Microscopy with Coherent X-Rays

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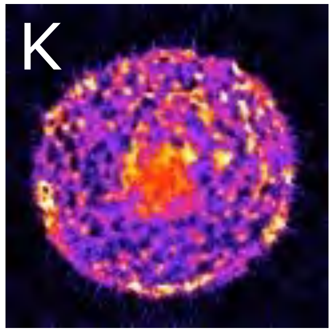
DESY

X-Ray Microscopy

Broad field of applications:



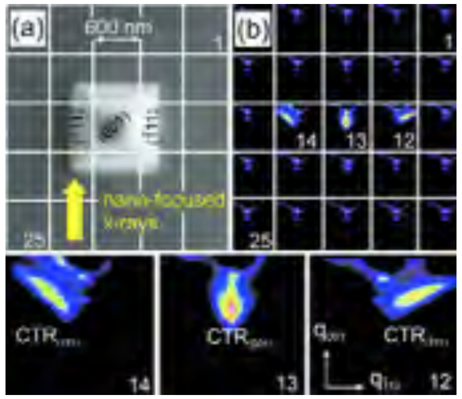
- Physics, chemistry, biology, earth- and environmental science, nano-technology, ...
- Main advantage: large penetration depth

  → in-situ and in-operando studies

- X-ray analytical contrasts: XRD, XAS, XRF, ...

  → atomic scale resolution

quantum dots



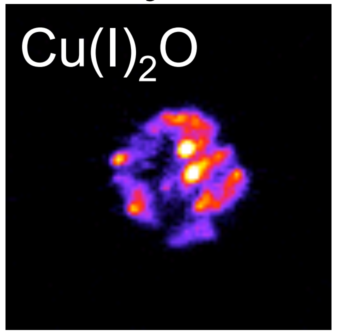
M. Hanke, et al.,
APL **92**, 193109 (2008)

Today: „mesoscopic gap“

real-space resolution: down to about 10 nm

XRD and XAS: atomic scale

catalysts



What happens on (mesoscopic) 1 - 10 nm scale?

X-Ray Microscopy

Today: „mesoscopic gap“

real-space resolution: down to about 10 nm

XRD and XAS: atomic scale

What happens on (mesoscopic) 1 - 10 nm scale?

Many interesting physics and chemistry questions:

investigate local states:

> individual defects (0D): changes in electron density, charge ordering
> (structural) domain boundaries (2D), e. g., in multiferroics
> mesoscopic dynamics at (solid-state) phase transitions
> catalytic nanoparticles (activity in operando)
> ...

Mesoscale also very important for nanotechnology (e. g., defects in devices)!

Current State of X-Ray Microscopy

Conventional x-ray microscopy

→ optics limit spatial resolution: diffraction limit

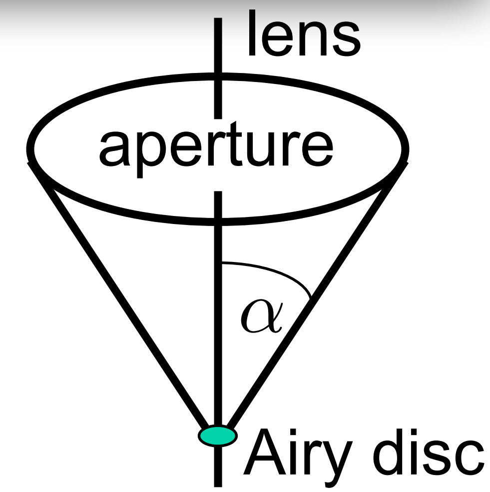
$$d = \frac{\lambda}{2n\sin\alpha}$$

(typically: a few tens of nanometers)

optics are technology limited!

Theoretical extrapolation of x-ray optical performance to the atomic level.

[PRB **74**, 033405 (2006); H. Yan, et al., PRB **76**, 115438 (2007)]



Coherent x-ray imaging techniques (CXDI, ptychography)

→ no imaging optic!

→ limited by statistics of far-field diffraction patterns ...

highest resolution: a few nanometers, focusing coherent beam

[PRL **101**, 090801 (2008); Y. Takahashi, et al., PRB **80**, 054103 (2009);
A. Schropp, et al., APL 100, 253112 (2012)]

Free Propagation of X-Rays

X-rays are electromagnetic radiation

propagation is described by homogeneous Maxwell equation.

Simplification: scalar wave field (small angles, paraxial)

$$\nabla^2 \varphi - \frac{1}{c^2}\frac{\partial^2 \varphi}{\partial t^2} = 0, \quad \varphi\text{: scalar wavefield}$$

Monochromatic radiation: Helmholtz equation

$$\nabla^2 \psi_\omega(\vec{r}) - k^2 \psi_\omega(\vec{r}) = 0, \quad \varphi(\vec{r}, t) = \psi_\omega(\vec{r}) \cdot e^{i\omega t}, \quad k = \frac{\omega}{c}$$

Polychromatic radiation is superposition of different frequencies ω

Free Propagation of X-Rays

Helmholtz equation

$$\nabla^2 \psi_\omega(\vec{r}) - k^2 \psi_\omega(\vec{r}) = 0, \quad \varphi(\vec{r}, t) = \psi_\omega(\vec{r}) \cdot e^{i\omega t}, \quad k = \frac{\omega}{c}$$

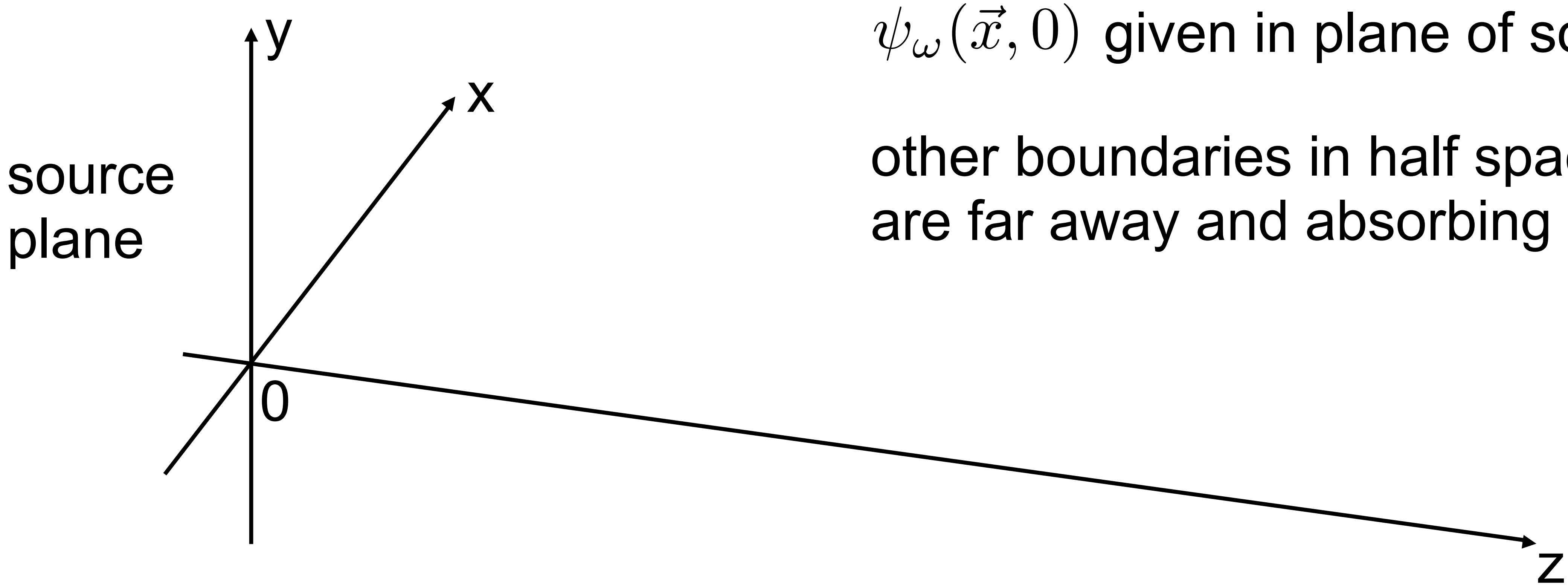
can be solved with appropriate boundary conditions using Green's theorem (Born & Wolf, pp. 417-425).

Boundary conditions:

New nomenclature: $\vec{r} = (\vec{x}, z)$

$\psi_\omega(\vec{x}, 0)$ given in plane of source

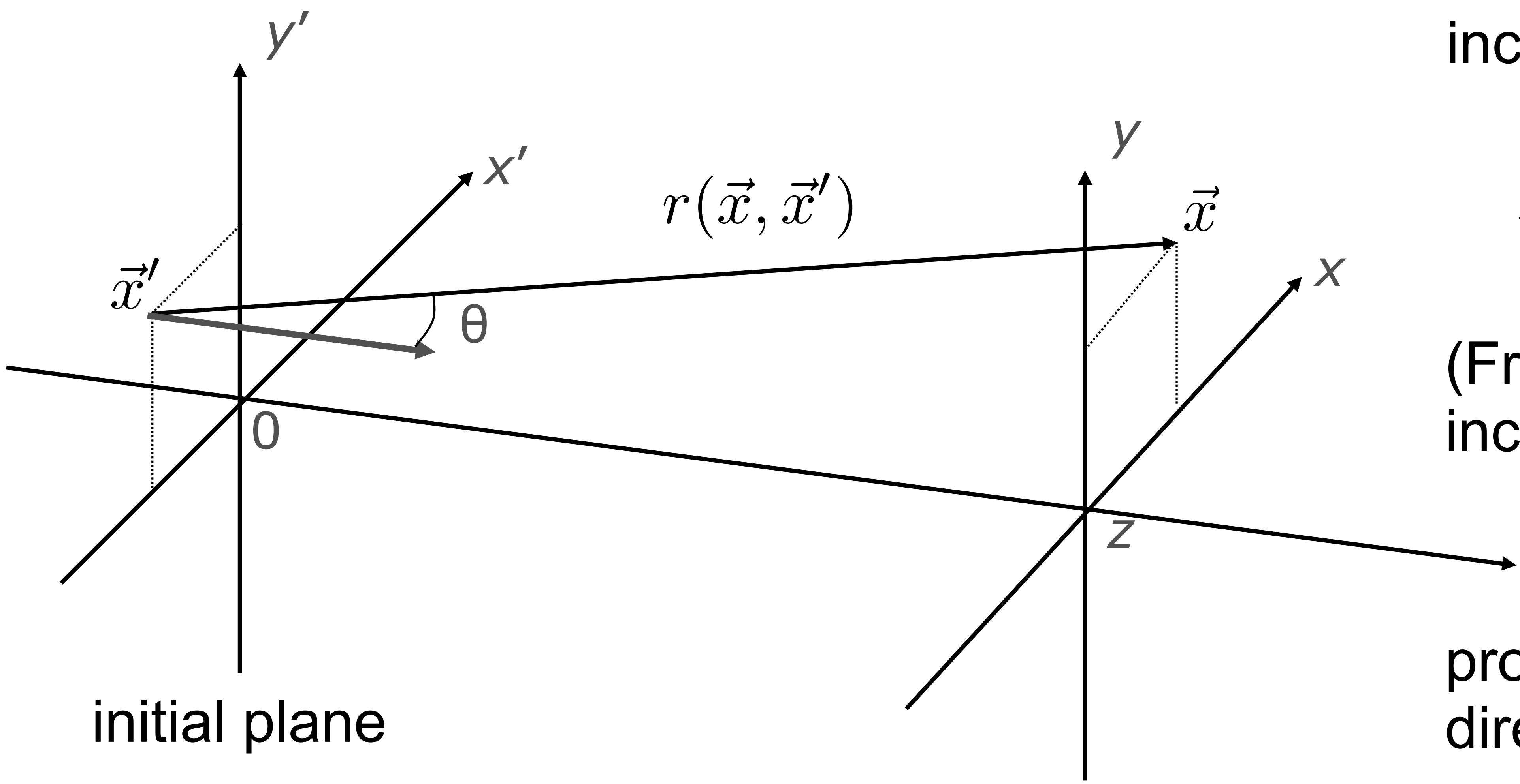
other boundaries in half space *z* > 0 are far away and absorbing



Free Propagation of X-Rays

Particular solution is the Fresnel-Kirchhoff integral:
(Propagation mainly along the *z* direction)

$$\psi_z(\vec{x},\omega) = \int \psi_0(\vec{x}',\omega) \cdot \frac{e^{ikr(\vec{x},\vec{x}')}}{r(\vec{x},\vec{x}')} \cdot \Lambda(\vec{x},\vec{x}')dx'dy'$$



inclination factor:

$$\Lambda(\vec{x},\vec{x}') = \frac{-i\cos\theta}{2\lambda}$$

(Fresnel integral, inclined incidence)

propagation direction

Modeling Objects

X-rays interact with electrons in sample.
Sample can be described by complex index of refraction:

$$n(x, y, z) = 1 - \delta(x, y, z) + i\beta(x, y, z)$$

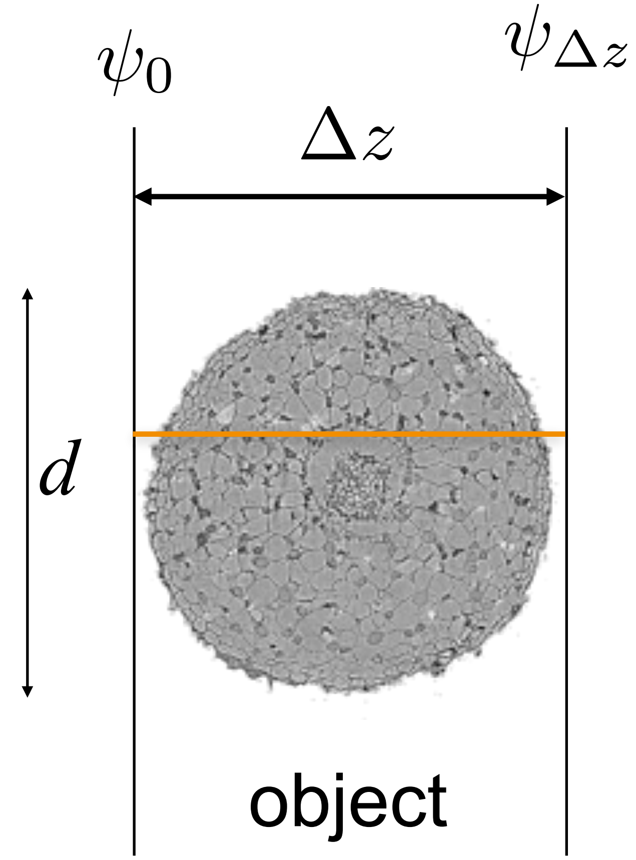
Thin sample:

No multiple scattering
(1. Born approximation)

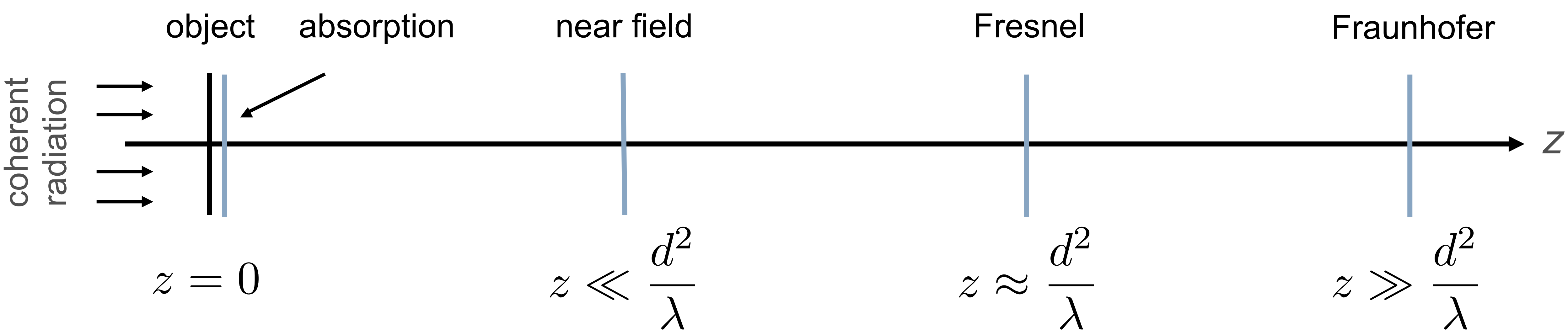
$$\psi_{\Delta z}(\vec{x}, \omega) = O_{\Delta z}(\vec{x}) \cdot \psi_0(\vec{x}, \omega)$$

With the transmission function

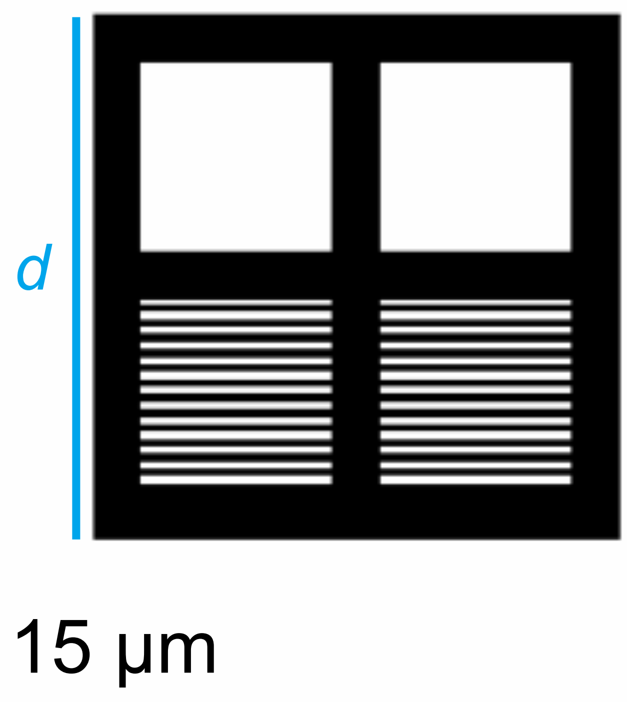
$$O_{\Delta z}(\vec{x}) = e^{ik \int n \, dz} = e^{ik\Delta z} \cdot e^{-ik \int \delta \, dz} \cdot e^{-k \int \beta \, dz}$$



Coherent Imaging



object: Cu

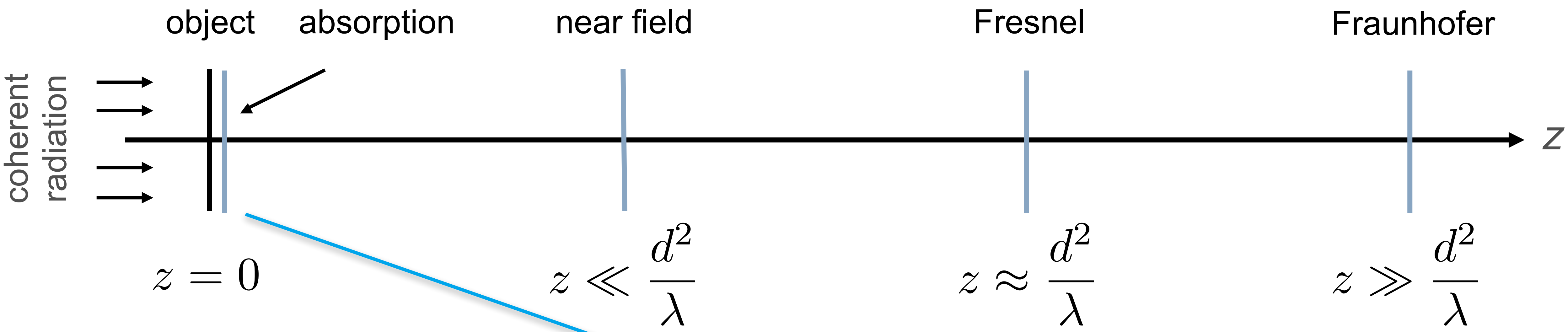


thickness:
- frame: 2 µm
- thin stripes: 0.5 µm

energy: 20 keV

characteristic distance: $d^2/\lambda = (30\ \mu\mathrm{m})^2/0.62\ \text{Å} = 14.5\ \mathrm{m}$

Coherent Imaging



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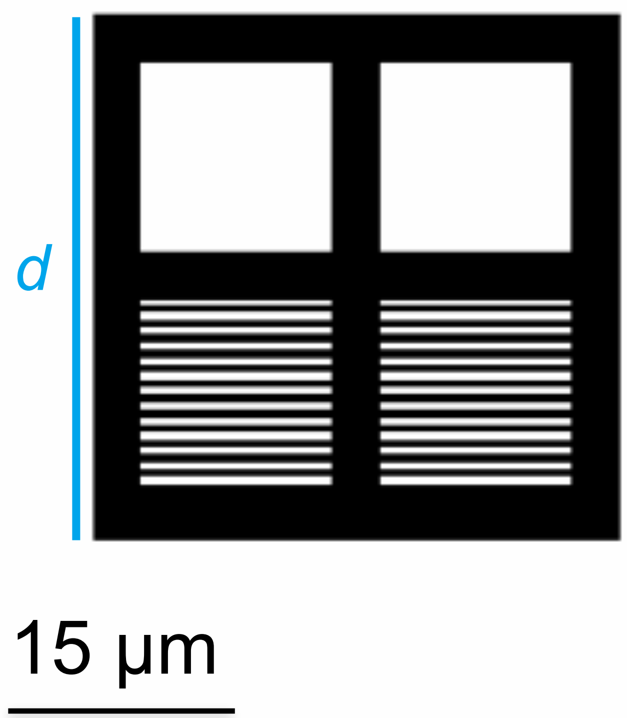

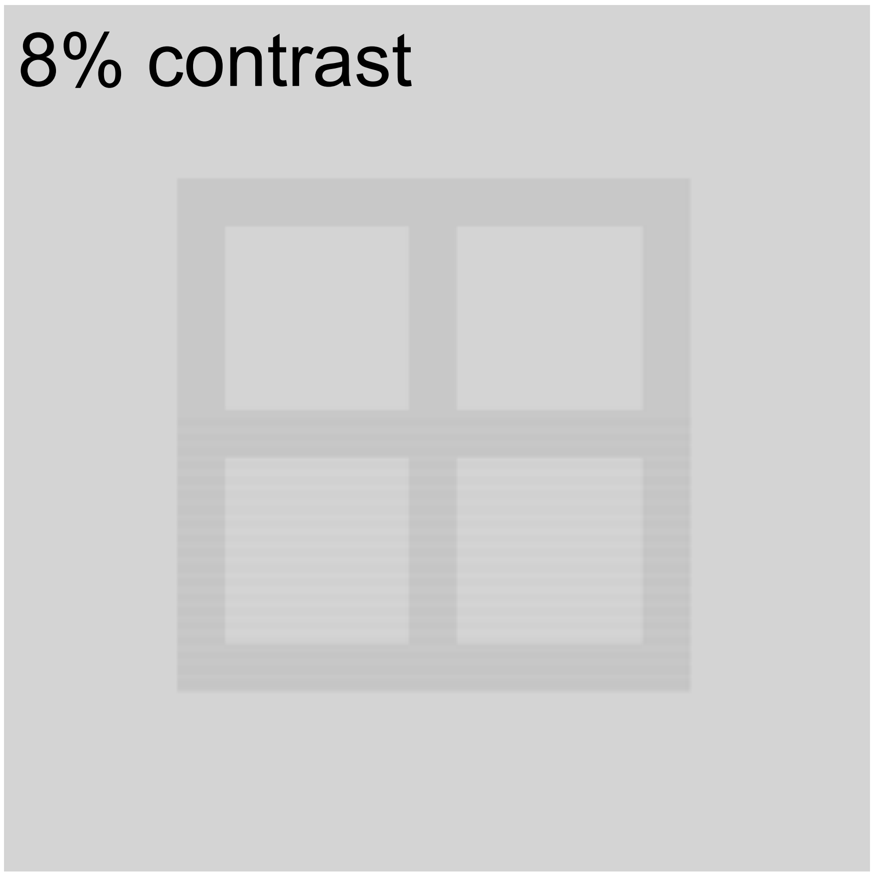

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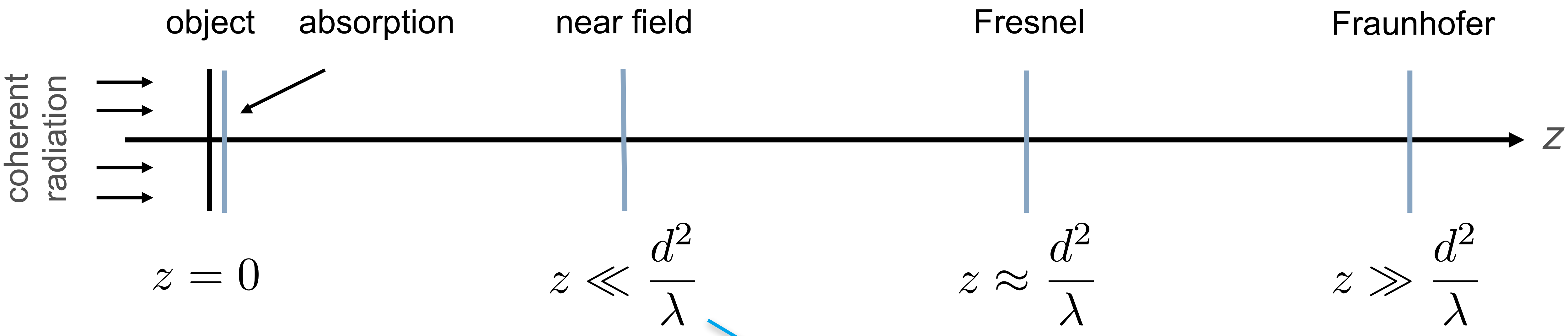
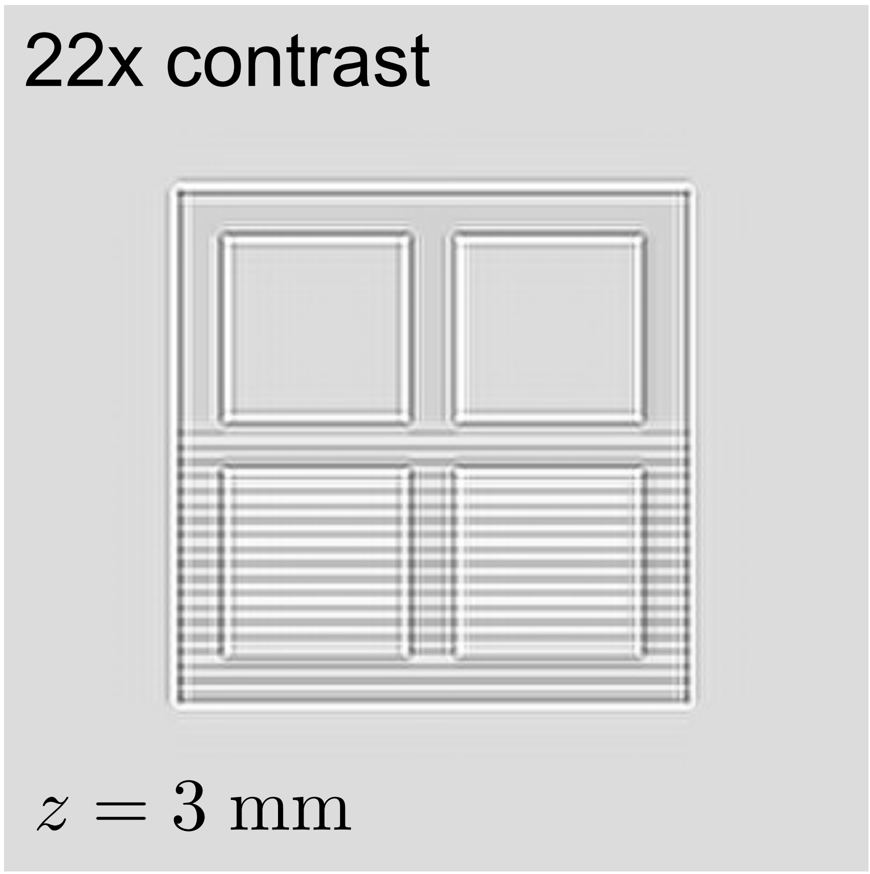


object: Cu

15 µm



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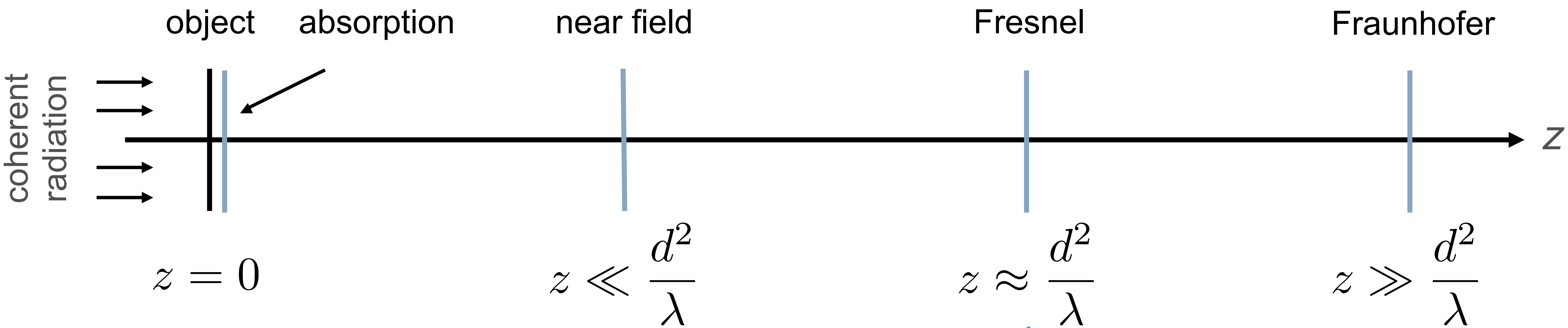
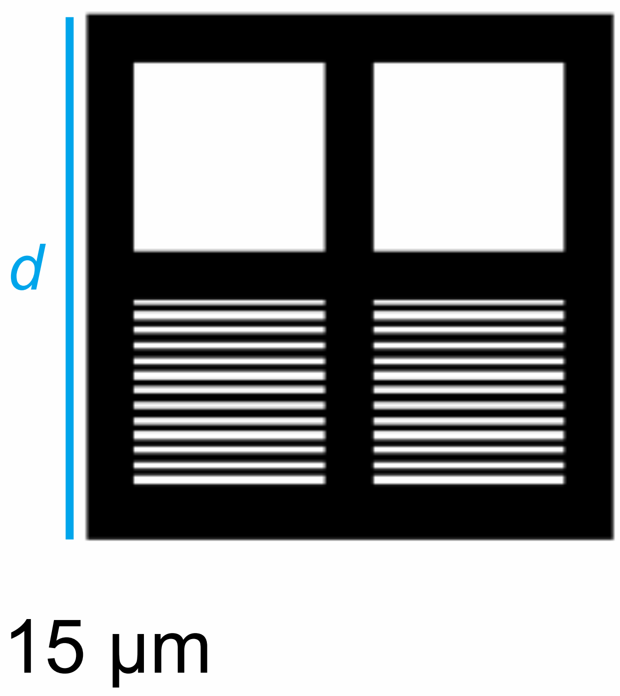
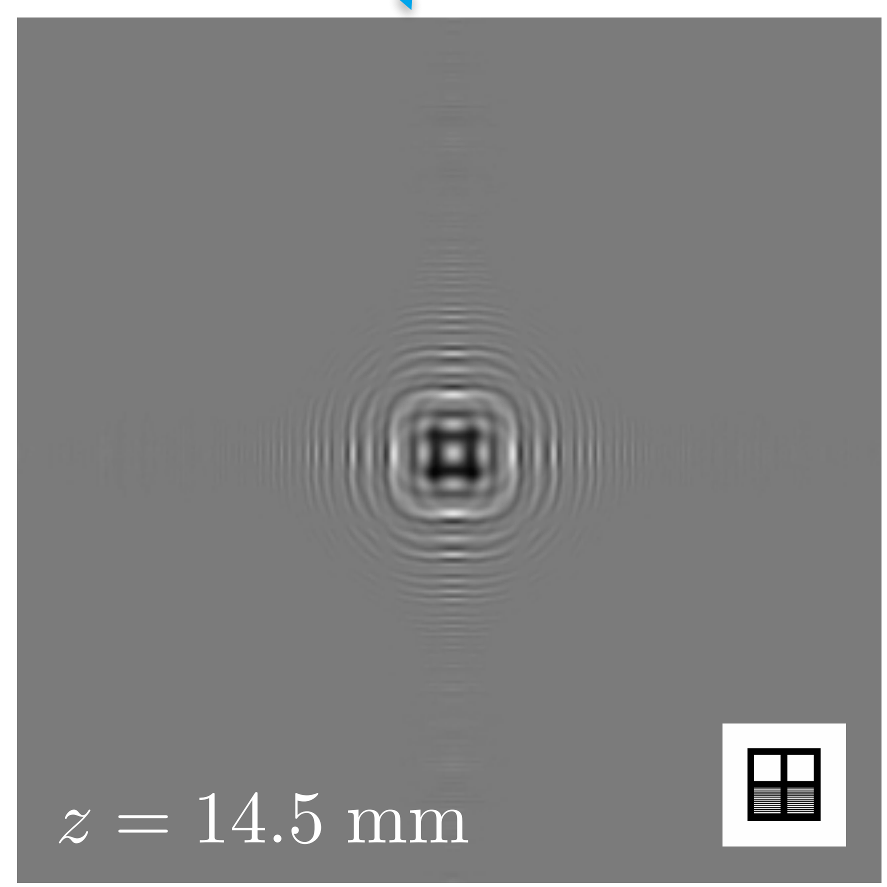
Coherent Imaging



object: Cu





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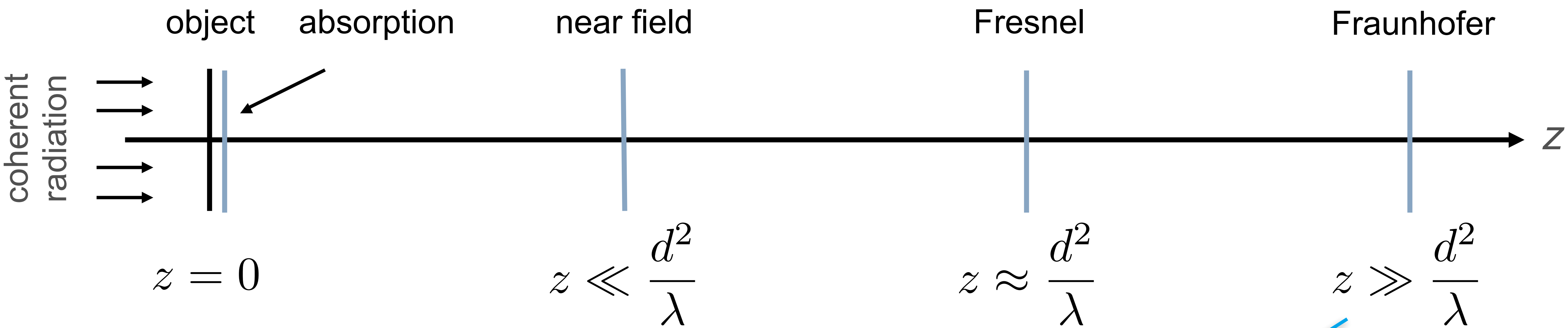
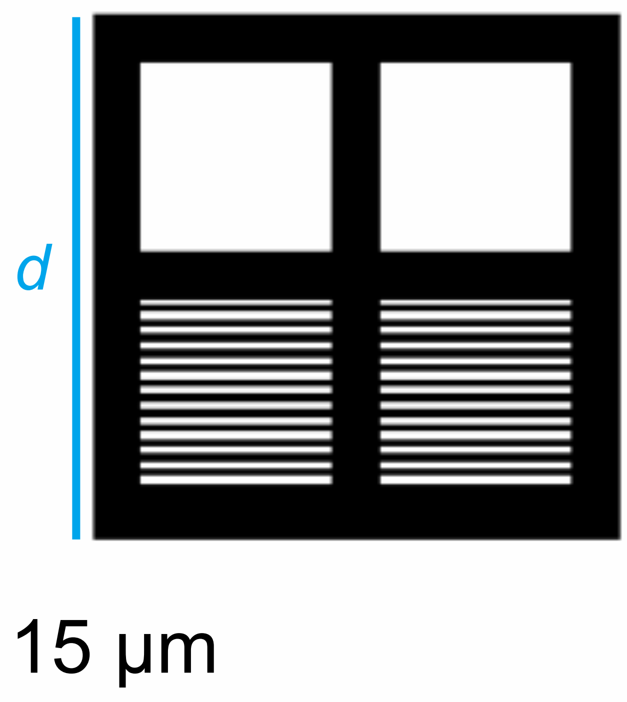
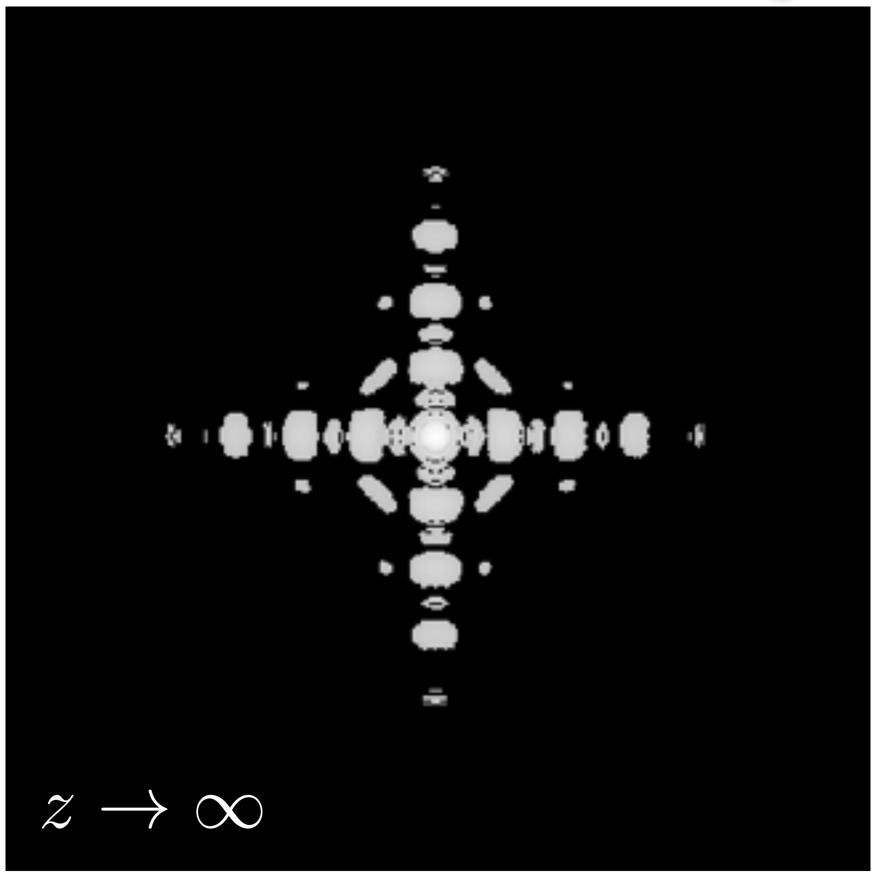
Coherent Imaging



object: Cu





characteristic distance: $d^2/\lambda = (30\ \mu\mathrm{m})^2/0.62\ \text{Å} = 14.5\ \mathrm{m}$

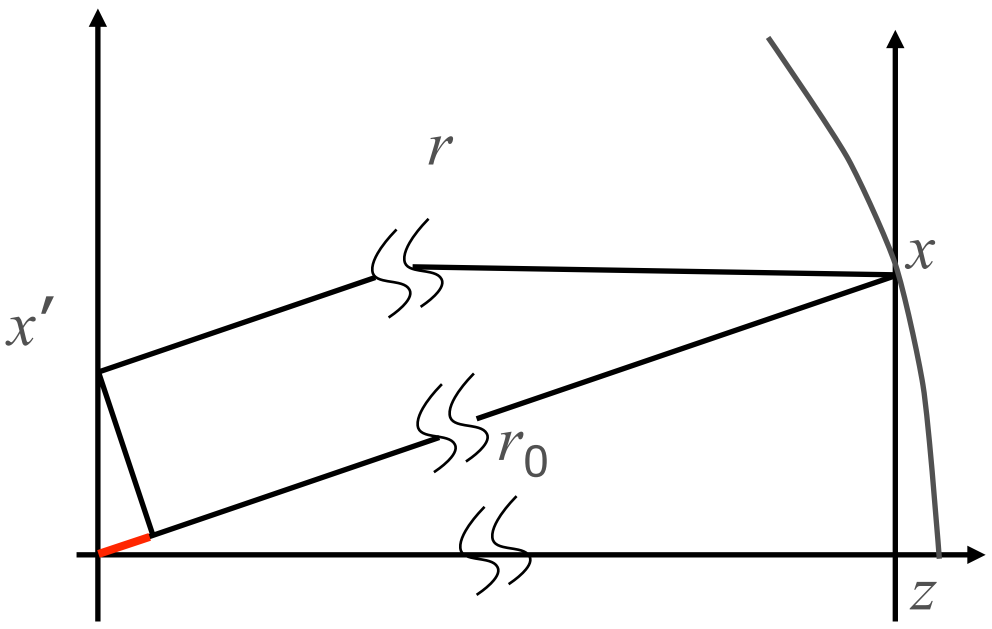
Fraunhofer Diffraction: Far Field

Extreme far field:

$$r = r_0 - \frac{x}{r_0}x' - \frac{y}{r_0}y'$$

with

$$r_0 = \sqrt{z^2 + x^2 + y^2}$$



$$\psi_z(\vec{x},\omega) = -\frac{ie^{ikr_0}}{2\lambda r_0}\int \psi_0(\vec{x}',\omega)\cdot\exp\left\{-ik\frac{xx'+yy'}{r_0}\right\}dx'dy'$$

$$= -\frac{ie^{ikr_0}}{2\lambda r_0}\int \psi_0(\vec{x}',\omega)\cdot\exp\left\{-i\vec{\xi}\vec{x}'\right\}dx'dy', \quad \vec{\xi} = \frac{k}{r_0}\begin{pmatrix} x \\ y \end{pmatrix}$$

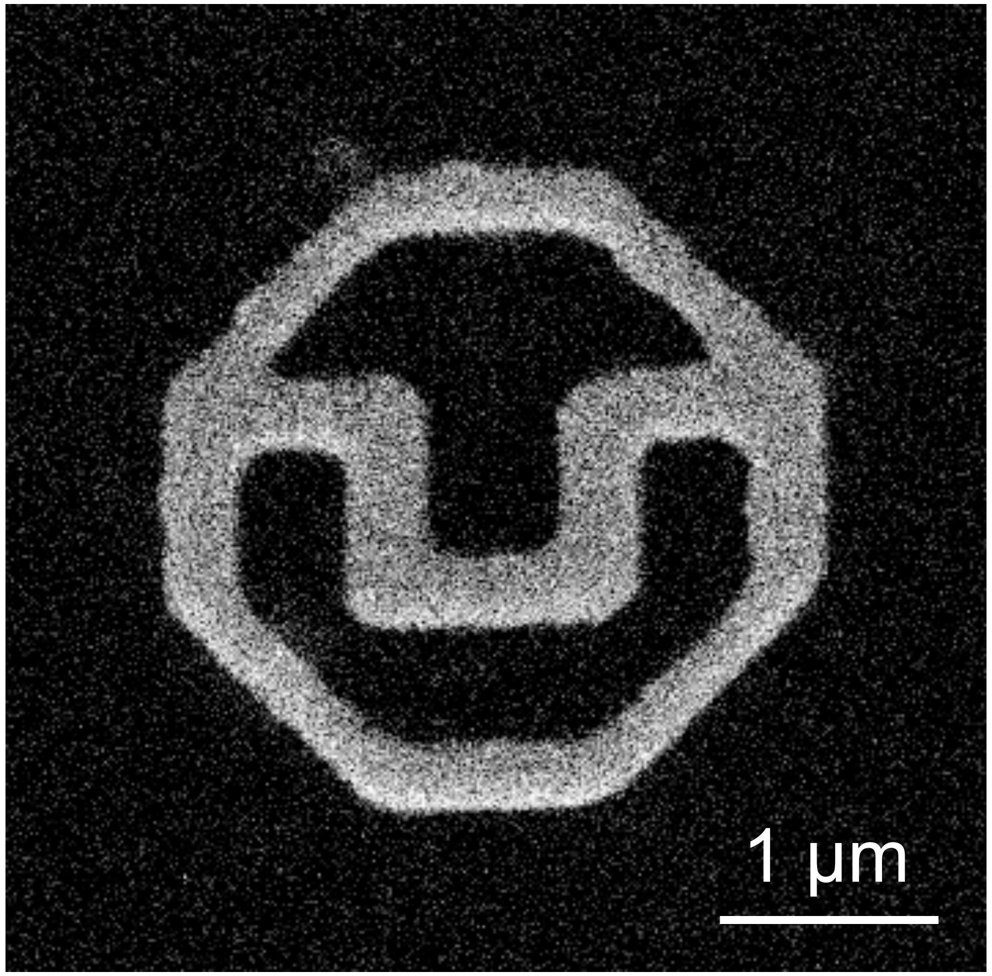
cos in inclination vanishes due to projection on sphere!

Far field is Fourier transform of wave field in initial plane!

Fraunhofer Diffraction: Far Field

Example: (E = 8 keV)

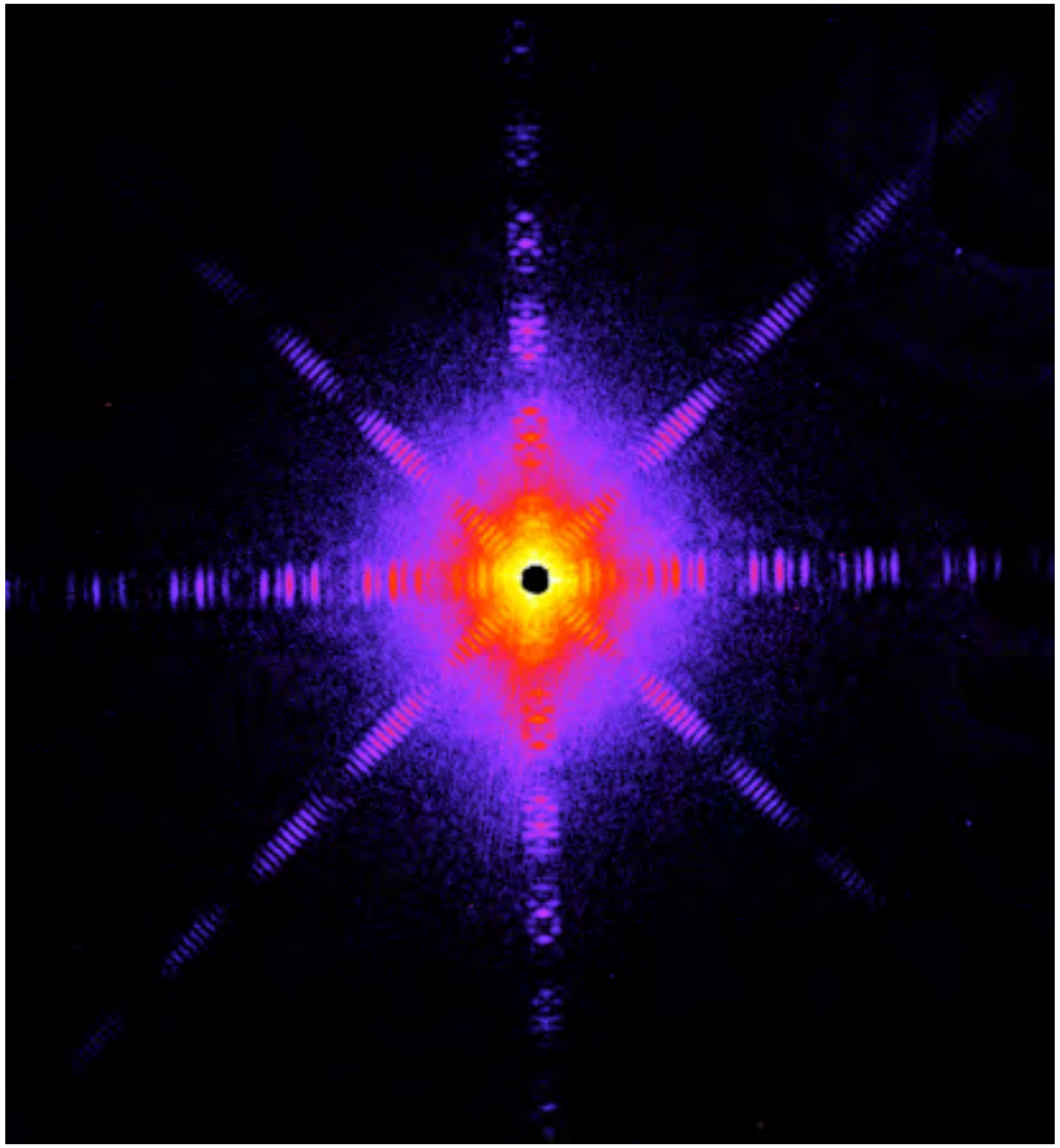
Au (150 nm) on Si_3N_4:



$$\frac{(3\ \mu\mathrm{m})^2}{1.55\ \mathrm{\AA}} = 58\ \mathrm{mm} = z$$

far-field

image



L_2 = 3.1 m

Coherence

So far, we considered the propagation of pure states only!

