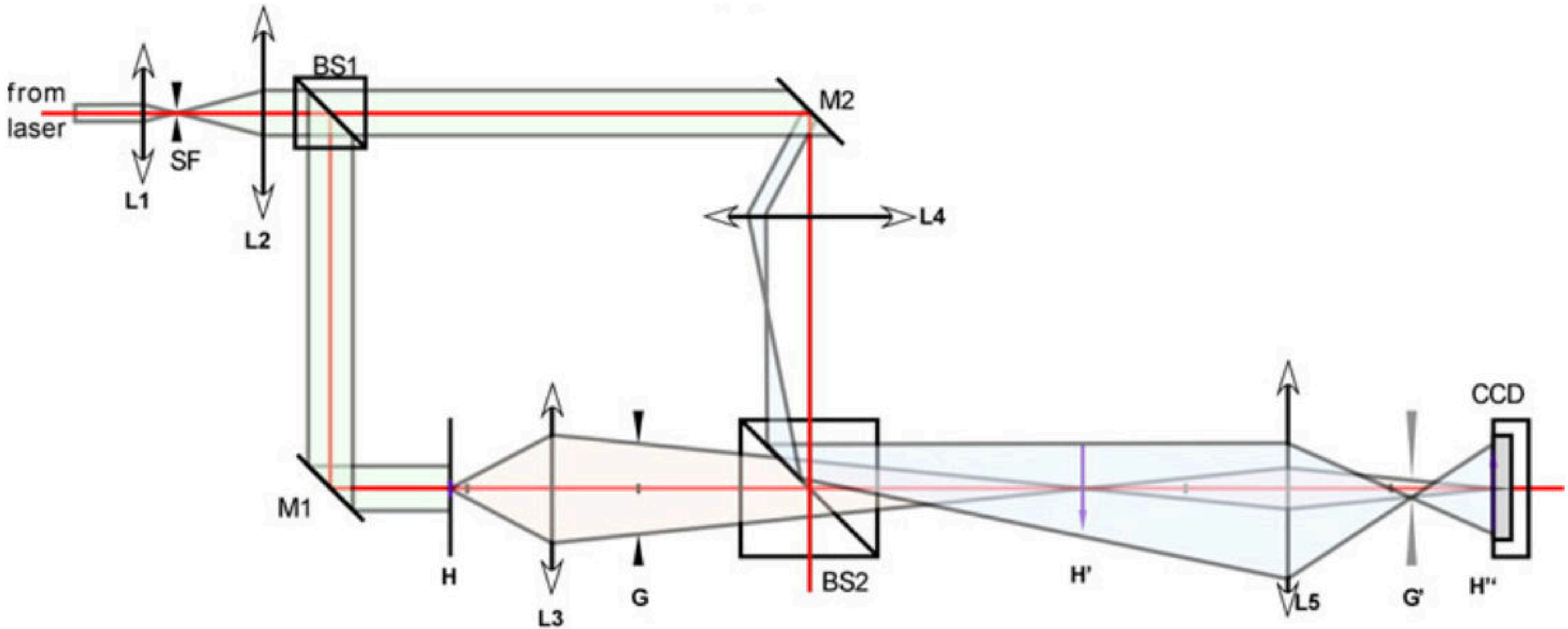
Tilted reference

Fringe interferometry



Twyman-Green interferometer

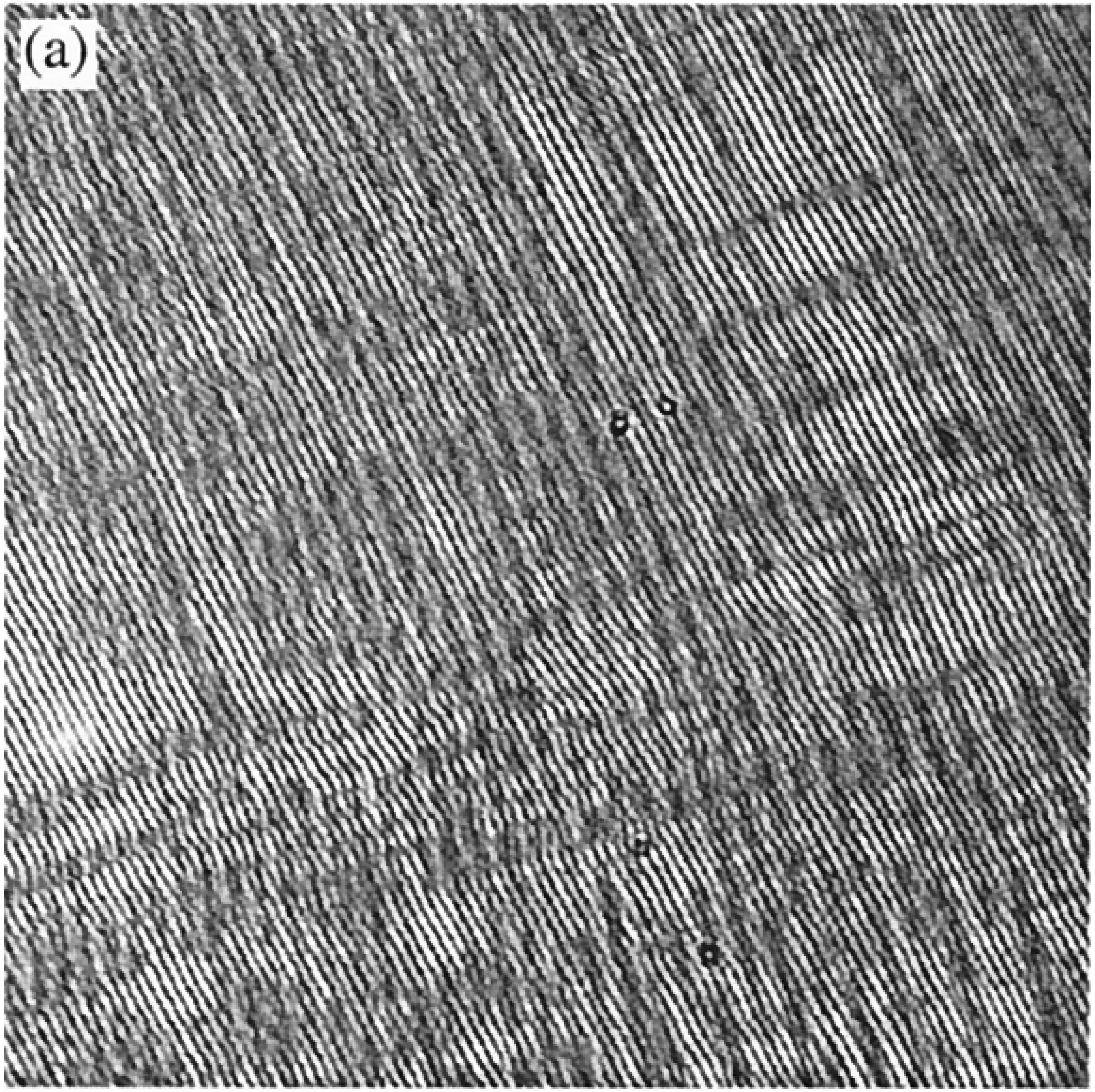
Visible light interferometer



Mach-Zehnder interferometer

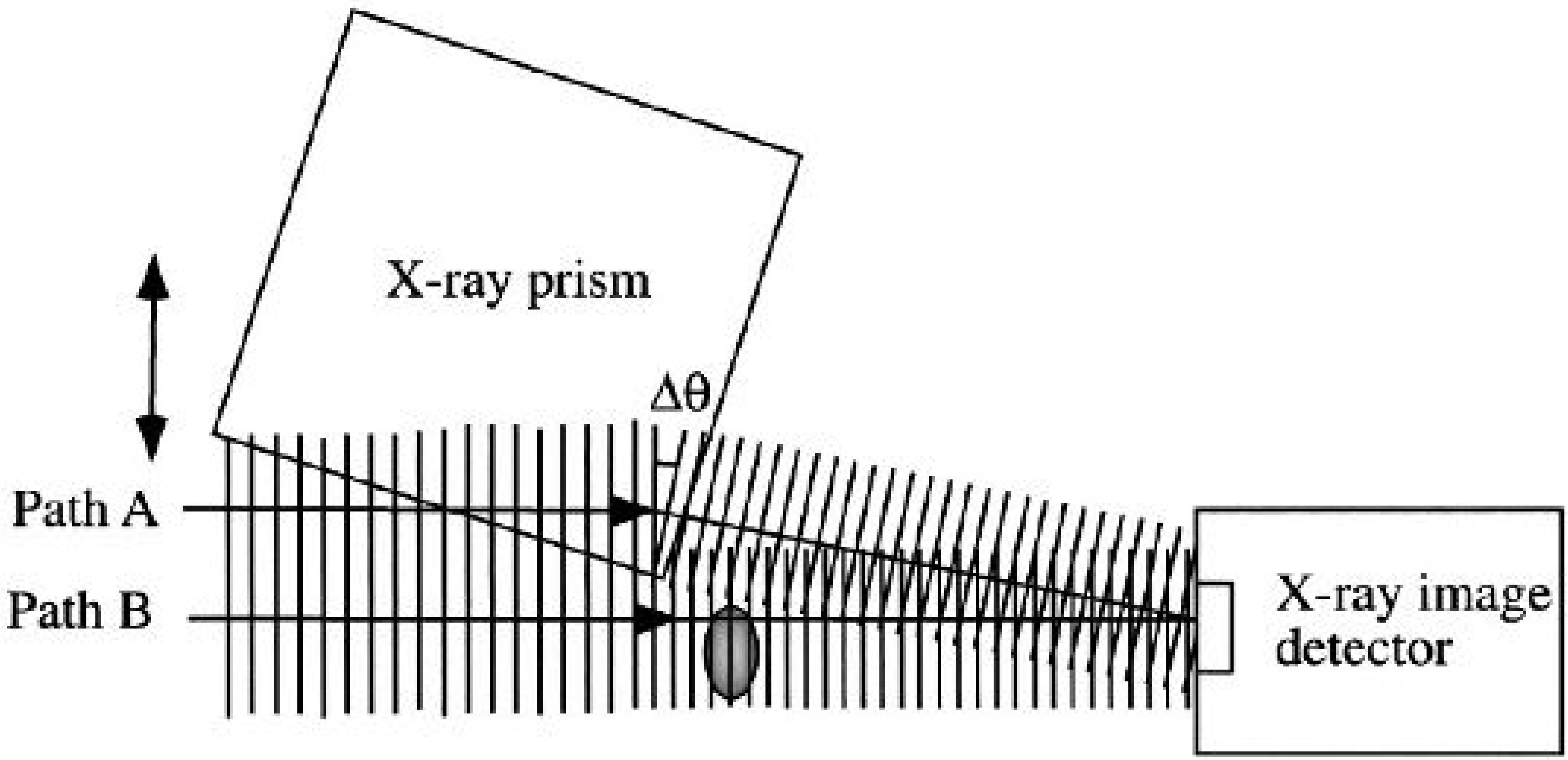
Source: M. K. Kim, SPIE Rev. **1**, 018005 (2010).

Fringe interferometry



Source: Cuche et al. Appl. Opt. **39**, 4070 (2000)

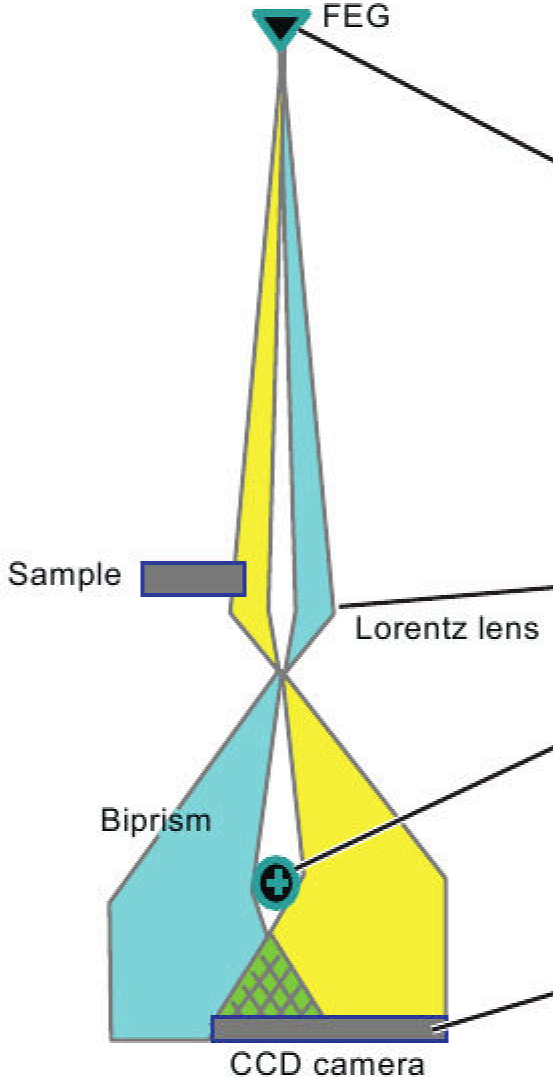
Off-axis X-ray holography



Source: Y. Kohmura, J. Appl. Phys. **96**, 1781-1784 (2004)

Off-axis electron holography

Electron microscopy

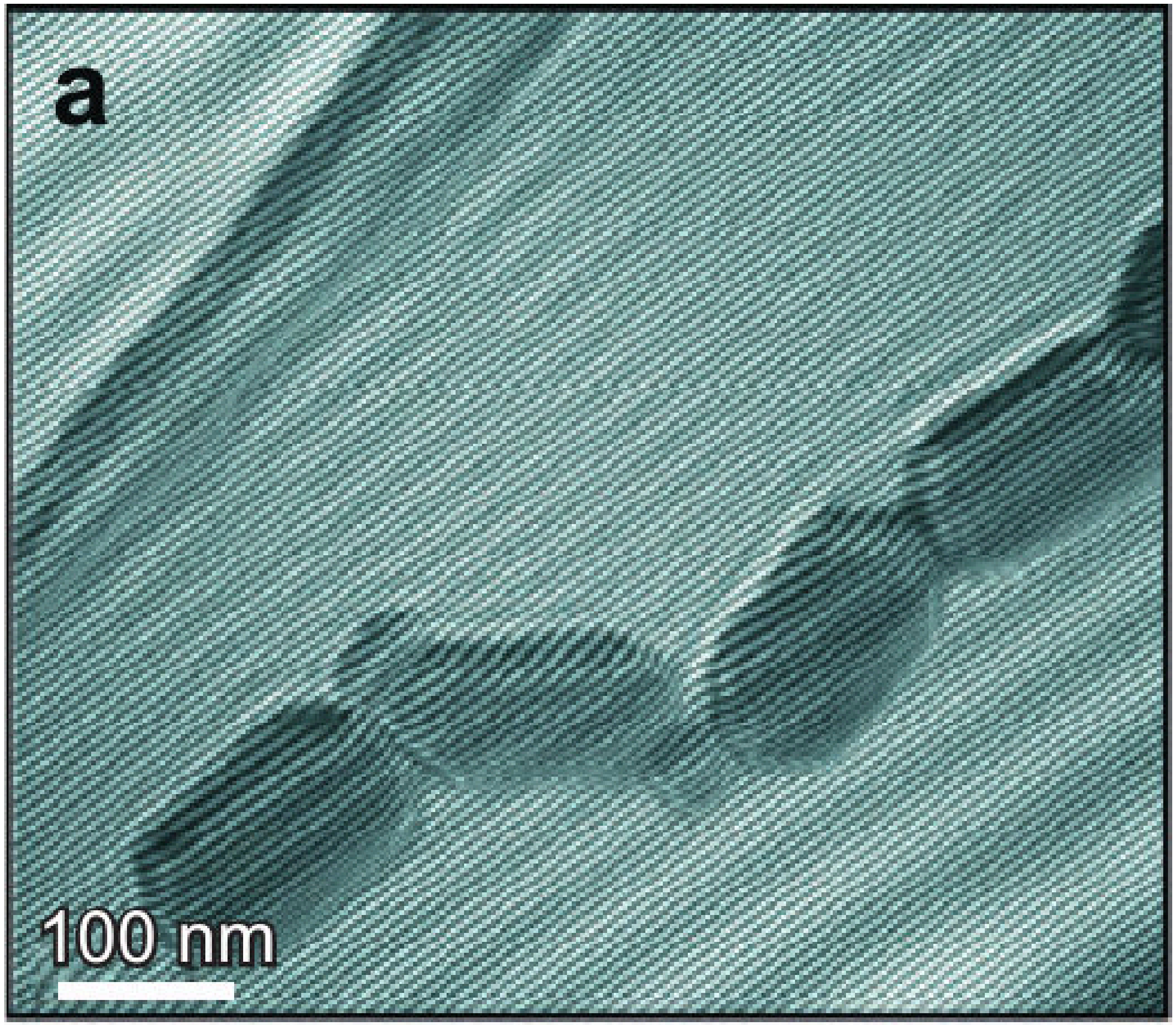


Hologram

Philips CM200 FEG

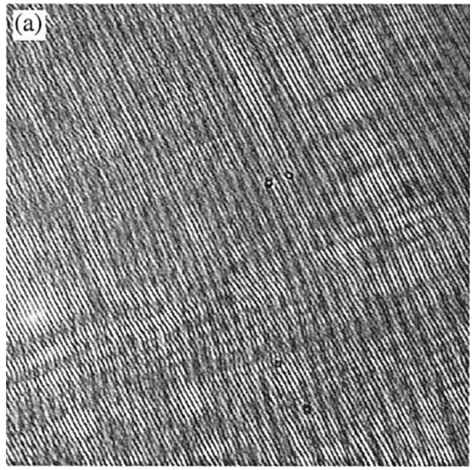
Source: M. R. McCartney, Ann. Rev. Mat. Sci. **37** 729-767 (2007)

