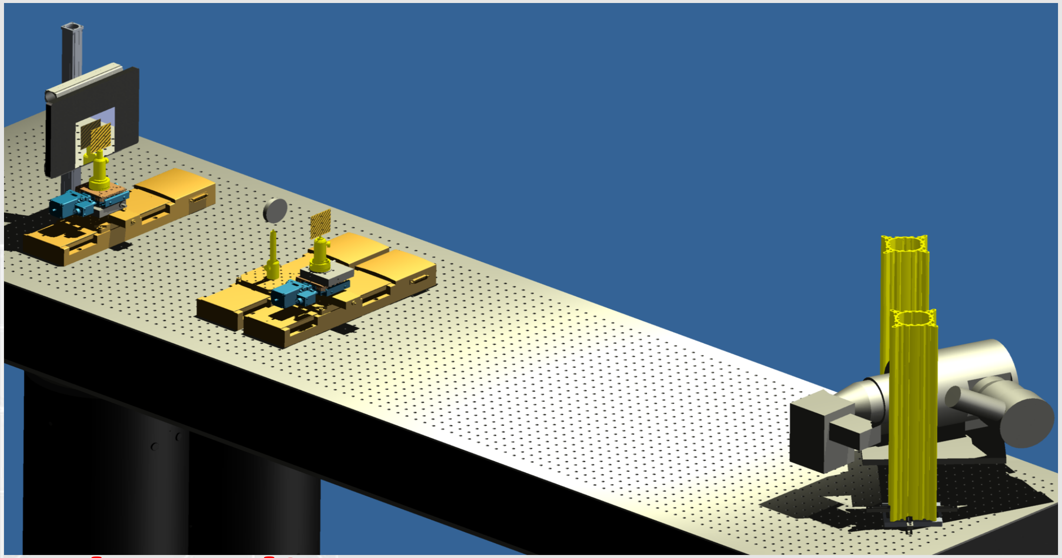
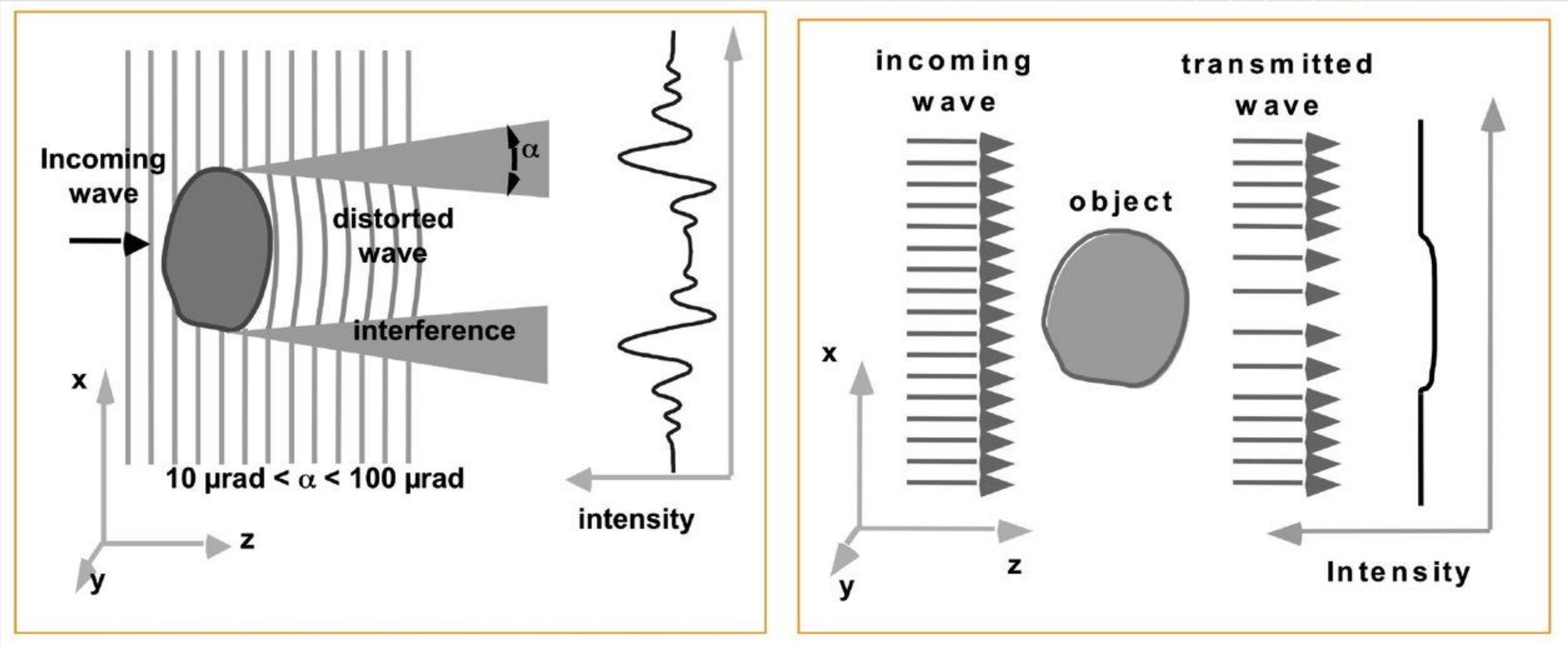
The evolution of edge-illumination X-ray phase contrast imaging and its prospective clinical translation to breast-related applications



Sandro Olivo, Spokesperson, AXIm Group
(https://www.ucl.ac.uk/medphys/research/axim)
Medical Physics and Bioemedical Engineering, UCL

Phase Contrast Imaging vs. Conventional Radiology



Refractive index: $n = 1 - \delta + i\beta$; $\delta \gg \beta$ ->
phase contrast ($\Delta I/I_0 \sim 4\pi\delta\Delta z/\lambda$) >> absorption contrast ($\Delta I/I_0 \sim 4\pi\beta\Delta z/\lambda$)

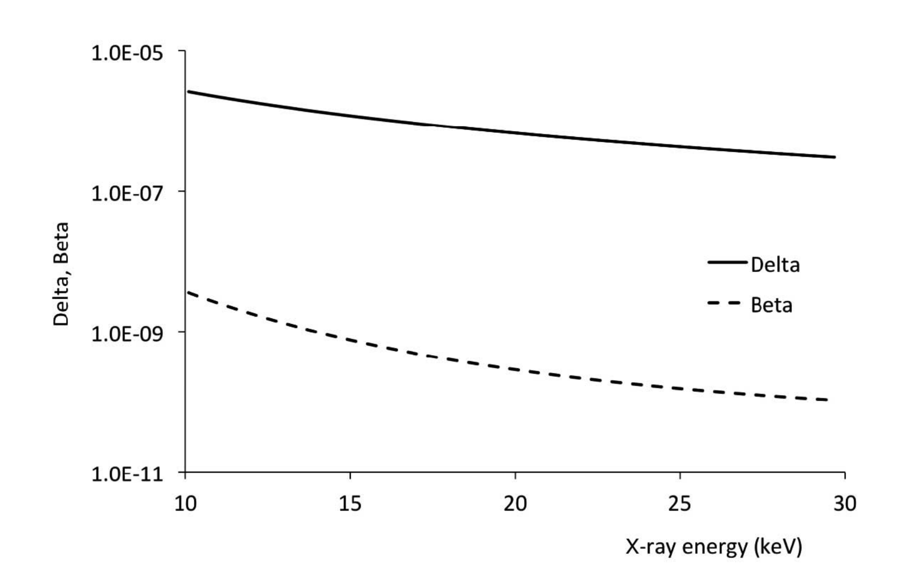
Two possible approaches:
- **detect interference patterns**
- **detect angular deviations**

$$n = 1 - \delta + i\beta,$$

$$\mu = \frac{4\pi\beta}{\lambda}$$

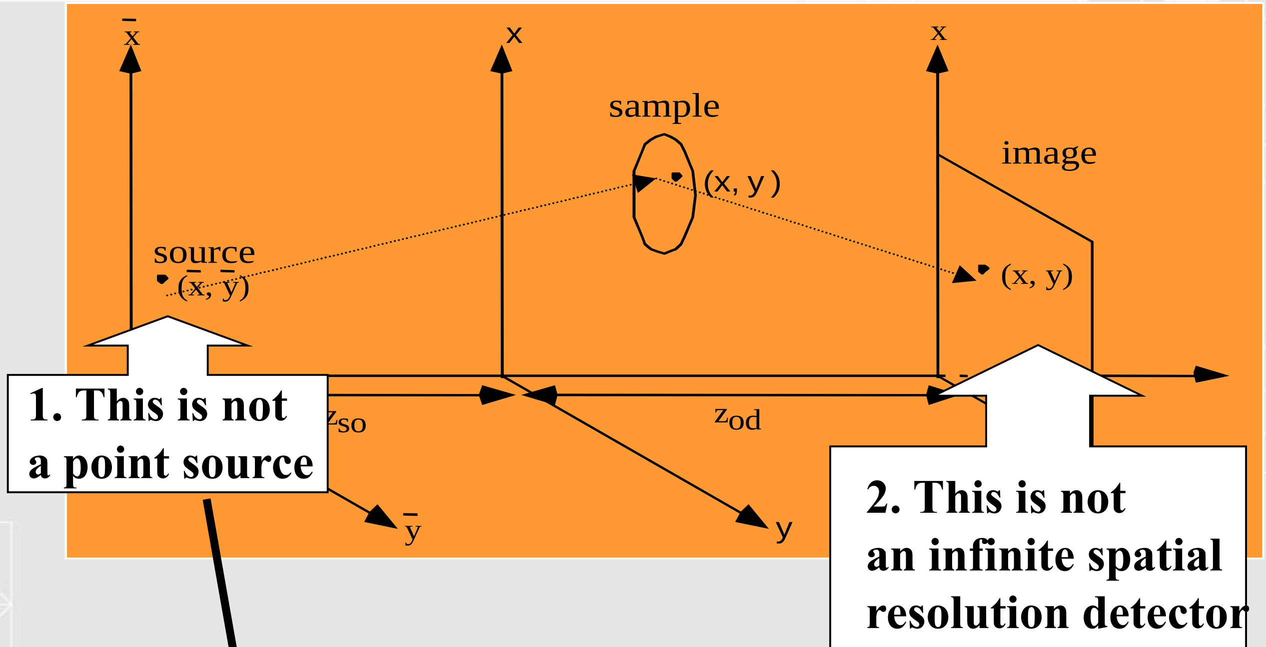
$$\Phi(x, y) = \frac{2\pi}{\lambda} \int_{\mathrm{object}} \delta(x, y, z) \mathrm{d}z,$$

$$\delta = \frac{r_e \rho_e \lambda^2}{2\pi}$$



Note 1) ~ 3 orders of magnitude larger 2) decreases more slowly with x-ray energy

How can we model it?

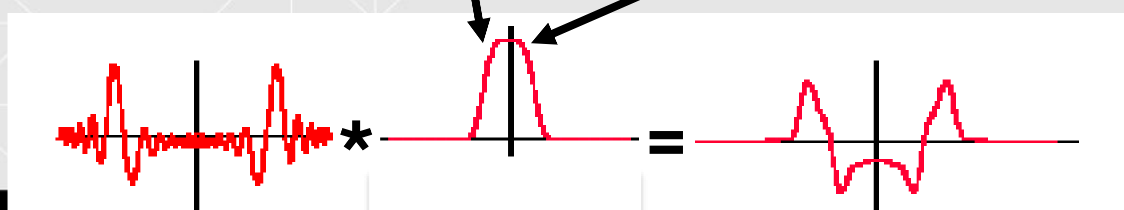


without the object:

$$E(x,y) = \frac{1}{r}\exp(i2\pi r/\lambda)$$

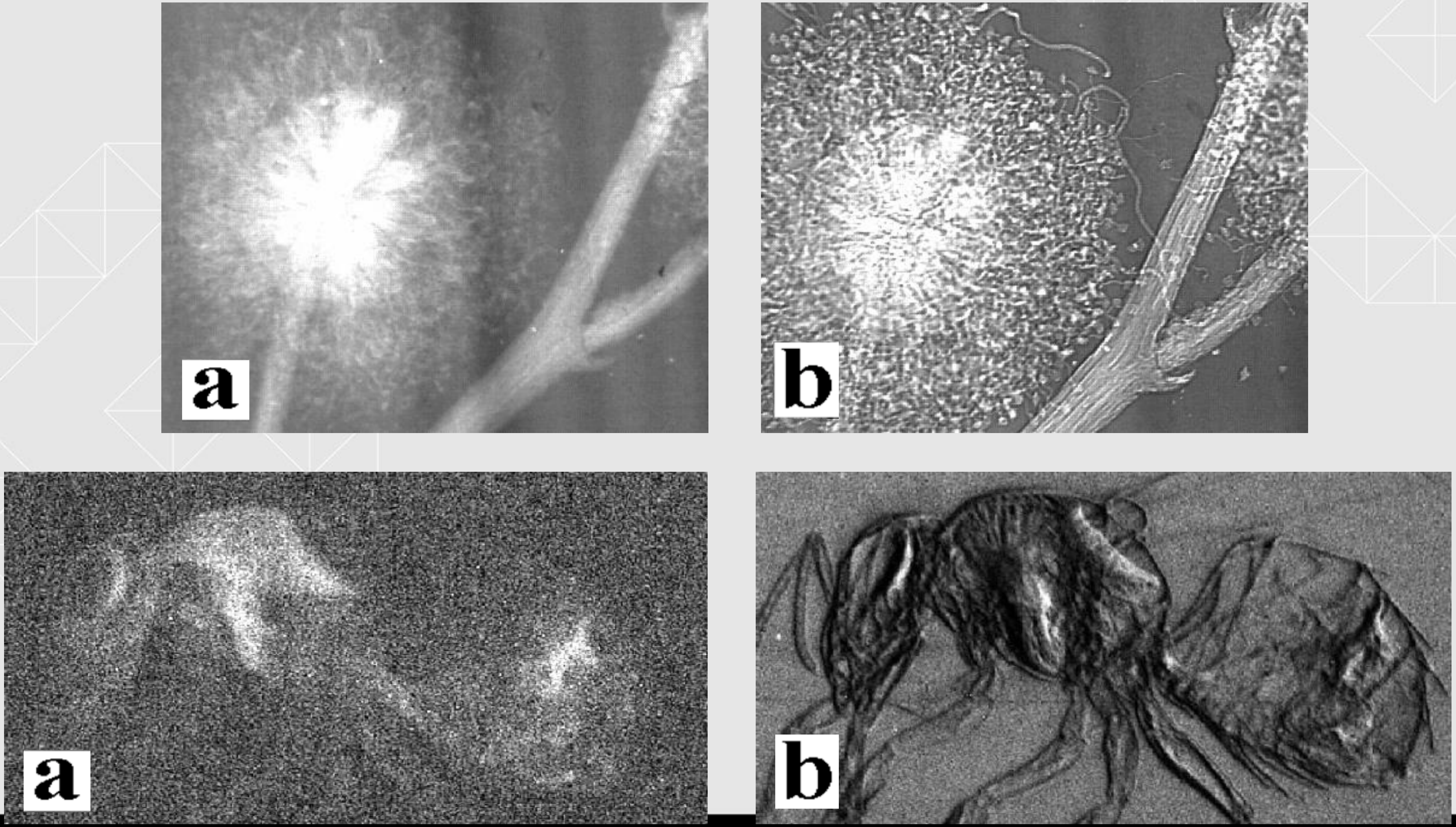
with the object in, it is effectively described by the Fresnel/Kirchoff integral

$$E(x,y) = \frac{1}{\sqrt{i\lambda z_{so} z_{od}(z_{so}+z_{od})}}\exp\{\frac{2\pi i}{\lambda}[z_{so}+z_{od}+\frac{(y-\bar{y})^2}{2(z_{so}+z_{od})}]\}\times\int_{-\infty}^{+\infty} dX \exp\{\frac{\pi i}{\lambda}[\frac{(\bar{x}-X)^2}{z_{so}}+\frac{(X-x)^2}{z_{od}}]\}\exp[i\Phi(X)]$$



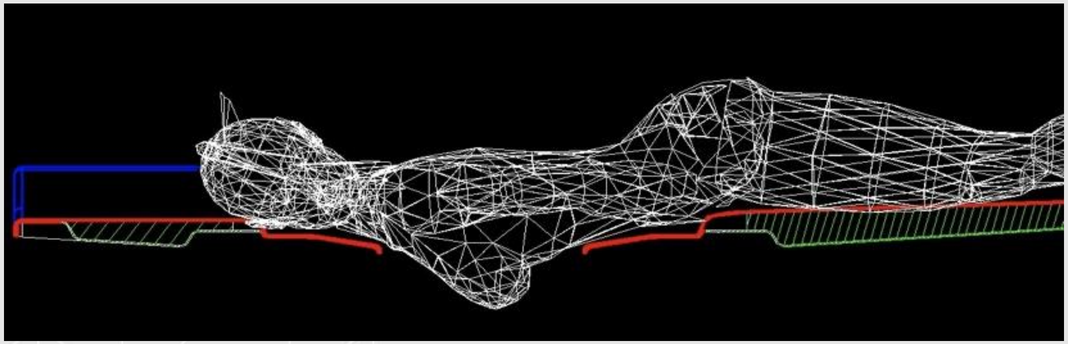
A. Olivo NIM A 548 (2005) 194-9

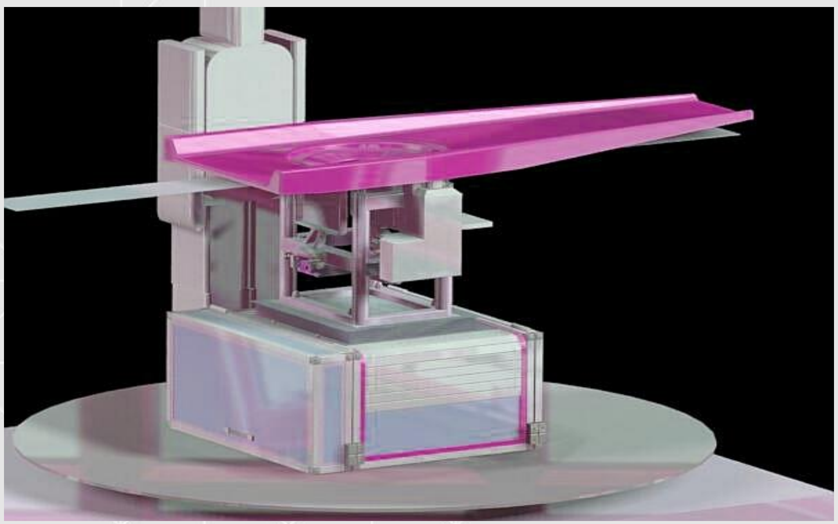
a) absorption b) phase contrast

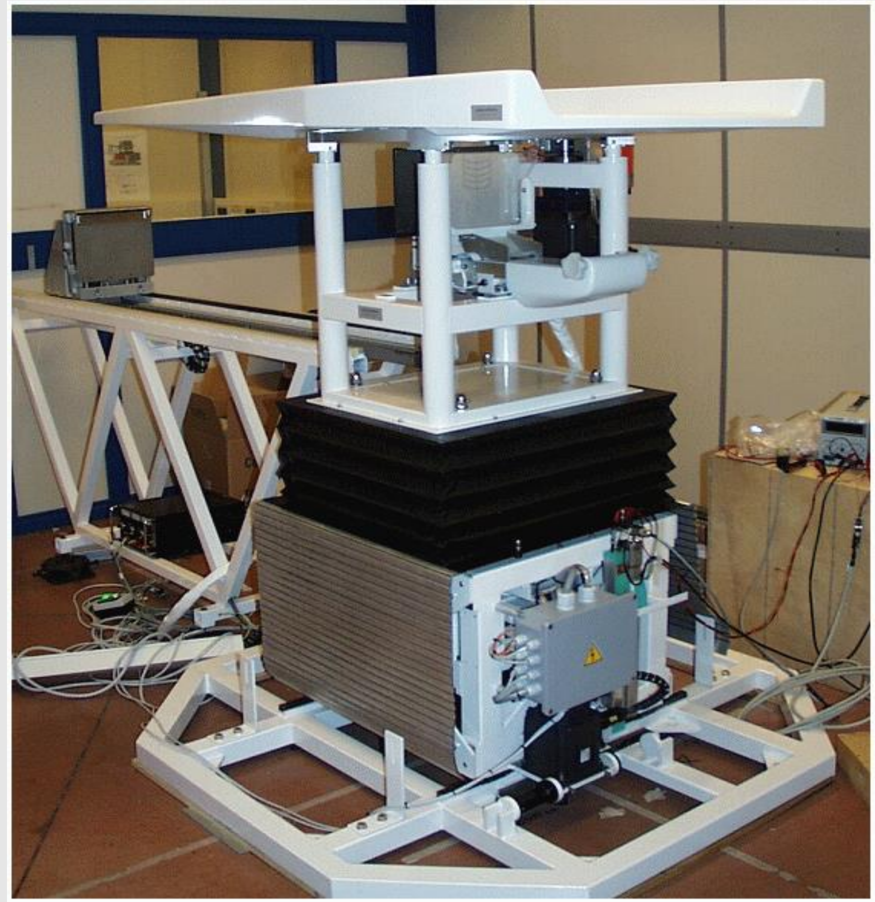


DiMichiel *et al* Proceedings of MASR1997

Which led to the realization of a dedicated mammography system in TS





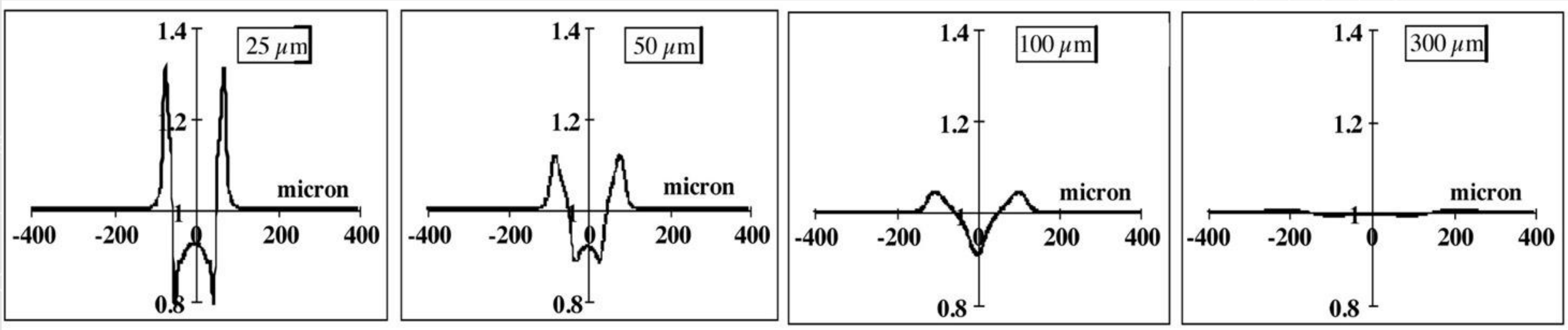


Castelli et al. Radiology 259 (2011) 684-94

FSP works wonders when implemented with a spatially coherent source – why ask for more?

- It suffer immensely when transferred to conventional sources:

the spread associated with projected source size becomes too large and kills the signal.



Moreover:

The system has little flexibility - only d_{sd} can be changed

But:

Amazing stuff @ synchrotrons, e.g. check out Cloetens' work at the ESRF
+ straightforward use e.g. coupled with Paganin's single distance phase retrieval

Olivo *et al.* Med. Phys. 28 (2001)1610-19

Remember from a few slides ago: I can also exploit small angular deviations (x-ray refraction)

When crossing an object with negligible absorption (β~0) but with $\delta \neq 0$, the X-ray wavefield changes from

$$\Psi = \Psi_0 \exp(-ikz)$$

to

$$\Psi = \Psi_0 \exp[i(-kz + \phi)]$$

with

$$\phi(x, y) = -r_e \lambda \int_{object} \rho_e(x, y, z) dz$$

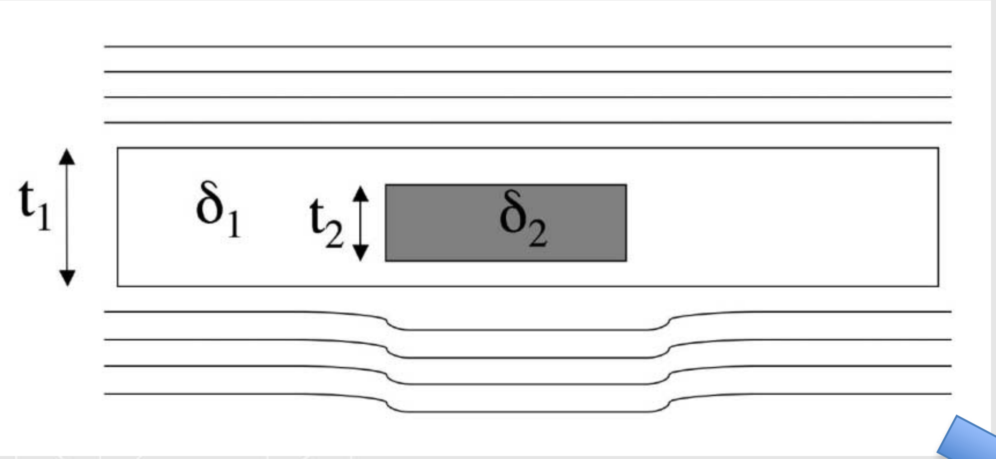
(r_e classical electron radius, λ incident radiation wavelength, ρ_e electron density)

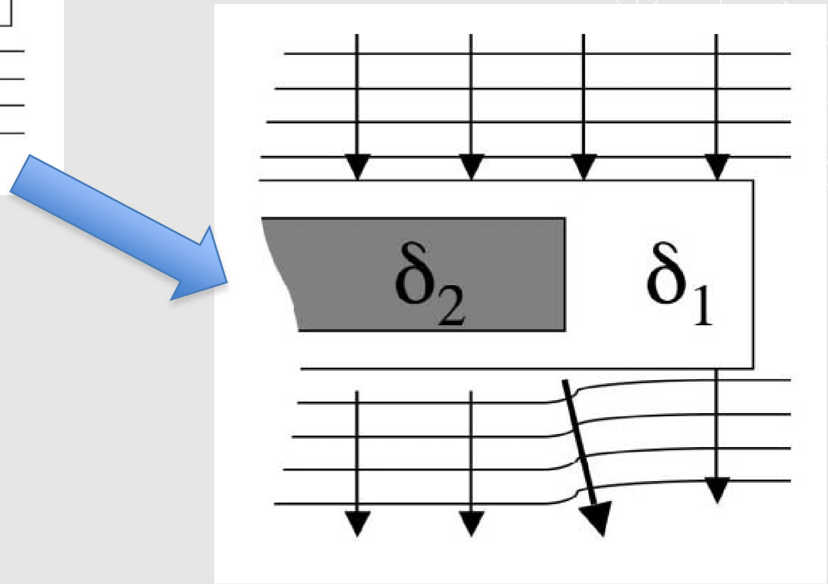
The new wavevector is therefore:

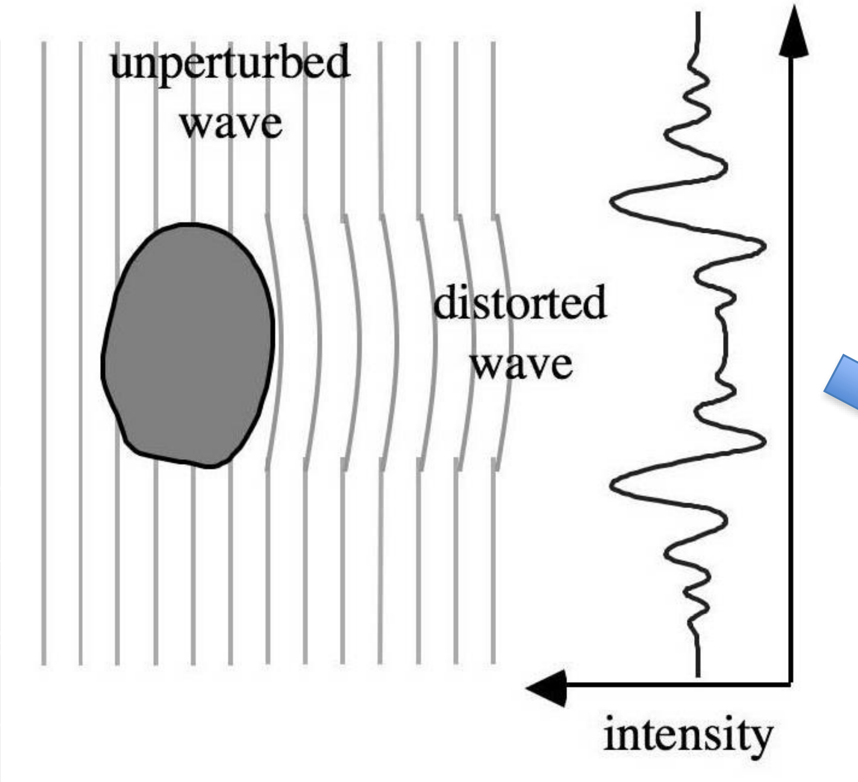
$$\vec{k}' = \left(\frac{\partial \phi}{\partial x}, \frac{\partial \phi}{\partial y}, \frac{2\pi}{\lambda}\right) = \vec{\nabla}_{xy} \phi + k\hat{z}$$

and the angular deviation (relative to the Initial propagation direction) is given by:

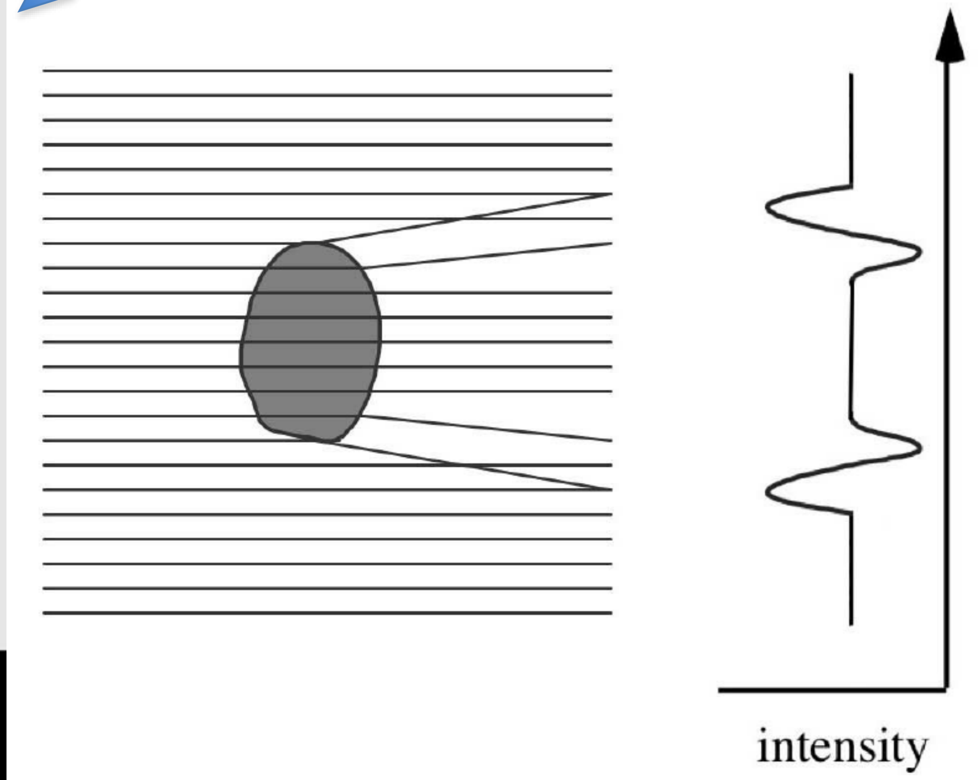
$$\alpha \cong \frac{1}{k} \left| \vec{\nabla}_{xy} \phi(x, y, \lambda) \right|$$


t1
δ1
t2
δ2


δ2
δ1

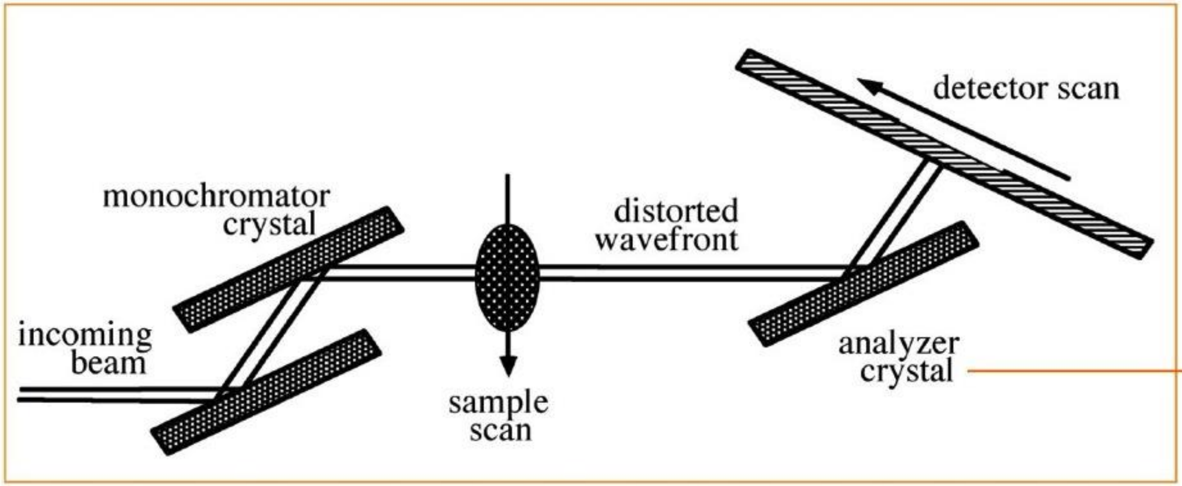


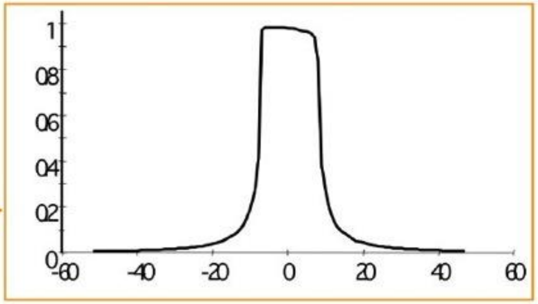
NB you can also model FSP on the same basis; if coherence is relaxed, you will get approximately the same results.



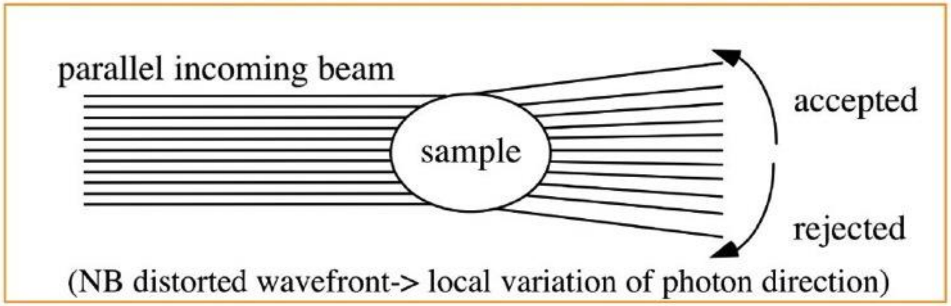
Other methods to perform phase contrast imaging:

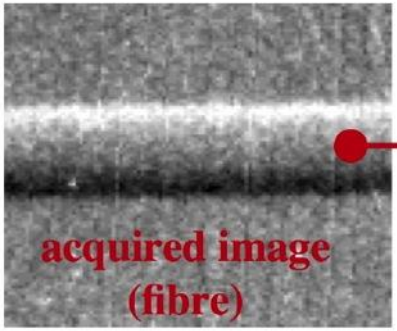
"Analyzer Based Imaging" (ABI)





a small misalignment makes it more sensitive:

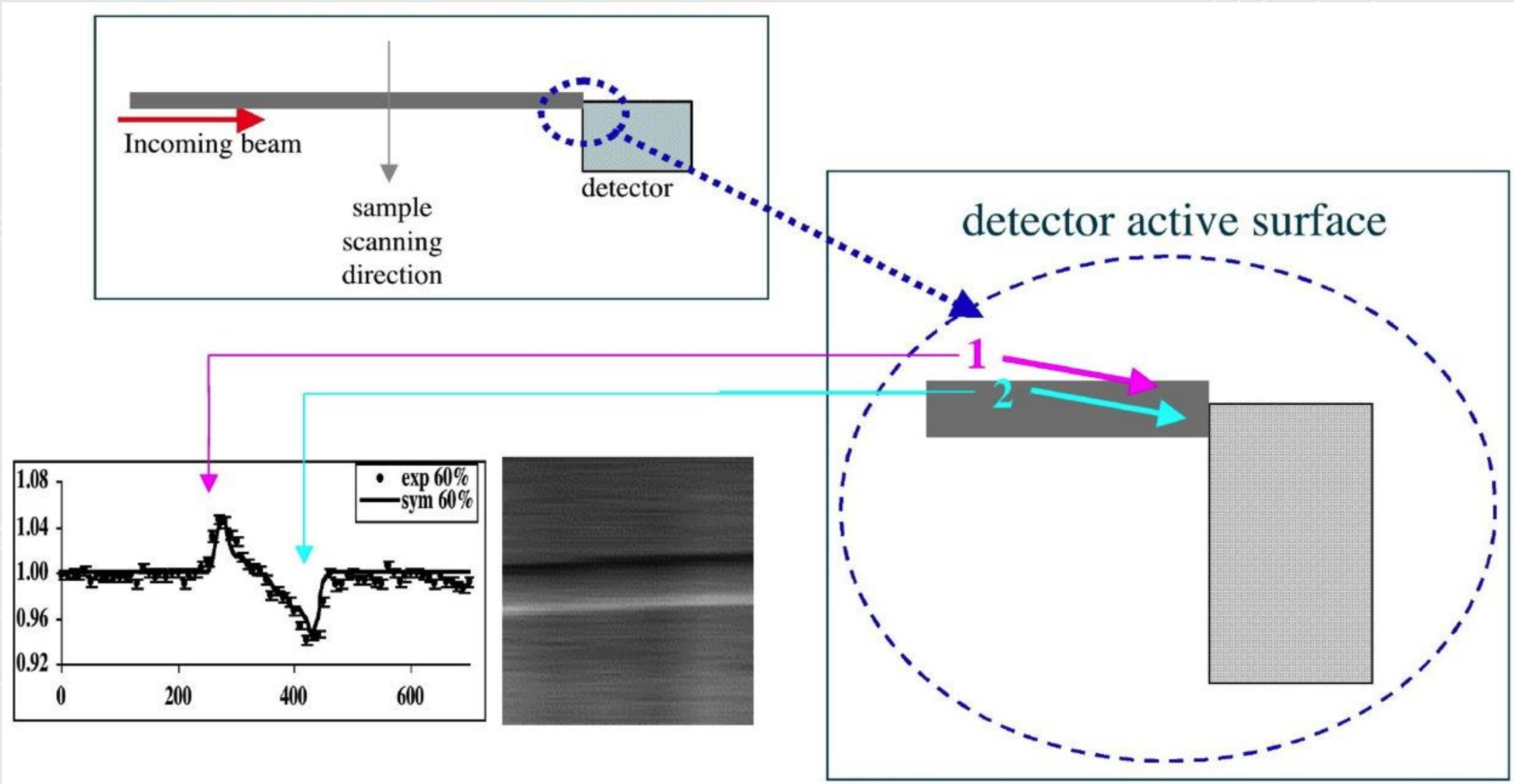




NOTE: NO ABSORPTION

Davis et al, Nature 373 (1995) 595-8; Ingal & Beliaevskaya, J. Phys. D 28 (1995) 2314-7, Chapman *et al*, Phys. Med. Biol. **42** (1997) 2015-25 - **but even before that Forster**

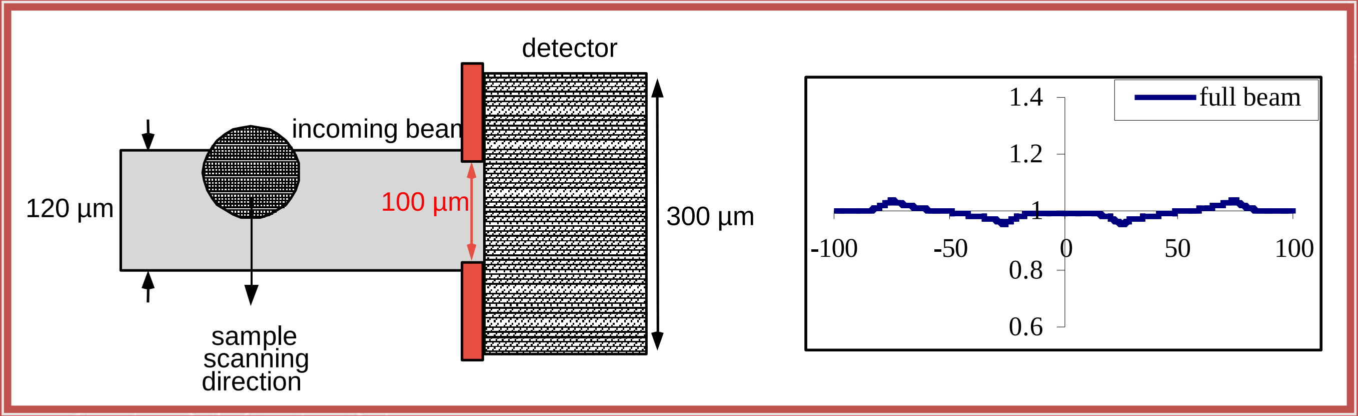
A different way to obtain a similar effect: The Edge Illumination Technique

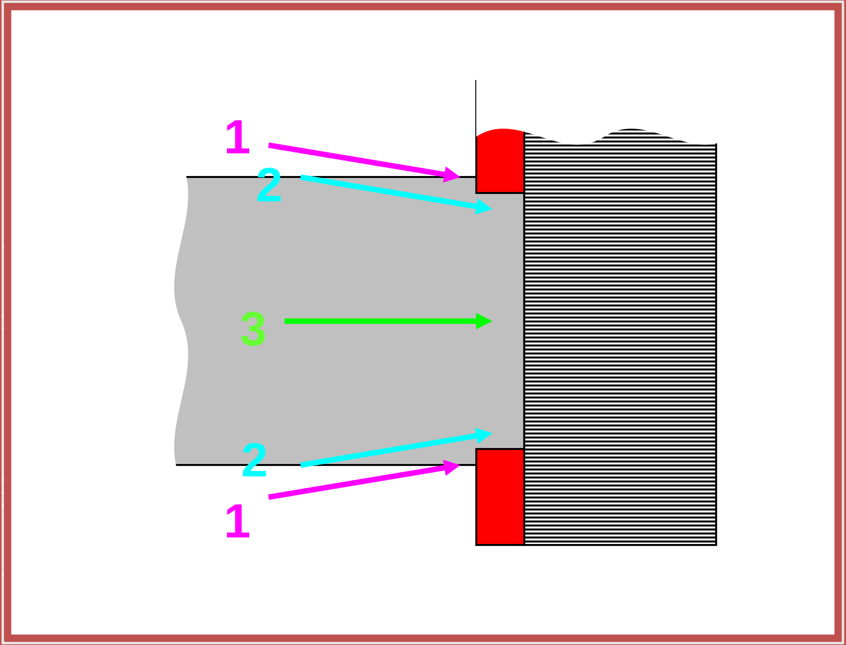


Provides results similar to ABI but opens the way to the use of **divergent and polychromatic beams**

Olivo *et al.* Med. Phys. 28 (2001)1610-19

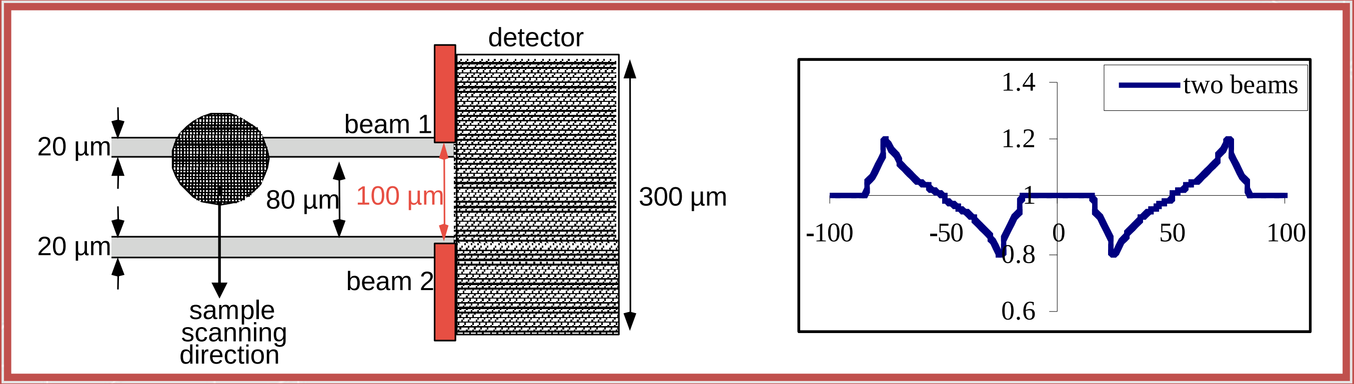
How did the idea come about? (1)



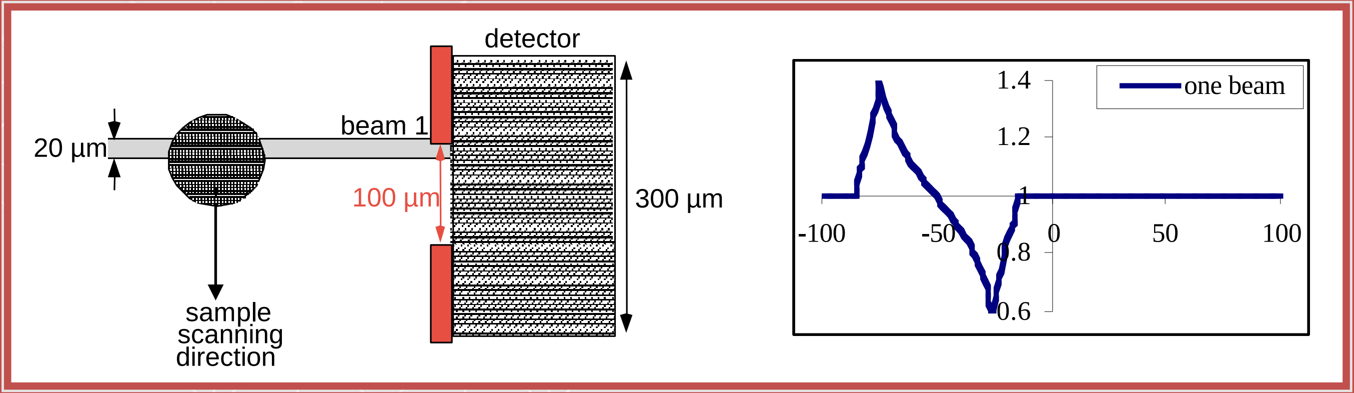


A Olivo *PhD dissertation* University of Trieste, 1999

How did the idea come about? (2)

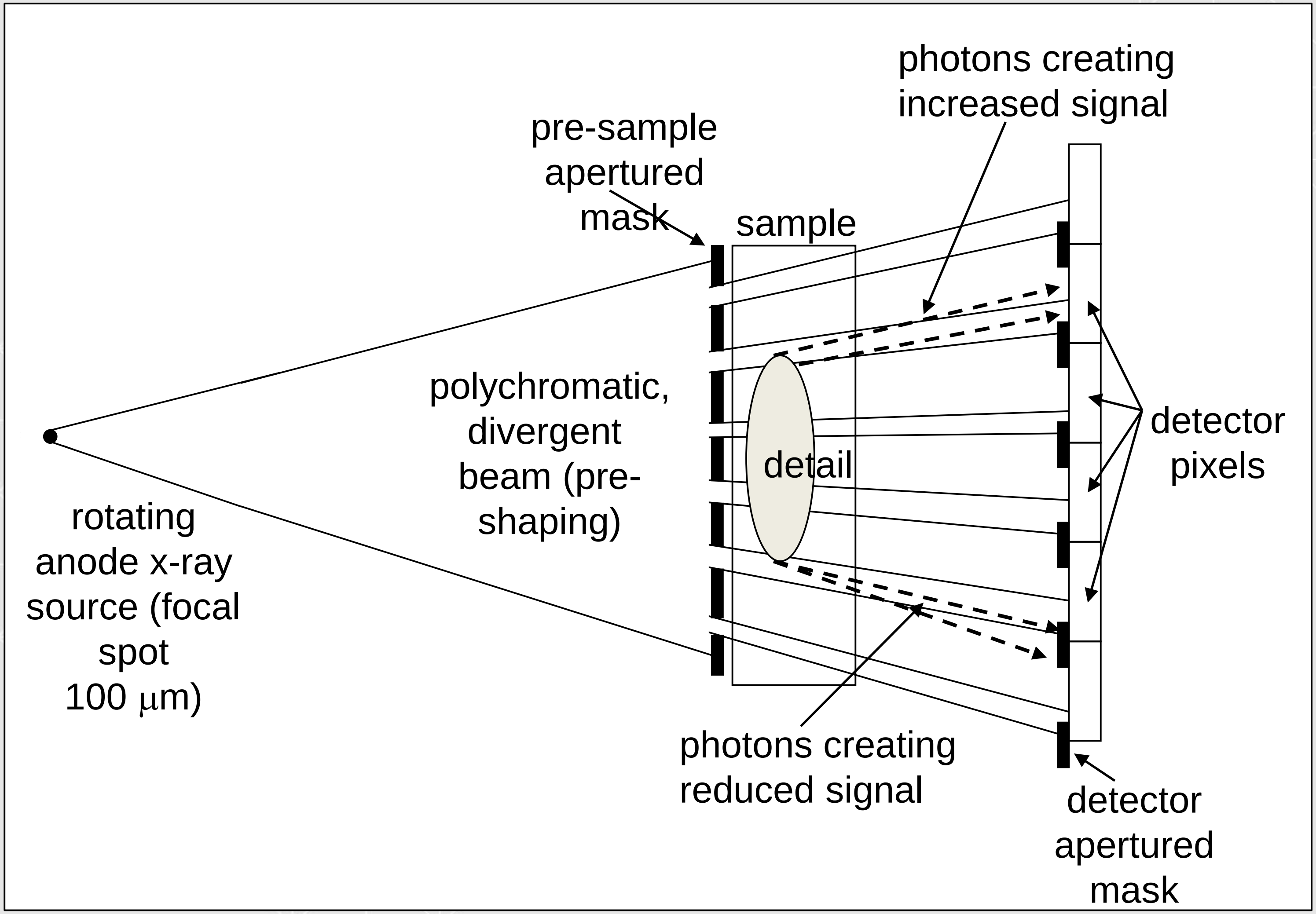


PLUS you become independent from the pixel size!



A Olivo *PhD dissertation* University of Trieste, 1999

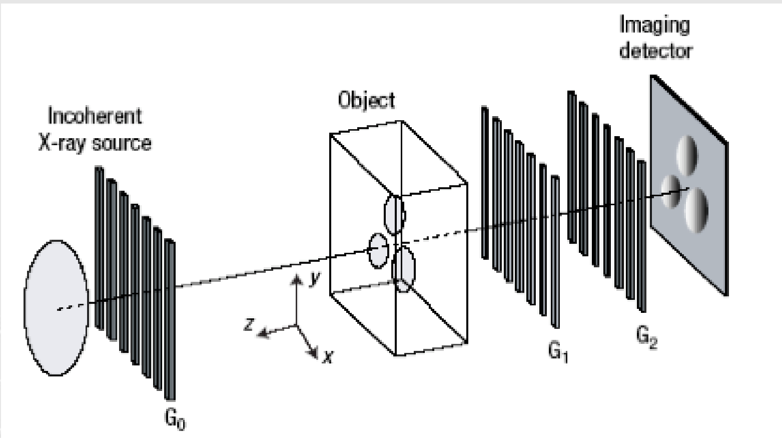
THE METHOD CAN BE ADAPTED TO A DIVERGENT AND POLYCHROMATIC (=conventional) SOURCE

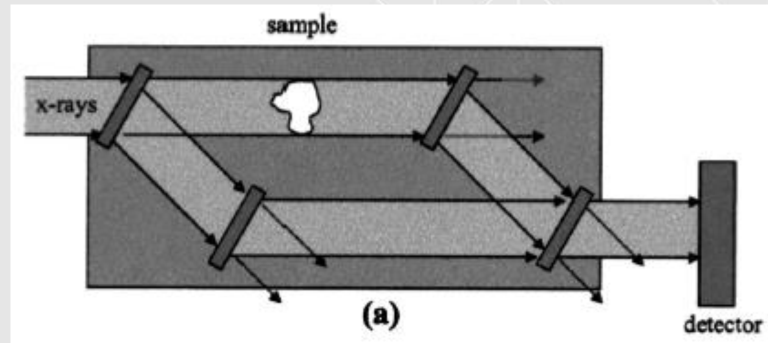


NB for those of you who are familiar with grating (or Talbot, or Talbot-Lau) interferometers **this isn't one!**

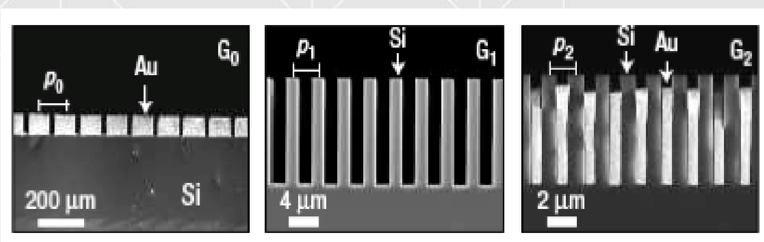
Olivo and Speller Appl. Phys. Lett. 91 (2007) 074106

Interlude: **the TALBOT/LAU interferometer:** much smaller pitches, and based on a coherent effect

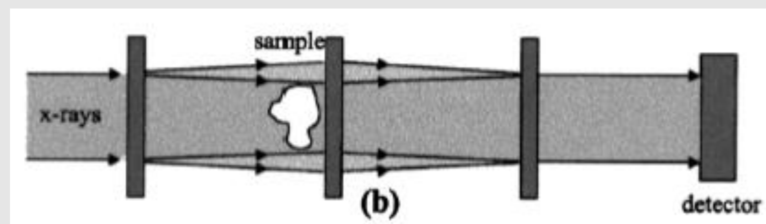




The classic, "Bonse-Hart" interferometer



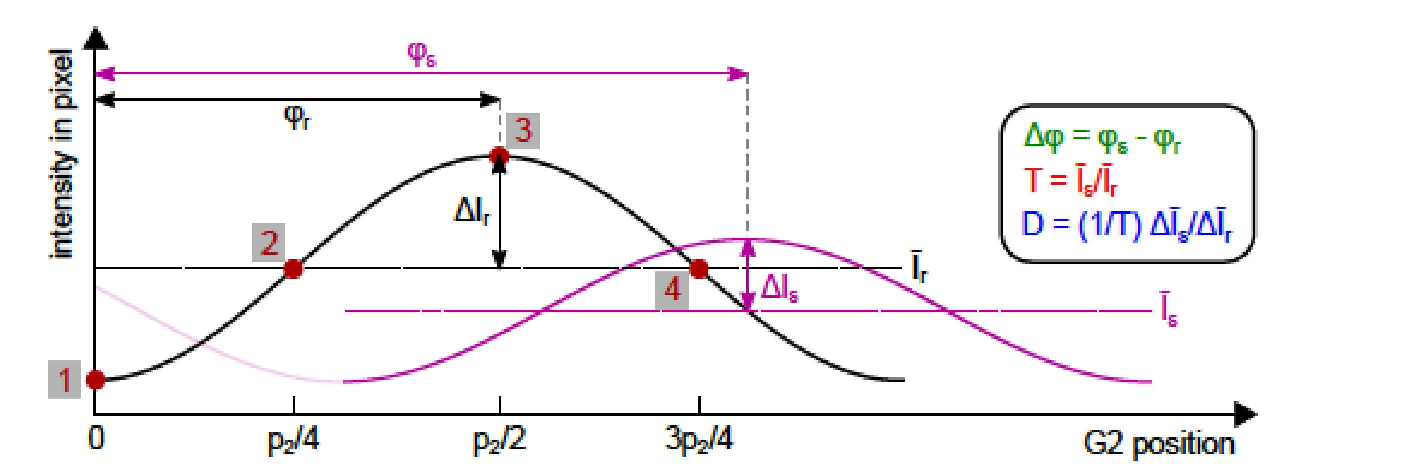
The used gratings, obtained through microfabrication techniques