The ideal experiment:

- prepare probe (x-ray beam) in well defined initial state:

  $\psi_\omega(\vec{x}, 0)$ unimodal source

- propagate through **fixed** experimental setup

$$\psi_\omega(\vec{x}, \mathrm{det}) = \int P(\vec{x}, \vec{x}'')\psi_\omega(\vec{x}'', 0)\; d^2x''$$

  Also sample static and in well-defined state!

- detection:

  probability to detect photon ~ $|\psi_\omega(\vec{x}, \mathrm{det})|^2$

  Repeat experiment many times under identical conditions!!

Coherence

Main problem:

We have no full control over the experiment:

- initial state not fully determined: ensemble of initial states that are realized statistically:

$\psi_{\omega_i}(\vec{x}, 0)$ from statistical ensemble with density ρ_i

- experimental setup varies in time

$$\psi_{\omega_{(i,j)}}(\vec{x}, \text{det}) = \int P(\vec{x}, \vec{x}'', t_j)\psi_{\omega_i}(\vec{x}'', 0)\; d^2x''$$

dynamics of sample and setup described by *j*.

time dependence of sample (dynamics)!

- detection:

$$I_{\text{det}}(\vec{x}) = \sum_{i,j} \rho_{(i,j)} \cdot |\psi_{\omega_{(i,j)}}(\vec{x}, \text{det})|^2$$

ensemble average under assumption of ergodicity!

Coherence

Main problem:

What information can be extract from

$$I_{\mathrm{det}}(\vec{x}) = \sum_{i,j} \rho_{(i,j)} \cdot |\psi_{\omega_{(i,j)}}(\vec{x}, \mathrm{det})|^2$$

about the experiment! Can we deduce

$$\psi_{\omega_{(i,j)}}(\vec{x}, \mathrm{det}) \quad \text{and} \quad \rho_{(i,j)} \ ?$$

If the states $\psi_{\omega_{(i,j)}}(\vec{x}, \mathrm{det})$ are very different, e. g., when the initial state is badly prepared, this becomes more and more difficult!

$\longrightarrow$ Intensity washes out

coherence:

visibility of interference: how much does $I_{\mathrm{det}}(\vec{x})$ resemble the probability density $|\psi_{\omega_{(i,j)}}(\vec{x}, \mathrm{det})|^2$?

Coherence

Visibility of interference:

how much does $I_{\mathrm{det}}(\vec{x})$ resemble the probability density $|\psi_{\omega_{(i,j)}}(\vec{x}, \mathrm{det})|^2$?

States $\psi_{\omega_{(i,j)}}(\vec{x}, \mathrm{det})$ must be sufficiently similar that the interference fringes are not washed out!

Influence of the source

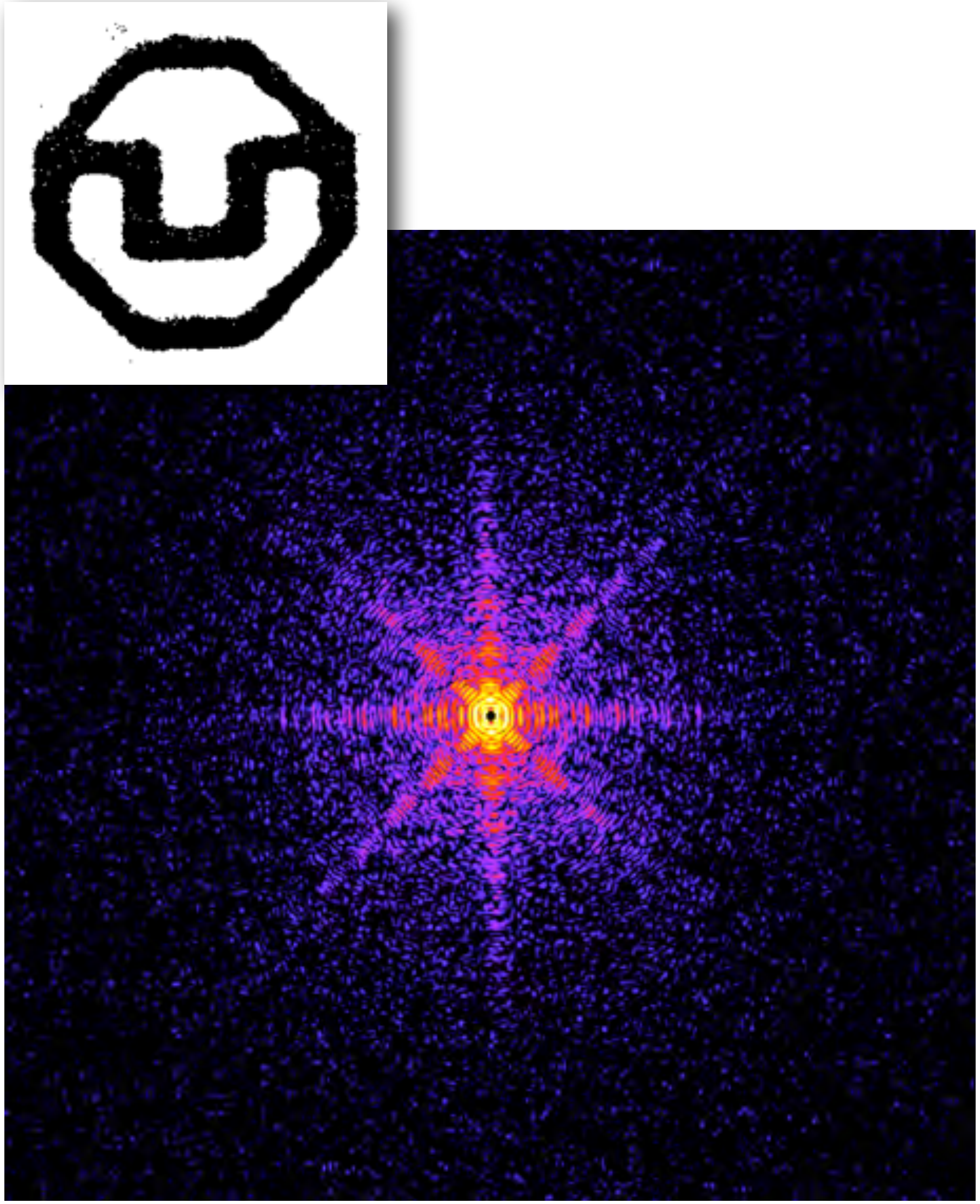
- transverse coherence

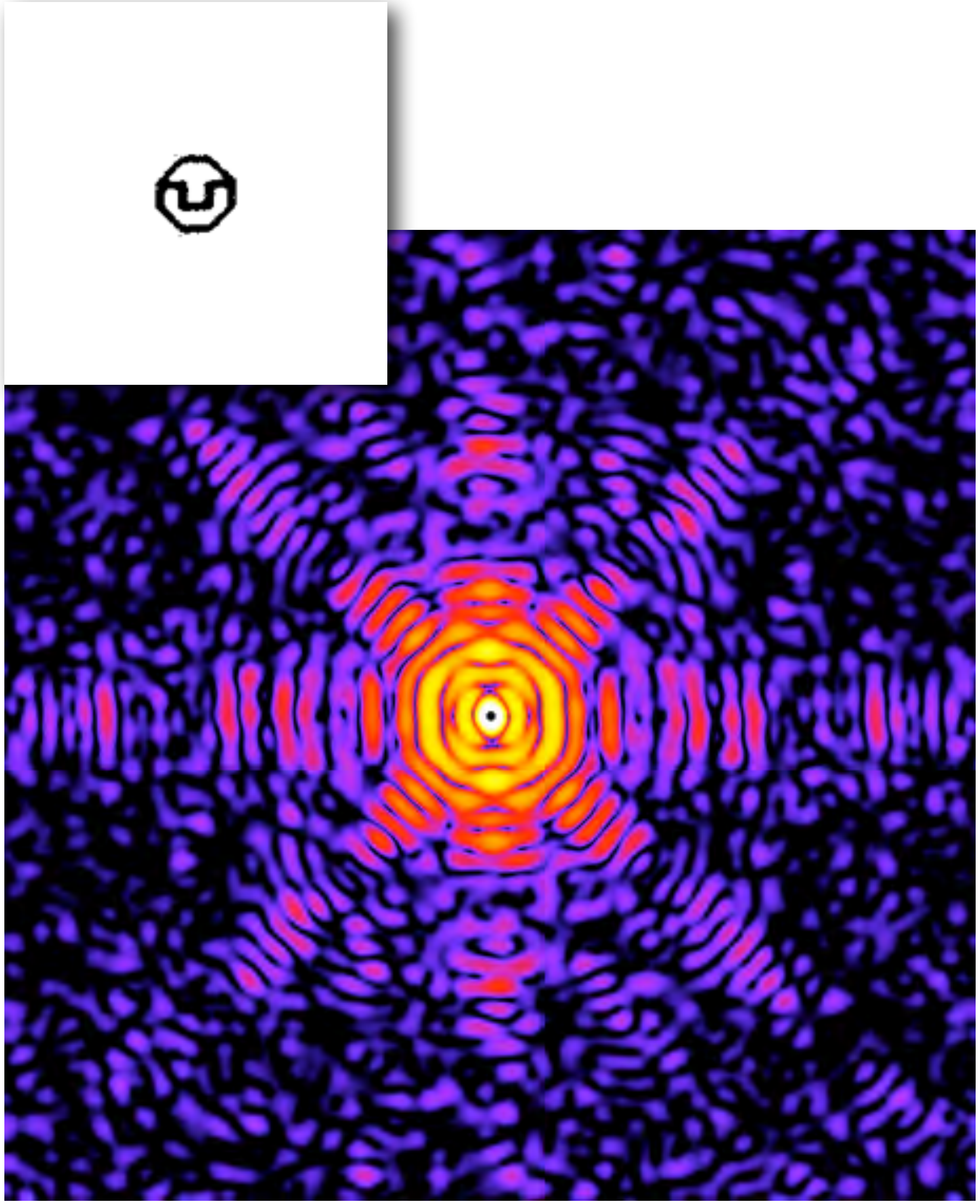
  spatial differences of $\psi_{\omega_{(i,j)}}(\vec{x}, \mathrm{det})$ as function of *i*.

- longitudinal coherence

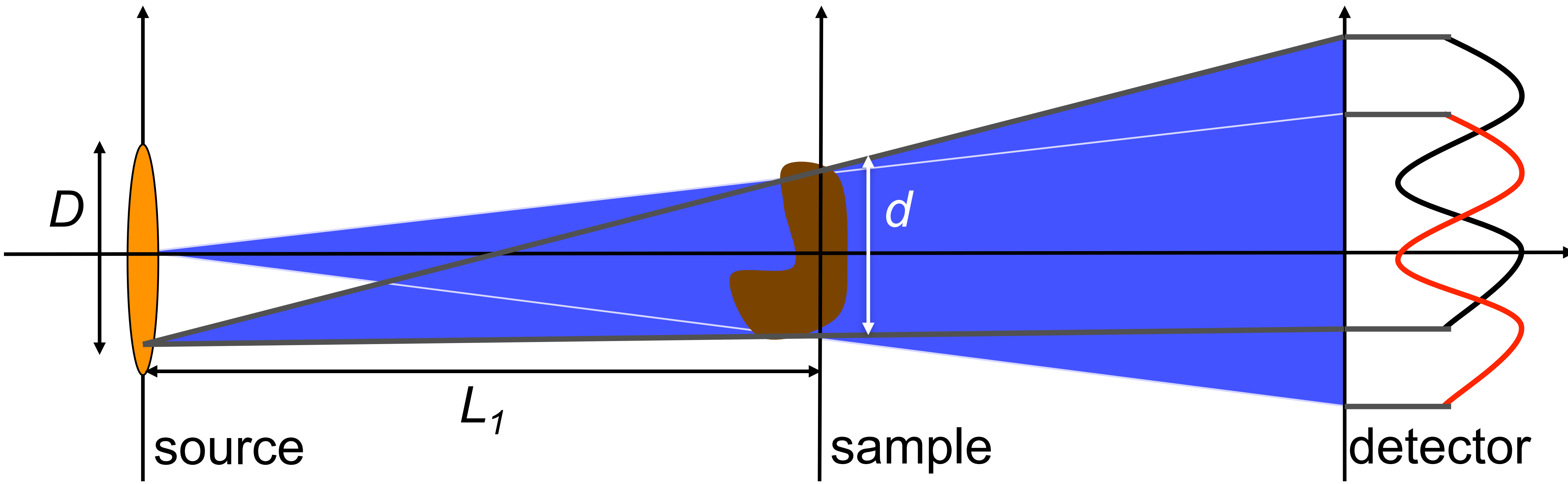
  energetic differences of $\psi_{\omega_{(i,j)}}(\vec{x}, \mathrm{det})$ as function of *i*.

Example: speckle size varies inversely with object size





Transverse Coherence



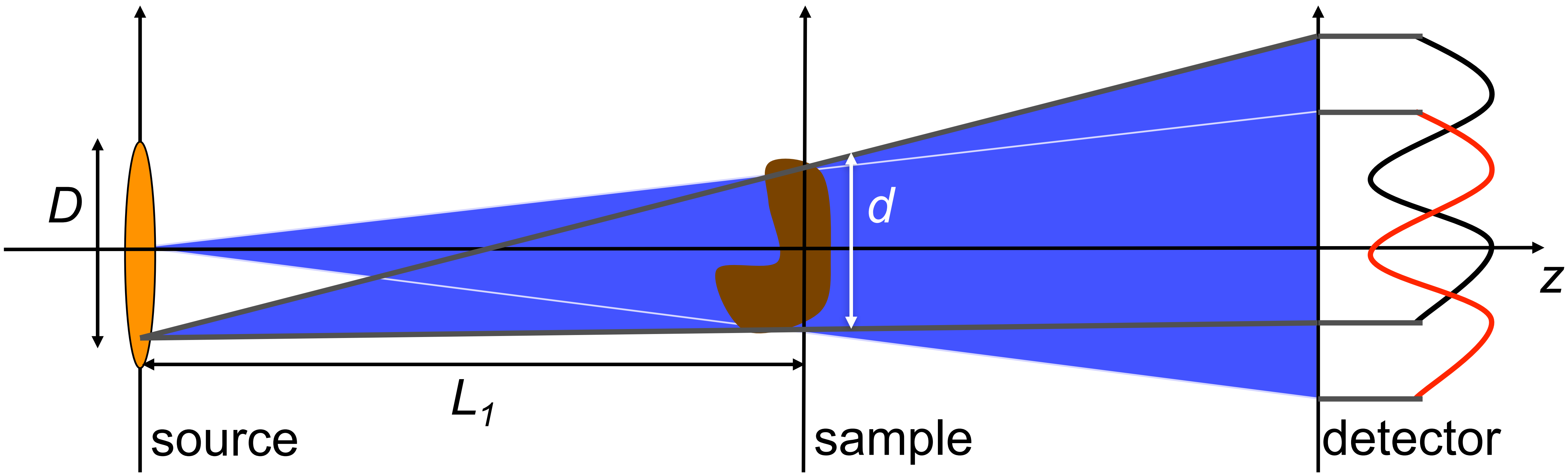
Interference observable:

$$\frac{\lambda}{d} > \frac{D}{L_1}$$

$\frac{\lambda}{d}$: angle between two speckles as seen from sample

$\frac{D}{L_1}$: angle of source as seen from sample

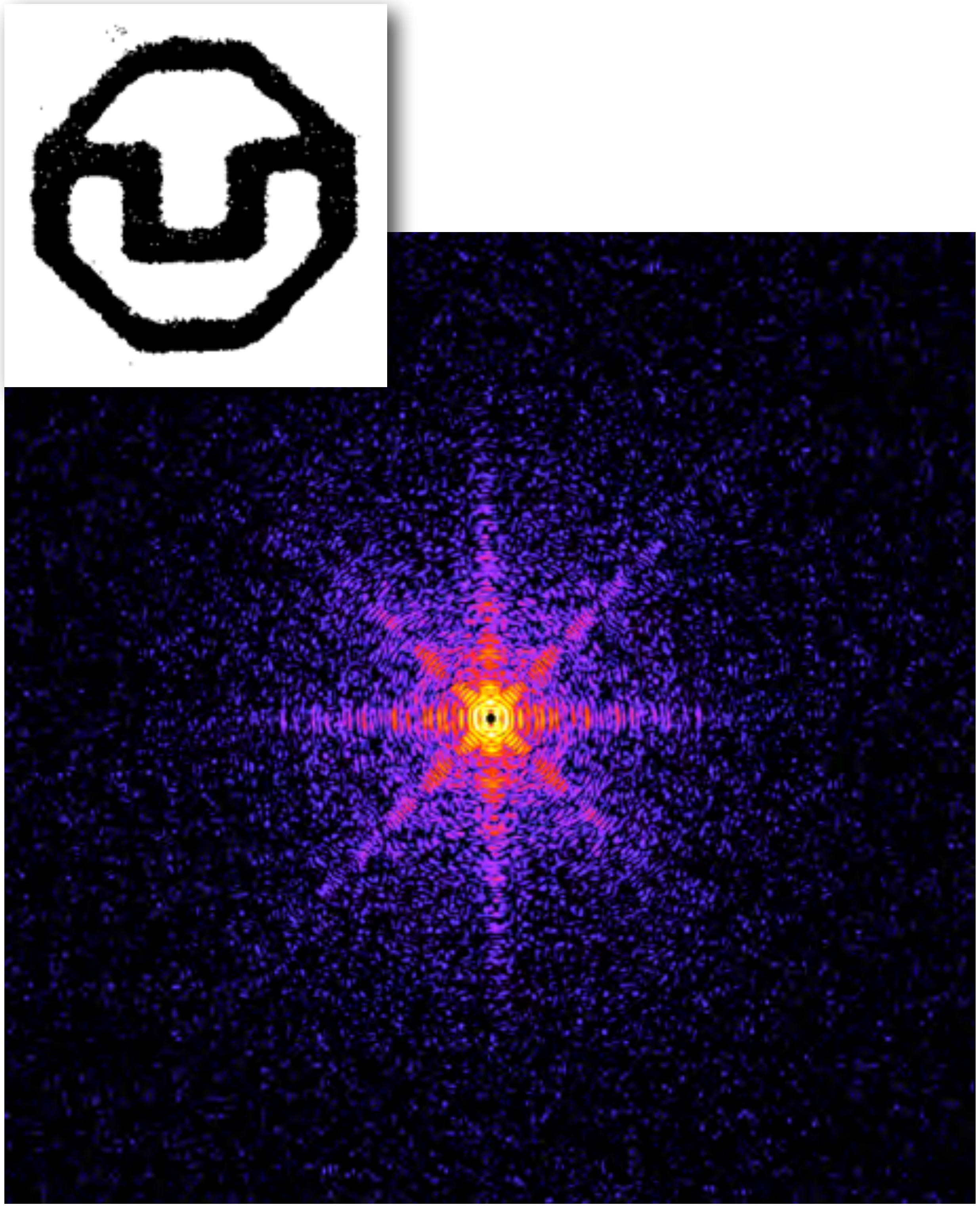
Transverse Coherence

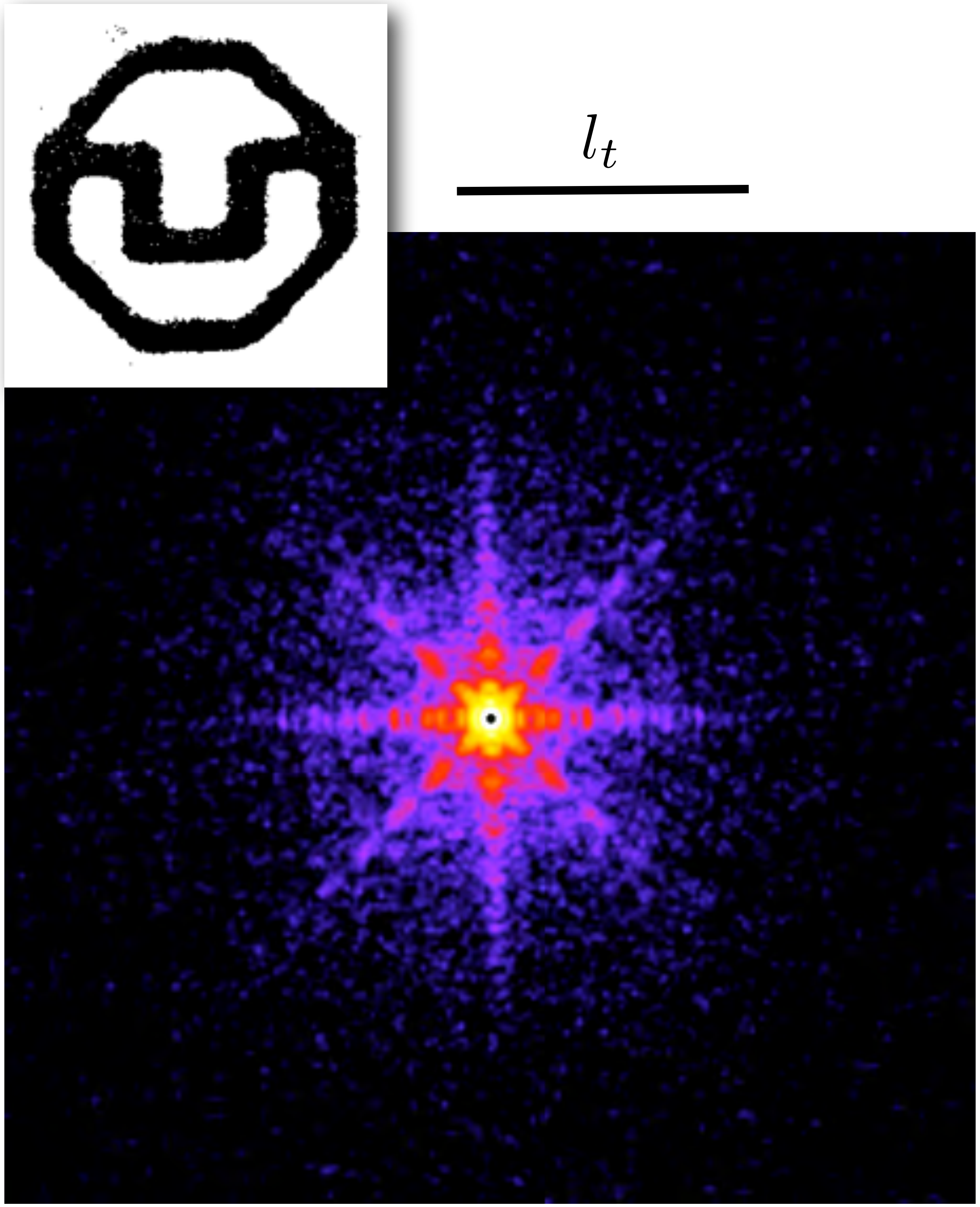


Transverse coherence length:

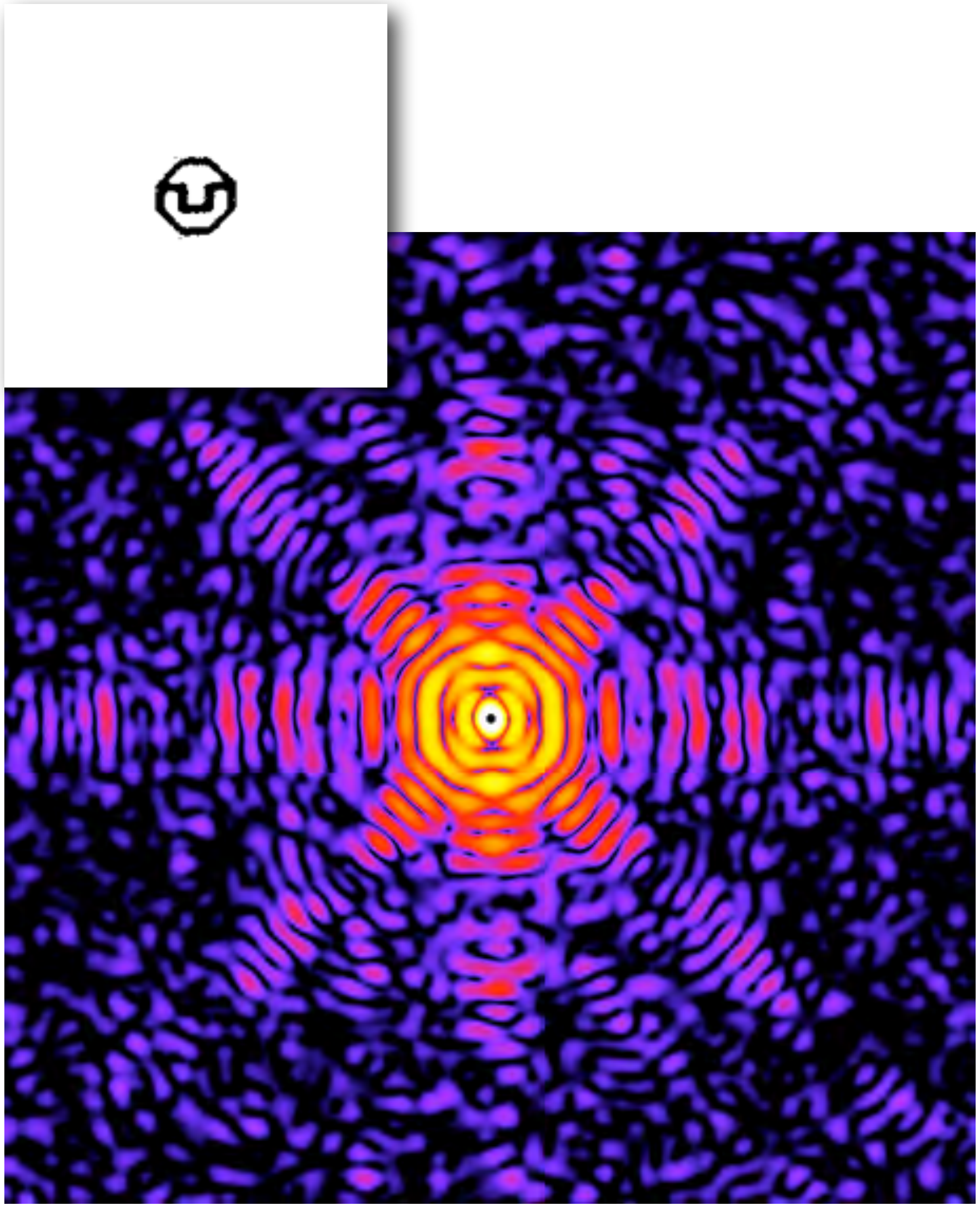
$$l_t = \frac{\lambda L_1}{D} \longrightarrow d < l_t \text{ : interference visible}$$

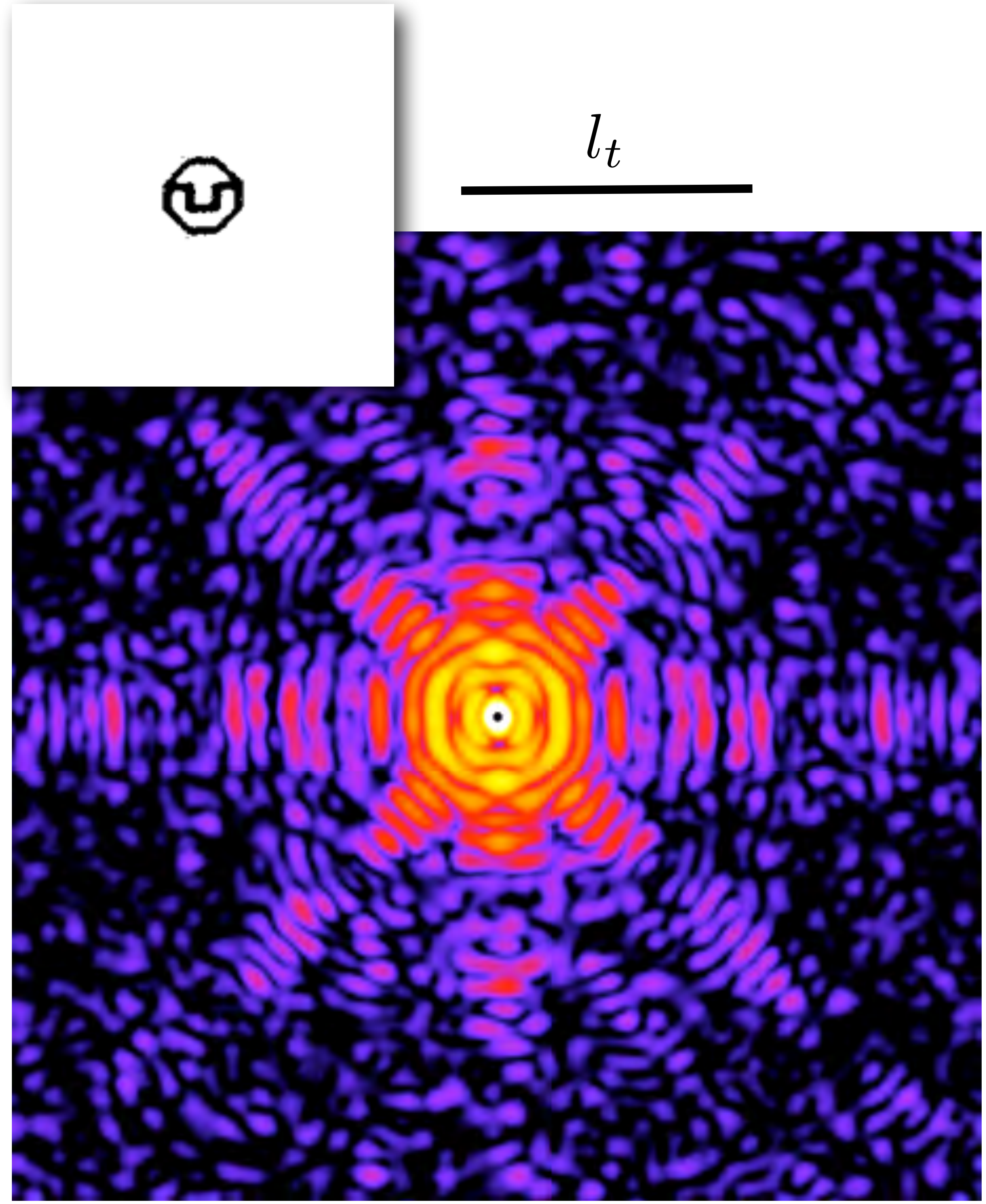
Example: Transverse Coherence Length





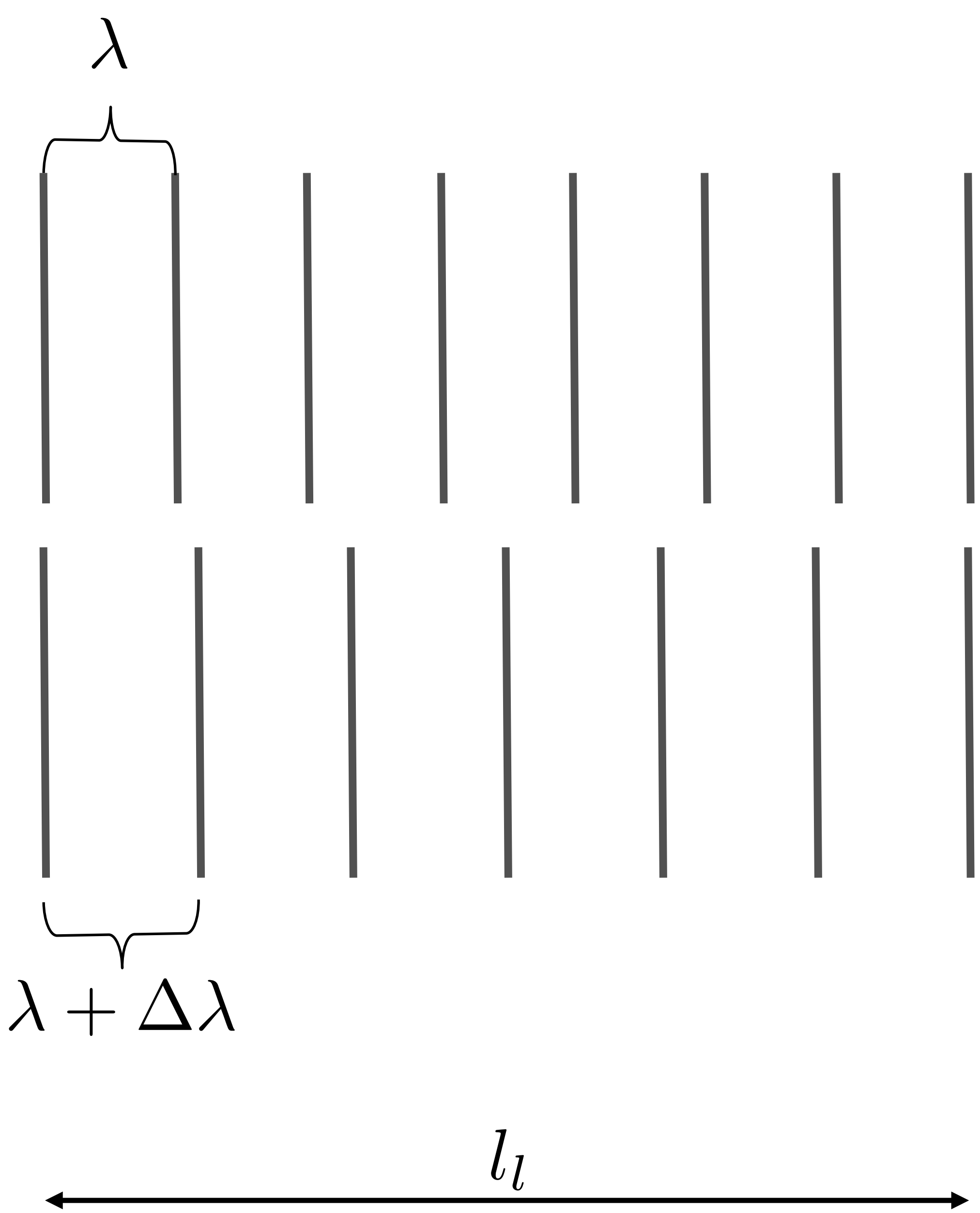
Example: Transverse Coherence Length





Longitudinal Coherence: Monochromaticity

Wave packet generated from superposition of monochromatic waves:



$$(n+1)\lambda = n(\lambda + \Delta\lambda)$$

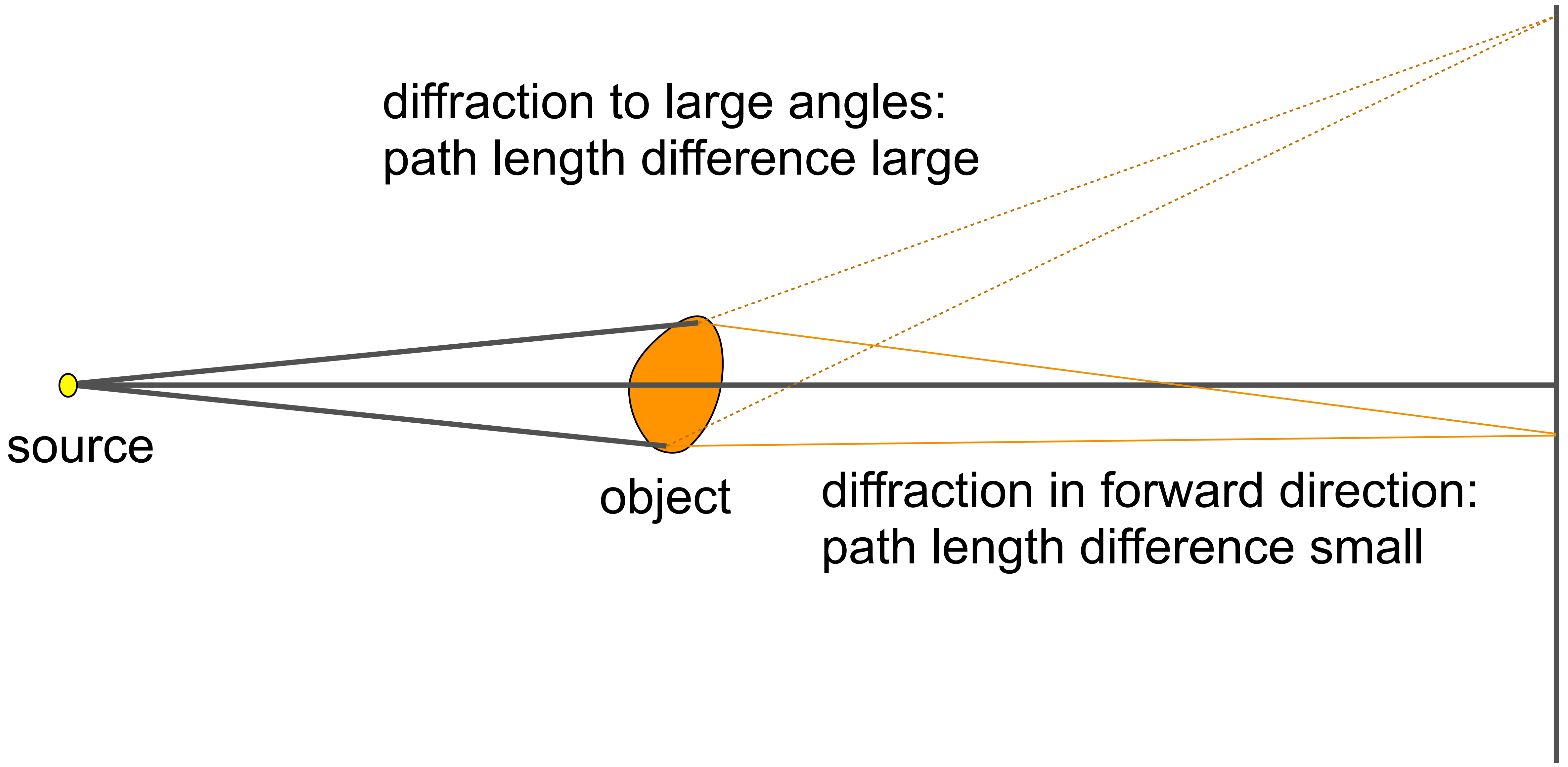
$$n = \frac{\lambda}{\Delta\lambda}$$

$$l_l = \lambda\frac{\lambda}{\Delta\lambda}, \quad n \gg 1$$

l_l characteristic length of wave packet

Longitudinal Coherence: Monochromaticity

Difference in length of different paths through sample must not exceed l_l:

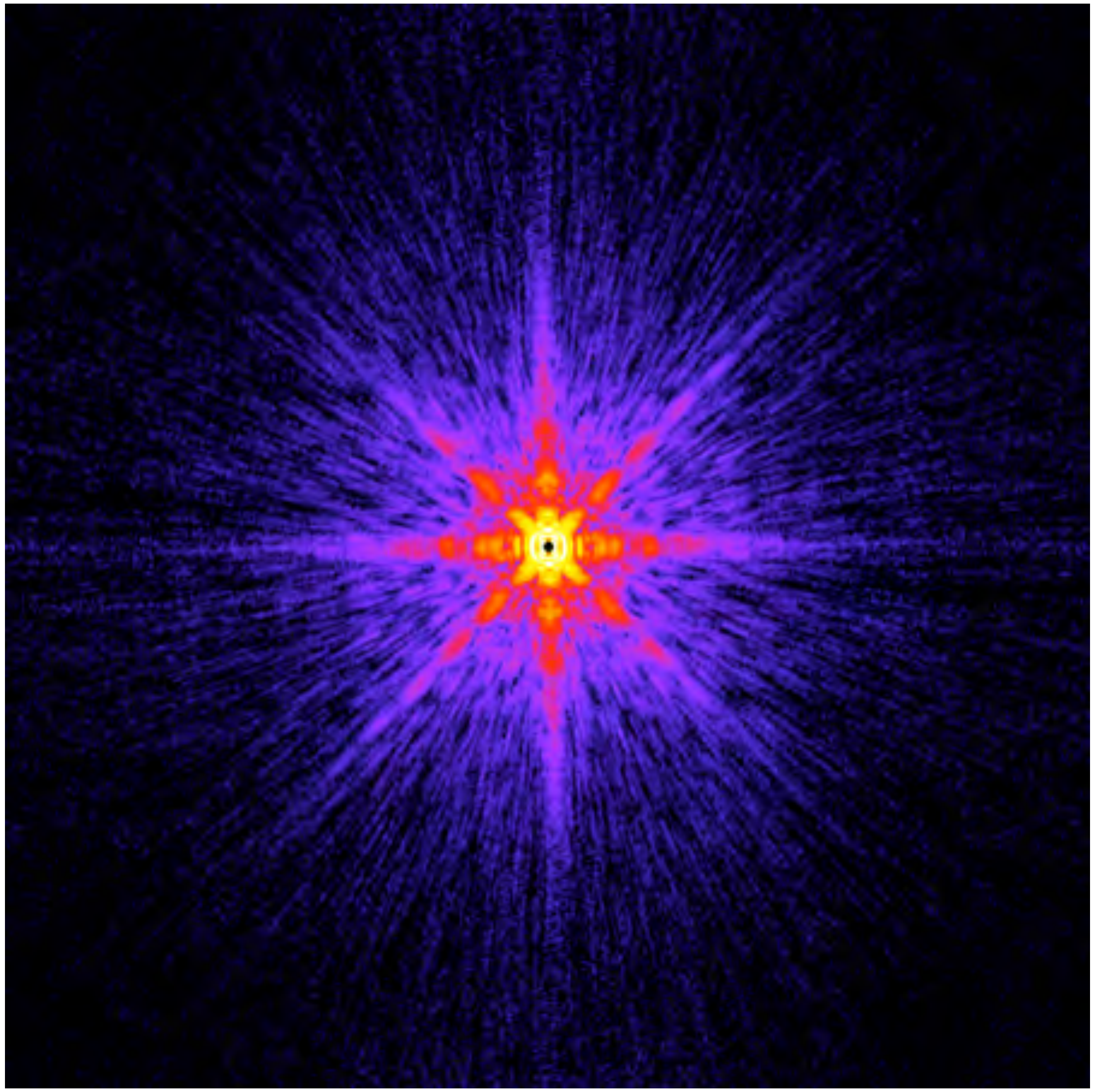


reduction of longitudinal coherence destroys visibility of interference at large momentum transfer!

