OPTICS

The science of light

P. Ewart

- Lecture notes: On web site

  NB *outline notes!*

- Textbooks:

  Hecht, *Optics*

  Klein and Furtak, *Optics*

  Lipson, Lipson and Lipson, *Optical Physics*

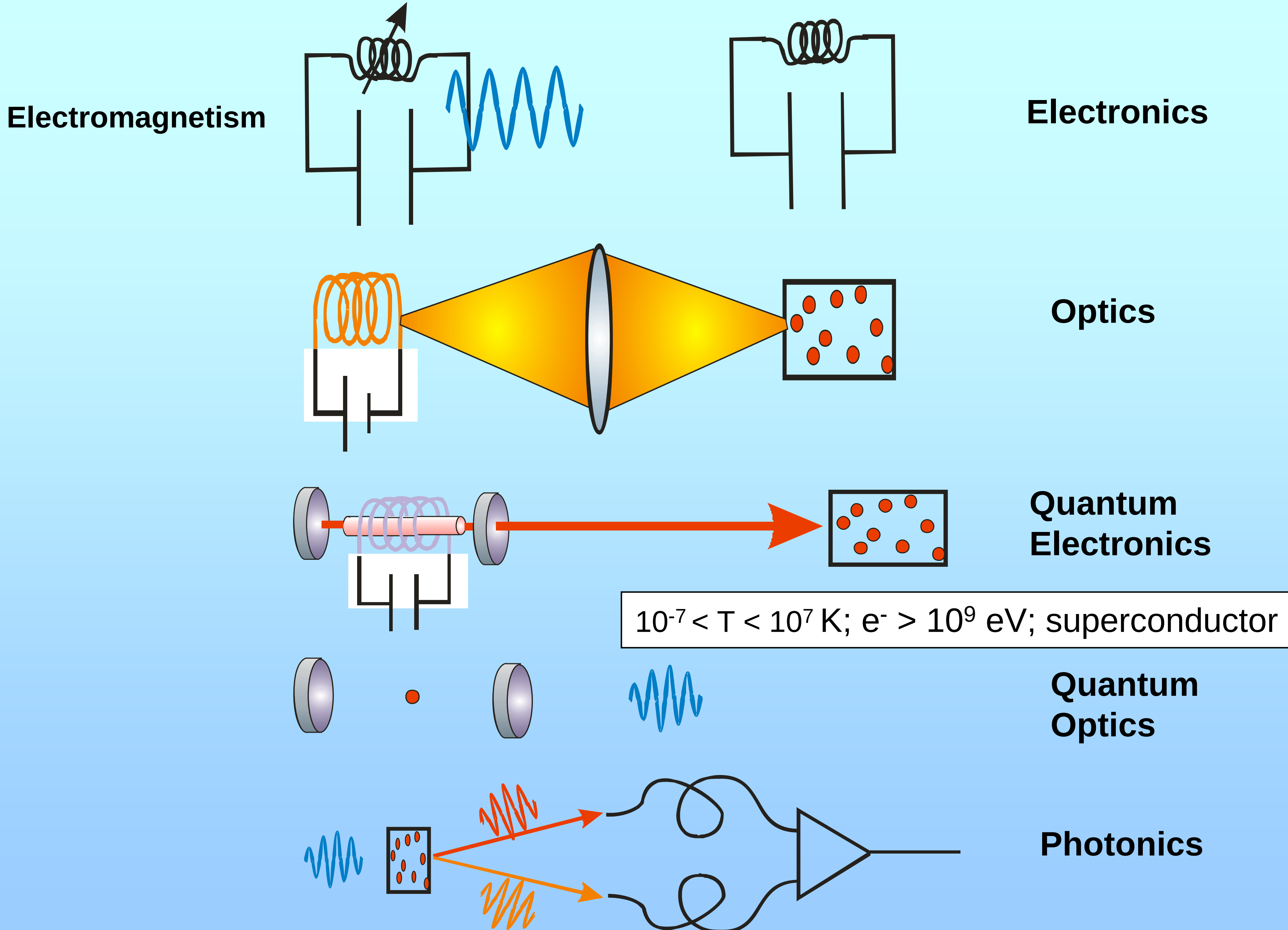
  Brooker, *Modern Classical Optics*

- Problems: Material for four tutorials plus past Finals papers A2

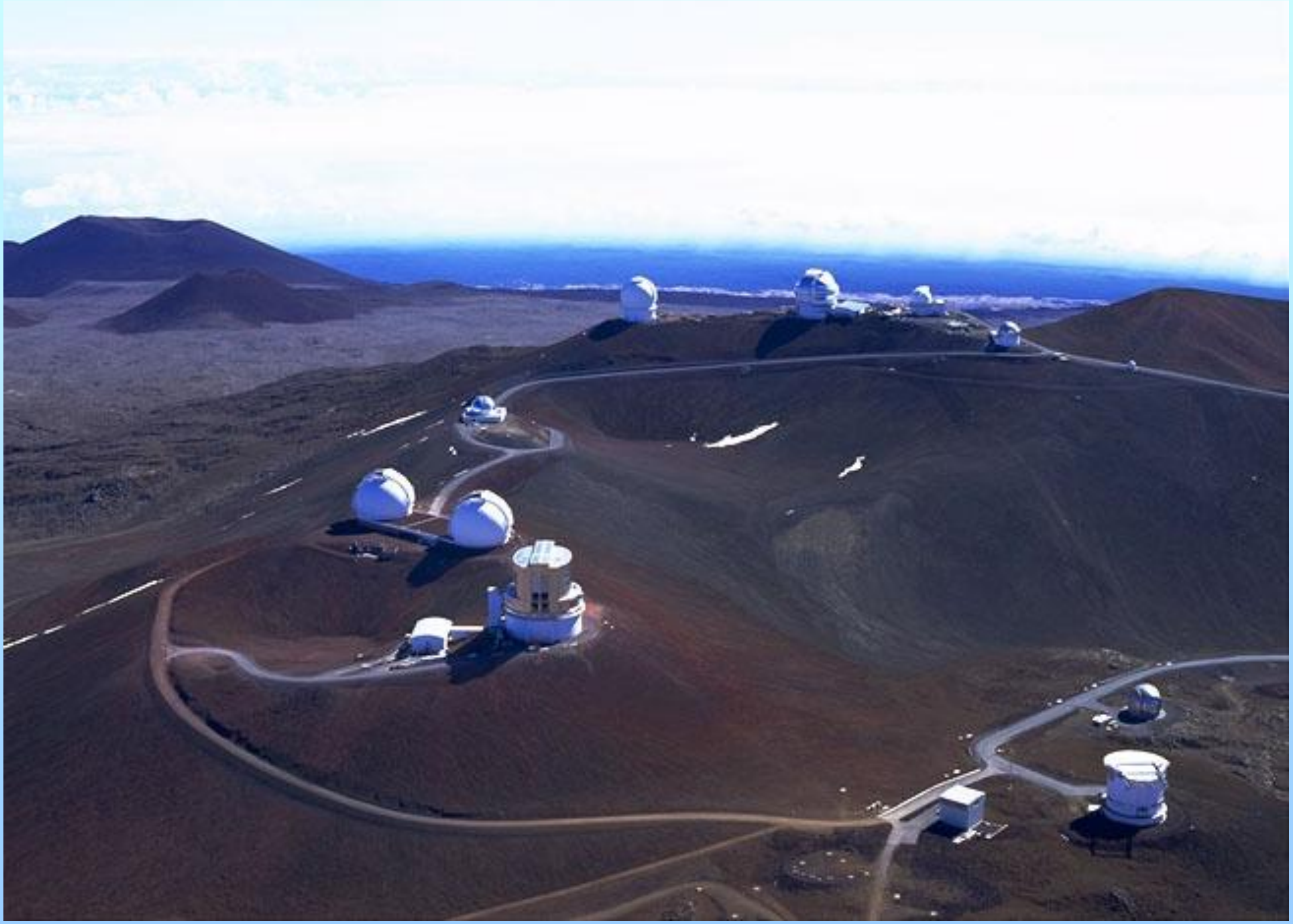
- Practical Course: Manuscripts and Experience

Structure of the Course

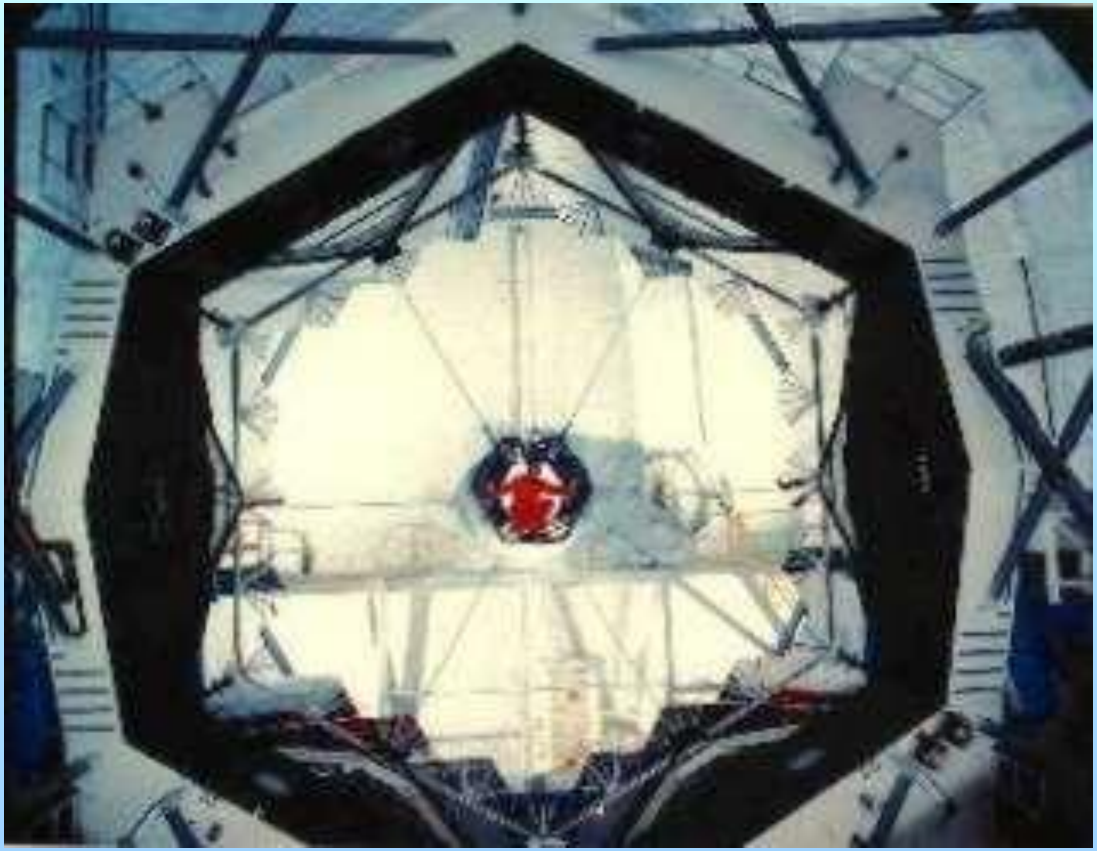
1. Geometrical Optics
2. Physical Optics (Interference)
   Diffraction Theory (Scalar)
   Fourier Theory
3. Analysis of light (Interferometers)
   Diffraction Gratings
   Michelson (Fourier Transform)
   Fabry-Perot
4. Polarization of light *(Vector)*


Electromagnetism
Electronics
Optics
Quantum Electronics
$10^{-7} < T < 10^{7}$ K; $e^{-} > 10^{9}$ eV; superconductor
Quantum Optics
Photonics

Astronomical observatory, Hawaii, 4200m above sea level.



Multi-segment
Objective mirror,
Keck Obsevatory

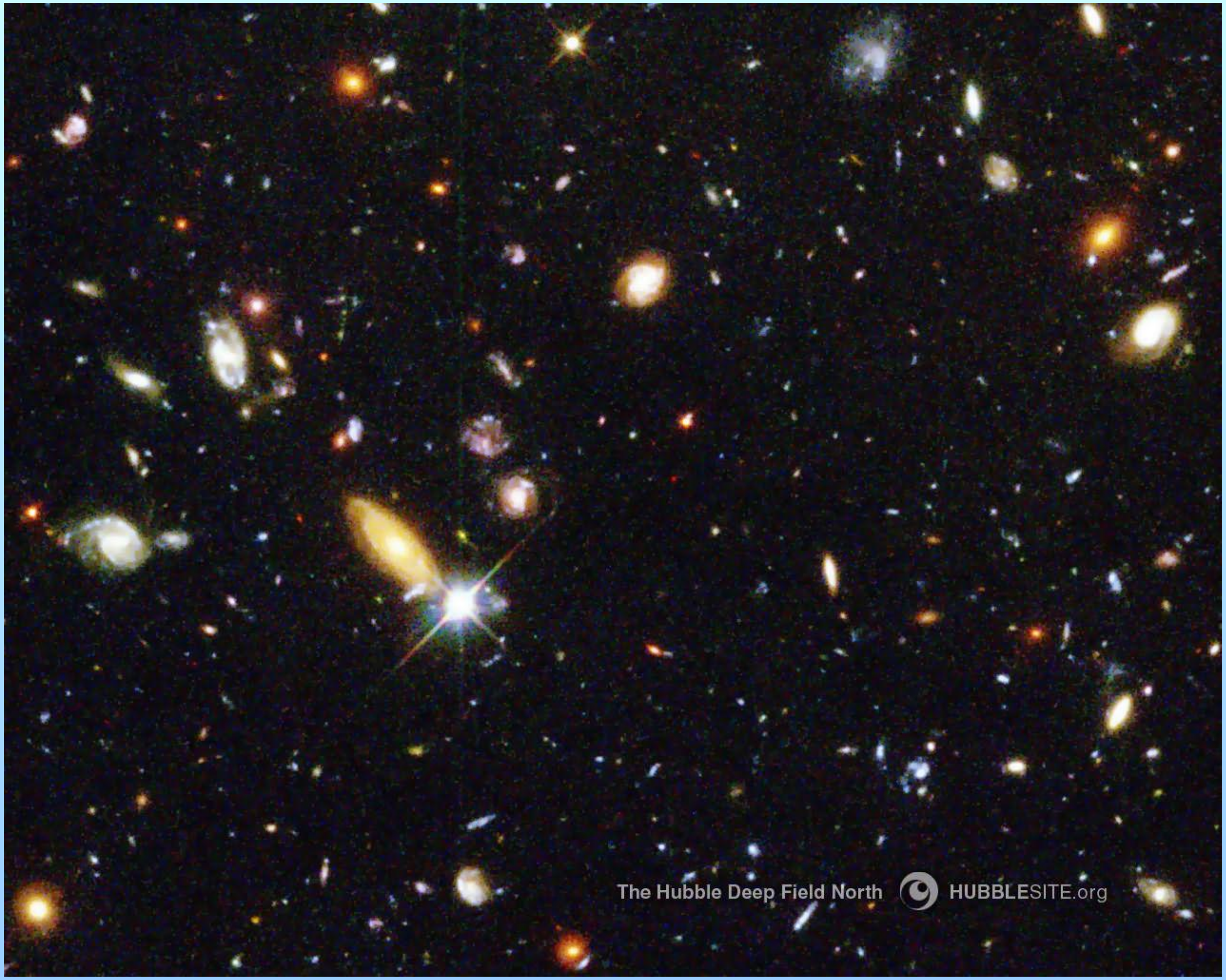


Hubble Space Telescope, HST,
In orbit

HST Deep Field

Oldest objects in the Universe:

13 billion years

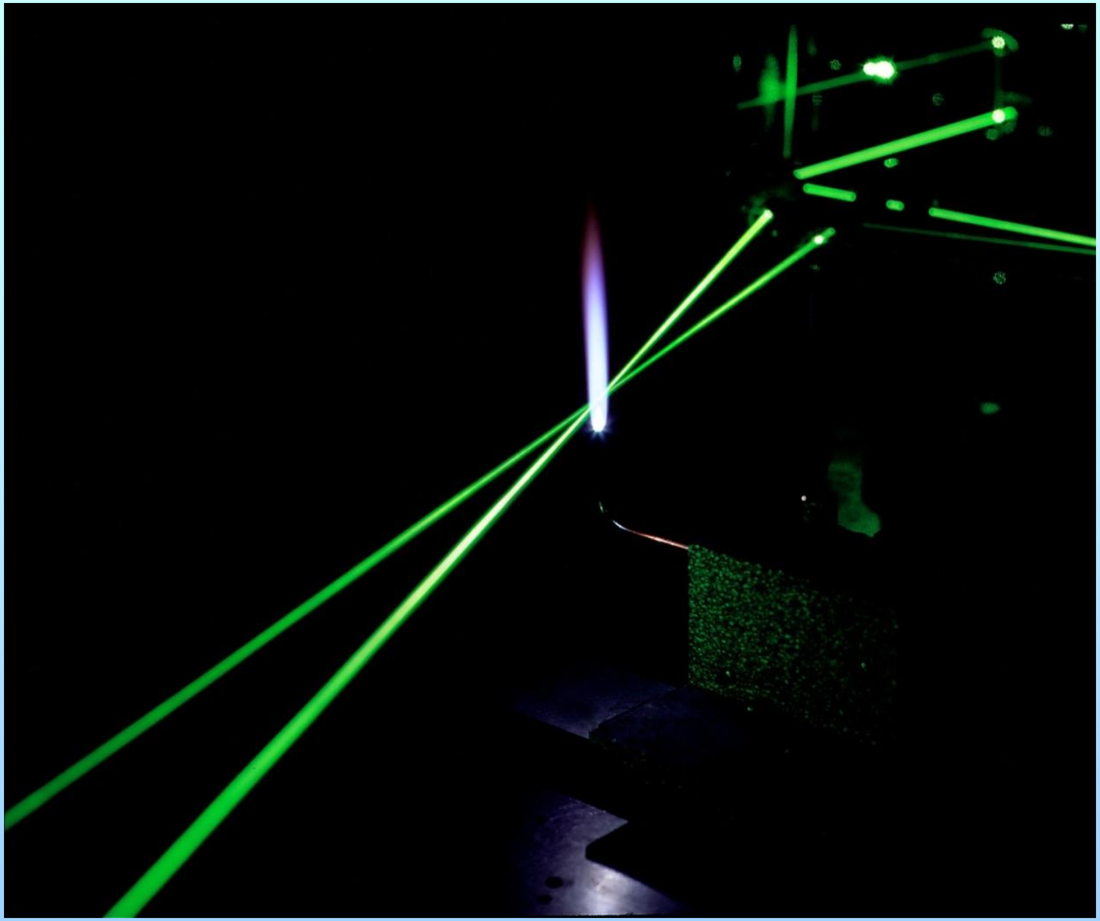


HST Image: *Gravitational lensing*

SEM Image: Insect head

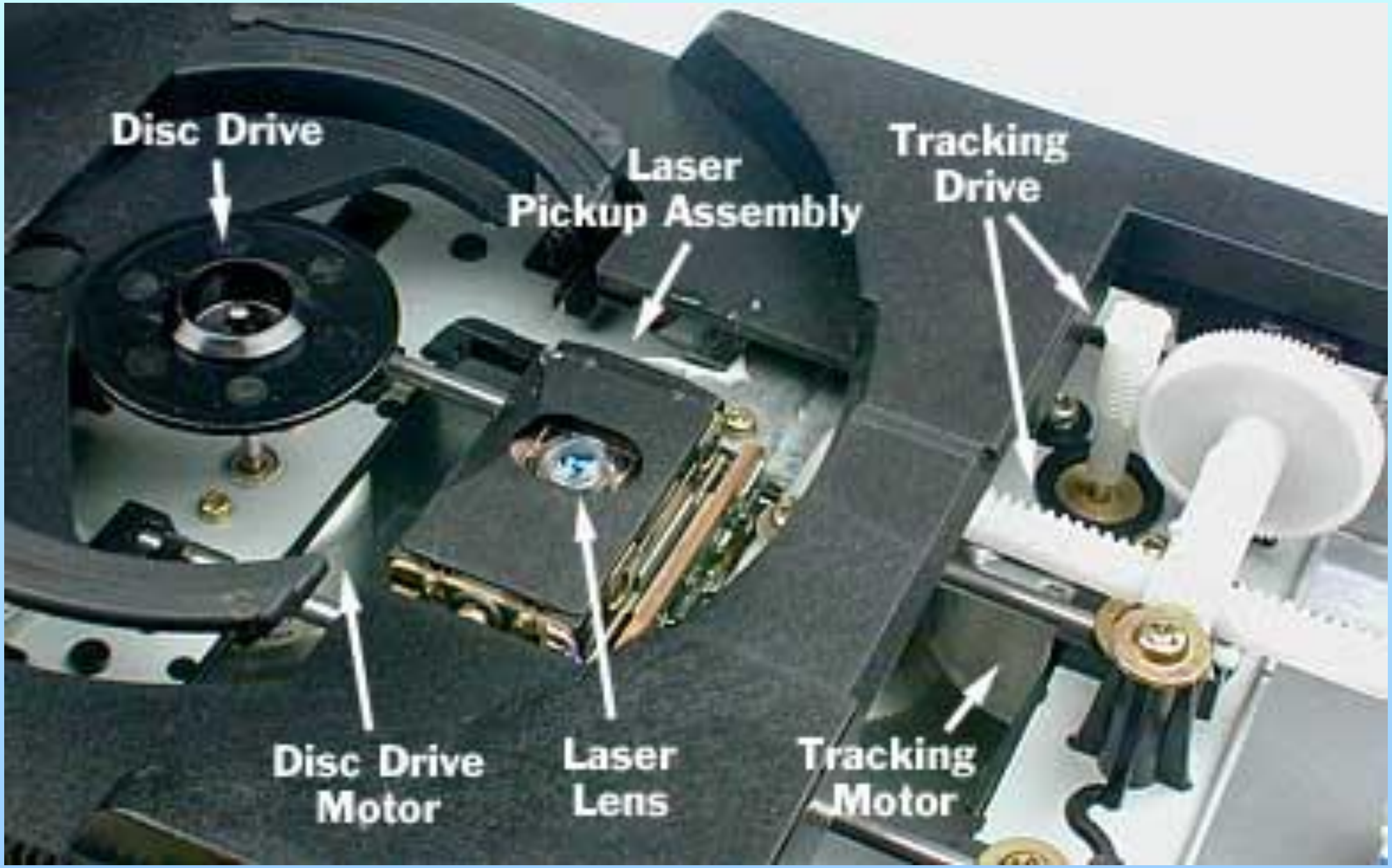
Coherent Light:

Laser physics:



Holography,
Telecommunications
Quantum optics
Quantum computing
Ultra-cold atoms
Laser nuclear ignition
Medical applications
Engineering
Chemistry
Environmental sensing
Metrology ……etc.!

CD/DVD Player: optical tracking assembly



Optics in Physics

- Astronomy and Cosmology
- Microscopy
- Spectroscopy and Atomic Theory
- Quantum Theory
- Relativity Theory
- Lasers

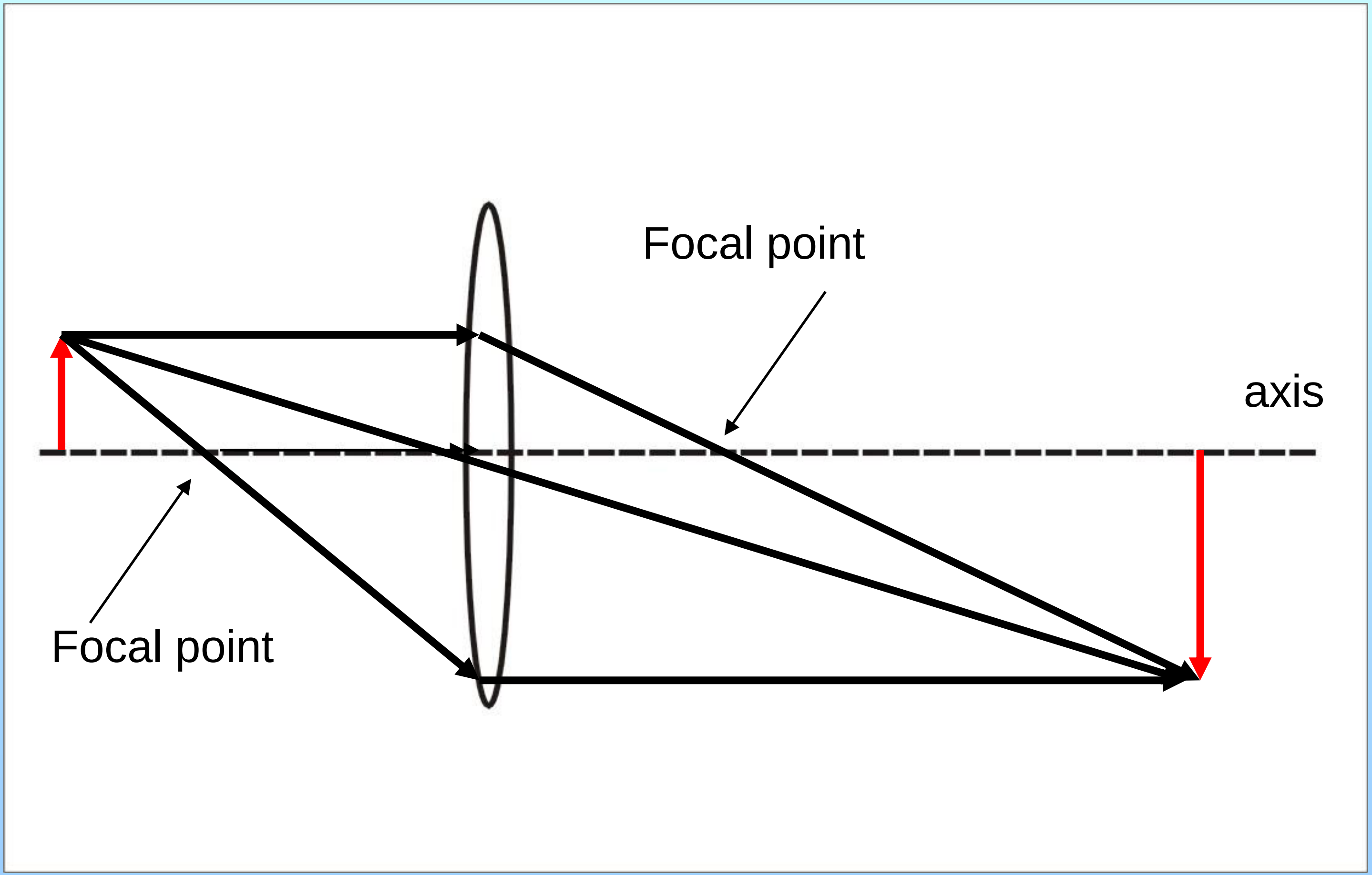
Geometrical Optics

- Ignores wave nature of light
- Basic technology for optical instruments
- Fermat's principle:

"Light propagating between two points follows a path, or paths,

for which the time taken is an extremum"

