Fourier Transform Holography

Single Shot Imaging on a Photon Budget

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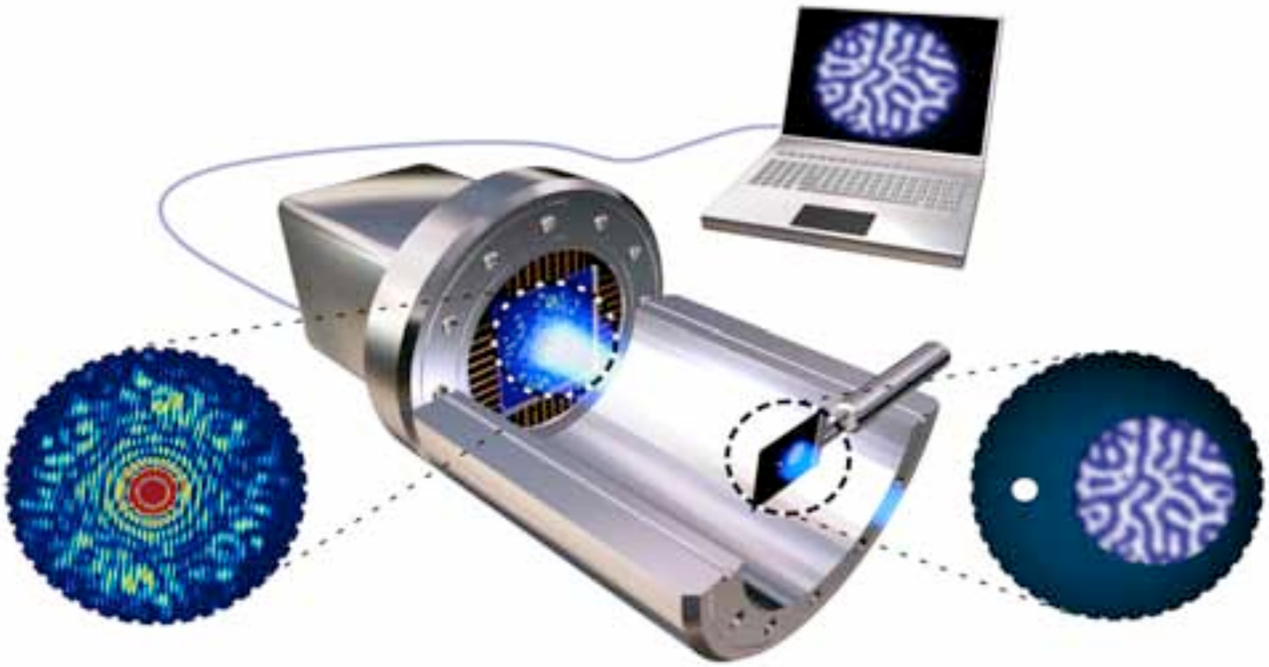
The General Idea

- Lensless imaging with soft x-rays
- Fourier transform holography
- High spatial resolution
- Full field



Outline

- Motivation and the phase problem
- Fourier Transform Holography (FTH)
- Experimental Instruments
- Capabilities of FTH for stroboscopic imaging
  - Improve image quality
  - Extend the field of view
  - Record multiple image with a single pulse
  - Extend the dynamic range of detection

Synchrotron Light Sources

BESSY
Berlin, Germany

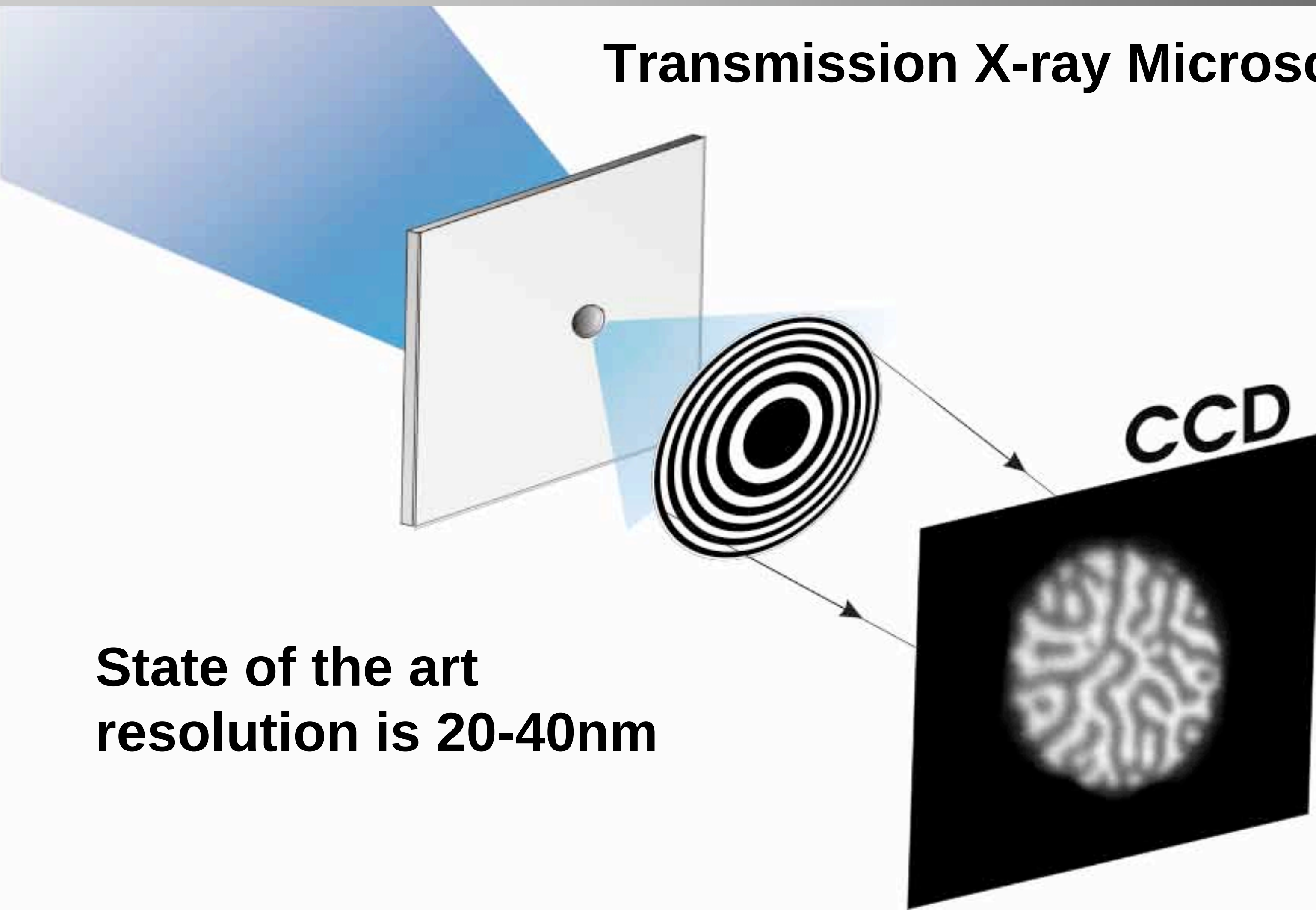
SSRL at SLAC
Menlo Park, California

Tunable light source:
- Energy
- Polarization

Soft x-rays:
- E=100eV – 1000 eV
- λ =12.4 nm – 1.2 nm

Full Field X-ray Microscopy – Real Space Imaging

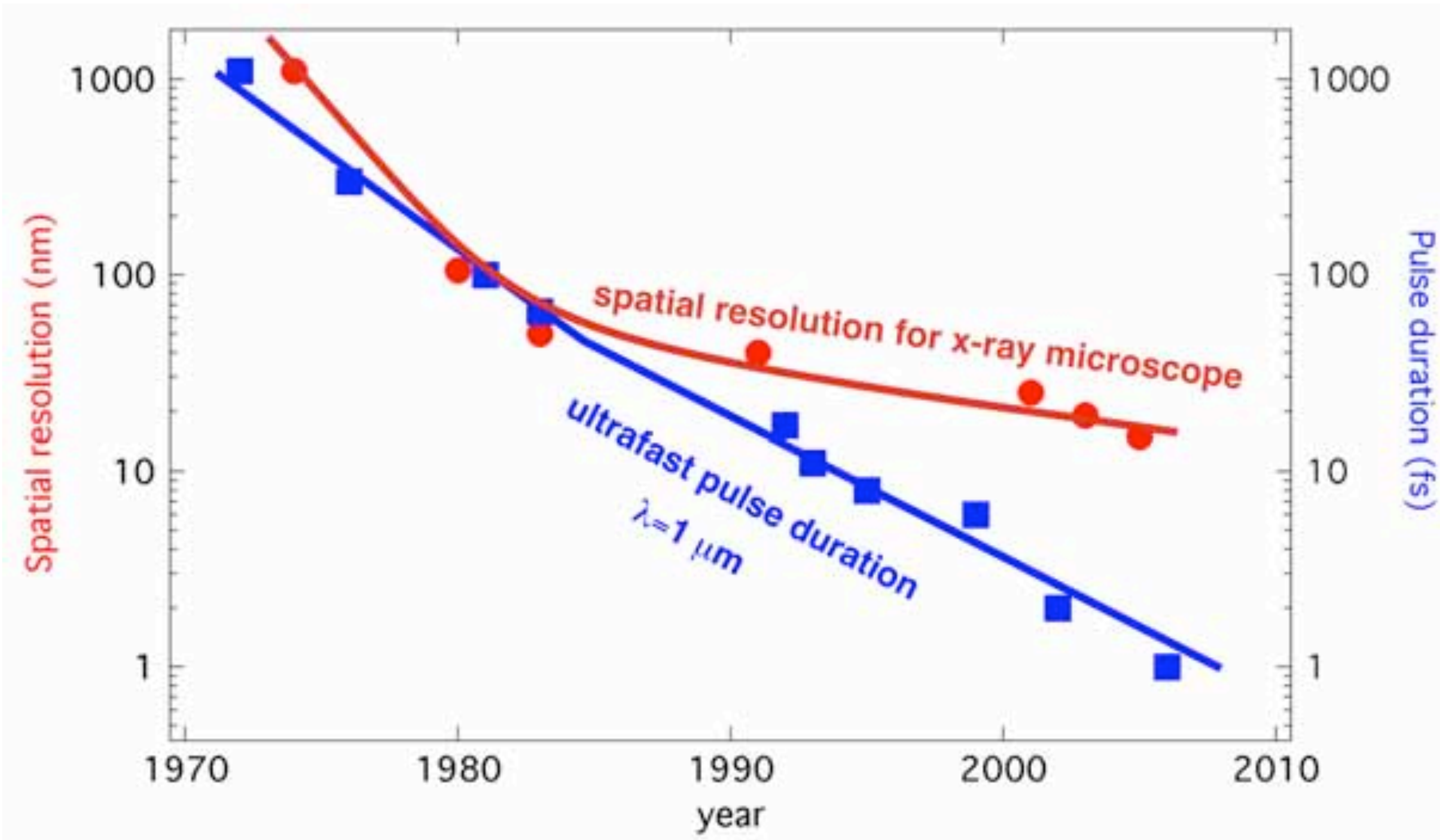
Transmission X-ray Microscopy



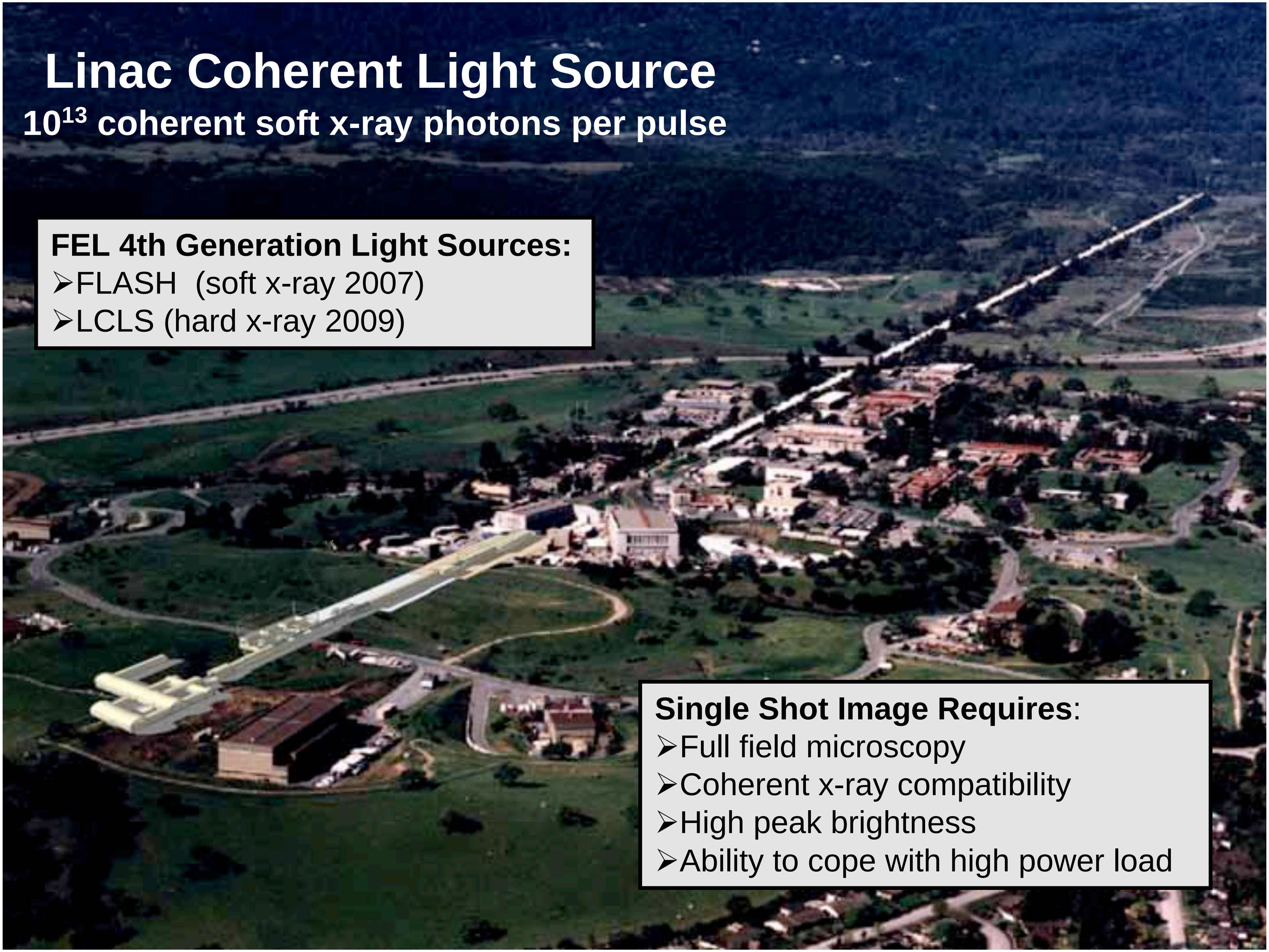
Magnetic Worm Domain Pattern

State of the art resolution is 20-40nm

Progress in the Ultrafast and Ultrasmall

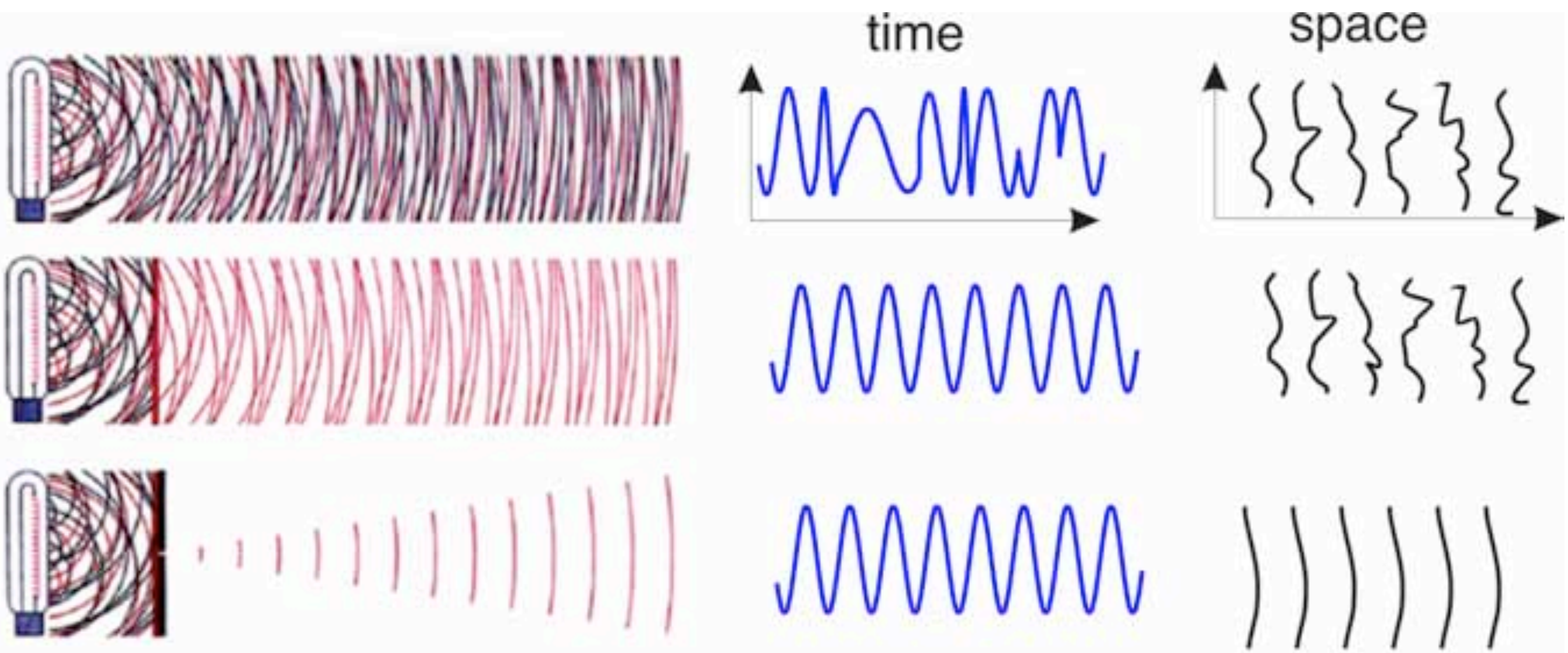


No ultrafast probe of structure on the nanoscale



Linac Coherent Light Source
10^13 coherent soft x-ray photons per pulse
FEL 4th Generation Light Sources:
➢FLASH (soft x-ray 2007)
➢LCLS (hard x-ray 2009)
Single Shot Image Requires:
➢Full field microscopy
➢Coherent x-ray compatibility
➢High peak brightness
➢Ability to cope with high power load

