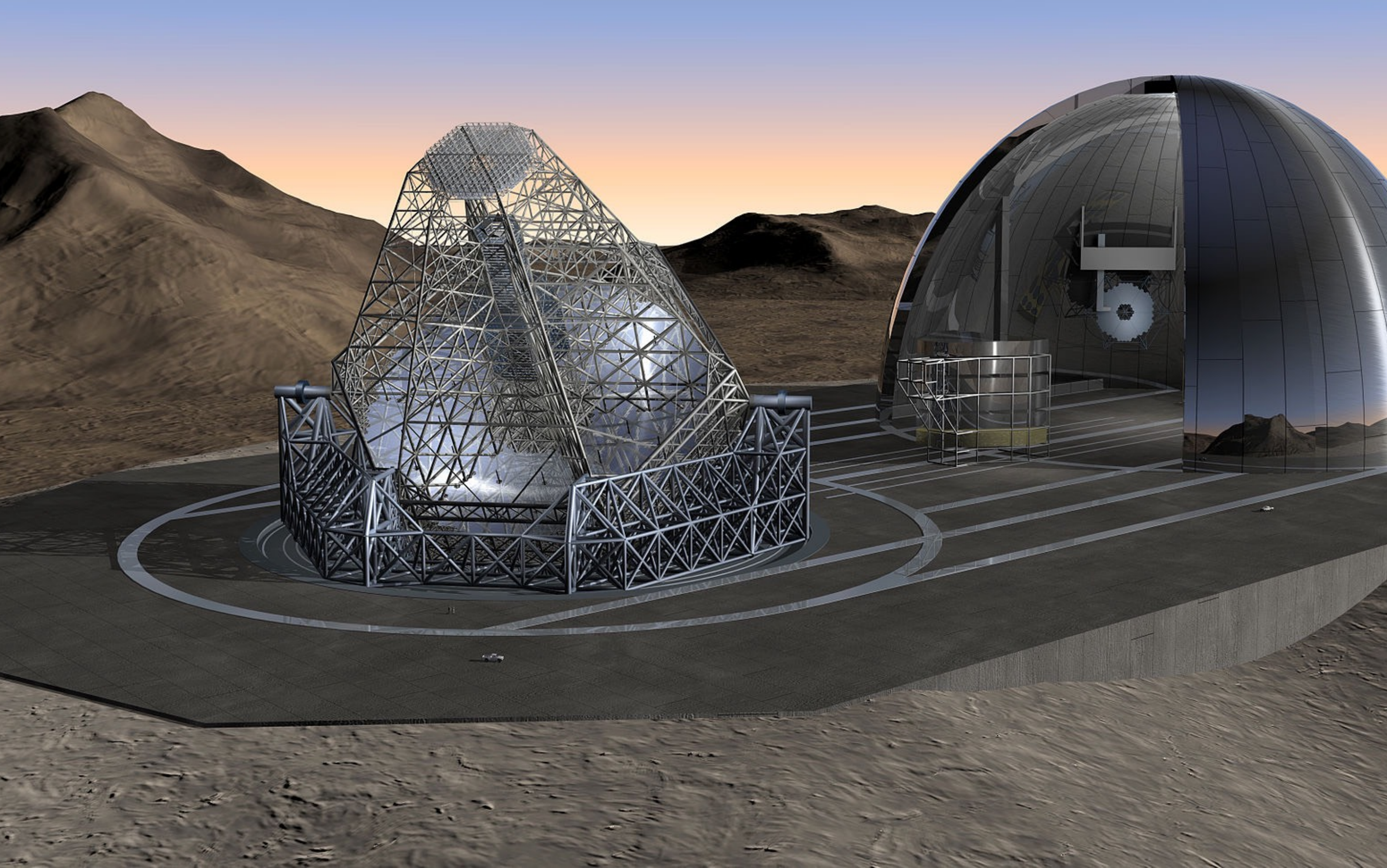
Chap 6: Astronomical Instruments



Part I: Spectral Formation & Atomic Transitions

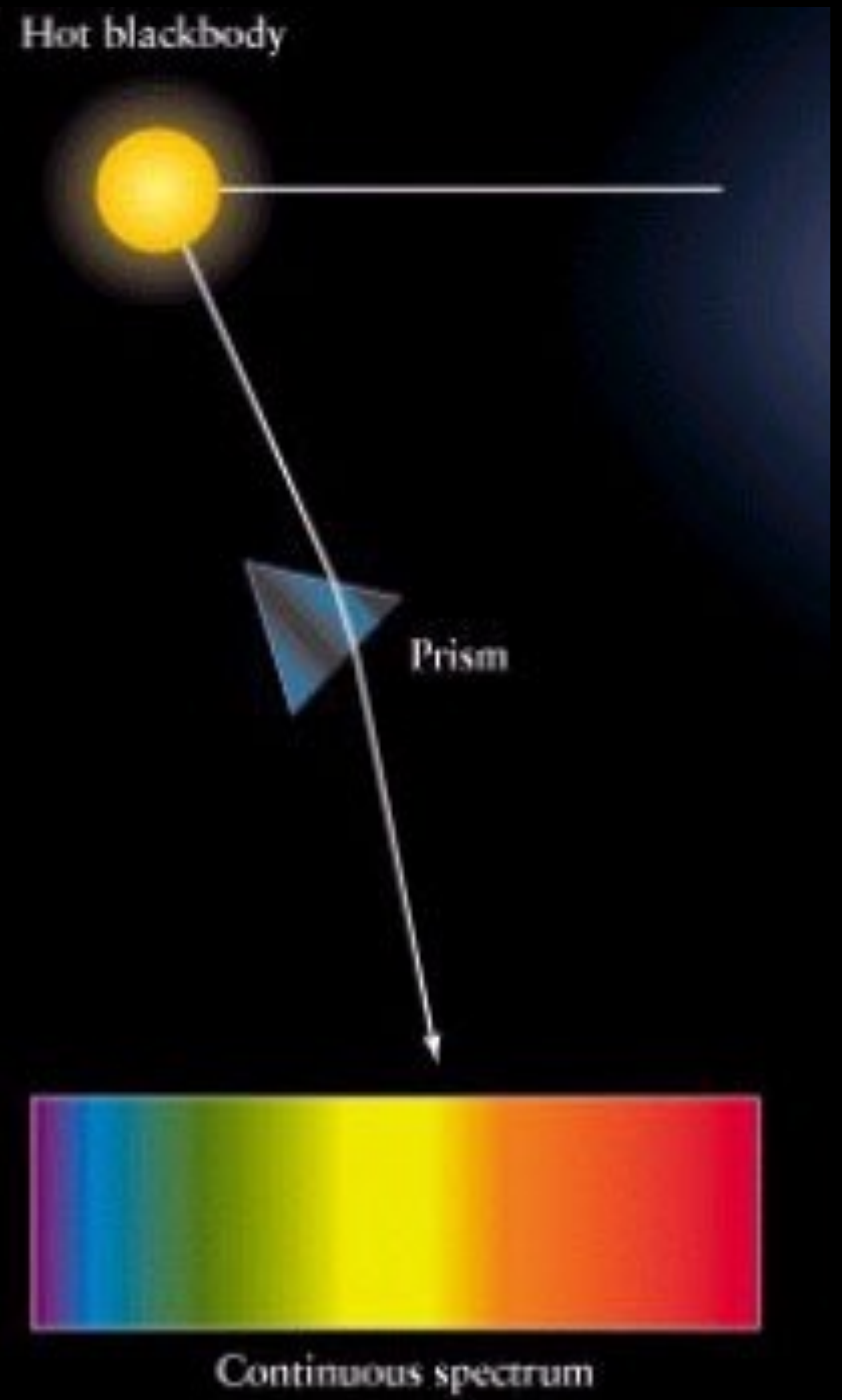
- **Kirchhoff's laws of Spectroscopy**: the formation of three types of spectra
  - Continuum, Absorption lines, Emission Lines
- **Atomic and ionic transitions**
  - Bohr's model of Hydrogen atoms
  - Discrete energy levels of atoms/ions when they are far apart from one another (i.e., gas phase, not solid)
