An overview of coherent X-ray microscopy techniques

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Seminar
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Introduction

Introduction

- Motivation to phase contrast hard X-ray microscopy
- Basic concepts: X-ray wave propagation, coherence…

Phase-contrast hard X-ray microscopy

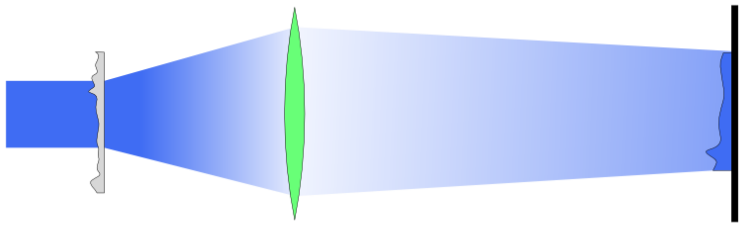
- Zernike phase-contrast microscopy
- Holo-tomography
- Coherent diffraction imaging
- Ptychography

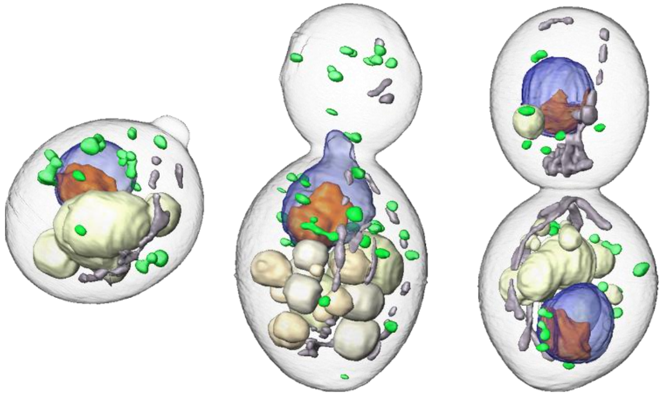
Outlook

- High-brilliance synchrotron sources

Conventional X-ray microscopy

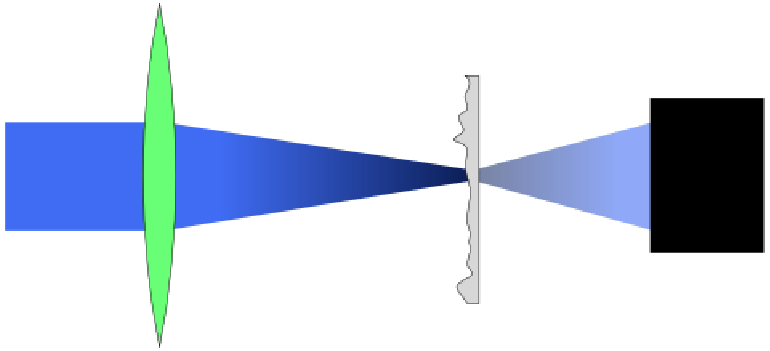
full-field microscopy:



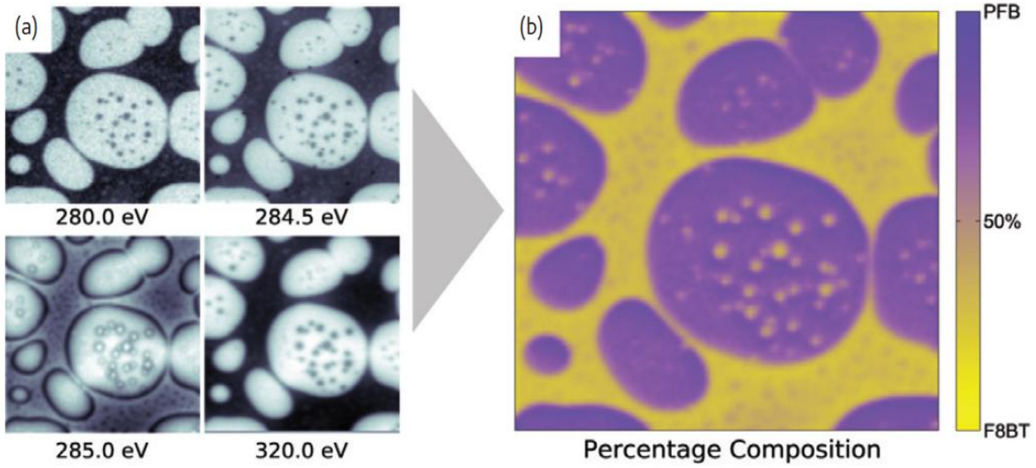


M. Uchida *et al.*,
Yeast **28**, 227 (2011)

scanning transmission microscopy (STXM):



B. Watts *et al.*,
Materials Today
15, 148 (2012)

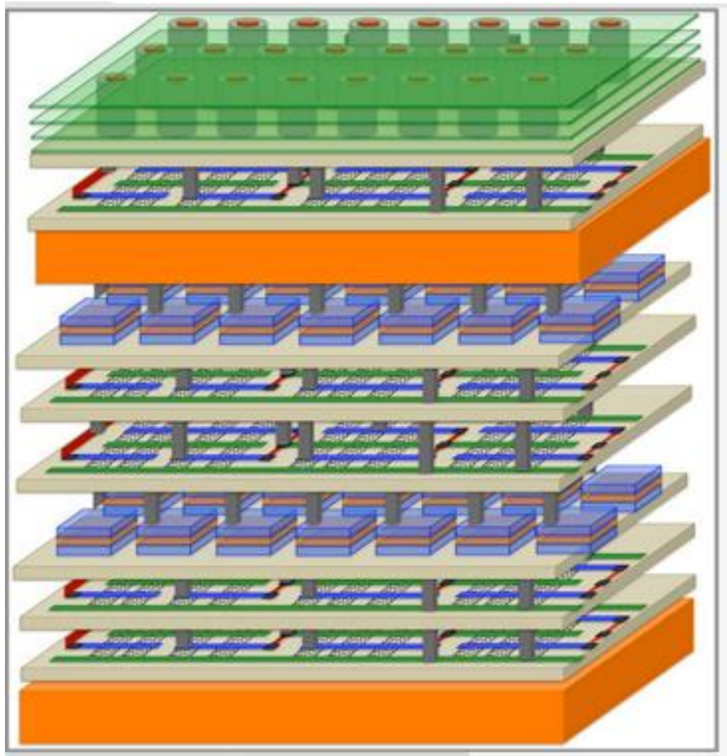


- Typically with Fresnel zone plates in the soft X-ray regime (e.g. in the water window)
- Resolution can reach 25-30 nm, but depth of focus limited to about 1 μm

Imaging bulk samples with hierarchical structures

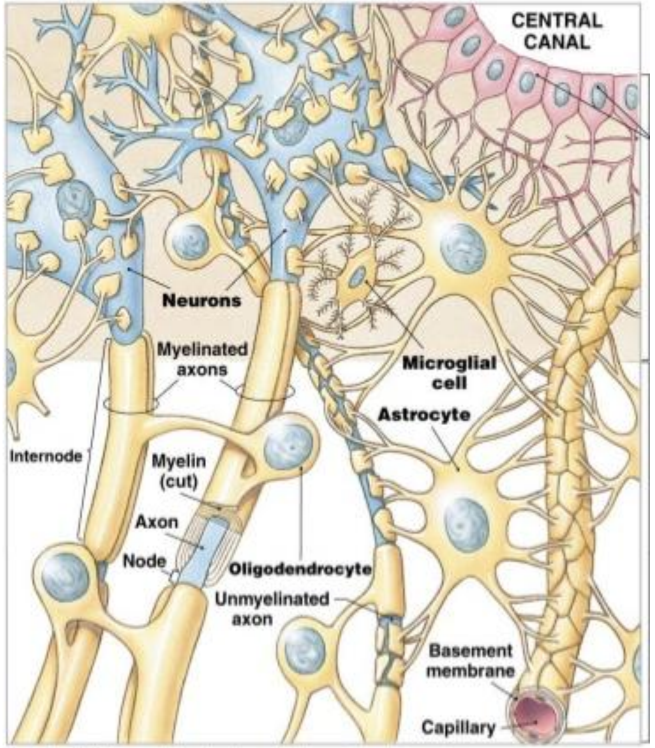
PSI

Computer chip



https://www.livescience.com/52207-faster-3d-computer-chip.html

Nervous tissue



Thickness from 10 to 100 μm

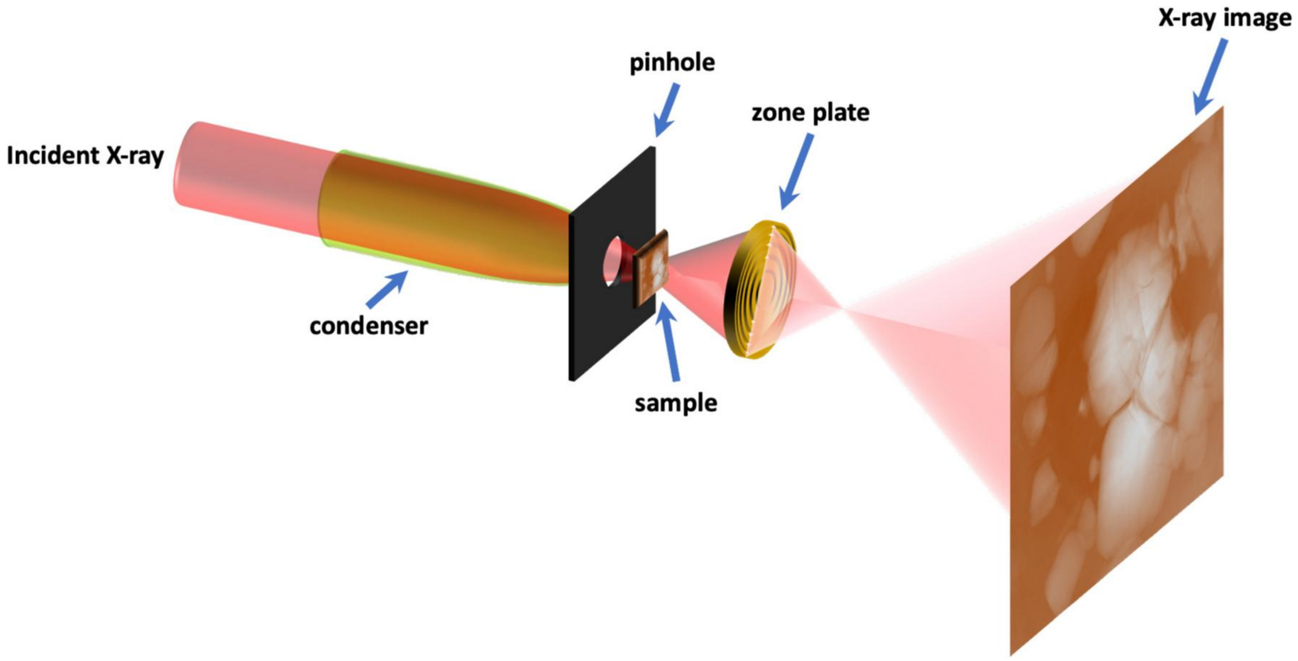
Resolution from 10 to 100 nm

Energy > 2 keV

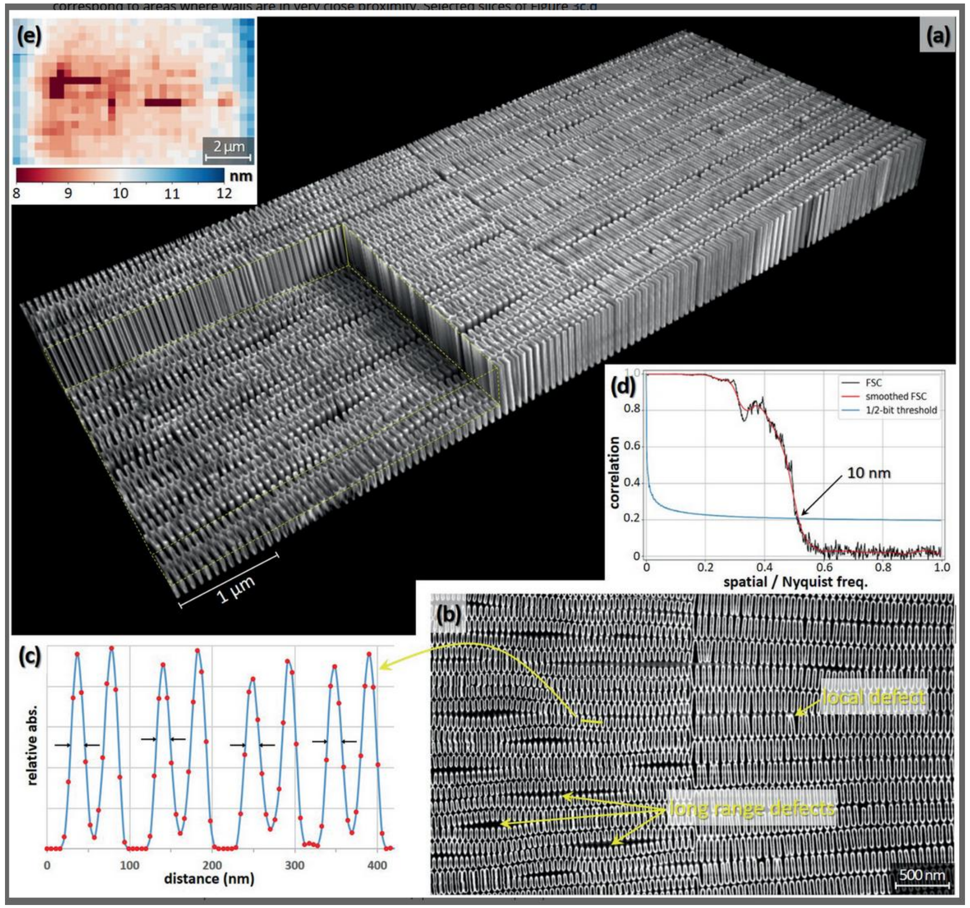
Challenges:

- Low absorption
- Fabrication aberration-free, high-resolution lenses

Hard X-ray transmission microscopy with absorption contrast



S. Spence *et al.*, Nanotechnol. **32**, 442003 (2021)



V. De Andrade *et al.*, Adv. Mater. **33**, 2008653 (2021)

Absorption and phase contrast

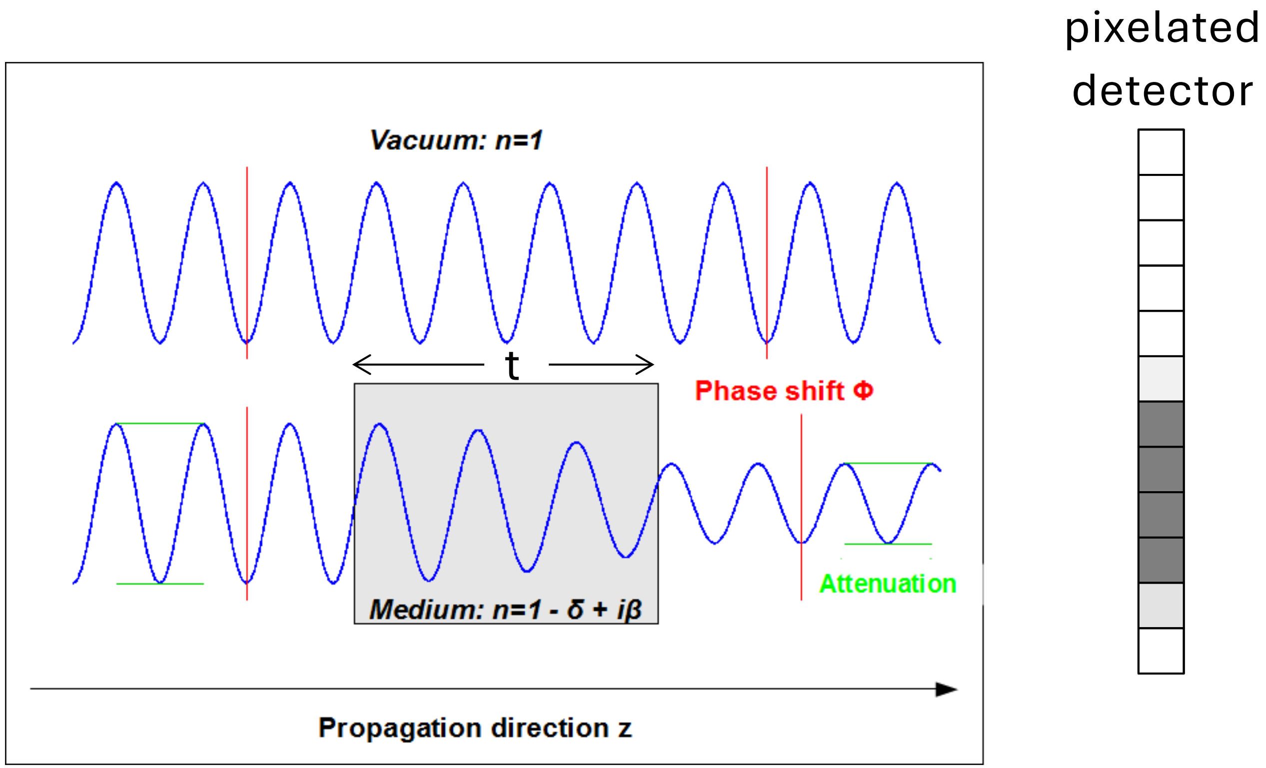
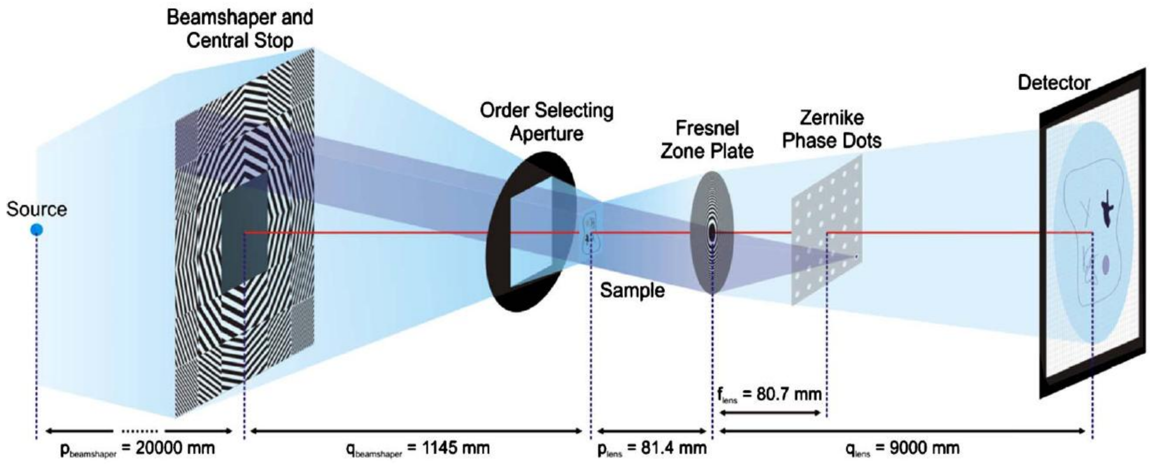


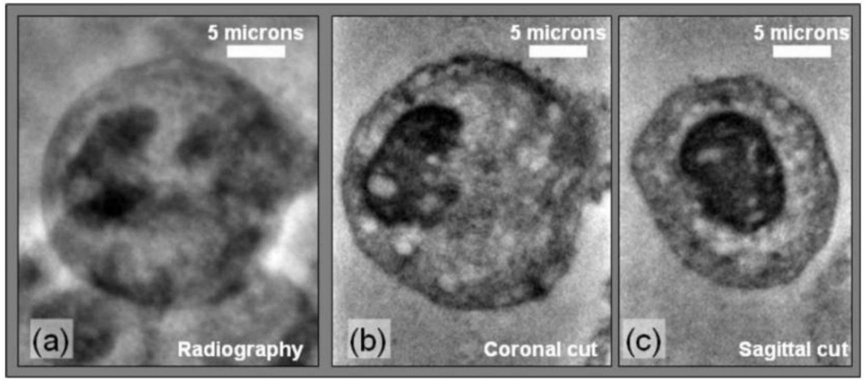
Image from “Phase-contrast X-ray imaging” in Wikipedia:
https://en.wikipedia.org/wiki/Phase-contrast_X-ray_imaging

For hard X-rays: $\delta >> \beta$

Full-field microscopy with Zernike phase contrast

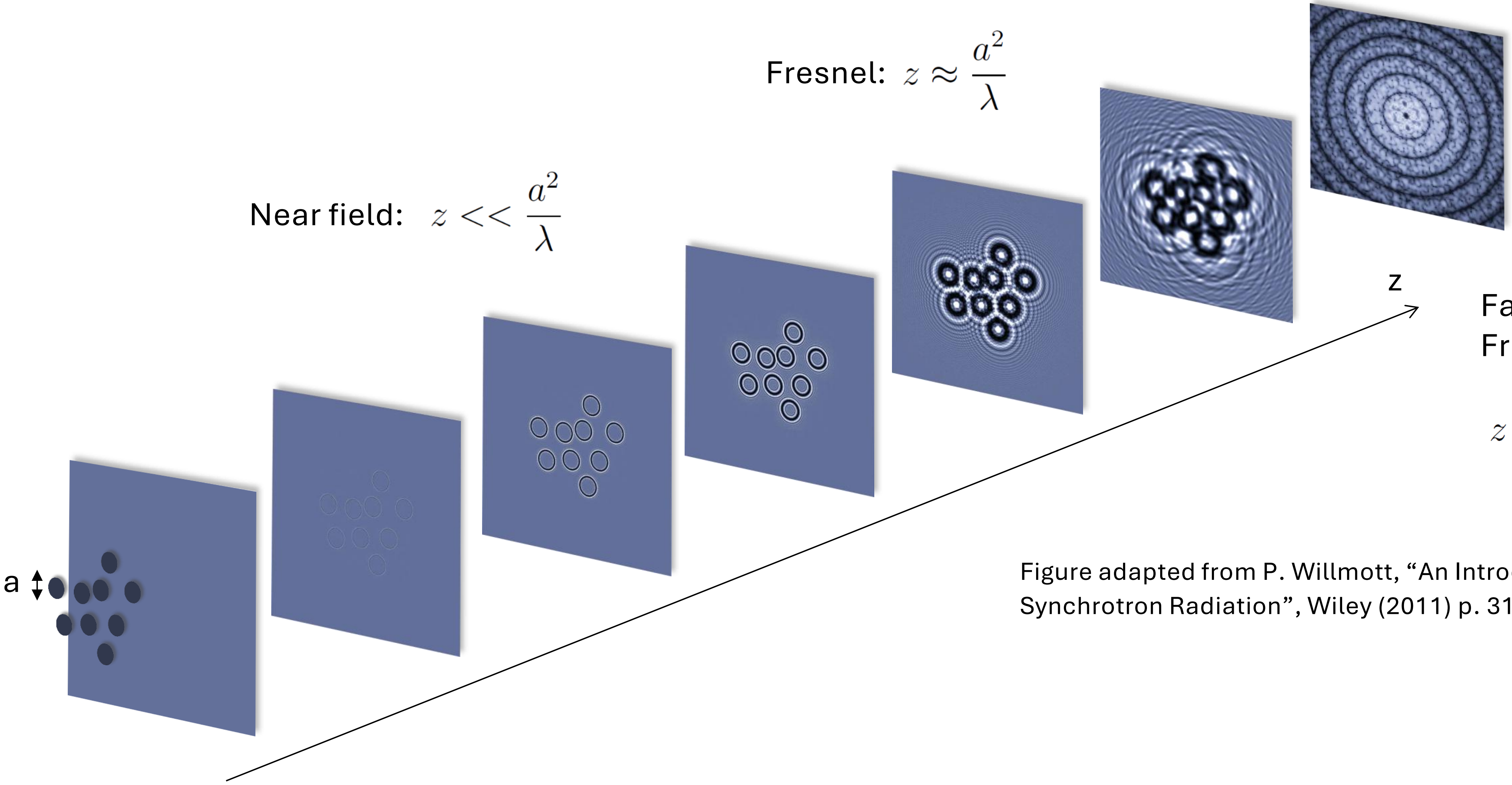
M. Stampanoni *et al.*, Phys. Rev. B **81**, 140105(R) (2010)





- Holes matching custom illumination
- The transmitted beam goes through the holes
- The beam which is refracted by the sample go through the phase-shift mask
- Both parts contribute to a phase-contrast image on the detector
- Low coherence requirement. Problems if the beam has a high degree of coherence

Wave propagation reveals phase contrast



Near field: $z << \frac{a^2}{\lambda}$

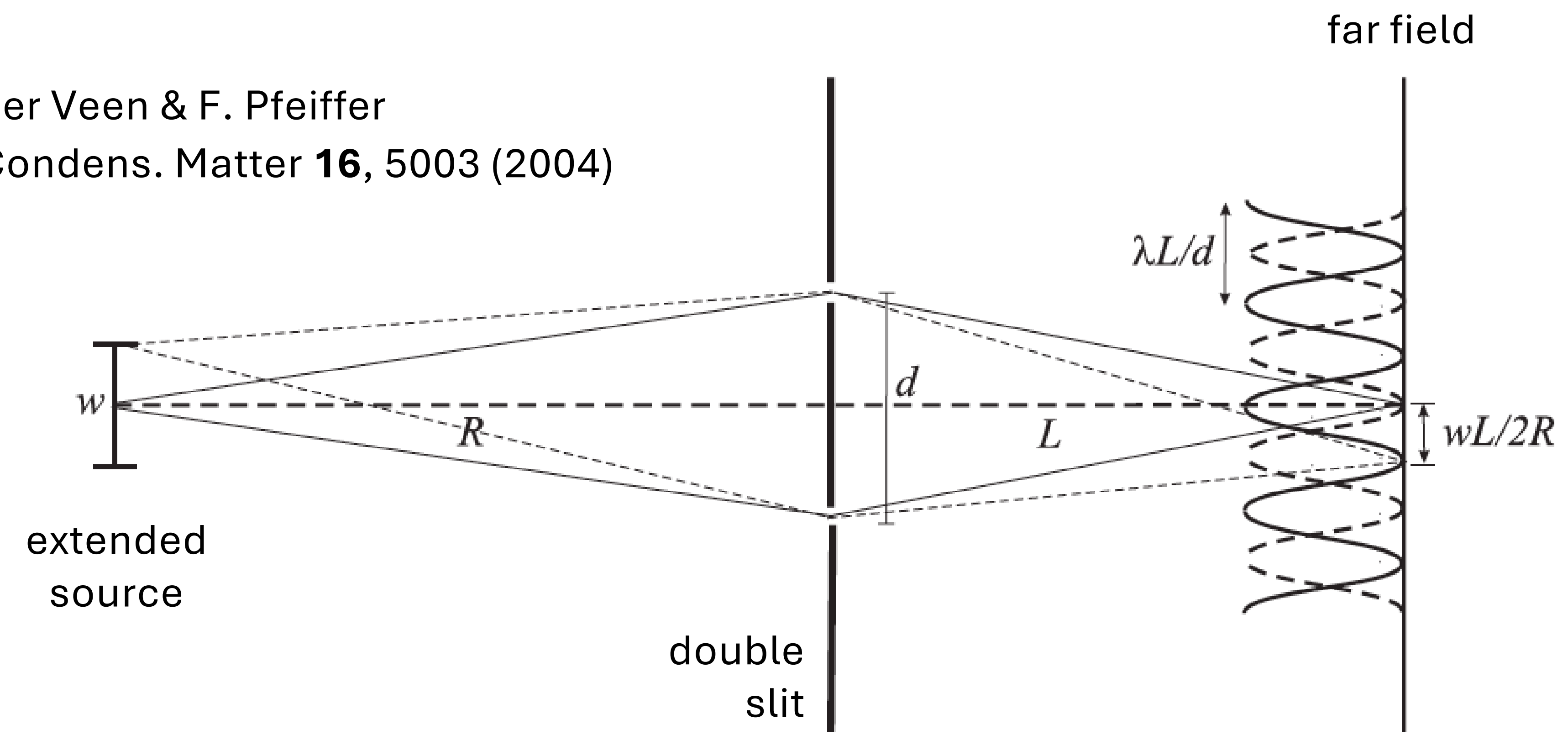
Fresnel: $z \approx \frac{a^2}{\lambda}$

Far field or Fraunhofer: $z >> \frac{a^2}{\lambda}$

Figure adapted from P. Willmott, “An Introduction to Synchrotron Radiation”, Wiley (2011) p. 314

Transversal coherence

J. F. Van der Veen & F. Pfeiffer
J. Phys.: Condens. Matter **16**, 5003 (2004)

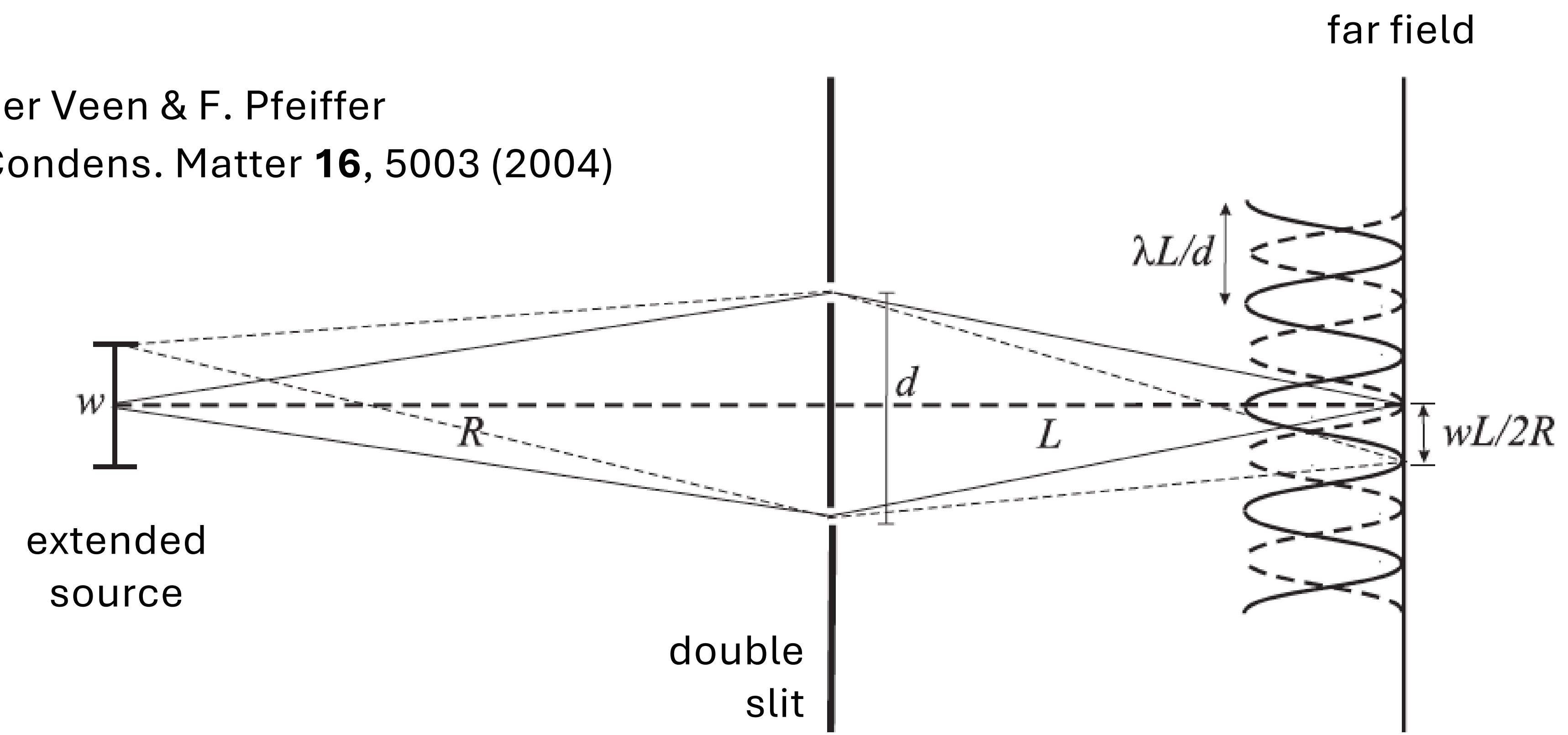


Transversal coherence length: $$\xi_t = \frac{\lambda R}{w}$$

Maximum distance between two slits such that they produce constructive interference when illuminated by an extended source size