Coherence

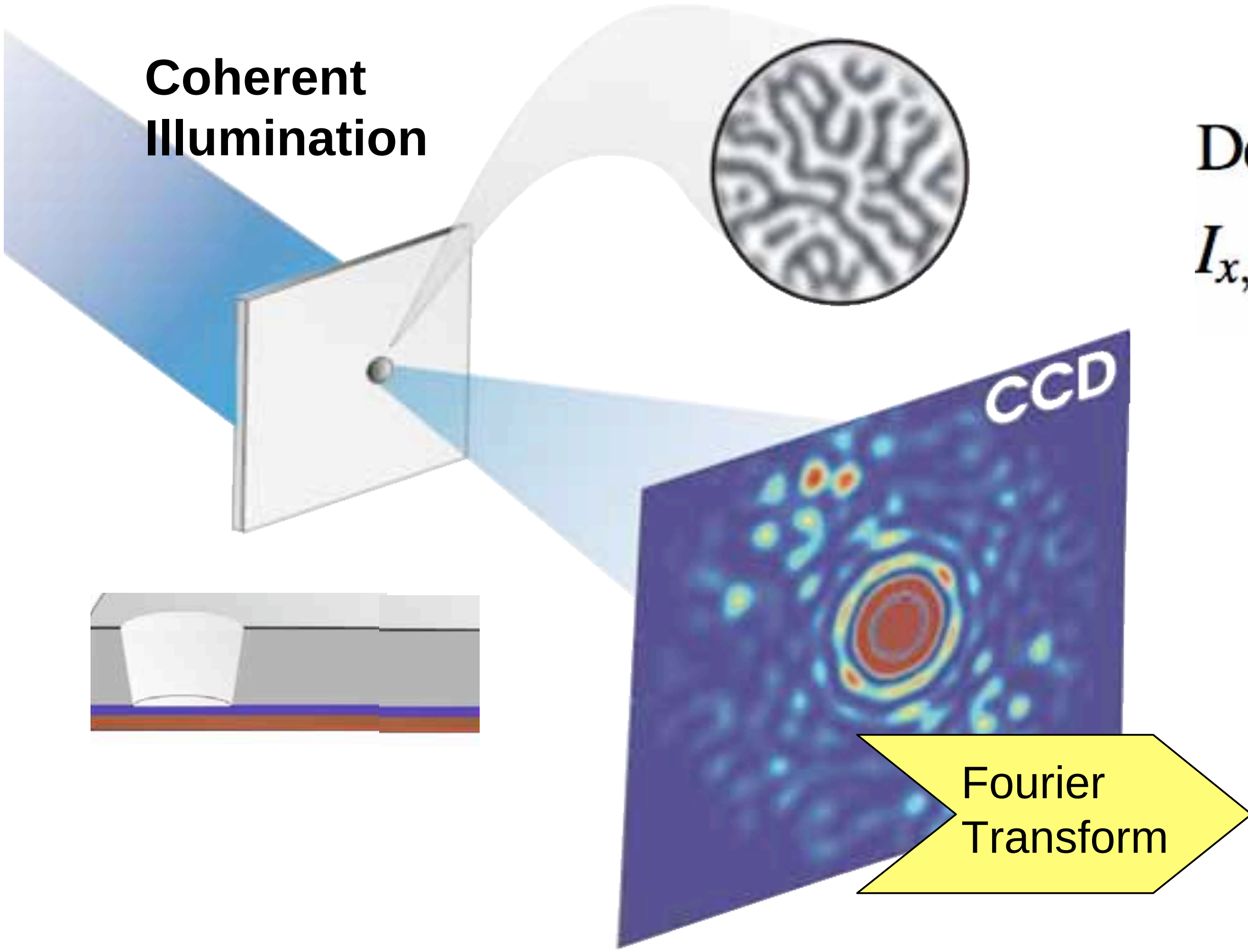


Adapted from
A. Schawlow
Sci. Am. **219**, 120 (1968)

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

$$\xi_t = \frac{\lambda z}{D}$$

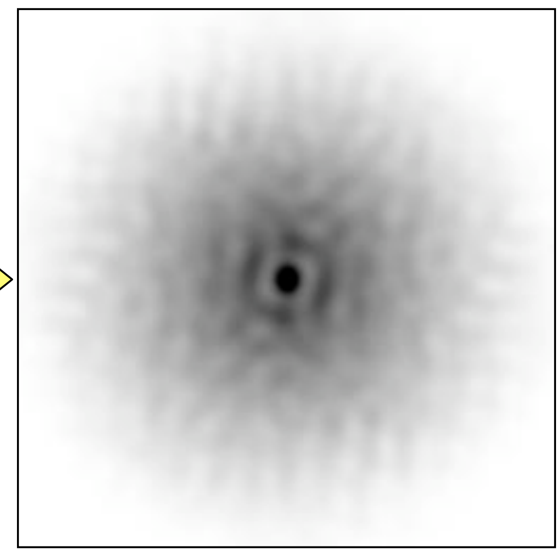
The Phase Problem



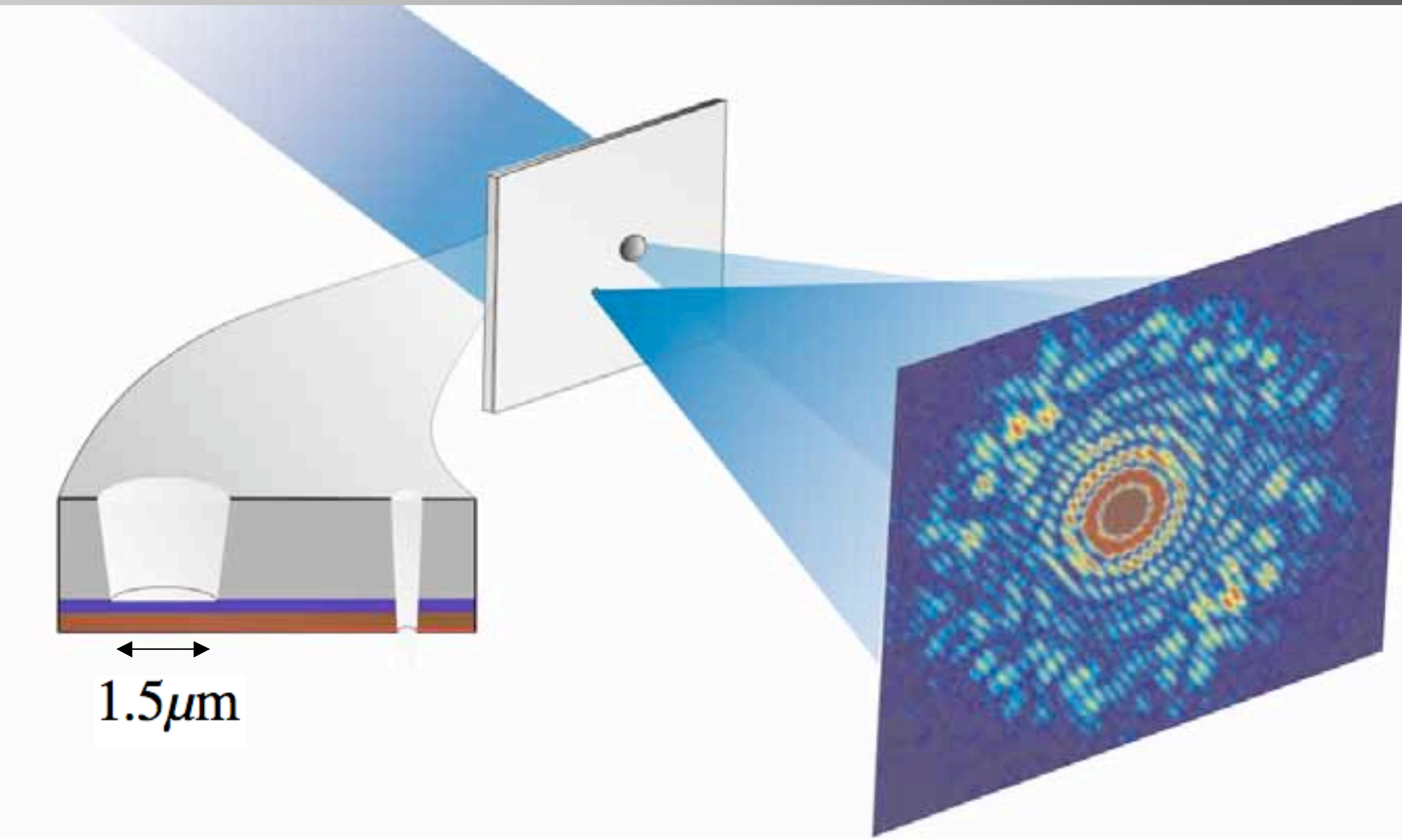
Detected Intensity

$$I_{x,y} = |A_{x,y}e^{i\phi_{x,y}}|^2$$

Autocorrelation



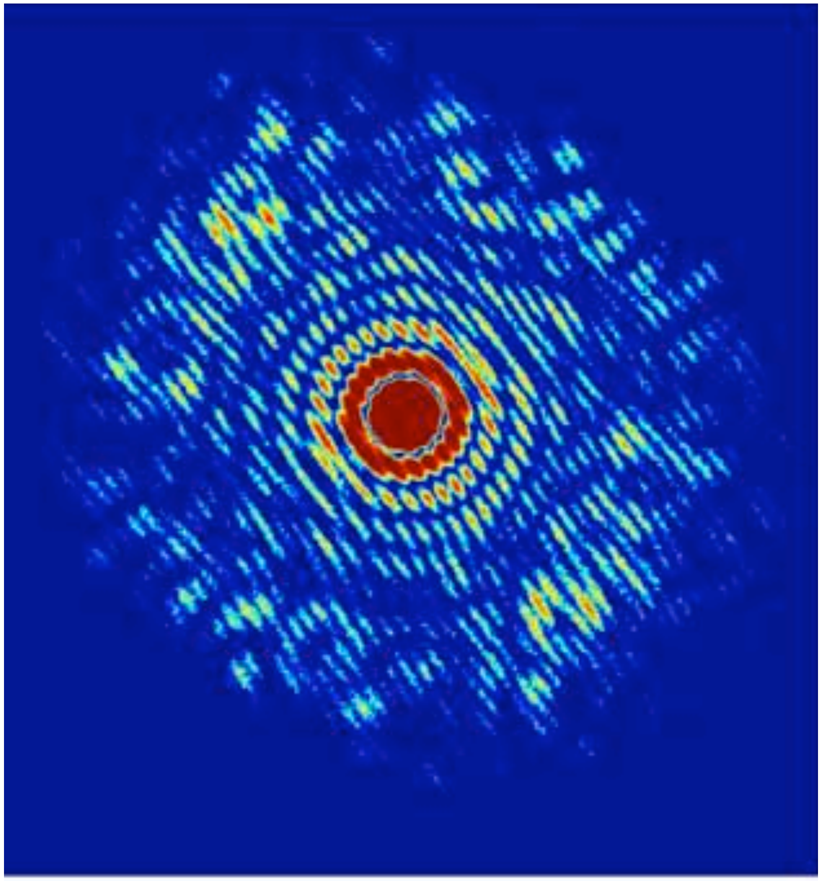
Fourier Transform Holography



S. Eisebitt, J. Lüning, W. F. Schlotter, M. Lörgen, O. Hellwig, W. Eberhardt, and J. Stöhr. Lensless Imaging of Magnetic Nanostructures by x-ray Spectro-holography. Nature, 432 p885, 2004.

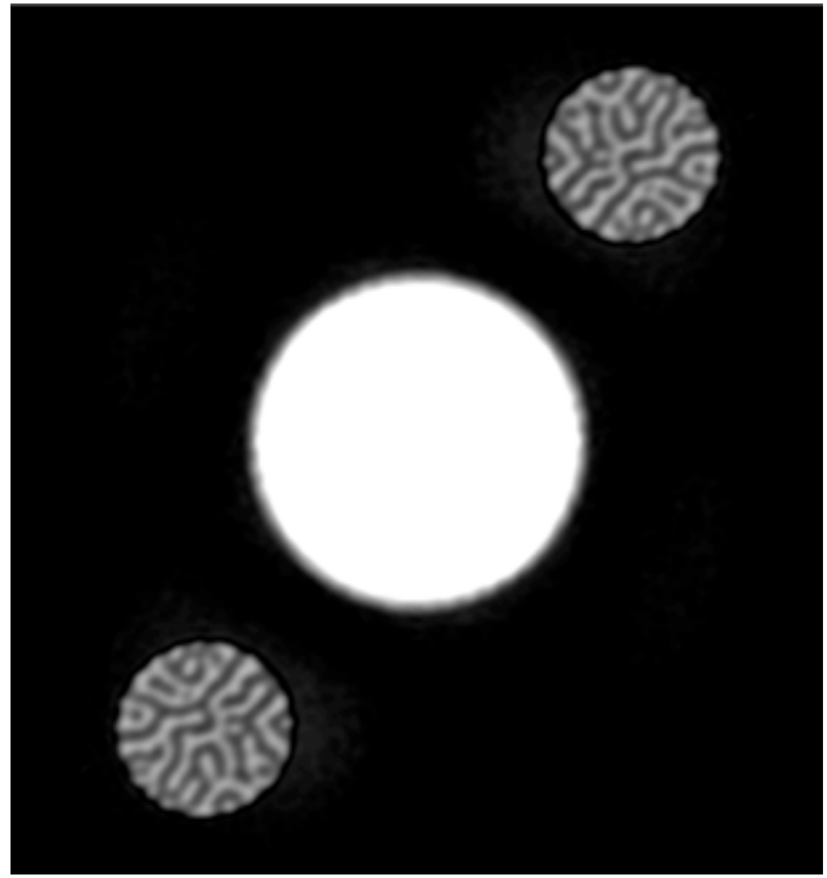
A Lensless Image

Intensity

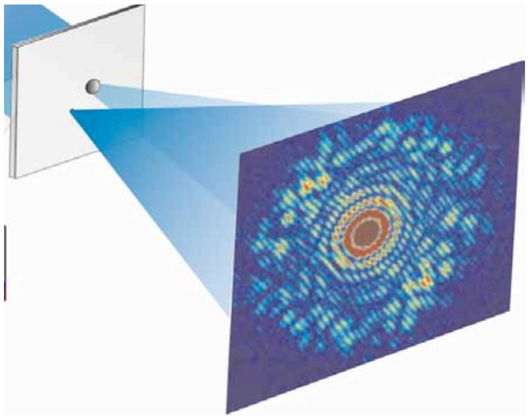


Fourier Transform Hologram

2D Fourier Transform



Got Phase?

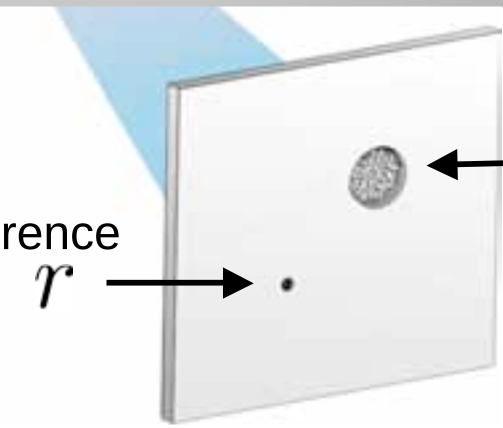


1) Fourier Holography

- •1963-1965 FTH with visible light
  - –Winthrop & Worthington
  - –Stroke & Falconer
- •1972 FTH at λ= 6.0 nm
  - –Aoki & Kikuta
- •1991 FTH at λ= 3.4 nm
  - –McNulty *et. al*

