# Physics 1901

# Experimental Astronomy – Graduate Course Autumn (Apr-May 2014)

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# Course Philosophy

- Alternate between Physical fundamentals: Why instruments look and work the way they do.
- And cool examples: How they work the way that they do.
- On the way we will try and leave you with some useful tools.

# Background: Astronomy is Different

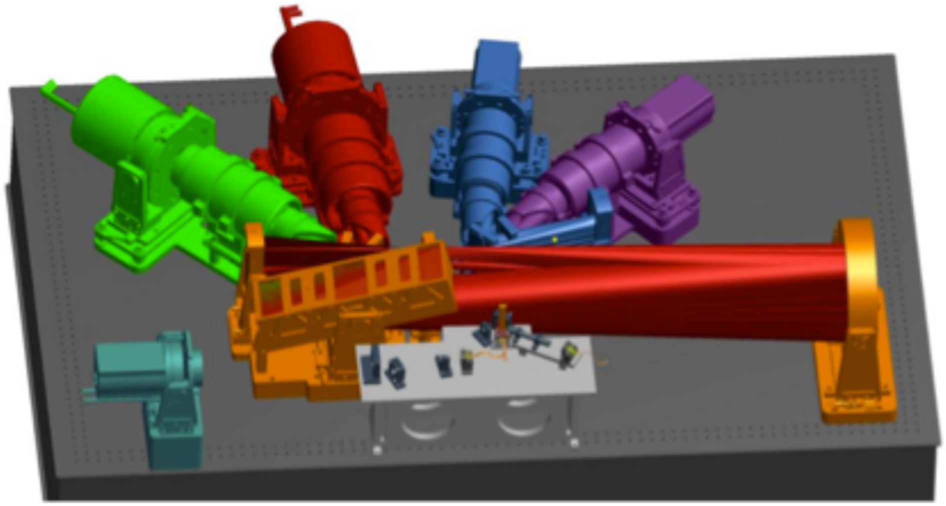
- Universe is the laboratory
- Telescopes are our window into the laboratory
- We can only observe, no interaction
- Limited to phenomena, occurring in the past
- Must take interpret a “snapshot”
- Have only the properties of light
- Cannot measure directly, must infer from the measurement of light.

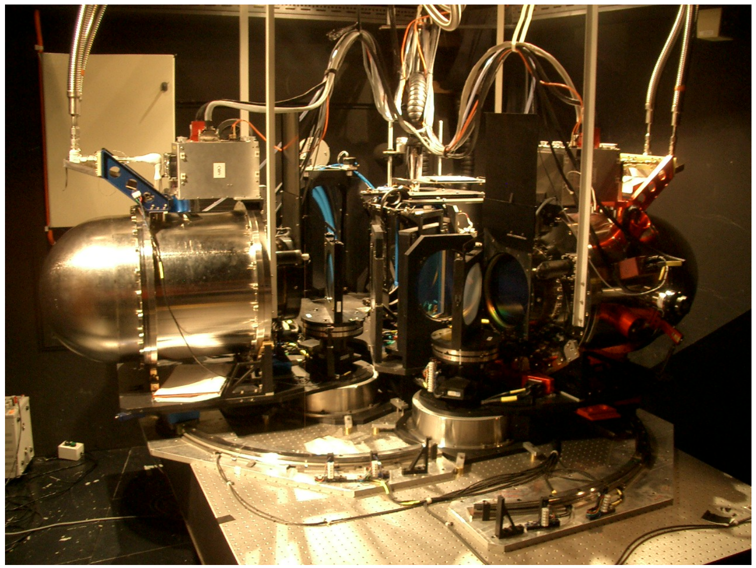
# Properties of light

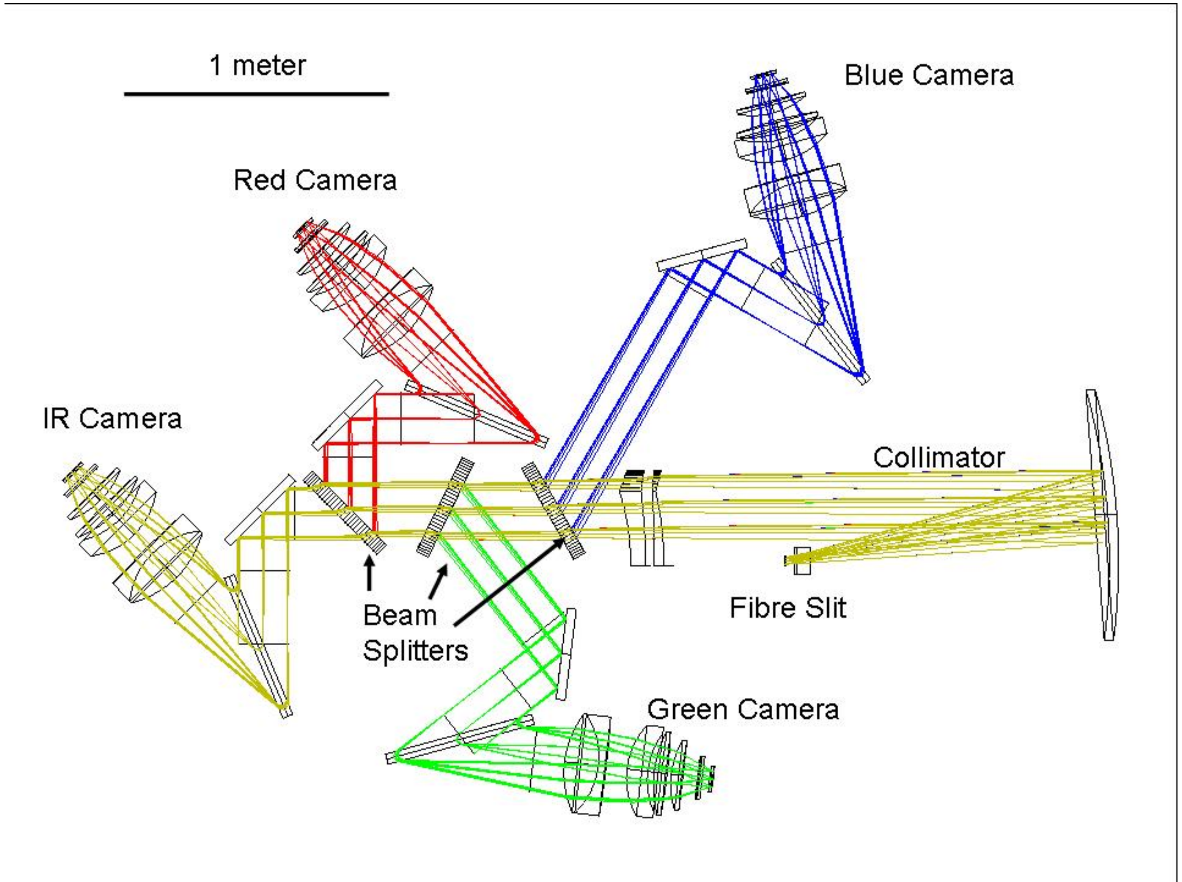
- Intensity, flux, radiance, amplitude
- Angle of arrival, position, image
- Wavelength, frequency, color
- Angular momentum, spin, polarization
- Time variation (in some cases)
- Phase

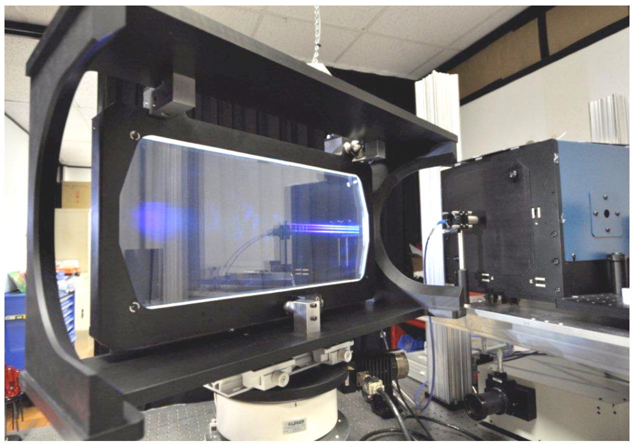
# Some questions:
# (which you should be able to answer at the end of the course)

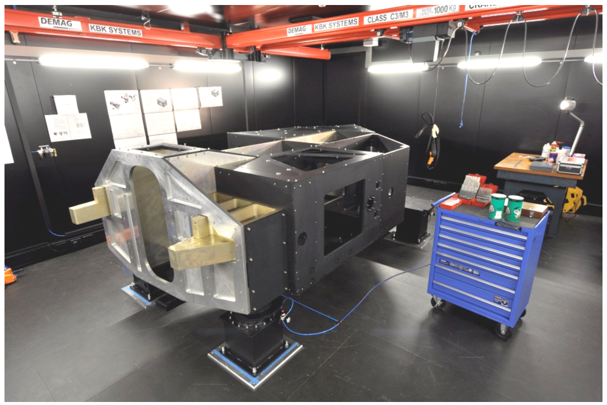
- What are the parts of a spectrograph
- Why are spectrographs so big?
- What sets the sensitivity?
- How do I estimate the exposure time?

