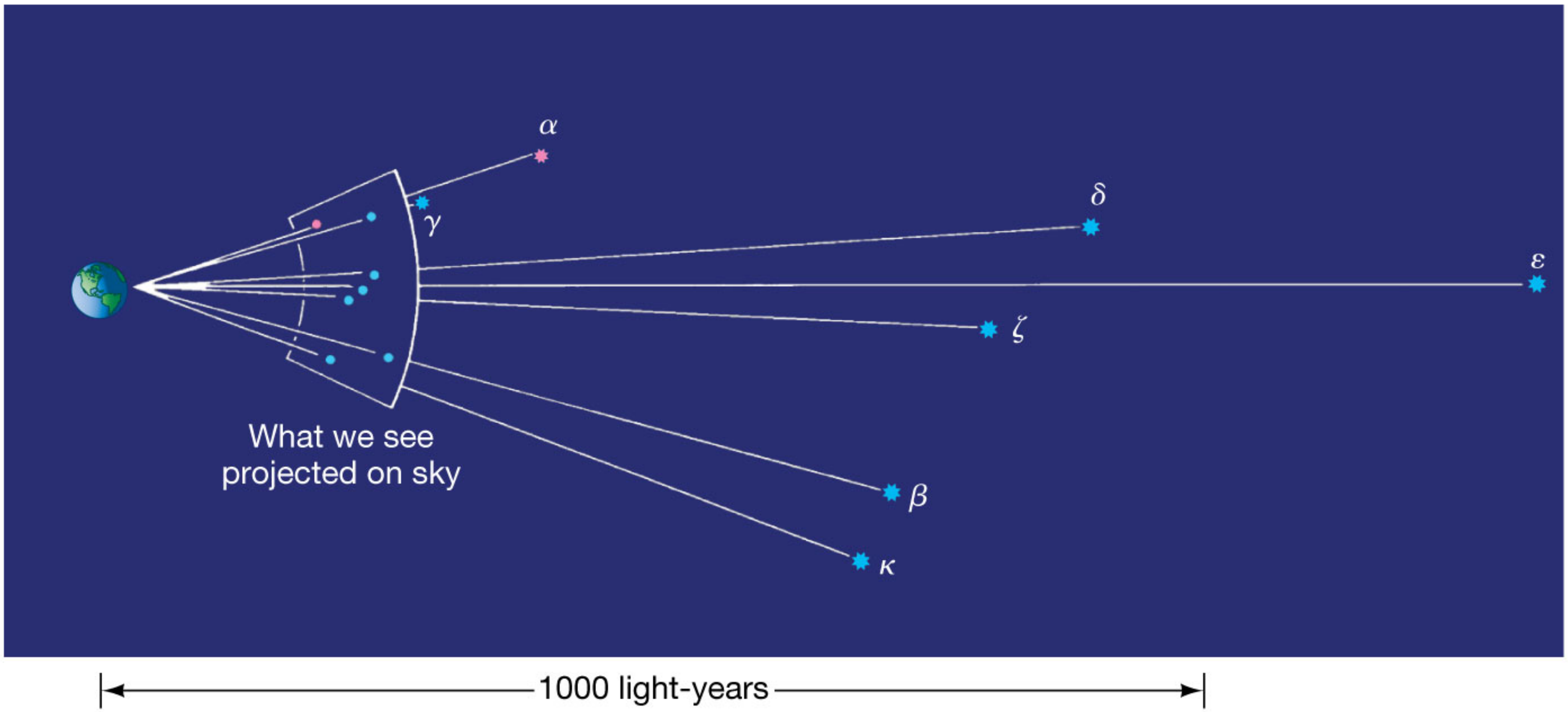
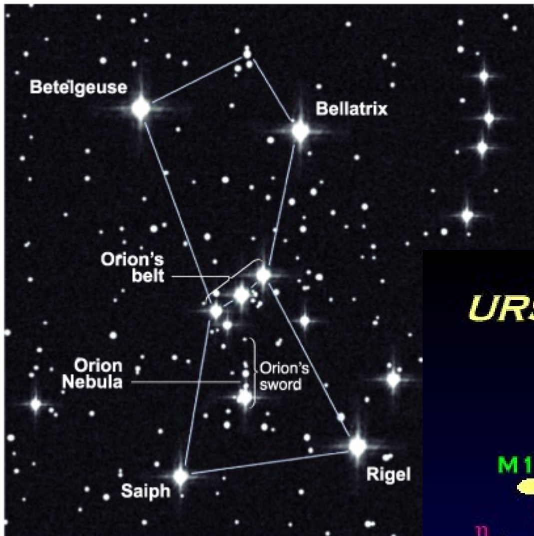
The sky and how we observe it.

See C&M Chap. 1 & 5 (plus the magnitude scale in Chap. 17)

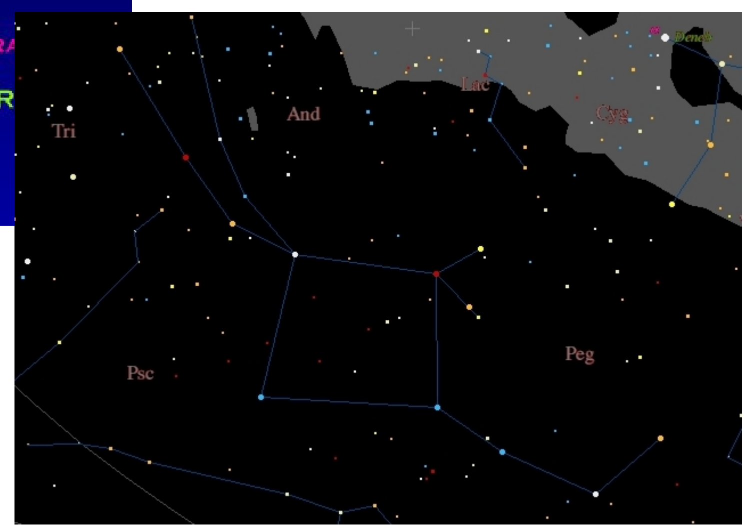
Constellations and asterisms

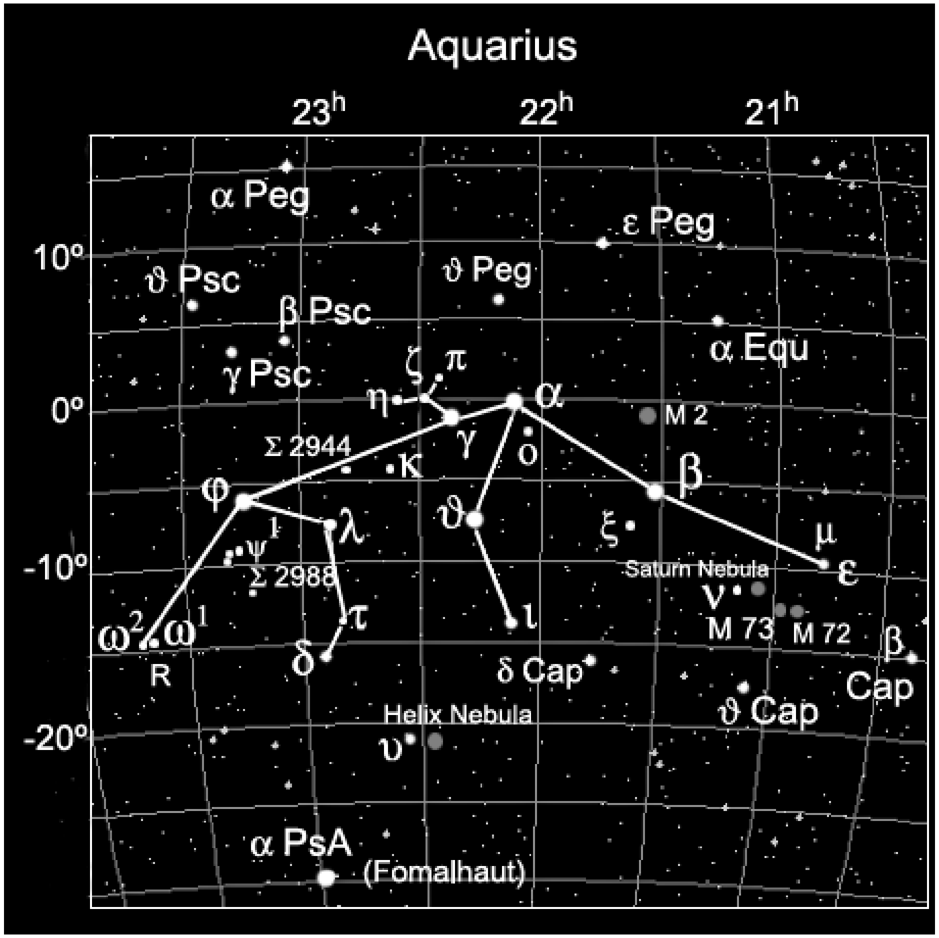
Stars in constellations are not necessarily associated with one another, as shown in this 3D view of Orion.




Betelgeuse
Bellatrix
Orion's belt
Orion Nebula
Orion's sword
Saiph
Rigel


URSA MAJOR
CAMELOPARDALIS
DRACO
M82
M81
M101
80
ALCOR
ALKAID
MIZAR
ALIOTH
MEGREZ
DUBHE
MERAK
M97
NÉBULEUSE PLANÉTAIRE DU HIBOU
PHECDA
TALITHA
CANES VENATICI
TANIA BOREALIS
TANIA AUSTRA
ALULA BOREALIS
ALULA AUSTRALIS
LEO MINOR


Tri
And
Lac
Cyg
Psc
Peg

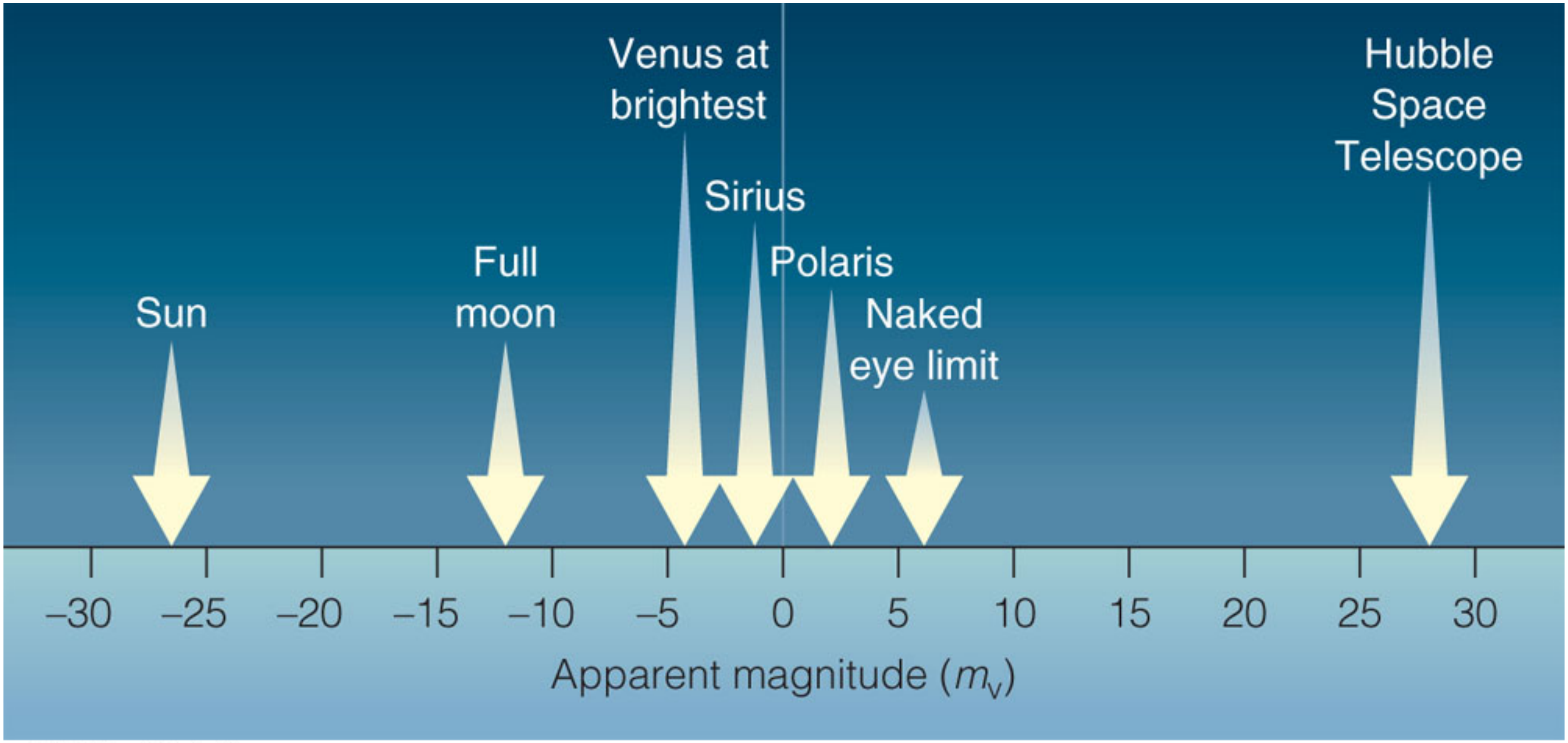


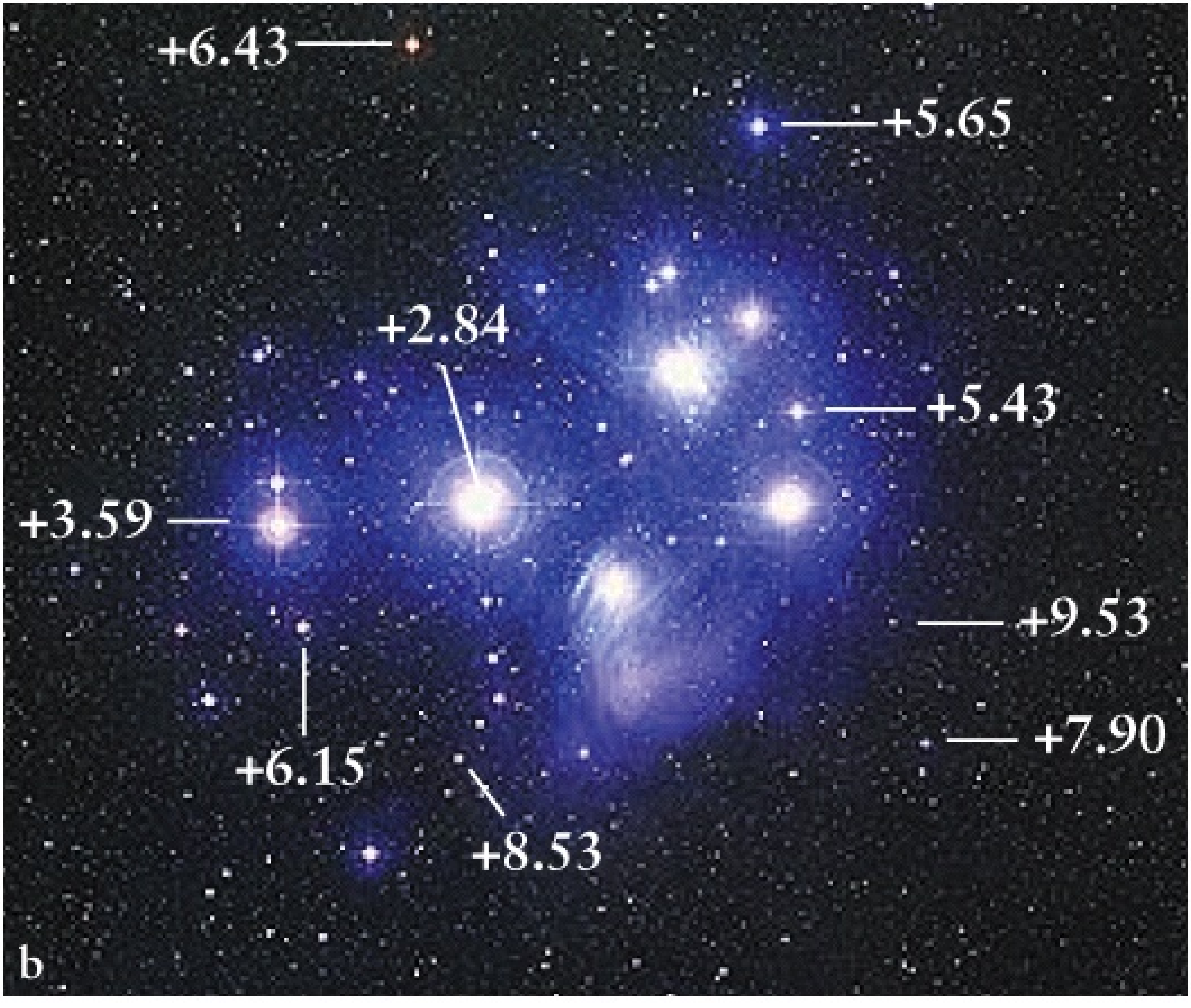
α β γ δ ε ζ

η θ ι κ λ μ

ν ξ ο π ρ σ

τ υ ϕ χ φ ω


Venus at brightest
Hubble Space Telescope
Sirius
Full moon
Polaris
Sun
Naked eye limit
–30 –25 –20 –15 –10 –5 0 5 10 15 20 25 30
Apparent magnitude (m_V)


+6.43
+5.65
+2.84
+5.43
+3.59
+9.53
+7.90
+6.15
+8.53
b

Magnitudes follow of a system of powers based on the value of 2.512 (rounded to 2.5 here for convenience).

Magnitude difference	brightness ratio
1	2.5
2	2.5 x 2.5=6.3
3	2.5 x 2.5 x 2.5 = 16

$$m_1 - m_2 = -2.5 \log_{10} (f_1/f_2)$$

$$f_1/f_2 = 10^{-0.4(m1 - m2)}$$

Example: how many times fainter can Hubble see than the naked eye limit?

$f_1/f_2 = 10^{-0.4(m1 - m2)}$

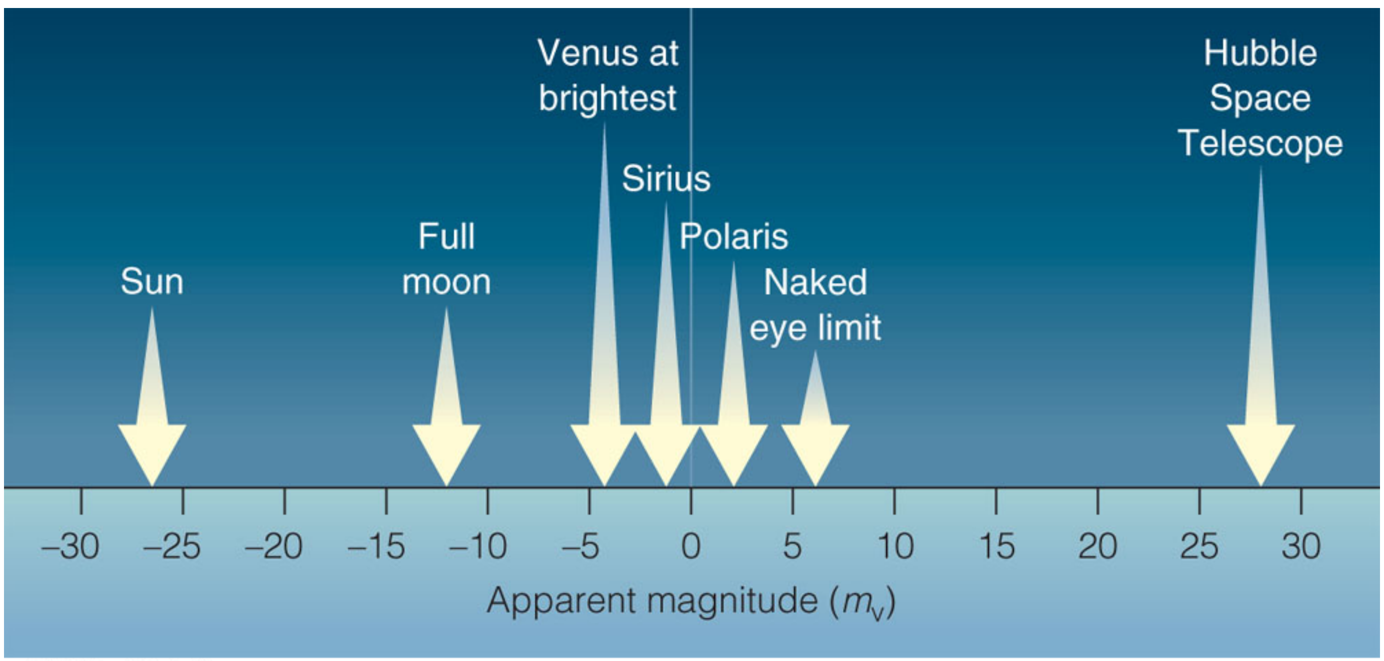
$= 10^{-0.4(6 - 28)}$

$= 6.3 \times 10^8$

= 630 million

Or: $2.512^{(28-6)}$

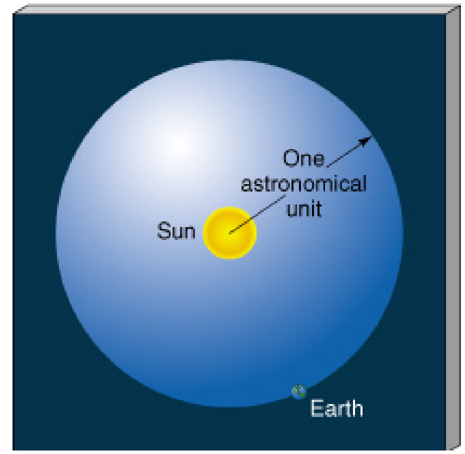
$= 6.3 \times 10^8$

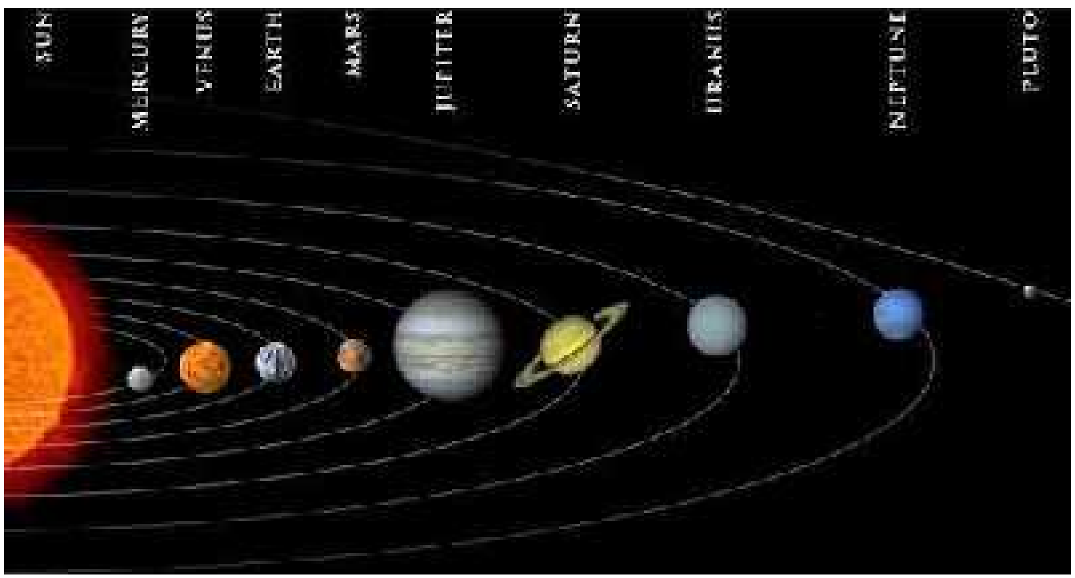


Aside: Some distance measures

An astronomical unit (AU) is the **average** distance between the earth and the sun.

1 AU = 1.5 x 10^{8} km (150 million km)





Question: if Jupiter is 5 times more distant from the sun than the earth, what is the distance between the sun and Jupiter?

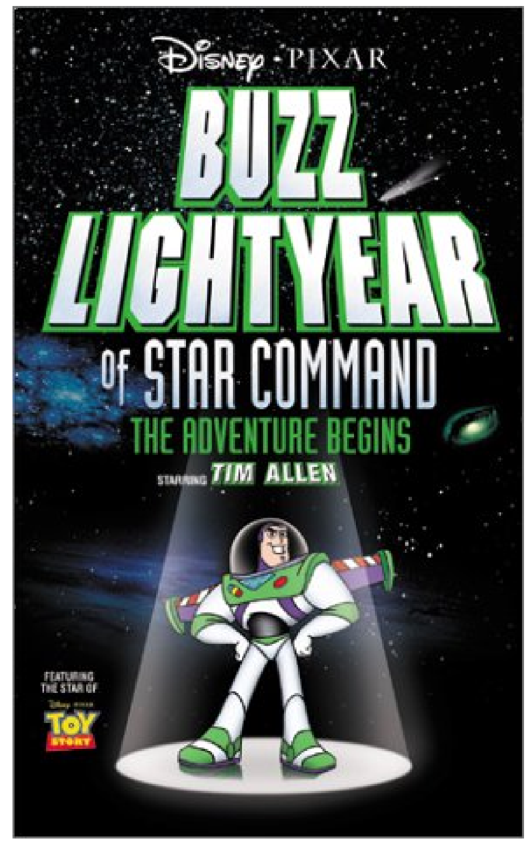
AU are convenient for the solar system, but what about distances to other stars?

The nearest star to the sun is Proxima Centauri at 4×10^{13} km (40 million, million km) away. How many AU is that?

$1 \text{ AU} = 1.5 \times 10^8$ km

$4 \times 10^{13} / 1.5 \times 10^8 = 2.7 \times 10^5$ AU!!

So, for distances to stars we use a different unit: the light year.



Definition: One light year is the distance that light travels in one year. What is a light year in kilometres?