True imaging technique

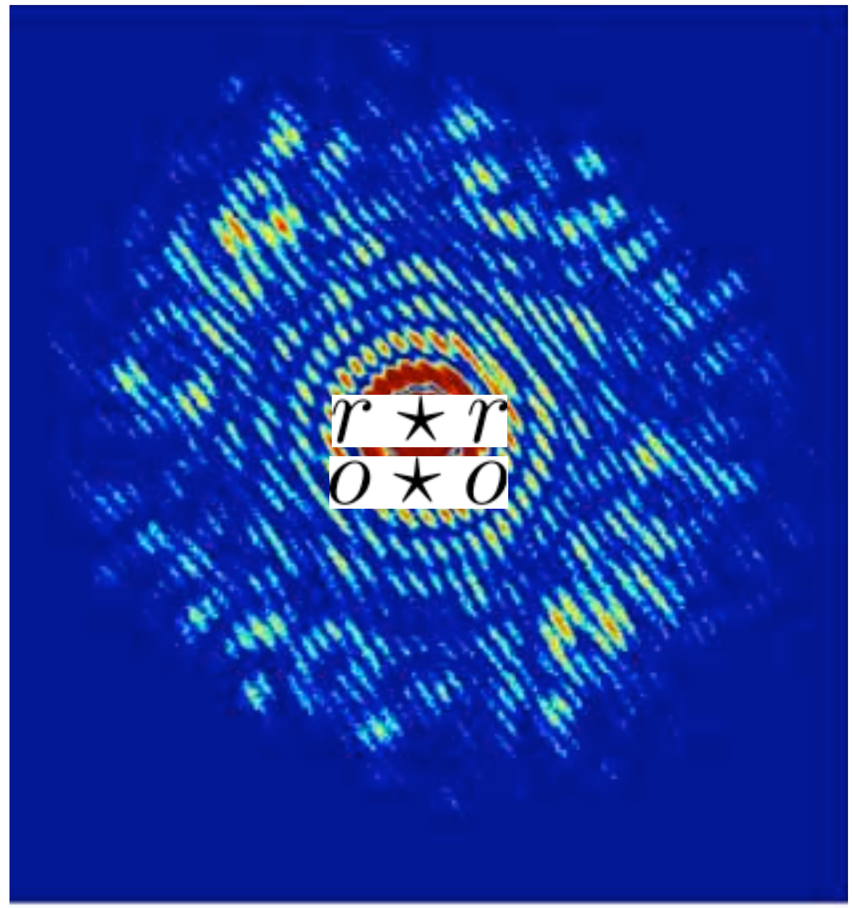
Reconstructing the Object



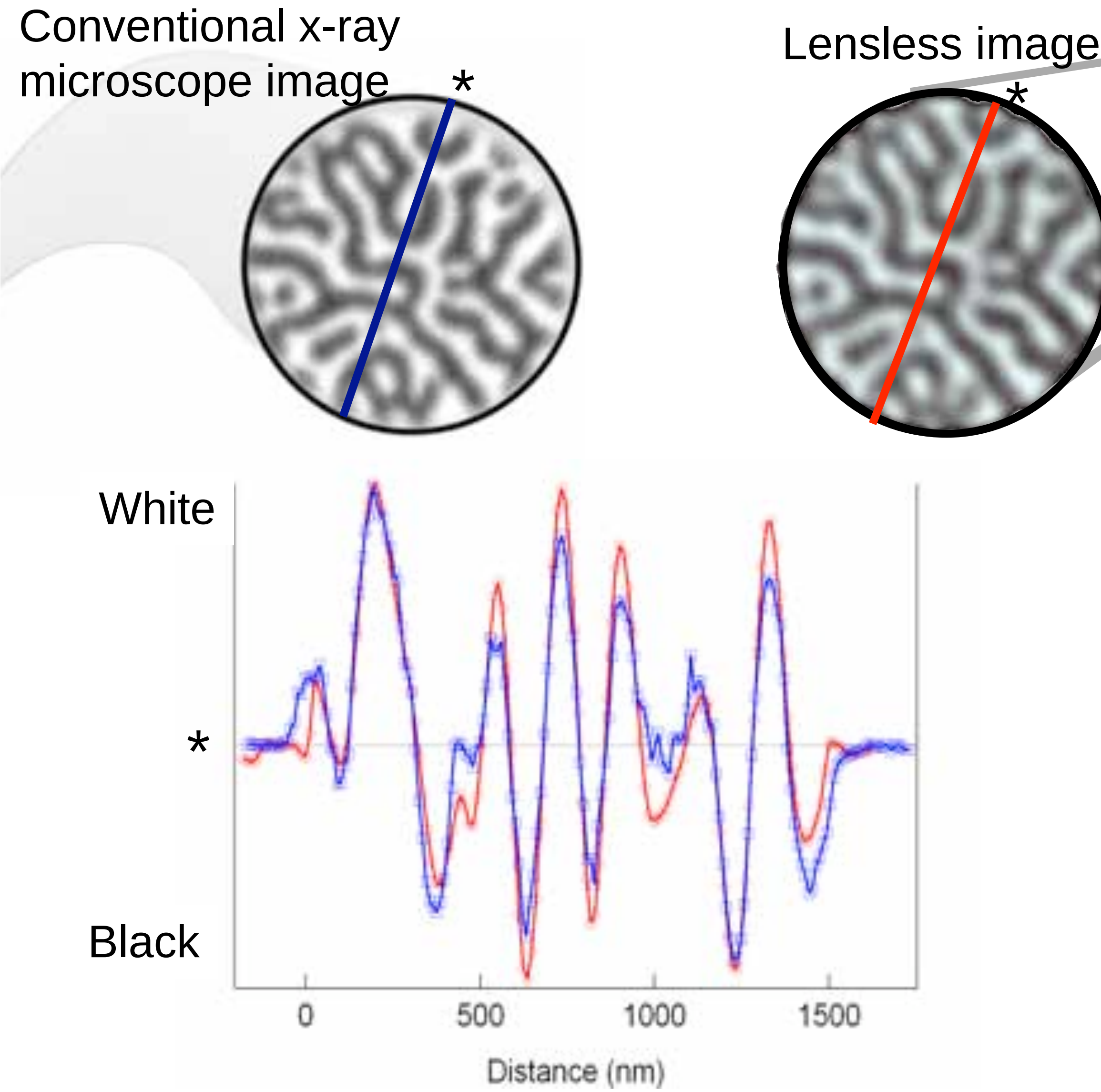
$$
\begin{aligned}
&= |\mathcal{F}\{r+o\}|^2 \\
&= |R+O|^2 \\
&= |R|^2 + |O|^2 + OR^* + RO^*
\end{aligned}
$$

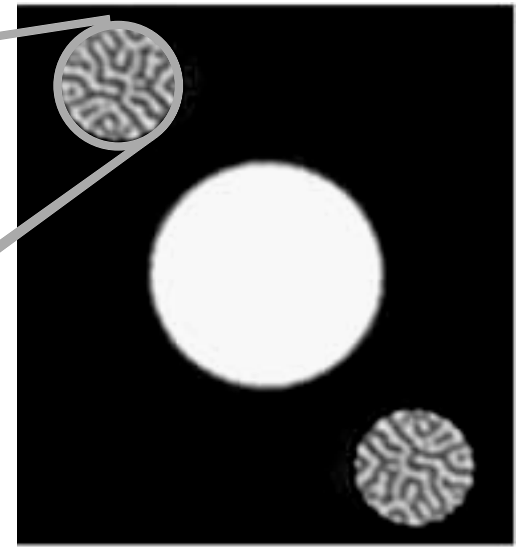
$\mathcal{F}\{\text{Hologram Intensity}\}$

$r \star r + o \star o + o \star r + r \star o$



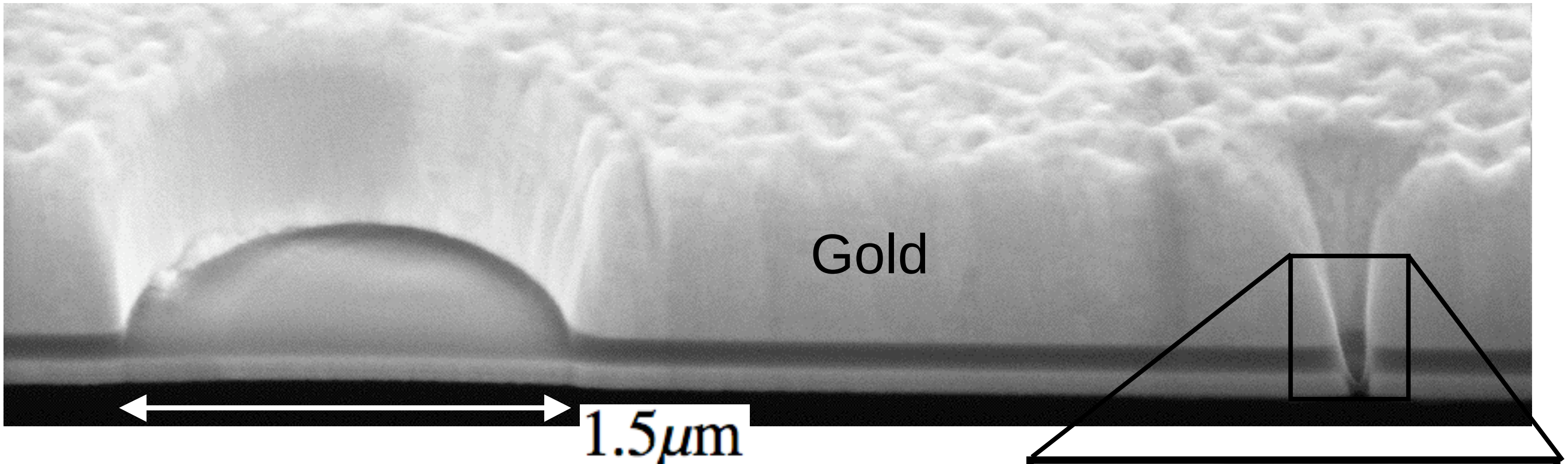
Lensless Imaging with 50nm Resolution



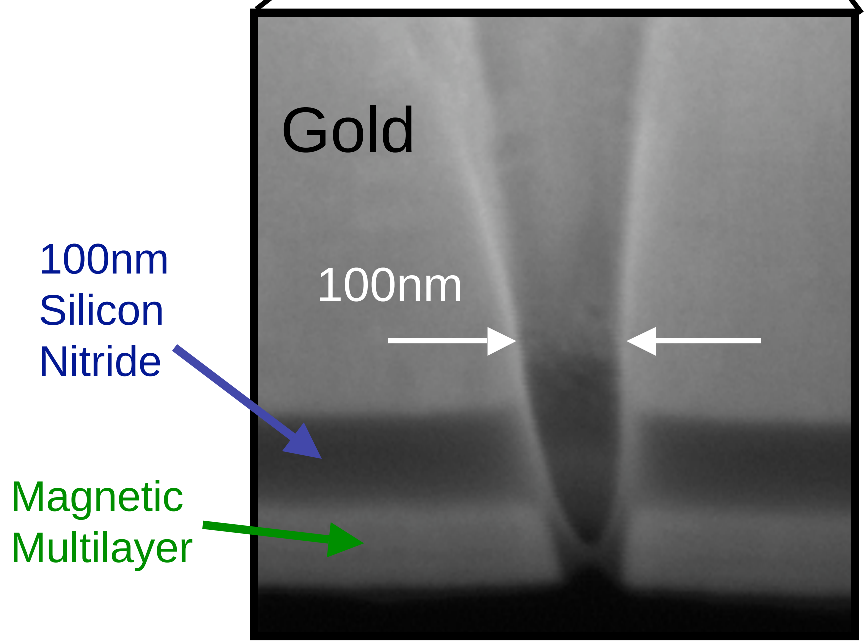


Fourier transform holography is an imaging method

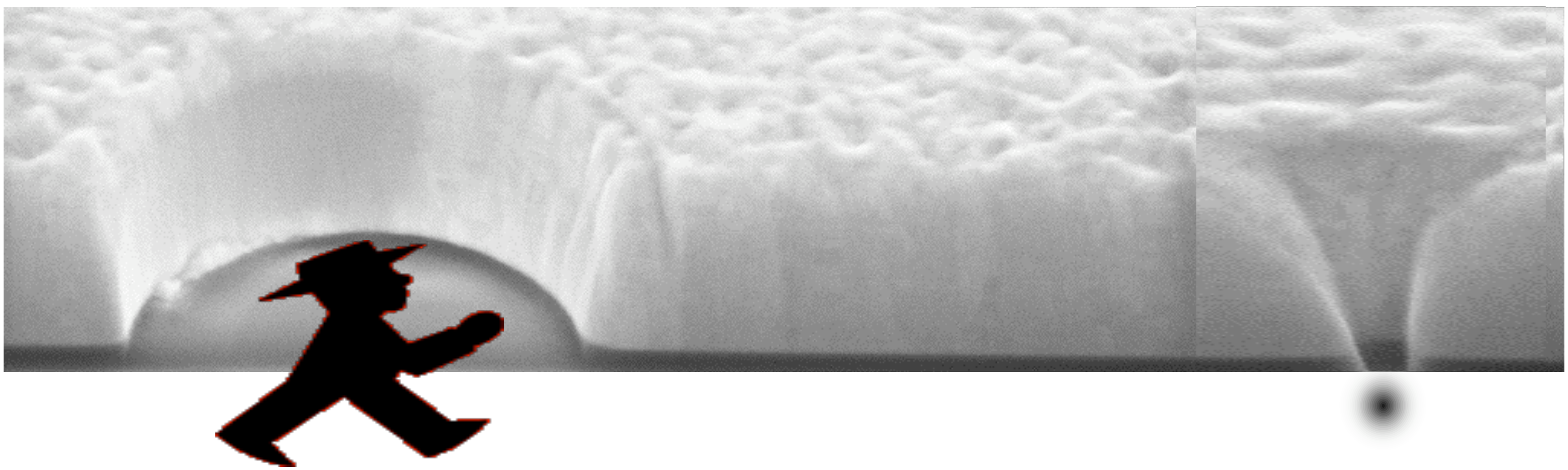
Integrated Sample Structure



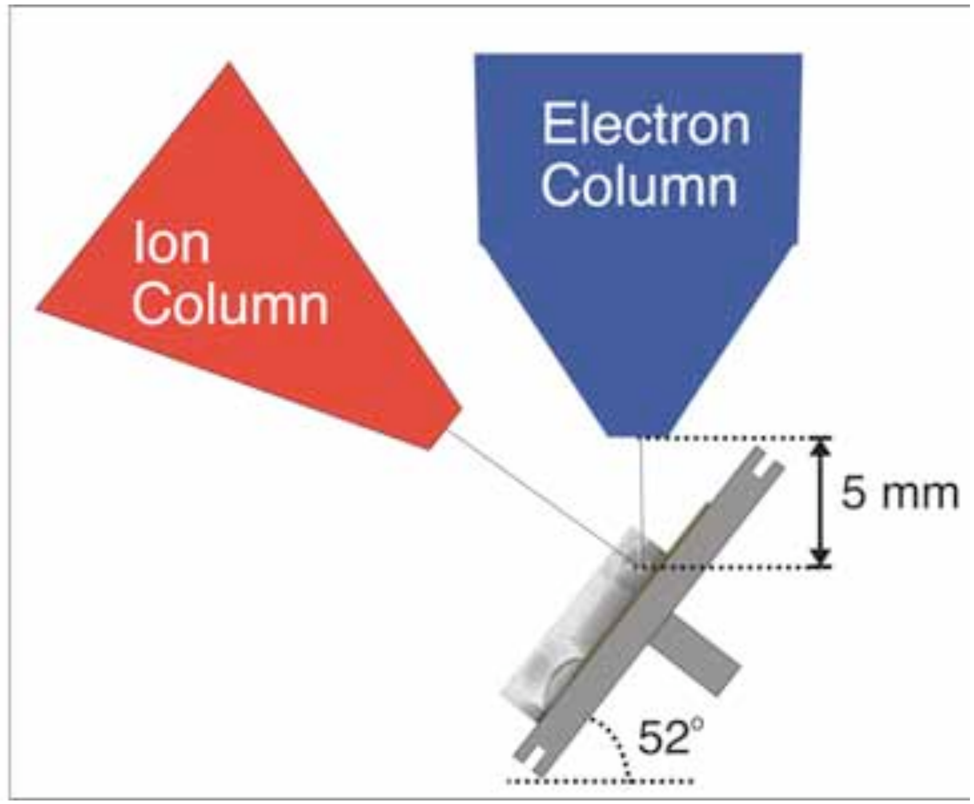
- Patterned with focused ion beam milling
- Unity transmission reference
- Mask and sample fixed



