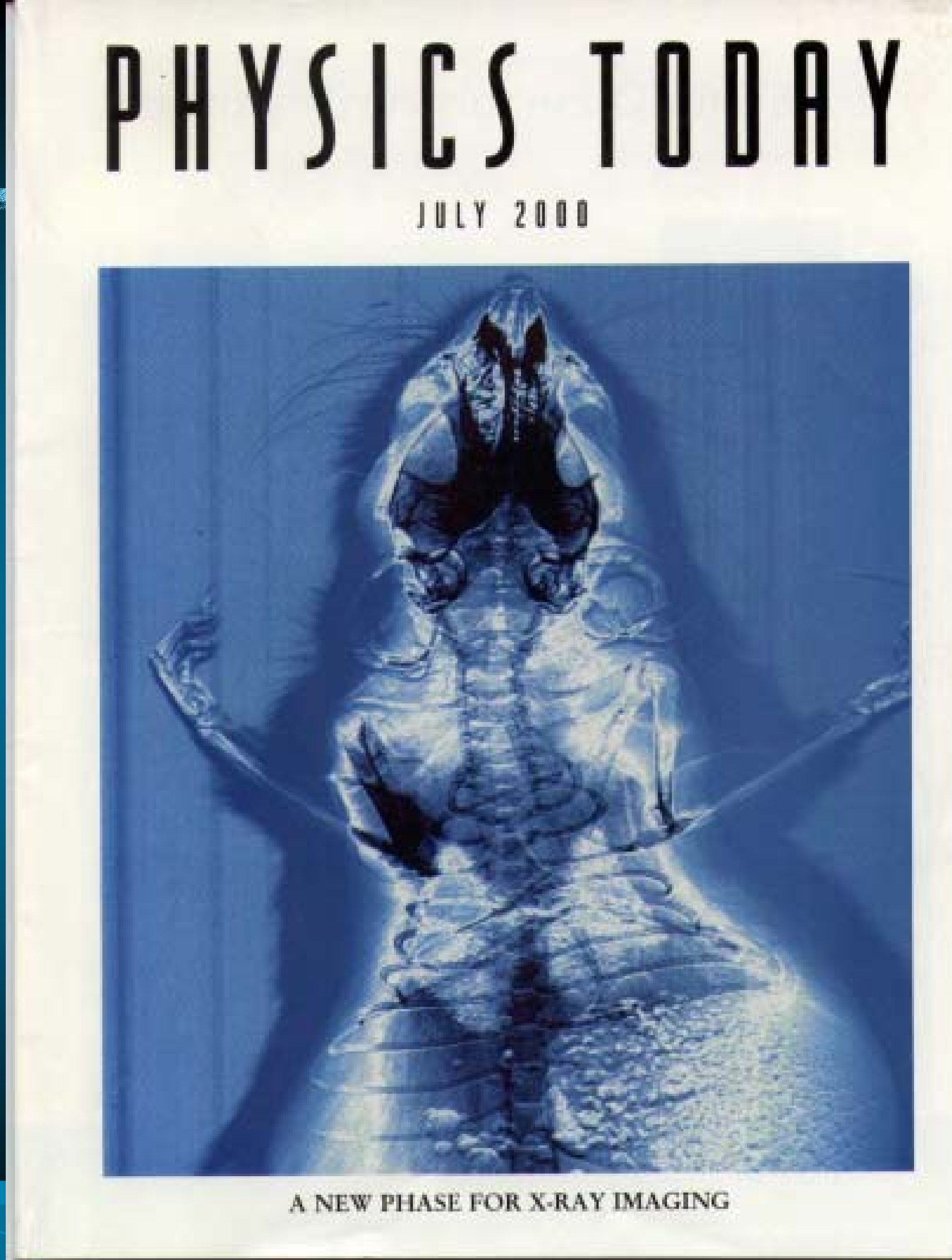
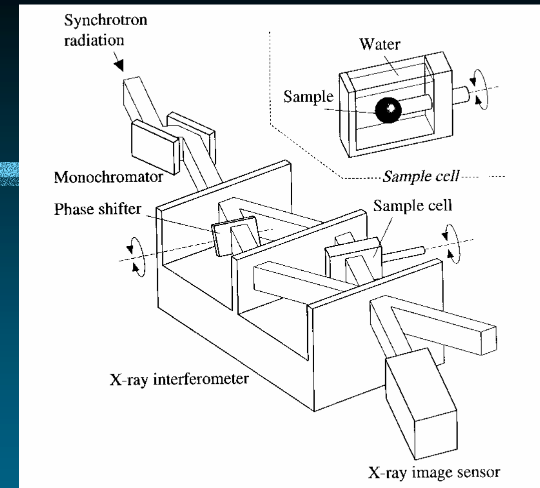

PHYSICS TODAY
JULY 2000
A NEW PHASE FOR X-RAY IMAGING

PC Imaging - Terminology



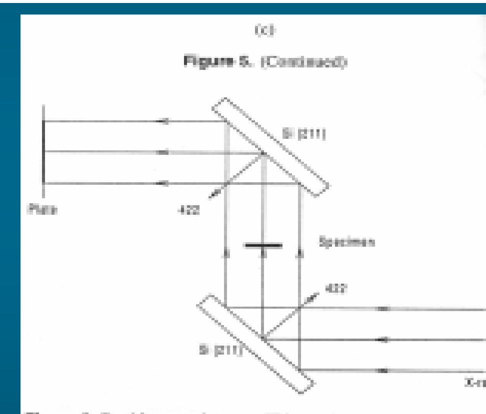
1. Interferometry

2. Double-Crystal Techniques

DEI – Diffraction Enhanced Imaging

ABI – Analyzer-Based Imaging

SAXS - Imaging



3. Propagation-Based Imaging (PBI)

In-Line imaging/holography (PCX) cf Gabor

Refraction Enhanced Imaging (REI)

Non-interferometric imaging

Lensless imaging

Emerging Opportunities for Hard X-Ray PCI

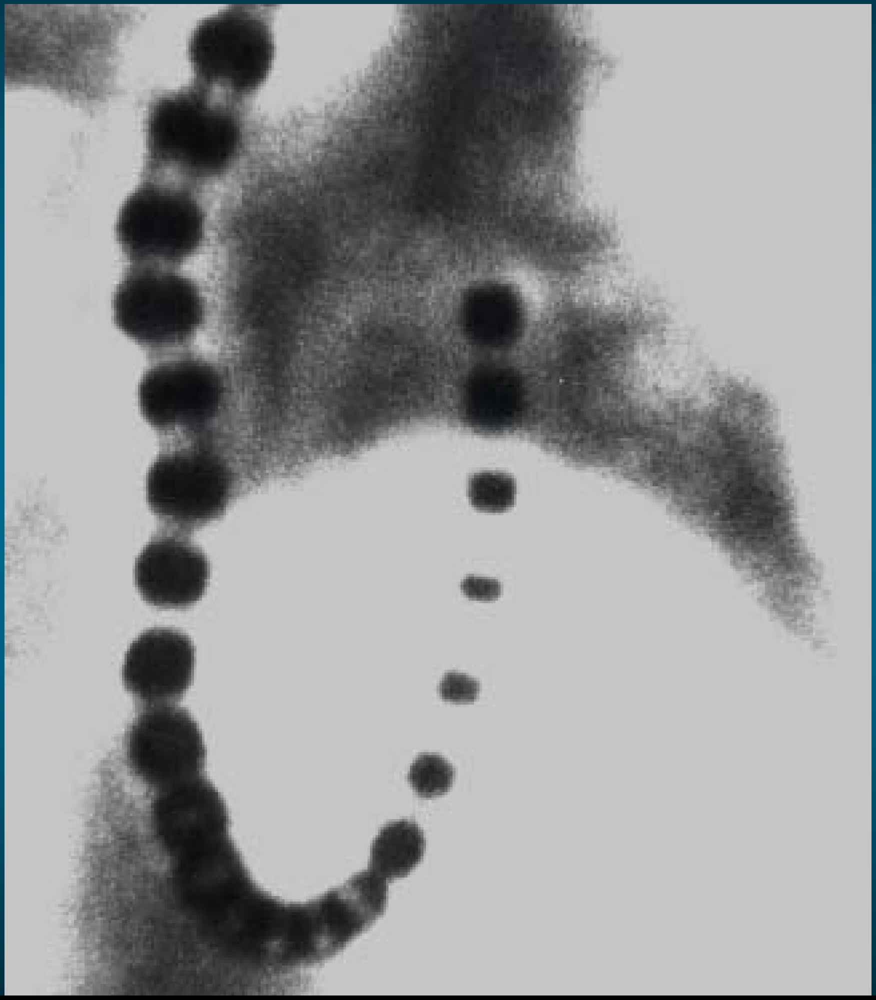
Themes

- Different techniques and results for PCI
- Challenges and Opportunities for hard X-ray PCI
- Quantitative information extraction from PC images
- High speed and “pink beam” methods
- “Virtual X-ray optics” - grand unification of all PC methods
- Combined methods (e.g. PCI and SAXS)
- Clinical medical applications?
- How to design the ultimate PC imaging BL?

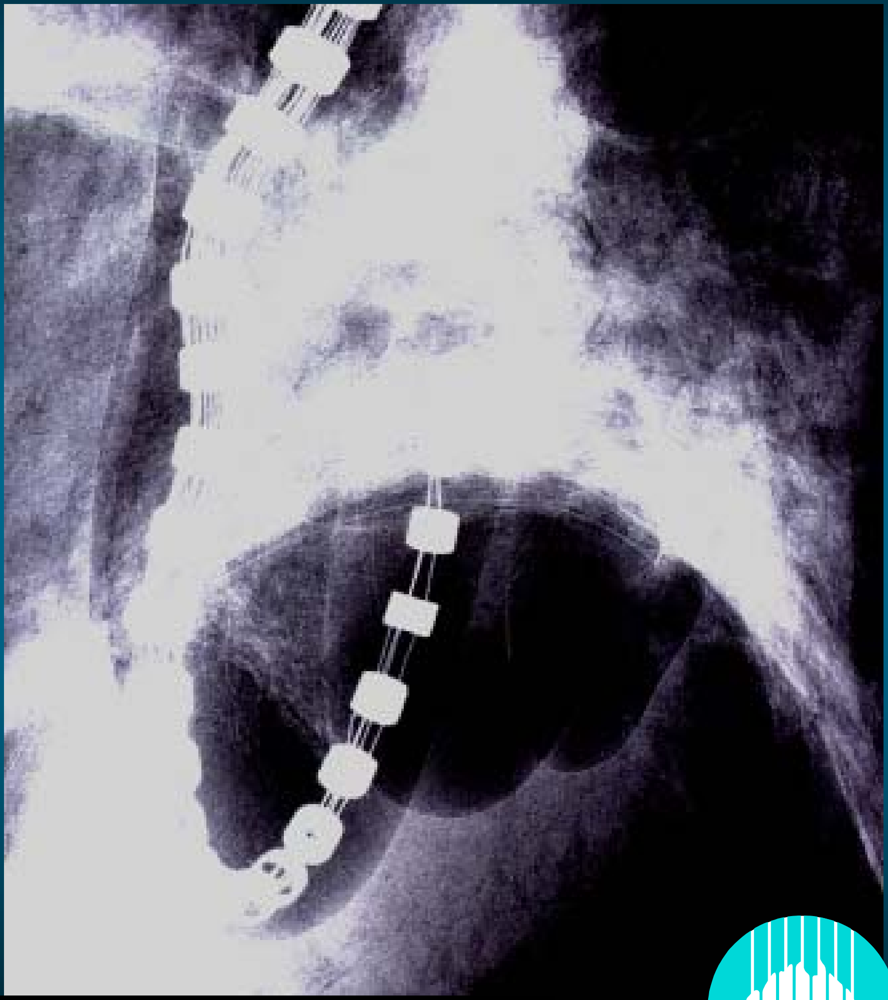
Acknowledgements for Mouse & Wallaby Results

- Dr Jane Whitley, Department of Primary Industries, Victoria, Aust.
- Drs Naoto Yagi and Kentaro Uesugi, SPring-8, Japan
- Prof Rob Lewis, Monash University, Aust.

Phase-Contrast Radiography

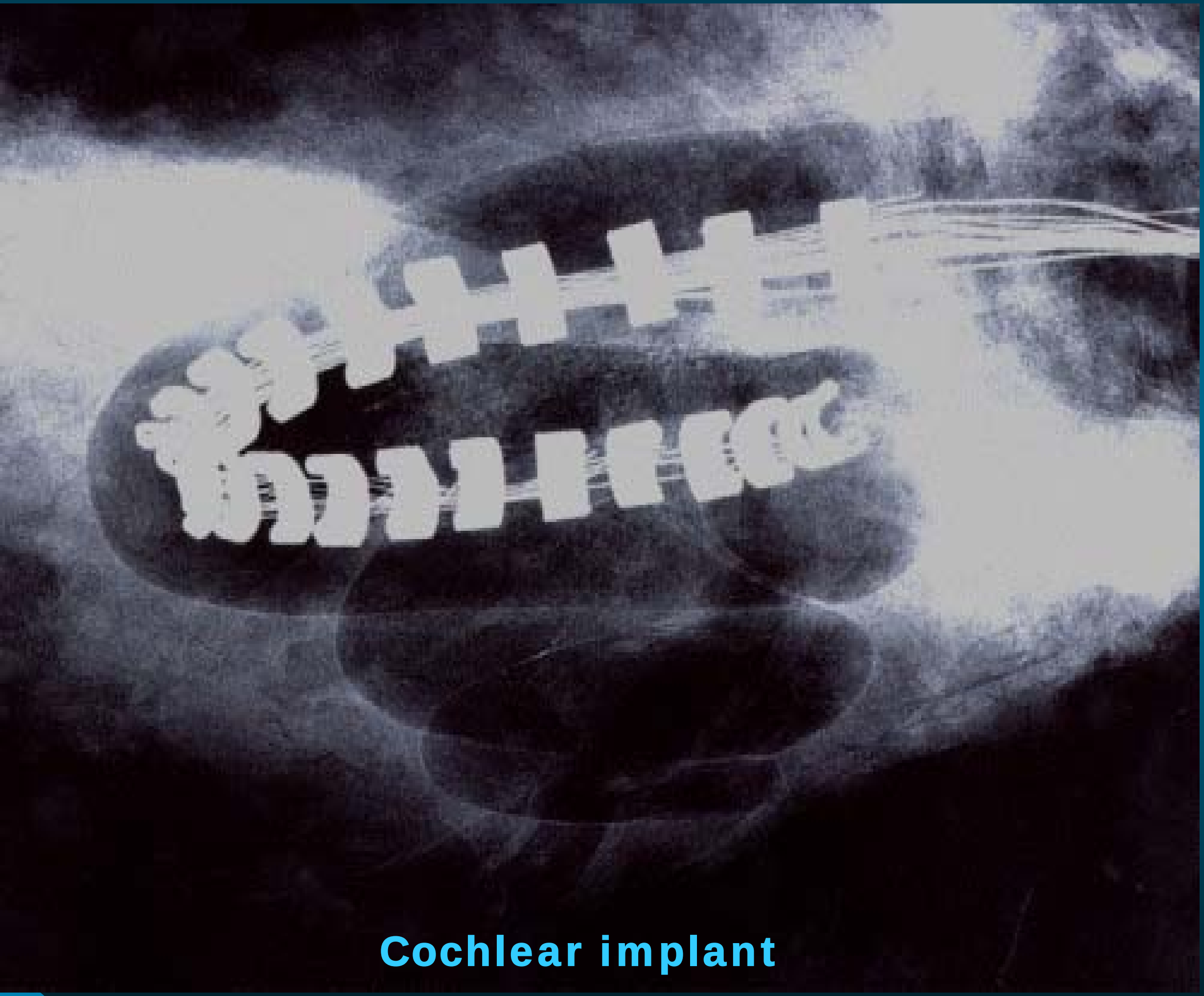


Conventional

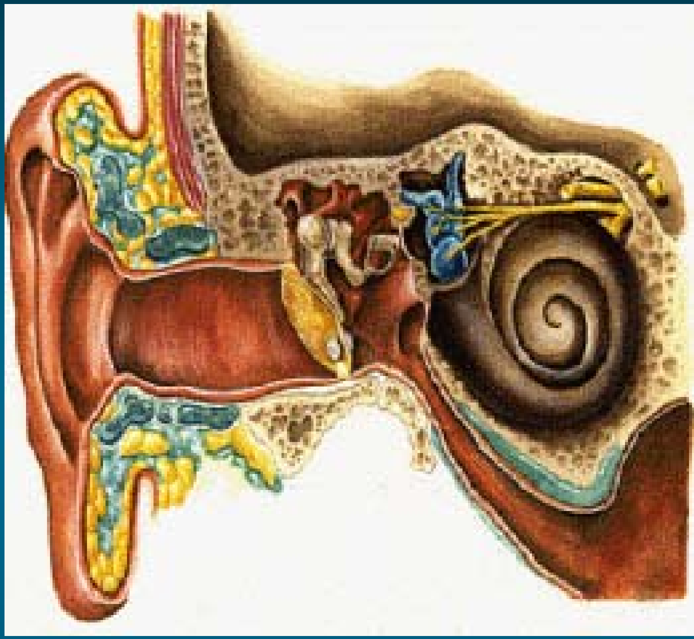


In-Line microfocus

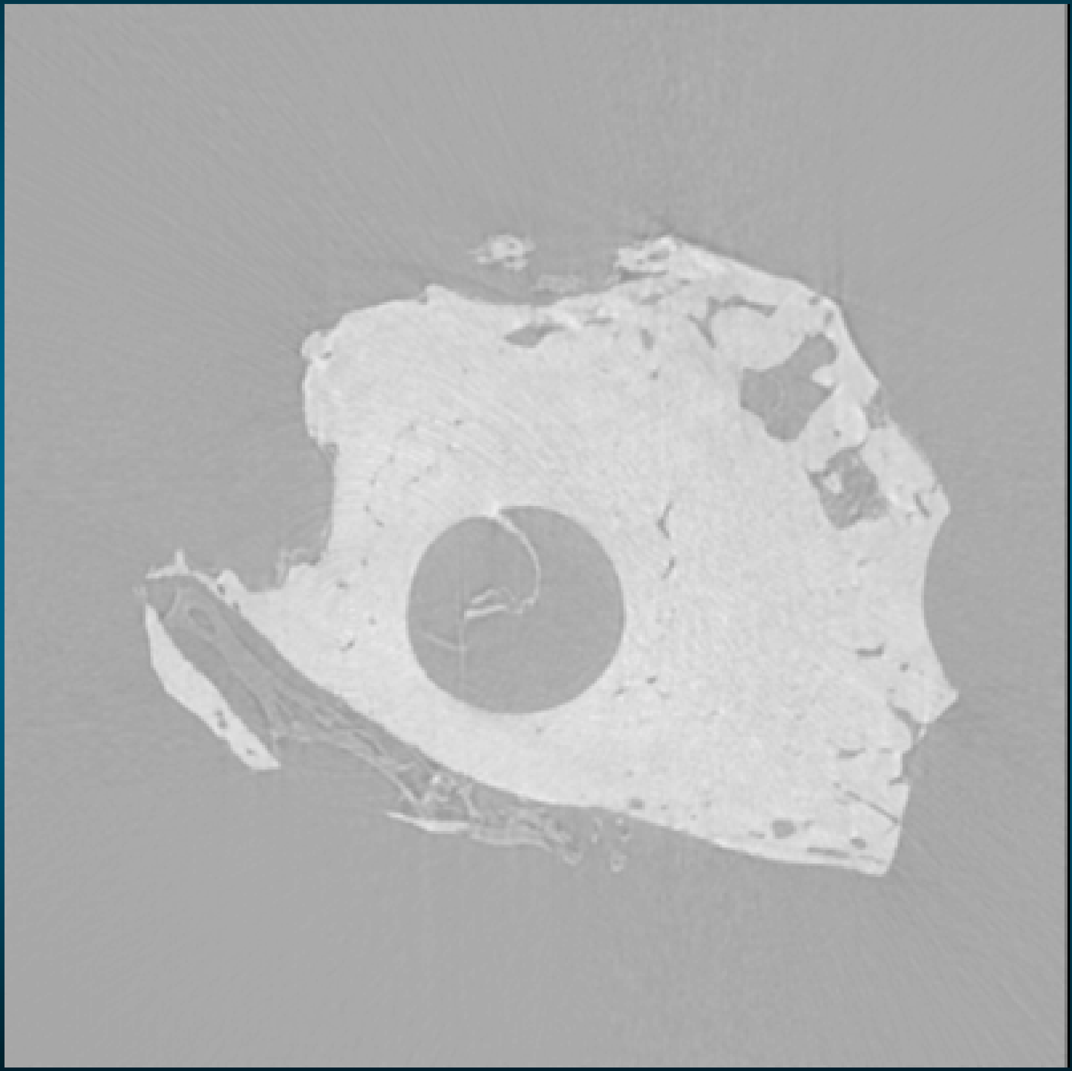
Phase-Contrast Radiography – Lab-based microfocus source