  - Identification of chemical elements in spectra

Three Types of Spectra

Kirchhoff's Laws of Spectroscopy

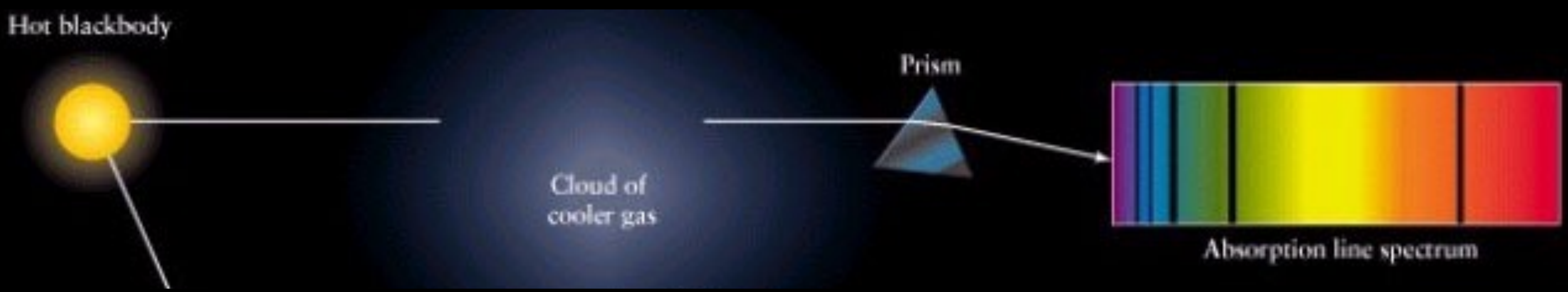
Kirchhoff's Three Laws of Spectroscopy

Law 1 A hot opaque body, such as a perfect blackbody, or a hot, dense gas produces a **continuous spectrum** -- a complete rainbow of colors with without any specific spectral lines.

