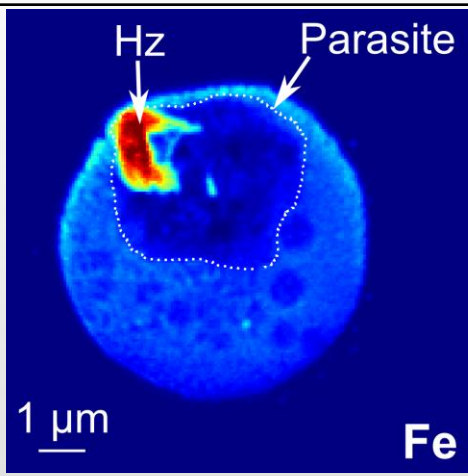
DLSR for nanoprobe and full-field imaging

P. Cloetens
S. Bohic, R. Tucoulou, H. Suhonen
A. Rack, P. Tafforeau
M. Langer (Creatis, INSA-Lyon)

Thoughts from a methodological point of view:
Temporal resolution
Achievable spatial resolution
Coherence - Dose - Energy

Scientific drivers

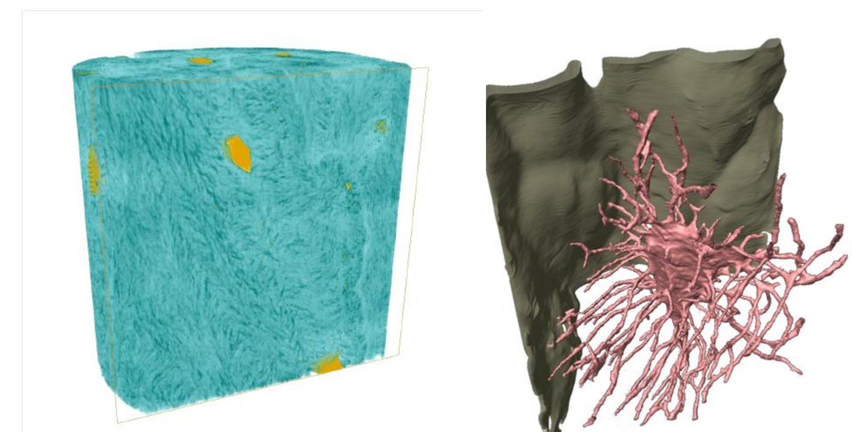
Biomedical Research: Sub-cellular processes



Anti-malarian drugs
Dubar et al, *Chem. Commun.*

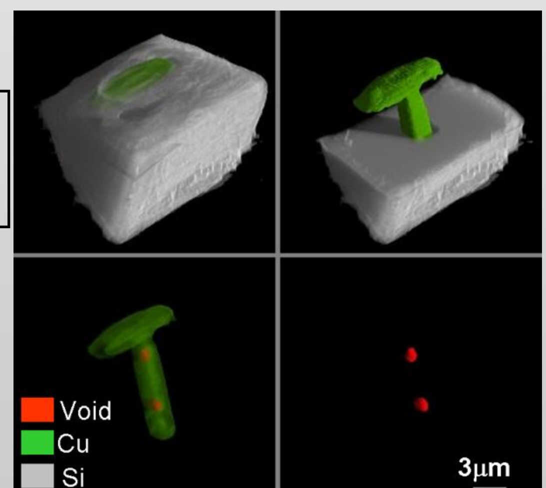
ID16A-NI

Biomedical Engineering: Tissue-level



Bone ultrastructure; Langer et al, *PloS One*

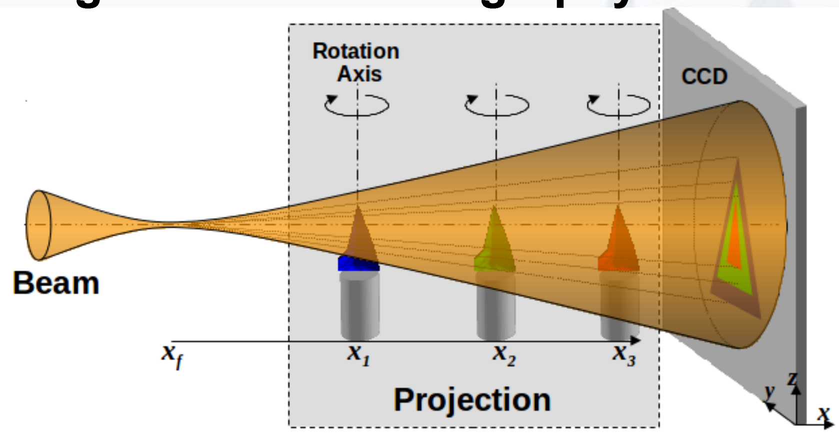
Nano/Micro-Technology: 3D Integration



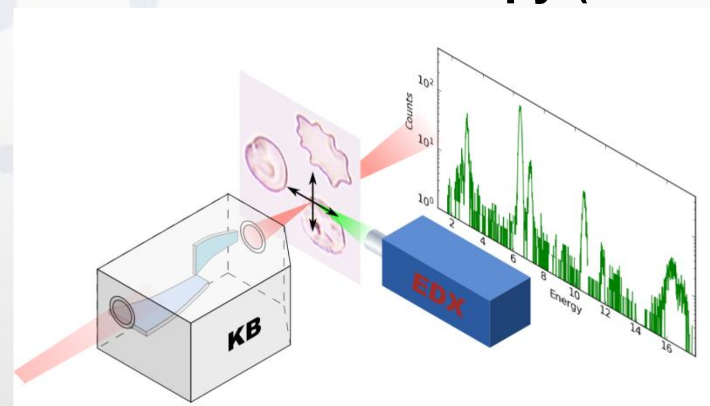
Voids in Through-Si-via
Bleuet et al (CEA-Leti)

Experimental techniques

Magnified HoloTomography

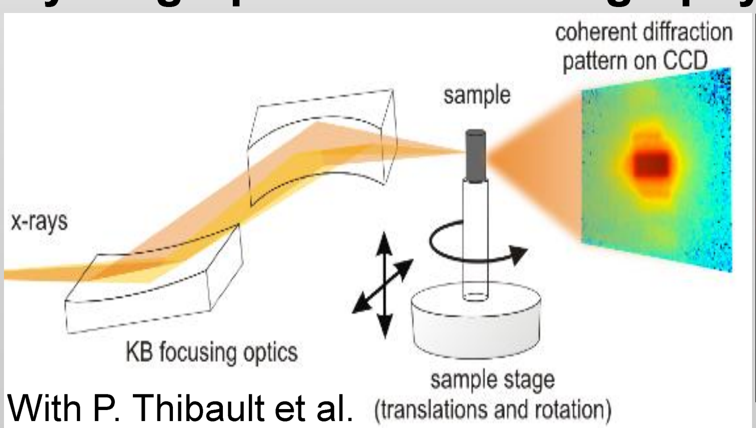


X-ray Fluorescence Microscopy (2D/3D)

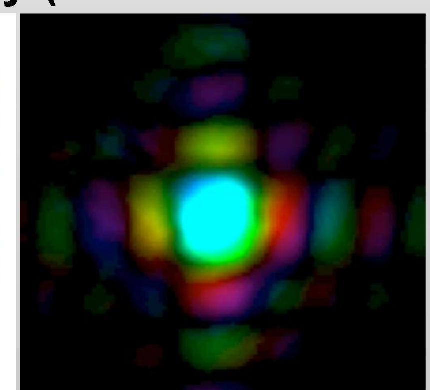


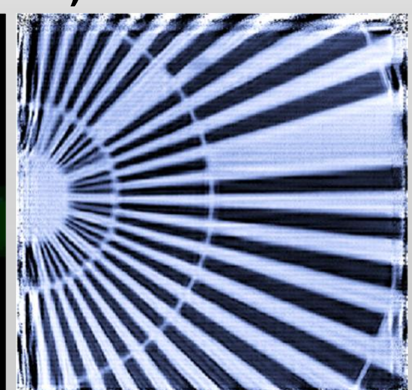
Electron Density distribution ← **ID16A-NI** → **(Trace) Element distributions**

Ptychographic Nano-Tomography (ultimate resolution)



With P. Thibault et al.

