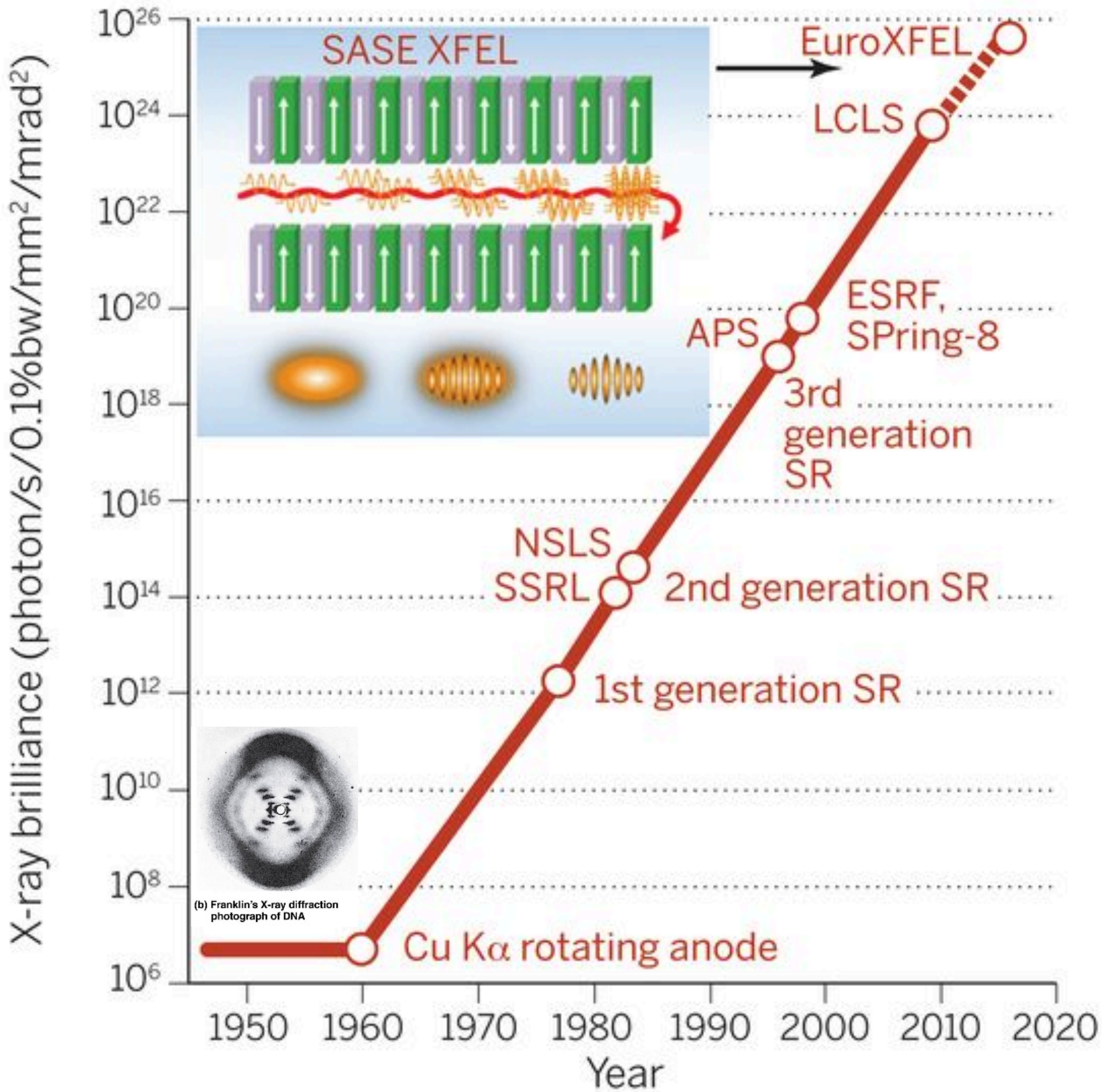
Requirements for Ultrafast Imaging and X-ray Holography

Tais Gorkhover

Stanford PULSE Institute, SLAC

History of X-ray sources



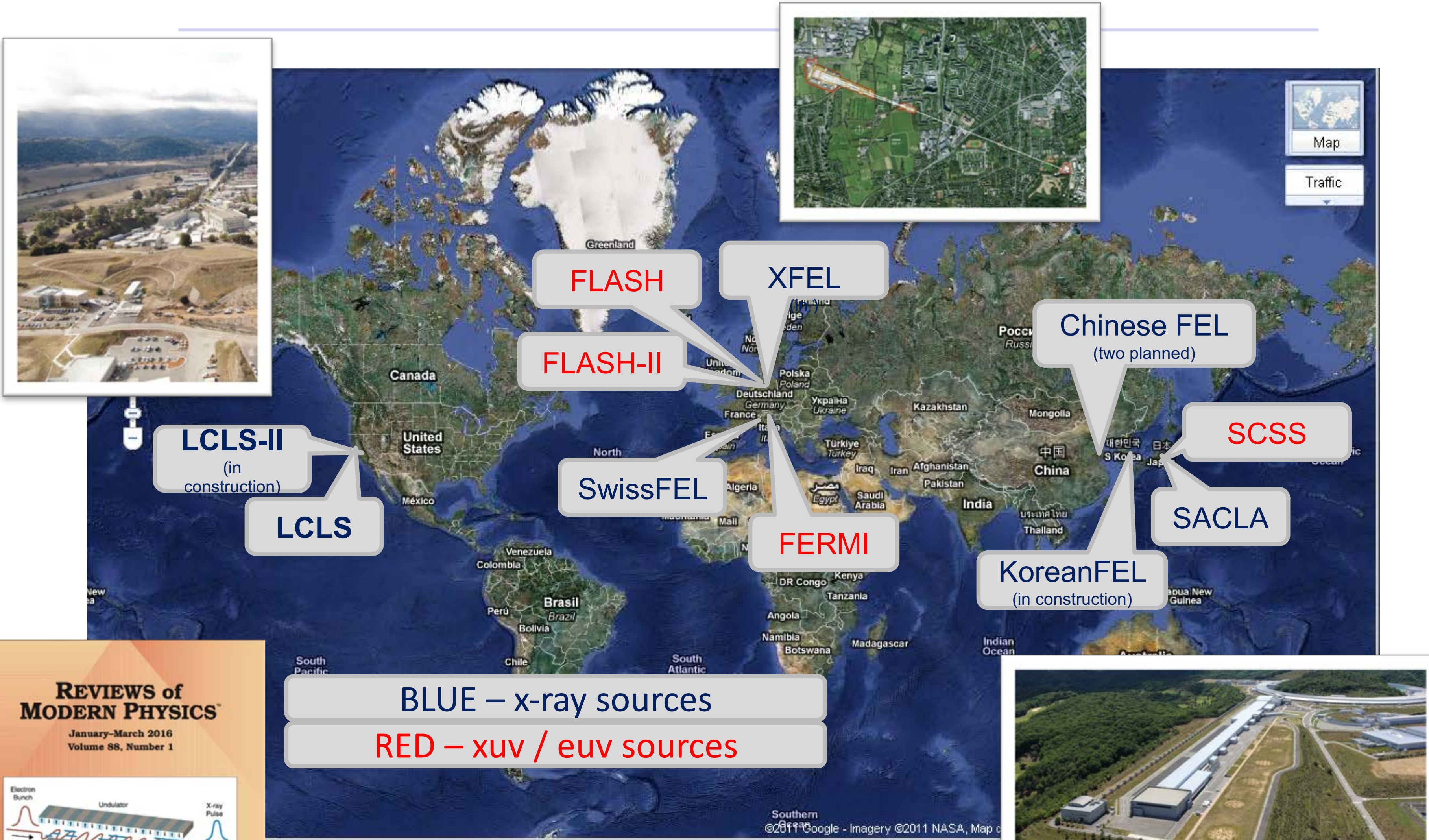
Miao, Jianwei, et al. *Science* 348.6234 (2015): 530-535

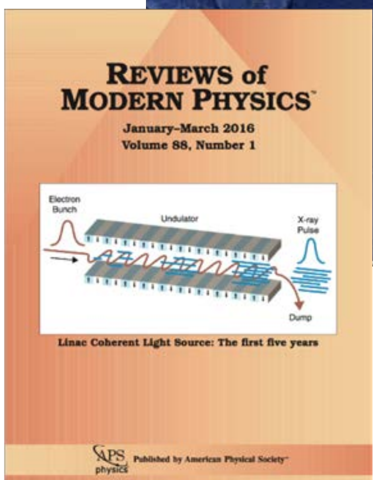
X-ray free electron lasers

10^{11-13} X-ray photons in a single, few fs pulse

are sources of intense X-ray ***coherent*** radiation

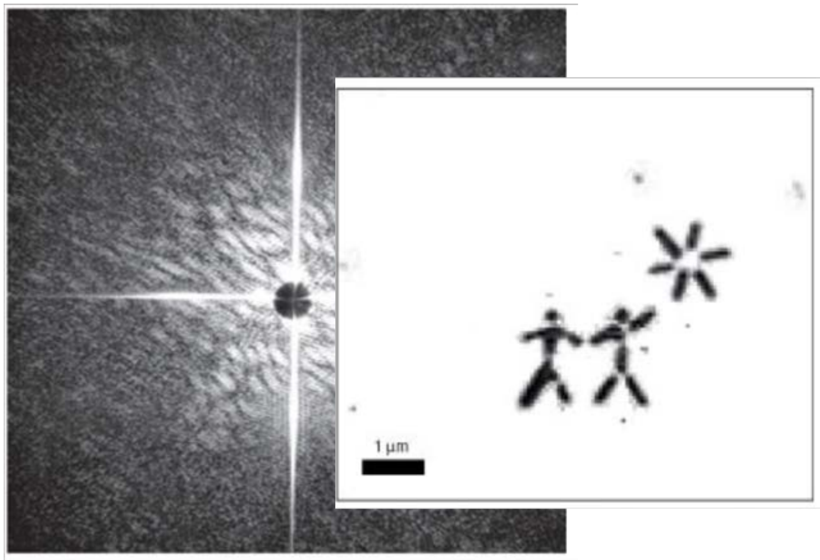
More X-ray FEL facilities

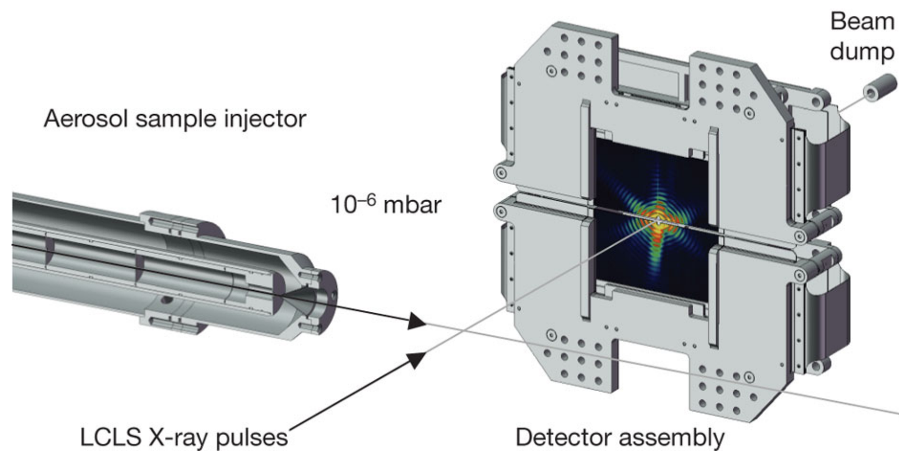




Bostedt et al., Rev. Mod. Phys. 88 (2016)

Diffraction-before-destruction principle





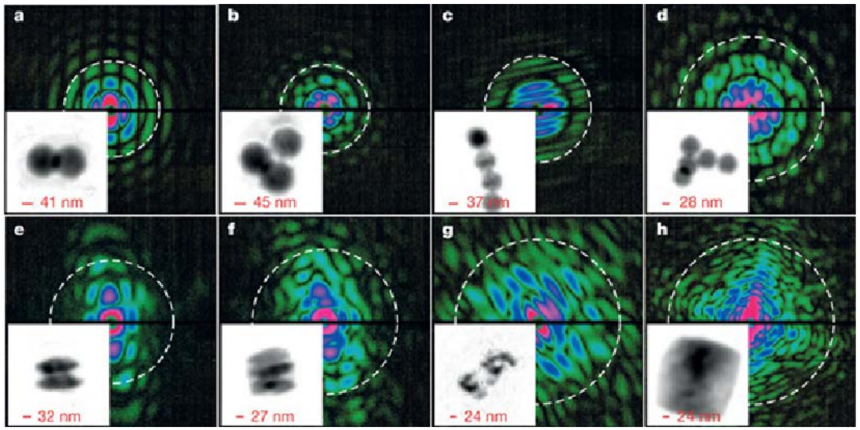
Chapman *et al.* *Nature Physics* **2**, 839–843 (2006)

