Today: making X-ray tomography <u>better</u>

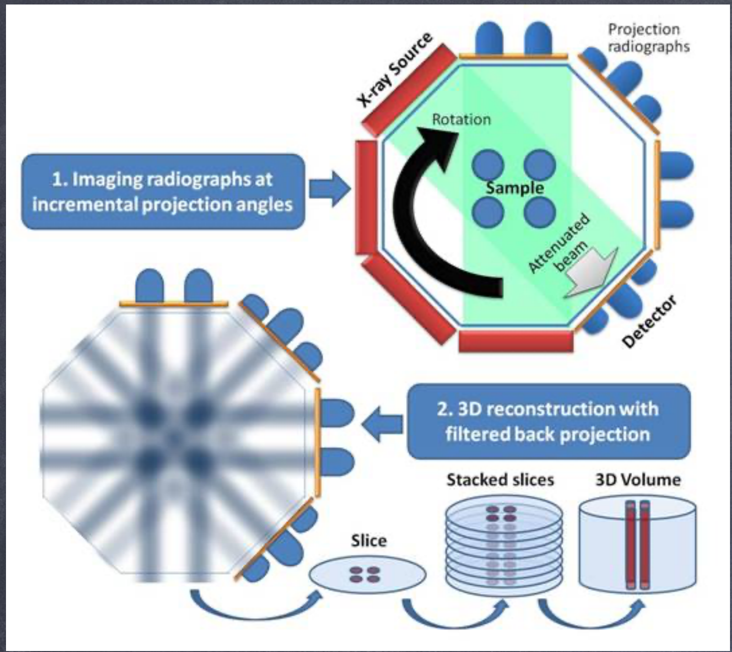
PHY127 FS 2026

Prof. Ben Kilminster

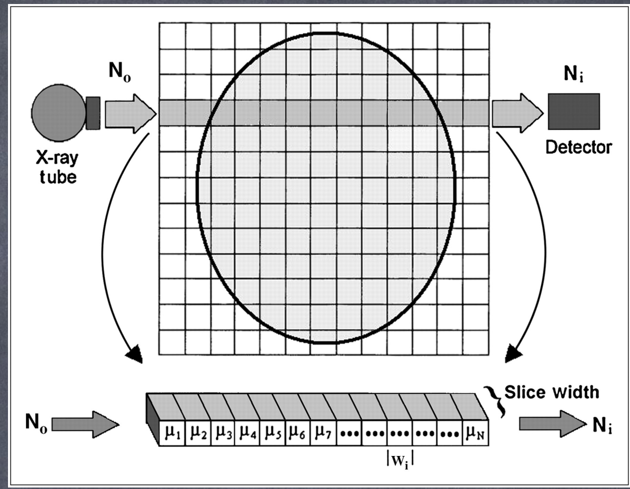
Lecture 10

May 8th, 2026

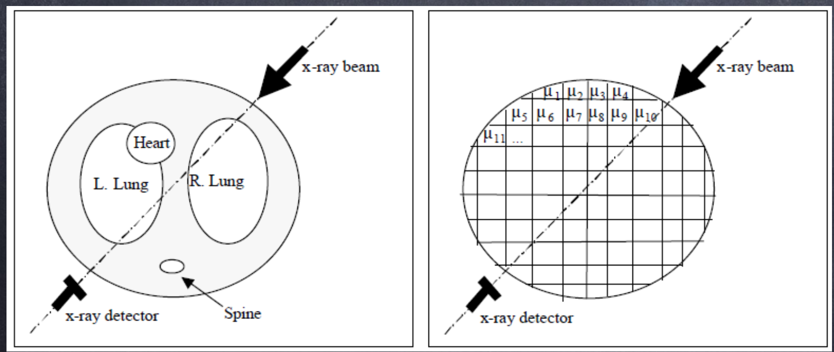
Review :



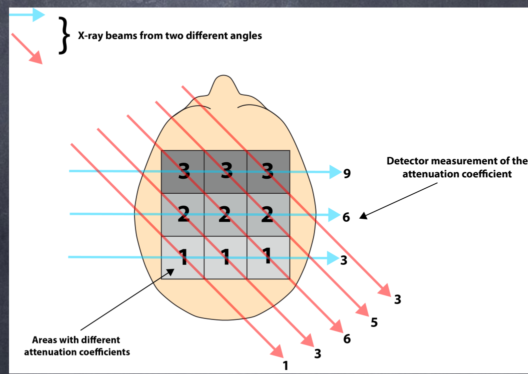
X-ray Source
Projection radiographs
Rotation
Sample
Attenuated beam
Detector
1. Imaging radiographs at incremental projection angles
2. 3D reconstruction with filtered back projection
Stacked slices
3D Volume
Slice



N_0
N_i
X-ray tube
Detector
Slice width
μ_1 μ_2 μ_3 μ_4 μ_5 μ_6 μ_7 ••• ••• ••• ••• ••• μ_N
$|w_i|$

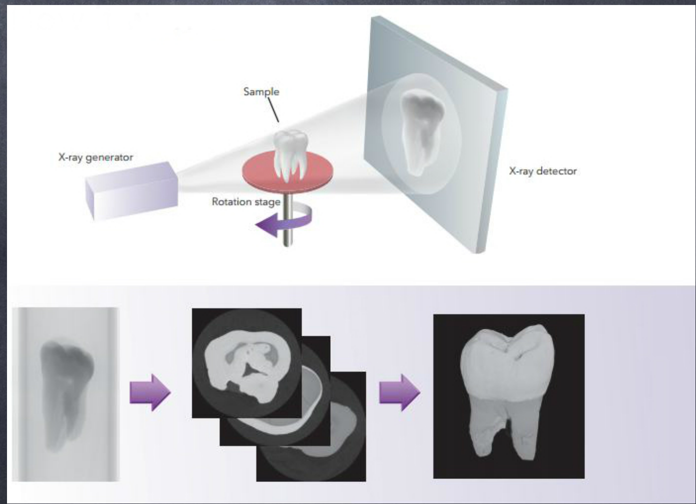


x-ray beam
Heart
L. Lung
R. Lung
Spine
x-ray detector
x-ray beam
μ_1 μ_2 μ_3 μ_4
μ_5 μ_6 μ_7 μ_8 μ_9 μ_{10}
μ_{11} ...
x-ray detector



X-ray beams from two different angles
Detector measurement of the attenuation coefficient
Areas with different attenuation coefficients


ZEISS
Xradia Context


Sample
X-ray generator
Rotation stage
X-ray detector

Here is a practical user guide if you want to learn more.

μCT guide

(non-destructive)

Laboratory x-ray micro-computed tomography: a user guideline for biological samples

Anton du Plessis,[1,2] Chris Broeckhoven,[3] Anina Guelpa,[1] and Stephan Gerhard le Roux[1]

Associated Data

▸ Supplementary Materials

Abstract

Go to: ▸

Laboratory x-ray micro–computed tomography (micro-CT) is a fast-growing method in scientific research applications that allows for non-destructive imaging of morphological structures. This paper provides an easily operated “how to” guide for new potential users and describes the various steps required for successful planning of research projects that involve micro-CT. Background information on micro-CT is provided, followed by relevant setup, scanning, reconstructing, and visualization methods and considerations. Throughout the guide, a Jackson's chameleon specimen, which was scanned at different settings, is used as an interactive example. The ultimate aim of this paper is make new users familiar with the concepts and applications of micro-CT in an attempt to promote its use in future scientific studies.

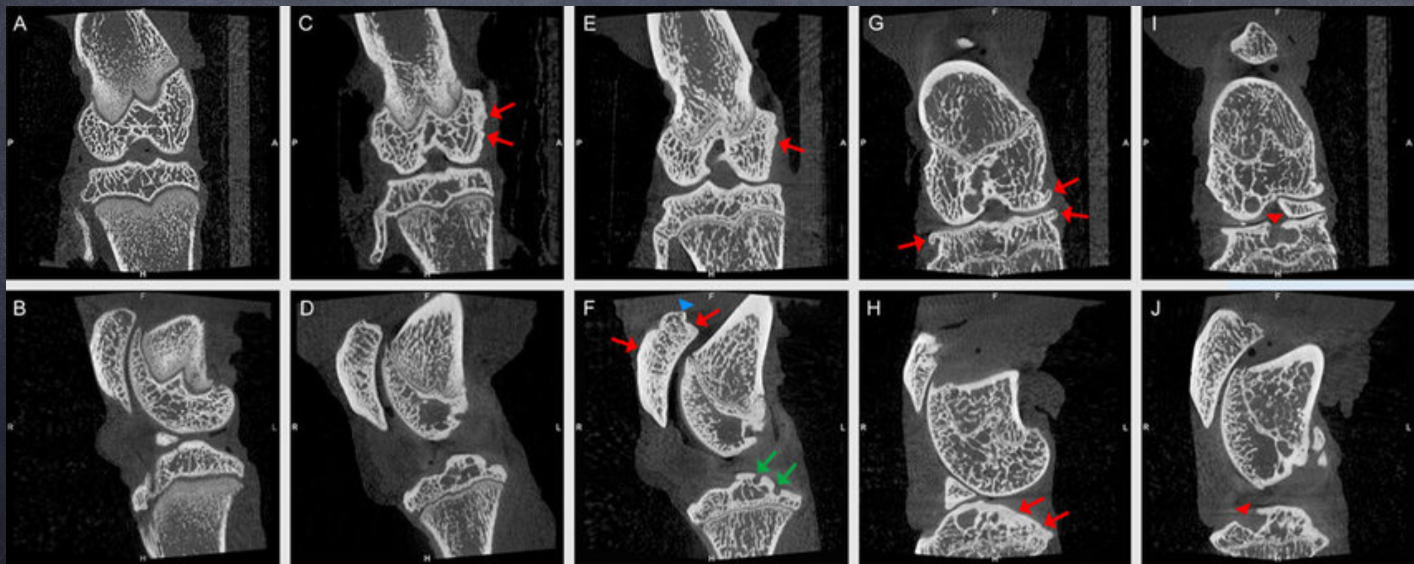
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5449646/

Biological applications of micro-CT

Related Stories

Micro-CT has been successfully applied to biological imaging in the following areas:

- In vivo imaging of head / knee
- Bone analysis
- Lung tumor detection in vivo and ex vivo
- Imaging and quantification of tumors
- Ex vivo imaging of the rabbit brain
- Phenotyping of the mouse kidney
- Imaging of mouse heart calcification and chest of live animals using contrast agents in vivo
- Imaging of tooth and jaw bone in mice



Representative photos from microCT evaluation of knee joints using the novel scoring system. (A) Dorsal and (B) sagittal reconstructions from a 2 month old Hartley guinea pig with no clinically significant OA lesions.

Example of a commercial micro CT system

Quantum GX2 microCT Imaging System

Image beyond bone – into oncology, cardiovascular and pulmonary diseases, and much more, with the Quantum GX2 microCT imaging system. With the Quantum GX2, flexibility is key. Combining the ability to perform high speed, low dose scans, ideal for longitudinal studies, across multiple species (mice, rats, rabbits) with high resolution ex vivo scanning, the Quantum GX2 microCT imaging system offers the flexibility and performance you need to not just image, but further understand your disease models.

