Astro 500

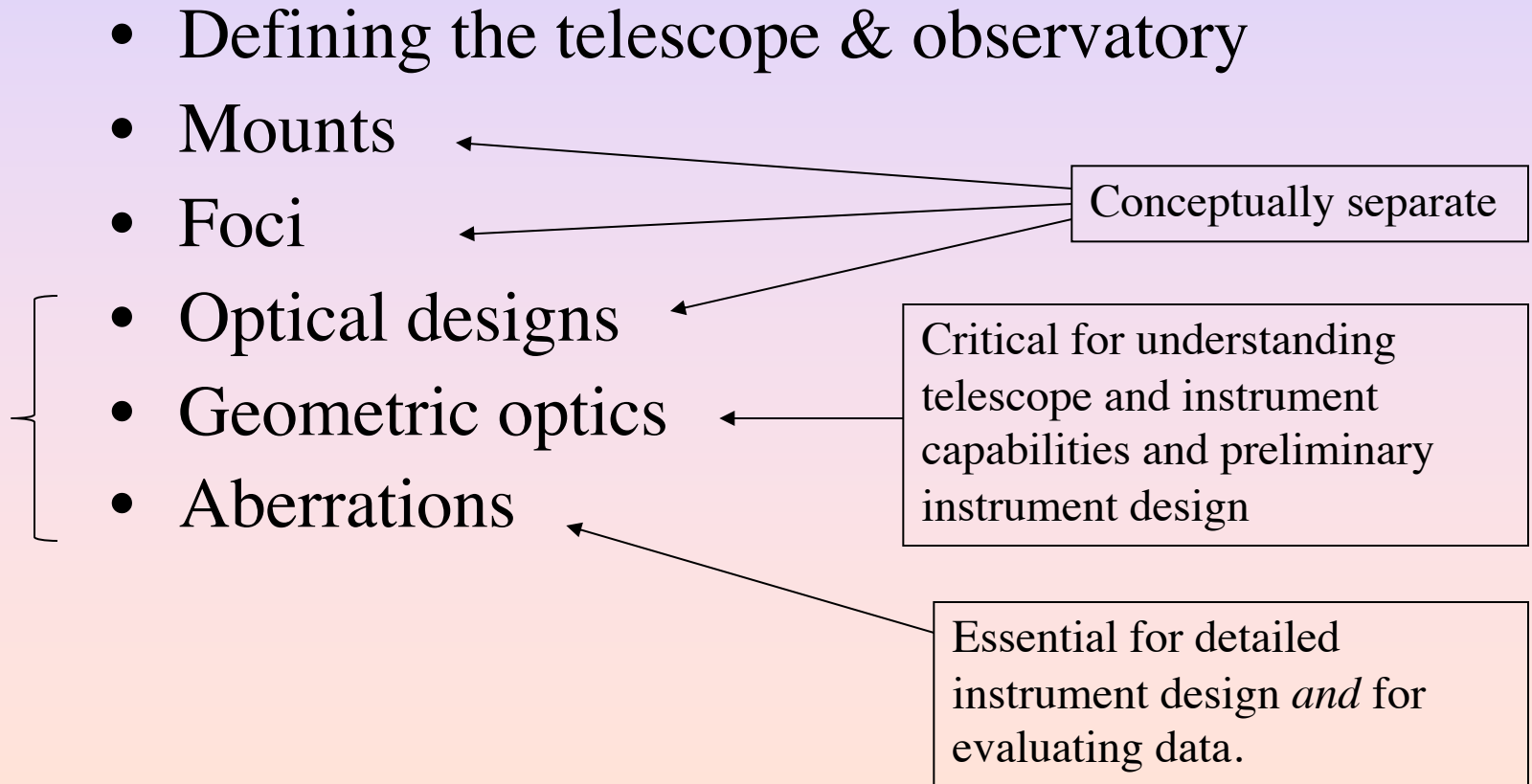**Techniques of Modern Observational Astrophysics**

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Telescopes & Optics

Outline

- Defining the telescope & observatory
- Mounts
- Foci
- Optical designs
- Geometric optics
- Aberrations

Conceptually separate

Critical for understanding telescope and instrument capabilities and preliminary instrument design

Essential for detailed instrument design *and* for evaluating data.

Telescopes as Facilities

- The Observatory: far more than telescope

  ➢ Opto-mechanical and thermal control
  ➢ Acquisition & guiding
  ➢ Telemetry and sensing
  ➢ Instrumentation and instrument interfaces (ports)
  ➢ Software for telescope and instrument control
  ➢ Technical support and maintenance
  ➢ Data storage and transfer
  ➢ Software pipelines for data reduction and analysis
  ➢ Environment for observer and operator
  ➢ Personnel management, technical and scientific leadership

Telescopes: broader relevance

- Telescopes are examples of optical systems serving as cameras, i.e., producing images from sources at infinity (collimated light).

- Spectrographs and re-imaging systems essentially use variants of these systems as collimators and cameras.

Telescopes

- What parameters define telescopes?
  - Collecting Area (A)
  - FOV (Ω)
  - Image Quality
  - Cost
  - Throughput
  - Spectral range
  - Plate scale/Magnification
  - Pointing/tracking

highly coupled

Telescopes as cameras

Telescopes

We will focus on optical/IR telescopes;
Most of this parameter space is relevant for
light collection at other wavelengths.