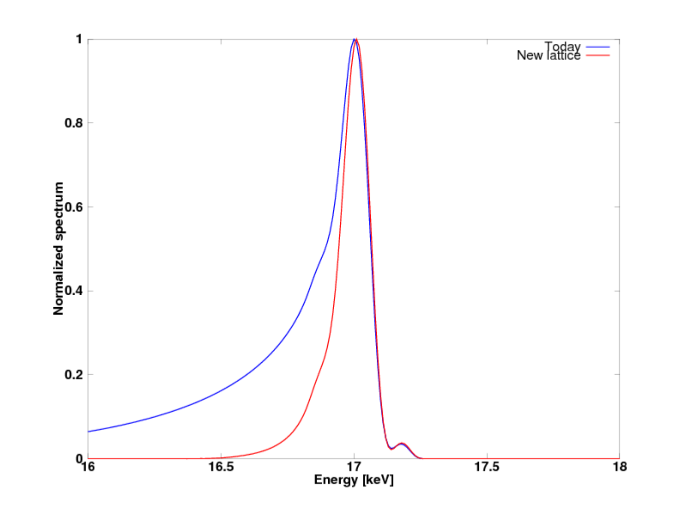

Probe


Object

Phase II, benefits for ID16A Nano-Imaging

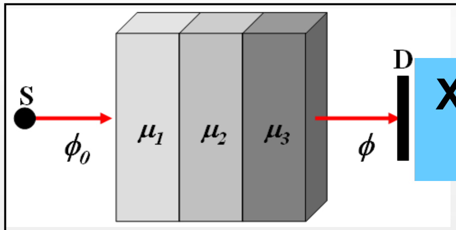
	Current lattice	New lattice	Gain
Peak spectral flux [ph/s/0.1% bw]	$6.4\ 10^{12}$	$1.7\ 10^{13}$	2.7
Bandwidth [%]	1.01 (Low energy tail)	0.74 (~ no tail)	0.73
Flux on sample [ph/s]	**$2\ 10^{12}$**	**$4\ 10^{13}$**	**20**
Focus size [H x V in nm]	14 x 9	11 x 9	0.79
Flux density on sample [ph/s/nm^2]	**$1.6\ 10^{10}$**	**$4.0\ 10^{11}$**	**25**

Calculated values

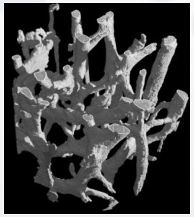


Bandwidth undulator harmonic @ 17 keV

X-Ray tomography methods

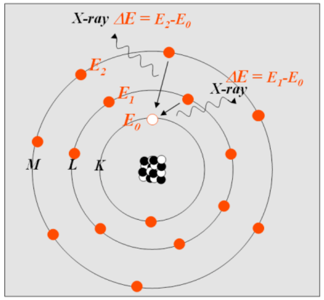


X-ray Absorption & Phase Contrast



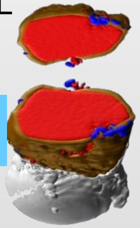
3D morphology

"Easy" & fast



Golosio et al, APL

X-ray Fluorescence

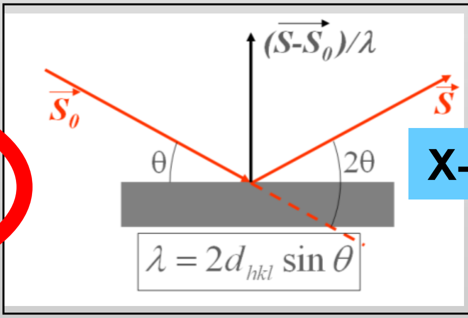


3D chemistry

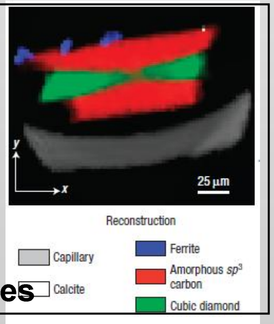
Towards routine
Time consuming

in 2010

State of the art but
Time consuming



X-ray Diffraction



3D crystal phases

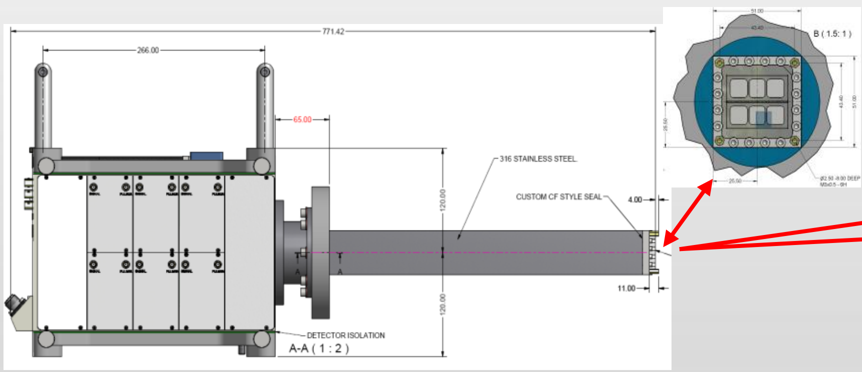
P. Bleuet et al., Nature Materials **7**, 468 - 472 (2008)

Courtesy of P. Bleuet

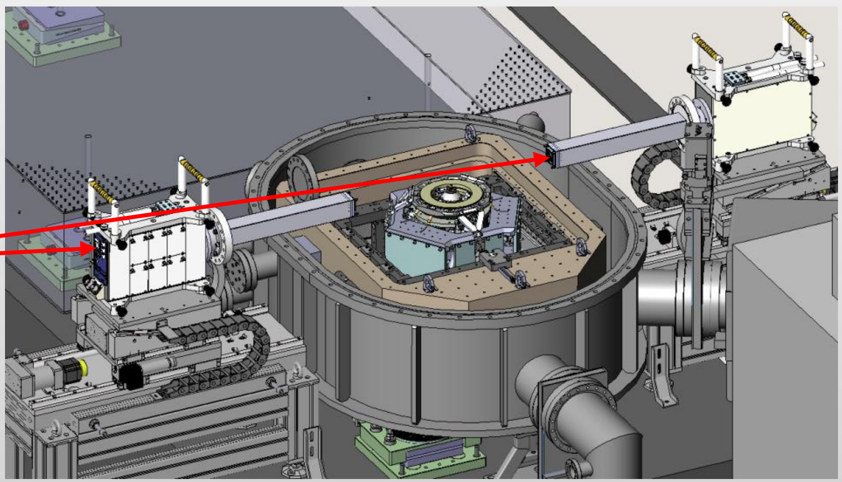
Energy dispersive detectors

Two identical detectors:
2 x PNdetector SDD 6 element arrays = **2 x 540mm²**
energy range ~2…25keV,
global ***throughput* count rate to ~6Mcps**
Fast spectra readout to 1kHz, based on existing XIA-XMAP pulse processors or Xspress 3

Operation in vacuum ~10⁻⁷mbar, confined space need for ~30mm approach to sample for **large detection solid angle**.



Detectors produced by SGX Sensortech



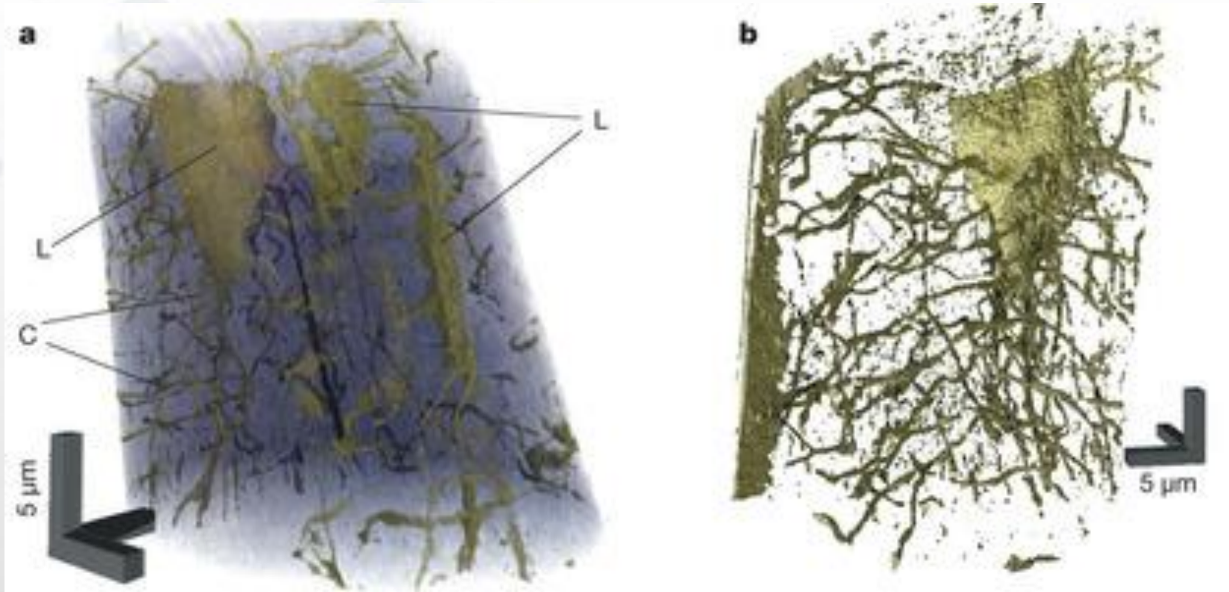
detectors shown in retracted position F Villar 20130319

