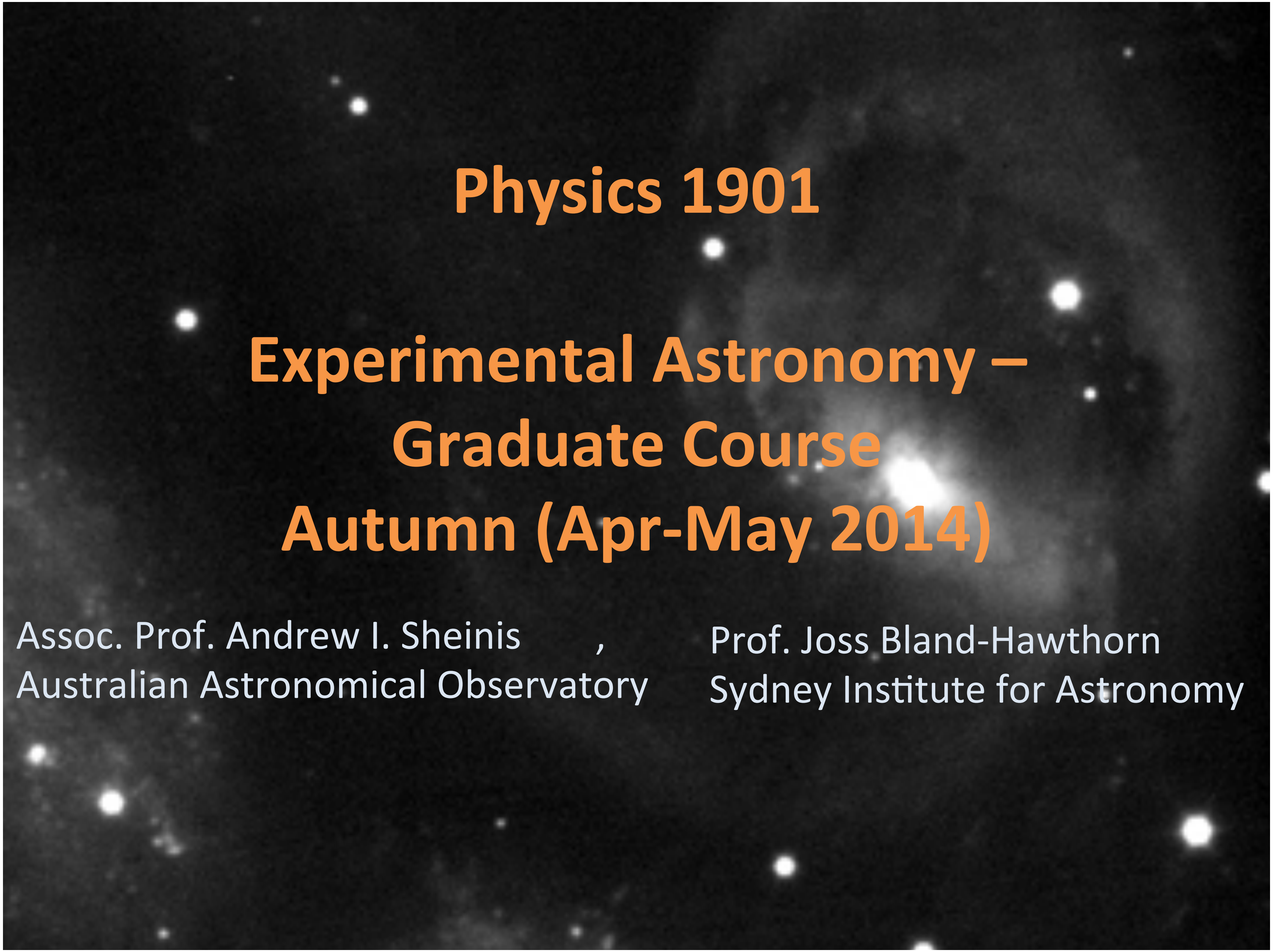
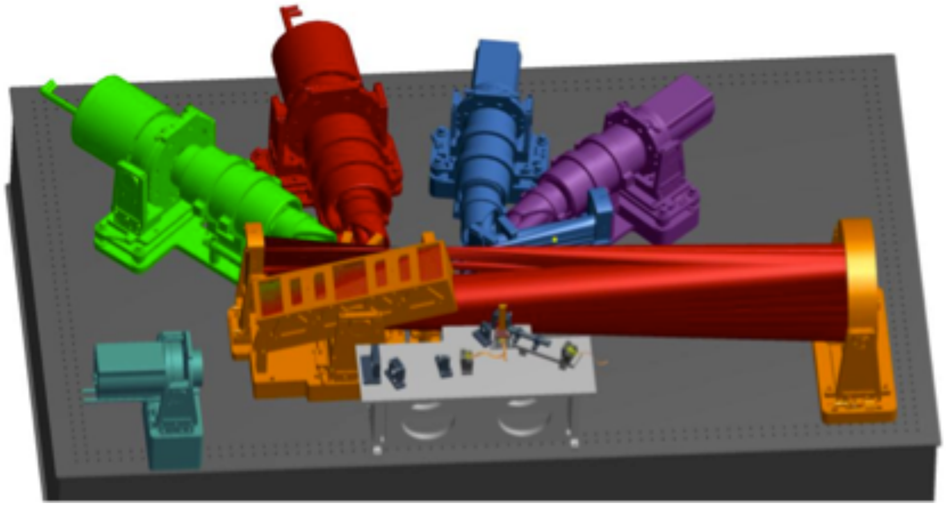
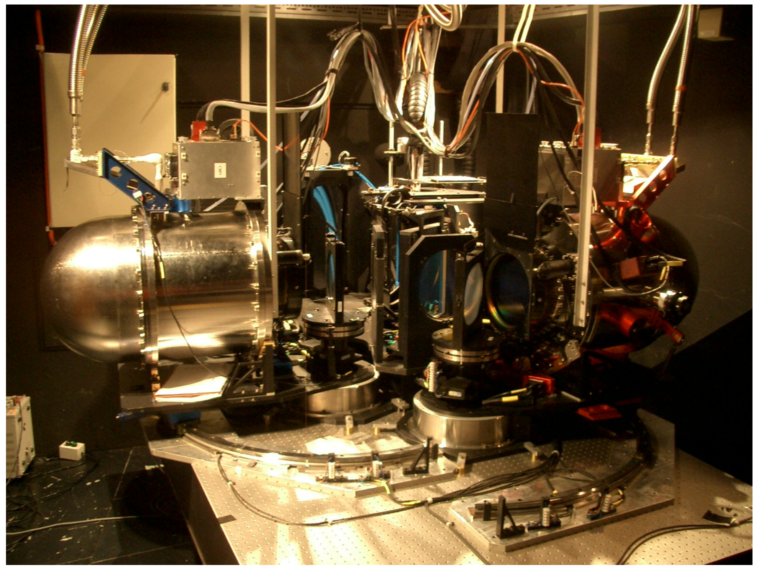
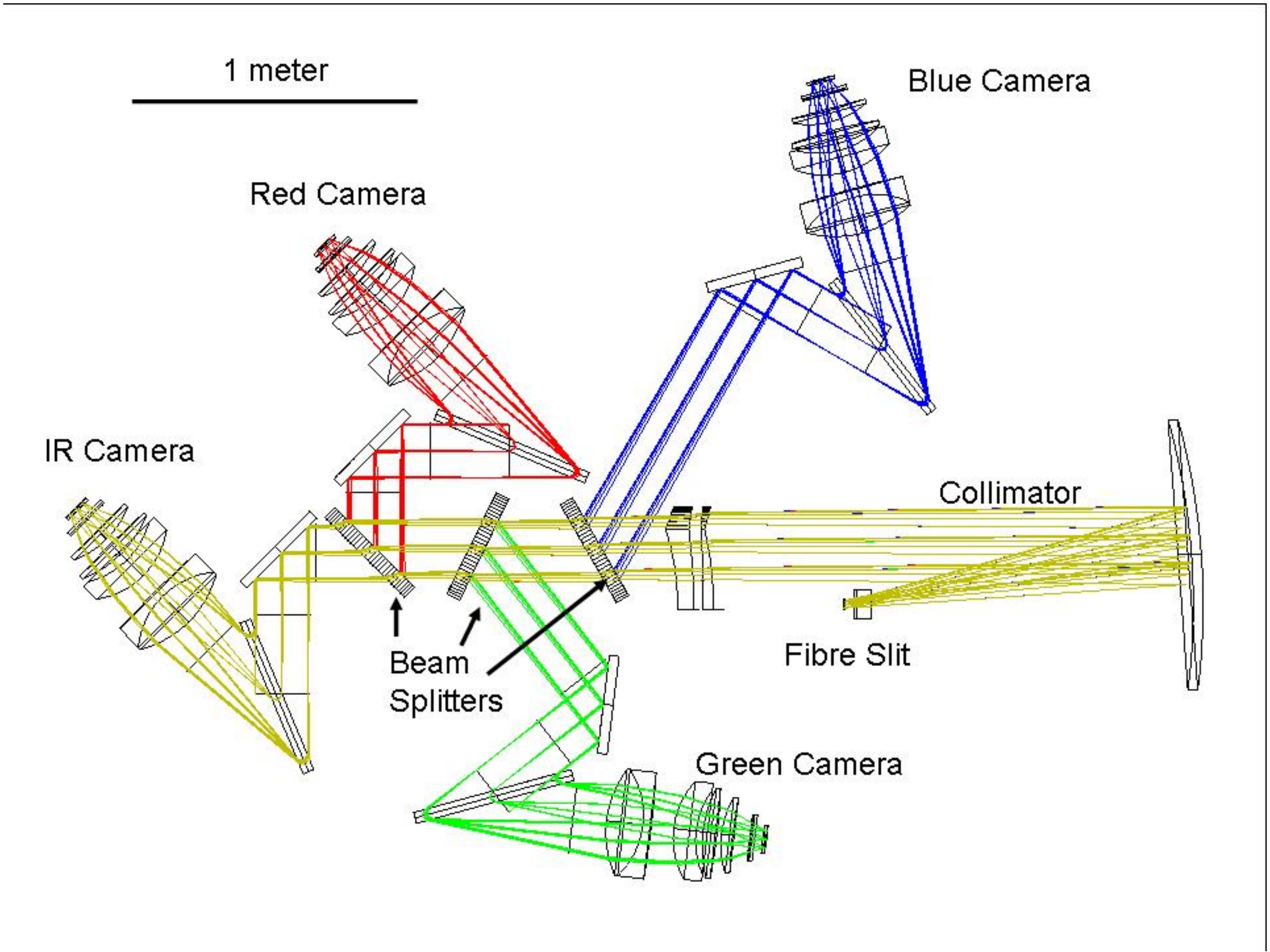

Physics 1901
Experimental Astronomy –
Graduate Course
Autumn (Apr-May 2014)
Assoc. Prof. Andrew I. Sheinis ,
Australian Astronomical Observatory
Prof. Joss Bland-Hawthorn
Sydney Institute for Astronomy

Some questions:
(which you should be able to answer at the end of the course)

- What are the parts of a spectrograph
- Why are spectrographs so big?
- What sets the sensitivity?
- How do I estimate the exposure time?