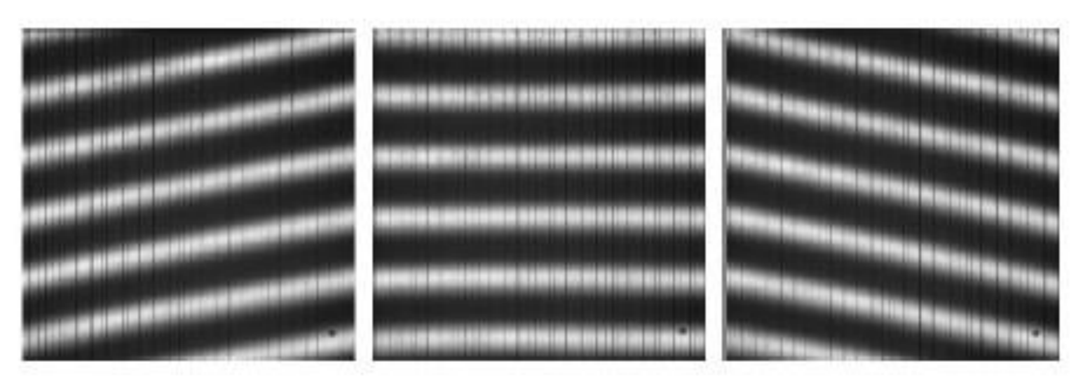
The shearing interferometer

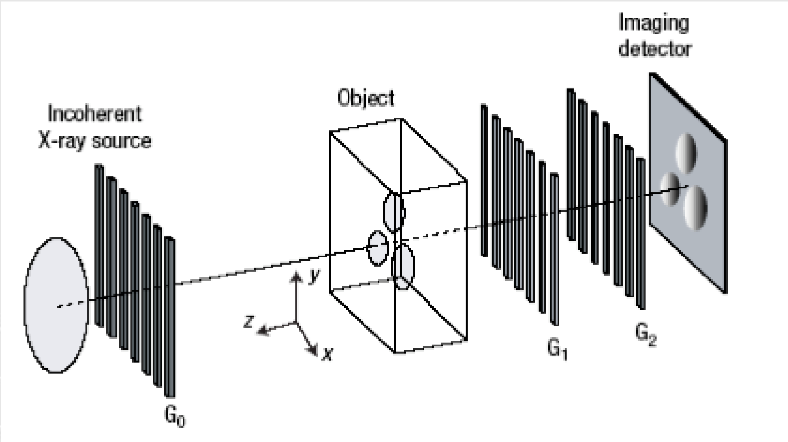
Synchrotron: David et al APL 81 (2002) 3287-9, Momose et al Jpn J Appl Phys 42 (2003) L866-8; Lab source Pfeiffer *et al*, Nature Physics **2** (2006) 258-61

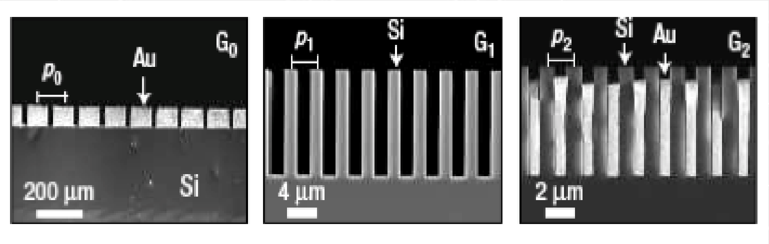
1. Phase stepping



2. Moirè fringes







The used gratings, obtained through microfabrication techniques

- increased exposure times (source grating covering most of the source, silicon substrates, limited angular acceptance)

- chromaticity (reduced fringe visibility away from design energy)

- the sensitivity to environmental vibrations (pitches of a few μm -> required tolerance pitch/10 (Weitkamp *et al*, 2005), plus phase stepping -> tens of nm (!) (Zambelli et al, 2010)

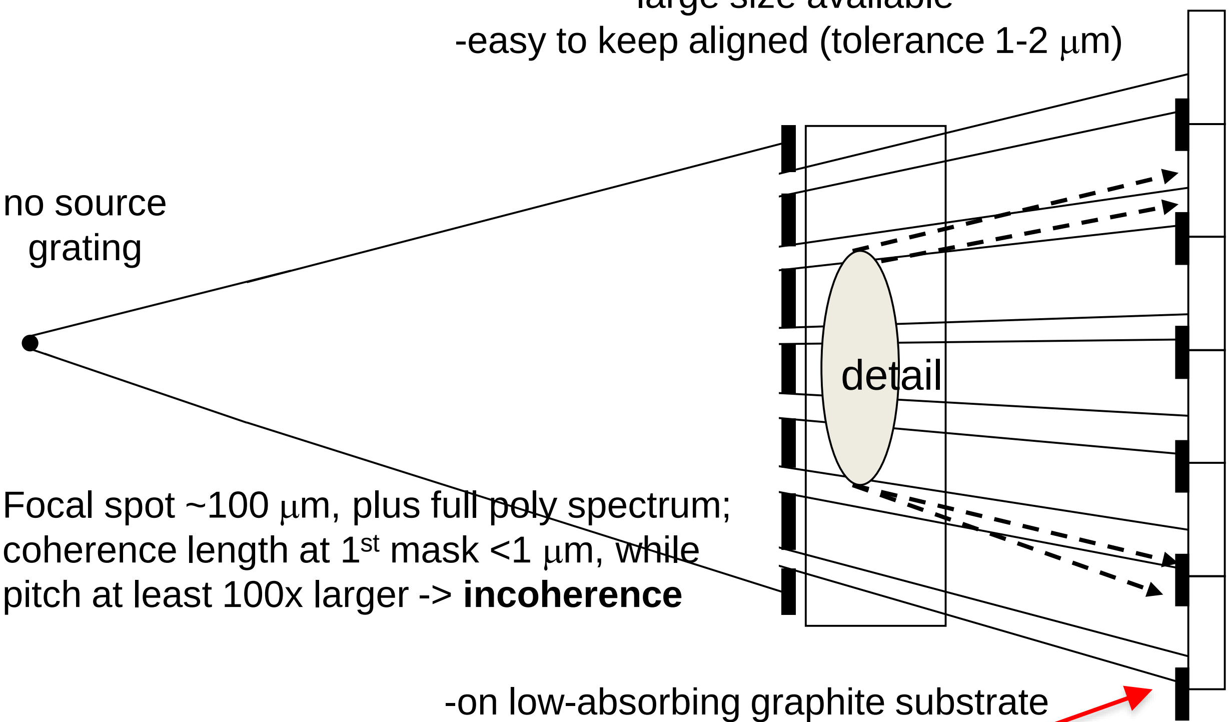
- inefficient dose delivery: detector grating ->50% fill-factor, + absorption in Si (40% through 1x300 µm wafer, 60% through 2 wafers, and normally wafers are THICKER)

- the field of view is currently limited to ~6x6 cm^2

THE METHOD CAN BE ADAPTED TO A DIVERGENT AND POLYCHROMATIC (=conventional) SOURCE

LARGE mask pitch (e.g. 50-200 μm)
-easy to fabricate
-large size available
-easy to keep aligned (tolerance 1-2 μm)

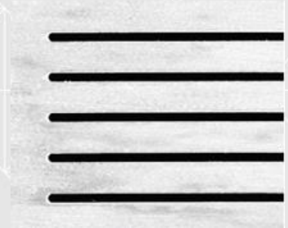
no source grating



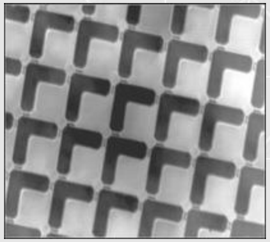
Focal spot ~100 μm, plus full poly spectrum; coherence length at 1st mask <1 μm, while pitch at least 100x larger -> **incoherence**

-on low-absorbing graphite substrate
-pre-sample, protects sample!
-only source of extra dose, can be kept to a small fraction!
(even zero – see Olivo *et al* Med Phys 40 (2013) 090701)

Masks can be:

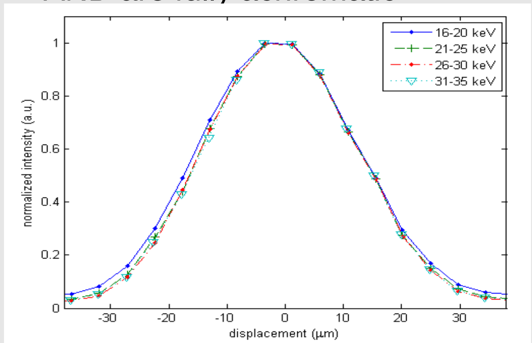


OR:



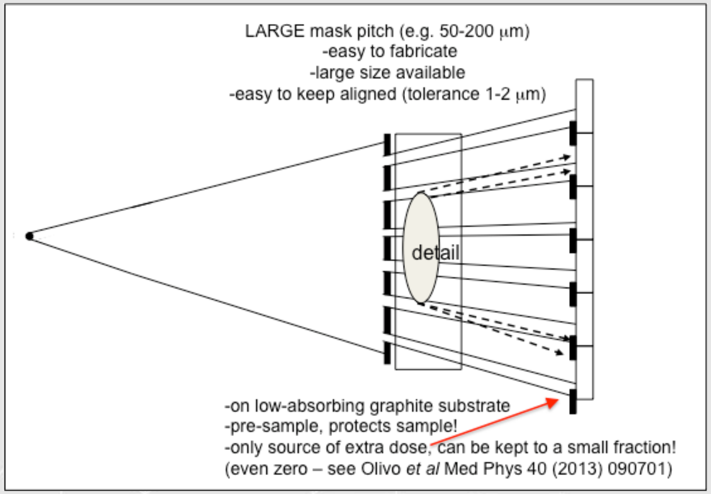
For 2D sensitivity (see Olivo *et al* APL **94** (2009) 044108)

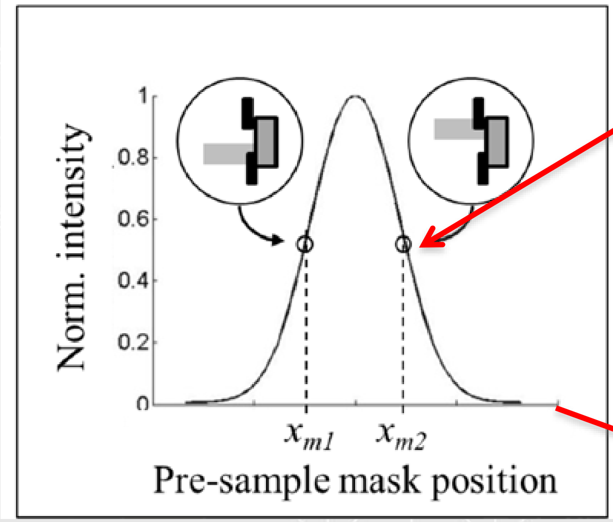
AND are fully achromatic



(Endrizzi *et al*, Opt Exp **23**, 2015)

Compared to grating interferometry, we use much larger periods, which has important consequences:





1) Beamlets do not overlap/interfere (NB they wouldn't anyway as beam not sufficiently coherent)
2) The mask period has **no influence whatsoever on the sensitivity** – only on the spatial resolution.
3) The sensitivity is an issue of the **individual beamlet**, in particularly of the slopes of its shape.

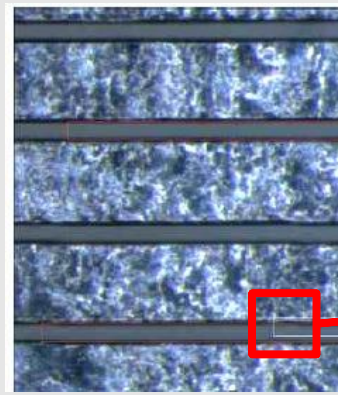
the aim of the mask is simply to repeat the EI condition multiple times in space

note also that typically we have extremely low "visibility"

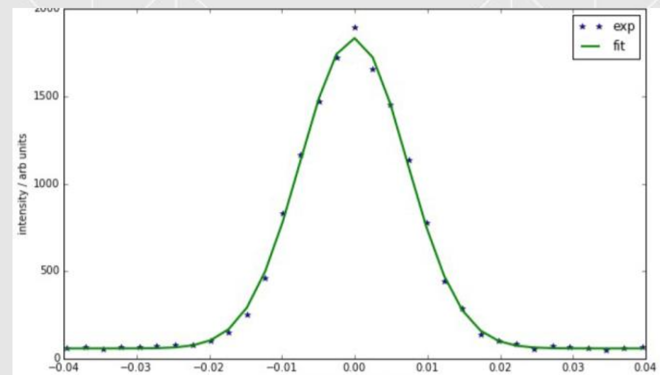
Olivo and Speller Phys. Med. Biol. 53 (2008) 6461-74; Diemoz *et al* Appl. Phys. Lett. 103 (2013) 244104

Other consequences of the “large” mask period:

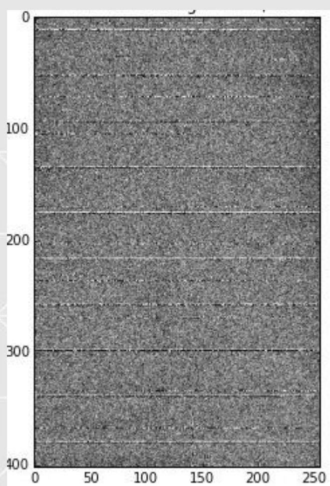
1) Large, substrate-less masks can be fabricated at very low cost by laser ablation on tungsten foil. Early tests show a) negligible offset and b) image quality comparable to that of masks obtained via lithography.



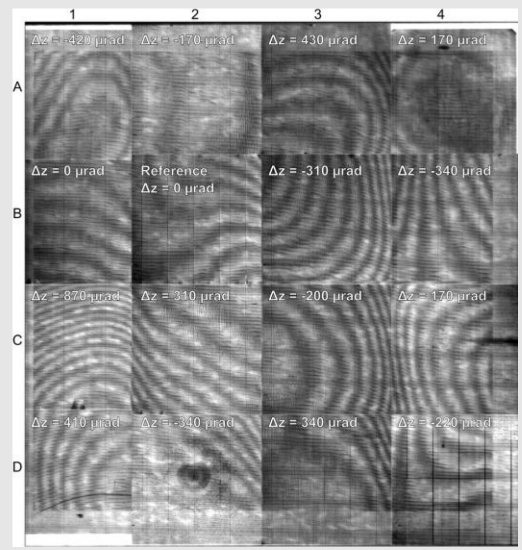
Courtesy K. Jefimovs & R. Brönnimann, EMPA



2) Whatever the fabrication method, flat fields are flat! This is what enables easy access to **single-shot** methods, as the same illumination level can be assumed throughout the field of view (more later).



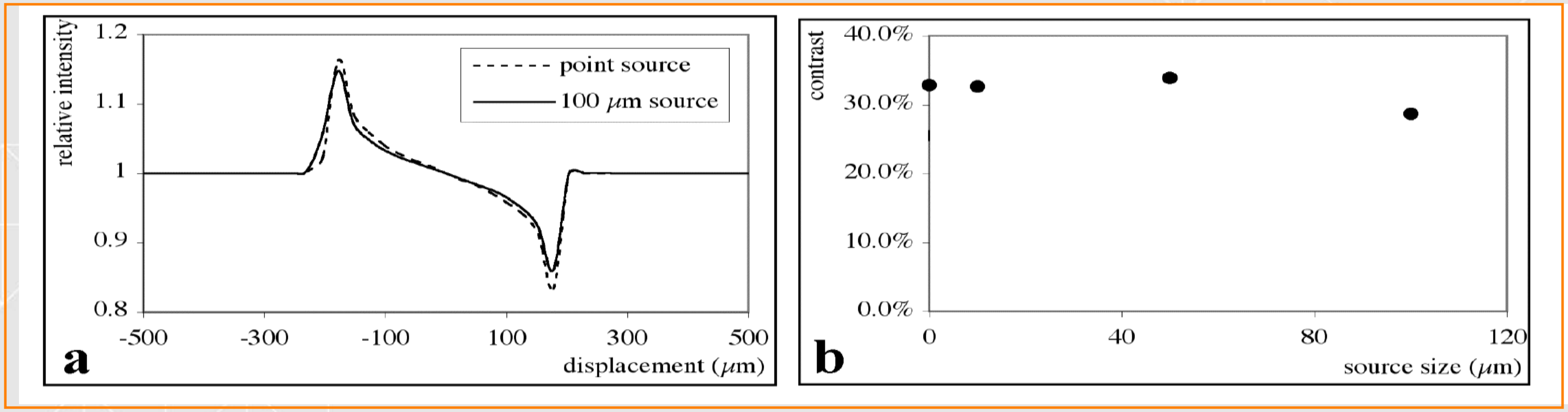
EI (non-tiled masks)



GI (tiled gratings)

Modregger *et al* Phys. Rev. Lett. 118 (2017) 265501; Schröter *et al* J. Phys. D: Appl. Phys. 50 (2017) 225401

Little loss of signal intensity for source sizes up to 100 µm



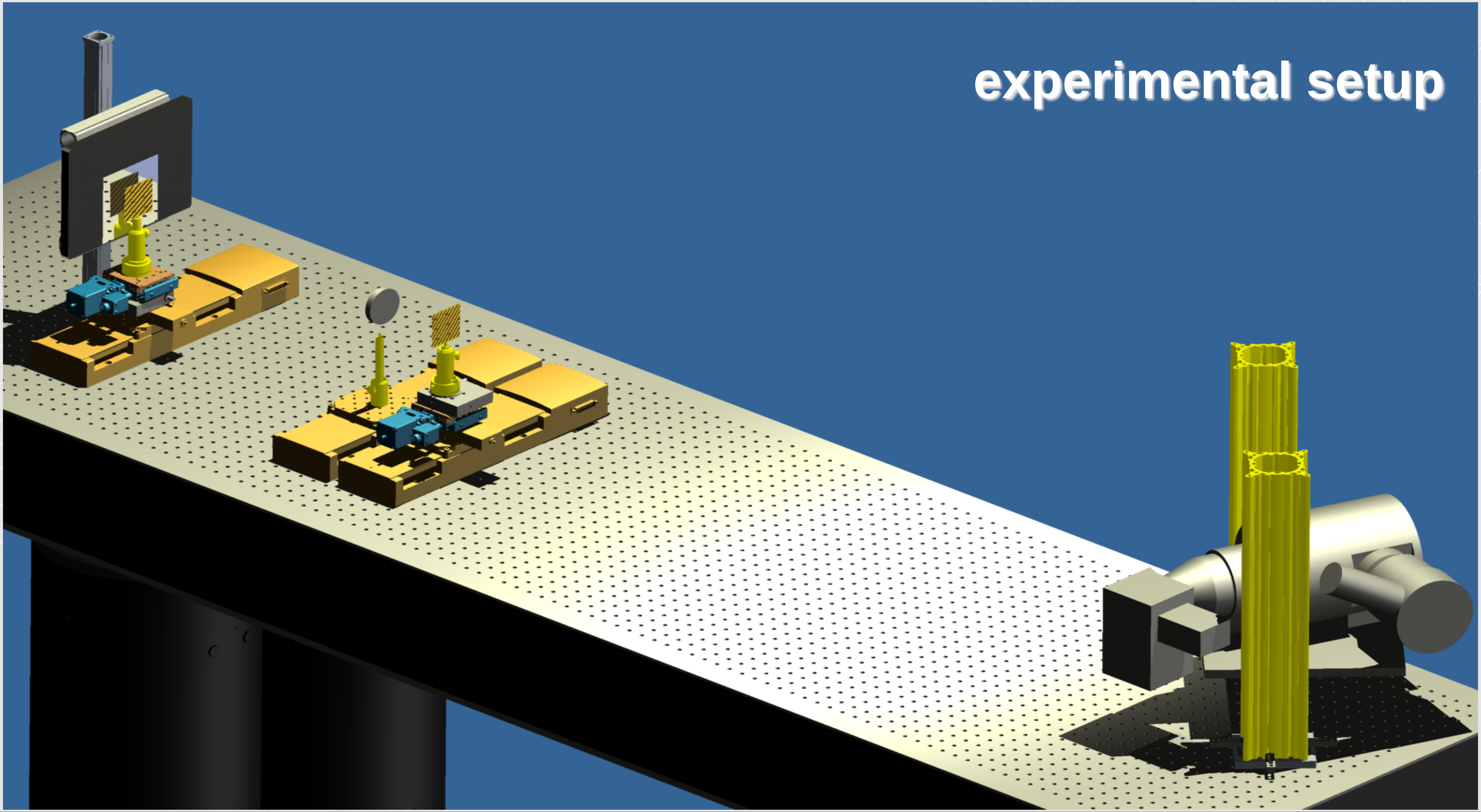
Which can be achieved with state-of-the-art mammo sources

Why?

1) Because we are only relying on refraction, which survives under relaxed coherence conditions;
2) Because we are use aperture pitches matching the pixel size, i.e. BIG: the projected source size remains < pitch, and therefore blurring does “not” occur.

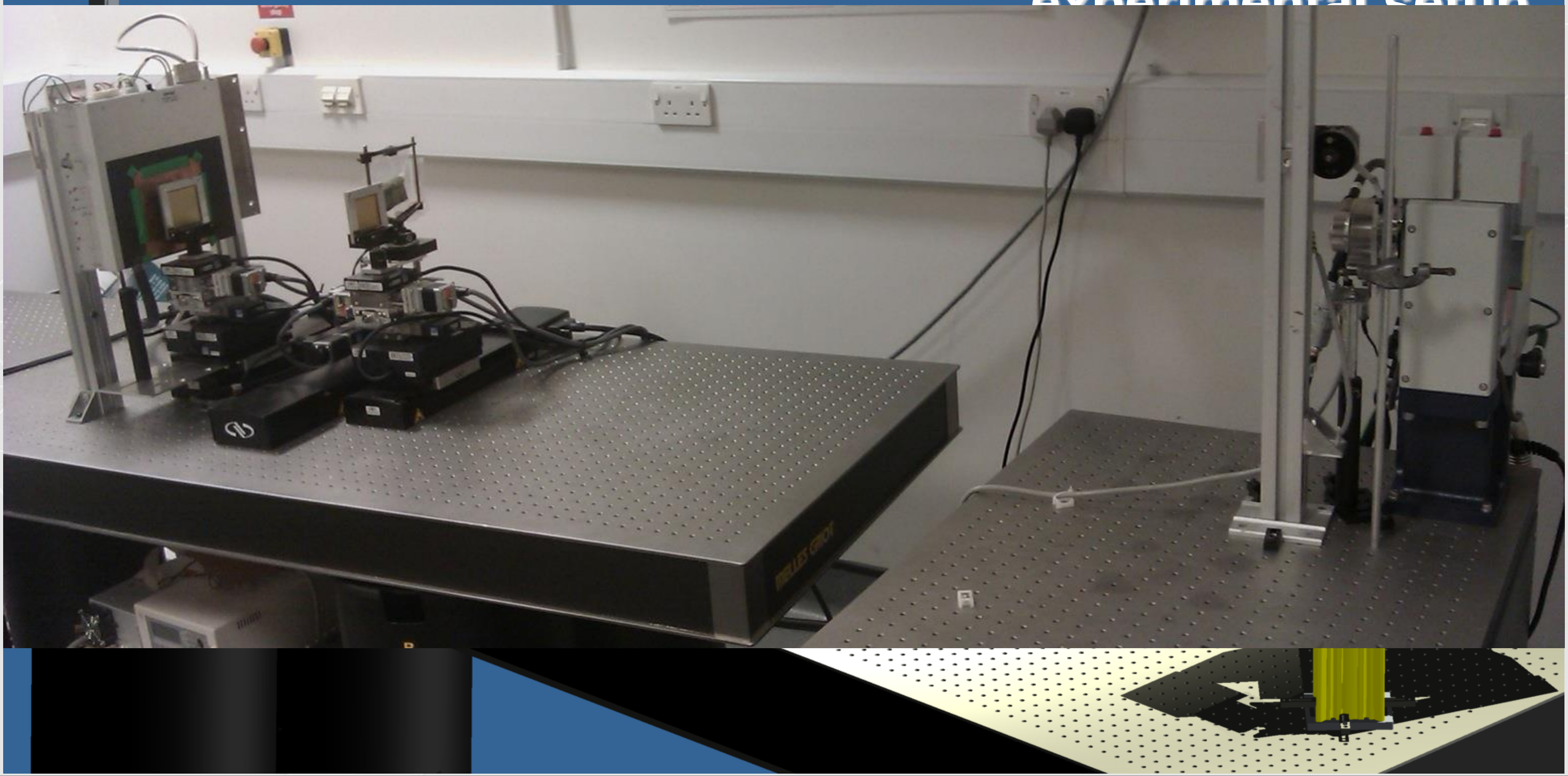
Olivo and Speller Phys. Med. Biol. 52 (2007) 6555-73

experimental setup

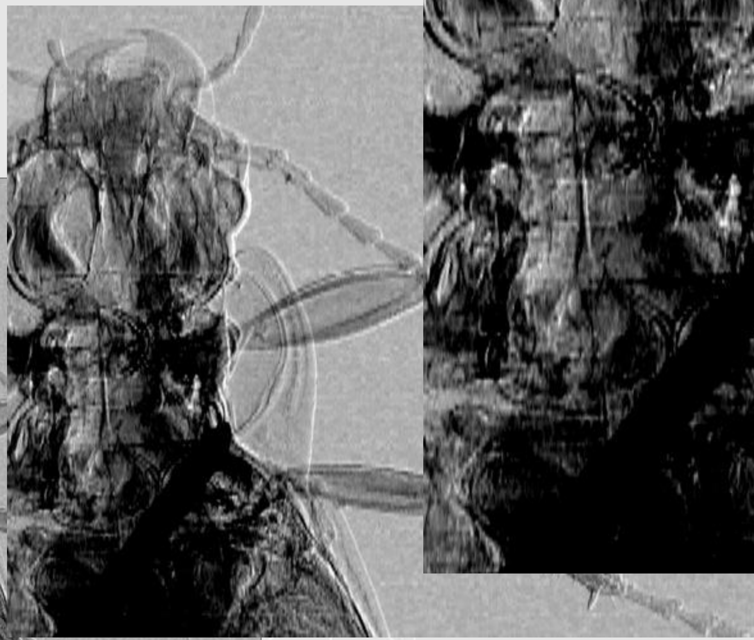


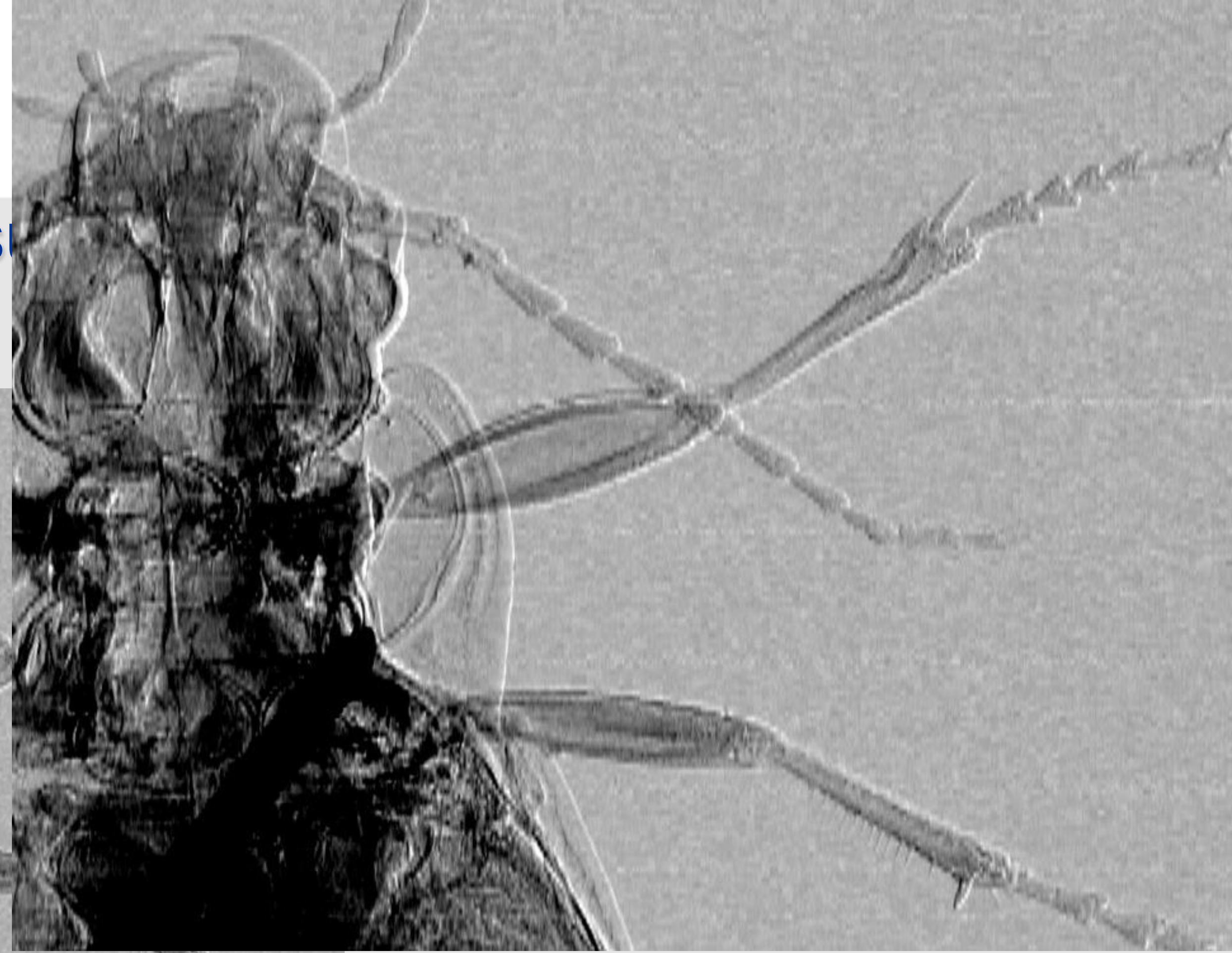
UCL

experimental setup

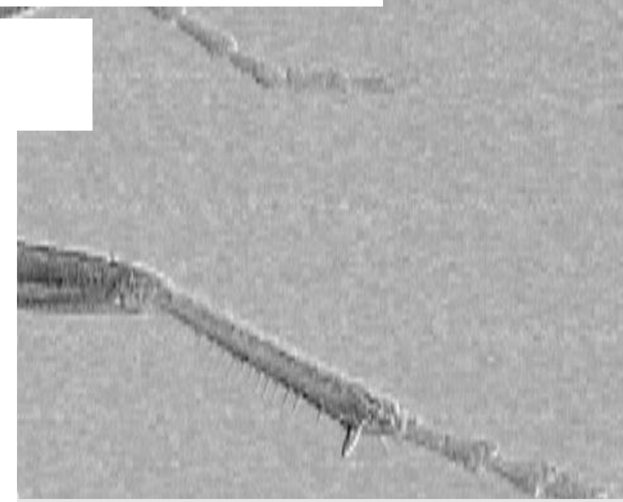


Preliminary results: the “us





Prelimir



RESEARCH HIGHLIGHTS

Selections from the scientific literature

APPLIED PHYSICS

Better X-ray vision

A new technique allows fainter features to be imaged by X-rays.