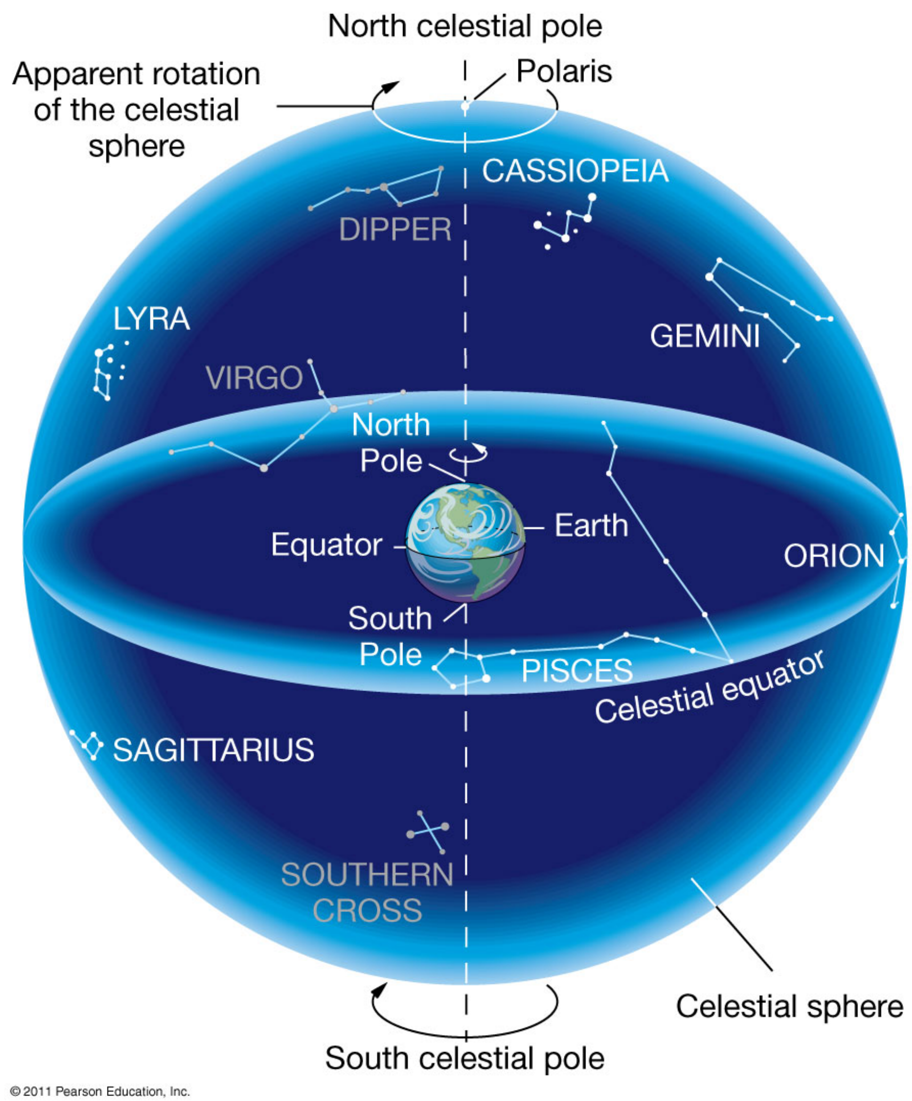
Light travels at 3×10^5 km/s. First we need to calculate how many seconds in a year:
$60 \times 60 \times 24 \times 365 = 3.15 \times 10^7$ seconds.

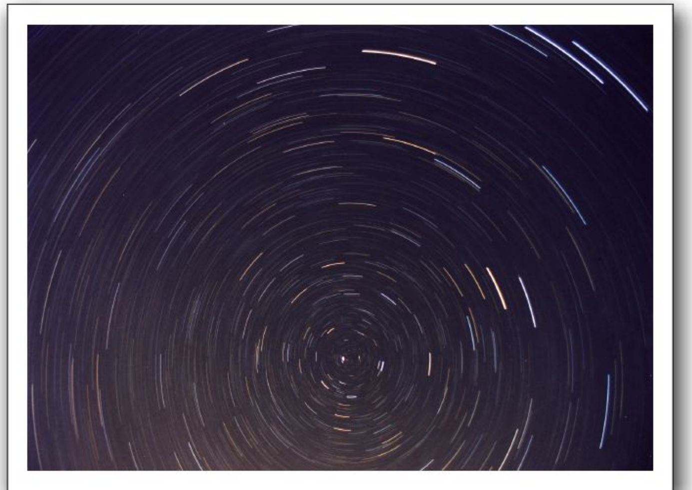
distance= speed x time = $(3\times 10^5) \times (3.15 \times 10^7)$
1 light year = 9.5×10^{12} km

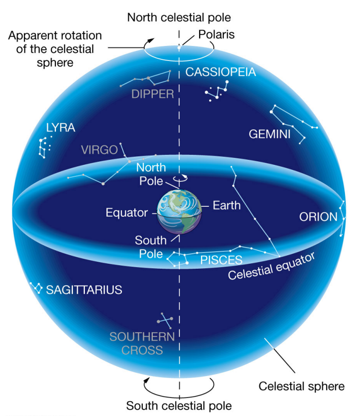
Let's return to Proxima Cen. which is 4×10^{13} km away. How many light years is this?

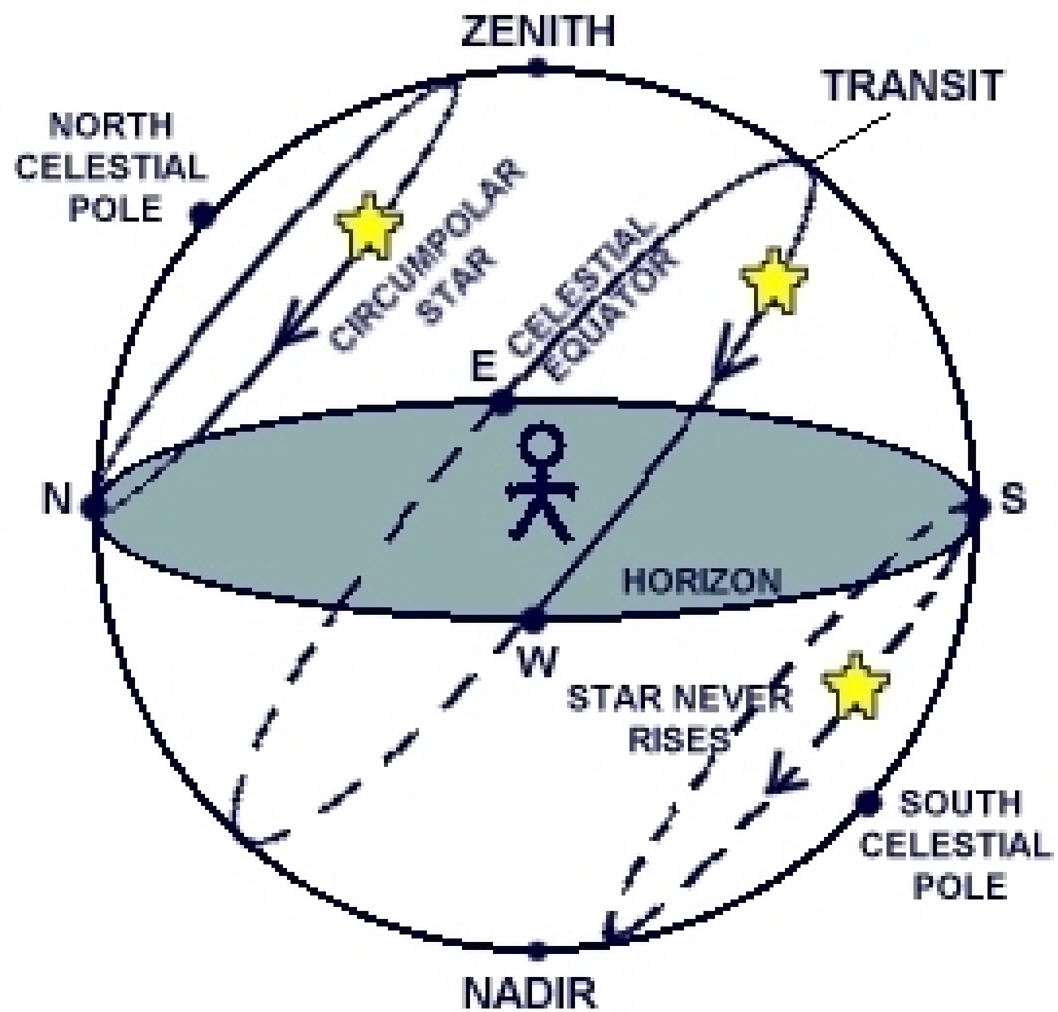
$4 \times 10^{13} / 9.5 \times 10^{12} = 4.2$ light years

The Celestial Sphere

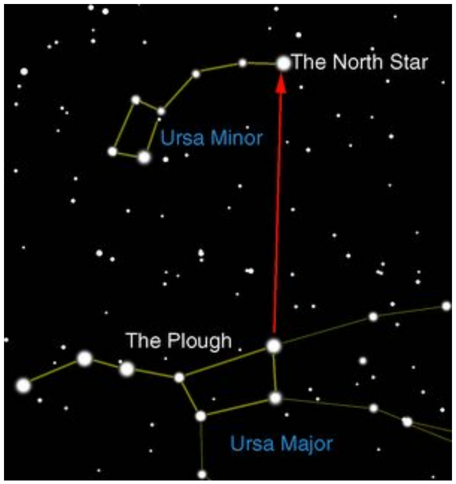


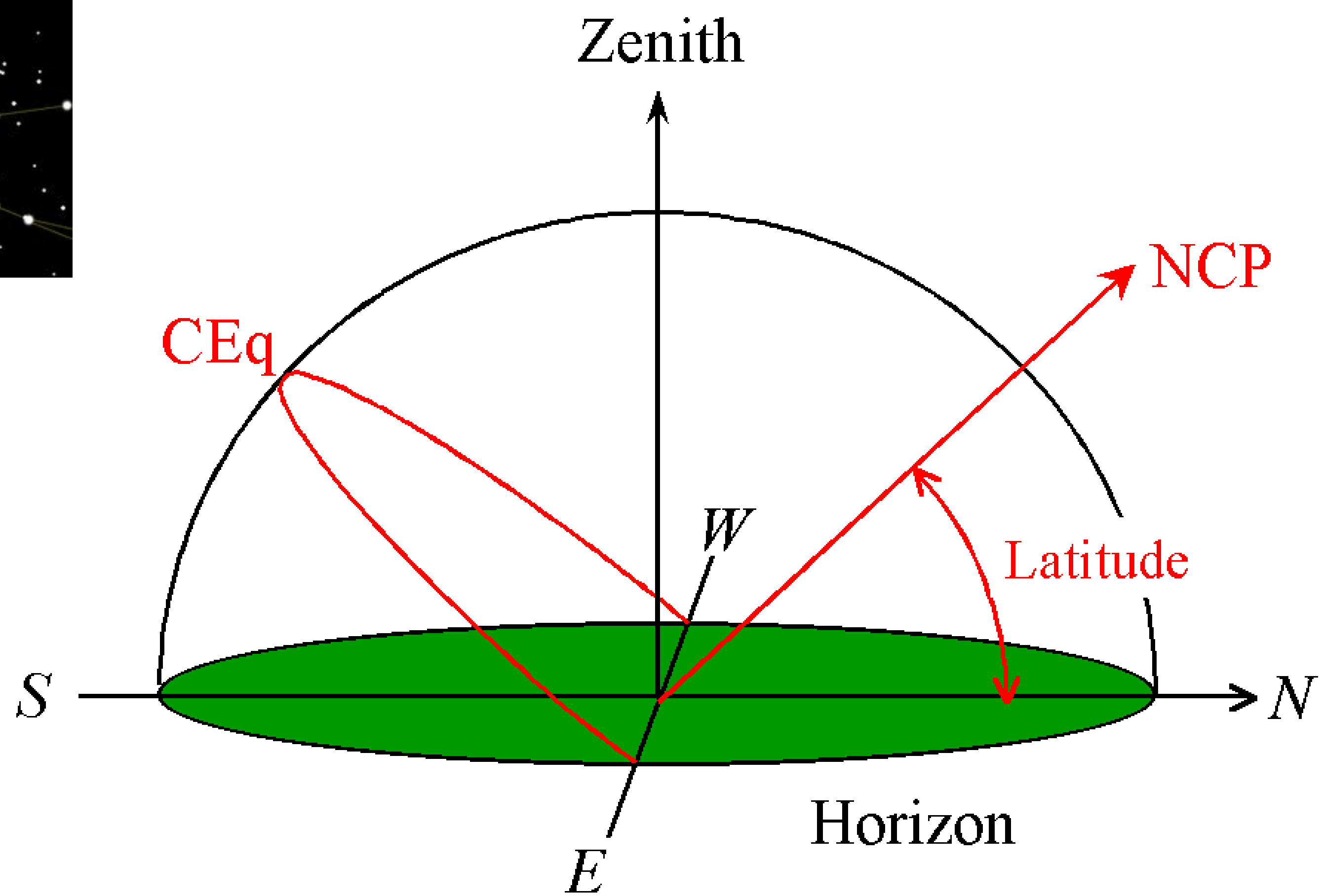


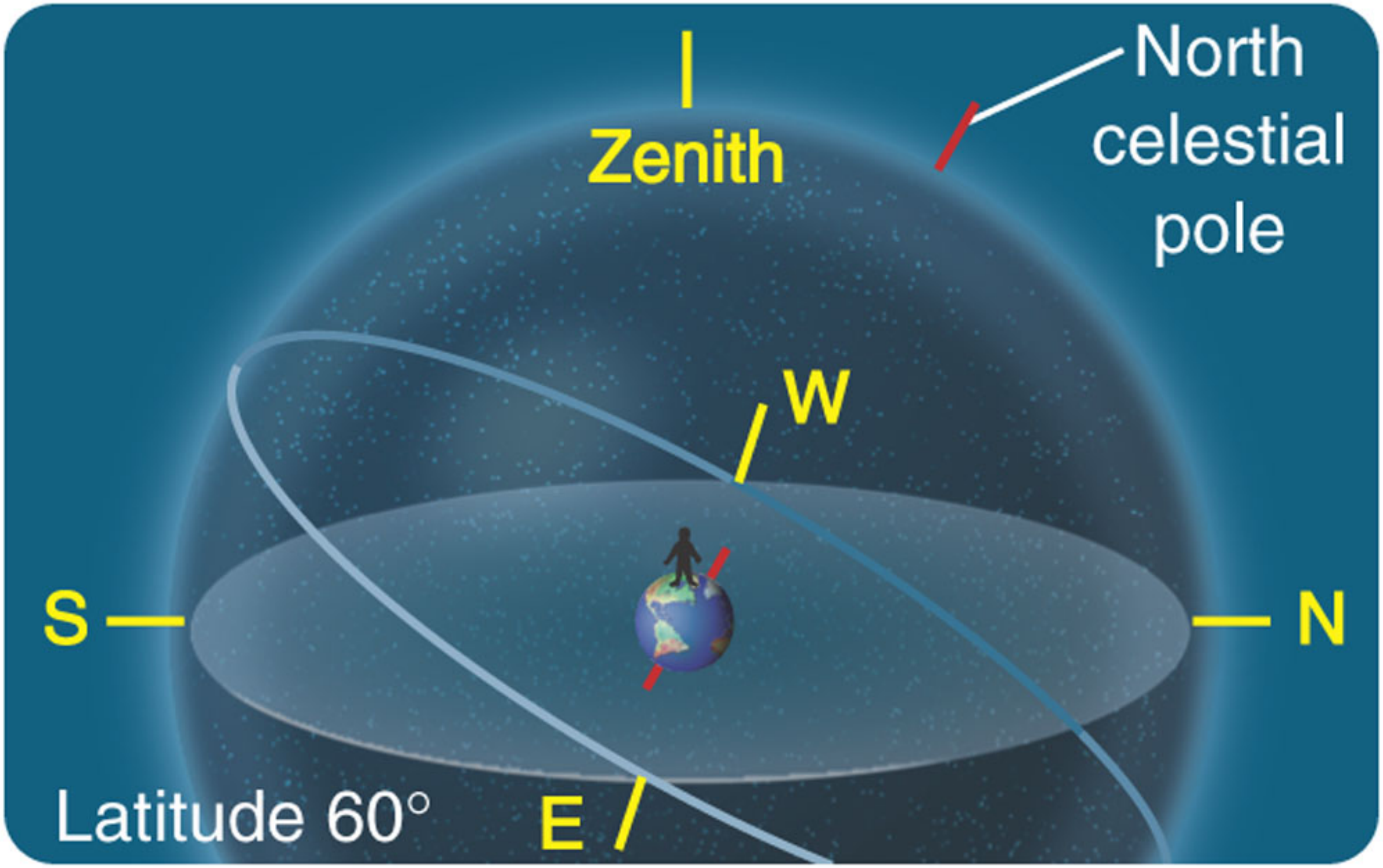

North celestial pole
Apparent rotation of the celestial sphere
Polaris
CASSIOPEIA
DIPPER
LYRA
GEMINI
VIRGO
North Pole
Equator
Earth
ORION
South Pole
PISCES
Celestial equator
SAGITTARIUS
SOUTHERN CROSS
Celestial sphere
South celestial pole

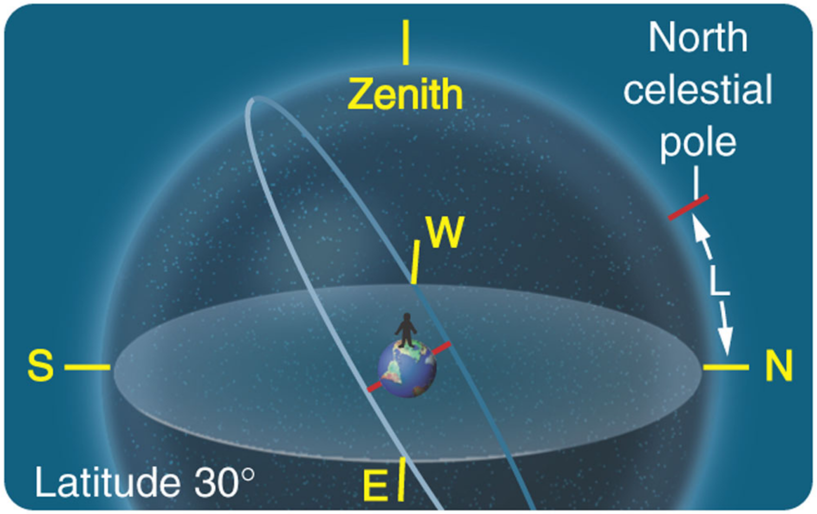

ZENITH
TRANSIT
NORTH CELESTIAL POLE
CIRCUMPOLAR STAR
CELESTIAL EQUATOR
E
N
S
HORIZON
W
STAR NEVER RISES
SOUTH CELESTIAL POLE
NADIR

Angle of elevation of pole star tells us latitude.



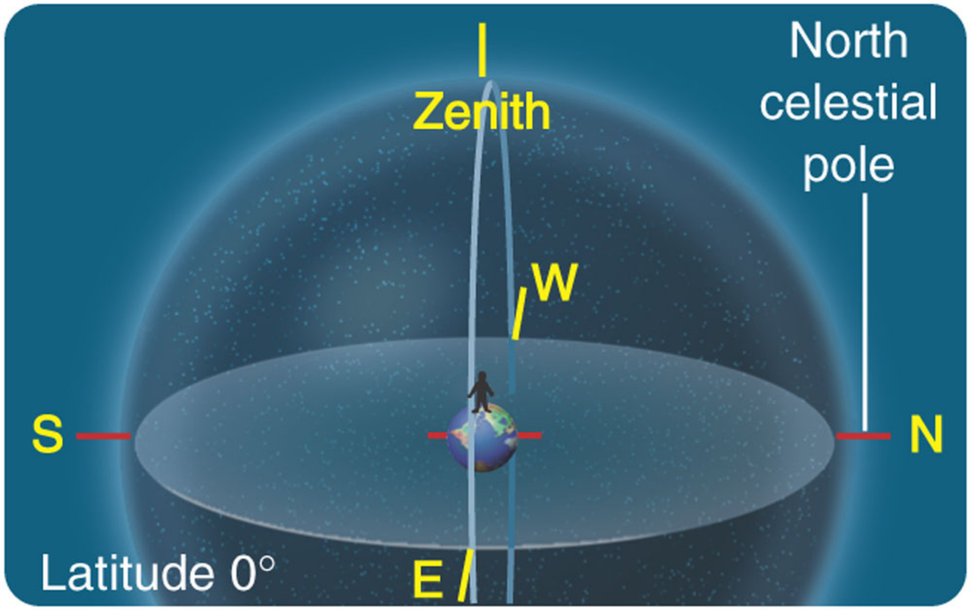



Zenith
North
celestial
pole
W
S
N
E
Latitude 60°

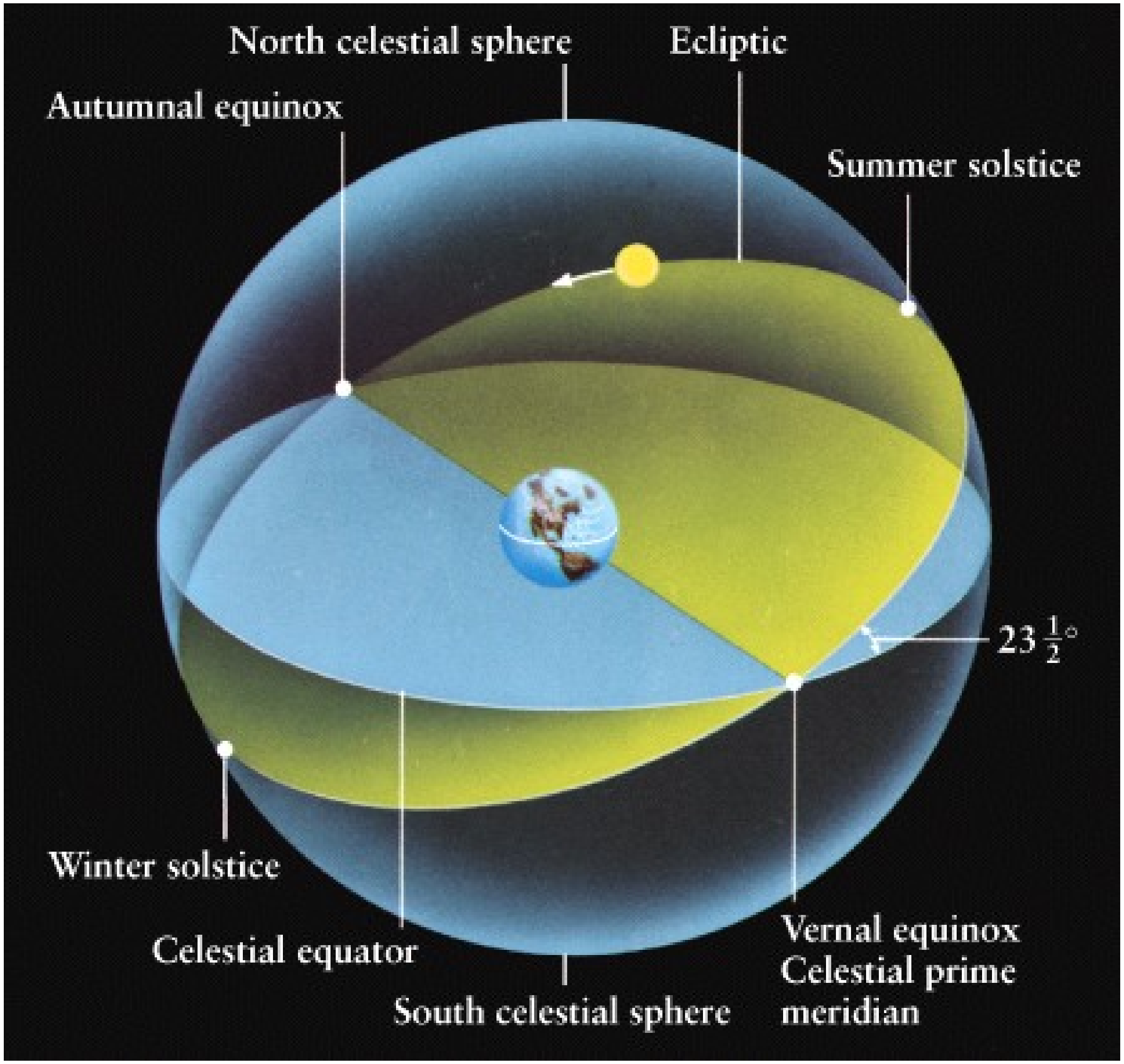


The orbits of stars are drawn as circles that connect east and west (because they rise in the east and set in the west).

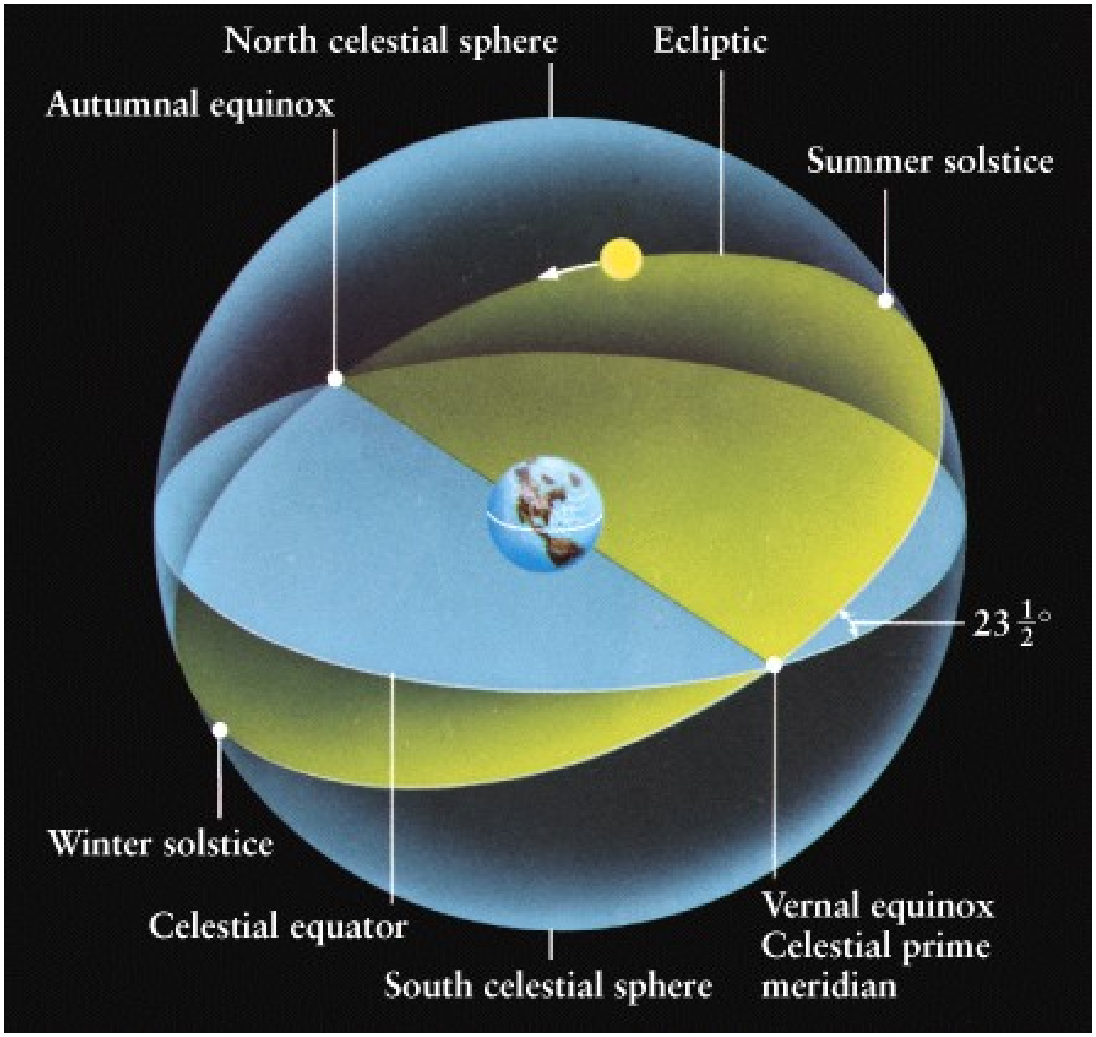
Drawing a horizon diagram helps us understand why no stars appear circumpolar if we are at the equator (latitude 0).