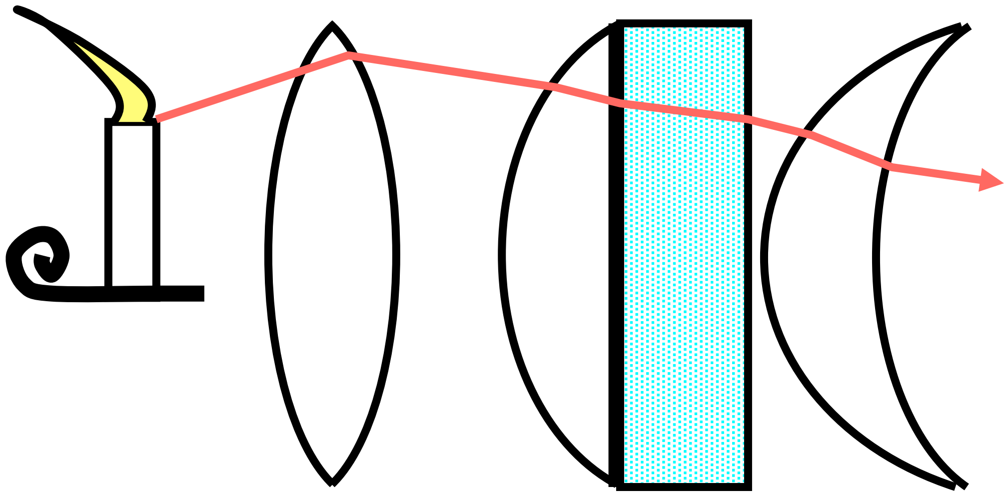





1 meter
Blue Camera
Red Camera
IR Camera
Collimator
Fibre Slit
Beam
Splitters
Green Camera

ABCD Matrix Concepts

- Ray Description
  - Position
  - Angle
- Basic Operations
  - Translation
  - Refraction
- Two-Dimensions
  - Extensible to Three



Ray Vector $$\mathcal{V}_1 = \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

Matrix Operation $$\mathcal{V}_{out} = \mathcal{M}\mathcal{V}_{in}$$

System Matrix $$\mathcal{M}_{25} = \mathcal{R}_5 \mathcal{T}_{45} \mathcal{R}_4 \mathcal{T}_{34} \mathcal{R}_3 \mathcal{T}_{23}$$

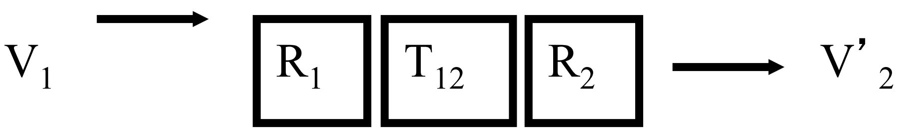
Cascading Matrices (1)

Generic Matrix:

$$\mathcal{M} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}$$

Determinant (You can show that this is true for cascaded matrices)

$$Det \quad \mathcal{M} = \frac{n}{n'}$$



Light Travels Left to Right, but Build Matrix from Right to Left

$$\begin{pmatrix} x_2' \\ \alpha_2' \end{pmatrix} = \mathcal{R}_2 \begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix}$$

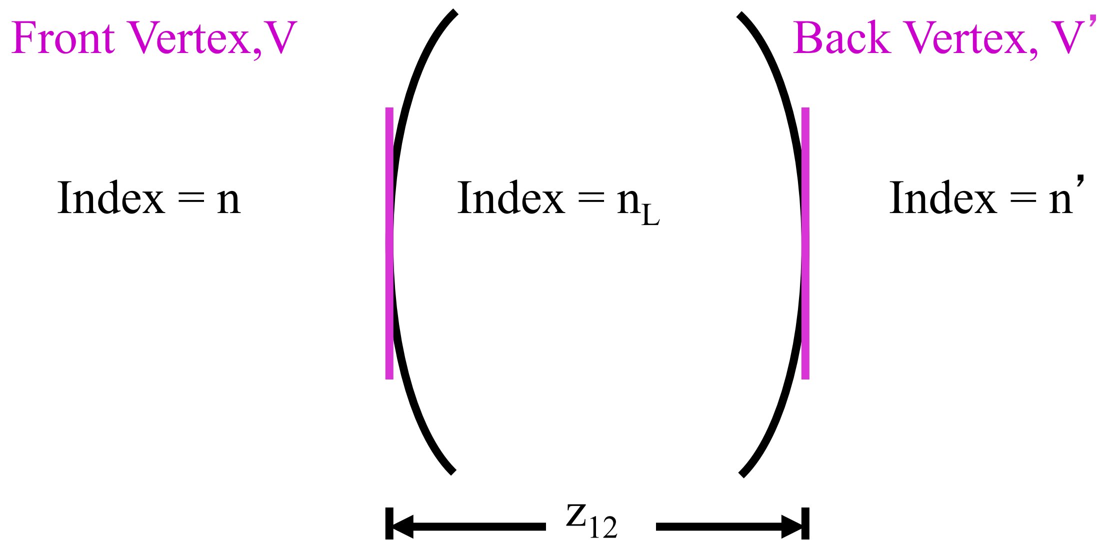
$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = \mathcal{T}_{12} \begin{pmatrix} x_1' \\ \alpha_1' \end{pmatrix}$$

$$\begin{pmatrix} x_1' \\ \alpha_1' \end{pmatrix} = \mathcal{R}_1 \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

$$\begin{pmatrix} x_2' \\ \alpha_2' \end{pmatrix} = \mathcal{R}_2 \mathcal{T}_{12} \mathcal{R}_1 \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

$$\mathcal{M}_{12} = \mathcal{R}_2 \mathcal{T}_{12} \mathcal{R}_1$$

The Simple Lens (Matrix Way)

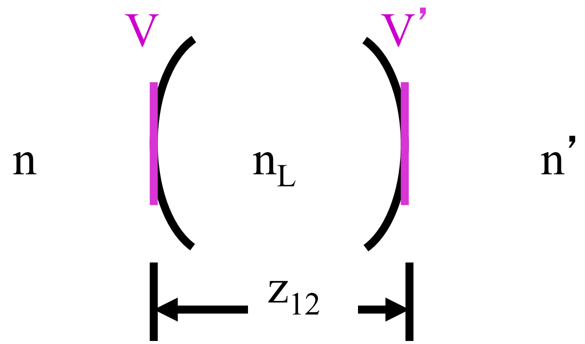


$$\mathcal{M}_{VV'} = \mathcal{R}_2 \mathcal{T}_{12} \mathcal{R}_1$$

Building The Simple Lens Matrix

$$\mathcal{M}_{VV'} = \mathcal{R}_1 \mathcal{T}_{12} \mathcal{R}_1$$

$$= \begin{pmatrix} 1 & 0 \\ \frac{-P_2}{n_2'} & \frac{n_2}{n_2'} \end{pmatrix} \begin{pmatrix} 1 & z_{12} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-P_1}{n_1'} & \frac{n_1}{n_1'} \end{pmatrix}$$



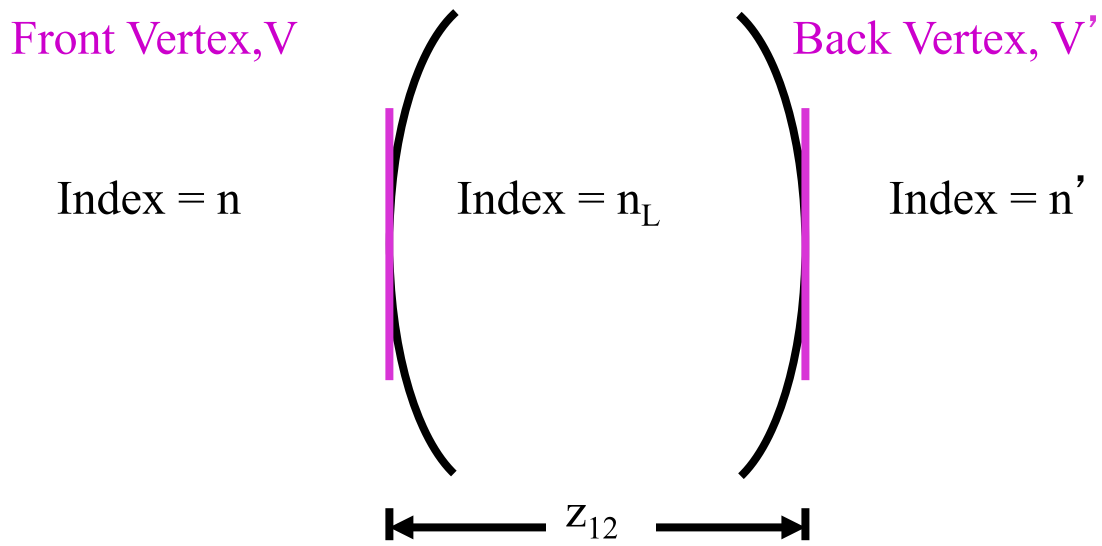
$$n_1 = n \qquad n_2' = n' \qquad n_1' = n_2 = n_\ell$$

Simple Lens Matrix

$$\begin{pmatrix} 1 & 0 \\ \frac{-P_2}{n'} & \frac{n_\ell}{n'} \end{pmatrix} \begin{pmatrix} 1 & z_{12} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-P_1}{n_\ell} & \frac{n}{n_\ell} \end{pmatrix}$$

The Equivalent Lens, Using the System Matrix to get everything you need!

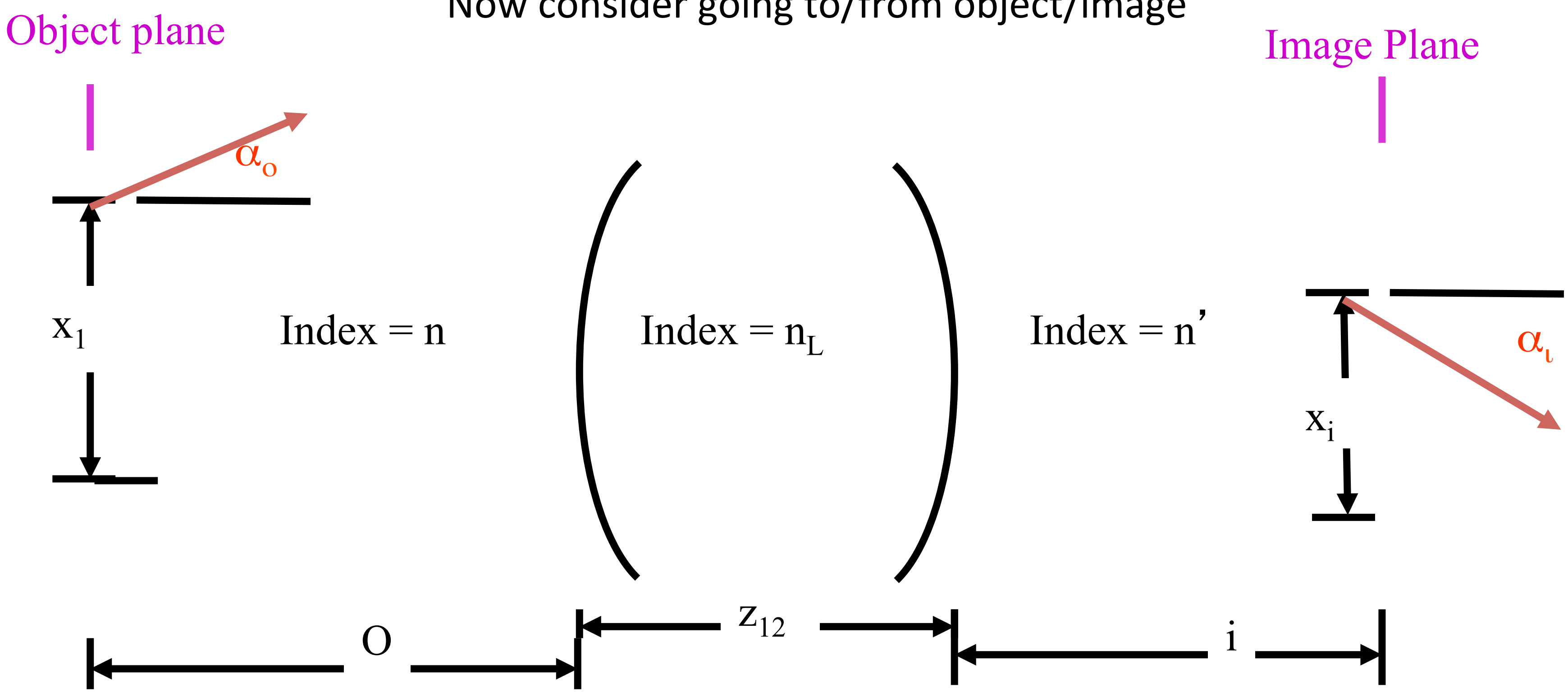
Here is what we did last time for a lens system



$$\mathcal{M}_{VV'} = \mathcal{R}_2 \mathcal{T}_{12} \mathcal{R}_1$$

The Equivalent Lens, Using the System Matrix to get everything you need!

