A Light for Science

European Synchrotron Radiation Facility

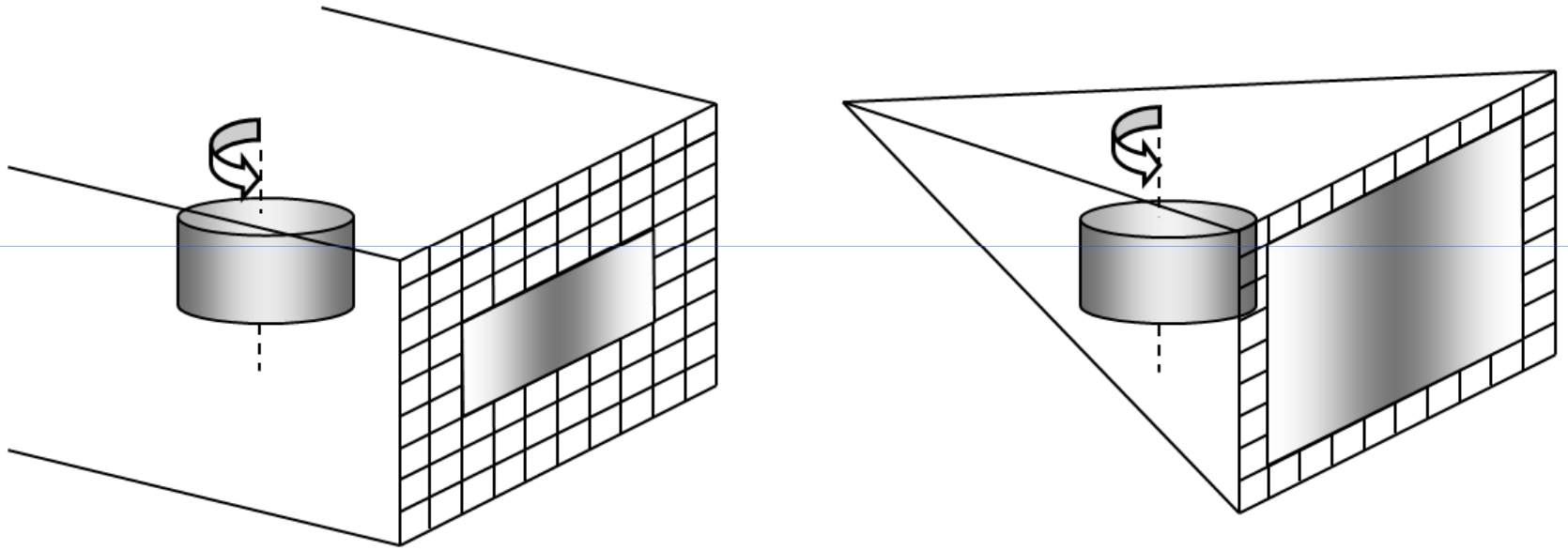
X-ray imaging

Alexander Rack
European Synchrotron Radiation Facility, France

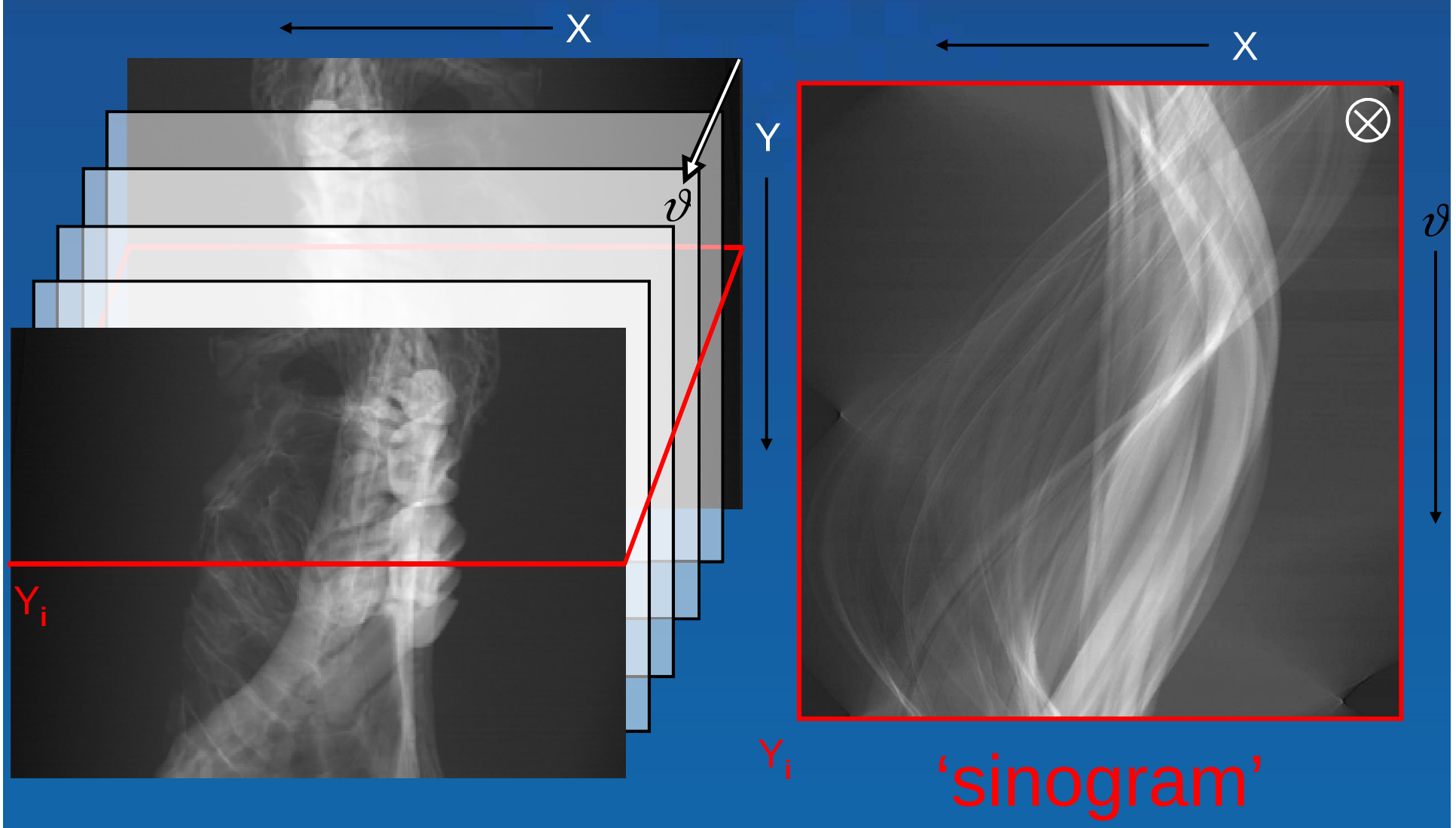
Introduction

- X-ray Imaging, Contrast & Spatial Resolution -

Full-field X-ray Imaging



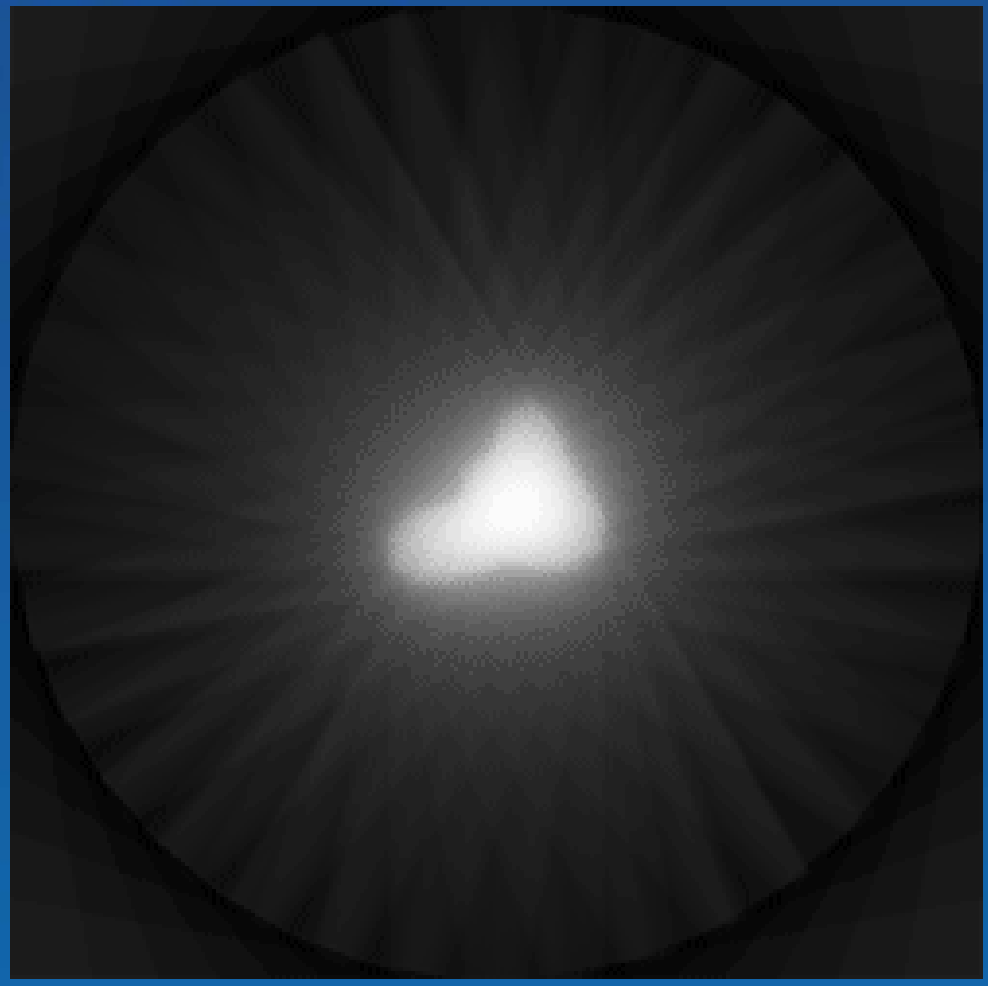
Tomographic Reconstruction



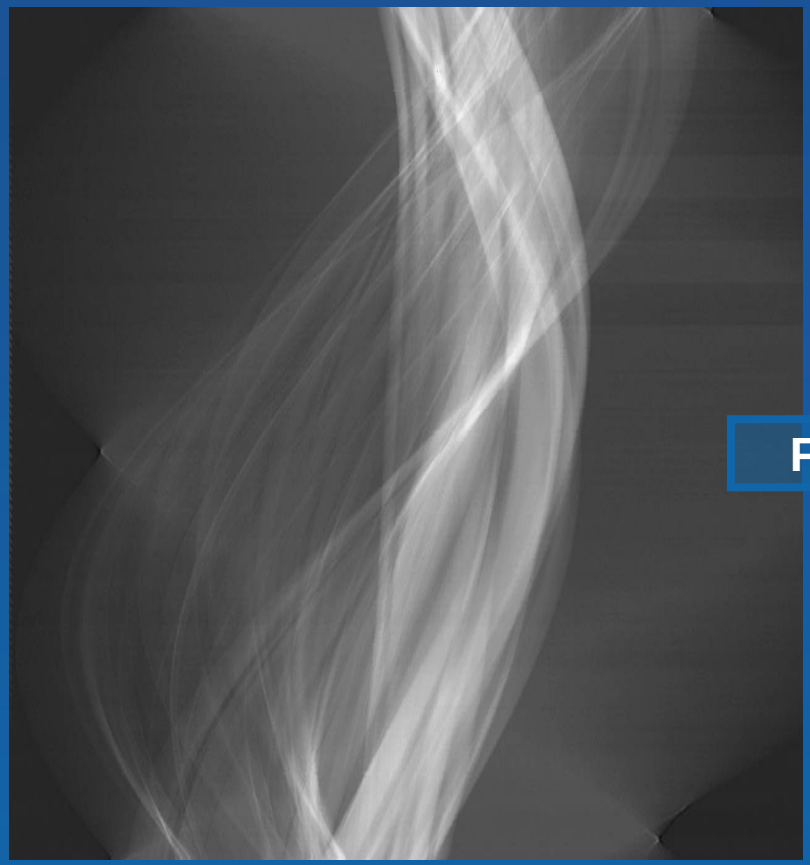
(Filtered) Backprojection

$$\frac{\text{number of projections}}{\text{pixels per line}} \geq \frac{\pi}{2}$$

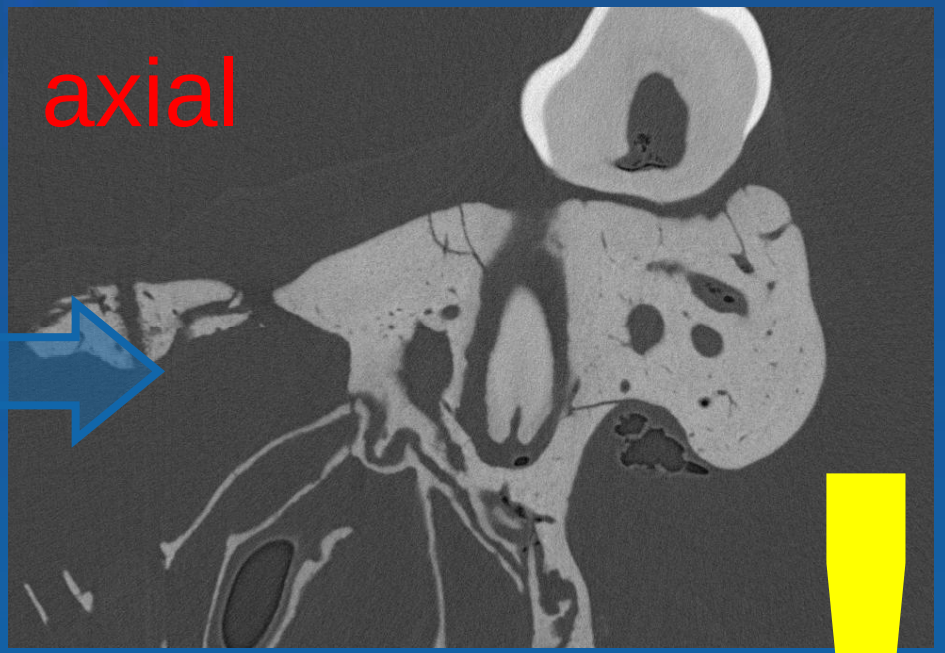
(Shannon's theorem)



Tomographic Reconstruction

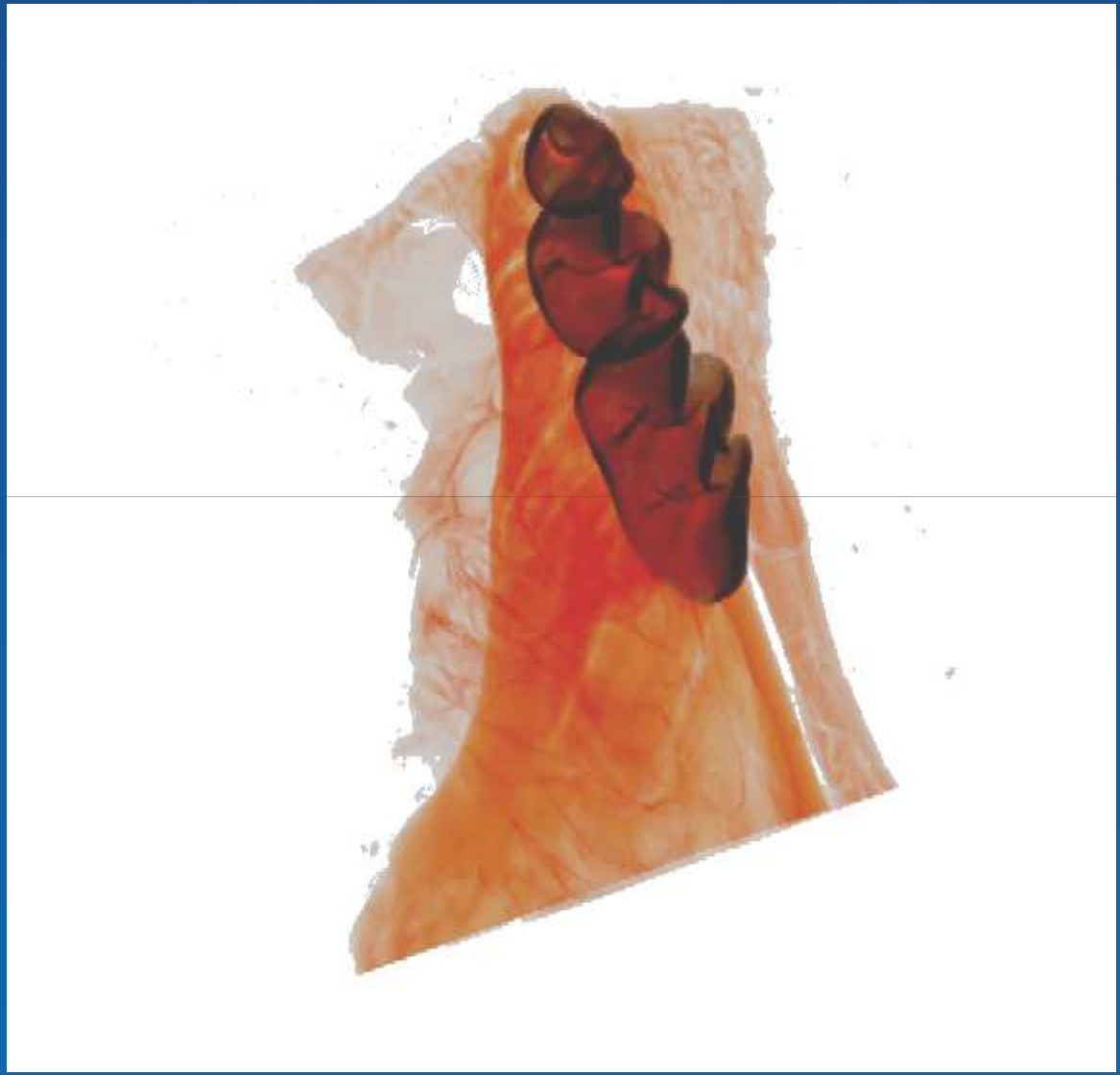


FBP

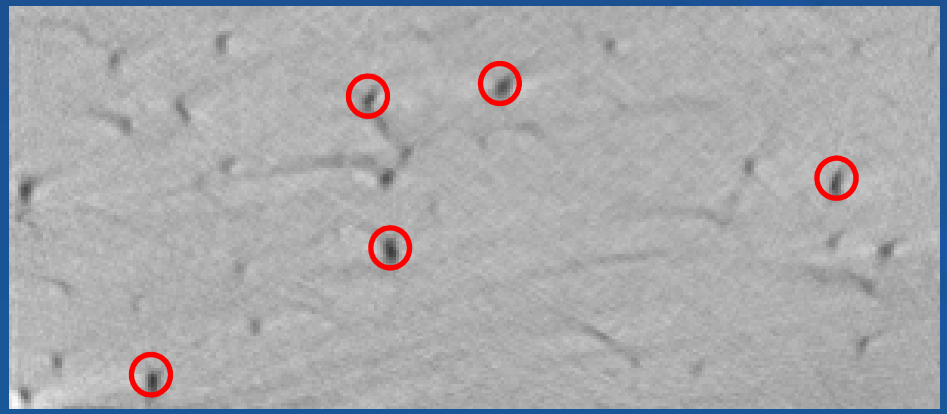


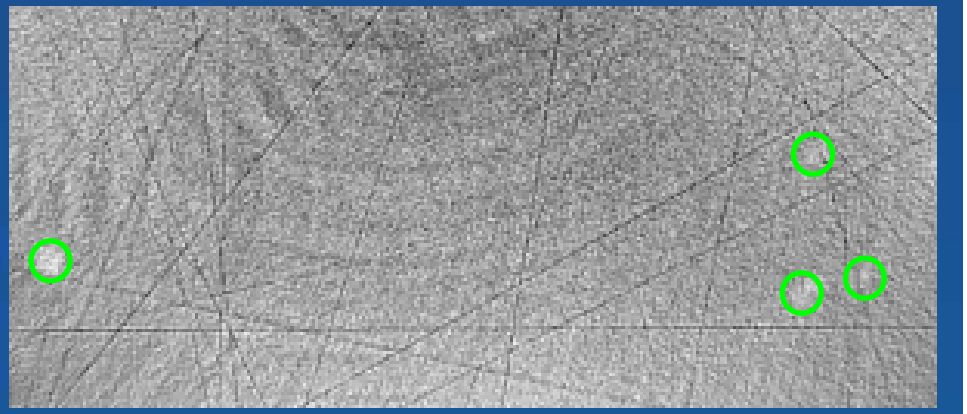
!