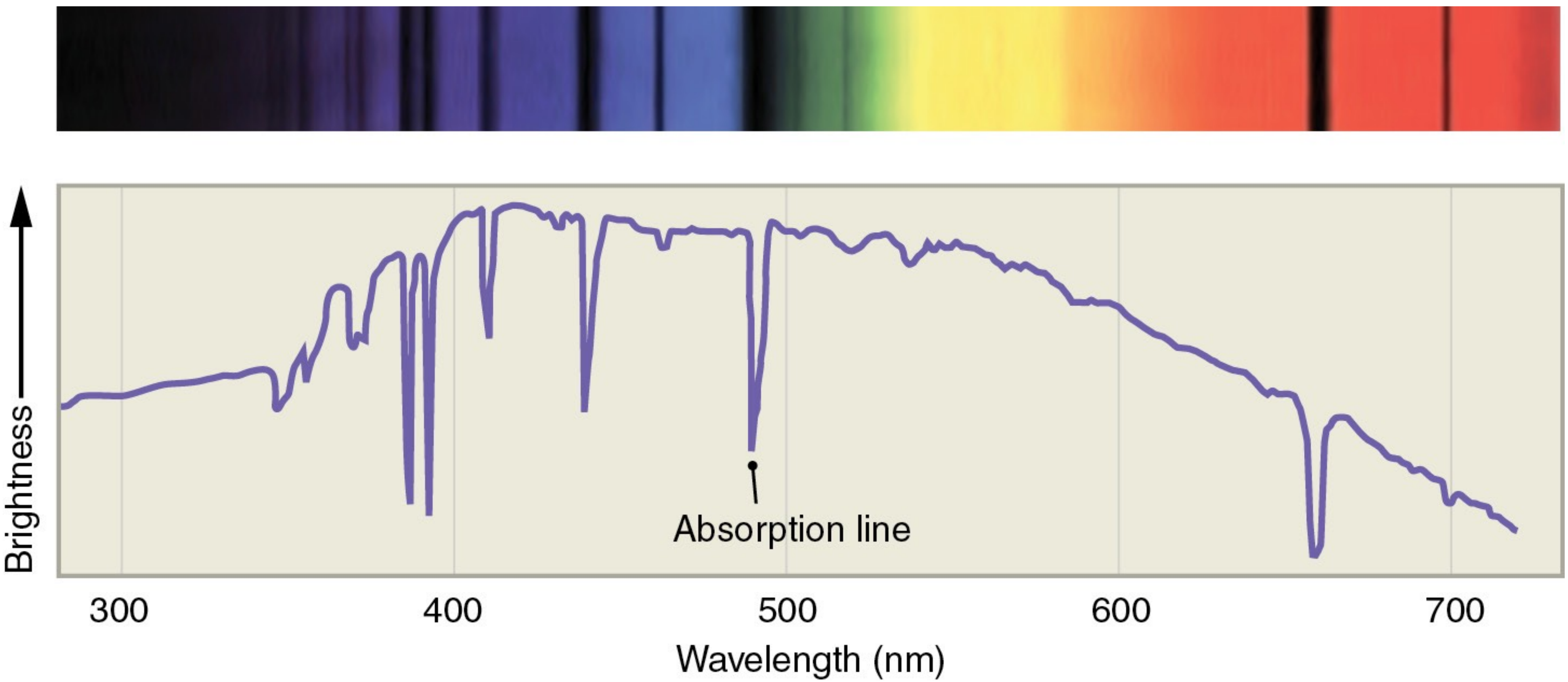


Kirchhoff's Three Laws of Spectroscopy

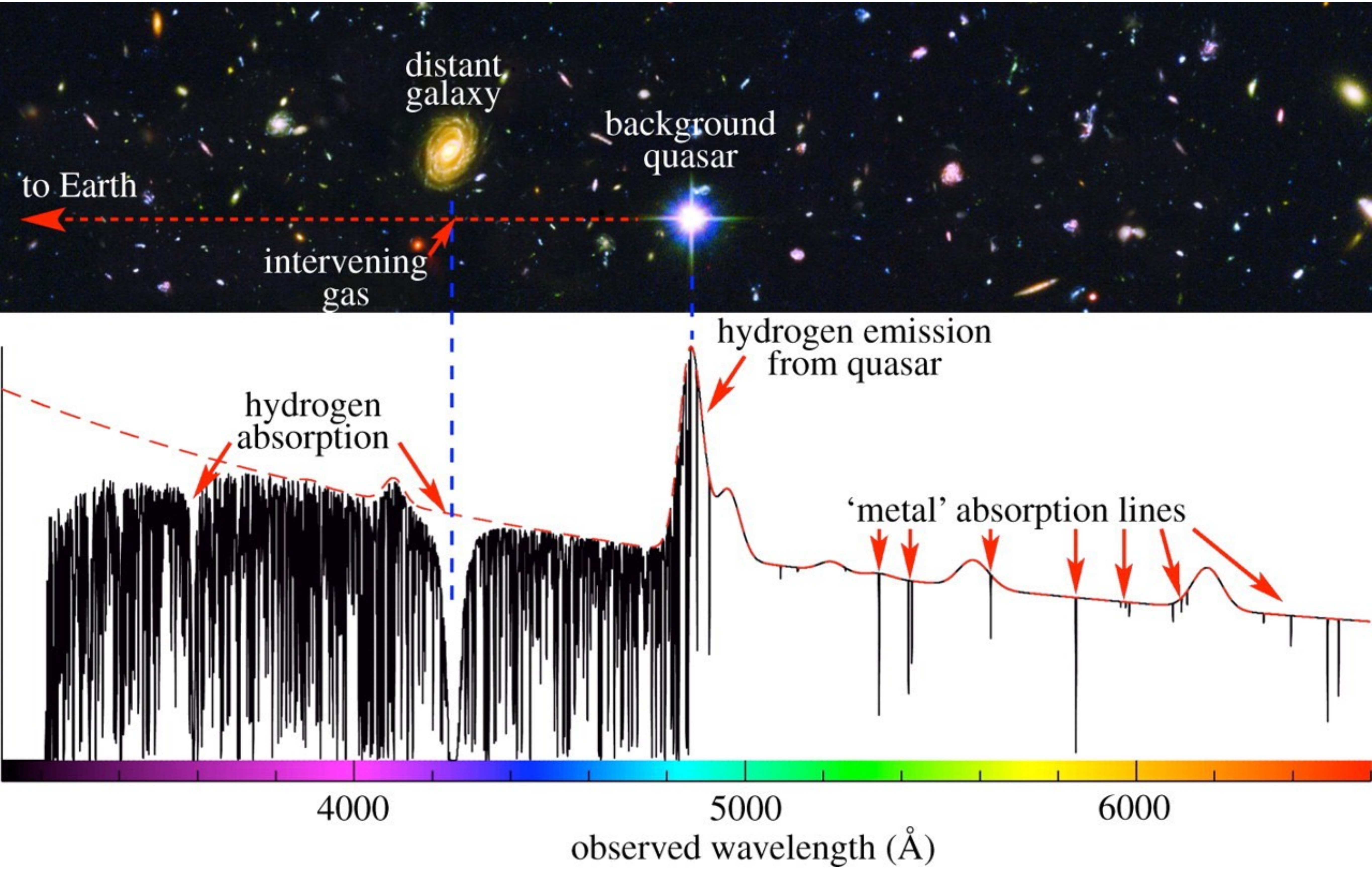
Law 3 A cloud of cool gas in front of a source of a continuous spectrum produces an **absorption line spectrum** - a series of dark spectral lines among the colors of the continuous spectrum.



