Perspectives for X-ray phase-contrast imaging at SOLEIL with an upgraded storage ring

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Phase contrast: what and why (a reminder)

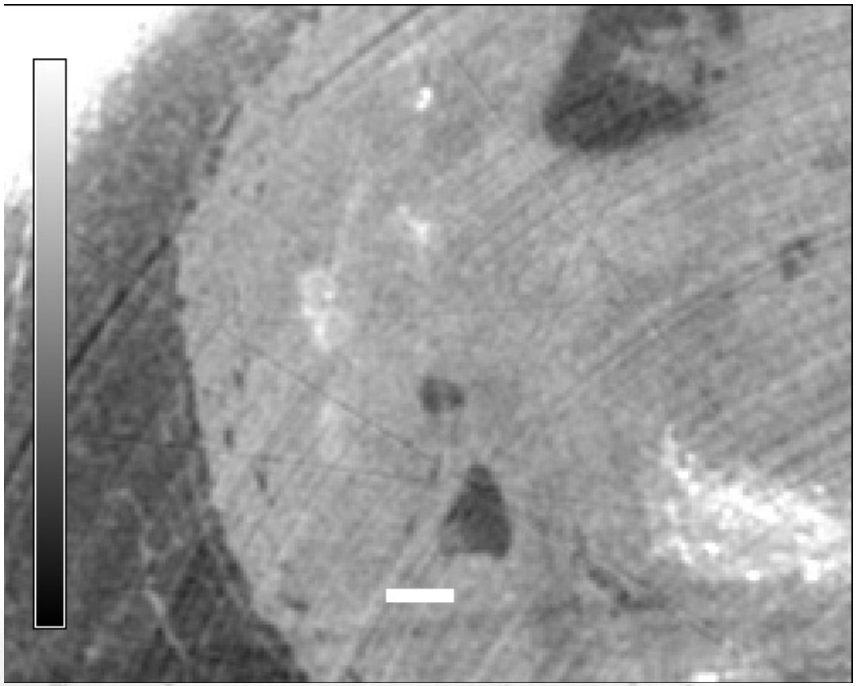
- Radiography and radiographic tomography (i.e., transmission imaging)
- Two contrast mechanisms
  - Attenuation (“absorption contrast”)
  - Refraction (“phase contrast”)
- Phase contrast much stronger …
  - Especially for low Z and at short λ
- … but not as easy to obtain as absorption contrast

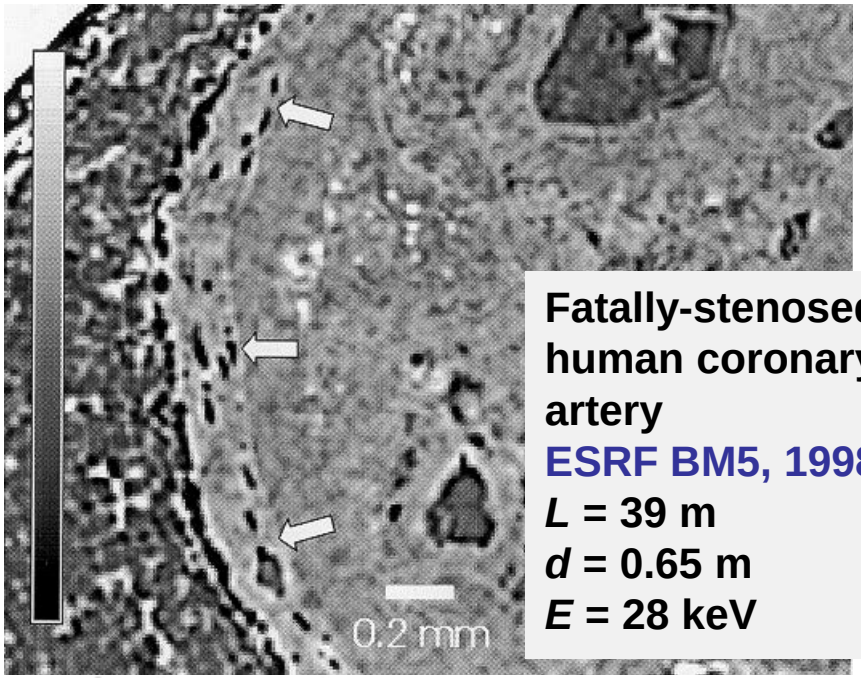
Phase contrast: what and why (a reminder)