Example: Longitudinal Coherence Length

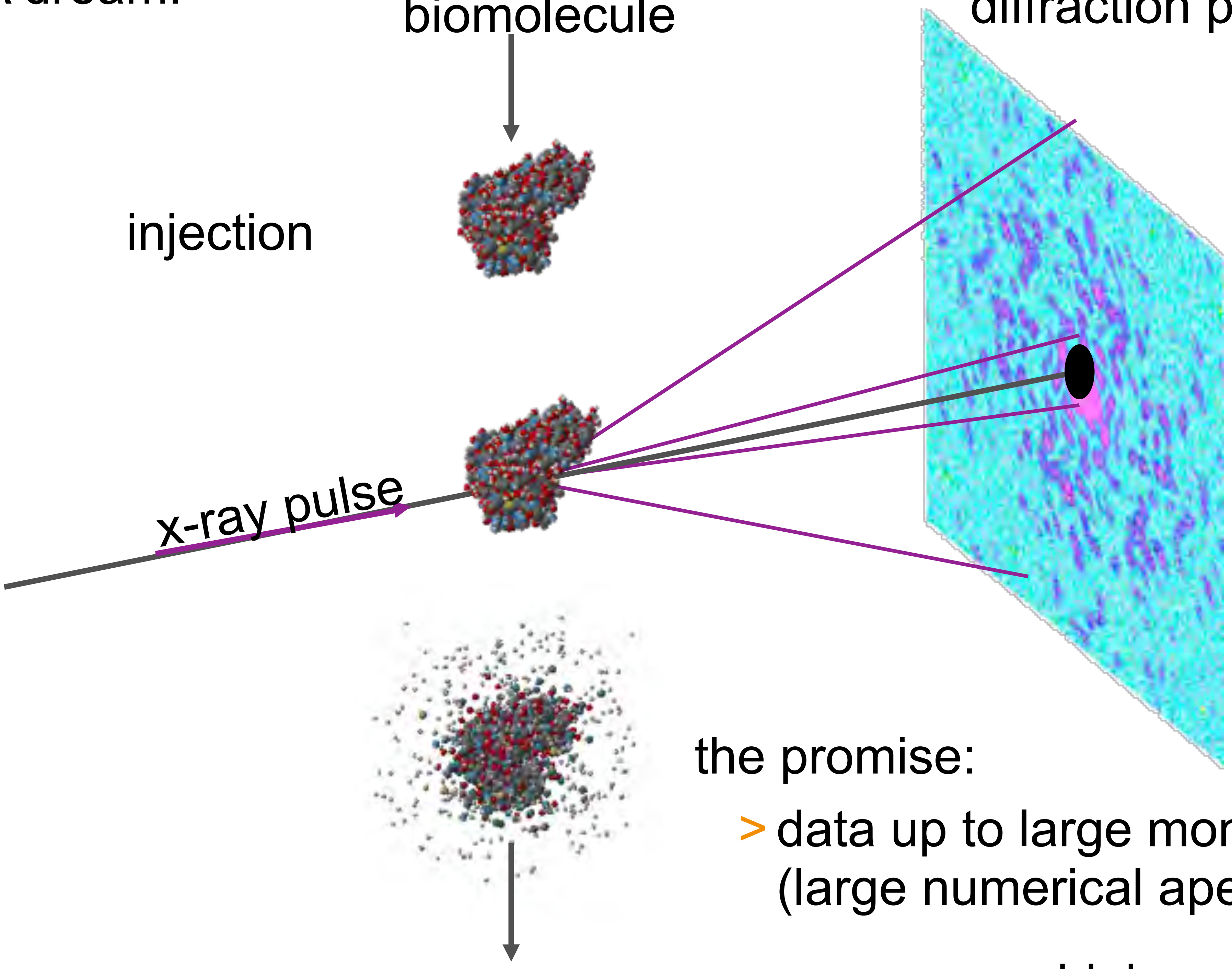
Diffraction grating in lights of the bus to Kyoto

$$\frac{\Delta\lambda}{\lambda} = 0.12$$



Lensless Imaging: Coherent Diffraction Imaging

A dream:

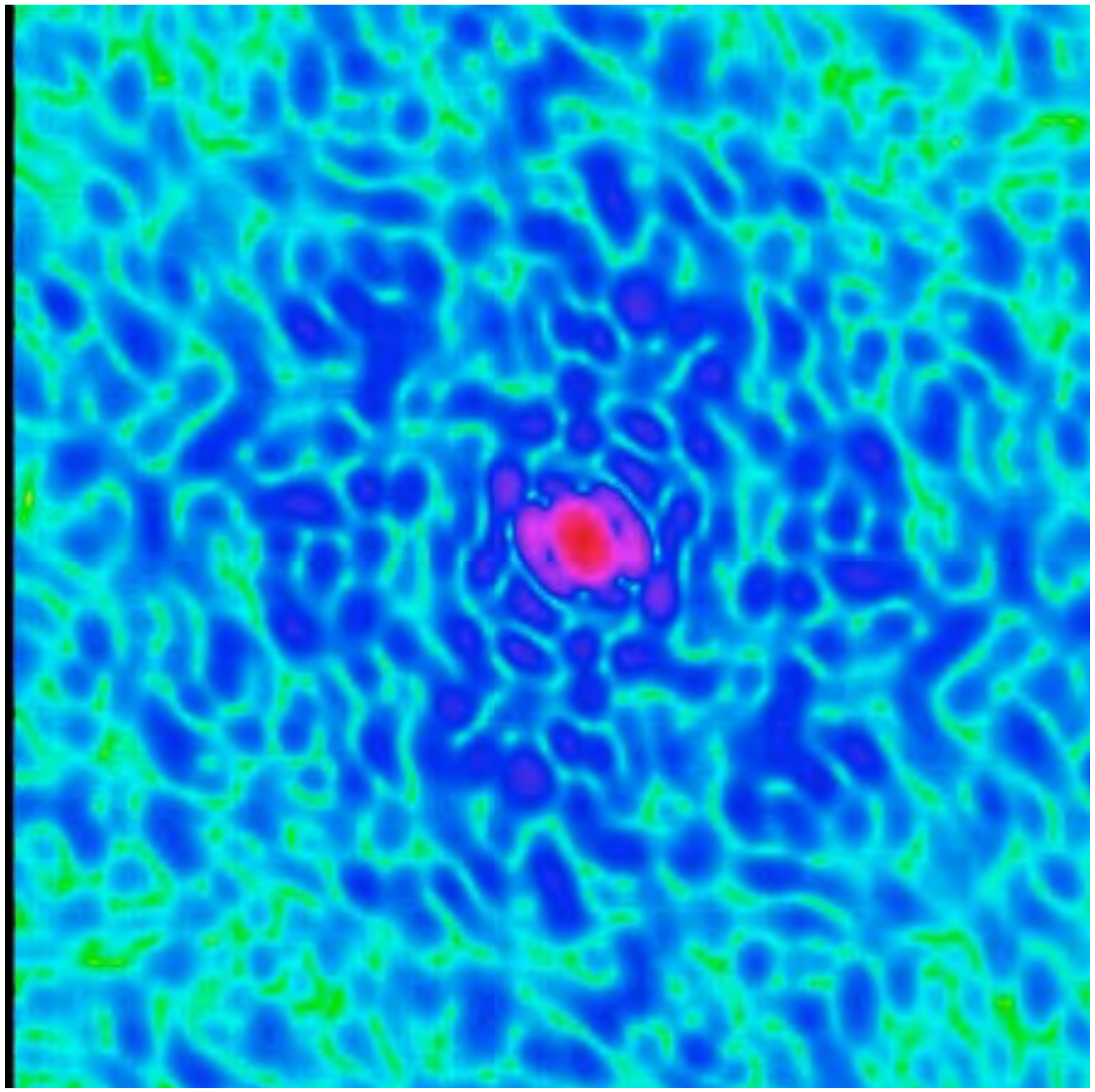


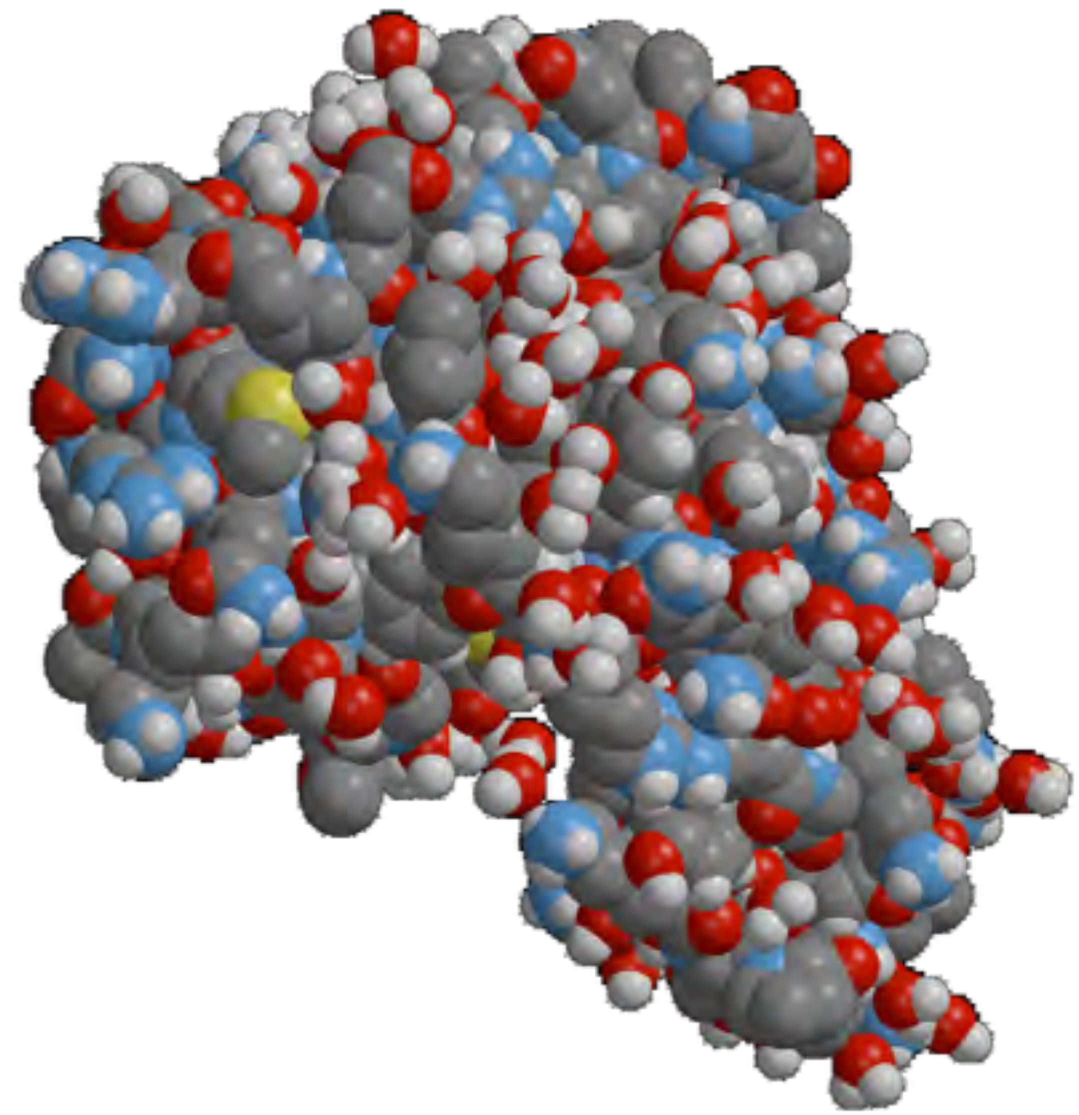
the promise:

> data up to large momentum transfer q (large numerical aperture NA)

→ high resolution

Reconstruction by Phase Retrieval



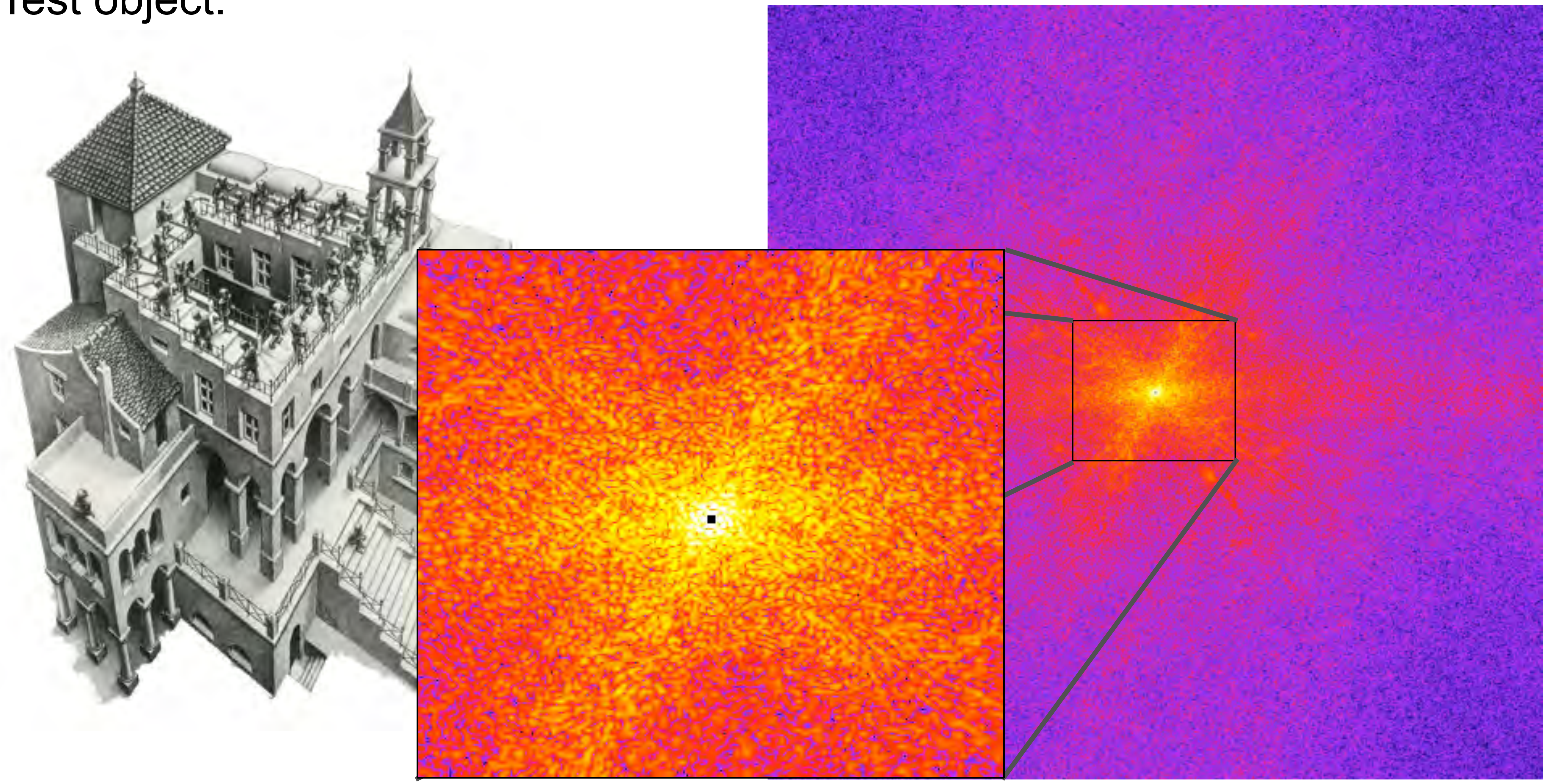


Difficulty: no direct image

Diffraction pattern: intensity (phase of wave field lost)

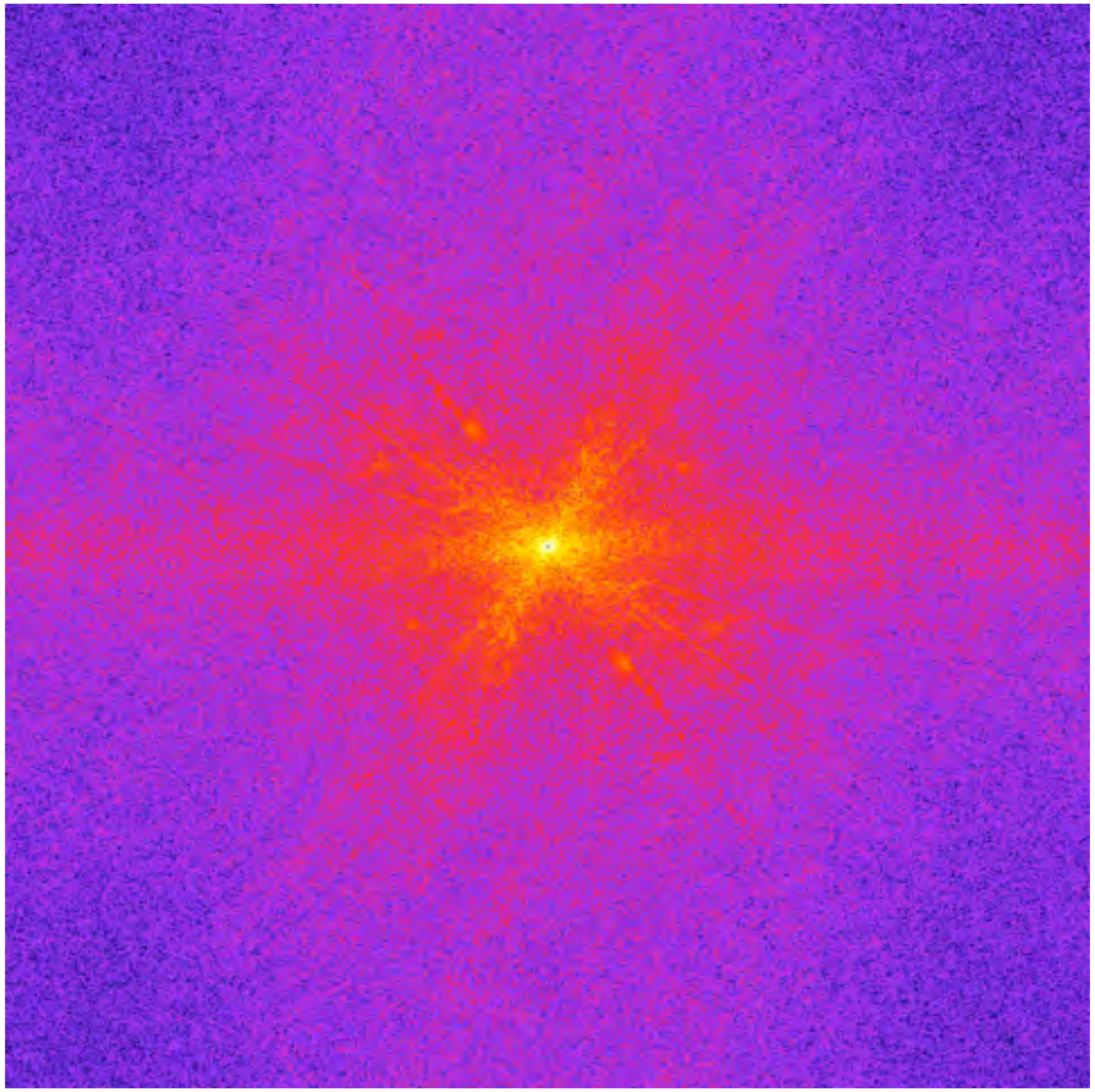
What Information is Coded in Phase and Modulus?

Test object:

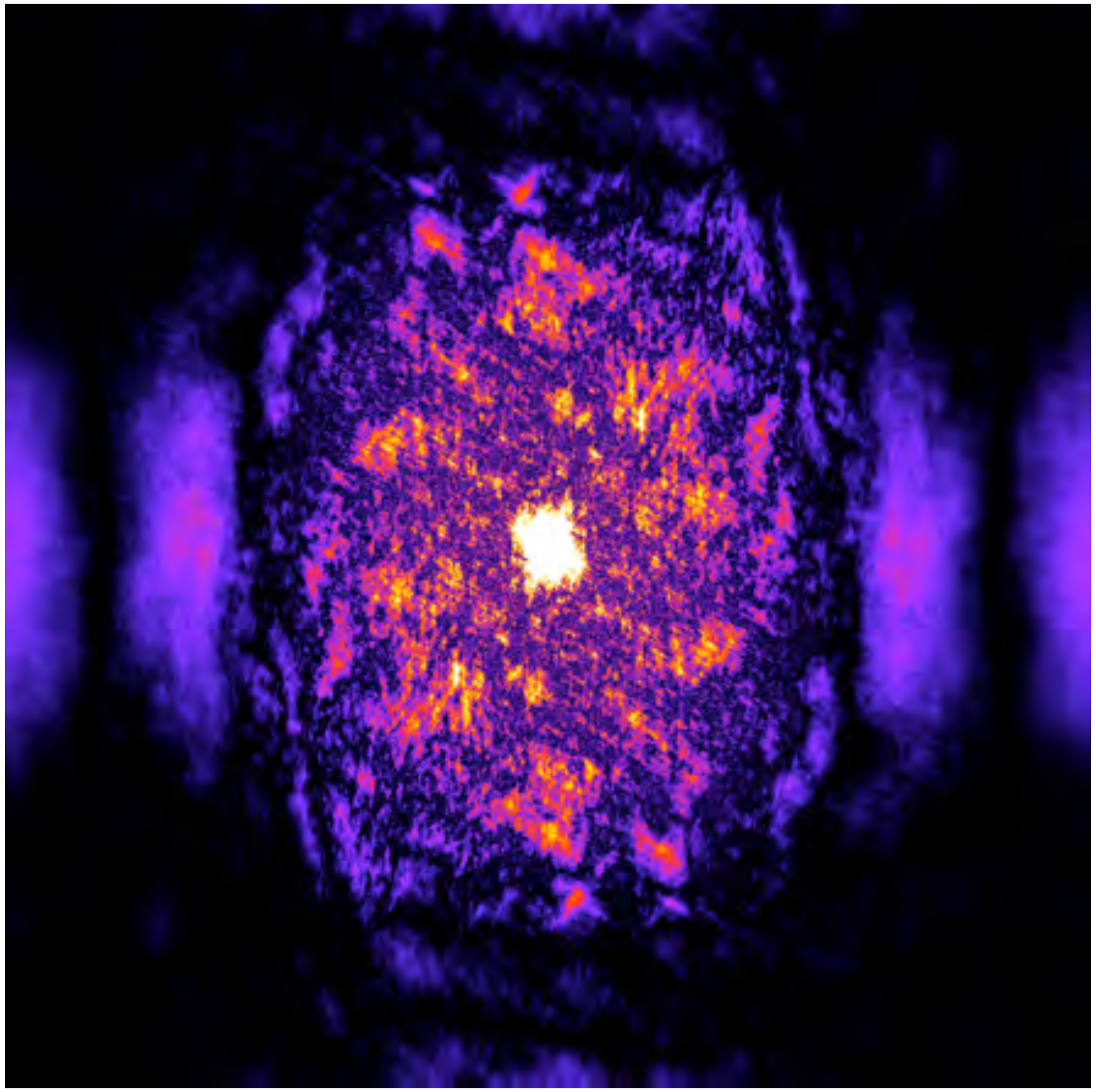


What Information is Coded in Phase and Modulus?

Amplitudes:
square root of diffraction pattern



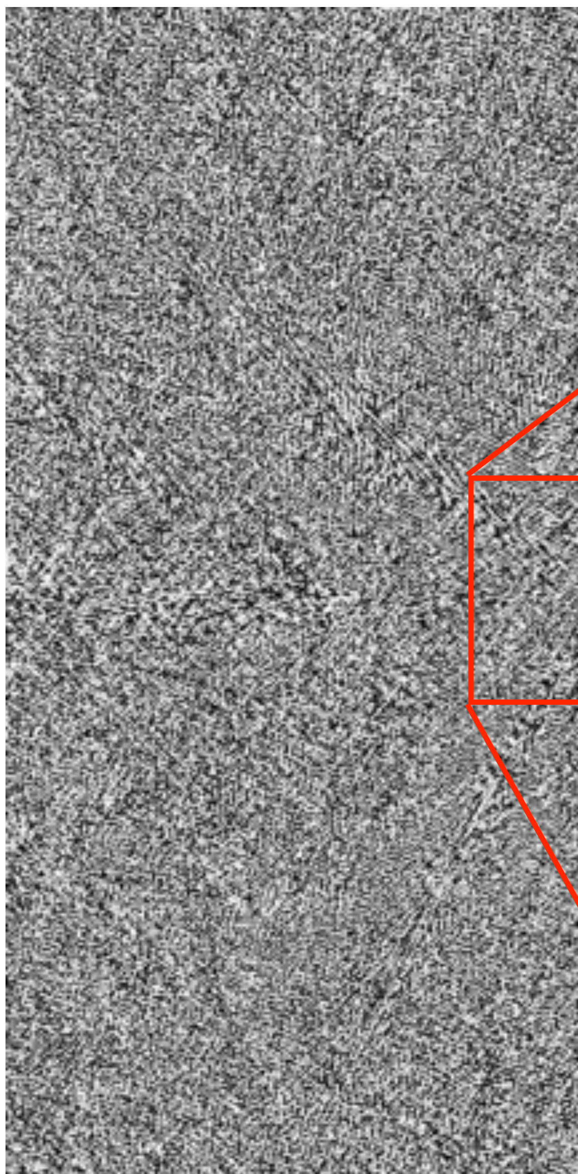
FFT^{-1}

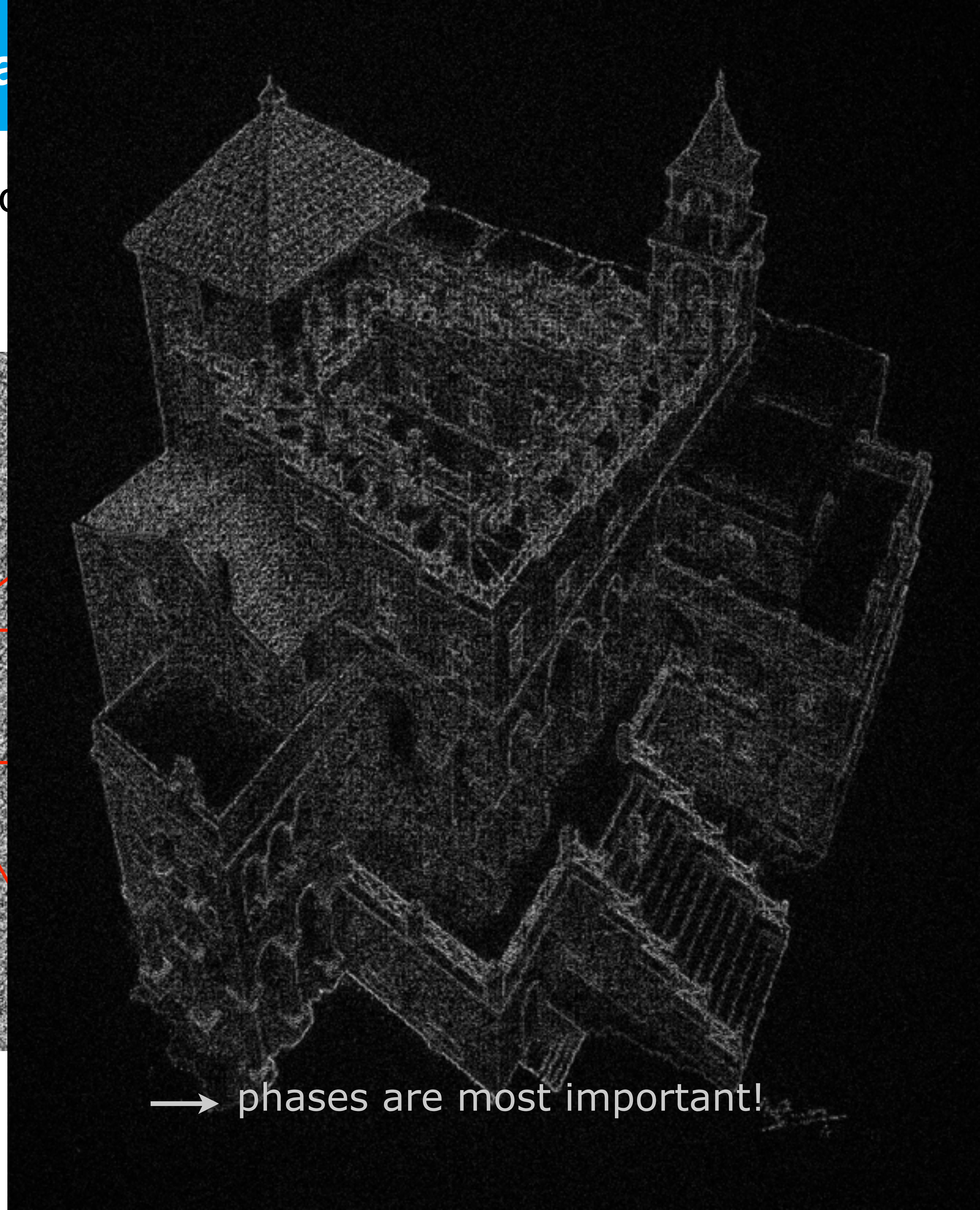


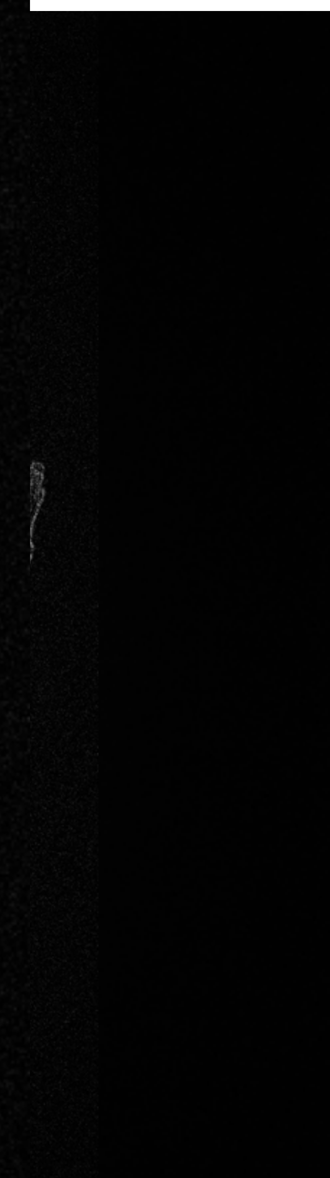
What Informa

Phase: modulus c

(shown: real part







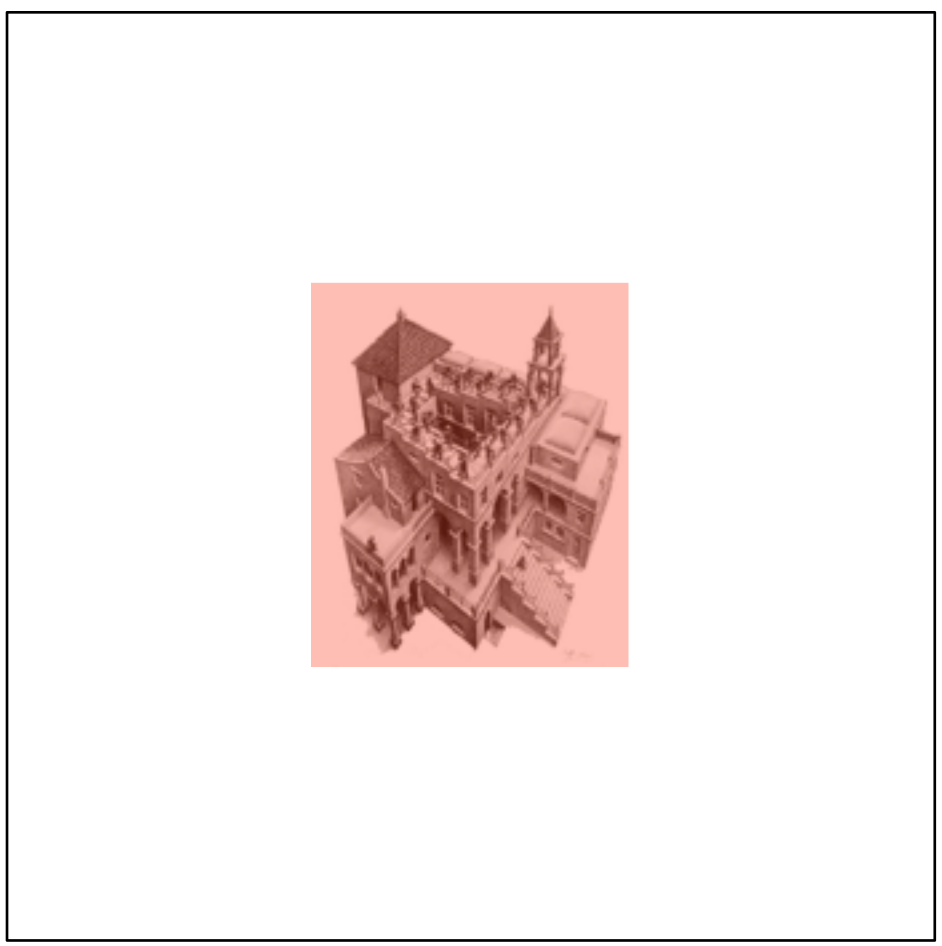
Phase Problem: Information Lost

Is diffraction pattern unique?

> NO! Half of the information is missing!
> (complex amplitudes vs. real diffraction pattern)

What additional information can be used to help solve the problem?

> Knowledge of part of the object:



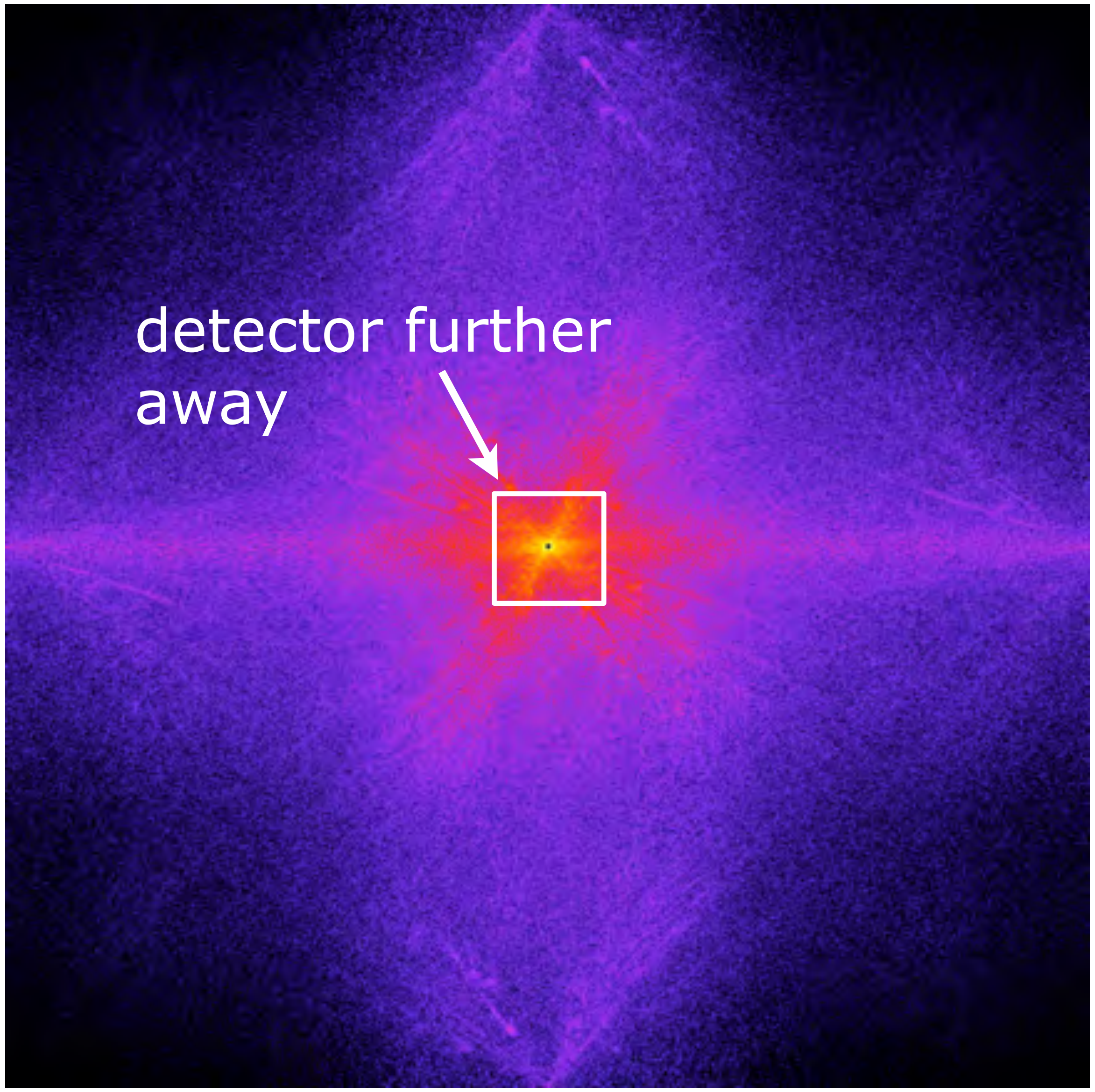
Example:

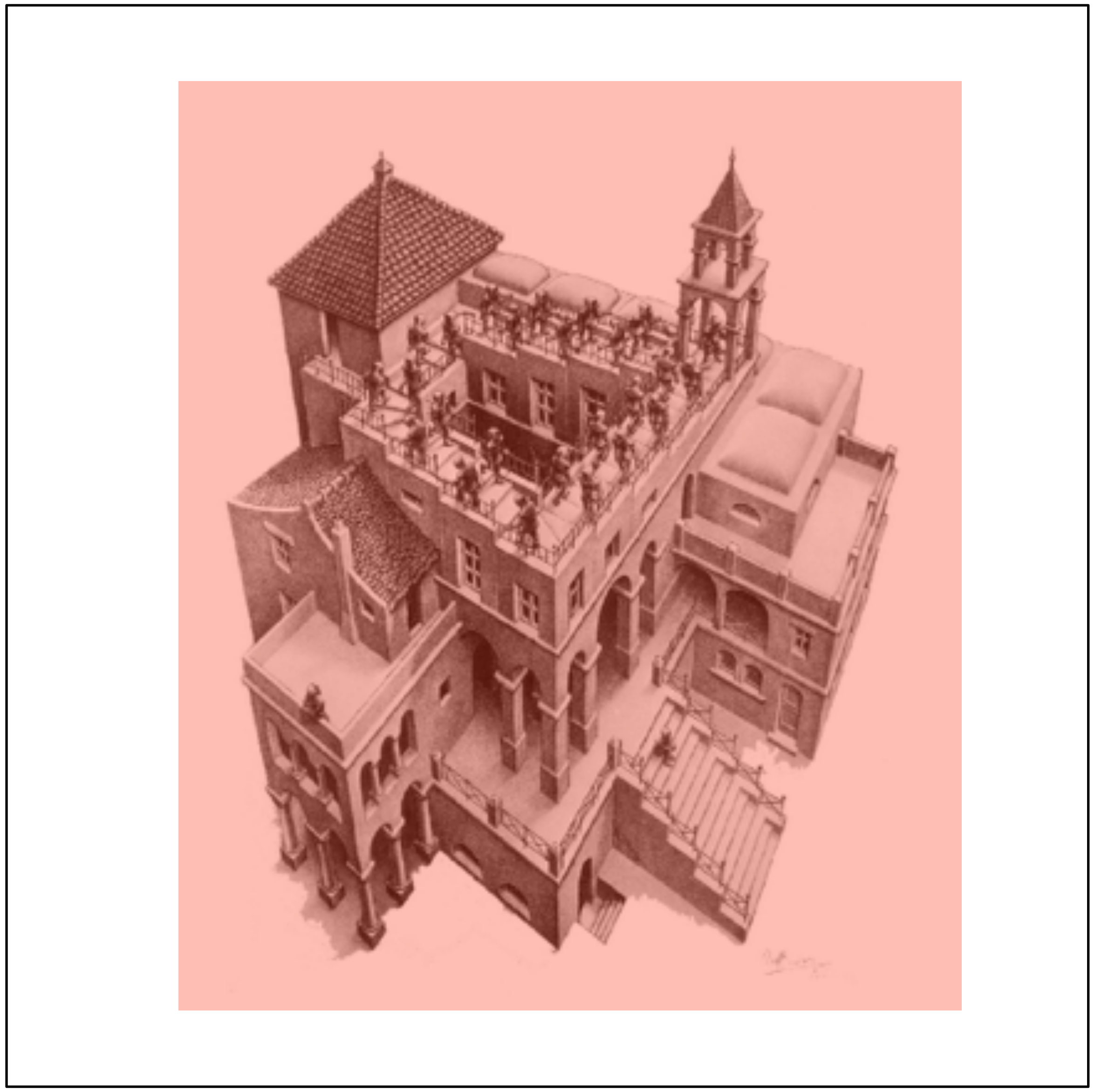
> Object confined to certain area!
> (rest of image empty)
>
> Support constraint!

> Object must be positive: positive electron density [small (real) object]

→ Number of unknowns reduced below the number of measured data!

How to Obtain a Large Support?

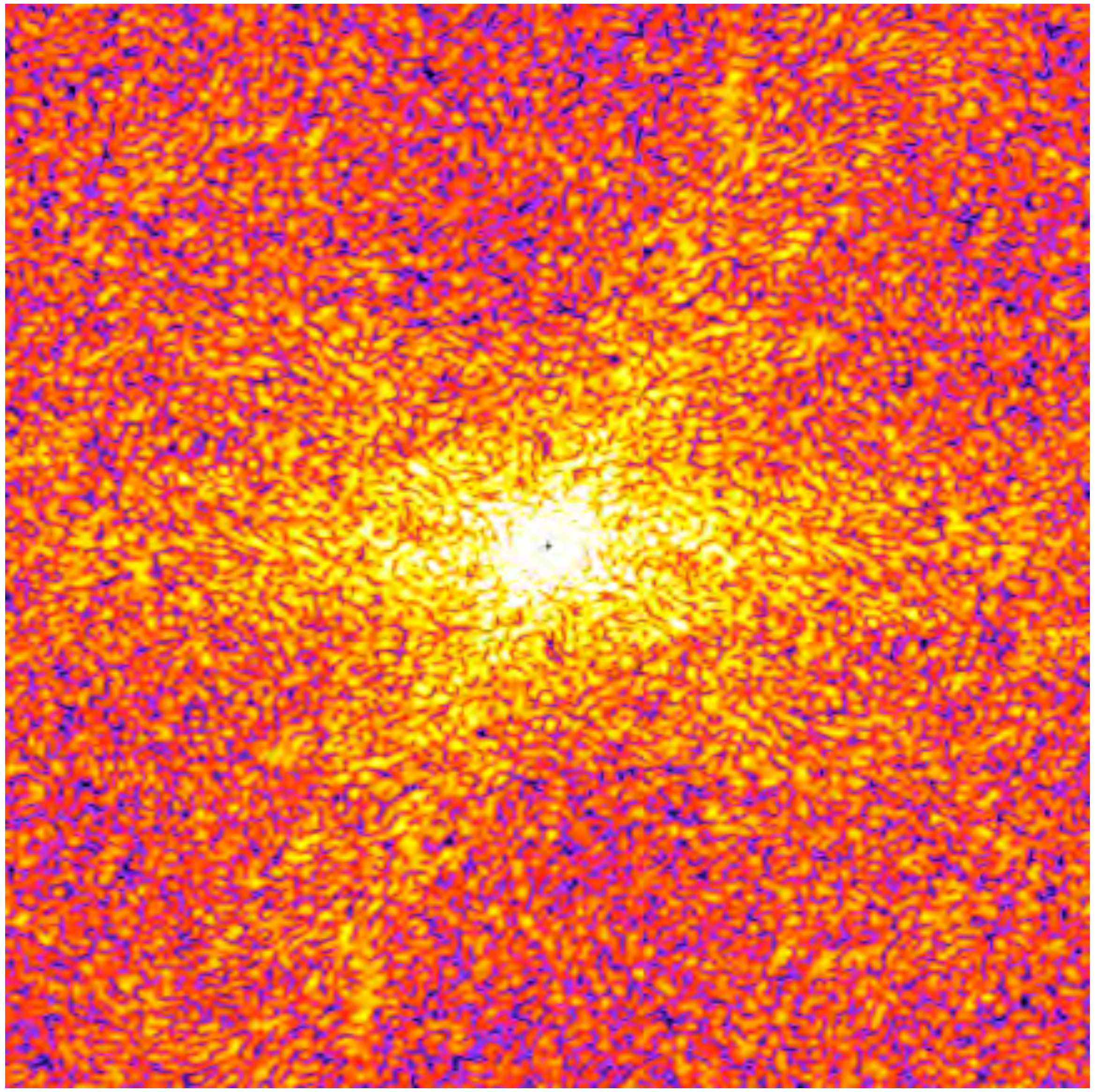


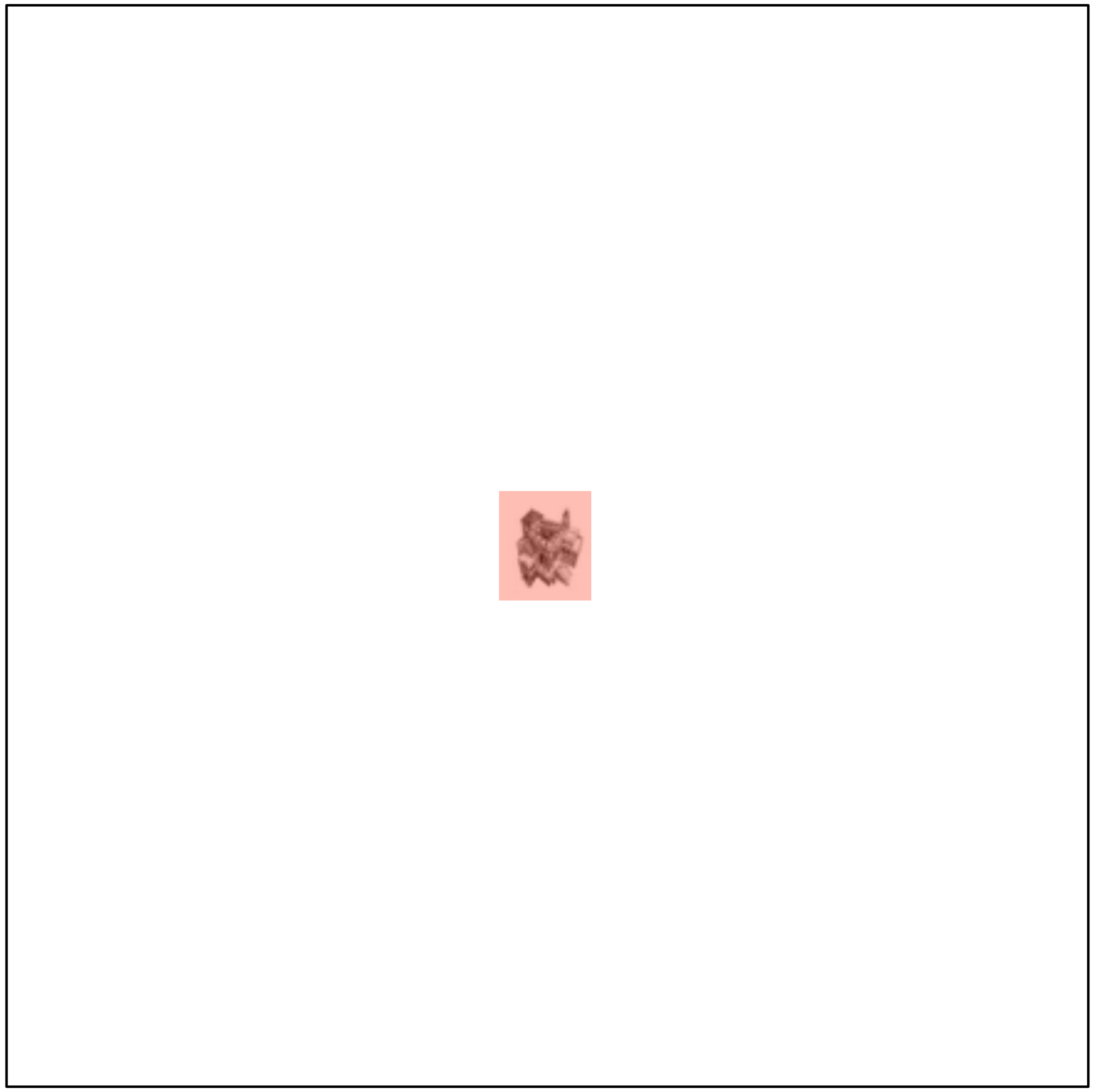


2k x 2k detector

Large pixel and large field of view: number of unknowns too large!

How to Obtain a Large Support?



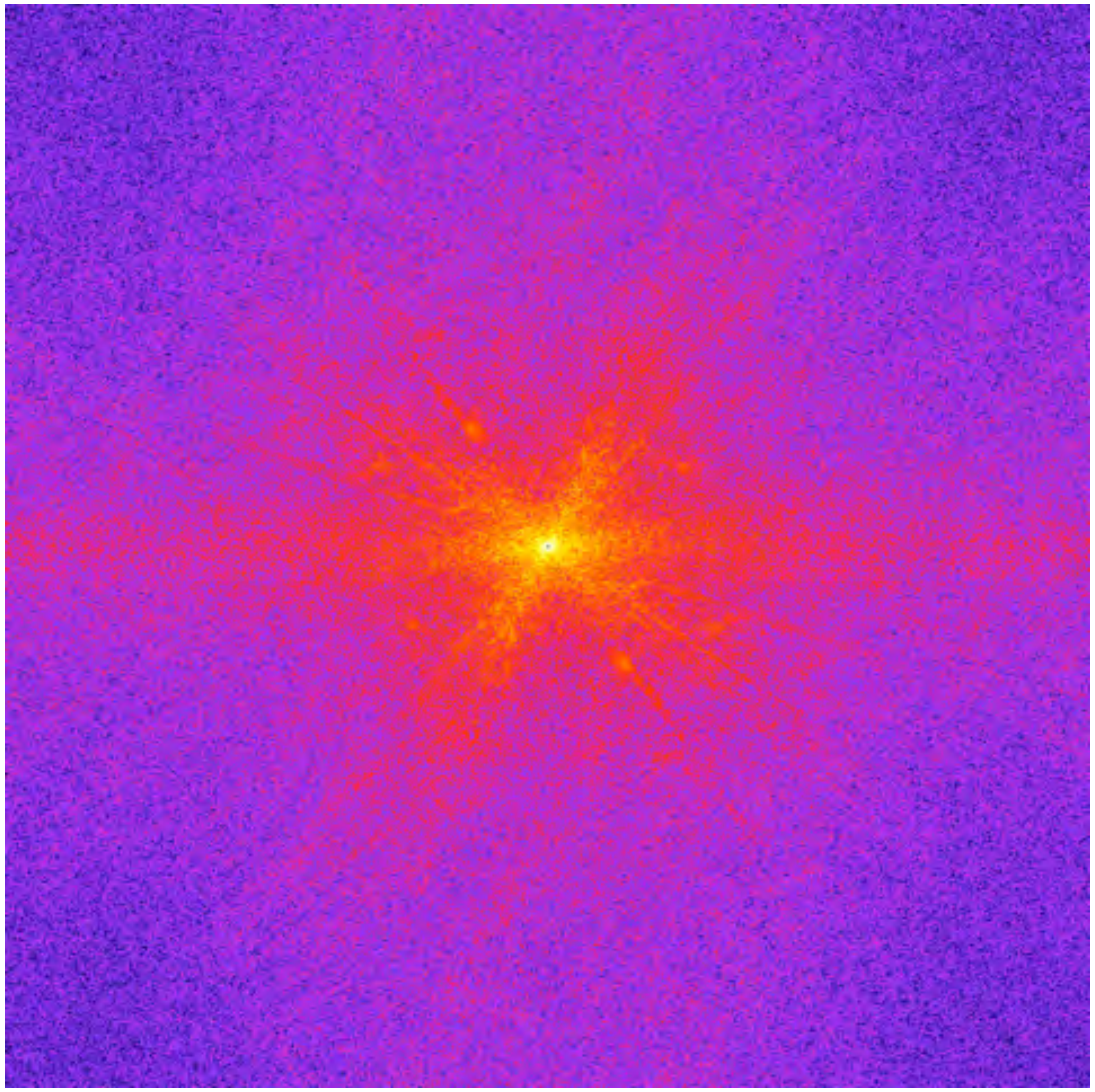


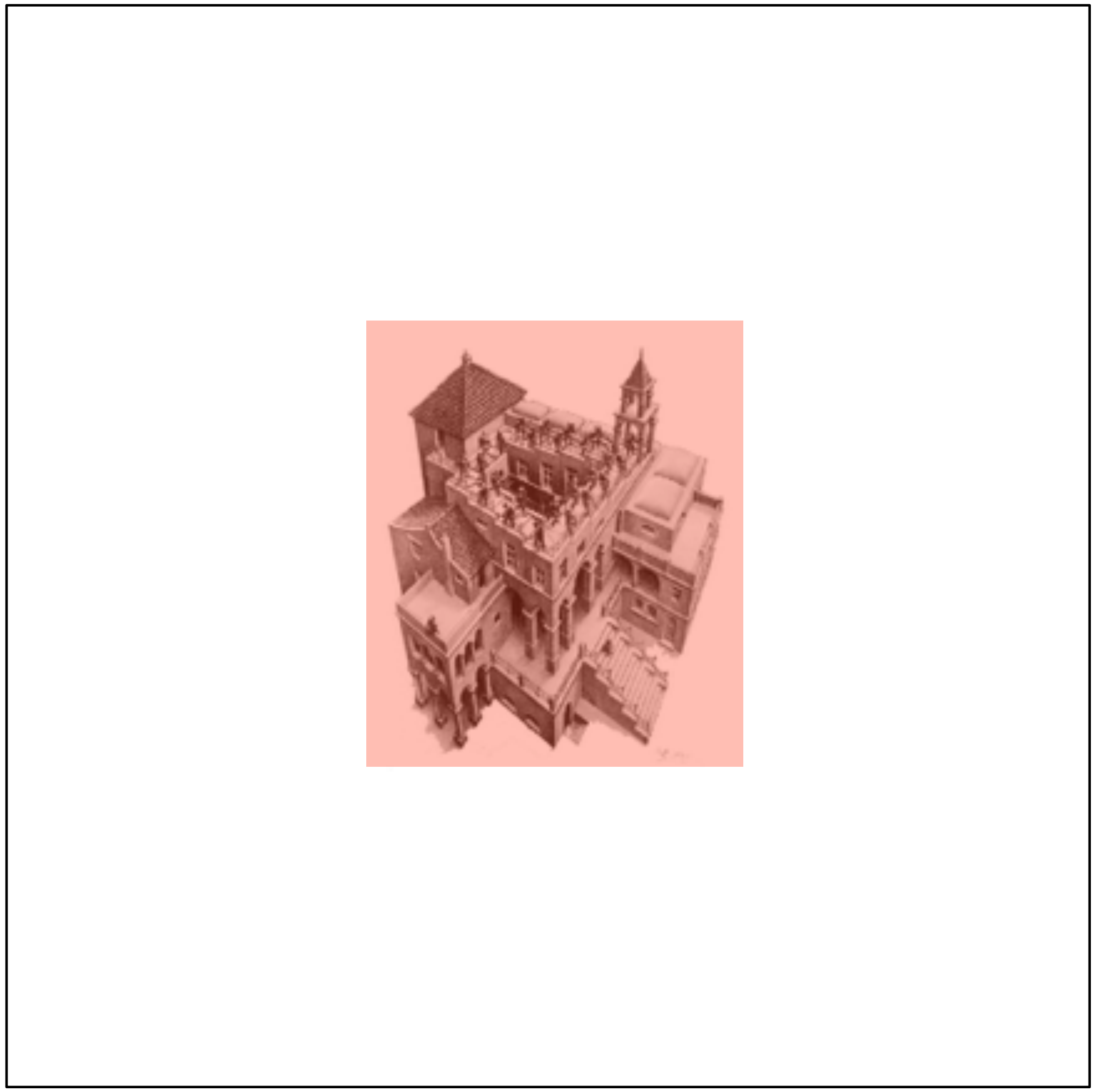
2k x 2k detector

Small pixel and small field of view:

very few unknowns (a lot of redundant information)!