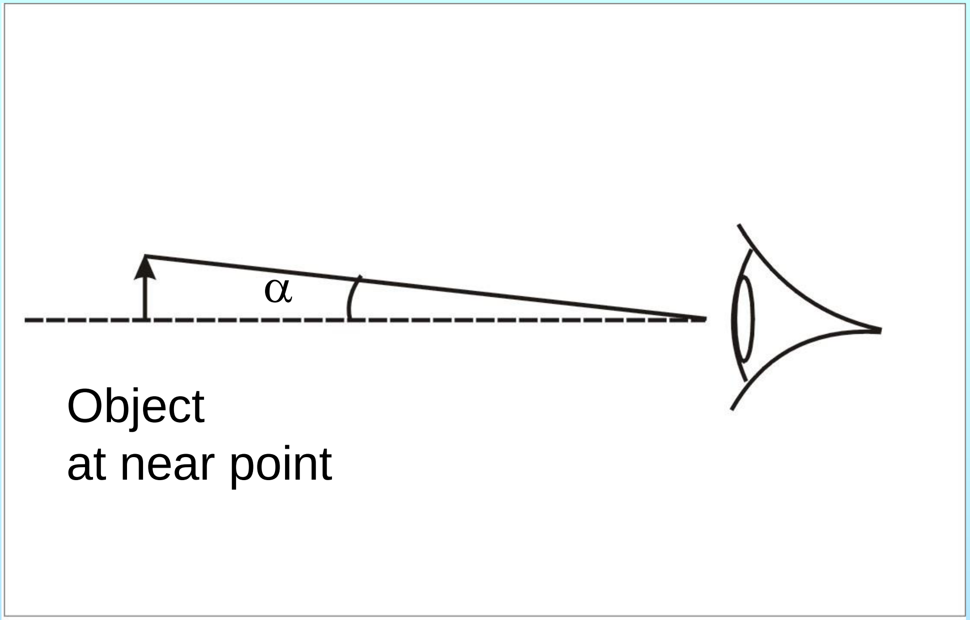
Ray tracing - revision

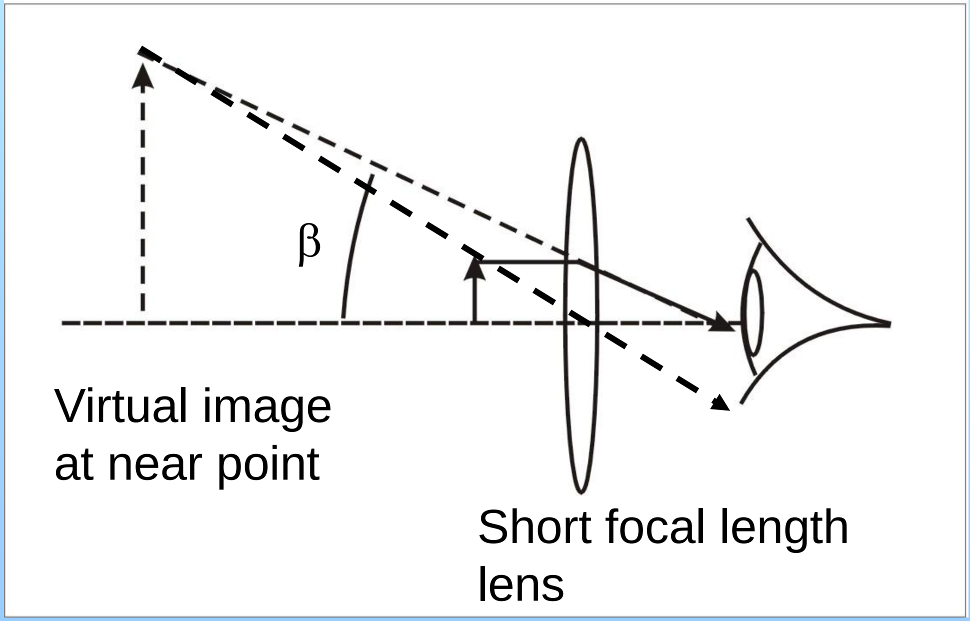


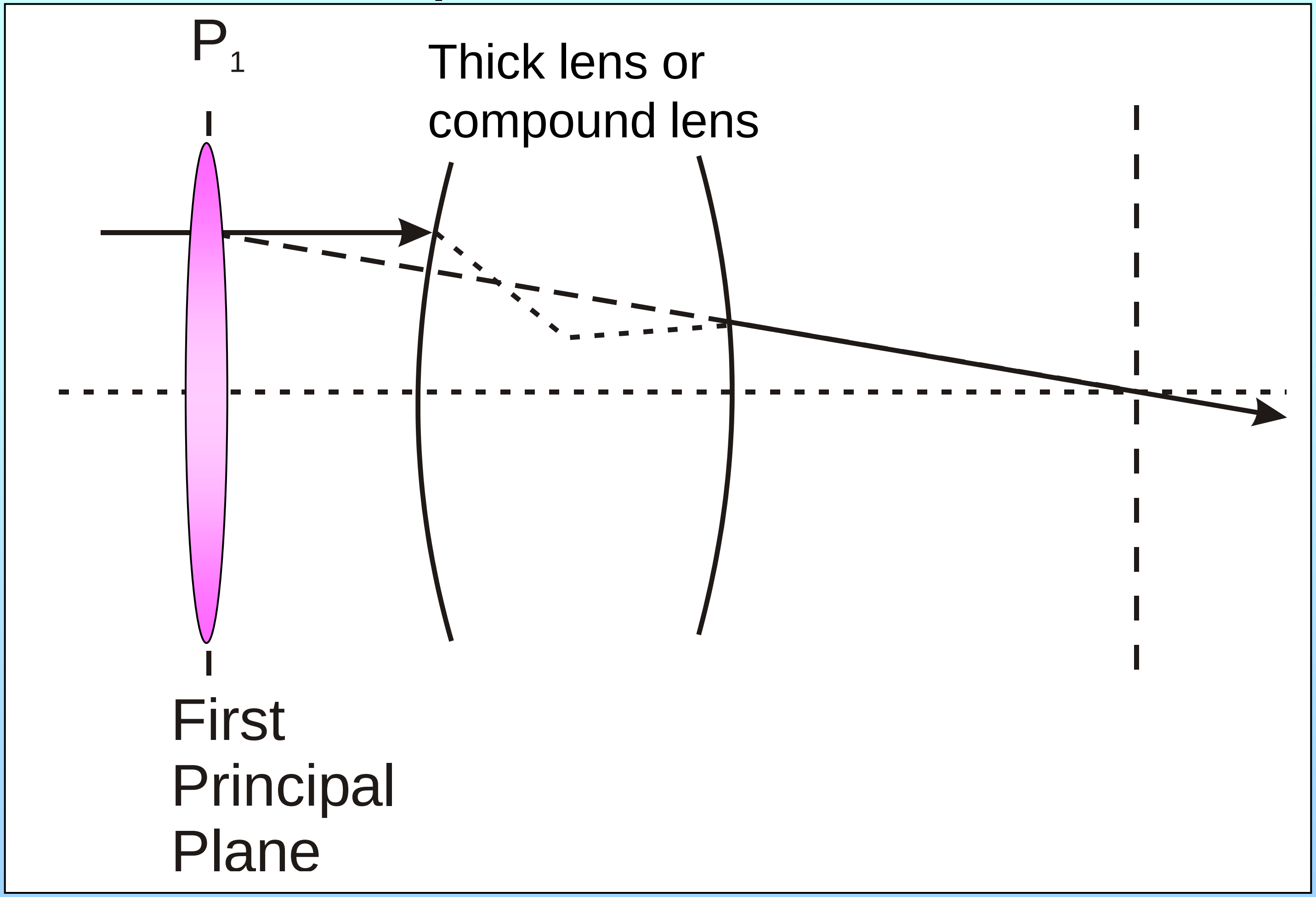
Simple magnifier

Magnifier:
angular magnification
= β/α

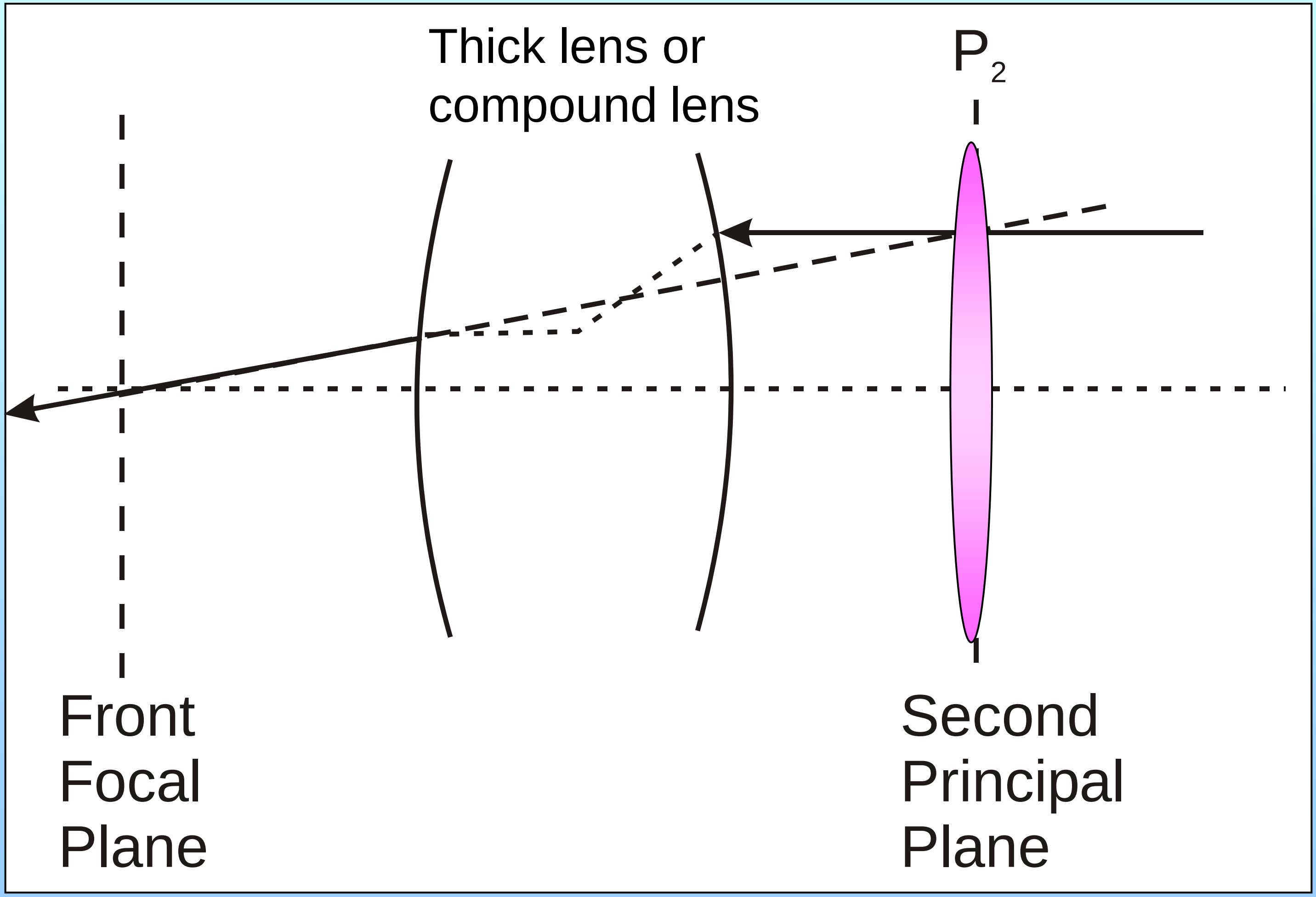
Eyepiece of
Telescopes,
Microscopes etc.