Examples of Telescopes

➢ Refracting
  o Galilean (1609)
  o Keplerian (1611)
➢ Reflecting (4x harder to make!)
  o Newtonian (1672)   *Why?*
  o Gregorian (1673)
  o Cassegrain (1668)
  o Ritchey-Cretien (1927)
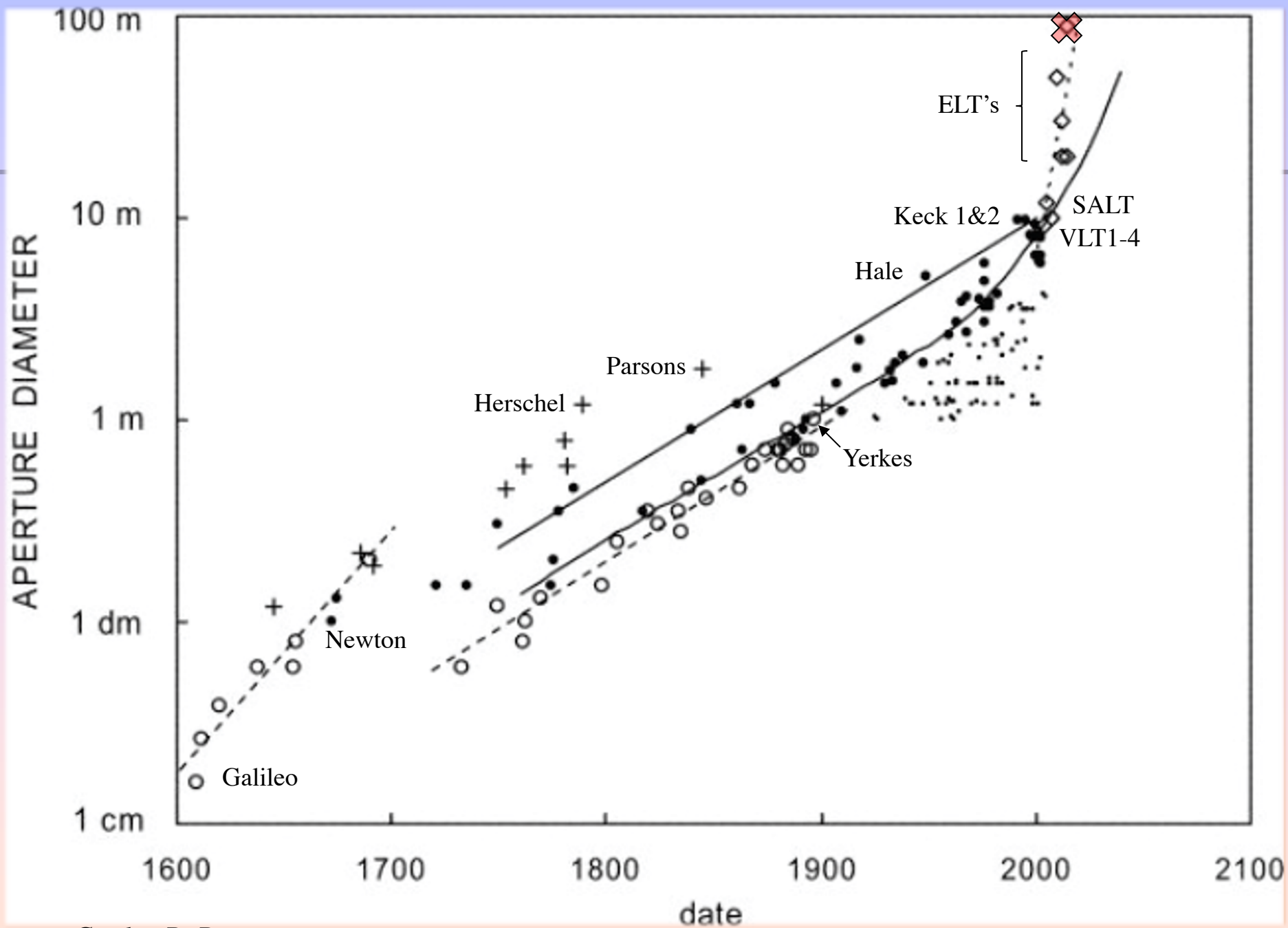➢ Catadioptric
  o Schmidt (1931)
  o Maksutov (1944)

➢ Multi-mirror
  o MMT (1977)
  o Keck (1992)
  o HET (1996), SALT (2005)
  o all ELT's (2014+)

Trends to larger collecting area, but more compact in mounting and focal-ratio (speed).

Credit: R. Racine

Telescope Mounts

➢ Equatorial*
  - o German (Yerkes)
  - o English Yoke or English Cross ◄┈┈┈┈┈┈┈┈┈┈┈┈
  - o Fork (Shane 3m)
  - o Horseshoe (CTIO & KPNO 4m) ◄┈┈┈┈┈┈┈┈

➢ Alt-Az (Altitude-Azimuth) ┈┈┈┈┈┈┈┈┈┈┈┈

  3.5-4.5m
  - o ARC, WIYN, ARC, SOAR

  6.5-10m
  - o Keck, VLT, Subaru, LBT, MMT
       Megallan   First: 1977

➢ Transit
  - o Arecibo (radio)
  - o LMT - liquid mirror telescope

➢ Transit-Azimuth
  - o HET, SALT

Easiest for tracking

Best for flexure, but pointing limitations

Best compromise

Most compact but requires computer control; has field rotation

Cheapest but limited sky coverage (40%)

Cheap and up to 70% sky coverage

*https://en.wikipedia.org/wiki/Equatorial_mount
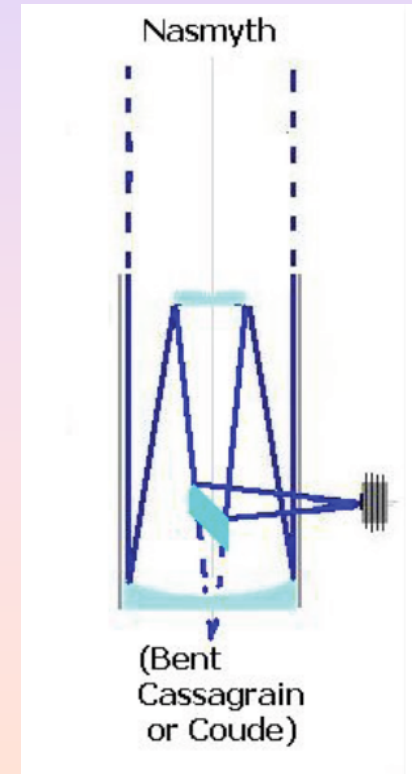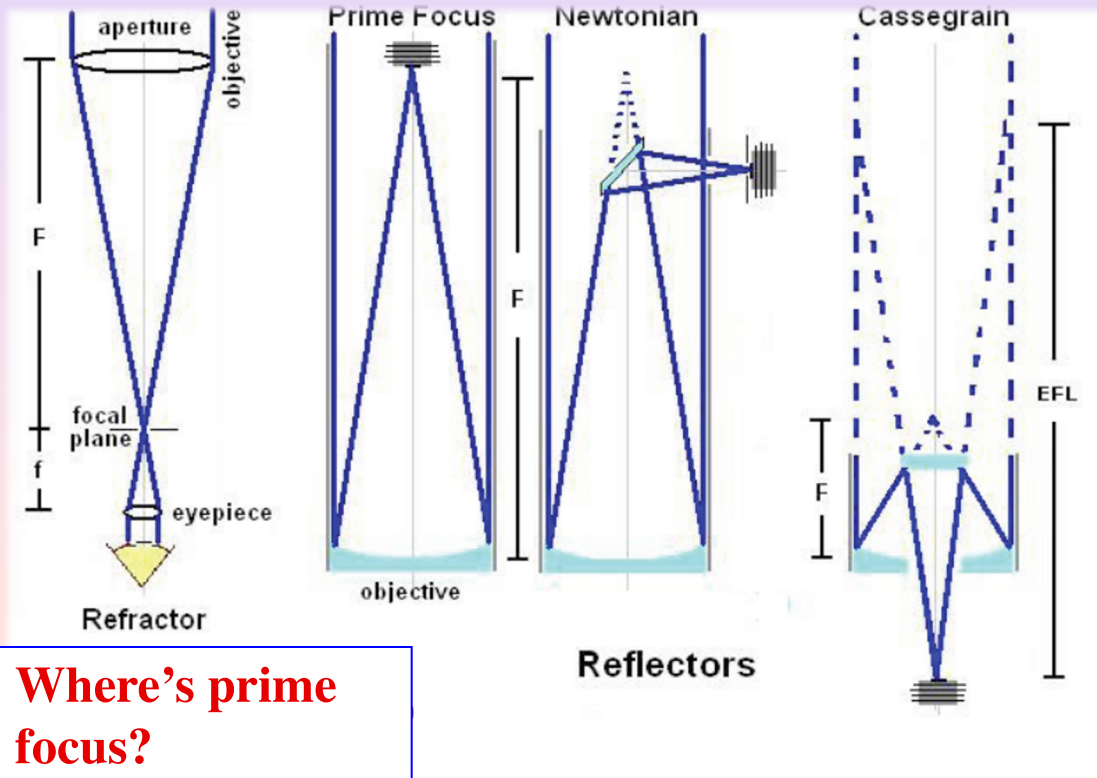
Telescope Foci

- Prime
- Newtonian
- Cassegrain

What's the difference?