Conventional X-ray imaging relies on the absorption and scattering of X-ray photons by the object being imaged. But X-ray phase-contrast imaging instead detects changes in the photons' direction and velocity.

A. OLIVO ET AL.

Alessandro Olivo and his colleagues at University College London used a conventional X-ray source outfitted with grated masks — one in front of the object for imaging and one behind it. The masks were offset slightly from one another so that they filtered out some of the photons, reducing background noise. The detector measures by how much photons have deviated from their path, capturing different image data from conventional X-ray imaging and boosting the visibility of fine detail.

The team used its technique to image biological specimens such as a beetle (pictured), as well as samples of interest for medical imaging, materials science and security inspection.

Appl. Optics 50, 1765–1769 (2011)

© 2011 Macmillan Publishers

Nature 472 (2011) p. 392

ADVANCES

PHYSICS

Can You See Me Now?

A new x-ray technique may herald improved baggage screening and mammograms

X-rays can help reveal anything from bombs hidden in luggage to tumors in breasts, but some potentially vital clues might be too faint to capture with conventional methods. Now a new x-ray technique adapted from atom smashers could resolve more key details.

Conventional x-ray imaging works much like traditional photography, relying on the light—in this case, x-rays—that a target absorbs, transmits and scatters. To make out fine details, one typically needs a lot of x-rays, either over time, which can expose targets to damaging levels of radiation, or all at once from powerful sources such as circular particle accelerators, or synchrotrons, which are expensive.

Instead physicist Alessandro Olivo of University College London and his colleagues suggest imaging an object by looking for very small deviations in an x-ray's direction as it moves through that object. Their idea is to take such x-ray phase-contrast imaging, which has been used in synchrotrons for more than 15 years, and use it with conventional x-rays.

The scientists rig conventional x-ray sources with gold grates that are 100 microns or so thick—one in front of a target and one behind it. The holes on one grate do not line up exactly with the holes on the other, meaning x-rays that passed in straight lines through the first grate would get filtered out by the second, lowering background noise. The detector then analyzes only the photons that deviated in direction as they passed through the object. This can lead to at least 10 times greater contrast than conventional imaging—"all details are more clearly visible, and details classically considered very hard to detect become detectable," Olivo says of findings reported recently in *Applied Optics*. Whereas bombs are usually visible in conventional x-ray imaging, they can be confused with other materials such as plastics or liquids. The scientists are now pushing imaging sensitivity even further with new grating designs and are working on 3-D scanning techniques by coming at the target from multiple angles.

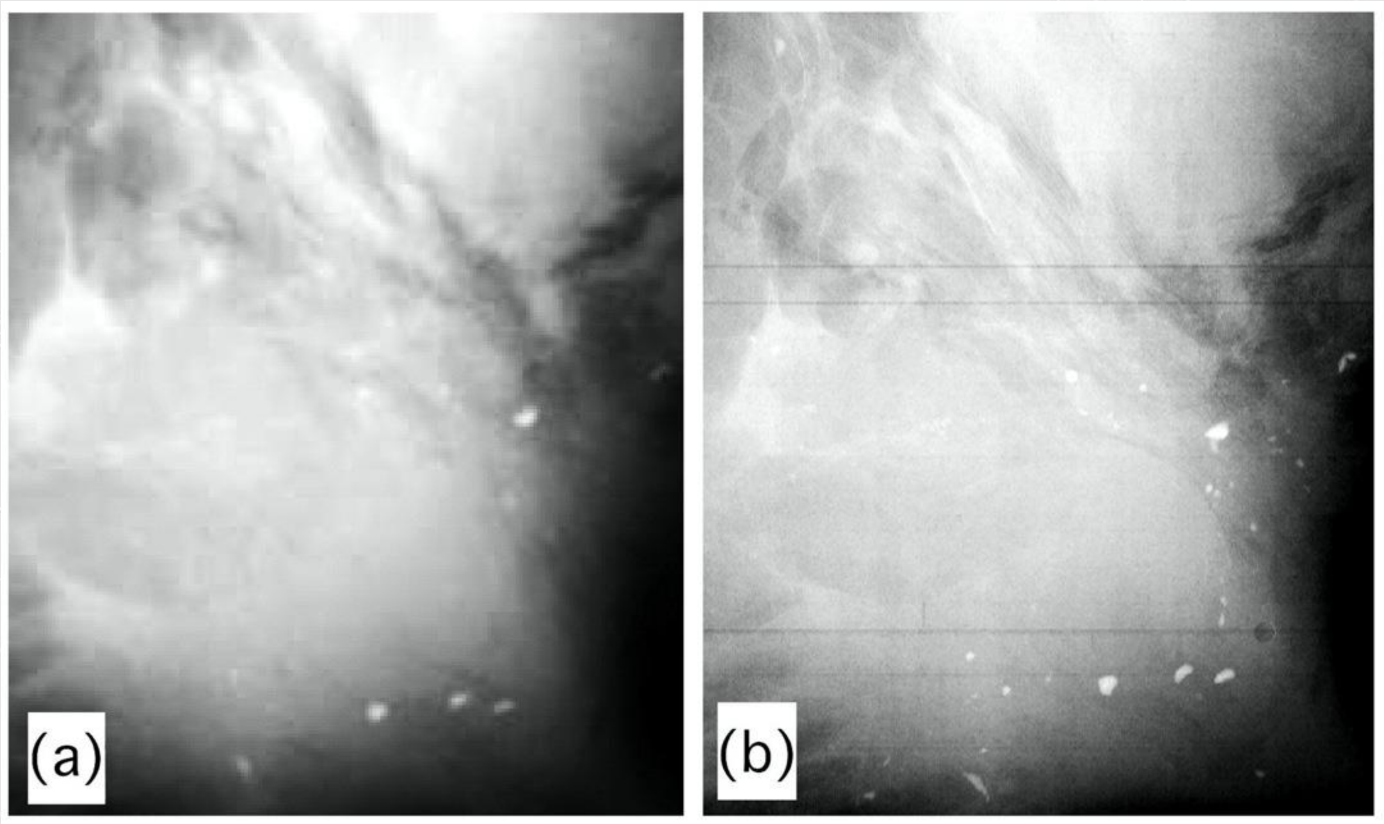
This system can generate images in just seconds, far quicker than other x-ray phase-contrast techniques, which cannot exert as much power during scanning and thus require minutes, says radiation physicist David Bradley of the University of Surrey in England, who did not take part in this study. But it remains unclear if this system could work fast enough for security scanning, says materials scientist Philip Withers of the University of Manchester in England. Withers does think the technology could lead to better medical imaging, as well as improvements in detecting defects in materials used in aerospace work.

—Charles Q. Choi

Olivo's x-ray of a chive plant

UCL ENGINEERING
Change the world

Preliminary results - mammo



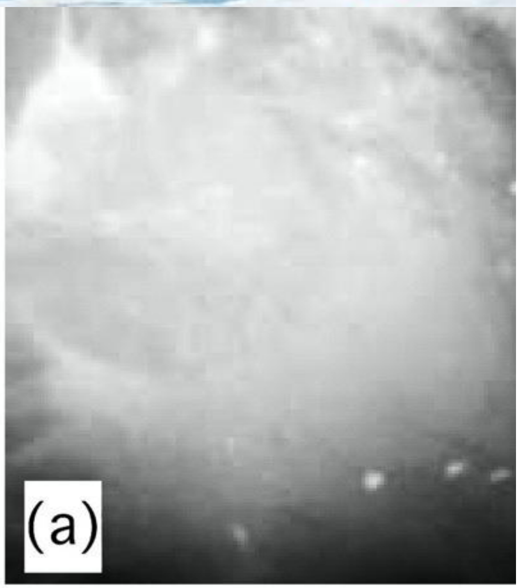
(a): GE senographe Essential ADS 54.11; 25 kVp, 26 mAs

(b): coded-aperture XPCi, 40 kVp, 25 mA – **ENTRANCE** dose 7 mGy (< mammo!)

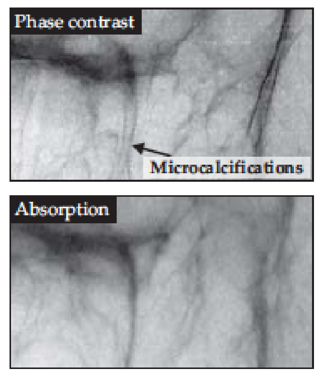
It has to be said the tissue was 2.5 cm thick -> we expect ~ same dose for thicker tissues

Olivo et al Med. Phys. (letters) 40 (2013) 090701

www.physicstoday.org
physics today
A publication of the American Institute of Physics
October 2013
volume 66, number 10



Low-dose phase-contrast mammography. Small, treatable tumors are difficult to spot in mammograms because healthy and cancerous tissues differ little in how they absorb x rays. But absorption isn't the only source of contrast. As x rays pass through an inhomogeneous medium, they can acquire differences in phase—even if the medium is a uniform absorber. Early attempts at phase-contrast imaging required a synchrotron or other bright, coherent source of x rays. Now Alessandro Olivo of University College London and his collaborators have built a prototype machine that performs phase-contrast mammography with a conventional x-ray tube at clinically acceptable doses. The setup works by masking the x-ray source with an array of hundreds of narrow, closely spaced holes. Each beam that emerges points at a single pixel of a flat-panel detector. The detector is also masked—such that half the x rays from each beam are prevented from reaching their designated pixel. When an object is placed between the source and the detector, the beams suffer either absorption or, thanks to a change in phase, refraction. Because of the setup's geometry and the small angles of refraction involved, some refracted photons will still reach their pixel, but others will miss and hit the mask. Enough photons are diverted to the mask that they boost the contrast of what would otherwise be a conventional absorption image. Olivo's team tested its setup on donated samples of cancerous breast tissue. Microcalcifications that presage cancer showed up more clearly in the phase-contrast image than in an absorption image.
(A. Olivo et al., *Med. Phys.* **40**, 090701, 2013.) —CD

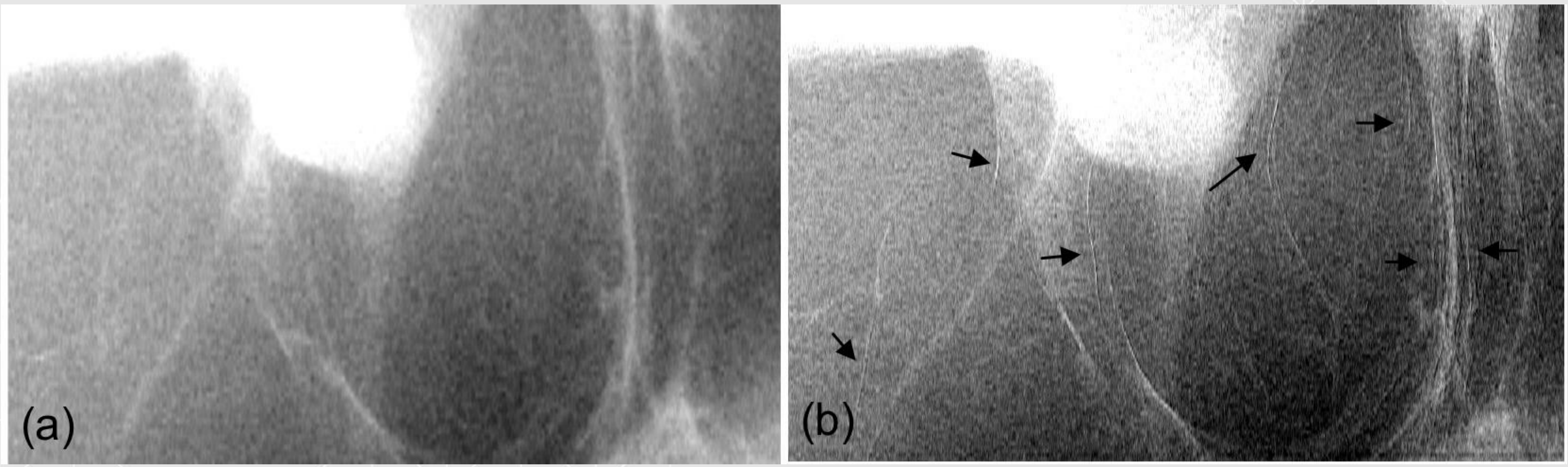


(a): GE senographe Essential AD
(b): coded-aperture XPCi, 40 kV < mammo!)

It has to be said the tissue was 2.5 cm th s

UCL ENGINEERING
Change the world

Low dose mammo – thin tumour strands

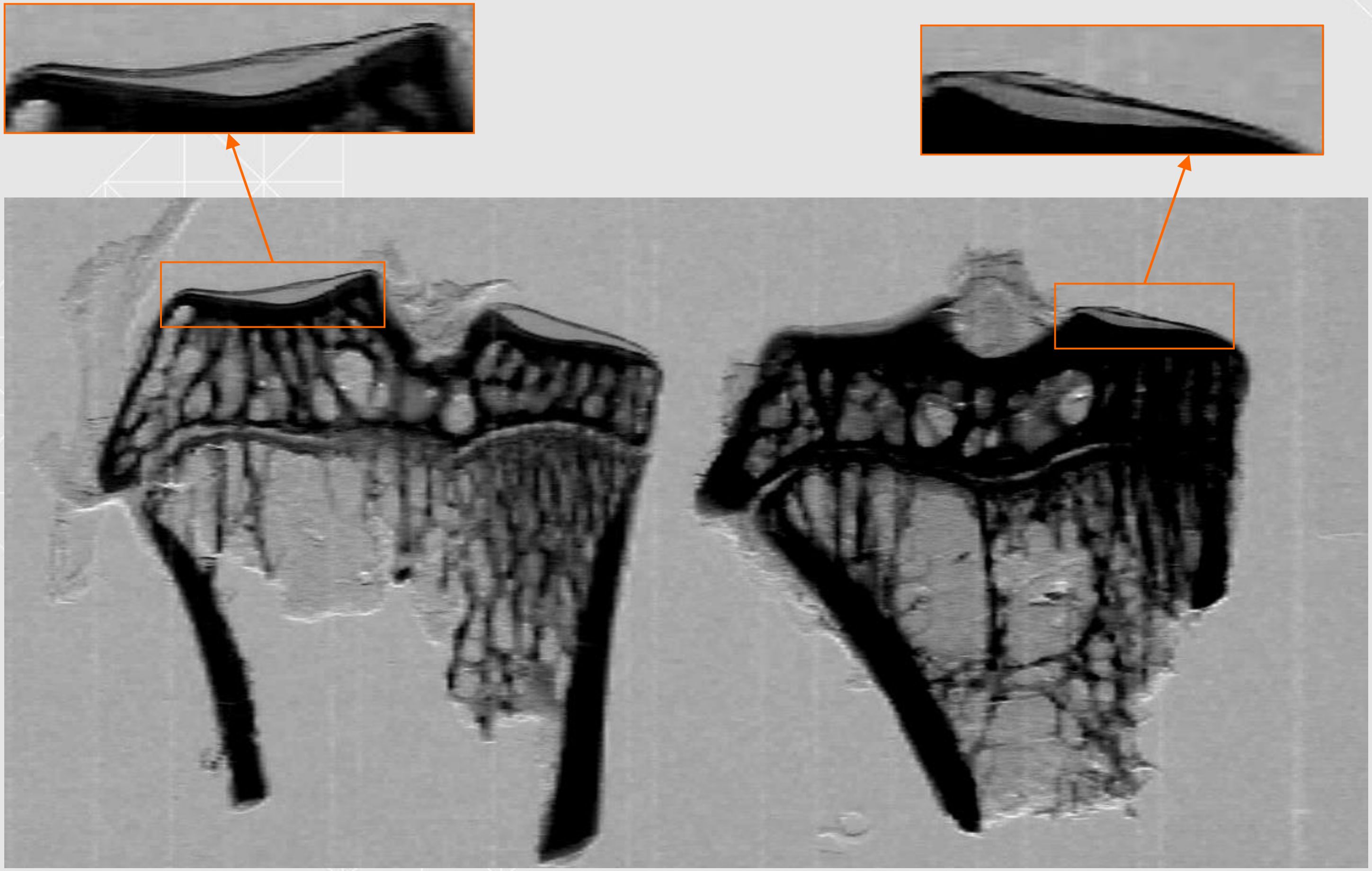


(a): GE senographe Essential ADS 54.11; 25 kVp, 26 mAs
(b): lab-based EI XPCi, 40 kVp, 25 mA – entrance dose 7 mGy
Tissue 2 cm thick

Unpublished – a similar result can be found in Olivo et al Med. Phys. (letters) 40 (2013) 090701

Preliminary results - cartilage imaging

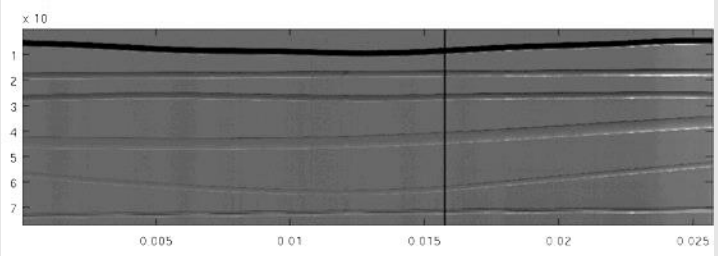
Rat cartilage, ~ 100 µm thick, invisible to conventional x-rays

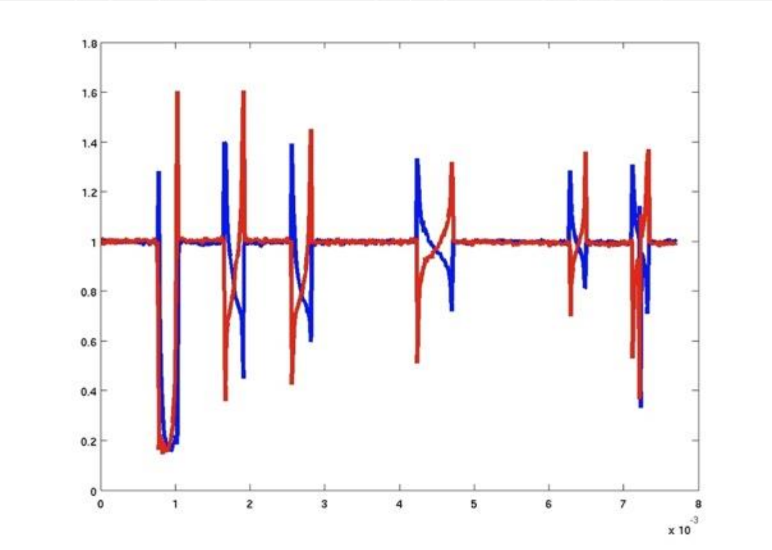


Marenzana *et al*, Phys. Med. Biol. 57 (2012) 8173-84

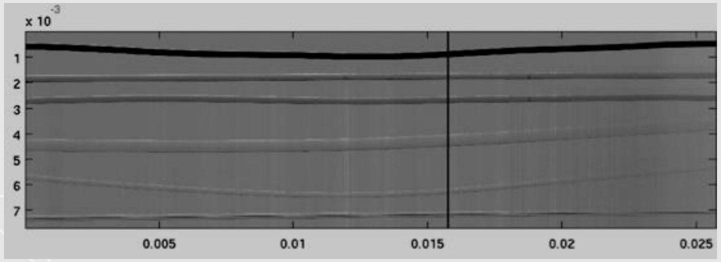
Quantitative phase contrast imaging

"SLOPE -"

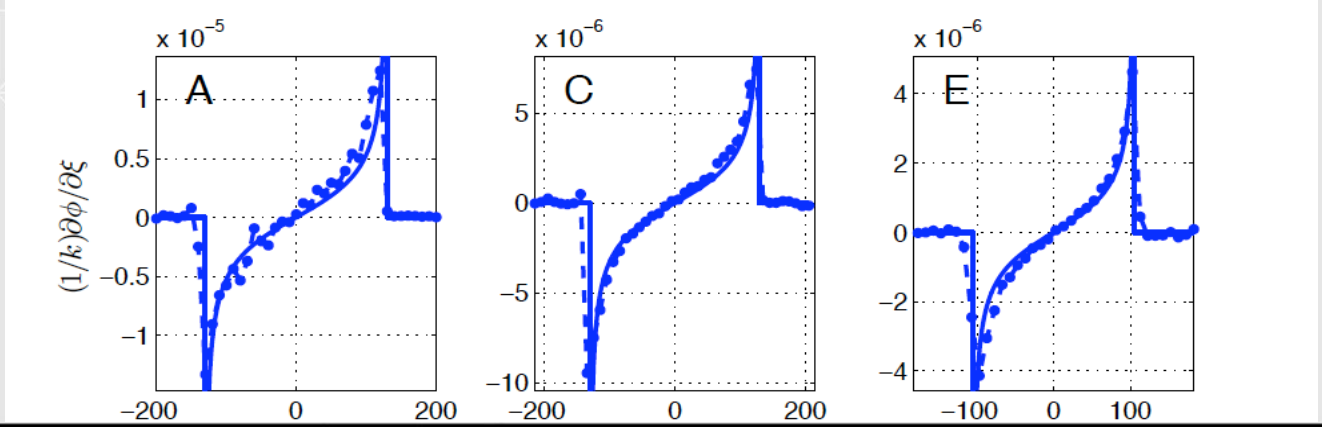




"SLOPE +"



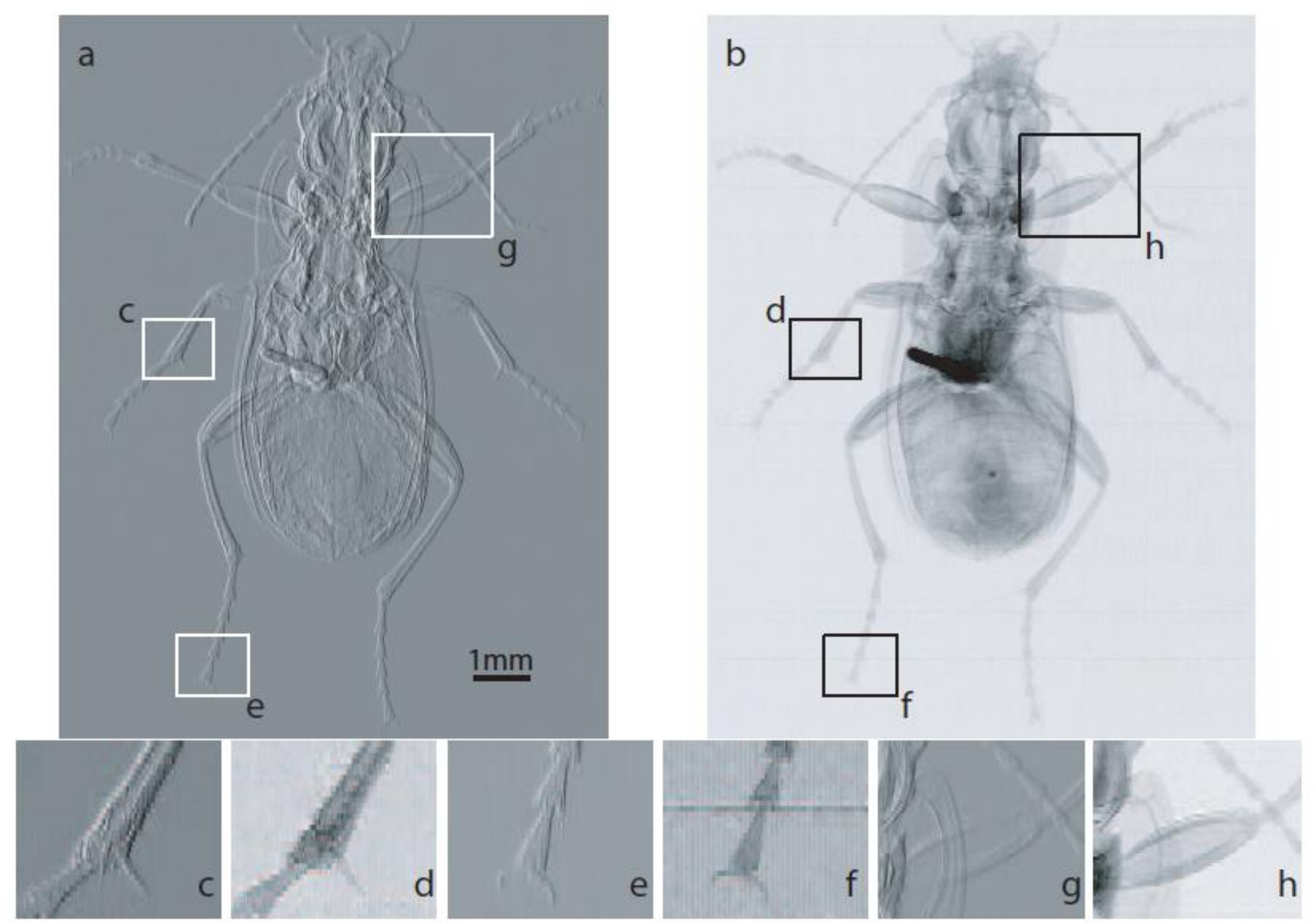
Titanium Aluminum PEEK



Highly precise retrieval, for both high and low Z materials, up to high gradients where other methods break down

Munro *et al* Opt. Exp. 21 (2013) 647-61

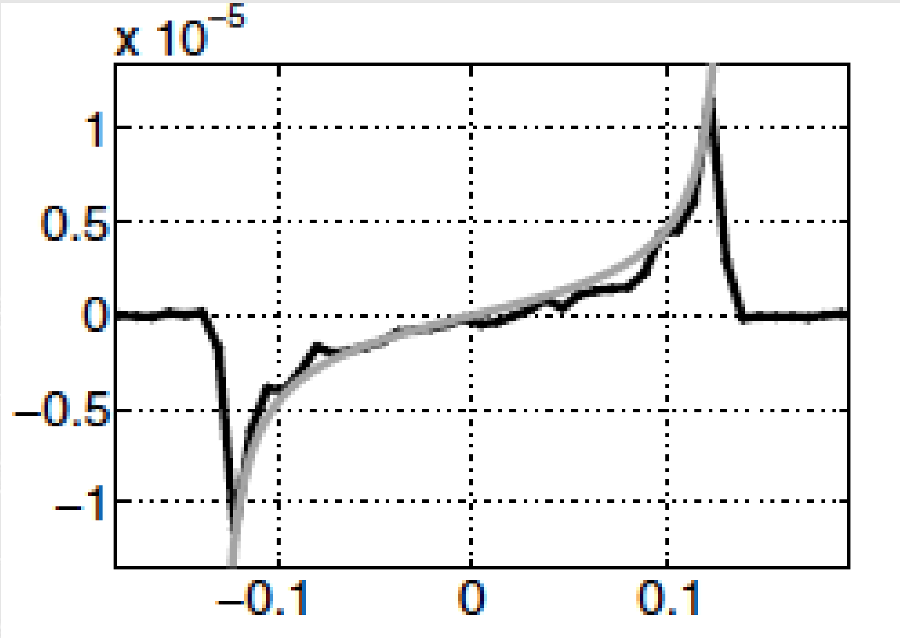
Quantitative phase contrast imaging



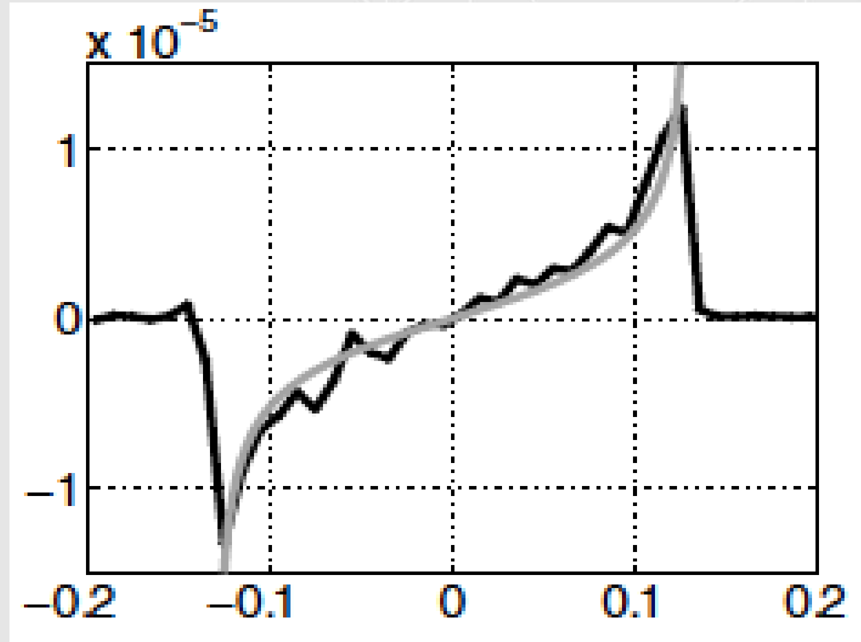
P. Munro *et al*, *PNAS* 109 (2012) 13922-7

Phase retrieval with synchrotron and conventional sources:

Ti filament: retrieved @ synchrotron



and with conventional source!