Transversal coherence

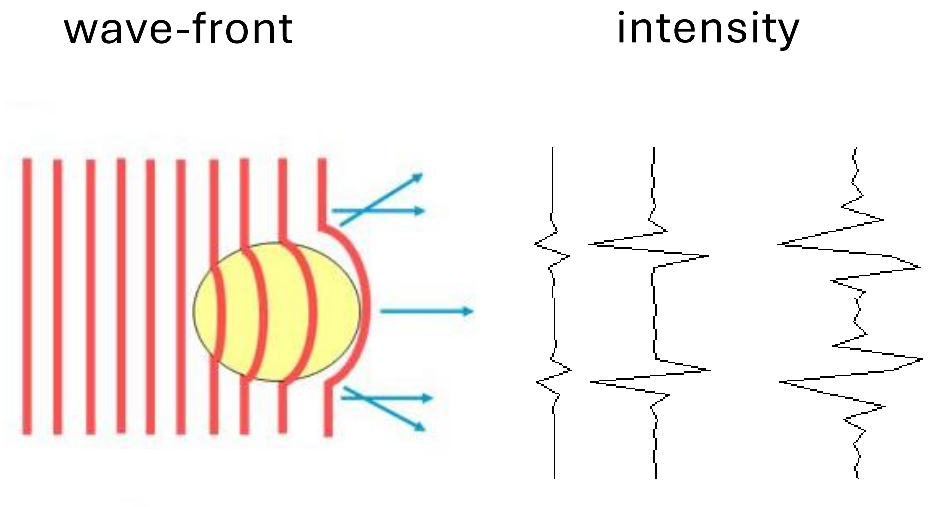
J. F. Van der Veen & F. Pfeiffer
J. Phys.: Condens. Matter **16**, 5003 (2004)



Transversal coherence length: $$\xi_t = \frac{\lambda R}{w}$$

λ = 1 Å
R = 50 m
w_v = 20 μm ➔ ξ_v = 250 μm
w_h = 200 μm ➔ ξ_h = 25 μm

Propagation-based phase contrast

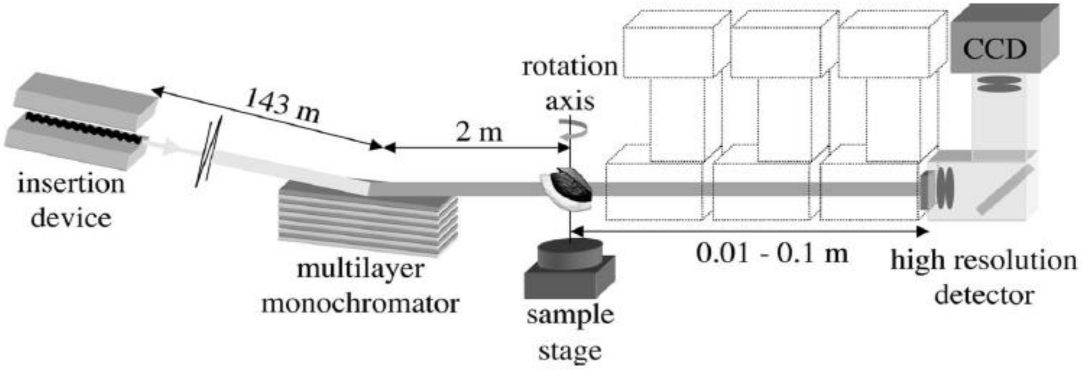


$$I \propto \frac{\partial^2 \phi}{\partial x^2} \quad (*)$$

- Interference between refracted wave and incoming beam: aka **in-line holography**
- Intensity fringes build up in the near field, especially at the edges of the sample

(*) See e.g. P. C. Diemoz *et al.*, Opt. Express **20**, 2789 (2012)

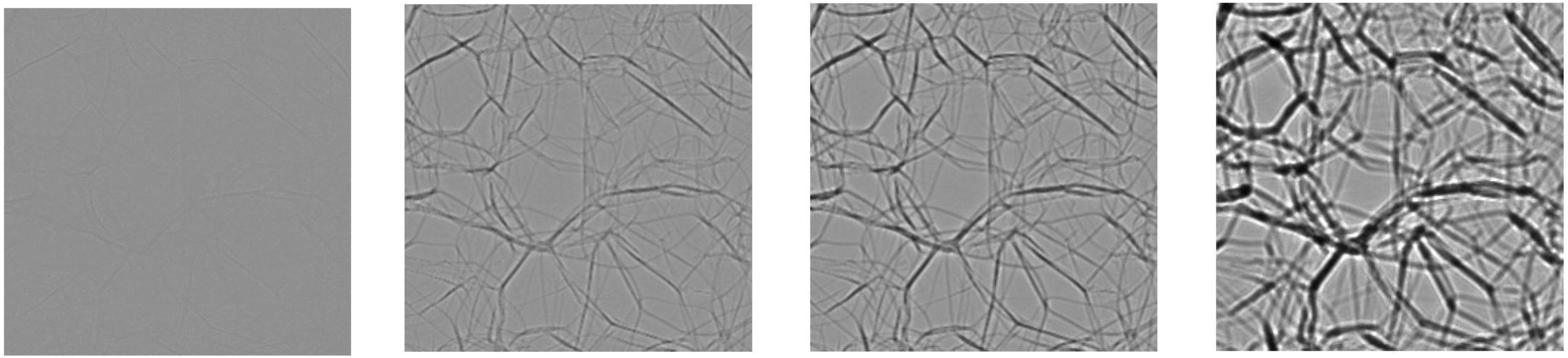
Propagation-based phase contrast



P. Cloetens *et al.*,
PNAS **103**, 14626 (2006)

Polystyrene foam
λ = 0.69 Å

d = 0.01 m | d = 0.12 m | d = 0.22 m | d = 0.91 m

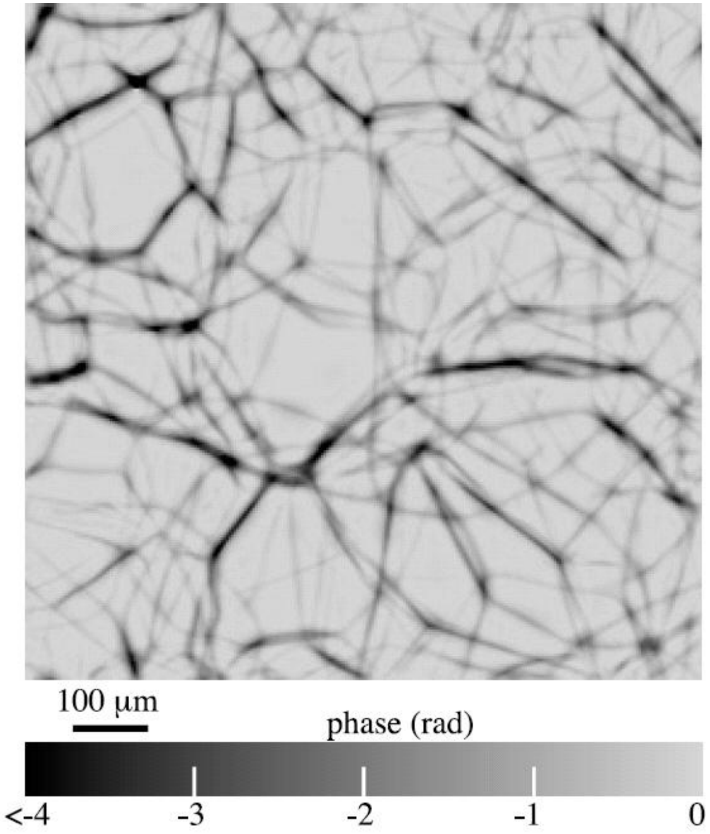


100 µm

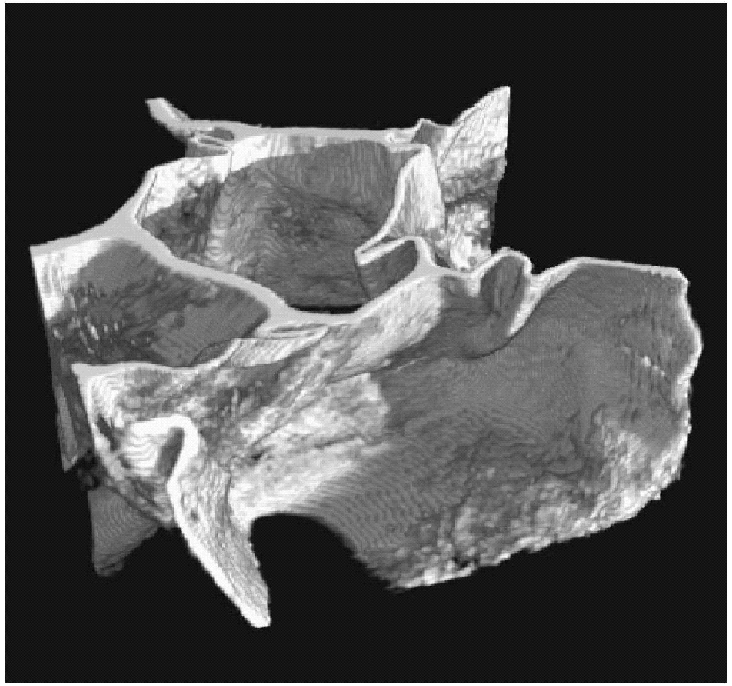
P. Cloetens *et al.*, J. Phys D: Appl. Phys **32**, A145 (1999)

Propagation-based phase contrast: holotomography

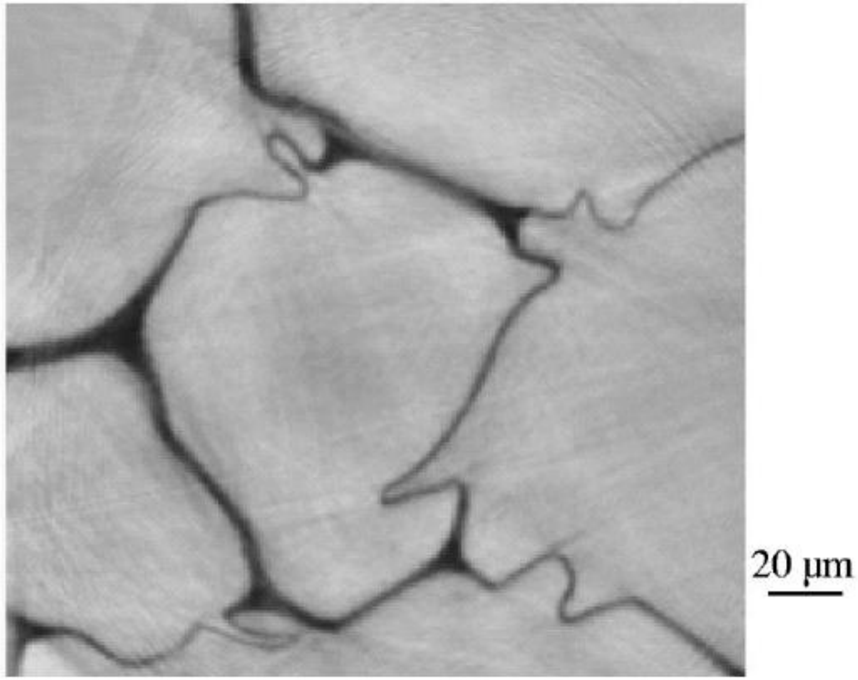
Quantitative phase image obtained with a reconstruction algorithm



Tomographic reconstruction



Slice through tomographic reconstruction

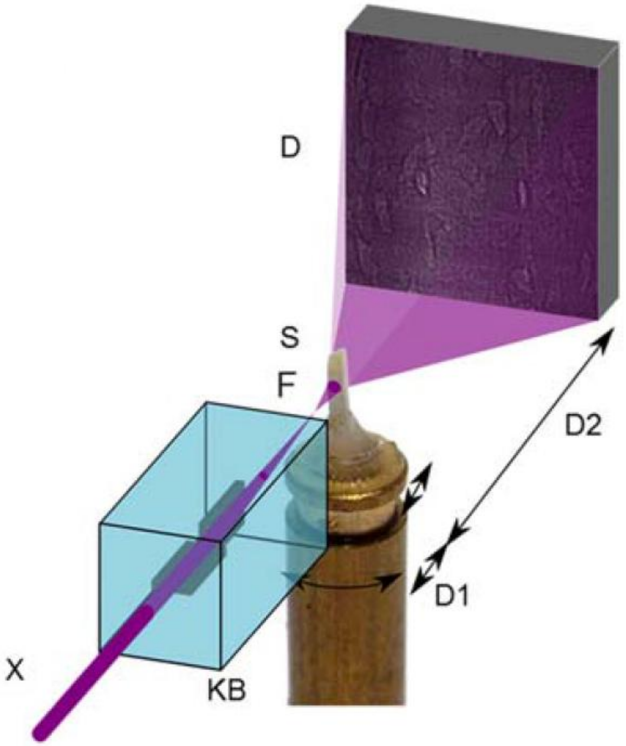


P. Cloetens *et al.*, Appl. Phys. Lett. **75** 1912 (1999)

P. Cloetens *et al.*, J. Phys D: Appl. Phys **32**, A145 (1999)

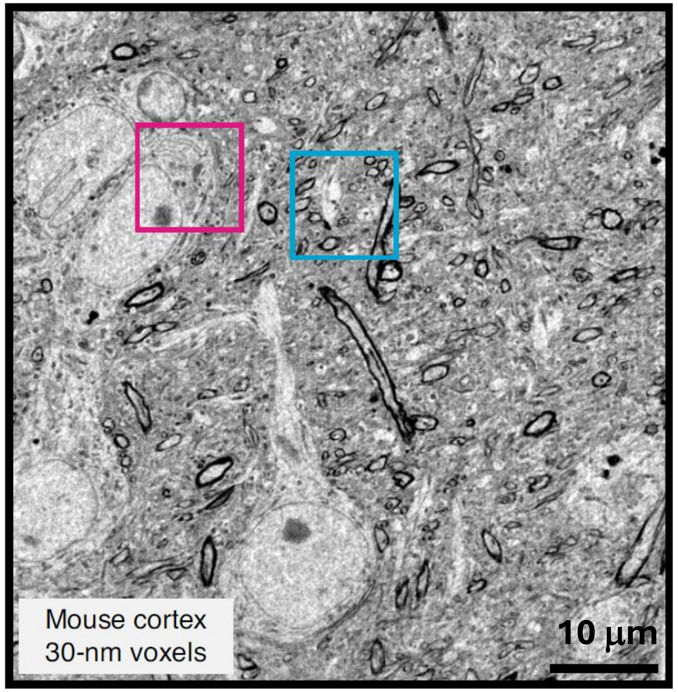
Propagation-based imaging with magnification

PSI



- Focused beam creates divergent illumination onto the specimen
- Resolution limited to focus size
- Similar algorithms as in propagation-based phase-contrast imaging
- Equivalent propagation distance D and magnification M:

$$D = \frac{D_1 D_2}{D_1 + D_2} \qquad M = \frac{D_1 + D_2}{D_1}$$



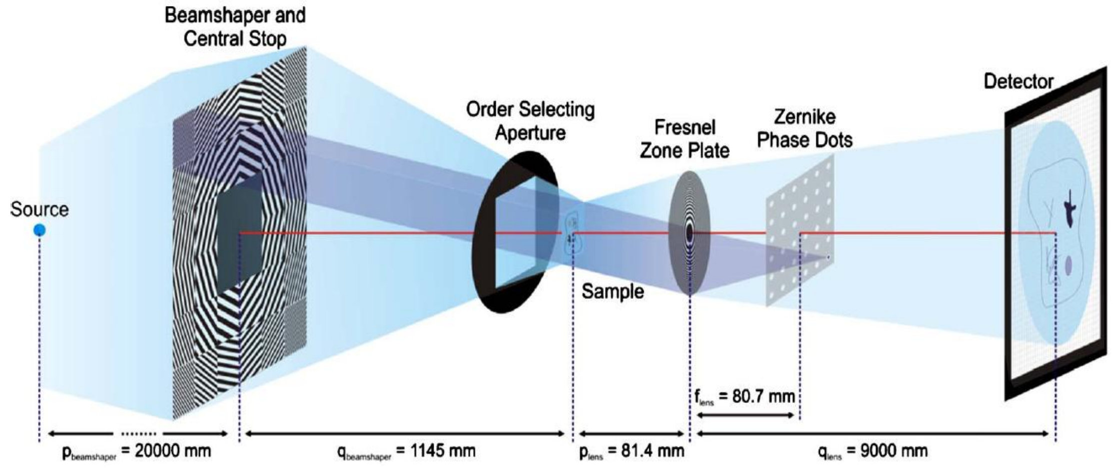
A. T. Kuan et al.,
Nat. Neurosci. **23**, 1637-1643 (2020)

