РЕНТГЕНОВСКАЯ МИКРОСКОПИЯ И МИКРОТОМОГРАФИЯ - ИСТОРИЯ И РАЗВИТИЕ

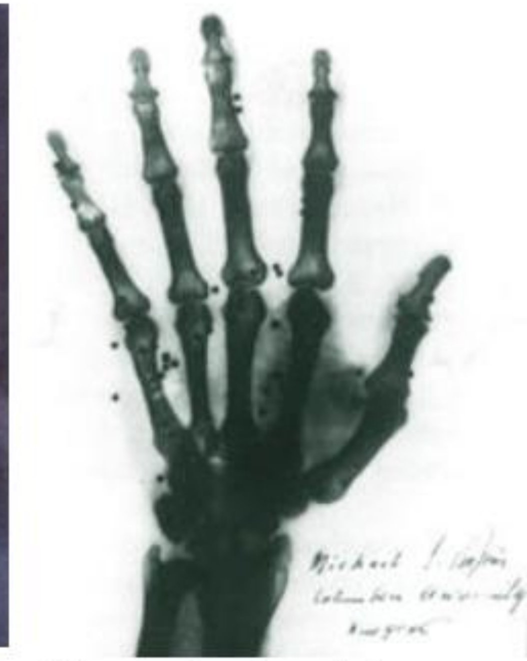
Сенин Р. А.

НИЦ «Курчатовский институт»

First steps

Wilhelm Röntgen
Universität Würzburg
Dec. 1895

Michael Pupin
Columbia University/New York
Feb. 1896



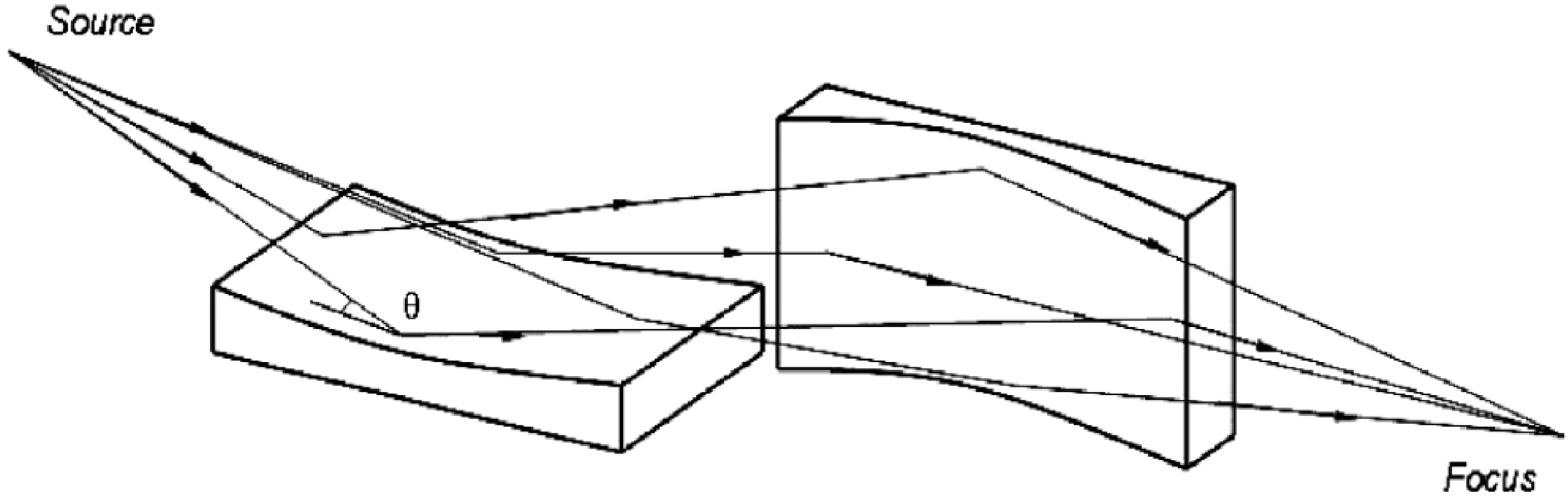
"This is of the hand of a gentleman resident in New York, who, while on a hunting trip in England a few months ago, was so unfortunate as to discharge his gun into his right hand, no less than forty shot lodging in the palm and fingers. The hand has since healed completely; but the shot remain in it, the doctors being unable to remove them, because unable to determine their exact location. The result is that the hand is almost useless, and often painful." - Cleveland Moffett, McClure's Magazine, April 1896

Röntgen first experiments

after W.C. Röntgen
Über eine neue art von Strahlen.
Phys.-Med. Ges., Würzburg, **137**, p. 41, (1895)
*English translation in Nature **53**, p. 274*

- **Photographic plates and film are"susceptible to x-rays", providing avaluable means of recording the effects..."**
- **"... The refractive index.... cannot be more than 1.05 at most.... X-rays cannotbe concentrated by lenses…"**
- **"... Detection of interference phenomena has been tried without success, perhaps only because of their feeble intensity..."**

