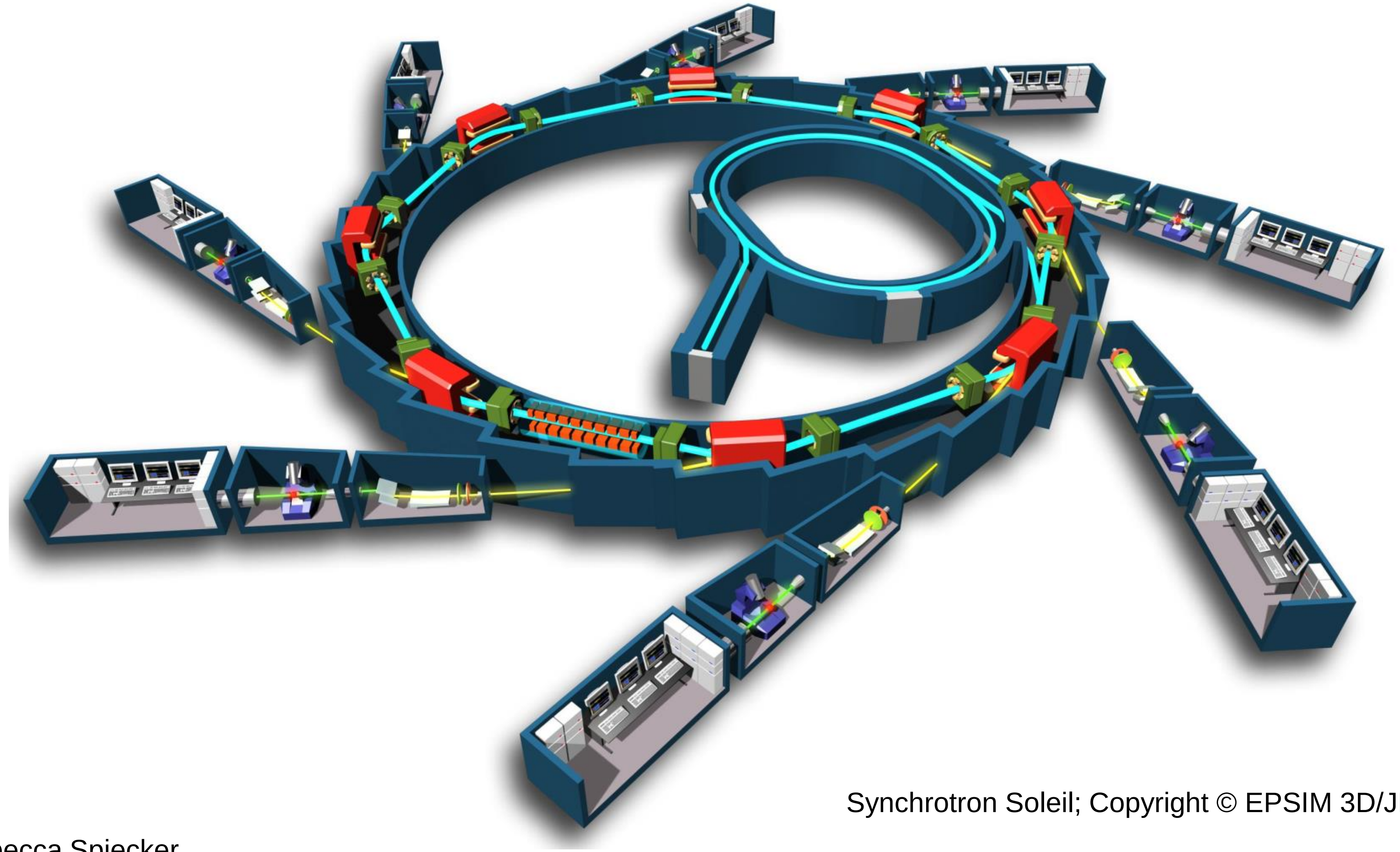
Bragg Magnifier Optics for Dose-Efficient X-Ray Imaging with µm-Resolution

R. Spiecker, H. Hessdorfer, A. Biswal, P. Pfeiffer, M. Hurst, V. Bellucci, A. Cecilia, T. Faragó, A. Herz, R. Hofmann, D. Novikov, M. Zuber, M. Shcherbinin, E. Hamann, T. van de Kamp, and T. Baumbach

Synchrotron X-ray imaging

Karlsruhe Institute of Technology

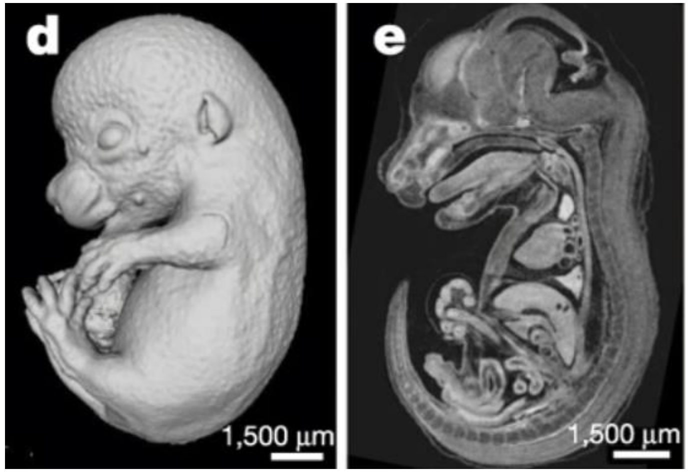
- Particle accelerator to create intense X-ray beams

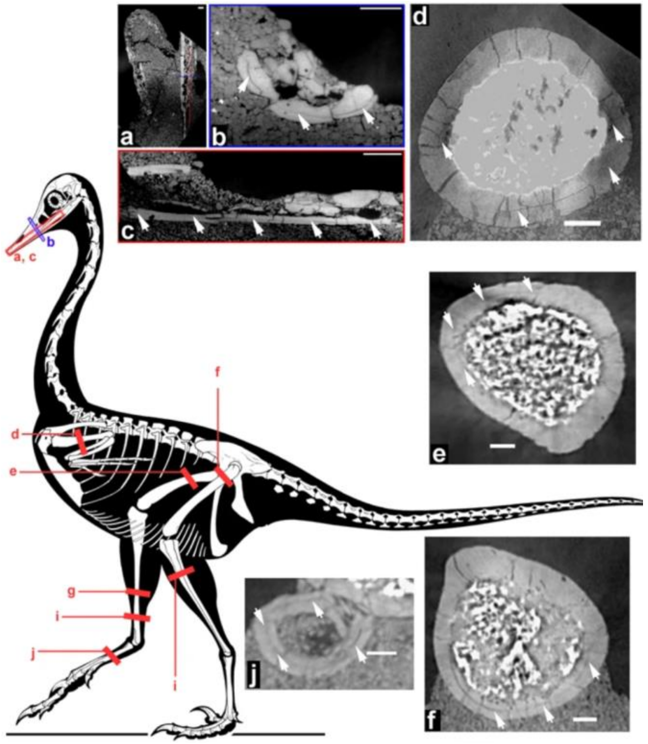


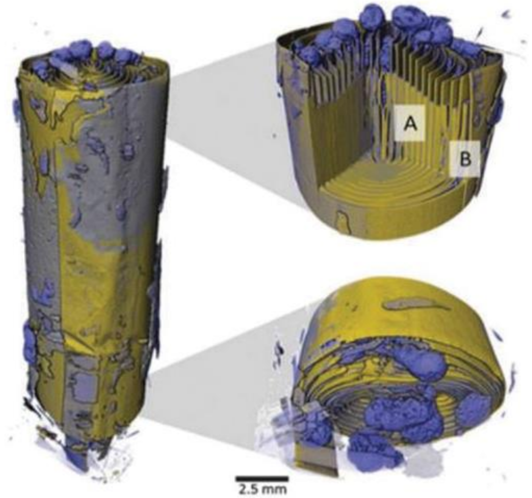
Synchrotron Soleil; Copyright © EPSIM 3D/JF Santarelli

Synchrotron X-ray imaging

- Particle accelerator to create intense X-ray beams
- Full-field X-ray imaging to view the interior of a broad range of samples