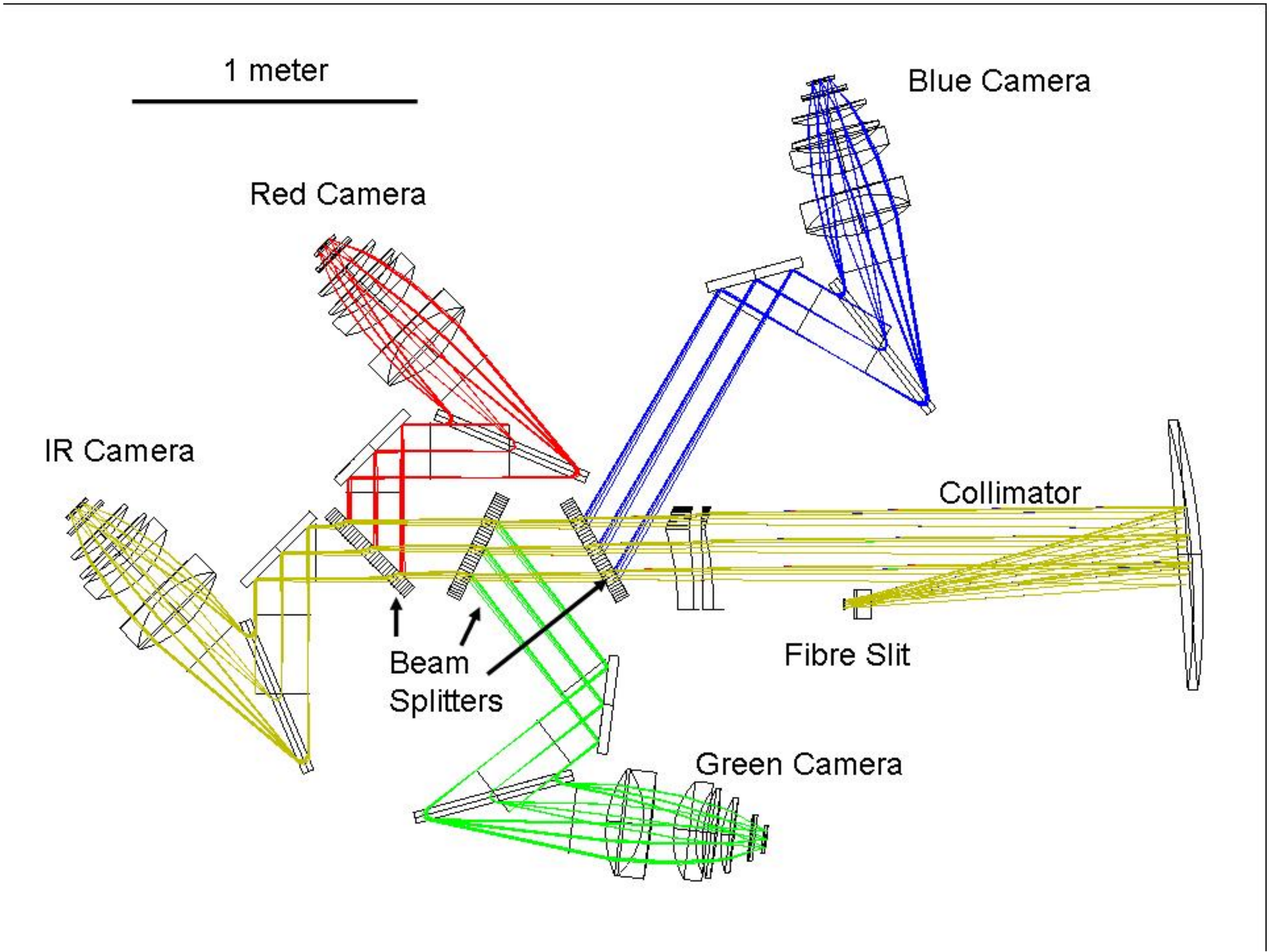





1 meter
Blue Camera
Red Camera
IR Camera
Collimator
Beam
Splitters
Fibre Slit
Green Camera






1 meter
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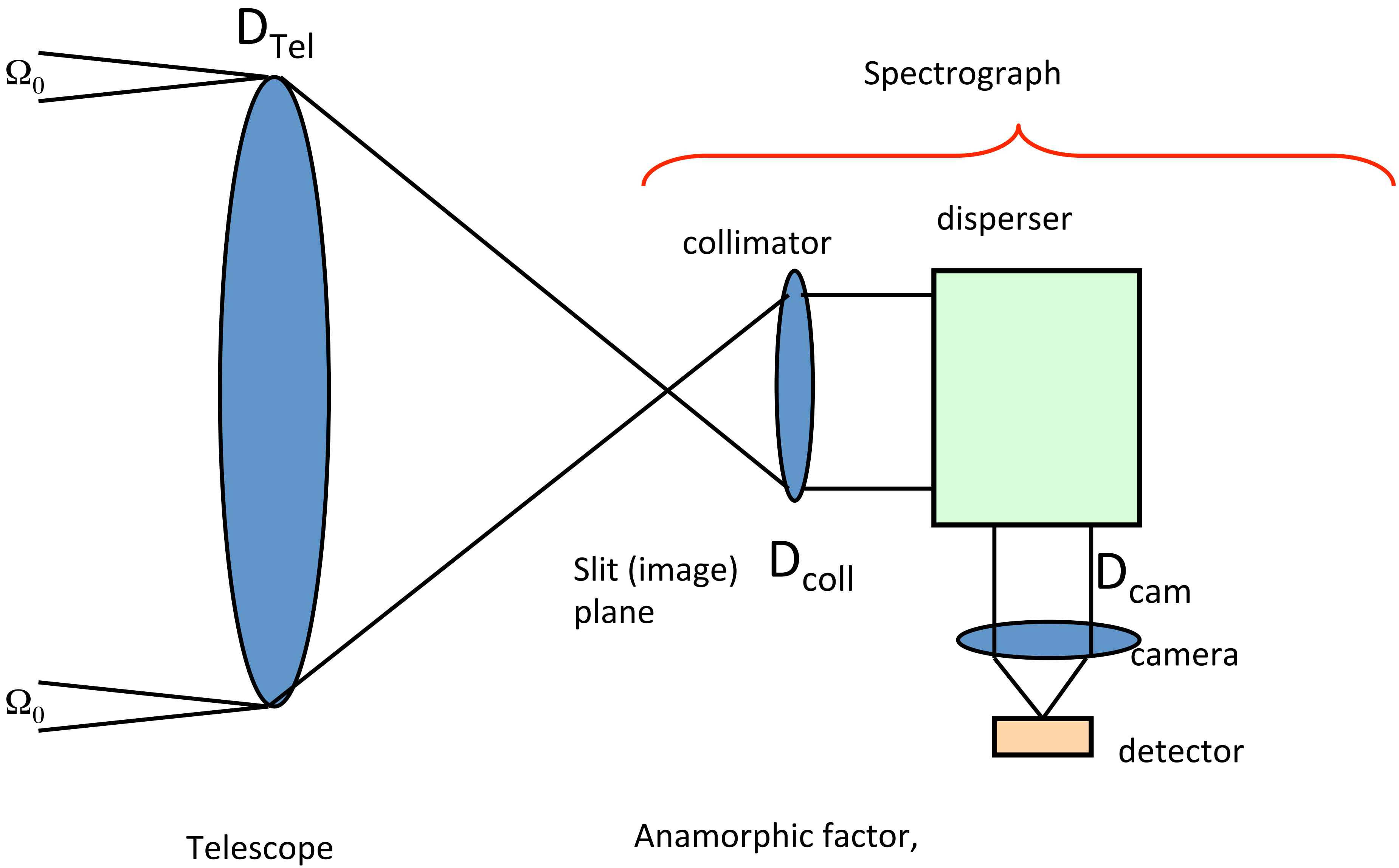



Anamorphic factor,

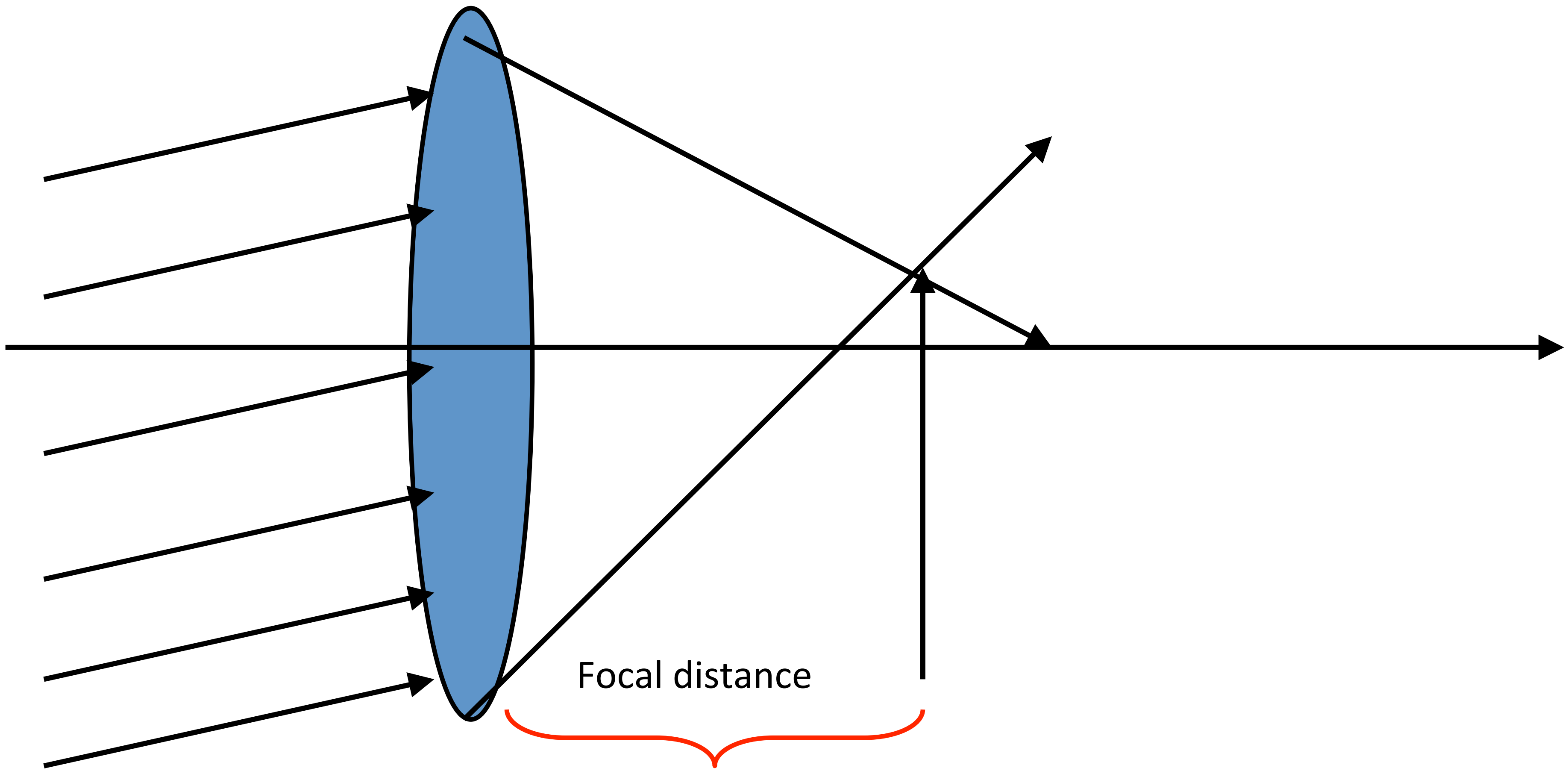
$$r = D_{coll}/\,D_{cam}$$

# All about lenses

- Why do lenses form images?
- How do they form images?
- How to describe the process?
- What if I have multiple lenses?