References and Resolution



Focused Ion Beam Milling



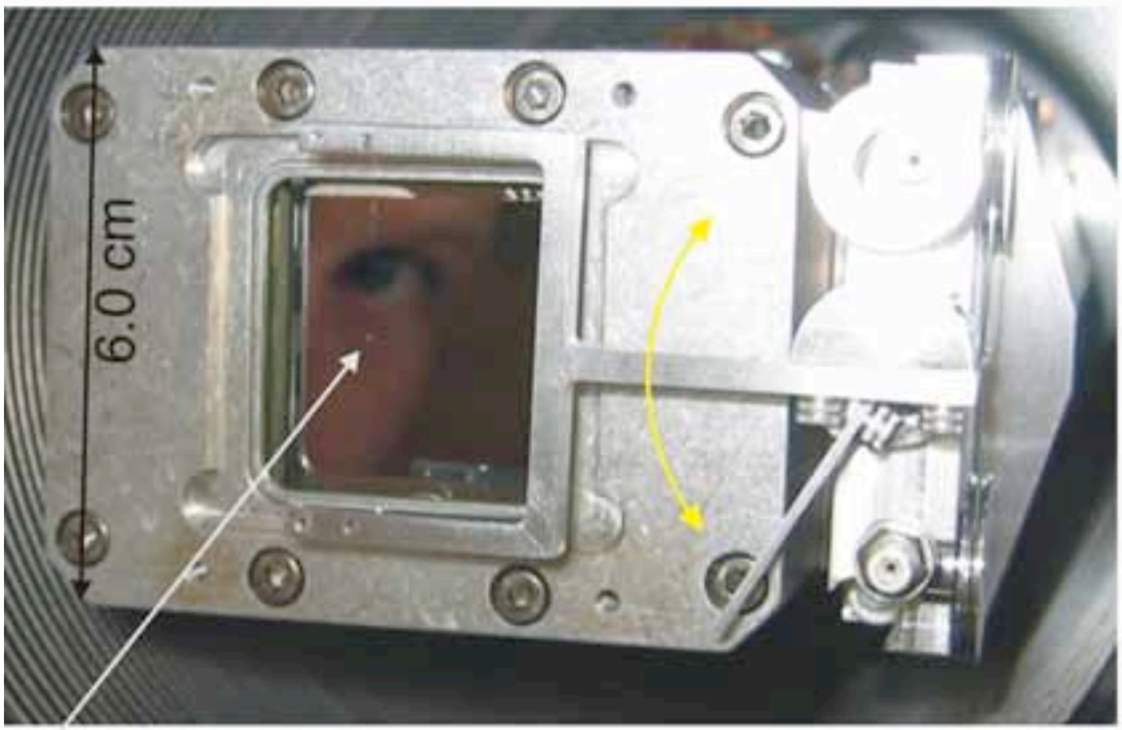
FEI Strata 235 DB
Dual Beam FIB

Ion Beam Milling
- Ga^+ @ 30 kV
- Current ~ 1pA - 20nA

CCD and Beam-stops

Commercial CCD Camera

- Princeton Instruments PI-MTE
- In-vacuum operation 10^{-6} Torr



epoxy bead beamstop on support wire

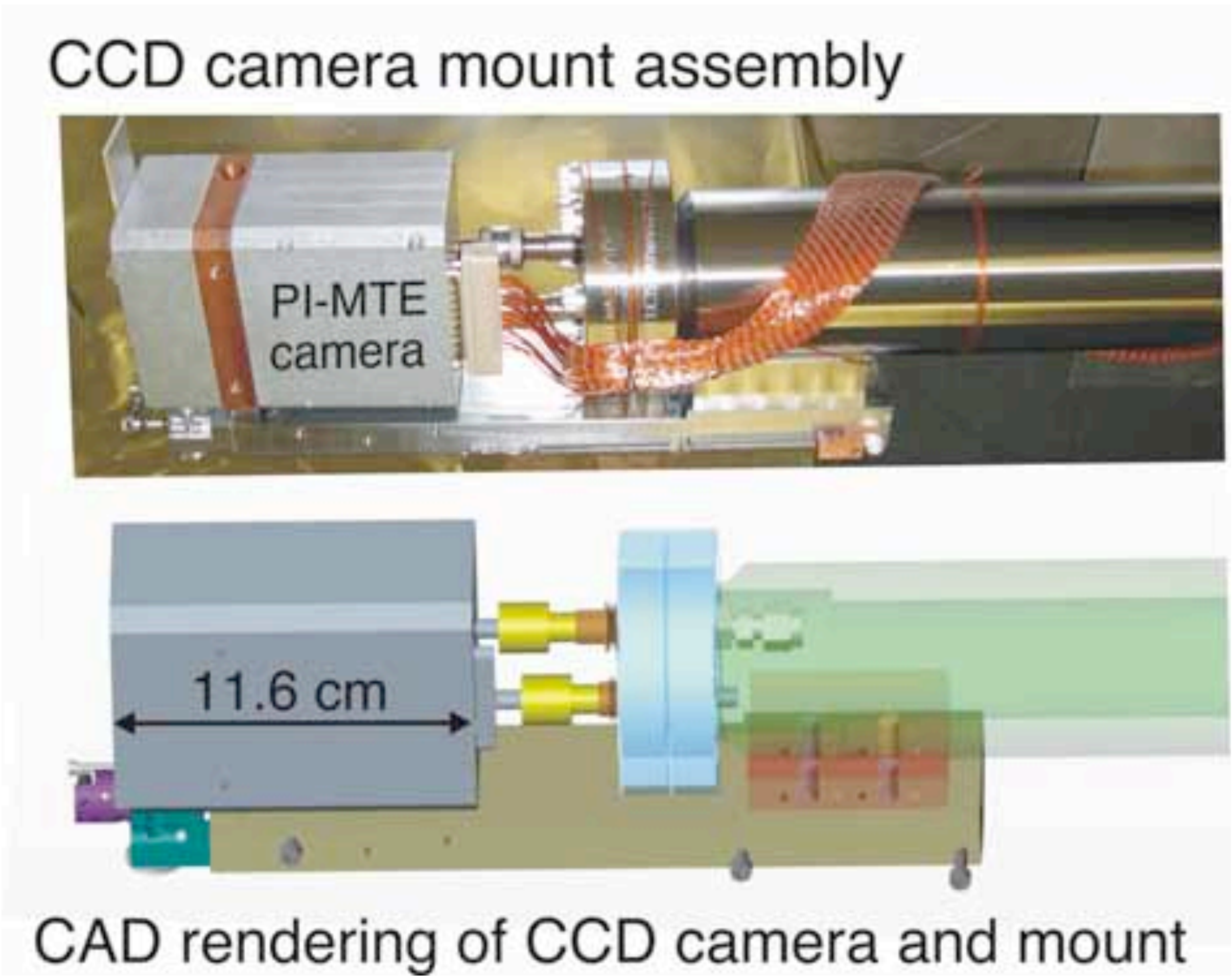
PI-MTE 1300 x 1340B

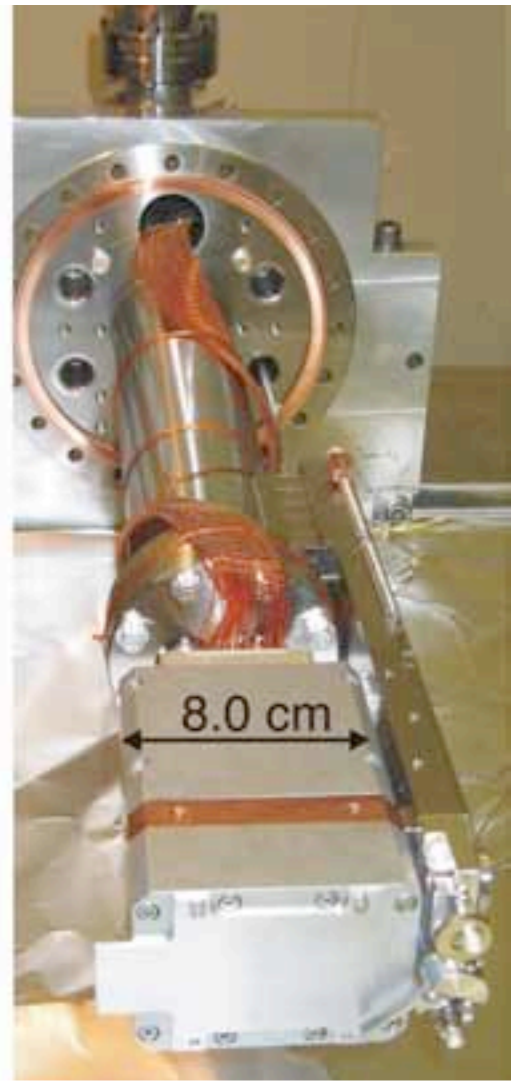
- Backside illuminated
- 1300 x 1340 pixels
- 20 μm pixel pitch

- ADC @ 1MHz
  - Depth: 16-bit
  - Noise: 10 e^- rms

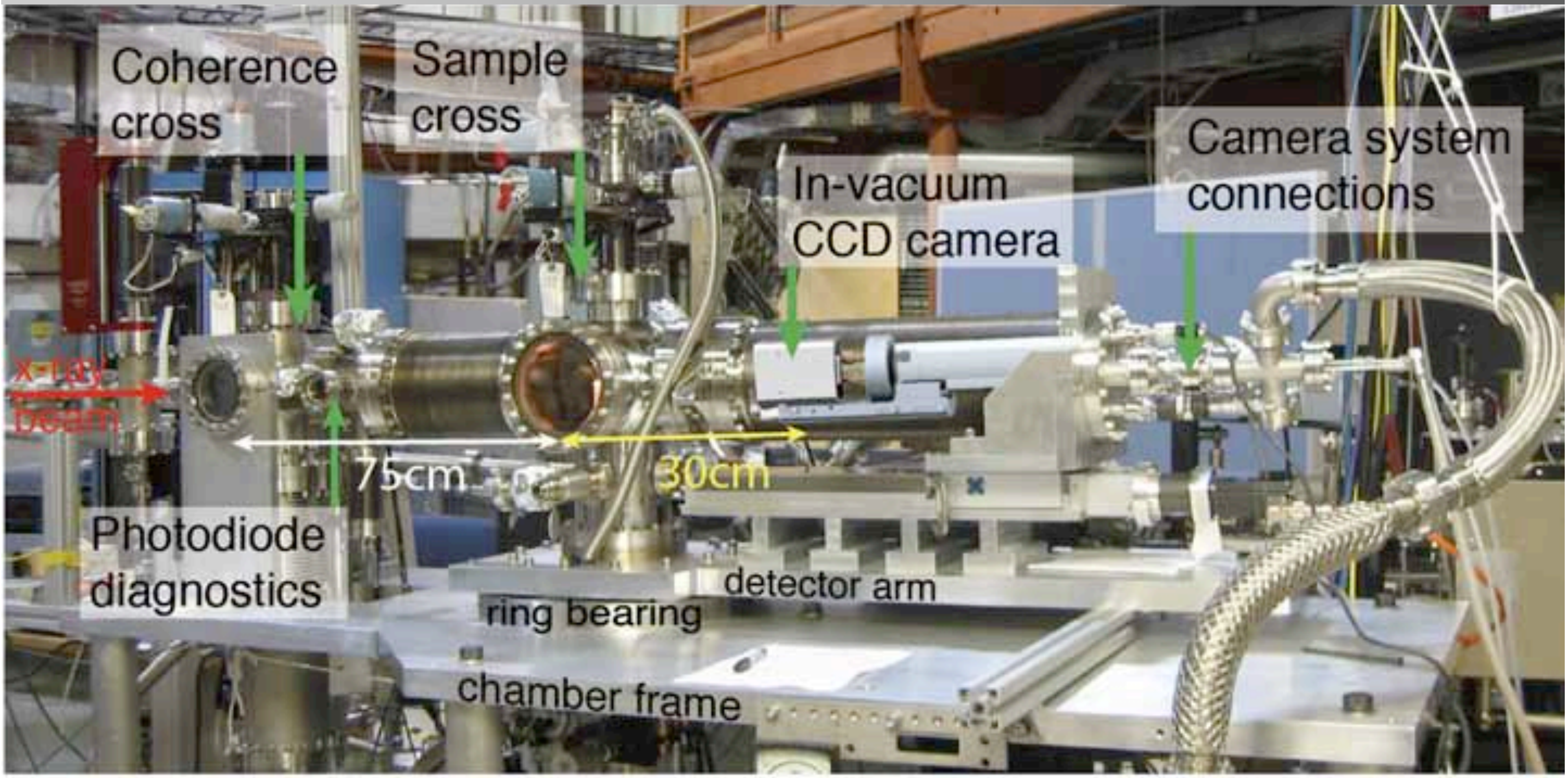
- Dynamic range
  - 200k e^- full well
  - 10^3 800eV photons

In Vacuum Soft X-ray CCD





Coherent Scattering Endstation



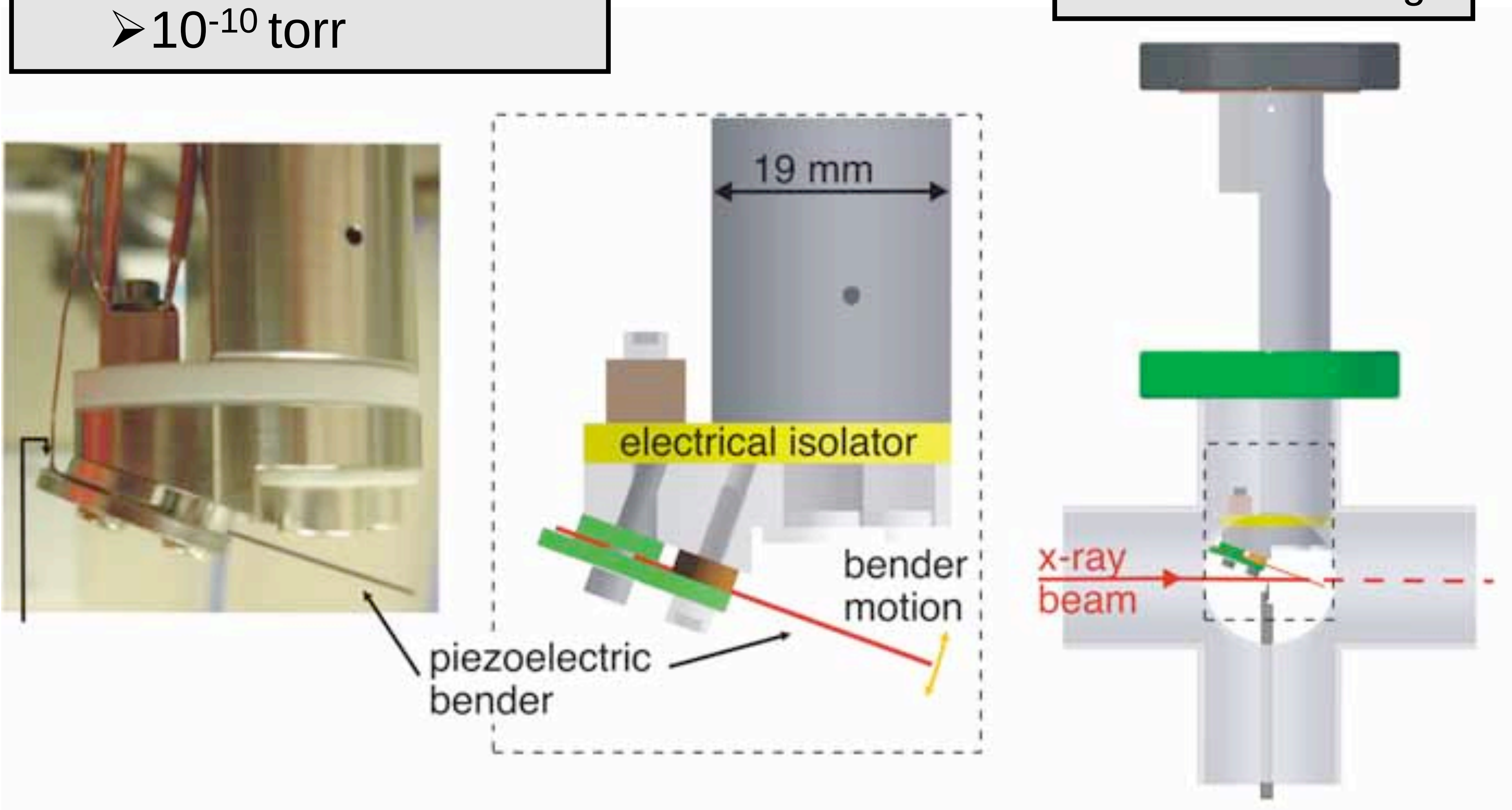
SSRL Beamline 5-2

UHV Beam Shutter

Operation Parameters

- 5 ms response
- 10^{-10} torr

2.75 inch CF flange



Single Shot Imaging on a Photon Budget

Single Shot Imaging on a Photon Budget

Experimental Transaction	Photon Flow	
	In	Out
Number of Photons per Pulse	10^{13}	
High Image Contrast		$N\gamma$
High Image Spatial Resolution		$N\gamma N\gamma$
High Image Signal-to Noise Ratio		$N\gamma N\gamma N\gamma$
Huge Image Field of View		$N\gamma N\gamma N\gamma N\gamma$
Multiple Images (M images)		$MN\gamma$