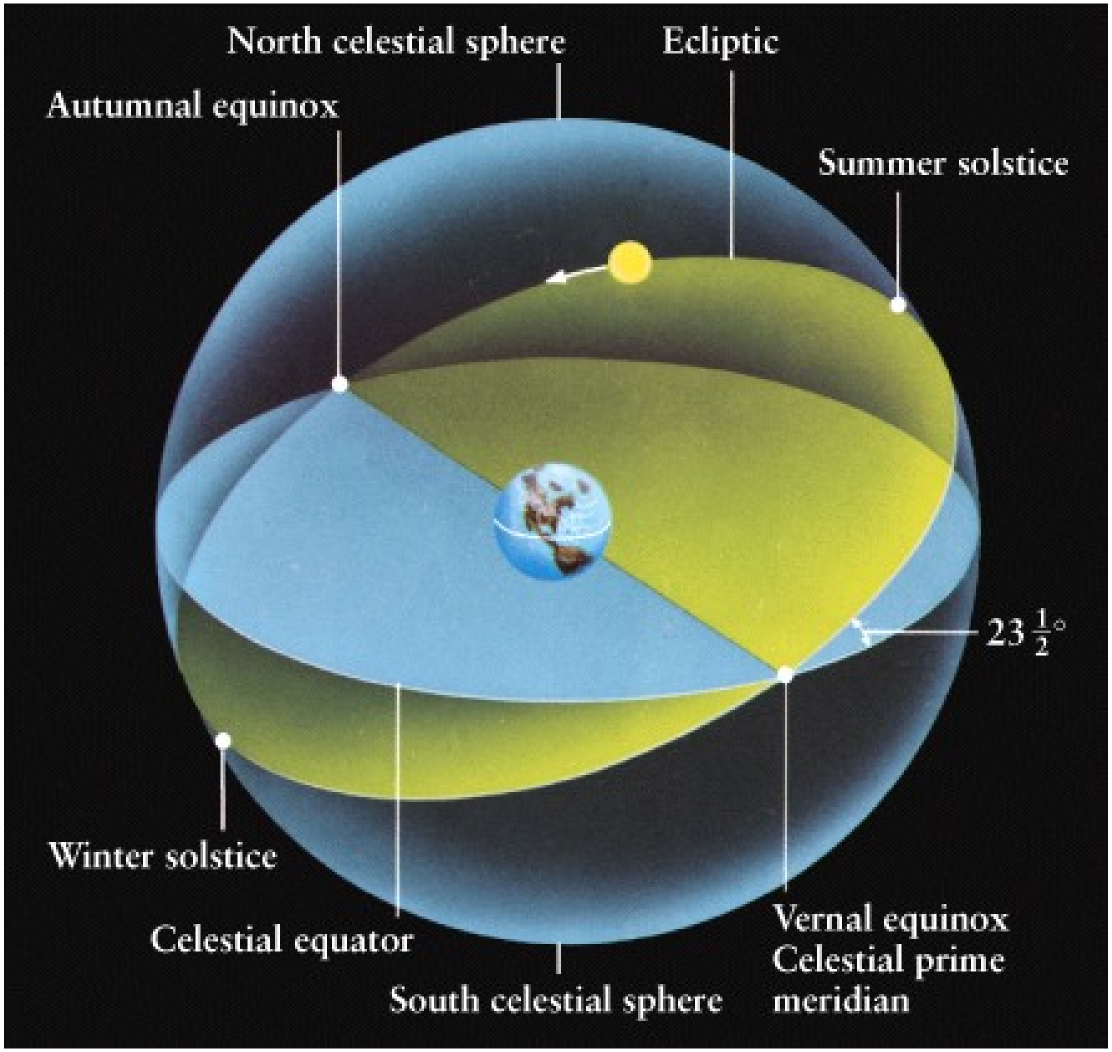
The sun's apparent motion through the sky defines the ecliptic.

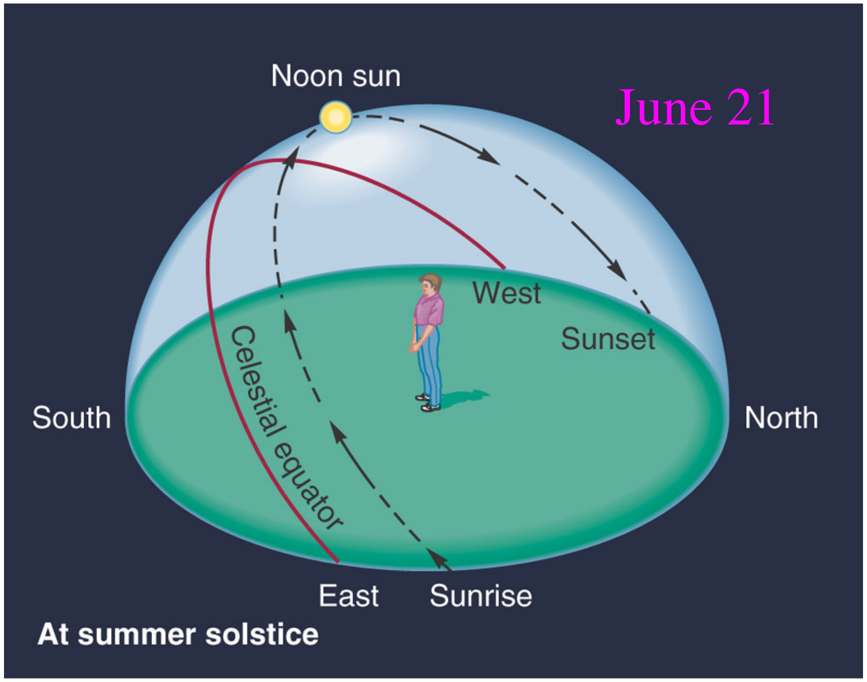


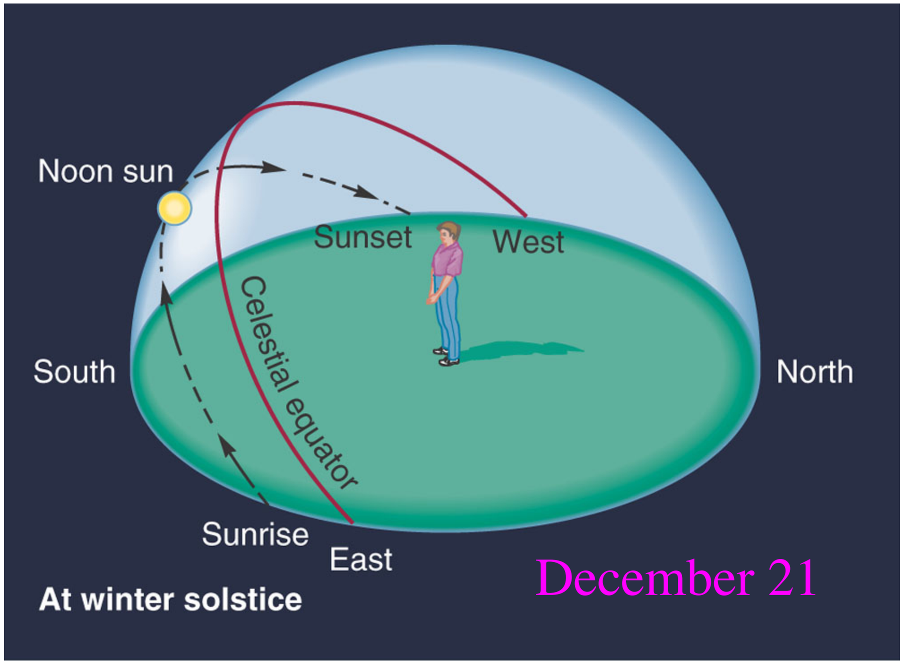
The northernmost point of the ecliptic is called the summer solstice, similarly for the winter solstice in the south.



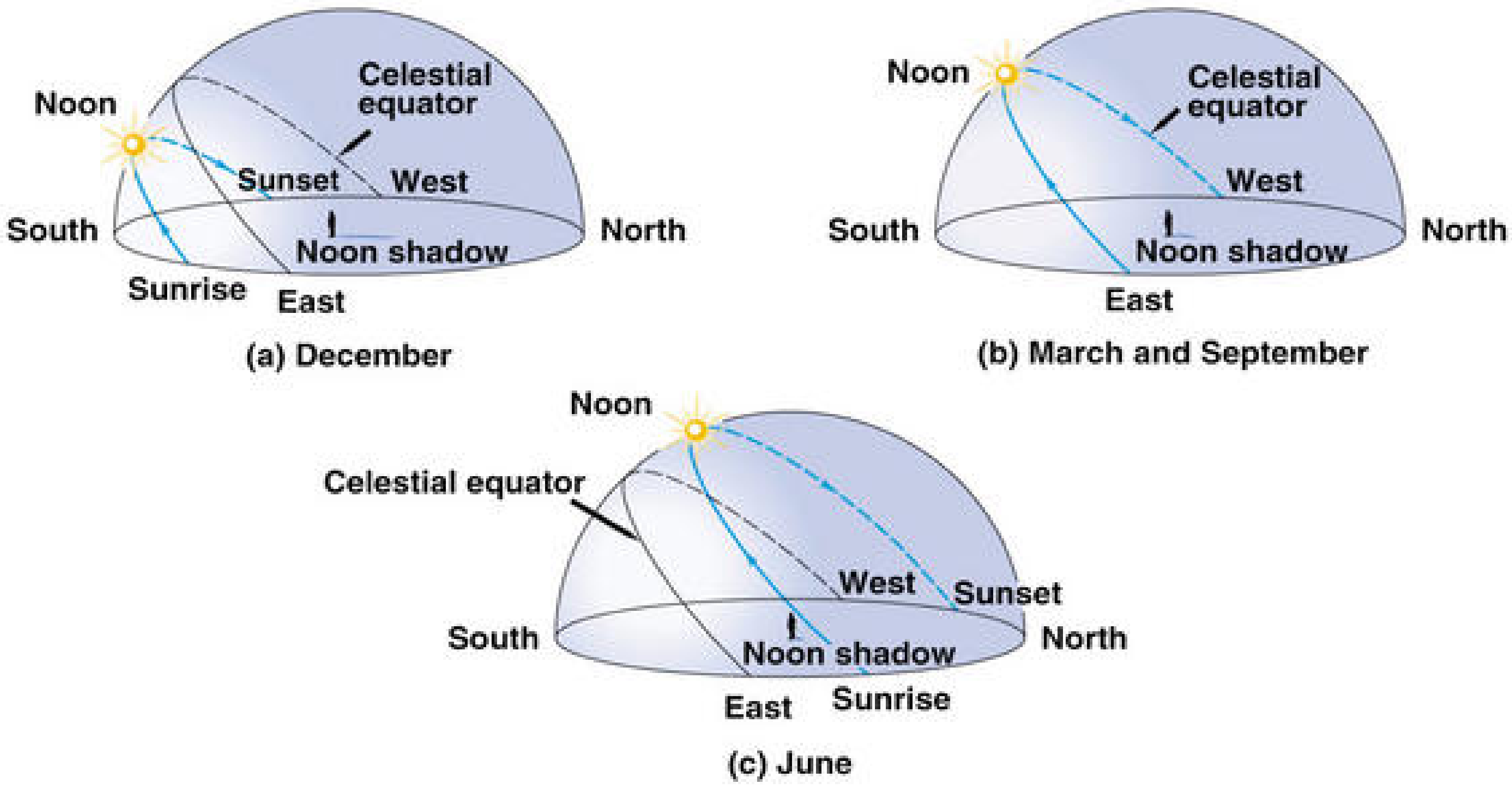
The points on the sky where the celestial equator crosses the ecliptic are called the equinoxes.



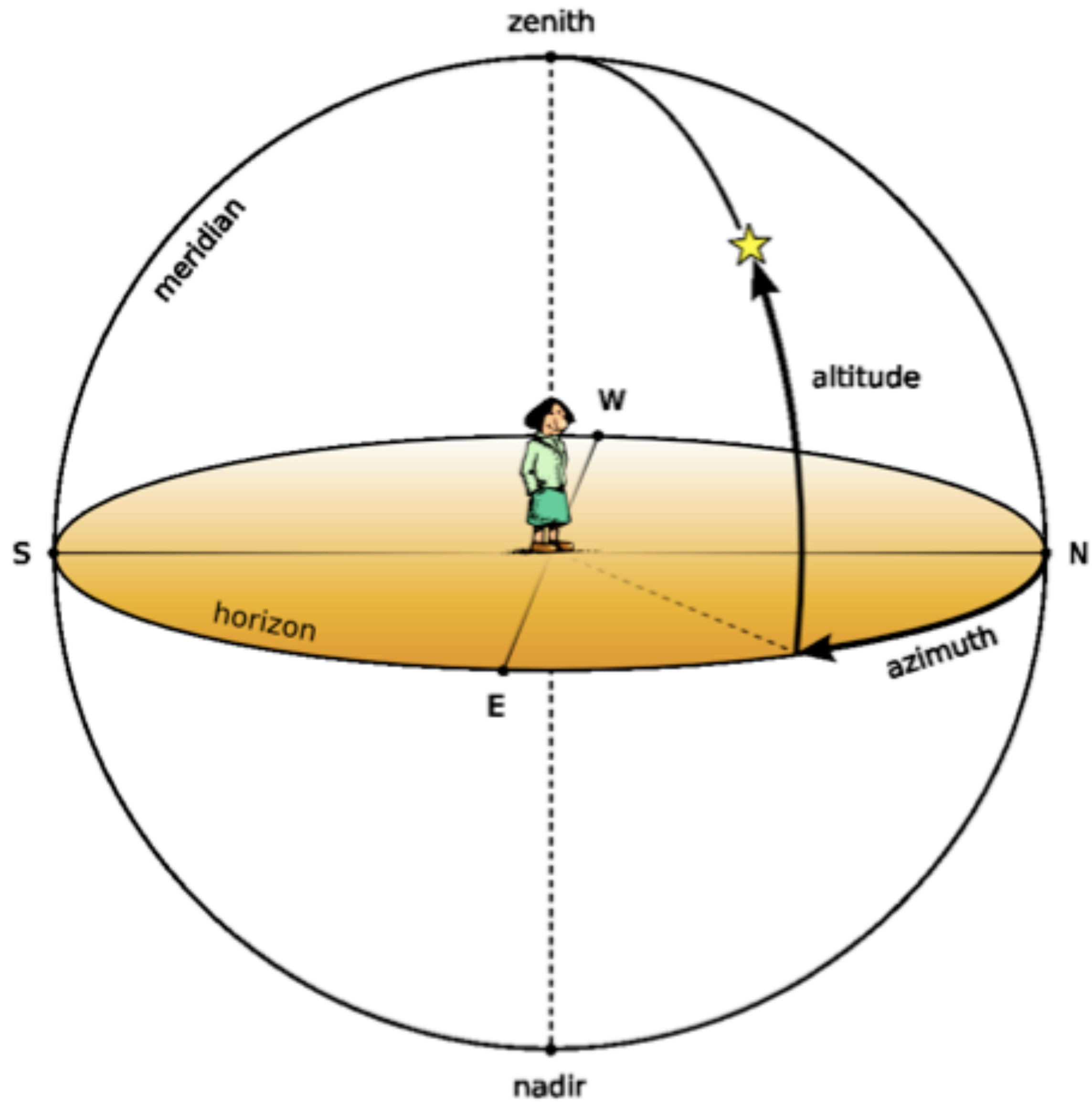

Noon sun
June 21
West
Sunset
South
North
Celestial equator
East
Sunrise
At summer solstice


Noon sun
Sunset
West
South
North
Celestial equator
Sunrise
East
December 21
At winter solstice

Equinoxes:


Noon
Celestial
equator
Sunset
West
South
North
Noon shadow
Sunrise
East
(a) December
Noon
Celestial
equator
West
South
North
Noon shadow
East
(b) March and September
Noon
Celestial equator
West
Sunset
South
North
Noon shadow
East
Sunrise
(c) June

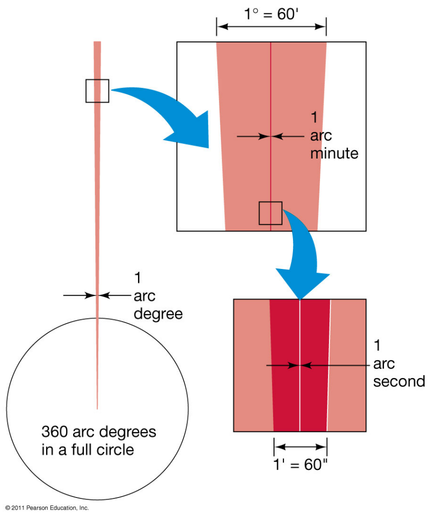
Altitude and azimuth:



Math detour - angles!

Degrees (º), minutes (′) and seconds (″) of arc.

- 60 ″ = 1 ′, 60 ′ = 1º, 360 º = full circle
- 60 arcsec = 1 arcmin, 60 arcmin = 1 deg.
- 3600 arcsec = 1 deg.



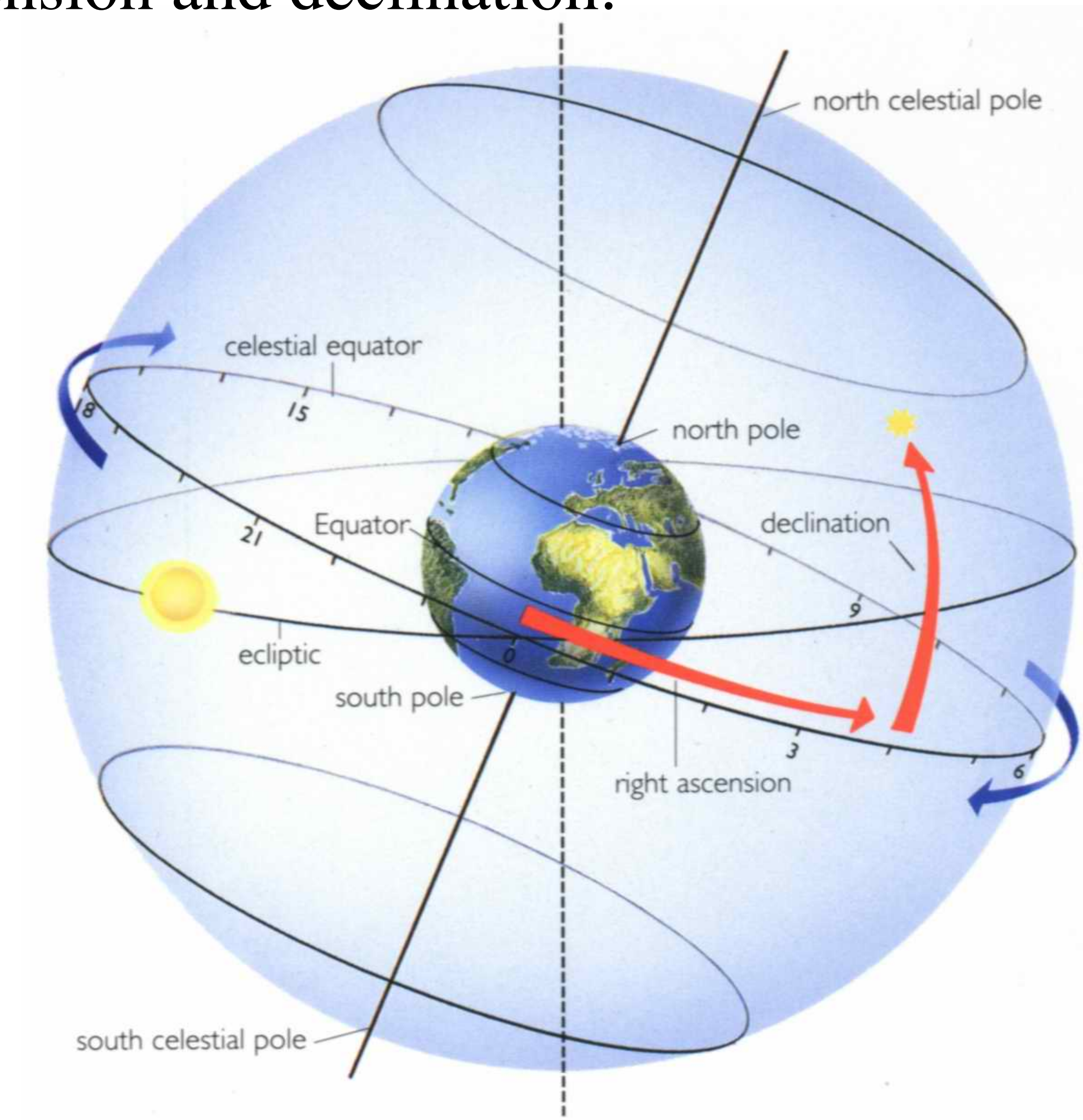
Hours (h), minutes (m) and seconds (s) of time.

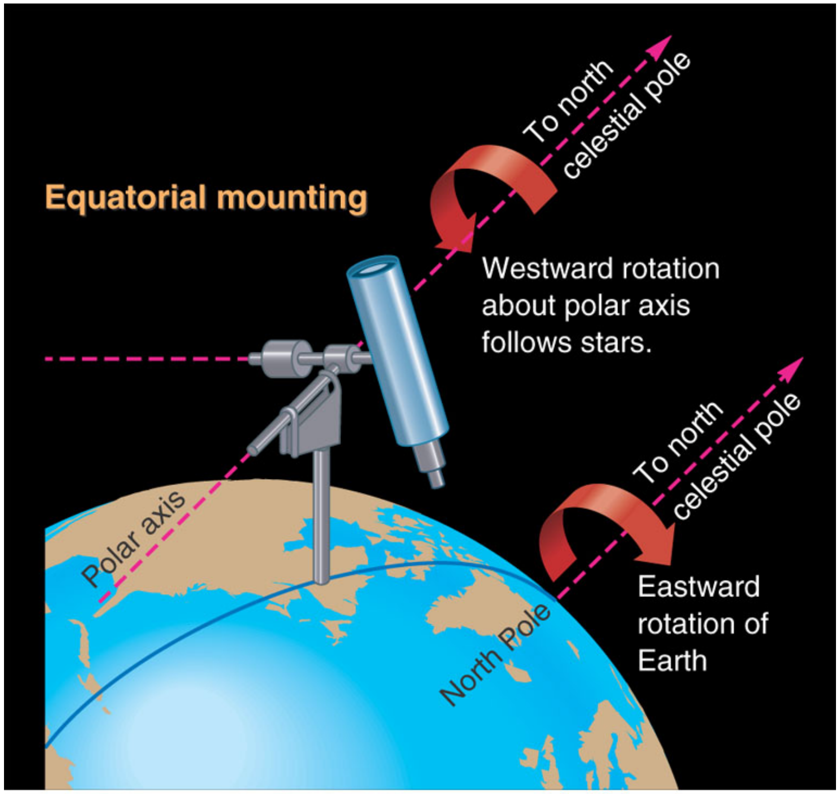
- 60 s = 1 m, 60 m = 1 h, 24 h = full circle
- 1 hour = 15 degrees

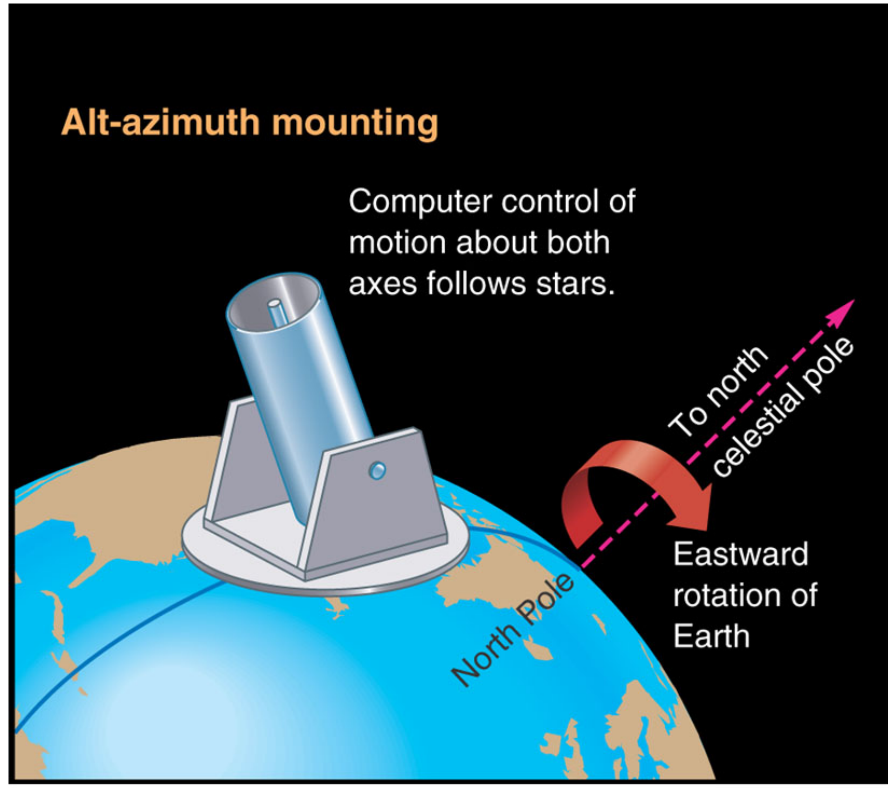
Radians (rad)

