X-ray Phase-Contrast

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Computational Medical Imaging

Sarntal

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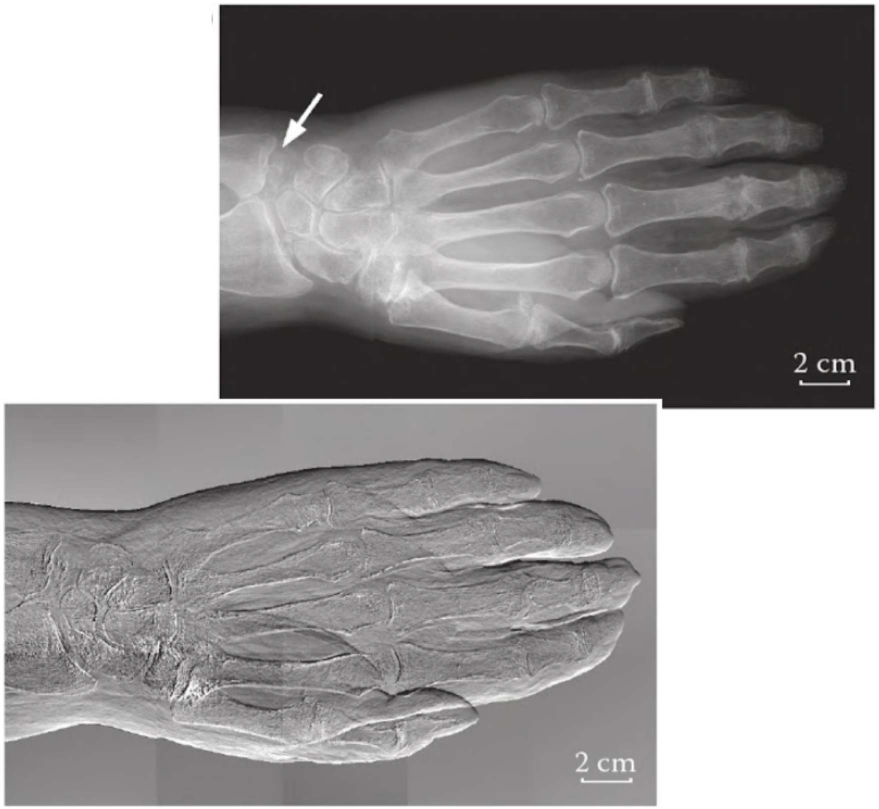
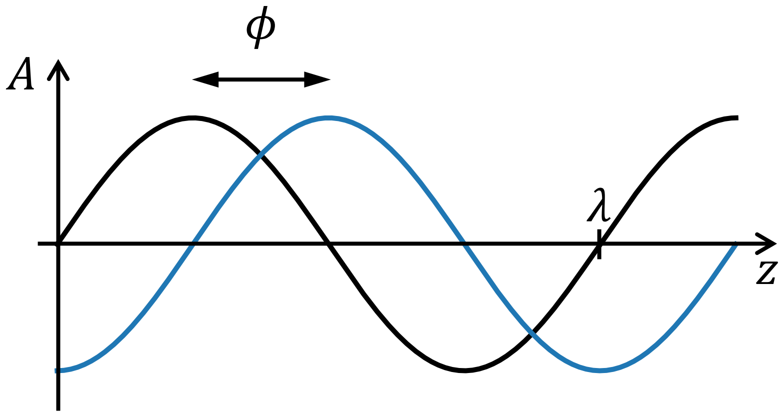


[Anastasio12, Fig. 3.3]

Electromagnetic waves – a closer look

Plane wave:

- Amplitude A
- Wavelength λ
- Phase ϕ

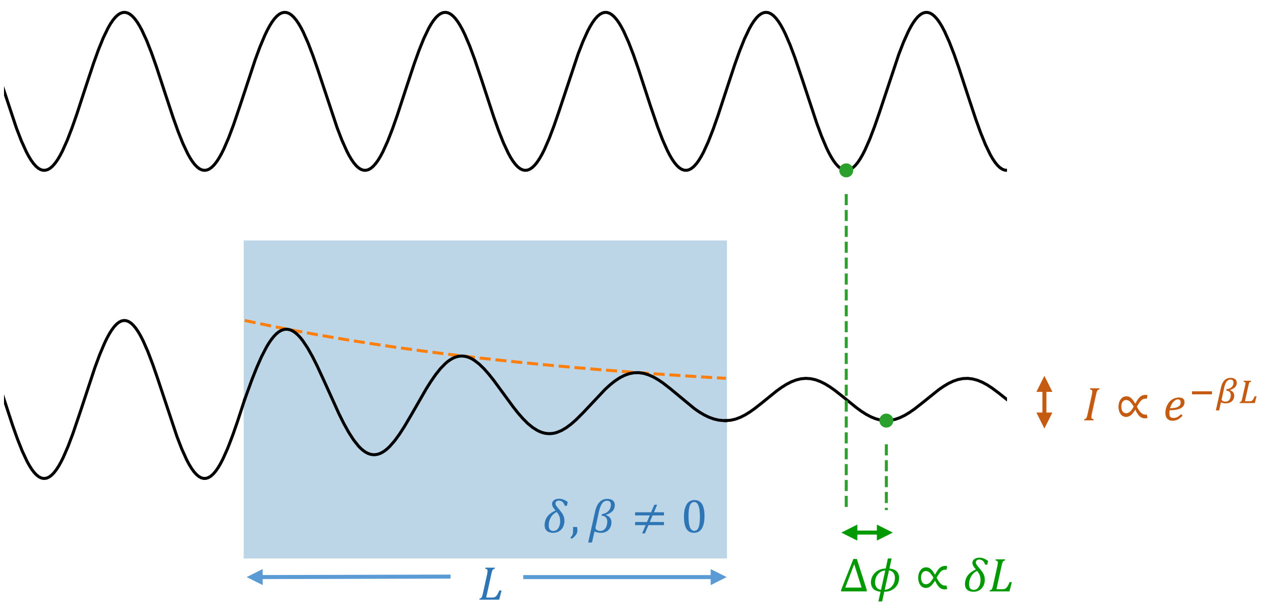


Sensor measures $I \propto A^2$

Electromagnetic waves – refractive index

$$n = 1 - \delta + i\beta$$

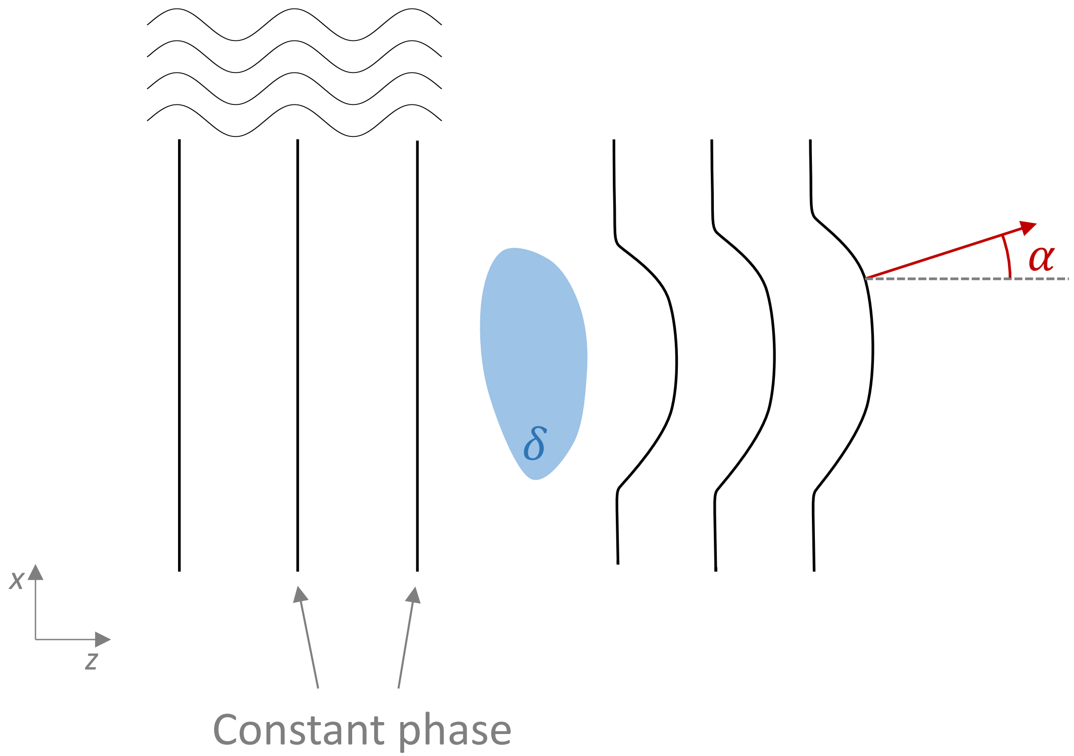
δ: phase shift / refraction
β: attenuation / absorption