Kirchoff’s Laws: Continuous and Absorption Spectra

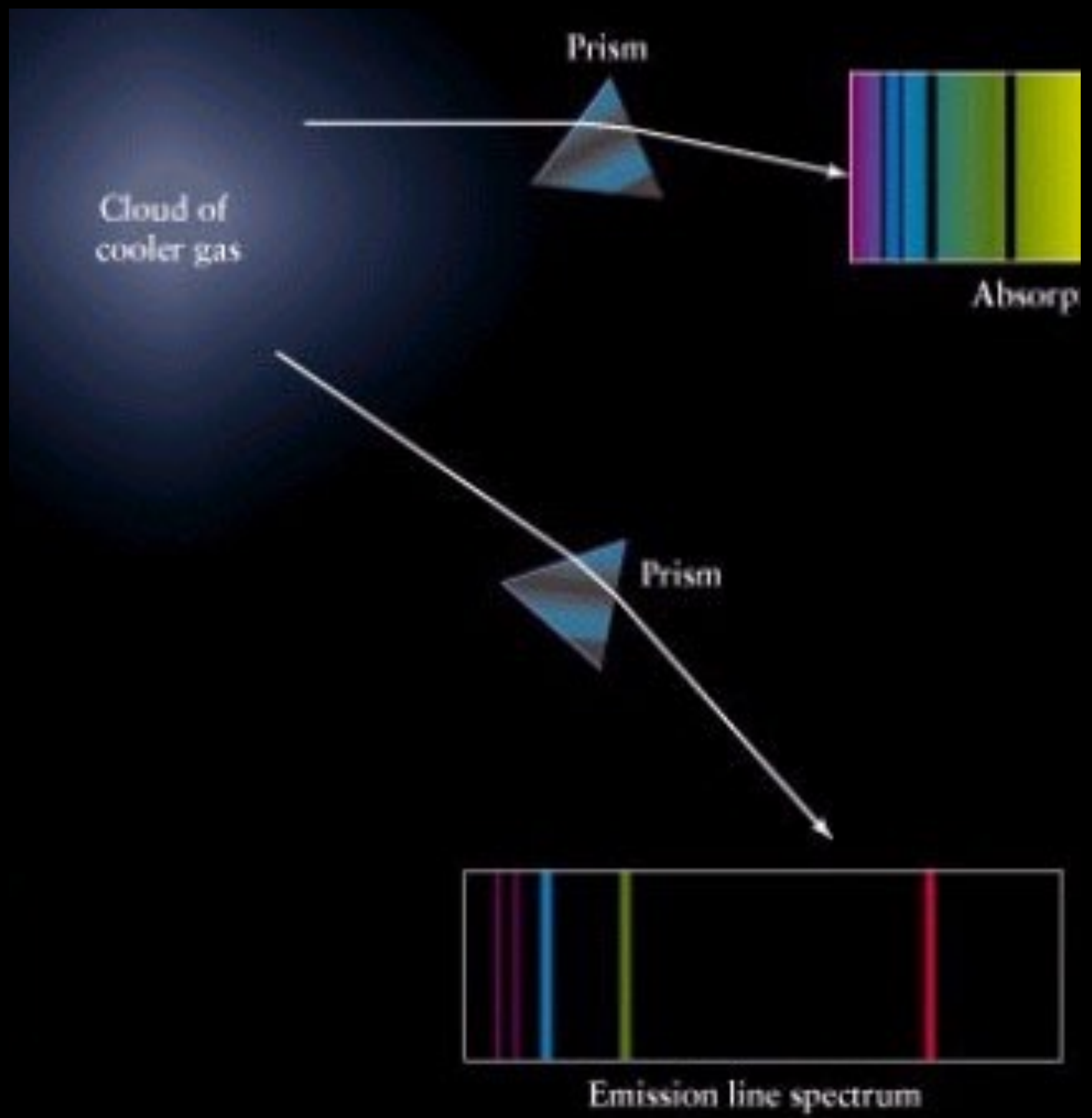


Absorption Lines in Quasar Spectra Reveal the Intergalactic Medium

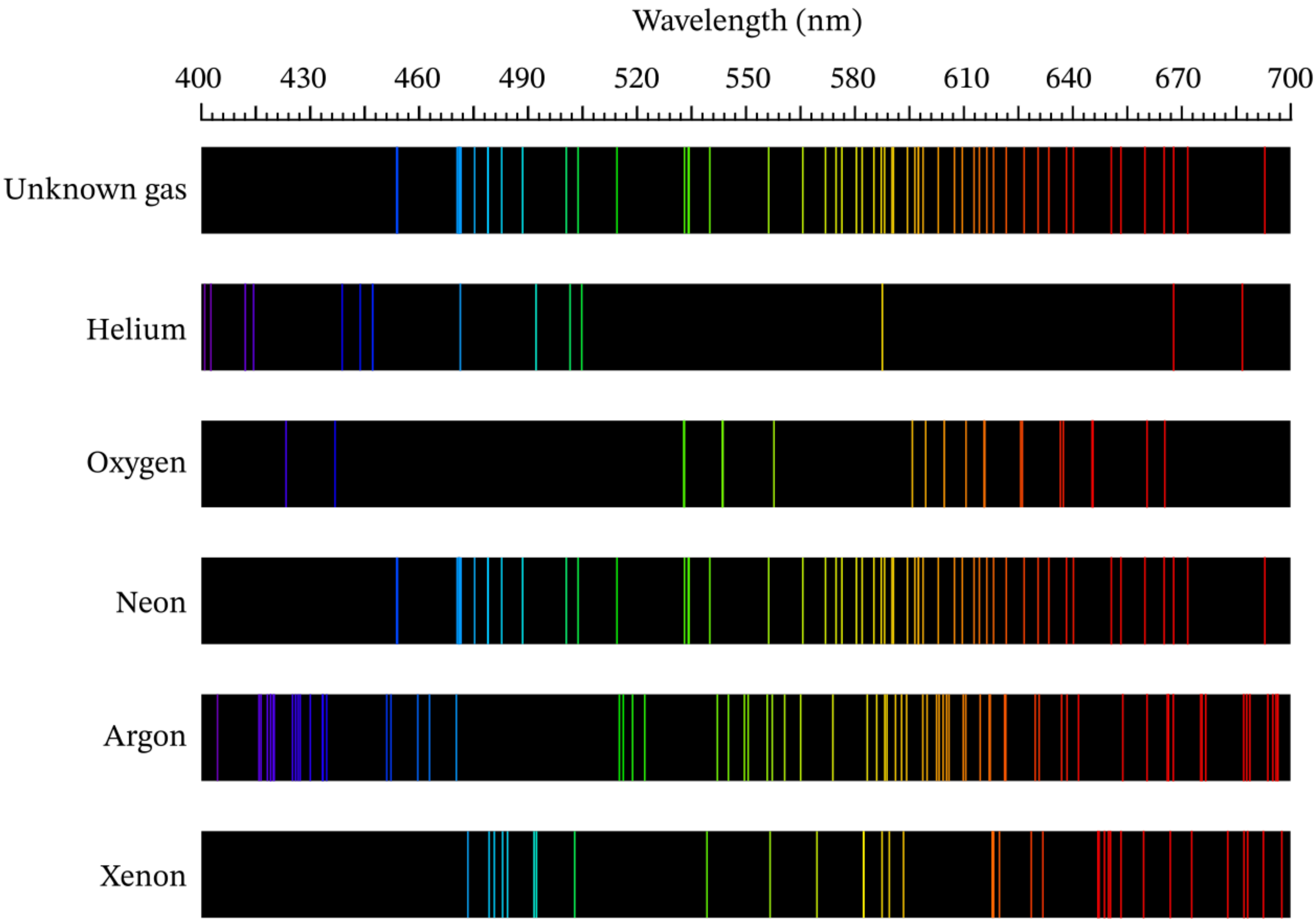