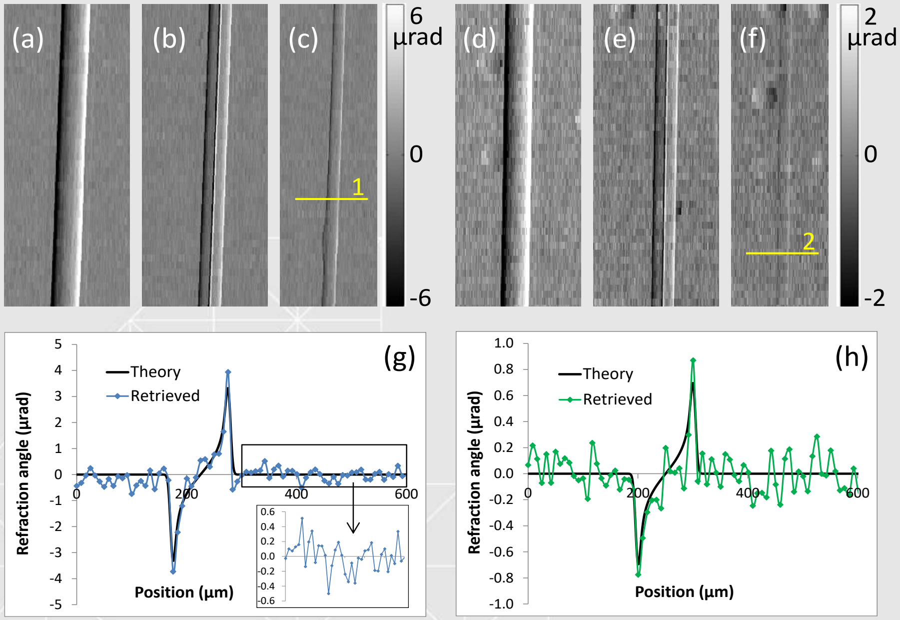
@ conventional source: incoherence modelled as beam spreading – the movement of the "spread" beam is then tracked and referred back to the phase shift that caused it.

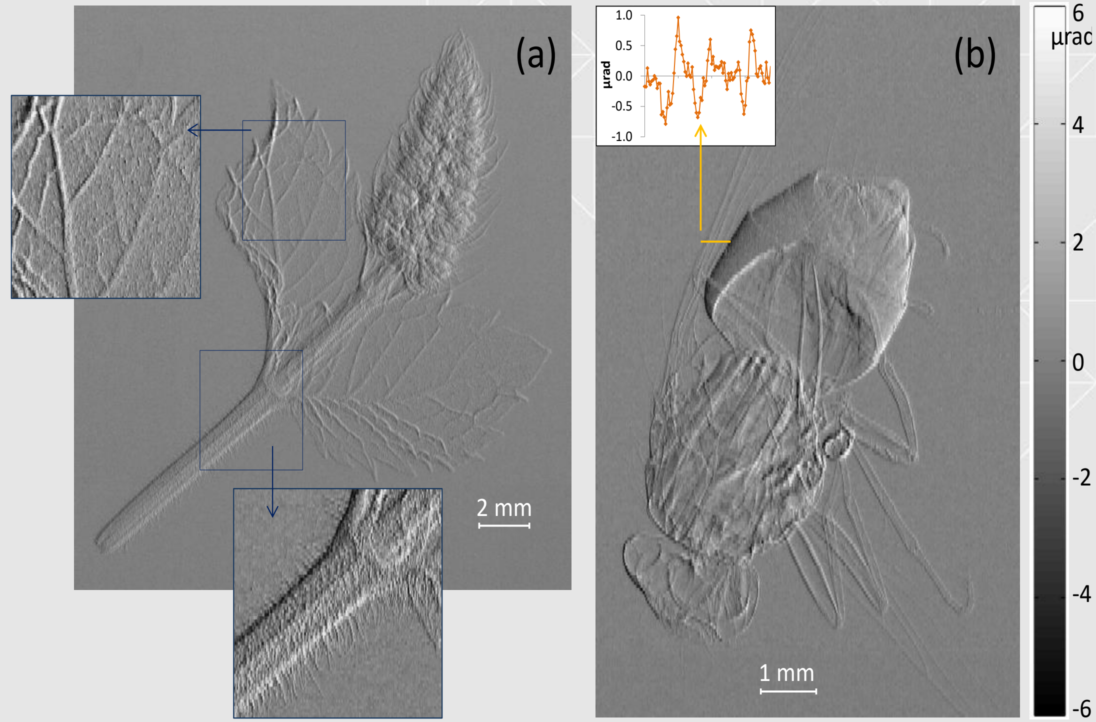
But with lots of care as far as "effective energy" is concerned!

(See Munro & Olivo Phys. Rev. A **87** (2013) 053838)

Munro *et al*, *PNAS* 109 (2012) 13922-7

More on the sensitivity of the lab system:





$$\Delta\theta_{x,eff} = \frac{1}{z_{od}} R^{-1}\left(\frac{I_{obj,+}}{I_{obj,-}}\right)$$

$$\sigma\left(\Delta\theta_{x,eff}\right); \quad \frac{\sqrt{C\left(x_{e,+}\right)}}{z_{od}\sqrt{2TI_0}\left[\rho_{ref,n}\left(x_{e,+}\right) - \rho_{ref,n}\left(x_{e,+}+d\right)\right]}$$

This gives a phase sensitivity of ~ 270 nRad, with only 2 images x 7s exposure each; same as reported by Thuring (Stampanoni’s group) for GI. Revol reported a sensitivity of about 110 nRad but with 12 x 7s frames – as one can expect the value to scale with sqrt(exp time), that also fits.

Diemoz *et al*, Appl. Phys. Lett. 103 (2013) 244104

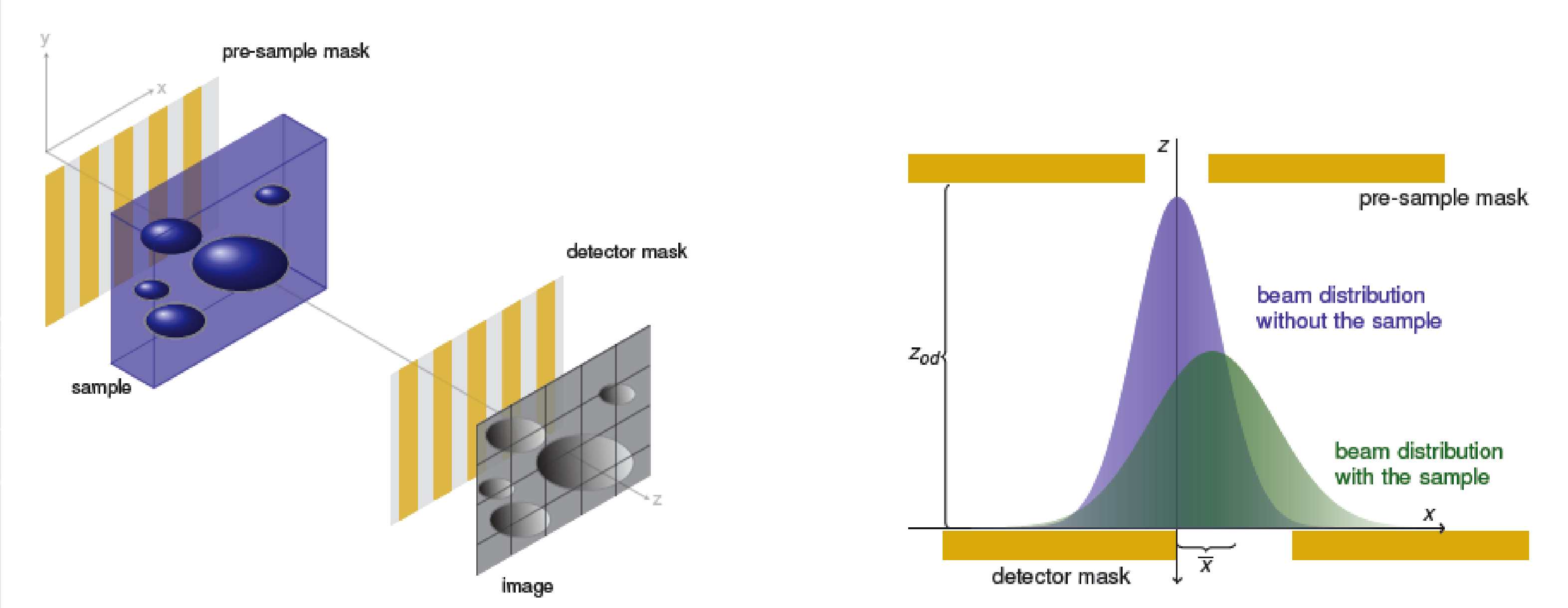
Following Munro's PNAS paper, other retrieval methods were developed:

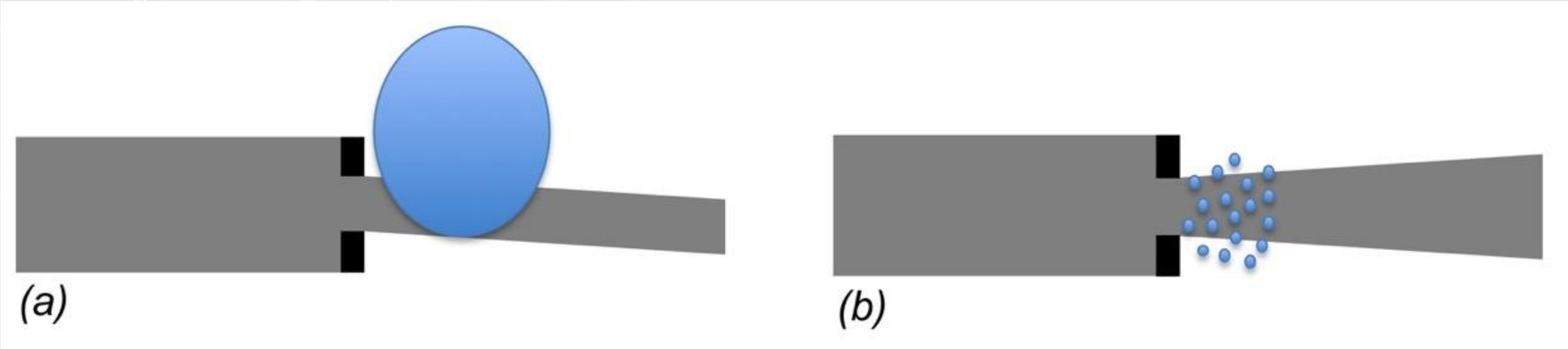
1) Inversion of the illumination curve (Munro et al Opt. Exp. **21** (2013) 11187; Diemoz et al Phys. Rev. Lett. **110** (2013) 138105): does not impose restricting conditions, simpler, requires experimental measurement of IC.

1) "Reverse Projections" (Hagen et al J. Phys. D: Appl. Phys. **49** (2016) 255501): CT only, exploits symmetry between projections acquired at angles θ and θ+180º – inspired by work from Zhang and Zhu.

1) "Single Shot" (Diemoz et al J. Synchrotron Rad. **22** (2015) 1072): an adaptation to EI of Paganin's approch, requires simplifications but works reliably in many cases, recently adapted to lab setup allows ultra-fast phase CT acquisitions (minutes; Diemoz *et al* Phys. Rev. Appl. **7** (2017) 044029).

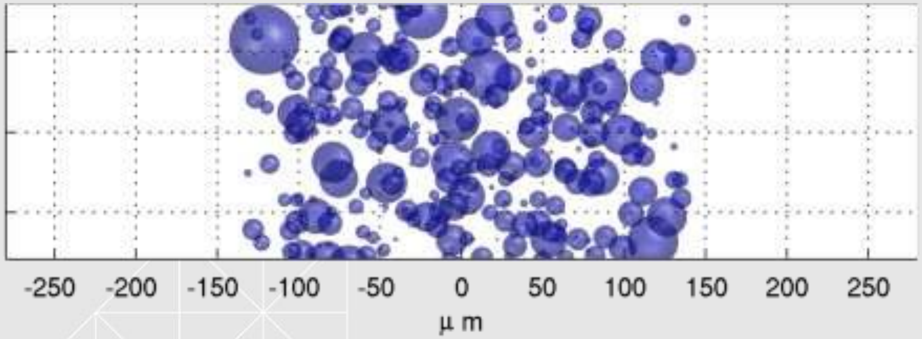
Three-shot DARK FIELD IMAGING retrieval

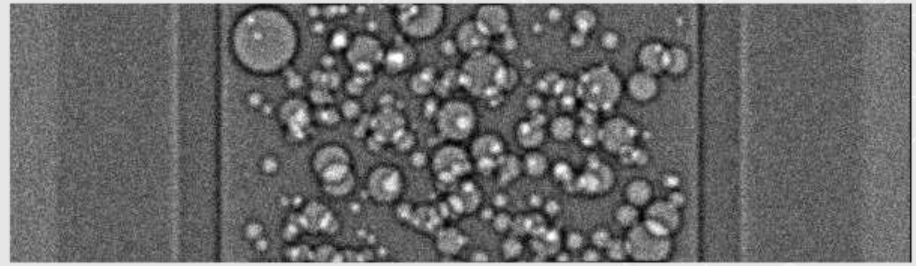




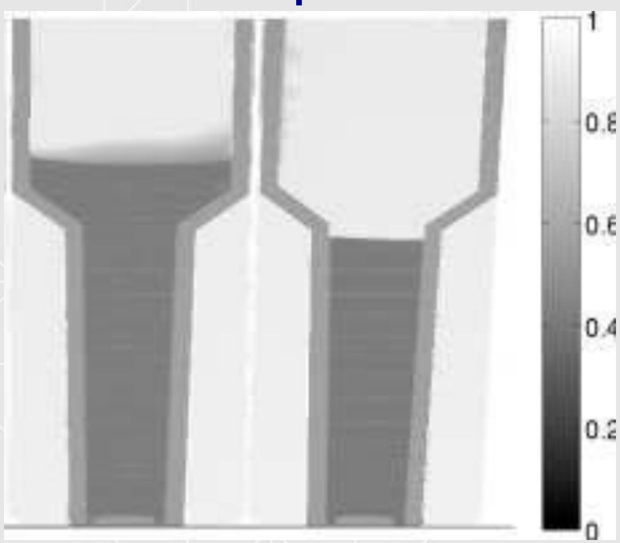
Endrizzi *et al*, Appl. Phys. Lett. 104 (2014) 024106

Microbubbles:
a new concept of “phase-based” x-ray contrast agent



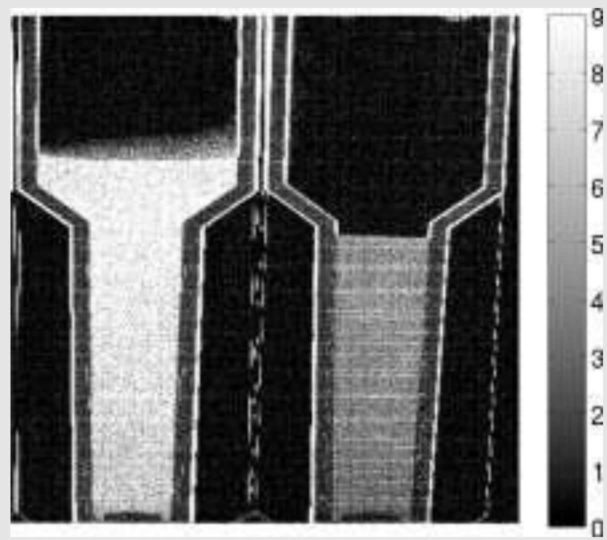


absorption



bubbles no bubbles

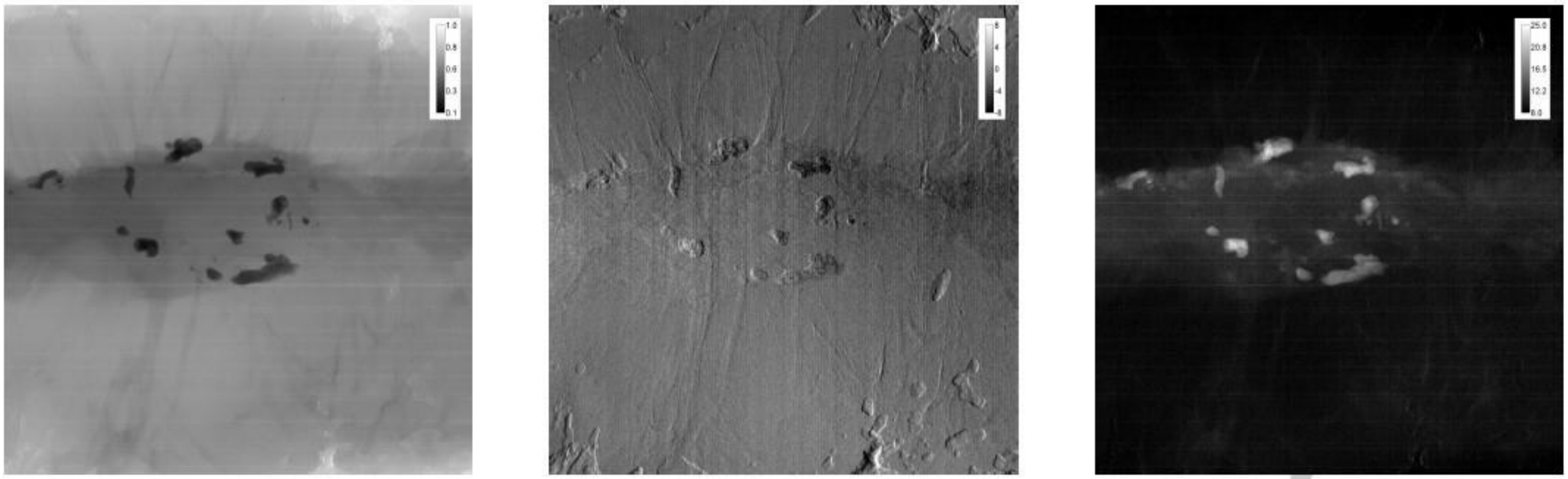
dark field



bubbles no bubbles

Millard et al. Appl. Phys. Lett. 103 (2013) 114105

DARK FIELD IMAGING of breast calcifications
3 images only, still within clinical dose limits!



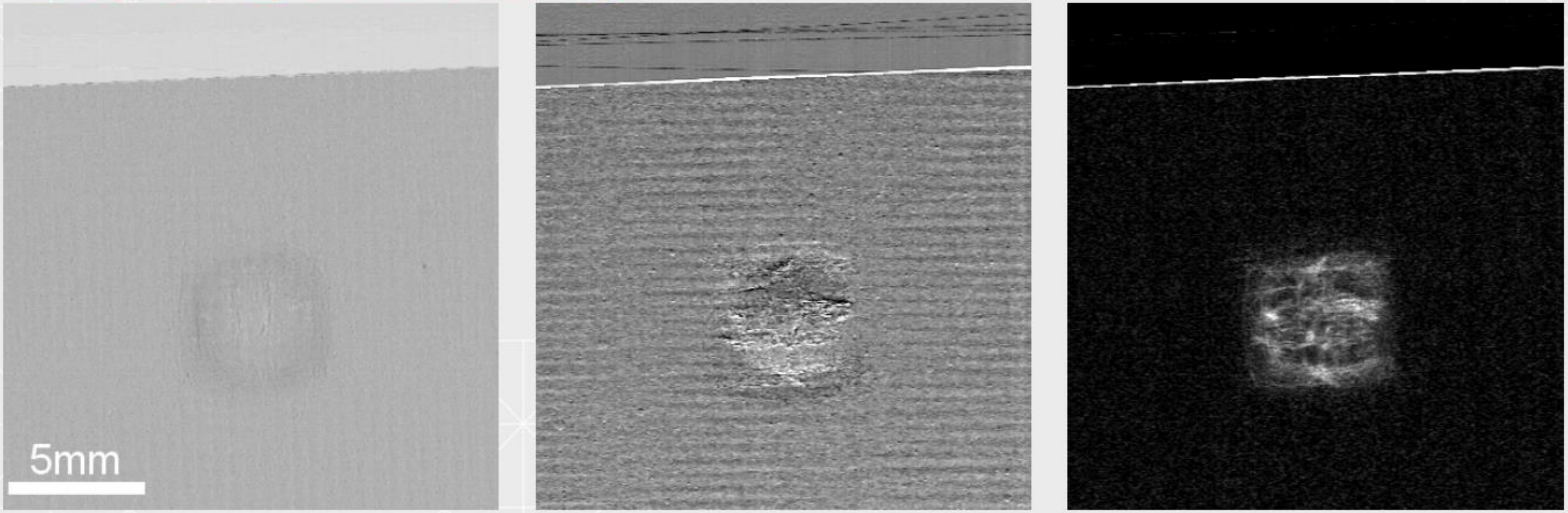
(a) transmission (relative intensity) (b) refraction (μrad) (c) scatter (μrad)

ENTRANCE dose 12 mGy (still compatible with mammo)

Endrizzi *et al*, Appl. Phys. Lett. 104 (2014) 024106

Non-medical applications: testing of composite materials/2

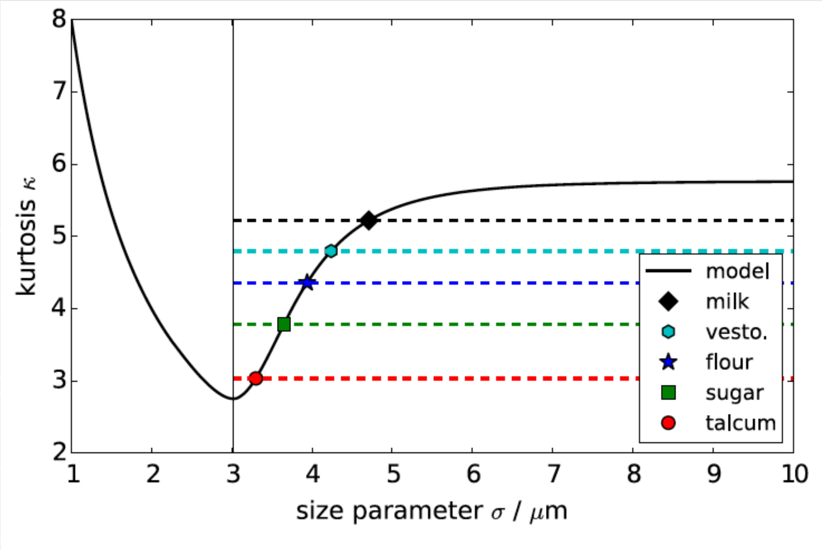
what's the shape of the damage?



