



Focusing Delivery Schemes: a comparative analysis for Extreme UltraViolet Ultrafast tabletop ptychography

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ULTRAIMAGE

HYPER



Fondazione
CARIPLO



Outline

- Imaging with EUV/X-Ray light



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- Coherent Diffractive Imaging (CDI) and Ptychography



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- Ptychography in the EUV regime

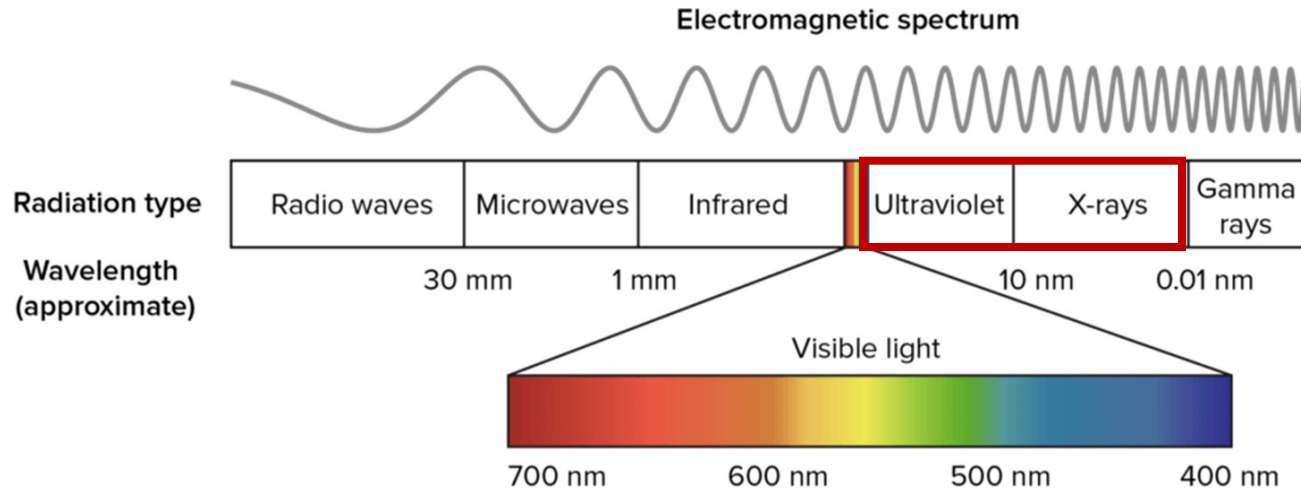


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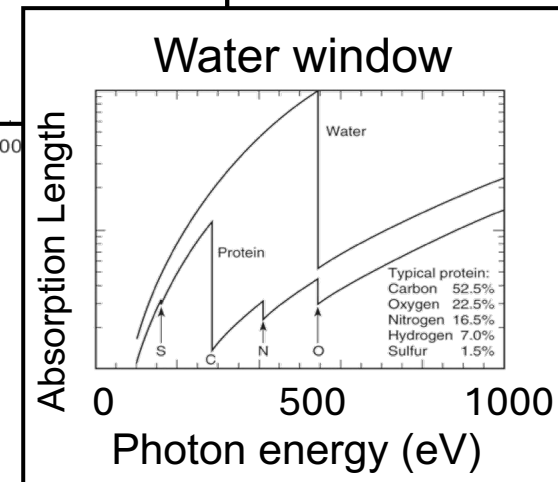
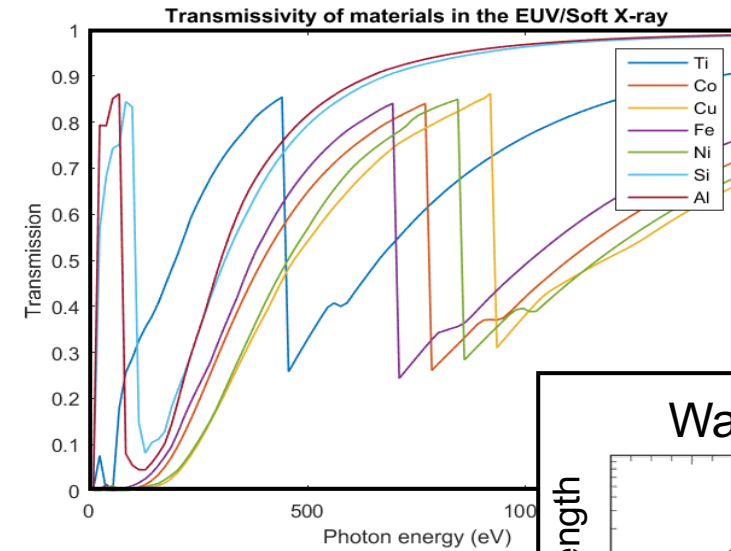
- Imaging with EUV/X-Ray light
- Coherent Diffractive Imaging (CDI) and Ptychography
- Ptychography in the EUV regime
- EUV beam delivery in ultrafast ptychography



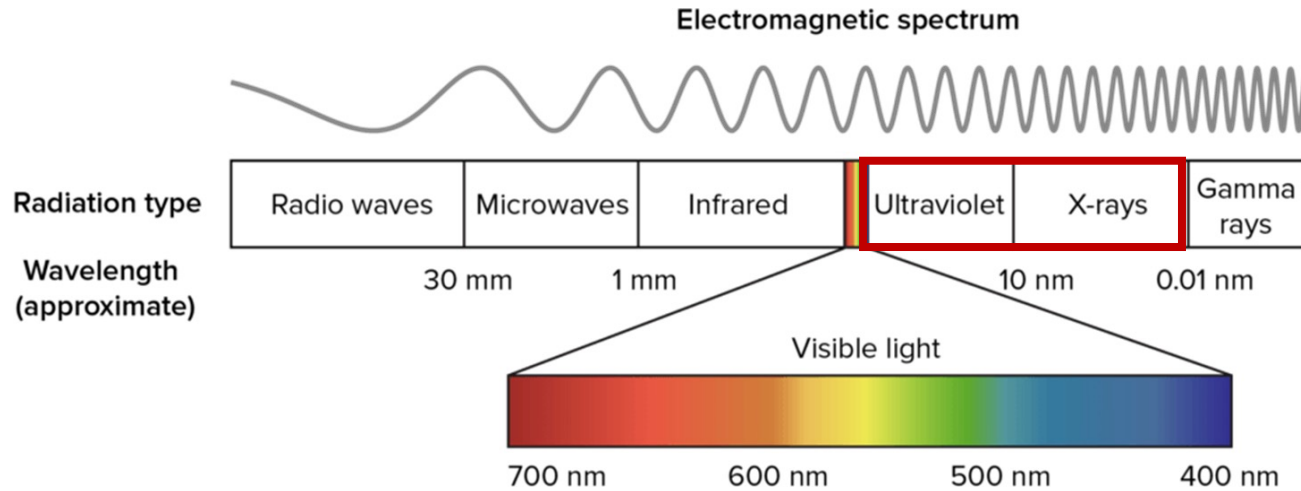
Imaging with EUV/ X-Ray light



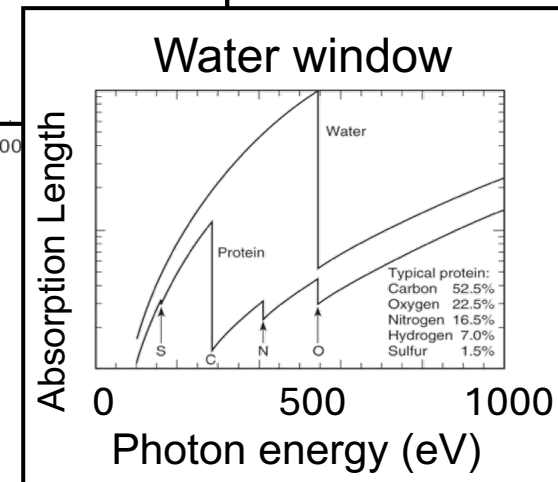
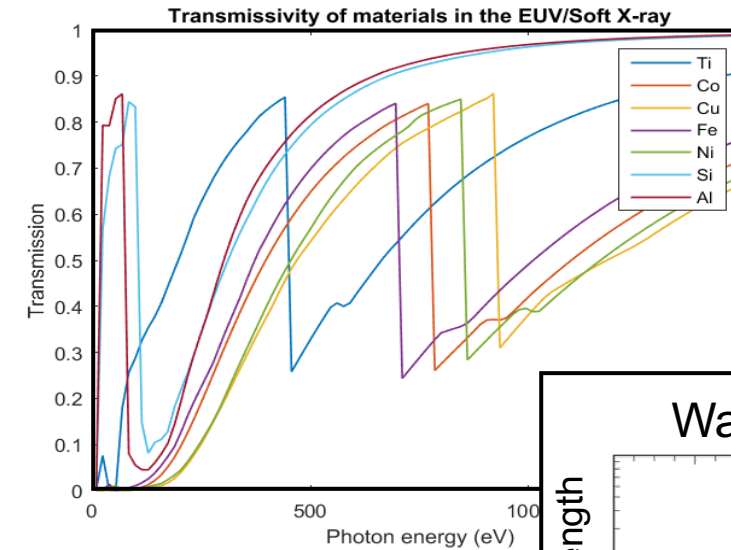
- Short wavelength: **High resolution** $\Delta r = \frac{\lambda}{2 \cdot NA}$



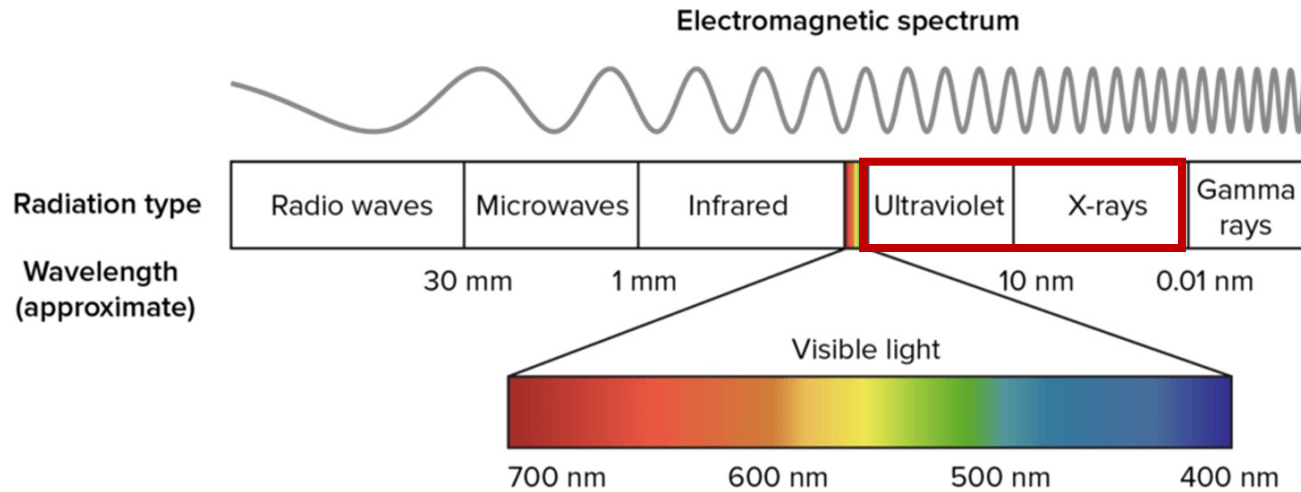
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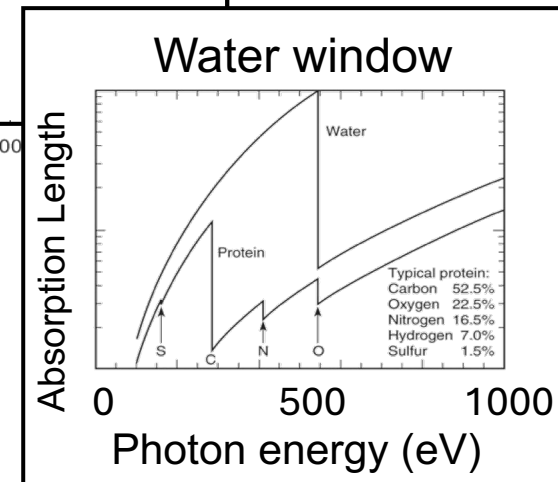
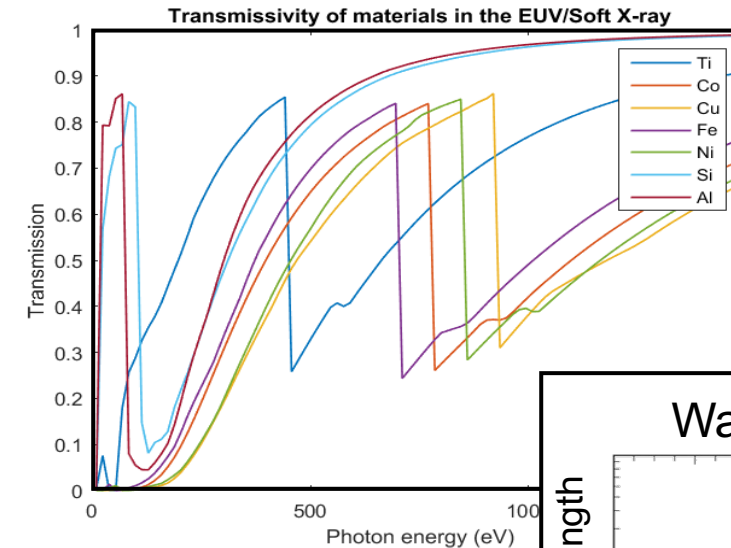
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- Absorption edges: **Excellent elemental specificity**



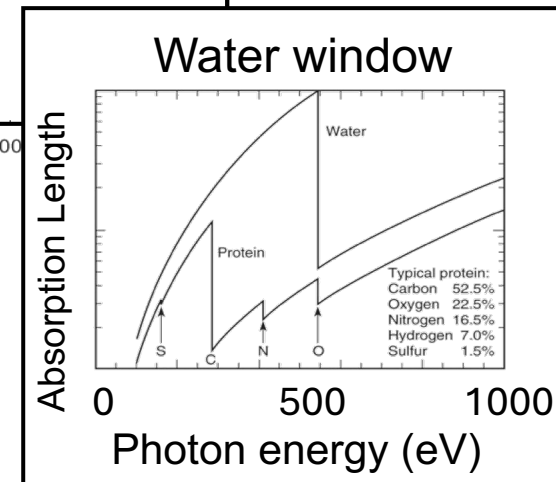
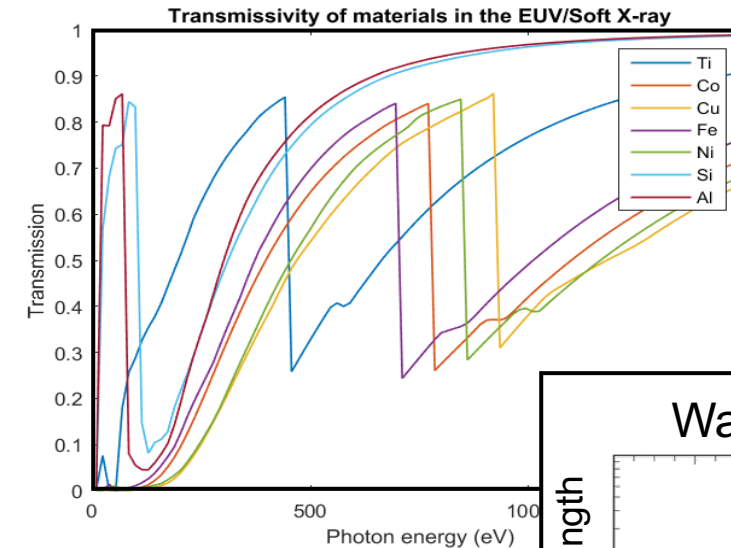
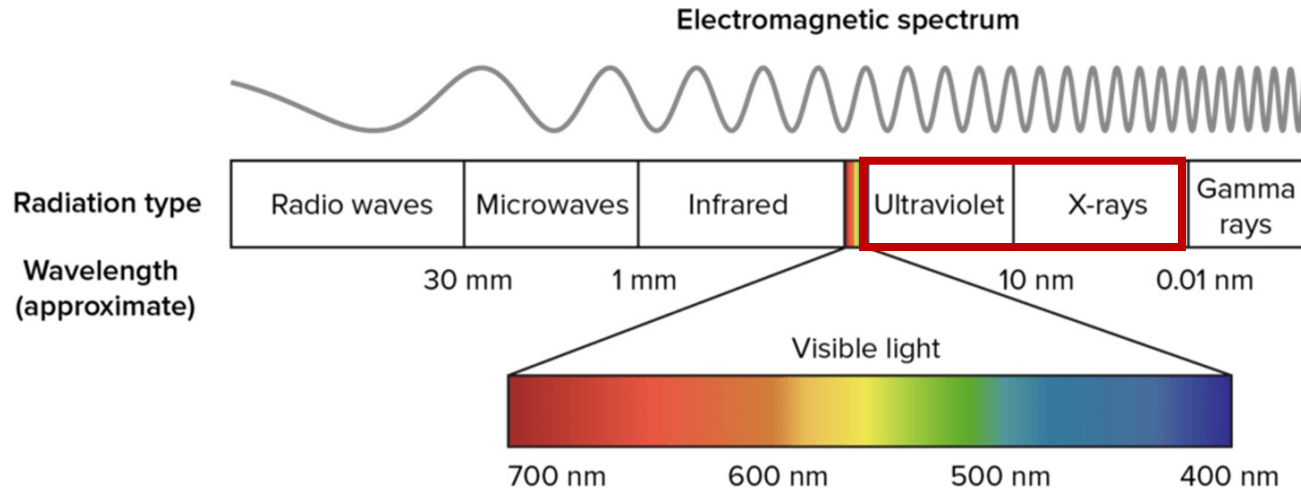
Imaging with EUV/ X-Ray light



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- Penetrate thick objects: **Image through multiple layers**

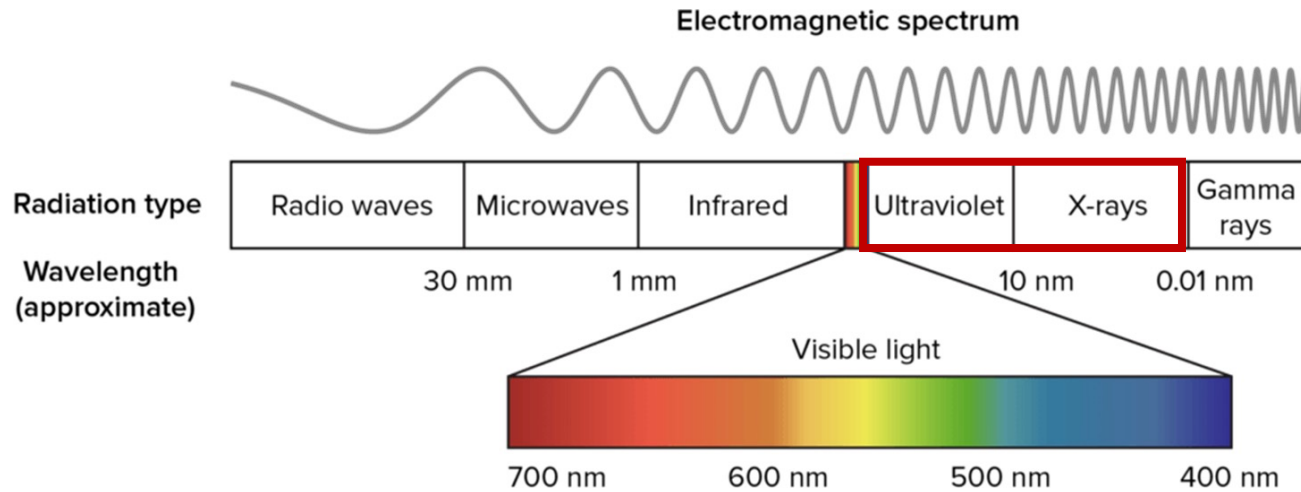


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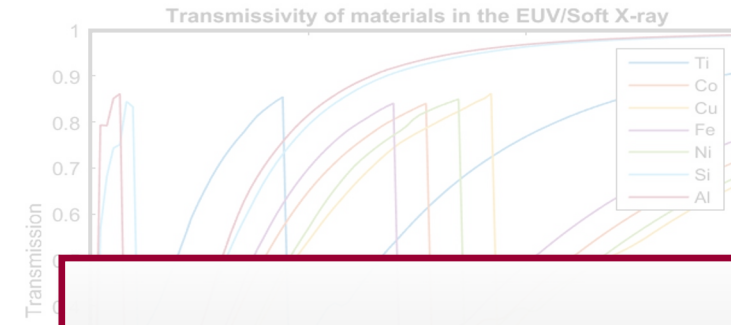


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- Availability of pulsed X-Ray sources: **“Snapshots” of ultrafast processes (fs-ns scale)**

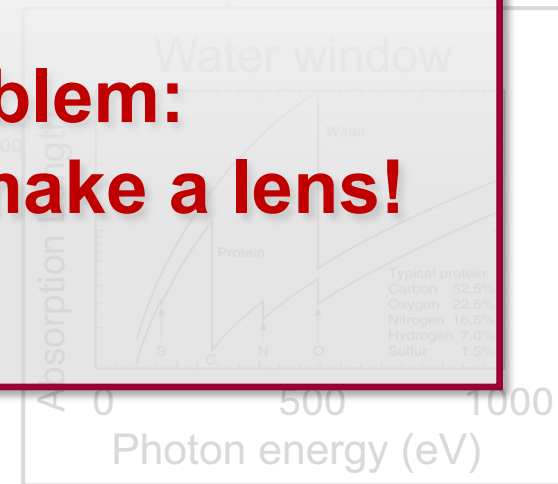
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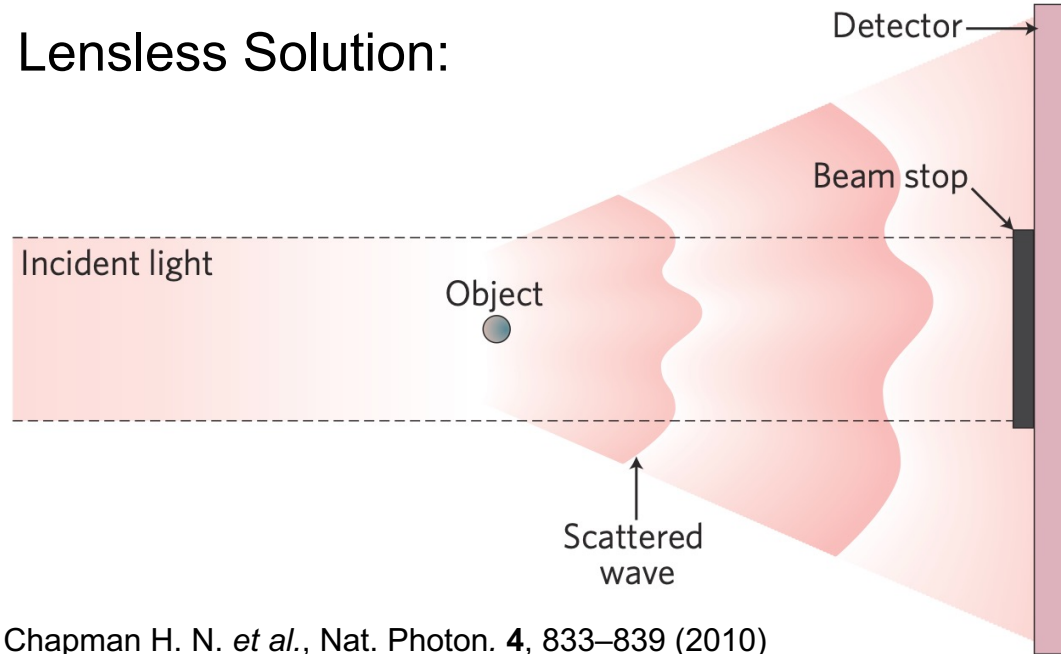
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Problem:
we can't make a lens!



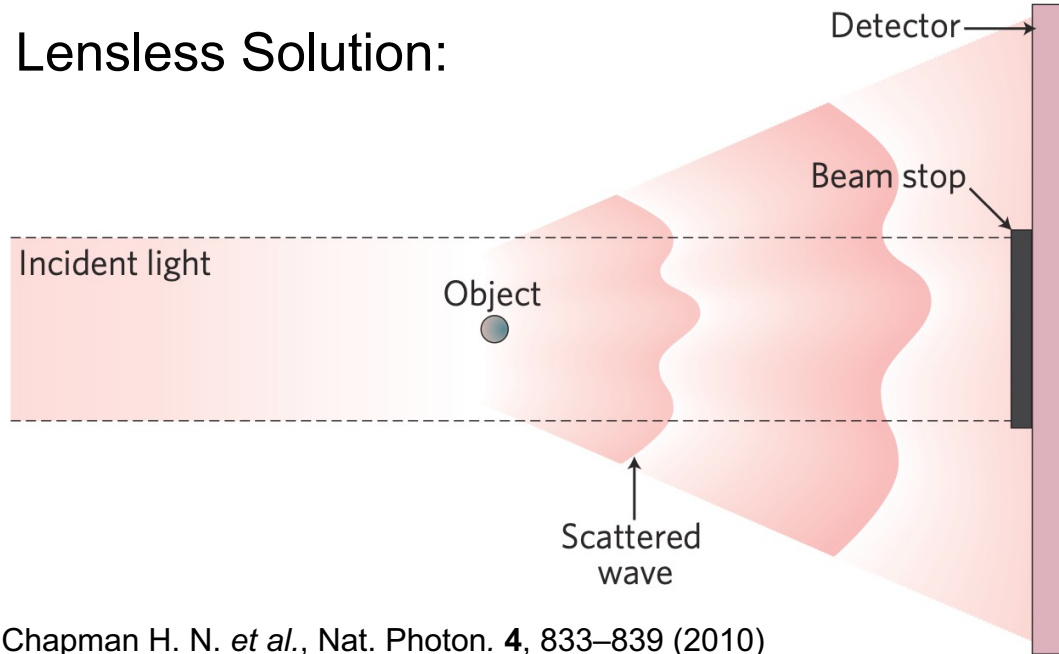
Imaging with EUV/ X-Ray light



Chapman H. N. *et al.*, Nat. Photon. **4**, 833–839 (2010)

Imaging with EUV/ X-Ray light

Lensless Solution:



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Scattered Wave:

$$\psi_s = A e^{i\phi}$$

Amplitude

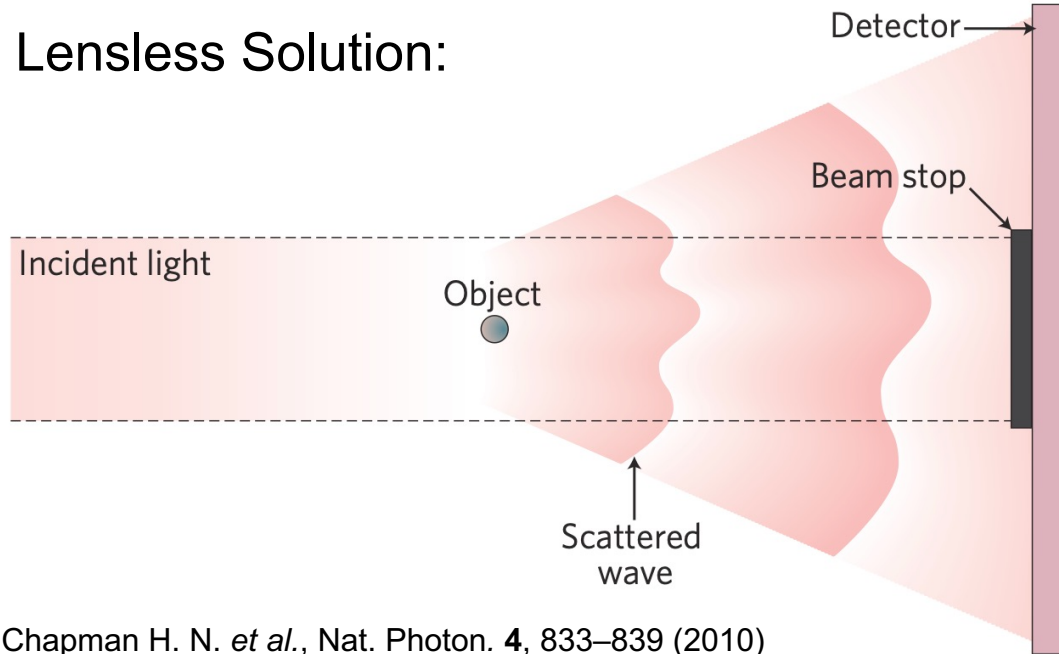
Phase

Absorption

Structure

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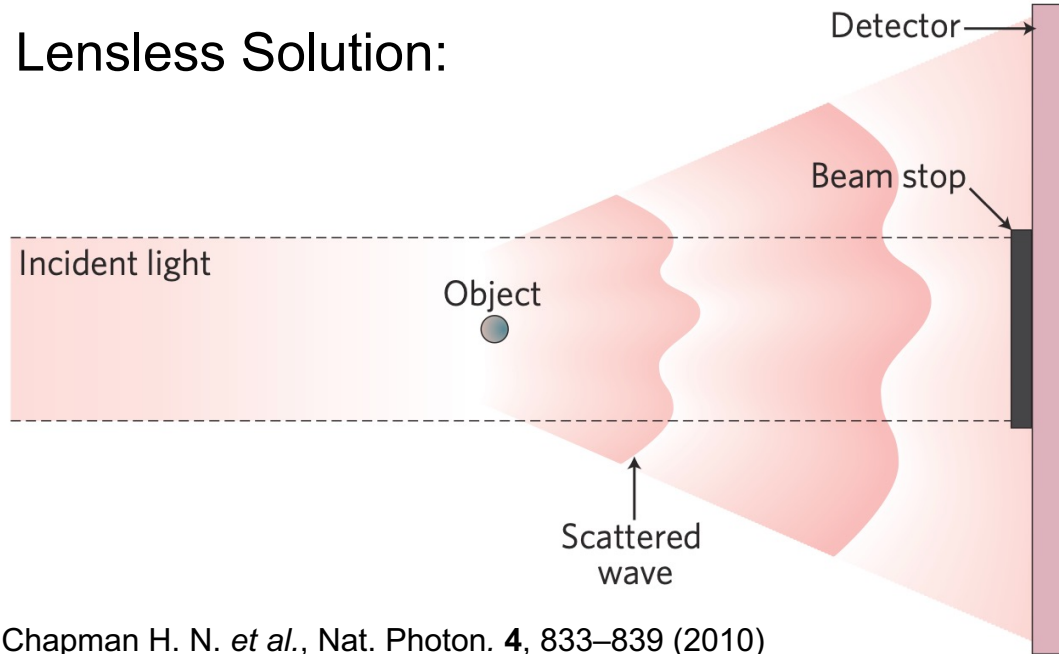
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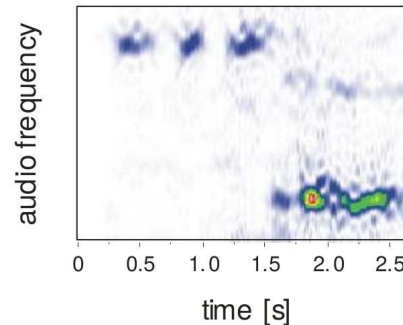
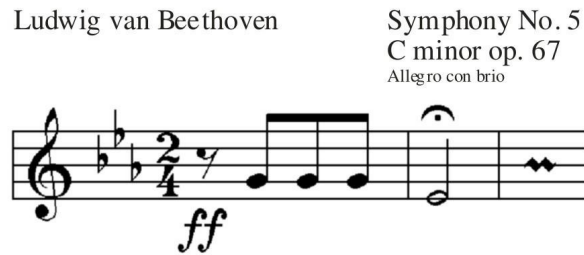
$$I = \psi_s \psi_s^* = |A|^2$$

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Cerullo, Lectures at EPFL [Ultrafast Nonlinear Optics and Spectroscopy], (2020)

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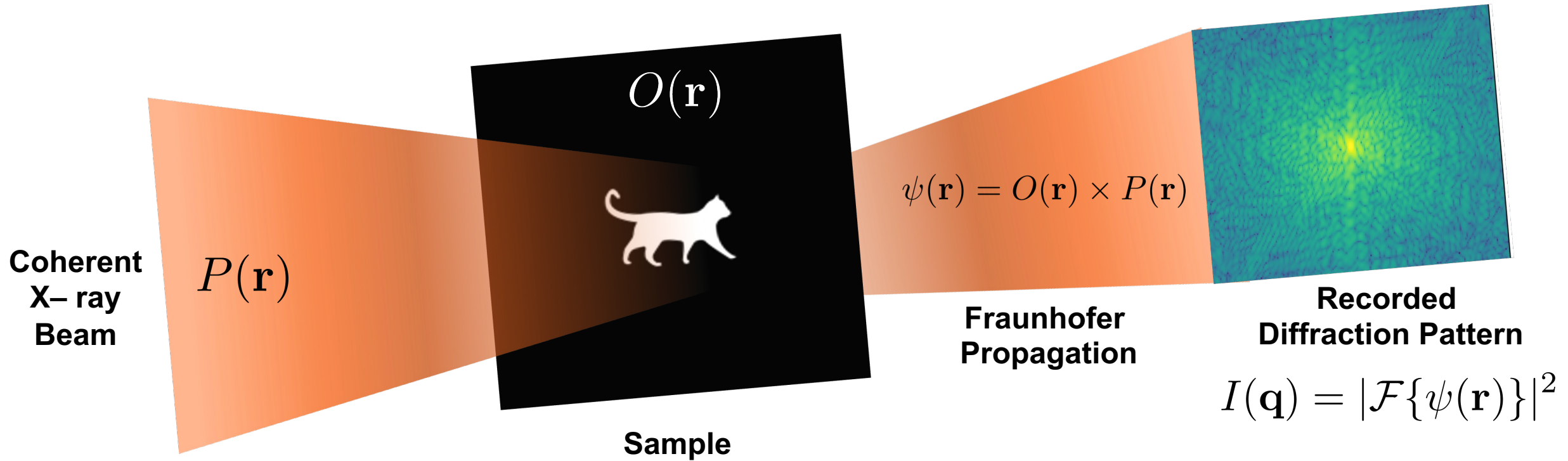
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Imaging with EUV/ X-Ray light

No phase, no image. How can we reconstruct an object using only the intensity of its diffraction pattern?



PHASE RETRIEVAL PROBLEM

Coherent Diffractive Imaging (CDI)

Takajo *et al.*, J. Opt. Soc. Am. A **15**, 2849–2861 (1998)
Elser *et al.*, J. Opt. Soc. Am. A **20**, 40-55 (2003)
Marchesini *et al.*, Rev. Sci. Instrum. **78**, 011301 (2007)

Given the prior knowledge of:

A. Support: a region of space where the object has non-zero density $supp(\text{img}) = \text{img}$

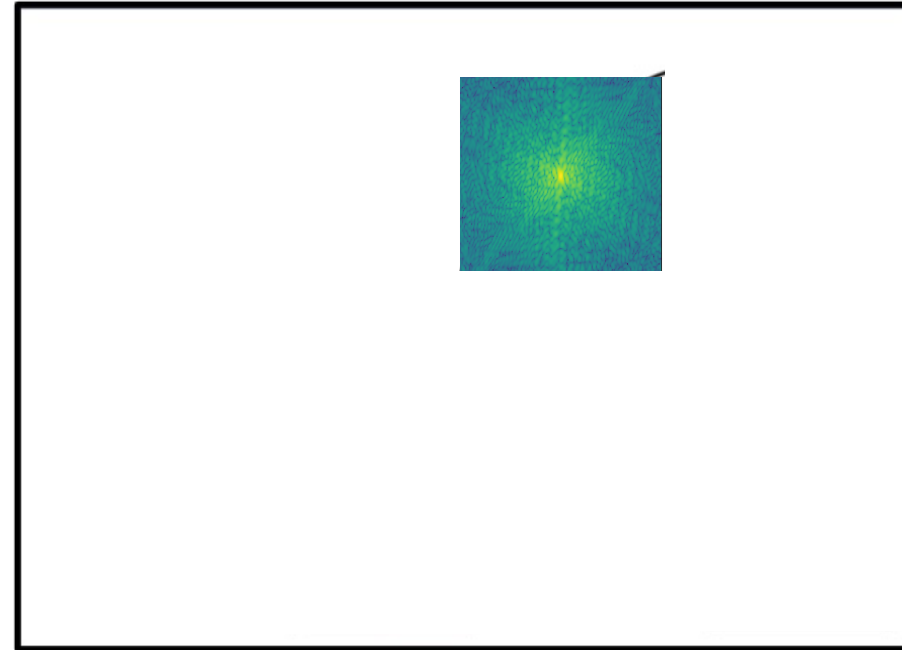
B. Amplitude: $\sqrt{I(\mathbf{q})}$

A. SUPPORT (or ATOMICITY) CONSTRAINT

$$(P_S O)(\mathbf{r}) = \begin{cases} O(\mathbf{r}), & \mathbf{r} \in S \\ 0, & \mathbf{r} \notin S \end{cases}$$

B. MAGNITUDE CONSTRAINT

$$(P_M \hat{O})(\mathbf{q}) = \sqrt{I(\mathbf{q})} \frac{\hat{O}(\mathbf{q})}{|\hat{O}(\mathbf{q})|}$$



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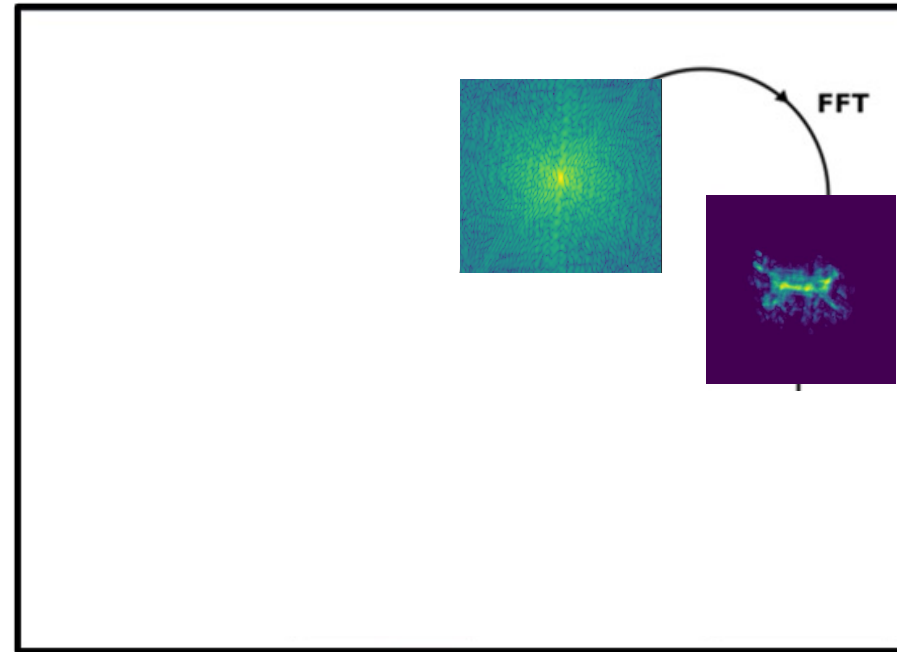
$$\text{supp}\left(\begin{array}{c} \text{cat} \end{array} \right) = \text{cat}$$