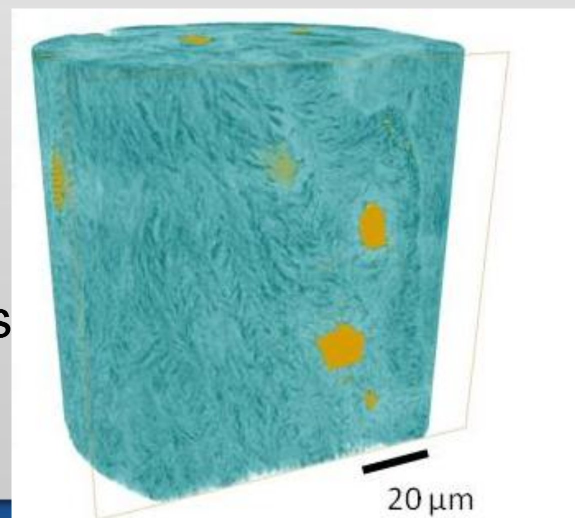
J. Morse, P. Cloetens, R. Tucoulou, G. Martinez Criado, E. Gagliardini, F. Villar, C. Cohen

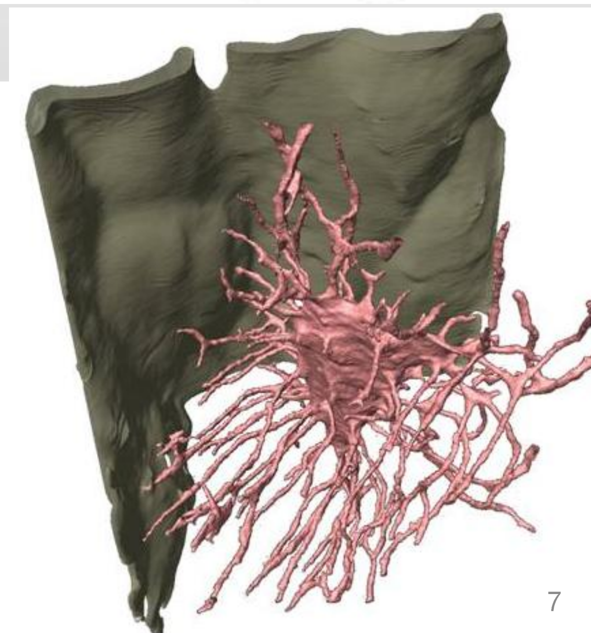
Next generation fluorescence detectors: merge SDD and Maia technologies

Ptychography vs Holotomography

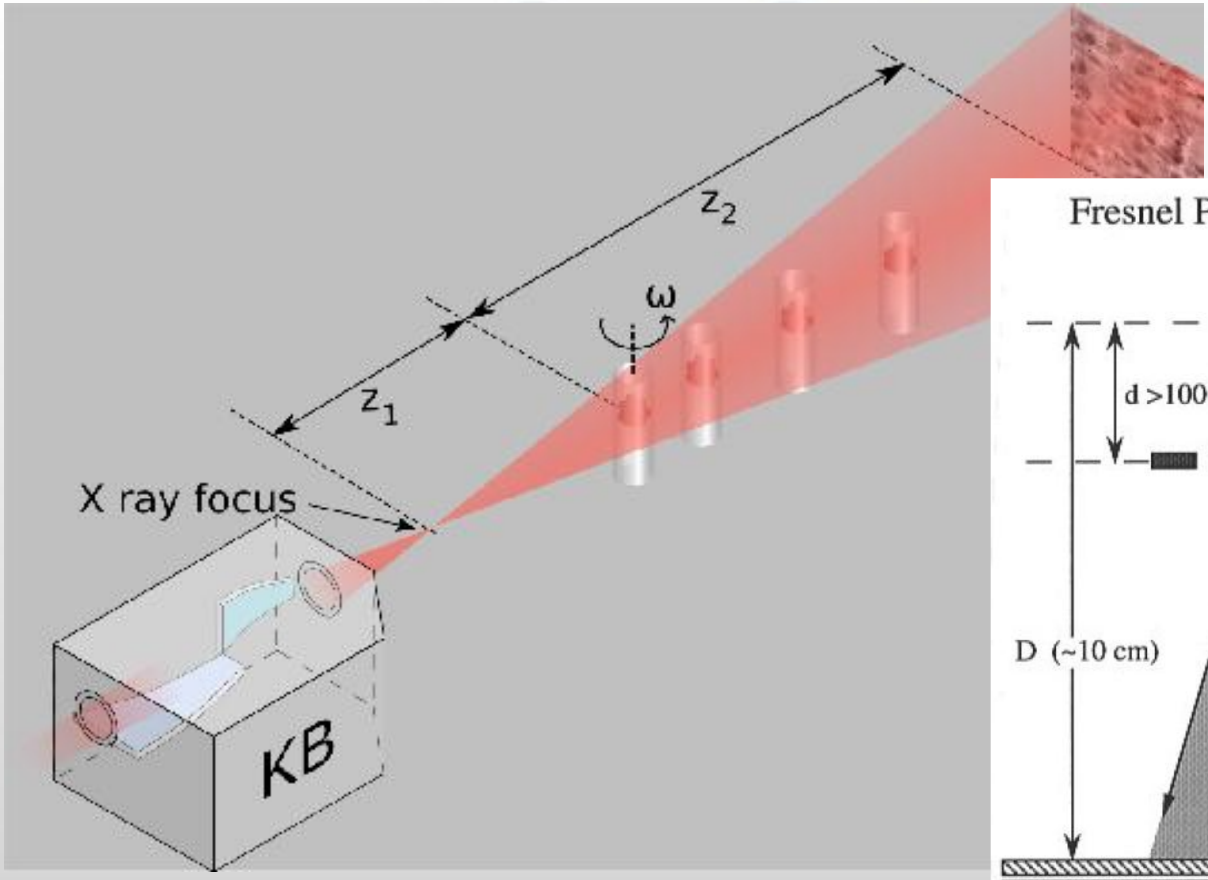
- Ptychography
  - Scanning
  - ~24 h / (small) sample
  - Non-local tomography
  - Detector requirements
  - No optics – high res
  - Quantification better
- Holotomography
  - Full field (fast)
  - ~2 h / (large) sample
  - Local tomography
  - Easy detector
  - Optics – stability limits res
  - Sensitivity seems higher

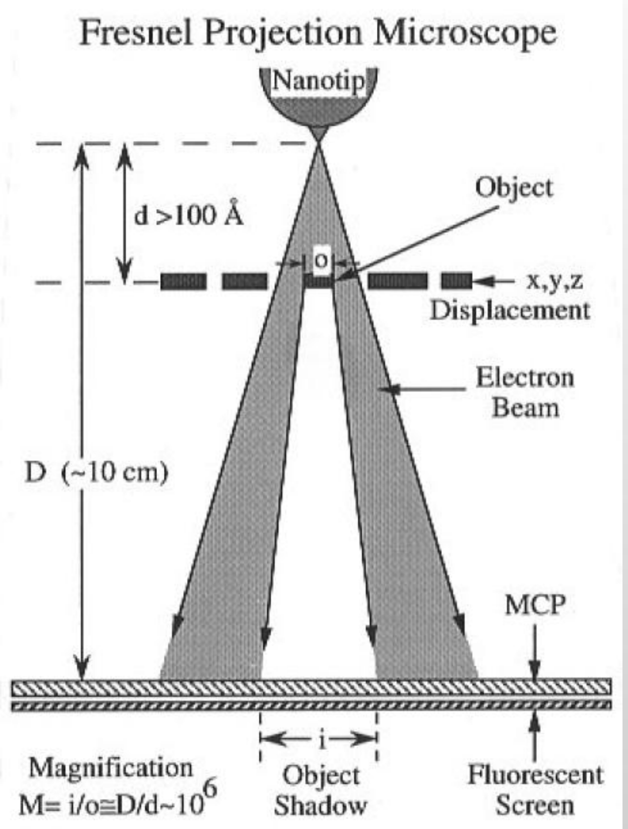






Fresnel projection microscopy



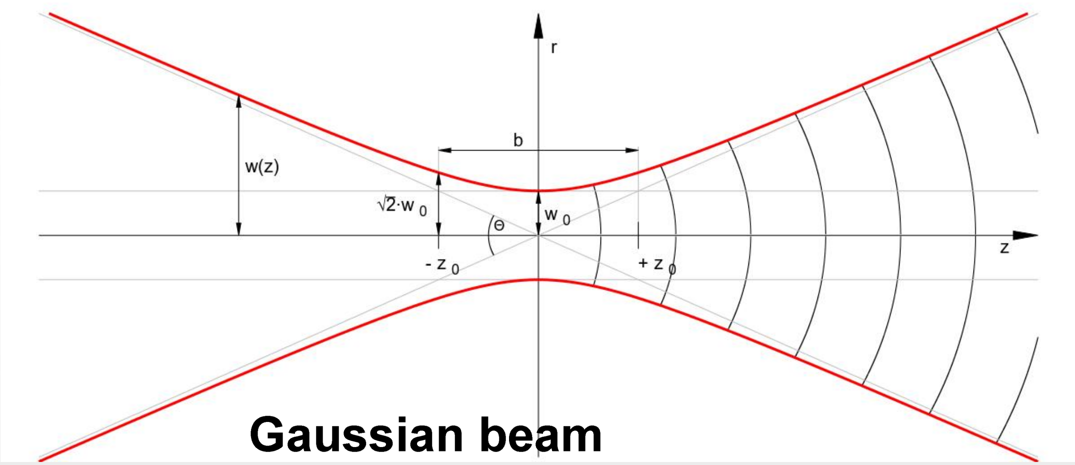


Magnification $M = \frac{z_1 + z_2}{z_1}$

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

Vi Thien Binh et al.
Scanning Microscopy, 12, 93 (1998)
Morton GA, Ramberg EG
Phys Rev 56, 705 (1939)