M. Langer *et al.*, PLOS ONE **7**, e35691 (2012)
R. Mokso *et al.*, Appl. Phys. Lett. **90**, 144104 (2007)

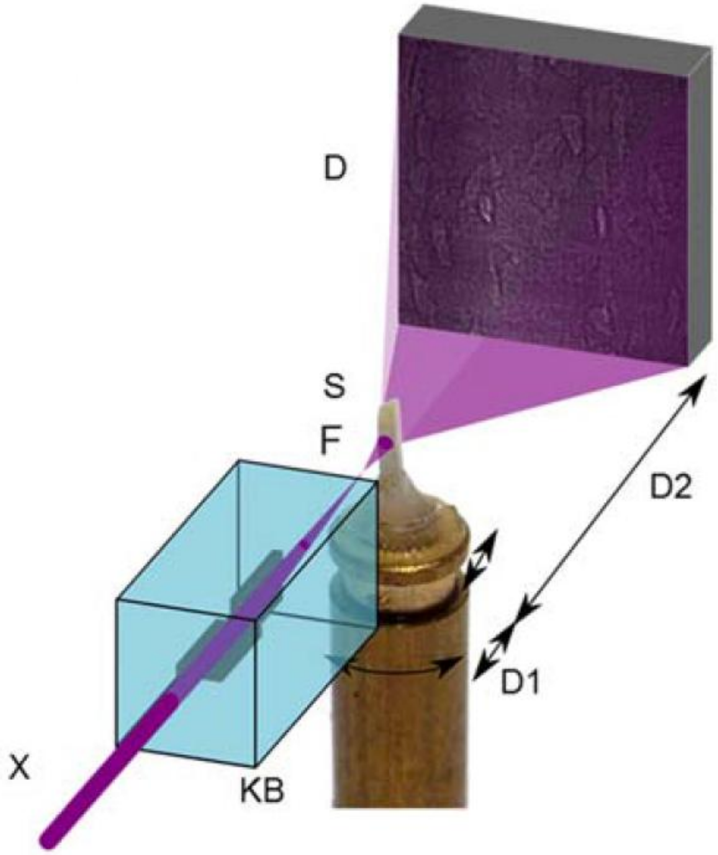
Also knows as **holo-nanotomography**

Lens- or focusing-based hard X-ray microscopy methods

Full-field microscopy with Zernike phase-contrast
M. Stampanoni *et al.*, Phys. Rev. B **81**, 140105(R) (2010)



Nano-holotomography
M. Langer *et al.*, PLOS ONE **7**, e35691 (2012)



Wave propagation reveals phase contrast

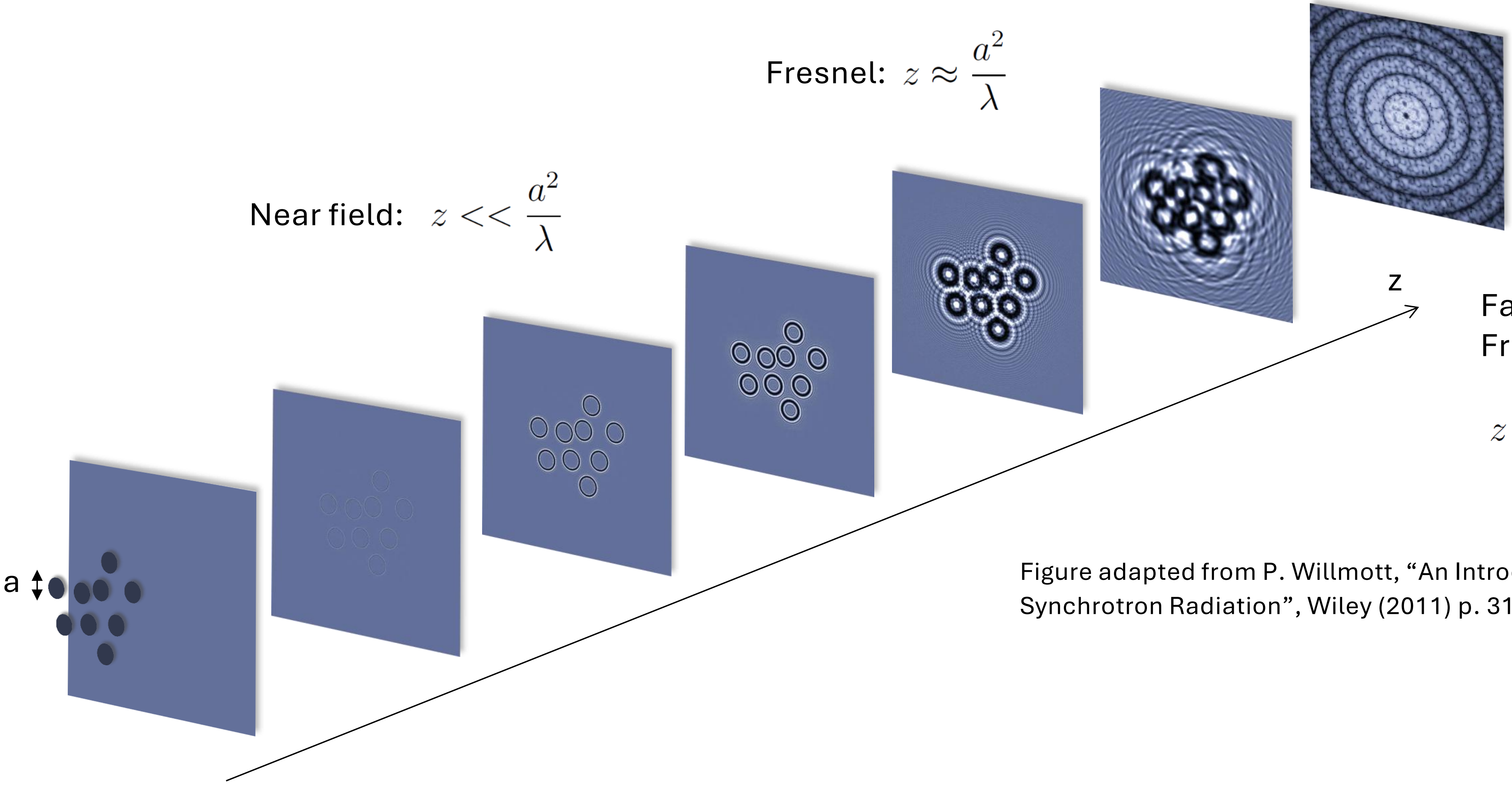


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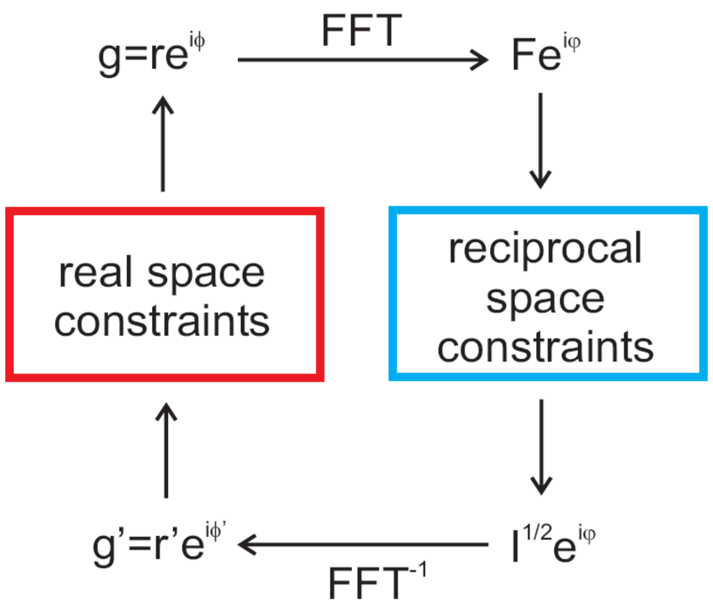
Figure adapted from P. Willmott, “An Introduction to Synchrotron Radiation”, Wiley (2011) p. 314

Coherent diffraction imaging (CDI)

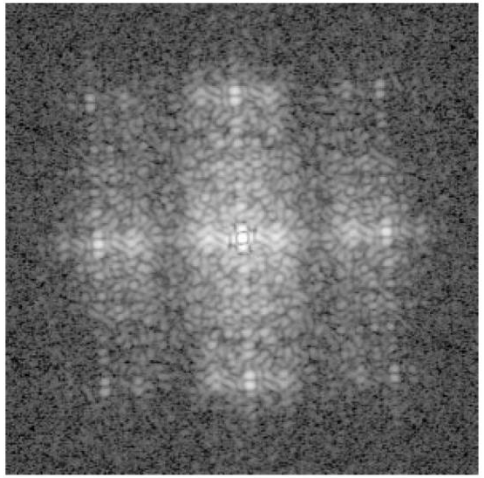
PSI

Iterative phase retrieval algorithm

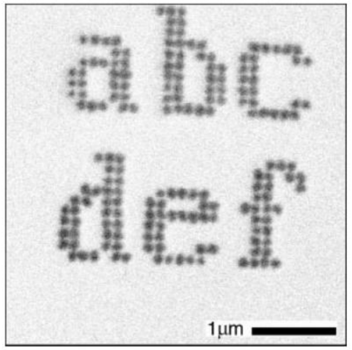
support constraint



oversampling



J.R. Fienup Appl. Opt. **21**, 2758 (1956)

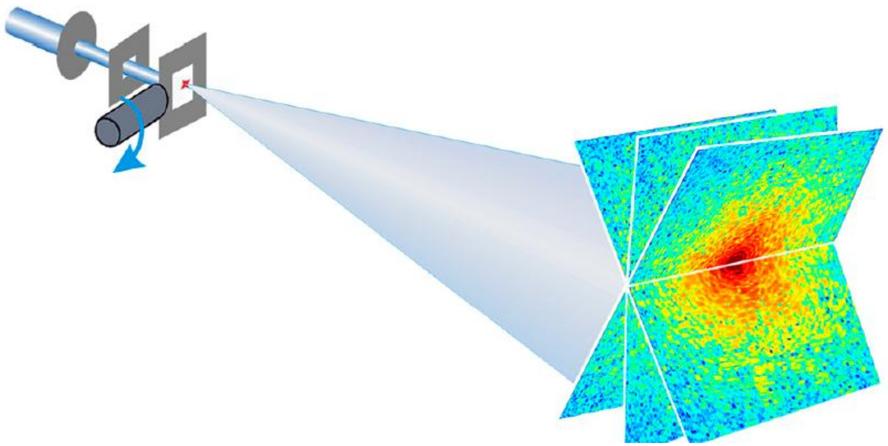


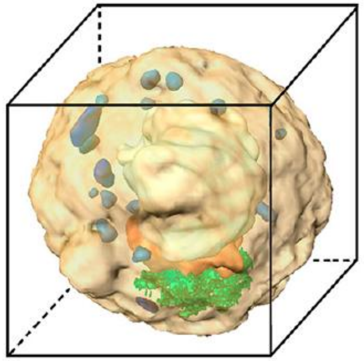
Sample consisting of 100 nm Au nanodots

- Resolution not limited by optics

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

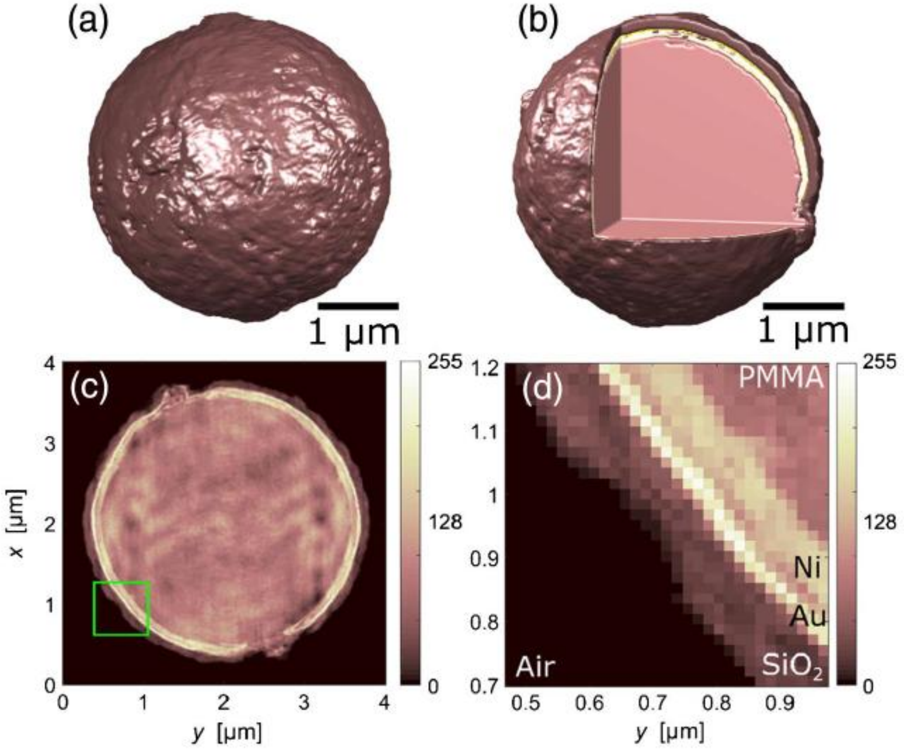
Coherent diffraction imaging (CDI) on single cells





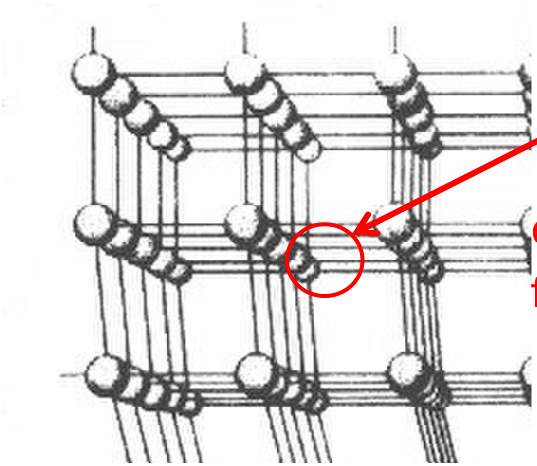
H. Jiang *et al.*,
PNAS **107**, 11234 (2010)

- Metal-coated polymer micro-sphere



E. T. B. Skjønsfjell *et al.*,
J. Opt. Soc. Am. A **35**, 7-17 (2018)

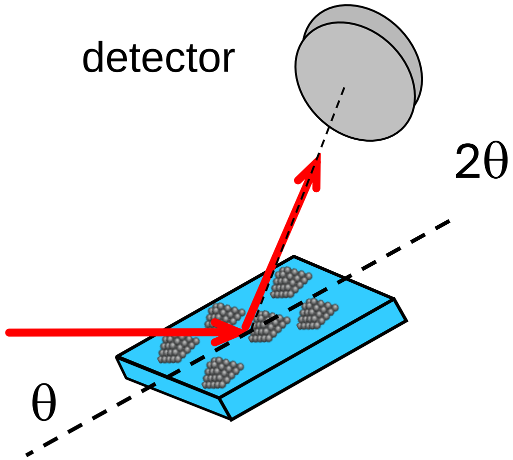
Bragg coherent diffraction imaging (Bragg CDI)