- Folded Cassegrain
- Nasmyth
- Coude

aperture objective

F

focal plane

f

eyepiece

Refractor

Prime Focus

F

objective

Newtonian

Cassegrain

F

EFL

Reflectors

Nasmyth

(Bent Cassagrain or Coude)

Where's prime focus?

Types of Telescopes

Category	Primary	Secondary	Corrector	Name	Principal Aberrations
Singlet lens	Spherical			refractor	spherical + chromatic
Singlet mirror	Paraboloid mirror			Newtonian	coma + astigmatism
Doublet mirrors	Paraboloid	Hyperbaloid		Cassegrain	coma
	Hyperbaloid	Hyperbaloid		Ritchey-Chertien (RC)	astigmatism (twice Cassegrain field)
	Parabaloid	Ellipsoid		Gregorian	field curvature
	Ellipsoid	Spherical		Dall-Kirkham	
	Ellipsoid	Ellipsoid		Aplonatic Gregorian (AG)	best images but large obstruction
Multiplets	Spherical		Aspheric lens or achromate doublet	Schmidt	v. wide field
	Spherical	Hyperbaloid	Aspheric lens	Schmidt-Cassegrain	"
	Spherical	Spherical	Spherical meniscus lens	Maksutov	"
	Spherical		4-mirror asphere	HET, SALT	Low cost

Singlets
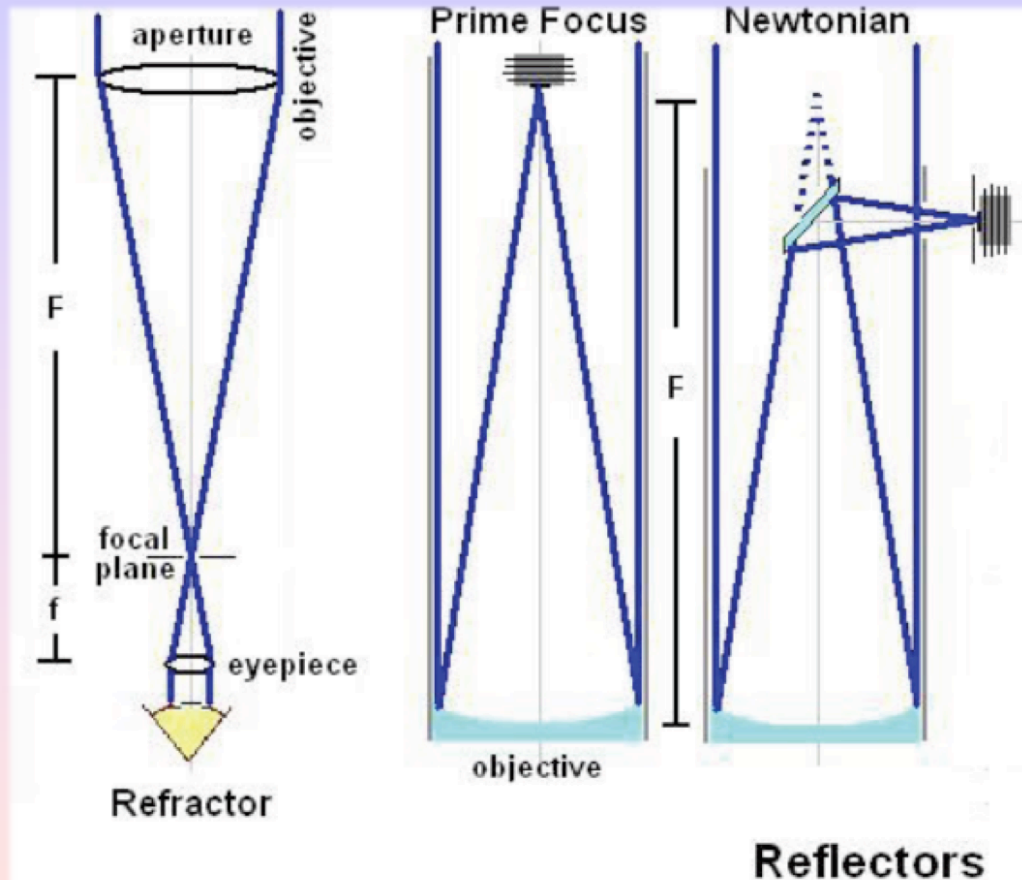
(from John Oliver's web page)

Doublets*

Gregorian

Nasmyth

Cassegrain

EFL

F

F

(Bent Cassagrain or Coude)