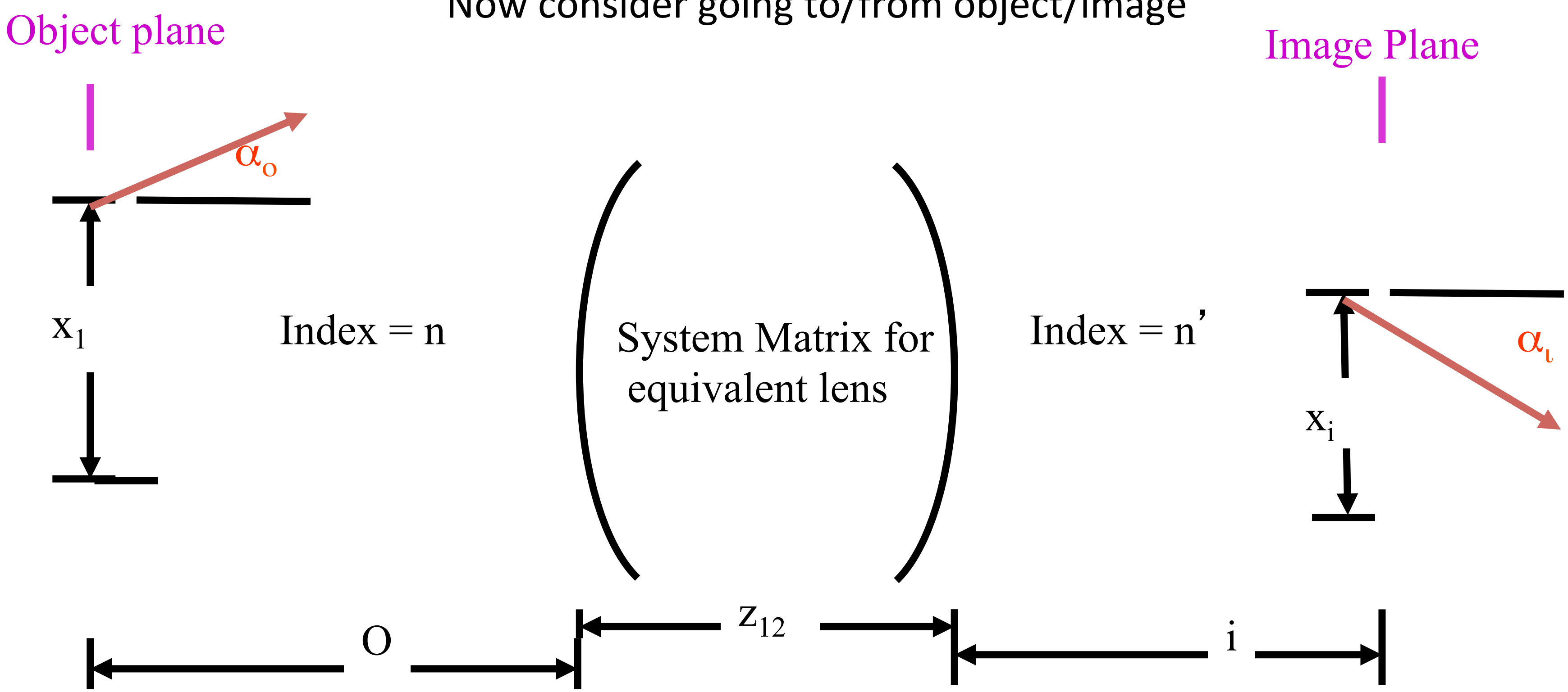
Now consider going to/from object/image



$$M_{oi} = \tau_{32} R_2 \tau_{21} R_1 \tau_1$$

The Equivalent Lens, Using the System Matrix to get everything you need!

Now consider going to/from object/image



$$M_{oi} = \tau_{32} R_2 \tau_{21} R_1 \tau_1$$

The Equivalent Lens, Using the System Matrix to get everything you need!

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$$

$$M_{oi} = \tau_{32} R_2 \tau_{21} R_1 \tau_1$$

The Equivalent Lens, Using the System Matrix to get everything you need!

$$M = \begin{pmatrix} H & G \\ F & E \end{pmatrix}$$

$$x_n^{'} = Hx + G\gamma$$

$$\gamma_n^{'} = Fx + E\gamma$$

$$M_{oi} = \tau_{32} R_2 \tau_{21} R_1 \tau_1$$

Where

$$H = A + iC$$

$$G = -o - ioC + B + oD$$

$$F = C$$

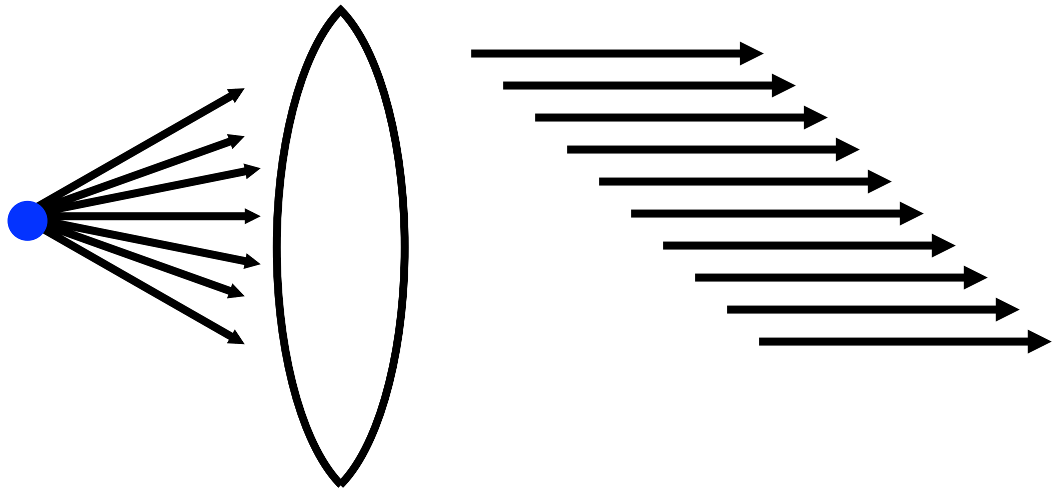
$$E = D - Co$$

Using the System Matrix
Case 1: E=0

Output angle independent of input angle

$$x_n^{'} = Hx + G\gamma$$

$$\gamma_n^{'} = Fx + E\gamma$$



$$o = \frac{D}{C}$$

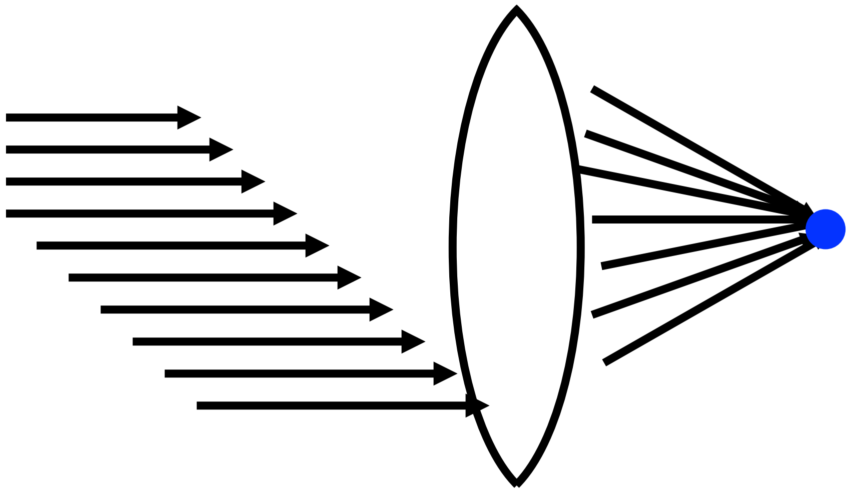
Front focal distance!

Using the System Matrix
Case 2: H=0

Output height independent of input height
Output height proportional to input angle

$$x_n' = Hx + G\gamma$$

$$\gamma_n' = Fx + E\gamma$$

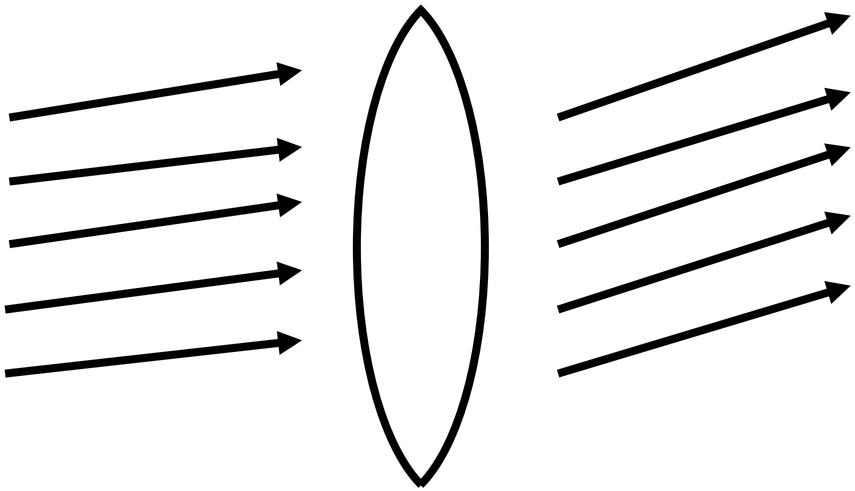


$$i = \frac{-A}{C}$$

Back focal distance!