Part Number CLS149276

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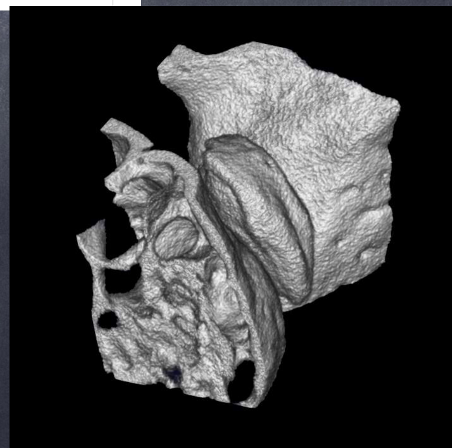
The Quantum GX2 microCT scanner is a true multispecies preclinical imaging system, offering the flexibility to enable longitudinal in vivo imaging as well as ex vivo sample scanning. With a 163mm imaging bore, an entire rabbit can be placed inside the scanner for in vivo scanning, while the 18mm FOV allows for high resolution scanning of ex vivo samples. Combined with PerkinElmer's 3-dimensional optical imaging systems, and automated bone analysis software (AccuCT™), the Quantum GX2 microCT imaging system provides maximal flexibility and function. Whether your research focus is oncology, cardiovascular disease, orthopedics or pulmonary disease, the Quantum GX2 is versatile enough to deliver the results you need.

Key Features

- High resolution (2.3 micrometer voxel size)
- High-speed (scans as fast as 3.9 seconds)
- Low-dose imaging for longitudinal in vivo studies
- Four Field Of Views (FOVs) – 18, 36, 72, and 86 mm
- Multispecies imaging capabilities (Zebrafish/mouse/rat/guinea pig/rabbit)
- Two-phase retrospective respiratory and cardiac gating
- Seamlessly co-registration of functional optical signals (from IVIS® Spectrum or FMT®) with microCT imaging data

Combine the Quantum GX2 microCT imaging with PerkinElmer's other in vivo imaging modalities (optical and PET) to gain greater insight into disease progression and treatment response non-invasively.



Some examples of μCT scans :

Fig. 1 | *Micro-CT cross-section image of a human vertebral body, at 17.4 μm pixel size (3936 × 3936 pixel, 68.5 × 68.5 mm).*

human Vertebra - spinal bone

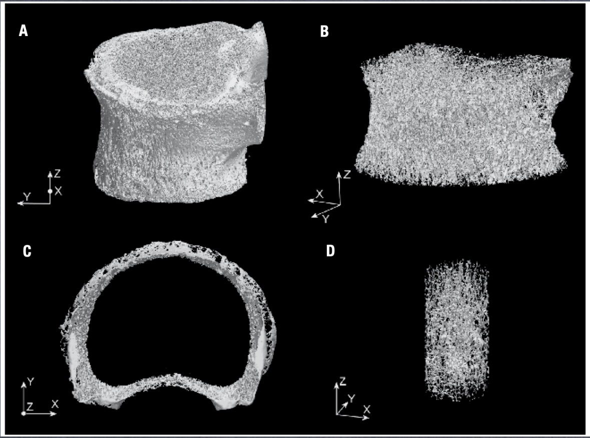
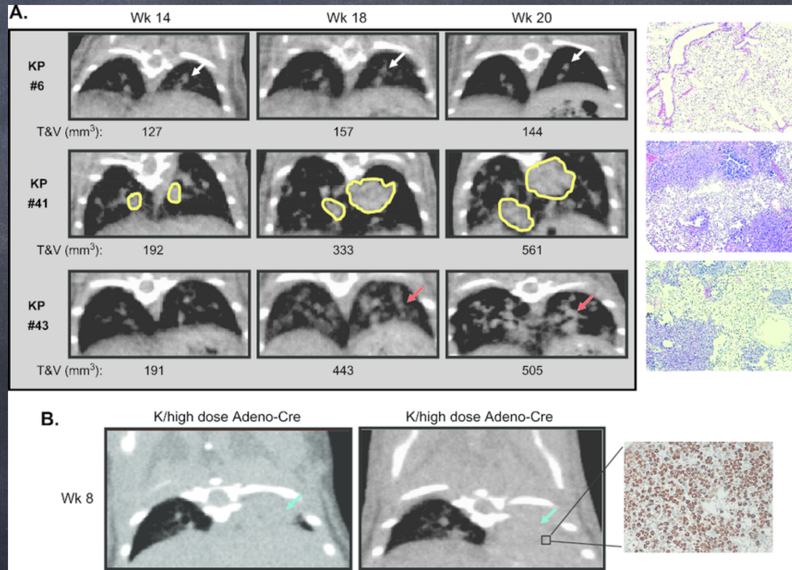
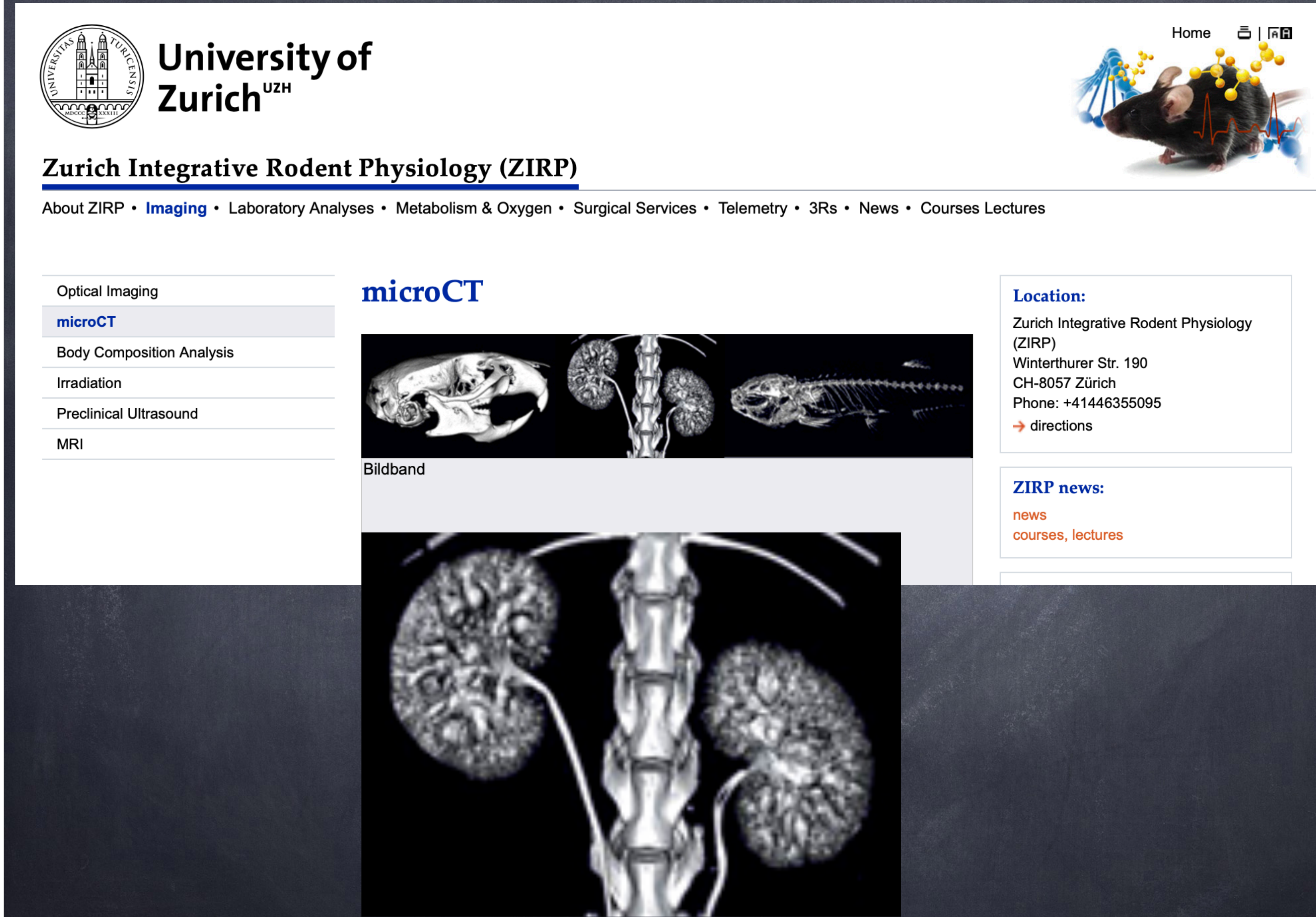


Fig. 2 | *Three-dimensional micro-CT images of a vertebral body scanned at 17.4 μm pixel size. (A) entire vertebral body (B) trabecular bone compartment (VOI) within the endplates, over which the trabecular bone morphometric parameters were calculated (C) cortical bone compartment, superior-inferior view (D) cylindrical subvolume of trabecular bone, 10 mm in diameter, 20 mm in height.*



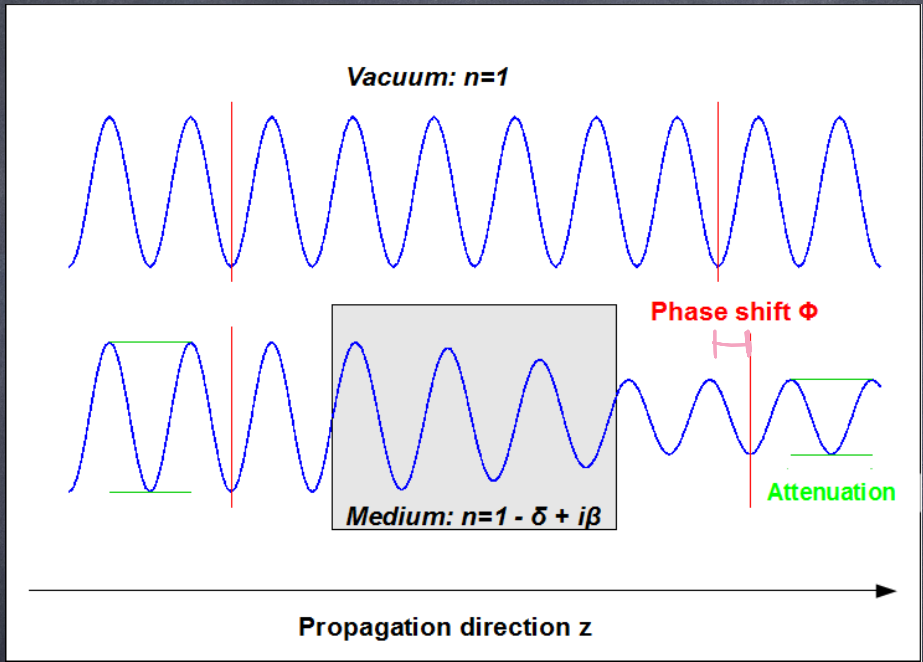
Lung tumor identification in mouse

we have one here!