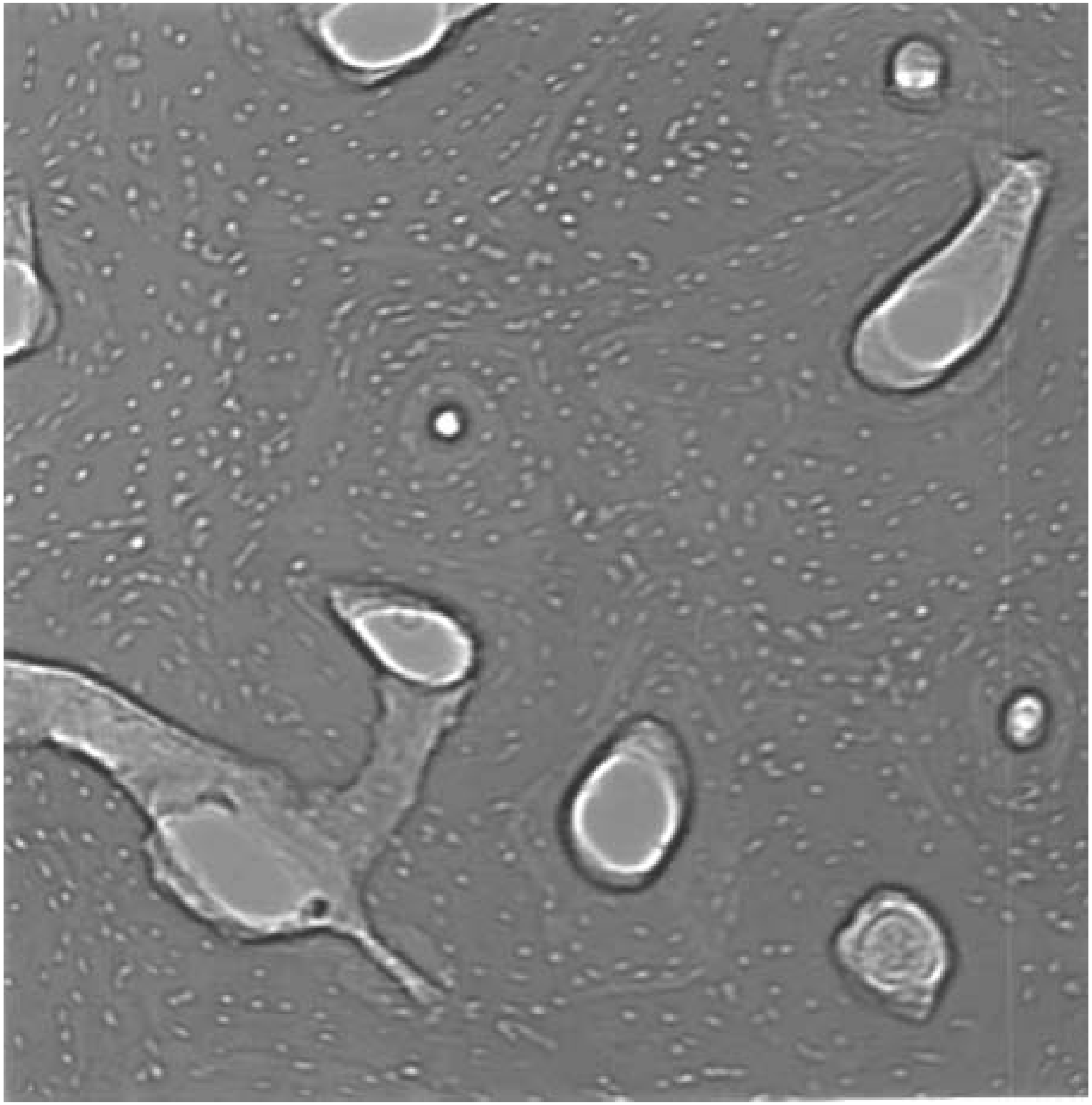
Cochlear implant



Tomographic data for cochlear implant (SR)



Thin cross-section of human femur (smallest features of order 5 micron



Some Challenges and Opportunities for

Hard X-ray Phase-Contrast Imaging and CT using SR

1. Improved understanding of and ability to meaningfully interpret phase- contrast images (of various types).

2. Quantitative compositional analysis at high spatial resolution (e.g. different types of soft-tissue cf MRI).

3. Improved contrast for large features (e.g. globular masses).

4. Improved resolution and contrast for specific types of features - including possible new and improved contrast mechanisms. Combined methods (?), e.g. PC and SAXS.

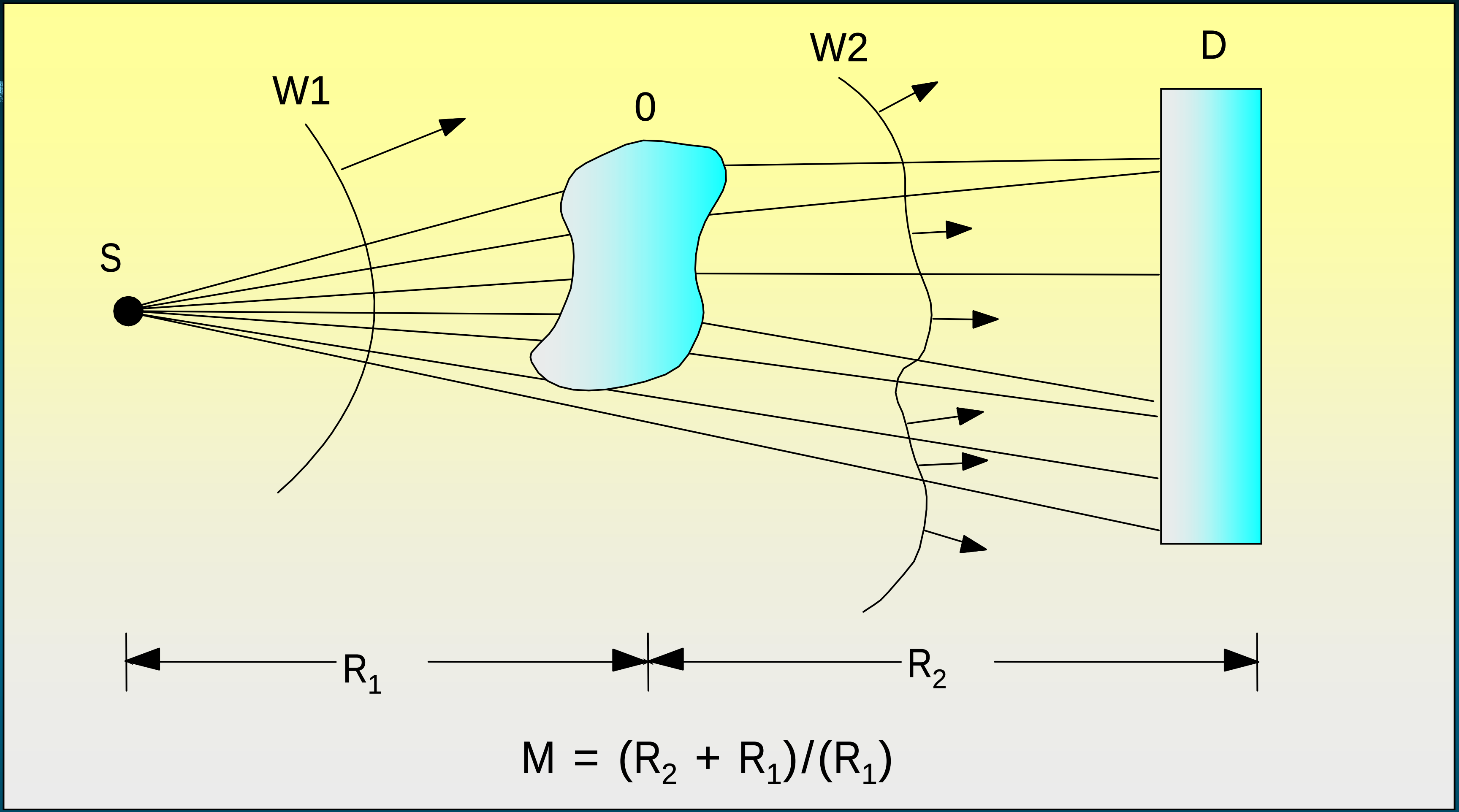
5. High-speed imaging to remove motion artifacts and study dynamic processes (say ~ 1 msec).

6. Ultrafast imaging – ≤ nanosecond (single pulse)

7. Live human patient studies using PCI **(cf Röntgen).**

How to best design a

PC imaging BL?



Basic Geometry for In-Line PCI
(cf *In-Line Holography* – Gabor, 1948)

1. Improve ability to meaningfully interpret phase-contrast images (of various types)

Generalized refractive index for x-rays

$$n(\lambda) = 1 - \delta(\lambda) - i\,\beta(\lambda)$$

Relationship for phase

$$\phi(x,y,z,k) = -k \int \delta(x,y,z';k)\, dz' = \frac{2\pi r_e}{k} \int \rho(x,y,z')\, dz' = O(\lambda) = O(1/E)$$

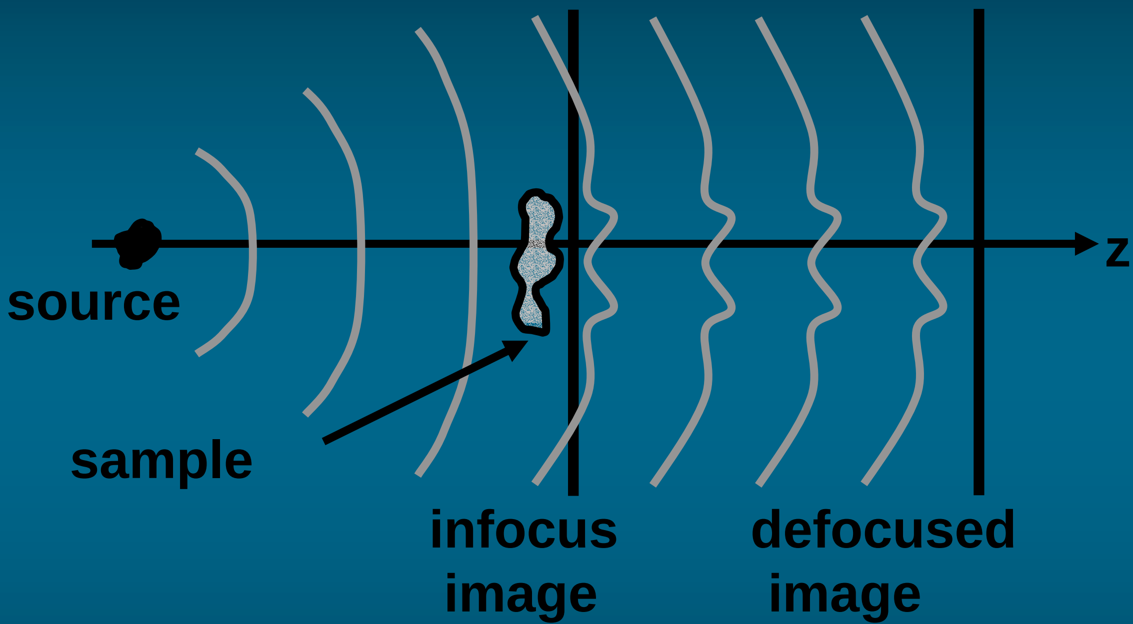
where

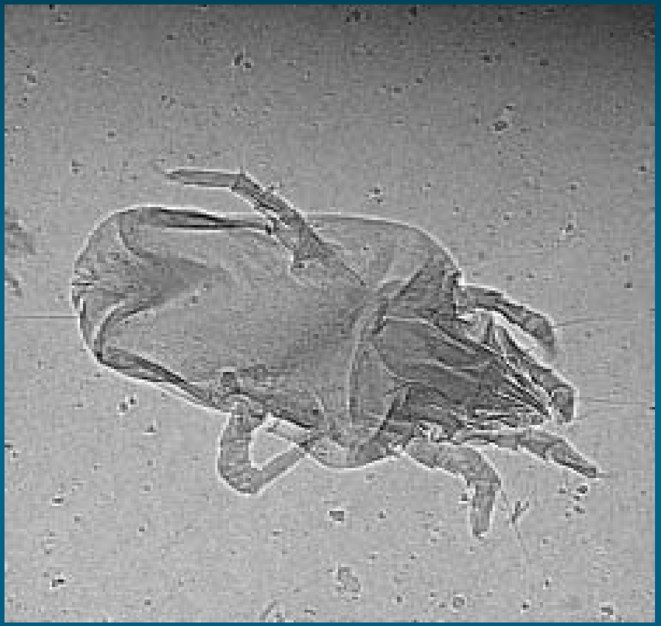
$k = 2\pi/\lambda$

r_e - classical electron radius

ρ = electron density

Phase retrieval - a simple case

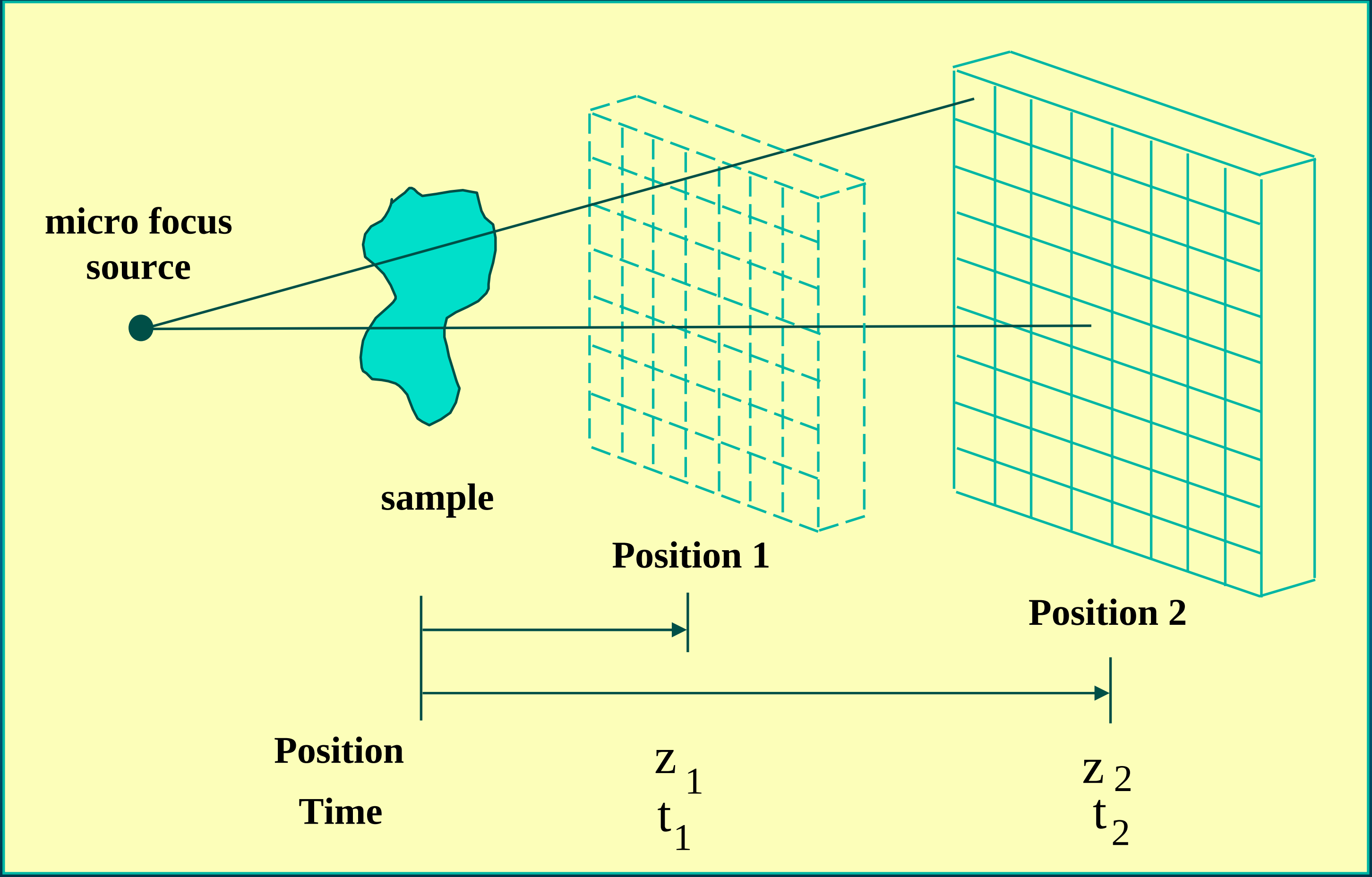




$$\psi(x,y,z=0)=I_0^{-ik\delta/\mu}\left(\frac{M^2}{1-\mu^{-1}M^{-1}\delta\Delta z\nabla_\perp^2}I(Mx,My,z=\Delta z)\right)^{\frac{1}{2}+ik\delta/\mu}.$$