# Rule #1

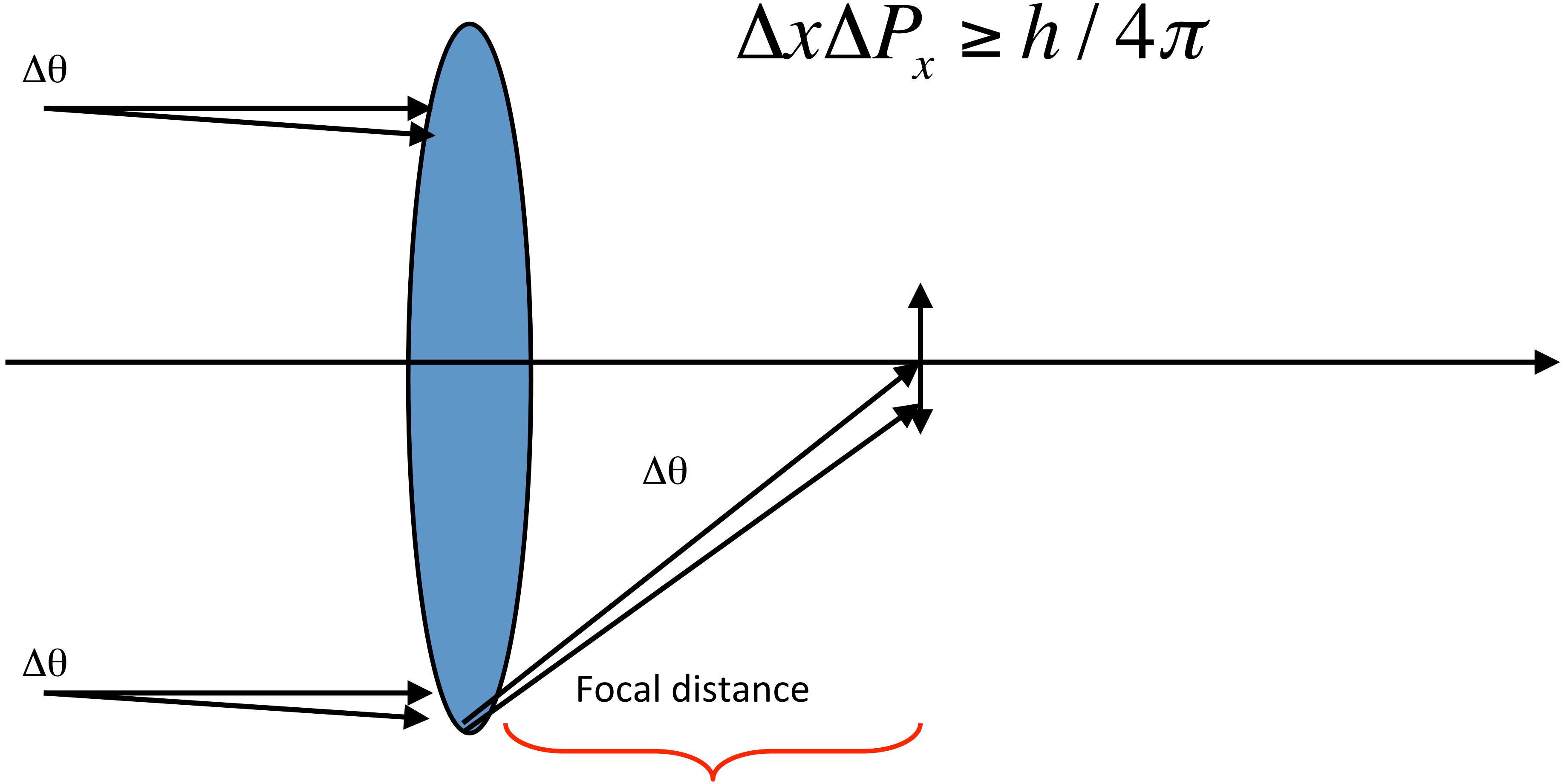
- Parallel rays focus to a point (sort of)



# Rule #1

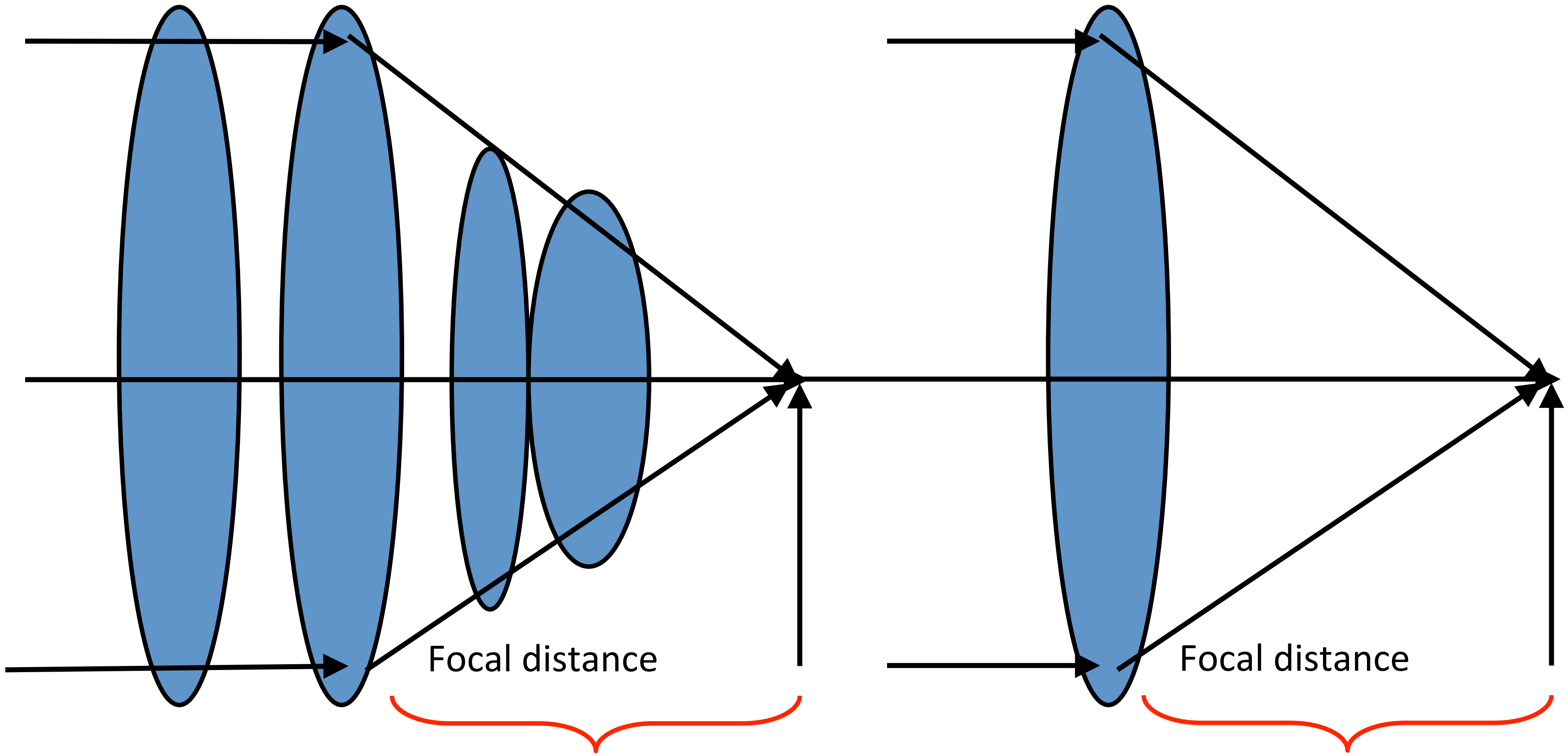
- Parallel rays focus to a point (sort of)

$$\Delta x \Delta P_x \geq h / 4\pi$$



# Rule #2

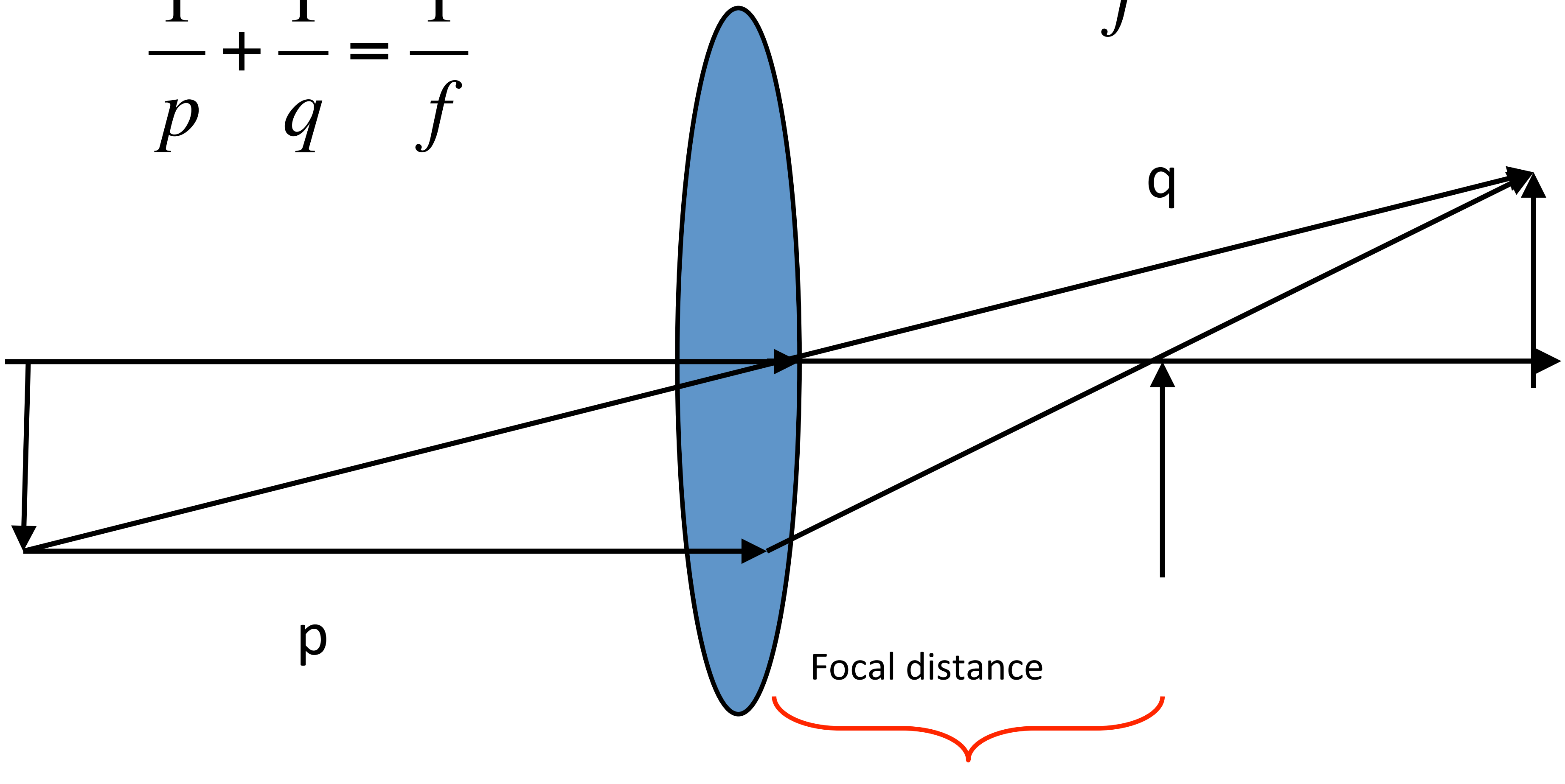
Any system of lenses can be represented by an equivalent lens of the same EFL