Seibert *et al.* *Nature* **470**, 78-81 (2011) doi:10.1038/nature09748

Potential: High resolution imaging of non-crystaline nanospecimen on the single particle level

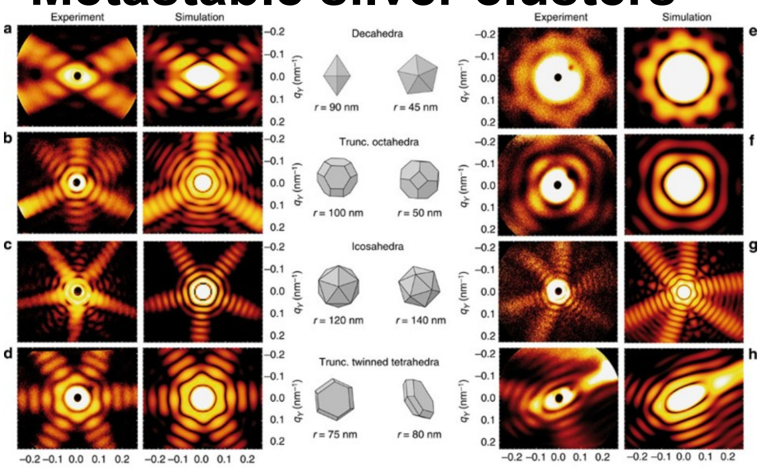
Diffraction-before-destruction imaging

Soot particles



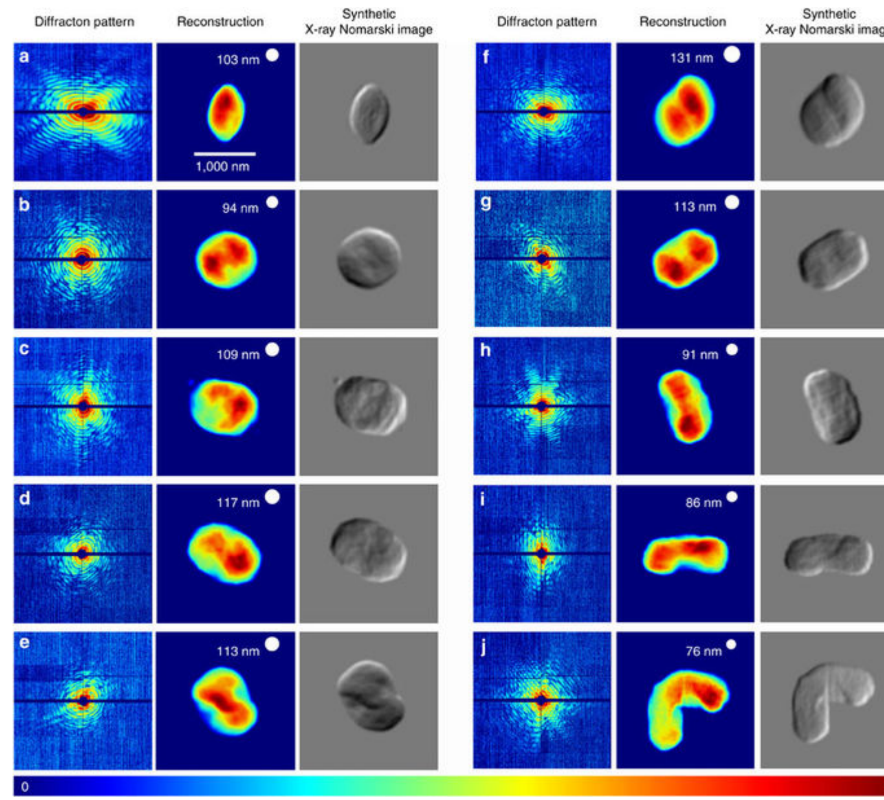
Loh, N. D., et al. *Nature* 486.7404 (2012): 513.

Metastable silver clusters



Barke, Ingo, et al. *Nat. Comm.* 6 (2015).

Living cyanobacteria



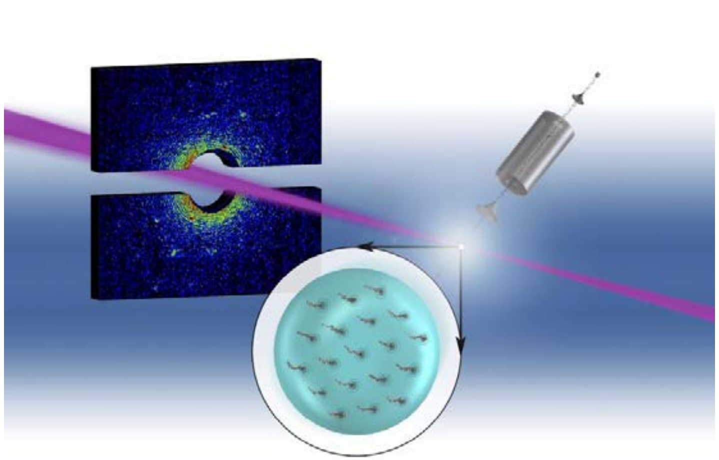
van der Schot, *Nat. Comm.* 6:5704 doi: 10.1038/ncomms6704 (2015)

Tais Gorkhover, 2nd ACHIP Application Meeting 2019

Ultrafast X-ray diffraction imaging

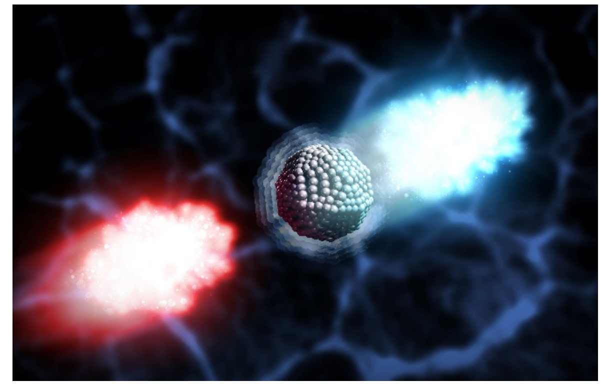
Ultracold

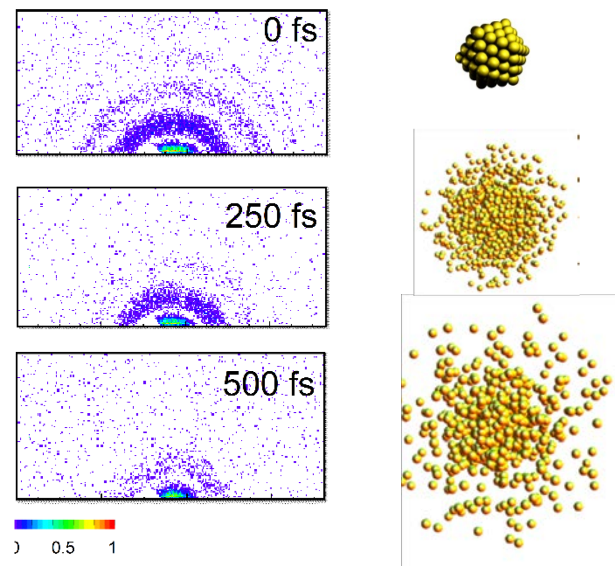
L.Gomez *et al., Science*, 22 August 2014



Ultrahot

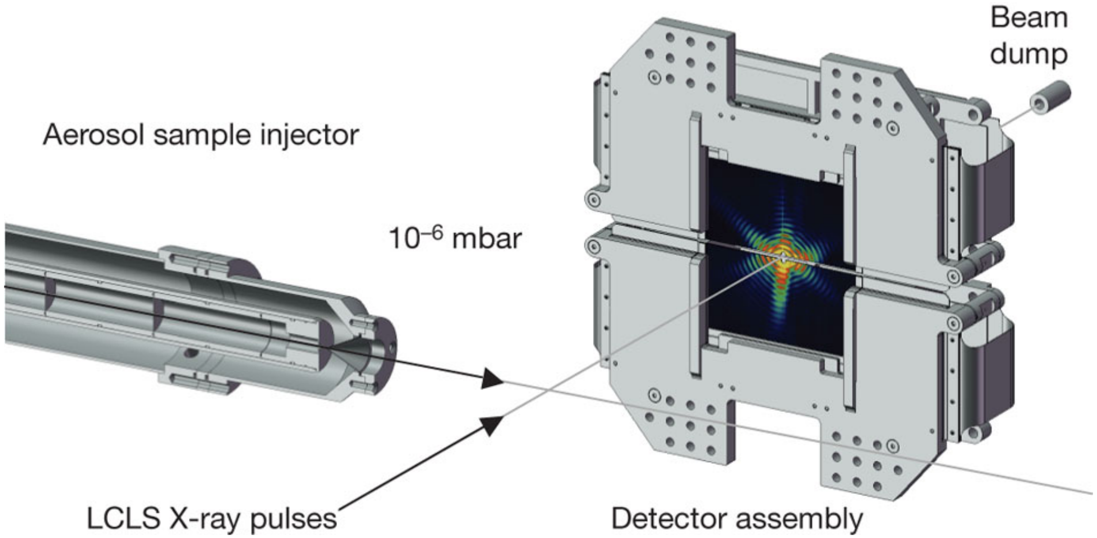
T. Gorkhover *et al, Nature Photonics* 10, (2016)

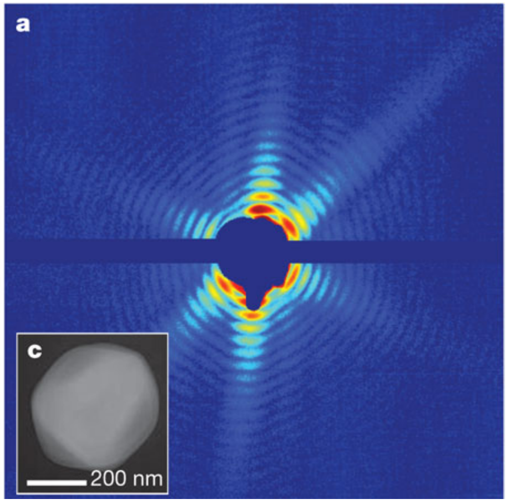




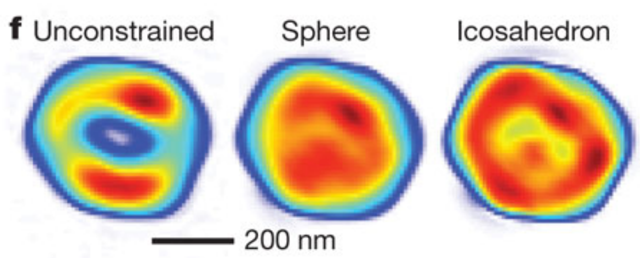
Tais Gorkhover, 2nd ACHIP Application Meeting 2019

Diffraction-before-destruction principle





Seibert *et al.* *Nature* **470**, 78-81 (2011) doi:10.1038/nature09748

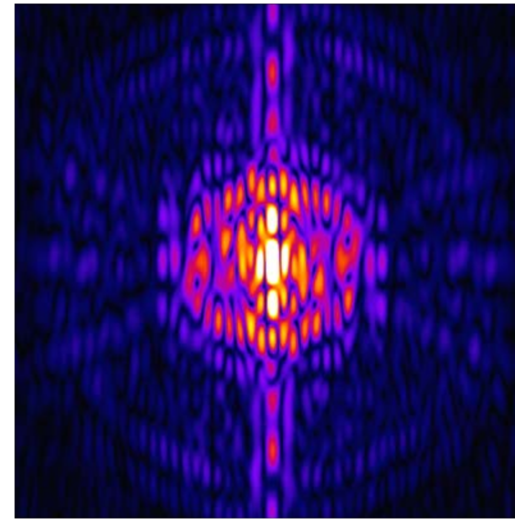


High resolution imaging of non-crystaline nanospecimen on the single particle level

Phase problem: reconstruction of the strucuture often not uniquely defined

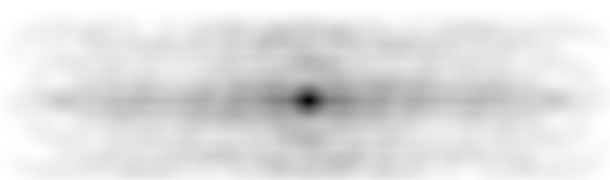
X-ray diffraction imaging

image



Inverse FFT

reconstruction



Coherent X-ray diffraction imaging: phase information is (almost) lost, need for complex iterative algorithms