Electromagnetic waves – wave front

$$n = 1 - \delta + i\beta$$

δ: phase shift / refraction
β: attenuation / absorption



Refraction angle

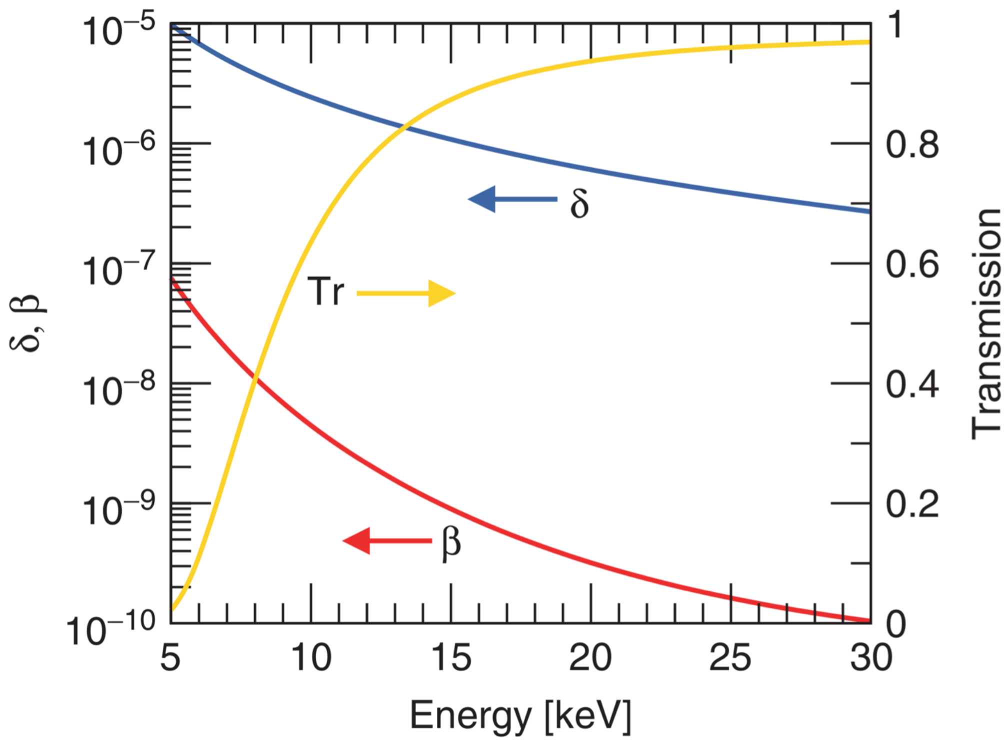
$$\alpha \propto \frac{\partial \phi}{\partial x}$$

For X-rays: microradians

Electromagnetic waves – contrast

$$n = 1 - \delta + i\beta$$

δ: phase shift / refraction
β: attenuation / absorption



→ phase shift larger than attenuation

→ higher contrast at lower radiation dose

[Willmott11, Fig. 7.10]

Measuring the phase

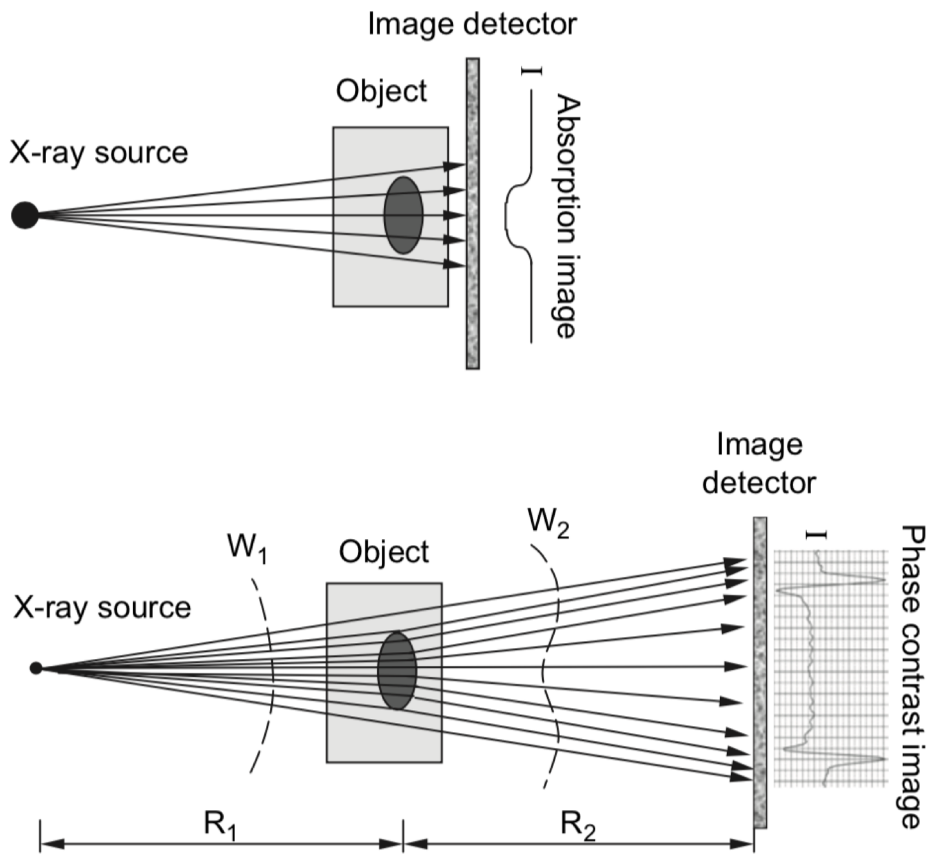
“Phase problem”

↓

Convert phase to intensity modulation:

- free-space propagation methods
- analyser-based methods
- interferometric methods

Free-space propagation methods

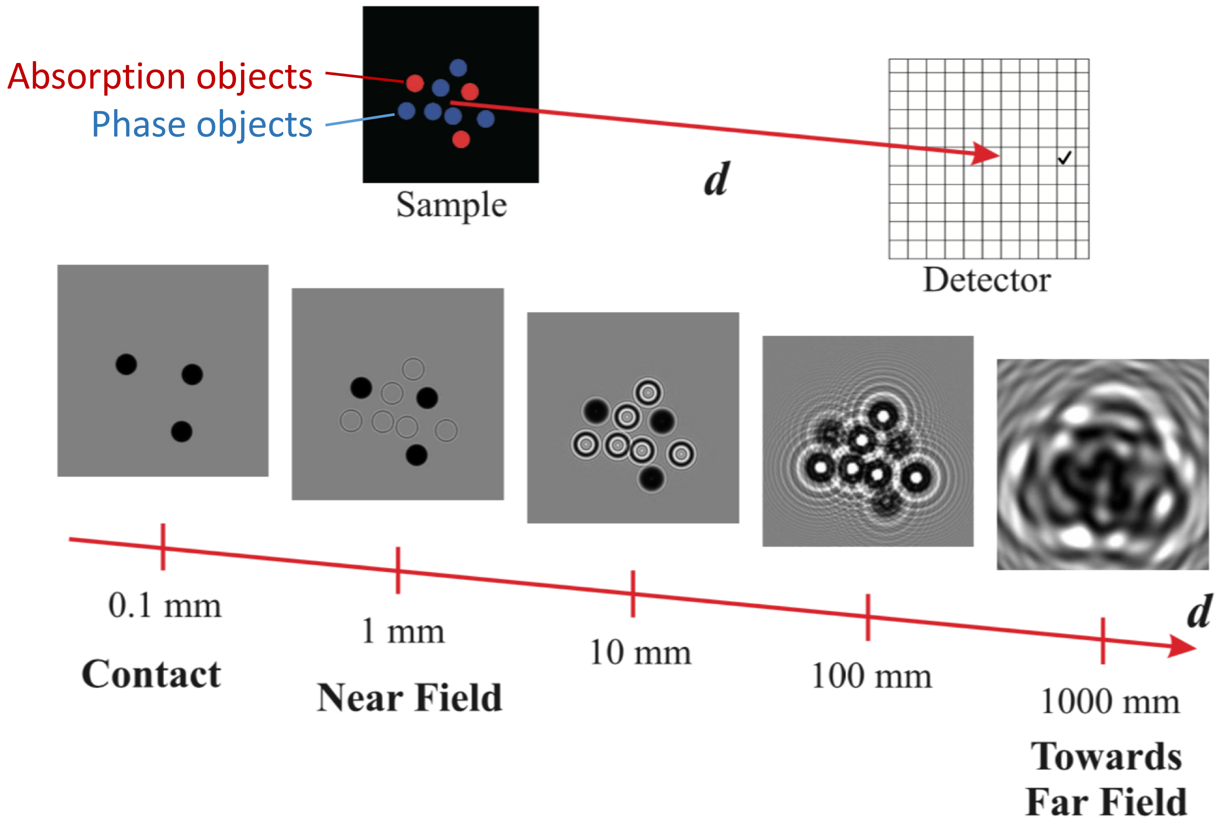


Diffraction + interference

→ Edge enhancement effects

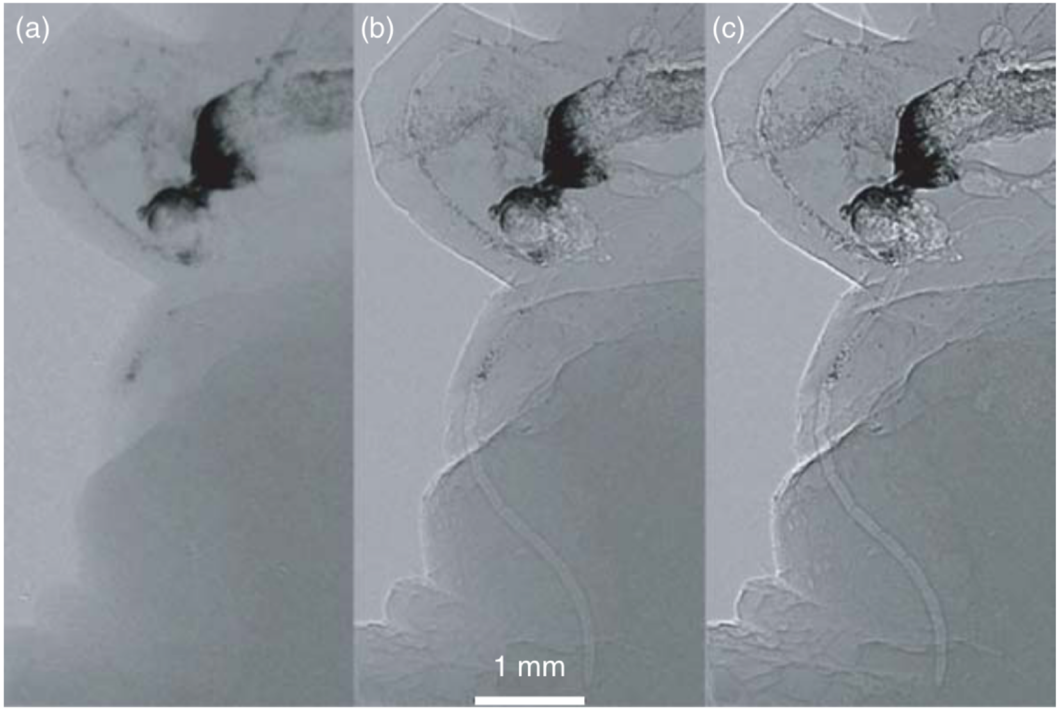
[Zhou08, Fig. 2]