How to Obtain a Large Support?



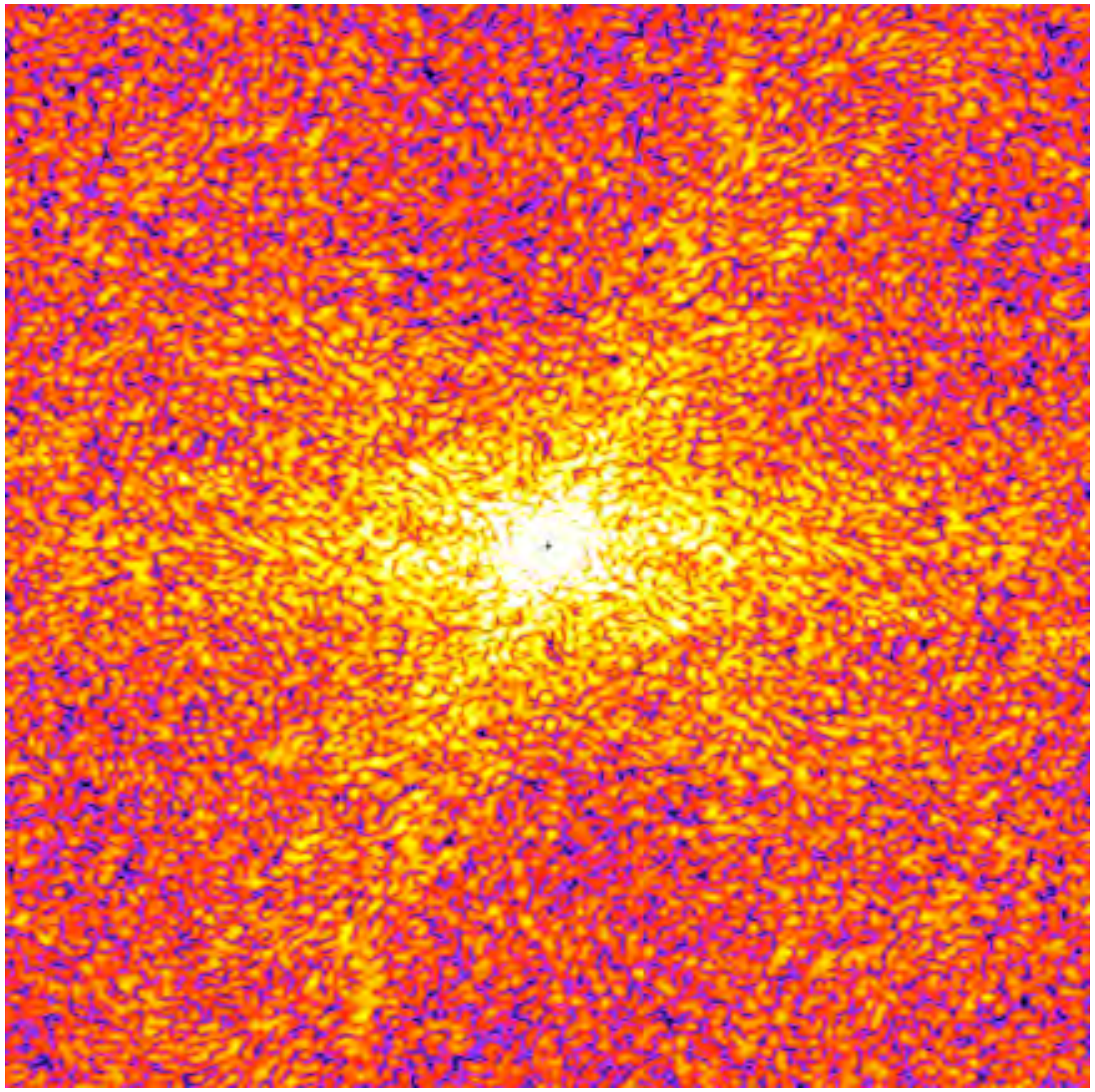


2k x 2k detector

pixel half the size as in first example:

sufficiently few unknowns & high information content!

Right Information Content: Oversampling



important result:

in order for the diffraction pattern to contain sufficient information to recover the real and imaginary part of the field amplitude, the speckles have to be nicely resolved:

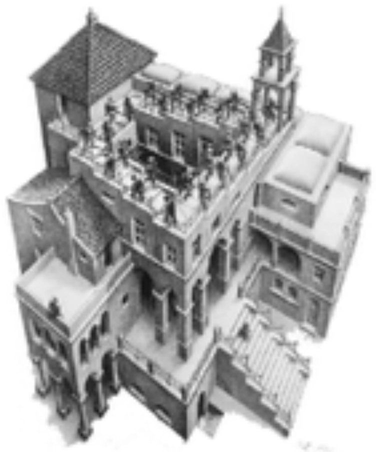
appropriate sampling:

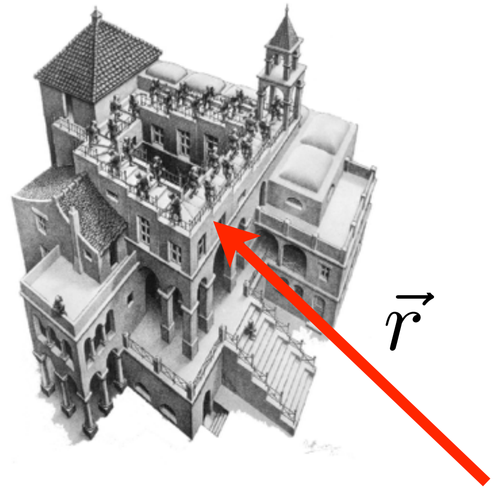
oversampling

Is Solution Now Unique?

No!! Object can be arbitrarily shifted!

Both objects yield same diffraction pattern!



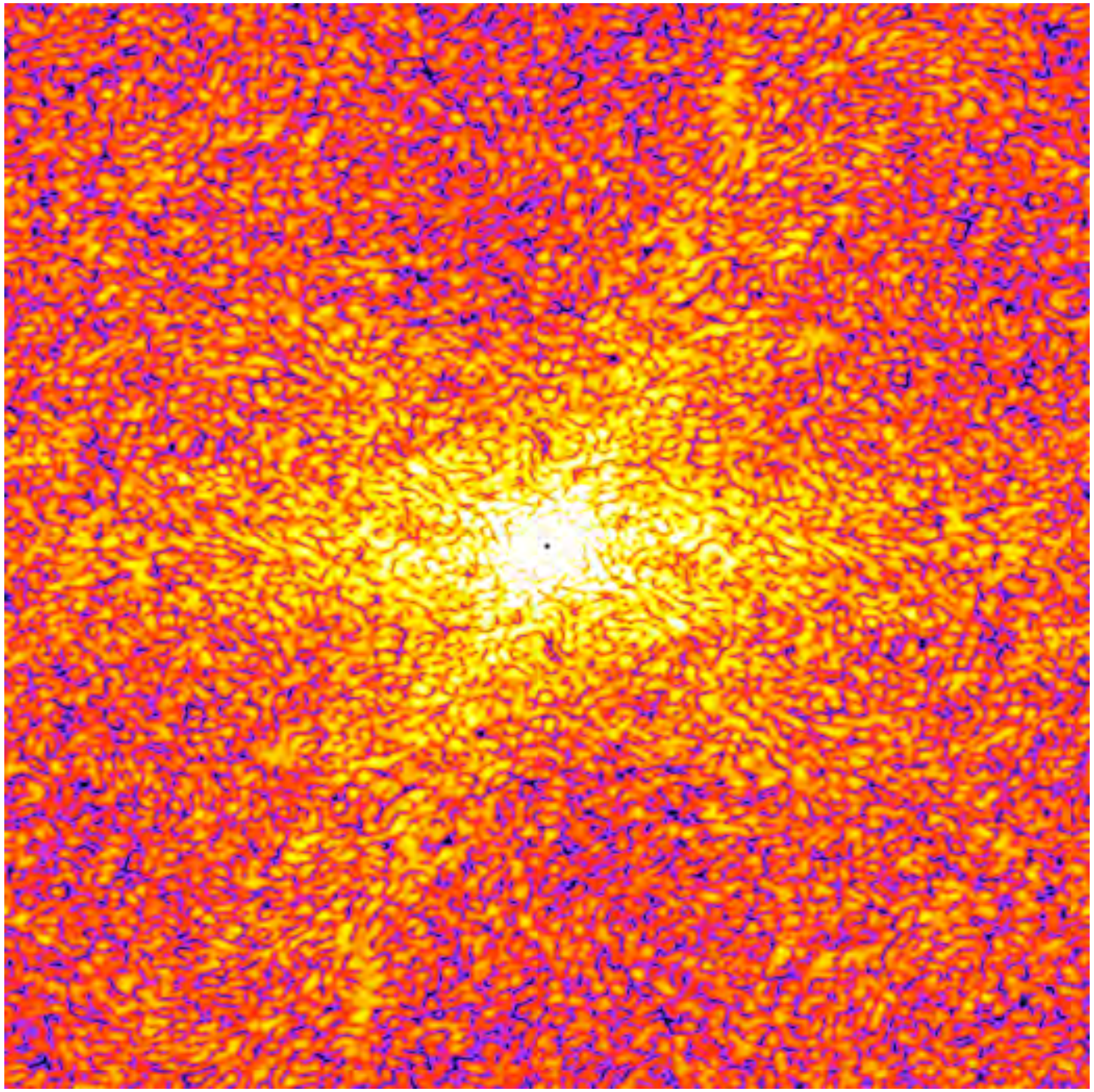


Fourier transform:

additional phase: $e^{-i\vec{q}\cdot\vec{r}}$

vanishes when taking absolute square of amplitude!

Is Solution Now Unique?



Diffraction pattern nearly point symmetric!

transmission function:

- real:
  pure absorption

  FT symmetric
- imaginary:
  pure phase object

  FT anti-symmetric

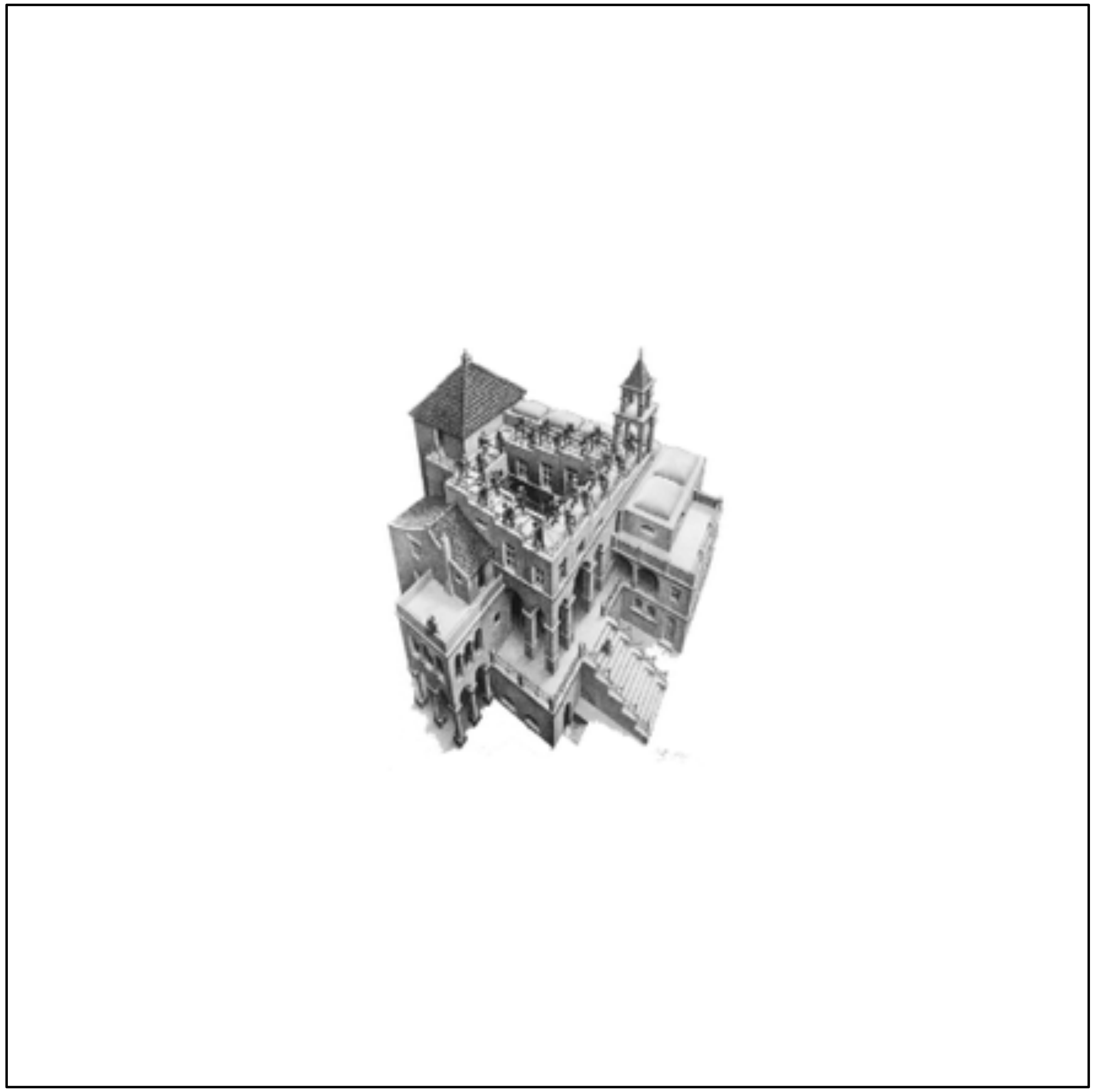
In both cases:

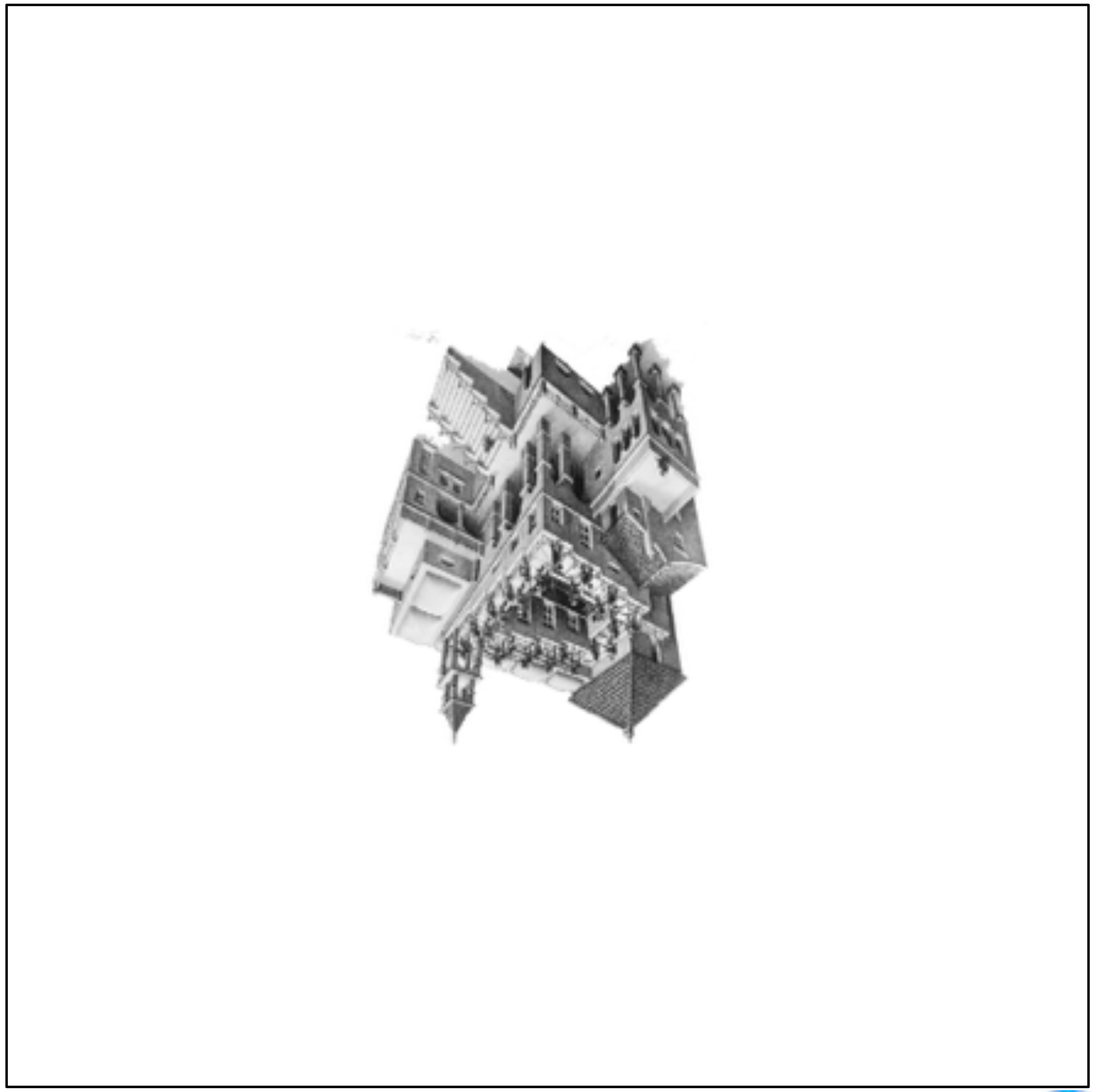
Diffraction pattern has point symmetry!

Is Solution Now Unique?

No!! Object and its point inversion are both solutions

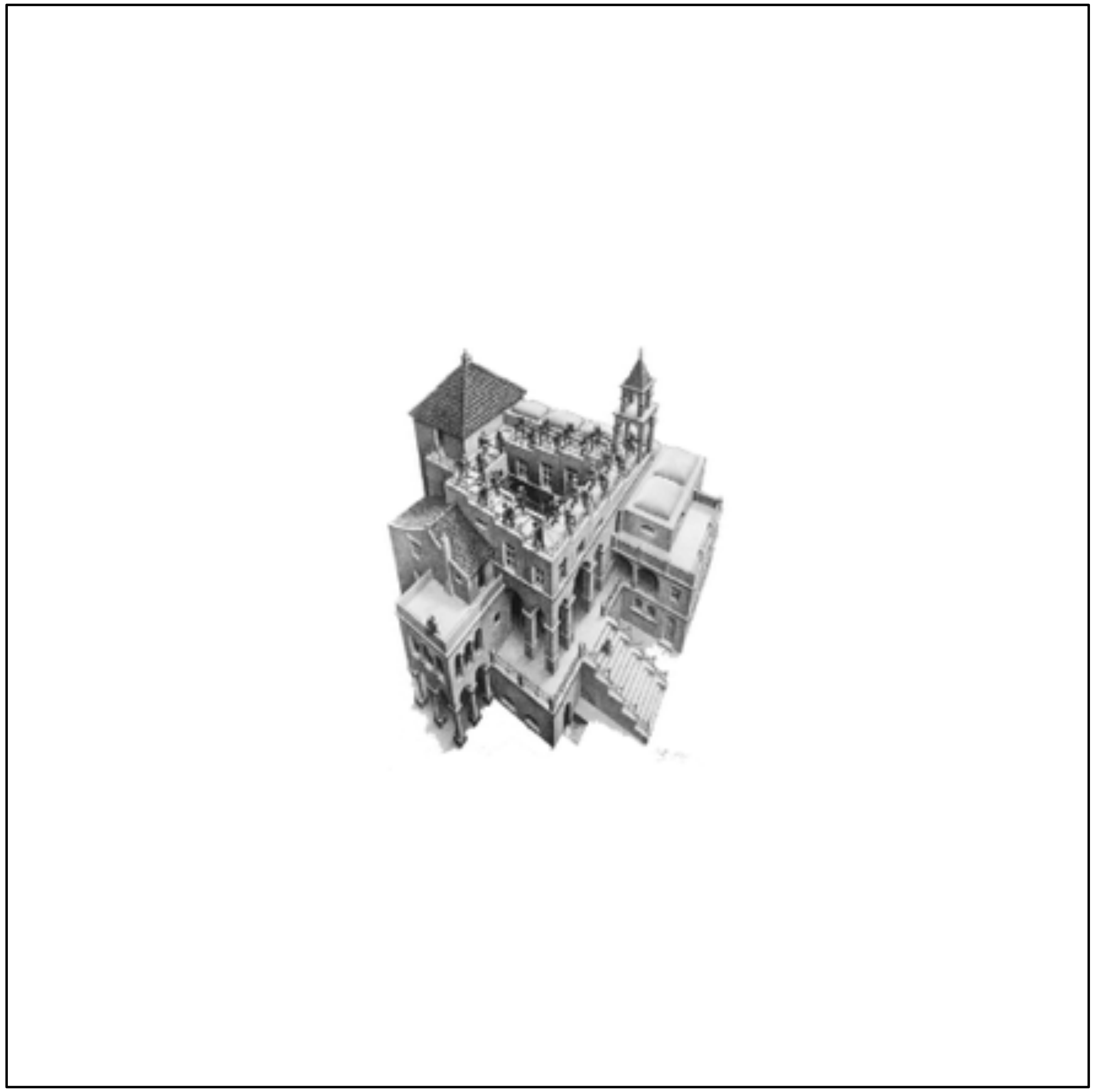
Both objects yield same diffraction pattern!

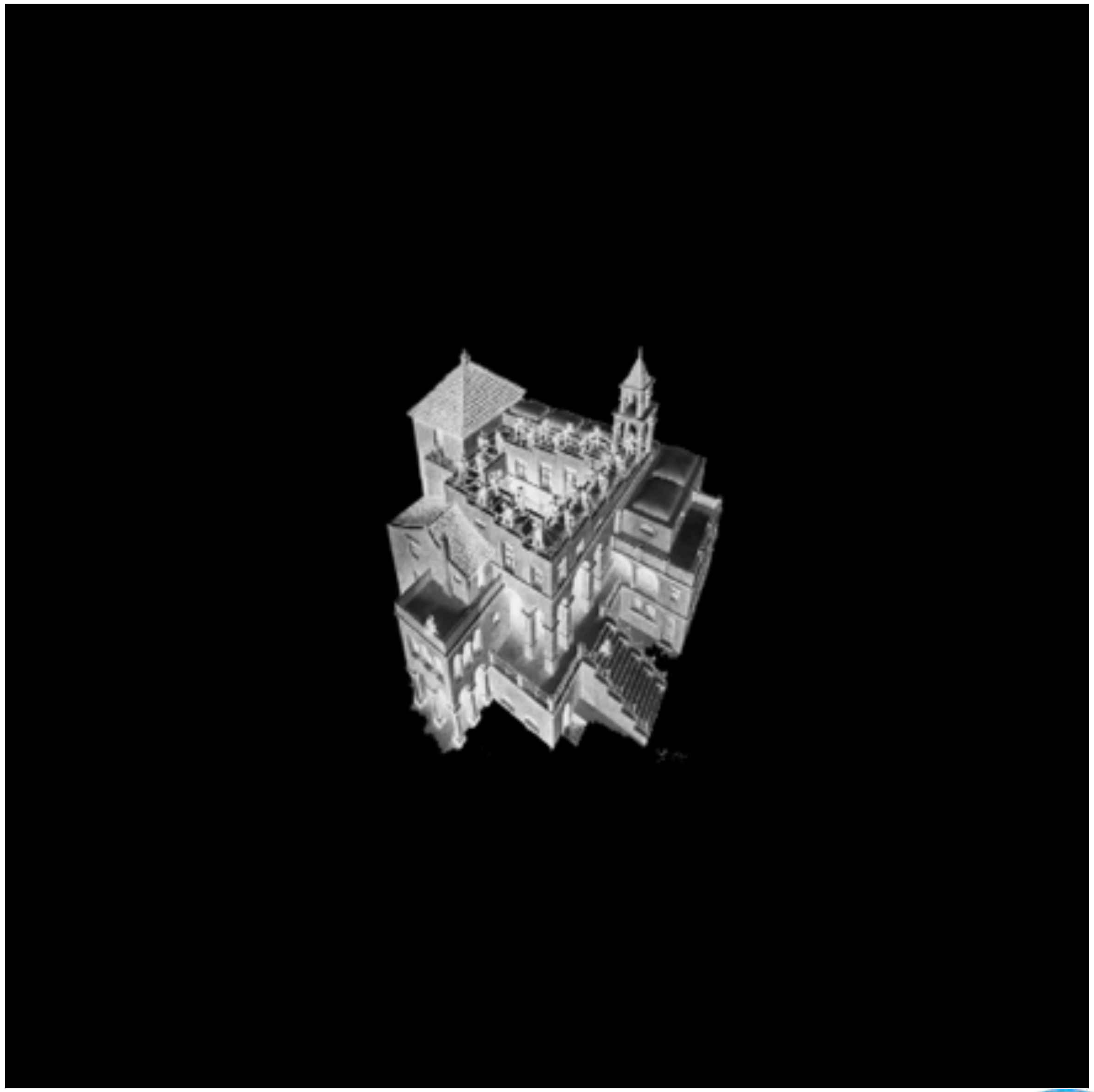




Is Solution Now Unique?

No!! Object and its point inversion are both solutions
Both objects yield same diffraction pattern!
(except for central beam usually covered by beam stop.)





Babinet's theorem!!

Iterative Phase Reconstruction

$$
\begin{tikzcd}
\psi_i(\vec{x}, \mathrm{obj}) \arrow[r, "\text{FFT}"] & \psi_i(\vec{q}, \mathrm{obj}) \arrow[d] \\
\text{real-space constraint} \arrow[u] & \text{Fourier-space constraint} \arrow[d] \\
\psi_i'(\vec{x}, \mathrm{obj}) \arrow[u] & \psi_i'(\vec{q}, \mathrm{obj}) \arrow[l, "\text{FFT}^{-1}"]
\end{tikzcd}
$$

real-space constraint:

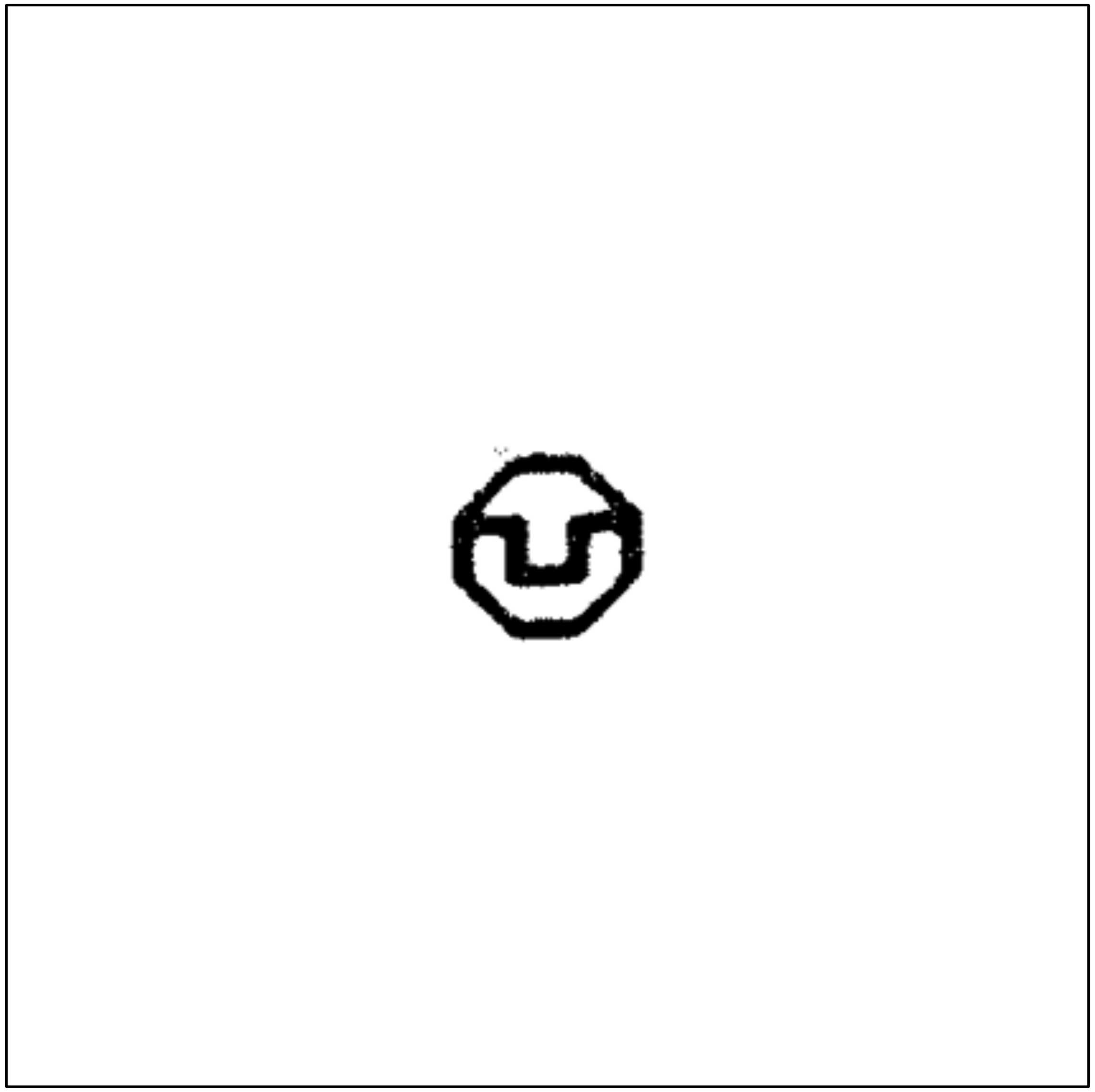
- support
- positivity
- ...

Fourier-space constraint:

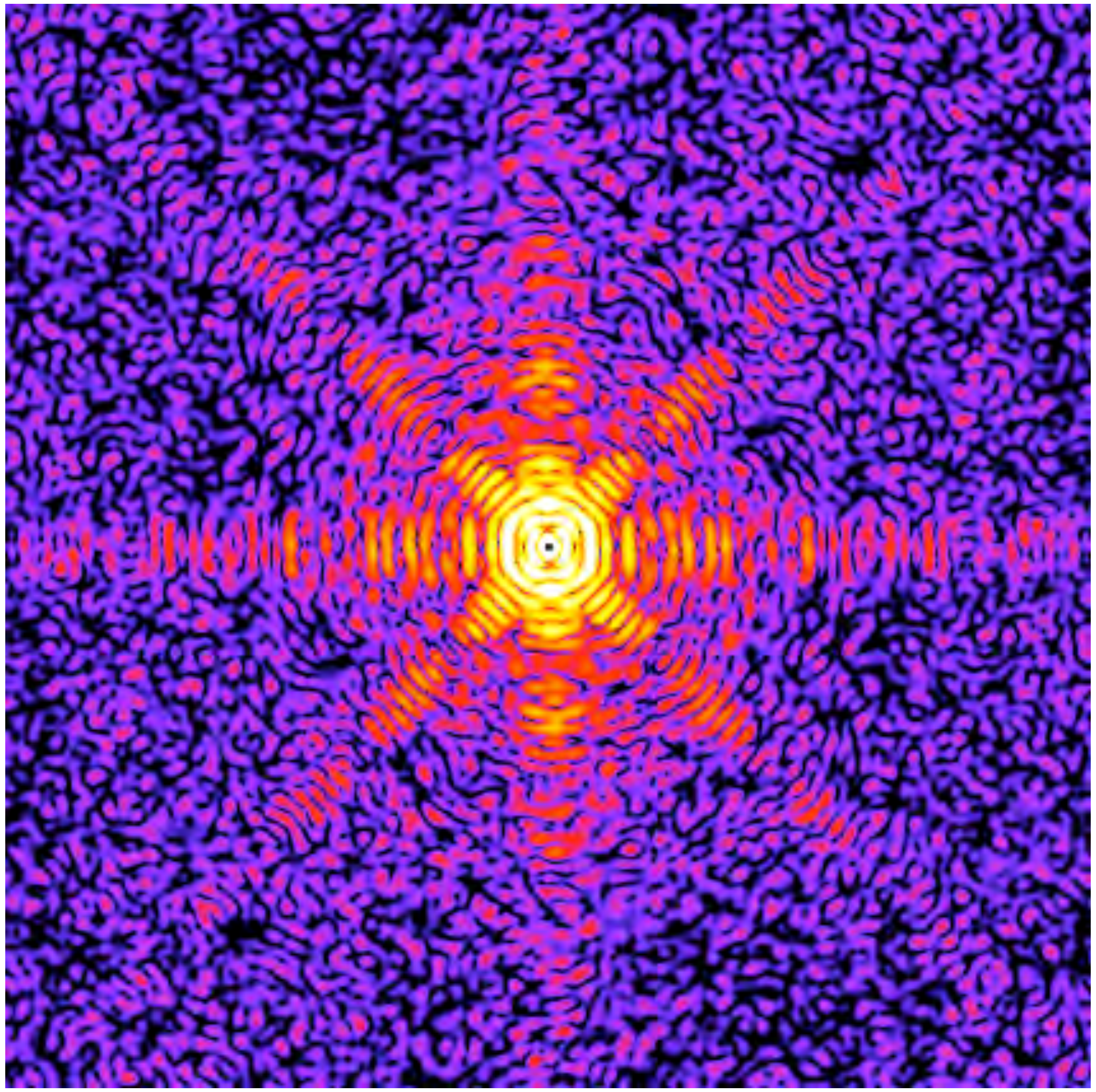
$$\psi_i'(\vec{q}, \mathrm{obj}) := \frac{\psi_i'(\vec{x}, \mathrm{obj})}{|\psi_i'(\vec{q}, \mathrm{obj})|} \cdot \sqrt{I_{\mathrm{det}}(\vec{q})}$$

R.W.Gerchberg & W.O. Saxton, *Optic* (1972) **35**, 237
J.R. Fienup, *Appl Opt.* (1982). **21**, 2758
R.P. Millane & W.J. Stroud, *J. Opt. Soc. Am.* (1997) **A14**, 568