Paganin, Mayo, Gureyev *et al.*, Journal of Microscopy (2002), 206, pp33

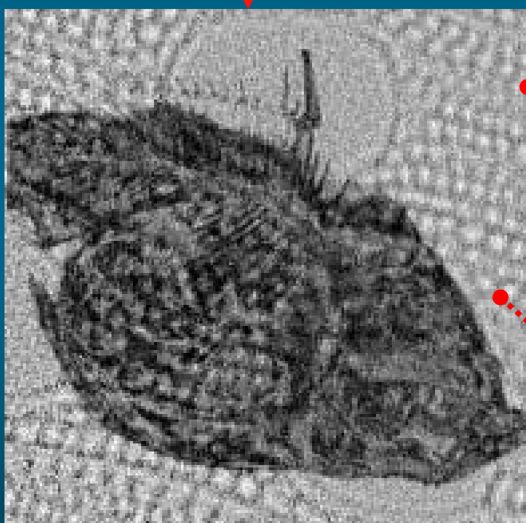
The 2-Position Method of Determining Separate Absorption and Phase-Contrast Images



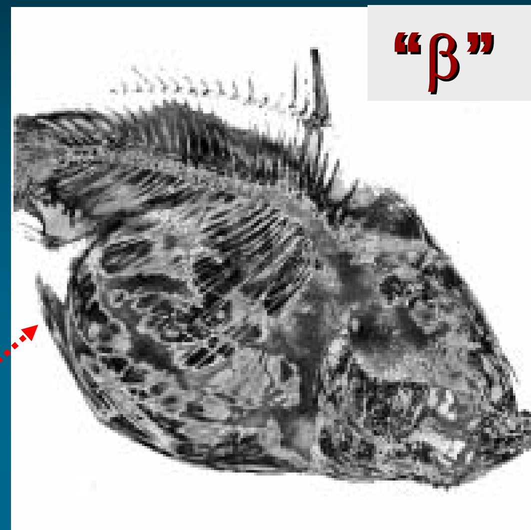
Role of Phase Retrieval in In-Line Imaging

1. Separation of Phase from Amplitude Contrast (Multi-Distance)

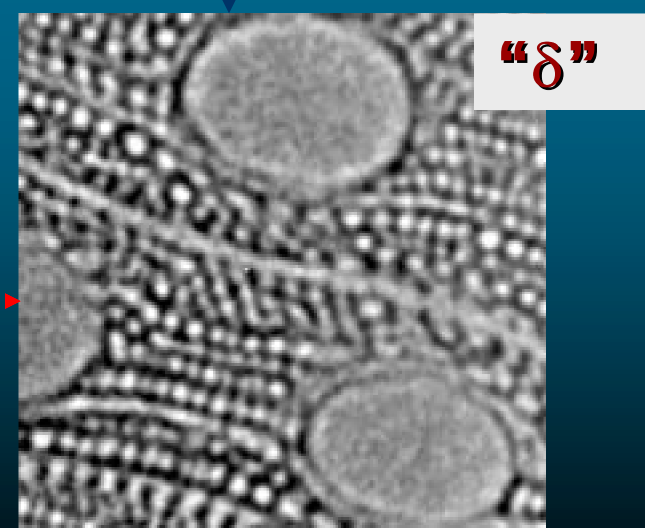
"Experimental" in-line image (amplitude/phase)



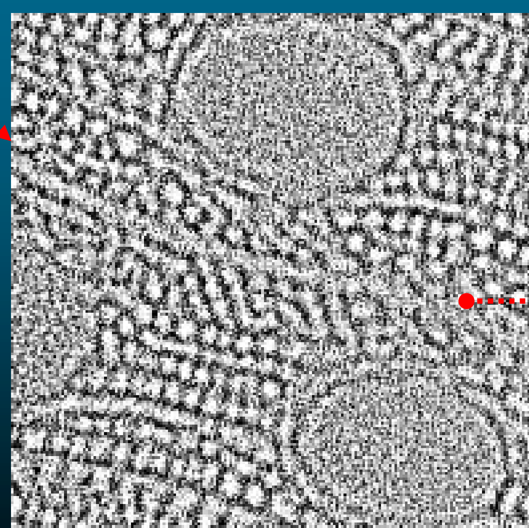
Extracted intensity $\exp[-\mu t(x,y)]$



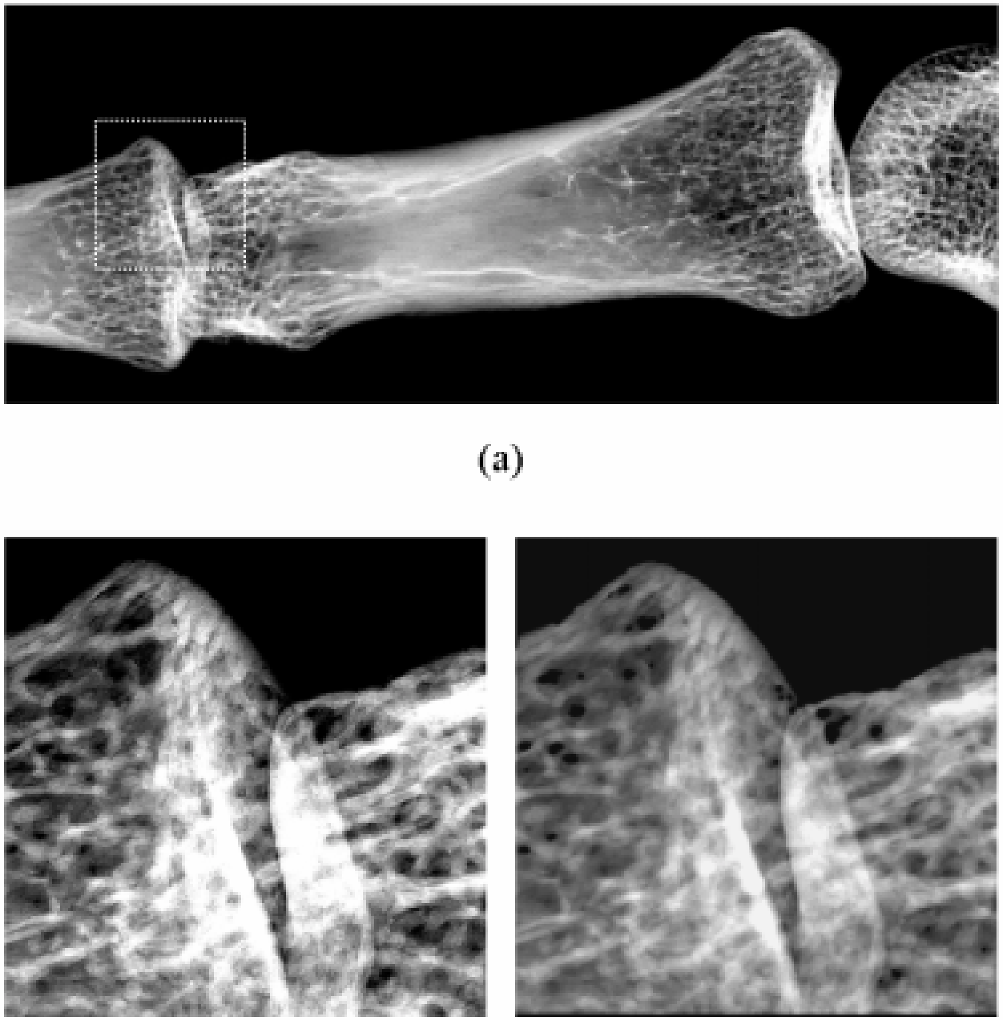
Extracted phase $\varphi(x,y)$



Extracted phase Laplacian $\nabla^2\varphi(x,y)$



Quantitative phase determination => i.e. thickness extraction



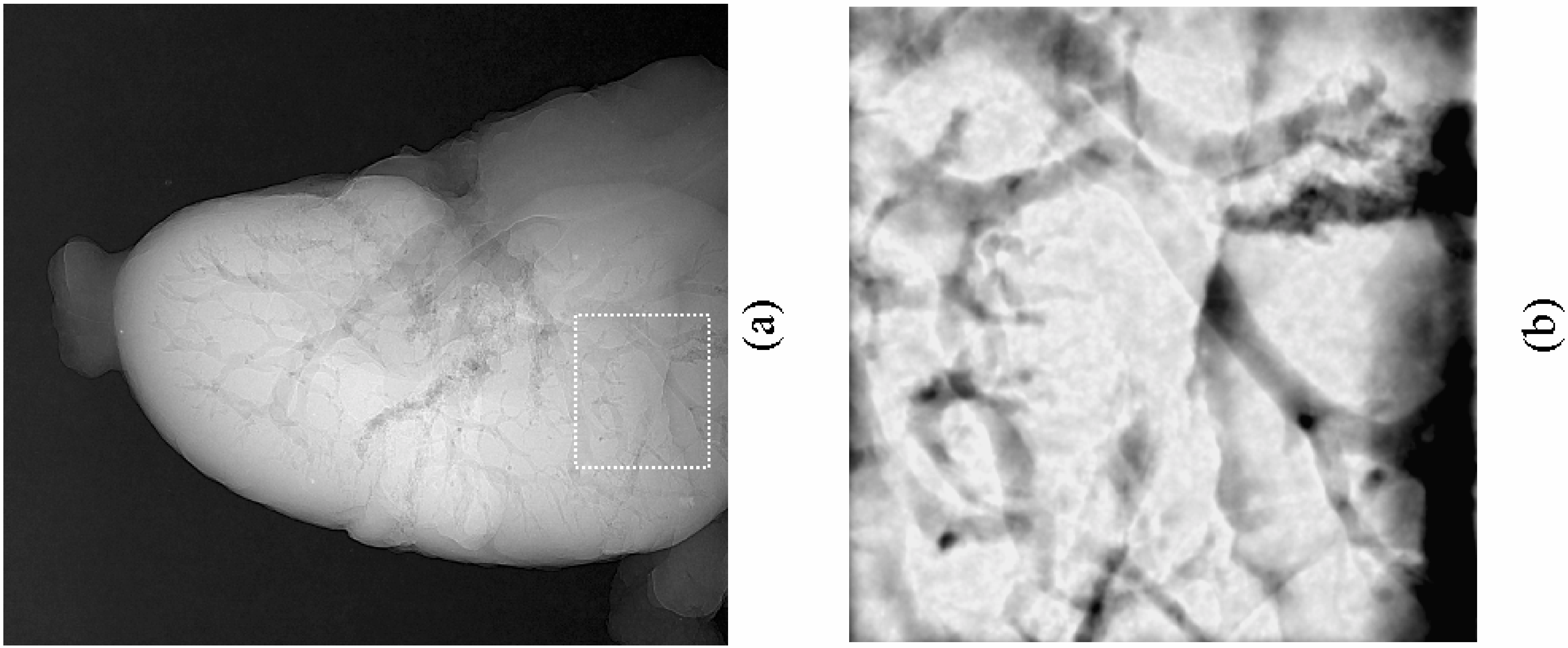
(a)

(b)

(c)

Determination of projected thickness of apatite (bone mineral)

Quantitative phase determination
=> i.e. thickness extraction



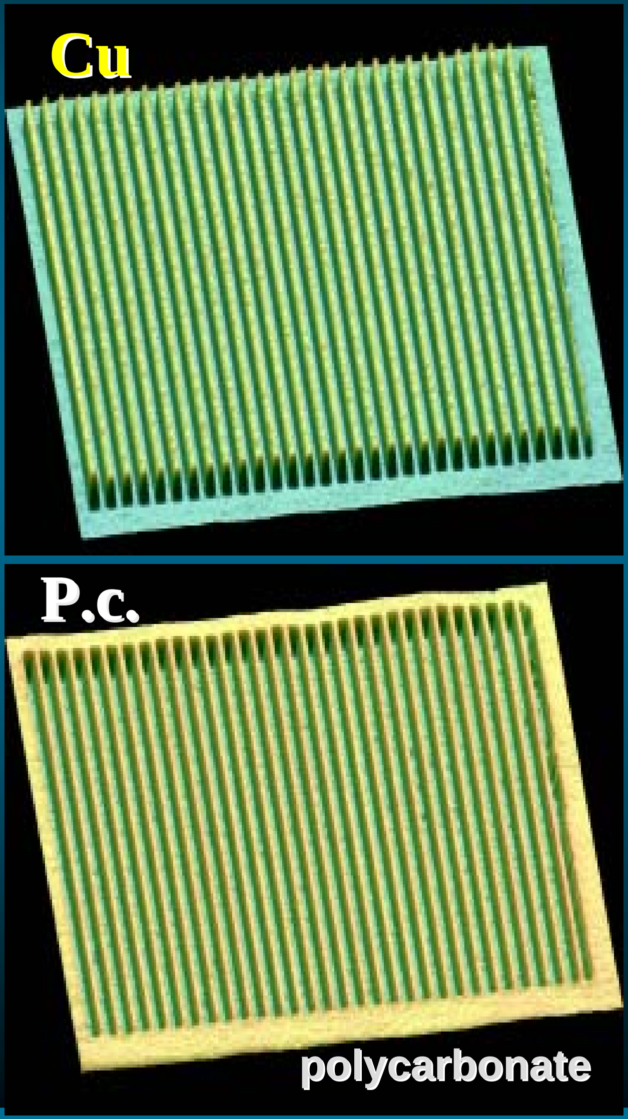
Excised mouse kidney - thickness determination

Role of Phase Retrieval in In-Line Imaging
(Data recorded on ID-22 at ESRF)

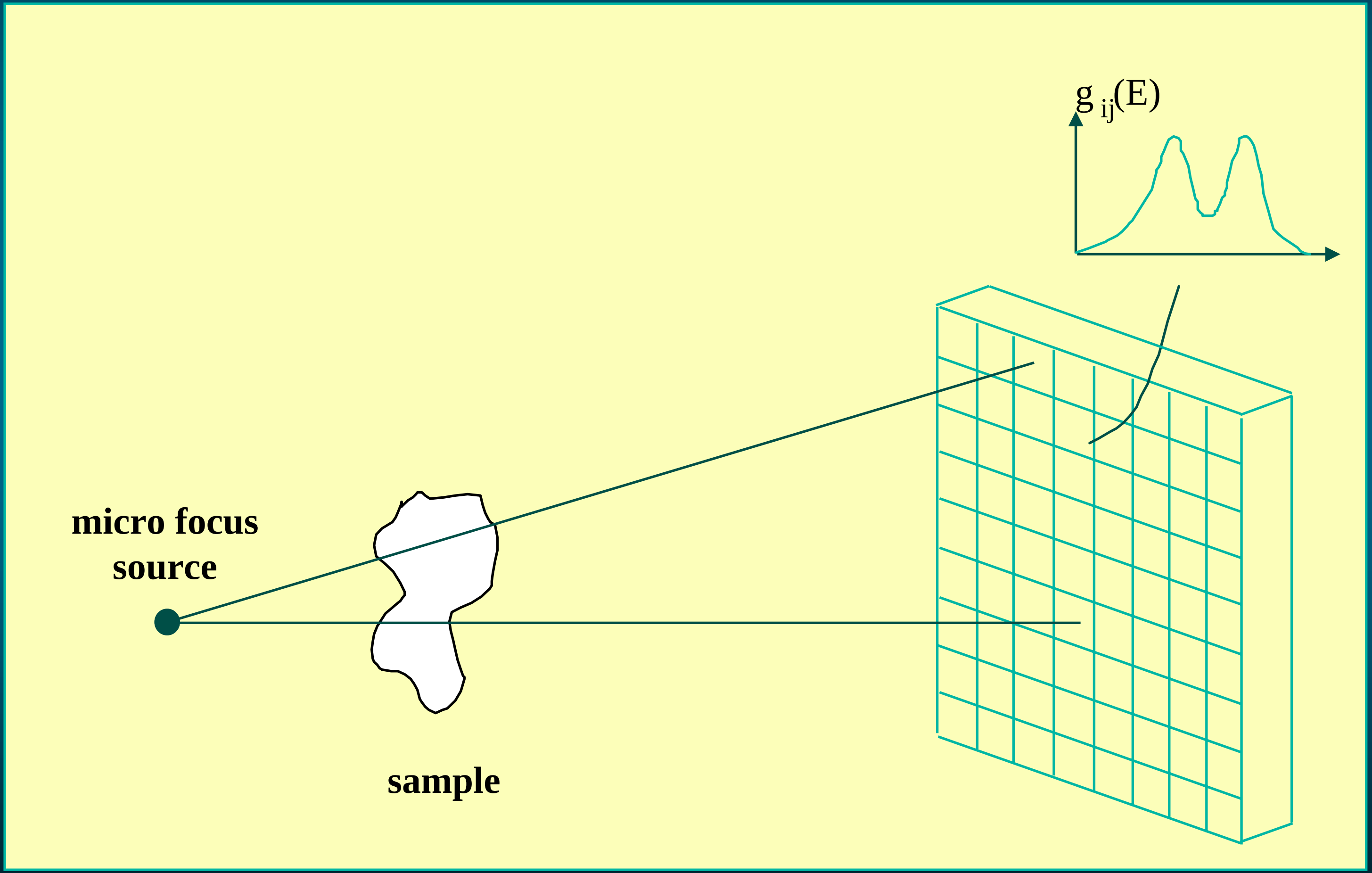
Elemental analysis

In-line images

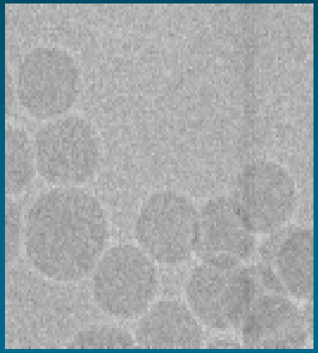
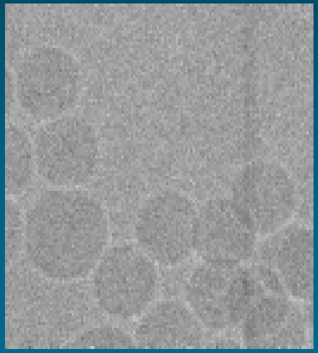
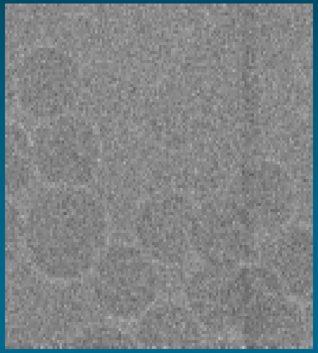
phase retrieval



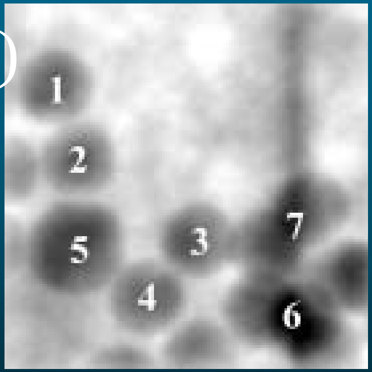
2-D Detector Method for Determining Phase/Amplitude Retrieval

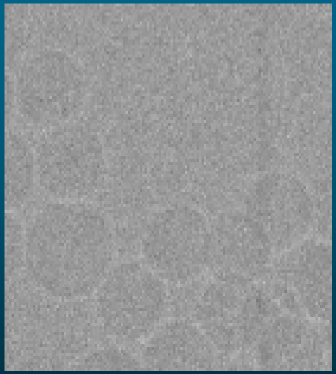


Phase/Amplitude Retrieval from Multi-Energy In-Line Images. Experimental Example (cont.)