Another technique to improve CT scans:

Phase-contrast X-ray imaging



k: wave number $= \frac{2\pi}{\lambda}$

ρ_a : atomic number density

σ_a : absorption cross-section

p: phase-shift cross-section

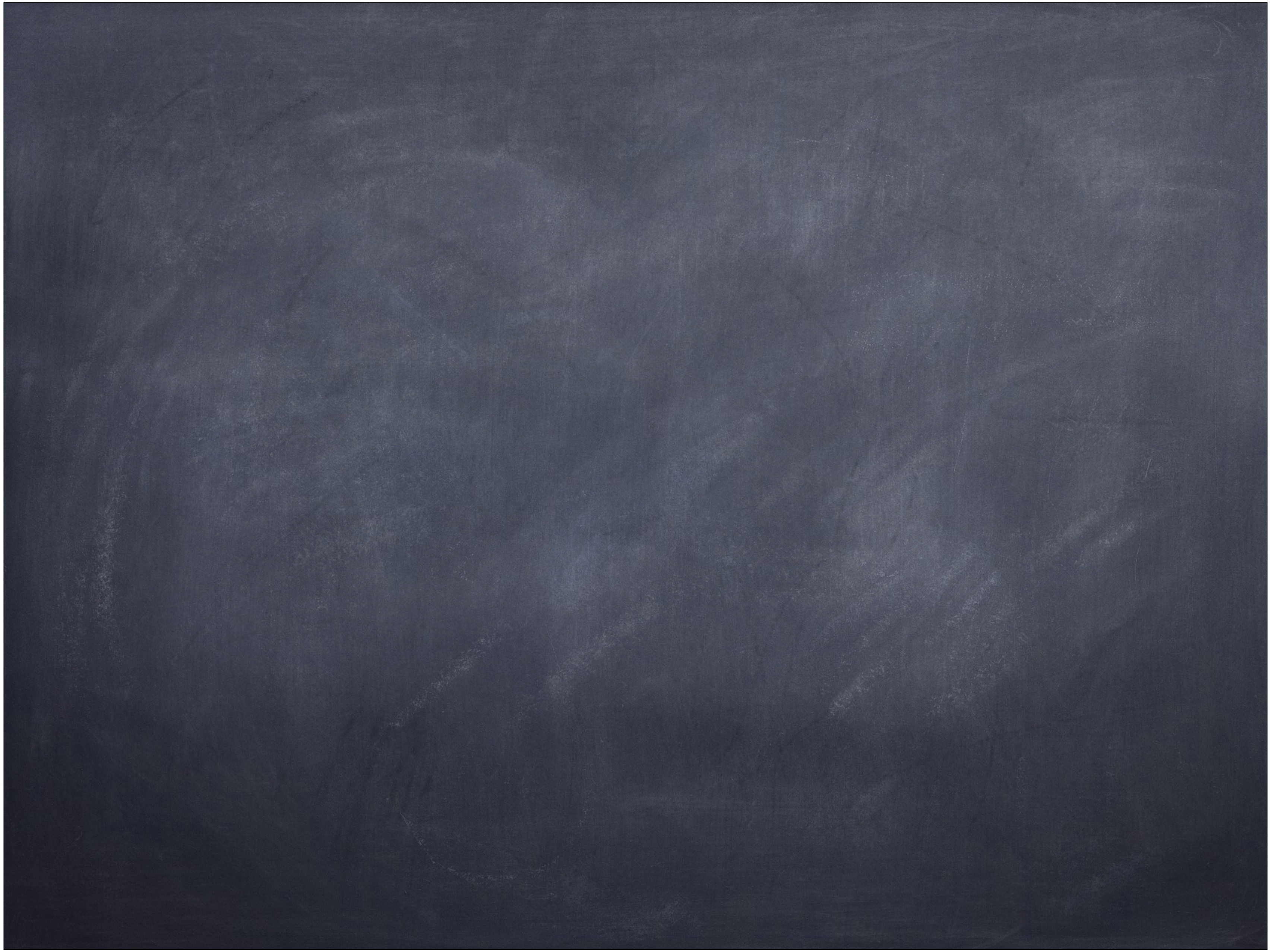
$p = \frac{2\pi Z r_0}{k}$

Z: atomic number

r_0: classical electron radius

1 barn $= 10^{-28}$ m^2

k_0 : length of wave with $\lambda = 1E{-10}$ m (1 Å)



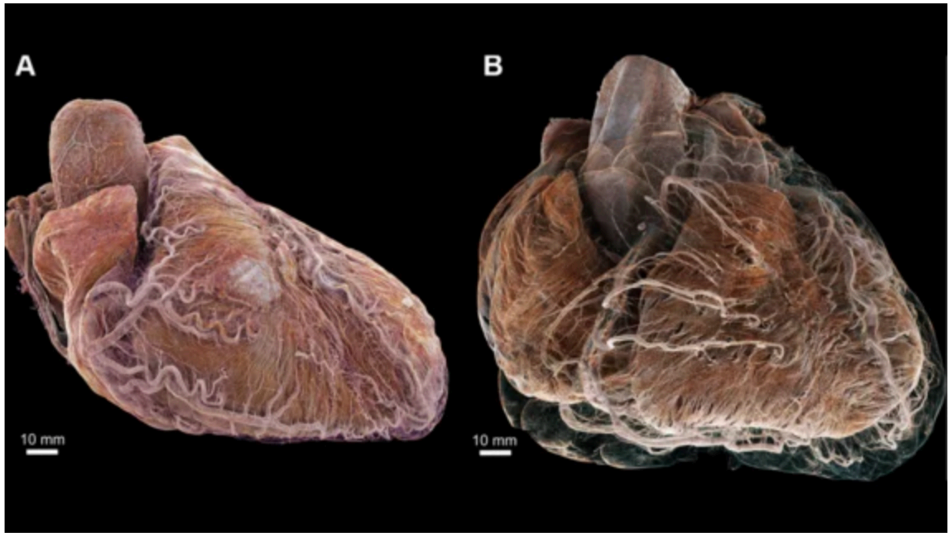
Absorption X-ray vs. phase-contrast X-ray

(In-ear headphone)

Always new developments going on

New imaging technique captures human heart with 'unprecedented detail'

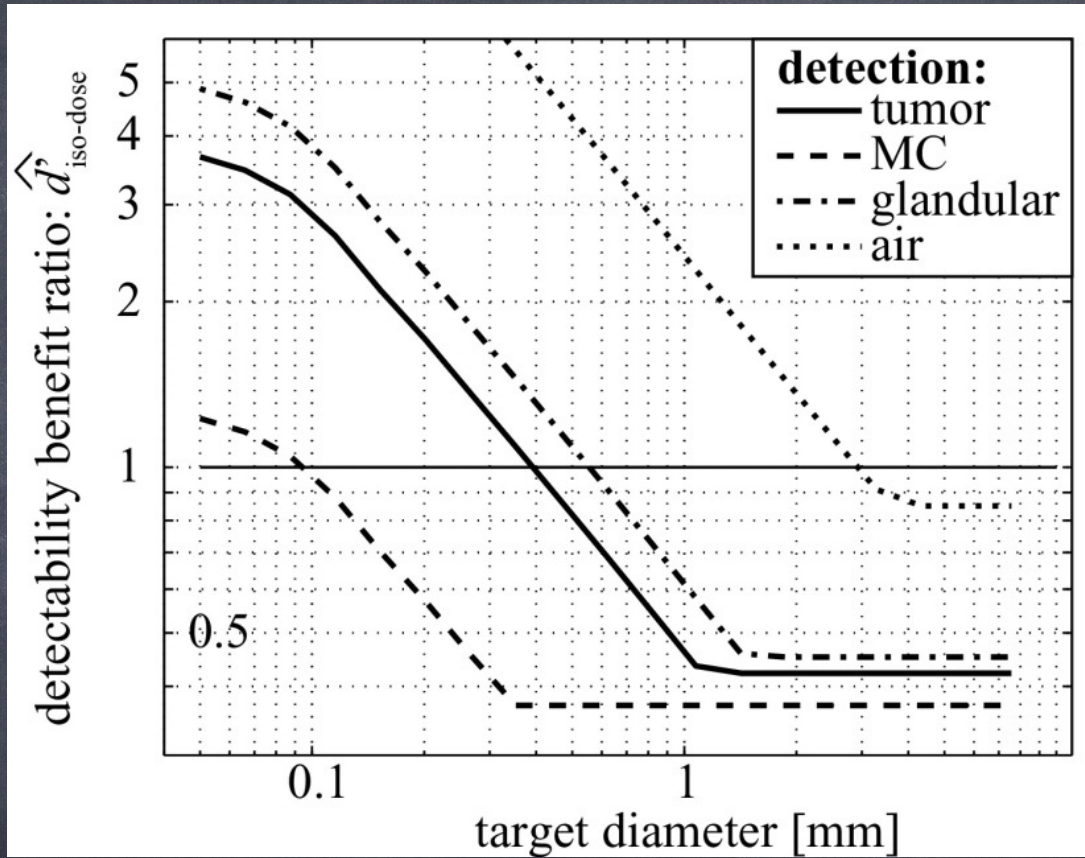
Michael Walter | July 17, 2024 | Cardiovascular Business | Cardiac Imaging



Images of the heart create using a new X-ray technique, hierarchical phase-contrast tomography (HiP-CT). The technology enables CT imaging of the heart and the ability to zoom in to the cellular level with unprecedented detail. Images courtesy of RSNA.

Link to article

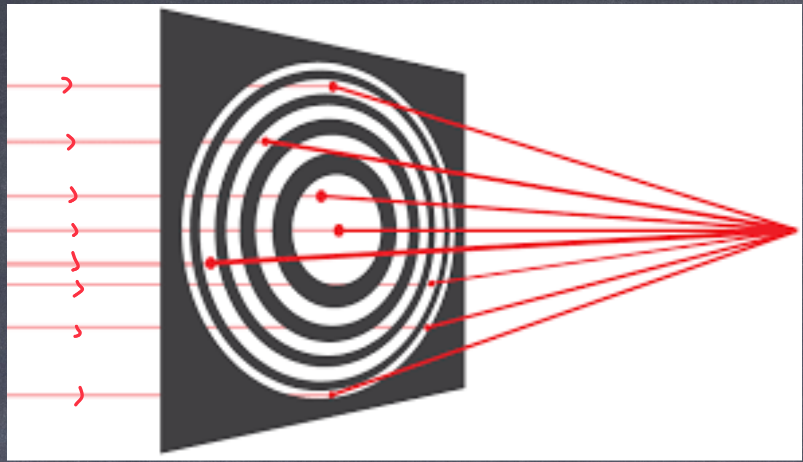
Benefit of phase contrast depends on tissue type & target size.

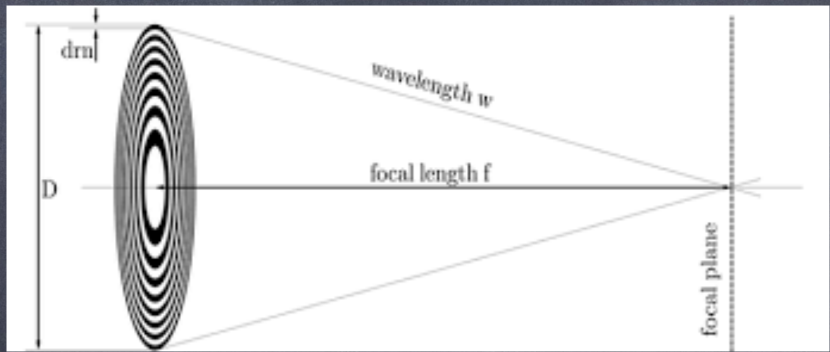


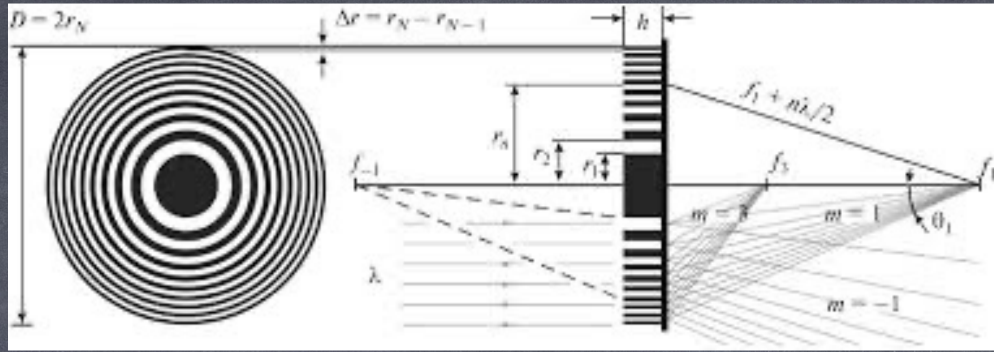
The benefit of phase contrast mammography relative to absorption contrast for (1) a tumor structure ("tumor"), (2) a glandular structure ("glandular"), (3) a microcalcification ("MC"), and (4) an air cavity ("air") as a function of target size at optimal energy and equal dose.[97]