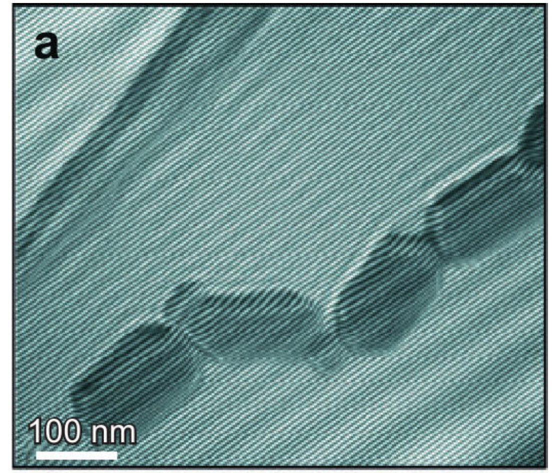
Off-axis electron holography



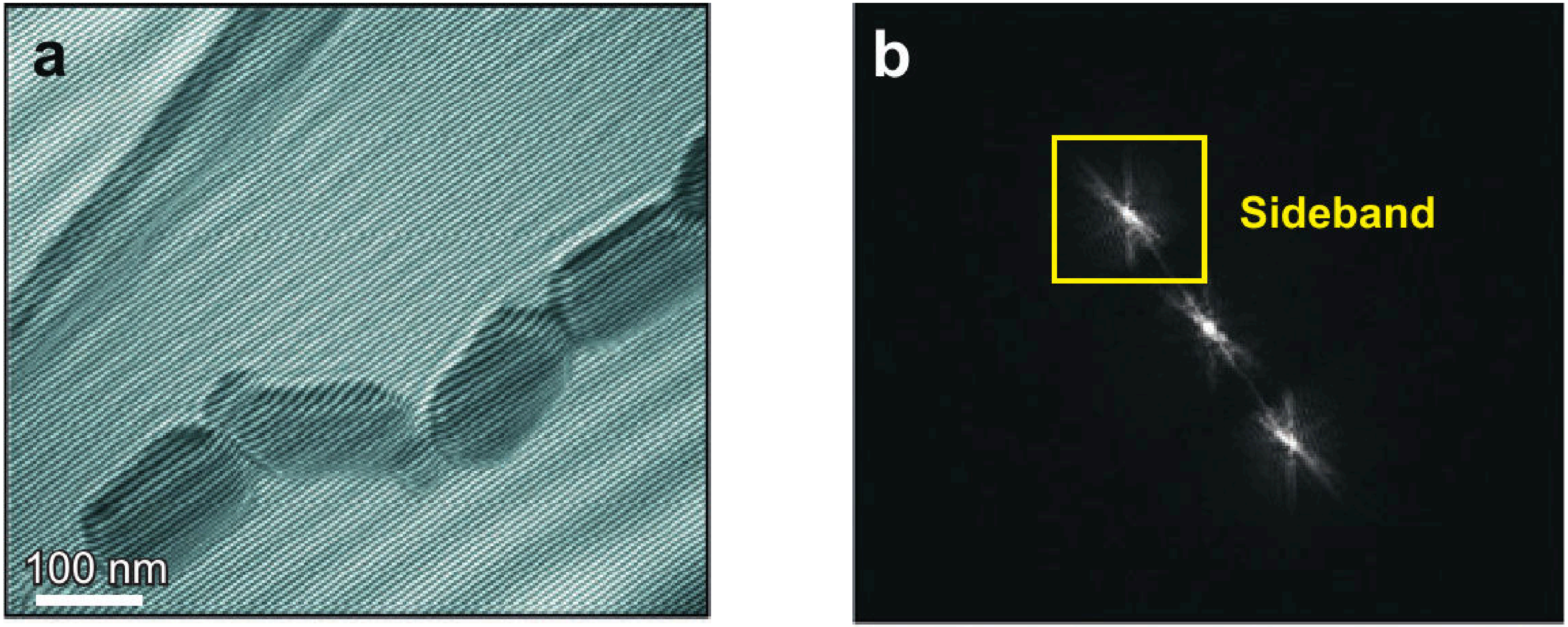
Source: M. R. McCartney, Annu. Rev. Mat. Sci. **37** 729-767 (2007)

Fringe interferometry



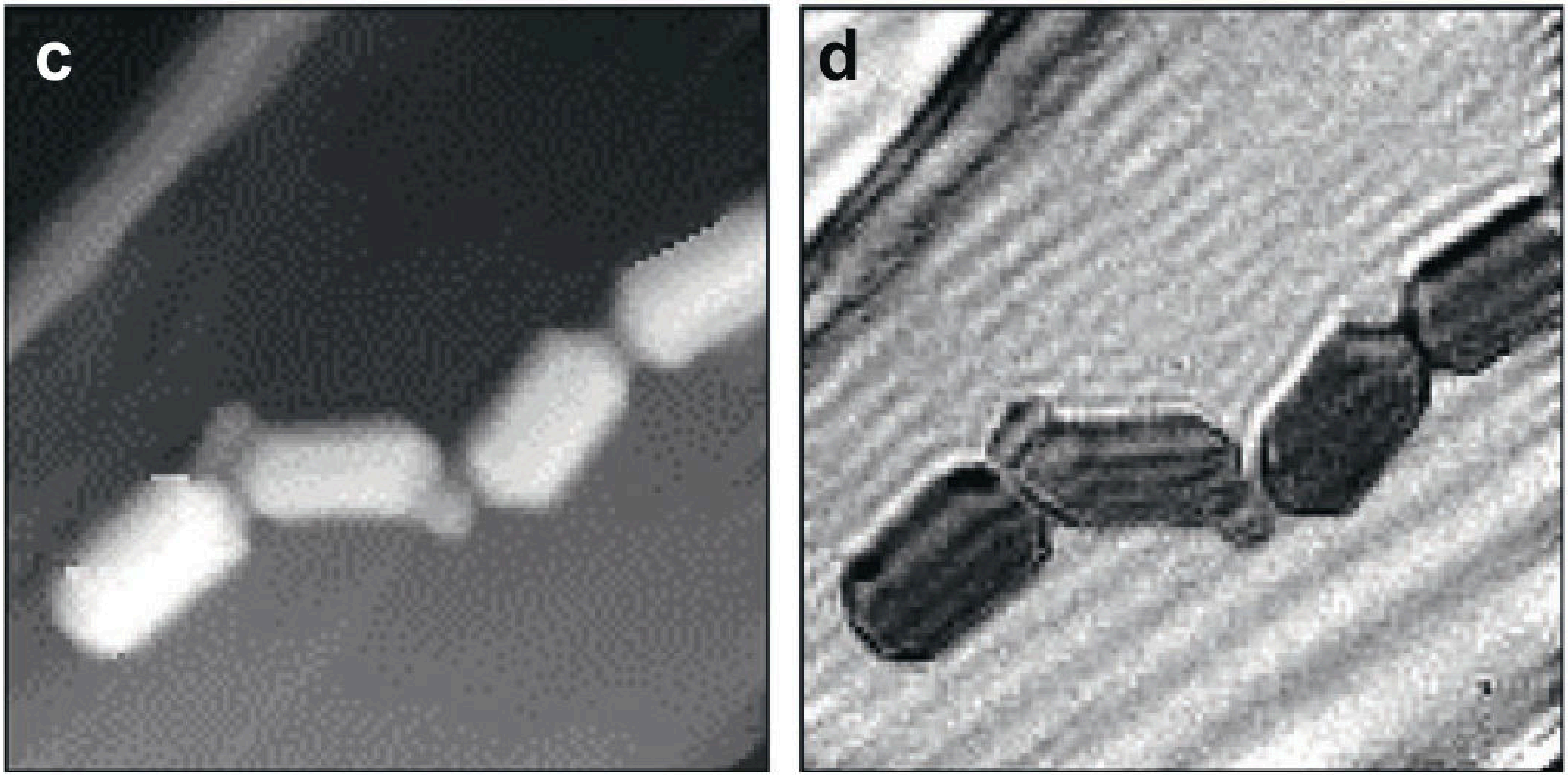


Off-axis holography



Source: M. R. McCartney, Annu. Rev. Mat. Sci. **37** 729-767 (2007)

Off-axis holography



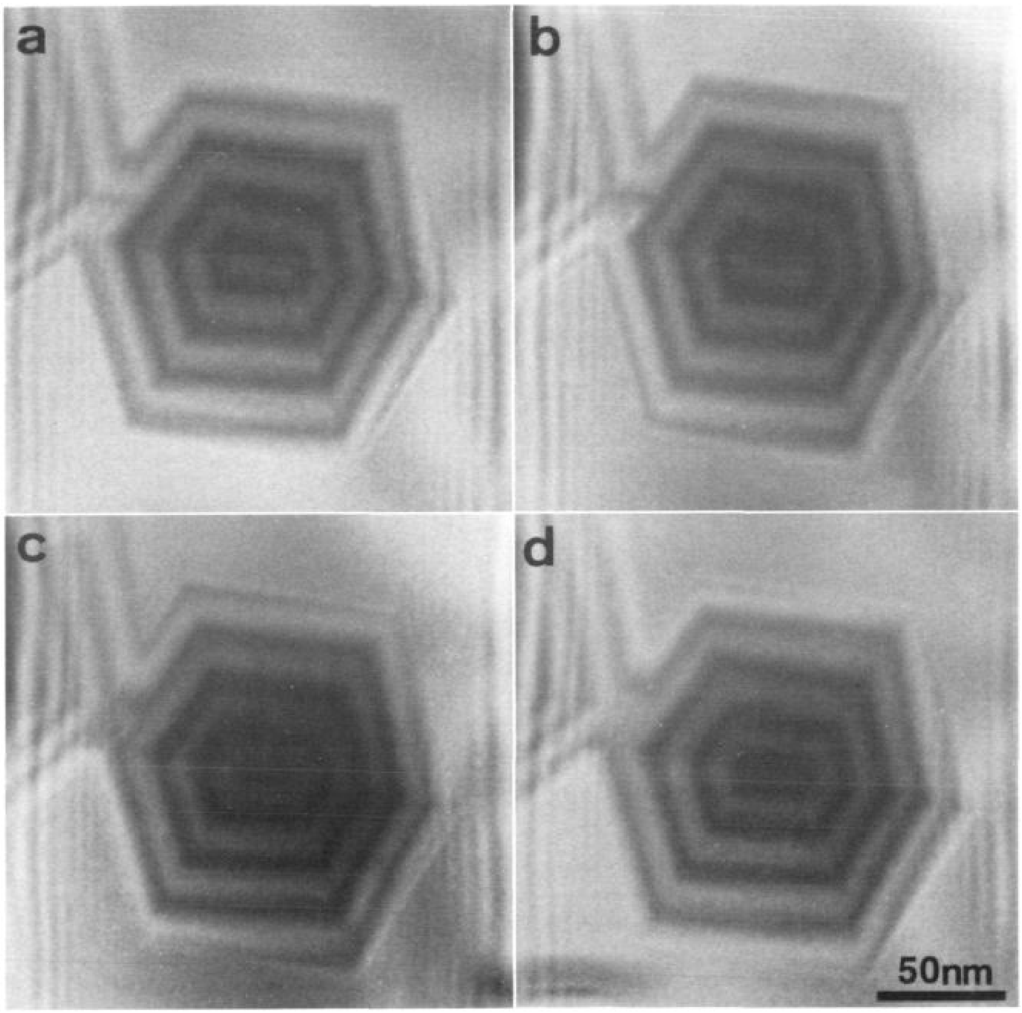
Source: M. R. McCartney, Annu. Rev. Mat. Sci. **37** 729-767 (2007)

Phase stepping

- Encoding phase **and** amplitude in a single image has a price: resolution

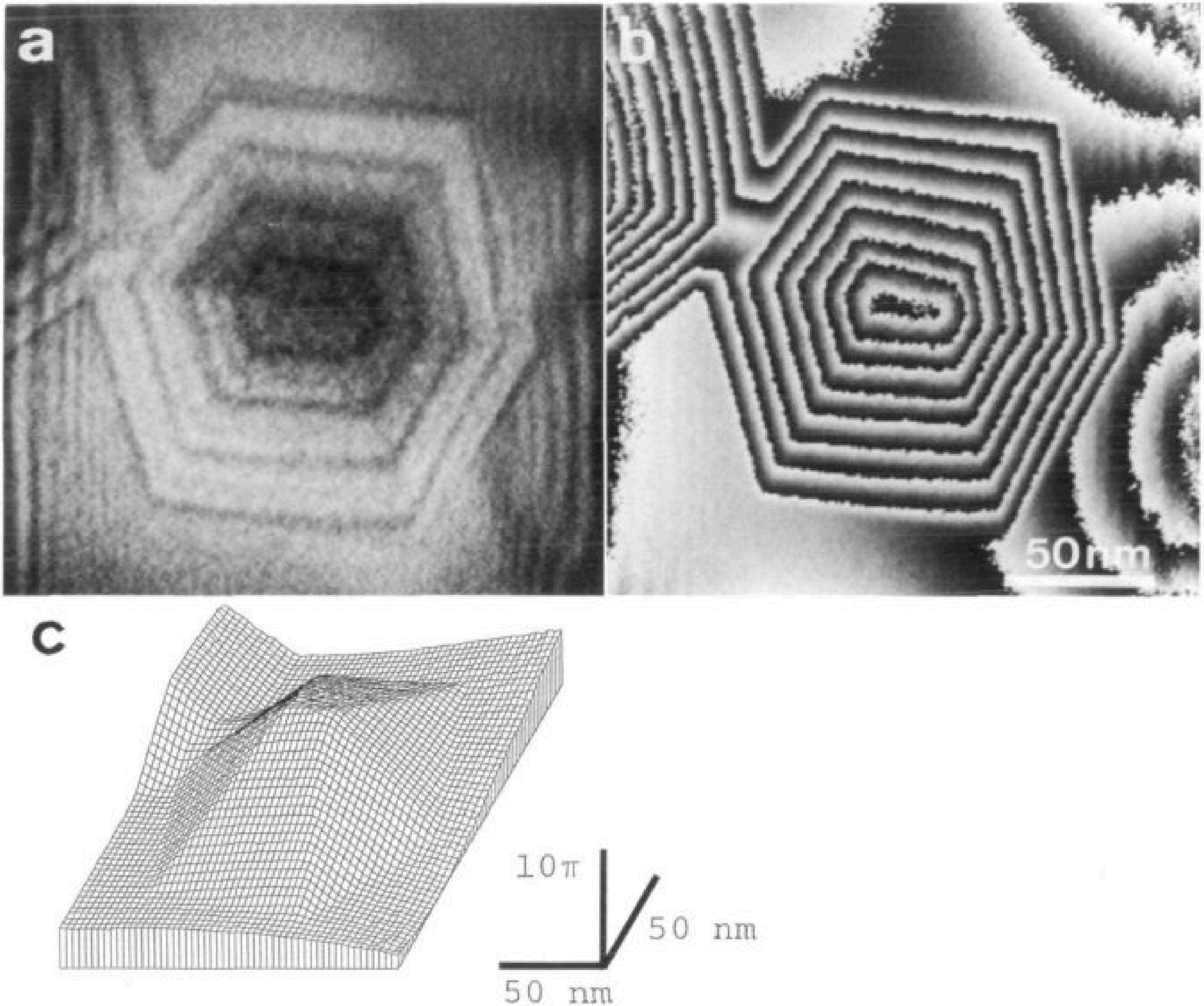
  $\rightarrow$ Take more than one image, changing the reference in each.