Photon Frugal

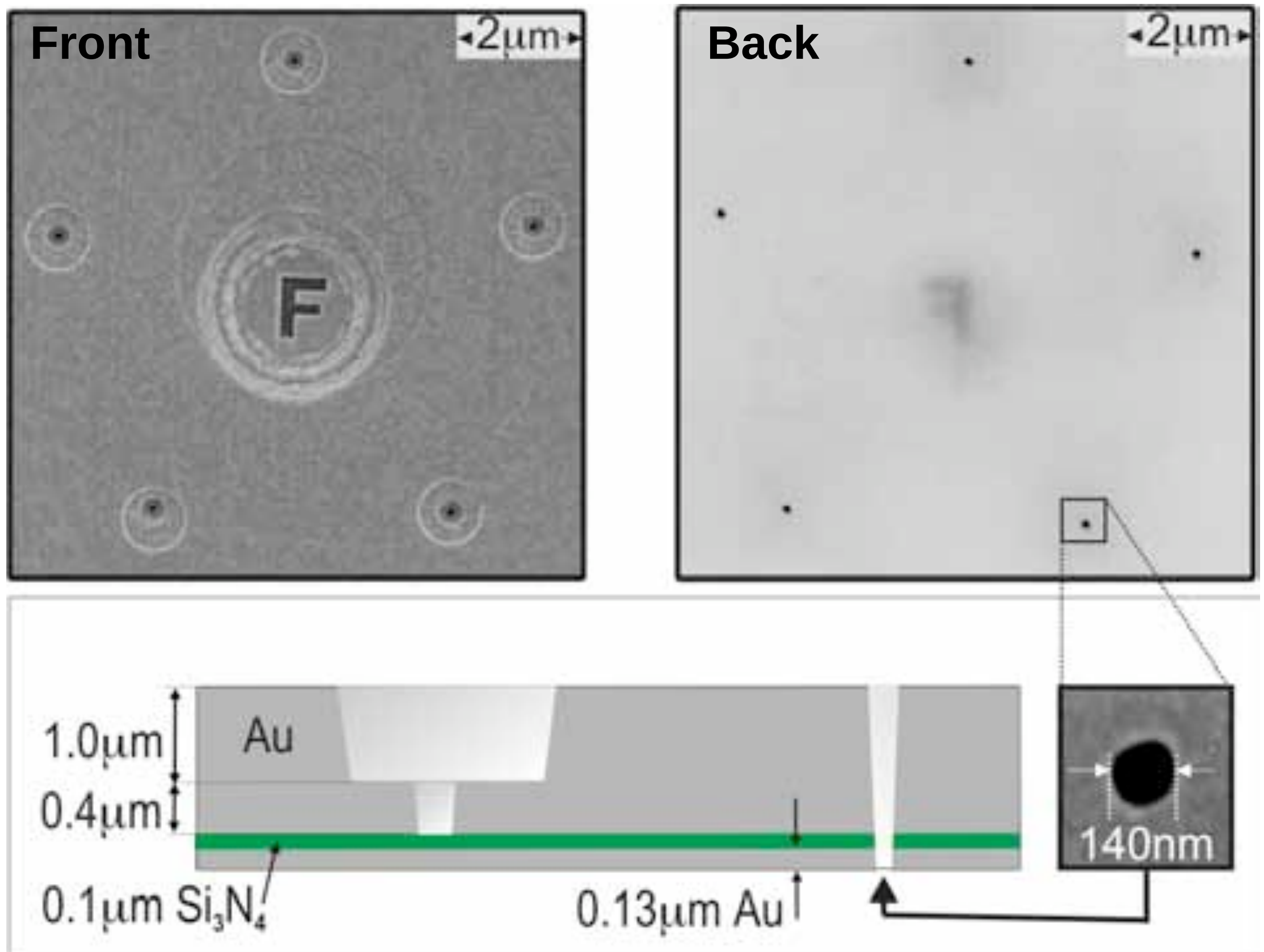
Five Images for the Price of One

Multiple Reference Holes

FTH Mask

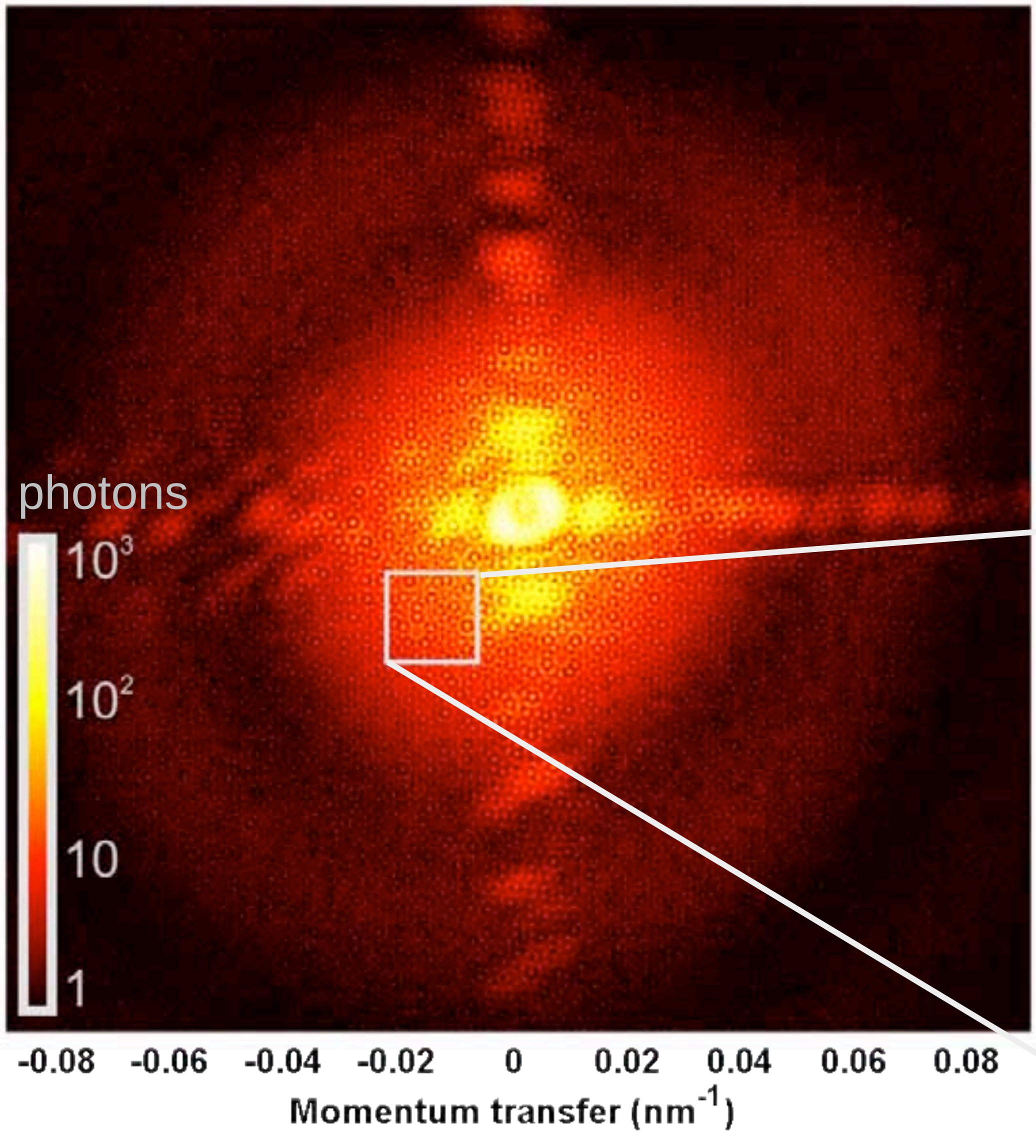
- ➢Focused Ion Beam milling was used to pattern the Au structure.
- ➢The block letter F is the sample and has an intensity transmittance of 12% at 780eV
- ➢All five reference holes penetrate the entire structure with a mean diameter of 140±6nm

Fourier Transform Holography Mask



W. F. Schlotter, R. Rick, K. Chen, et. al., Appl. Phys. Lett. 89 (2006)

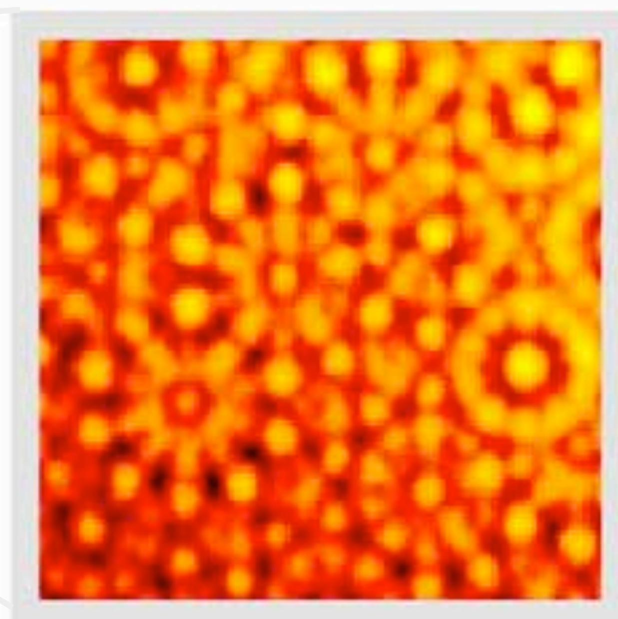
Coherent Diffraction Pattern



Soft x-ray Fourier transform hologram of FTH mask. E= 780eV

The common logarithm of the detected intensity is plotted.

The hologram contains ~$7*10^6$ photons (E= 780eV).



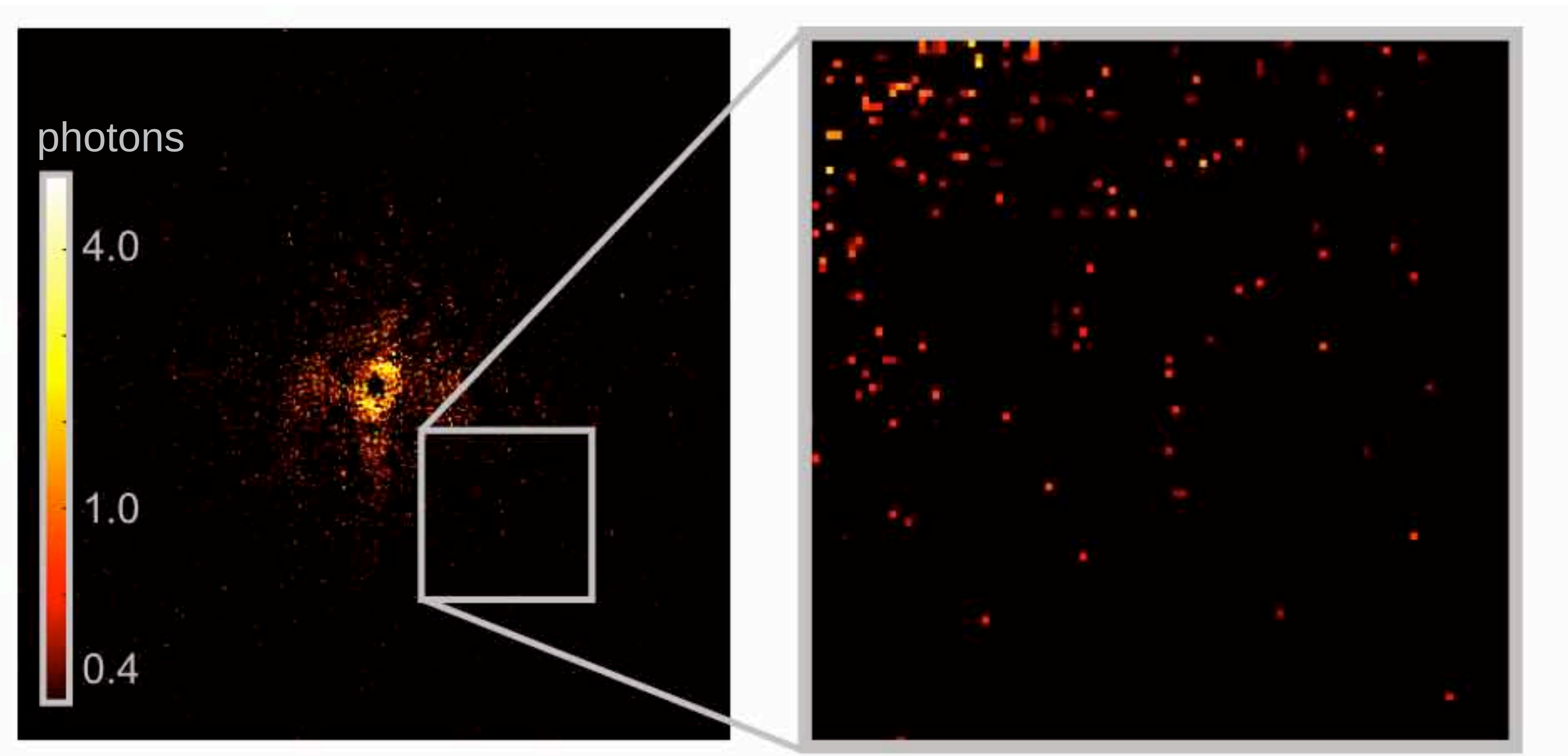
Autocorrelation

- The squared magnitude of the complex autocorrelation is shown.
- Sub-Images ready for extraction.
- Five sub-images are essentially identical and have the same orientation
- They can be aligned for averaging by cross correlation.

W. F. Schlotter, R. Rick, K. Chen, et. al., Appl. Phys. Lett. 89 (2006)

Weak Illumination

Low photon hologram **Enlargement containing ~110 photons**

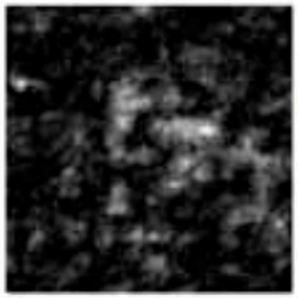


Hologram recorded with weak illumination contains only $2.5*10^3$ **photons.**

Single photon detection events are clearly visible.

Reconstruction and SNR

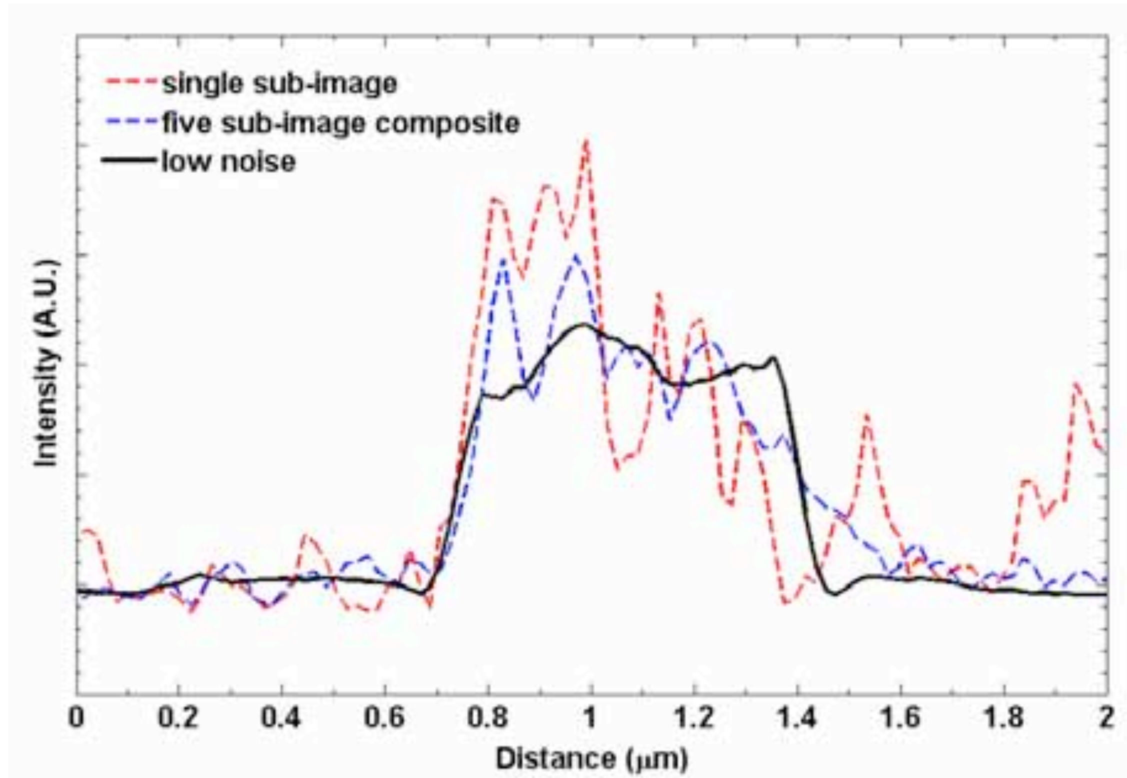
Single sub-image



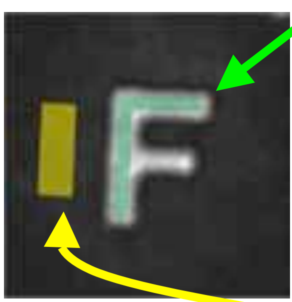
$\mathrm{SNR}_1 \sim 3$

5 sub-image composite

$\mathrm{SNR}_5 \sim 9$



Low Noise



Signal, s, is the mean value of pixel on the sample

Noise, σ_b, is the standard deviation of the pixels in the surrounding area.

Signal to Noise Ratio (SNR)

$$\mathrm{SNR}_N = s/\sigma_b$$

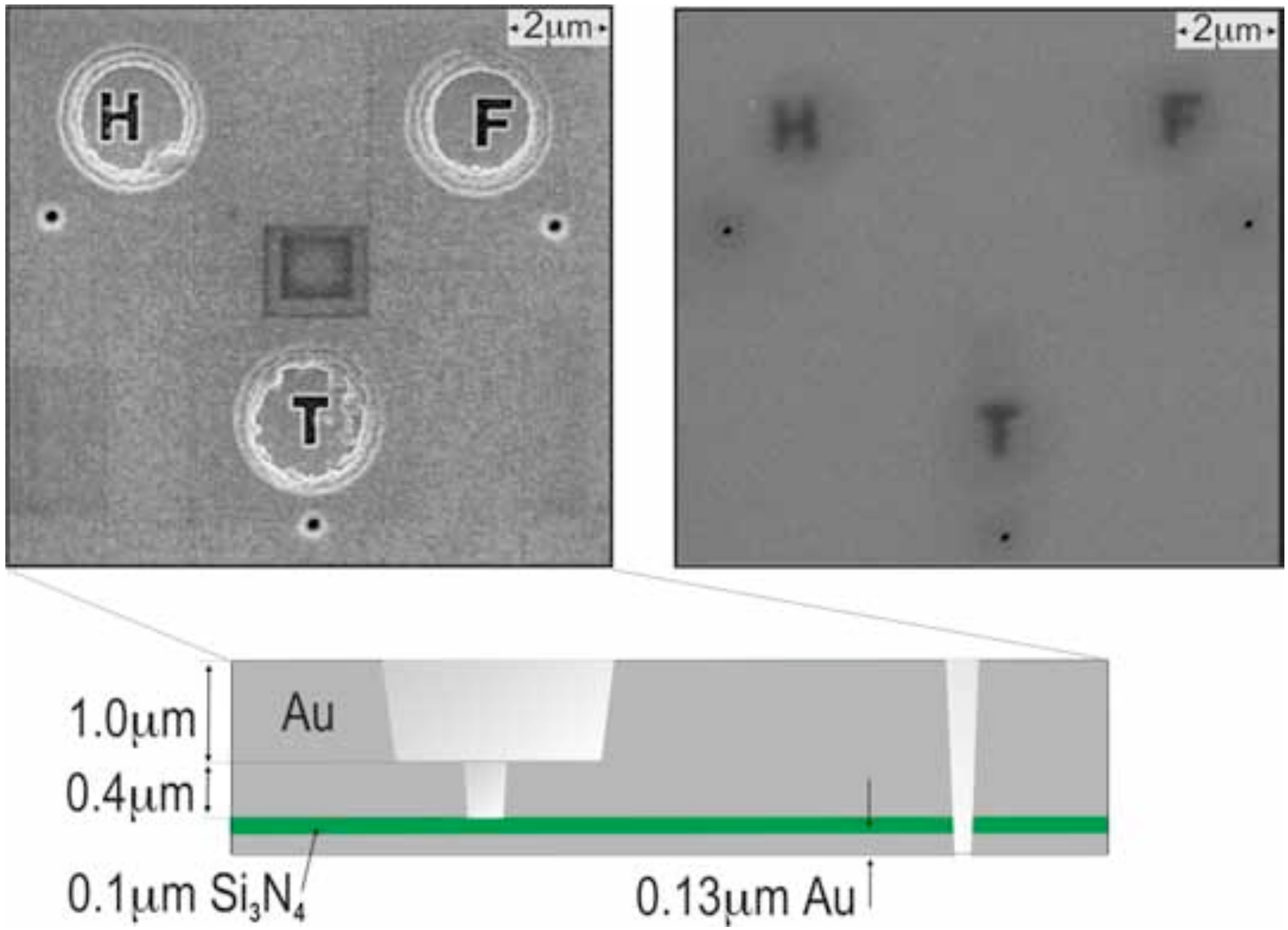
Where N is the number of images averaged in the composite sub image.