Volume Image = Stack of Slices



X-ray Contrast: Absorption

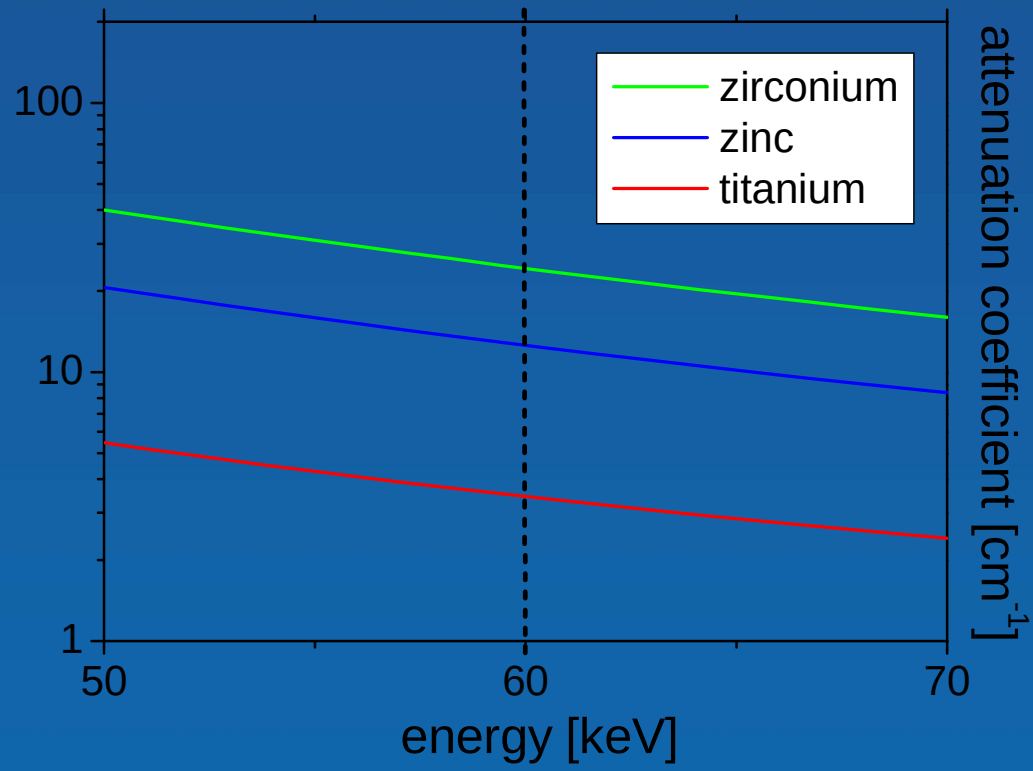




$Zn+TiH_2$ bulk

pre-cursor:

0.50 vol%

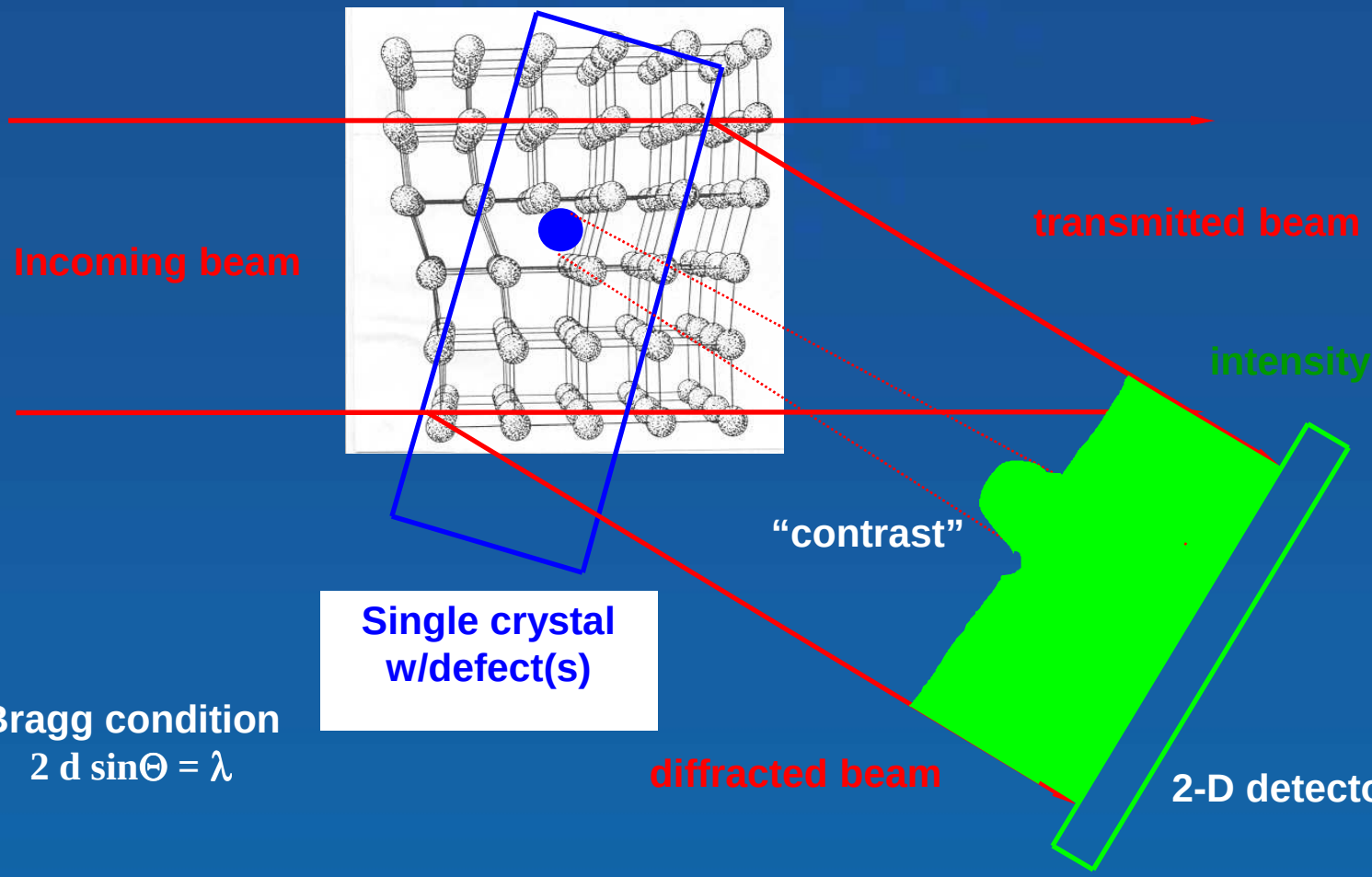


$Zn+ZrH_2$ bulk

pre-cursor:

0.66 vol%

X-ray Topography



courtesy: J. Härtwig (ESRF)

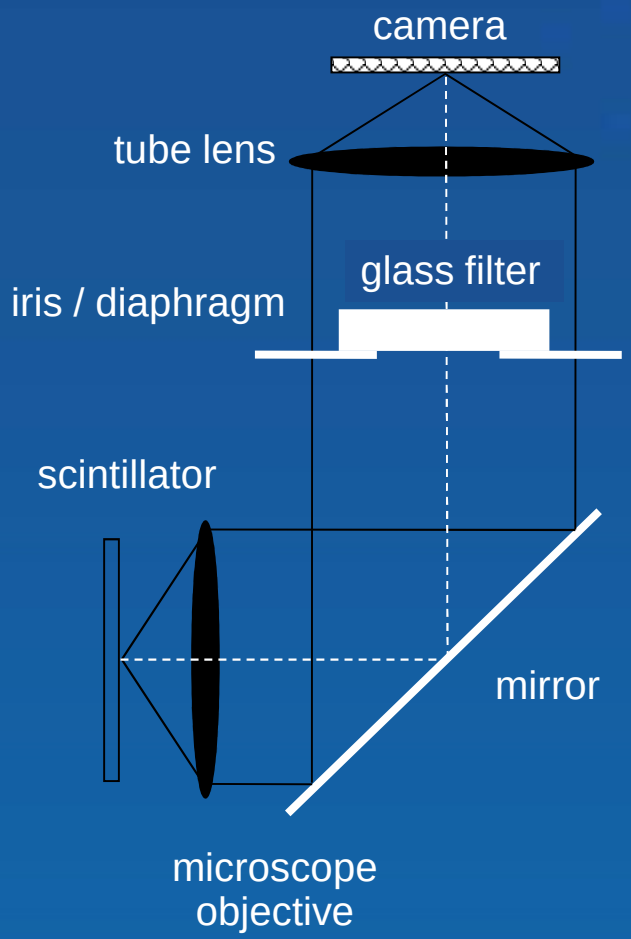
The Quest for the ideal X-ray Detector

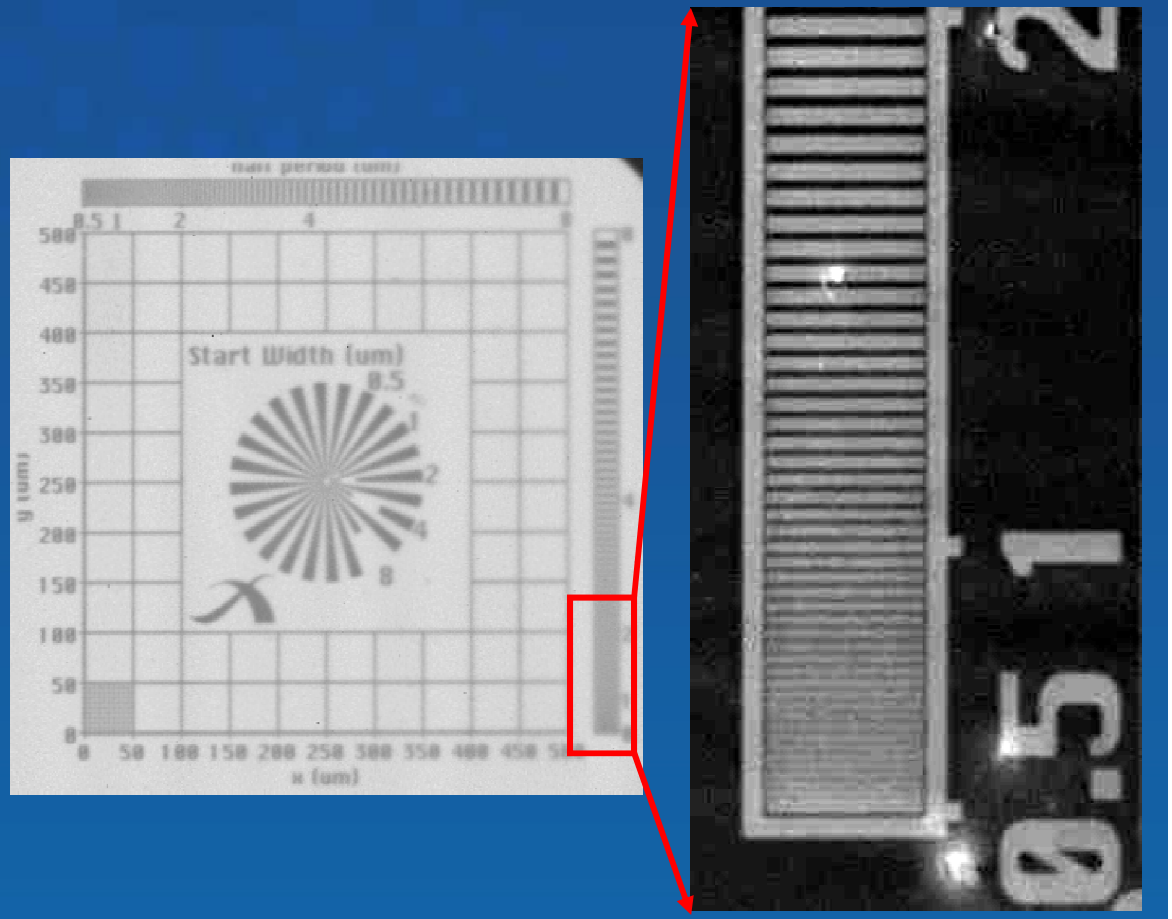
energy-dispersive	scanning	2D/3D XRF, XAS	*silicon drift diode*
high resolution full-field	full-field	magnified (holo-)µCT	*indirect detection*
single photon counting	scanning	ptychography	*pixel detector vs. integrating*
very large field of view	scanning / full-field	2D/3D XRD	*CCD w/taper*

dynamic range, efficiency, noise, read-out, radiation hardness ...

Detector: Micrometer Resolution

Bonse, Busch 1996





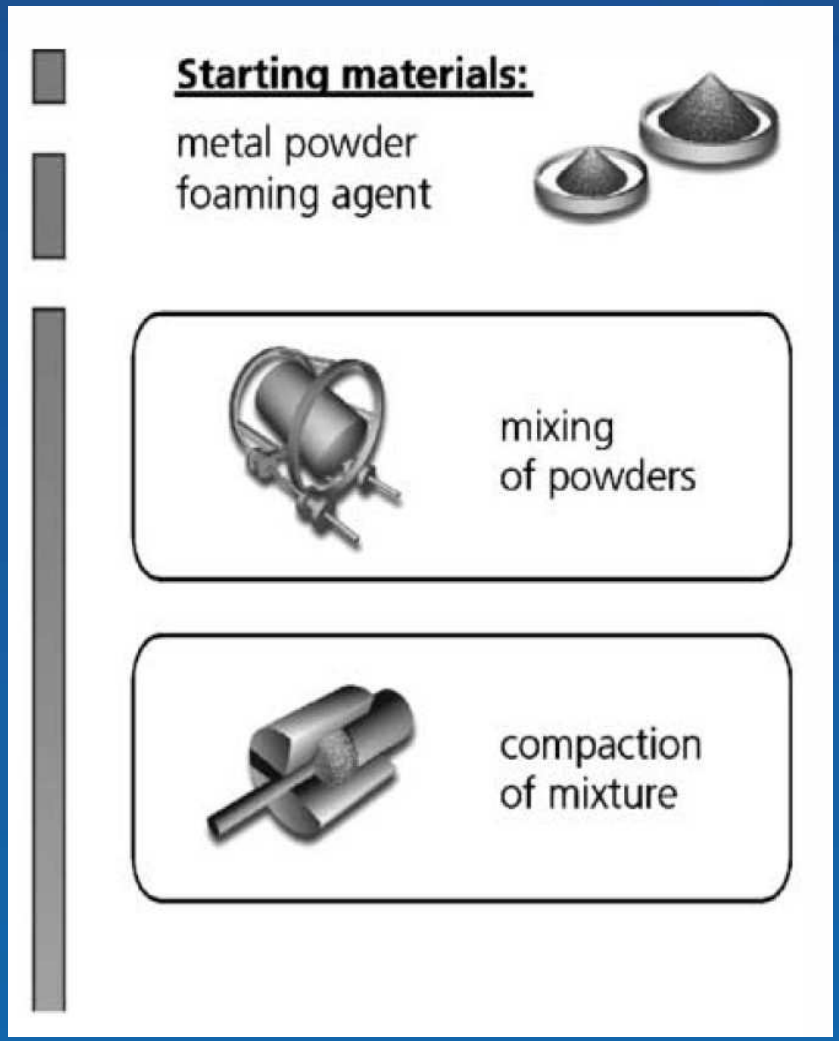
resolution, efficiency

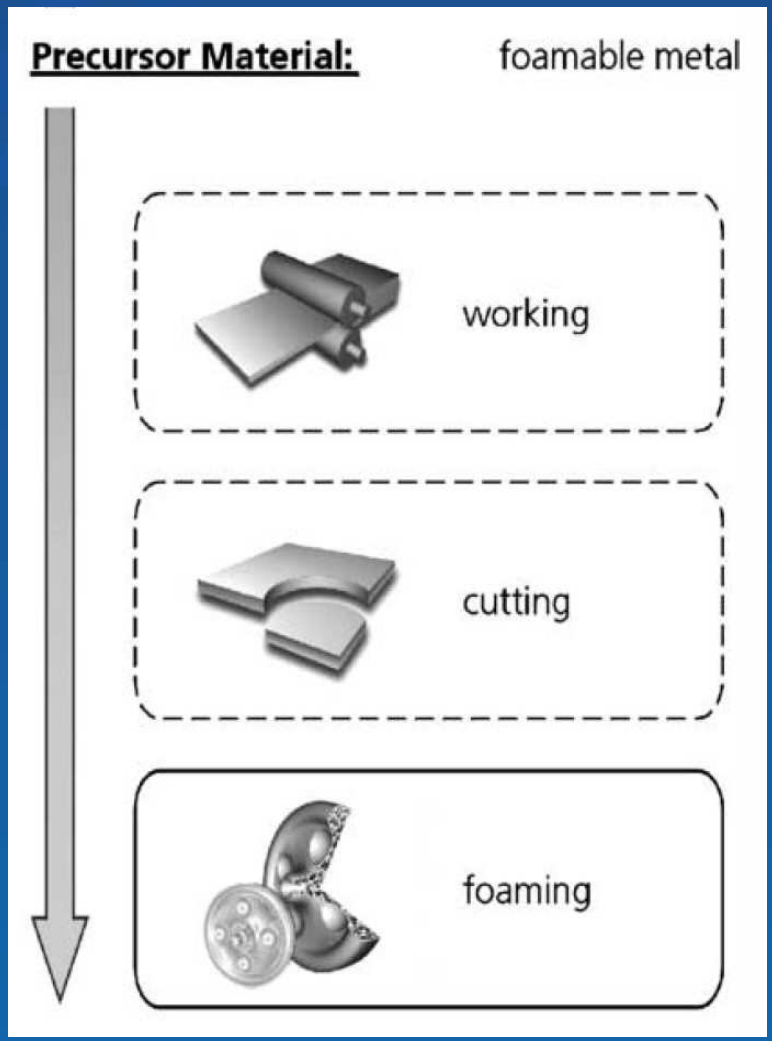
Rack et al., Nucl Instr Meth B 267 (2009)