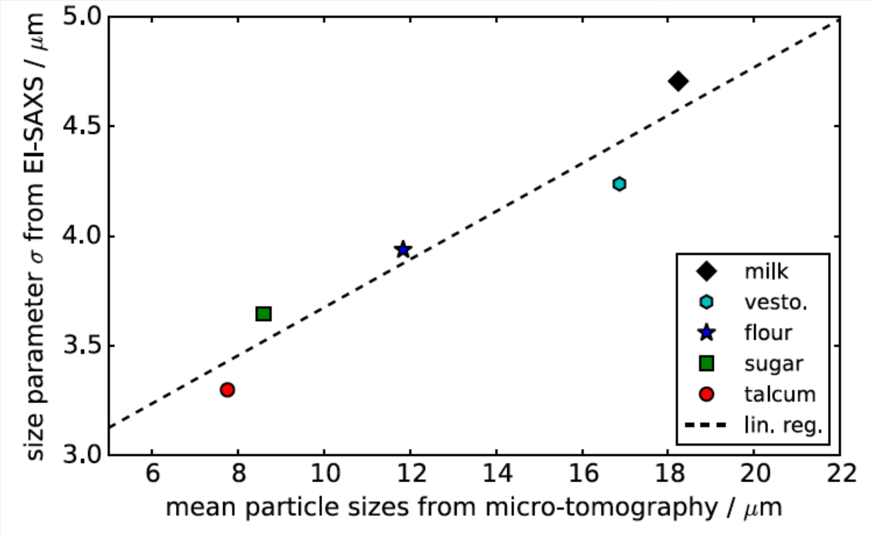
Unpublished – courtesy of M. Endrizzi

It can be made quantitative:

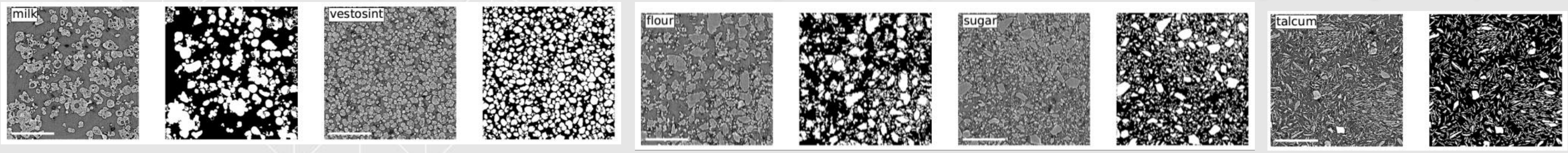
Theoretical curve fits experimental data; inversion point depends on aperture size -> can be selected in advance



The experimentally validated model can be used to calibrate the system and extract size parameter directly from USAXS data

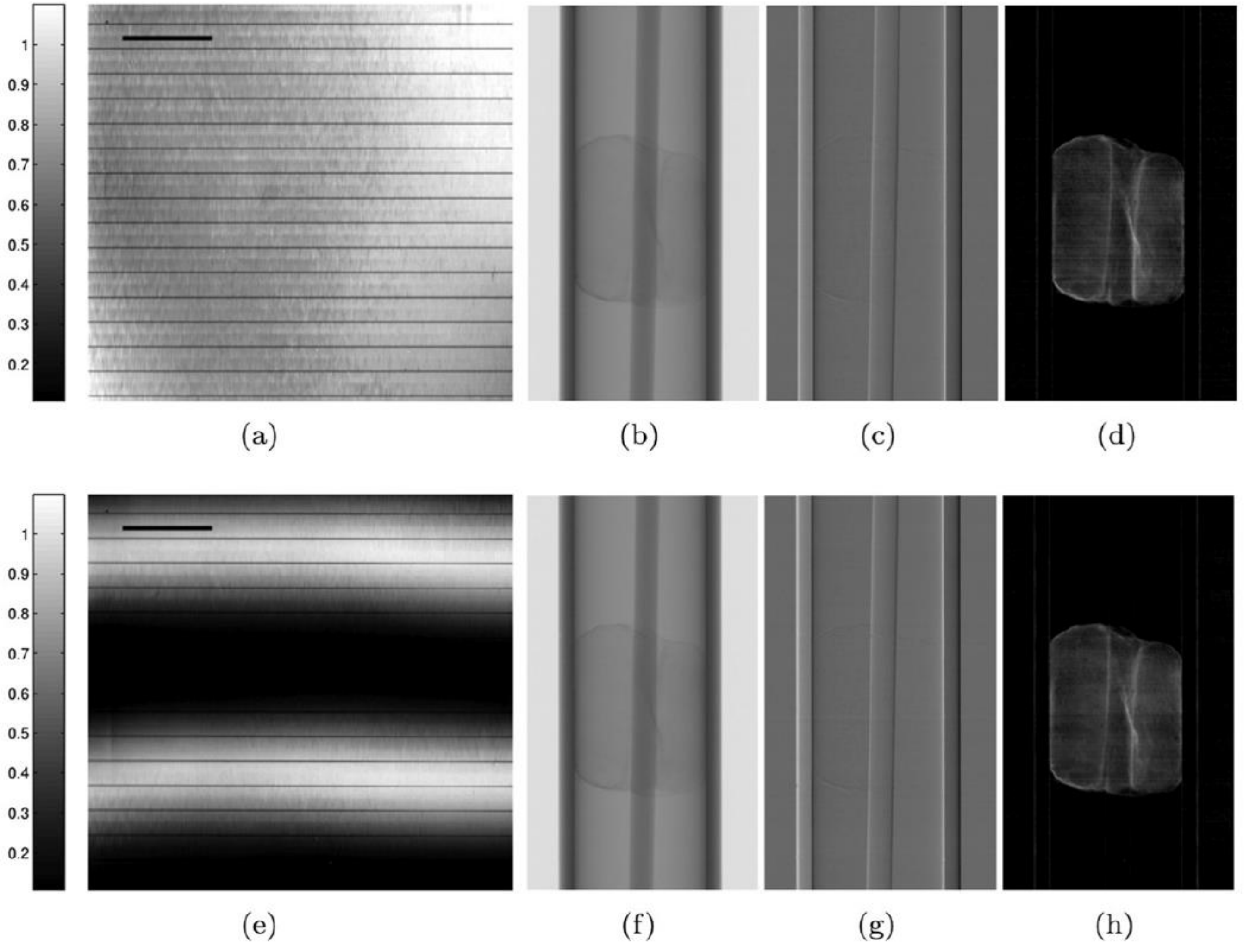


(validation obtained by segmenting nano-CT images of the powders and extracting average size)



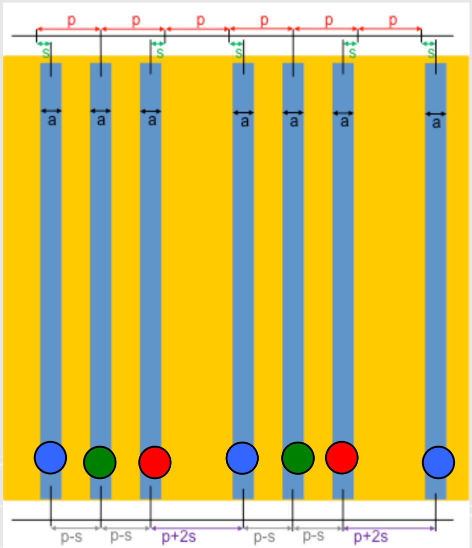
Modregger et al. Phys. Rev. Lett. 118 (2017) 265501

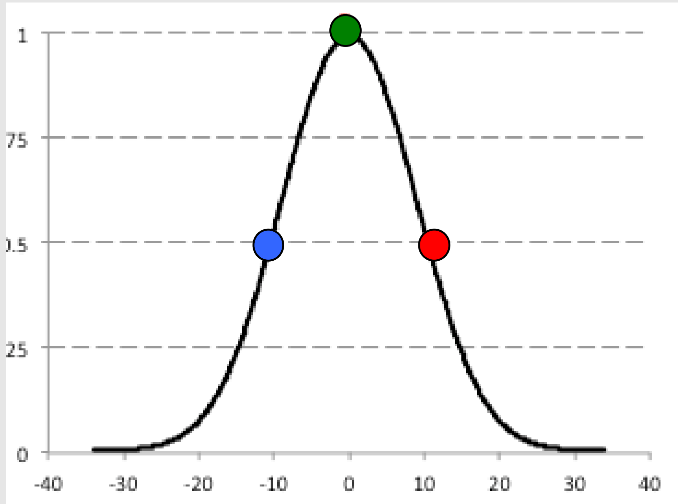
Importantly, the 3-image retrieval method removes the need to align the masks…

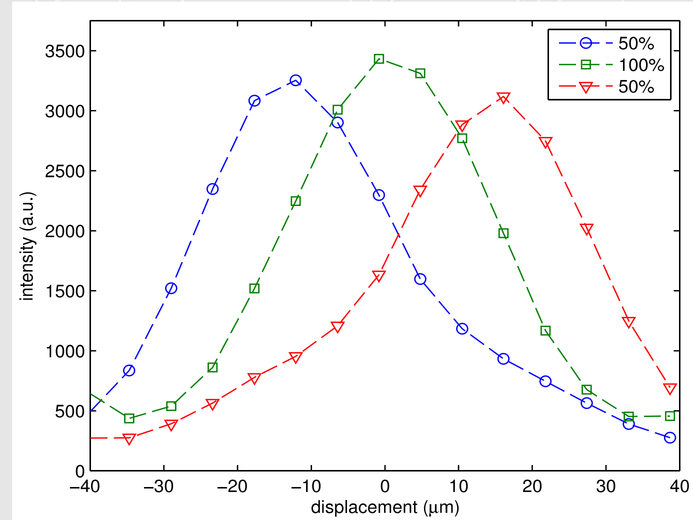


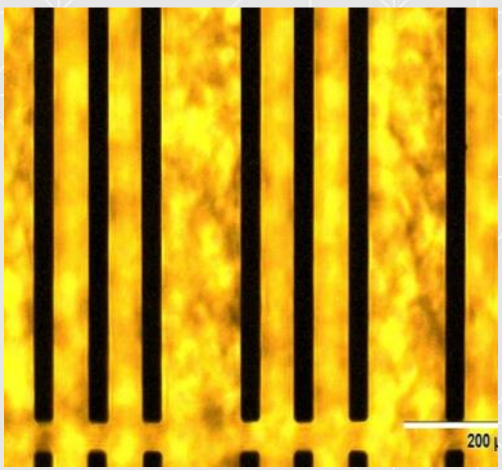
Endrizzi *et al*, Appl. Phys. Lett. 107 (2015) 124103

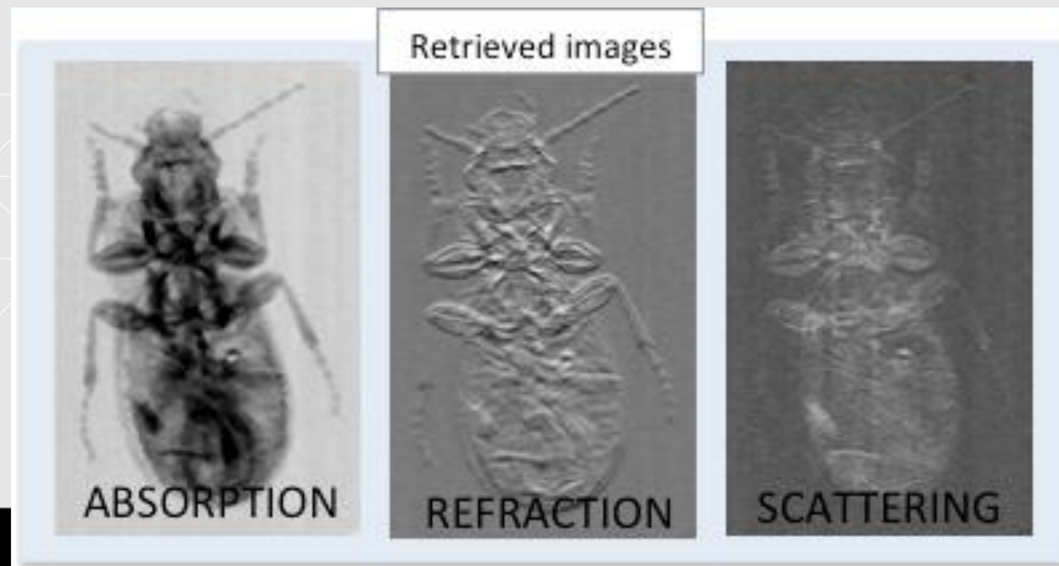
But you still need to displace the pre-sample mask at each step; **in scanned acquisitions, use ASYMMETRIC** masks!





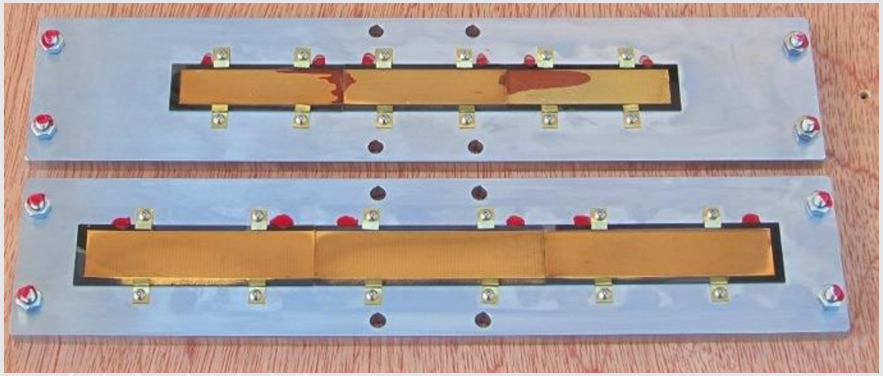


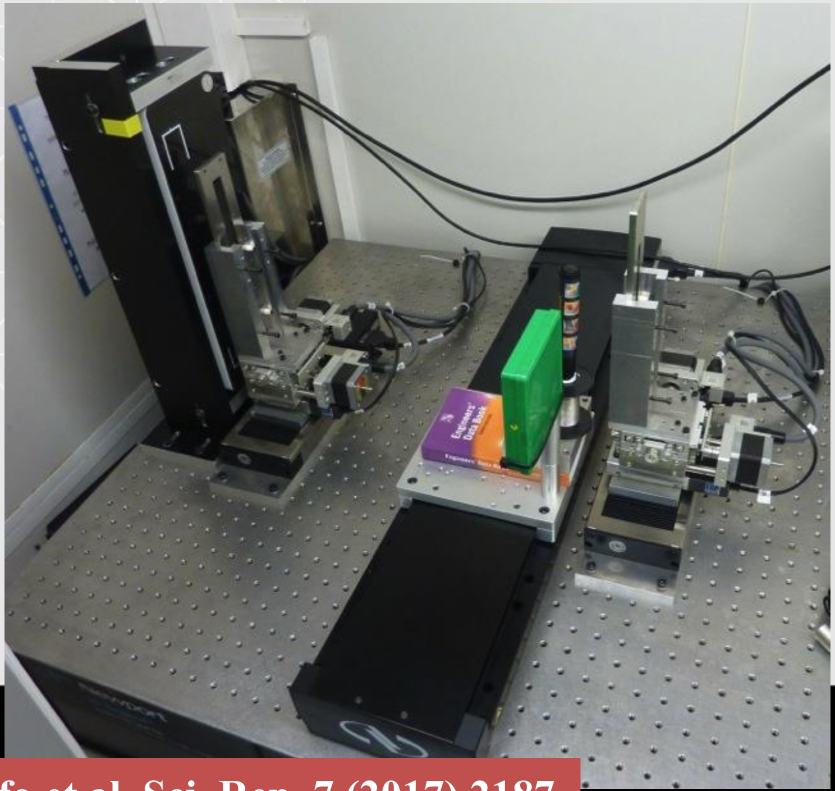




Endrizzi *et al*, Sci. Rep. 6 (2016) 25466

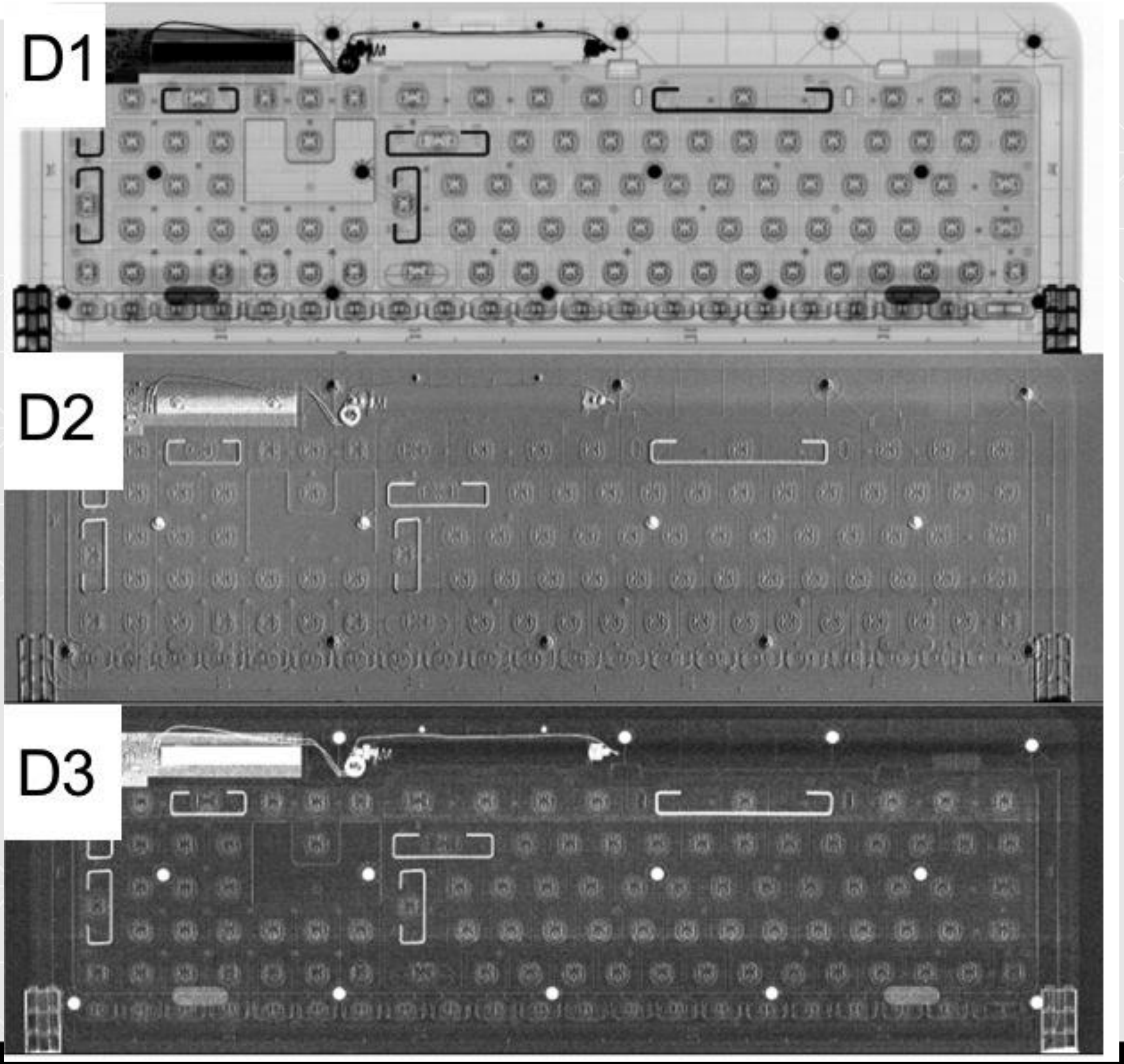
Used to build large FoV (20 x 50 cm^2), high-energy pre-commercial prototype (results will be presented at IEEE 2016)





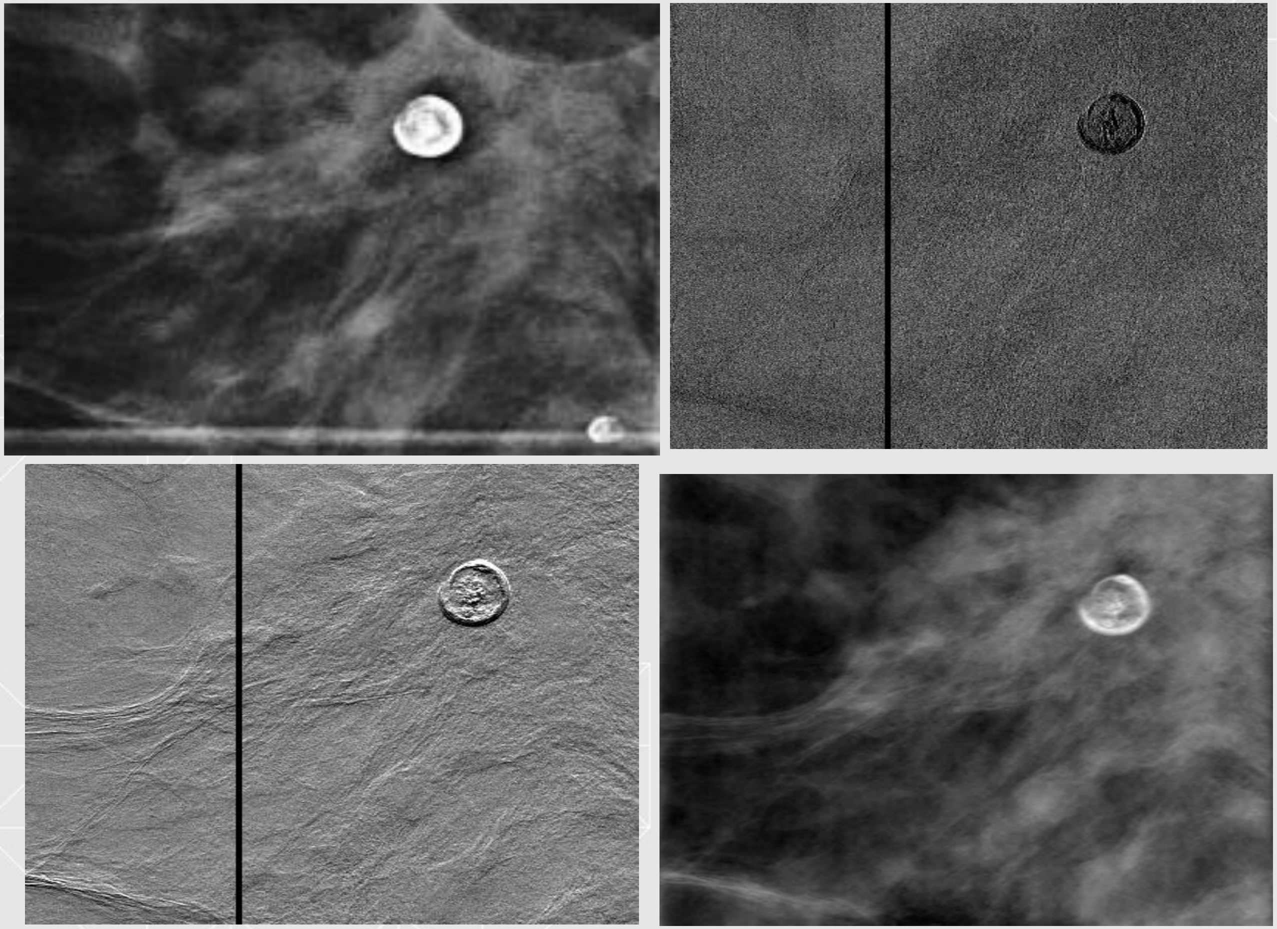
Astolfo et al. Sci. Rep. 7 (2017) 2187

…but OK I'll show you a snippet…



Astolfo et al. Sci. Rep. 7 (2017) 2187

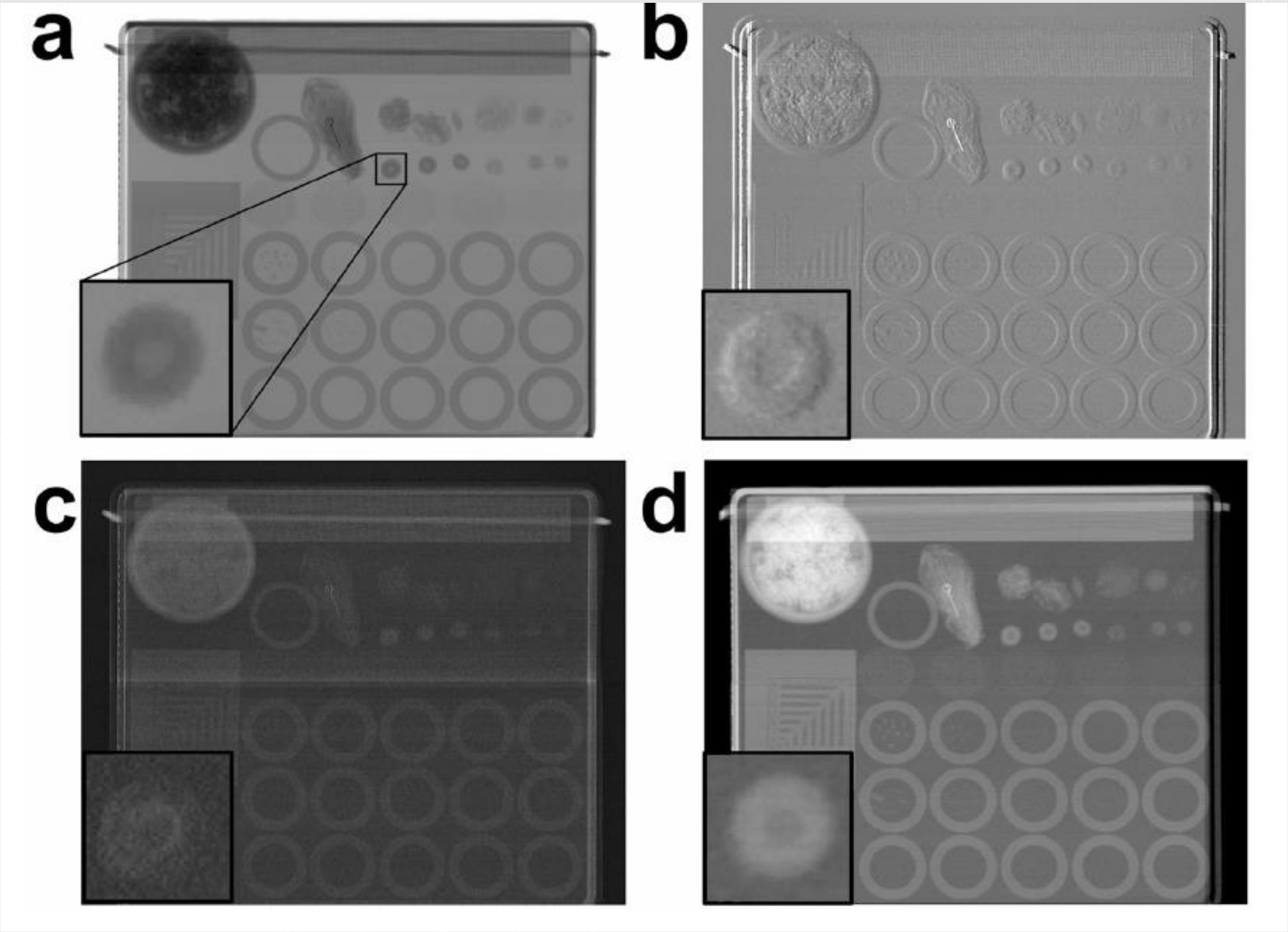
Use of ultra-high sensitivity to obtain significant dose reductions in mammography



Total entrance dose = 0.115 mGy

Diemoz et al, Phys. Med. Biol. 61 (2016) 8750

First attempt at translation (on realistic, 5 cm thick mammo phantom)

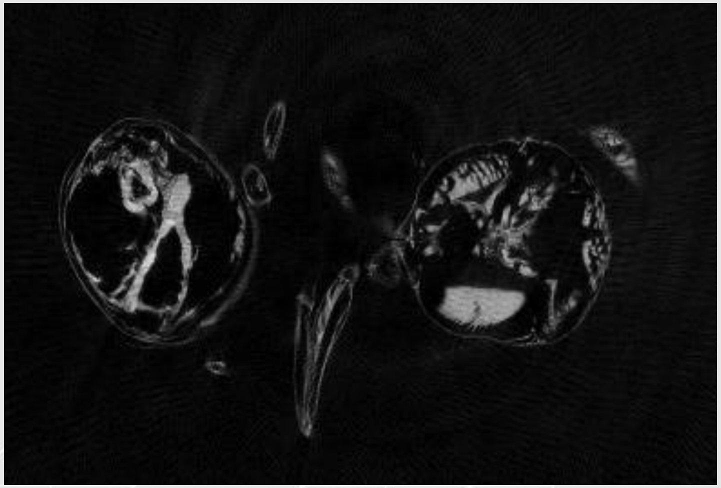


The pre-commercial system shown in the previous slide was used in two ways: a-c) multimodal use (attenuation, differential phase, dark field); **entrance** dose 2 mGy; d) “single-shot” retrieval, **entrance** dose 0.15 mGy.

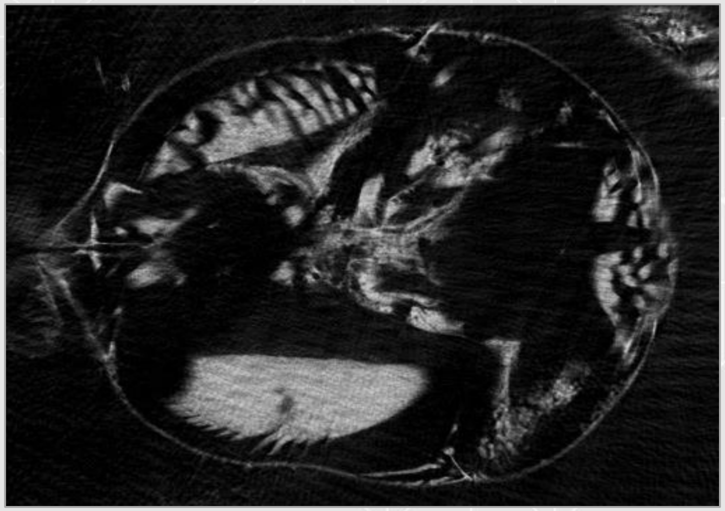
To be compared with standard entrance doses in mammo of 10-12 mGy.