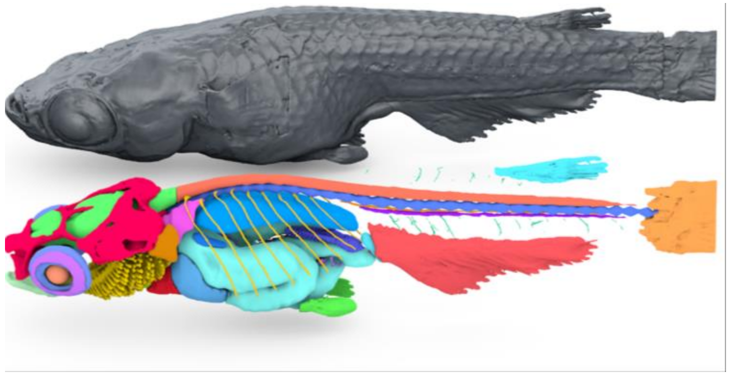


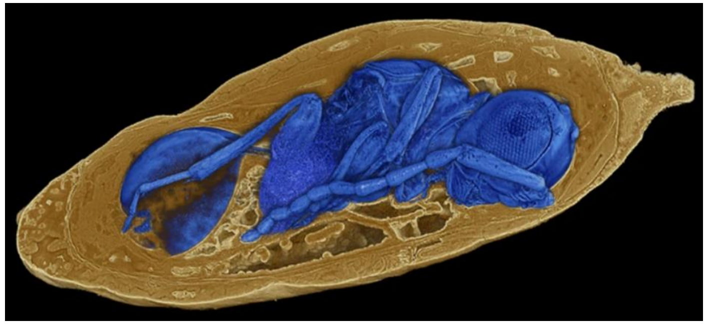
[M. Dickinson et al., *Nature* **537**, 508–514 (2016)] [A. Cau et al., *Nature* **552**, 395–399 (2017)] [F. Tang et al., *Small Methods* 2021, 5, 2100557]

KIT Light Source

Imaging for life science

- Interdisciplinary team of physicists, computer scientists and biologists
- Method development and application for studies on the morphology of biological specimens

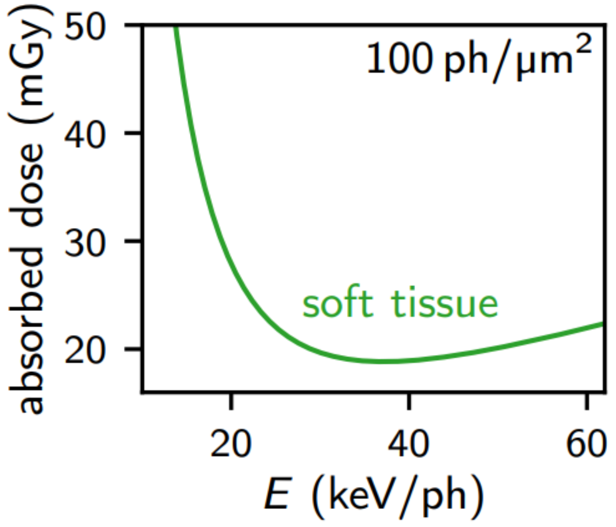




Motivation

- Dose-efficient µm-resolution X-ray imaging, e.g., living biological samples

  → **minimize absorption** by using optimized energy window (30-50 keV)



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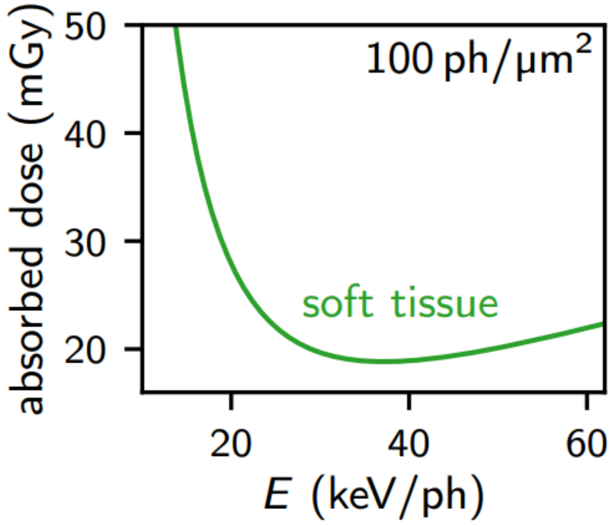
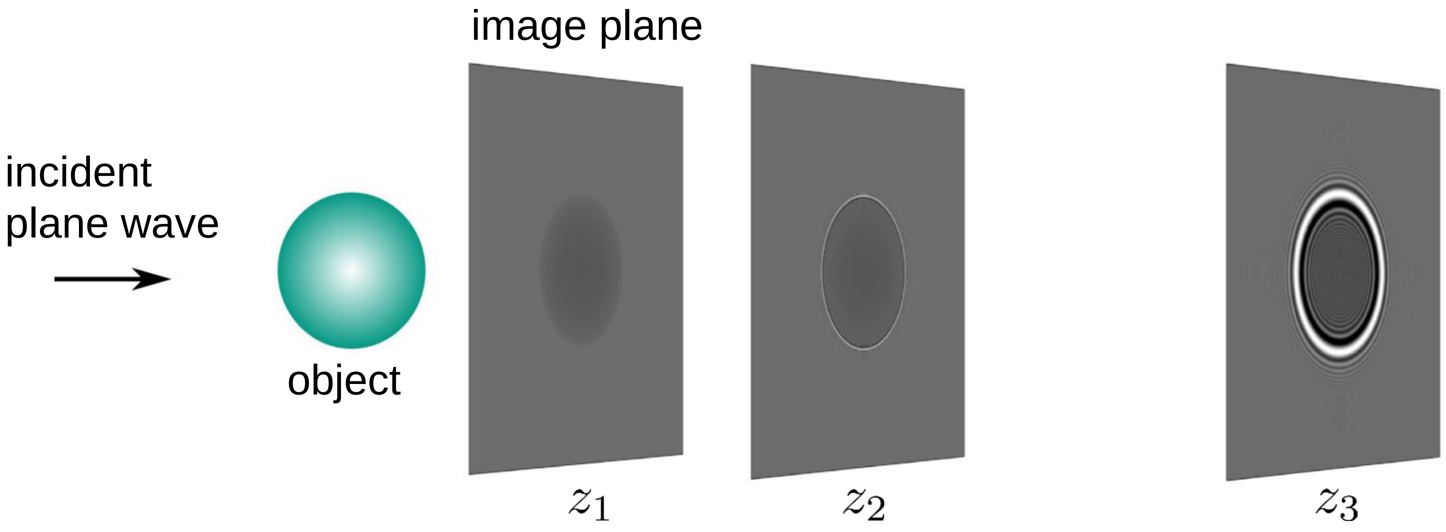
  → **increase contrast** by propagation-based phase contrast imaging



$$\psi_z(x,y) = \frac{1}{2\pi} \iint T_{\mathrm{obj}}(k_x,k_y) \cdot e^{iz\sqrt{k^2-k_x^2-k_y^2}} e^{i(k_x x + k_y y)} \mathrm{d}k_x \mathrm{d}k_y$$



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  → **increase contrast** by propagation-based phase contrast imaging