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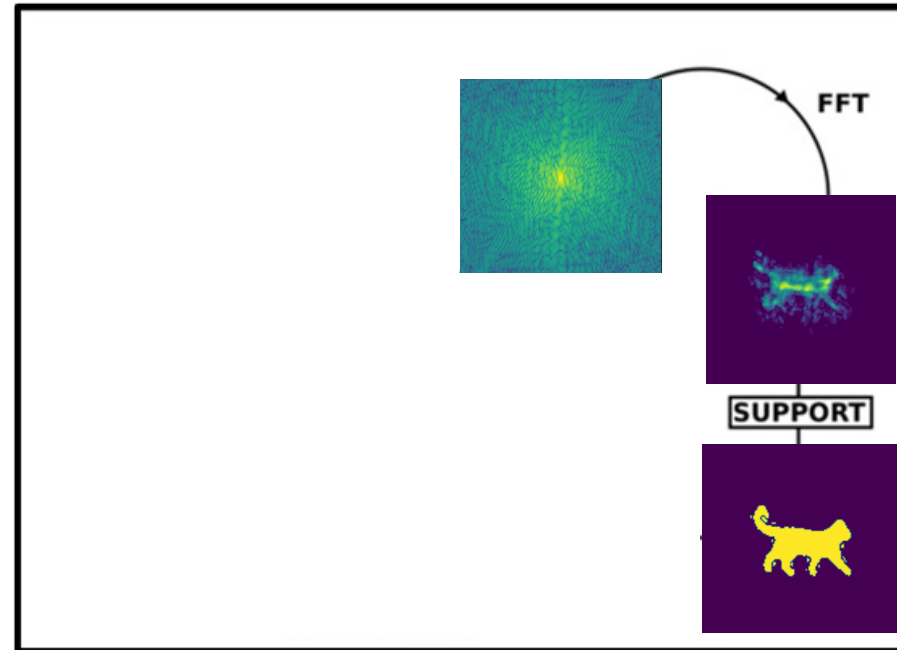
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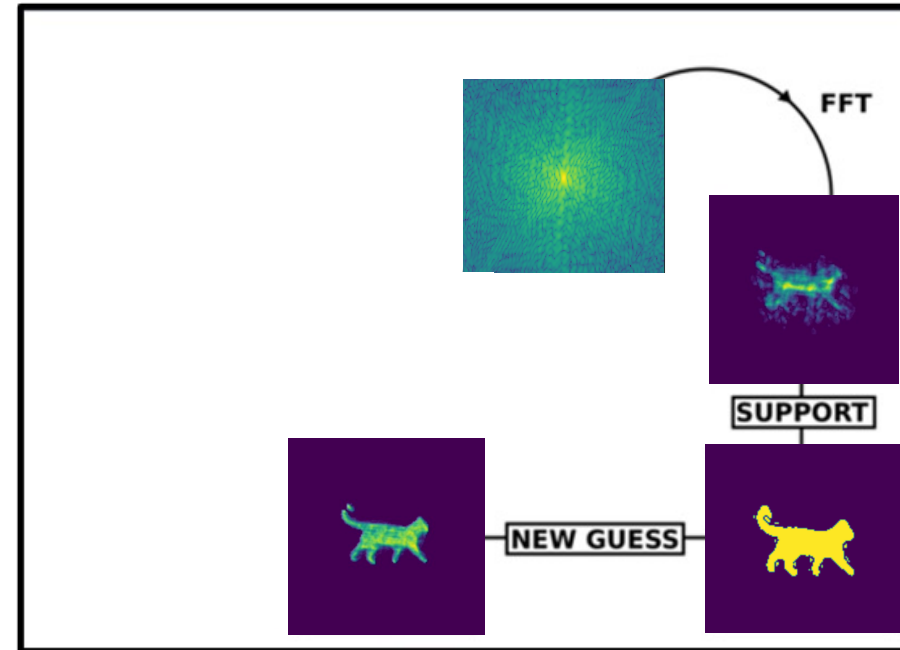
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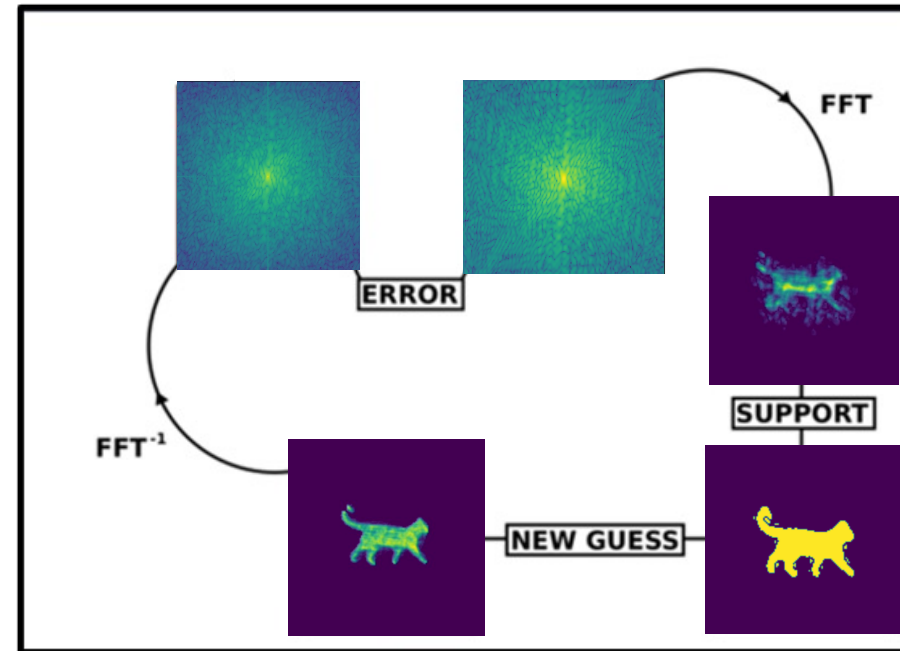
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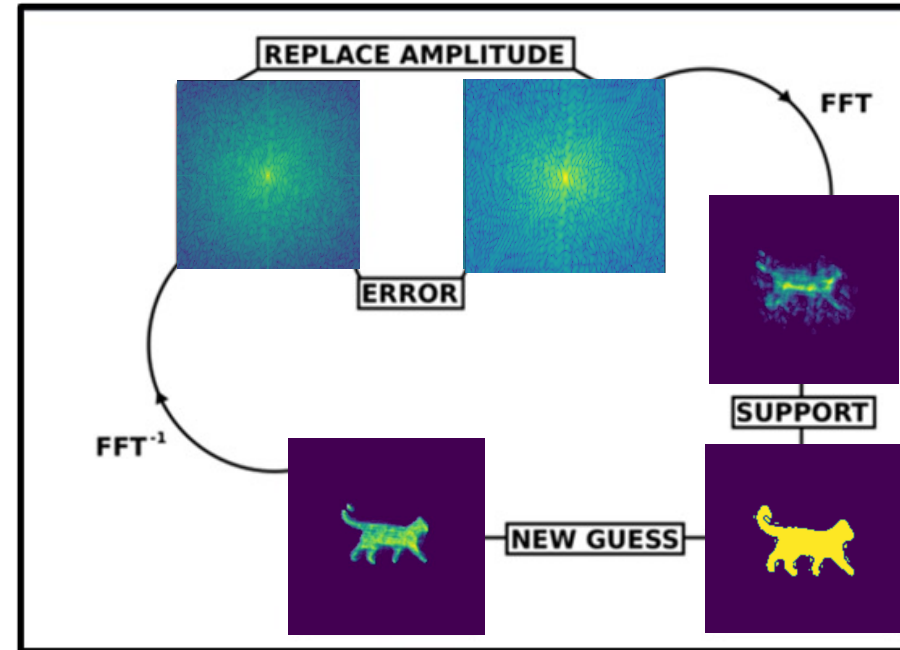
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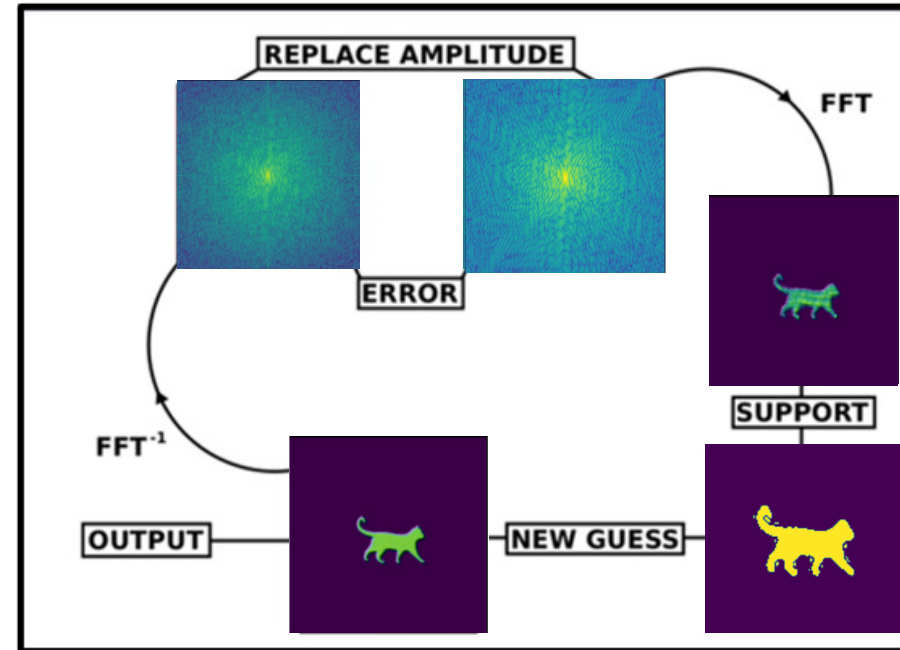
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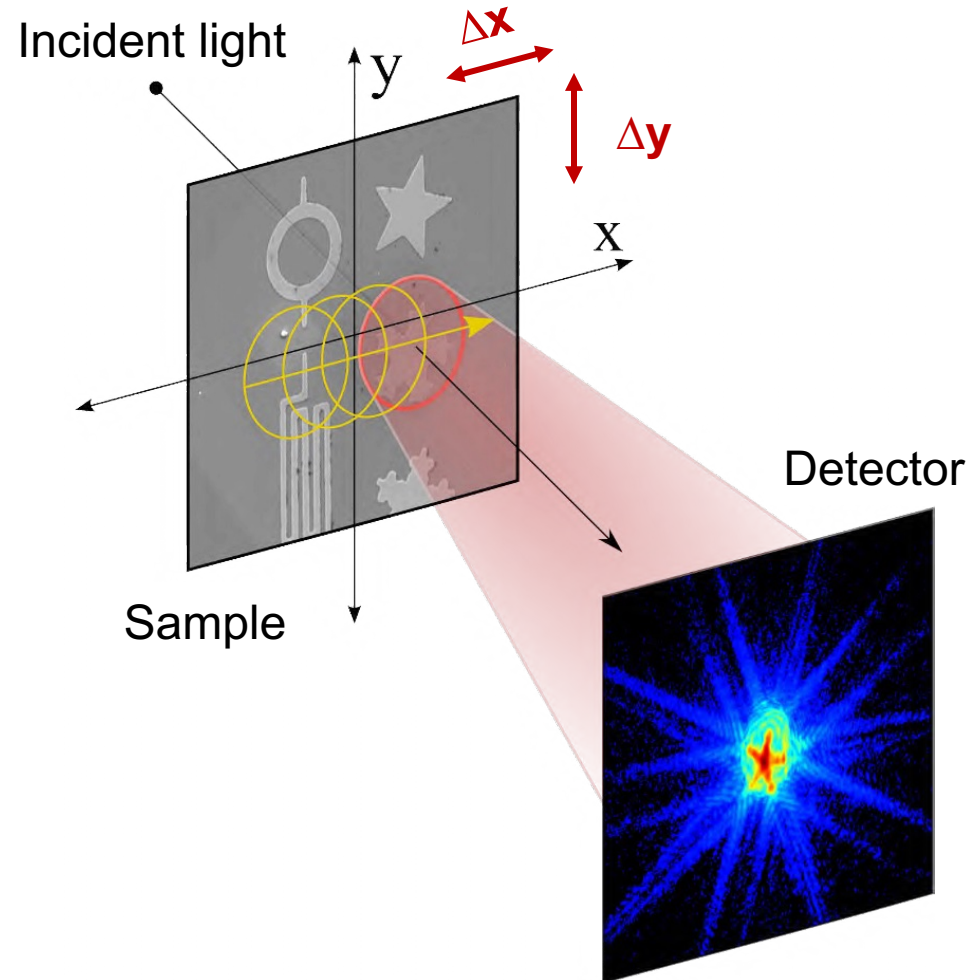
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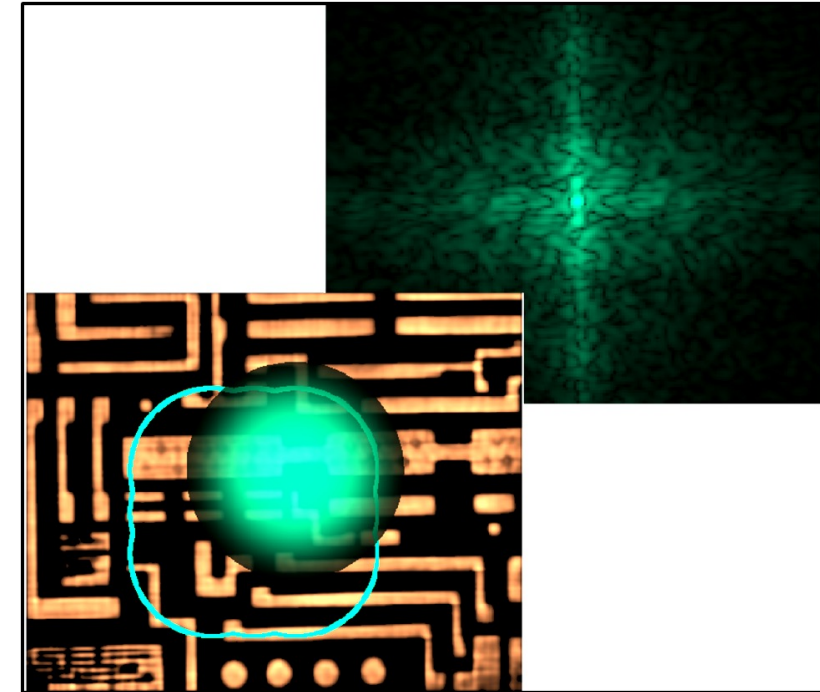
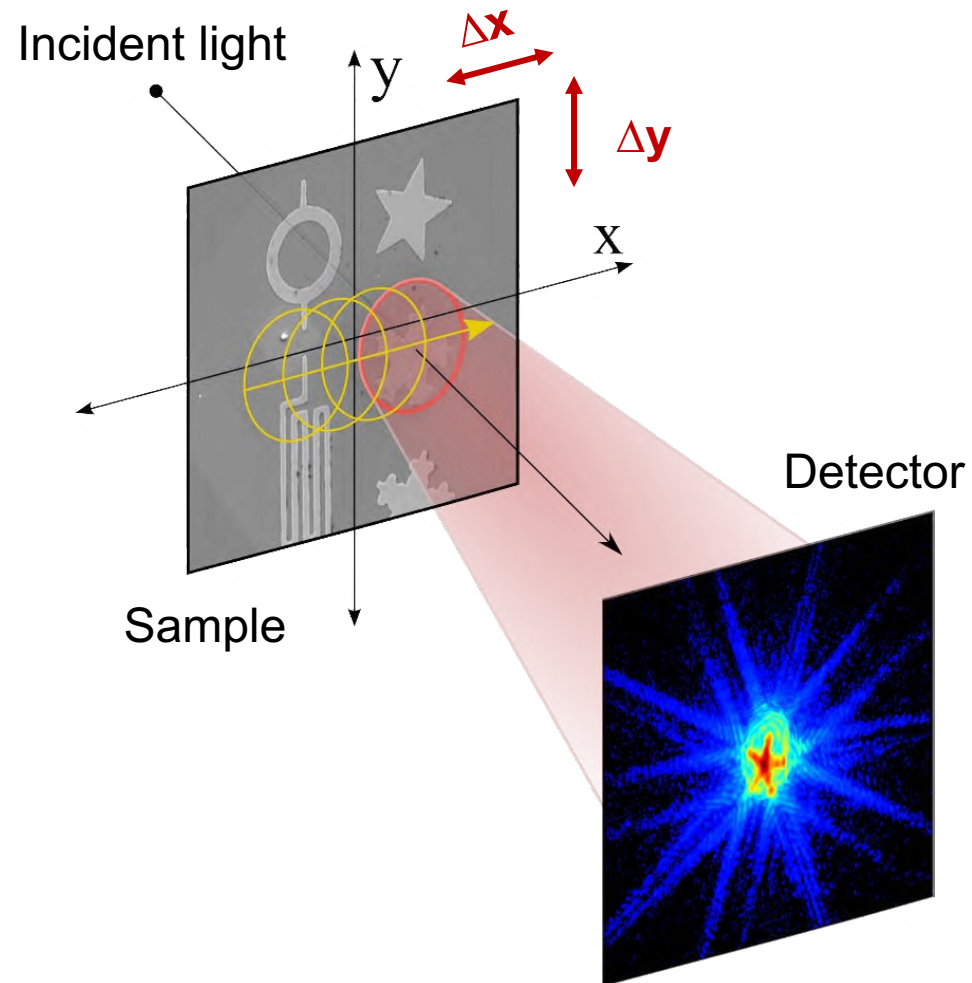
Ptychographic CDI



Ptychography replaces the requirement for a known support with redundancy from overlapping measurements.

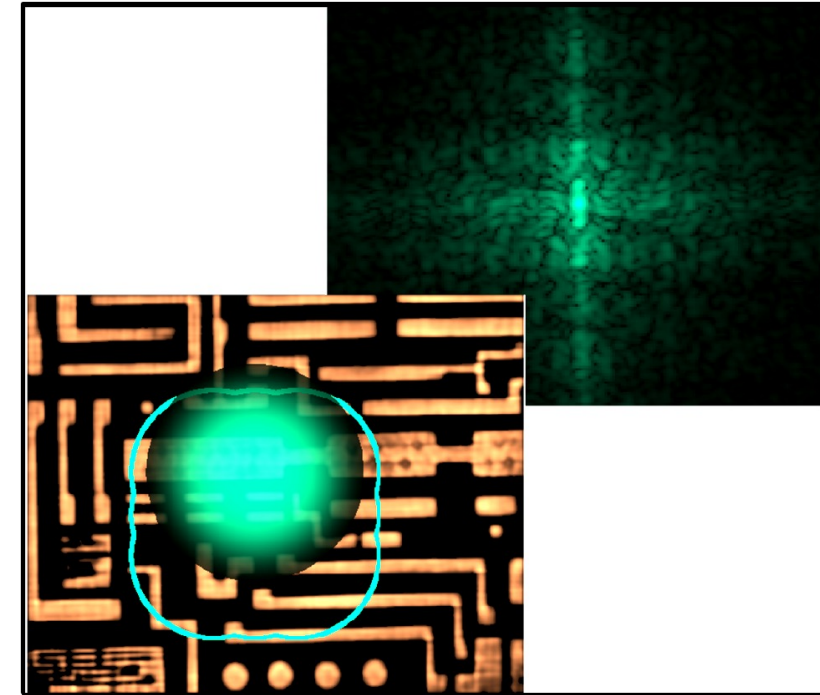
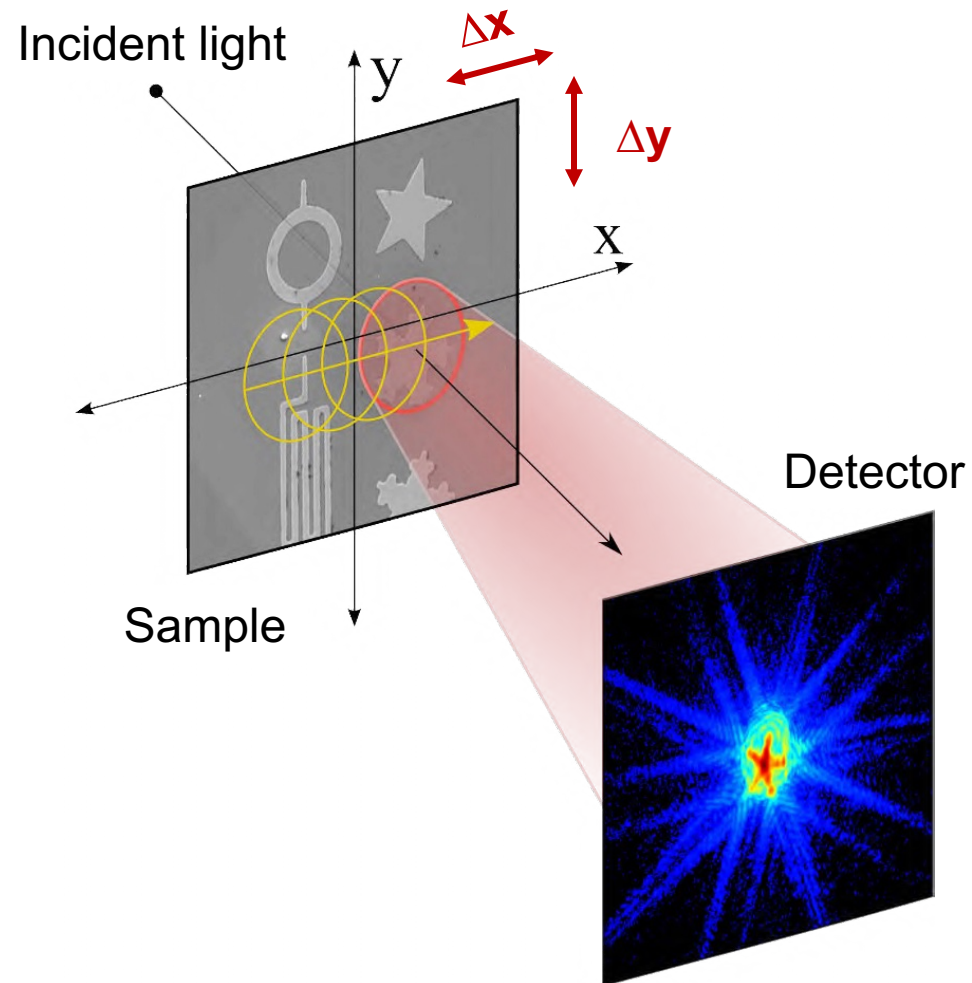
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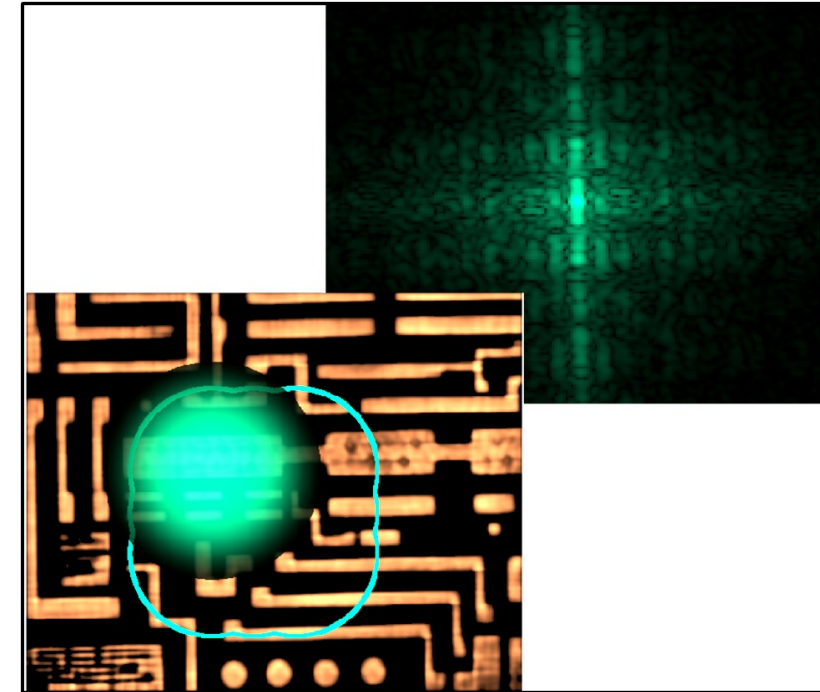
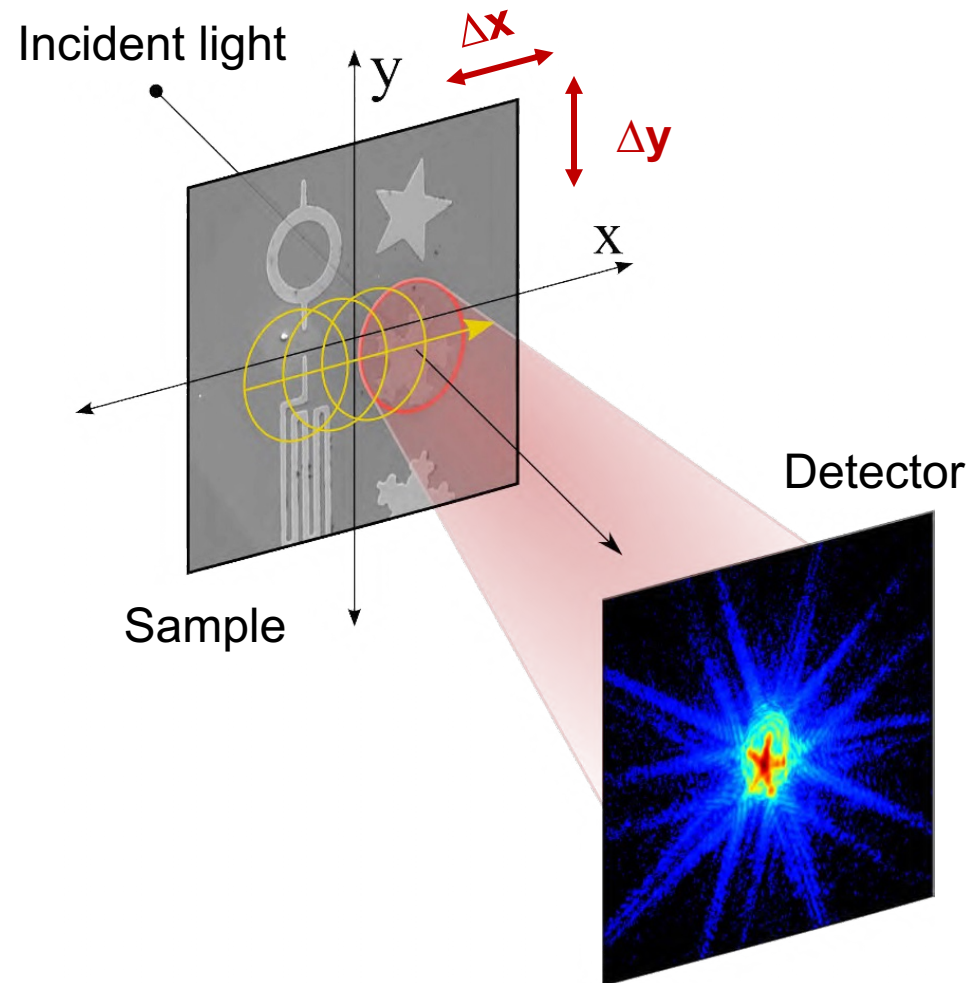
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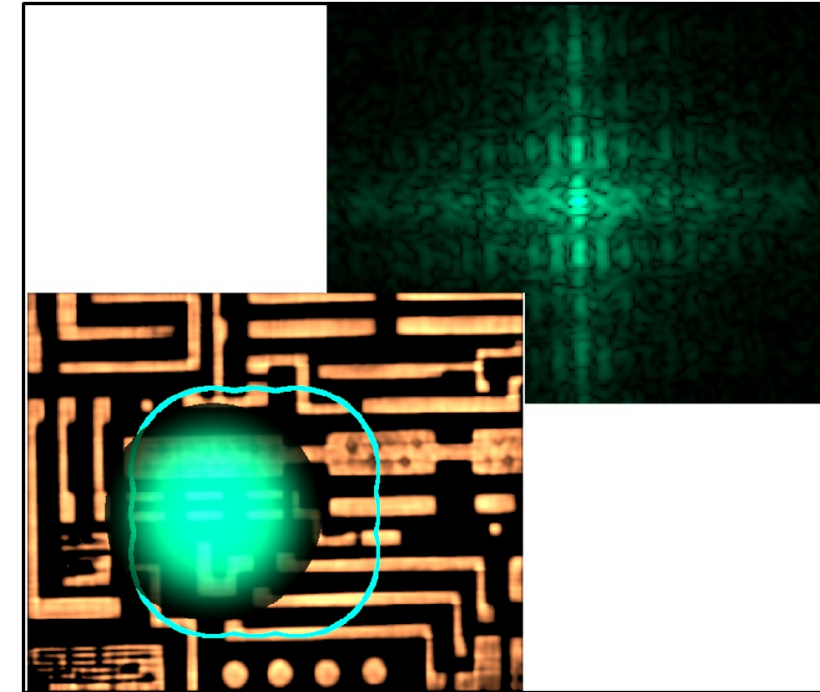
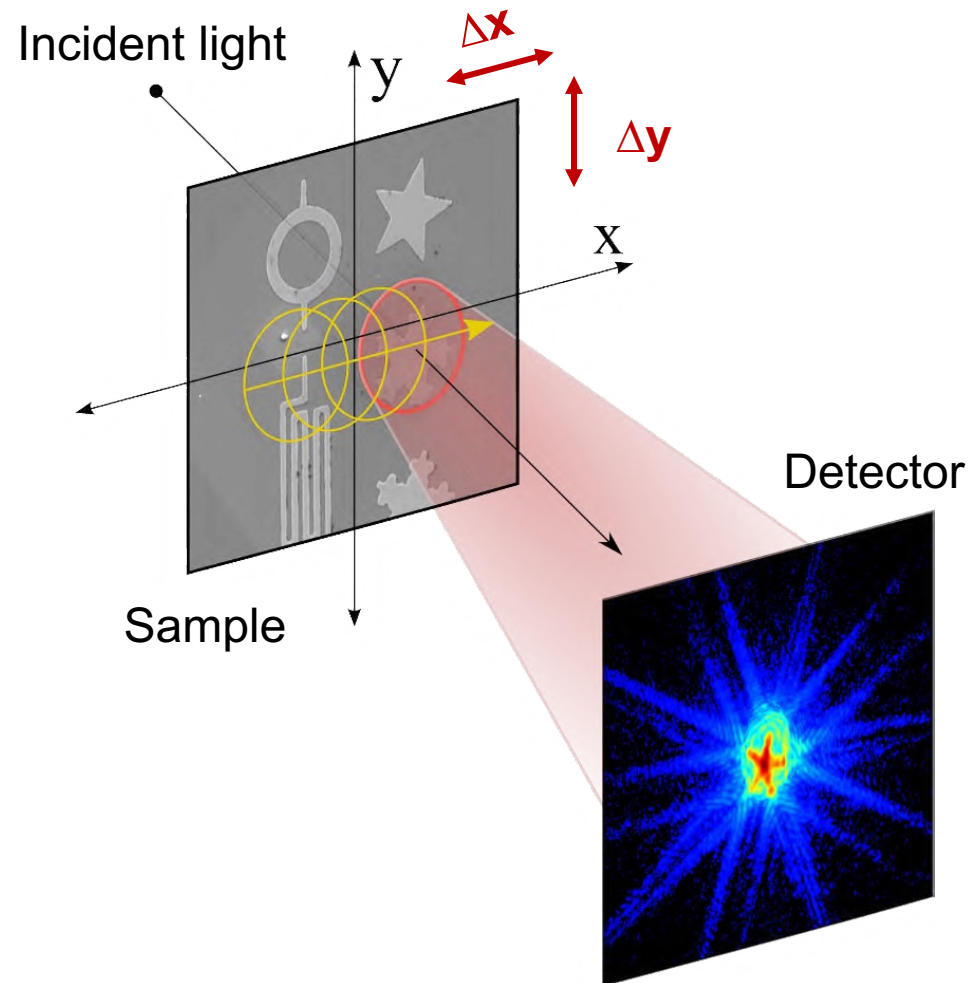
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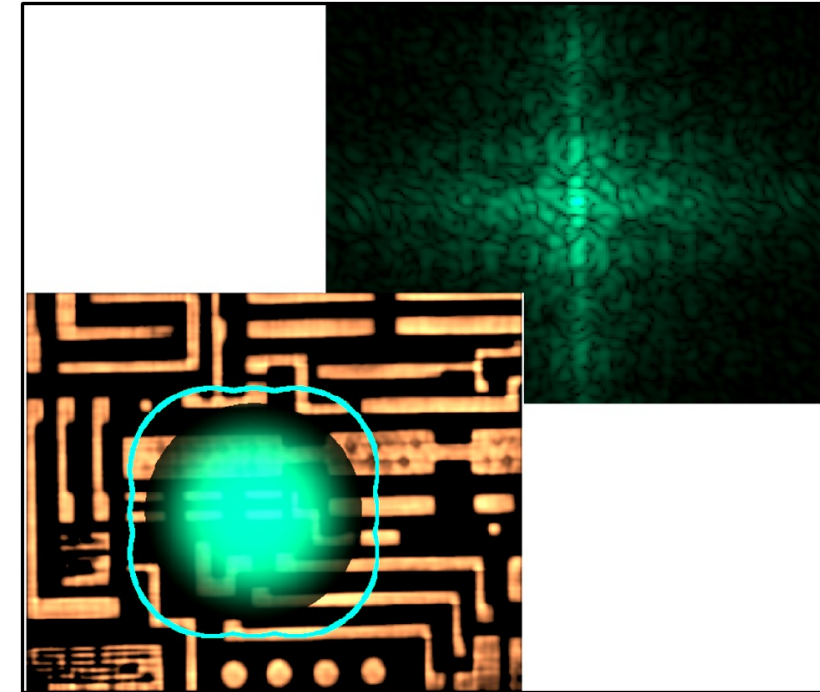
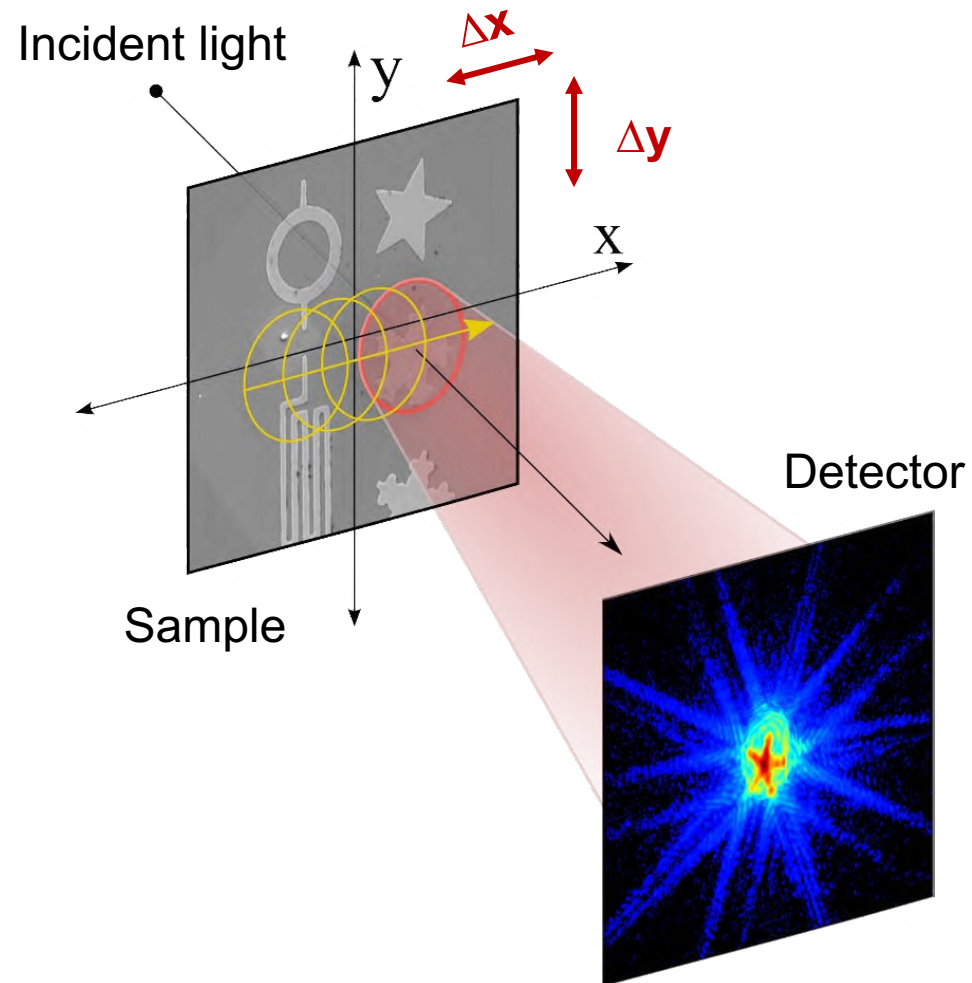
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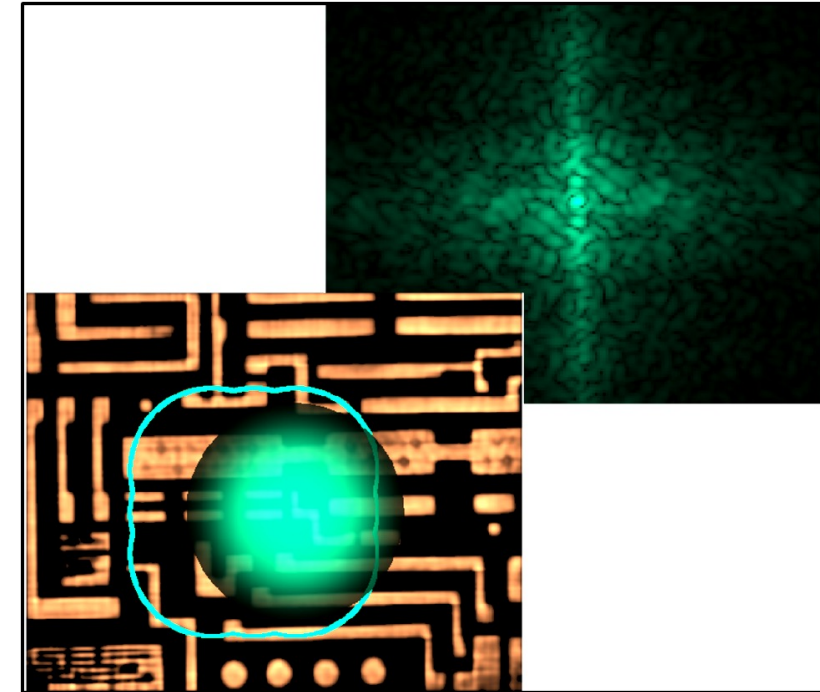
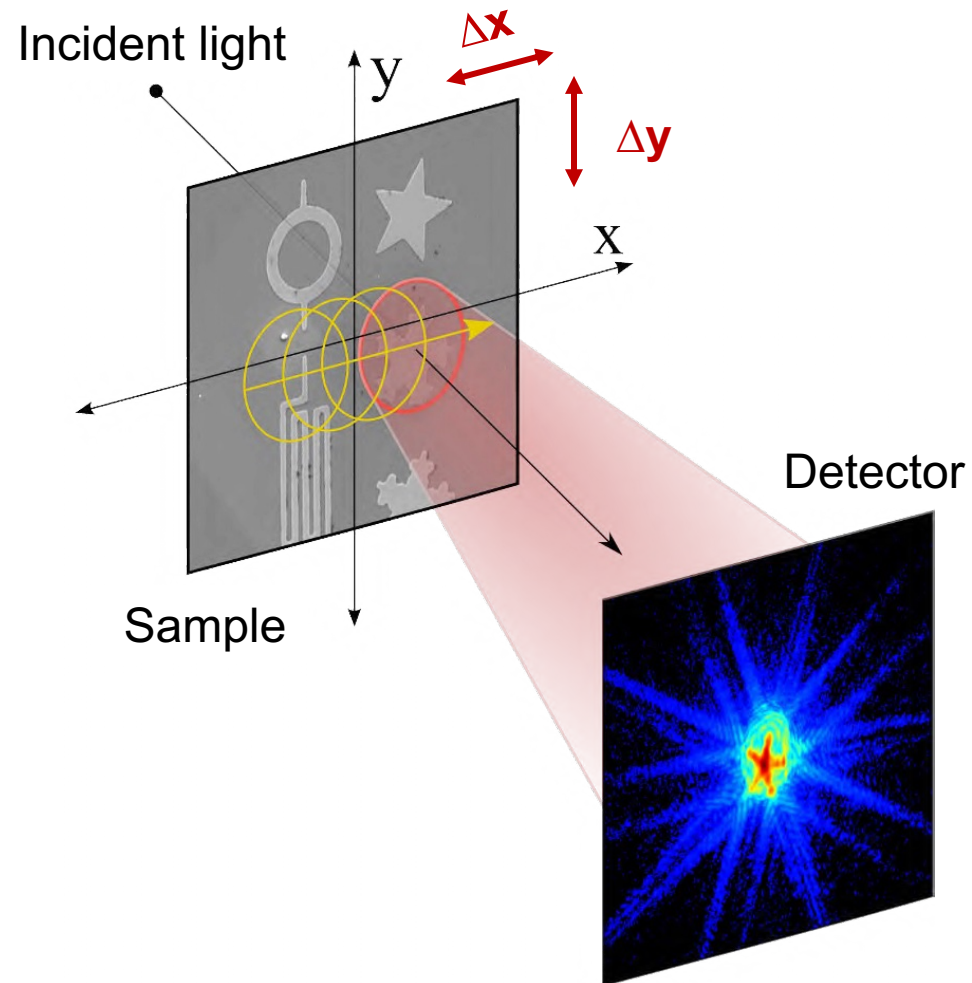
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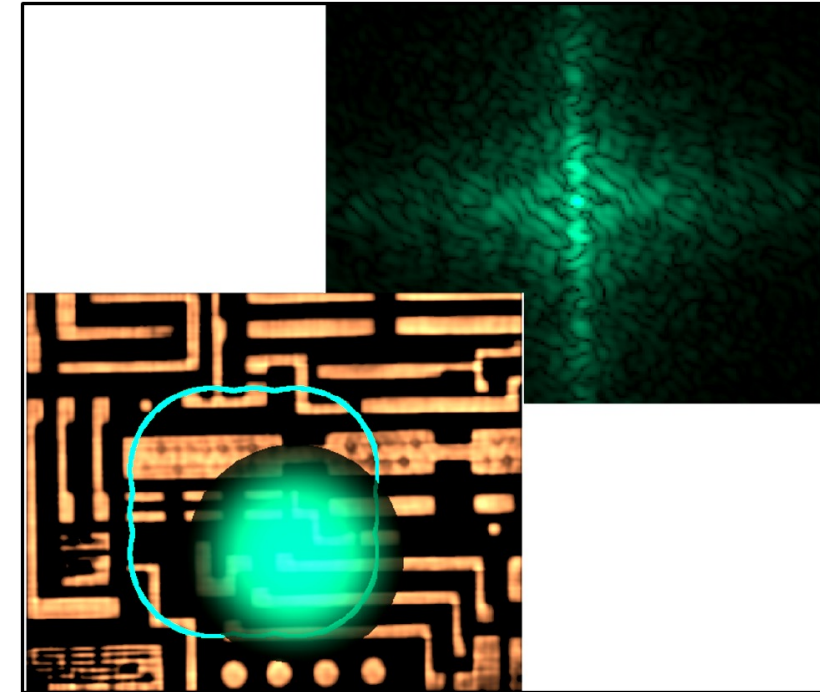
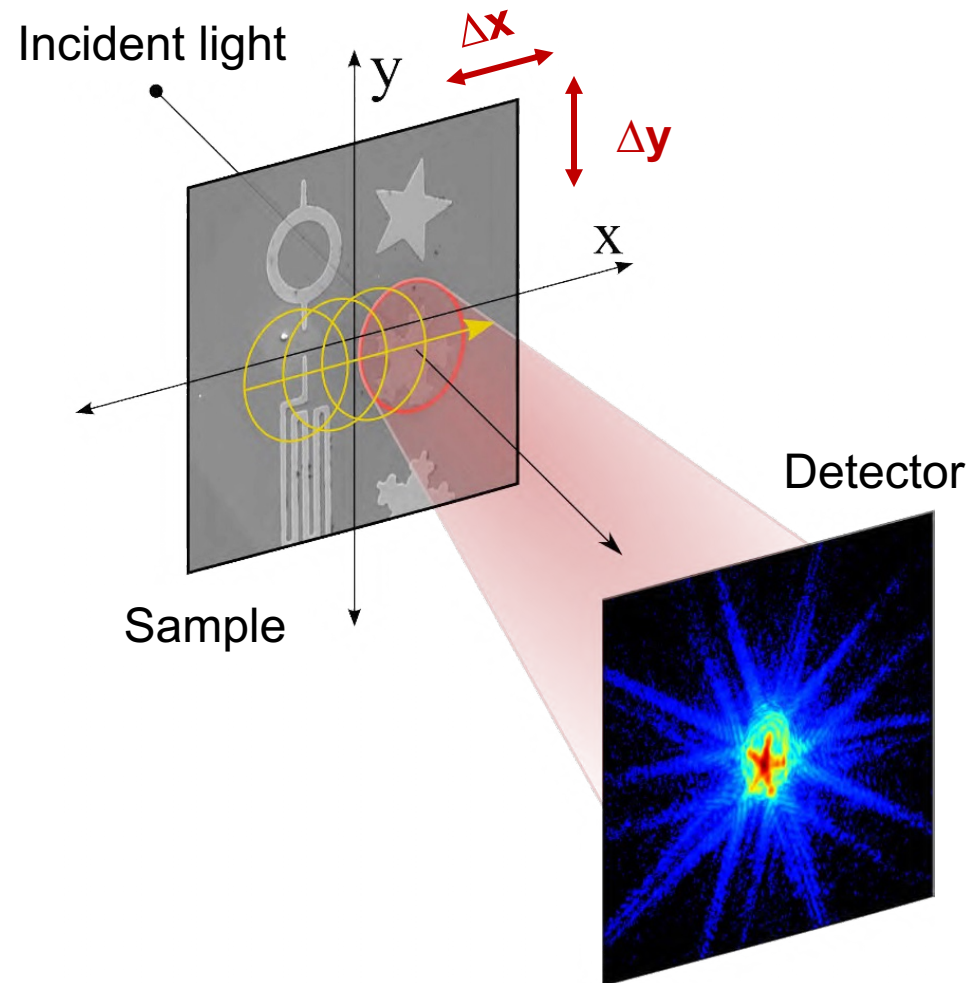
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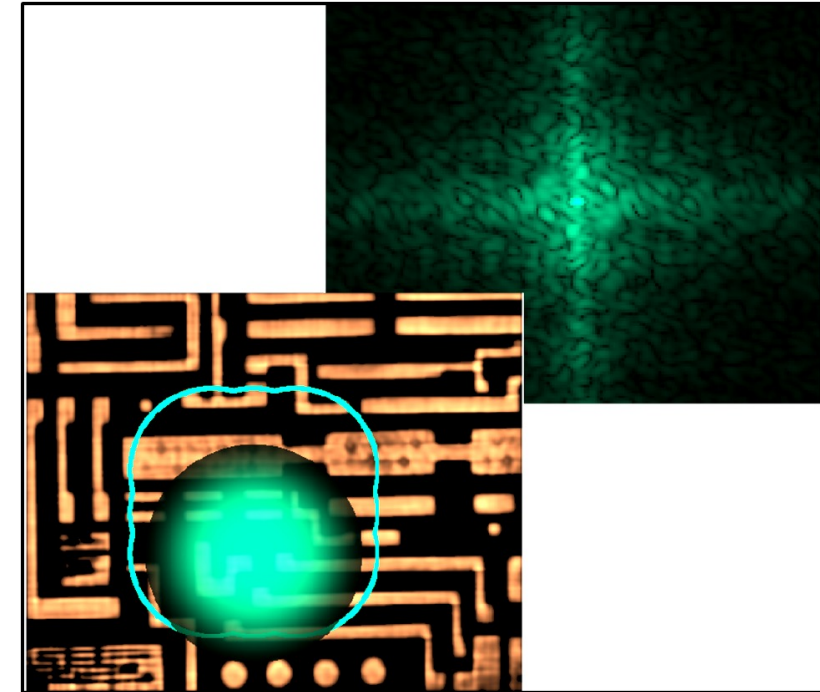
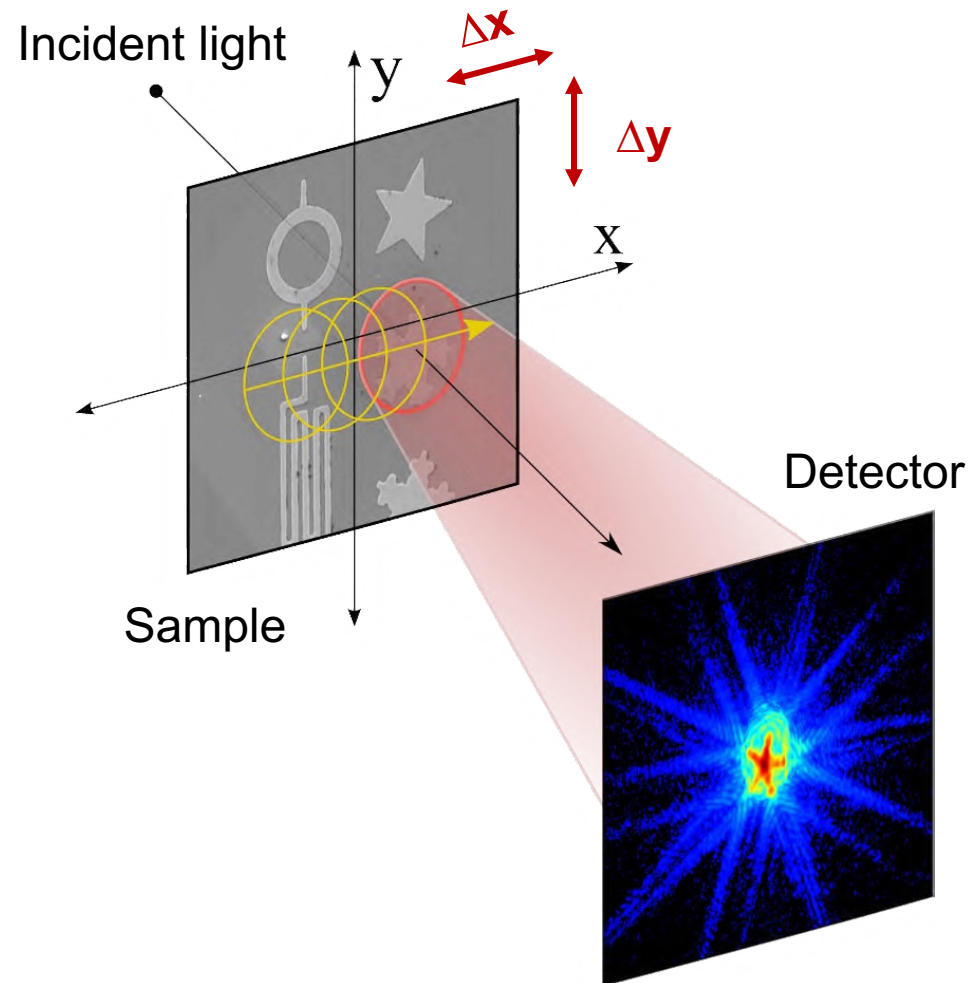
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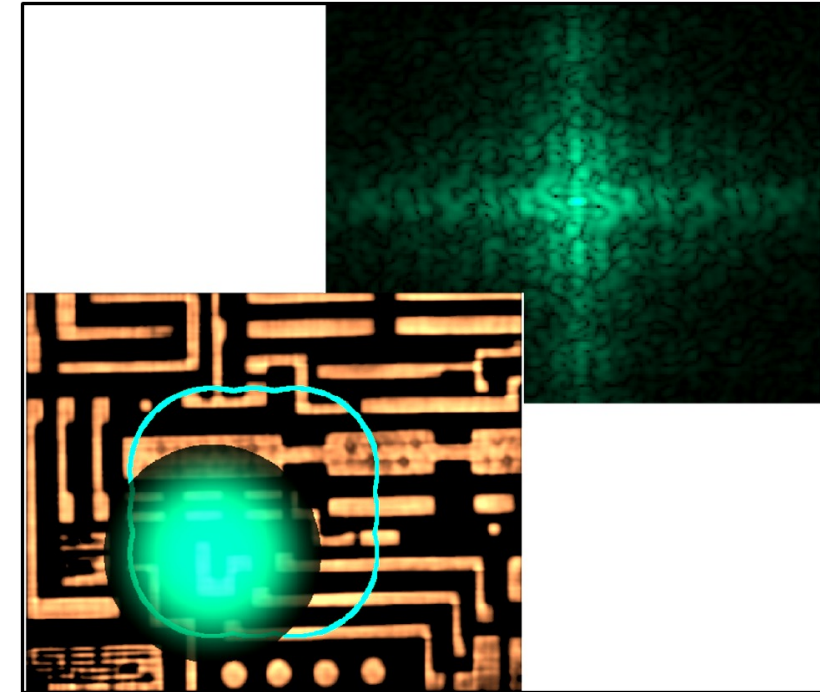
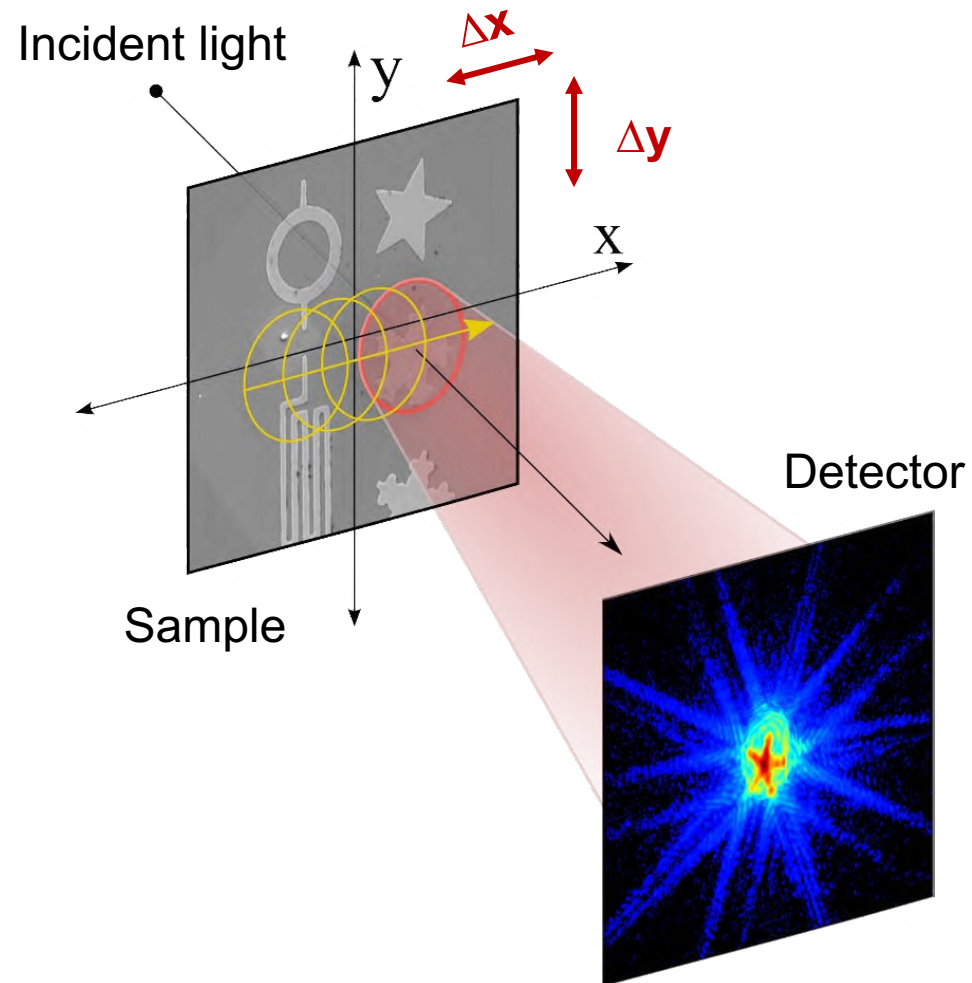
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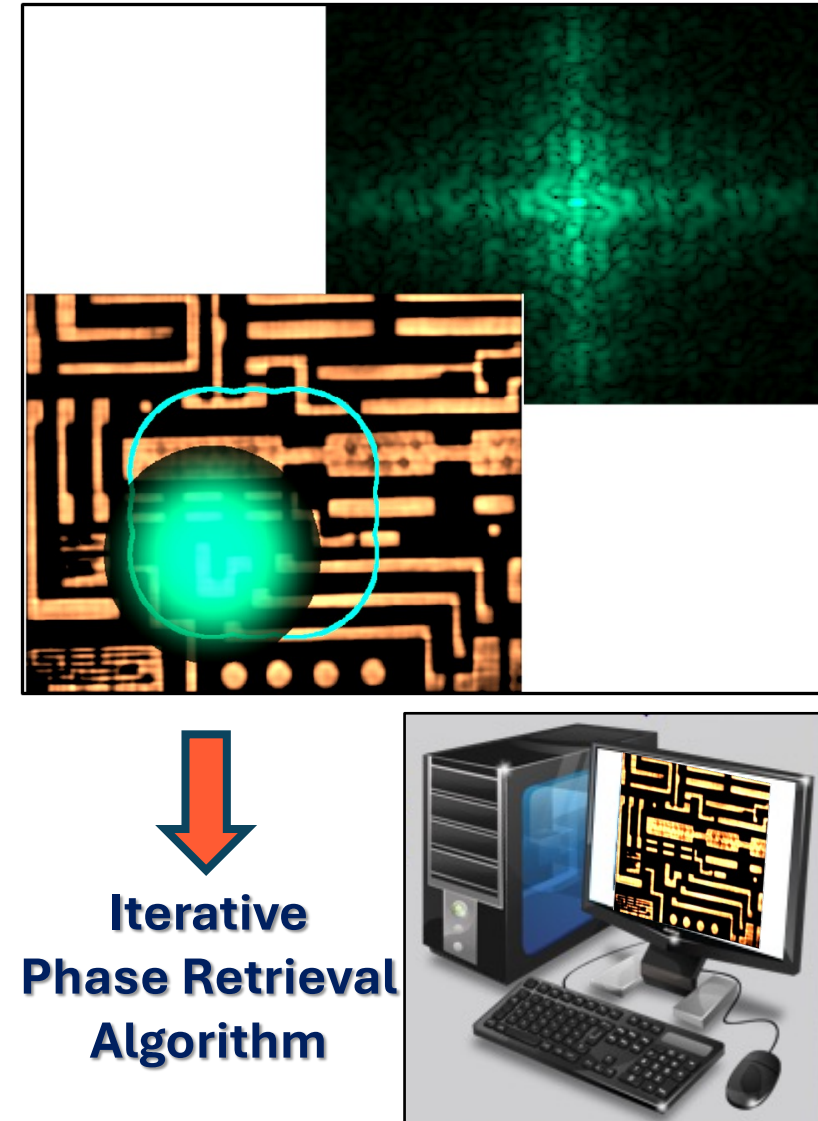
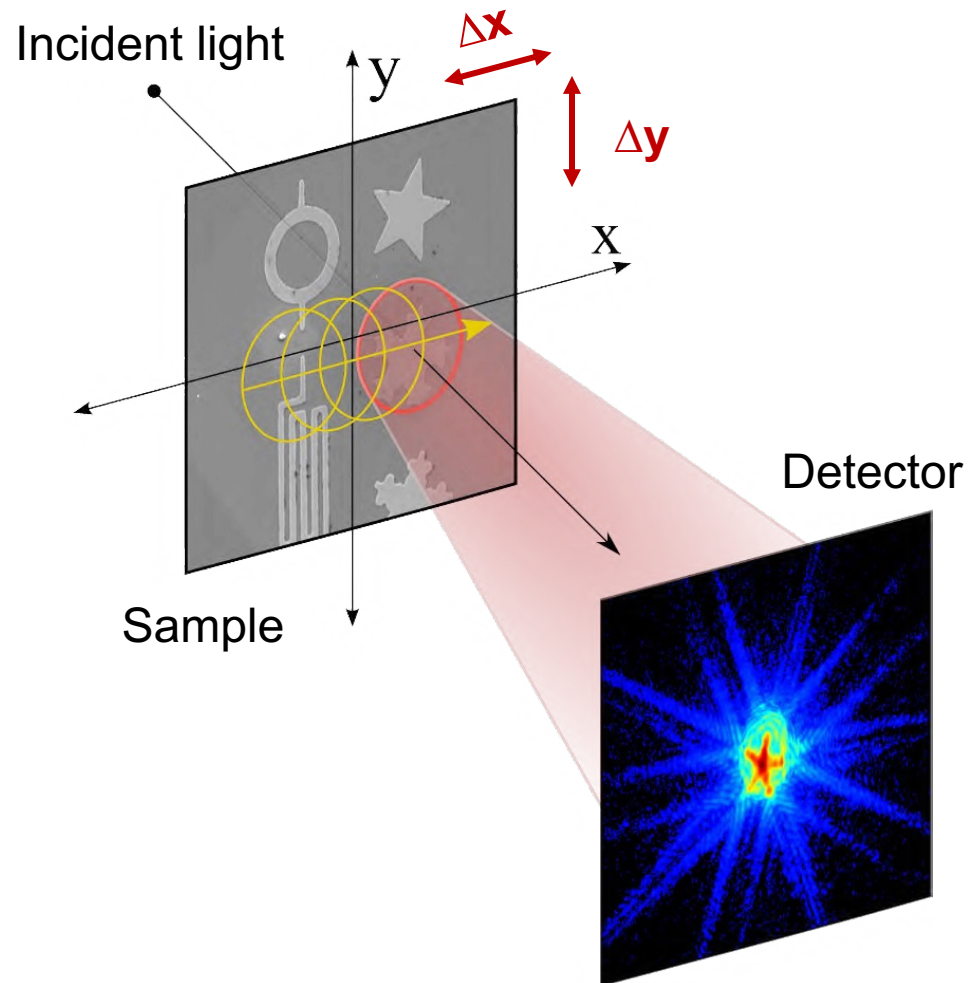
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Miao *et al.*, Nature, **400**, 342 (1999)
Chapman *et al.*, Nat. Photonics, **4**, 833 (2010)
Rodenburg *et al.*, Phys. Rev. Lett. **98**, 034801 (2007)
Thibault *et al.*, Science **321**, 379 (2008)
Maiden *et al.*, Ultramicroscopy **109**, 1256 (2009)