Fringe scanning



Source: K. Harada, J. Electron Microsc. **39** 470-476 (1990)

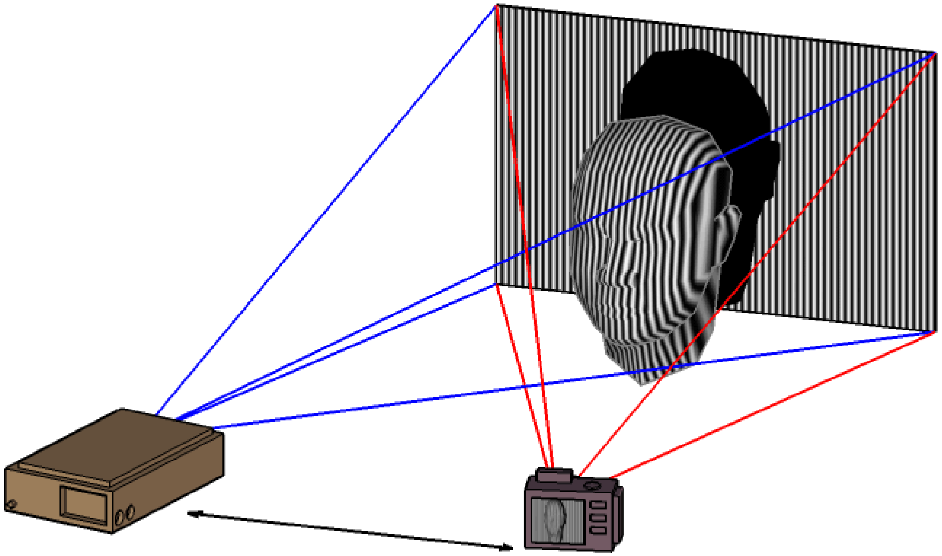
Fringe scanning

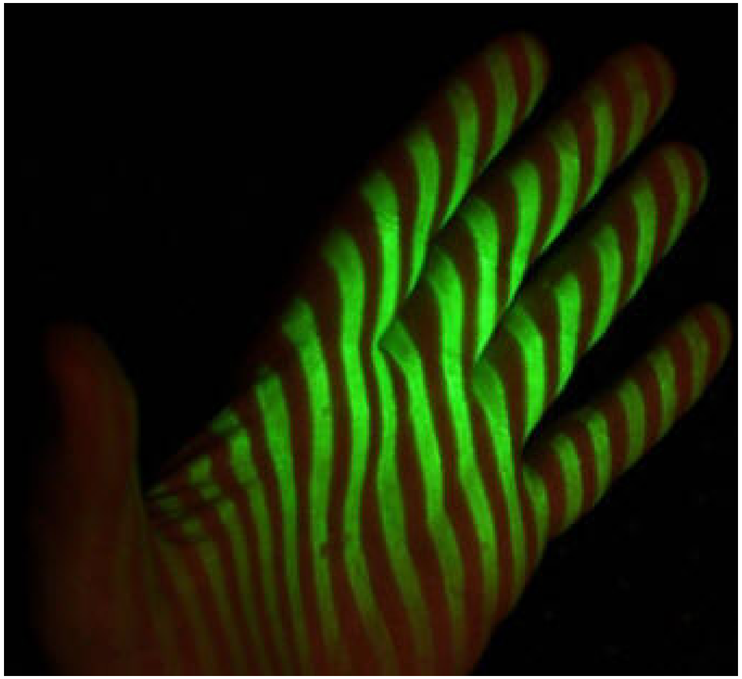


Source: K. Harada, J. Electron Microsc. **39** 470-476 (1990)

Structured light sensing

- Project a structured light pattern onto sample
- Distortions of light pattern allow reconstruction of sample shape





Phase unwrapping

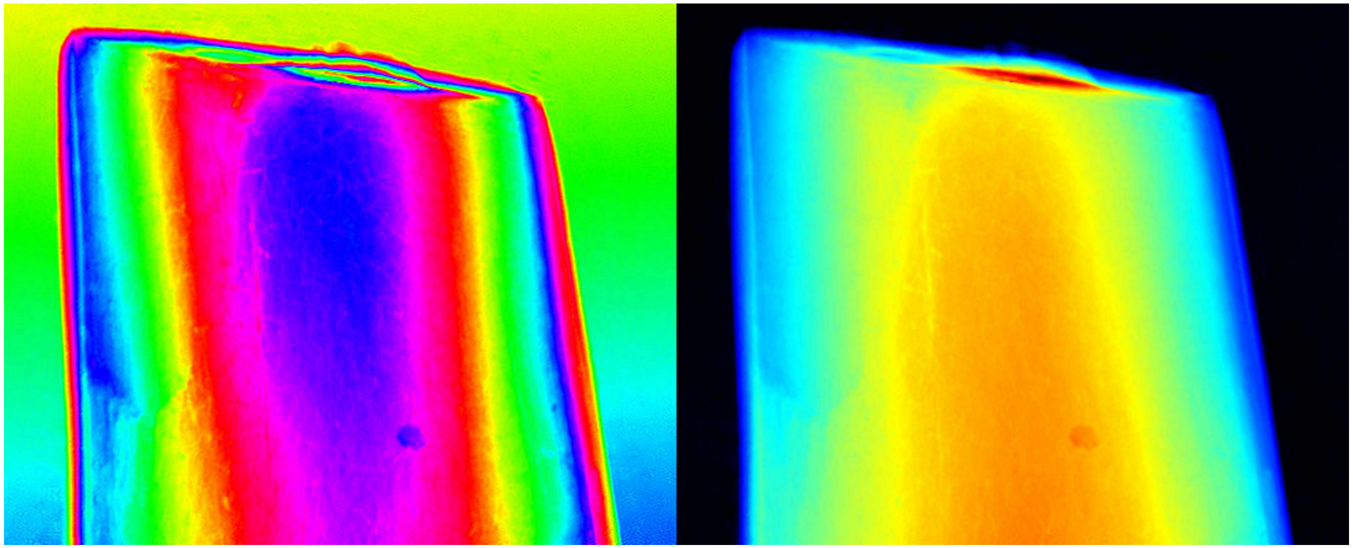
- Phase is measured only in the interval [0, 2π)
- Physical phase shifts (which can be larger) are wrapped on this interval

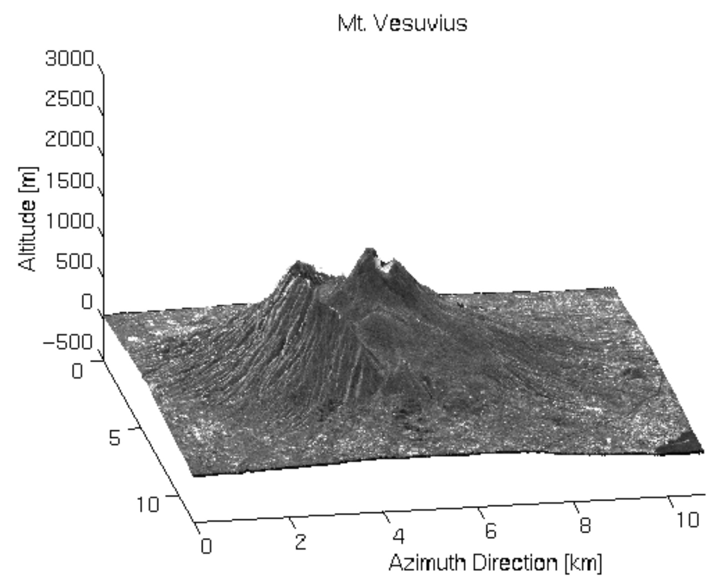
  $\rightarrow$ Any multiple of 2π is possible

- Unwrapping: use correlations in the image to guess the total phase shift.
- Main difficulties:
  - aliasing: phase shifts are too rapid for the image sampling
  - noise: produces local singularities (vortices)
- Many strategies exist

Complex-valued images

Phase unwrapping

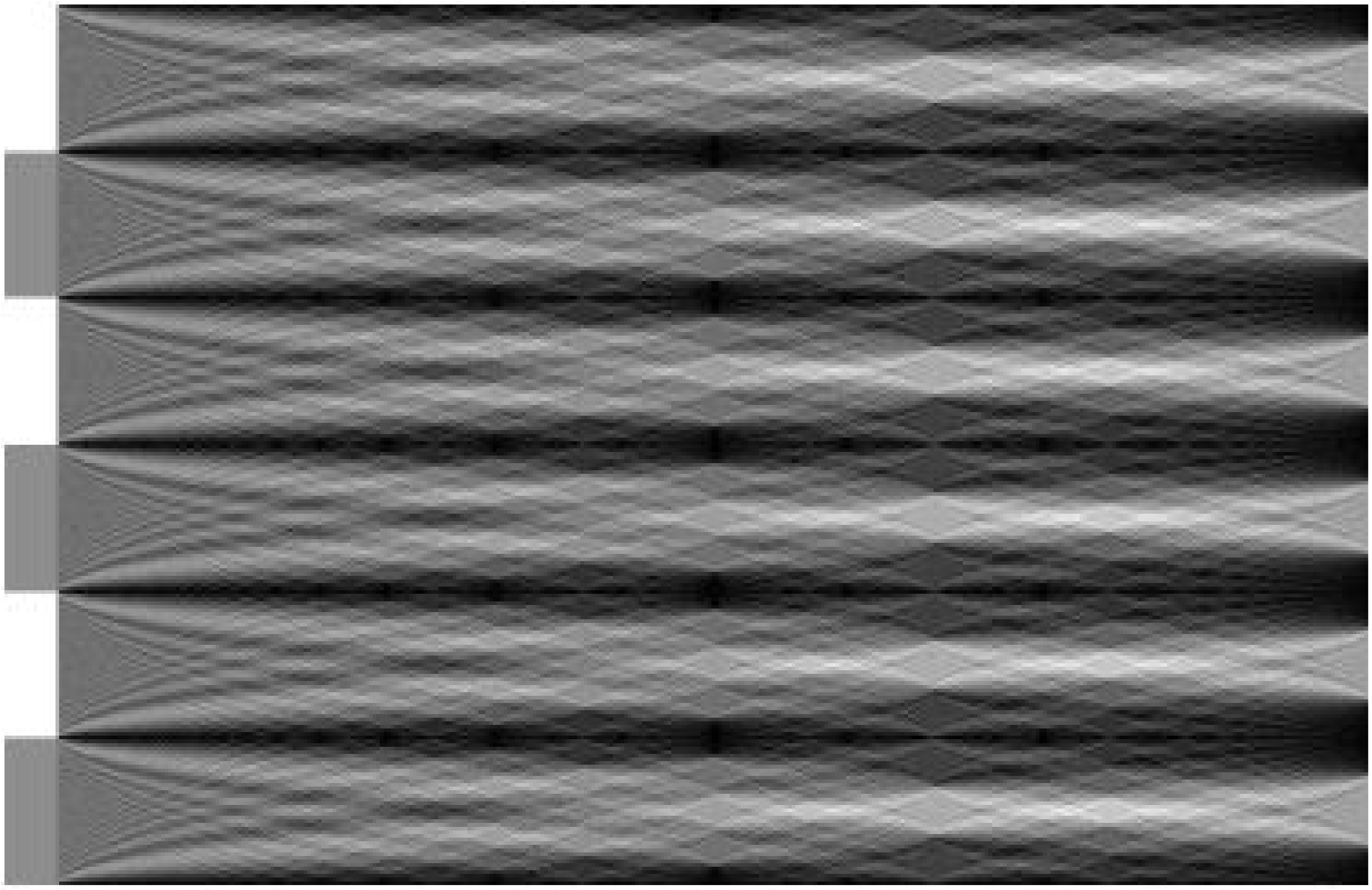




Source: http://earth.esa.int/workshops/ers97/program-details/speeches/rocca-et-al/

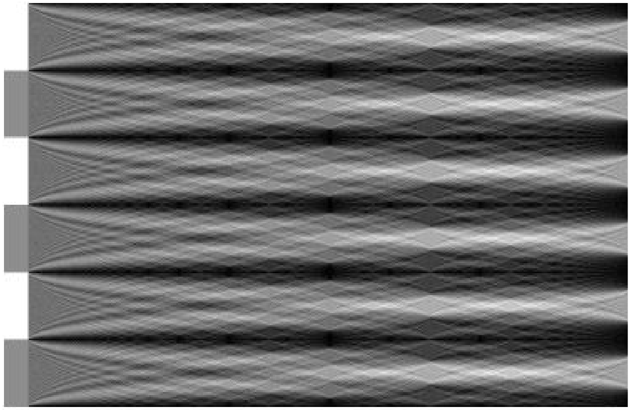
Grating interferometry

Diffraction from a grating



Grating interferometry

Diffraction from a grating



Grating interferometry

Observing the interference between two (slightly offset) copies of the same sample.