Free-space propagation methods



[Als-Nielsen11, Fig. 9.2]

Free-space propagation methods

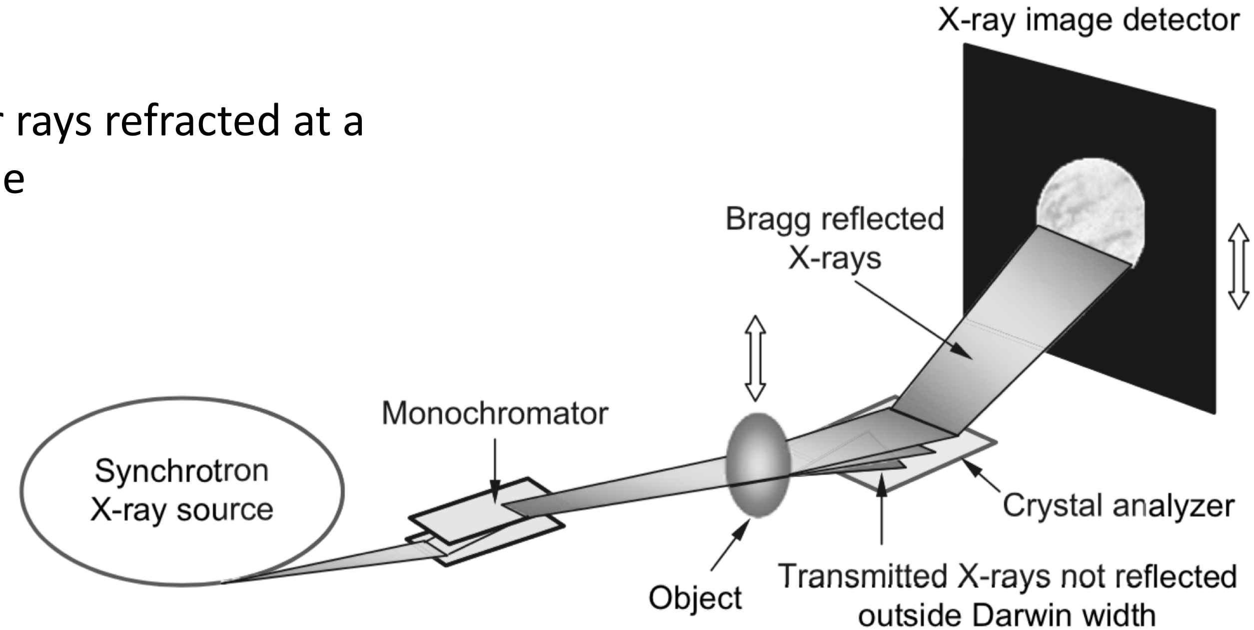


$d = 10\text{mm}$ $d = 500\text{mm}$ $d = 990\text{mm}$

[Willmott11, Fig. 7.14]

Analyser based methods

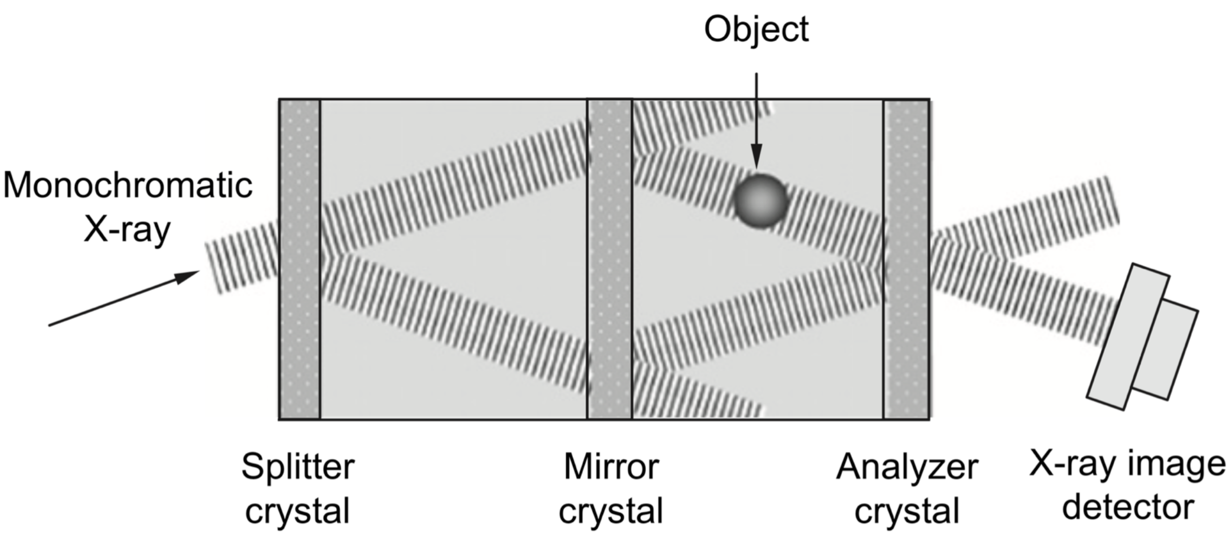
Selective for rays refracted at a specific angle



[Zhou08, Fig. 4]