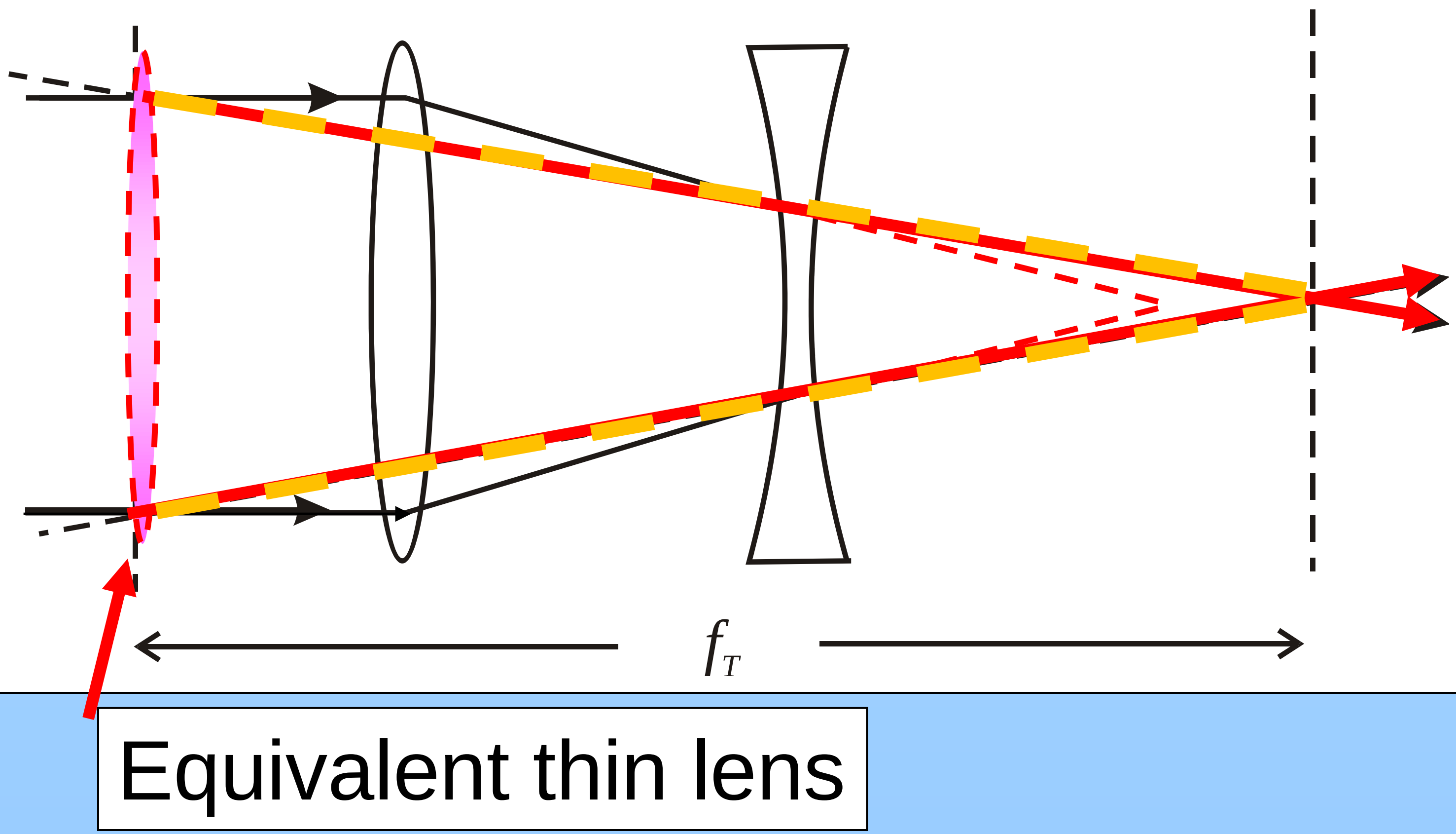


Location of
equivalent thin lens

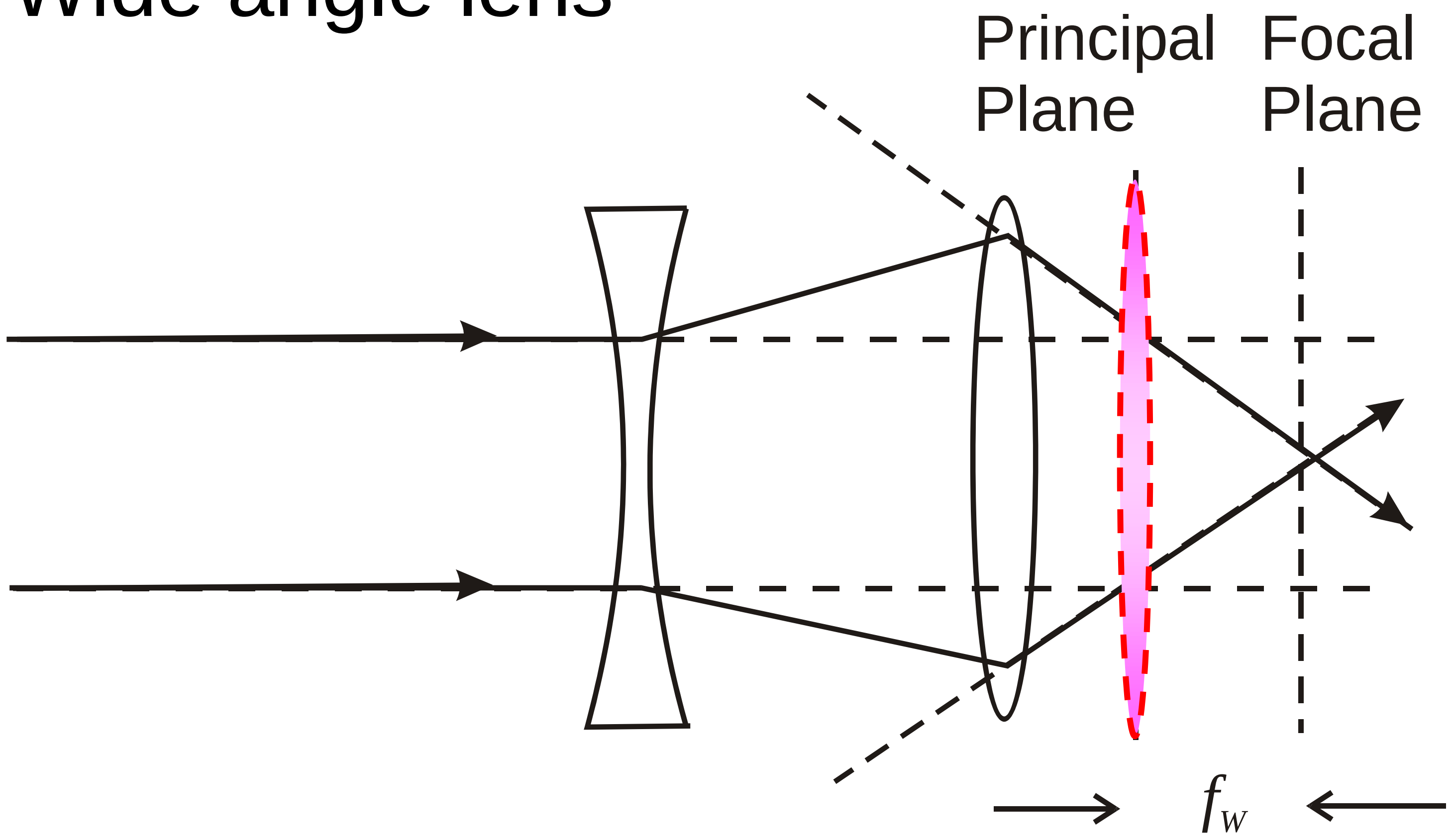


Thick lens or
compound lens
P_2
Front
Focal
Plane
Second
Principal
Plane

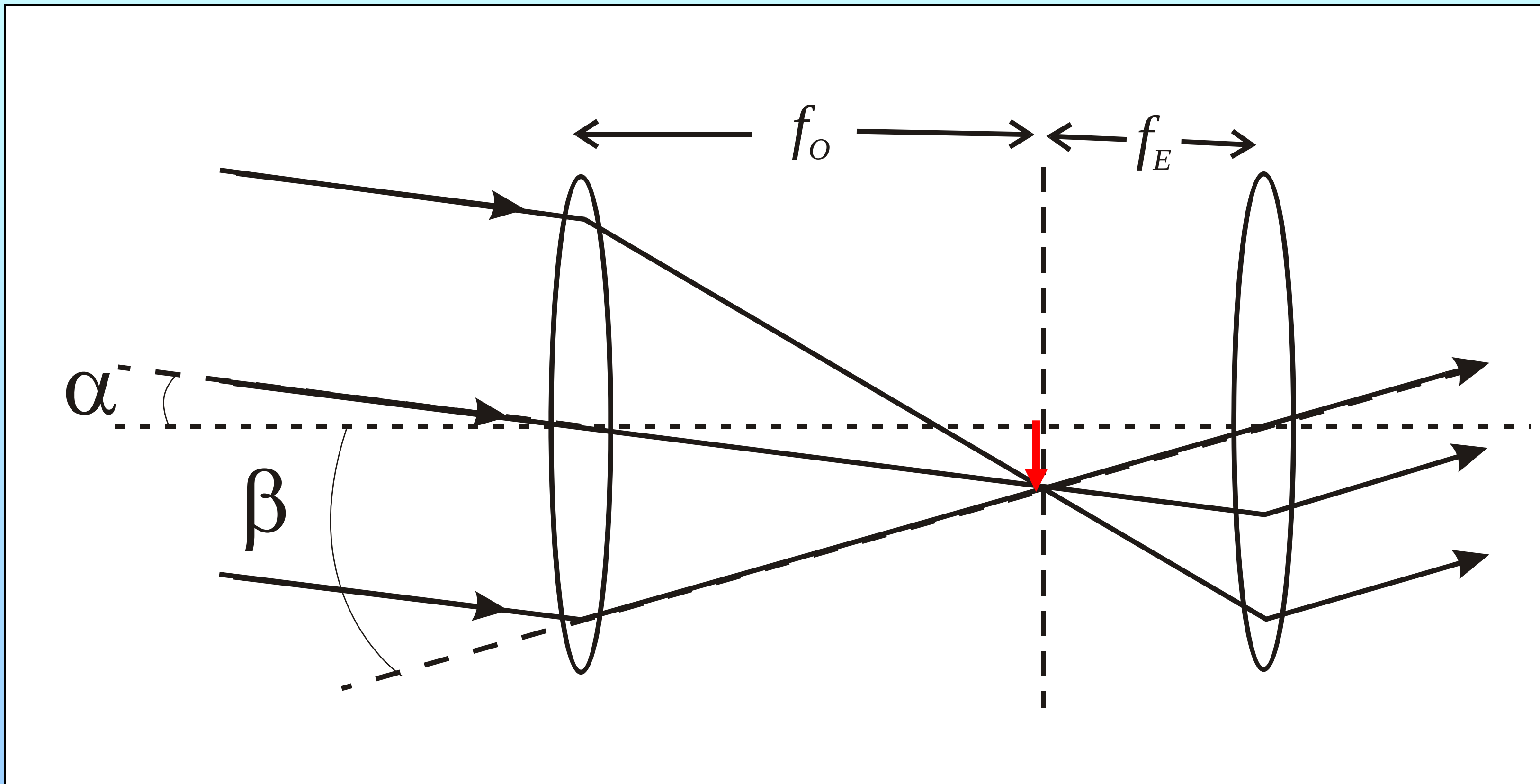
Telephoto lens



Wide angle lens

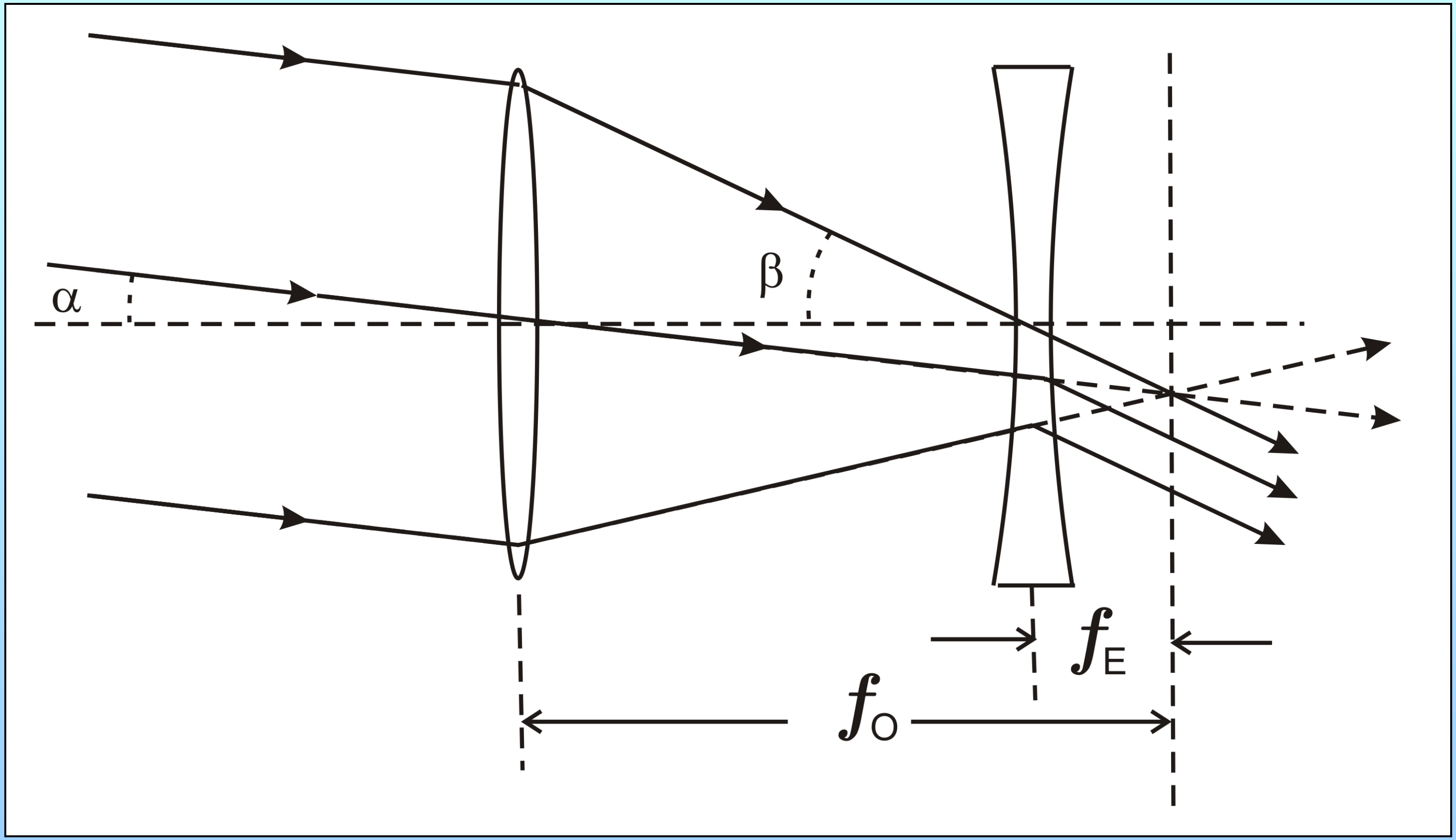


Astronomical Telescope



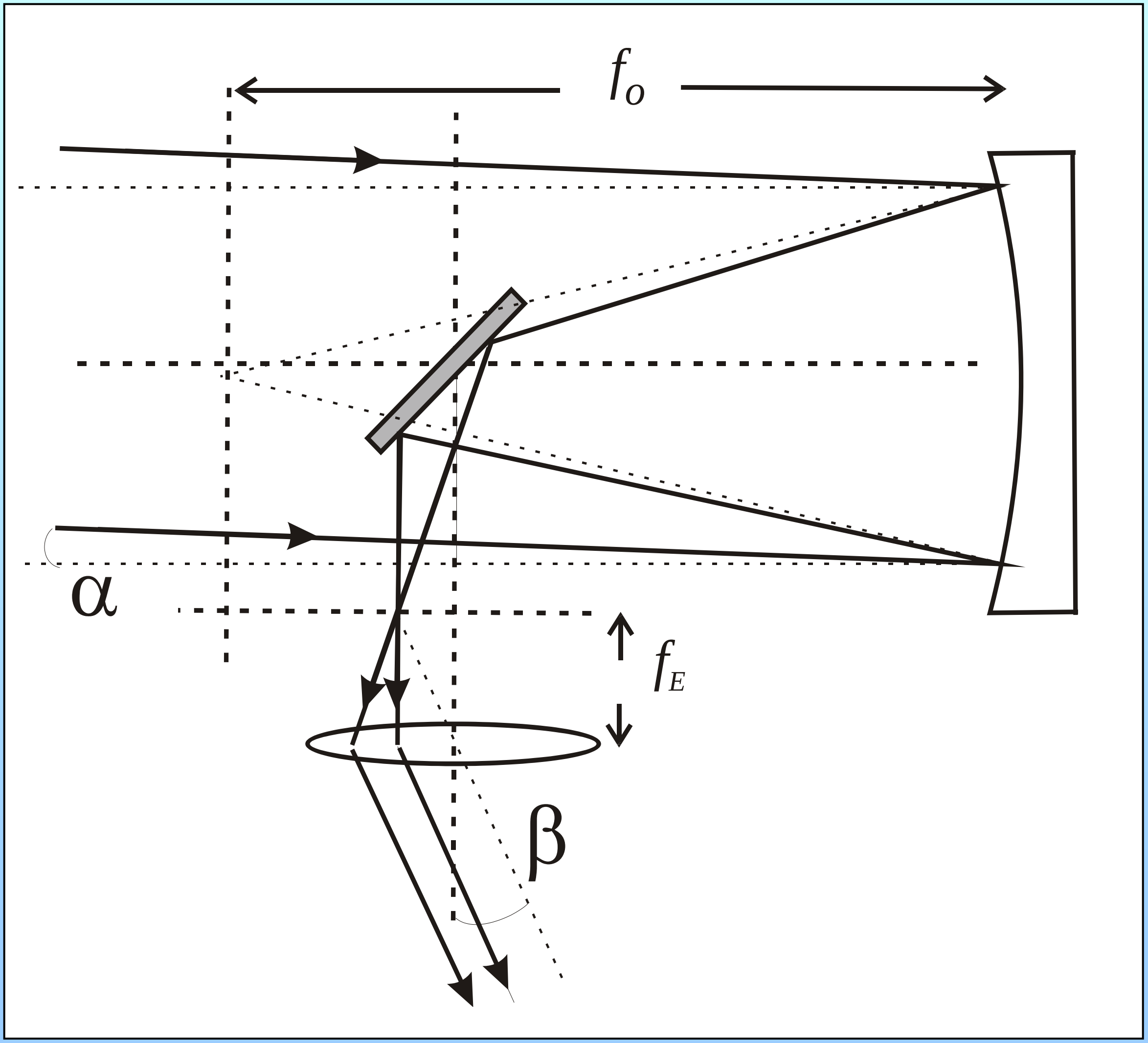
angular magnification = β/α = f_o/f_E

Galilean Telescope



angular magnification = β/α = f_o/f_E

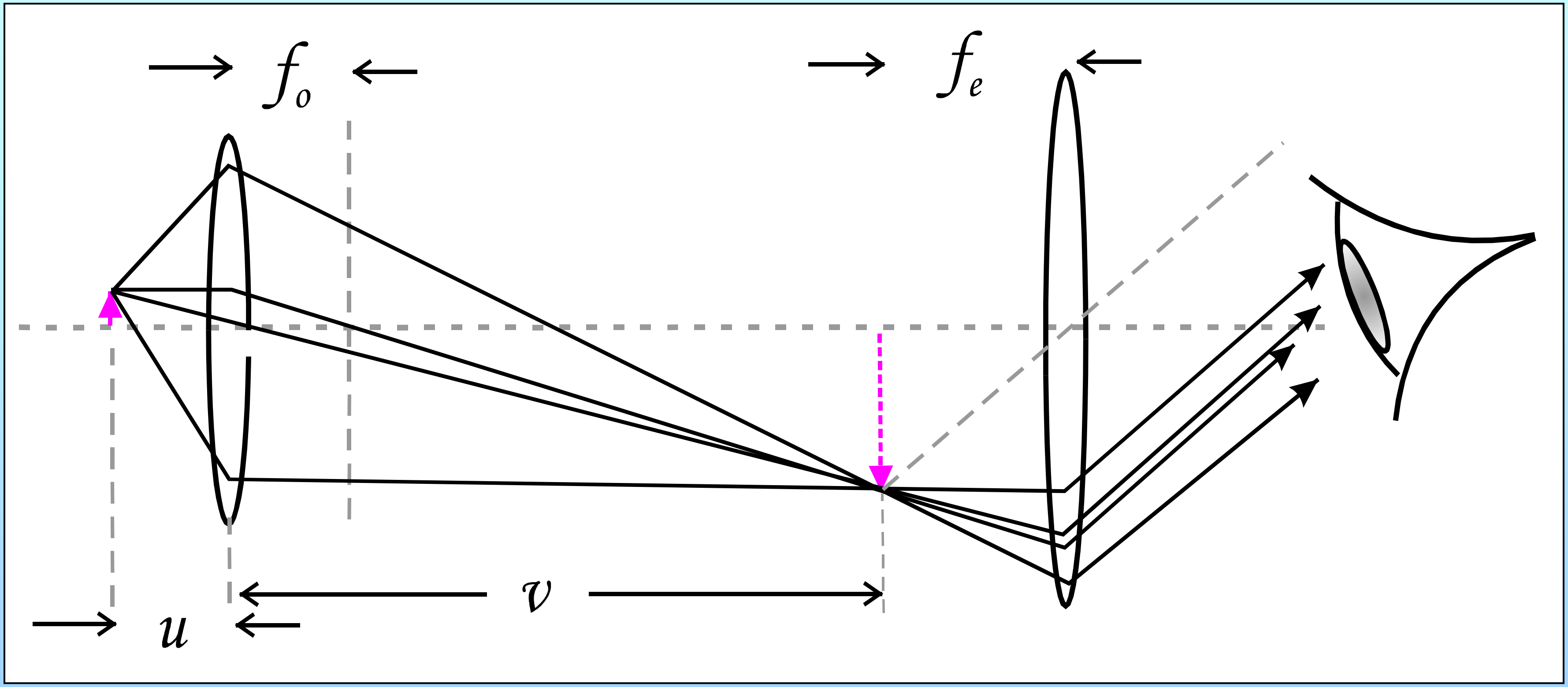
Newtonian Telescope



angular magnification = β/α

= $\boldsymbol{f_o/f_E}$

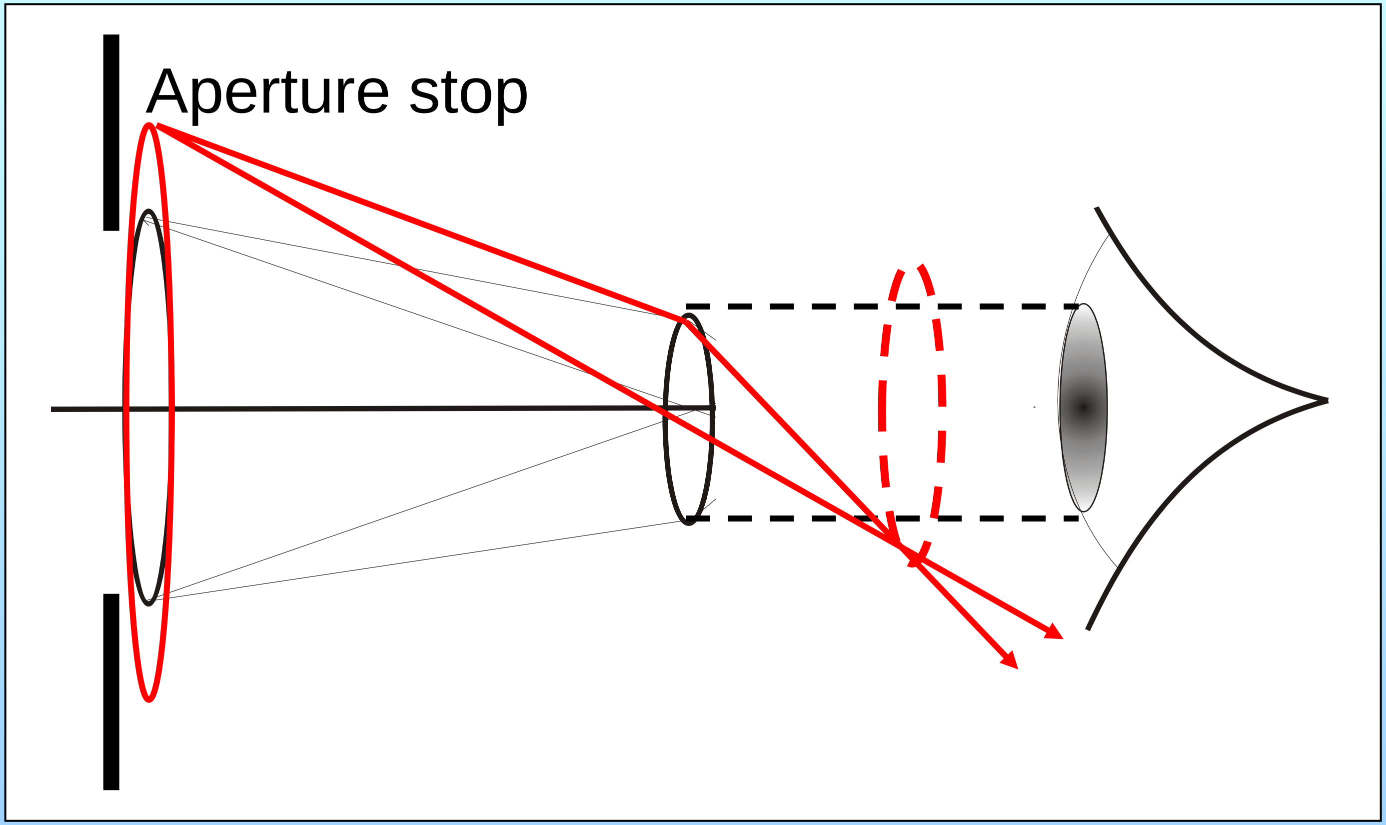
The compound microscope



Objective magnification = v/u

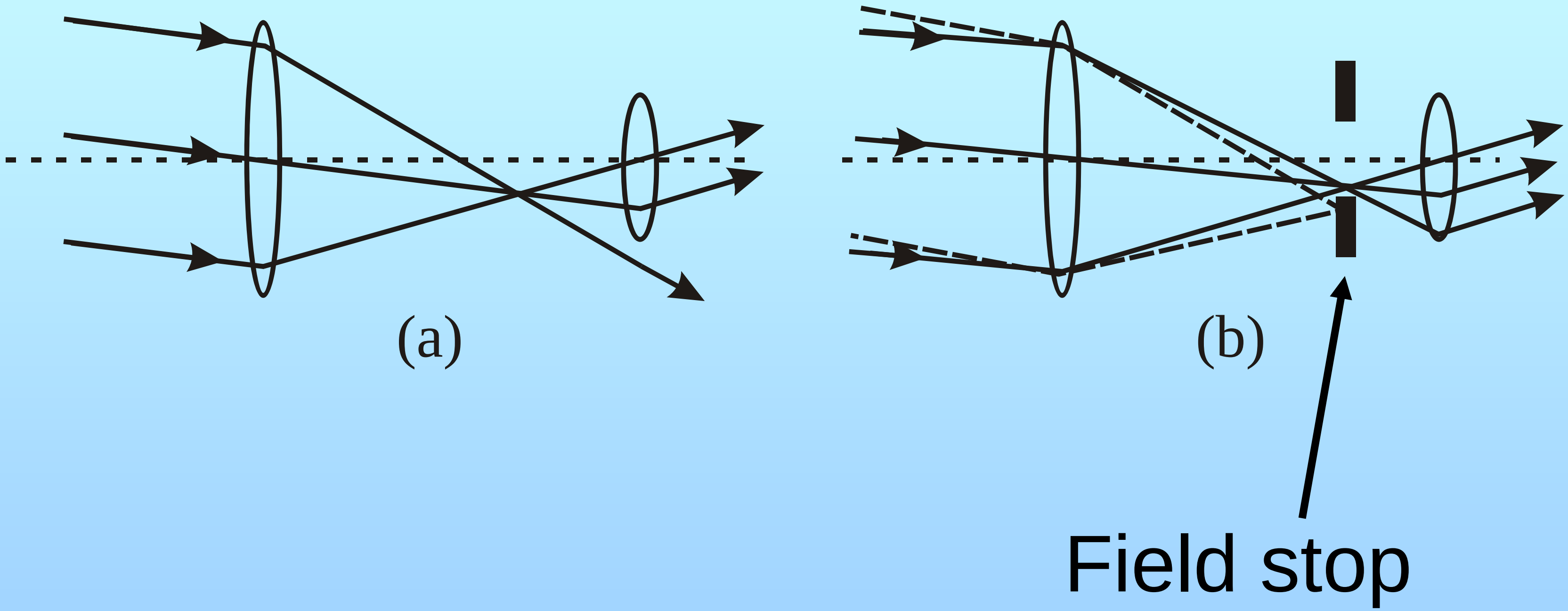
Eyepiece magnifies real image of object

What size to make the lenses?



Eye piece ~ pupil size

Objective: Image in eye-piece ~ pupil size

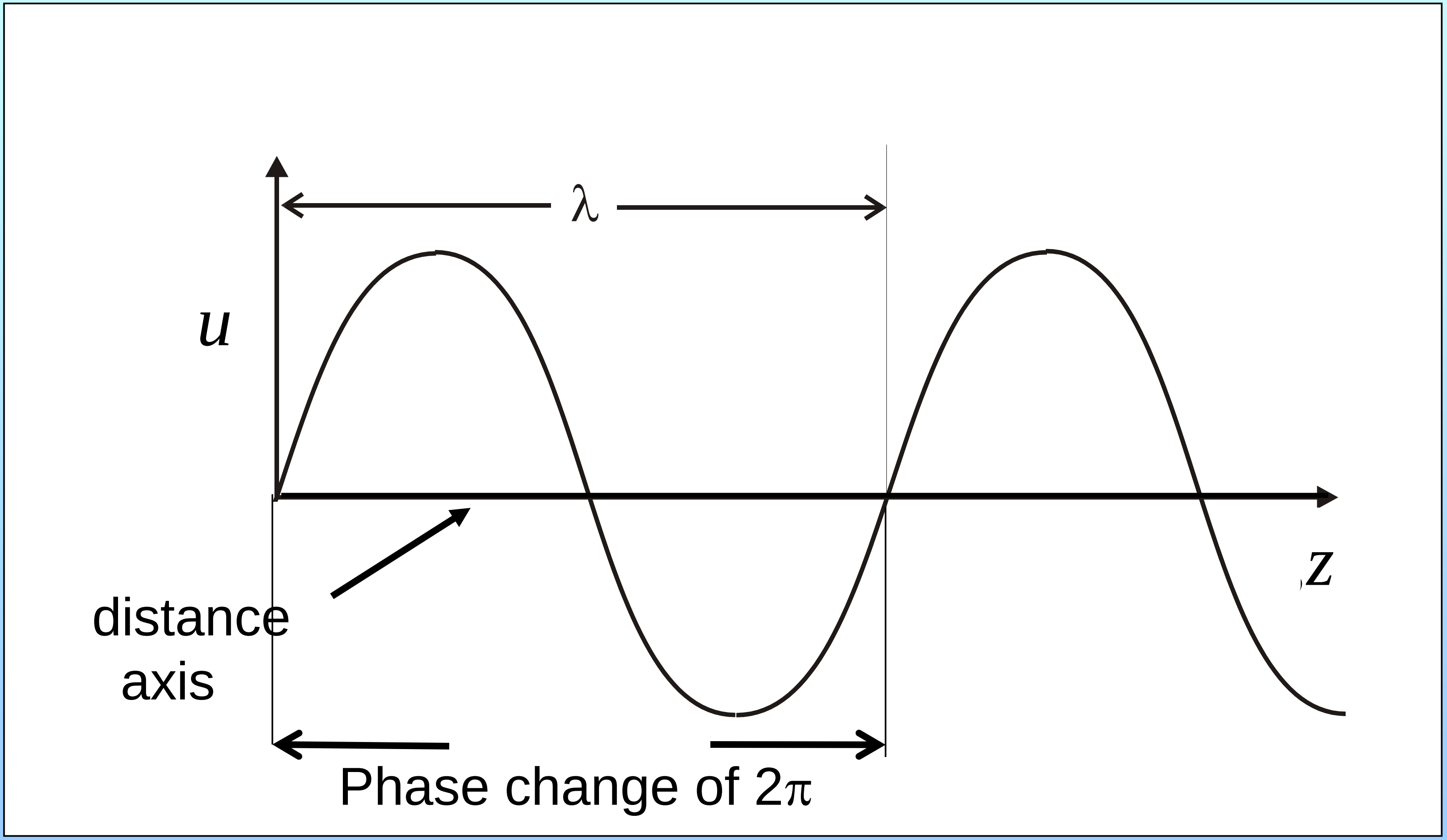

(a)
(b)
Field stop

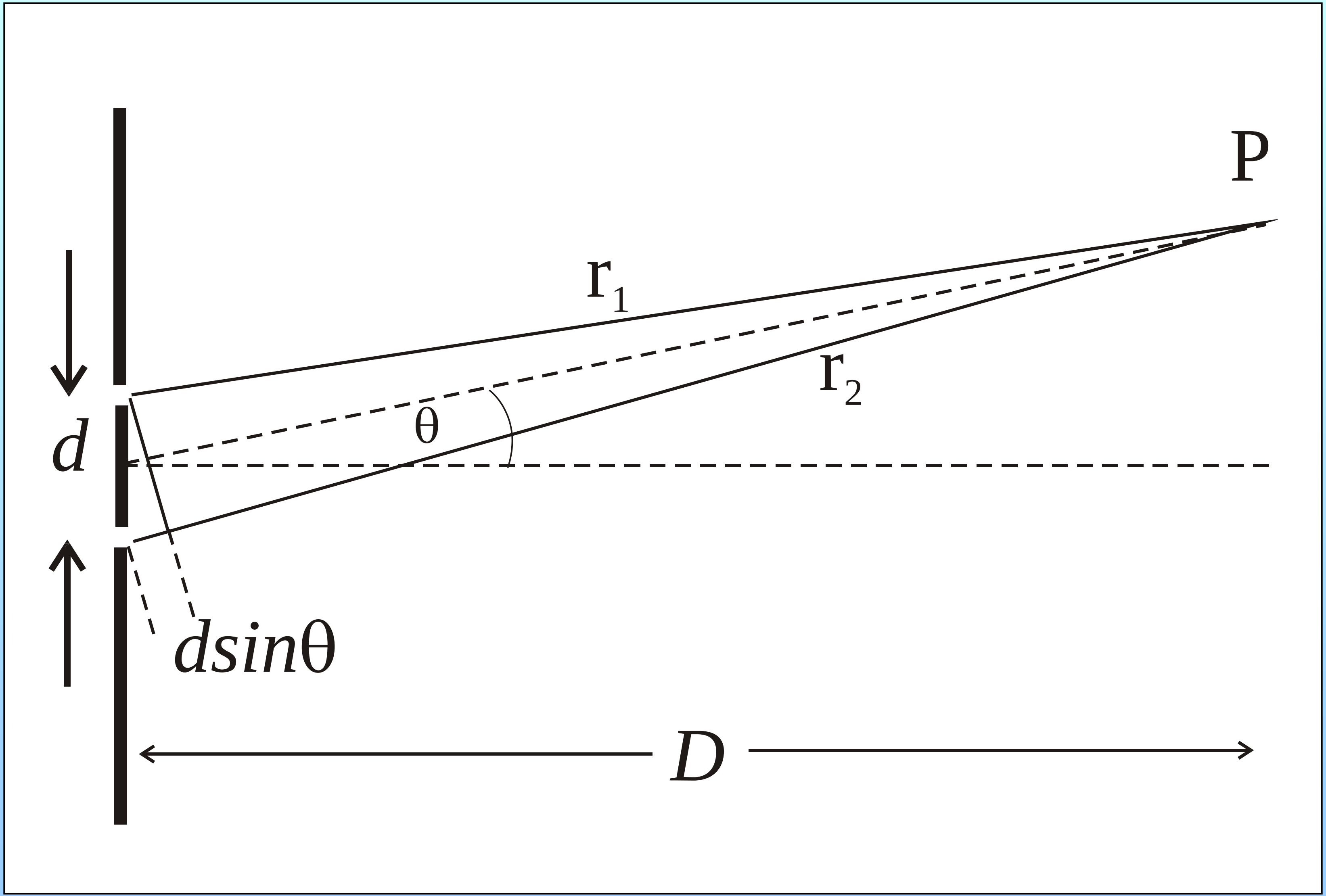
ILLUMINATION OF OPTICAL INSTRUMENTS

$$f/no. : \frac{\text{focal length}}{\text{diameter}}$$

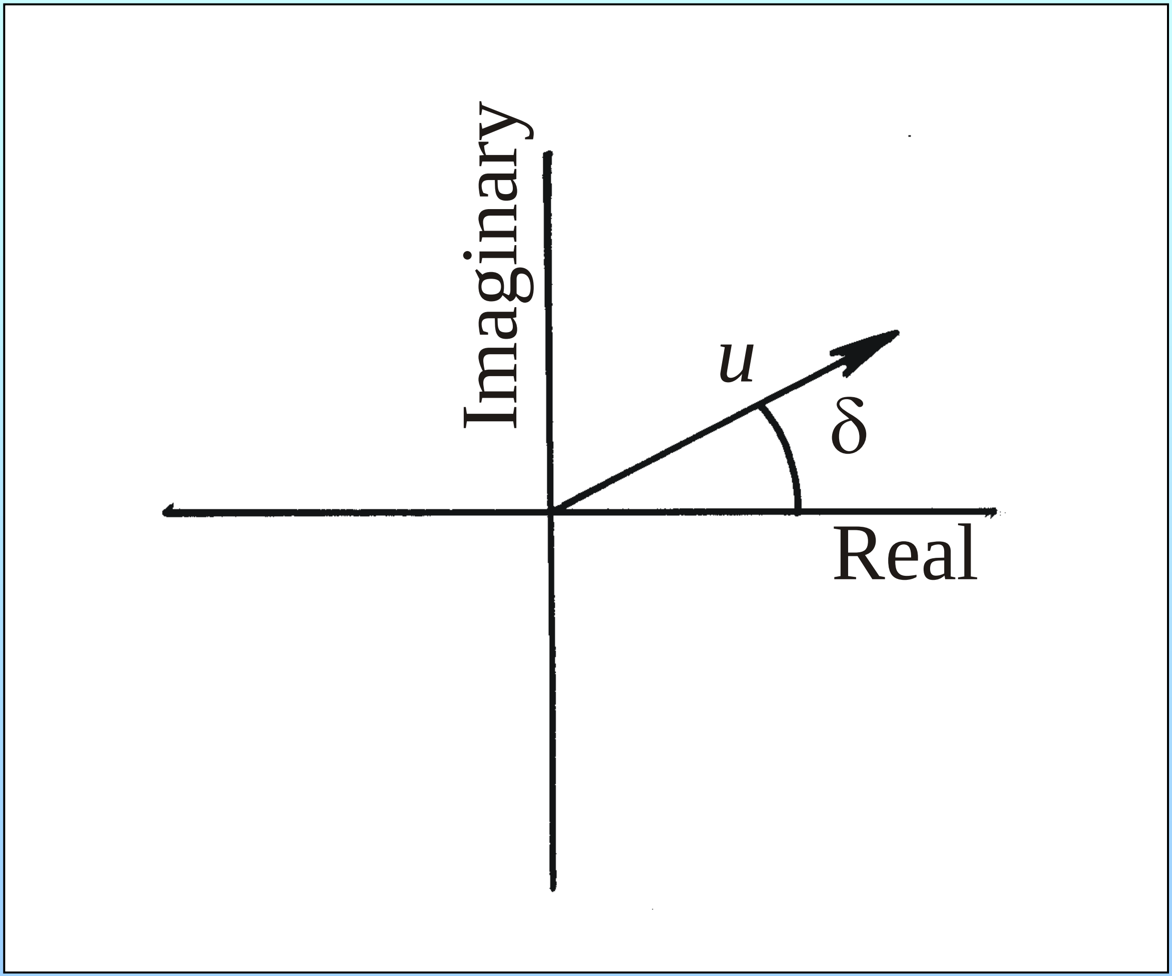
Lecture 2: Waves and Diffraction

- Interference
- Analytical method
- Phasor method
- Diffraction at 2-D apertures