Ptychographic CDI



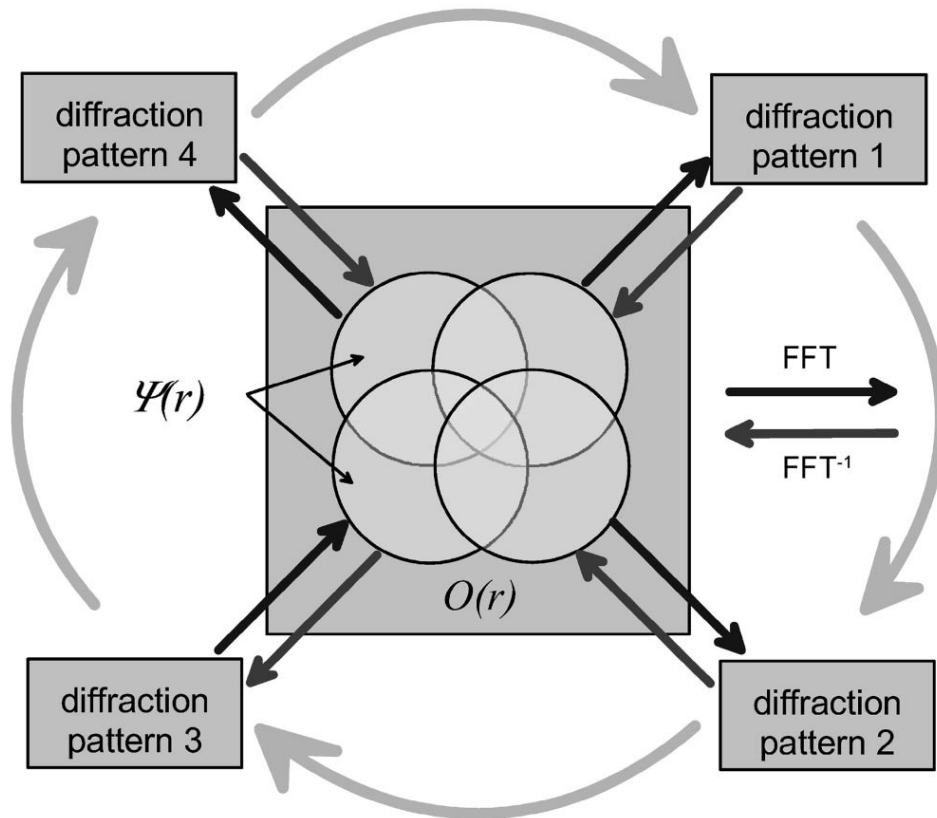
- Fienup, Opt. Lett. **3**, 27 (1978)
Miao *et al.*, Nature, **400**, 342 (1999)
Chapman *et al.*, Nat. Photonics, **4**, 833 (2010)
Rodenburg *et al.*, Phys. Rev. Lett. **98**, 034801 (2007)
Thibault *et al.*, Science **321**, 379 (2008)
Maiden *et al.*, Ultramicroscopy **109**, 1256 (2009)

Ptychographic CDI



Ptychographic CDI

Iterative Phase Retrieval Algorithm



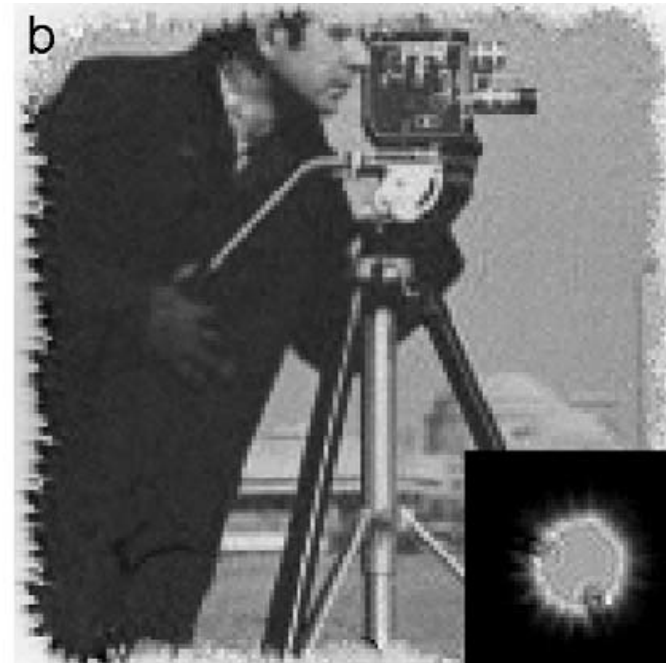
Rodenburg *et al.*, Phys. Rev. Lett. **98**, 034801 (2007)

An improved ptychographical phase retrieval algorithm for diffractive imaging

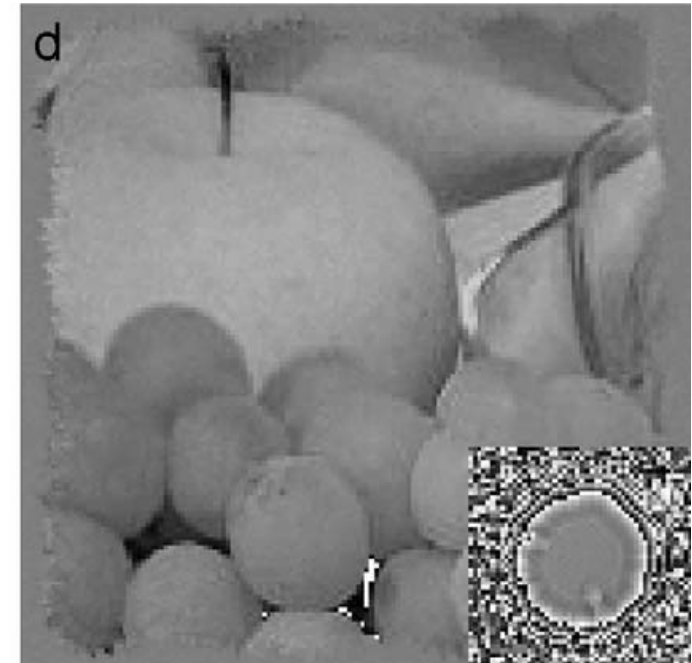
Andrew M. Maiden *, John M. Rodenburg

Department of Electrical and Electronic Engineering, University of Sheffield, S1 3JD, UK

AMPLITUDE



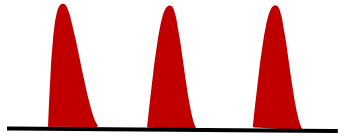
PHASE



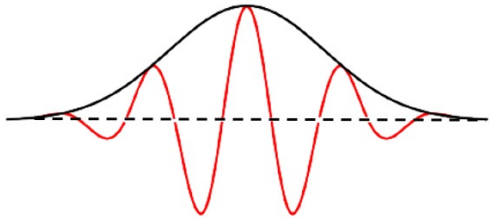
Maiden *et al.*, Ultramicroscopy **109**, 1256 (2009)

High Harmonic Generation (HHG)

35 fs, 5-10 kHz, 15 W, 785 nm



**Intense
laser pulses**

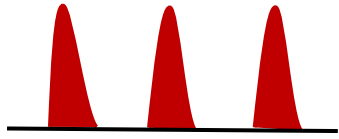


L'Huillier, Rev. Mod. Phys. **96**, 030503 (2024)
Rundquist *et al.*, Science **280**, 1412–1415 (1998)
Redman *et al.*, Science **298**, 1581 (2002)

Agostini, Rev. Mod. Phys. **96**, 030501 (2024)
Kapteyn *et al.*, Phys. Today **58**, 39–46 (2005)
Popmintchev *et al.*, Nature Photon. **4**, 822–832 (2010)

High Harmonic Generation (HHG)

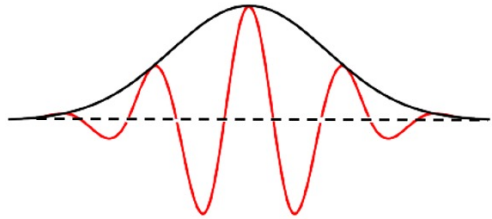
35 fs, 5-10 kHz, 15 W, 785 nm



**Intense
laser pulses**



Noble gas (Ar, He) in a waveguide



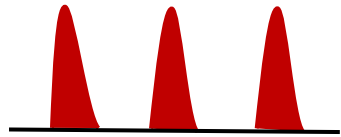
**Highly nonlinear process: up converts the
driving laser to shorter wavelengths**

L'Huillier, Rev. Mod. Phys. **96**, 030503 (2024)
Rundquist *et al.*, Science **280**, 1412–1415 (1998)
Redman *et al.*, Science **298**, 1581 (2002)

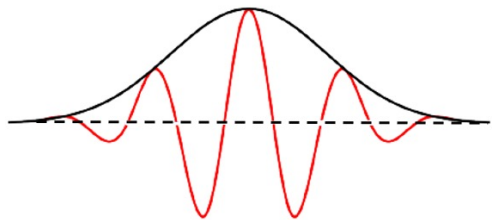
Agostini, Rev. Mod. Phys. **96**, 030501 (2024)
Kapteyn *et al.*, Phys. Today **58**, 39–46 (2005)
Popmintchev *et al.*, Nature Photon. **4**, 822–832 (2010)

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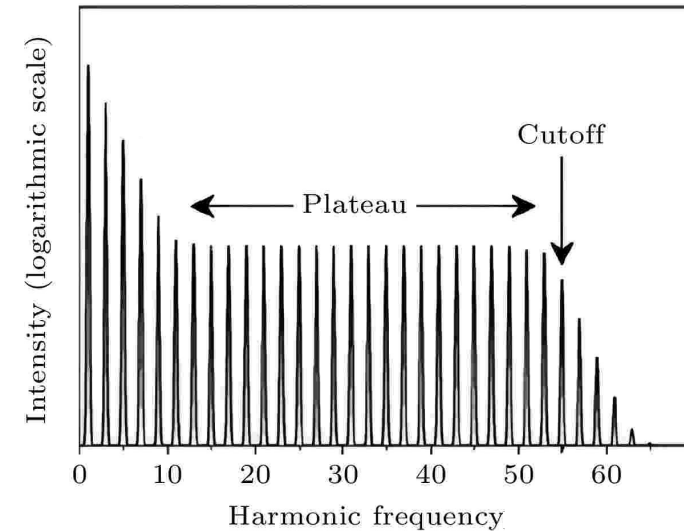
**Intense
laser pulses**



Noble gas (Ar, He) in a waveguide



Chen-Yu *et al.*, Acta Phys. Sin. **72**, 1-27 (2023)

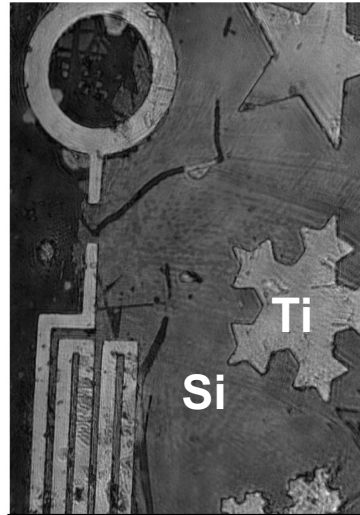
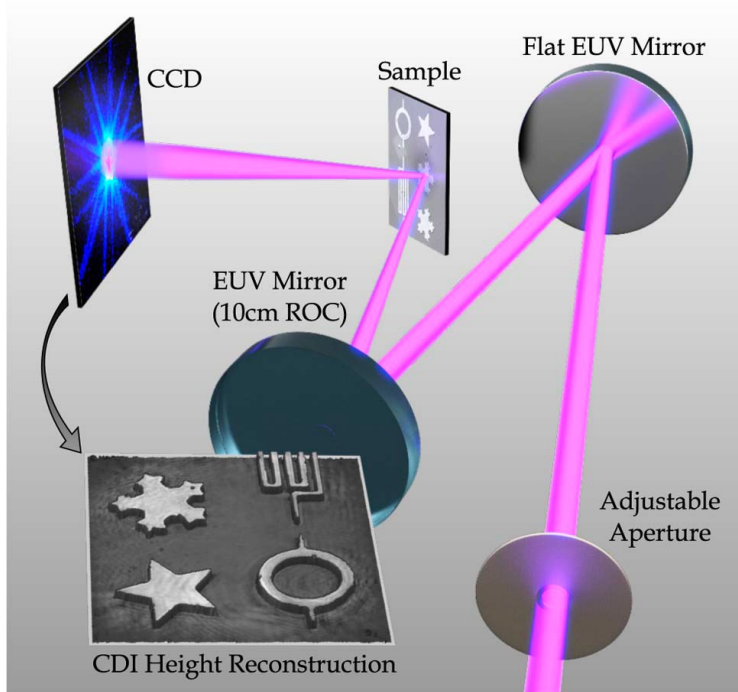


**Highly nonlinear process: up converts the
driving laser to shorter wavelengths**

L'Huillier, Rev. Mod. Phys. **96**, 030503 (2024)
Rundquist *et al.*, Science **280**, 1412–1415 (1998)
Redman *et al.*, Science **298**, 1581 (2002)

Agostini, Rev. Mod. Phys. **96**, 030501 (2024)
Kapteyn *et al.*, Phys. Today **58**, 39–46 (2005)
Popmintchev *et al.*, Nature Photon. **4**, 822-832 (2010)

Ptychography in the EUV regime



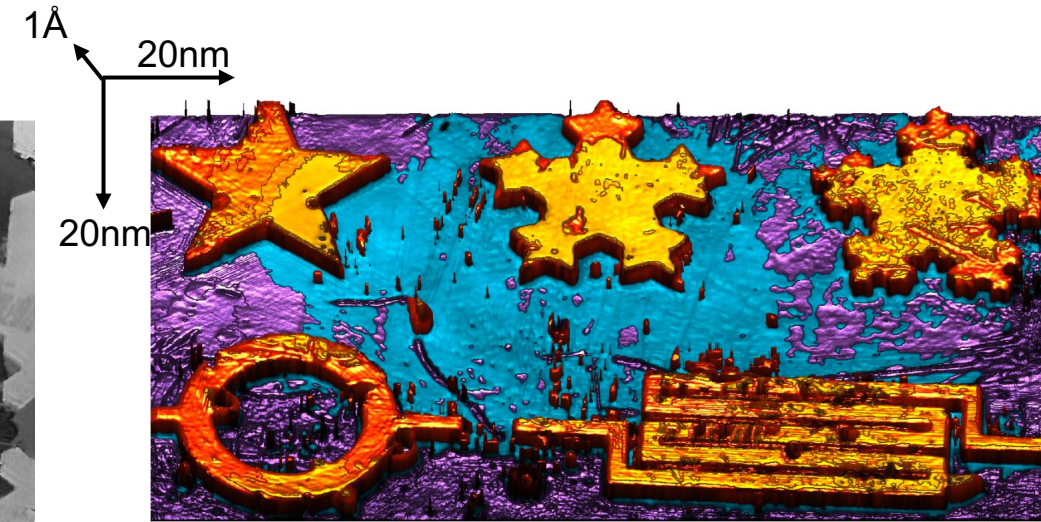
Amplitude:
Material Composition



Phase:
Topography

Zhang et al., Ultramicroscopy **158**, 98 (2015)
Tanksalvala et al., Sci. Adv. **7**, eabd9667 (2021)

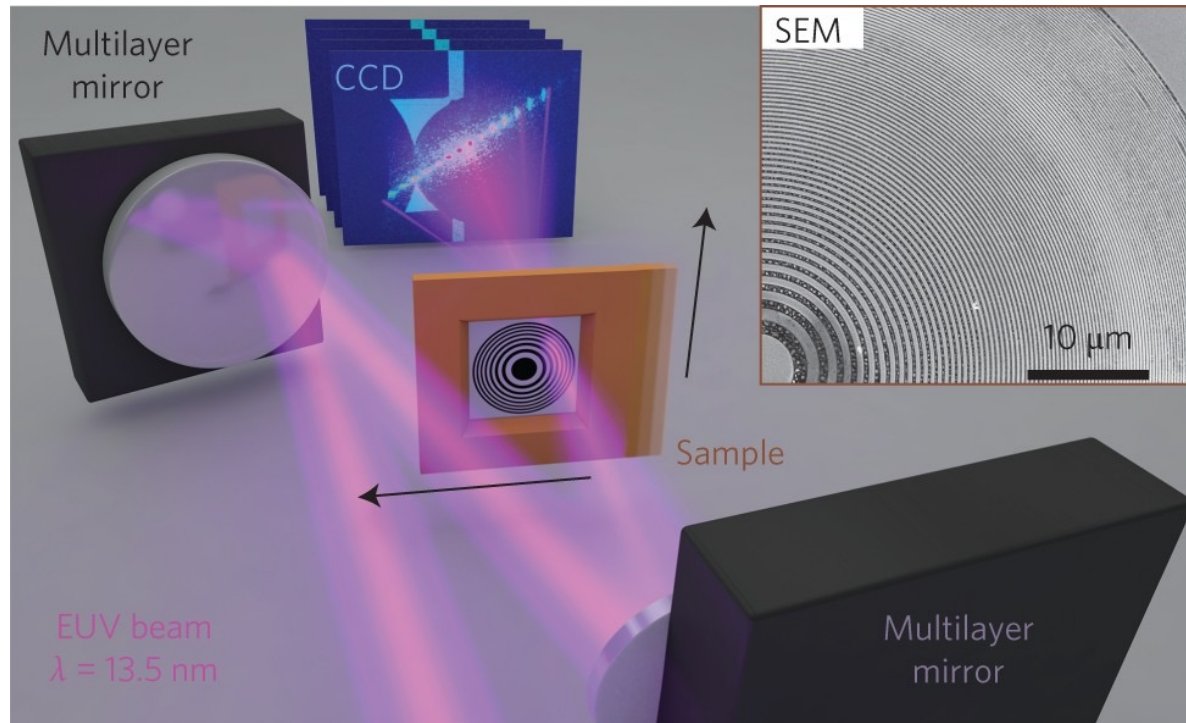
- Excellent **stability** of harmonic sources
- Unique **chemical and phase sensitivity** of EUV reflectometry
- State of the art **ptychographic imaging algorithms**



- Refractive index of the elements
- Phase changes upon reflection

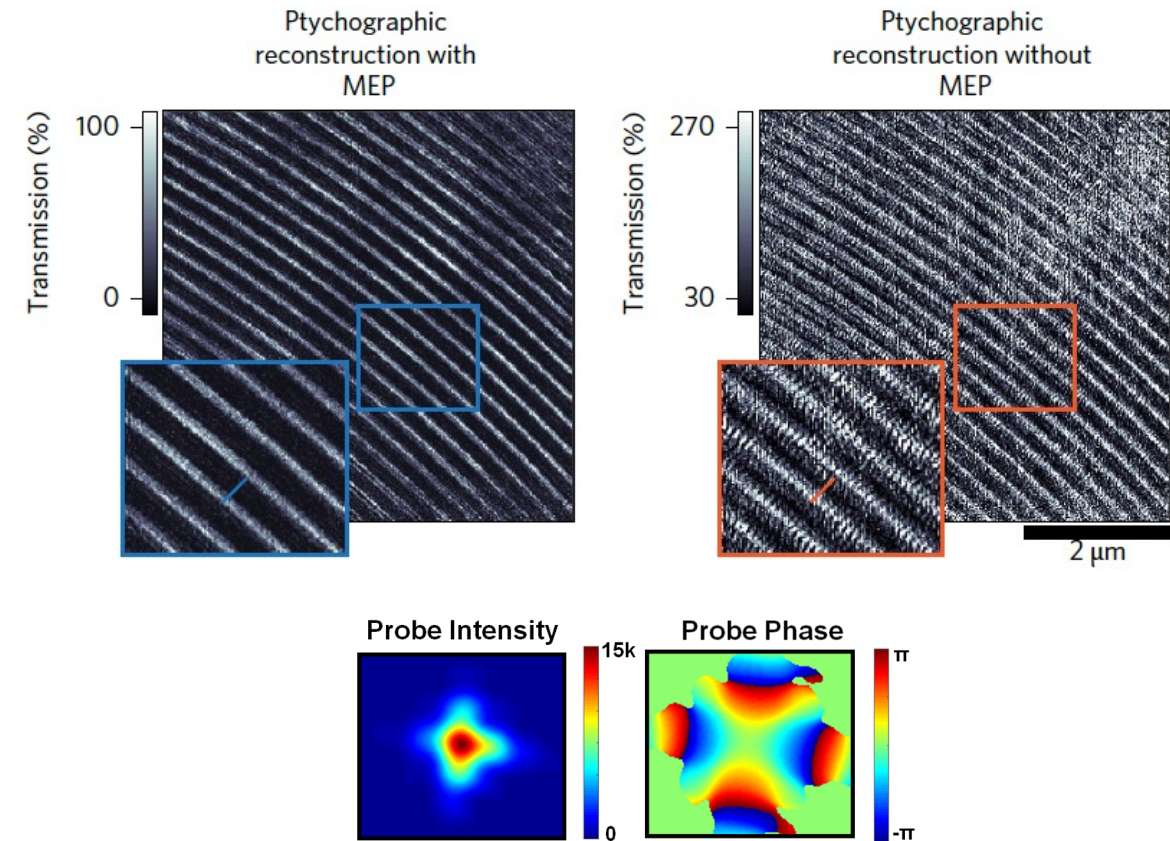
EUV ptychography enables chemically sensitive and high-resolution reconstruction of surface structures

Ptychography in the EUV regime



Gardner *et al.*, Nat. Photonics **11**, 259–263 (2017)

Modulus Enforced Probe (MEP) have extended the technique to periodic samples

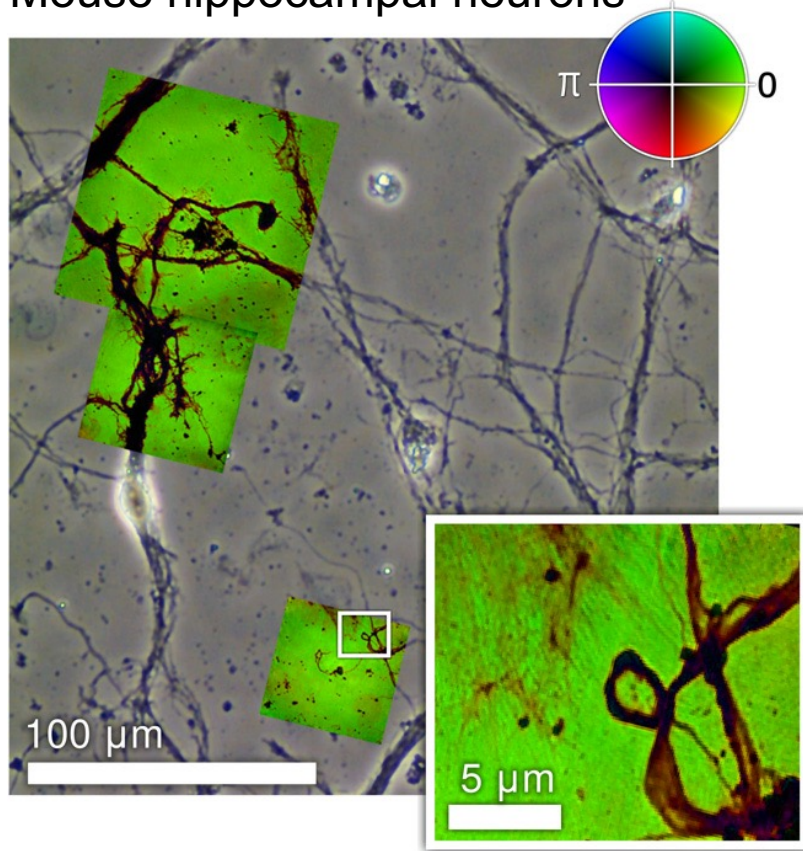


- Reduces cross-talk between the sample and probe reconstructions
- Reduces artifacts from the periodic sample