EFL
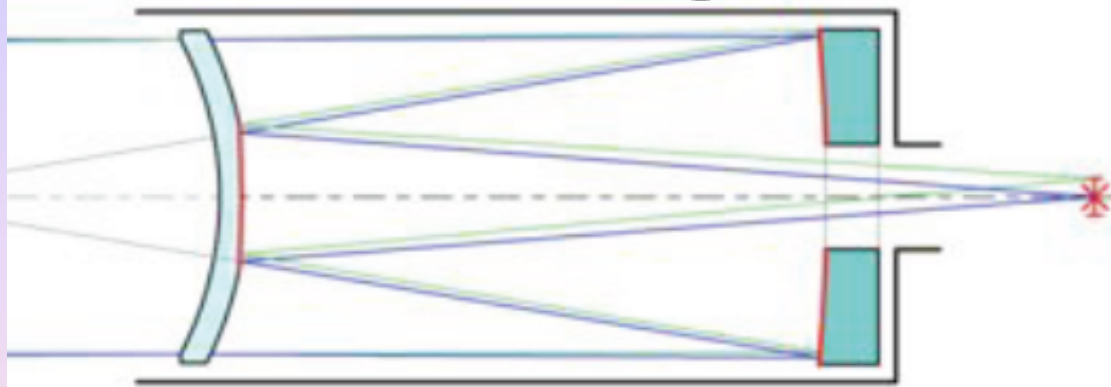
F
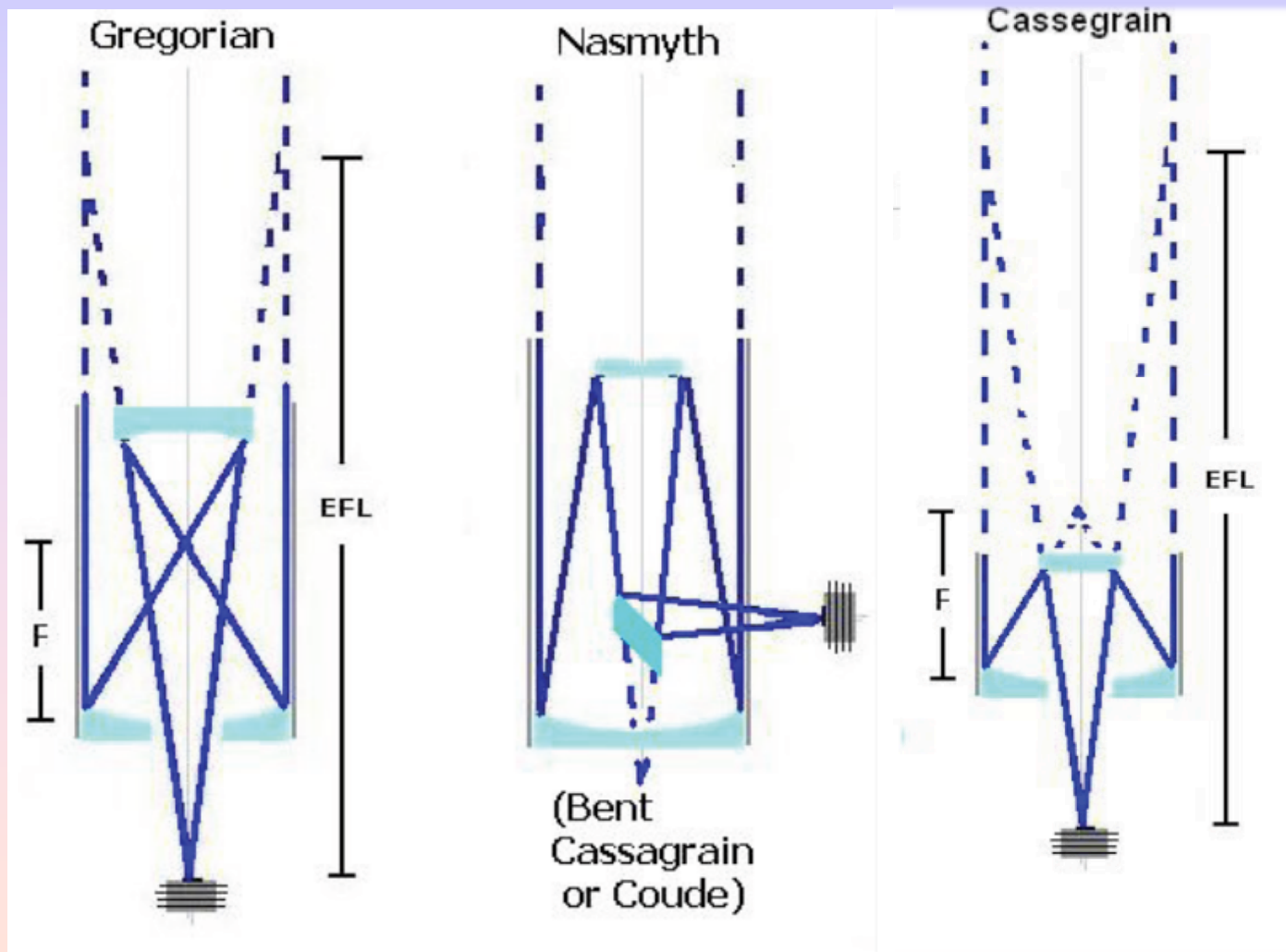
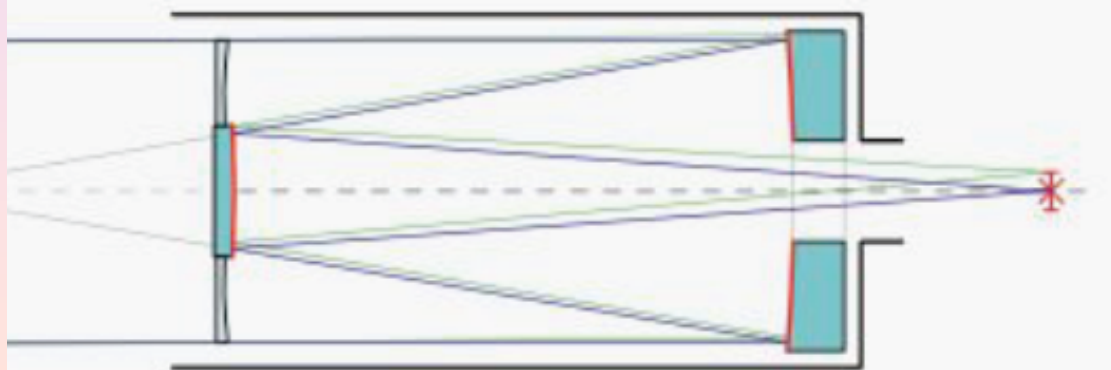*with a confusing mixture of labels for telescope types and foci

Multiplets: Catadioptrics
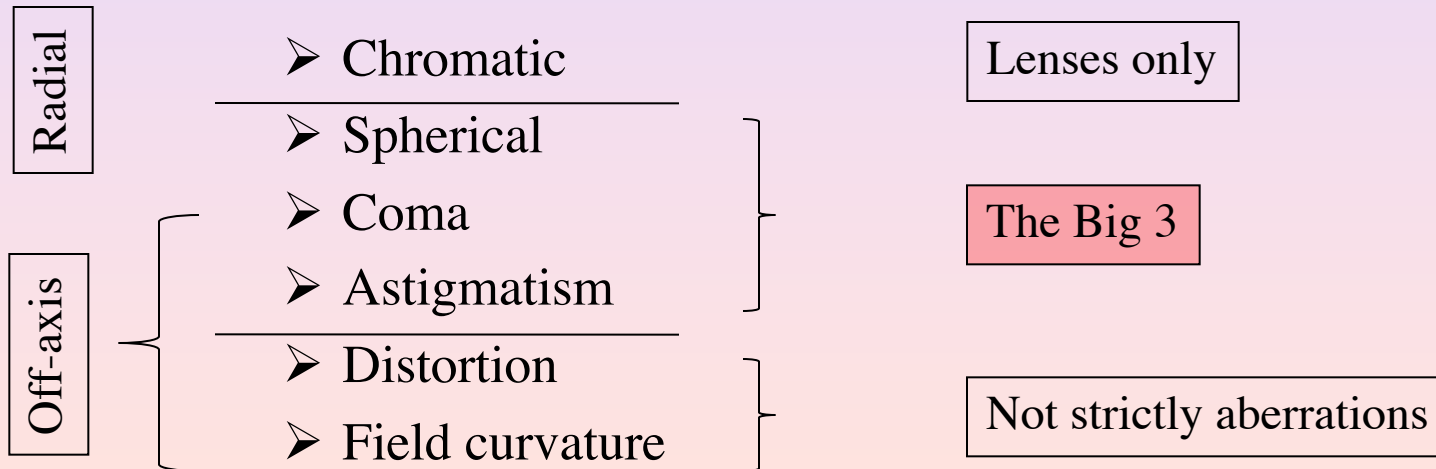

Matsukov-Cassegrain

Spherical Primary

Schmidt-Cassegrain

wikipedia

Why different designs?

