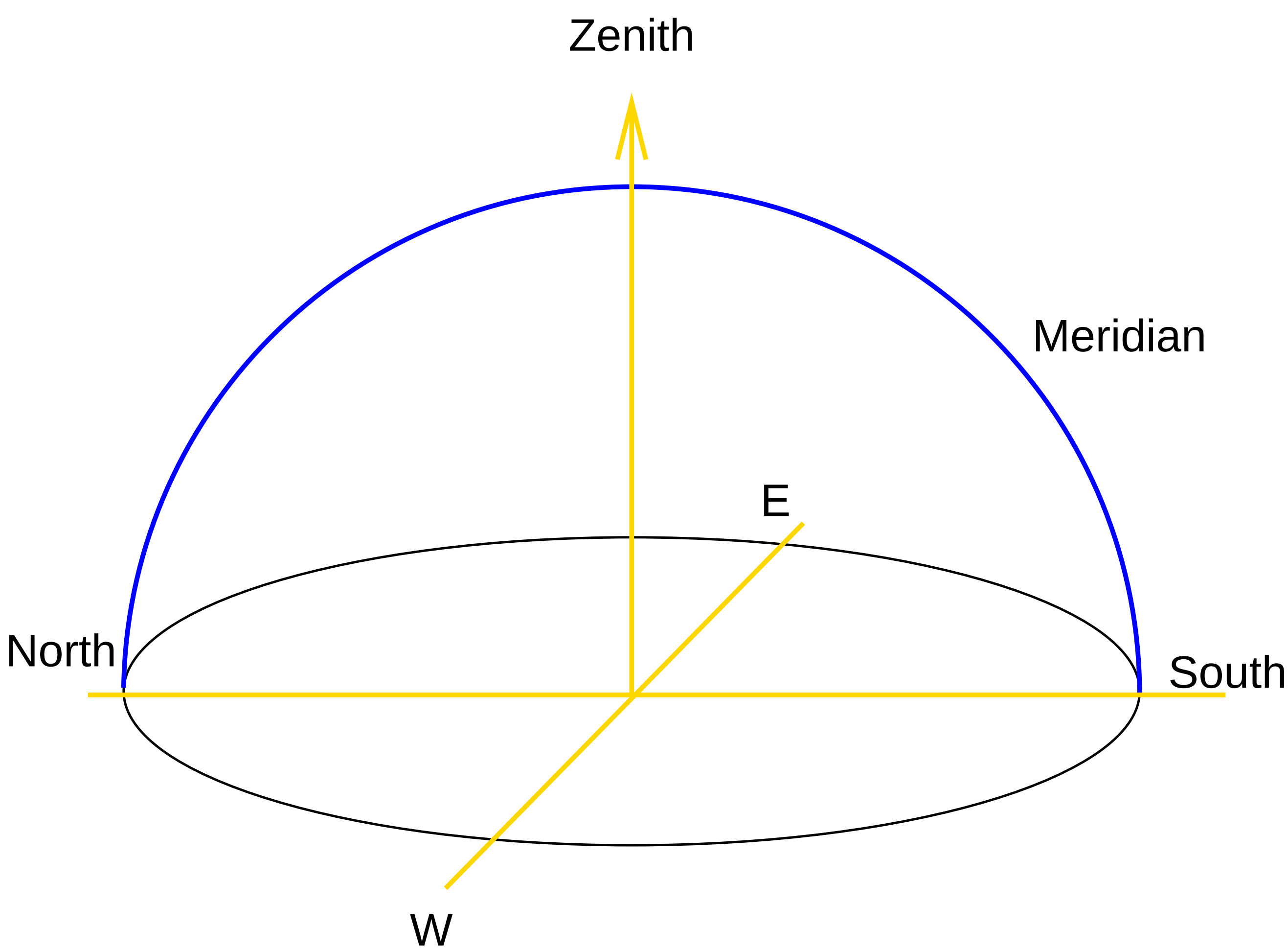
Introduction

We now move away from solar system $\Longrightarrow$ before we can continue with science, we need to understand

- where astronomical objects are $\Longrightarrow$ coordinate systems
- how astronomical measurements are made $\Longrightarrow$ telescopes

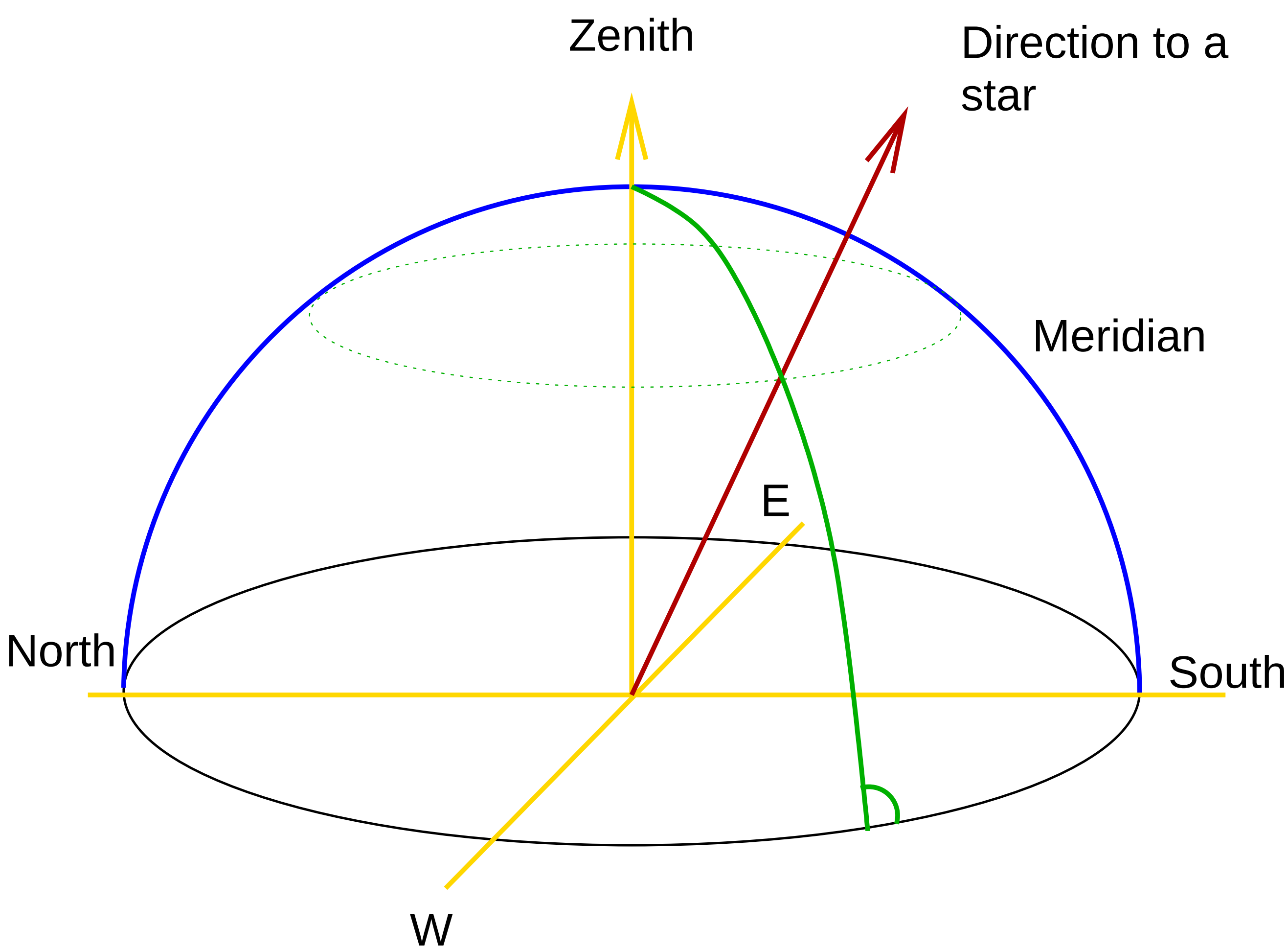
Horizon System, I



Position on sky:

after Giese

Horizon System, II

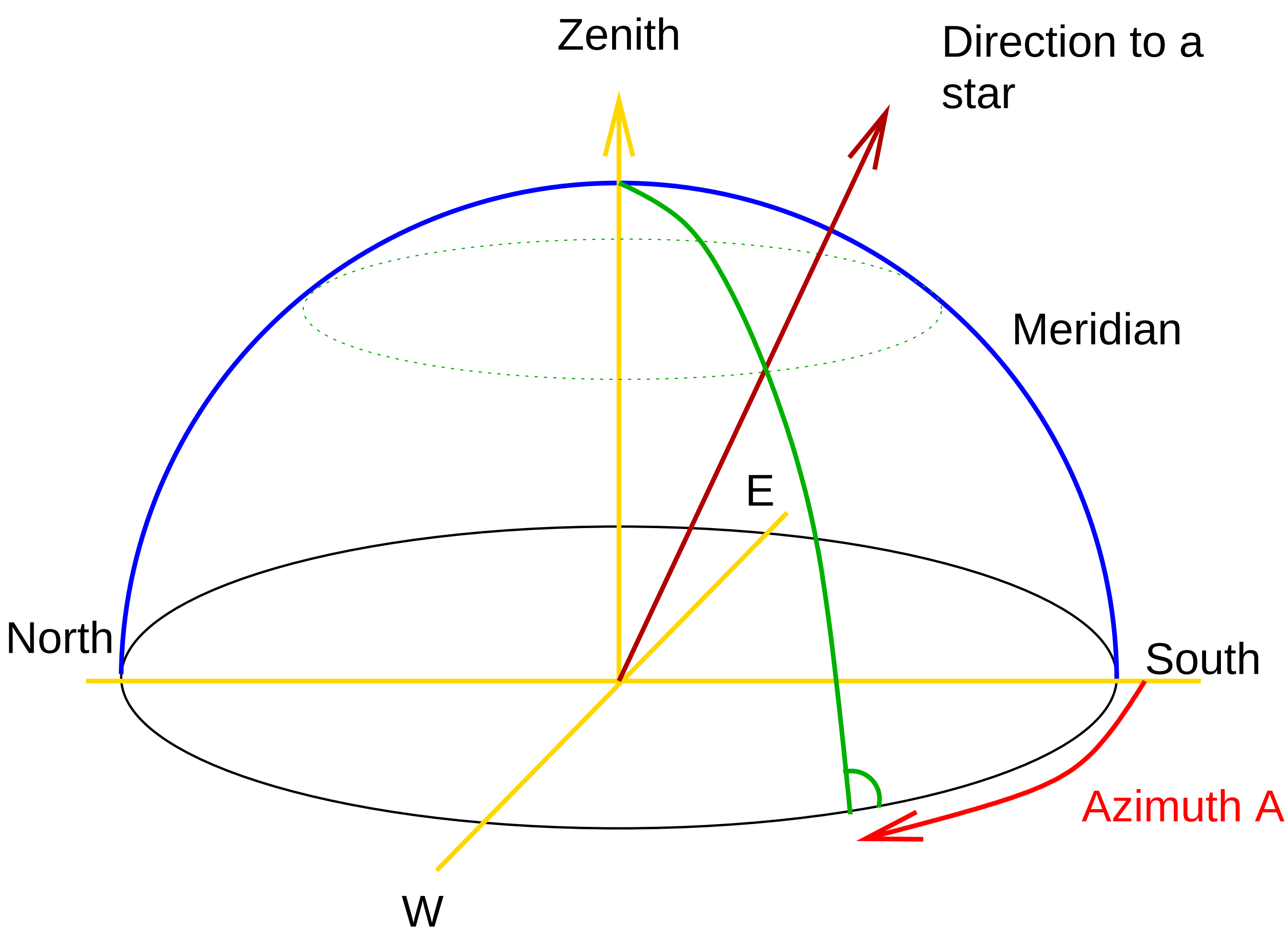


after Giese

Position on sky:

- Define position by giving direction to star.