Ptychography in the EUV regime

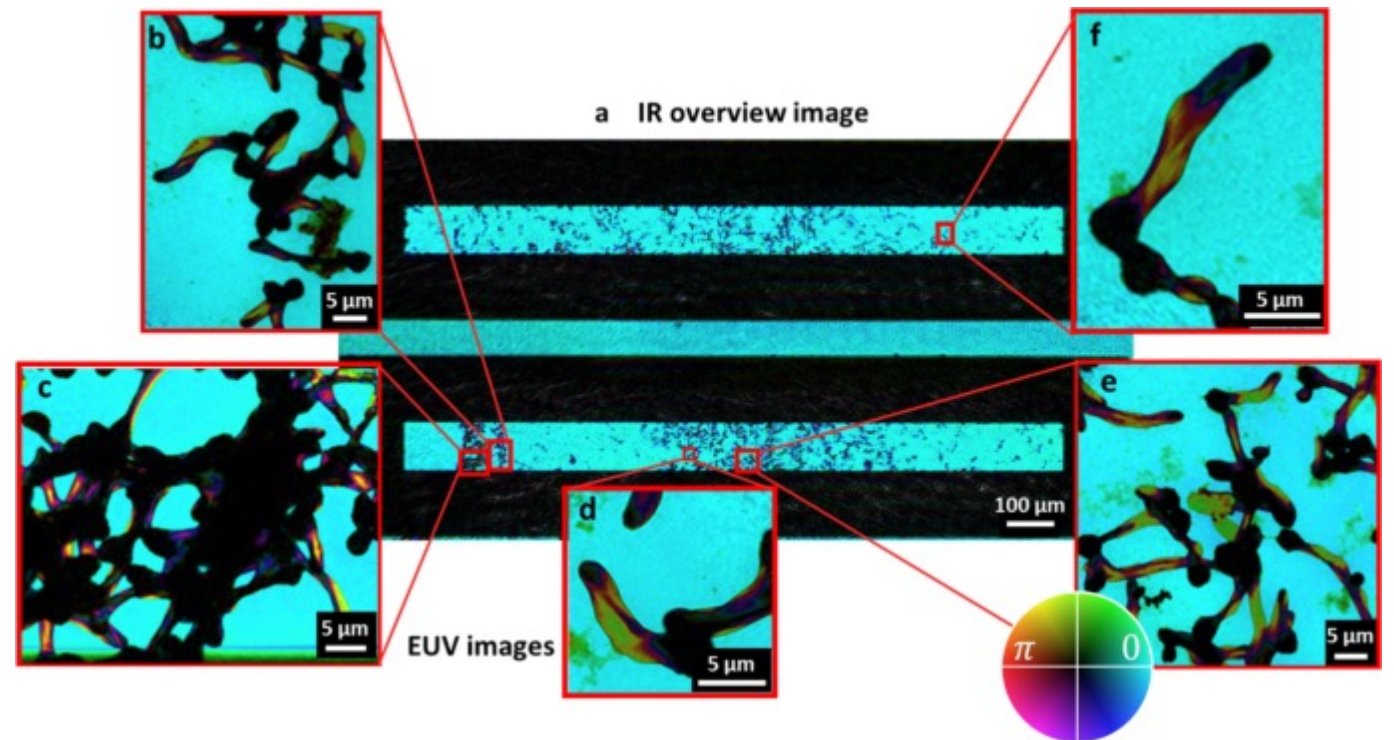
Biological samples: high-resolution, chemically sensitive, and label-free imaging

Mouse hippocampal neurons



Baksh *et al.*, Sci. Adv. **6**, eaaz3025 (2020)

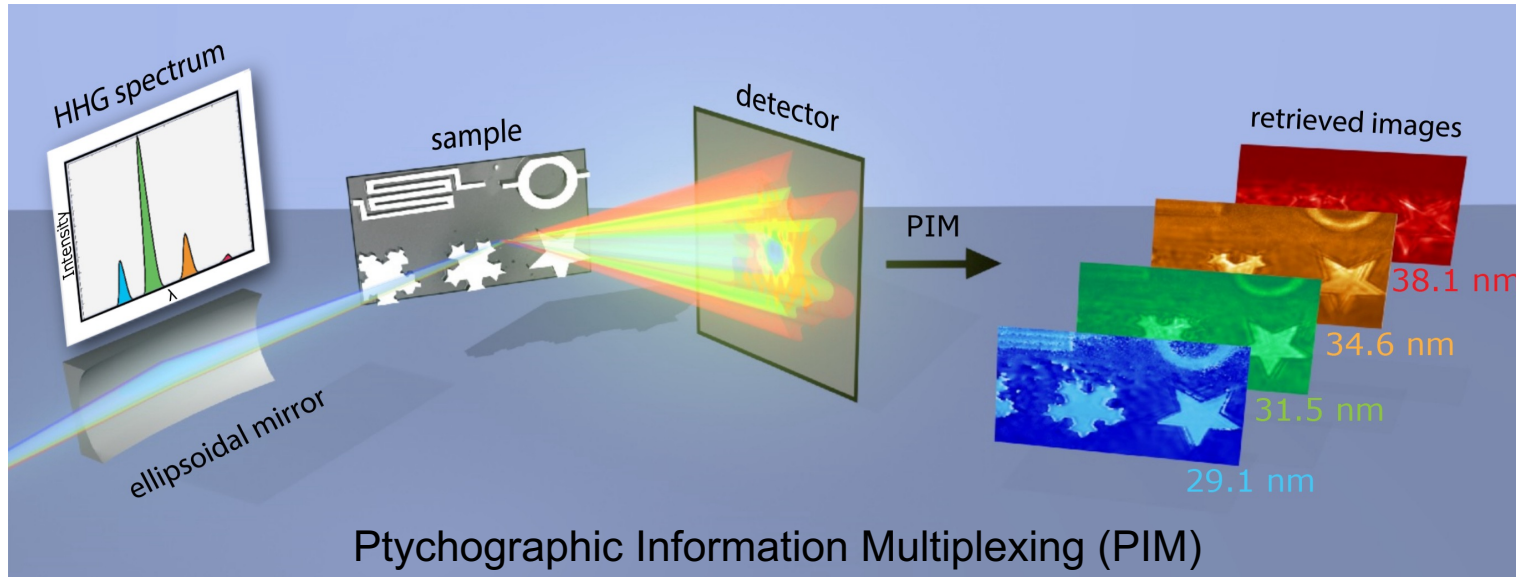
- Fungus *Aspergillus nidulans*
- Bacteria *Escherichia coli*



Liu *et al.*, PhotonIX **4**, 6 (2023)

Ptychography in the EUV regime

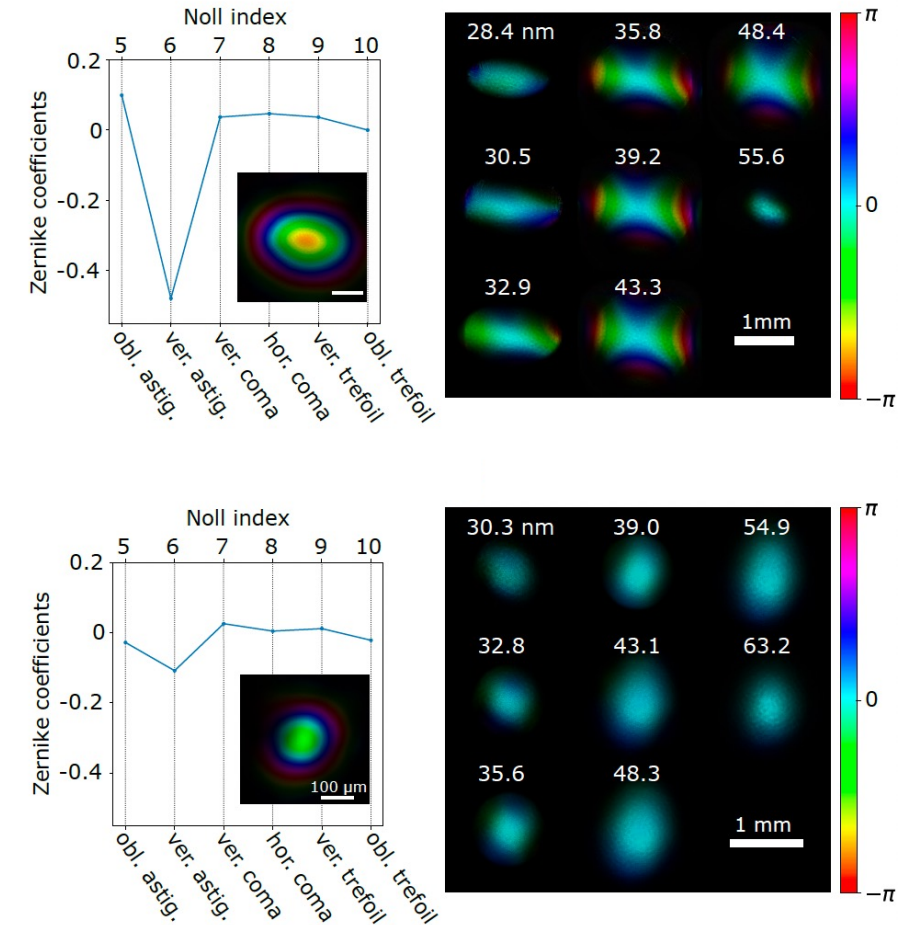
Ptychography as a high-resolution multi-wavelength EUV wavefront sensor



Zhang *et al.*, Opt. Express **24**, 18745 (2016)

Liu *et al.*, Phys. Rev. Res. **5**, 043100 (2023)

- **Hyperspectral EUV Imaging:** PIM reconstruction enables multi-wavelength imaging without monochromators.
- **Harmonic-Resolved Characterization:** Reveals **spatial dispersion** and **chromatic aberrations** affecting attosecond experiments.

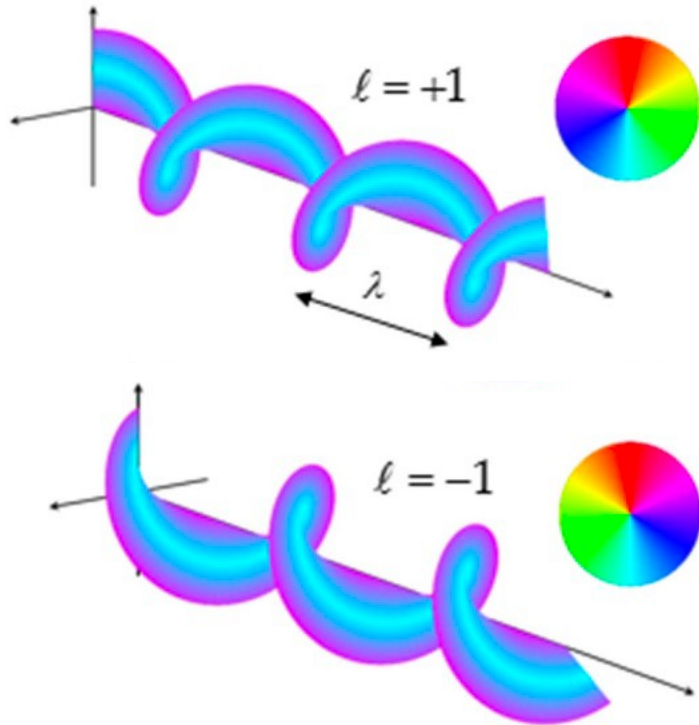


Du *et al.*, Optica **10**, 255–263 (2023)

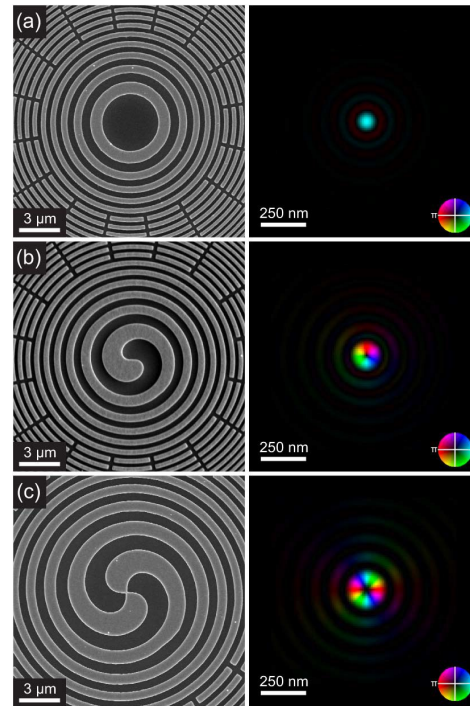
Ptychography in the EUV regime with OAM

- **Structured probes** introduce spatial diversity, **enhancing reconstruction**
- **A broad angular spectrum** spreads intensity and **increases signal-to-noise ratio** by reducing overexposure

$$E(r, \phi, z) = A(r, z) e^{i\ell\phi}$$

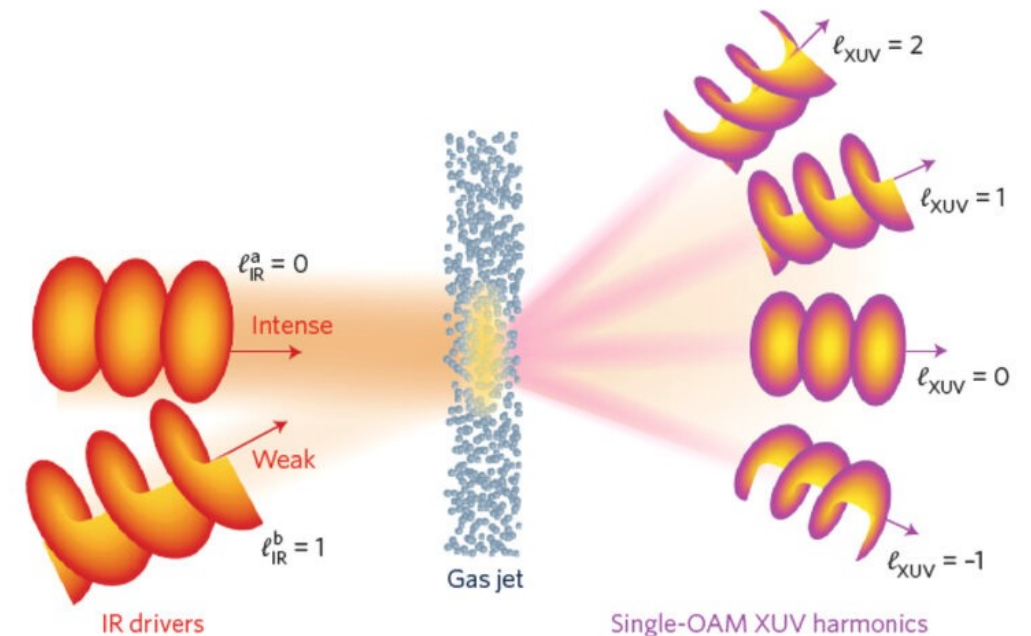


Spiral Fresnel Zone Plates



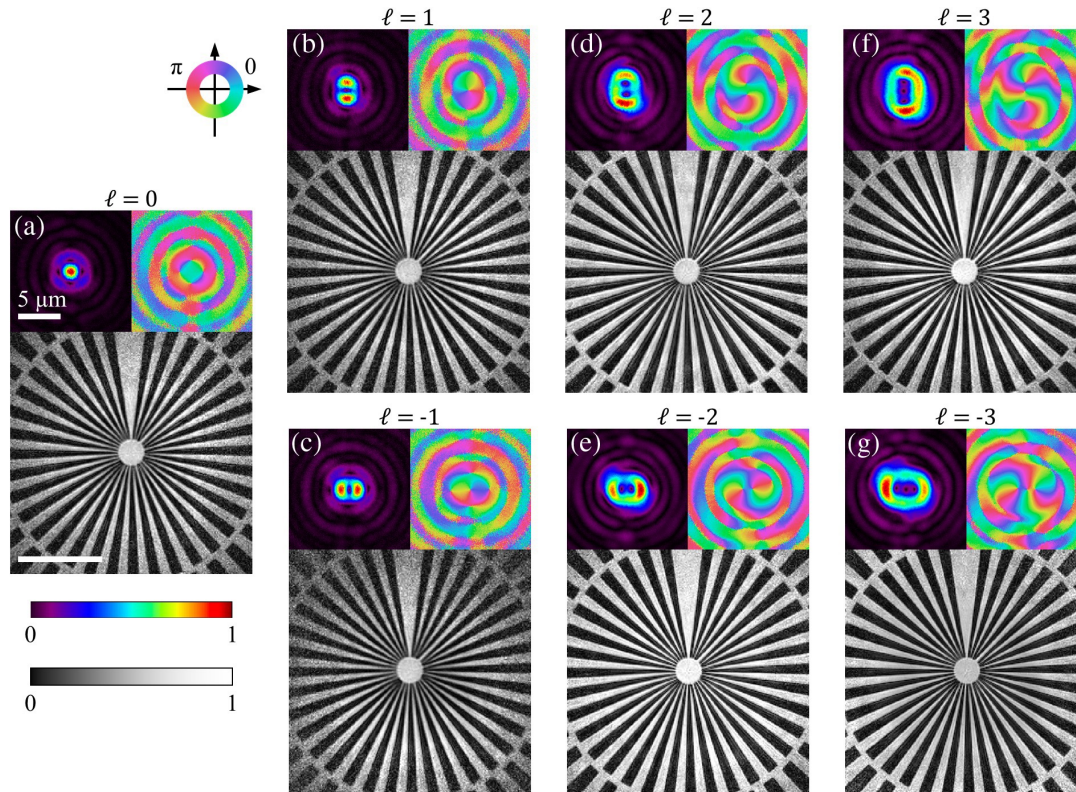
Vila-Comamala *et al.*, Opt. Lett. **39**, 5281-5284 (2014)

Driving the HHG process using OAM

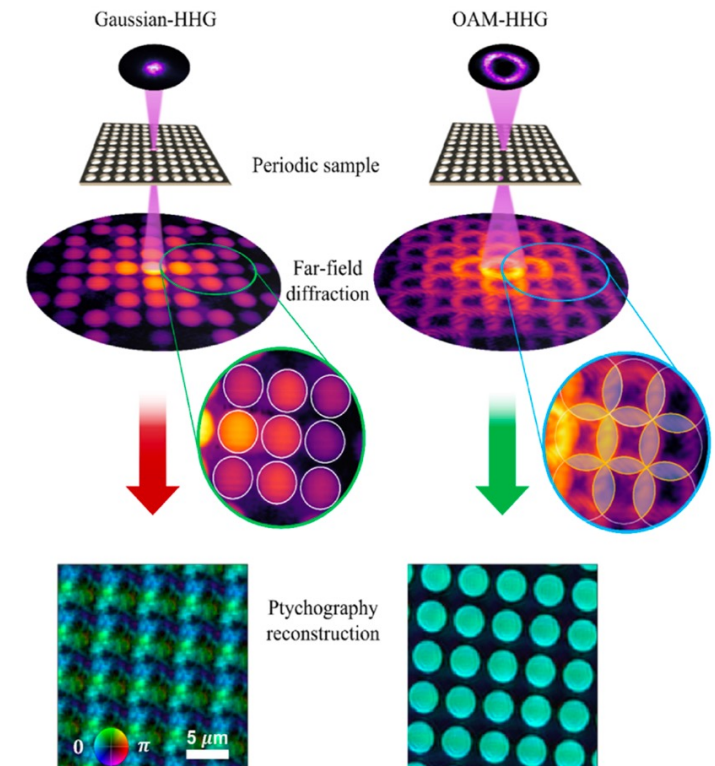


Hernández-García *et al.*, Phys. Rev. Lett. **111**, 083602 (2013)

Ptychography in the EUV regime with OAM



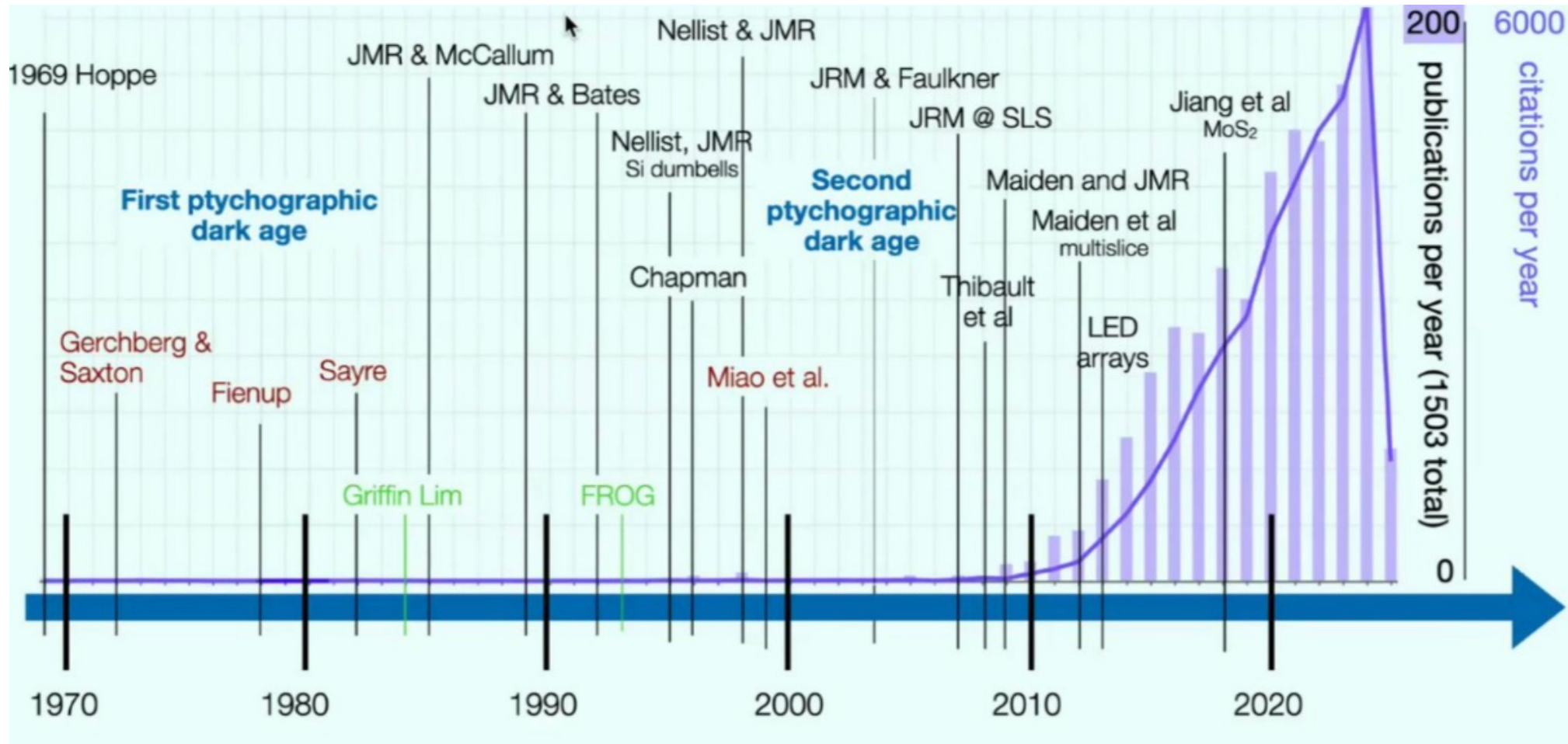
Pancaldi *et al.*, *Optica* **11**, 403 (2024)



Wang *et al.*, *Optica* **10**, 1245–1252 (2023)

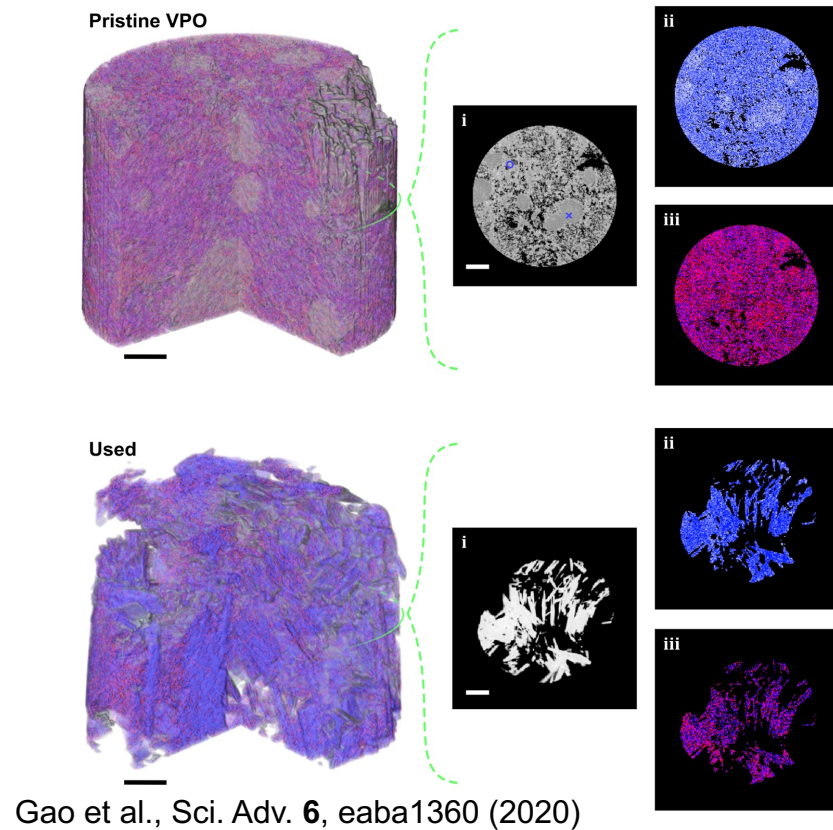
OAM beams enhance EUV ptychography performance, improving reconstruction quality and enabling chiral-sensitive modalities such as dichroic imaging.

Trends and future opportunities

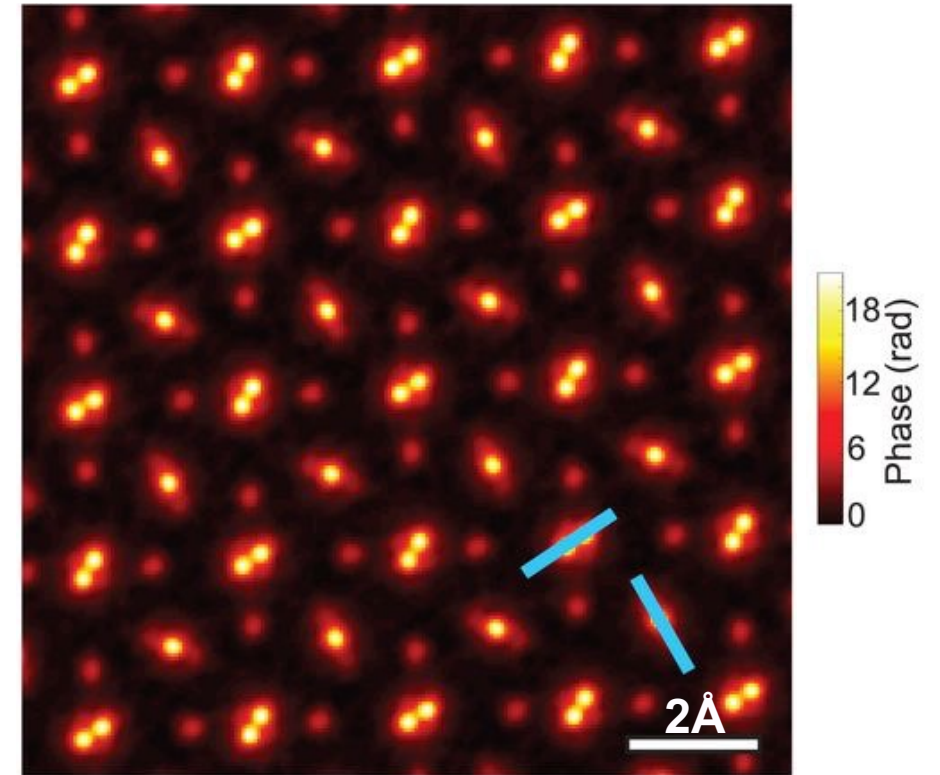


From H. Chapman (CFEL Hamburg) presentation during John Rodenburg Celebration Seminar

Trends and future opportunities



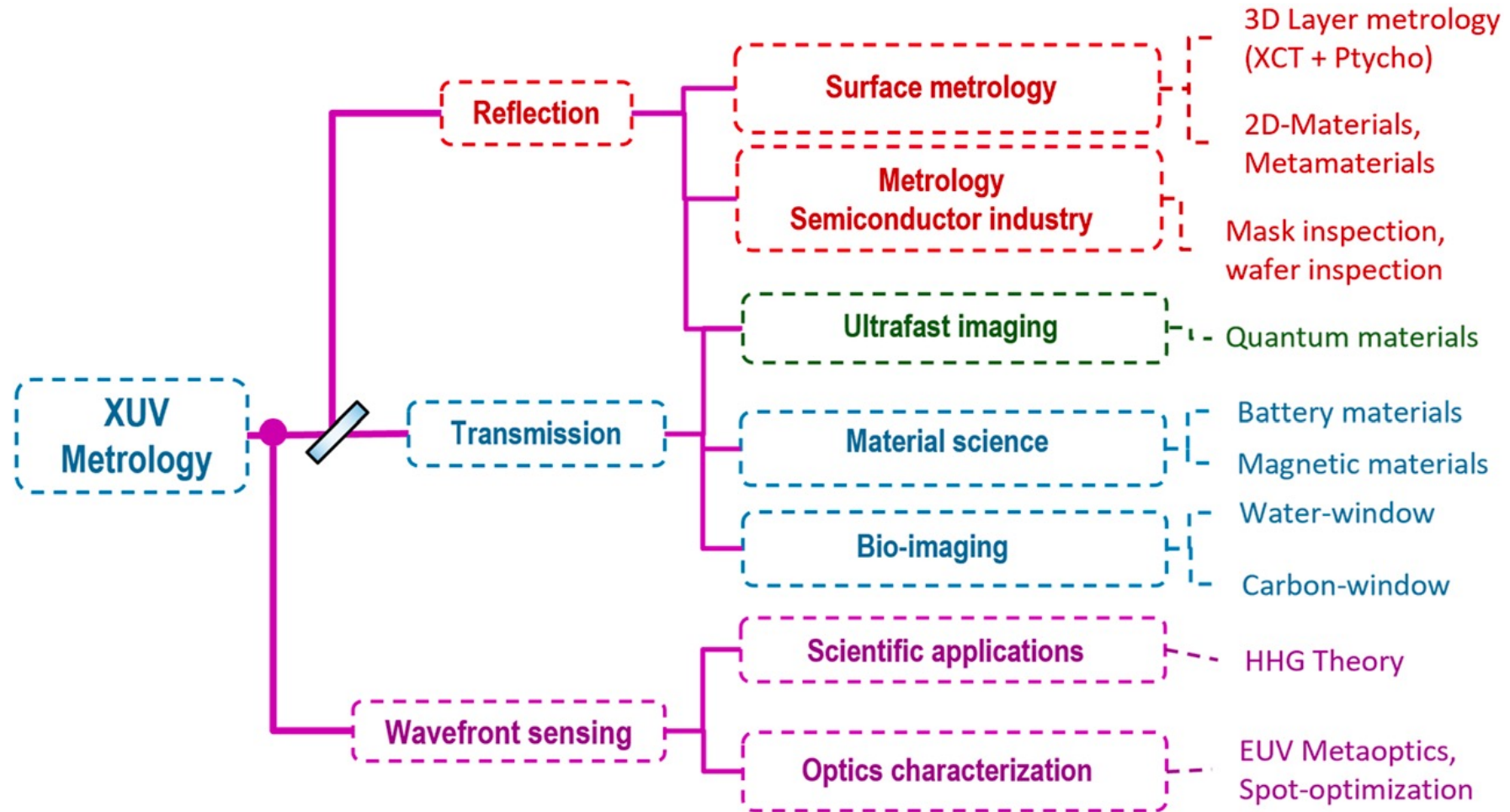
Ptychographic spectro-tomography enables **3D chemical mapping below 30 nm**, revealing local **structural and compositional changes**.



Chen et al., Science **372**, 826–831 (2021)

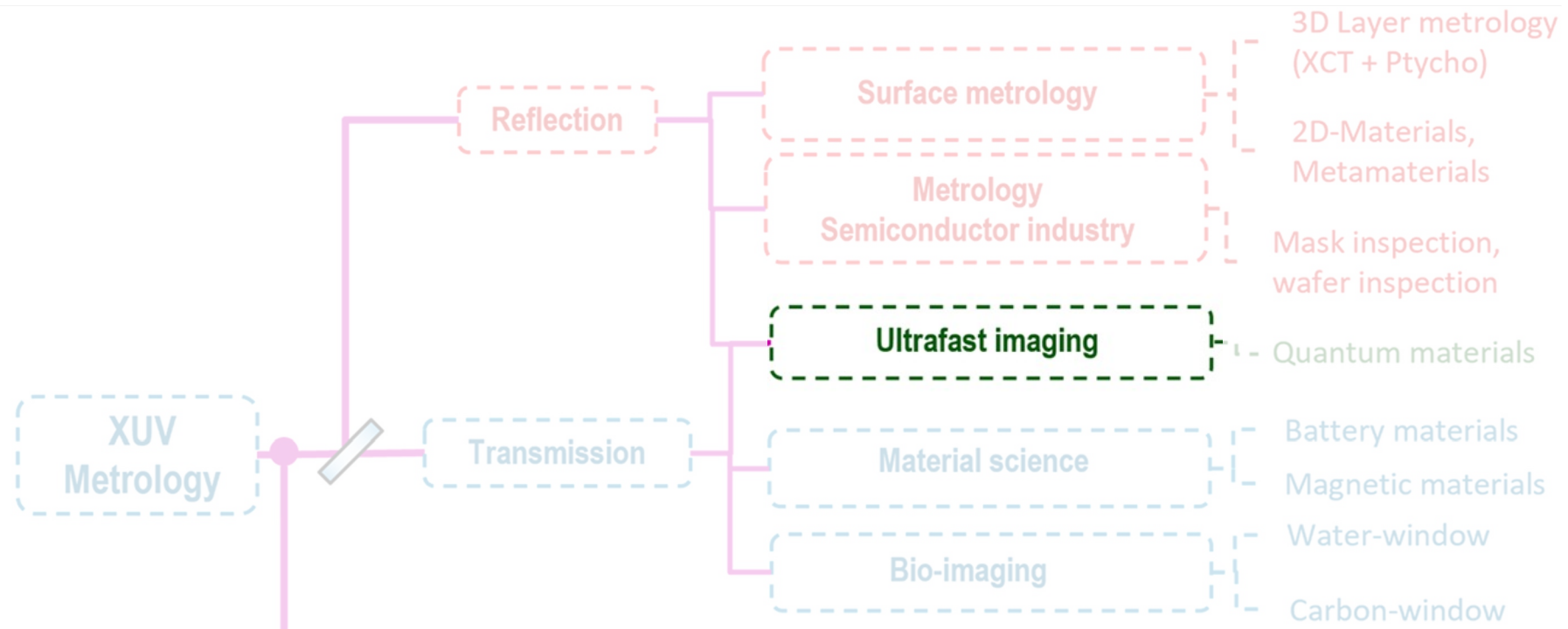
Electron ptychography now reaches the ultimate resolution limit imposed by thermal vibrations enabling imaging of materials at the **atomic scale**.

Trends and future opportunities



Eschen *et al.*, APL Photon. **10**, 050901 (2025)

Trends and future opportunities



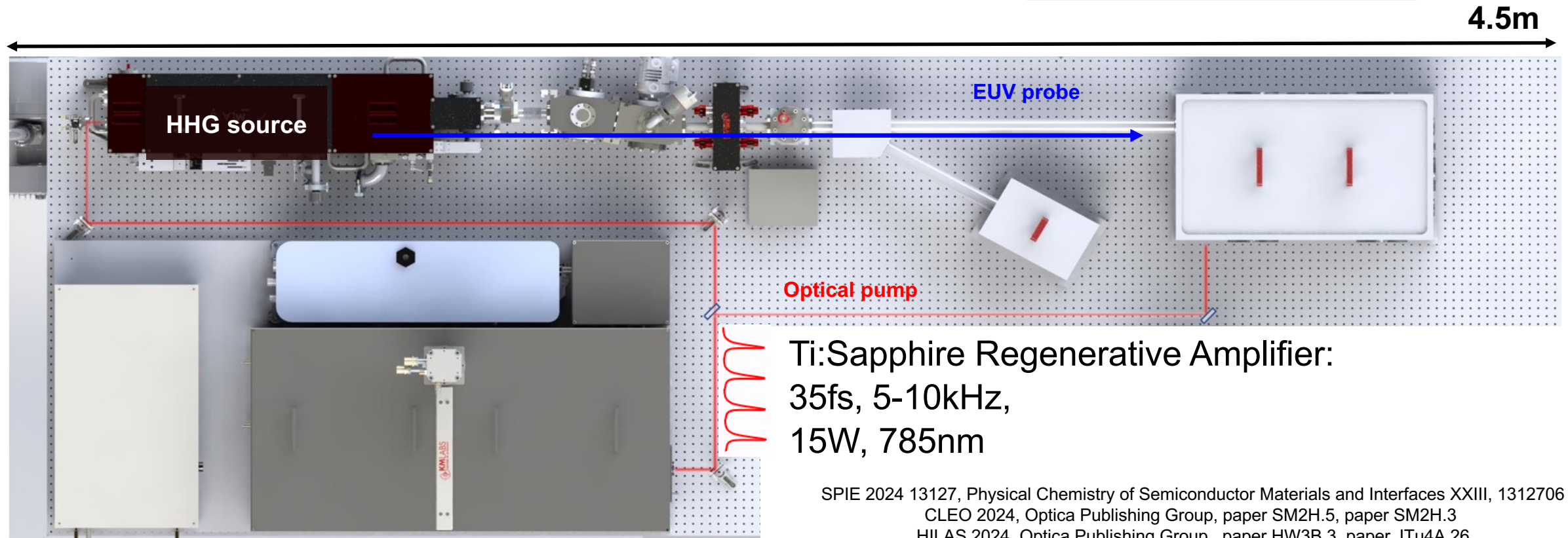
What are the key rules of engagement for EUV beam delivery in case you want to build a tabletop beamline for ultrafast ptychography applications?

