# Lensless Imaging with Coherent Extreme Ultraviolet Radiation

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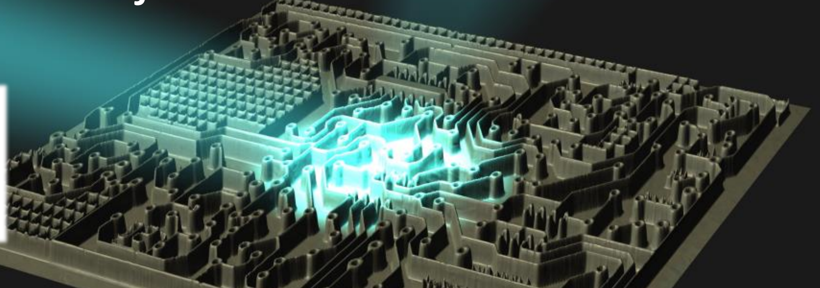

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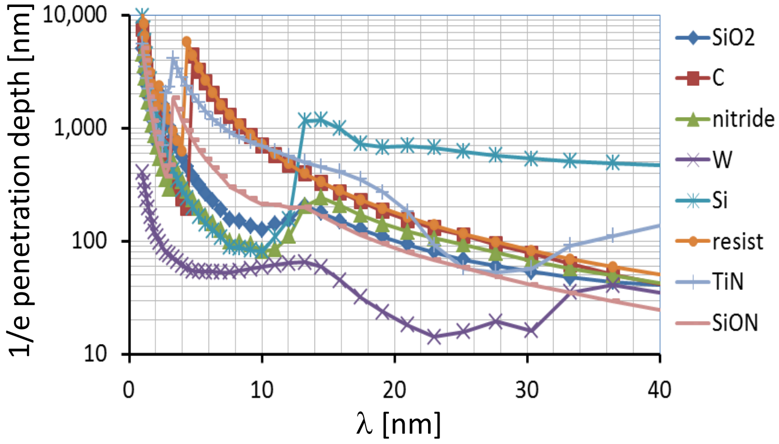
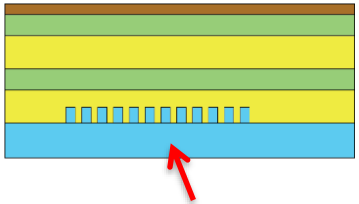
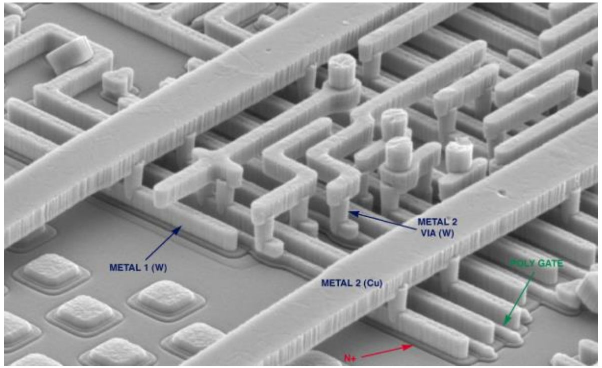
# Imaging and metrology with soft-X-ray sources

Soft-X-ray-based metrology may have the capability to meet future wafer metrology needs:



Structure of interest (metrology mark, device structure)

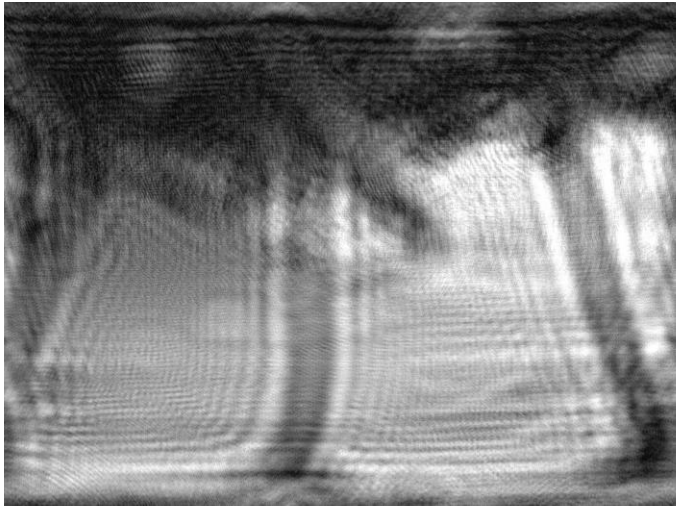



- Element-selectivity → most elements have specific spectral transmission windows

- High resolution → shorter wavelengths lead to smaller diffraction limit

# Information contained in an ‘image’

Information contained in an image may be more than what appears in a ‘focused’ projection



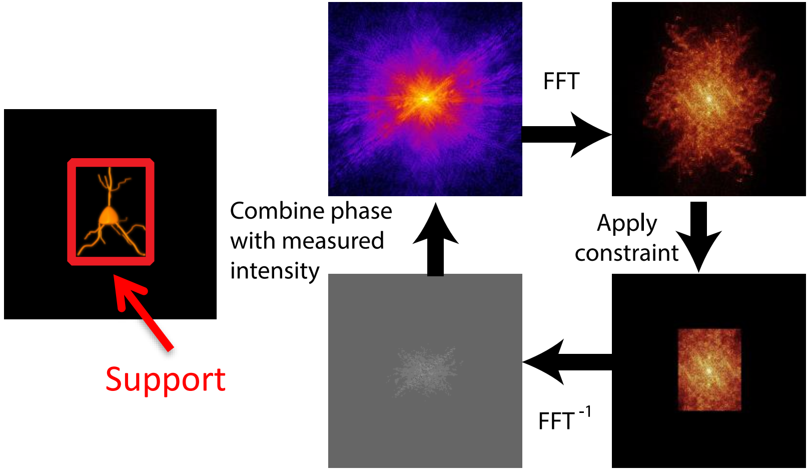
**Computational imaging aims to retrieve information numerically from diffraction patterns:**

- May remove limitations in image quality caused by lens aberrations
- Add contrast mechanisms (e.g. phase contrast)
- The extreme version of this concept is imaging without lenses at all

# Computational phase retrieval – different approaches

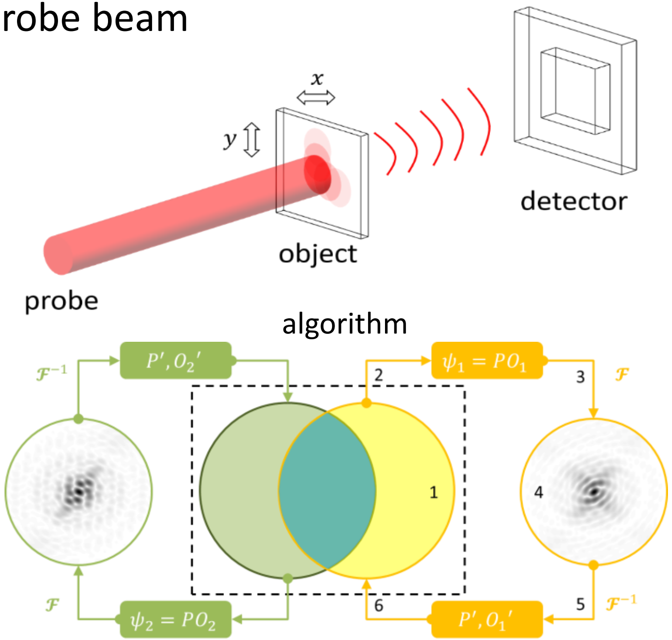
**Support constraints:**

Prior object knowledge constrains solution




**Ptychography:**

Spatial translation through a confined probe beam



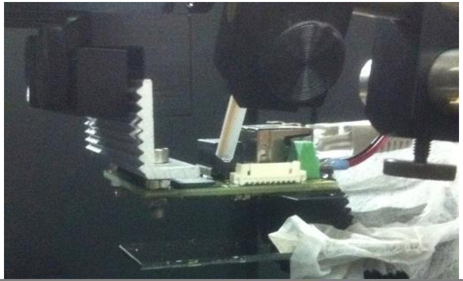

J.R. Fienup, Appl. Opt. **21**, 2758, (1982)