# Thin lens

$$\frac{1}{f} = \phi$$

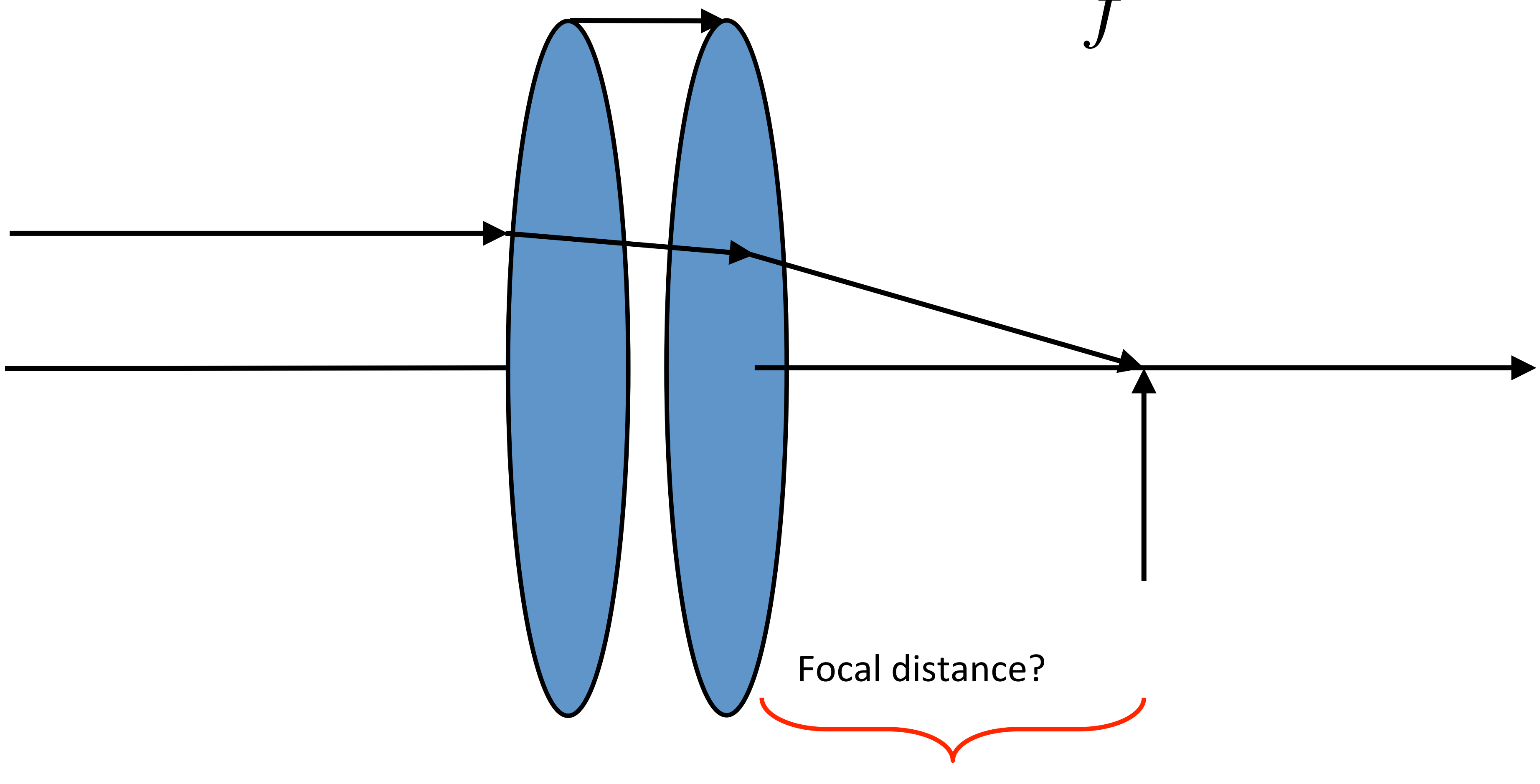
$$\frac{1}{p} + \frac{1}{q} = \frac{1}{f}$$