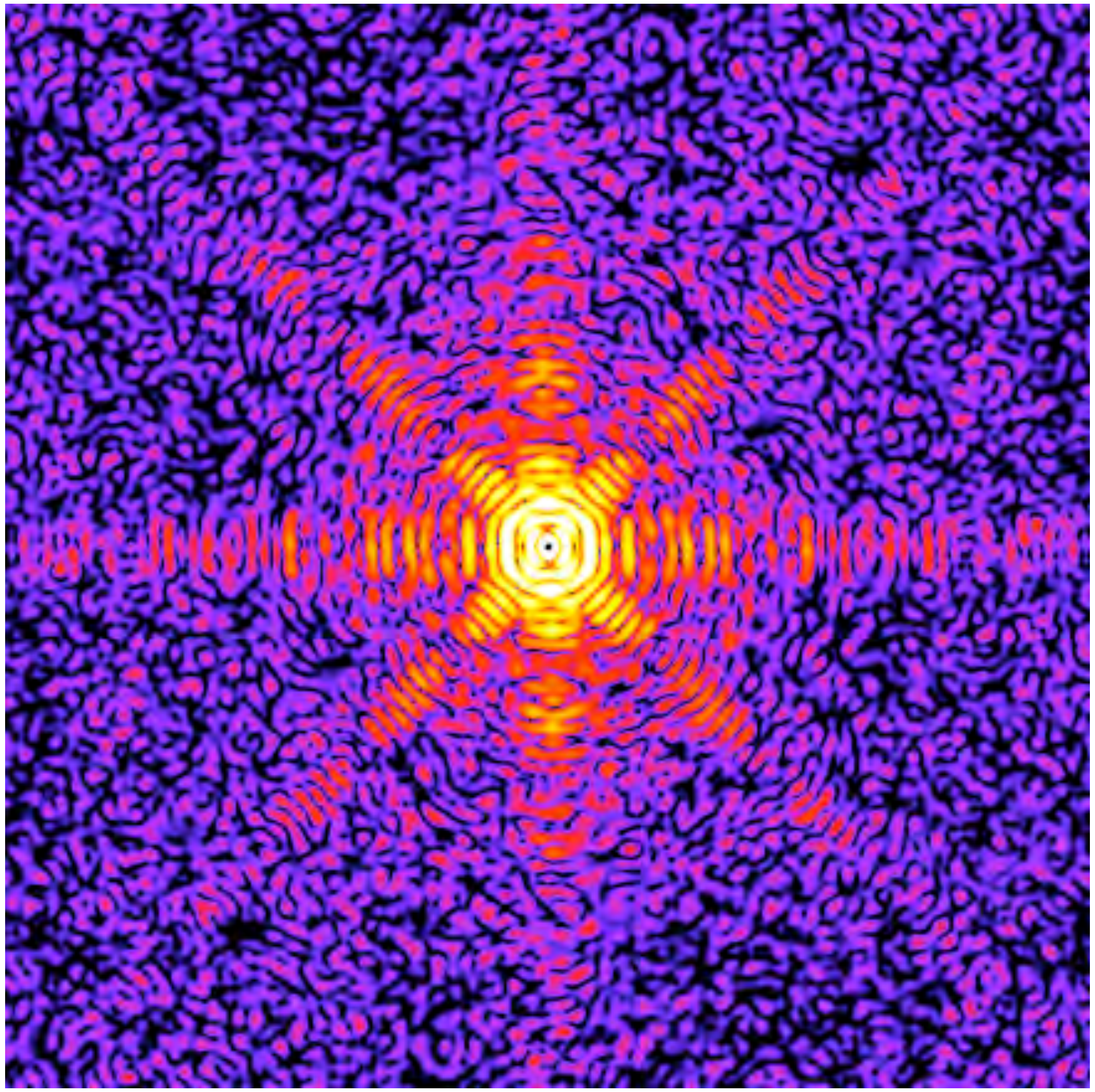
Example

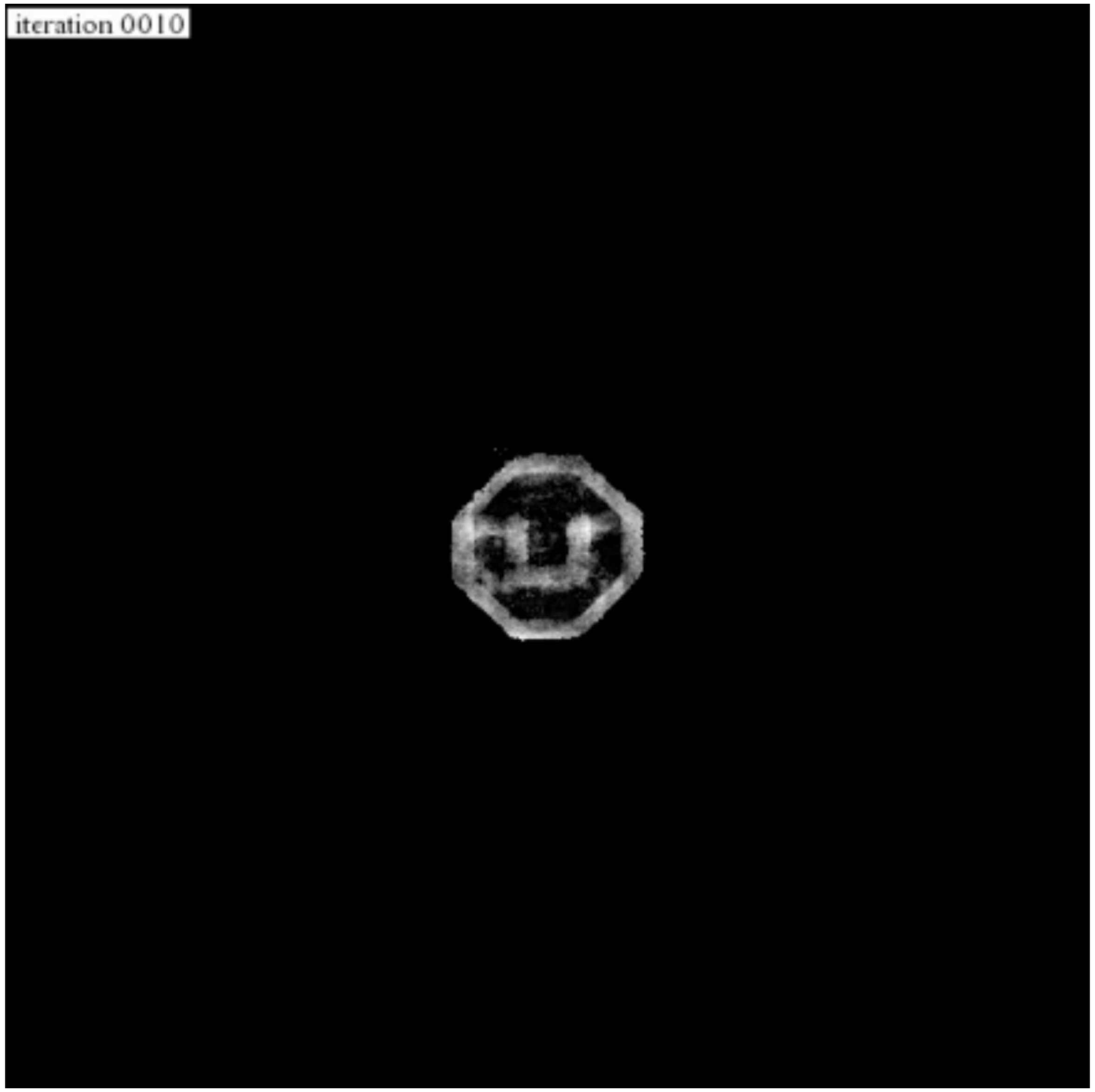


FT

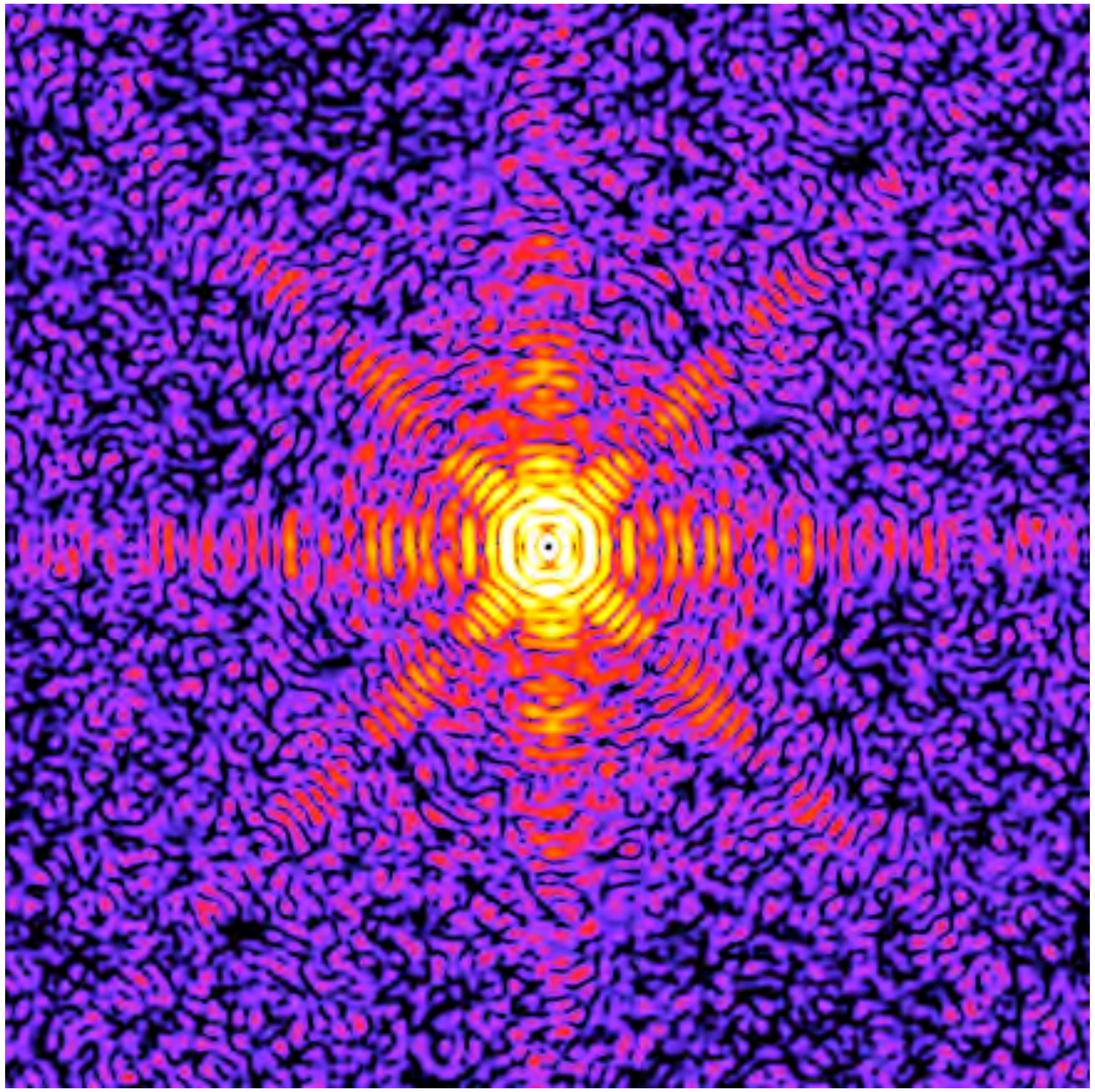


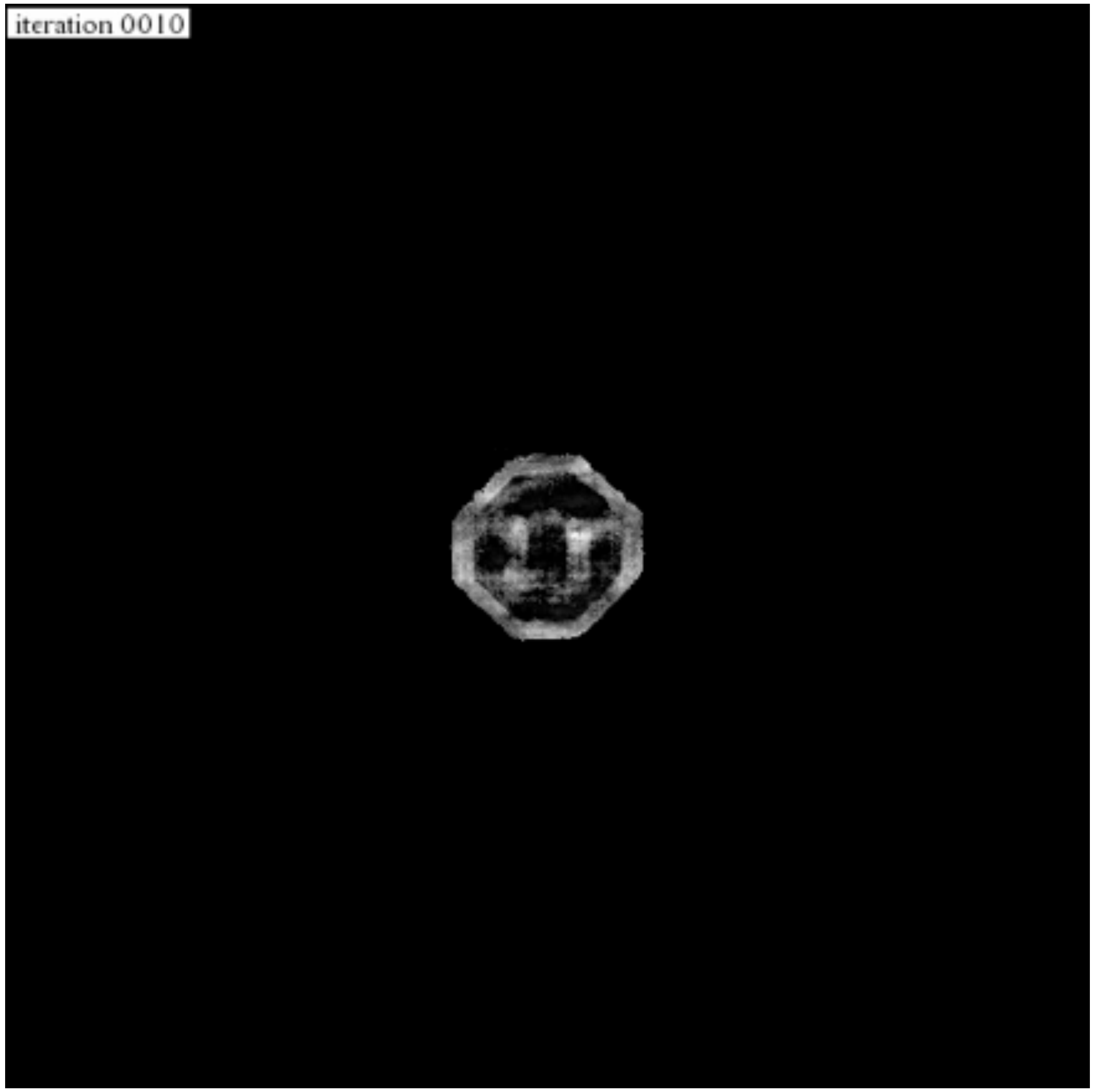
Reconstruction





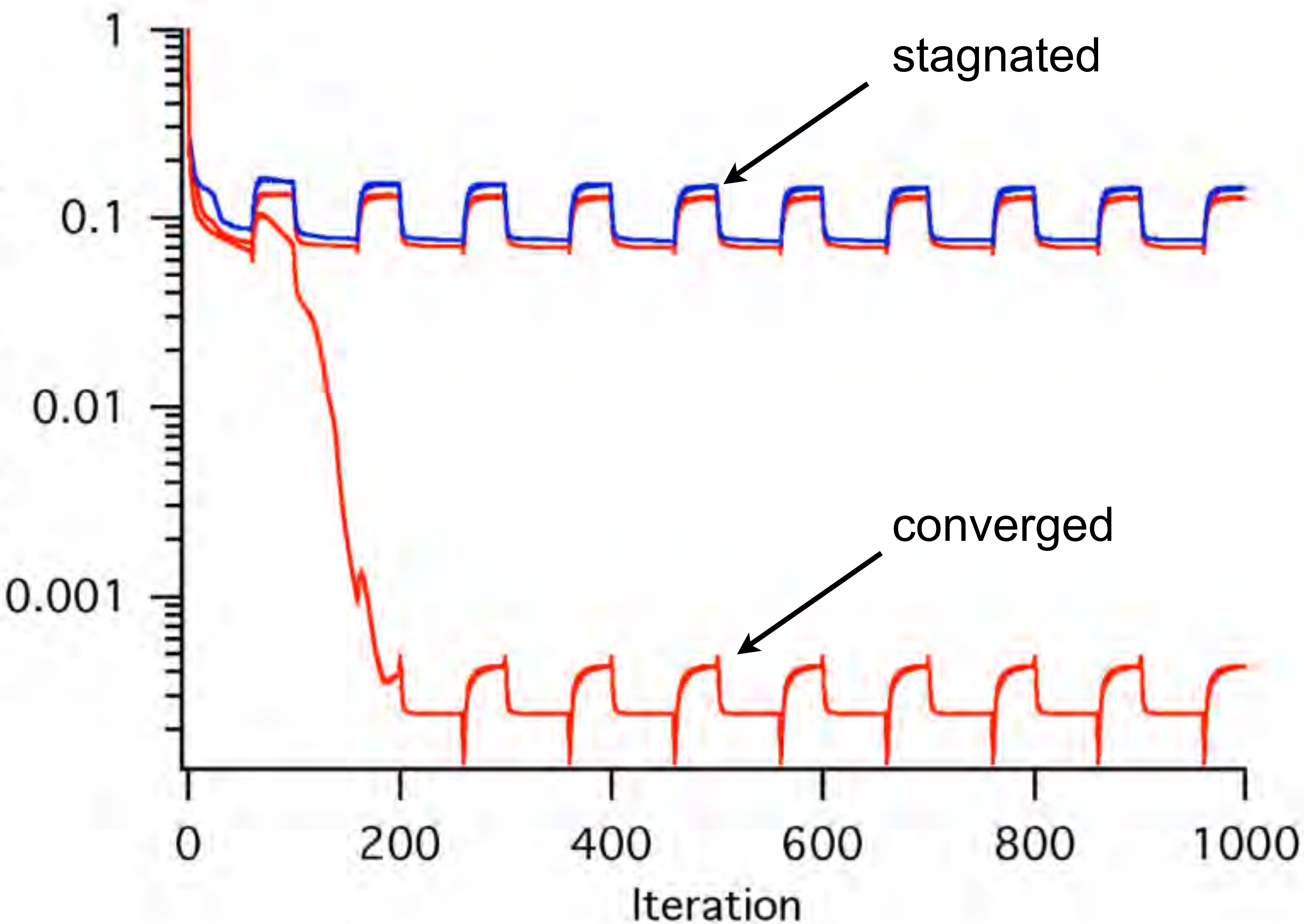
Reconstruction: Stagnation





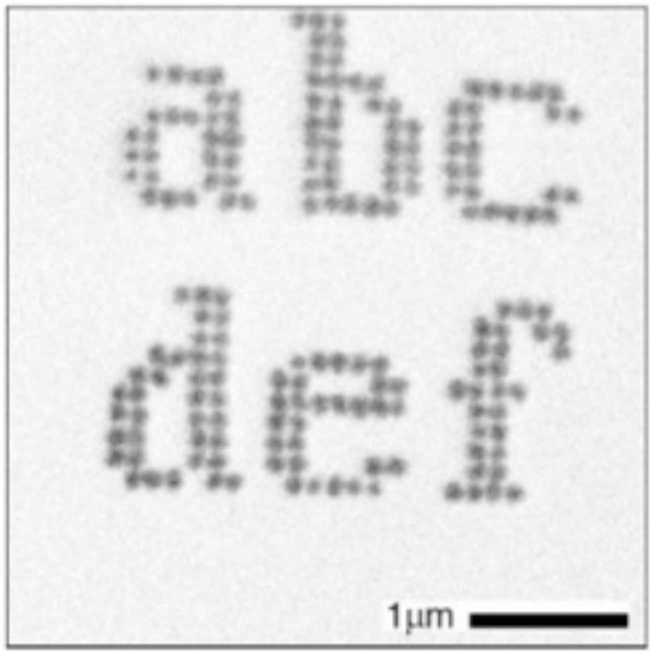
Repeat Reconstruction

Deviation of model from diffraction pattern:

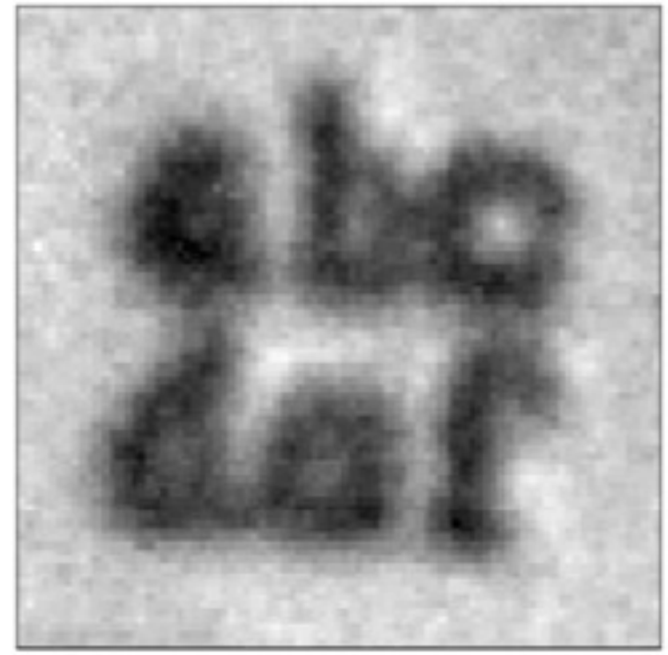


Coherent Diffraction Imaging with Soft X-Rays

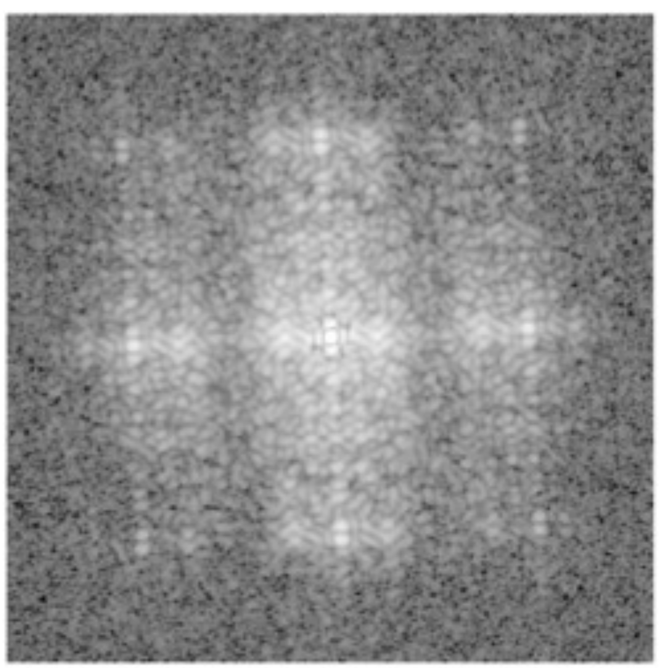
Object: Gold on Si_3N_4



light micrograph:



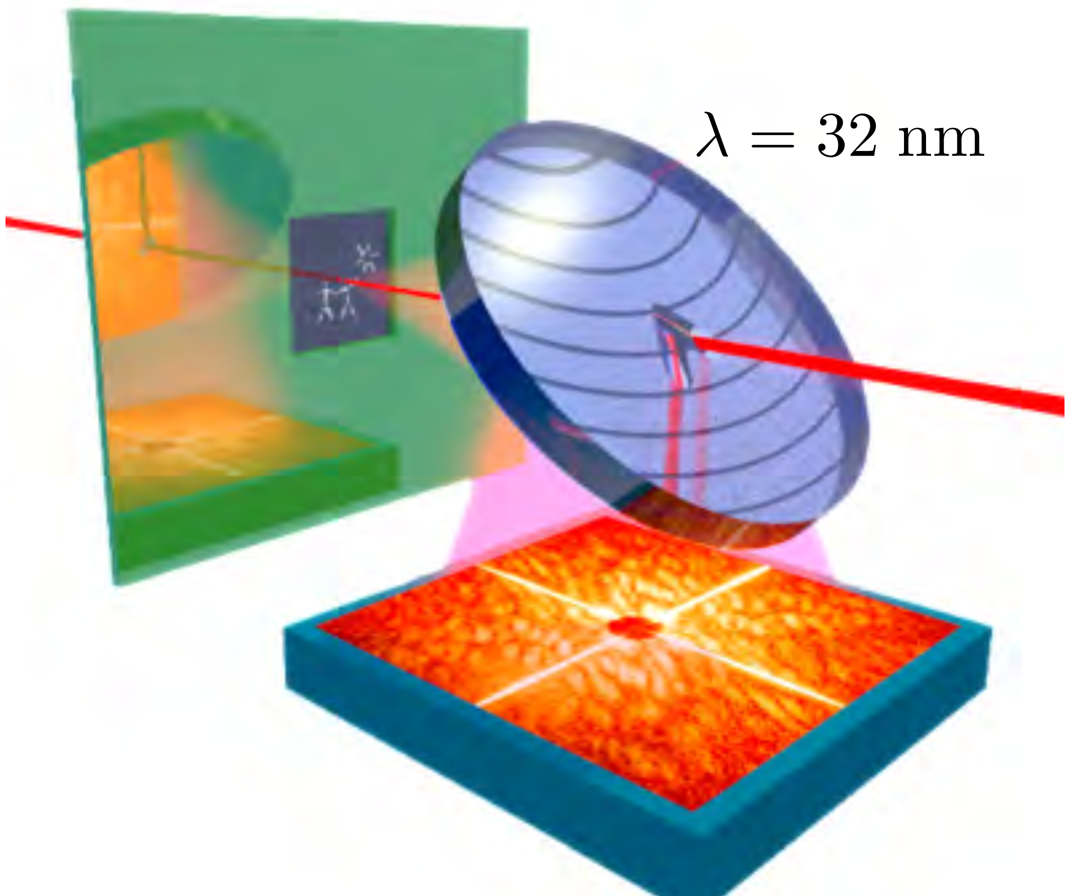
diffraction pattern:

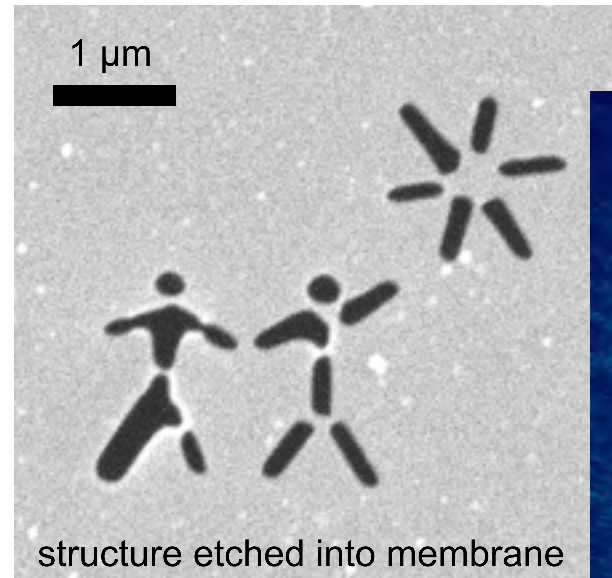


reconstruction:

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

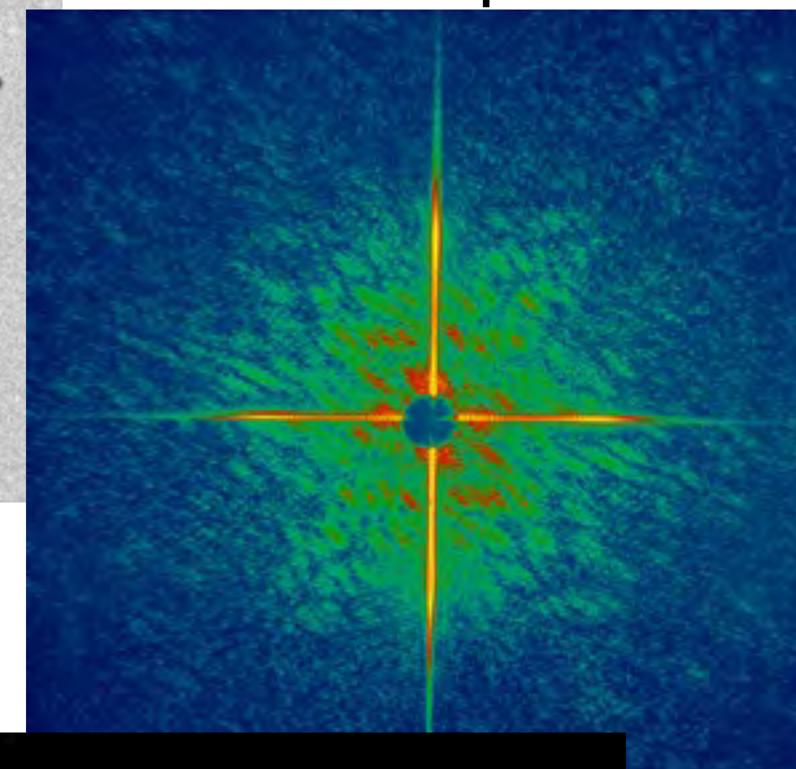
XFEL: Image and Destroy





structure etched into membrane

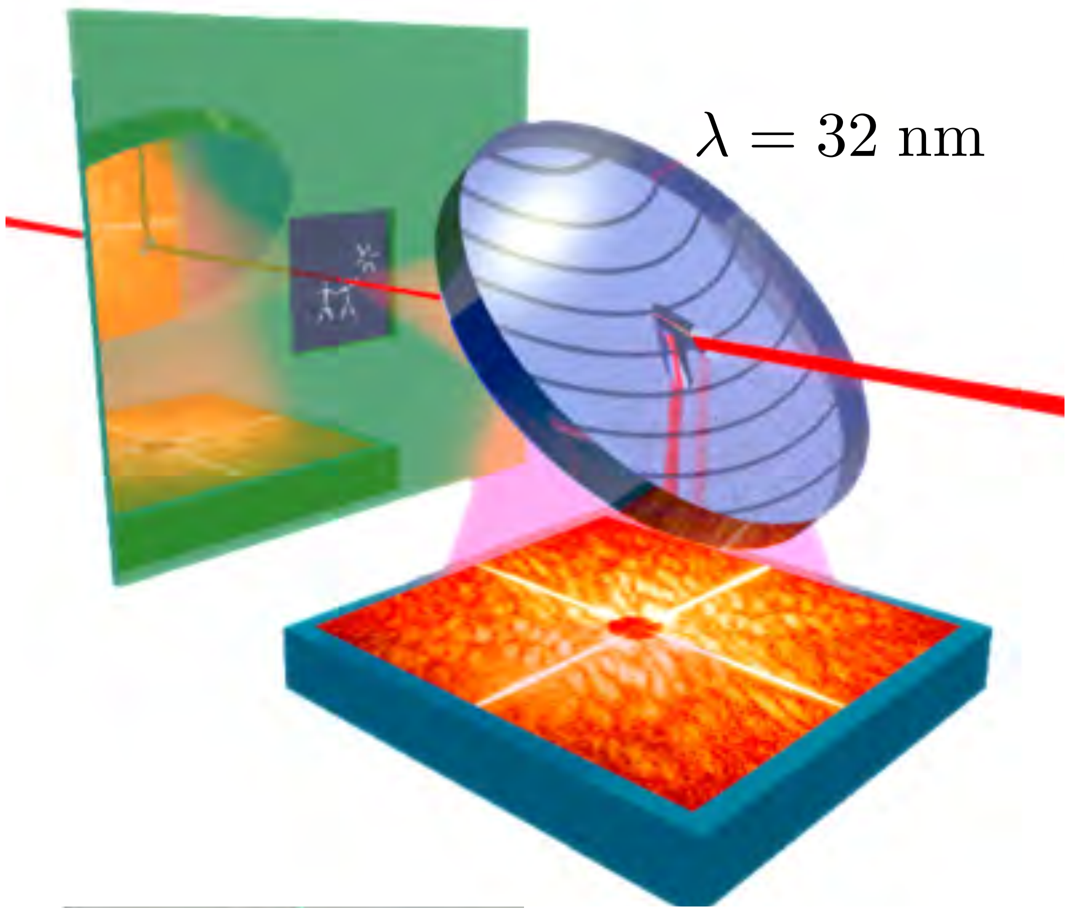
single-pulse diffraction pattern



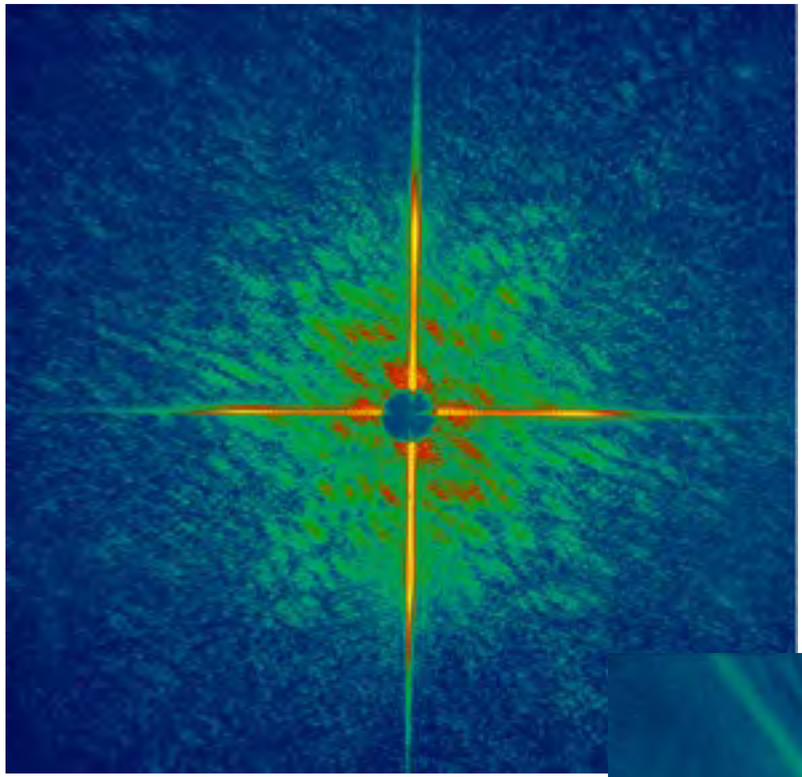
reconstruction

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

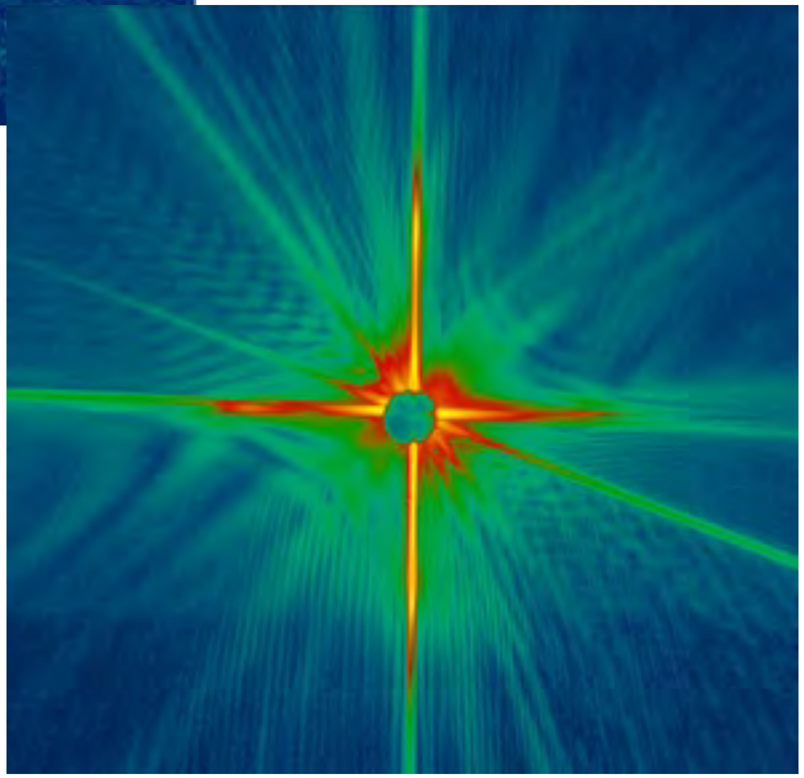
XFEL: Image and Destroy

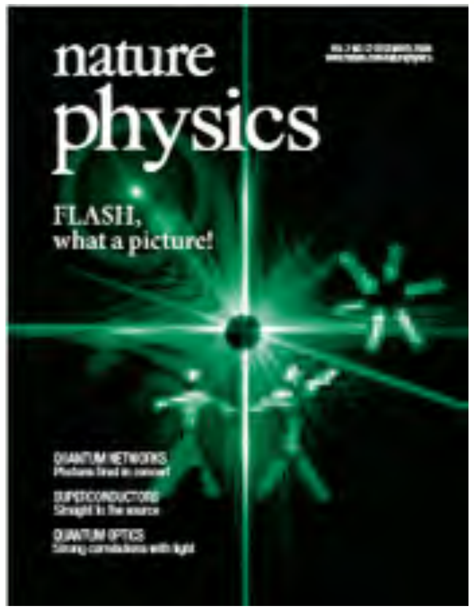


first pulse



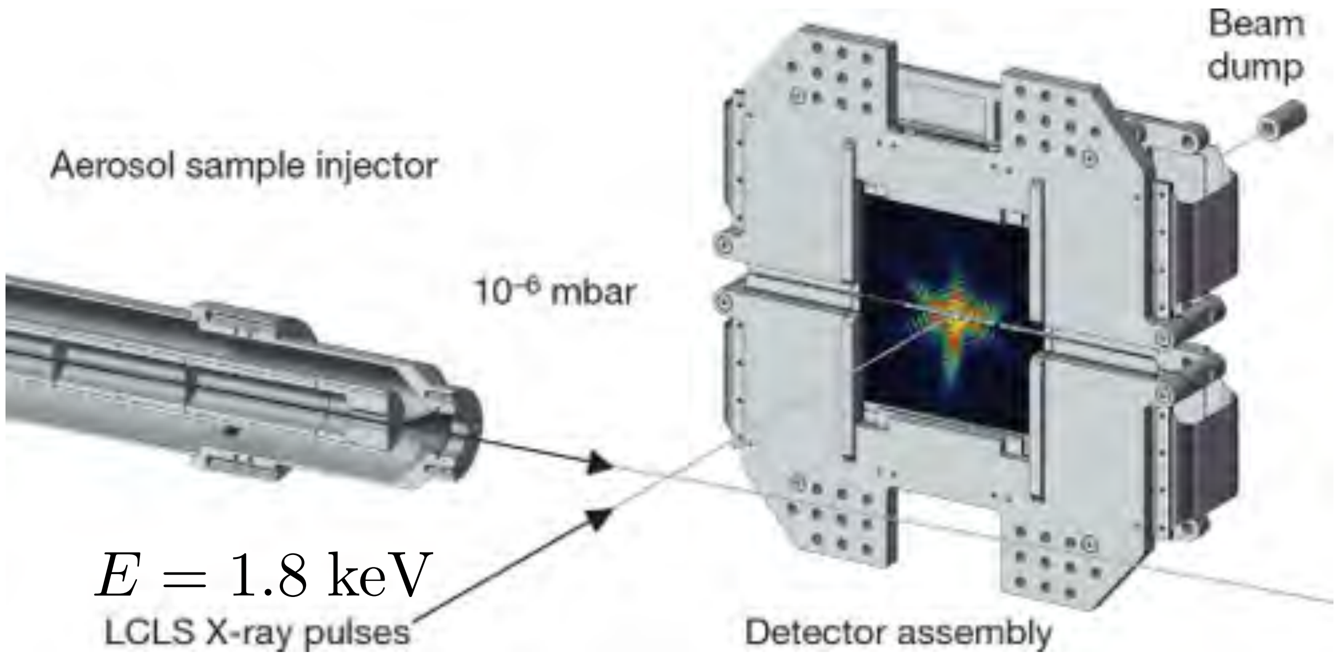
second pulse:
sample destroyed

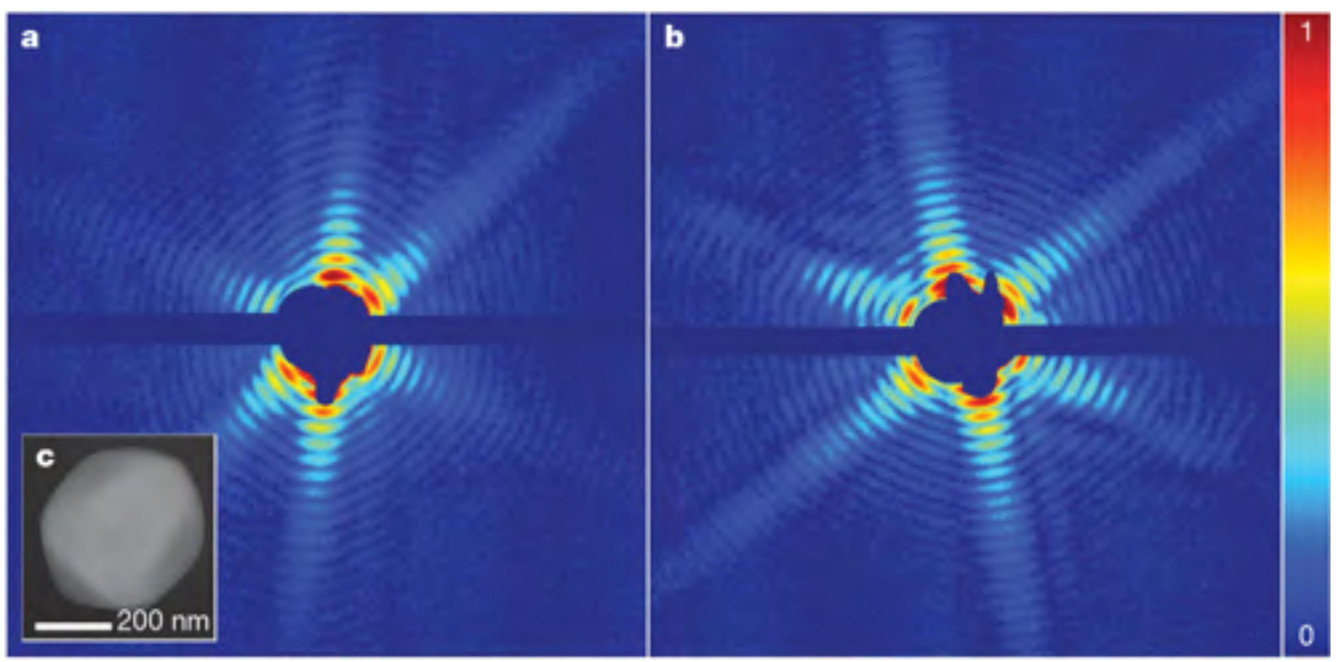


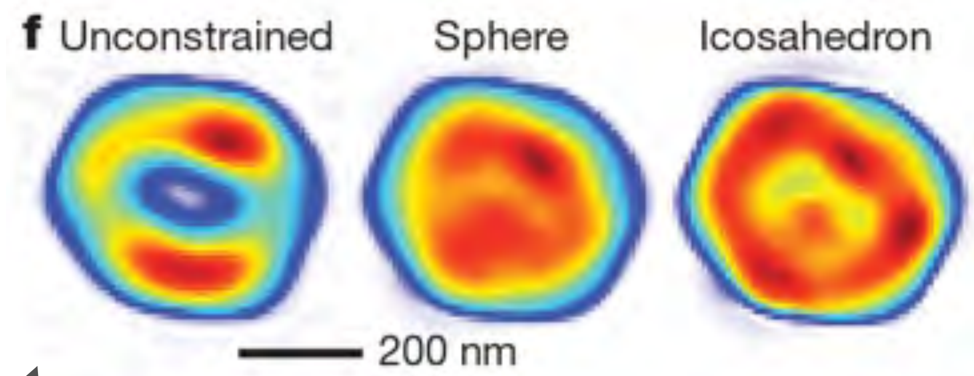


H. Chapman et al.,
Nature Phys. 2, 839 (2006)

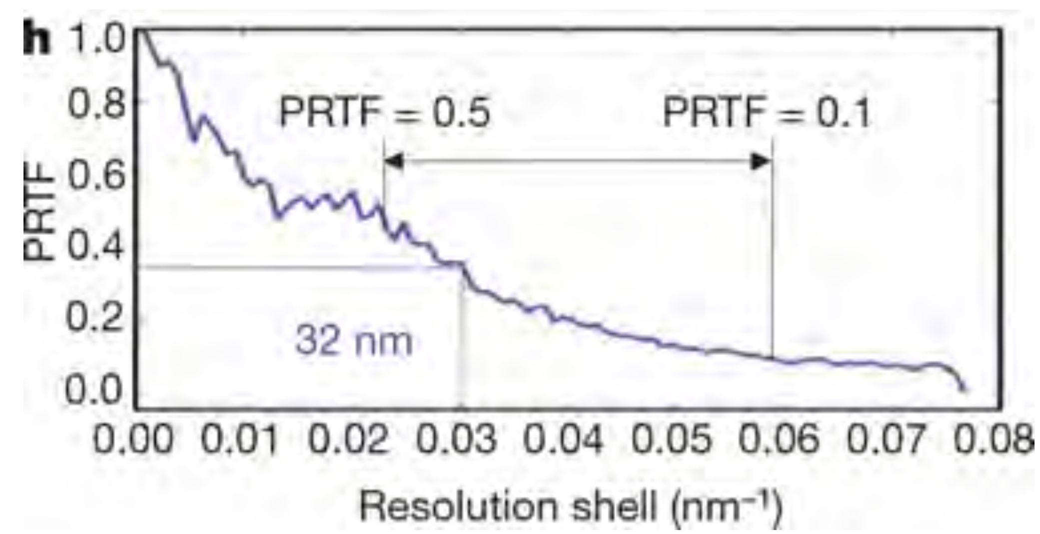
CXDI of Biological Samples: Mimivirus







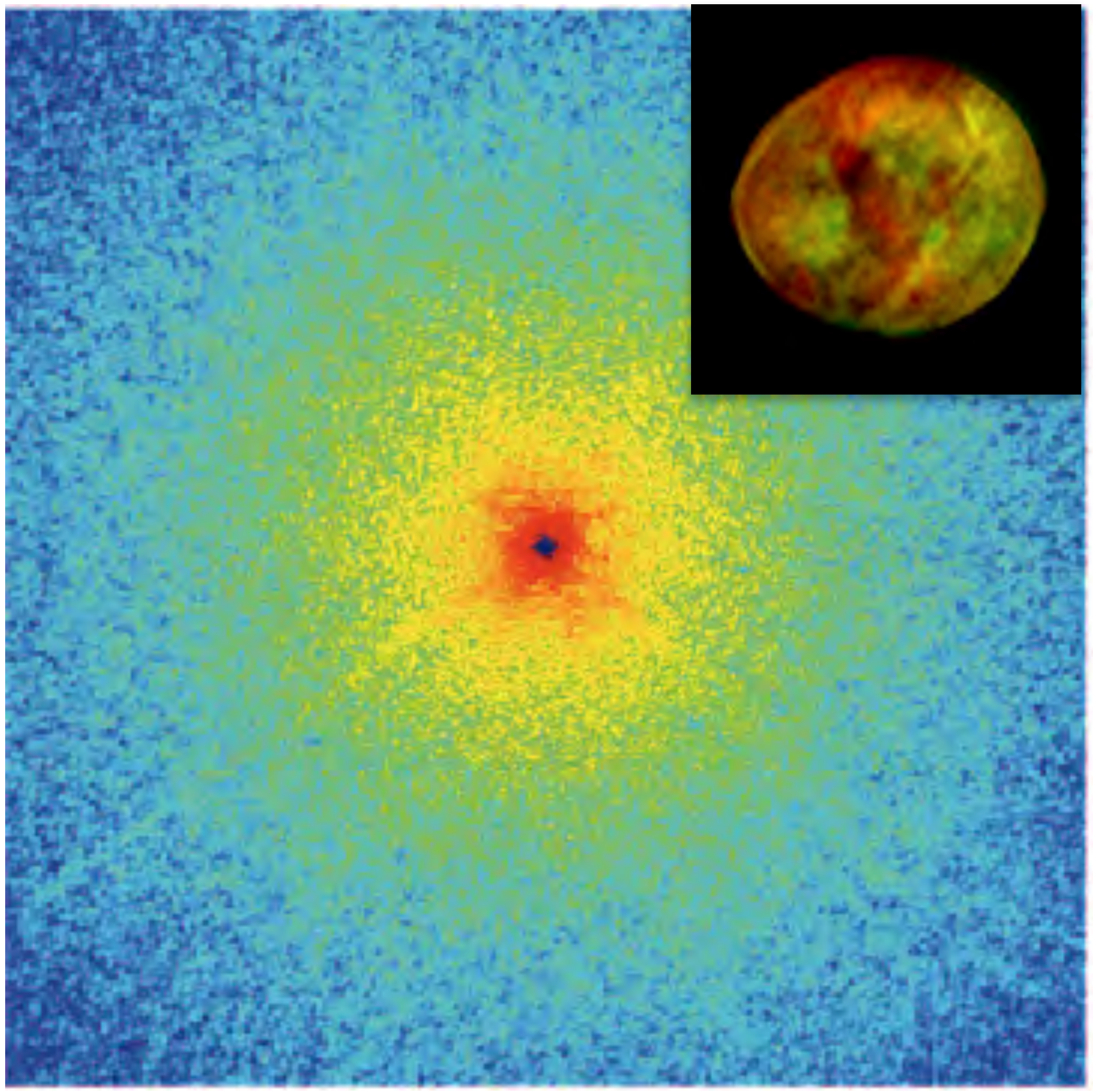
reconstruction

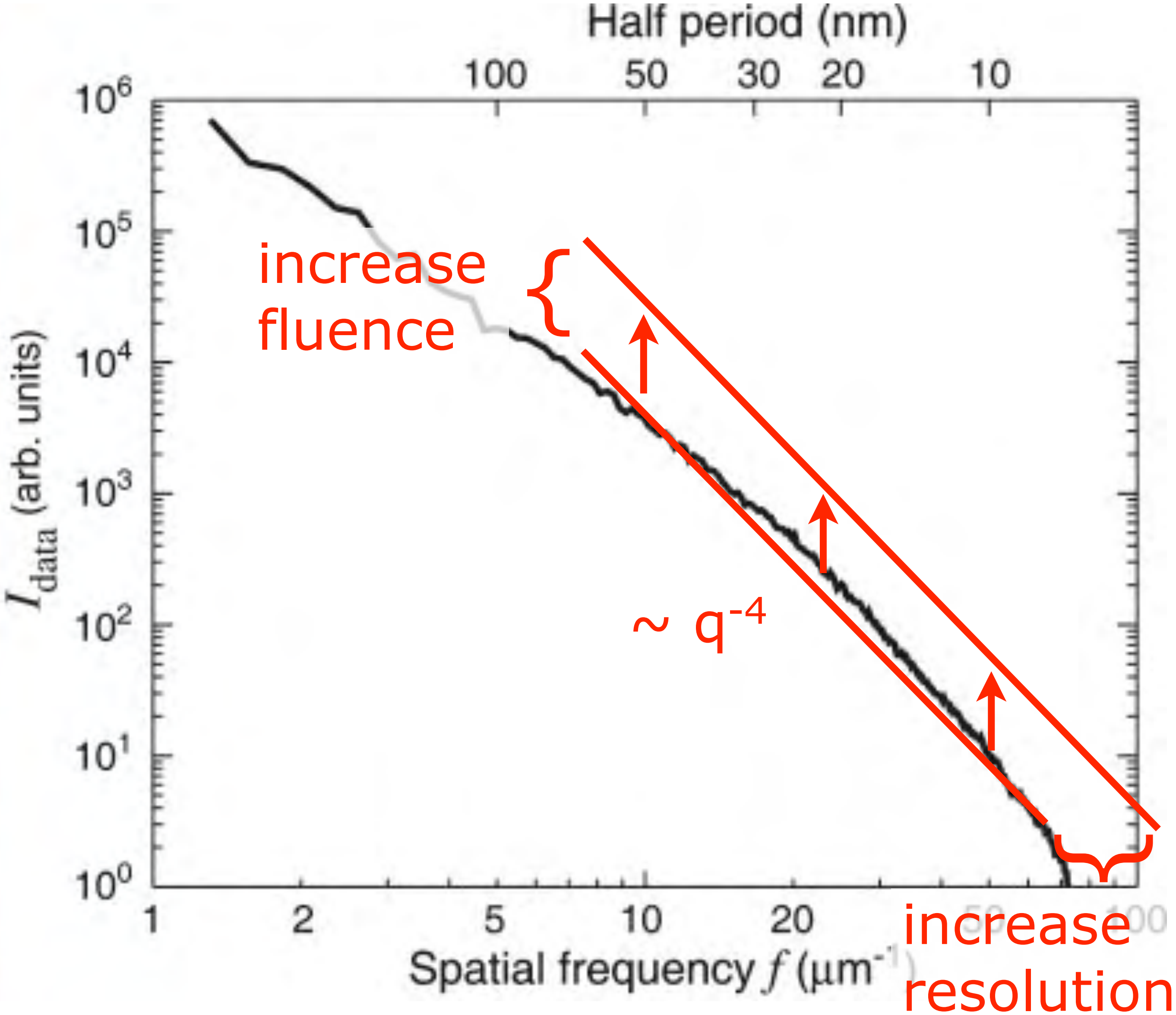


M. Seibert, et al.,
Nature **469**, 78 (2011)

Spatial Resolution

Diffraction pattern of
a yeast cell:



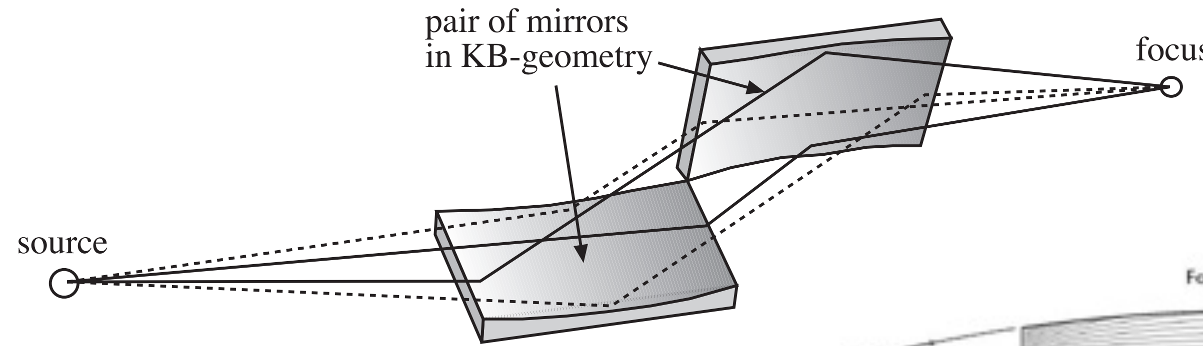


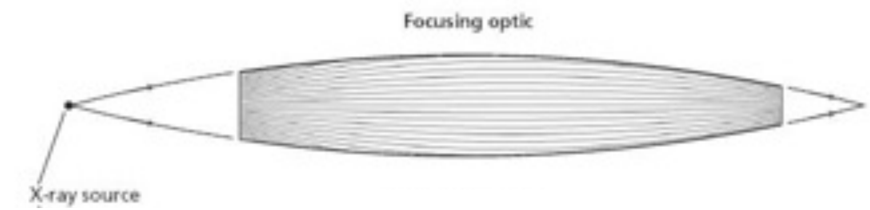
D. Shapiro, et al., PNAS **102**, 15343 (2005).
$E = 750 \text{ eV}$

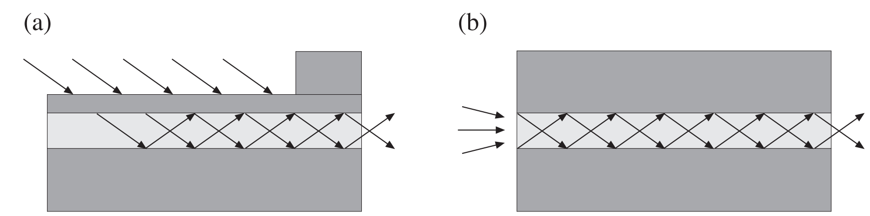
Nanofocusing Optics

reflection:

- mirrors (25 nm)
- capillaries
- wave guides (~10 nm)

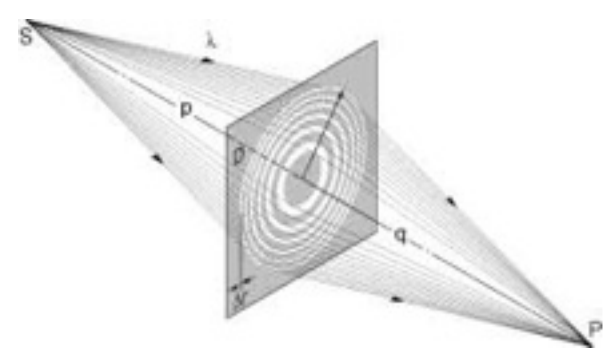


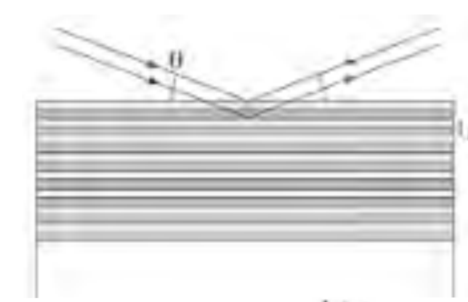


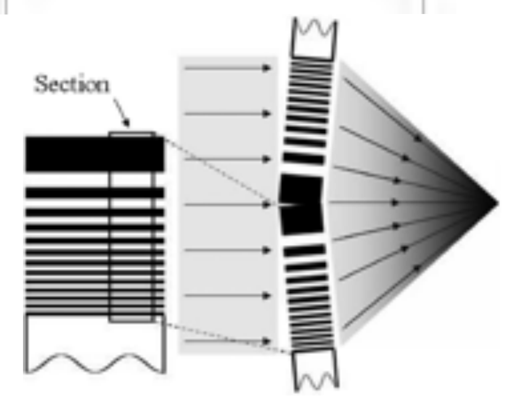


diffraction:

- Fresnel zone plates (~20 nm)
- multilayer mirrors (7 nm)
- multilayer Laue lenses (16 nm)
- bent crystals

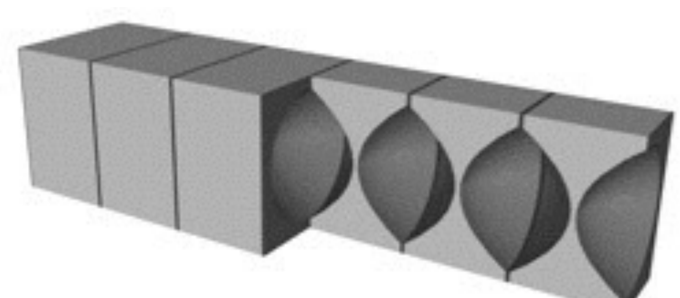






refraction:

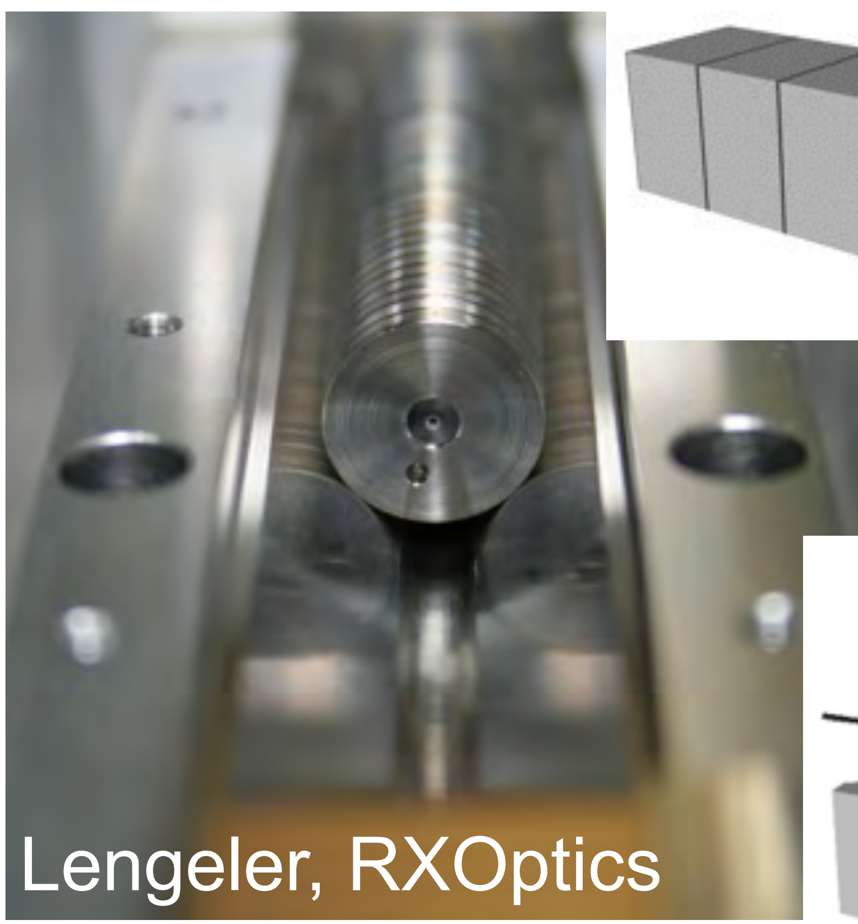
- lenses (43 nm, 18 nm)