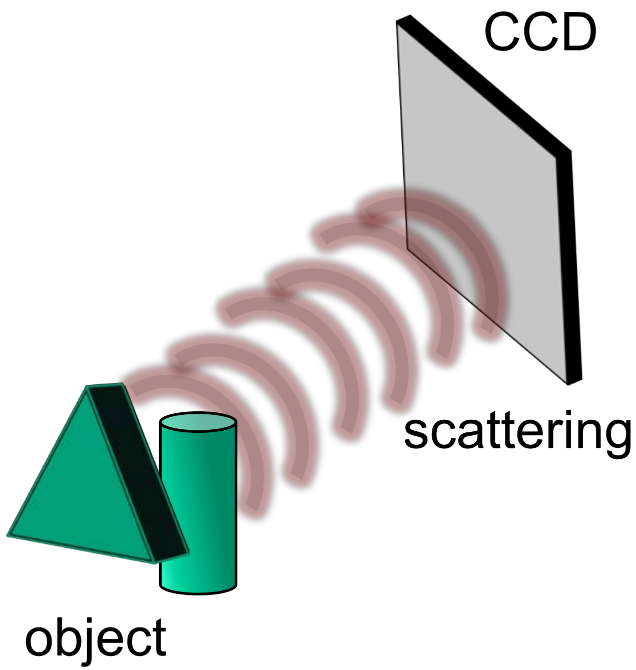
$$I(x,y)$$

$$= |\psi_s(x,y)|^2$$

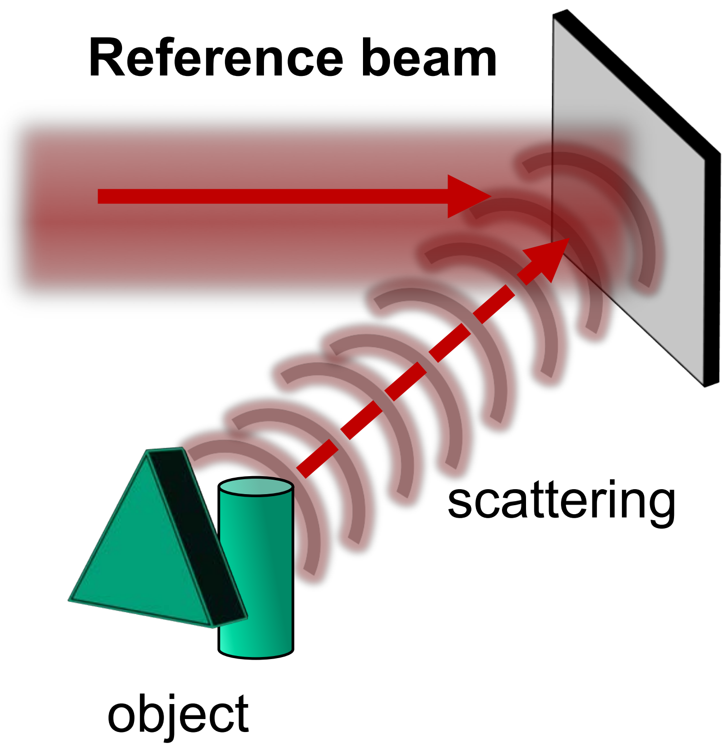
$$= \left|A_s(x,y)e^{i\varphi_s(x,y)}\right|^2 = |A_s(x,y)|^2$$

Overcoming the phase problem

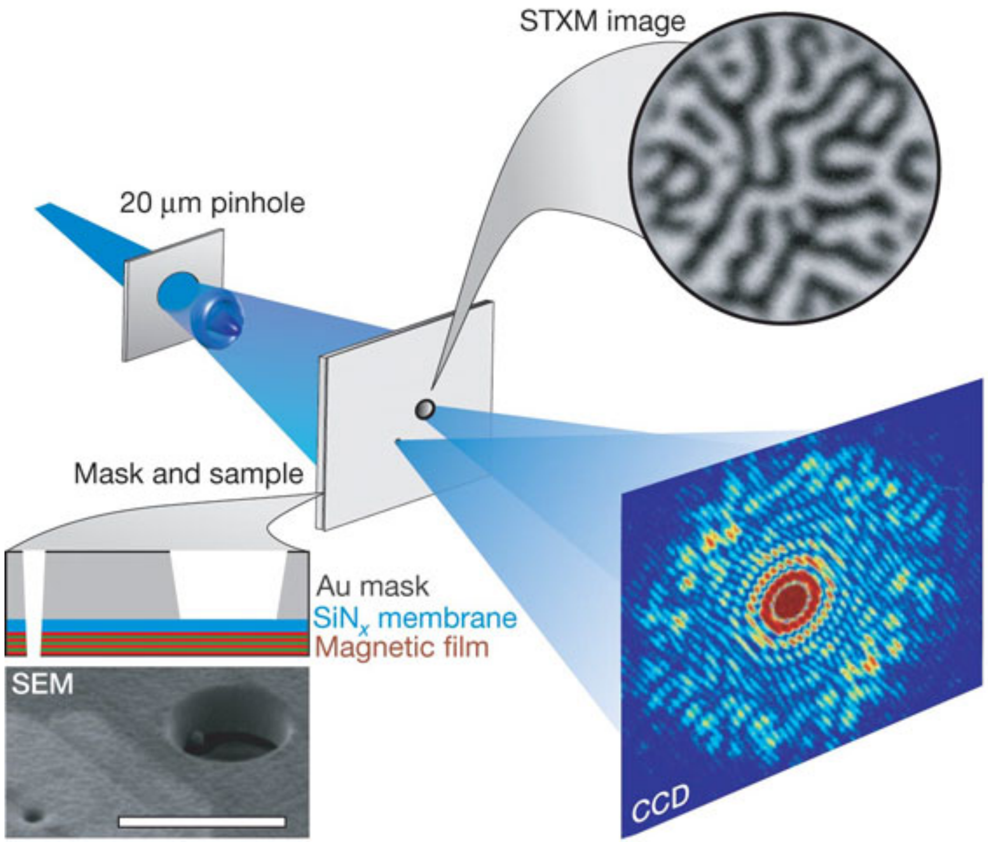
Coherent imaging diffraction



Holography



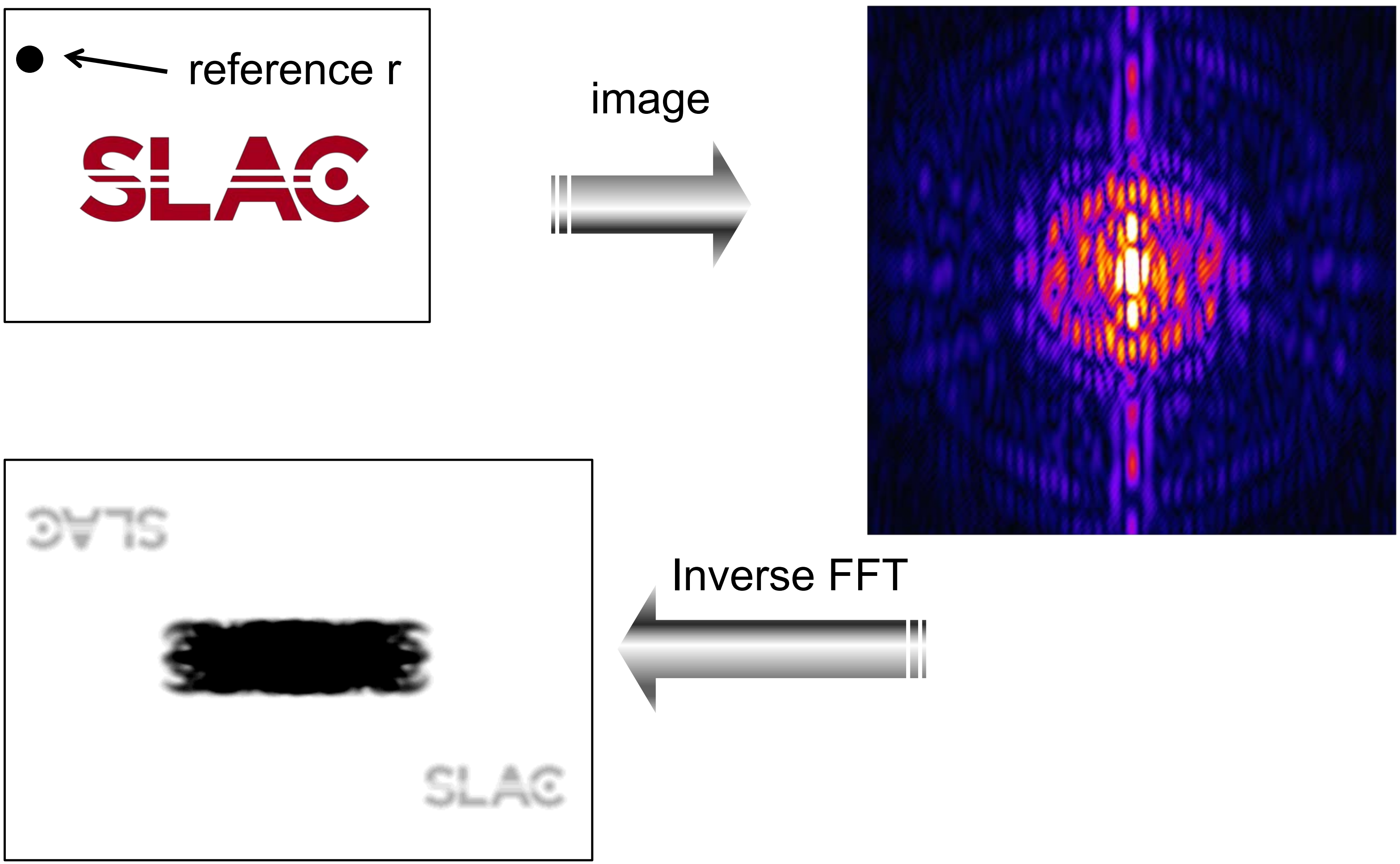
Lenseless X-ray Fourier holography



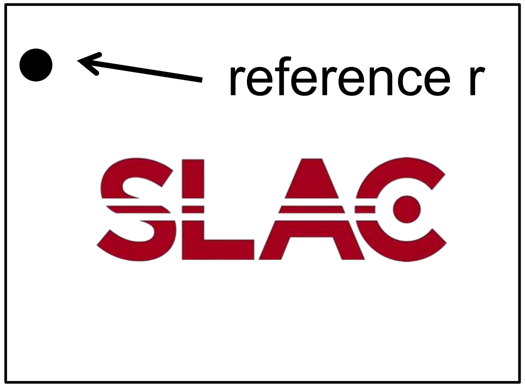
Eisebitt,S., et al., Nature **432**, 885 (2004)

Encoding the phase information directly into the image!