Horizon System, III

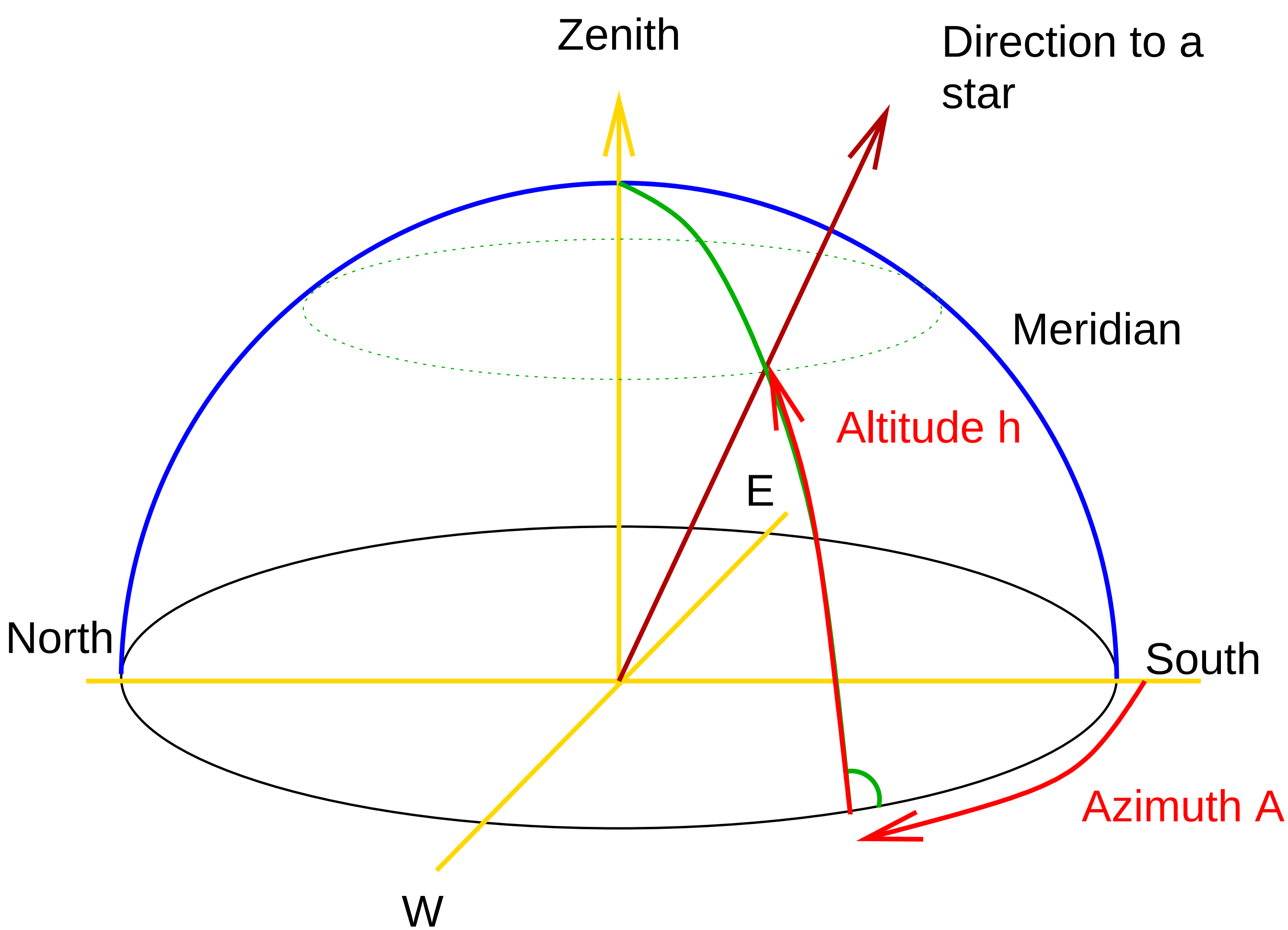


after Giese

Position on sky:

- Define position by giving direction to star.
- Azimuth A: angle in horizontal S-W-N-E

Horizon System, IV

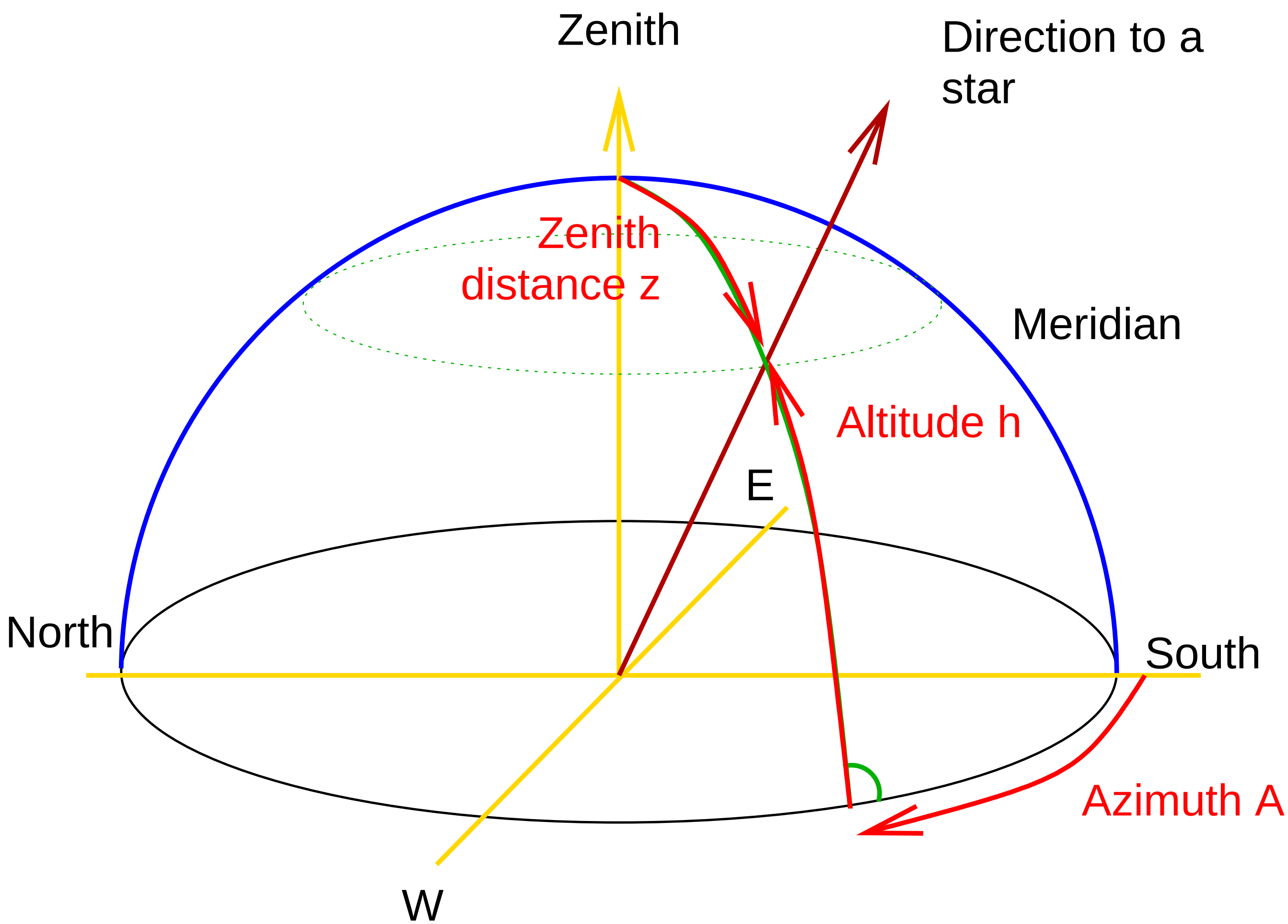


after Giese

Position on sky:

- Define position by giving direction to star.
- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith

Horizon System, V

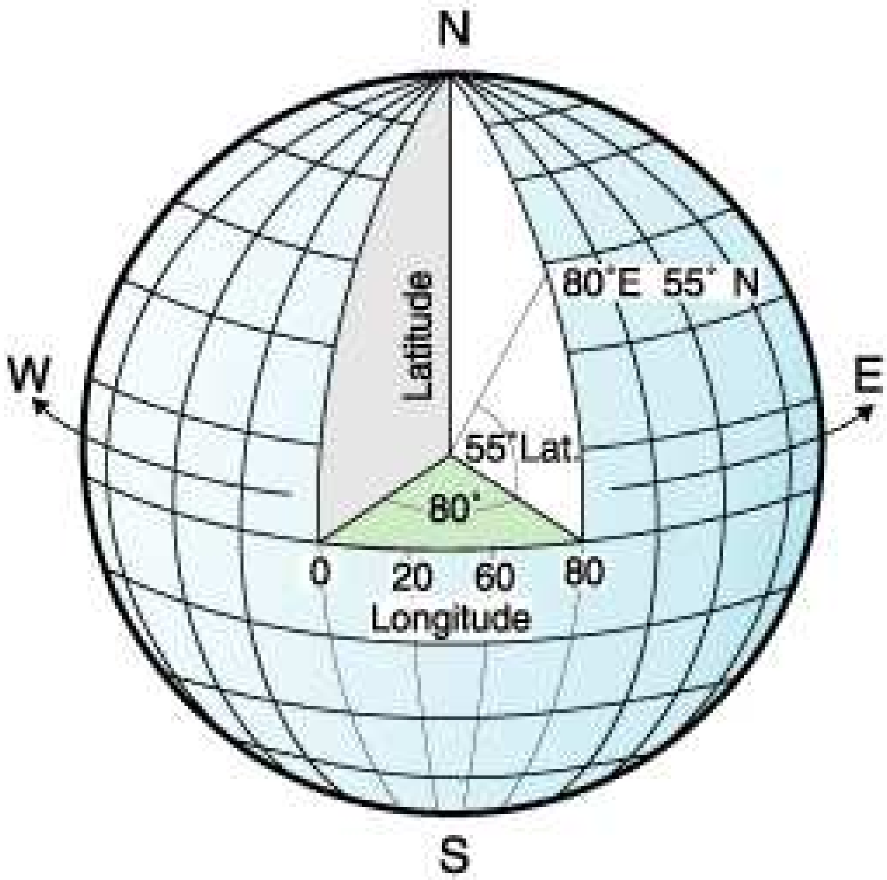


after Giese

Position on sky:

- Define position by giving direction to star.
- Azimuth A: angle in horizontal S-W-N-E
- Altitude h: angle from horizon towards zenith
- Zenith distance z: $z = 90^\circ - h$

Equatorial System, I

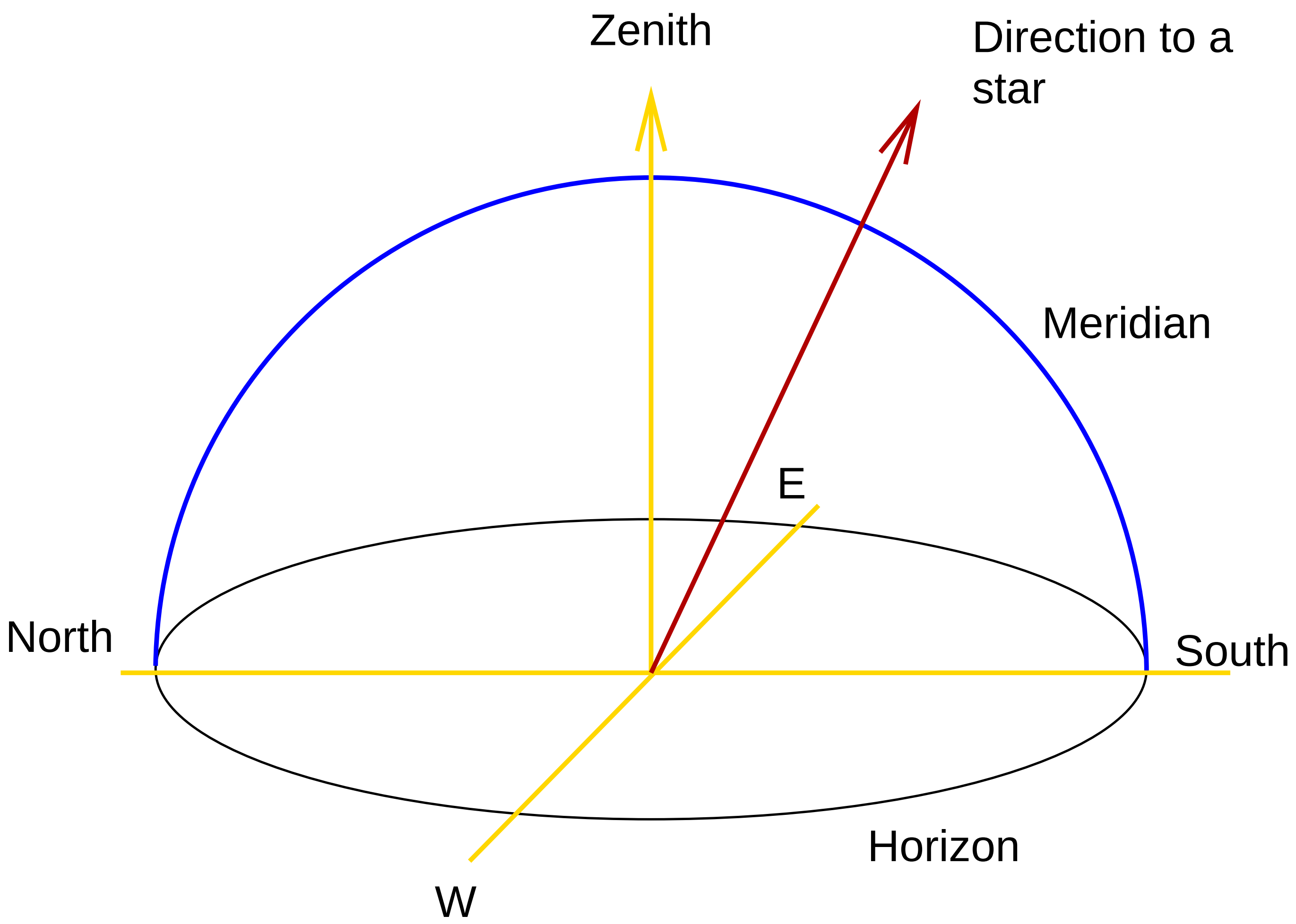


Problem: Earth rotates

$\Longrightarrow$ A and h change with time

$\Longrightarrow$ need coordinates "fi xed" on celestial sphere, similar to geographic latitude, φ, and longitude, λ, on Earth.