Metallic Foams

- Microtomography & Image Analysis -

Metal foaming production route



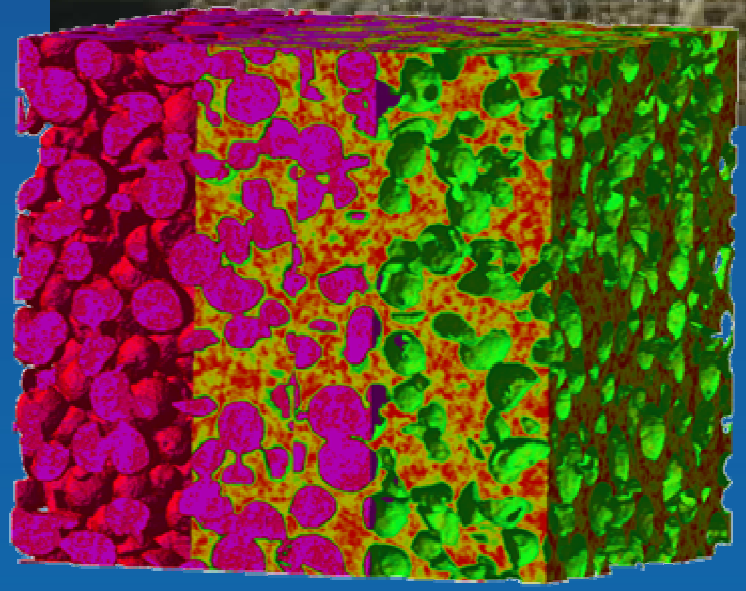


J. Banhart, Prog Mat Sci (2001)

Metallic Foams

HZB Berlin

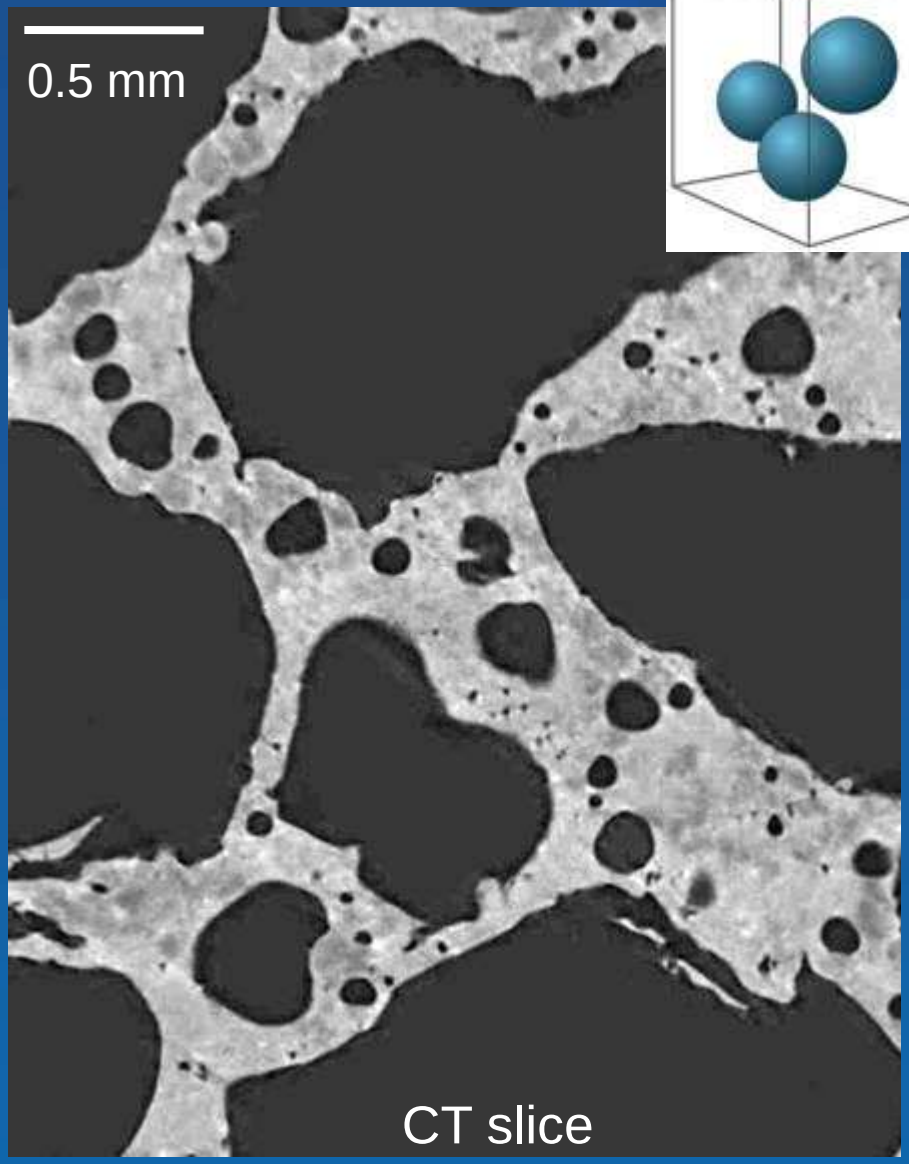
1 cm



1 mm

Fraunhofer IFAM Bremen

Metallic Foams - Microtomography



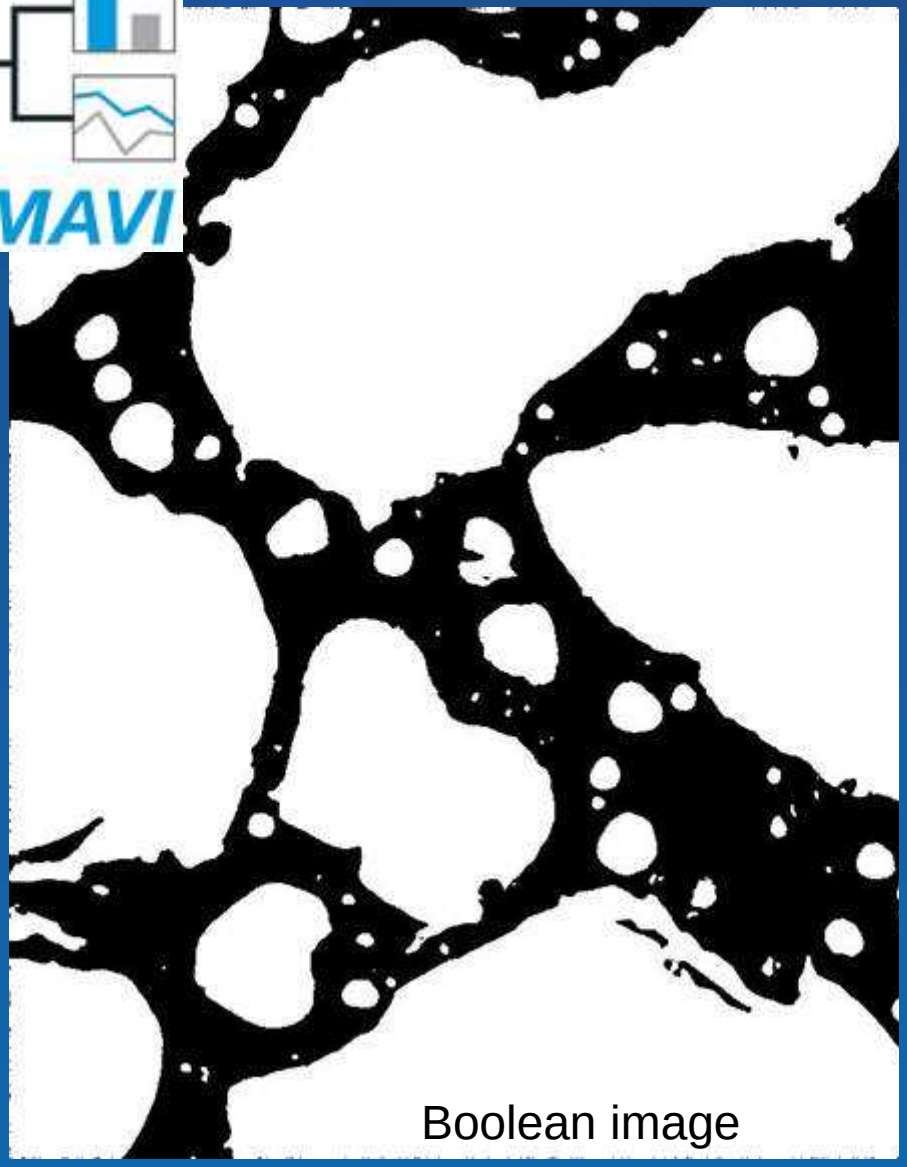
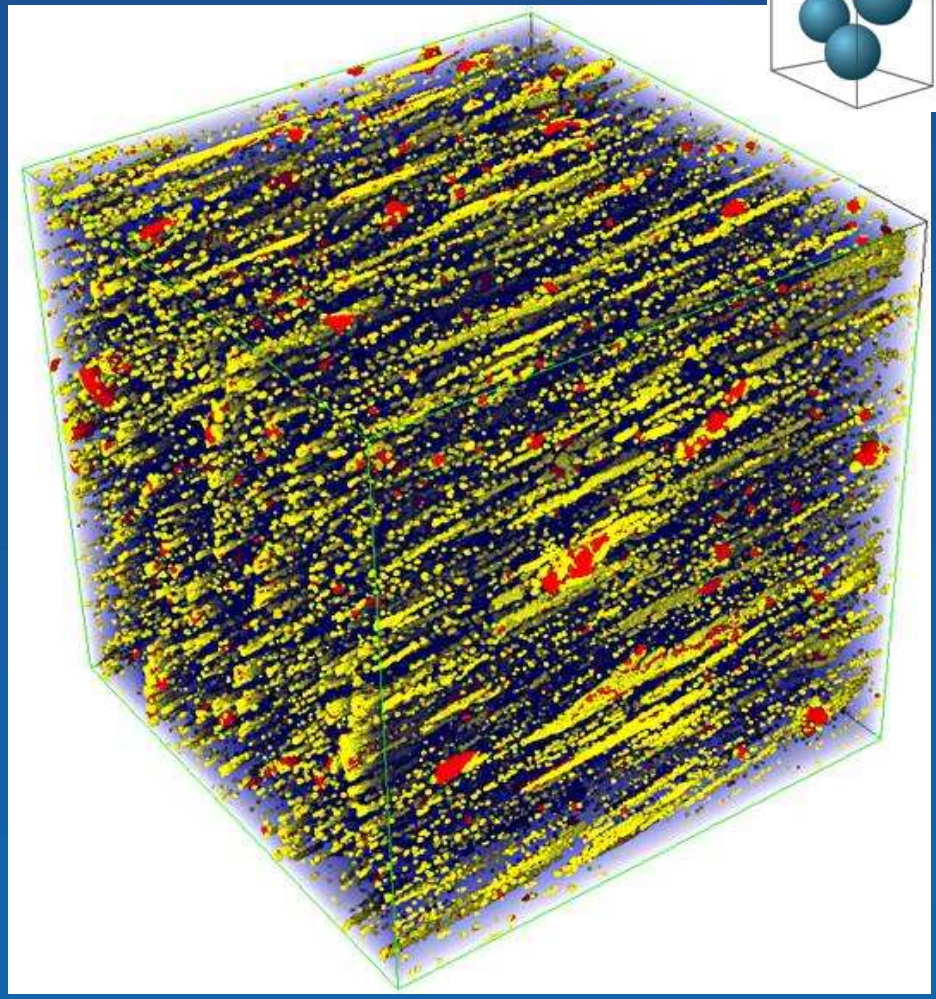
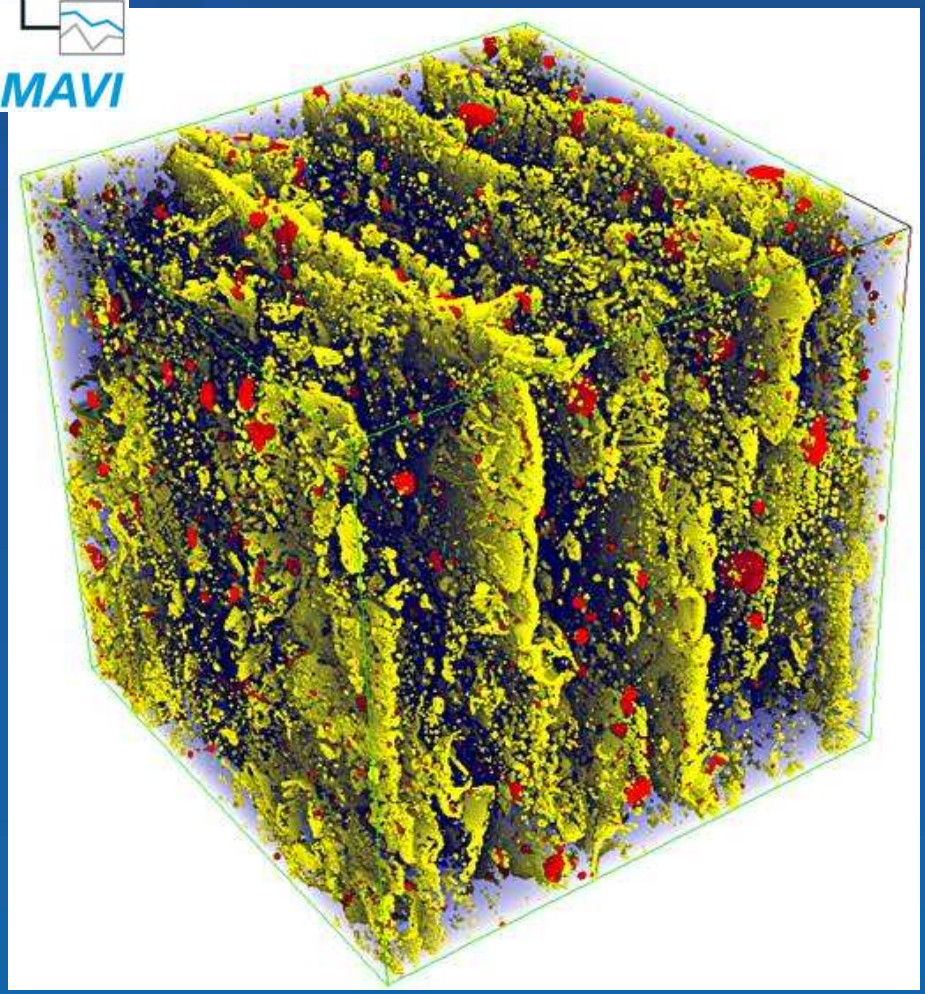


Image Analysis

MAVI





Al6061 (commercial AlSi alloy)

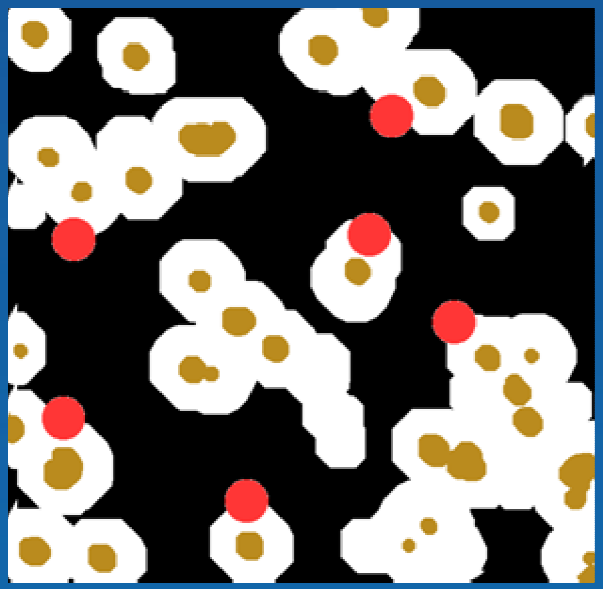
AlSi7 (elemental Al-Si mixture)

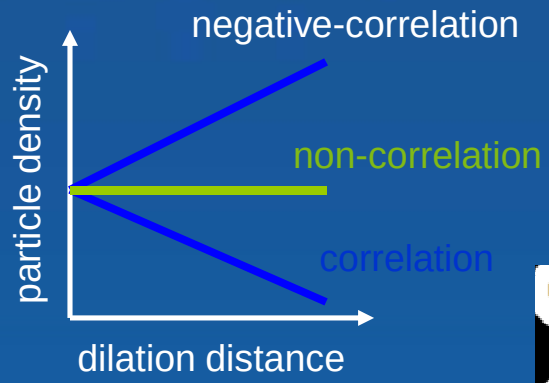
Image Analysis

pore dilation ⊠ calculation of the particle density found in each poor neighborhood

decreasing/increasing particle density

correlation/negative-correlation





particle pores

pore neighborhood

Helfen, Ohser, Schladitz et al., Proc. SPIE 2003

constant particle density

non-correlation

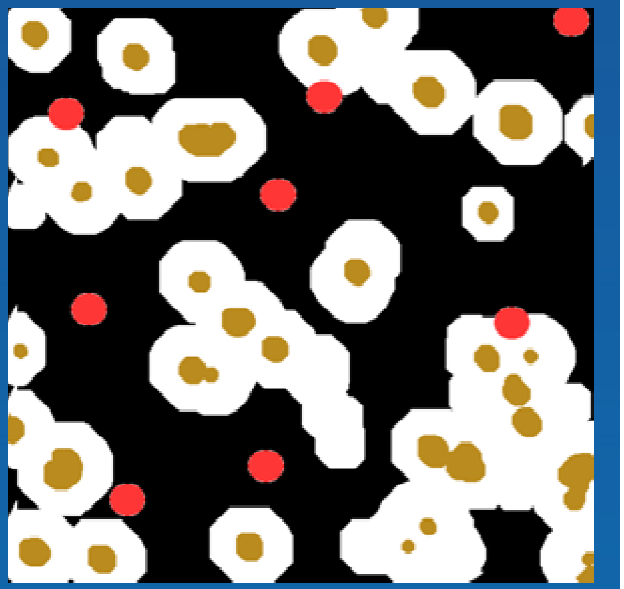
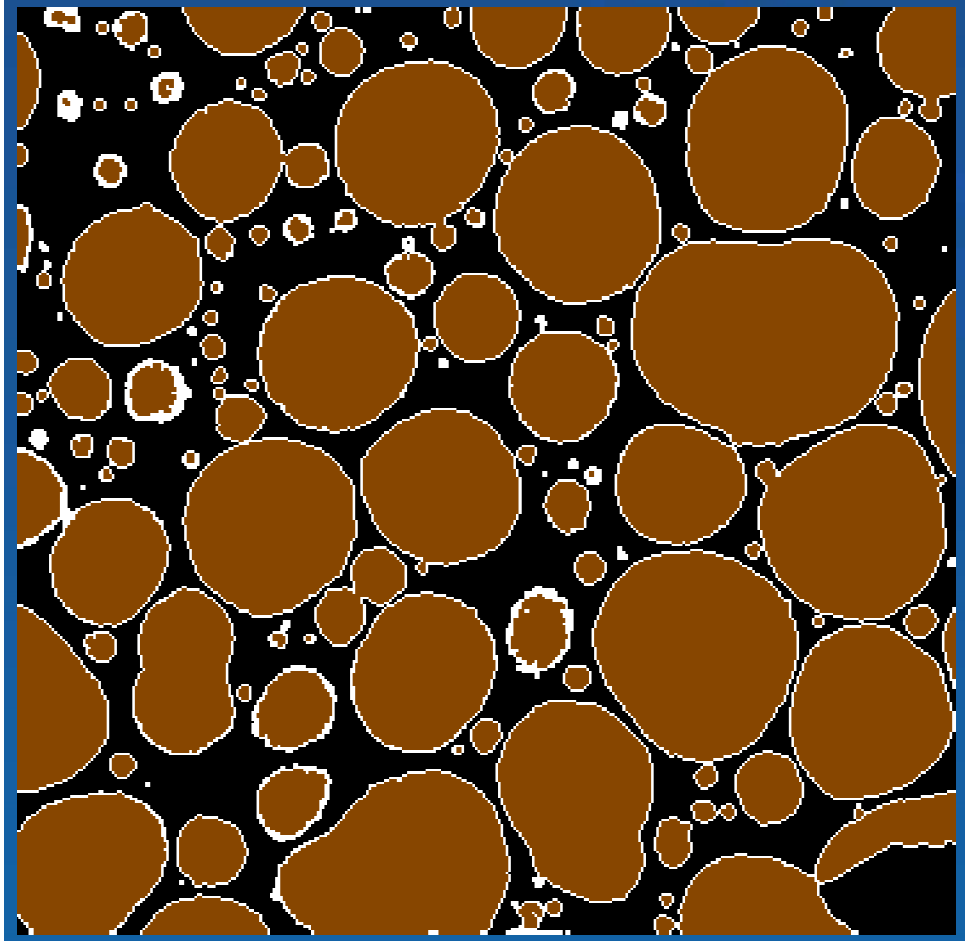
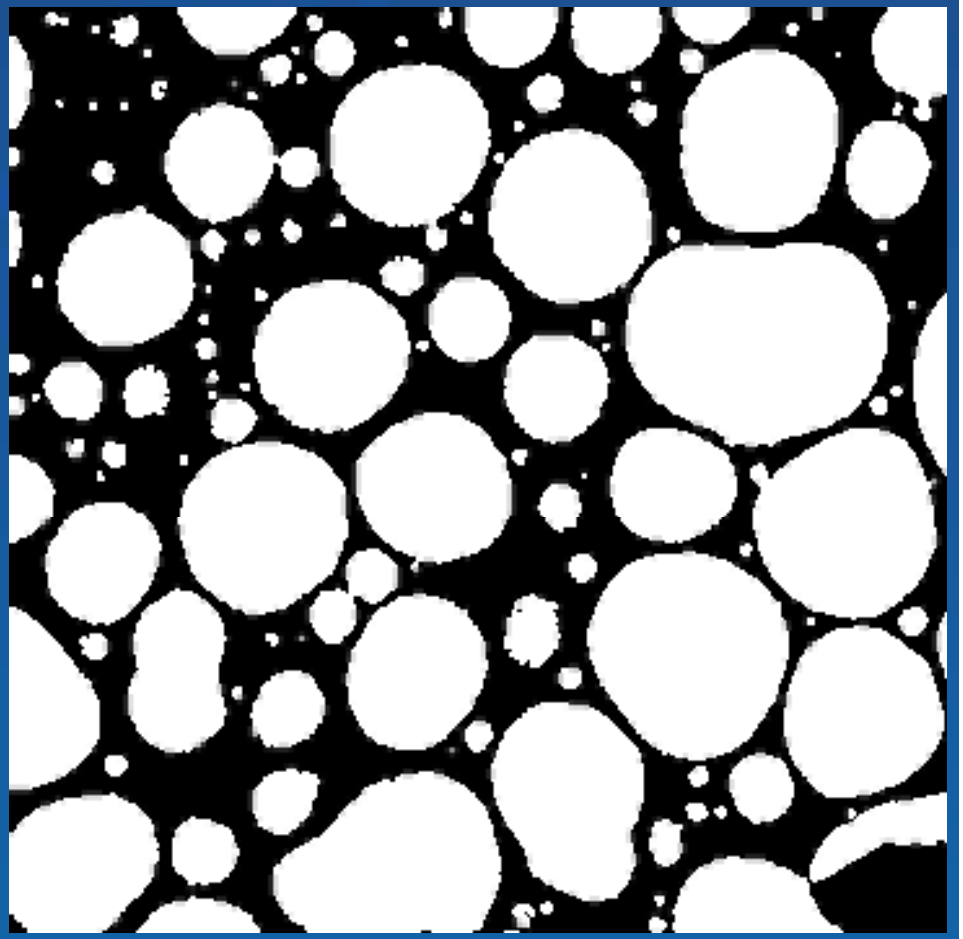