Kirkpatric & Baez microscope



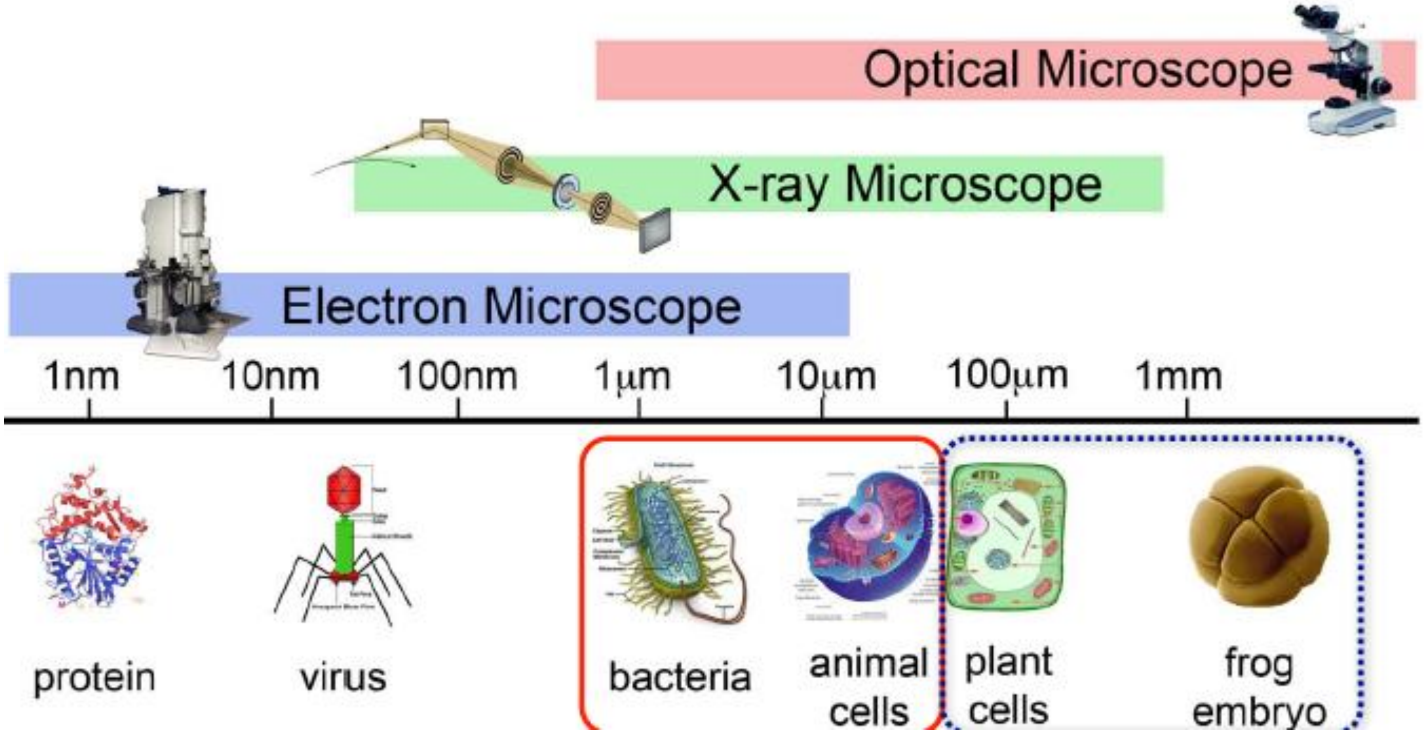
Kirkpatrick P and Baez A V 1948

Journal of the Optical Society of America V 38 pp.766–774

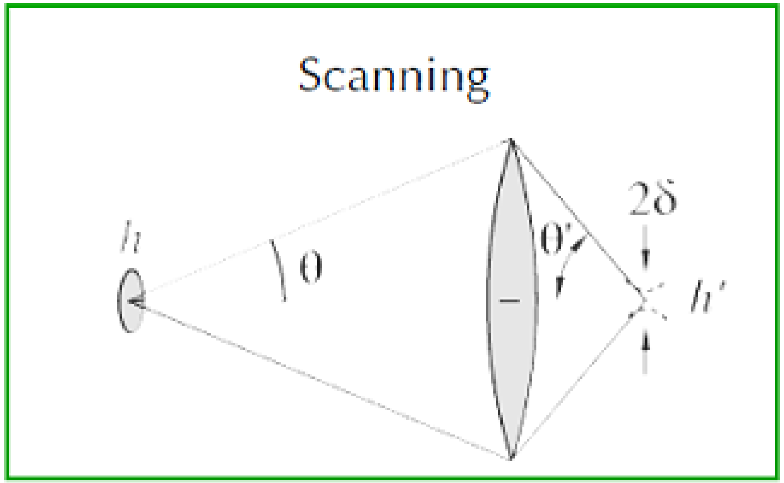
X-ray optics milestones

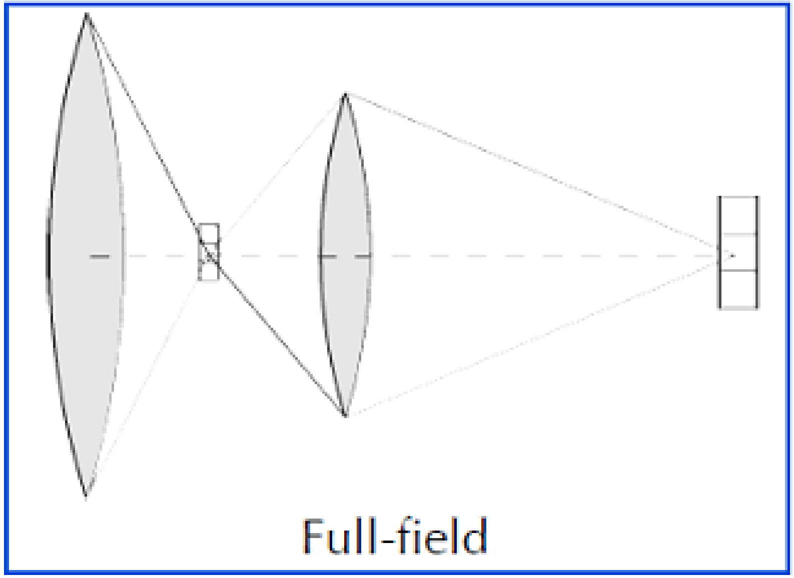
- 1896 X-ray absorption (Röntgen – filters)
- 1912 Bragg diffraction (Laue - monochromators)
- 1913 Radiography (Goby – imaging)
- 1922 Specular reflection (Compton - mirrors)
- 1948 X-ray curved mirrors (Kirkpatrick and Baez)
- 1960 X-ray Fresnel zone plates (Baez)
- 1972 X-ray mulilayers (Spiller, Barbee, Underwood)
- 1987 Bragg-Fresnel optics (Aristov)
- 1994 Capillaries (Bilderback)
- 1996 Compound Refractive Lenses (Suehiro, Snigirev)

X-ray microscopy: Bridging the gap between electron and light microscopy



Scanning or full-field?

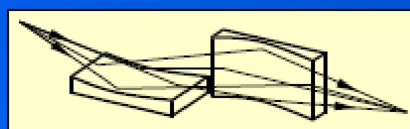
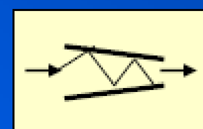
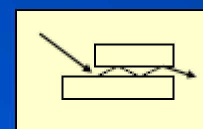
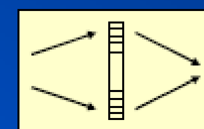
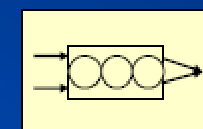




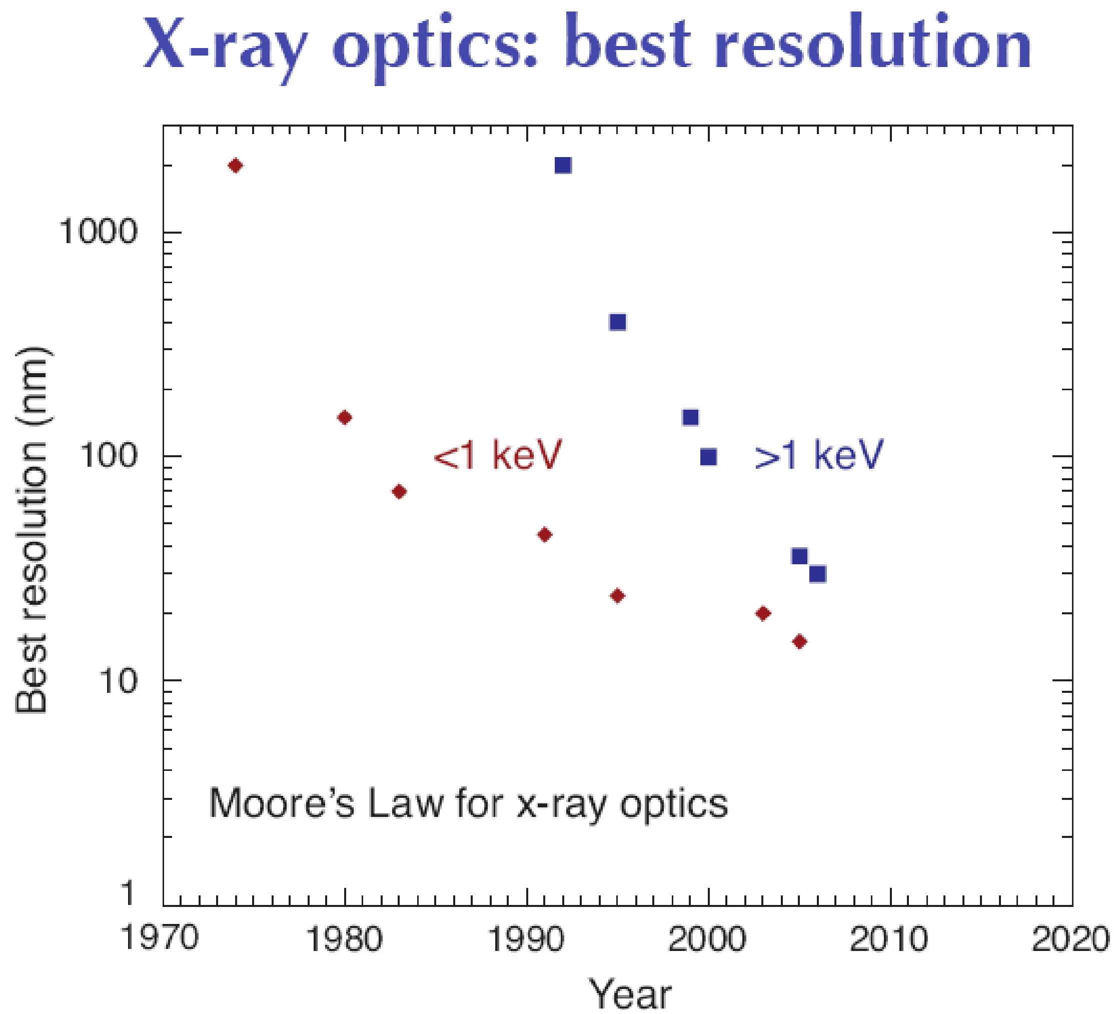
Hard x-rays or soft?

A. Snigirev, August 2007

Focusing Optics for Hard X-rays (E > 6 keV)

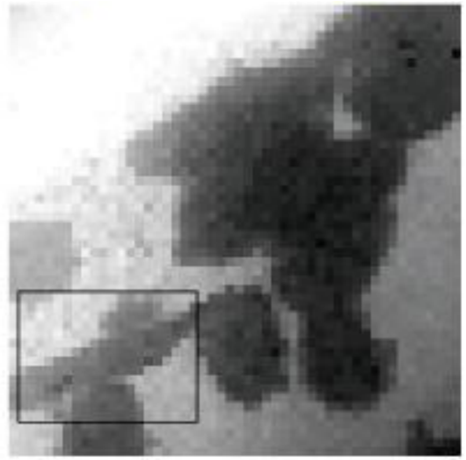
	reflective				*diffractive*	*refractive*
	Kirkpatrick Baez systems		Capillaries	Waveguides	Fresnel Zone plates	Refractive lenses
	mirrors Kirkpatrick Baez, 1948	multilayers Underwood Barbee, 1986	Kreger 1948	Feng et al 1993	Baez 1952	Snigirev et al, 1996
						
Energy	< 30 keV	< 80keV	< 20keV	< 20keV	< 30 keV (80)	<1 MeV
Bandwidth ΔE/E	w. b.	10^{-2}	w.b.	10^{-3}	10^{-3}	10^{-3}
resolution	**25 nm** @15keV Mimura 2006	**41x45nm^2** @24keV Hignette 2006	**50 nm** Bilderback 1994	**40x25 nm^2** Salditt 2004	**30 nm** @20 keV Kang, 2006 <ins>17 nm</ins>, 2007	**50 nm**@20keV Schroer, 2004 **150nm**@50keV Snigirev,2006

Moore’s law for x-ray optics



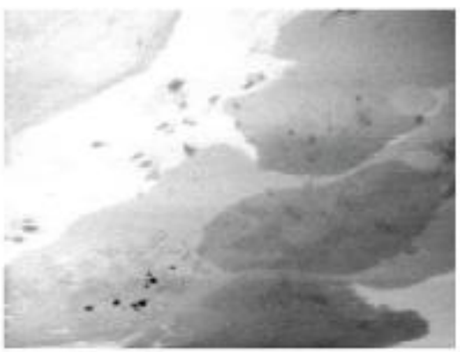
Radiation degradation

- X-rays are ionizing radiation. The dose per high resolution image is about 100,000 times what is required to kill a person
- Makes it hard to view living cells!