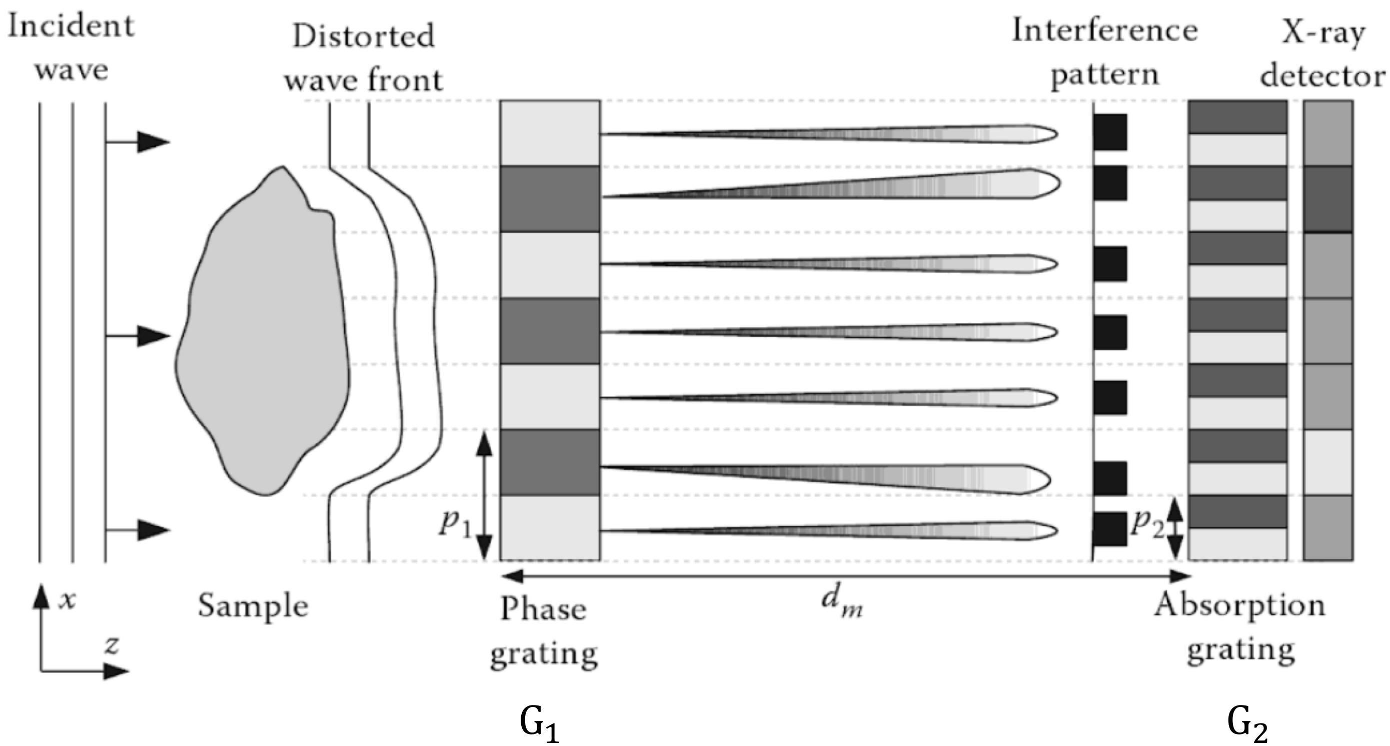
Interferometric methods

Triple Laue-type interferometer



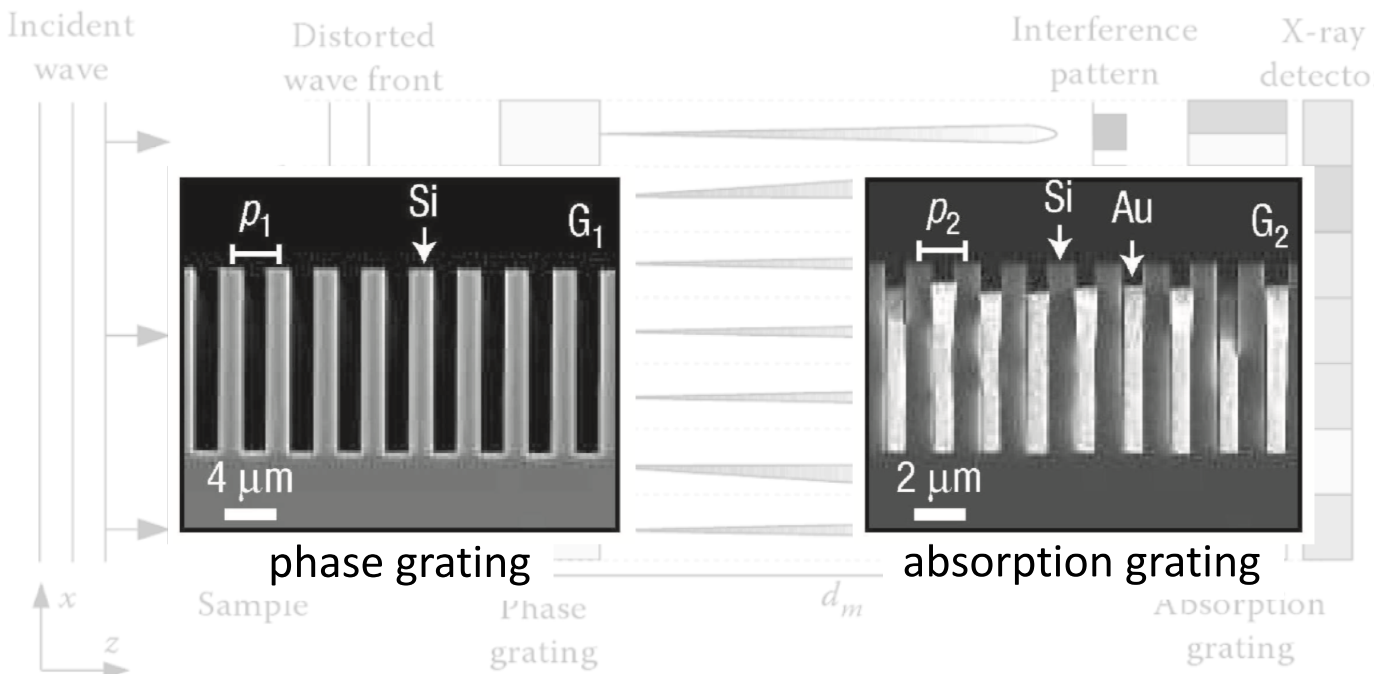
[Zhou08, Fig. 6]

Grating based interferometry



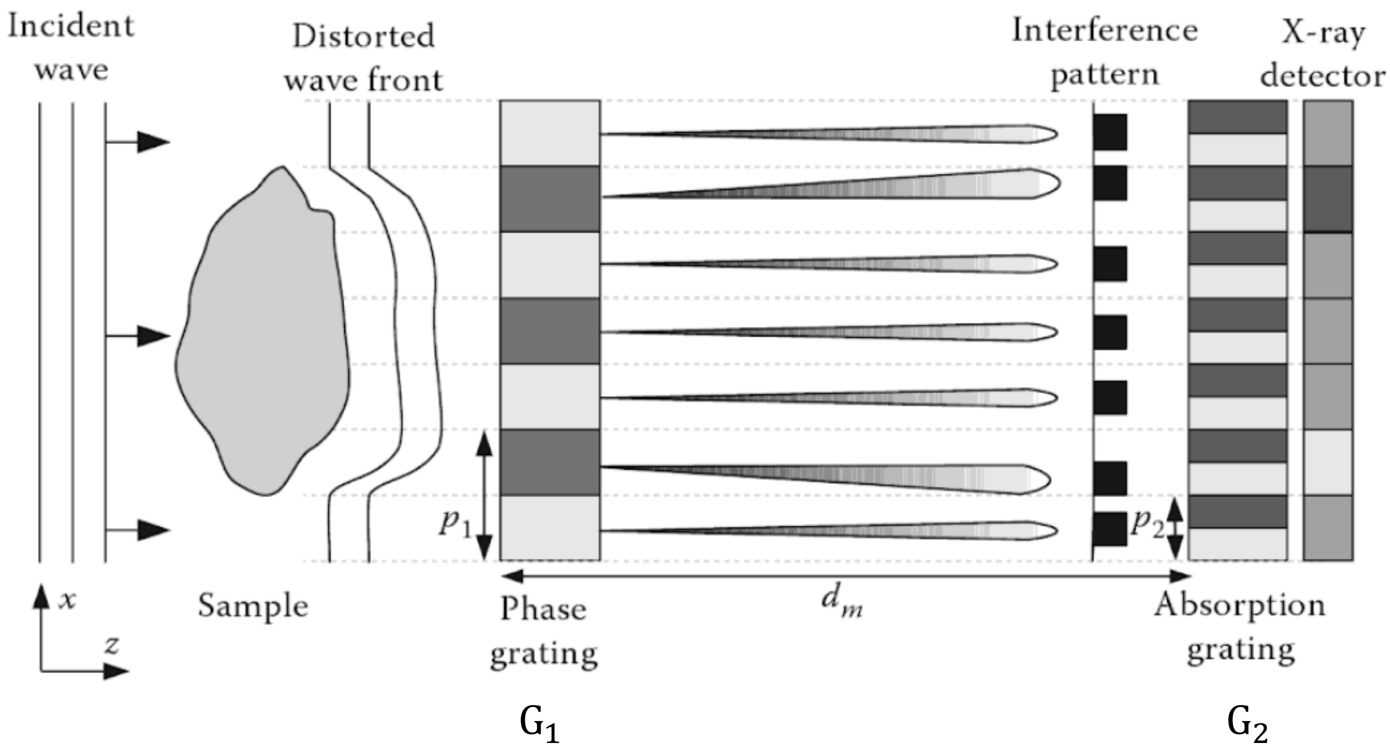
[Anastasio12, Fig. 3.1]

Grating based interferometry



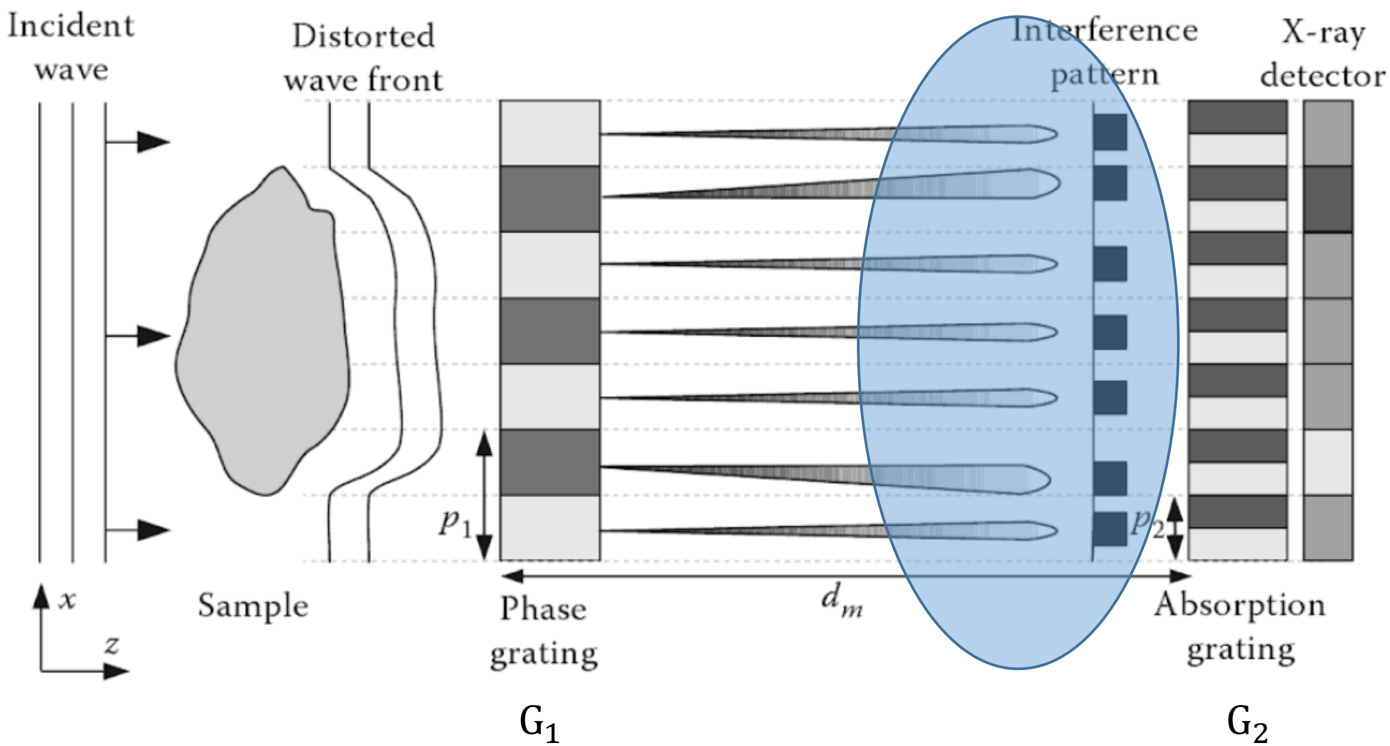
[Als-Nielsen11, Fig. 9.16]