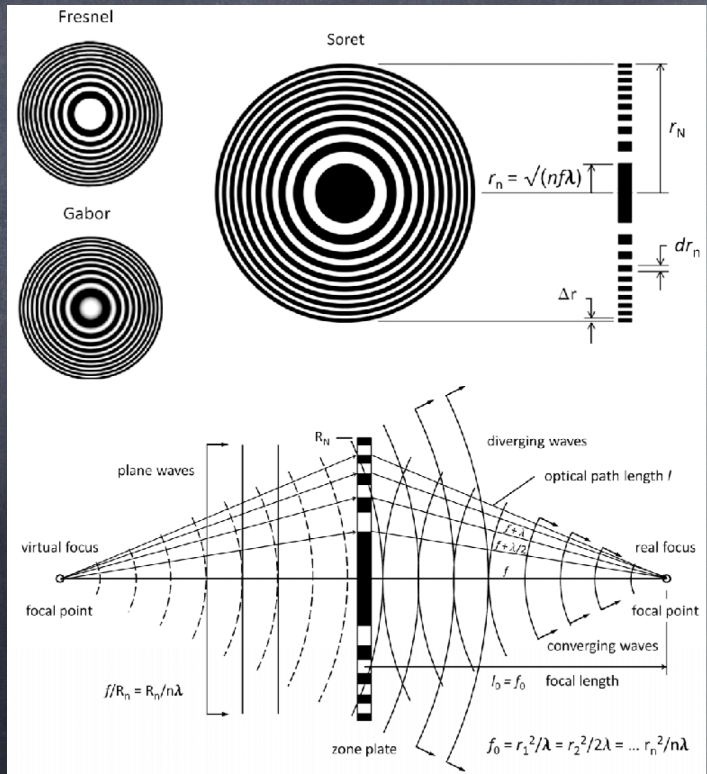
https://en.wikipedia.org/wiki/Phase-contrast_X-ray_imaging#Phase-contrast_x-ray_imaging_in_medicine

Another improvement to CT scans:



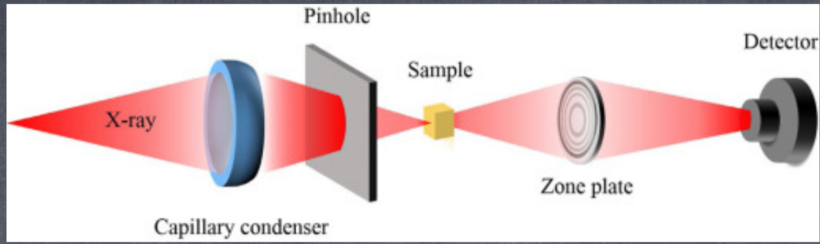

drn
D
wavelength w
focal length f
focal plane


D = 2r_N
Δr = r_N − r_{N−1}
h
f_1 + nλ/2
r_N
r_2
r_1
f_{−1}
f_3
f_1
m = 3
m = 1
θ_1
λ
m = −1


Fresnel
Soret
Gabor
r_N
r_n = √(nfλ)
dr_n
Δr
R_N
diverging waves
optical path length l
plane waves
virtual focus
real focus
f+λ
f+λ/2
f
focal point
focal point
converging waves
l_0 = f_0
focal length
f/R_n = R_n/nλ
zone plate
f_0 = r_1²/λ = r_2²/2λ = ... r_n²/nλ

Fresnel zone plate:

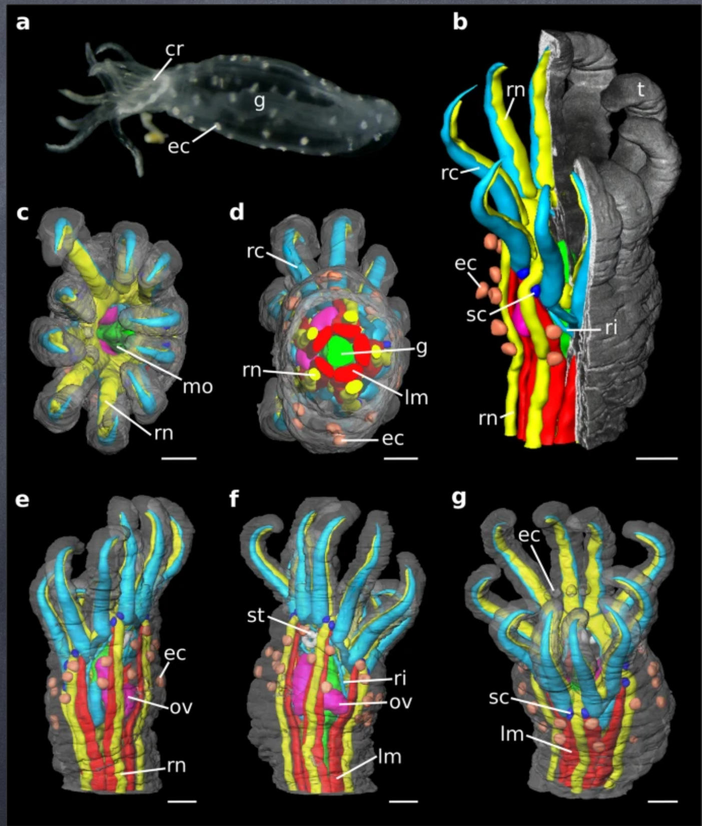
Nano CT



(For x-rays, Fresnel zone plate is typically Gold, Nickel, Tungsten, Platinum, Iridium deposited on a silicon substrate using electron-beam lithography + electroplating)

Combining small X-ray focal spots with cone beam geometry, this NanoCT setup reaches resolutions down to 100 nm and is highly versatile respective to sample sizes[10,16,17].

Worm ~ 1mm length



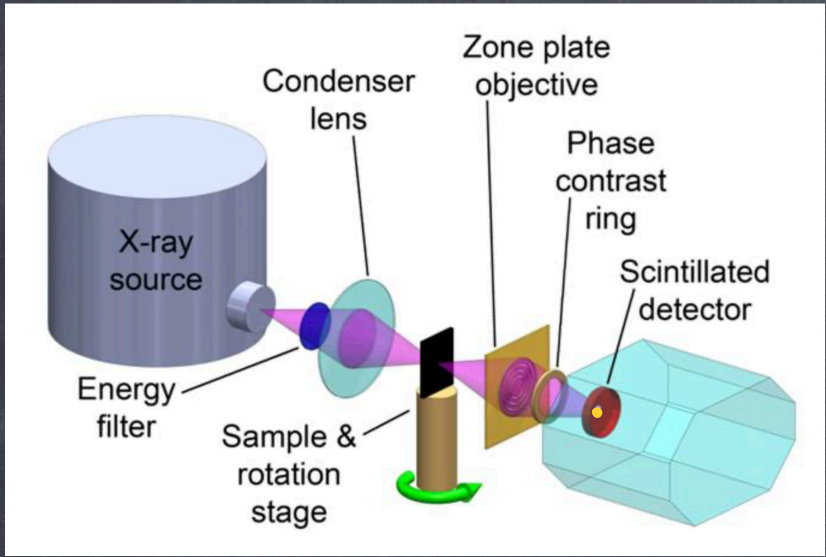
Nanoscopic X-ray tomography for correlative microscopy of a small meiofaunal sea-cucumber

Simone Ferstl, Thomas Schwaha, Bernhard Ruthensteiner, Lorenz Hehn, Sebastian Allner, Mark Müller, Martin Dierolf, Klaus Achterhold & Franz Pfeiffer

Scientific Reports **10**, Article number: 3960 (2020) | Cite this article

https://www.nature.com/articles/s41598-020-60977-5

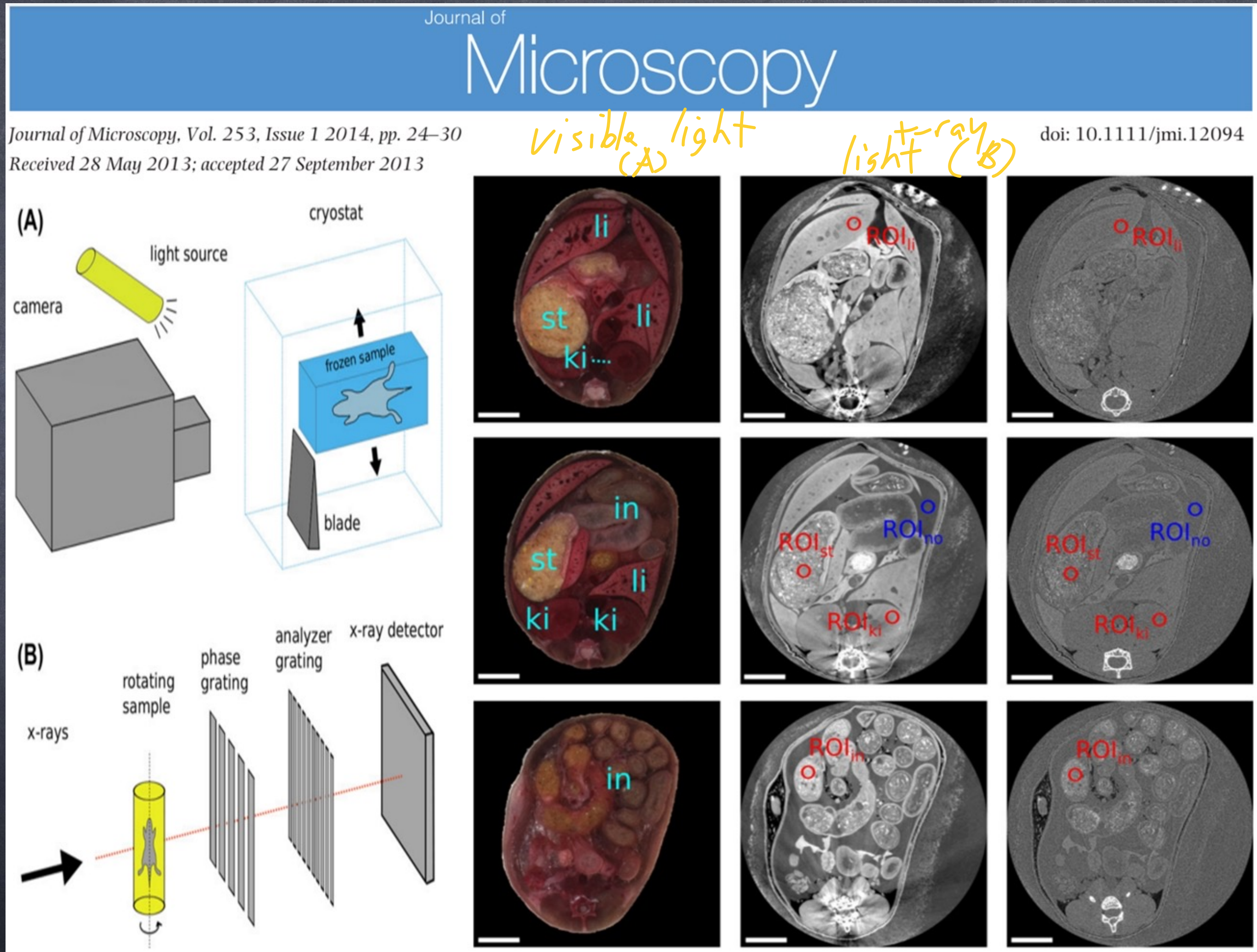
Combining techniques for more precise imaging