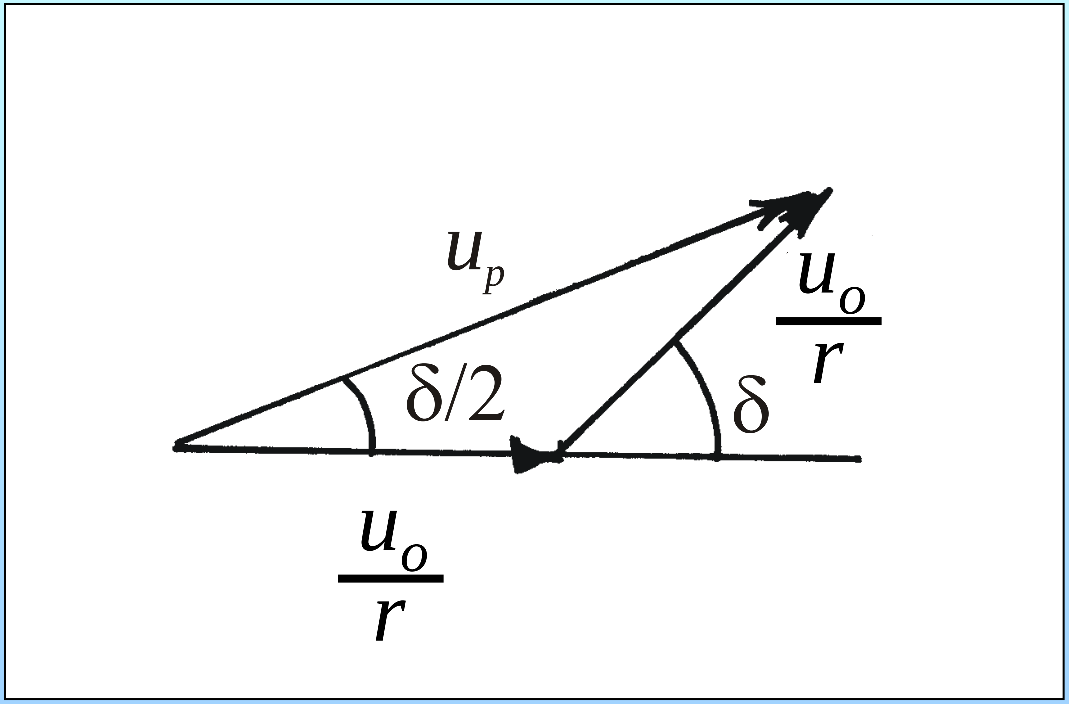

λ
u
z
distance
axis
Phase change of 2π


P
r1
r2
θ
d
dsinθ
D

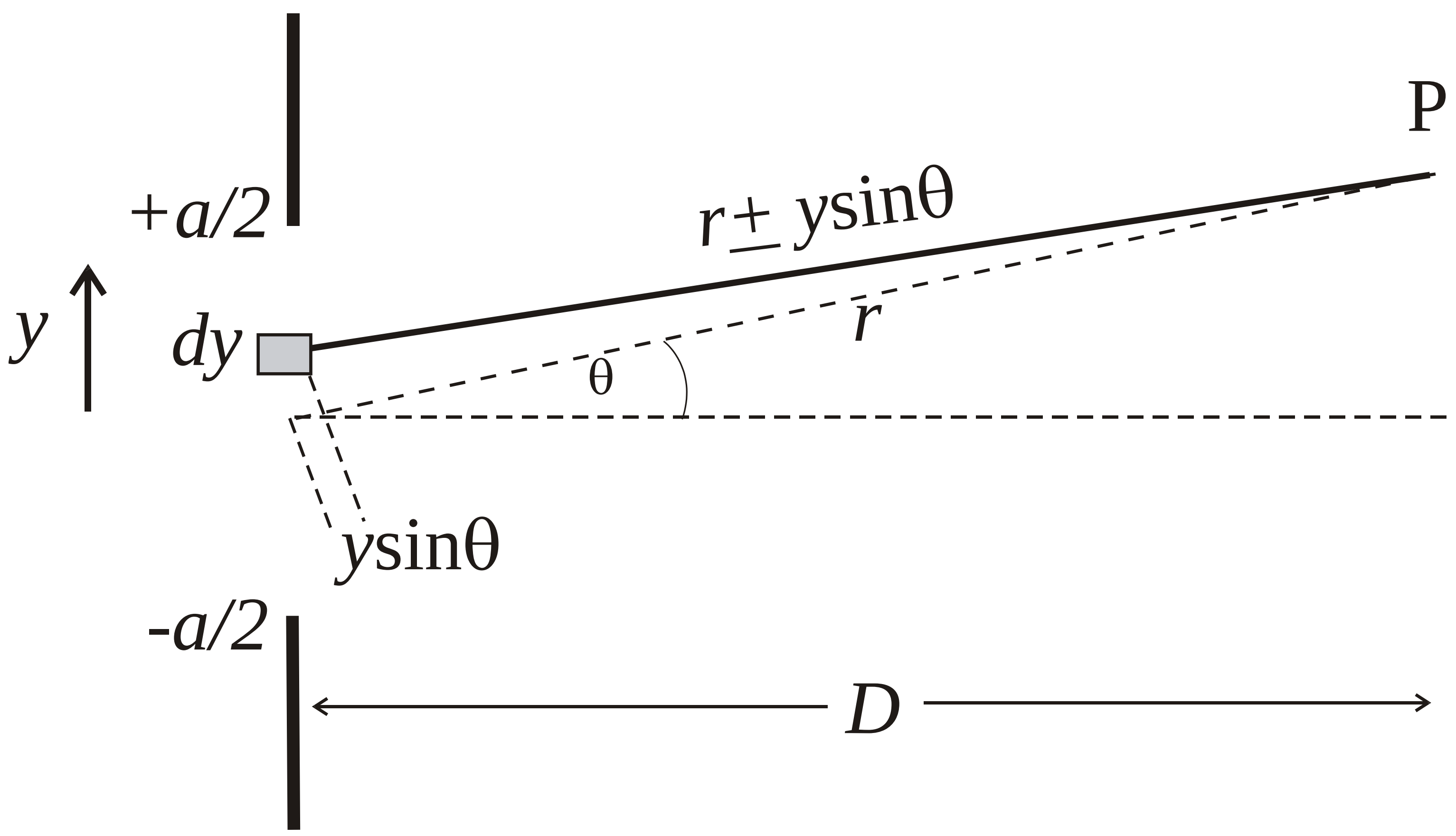
Phasor diagram



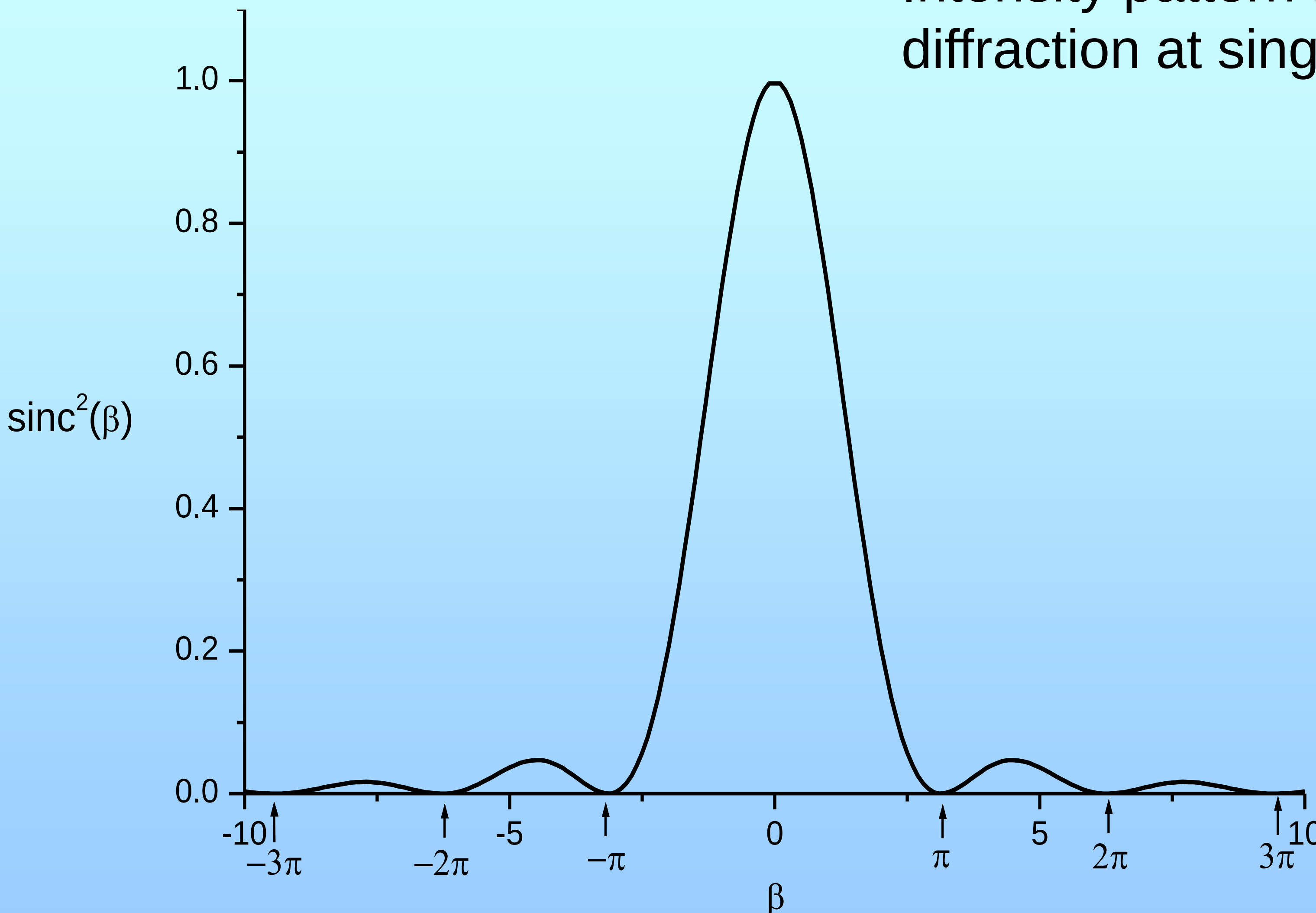
Phasor diagram for 2-slit interference

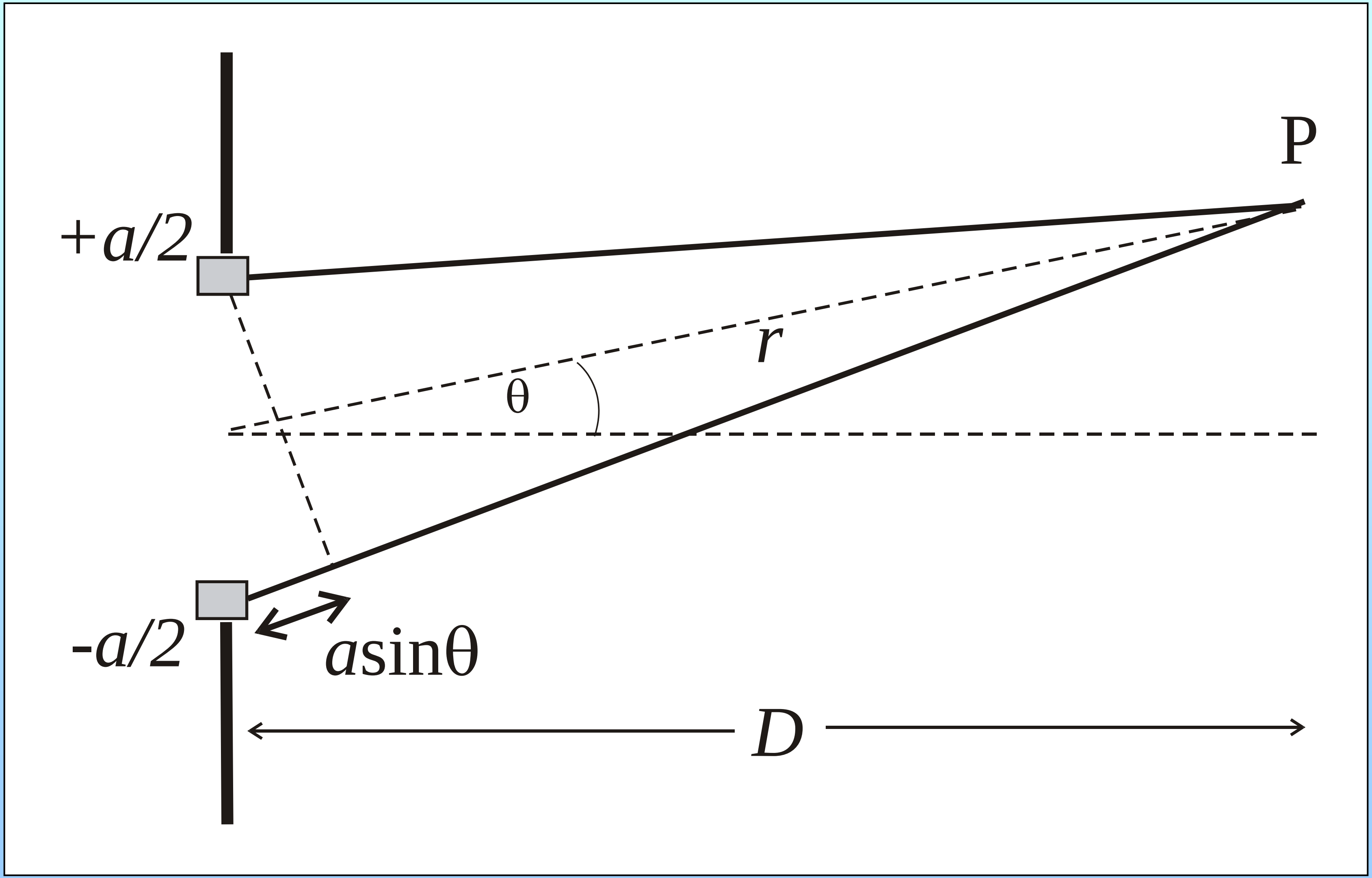


Diffraction from a single slit

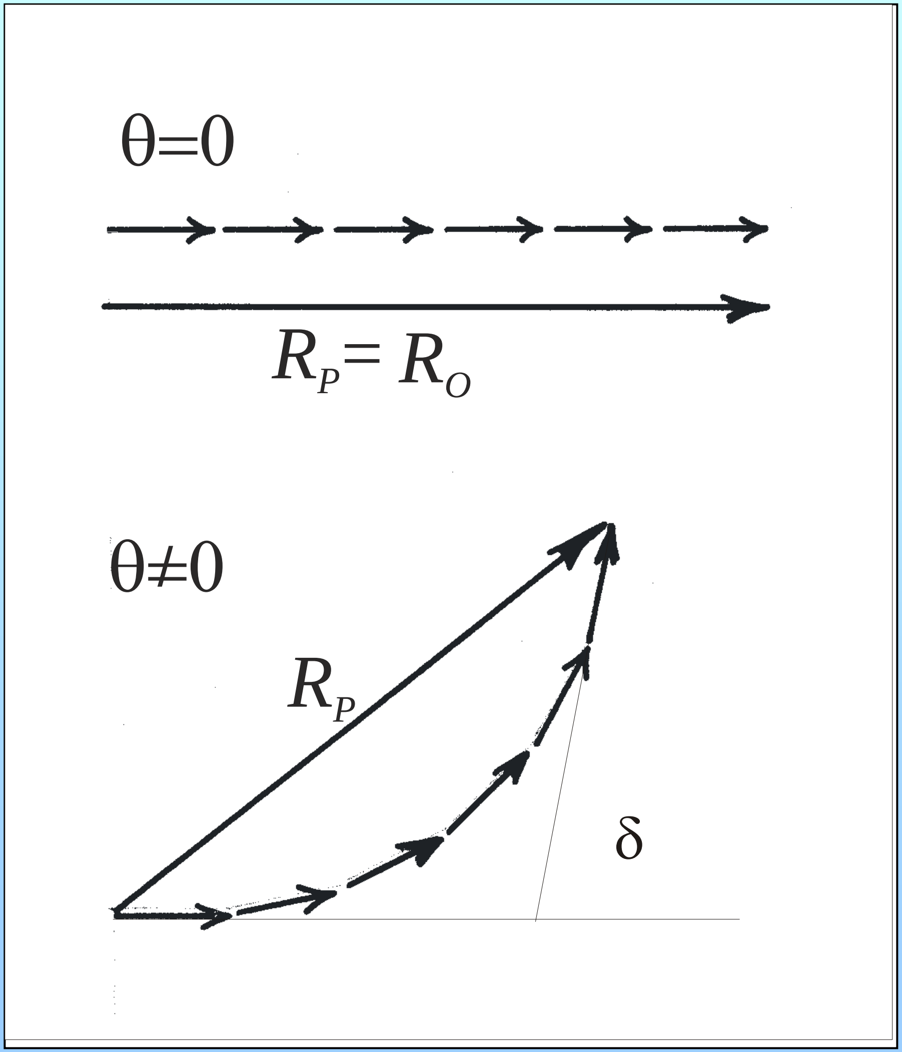


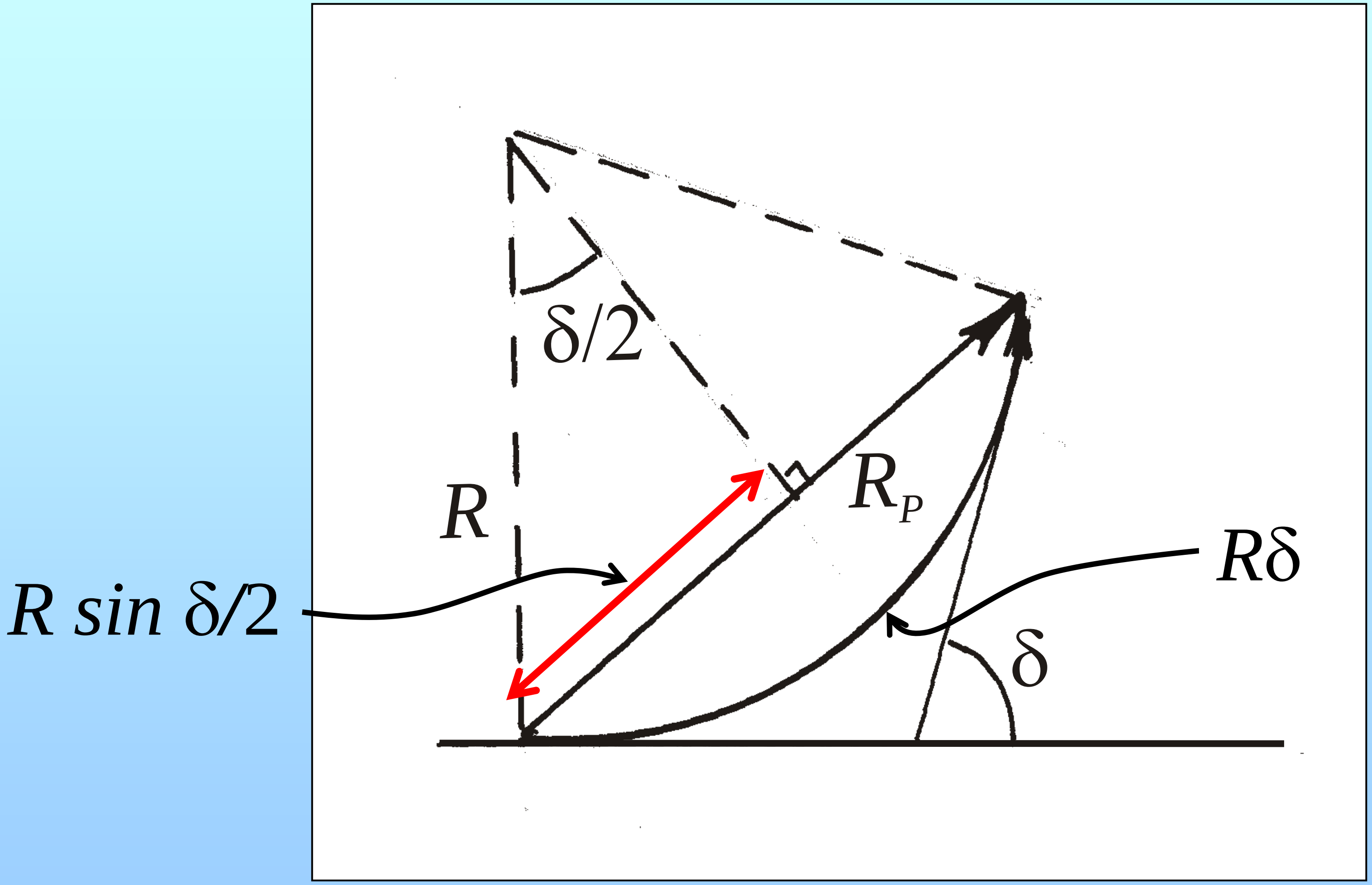
Intensity pattern from diffraction at single slit