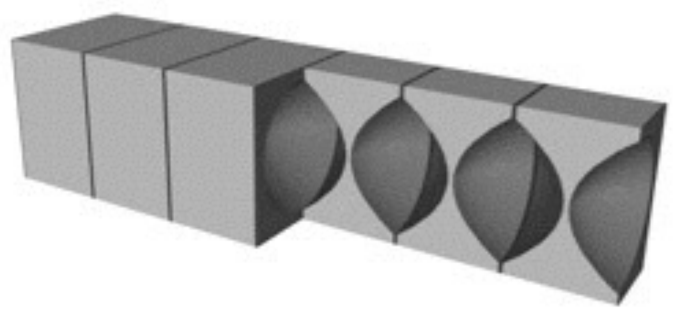


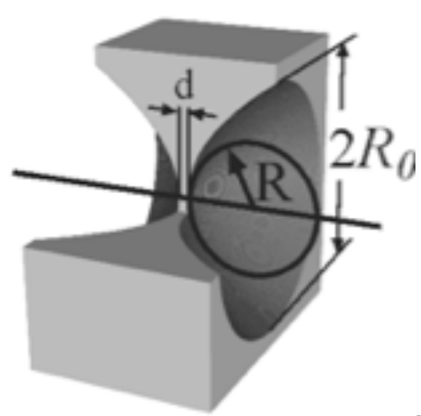
Refractive X-Ray Lenses

- first realized in 1996 (Snigirev et al.)
- a variety of refractive lenses have been developed since
- applied in full-field imaging and scanning microscopy
- most important to achieve optimal performance:

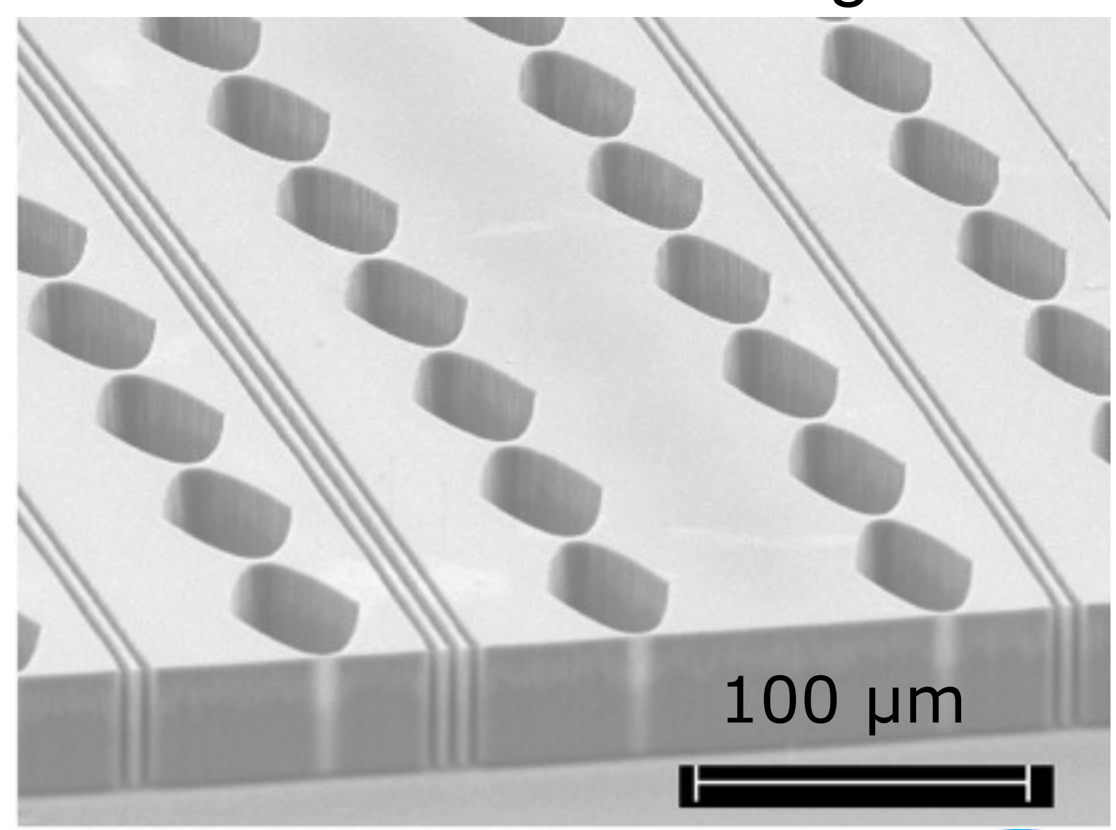
parabolic lens shape







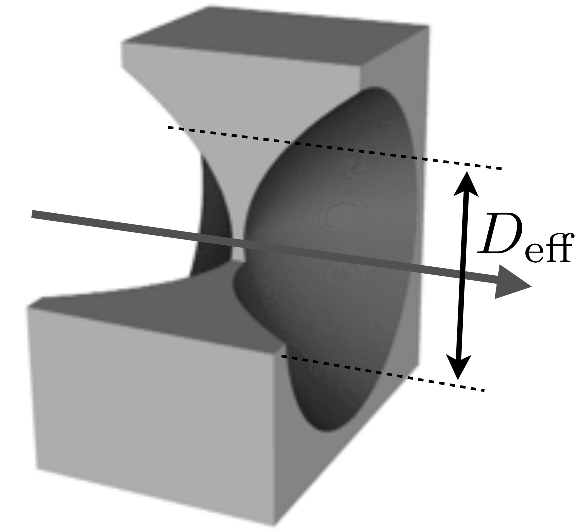
nanofocusing lenses



Nanofocus

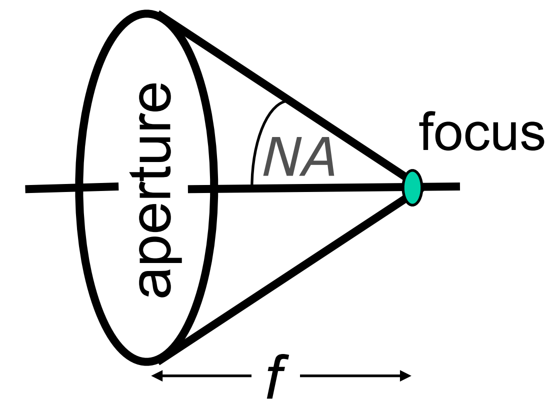
Large focal length *f*: aperture limited by absorption

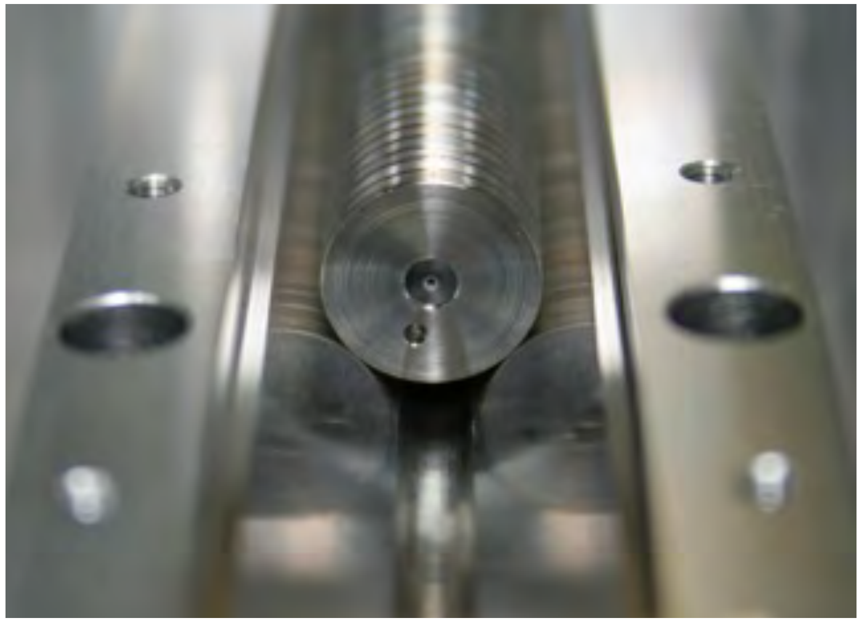
$$D_{\text{eff}} = 4\sqrt{\frac{f\delta}{\mu}} \propto \sqrt{f}$$



→ minimize *μ*/*δ* (⇒ small atomic number *Z*)

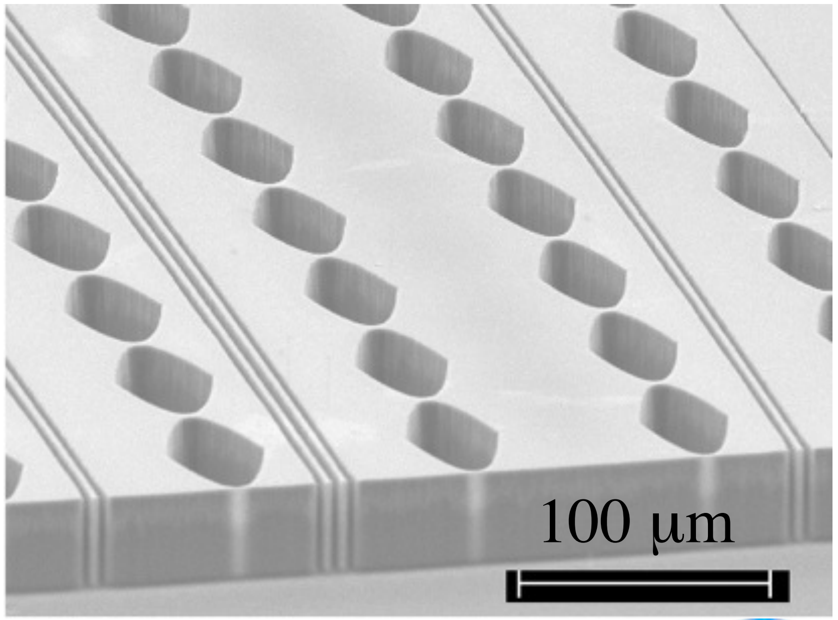
→ $NA = \frac{D_{\text{eff}}}{2f} \propto \frac{1}{\sqrt{f}}$ (⇒ minimize focal length *f*)



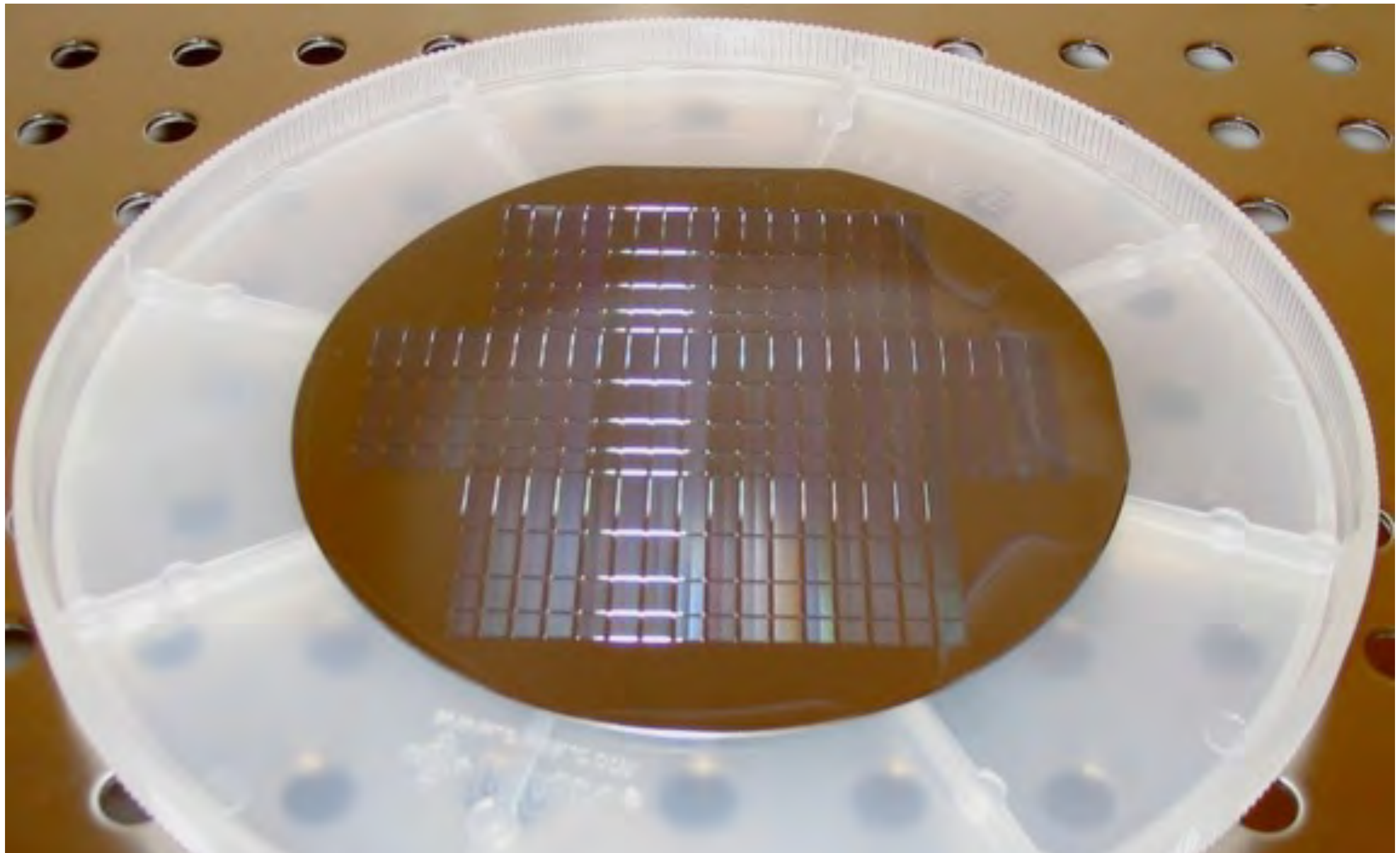


transition to nanofocusing lenses (NFLs)

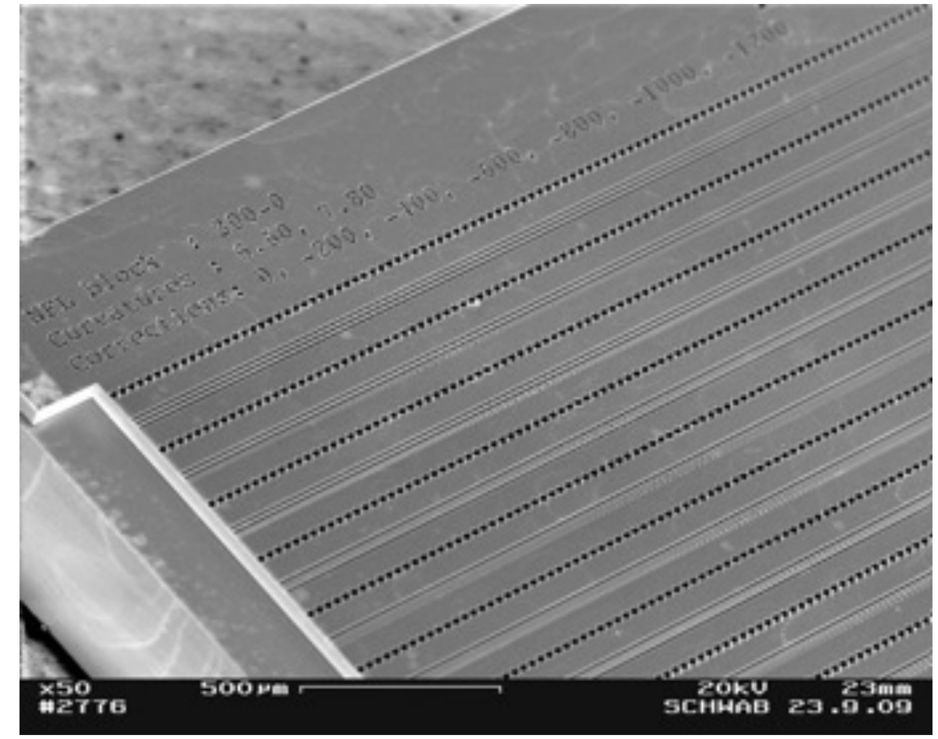
→

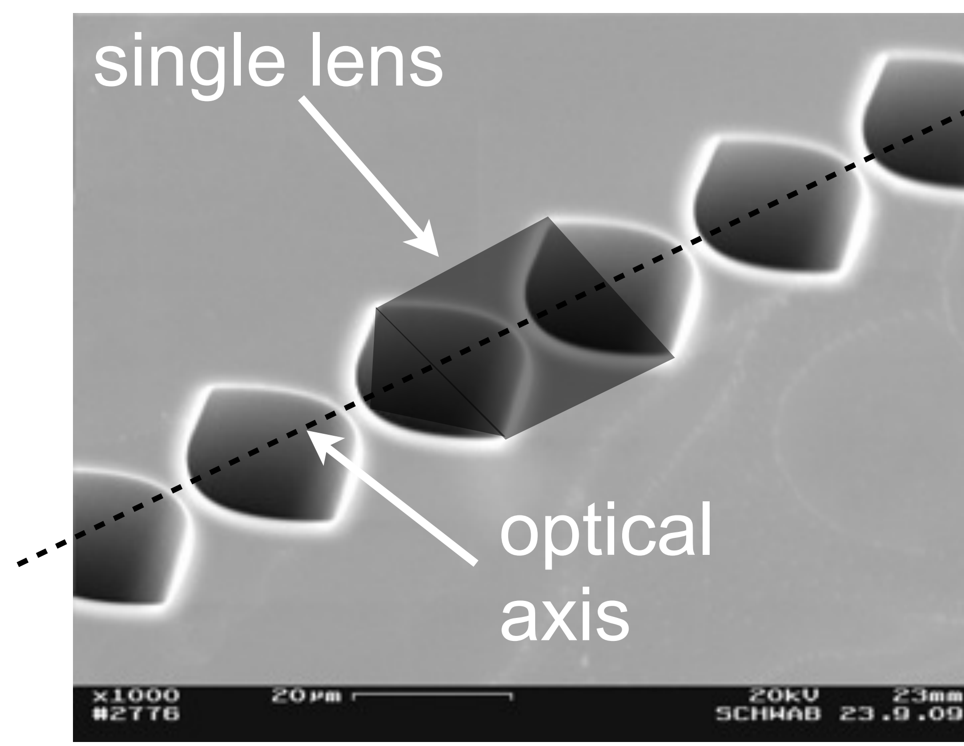


Nanofocusing Lenses (NFLs) Made of Silicon



Made at IHM at TU Dresden together with SAW Components.





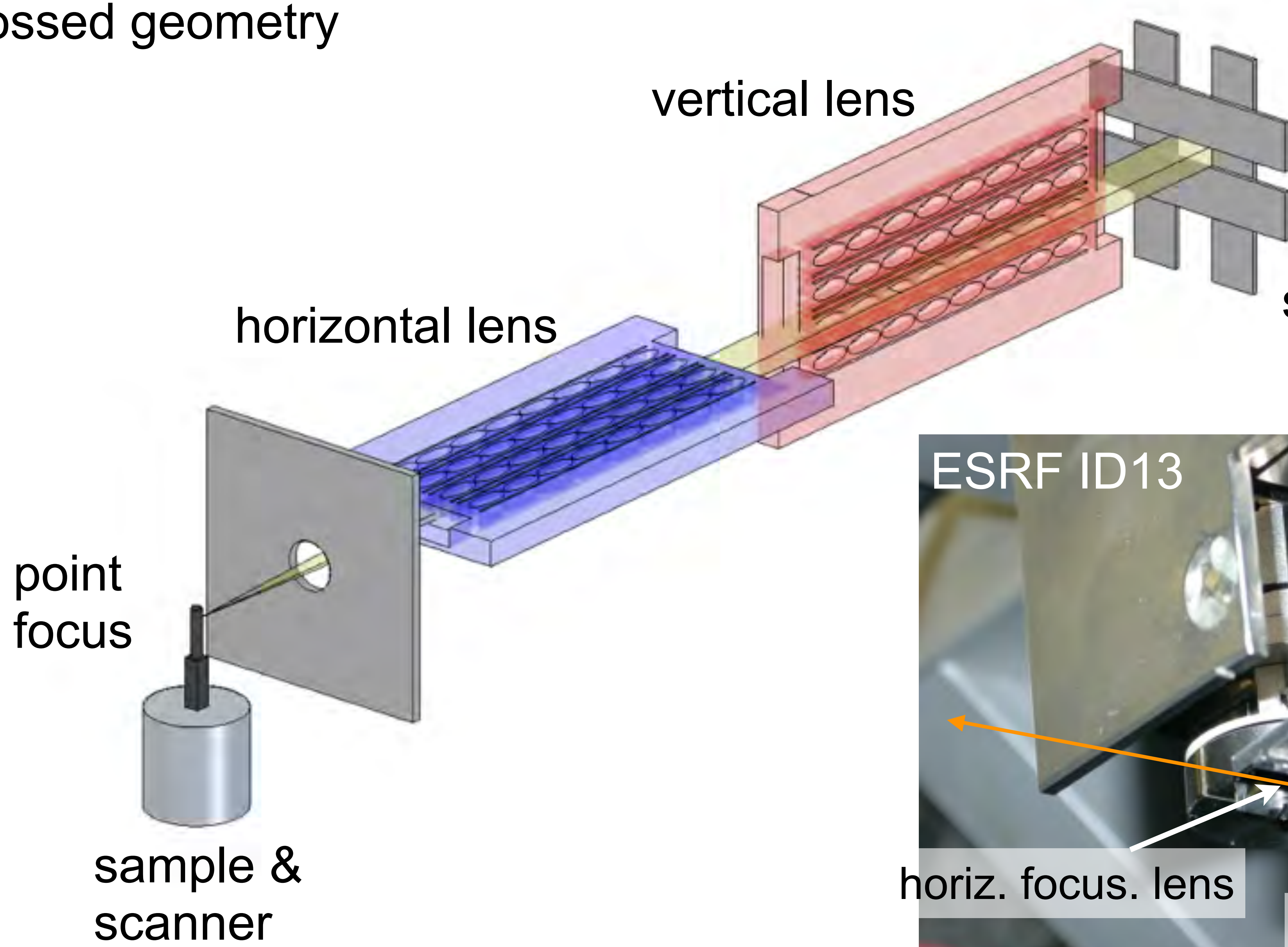
3136 NFLs on wafer!
about 600000 single lenses!

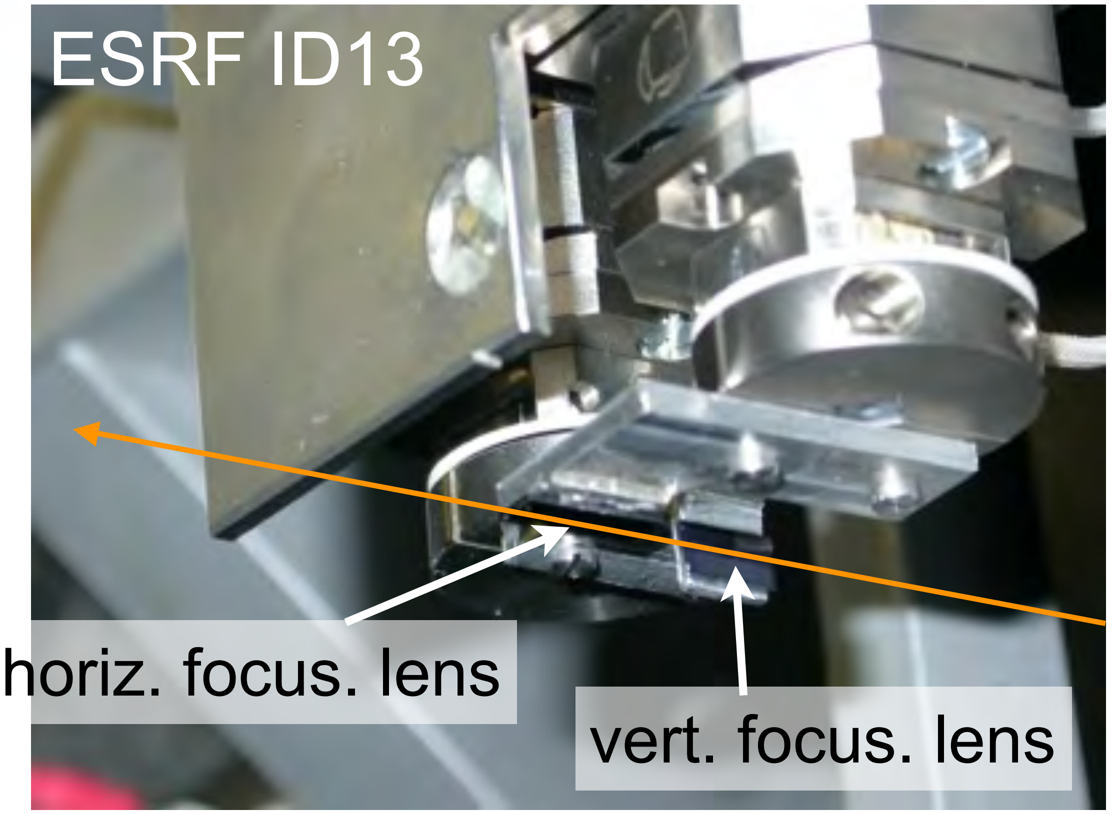
→ high accuracy, reproducibility

APL **82**, 1485 (2003).

Nanofocusing Lenses (NFLs)

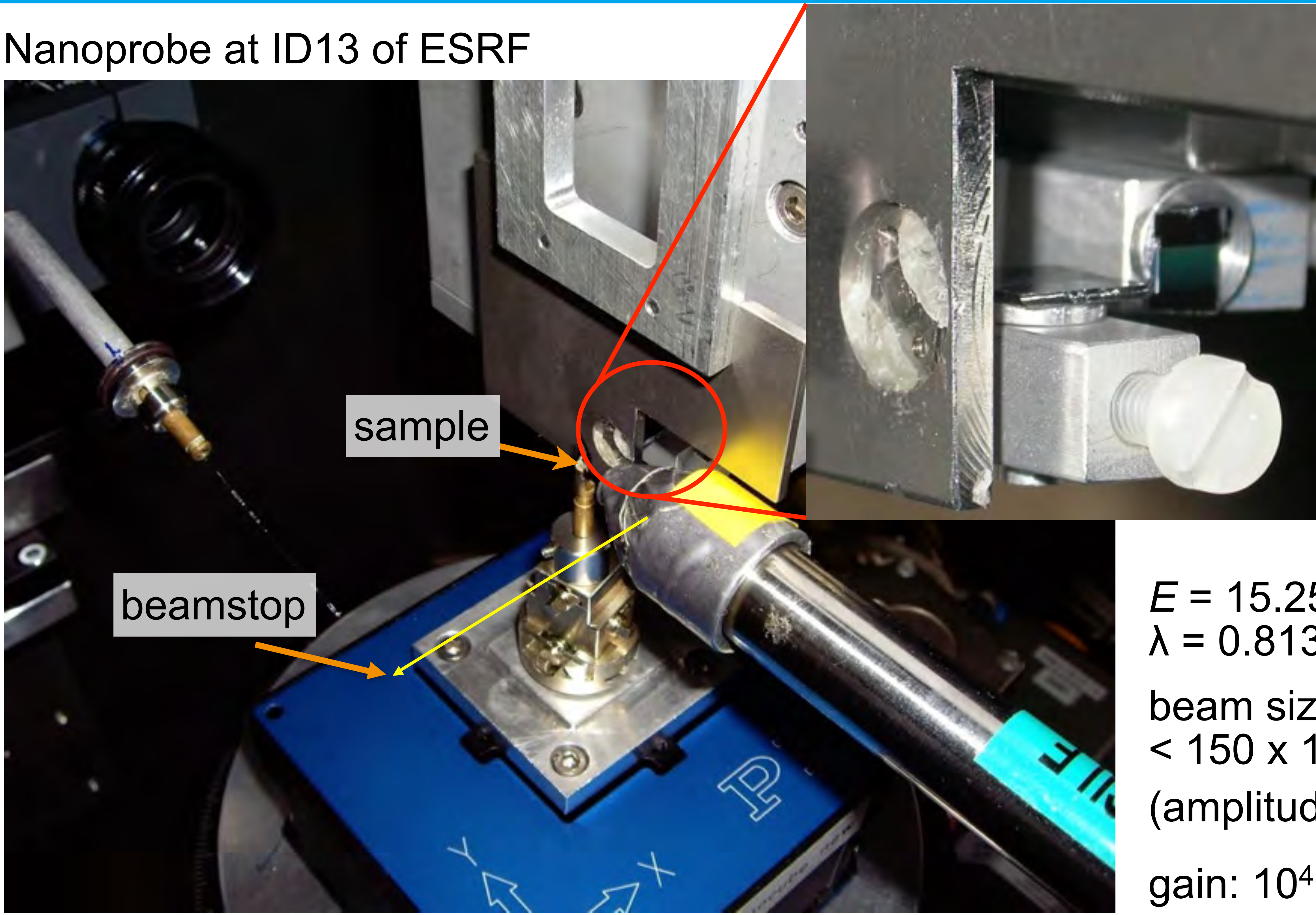
point focus requires two lenses in crossed geometry





Nanoprobe: Coherent X-Ray Diffraction Imaging

Nanoprobe at ID13 of ESRF

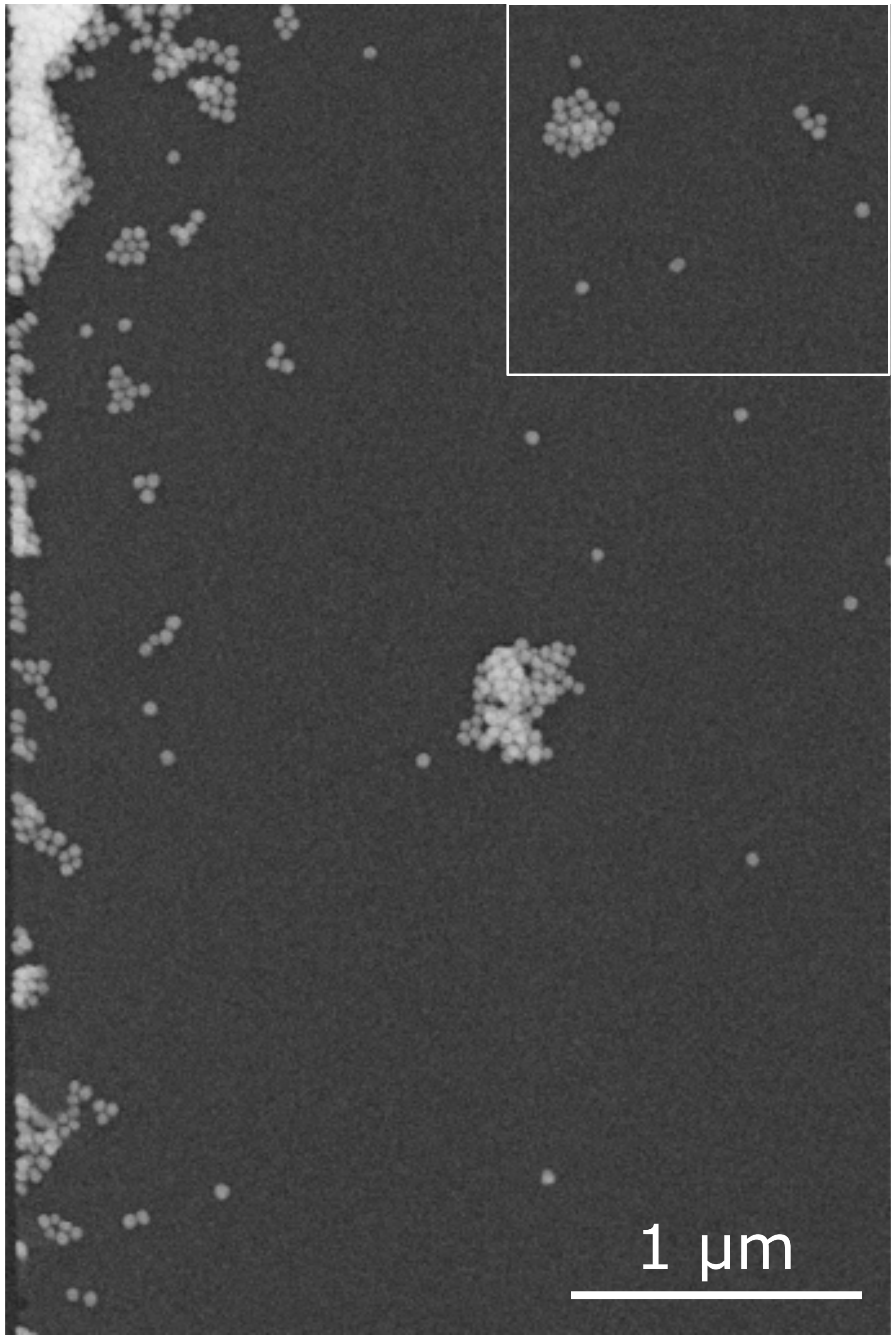


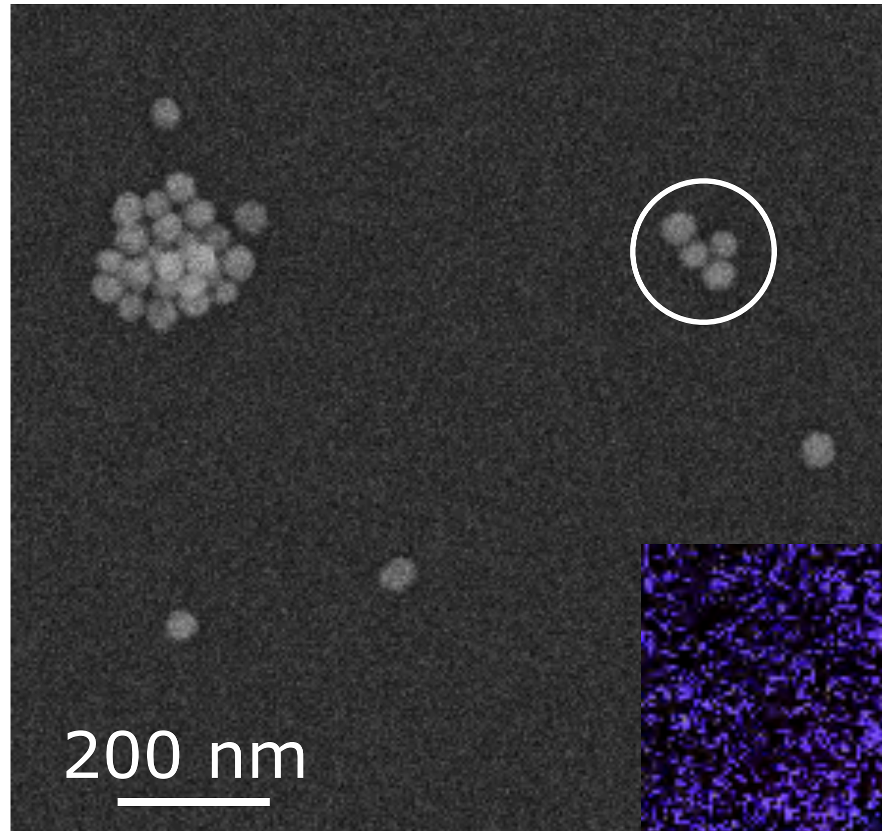
E = 15.25 keV
λ = 0.813 Å

beam size:
< 150 x 150 nm^2
(amplitude)

gain: 10^4

Imaging of Small Objects





4 gold particles:

diameter ~ 40 nm

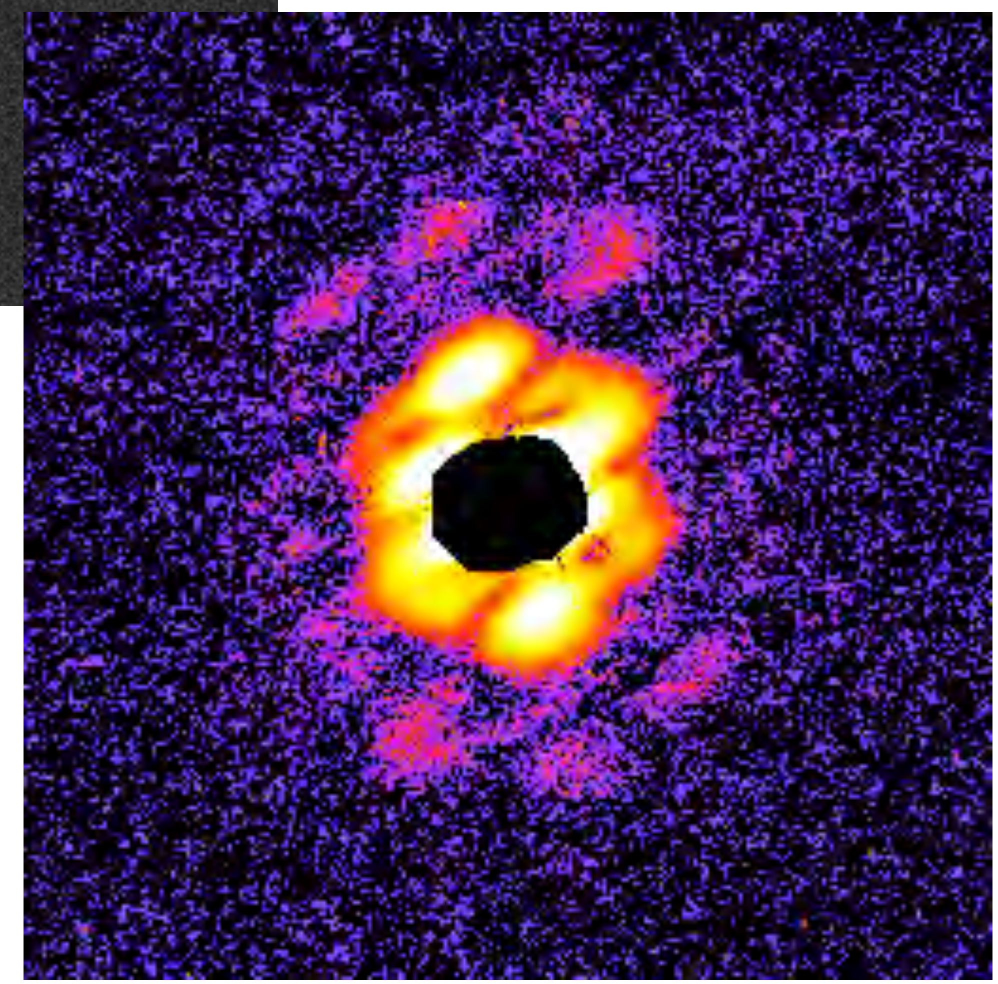
→ $7.5 \cdot 10^6$ atoms

fluence:

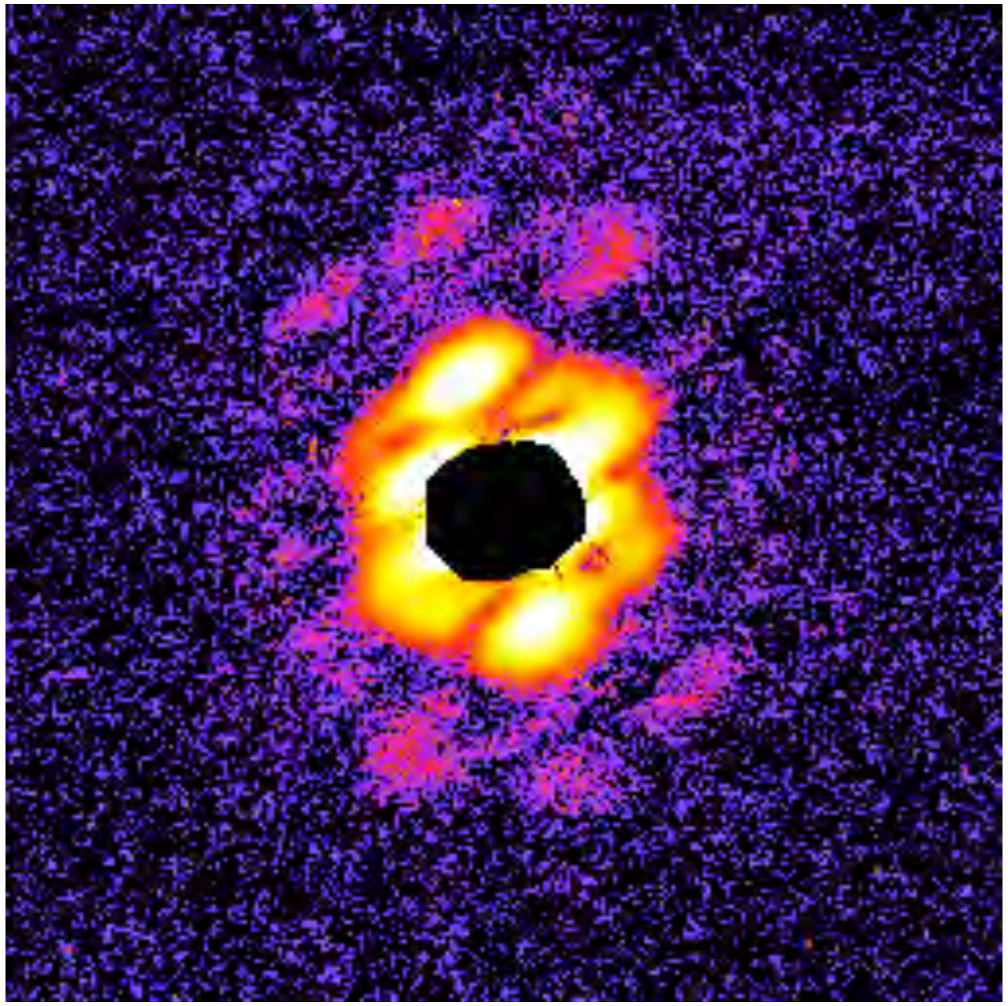
$1 \cdot 10^5$ ph/nm^2

dose:

$1 \cdot 10^{10}$ ph

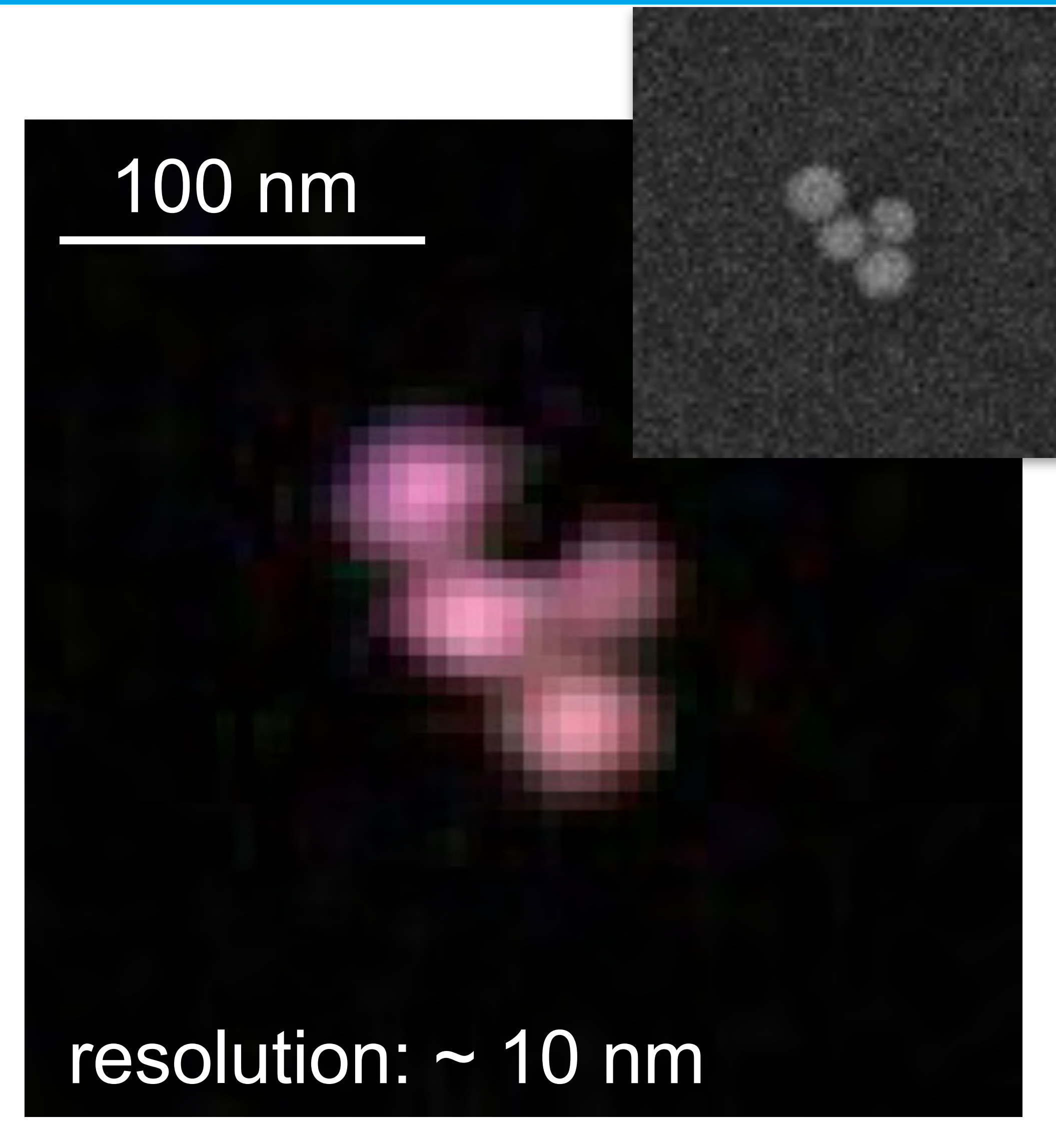


Reconstruction

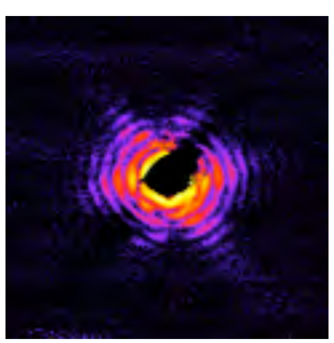


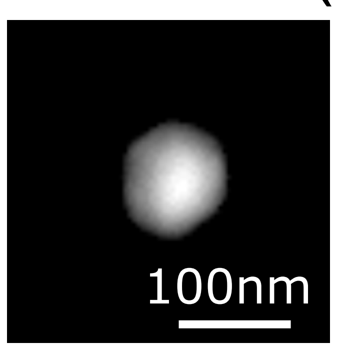
HIO

shrink wrap



record resolution: 5 nm ($1.5 \cdot 10^6$ ph/nm^2)





diffraction at single gold particle

PRL **101**, 090801 (2008).