  → **optimize photon detection** efficiency

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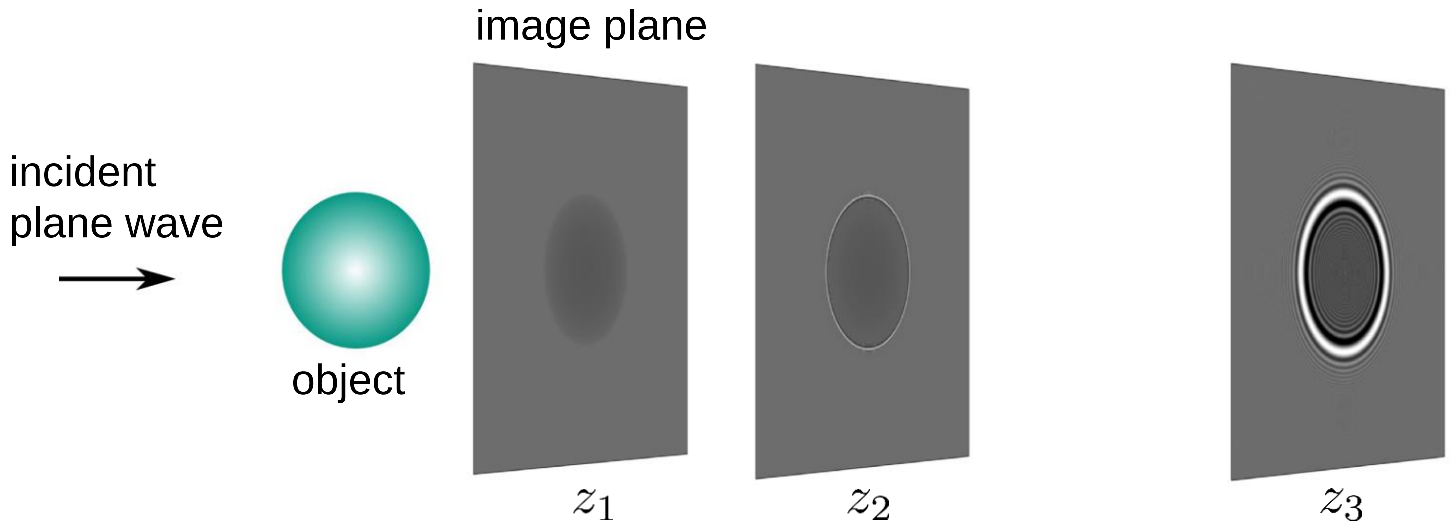
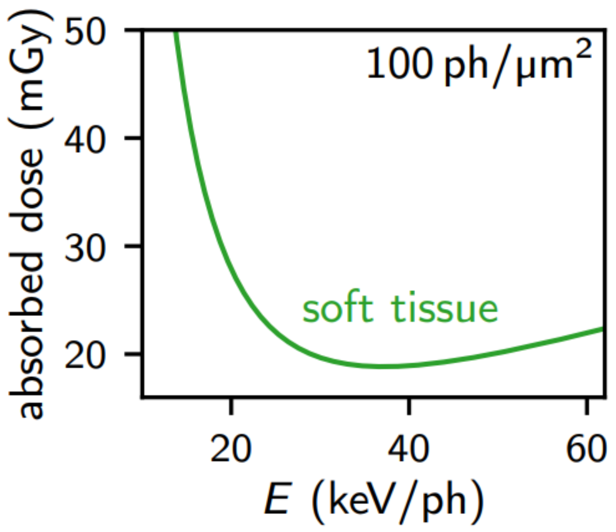
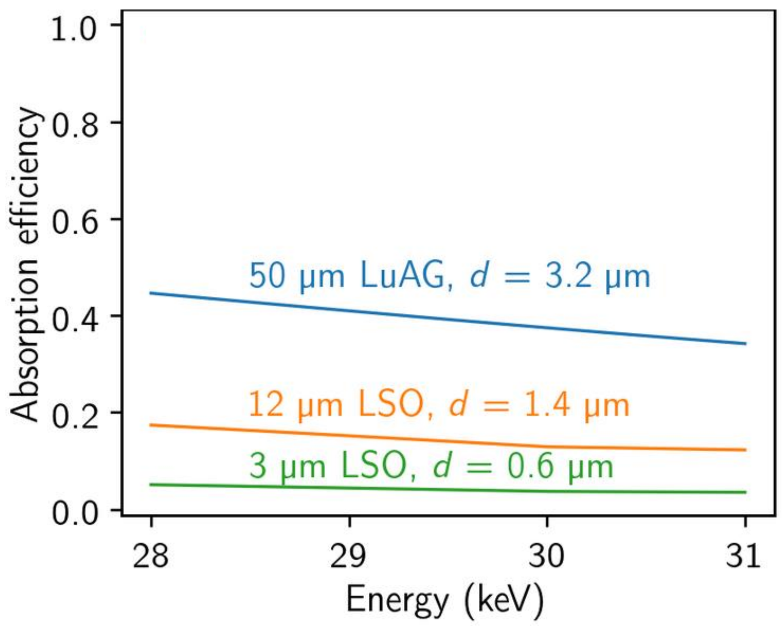


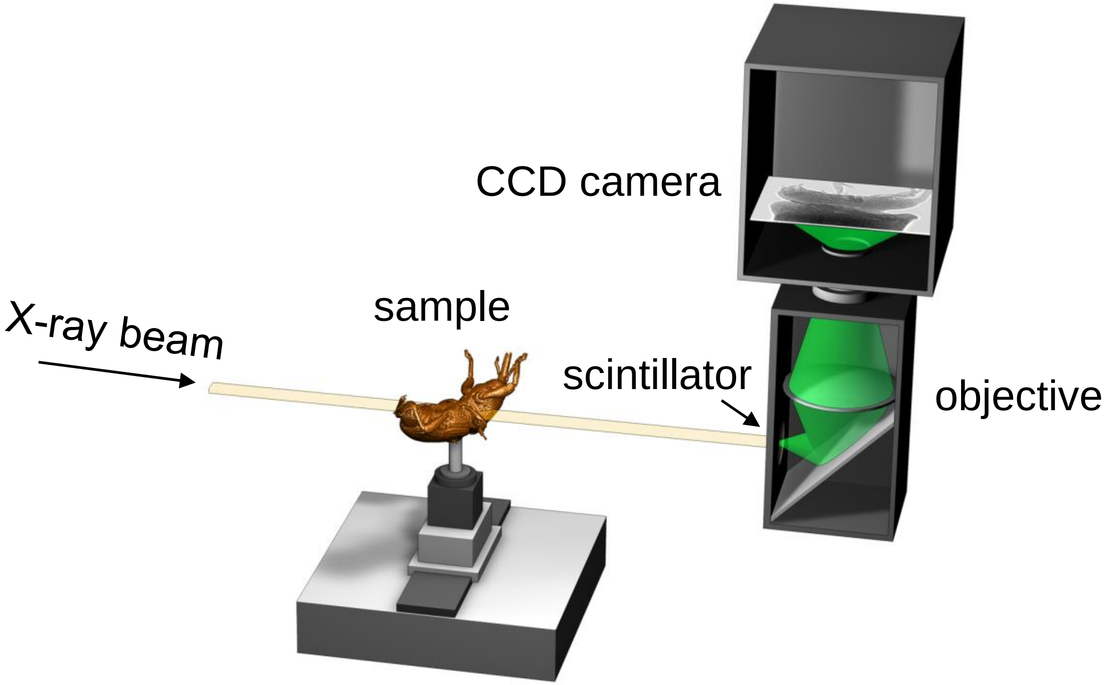


Conventional indirect detector systems

- State-of-the-art imaging with scintillator and optical magnification
- Thin scintillator needed for high resolution d