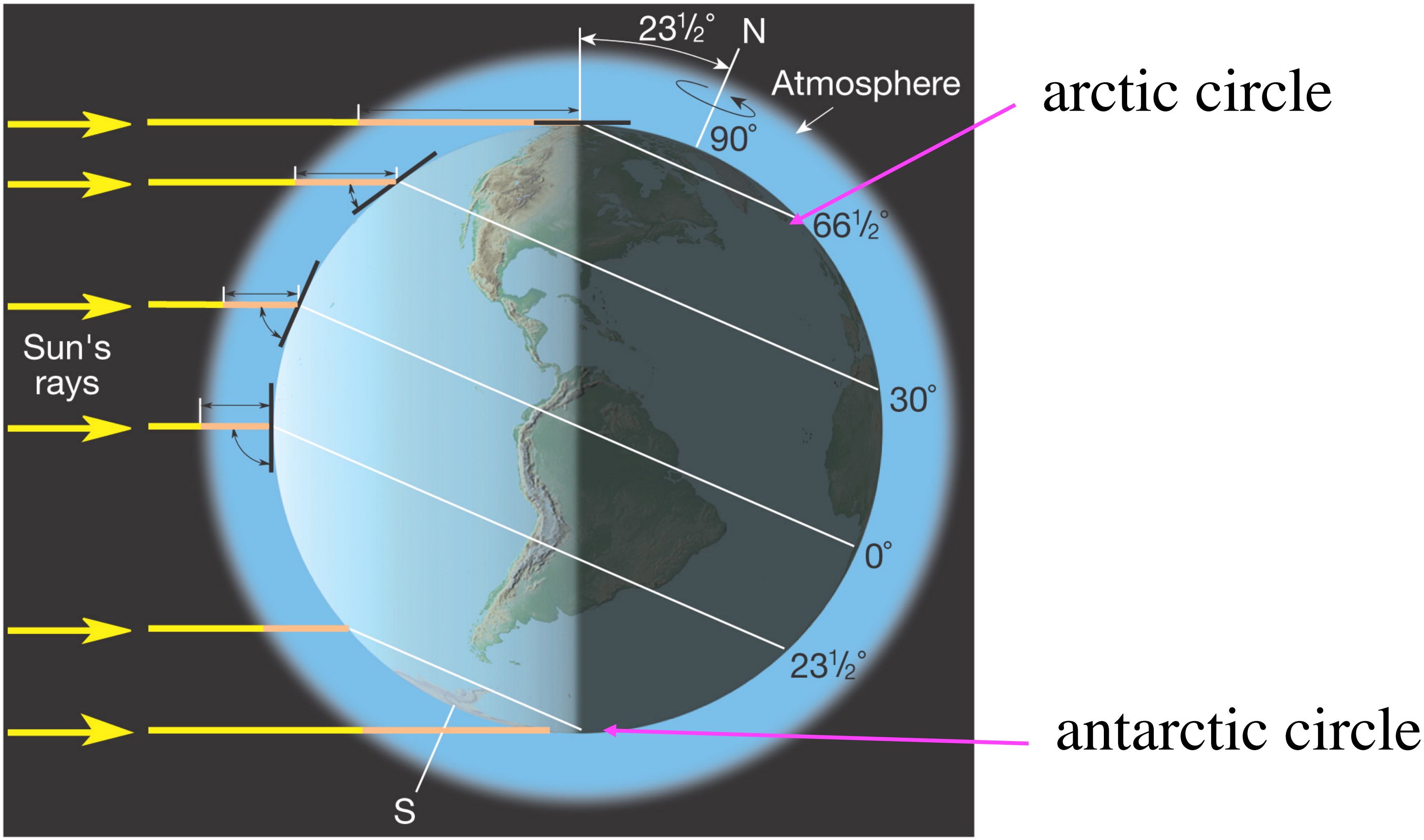
- 2π rad = 360 deg.
- 1 rad = 57.29 deg = 206265 arcsec

Right ascension and declination:

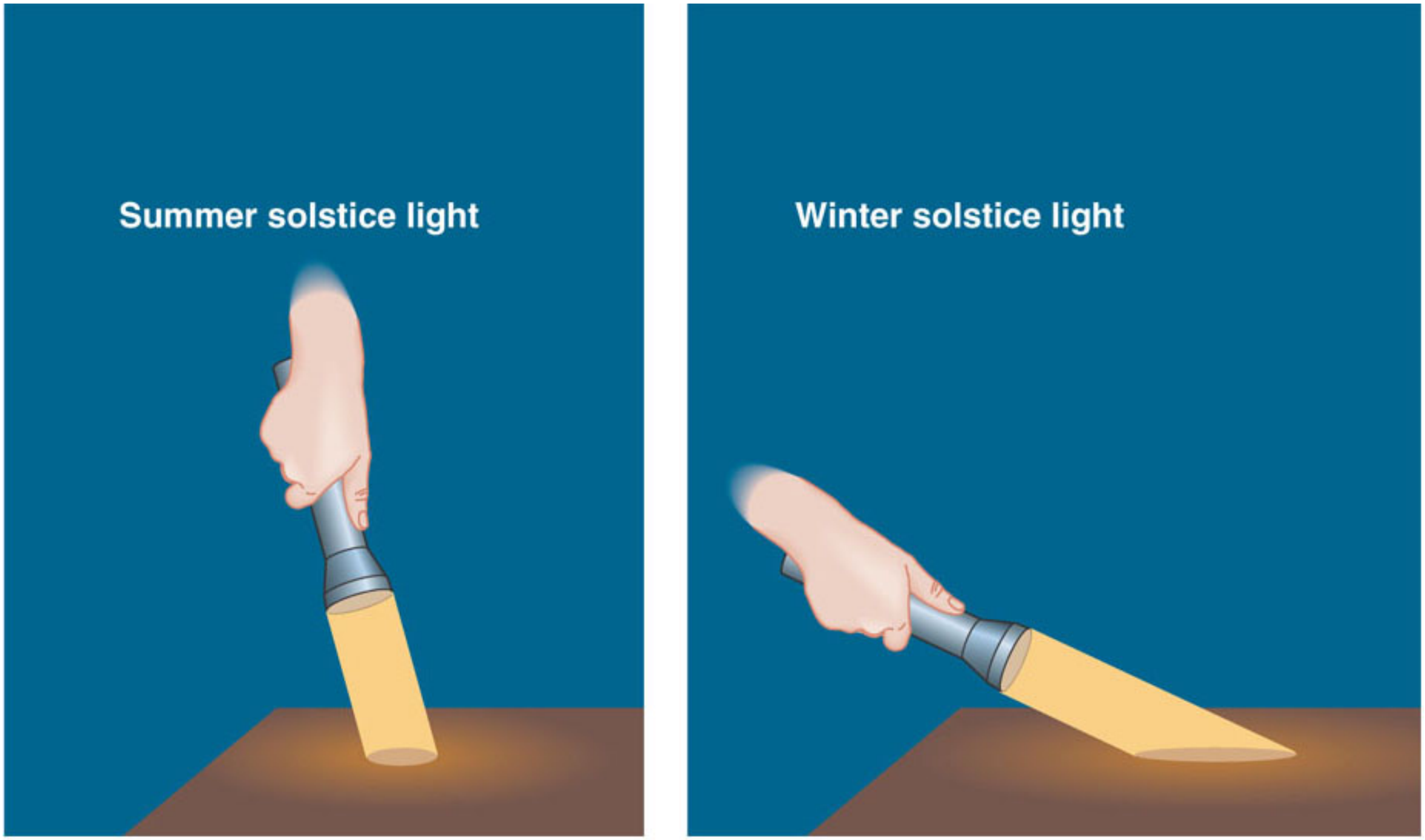



Equatorial mounting
To north celestial pole
Westward rotation about polar axis follows stars.
To north celestial pole
Polar axis
North Pole
Eastward rotation of Earth

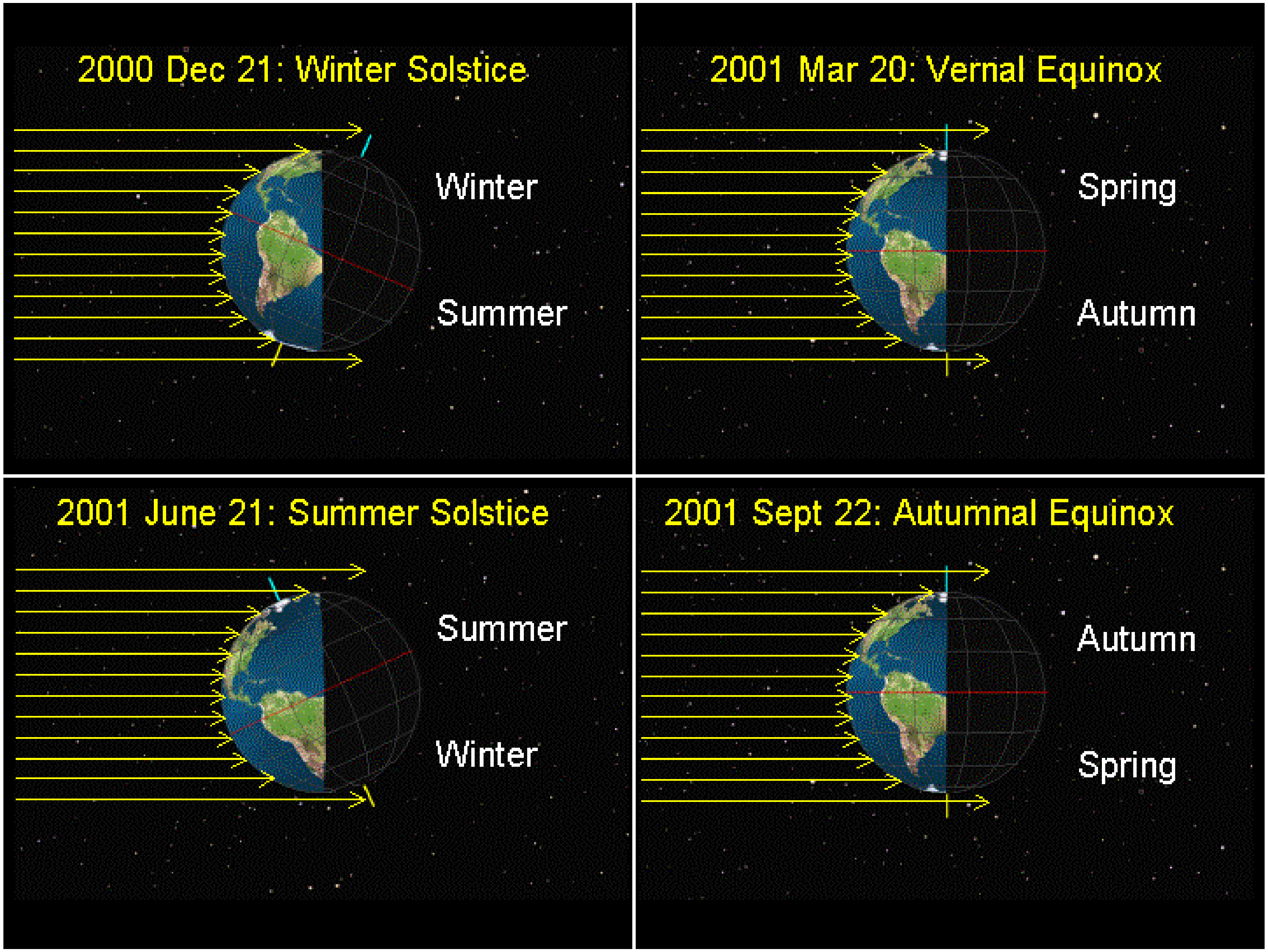

Alt-azimuth mounting
Computer control of motion about both axes follows stars.
To north celestial pole
North Pole
Eastward rotation of Earth


23½°
N
Atmosphere
90°
66½°
30°
0°
23½°
Sun's rays
S
arctic circle
antarctic circle

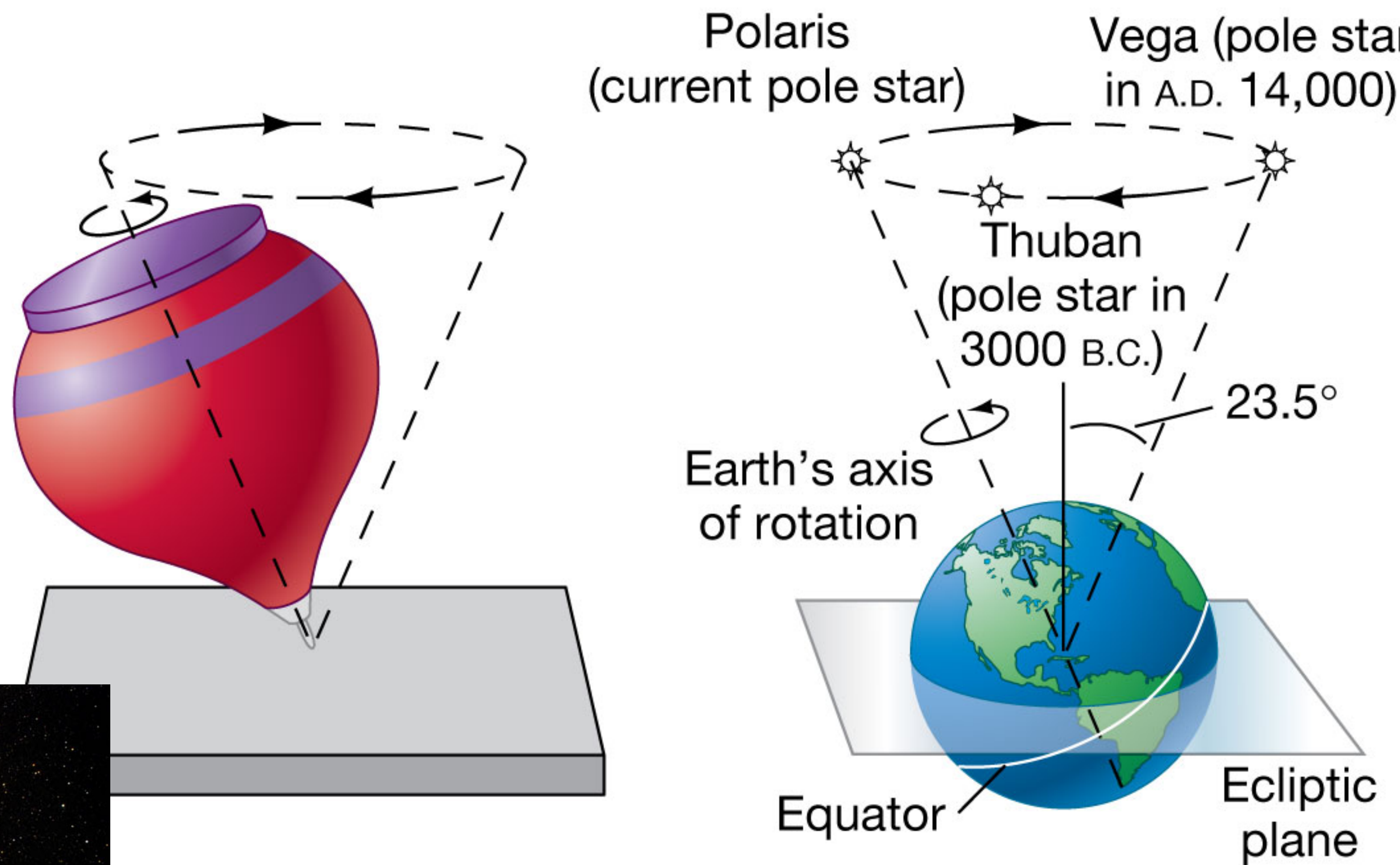
The 23.5° tilt is also the reason for the seasons.



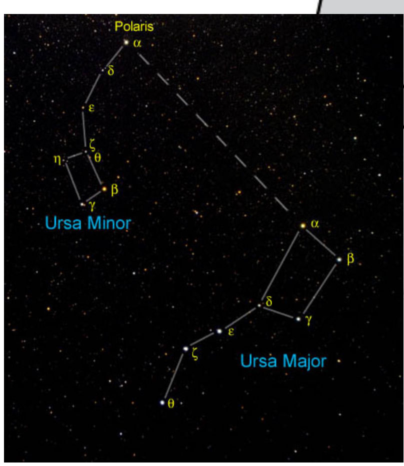
At the equinoxes:



Precession:

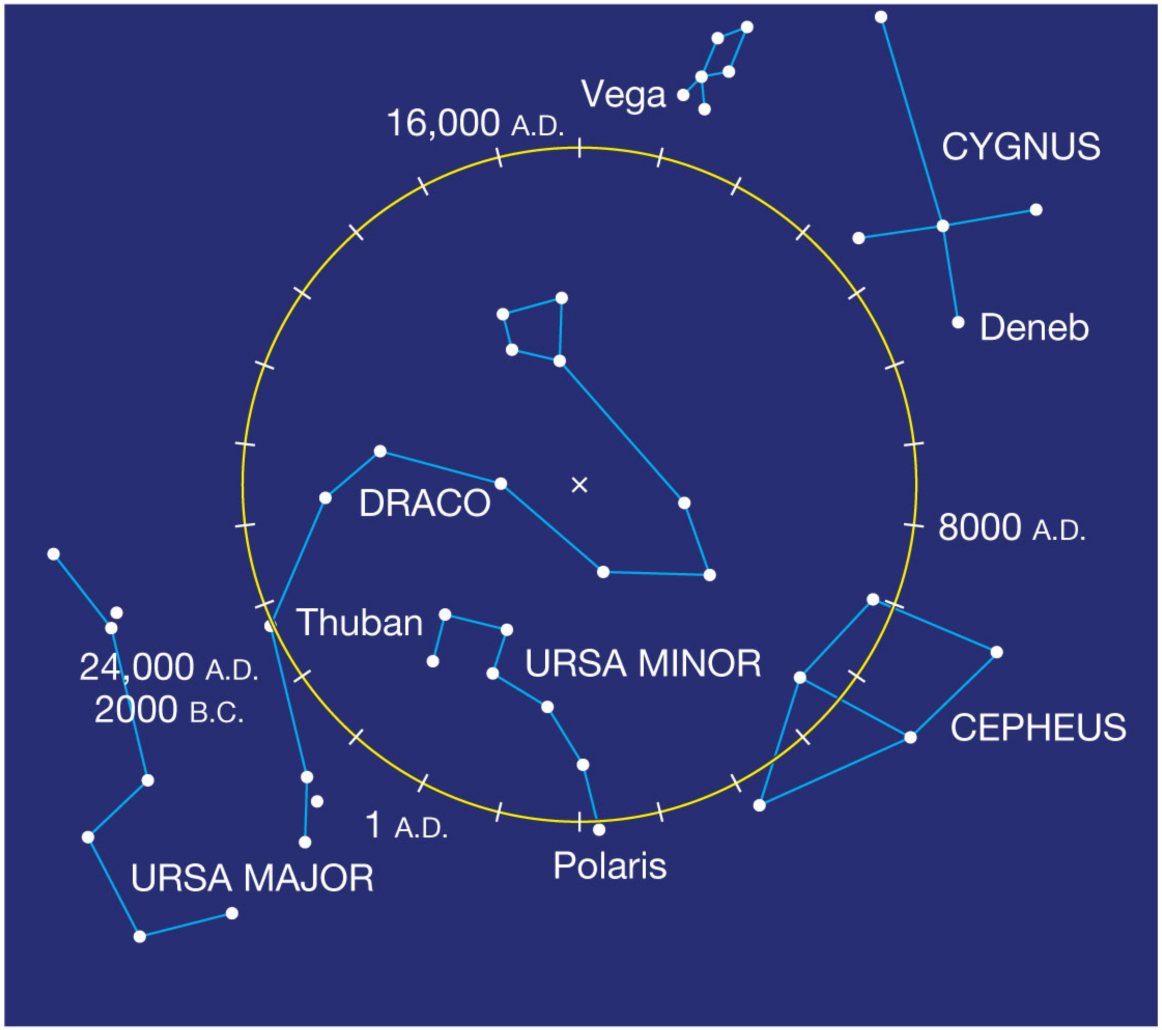


Polaris (current pole star)
Vega (pole star in A.D. 14,000)
Thuban (pole star in 3000 B.C.)
23.5°
Earth's axis of rotation
Equator
Ecliptic plane

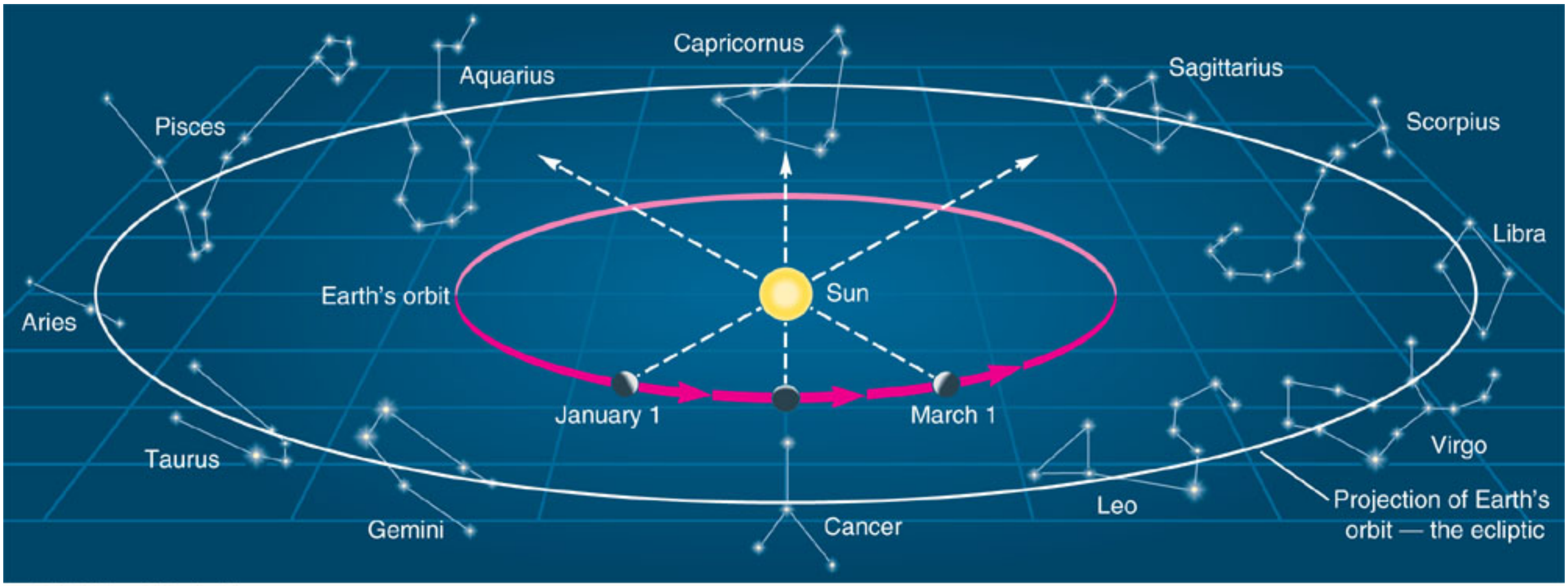


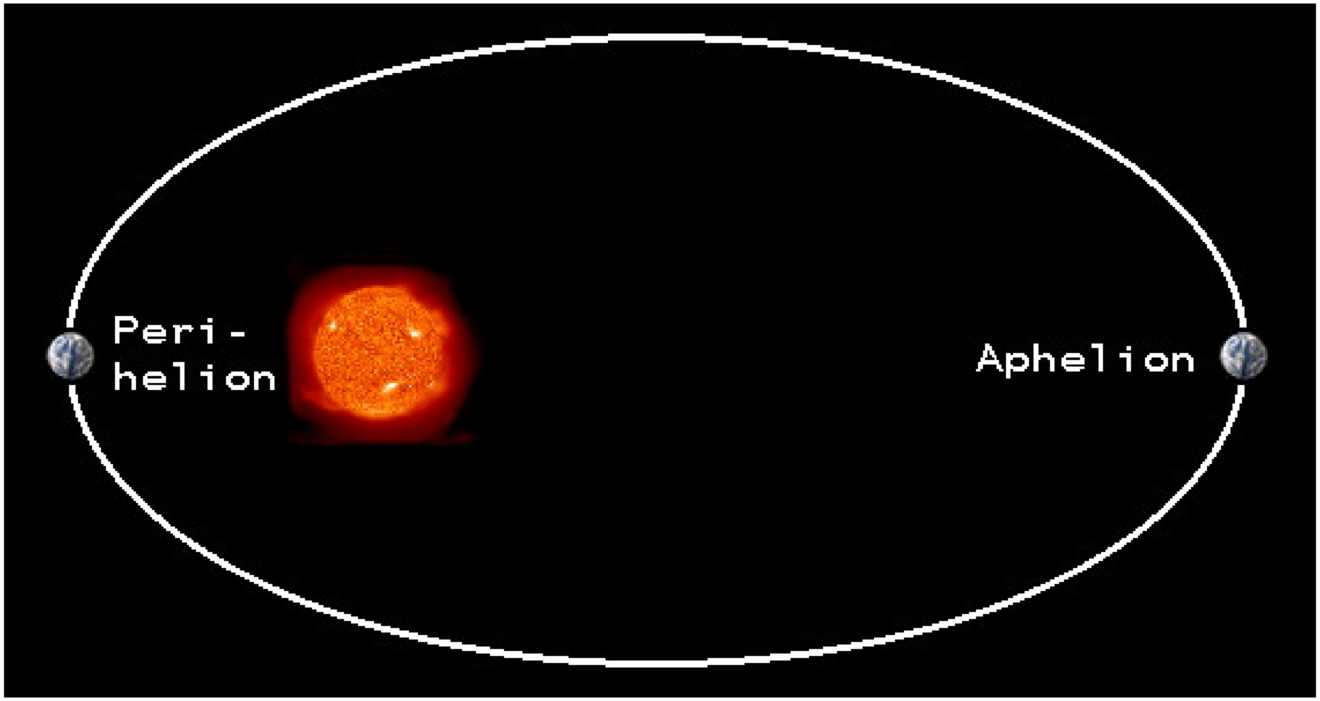
Polaris
Ursa Minor
Ursa Major

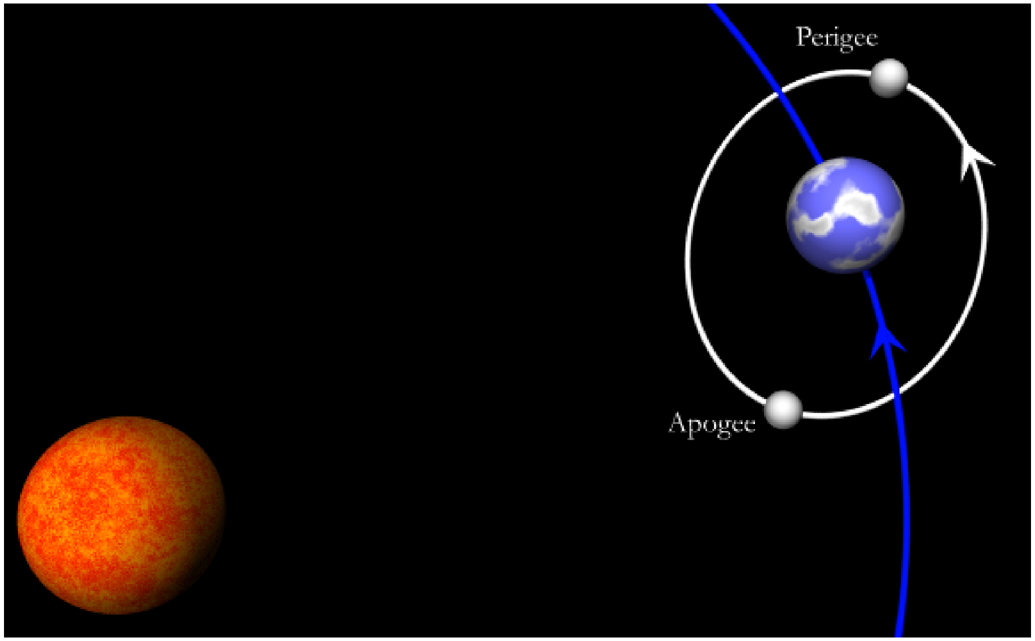
The precession makes a full circle once in every 26,000 years.