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

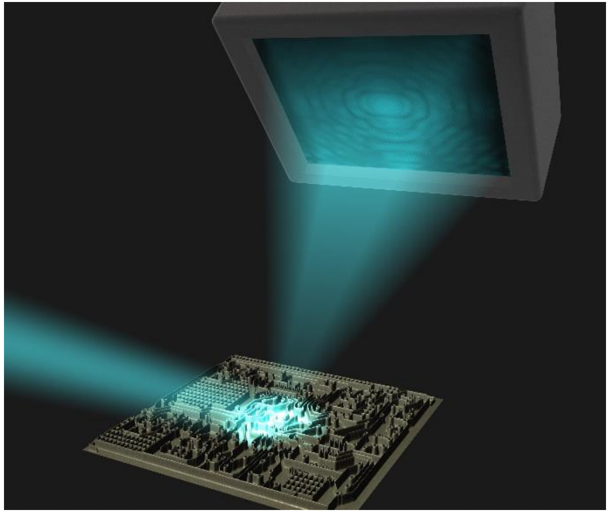
J.M. Rodenburg et al, Appl. Phys. Lett. **21**, 4795 (2004)

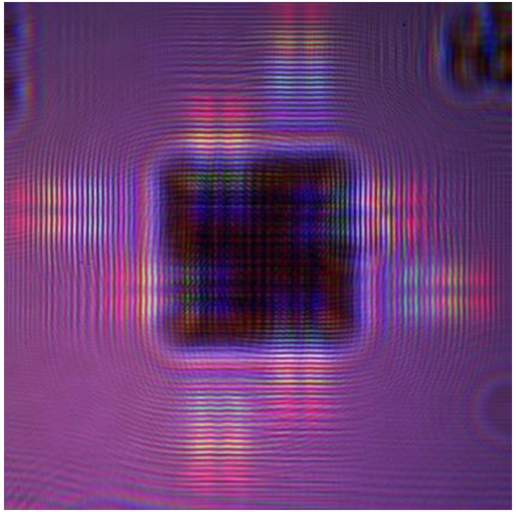
P. Thibault et al., Science **321**, 379 (2008)

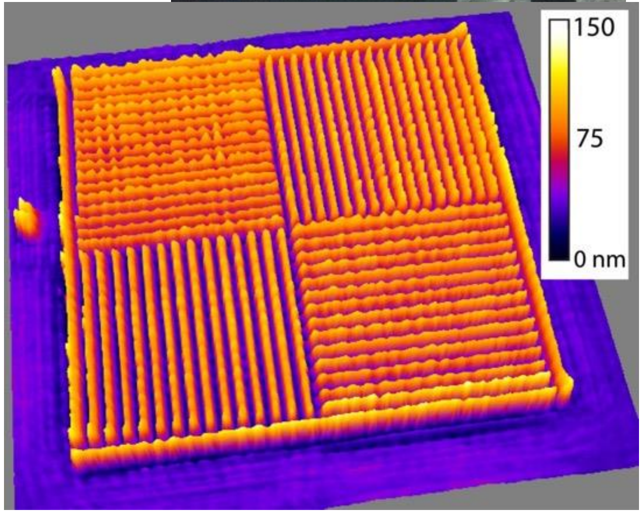
# Lensless imaging with visible light



Proof-of-concept measurement with simple optical setup:








- Quantitative phase-retrieval: measurement of structure height (sub-wavelength)
- Focus-determination happens numerically (direct correction for alignment drift)
- Aberration-correction by computer (tilts, curvatures)

Noom, Eikema, Witte, Opt. Lett. **39**, 193 (2014).

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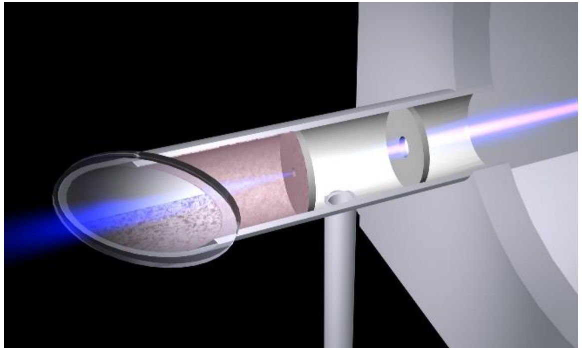
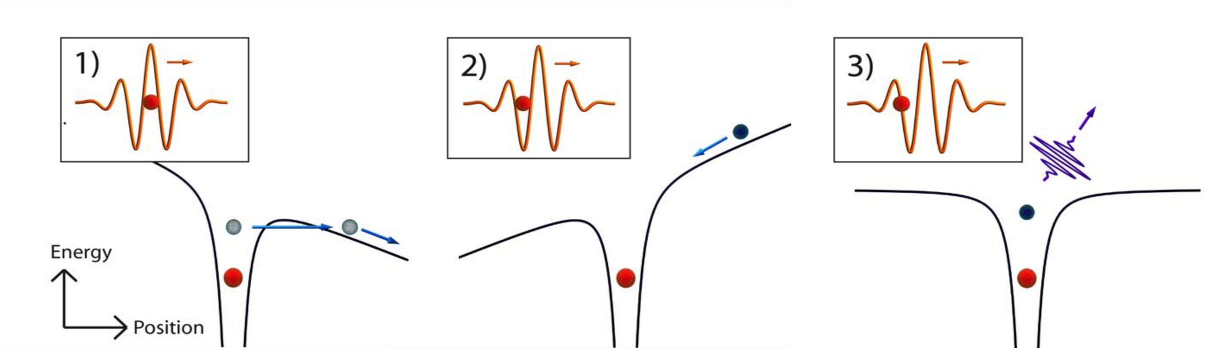
# High harmonic generation

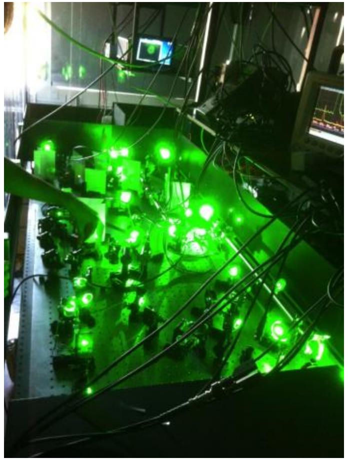


Laser modifies Coulomb potential → electron tunnels and accelerates

Field changes sign → electron returns to the parent ion

Recollision, electron energy converted into EUV photon



- Compact source of fully coherent extreme ultraviolet (EUV) radiation
- >nJ/pulse, ~kHz rep. rate → µW flux (sufficient for imaging applications)
- Process driven by an intense ultrafast laser source

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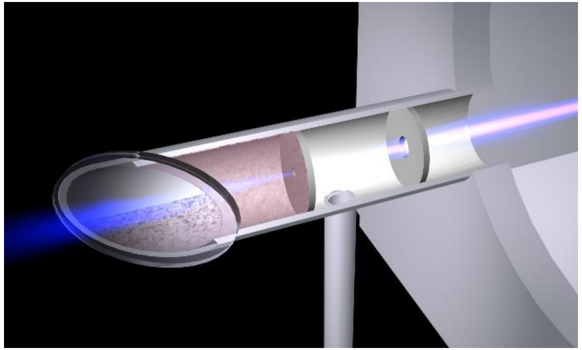
# High harmonic generation