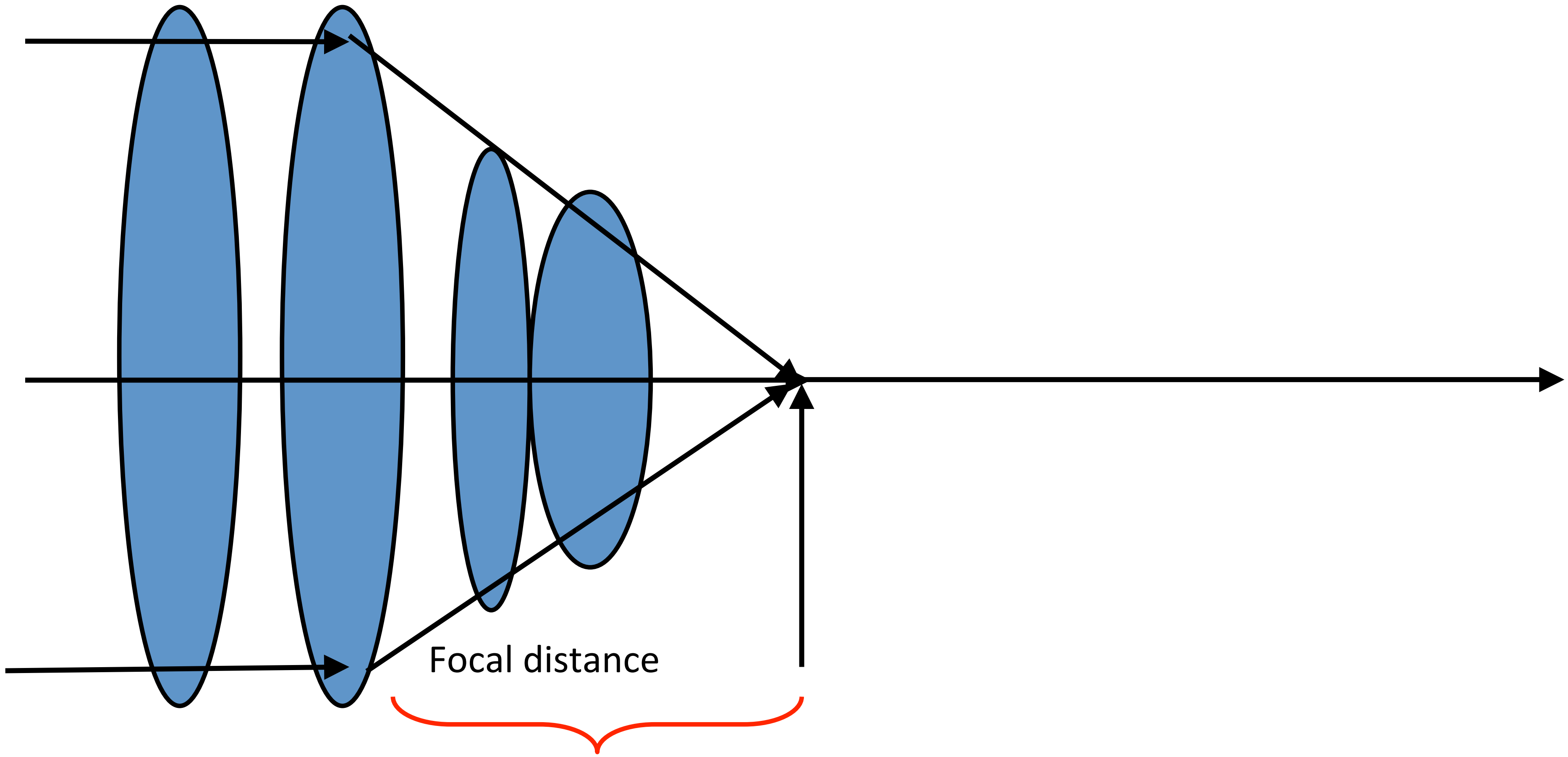
# Two Thin lens

$$\phi_{system} = \phi_1 + \phi_2 - t\phi_1\phi_2$$

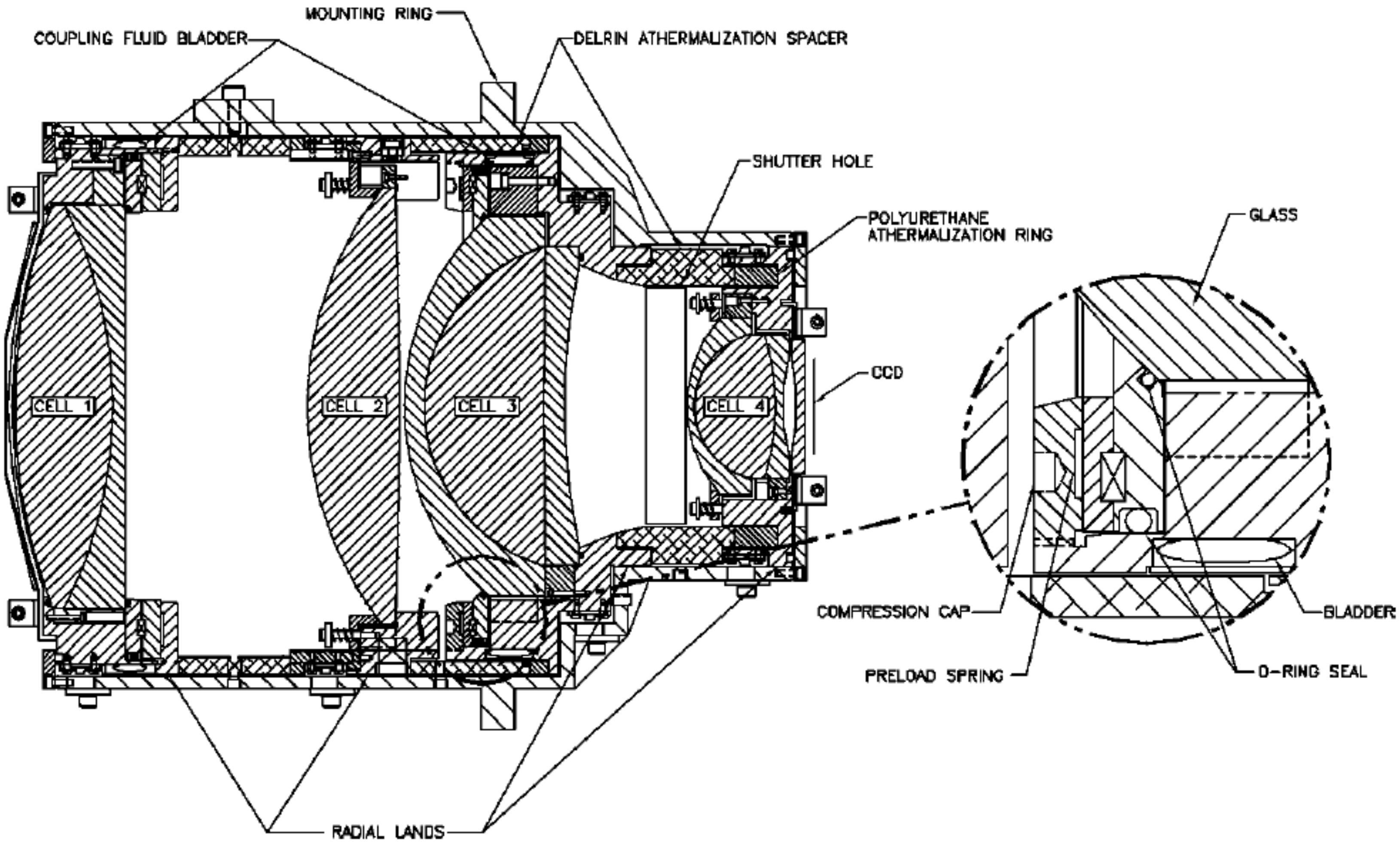
$$\frac{1}{f} = \phi$$



# How to deal with this?

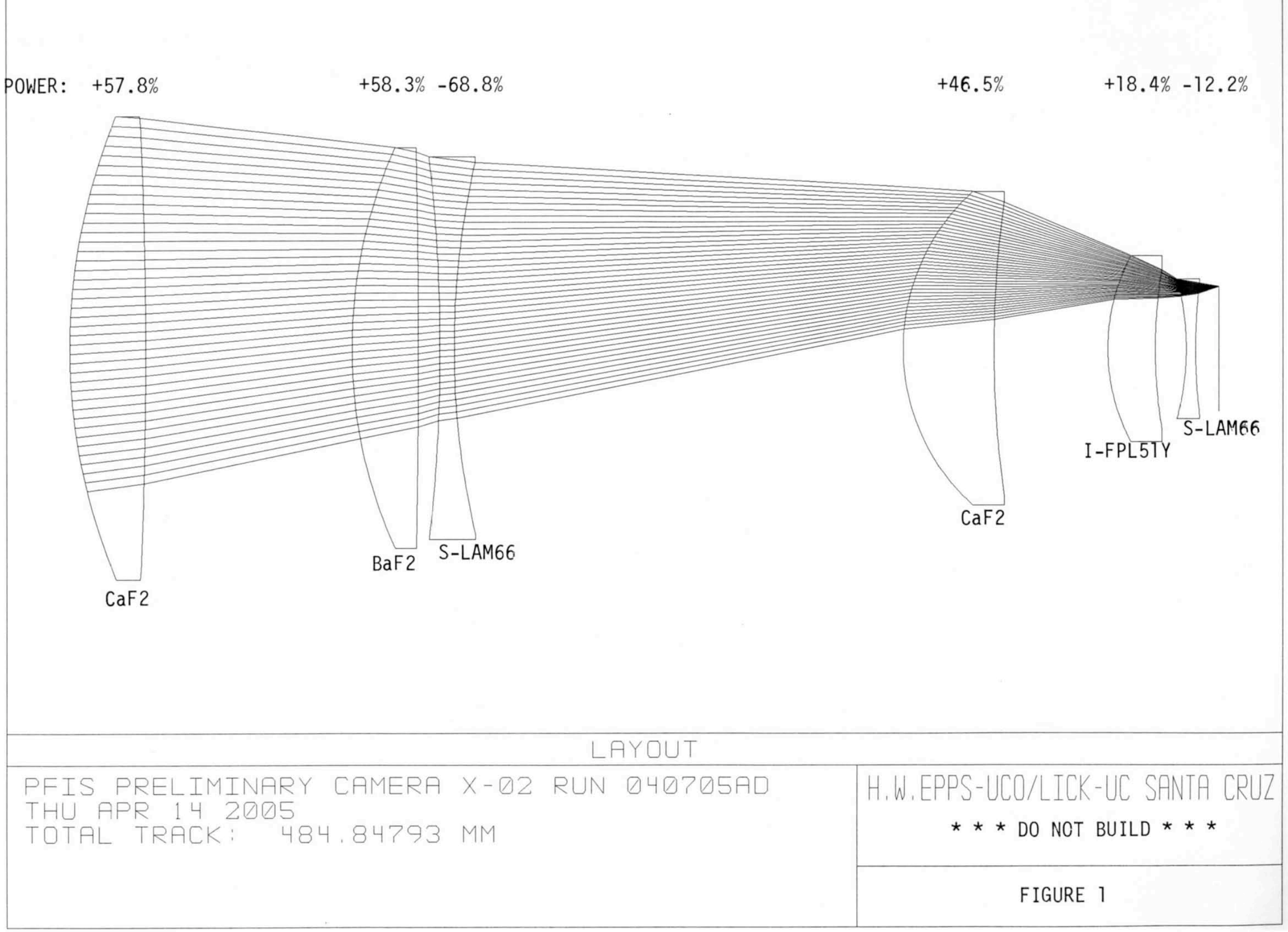


# Or this?




Sheinis et al, *Proc. SPIE* Vol. **3786**, p. 413-426.1999.

# Or this?



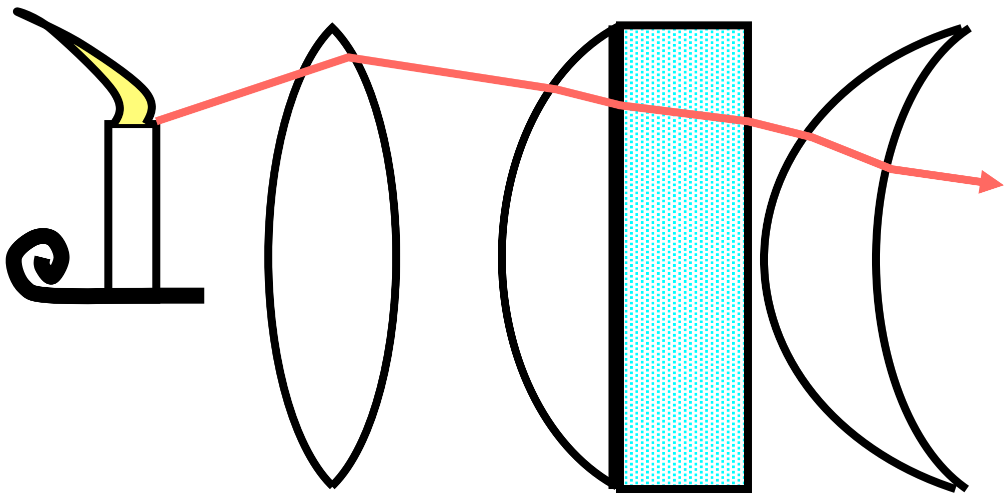
POWER: +57.8%
+58.3% -68.8%
+46.5%
+18.4% -12.2%
CaF2
BaF2
S-LAM66
CaF2
I-FPL51Y
S-LAM66
LAYOUT
PFIS PRELIMINARY CAMERA X-02 RUN 040705AD
THU APR 14 2005
TOTAL TRACK: 484.84793 MM
H.W.EPPS-UCO/LICK-UC SANTA CRUZ
* * * DO NOT BUILD * * *
FIGURE 1

# Need a tool to describe lenses

- Paraxial raytrace?