High Resolution
Huge Field of View

Extended Field of View Test

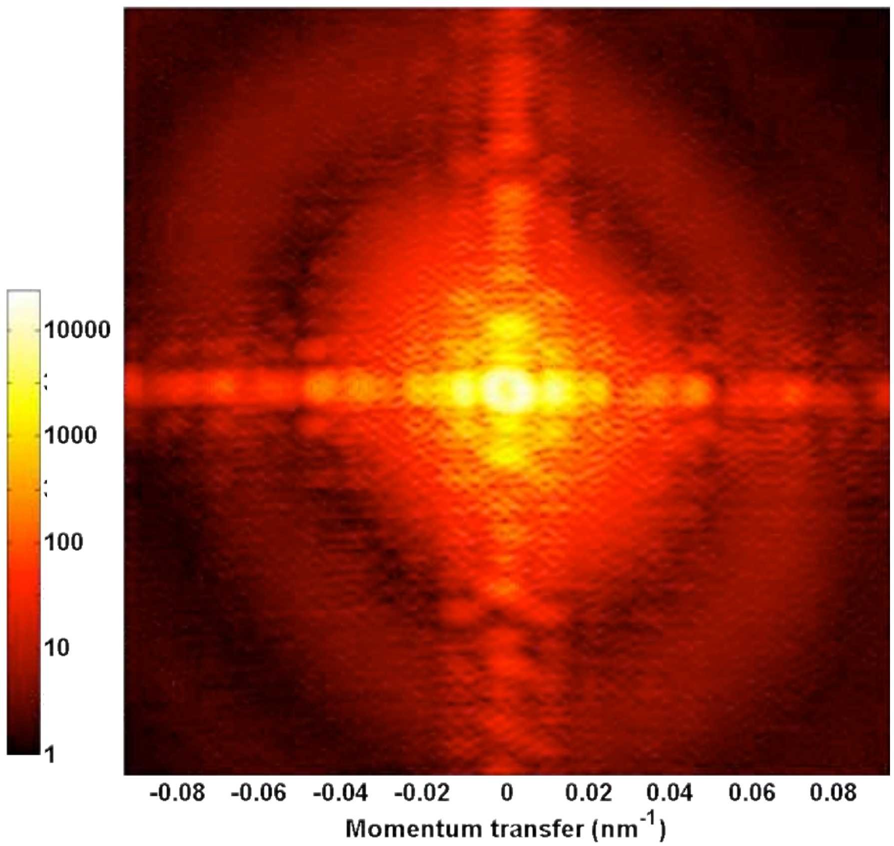
Holographic Mask

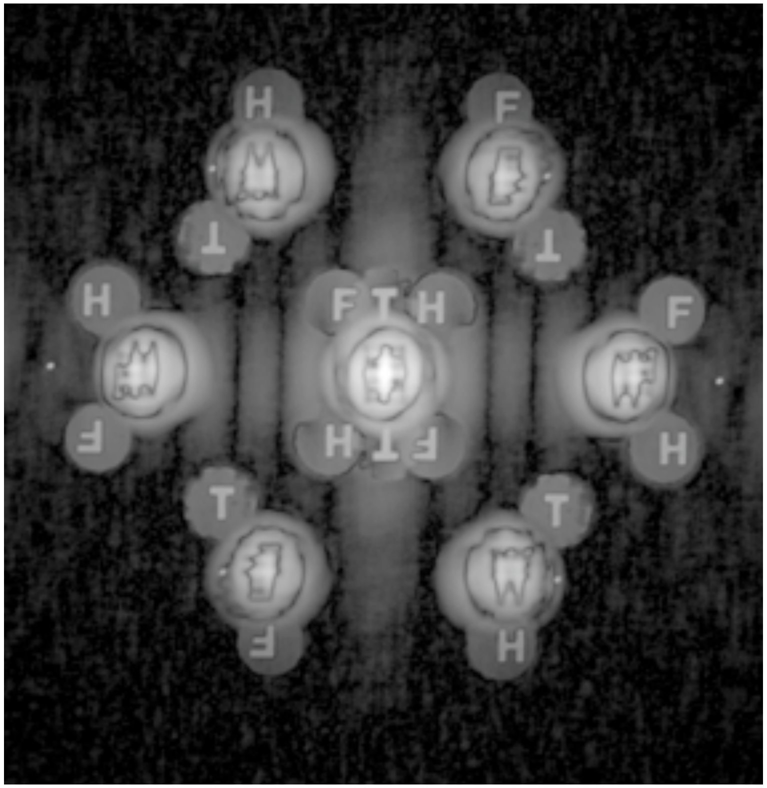
- Strategic reference and object hole arrangement enables an effective increase in field of view.
- Idea introduced with visible light by J. Goodman in 1968.