(a)

(b)

(c)


Experimental images at (a) λ=3.8 Å; (b) 7.3 Å and (c) 2.5 Å

(d)


(e)


	Theory	Sphere 1	Sphere 2	Sphere 3	Sphere 4
$-\varphi_{max}$	3.25	3.20	3.53	3.57	3.12
M_{max}	0.055	0.061	0.070	0.053	0.056

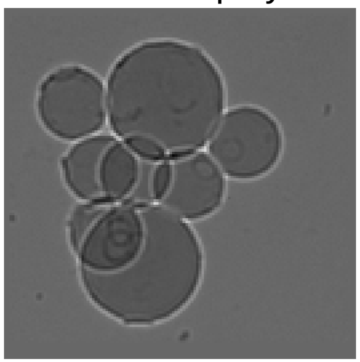
Reconstructed phase (d) and intensity (e)

Gureyev, Mayo, et al PRL, 86, 5827 (2001)

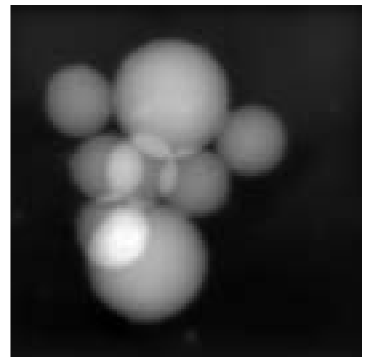
Projected thickness determination for polychromatic sources

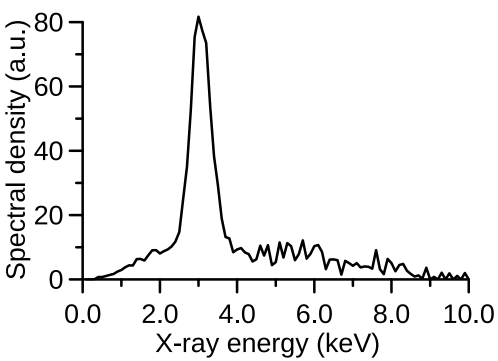
EXPERIMENTAL DEMONSTRATION OF QUANTITATIVE IN-LINE IMAGING WITH PARTIALLY COHERENT X-RAYS

In-line image of 5.3 µm and 9.0 µm latex spheres obtained with polychromatic X-rays

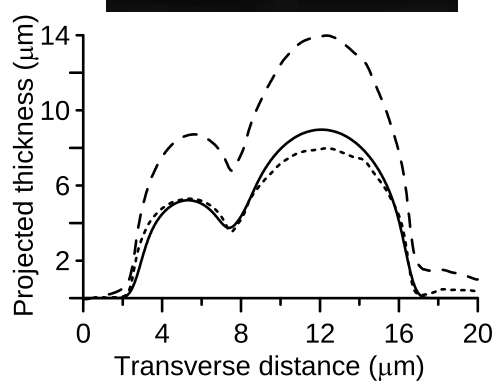


Reconstructed projected thickness distribution





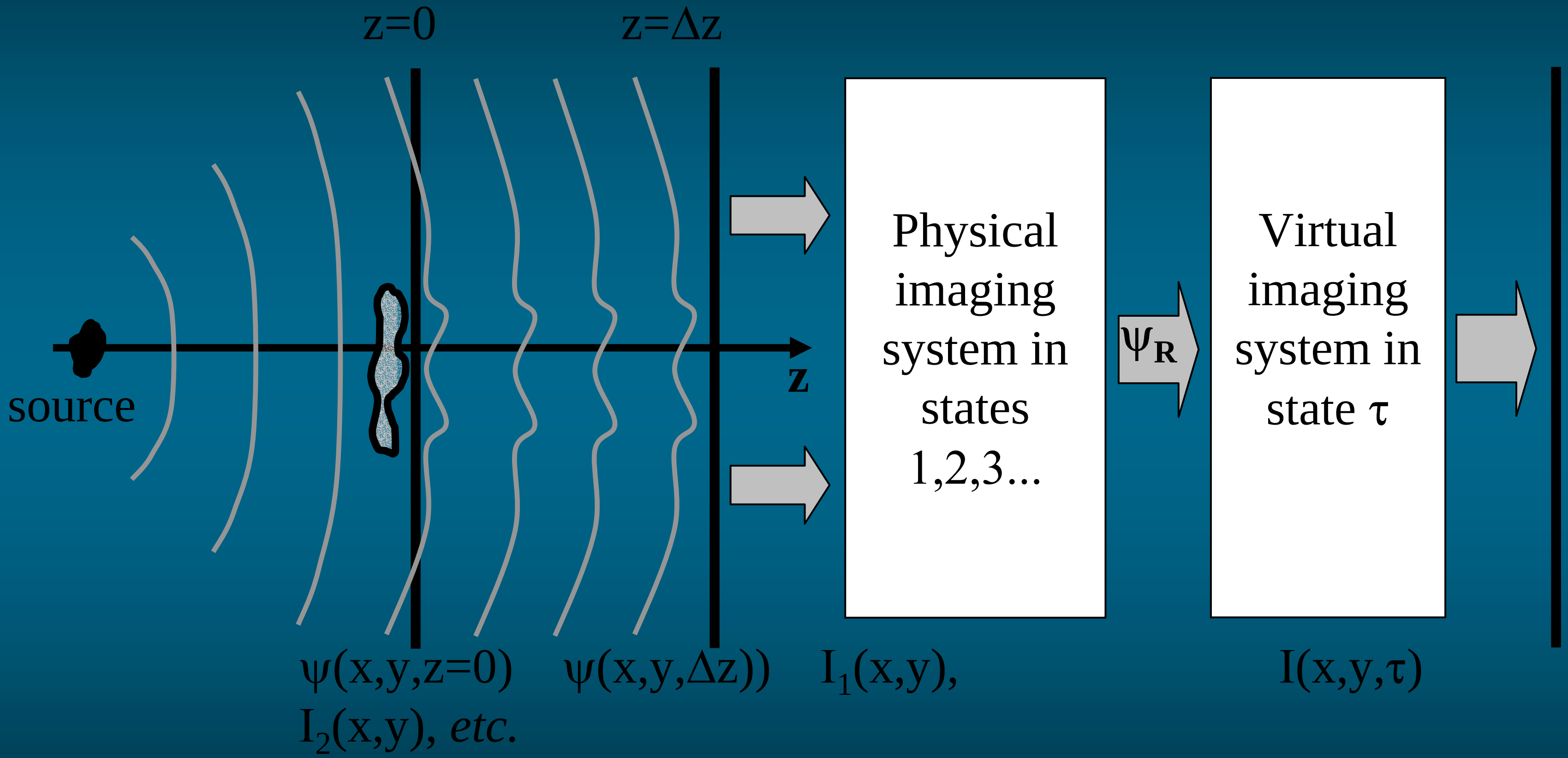
Incident X-ray spectrum (XUM@10 kV; Ag foil)



Reconstructed thickness (dots); monochromatic reconstruction (dashes); expected (solid line).

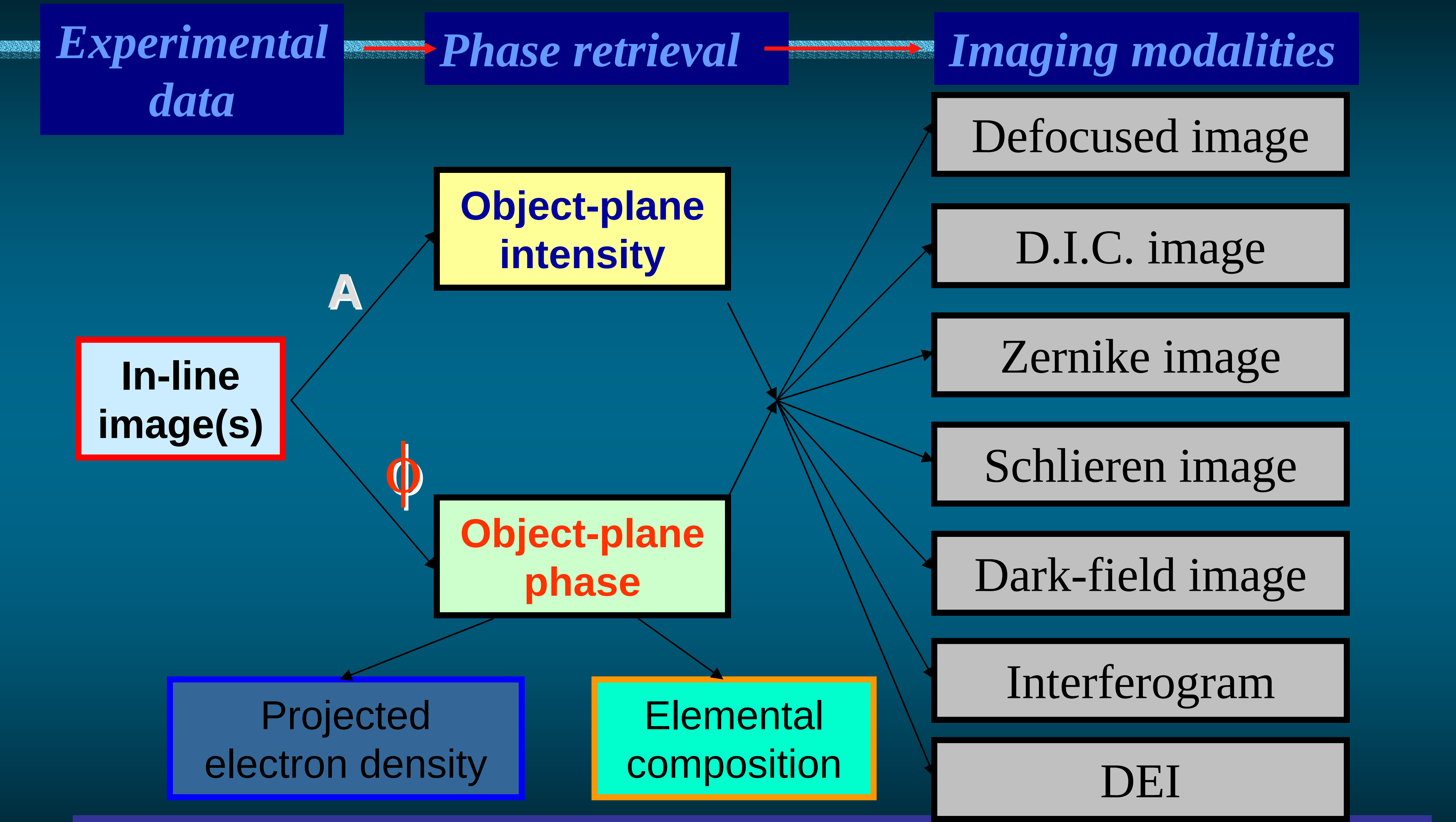
Gureyev, Paganin, et al PRL, Aug 2004.

Software optical elements ("Virtual X-Ray Optics") - mathematical lenses for X-ray imaging

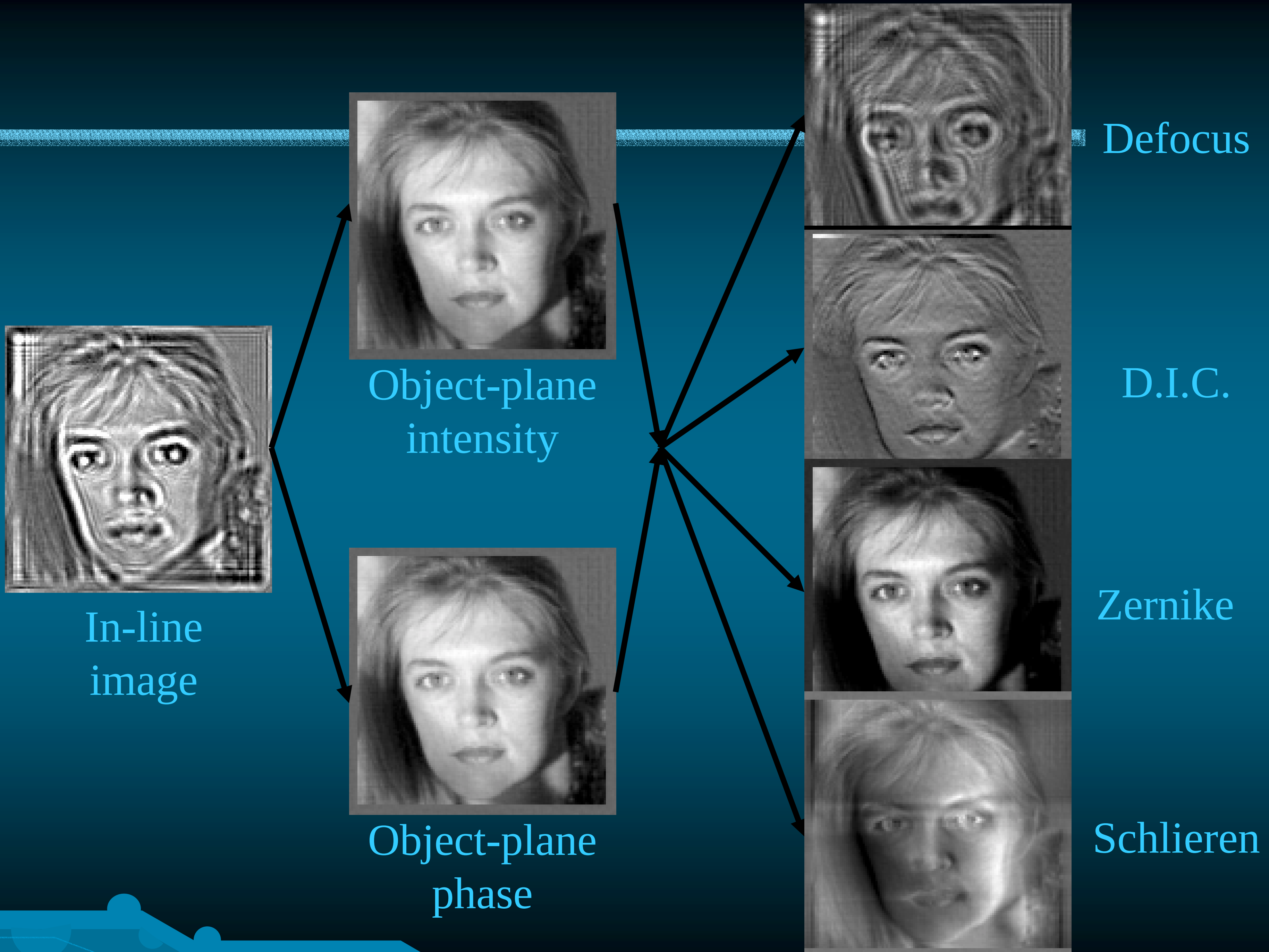


Paganin, Gureyev *et al.*, J. Microscopy (2004), 214, pp315-27.