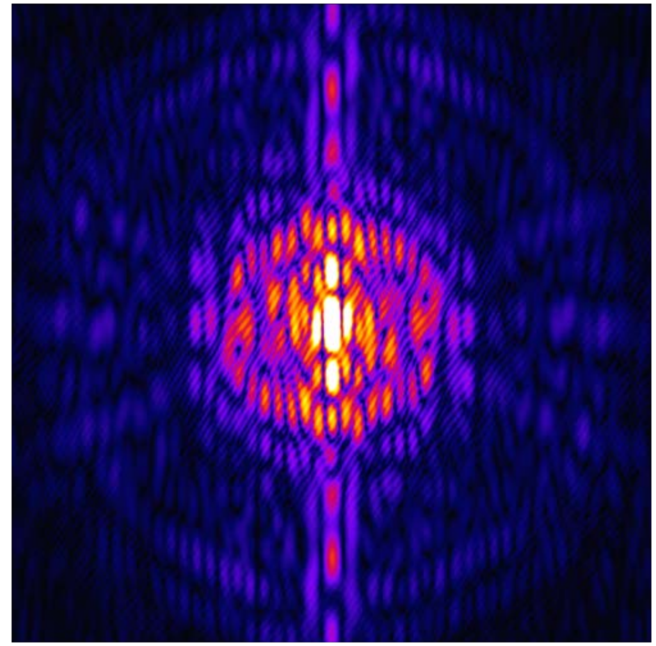
Lenseless X-ray Fourier holography



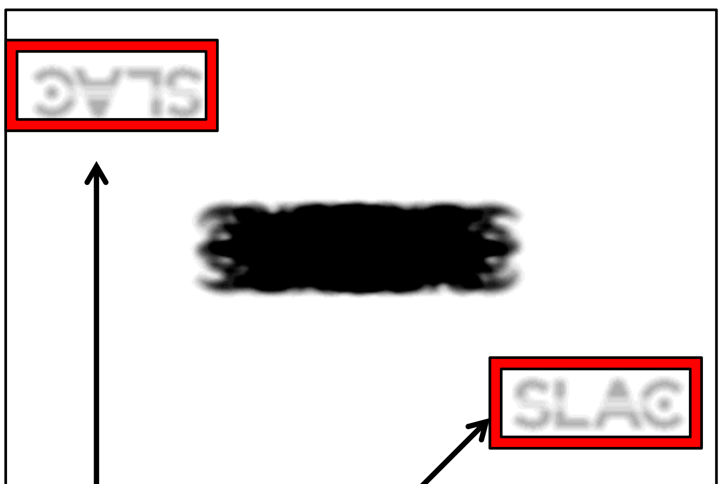
Lenseless X-ray Fourier holography



image



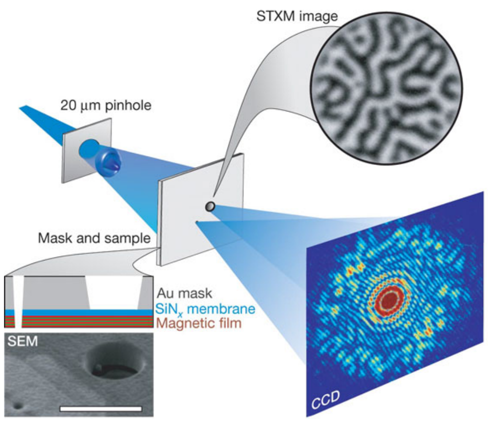
Inverse FFT



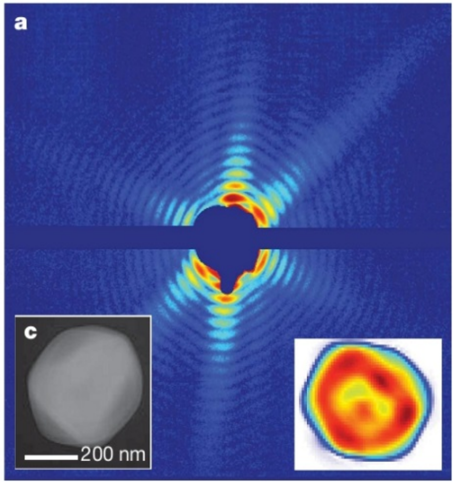
cross correlation terms

$$
\begin{aligned}
&= |\mathcal{F}\{r+o\}|^2 \\
&= |R+O|^2 \\
&= |R|^2 + |O|^2 + OR^* + RO^*
\end{aligned}
$$

Motivation for „in-flight“ holography



+



Eisebitt,S., et al., Nature **432**, 885 (2004)
Geilhufe,J. et al., Nature Communications 5, 3008 (2014)

M. M. Seibert et al., Nature 470, 78 (2011)

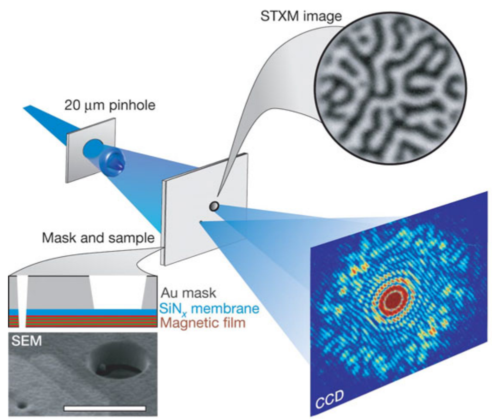
X-ray Fourier holography

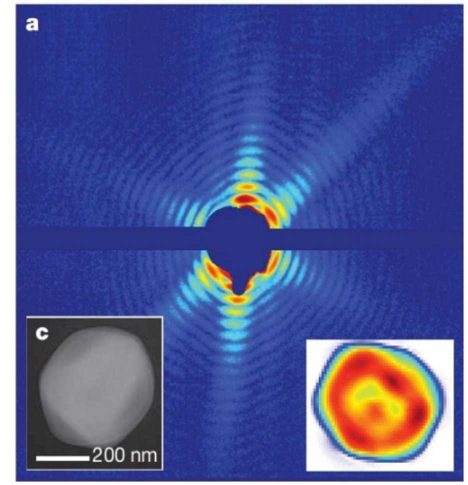
Single nanoparticle imaging

=

?

„In-flight“ holography





Eisebitt,S., et al., Nature **432**, 885 (2004)

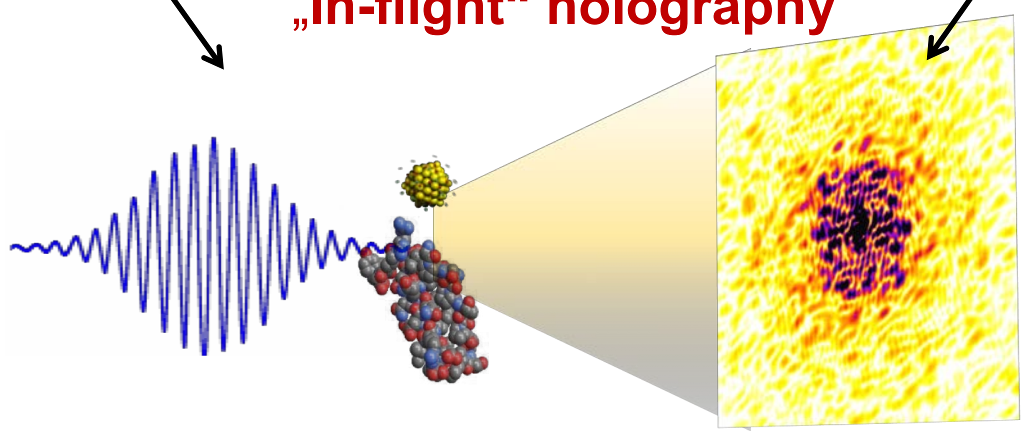
Geilhufe,J. et al., Nature Communications 5, 3008 (2014)

M. M. Seibert et al., Nature 470, 78 (2011)

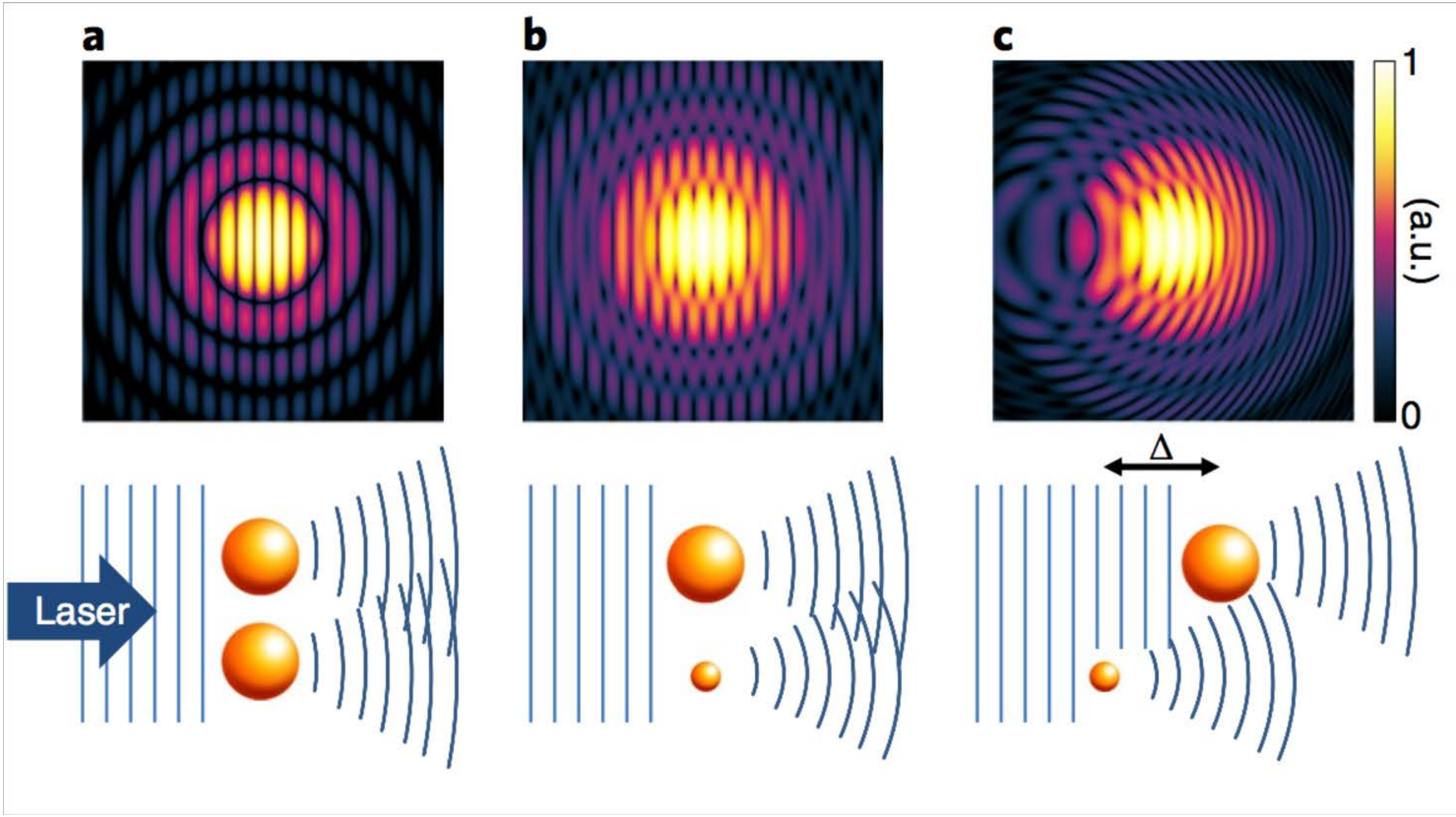
X-ray Fourier holography

Single nanoparticle imaging

„In-flight“ holography

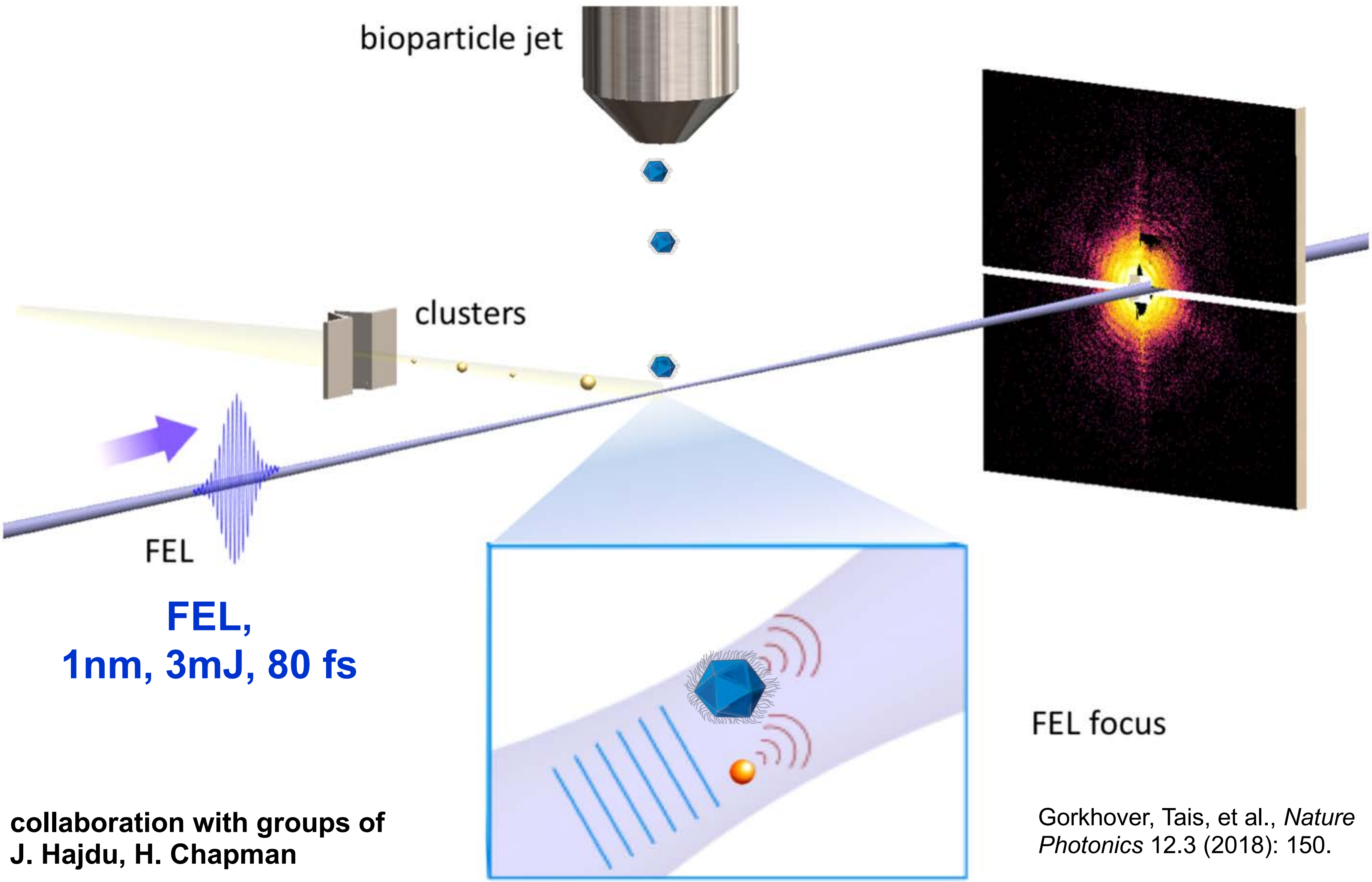


In-flight holography principle



Gorkhover, Tais, et al., *Nature Photonics* 12.3 (2018): 150.