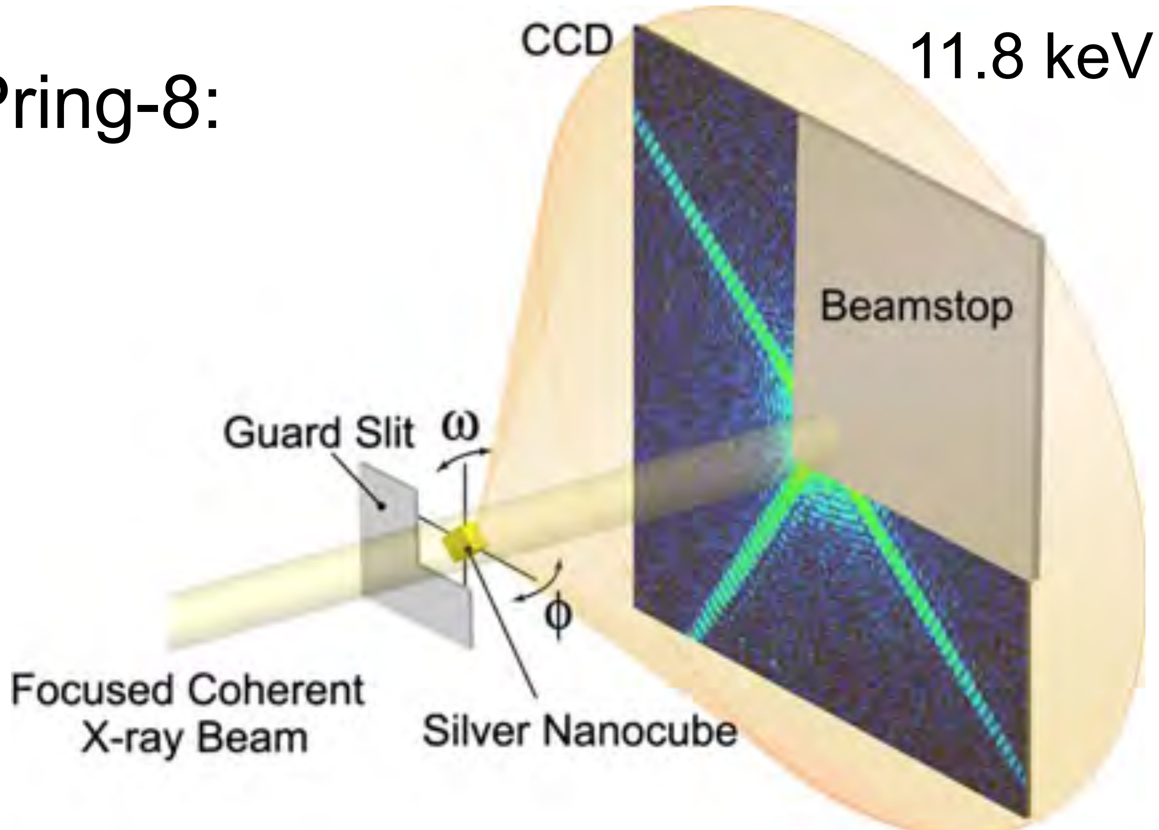
4 gold particles:

- fluence 10 x smaller
- resolution reduced by

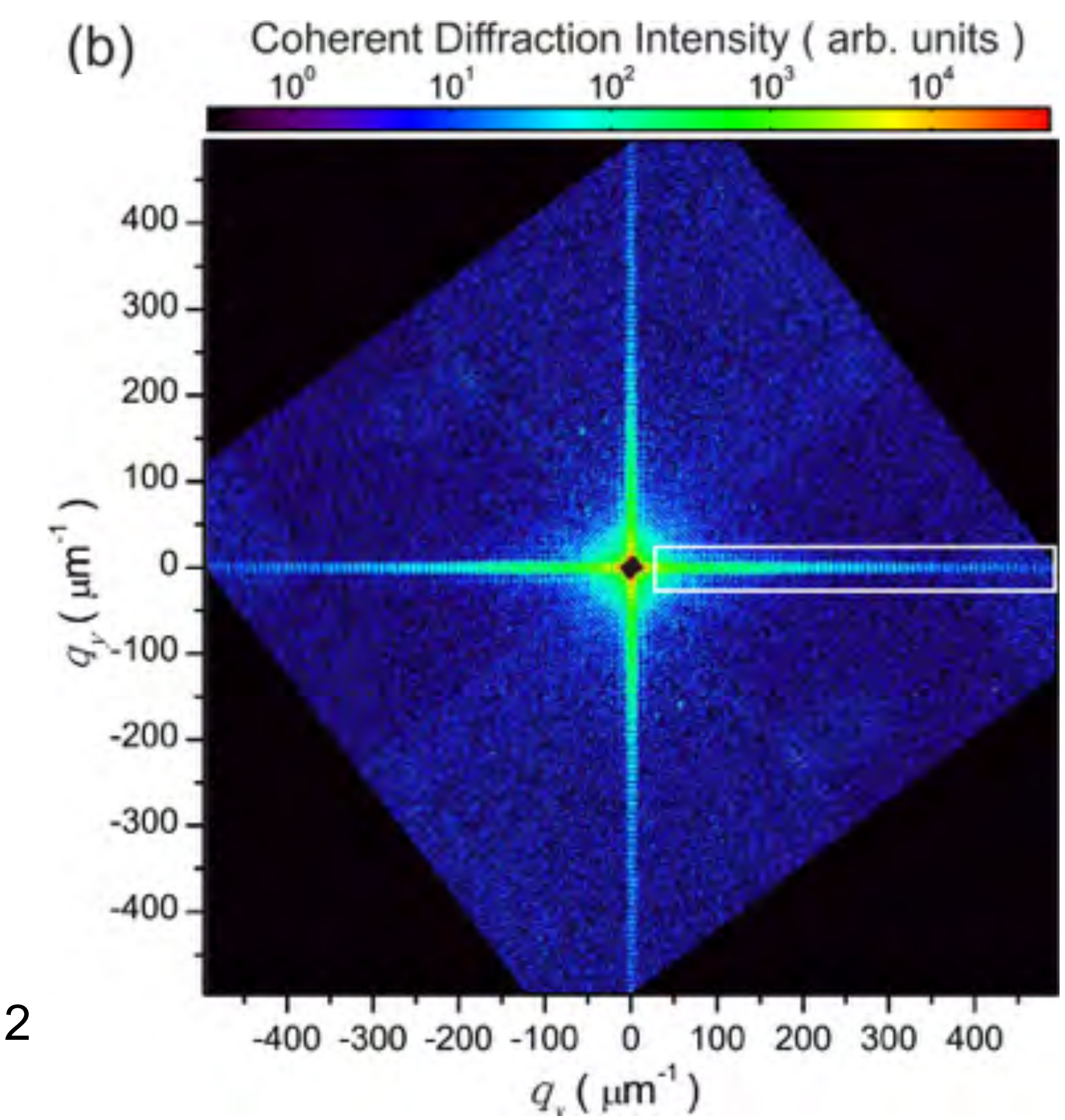
$$\sqrt[4]{10} \approx 1.8$$

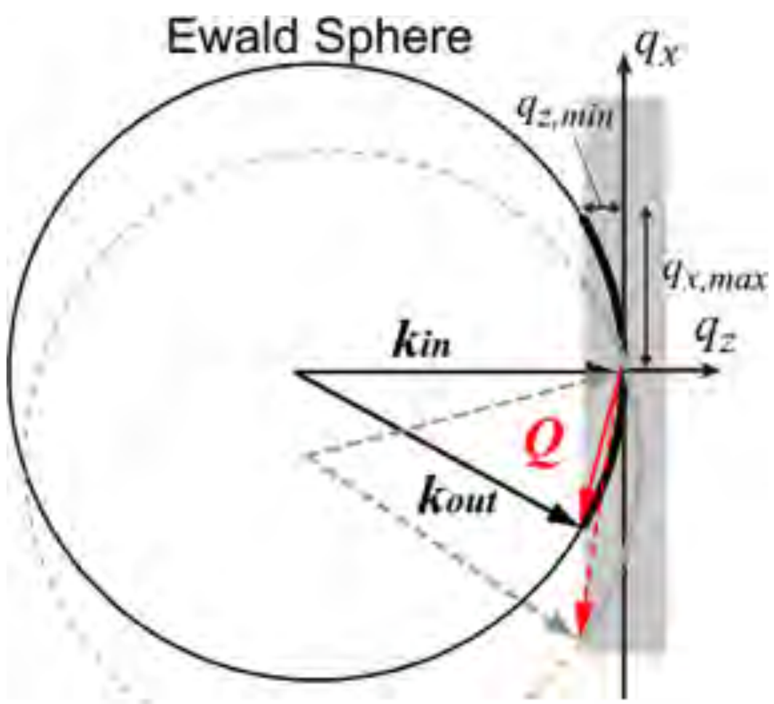
CXDI of Silver Nanocube

SPring-8:



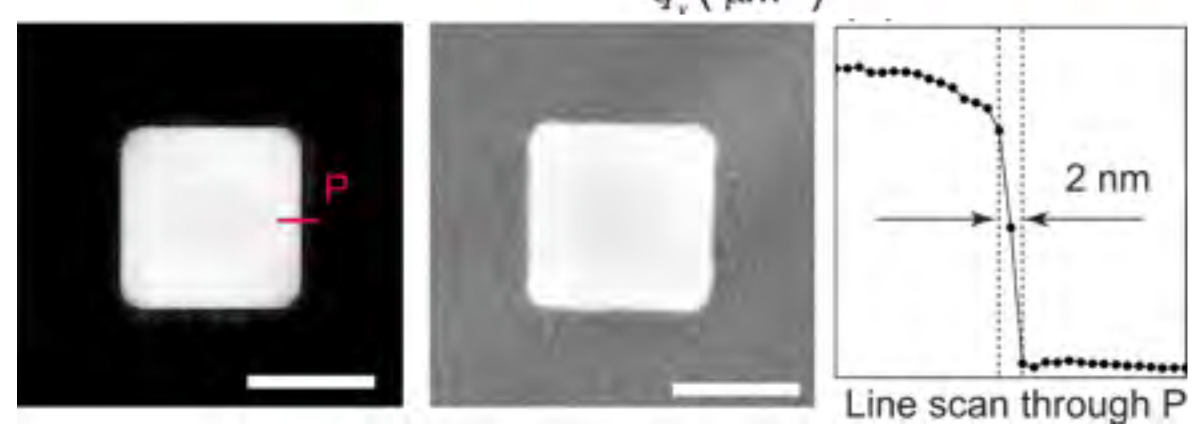
11.8 keV





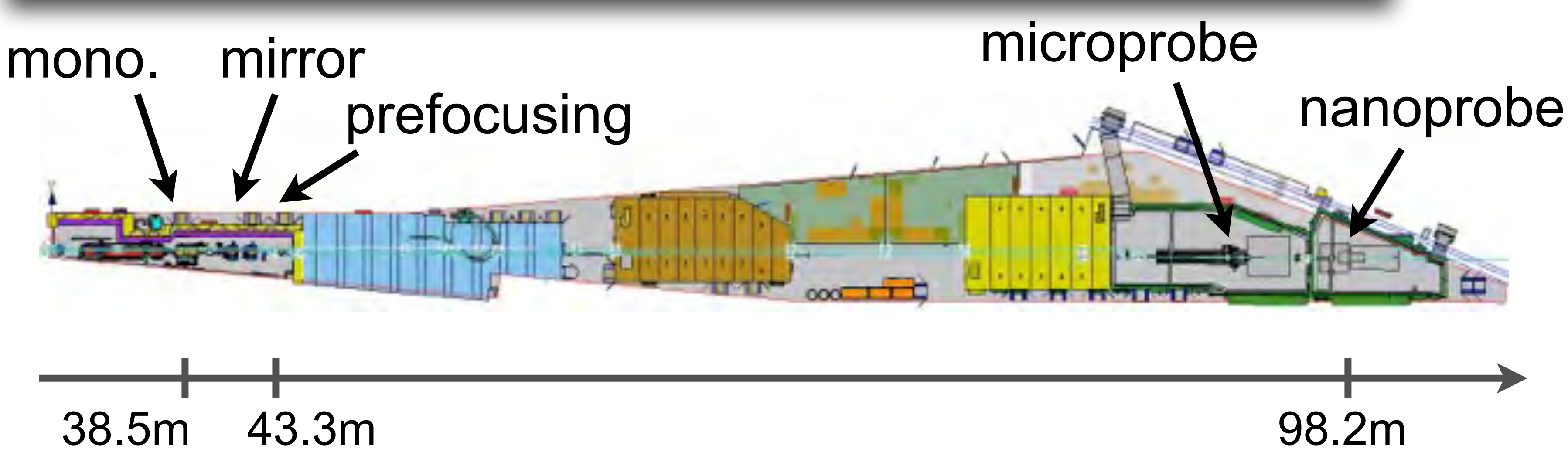
total fluence:

$16 \cdot 10^6$ ph/nm^2



Y. Takahashi, et al., Phys. Rev. B, **80**, 054103 (2009).

Hard X-ray Scanning Microscopy at PETRA III



Microscope:

~98 m from source

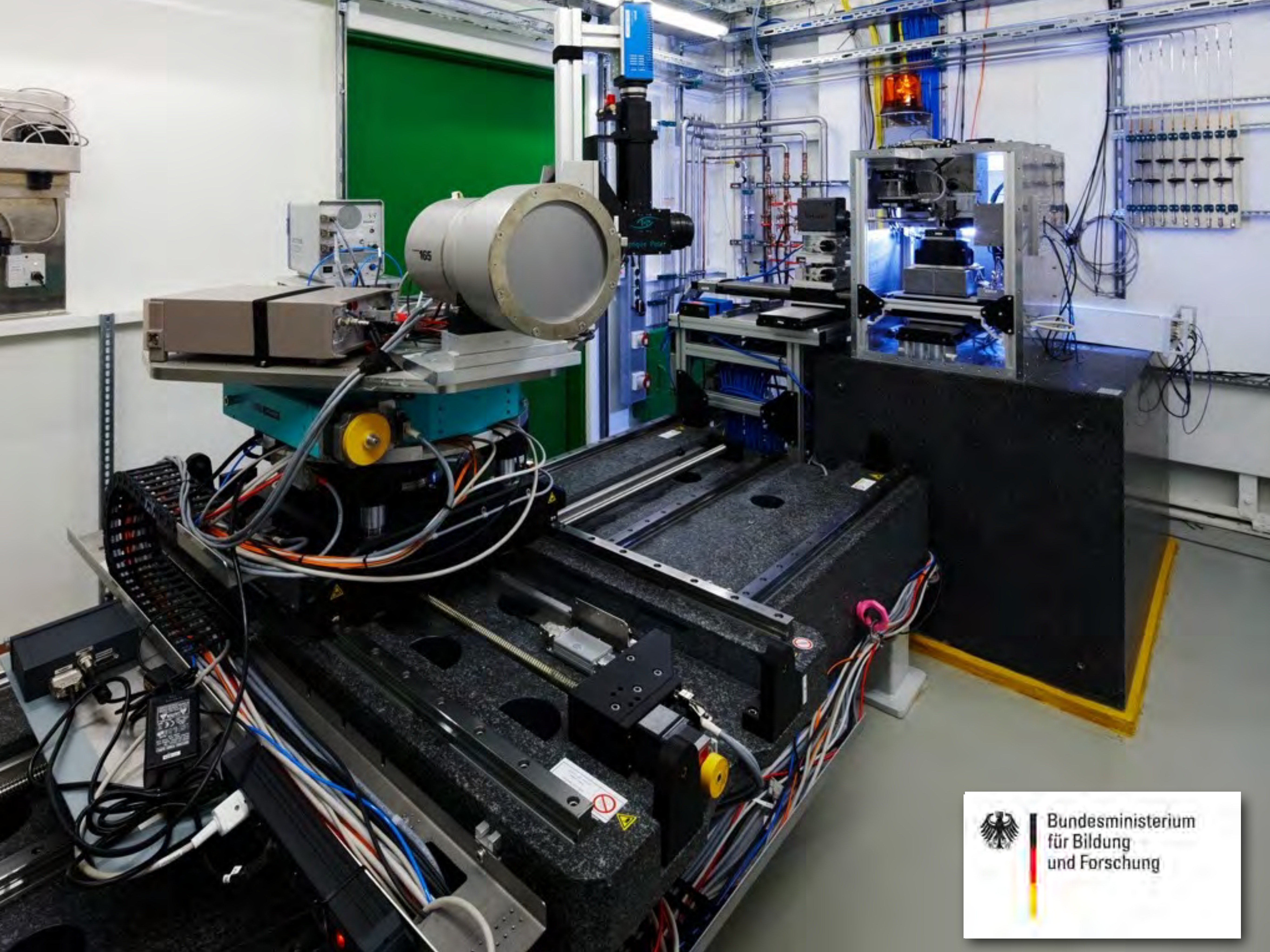
different contrasts:

- > fluorescence
- > diffraction (SAXS, WAXS)
- > absorption (XAS)
- > ptychography & CXDI

spatial resolution:
down to < 50 nm
down to < 5 nm (CXDI)

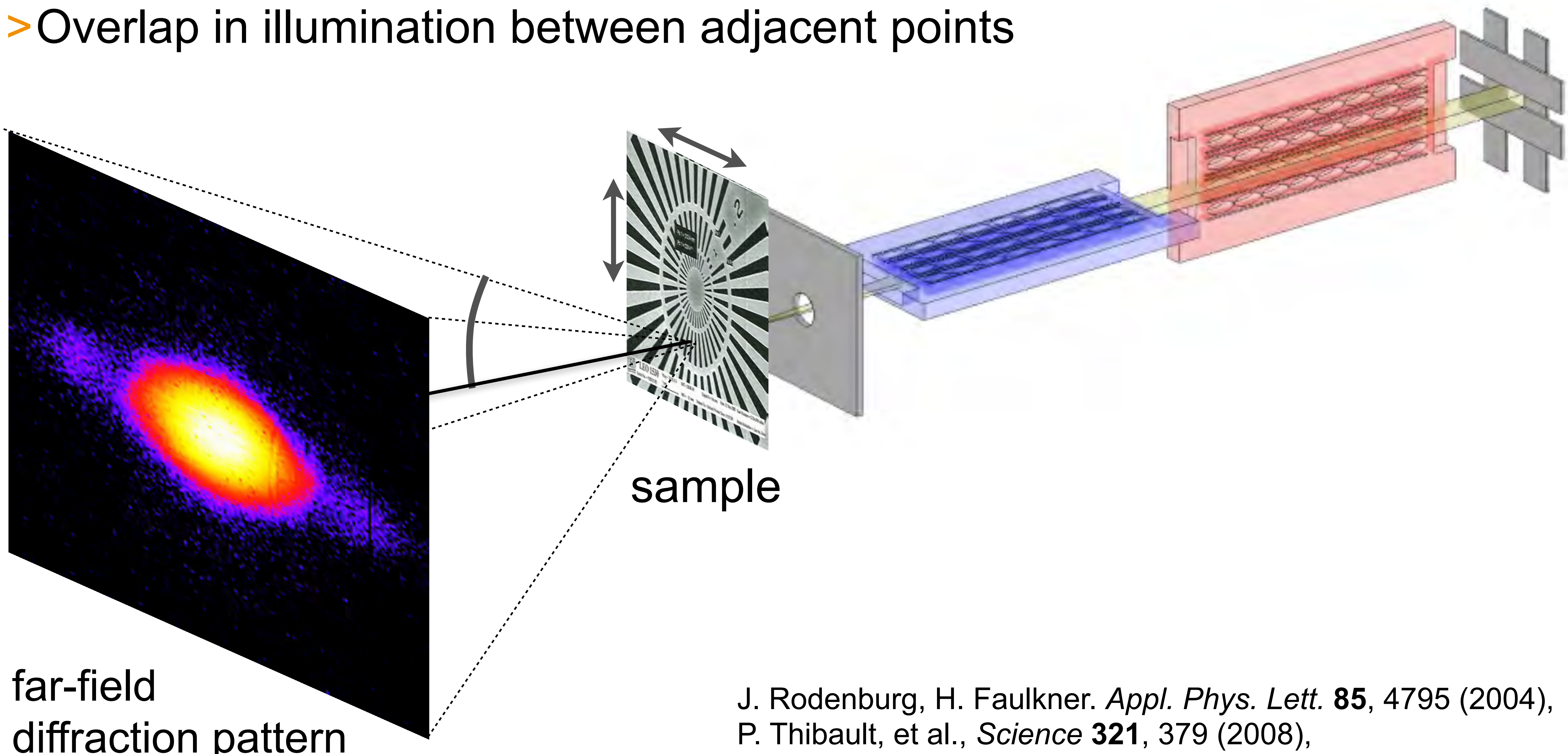
X-ray energy:
10 - 50 keV

Nucl. Instrum. Meth. A **616** (2-3), 93 (2010).


Bundesministerium
für Bildung
und Forschung

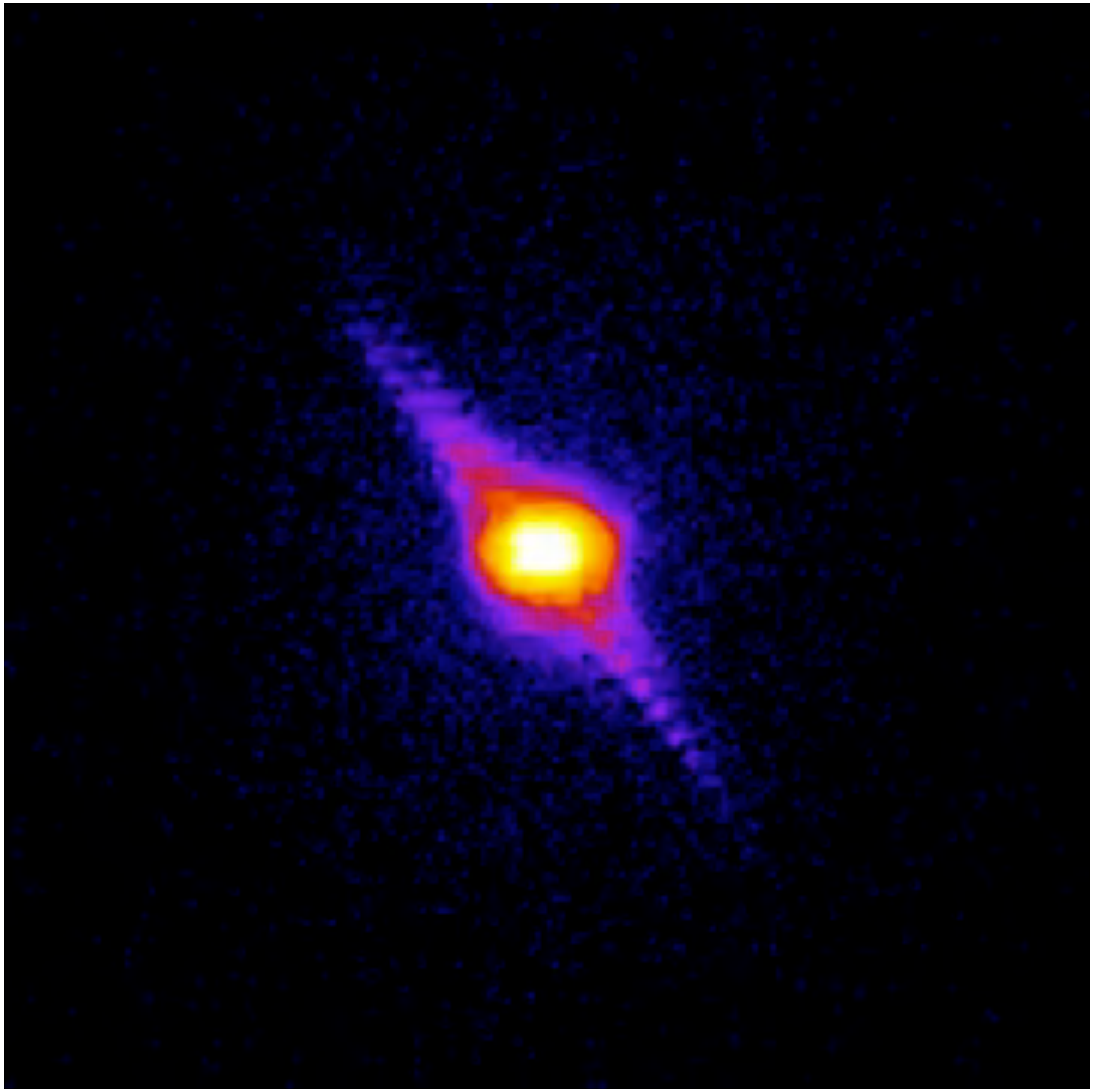
Scanning Coherent Diffraction Imaging: Ptychography

- Sample is raster scanned through confined beam
- At each position of scan: diffraction pattern is recorded
- Overlap in illumination between adjacent points



J. Rodenburg, H. Faulkner. *Appl. Phys. Lett.* **85**, 4795 (2004),
P. Thibault, et al., *Science* **321**, 379 (2008),
A. Schropp, et al., *Appl. Phys. Lett.* **96**, 091102 (2010),
M. Dierolf, et al., *Nature* **467**, 436 (2010).

Ptychographic Microscopy



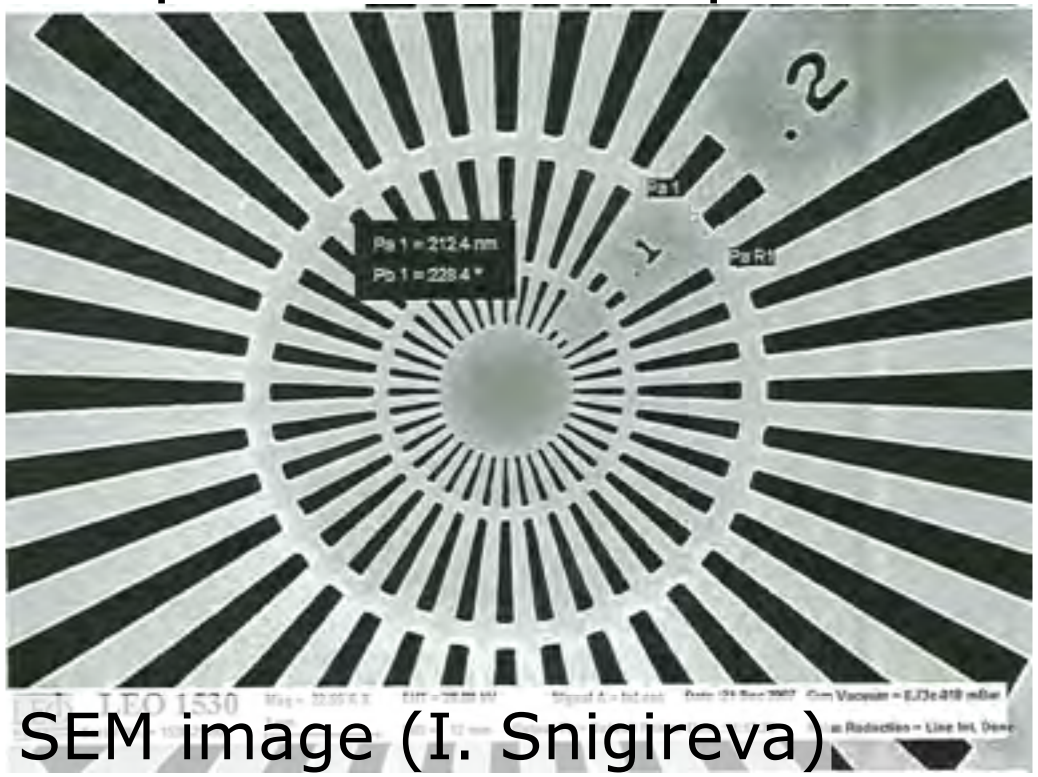
Experiment at P06:

detector:
Pilatus 300k (172µm pixel size)

sample-detector distance:
2080 mm

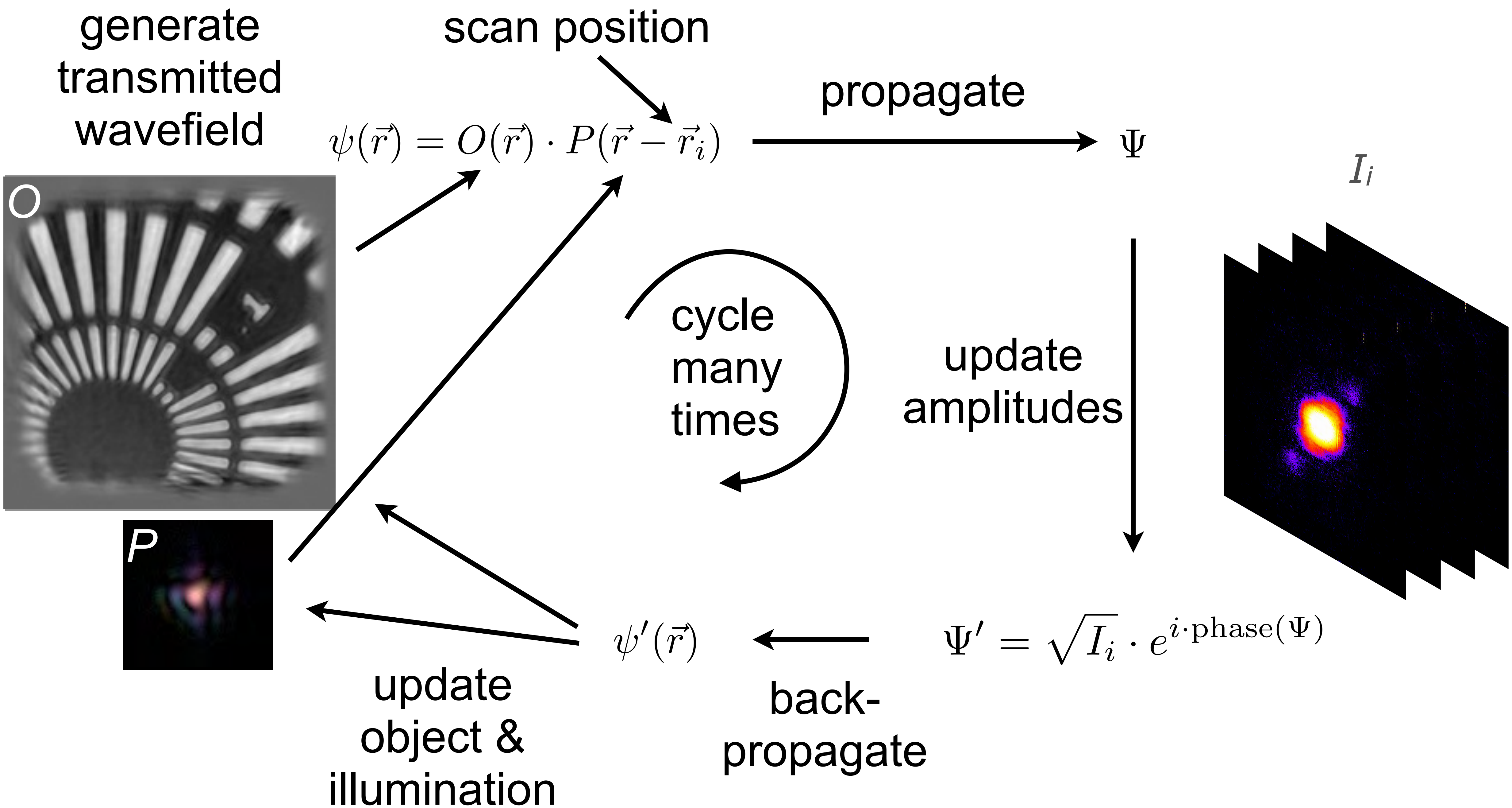
exposure time:
1.5 s per point

Sample: NTT AT test pattern



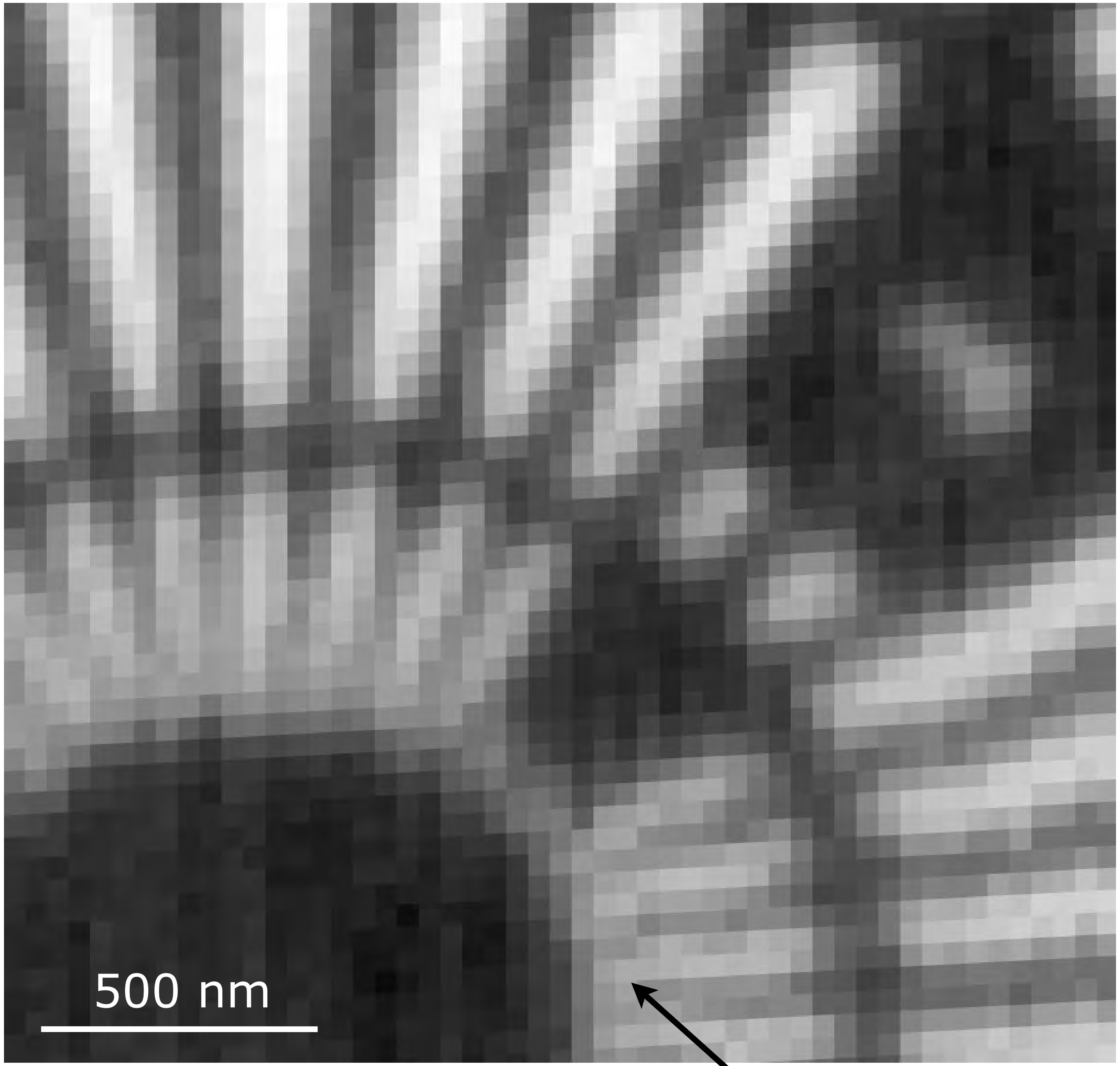
SEM image (I. Snigireva)

Ptychography: Reconstruction



Maiden & Rodenburg, Ultramicroscopy **109**, 1256 (2009).

Scanning Microscopy: Fluorescence Imaging

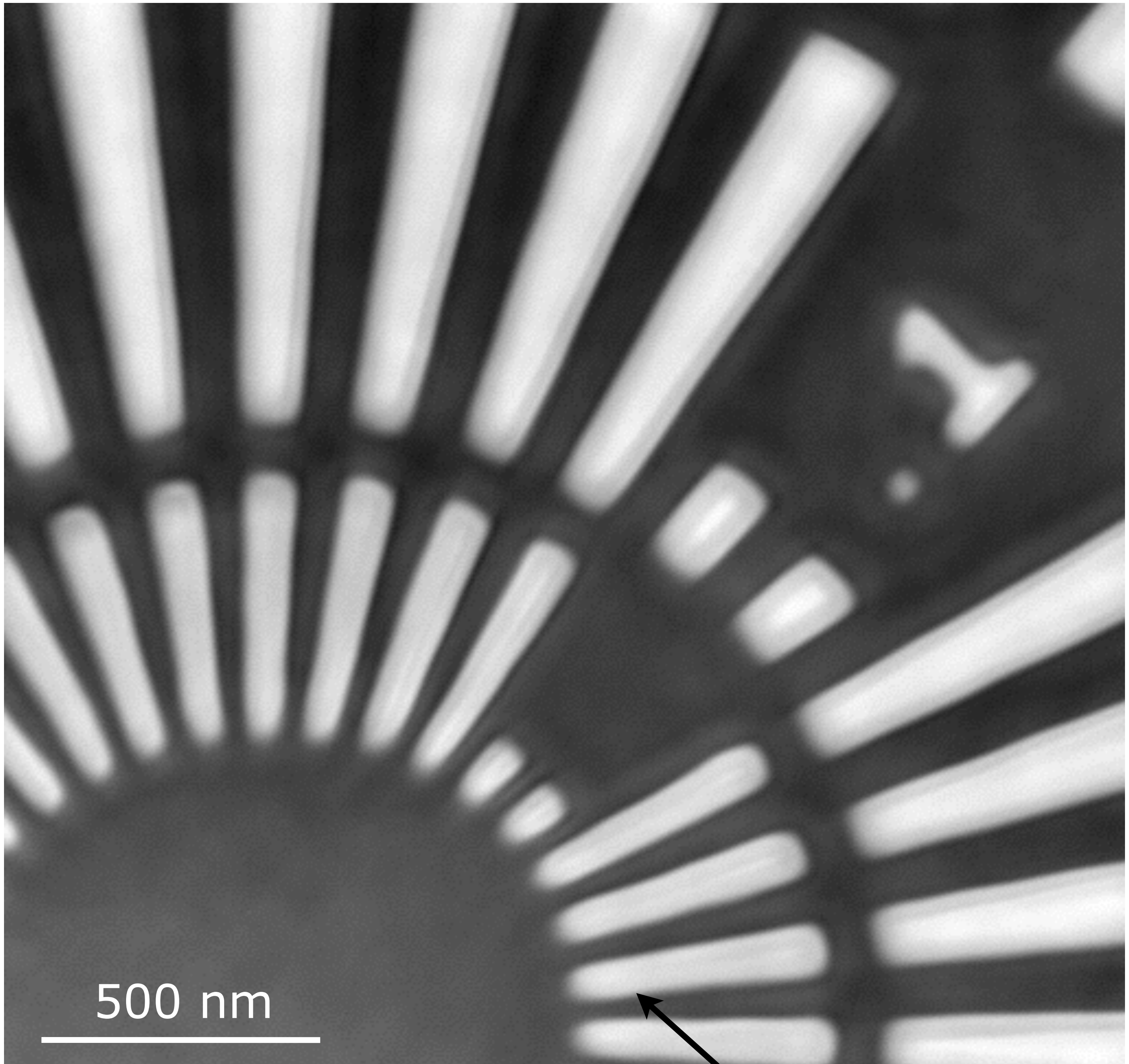


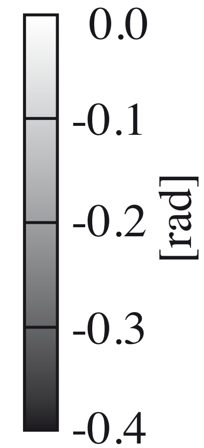
50 nm lines and spaces

Ta Lα fluorescence

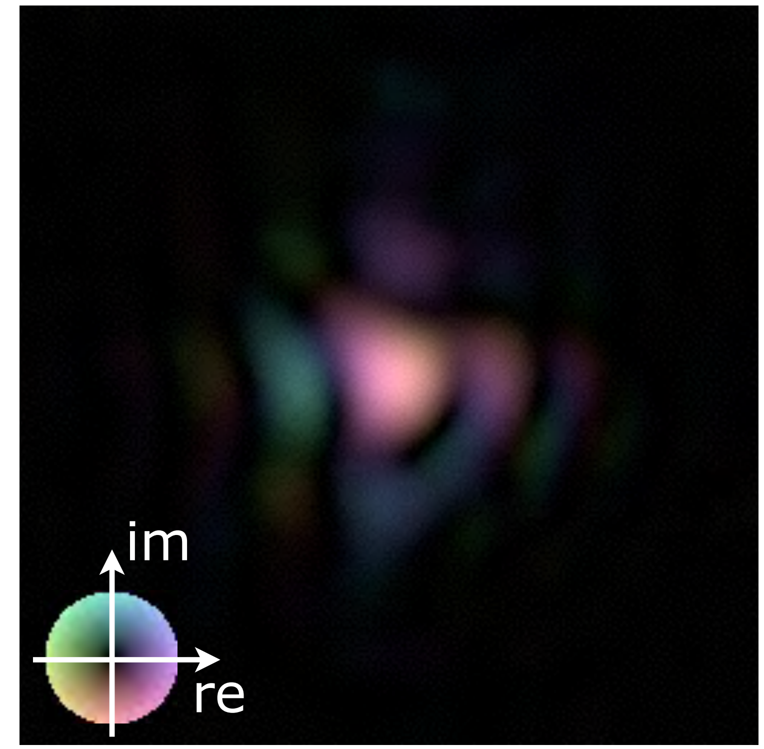
E = 15.25 keV
50 x 50 steps of 40 x 40 nm^2
2 x 2 μm^2 FOV
exposure: 1.5 s per point

Scanning Microscopy: Ptychography





50 nm lines and spaces

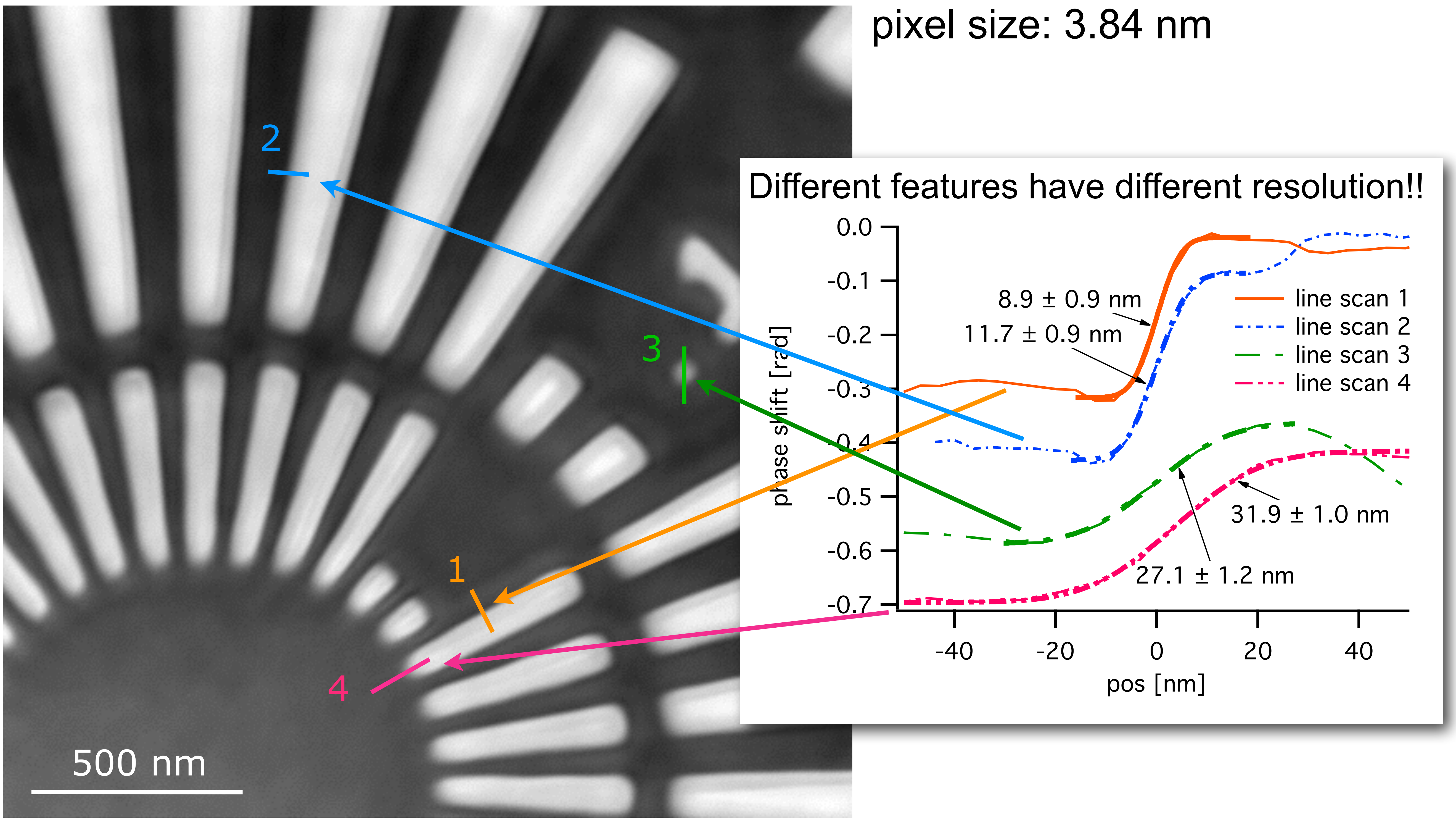


A. Schropp, et al., APL **96**, 091102 (2010),
S. Hönig, et al., Opt. Exp. **19**, 16325 (2011).

E = 15.25 keV
50 x 50 steps of 40 x 40 nm^2
2 x 2 µm^2 FOV
exposure: 1.5 s per point
detected fluence: 2.75·10^4 ph/nm^2

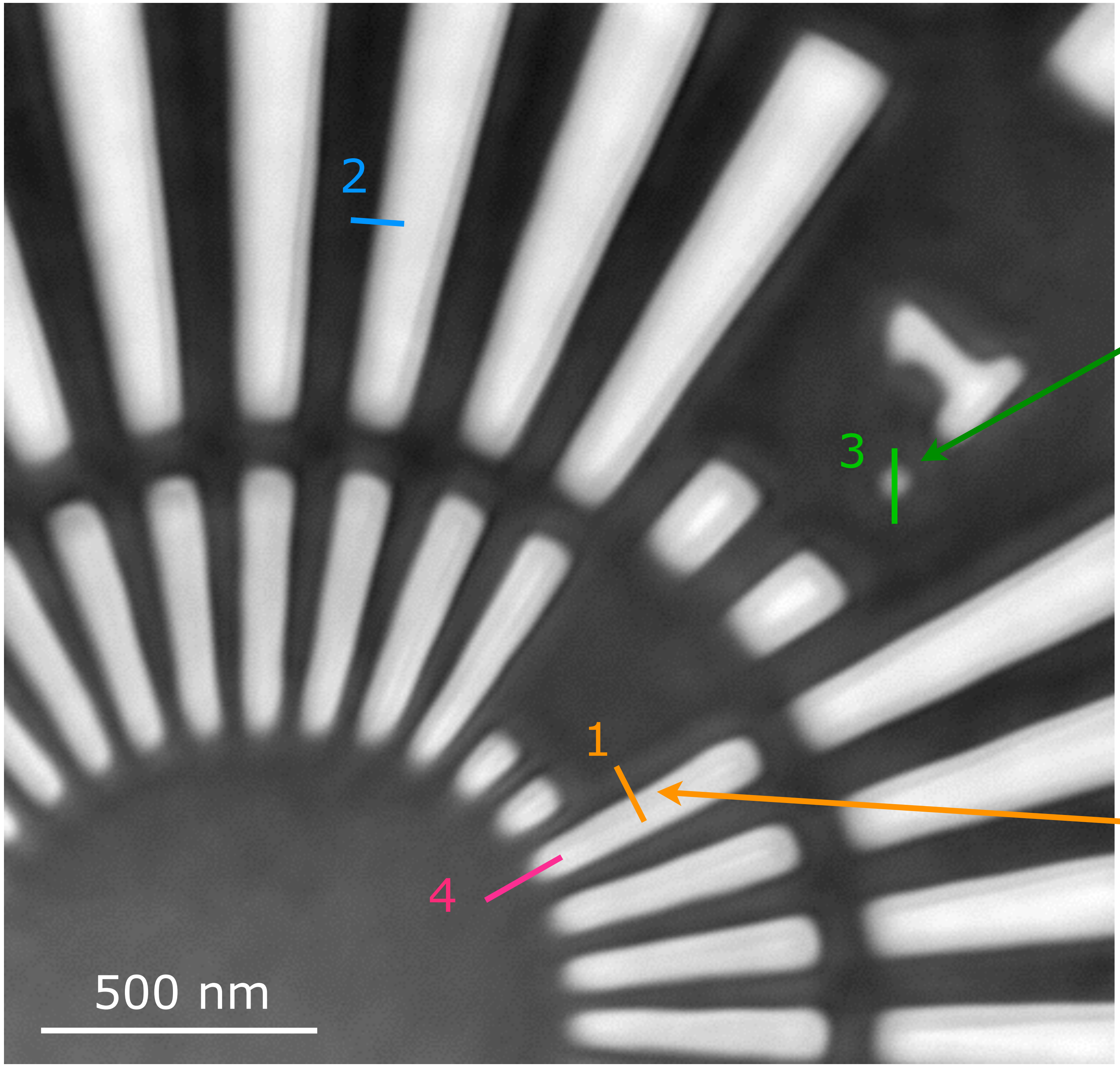
A. Schropp, et al., APL **100**, 253112 (2012).