Fresnel projection microscopy



Gaussian beam

Factors limiting the spatial resolution:

Fresnel diffraction : $1/2\sqrt{\lambda D}$

Phase retrieval through *phase diversity*

Different distances

Different lateral positions with respect to structured illumination

Incoherent contributions to the nanofocus $\mu_{12}(\lambda D f)$

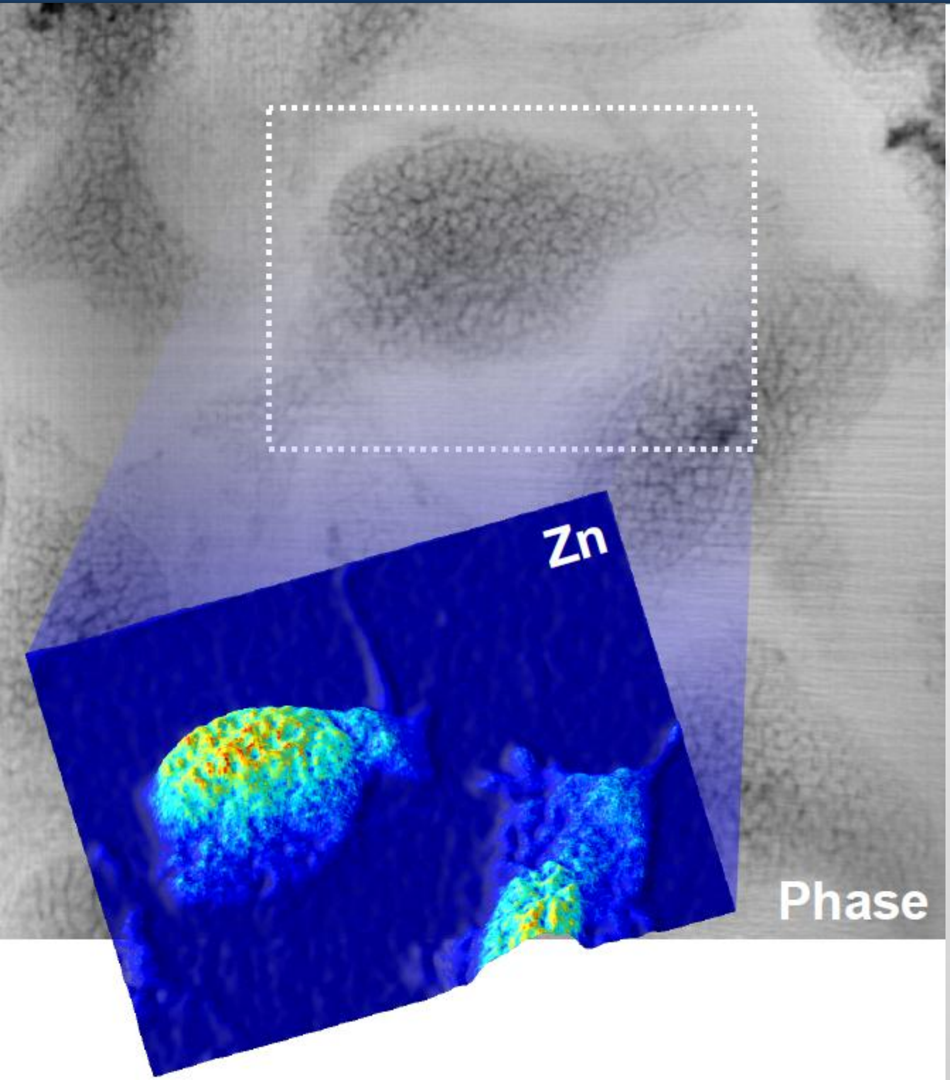
Mechanical vibrations

Electron source size

Not just brightness, coherence limited

1 nm contribution, demagn. 1000 → 1 μm source size

ID16A-NI: Sub-cellular processes



Combined Phase and X-ray Fluorescence Imaging

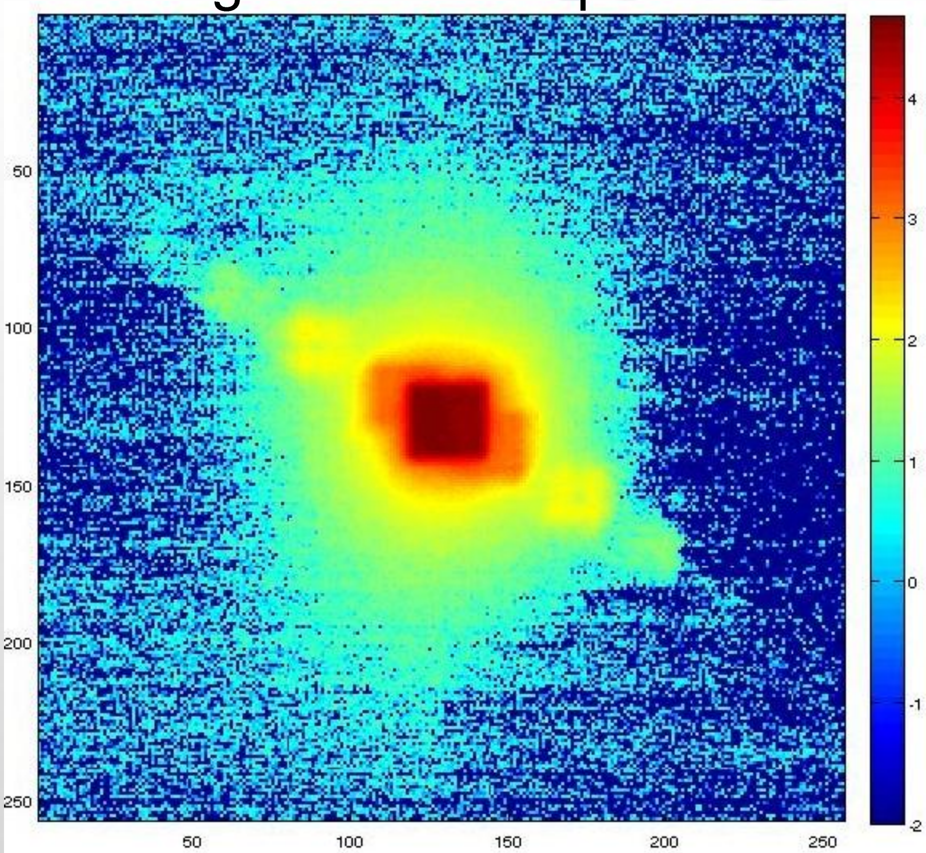
Absolute quantification of mass fractions

E.Kosior et al. J. Struct. Biol. 177 (2012)

Do this simultaneously by combining ptychography and fluorescence?