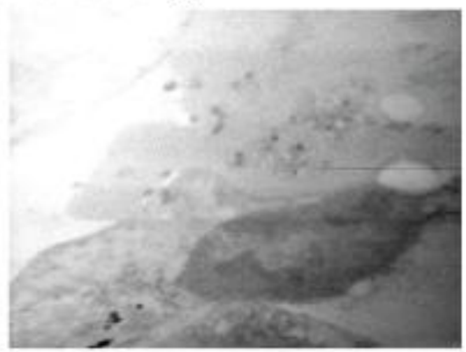


10 μm
$6.0 \cdot 10^2$ Gray, ET=2 min.

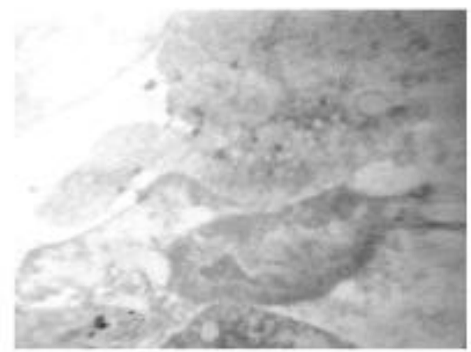
Experiment by V. Oehler, J. Fu, S. Williams, and C. Jacobsen, Stony Brook using specimen holder developed by Jerry Pine and John Gilbert, CalTech



5 μm
$1.2 \cdot 10^5$ Gray, ET=9.5 min.



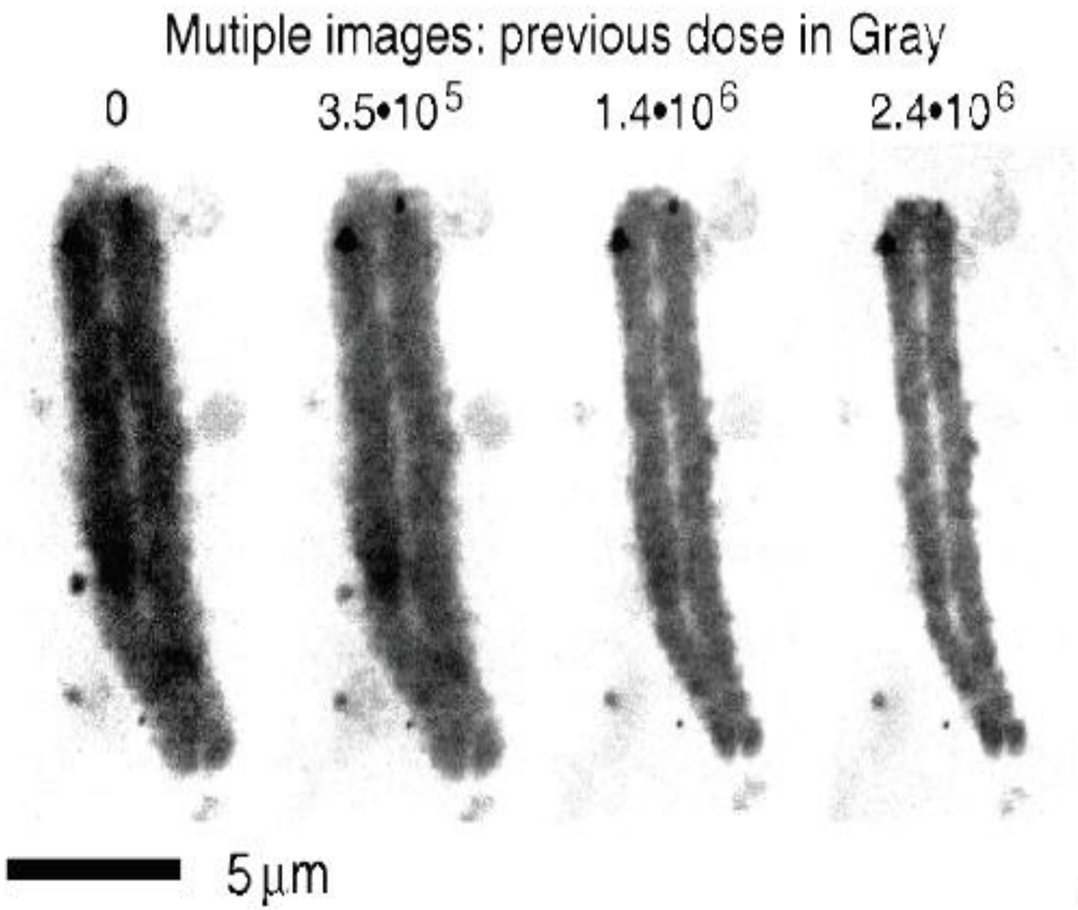
5 μm
$2.4 \cdot 10^5$ Gray, ET=17 min.



5 μm
$3.7 \cdot 10^5$ Gray, ET=24.5 min.

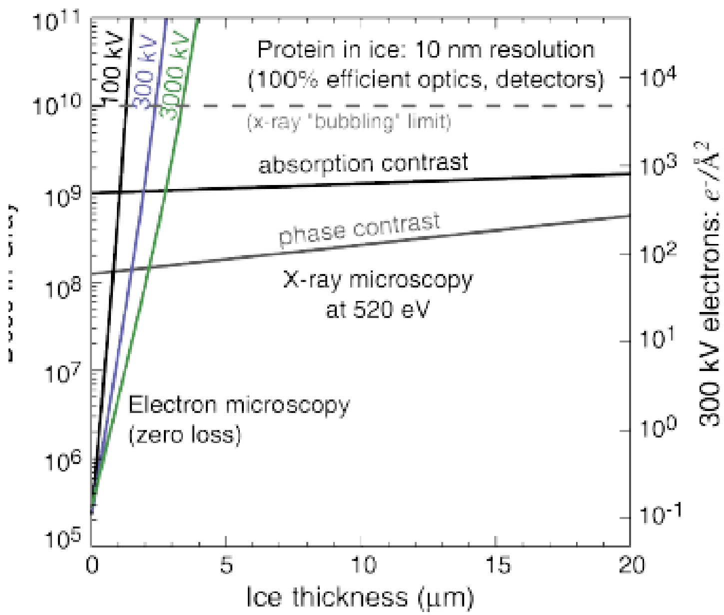
Radiation degradation

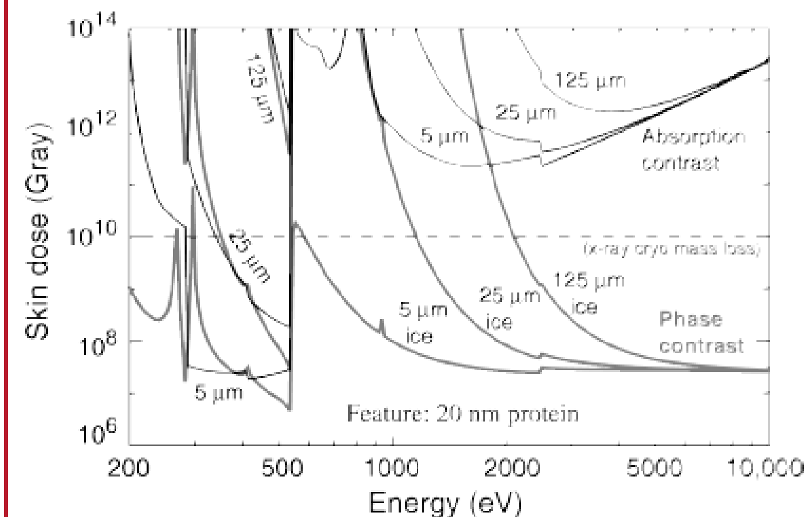
- Chromosomes are among the most sensitive specimens.
- V. faba chromosomes fixed in 2% glutaraldehyde. S. Williams et al., J. Microscopy **170**, 155 (1993)
- Repeated imaging of one chromosome shows mass loss, shrinkage



Electrons vs. soft X-rays

X-rays: better for thicker specimens. Sayre *et al.*, *Science* **196**, 1339 (1977); Schmahl & Rudolph in **X-ray Microscopy: Instrumentation and Biological Applications** (Springer, 1987)