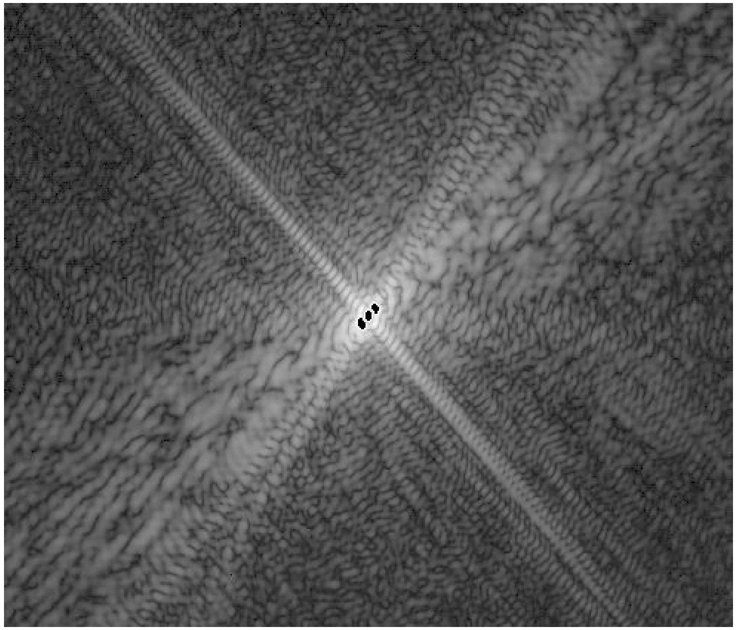
Grating interferometry

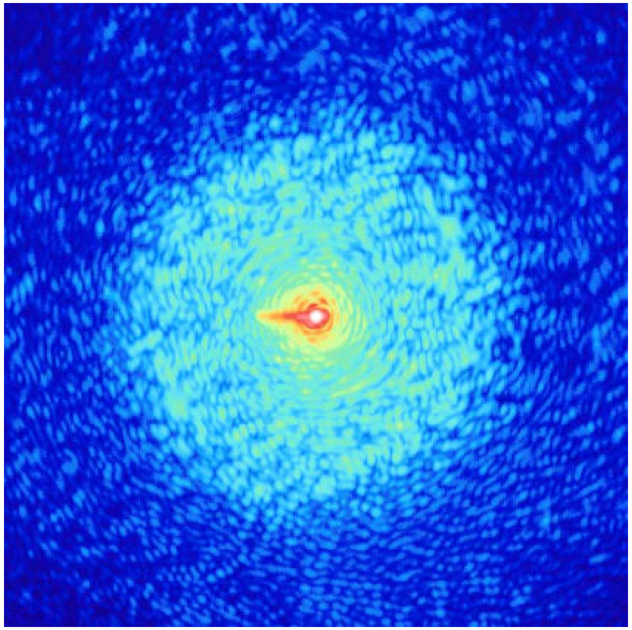
Observing the interference between two (slightly offset) copies of the same sample.

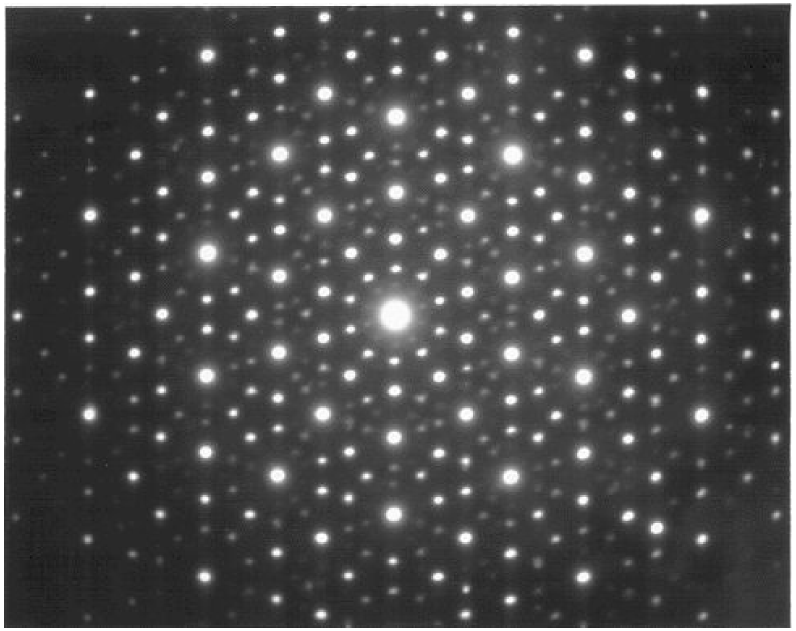
Far-field diffraction

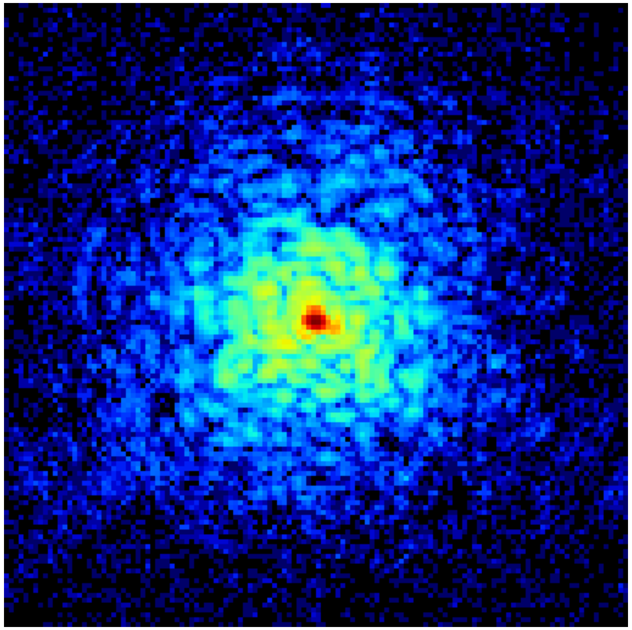
The Fraunhofer regime

Diffraction patterns









Diffraction and autocorrelation

Fourier transform holography

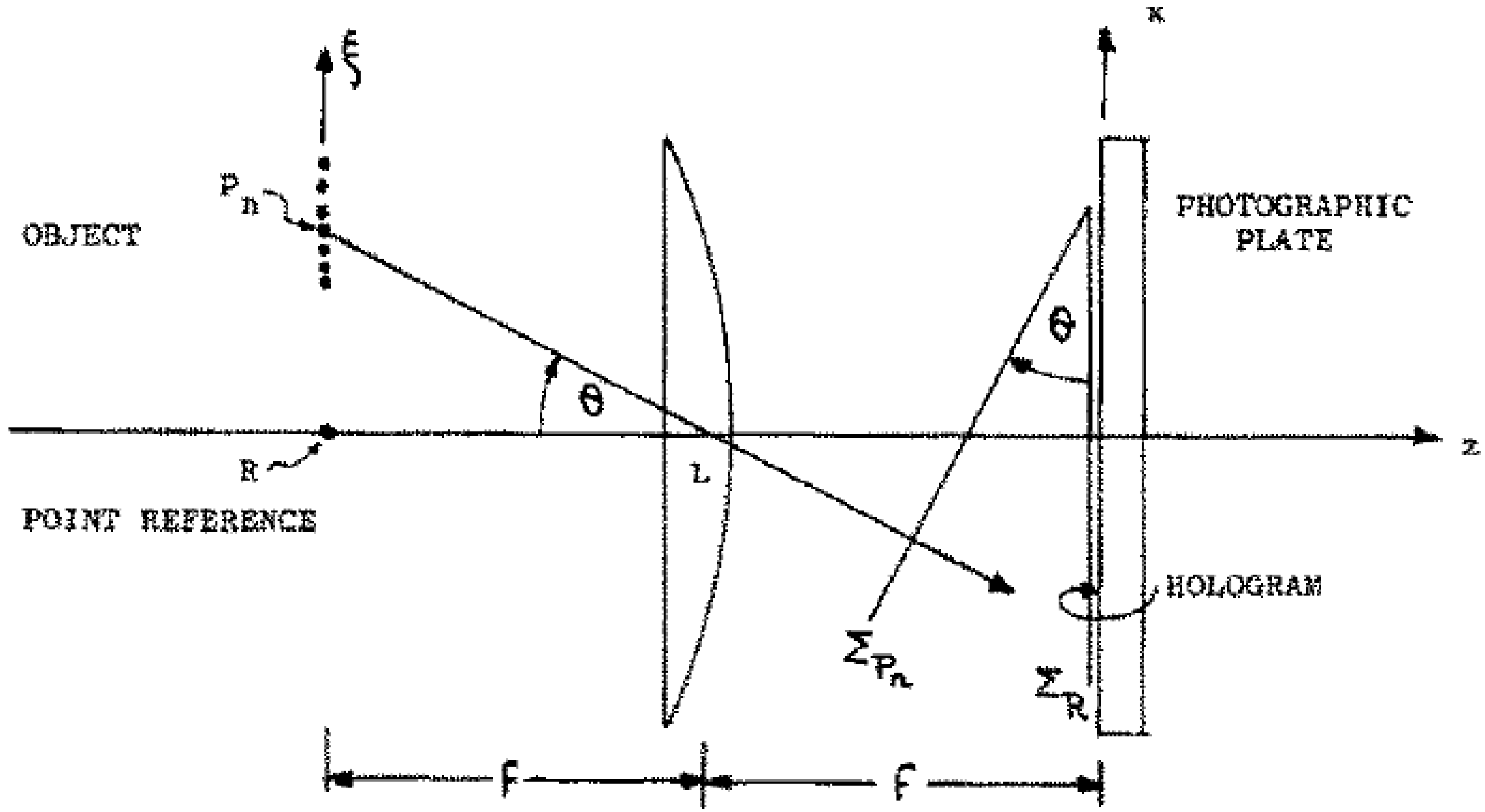
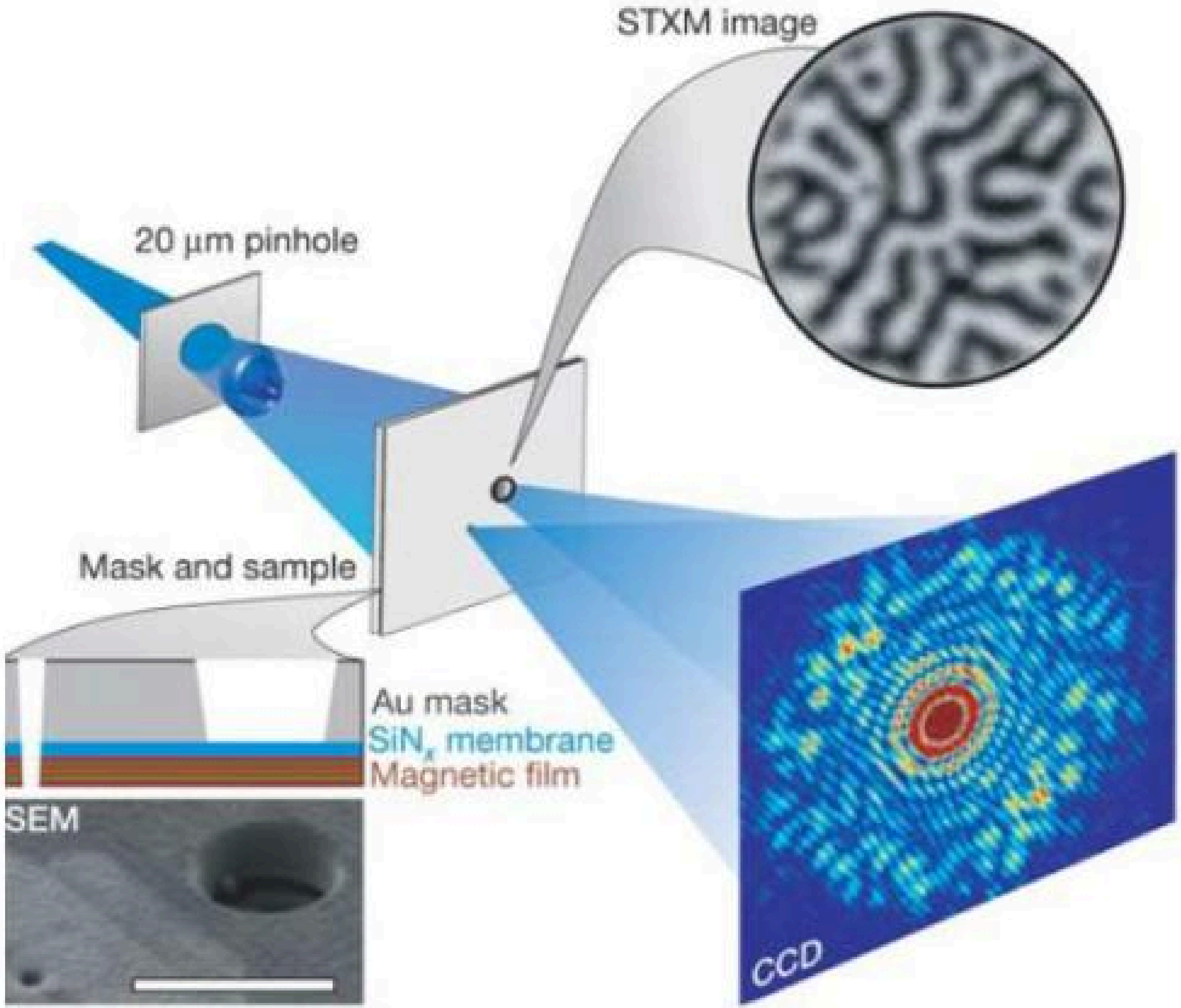


Fig. 1. Recording of a Fourier-transform hologram with a lens *L*. Σ_R = reference wavefront.

Source: G. Stroke, Appl. Phys. Lett. **6**, 201-203 (1965).

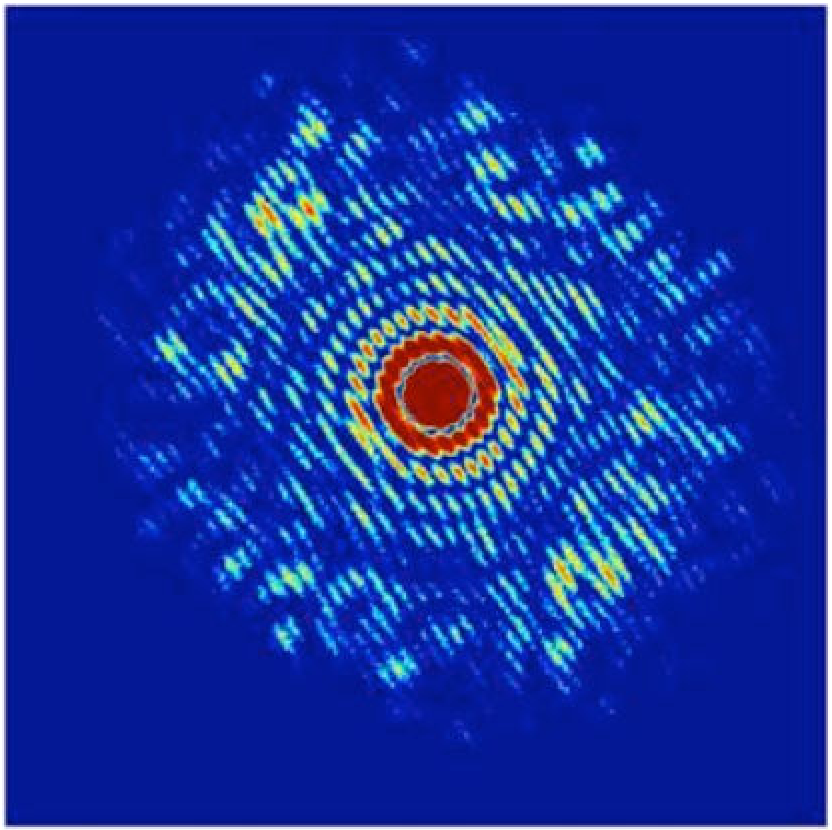
Fourier transform holography

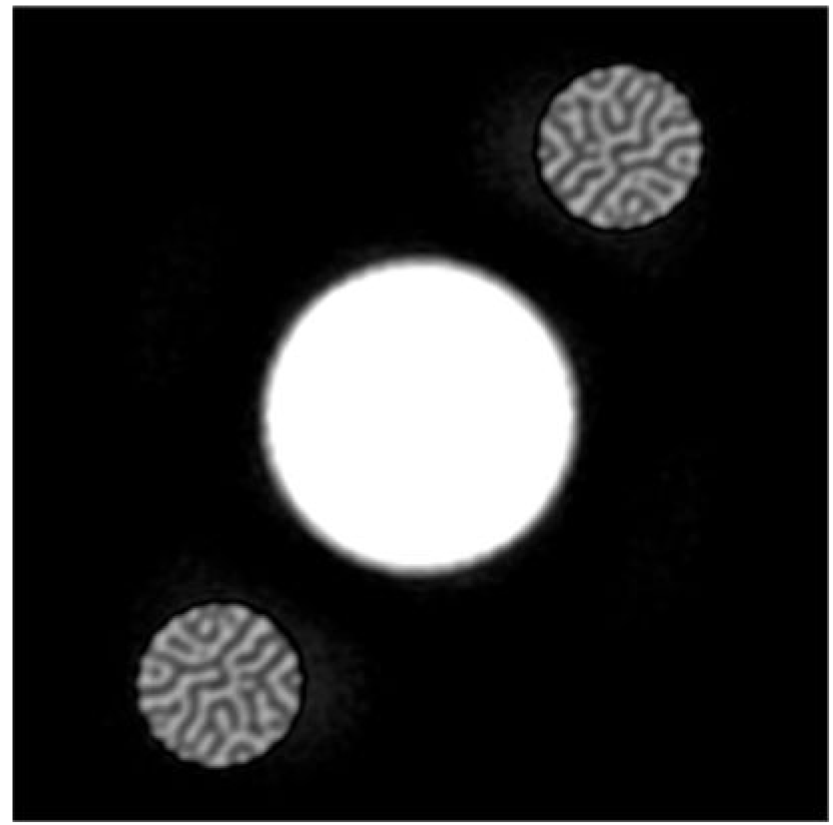


Source: S. Eisebitt et al., Nature **432**, 885-888 (2004).