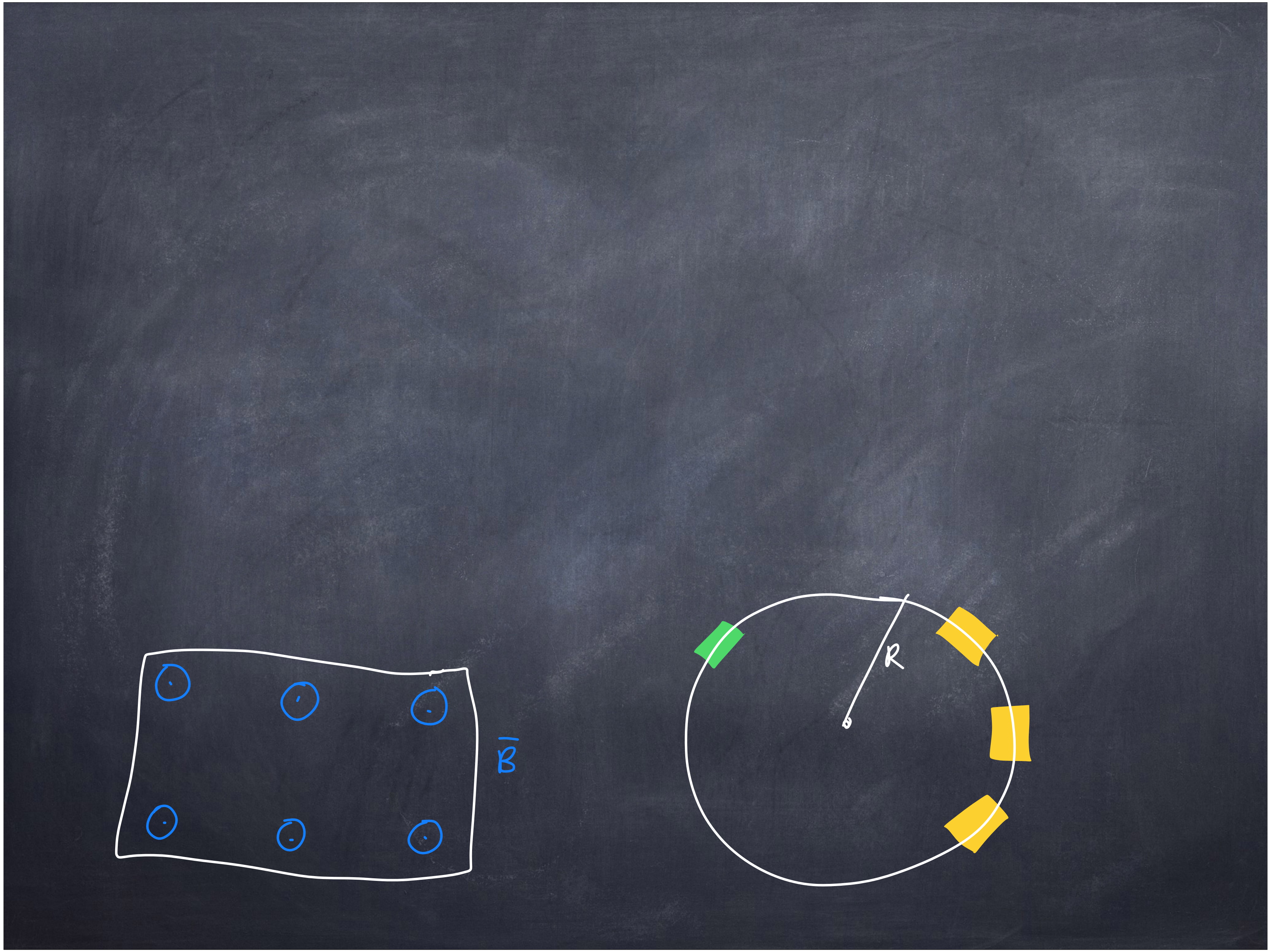


https://www.cmu.edu/me/xctf/facility/index.html

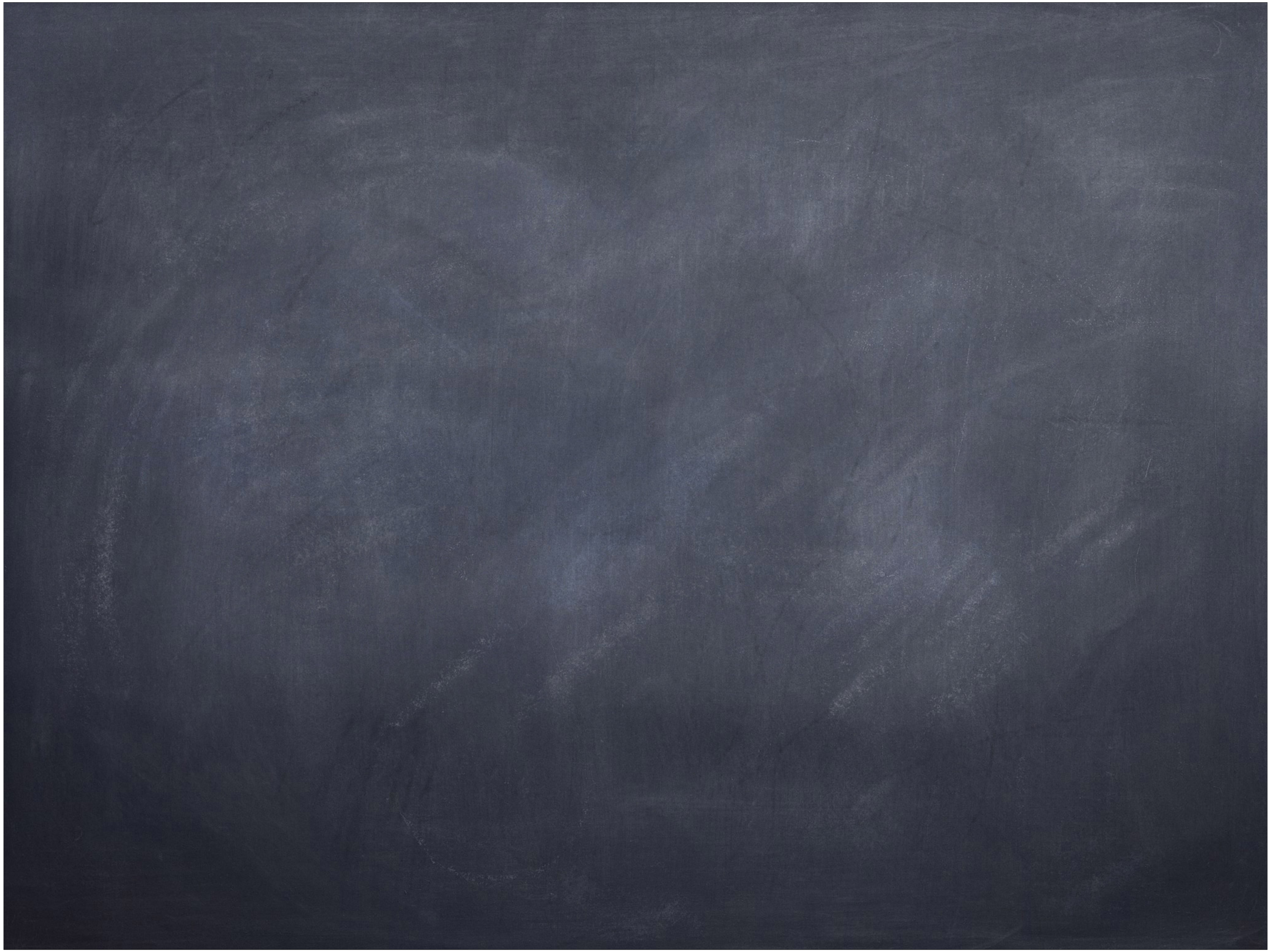
The UltraXRM-L200 achieves its resolution using a laboratory X-ray source (rotating copper anode) that emits X-ray with a photon energy level of 8 keV. As the schematic below shows, the X-ray beam passes through a mono-capillary condenser lens that uses grazing incidence reflection to efficiently focus the X-rays on the sample. This efficient condenser is key to using a laboratory X-ray source rather than a synchrotron beam. After passing the sample, the X-rays are focused onto the detector using a Fresnel zone plate objective. The zone plate objective consists of high aspect ratio concentric gold rings. The maximum resolution of an X-ray transmission microscope is related to the minimum spacing of the gold rings. The 35 nm spacing of the high resolution zone plate in the UltraXRM-L200 yields a theoretical Rayleigh criterion resolution of 43 nm. After the zone plate, the X-ray beam passes by a gold phase ring for Zernike phase contrast (if in phase contrast mode). The ring phase shifts X-rays not diffracted by the sample, causing interference between the undiffracted X-rays and those diffracted by the sample and resulting in a negative phase contrast image. Subsequently, the X-rays intercept a scintillation screen coupled to a CCD detector.

Benefits of x-rays vs. microscopes (visible light)




B
R

synchrotrons accelerate charged particles



Examples of synchrotrons

European Synchrotron Radiation Facility (ESRF) in Grenoble, France

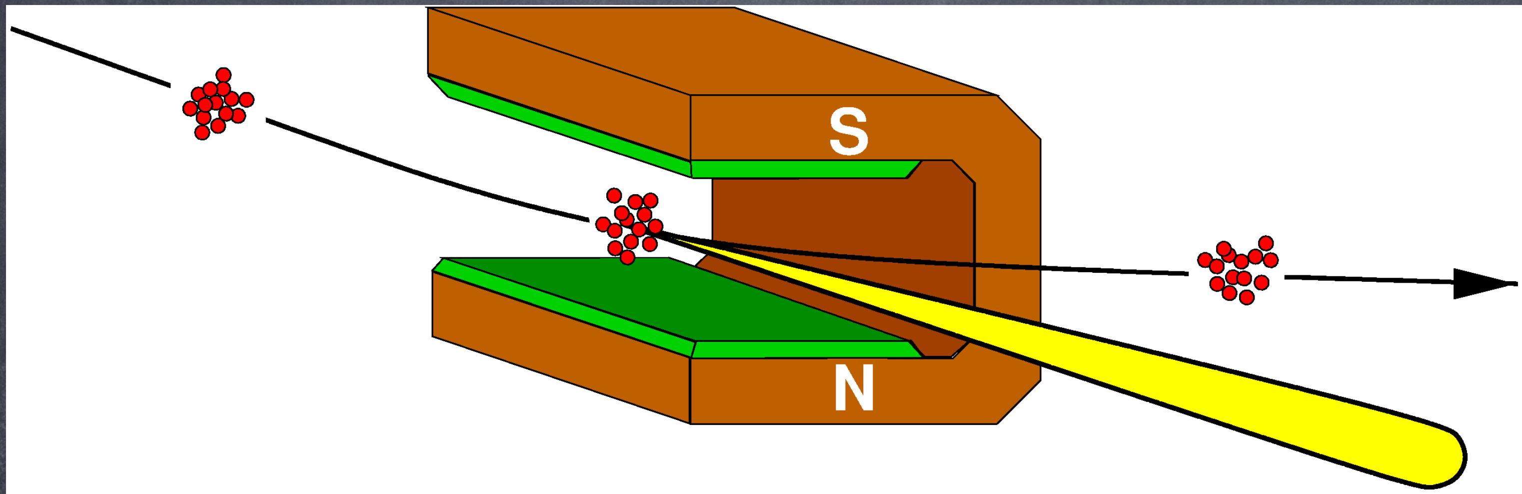
13 member countries: France, Germany, Italy, the UK, Spain, Switzerland, Belgium, the Netherlands, Denmark, Finland, Norway, Sweden, Russia

Most powerful X-ray synchrotron

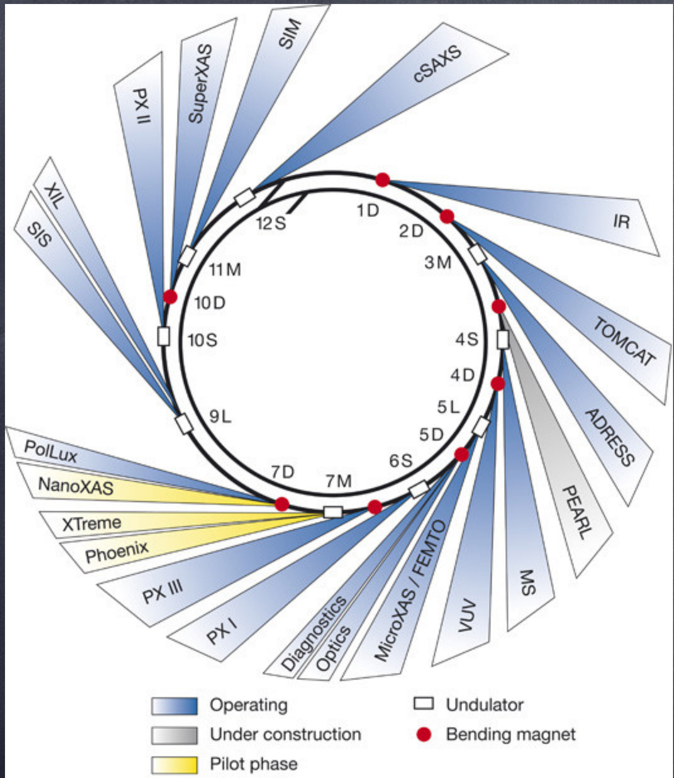
10,000 billion more powerful than X-rays used in the medical field.