Image Analysis



First dilation step



Dilation of pore volume in successive steps

Spatial Cross-Correlations

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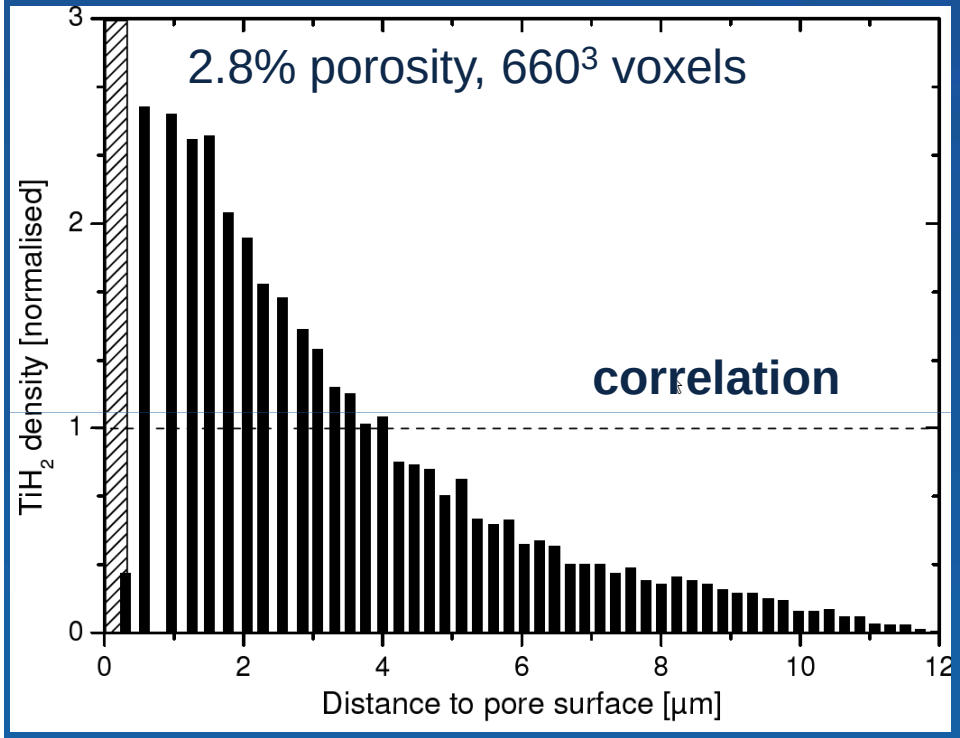
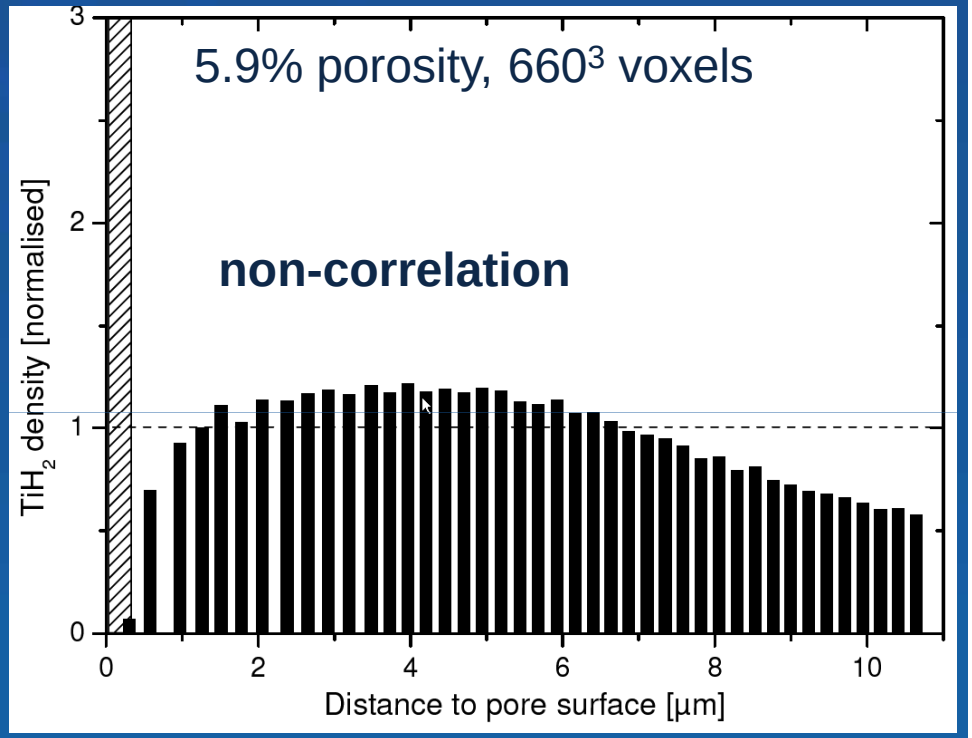
Al6061 (commercial AlSi alloy)



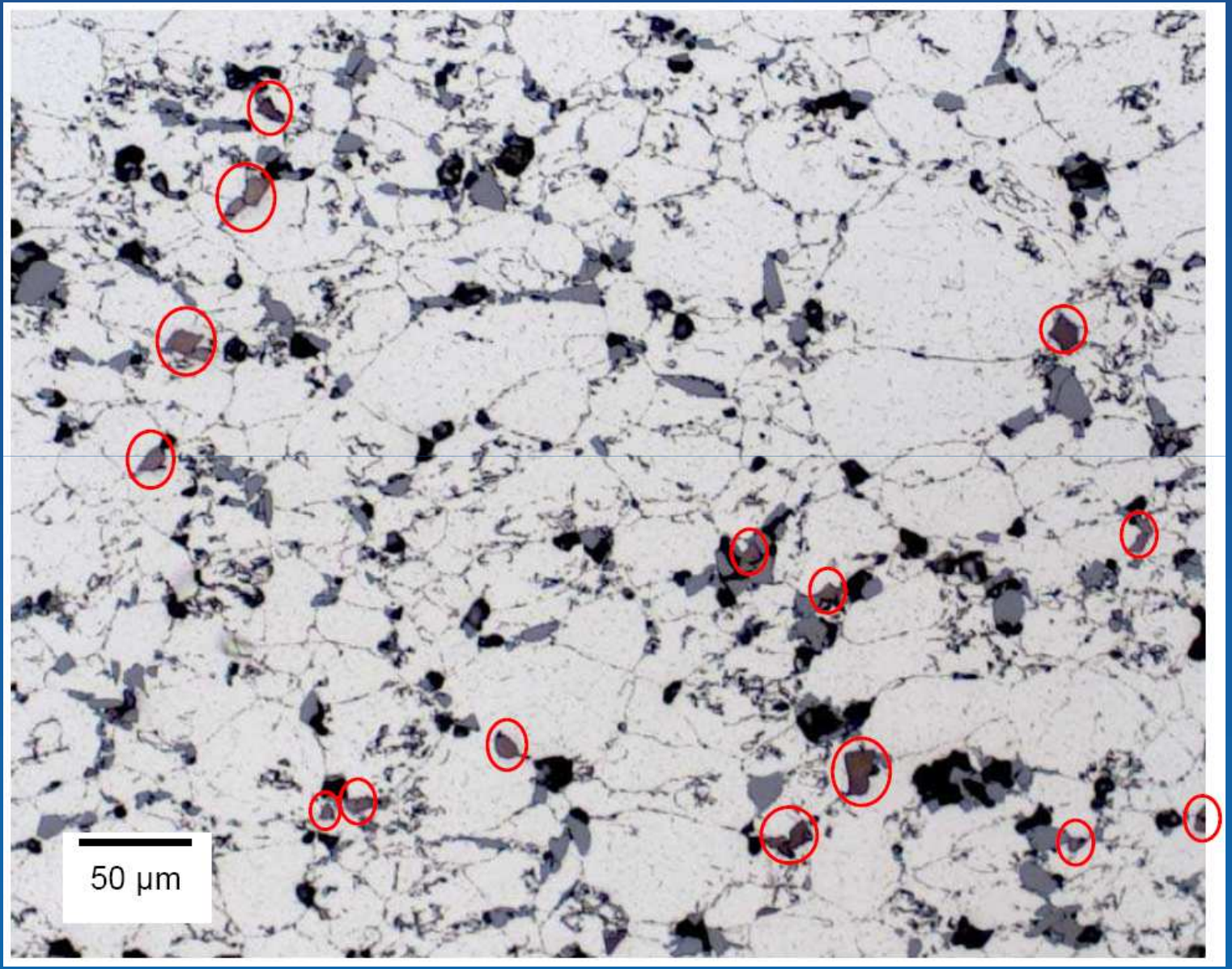
AlSi7 (elemental Al-Si mixture)



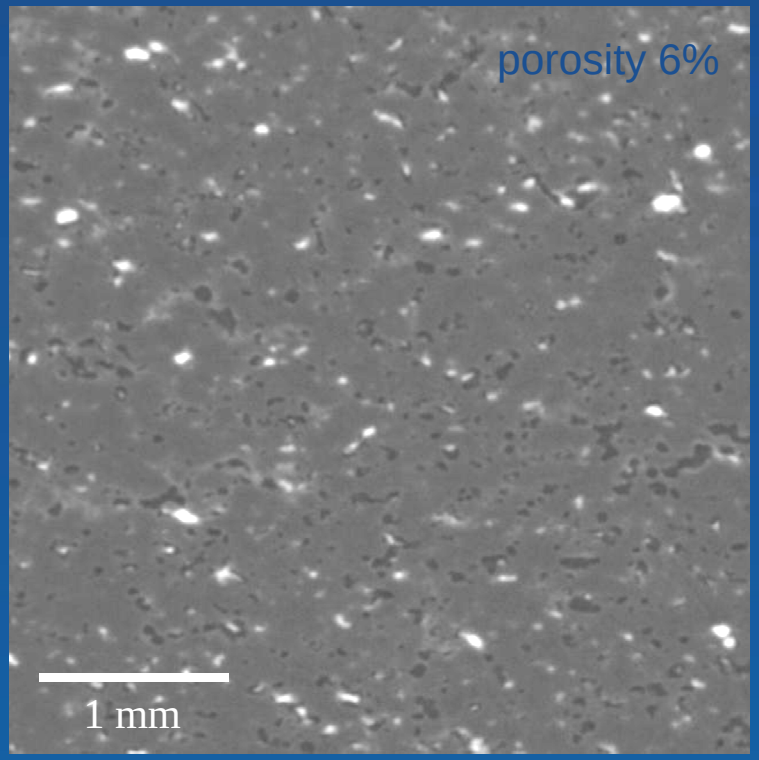
$$t_2(r) = \frac{F_{\Xi,\Psi'}(r)}{F_{\Xi,\overline{\Xi^c}}(r)}, \qquad r \geq 0$$

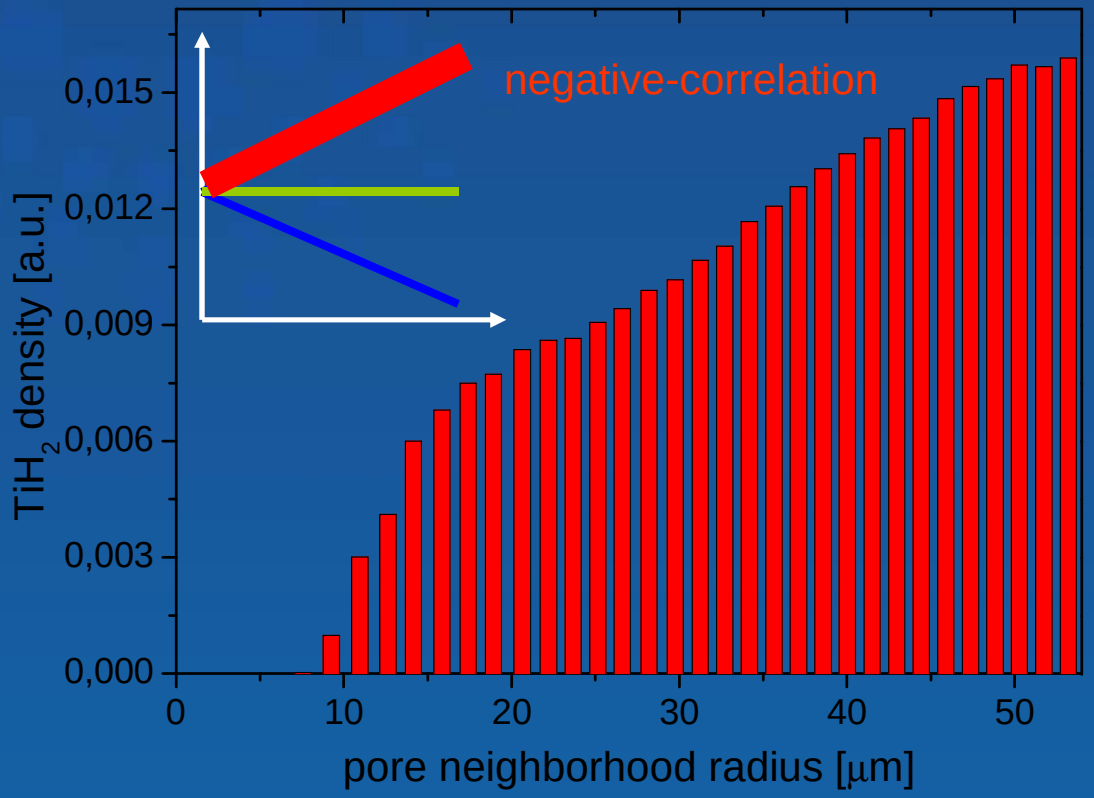
Rack, Ohser, Schladitz, Helfen et al., Journal Microscopy, 2008