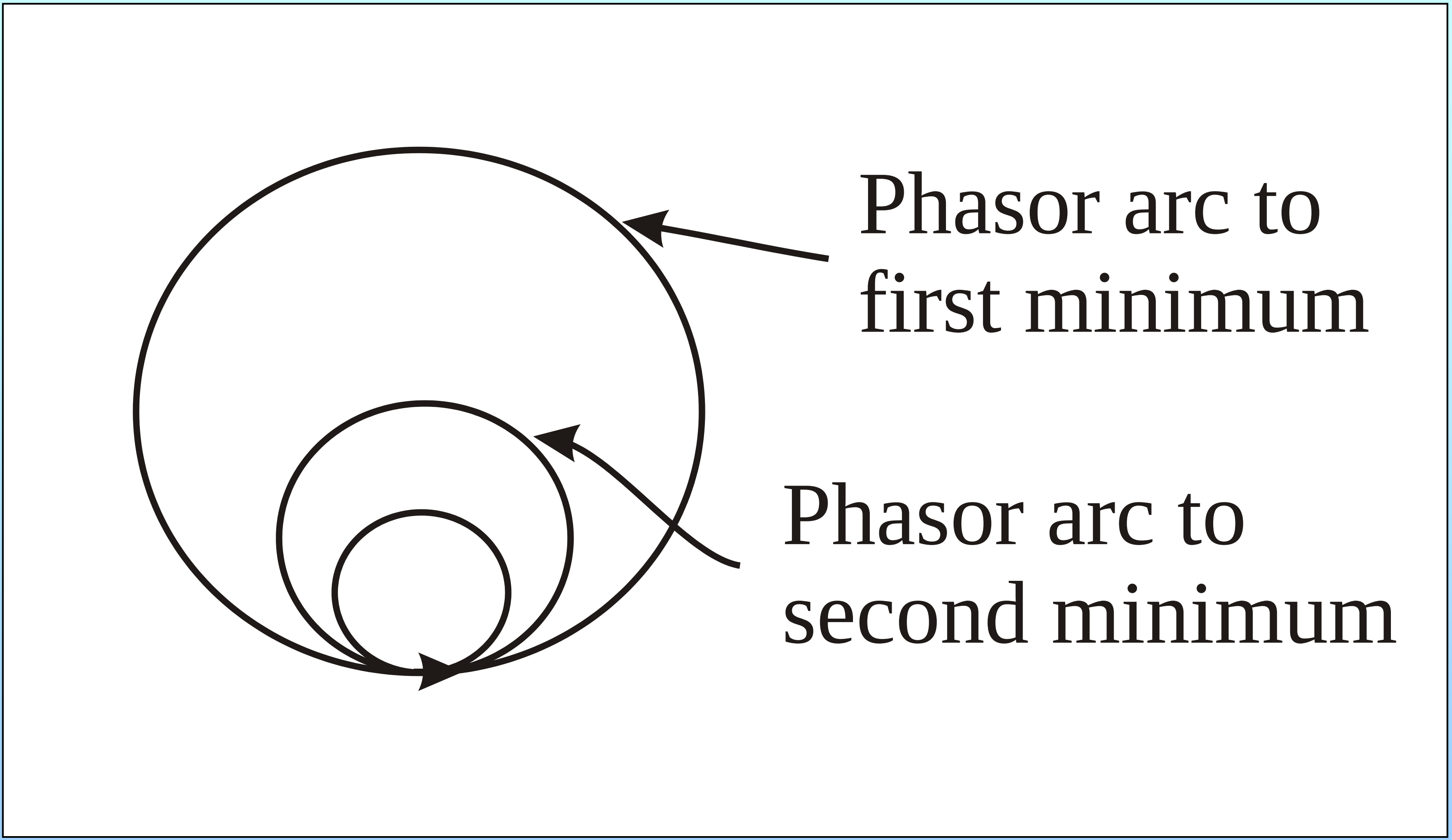


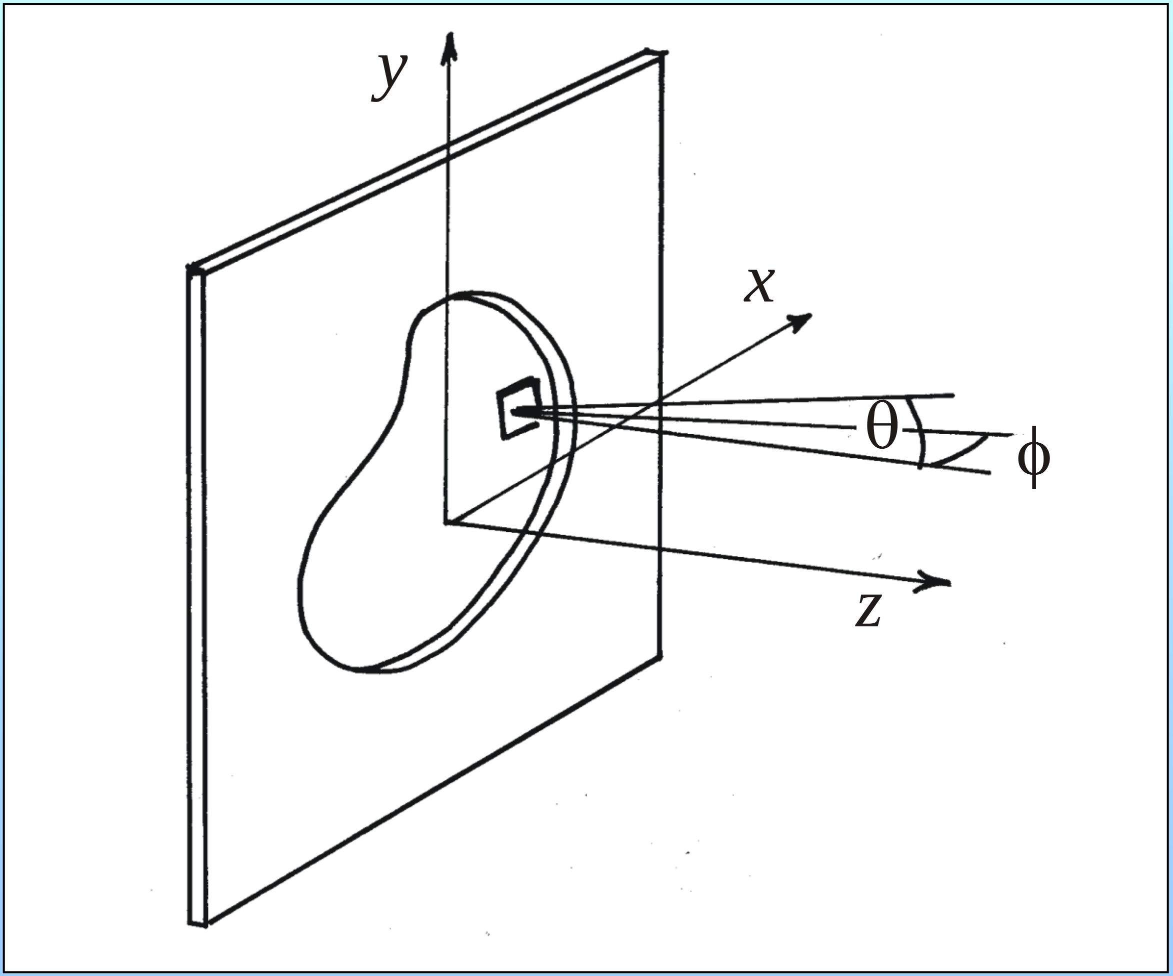

P
+a/2
r
θ
-a/2
asinθ
D

Phasors and resultant at different angles θ

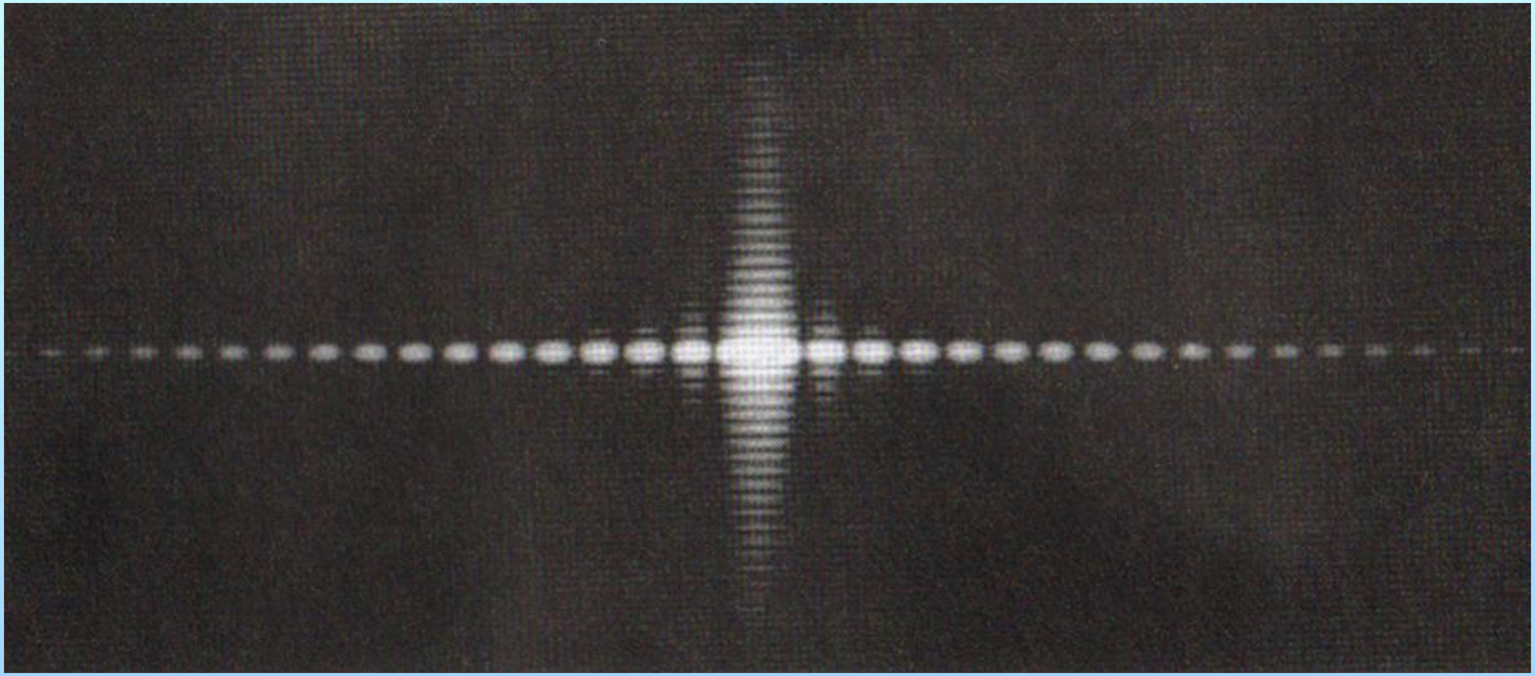



δ/2
R
R_P
Rδ
R sin δ/2
δ

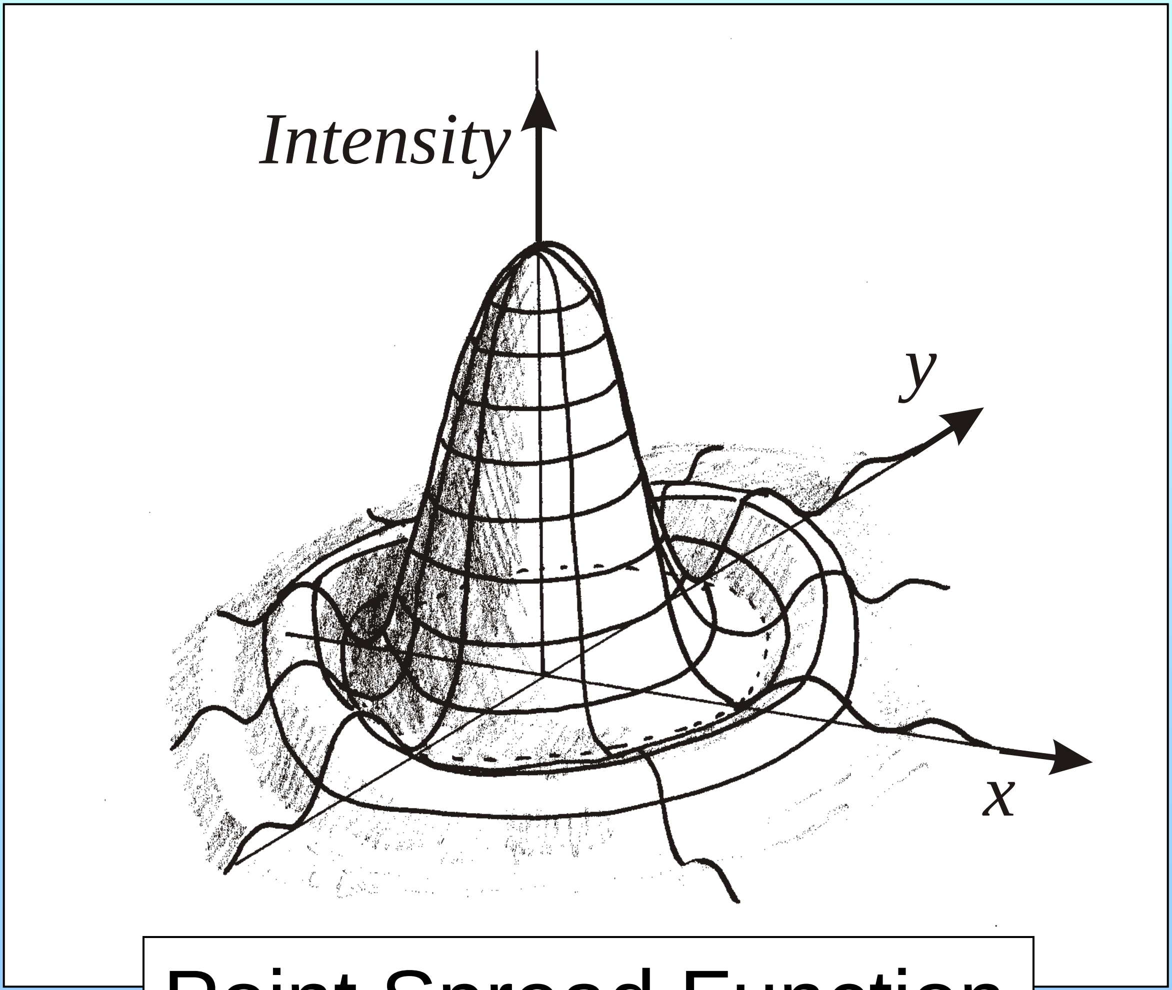

Phasor arc to first minimum
Phasor arc to second minimum


y
x
θ
ϕ
z

Diffraction from a rectangular aperture

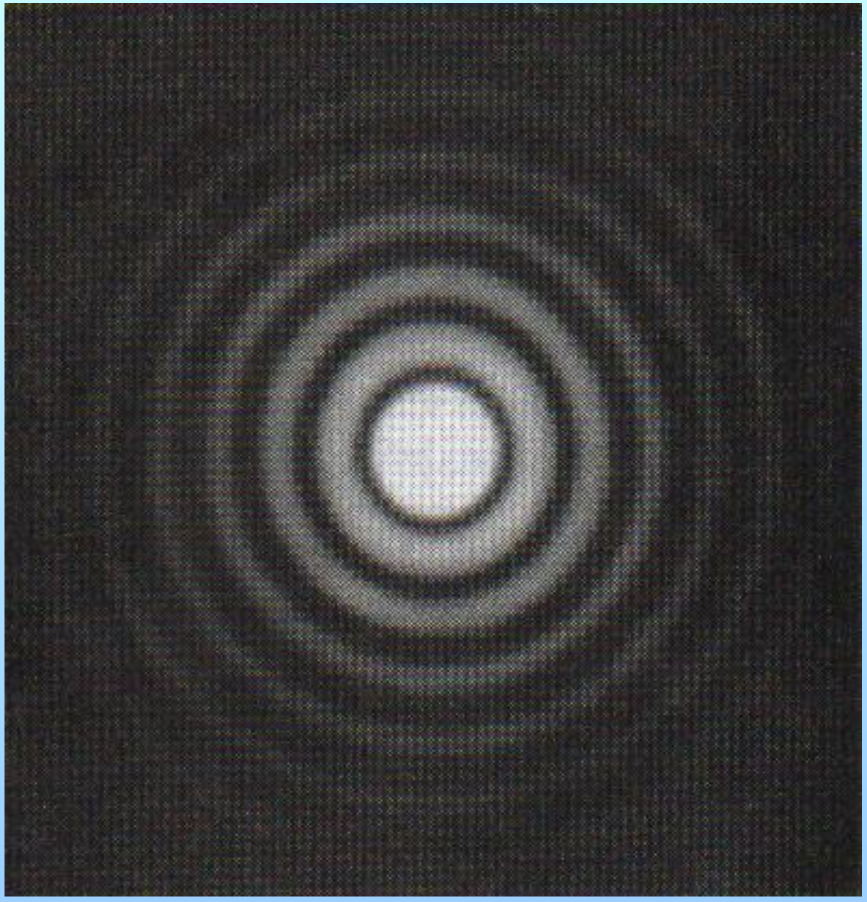


Diffraction pattern from circular aperture

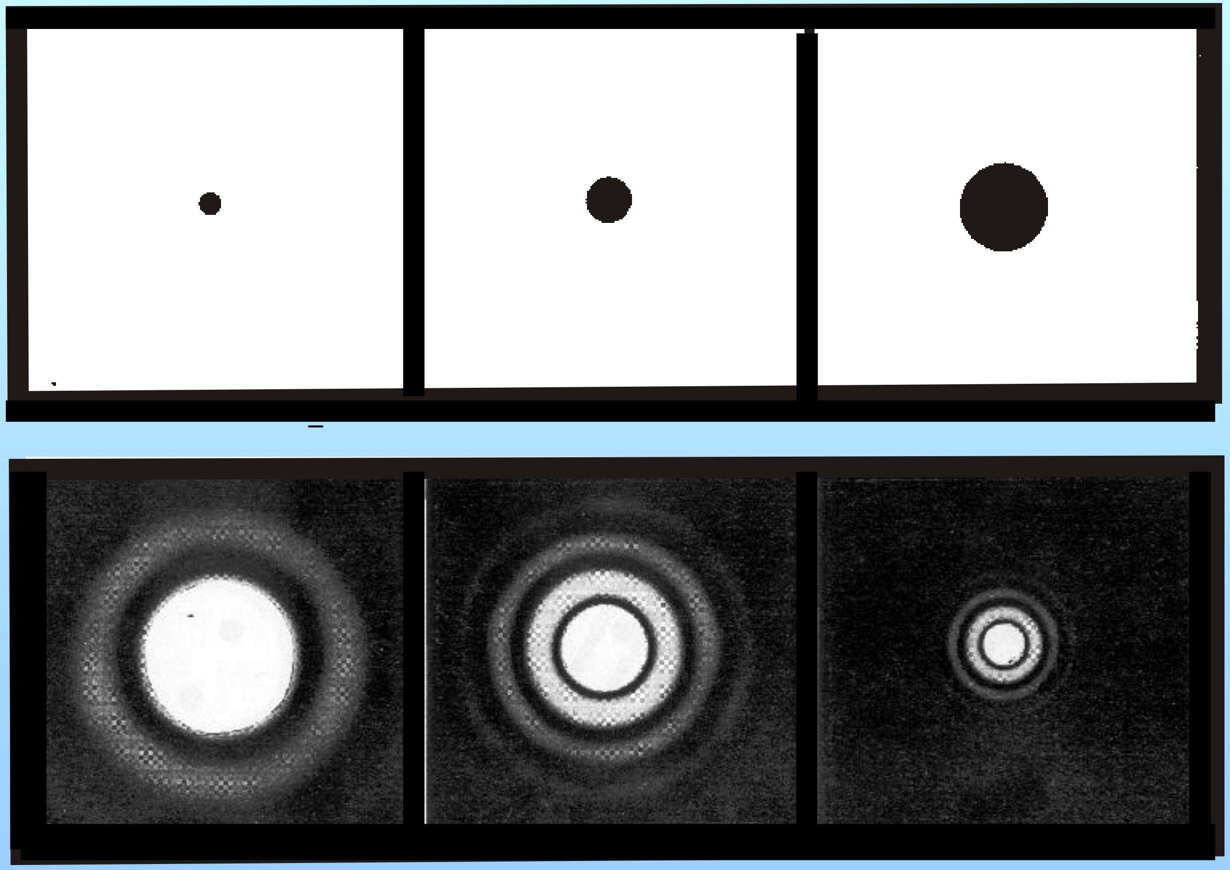


Point Spread Function

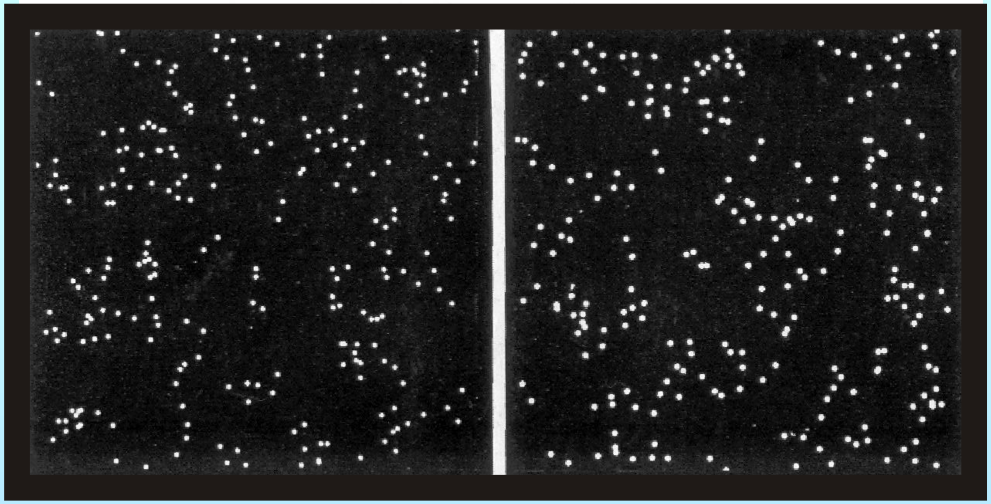
Diffraction from a circular aperture



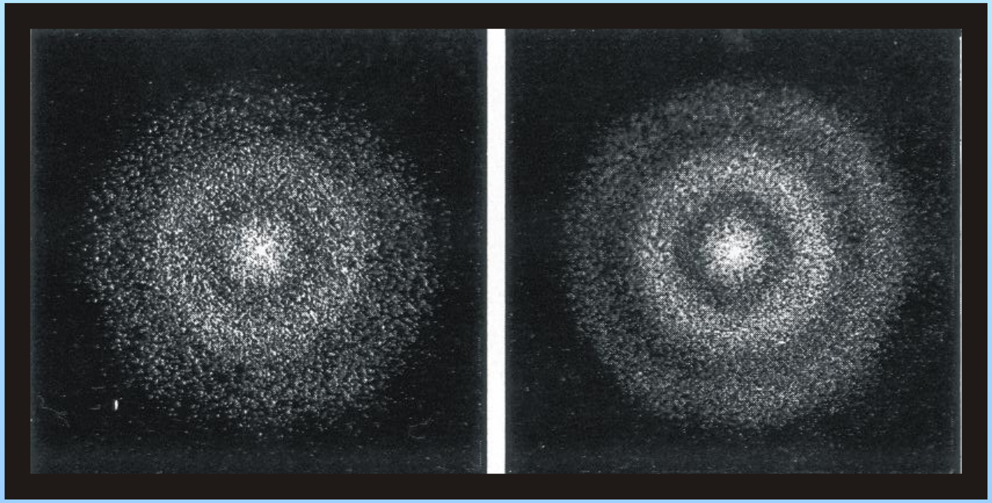
Diffraction from circular apertures



Dust pattern



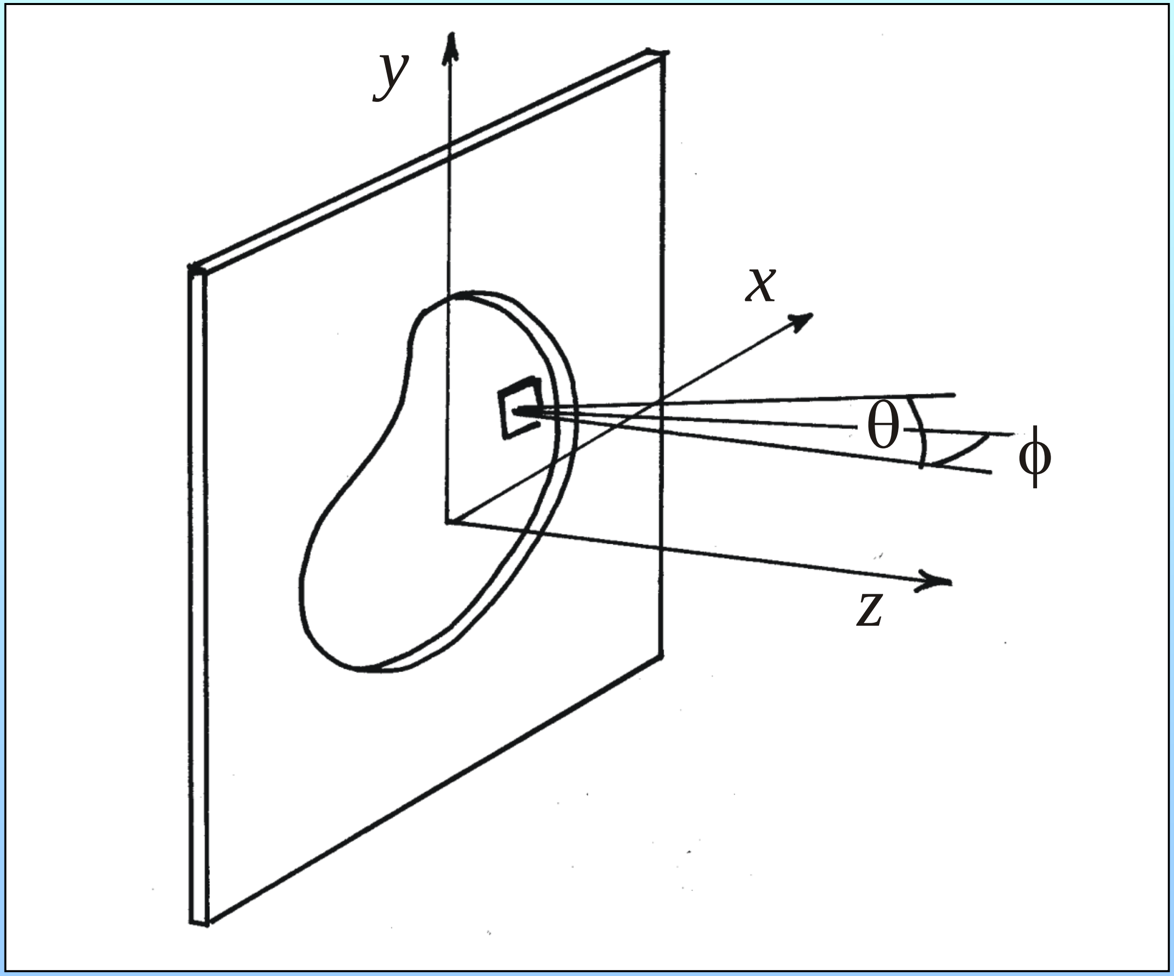
Diffraction pattern



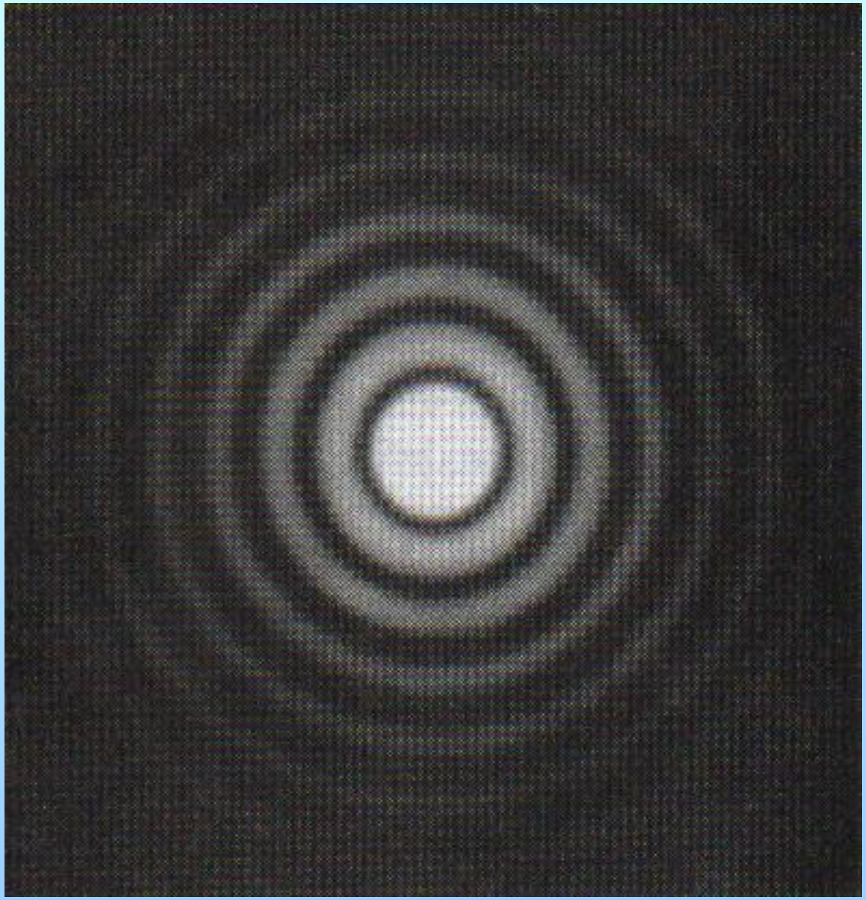
Basis of particle sizing instruments

Lecture 3: Diffraction theory and wave propagation

- Fraunhofer diffraction
- Huygens-Fresnel theory of wave propagation
- Fresnel-Kirchoff diffraction integral


y
x
θ
ϕ
z

Diffraction from a circular aperture

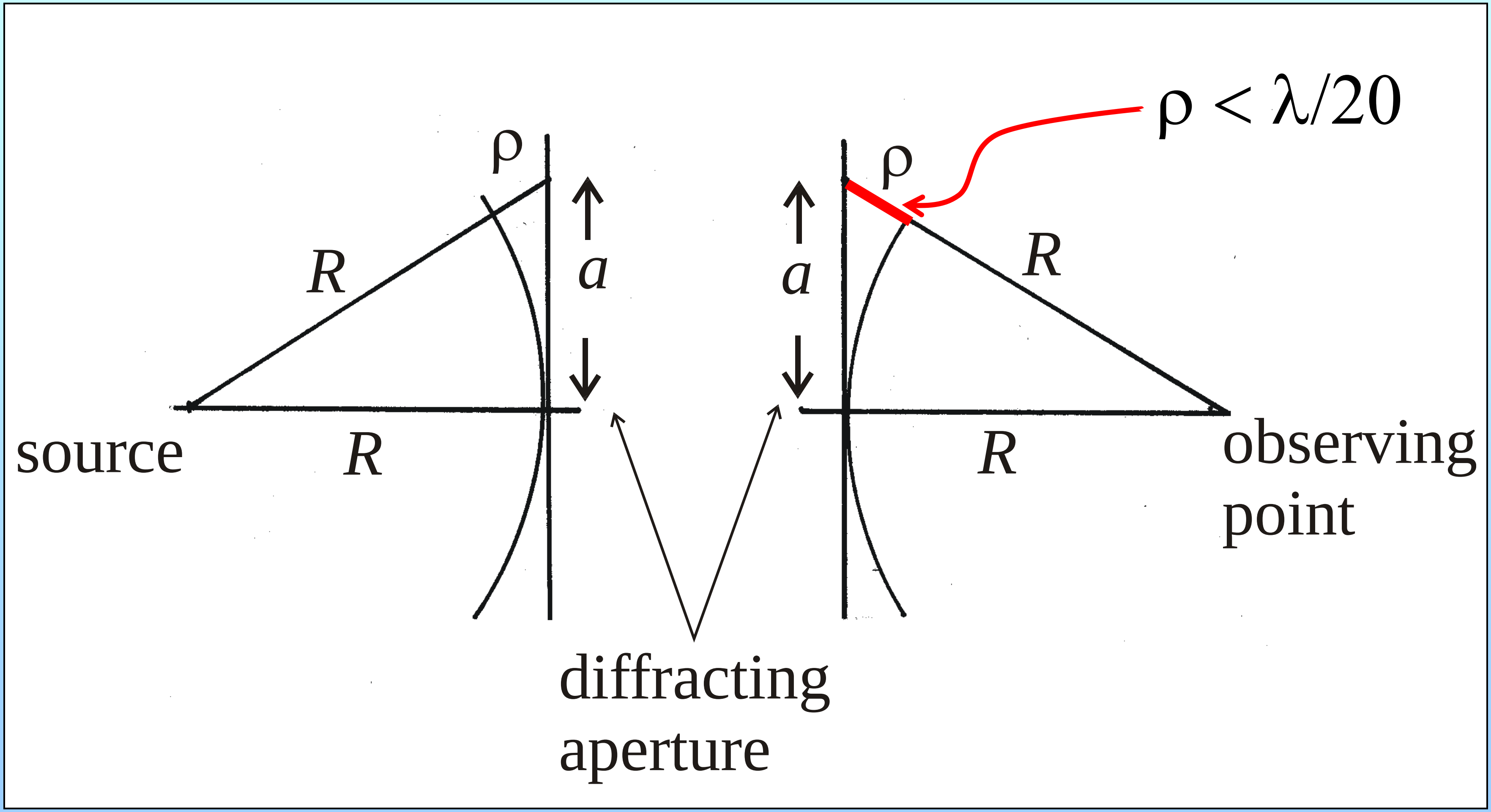


Fraunhofer Diffraction


Joseph von Fraunhofer
(1787-1826)

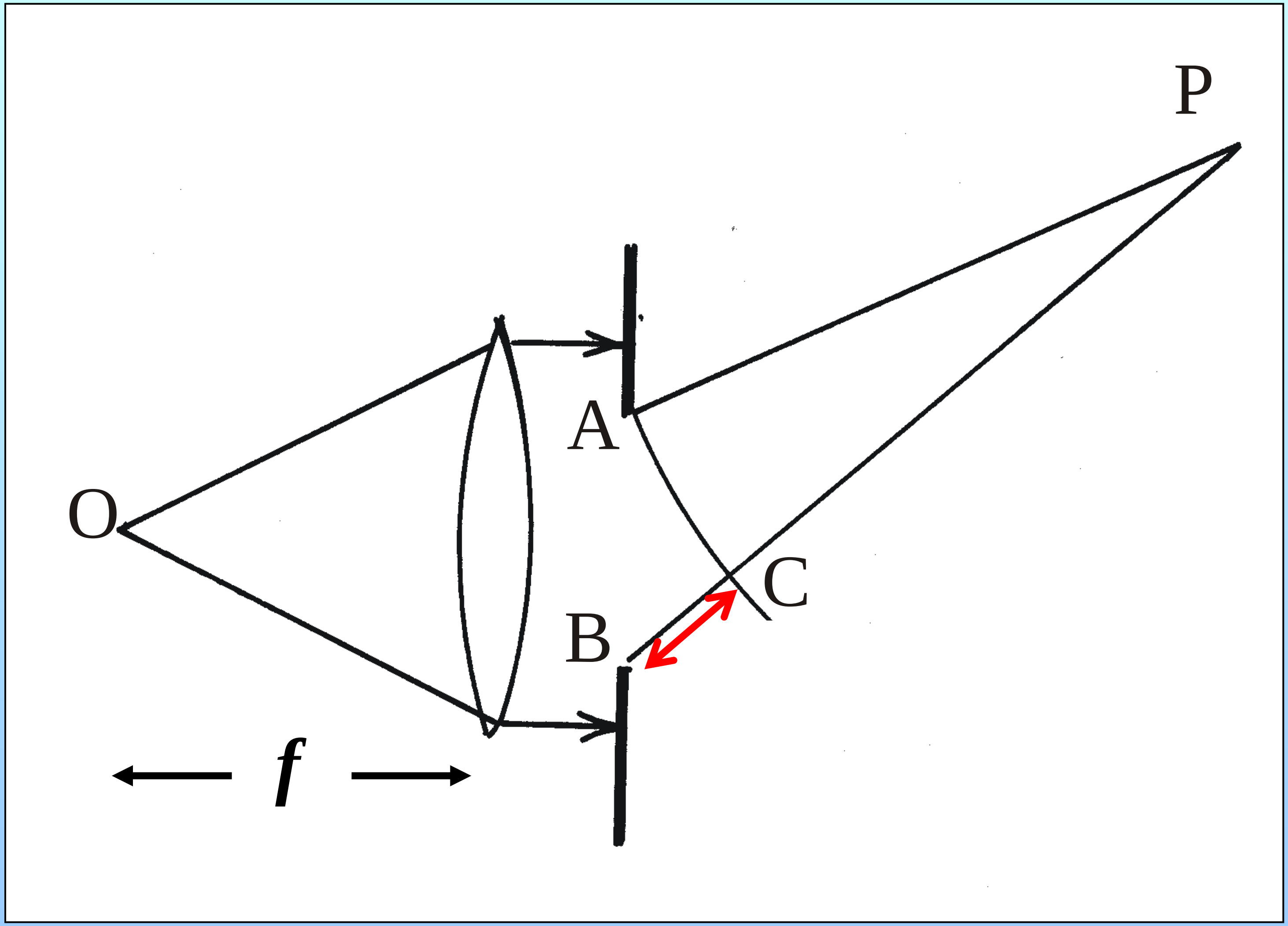
A diffraction pattern for which the phase of the light at the observation point is a ***linear function*** of the position for all points in the diffracting aperture is Fraunhofer diffraction

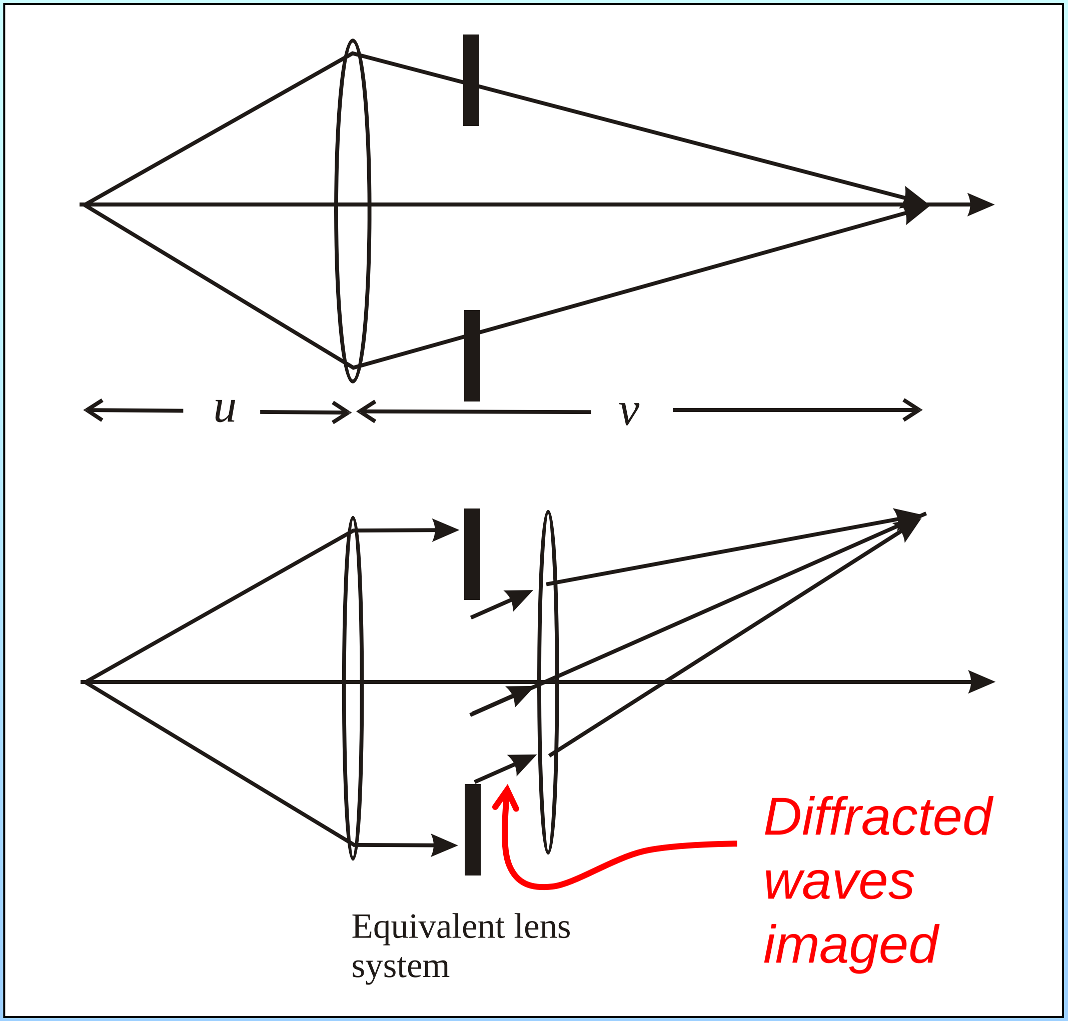
How linear is linear?


ρ < λ/20
ρ
ρ
R
a
a
R
source
R
R
observing
point
diffracting
aperture

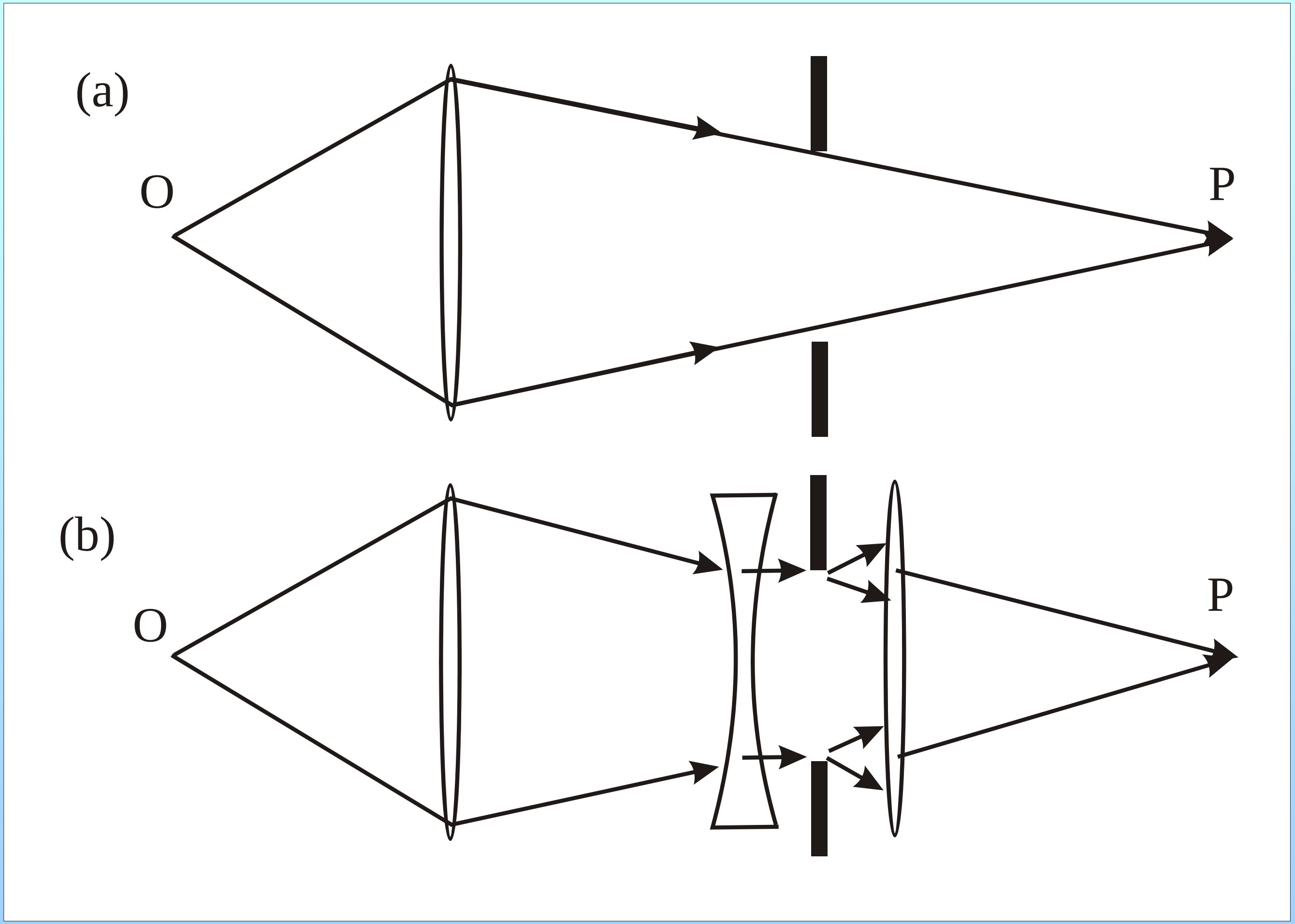
Fraunhofer Diffraction

A diffraction pattern formed in the image plane of an optical system is Fraunhofer diffraction


P
A
O
C
B
f



Fraunhofer diffraction: in image plane of system

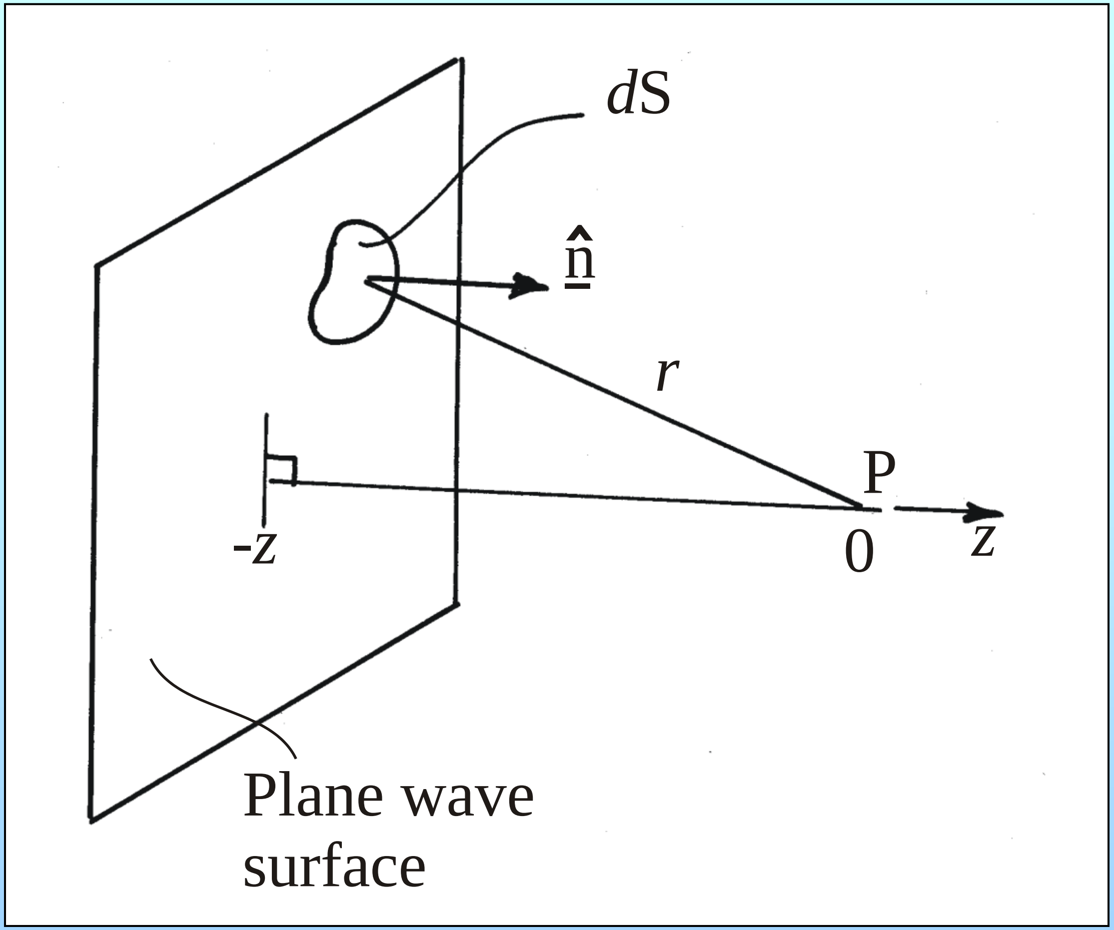


Equivalent lens system:

Fraunhofer diffraction is independent of aperture position

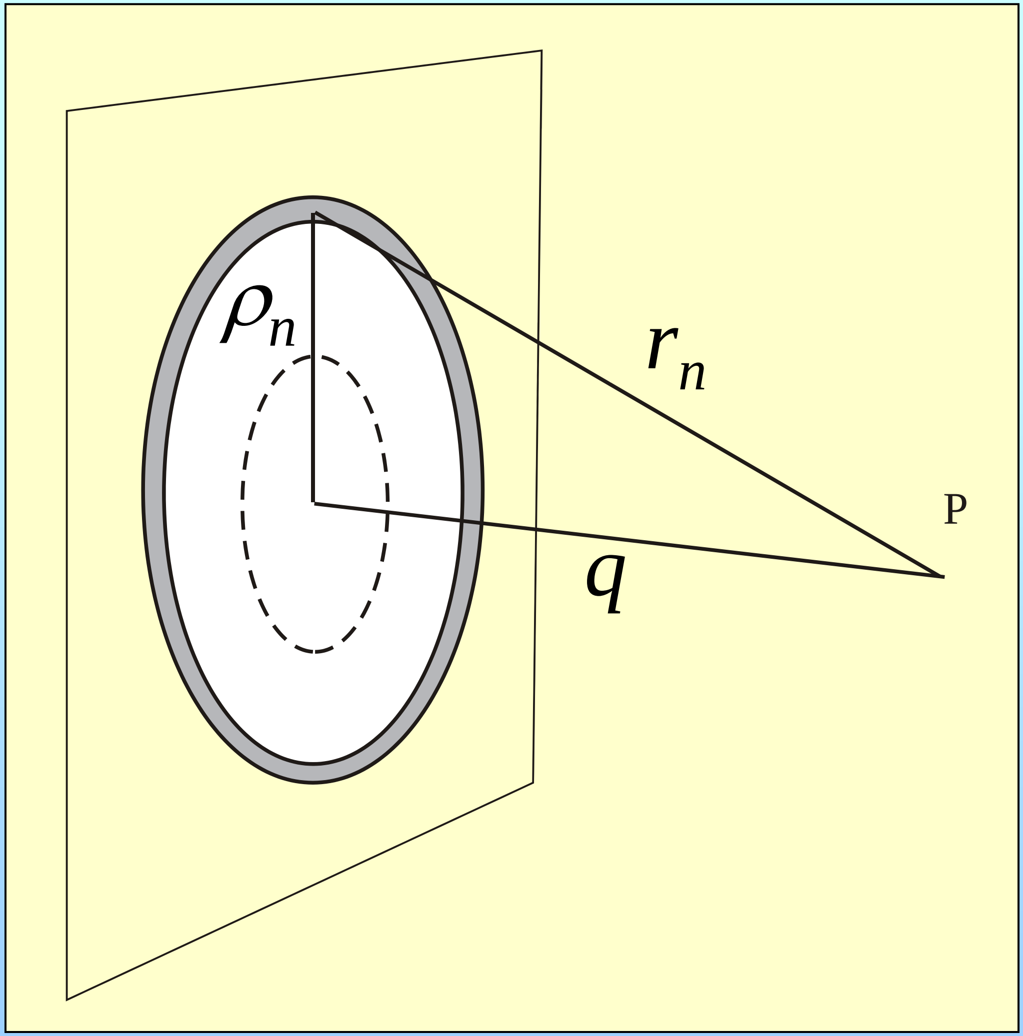
Fresnel's Theory of wave propagation

Augustin Fresnel
(1788-1827)

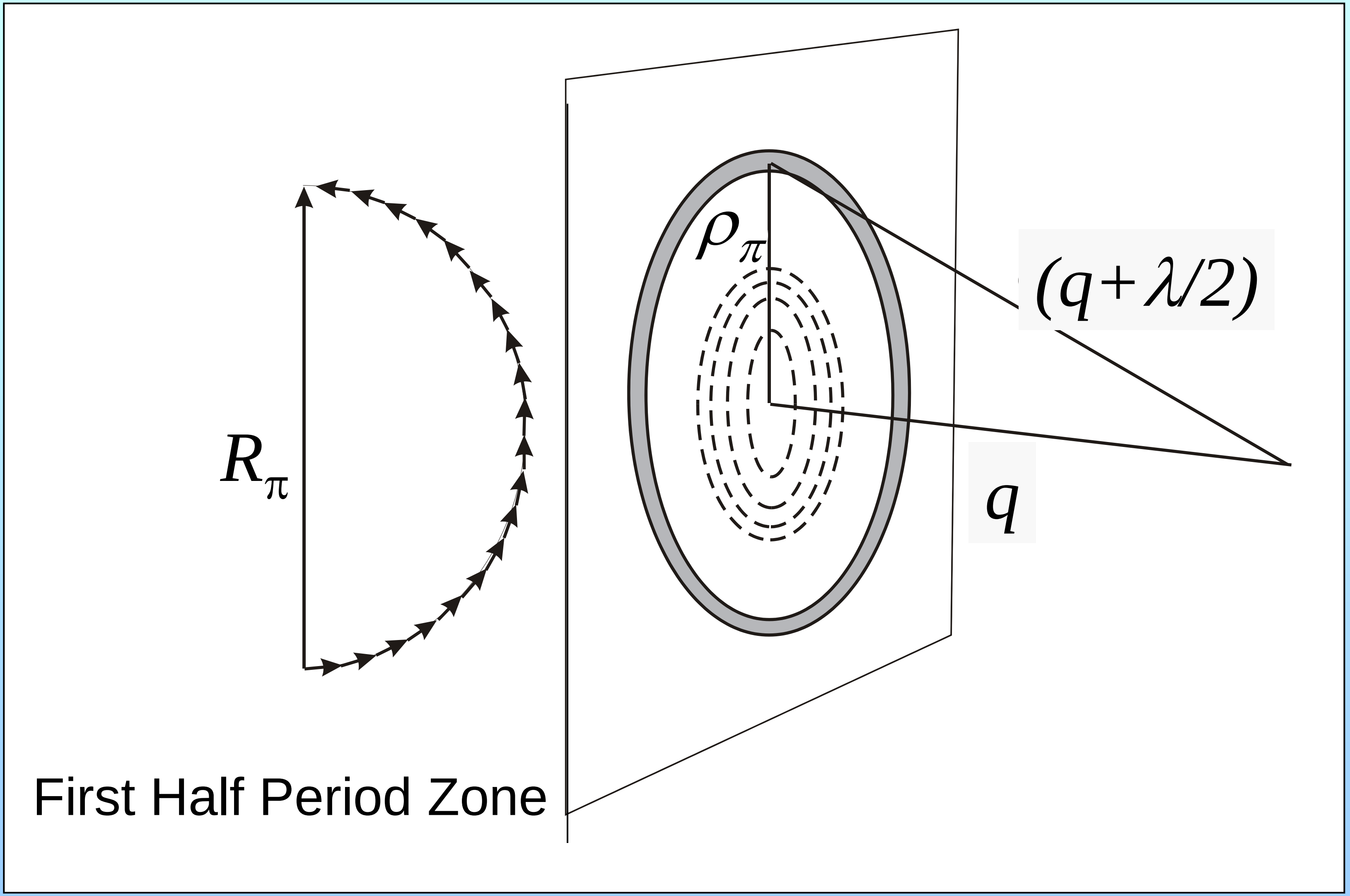


unobstructed

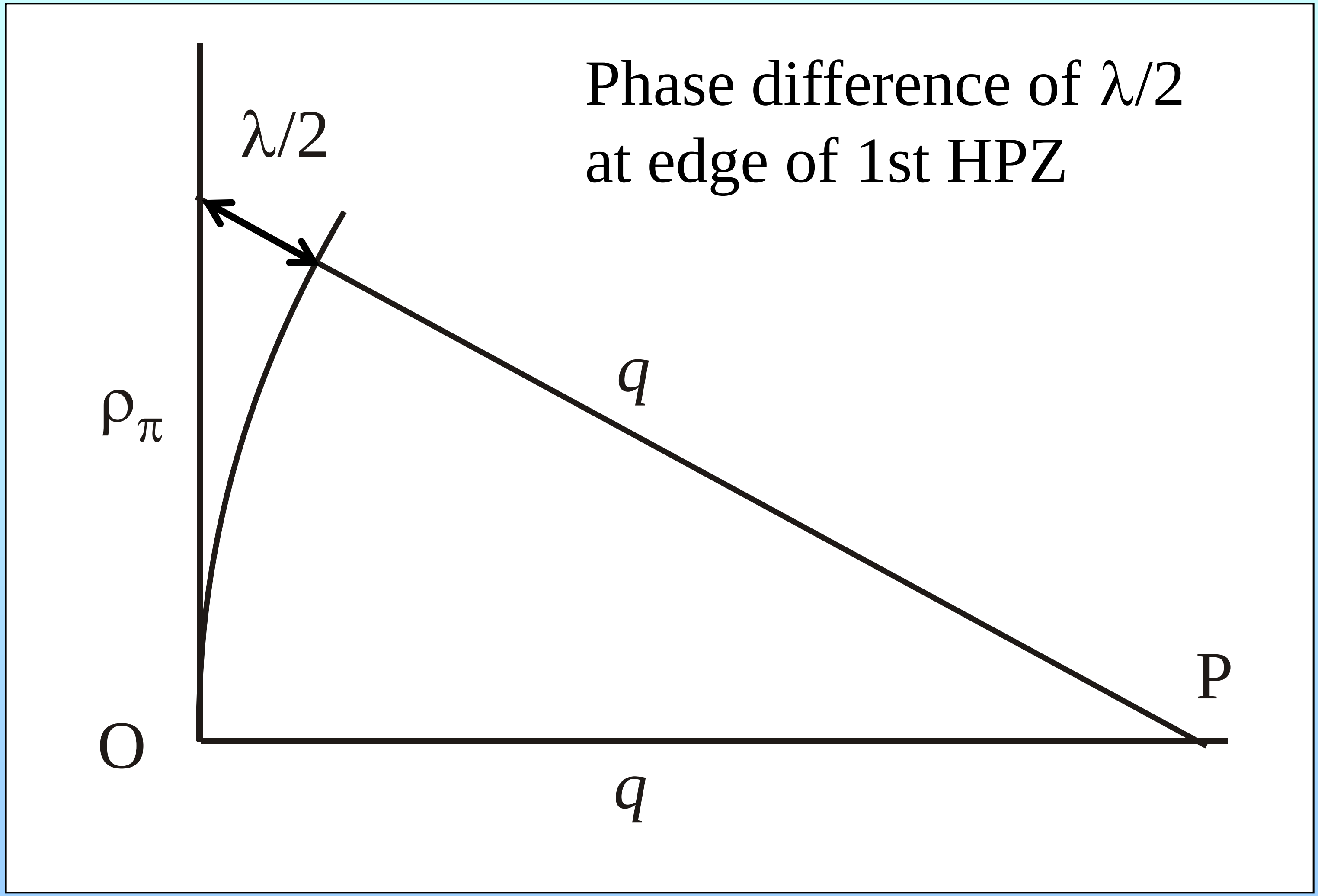
Huygens secondary sources on wavefront at -z radiate to point P on new wavefront at $z = 0$