Swiss Light Source (SLS) at PSI, Switzerland (45 minutes away)

How are X-rays produced in a synchrotron?



Swiss Light Source (SLS)



TOMCAT (A beamline for TOmographic Microscopy and Coherent rAdiology experimenTs)

https://www.psi.ch/en/sls/tomcat

TOMCAT beam line

Technical Data

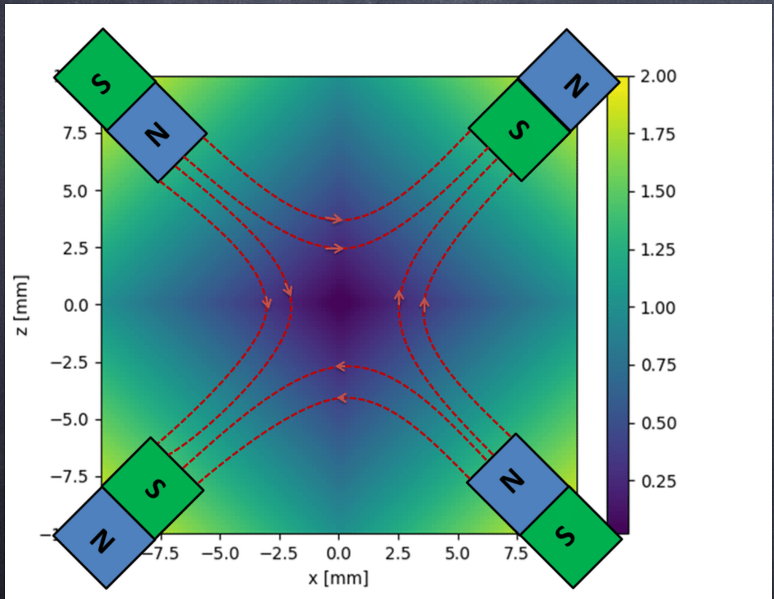
Energy range	8-45 keV
Highest 3D spatial resolution	ca. 1 µm in parallel beam geometry ca. 200 nm in full-field geometry
Max. temporal resolution	20 Hz
Available techniques	- Absorption-based tomographic microscopy - Propagation-based phase contrast tomographic microscopy - Ultra-fast tomographic microscopy - Grating interferometry - Absorption and phase contrast nanotomography
Available devices for in situ sample conditioning	- Laser-based heating system - Cryojet and cryo-chamber

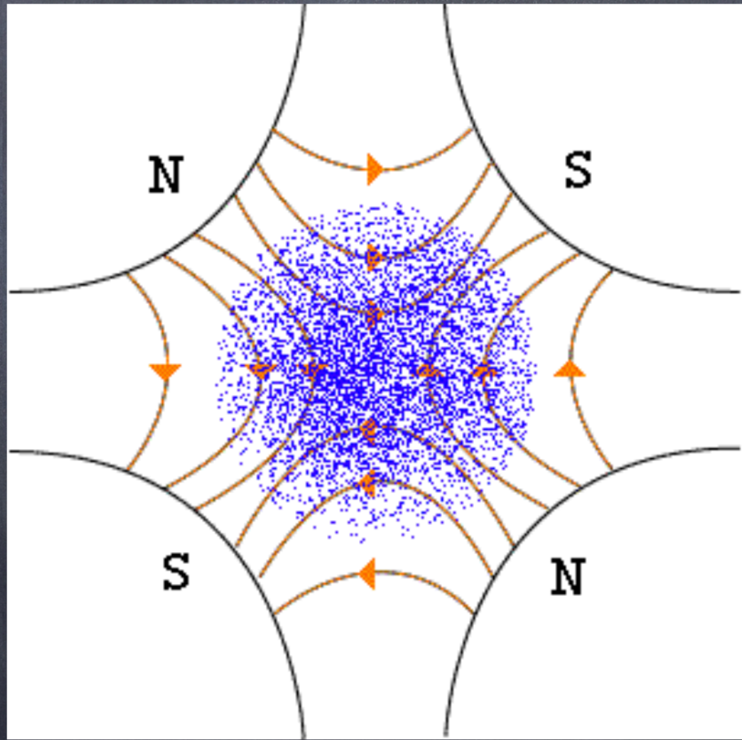
65 nm pixel size (resolution)

Absorption-based and phase contrast imaging are routinely performed with isotropic voxel sizes ranging from 0.16 to 11 µm (fields-of-view (h x v) of 0.4 x 0.3 mm2 and 22 x 3-7 mm2, respectively) in an energy range of 8-45 keV. Phase contrast is obtained with simple edge-enhancement, propagation-based techniques [2, 3] or through grating interferometry [4].

A temporal resolution of a few (< 5) minutes can also be achieved with the hard X-ray full-field microscope setup [8] delivering a pixel size of 65 nm for microscopic samples (~75x75 µm2 field-of-view).

Beam optics focus electron bunches



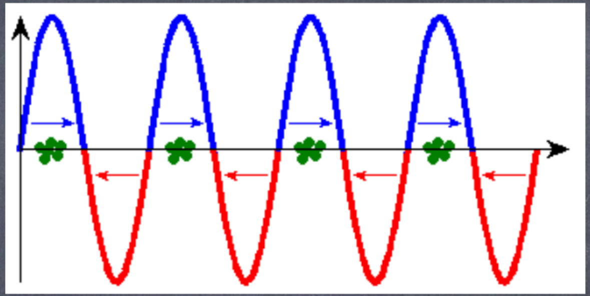


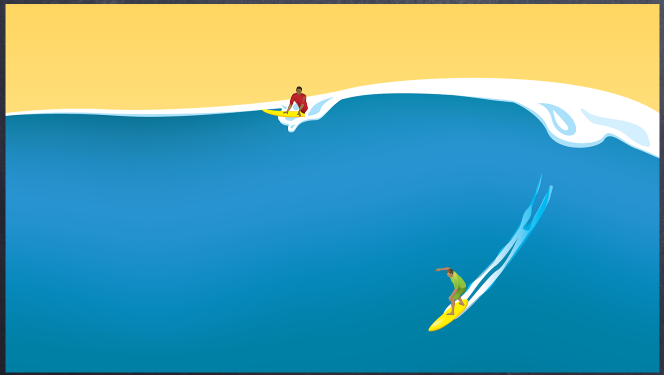
How to accelerate electrons

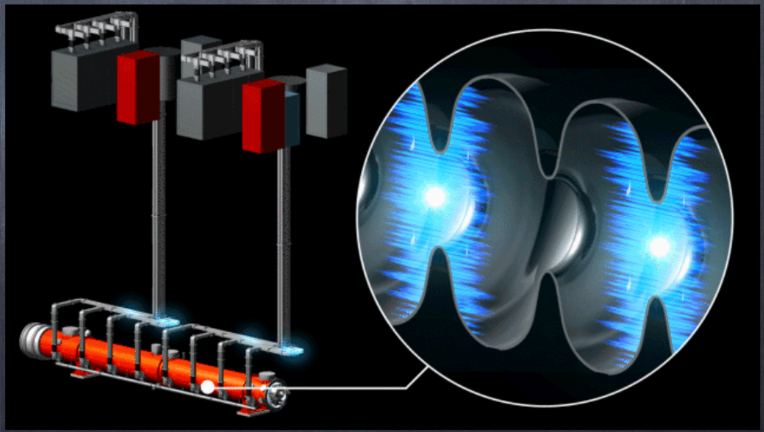
"Radio-frequency" accelerator

RF acceleration (YouTube video here https://www.youtube.com/watch?v=mu4m7wSnpD0)

E







Superconducting RF cavities

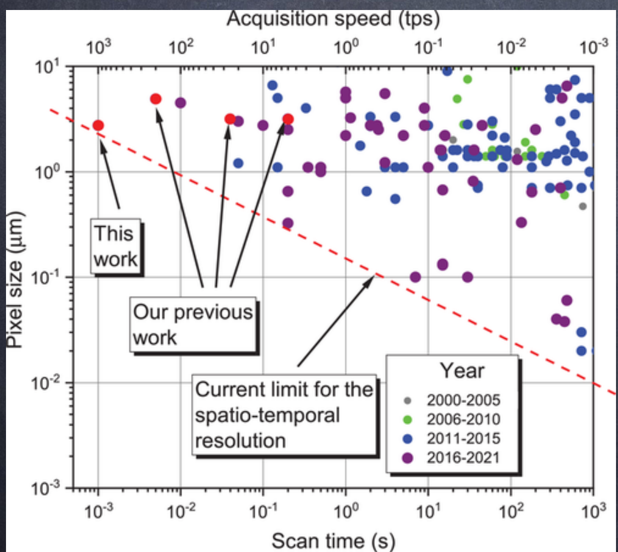
Time resolution with synchrotrons

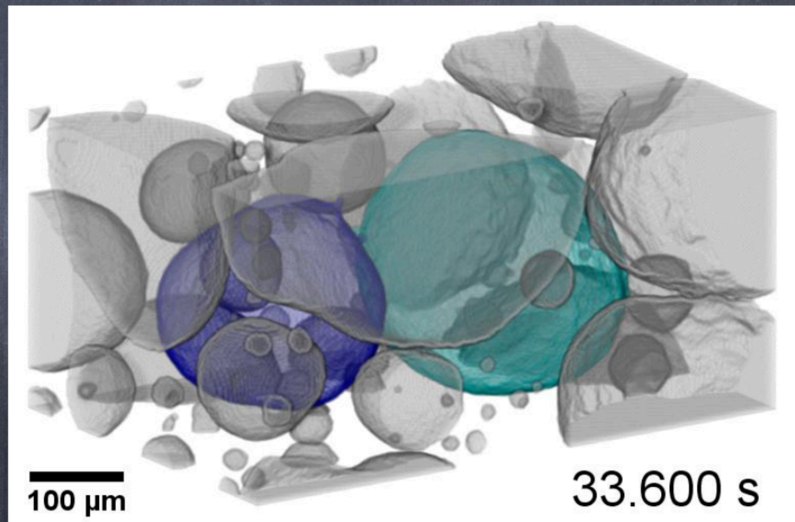
24 September 2021

X-ray microscopy with 1000 tomograms per second

Research Using Synchrotron Light | Materials Research | Matter and Material

A team at the Swiss Light Source SLS have set a new record using an imaging method called tomoscopy.