- Trade-offs primarily between cost, desired field of view (at given image-quality) and collecting area.

- Image-quality and field-of-view concern aberrations.

- 6 principal aberrations:

Radial
- ➤ Chromatic

Off-axis
- ➤ Spherical
- ➤ Coma
- ➤ Astigmatism
- ➤ Distortion
- ➤ Field curvature

Lenses only

The Big 3

Not strictly aberrations

Optics

- Geometric Optics
  - ➤ Reflection
  - ➤ Refraction
  - ➤ Thin lens
  - ➤ Spherical optics
  - ➤ Conics

  - ➤ Stops
  - ➤ Pupils
  - ➤ Chief rays
  - ➤ Marginal ray
  - ➤ System design

  - ➤ Telescope summary

Where we're headed

- Aberrations
  Chromatic
  Spherical
  Coma
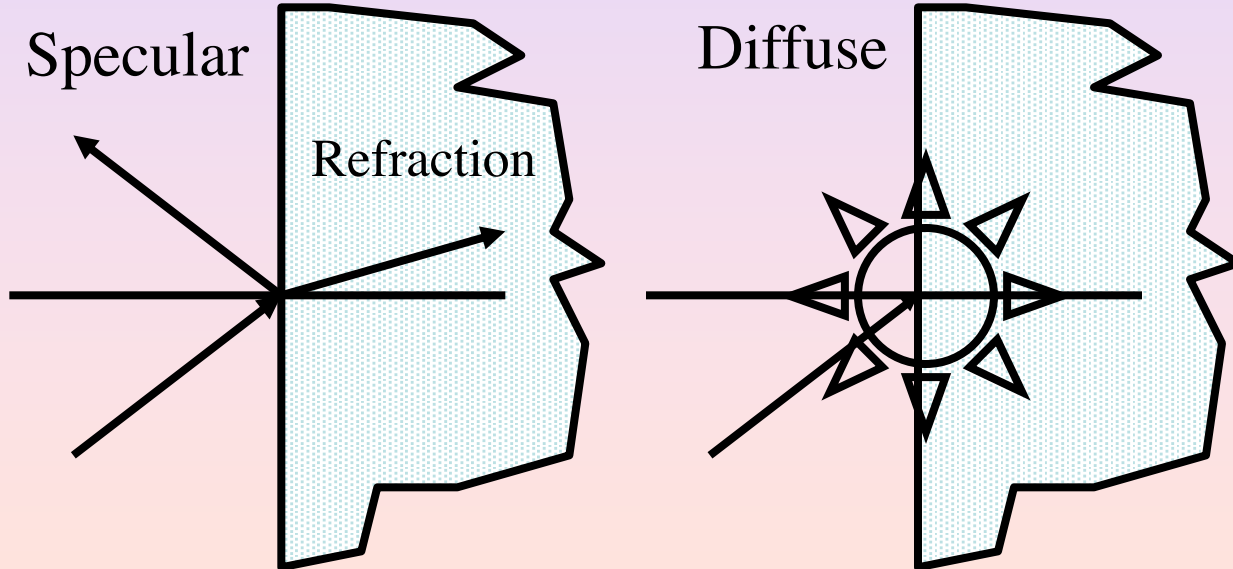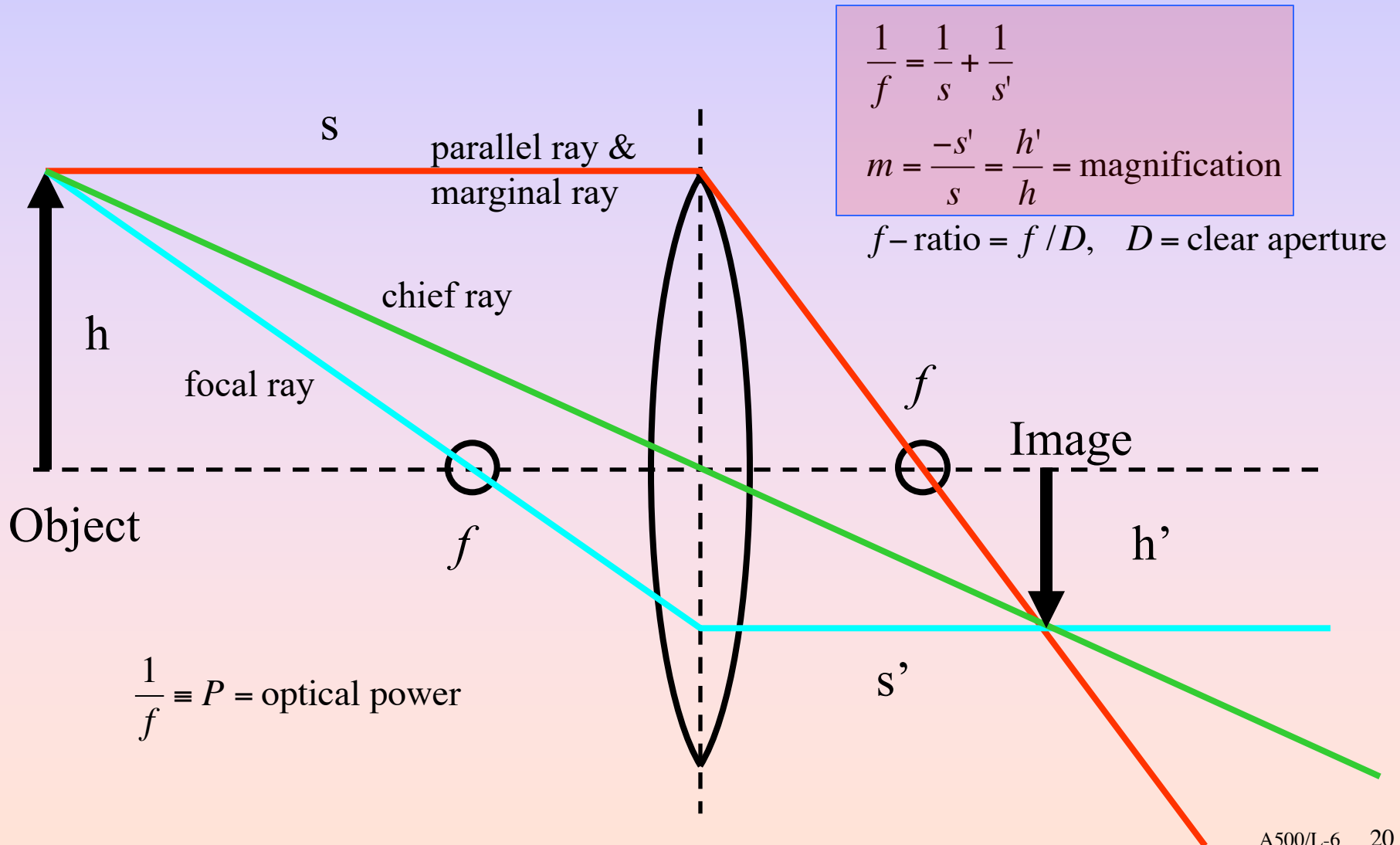 Astigmatism
  Distortion
  Field curvature