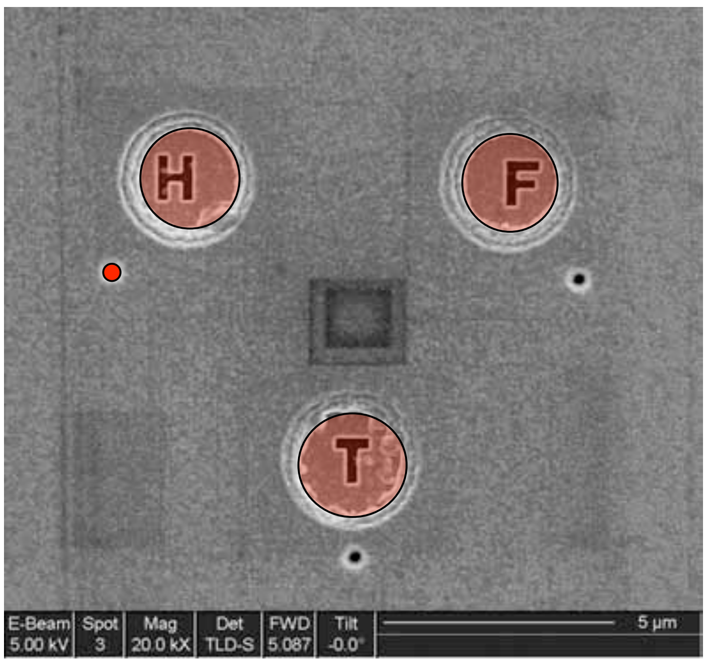
W.F. Schlotter, *et. al*, Submitted

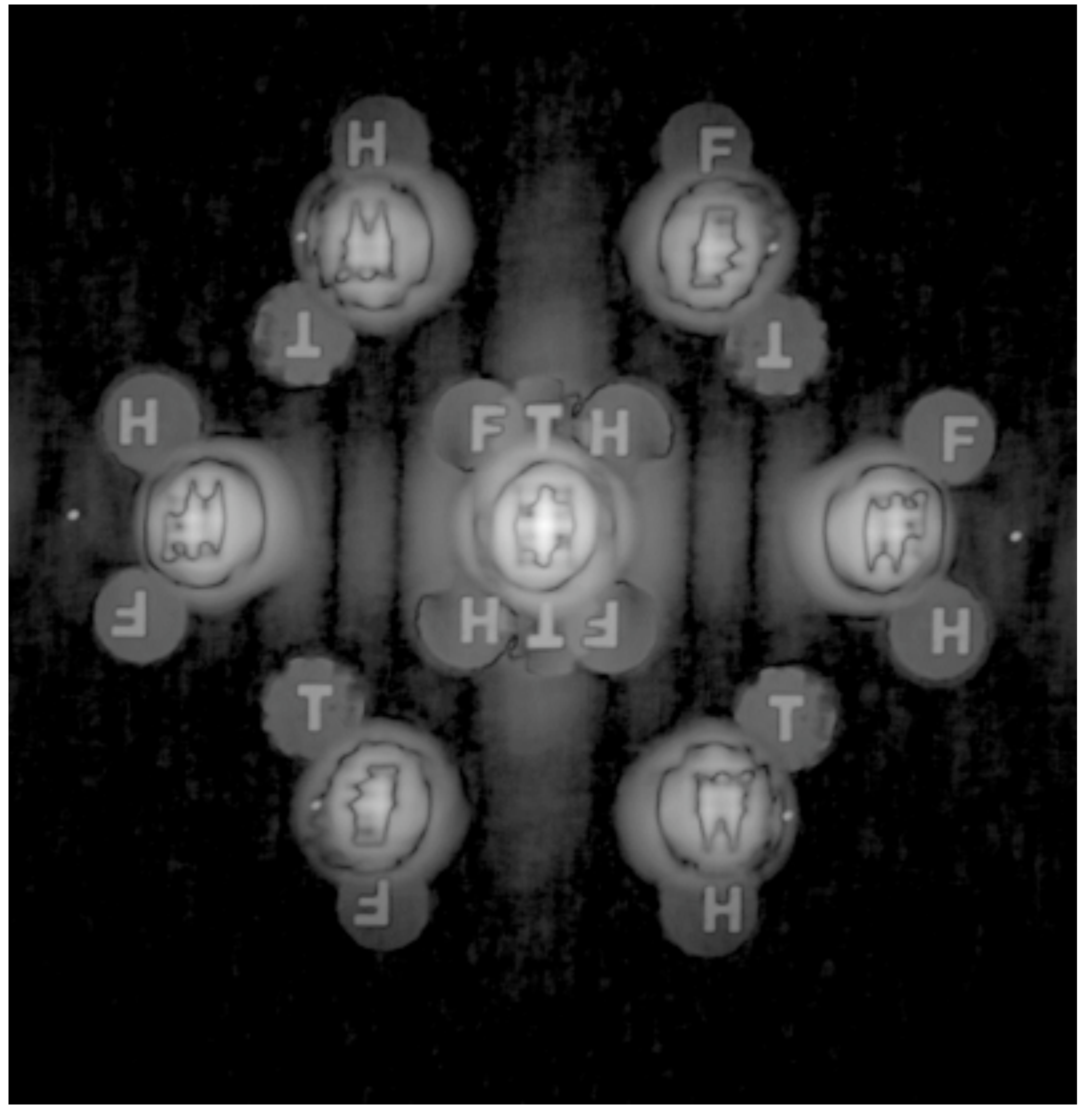
Hologram and reconstruction



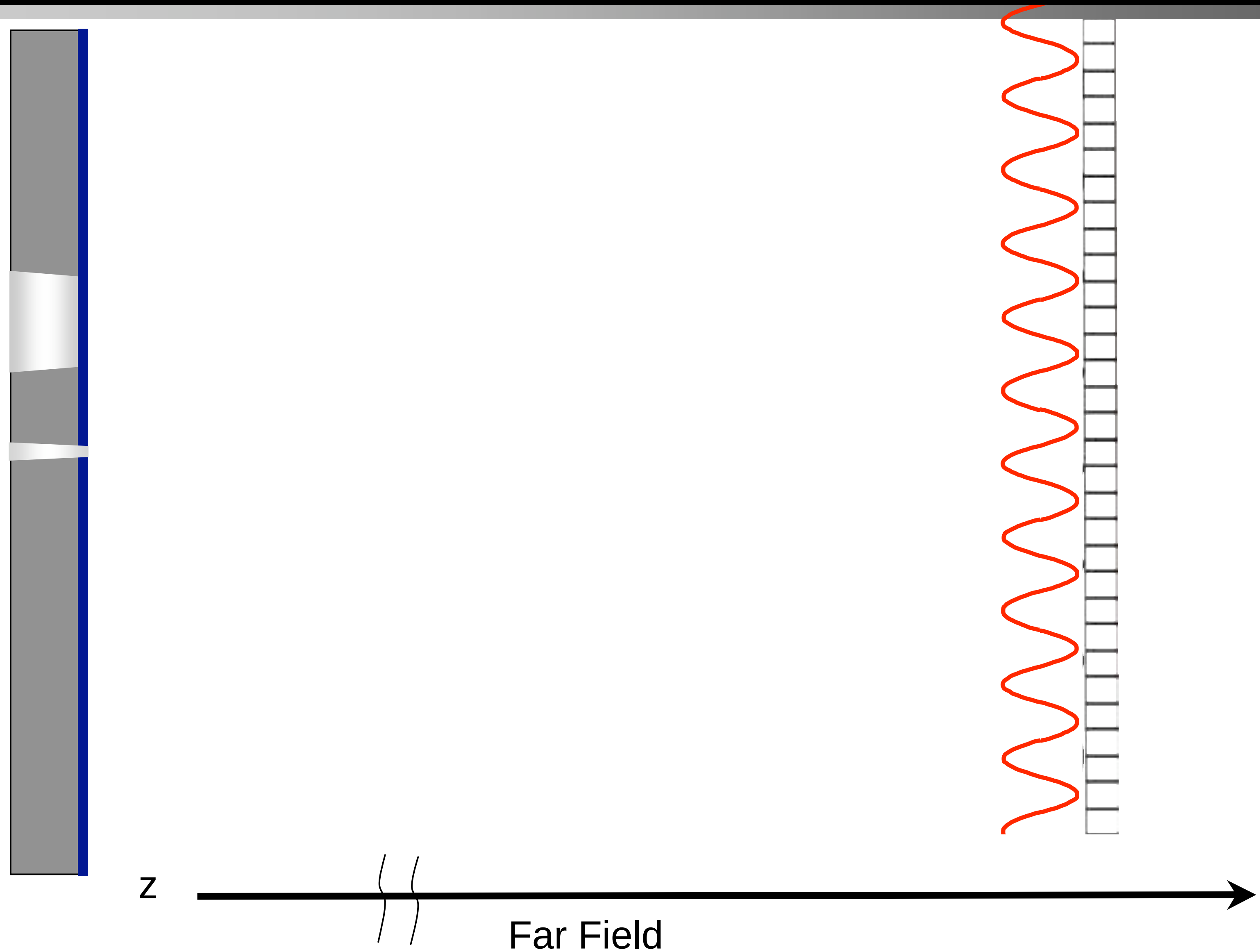


Comparing real space images



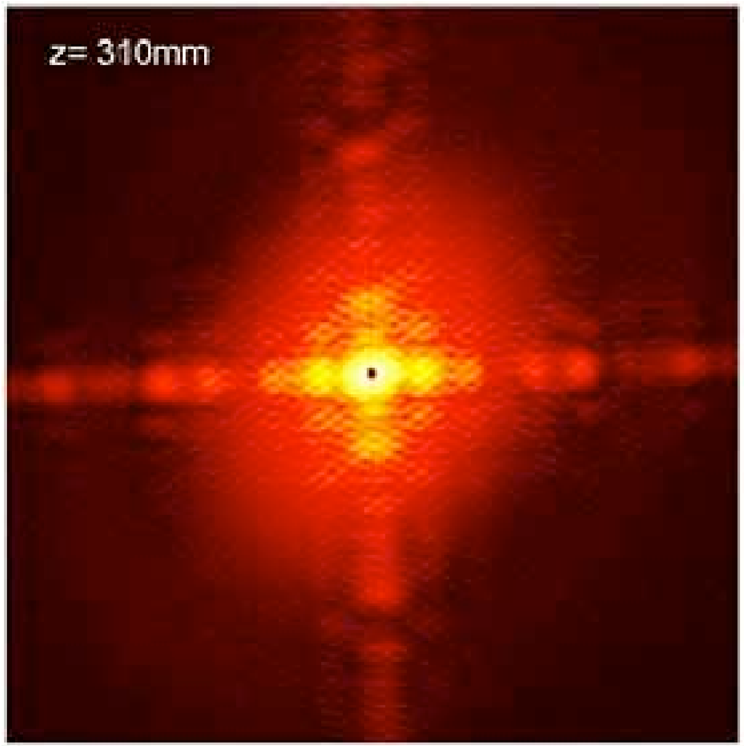


Resolving Fringes

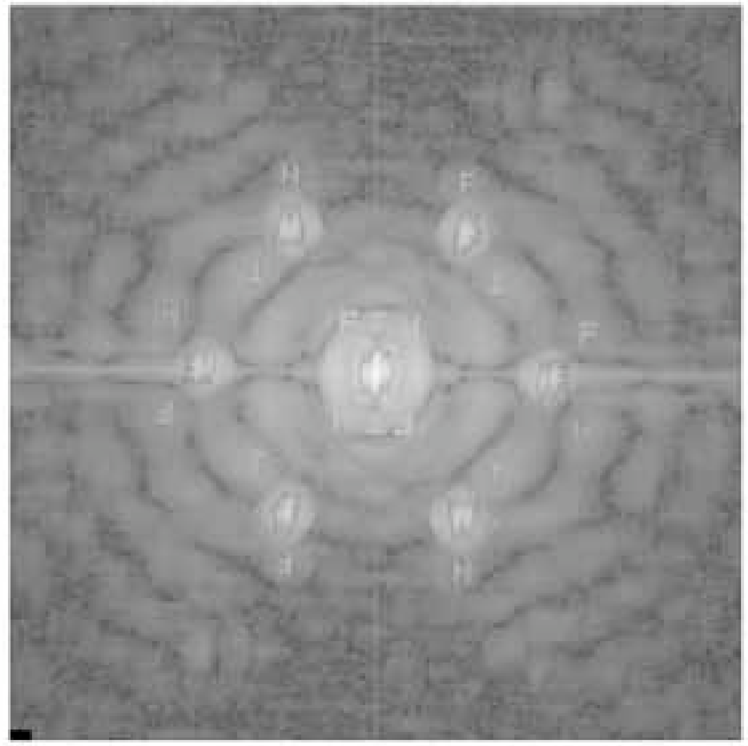


Camera Translation: Zoom

Hologram



Autocorrelation

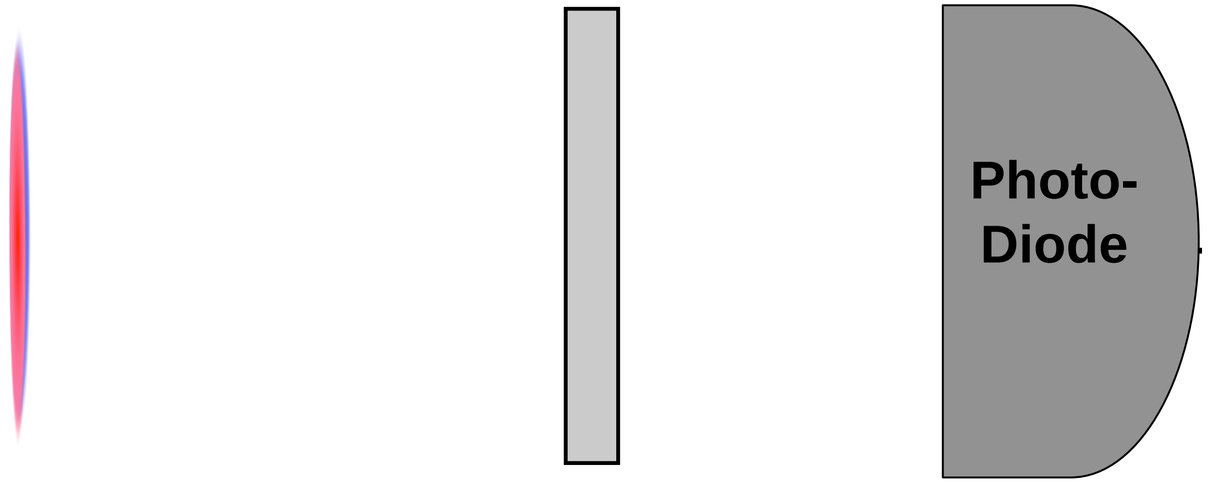


$1\,\mu m$

Single Shot Stopwatch

Pump Probe

➢Temporal resolution set by delay synchronization



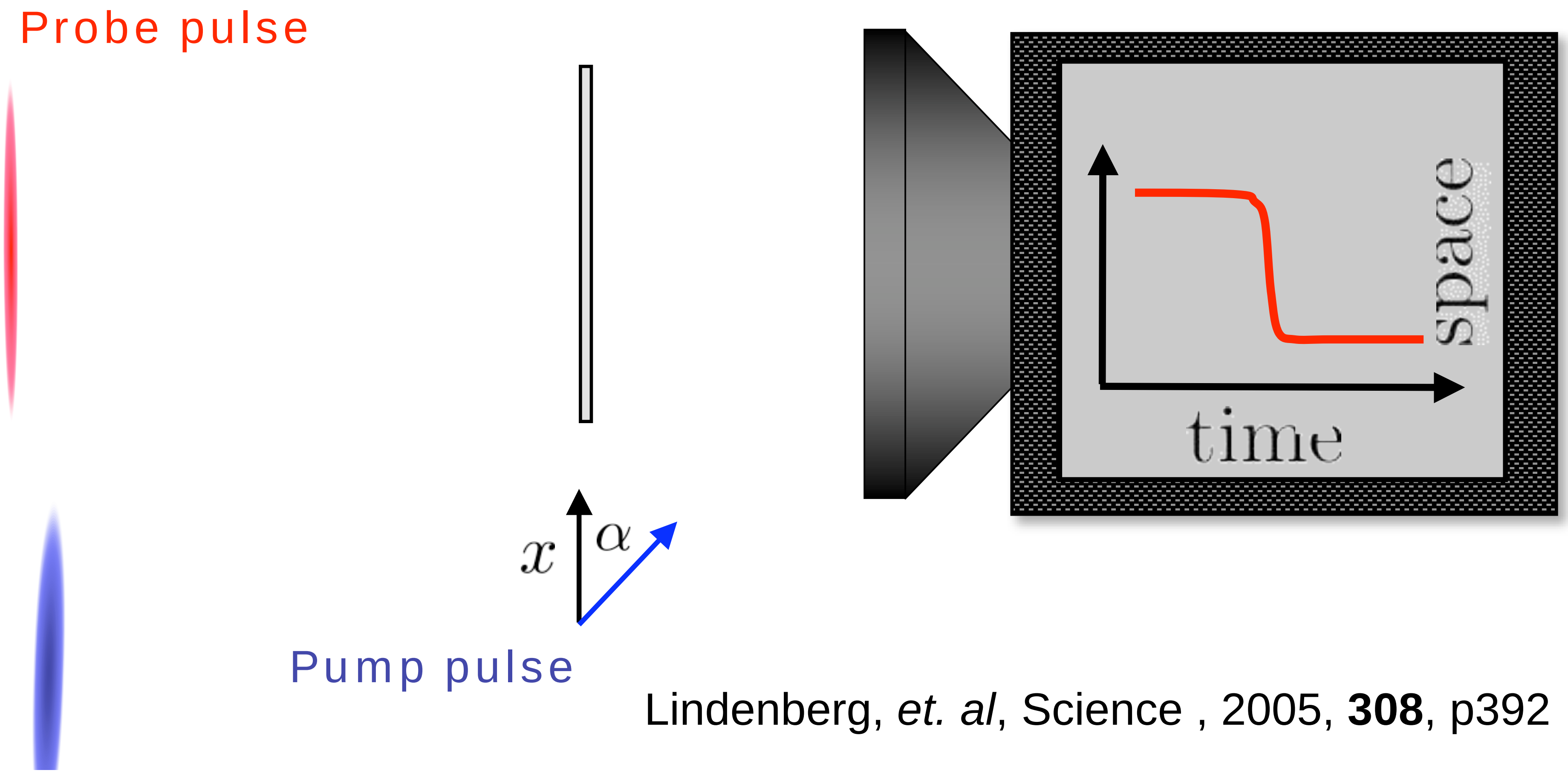
$$\text{probe} \rightarrow t_2$$

$$\text{pump} \rightarrow t_1$$

Cross-Beam Pump Probe

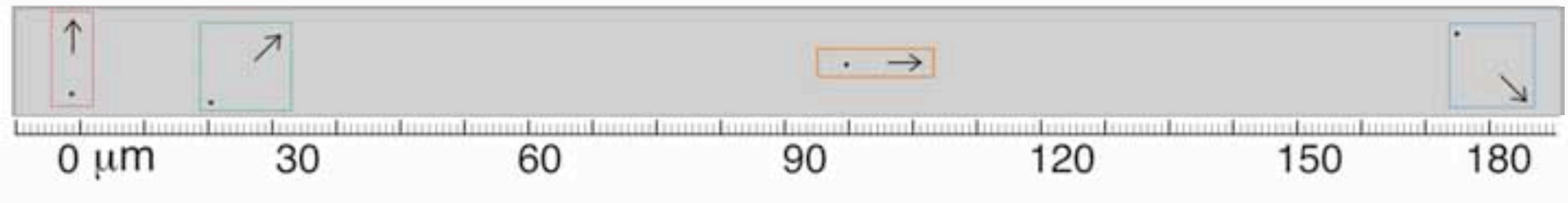
➢Resilient to pulse arrival jitter

$$t(x) = x\frac{\cos(\alpha)}{c}$$

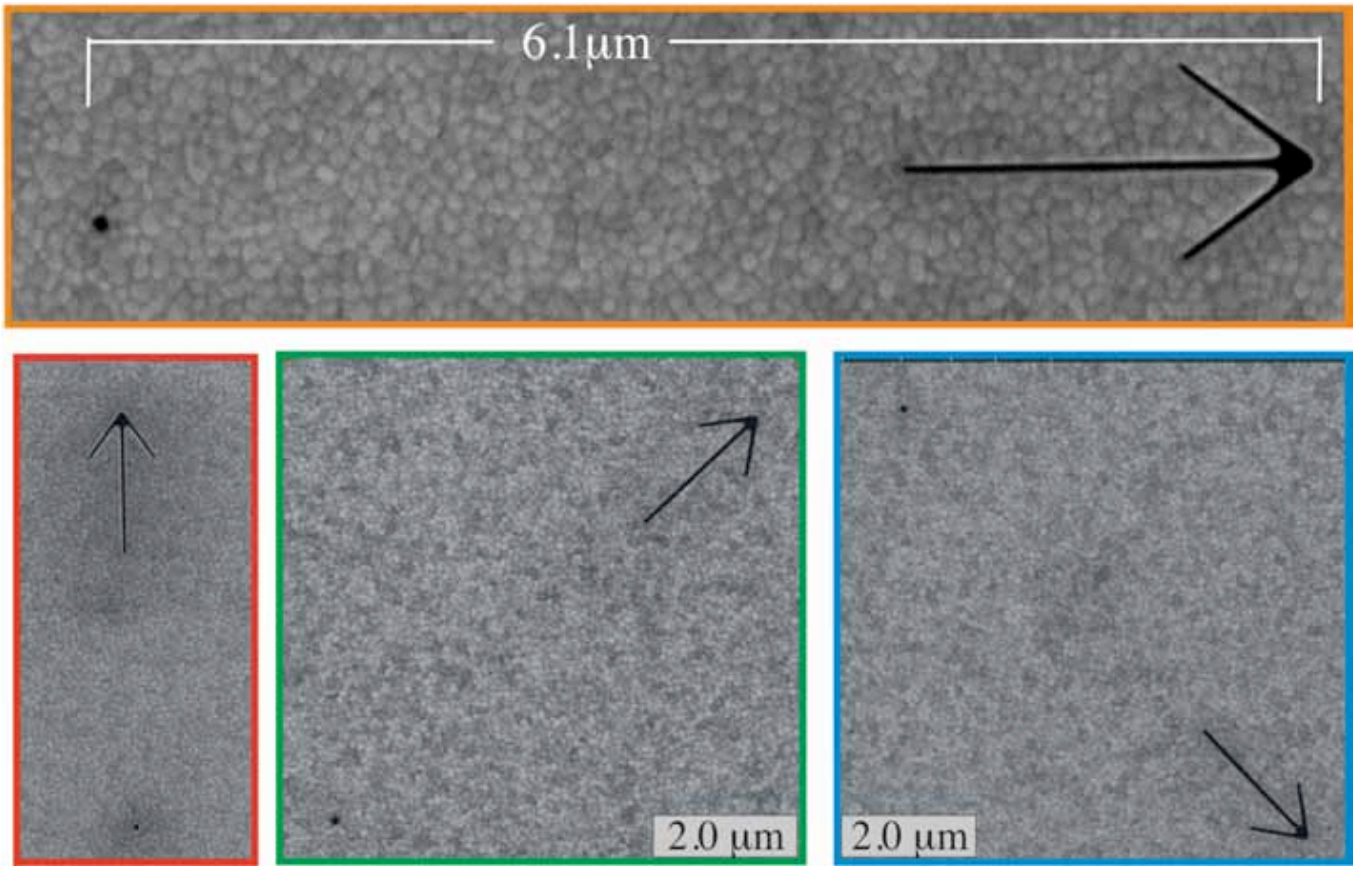


Lindenberg, *et. al*, Science , 2005, **308**, p392

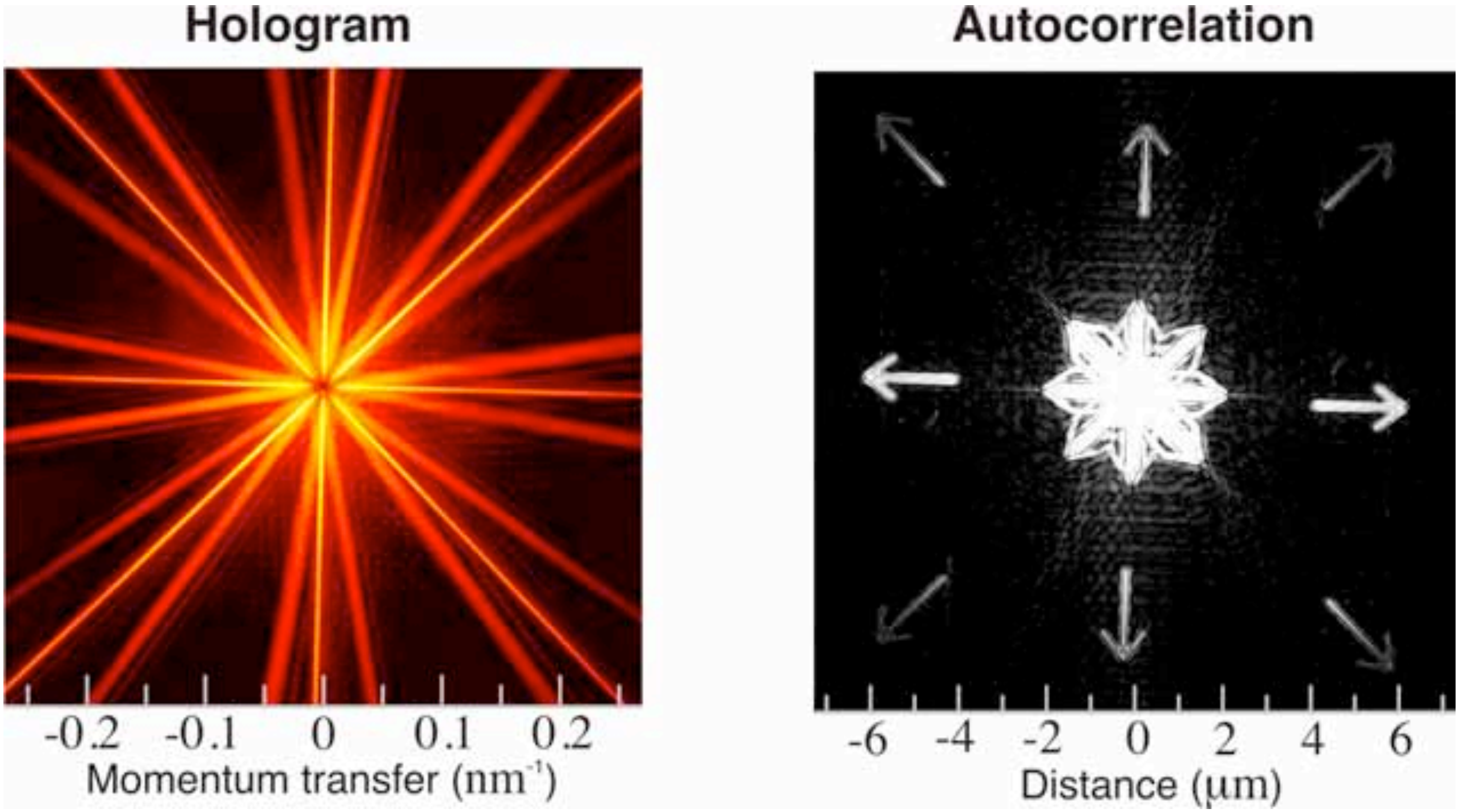
Panoramic Imaging over 180 µm



- **The 70nm reference holes will provide high resolution reconstructions of the arrow structures.**

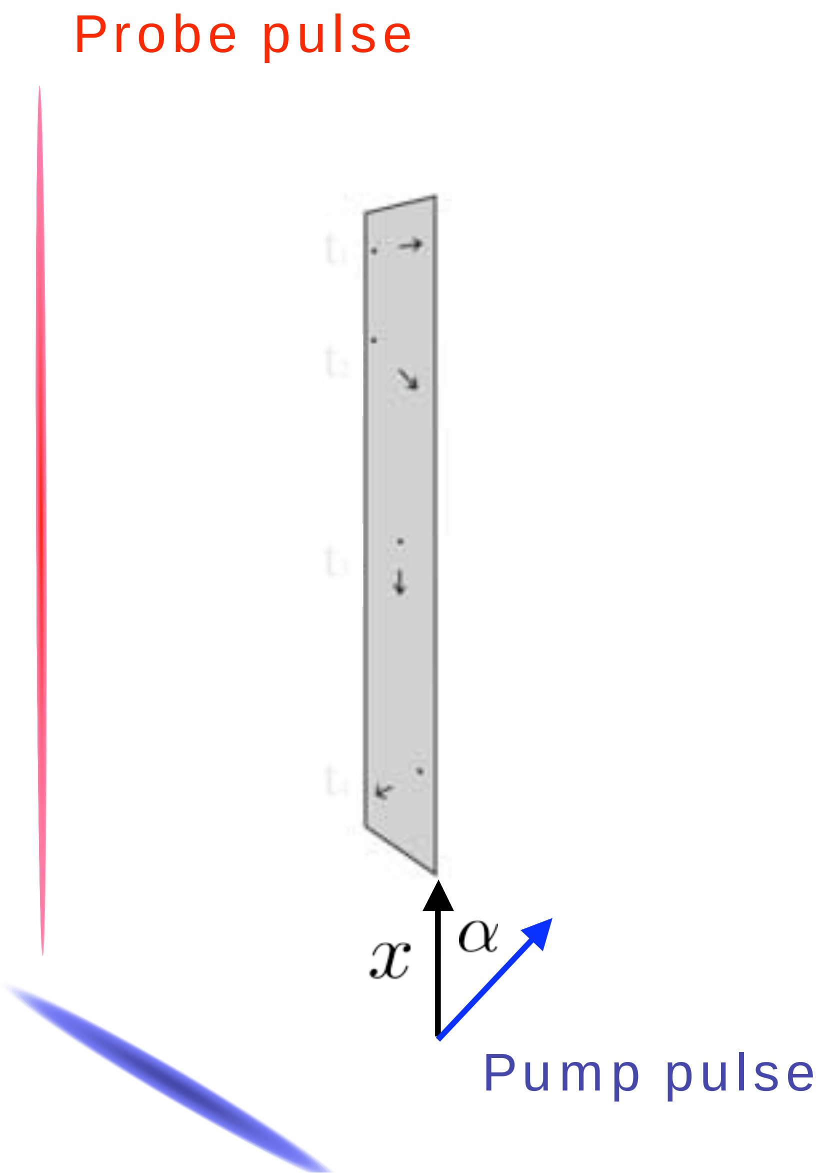


Panoramic Field of View

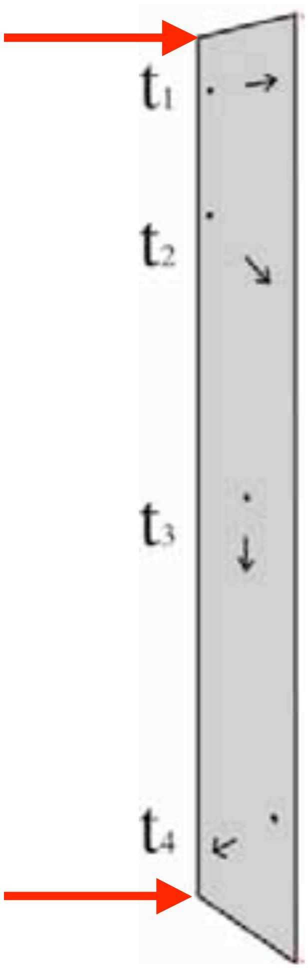


W.F. Schlotter, *et. al*, Optics Letters, Accepted

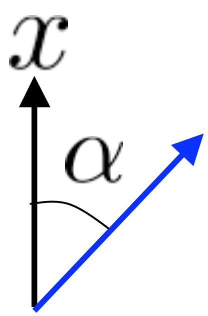
Toward Ultrafast Evolution

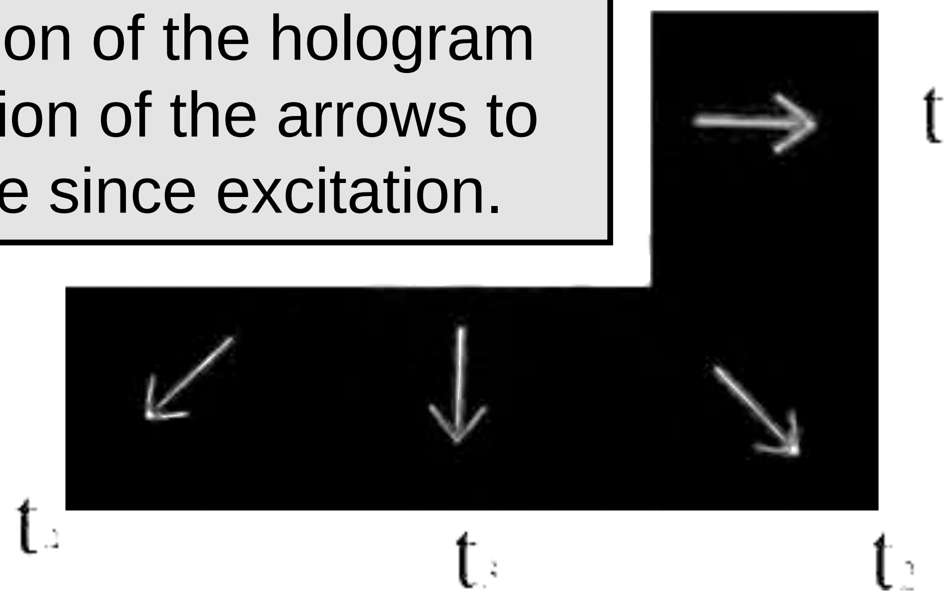


Single Shot Stopwatch



The reconstruction of the hologram relates the position of the arrows to their relative time since excitation.