(b)

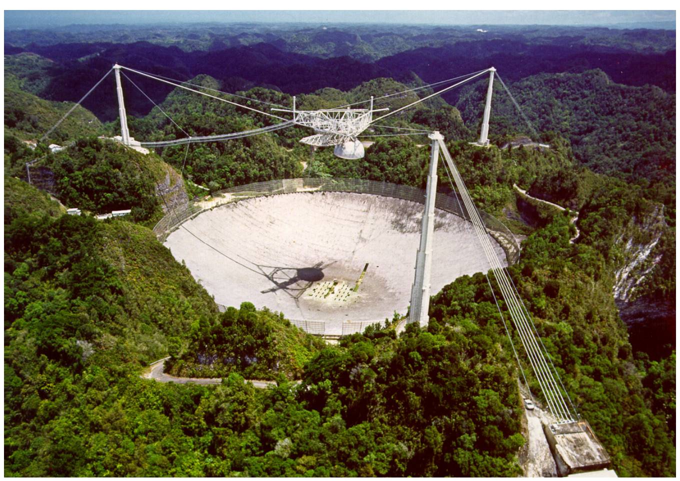

Capricornus
Aquarius
Sagittarius
Pisces
Scorpius
Libra
Earth's orbit
Sun
Aries
January 1
March 1
Taurus
Virgo
Leo
Projection of Earth's orbit — the ecliptic
Gemini
Cancer


Peri-
helion
Aphelion

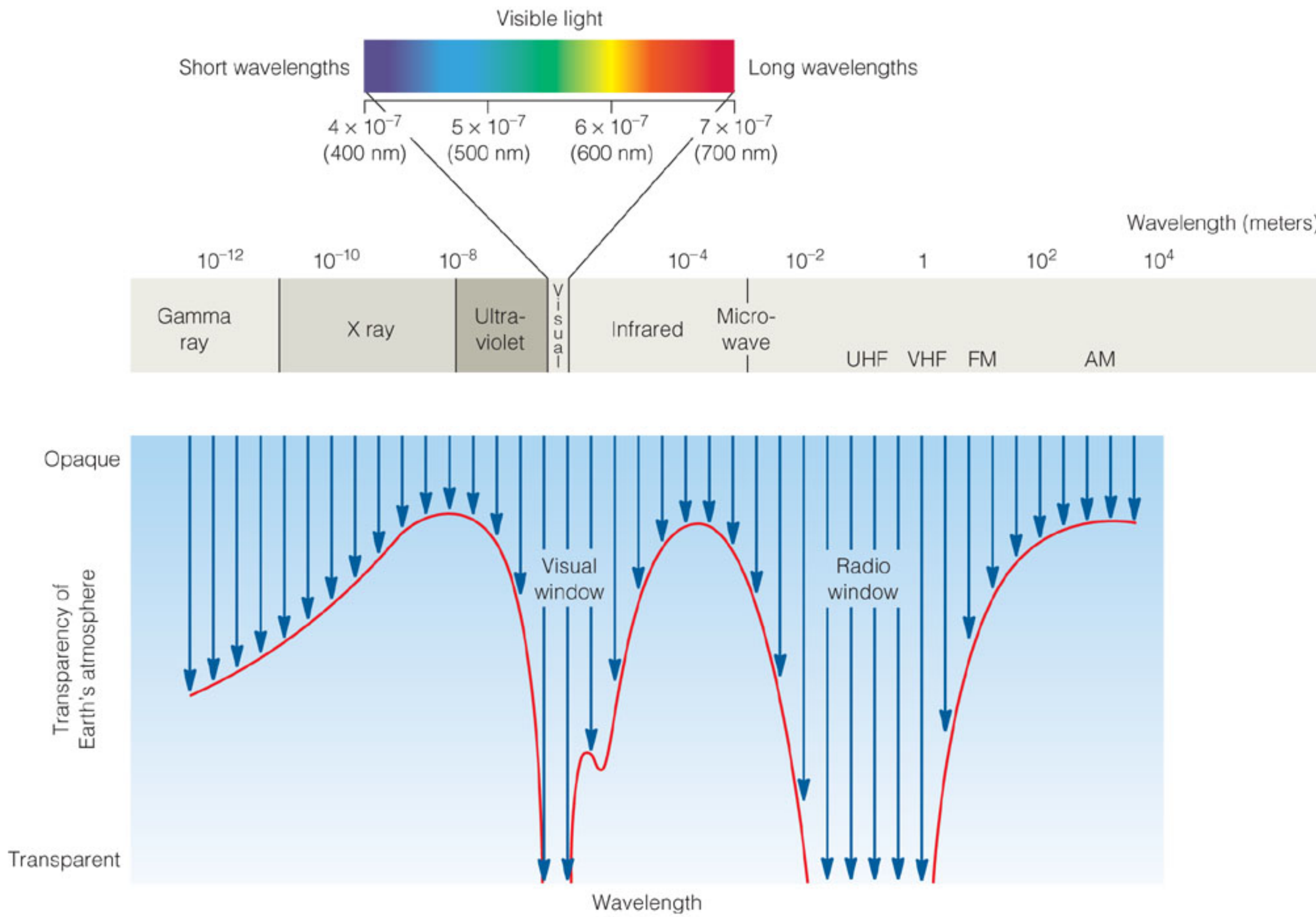

Perigee
Apogee

VLT at Paranal

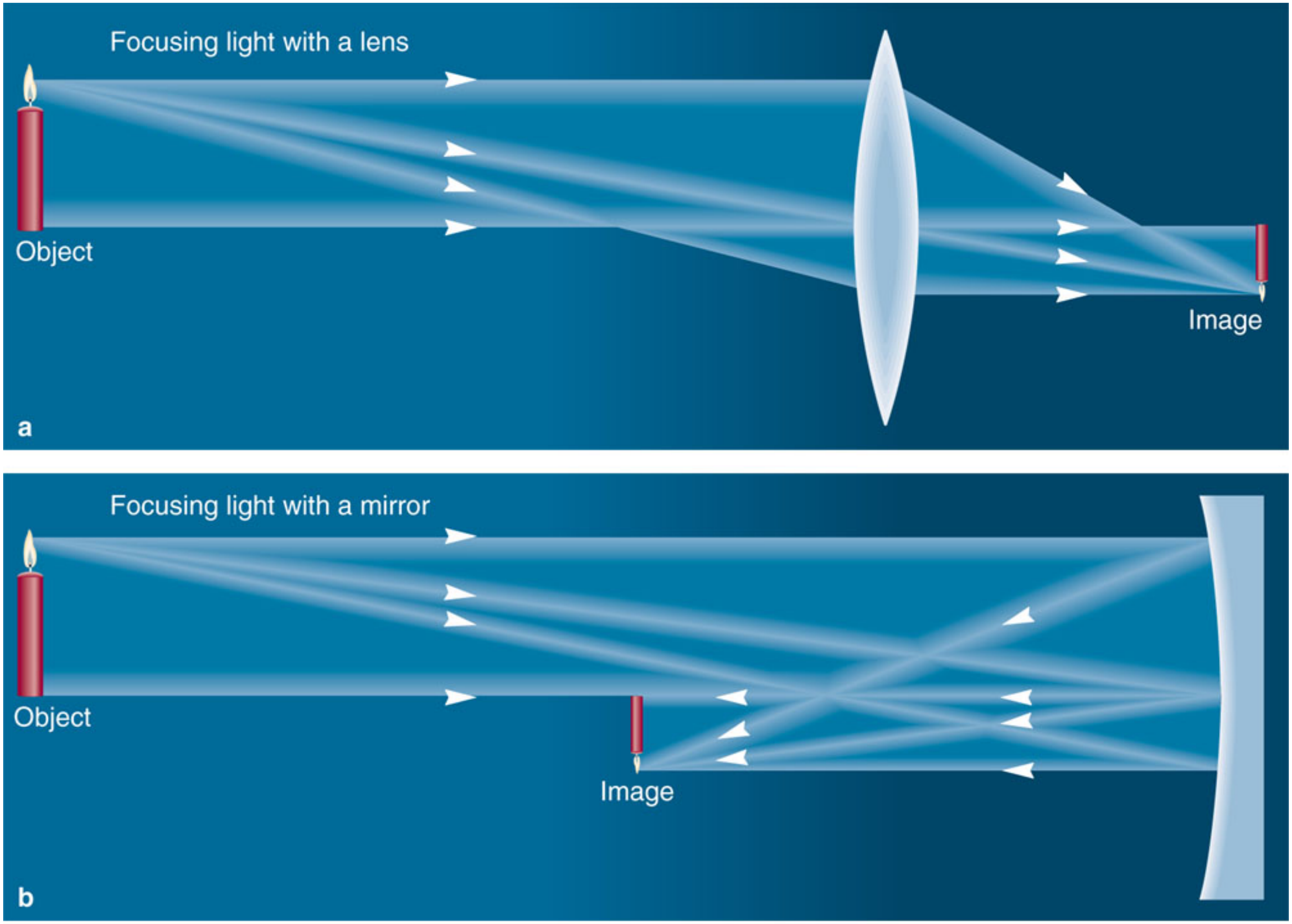
ESO PR Photo 43a/99 (8 December 1999)

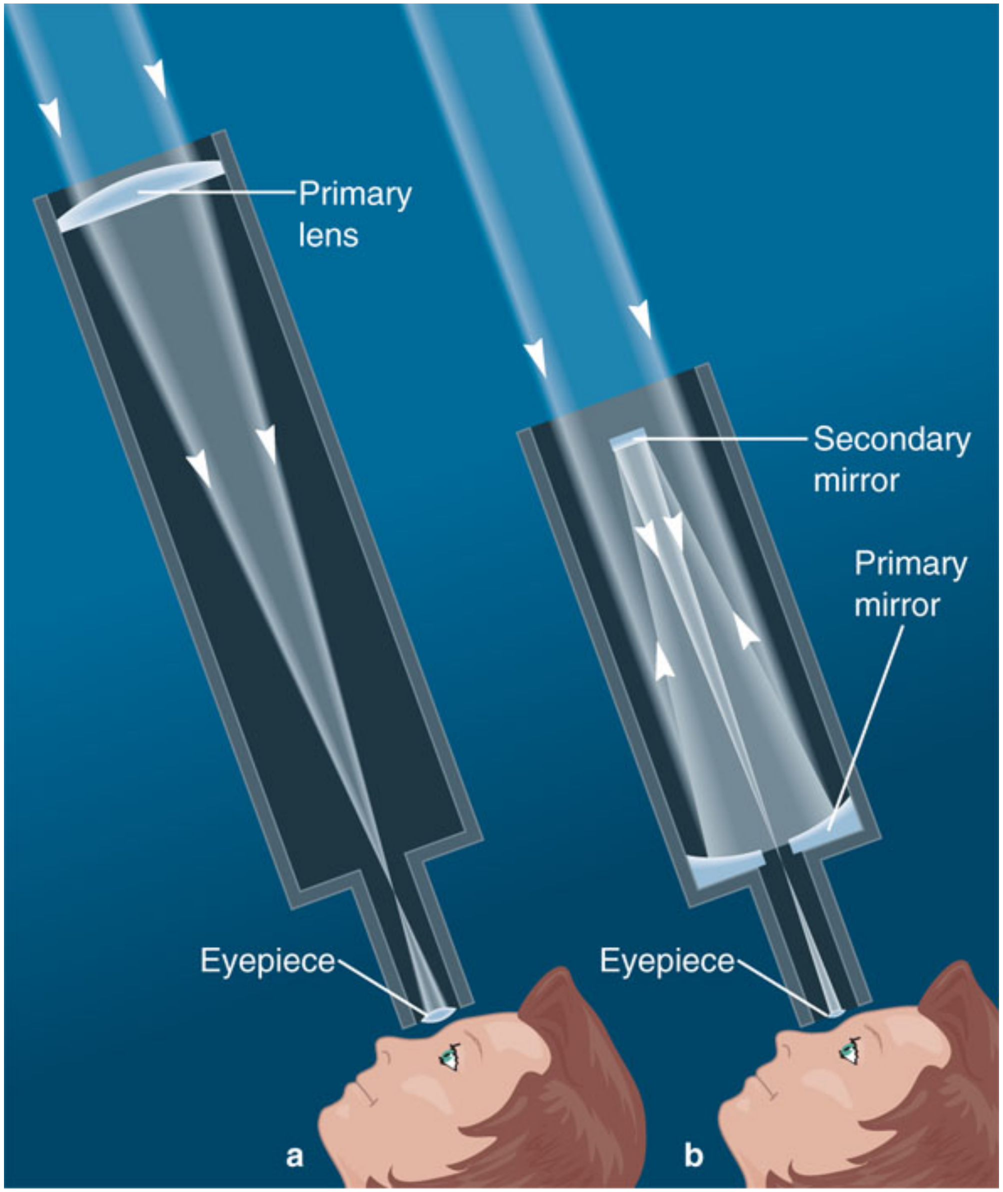


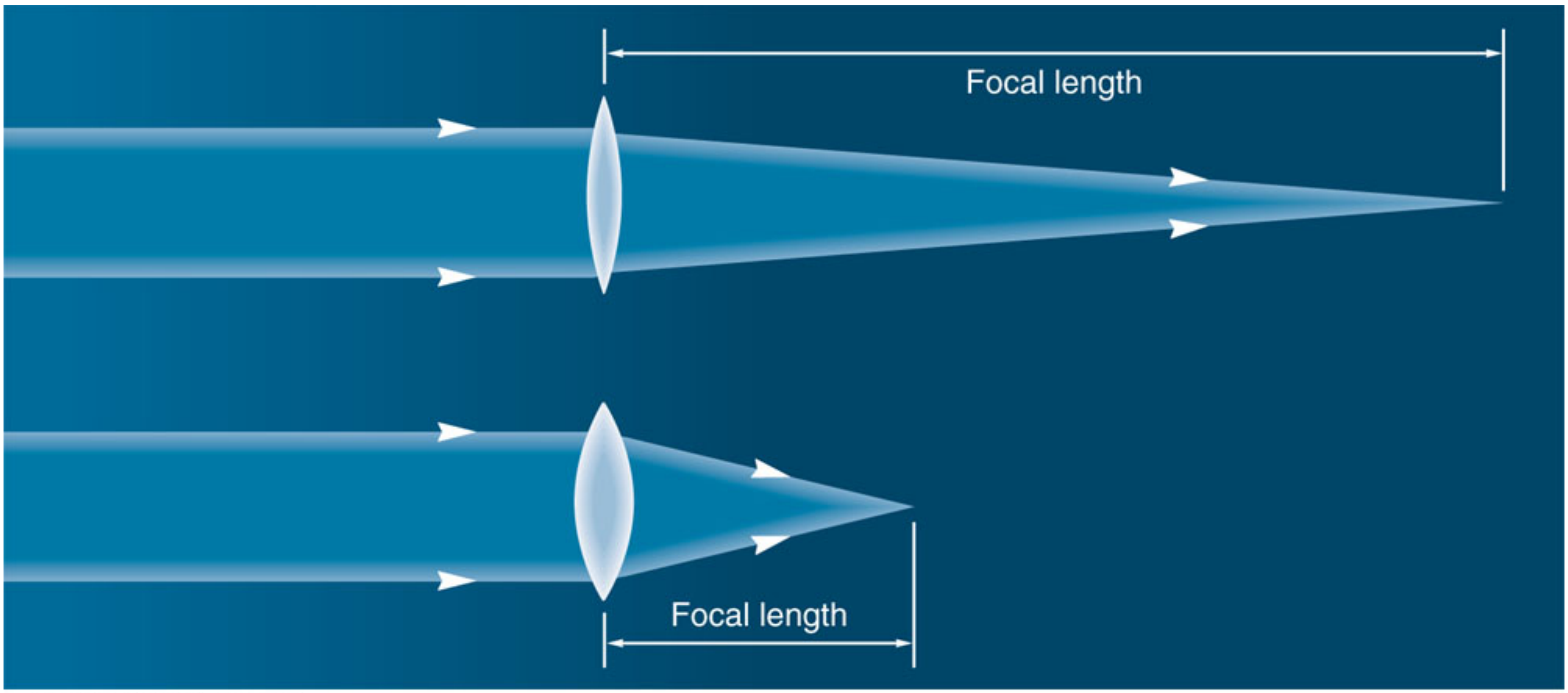
Ground or space observatory?



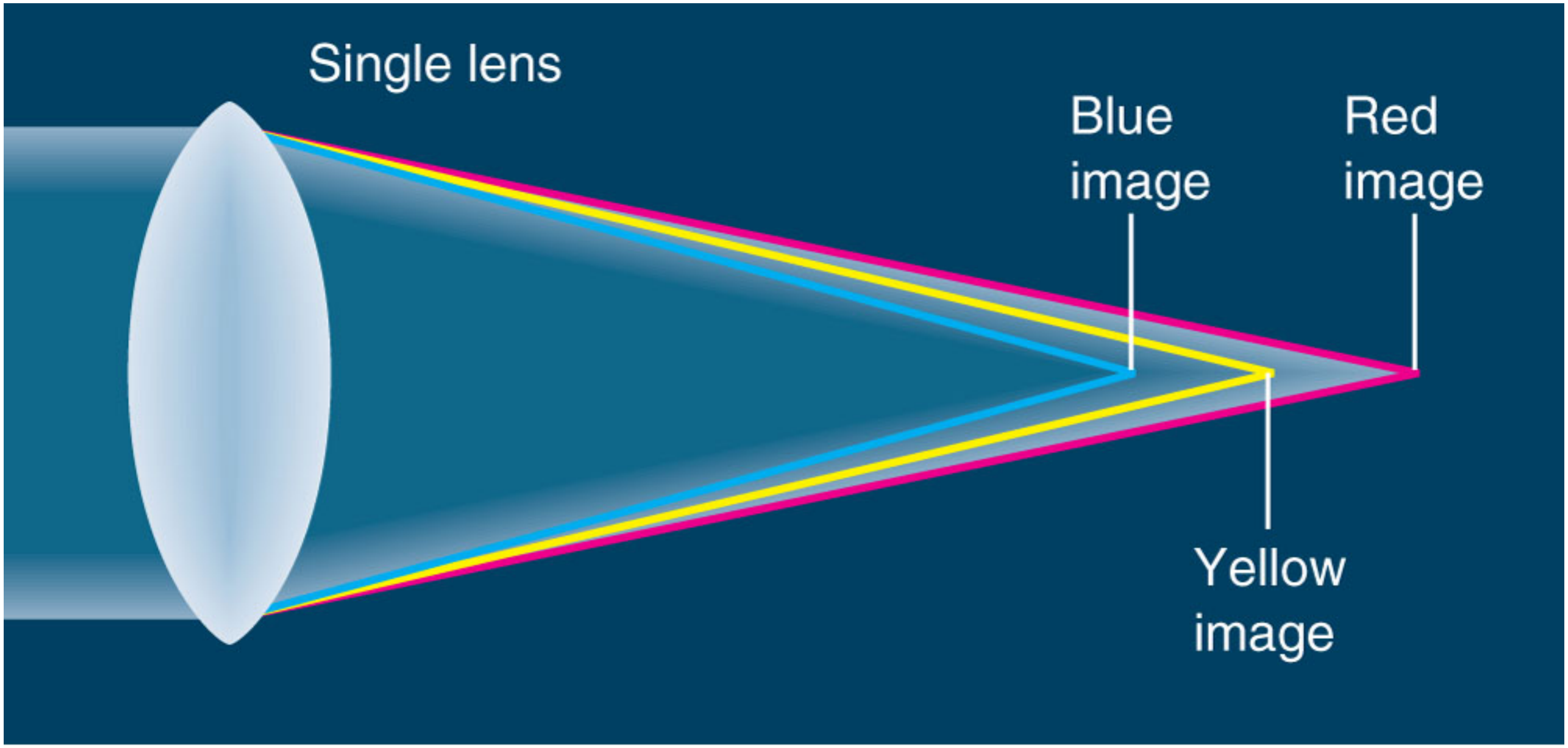
$1\text{m} = 1000\text{ mm} = 10^6\ \mu\text{m} = 10^9\text{ nm} = 10^{10}\text{Å}.$


Focusing light with a lens
Object
Image
a
Focusing light with a mirror
Object
Image
b


Primary lens
Eyepiece
a
Secondary mirror
Primary mirror
Eyepiece
b


Focal length
Focal length

Chromatic aberration:



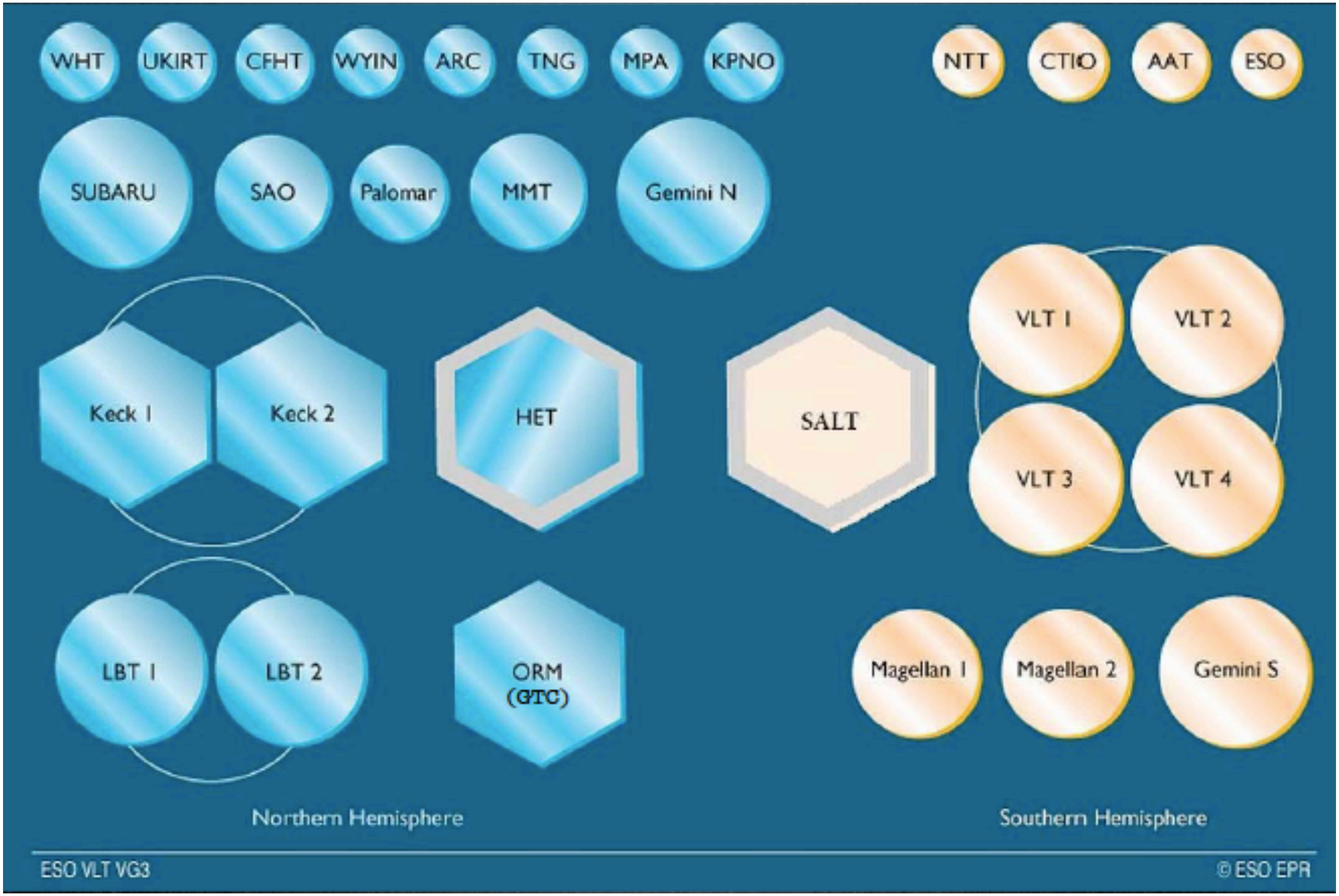
The magnification of a telescope is simply given by

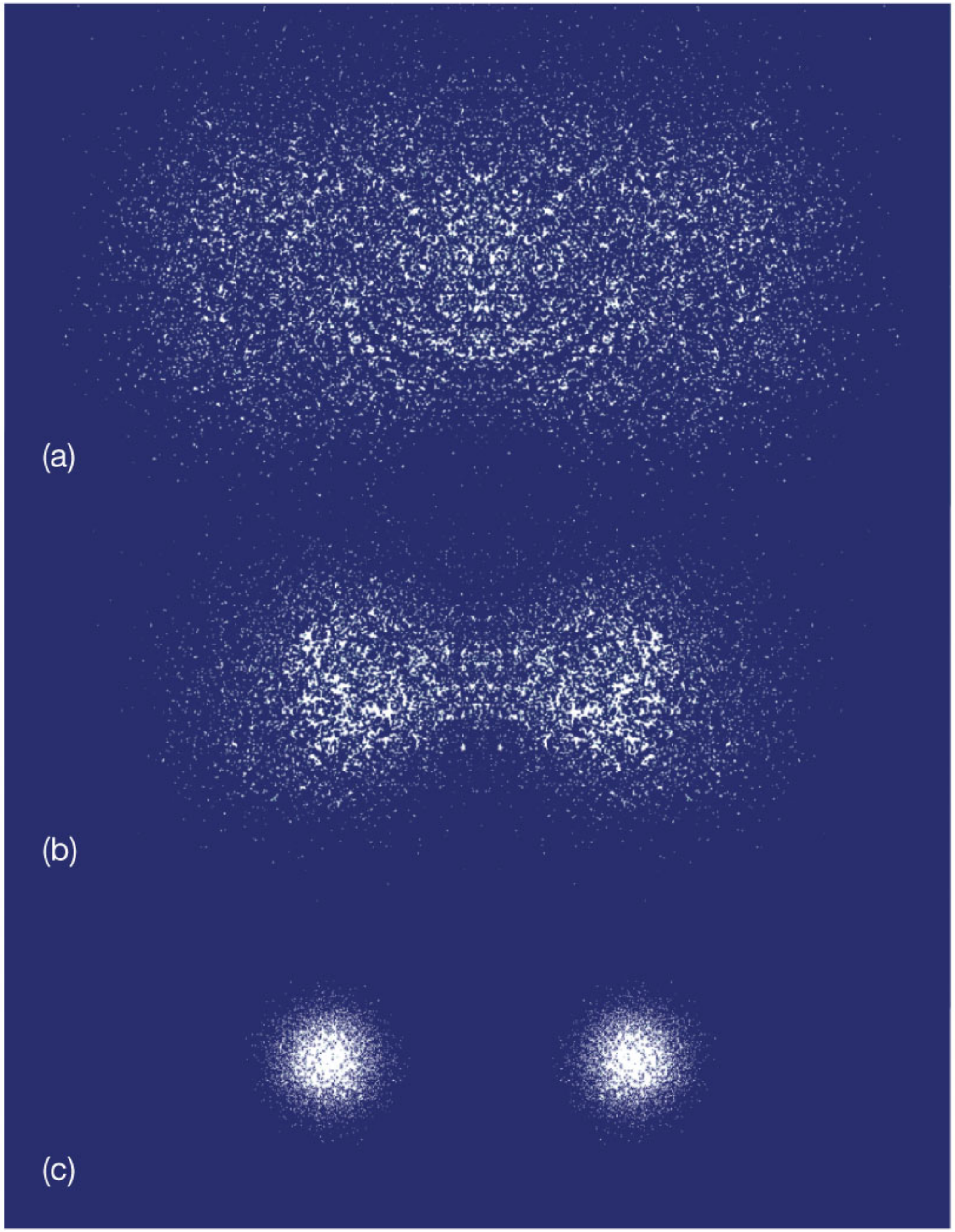
$$M = \frac{\text{focal length of objective}}{\text{focal length of eyepiece}} = \frac{F_o}{F_e}$$

However, the magnification power of a telescope is far from its most important property; don't be fooled into buying telescopes that claim very high powers of magnification!!