Example: Spanne, Raven, Snigireva, Snigirev, Phys. Med. Biol. 44 (1999) 741–749

Absorption tomogram

Phase-contrast tomogram





Fatally-stenosed human coronary artery
ESRF BM5, 1998
***L* = 39 m**
***d* = 0.65 m**
***E* = 28 keV**

SOLEIL beamlines for tomography

Beamline	PSICHÉ	PUMA	ANATOMIX
Energy range	20 – 100 keV	15 – 60 keV	5 – 25 keV
Max beam size	15 x 5 mm^2 (H×V)	20 × 10 mm^2 (H×V)	40 × 6 mm^2 (H×V)
Min pixel size	1 µm	1 µm	XRM: 30 nm Other: 0.2 µm
Source	Wiggler	Wiggler	Undulator
Spectral modes	1. Filtered white 2. Crystal mono	1. Filtered white 2. Crystal mono	1. Filtered white 2. Multilayer 3. Crystal mono
Other	High-pressure tomography	Ancient materials	Various phase-contrast options
Operational	Since 2014	**2018** 	**2018** 

Proposal 20160534 : Origins of tuberculosis

new insights from x-ray microtomography analysis of ancient bones

Psiché

CNRS LE JOURNAL

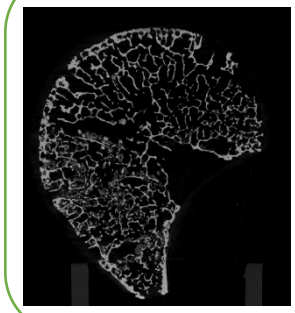
The oldest known case of human TB : Excavating the birthplace of Syrian agriculture.
Dja'de el Mughara (9310-8290 BC cal)

3D quantitative micro-tomography , (spatial resolution 1 - 10 µm) is a non-invasive method which can produce a visible and quantitive information on the consequences of pathologies on bone micro-structure, without using bone sectioning as used in a palaeo-histological approch.

3D quantitative micro-tomography was used to study the micro-structures in bone (canaliculi, trabeculae) and in the periosteal system. The method was applied to a lumbar vertebra from a young individual (approximately 5 years of age), taken from the ancient Neolithic site of Dja'de in Syria, in order to identify signs of early vertebral infection.
The body of the vertebra was scanned to a resolution of 3µm. A virtual horizontal section, taken from the 3D reconstruction, enabled the identification of a focal lesion in the left anterior lateral region. Two regions of interest (one in a healthy part of the vertebra, the other showing the pathology) were chosen. After segmentation, these showed local differences in the bone micro-architecture (in particular, the number and thickness of trabeculae). It was therefore possible to make a paleo-pathological diagnosis of early stage bone pathology resulting from TB infection. Here the infection propagated by blood, via the equatorial branch of the vertebral artery (3rd lumbar). This diagnosis, based on micro-morphology, has been confirmed by molecular biology.

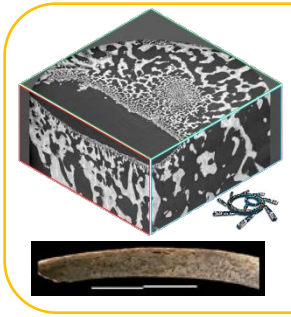
CT-scan : Macro-morphology in 3D

3D reconstruction (CT-scan, 4mm resolution) of an advanced vertebral tuberculous disease (Pott disease) [1]