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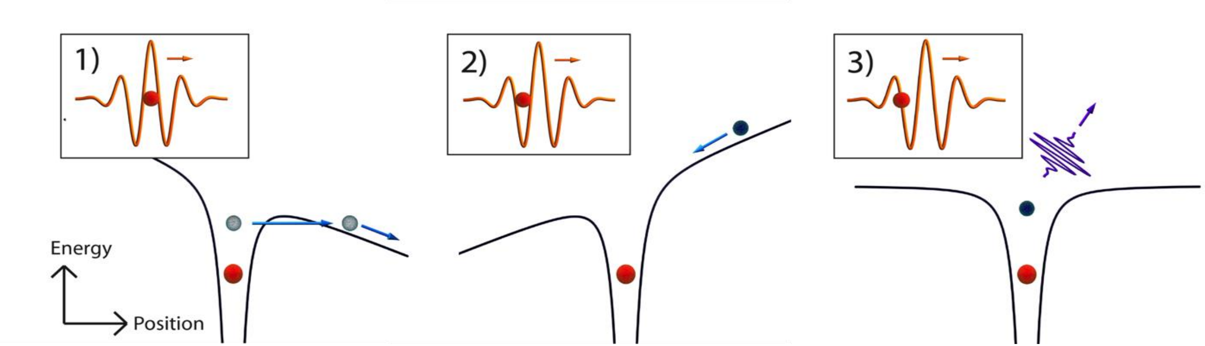
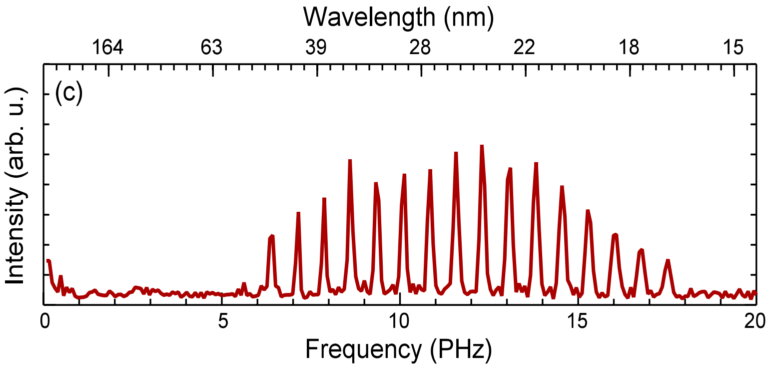
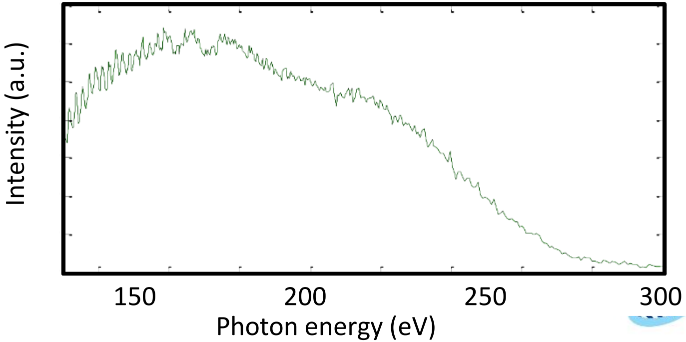



**Typical spectra:**

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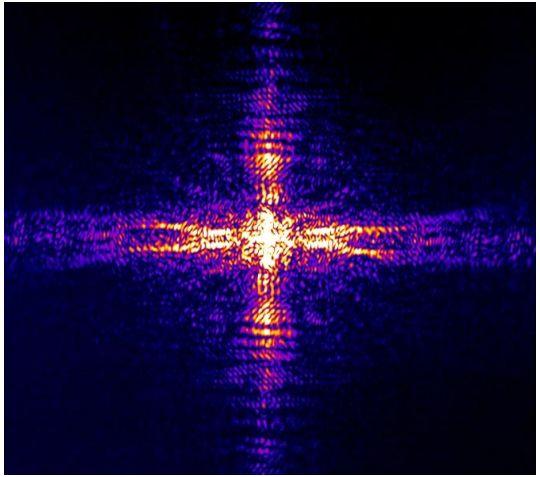
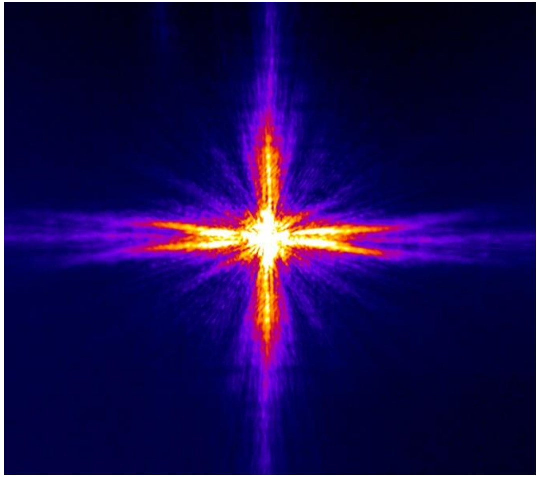
# Bandwidth limitations in lensless imaging

- Diffraction angle is directly proportional to wavelength.
- Broadband sources lead to blurred diffraction patterns:

Monochromatic:



Broadband:



- Limits the resolution, in extreme cases prevents image reconstruction.
- Spectral filtering is possible, but at the cost of serious flux reduction.

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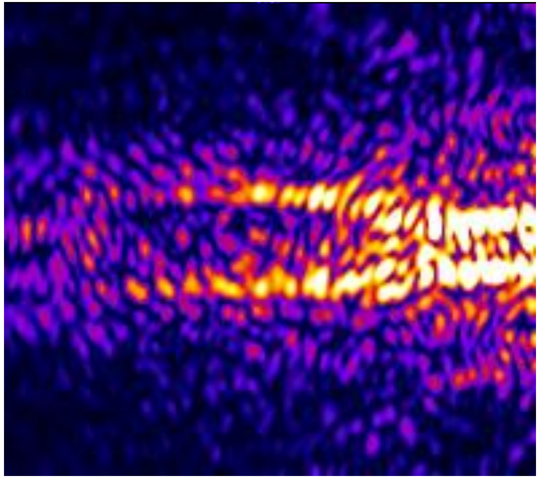
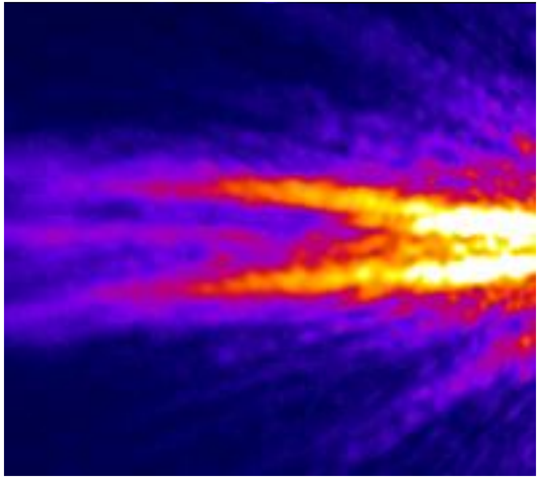


Broadband:



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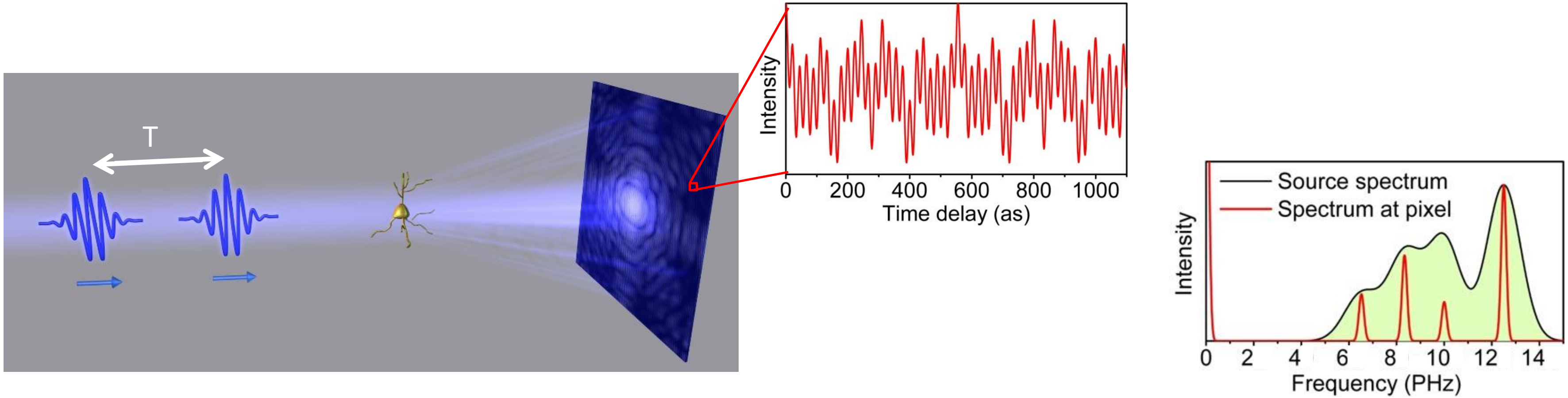
# Two-pulse Fourier-transform imaging

- Combination of imaging and Fourier transform spectroscopy
- On each CCD pixel, a Fourier-transform spectrum is recorded of the light diffracted onto that specific pixel.

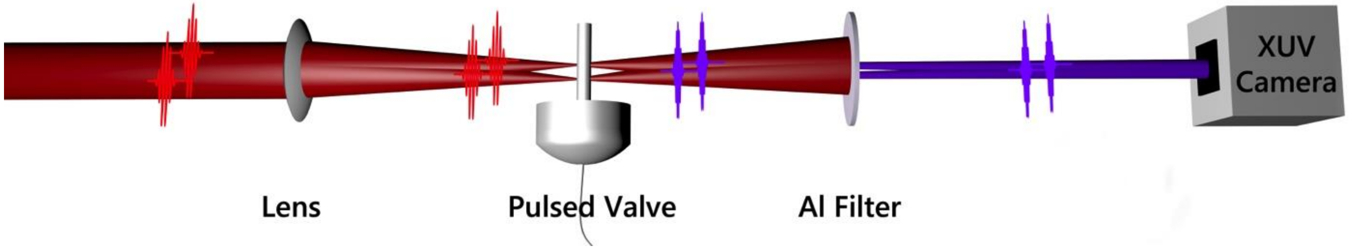



- Allows reconstruction of ‘monochromatic’ diffraction patterns for all spectral components
- The full spectrum is used throughout the entire measurement.

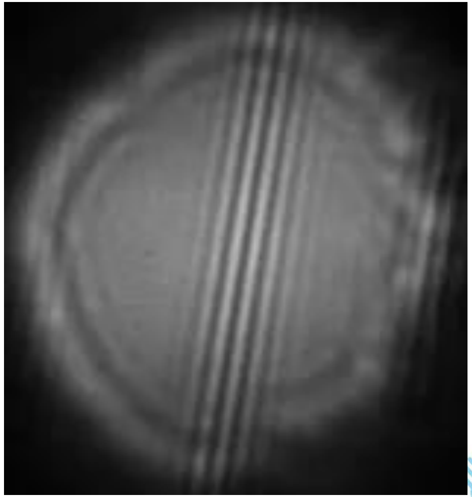
Witte, Tenner, Noom, Eikema, Light: Sci. Appl. **3**, e163 (2014)

# EUV interferometry

HHG setup combined with ultra-stable common-path interferometer:




- HHG in Argon with >1 mJ ~20 fs pulses
- Individual pulses should not influence each other during the HHG process → spatially separated HHG zones.
- Collinear beams, overlap after finite distance due to beam divergence.



Jansen, Rudolf, Freisem, Eikema, Witte, Optica **3**, 1122 (2016)

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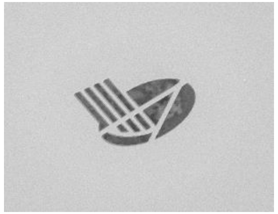
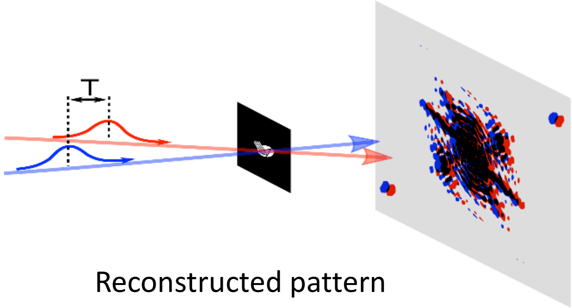
# High-resolution, spectrally resolved EUV imaging

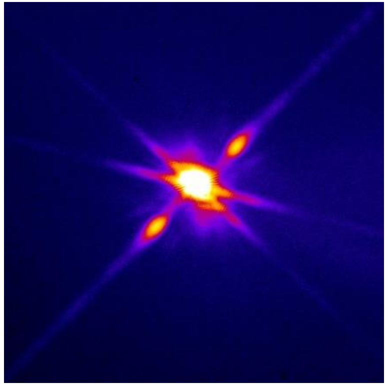
- Fourier transform spectroscopy retrieves well-defined monochromatic diffraction patterns
- Image reconstruction from these patterns yields diffraction-limited images

SEM image:

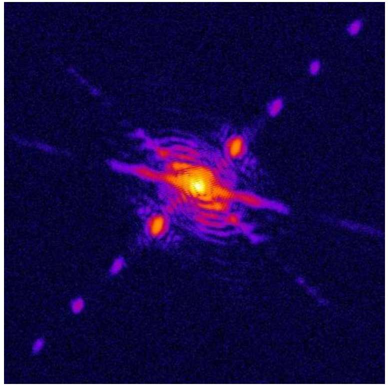


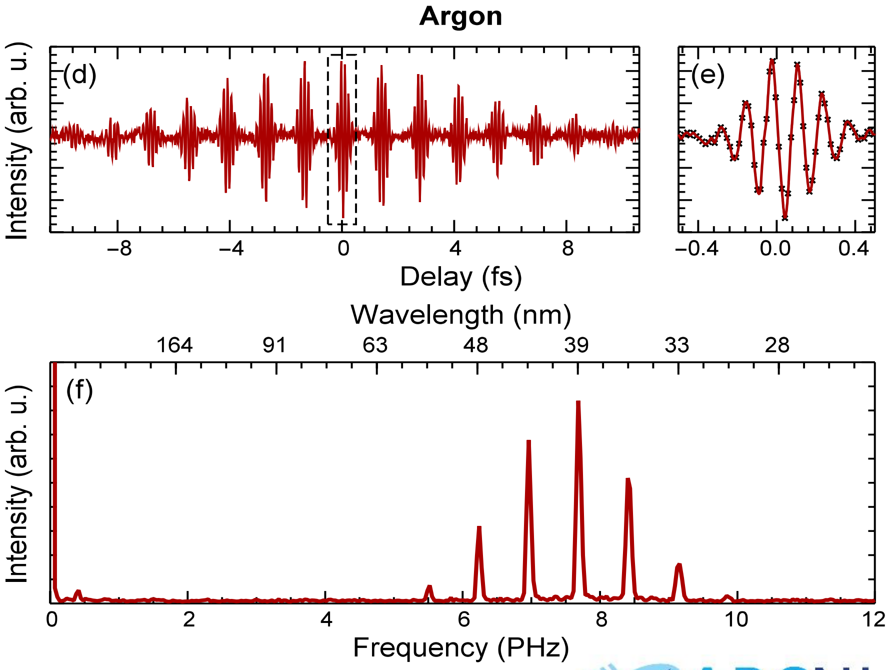



Broadband diffraction:



Reconstructed pattern (from FTS) at λ=32 nm:



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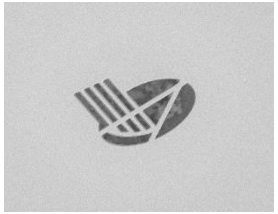

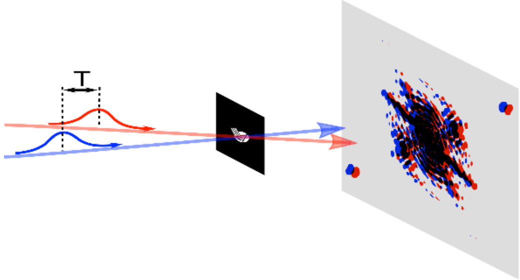

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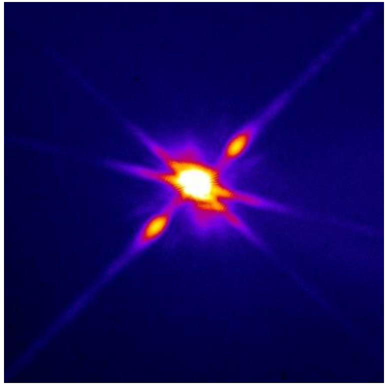

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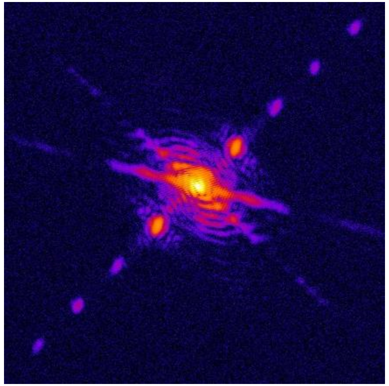
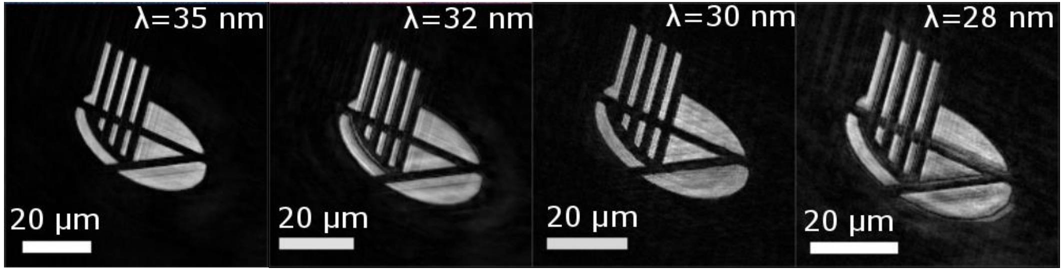


Retrieved object images for different harmonics:




G.S.M. Jansen, A. de Beurs, X. Liu, K.S.E. Eikema, S. Witte, Opt. Express **26**, 12479 (2018)

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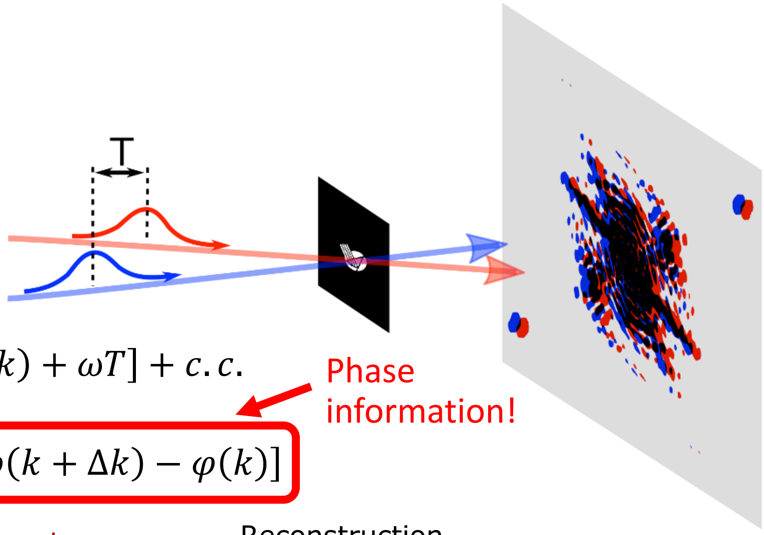
# Diffractive shear interferometry

Our diffraction pattern is produced by two displaced coherent beams, so we measure:




$$I = |E(k) + E(k + \Delta k)|^2$$
$$= A(k)^2 + A(k + \Delta k)^2 + A(k)A(k + \Delta k)\exp[i\varphi(k + \Delta k) - \varphi(k) + \omega T] + c.c.$$

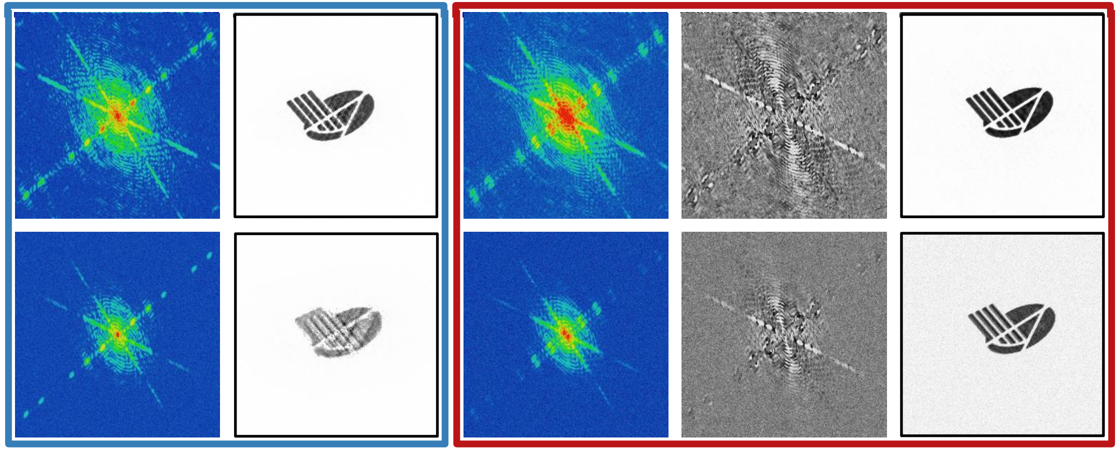
Phase information!

After FTS and selecting one spectral component we retrieve:

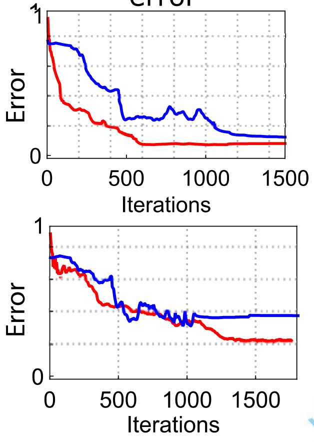
$$I = A(k)A(k + \Delta k)\exp[i\varphi(k + \Delta k) - \varphi(k)]$$