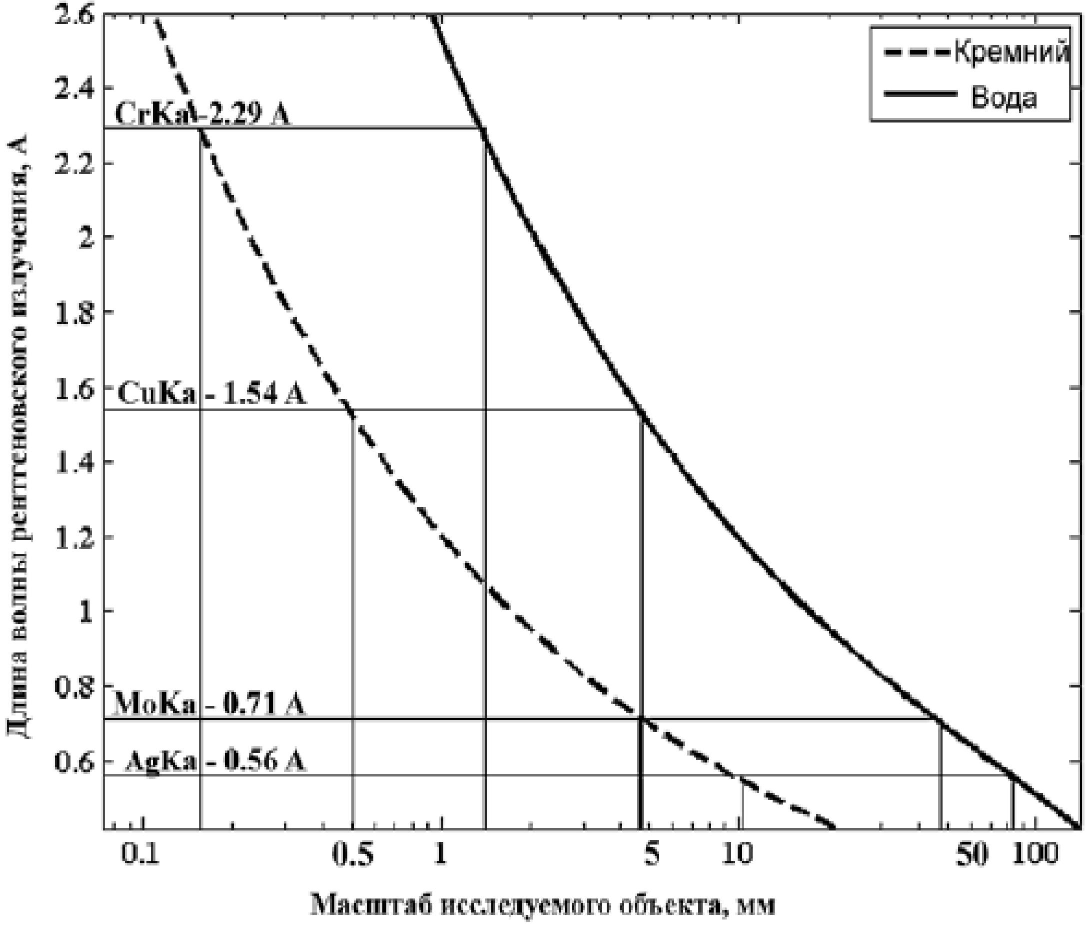




Phase contrast is important!

These plots: based on Jacobsen, Medenwaldt, and Williams, in **X-ray Microscopy & Spectromicroscopy** (Springer, 1998)

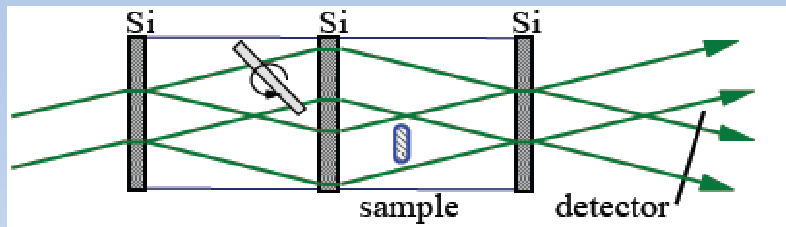
Hard X-ray: Choosing optimal wavelength



В.Е.Асадчиков, А.В.Бузмаков, Д.А.Золотов и др. Кристаллография, 2010, том 55, № 1, с. 167–176

Imaging phase

Phase sensitive imaging



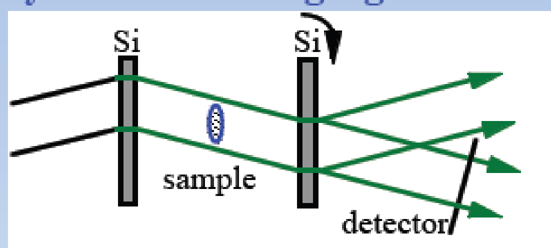
φ

Interference with reference beam

Ando & Hosoya, 1972

Bonse; Momose

Analyser based imaging

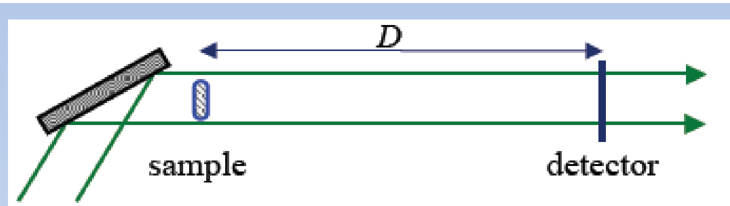


$\frac{d\varphi}{dx}$

Analyser
as angular filter

Zaumseil, 1980

Belyaevskaia & Ingal, Chapman



$\frac{d^2\varphi}{d^2x}$

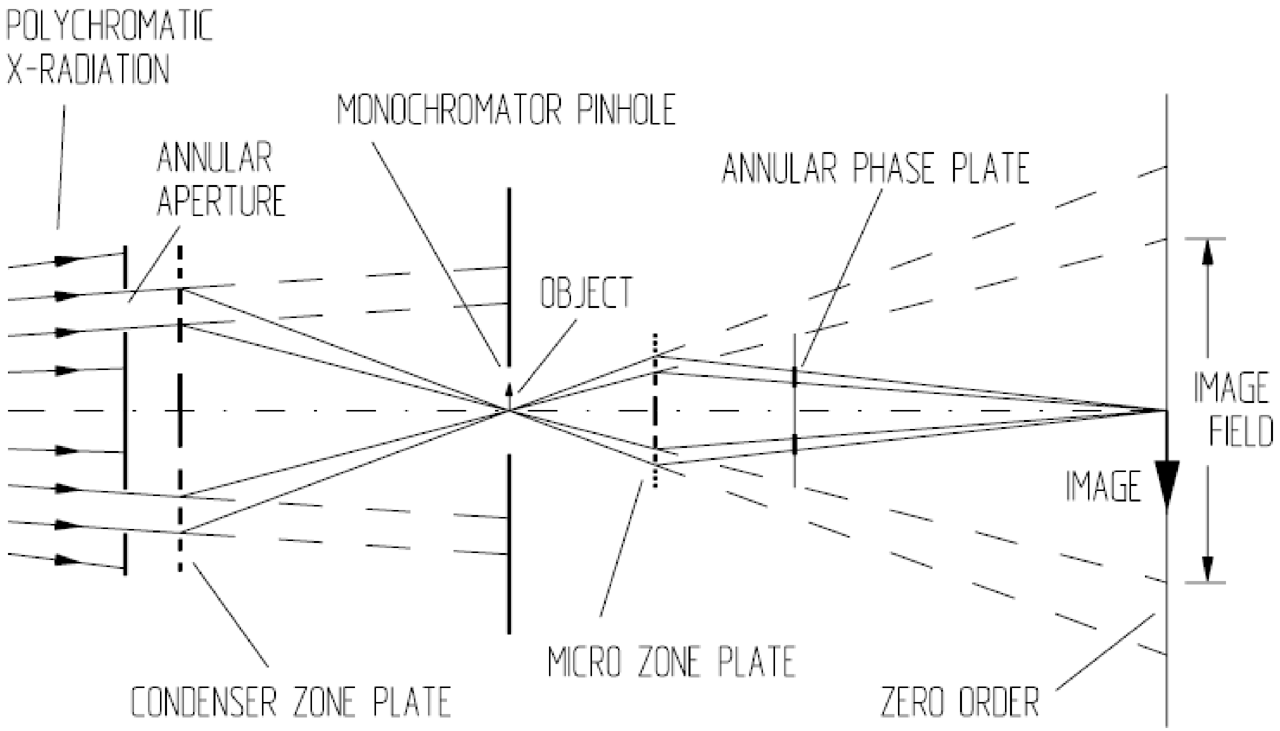
Fresnel diffraction

Hartman (1994)