Reading

- Walker - ok place to start
- Schroeder - ferocious, but very rigorous and remarkably general and complete
- McLean - fairly complete, but missing basics
- *Recommend*:
  1. Start with Walker to get an overview
  2. Pick up McLean *and* a basic optics book (e.g., Meyer-Arendt, "Introduction to Classical and Modern Optics") and work out quoted results; return to Walker to reconcile results and nomenclature.
  3. Then hit Schroeder's text running to go to expert level.
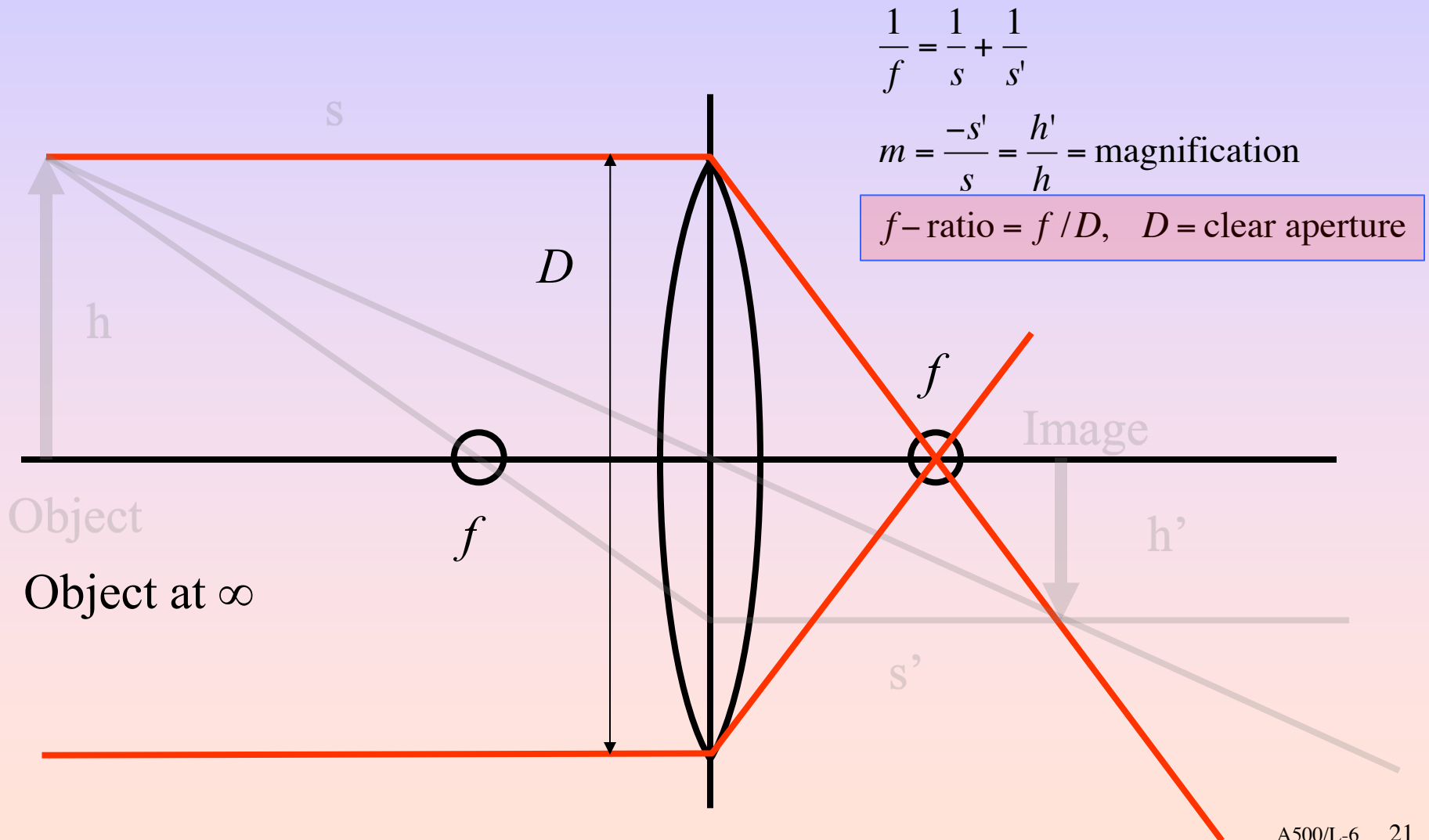
Some Everyday Concepts
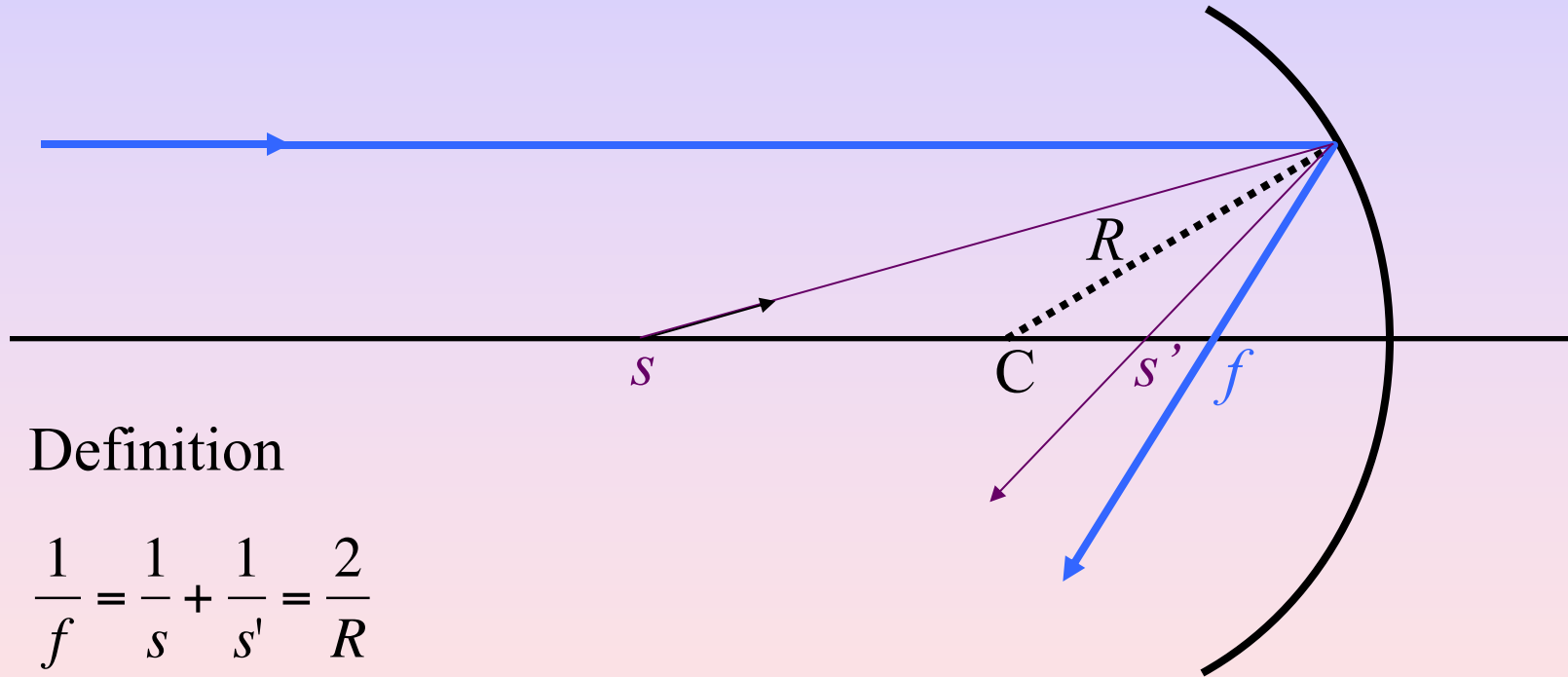
- Specular and Diffuse Reflection
- Refraction