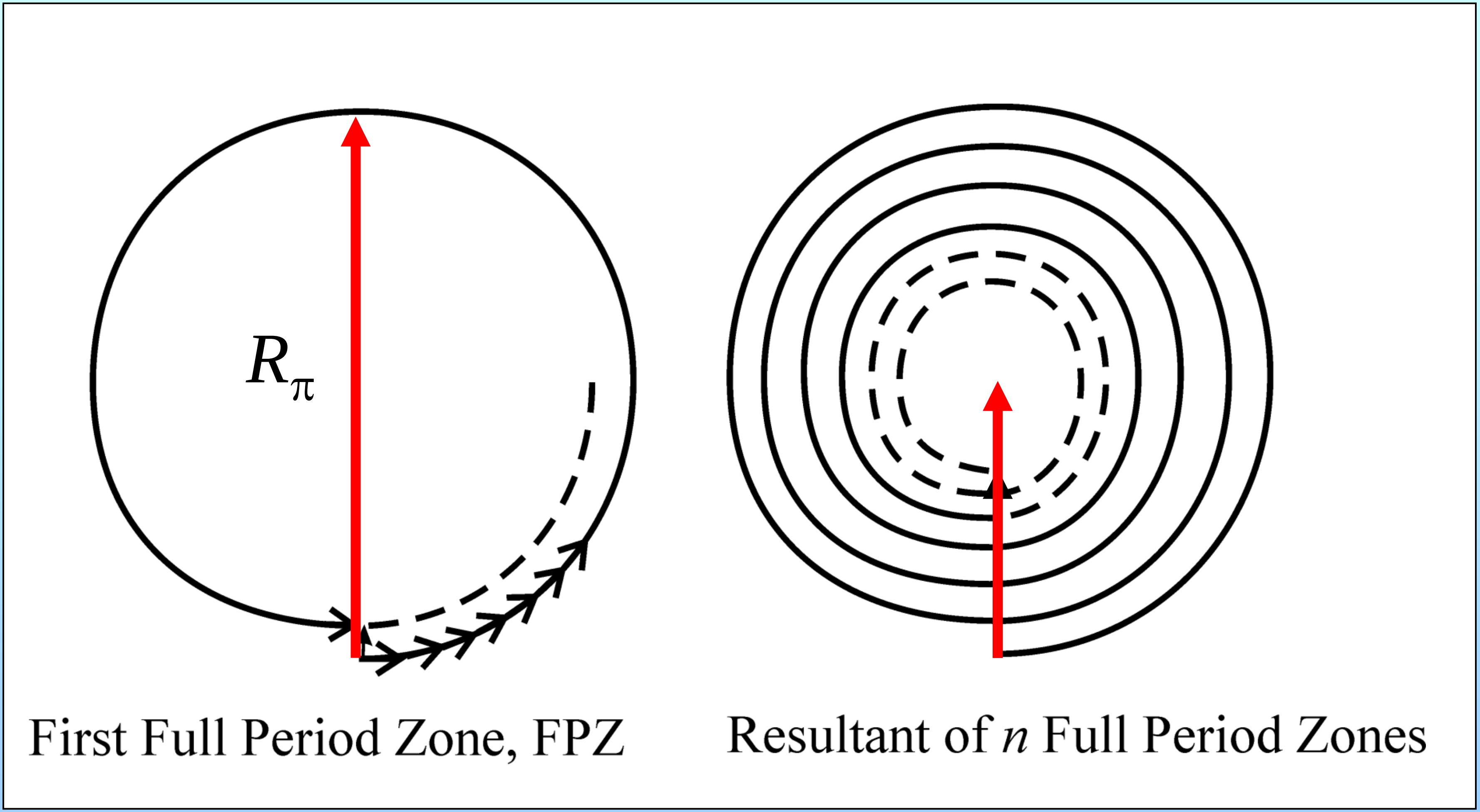


Construction of elements of equal area on wavefront



Resultant, R_π, represents amplitude from 1st HPZ

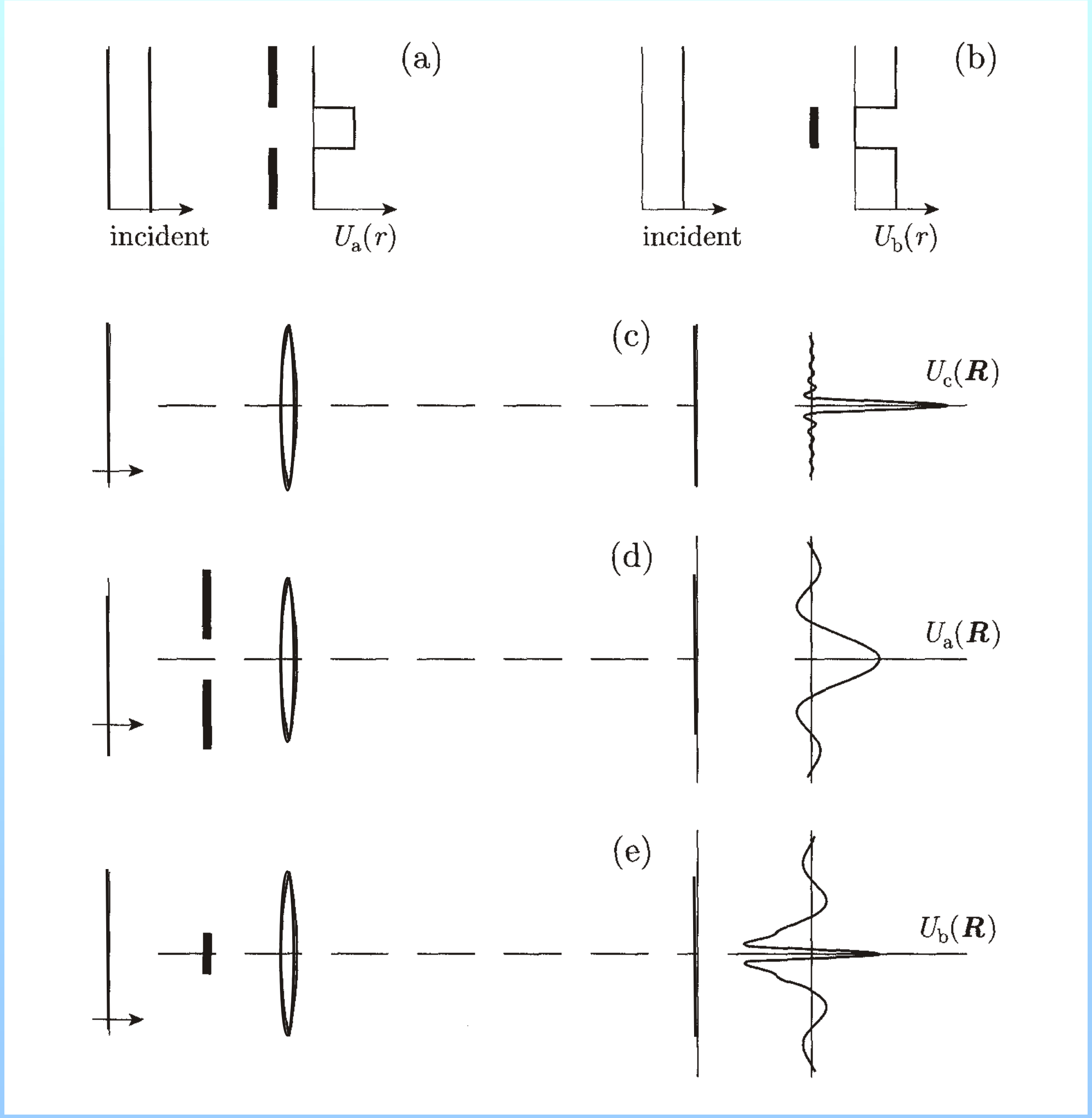

Phase difference of λ/2
at edge of 1st HPZ
λ/2
ρπ
q
P
O
q



As n ⇨ *infinity* resultant ⇨ ½ diameter of 1st HPZ

$$u_p = -\frac{i}{\lambda}\int \frac{u_o \mathrm{d}S}{r}\,\eta(\mathrm{n},\mathrm{r})\,e^{ikr}$$

Babinet's Principle

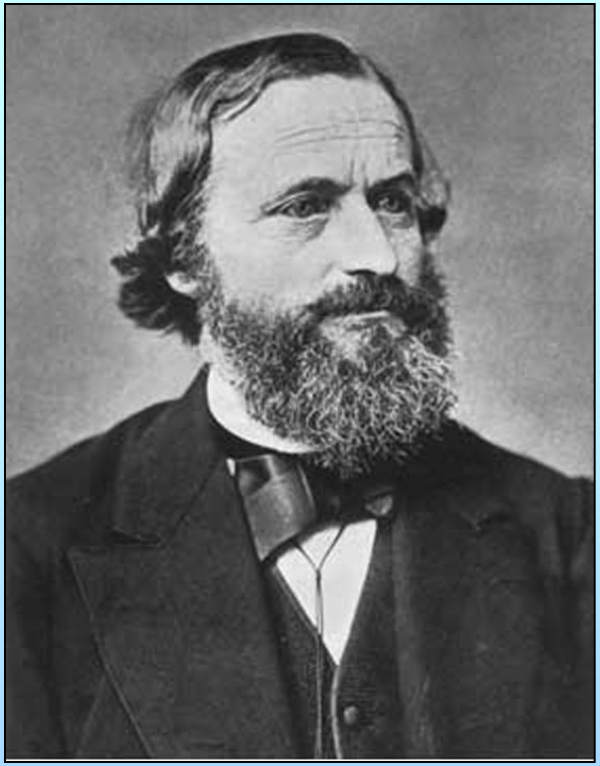


Lectures 1 - 3: The story so far

- Geometrical optics
  No wave effects
- Scalar diffraction theory:
  Analytical methods
  Phasor methods
- Fresnel-Kirchoff diffraction integral:
  propagation of plane waves

Joseph Fraunhofer
(1787 - 1826)

Augustin Fresnel
(1788 - 1827)



Gustav Robert Kirchhoff
(1824 –1887)

Phase at observation is linear function of position in aperture:

$$\delta = k \sin\theta \, y$$

$$u_p = -\frac{i}{\lambda}\int \frac{u_o \mathrm{d}S}{r}\,\eta(\mathrm{n},\mathrm{r})\, e^{ikr}$$

Fresnel-Kirchoff Diffraction Integral

Lecture 4: Fourier methods

- Fraunhofer diffraction as a Fourier transform
- Convolution theorem – solving difficult diffraction problems
- Useful Fourier transforms and convolutions

Fresnel-Kirchoff diffraction integral:

$$u_p = -\frac{i}{\lambda}\int \frac{u_o \mathrm{dS}}{r}\eta(\underline{n}.\underline{r})e^{ikr}$$

Simplifies to:

$$u_p \Rightarrow A(\beta) = \alpha \int_{-\infty}^{\infty} u(x)e^{i\beta x}\mathrm{d}x$$

where $\beta = \mathrm{k}\sin\theta$

Note: $A(\beta)$ is the Fourier transform of $u(x)$

The Fraunhofer diffraction pattern is the Fourier transform of the amplitude function in the diffracting aperture

The Convolution function:

$$h(x) = f(x) \otimes g(x) = \int_{-\infty}^{\infty} f(x').g(x-x').\mathrm{d}x'$$

The Convolution Theorem:

The Fourier transform, F.T., of $f(x)$ is $F(\beta)$
F.T., of $g(x)$ is $G(\beta)$
F.T., of $h(x)$ is $H(\beta)$

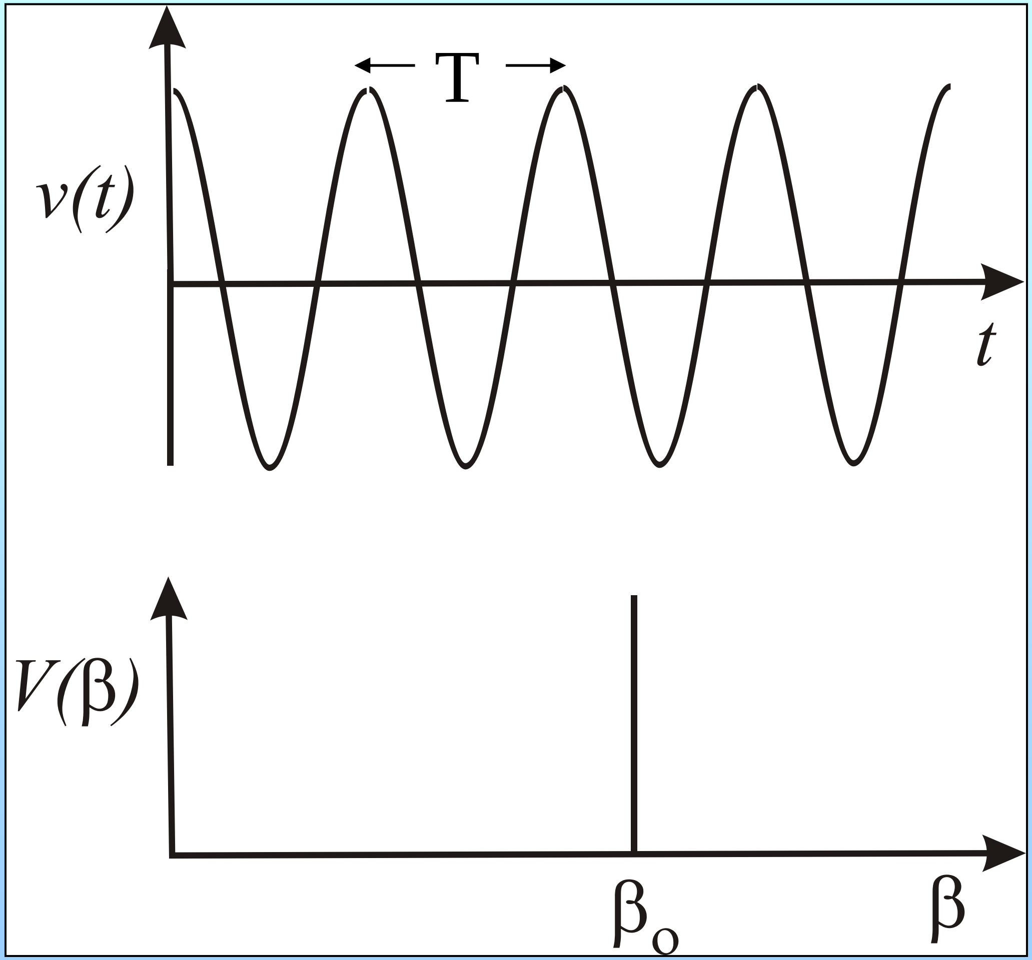
$$H(\beta) = F(\beta).G(\beta)$$

The Fourier transform of a convolution of *f* and *g* is the product of the Fourier transforms of *f* and *g*

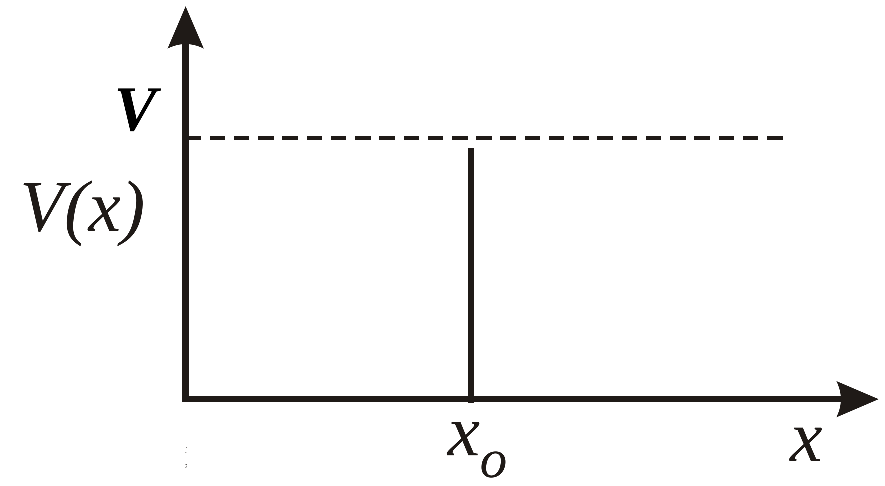
Monochromatic Wave

$\beta_o = 2\pi/T$

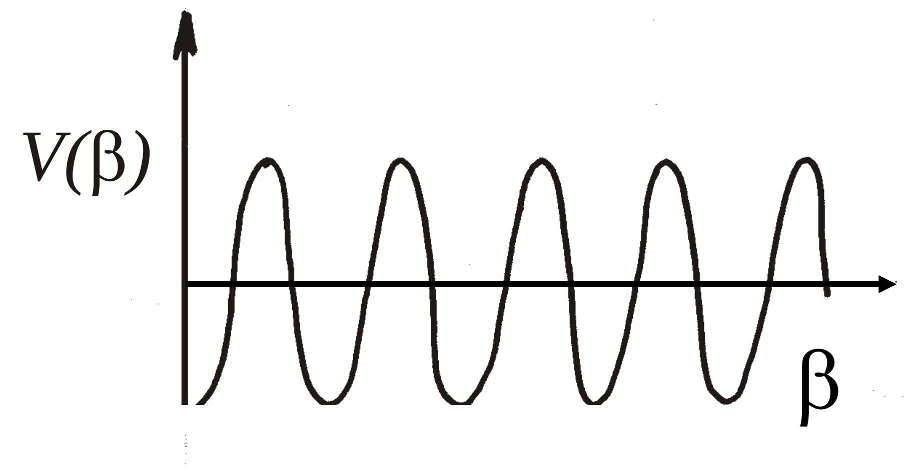
Fourier Transform



δ-function



Fourier transform

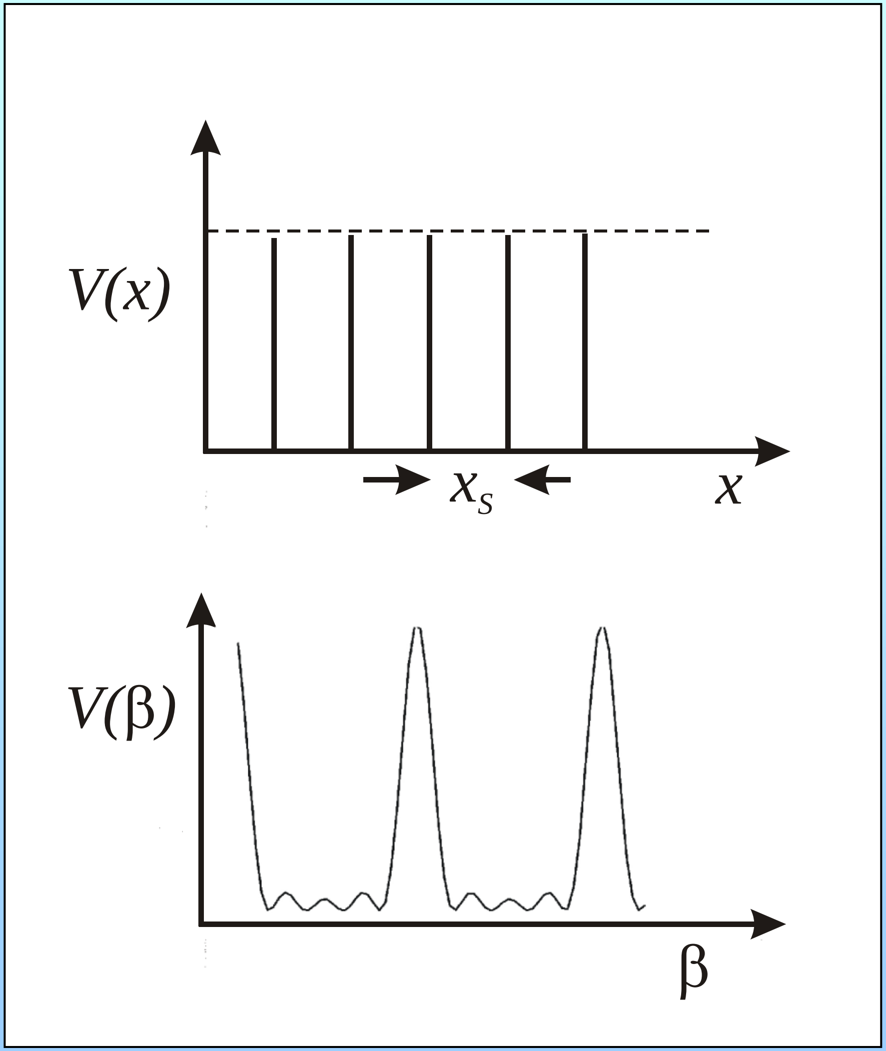


Power spectrum

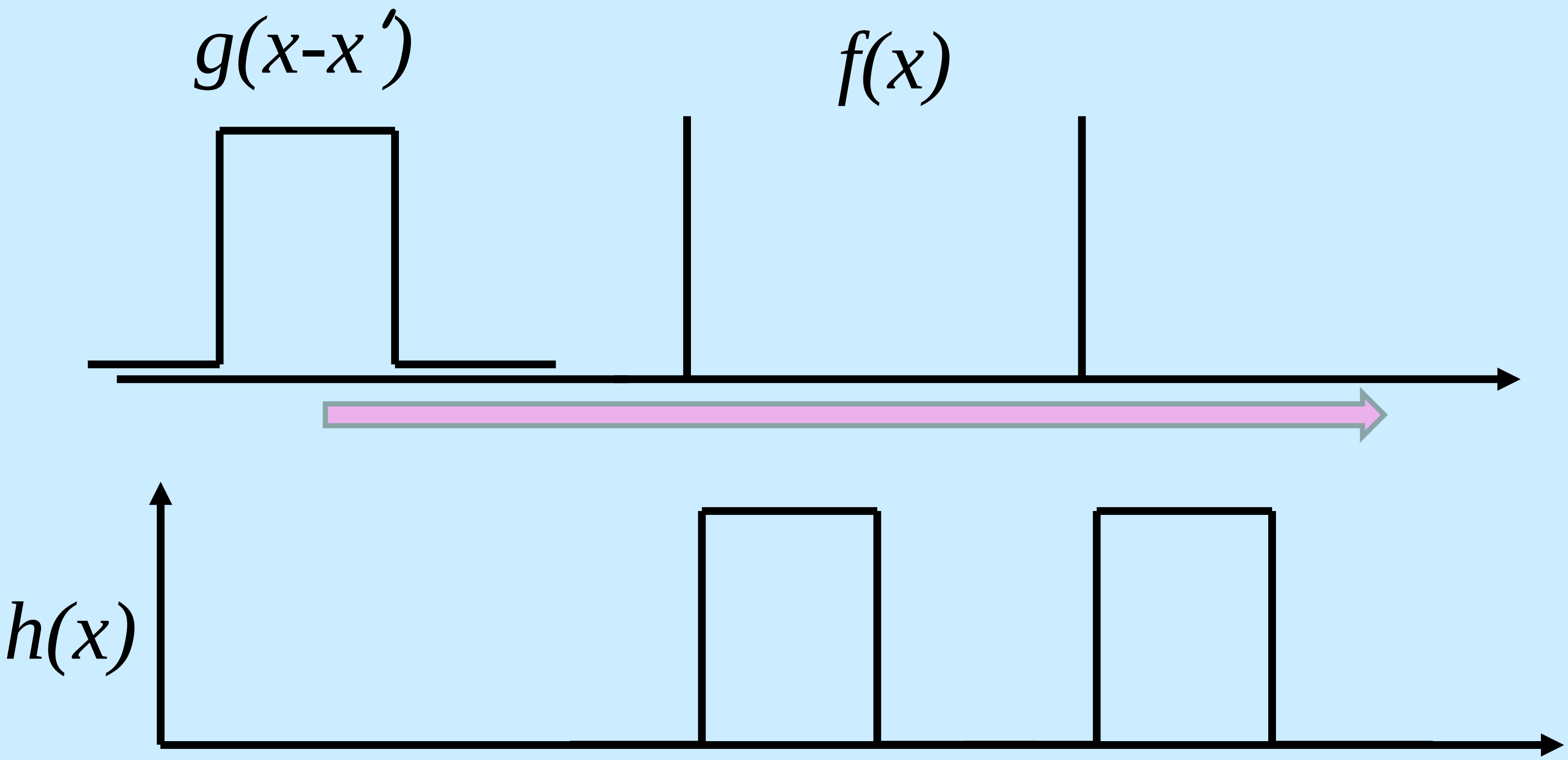
$$V(\beta)V(\beta)^* = V^2$$
$$= \text{constant}$$

Comb of δ-functions

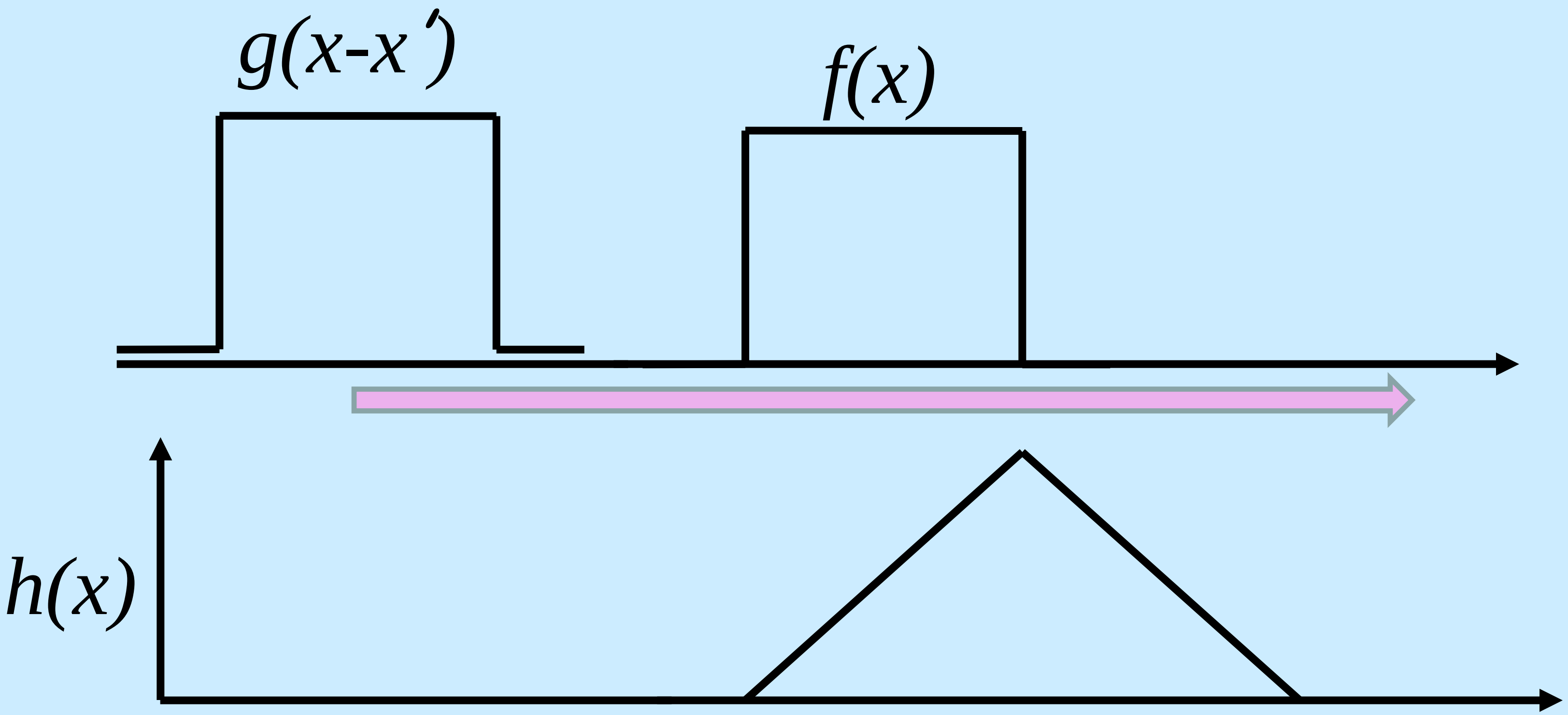
Fourier transform



Constructing a double slit function by convolution



Triangle as a convolution of two "top-hat" functions



This is a self-convolution or Autocorrelation function

- Heat transfer theory:
  - *greenhouse effect*
- Fourier series
- Fourier synthesis and analysis
- Fourier transform as analysis