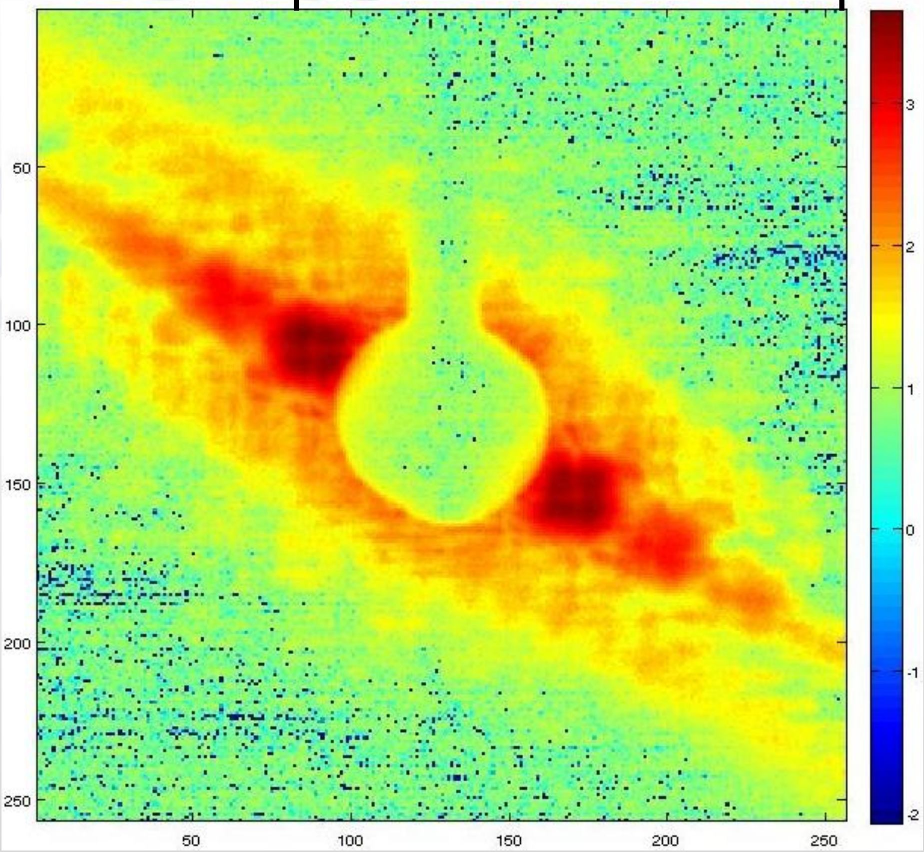
Ptychography with a pink nanoprobe

Single diffraction pattern



30 ms with 100x attenuation

Diffraction pattern with beamstop



30 ms, no attenuation

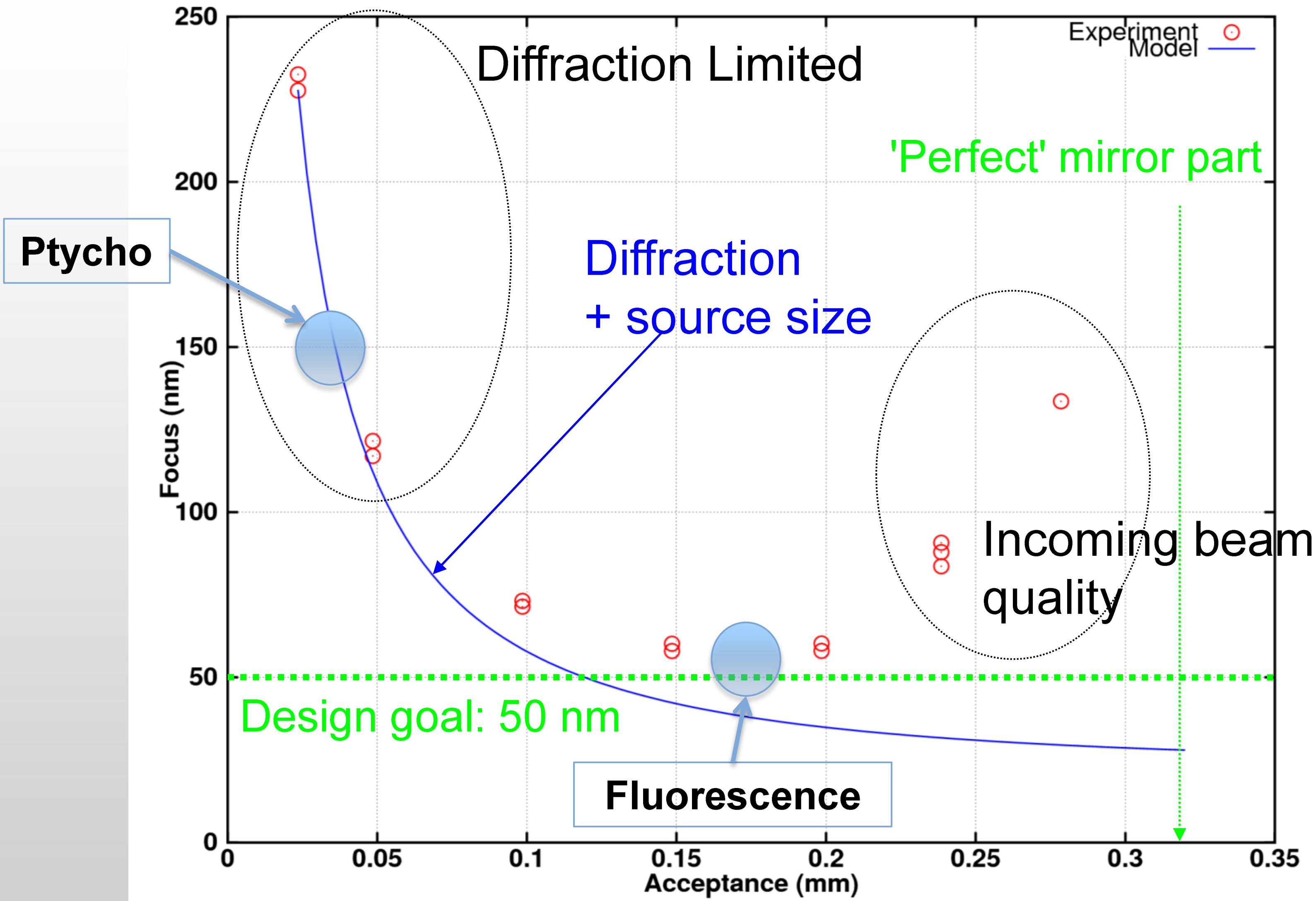
KB slits closed to 70 (V) mm x 35 (H) mm

→ Sufficiently coherent beam

→ Focus increased to 150 nm (diffraction)

P-CDI on ID22NI, M. Dierolf, P. Thibault, B. Benders, F. Pfeiffer

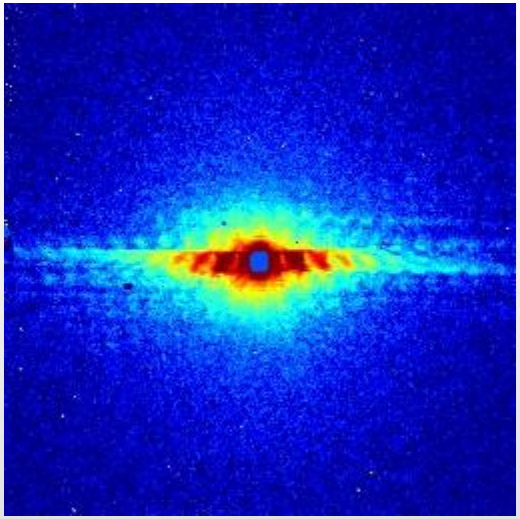
Nano-focusing

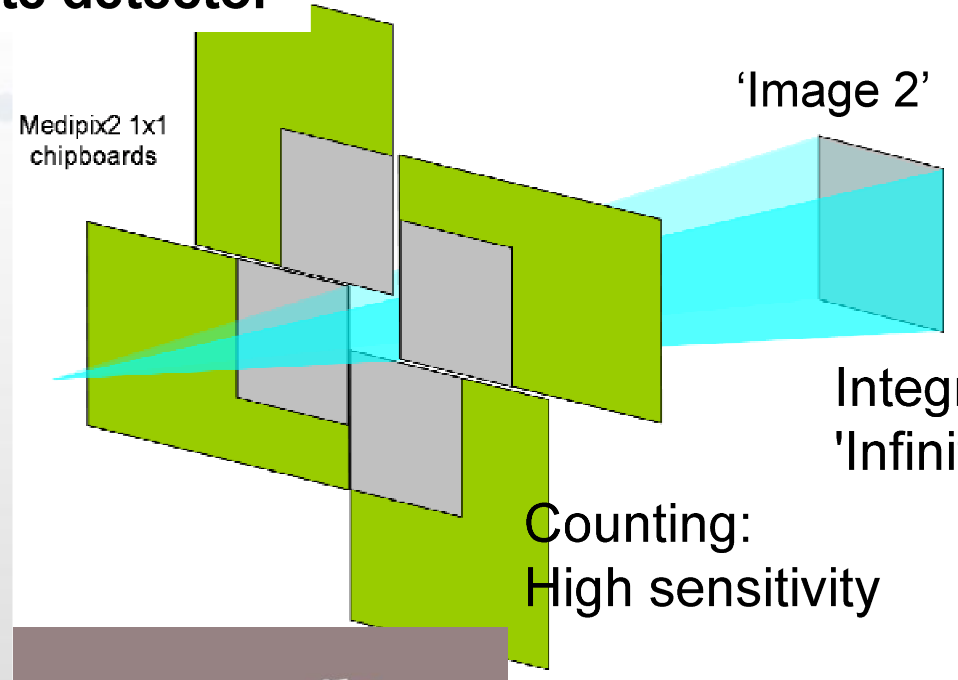


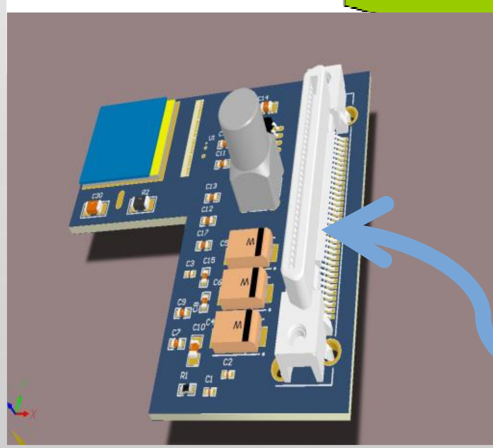
- Trade-off coherence – flux – focus (factor 40 in flux)
- Coherent nanofocus required (not the case today)