# ABCD Matrix Concepts

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

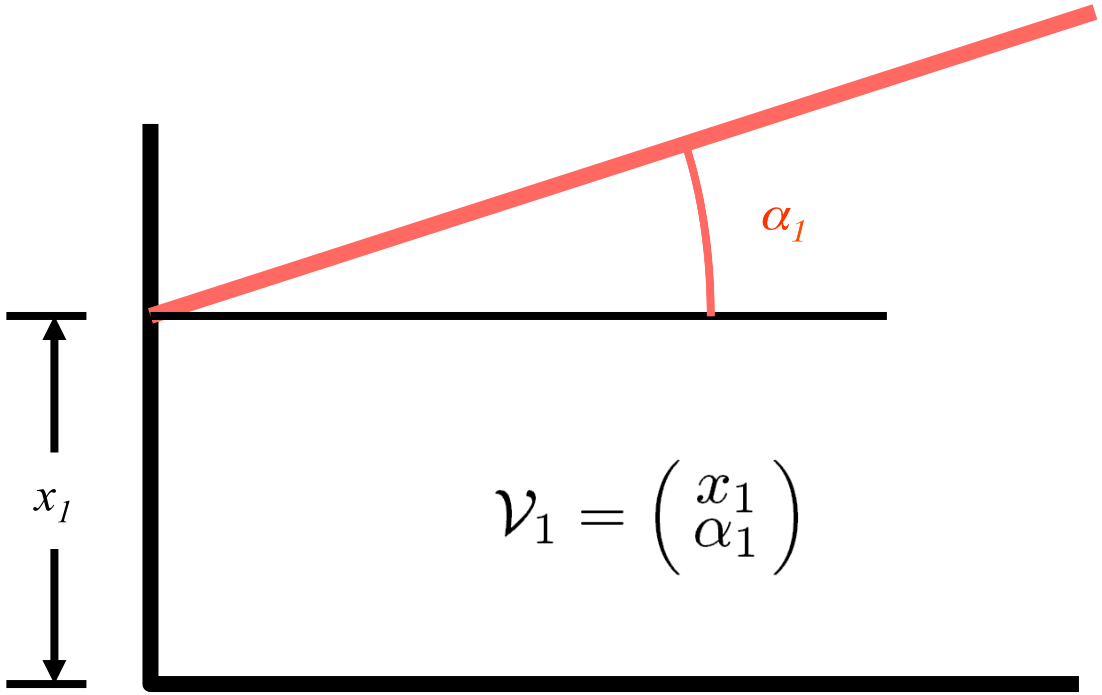


Ray Vector $\mathcal{V}_1 = \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$

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

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

# Ray Definition

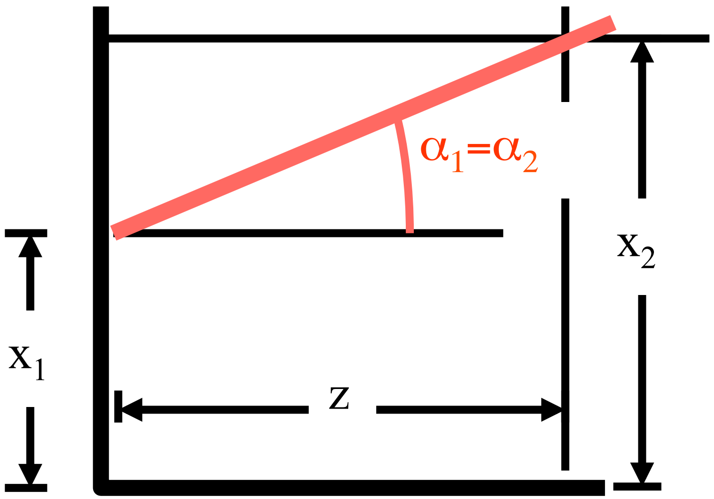


# Translation Matrix

- Slope Constant
- Height Changes

$$x_2 = x_1 + z \left.\frac{dx}{dz}\right|_{x_1}$$

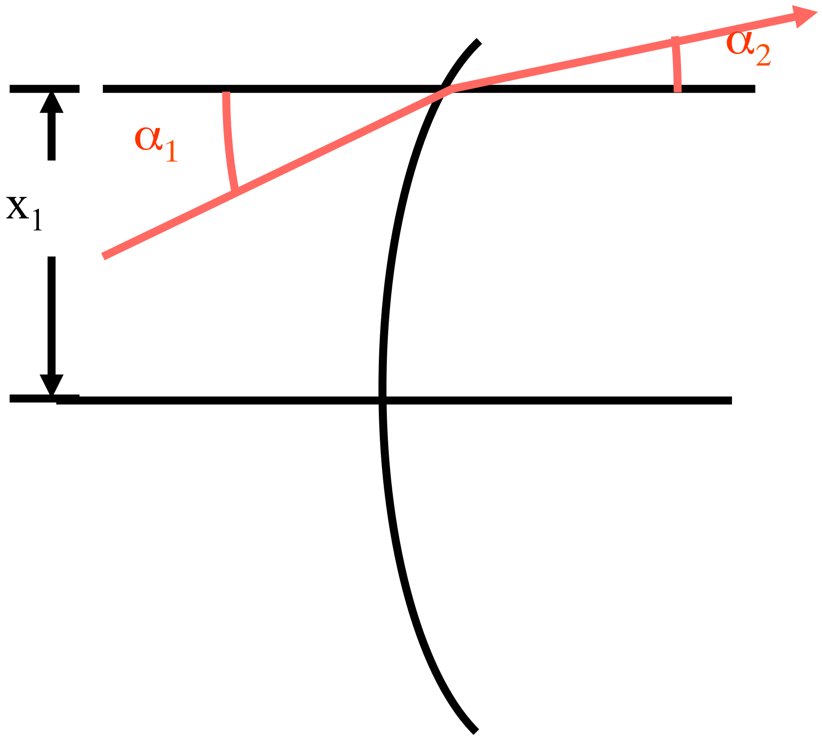
$$\alpha_2 = \alpha_1$$




$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = \begin{pmatrix} 1 & z \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix} = \mathcal{T}_{12} \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

# Refraction Matrix (1)

- Height Constant
- Slope Changes




$$x_1' = x_1$$

$$n\theta = n'\theta'$$ (θ Ref. to Normal)

$$\phi = x_1/R_1 \qquad \theta_1 = \phi + \alpha_1 \qquad \theta_1' = \phi + \alpha_1'$$

$$n_1'\left(\phi + \alpha_1'\right) = n_1\left(\phi + \alpha_1\right)$$

$$\alpha_1' = \frac{n_1 - n_1'}{n_1' R_1} x_1 + \frac{n_1'}{n_1'}\alpha_1$$

$$\begin{pmatrix} x_1' \\ \alpha_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{n_1 - n_1'}{n_1' R_1} & \frac{n_1}{n_1'} \end{pmatrix} \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

# Refraction Matrix (2)

Previous Result

$$\begin{pmatrix} x_1' \\ \alpha_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{n_1 - n_1'}{n_1' R_1} & \frac{n_1}{n_1'} \end{pmatrix} \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

Recall Optical Power

$$P_1 = \frac{n_1' - n_1}{R_1}$$

$$\begin{pmatrix} x_1' \\ \alpha_1' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -P_1/n_1' & n_1/n_1' \end{pmatrix} \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix} = \mathcal{R}_1 \begin{pmatrix} x_1 \\ \alpha_1 \end{pmatrix}$$

$$\mathcal{R}_1 = \begin{pmatrix} 1 & 0 \\ \frac{-\text{Power}}{\text{Final Index}} & \frac{\text{Initial Index}}{\text{Final Index}} \end{pmatrix}$$

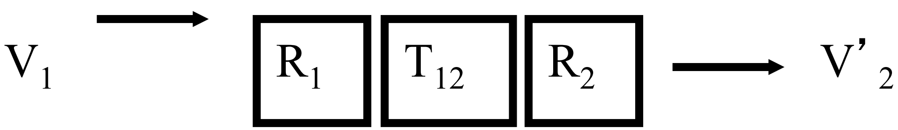
# Cascading Matrices (1)

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

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

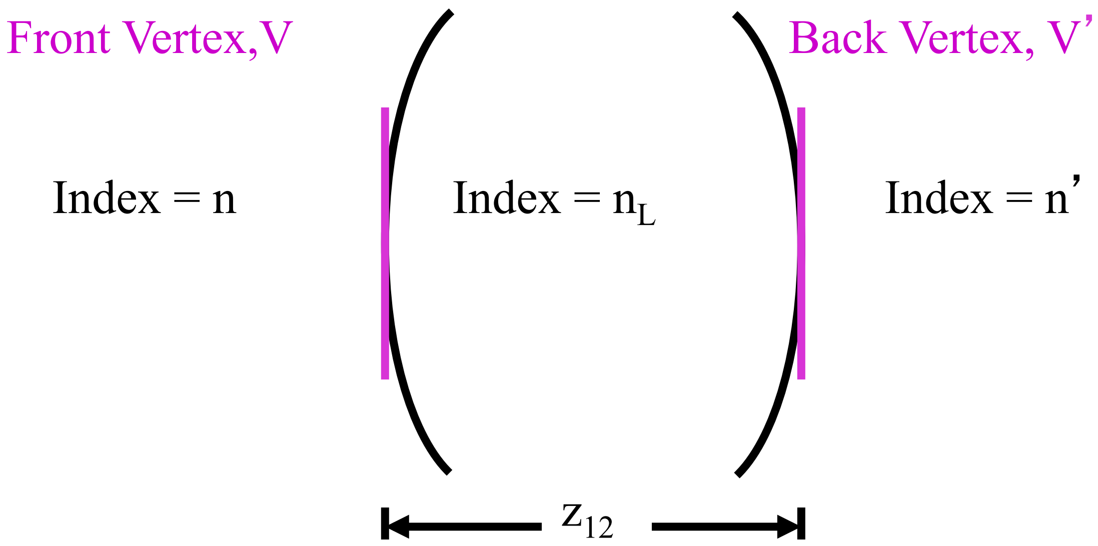
$$\begin{pmatrix} x_2 \\ \alpha_2 \end{pmatrix} = \mathcal{T}_{12} \begin{pmatrix} x'_1 \\ \alpha'_1 \end{pmatrix}$$