Grating based interferometry



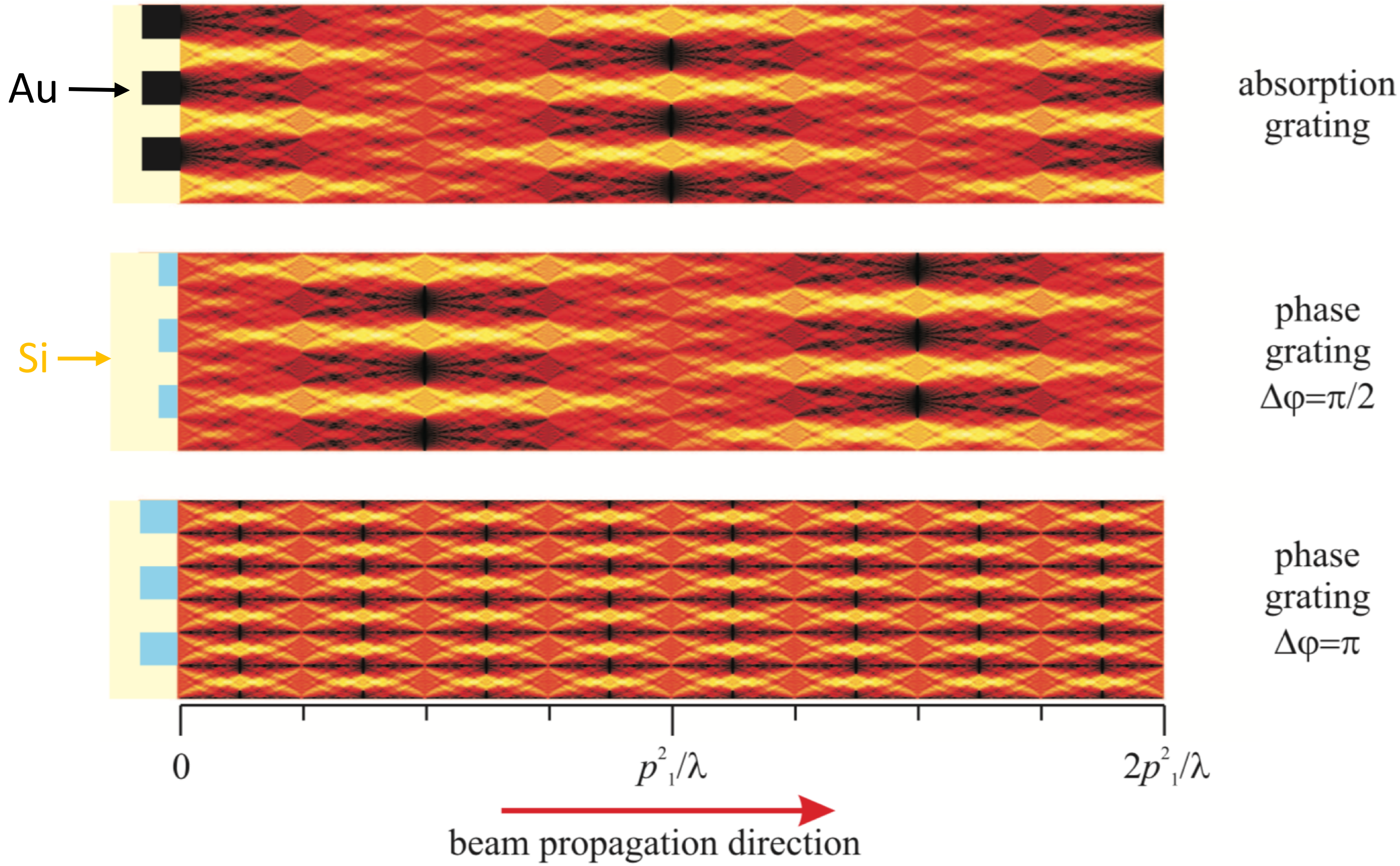
[Anastasio12, Fig. 3.1]

Grating based interferometry



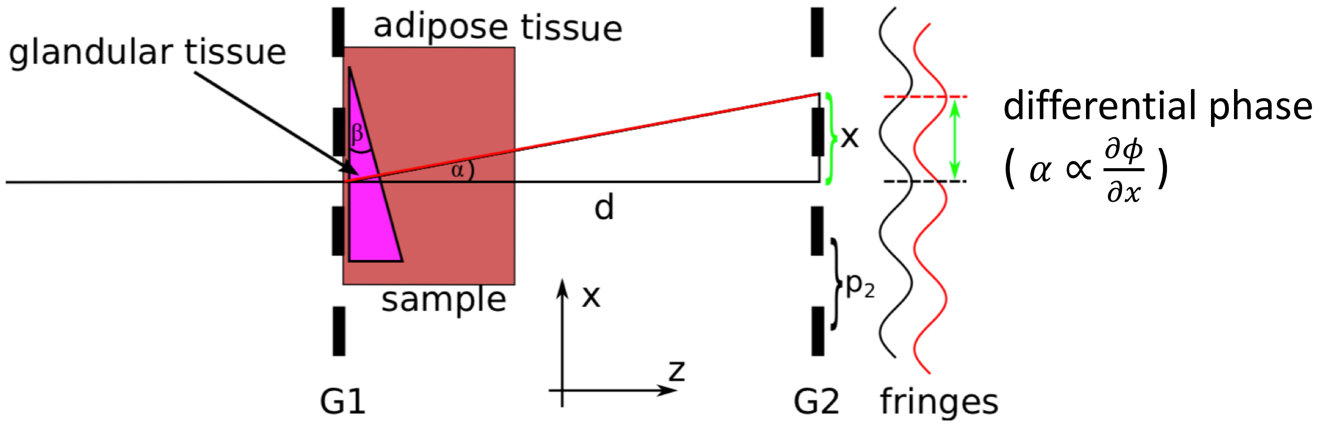
[Anastasio12, Fig. 3.1]

Grating based interferometry - Talbot effect



[Als-Nielsen11, Fig. 9.16]

Grating based interferometry - measurement



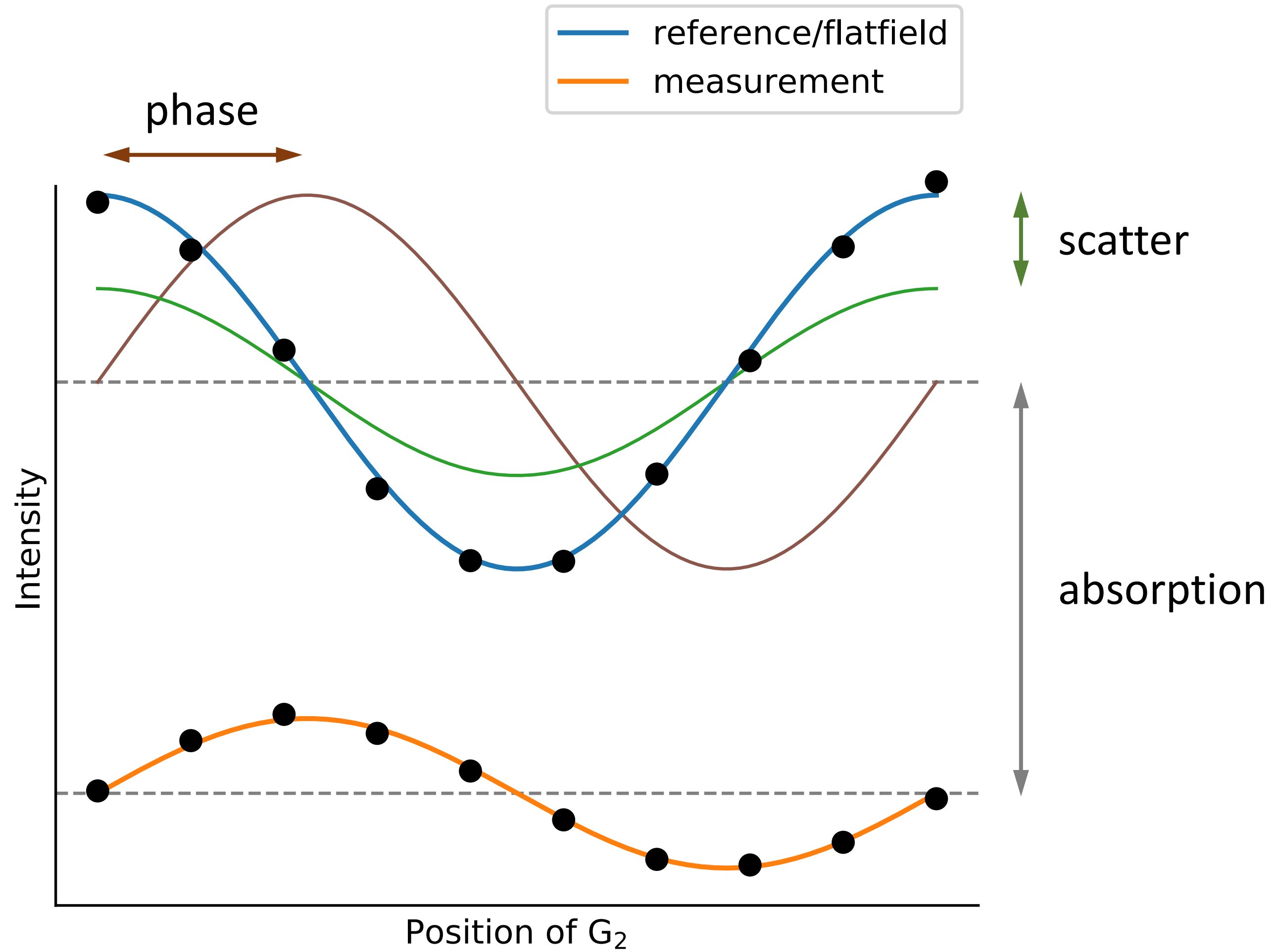
Optimize propagation distances and grating periods