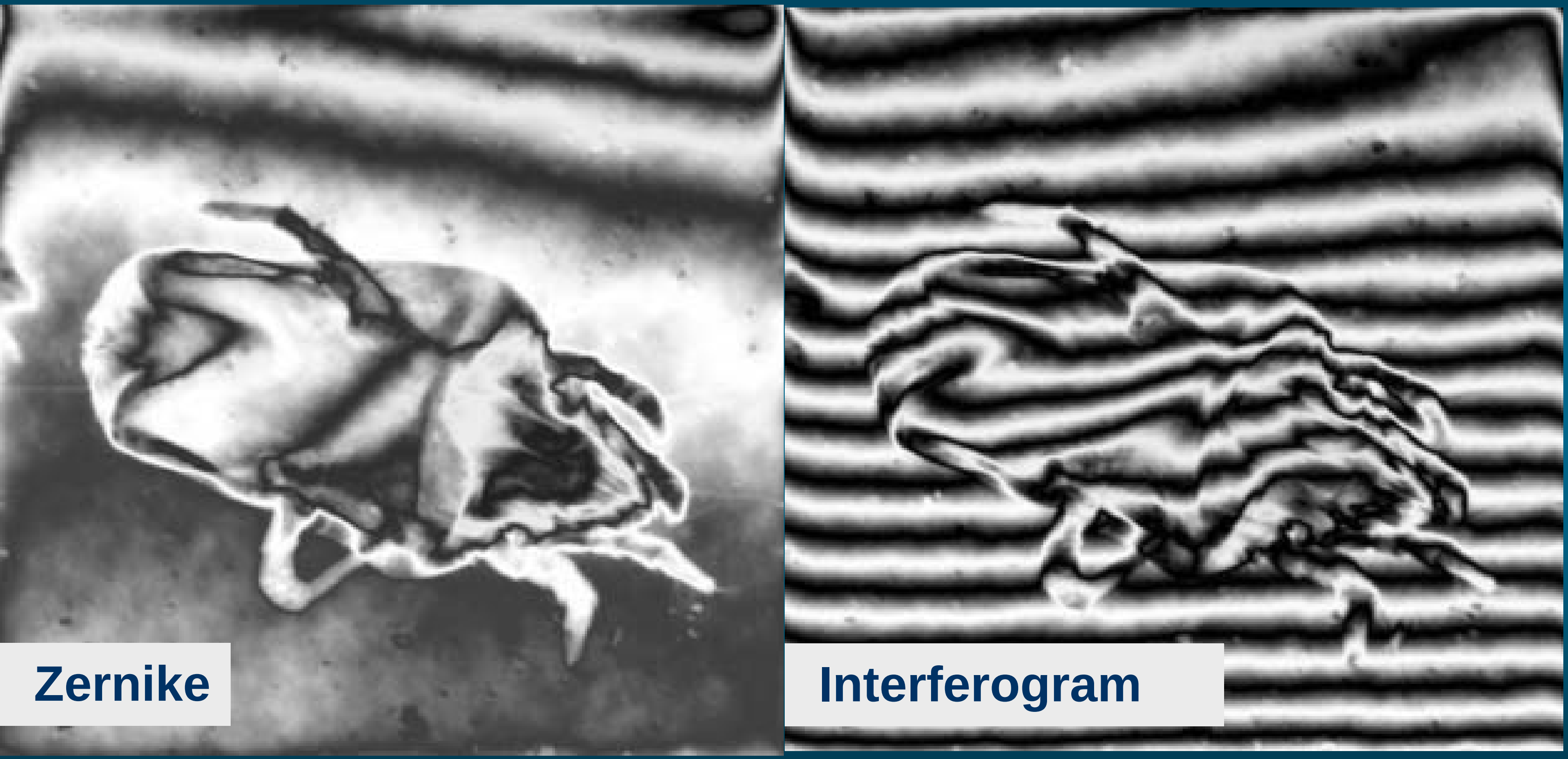
INFORMATION EXTRACTION FROM IN-LINE IMAGES



Phase/amplitude retrieval allows one to simulate in software various imaging modalities that otherwise would require special hardware


In-line image
Object-plane intensity
Object-plane phase
Defocus
D.I.C.
Zernike
Schlieren

Virtual X-Ray Optcs: “X-Ray Omni-microscopy”

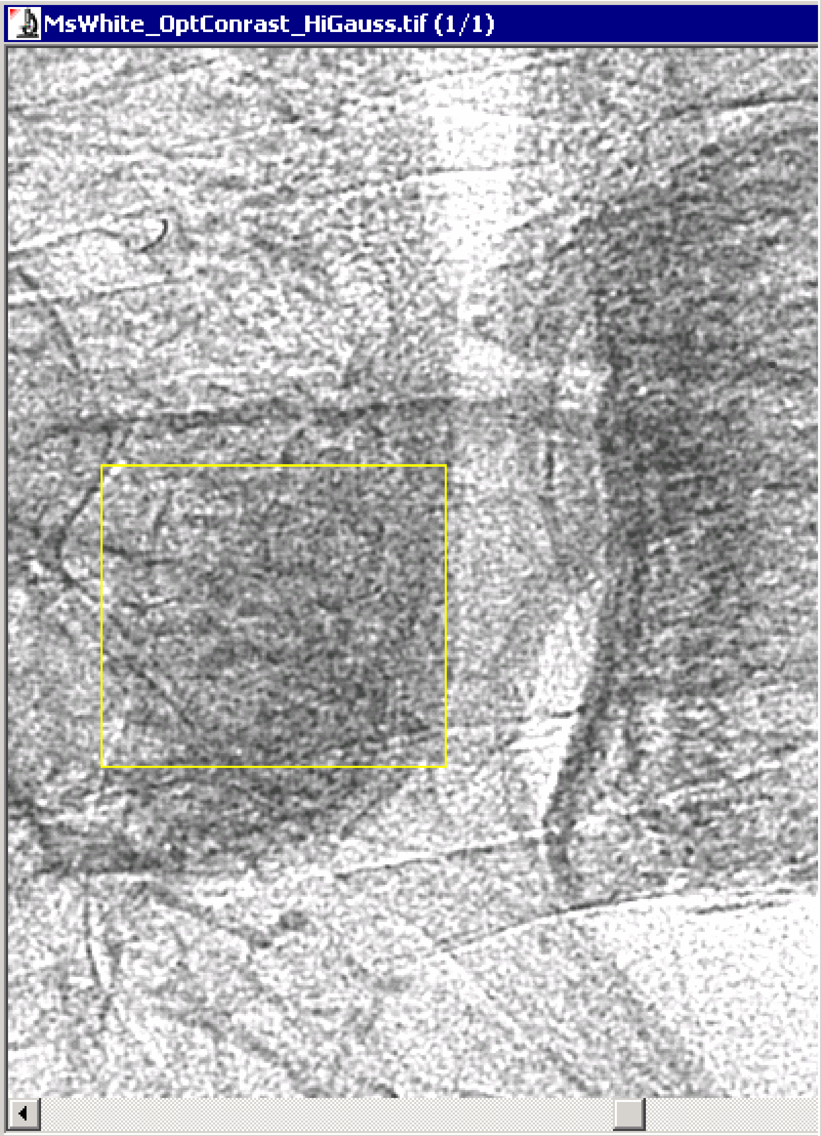


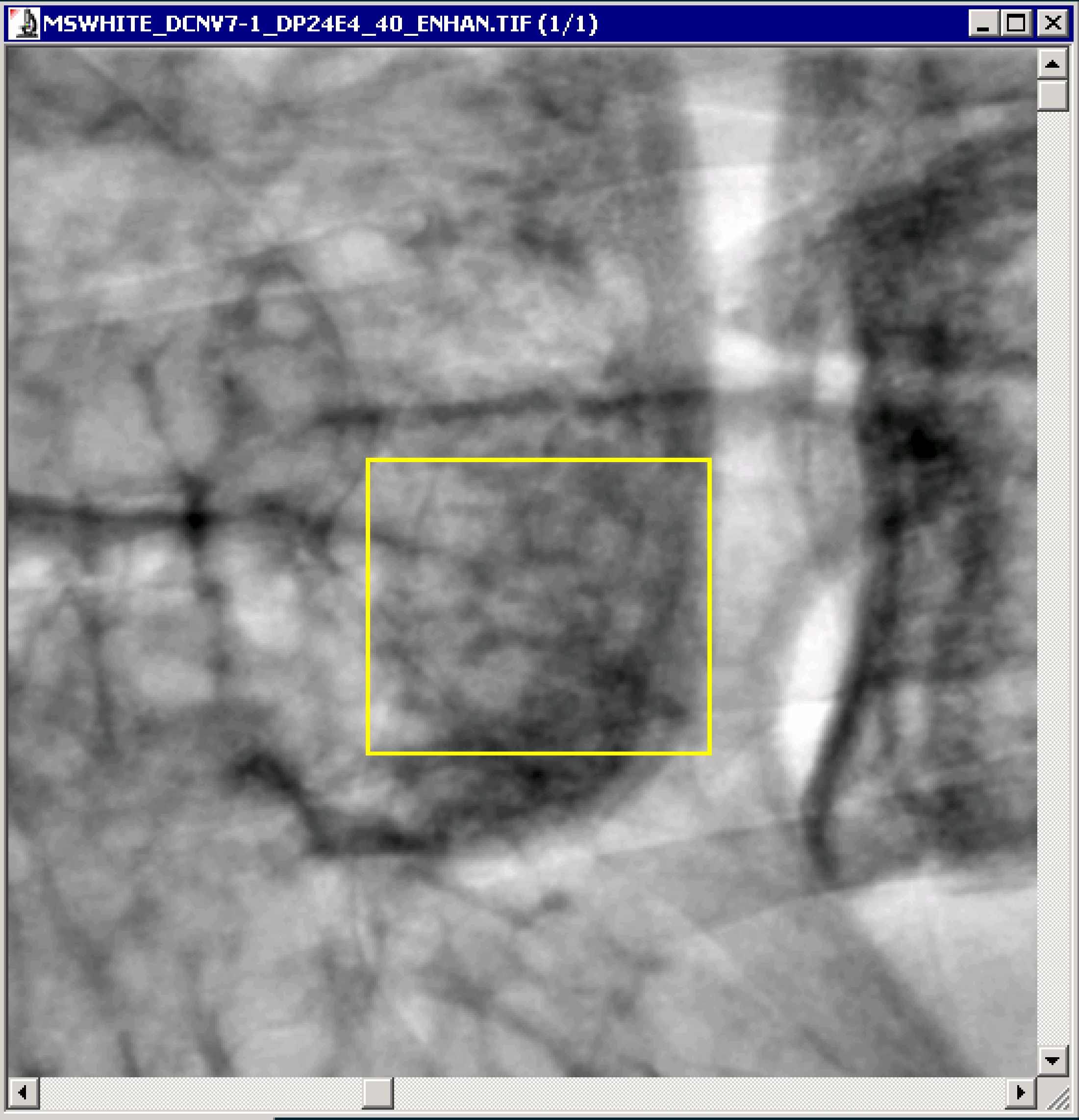
Paganin, Gureyev *et al.*, Journal of Microscopy (2004) , 214 pp 315-327

D2: Mathematical lenses: X-Ray Omni-microscopy (slide 3 of 3)

Paganin, Gureyev *et al.*, Journal of Microscopy (2004)

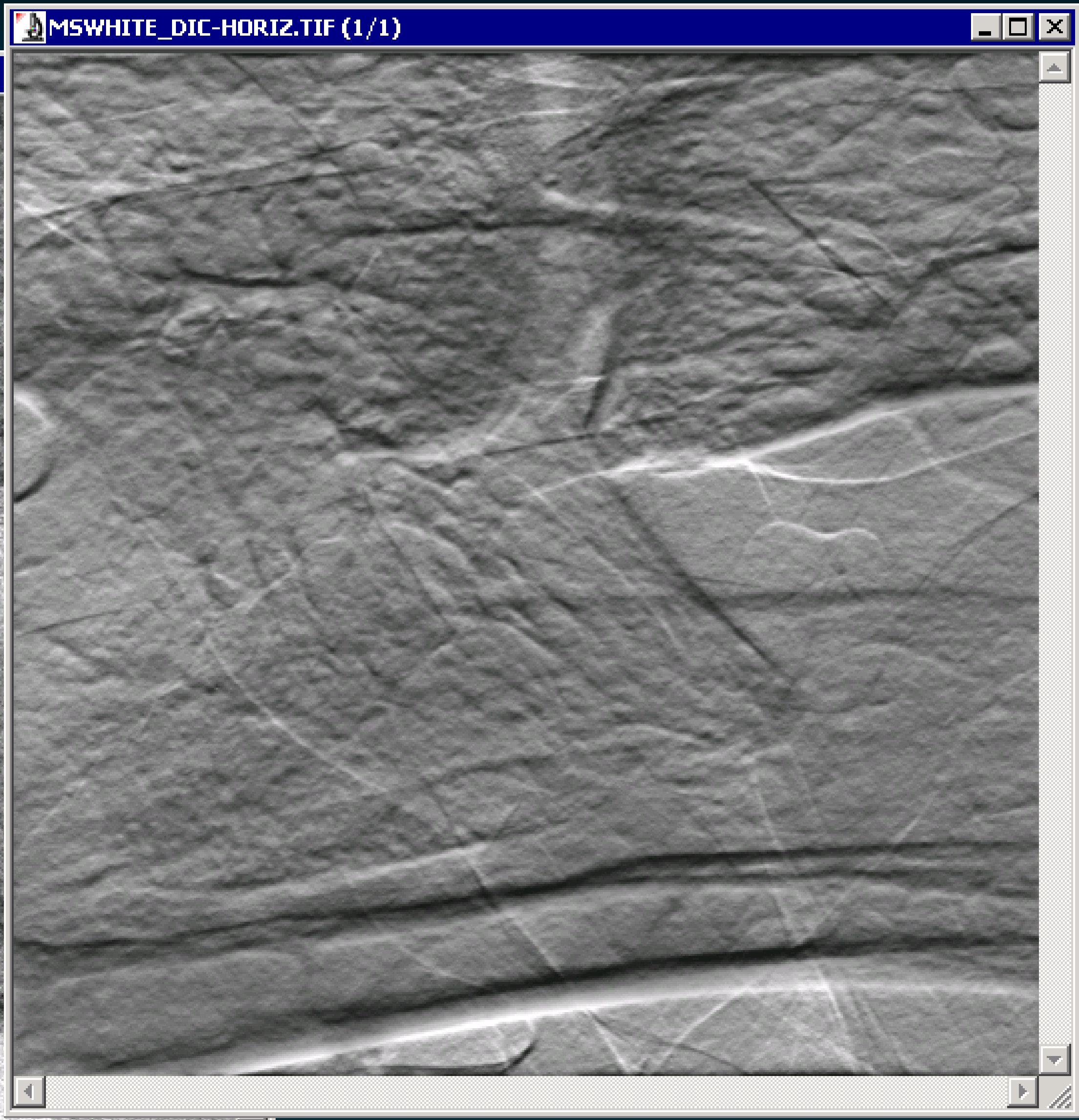
"TRUE-DENSITY" IMAGING





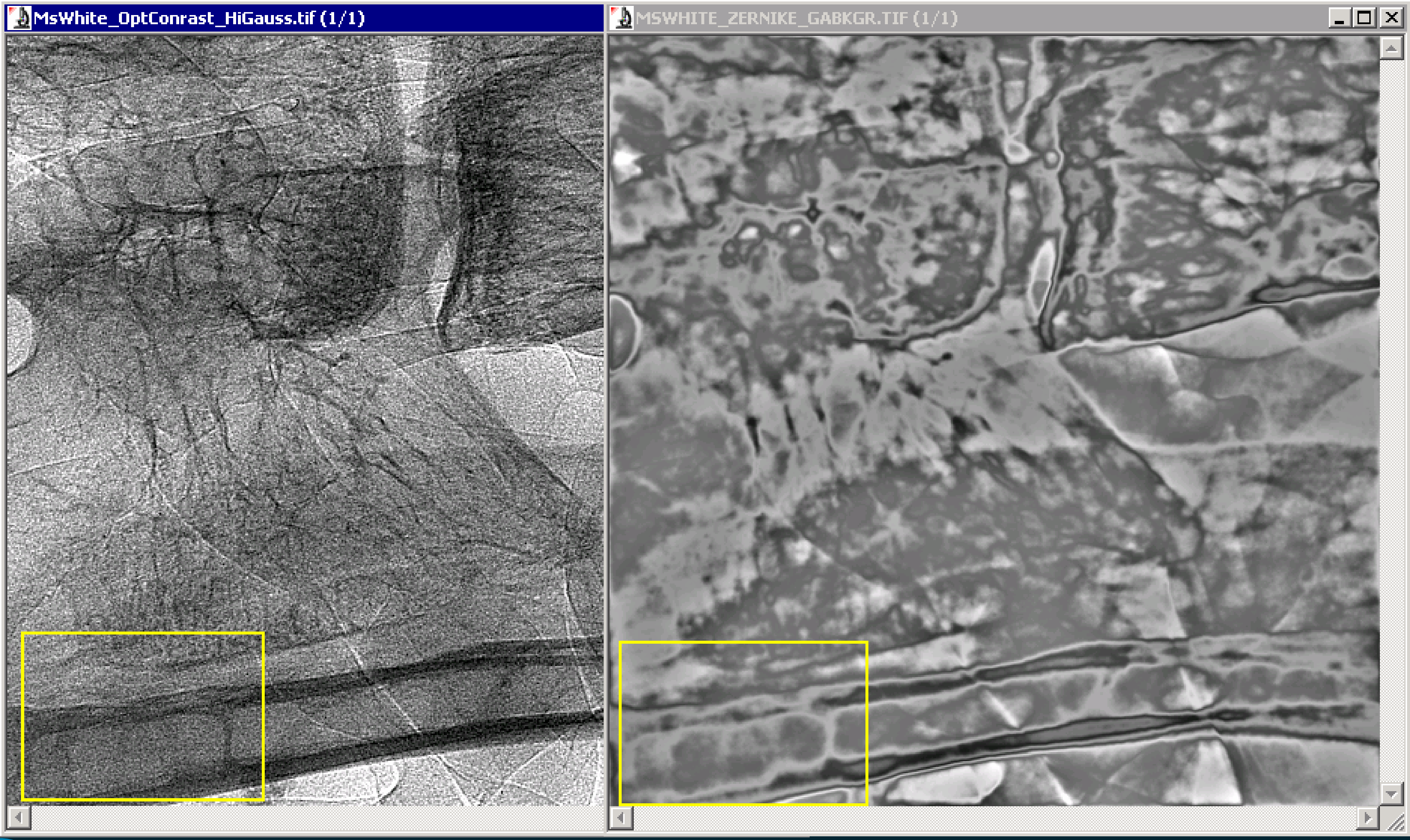
Some Image Analysis plus Phase Retrieval and Enhancement

DIC CONTRAST (EMPHASIZED DIRECTIONS)



Simulated DIC (Nomarsky) mode with horizontal shift

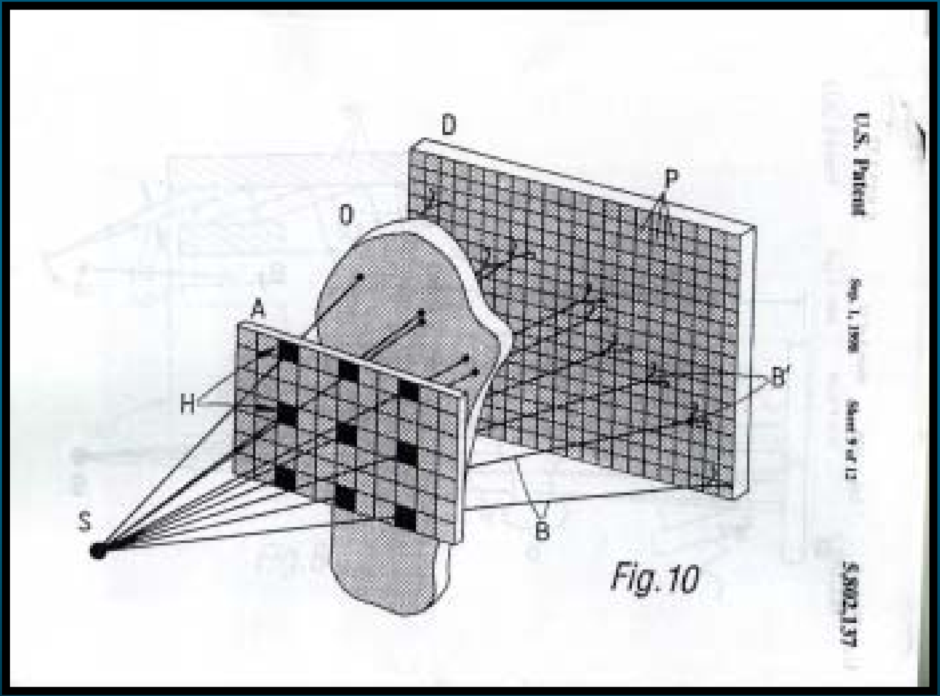
ZERNIKE CONTRAST (EMPHASIZED AREAS)