Specular

Diffuse

Refraction

The Thin Lens

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

$$m = \frac{-s'}{s} = \frac{h'}{h} = \text{magnification}$$

$$f-\text{ratio} = f/D, \quad D = \text{clear aperture}$$

s

parallel ray &
marginal ray

chief ray

h

focal ray

f

Image

Object

f

h'

$$\frac{1}{f} \equiv P = \text{optical power}$$

s'

The Thin Lens

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$$

$$m = \frac{-s'}{s} = \frac{h'}{h} = \text{magnification}$$

$$f - \text{ratio} = f / D, \quad D = \text{clear aperture}$$

s

D

h

f

f

Image

Object

h'

Object at ∞

s'

Spherical Optics
Focal Length Defined

Definition

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} = \frac{2}{R}$$

Object at Infinity

$$\frac{1}{s'} = \frac{1}{f} \qquad \frac{1}{s'} = \frac{2}{R}$$

$f = R/2$ is referred to as the *paraxial* focal-length

Snell's Law

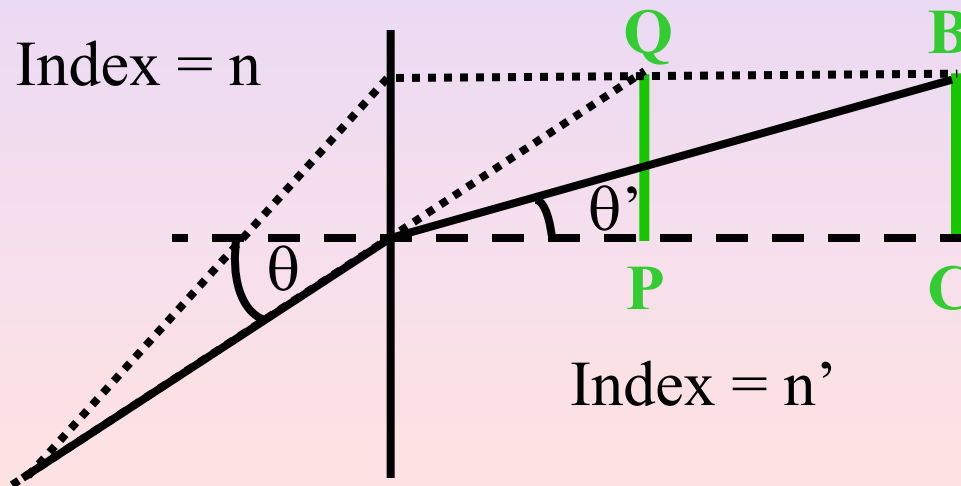$$n \sin \theta = n' \sin \theta'$$

n and n' depend on λ

$$\frac{1}{V} = (n_F - n_C)/(n_D - 1)$$

= dispersive power

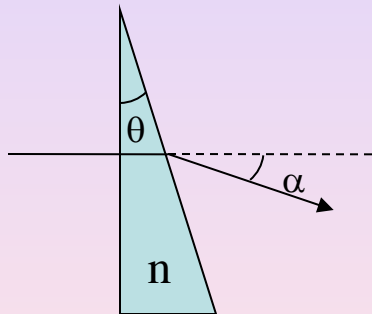*F,D,C:* solar-spectrum
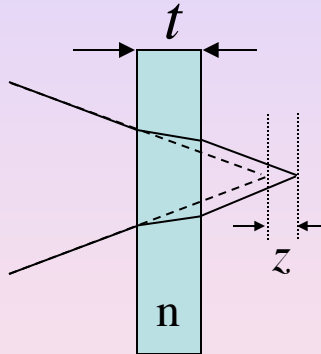Fraunhofer lines (486, 589, 656 nm).
V vs n is called a glass table.

Index = n

Q   **B**

θ'

P   **C**

θ

Index = n'