Fourier transform holography

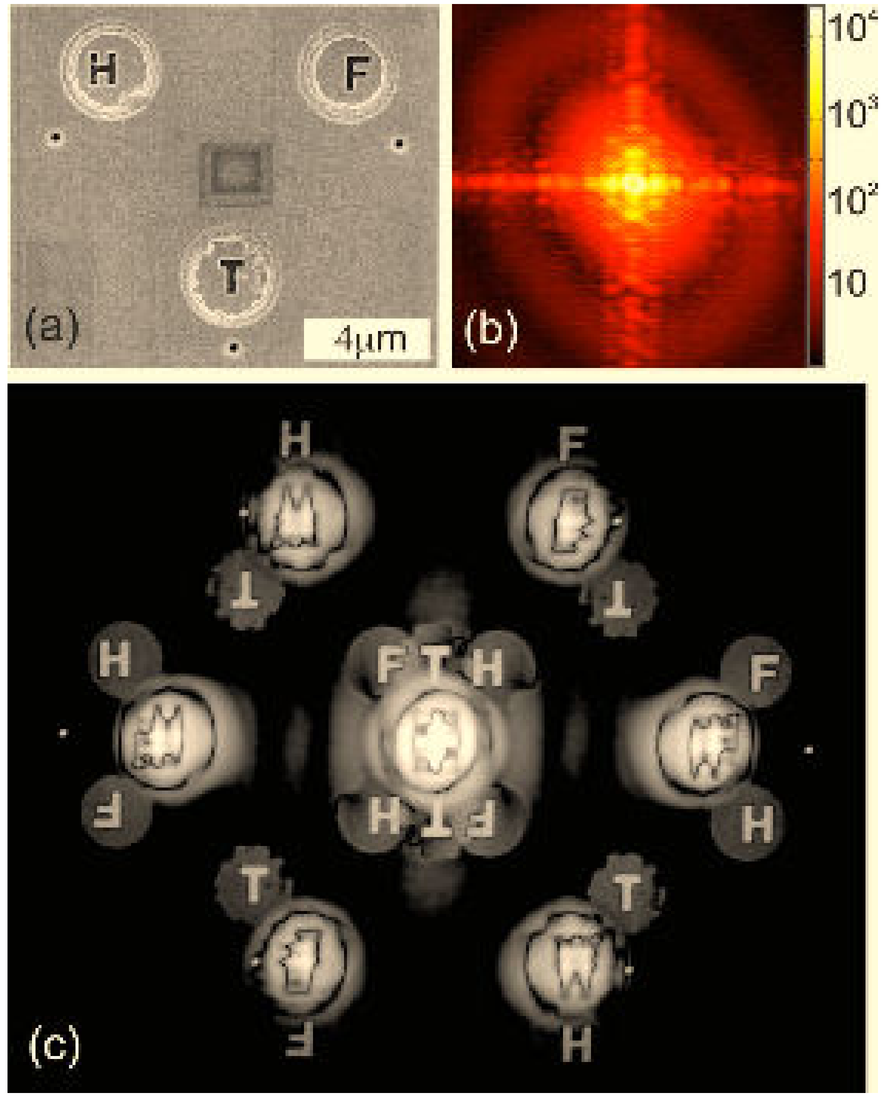
Fourier transform holography





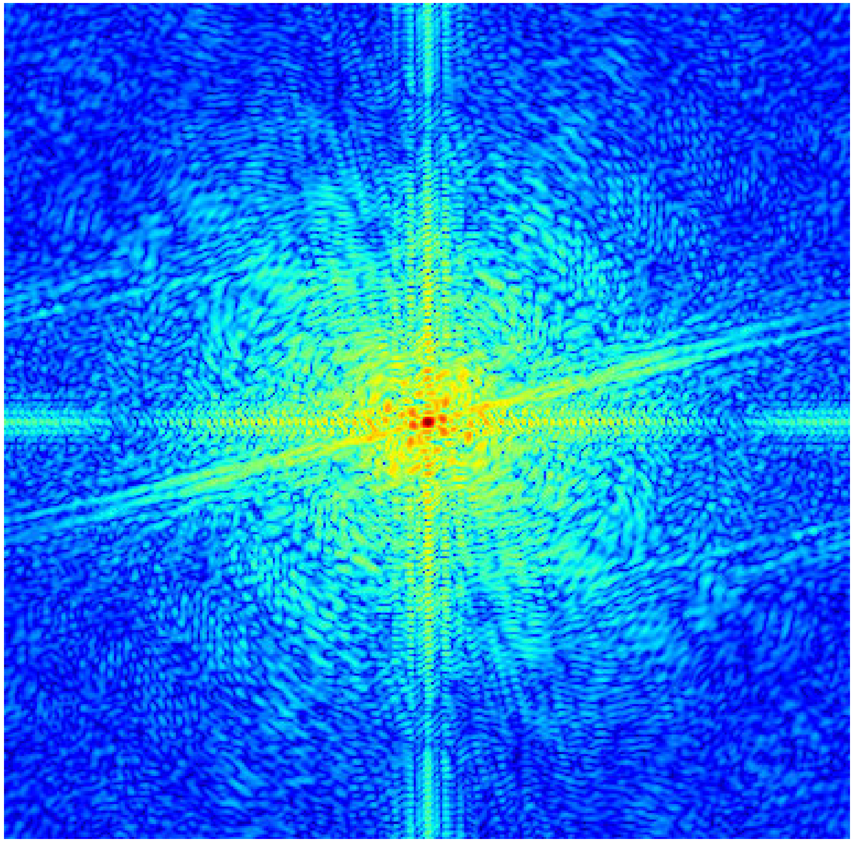
Fourier transform holography

Multiple references

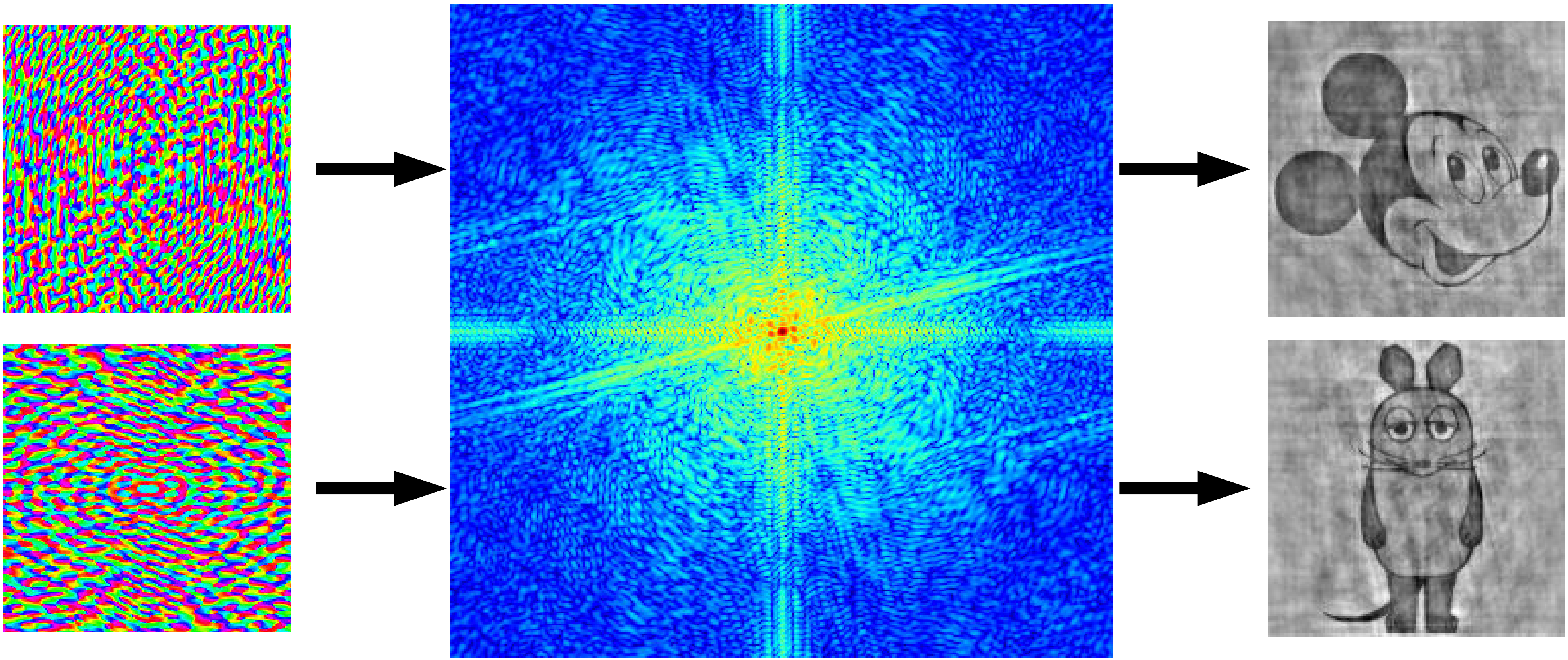


Source: W. Schlotter et al., Opt.. Lett. **21**, 3110-3112 (2006).