Cloetens; Snigirev; Wilkins

By the courtesy P.Cloetens, HERCULES lectures, ESRF

Zernike phase contrast

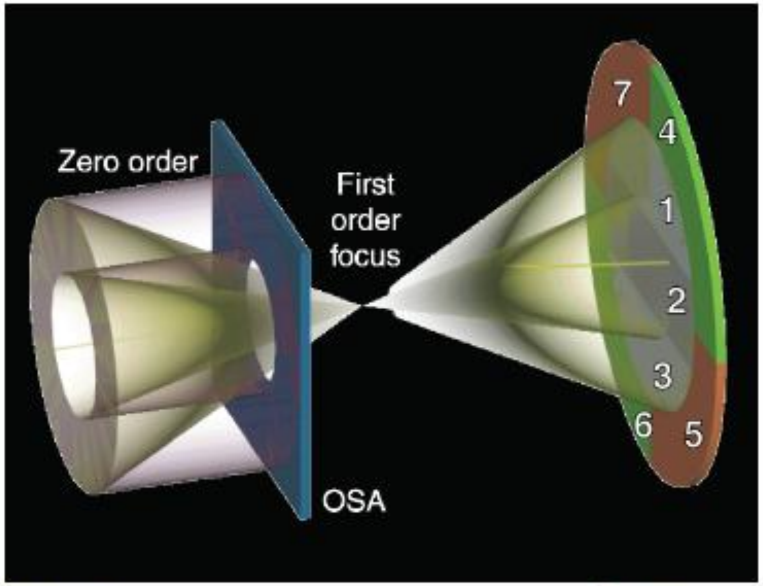


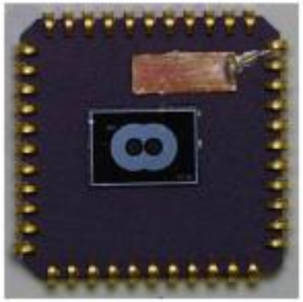
From Kirz, Jacobsen, and Howells, Q. Rev. Biophys. 28, 33-130 (1995)

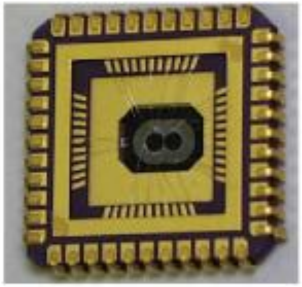
Fast phase contrast detector

M. Feser, B. Hornberger, C. Jacobsen (Stony Brook); P. Rehak, G. de Geronimo (BNL Instrumentation); L. Strüder, P. Holl (MPI München)

- Silicon drift detector
- Simultaneous recording of bright field, dark field, differential contrast at msec pixel times
- No significant upper limit to signal rate. Acceptable dark noise (~8 photons/msec equivalent; room temperature)
- High quantum efficiency (>90%)



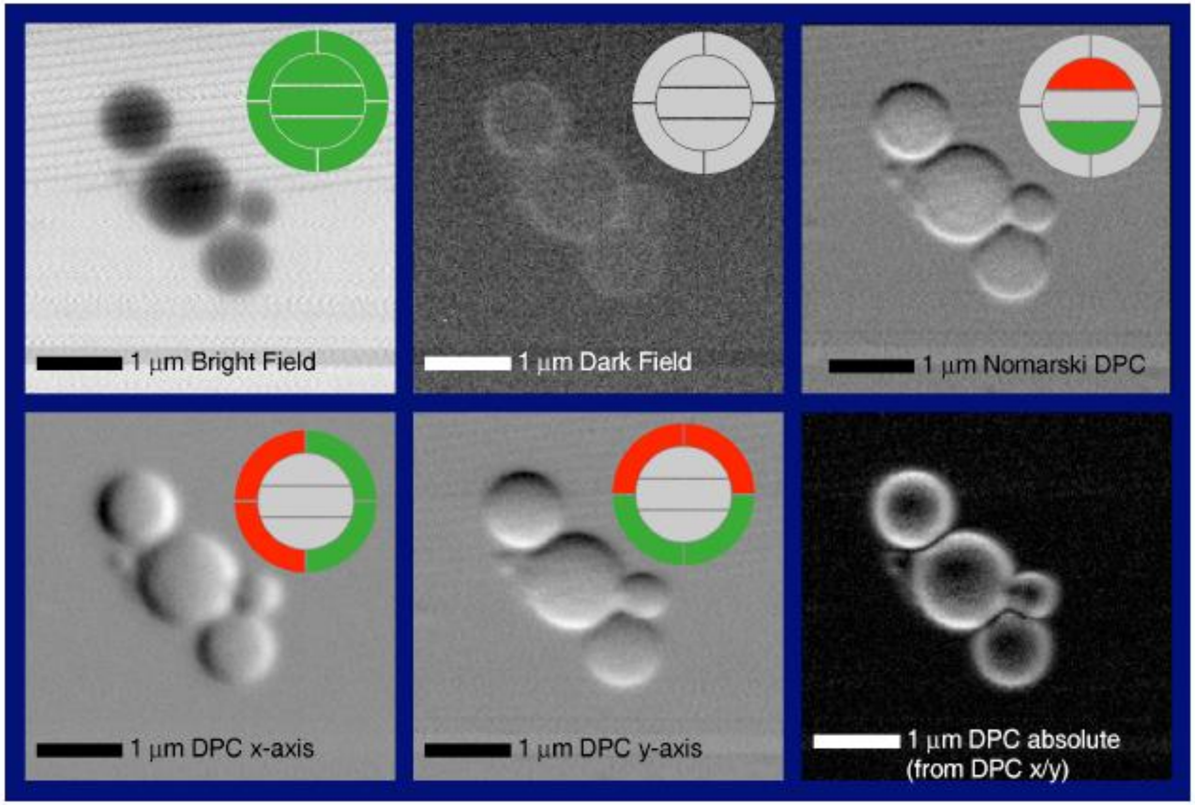




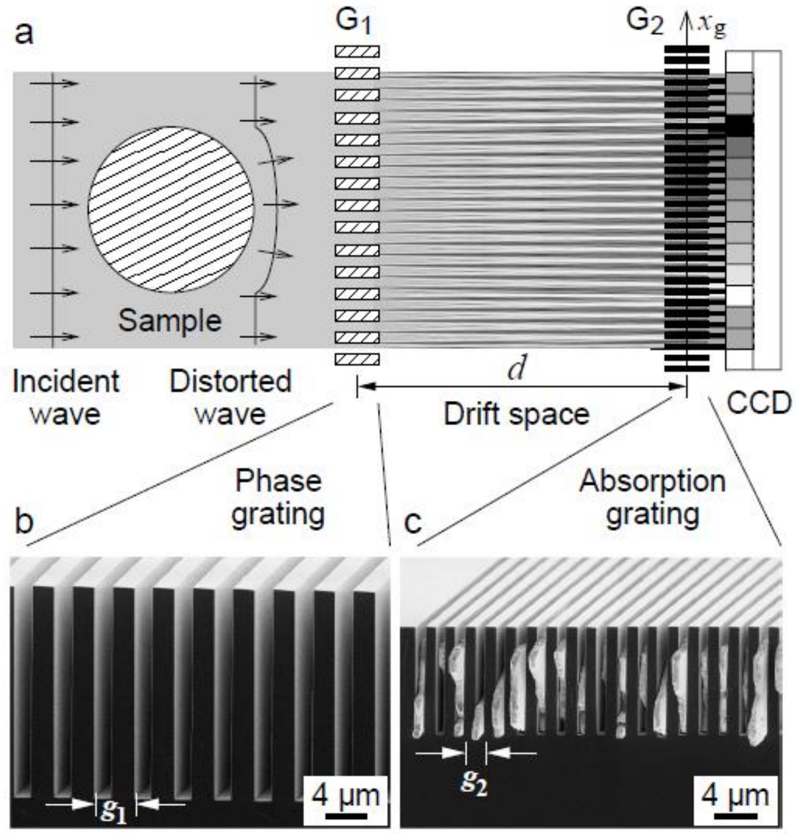
Assembly: 40 mm across
Active area: 600 μm