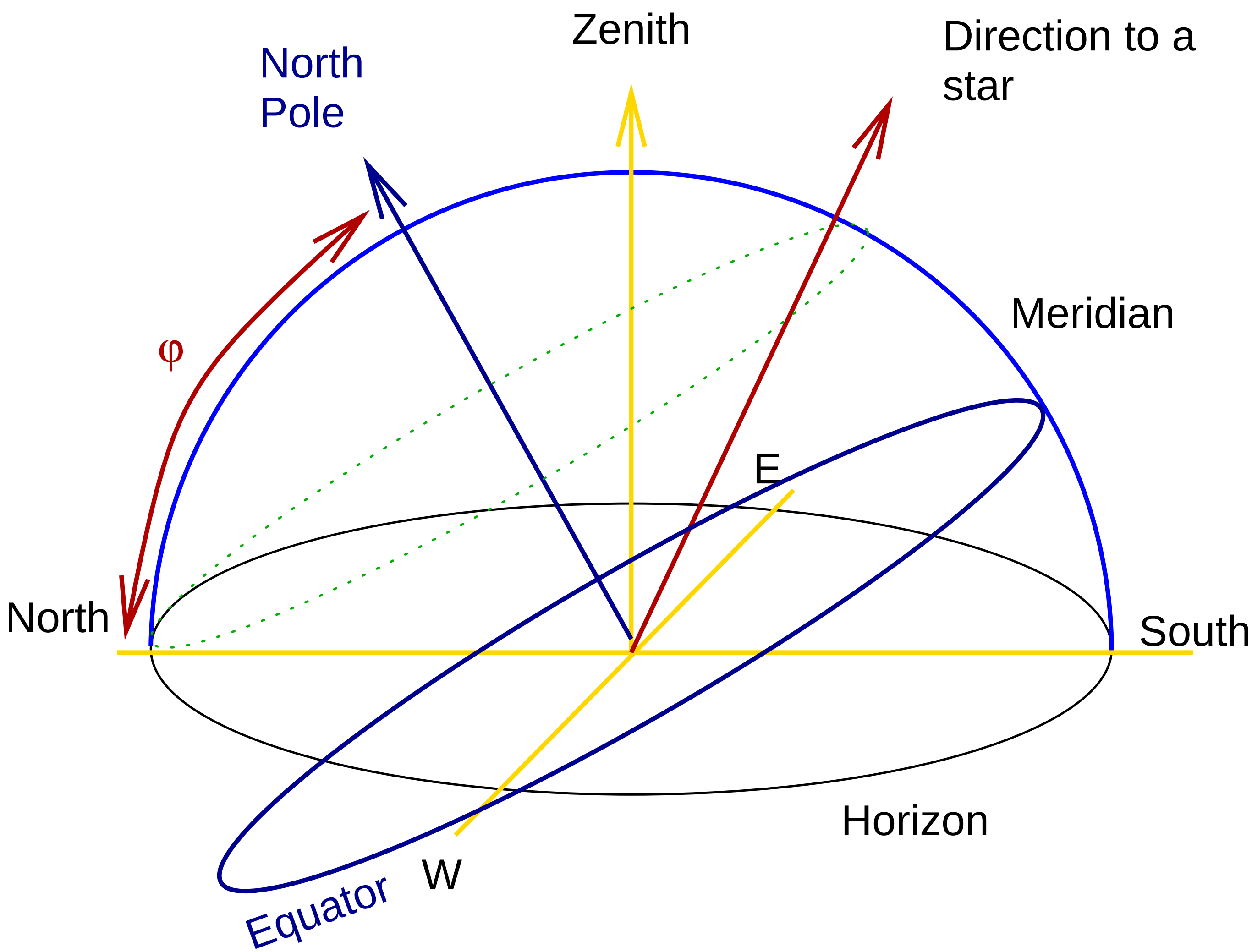
Equatorial System, II



Let's look at our star again.

after Giese

Equatorial System, III



after Giese

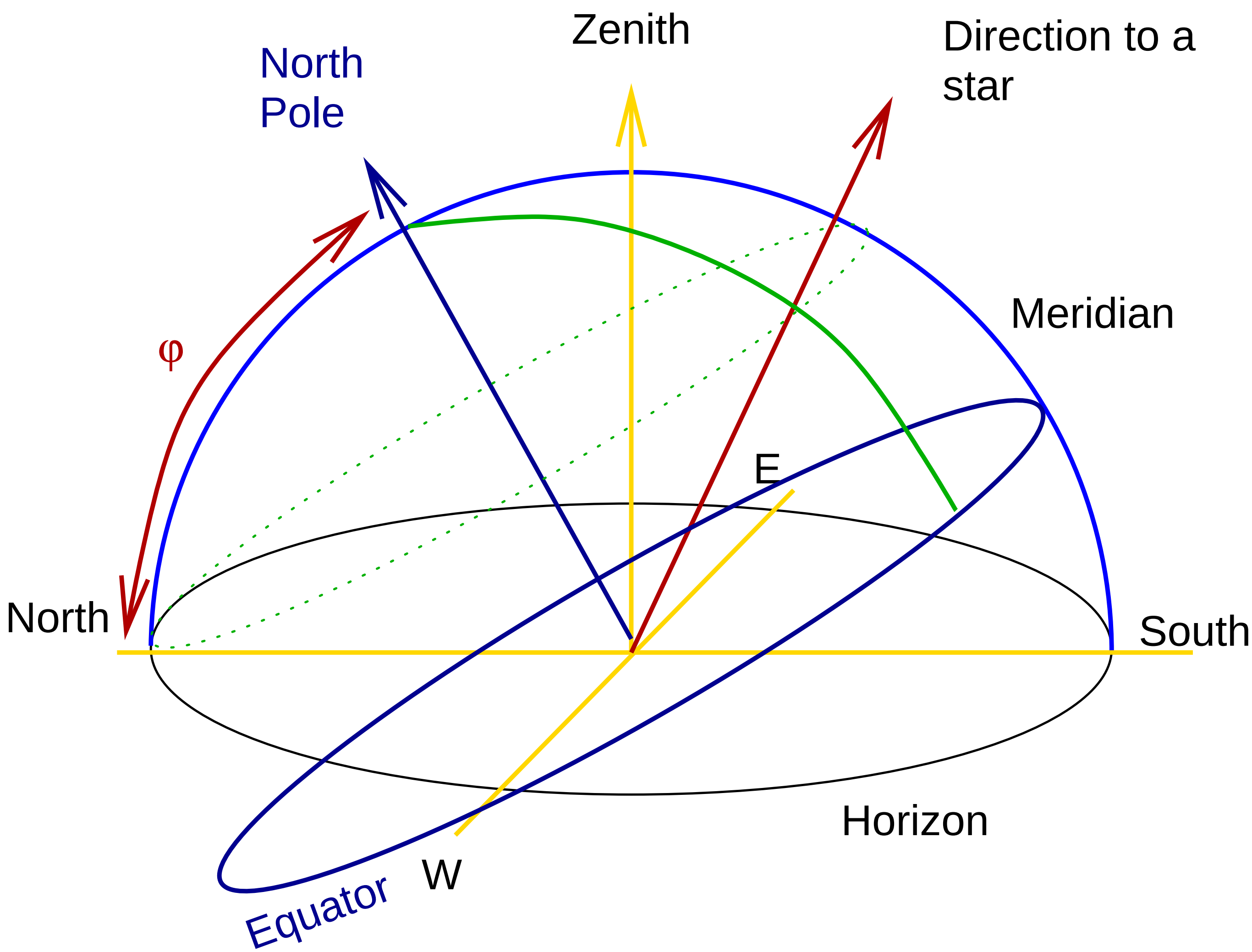
Let's look at our star again.

Rotation of Earth: Stars move over sky around celestial north pole.

North pole has altitude φ above horizon.


© Joe Orman

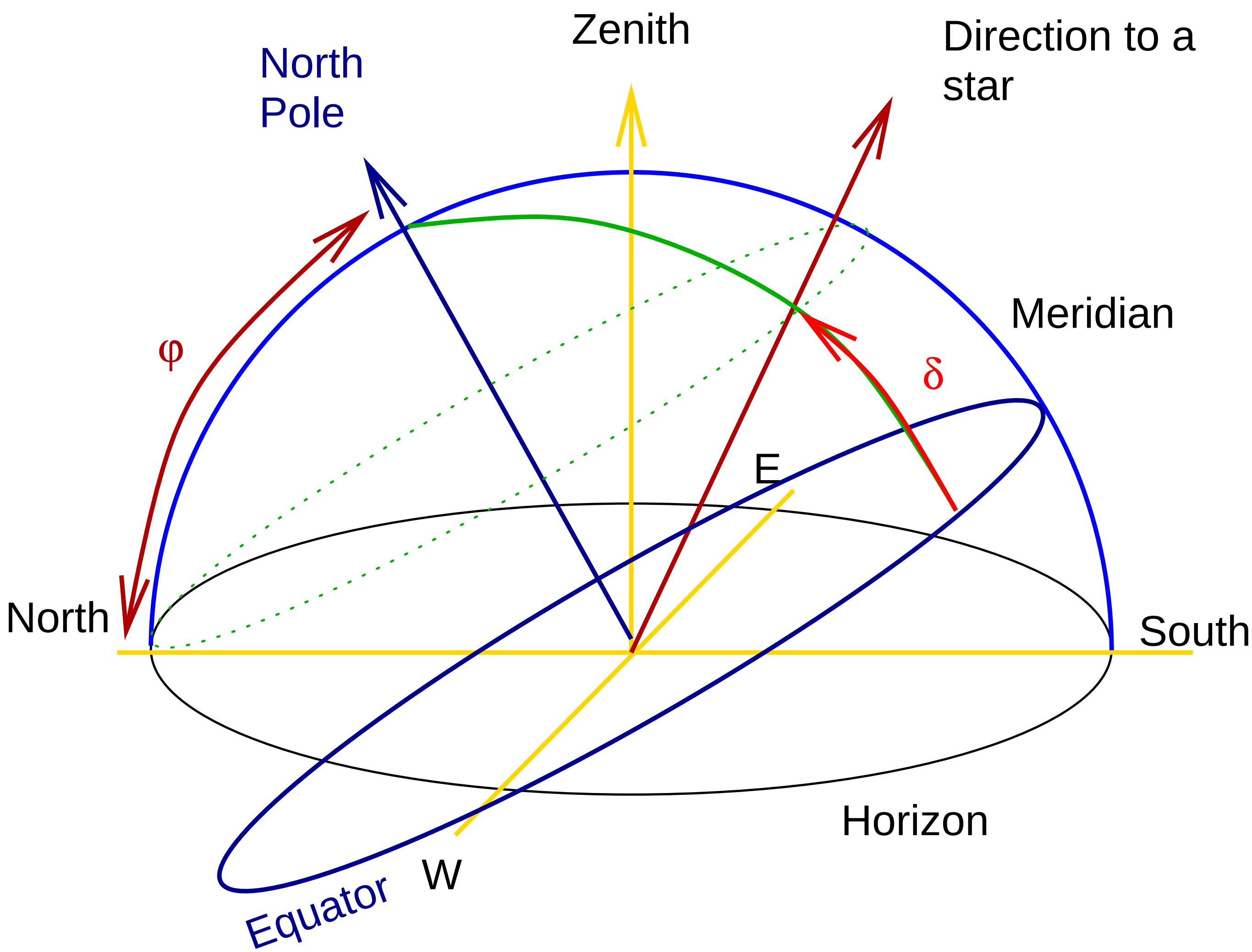
Equatorial System, V



Define coordinates with respect to celestial equator

after Giese

Equatorial System, VI

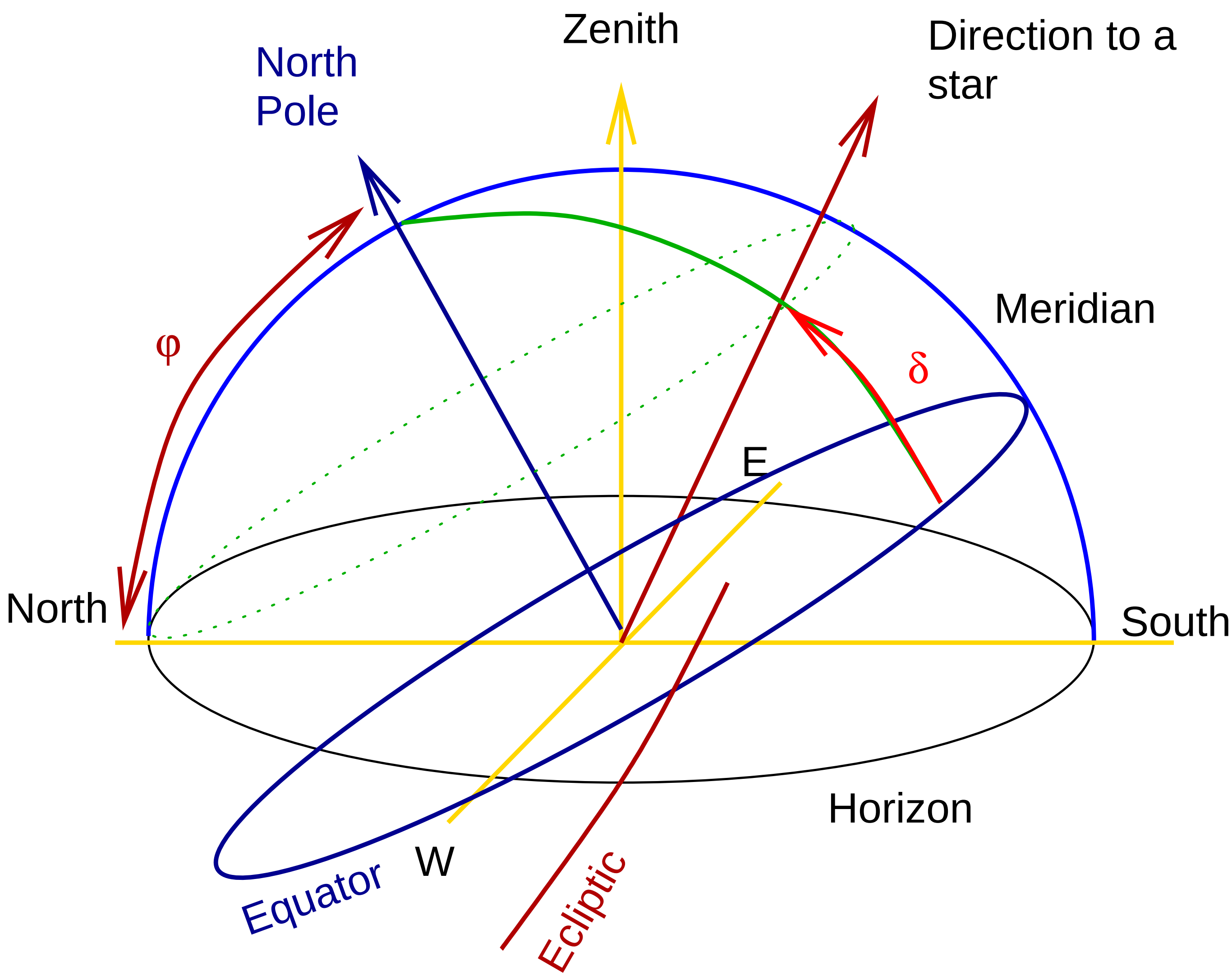


Define coordinates with respect to celestial equator

- Declination δ: angle from equator to star, measured in degrees (equivalent to latitude)