The Ptychography detector challenge

Ptychography composite detector







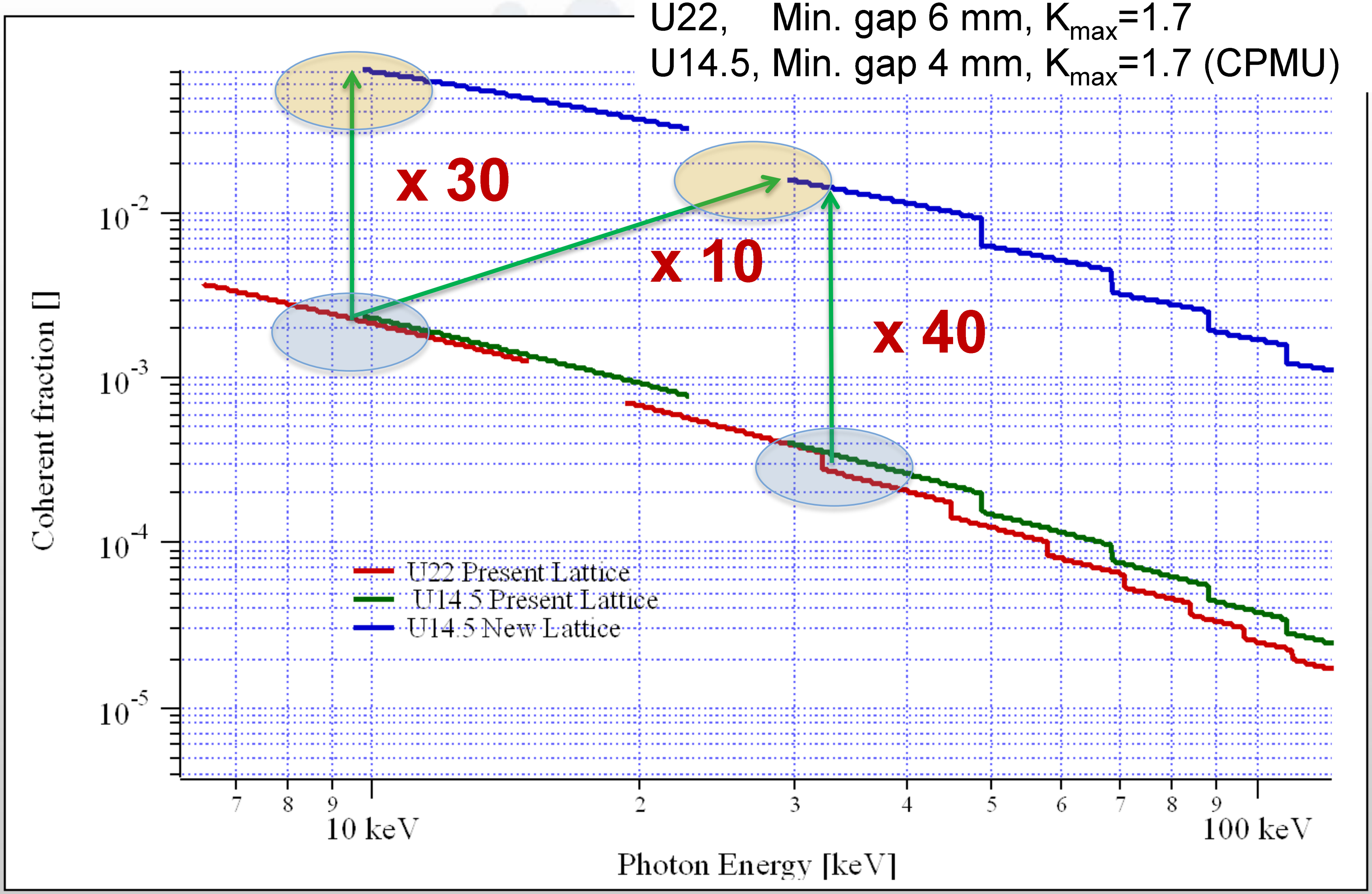
- Integrating + counting part
- Four Medipix modules with central hole

C. Ponchut, J.M. Rigal, C. Jarnias, D. Pothin, P. Cloetens

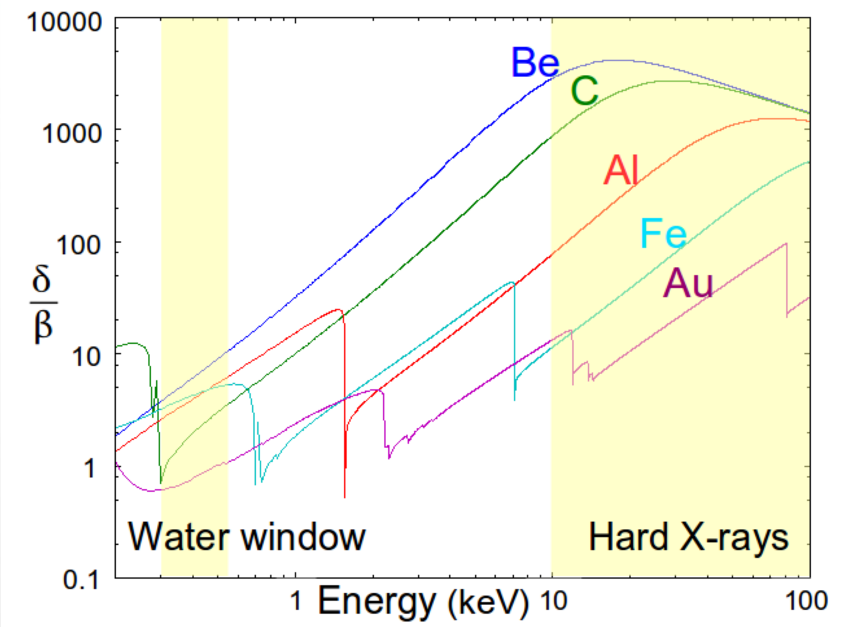
Coherence at lower horizontal emittance

With new short period cryogenic undulators

U22, Min. gap 6 mm, K_{max}=1.7
U14.5, Min. gap 4 mm, K_{max}=1.7 (CPMU)