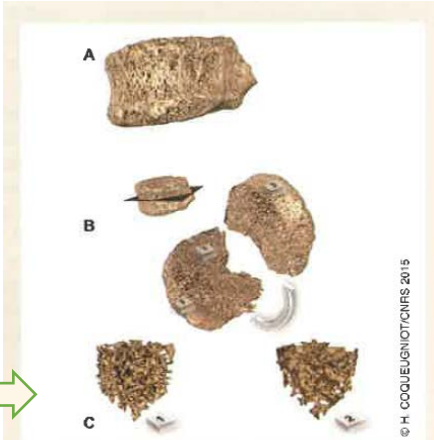
µCT-scan : Pathological micro-architecture

A micro-CT section(3µm resolution) of an early stage tuberculous vertebral disease (Ancient Neolithic) [1,2]



SR : Elementary micro-lesions

Costal tuberculosis (phase contrast, 2,4µm resolution) (Ancient Neolithic)[2,3]



A. 3D reconstruction of a 3rd lumbar vertebra, from a child of roughly 5 years old (taken from the Ancient Neolithic site of Dj'ade-El-Mughara). Evidence of tubercular infection is visible.

B. Virtual horizontal section from the vertebra shows a focal lesion(µ-CT scan, resolution 3 µm, calculated using the TIVMI software [http://projets.pacea.u-bordeaux.fr/TIVMI/]).

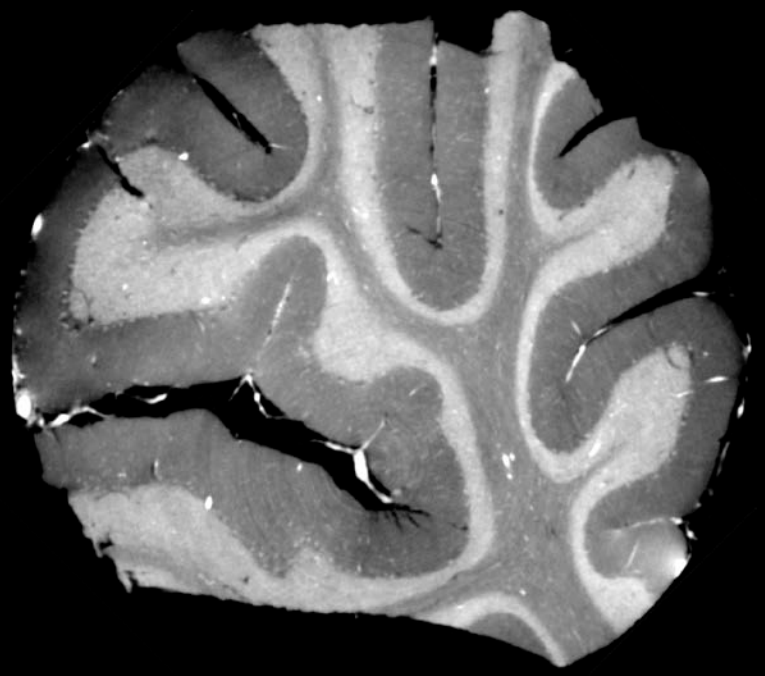
C. Enlarged 3D region after segmentation showing a decreased number of thicker trabeculae, indicative of an infection passed by the blood stream.

[1] Coqueugniot H. *et al*.., 2015. Three-dimensional imaging of past skeletal TB: from lesion to process. *Tuberculosis*, 95 : S73-S79. ; [2] Baker O *et al*.., 2015. Human tuberculosis predates domestication in ancient Syria. *Tuberculosis,* 95 : S4-S12. ; [3] Coqueugniot *et al*. Proposal 20160534, 9-14 nov, under analysis.....