after Giese

Equatorial System, VII



after Giese

Define coordinates with respect to celestial equator

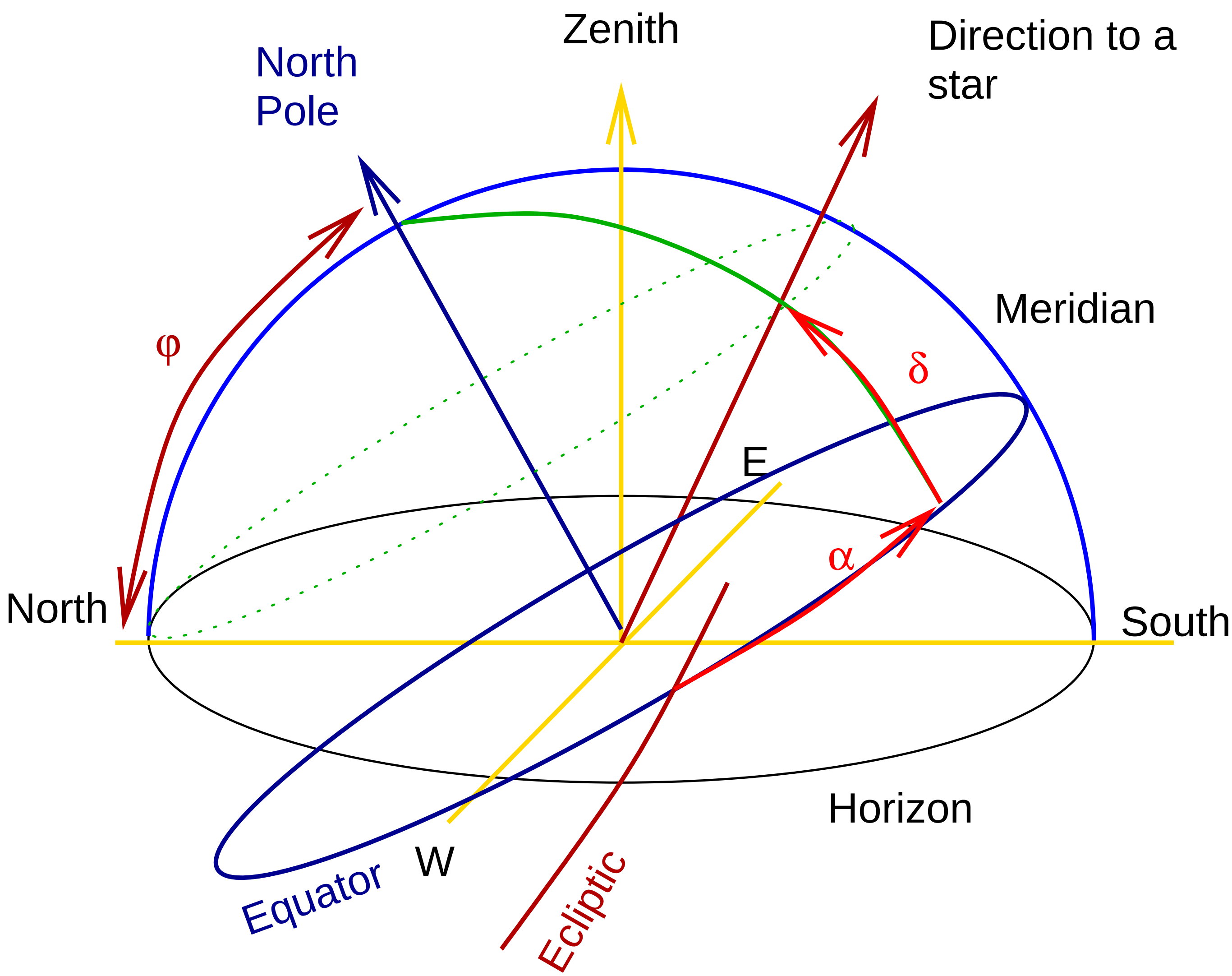
- Declination δ: angle from equator to star, measured in degrees (equivalent to latitude)

Equivalent to longitude more difficult: need a “Greenwich meridian”.

$\Longrightarrow$ Defined by crossing of ecliptic (apparent path of Sun on sky) with equator: “ascending node”, “vernal equinox” (Frühlingspunkt)

(location of Sun on 21 March)

Equatorial System, VIII

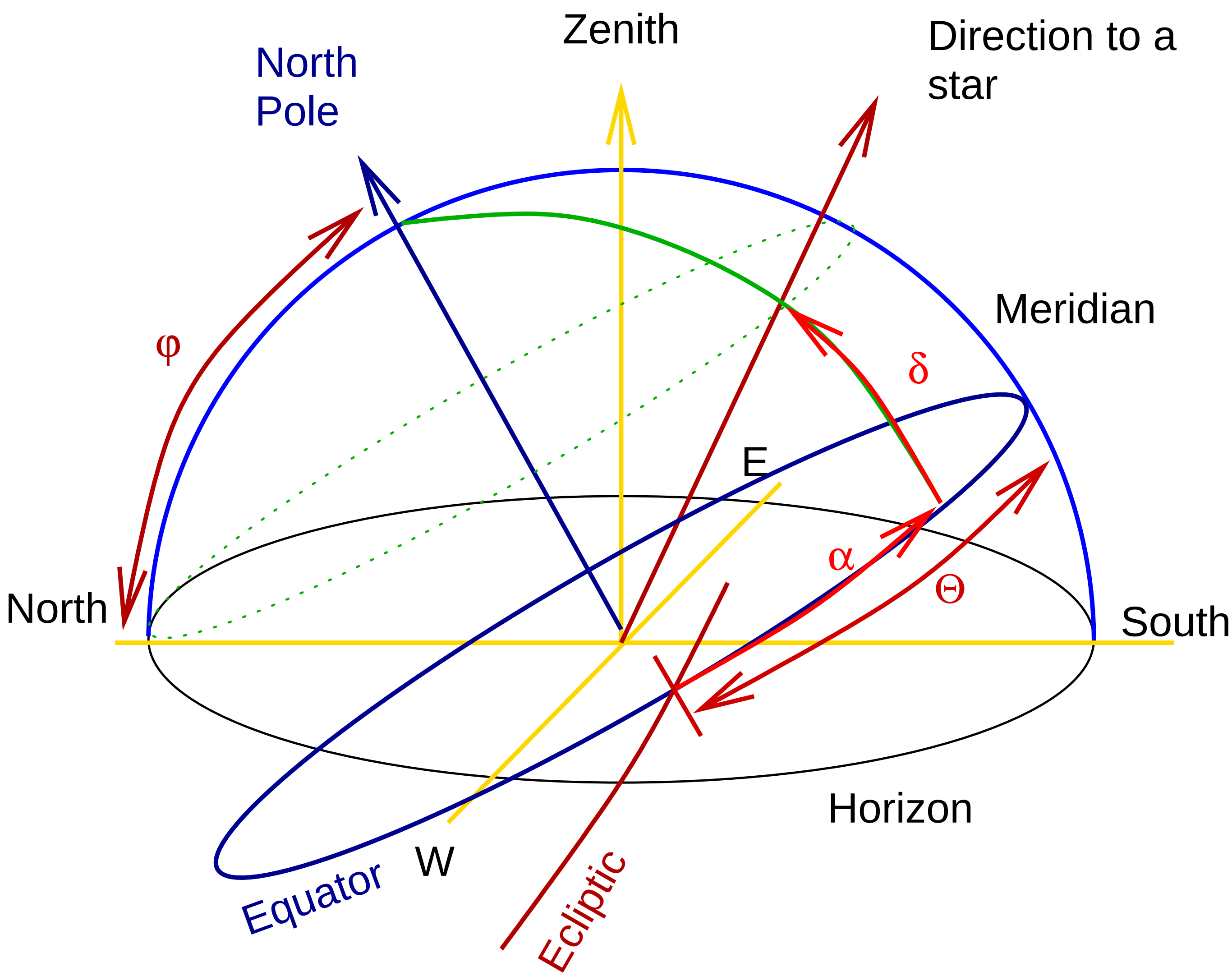


after Giese

Define coordinates with respect to celestial equator

- Declination δ: angle from equator to star, measured in degrees (equivalent to latitude)
- Right ascension α: angle from vernal equinox to star, measured in easterly direction.

Siderial Time, I



Define siderial time: 24 h correspond one rotation of the celestial sphere.

0 h siderial time = time when vernal equinox passes through meridian.

$\Longrightarrow$ Local siderial time: Right ascension of stars passing through meridian.

Right Ascension is measured in hours, minutes, and seconds

1 h corresponds to 15°.
α increases towards East.

Siderial Time, II

Note: Siderial time $\neq$ common time

Common time: 24 h between culminations of the Sun (i.e., passes of Sun through meridian).

BUT

Sun moves on sky towards east

$\Longrightarrow$ one "solar day" takes slightly longer than one rotation of the Earth

Angular speed of Sun: 360° degrees in 365.25 days, i.e., $0.9856^\circ\,\mathrm{d}^{-1}$.

$\Longrightarrow$ During 365.25 days the Earth rotates 364.25 times

$\Longrightarrow$ Earth's rotation takes $24\,\mathrm{h} \times 364.25/365.25 = 23\,\mathrm{h}\ 56\,\mathrm{minutes}$.

Precession and Nutation

There is one last problem, however:

Earth is $\sim$ rotational ellipsoid, orbits of Sun and Moon are *not* in plane of equator

(Earth's axis has tilt of $\sim$23.5°, moon's orbit tilted by 7° against ecliptic)

$\Longrightarrow$ Sun and Moon excert torques onto Earth

Earth's rotational axis is not stable in space.

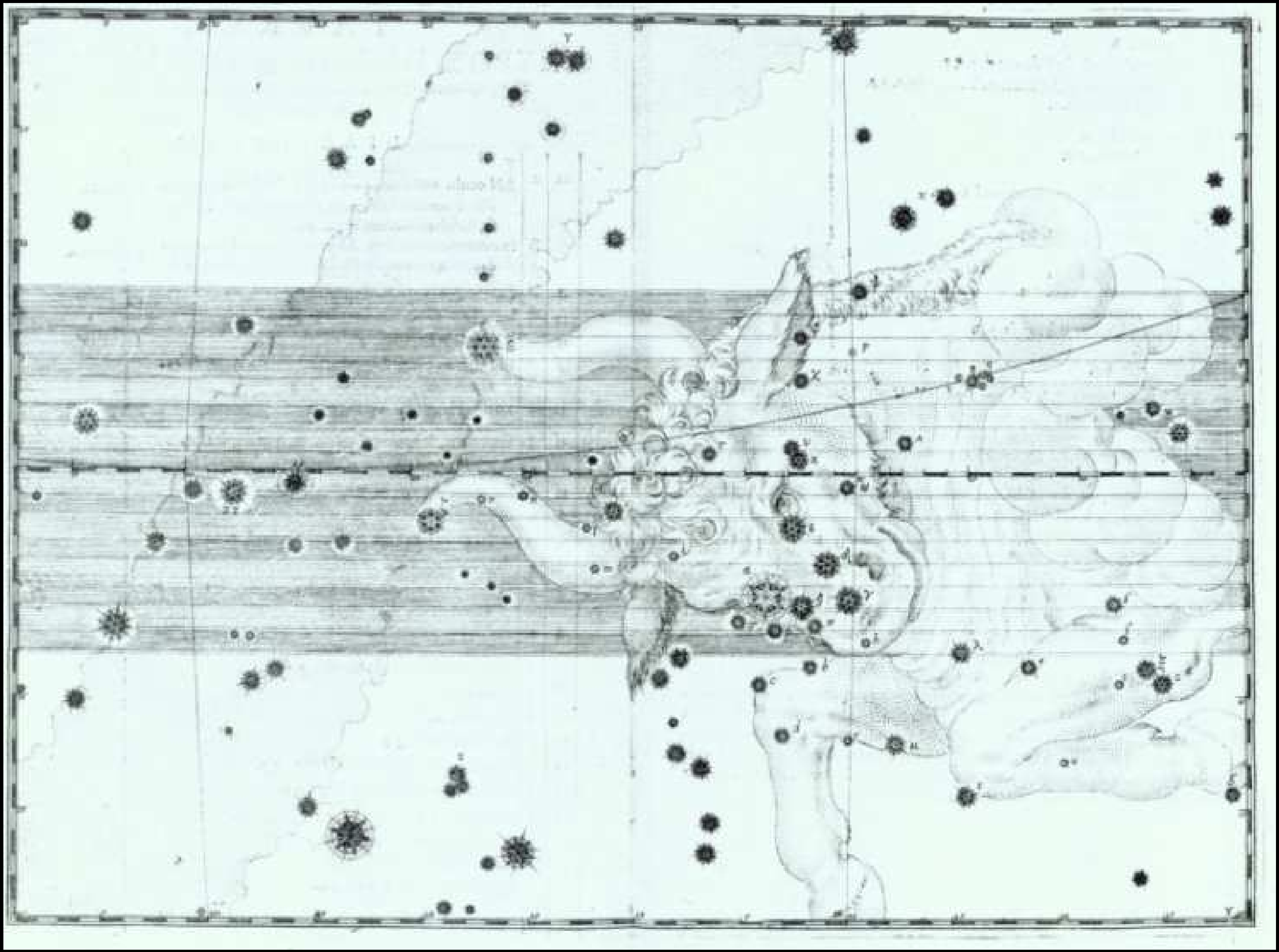
Two major effects:

lunisolar precession: Earth's axis rotates around pole of ecliptic once every 25800 years ($\sim 50''$ per year).