Joseph Fourier (1768 –1830)

Lecture 6: Theory of imaging

- Fourier methods in optics
- Abbé theory of imaging
- Resolution of microscopes
- Optical image processing
- Diffraction limited imaging

Fresnel-Kirchoff diffraction integral:

$$u_p = -\frac{i}{\lambda}\int \frac{u_o \mathrm{dS}}{r}\eta(\underline{n}.\underline{r})e^{ikr}$$

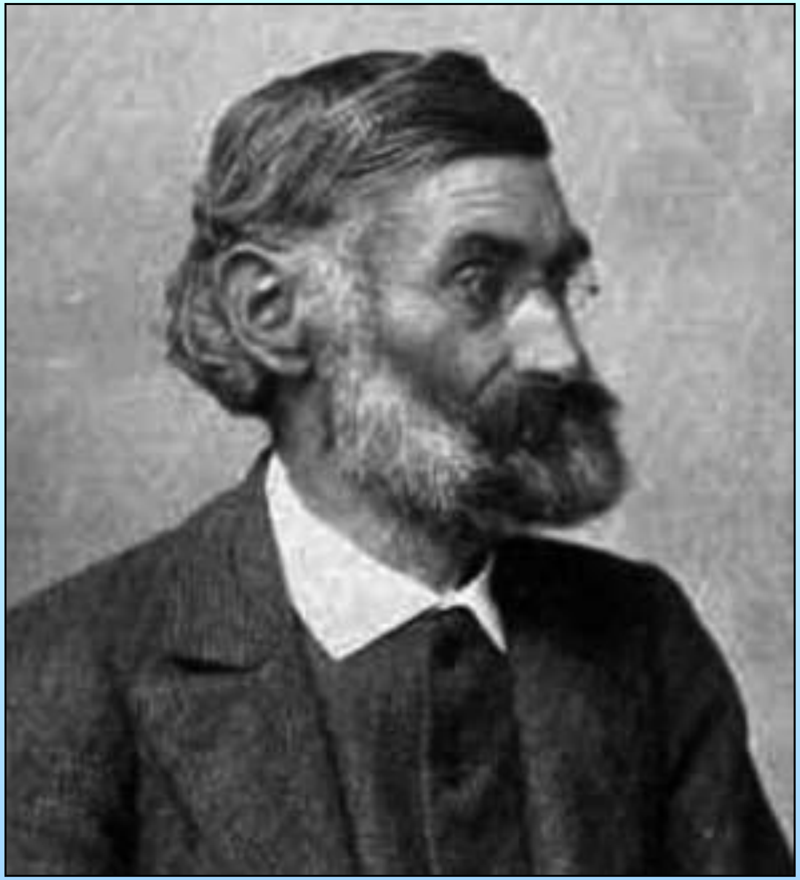
Simplifies to:

$$u_p \Rightarrow A(\beta) = \alpha \int_{-\infty}^{\infty} u(x) e^{i\beta x} \mathrm{d}x$$

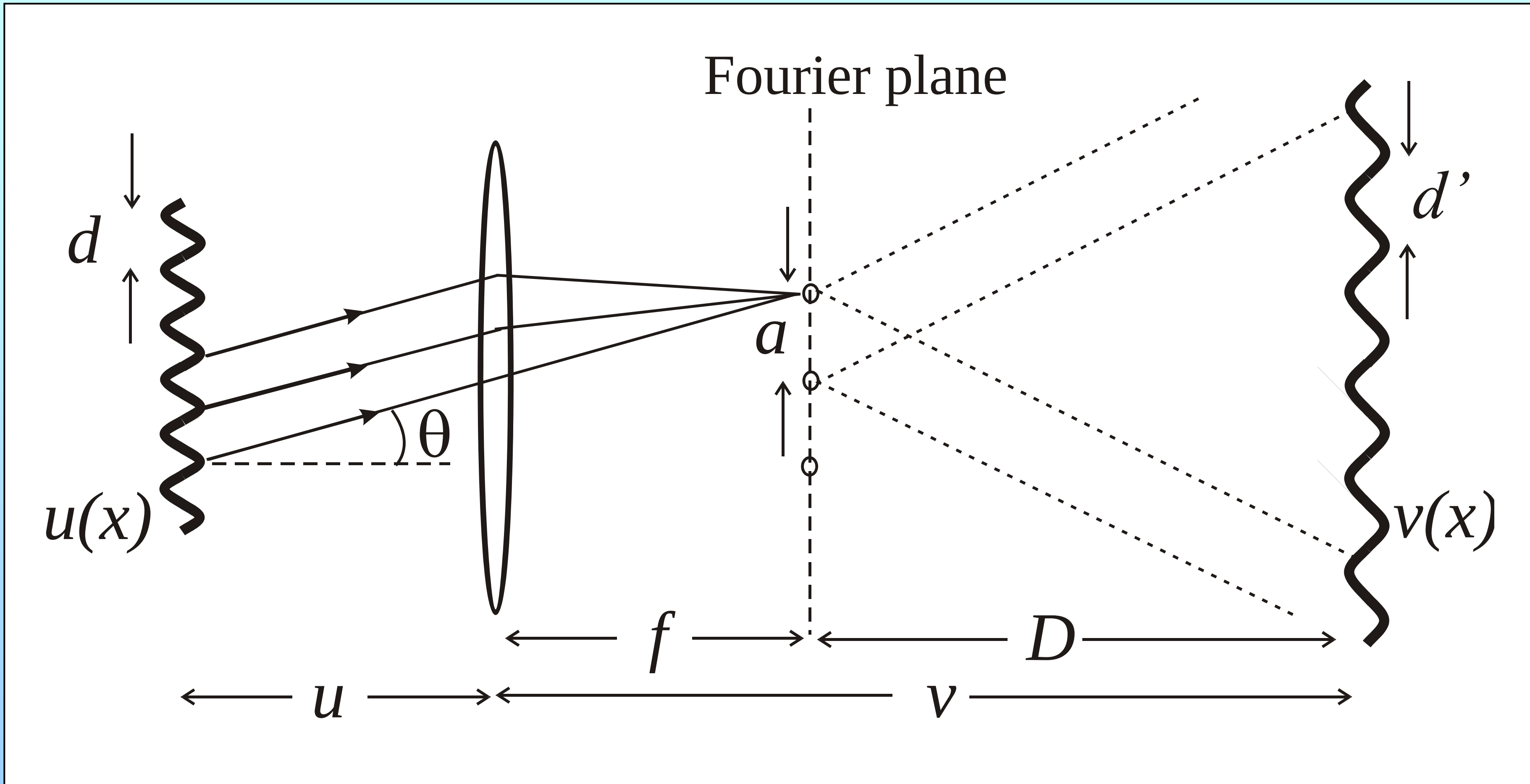
where $\beta = \mathrm{k}\sin\theta$

Note: $A(\beta)$ is the Fourier transform of $u(x)$

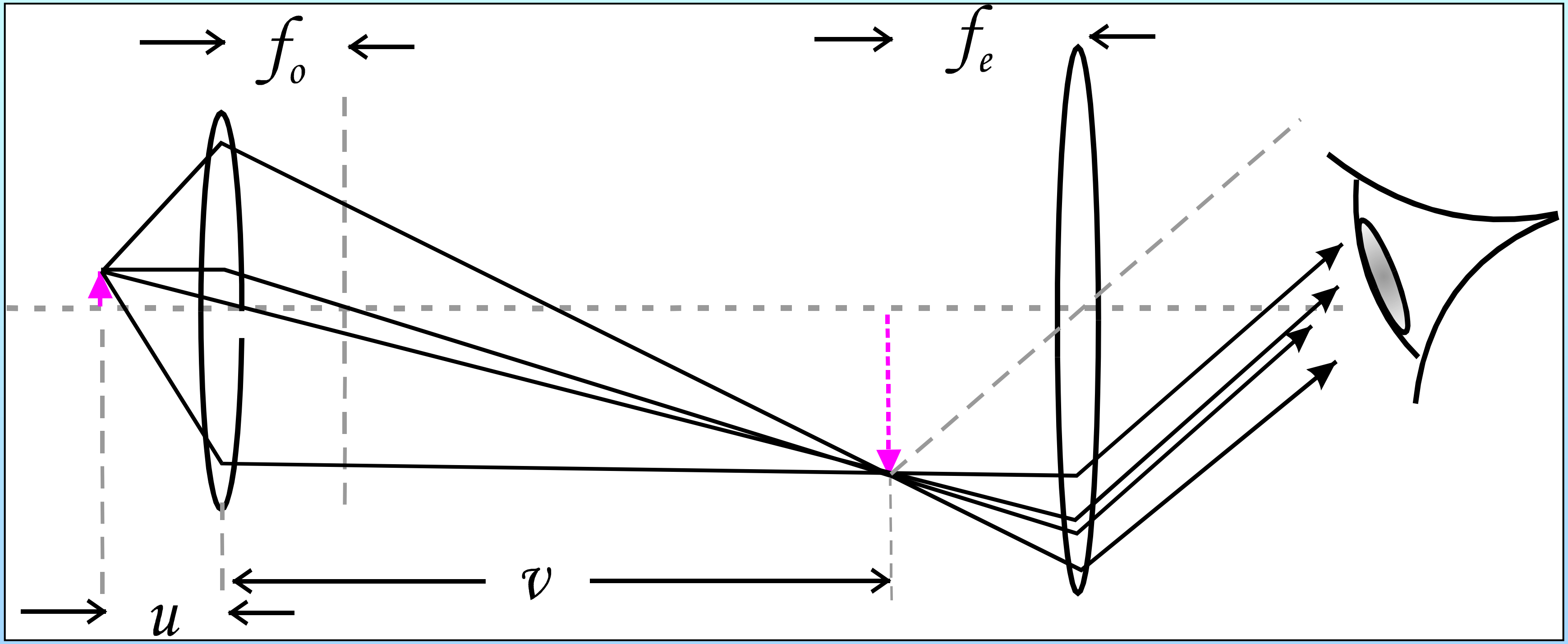
The Fraunhofer diffraction pattern is the Fourier transform of the amplitude function in the diffracting aperture



Ernst Abbé (1840 -1905)


Fourier plane
d
u(x)
θ
a
d'
v(x)
f
D
u
v

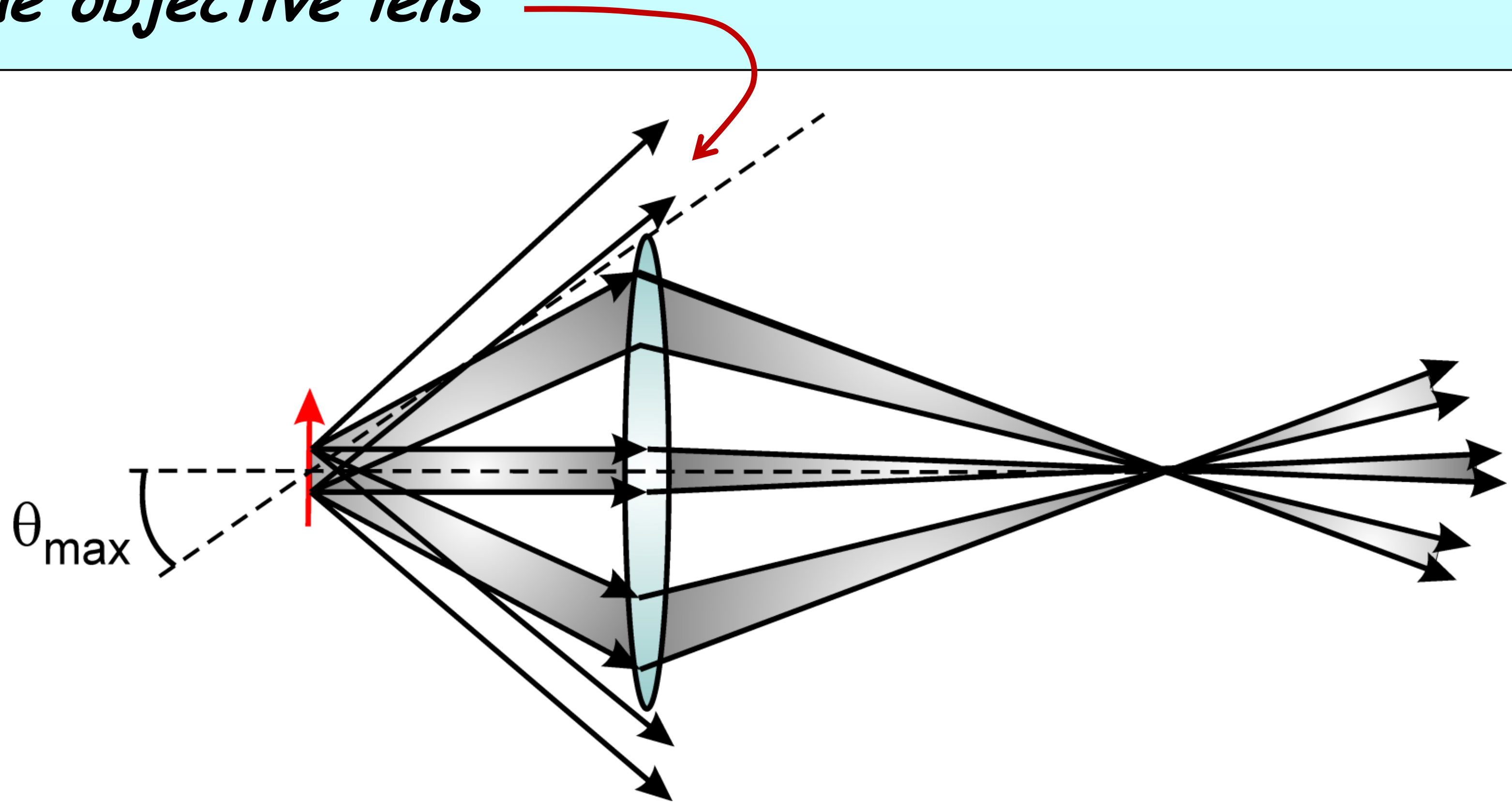
The compound microscope



Objective magnification = v/u

Eyepiece magnifies real image of object

Diffracted orders from high spatial frequencies miss the objective lens



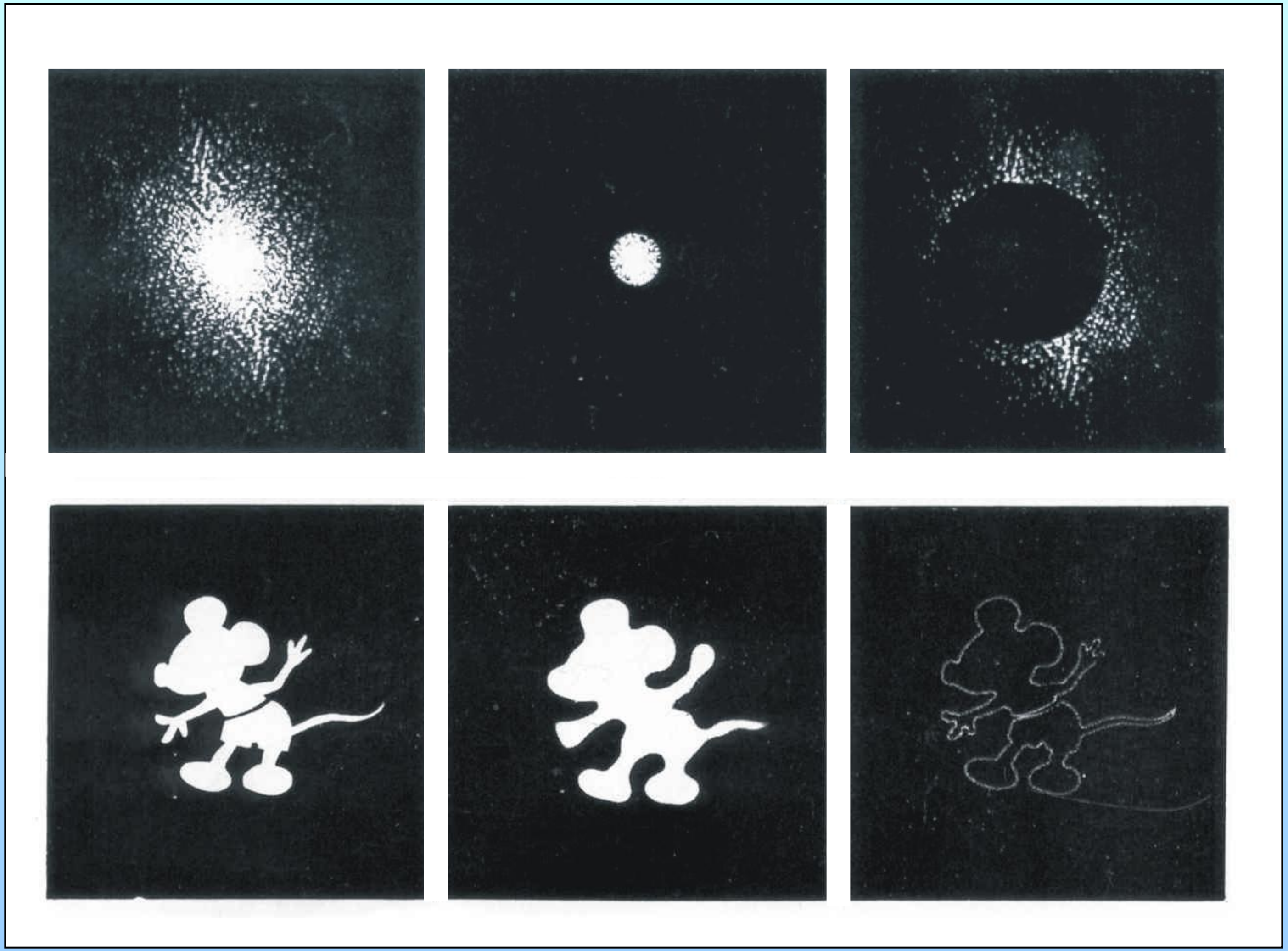
θ_{max} *defines the numerical aperture… and resolution*

So high spatial frequencies are missing from the image.

Image processing

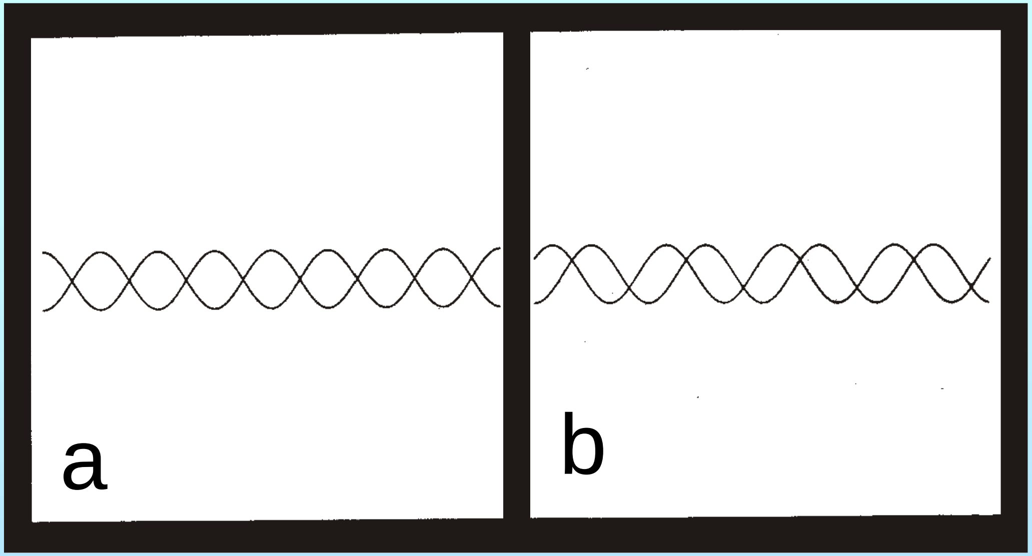
Fourier plane

Image plane

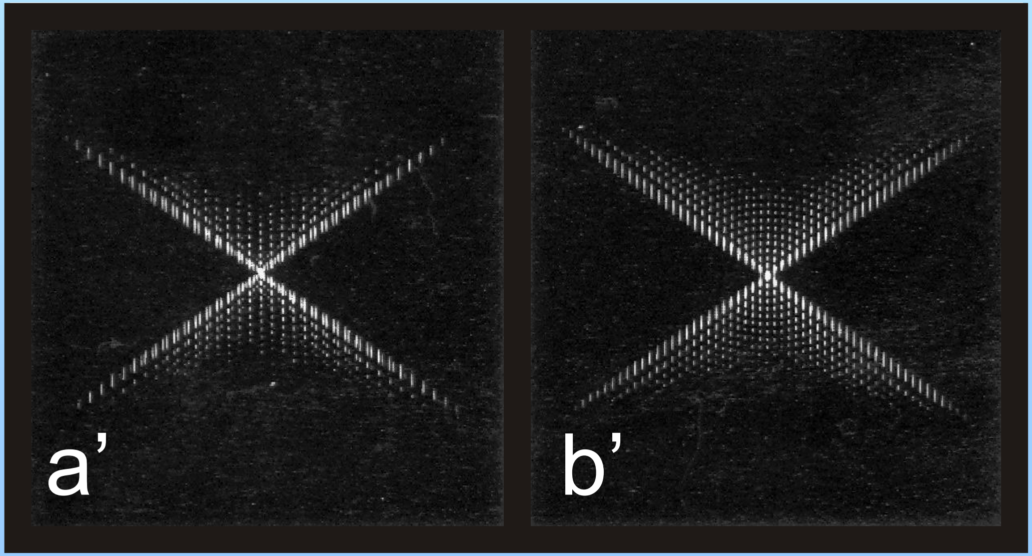


Optical simulation of "X-Ray diffraction"

(a) and (b) show objects:
double helix
at different angle of view

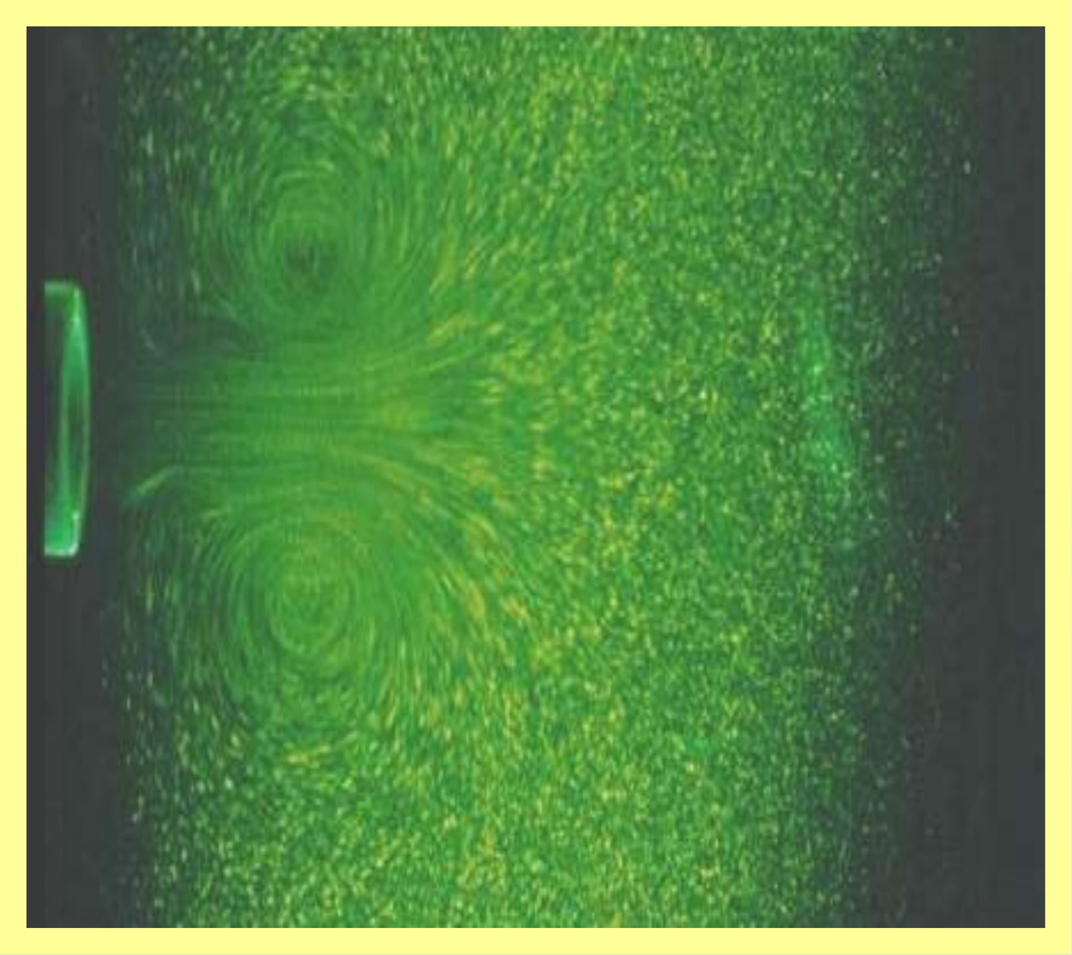


Diffraction patterns of
(a) and (b) observed in
Fourier plane



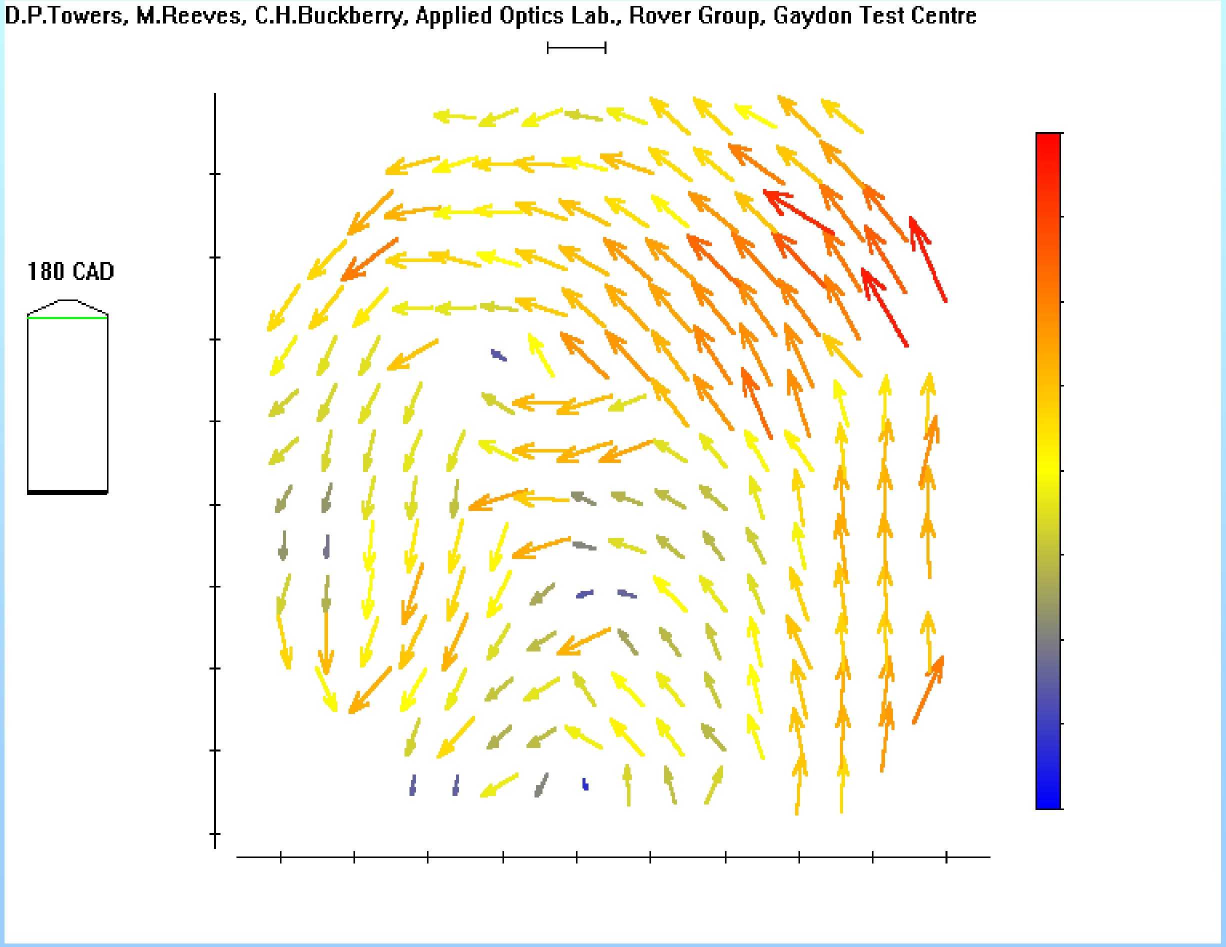
Computer performs
Inverse Fourier transform
To find object "shape"

