

# Einführung in die Biophysik

## Vorlesung 3 – Hochauflösende Bildgebung

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# Erste radiographische Anwendungen



1896  
Michael Pupin  
Columbia University, New York

# Erste radiographische Anwendungen



# Das „Pedoskop“



## Von innen:

- Röntgenquelle
- Detektor

Gesamtgewicht

0.5 - 1.5 t

Rotationsgeschwindigkeit

3.5 Hz

Abstand Röhre–Detektor

1.1 m



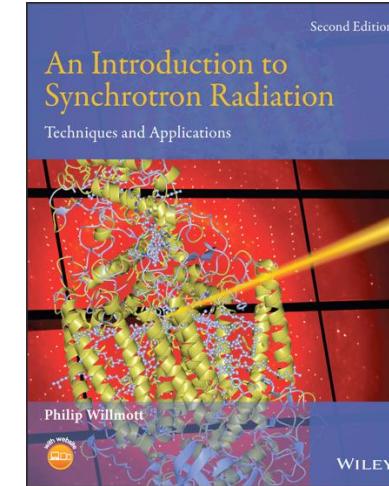
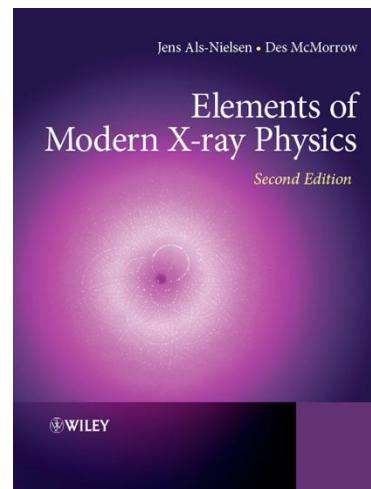
# Inhalt - hochauflösende Bildgebung

## Teil I: Röntgenquellen

- Synchrotronquellen
- Sonstige Röntgenquellen
- Kohärenz

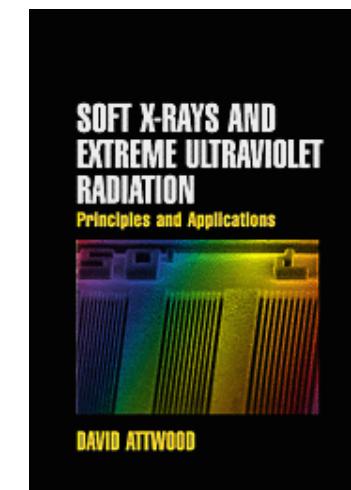
## Teil II: Phasenkontrast Bildgebung

- Grundlagen
- Verschiedene Methoden
- Anwendungen



<https://onlinelibrary-wiley-com.eaccess.tum.edu/doi/epub/10.1002/9781119280453>

<https://onlinelibrary-wiley-com.eaccess.tum.edu/doi/epub/10.1002/9781119998365>



<https://www.cambridge-org.eaccess.tum.edu/core/books/soft-xrays-and-extreme-ultraviolet-radiation/frontmatter/0A62989C054260686BA6A5A4593DBD2C>

# Thema Röntgenquellen

Fragen, die Sie am Ende jeder behandelten Methode beantworten können sollten:

- Nach welchem Prinzip wird die Strahlung erzeugt?
- Was kann diese Quelle im Vergleich zur konventionellen Röntgenröhre?

ausführlichere Behandlung in folgenden Vorlesungen im Master:

- Modern X-ray Physics (Dr. Achterhold/Dr. Dierolf)

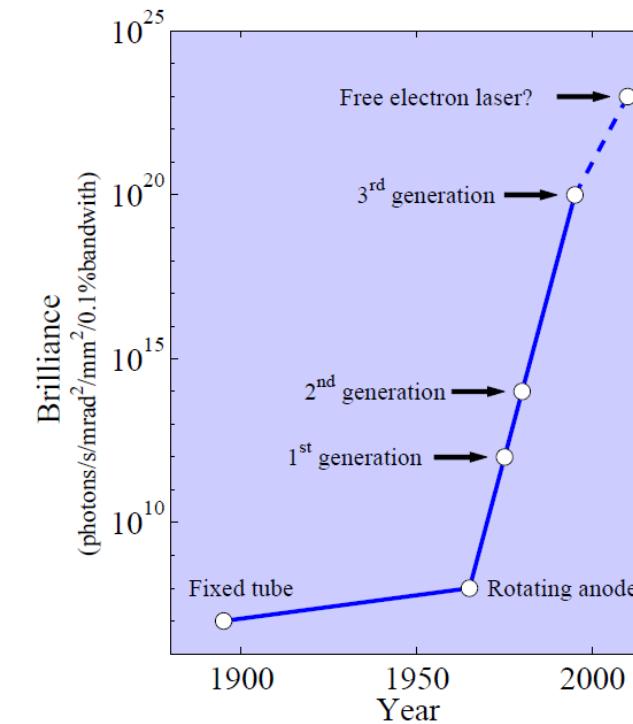
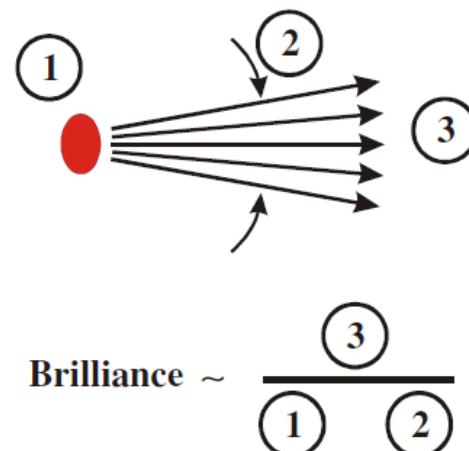
## Als Maßeinheit für die Stärke einer Röntgenquelle:

$$\text{Brillanz} = \frac{\text{Anzahl an Photonen}}{\text{Zeit} \times \text{Quellfläche} \times \text{Raumwinkel} \times \text{Bandpass}}$$

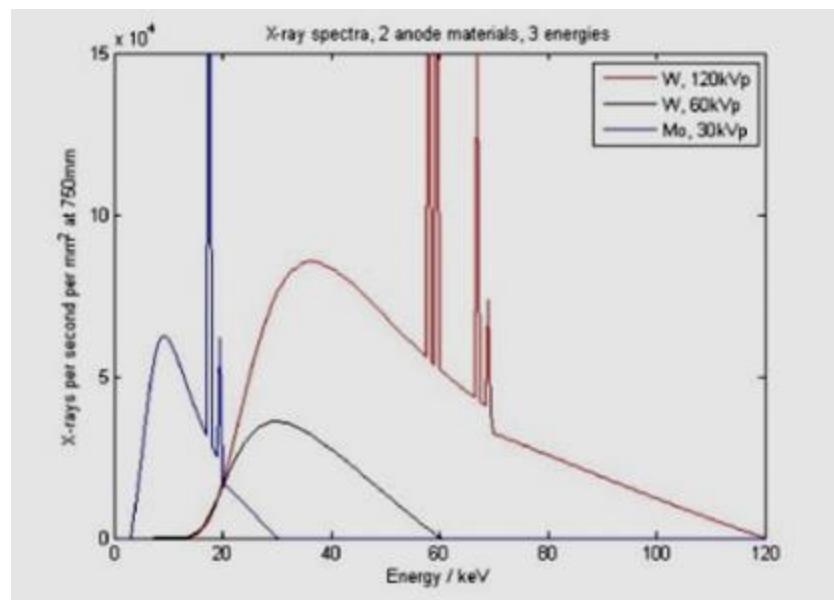
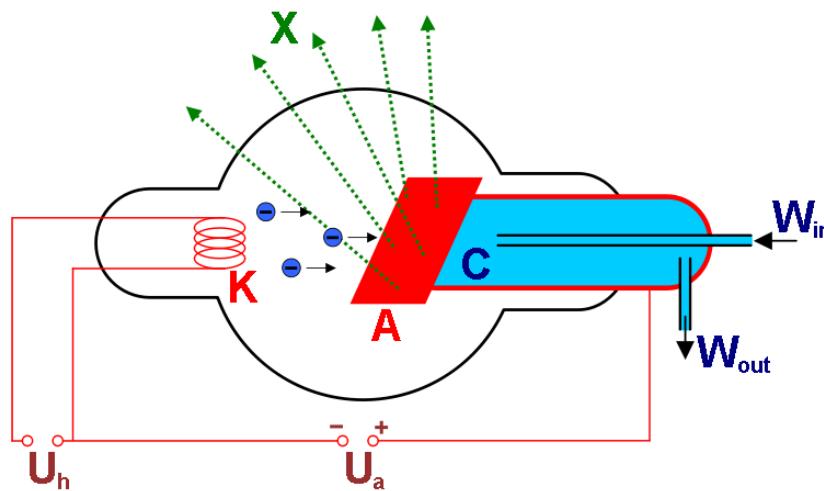
Einheit: ph / (sec mm<sup>2</sup> mrad<sup>2</sup> 0.1 % BW)

$$\Rightarrow B = 10^9 \times 1 \times 4 / 500 [\text{ph} / (\text{sec mm}^2 \text{ mrad}^2 0.1 \% \text{ BW})]$$

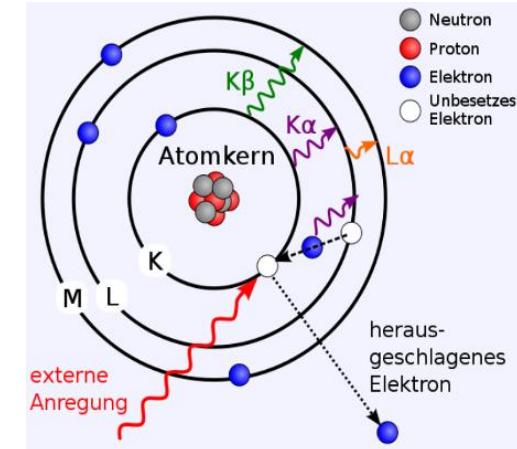
$$\Rightarrow B = 8 \times 10^6 \text{ ph} / (\text{sec mm}^2 \text{ mrad}^2 0.1 \% \text{ BW})$$



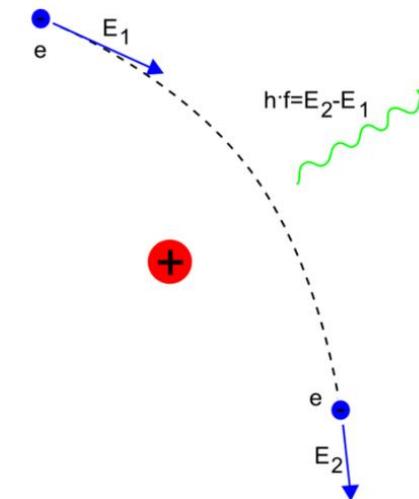
# Röntgenröhre



## Charakteristische Röntgenstrahlung

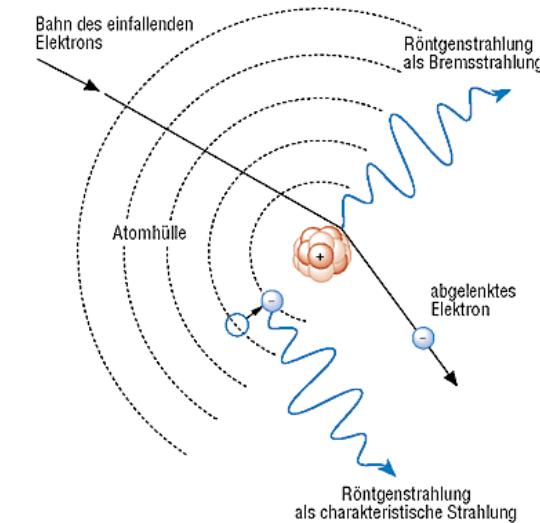


## Bremsstrahlung



## Prinzip der Röntgenerzeugung am Synchrotron:

- Bremsstrahlung:  
Beschleunigung eines Elektrons  
im (periodischen) Magnetfeld

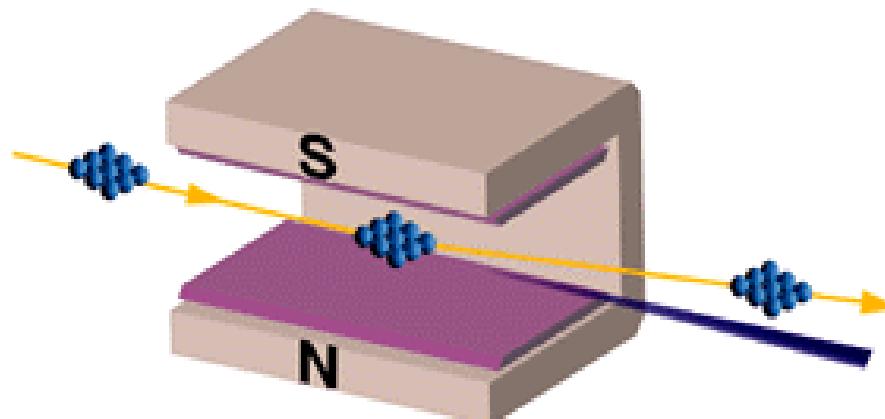


Typische Magnetfelder:

1-2 Tesla

Typische Elektronenenergien:

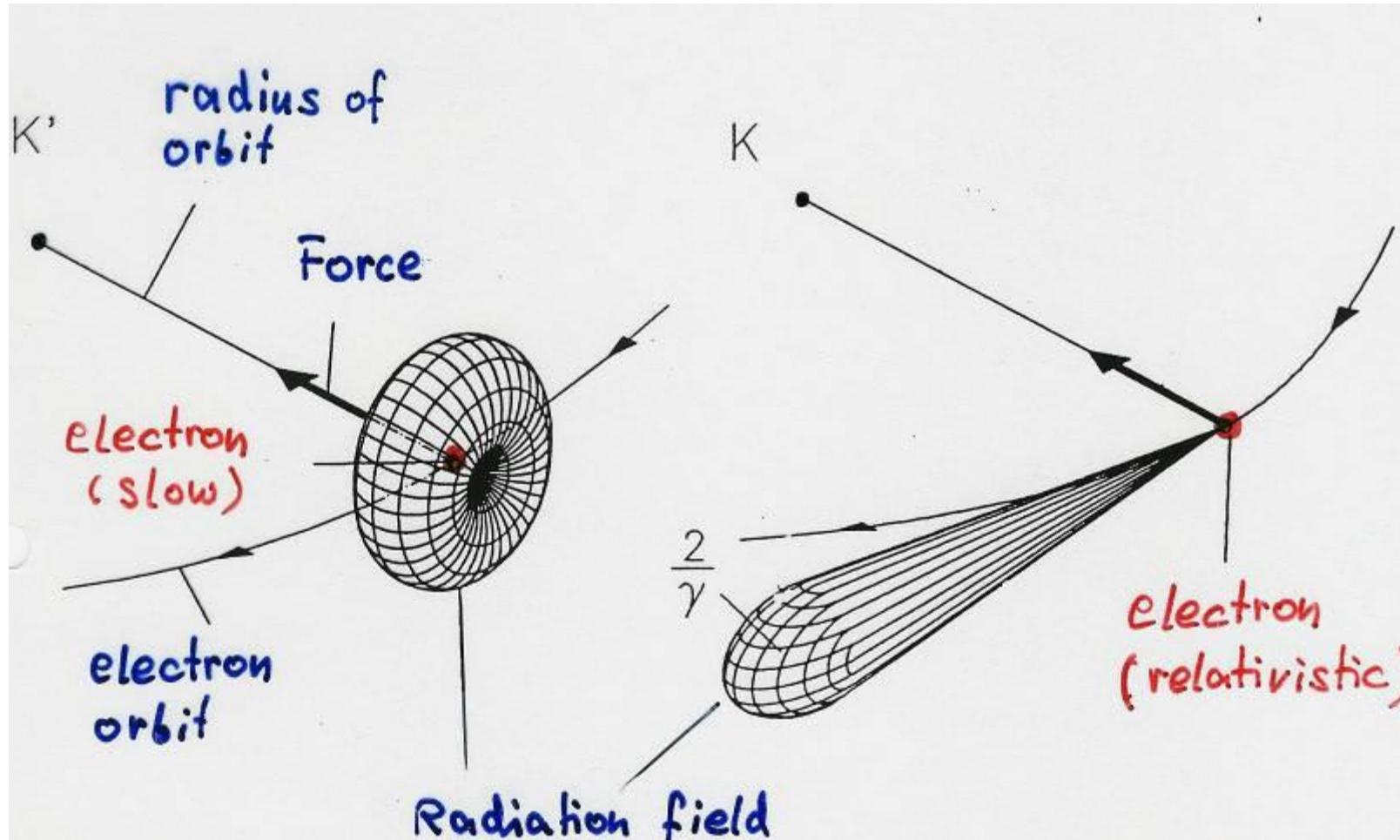
1-5 GeV



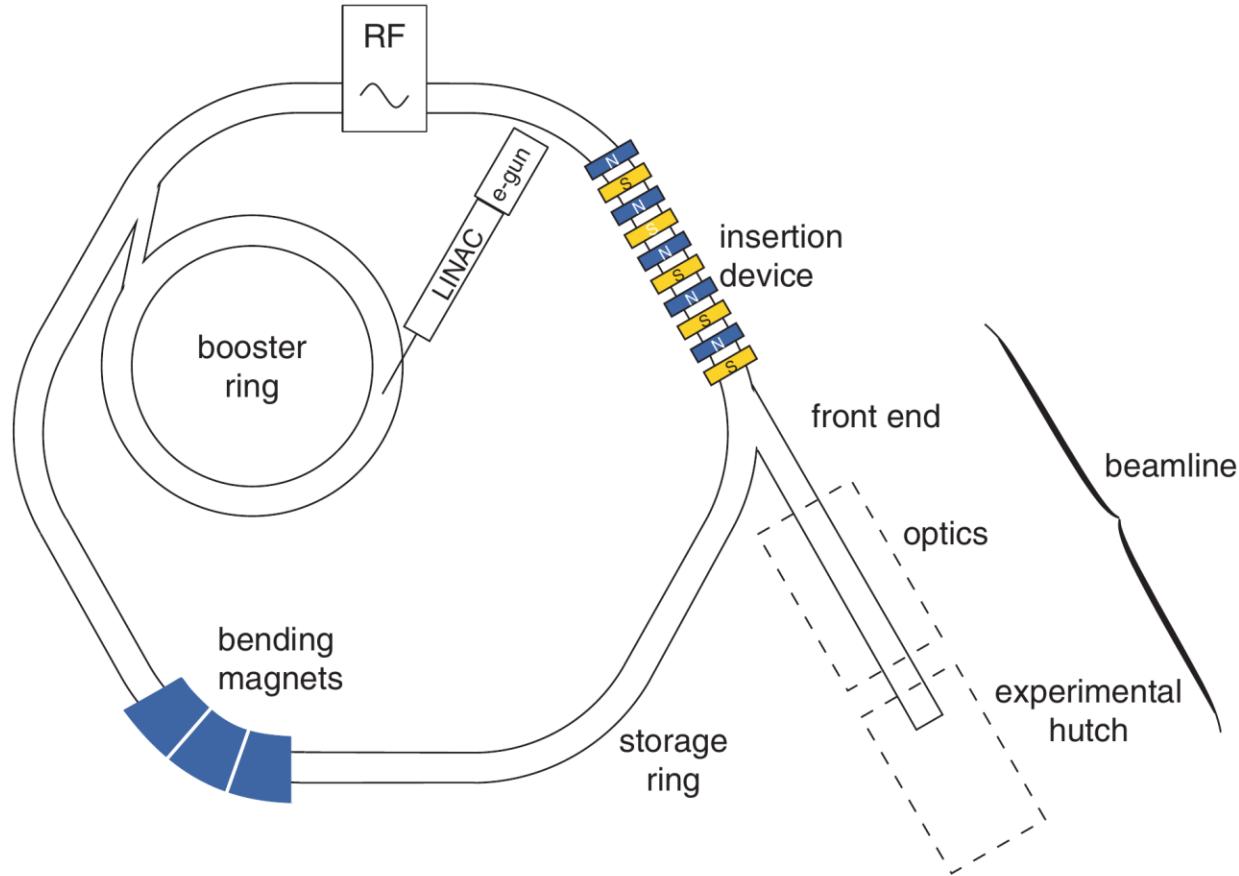
# Hohe Brillanz durch Lorentz-Kontraktion

