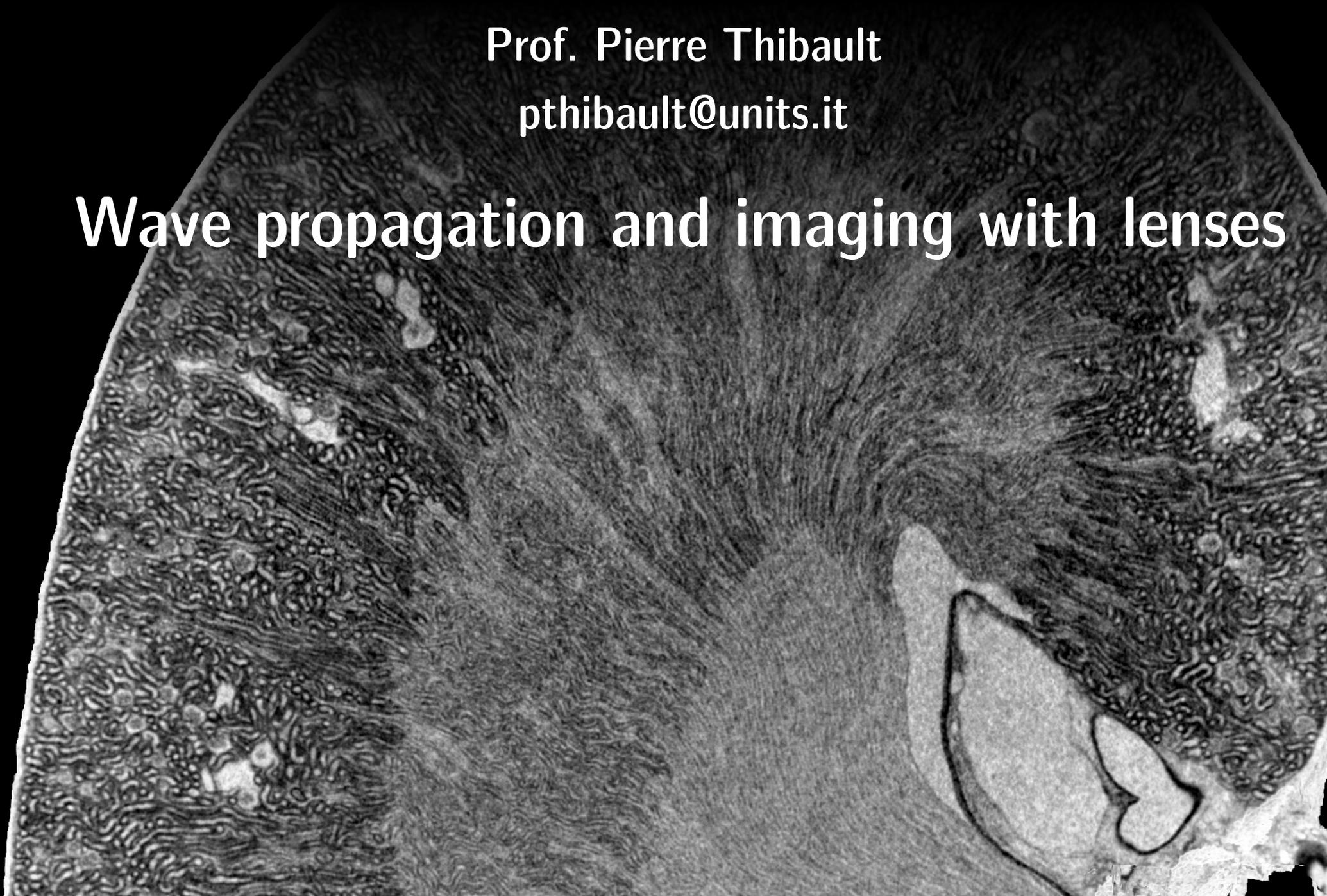


# Image Processing for Physicists

Prof. Pierre Thibault

[pthibault@units.it](mailto:pthibault@units.it)

## Wave propagation and imaging with lenses



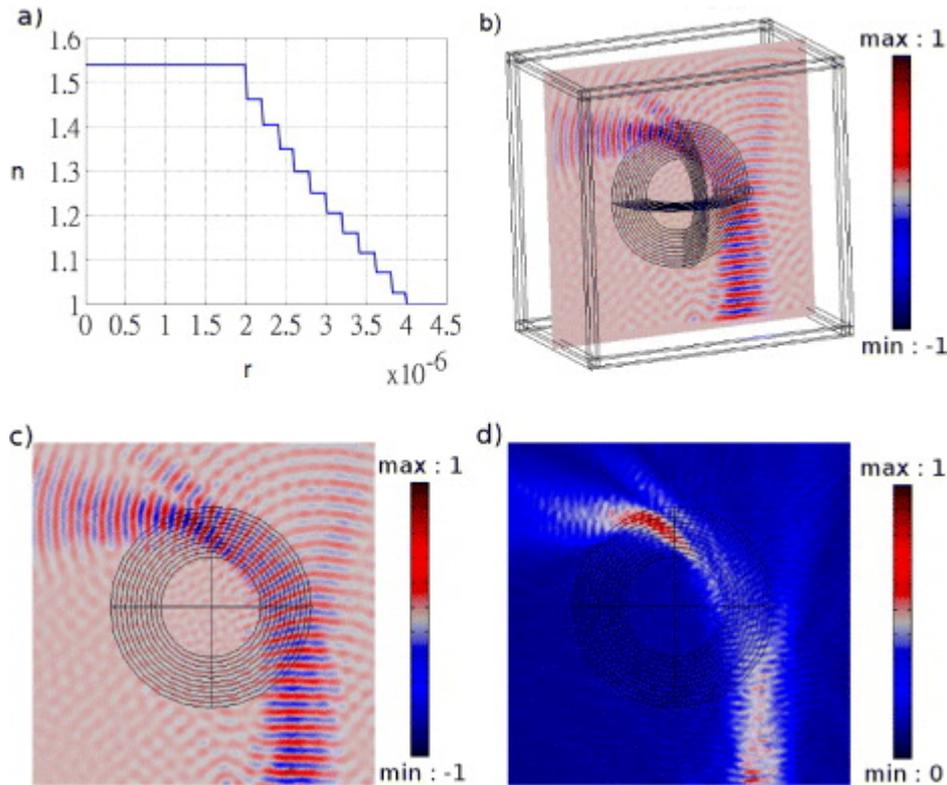
# Overview

- Propagation modelization
- Wave propagation:
  - Near-field regime
  - Far-field regime

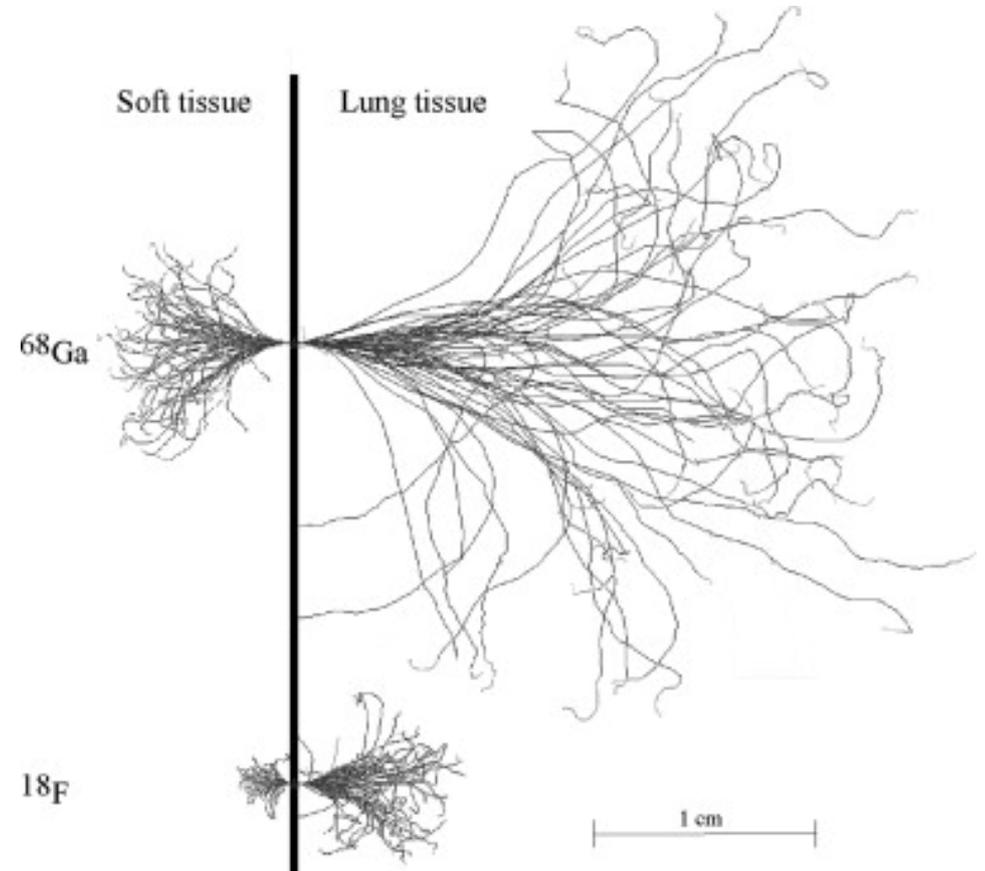
# Propagation modeling

- Motivations:

## 1. Validation



Finite element simulation of an electromagnetic field in a dielectric



Monte Carlo simulation of positrons trajectories resulting from  $^{68}\text{Ga}$  and  $^{18}\text{F}$  decay.

sources: T.M. Chang *et al.* New J. Phys. (2012)  
A. Sanchez-Crespo, Appl. Rad. Isotopes (2012)

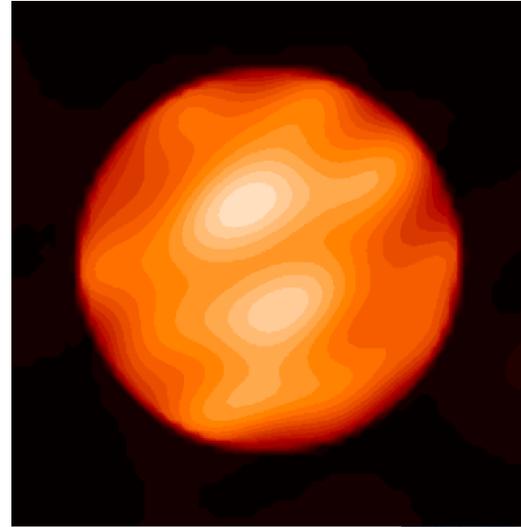
# Propagation modeling

- Motivations:

## 2. Inversion



Image reconstruction from sound wave propagation (ultrasonography)



The surface of Betelgeuse reconstructed from interferometric data (IOTA)



sources: wikipedia

Haubois *et al.* *Astronom. & Astrophys.* (2009)

# Propagation modeling

- Particles
  - Model particle tracks (rays) through different media
  - Model may include: refraction, force fields, particle decay and interactions
  - Not included: diffraction
- Wave
  - Model the interaction of a field with a medium
  - Can be very complicated → approximations are needed

# Propagation modeling

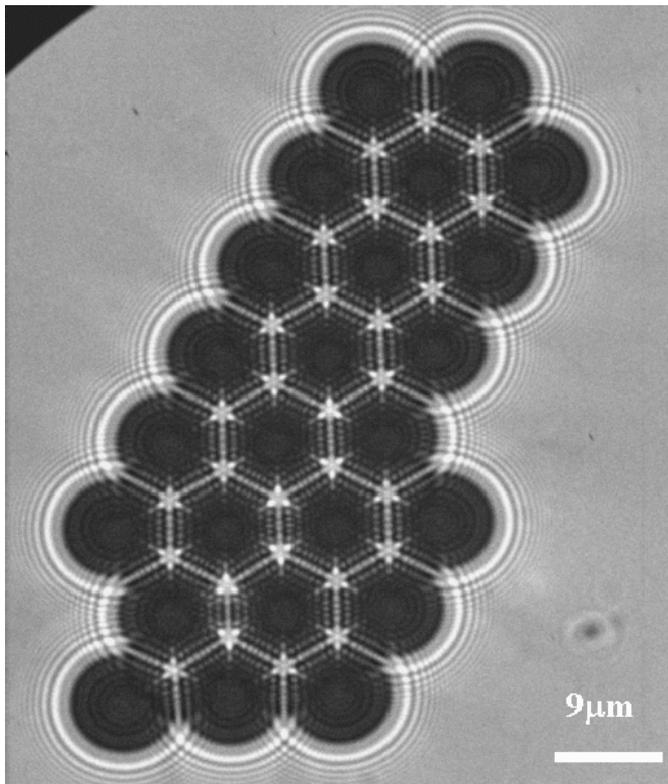
Starting point: Helmholtz equation

- for EM field: neglect polarization (scalar wave approximation)
- for electron wave, assume high energy electrons

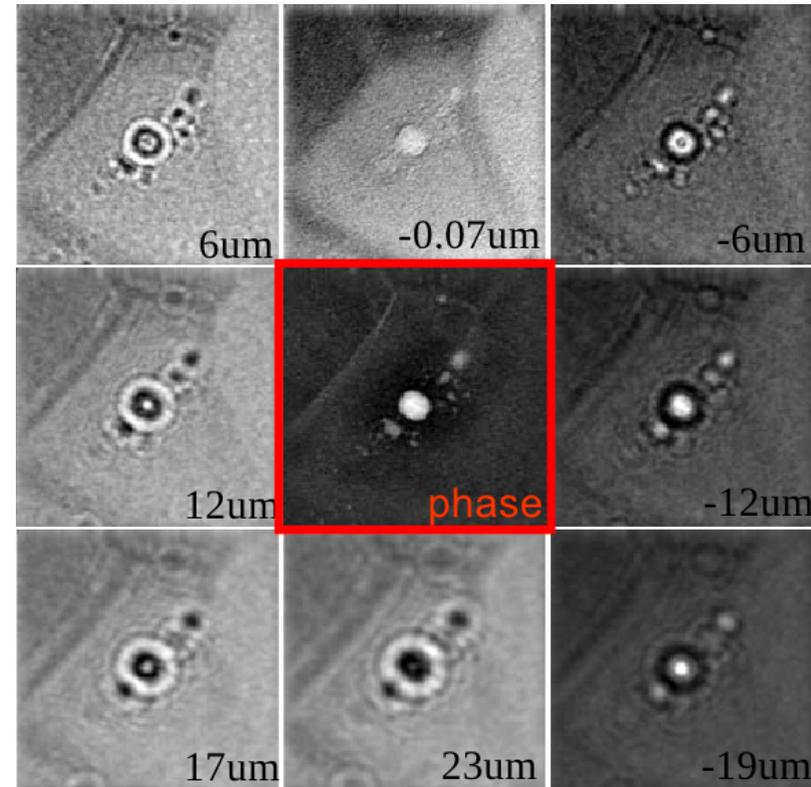
# Propagation modeling

- Useful to:
  - better understand optical systems
  - understand diffraction, holography, phase contrast, interferometry, ...

X-ray hologram



TEM through-focus series



sources: Mayo *et al.* Opt. Express (2003)  
<http://www.christophtkoch.com/Vorlesung/>