  → not efficient at high energies

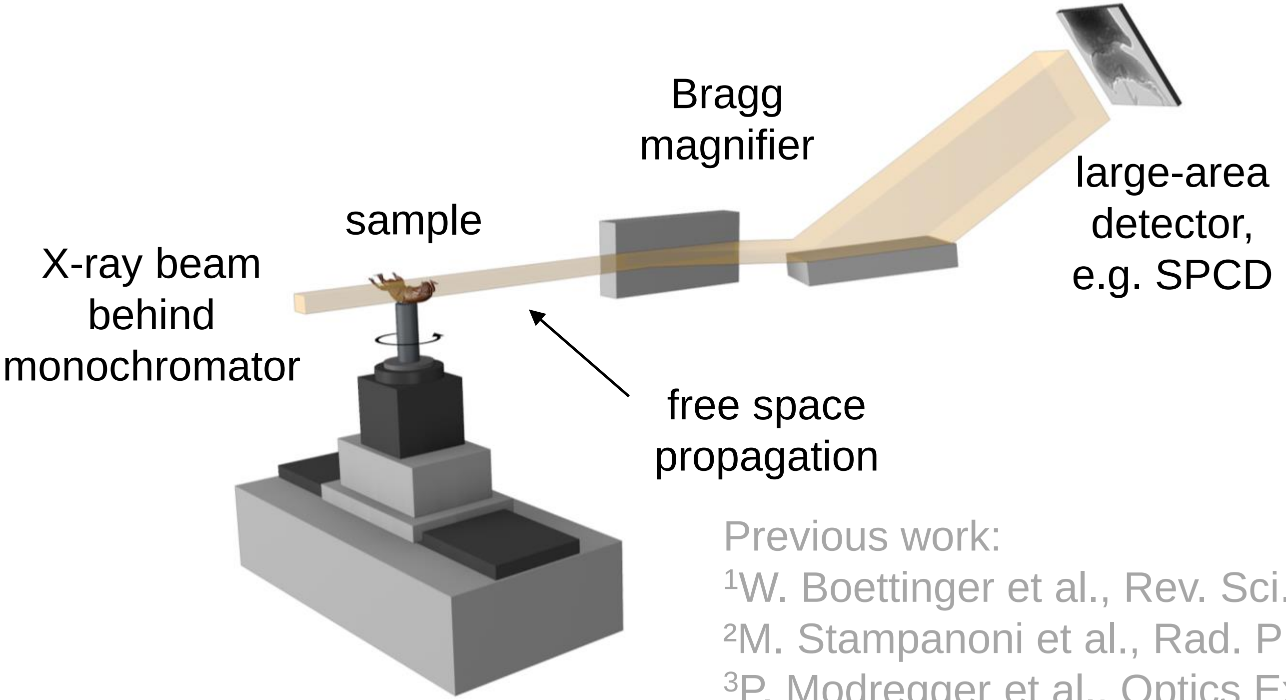


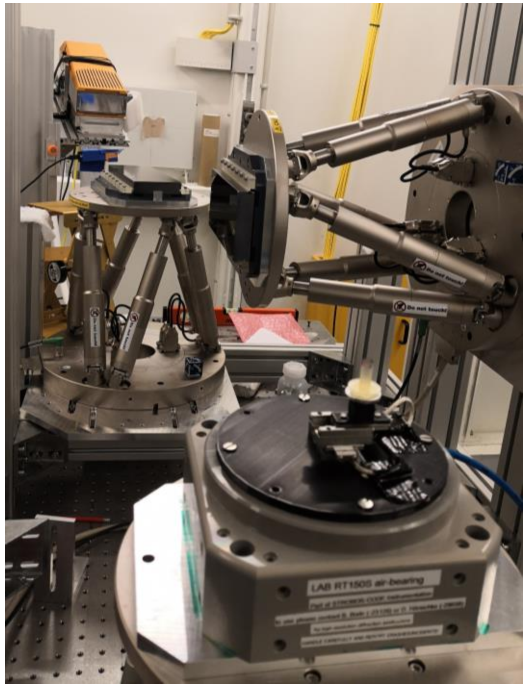


T. dos Santos Rolo et al., PNAS 111 (2014)

Bragg magnifier detector system

- Approach: use highly efficient large-area detector with Bragg magnifier[1-5] (BM)
  - Adjustable magnification and resolution

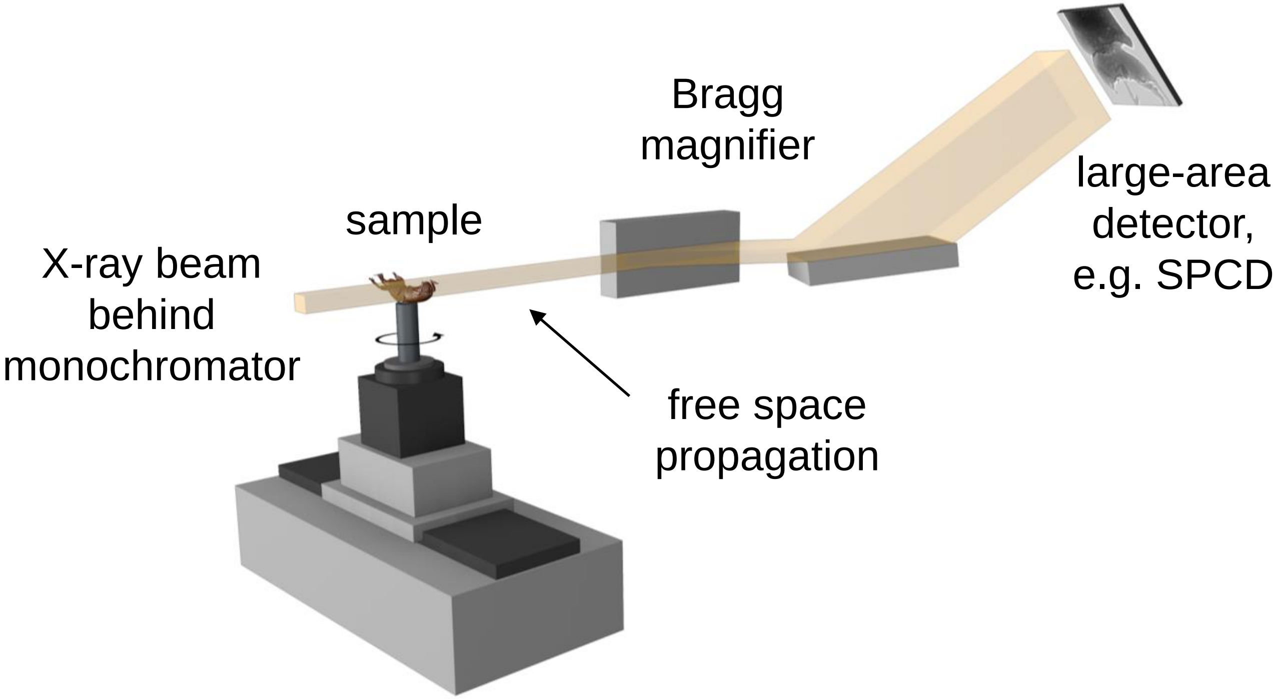


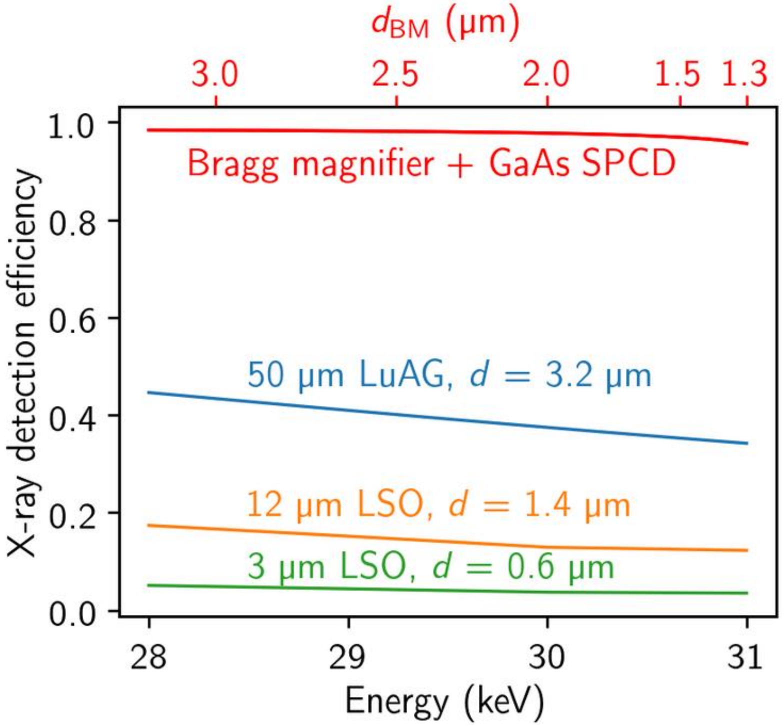


Previous work:
[1]W. Boettinger et al., Rev. Sci. Instrum. 50 (1979)
[2]M. Stampanoni et al., Rad. Phys. Chem. 75 (2006)
[3]P. Modregger et al., Optics Express 17 (2009)
[4]P. Vagovic et al., Optics Express 23 (2015)

Bragg magnifier detector system

- Approach: use highly efficient large-area detector with Bragg magnifier[1-5] (BM)
  - Adjustable magnification and resolution
  - Up to ~10-fold increased detection efficiency compared to indirect detectors