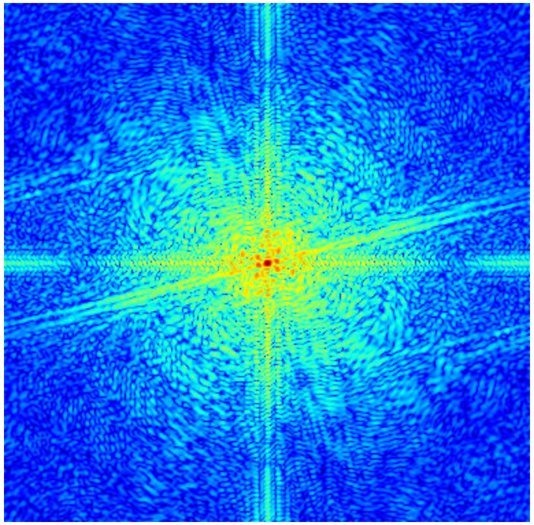
Coherent diffractive imaging

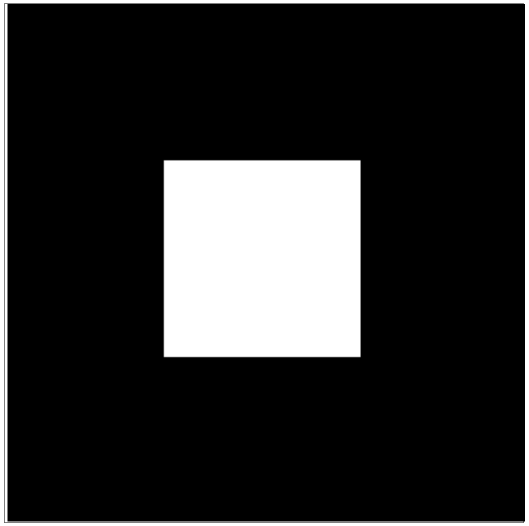


The phase problem

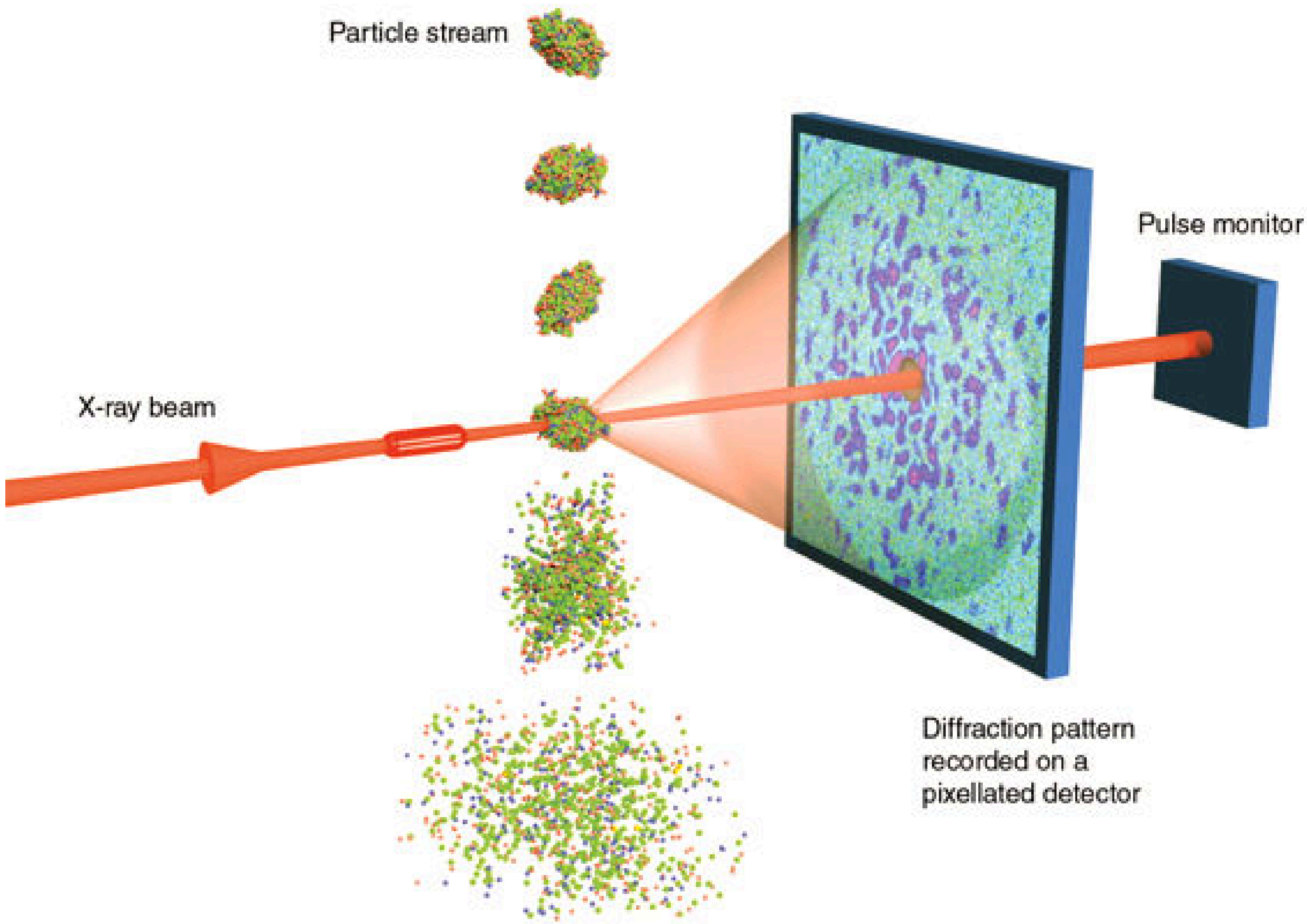


Coherent diffractive imaging





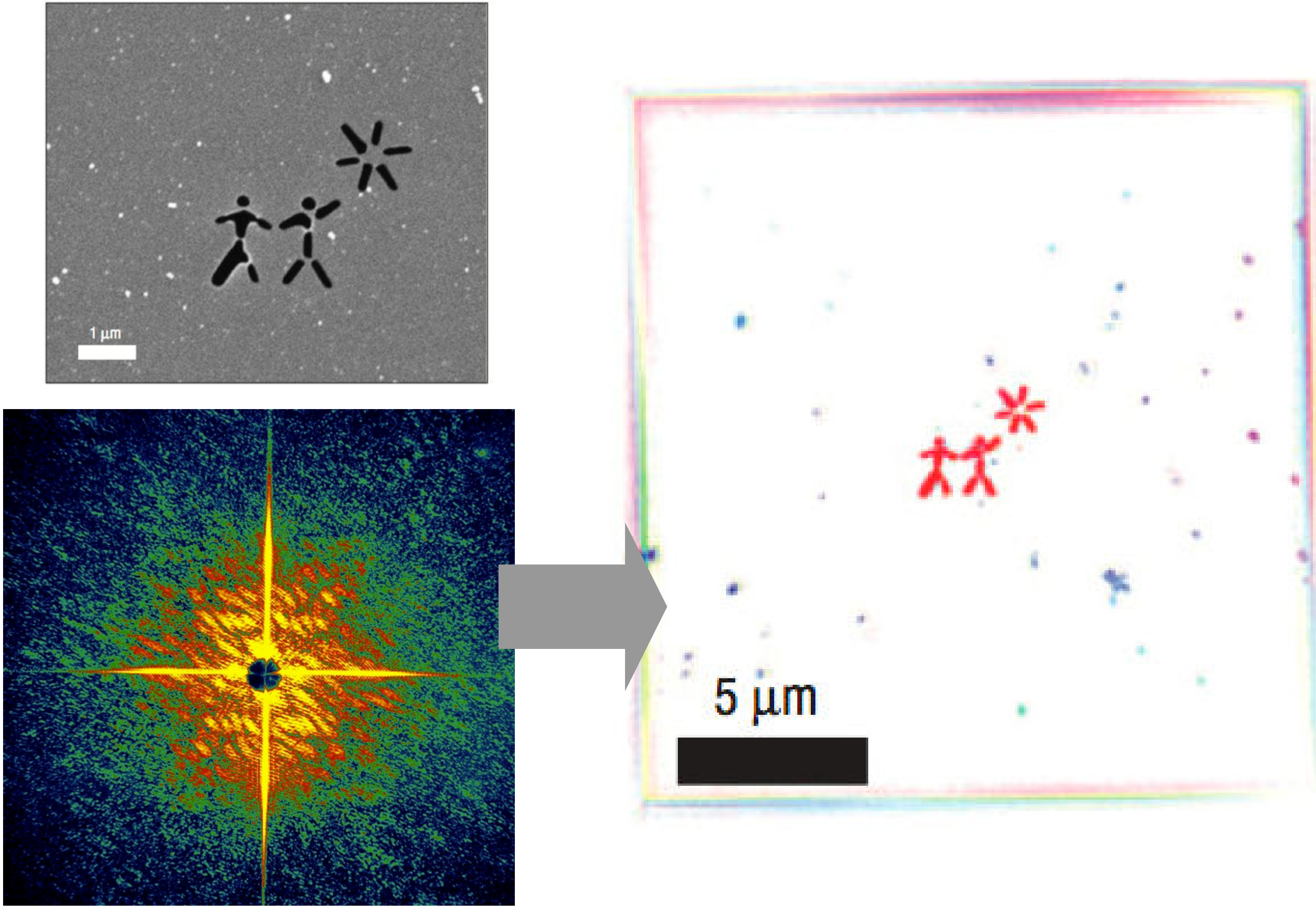
Radiation damage limits on radiation



R. Neutze *et al*, Nature **406**, 752 (2000)

K. J. Gaffney *et al*, Science **316**, 1444 (2007)

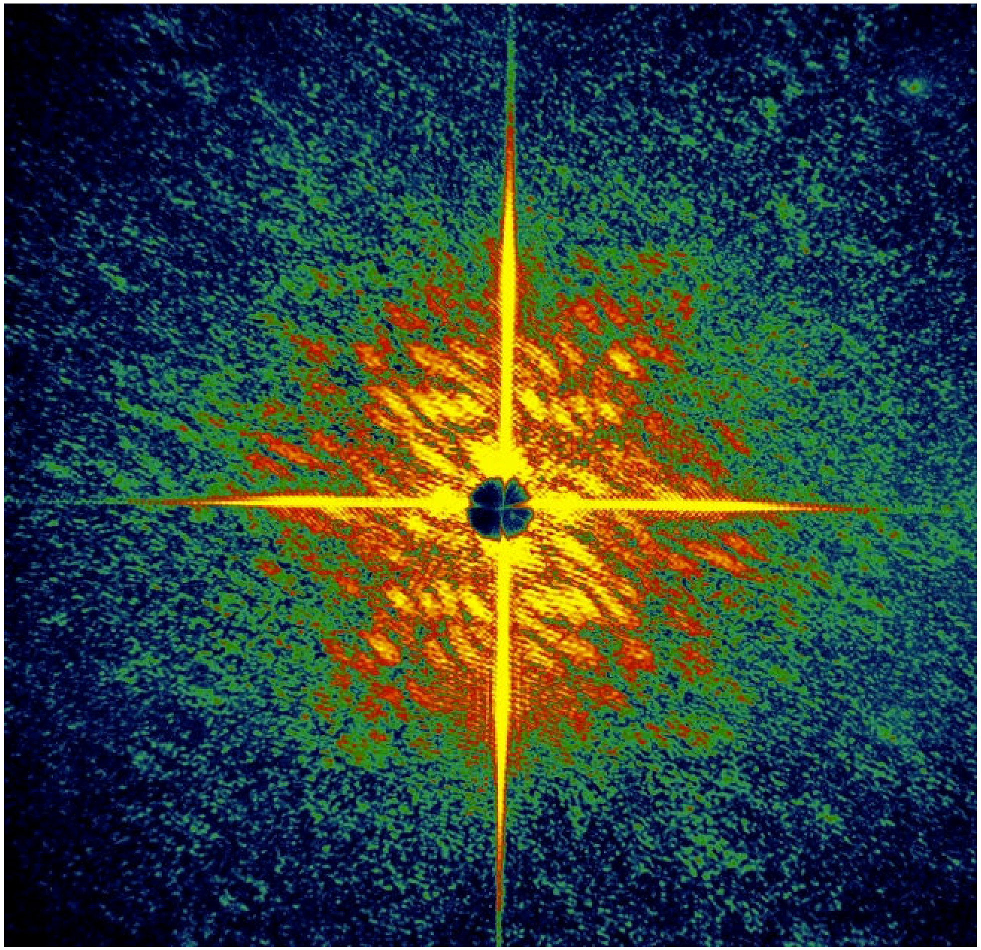
“Diffraction before destruction”

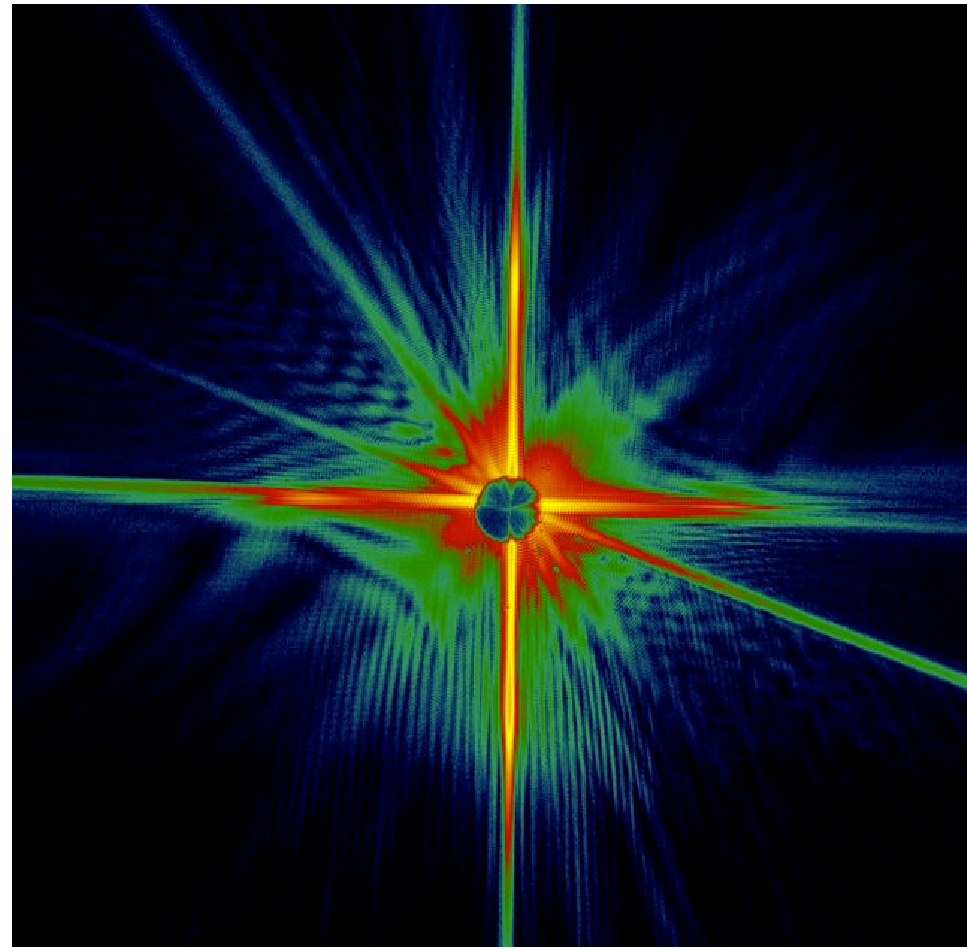


H. N. Chapman *et al*, Nat. Phys. **2**, 839 (2006)

“Diffraction before destruction”

The imaging pulse vaporized the sample





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

Ptychography

- Scanning an isolated illumination on an extended specimen
- Measure full coherent diffraction pattern at each scan point
- Combine everything to get a reconstruction

Dynamische Theorie der Kristallstrukturanalyse durch Elektronenbeugung im inhomogenen Primärstrahlwellenfeld

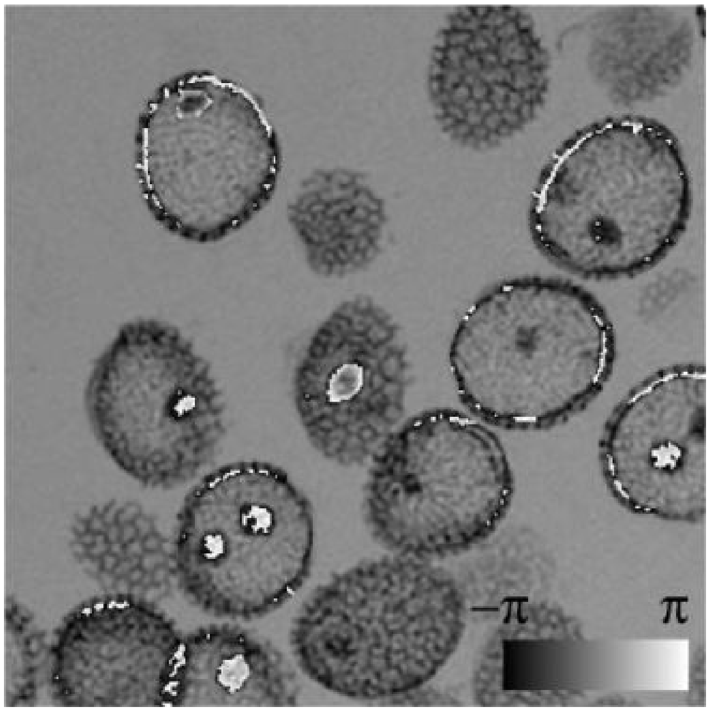
Von R. Hegerl und W. Hoppe

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.

Ptychography

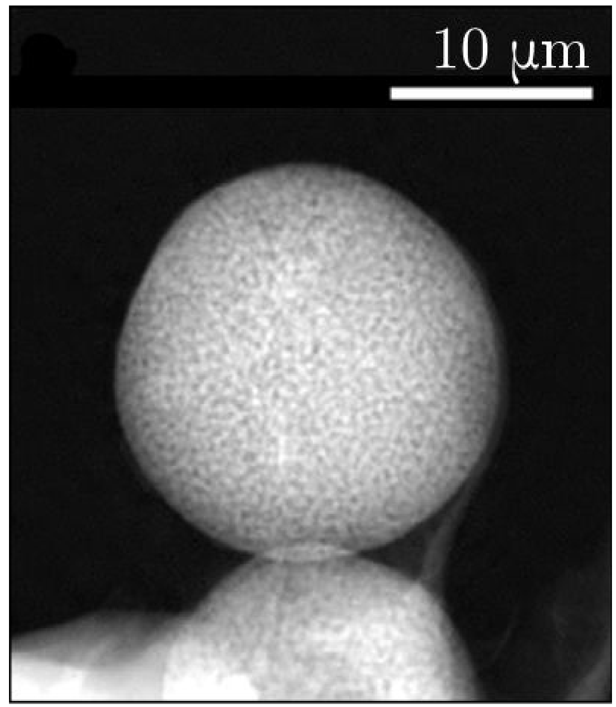
A few examples

Visible light



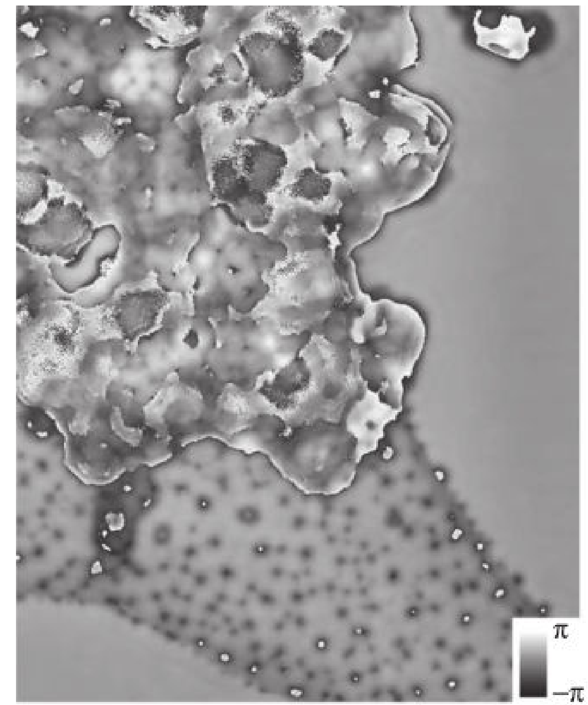
A. Maiden *et al.*, Opt. Lett. **35**, 2585-2587 (2010).