# The physics of propagation

# The physics of propagation

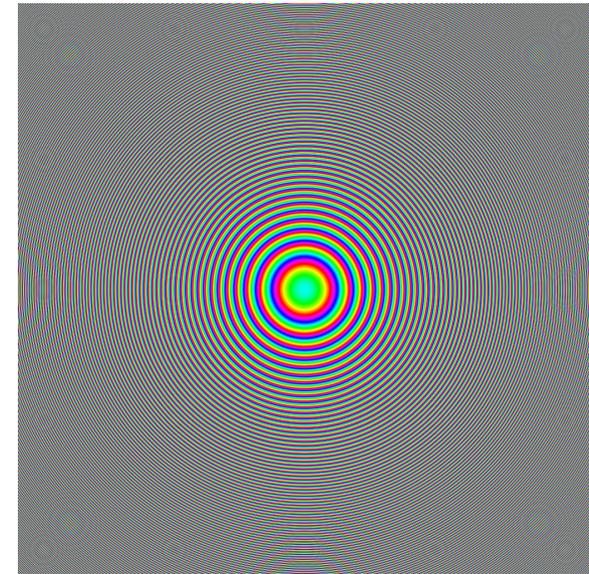
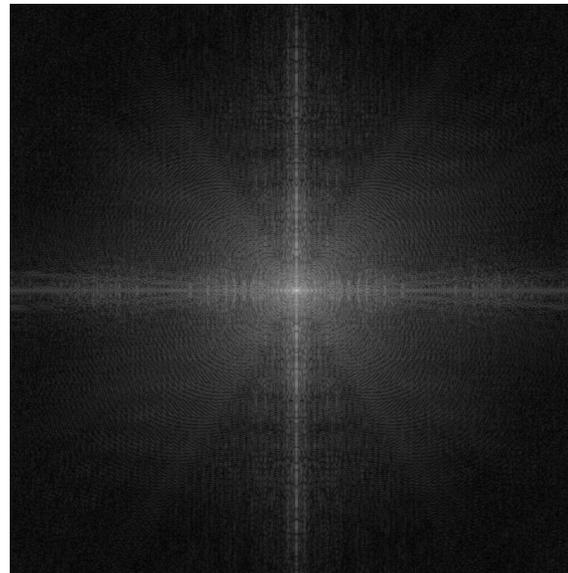
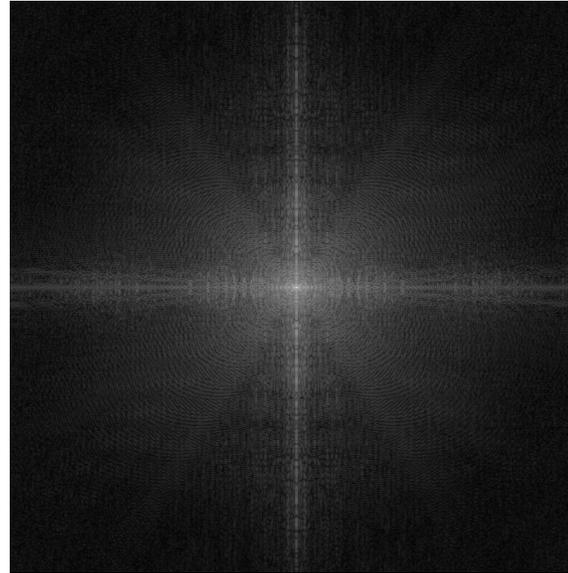
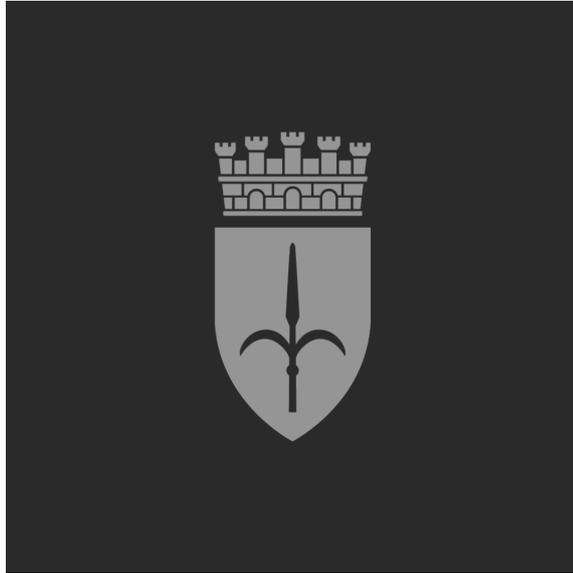
Angular spectrum representation