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

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

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

# The Simple Lens (Matrix Way)



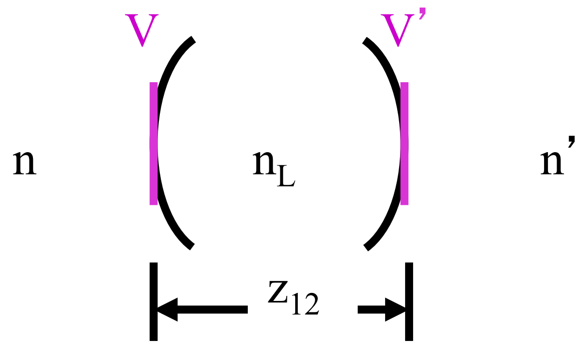

$$\mathcal{M}_{VV'} = \mathcal{R}_2 \mathcal{T}_{12} \mathcal{R}_1$$

# Building The Simple Lens Matrix

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

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

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




Simple Lens Matrix

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

# The Thin Lens Again

Simple Lens Matrix

$$\begin{pmatrix} 1 & 0 \\ \frac{-P_2}{n'} & \frac{n_\ell}{n'} \end{pmatrix} \begin{pmatrix} 1 & z_{12} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{-P_1}{n_\ell} & \frac{n}{n_\ell} \end{pmatrix} \longrightarrow \mathcal{M}_{VV'} = \begin{pmatrix} 1 & 0 \\ -\frac{P_t}{n'} & \frac{n}{n'} \end{pmatrix}$$

$$z_{12} = 0$$

$$P_t = P_1 + P_2$$

In General: $P_1 = \frac{n_\ell - n}{R_1}$ $P_2 = \frac{n' - n_\ell}{R_2}$

Glass in Air $P_1 = \frac{n_\ell - 1}{R_1}$ $P_2 = -\frac{n_\ell - 1}{R_2}$

# Thin Lens in Air Again

$$P_1 = \frac{n_\ell - 1}{R_1} \qquad P_2 = -\frac{n_\ell - 1}{R_2} \qquad P_t = P_1 + P_2$$

$$\mathcal{M}_{VV'} = \begin{pmatrix} 1 & 0 \\ -P_t & 1 \end{pmatrix}$$

$$P_t = \frac{1}{f}$$

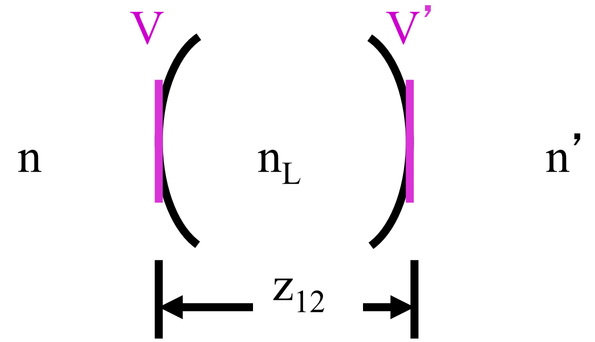
$$\frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2}\right]$$

# Thick Lens Compared to Thin

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

Thin Lens Plus Correction

$$\text{Geometric Thickness} = z'_{12} = \frac{z_{12}}{n_\ell}$$



# Matrix example 1

Example #1, the Keck Telescope

$$R2 := \begin{pmatrix} 1 & 0 \\ \frac{-2}{-4.737} & -1 \end{pmatrix} \quad R1 := \begin{pmatrix} 1 & 0 \\ \frac{-2}{-34.972} & -1 \end{pmatrix} \quad T12 := \begin{pmatrix} 1 & -15.395 \\ 0 & 1 \end{pmatrix}$$

$$SYS := R2 \cdot T12 \cdot R1$$

$$SYS = \begin{pmatrix} 0.12 & 15.395 \\ -6.7 \times 10^{-3} & 7.5 \end{pmatrix}$$

$$f := \frac{-1}{SYS_{1,0}}$$

$$f = 149.245$$

$$R3 := \begin{pmatrix} 1 & 0 \\ \frac{-1}{2.286} & 1 \end{pmatrix} \quad R4 := \begin{pmatrix} 1 & 0 \\ \frac{-1}{0.307} & 1 \end{pmatrix}$$

$$T23 := \begin{bmatrix} 1 & (17.8469 + 2.286) \\ 0 & 1 \end{bmatrix} \quad T34 := \begin{pmatrix} 1 & 2.54 \\ 0 & 1 \end{pmatrix}$$

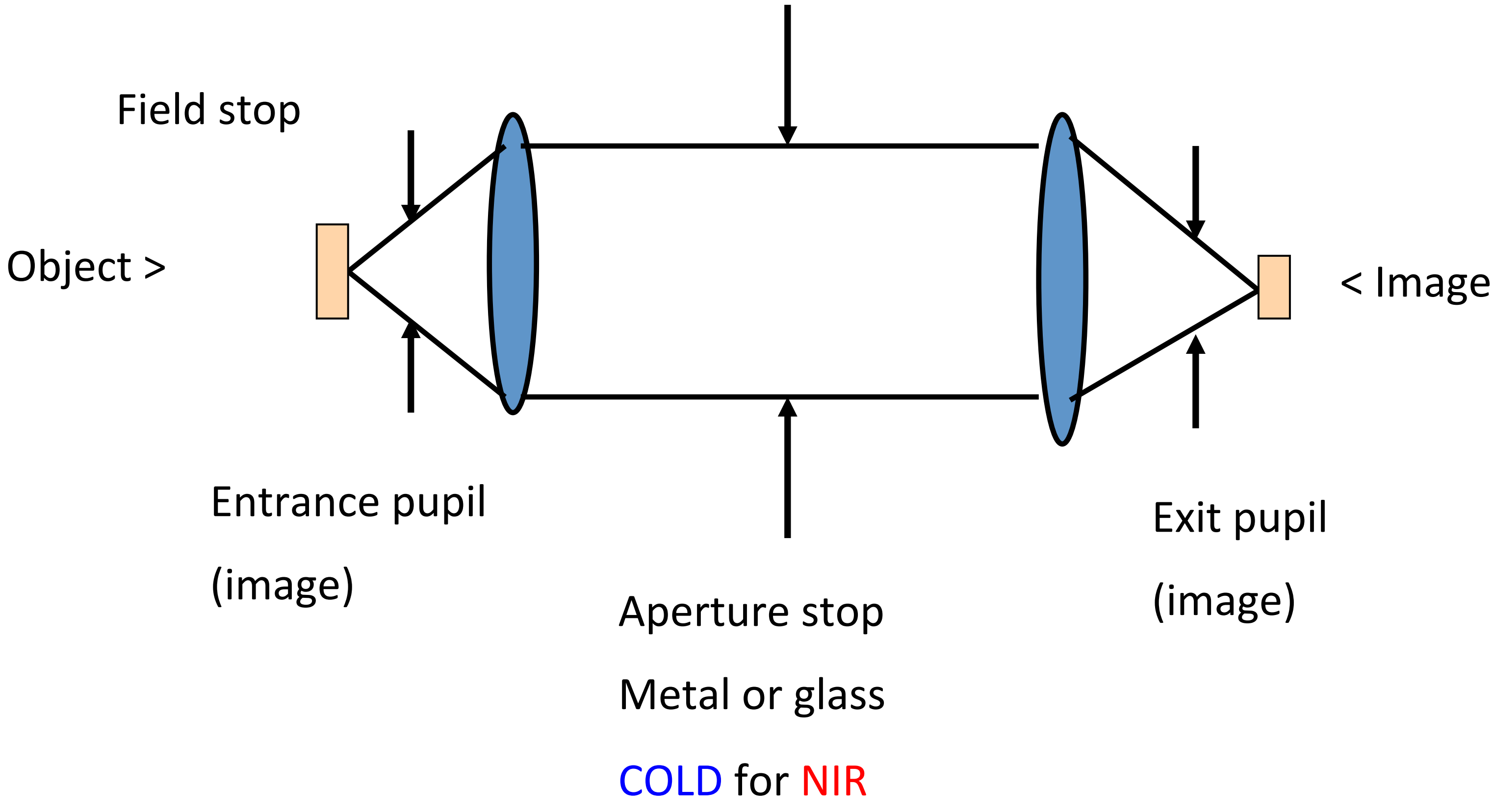
$$SYS2 := R4 \cdot T34 \cdot R3 \cdot T23 \cdot R2 \cdot T12 \cdot R1$$

$$SYS2 = \begin{pmatrix} -0.015 & 0.562 \\ 0.05 & -67.117 \end{pmatrix}$$

$$efl := \frac{-1}{SYS2_{1,0}}$$

$$efl = -20.043$$

# Basic optics definitions



- Entrance Pupil is the image of the stop in all optics *up*stream of the stop.
- Aperture Stop, the physical aperture (metal, or lens edge) that limits the bundle of rays through the system for any field point. In Astronomy, this usually is the primary mirror for optical systems and the secondary mirror for NIR systems, not always . For NIR systems this is usually imaged onto a cold aperture somewhere inside the Dewar. (often with an Offner relay, (A. Offner, Opt. Eng 14, 131, 1975))
- Exit pupil is the image of the stop in all optics *down*stream of the stop.

# Cameras

- Reflective
  - Two Mirror correct for spherical and coma
  - Un-obscured 3-mirror an-astigmat corrects for spherical, coma and astigmatism, (Paul-Baker, Merseinne Schmidt) (i.e Angel, Woolf and Epps, 1982 SPIE, 332, 134A)
- Transmissive
  - Epps cameras
- Catadioptric
  - Schmidt