The most important property of a telescope is its size. Number of photons collected scales like d^2.

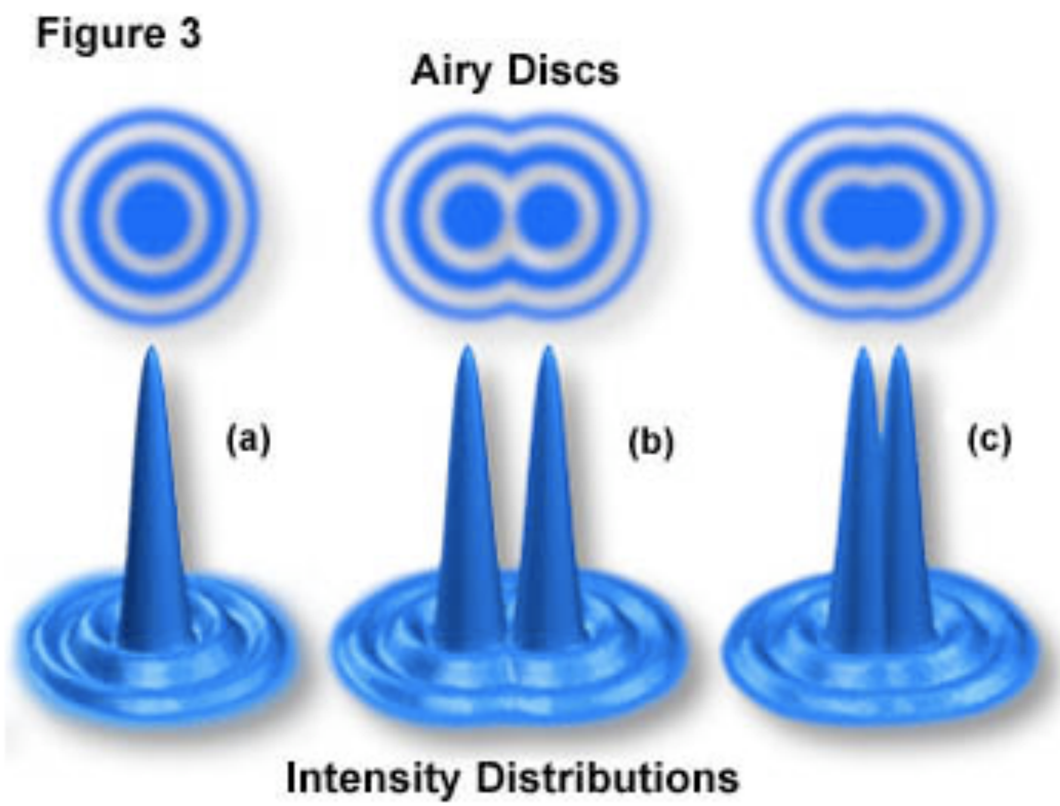
Telescope	Mirror size	Location
South African Large Telescope	11 m (but only uses 6 m)	South Africa
Keck	Two 10 m telescopes	Hawaii
VLT	Four 8 m telescopes	Chile
Gemini	Two 8 m telescopes	Hawaii/Chile
Subaru	8 m	Hawaii
Hubble Space Telescope	2.4 m	Low earth orbit


WHT
UKIRT
CFHT
WYIN
ARC
TNG
MPA
KPNO
NTT
CTIO
AAT
ESO
SUBARU
SAO
Palomar
MMT
Gemini N
VLT 1
VLT 2
Keck 1
Keck 2
HET
SALT
VLT 3
VLT 4
LBT 1
LBT 2
ORM
(GTC)
Magellan 1
Magellan 2
Gemini S
Northern Hemisphere
Southern Hemisphere
ESO VLT VG3
© ESO EPR


(a)
(b)
(c)

For a given mirror or lens size, there is a limiting resolution that can be achieved. This is known as the diffraction limit.

Diffraction limit equation: $\Delta\theta$ (rad) ~ λ/D

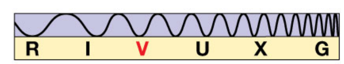


Resolution is a measure of the smallest detail that can be seen at a particular wavelength, usually measured in arcseconds.

$$\text{Resolution (arcsec)} = \frac{\text{wavelength } (\mu\text{m})}{\text{mirror diameter (m)}} \times 0.25$$

(a)

(d)



Low resolution

High resolution

Aside: The small angle formula

This important formula allows us to calculate the true diameter of an object if we know its distance and its angular diameter (apparent size expressed in an angle). More on this next lecture.

$$\frac{\text{angular diameter (arcsecs)}}{206{,}265} = \frac{\text{linear diameter}}{\text{distance}}$$

The diameter and the distance are always in the same units, e.g. centimetres, metres, kilometres, lightyears. The units themselves don't matter, as long as they're the same.

Example: What size optical telescope do we need to 'resolve' (ie see the scale of) an arena on the moon?

First use small angle to estimate angular size of a 100 m arena on the moon which is at a distance of 3.8×10^8 m:

$$\text{angular size} = \frac{\text{physical size}}{\text{distance}} \times 206265 = \frac{100}{3.8 \times 10^8} \times 206265$$

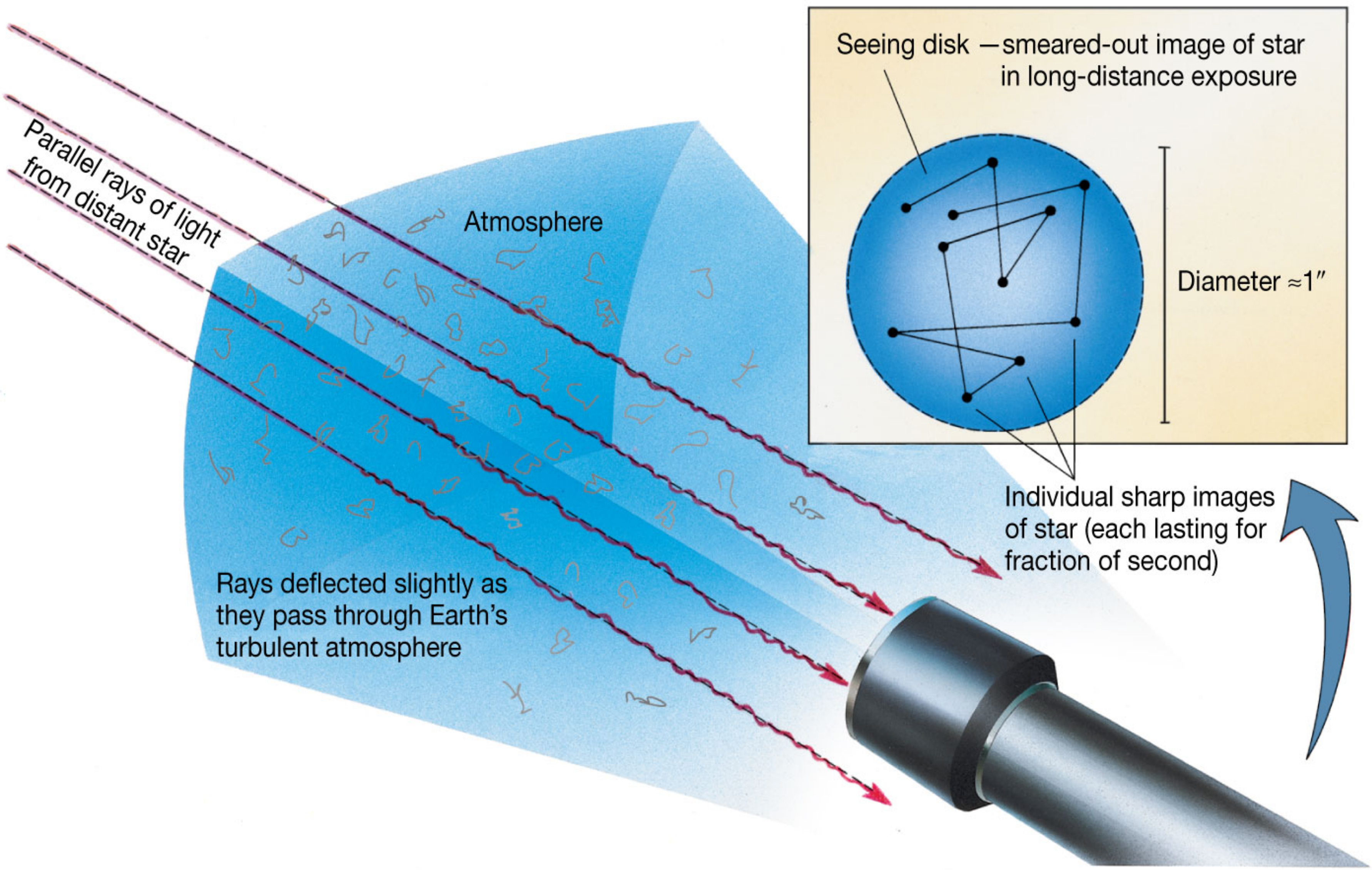
$$= 0.05 \text{ arcseconds}$$

Next use the resolution formula in the optical, chose λ=500 nm and set resolution to 0.05 arcsecs:

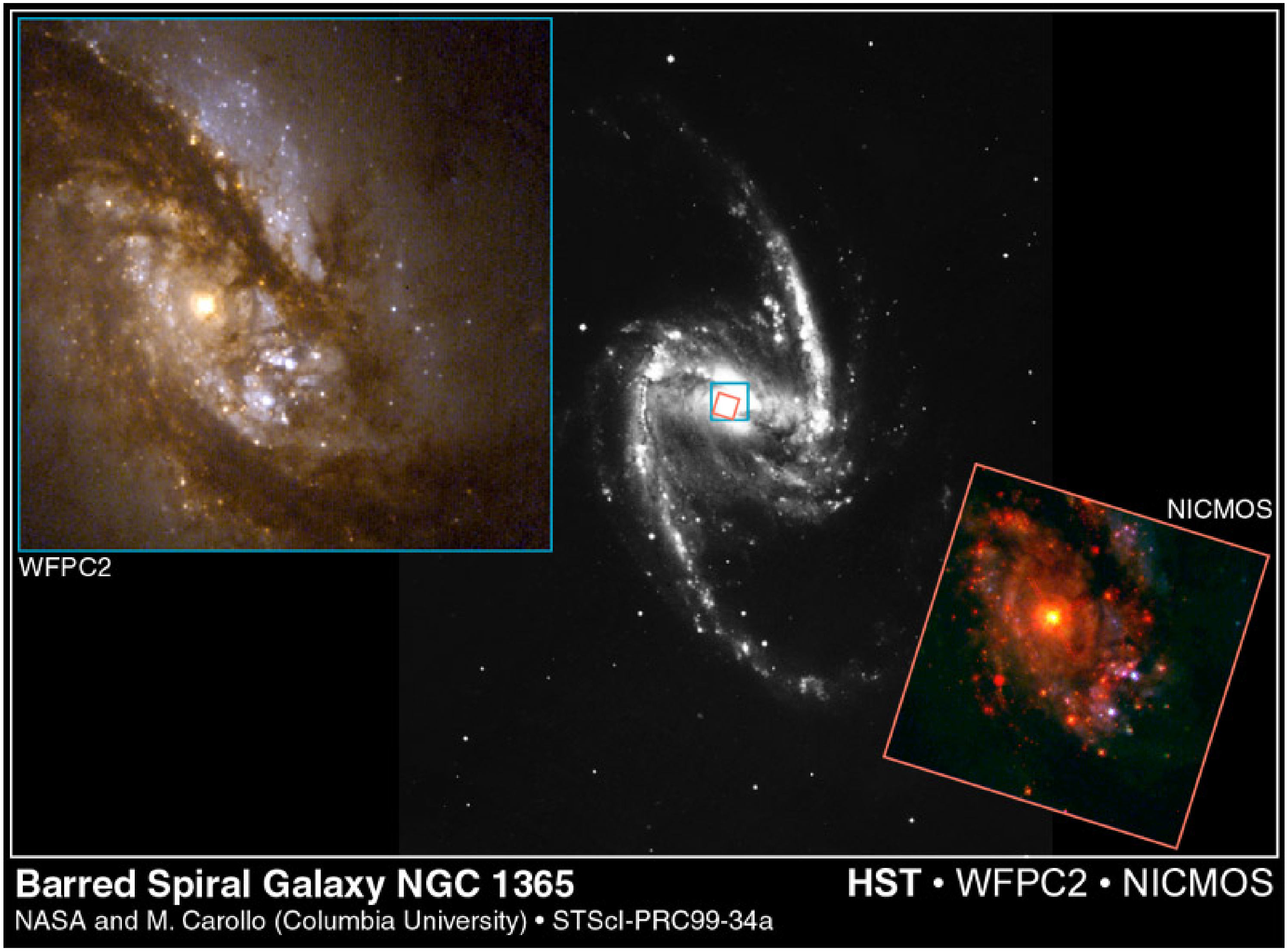
$$\text{Diameter} = \frac{\text{wavelength (m)}}{\text{resolution}} \times 251643 = \frac{500 \times 10^{-9}}{0.05} \times 251643$$

$$= 2.5 \text{ m}$$

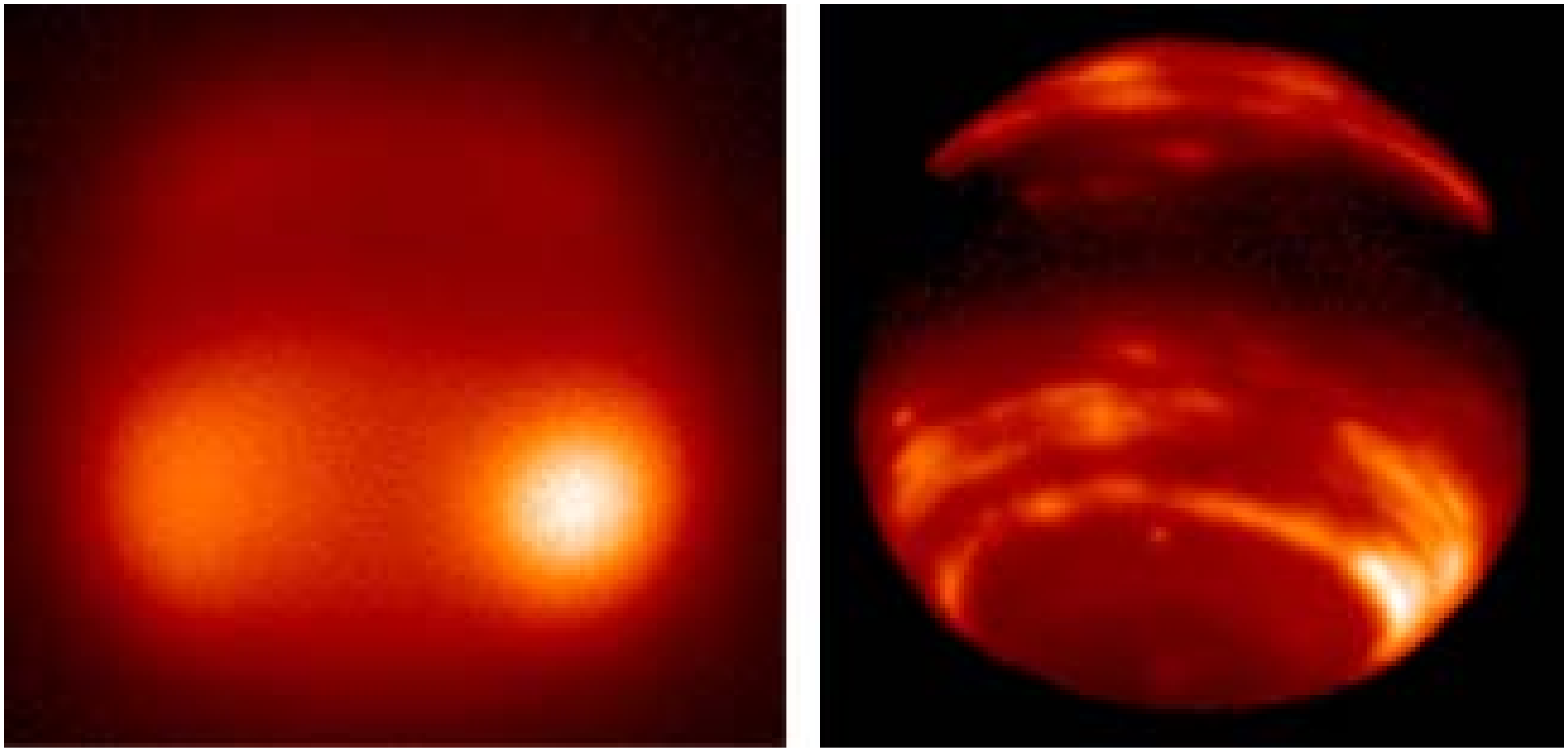
In practice, the atmosphere blurs the image: seeing.
Seeing is typically 5 arcsec in Victoria and <1arcsec in Hawaii.



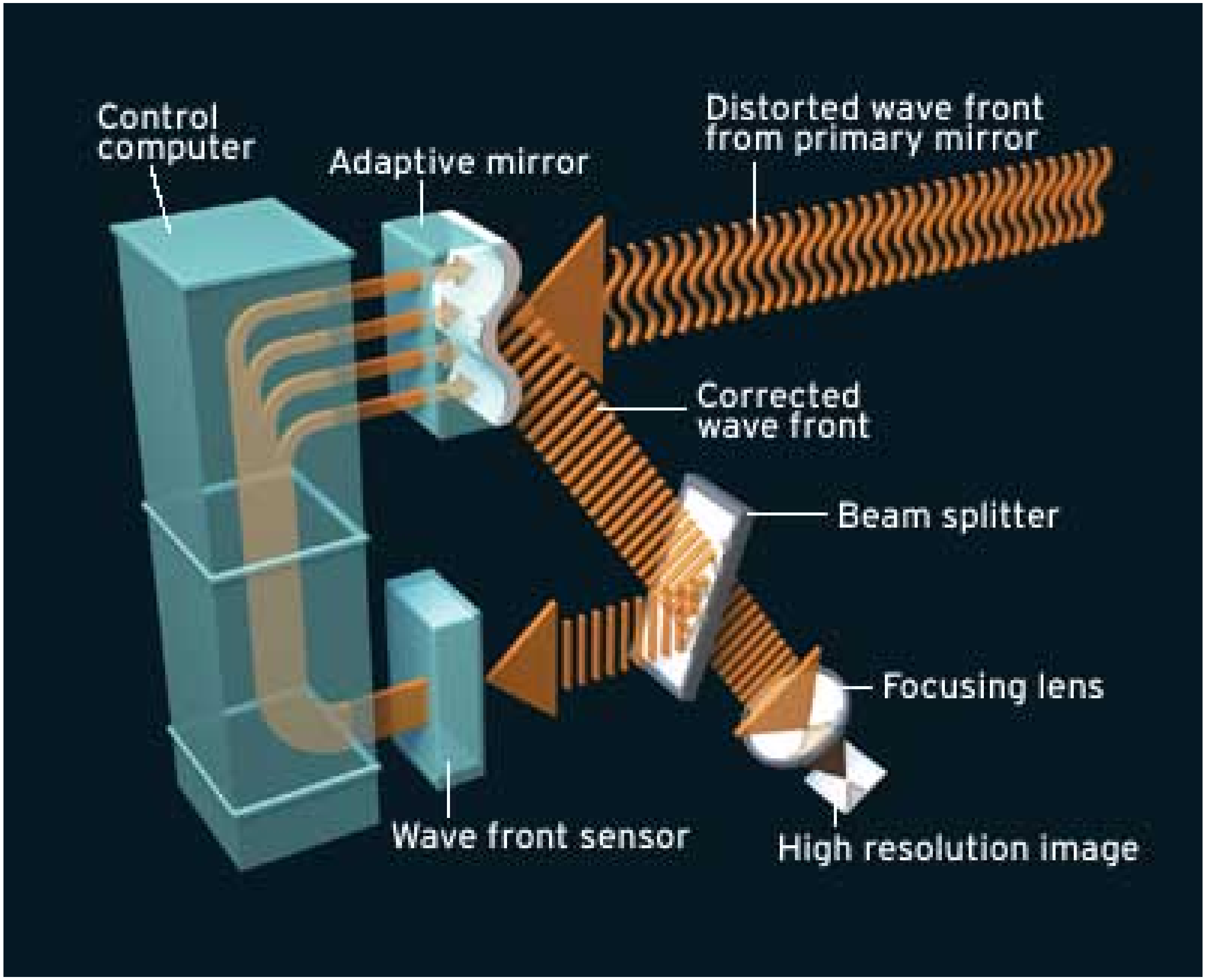
A telescope in space can truly work at its diffraction limit.



The effects of the atmosphere can be overcome by adaptive optics (AO) which uses a deformable mirror to exactly compensate for the shape of the atmospheric turbulence.

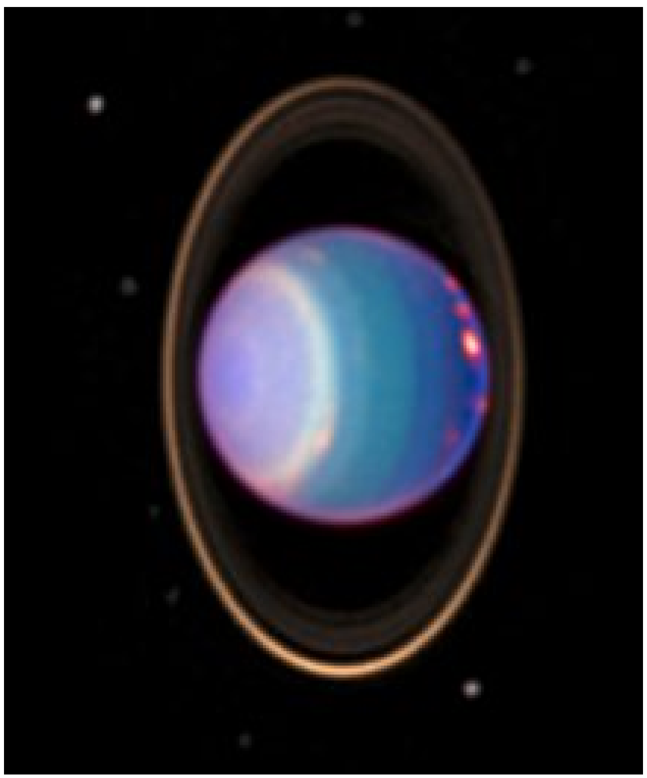


Neptune without and with Keck+AO


Control computer
Adaptive mirror
Distorted wave front from primary mirror
Corrected wave front
Beam splitter
Focusing lens
Wave front sensor
High resolution image

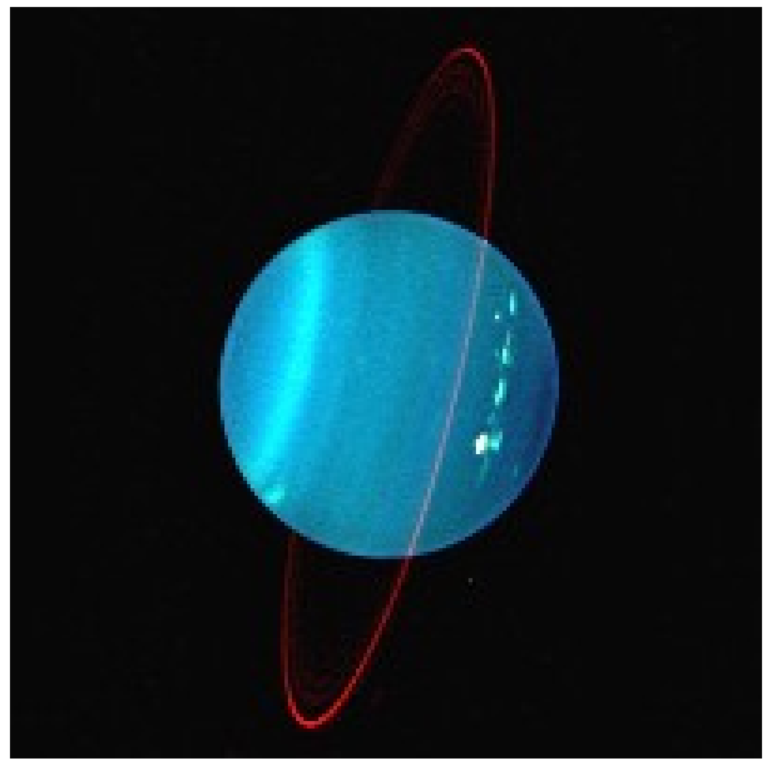
AO allows telescopes to work at their diffraction limit ie give images with the maximum resolution of λ x 251,643/D. A large ground-based telescope with AO gives images sharper (ie with better resolution) than HST.

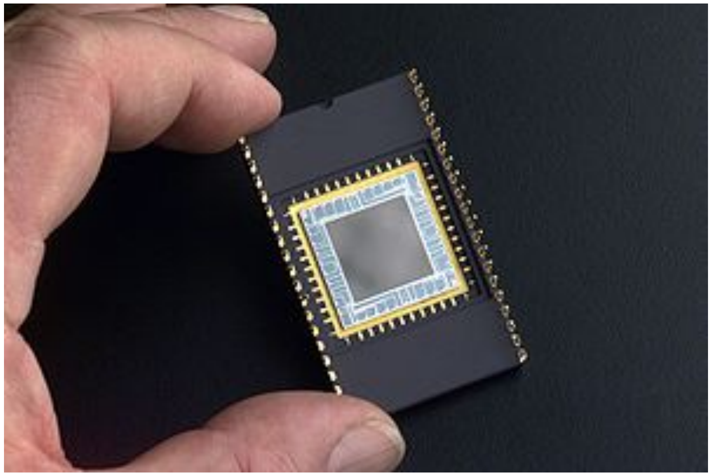
Optical HST image



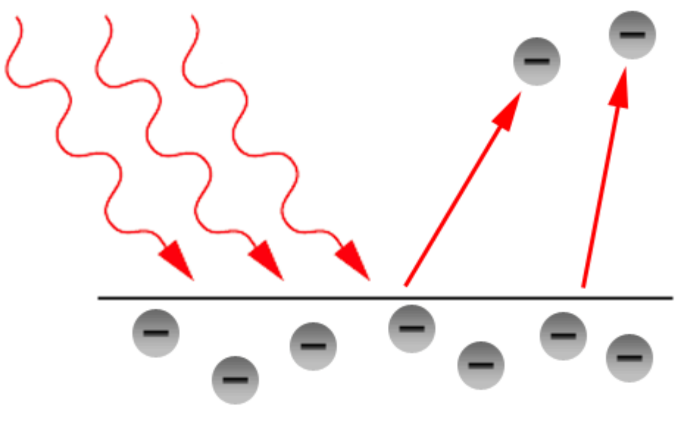
Uranus

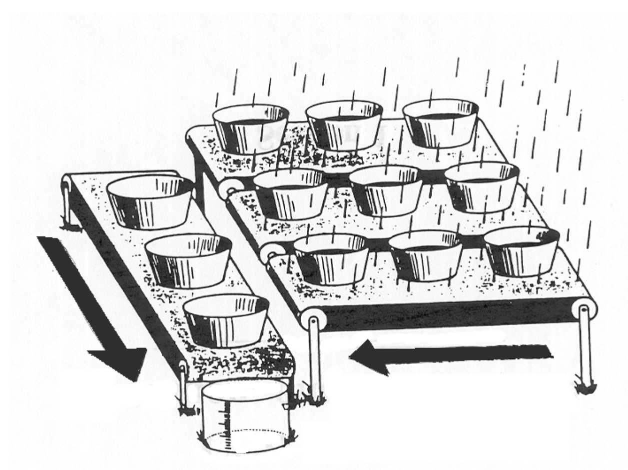
Keck+AO infra-red image





Images are recorded on a charge couple device (CCD), contain a tiny capacitor in every cell “pixel” that accumulates charge through the photoelectric effect.