Single-beam CDI

Diffractive Shear Interferometry



Reconstruction error

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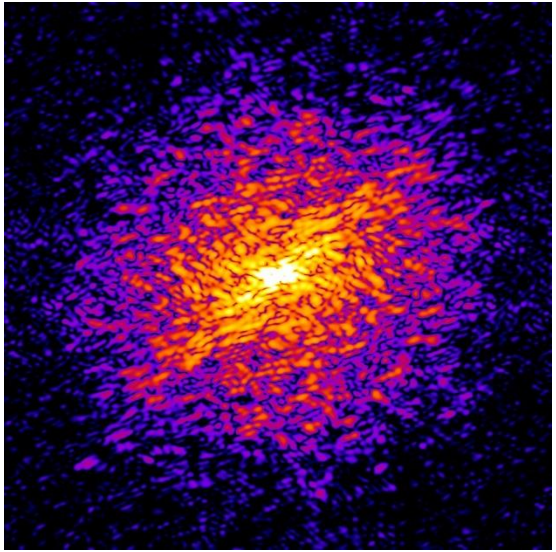
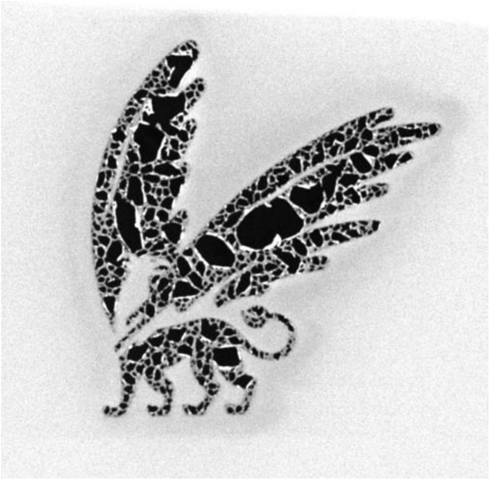
# EUV imaging for grayscale (non-binary) objects

'Grayscale' intensity objects lead to more complex diffraction patterns:

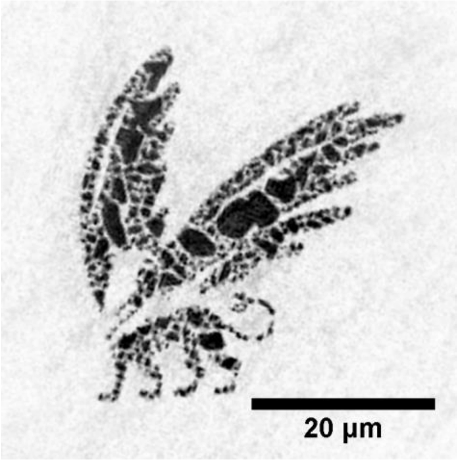
Measured diffraction pattern ($\lambda$ =30 nm):



SEM image:



Reconstructed EUV image:




- Good contrast reconstruction, both amplitude and phase.
- Resolution near diffraction limit of 0.25 $\mu$m

G.S.M. Jansen, A. de Beurs, X. Liu, K.S.E. Eikema, S. Witte, Opt. Express **26**, 12479 (2018)

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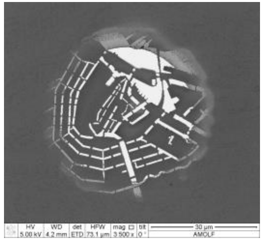
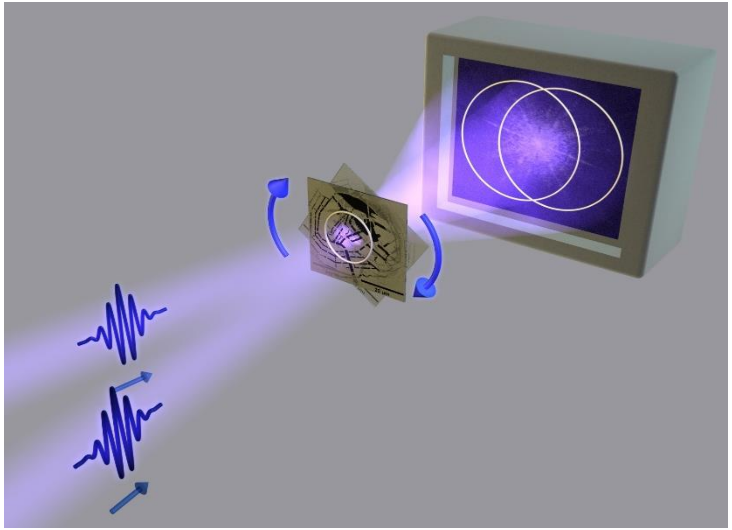
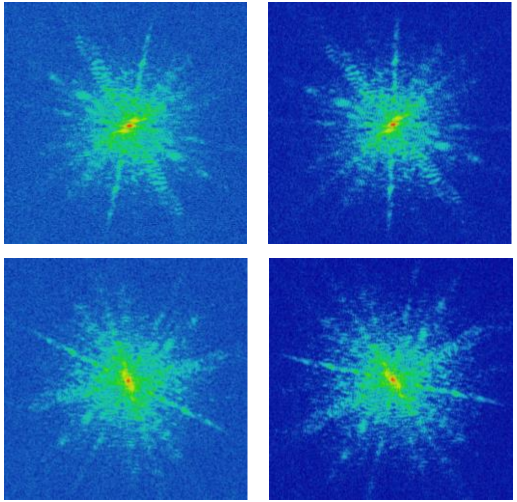
# Rotational diversity for improved phase retrieval



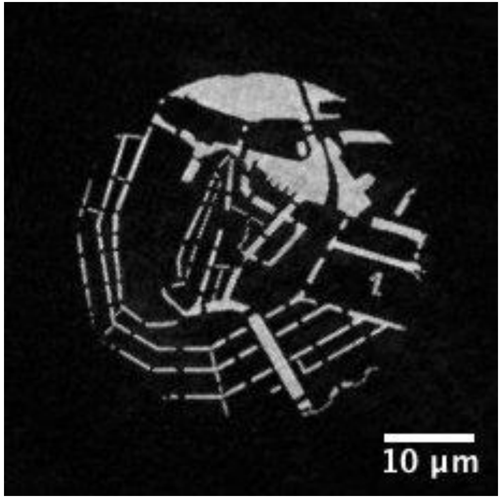
Rotating the object in our two-beam geometry breaks symmetry, giving rise to additional diversity and improved algorithm convergence



Diffraction intensities for different object angles:



Reconstructed image ($\lambda = 30$ nm):




A. de Beurs, X. Liu, G.S.M. Jansen, K.S.E. Eikema, S. Witte, submitted

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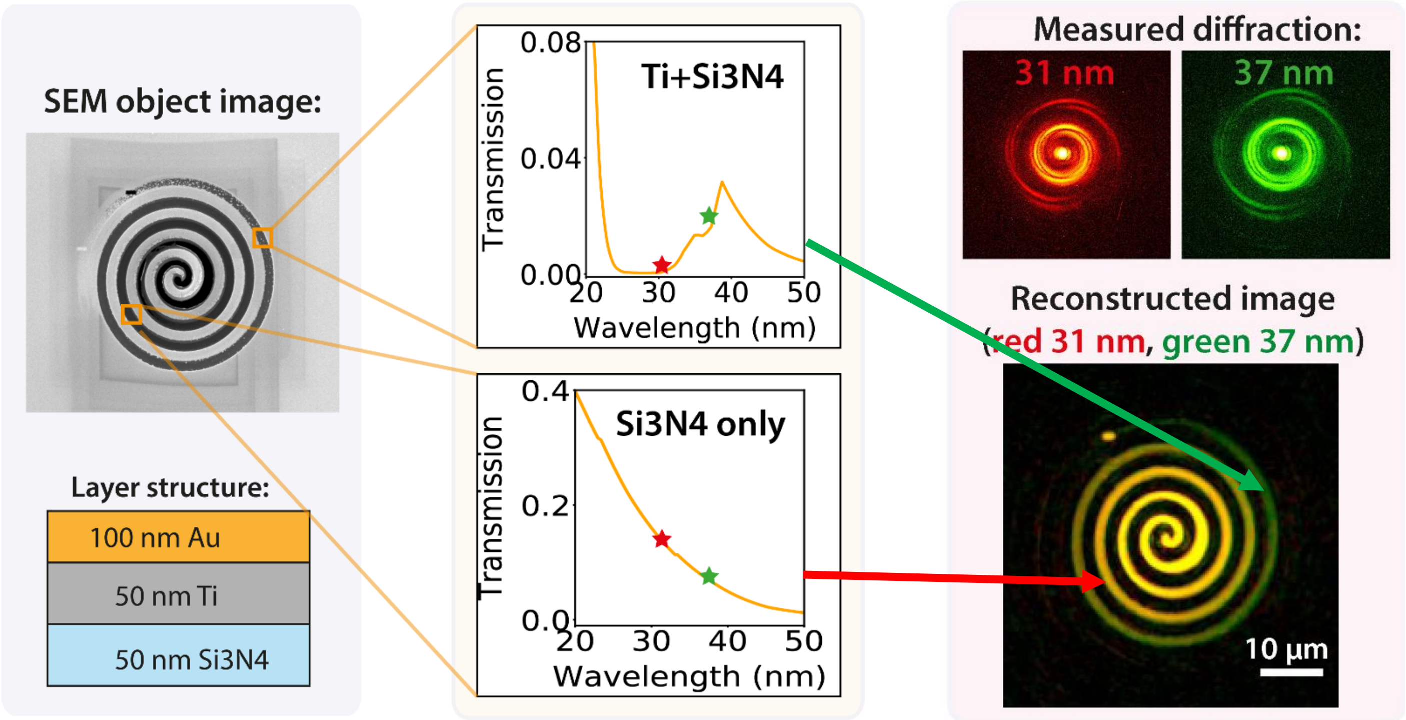
# Resolving different combinations of elements