Metallographic image of AlSi7



Metallschäume - AlSiCu

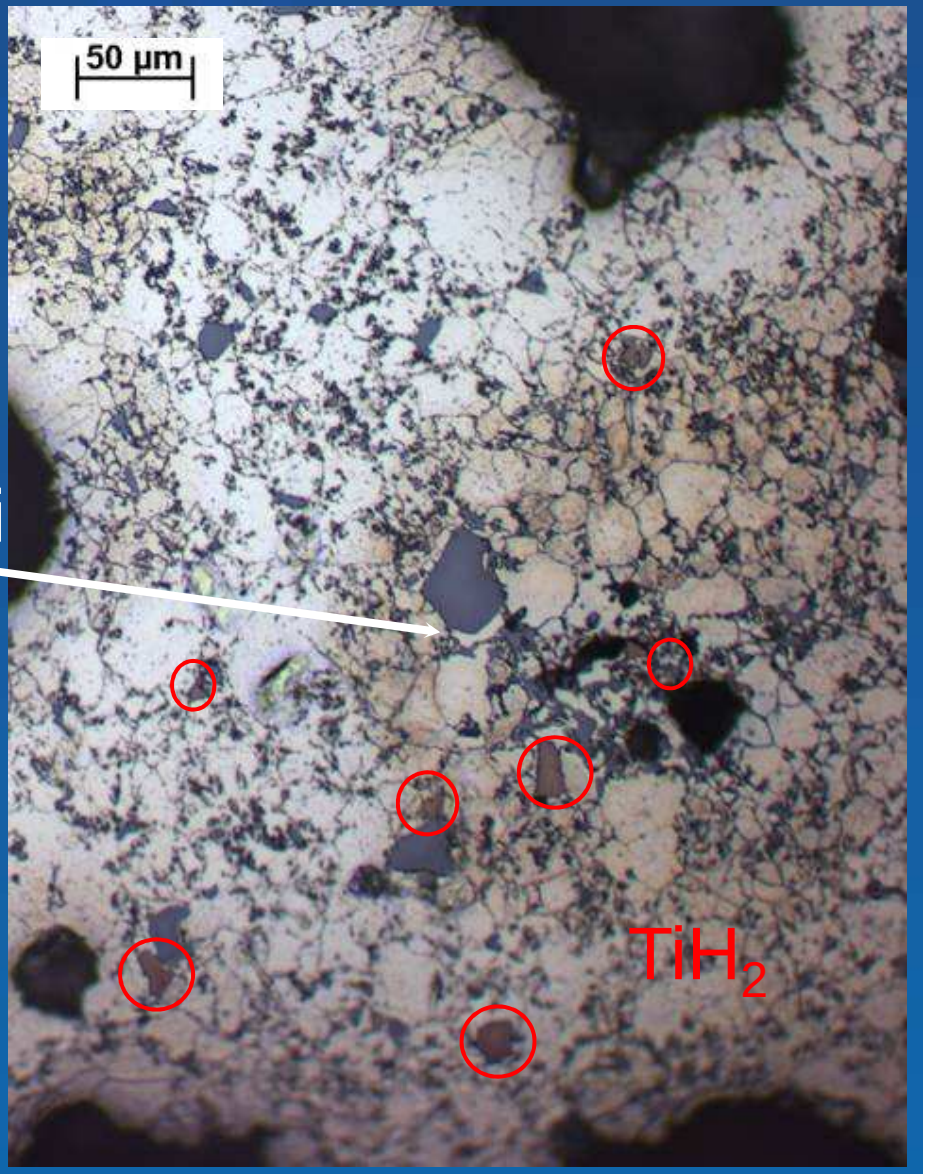




spatial negative-correlation between pores and blowing agent

Rack, Bütow, Banhart, et al., Acta Materialia 2009

Metallic Foams - AlSiCu

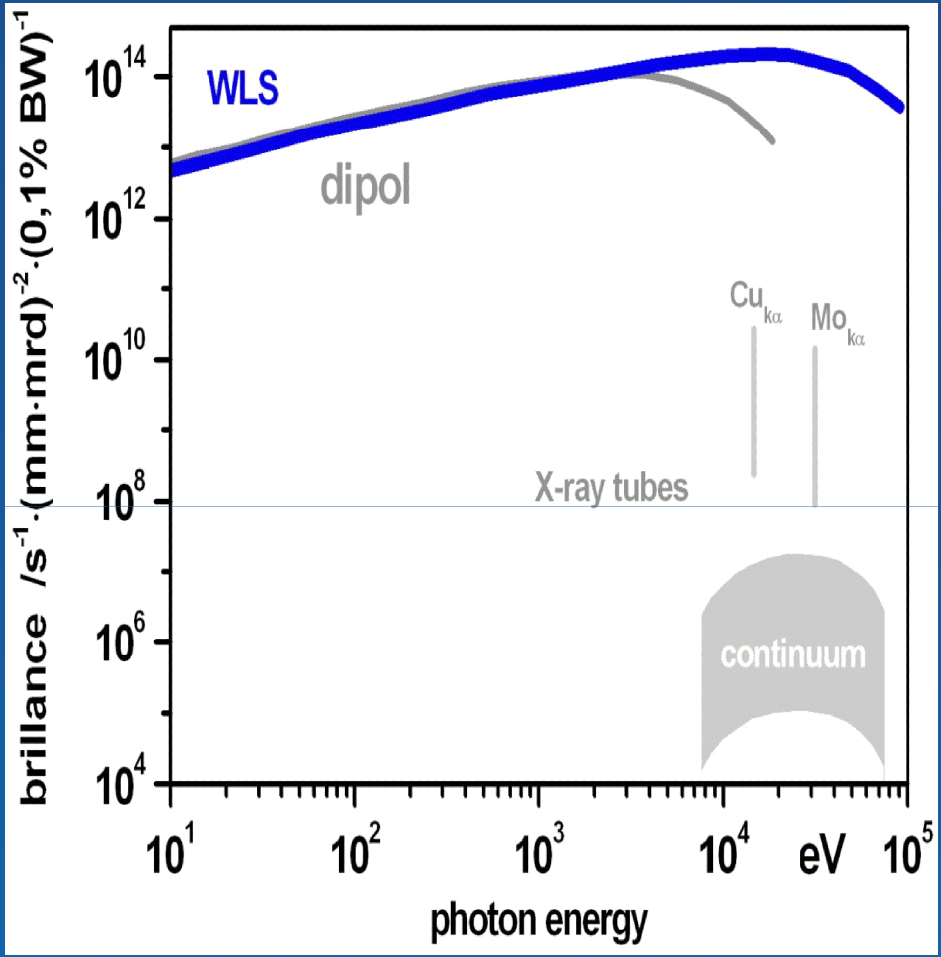


Exploiting Contrast with Tomography

- Synchrotron Light Sources, Scanning Techniques -

Synchrotron Light Sources

Synchrotron Light



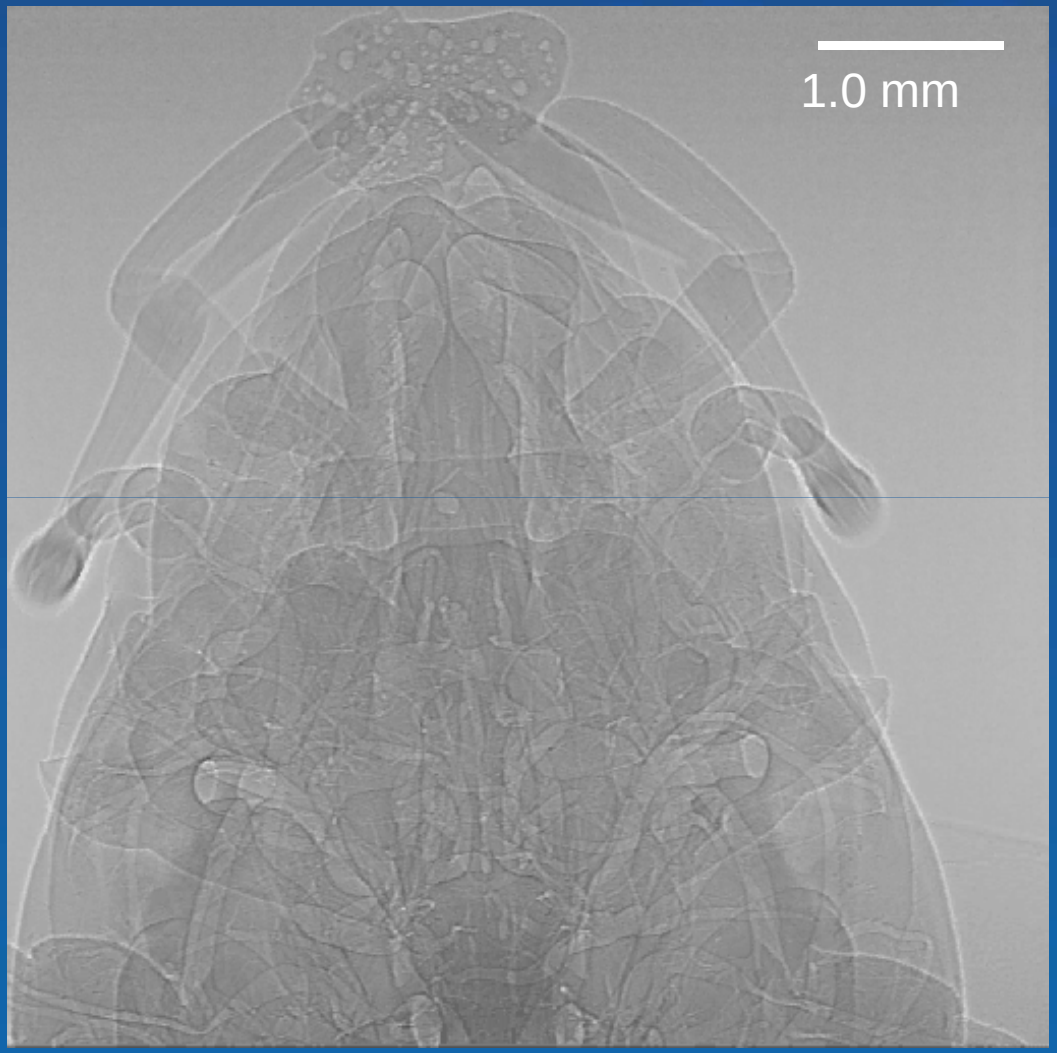
B.R. Müller et al., DGZfP 2005

- higher flux → allows the use monochromators:
  - higher contrast
  - no beamhardening artifacts
- quasi parallel beam
- partial spatial coherence - use of different contrast modes for higher sensitivity, e.g. the local electron density (holo-CT)

<u>but:</u>

- relative expensive
- only limited amount of beamtime available

Periplaneta americana (Schabe)

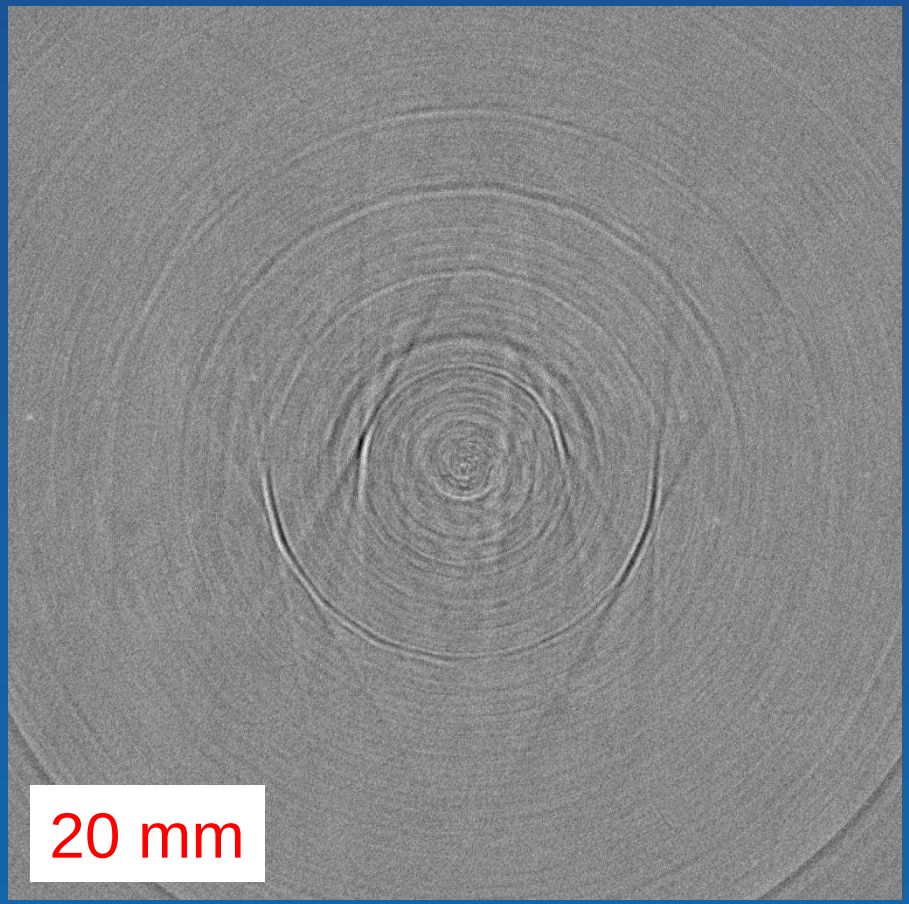


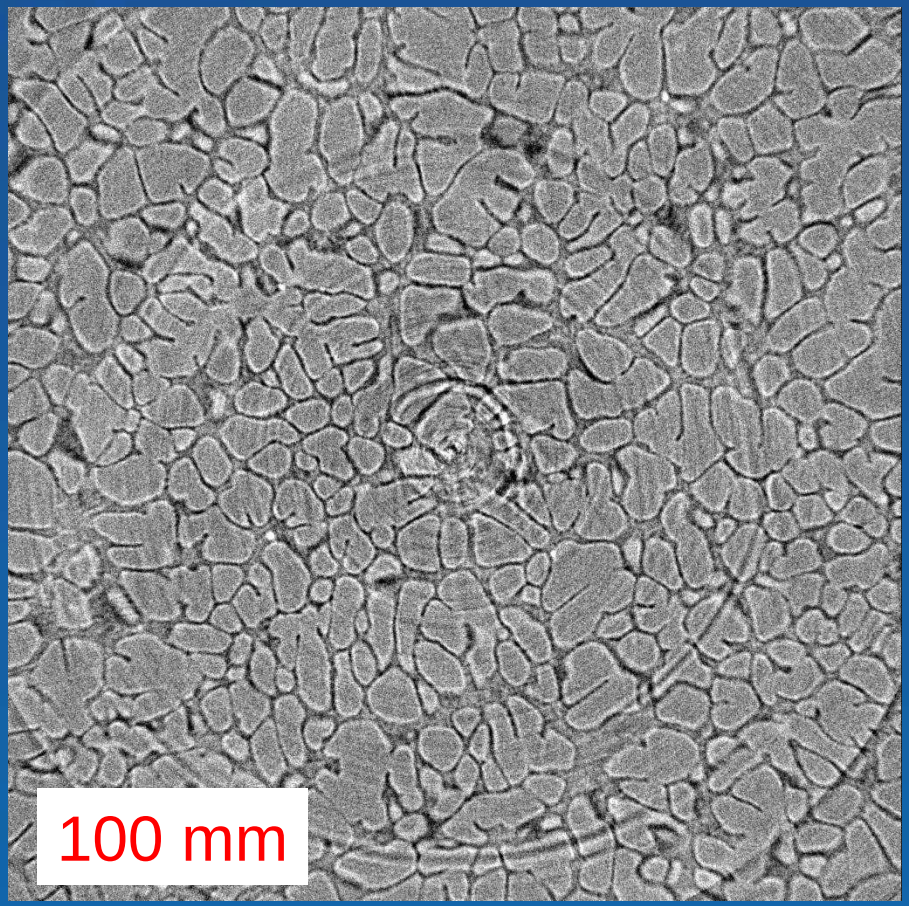
- mouthpart kinematics during feeding
- 125 FPS
- 15 µm spatial detector resolution
- Betz, Rack et al., Synch Rad News `08 & J. Exp. Biol. `14
- Westneat, Betz et al., Science `03
- TopoTomo @ ANKA

X-ray Phase Contrast

commercial Aluminum alloy A357 (Al, Si, Mg)

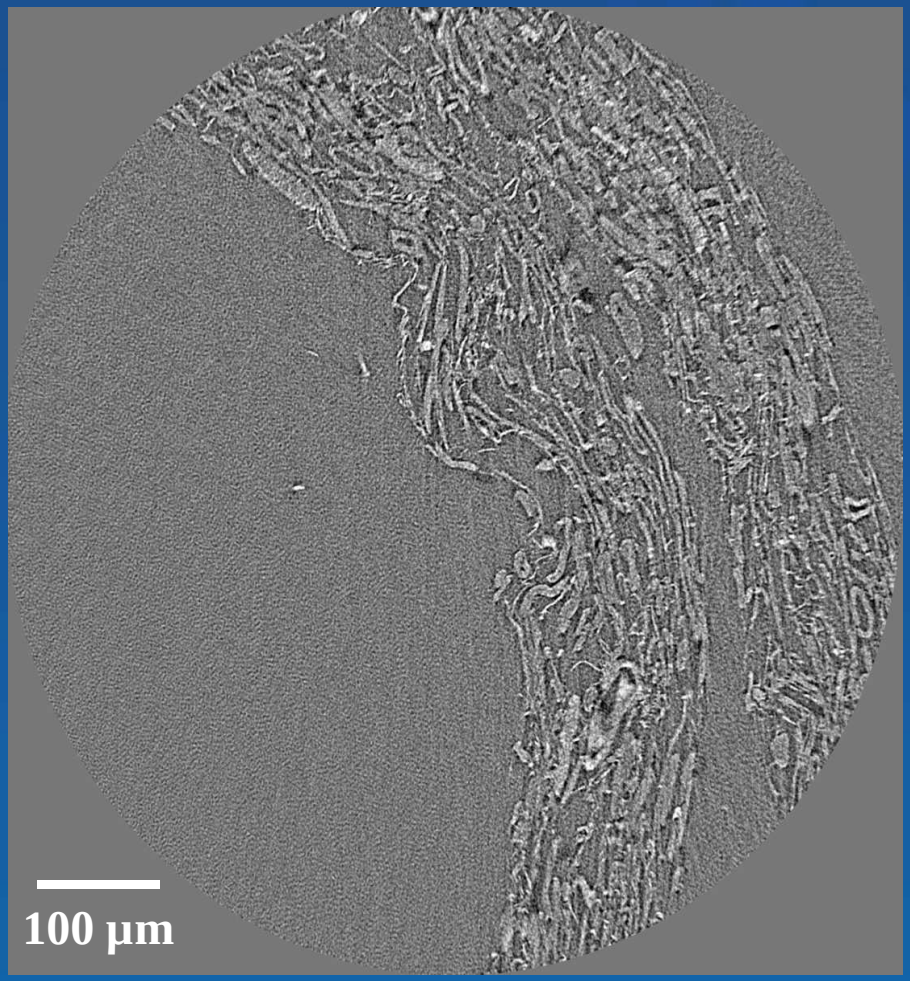
(18 keV, 0.8 µm pixel size / <2 µm resolution)



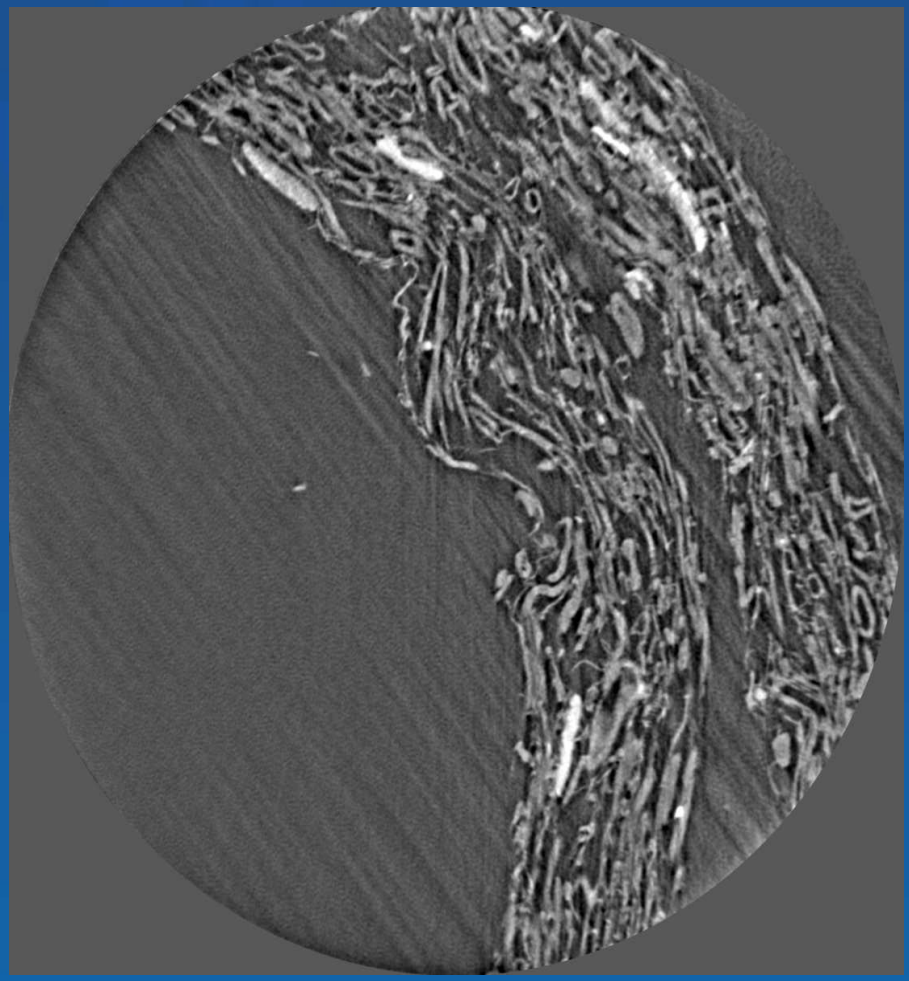


Simon Zabler, PhD thesis

Multi-Constituent: Recycled Paper



standard reconstruction

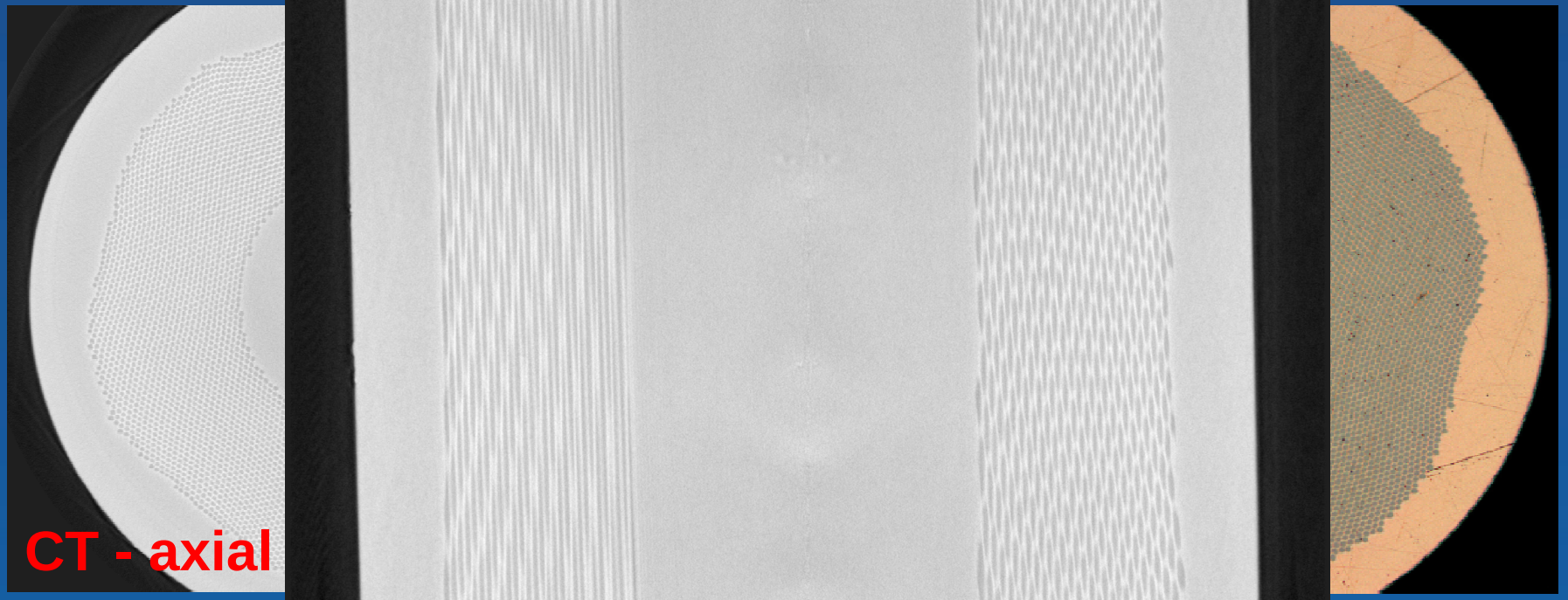


ANKAphase retrieval

8 keV, 0.7 µm pixel size, Si (111) mono (ESRF-ID22)