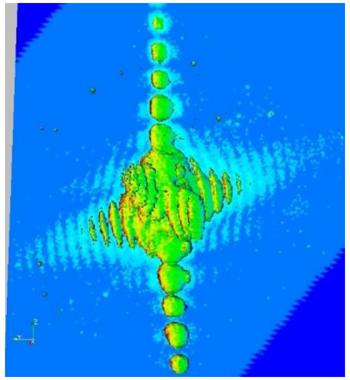


$\vec{R} = \vec{R}_c + \vec{u}$

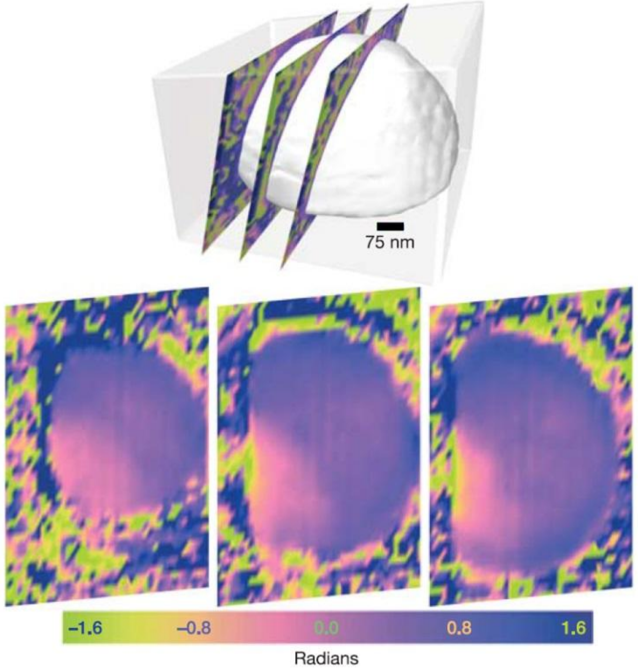
displacement field

Image source(*)





3D displacement field in nano-crystals



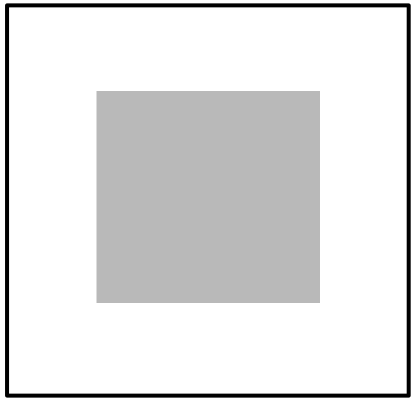
M. Pfeifer *et al.*, Nature **442** (2006) 63

(*) http://www.tf.unikiel.de/matwis/amat/def_en/kap_5/backbone/r5_2_1.html

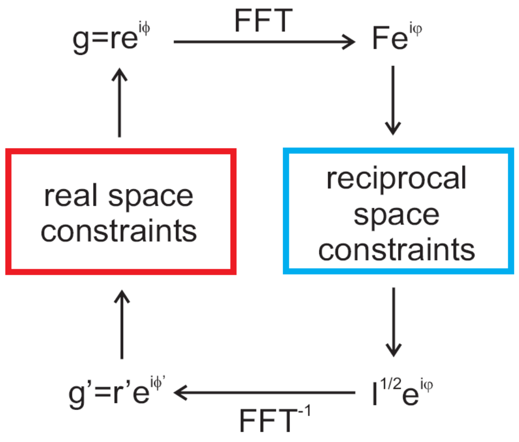
CDI: practical limitations

PSI

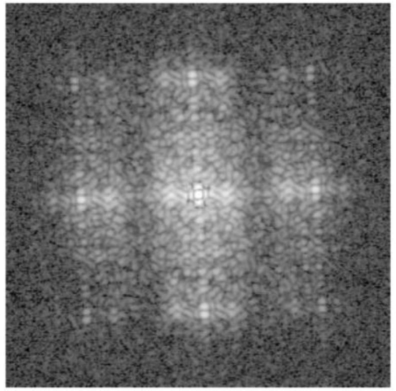
support constraint



Iterative phase retrieval algorithm



oversampling

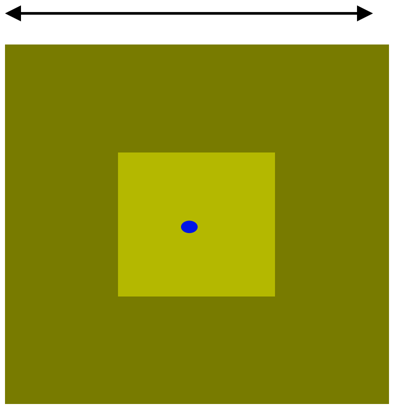


J.R. Fienup,
Appl. Opt. **21**, 2758 (1956)
J. Miao *et al.*,
Nature **400**, 342 (1999)

- Nyquist sampling ⇒ confined sample
- Typical beamline setups
  - Sample-detector ~ 5 m
  - Pixel size ~ 50 μm
  - Wavelength ~ 1-2 Å

  ⇒ Sample size < a few micron
- Convergence

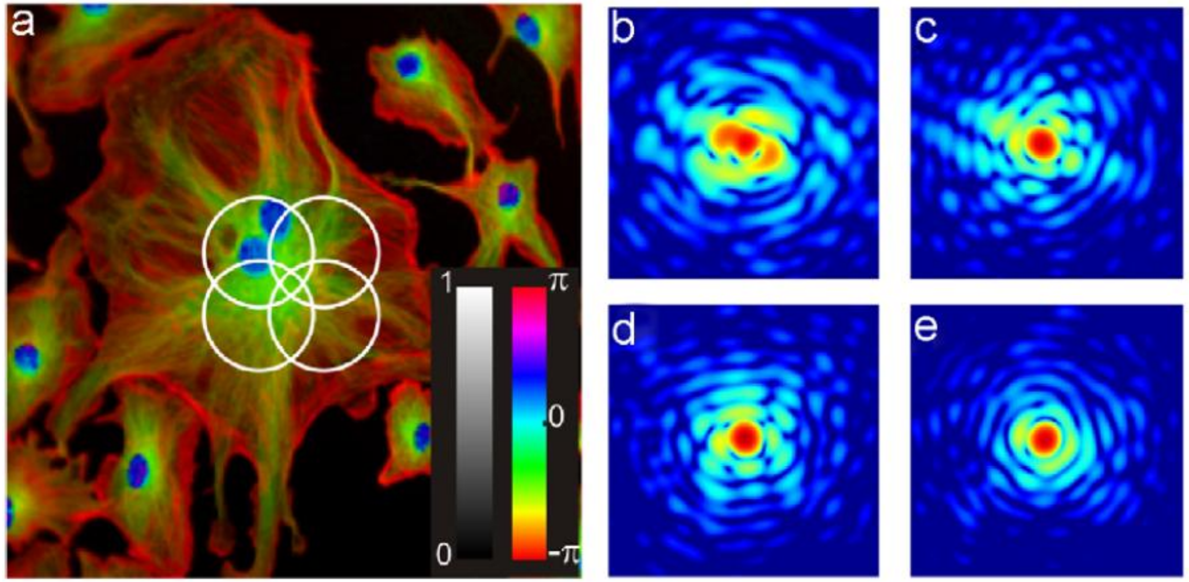
3 mm



These limitations can be overcome using a modulator or a structured illumination

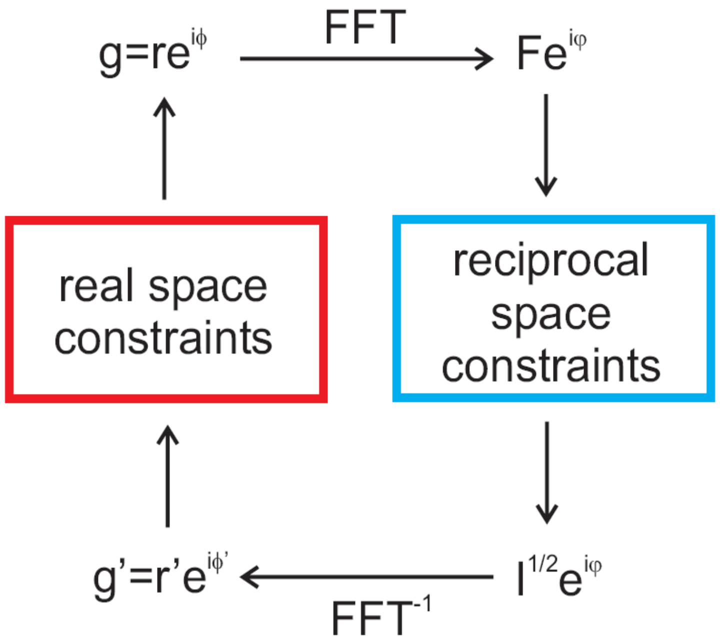
Ptychography

Coherent diffraction patterns from overlapping illuminated areas



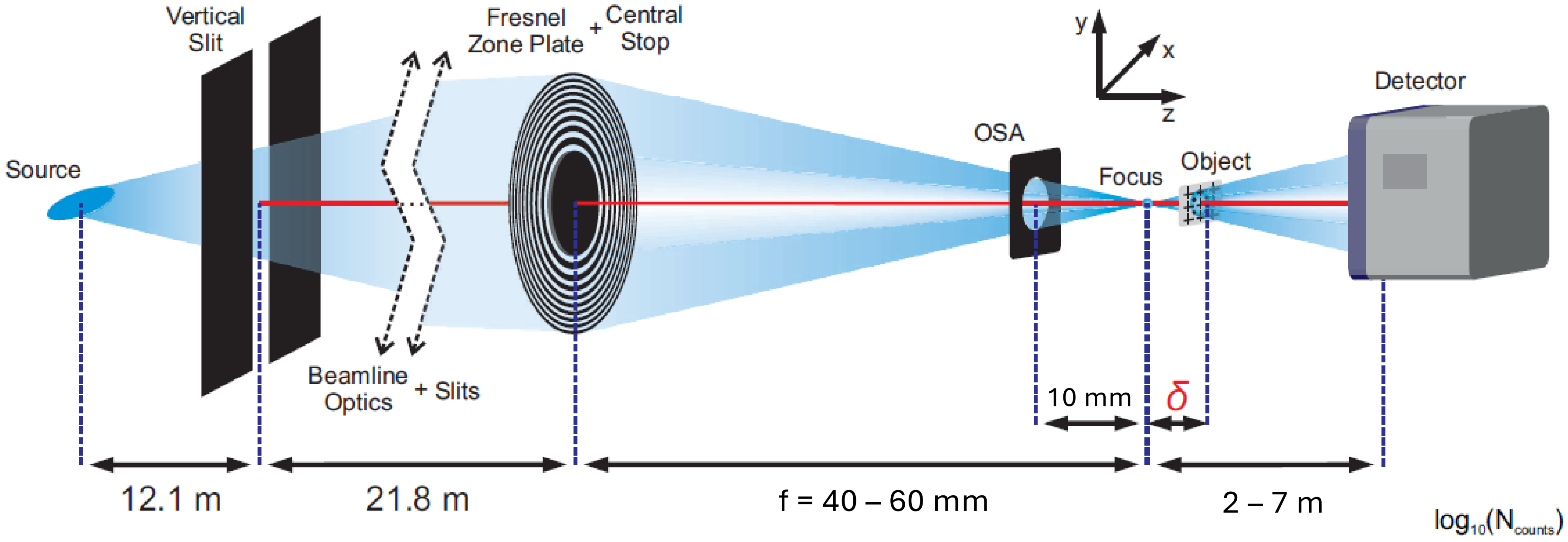
- Absorption and phase contrast
- Resolution not limited by a lens!
- In practice limited by mechanical stability and thermal drifts

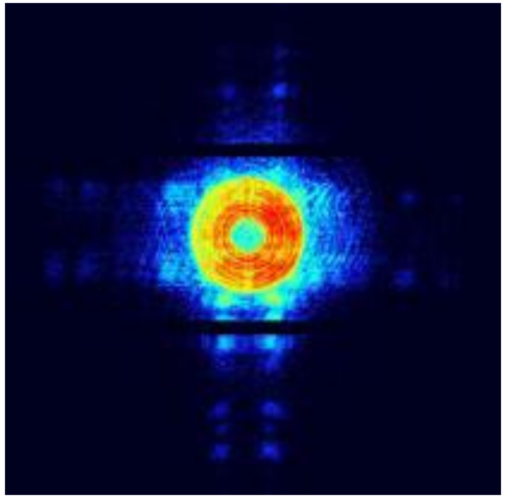
Iterative phase retrieval algorithms to reconstruct complex-valued transmissivity



H. M. L. Faulkner & J. M. Rodenburg, Phys. Rev. Lett. **93**, 023903 (2004)

A typical X-ray ptychography setup



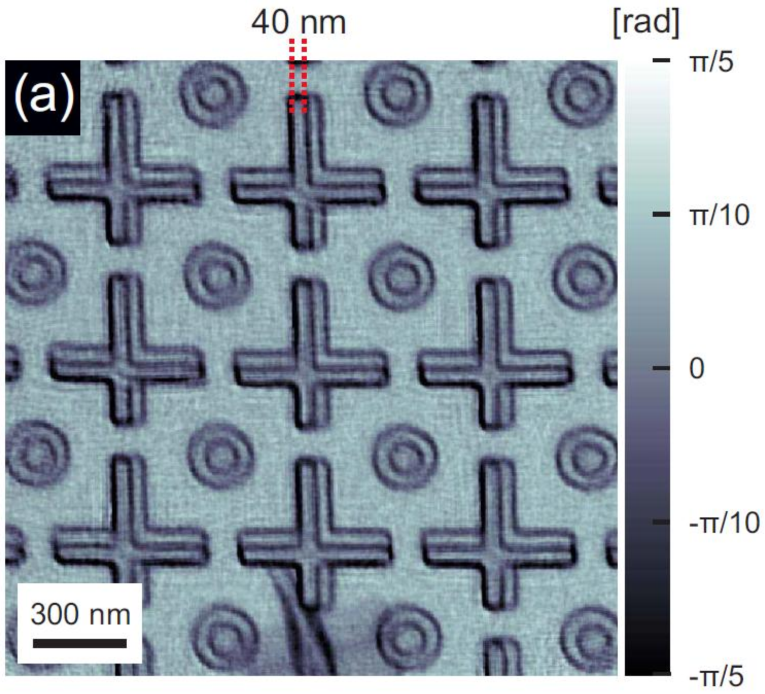


coherent flux:
5×10^8 photons/s
@ 6.2 keV

J. Vila-Comamala *et al.*, Opt. Express **19**, 21333 (2011)

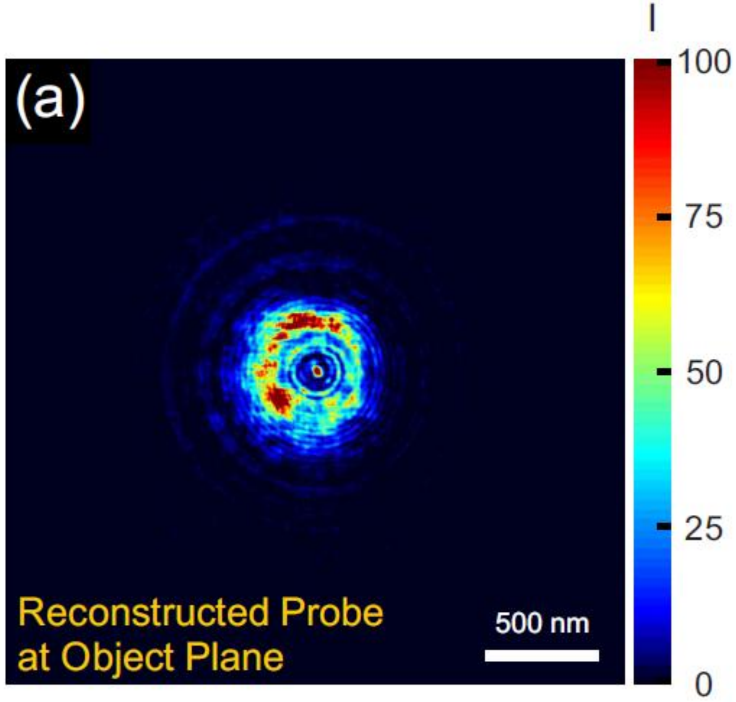
Simultaneous probe reconstruction with ptychography