- for visibility
- for resolution

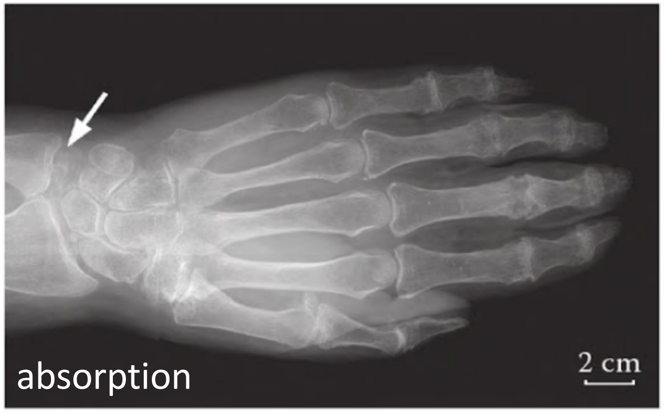
→ π-phase grating and high fractional Talbot order

[Gromann16, Fig. 1]

Grating based interferometry - signal retrieval



Grating based interferometry - signal retrieval

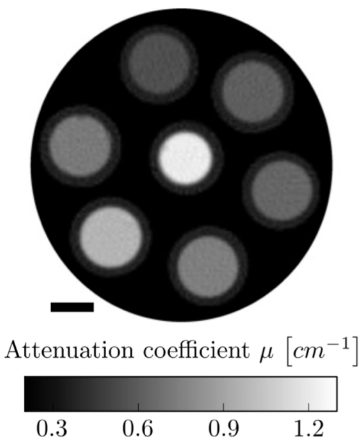


→ Multimodal imaging

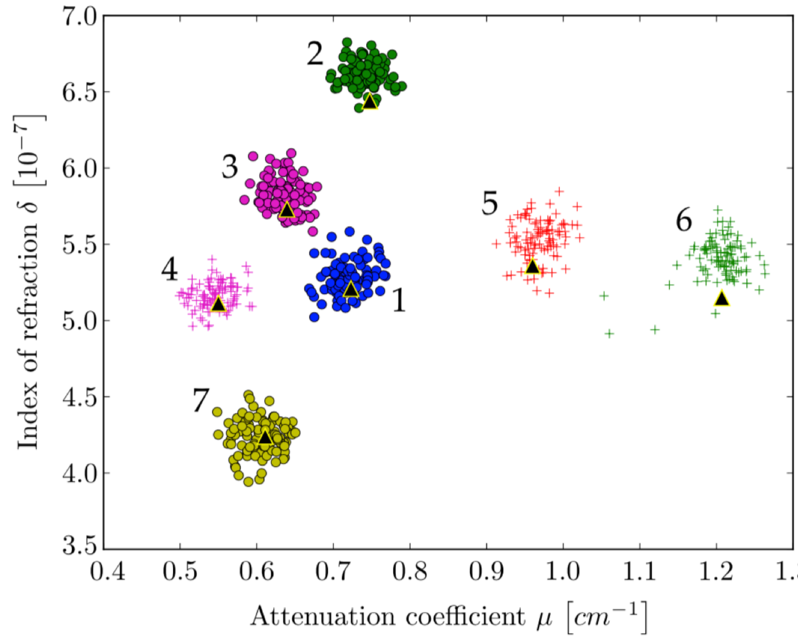
[Anastasio12, Fig. 3.3]

Multimodal imaging

CT of different fluids:



Differentiate by attenuation **and** refraction:



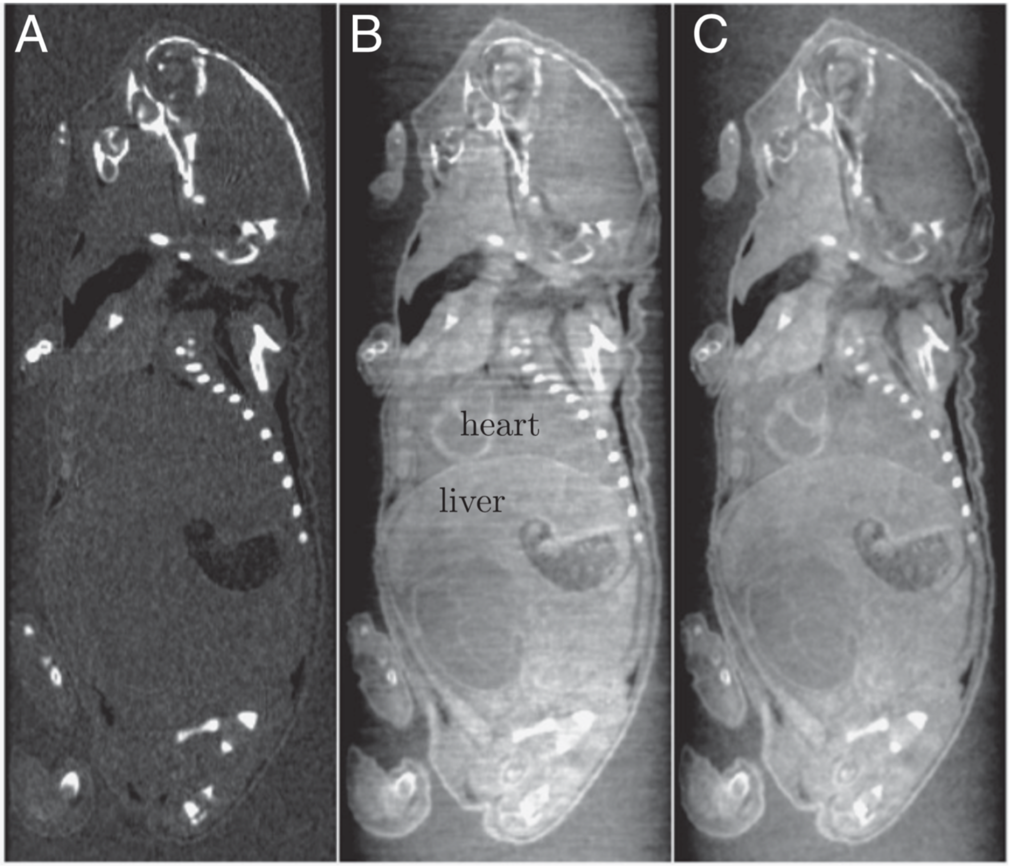
[Eggl06, Fig. 1+2]

Multimodal imaging

absorption signal:
position of highly dense materials

→ iterative reconstruction with weighted pixels

→ reduced stripe artifacts and noise



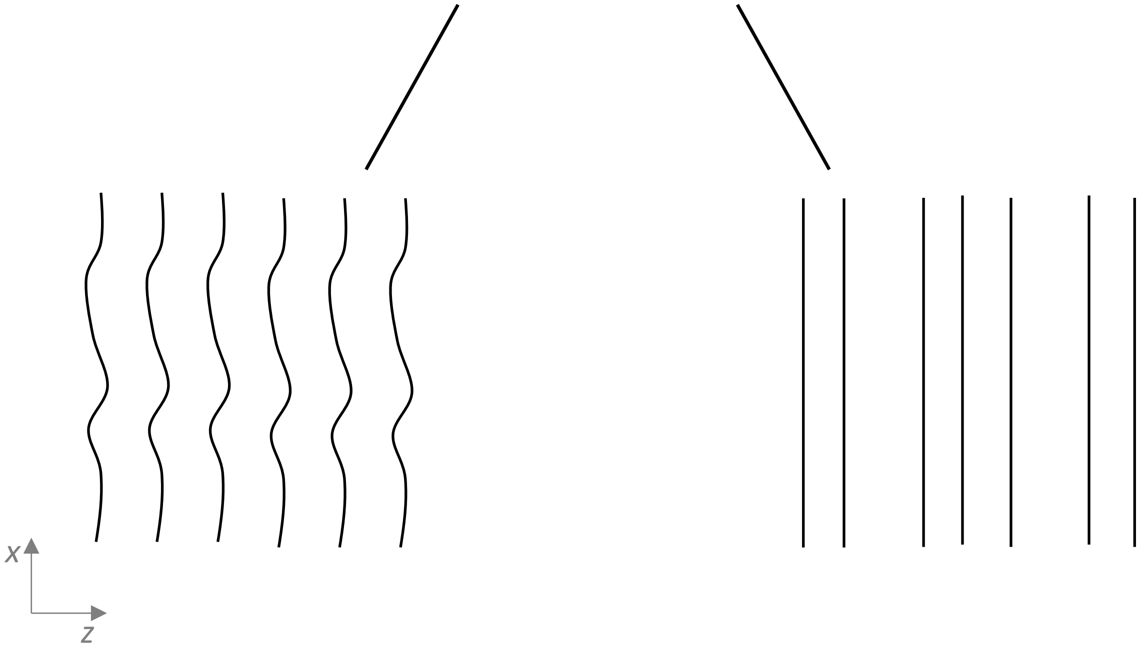
absorption | phase (FBP) | phase (iterative reconstruction)