Ohser et al. Image Analysis & Stereol. 28 (2009); Weitkamp, Rack et al., J Synch Rad 18 (2011)

High Energy & High Resolution



- Nb-
- 0.5
- app
- co-(n)

Diffraction Contrast Tomography

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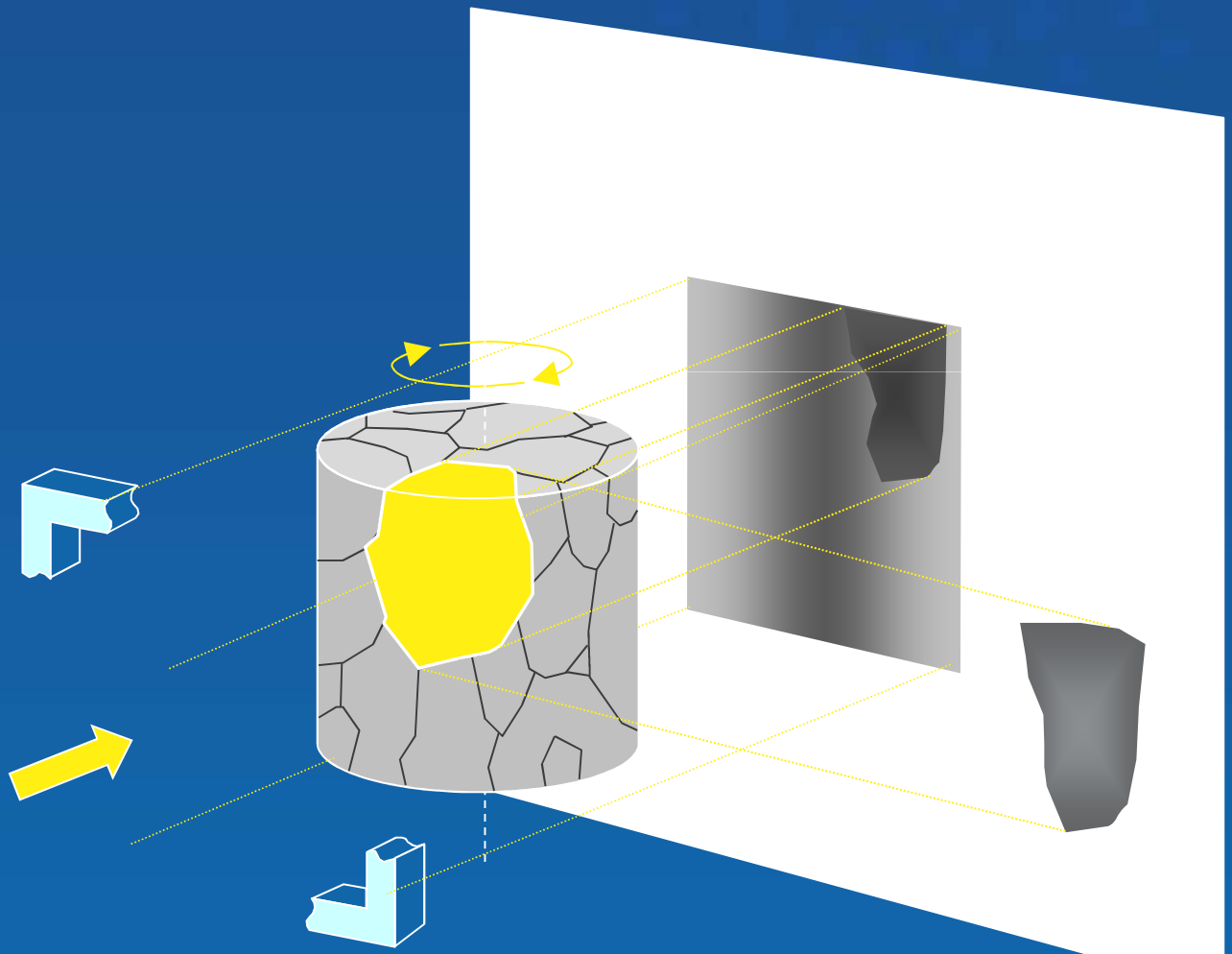
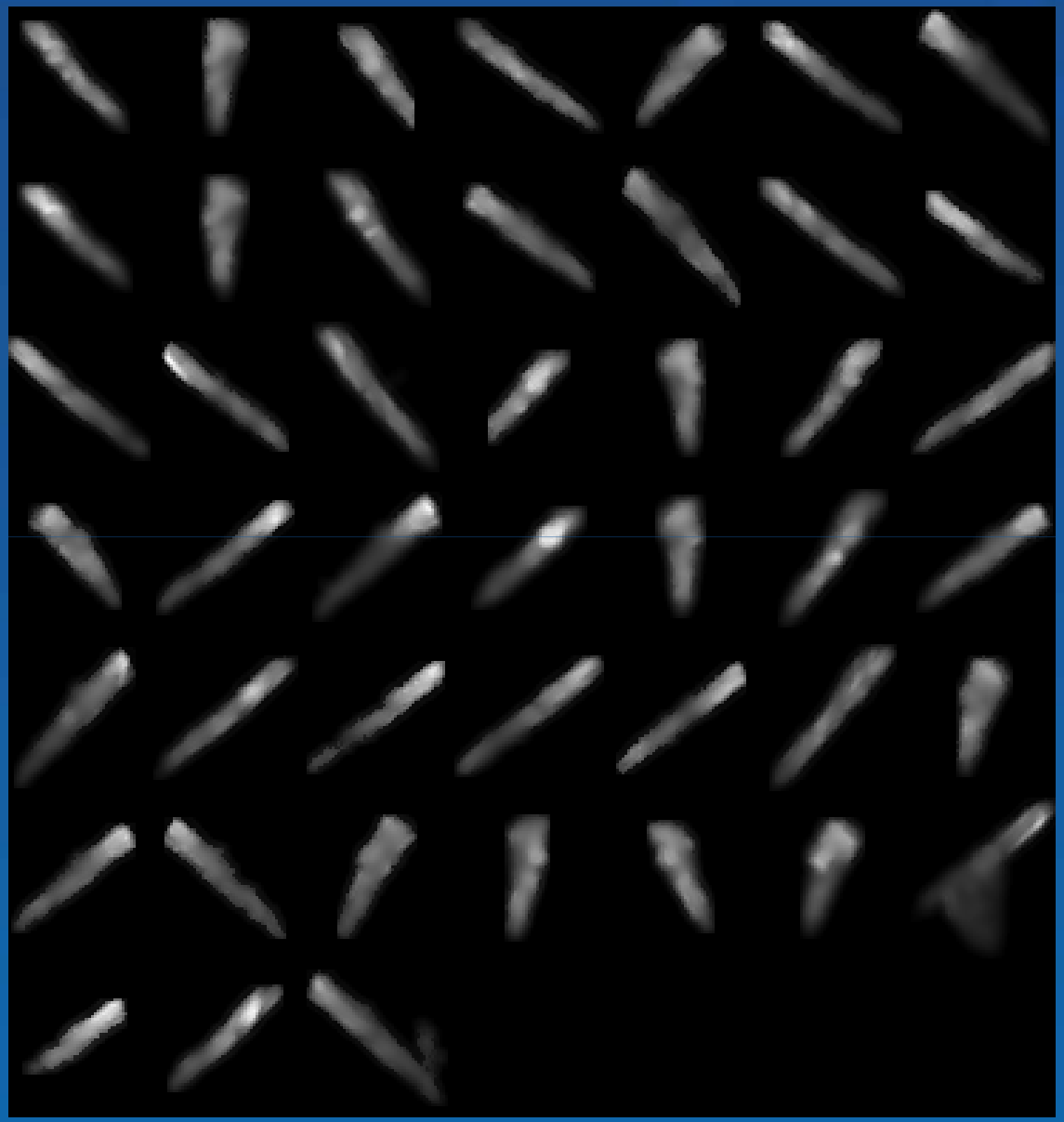
Conventional tomography setup, large detector with high dynamic range, use slits to confine the beam to sample, monochomatic beam ($\Delta\lambda/\lambda \sim 10^{-4}$), continuous rotation, large number of images (7200 /360°).

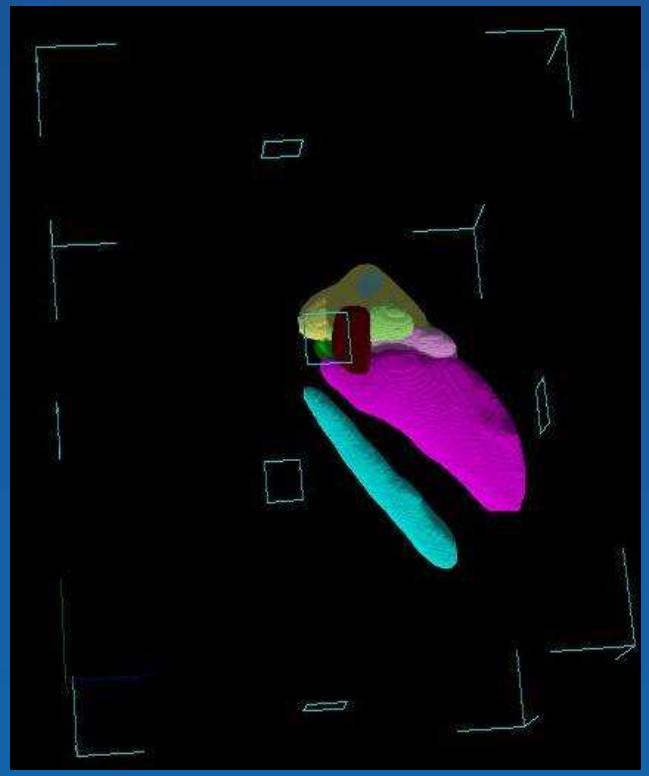


W. Ludwig et al. Rev. Sci. Instr. 2009

- During rotation, grains pass through Diffracting alignments
- grains with small spreads in orientation:
- "extinction" spot visible in direct beam
- both spots can be approximated as grain projections

Chironex fleckeri





Sötje et al., Marine Biology (2009)

Scanning CT: Multimodal Contrast

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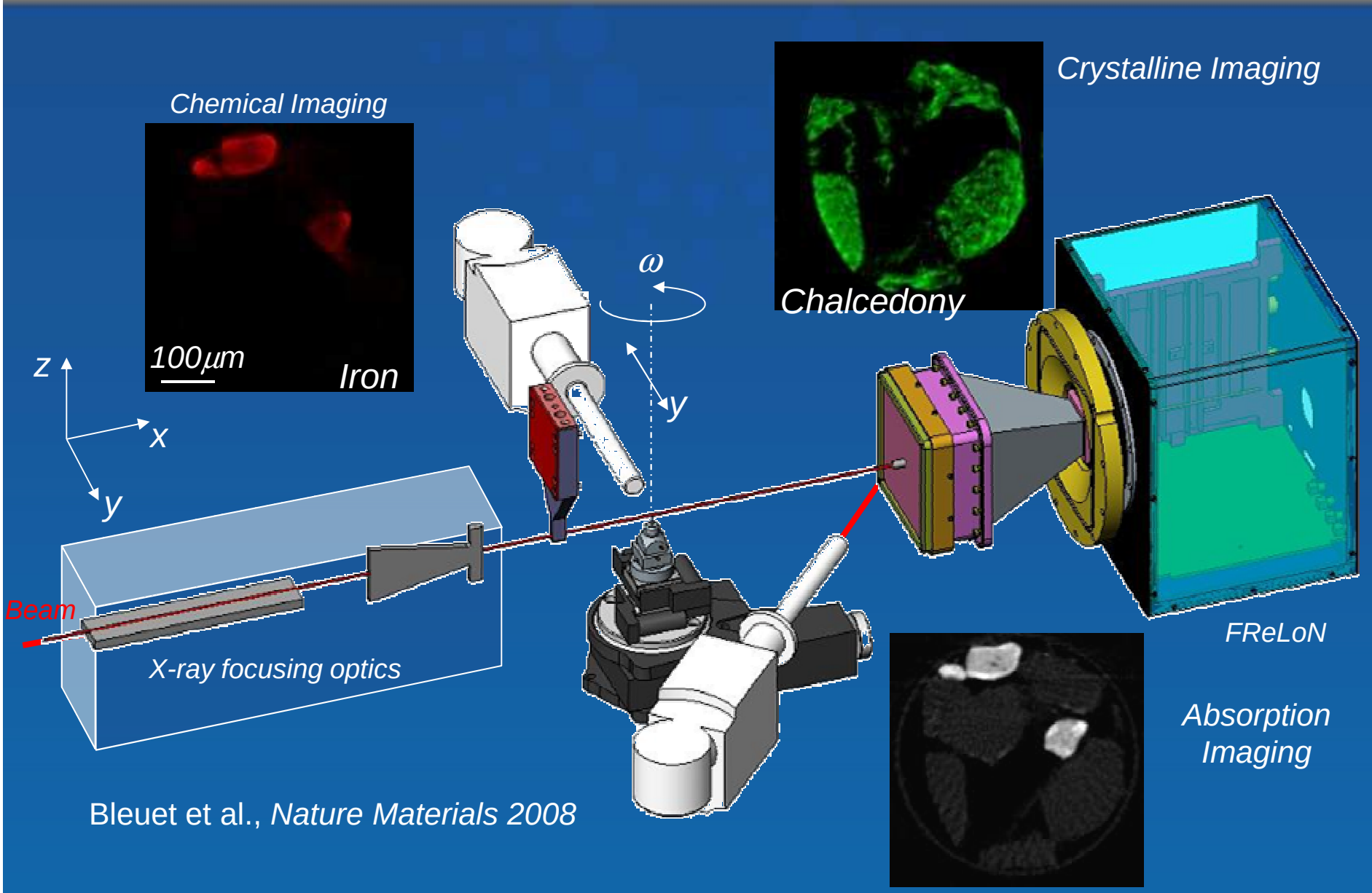
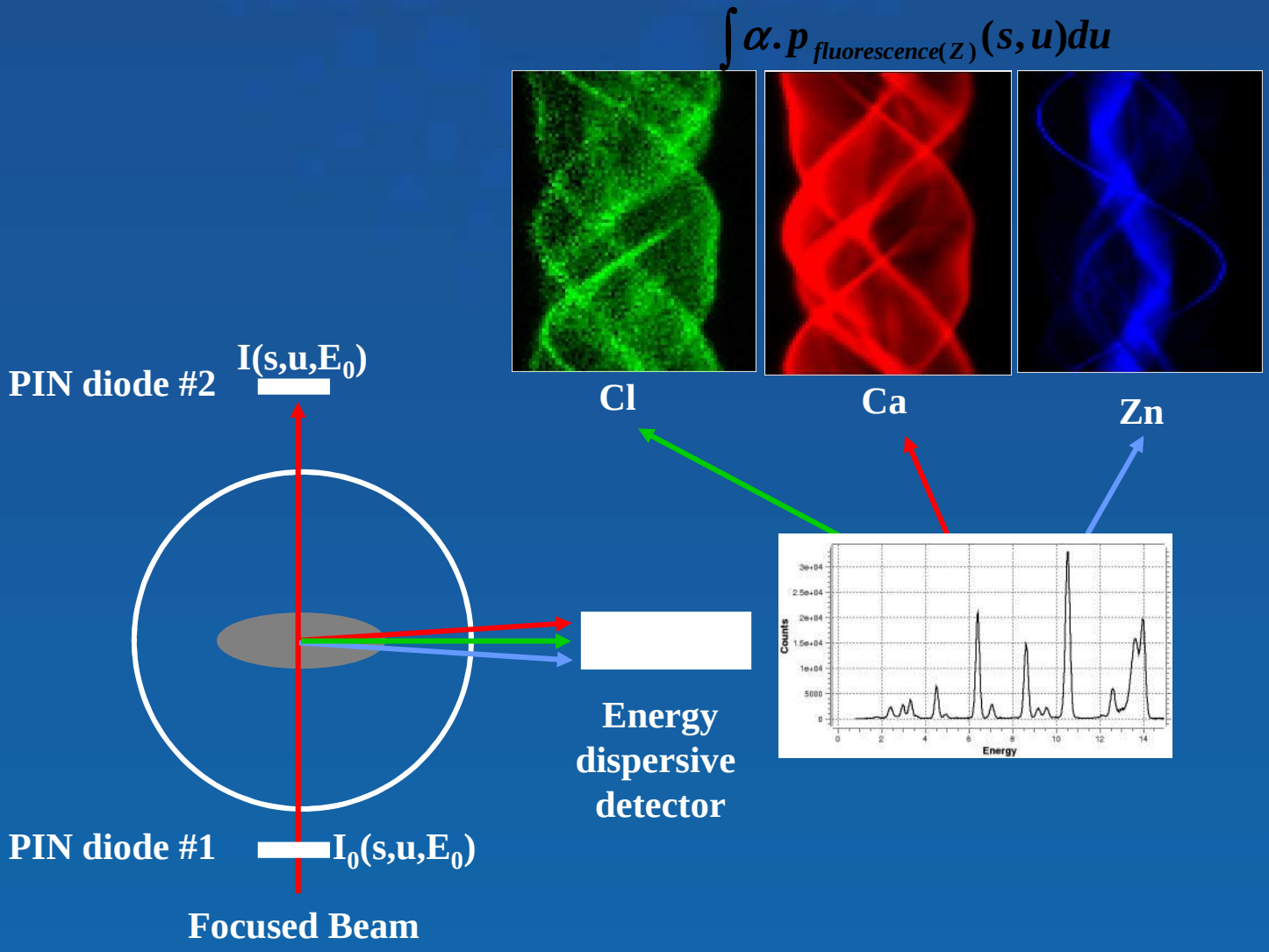