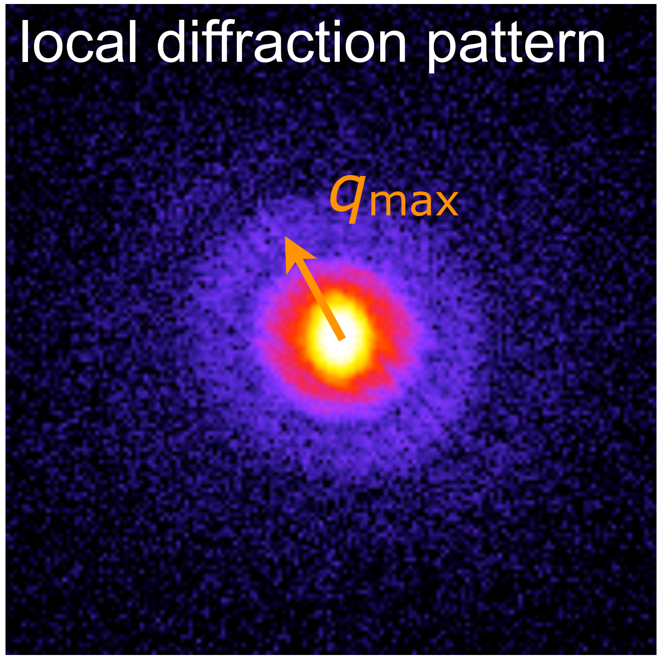
Scanning Microscopy: Ptychography



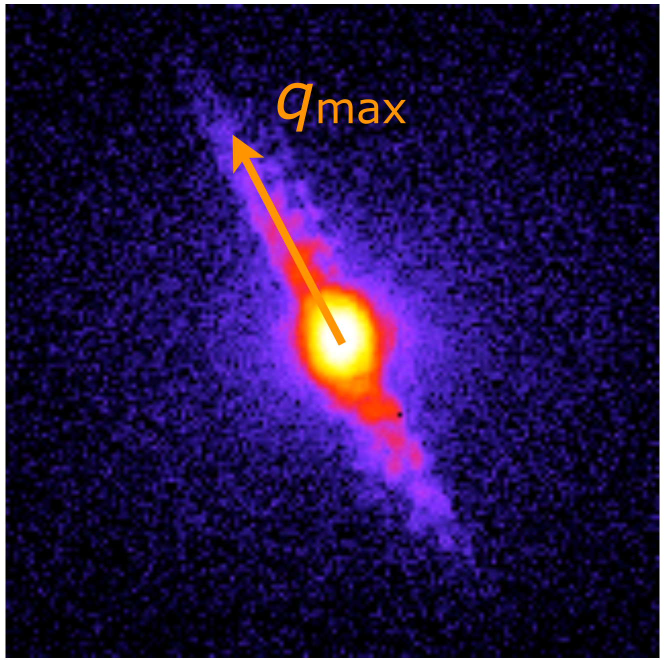
A. Schropp, et al., APL **100**, 253112 (2012).

Scanning Microscopy: Ptychography





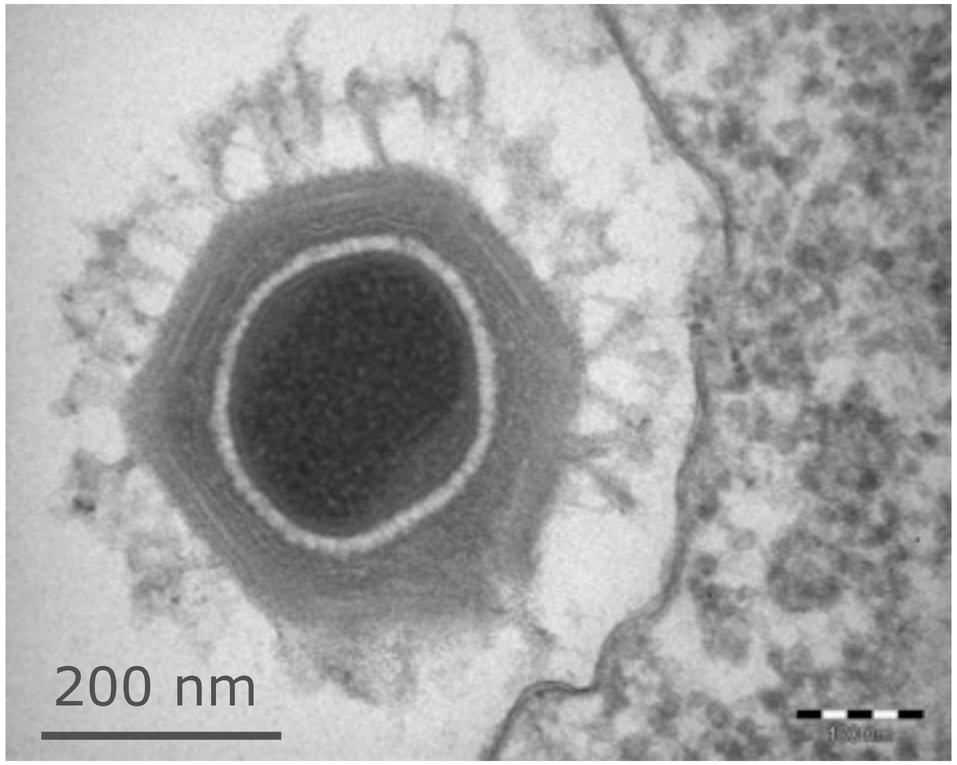
Resolution of a feature depends on its structure factor!

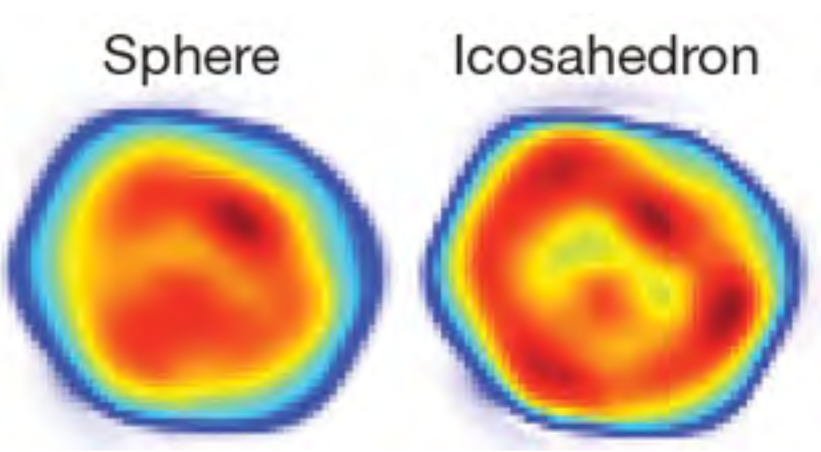


A. Schropp, et al., APL **100**, 253112 (2012).

Contrast in Coherent Diffraction Imaging

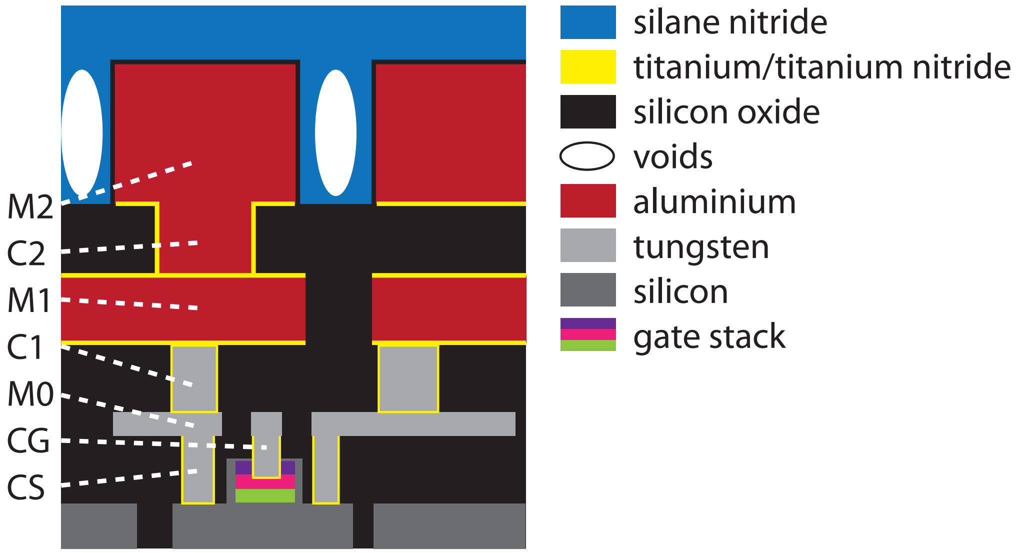
Mimivirus (TEM)



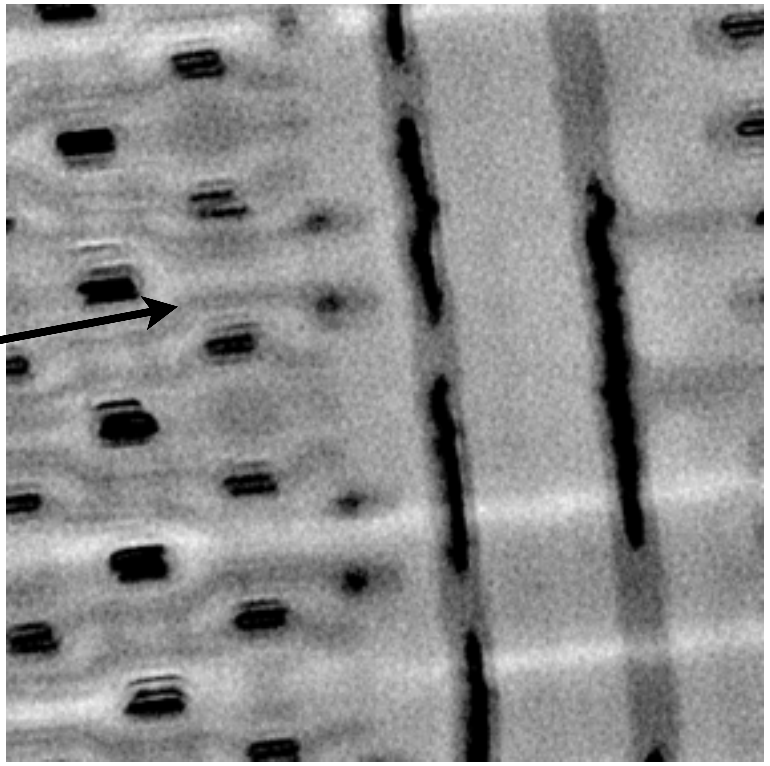


M. Seibert, et al., Nature **469**, 78 (2011).

Microchip



Only tungsten!
Where is the
Al, Si, ... ?



A. Schropp, et al., J. Microscopy, **241**(1), 9 (2011).

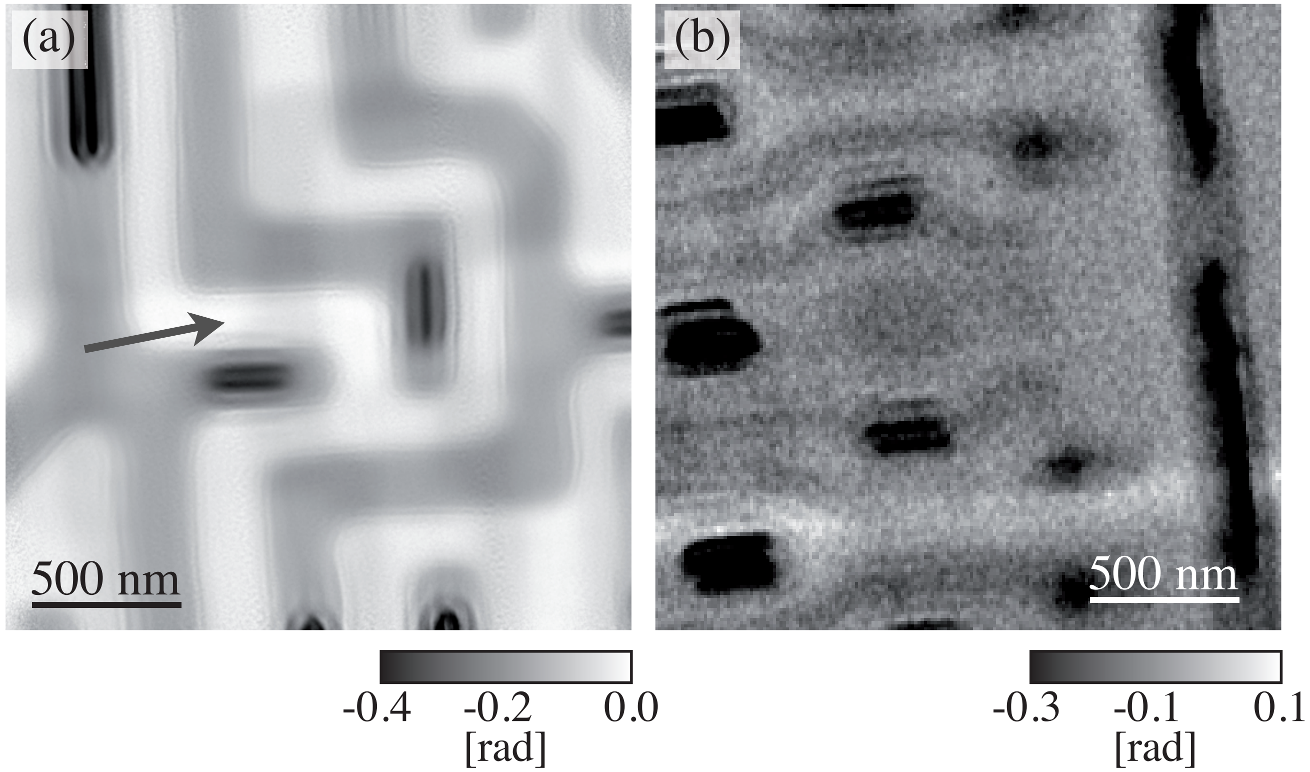
Resolution and Contrast in Ptychography

For a given feature: $\underbrace{I_c \cdot t}\cdot\underbrace{\left(\frac{d\sigma}{d\Omega}\right)_d}\Delta\Omega_d$

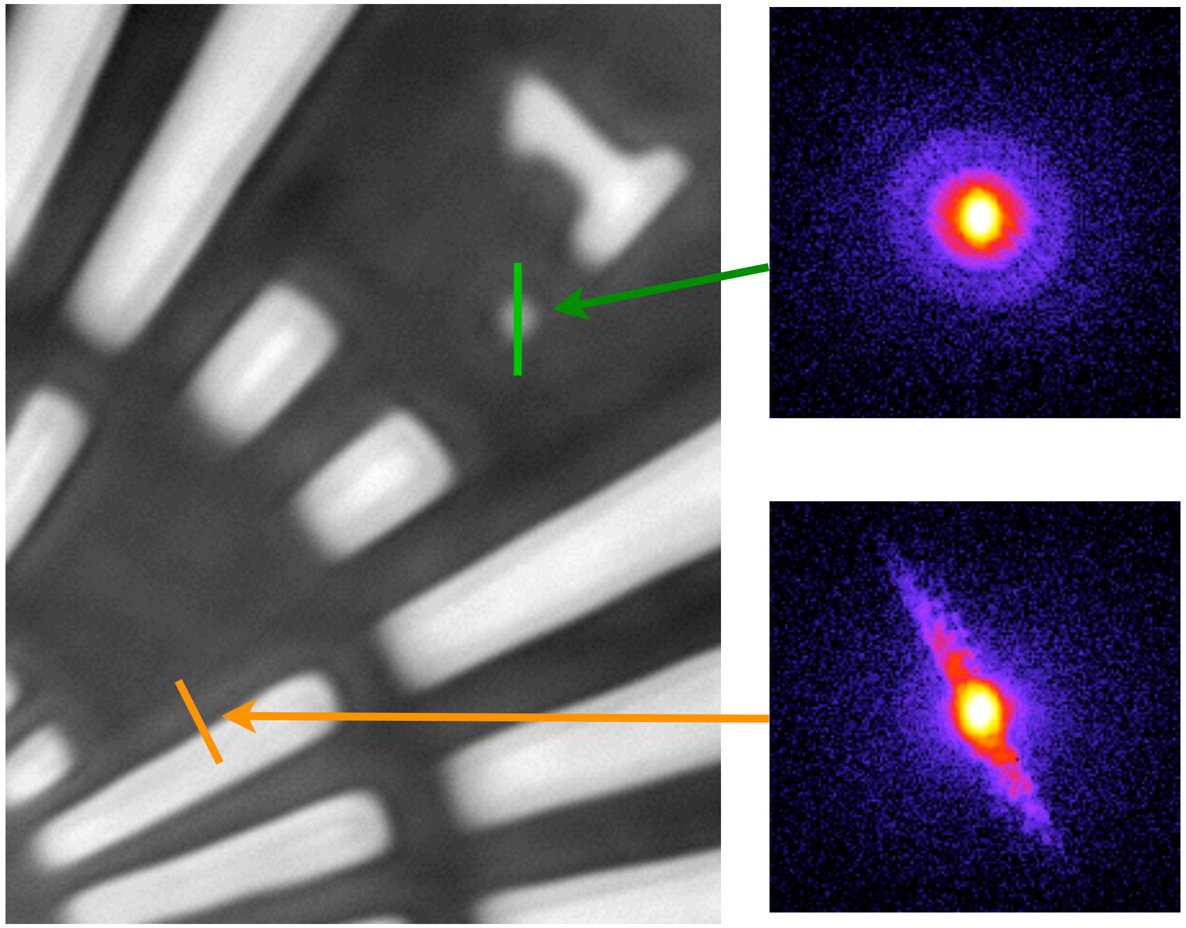
Signal = fluence * scattering cross section

coherent fluence on feature:

$6.7\cdot10^3$ ph/nm^2 $3.9\cdot10^2$ ph/nm^2



~ structure factor of feature:



Schropp & Schroer, NJP **12**, 035016 (2010).

Imaging at the X-Ray Free-Electron Laser

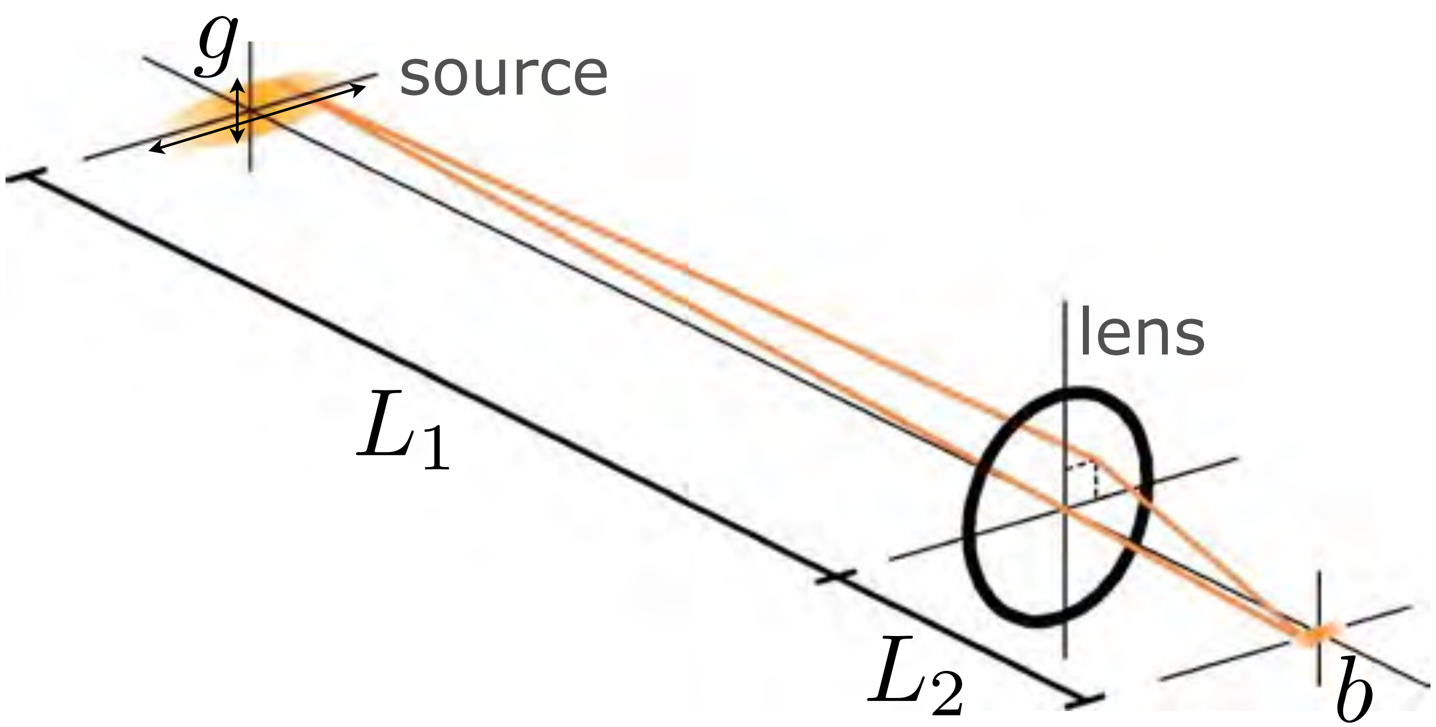
Linac Coherent Light Source (LCLS at SLAC)

- short, dense electron bunches
- long undulator

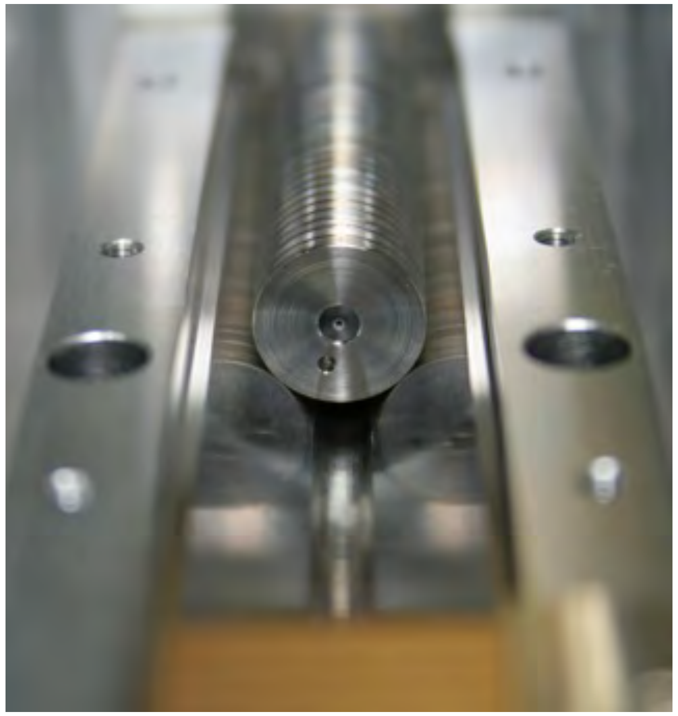
→ ultra short, very intense x-ray pulses (10 - 100 fs)

Investigating the dynamics of matter on nanoscale.

Focusing Hard X-Ray FEL Pulses



Diffraction limited imaging of source



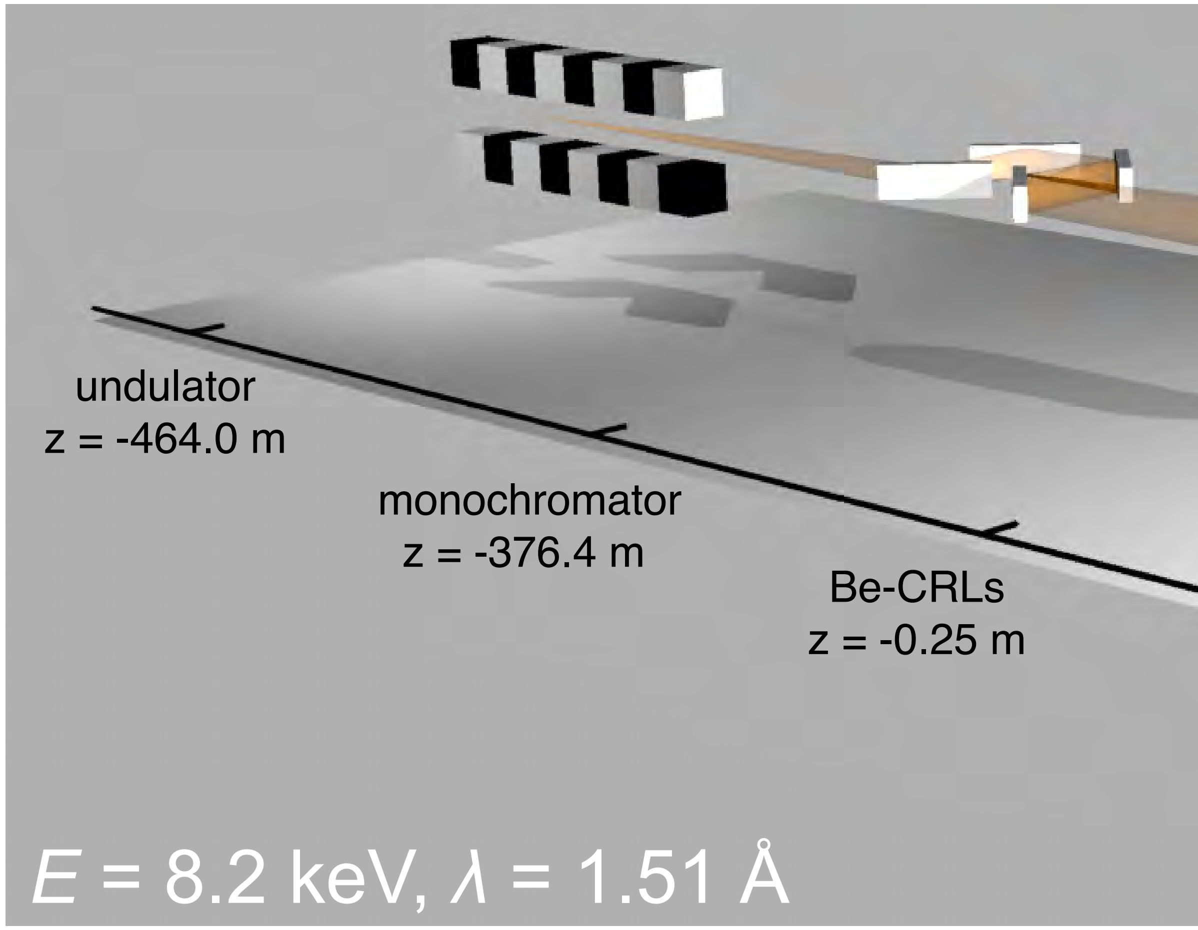
X-ray optics:

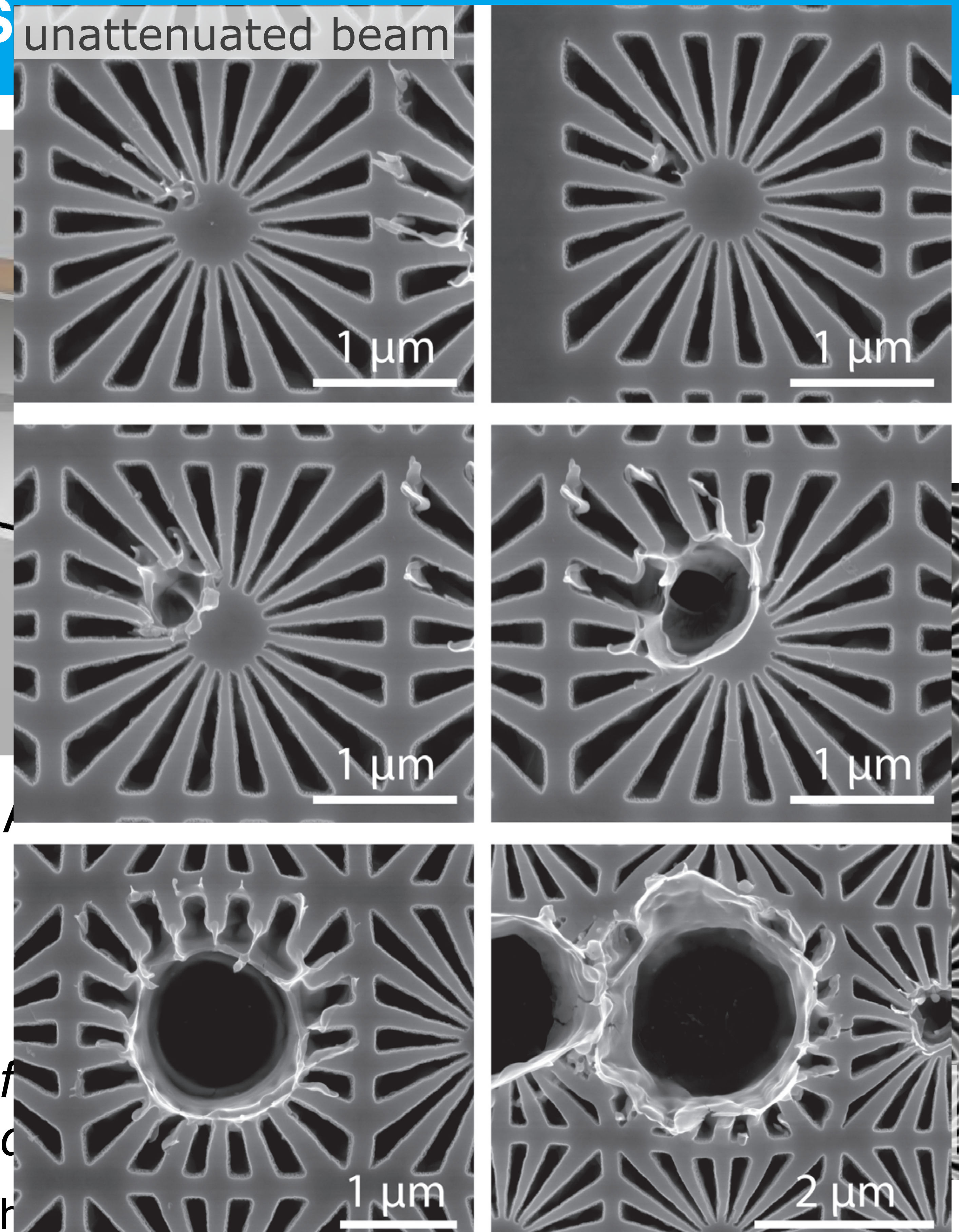
beryllium parabolic refractive x-ray lenses

B. Lengeler, RXOptics

Focusing needed:

- increase fluence for imaging
  - → resolution determined by fluence on sample
- increase intensity on sample
  - → induce non-linear optical effects
- increase energy deposited in sample
  - → create matter in extreme conditions
- ...





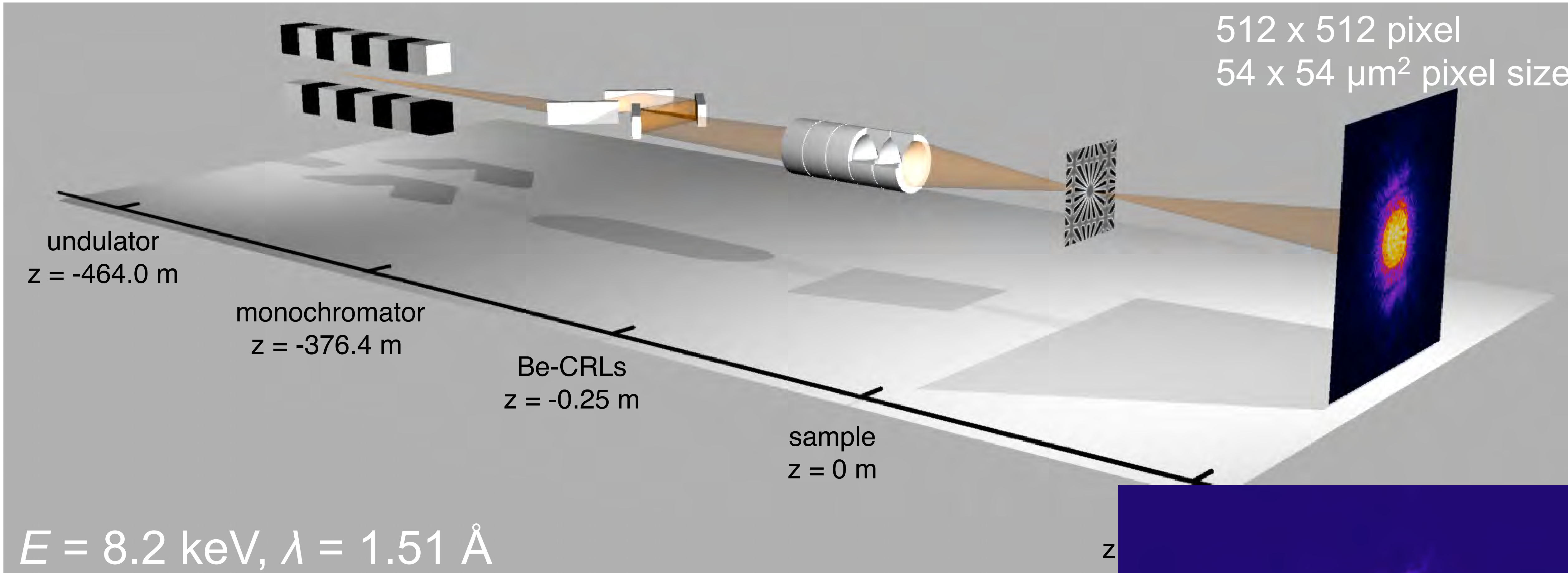
monochrom. beam: $\frac{\Delta E}{E} \approx 10^{-4}$

Focusing by CRLs:

- N = 20
- R = 50 µm
- 300 µm aperture

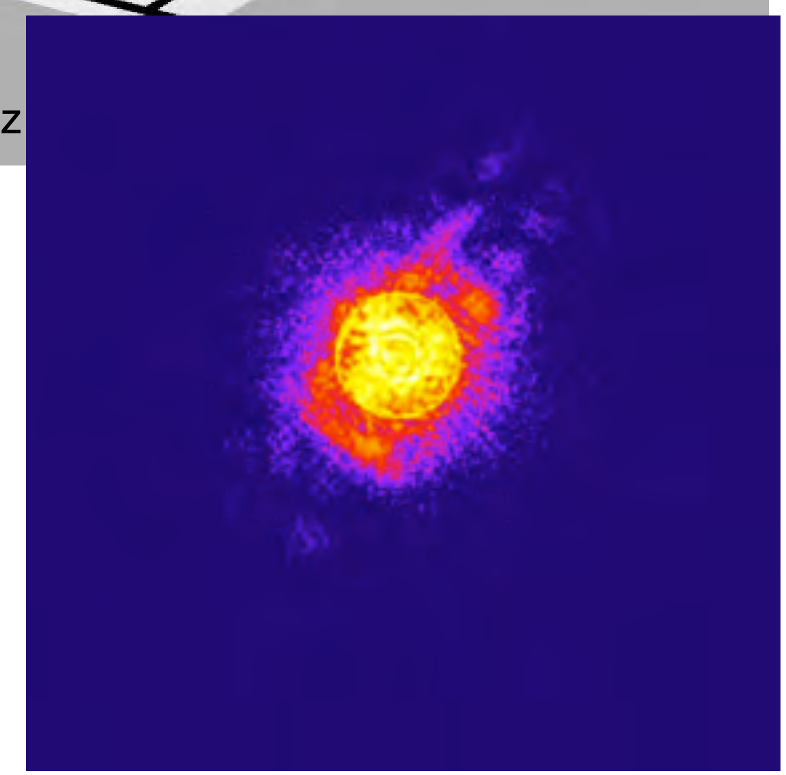
A. Sch

Experiment at MEC at LCLS



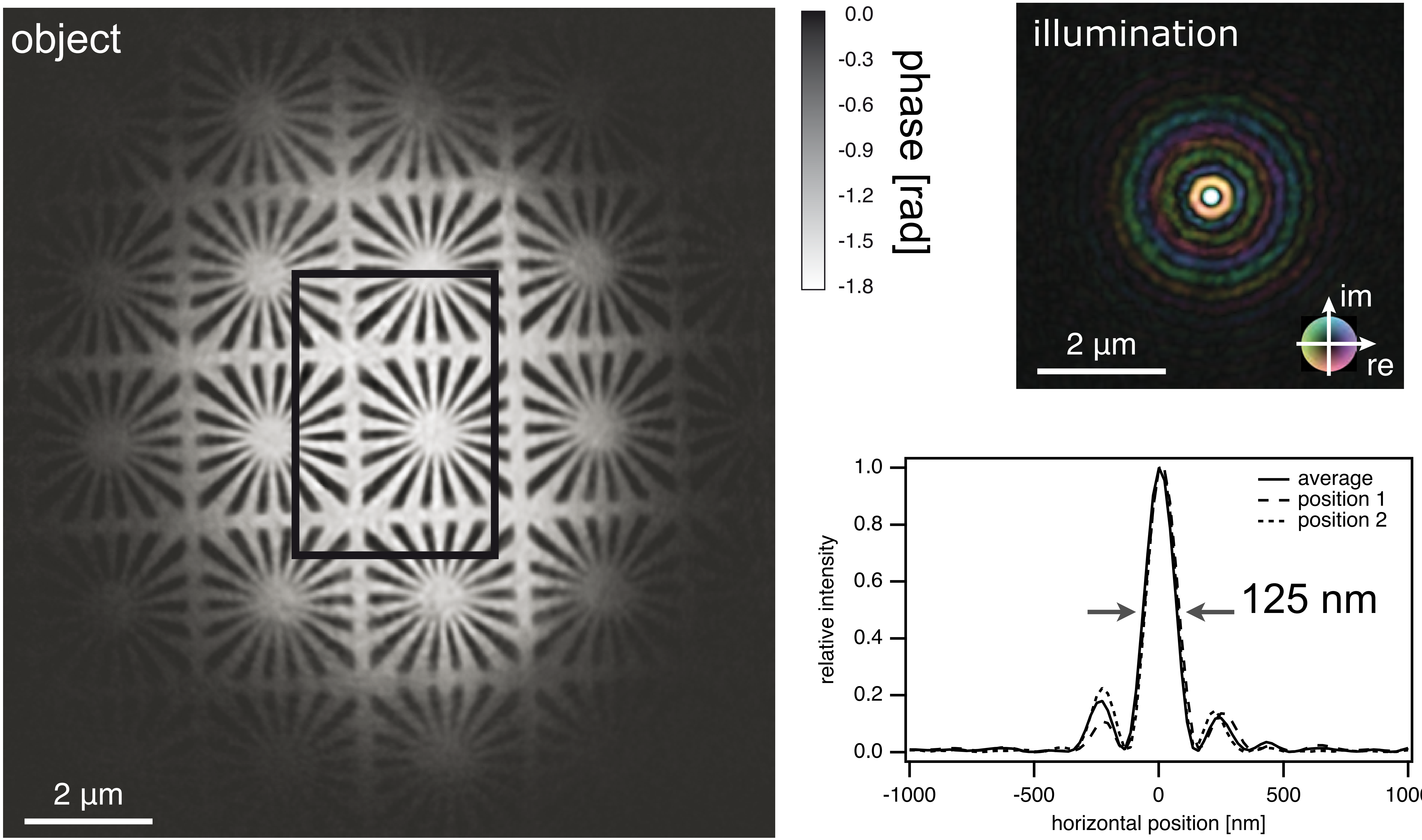
Ptychogram:

20 x 20 steps
100 x 100 nm^2 step size
single shot exposure: 2 exposures per point
384 out of 400 (800) images for reconstruction



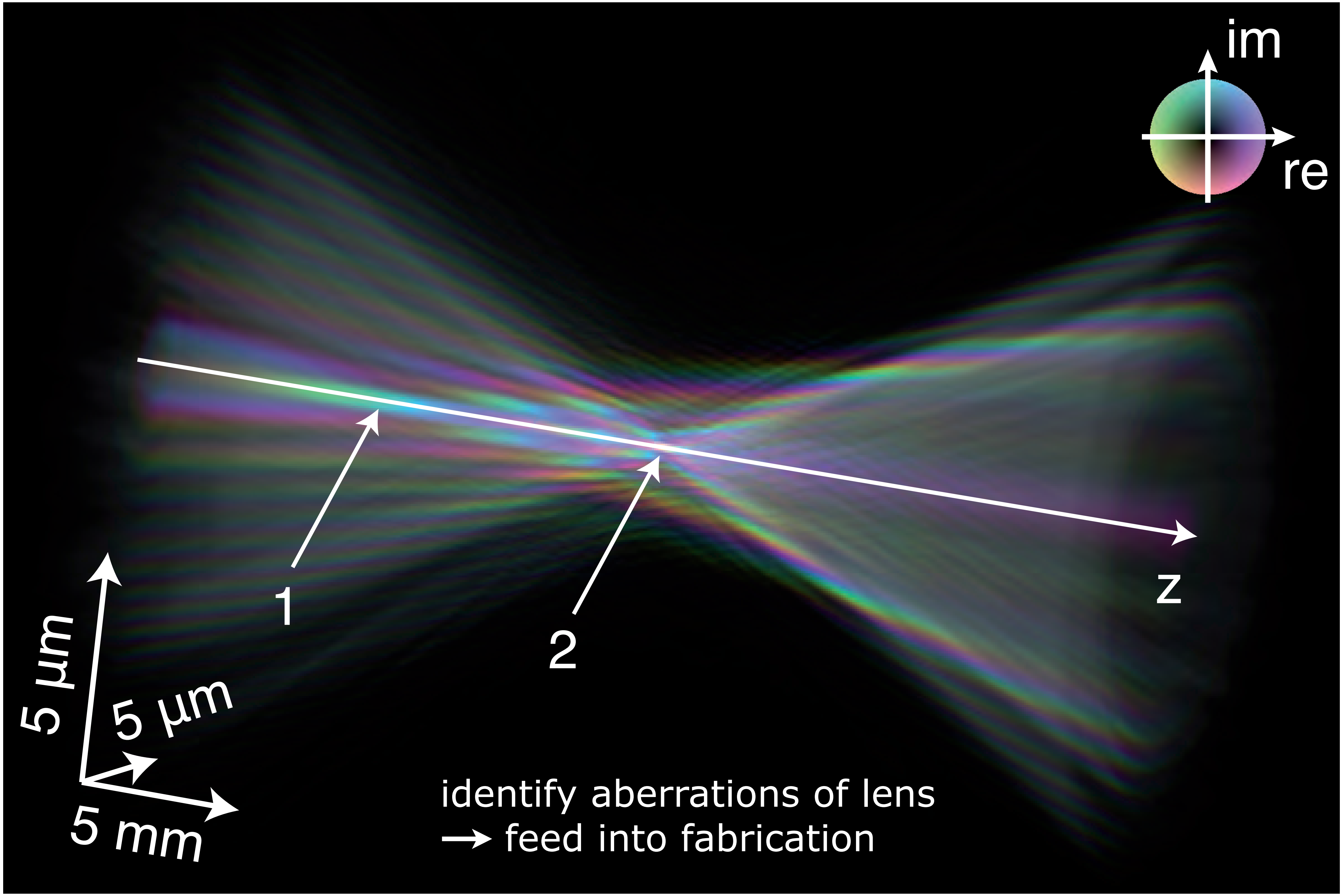
A. Schropp, et al., Sci. Rep. **3**, 1633 (2013).

Reconstruction



A. Schropp, et al., Sci. Rep. **3**, 1633 (2013).

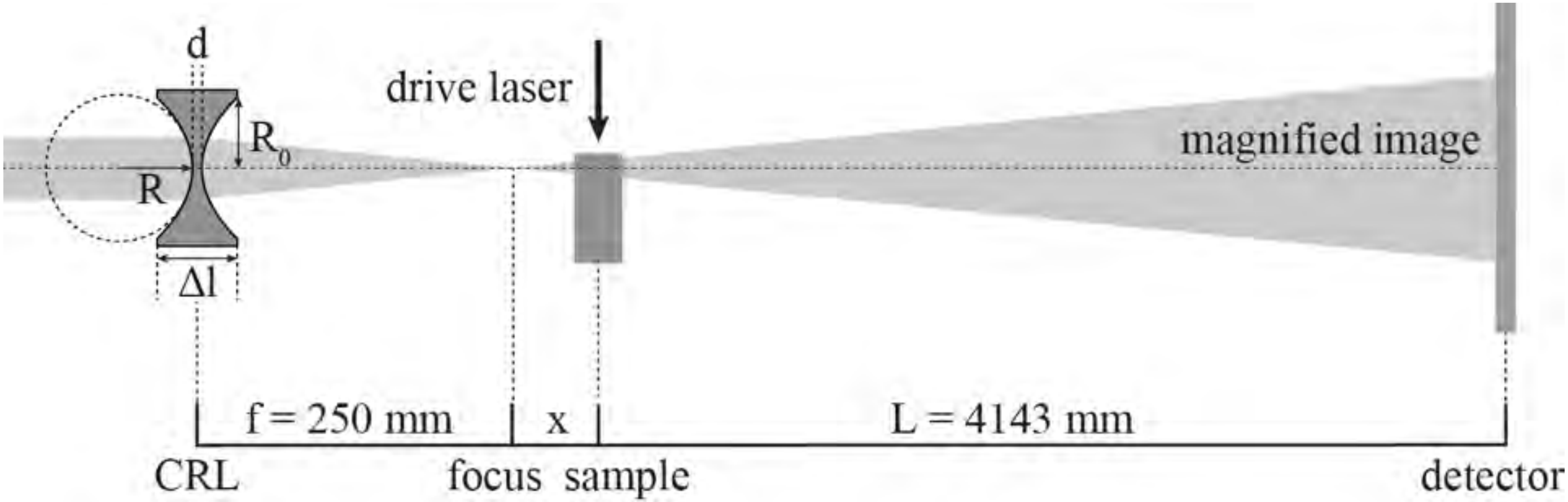
Nanofocused LCLS Beam Profile



A. Schropp, et al., Sci. Rep. **3**, 1633 (2013).

High Resolution X-Ray Imaging at XFEL Sources

Method: magnifying phase contrast imaging



- imaging with secondary point source: efficient use of fluence
- phase contrast: for quantitative results, phase retrieval required

Alternatively:

Time-resolved diffraction in focus of nanobeam

An X-Ray Microscopists Dream

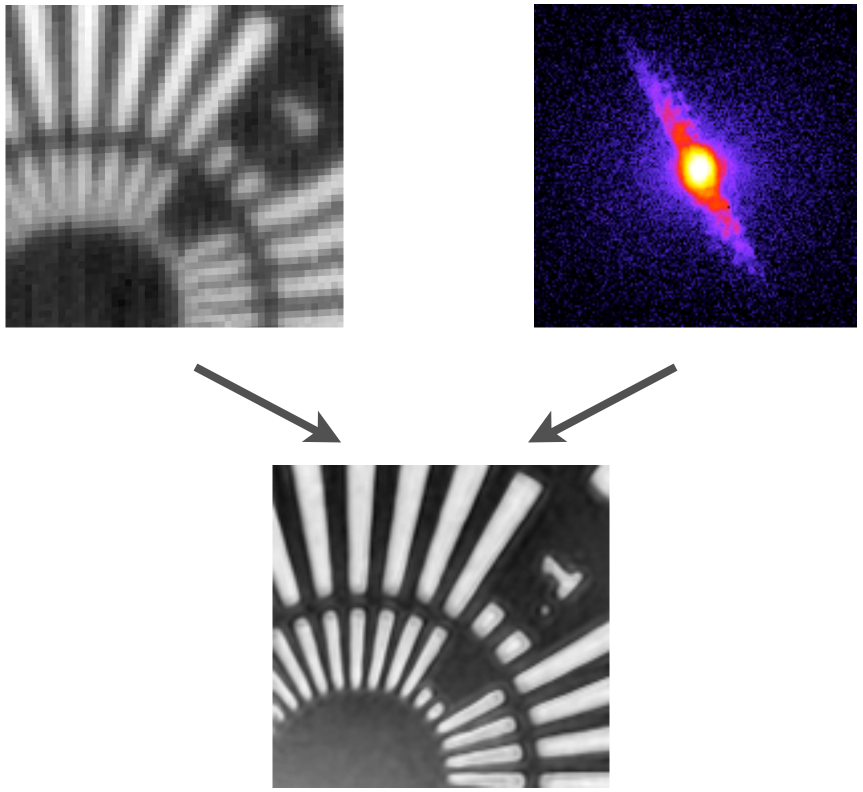
Quantitive in-situ measurement of physical properties of matter

- on all relevant length scales
- on all relevant time scales

Key technology: brilliant, coherent x-rays with time structure

Fusion of real and reciprocal space:

→ access to all length scales
(in principle) from Å to millimeters



Requirement: a lot of coherent light

→ X-ray free-electron lasers

→ diffraction limited storage rings