Simultaneous Availability Of Contrast Modes

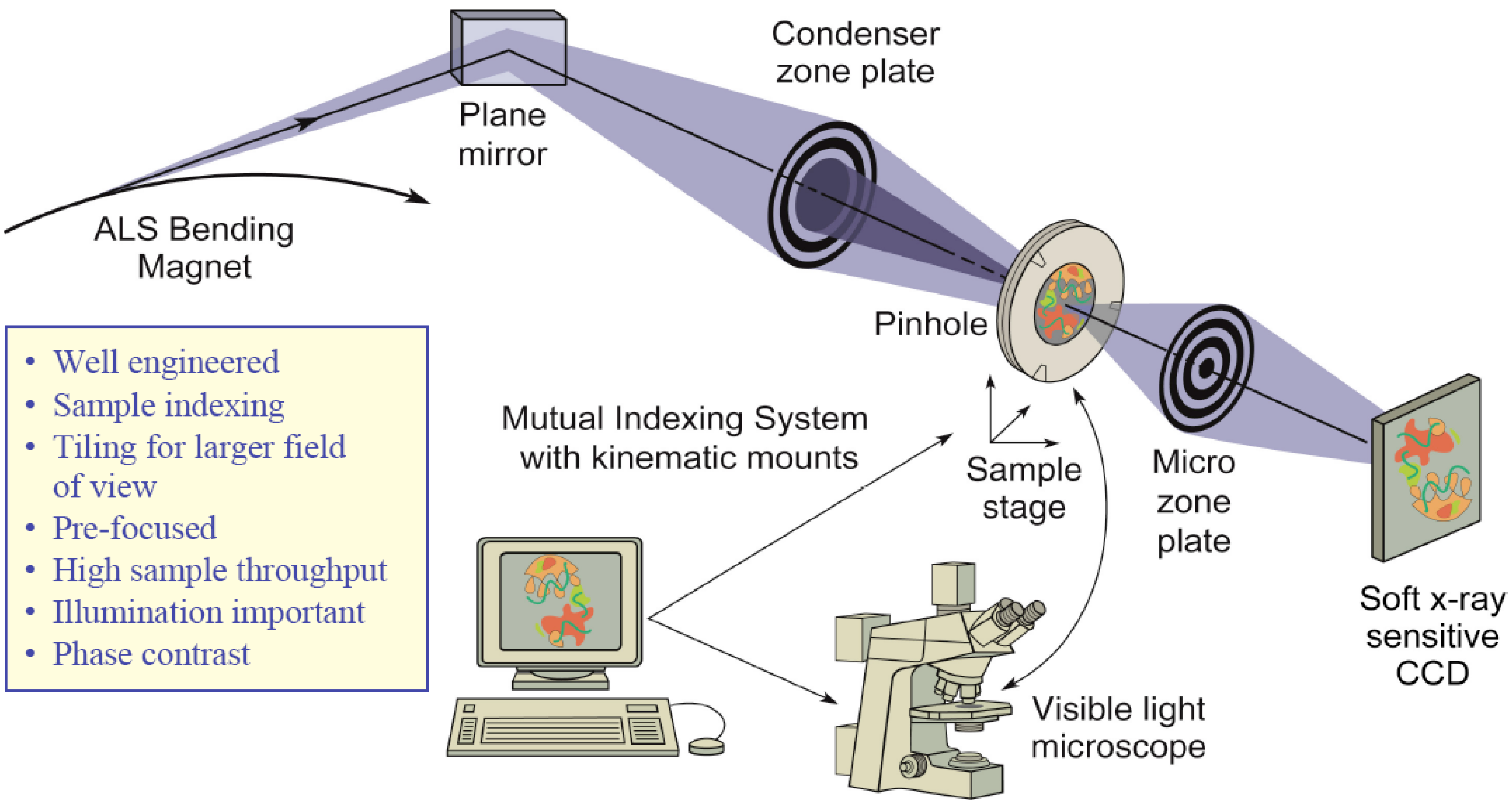
- Silica spheres 1 μm diameter or less
- Differential phase contrast filters out intensity fluctuations of the source!



Talbot interferometer

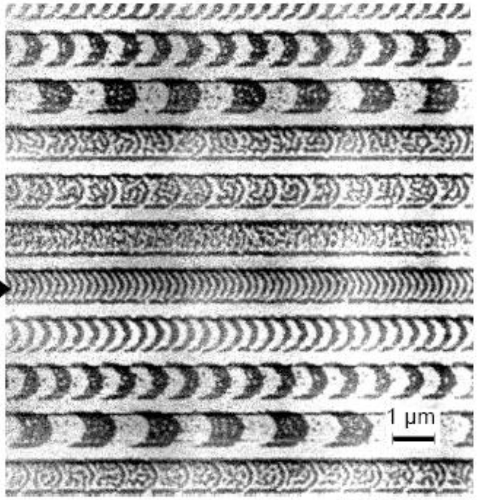


High Resolution Zone-Plate Microscope XM-1 at the ALS



- Well engineered
- Sample indexing
- Tiling for larger field of view
- Pre-focused
- High sample throughput
- Illumination important
- Phase contrast

Magnetic Recording Materials

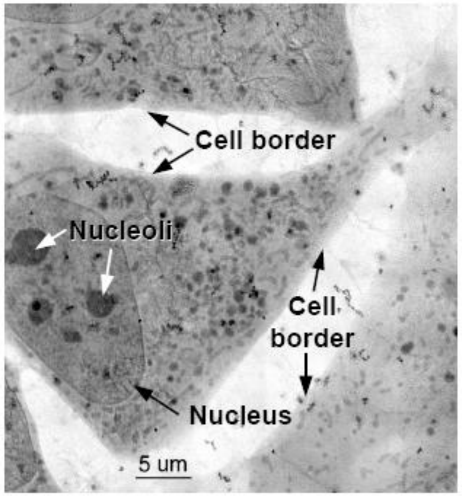


Fe L_3 @ 707.5 eV

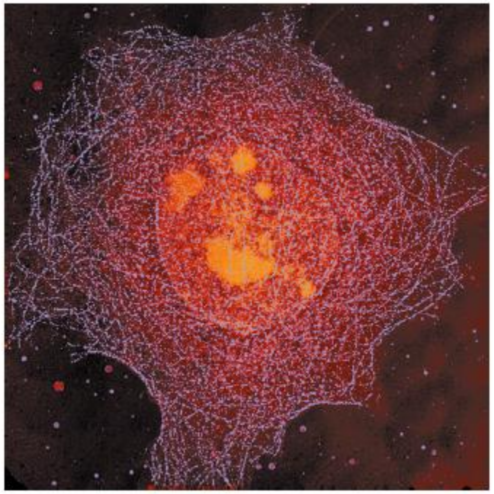
FeTbCo Multilayer
with Al Capping Layer

Courtesy of P. Fischer (Max Planck)
and G. Denbeaux (CXRO/LBNL)

Cryo Microscopy for the Life Sciences



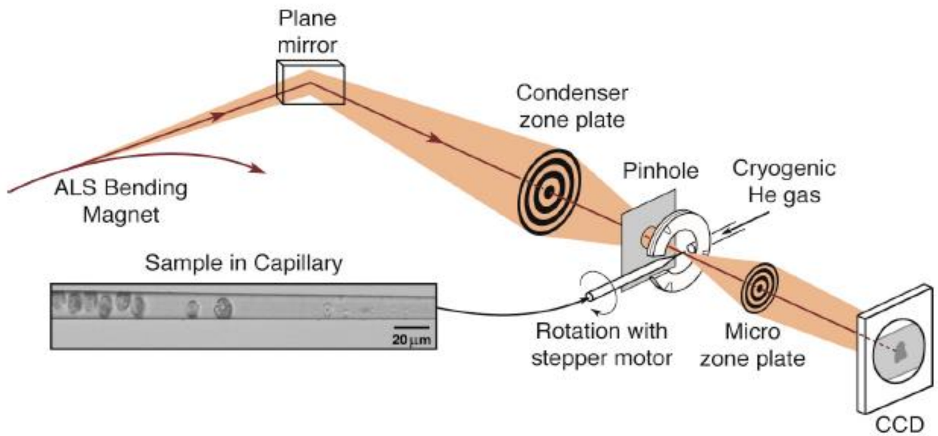
Cryo X-Ray Microscopy
of 3T3 Fibroblast Cells



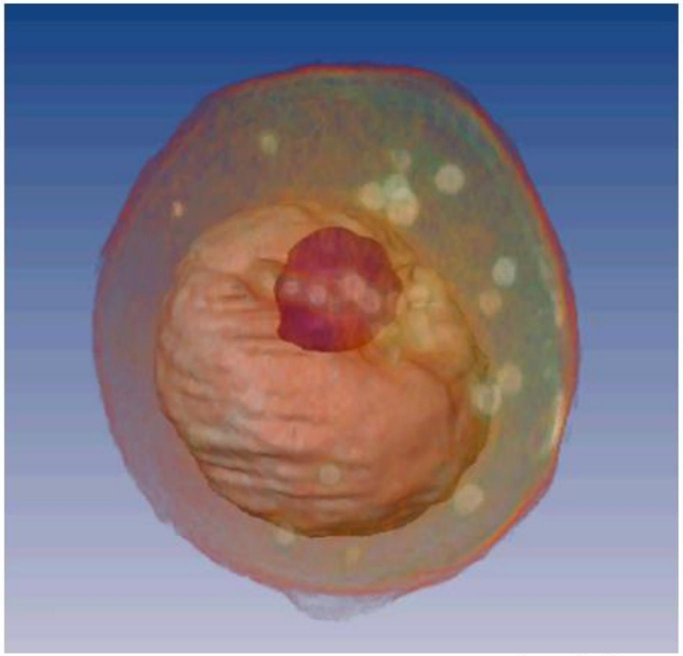
Protein Labeled
Microtubule Network

Courtesy of C. Larabell (UCSF)
and W. Meyer-Ilse (CXRO/LBNL)