Kirchhoff's Three Laws of Spectroscopy

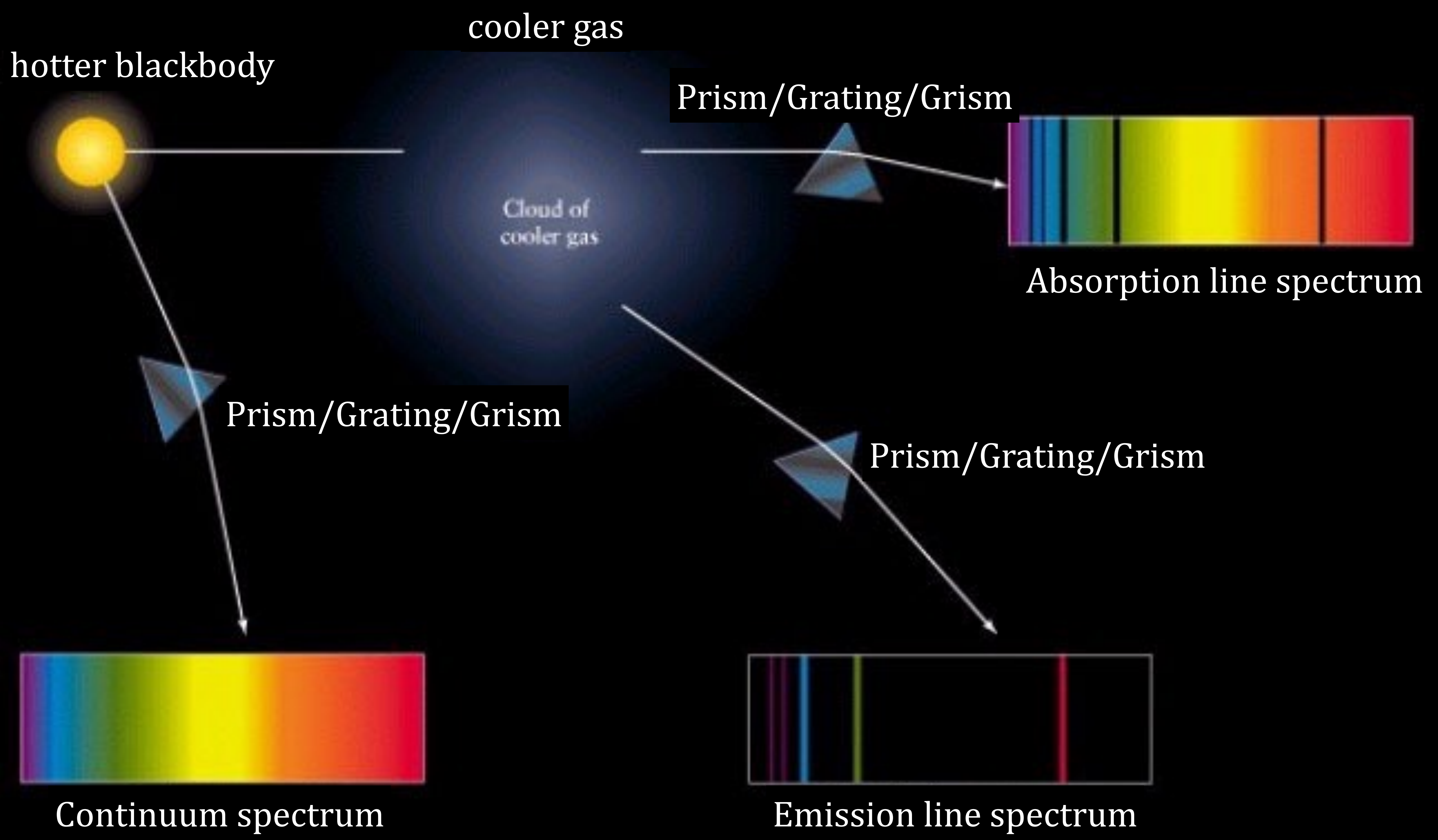
Law 2 The same gas cloud produces an **emission line spectrum** - a series of bright spectral lines against a dark background - when viewed sideways