Ultrafast EUV Microscope



- Nyquist sampling condition

$$\sigma = \frac{\lambda z}{pD} > 2$$



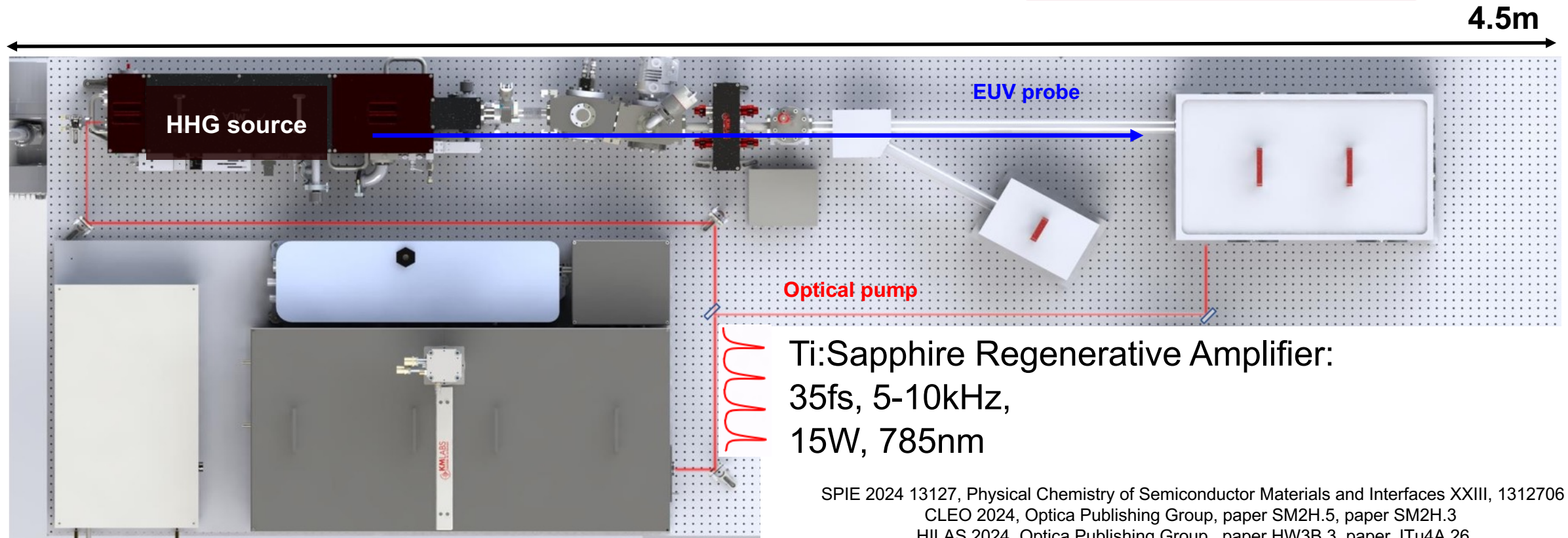
SPIE 2024 13127, Physical Chemistry of Semiconductor Materials and Interfaces XXIII, 1312706
CLEO 2024, Optica Publishing Group, paper SM2H.5, paper SM2H.3
HILAS 2024, Optica Publishing Group, paper HW3B.3, paper JTu4A.26

Ultrafast EUV Microscope



- Nyquist sampling condition
- Compactness and Robustness to misalignments

$$\sigma = \frac{\lambda z}{pD} > 2$$



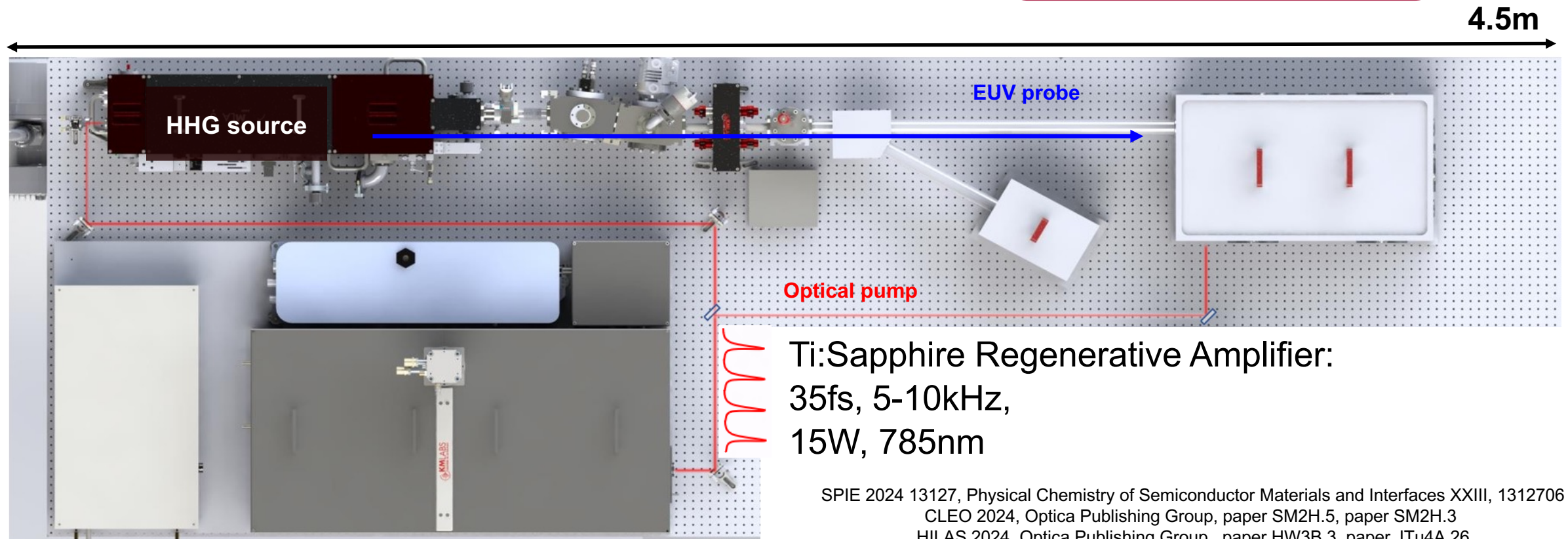
SPIE 2024 13127, Physical Chemistry of Semiconductor Materials and Interfaces XXIII, 1312706
CLEO 2024, Optica Publishing Group, paper SM2H.5, paper SM2H.3
HILAS 2024, Optica Publishing Group, paper HW3B.3, paper JTU4A.26

Ultrafast EUV Microscope



- Nyquist sampling condition
- Compactness and Robustness to misalignments
- Fast and accurate image reconstruction

$$\sigma = \frac{\lambda z}{pD} > 2$$

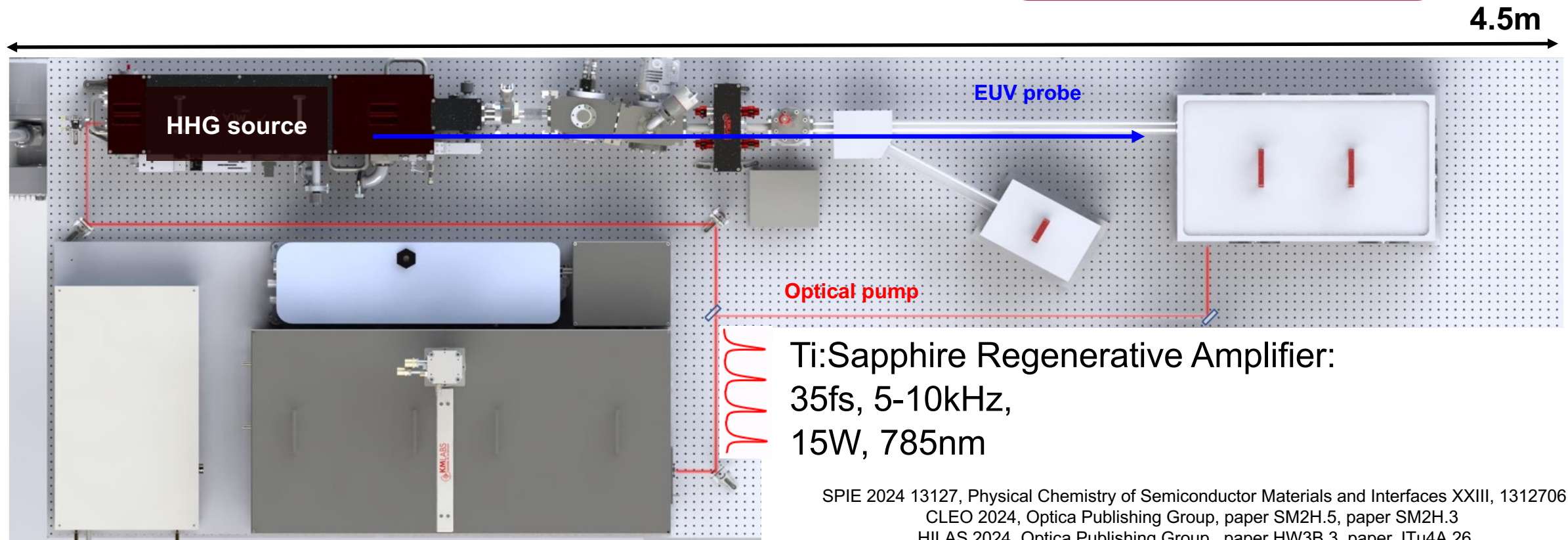


SPIE 2024 13127, Physical Chemistry of Semiconductor Materials and Interfaces XXIII, 1312706
CLEO 2024, Optica Publishing Group, paper SM2H.5, paper SM2H.3
HILAS 2024, Optica Publishing Group, paper HW3B.3, paper JTU4A.26

Ultrafast EUV Microscope

- Nyquist sampling condition
- Compactness and Robustness to misalignments
- Fast and accurate image reconstruction
- High throughput in presence of high computational demand

$$\sigma = \frac{\lambda z}{pD} > 2$$



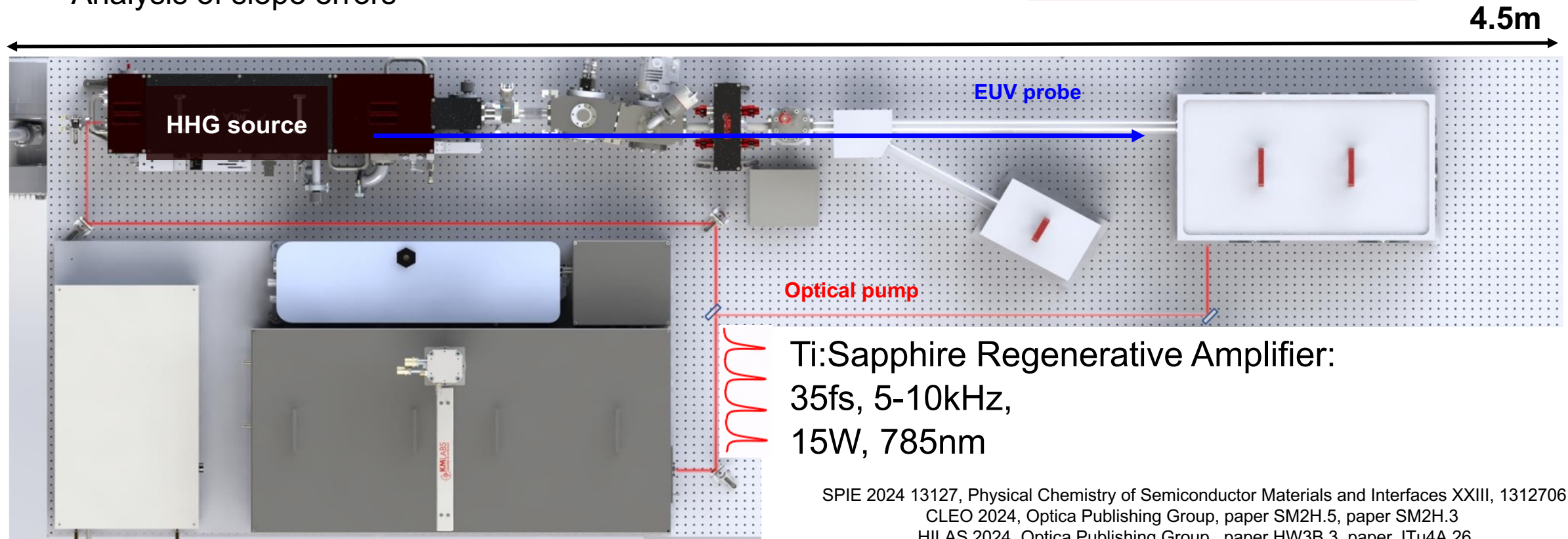
SPIE 2024 13127, Physical Chemistry of Semiconductor Materials and Interfaces XXIII, 1312706
CLEO 2024, Optica Publishing Group, paper SM2H.5, paper SM2H.3
HILAS 2024, Optica Publishing Group, paper HW3B.3, paper JTU4A.26

Ultrafast EUV Microscope



- Nyquist sampling condition
- Compactness and Robustness to misalignments
- Fast and accurate image reconstruction
- High throughput in presence of high computational demand
- Analysis of slope errors

$$\sigma = \frac{\lambda z}{pD} > 2$$



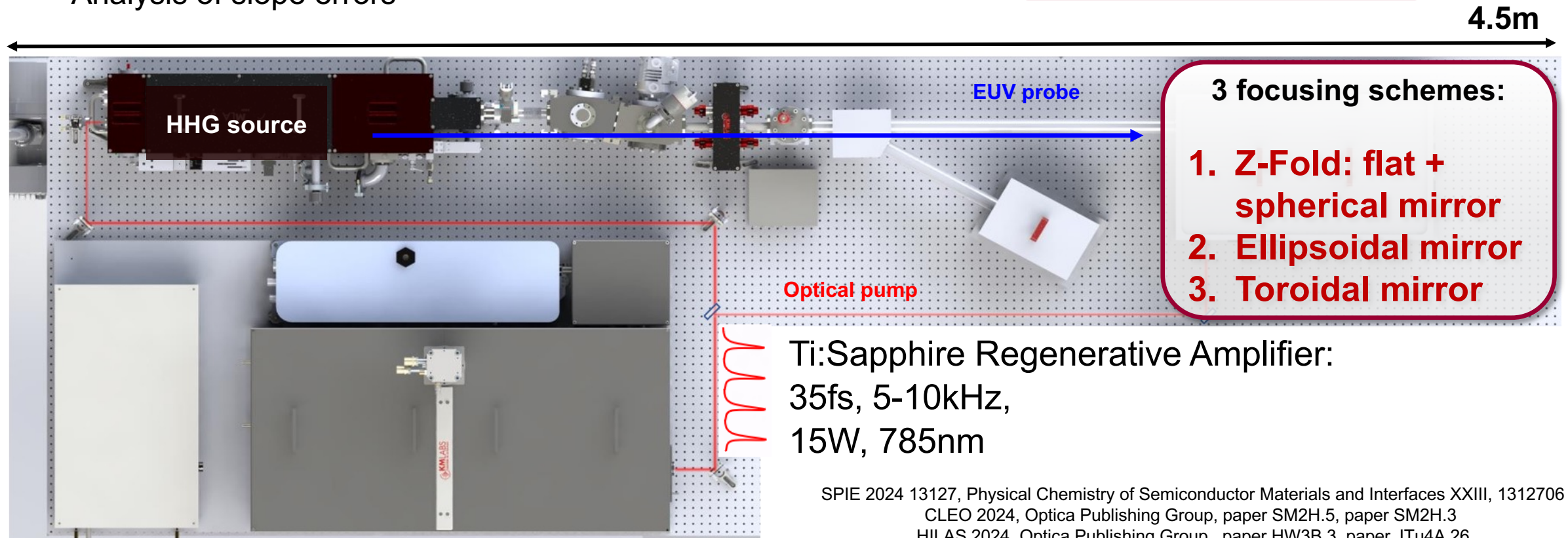
SPIE 2024 13127, Physical Chemistry of Semiconductor Materials and Interfaces XXIII, 1312706
CLEO 2024, Optica Publishing Group, paper SM2H.5, paper SM2H.3
HILAS 2024, Optica Publishing Group, paper HW3B.3, paper JTU4A.26

Ultrafast EUV Microscope



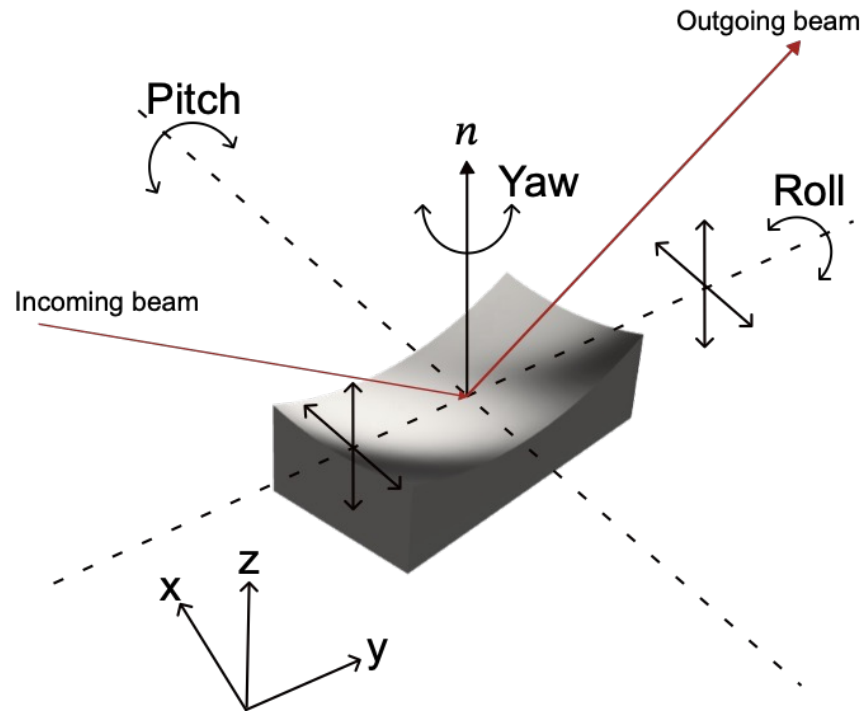
- Nyquist sampling condition
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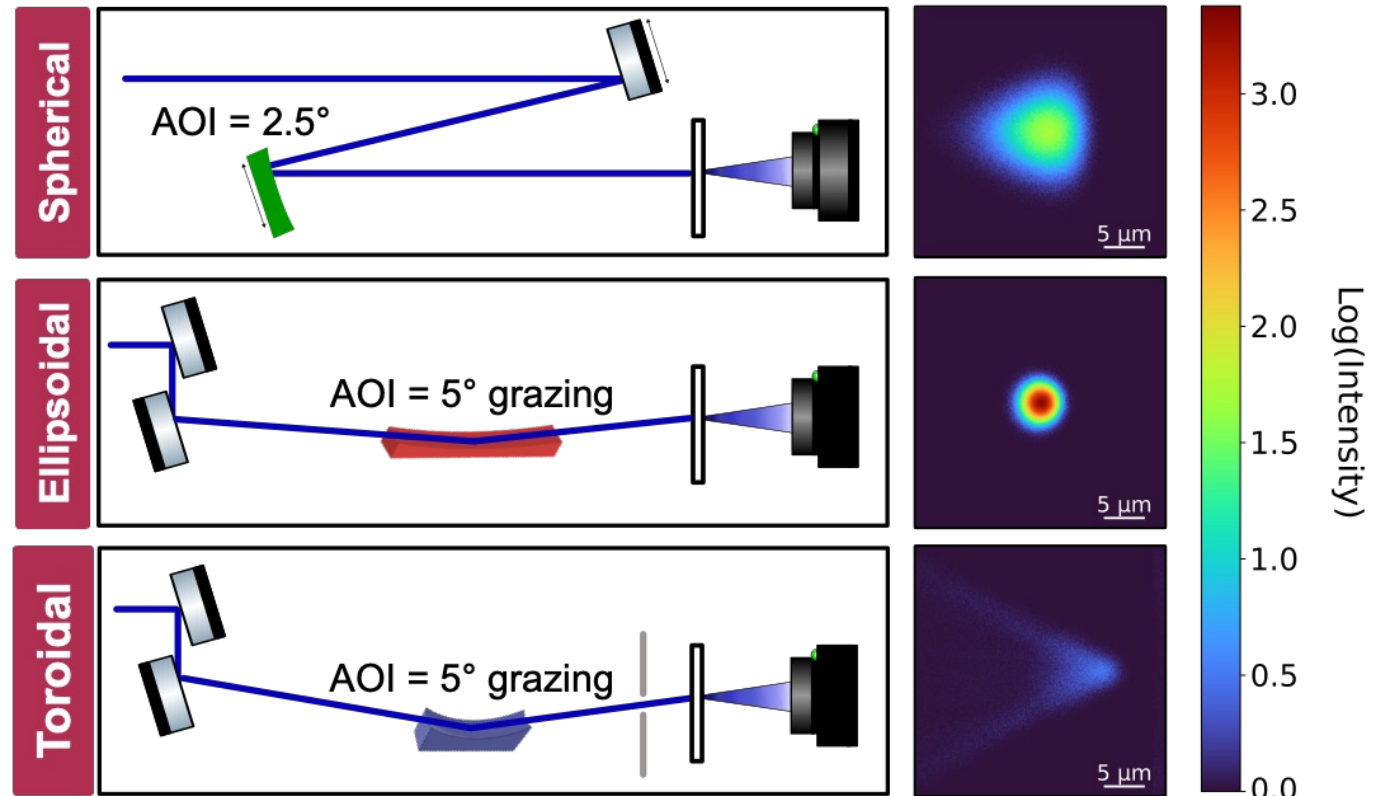


SPIE 2024 13127, Physical Chemistry of Semiconductor Materials and Interfaces XXIII, 1312706
CLEO 2024, Optica Publishing Group, paper SM2H.5, paper SM2H.3
HILAS 2024, Optica Publishing Group, paper HW3B.3, paper JTU4A.26

Ray Tracing Simulations

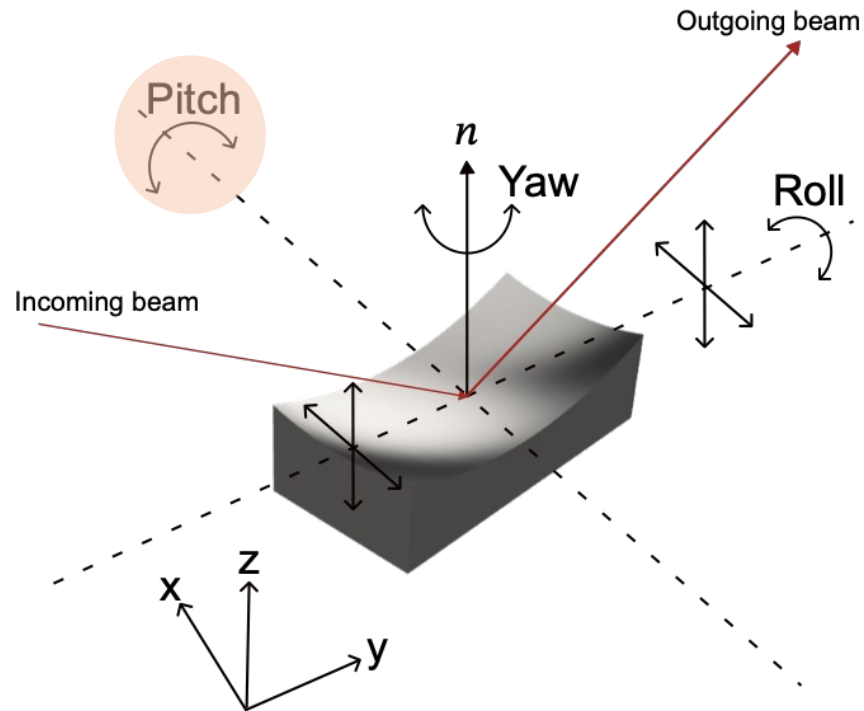


A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in submission*

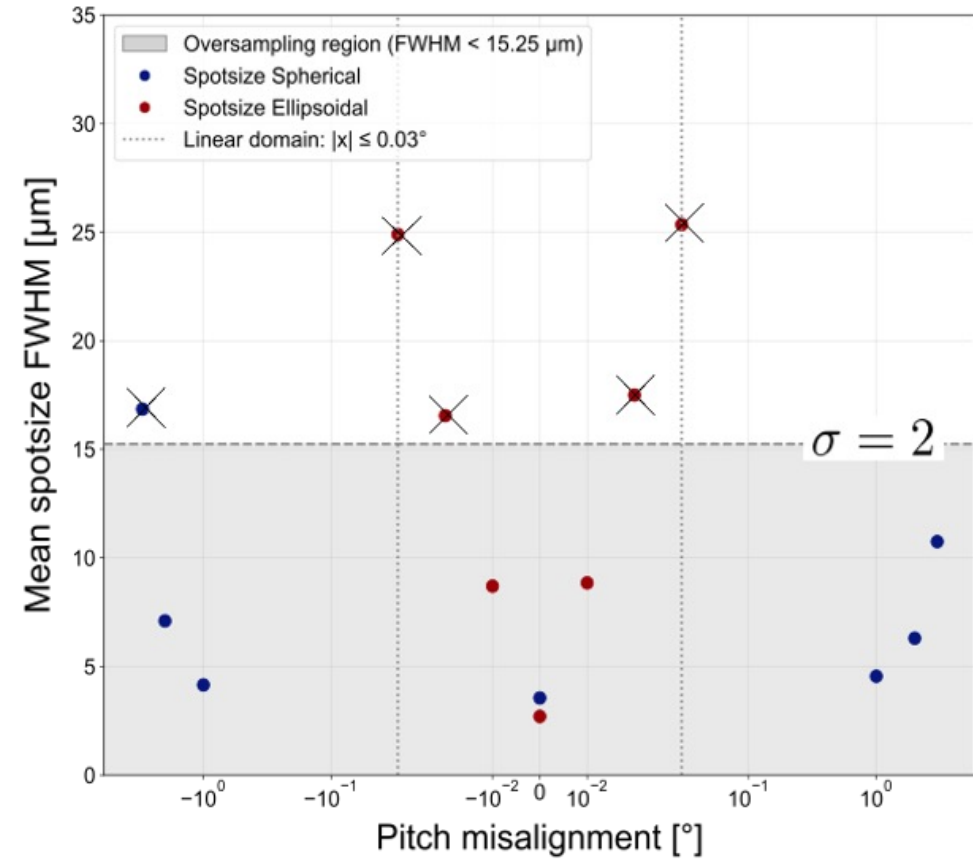


By harnessing ray tracing simulations, we aim to understand how **misalignments**, **slope errors**, and then **both**, translate into changes in **oversampling** and **misalignment robustness**.

Ray Tracing Simulations

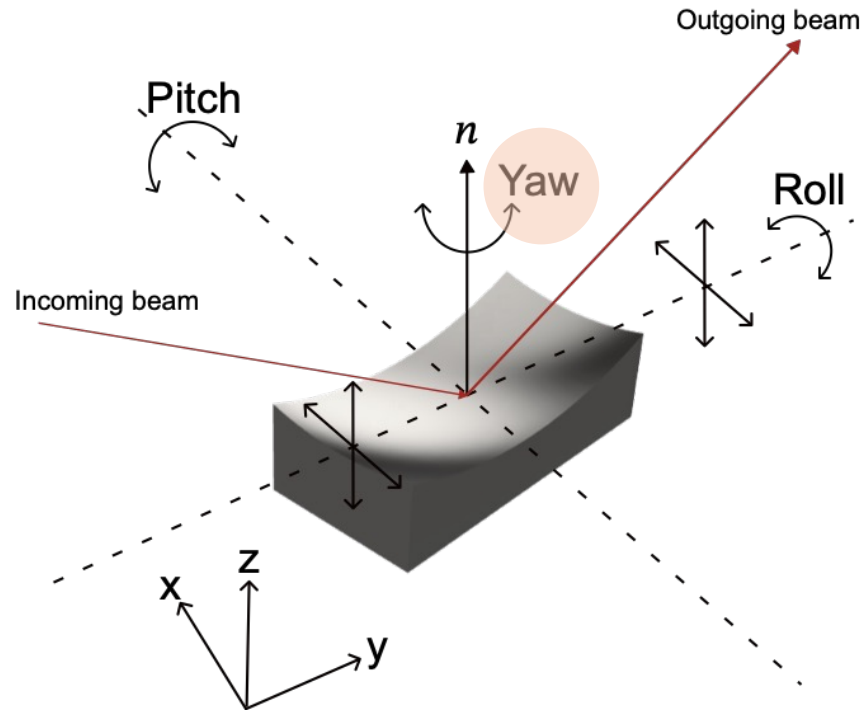


A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in submission*



Z-fold is the most robust to misalignments, preserving beam diameter with up to 100× greater pitch tolerance.

Ray Tracing Simulations

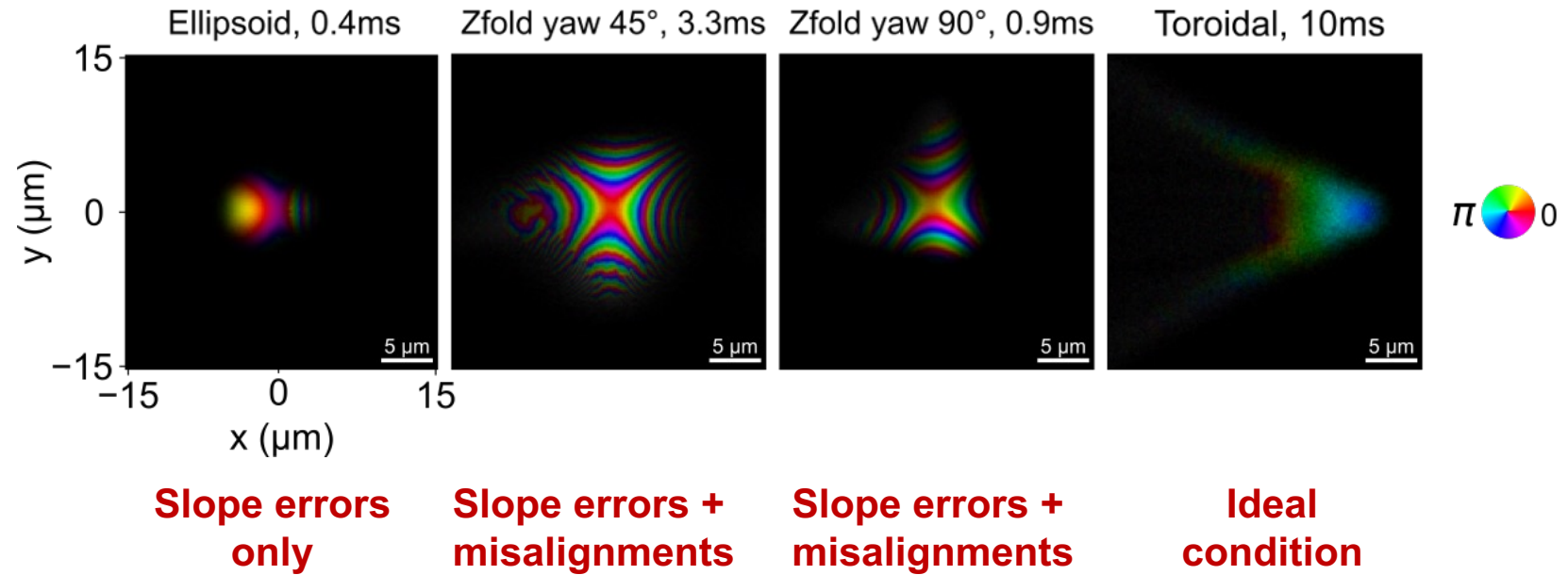


A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in submission*

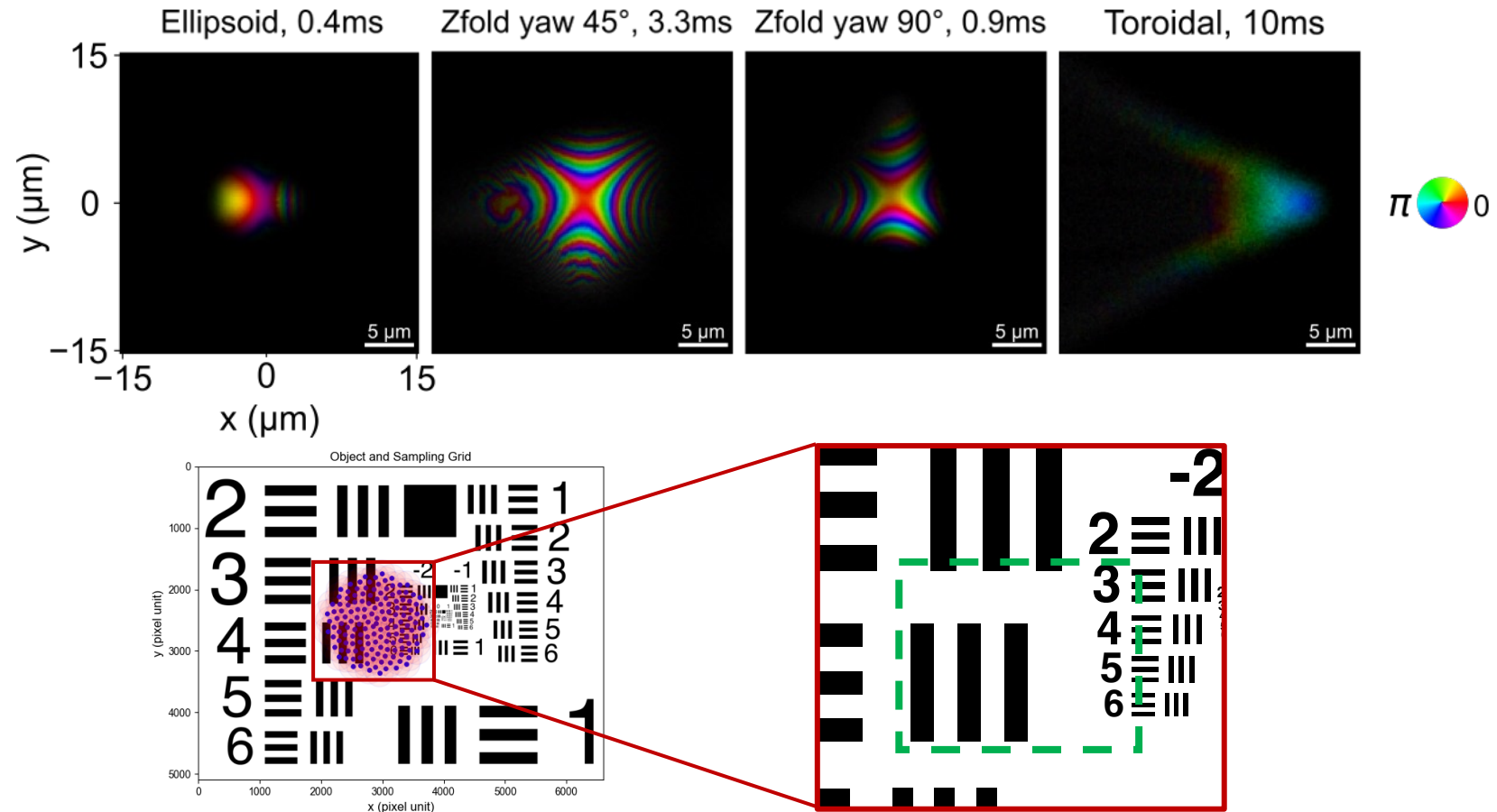
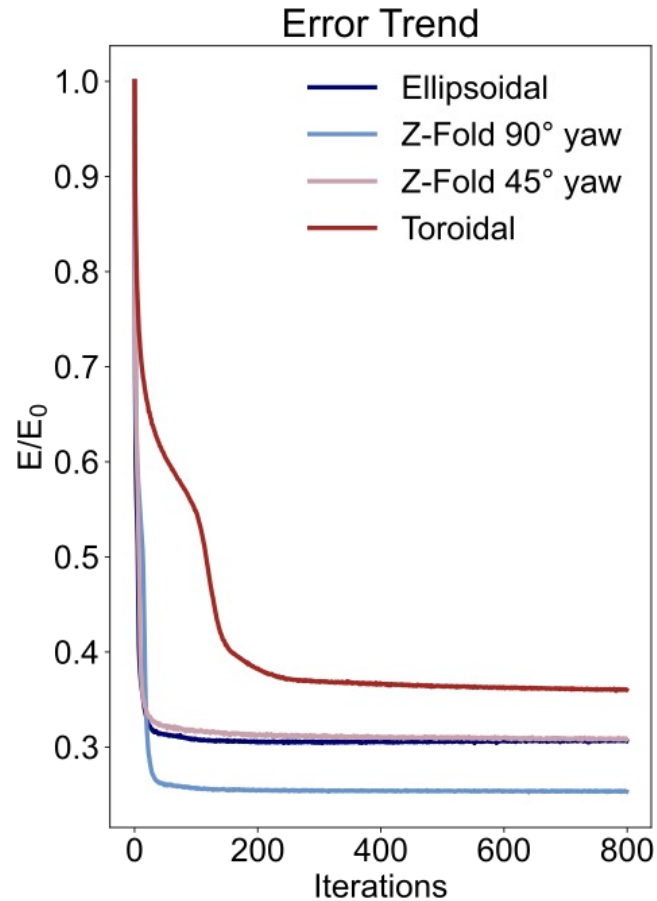


- For each configuration, slope errors change the beam shape by introducing aberrations, without drastically altering its size.
 - **Z-fold's spherical mirror can exploit slope error and yaw to improve beam size and oversampling.**

Results from ePIE Reconstructions

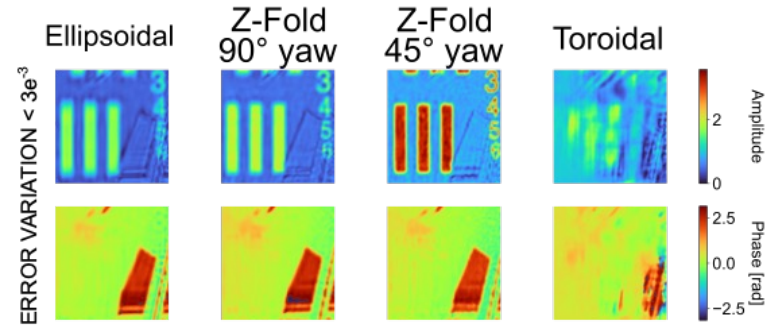
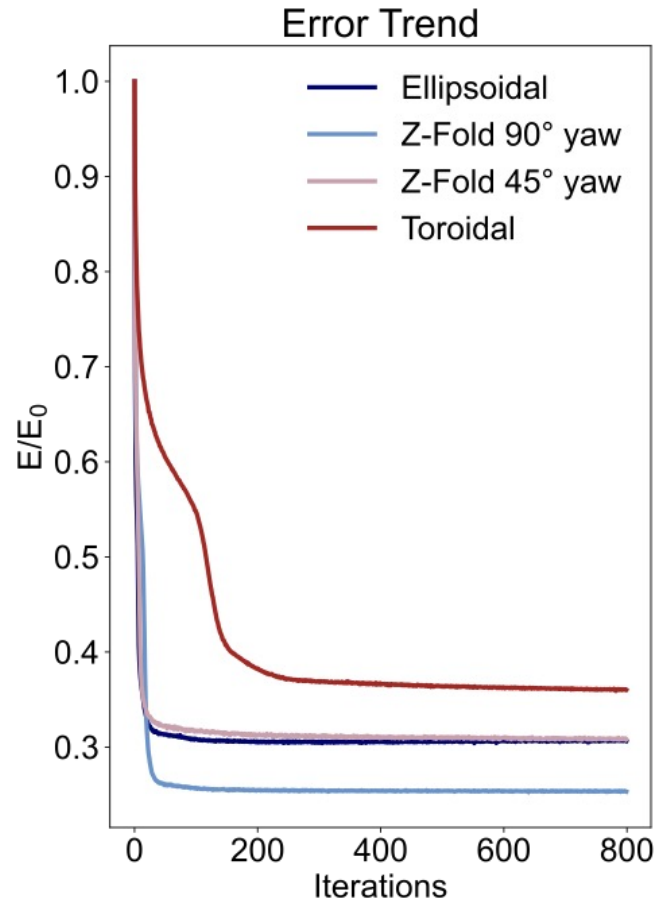


Results from ePIE Reconstructions

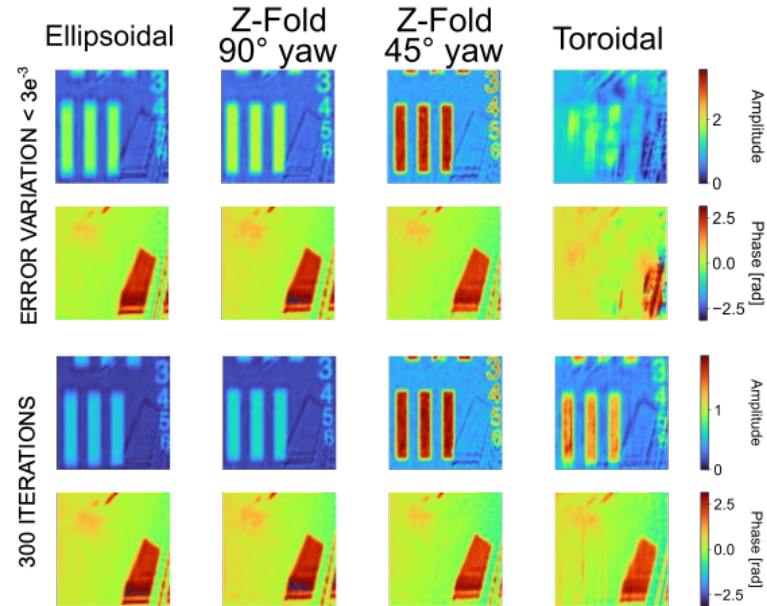
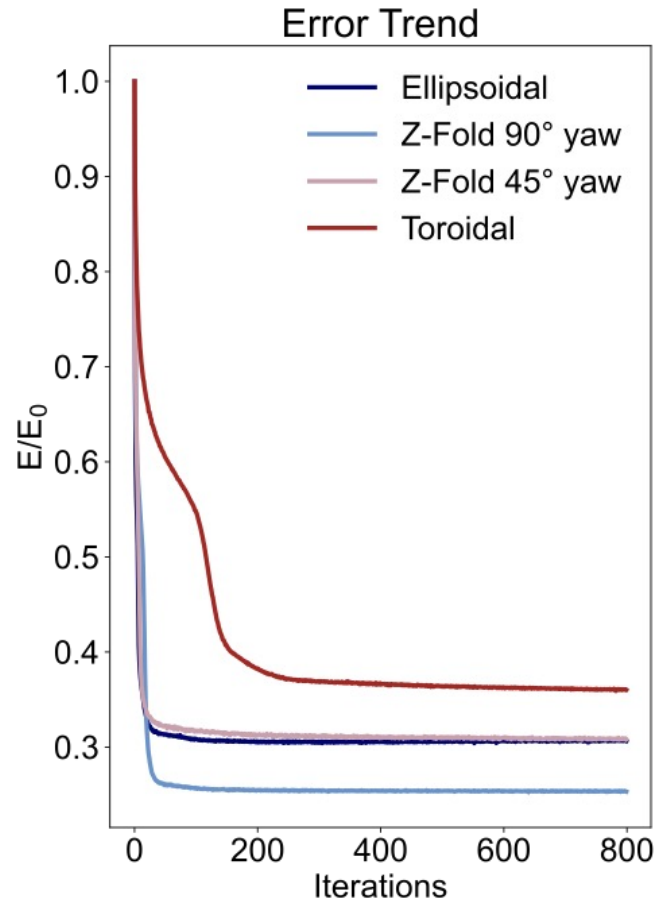


Ellipsoidal and Z-fold configurations converge faster than the toroidal. While the ellipsoid takes longer overall due to higher data volume, the **Z-fold can achieve lower residual errors in less time.**