[Eggl06, Fig. 3]

Requirement: Coherence

Until now: monochromatic, plane wave

Reality: limited spatial and temporal coherence



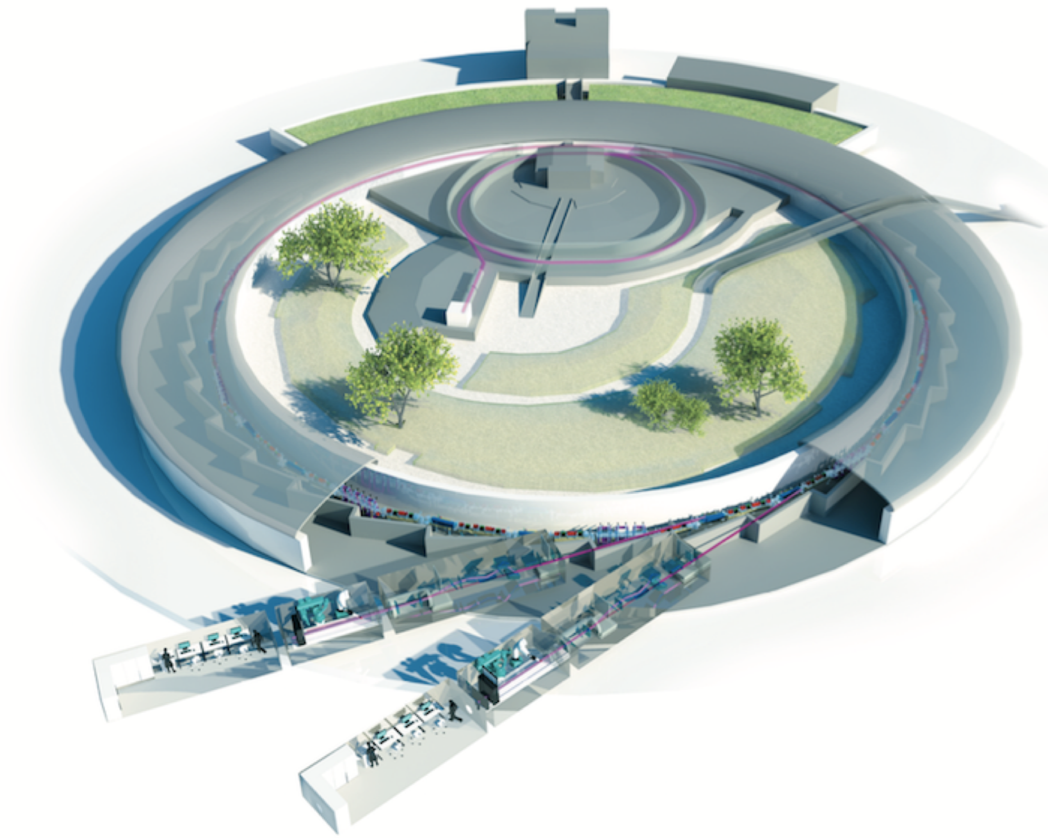
Synchrotron

Accelerate charged particle

→ wave emission

Problem:

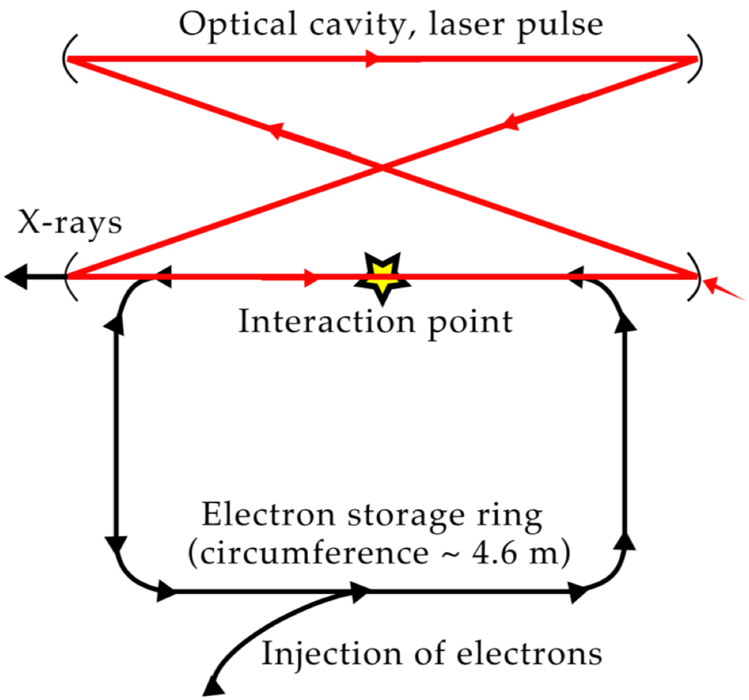
high energies, huge facilities



European Synchrotron Radiation Facility [www.esrf.eu]

Compact synchrotron light source (CLS)

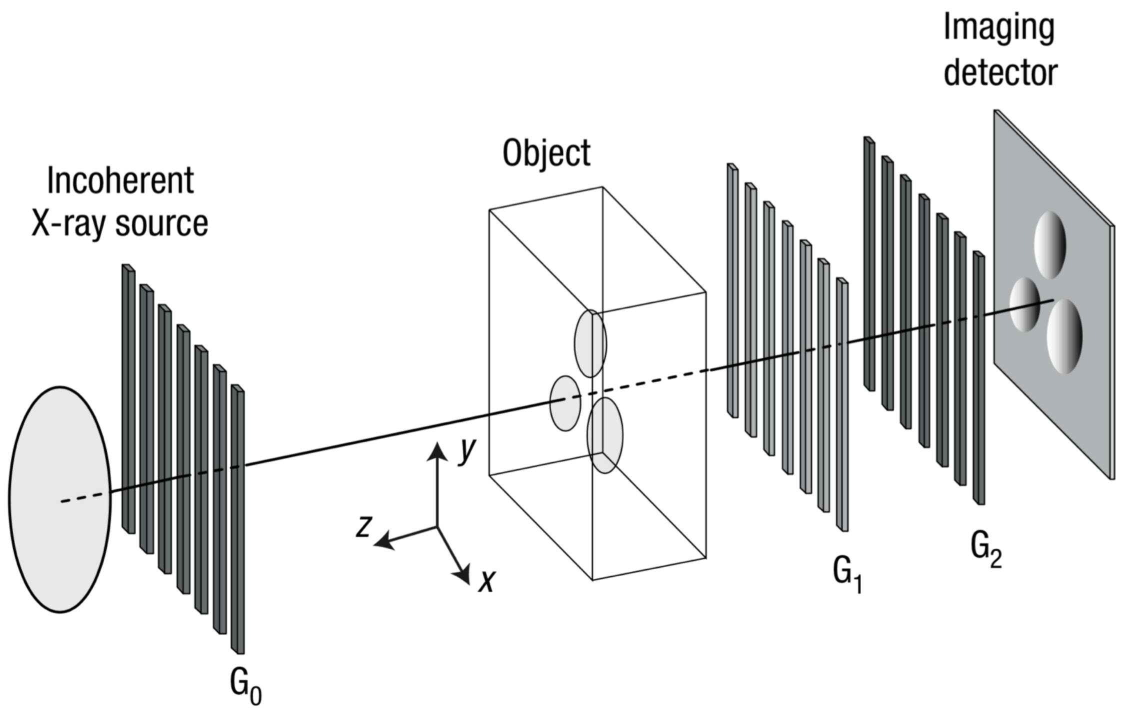
- Laser driven
- Generates X-rays by inverse Compton effect



[Eggl06, Fig. 5]

Source grating

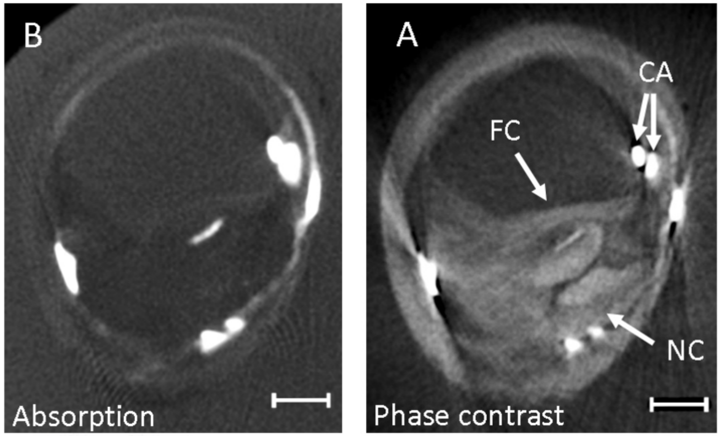
- Additional source grating with specific spacing
- Allows application of conventional X-ray tubes



[Pfeiffer06, Fig. 1a]