Experimental setup in LAMP



FEL,
1nm, 3mJ, 80 fs

collaboration with groups of J. Hajdu, H. Chapman

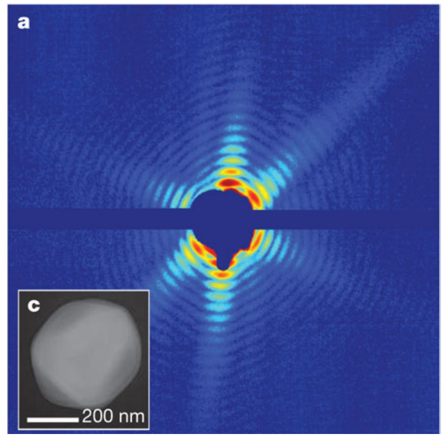
Gorkhover, Tais, et al., *Nature Photonics* 12.3 (2018): 150.

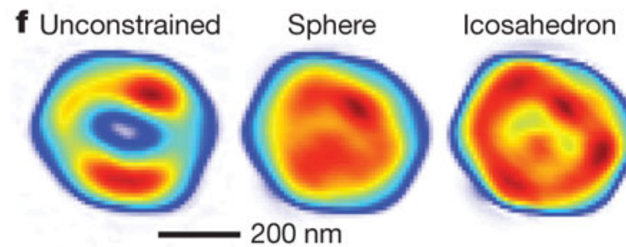
Comparison with phase retrieval

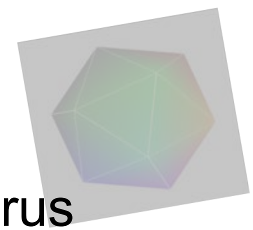
diffraction

reconstruction

without holography

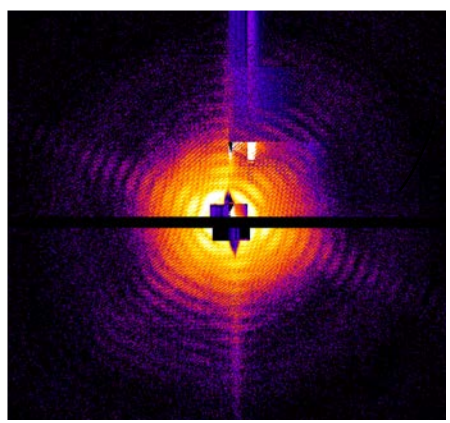


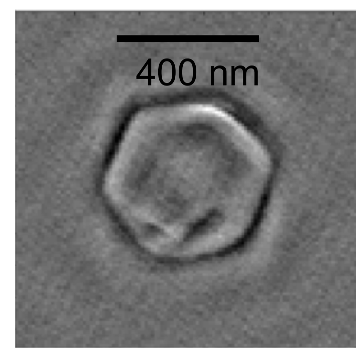




Mimi virus

with holography

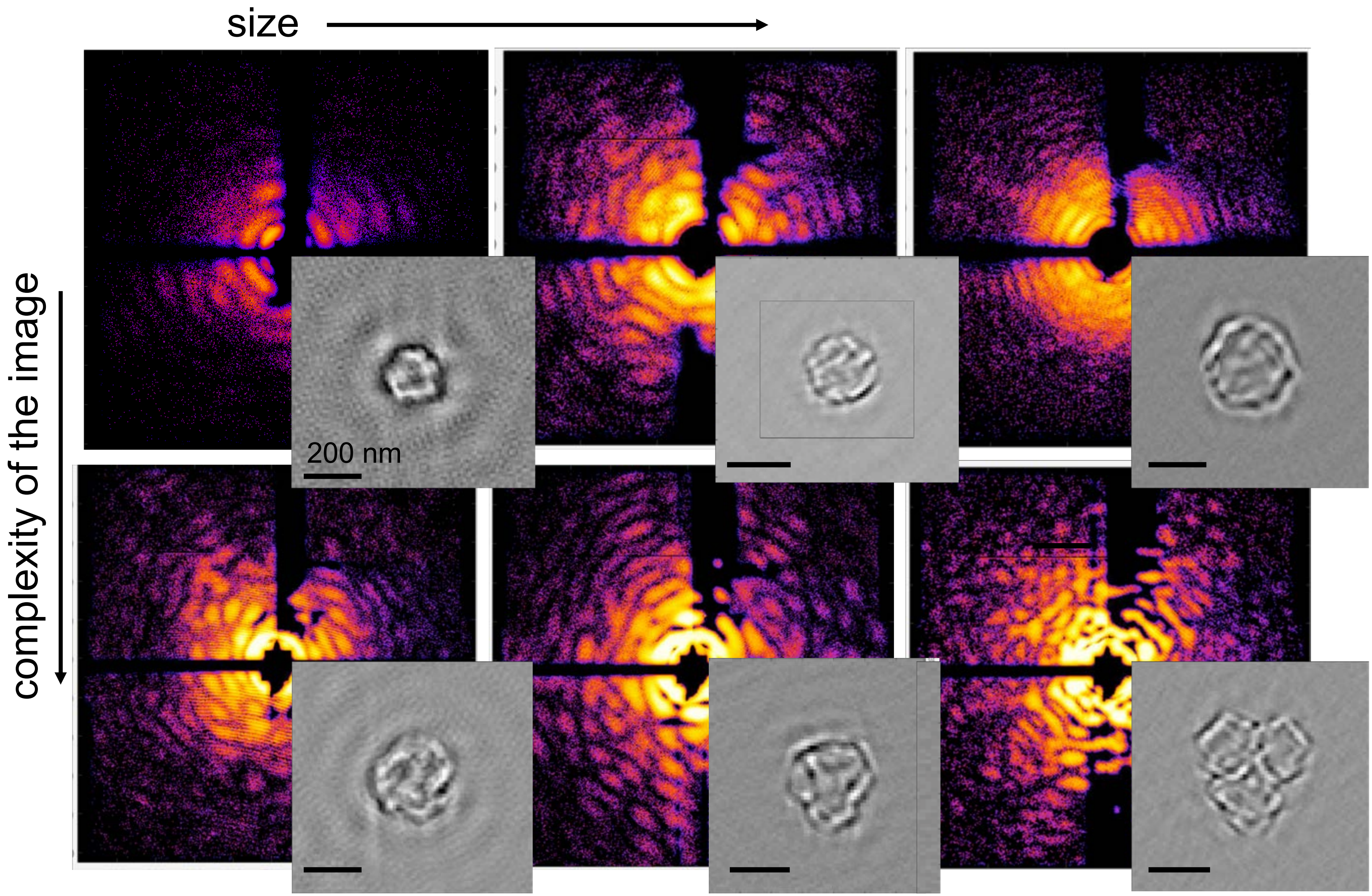




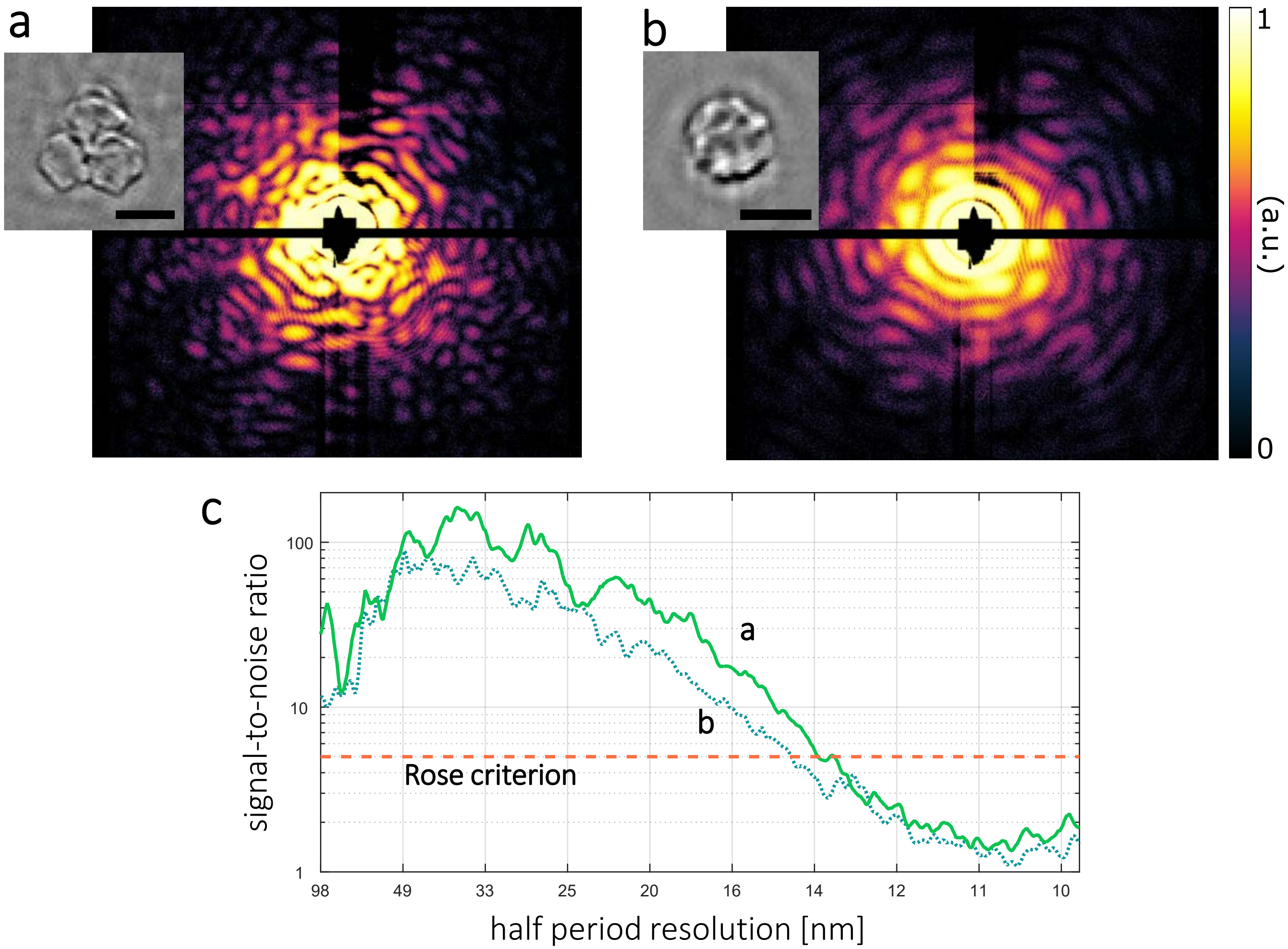
Gorkhover, Tais, et al., *Nature Photonics* 12.3 (2018): 150.