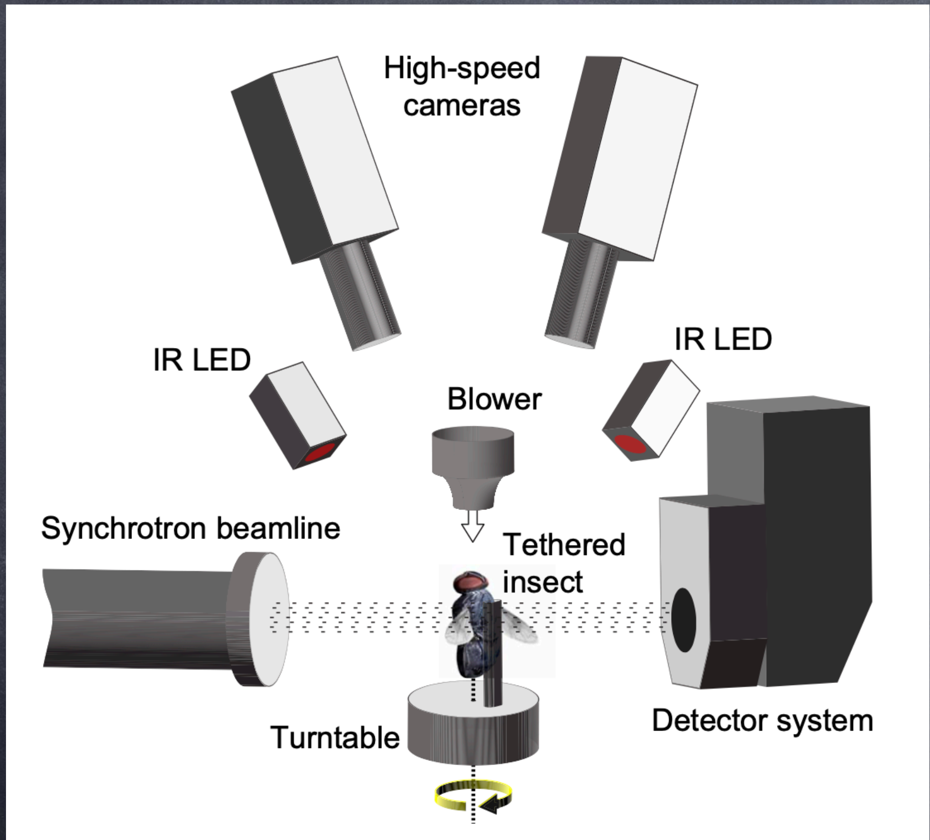




100 µm Bubble coalescence

https://onlinelibrary.wiley.com/doi/10.1002/adma.202104659

An example of time resolved CT using synchrotron



https://doi.org/10.1371/journal.pbio.1001823

https://pubmed.ncbi.nlm.nih.gov/18682361/

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Muscles and tracheal network *during* flight

Von Prof. Marco Stampanoni / ETHZ und PSI

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Surreal X-ray movie reveals how a fly beats its wings

21:00 25 March 2014 by Jacob Aron

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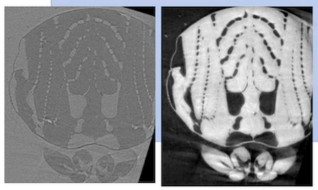

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Science & Environment

Scientists film inside a flying insect

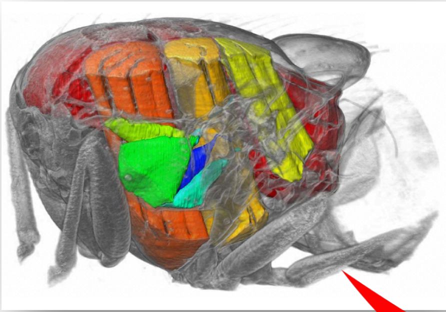
By Victoria Gill

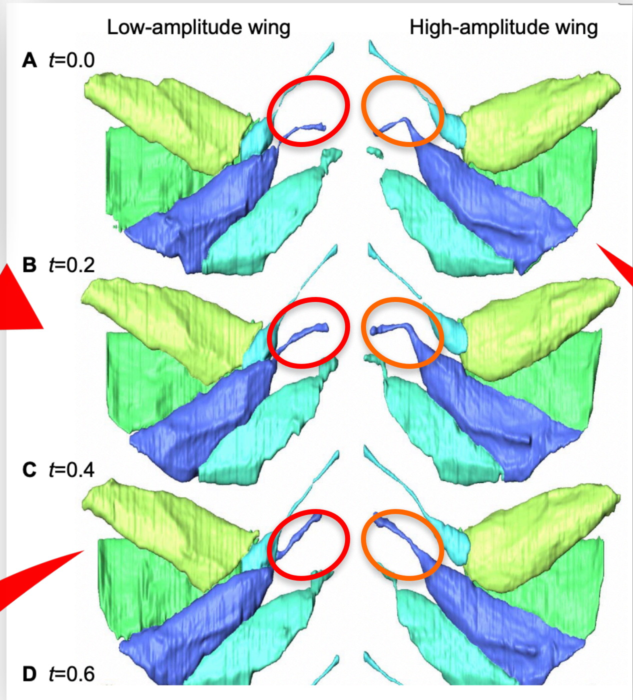
Science reporter, BBC News

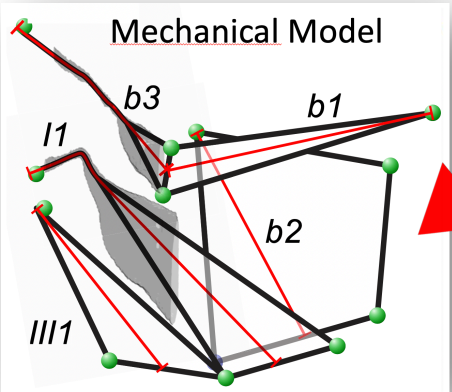
26 March 2014 Science & Environment

Walker et al., PloS Biology (2014) & Mokso et al., SciRep (2015)

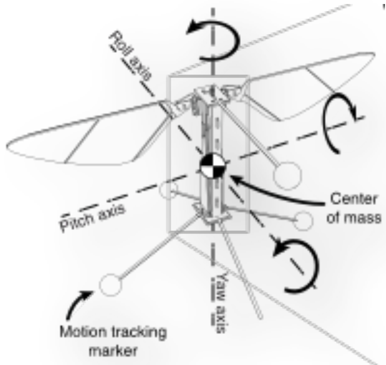
Dynamic X-ray microscopy boosting the development of bio-inspired robotics





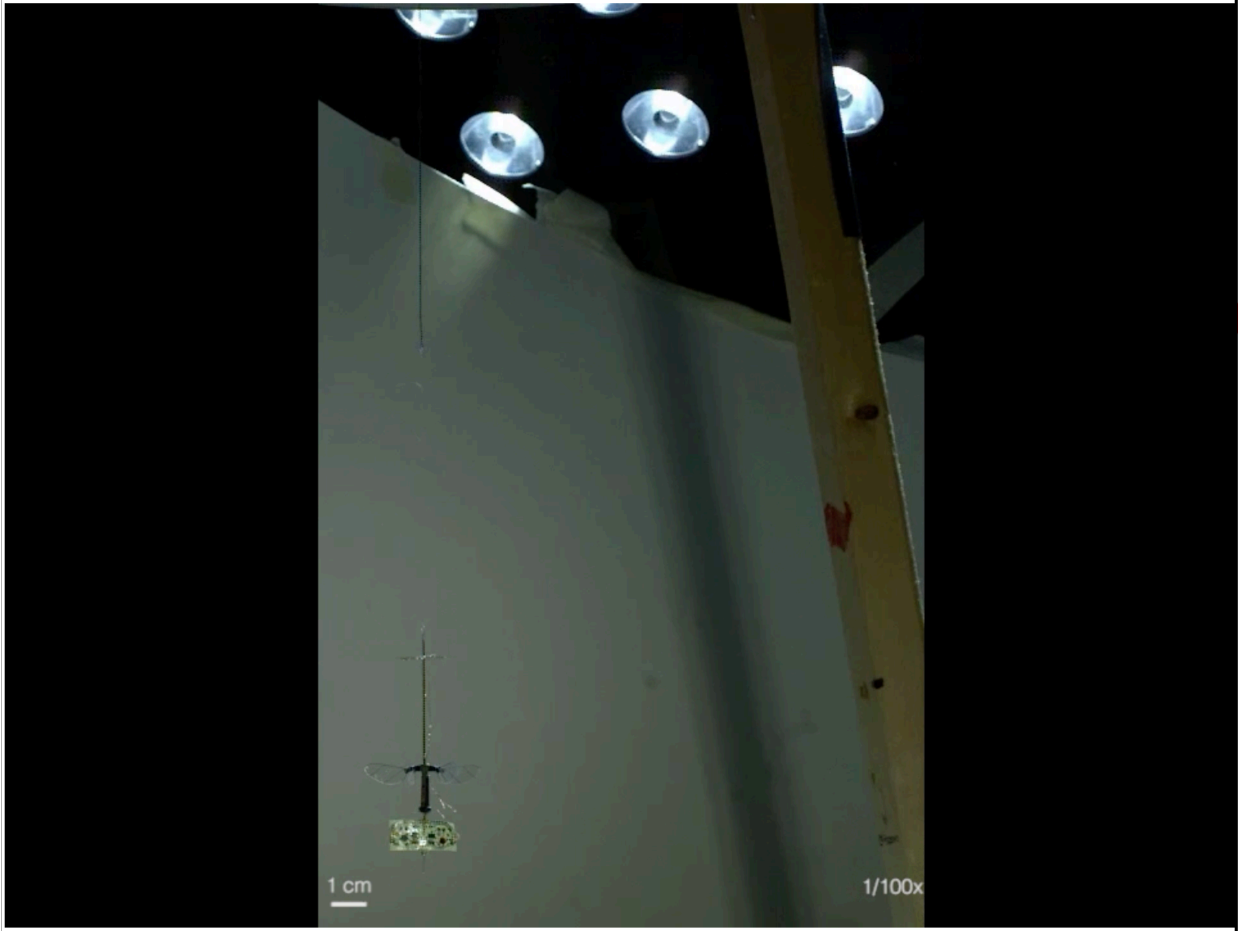


Walker S. et al., PloS Biology (2014)