Using the System Matrix
Case 3: F=0

Output angle independent of input height
Telescope condition!



$$x_n' = Hx + G\gamma$$

$$\gamma_n' = Fx + E\gamma$$

$$E = \frac{\gamma'}{\gamma}$$

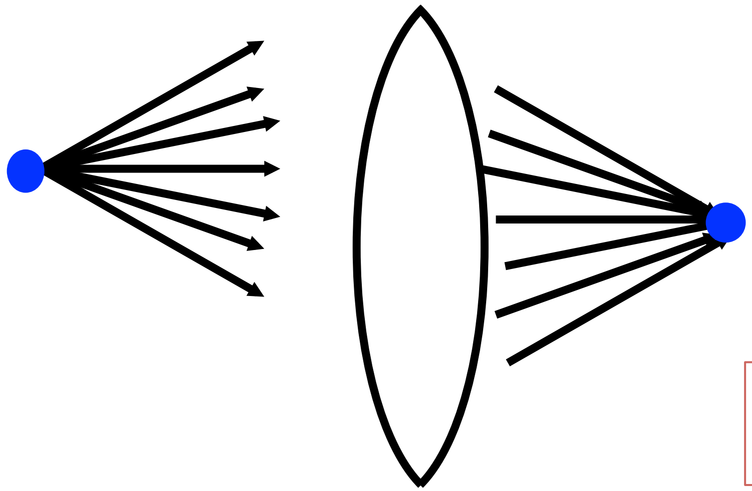
Angular magnification

Using the System Matrix
Case 3: G=0

Rays emitted at a fixed height
arrive at a fixed height independent of angle

$$x_n^{'} = Hx + G\gamma$$

$$\gamma_n^{'} = Fx + E\gamma$$

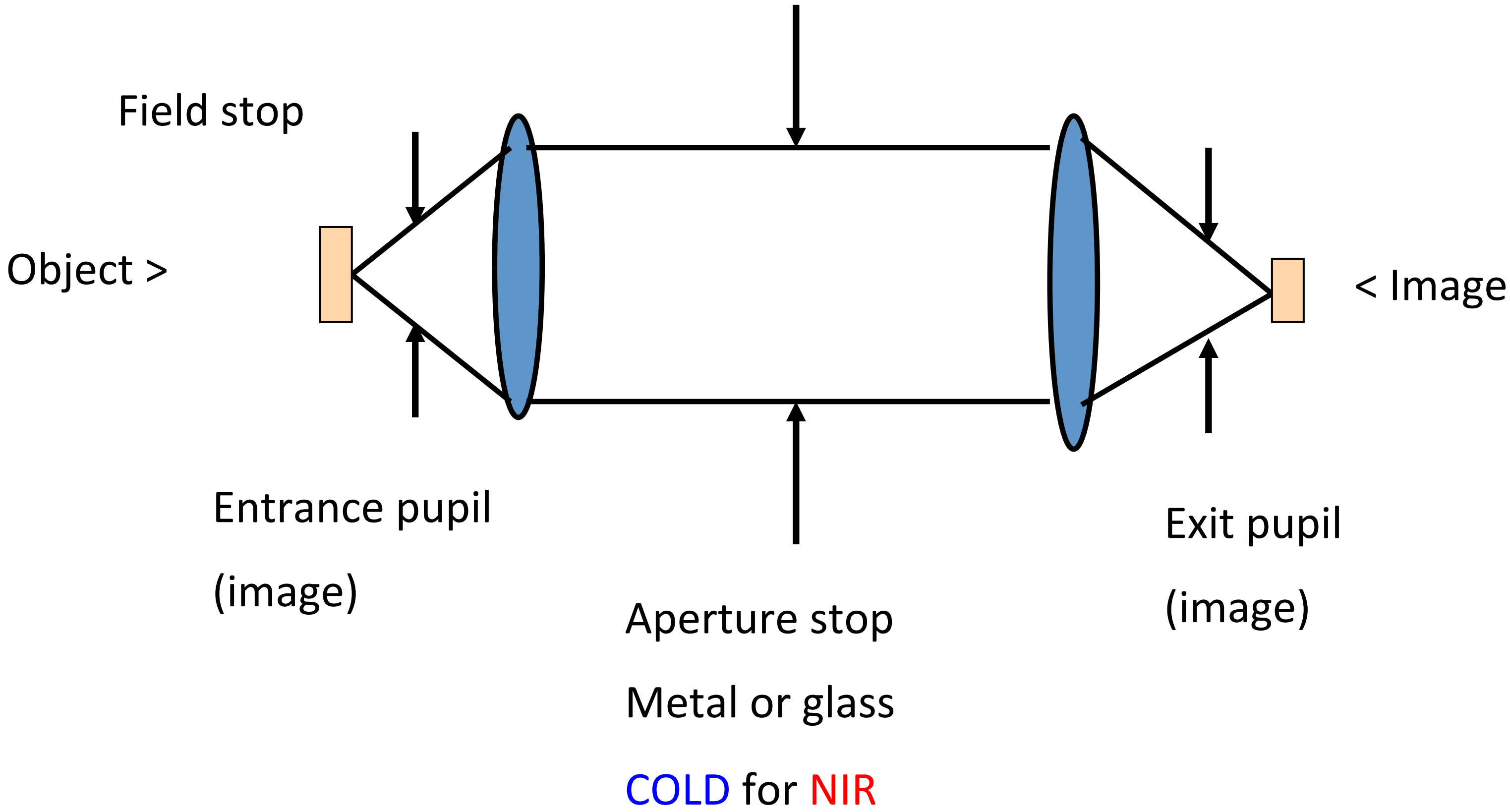


Object and image distances!

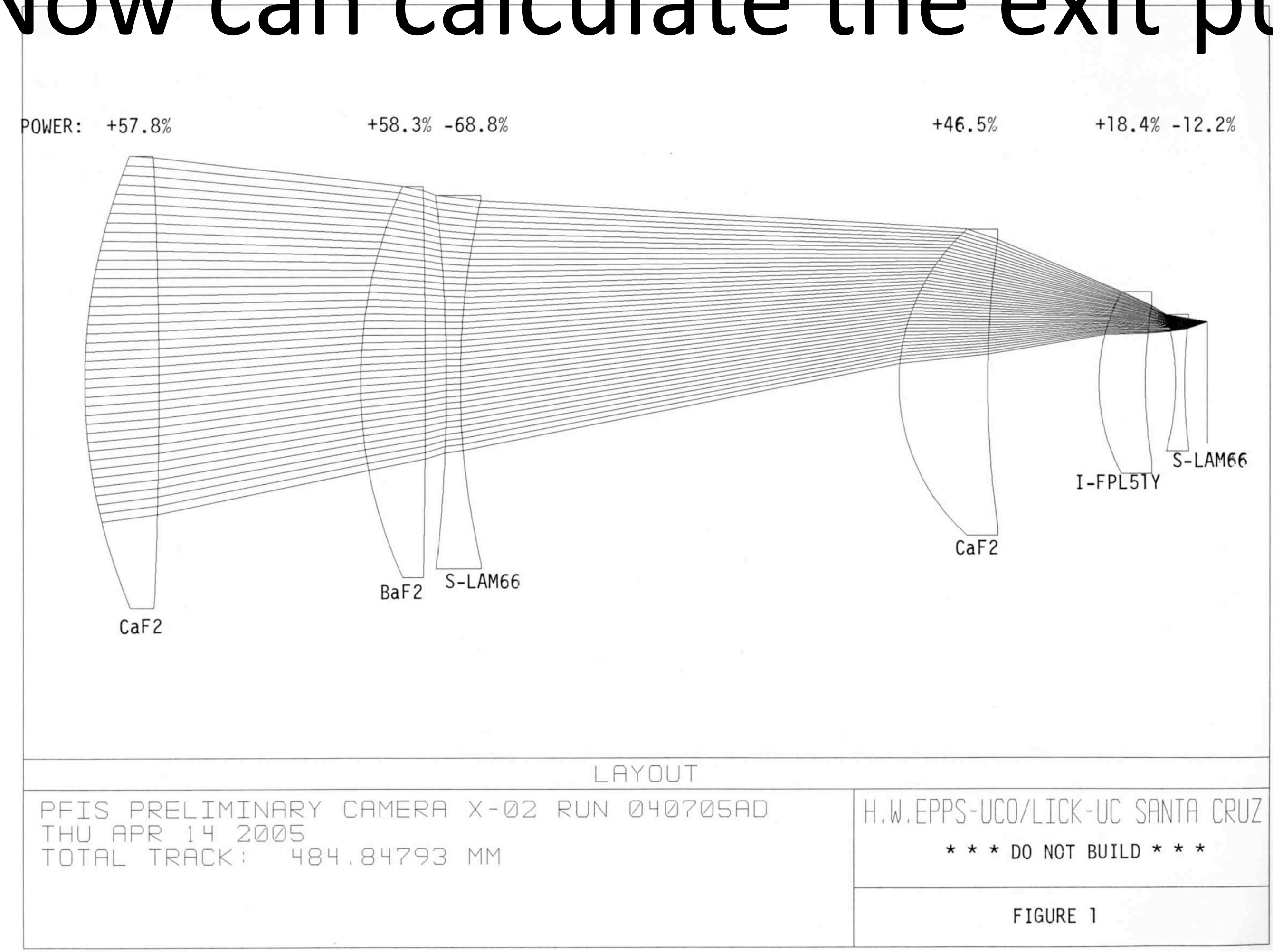
$$i = \frac{Ao - B}{D - Co}$$

$$o = \frac{B + Di}{A + Ci}$$

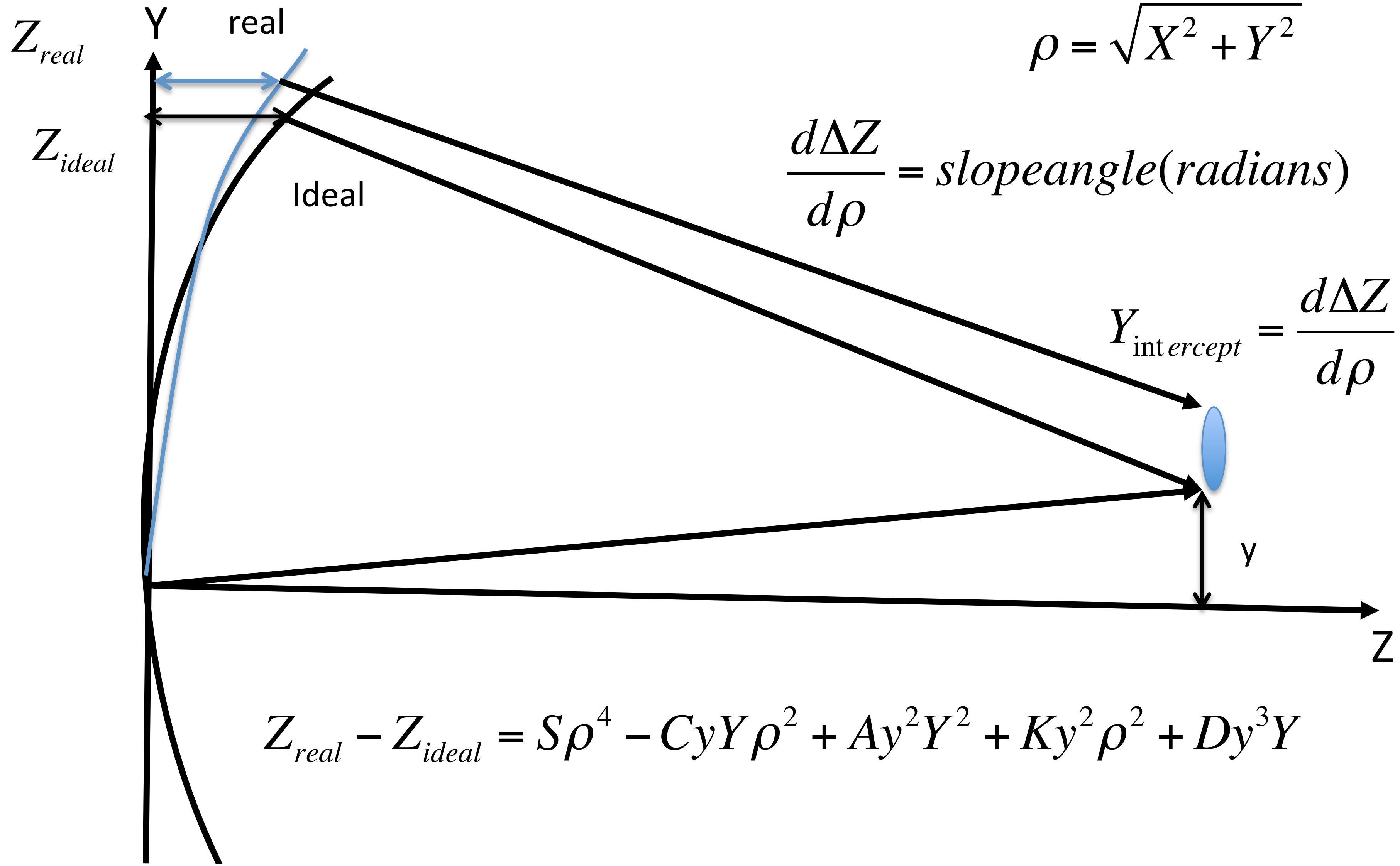
Now you can use the matrix representation to solve for Entrance Pupil and Exit Pupil for any system!