X-ray grating imaging vs. MRI

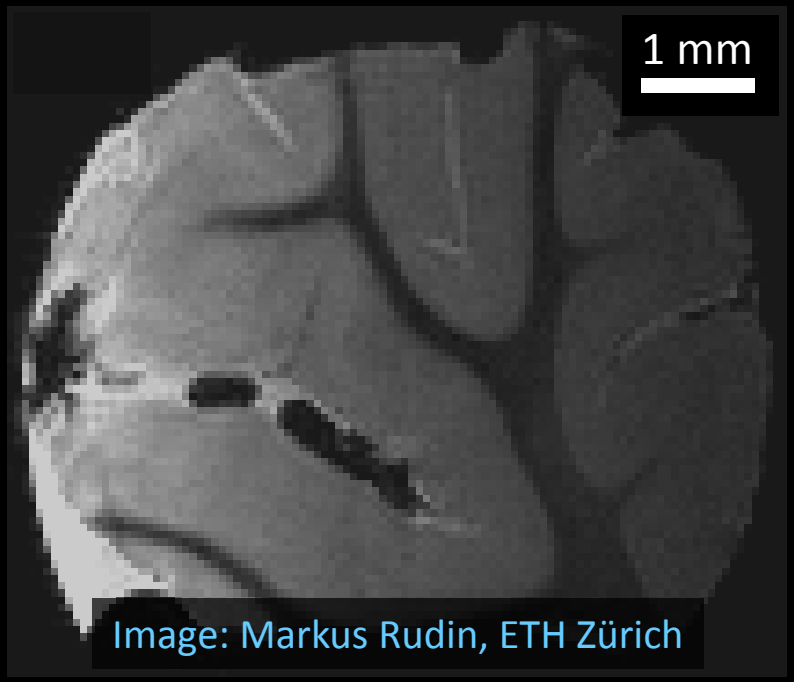
Georg Schulz & Bert Müller, Biomaterials Science Center, University of Basel

X-ray grating-based phase contrast:



- ID19, ESRF, 23 keV, 9th Talbot order
- Field of view $(10\ mm)^3$
- Voxel size: $(5\ \mu m)^3$
- Scan time: 4 hours

Magnetic resonance microscopy:

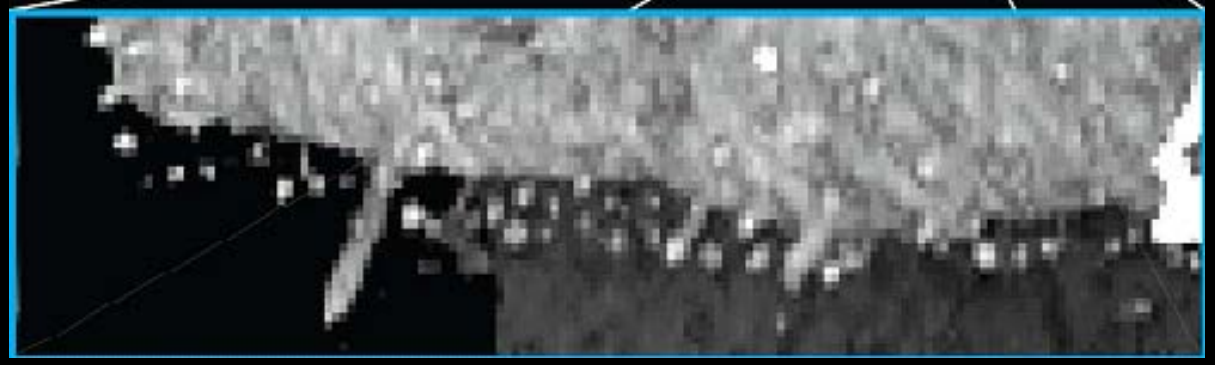


- ETH Zürich, Bruker scanner 9.4 T
- Field of view $(16\ mm)^3$
- Voxel size: 63 x 63 x 125 μm^3
- Scan time 9 hours

Details: Purkinje cells

G. Schulz, T. Weitkamp, I. Zanette et al., J. R. Soc. Interface **7** (2010) 1665

- Individual cells in the brain are visualized with X rays without staining agent
- Here: Purkinje cells, the largest cells in the brain
- Machine upgrade
  → Smaller source size
  → higher resolution in X-ray refraction angle
  → can resolve finer structures