# Forward propagation

# Forward propagation

# Forward propagation

A numerical recipe

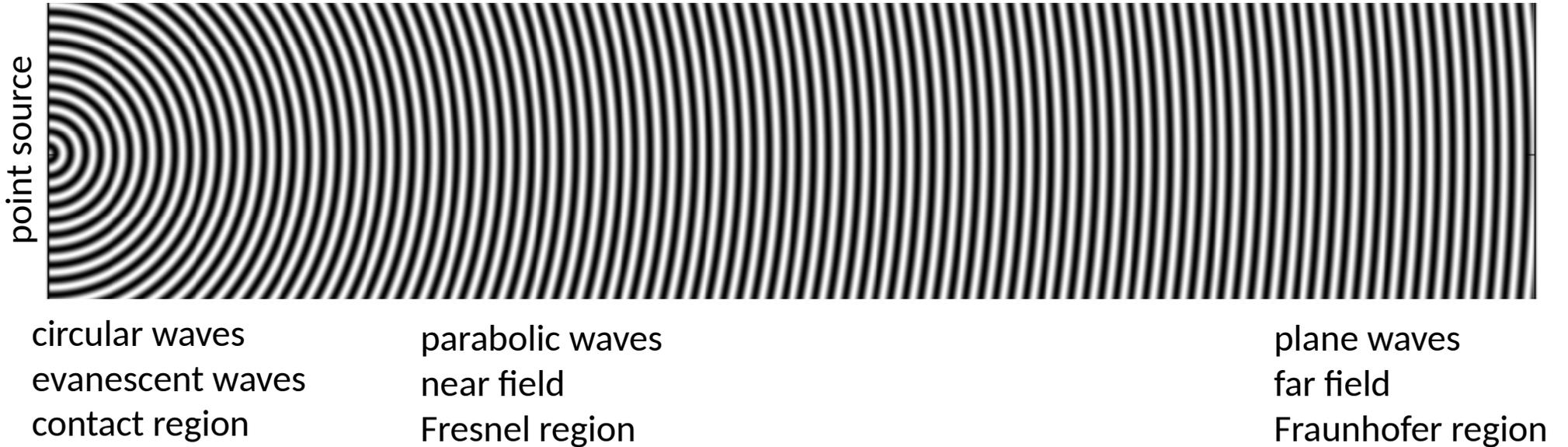


# Near field, far field

# Back focal plane of a lens

# Back focal plane of a lens

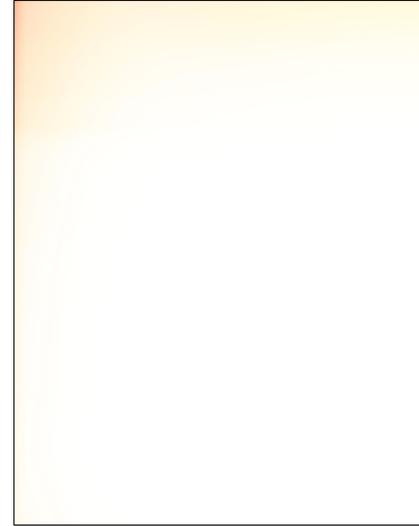
# Plane waves, point sources



# Why optical elements?



with objective lens

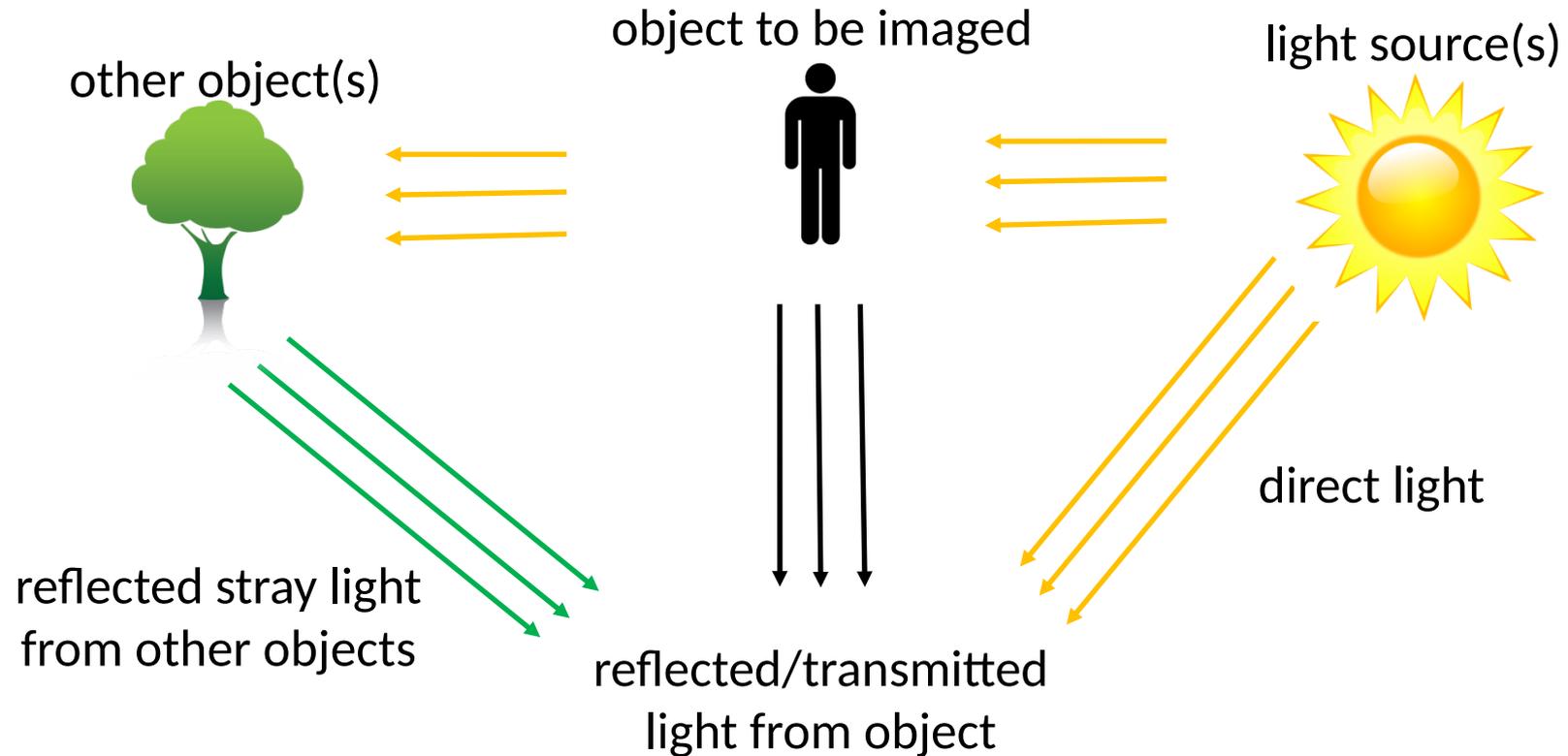


without objective lens



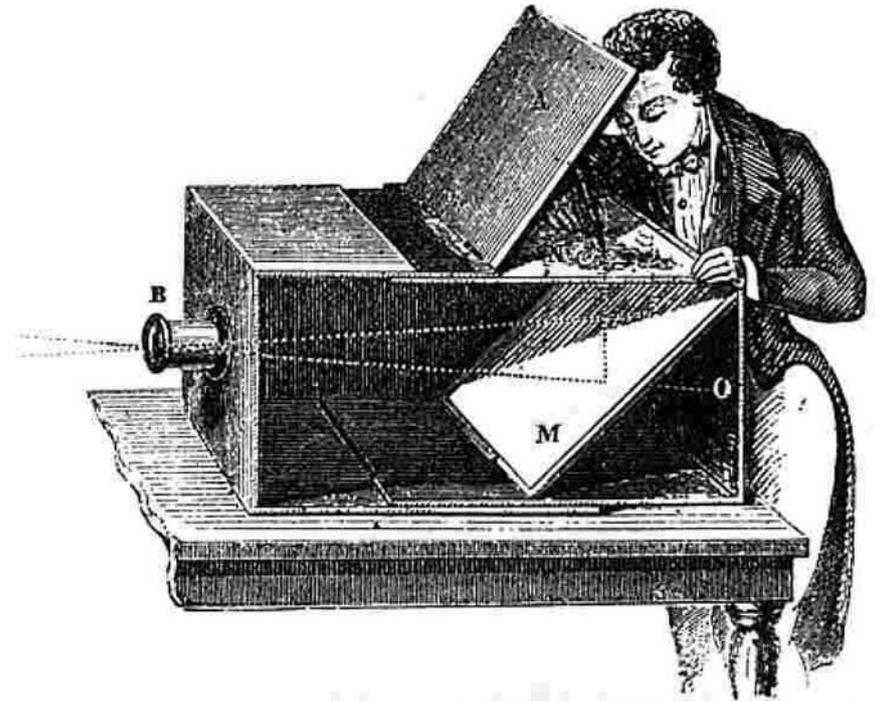
# Why optical elements?

- Information from many sources overlaps in detector plane
- Need models to understand image forming systems



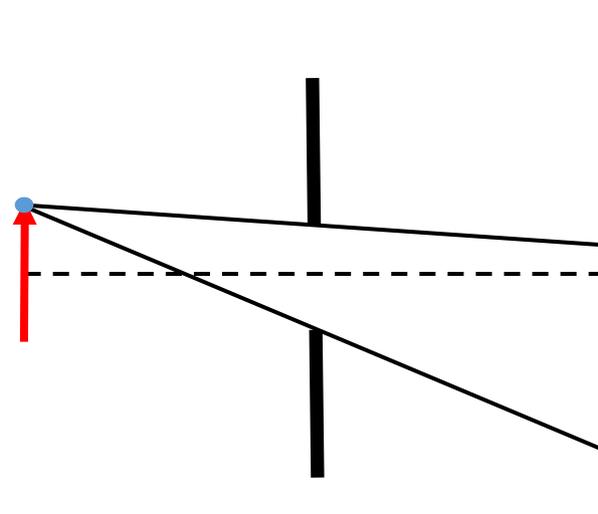
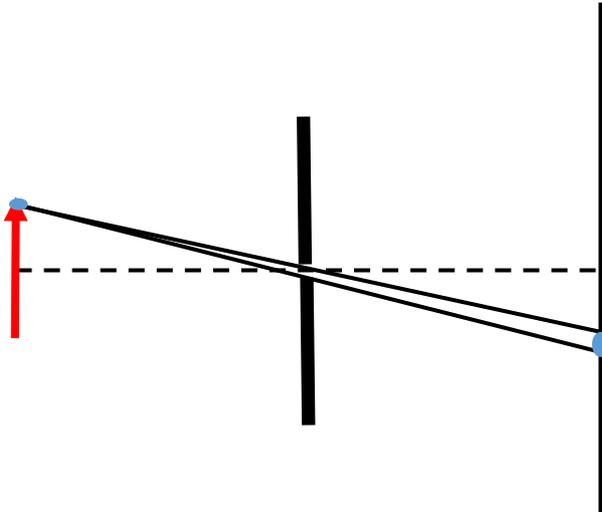
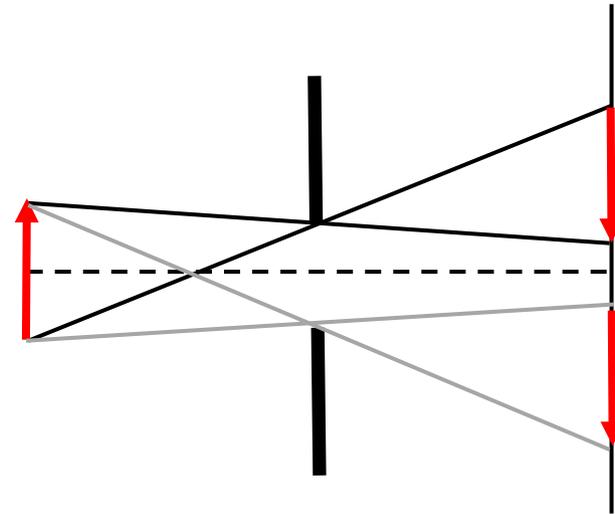
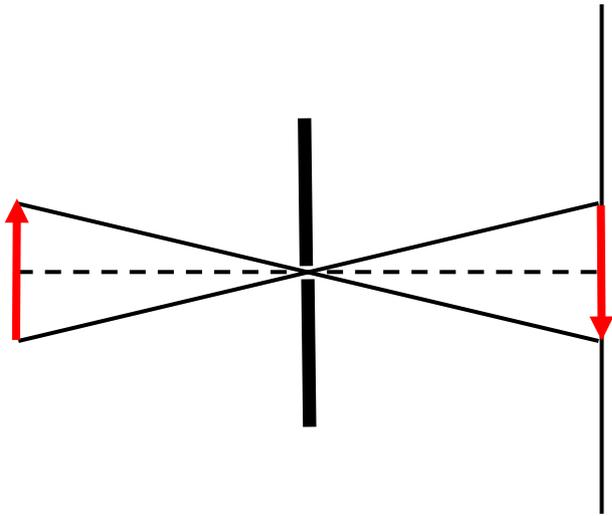
# Pinhole camera model