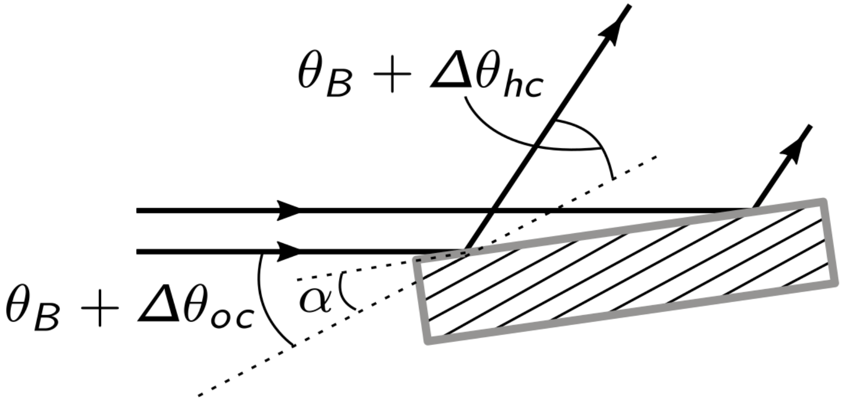




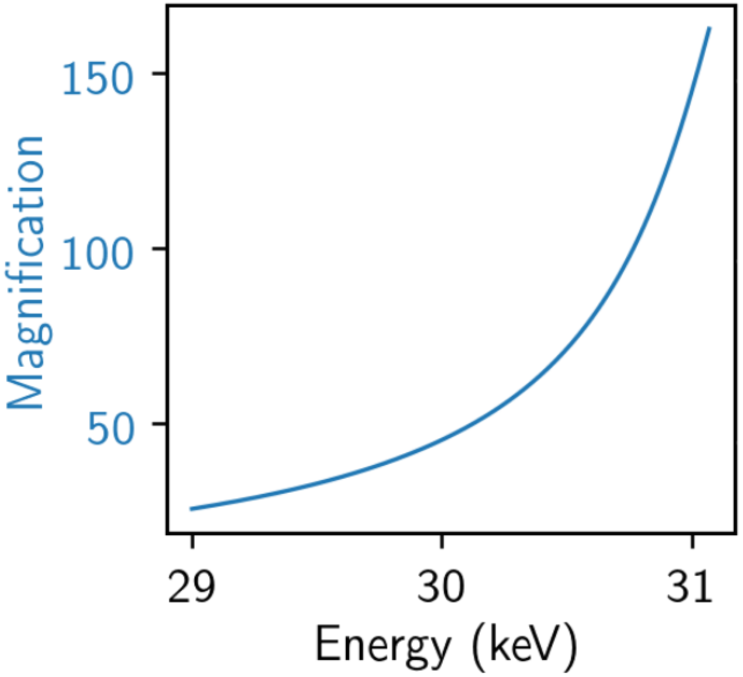
Working principle and realization

- Magnification M of the X-ray beam by asymmetric Bragg diffraction
- Designed for 29 – 31 keV (assymetry angle α, crystal size)

$$M = \frac{\sin(\theta_B + \Delta\theta_{hc} + \alpha)}{\sin(\theta_B + \Delta\theta_{oc} - \alpha)}$$



Adapted from Spal, *Phys. Rev. Let.* **86** No. 14, 3044-3047, 2001.



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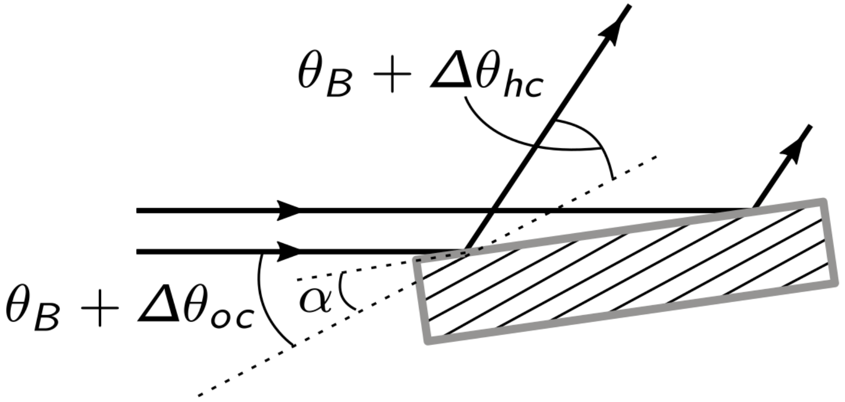

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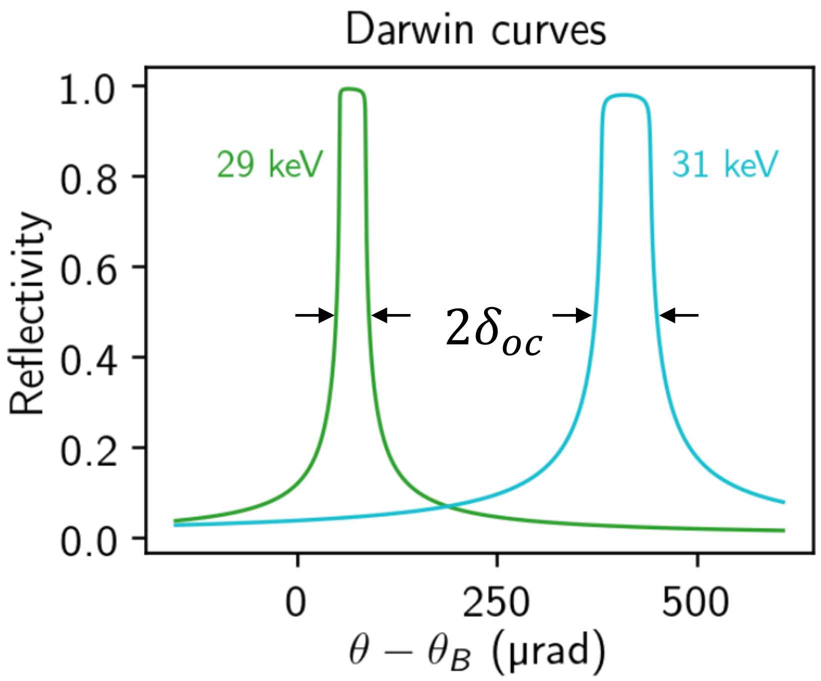
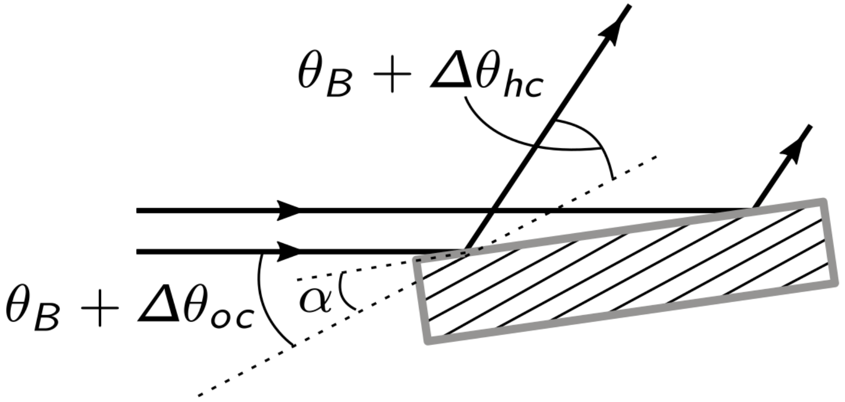


Working principle and realization

- Magnification M of the X-ray beam by asymmetric Bragg diffraction
- Designed for 29 – 31 keV (assymetry angle α, crystal size)
- Resolution $d = \frac{\lambda}{\delta_{oc}} \geq$ 1.3 µm



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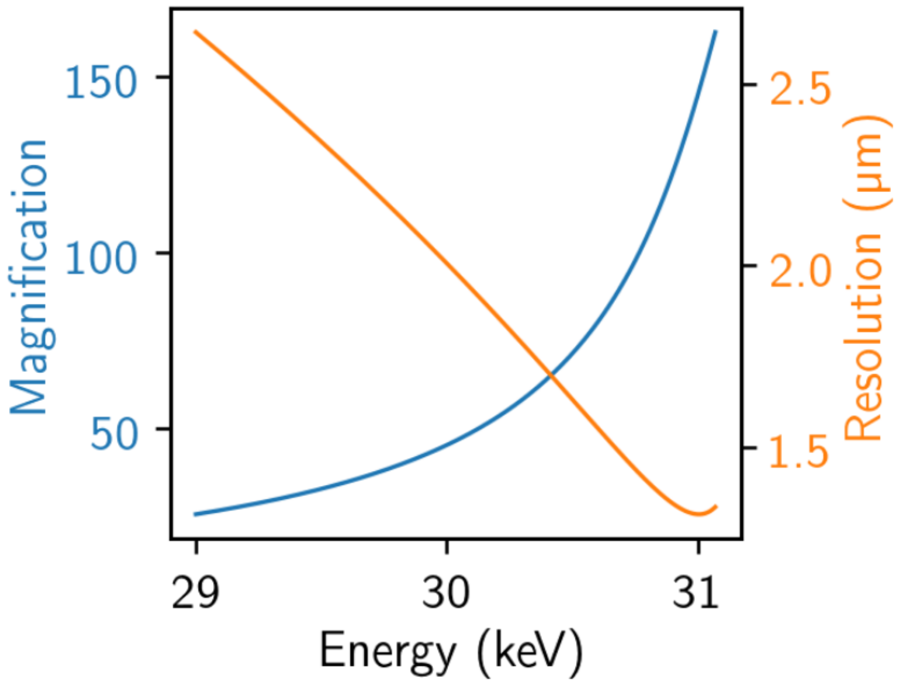
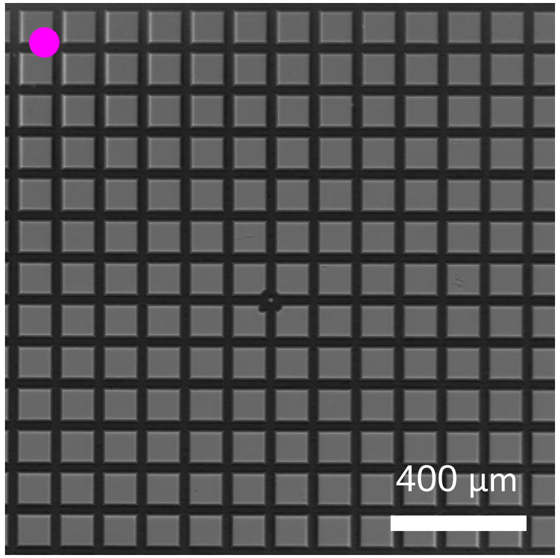
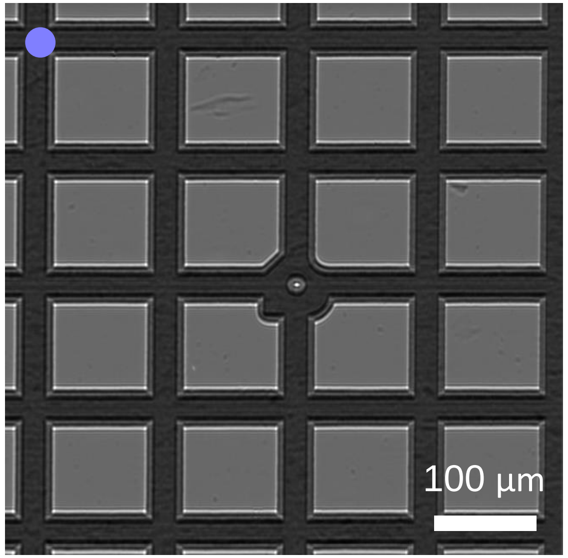