Already discovered by Hipparcus in $\sim$200 BC!

nutation: "Wobble" with $\sim$18 year periodicity caused by short-term perturbations caused by Moon and Sun.

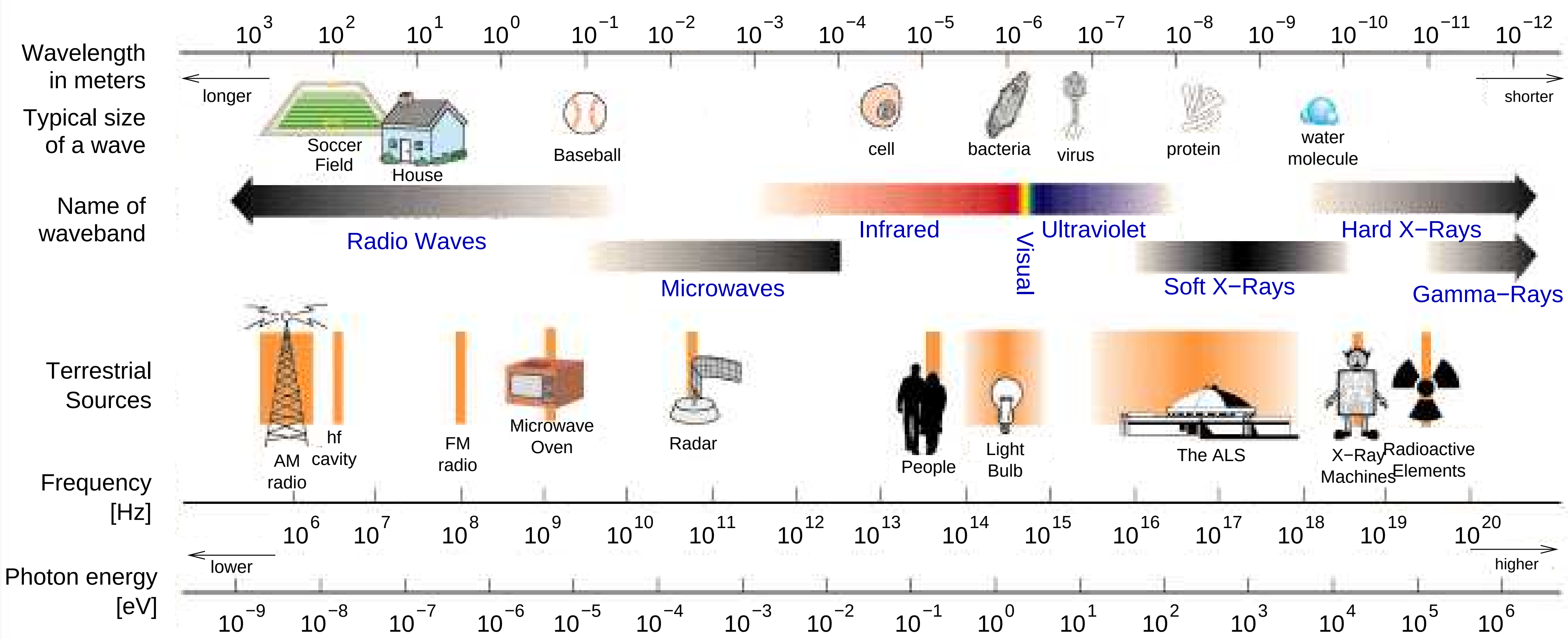
$\Longrightarrow$ Need to state epoch for coordinates. Typically use 1950.0 or 2000.0.



Bayer's Uranometria (1603; University of Illinois collections)

Aldebaran = α Tau: $\alpha_{\mathrm{J2000.0}} = 04^{\mathrm{h}}35^{\mathrm{m}}55.2387^{\mathrm{s}}$, $\delta_{\mathrm{J2000.0}} = +16^\circ 30' 33.485''$
corresponding to $\alpha_{\mathrm{B1950.0}} = 04^{\mathrm{h}}33^{\mathrm{m}}02.9^{\mathrm{s}}$, $\delta_{\mathrm{B1950.0}} = +16^\circ 24' 37.6''$

THE ELECTROMAGNETIC SPECTRUM



Electromagnetic Spectrum, II

As we all know, light can be characterized by

Wavelength: λ, measured in m, mm, cm, nm, Å.

Frequency: ν, measured in Hz, MHz.

Energy: E, measured in J, erg, Rydbergs, eV, keV, MeV, GeV.

Temperature: T, measured in K.

These quantities are related:

$$\lambda\nu = c \qquad E = h\nu \qquad T = E/k \tag{8.1}$$

where

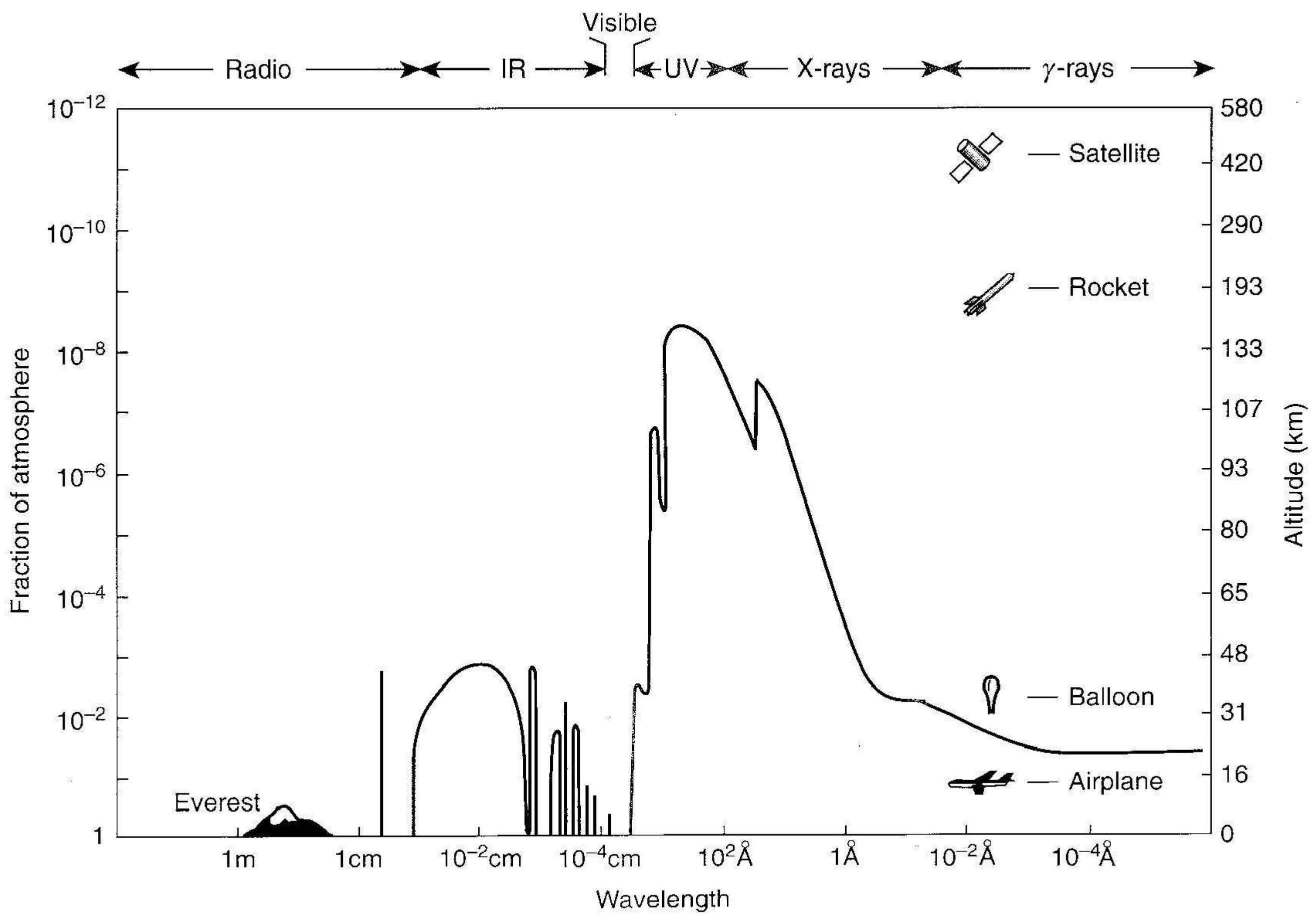
$$c = 299792458\,\mathrm{m\,s^{-1}} \tag{8.2}$$

$$h = 6.6260693(11) \times 10^{-34}\,\mathrm{J\,s} \tag{8.3}$$

$$k = 1.3806505(24) \times 10^{-23}\,\mathrm{J\,K^{-1}} \tag{8.4}$$

Constants are 2002 CODATA values, `http://physics.nist.gov/cuu/Constants/index.html`
uncertainty is 1σ in units of last digit shown.

Earth's Atmosphere



Charles & Seward, Fig. 1.12

Earth's atmosphere is opaque for all types of EM radiation except for optical light and radio.

$\Longrightarrow$ Astronomy is today multi-wavelength astronomy, although optical studies are still the most important

$\Longrightarrow$ For time reasons only optical telescopes will be discussed.

Introduction

Scientific purposes of a telescope:

1. Collect light, lots of light, to show faint objects (“Light bucket”)
2. Resolve small features

Instrumentation used. . .

1. to make images
   $\Longrightarrow$ Imaging (with Charge Coupled Devices [CCDs], formerly also with film)
2. to measure spectra
   $\Longrightarrow$ Spectrographs
3. to measure stellar brightness
   $\Longrightarrow$ Photometers (often CCDs, but there are also dedicated photometers for msec-resolution photometry)

Reflectors, I

To collect light, we have two possibilities:

1. Lenses: Refractors

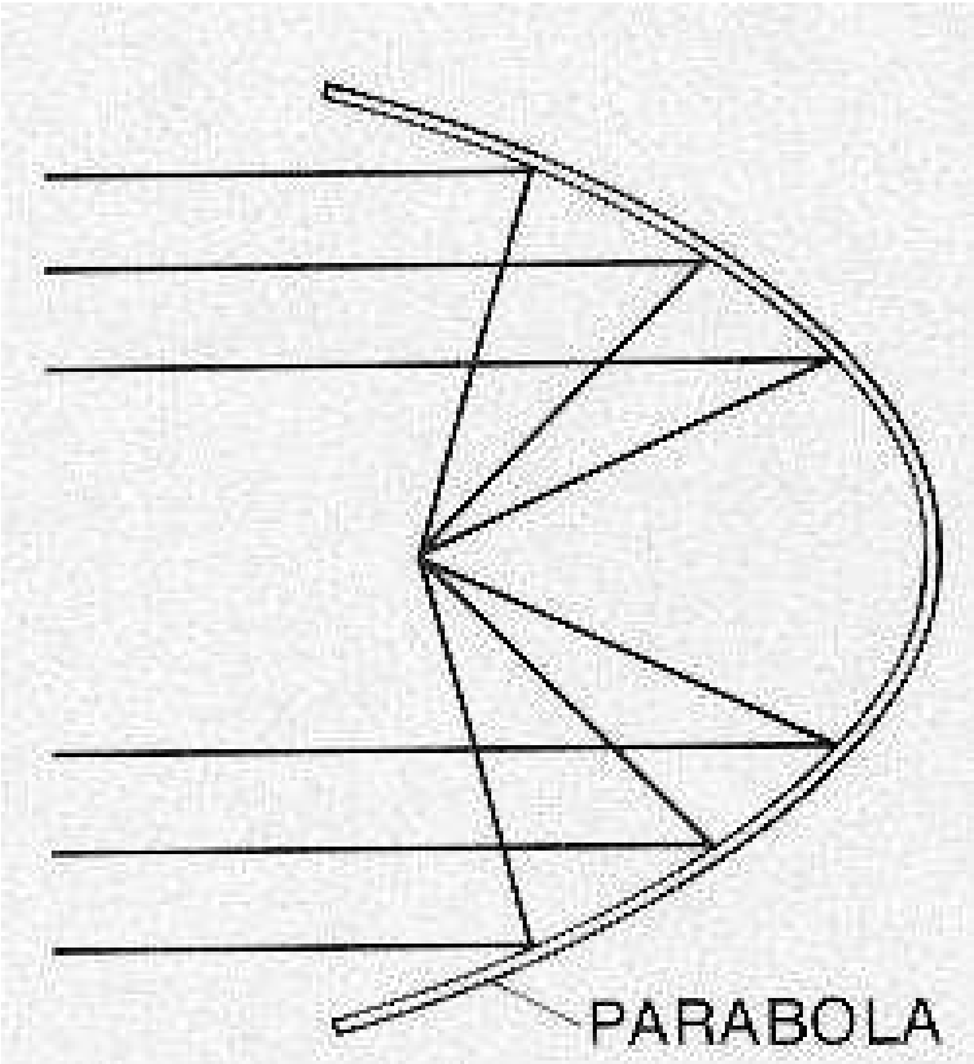
   Disadvantage: lens cannot be supported from the back $\Longrightarrow$ limits max. diameter to $\lesssim 2\,\mathrm{m}$

   $\Longrightarrow$ not of interest for science anymore.