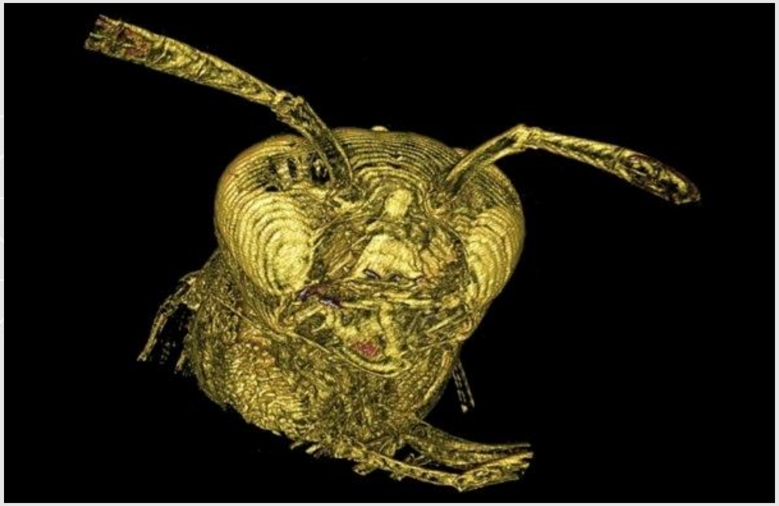
Astolfo *et al* Sci. Rep. 7 (2017) 2187

Early CT results



Soft tissue inside wasp thorax resolved





Dose **tens of mGy**, instead of tens of Gy!

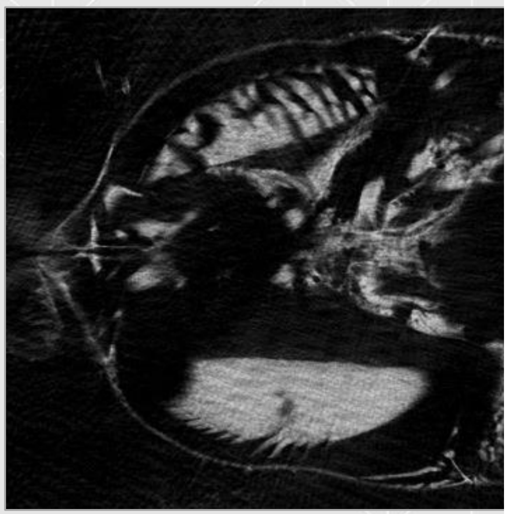
Hagen et al, Med. Phys. (letters) 41 (2014) 070701

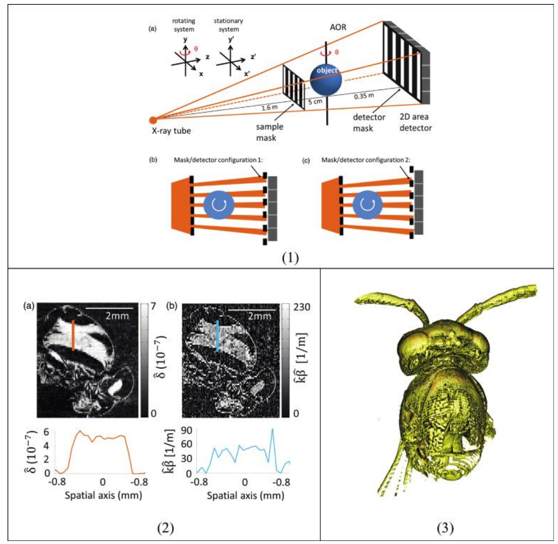
UCL ENGINEERING

Medical Physics

AVAILABLE ONLINE—See http://www.medphys.org July 2014 Volume 41, Number 7

The International Journal of Medical Physics Research and Practice





First experimentally acquired x-ray phase-contrast images acquired with ordinary x-ray source using edge-illumination method (EI PCi). (1) 3D schematic view of the laboratory implementation of tomographic EI XPCi. (a) Views from top showing two opposing edge illumination conditions, (b,c), achieved by shifting the sample mask appropriately. (2) Coronal tomographic images of a wasp showing the phase shift (a) and attenuation (b) images within the insect with profiles extracted across the indicated thorax region. (3) 3D volume rendering of the wasp derived from phase shift images.

[Figures 1, 2, and 3 from Hagen, Munro, Endrizzi, Diemoz, and Olivo, "Low-dose phase contrast tomography with conventional x-ray sources," Med. Phys. 41, 070701 (5pp.) (2014)].

Published by the American Association of Physicists in Medicine (AAPM) with the association of the Canadian Organization of Medical Physicists (COMP), the Canadian College of Physicists in Medicine (CCPM), and the International Organization for Medical Physics (IOMP) through the AIP Publishing LLC. *Medical Physics* is an official science journal of the AAPM and of the COMP/CCPM/IOMP.

***Medical Physics* is a hybrid gold open-access journal.**

Soft tissue inside wasp thorax resolved

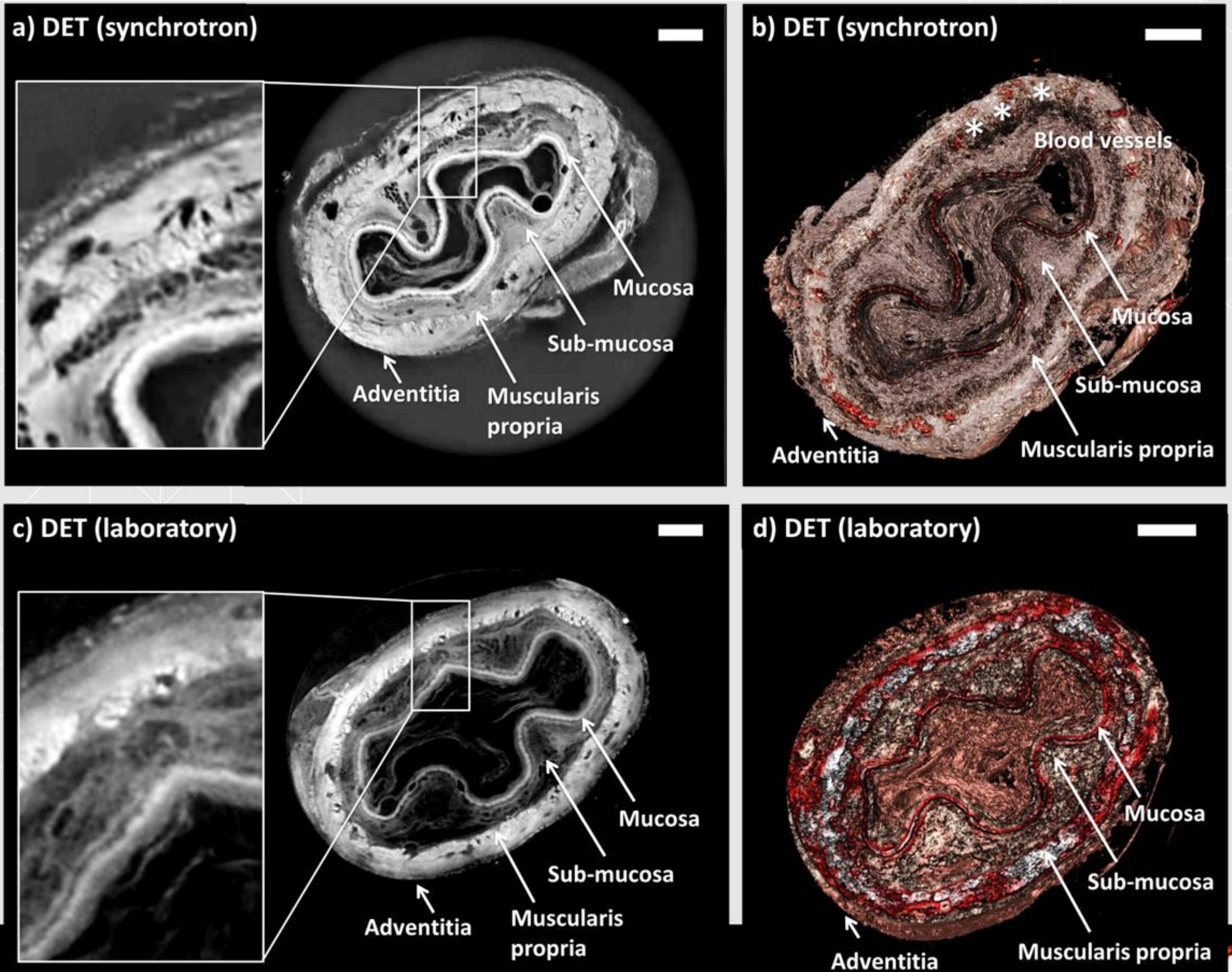
Dose **tens of mGy**, instead of tens of Gy!

Hagen et al, Med. Phys. (lett

UCL ENGINEERING
Change the world

First CT results

another example, fully decellularized tissue

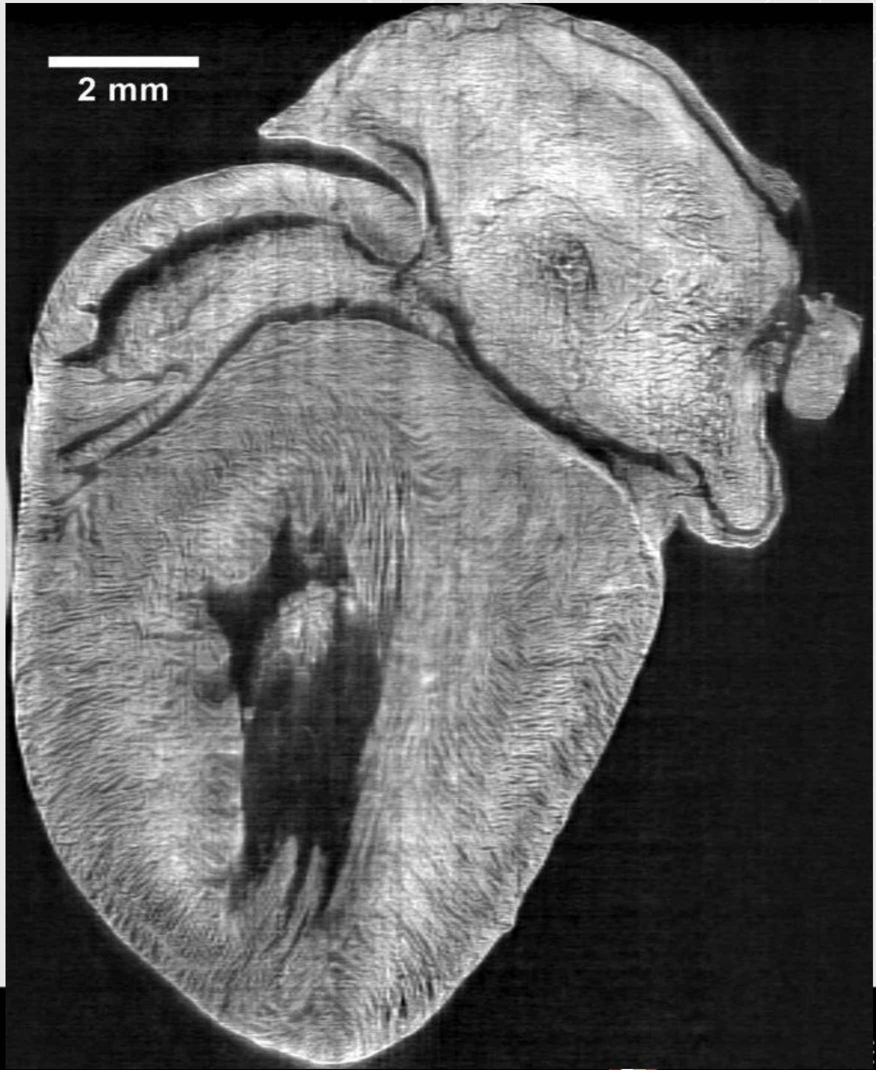


Hagen *et al*, Sci. Rep. 5 (2015) 18156

Rat heart

axial

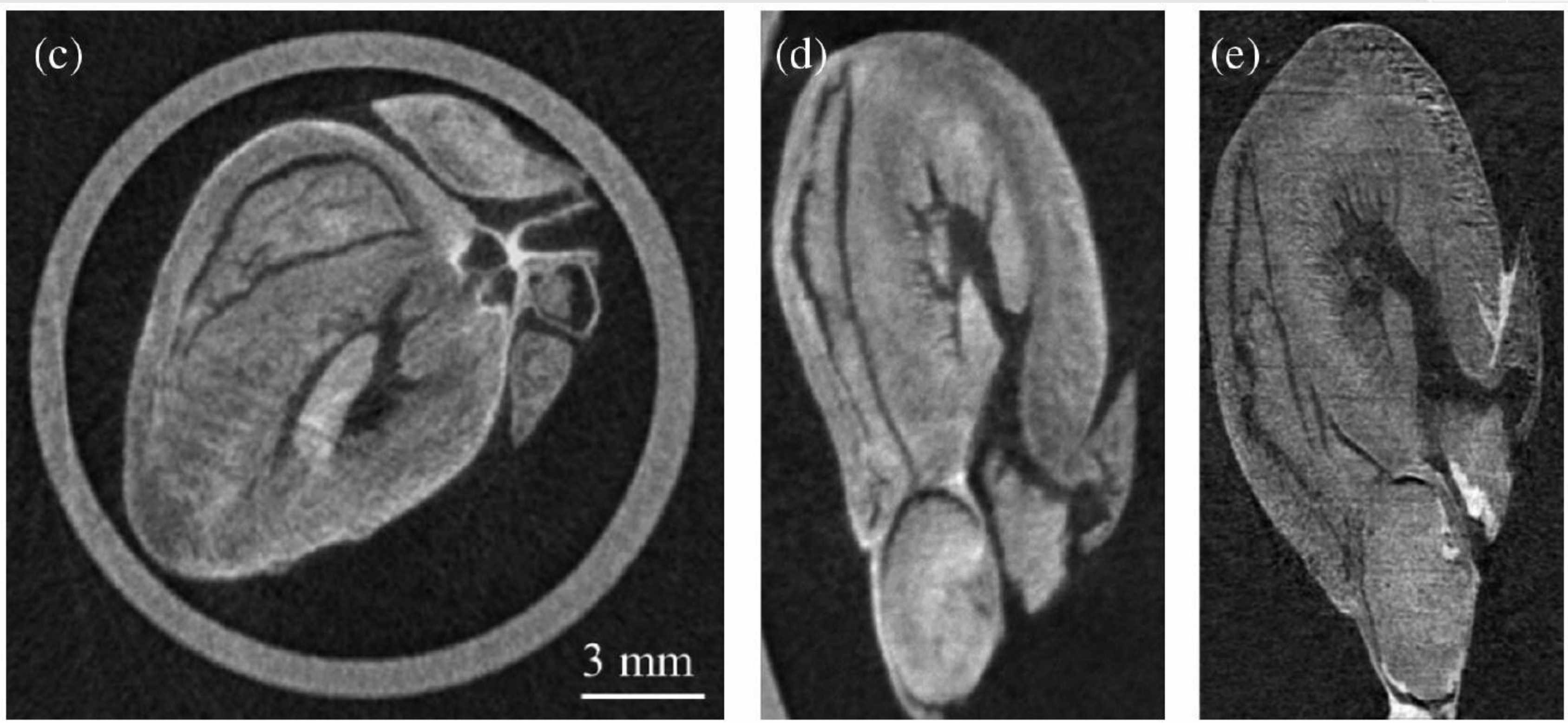
reslice



Zamir et al, Sci. Rep. 6 (2016) 31197

Rat heart – "single shot" lab CT version

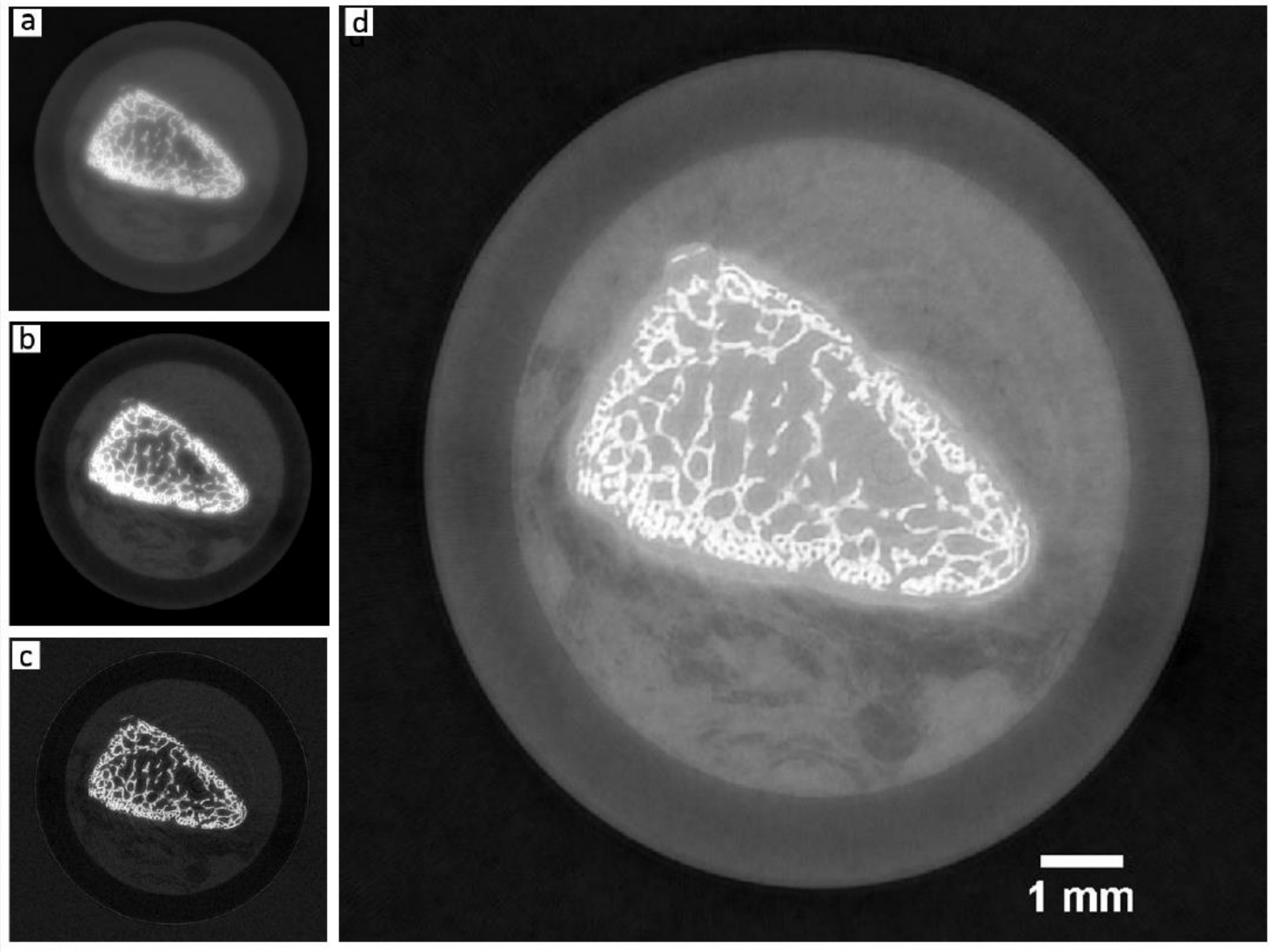
This was obtained through Diemoz's further adaptation of Paganin's single-shot retrieval to the polychromatic case with laboratory sources.



3' acquisition time. Previous record (EI + reverse projections, Hagen et al J. Phys. D: Appl. Phys. **49** (2016) 255501) was 25'. Most acquisitions reported in the literature take several hours.

Diemoz *et al* Phys. Rev. Appl. 7 (2017) 044029

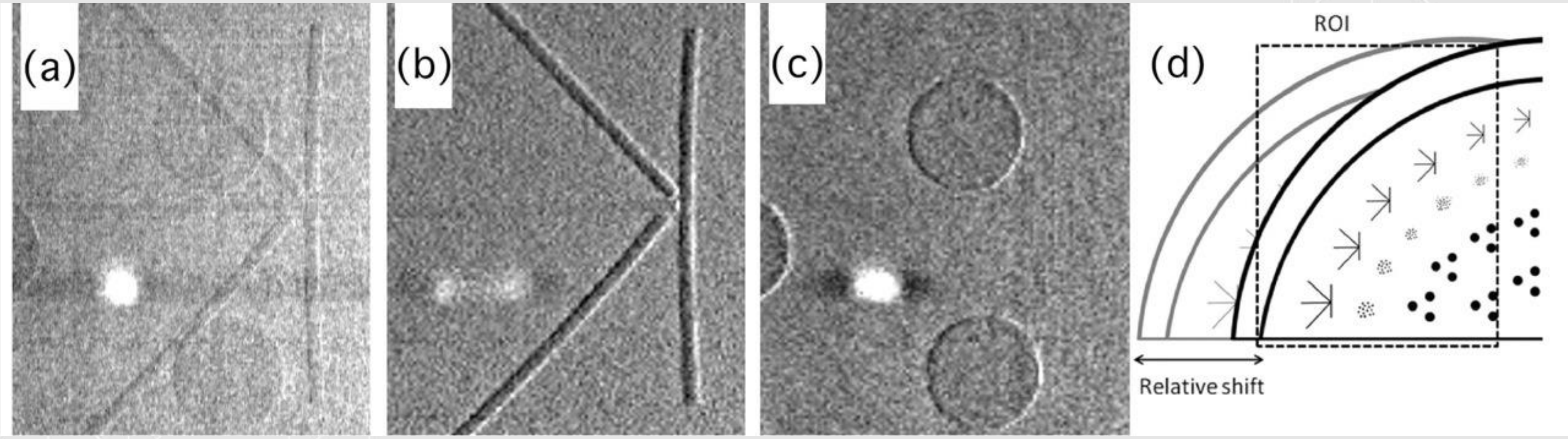
Diemoz's method recently extended to non-homogeneous materials following the work of Beltran et al

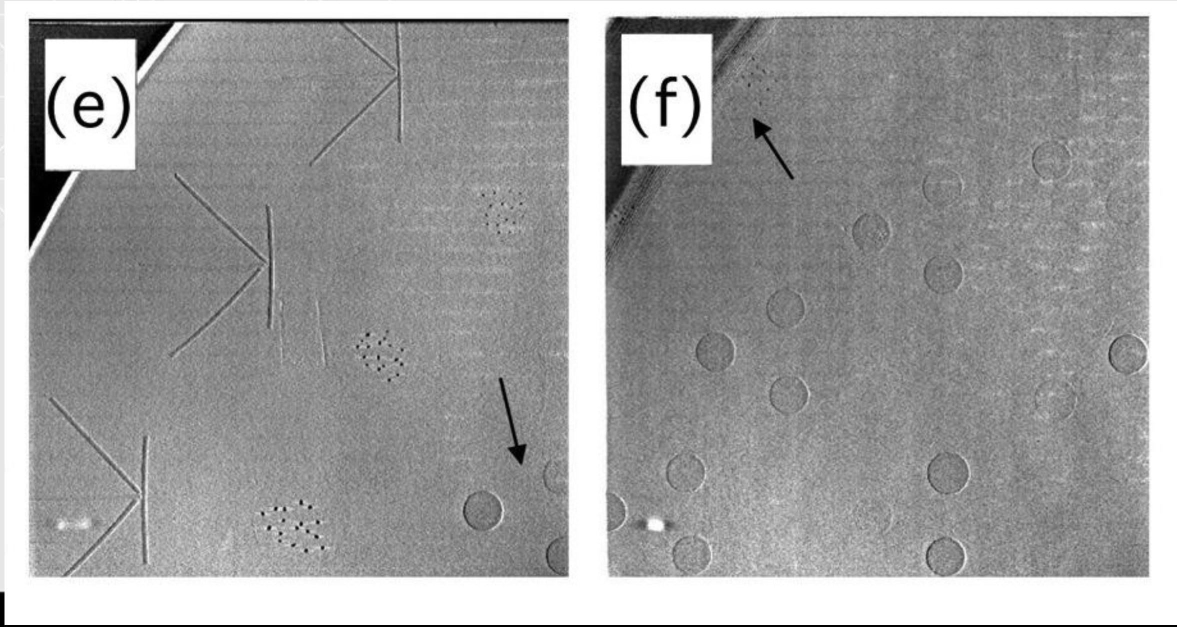


a) air-cylinder interface, b) intra-soft tissues, c) bone-soft tissue, d) spliced image. The paper also shows that the retrieved values are reliable through phantom work.