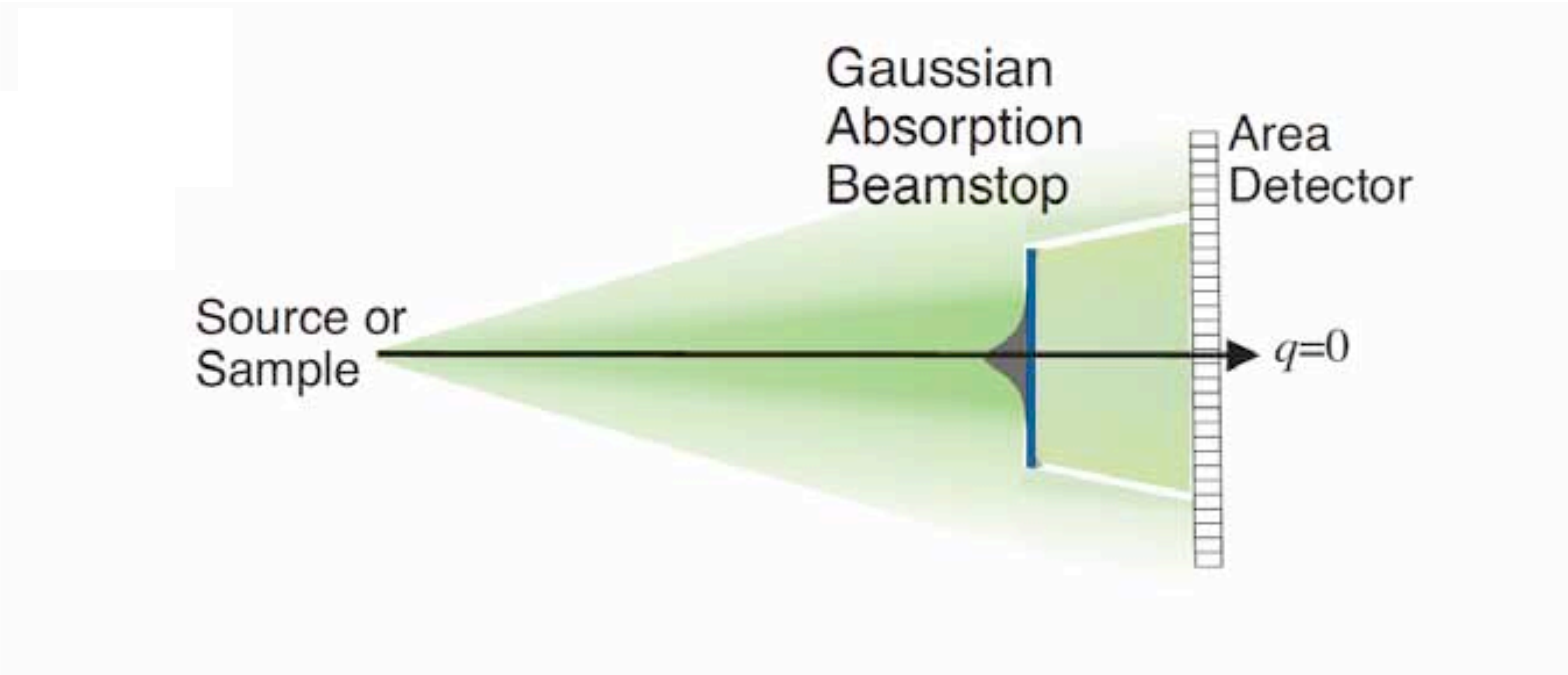
$$t(x) = x\frac{\cos(\alpha)}{c}$$

$$c = 0.3\ \mu\text{m/fs}$$

W.F. Schlotter, *et. al*, Optics Letters, Accepted

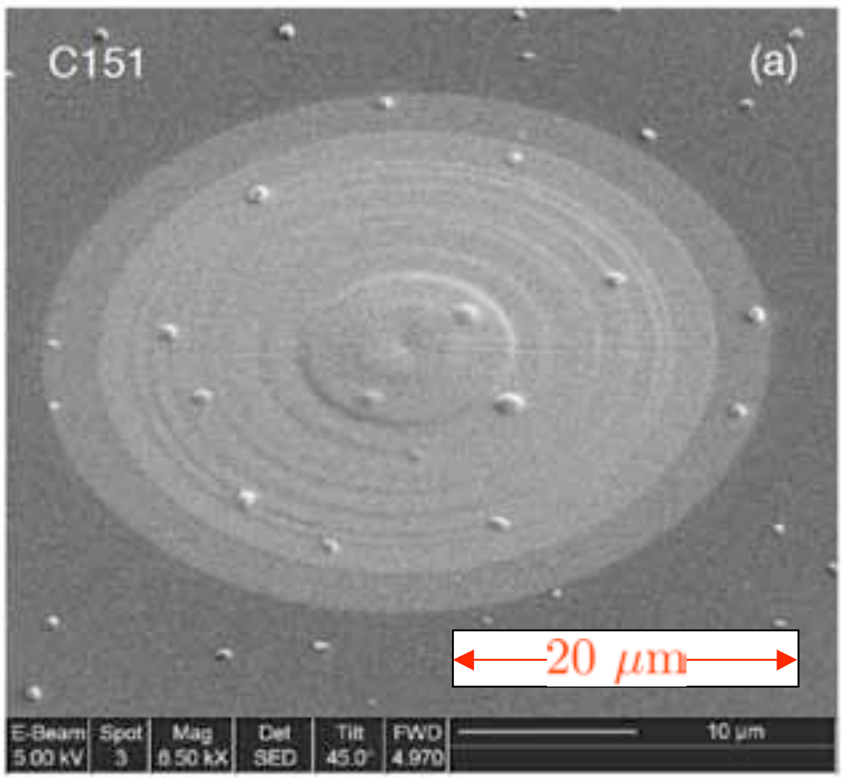
Increasing Dynamic Range

Gaussian Absorption Beamstop

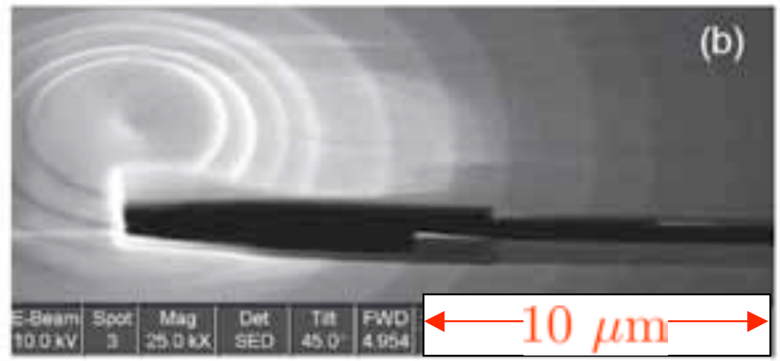


Patterned Prototype

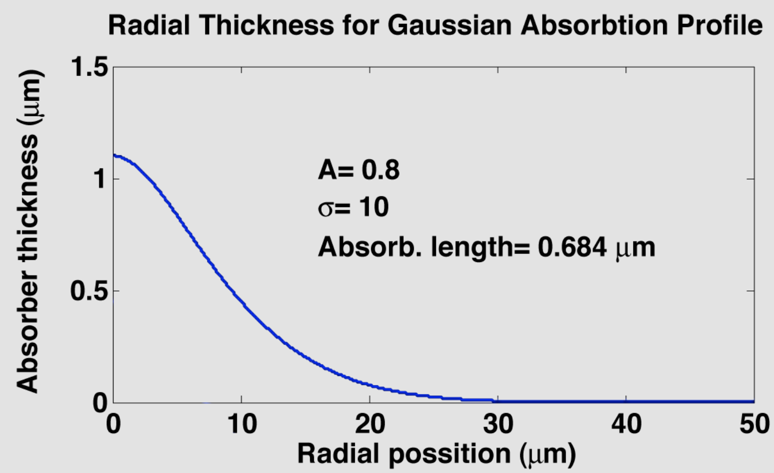
Concentric disks were formed by Focused Ion Beam Pt deposition



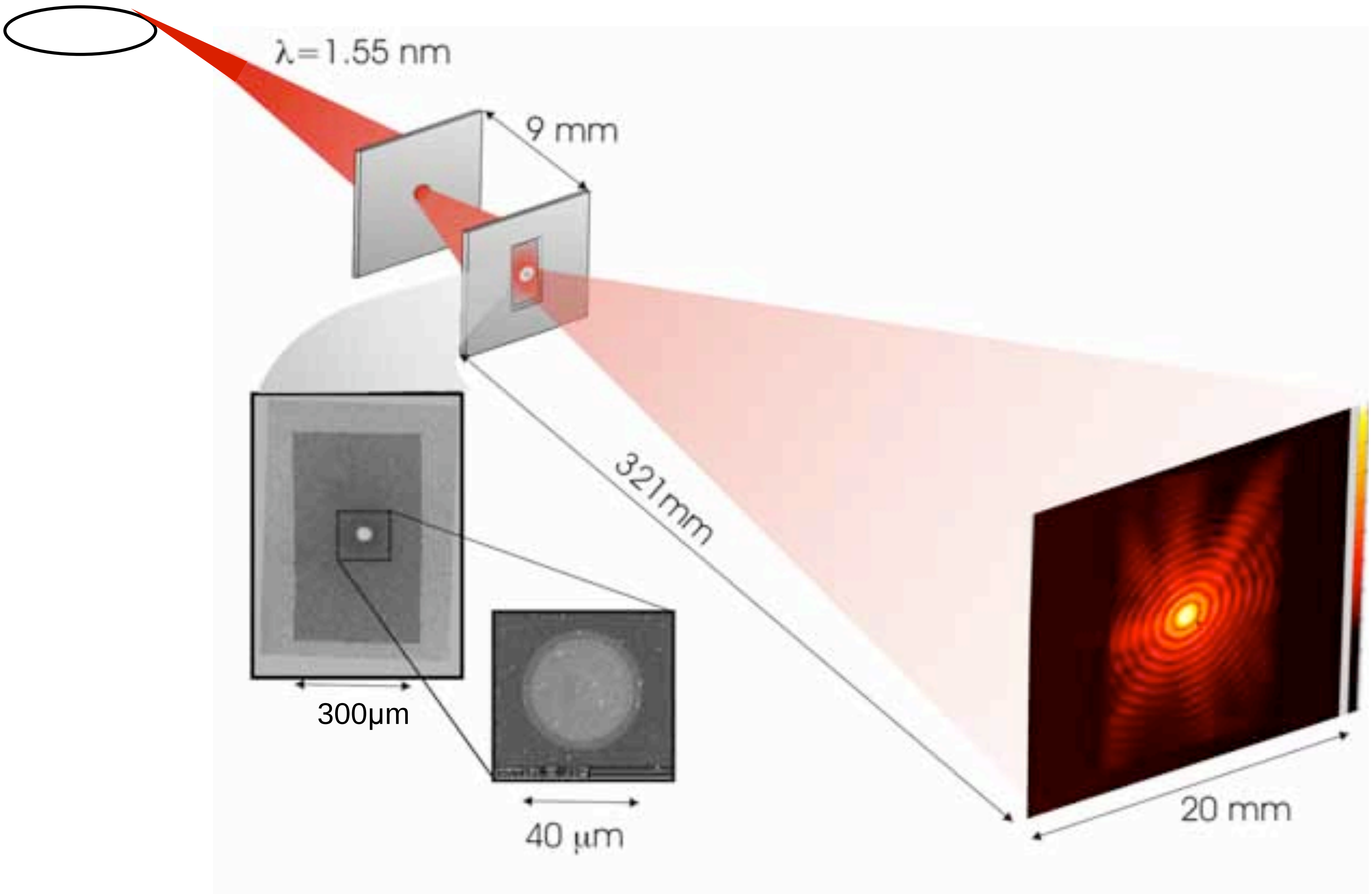
Sacrificial test sample



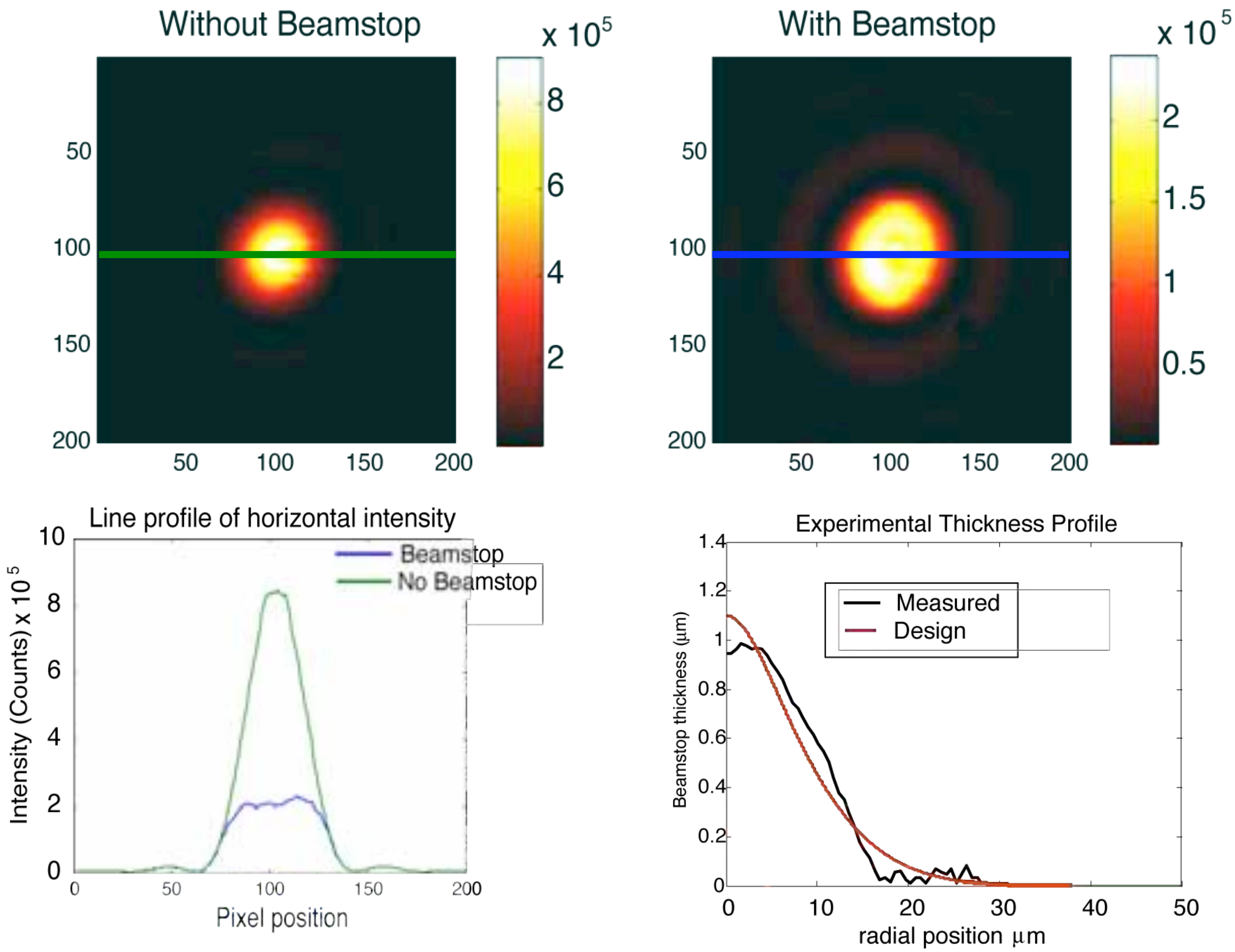
$$t(r) = -\ln(-A_o e^{\frac{-r^2}{2\sigma^2}} + 1)\mu$$



Testing the Beamstop

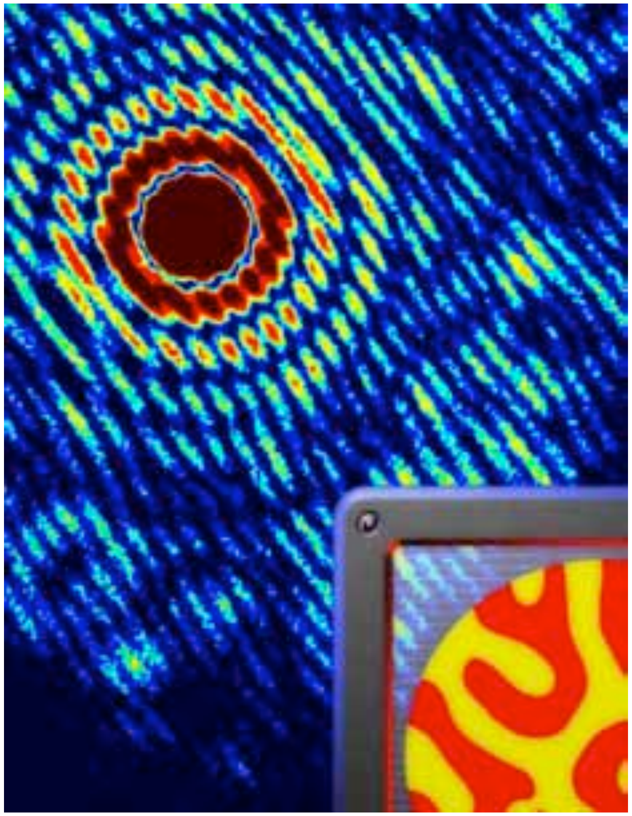


Enhanced Dynamic Range



Conclusions

- Lensless imaging at soft x-ray wavelength is robust and ready for single shot experiments
- Integrated mask is the key
- High spatial resolution
- Single shot
  - Improved SNR
  - Extended Field of View
  - Single shot clock
- Future is Bright



Coherence Crew

Ramon Rick
Kang Chen

Christian Günther
Stefan Eisebitt

Ian McNulty

Tai-Hee Kang

Shampa Sarkar
Andreas Scherz
Sujoy Roy
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