Fermat's principle: least time

An Aside: Implications of Snell's Law
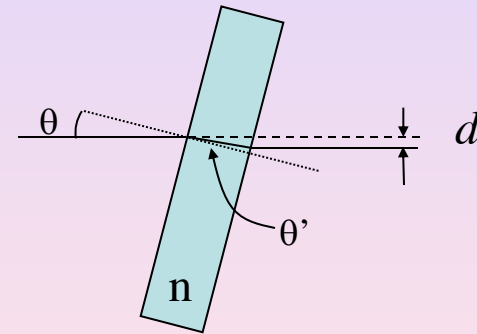
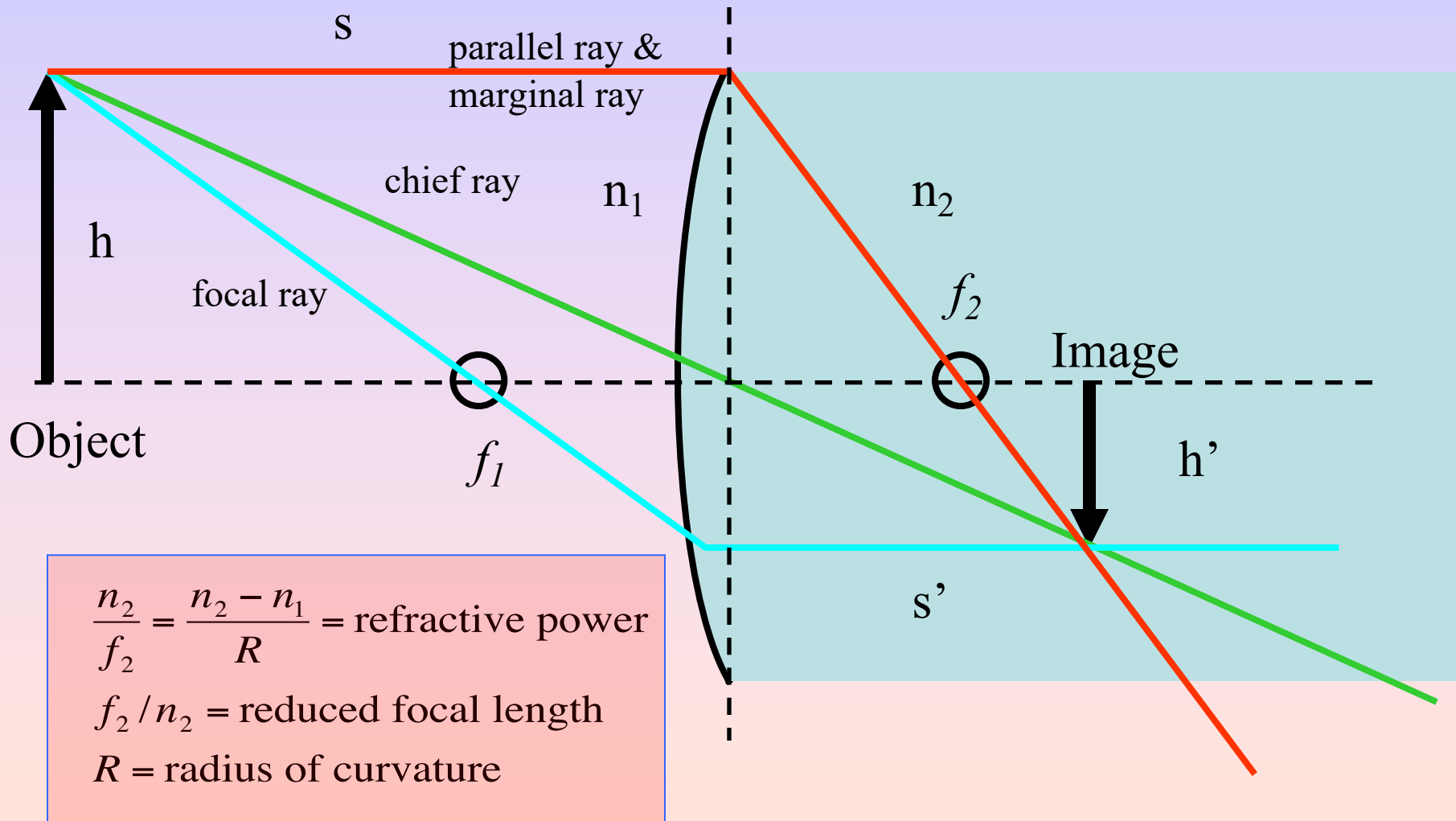$$\alpha \approx (n-1)\theta \qquad z \approx \frac{(n-1)t}{n} \qquad d \approx t\sin\theta\left(1 - \frac{\cos\theta}{n\cos\theta'}\right)$$
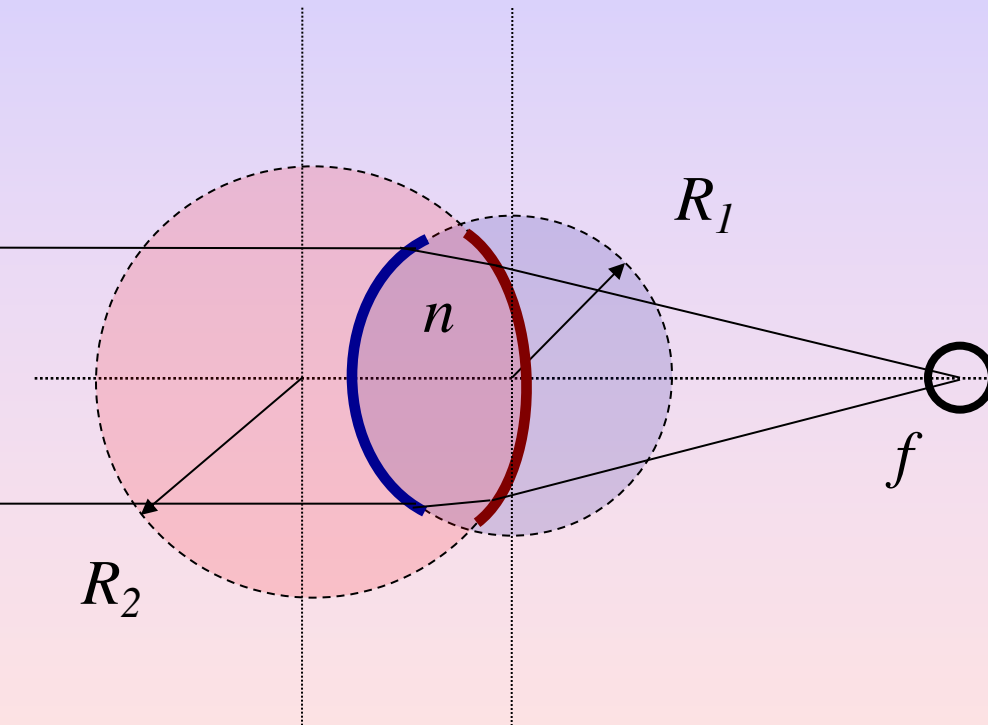

Impact of wedges and
and plane parallel plates
on an optical beam

If beam is converging,
astigmatism introduced.
Can be eliminated with wedge.

The Thick Lens

s

parallel ray & marginal ray

chief ray

n_1

n_2

h

focal ray

f_2

Image

Object

f_1

h'

s'

$$\frac{n_2}{f_2} = \frac{n_2 - n_1}{R} = \text{refractive power}$$

$f_2 / n_2 = \text{reduced focal length}$

$R = \text{radius of curvature}$

Optical Power, P

Two surfaces
- separation d
- index n

$$P \equiv \frac{1}{f} = P_1 + P_2 - \frac{d}{n}P_1P_2$$

R_1

n

R_2

f

Two-surface spherical lens in air or vacuum
- R_1, R_2 radii of curvature
- R>0: center of curvature behind lens

Lensmaker's formula:

$$P = \frac{1}{f} = (n-1)\left[\frac{1}{R_1} - \frac{1}{R_2} + \frac{d(n-1)}{nR_1R_2}\right]$$

$$\text{units}: \text{ dioptor } (\text{m}^{-1})$$