Now can calculate the exit pupil.



Geometric Theory of Aberrations (Eikonal analysis, what's an eikonal?)



$$\rho = \sqrt{X^2 + Y^2}$$

$$\frac{d\Delta Z}{d\rho} = slopeangle(radians)$$

$$Y_{intercept} = \frac{d\Delta Z}{d\rho} f$$

$$Z_{real} - Z_{ideal} = S\rho^4 - CyY\rho^2 + Ay^2Y^2 + Ky^2\rho^2 + Dy^3Y$$

Geometric Theory of Aberrations (Eikonal analysis)

$$Z_{real} - Z_{ideal} = S\rho^4 - CyY\rho^2 + Ay^2Y^2 + Ky^2\rho^2 + Dy^3Y$$

Where

$$Z = OPD$$

$$\frac{d\Delta Z}{d\rho} = slopeangle(radians)$$

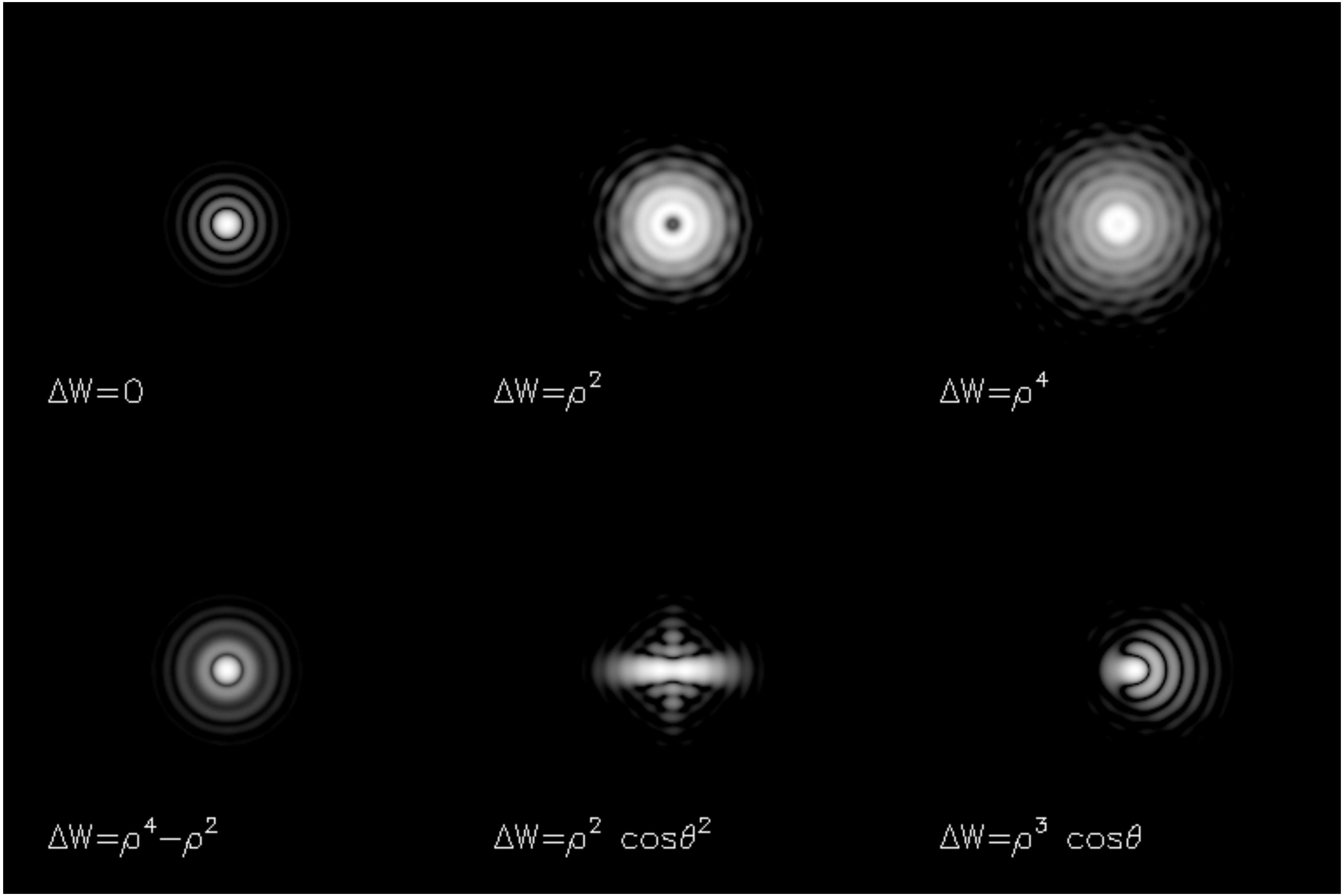
S= Spherical

C=Coma

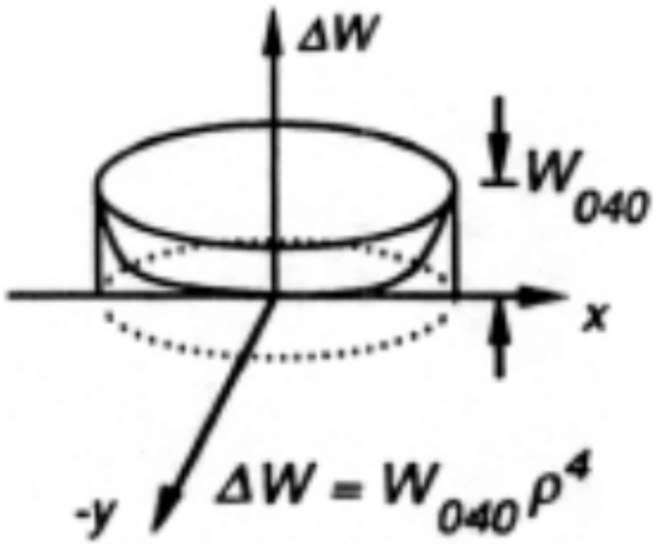
A=Astigmatism

K=Field Curvature

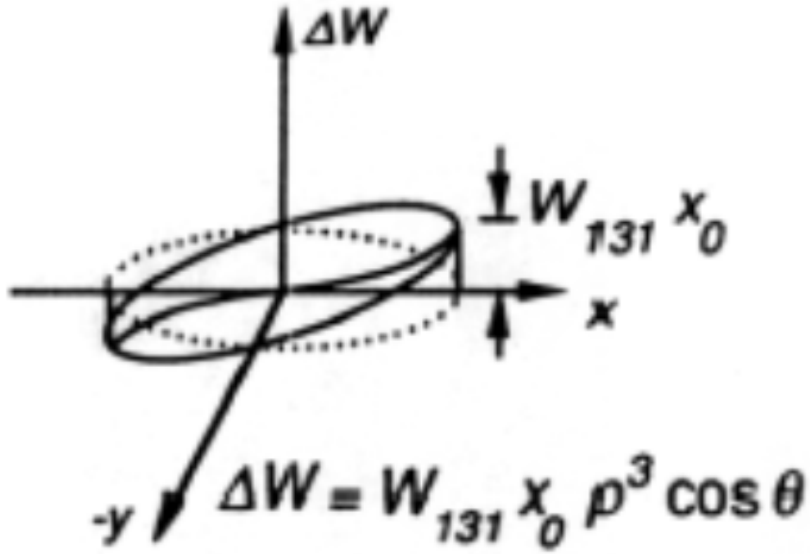
D=Distortion



ΔW=0
ΔW=ρ2
ΔW=ρ4
ΔW=ρ4−ρ2
ΔW=ρ2 cosθ2
ΔW=ρ3 cosθ



Spherical Aberration



Coma

Longitudinal and Transverse Spherical Aberration

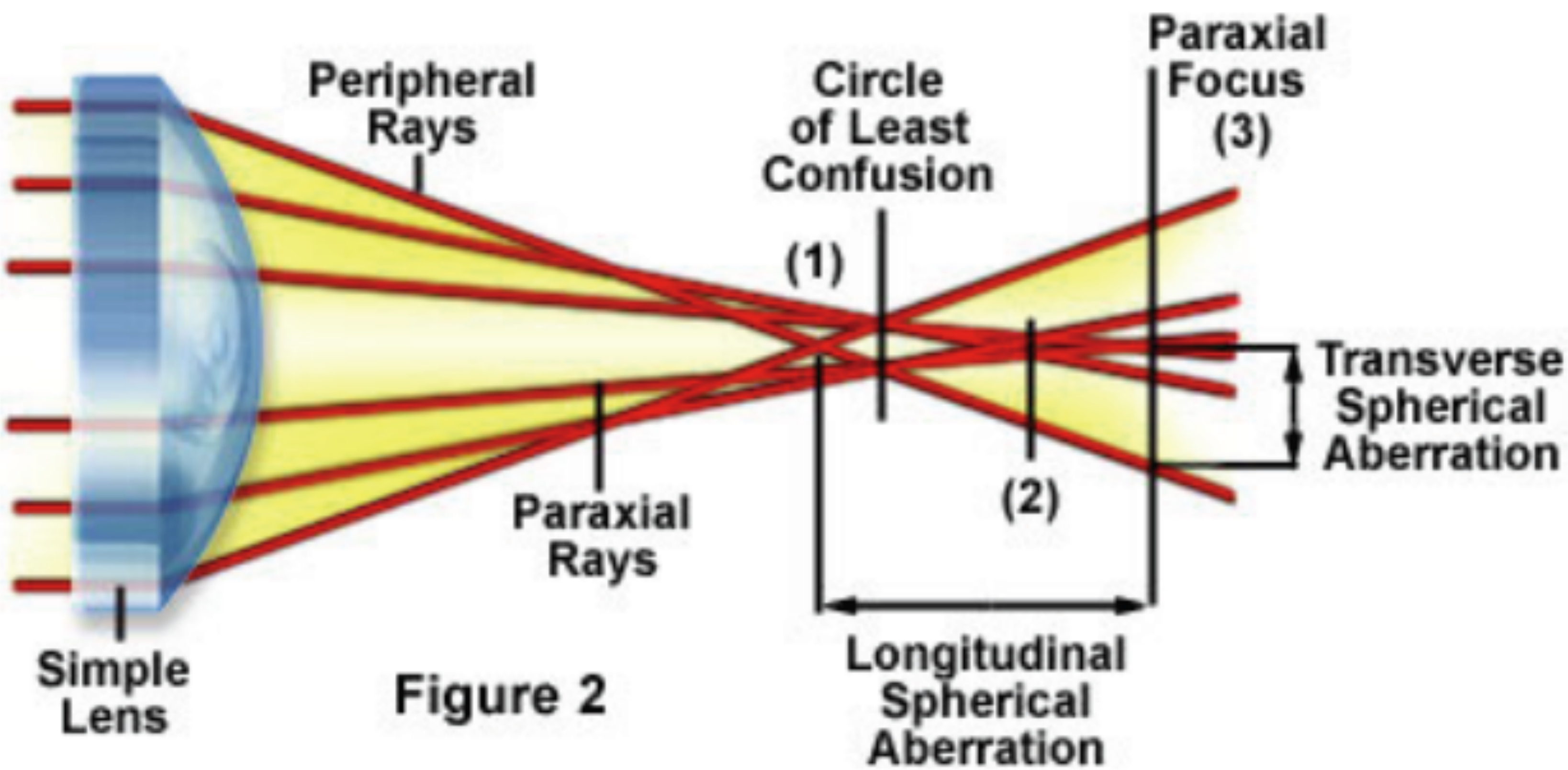
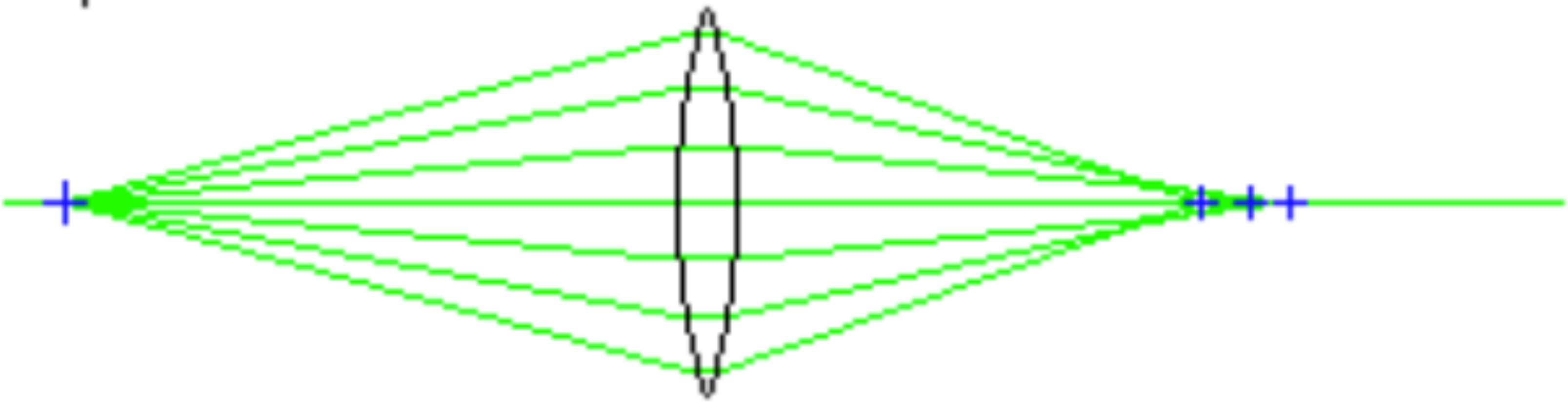
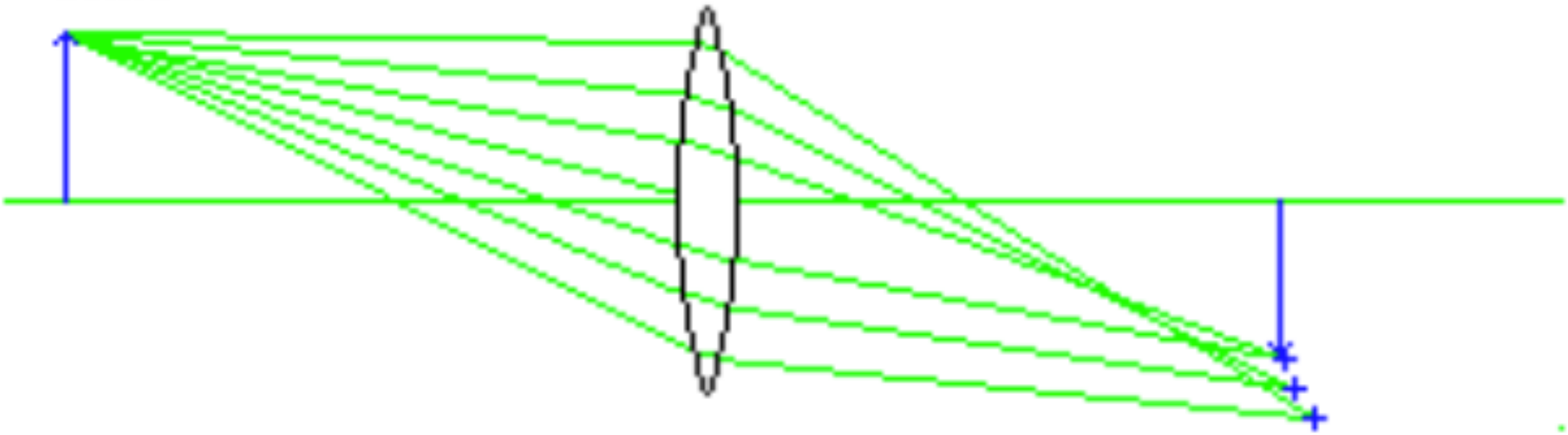