Bleuet et al., *Nature Materials 2008*

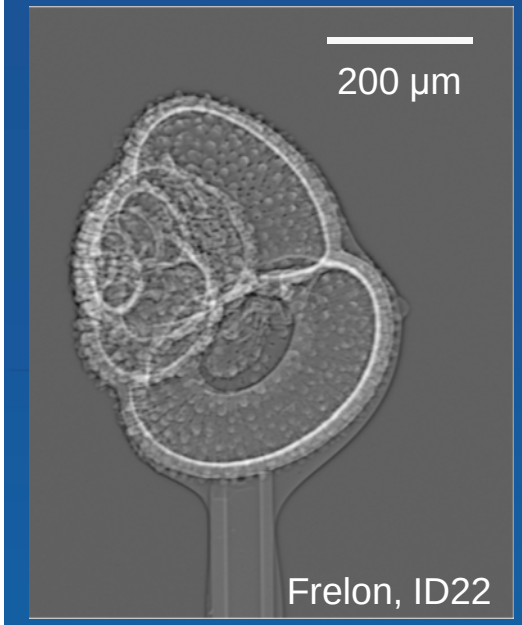
X-ray Fluorescence Tomography



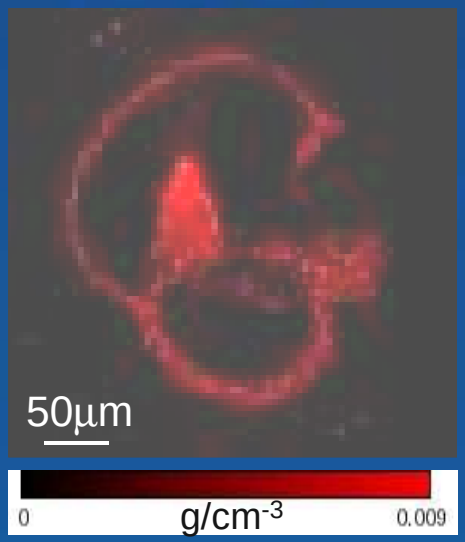
Bleuet et al., *SPIE*, 2006

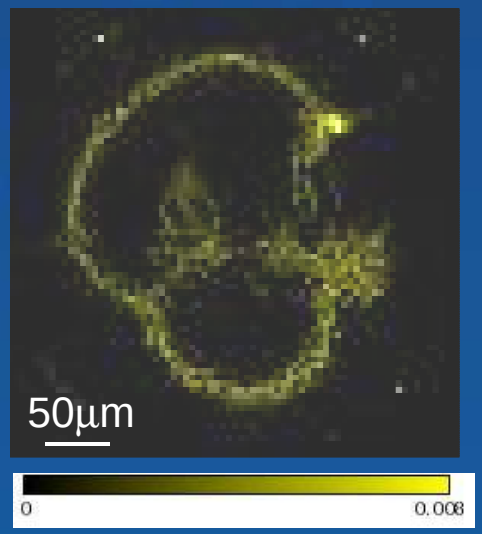
X-ray Fluorescence Tomography

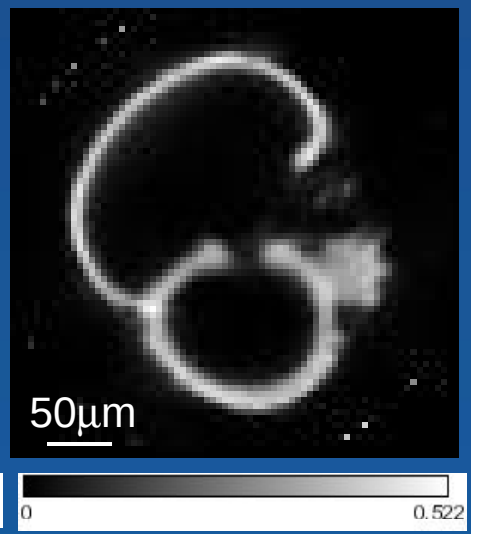
A Light for Science

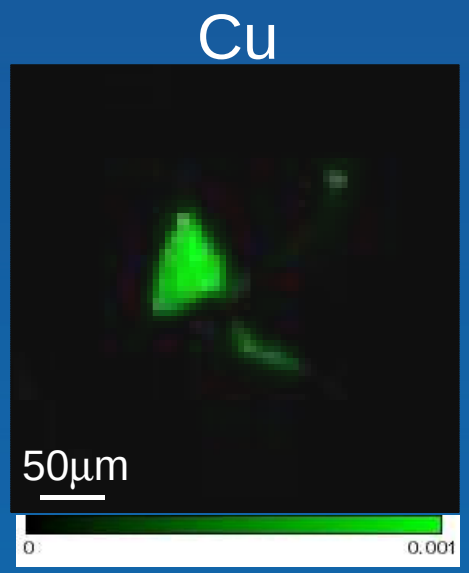


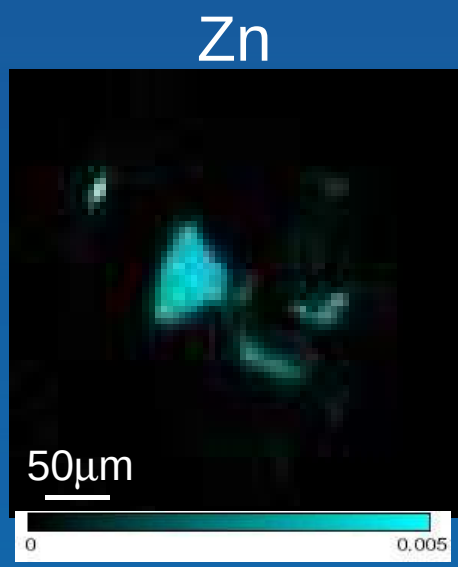
Globorotalia inflata











Access to the internal chemical distribution

Bleuet et al., *SPIE*, 2006

X-ray Powder Diffraction Tomography

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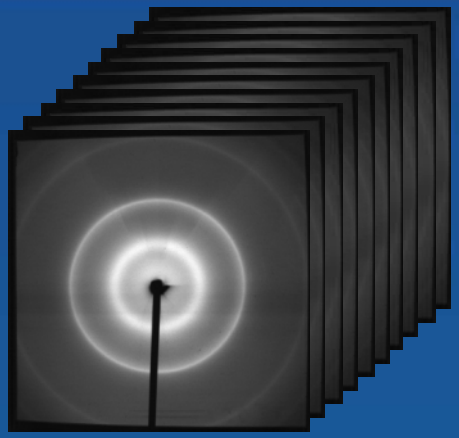
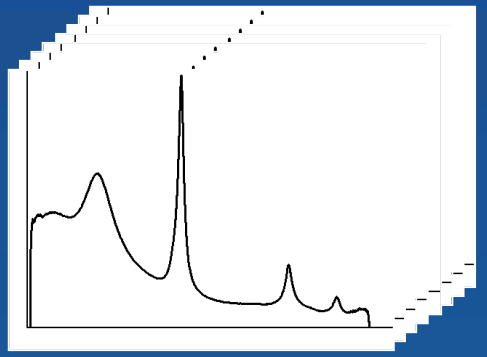
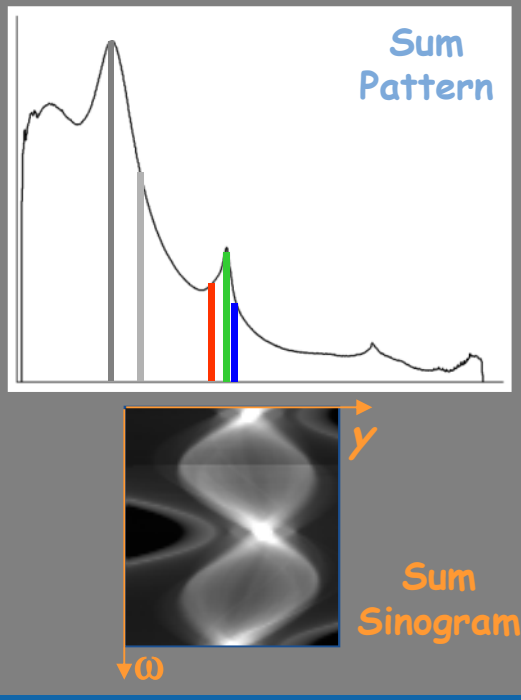


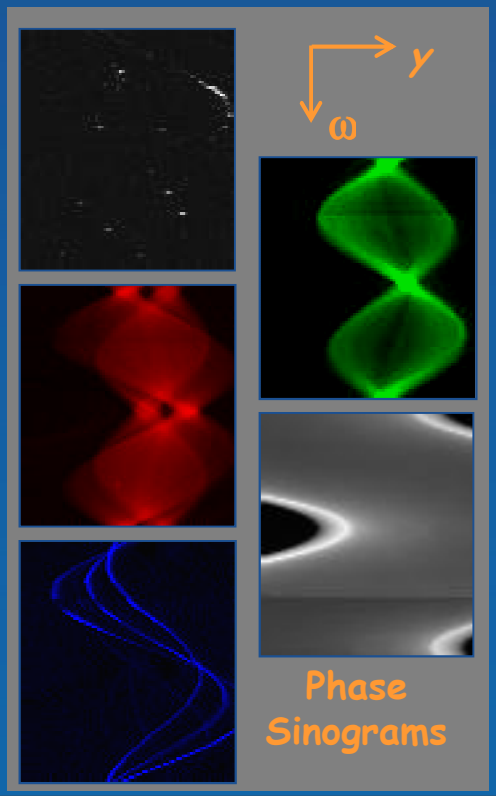
$N_y \times N_\omega$ Diffraction Images

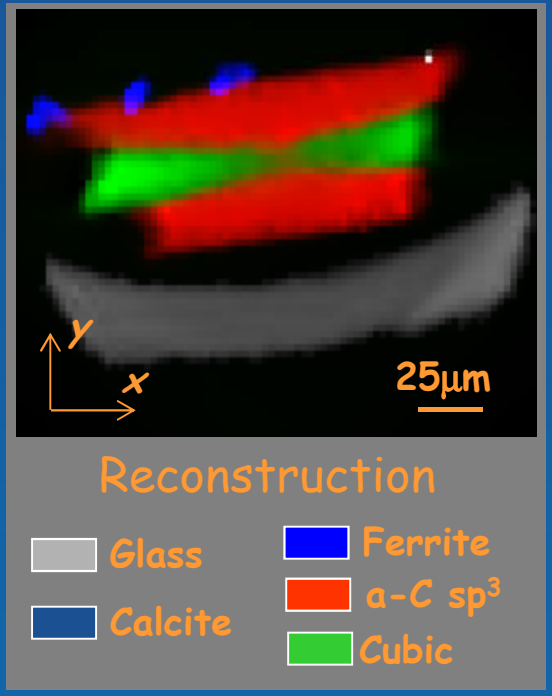
Azimuthal Integrations



$N_y \times N_\omega$ Diffraction Patterns

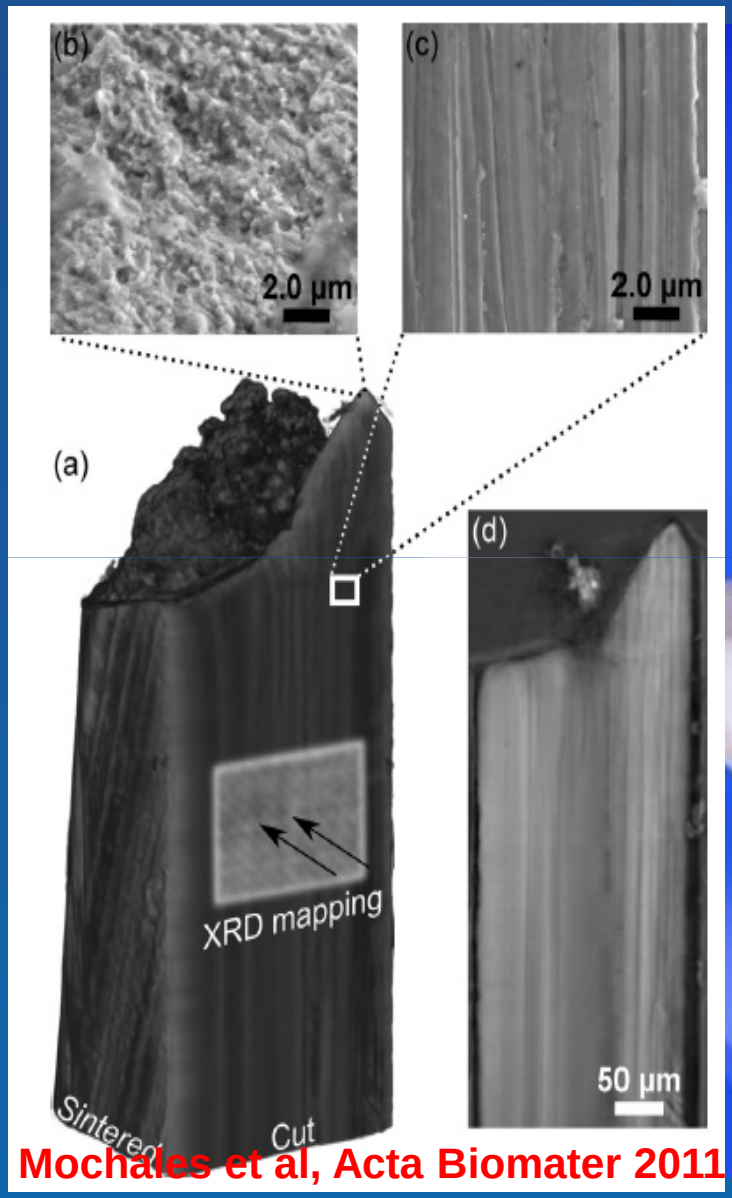




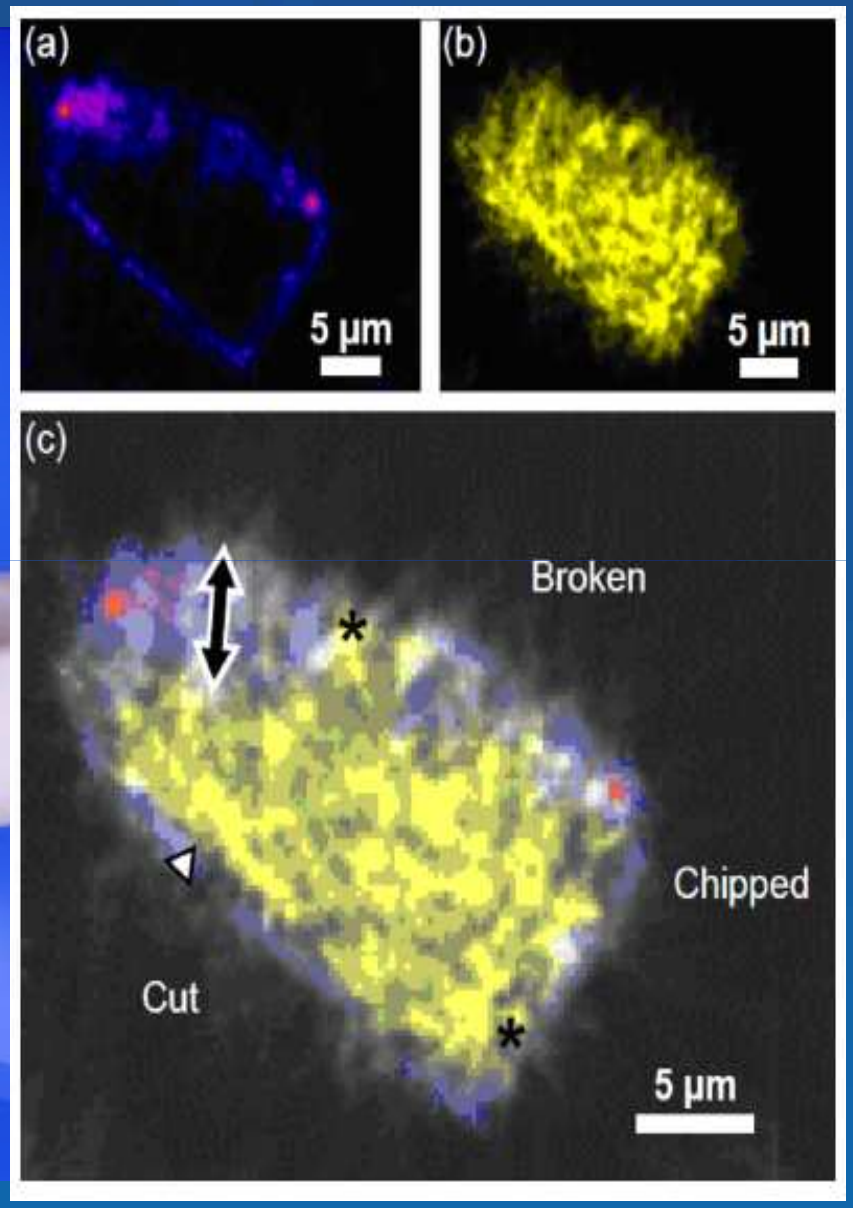


Bleuet et al., *Nature Materials 2008*

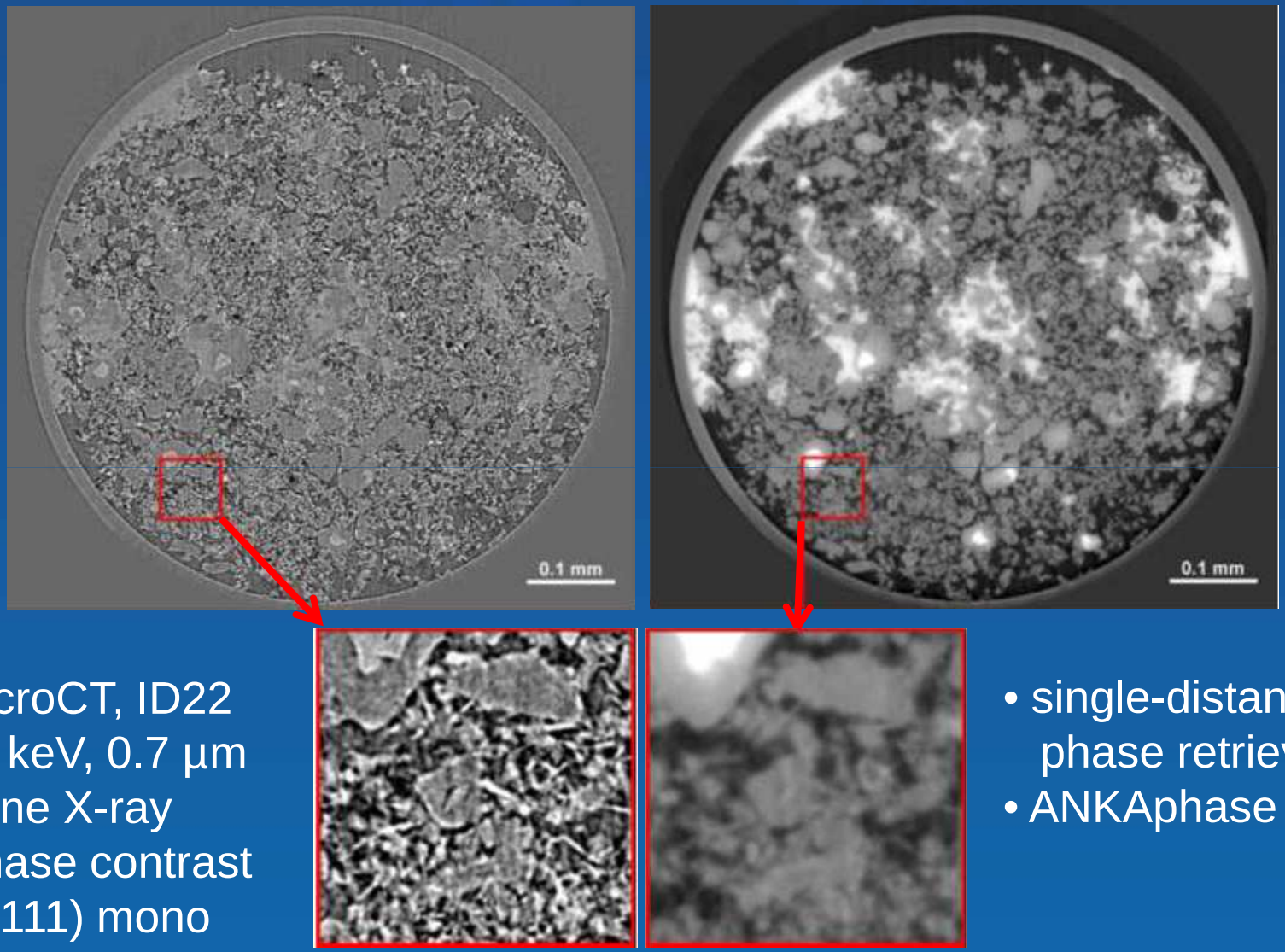
XRD-µCT: Mechanically Treated ZrO



Mochales et al, Acta Biomater 2011



Complex materials: cement



- microCT, ID22
- 14 keV, 0.7 µm
- inline X-ray phase contrast
- Si(111) mono

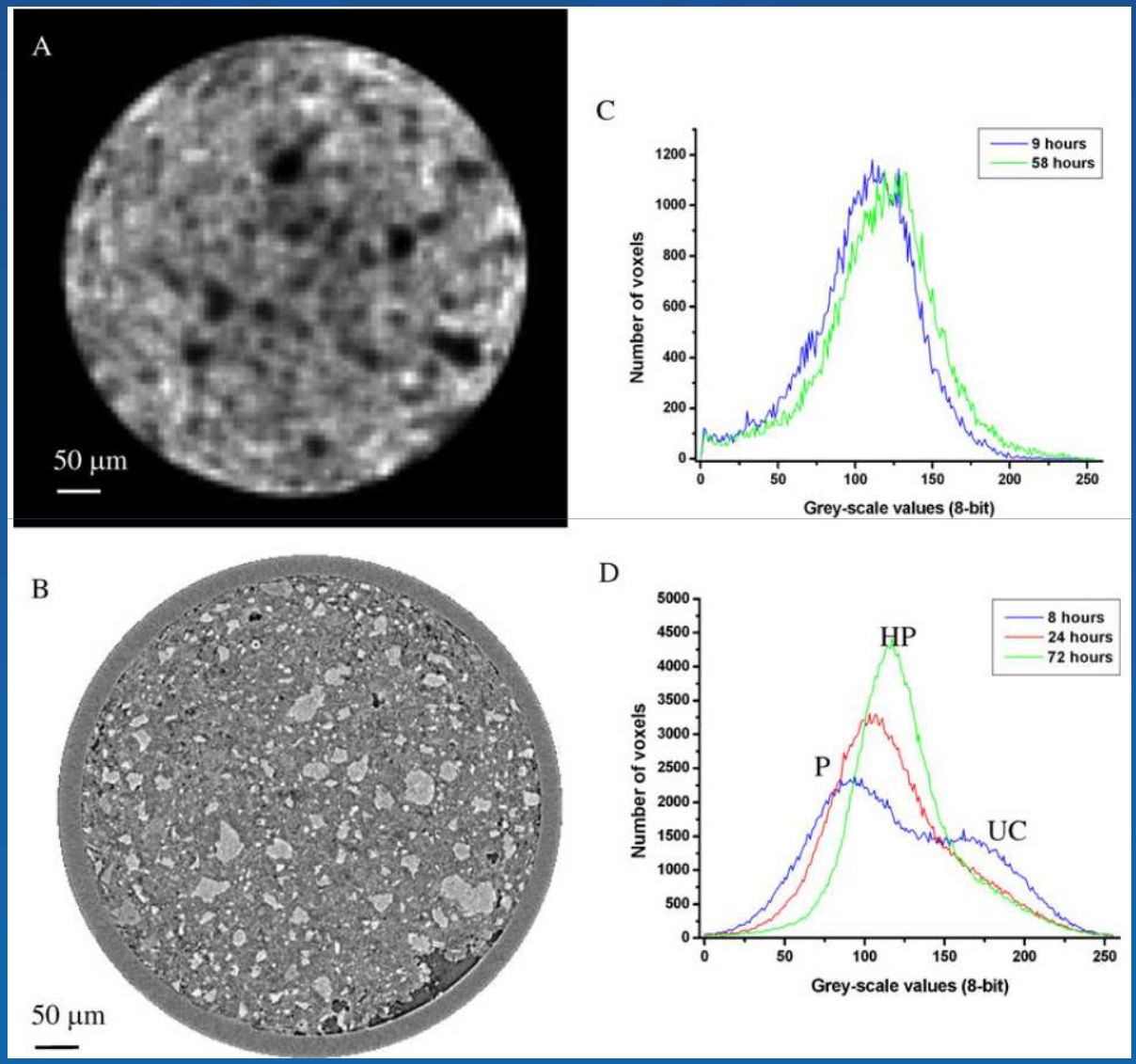
- single-distance phase retrieval
- ANKAphase