camera obscura



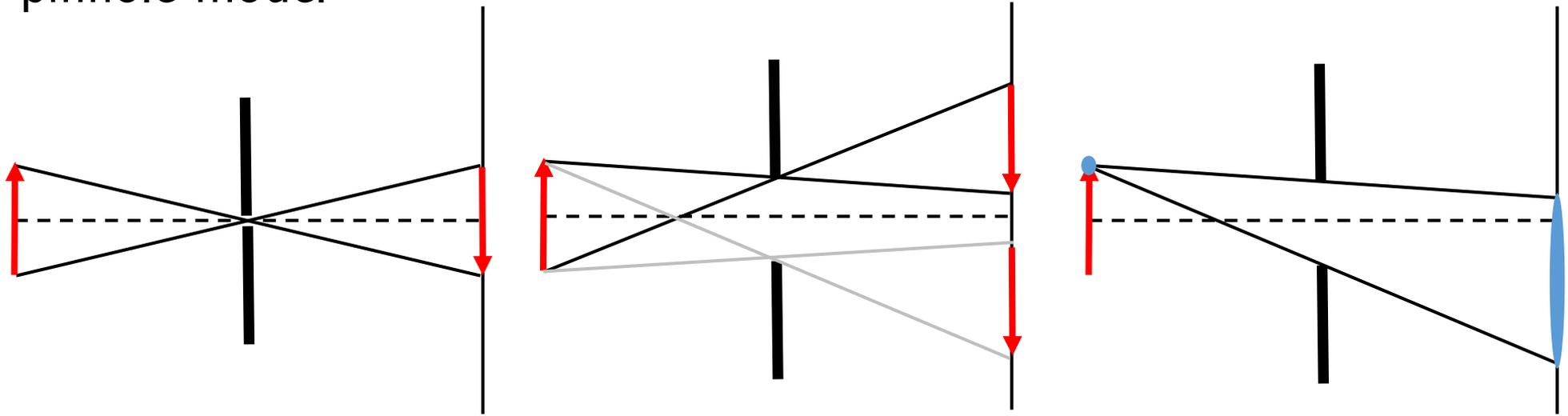
# Pinhole camera model

PSF determined by aperture width

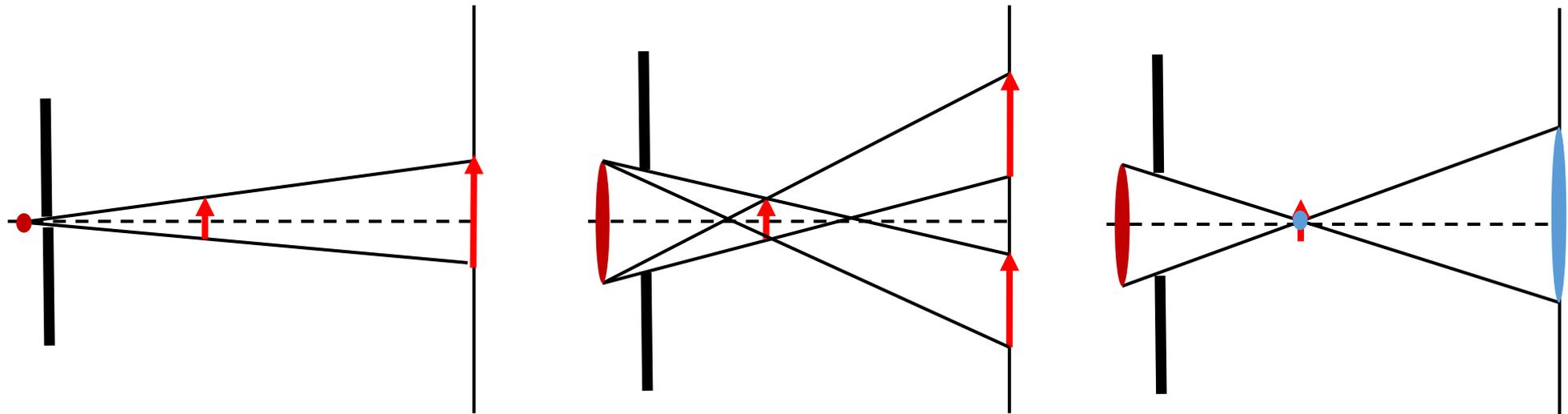


# Projection model

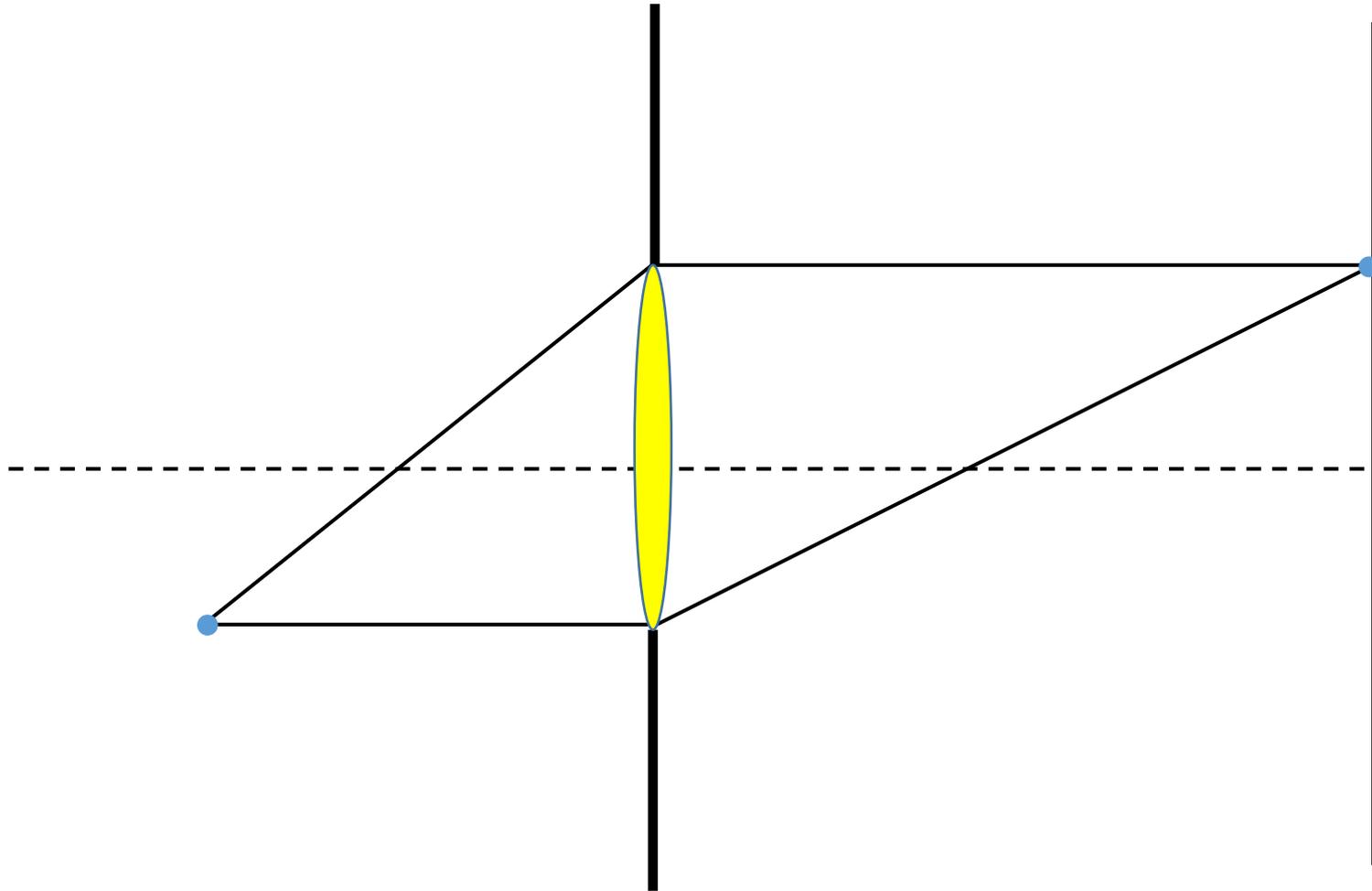
pinhole model



projection model

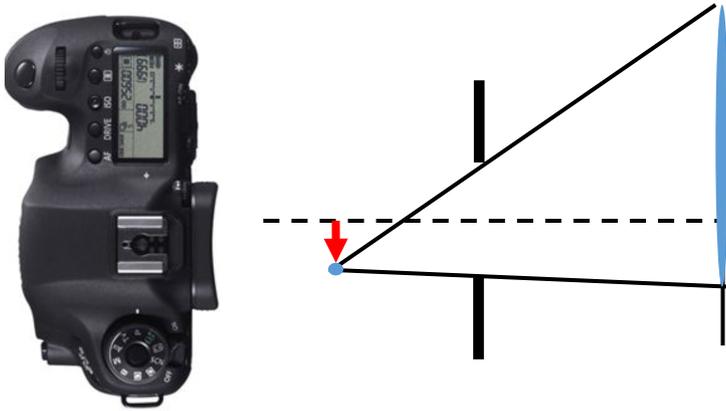


# Lens camera model

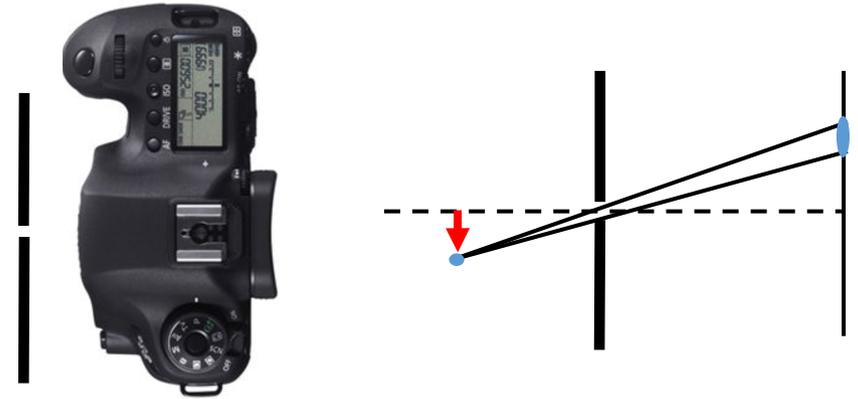


# Lens camera model

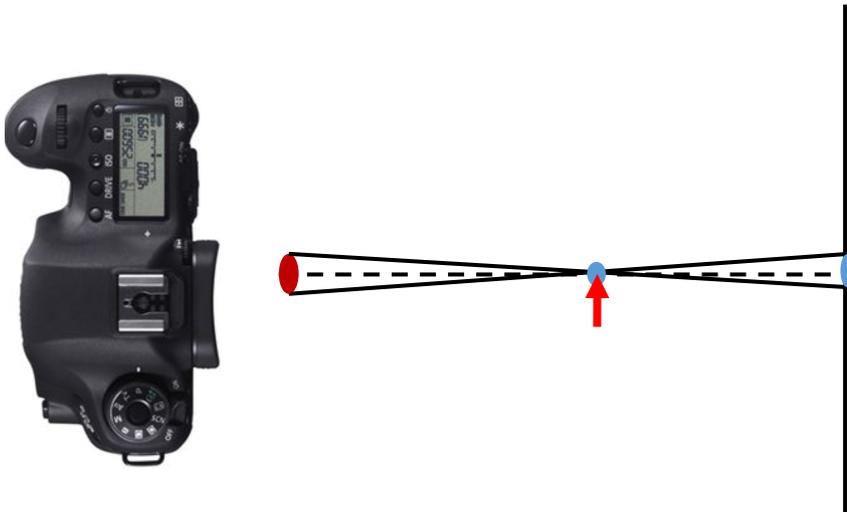
lensless model