Nanotomography of Cryogenic Fixed Cells



Soft X-Ray Nanotomography of a Yeast Cell

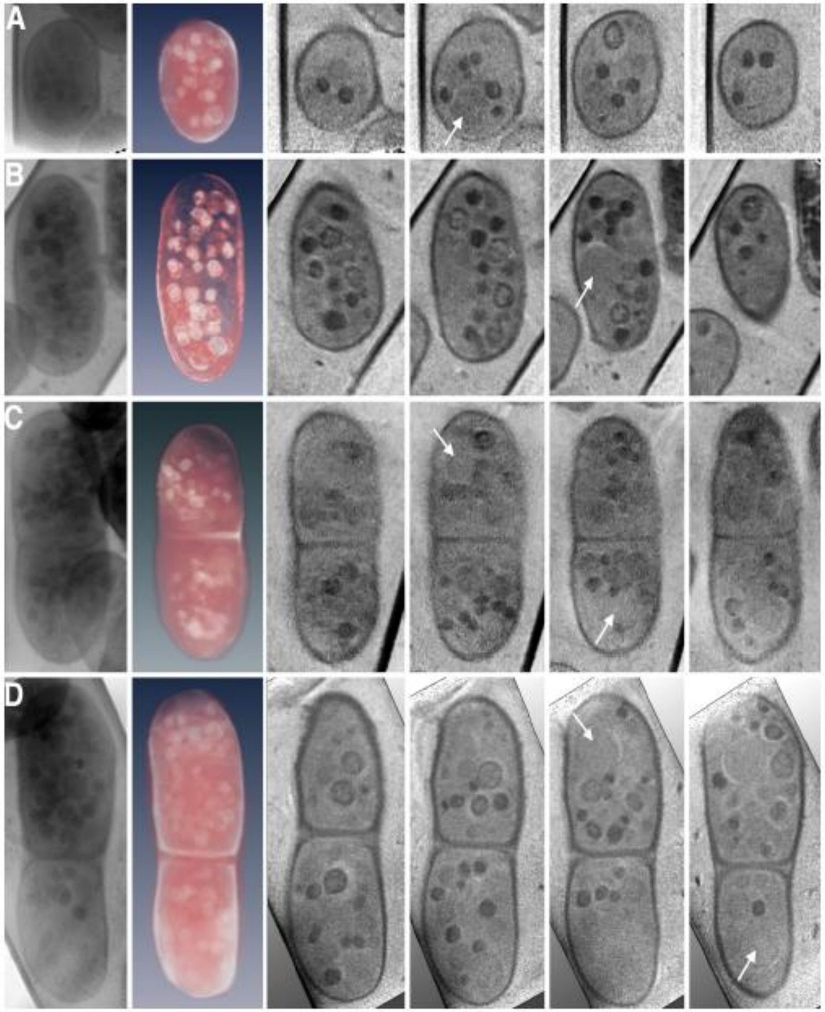


λ = 2.5 nm

C. Larabell and M. LeGros, *Molec. Bio. Cell* 15, 957 (2004)

NCXT

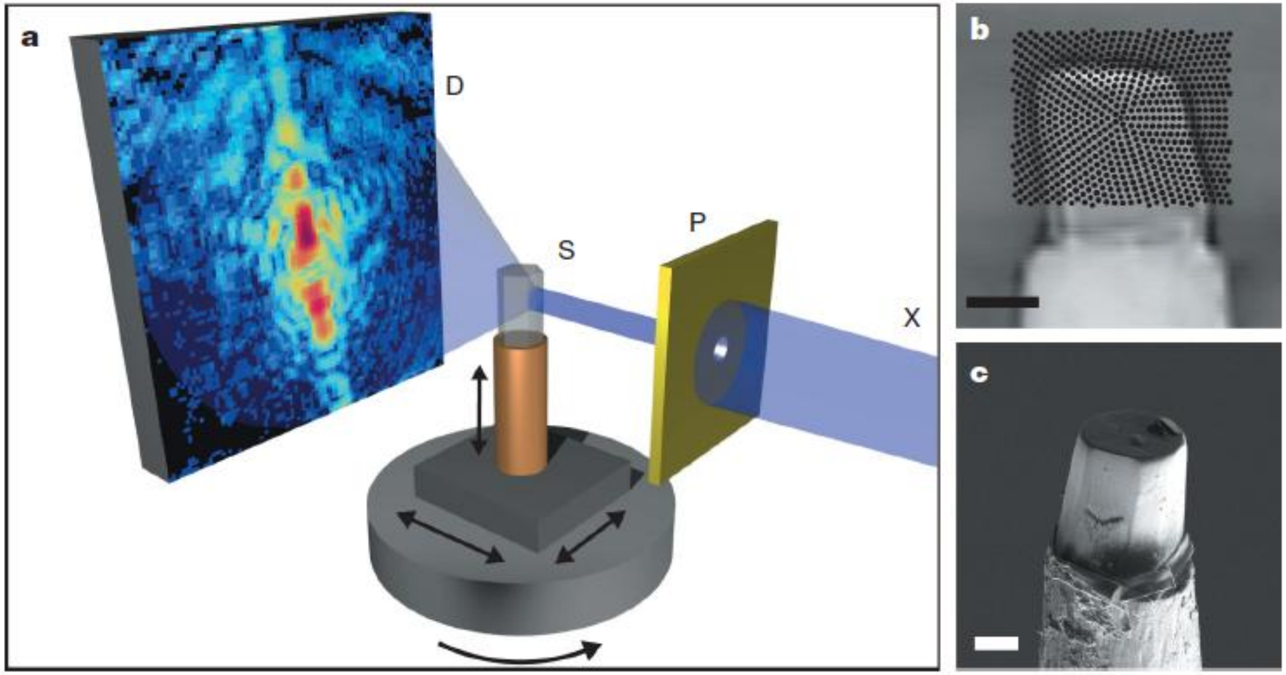
Schizosaccharomyces pombe



- Newborn cell
- Adult cell
- Dividing cell (early)
- Dividing cell (late)

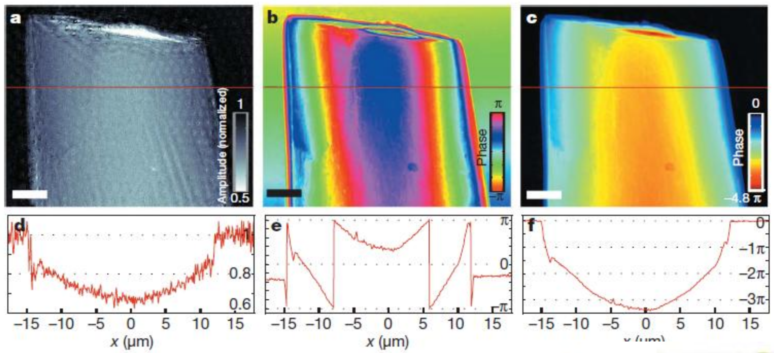
W. Gu, L. D. Etkin, M. A. Le Gros,
and C. A. Larabell. (2007) Differentiation. 75:529-535

Ptychographic X-ray computed tomography at the nanoscale



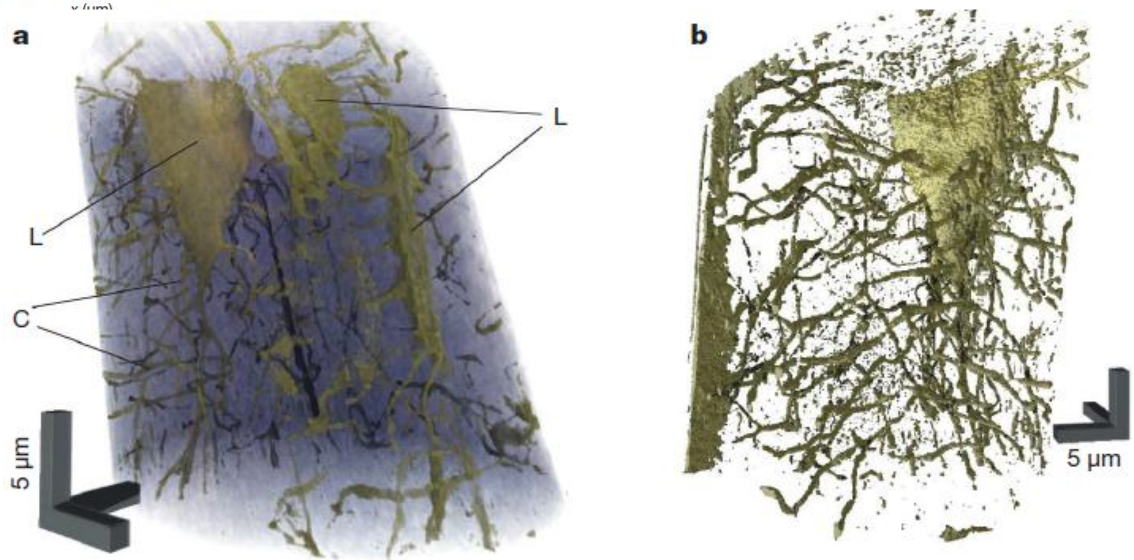
Dierolf M, Menzel A, Thibault P,et al. Nature, Vol 467, 2010, pp 436-440.