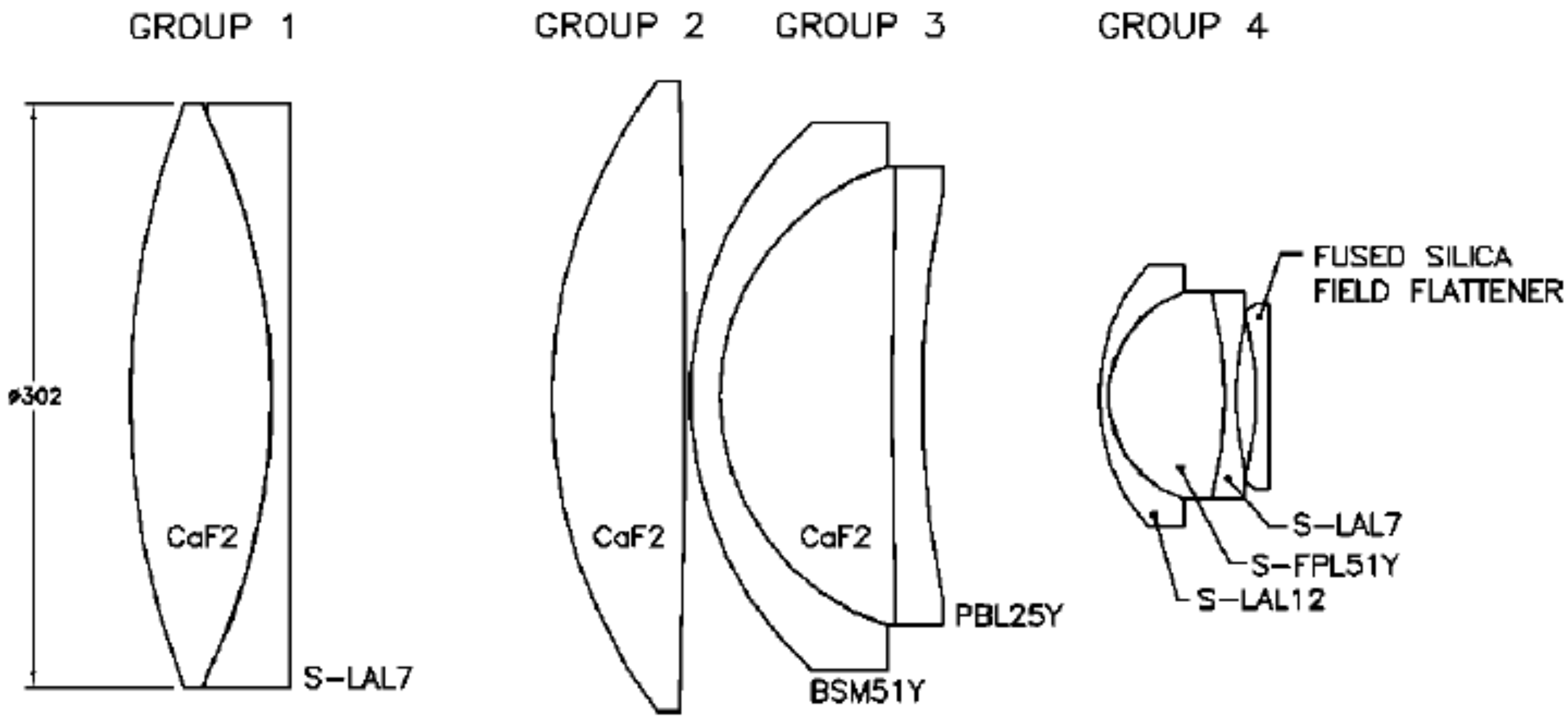
# Reflective Cameras

- Pro's
  - Off axis unobscured
  - Diamond turning is an option for NIR (visible), aspheres can be implemented inexpensively
    - Post polish for visible, nickel over aluminum
  - Metal mirrors, good thermal characteristics, can have mounts machined in
  - Fewer surfaces, better emissivity?
- Con's
  - Surface roughness > scattered light
  - Hard to align
  - Hard to diagnose

# Transmissive Cameras

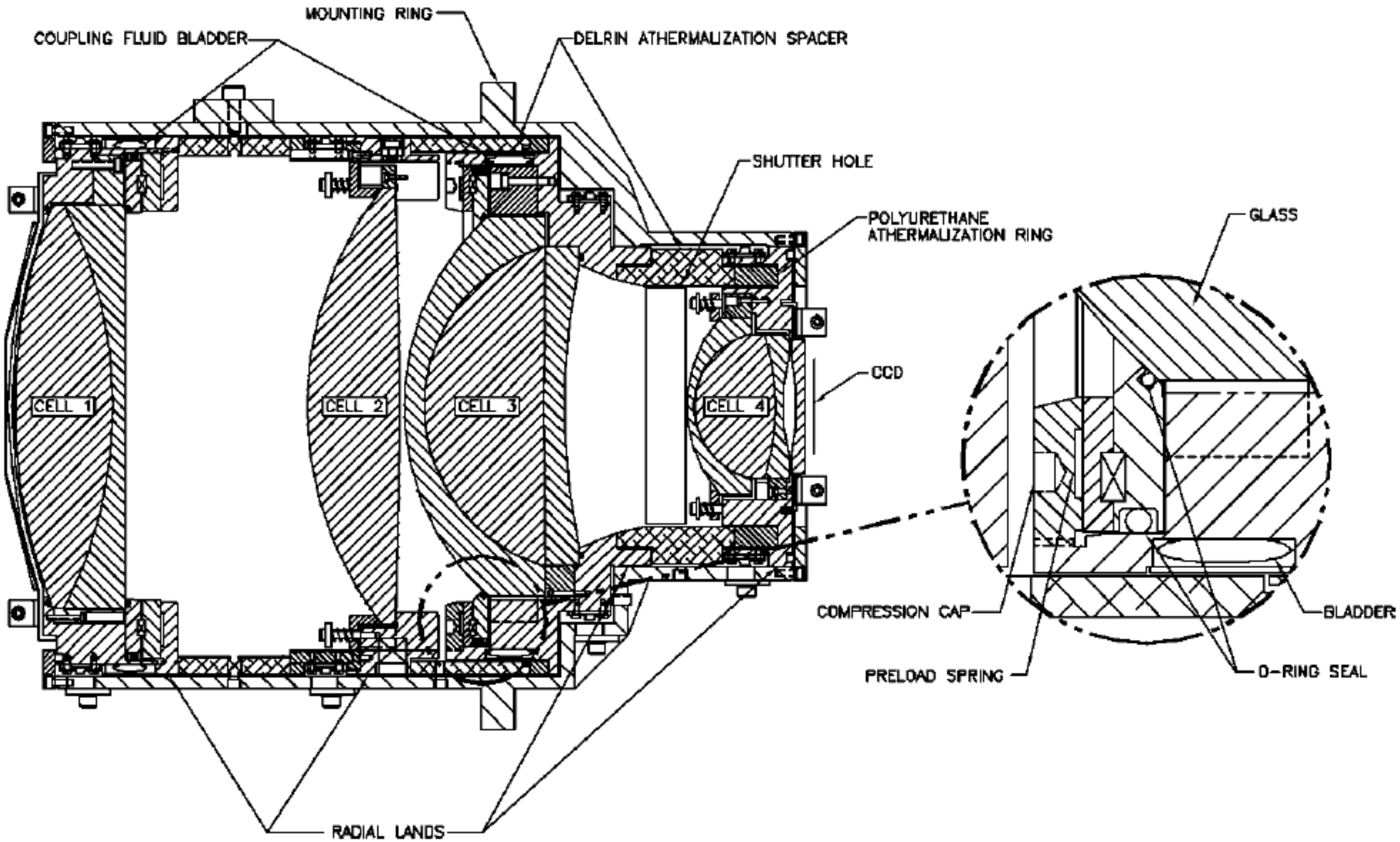
- Pro's
  - Unobscured,
  - All-spherical, or rotational symmetric aspheres on glass (by hand, expensive)
  - Diamond turning is an option for NIR (visible?), aspheres can be implemented expensively on limited number of materials usually crystals ($CaF_2$, $BaF_2$, ZnSe, Germanium, Silicon)
  - Alignment and diagnostics are easier.
- Con's
  - Mounting is harder, athermalization is harder
  - Surface roughness > scattered light off aspheres

# ESI Refractive camera




Epps and Miller, *1999SPIE* Vol. **3355**, 255b
Epps, *1999SPIE* Vol. **3355**, 111e

# ESI Refractive camera

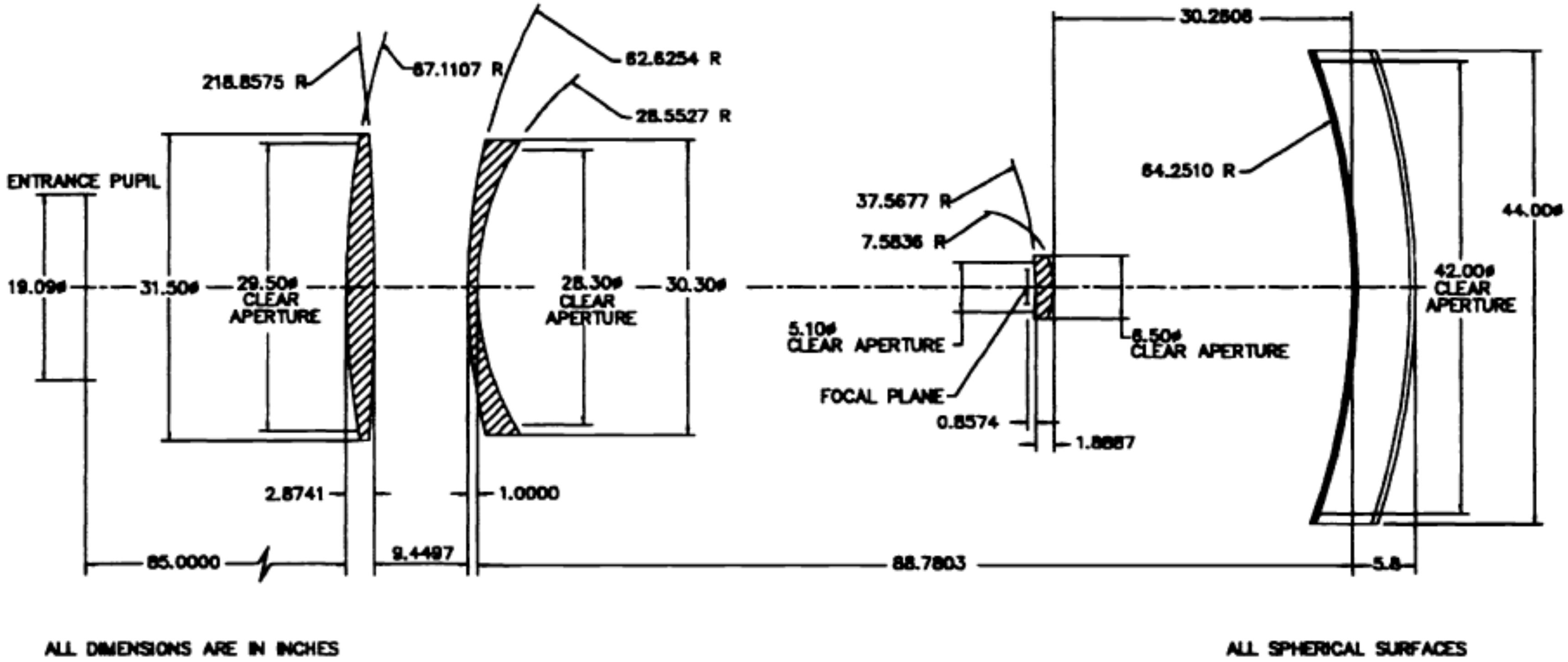



Sheinis et al, *Proc. SPIE* Vol. **3786**, p. 413-426.1999.

# Catadioptric Cameras

- Pro's
  - Schmidt cameras variations provide wide field coverage in straightforward design
  - Few surfaces
  - Can be all-spherical
- Con's
  - Obscurations
  - Hard to mount detectors
  - Smaller effective field size.

# Hires, Catadioptric Camera




Vogt et al, 1994SPIE 2198, 362

# End lecture 1