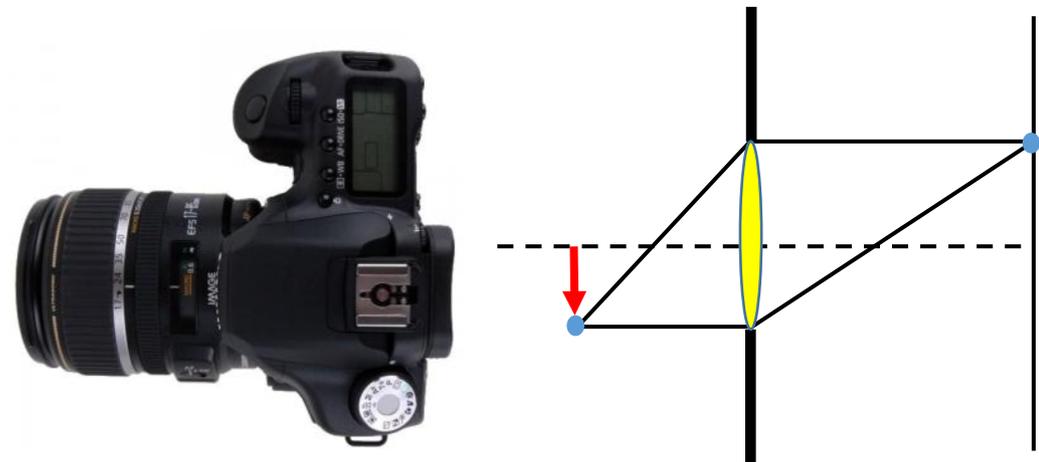
pinhole camera model



projection model

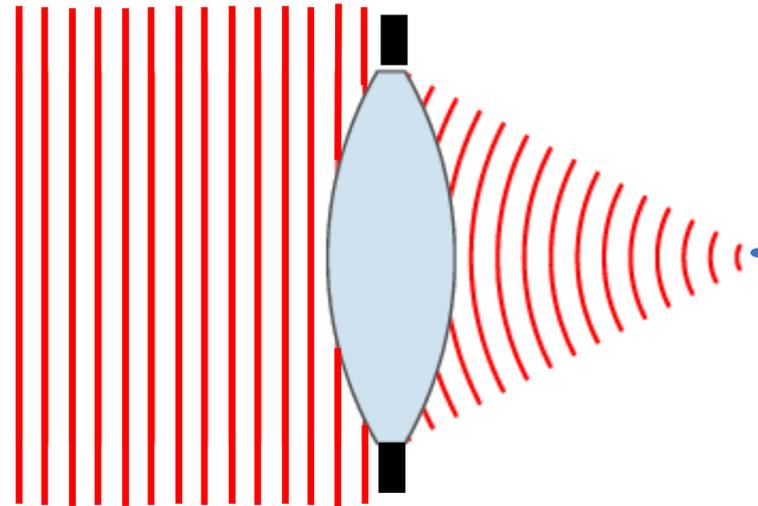


lens camera model

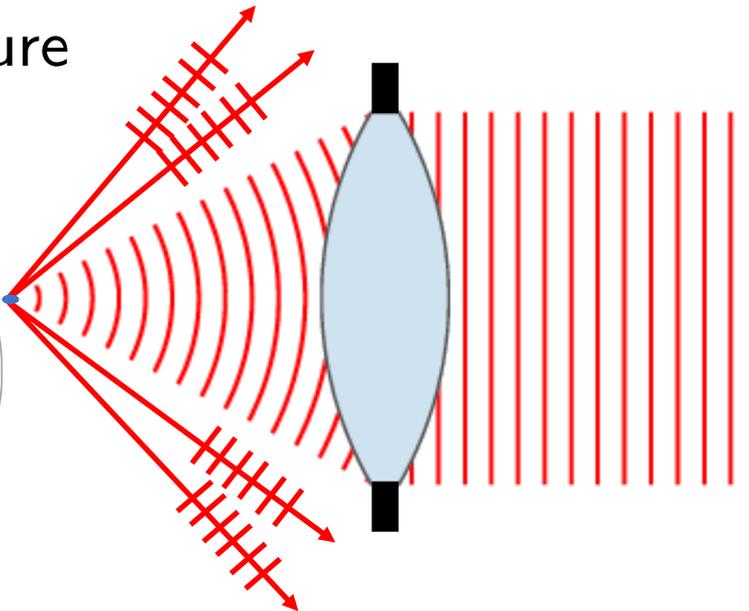
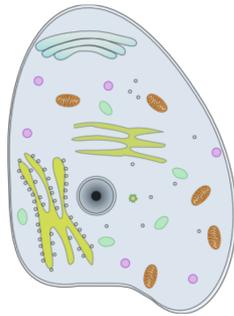
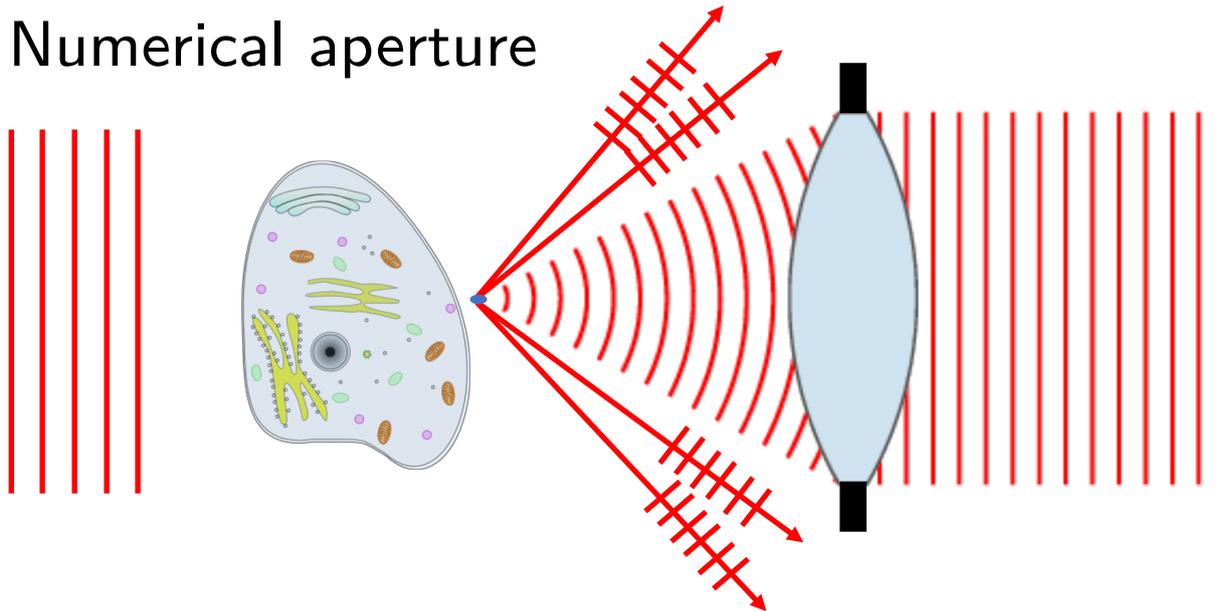


# Diffraction-limited imaging systems

- Rayleigh criterion



- Numerical aperture



# Scanning systems

## Transmission

- **Scanning Transmission Electron Microscopy**