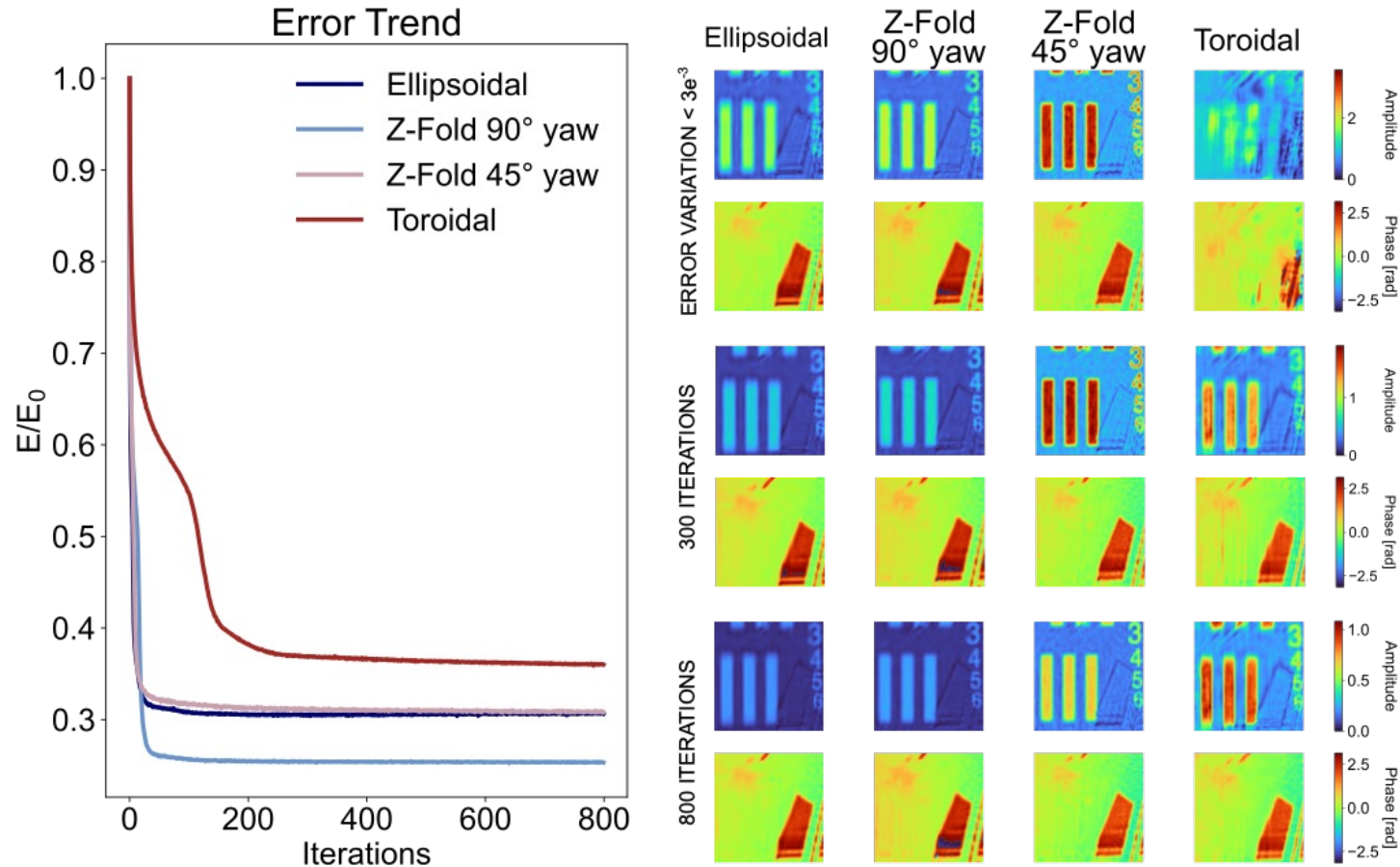
Results from ePIE Reconstructions



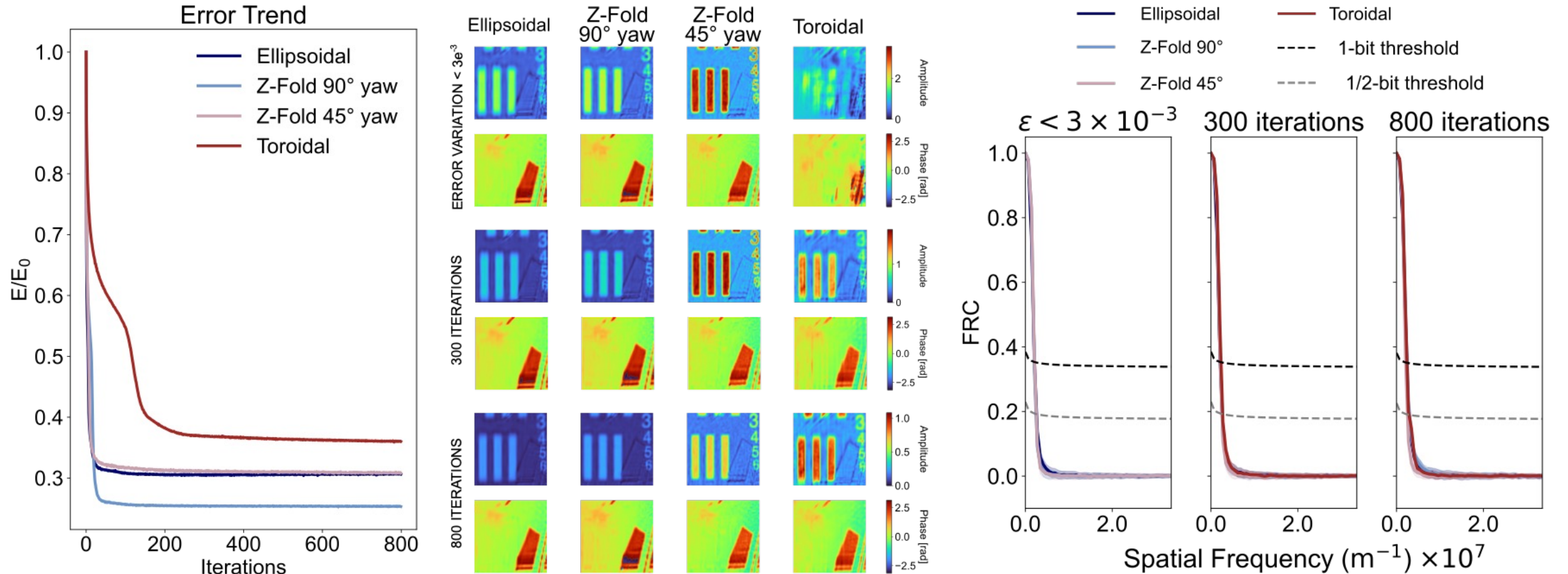
Results from ePIE Reconstructions



Results from ePIE Reconstructions



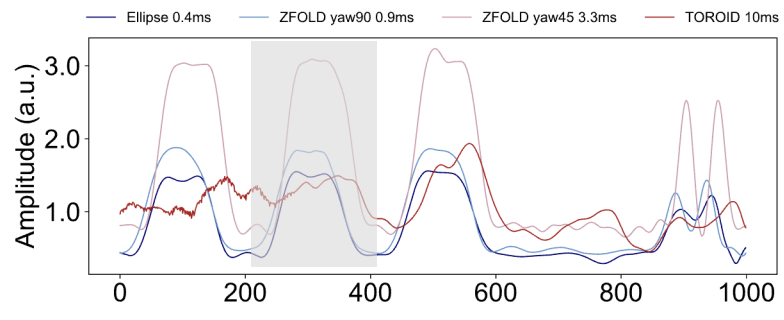
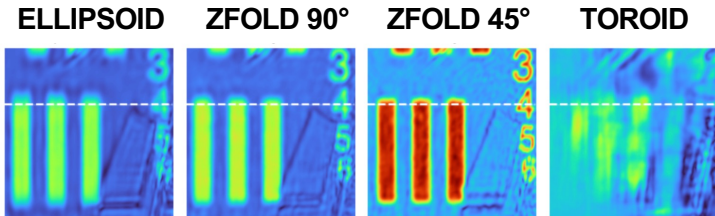
Results from ePIE Reconstructions



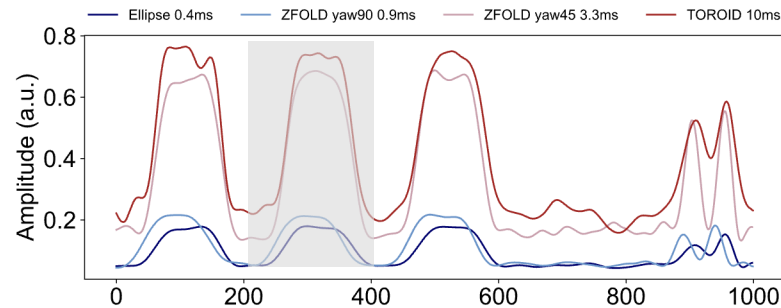
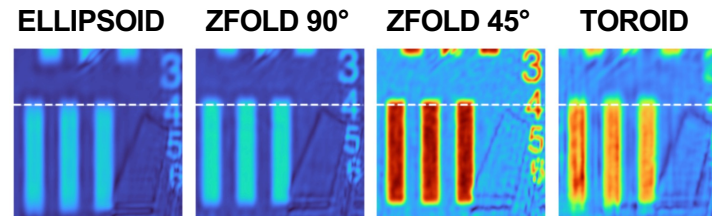
The resolution is ultimately limited by the signal-to-noise ratio (SNR): **under the same noise conditions, the three configurations provide comparable final resolution.**

A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in submission*

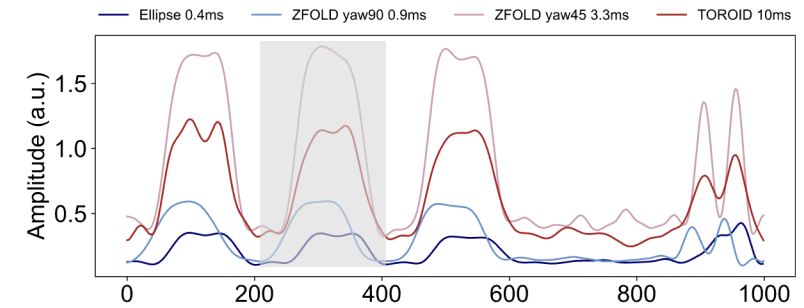
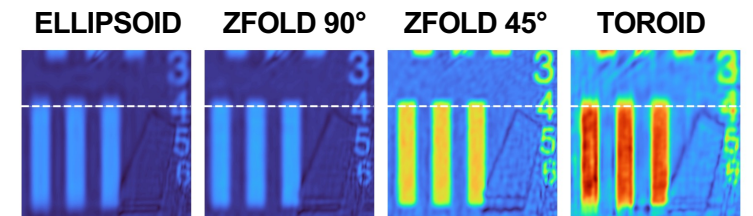
Results from ePIE Reconstructions



$$\epsilon < 3e^{-3}$$



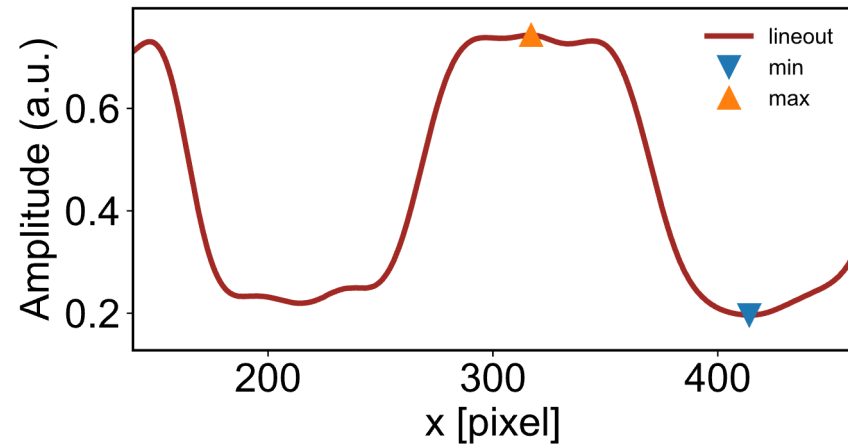
300 iterations



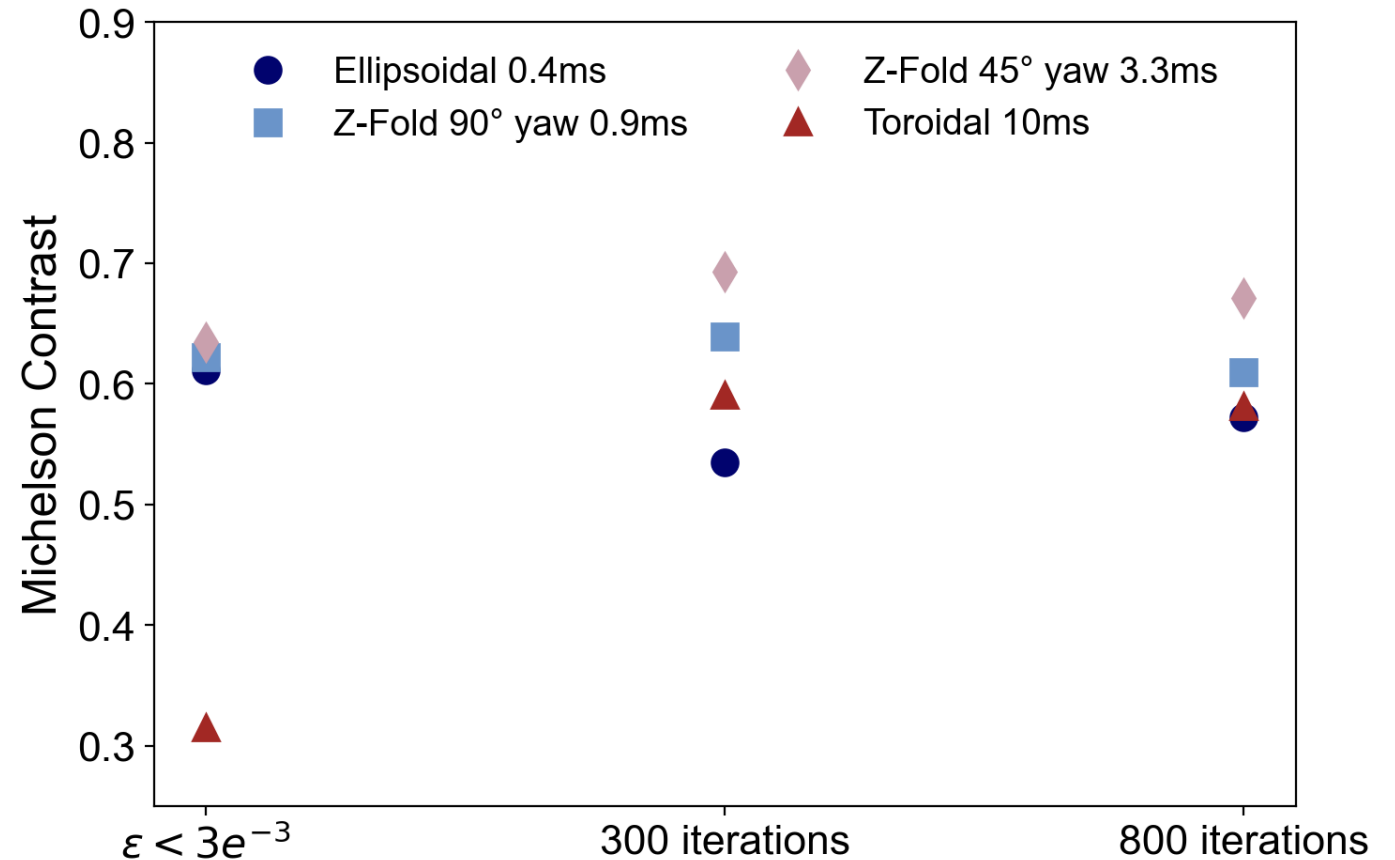
800 iterations

A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in submission*

Results from ePIE Reconstructions



$$C = \frac{A_{\max} - A_{\min}}{A_{\max} + A_{\min}}$$



A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in submission*

Results from ePIE Reconstructions

Z-fold configuration provides the best trade-off of speed, robustness to misalignments, and reconstruction quality for ultrafast ptychographic EUV imaging applications.

These results support the choice of the z-fold as a suitable option for building new ultrafast EUV imaging platforms.

A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in submission*

- Prof. Giulia Fulvia Mancini
- Carmelo Grova
- Nicola Giani
- Claudia A. M. Schrama
- Federico Bertelli
- Charles. S. Bevis
- Dr. Oliviero Cannelli (ATTO-CFEL)
- Prof. Giovanni Pellegrini (UniPv)
- Dr. Dmitry Karpov (ESRF)

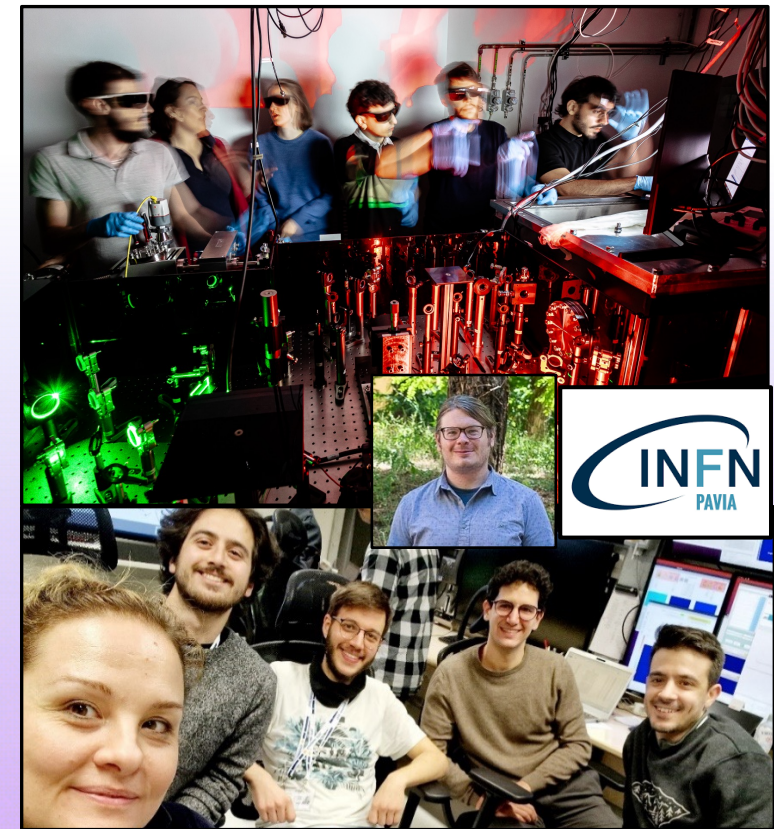


- Prof. Daniel Adams
- Jonathan Barolak
- David Goldberger



Elettra Sincrotrone Trieste

- Dr. Flavio Capotondi



- Dr. Lorenzo Raimondi

THALES • Dr. Luca Peverini

- Dr. Luca Rebuffi



- Dr. Christian-Y. Côté



ULTRAIMAGE

StG 851154

HYPER

PoC 101123123



Fondazione CARIPLO

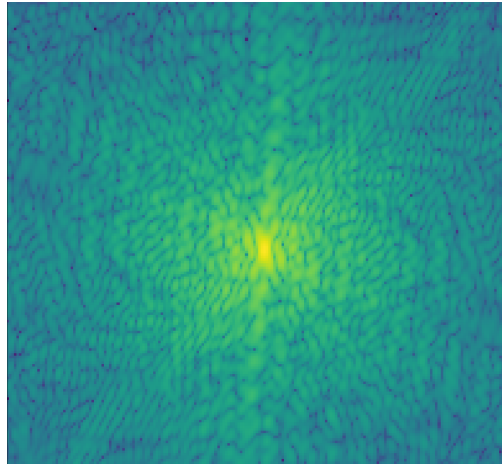


Backup

Coherent Diffractive Imaging (CDI)

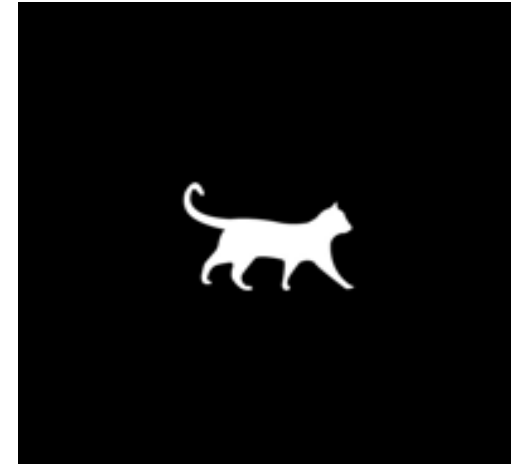
...a lensless imaging technique that aims to reconstruct the image of a sample from its diffraction data

What we measure:



$$\sqrt{I(\mathbf{q})} = |\psi(\mathbf{q})|$$

What we want to reconstruct:

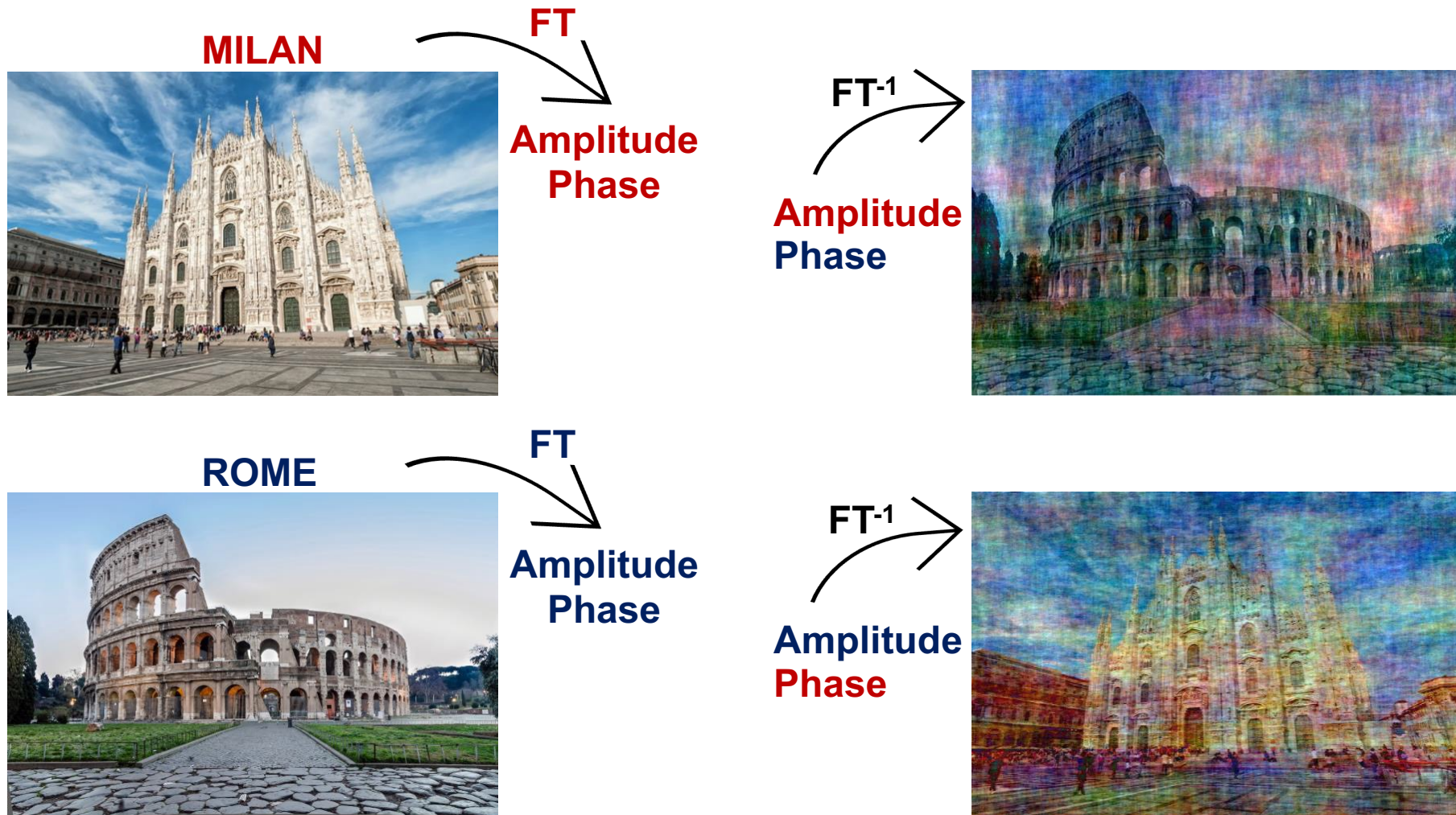


$$O(\mathbf{r})$$

???

$$\psi(\mathbf{q}) = \sqrt{I(\mathbf{q})} e^{-i\phi(\mathbf{q})} \longleftarrow \text{Lost}$$

Imaging with EUV/ X-Ray light

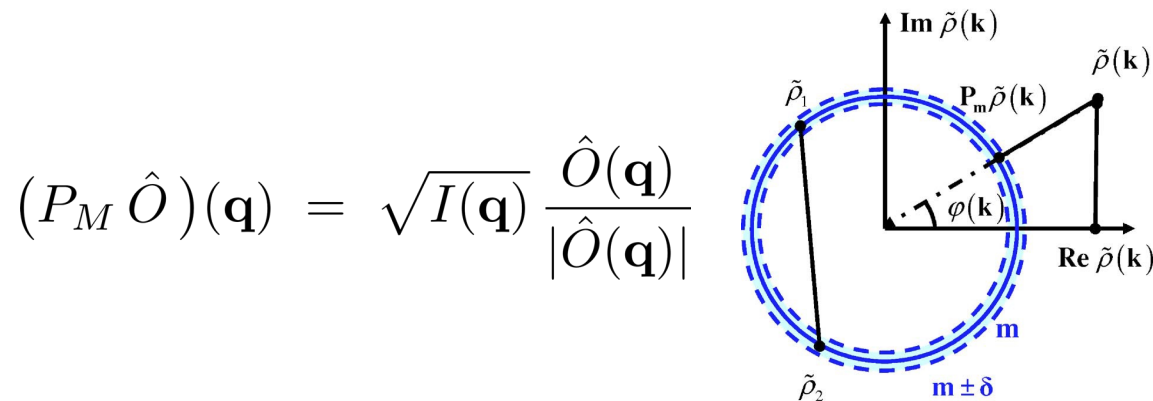


Coherent Diffractive Imaging (CDI)

In order to fulfill Magnitude (A) and Support (B) constraint, we need:

A. MAGNITUDE PROJECTION $\widehat{P}_M$

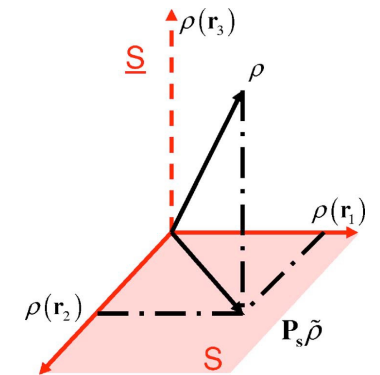
For every complex value $\hat{O}(\mathbf{q})$, we want to find the nearest point in Fourier space corresponding to the measured magnitude $\sqrt{I(\mathbf{q})}$.



B. SUPPORT PROJECTION $\widehat{P}_S$

Given a support region S as the set of real-space points such that our distribution $O(\mathbf{r}) \neq 0$, we want to take only the values that live in S .

$$(P_S O)(\mathbf{r}) = \begin{cases} O(\mathbf{r}), & \mathbf{r} \in S \\ 0, & \mathbf{r} \notin S \end{cases}$$



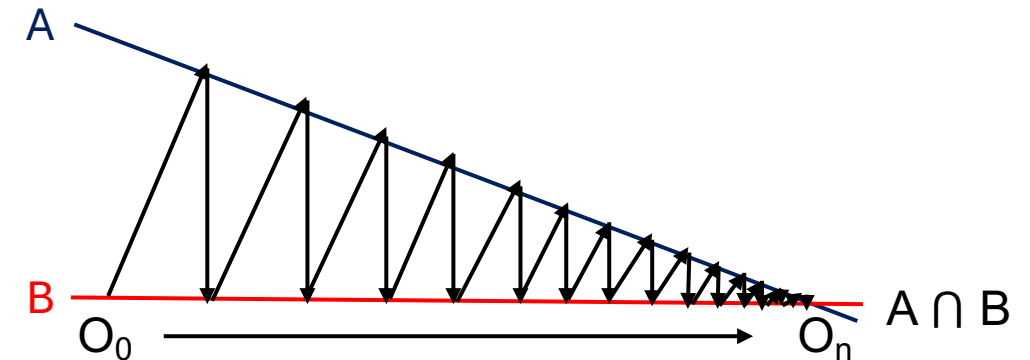
Coherent Diffractive Imaging (CDI)

Elser, J. Opt. Soc. Am. A 20, 40-55 (2003)

«Phase retrieval is the problem of finding an element in a large set that simultaneously has properties A, B, etc., given only the ability to find elements having these properties separately».

Alternating Projection Scheme:

- Starting from a random data distribution $O^{(0)}$
- Compute the $O^{(n+1)} = \text{PROJECTION}(O^{(n)})$
- Iterate until convergence



There are several schemes to apply these projections:

Error Reduction
Hybrid Input-Output
Difference Map

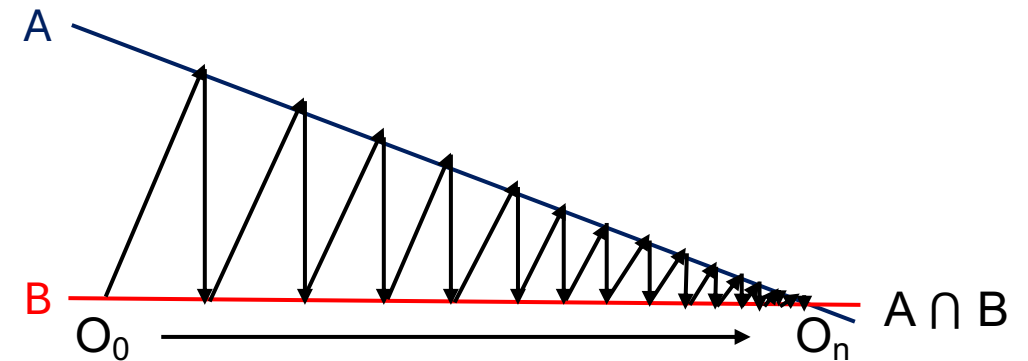
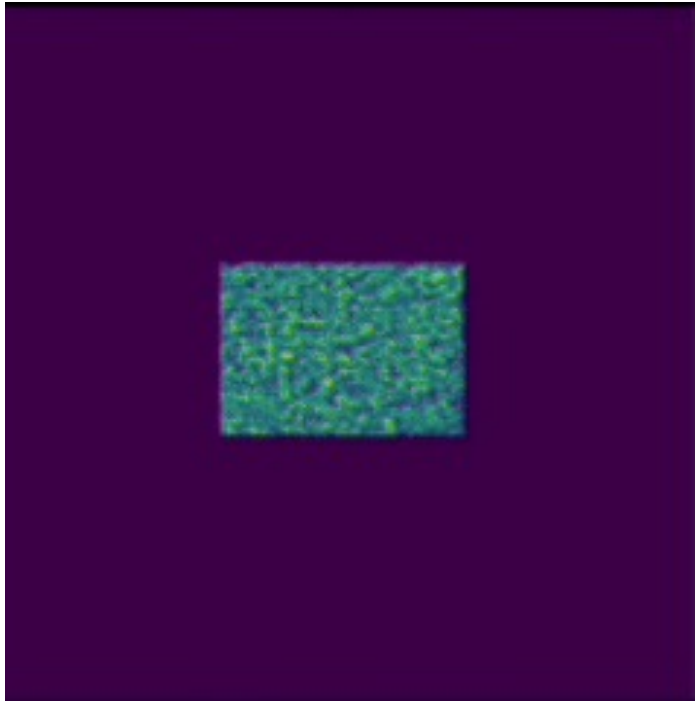
Coherent Diffractive Imaging (CDI)

Takajo *et al.*, J. Opt. Soc. Am. A **15**, 2849–2861 (1998)

Elser *et al.*, J. Opt. Soc. Am. A **20**, 40–55 (2003)

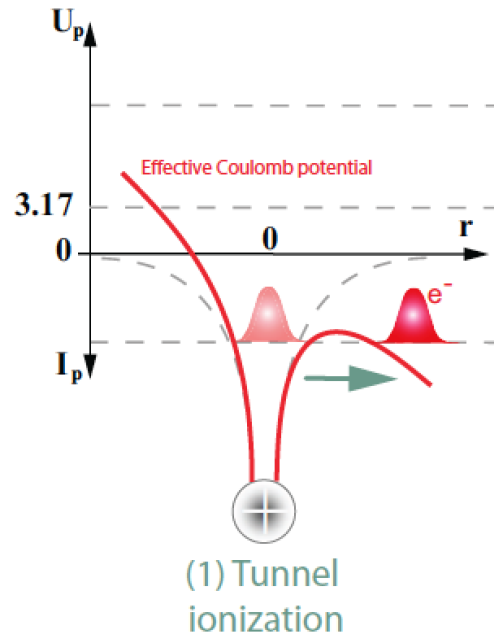
Marchesini *et al.*, Rev. Sci. Instrum. **78**, 011301 (2007)

Real time reconstruction every 10 iterations:



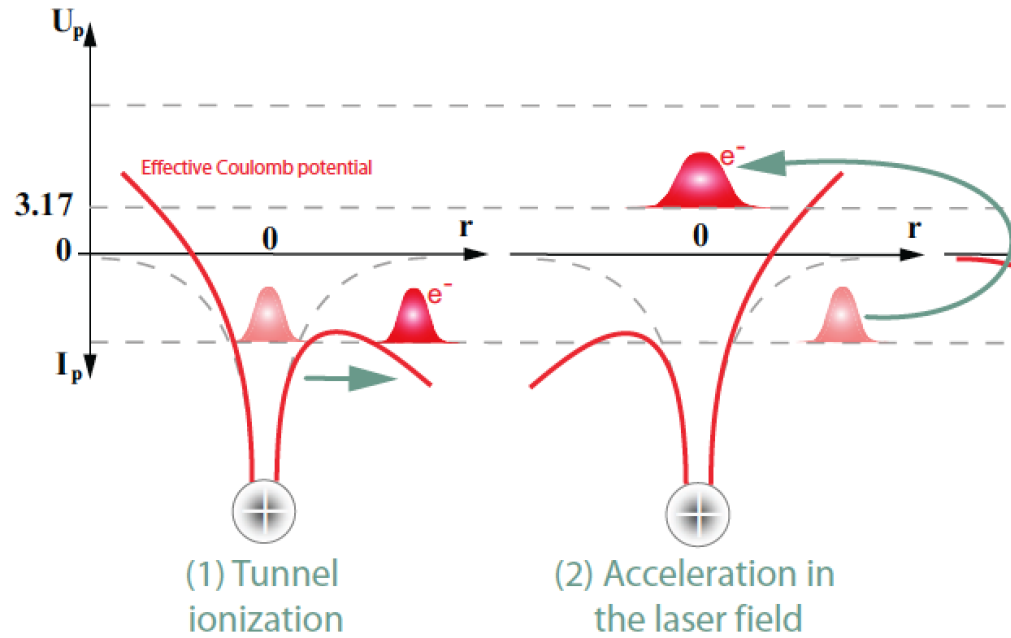
This iterative scheme relies on the prior knowledge of the support, but what if the object is extended and the support is unknown?

High Harmonic Generation (HHG)



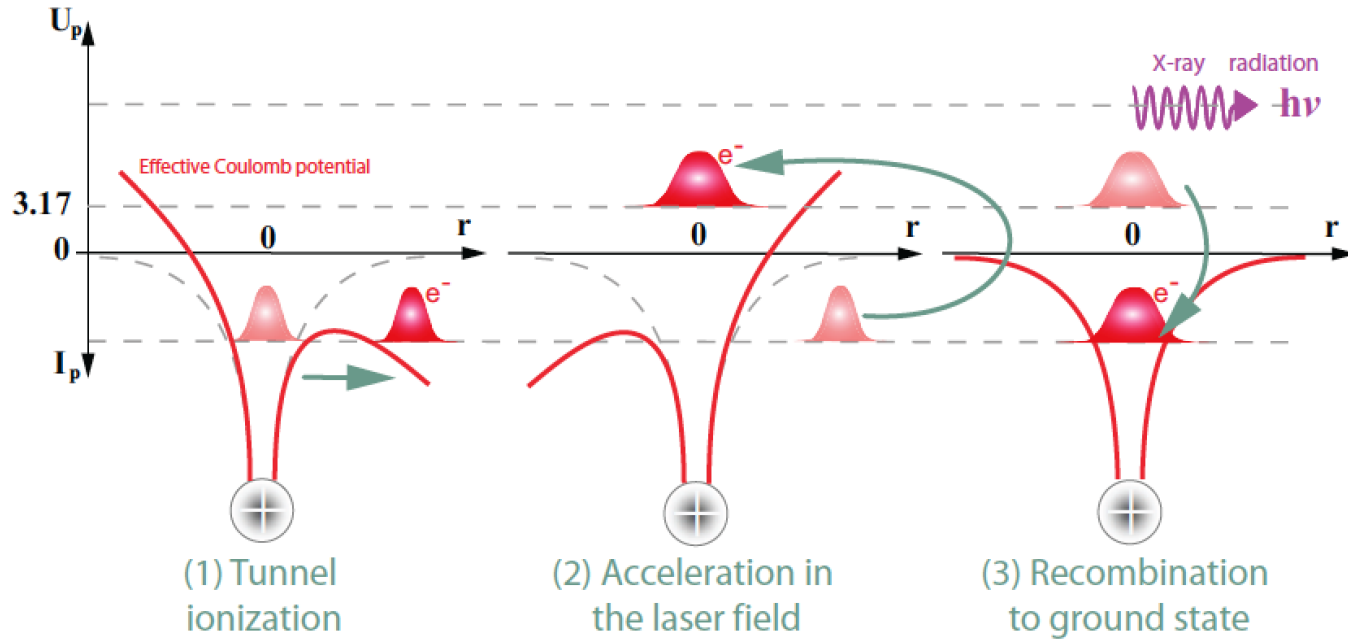
Corkum, Phys. Rev. Lett. **71**, 1994–1997 (1993)

High Harmonic Generation (HHG)

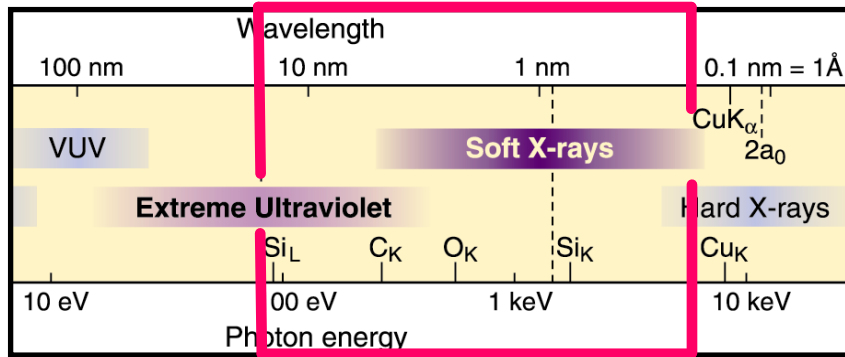


Corkum, Phys. Rev. Lett. **71**, 1994–1997 (1993)

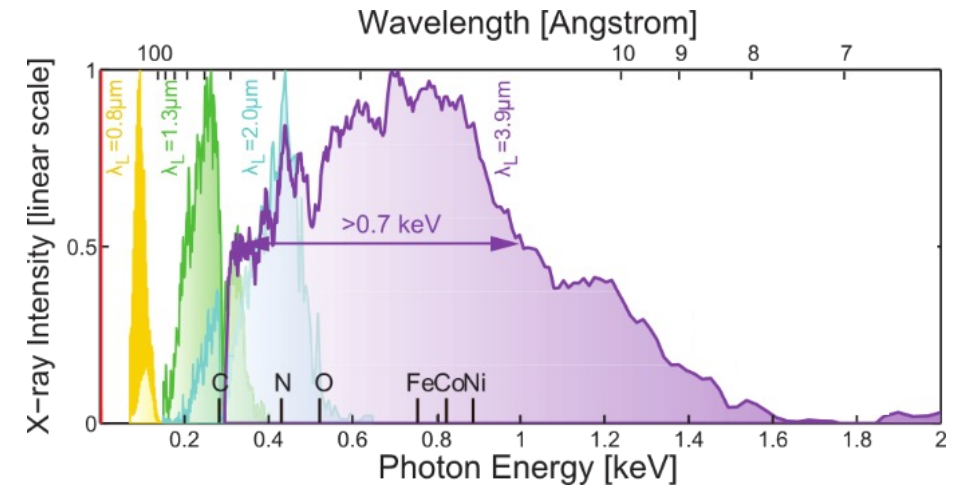
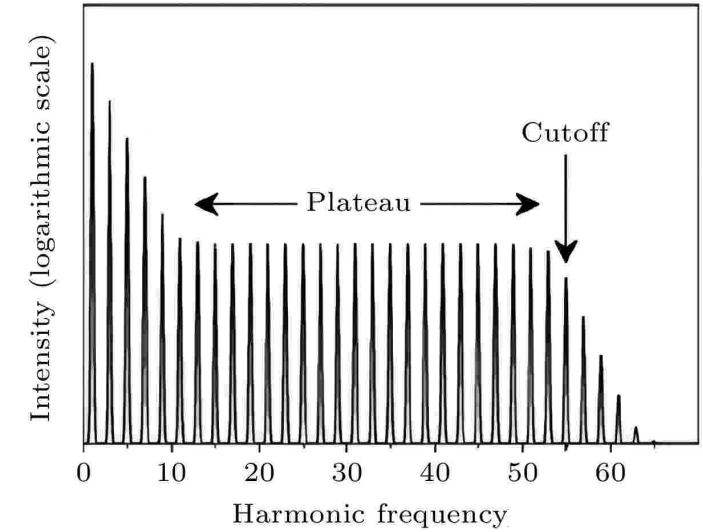
High Harmonic Generation (HHG)



Corkum, Phys. Rev. Lett. **71**, 1994–1997 (1993)