Experimental results – variable magnification

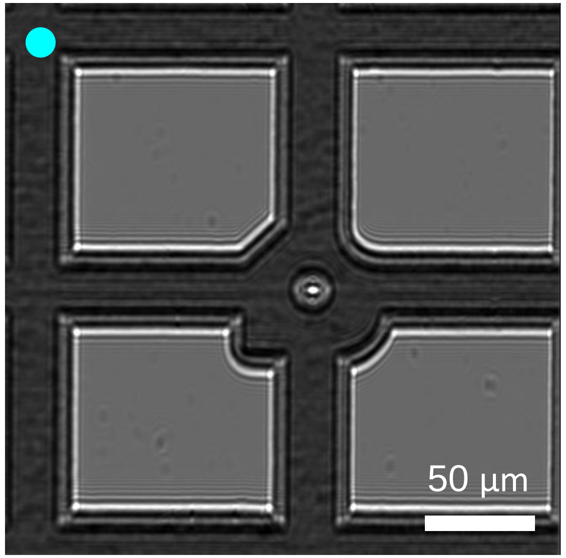
- Adjustable magnification by changing the energy and incidence angle*



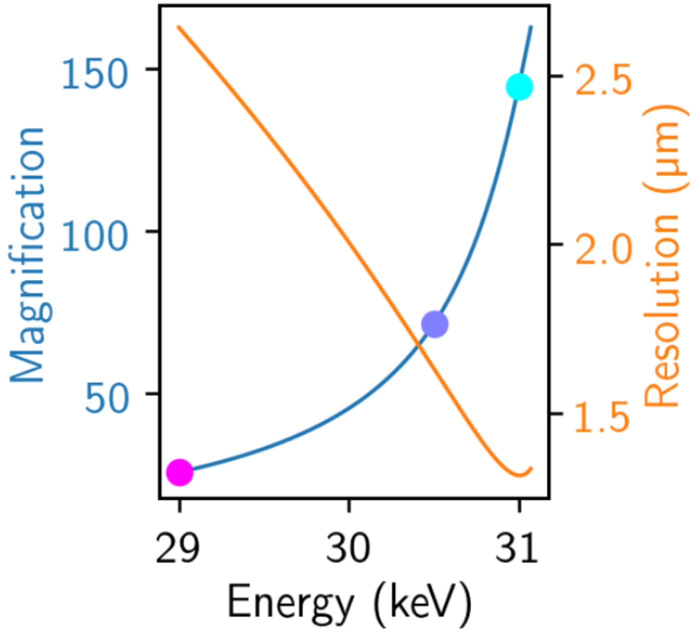
29.0 keV



30.5 keV



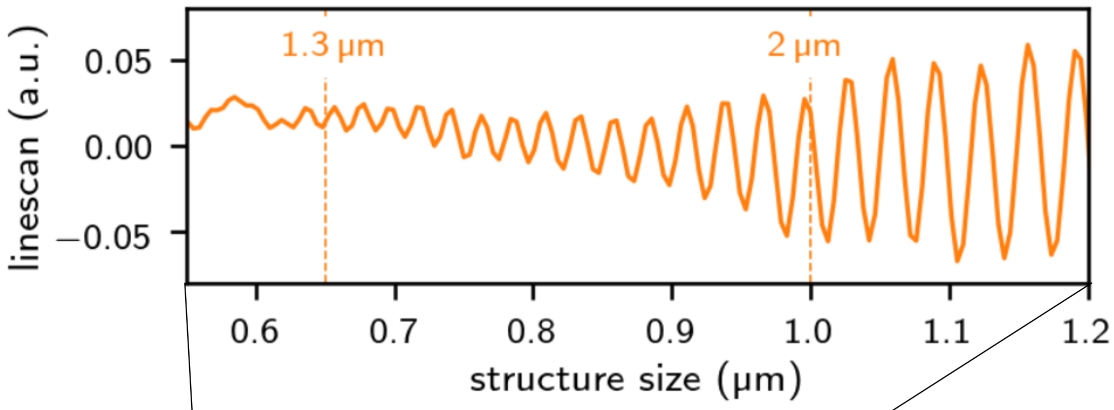
31.0 keV

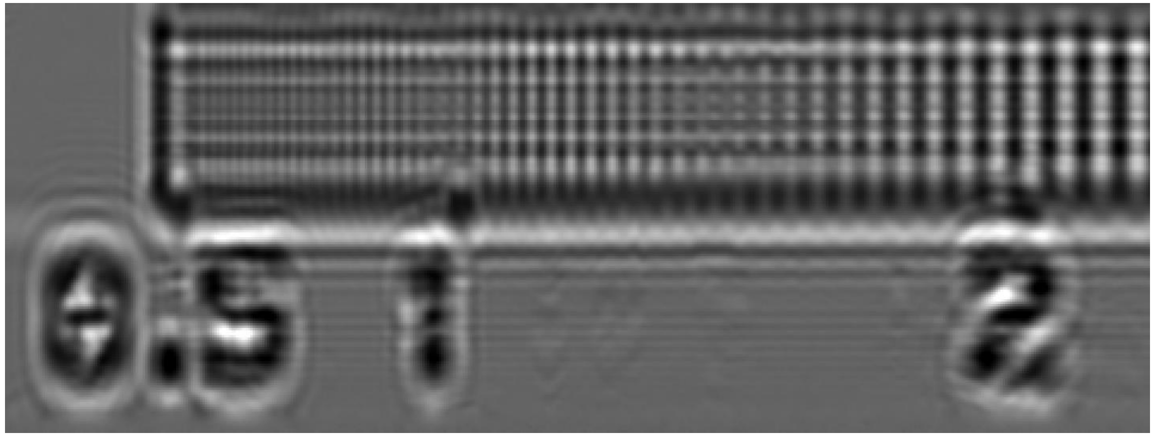


*DAQ at P23, PETRA III, DESY

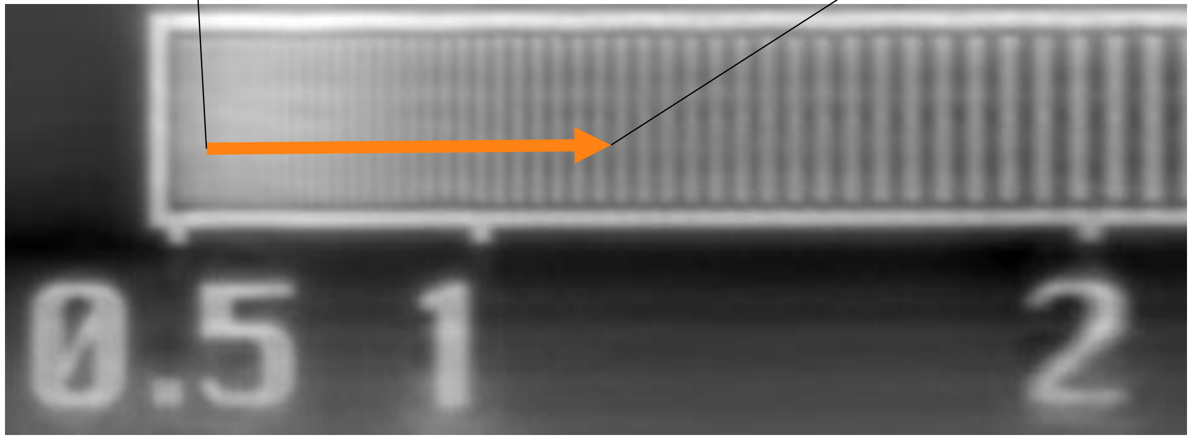
Experimental results - resolution

- Resolution of 1.3 µm at 31 keV confirmed





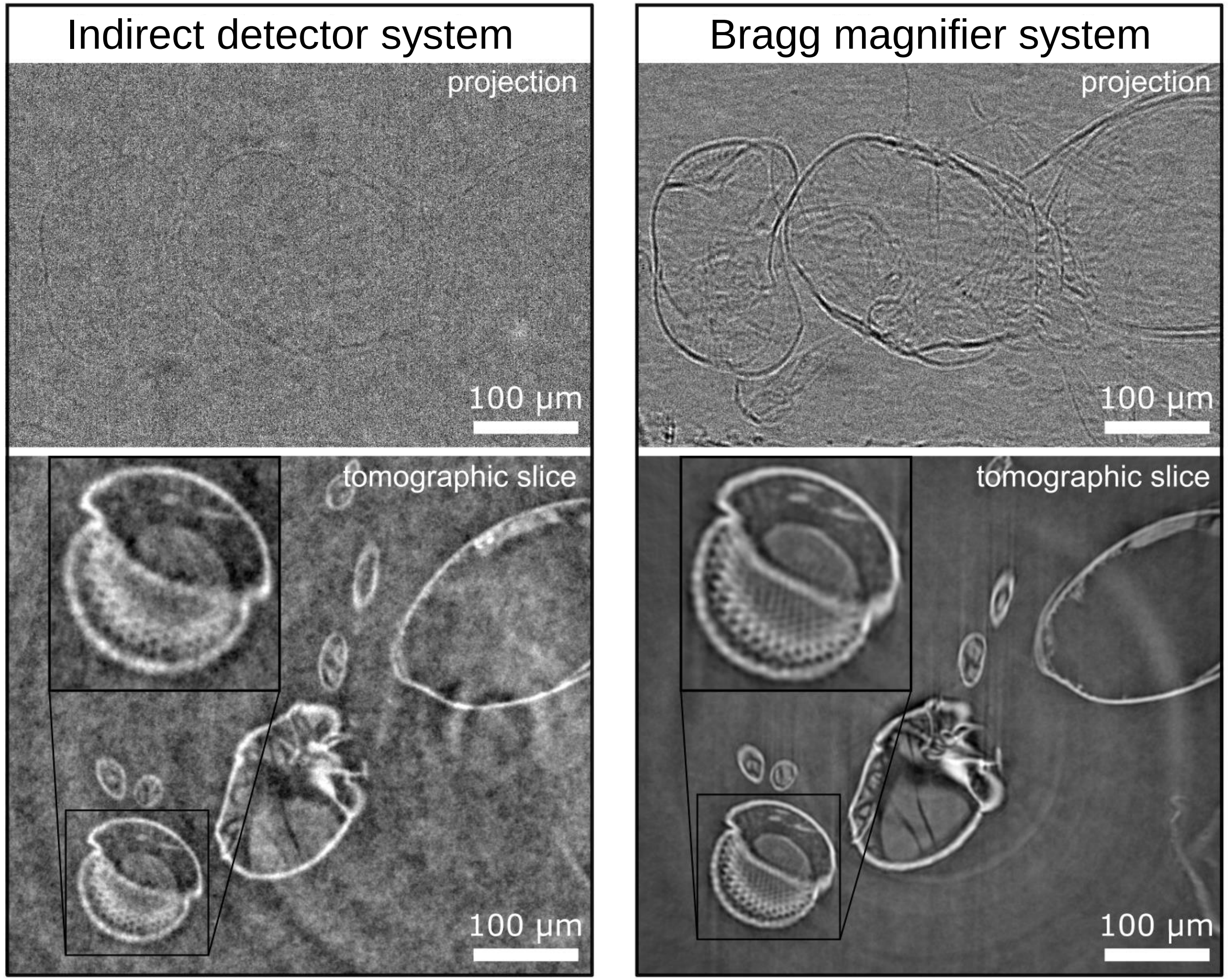
Flatfield corrected radiogram



Phase reconstruction*

*using https://gitlab.gwdg.de/irp/holotomotoolbox, L. Lohse et al., J. Synchrotron Rad. 27 (2020)

Comparison of BM and indirect system



- Same imaging conditions
- Indirect system:
  - 12 µm LSO scintillator
  - 10x objective, NA = 0.28
  - pco.edge 5.5