Phase image

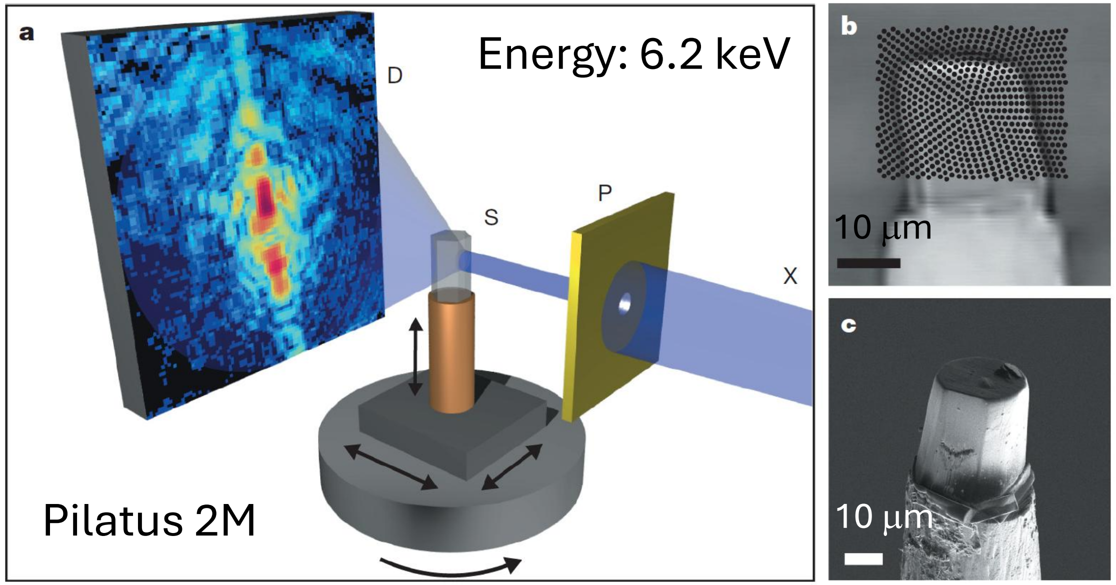


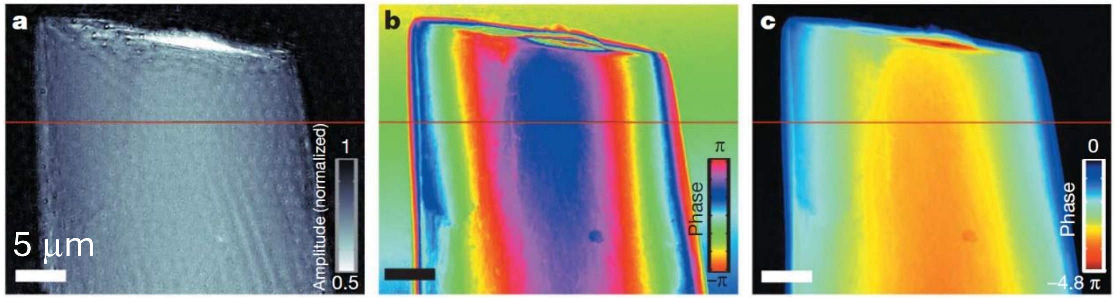
8 nm resolution
2×2 μm area
4 min

Illumination beam

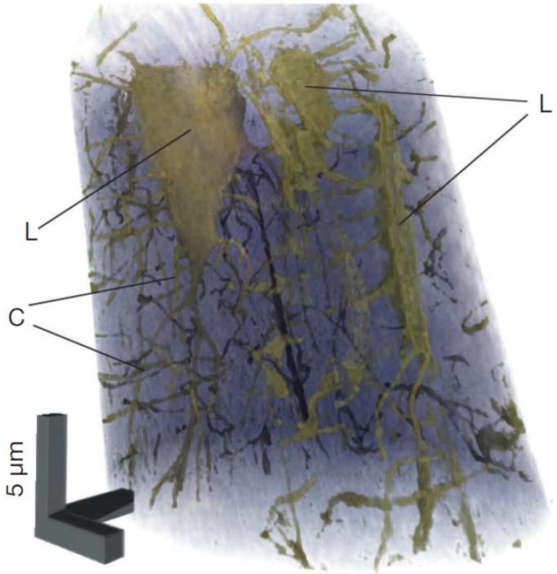


Ptychographic X-ray computed tomography (PXCT)





M. Dierolf *et al.*, Nature **467** (2010) 436



Mouse bone specimen

Voxel size: 65 nm
Resolution: 120 nm
Dose: 2MGy

Instrumentation for PXCT

PSI

OMNY: tOMography Nano crYo stage

M. Holler and J. Raabe

- Laser interferometry for relative positioning of sample and illumination optics
- Aimed 3D resolution: 10 nm
- Cryo stage in ultra-high vacuum
- First test setup in air at room temperature, still in user operation

M. Holler *et al.*, Rev. Sci. Instrum. **83**, 073703 (2012)
M. Holler *et al.*, Rev. Sci. Instrum. **89**, 043706 (2018)

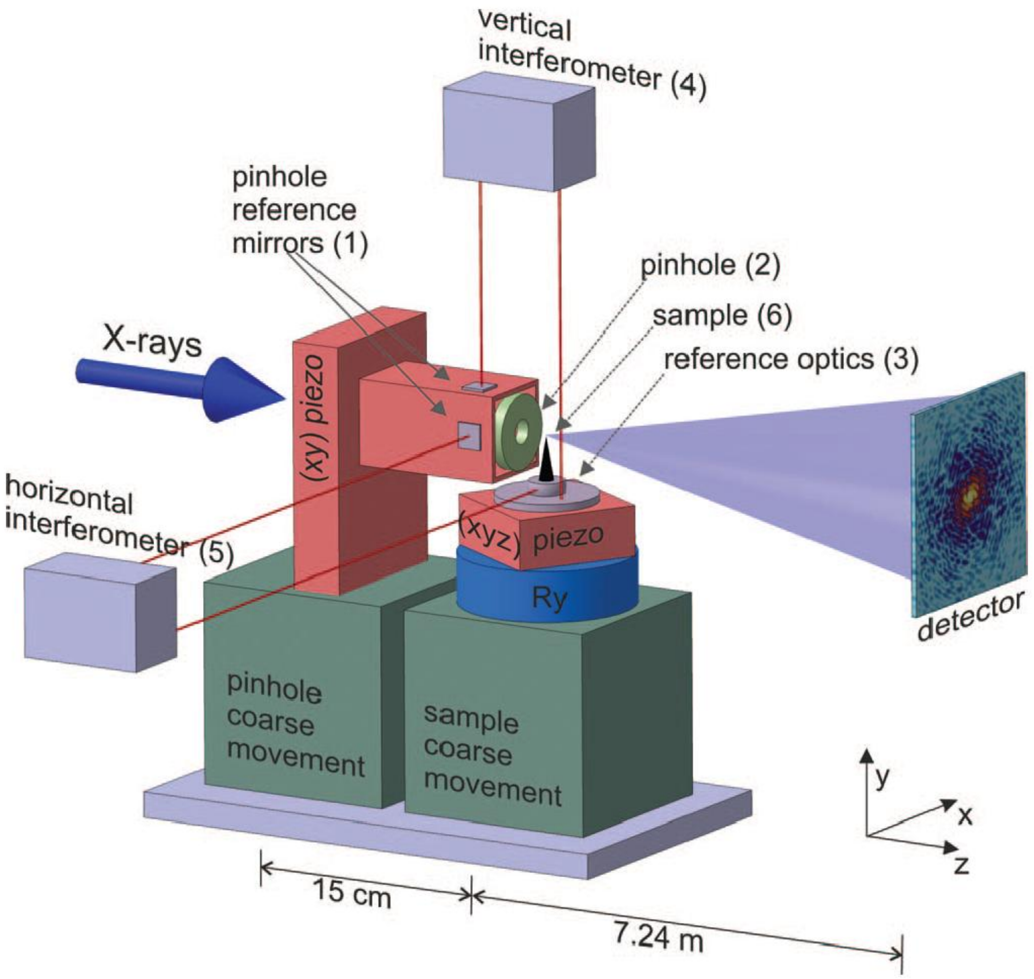
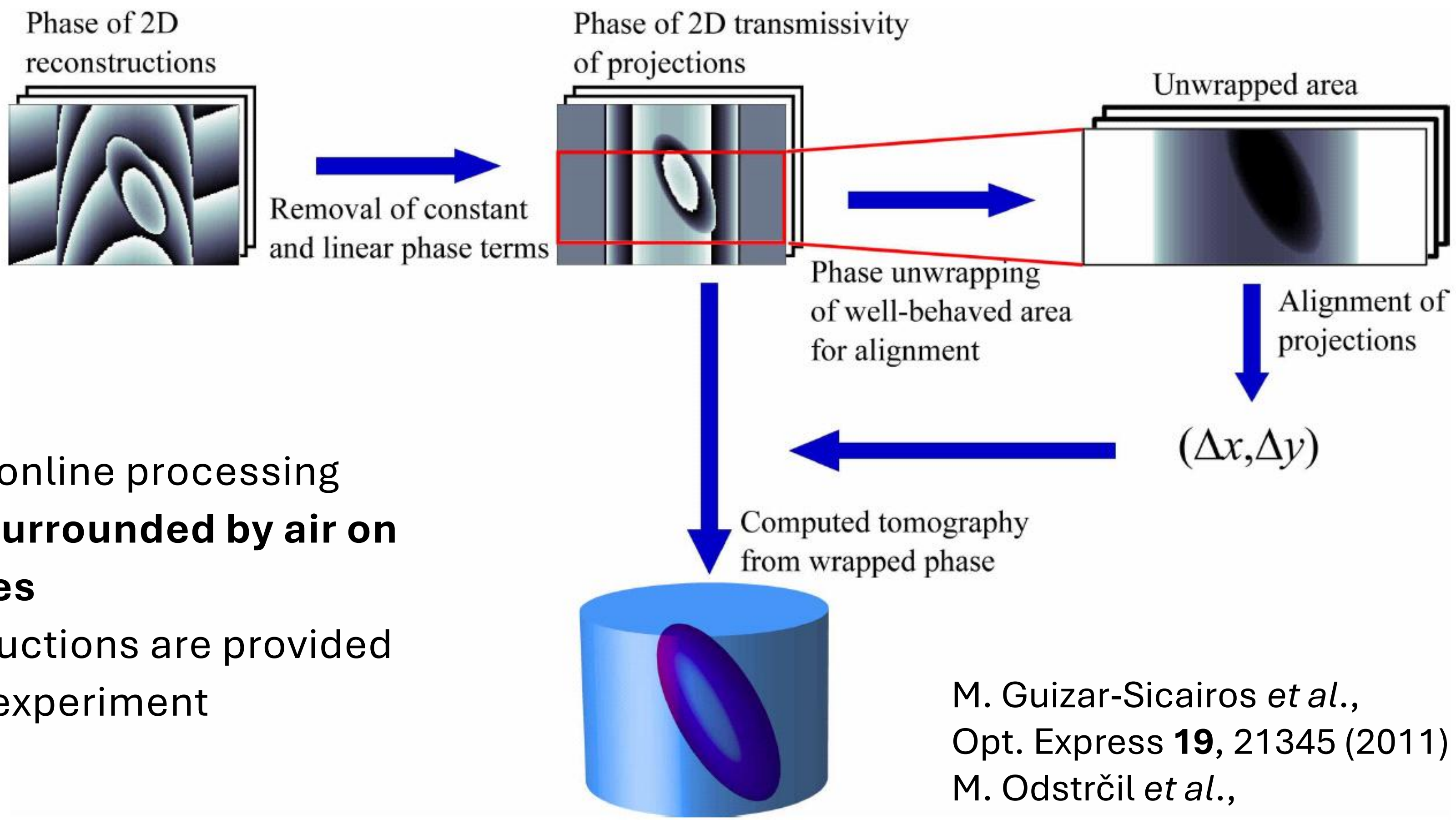


Image processing for PXCT

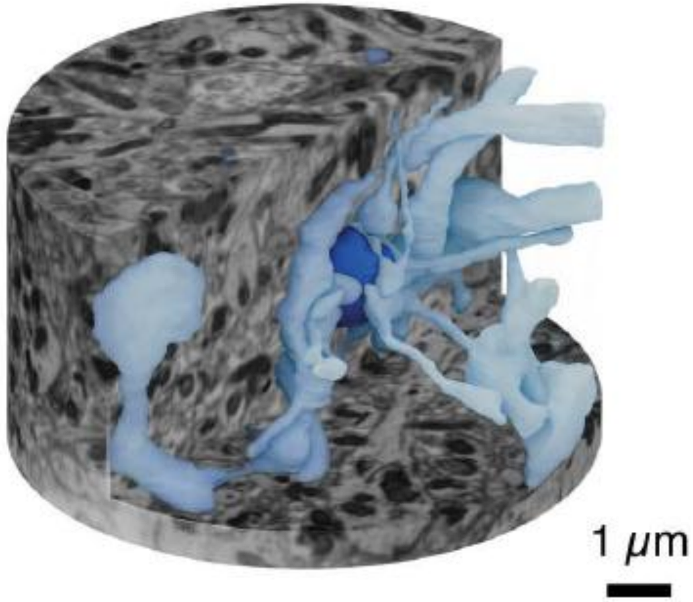


- Robust algorithms for online processing
- **Sample needs to be surrounded by air on both sides at all angles**
- Tomographic reconstructions are provided to the user during the experiment

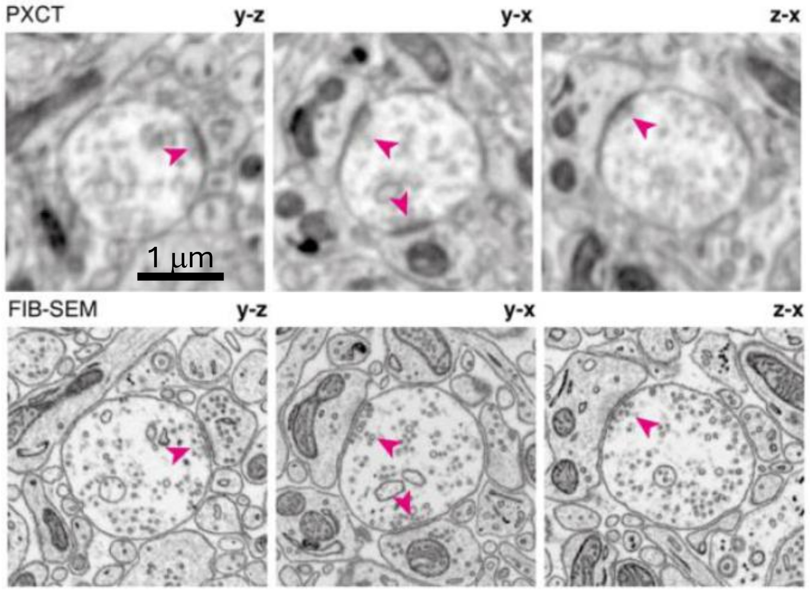
M. Guizar-Sicairos *et al.*,
Opt. Express **19**, 21345 (2011)
M. Odstrčil *et al.*,
Opt. Express **27**, 36637 (2019)