$v \ll c$

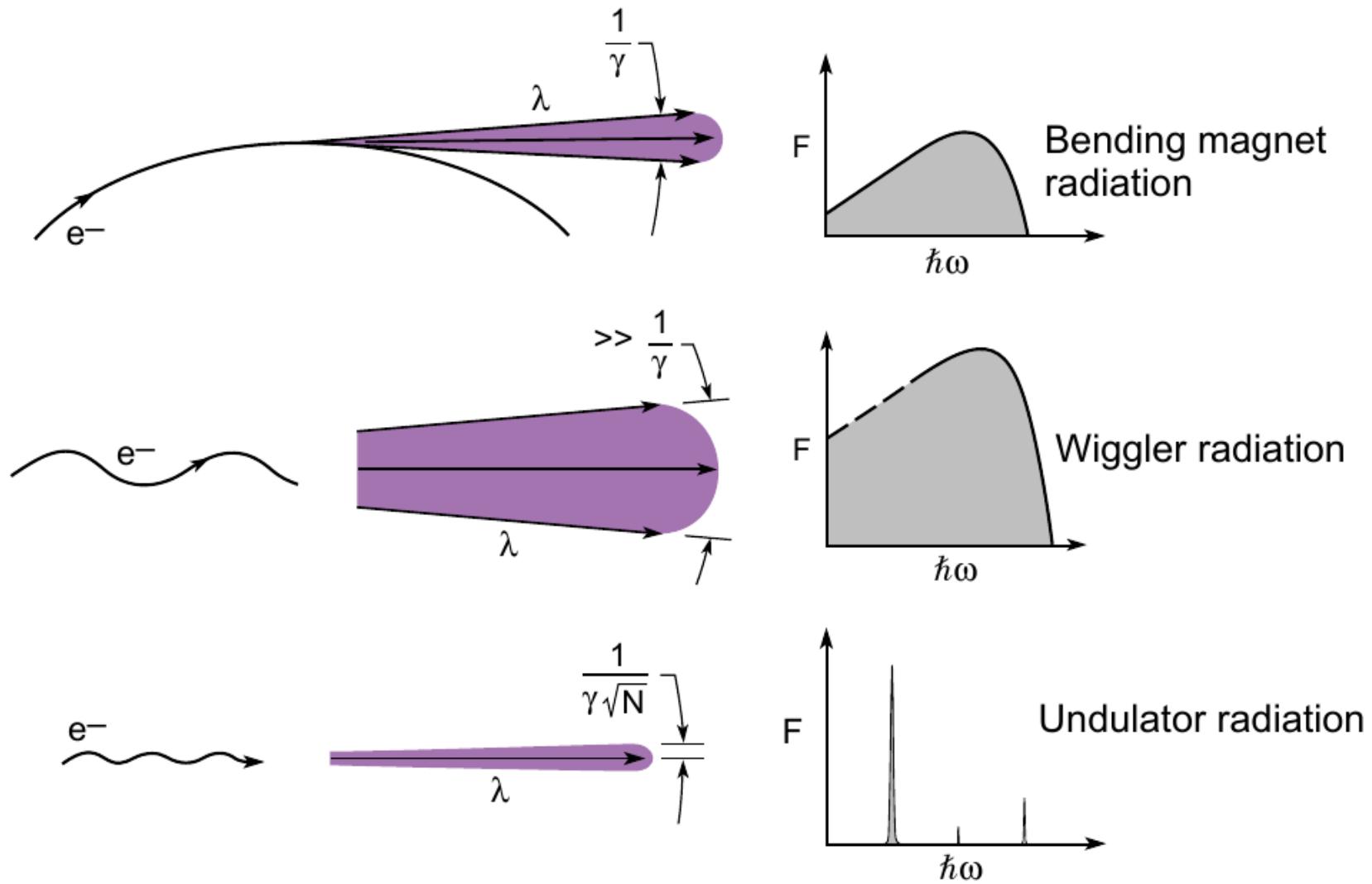
$v \approx c$



# Komponenten eines Synchrotron

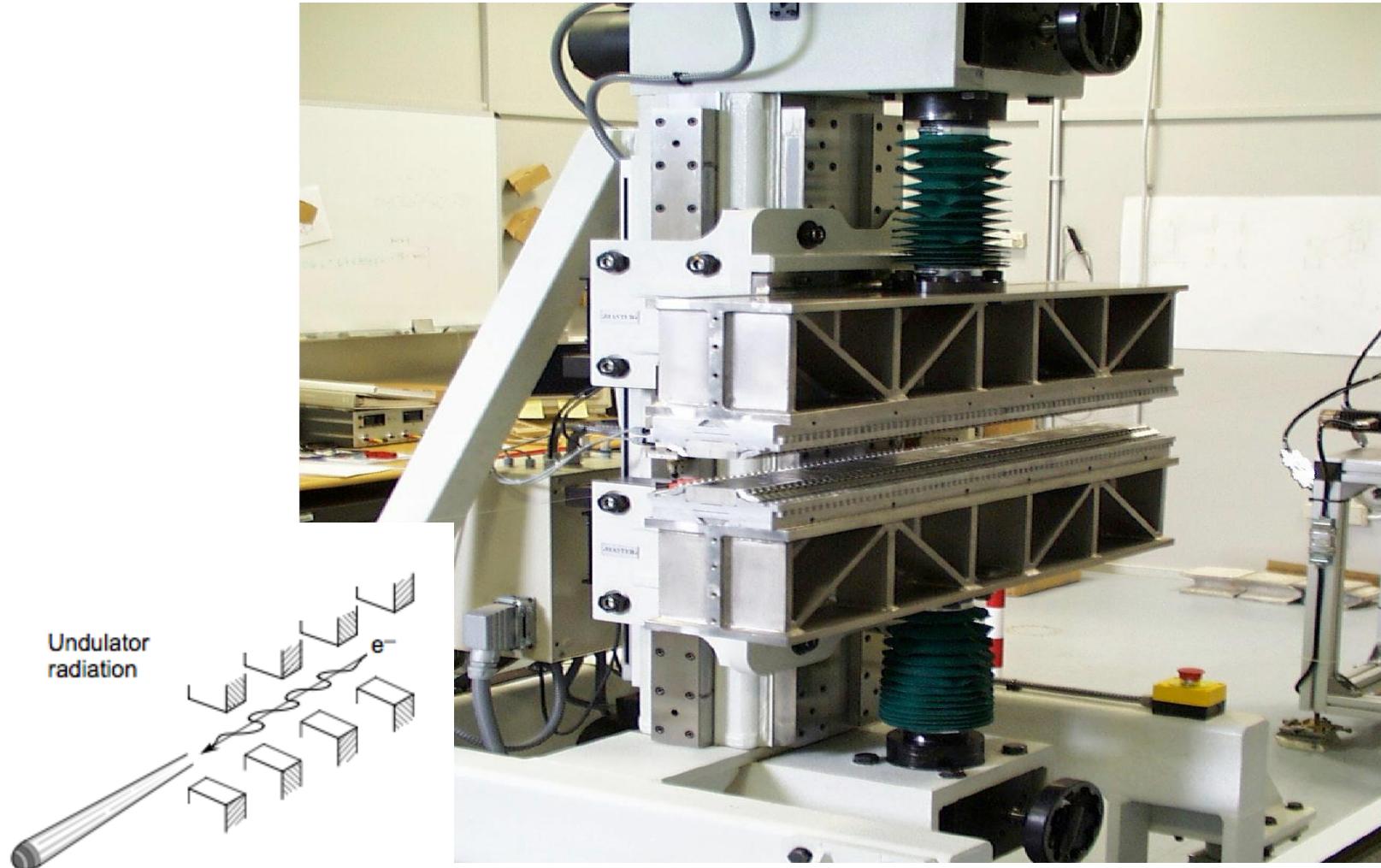


# Insertion Devices

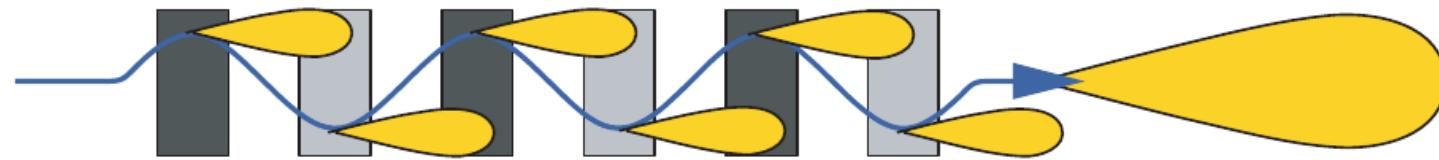


Attwood, Fig. 5.1 – 5.3

# Insertion Devices



(a) Wiggler

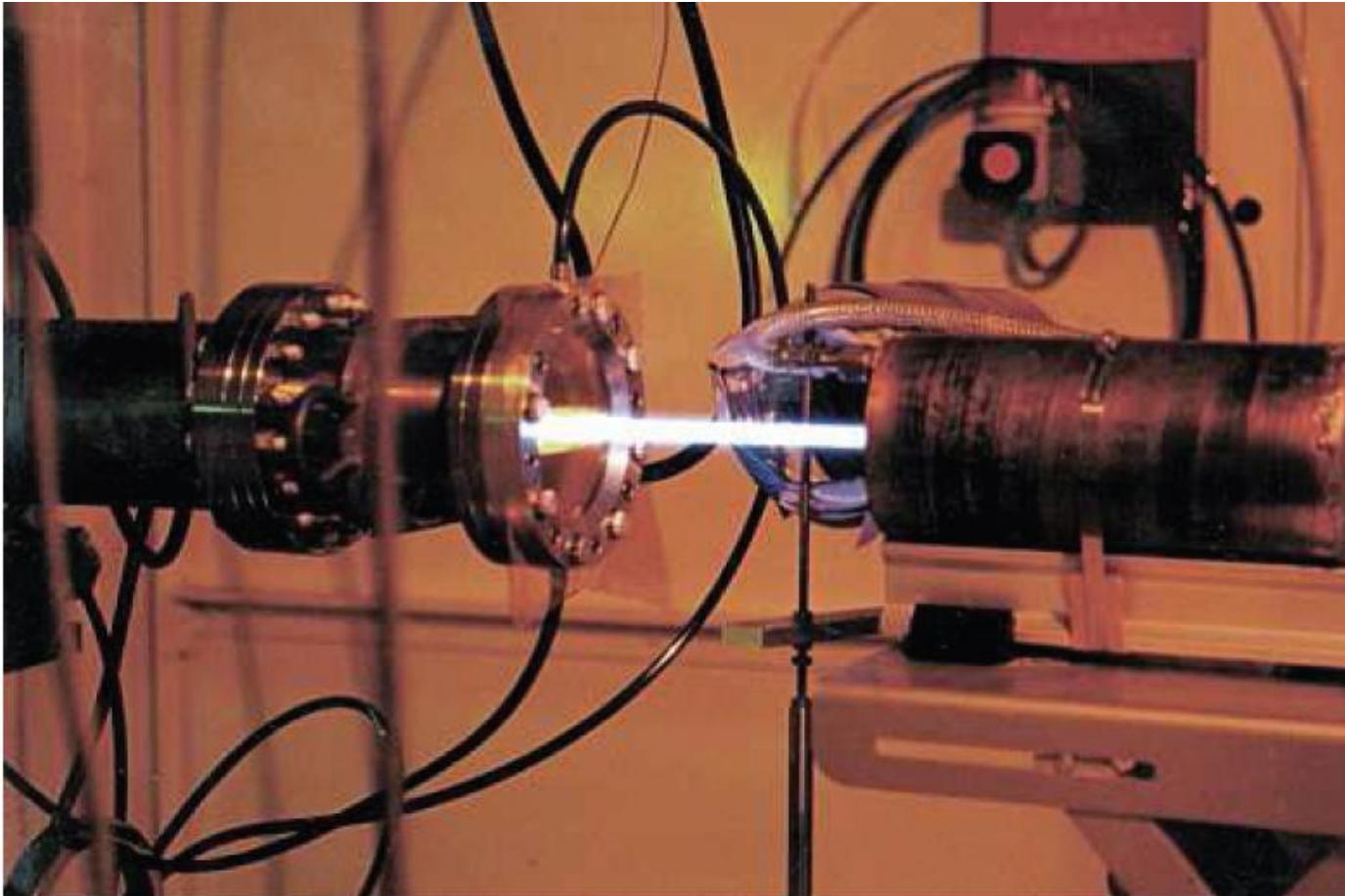


(b) Undulator



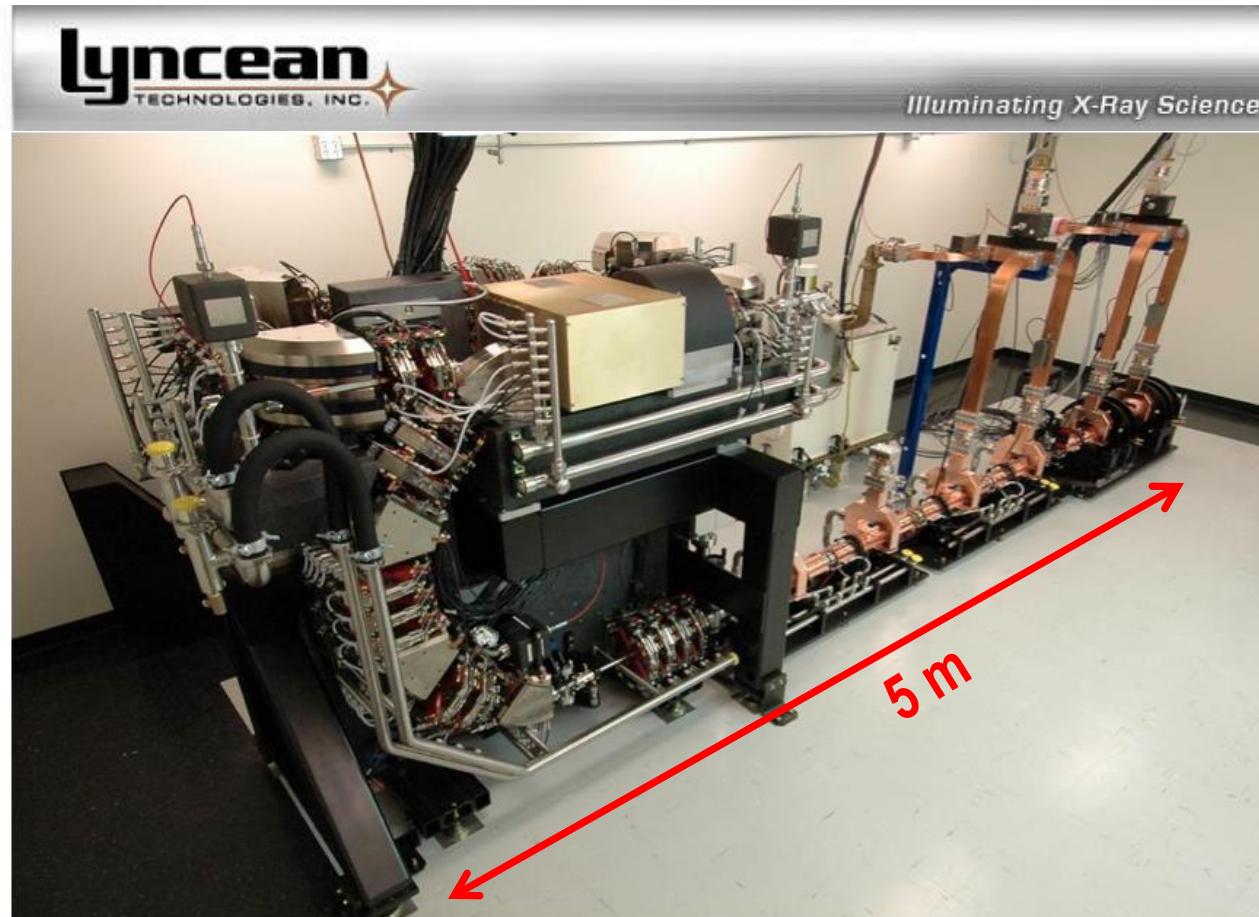
Willmott, Fig. 3.16

Als-Nielsen, Fig. 2.15

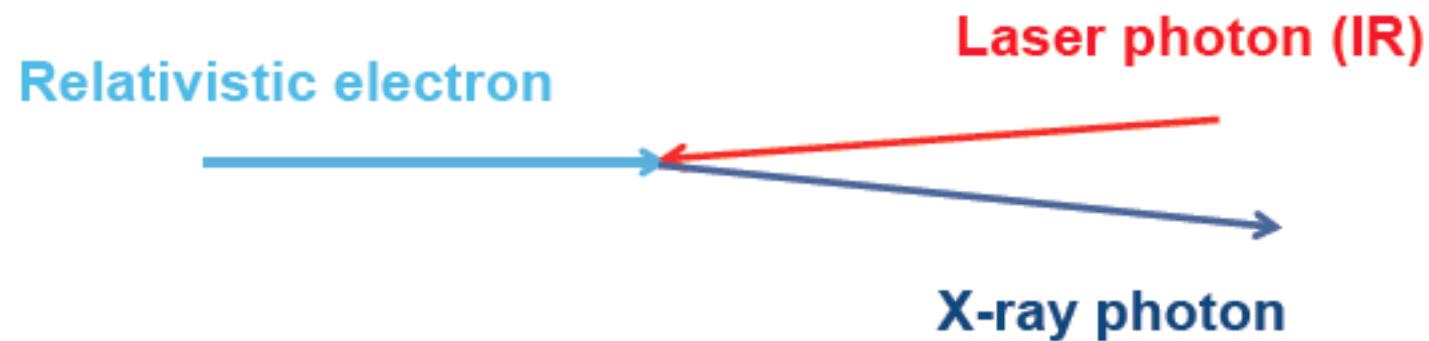


**Fig. 2.15** The white X-ray beam from the wiggler at the ID11 beamline, ESRF. The X-ray beam emerges from an evacuated beam tube with an intensity that is high enough to ionize air. (Image courtesy of Åke Kvick, ESRF.)

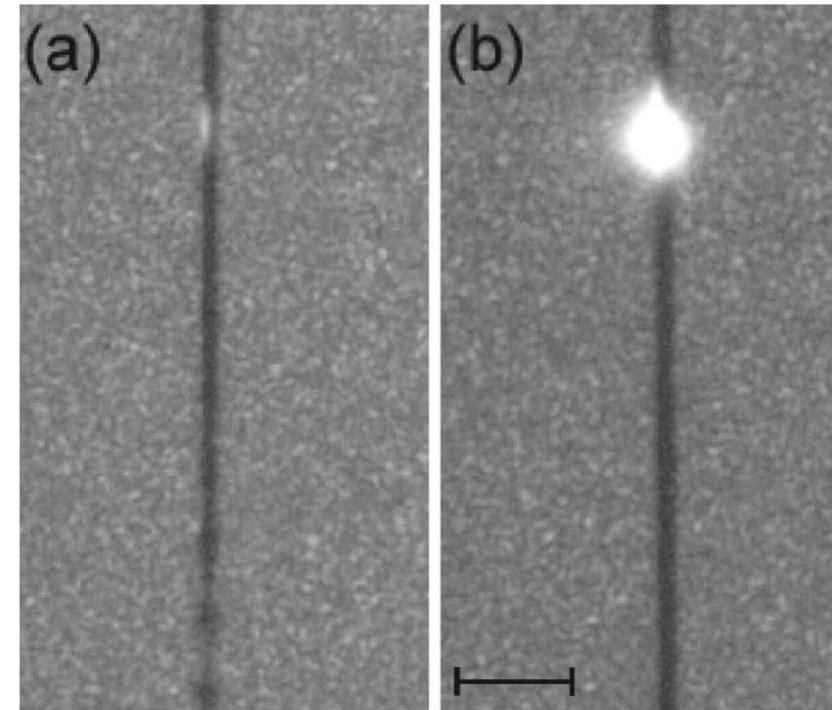
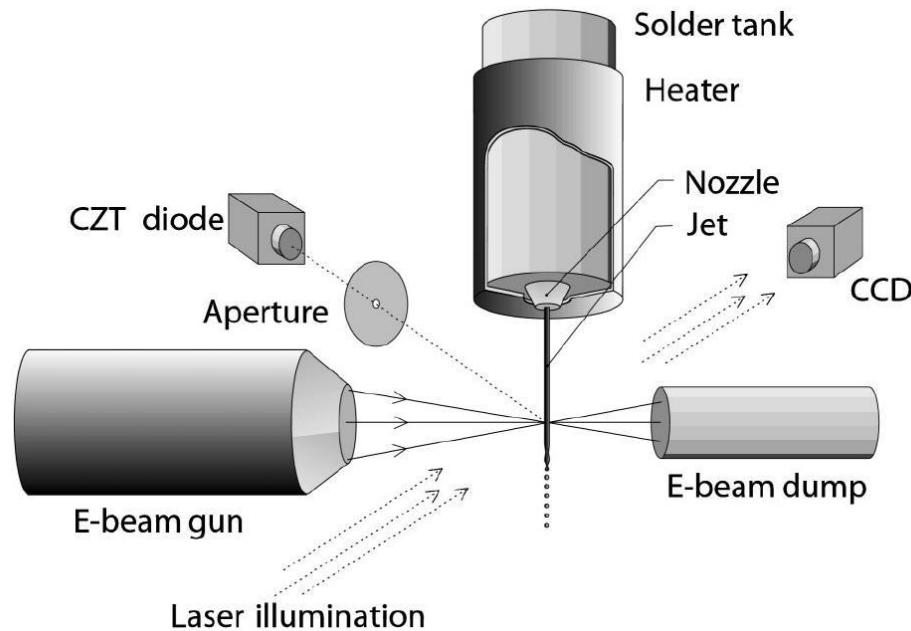
## Compact Light Source (CLS)



## Inverse Compton Scattering

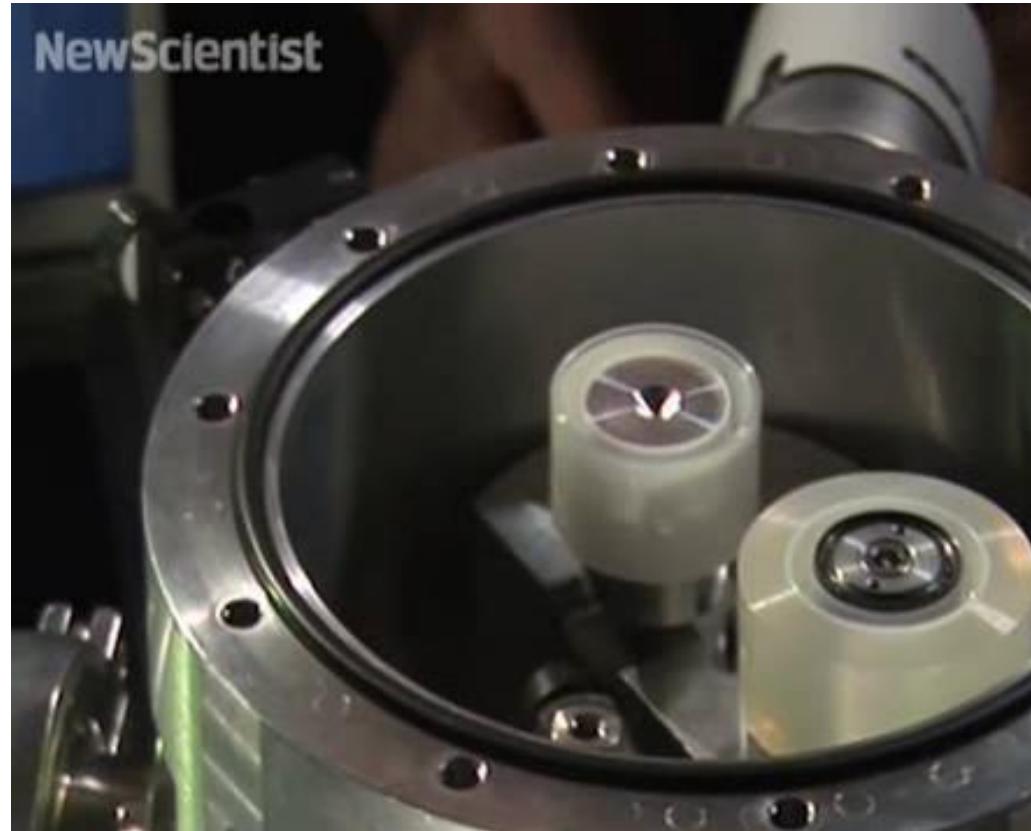


# Liquid-metal Anode Röntgenröhre



Hemberg, O., Otendal, M. & Hertz, H. M. Liquid-metal-jet anode electron-impact x-ray source. Applied Physics Letters 83, 1483 (2003).