- BM system:
  - M = 70x
  - Lambda SPCD (500 µm GaAs)

→ Increased detection efficiency of the BM system is clearly visible

DAQ at P23, PETRA III, DESY

Reconstruction using https://github.com/ufo-kit/tofu/, T. Faragó et al., J. Synchrotron Rad. 29 (accepted, 2022)

Dose-efficient *in vivo* imaging of *Trichogramma* wasps

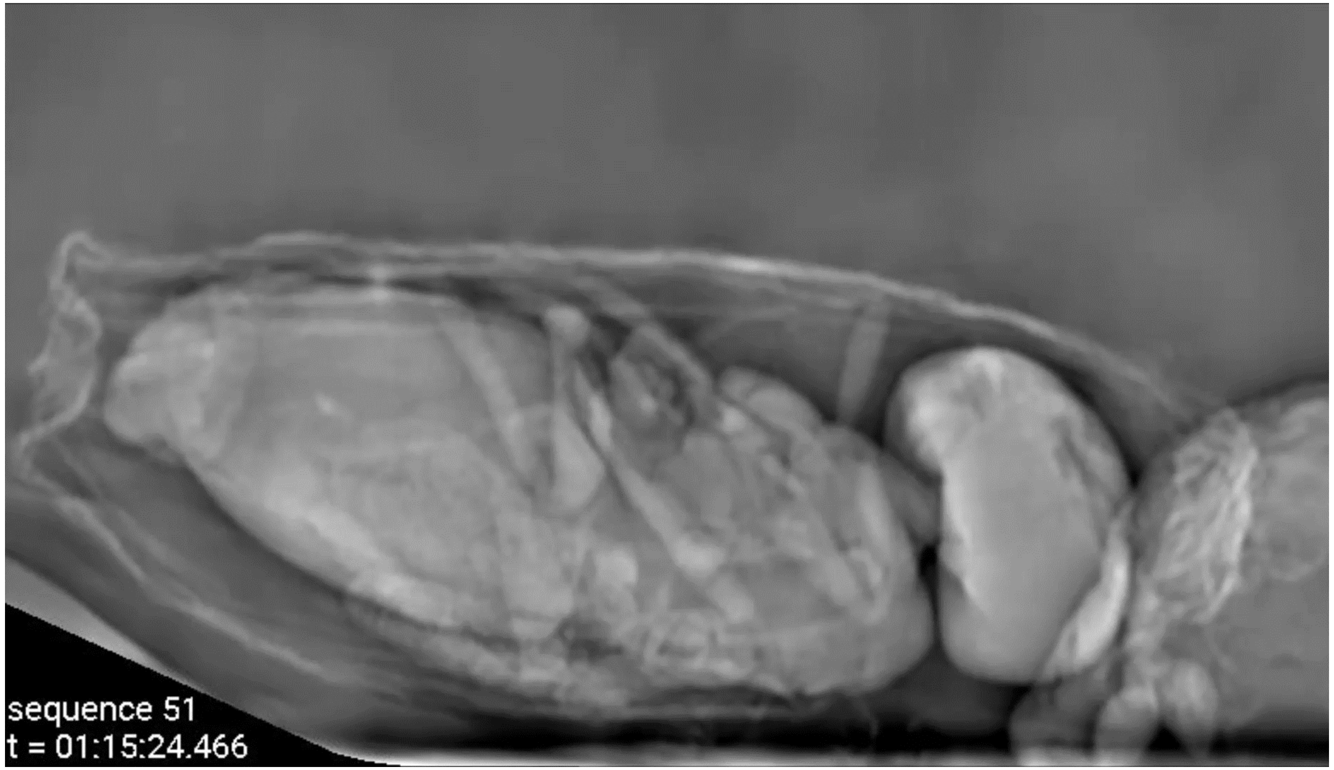
- Parasitoid wasps, e.g. *Trichogramma*, develop inside or on their host, e.g. butterfly or moth eggs

https://www.nuetzlinge.de/produkte/freiland/trichogramma-cacoeciae/

Tomogram of a *Trichogramma* wasp inside its host egg

Dose-efficient *in vivo* imaging of *Trichogramma* wasps

- Parasitoid wasps, e.g. *Trichogramma*, develop inside or on their host, e.g. butterfly or moth eggs
- BM allows dose-efficient imaging of *in vivo Trichogramma* in host egg