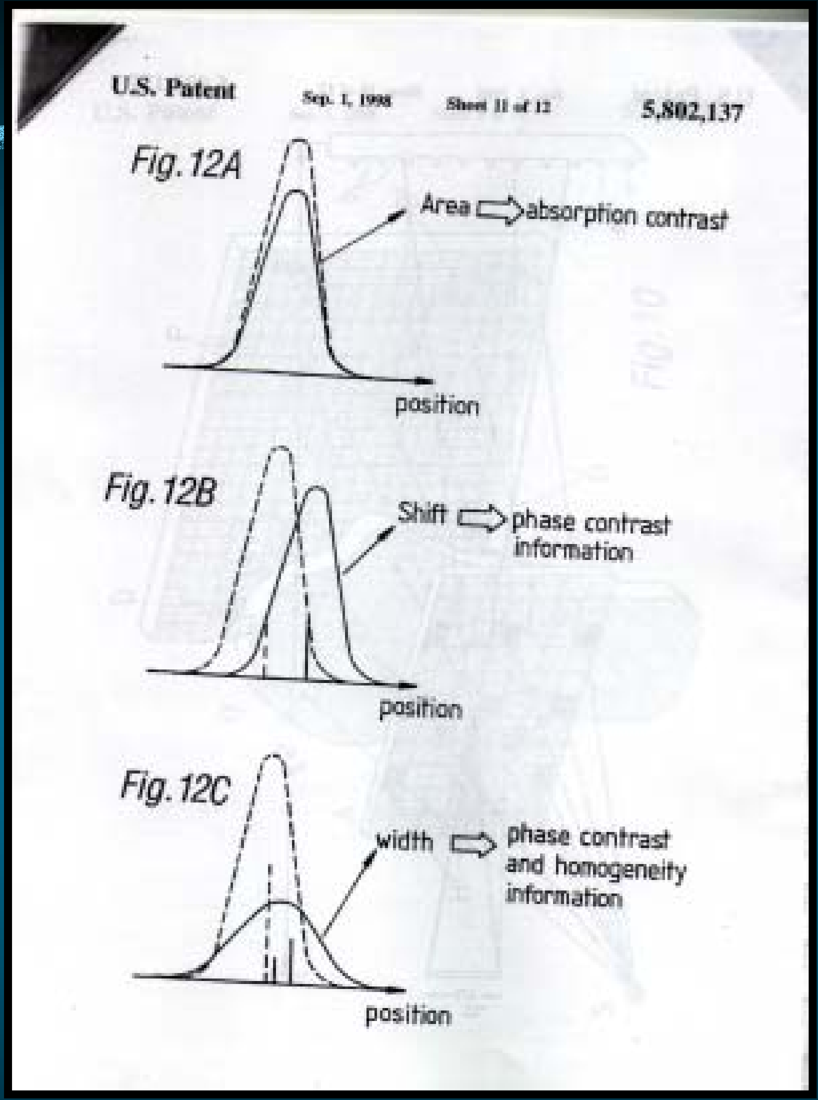


Simulated Zernike phase-contrast mode

Combined Imaging Methods

PCI and SAXS



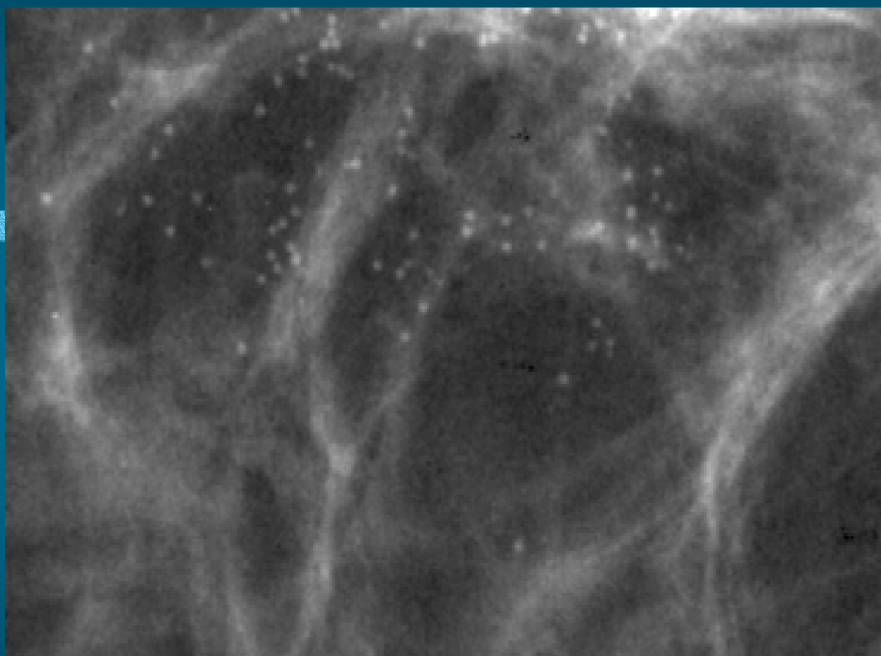


Wilkins, S.W. (1998), US Patent 5,802,137

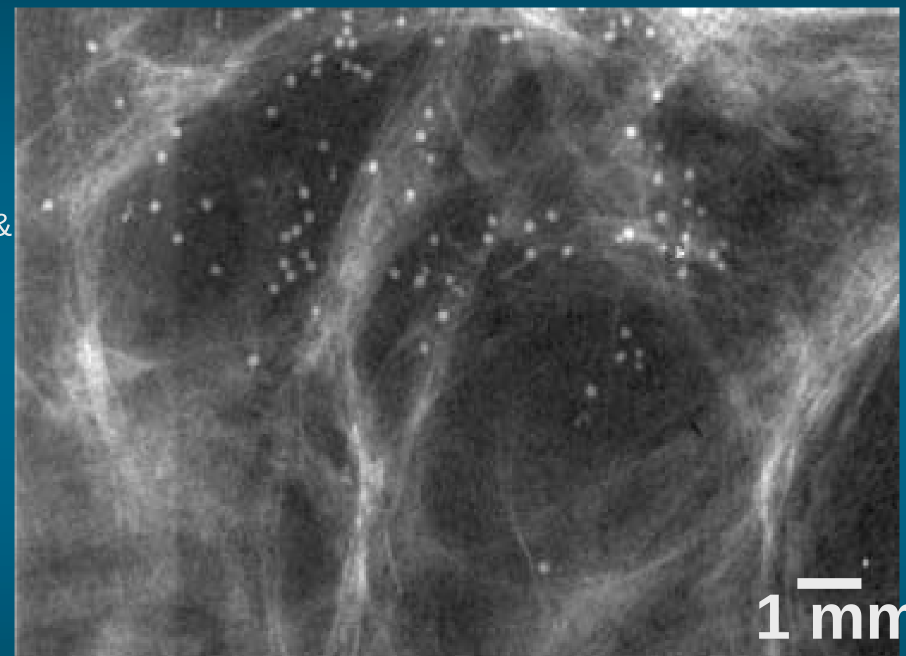
Clinical Medical Applications of Phase Contrast Imaging ?

Tissue sample

Absorption radiograph



Phase contrast



Thickness = 3 cm
Energy = 17 keV
Mead Glandular dose = 0.5 mGy

Giuliana Tromba et al, *Elettra*

The SYRMA project
(**SY**nchrotron **R**adiation for **Ma**mmography)

Agreement among the Public Hospital of Trieste, the University of Trieste and Elettra

Aim -> *In vivo* mammography studies on cases selected by the Radiologist.

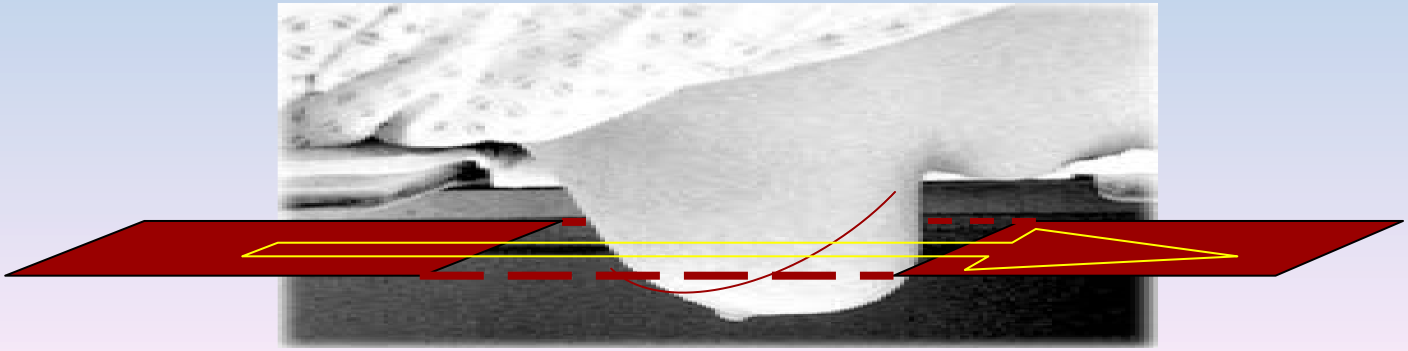
Target-> Dense breasts;

conventional radiographs with uncertain diagnosis;

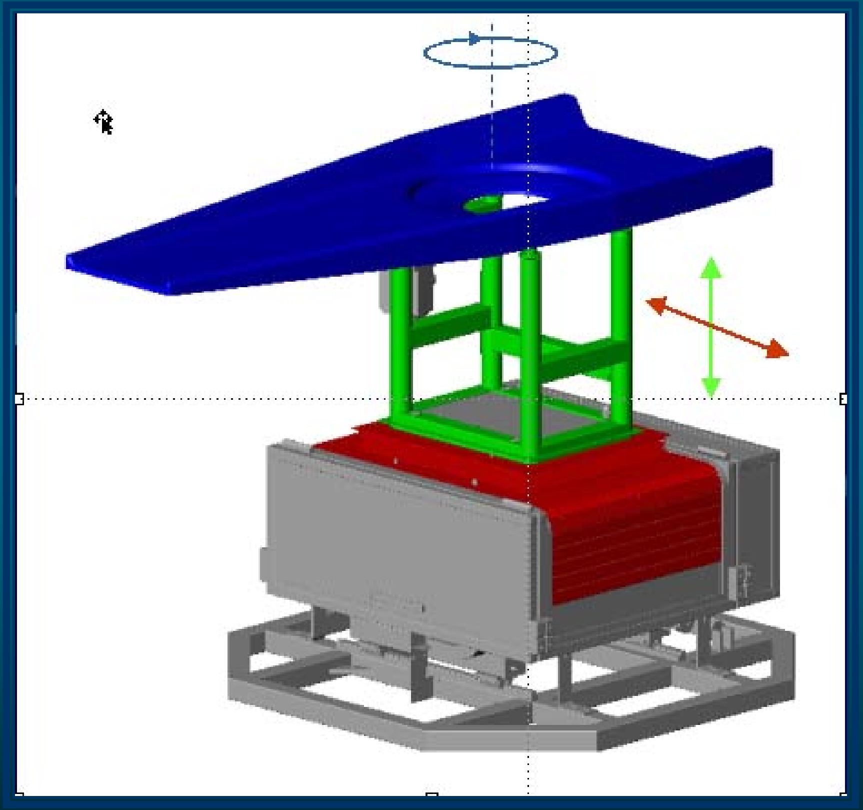
suspect of false positives.

Set-ups-> I Phase: PHC radiography with commercial detectors;

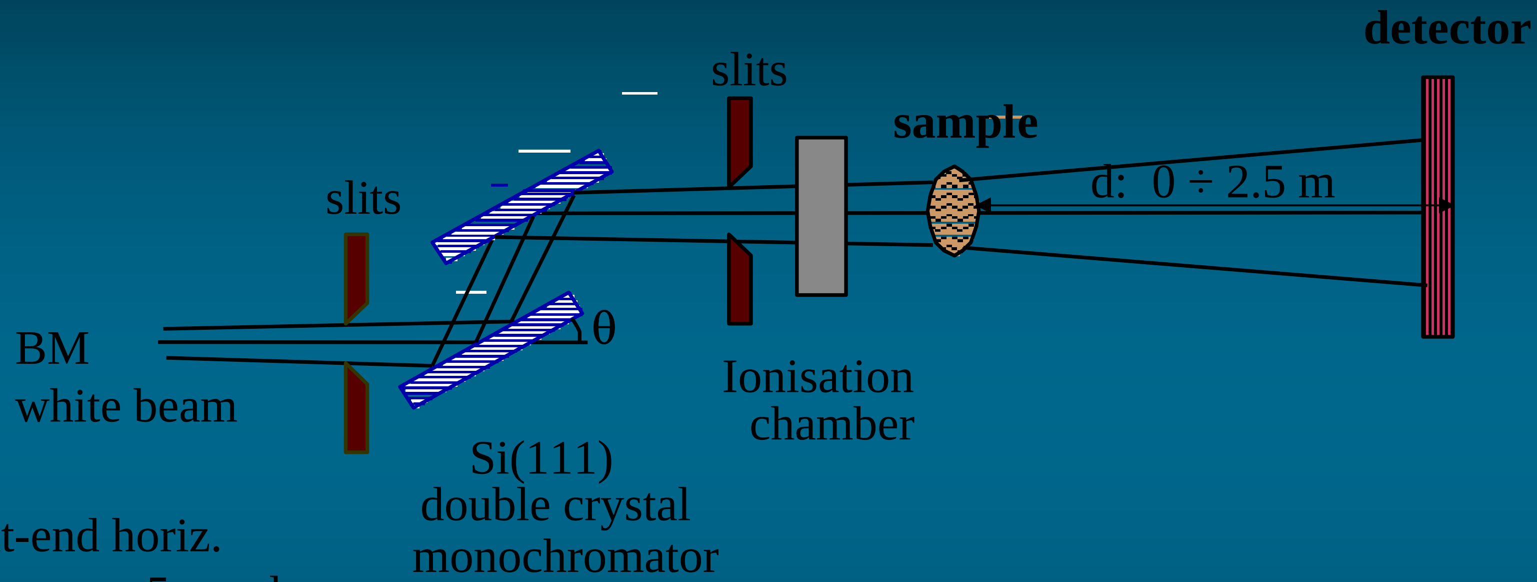
II Phase: low-dose tomography with custom Si microstrip detector.



Patient support



SYRMEP layout for In-Line imaging (Elettra, Trieste)



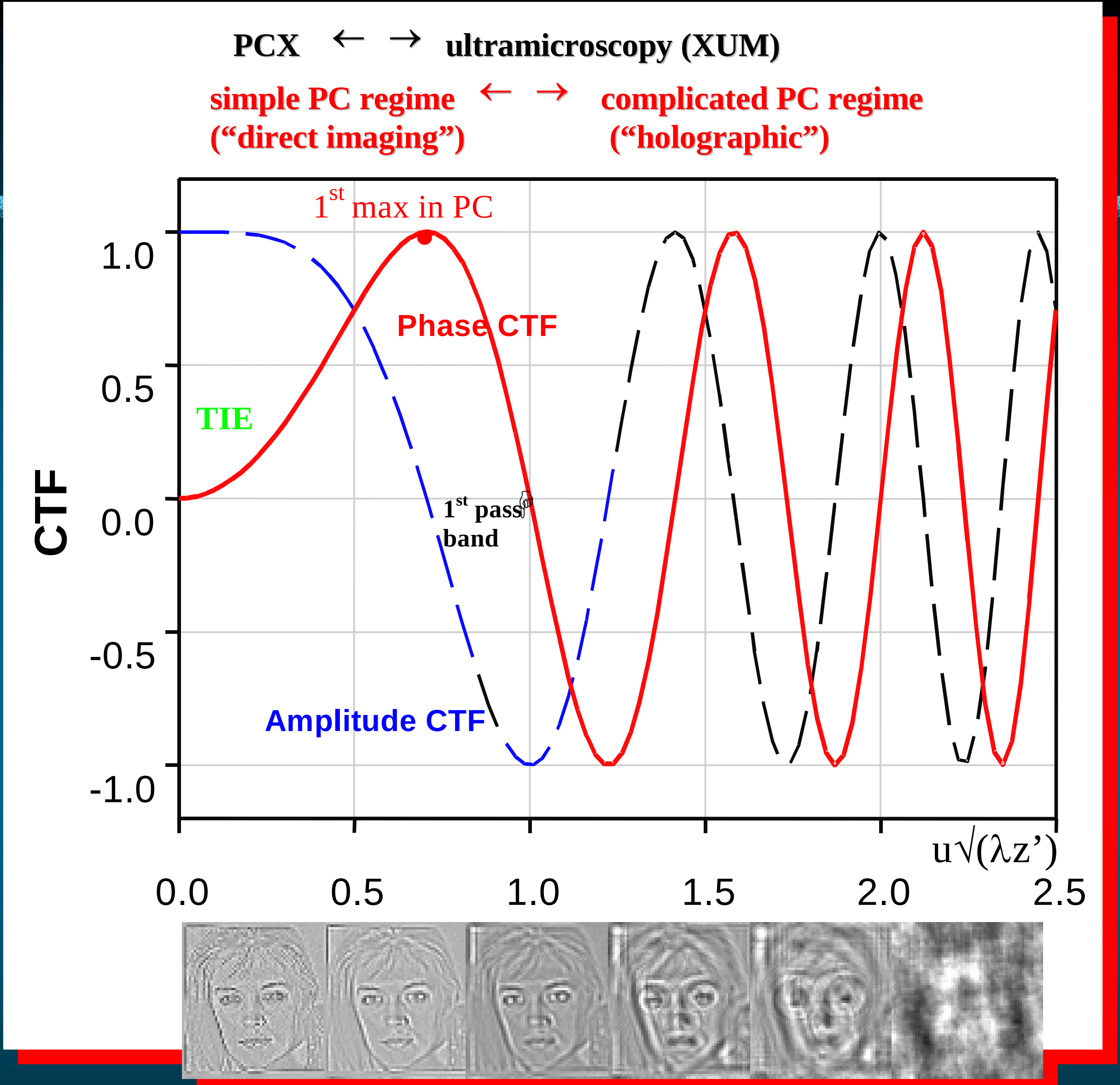
Front-end horiz.
acceptance: 5 mrad

Pushing the envelope of PCI…..!