Low-dose phase imaging

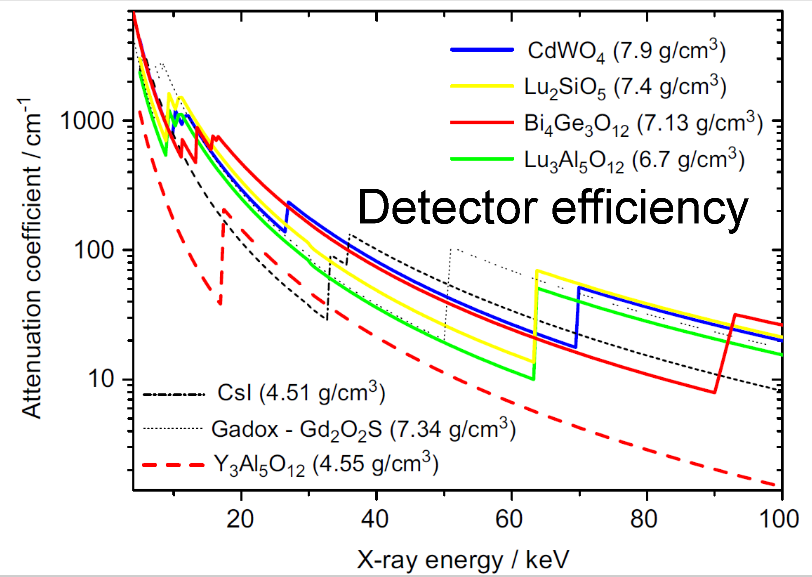


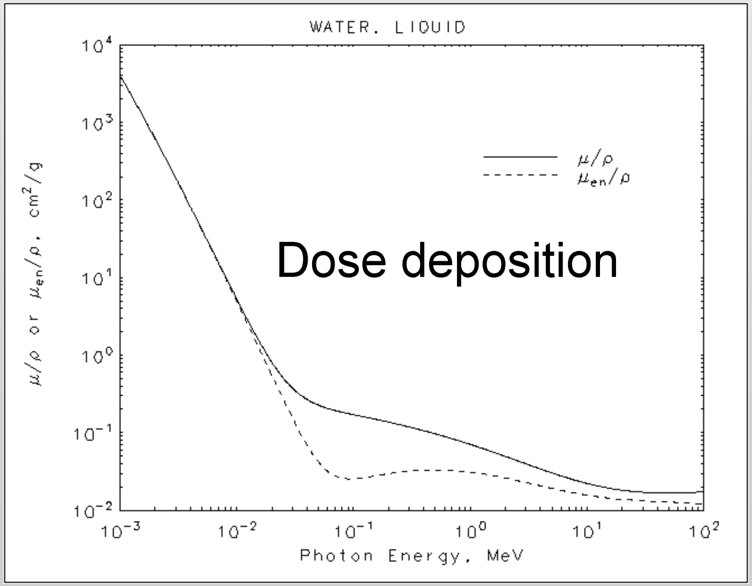
Phase contrast replaces absorption

Gain at **higher energies** until

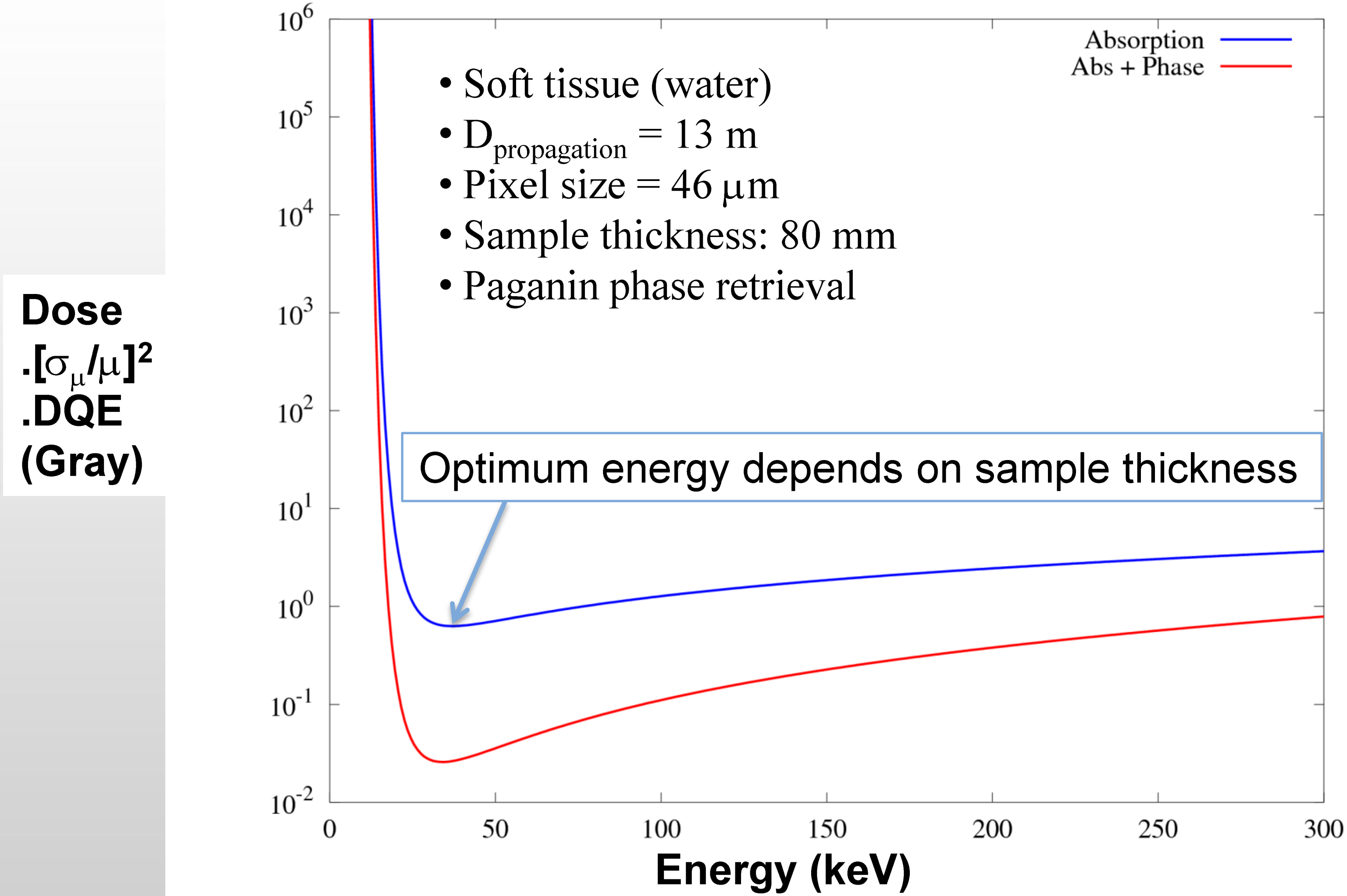
Compton scattering dominates

Potential gain of 100 or 1000



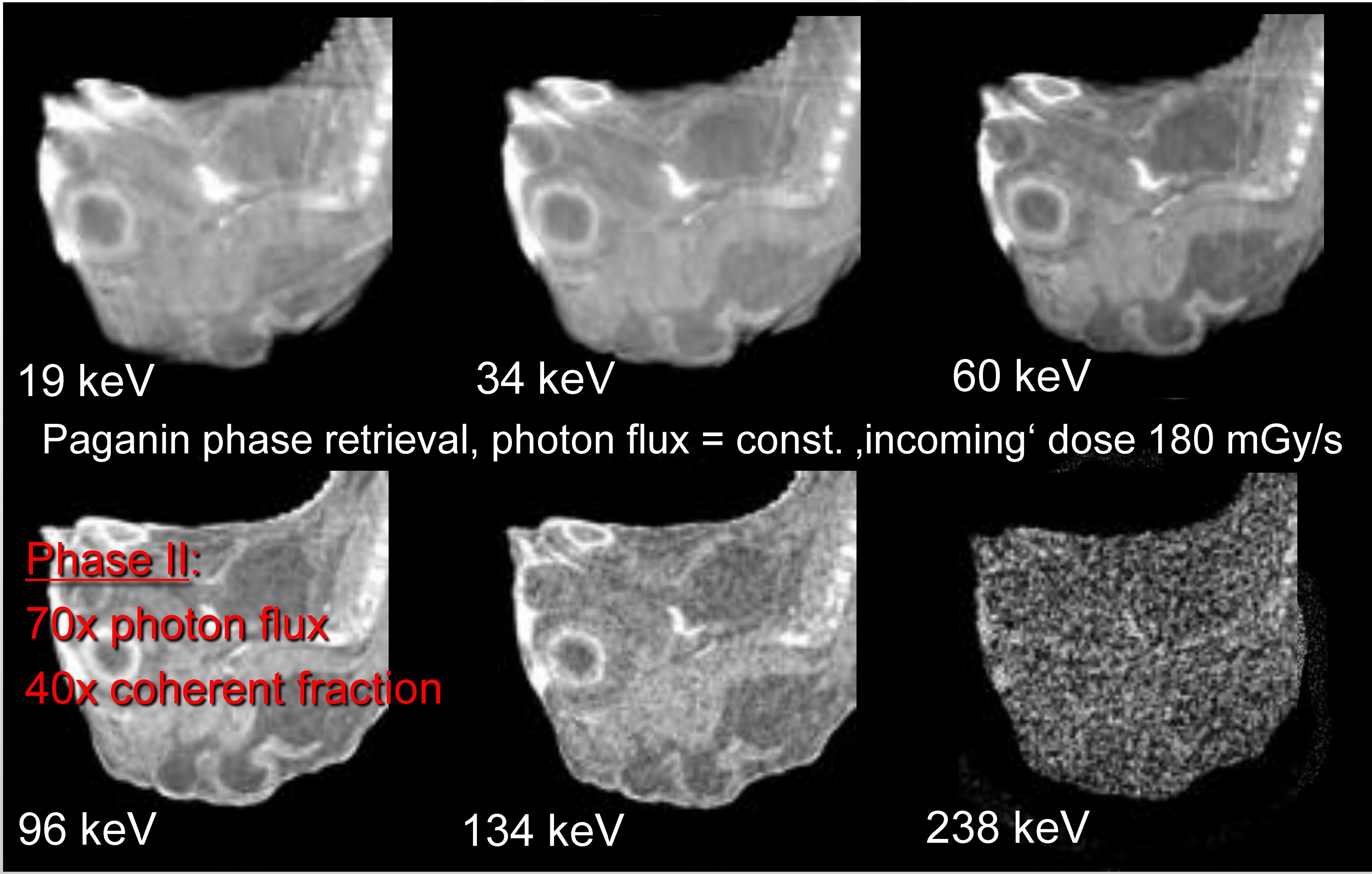


Low-dose phase imaging



Similar to absorption case in Flannery and Roberge, J. Appl. Phys. 62, 4668 (1987)

Feasibility: low dose phase imaging



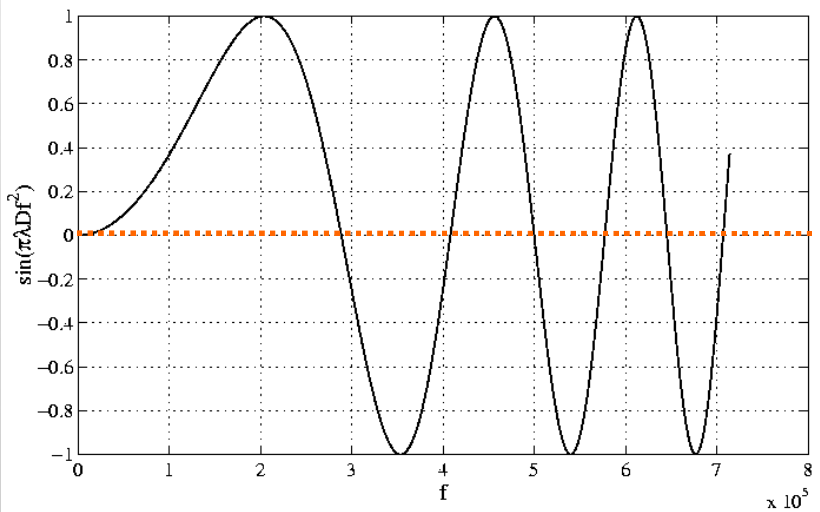
Crocodile embryo *ex vivo* ‚in air‘ - Rack, Tafforeau et al. (unpublished, ID19)