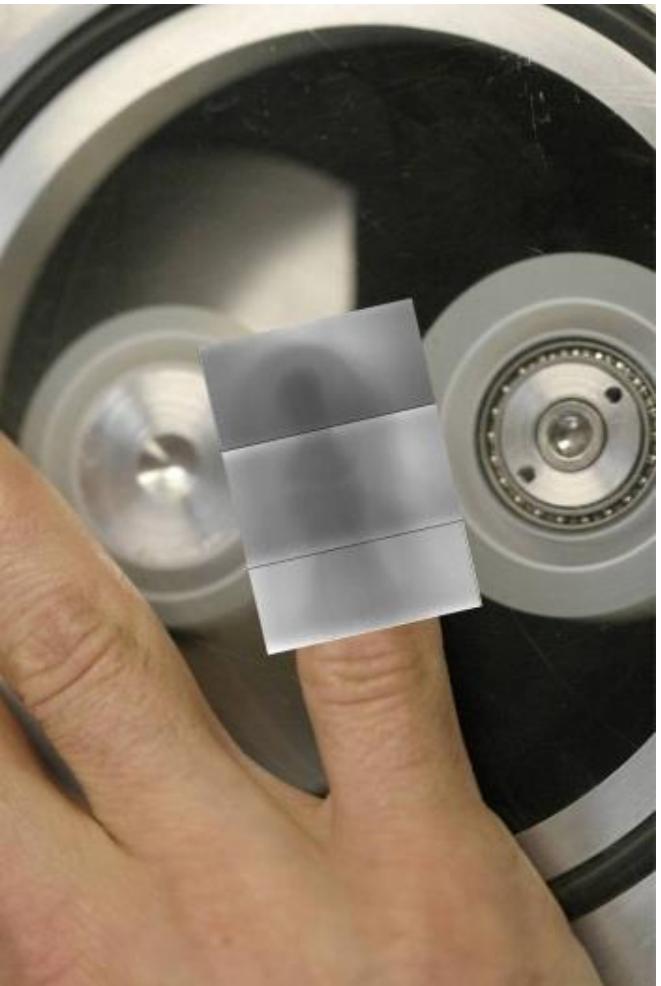
# „Tesafilem“ Röntgenquelle



full video: <http://www.youtube.com/watch?v=LQBjRF9mX1Y>

Camara, C. G., Escobar, J. V., Hird, J. R. & Puttermann, S. J. Correlation between nanosecond X-ray flashes and stick-slip friction in peeling tape. *Nature* 455, 1089–1092 (2008).

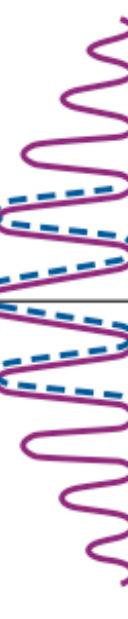
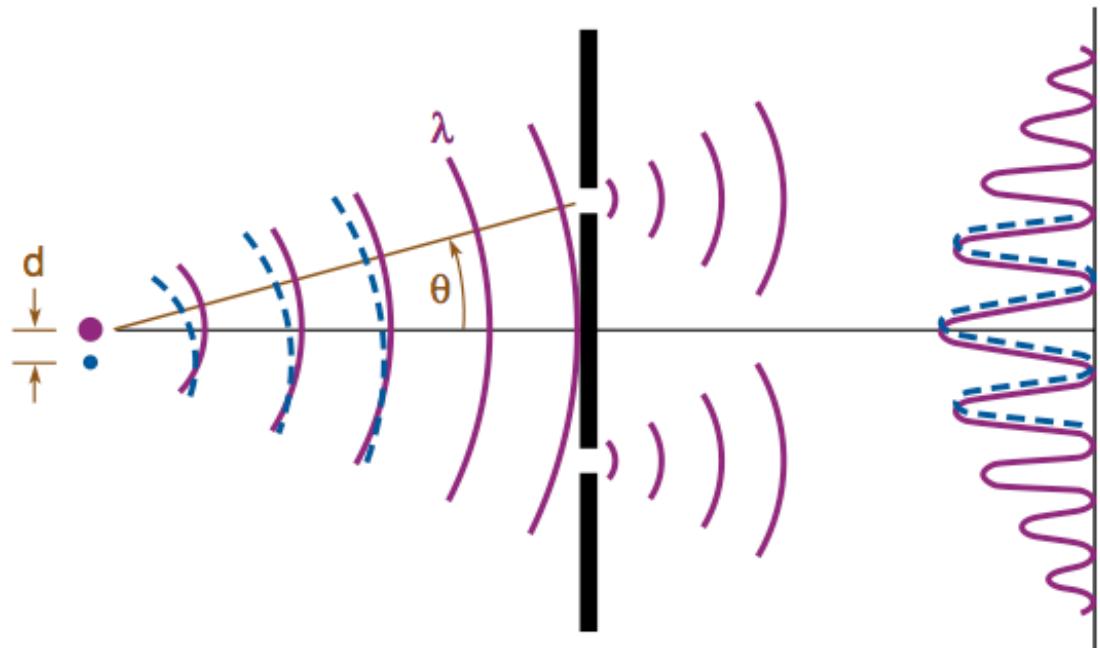
# „Tesafilm“ Röntgenquelle



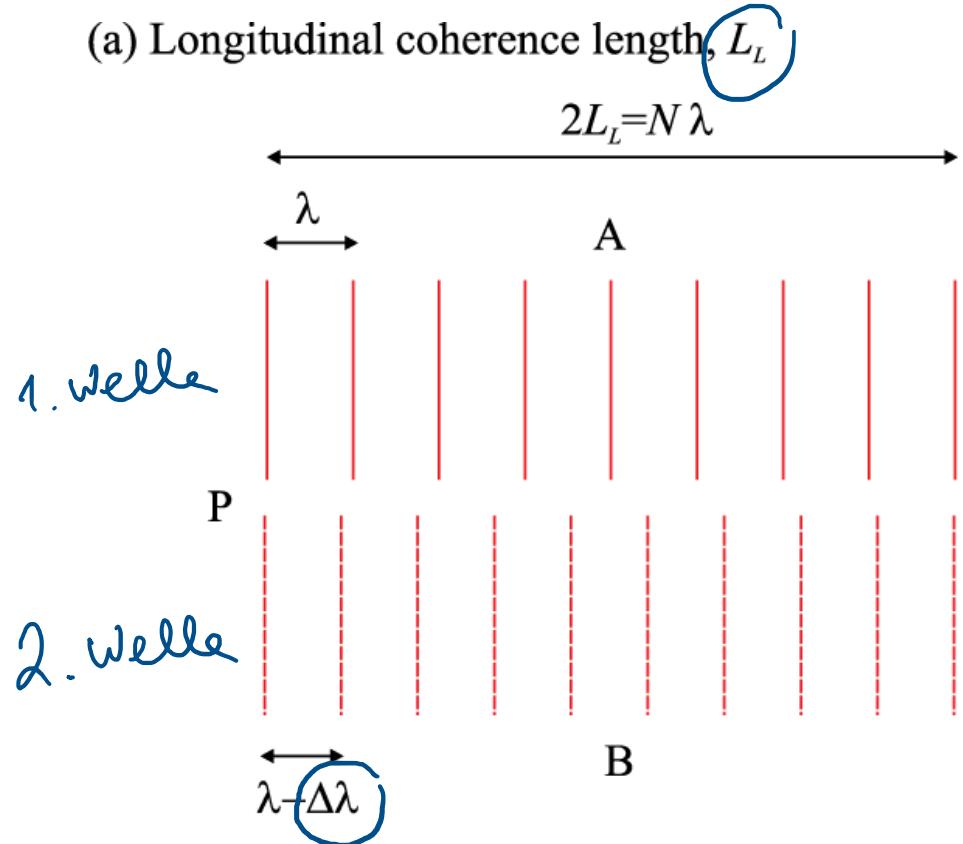
Camara, C. G., Escobar, J. V., Hird, J. R. & Puttermann, S. J. Correlation between nanosecond X-ray flashes and stick-slip friction in peeling tape. *Nature* 455, 1089–1092 (2008).

2 Fälle

- 1) longitudinale Kohärenz  $\rightarrow$  verschiedene Wellenlängen
- 2) transversale Kohärenz  $\rightarrow$  unterschiedliche Ausbreitungsrichtungen



# Longitudinale Kohärenz



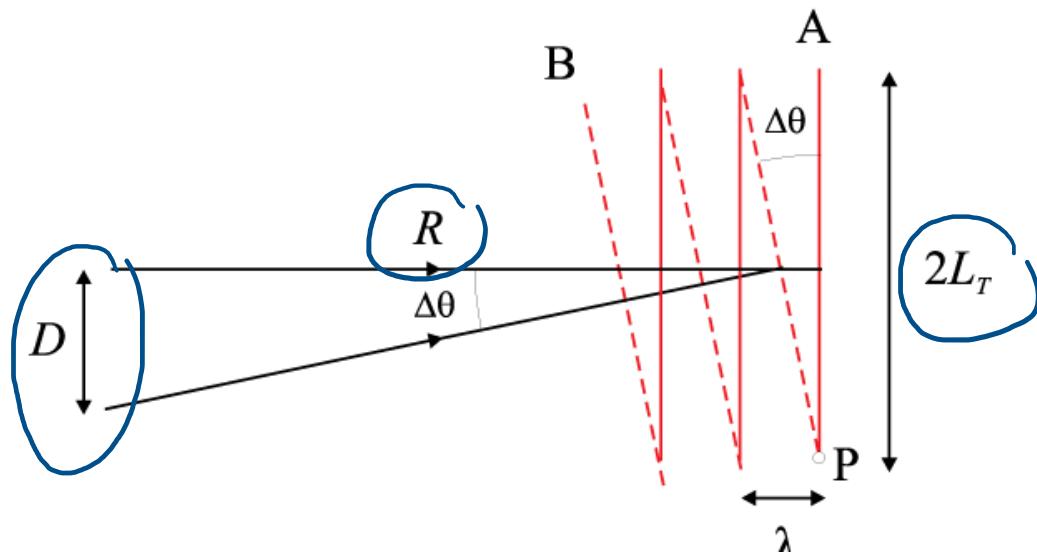
$$L_L = \frac{\pi^2}{2 \Delta x}$$

typische Kohärenzlängen

$$\sim 10^{-6} \text{ m}$$

Als-Nielsen Fig. 1.14

(b) Transverse coherence length,  $L_t$



$$L_t = \frac{\lambda}{2} \frac{R}{D}$$

typische Werte

$\sim 10 - 100 \mu\text{m}$

Als-Nielsen Fig. 1.14

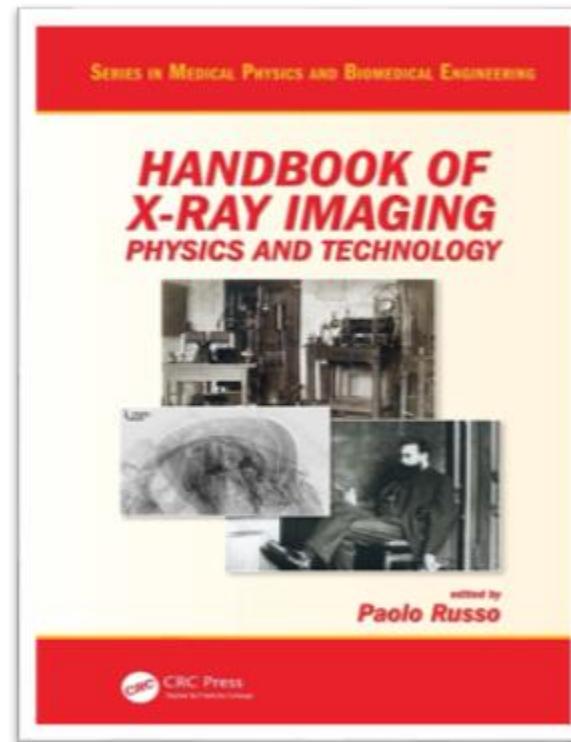
# Inhalt - hochauflösende Bildgebung

## Teil I: Röntgenquellen

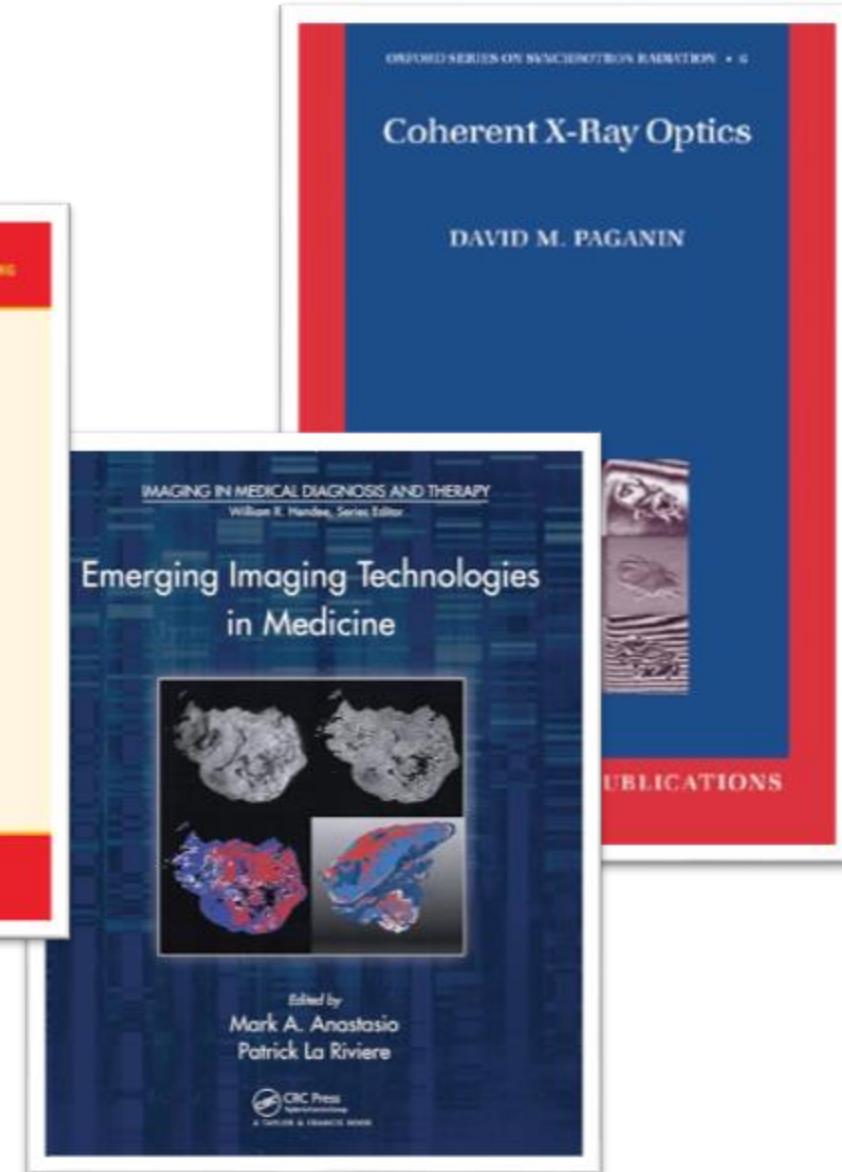
- Synchrotronquellen
- Sonstige Röntgenquellen
- Kohärenz

## Teil II: Phasenkontrast Bildgebung

- Grundlagen
- Verschiedene Methoden
- Anwendungen



no access over TUM -  
upload to Moodle



# Thema Phasenkontrast Bildgebung

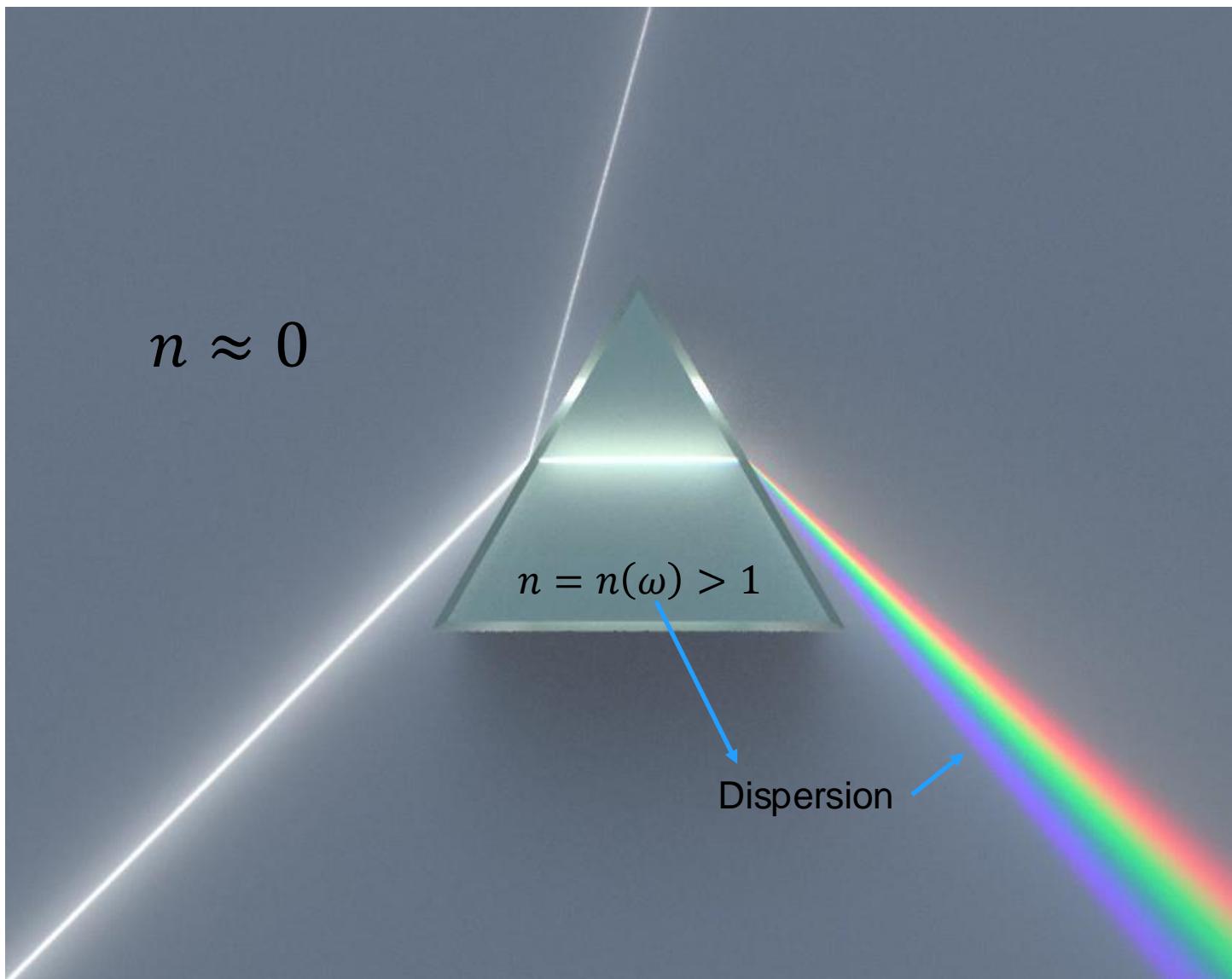
Fragen, die Sie am Ende jeder behandelten Methode beantworten können sollten:

- Was erzeugt den Kontrast?
- Welche Anforderungen an die Röntgenquelle gelten für die verschiedenen Methoden?