- **Scanning Transmission X-ray Microscopy**
- ...

## Indirect (reflection, scattering, fluorescence, ...)

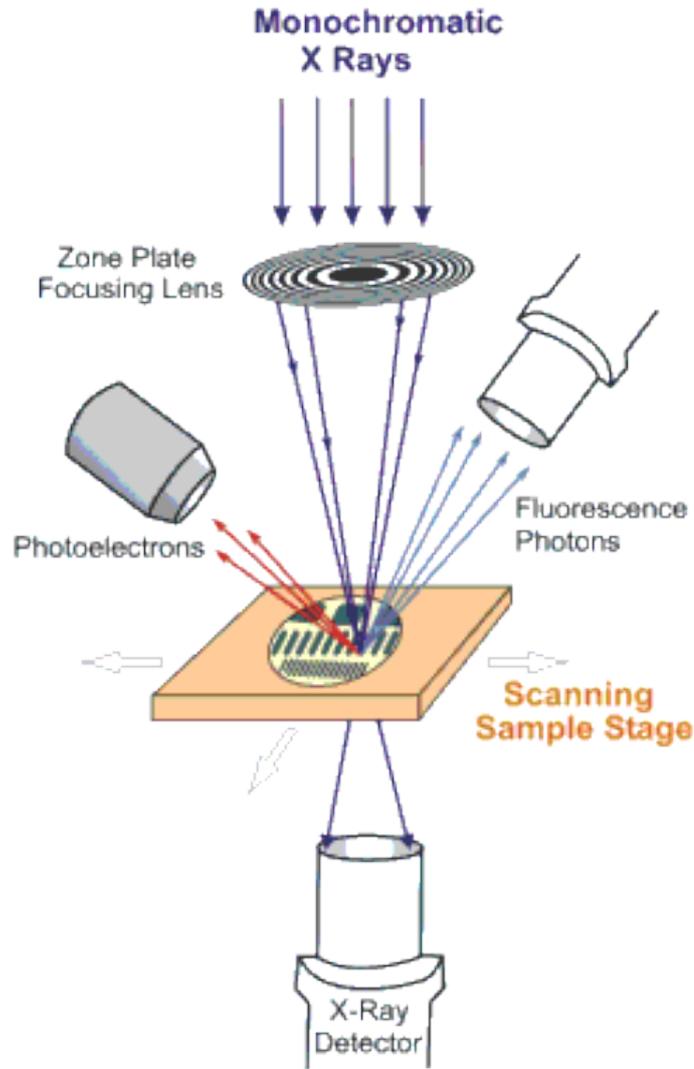
- **Laser Scanning Confocal Microscopy**
- **Scanning Electron Microscopy**
- **X-ray Fluorescence Microscopy**
- **PhotoEmission Electron Microscopy**
- ...

## Physical probe

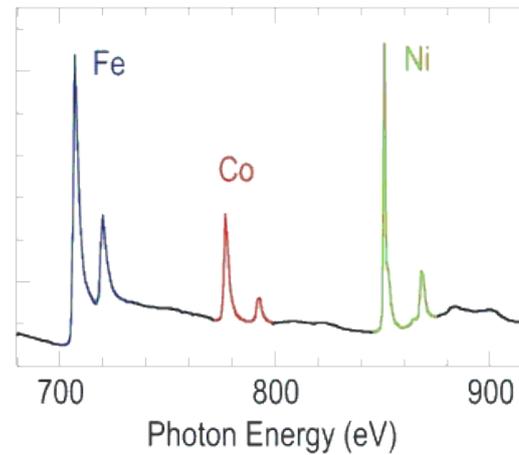
- **Atomic Force Microscopy**
- **Scanning Tunneling Microscopy**
- ...