Low-dose phase imaging

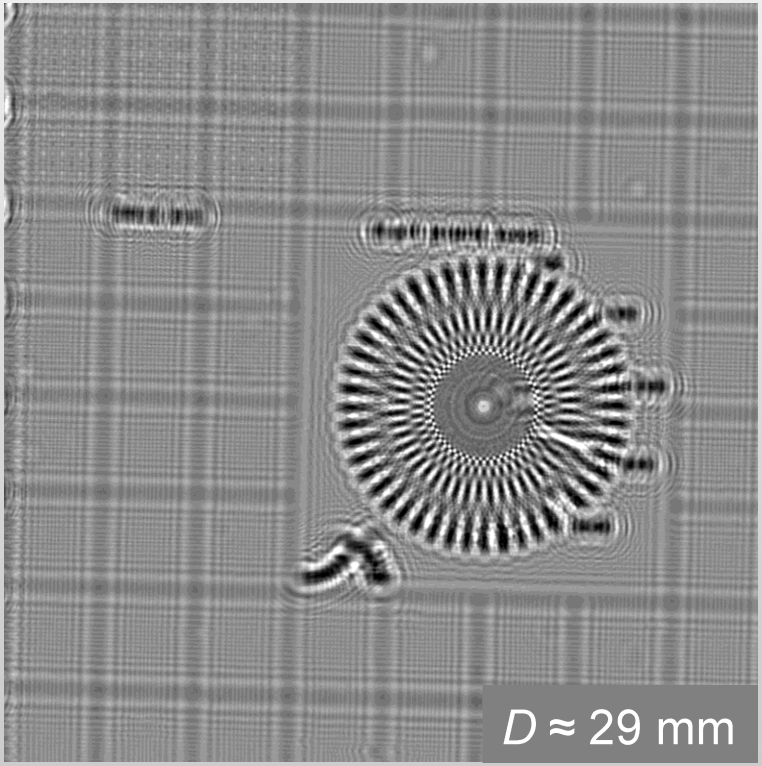
Rose criterion $\Delta a \geq \frac{5}{C\sqrt{f\,N}}$

Improve contrast by moving to a more holographic regime (larger defocus *D*)
Required dose decreases quadratically versus contrast

Requires *better coherence* $\mu_{12}(\lambda D f)$
Phase retrieval more difficult

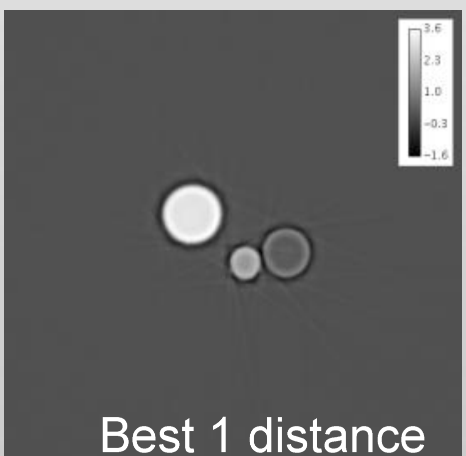


"transfer function"

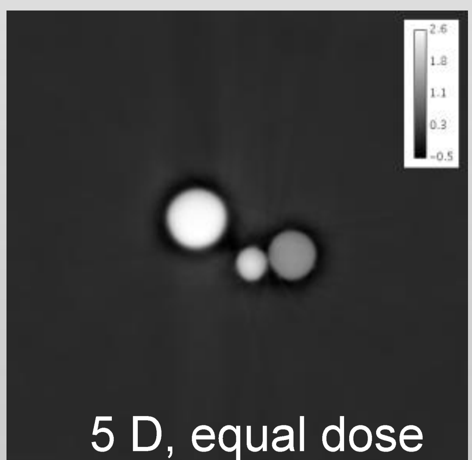


Dose fractionation

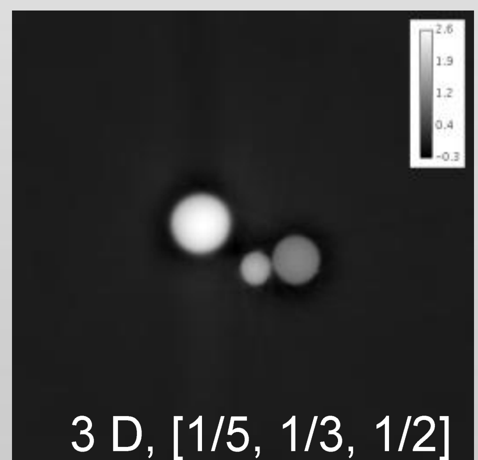
- Multiple distances -> higher dose?
- Acquire scans of phantom object using different number of distances (1-7) while keeping total dose constant
- Reconstruct phase tomograms with paganin’s method (1) and mixed approach
- Best 1 D – NE 30.9 %, RSD 1,7 %
- Best multiple D (5) – NE 16.9 %, RSD 1.7 %
- **Multiple distances can give better image quality at same dose**
- Optimization of dose delivery in each distance while keeping total dose constant
- Best conditions: 3 D, [1/6, 1/3, 1/2] fraction of dose
- NE 4.8 %, RSD 1.9 %
- Optimizing dose delivery in each distance can improve image quality
- SNR in longer distances most important
- MSc project Thibaut Frachon



Best 1 distance



5 D, equal dose

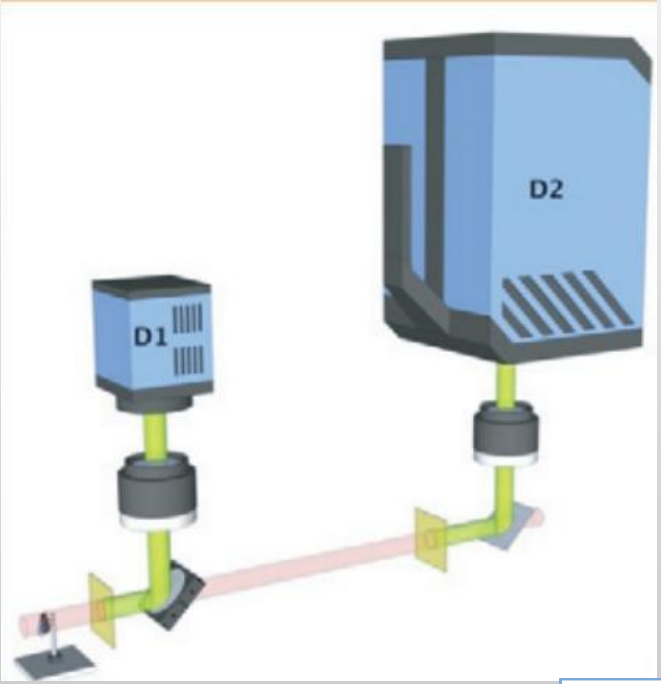


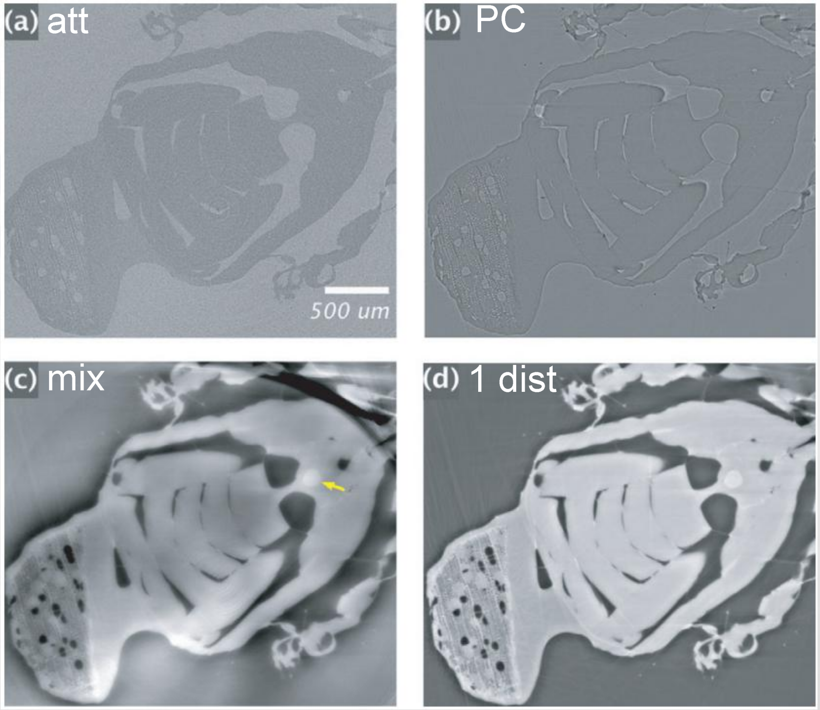
3 D, [1/5, 1/3, 1/2]

Low-dose phase imaging

Multiple distances in one shot

- Images at several distances requires time for camera displacement?
- Use a semi-transparent detector
- Attenuation and phase contrast (or two phase contrast images) in one shot





- One shot -> fast acquisitions
- Phase retrieval from one attenuation and one phase contrast image?
- Dream: attenuation and phase retrieval from two phase contrast images

Mokso et al, J Phys D, 22/11/2013

Fast, efficient (high E), 3D-detectors for imaging


Thank you for your attention