ausführlichere Behandlung in folgenden Vorlesungen im Master:

- Biomedical Physics I+II (Prof. Pfeiffer/Prof. Wilkens)
- Modern X-ray Physics (Dr. Achterhold/Dr. Dierolf)
- Image Processing in Physics (Prof. Herzen/Dr. Achterhold)
- Quantitative Bildgebung (Prof. Herzen)

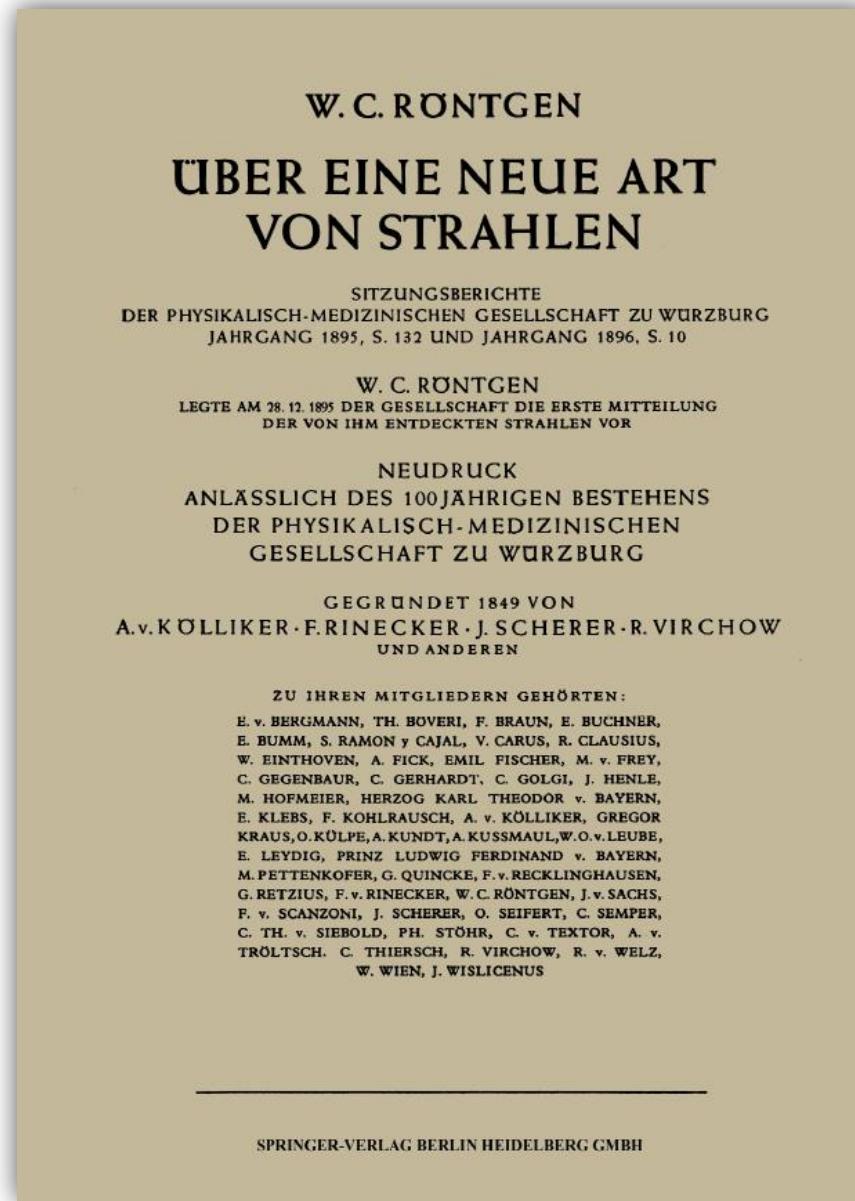
# Brechung vom sichtbaren Licht



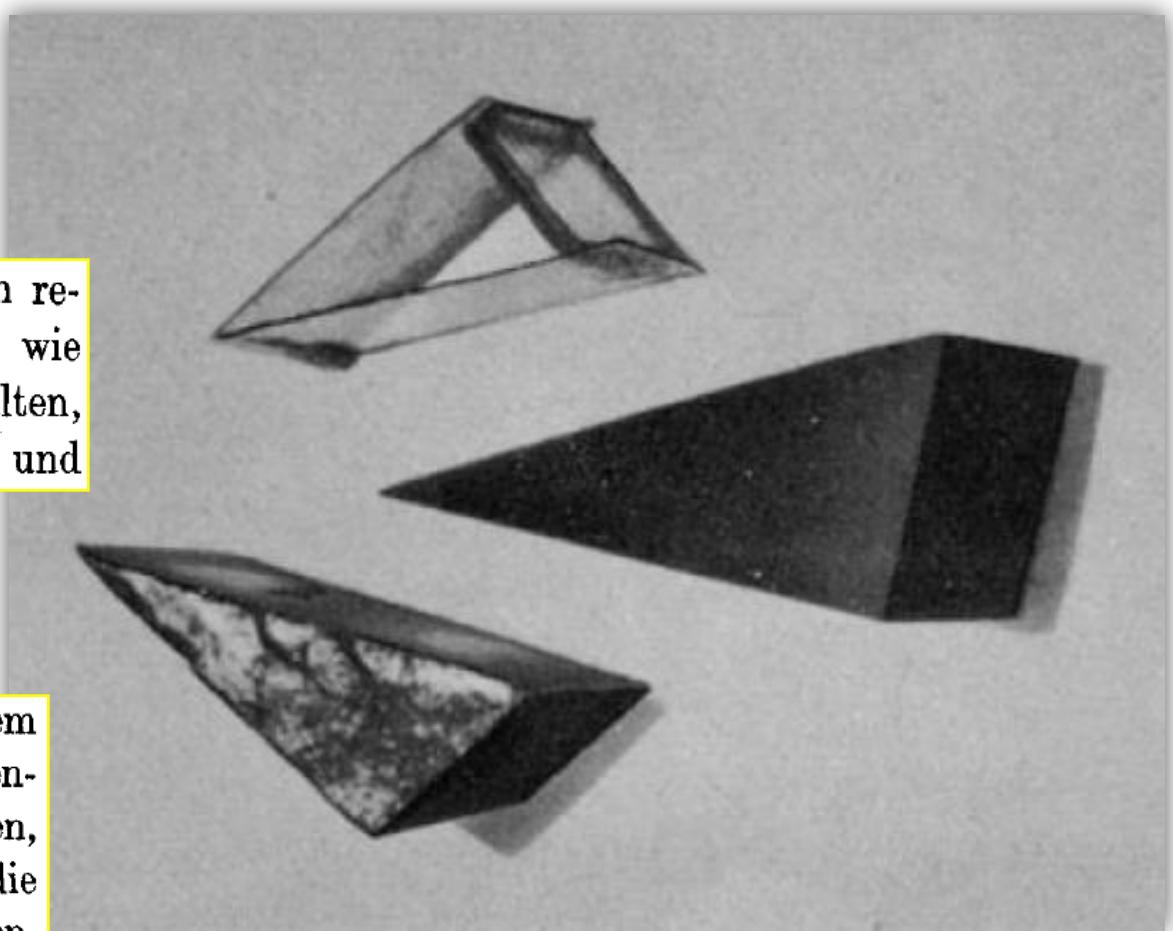
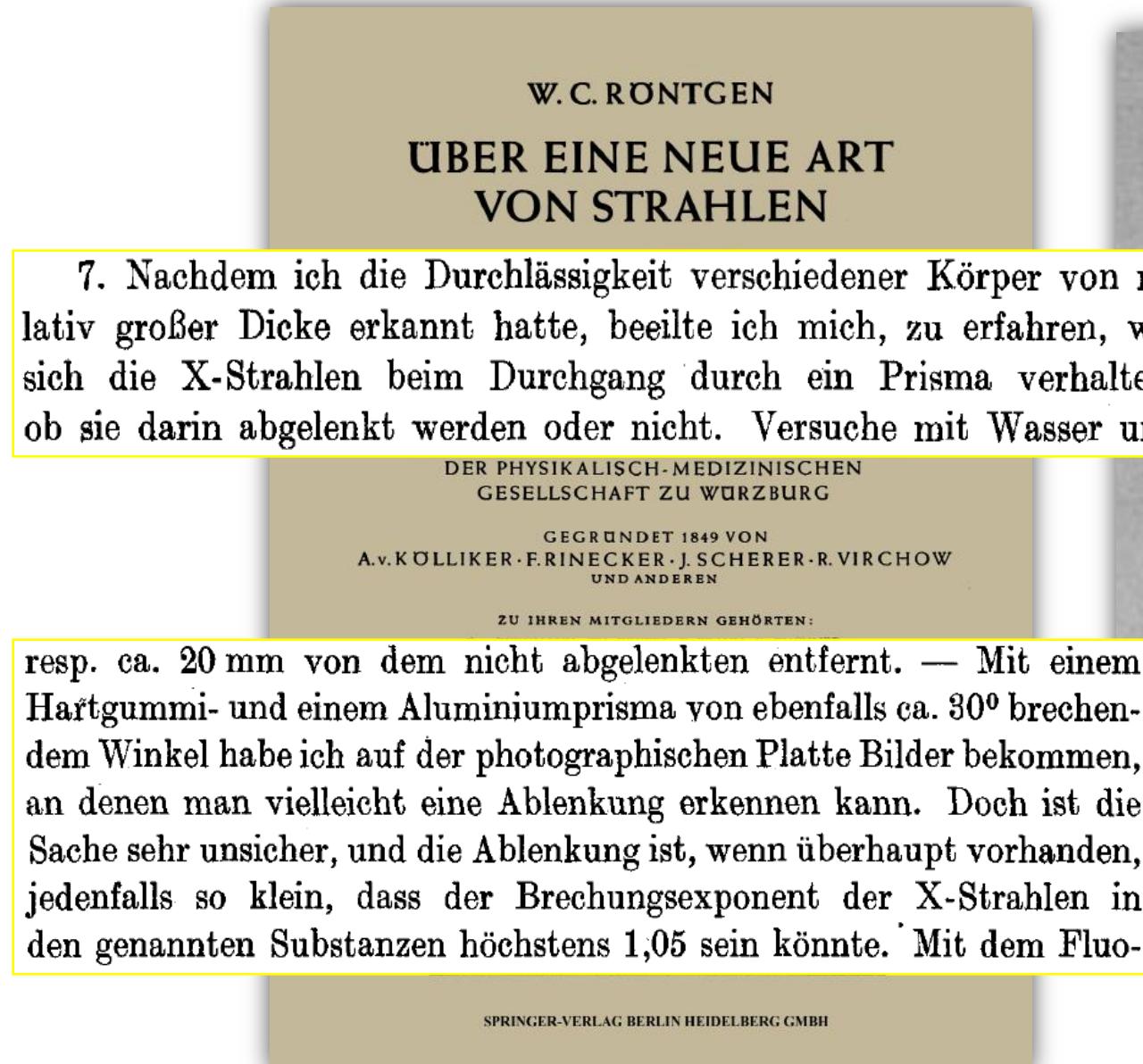
# 1895: Entdeckung der Röntgenstrahlen



Wilhelm Conrad Röntgen  
Nobel Prize 1901



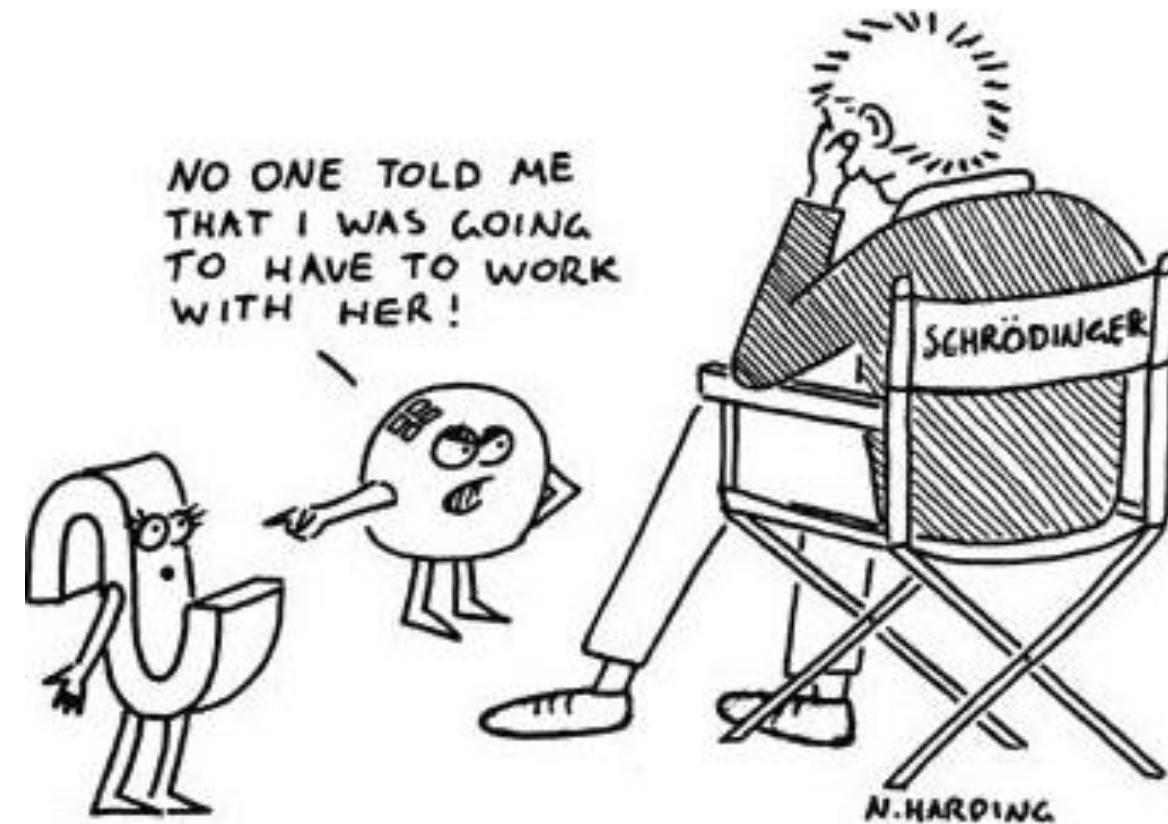
# 1895: Suche nach Brechung



# 1906: Röntgenstrahlen als Wellen

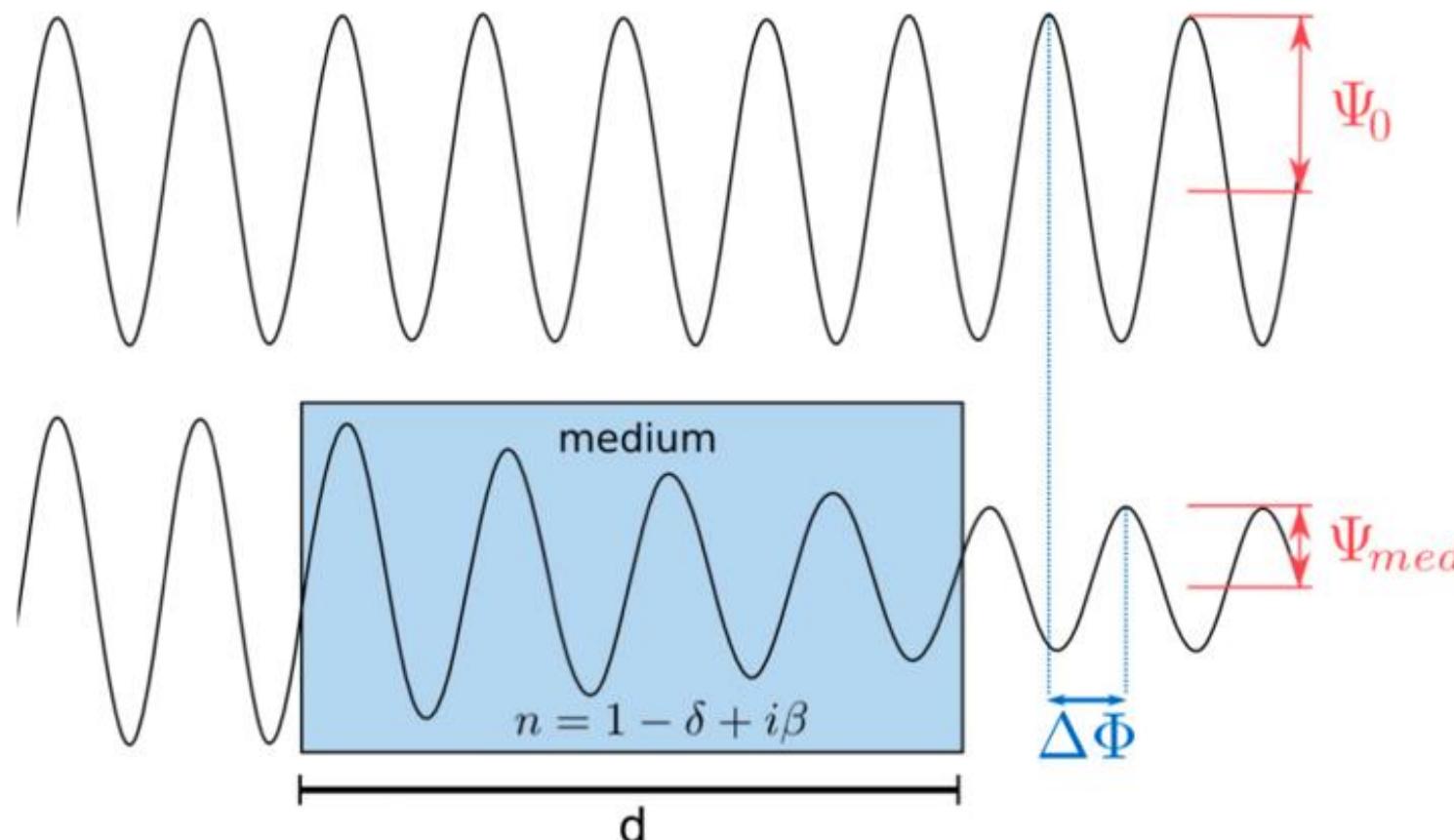


Charles Glover Barkla  
Nobel Prize 1917  
Discovery of the characteristic  
X-ray radiation of the elements



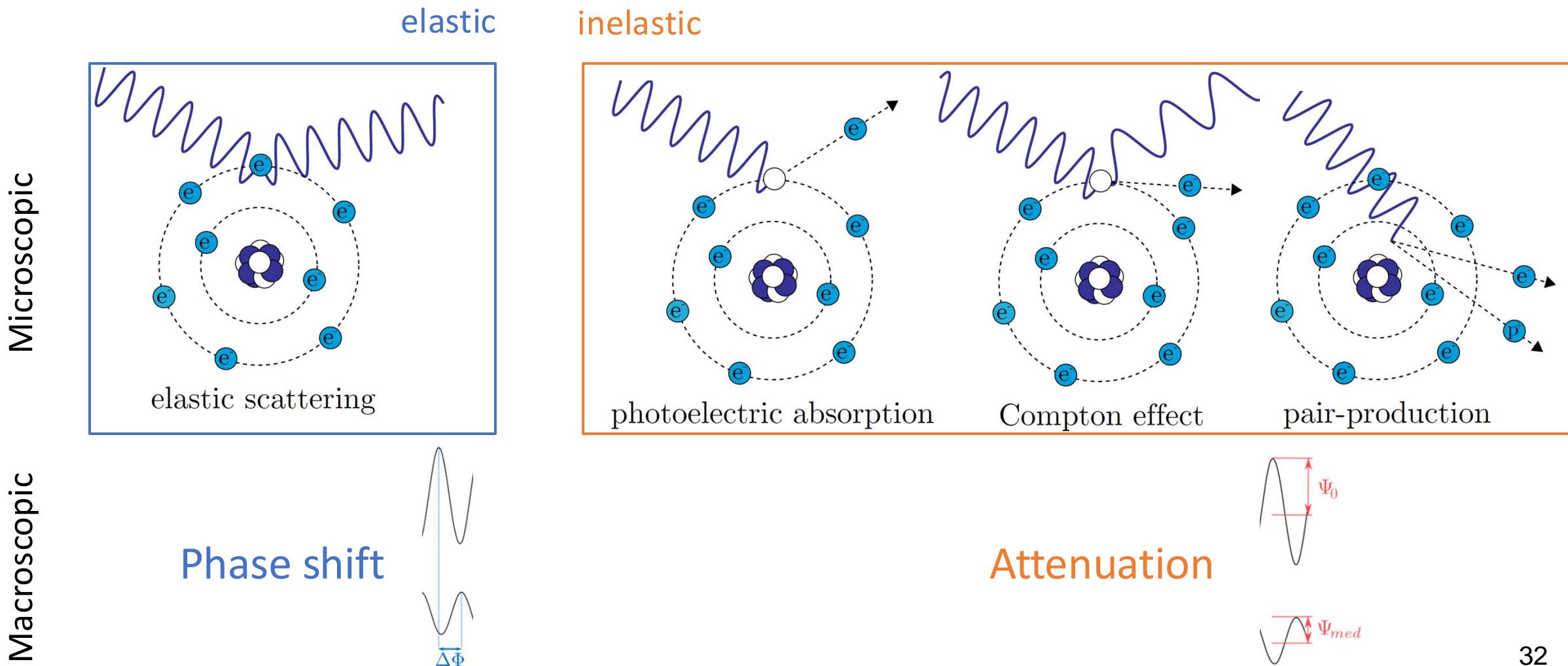
# Röntgenstrahlen als Welle

$$\Psi(\vec{r}, t) = \Psi_0 e^{i(\vec{k} \cdot \vec{r} - \omega t)}$$



# Brechnungsindex

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



# Brechungsindex

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

phase shift attenuation

$$\delta = \frac{2\pi\rho r_0}{k^2}$$

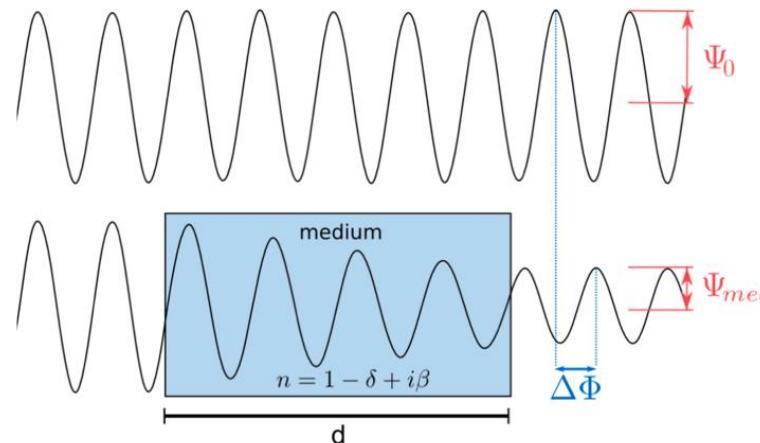
$$\mu = \frac{4\pi}{\lambda}\beta$$

- $\delta \propto$  electron density
- $\delta \propto E^{-2}$
- $\mu \propto Z^{3-4}$
- $\mu \propto E^{-3}$
- Lambert-Beer law:

$$I(d) = I_0 \exp(-\mu d)$$

# Röntgenstrahlen als Welle

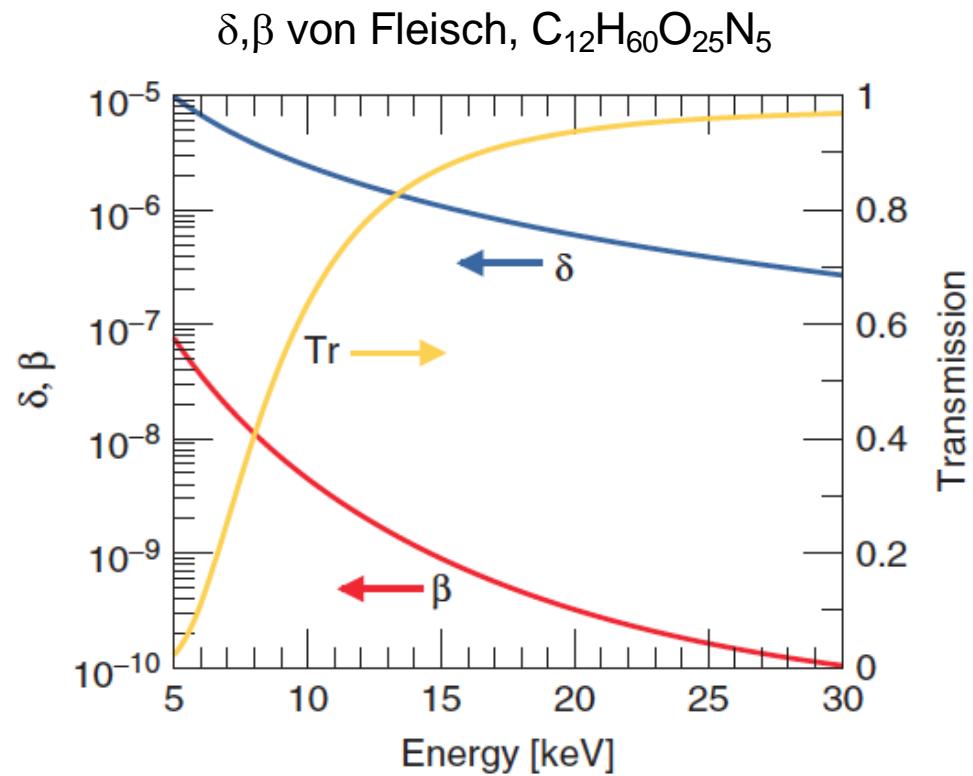
$$\Psi(\vec{r}, t) = \Psi_0 e^{i(\vec{k} \cdot \vec{r} - \omega t)}$$



$$\begin{aligned}\Psi_m(z, t) &= \Psi_0 e^{i(nkz - \omega t)} = \Psi_0 e^{-i\omega t} e^{(1-\delta)ikz} e^{-\beta kz} \\ &= \underbrace{\Psi_v(z, t)}_{\text{[phase-shift]}} \cdot \underbrace{e^{-i\delta kz}}_{\text{[attenuation]}} \cdot \underbrace{e^{-\beta kz}}_{\text{[attenuation]}}\end{aligned}$$

Aber: Wir können nur Intensitäten messen  $I = |\Psi|^2$

# Phasenkontrast



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

Willmott, Fig. 7.10

Bei hohen Energien weniger Absorption (geringere Dosis)  
und WW-Querschnitt für Phasenschub  $\sim 1000$  mal größer



Konventionelles  
MicroCT

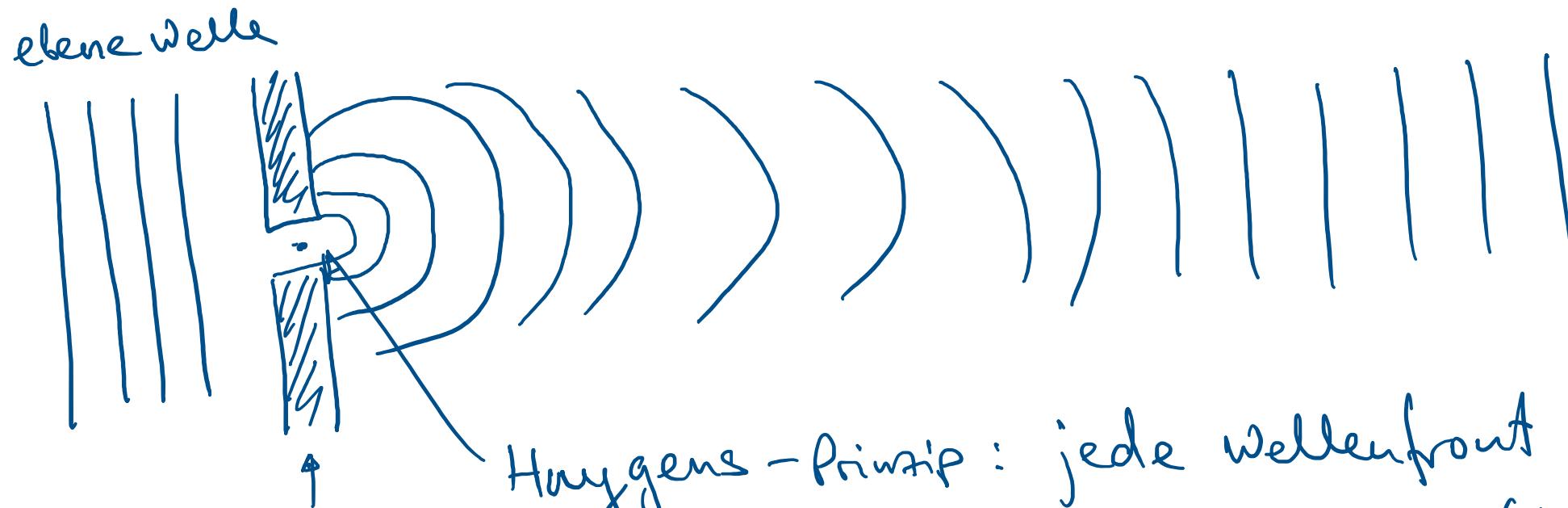


Phasenkontrast  
MicroCT



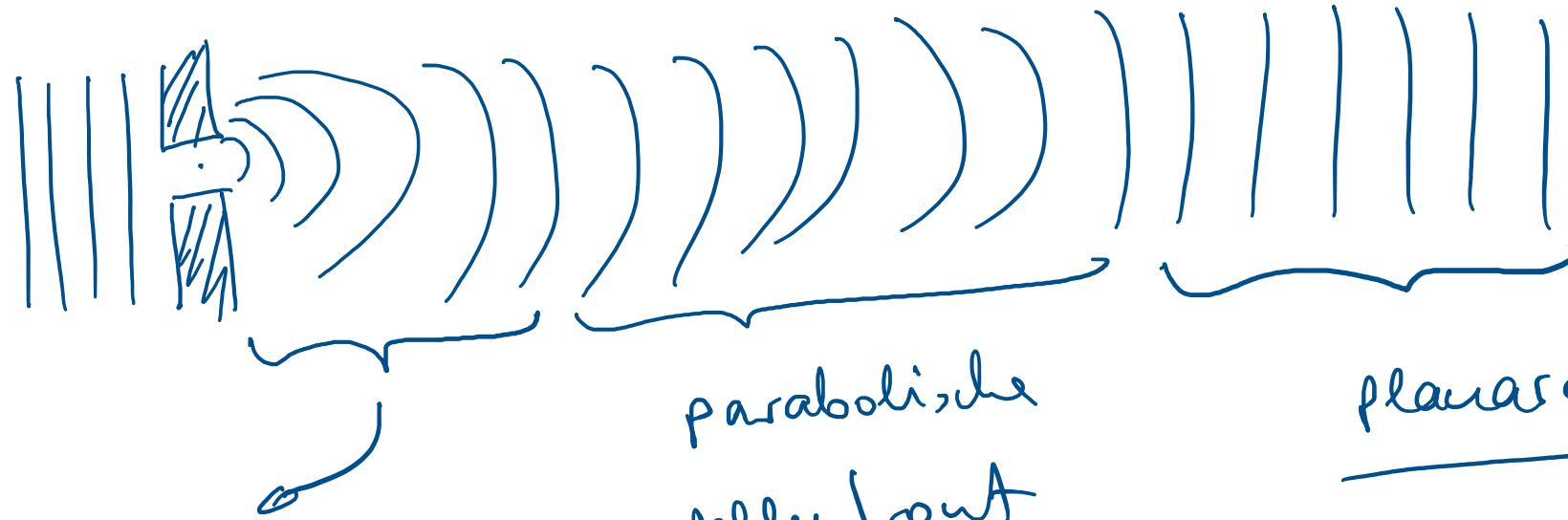
A. Tapfer and F. Pfeiffer *et al.*, „X-Ray Phase-Contrast CT of a Pancreatic Ductal Adenocarcinoma Mouse Model“, PLoS ONE 8, (2013).

## Propagation einer Welle



Huygens - Prinzip: jede Wellenfront setzt sich zusammen aus einer kohärenten Überlagerung von sphärischen Wellen

# Röntgenlicht als Welle



sphärische  
Wellenfront

parabolische  
Wellenfront

planare Wellen

Paraxial - Näherung  $\Rightarrow$  planare  
Wellen haben nur Komponenten  
mit einem sehr kleinen  
Winkel zur Ausbreitungsachse

$\alpha_z$  - sehr klein

Nahfeld (Fresnel Regime) und Fernfeld (Fraunhofer Regime)

$z_0$  - Propagationstestant

$b$  - die kleinste Struktur im Objekt

Fresnel Nummer

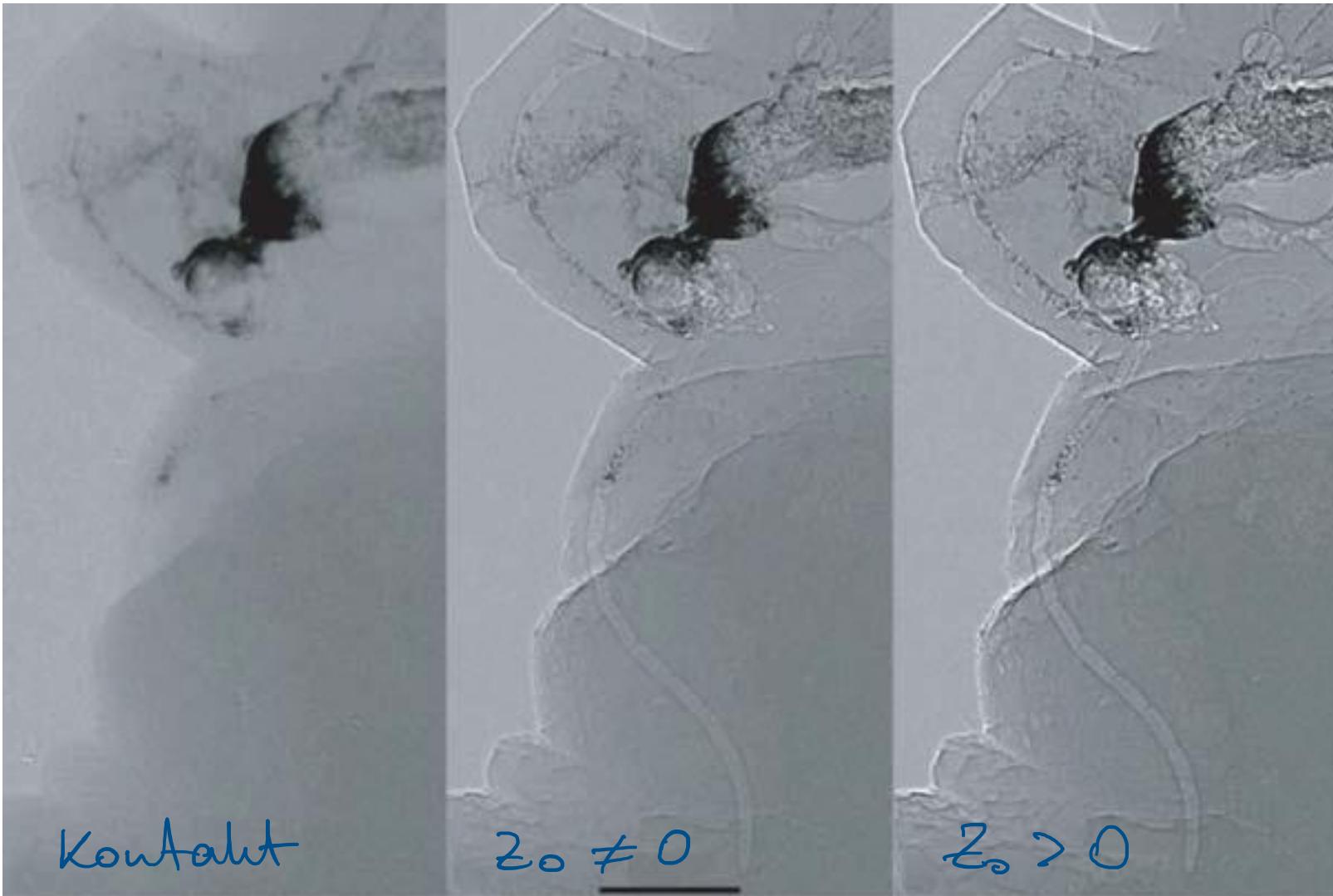
(zur Unterscheidung des Regimes)

$$N_F = \frac{b^2}{\lambda z_0}$$

1)  $z_0 \approx \frac{b^2}{\lambda} \rightarrow$  Fresnel Regime (Nahfeld)

2)  $z_0 \gg \frac{b^2}{\lambda} \rightarrow$  Fraunhofer Regime (Fernfeld)

# Beispiel Kantenverstärkung



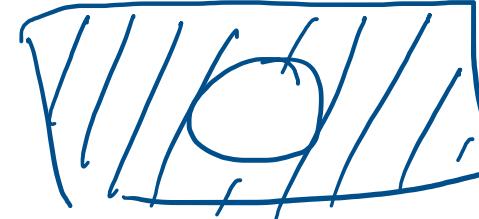
Fresnel - Regime  
Kantenverstärkung  
als Konsequenz  
der Propagation

Willmott, Fig. 7.14



# Beispiel Fraunhofer Regime

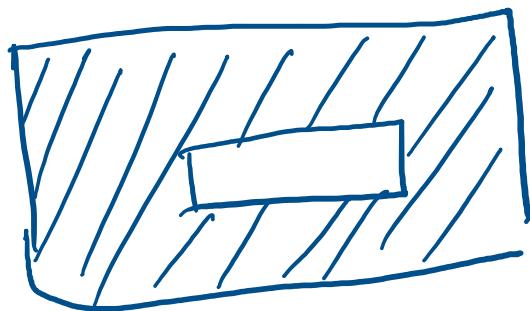
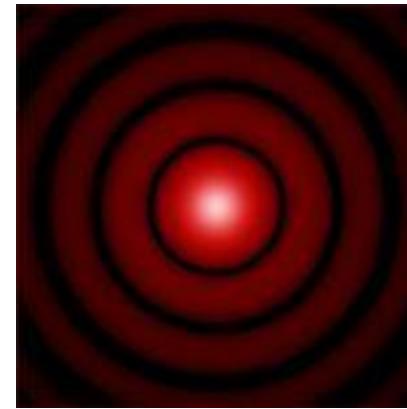
rechteckige Apertur



Source:

[http://upload.wikimedia.org/wikipedia/commons/thumb/1/18/Rectangular\\_diffraction.jpg/200px-Rectangular\\_diffraction.jpg](http://upload.wikimedia.org/wikipedia/commons/thumb/1/18/Rectangular_diffraction.jpg/200px-Rectangular_diffraction.jpg)

rechteckige Apertur

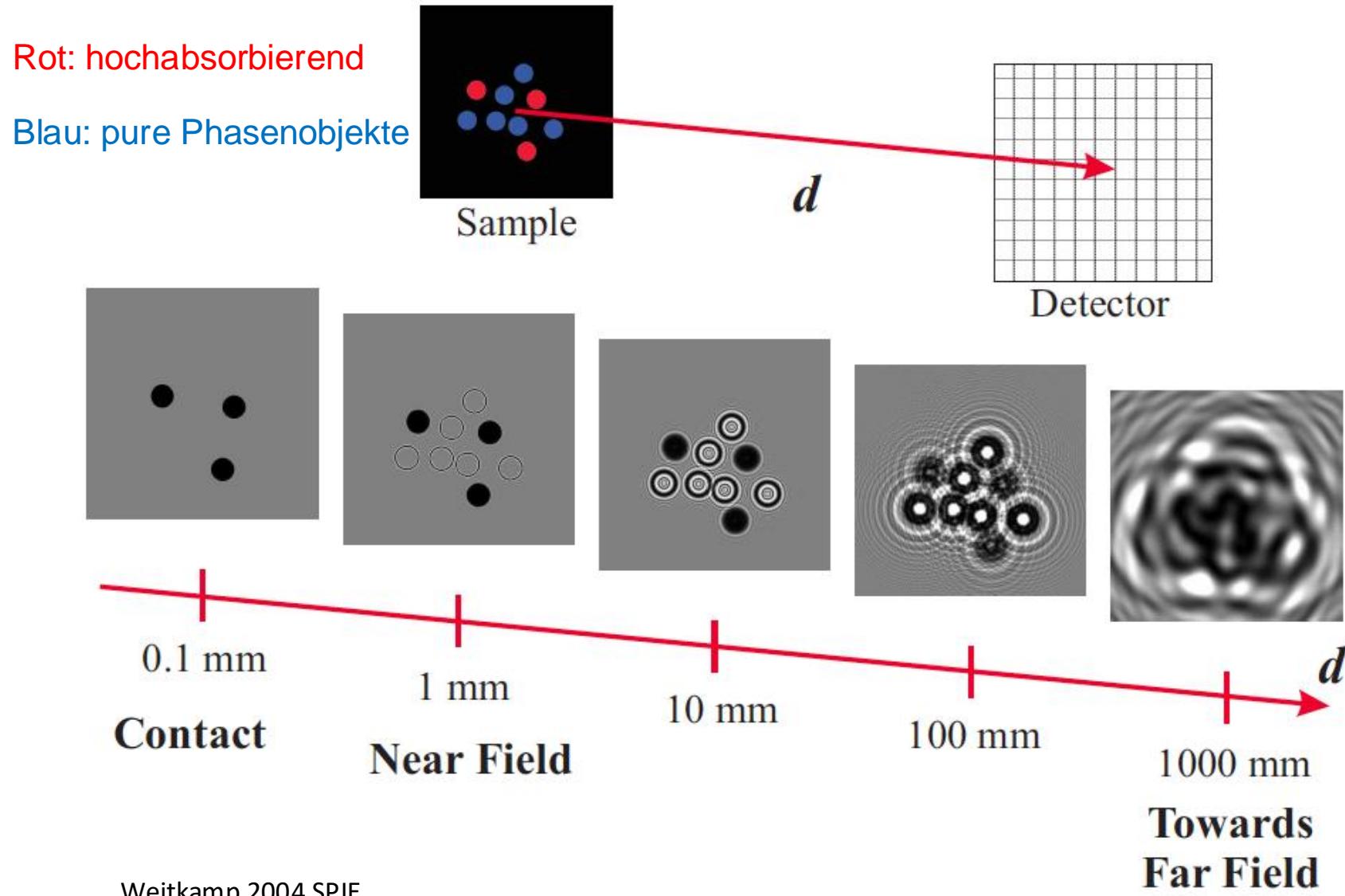


Source:

<http://upload.wikimedia.org/wikipedia/commons/9/96/Airy-pattern2.jpg>

Intensitätsverteilung  $\propto$  Quadrat der Fouriertransformierten des Objekts

# Nahfeld vs. Fernfeld

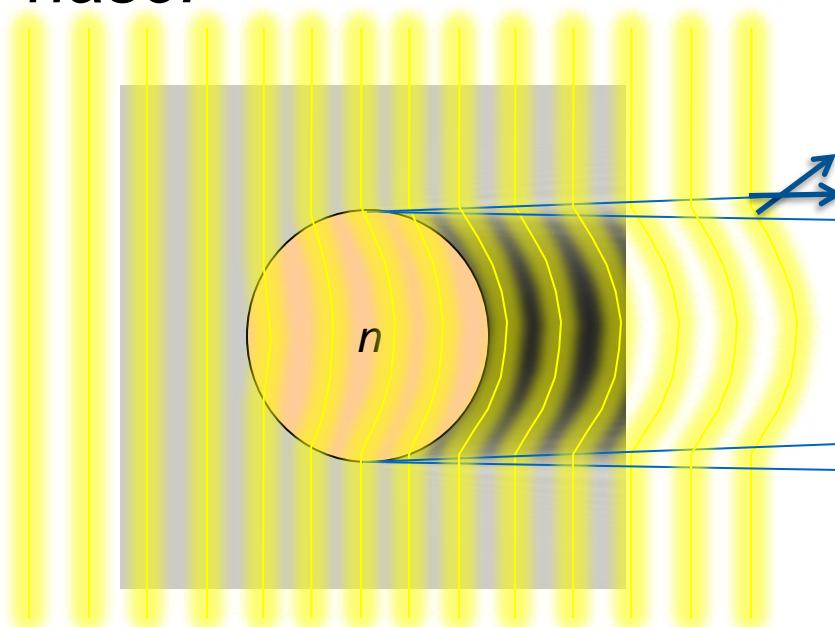


# Phasenkontrast Bildgebung

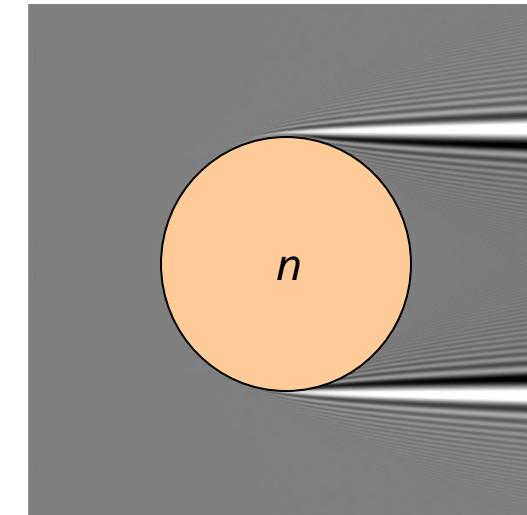
  

## (Bilder im Fresnel Regime (Nahfeld))

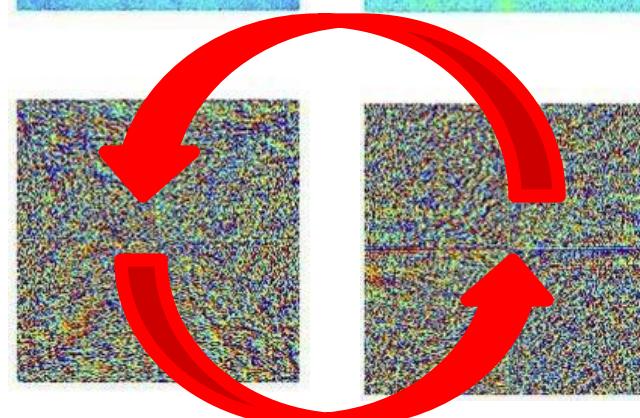
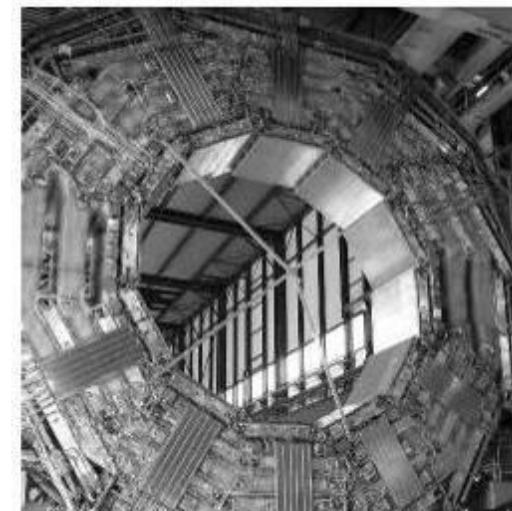
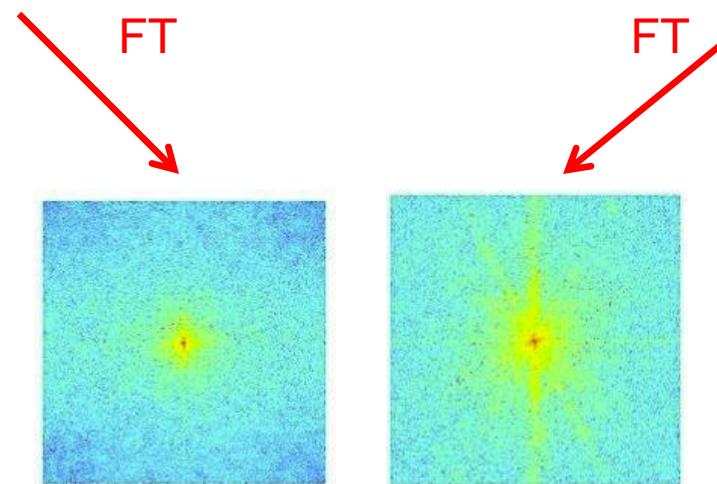
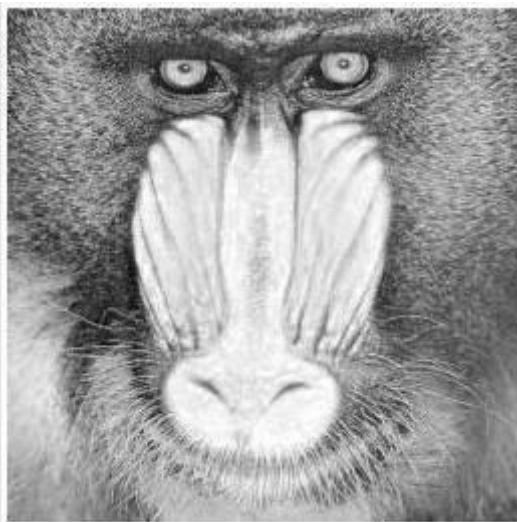
*Phase:*



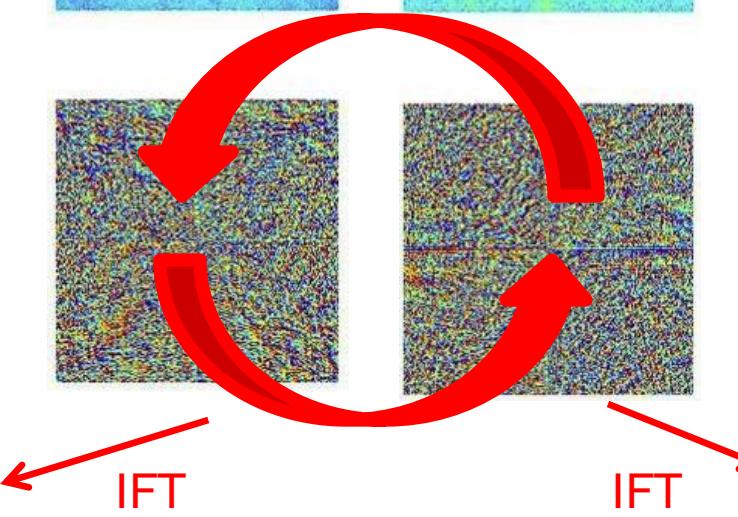
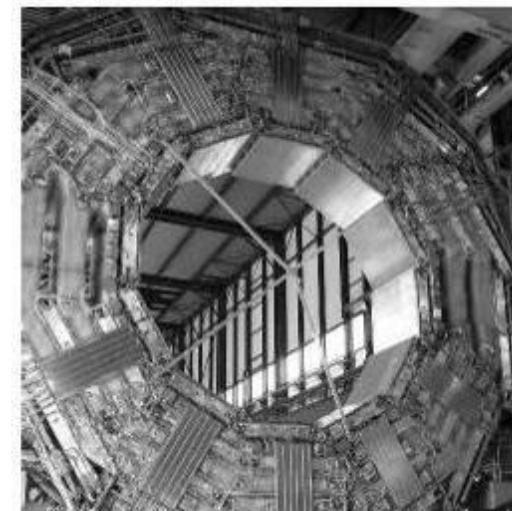
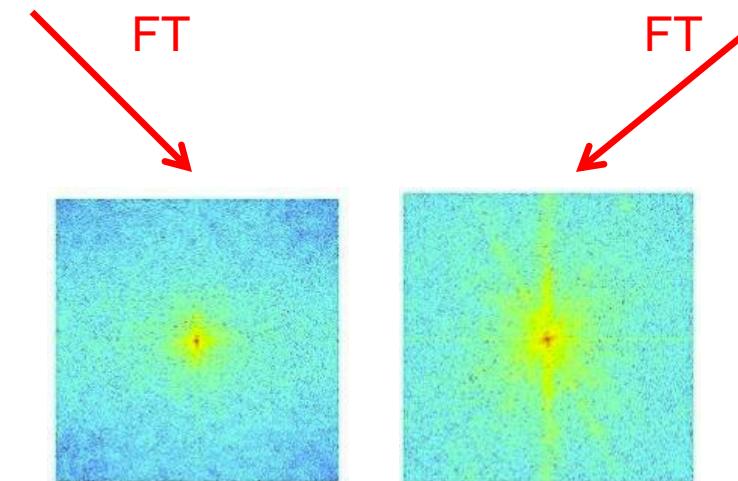
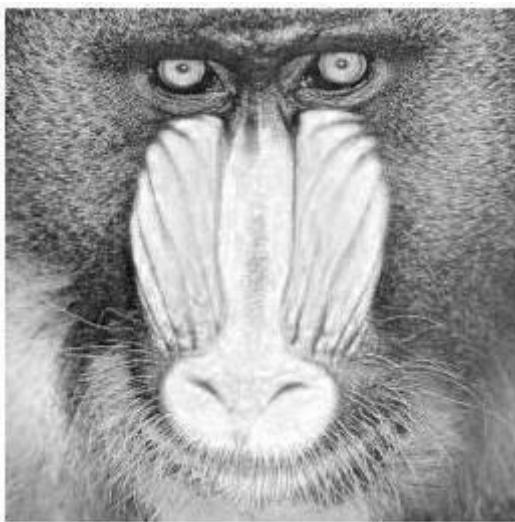
*Intensität:*



# Phasenproblem

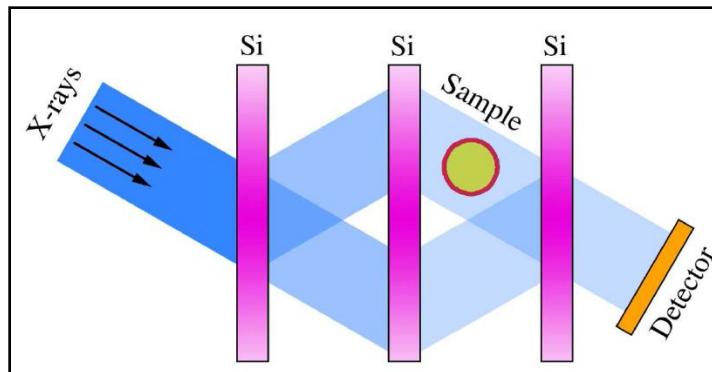


# Phasenproblem



$\Phi$

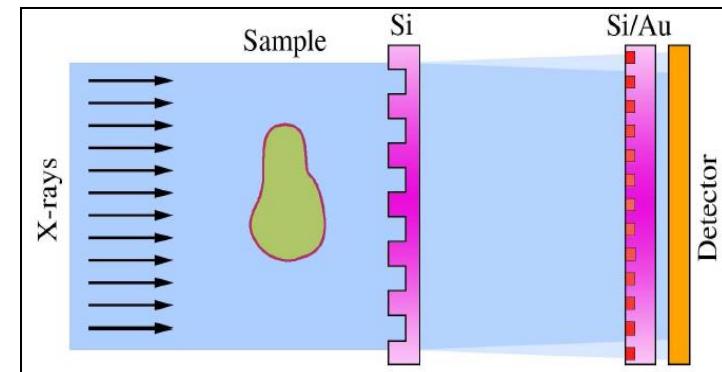
Kristall Interferometer



Bonse & Hart 1965

$d\Phi/dx$

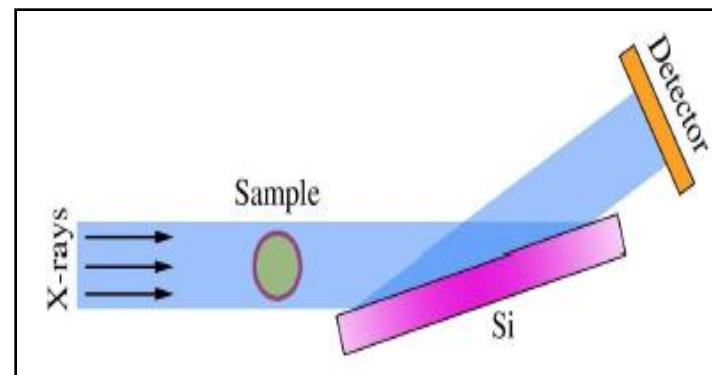
Gitterinterferometer



Momose 2003 & David 2002

$d\Phi/dx$

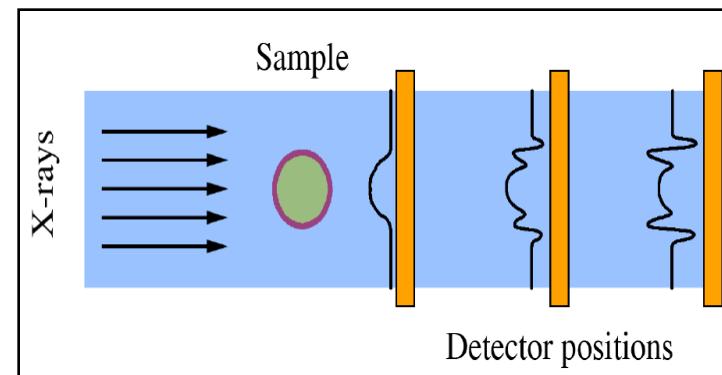
Kristall Analysator



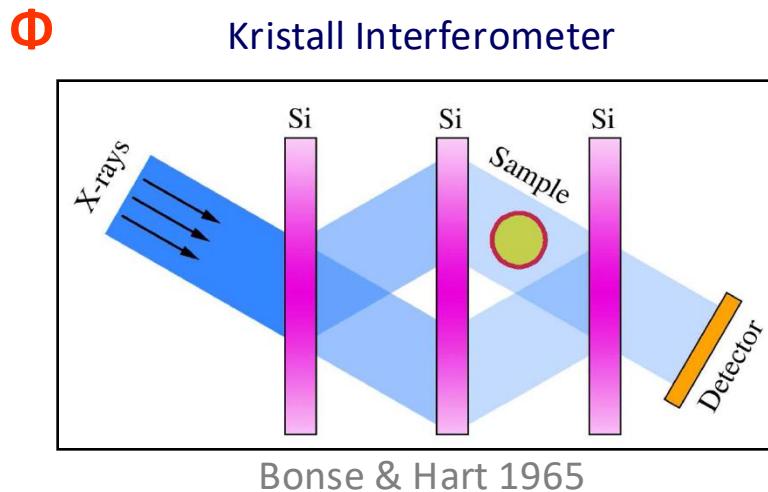
Förster 1980 & Davis 1995

$\Delta\Phi$

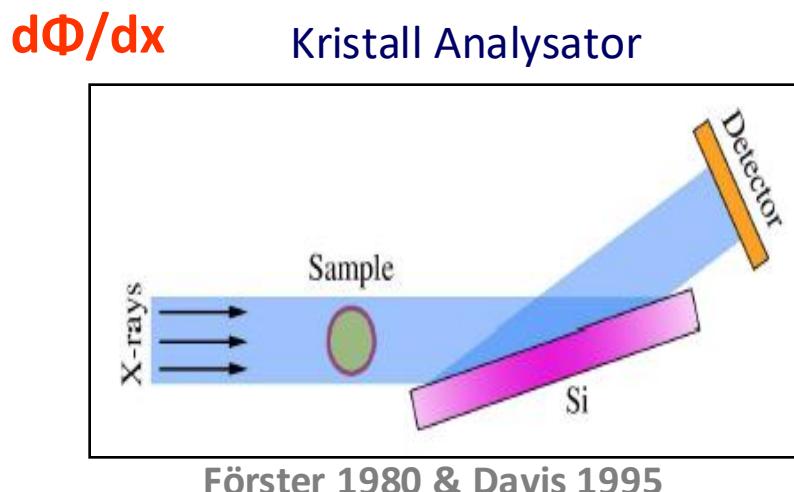
Propagationsbasiert



Snigirev 1995, Cloetens & Wilkens 1996



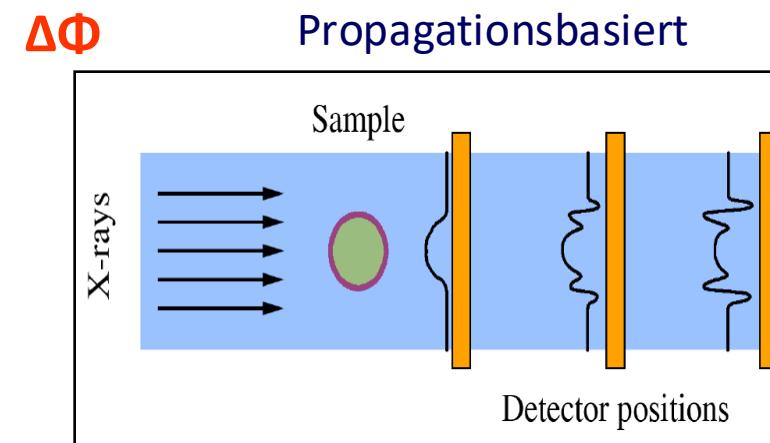
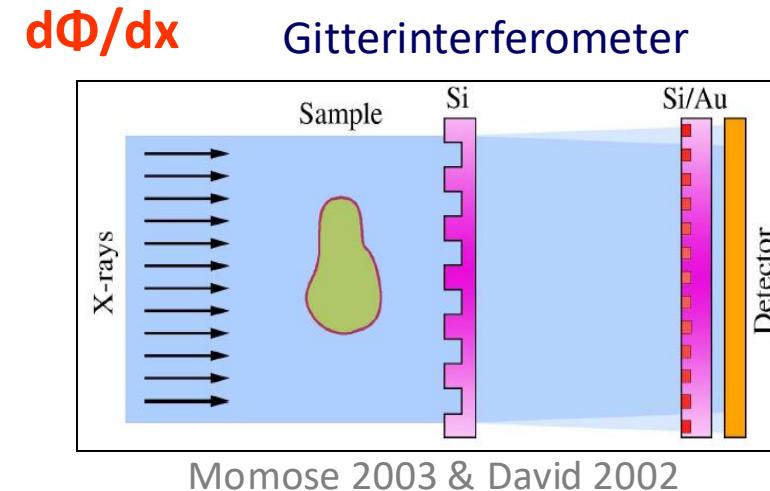
- ++ sehr hohe Sensitivität
- Anforderungen an Ausleuchtung  
sehr hoch
- sehr kleine Objekte, instabil



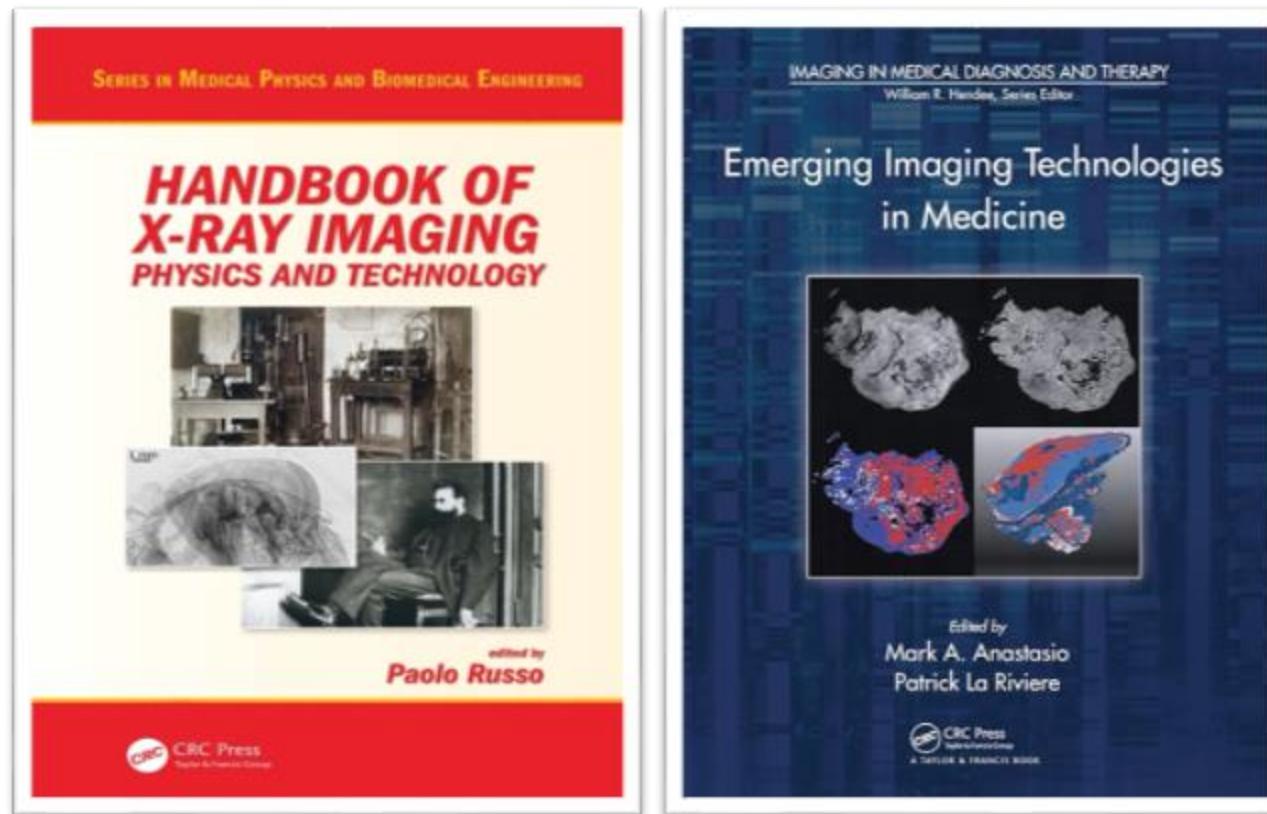
- ++ sehr hohe Sensitivität
- hohe Anforderung an Ausleuchtung
- schwierig quantitative Werte  
zu bekommen → Mix von Signalen  $\beta/\delta$