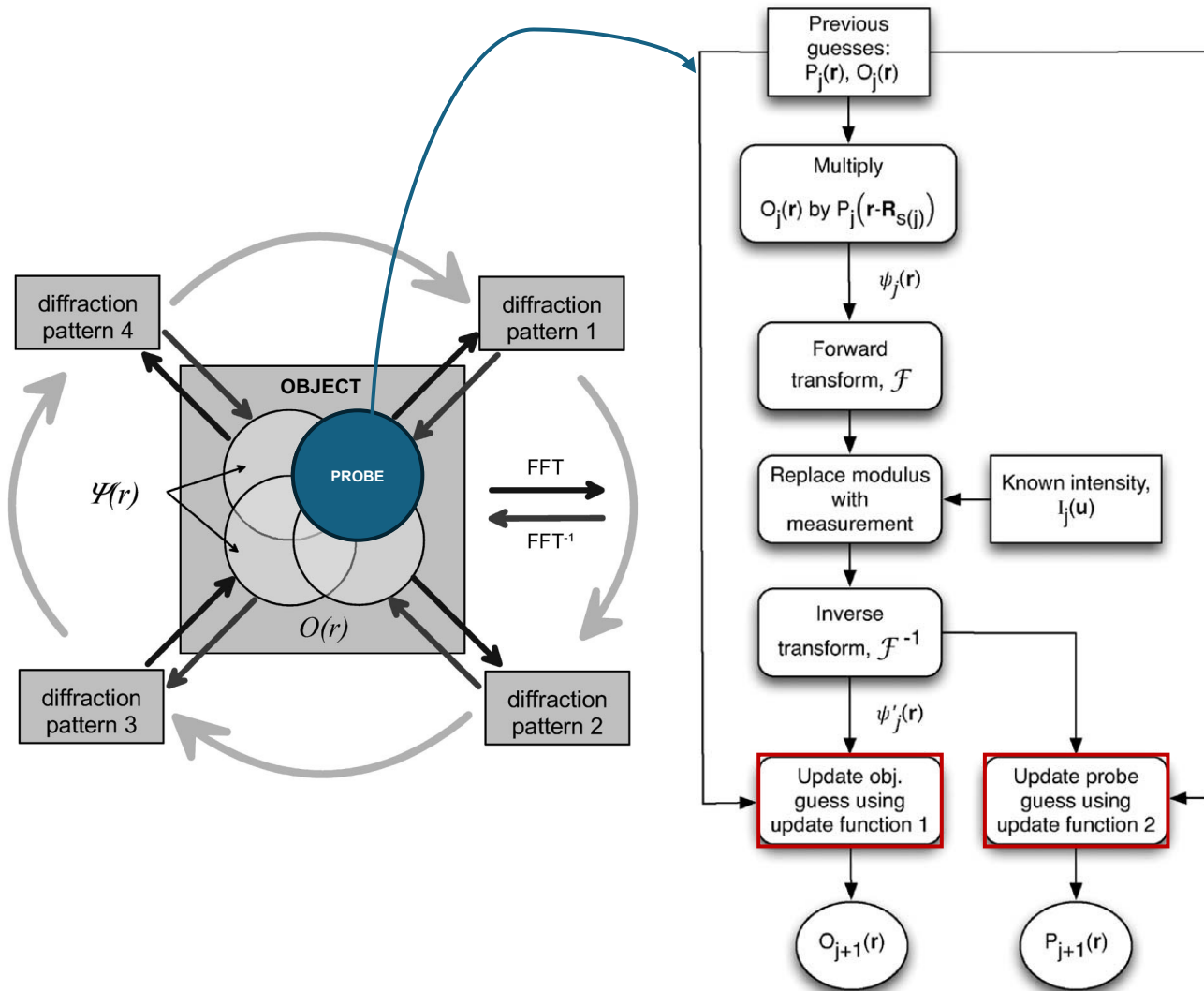


Chen-Yu *et al.*, Acta Phys. Sin. **72**, 1-27 (2023)



Popmintchev *et al.*, Science **336**, 1287–1291 (2012)

Ptychographic CDI



extended Ptychographic Iterative Engine (ePIE):

$$P(r) O(r) = \psi(r), \quad P_0(r) O_0(r) = \psi_0(r)$$

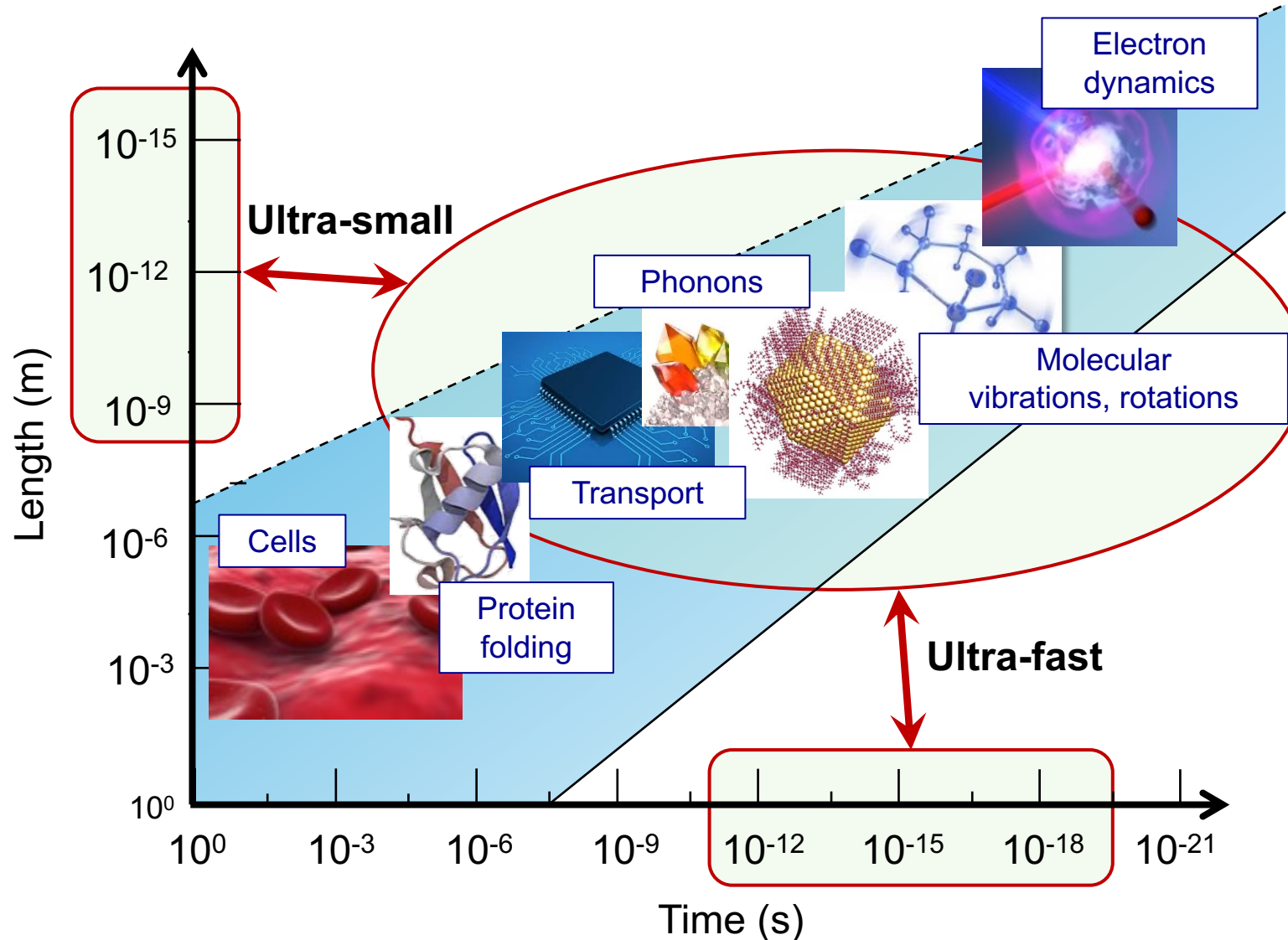
$$\psi_j(r) = P_j(r) O_j(r), \quad \Psi_j(q) = \mathcal{F}\{\psi_j\}(q)$$

$$\Psi'_j(q) = \sqrt{I_j(q)} \frac{\Psi_j(q)}{|\Psi_j(q)|}, \quad \psi'_j(r) = \mathcal{F}^{-1}\{\Psi'_j\}(r)$$

$$O_{j+1}(r) = O_j(r) + \alpha \frac{P_j(r)}{|P_j(r)|} (\psi_j(r) - \psi'_j(r))$$

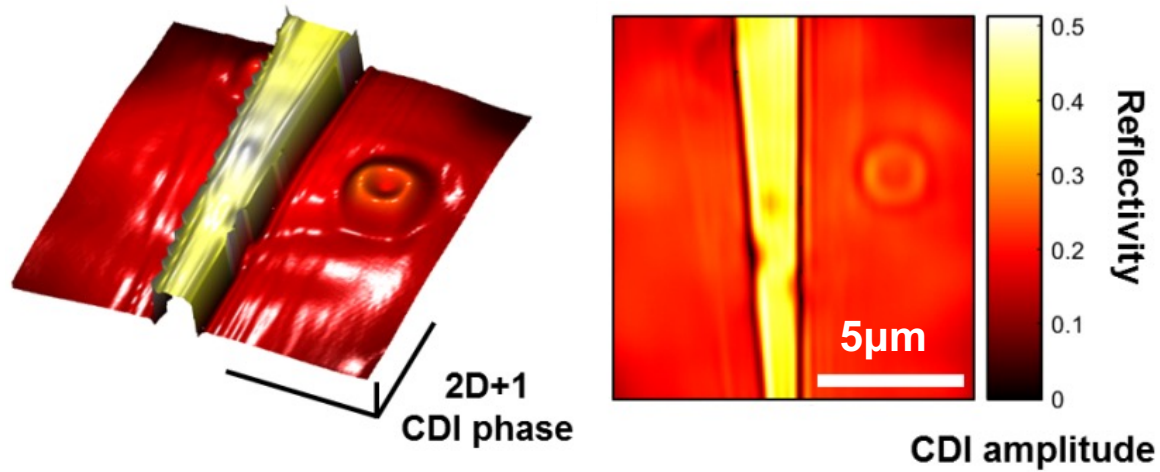
$$P_{j+1}(r) = P_j(r) + \beta \frac{O_j(r)}{|O_j(r)|} (\psi_j(r) - \psi'_j(r))$$

High Harmonic Generation (HHG)

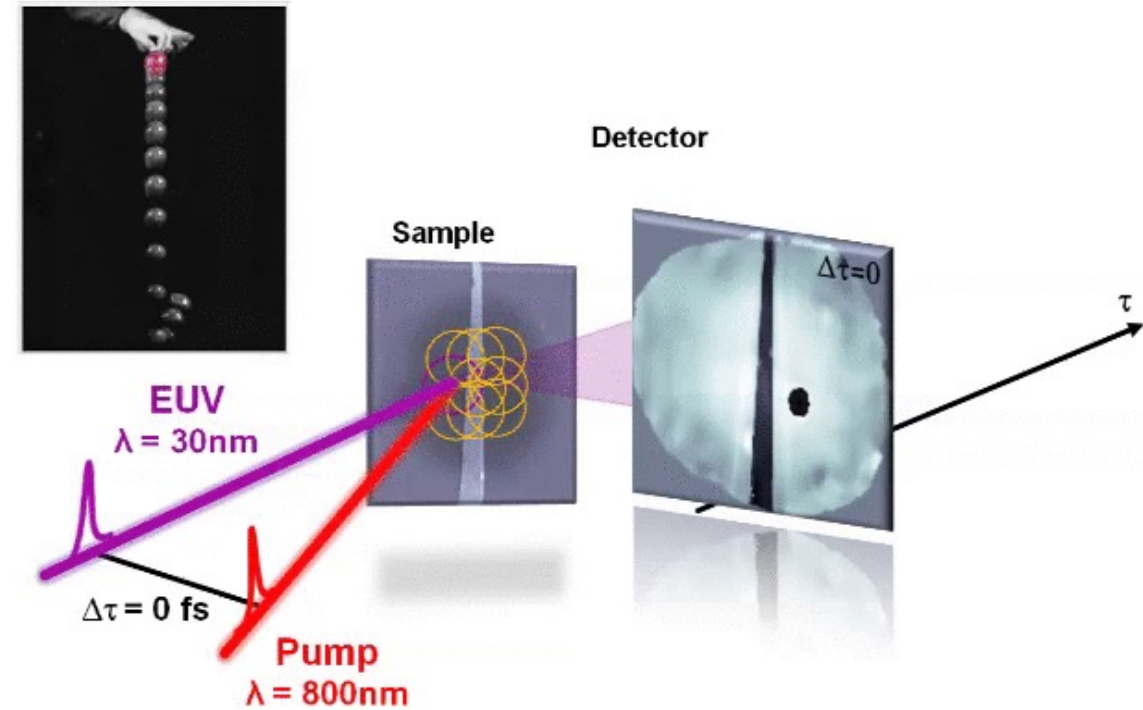


- Availability of pulsed laser-like sources: **Stroboscopic Imaging**
- Short wavelength: **High resolution**
- Absorption edges: **Excellent elemental specificity**
- Penetrate thick objects: **Image through multiple layers**

Ultrafast Ptychography

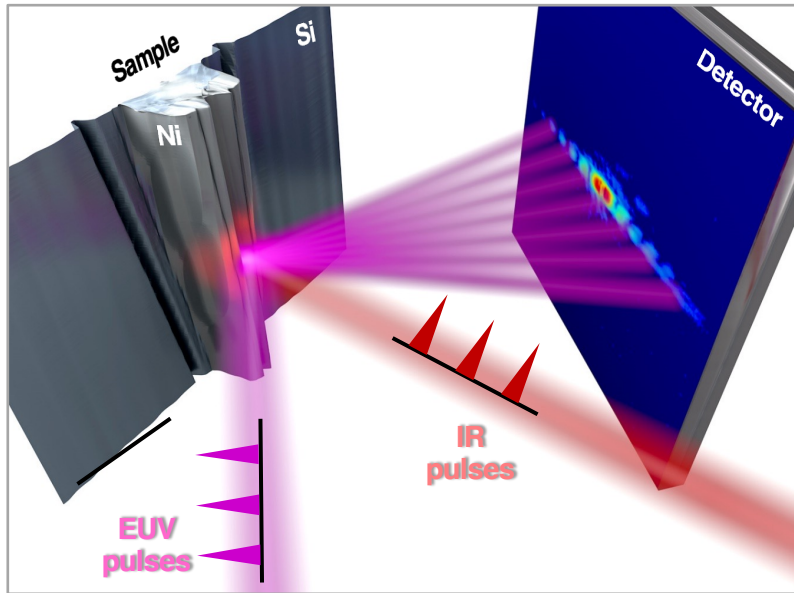


R. Karl et al., Sci. Adv. **4**, eaau4295 (2018)

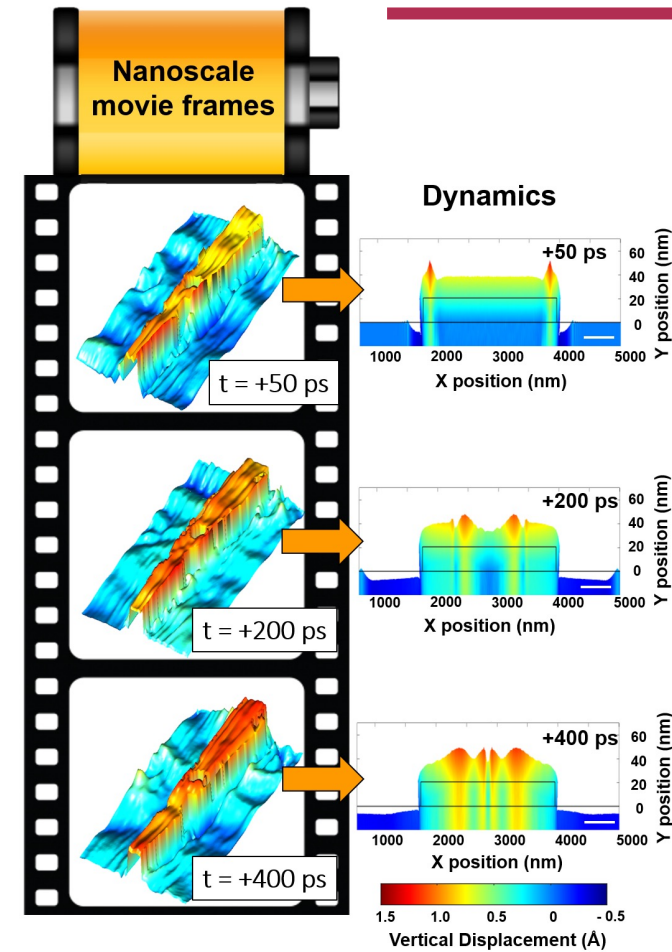


Demanding from the data acquisition and the reconstruction computational standpoints

Ultrafast Ptychography



R. Karl et al., Sci. Adv. 4, eaau4295 (2018)



What are the key criteria for successfully performing ultrafast ptychography experiments?

Ptychographic Coherent Diffractive Imaging

- Direct-space imaging

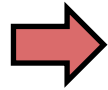


Microscope objective lens

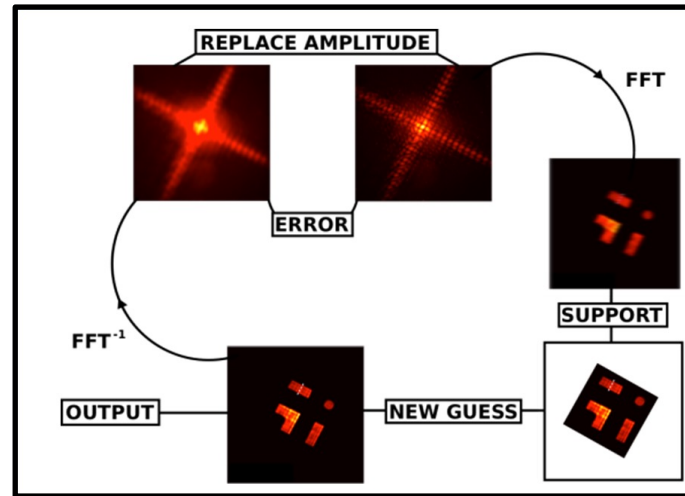


Image formation

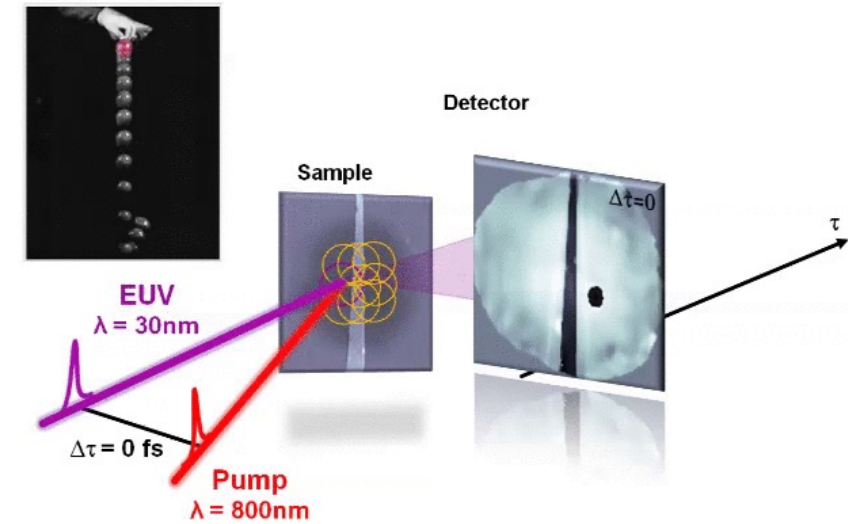
- Imaging with phase retrieval



Computer



Phase Retrieval algorithm



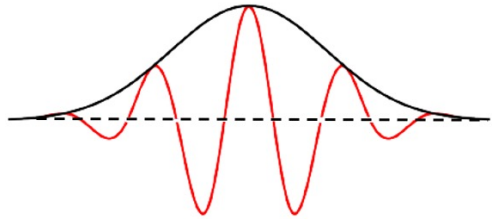
- R. Karl et al., Sci. Adv. **4**, eaau4295 (2018)
D. Goldberger et al. Optica **9**, 894-902 (2022)
J. R. Rouxel et al., Nat. Photonics **16**, 570-574 (2022)
Rodenburg et al., Phys. Rev. Lett. **98**, 034801 (2007)
Thibault et al., Science **321**, 379 (2008)
Maiden et al., Ultramicroscopy **109**, 1256 (2009)

High Harmonic Generation (HHG)

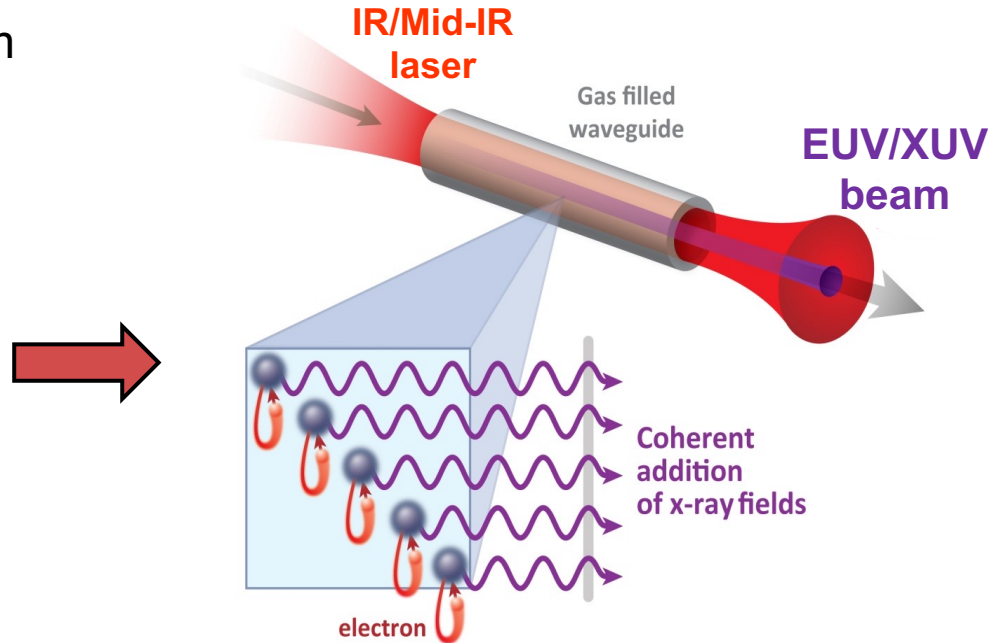
35 fs, 5-10 kHz, 15 W, 785 nm



**Intense
laser pulses**



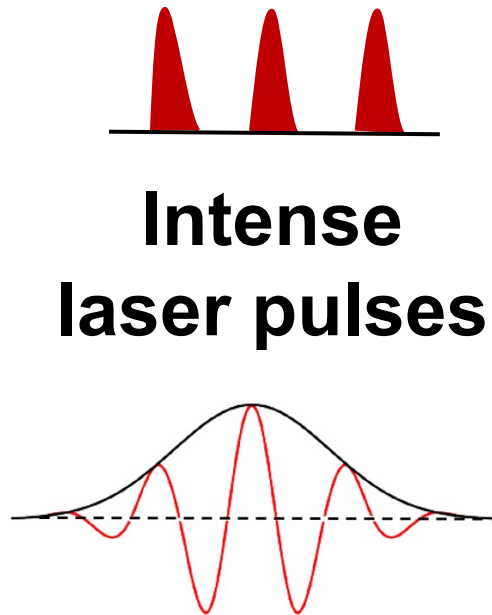
Noble gas (Ar, He) in a waveguide



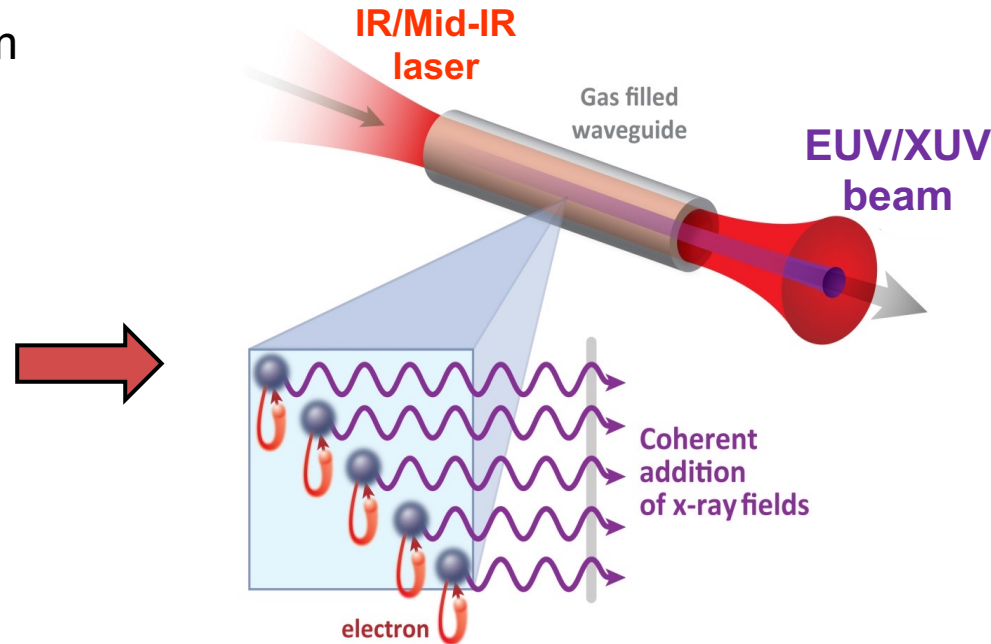
1. Ionization
2. Acceleration in the laser field
3. Recombination to ground state

High Harmonic Generation (HHG)

35 fs, 5-10 kHz, 15 W, 785 nm

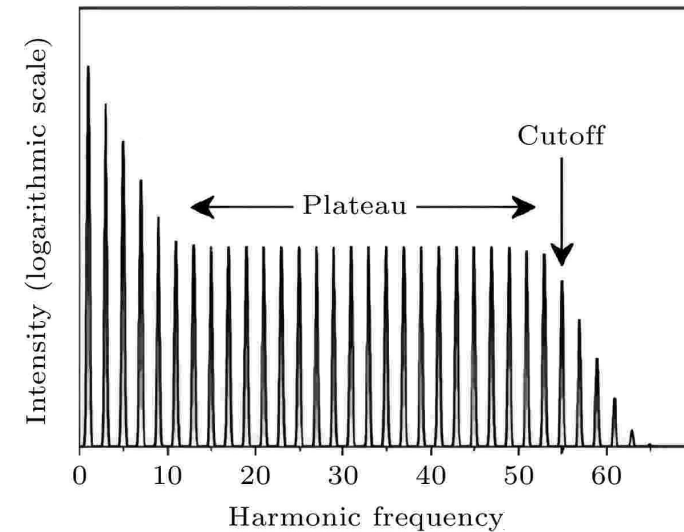


Noble gas (Ar, He) in a waveguide



Highly nonlinear process: up converts the
driving laser to shorter wavelengths

Chen-Yu *et al.*, Acta Phys. Sin. **72**, 1-27 (2023)

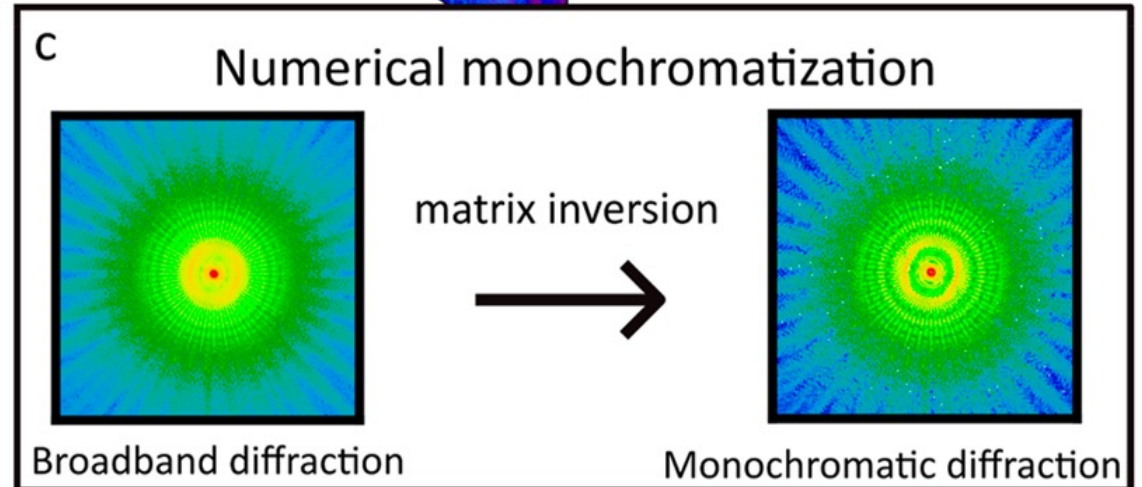
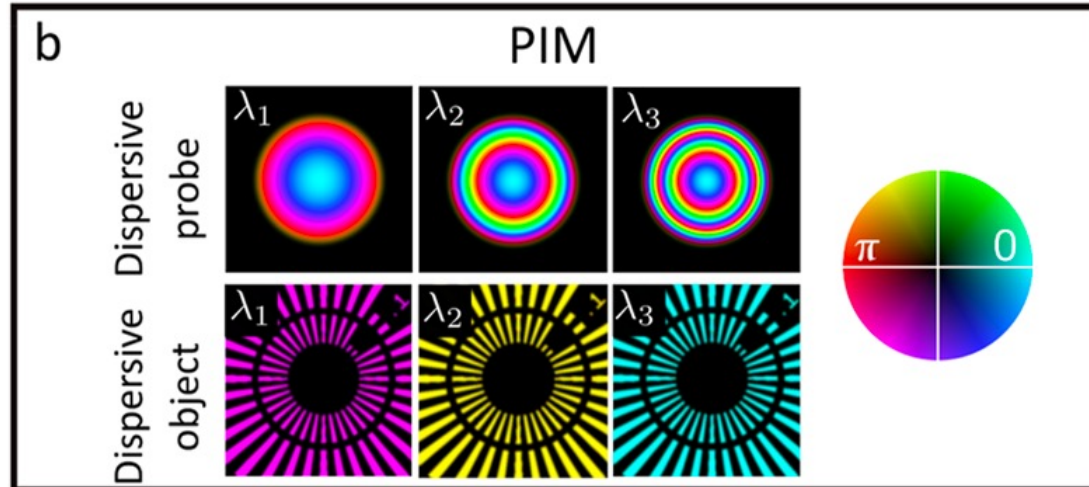
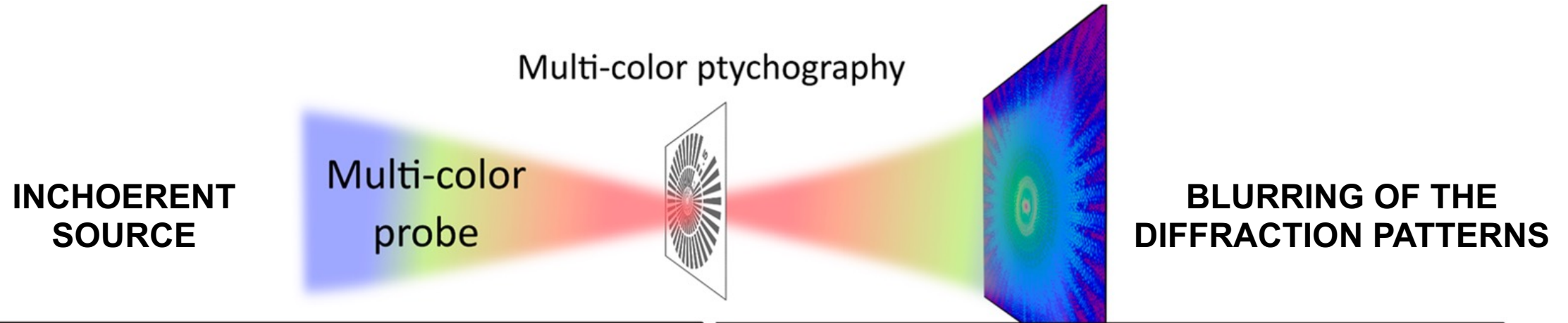


Rundquist *et al.*, Science **280**, 1412–1415 (1998)
Redman *et al.*, Science **298**, 1581 (2002)

Kapteyn *et al.*, Phys. Today **58**, 39–46 (2005)
Popmintchev *et al.*, Nature Photon. **4**, 822–832 (2010)

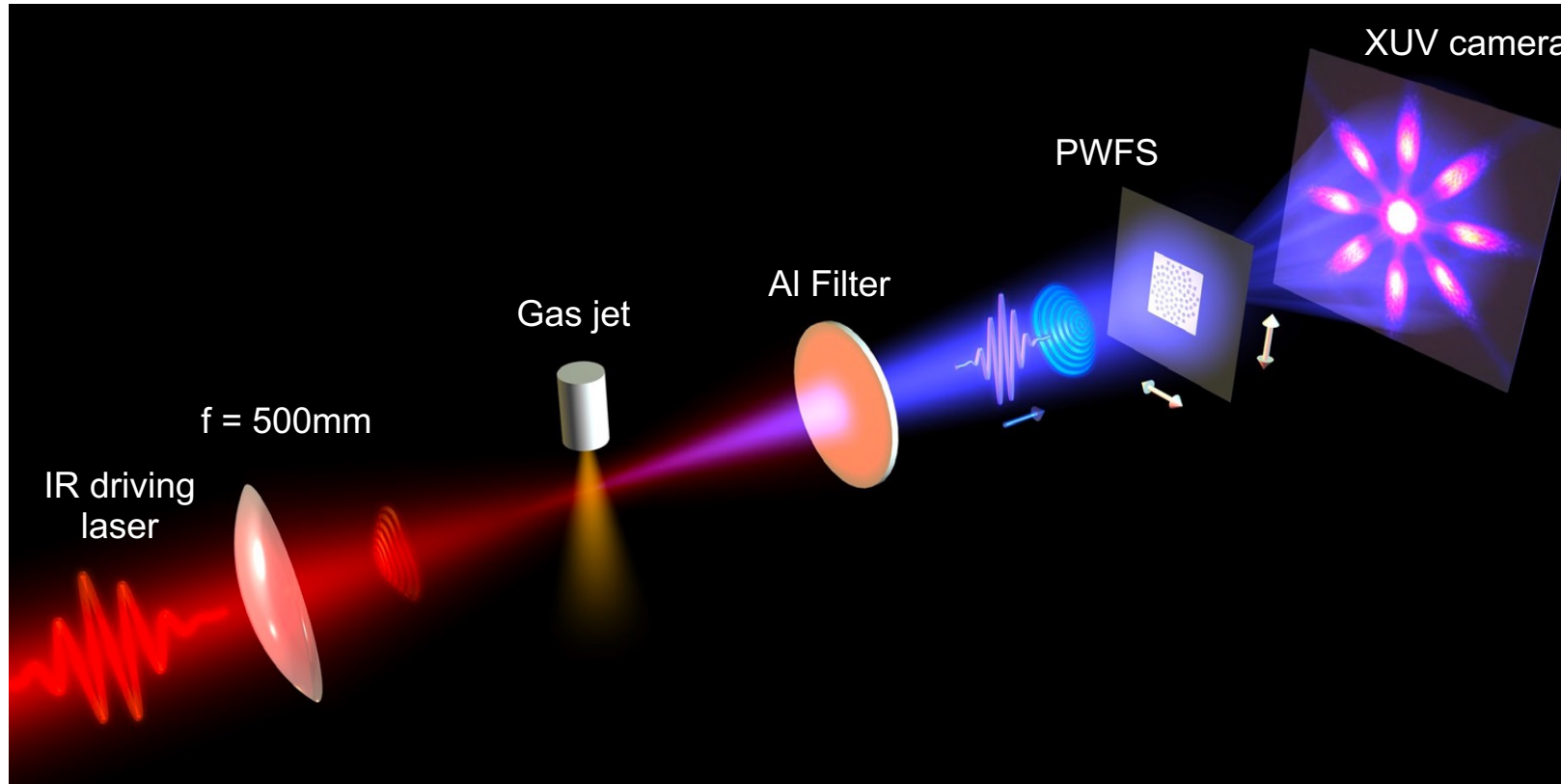
Ptychography in the EUV regime

Ptychography using broadband EUV radiation



Ptychography in the EUV regime

Ptychography as a high-resolution multi-wavelength EUV wavefront sensor



Du *et al.*, *Optica* **10**, 255–263 (2023)

Ptychography in the EUV regime

EUV ptychography in the presence of instabilities

Ptychography requires stable illumination regarding **power**, **position**, and **wavefront**; otherwise, the overlap between neighboring positions is no longer sufficiently defined, and reconstructions might fail.

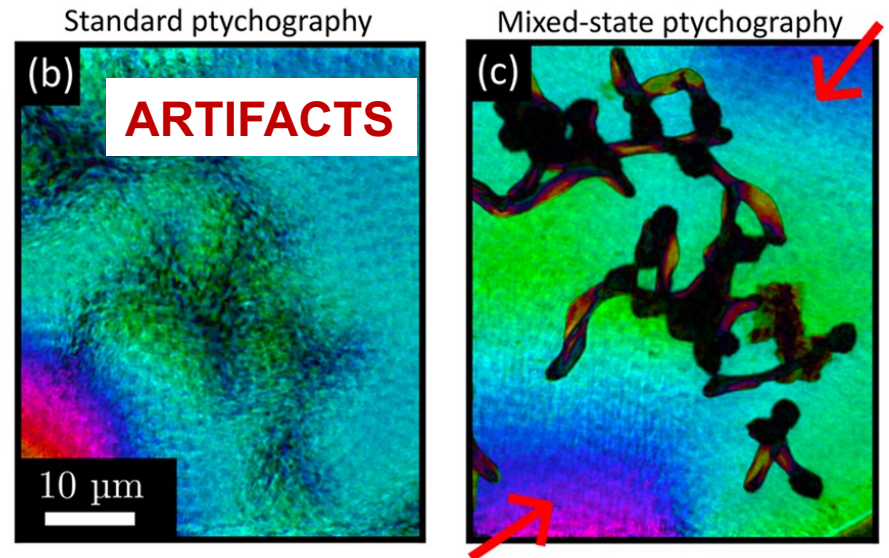
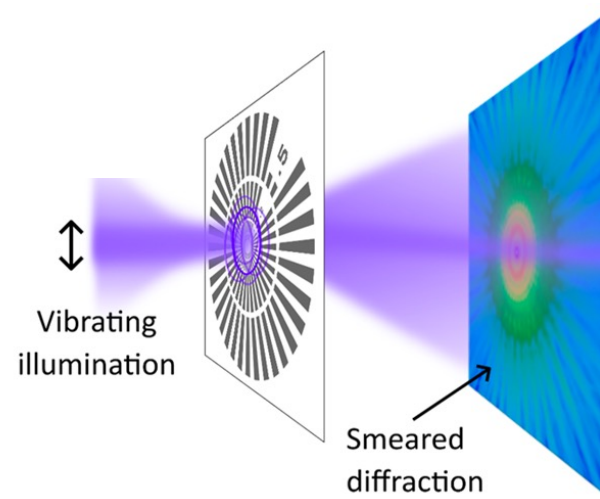
Liu *et al.*, PhotoniX **4**, 6 (2023)
Thibault *et al.*, Nature **494**, 68–71 (2013)

- **FAST VIBRATIONS**



MIXED STATE PTYCHOGRAPHY

Probe modelled as a coherent sum of partially coherent modes



Still smeared background

Ptychography in the EUV regime

EUV ptychography in the presence of instabilities

Ptychography requires stable illumination regarding **power**, **position**, and **wavefront**; otherwise, the overlap between neighboring positions is no longer sufficiently defined, and reconstructions might fail.

Liu *et al.*, PhotoniX **4**, 6 (2023)

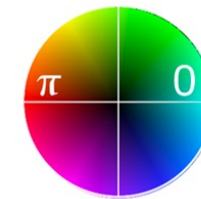
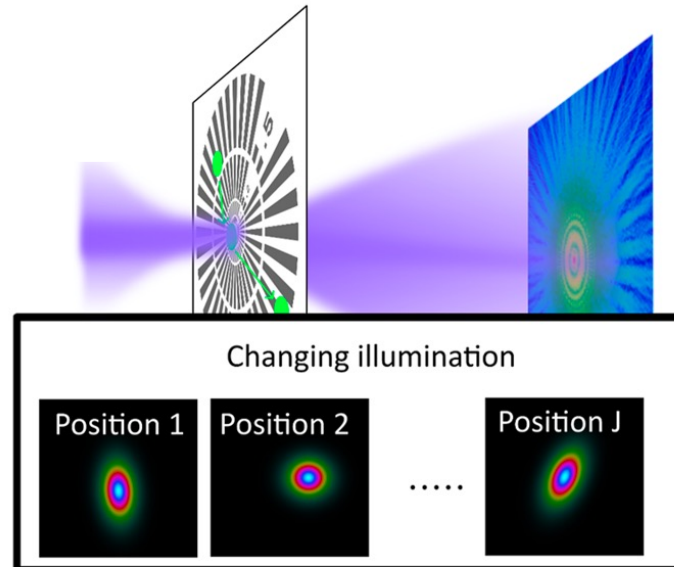
Odstrčil *et al.*, Opt. Express **24**, 8360–8369 (2016)

- **SLOW VIBRATIONS**

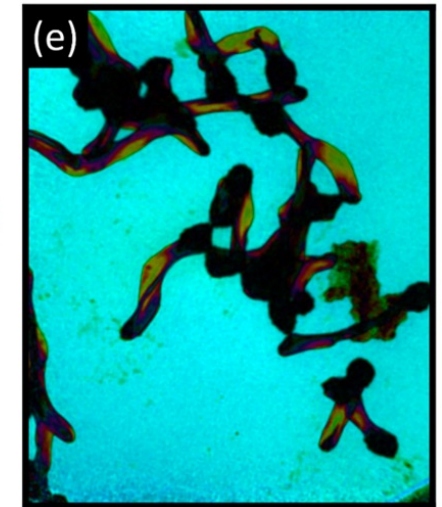


ORTHOGONAL PROBE RELAXATION (OPR)

Allows the probe to “breathe”: it can vary between scan positions, but only within a constrained set of orthogonal modes



Mixed-state ptychography + OPR



Ptychography in the EUV regime

Imaging with structured light beams

Structured probes improve reconstruction:

- Spatial diversity produces stronger diffraction changes between scan positions
- This improves deconvolution.