Parameters:

- 15 fps
- 30.4 keV
- 30 min exposure to X-rays
- 60 min total observation time
- 19 mGy per image
- total dose: 425 Gy

*DAQ at P23, PETRA III, DESY

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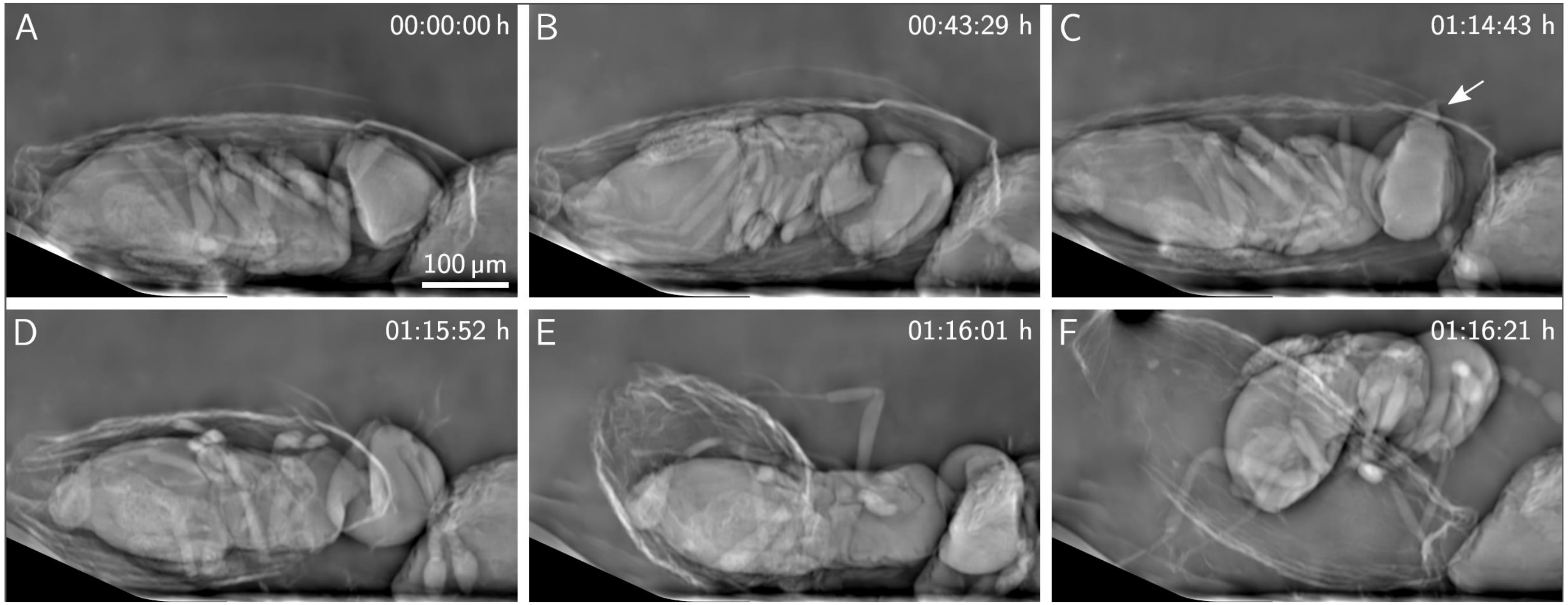

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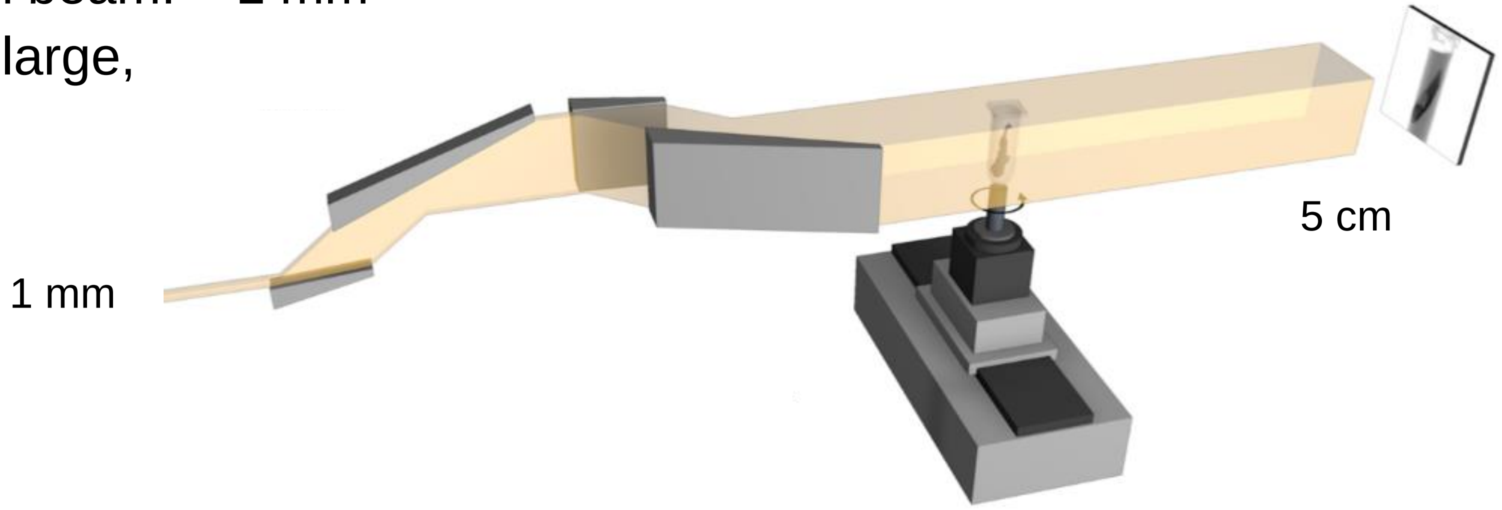
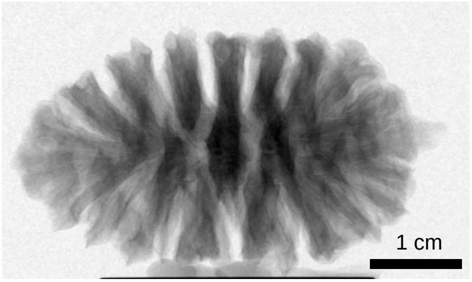
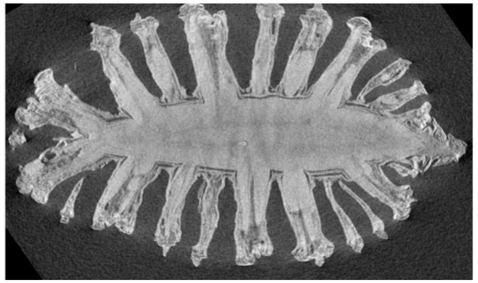
Further BM application: beam conditioner

- Diameter of synchrotron beam: ~ 1 mm
- BM enables imaging of large, cm-sized samples







5 cm large pine cone imaged with BM conditioner*

*DAQ at IMAGE beamline, KIT synchrotron

Summary and Outlook

- Bragg magnifier optics with high-Z SPCD enables superior detection efficiency at ~30 keV in comparison to indirect detector system
- Example of dose-efficient imaging: studying *in vivo Trichogramma* wasps emerging from their host egg
- Further application: BM as beam conditioner for large FoV imaging

→ Bragg magnifiers will be integrated into the HIKA station at PETRA III/IV, DESY (Hamburg)