# Phasenkontrastmethoden

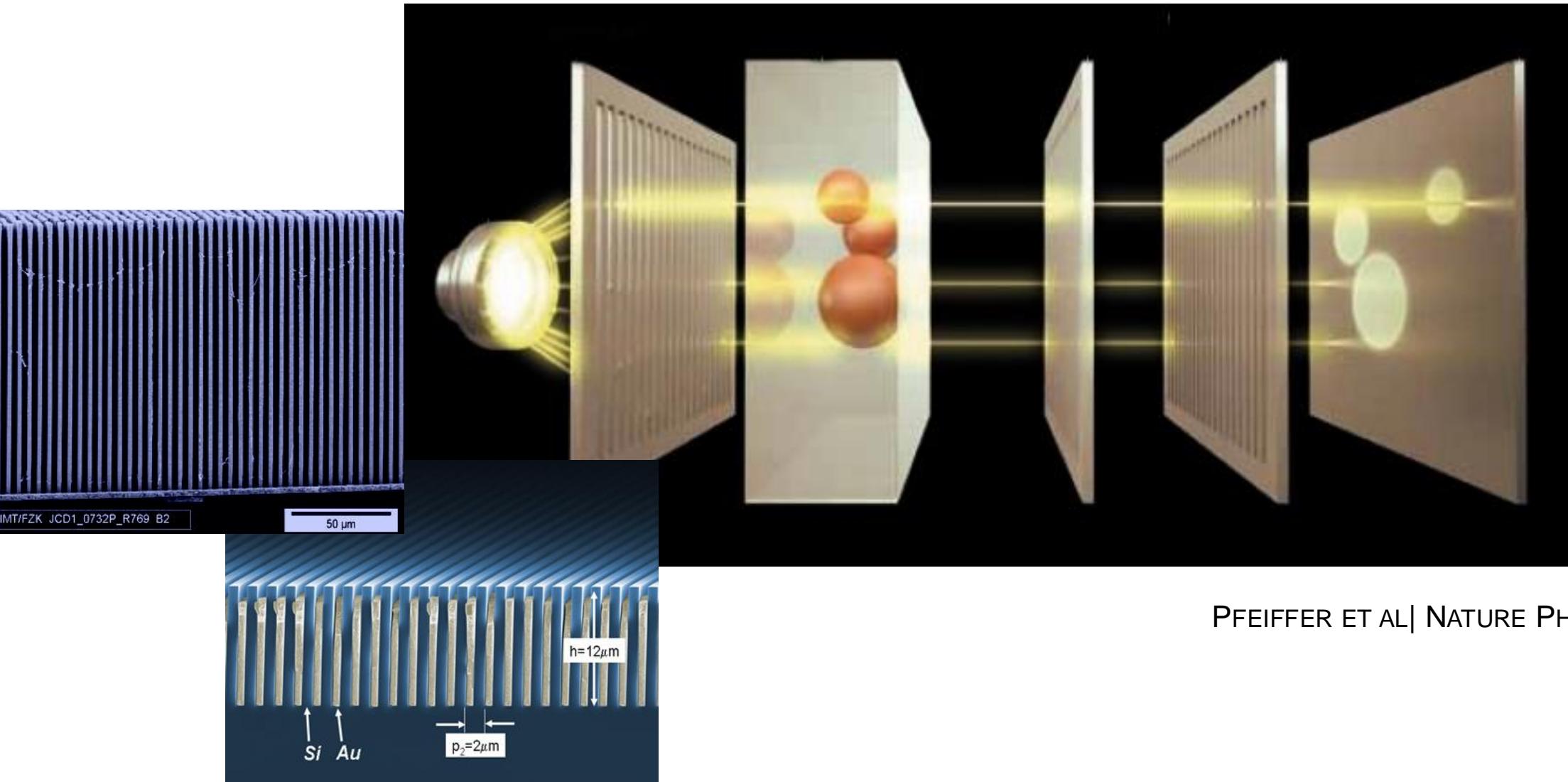
- ++ hohe Sensitivität, robust
- + + polychromatisch, nicht kohärent, divergent
- + + quantitativ, drei Signale
- Auflösung gering
  
- ++ sehr simpel
- ++ sehr hohe Auflösung
- hohe Kohärenz
- nicht quantitativ
- niedrige Sensitivität



# Grating-Based Imaging (GBI)

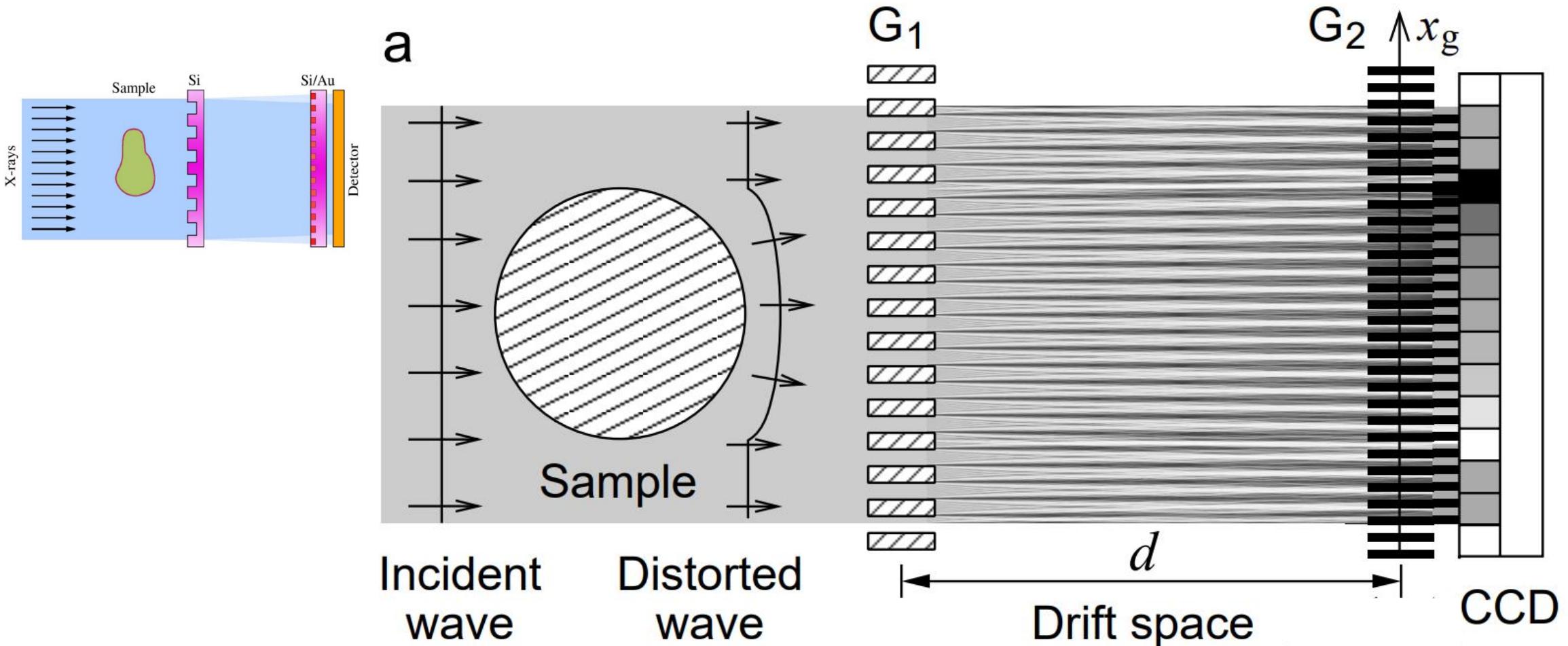


# Röntgen Phasenkontrast mit Gittern



PFEIFFER ET AL | NATURE PHYSICS | 2006

# Grating-Based Imaging - Basic Idea



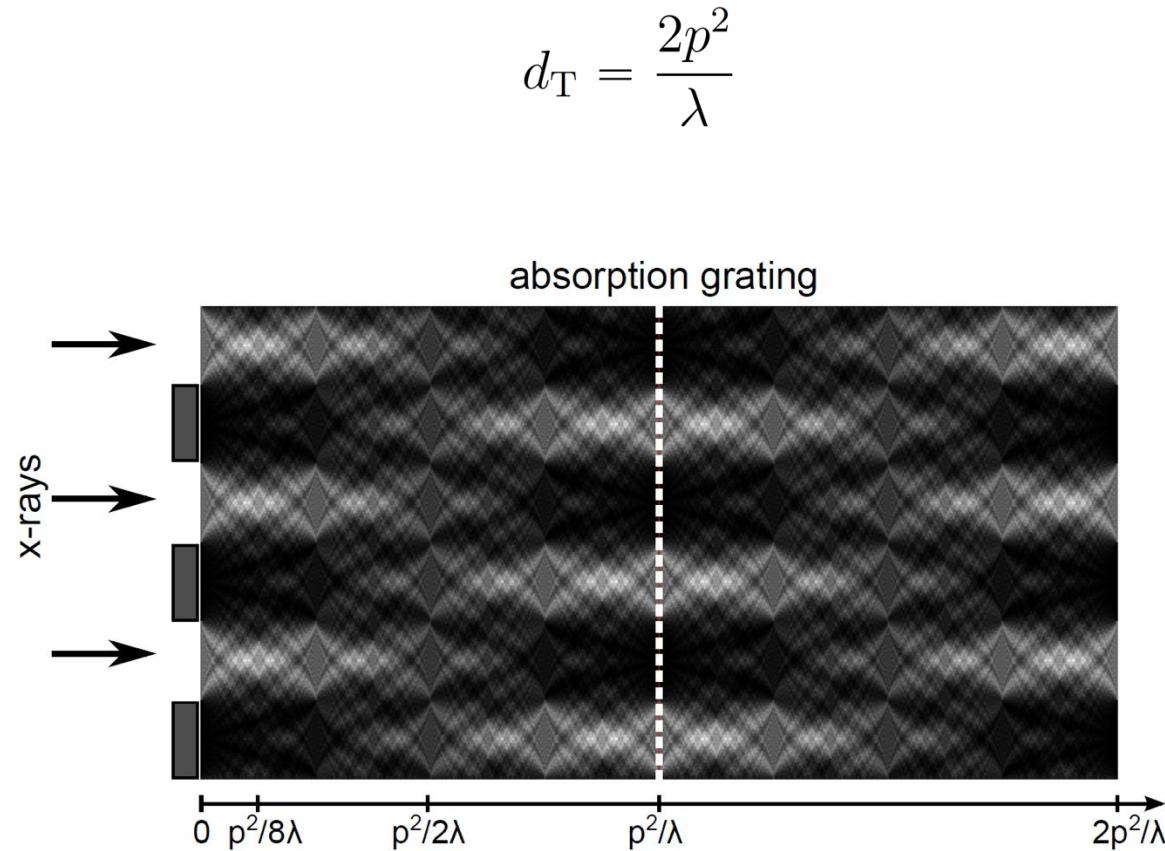
Weitkamp et al | Optics Express | 2005  
Pfeiffer et al | Nature Physics | 2006  
Pfeiffer et al | Nature Materials | 2008

# Talbot Effekt

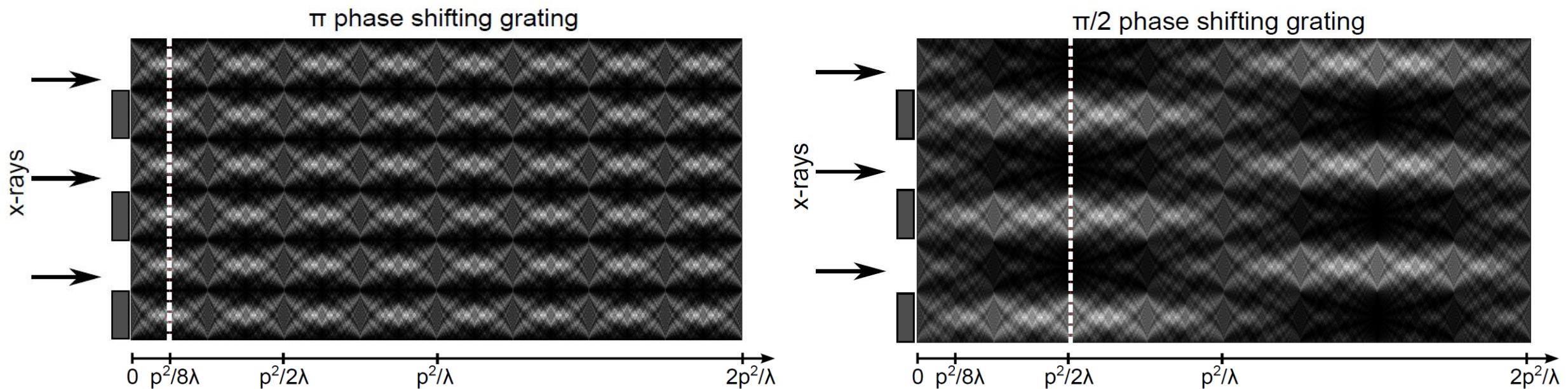
“a periodic wave front will repeat itself at certain distances”



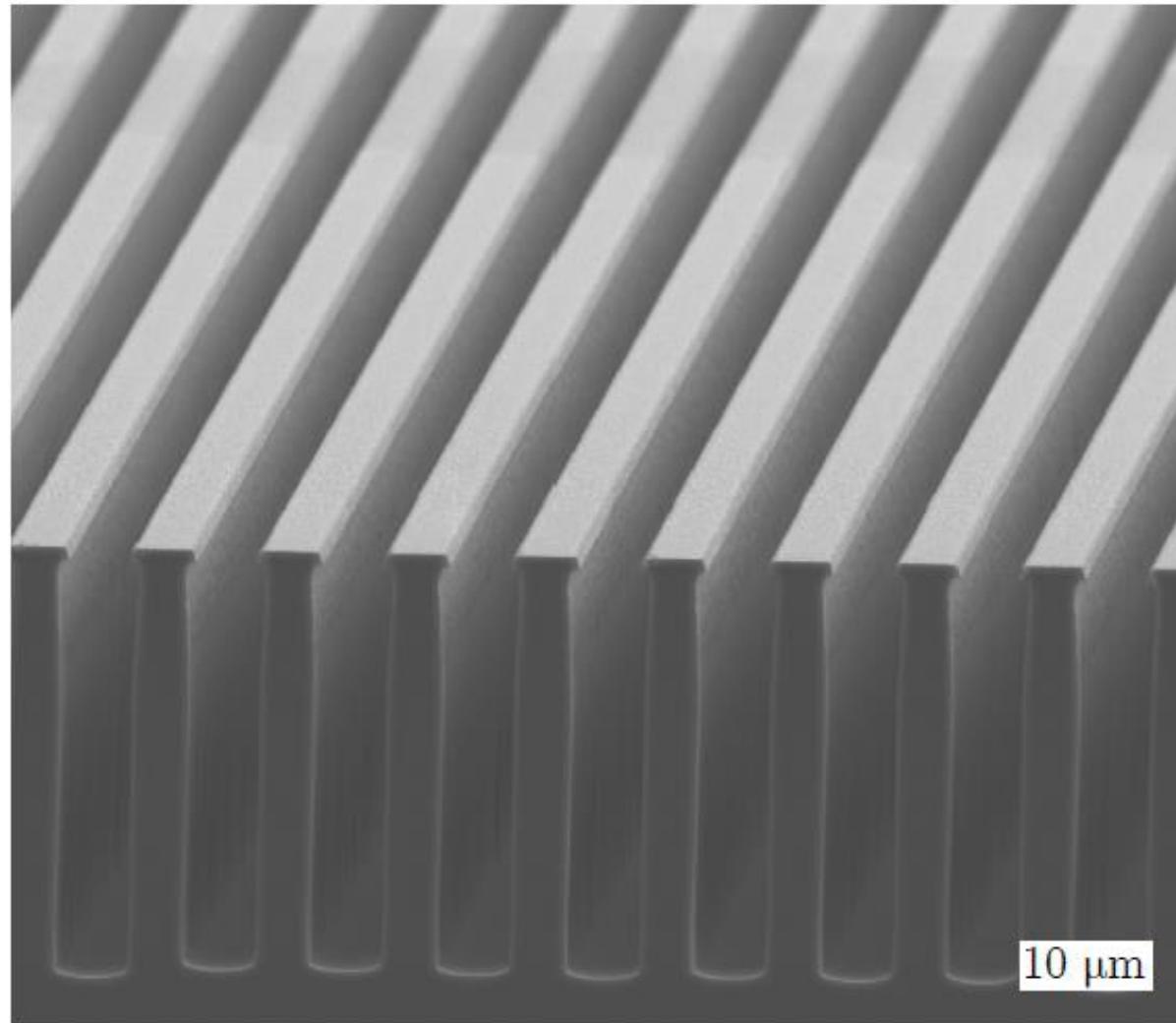
William Henry Fox Talbot 1844 (Inline media)



# Fractional Talbot Effect

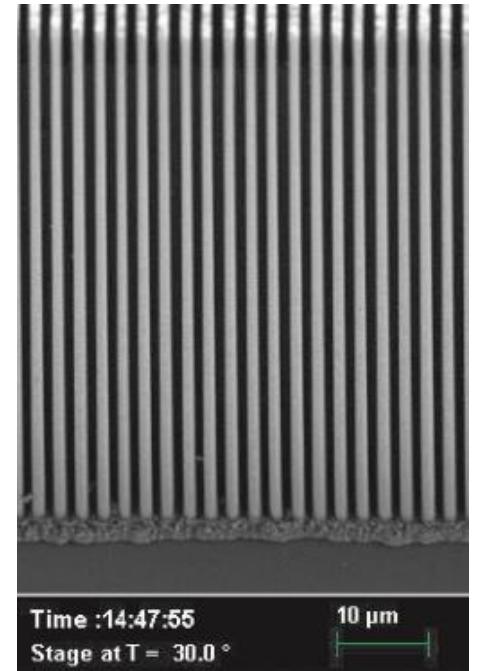
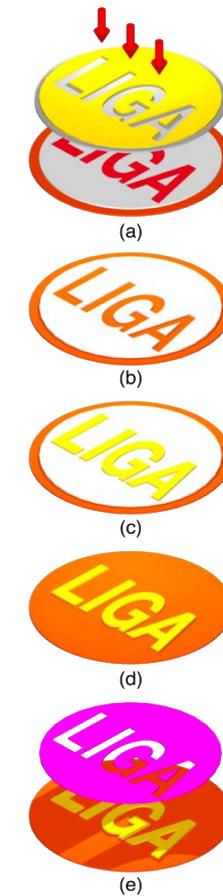
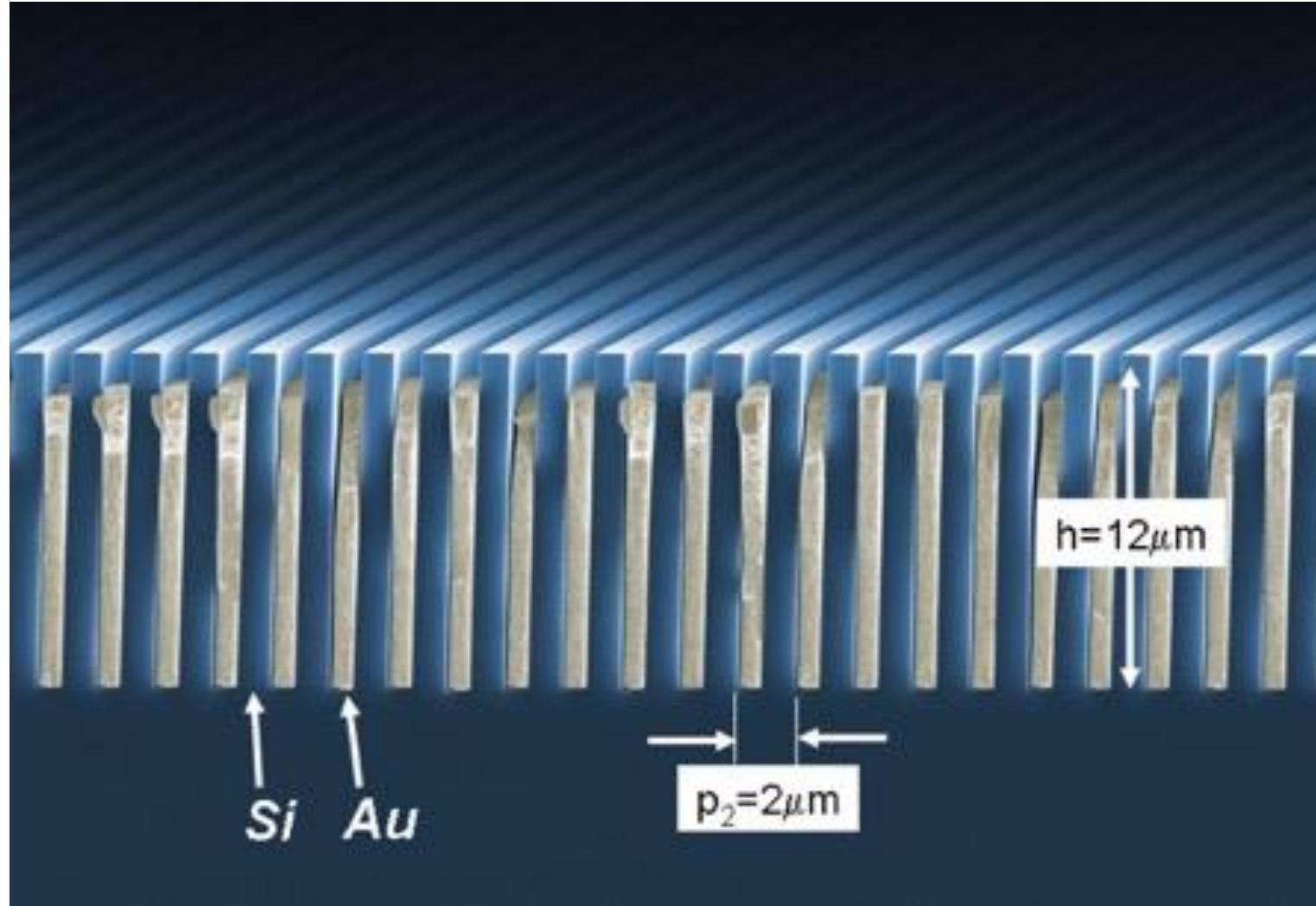