Detection of synapses in stained, resin-embedded tissue

3D electron density map



38 nm resolution
absorbed dose: 2.5×10^9 Gy



Adrian Wanner
PSI

Tomas Aidukas
PSI

Carles Bosch
Francis Crick Institute

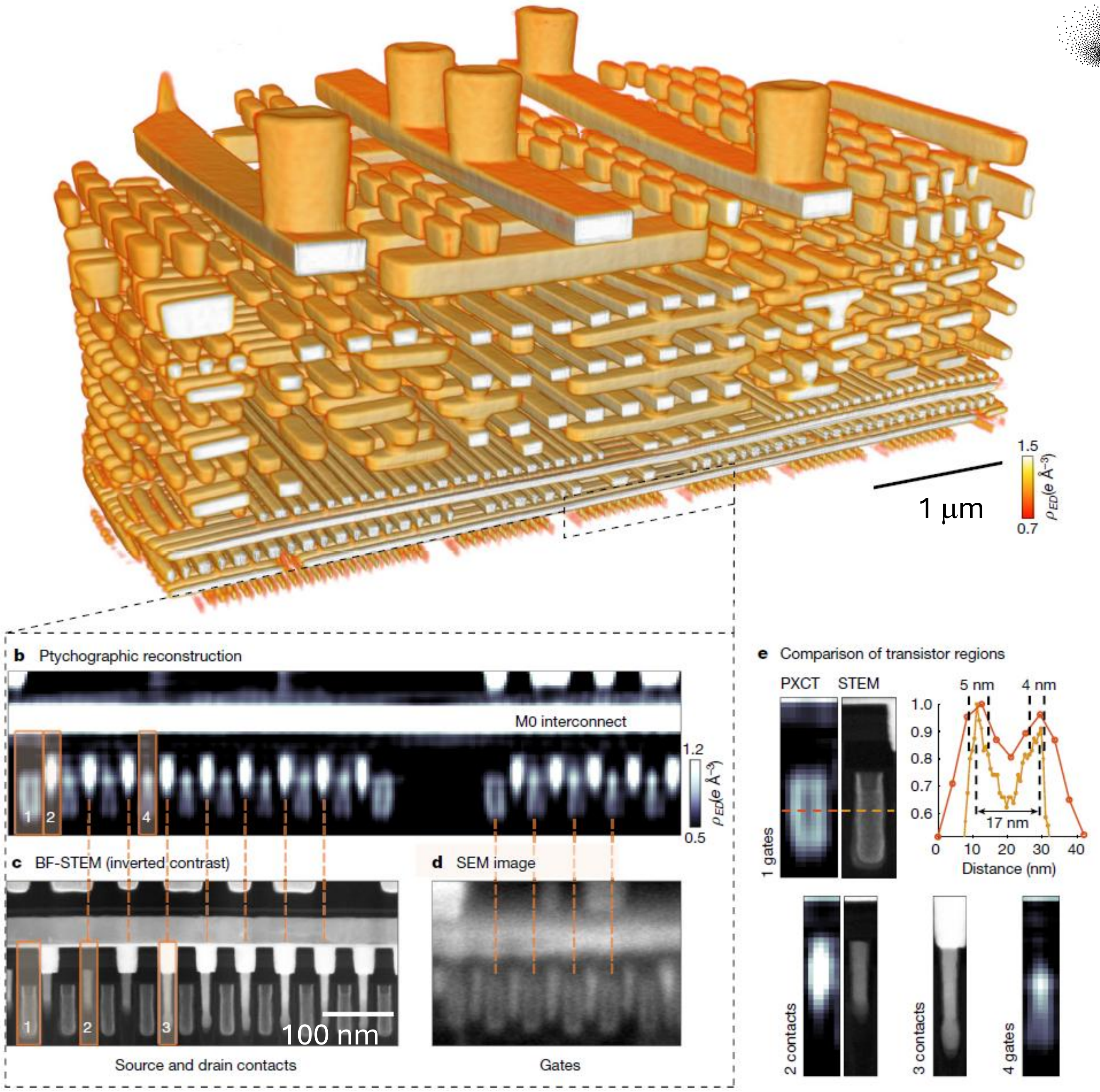
C. Bosch *et al.*,
bioRxiv (2024) doi: 10.1101/2023.11.16.567403
(in review)

- Novel sample preparation with radiation-hard resin
- Non-rigid tomographic reconstruction for sample deforming during acquisition

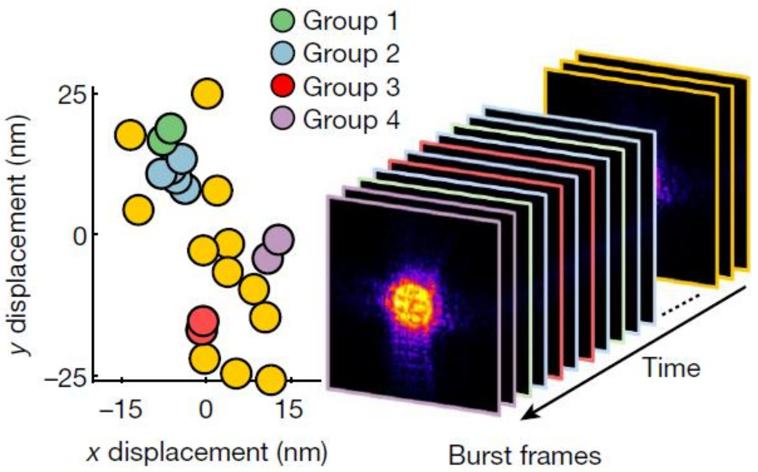
PXCT on 7 nm-node chip

4 nm 3D resolution
Burst ptychography
Record in hard X-ray microscopy

T. Aidukas *et al.*, Nature **632**, 81 (2024)

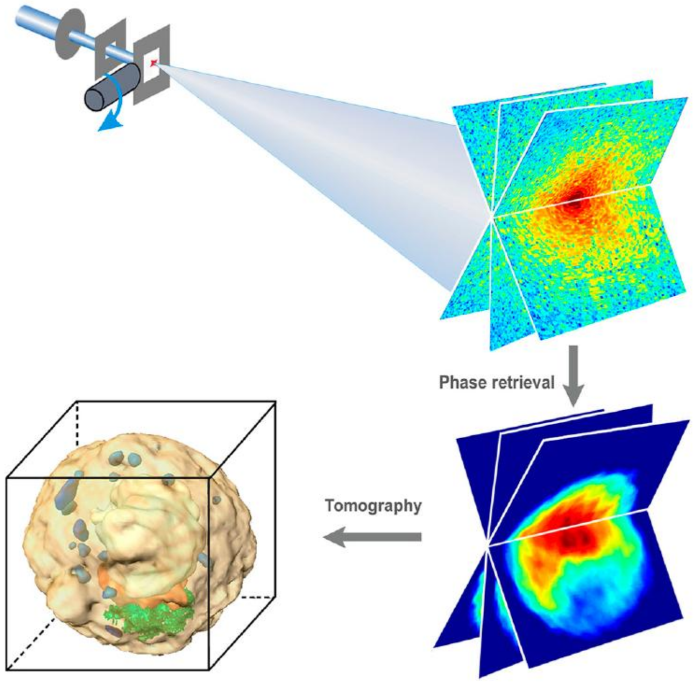


Tomas Aidukas



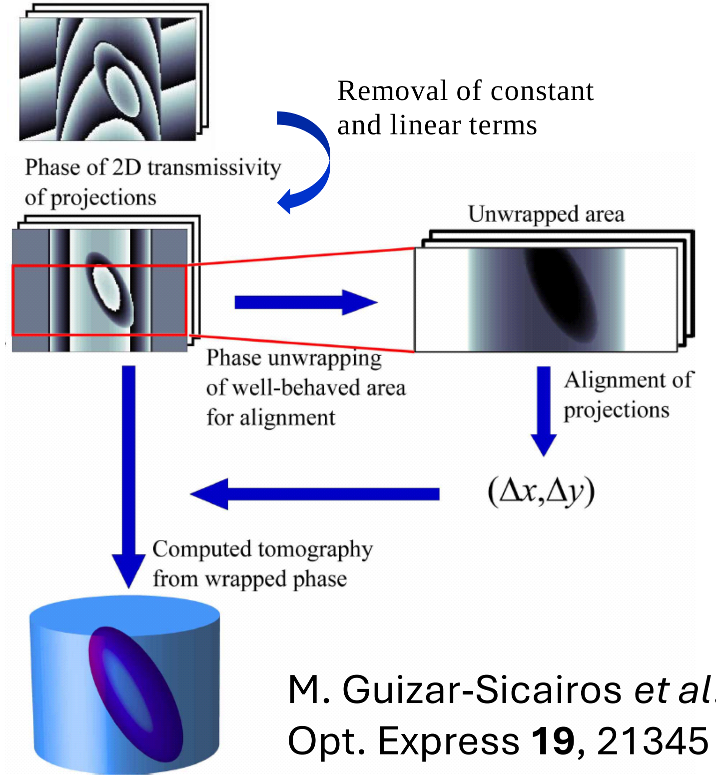
CDI vs ptychography

coherent diffraction imaging



H. Jiang *et al.*, PNAS **107**, 11234 (2010)

ptychography

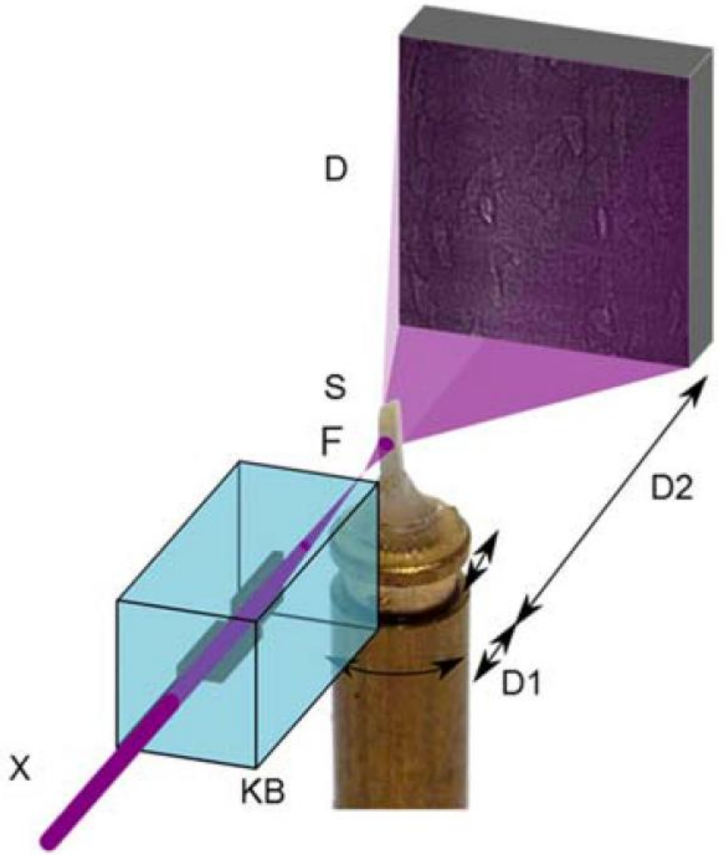


M. Guizar-Sicairos *et al.*, Opt. Express **19**, 21345 (2011)

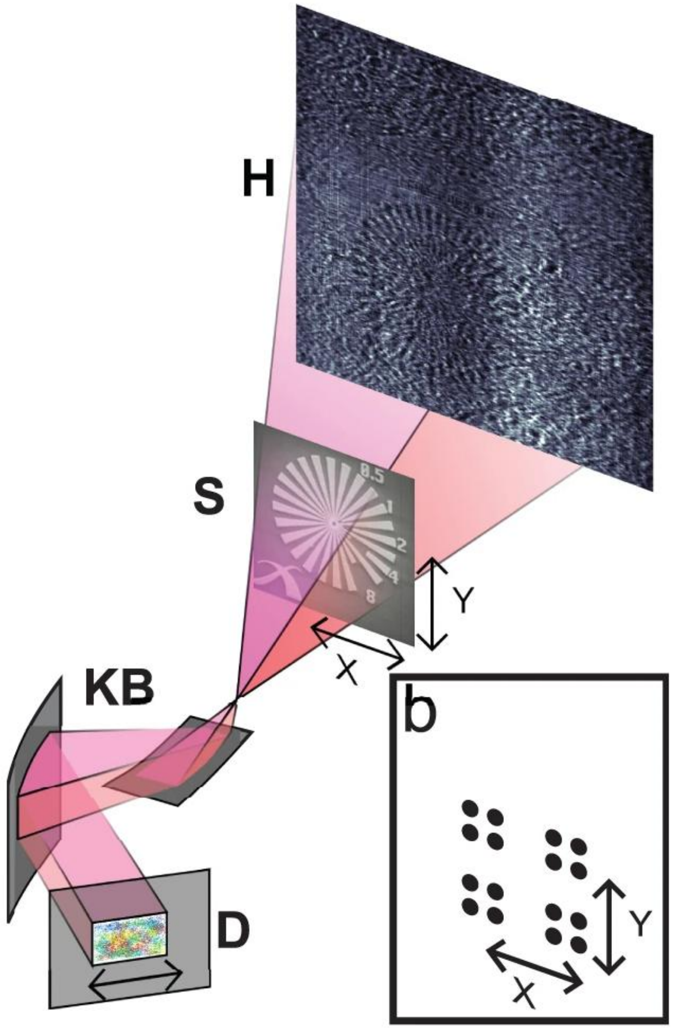
- 3D reconstruction from 3D reciprocal space: very robust to positioning accuracy
- Limited to isolated samples of a few microns

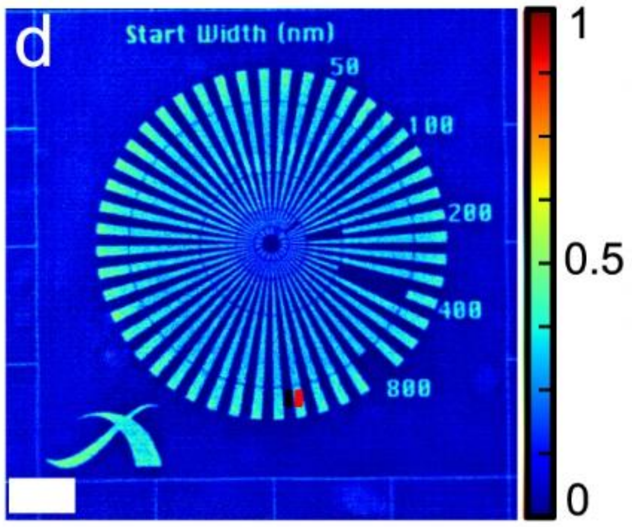
- Requires cutting-edge instrumentation for high-resolution scanning + rotation
- Applicable to large samples

Near-field ptychography



Nano-holotomography
M. Langer *et al.*, PLOS ONE **7**, e35691 (2012)



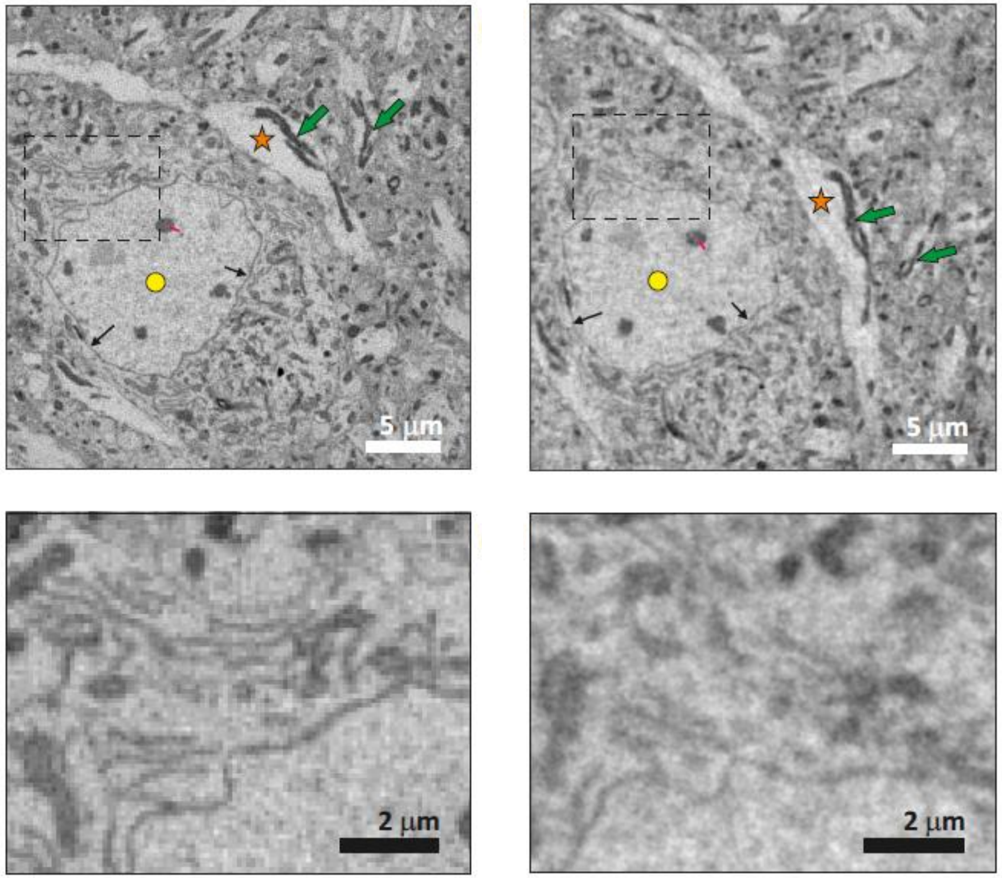


5 μm

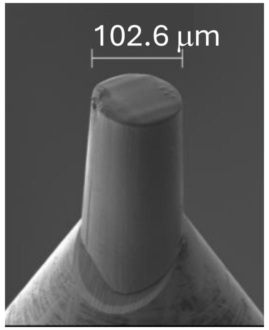
Near-field ptychography
M. Stockmar *et al.*, Sci. Rep. **3**, 1927 (2013)