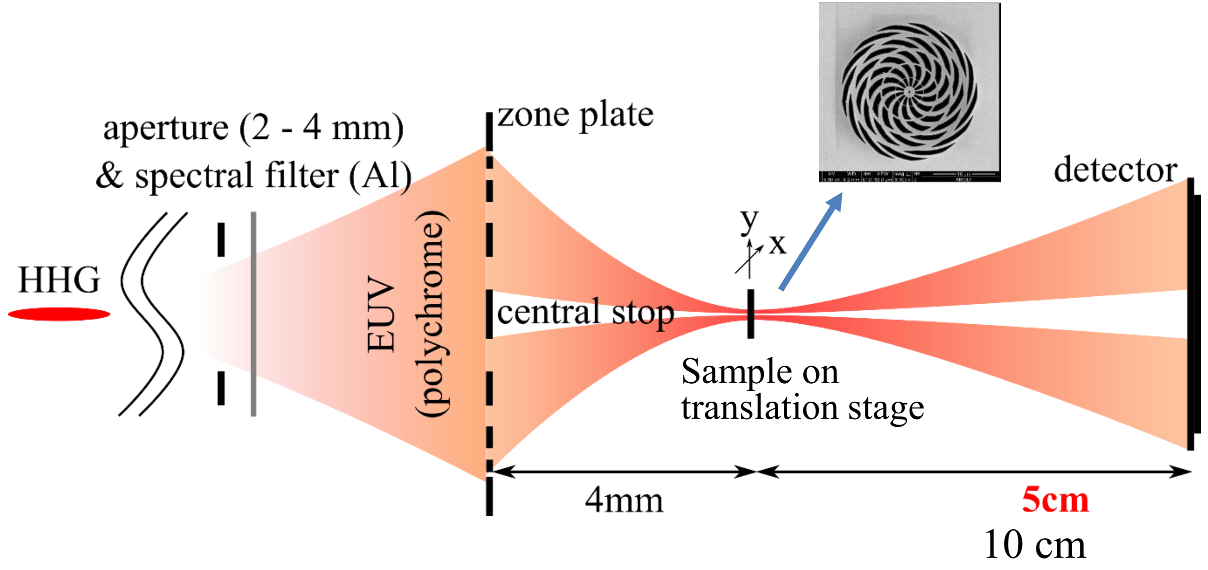
Diffractive samples with a spatially dependent response can be reconstructed at high resolution:

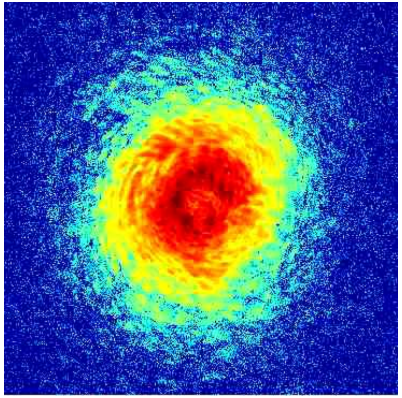



Experiment: Kevin Liu, Anne de Beurs

# Multi-wavelength HHG ptychography – using zone plates

- Ptychography enables robust, computational imaging
- Requires transverse object scanning through a confined light spot:



Experimental parameters:

- 300 scan positions
- 10s exposure time
- Argon ($\lambda = 32, 35, 38, 42, 47, 53$ nm)

Allows reconstruction of both the object image and the probe light field!

Experiment: Lars Loetgering, Kevin Liu, Anne de Beurs

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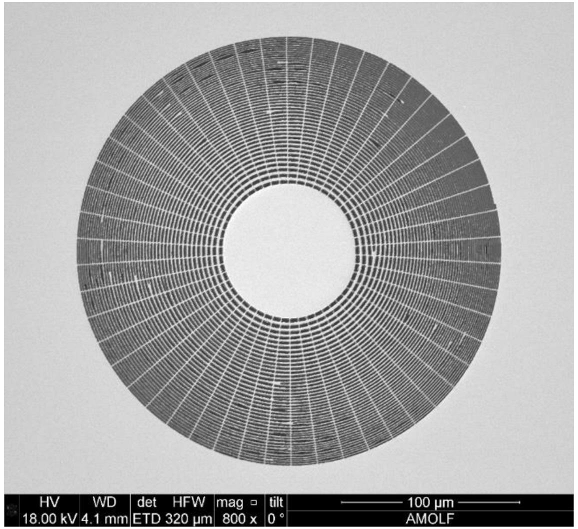
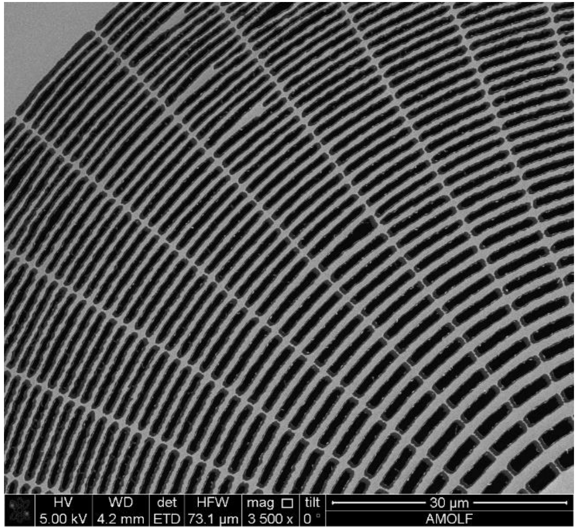
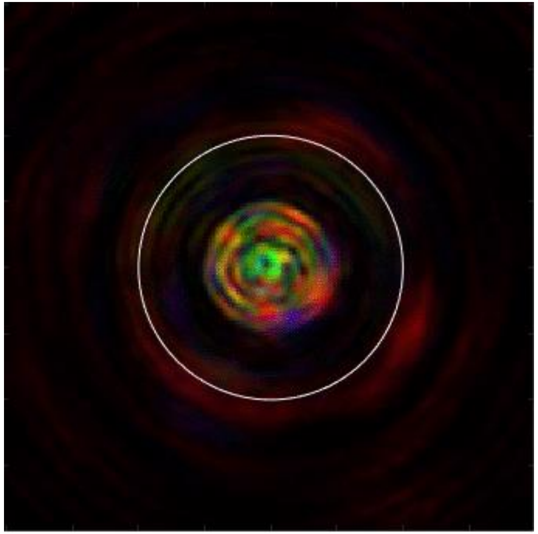
# Broadband diffractive HHG focusing

- Fresnel zone plates provide high-NA focusing, but are strongly wavelength dependent.
- Modifying the diffraction structure can provide a trade-off:



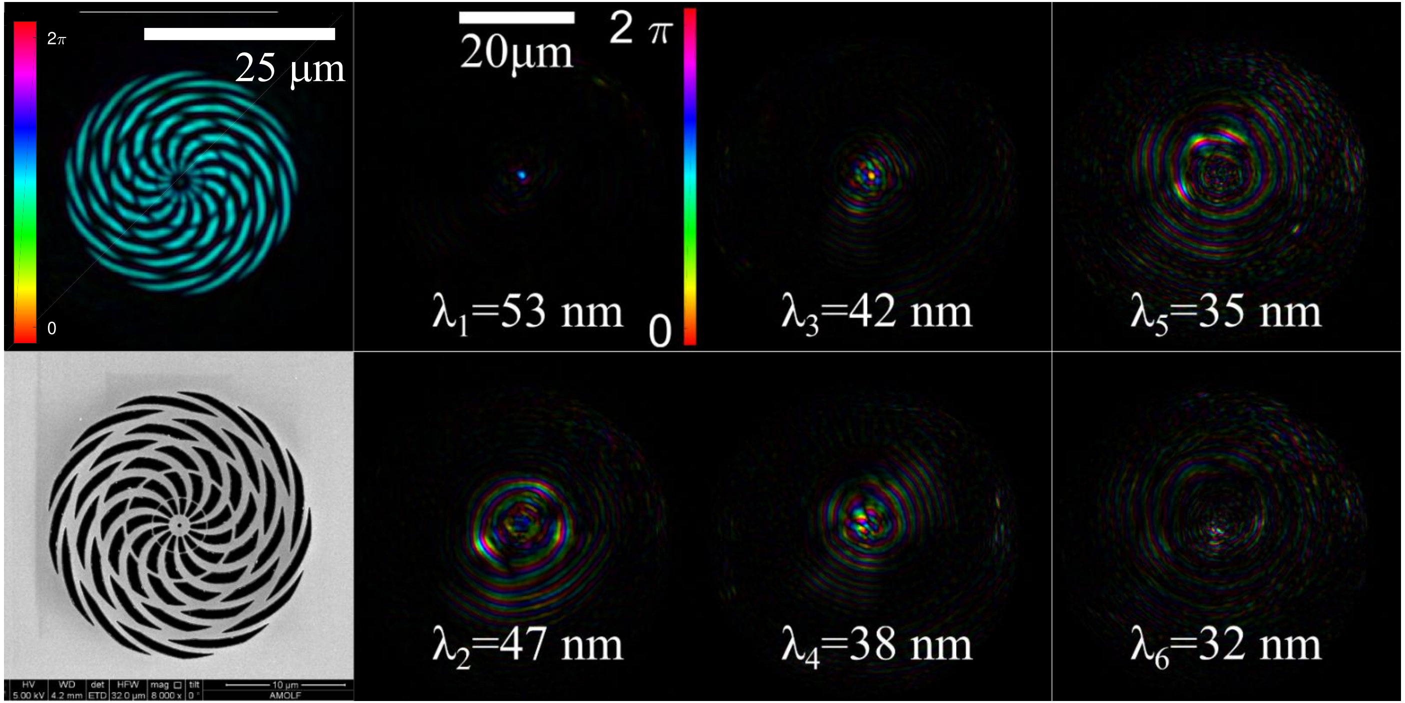



→ Leads to speckle-like beams rather than clean focal spots

→ Confines 6 harmonics ($\lambda$ = 32-53 nm) in a 10 µm spot

# HHG ptychography with six wavelengths

High-quality object image retrieved, as well as the ‘focused’ beam electric field at all wavelengths:




Experiment: Lars Loetgering, Kevin Liu, Anne de Beurs

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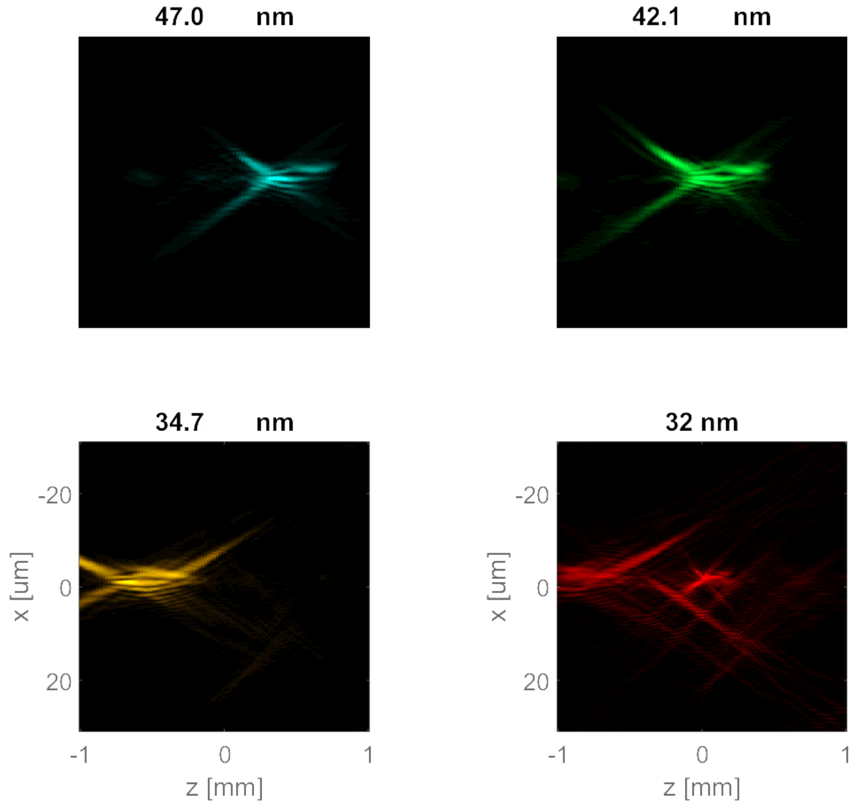
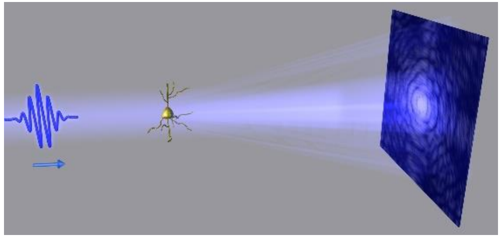
# Reconstructing the focused EUV beams

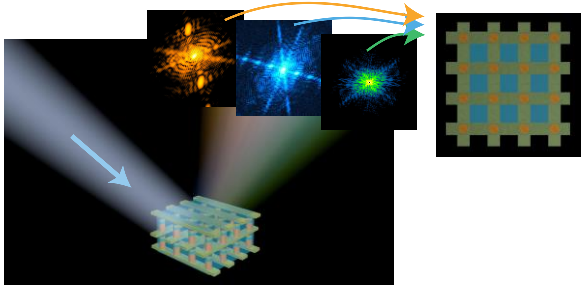
Because the fields are retrieved, the beams can be propagated through-focus numerically:



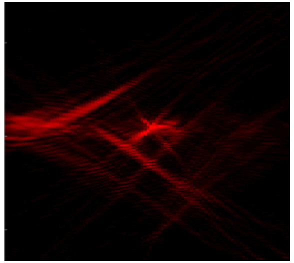
# Conclusions



Computational imaging is a powerful method that can extend the capabilities of microscopy



Broadband HHG sources may provide the means for imaging nanostructures with spectral resolution



Ptychography can be used to characterize complex light fields, in parallel with imaging and metrology

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# EUV Generation and Imaging @ ARCNL

**The team:**

Anne de Beurs
Kevin Liu
Alessandro Antoncecchi
Hao Zhang
Maisie Du
Lars Lötgering
Randy Meijer
Jan Mathijssen
Zeudi Mazzotta
Amelie Schulte
Nik Noest
Kjeld Eikema

**Recent (almost) graduates:**

Dirk Boonzajer Flaes
Matthijs Jansen
Tiago de Faria Pinto

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