# Scanning transmission X-ray microscopy

Scanning Transmission X-ray Microscopy  
STXM

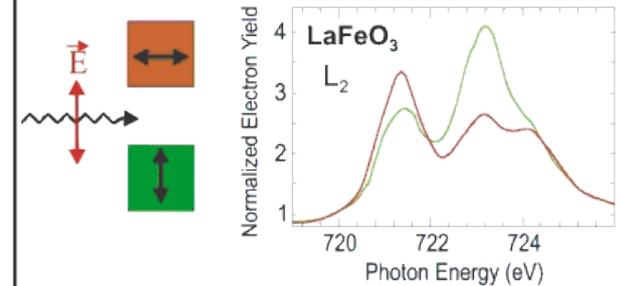


Tune x-ray **energy**  
for elemental specificity

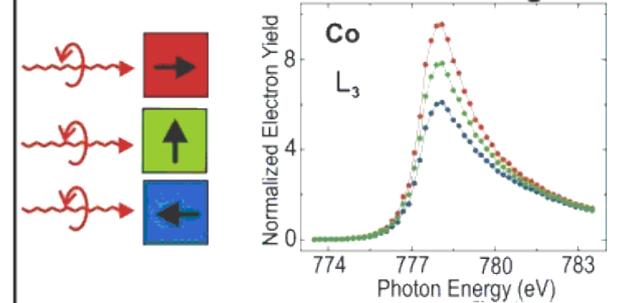


Tune x-ray **polarization**  
for magnetic specificity

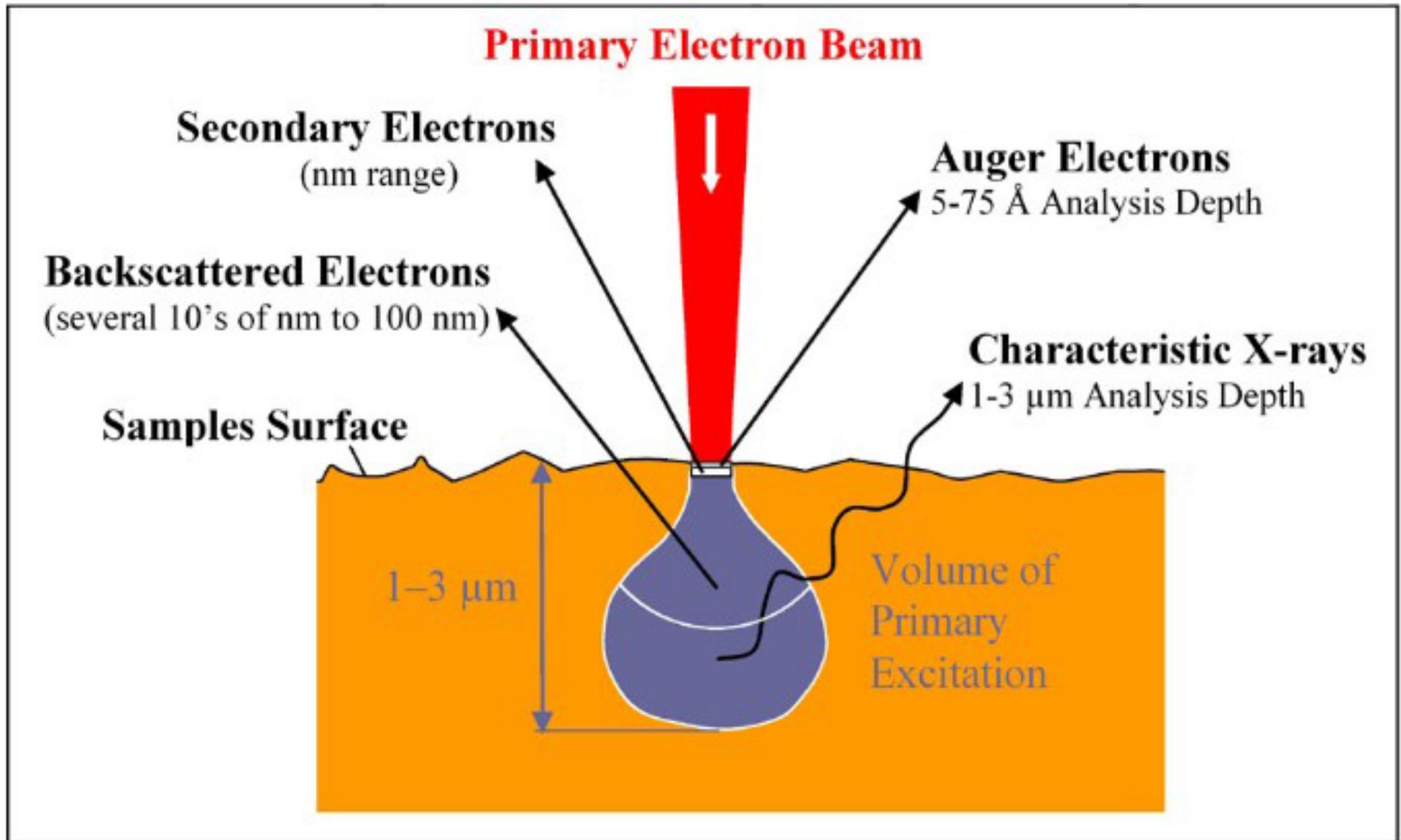
Linear Dichroism - Antiferromagnets



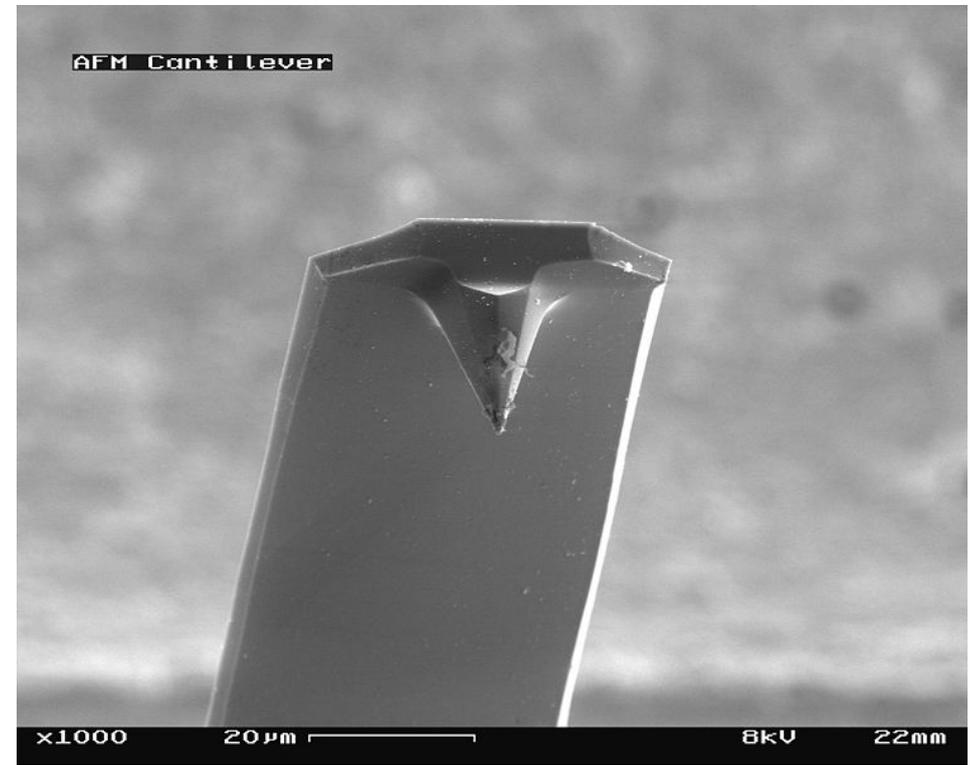
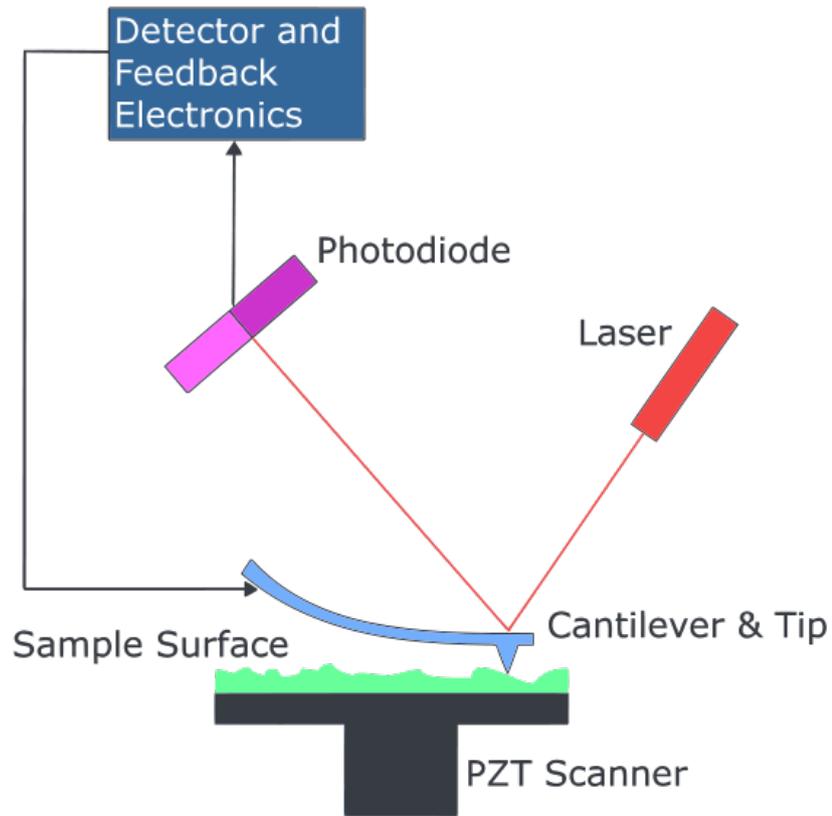
Circular Dichroism - Ferromagnets



# Scanning electron microscopy



# Atomic force microscopy



# Resolution in scanning systems

Resolution mainly limited by probe size

# Scanning vs. full field systems

Transmission probe: the reciprocity theorem