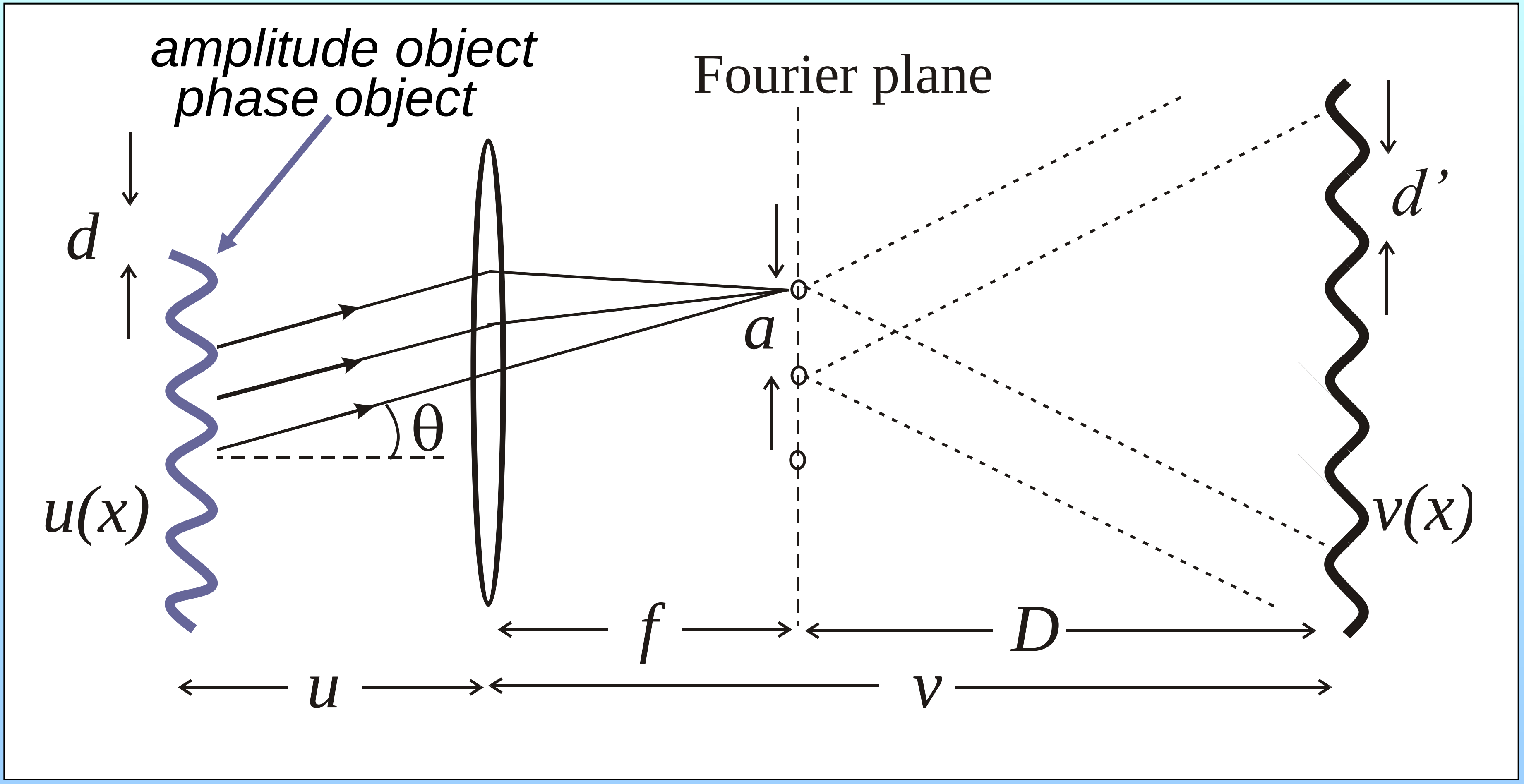
PIV particle image velocimetry



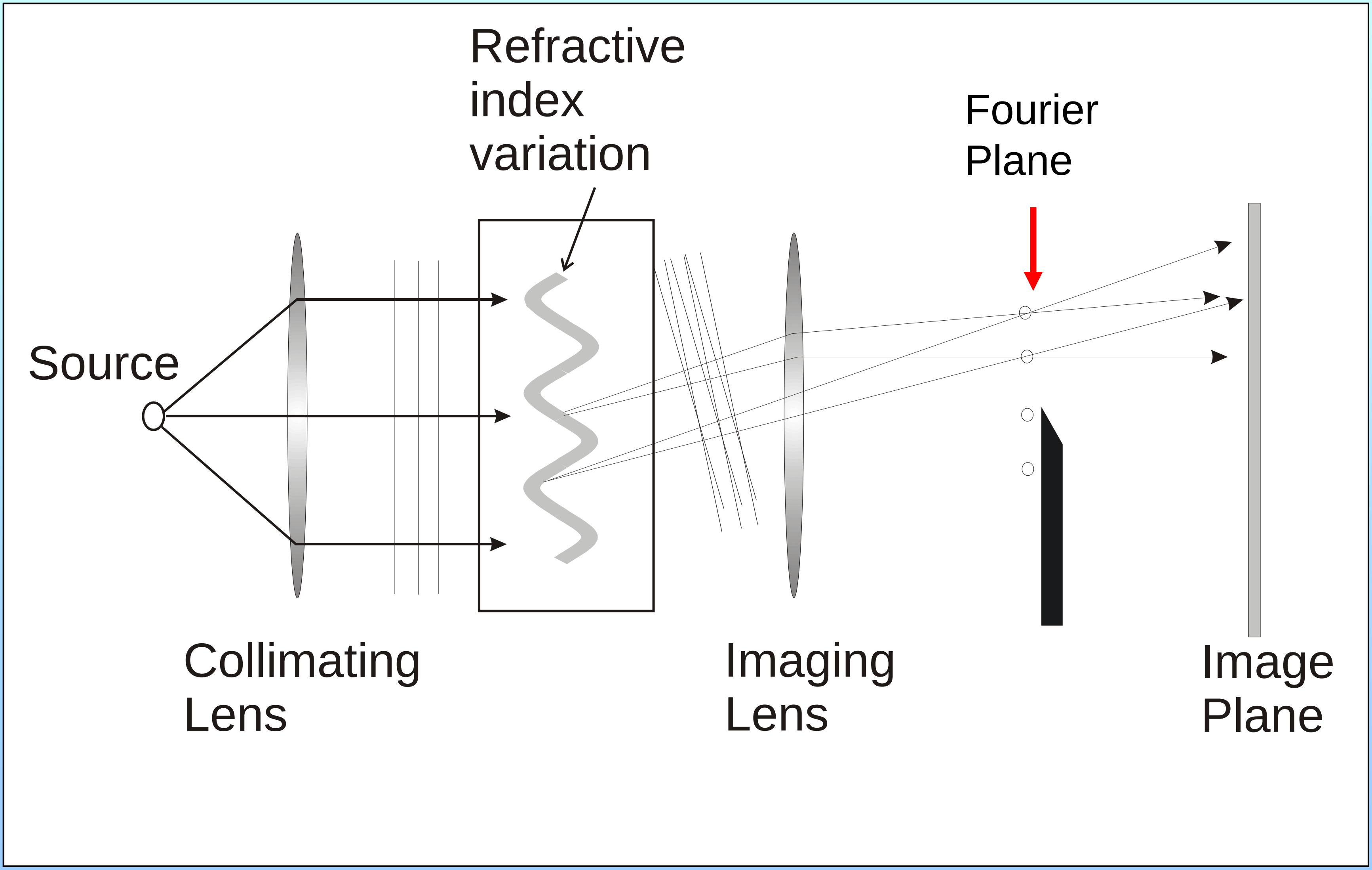
- Two images recorded in short time interval
- Each moving particle gives two point images
- Coherent illumination of small area produces “Young’s” fringes in Fourier plane of a lens
- CCD camera records fringe system – input to computer to calculate velocity vector

PIV particle image velocimetry




amplitude object
phase object
Fourier plane
d
d'
a
θ
u(x)
v(x)
f
D
u
v

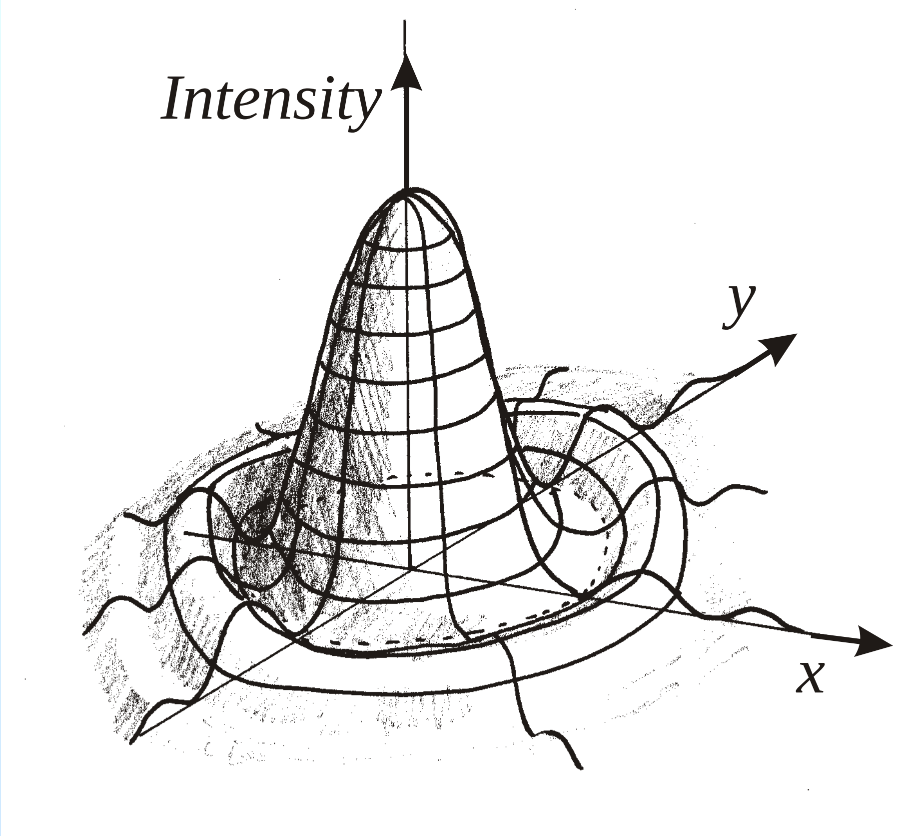
Schlieren photography



Schleiren photography in i.c.engine

Schlieren film of autoignition
Courtesy of Prof CWG Sheppard
University of Leeds

Diffraction pattern from circular aperture



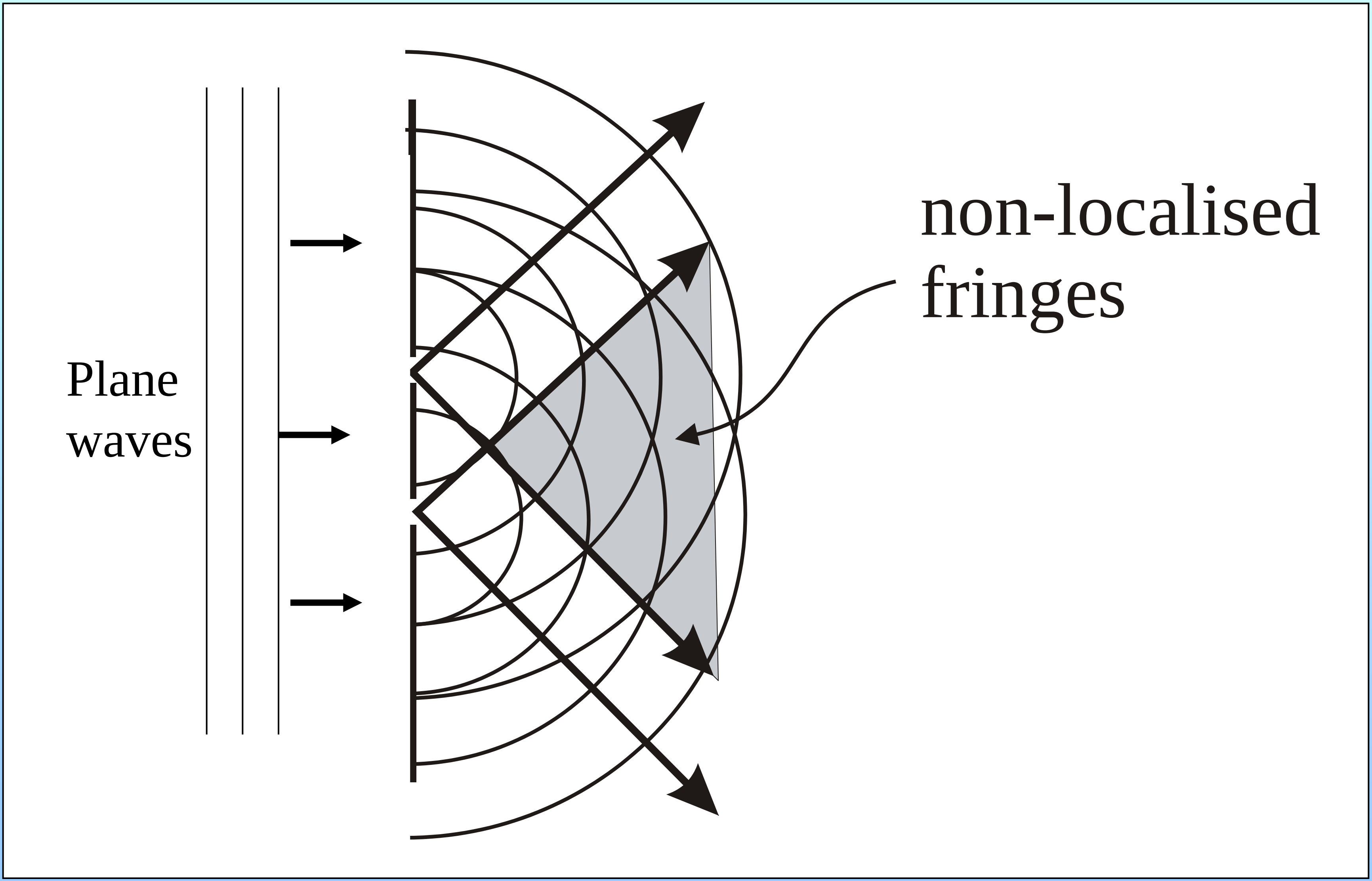
Point Spread Function, PSF

Oxford Physics: Second Year, **Optics**

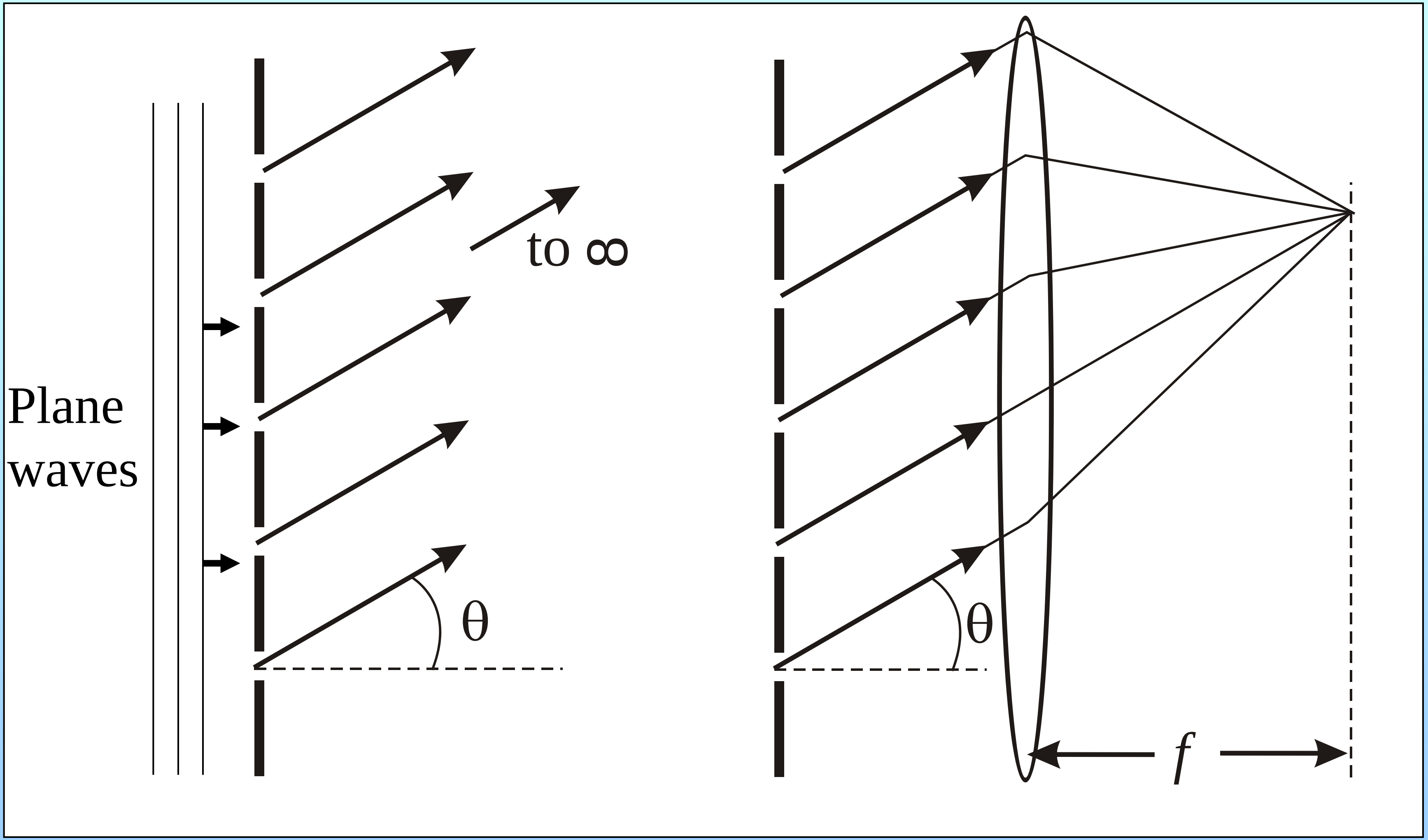
Lecture 7: Optical instruments and Fringe localisation

- Interference fringes
- What types of fringe?
- Where are fringes located?
- Interferometers

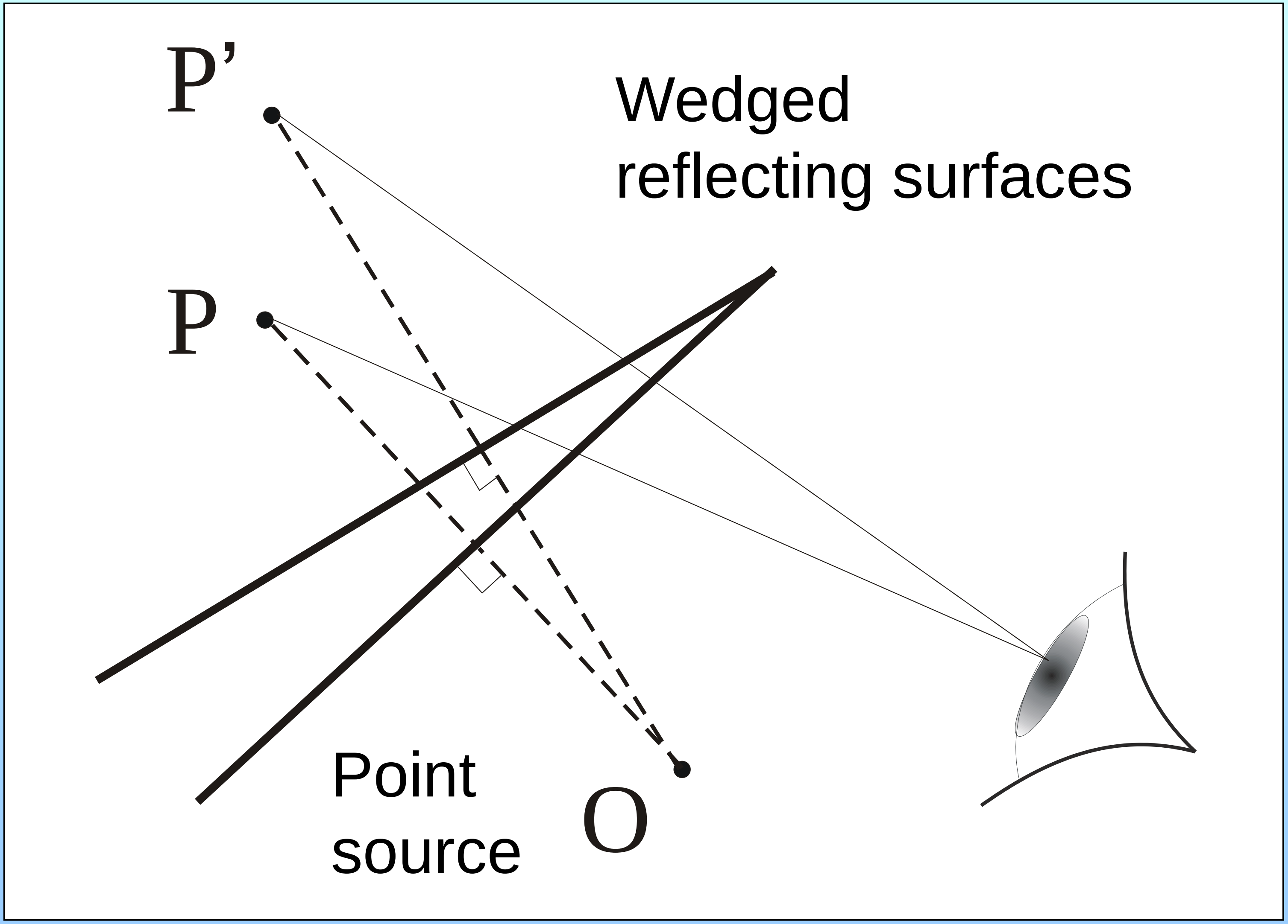
Young's slits

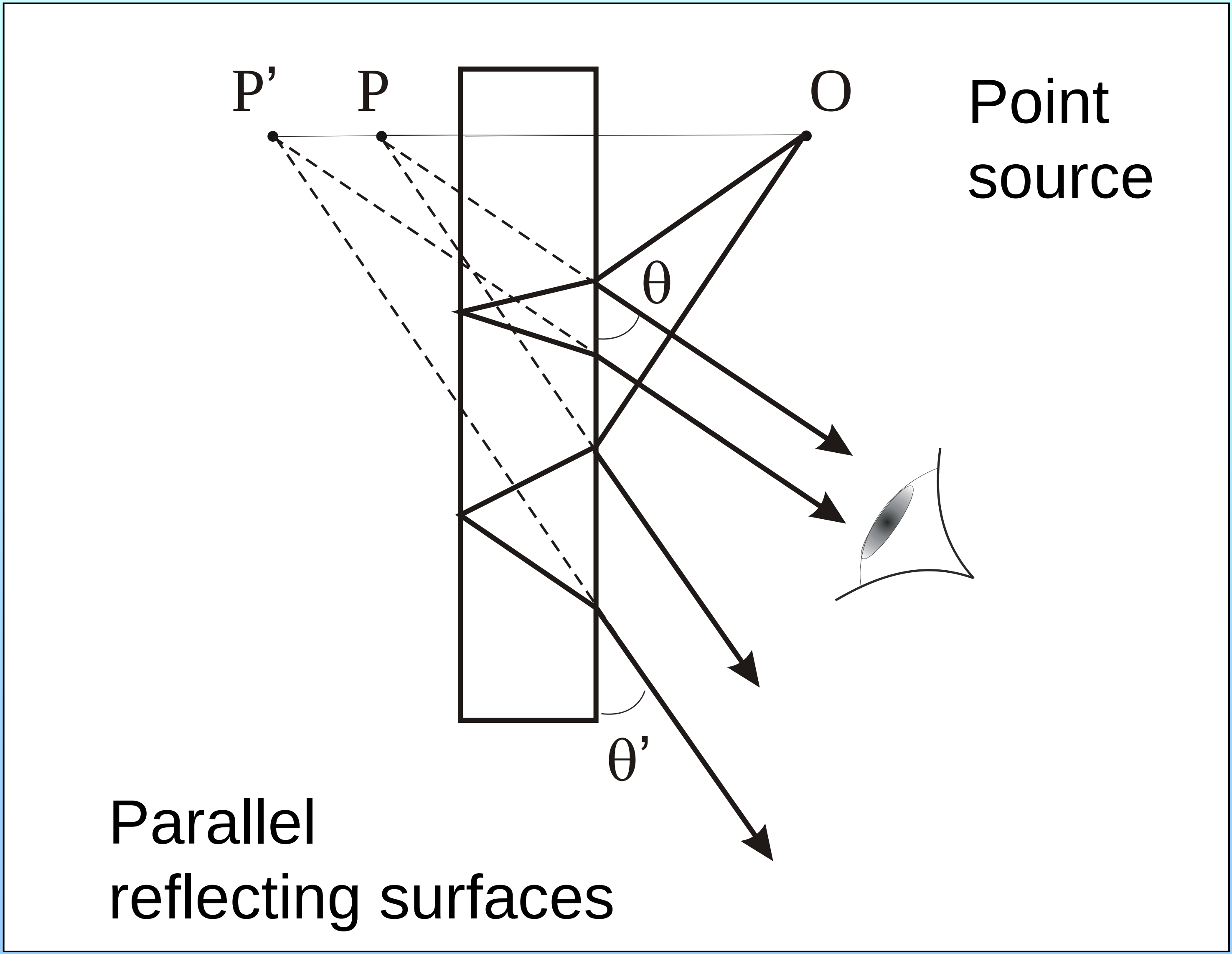


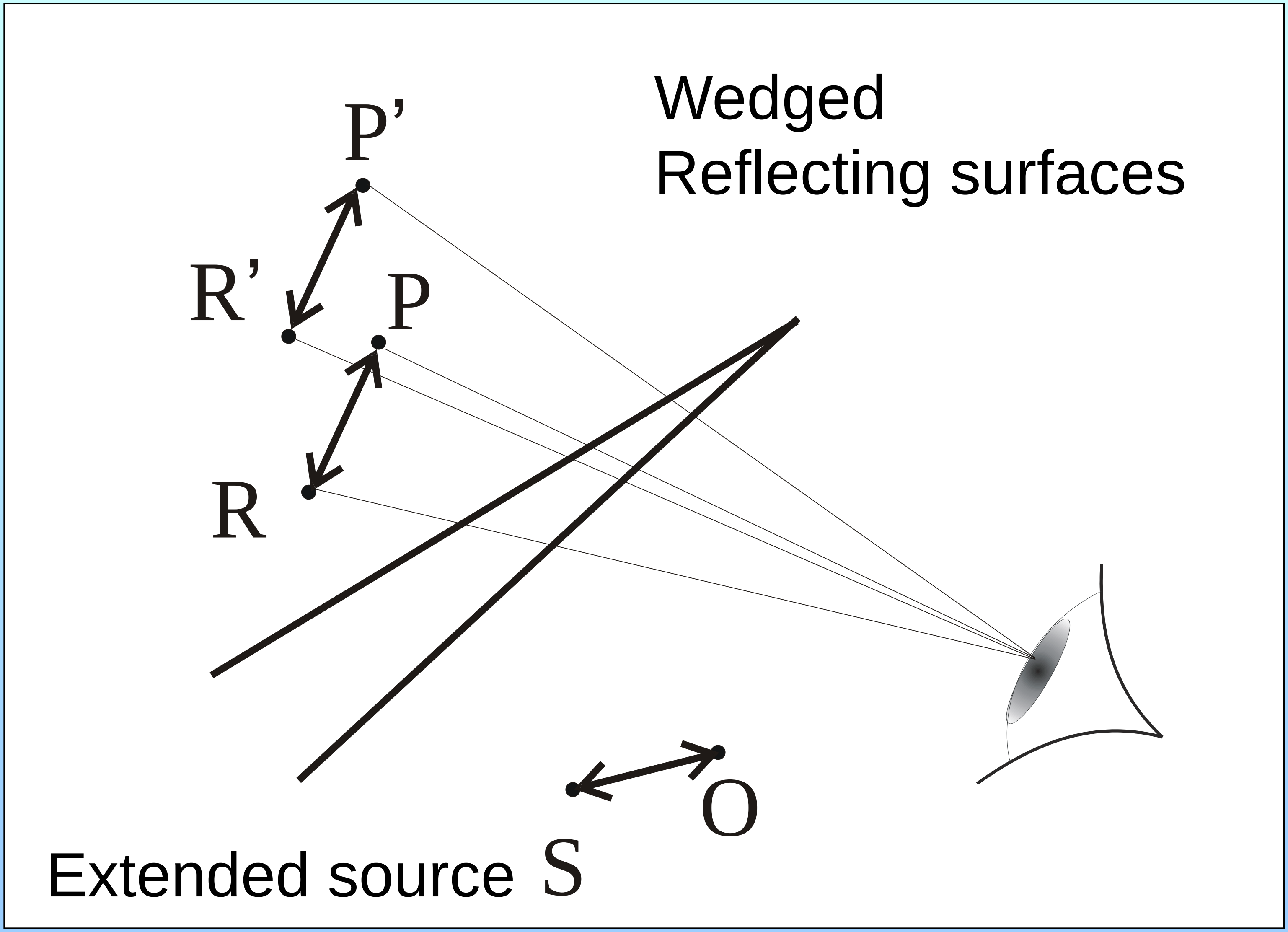
Diffraction grating



Fringes localised at infinity: Fraunhofer

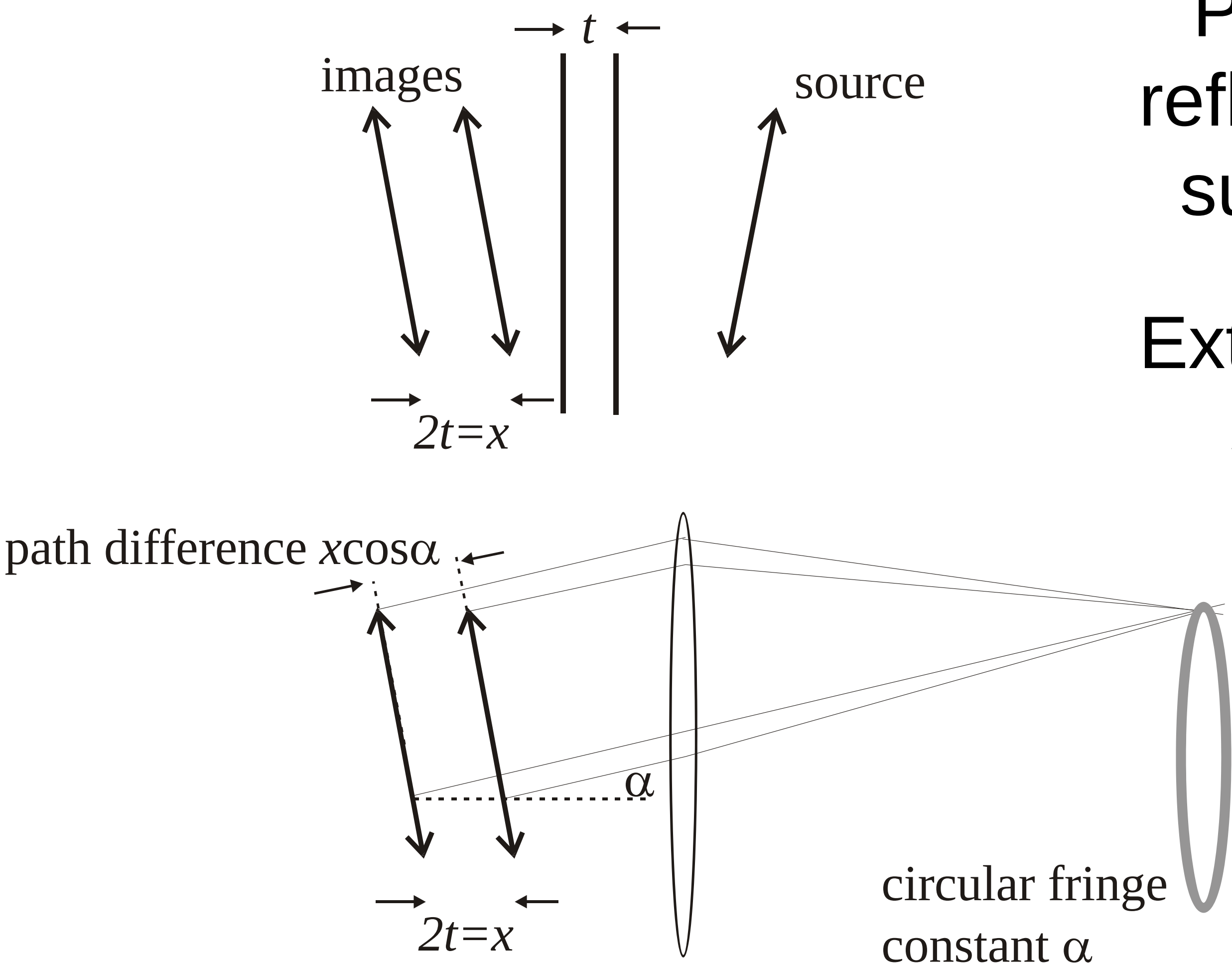

P'
Wedged
reflecting surfaces
P
Point
source
O


P'
P
O
Point source
θ
θ'
Parallel reflecting surfaces


Wedged
Reflecting surfaces
P'
R'
P
R
O
Extended source S

Parallel reflecting surfaces

Extended source



Summary: fringe type and localisation

	Wedged	Parallel
Point Source	Non-localised Equal thickness	Non-localised Equal inclination
Extended Source	Localised in plane of Wedge Equal thickness	Localised at infinity Equal inclination