Fast microtomography of solidifying Al-Cu

N. Limodin, L. Salvo, M. Suéry, M. Di Michiel, E. Boller

Furnace

Sample

CCD camera

optics

X rays

Rotation stage

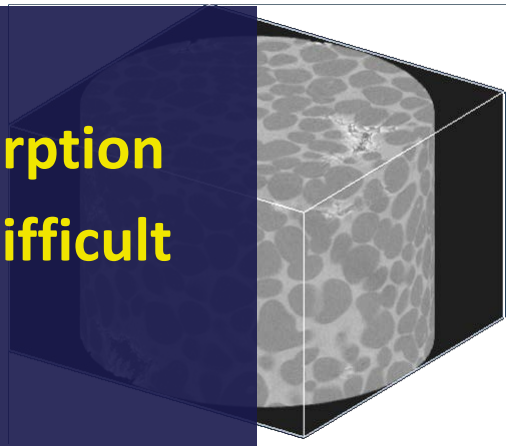
0°-180°

Radiographs

400 projections

3D rendering after reconstruction

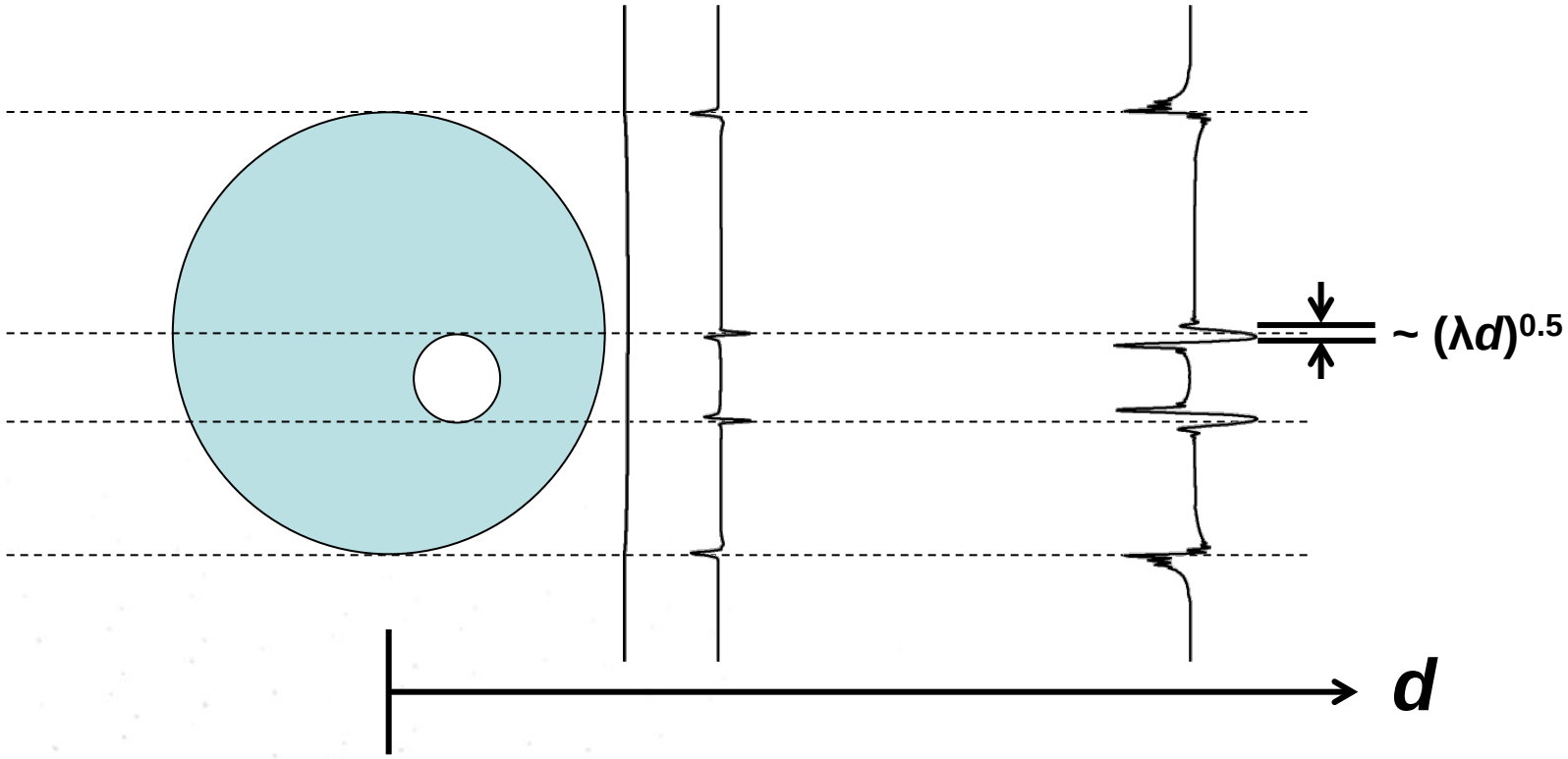
- Here: Al-Cu
  - Gives good contrast, even in absorption
  - Other alloys and composites even difficult for X-ray phase contrast today
  - Al-Si alloys or composites
  - Others
  - At the limit of even the most sensitive phase-contrast setups of today