Artioli et al., Int J Mater Res, 103 (2), 145 (2012)

Complex materials: cement

- XRD-µCT, ID22
- 2 µm x 4 µm spot, 18 keV
- 001 peak intensity
- 58 h hydration

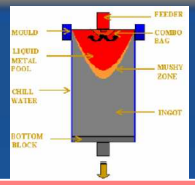
- microCT, ID22
- 14 keV, 0.7 µm
- inline X-ray phase contrast
- Si(111) mono



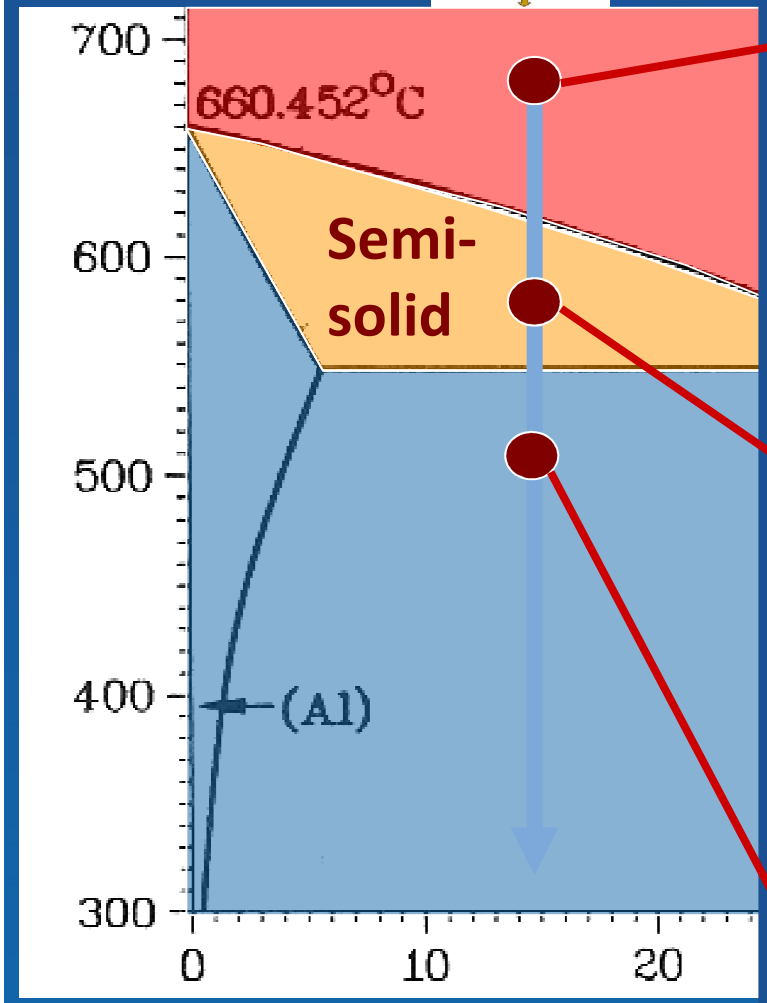
Artioli et al., Analyt. & Bioanalyt. Chem. (2010)

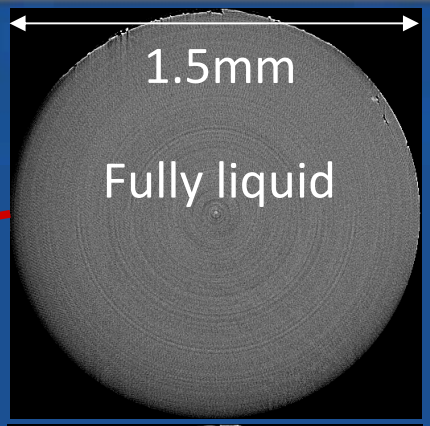
Time-resolved Microtomography

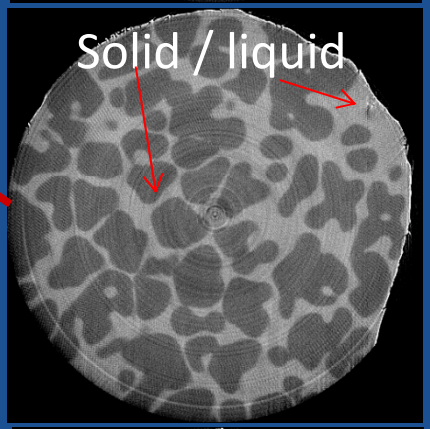
Solidifcation

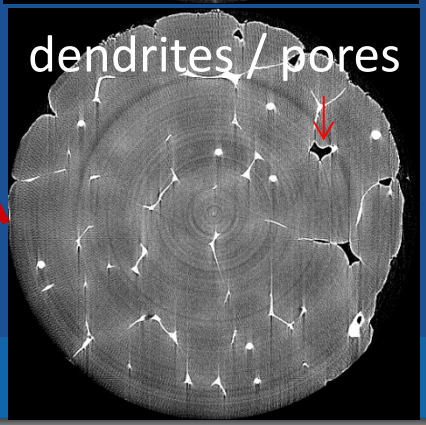


Temperature °C









Solid fraction evolution
Solid coherency
Dendrite growth
Pore formation

Relevant scale
1µm –few µm

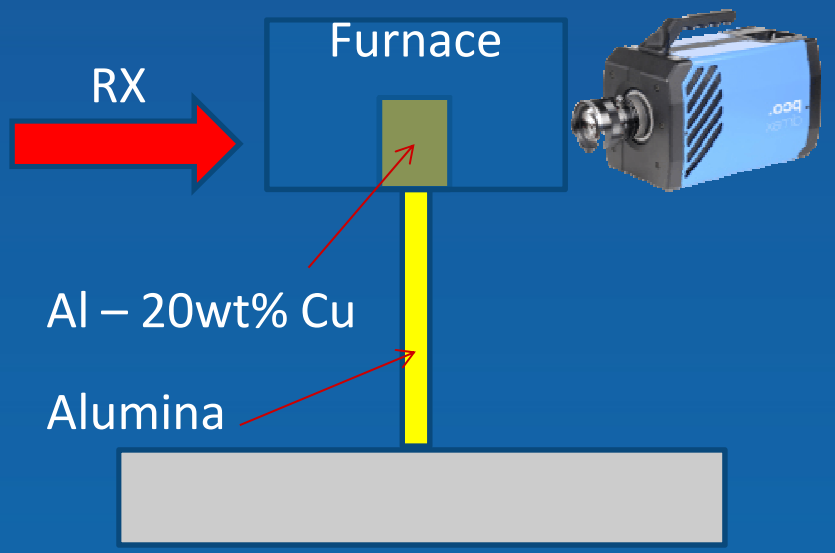
Typical cooling rates
0.1 – 10 °C/s

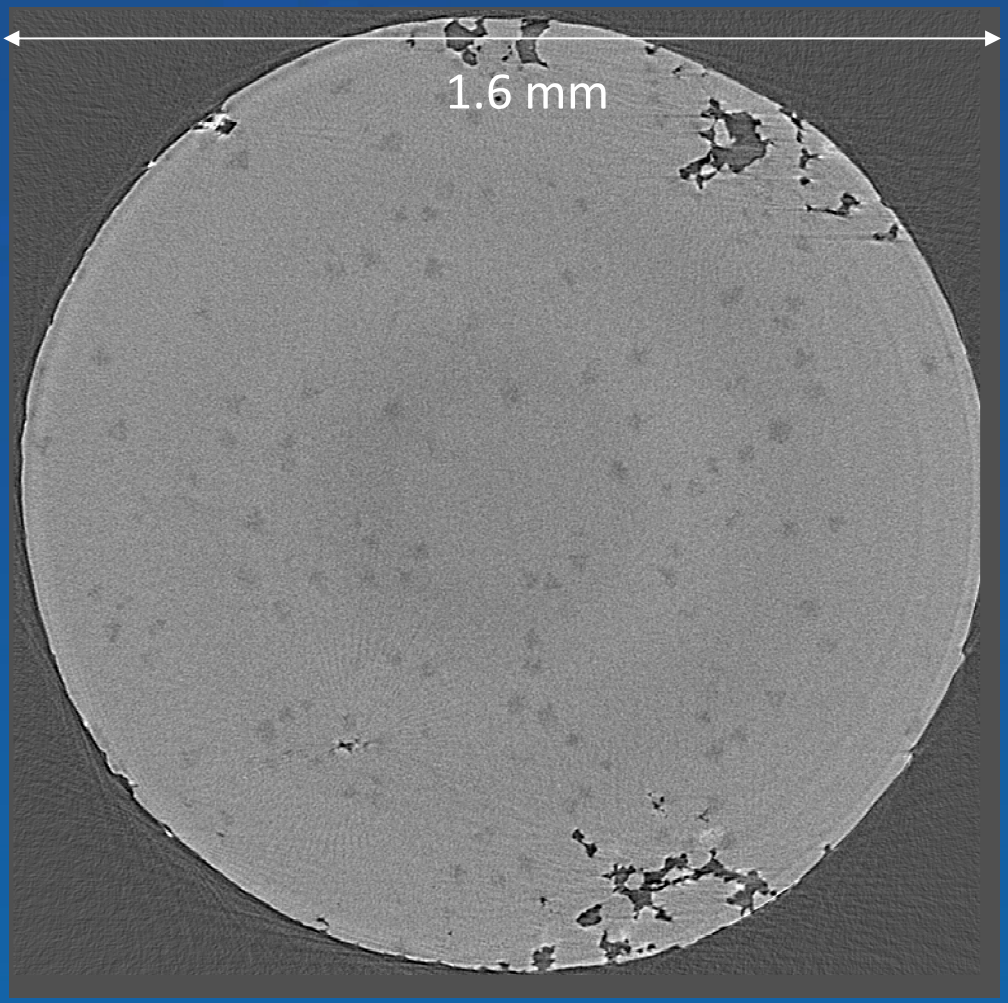
Courtesy Luc Salvo, CNRS

Ultrafast Tomography: Solidifcation

A Light for Science

Solidification Al 20% Cu
ID15A
PCO DIMAX, Size 780 x 600
600 projections, Optics 2.2µm
White beam (gap open)
Scan time 0.15 seconds
70 scans,





Solidification rate ~ 5°C/s
Solidification time 10s !!

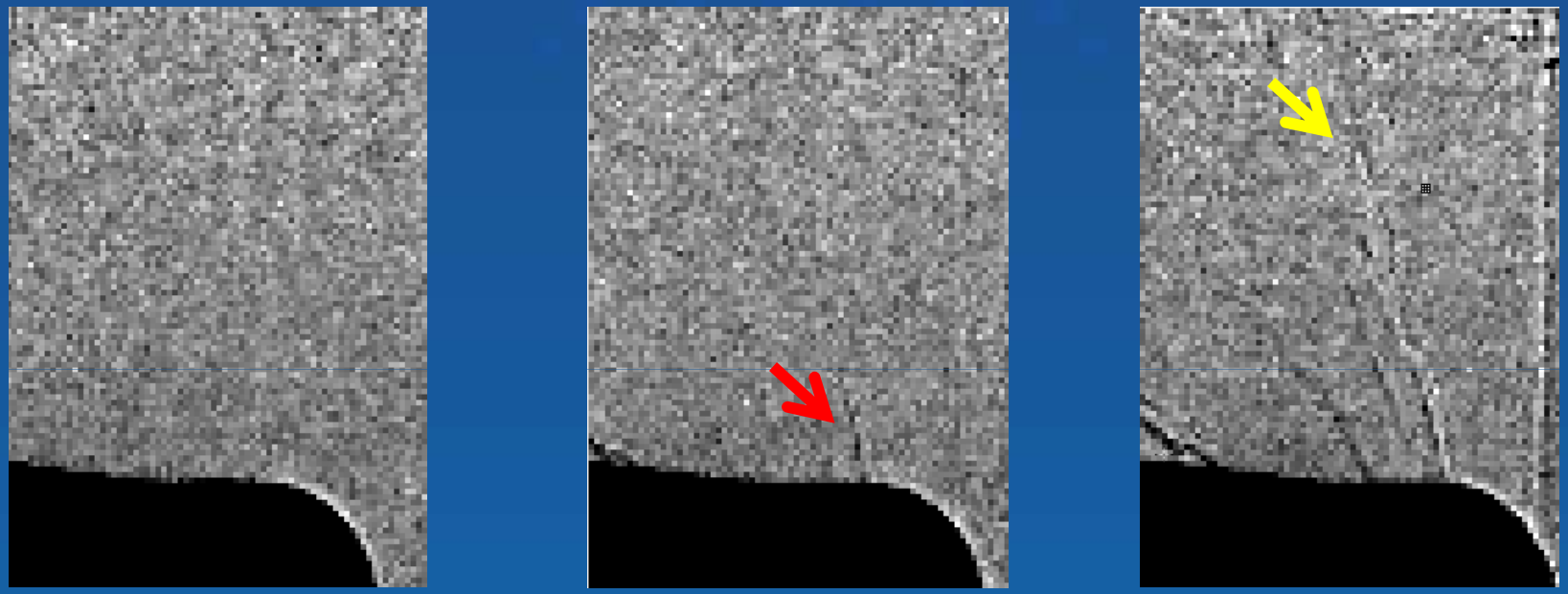
Courtesy Luc Salvo, CNRS

Ultimate Resolution in Time

Single-bunch Imaging: Crack Propagation

1 mm

35 µm pixel size, 500 LuAG:Ce



0 µs **28 µs** **56 µs**

2.4 µs exposure = 1 bunch / 35504 FPS (28 µs)

ID19: 1x 32u @ 11.5 mm (ca. 10 mA = single-bunch mode)

Rack, Scheel, Reichert et al., J Synch Rad 21, 815-818 (2014)

Single-bunch Imaging: Crack Propagation

1 mm

500 LuAG:Ce

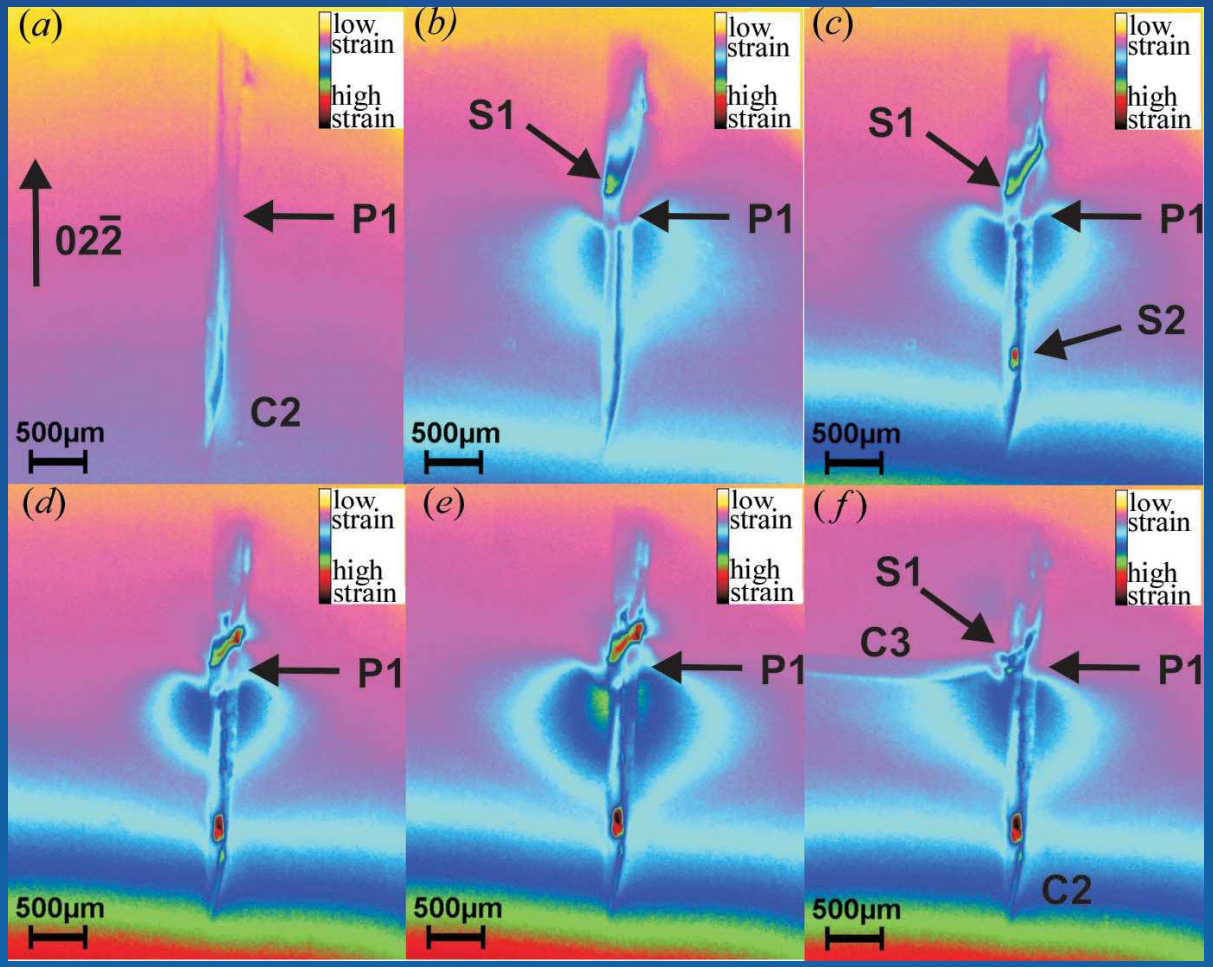
0 µs **28 µs** **140 µs**

2.26 µs … PS (28 µs)

ID19: 2… mm (6 mA)

Rack, Sche… 14)

Crack Propagation in Si Wafers



Danilewsky et al., "Crack propagation and fracture in Si wafers under thermal stress", J Appl Cryst 46 (2013)

Thanks for your attention!

Acknowledgments: Simon Zabler, Stefan Kirste, Jürgen Goebbels, Gerd Weidemann, Heinrich Riesemeier, ID19 @ ESRF, Alexander Bütow, Katja Schladitz, Joachim Ohser, Holger Kropf, Biljana Matijasevic-Lux, Olaf Dalügge, Christine Knabe, Michael Stiller, Christian Koch, Bernd Müller, Timm Weitkamp, Andreas Danilewsky, Thierry Martin, Angelica Cecilia, Tatjana Rack, Lukas Helfen, Peter Cloetens, Sondes Bauer-Trabelsi