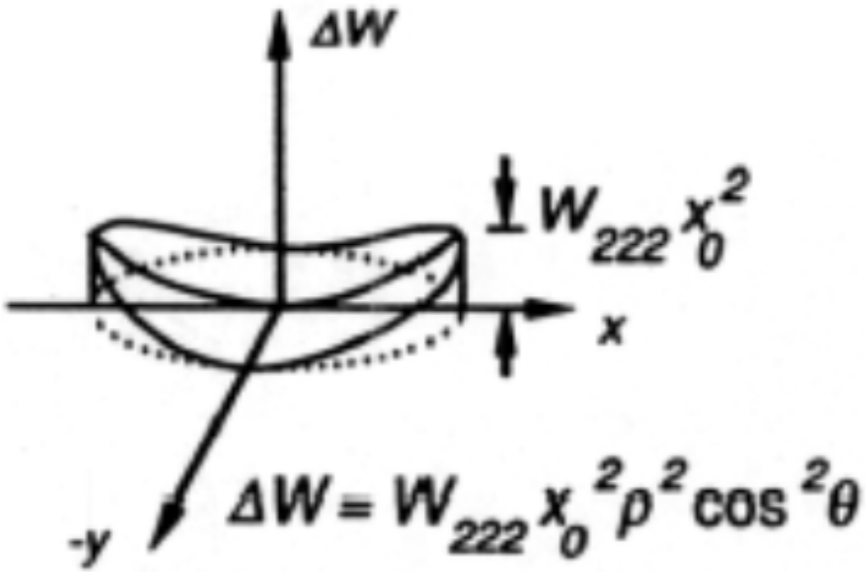
Figure 2

Spherical Aberration

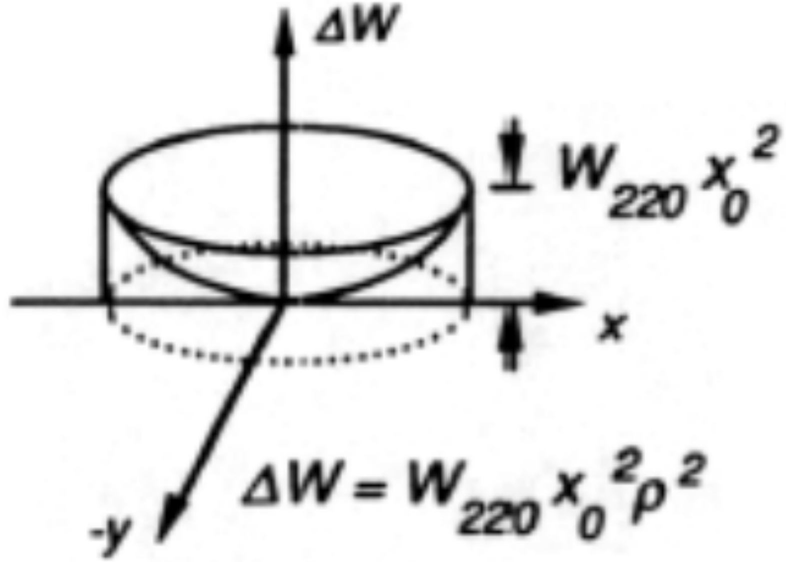


Coma





Astigmatism



Field Curvature

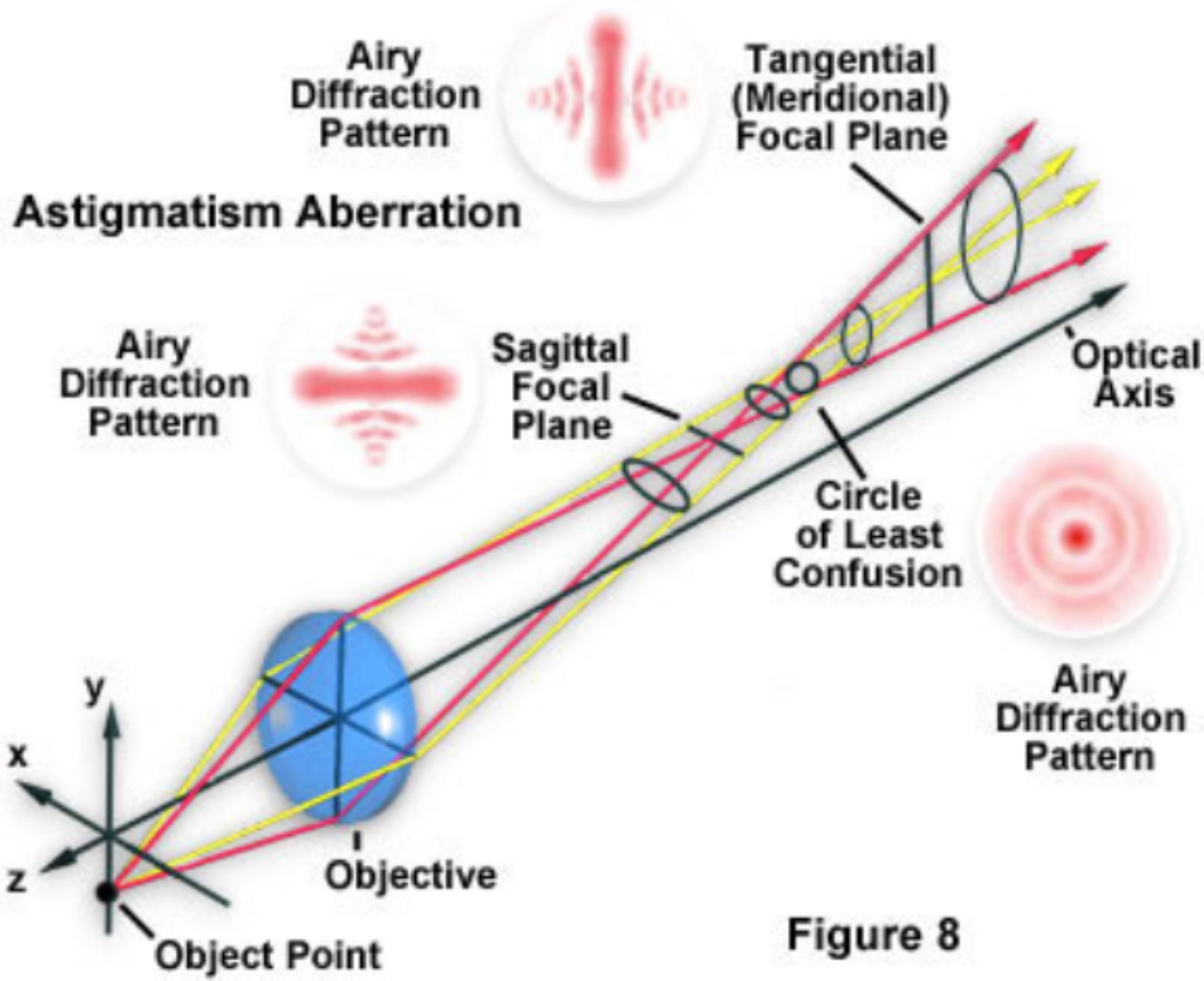
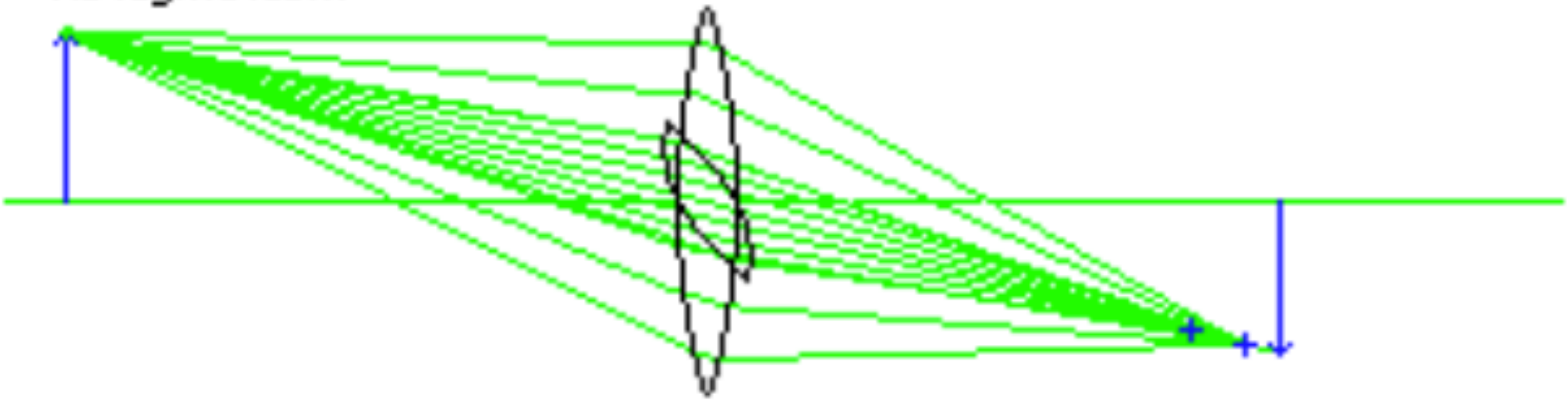
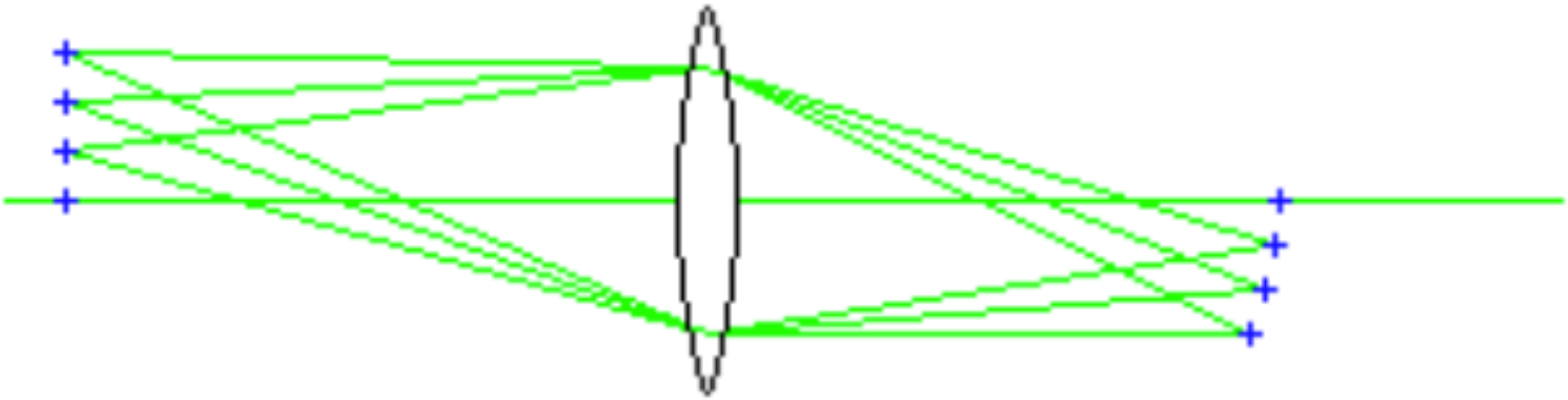