Experiment performed at ESRF-ID19

Slide courtesy E. Boller

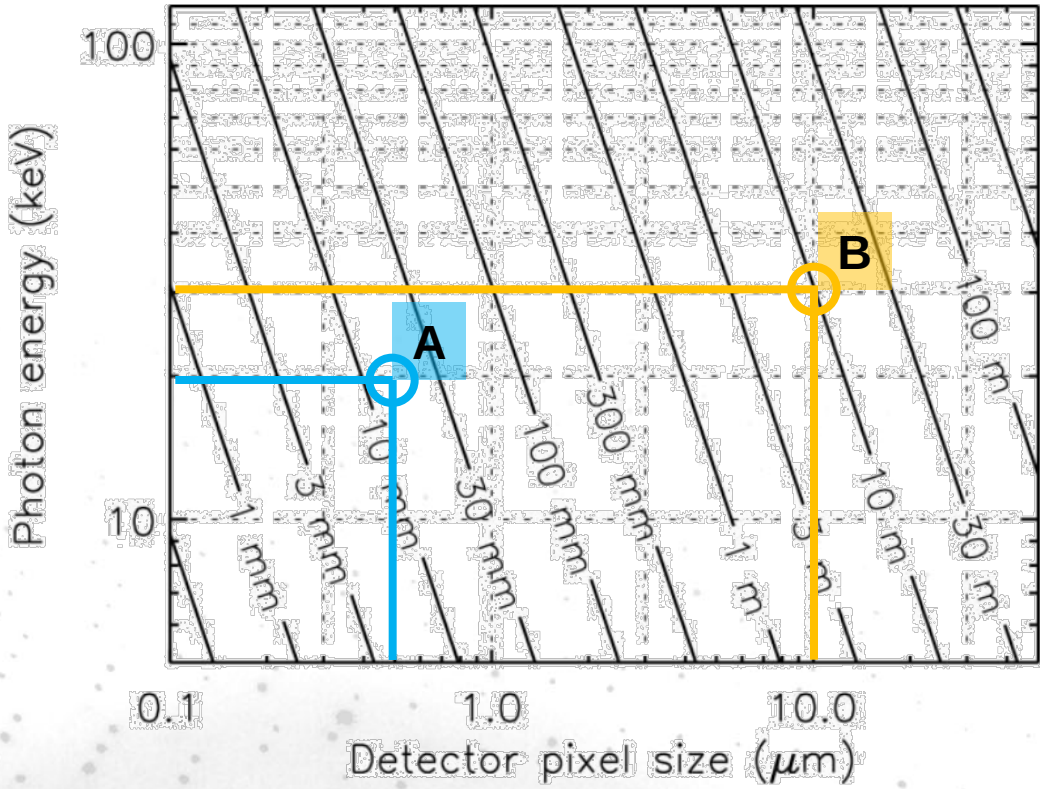
Inline phase contrast



- **Certain minimum distance *d* required, because of**
  1. **Technical constraints** (sample environment)
  2. **Need to get sufficient contrast** (increases approx. linearly with *d*)
  3. **Detector needs to resolve fringe pairs** (whose width scales as $d^{0.5}$)