X-rays



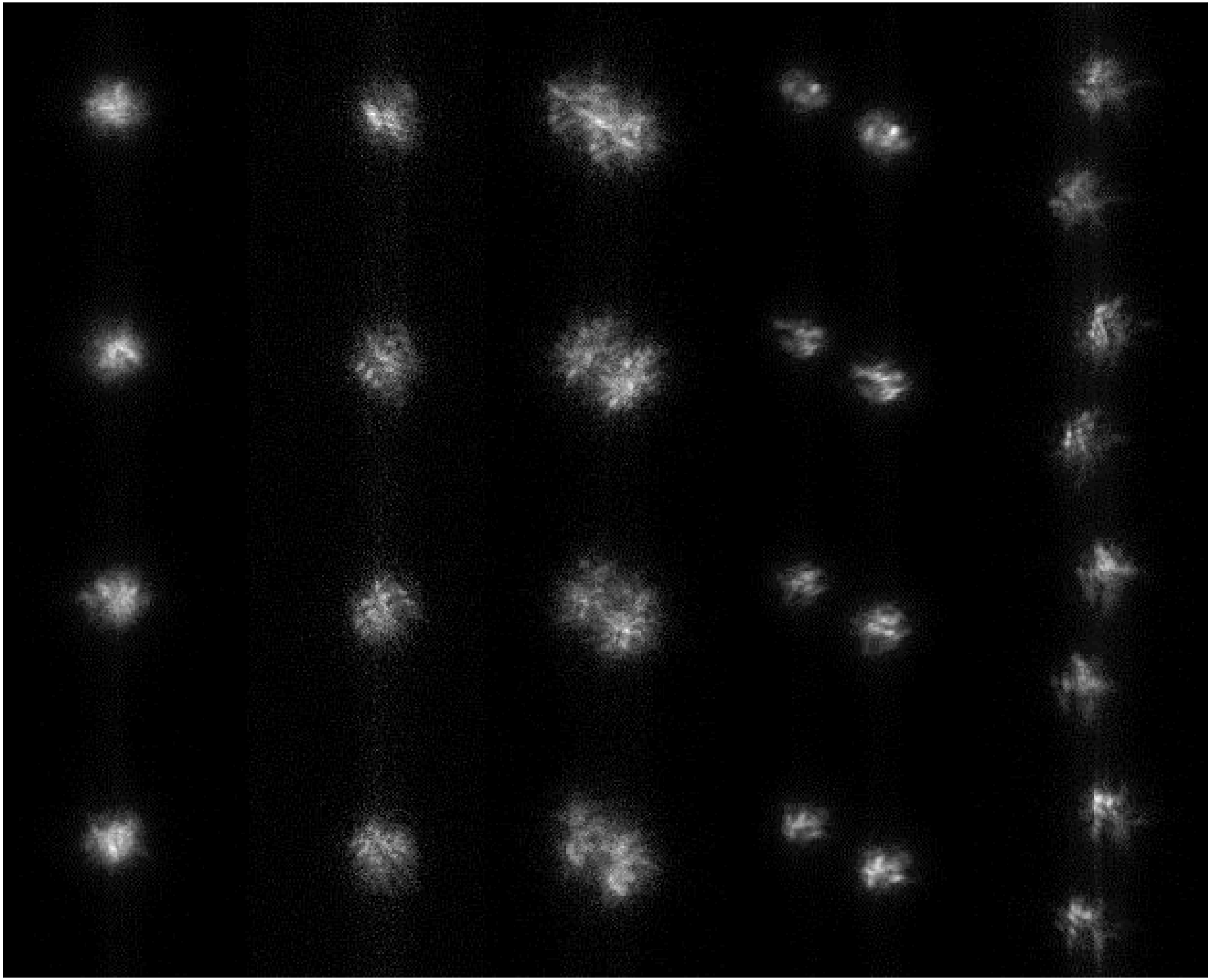
P. Thibault *et al.*, New J. Phys **14**, 063004 (2012).

electrons



M. Humphry *et al.*, Nat. Comm. **3**, 730 (2012).

Speckle imaging in astronomy



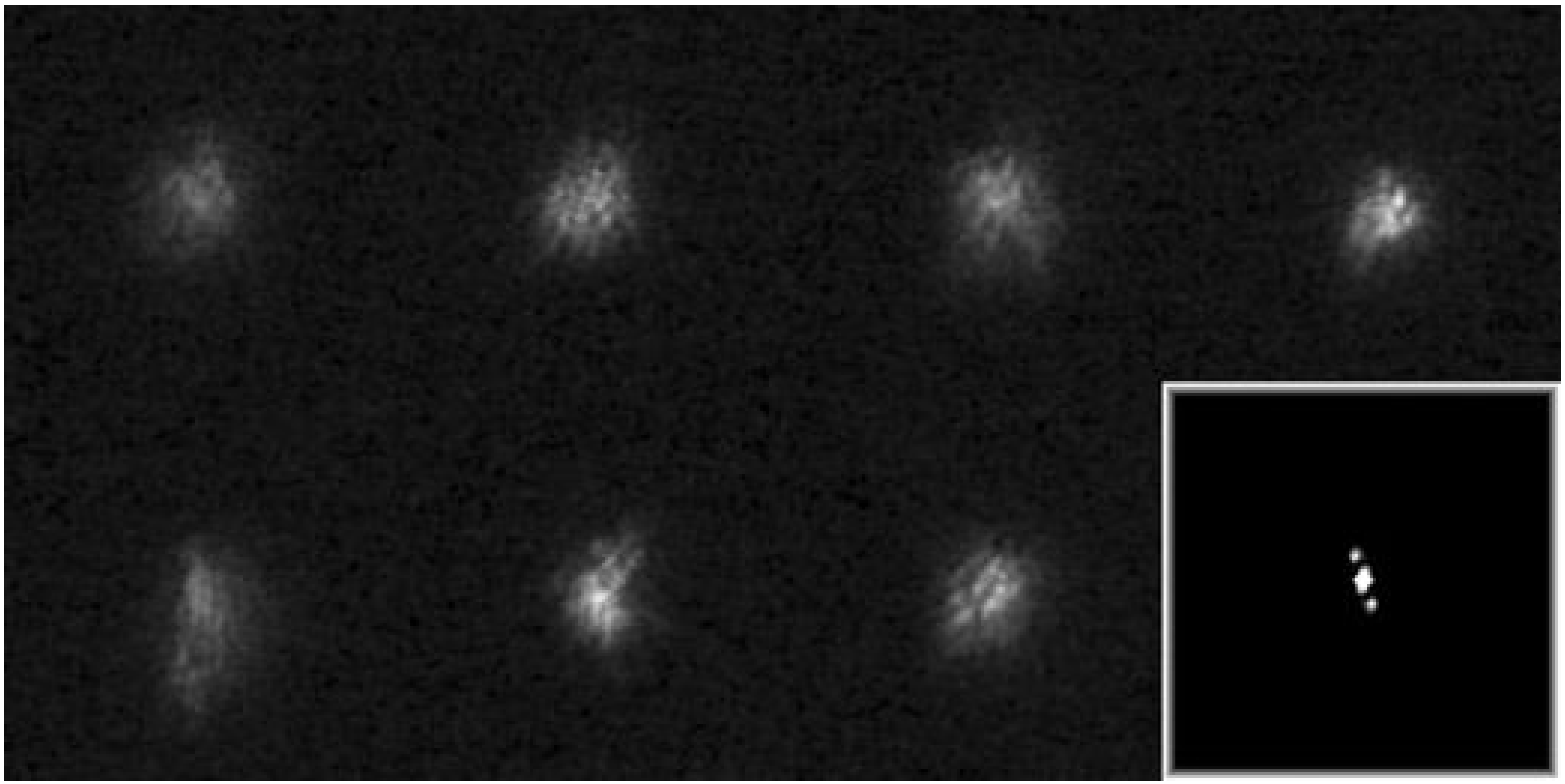
Source:http://www.cis.rit.edu/research/thesis/bs/2000/hoffmann/thesis.html

Speckle imaging in astronomy

Model

Speckle imaging in astronomy

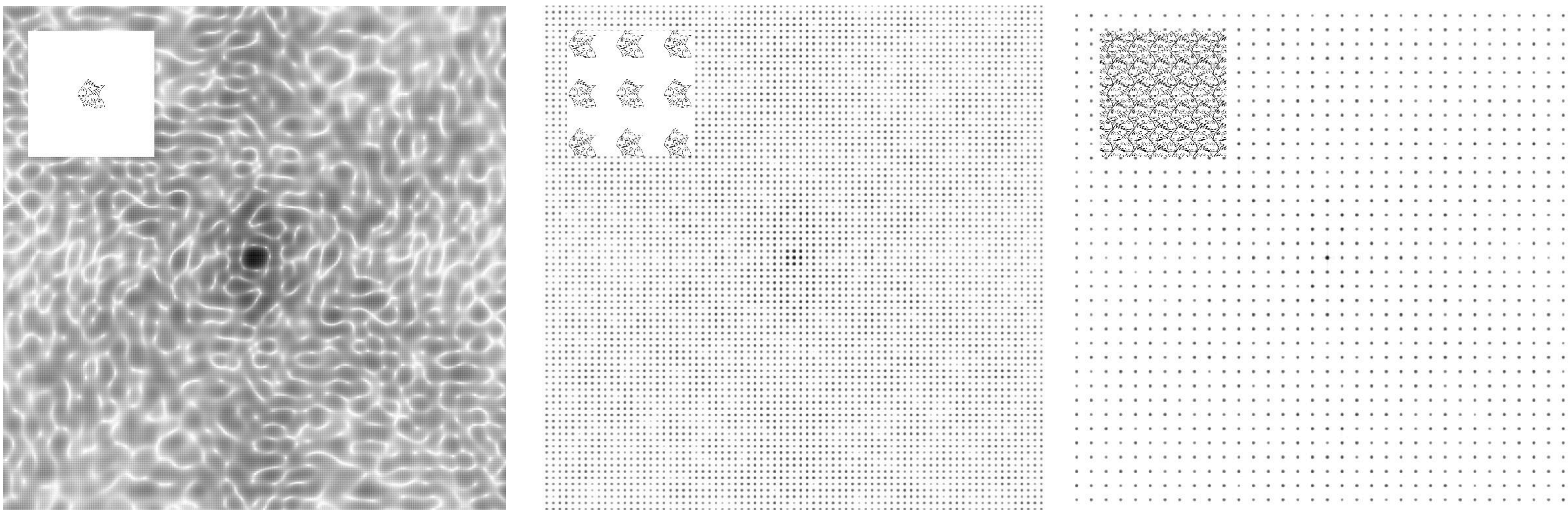
Retrieval of the autocorrelation



Source: http://www.astrosurf.com/hfosaf/uk/speckle10.htm

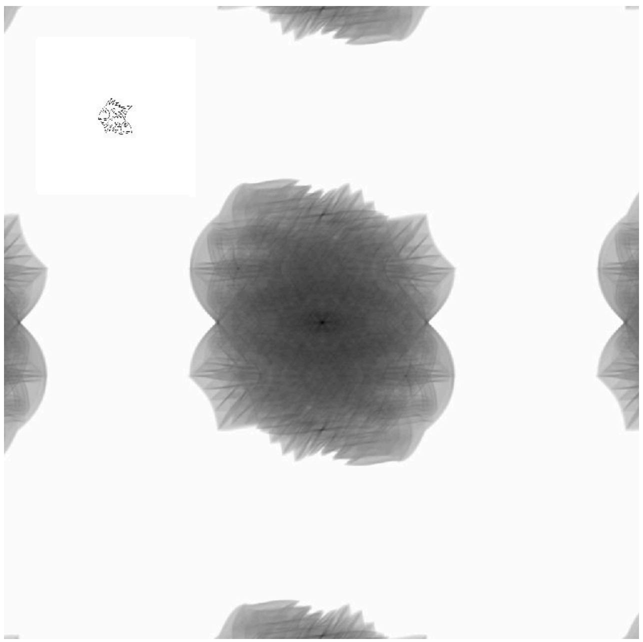
Crystallography

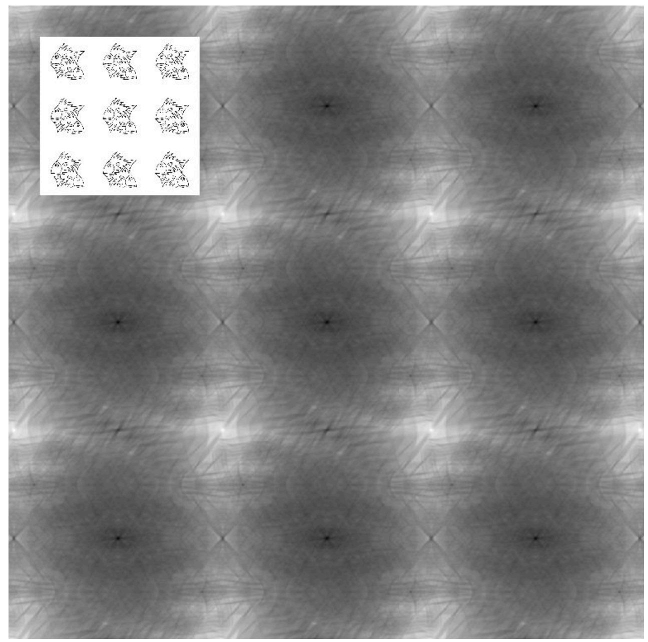
Diffraction by a crystal: Bragg peaks

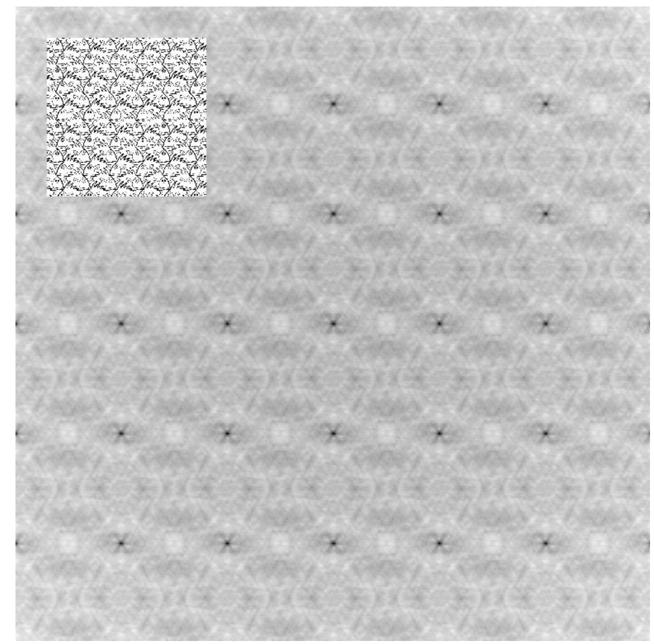


Crystallography

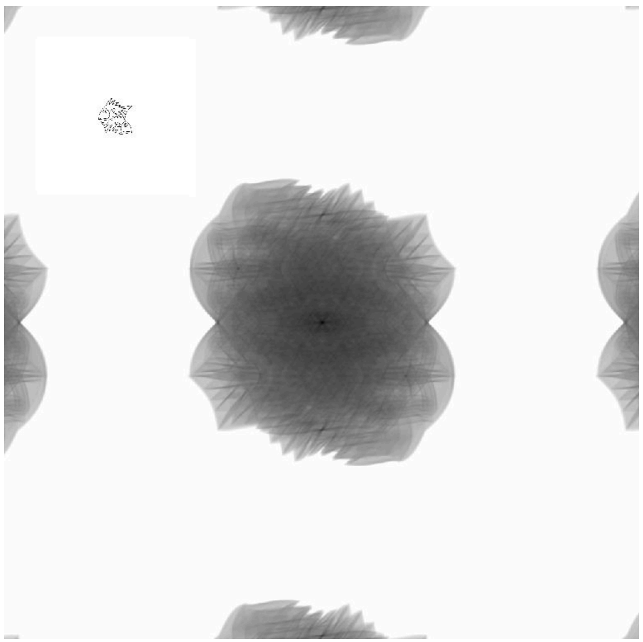
Fourier transform of intensity: autocorrelation