Example Emission Line Spectra



Kirchhoff's Empirical Laws of Spectral Formation

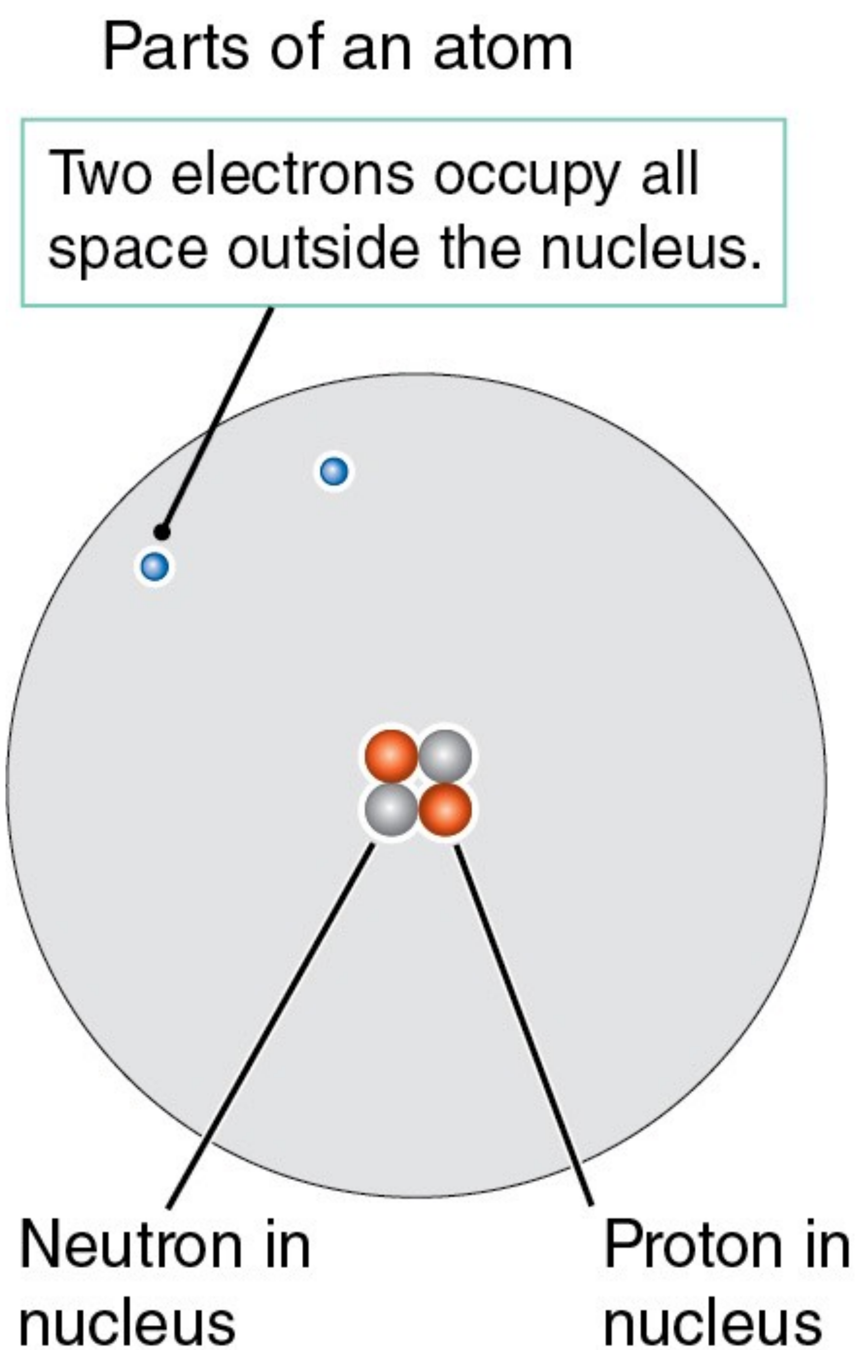


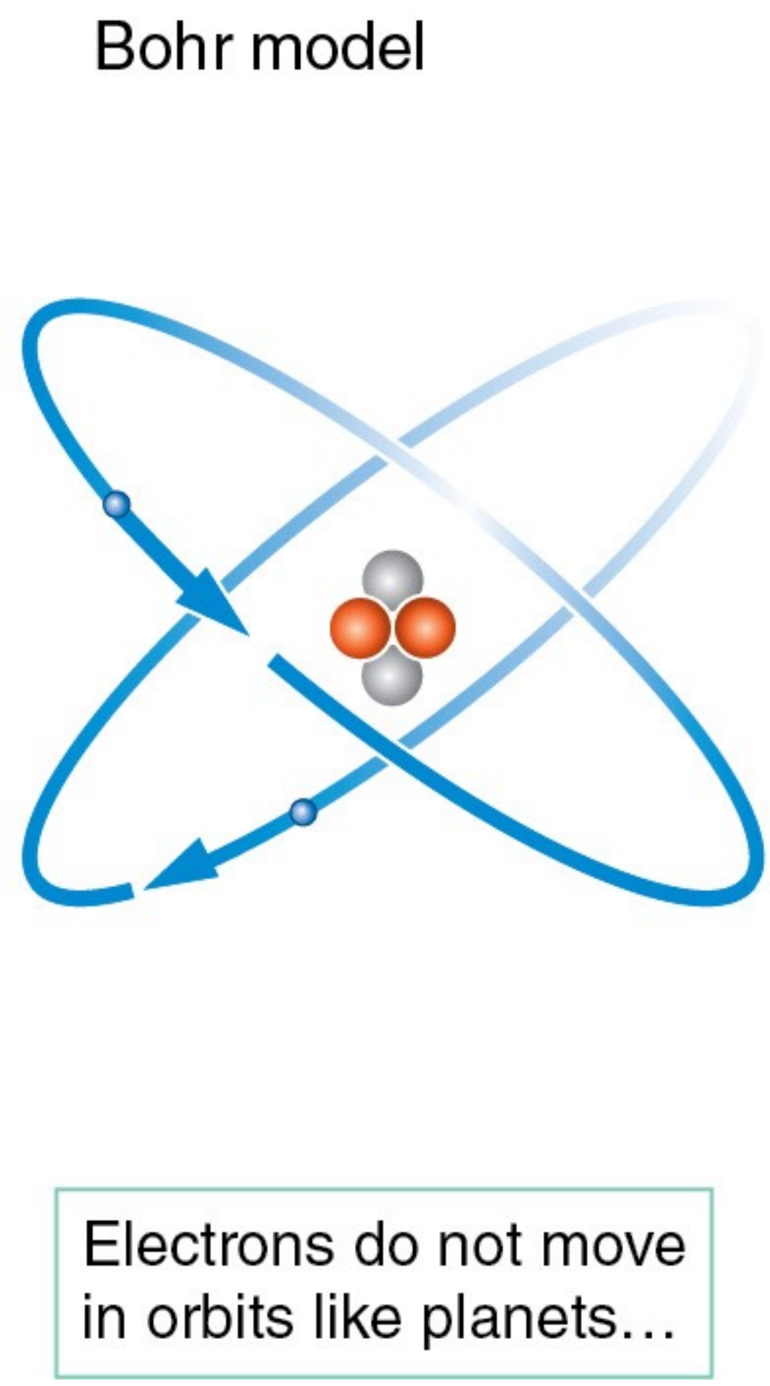
Atomic Transitions

use quantum mechanics to predict the