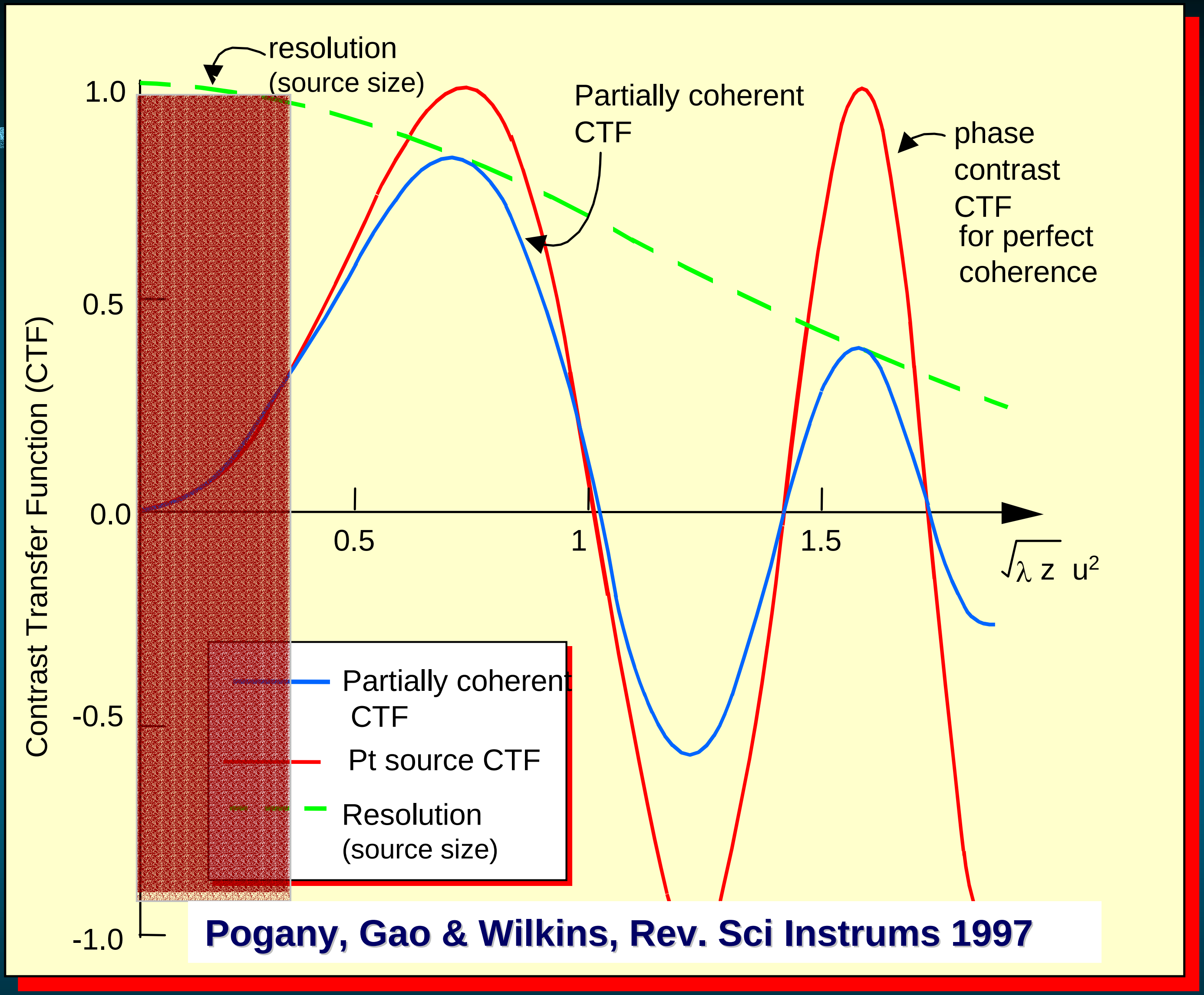
Regimes of X-ray imaging

near-field **intermediate field** **holographic**

(non-linear dependence on ϕ)

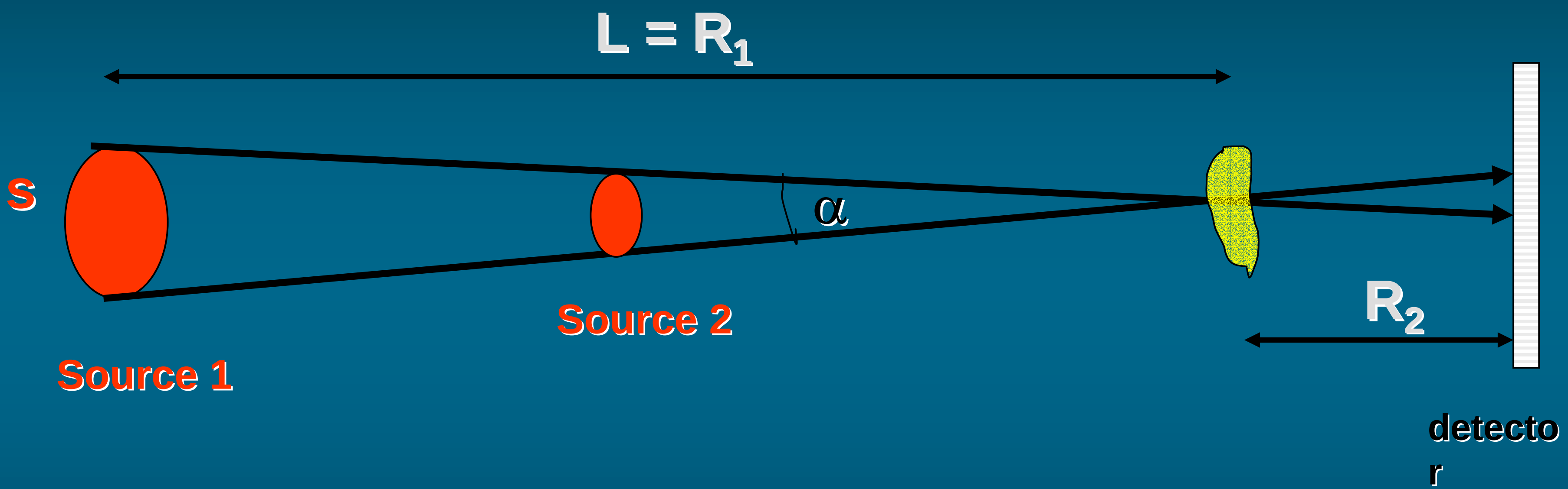


Contrast Transfer Function (CTF) for phase and absorption information contained in the object. The thumbnail images of "Holly" taken as a pure phase object show the effect on image structure of imaging in different regimes. Note: all images might in principle be used to try to obtain the same information about the object ("Holly")



Contrast Transfer Function showing effect of damping term due to finite source size

Spatial Coherence



Spatial coherence = λ L / s = λ / α

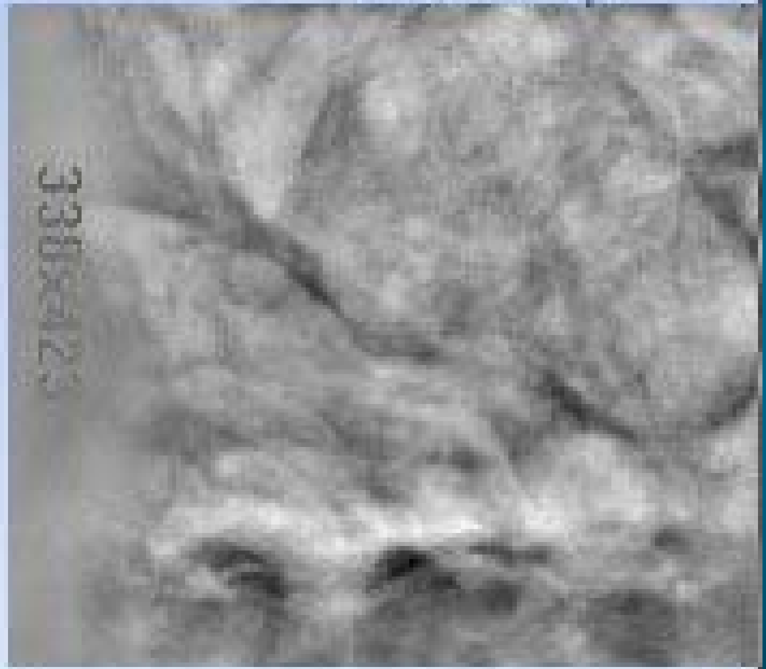
Holotomography

Breast Biopsy $\varnothing \approx 15$ mm ; pixel size = 7.5 µm

⇒ Huge distances: 0.03, 1, 4.3 and 8.8 m !

Phase Map

338x423



13 mm

Energy = 25 keV

E. Pagot, P Cloetens ,...

ESRF, ID-19

E. Pagot,

More coherence?

Distance to be most sensitive to lengthscale a:

$$D_{opt} = \frac{a^2}{2\lambda}$$

For example at $\lambda = 0.5$ Å (25 keV)

$a = 1\ \mu m \Rightarrow D = 10\ mm$

$a = 10\ \mu m \Rightarrow D = 1\ m$

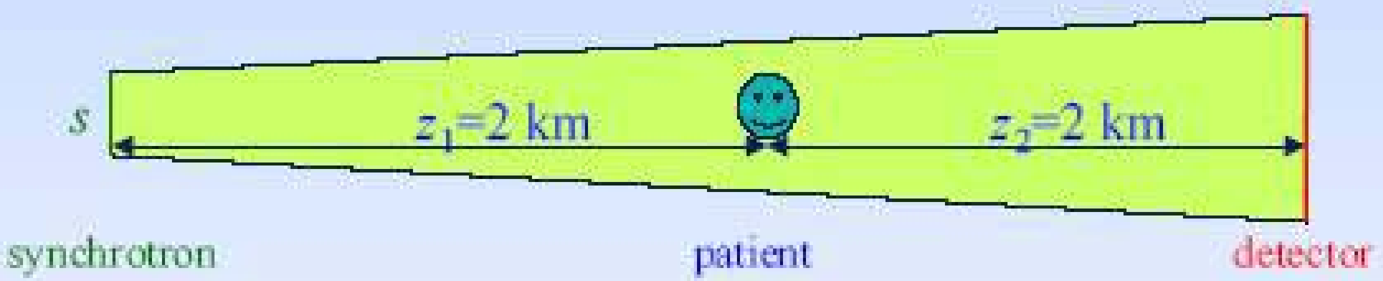
$a = 40\ \mu m \Rightarrow D = 16\ m$

$a = 0.3\ mm \Rightarrow D \approx 1\ km$

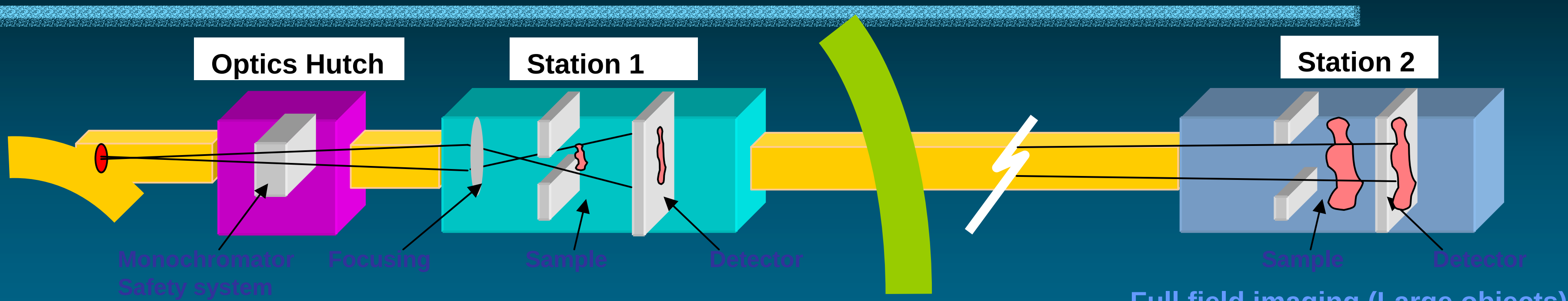
From Peter Cloetens, ESRF

(Berkeley Meeting, ‘03))

$$D = \frac{z_1 . z_2}{z_1 + z_2}$$



Hard X-ray Imaging Beamline for AS



Full field imaging,
Microprobe,
Radiotherapy

Full field imaging (Large objects)
Phase contrast imaging.
High spatial coherence

Key property is flexibility

Main parameters:

- Wide energy range 10 to ~ 120 keV (also including “white” beam).
- 1 close in station and one ~ 150-200m from source point
- High spatial resolution ~ 1 um (Station #1) ~ 10 um (Station #2)
- Large hutches to allow multiple modes of use & a variety of configurations (without compromise).
- Ultra-plane waves (e.g. topography).

Variety of applications:

- Biomedical (live small animal, biopsy, bone)
- Micro CT, Plane wave topography
- Industrial materials analysis and imaging
- Medical, both diagnosis and radiotherapy

CSIRO Team & Collaborations in PCI

CSIRO

Tim Gureyev, Peter Miller

Sherry Mayo, Andrew Pogany

Andrew Stevenson , Tim Davis,

Dachao Gao David Parry

Monash U

David Paganin Rob Lewis

ESRF

Anatoly Snigirev Irina Snigireva

Tim Weitkamp Carsten Raven

Photon Factory/KEK

Masami Ando K Hyodo

ASRP (Aust Synchrotron Research Program)

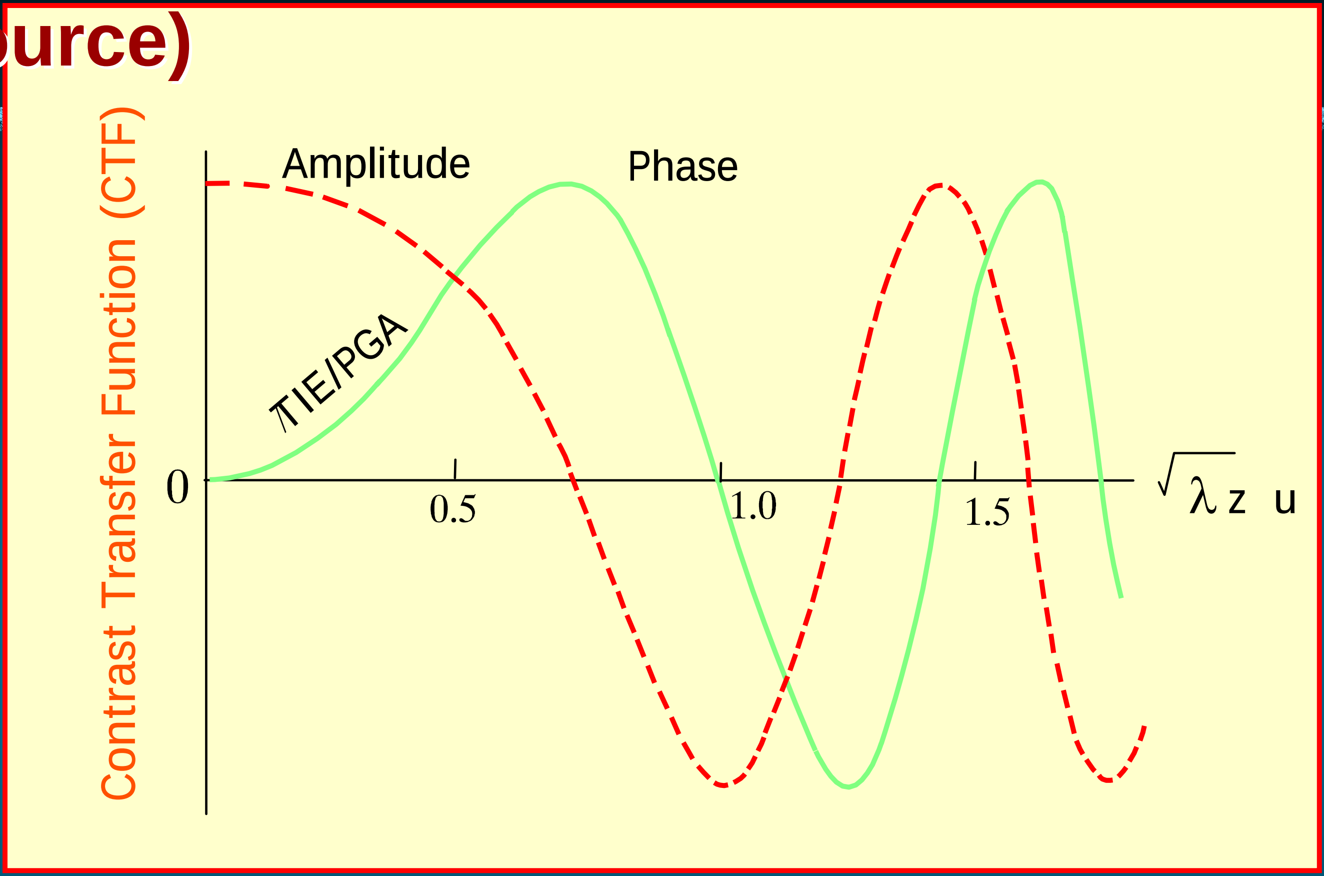
Richard Garret David Cookson

PLS (Korea)

H.S. Youn

XRT X-Ray Technologies Pty Ltd

Contrast Transfer Function for PCX (Point Source)



λ= X-ray wavelength

z = effective object-image distance = $R_1 R_2/(R_1+R_2)$

u = spatial frequency 1/d (d = line-pair separation)

Intensity (Contrast) from a Pure Phase Object

$$I((M_x, M_y; R_1 + R_2, k) = (I_0 / M^2)\left[I + \frac{R_2}{kM}\nabla \nabla_{xy}{}^2 \phi(x,y; R_1, k)\right]$$

$$= (I_o / M^2)\left[I - 2\pi \frac{2\pi r_e}{k} \nabla \oint \nabla^2{}_{xy} \rho(x,y,z)\, dz\right]$$

Relationship for phase

$$\phi(x,y,z,k) = -k \int \delta(x,y,z';k)dz' = \frac{2\pi r_e}{k} \int \int \rho(x,y,z')\, dz'$$

Where R_1 = source-object : R_2 = object-image

M = magnification

k = $2\pi/\lambda$ r_e - classical e radius, ρ = e density

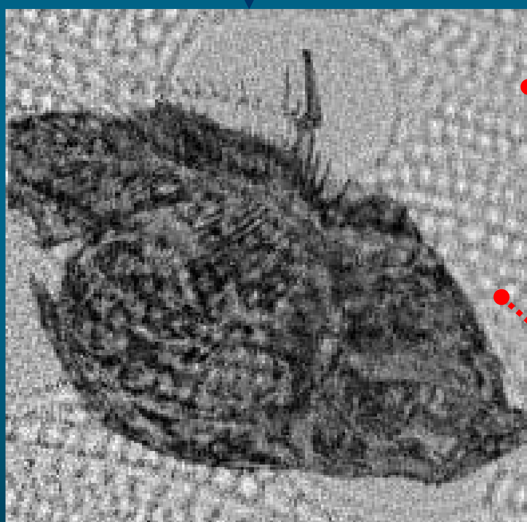
N.B.