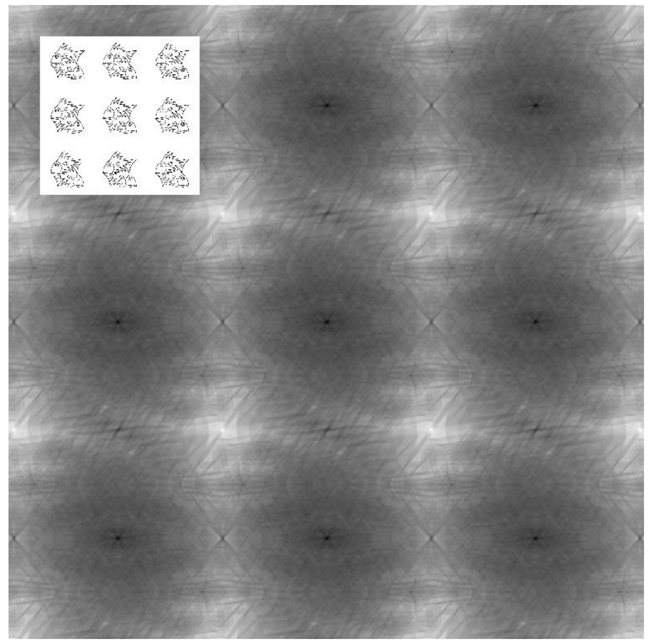


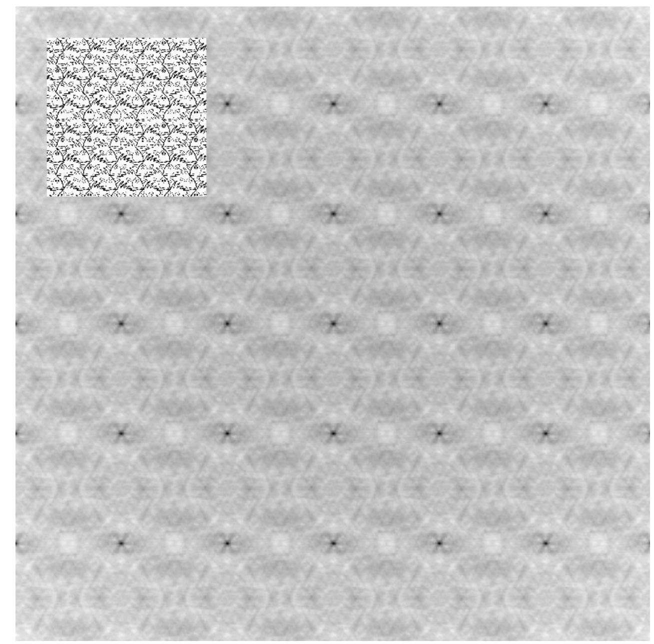




Crystallography

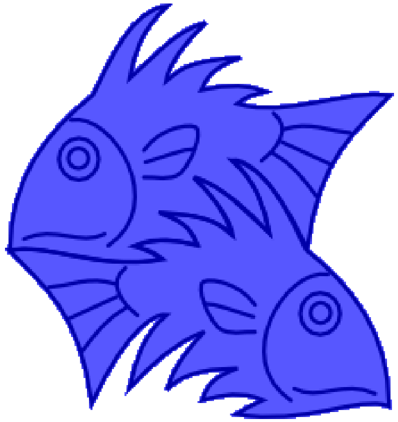




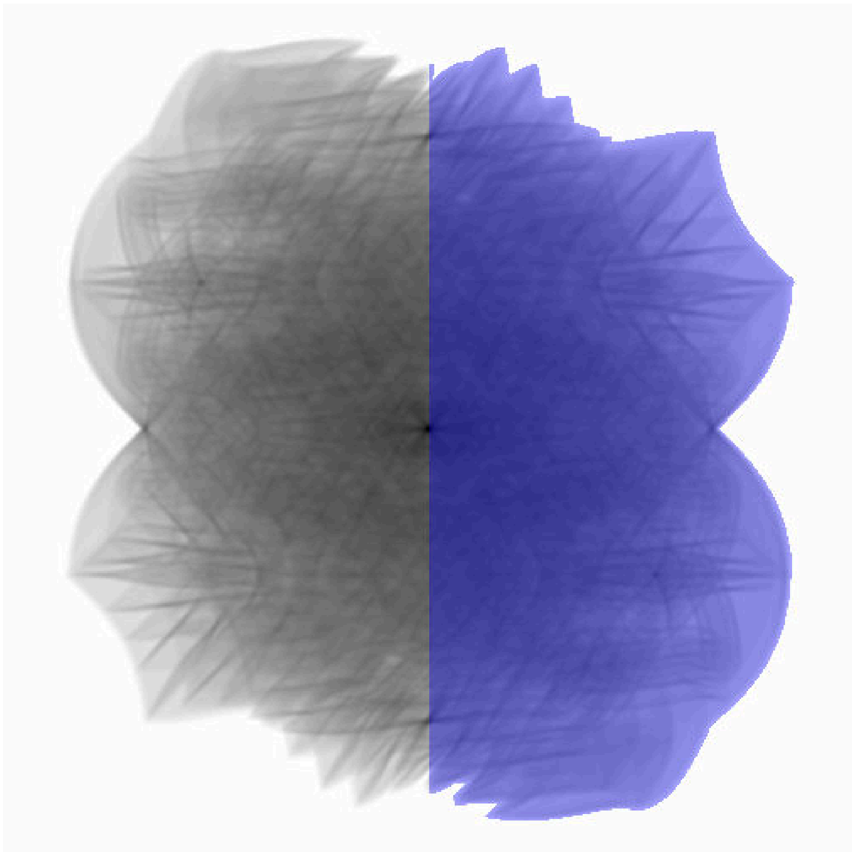


Crystallography

Problem is overconstrained with an isolated sample



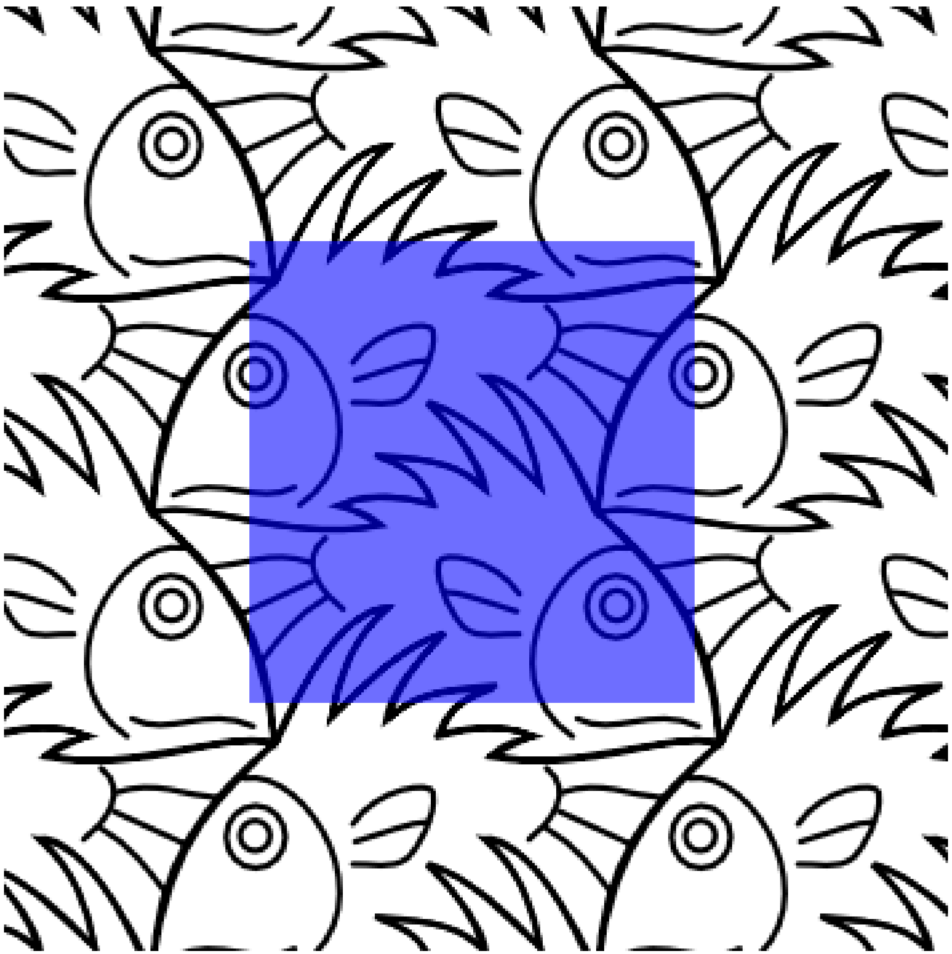
unknowns = N



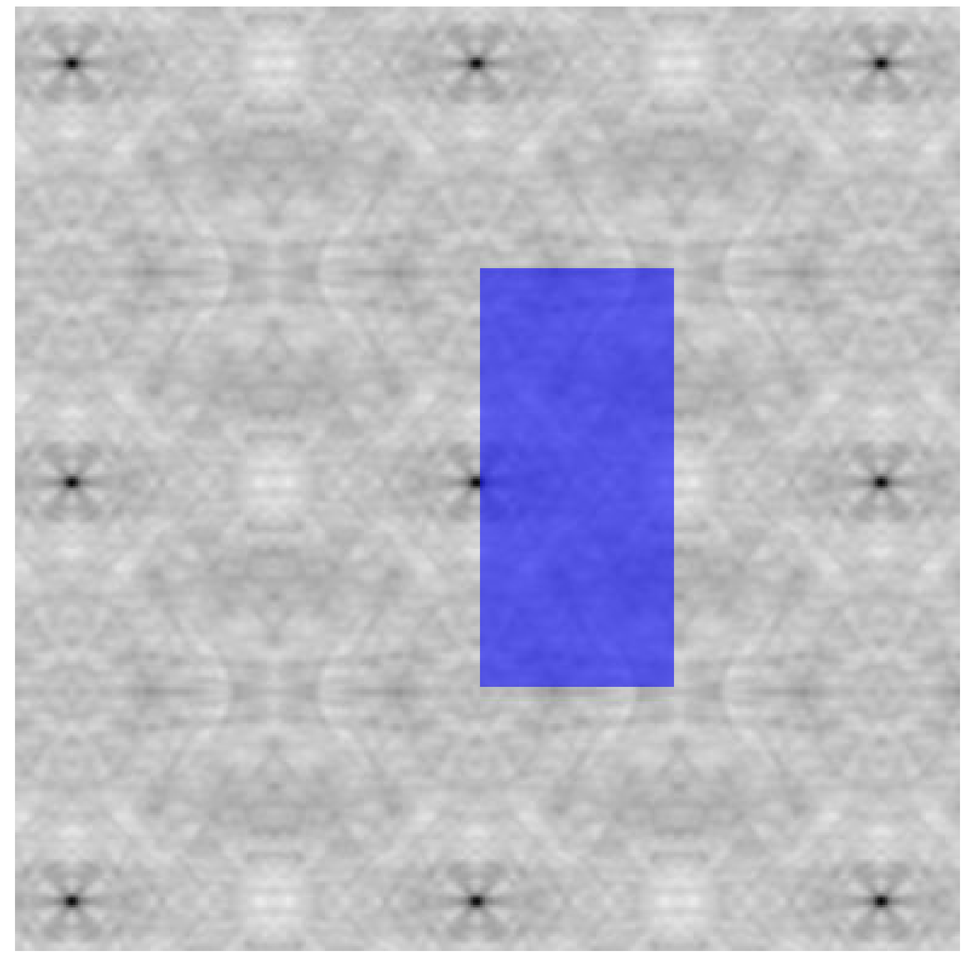
constraints ≥ 2N

Crystallography

Problem is **under**constrained with a crystal

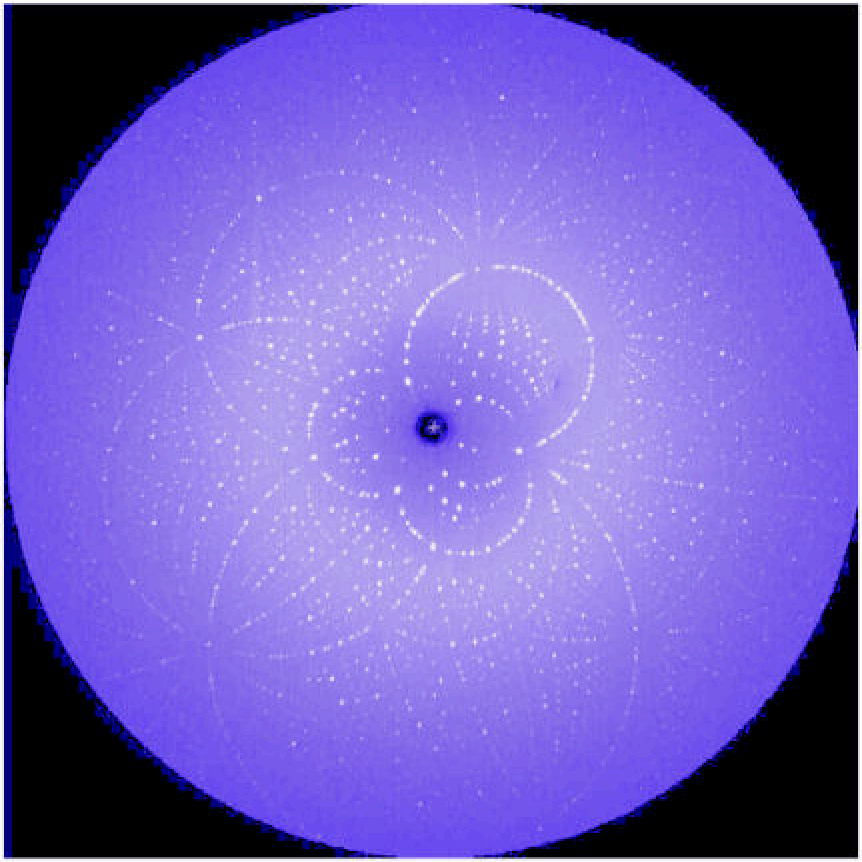


unknowns = N



constraints = N/2

Crystallography
Structure determination



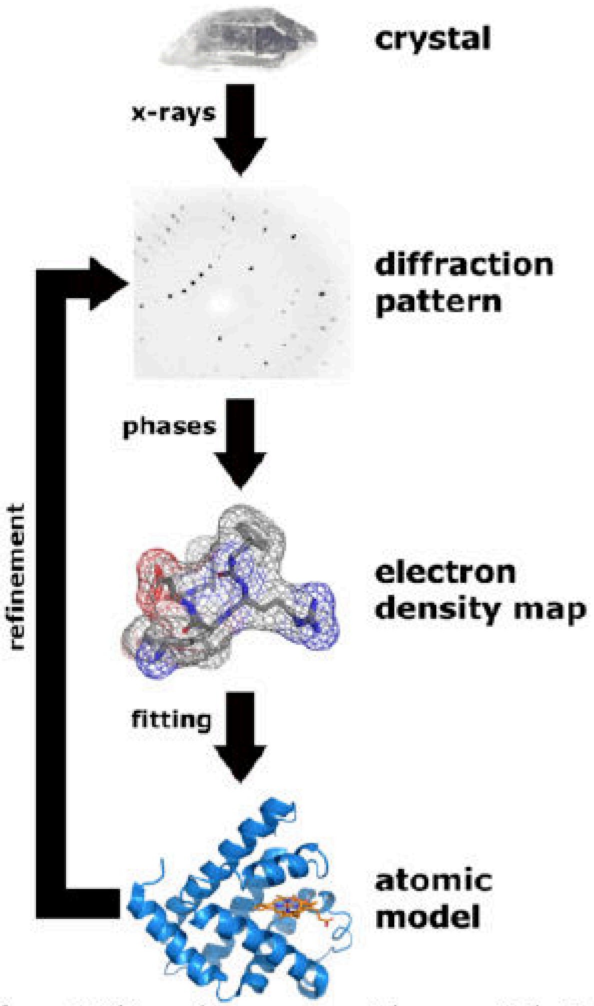


Image from Wikimedia courtesy Thomas Splettstoesser

Crystallography

Structure determination

- Hard problem: few measurements for the number of unknowns
- Luckily: crystals are made of atoms $\rightarrow$ strong constraint
- Also common: combining additional measurements (SAD, MAD, isomorphous replacement, ...)

Summary

Imaging from far-field amplitudes

- Used when image-forming lenses are unavailable (or unreliable) or to obtain more quantitative images.
- In general difficult because of the phase problem
- Solved with the help of additional information:
  - Strong *a priori* knowledge (e.g. CDI: support)
  - Multiple measurements (e.g. ptychography)