specific wavelengths of emission lines

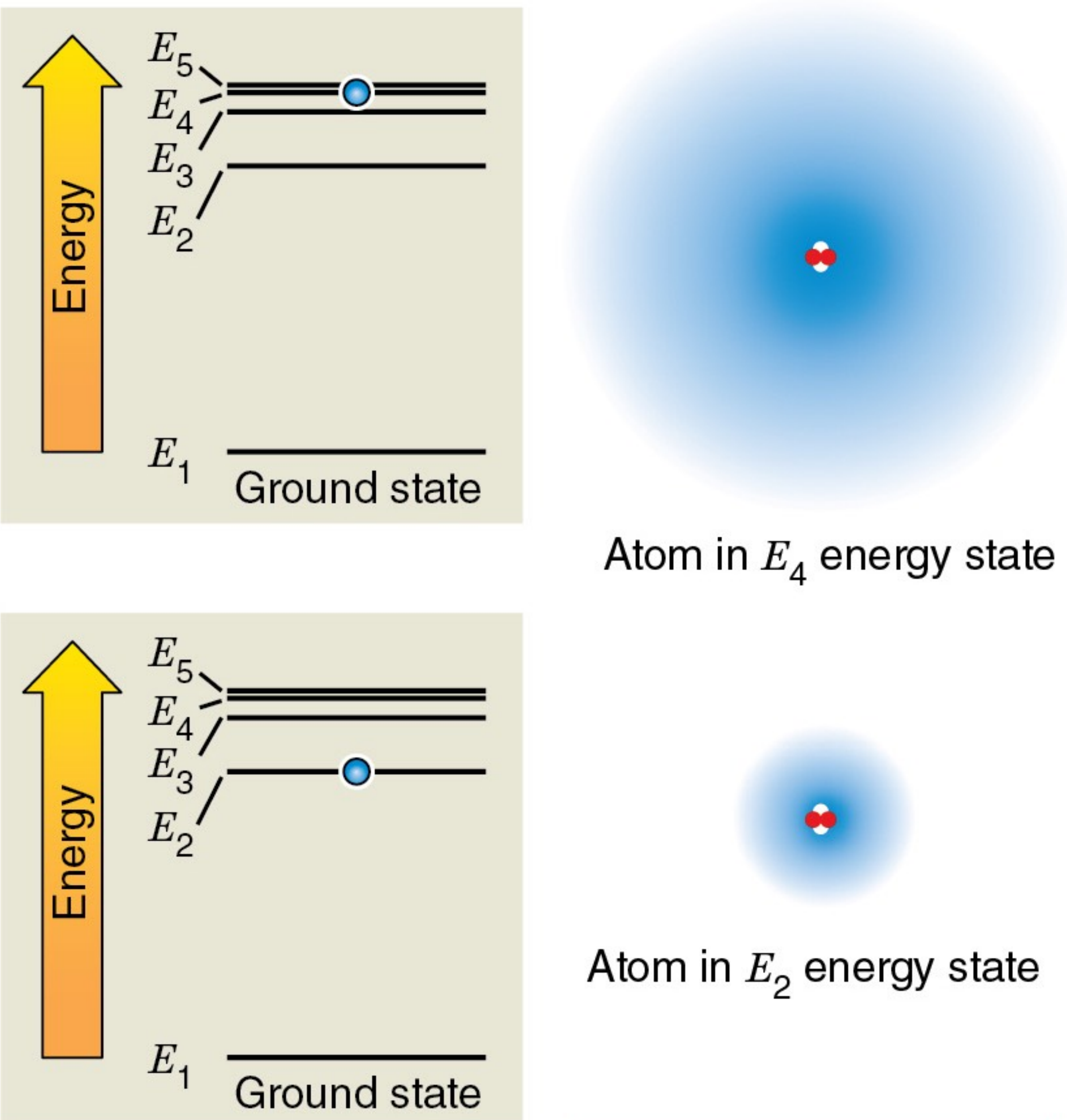
Atoms and Light – 1

- Atoms have a dense nucleus of **protons** and **neutrons**.
- **Electrons** surround the nucleus in a "cloud."