2. Mirrors: Reflectors

   Mirrors can be supported, instrument of choice for today, with diameters up to $11\,\mathrm{m}$

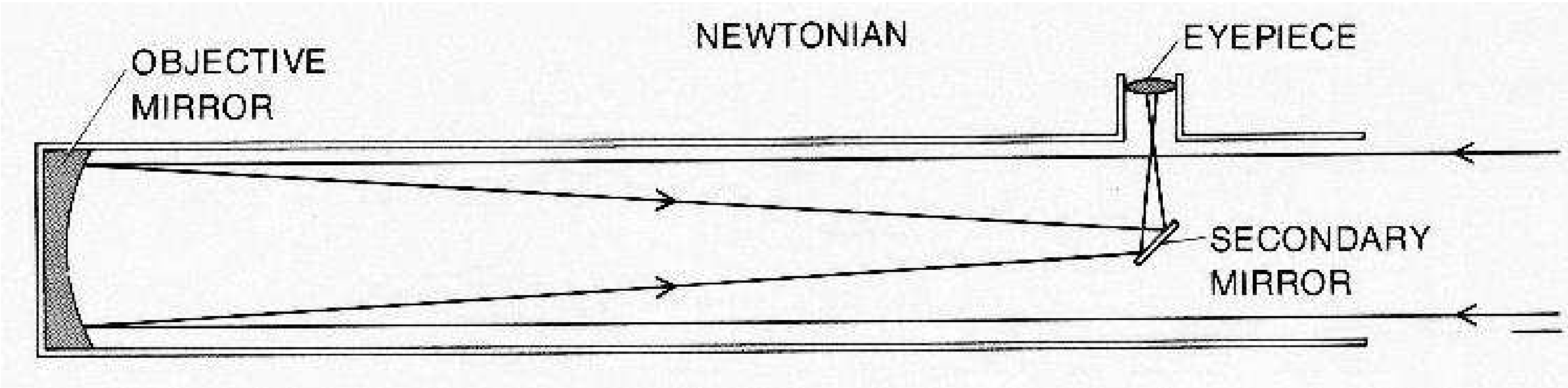
Reflectors, II



To form image: focus light with a parabolic mirror

Spherical mirrors show spherical aberration $\Longrightarrow$ *not* suited for astronomical telescopes, at least not without correction.

Newtonian Telescope

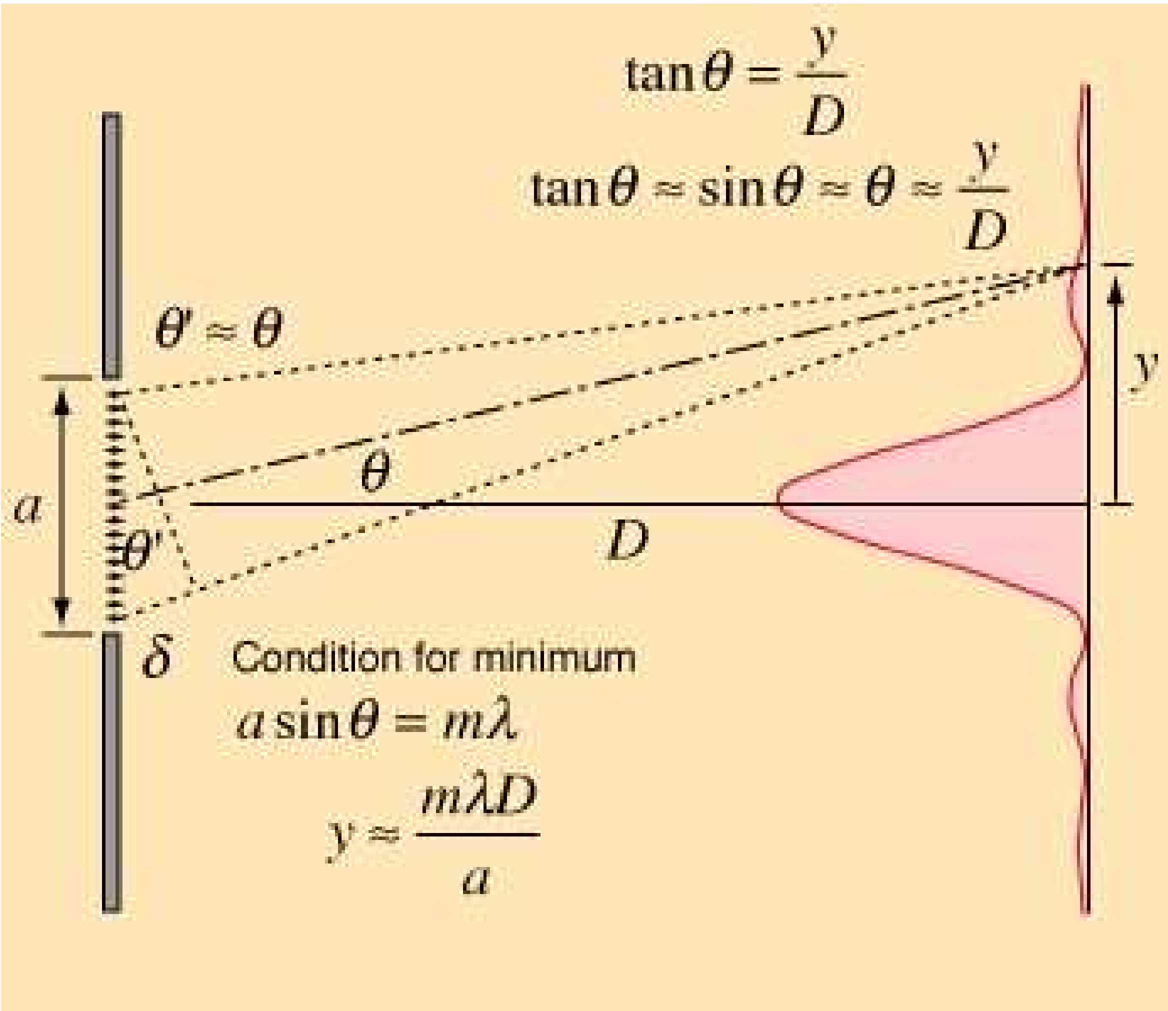


Newtonian telescope: reflector with parabolic mirror.

Common in cheaper telescopes.

Disadvantage: large size ($\sim$ focal length)

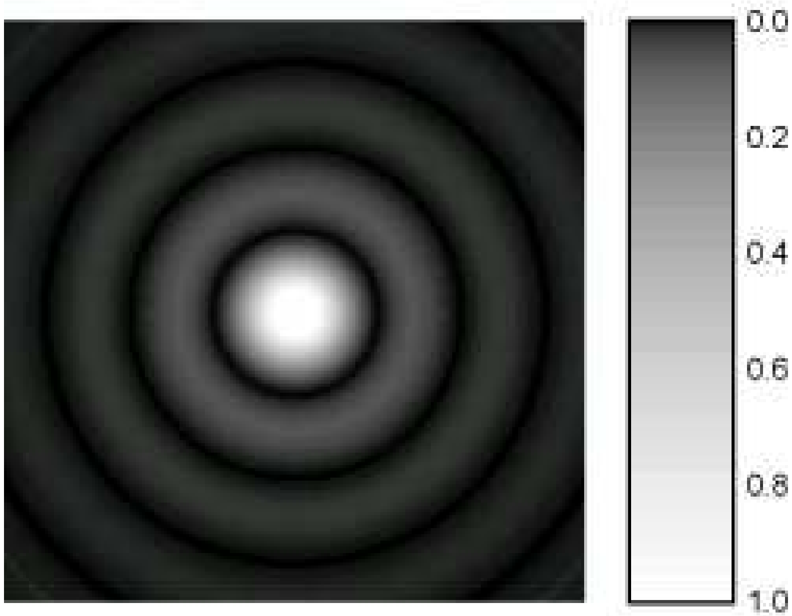
Resolution, I



GSU

Wave nature of light results in interference pattern caused by diffraction on optical elements in telescope (mainly aperture).

Resolution, II



Diffraction pattern on telescope aperture: Airy pattern

For a circular aperture with radius r:

$$I(\theta) \propto \pi^2 r^4 \left[\sum_{n=0}^{\infty} (-1)^n \frac{1}{n+1} \left(\frac{m^n}{n!} \right)^2 \right]^2 \tag{8.5}$$

$$\propto \frac{\pi^2 r^4}{m^2} \left(J_1(2m) \right)^2$$

where $m = \pi(r/\lambda)\sin\theta$ and where $J_1(x)$ s the Bessel function of the first kind of order unity.

$I(\theta)$ has minima for $m = 1.916, 3.508, 5.087, \ldots$, or

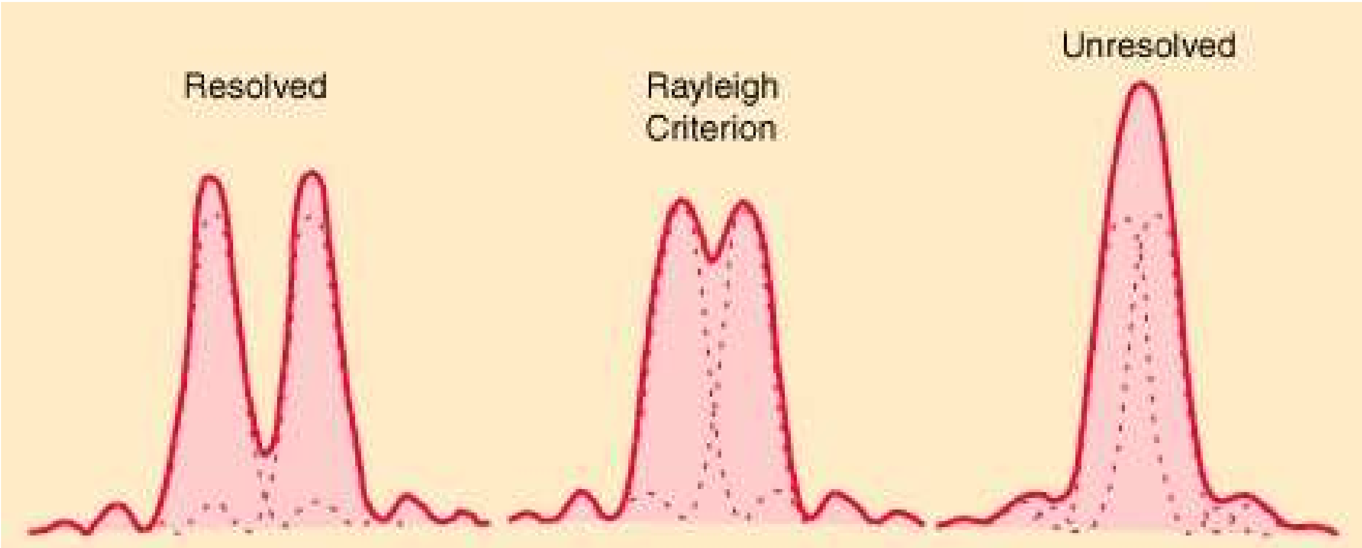
$$\sin\theta = \frac{1.916\lambda}{\pi r}, \frac{3.508\lambda}{\pi r}, \frac{5.087\lambda}{\pi r}, \ldots \tag{8.6}$$

or for θ small ($\sin\theta \sim \theta$) minima are found at:

$$\theta = \frac{1.220\lambda}{d}, \ldots \tag{8.7}$$

where d: diameter.