Example inline phase contrast (aka “propagation-based imaging”)

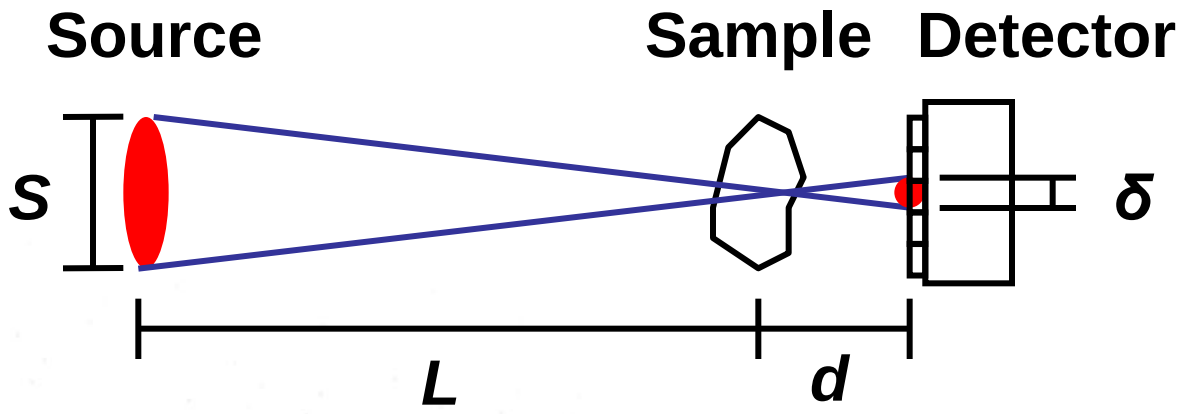
Critical distance d_c sample – detector, as function of pixel size and photon energy