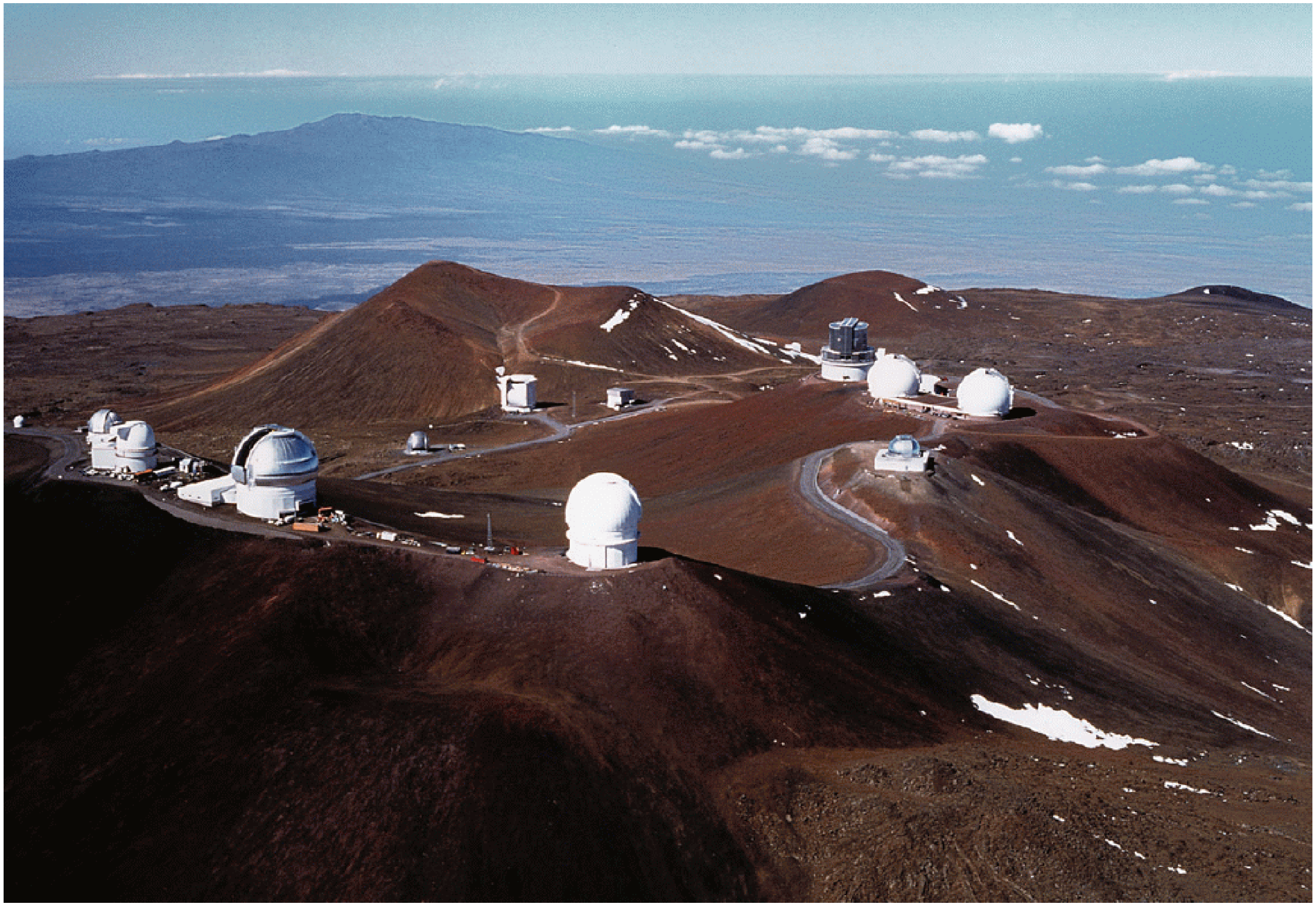


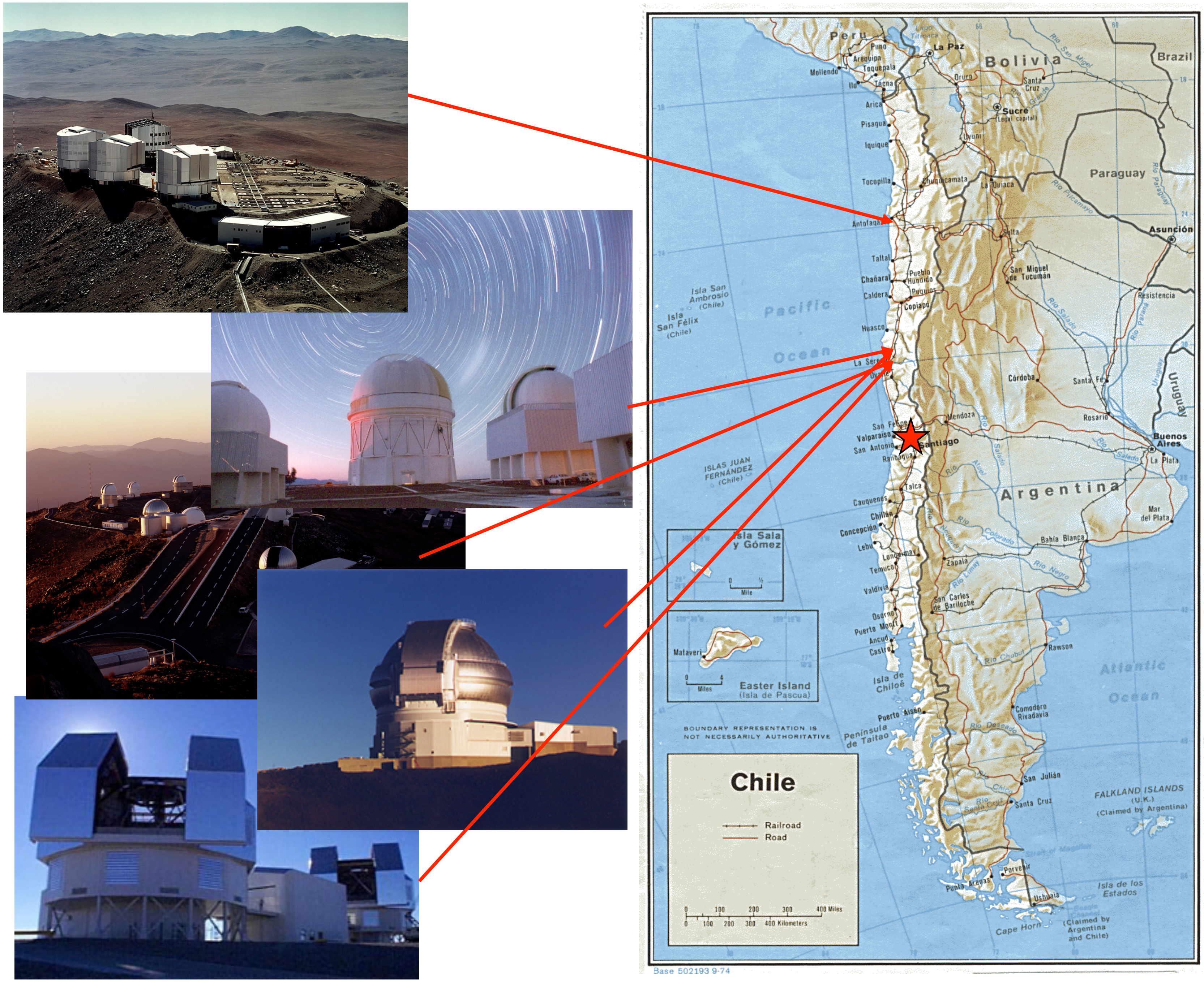
How do we choose a site for a professional optical telescope? Ideally we require that

- The sky is clear for much of the year
- We are on a mountain high enough to be above the clouds if they come along
- We are in a dry environment (red optical light gets absorbed by water vapour)
- We are far from light pollution
- We are in a place with a stable atmosphere to minimise image blurring due to turbulence

The ideal sites turn out often to be high desert mountains or extinct volcanoes!

Two of the major sites for optical astronomy are on the top of Mauna Kea on the Big Island of Hawaii, and in the Chilean Atacama desert.





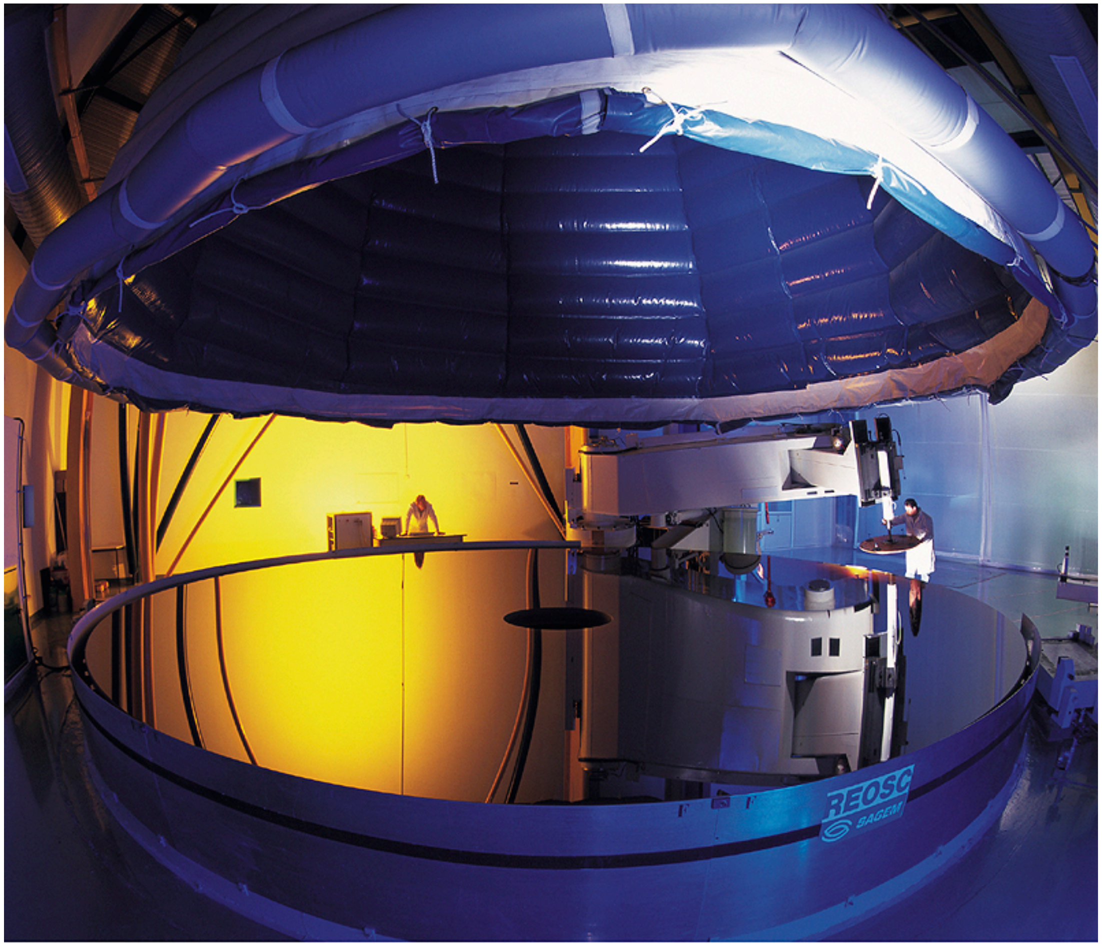
Peru
Bolivia
Brazil
Paraguay
Argentina
Uruguay
Pacific Ocean
Atlantic Ocean
La Paz
Sucre (Legal capital)
Asunción
Buenos Aires
Santiago
Antofagasta
La Serena
Valparaiso
Córdoba
Mendoza
Isla San Ambrosio (Chile)
Isla San Félix (Chile)
ISLAS JUAN FERNÁNDEZ (Chile)
Isla Sala y Gómez
Easter Island (Isla de Pascua)
Isla de Chiloé
FALKLAND ISLANDS (U.K.) (Claimed by Argentina)
Isla de los Estados
Cape Horn
BOUNDARY REPRESENTATION IS NOT NECESSARILY AUTHORITATIVE
Chile
Railroad
Road
Base 502193 9-74

The Very Large Telescope (VLT) is actually 4 8-m telescopes in northern Chile and are amongst the largest optical telescopes in the world.

VLT at Paranal

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

The mirror is polished for months so that its surface is perfect. There are no bumps larger than 8 nm!!



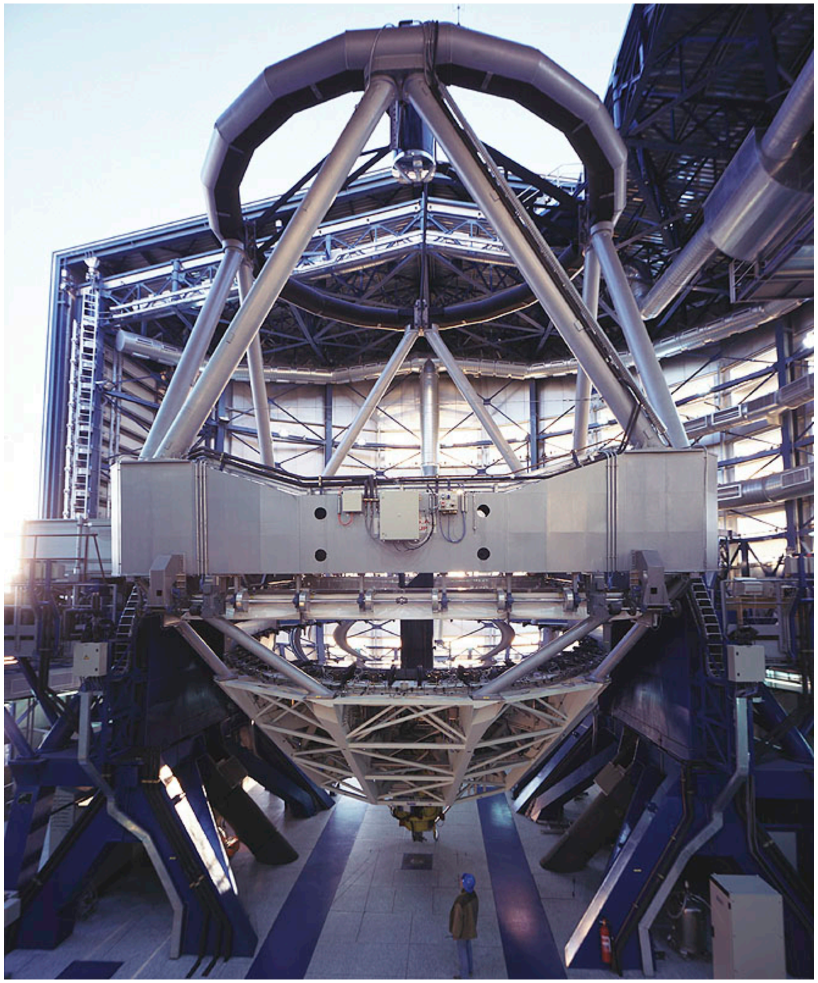
The Polished Fourth VLT 8.2-m Mirror at REOSC

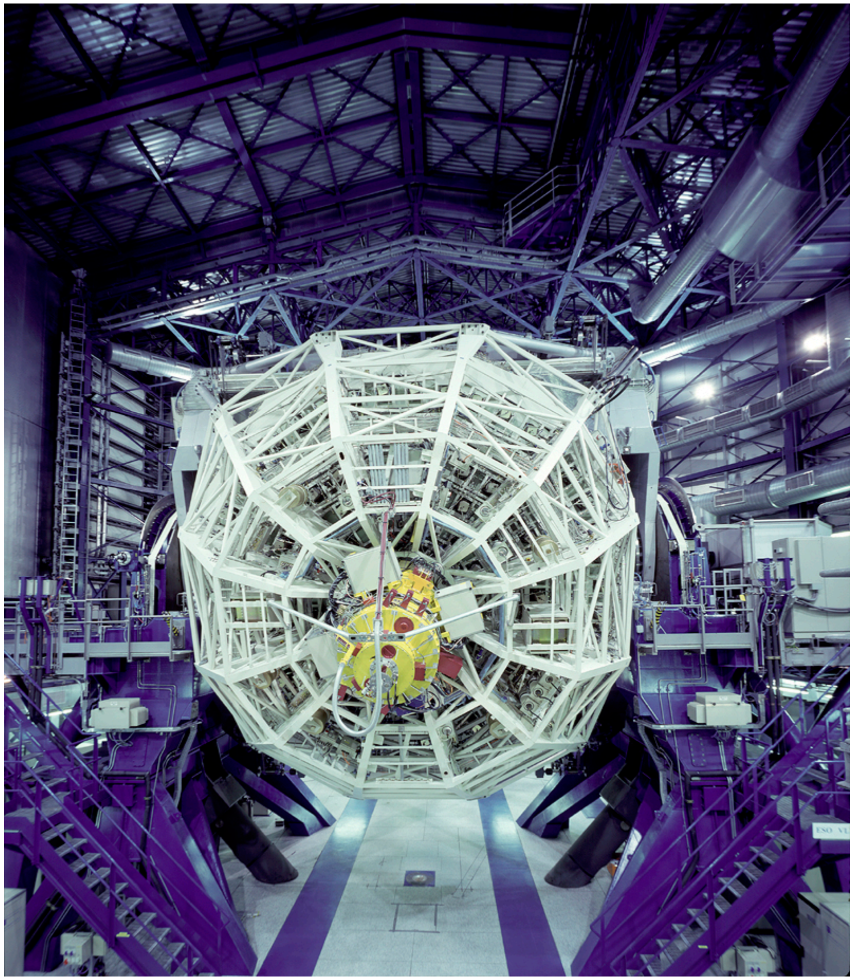
Photo: SAGEM

ESO PR Photo 44/99 (14 December 1999)

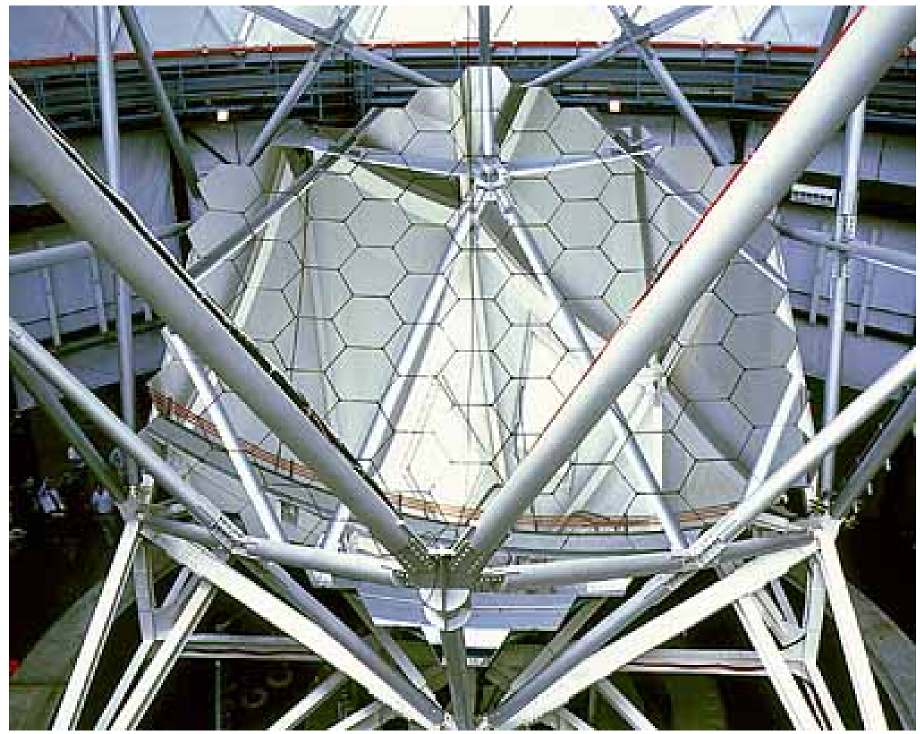
European Southern Observatory

The 230 ton mirror at the VLTs are set into a hydrolic base and its shape is changed by 150 mechanical arms.



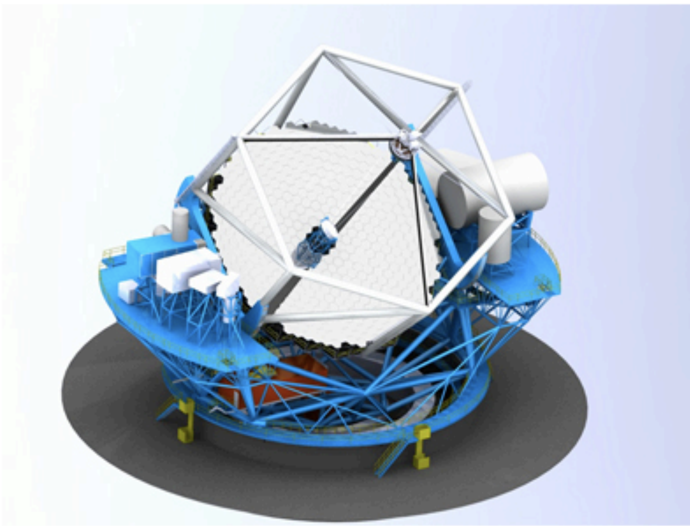


Due to the difficulty of manufacturing large mirrors that are thin enough to deform with mechanical arms, many large telescopes (such as the Keck 10-m telescopes) have segmented mirrors made of individual hexagons.



Astronomers control the telescope from a control room, which is often separate from the actual telescope. In fact, more and more observing is done 'remotely' where the astronomer designs their observations in advance and leaves an observatory employee to follow their detailed instructions.

The future: the Thirty Metre Telescope.



TMT Telescope

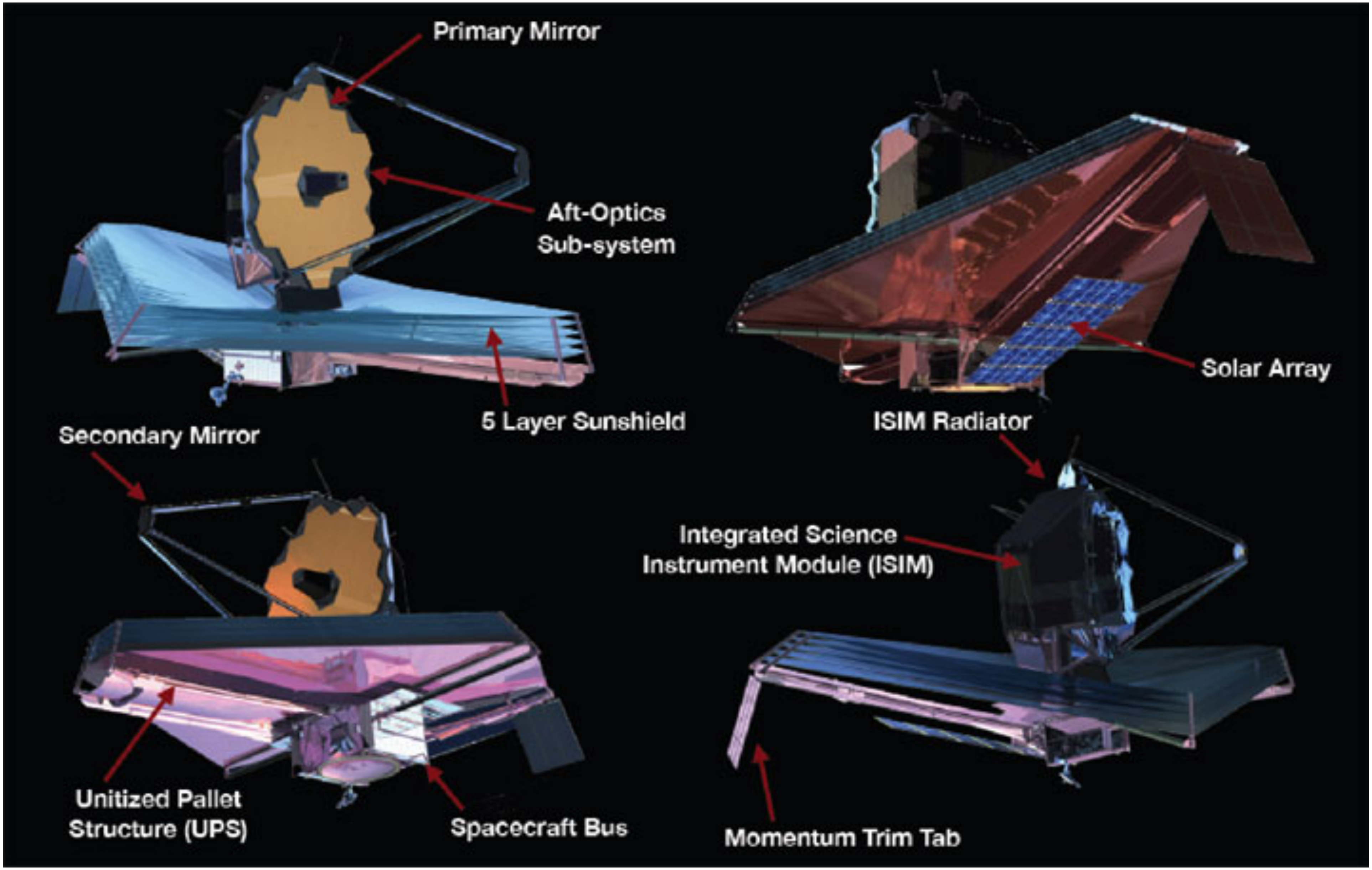
Facility with Calotte Enclosure (Canadian design)

Began construction on Hawaii in 2014, completion in 202?. A partnership between the Canada, India, China, Japan and UC/Caltech.