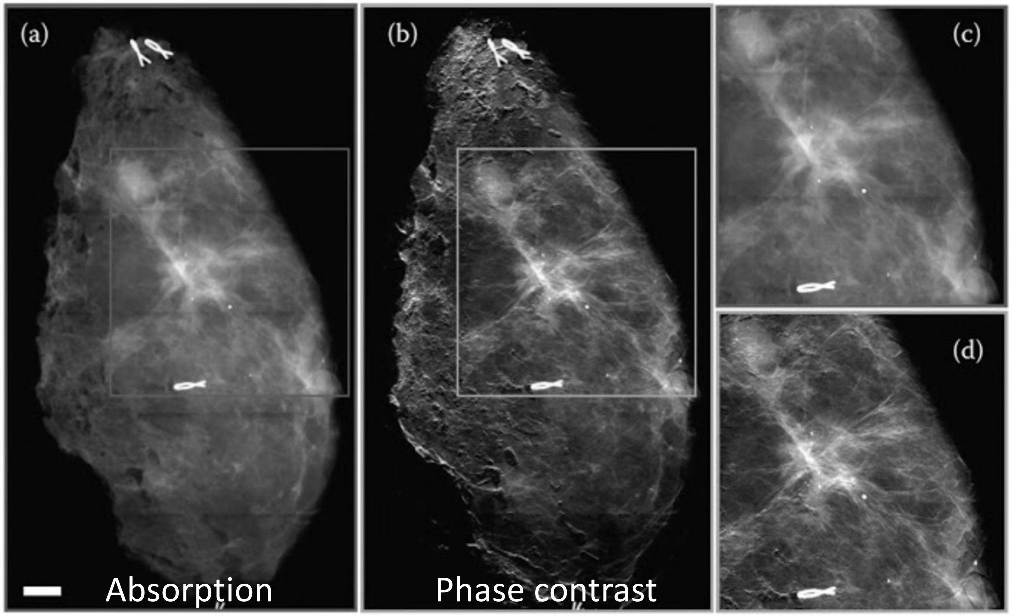
Results

- Atherosclerotic Plaque CT:



[Saam13]

- Mammography:



[Anastasio12]

Discussion

Literature

[Eggl06] E. Eggl et al., *PNAS* 112(18), 5567-5572 (2015)
[Pfeiffer06] F. Pfeiffer et al., *Nat. Phys.* 2, 258-261 (2006)
[Zhou08] S.A. Zhou and A. Brahme, *Phys. Med.* 24, 129-148 (2008)
[Willmott11] P. Willmott, An introduction to Synchrotron Radiation, *Wiley* (2011)
[Als-Nielsen11] J. Als-Nielsen and D. McMorrow, Elements of Modern X-ray Physics, Wiley (2011)
[Anastasio12] M.A. Anastasio and P.L. Riviere, Emerging Imaging Tech. in Medicine, CRC Press Inc (2012)
[Saam13] T. Saam, *PLOS ONE* 8(9), e73513 (2013)
[Gromann16] L. Gromann et al., Biomed. Opt. Express 7(2), 381-391 (2016)

Backup

Literature

[Eggl06]	E. Eggl et al., *PNAS* 112(18), 5567-5572 (2015)
[Pfeiffer06]	F. Pfeiffer et al., *Nat. Phys.* 2, 258-261 (2006)
[Zhou08]	S.A. Zhou and A. Brahme, *Phys. Med.* 24, 129-148 (2008)
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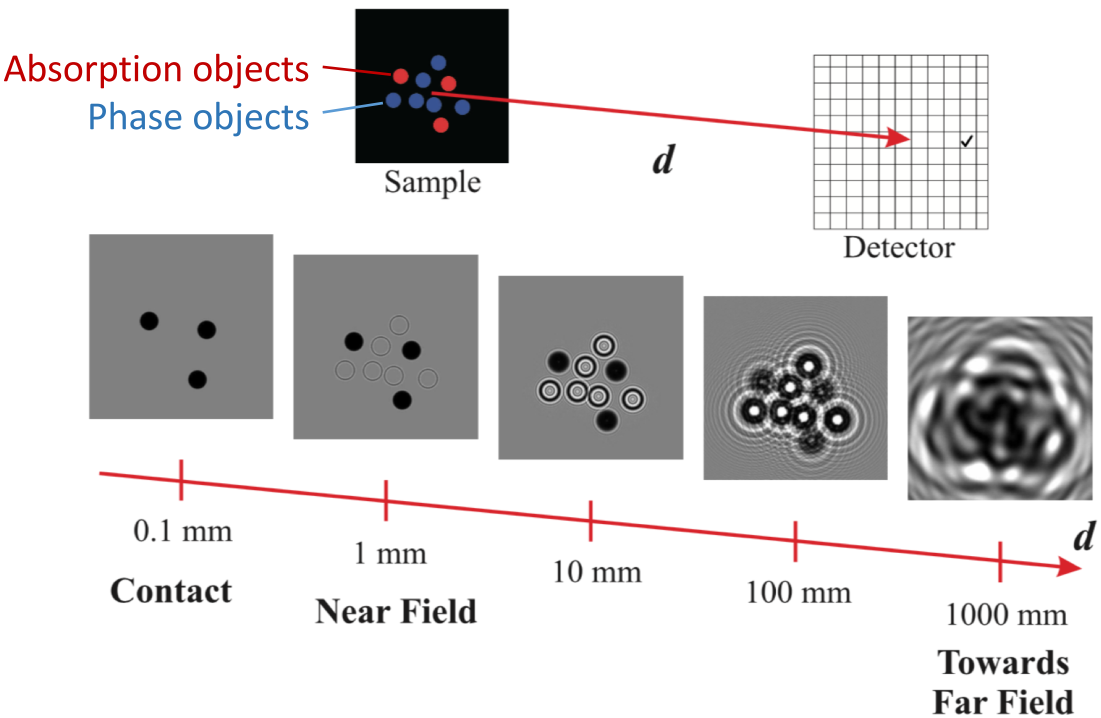
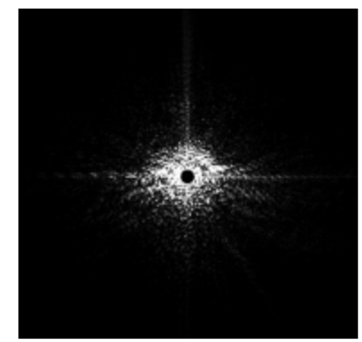
[Saam13]	T. Saam, *PLOS ONE* 8(9), e73513 (2013)
[Gromann16]	L. Gromann et al., Biomed. Opt. Express 7(2), 381-391 (2016)

Coherent diffraction imaging (CDI)



$FT^{-1}\{A, \phi\}$?

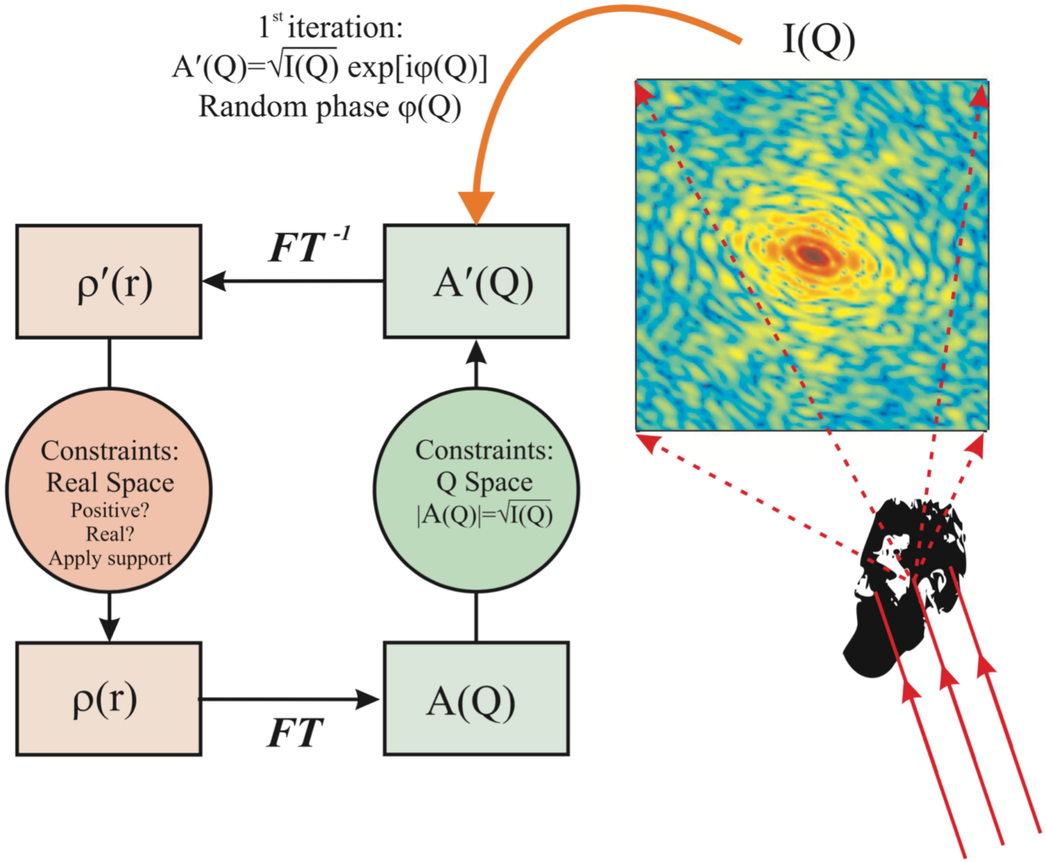


$A \propto FT\{\text{object}\}$

Fraunhofer diffraction

[Als-Nielsen11, Fig. 9.2]

CDI - Iterative Hybrid input output (HIO) algorithm



Ptychographical Iterative Engine (PIE):

Self-consistent reconstruction from multiple diffraction patterns

[Als-Nielsen11, Fig. 9.21]