Resolution, III



Resolution of telescope: ability to separate two (point-like) light sources

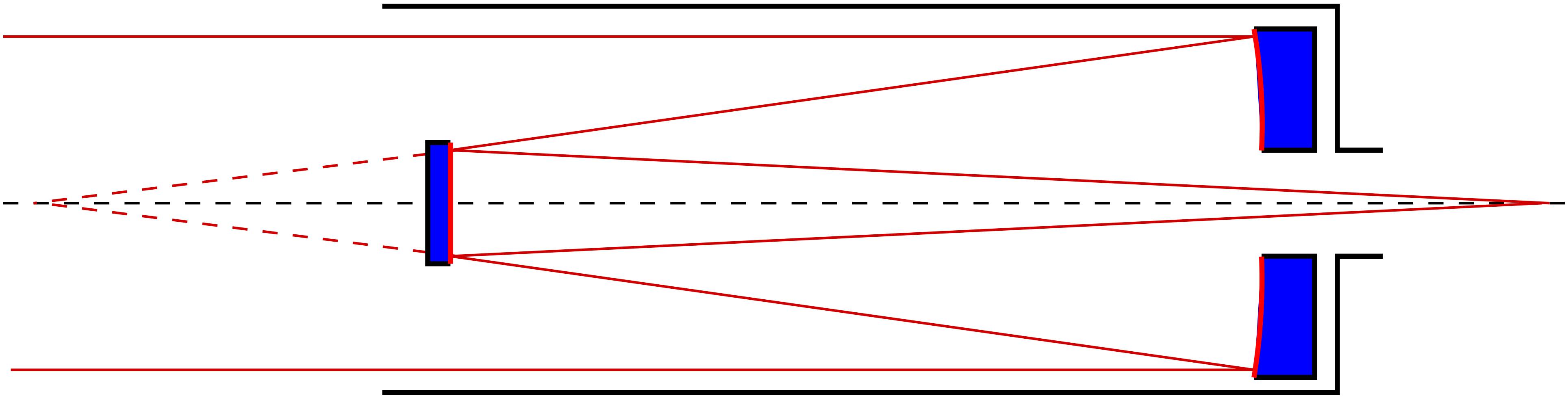
Rayleigh criterion for resolution: maximum of diffraction pattern of one source must fall into minimum of diffraction pattern of other source.

Therefore the diffraction limited resolution is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\text{cm}} \quad \text{for optical light} \tag{8.8}$$

Note: Rayleigh criterion is a criterion, not a law. Detailed object separability depends on ratio of intensities of two objects, in practice resolutions up to 3× smaller are acheivable.

Cassegrain Telescope



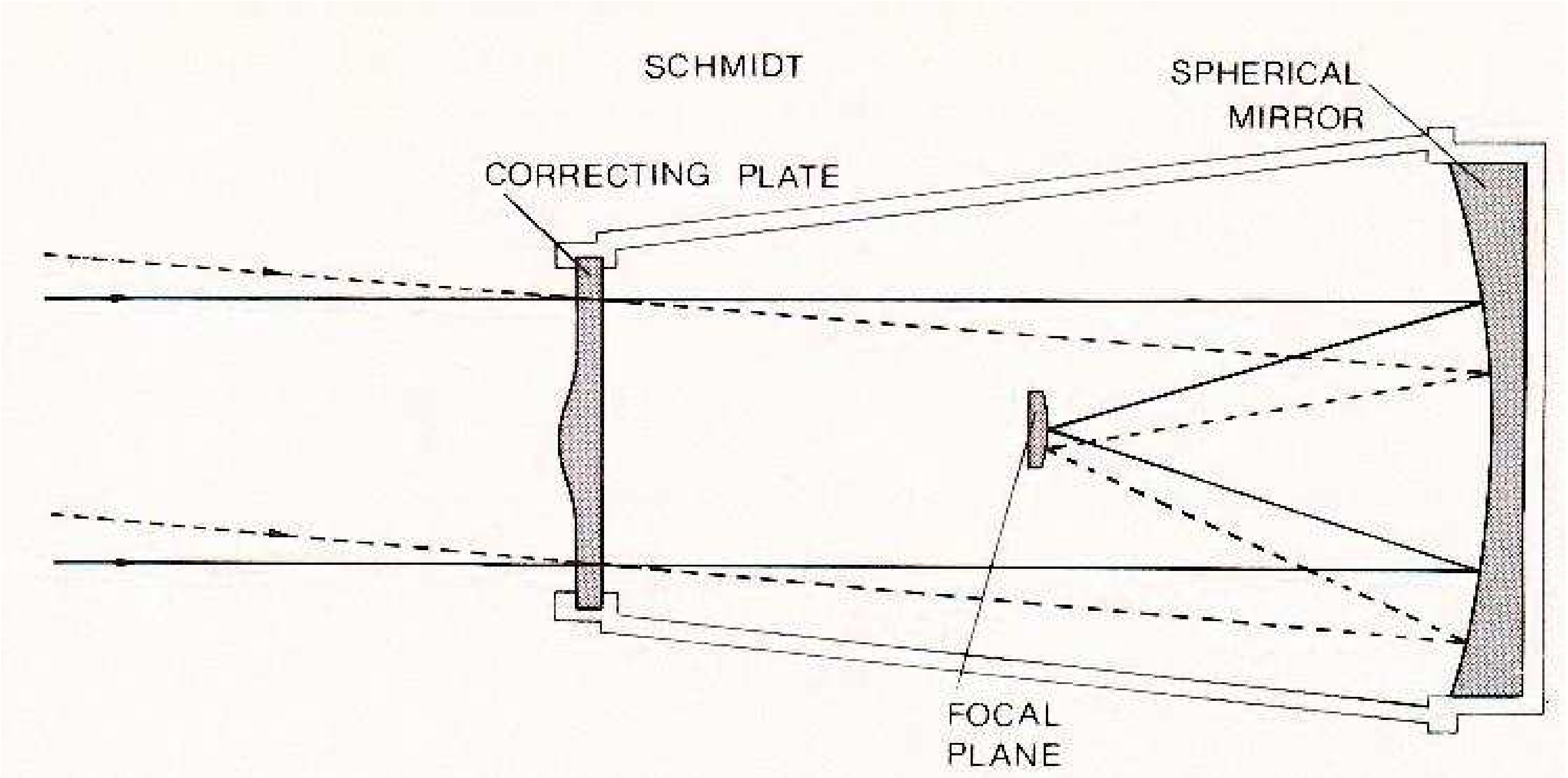
Cassegrain telescope, after Wikipedia

Cassegrain telescope: reflector with “folded optical path”

$\Longrightarrow$ Much shorter than Newtonian

$\Longrightarrow$ Telescope of choice for modern instruments

Schmidt Telescope



Schmidt telescope: Uses spherical mirror for larger fi eld view, correction plate used to correct for spherical aberration.

Many amateur telescopes are combination of Schmidt telescope and Cassegrain telescope $\Longrightarrow$ Schmidt-Cassegrain telescopes.

Example: Building of the European Southern Observatory's Very Large Telescope

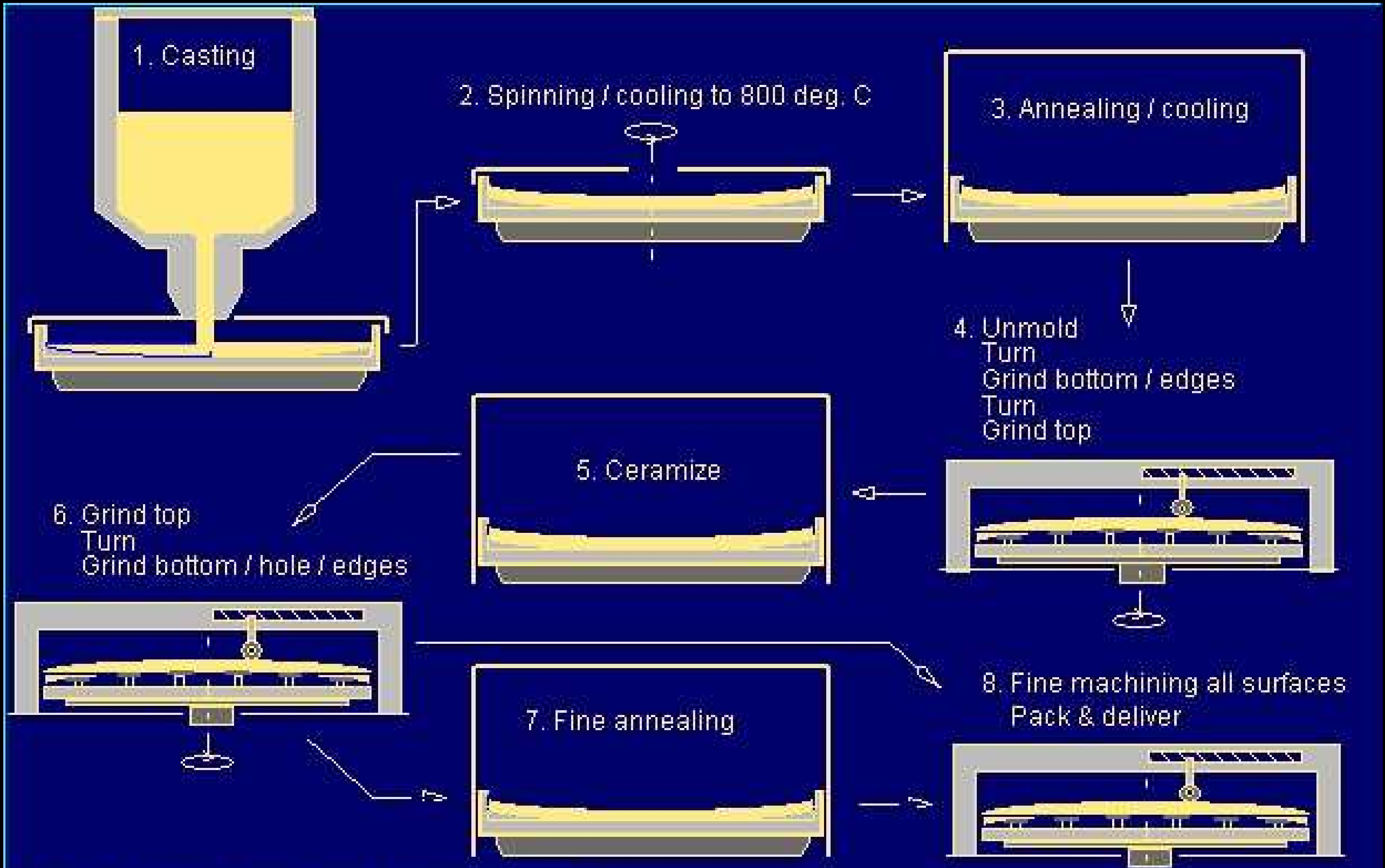
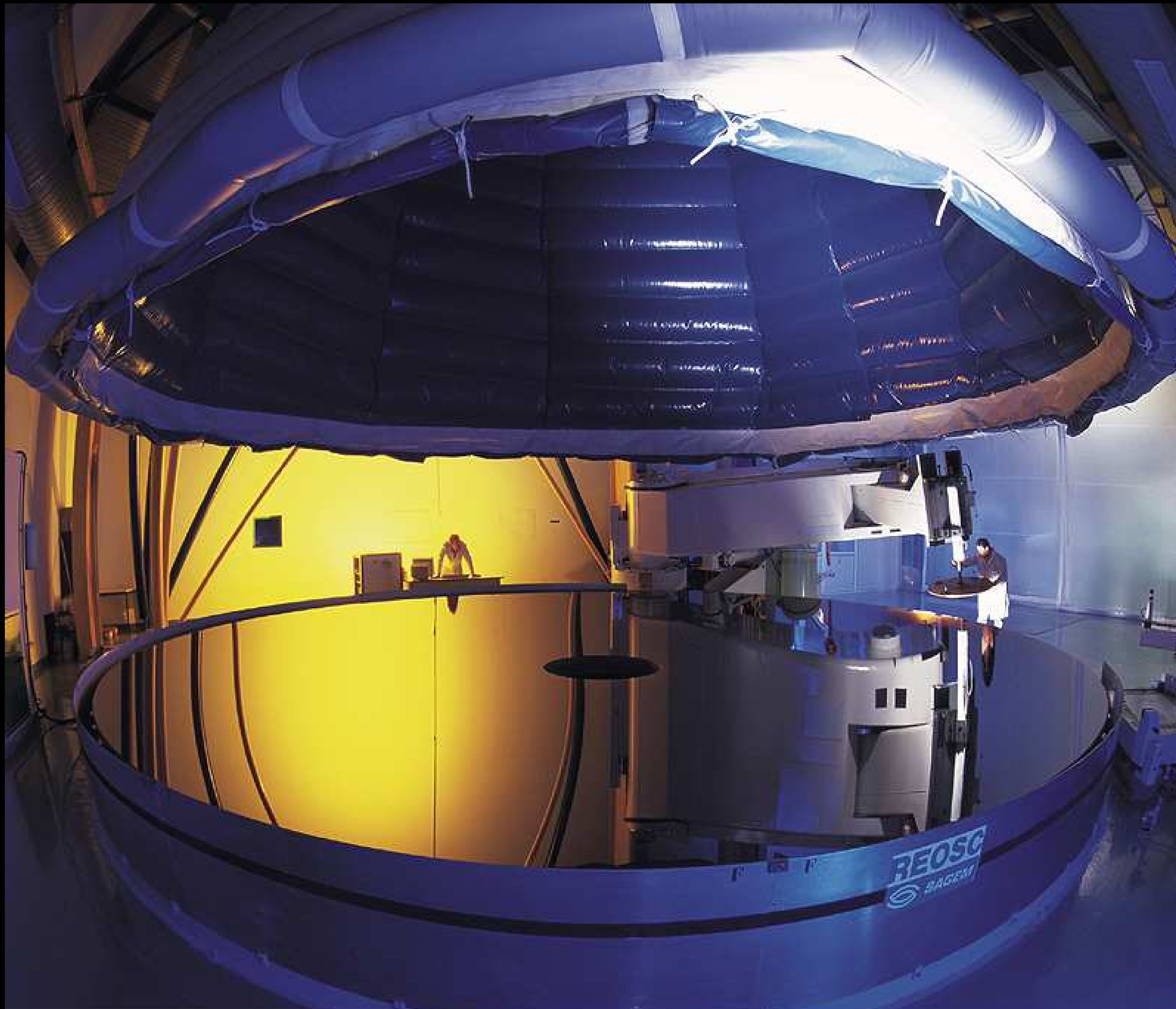