Zamir *et al* Opt. Exp. 25 (2017) 11984-96

Phase-enhanced tomosynthesis:

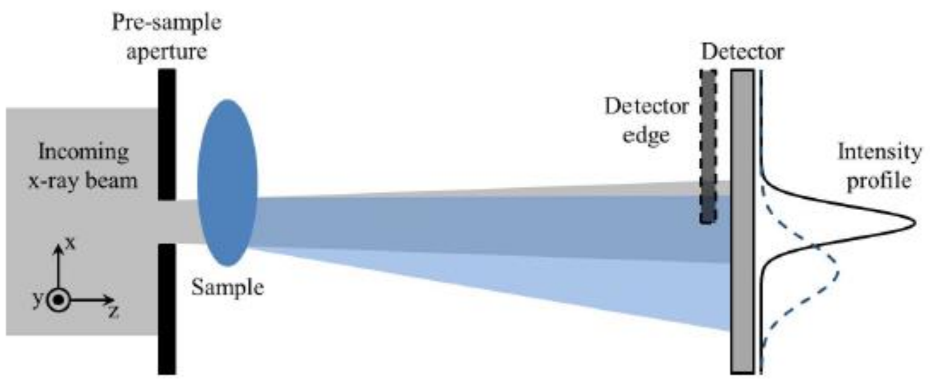


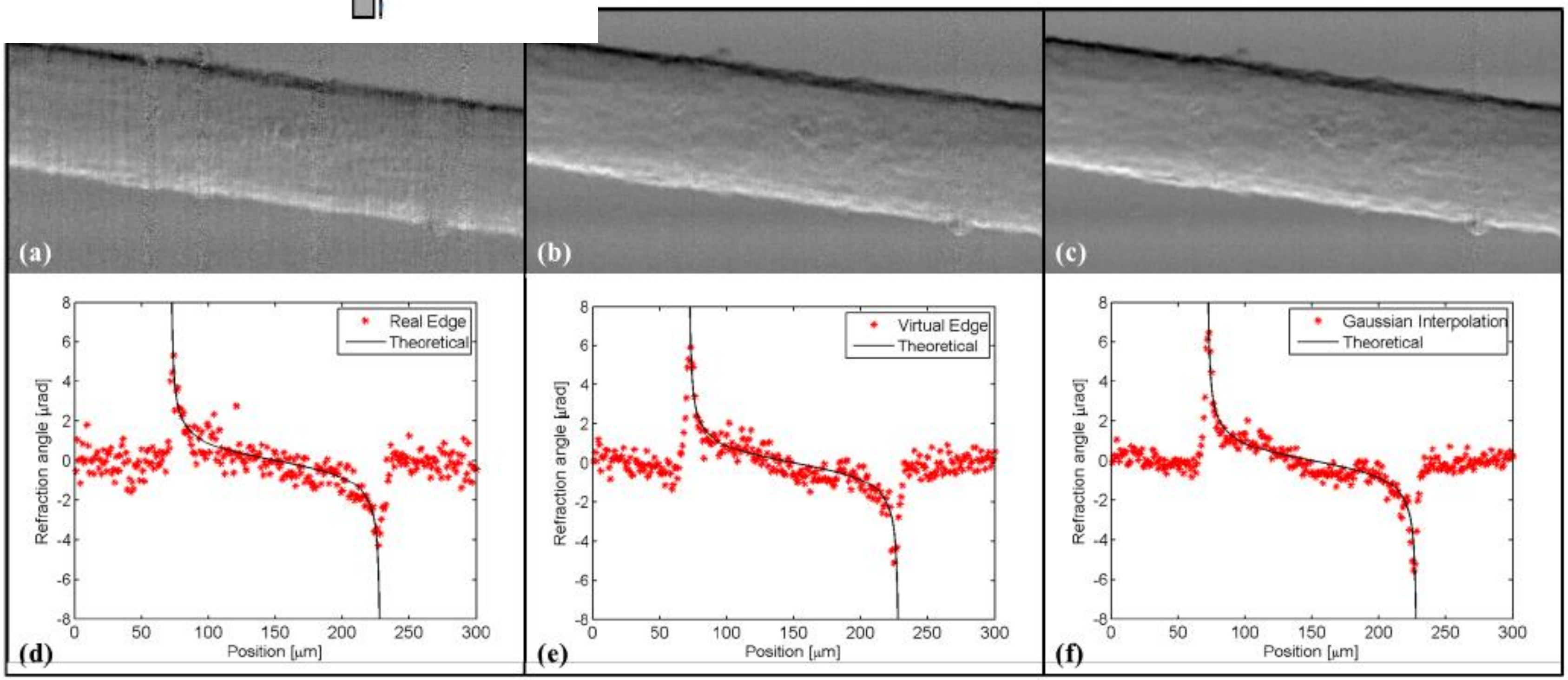


- 15 projections at 1º steps
- reconstructed with Dexela's proprietary "Separable Paraboidal Surrogates" iterative algorithm
- Sample thickness 3.4 cm
- **TOTAL entrance dose 11 mGy** (compatible with mammo)

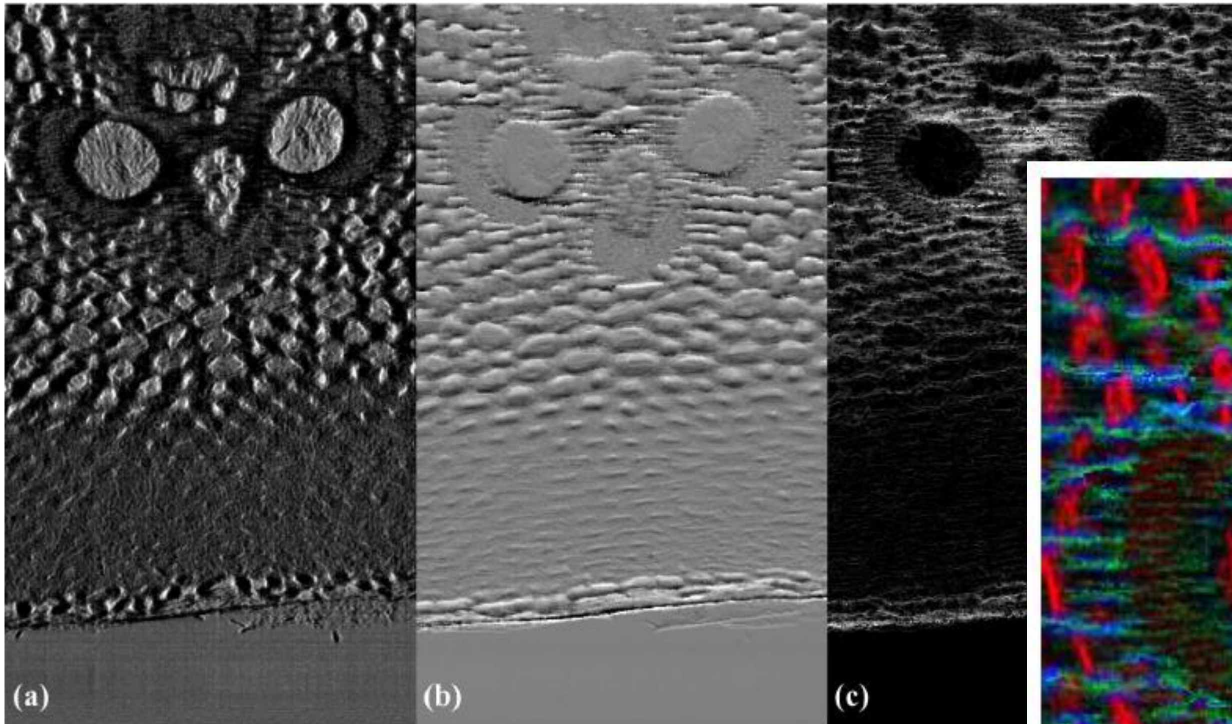
Szafraniec *et al* Phys. Med. Biol. 59 (2014) N1-N10

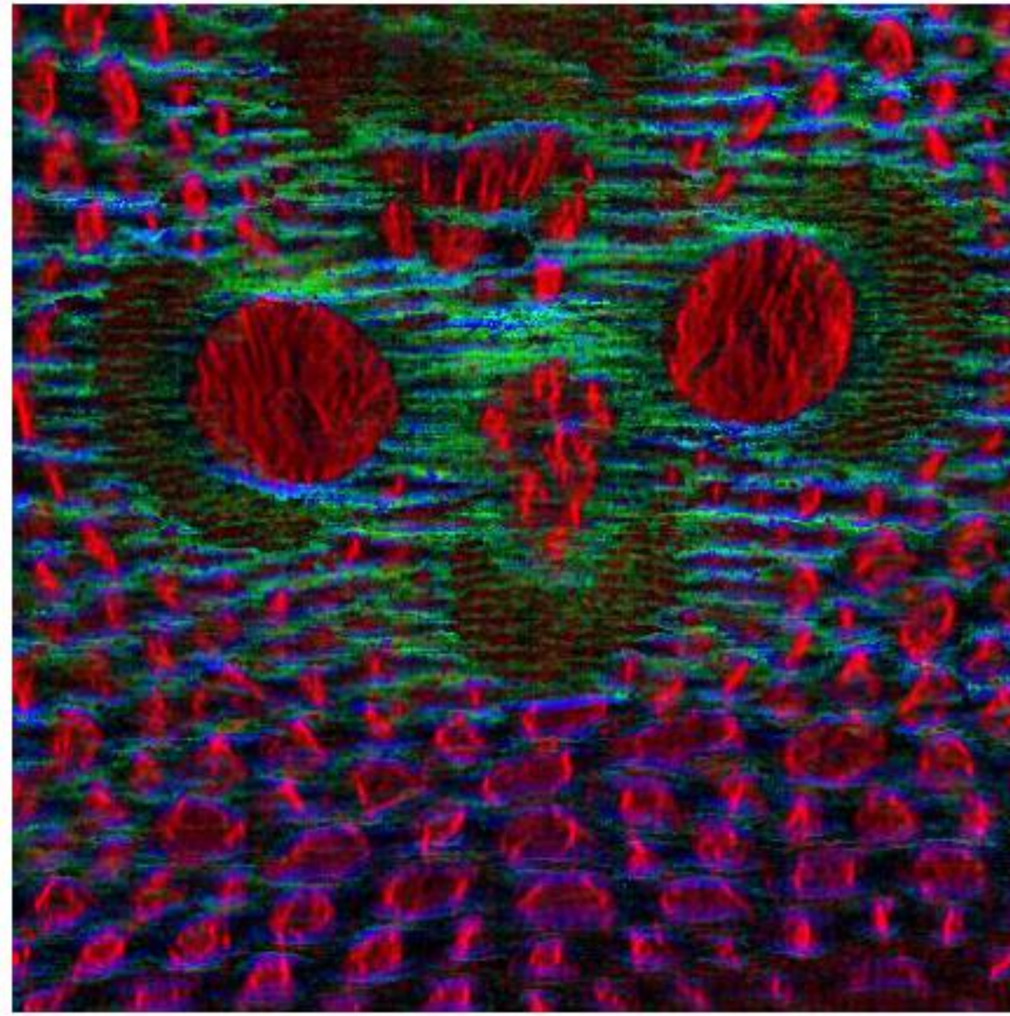
“virtual” edge/beam tracking





Vittoria et al Appl. Phys. Lett. 104 (2014) 134102

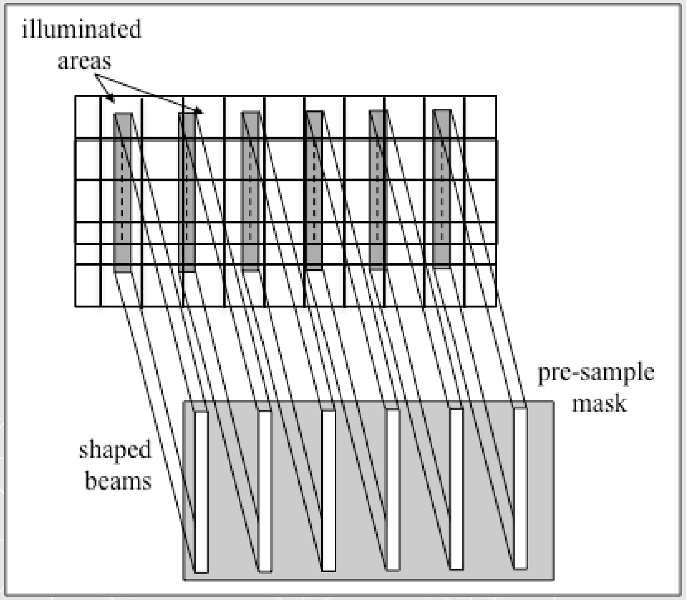


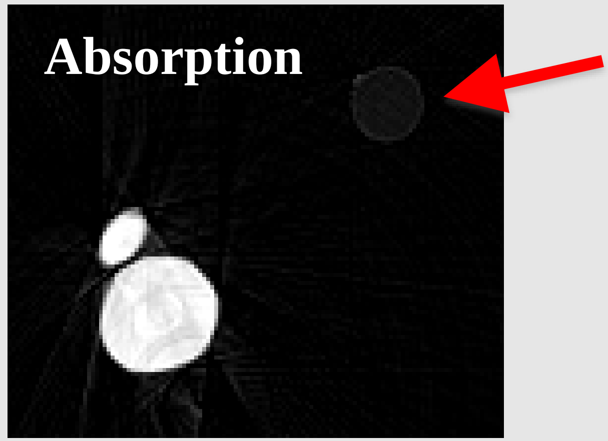


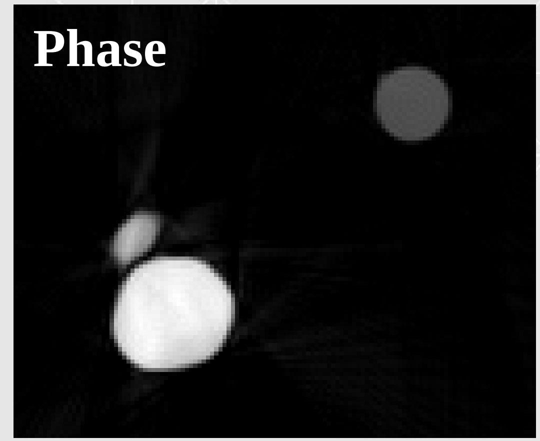
R abs
B |refr|
G scatt

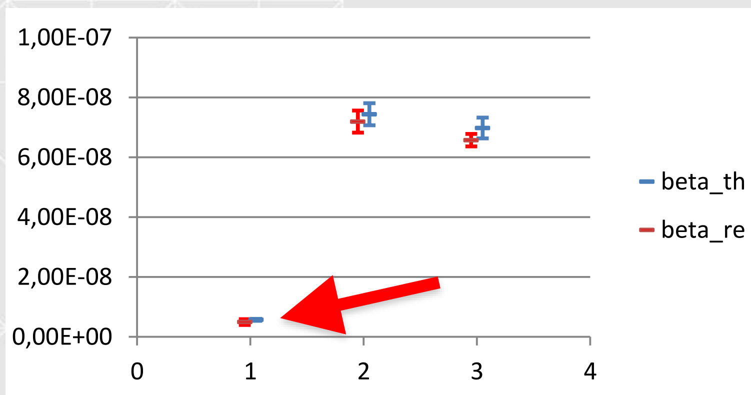
Vittoria et al Appl. Phys. Lett. 104 (2014) 134102

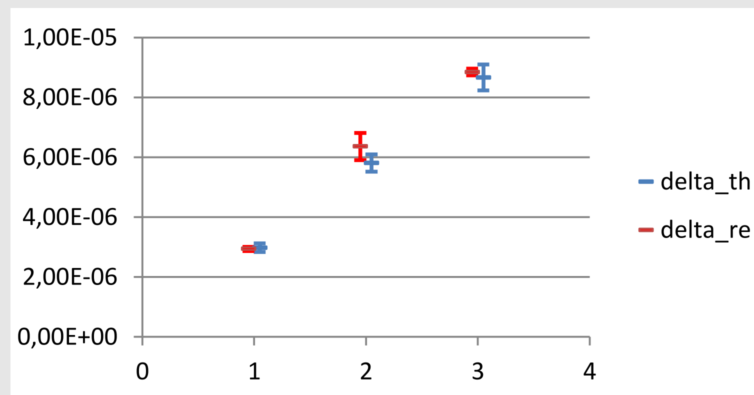
beam tracking – can be extended to CT via a mask





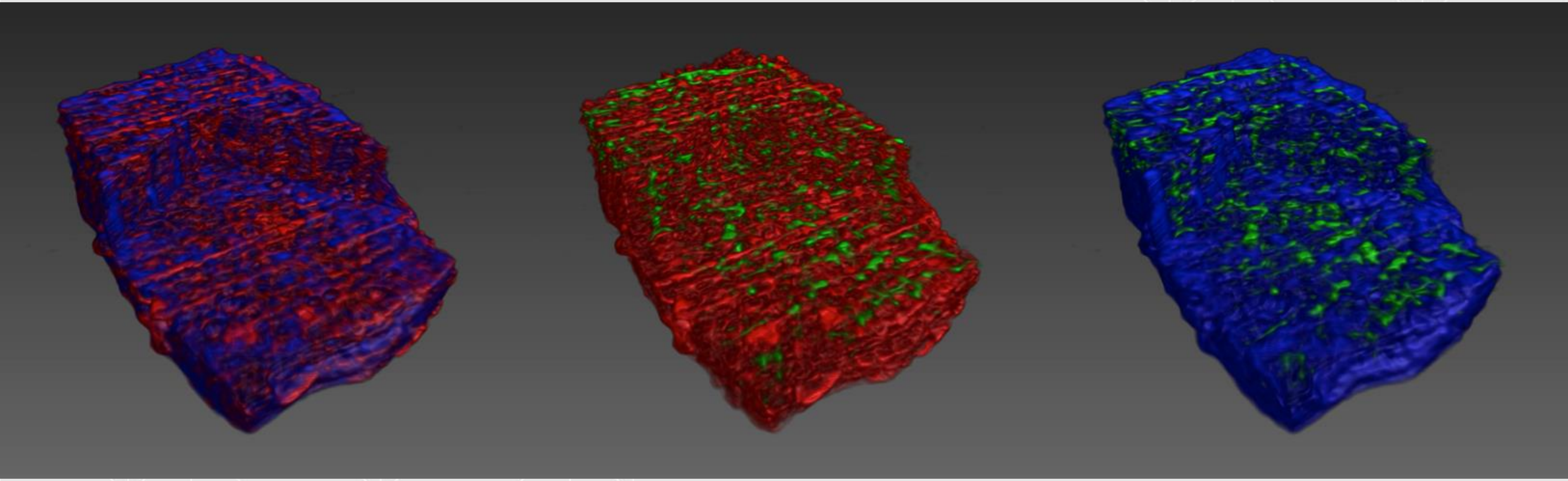






Vittoria *et al*, Sci. Rep. 5 (2015) 16318

beam tracking – can be extended to CT via a mask

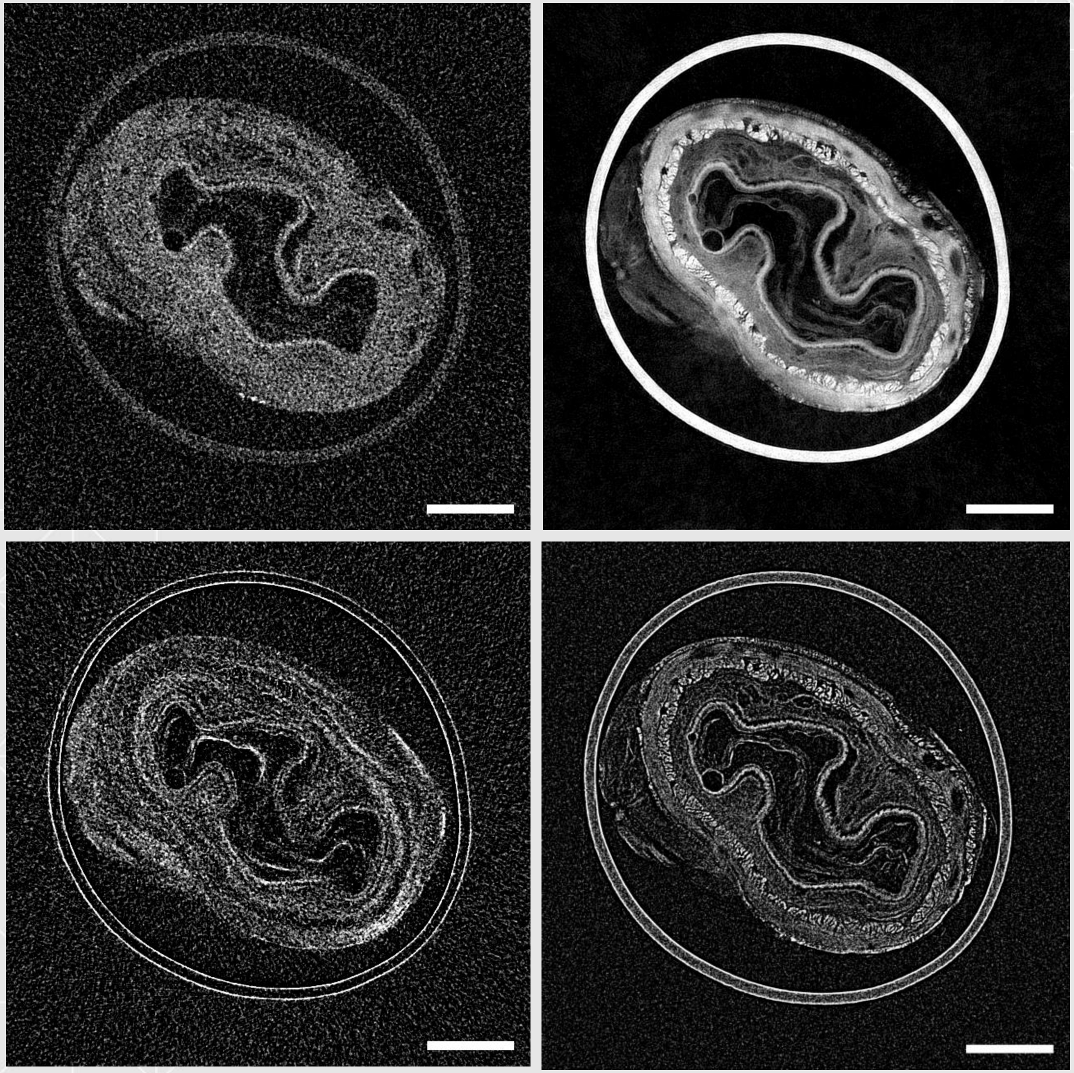


attenuation phase scattering

Vittoria *et al*, Sci. Rep. 5 (2015) 16318

translated to the lab, seems to work even better than the synchrotron! (trying to understand why before we publish…)

NB: here visibility is low because there just isn't enough contrast..

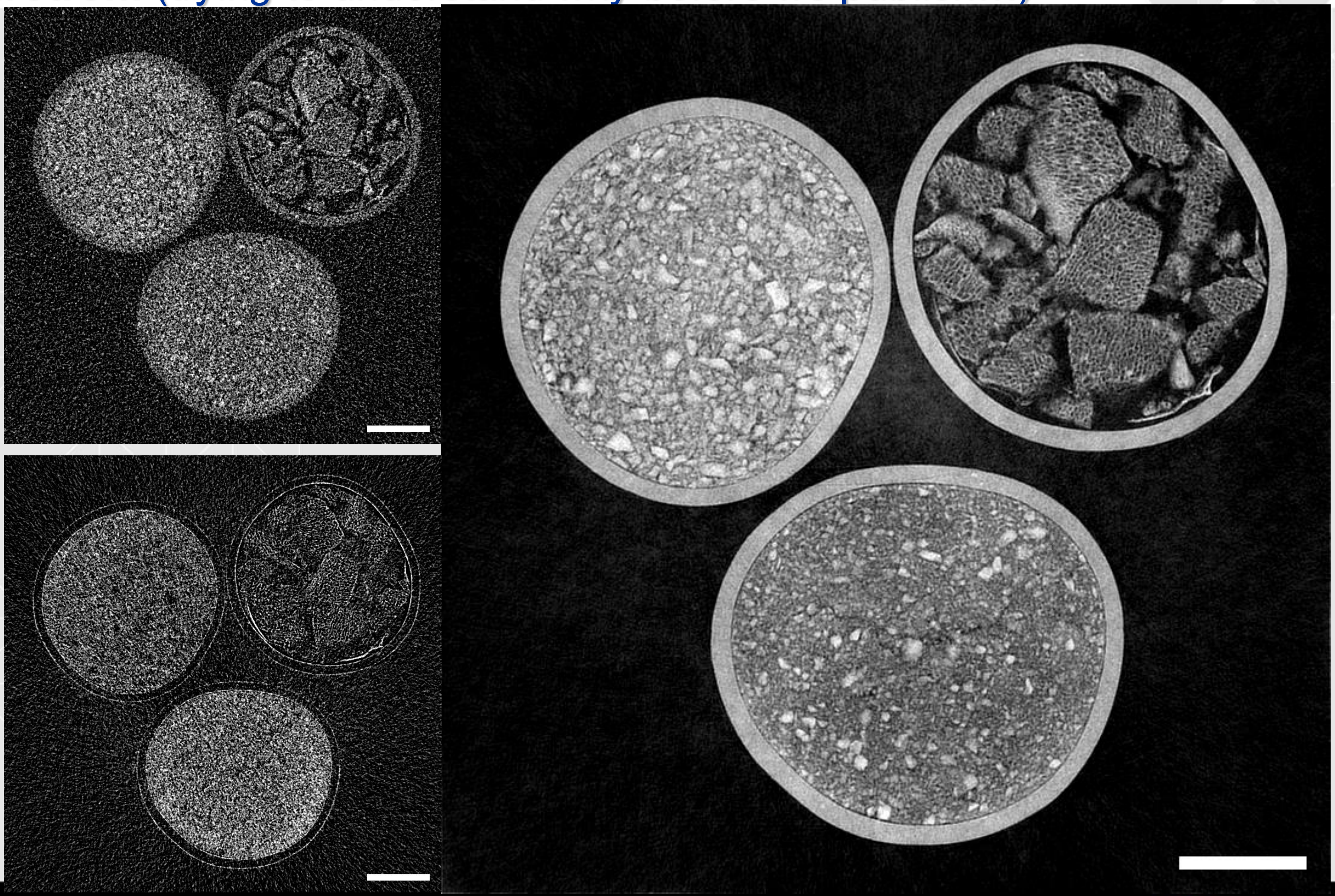


This is best of both worlds – as many photons as in the attenuation image, plus the enhanced contrast coming from the phase…

While here it it low because contrast is high, the number of scattered photons is low! (however it shows complementary features)

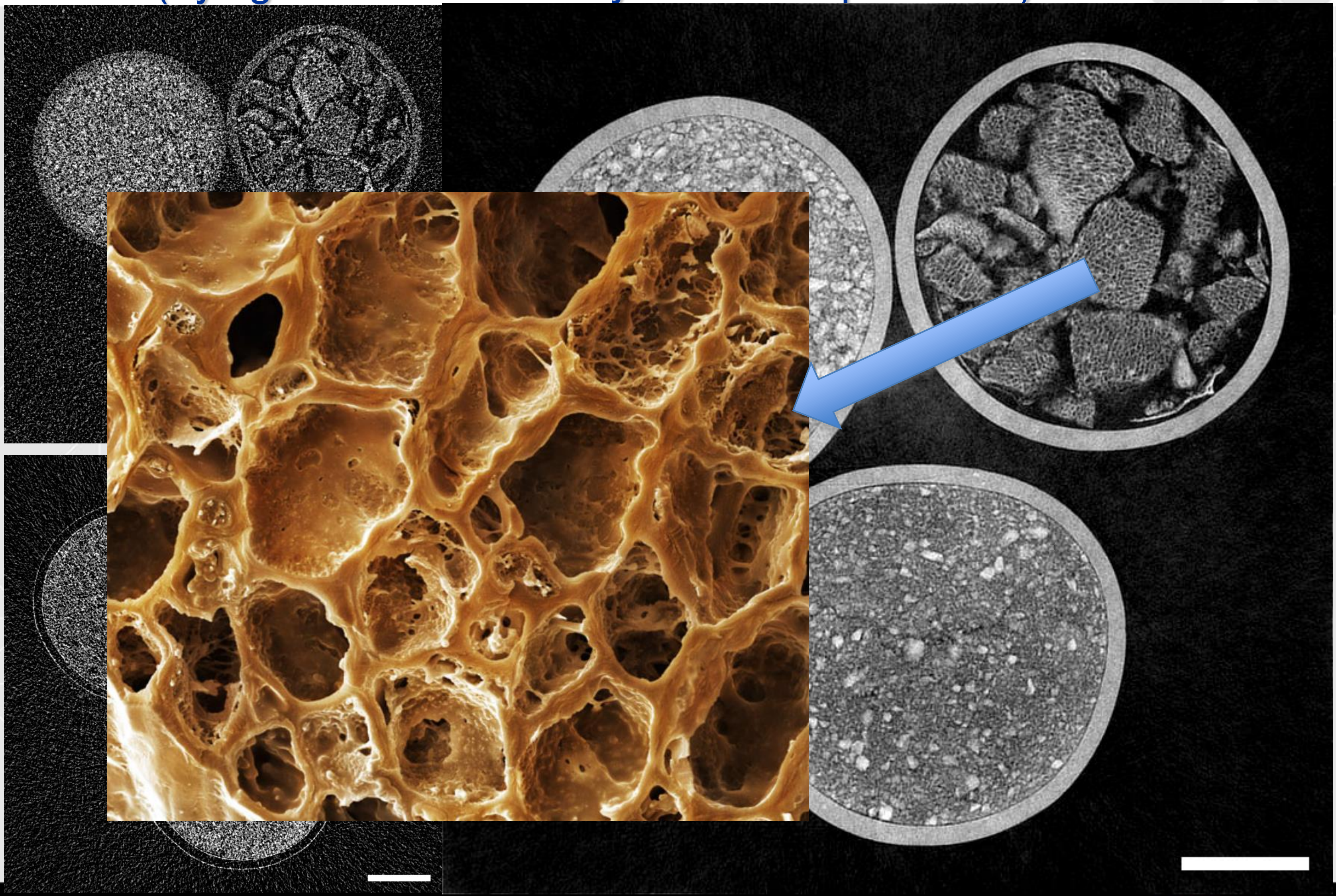
Vittoria et al. Phys. Rev. Appl. 8 (2017) 064009

translated to the lab, seems to work even better than the synchrotron! (trying to understand why before we publish…)



Vittoria et al. Phys. Rev. Appl. 8 (2017) 064009

translated to the lab, seems to work even better than the synchrotron! (trying to understand why before we publish…)



Vittoria et al. Phys. Rev. Appl. 8 (2017) 064009

Conclusions

XPCI has transformative potential on a range of applications – medical and not.

For years it has been considered restricted to synchrotrons, but techniques have emerged that enable implementations with conventional sources – opening the way to translation opportunities.

Several hurdles must be overcome - including system stability, scalability, alignment etc. The key ones are arguably excessive dose and acquisition time.

Our group is focusing on edge-illumination XPCi because we find that its non-interferometric, virtually incoherent nature (while remaining quantitative) makes it suitable for translation into real-world systems.

One key aspect is the possibility to implement single-shot methods, avoiding having to displace optical elements between acquisitions etc. We see this as absolutely essential in CT – e.g. continuous sample rotation is otherwise impossible.

By exploiting these properties, we managed to reach delivered doses and acquisition times compatible with real-world uses.

UCL ENGINEERING

BIG THANKS TO:

UCL

https://www.ucl.ac.uk/medphys/research/axim

EPSRC
Engineering and Physical Sciences Research Council

wellcome

10 Science & Technology Facilities Council
10 Years of Impact and Inspiration

Nikon

European Commission

Home Office

SBRI Government challenges. Ideas from business. Innovative solutions.

Innovate UK

THE ROYAL SOCIETY

ROYAL ACADEMY OF ENGINEERING

UCL ENGINEERING
Change the world