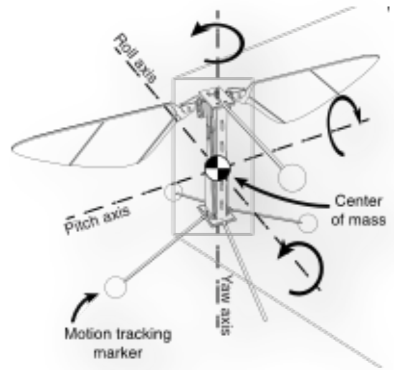


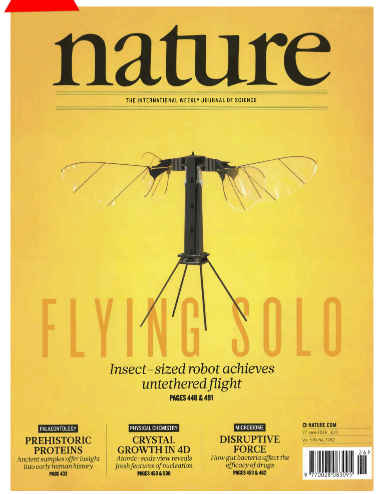
Jafferis et al., Nature 2019

Dynamic X-ray microscopy boosting the development of bio-inspired robotics



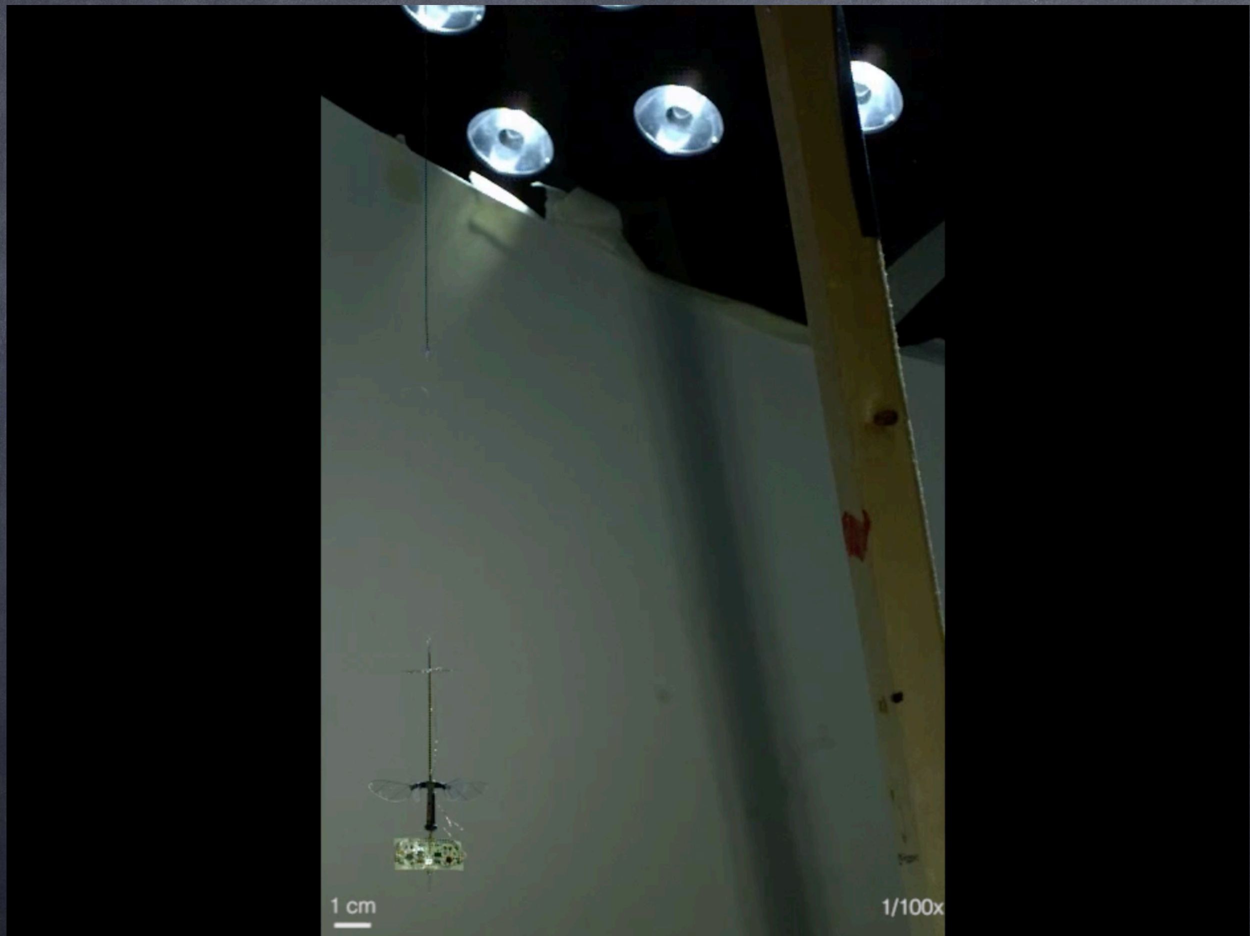
Walker S. et al., PloS Biology (2014)



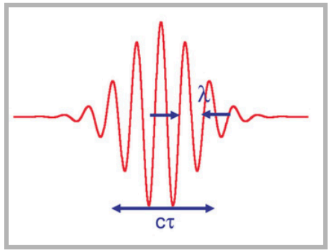


Jafferis et al., Nature 2019

An application of learning how flies "fly" and making robots to do it the same way:

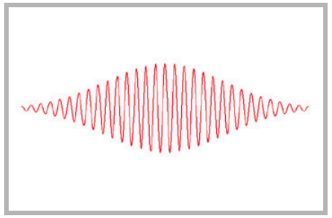


Even better time resolution



Wanted: short spatial and temporal resolution

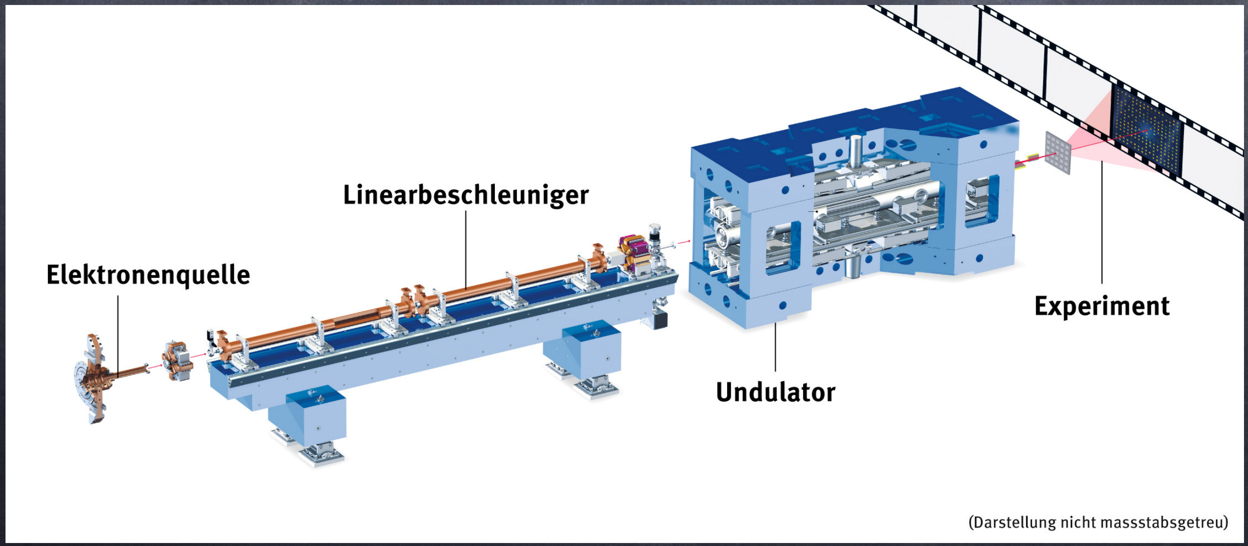
Lasers have poor spacial resolution due to long wavelength



Synchrotrons have a poor temporal resolution due to the long pulse length

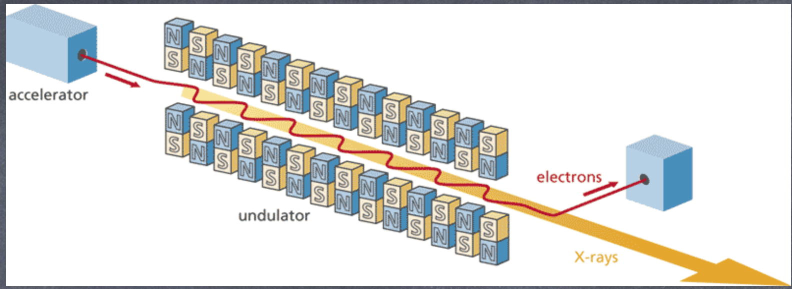
FELs fulfill both demands

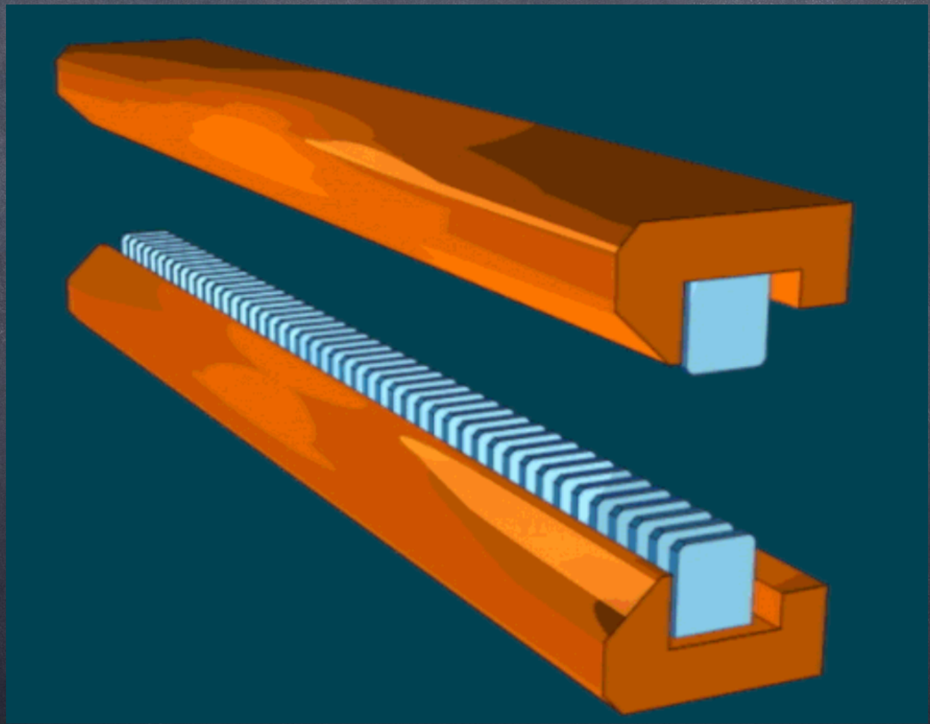
PSI Swiss FEL ("Free electron laser")



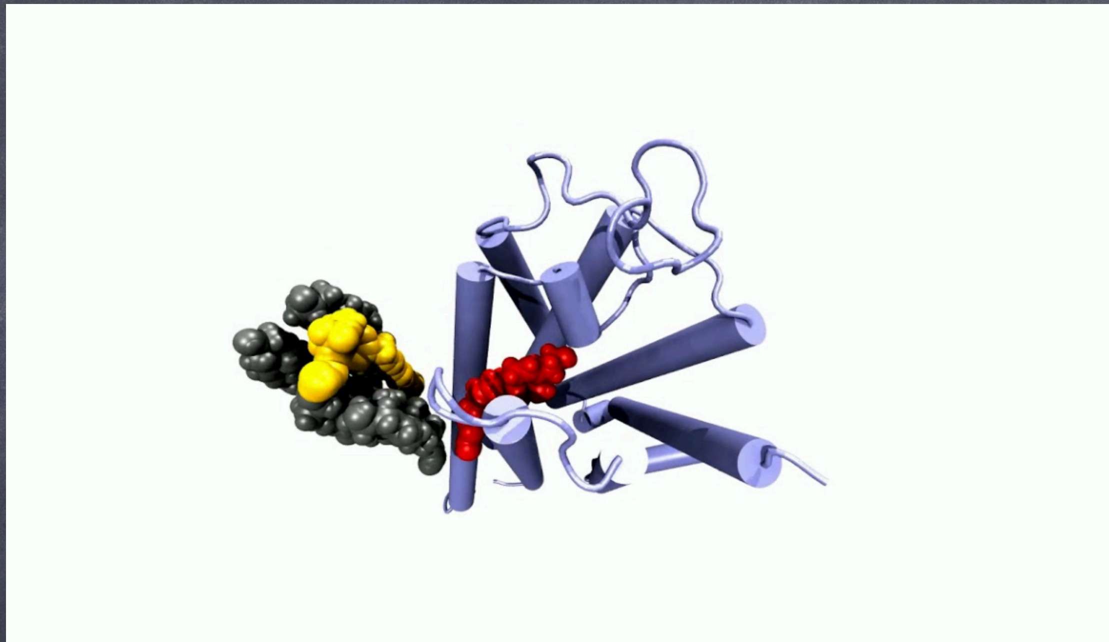
How a FEL works:

Undulator





X-ray free-electron laser SwissFEL



Watching receptor proteins change shape

Comparison of time and space resolution	Conventional laser	Synchrotron	Free-electron laser
Spatial resolution	100 nm	0.1nm	0.1 nm
Temporal resolution	10 fs (10E-15 s)	100 ps (100E-12 s)	10 fs (10E-15 s)
Experimental reach	Ultrafast dynamics at sub-cellular level	Fast atomic scale dynamics	Ultrafast atomic scale dynamics

Some references :

https://www.microphotonics.com/what-is-micro-ct-an-introduction/
https://www.microphotonics.com/how-does-a-microct-scanner-work/

Laboratory x-ray micro-computed tomography: a user guideline for biological samples
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5449646/

Useful references for a variety of radiation techniques :

https://astronuclphysics.info/Scintigrafie.htm#3

https://astronuclphysics.info/JadRadMetody.htm