Astigmatism Aberration
Airy Diffraction Pattern
Tangential (Meridional) Focal Plane
Airy Diffraction Pattern
Sagittal Focal Plane
Optical Axis
Circle of Least Confusion
Airy Diffraction Pattern
y
x
z
Objective
Object Point

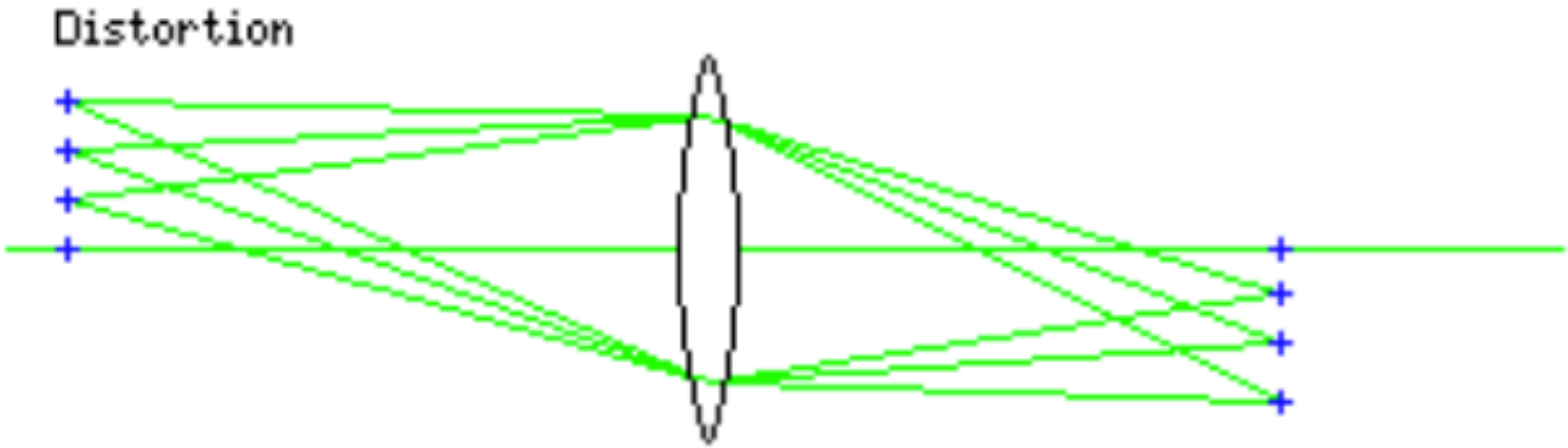
Figure 8

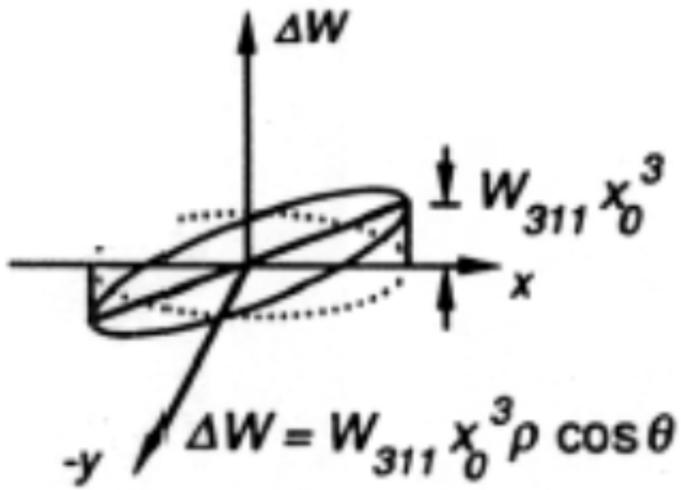
Astigmatism



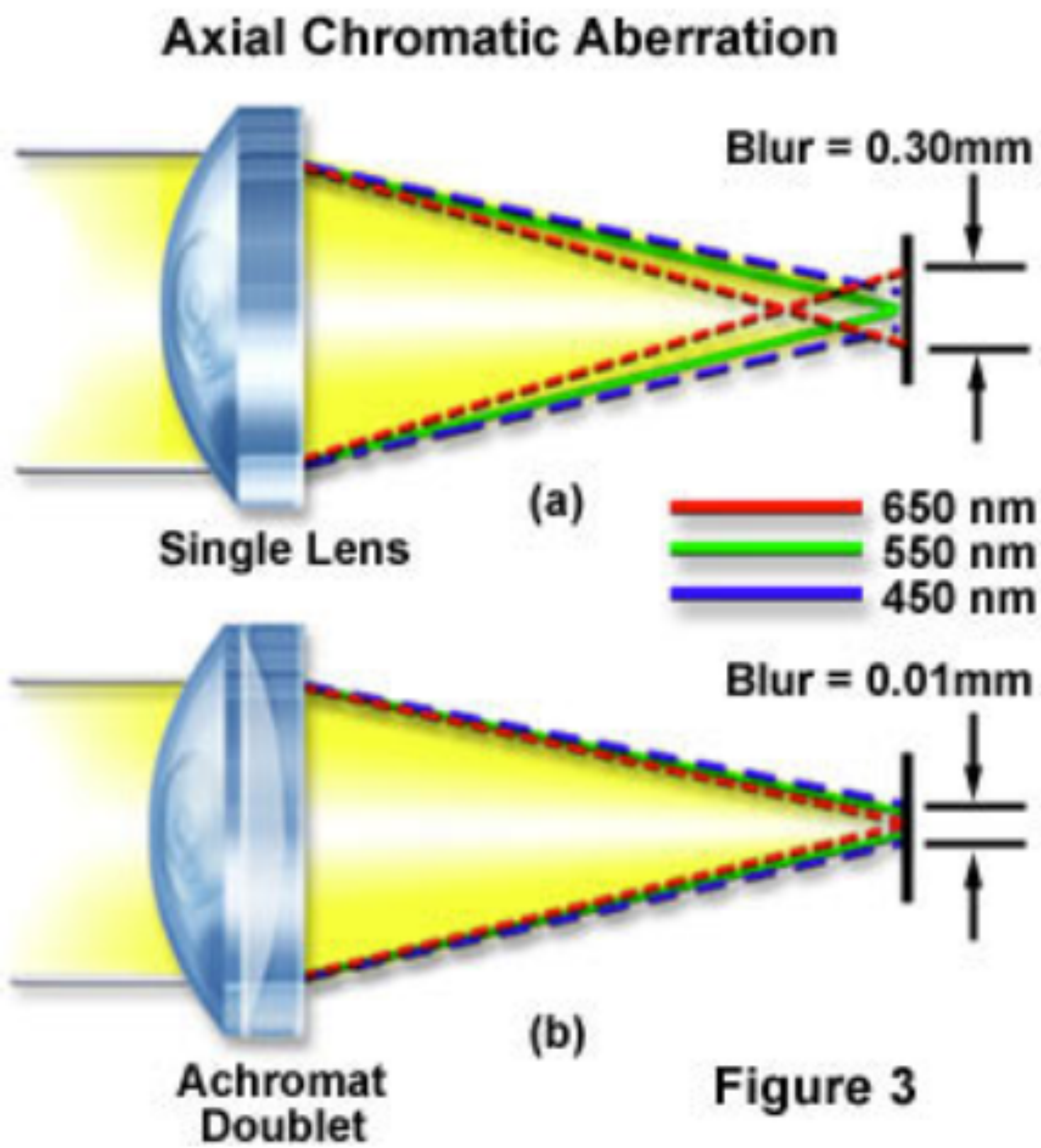
Curvature of Field







Distortion


Axial Chromatic Aberration
Blur = 0.30mm
(a)
Single Lens
650 nm
550 nm
450 nm
Blur = 0.01mm
(b)
Achromat
Doublet
Figure 3