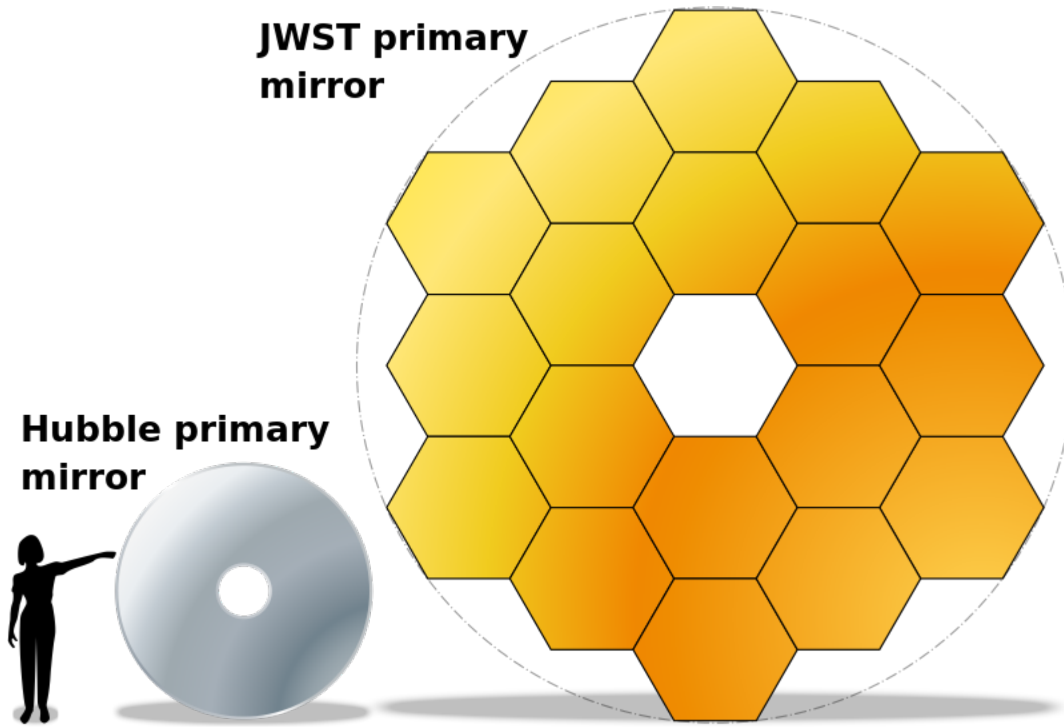
Total construction cost: $1.5bn
Instruments: $200m
Annual operations: $38m

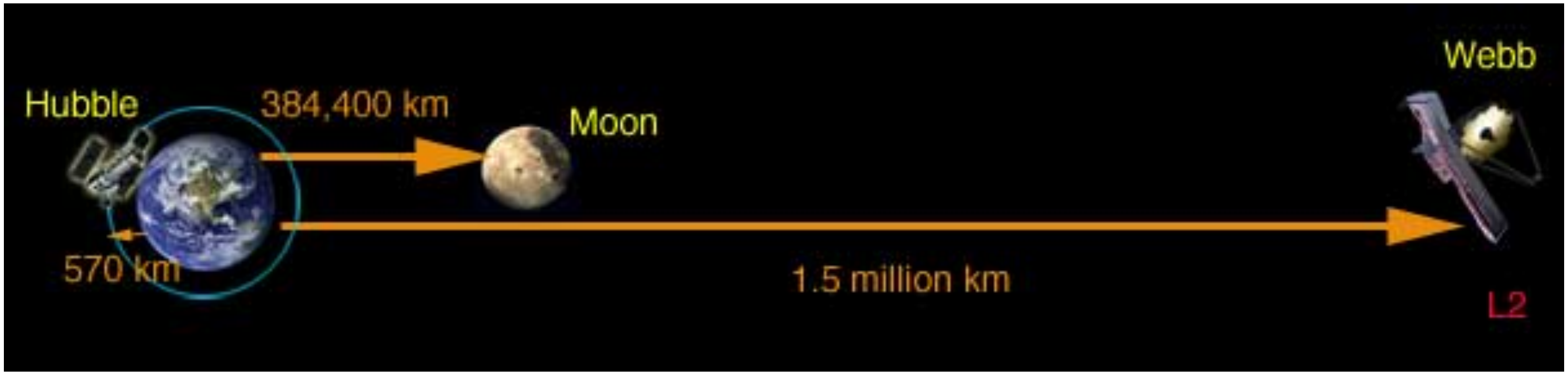
New knowledge: priceless!

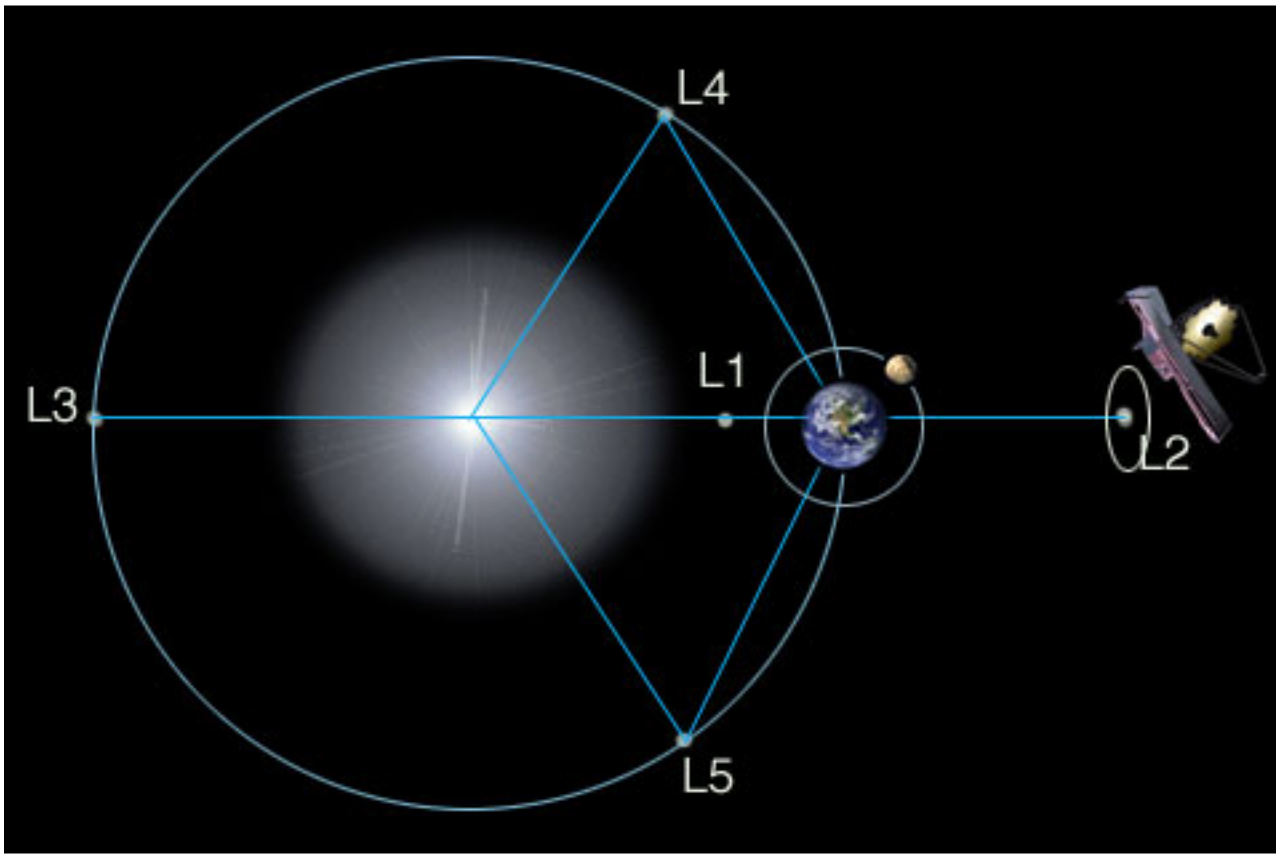
James Webb Space Telescope (JWST): 6.5m optical/NIR

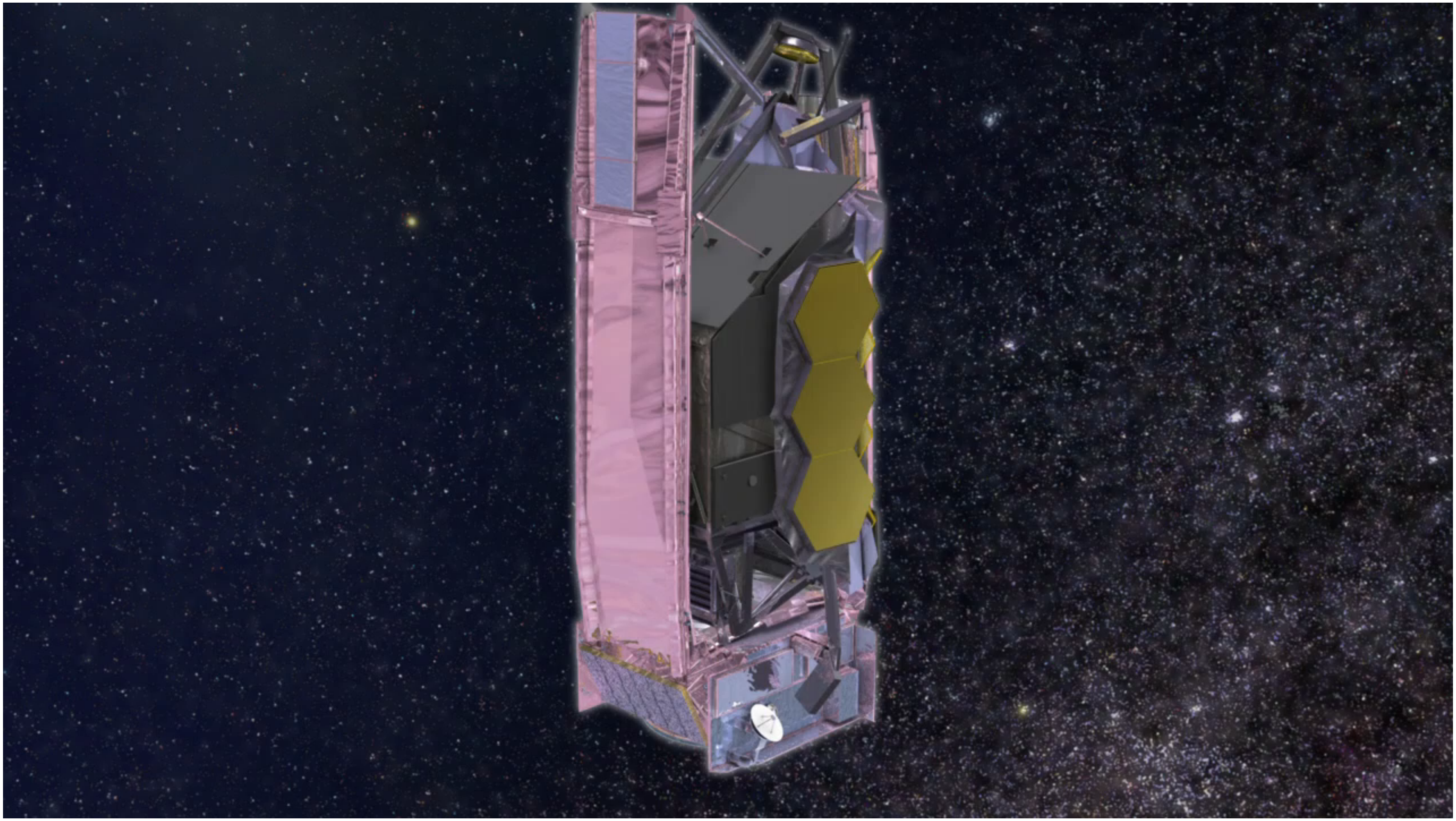



NASA

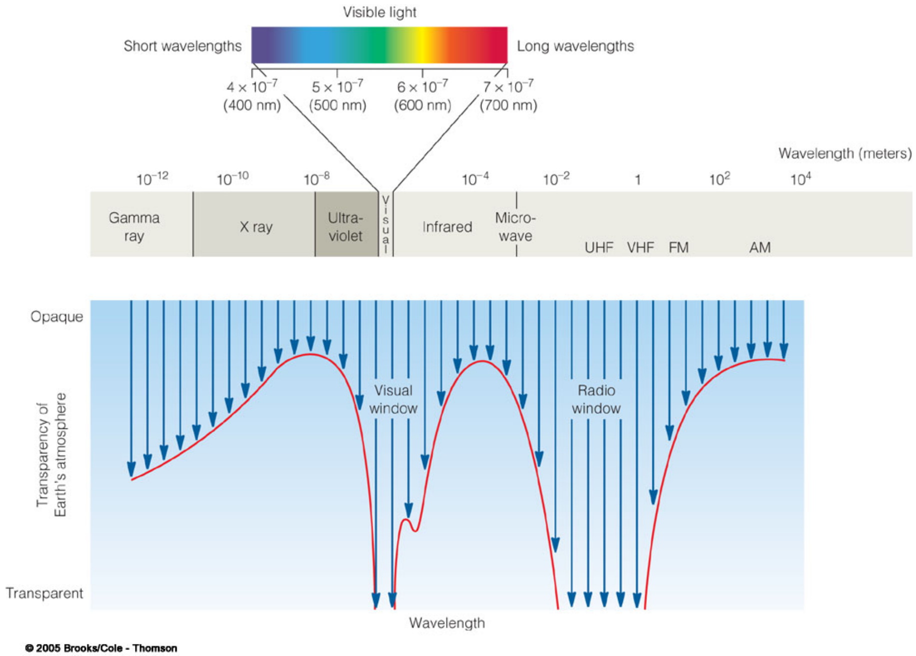

JWST primary mirror
Hubble primary mirror

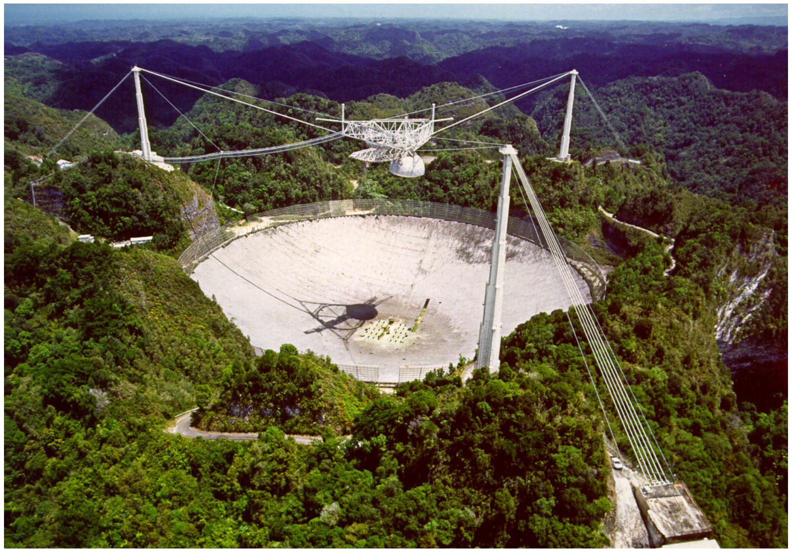

Hubble
384,400 km
Moon
Webb
570 km
1.5 million km
L2


L4
L1
L3
L2
L5

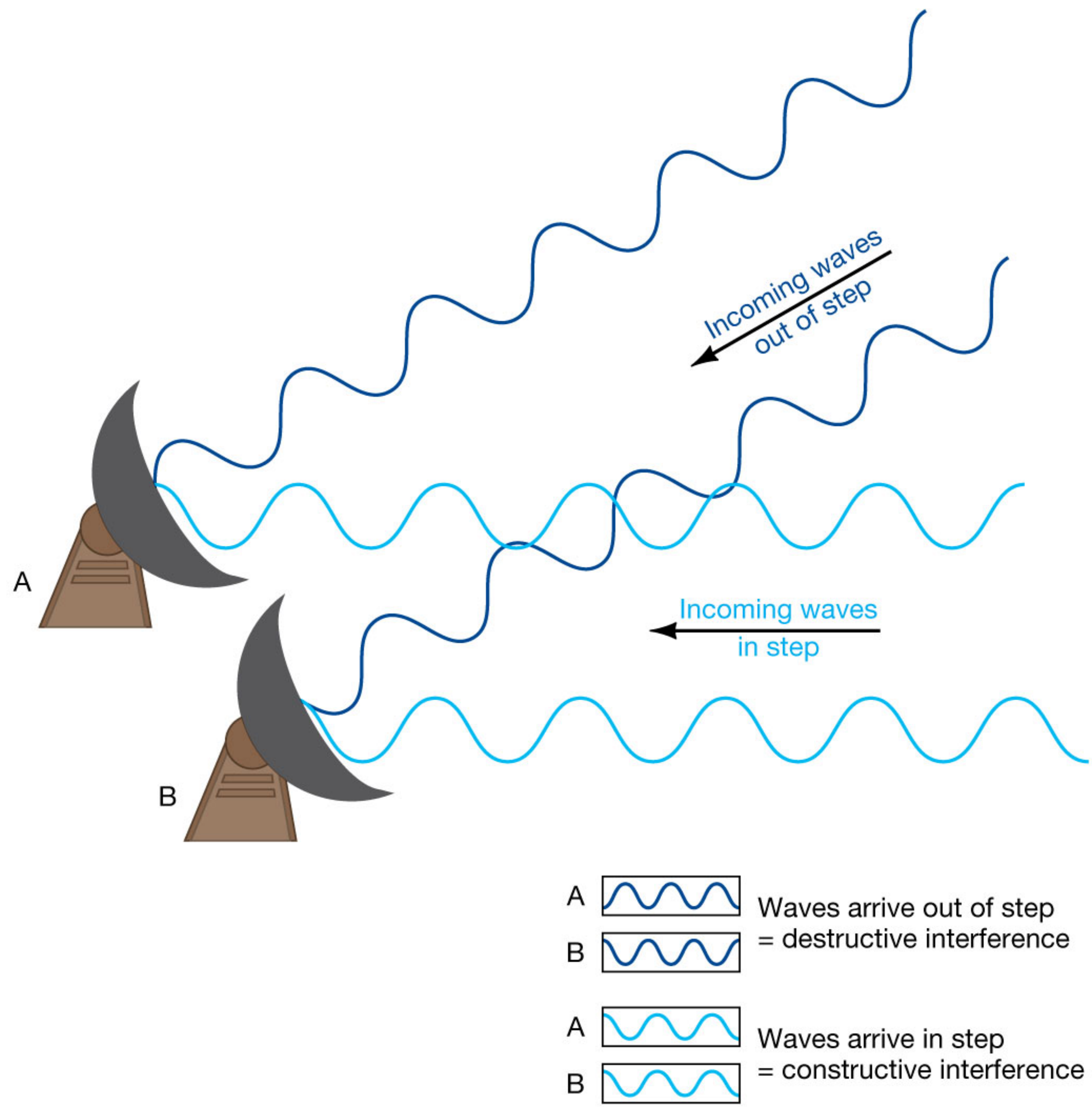


Ground-based observations can also be made at radio, sub-mm and millimetre wavelengths from the ground.



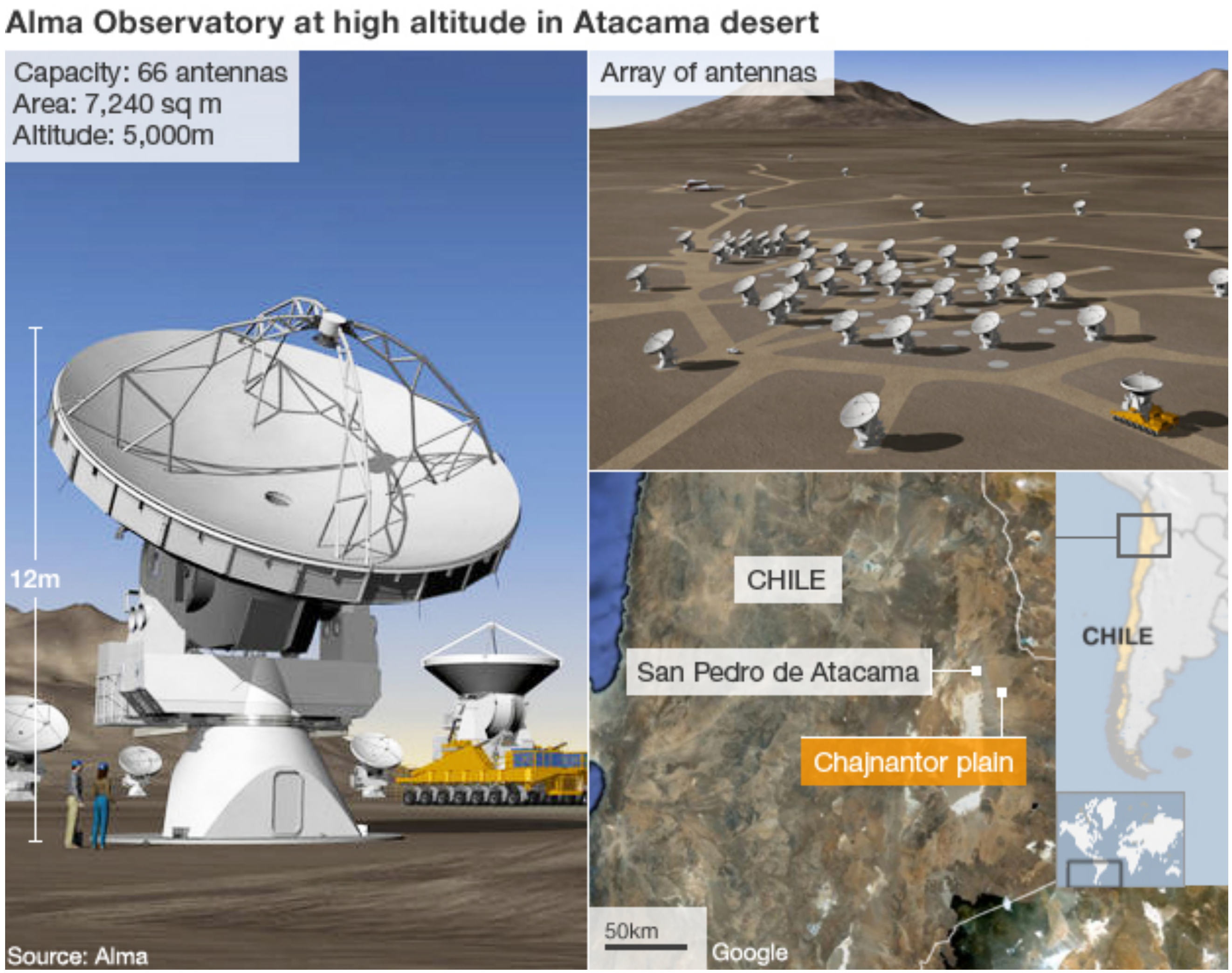


Advantages over optical astronomy: surfaces don't need to be as smooth. Can observe during the day!! Can combine antennas to produce an interferometer.

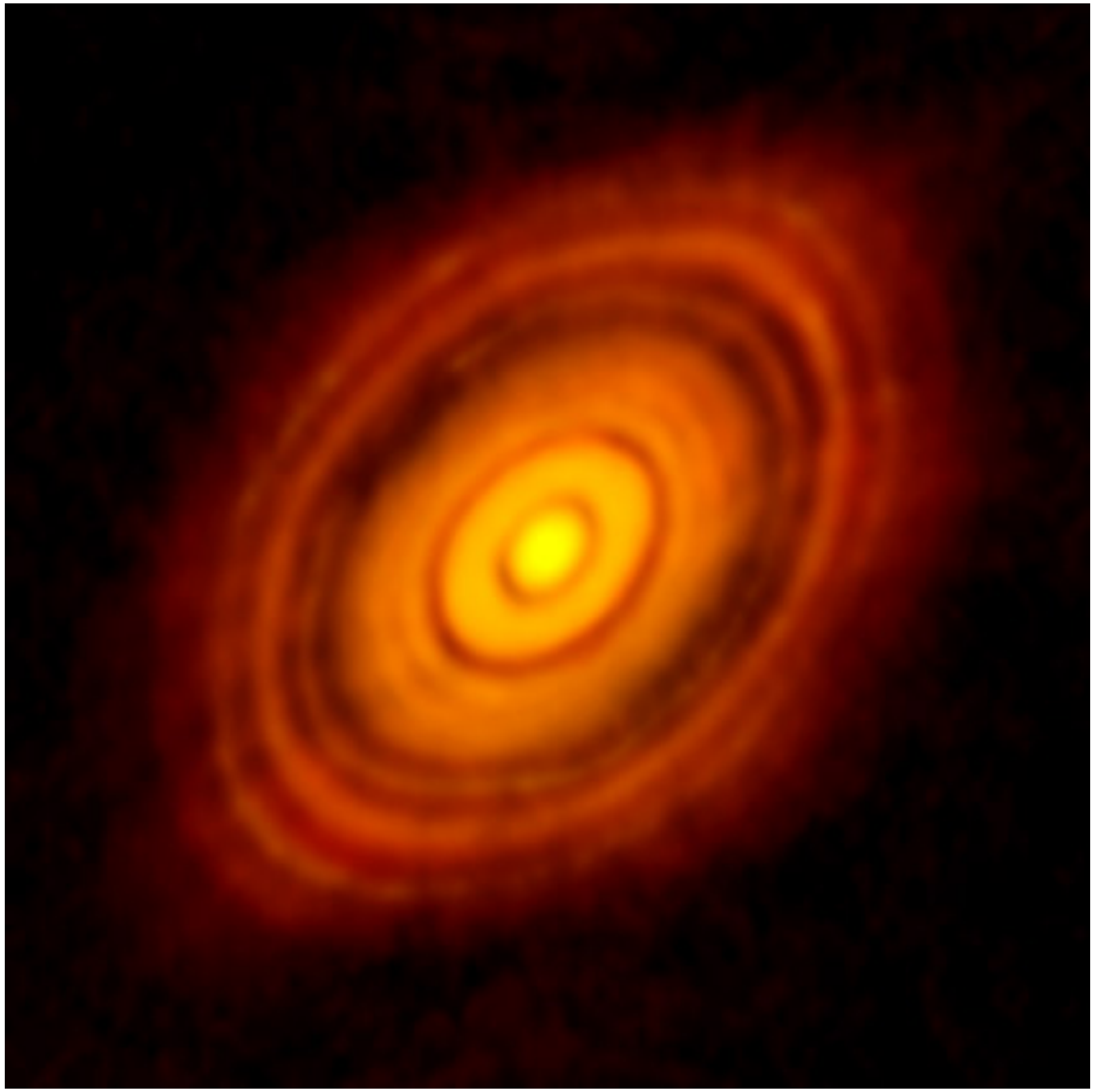

Incoming waves
out of step
Incoming waves
in step
A
B
A
B
Waves arrive out of step
= destructive interference
A
B
Waves arrive in step
= constructive interference

The Extended Very Large Array (VLA) has 27 dishes spread over 36 km.

Atacama Large Millimetre Array: ALMA
66 antennas over 16 km at 5000m altitude in Chile.



Proto-planetary disk discovered by ALMA in 2014.



Further ahead: SKA (built in Australia and S. Africa) collecting area of a square km! Construction starts in 2018, full operations in 2024. Antennas spread over 3000 km.