Seibert *et al. Nature* **470**, 78-81 (2011) doi:10.1038/nature09748

Inhomogeneuos sample set

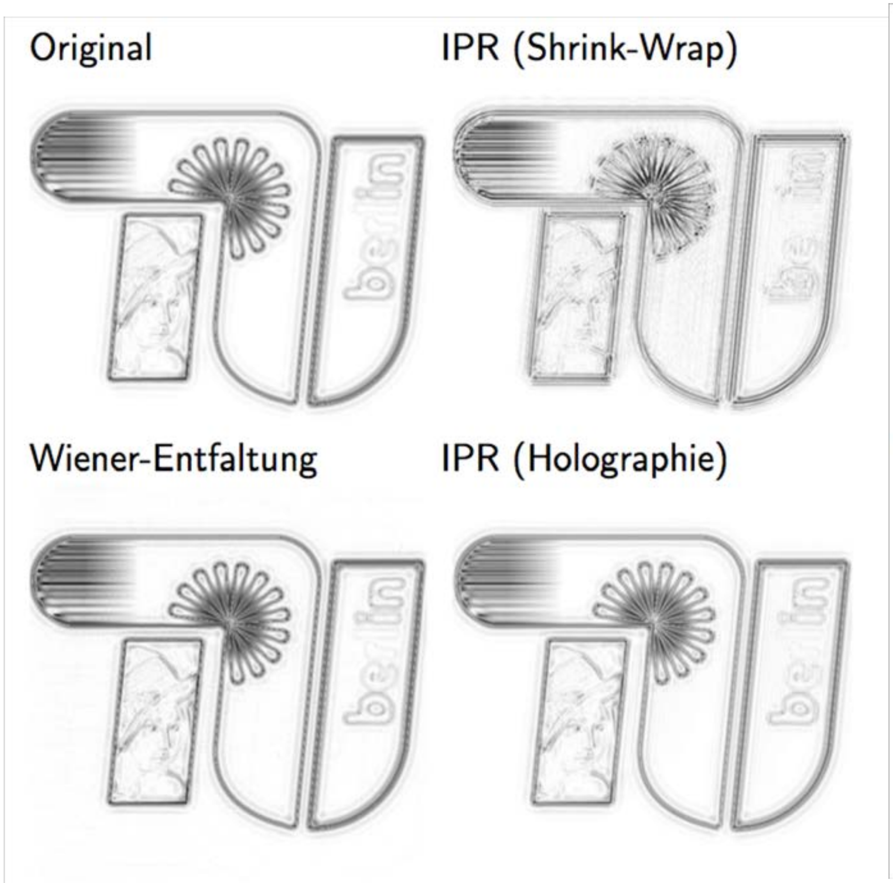


Resolution

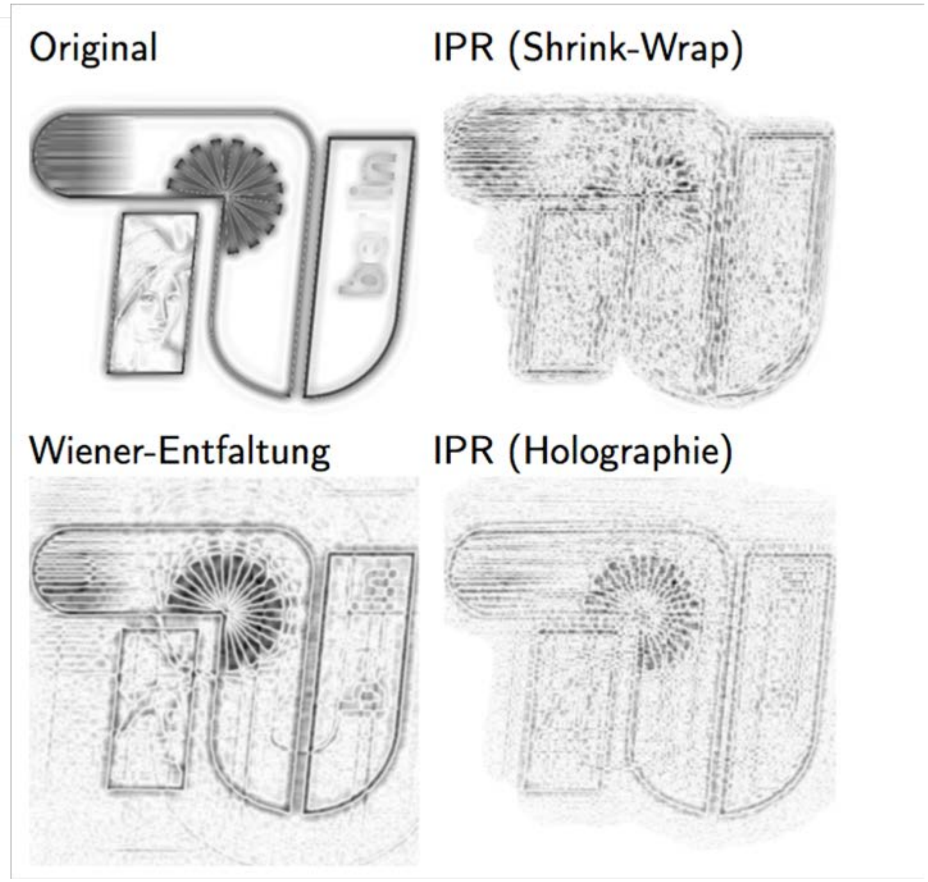


Gorkhover, Tais, et al., *Nature Photonics* 12.3 (2018): 150.

Holography is robust to noise and imperfections

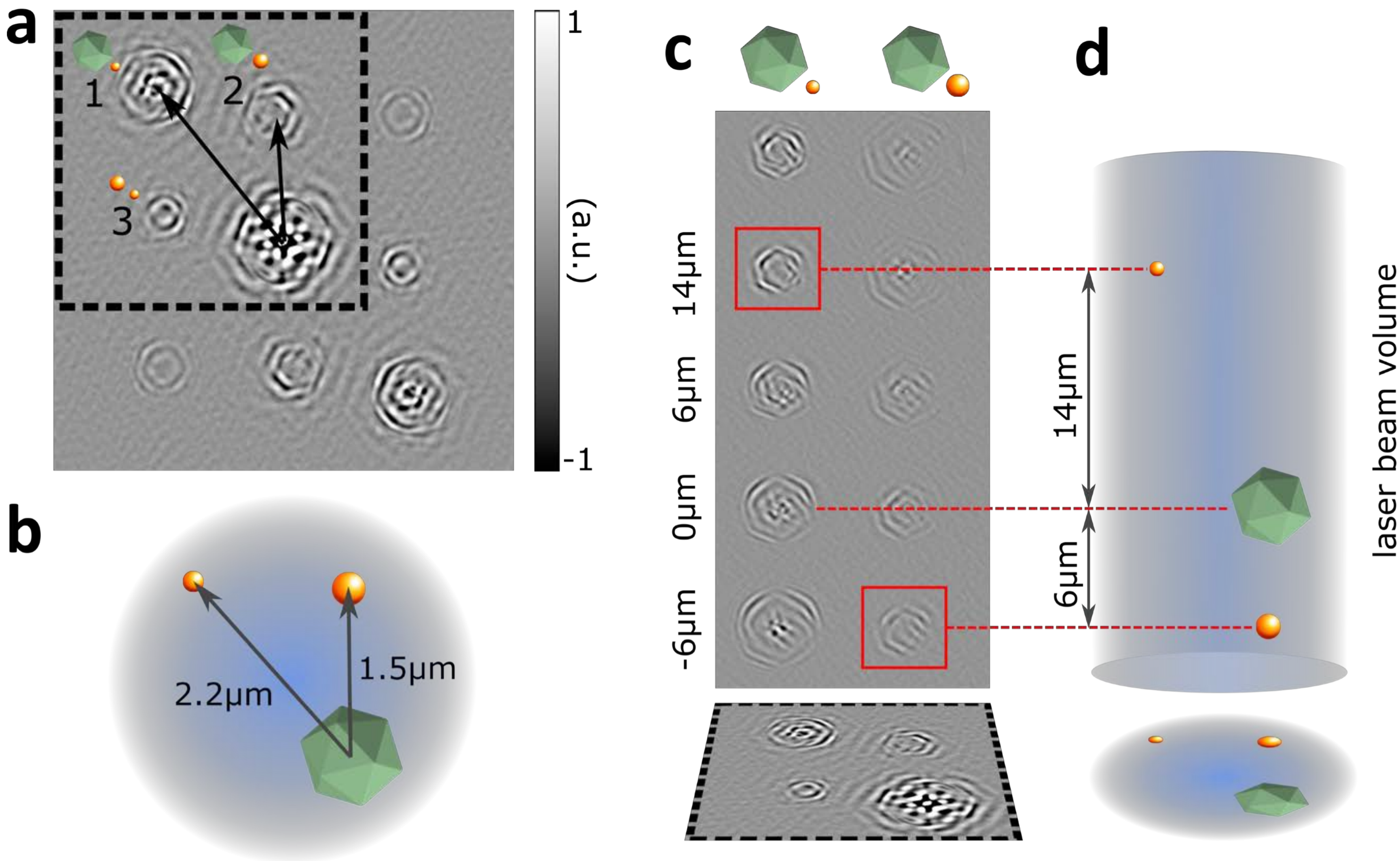


missing information



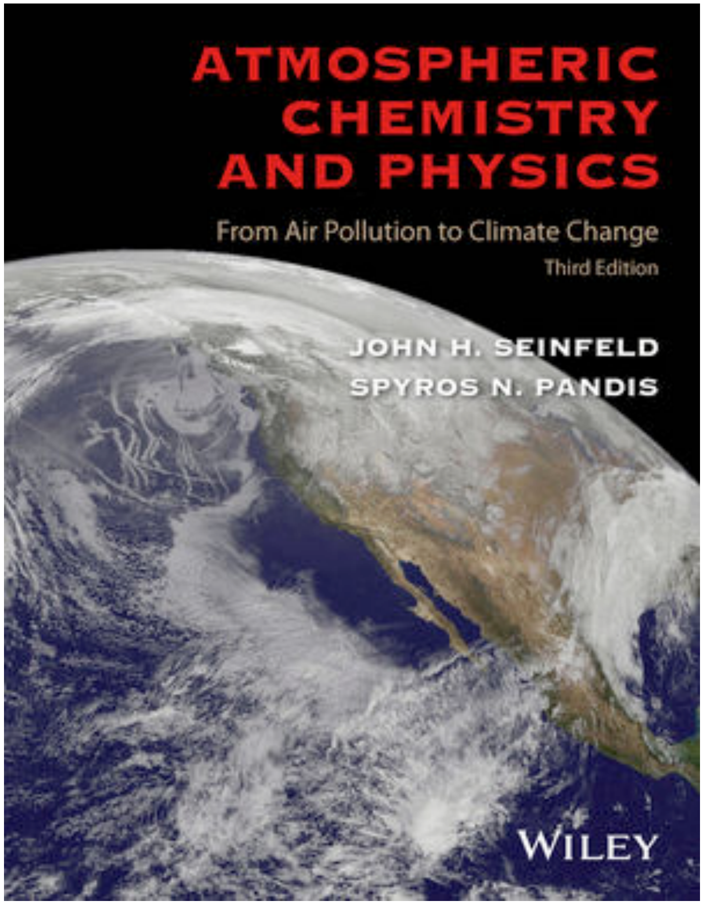
high noise level

3D walk through the FEL focus

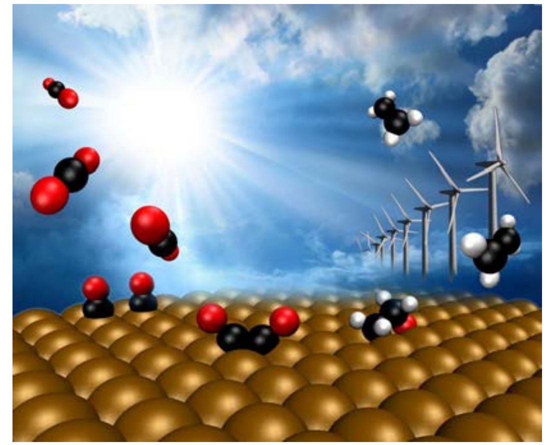


Gorkhover, Tais, et al., *Nature Photonics* 12.3 (2018): 150.