How to "fix" aberrations

$$Z_{real} - Z_{ideal} = S\rho^4 - CyY\rho^2 + Ay^2Y^2 + Ky^2\rho^2 + Dy^3Y$$

0 0 0 0

- On-axis > y=0

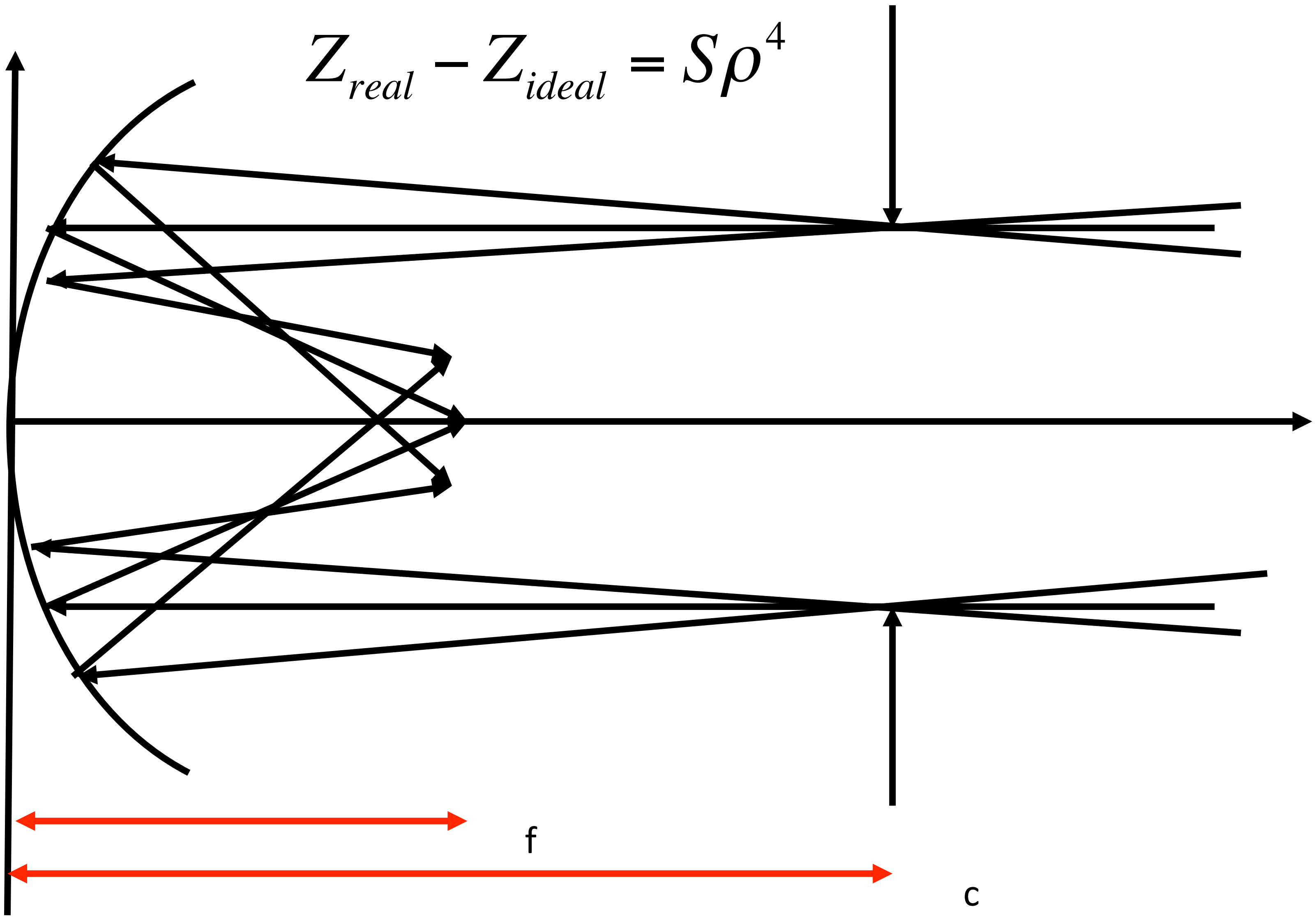
$$Z_{real} - Z_{ideal} = S\rho^4$$

$$Z_{real}^2 - A_1 Z_{real} - A_2\rho^2 = A_3$$

This is a parabola. Perfect image quality, zero field.

How to “fix” aberrations

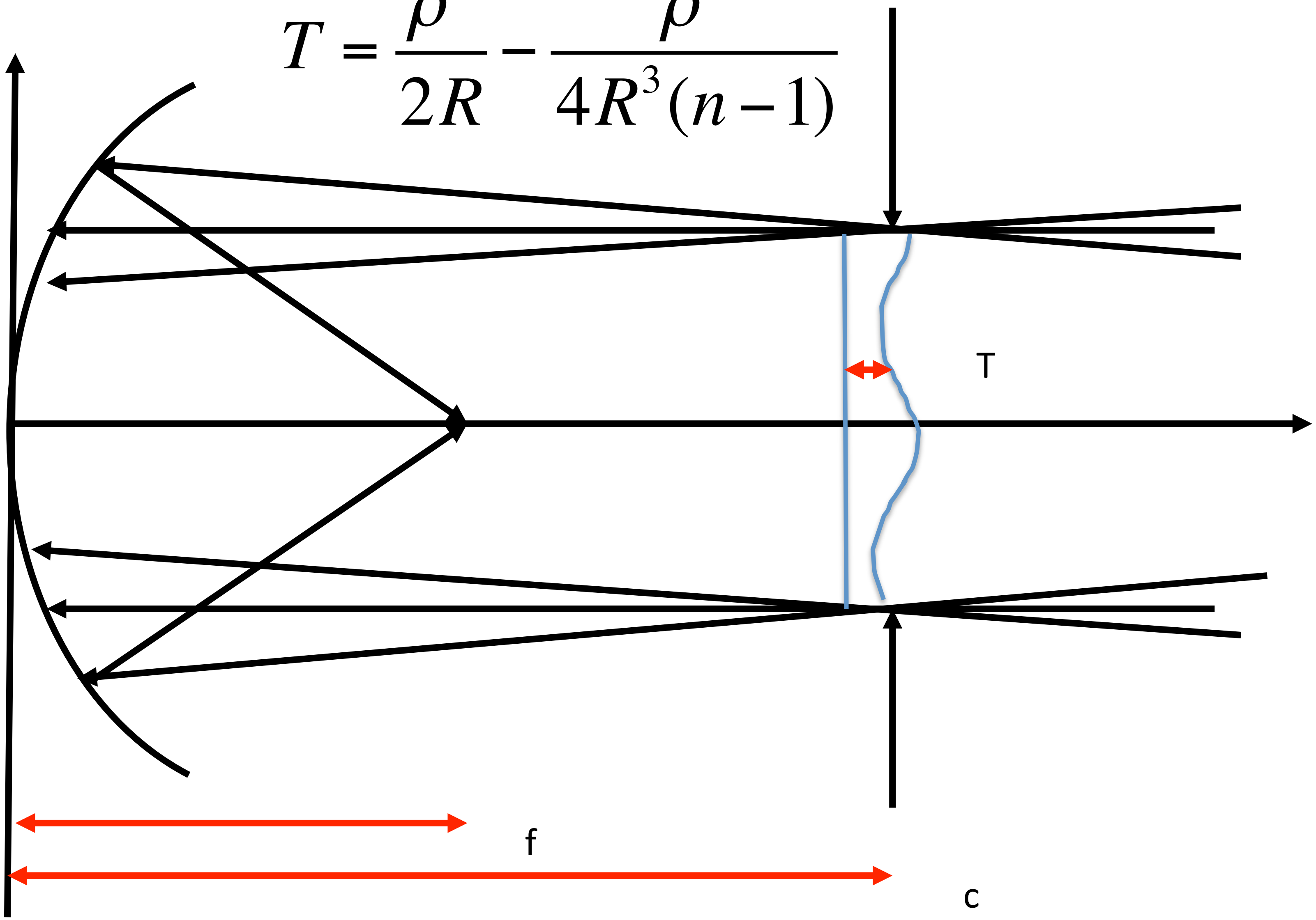
$$Z_{real} - Z_{ideal} = S\rho^4$$

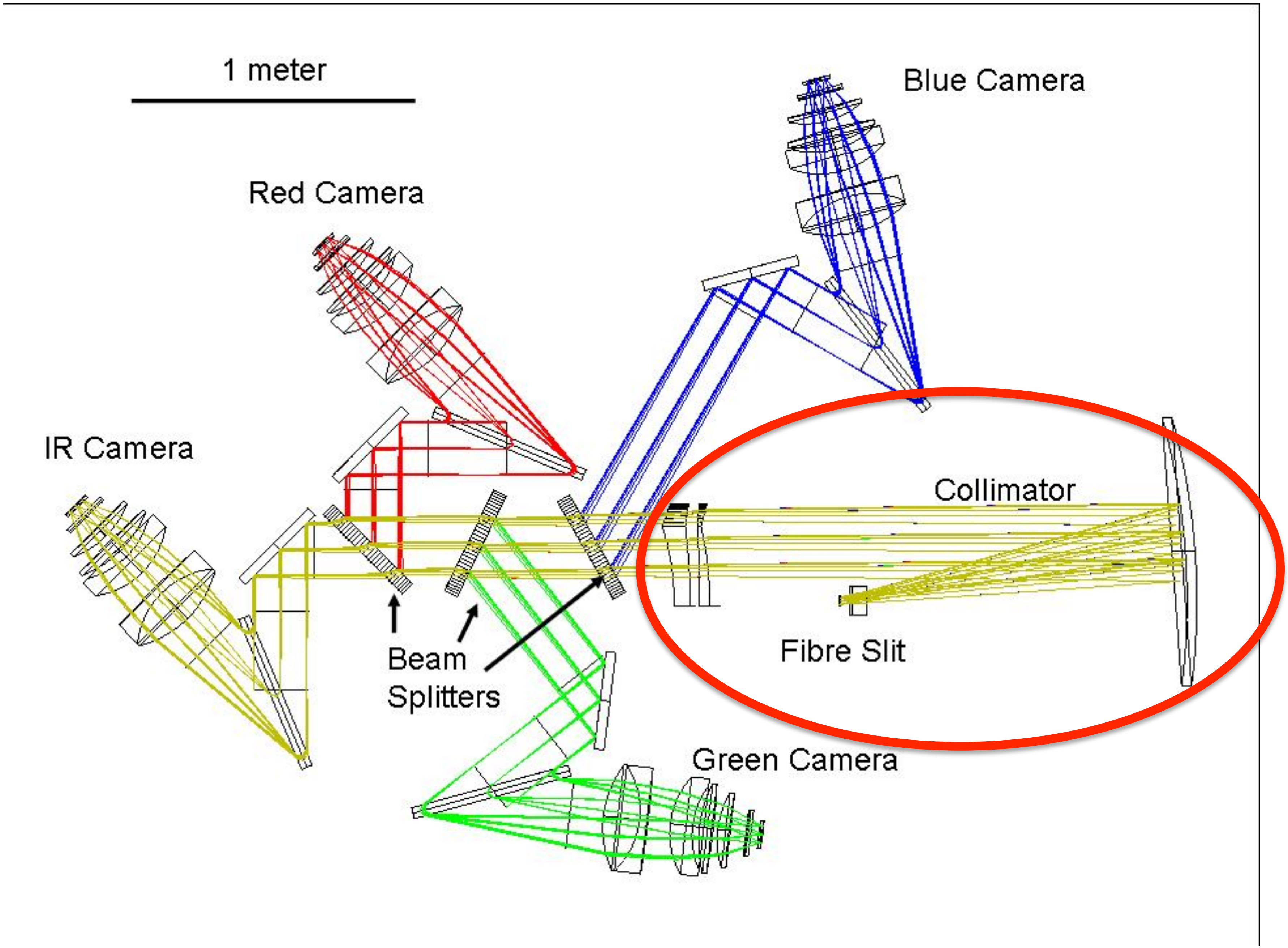


$$Z_{real} - Z_{ideal} = S\rho^4 = (n-1)T$$

$$T = \rho^4 / (S(n-1))$$

$$T = \frac{\rho^2}{2R} - \frac{\rho^4}{4R^3(n-1)}$$





1 meter
Blue Camera
Red Camera
IR Camera
Collimator
Beam
Splitters
Fibre Slit
Green Camera

End lecture 2