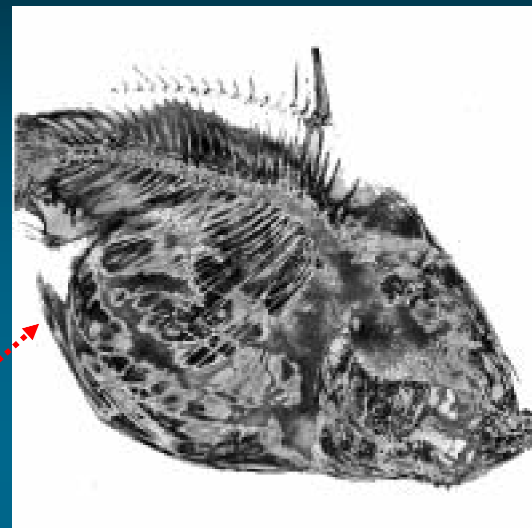
1. Edge enhancement
2. Contrast increase with R_2
3. Energy invariance of image

Role of Phase Retrieval in In-Line Imaging

1. Separation of Phase from Amplitude Contrast (Multi-Distance)

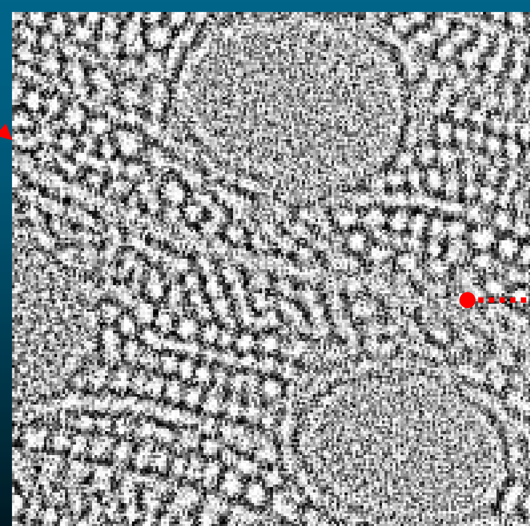
"Experimental" in-line image (amplitude/phase)





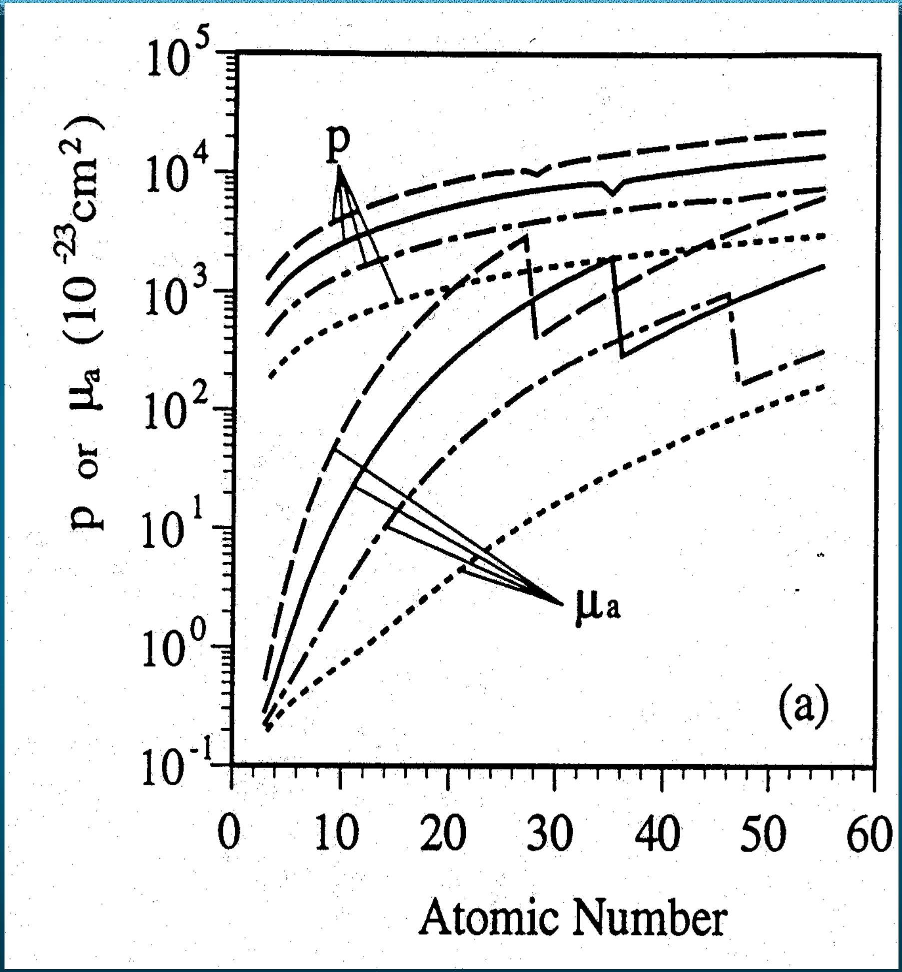
Extracted intensity exp[-μt(x,y)]

Extracted phase $\varphi(x,y)$

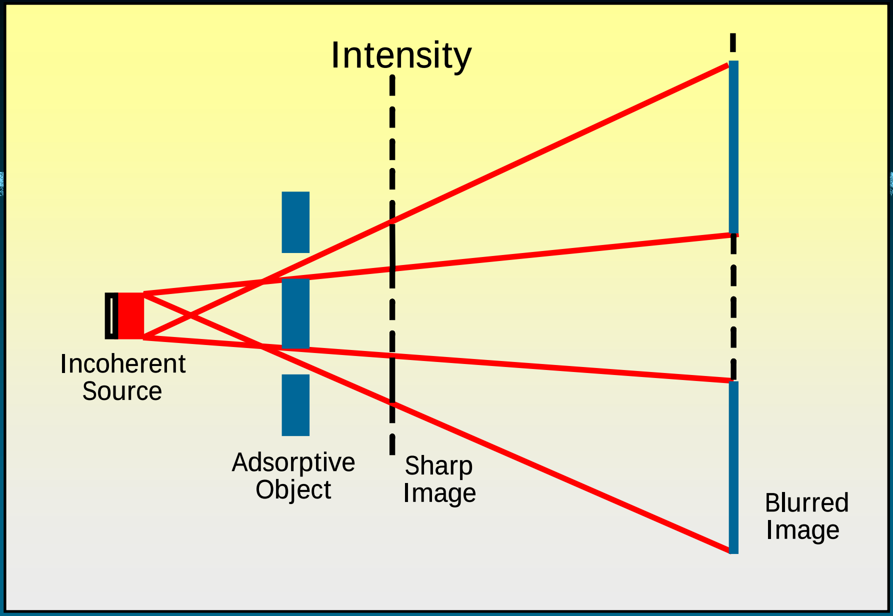


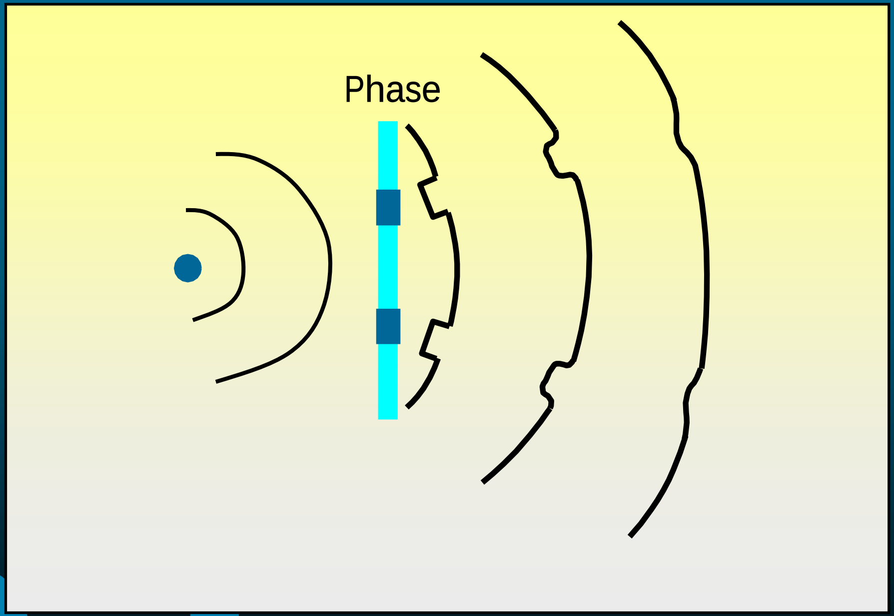
Extracted phase Laplacian – $\nabla^2\varphi(x,y)$

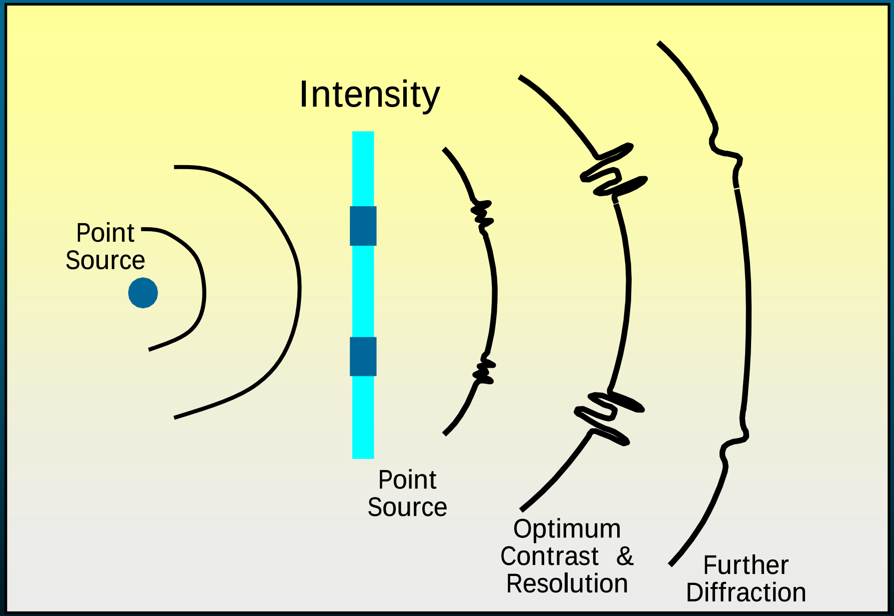
Absorption and Phase Cross-Sections



Calculated values for phase-shift cross-section p and absorption cross-section μ_a.as a function of atomic number (from Momose et al).


Intensity
Incoherent
Source
Adsorptive
Object
Sharp
Image
Blurred
Image


Phase


Intensity
Point
Source
Point
Source
Optimum
Contrast &
Resolution
Further
Diffraction

SAXS, Refraction & Absorption

RESEARCH PAPERS

Acta Cryst. (1994). A**50**, 686–690

A Unified Treatment of Small-Angle X-ray Scattering, X-ray Refraction and Absorption using the Rytov Approximation

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(*Received* 31 *January* 1994; *accepted* 30 *March* 1994)

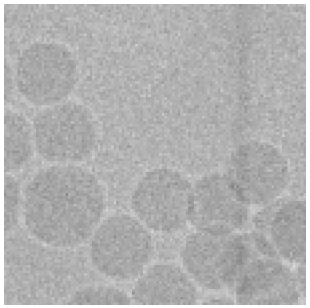
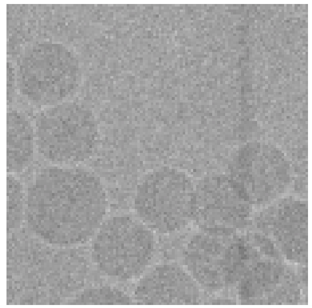
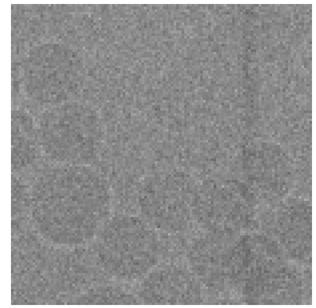
Abstract

The Helmholtz wave equation for X-rays in a dielectric medium is solved using the Rytov approximation for the X-ray phase perturbation. It is shown that under appropriate limits the solution yields the equations for small-angle X-ray scattering, X-ray refraction and absorption. This demonstrates that the Rytov approximation provides a unified treatment of small-angle X-ray phenomena.

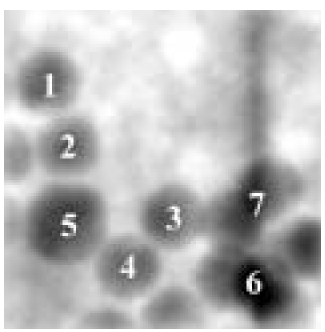
transition from diffraction to refraction (Berk & Hardman-Rhyne, 1986).

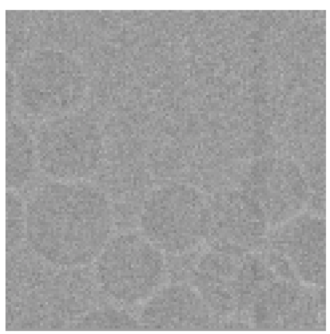
In this paper, an alternative treatment of the problem is given using the Rytov approximation (Rytov, 1937; from reference 11 in Chernov, 1960) for the phase shift in the X-ray beam as it traverses a dielectric medium. This approximation is well known in wave theory and optics and has similarities with the Born approximation (Devaney, 1981), although it is generally considered to be more accurate (Keller, 1969; Oristaglio, 1985). The phase perturbation is

Partial Coherence. Phase/Amplitude Retrieval from Multi-Energy In-Line Images

(a)

(b)

(c)


Experimental images at (a) λ=3.8 Å; (b) 7.3 Å and (c) 2.5 Å

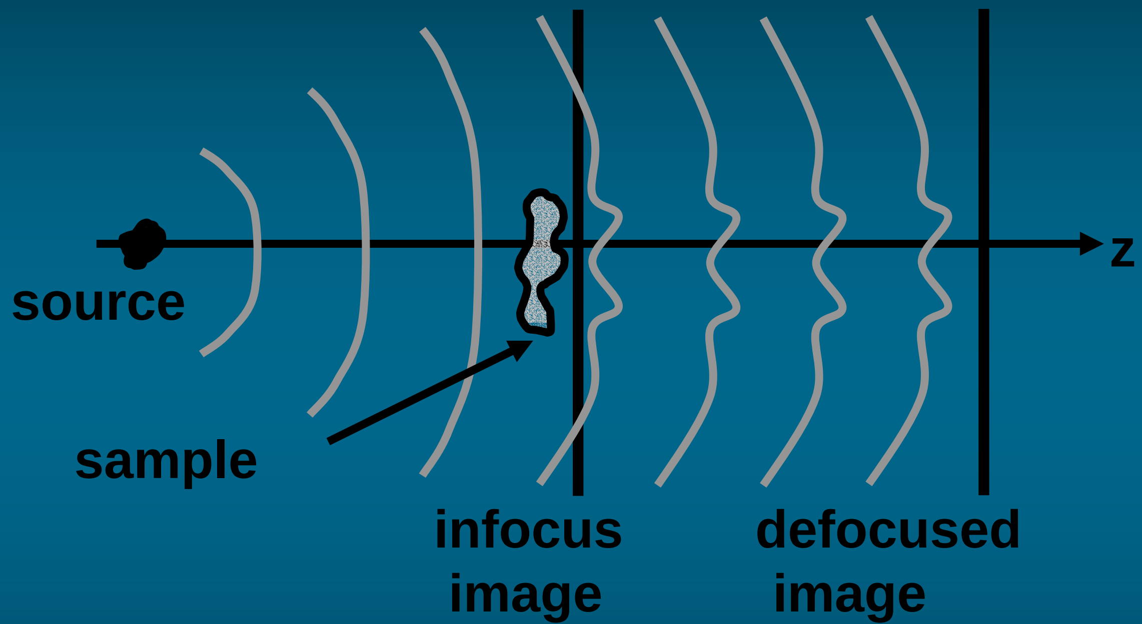
(d)


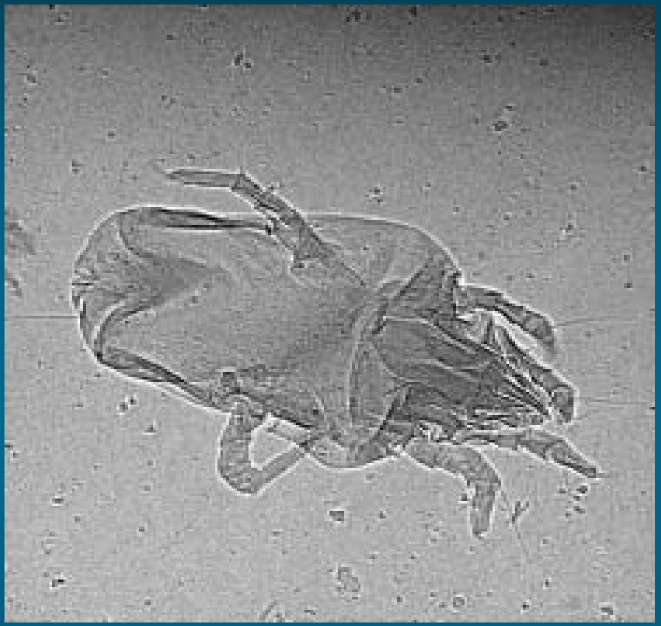
(e)


	Theory	Sphere 1	Sphere 2	Sphere 3	Sphere 4
$-\varphi_{max}$	3.25	3.20	3.53	3.57	3.12
M_{max}	0.055	0.061	0.070	0.053	0.056

Reconstructed phase (d) and intensity (e)

D2: Mathematical lenses: X-Ray Omni-microscopy (slide 1 of 3)





$$\psi\left(x,y,z=0\right)=I_0^{-ik\delta/\mu}\left(\frac{M^2}{1-\mu^{-1}M^{-1}\delta\Delta z\nabla_\perp^2}I(Mx,My,z=\Delta z)\right)^{\frac{1}{2}+ik\delta/\mu}.$$

Paganin, Gureyev *et al.*, Journal of Microscopy (2004),