A Pixel size 0.5 µm,
Energy 20 keV
→ $d_c \approx 15$ mm

B Pixel size 10 µm,
Energy 30 keV
→ **$d_c \approx 10$ m**

Spatial resolution: penumbral blurring



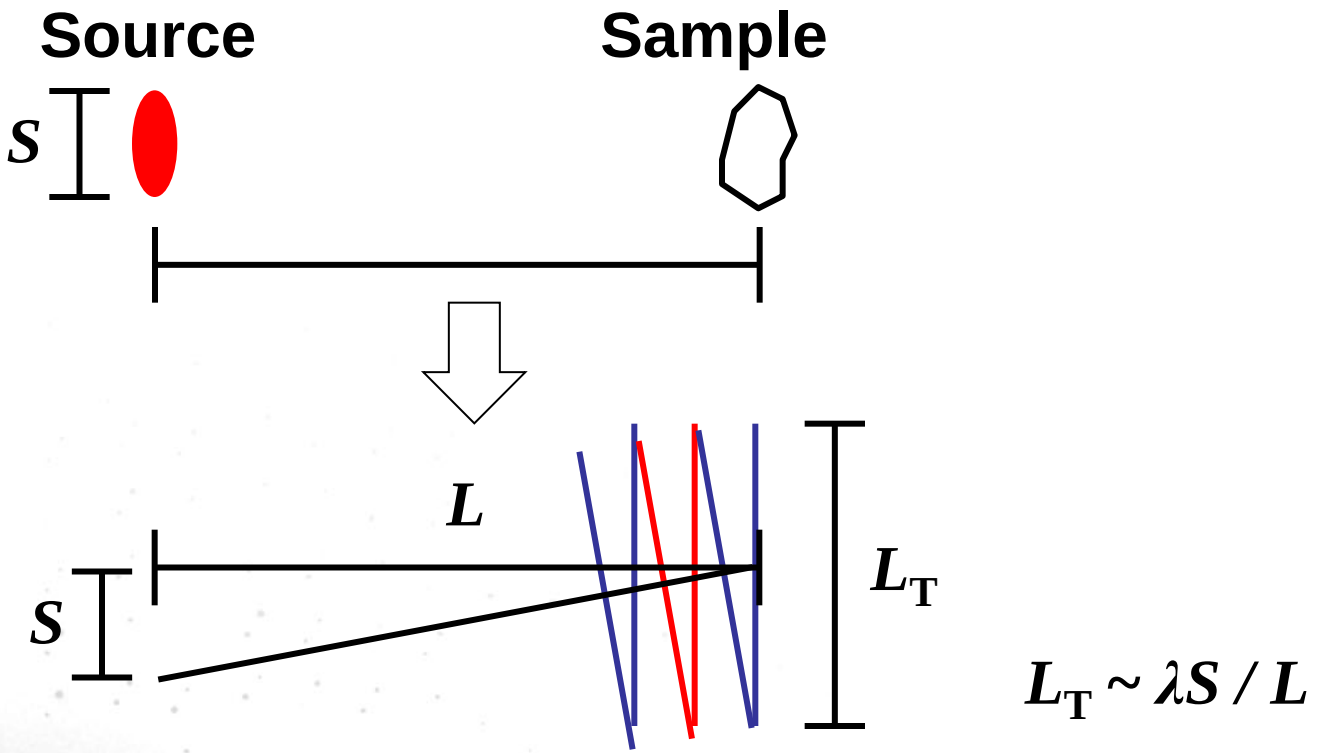
$$\delta = S\, d / L$$

Resolution limit due to source size S ("penumbral blurring")

Equivalent problem:

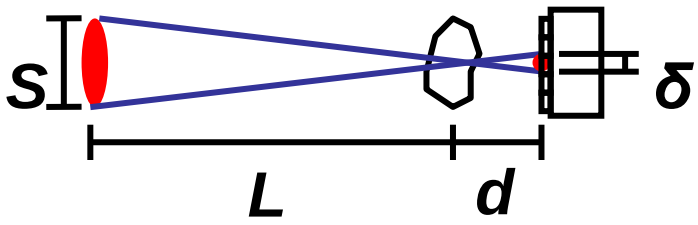
Spatial partial coherence

Chaotic X-ray source of non-zero size



L_T: transverse (or: spatial) coherence length

Inline phase contrast



- Distance between fringe pairs: ~$(\lambda d)^{0.5}$
  - For pixel size Δ, optimum propagation distance is of the order $d \sim \Delta^2/\lambda$
- But images are blurred by projected source size, width $\delta = (S/L) \cdot d$
  - → **No phase contrast detectable when working with *large pixels* (i.e., big samples)**
  - **Limit of resolution for which phase contrast is still detectable depends on source size**

Conclusion 1 / 3:
Effects of smaller horizontal photon source size for X-ray phase- contrast imaging

- Better phase contrast
  - For relatively short beamlines
    - **Phase contrast at medium spatial resolution (pixel sizes 10 µm and more) becomes accessible (needs long propagation distances)**
  - For long BLs (e.g. ANATOMIX): improved detection limit for weak refraction angles (approx 10×)
    - **Very weak density variations in matter**

Conclusion 2/3:
Effects of smaller horizontal photon source size for X-ray phase- contrast imaging

- BLs will become more sensitive to imperfections of beamline optics…
- … and need e^- beam stability (position, direction) matched to the new, smaller beam size.
- BLs can obtain much higher flux density in small spot by long-distance focusing (mirror or refractive lenses)
  - Potential for faster tomography in high resolution
  - Potential of using refractive lenses as monochromator

Conclusion 3/3: effects of monochromaticity

- Undulator harmonics become narrower with higher peaks
  - More monochromatic flux
    - How much more?
    - Monochromaticity (longitudinal coherence) → density resolution
    - Good for monochromatic imaging in general
    - Increased flux density
    - But we will need very good undulator phase errors as we work on higher harmonics

Figures of merit of beams for X-ray phase contrast

- **(Apparent) angular source size *s/L***
  (or equivalent: *transverse coherence length*)
- **Monochromaticity *λ/Δλ***
  (or equivalent: *longitudinal coherence length*)
- **Photon energy**
- **Beam size at sample**
- **Flux density**

} **Need to conserve these**

Thank you