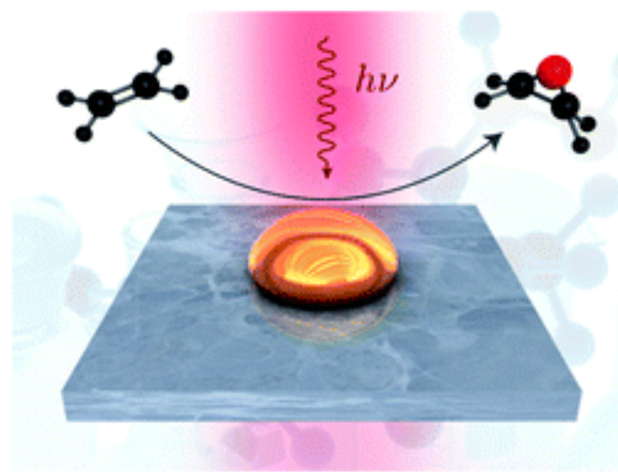
Application and outlook



Nucleation dynamics



Catalysis



Nanoplasmonics

SLAC NATIONAL ACCELERATOR LABORATORY

PULSE

Can we reach atomic resolution at single particle level?

These rather high dose densities are difficult to obtain with current and even upcoming x-ray sources. Here, we estimate under which experimental conditions individual atoms can be detected in a molecule or cluster using a single pulse of the XFEL without any additional chemical knowledge. Assuming a fixed coherent dose of about $D_c = 10^{12}$ photons pulse^{-1} for a free-electron laser source, this requires lossless focusing to an area of

$$A = \frac{D_c}{I_c \Delta t}.$$

already there

To detect single carbon atoms, the focused area must be smaller than $A \approx 10\,\mathrm{nm}^2$. Likewise, for gold atoms, the focused area must be below $A \approx 2000\,\mathrm{nm}^2$. For a circular focus, this corresponds to a focus diameter of $\approx 4\,\mathrm{nm}$ for carbon and $\approx 50\,\mathrm{nm}$ for gold. For one thing, this limits the

New Journal of Physics
The open-access journal for physics

Dose requirements for resolving a given feature in an object by coherent x-ray diffraction imaging

Andreas Schropp[1] and Christian G Schroer
Institute of Structural Physics, Technische Universität Dresden, D-01062 Dresden, Germany
E-mail: schropp@xray-lens.de

2010

2018: we can achieve d= 60-80 nm

In theory, we should be able to achieve atomic resolution for heavy atoms metal

Seiboth, F. *et al*. Perfect X-ray focusing via fitting corrective glasses to aberrated optics. *Nat. Commun.* **8**, 14623 (2017)

Can we reach atomic resolution at single particle level?

These rather high dose densities are
x-ray sources. Here, we estimate under w
be detected in a molecule or cluster using
chemical knowledge. Assuming a fixed coh
free-electron laser source, this requires loss

$$A = \frac{D_c}{I_c \Delta t}.$$

To detect single carbon atoms, the focused
gold atoms, the focused area must be below
to a focus diameter of ≈ 4 nm for carbon

New Journal of Physic
The open-access journal for physics

Dose requirements for resolving a given feature in object by coherent x-ray diffraction imaging

Andreas Schropp[1] and Christian G Schroer
Institute of Structural Physics, Technische Universität Dresden, D-01062 Dresden, Germany
E-mail: schropp@xray-lens.de

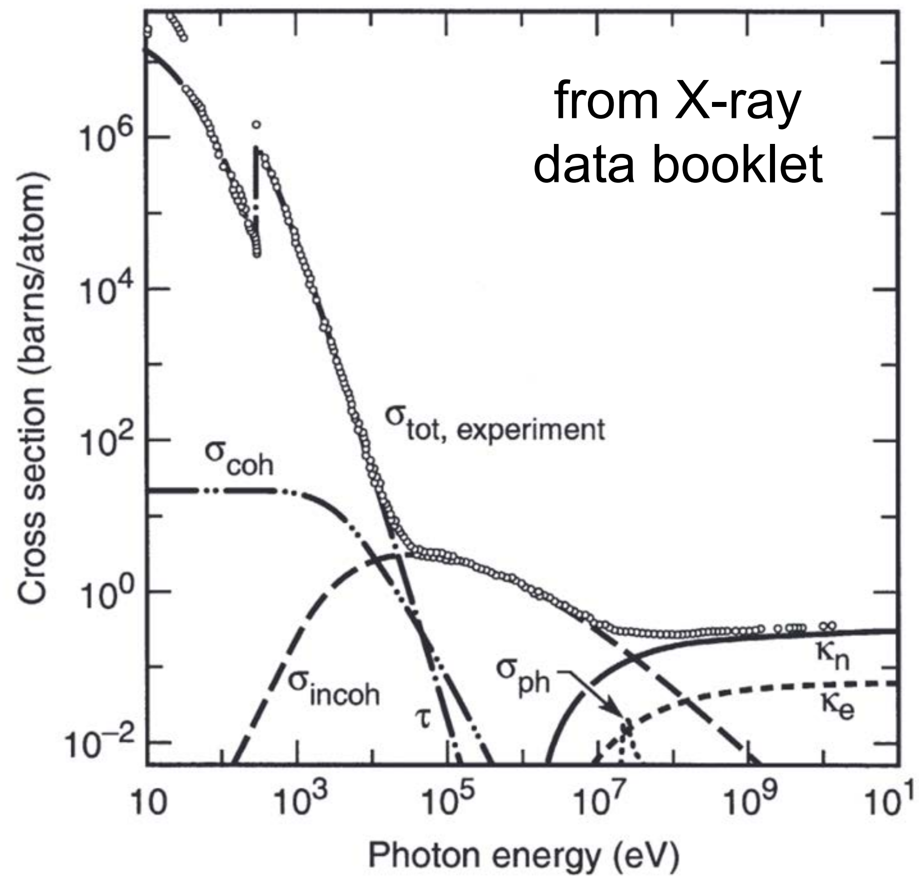
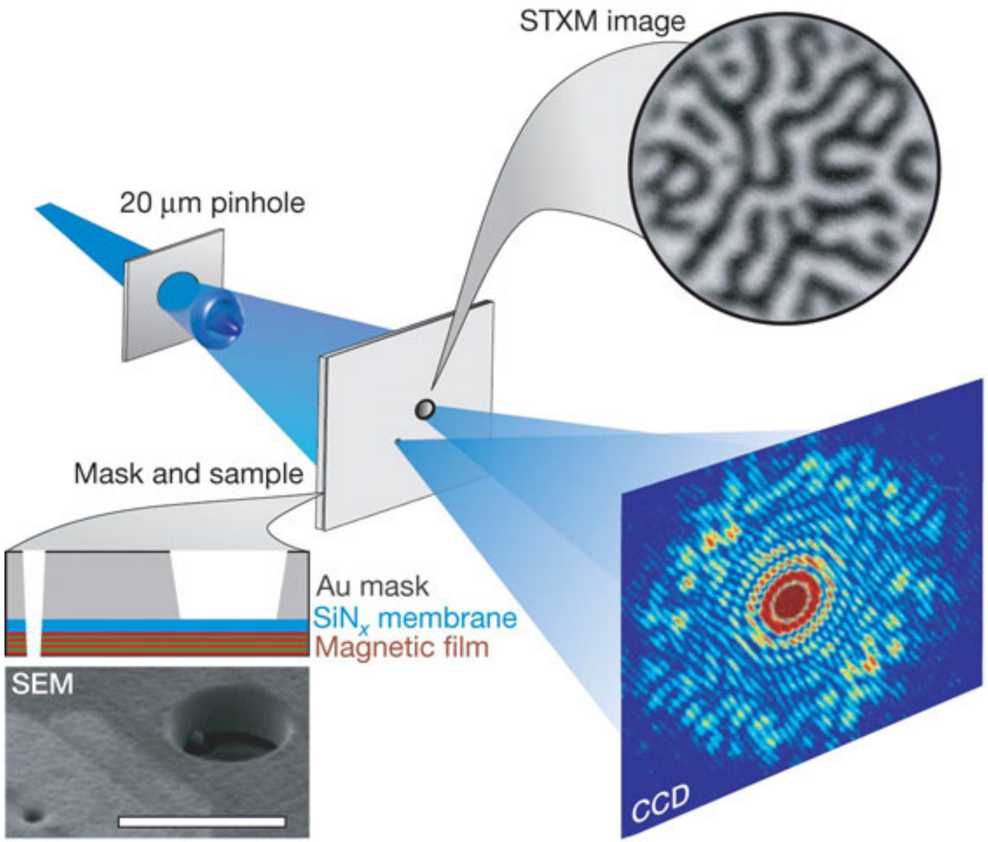


Fig. 3-1. *Total photon cross section σ_{tot} in carbon, as a*

Seiboth, F. *et al*. Perfect X-ray focusing via fitting corrective glasses to aberrated optics. *Nat. Commun.* **8**, 14623 (2017)

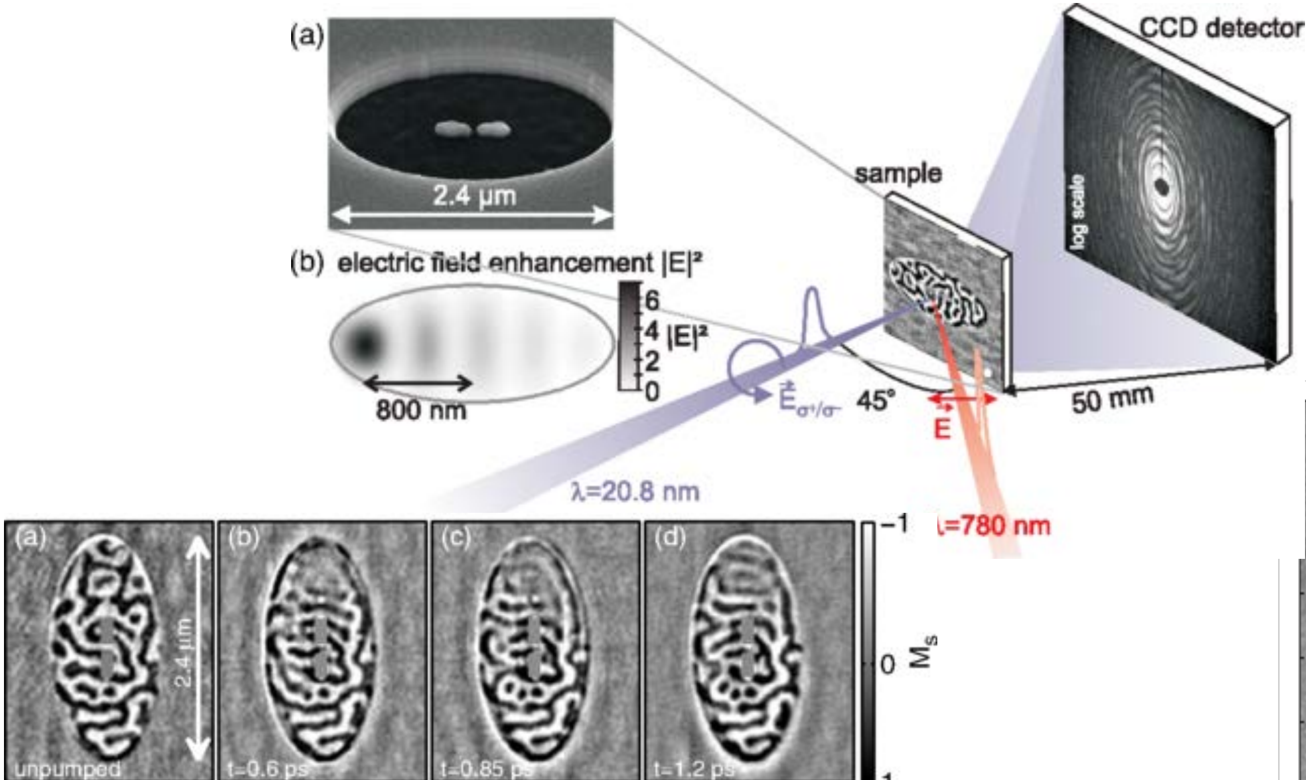
Soft X-ray synchrotron study (2004)

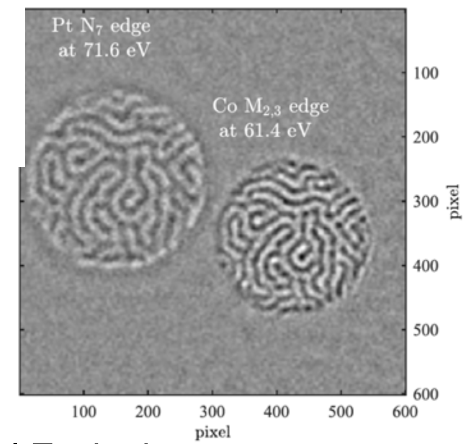


Eisebitt,S., et al., Nature **432**, 885 (2004)

Encoding the phase information directly into the image!