# Phasengitter G1



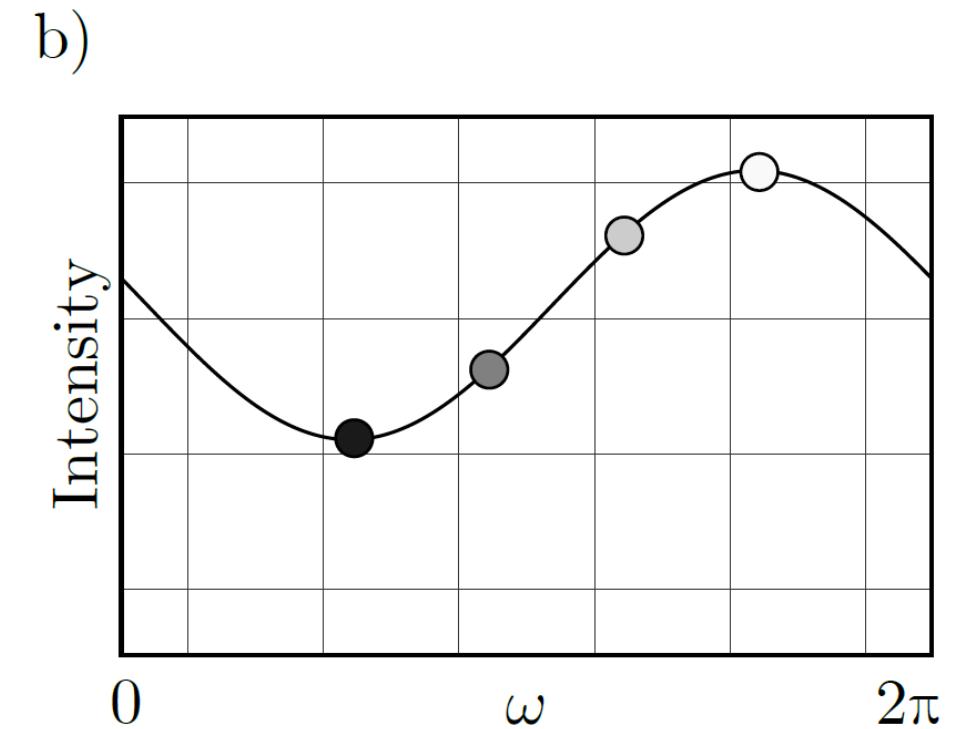
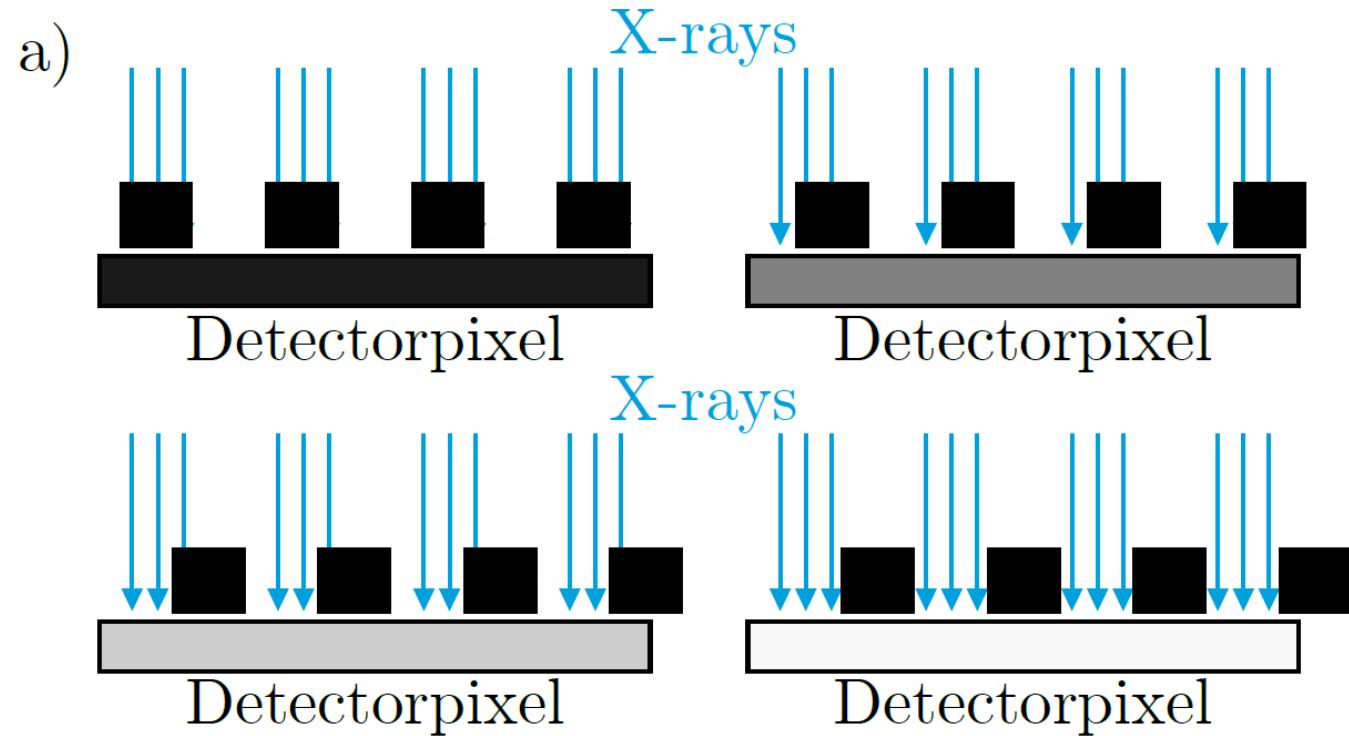
- Intensitätsmuster mit kleiner  $\mu\text{m}$  Periode
- Detektorpixel  $> 100 \mu\text{m}$

# Analysatorgitter G2



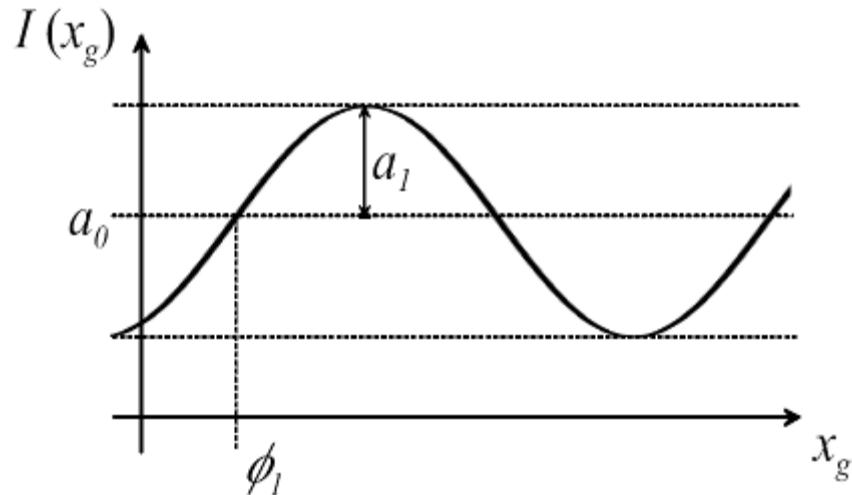
Schröter et al. | RSI | 2017

# Phasenstepping



# Signal Extraktion

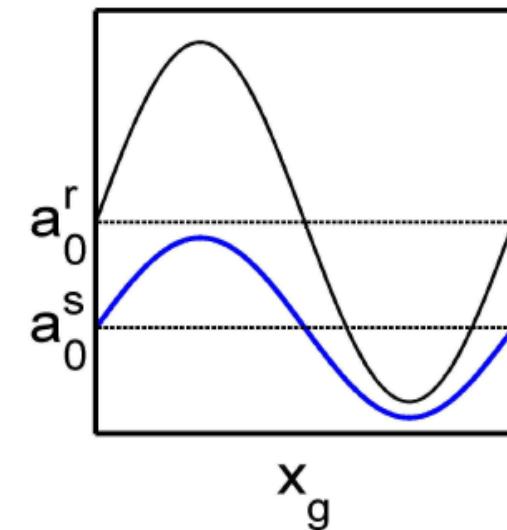
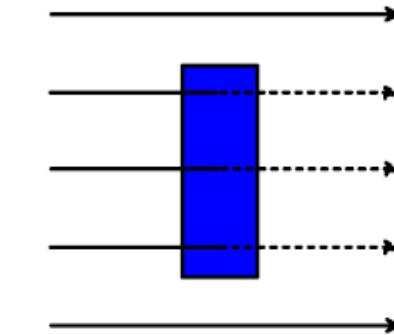
mit 'fringe scanning' oder 'phase stepping'



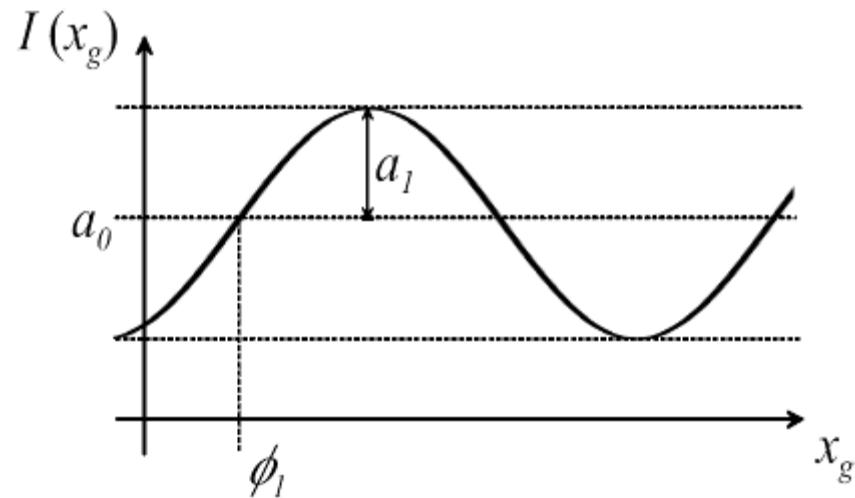
$$I(m, n, x_g) = \sum a_i(m, n) \cos(ikx_g + \phi_i(m, n))$$

$$\approx a_0(m, n) + a_1(m, n) \cos(kx_g + \phi_1(m, n))$$

transmission



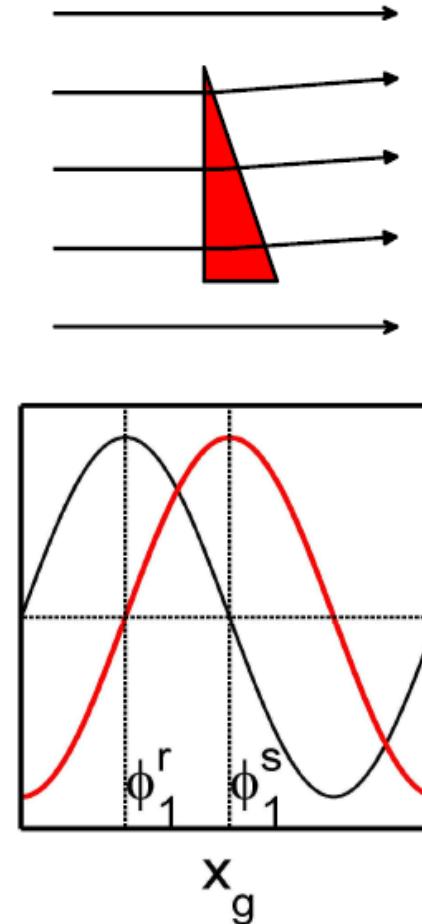
# Signal Extraction



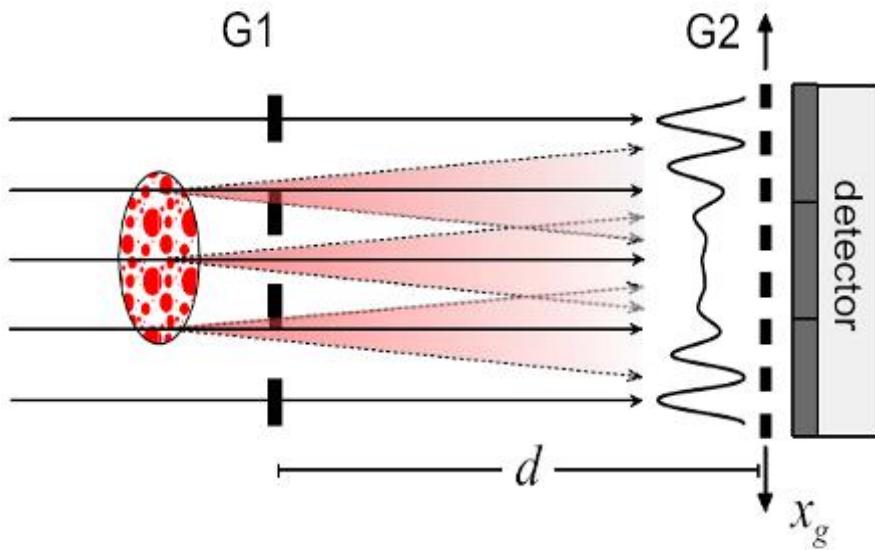
$$I(m, n, x_g) = \sum a_i(m, n) \cos(ikx_g + \phi_i(m, n))$$

$$\approx a_0(m, n) + a_1(m, n) \cos(kx_g + \phi_1(m, n))$$

phase  
gradient



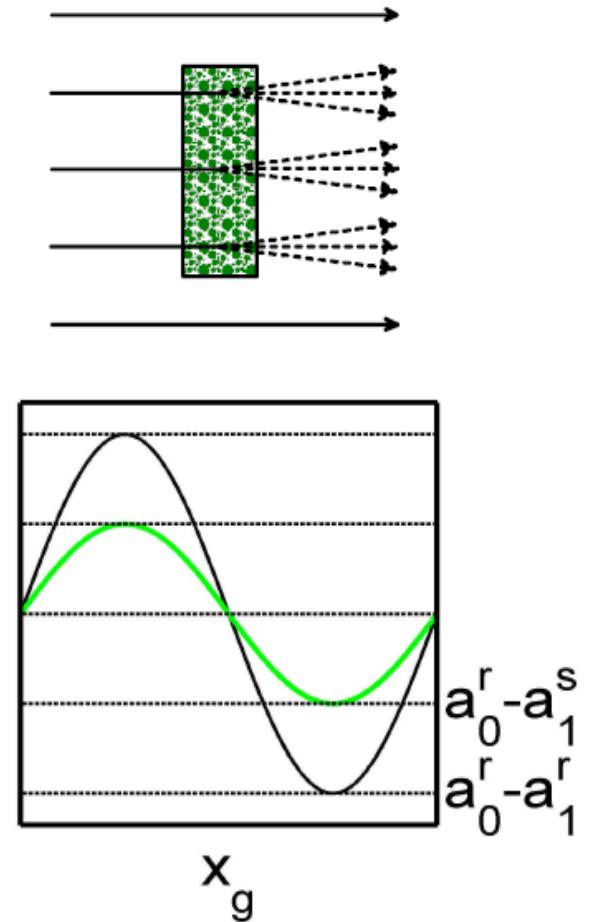
# Signal Extraction



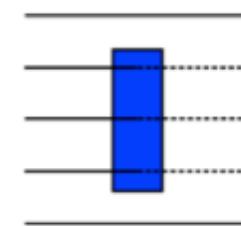
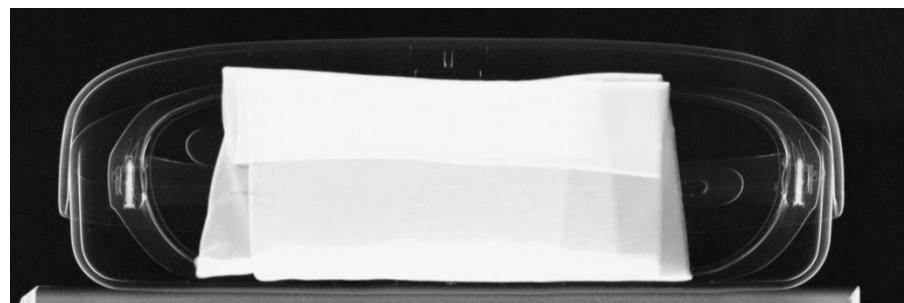
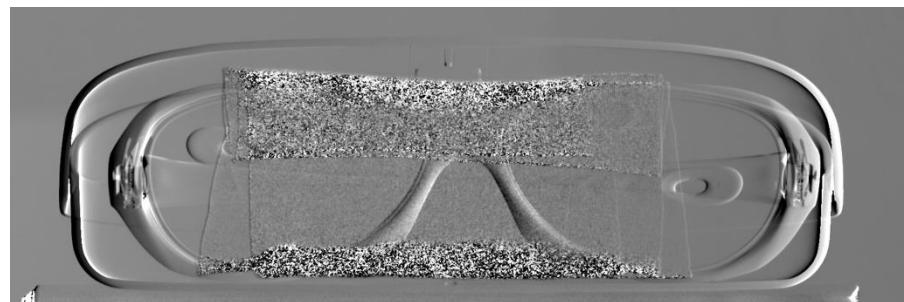
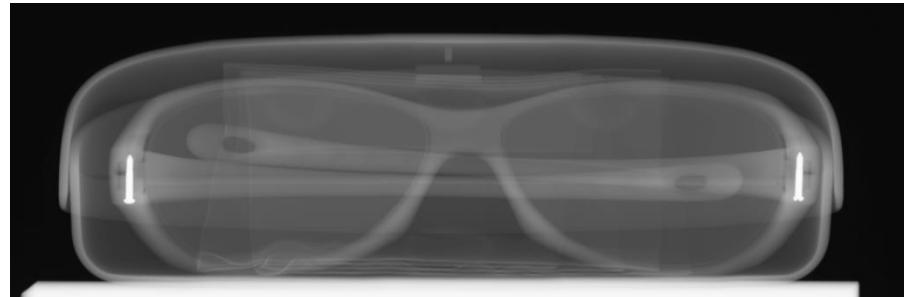
$$I(m, n, x_g) = \sum a_i(m, n) \cos(ikx_g + \phi_i(m, n))$$

$$\approx a_0(m, n) + a_1(m, n) \cos(kx_g + \phi_1(m, n))$$

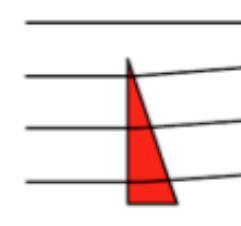
scattering/  
dark-field



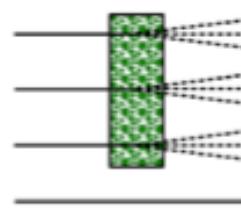
# Multimodale Information



ATTENUATION



PHASE



DARKFIELD

# Grating-Based Imaging mit Laborquelle

PHASENKONTRAST MICRO CT

SYNCHROTRON

2015

X-RAY TUBES

2019



AUFLÖSUNG: 20 µM

100 µM

40 µM

SCAN ZEIT: 10 MIN

2 TAGE

1 TAG

# Hausaufgaben

## Drei Aufgaben auf Moodle

- Aufgabe 1: zur Kohärenz
- Aufgabe 2: zu Röntgen-Phasenkontrast Methoden
- Aufgabe 3: zur Gitter-basierten Phasenkontrast Methode

**Vielen Dank für ihre  
Aufmerksamkeit!**