Figure 3. Mirror blanks manufacturing process

ESO

ESO



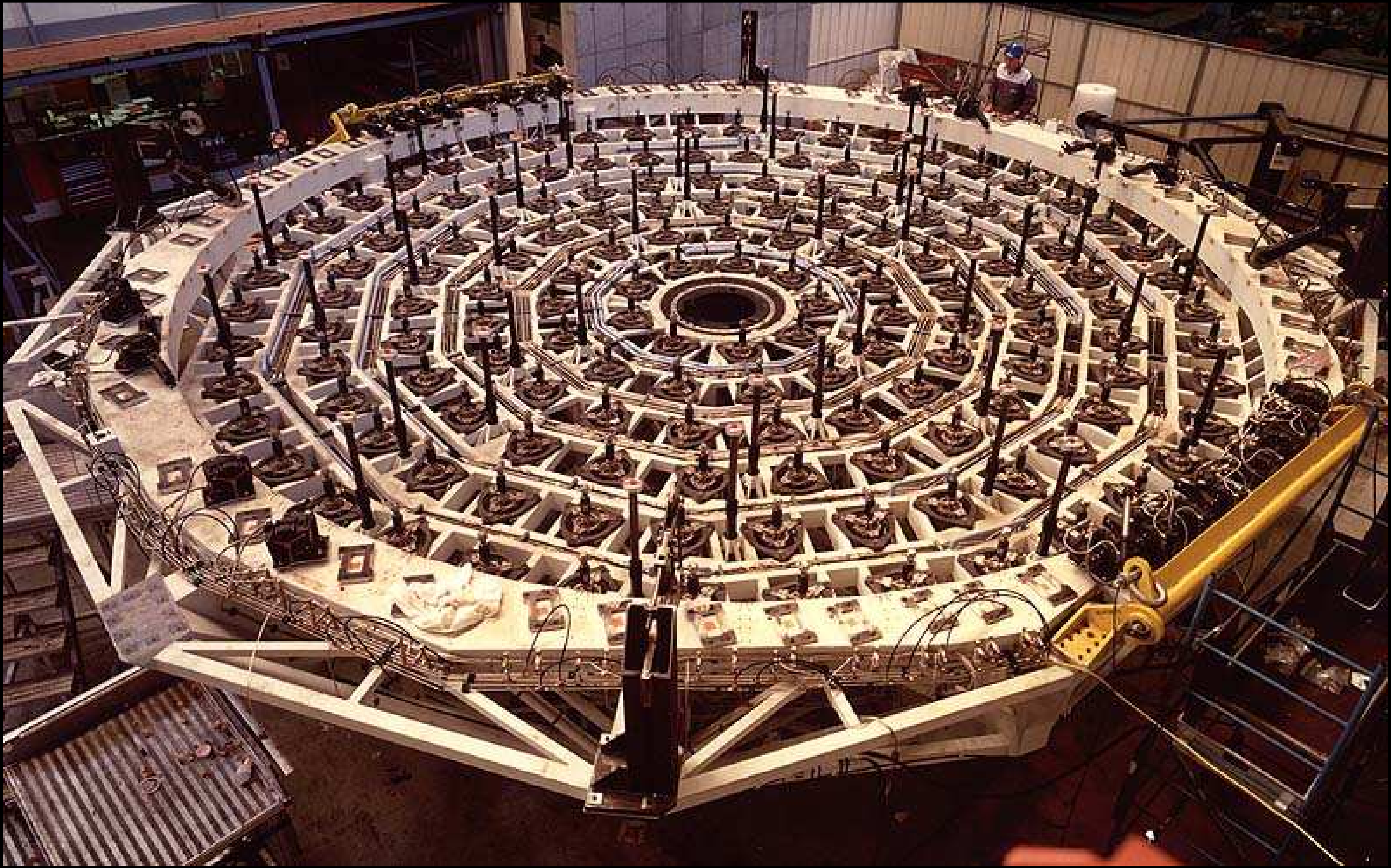
The Polished Fourth VLT 8.2-m Mirror at REOSC

Photo: SAGEM

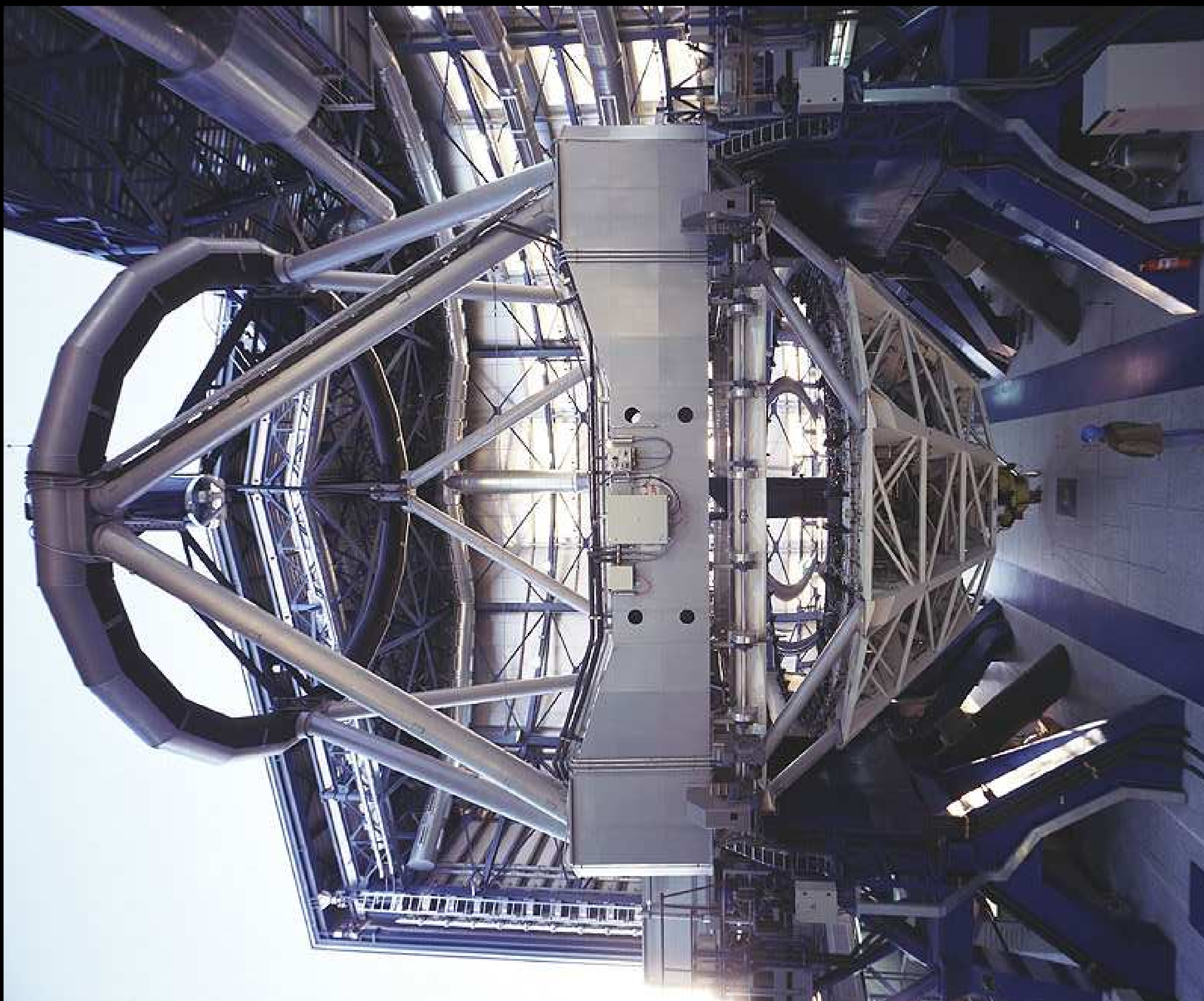
ESO PR Photo 44/99 (14 December 1999)

European Southern Observatory


REOSC



Mirror cell supporting the mirror, actuators keep mirror in shape ("adaptive optics", correcting all possible deformations of the mirror).



VLT at Paranal

ESO PR Photo 43a/99 (8 December 1999)

Active Optics, I

From Eq. (8.8), the resolution of a telescope of diameter d is

$$\alpha = \frac{1.220\lambda}{d} = \frac{12''}{D/1\,\mathrm{cm}} \tag{8.8}$$

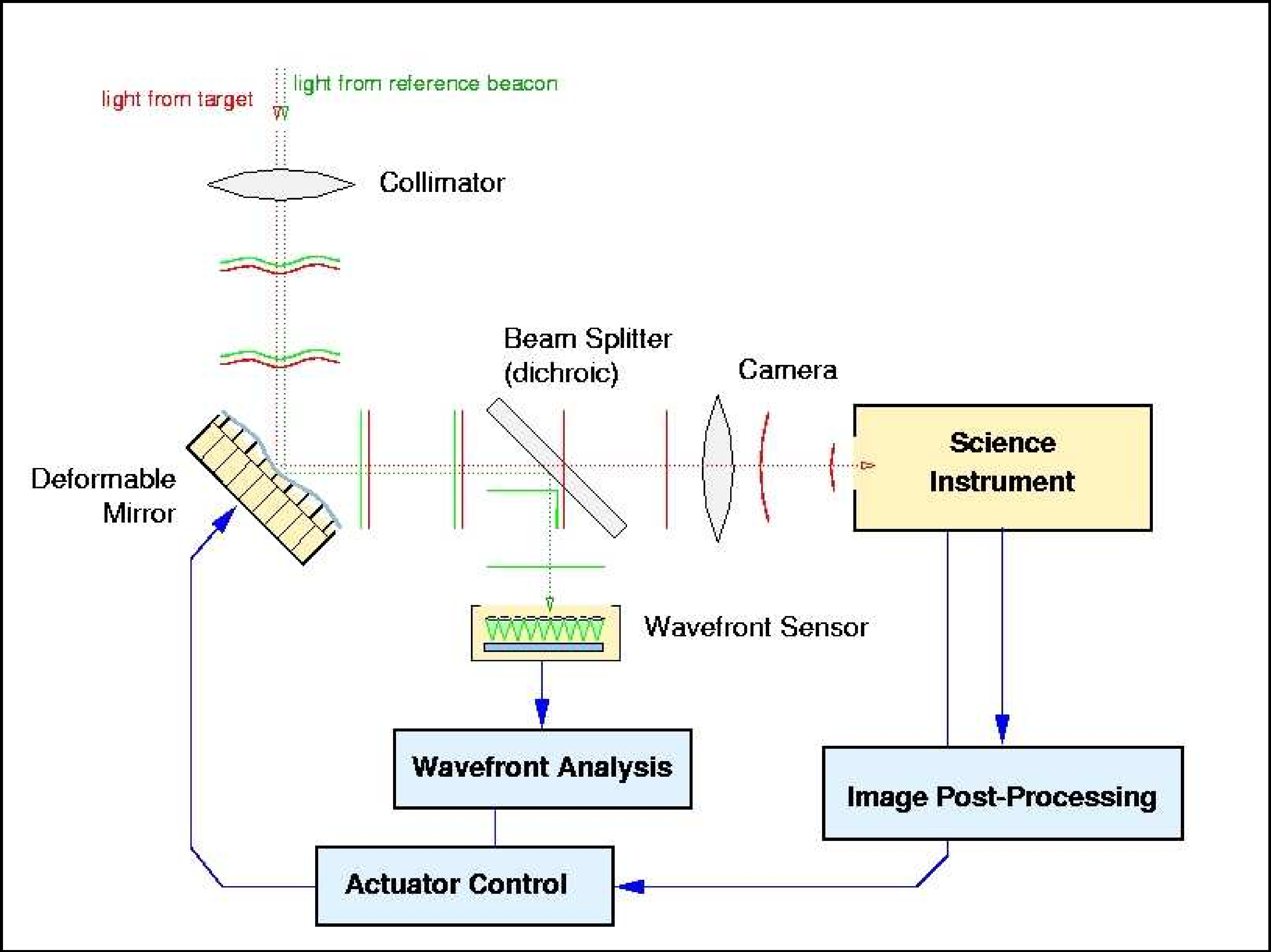
Problem: astronomical seeing

$\Longrightarrow$ turbulence in atmosphere smears pictures of stars to disks with $\theta \gtrsim 0.3''$

$\Longrightarrow$ Increasing telescope diameter to $\gtrsim$40 cm does *not* result in increase in resolution!

Solution to seeing problem: adaptive optics

. . . which only works in the IR so far, need to go to space for optical and UV



Scheme of an adaptive optics system (Lick observatory)

The AO system of Mt. Hopkins observatory, a 30 W laser (ⓒG. Furesz).

The AO system of Mt. Hopkins observatory, a 30 W laser (ⒸG. Furesz).

Active Optics, V

Gemini North/AURA

Picture of the galactic centre in the IR taken with the Gemini North

Active Optics, VI

Gemini North/AURA

Picture of the galactic centre in the IR taken with the Gemini North

. . . and corrected with adaptive optics

$\Longrightarrow$ Resolution: diffraction limited!

$$\theta = 1.22\,\mathrm{rad} \cdot \lambda/d \sim 70\,\mathrm{mas} \quad (8.9)$$

(for $d = 8\,\mathrm{m}$, $\lambda = 2.2\,\mu\mathrm{m}$)

Extrasolar Planets