Comparing PXCT and nano-holotomography

ptycho-tomography	**holo-tomography**
@ 6.2 keV	@ 17 keV
108 nm, 3.3e7 Gy	121 nm, 8.6e7 Gy



Heavy-metal-stained brain tissue

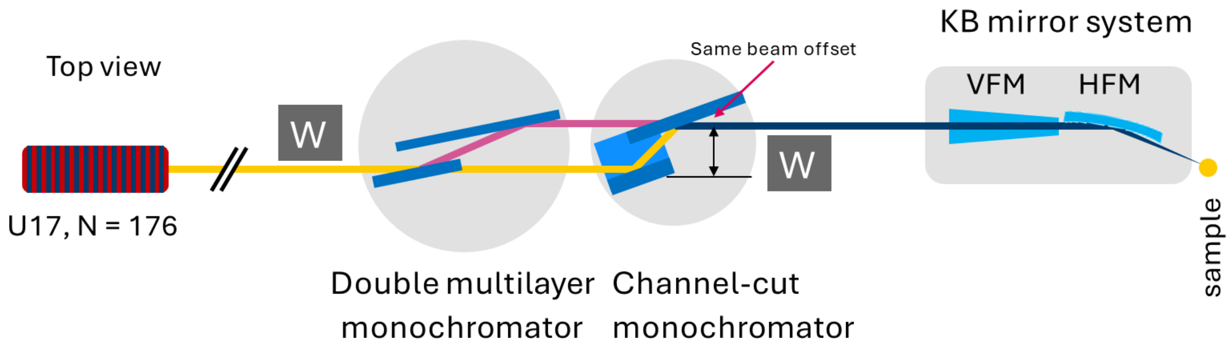


Alexandra
Pacureanu
ESRF

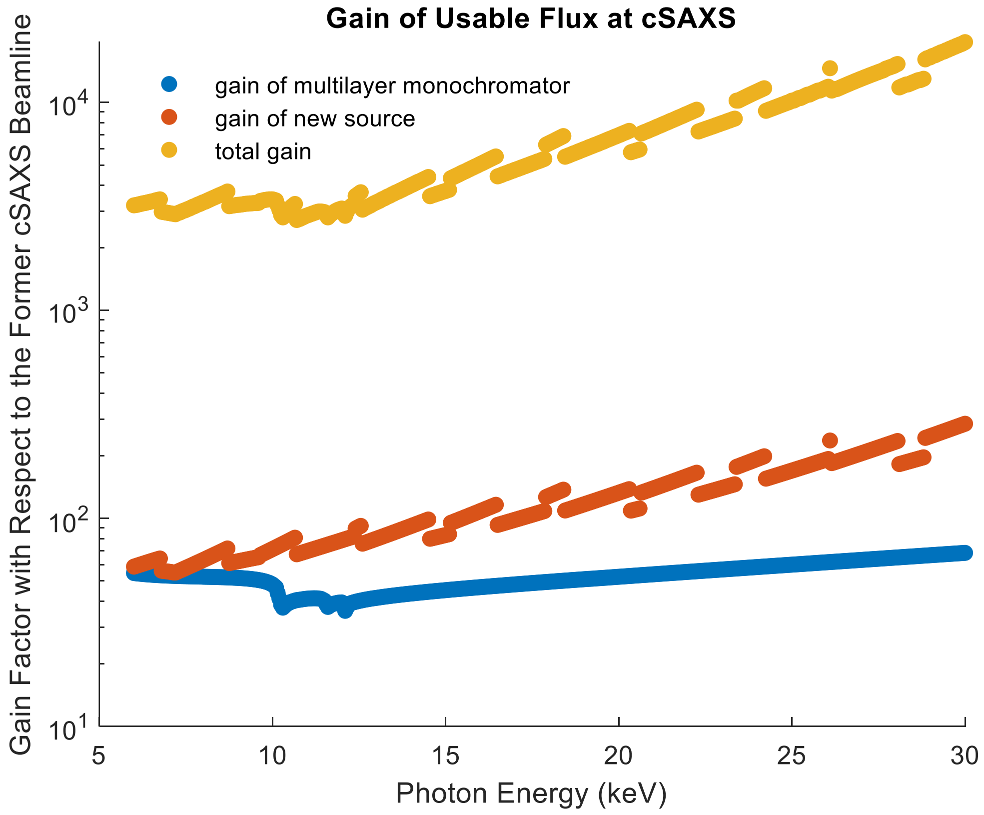
- Similar spatial resolution ~ 100 nm
- 2.5x less dose with ptycho-tomo
- 16x faster with holo-tomography (in resels/s)

Collaboration with
A. Pacureanu (ESRF, France)
C. Bosch & A. Schaefer (Francis Crick Inst., UK)
Manuscript in review

The upgrade: SLS 2.0 and cSAXS 2.0

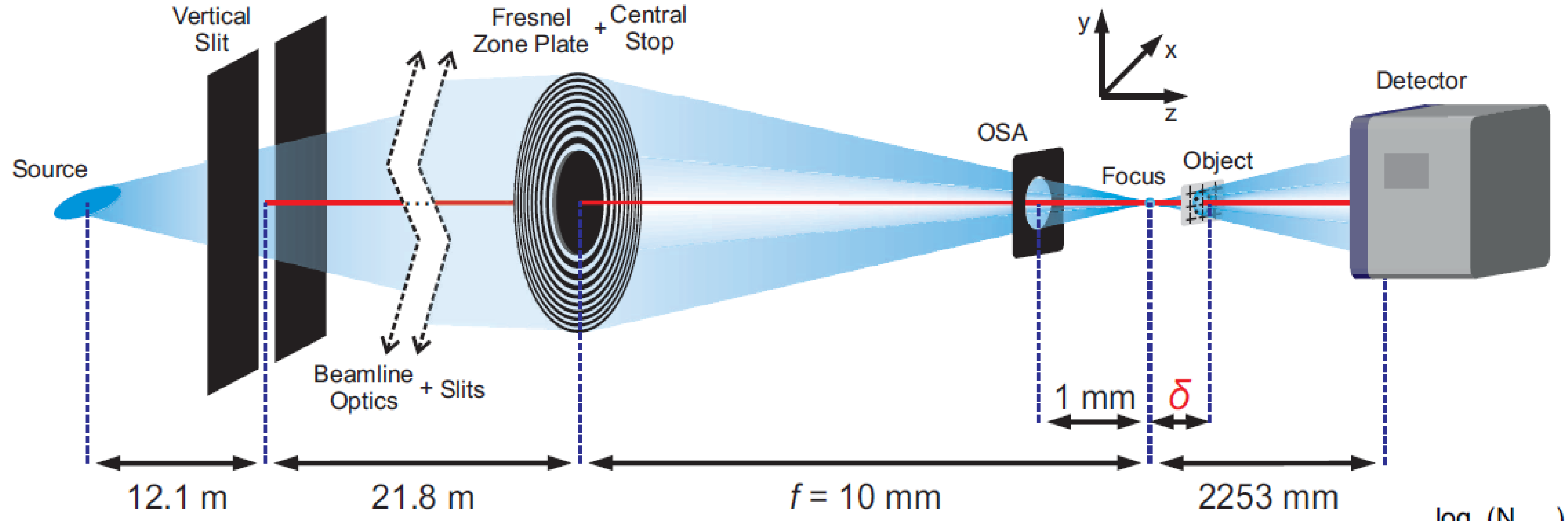


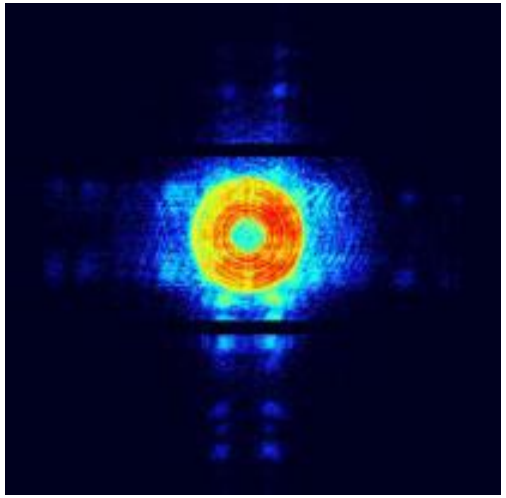
- ~ 30× more coherent flux with SLS 2.0
- ~ 3× more flux with new U17 undulator
- ~ 10× more flux with more efficient optics for PXCT
- ~ 40× more flux with broadband option
- Better beam stability



Slide courtesy of Benedikt Rösner

Benefits of upgraded source





$\log_{10}(N_{counts})$

coherent flux:
$5 \times 10^{\cancel{8}10}$ photons/s
@ 6.2 keV

J. Vila-Comamala *et al.*, Opt. Express **19**, 21333 (2011)

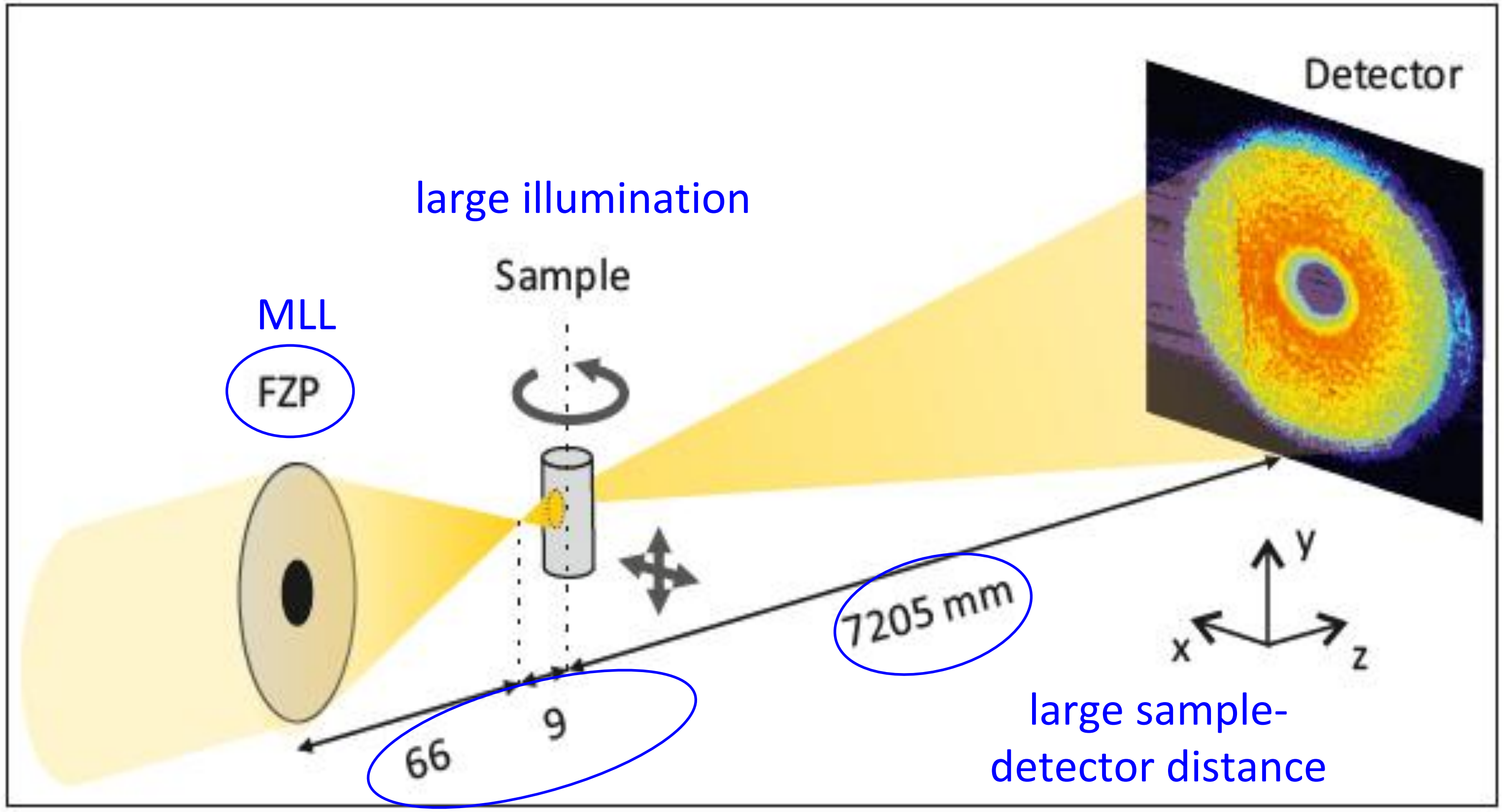
Radiation damage
Detector saturation

Proposals to overcome the challenge of high photon flux

I. Scan faster ⍰ careful, same flux density (photons/s/μm^2)

II. Spread flux on sample and on detector ⍰ no high-resolution scanning probe possible

Far/near-field ptycho
holotomography
high energy



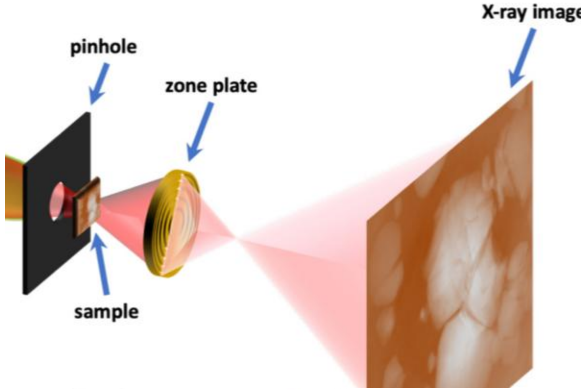
large
single photon counting
detector

CoDi

Conclusions – high-resolution hard X-ray microscopy

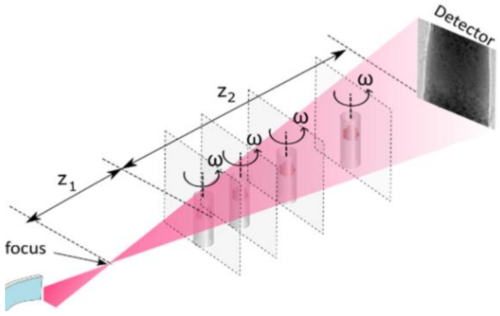
PSI

Transmission X-ray microscopy (TXM)
Very fast measurements
Inherently dose inefficient
Resolution limited by lens



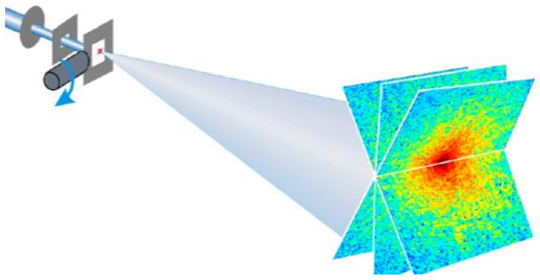
S. Spence *et al.*, Nanotechnol. **32**, 442003 (2021)

X-ray holo-nanotomography (XNH)
Fast measurements
Phase contrast
Resolution limited by focus



A. T. Kuan et al., Nat. Neurosci. **23**, 1637-1643 (2020)

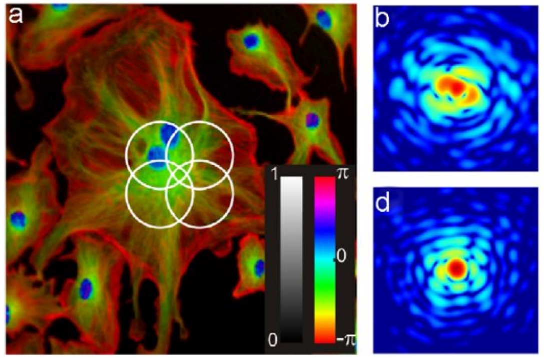
Coherent diffraction imaging (CDI)
Confined, small sample
Convergence issues
Ongoing developments



H. Jiang et al., PNAS **107**, 11234 (2010)

X-ray ptychography

Extended samples
Good convergence
Challenging experiment



T. Aidukas *et al.*, Nature **632**, 81 (2024)

Thank you for your attention
Questions?