EUV FEL 2014- today

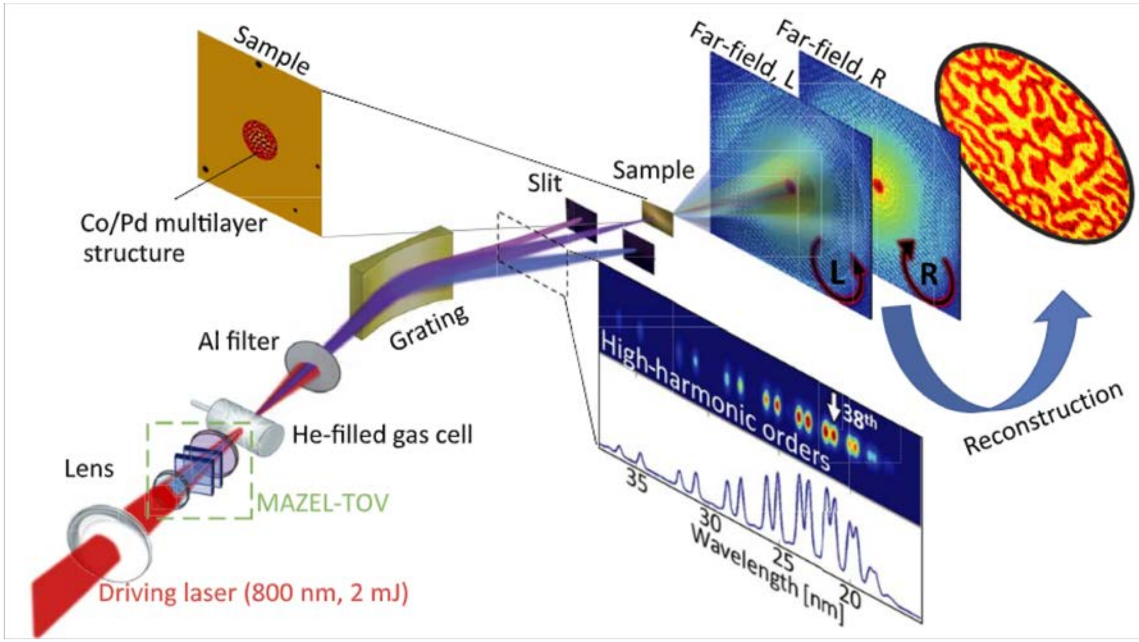




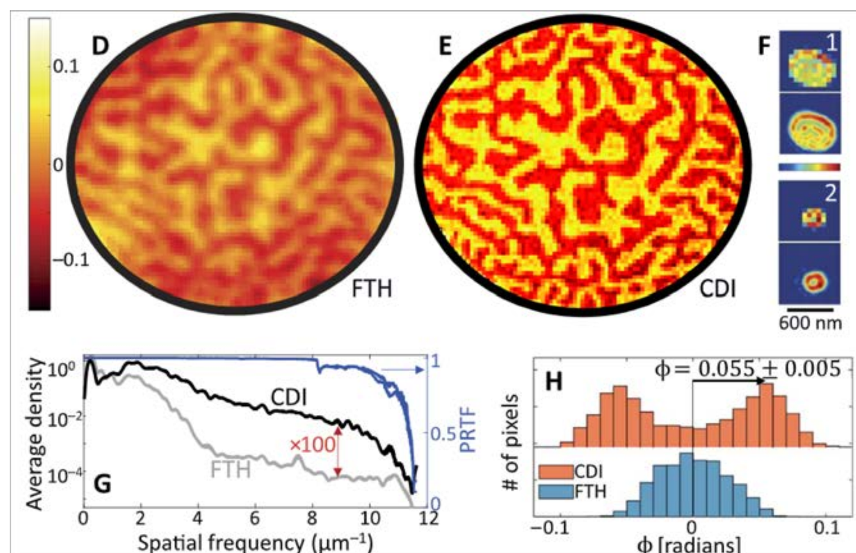
Imaging Ultrafast Demagnetization Dynamics after a Spatially Localized Optical Excitation
C. von Korff Schmising, B. Pfau, M. Schneider, C. M. Günther, M. Giovannella, J. Perron, B. Vodungbo, L. Müller, F. Capotondi, E. Pedersoli, N. Mahne, J. Lüning, and S. Eisebitt
Phys. Rev. Lett. **112**, 217203 – Published 29 May 2014

Multi-color imaging of magnetic Co/Pt heterostructures
Willems, Felix, Clemens von Korff Schmising, David Weder, Christian M. Günther, Michael Schneider, Bastian Pfau, Sven Meise et al. *Structural Dynamics* 4, no. 1 (2017): 014301.

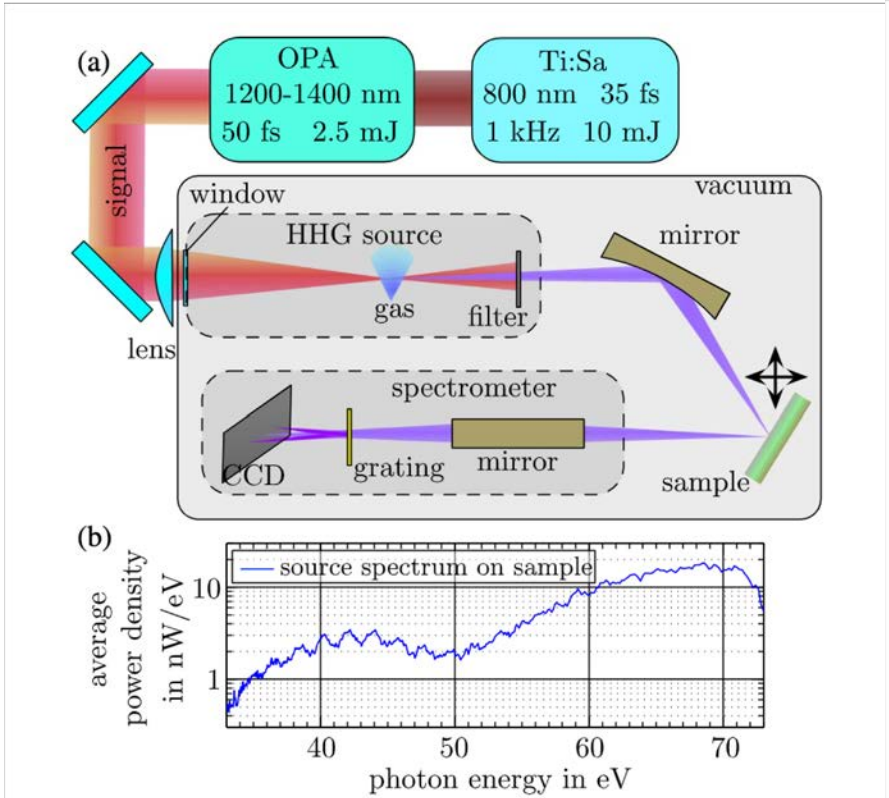
EUV HHG source - 2017

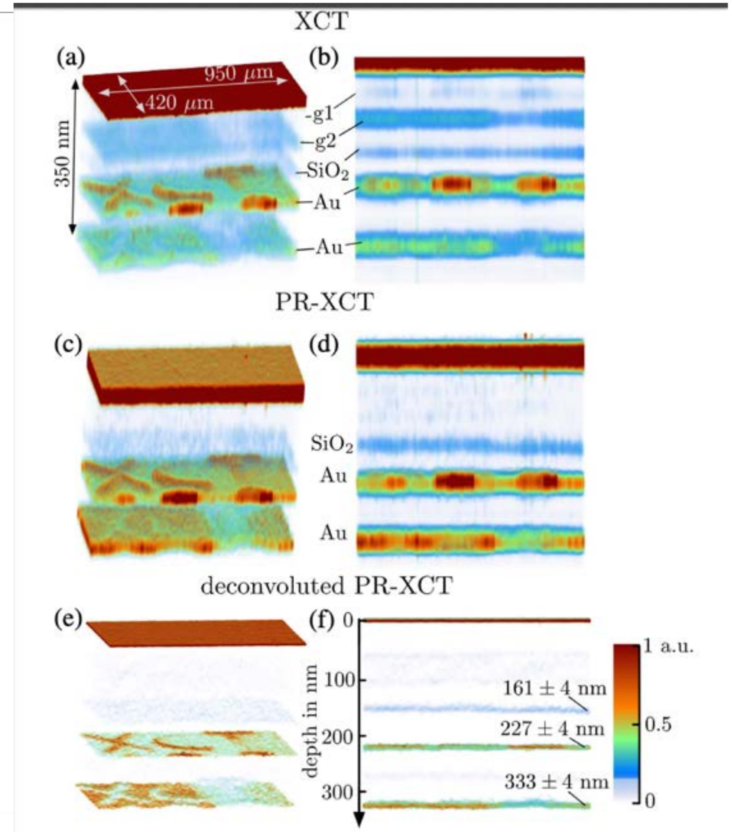


Kfir, Ofer, et al. "Nanoscale magnetic imaging using circularly polarized high-harmonic radiation." *Science advances* 3.12 (2017): eaao4641.



3D imaging still challenging





Fuchs, Silvio, et al. "Optical coherence tomography with nanoscale axial resolution using a laser-driven high-harmonic source." *Optica* 4.8 (2017): 903-906.

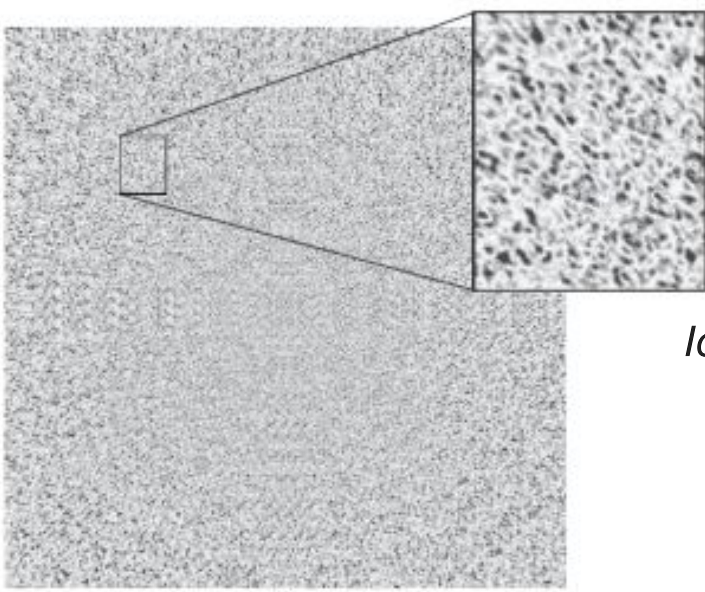
Imaging using new properties of intense, few or sub-femtosecond pulses

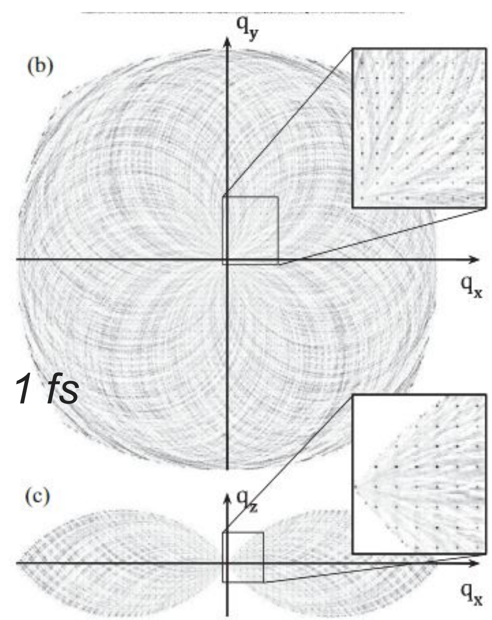
PRL **119,** 053401 (2017) PHYSICAL REVIEW LETTERS week ending 4 AUGUST 2017

Incoherent Diffractive Imaging via Intensity Correlations of Hard X Rays

Anton Classen,[1,2] Kartik Ayyer,[3] Henry N. Chapman,[3,4,5] Ralf Röhlsberger,[5,6] and Joachim von Zanthier[1,2,*]
[1]*Institut für Optik, Information und Photonik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany*
[2]*Erlangen Graduate School in Advanced Optical Technologies (SAOT), Universität Erlangen-Nürnberg, 91052 Erlangen, Germany*
[3]*Center for Free-Electron Laser Science, Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
[4]*Department Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
[5]*The Hamburg Centre for Ultrafast Imaging, Luruper Chaussee 149, 22761 Hamburg, Germany*
[6]*Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*
(Received 24 May 2017; published 31 July 2017)

(a)





Ideal for X-ray pulses < 1 fs