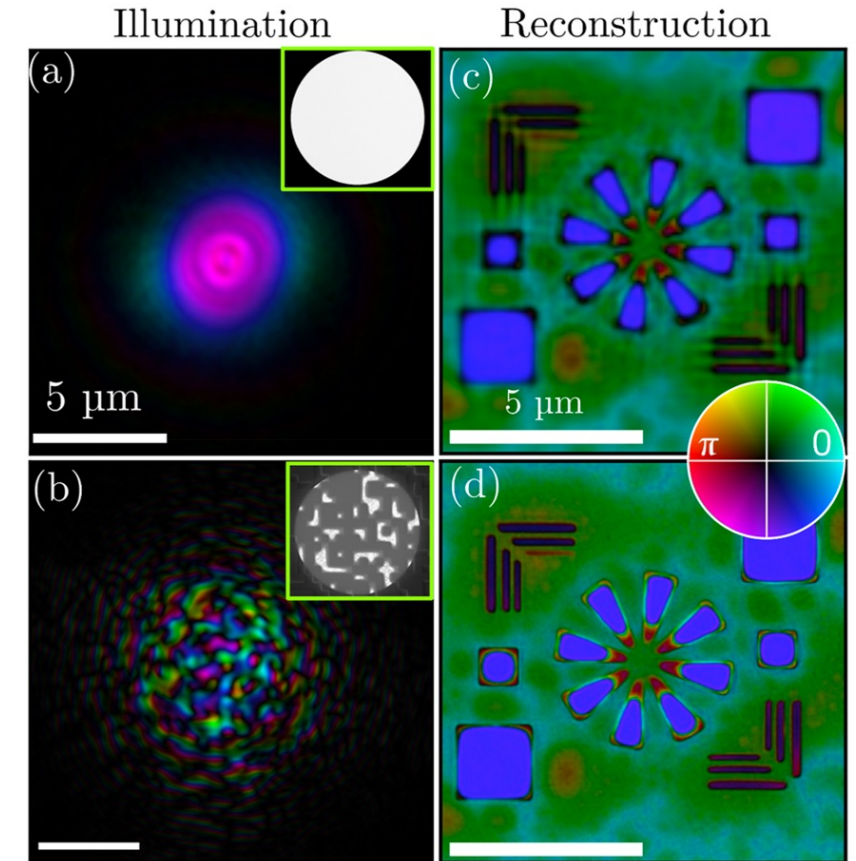
Broad angular spectrum helps detection:

- Spreads intensity across the detector
- Reduces overexposure
- Captures more photons

Tremendous difficulties in fabricating high-quality optics to shape the beam in this spectral range.

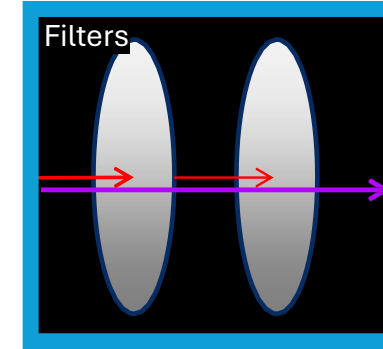
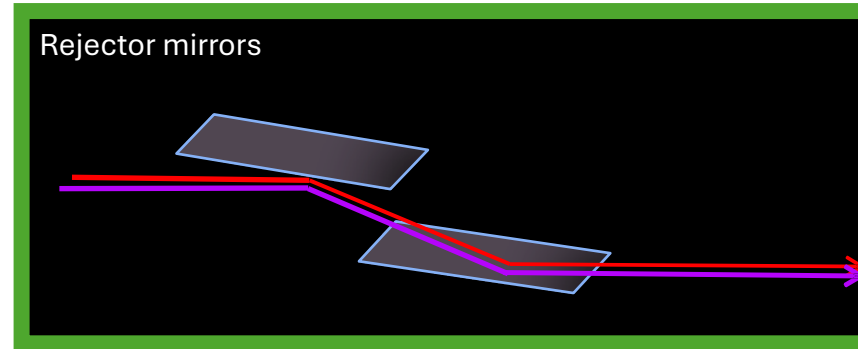
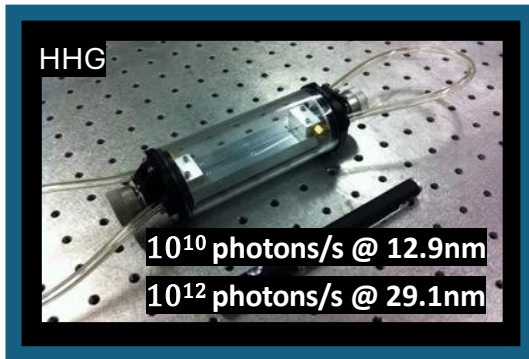
Odstrčil *et al.*, Opt. Express **27**, 14981-14997 (2019)
Eschen *et al.*, APL Photon. **10**, 050901 (2025)

MASK-BASED STRUCTURED ILLUMINATION PTYCHOGRAPHY

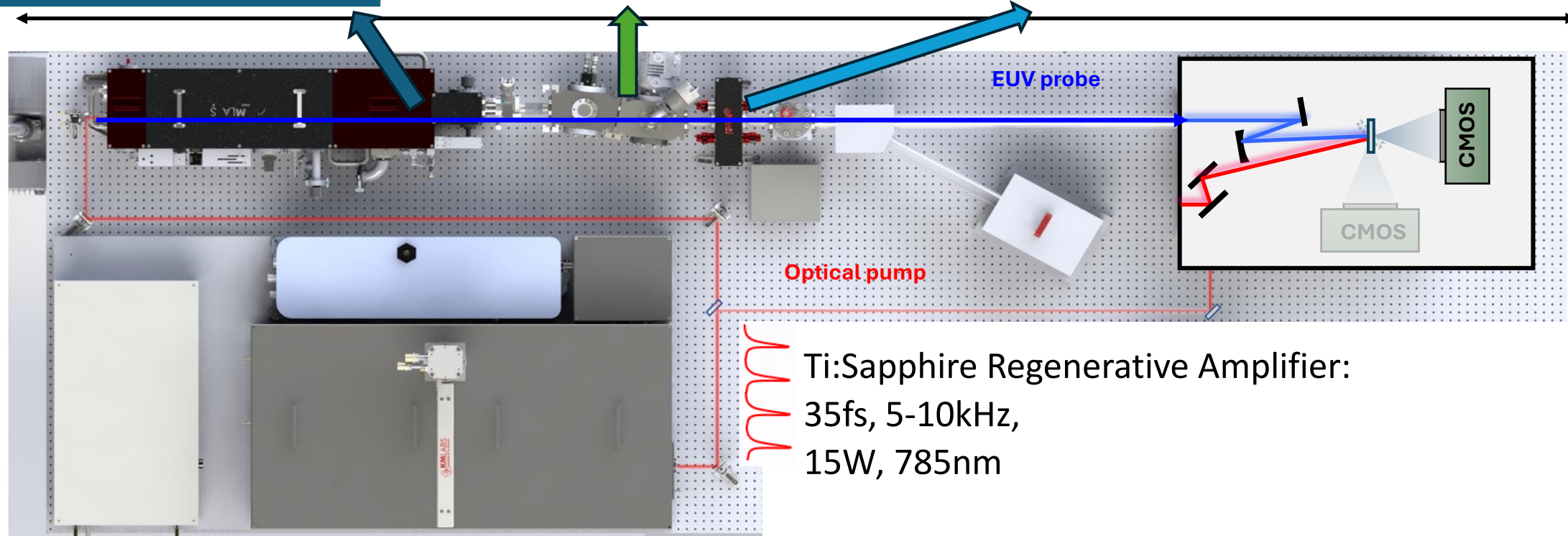


Eschen *et al.*, Opt. Express **32**, 3480–3491 (2024)

Ultrafast XUV Microscope



4.5m



GS algorithm: working principle

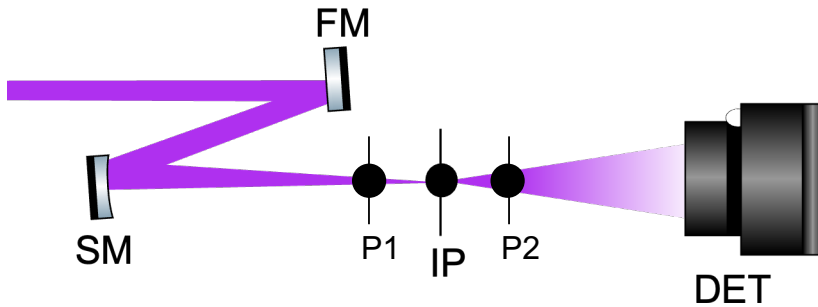
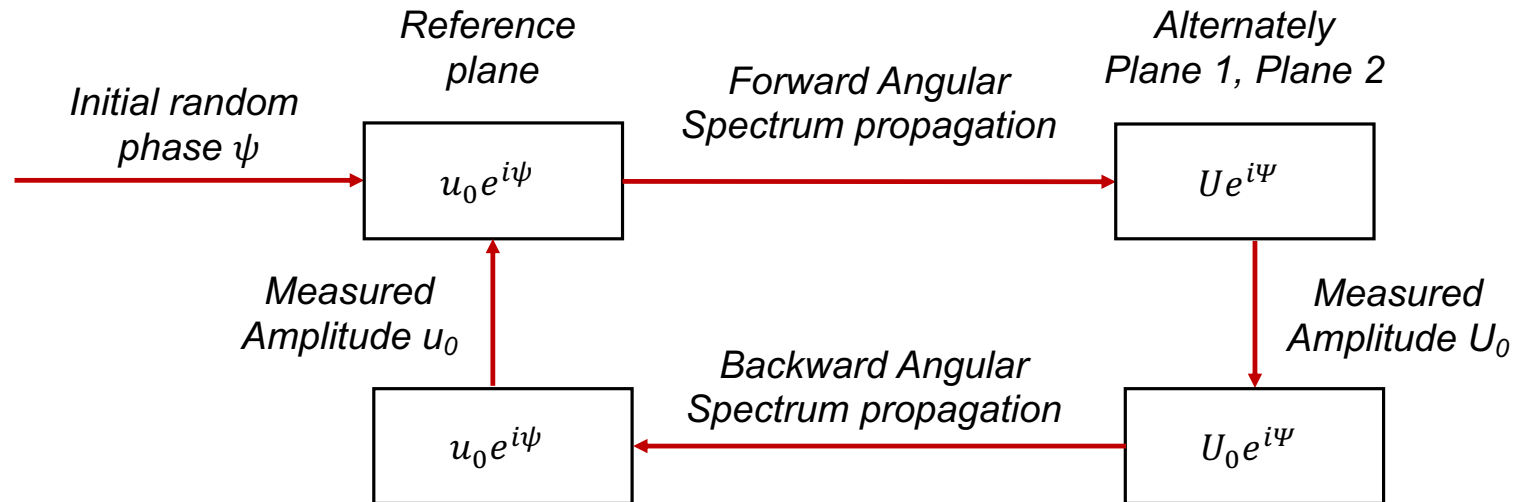


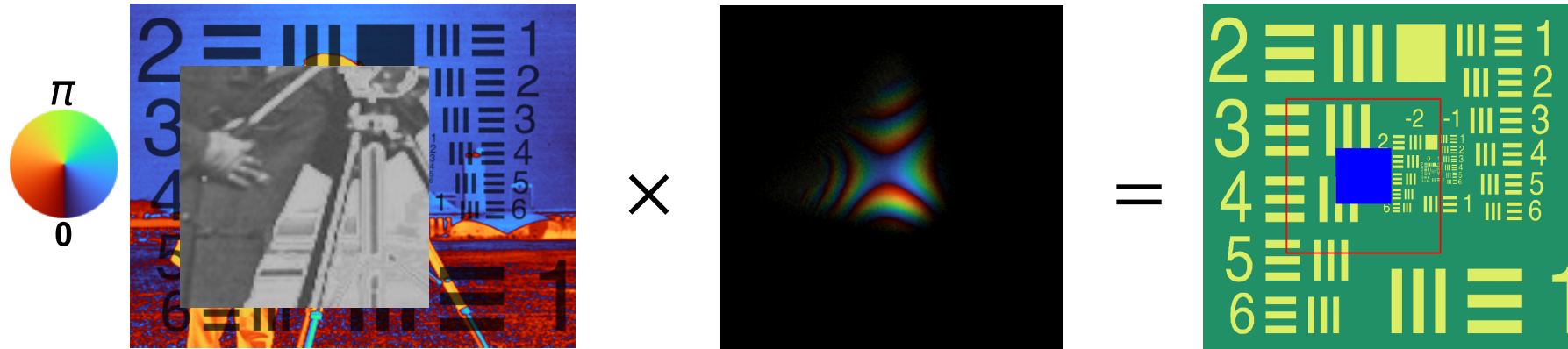
Image plane (IP) = reference plane



From Ground Truth to Noisy Measurement

$$O(\mathbf{r}) = A_O(\mathbf{r}) e^{i \varphi_O(\mathbf{r})}$$

$$P(\mathbf{r}) = A_P(\mathbf{r}) e^{i \varphi_P(\mathbf{r})}$$



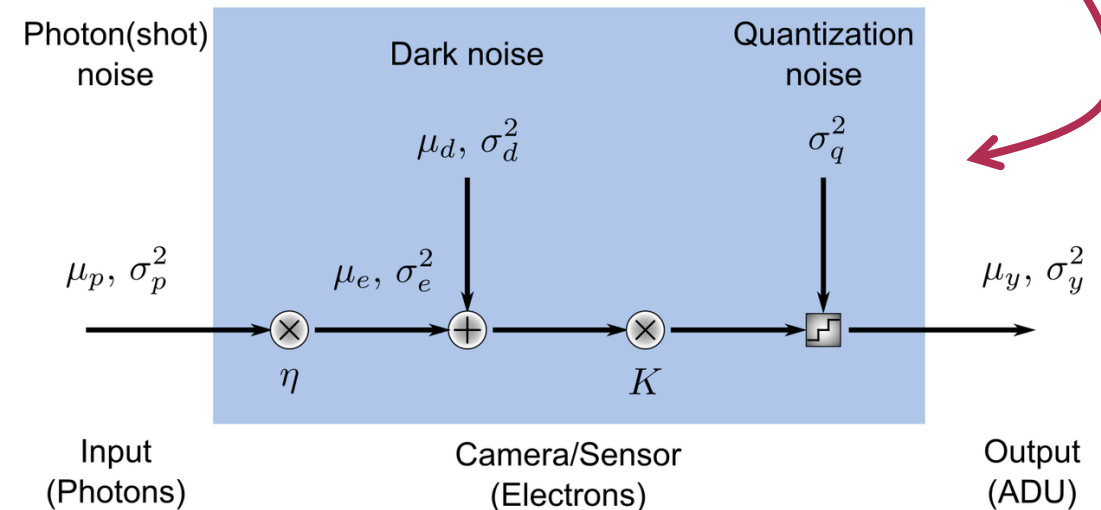
Exit Surface Wave

$$\Psi_n(\mathbf{r}) = O(\mathbf{r}) P(\mathbf{r} - \mathbf{R}_n)$$

$$I_n(\mathbf{q}) = |\mathcal{F}[O(\mathbf{r}) P(\mathbf{r} - \mathbf{R}_n)]|^2$$

Signal acquisition and noise sources

- **Shot Noise** (Poisson Distribution): σ_p^2
- **Quantum efficiency**: $\eta_{ph \rightarrow e^-}$
- Dark noise = **Read-Out Noise** + **Dark current**
(Normal Distribution): $\sigma_d^2 = \sigma_r^2 + \mu_I t_{exp}$
- **Sensitivity** K of the detector: $K_{e^- \rightarrow ADU}$
- **Quantization noise**: precision error based on detector's bit-depth



Loss Function & FRC

Real Space Exit surface wave:

$$\psi_x = Oe^{i\varphi} \times Pe^{i\theta}$$

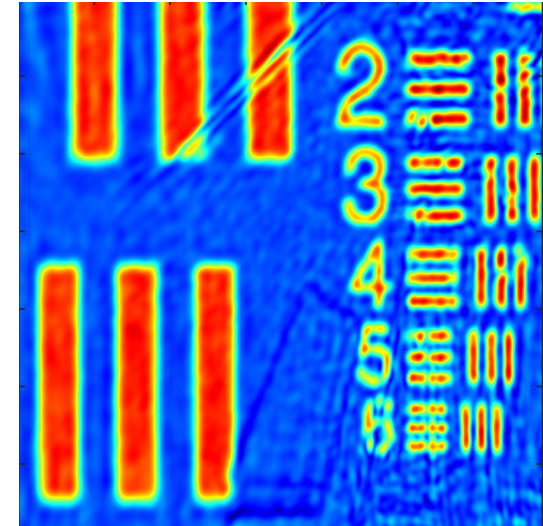
Diffraction Root Mean Square (DRMS) error:

$$\mathcal{L}(\Psi) = \sum_k \left| |\Psi_k| - \sqrt{I_k} \right|^2$$

$$\nabla \mathcal{L}(\psi_x) = (\psi_x - \psi'_x)$$

$$E = \frac{1}{N} \sum_{j=1}^N \left| |\psi_j - \psi'_j| \right|^2$$

Reconstructed object's amplitude



Loss Function & FRC

Real Space Exit surface wave:

$$\psi_x = Oe^{i\varphi} \times Pe^{i\theta}$$

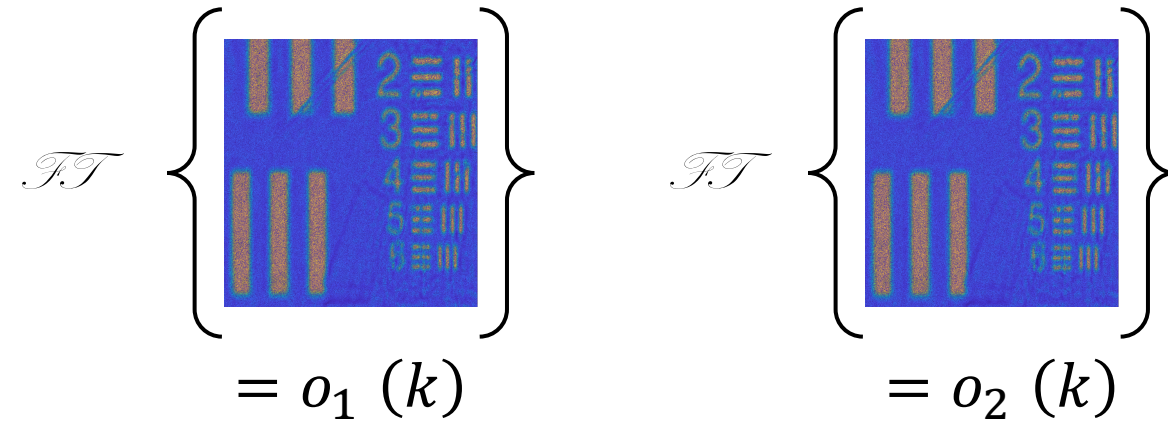
Diffraction Root Mean Square (DRMS) error:

$$\mathcal{L}(\Psi) = \sum_k \left| |\Psi_k| - \sqrt{I_k} \right|^2$$

$$\nabla \mathcal{L}(\psi_x) = (\psi_x - \psi'_x)$$

$$E = \frac{1}{N} \sum_{j=1}^N \left| |\psi_j - \psi'_j| \right|^2$$

Random splitting of the object in 2 subsets

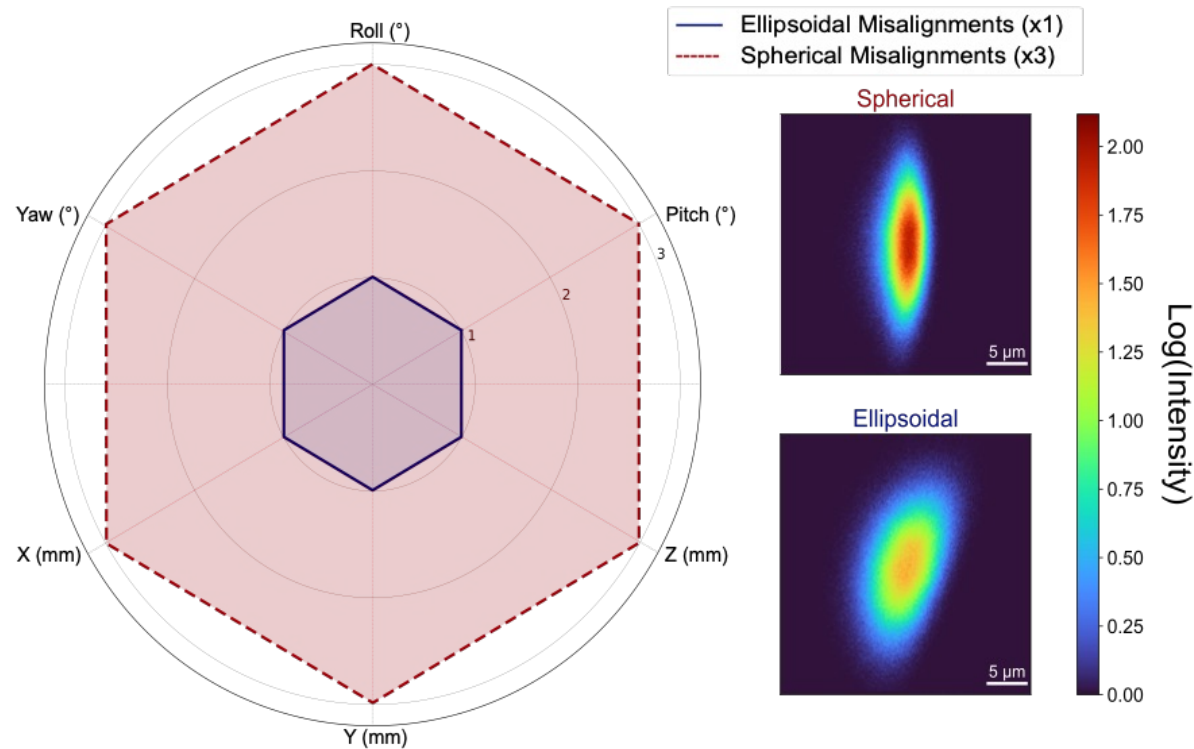


$$FRC(k) = \frac{\sum_{k_i \in k} o_1(k_i) o_2^*(k_i)}{\sqrt{\sum_{k_i \in k} |o_1(k)|^2 \sum_{k_i \in k} |o_2(k)|^2}}$$

Ray Tracing Simulations

Modular approach: ideal case, **misalignments**, slope errors, and both.

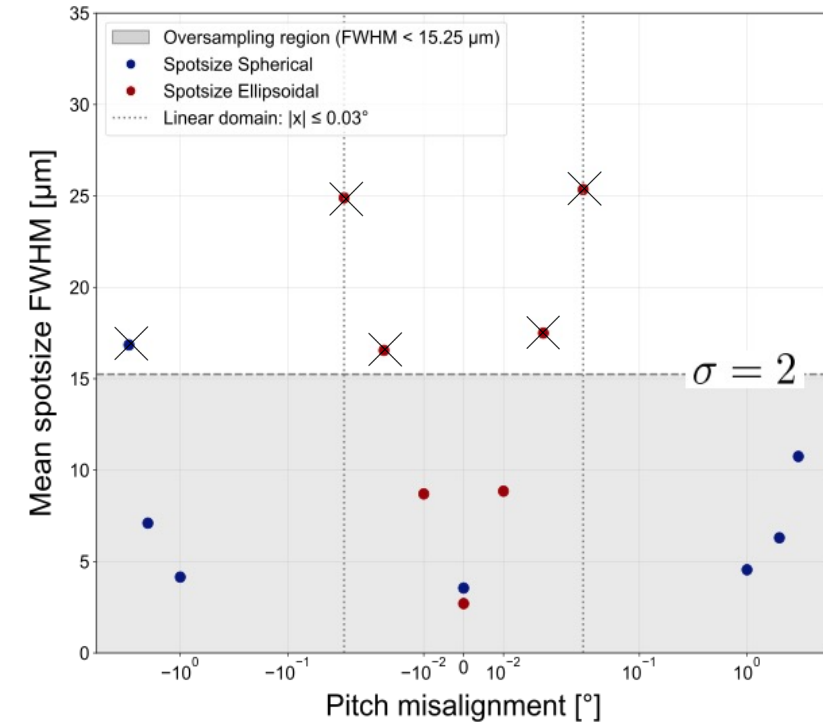
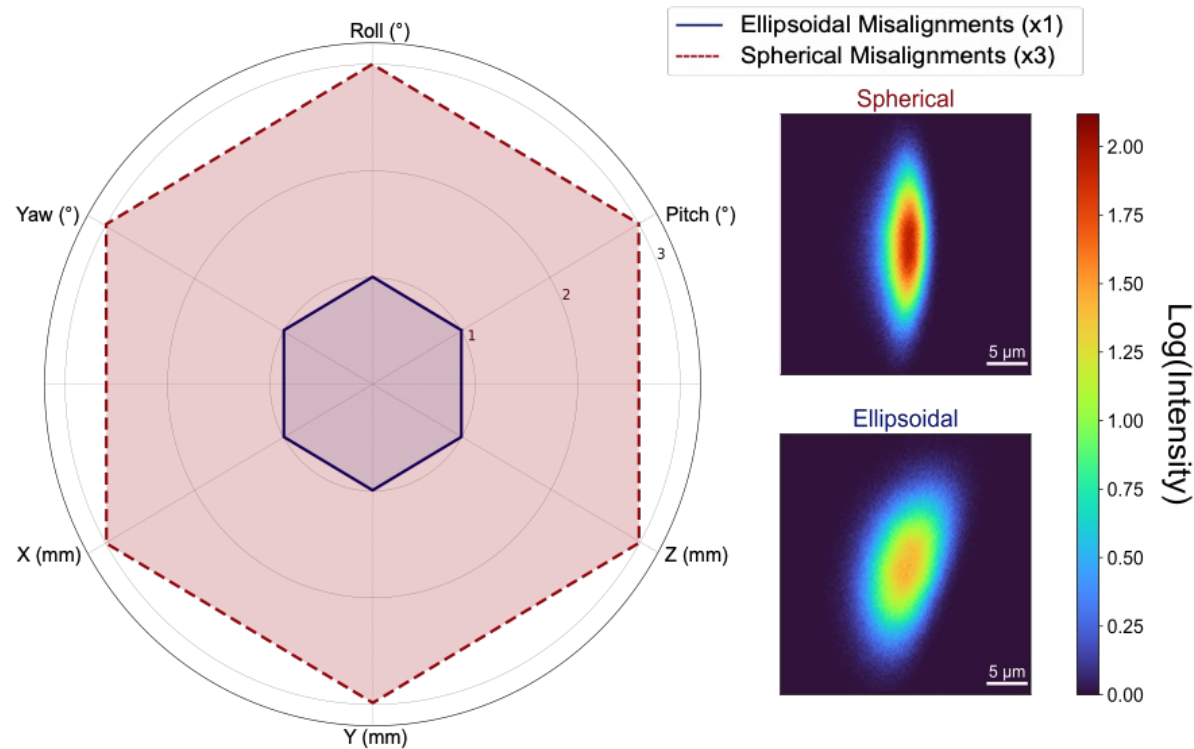
A. E. Mazzarone, C. Grova, J. J.
Barolak, D. E. Adams, C. Svetina, G. F.
Mancini, *in preparation*



Ray Tracing Simulations

Modular approach: ideal case, **misalignments**, slope errors, and both.

A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in preparation*



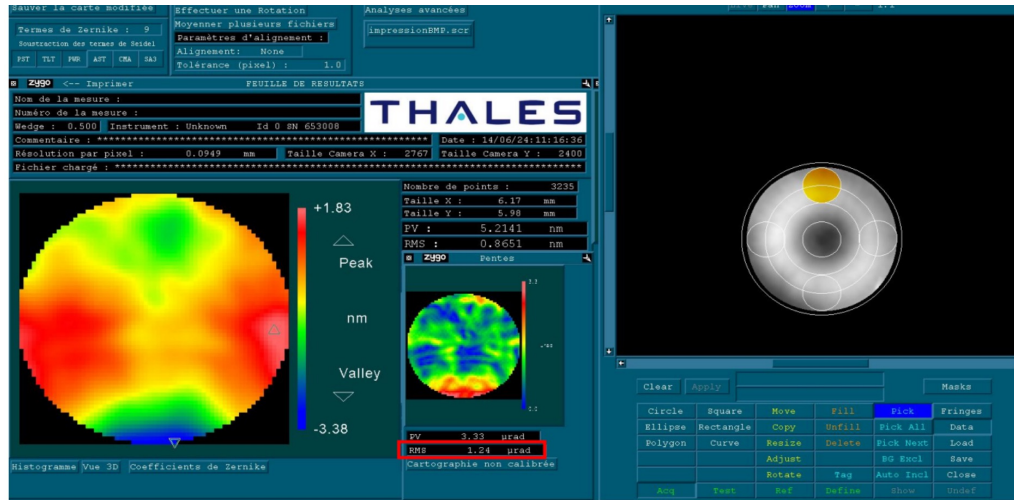
1. Z-fold preserves beam diameter even when the spherical mirror is misaligned **3× more than the ellipsoidal mirror**.
2. Z-fold's pitch tolerance is up to **100× greater than for the ellipsoidal mirror**.

Ray Tracing Simulations

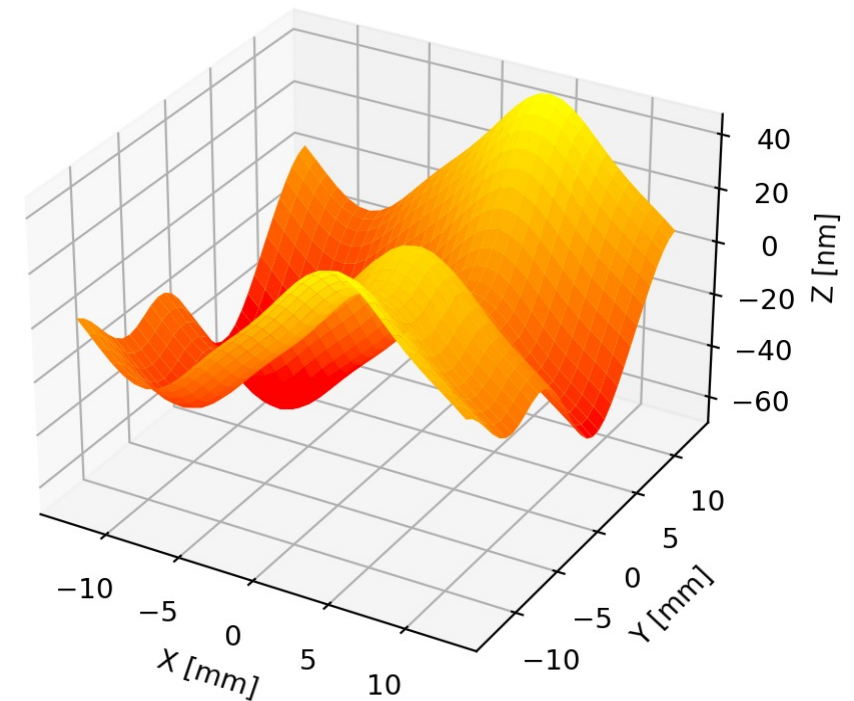
Modular approach: ideal case, misalignments, **slope errors**, and both.

Slope error characterization:

- White light interferometry
- Investigation at five locations



- Imperfections
- Lack of planarity
- Roughness

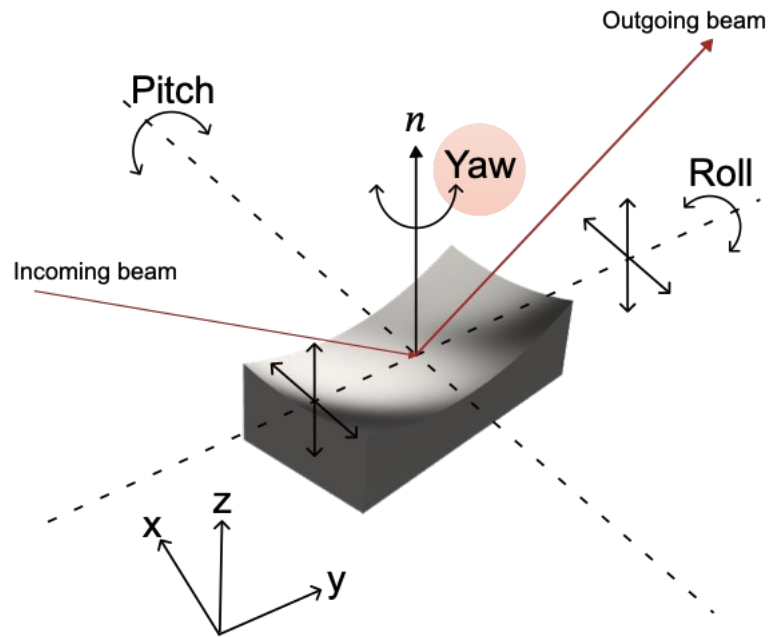


Slope errors change the beam shape by introducing aberrations such as coma, without drastically altering its size. However, they interact strongly with misalignments, amplifying their effects.

Ray Tracing Simulations

Modular approach: ideal case, misalignments, slope errors, and **both**.

A. E. Mazzarone, C. Grova, J. J. Barolak, D. E. Adams, C. Svetina, G. F. Mancini, *in preparation*

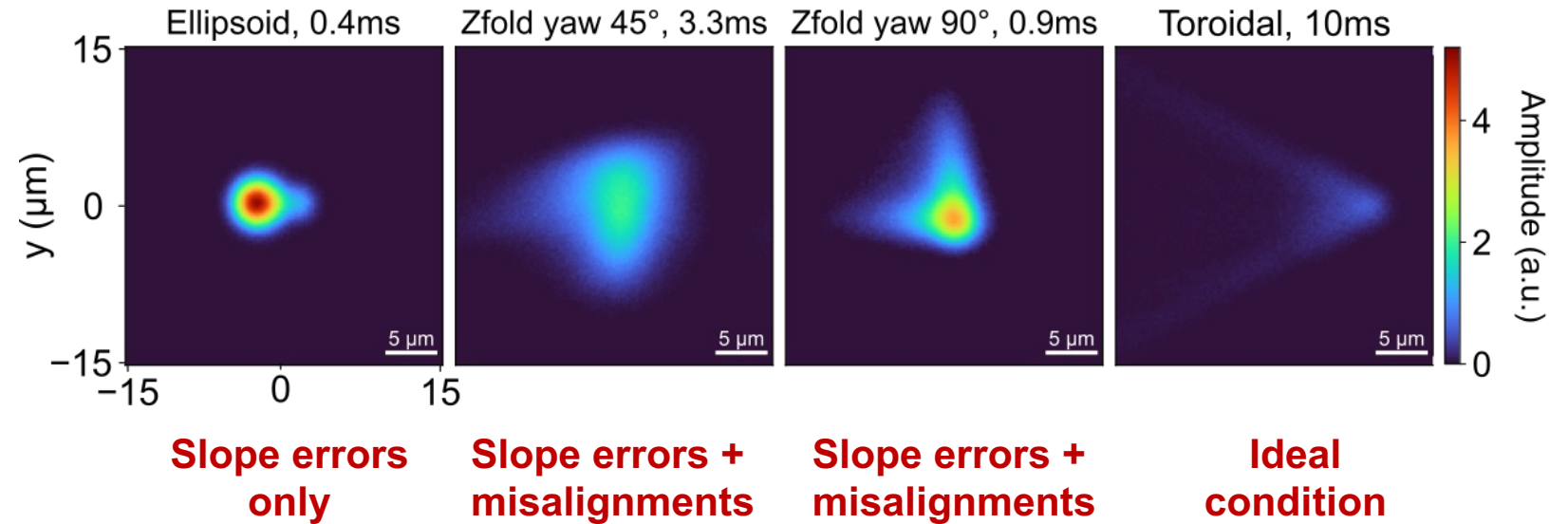


While the ellipsoidal scheme resists slope errors but strongly suffers from angular misalignments, the **Z-fold's** spherical mirror **can exploit slope error and yaw to improve beam size and oversampling**.

Ptychographic performance

How do geometric differences affect speed, acquisition time, and resolution in ptychographic imaging?

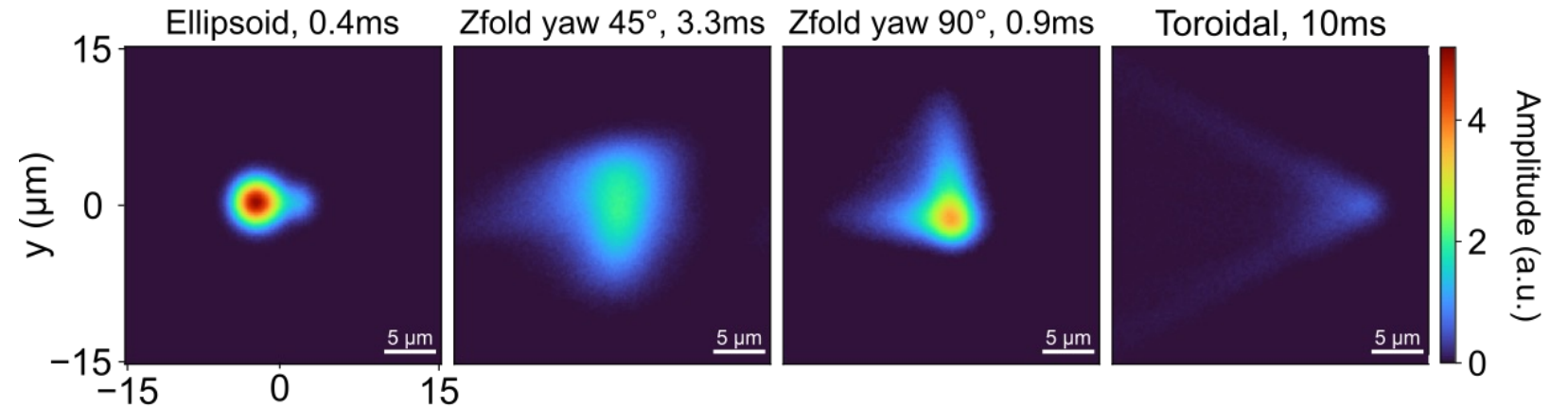
Amplitude from **Ray tracing**



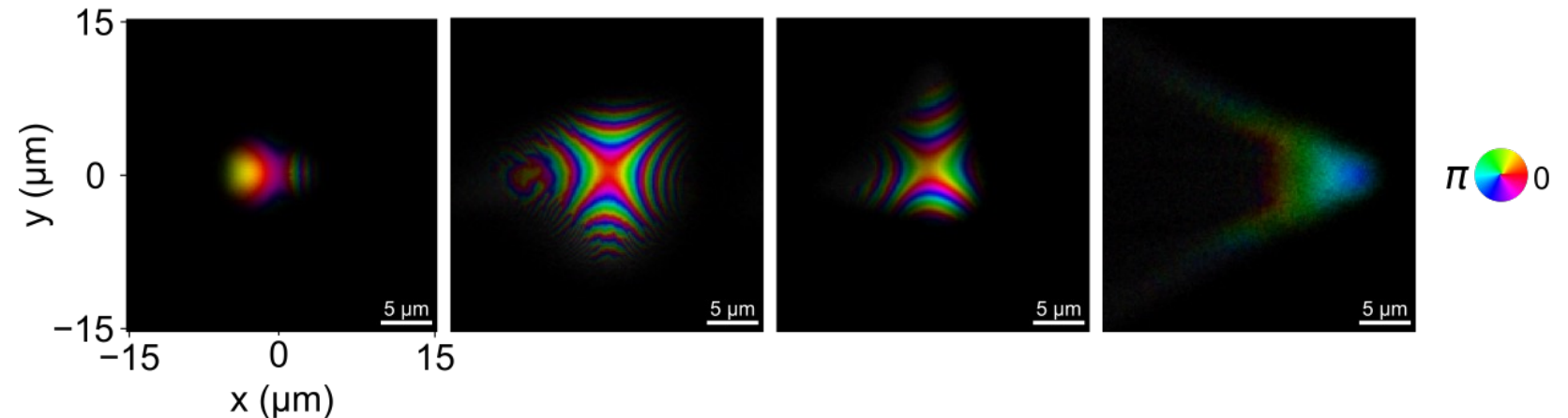
Ptychographic performance

How do geometric differences affect speed, acquisition time, and resolution in ptychographic imaging?

Amplitude from **Ray tracing**



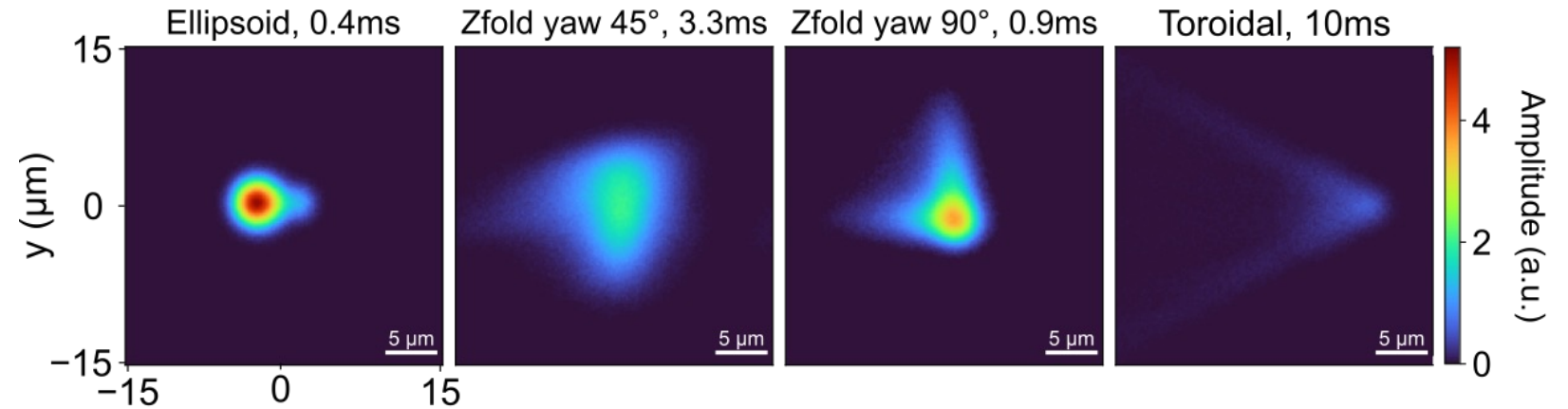
Phase retrieved from
Gerchberg-Saxton
algorithm



Ptychographic performance

How do geometric differences affect speed, acquisition time, and resolution in ptychographic imaging?

Amplitude from **Ray tracing**



Sunflower seeded Fermat Spiral
define the set of coordinates R_n .
Same FOV, same Overlap: 70%