Ptychographic X-ray computed tomography



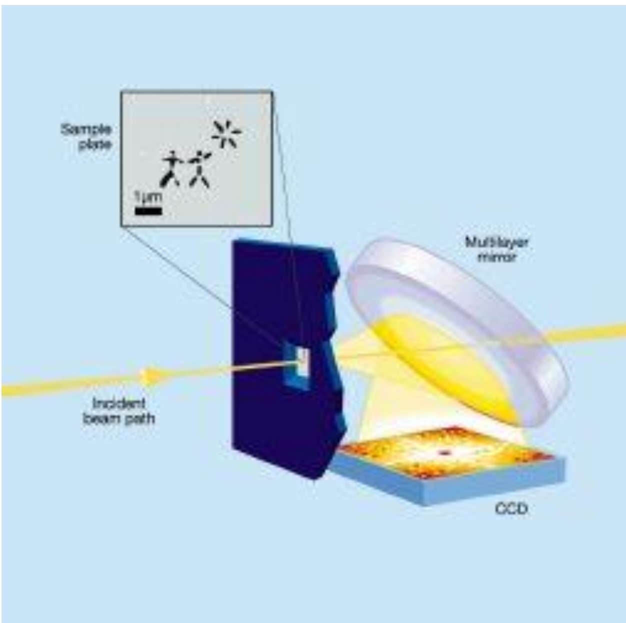
Spatial resolution - 150 nm

Dose:~2MGy
(2*10^{11} Photons total)

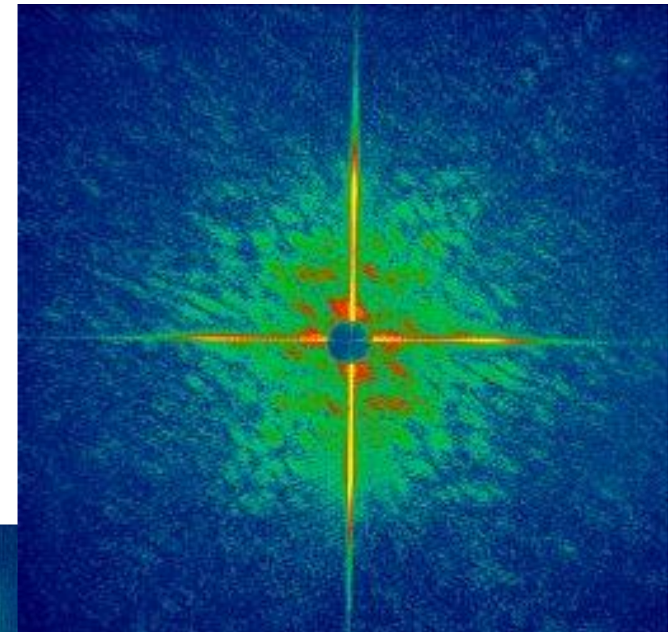


Dierolf M, Menzel A, Thibault P,et al. Nature, Vol 467, 2010, pp 436-440.

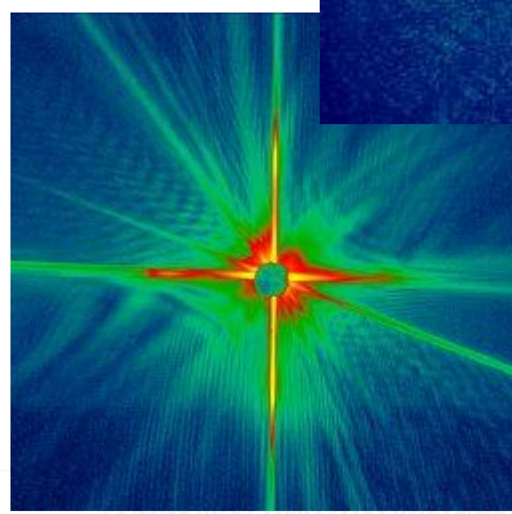
A single shot image



A nanoscale object can be imaged by a single femtosecond FEL pulse before the sample explodes

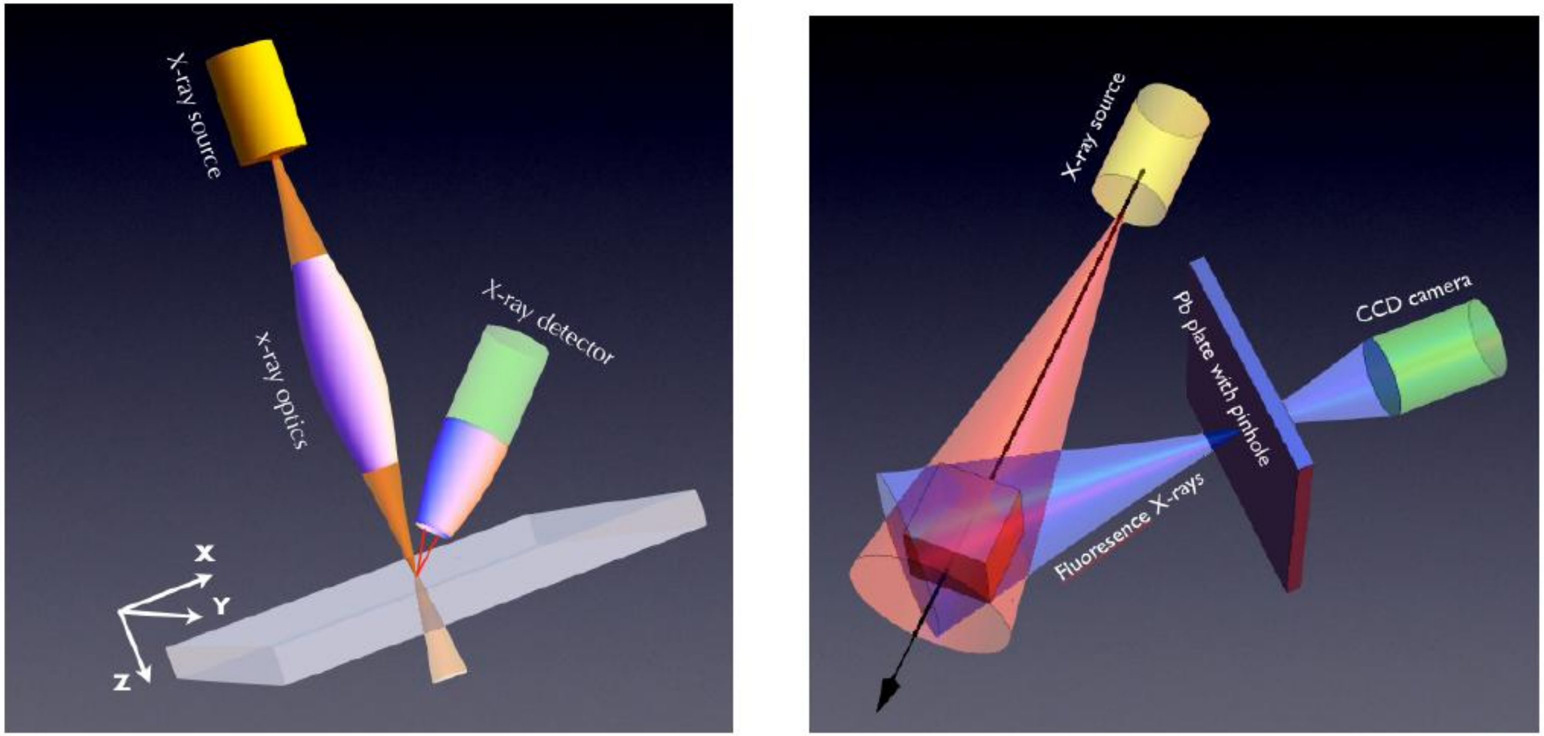


A coherent diffraction pattern recorded from a single 25 fs pulse



Diffraction pattern from a subsequent pulse showing that the sample was destroyed after recording the image

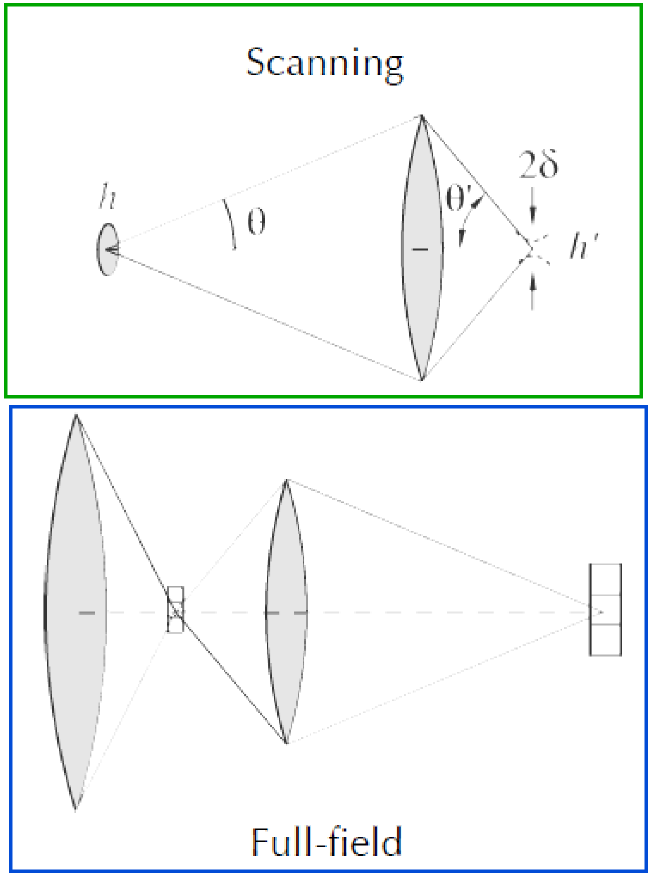
X-ray fluorescence microtomography



X. Liu, P. Bruyndonckx, and A. Sasov, Proc. SPIE 7804, 78041A-1 (2010).

Thank you for your attention!

Scanning or full-field?



Hard x-rays or soft?