Atoms and Light – 2



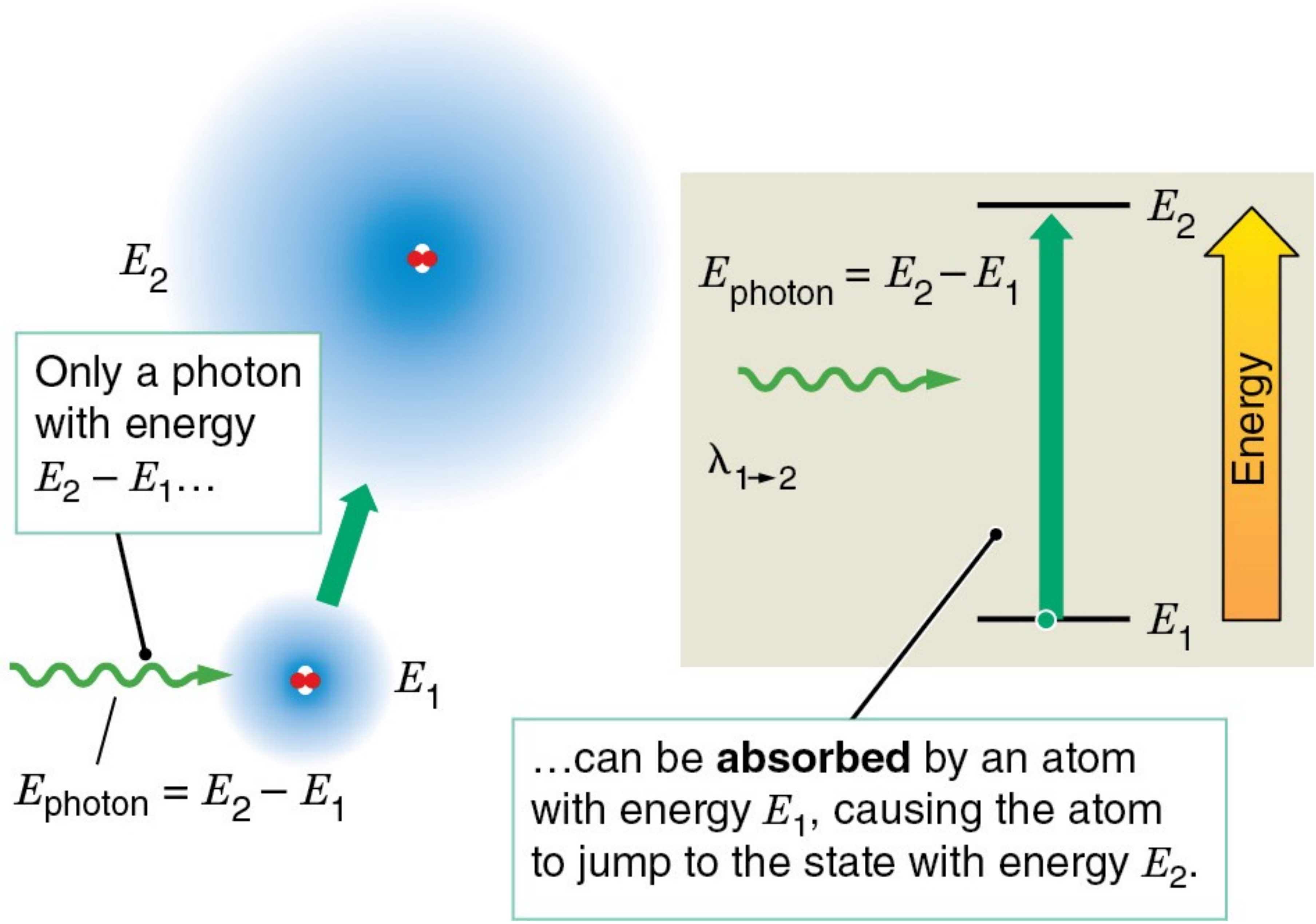
We use **energy level diagrams** to represent the allowed states of an atom.

Analogously, atoms exist in one allowed energy state or another, but never in between.

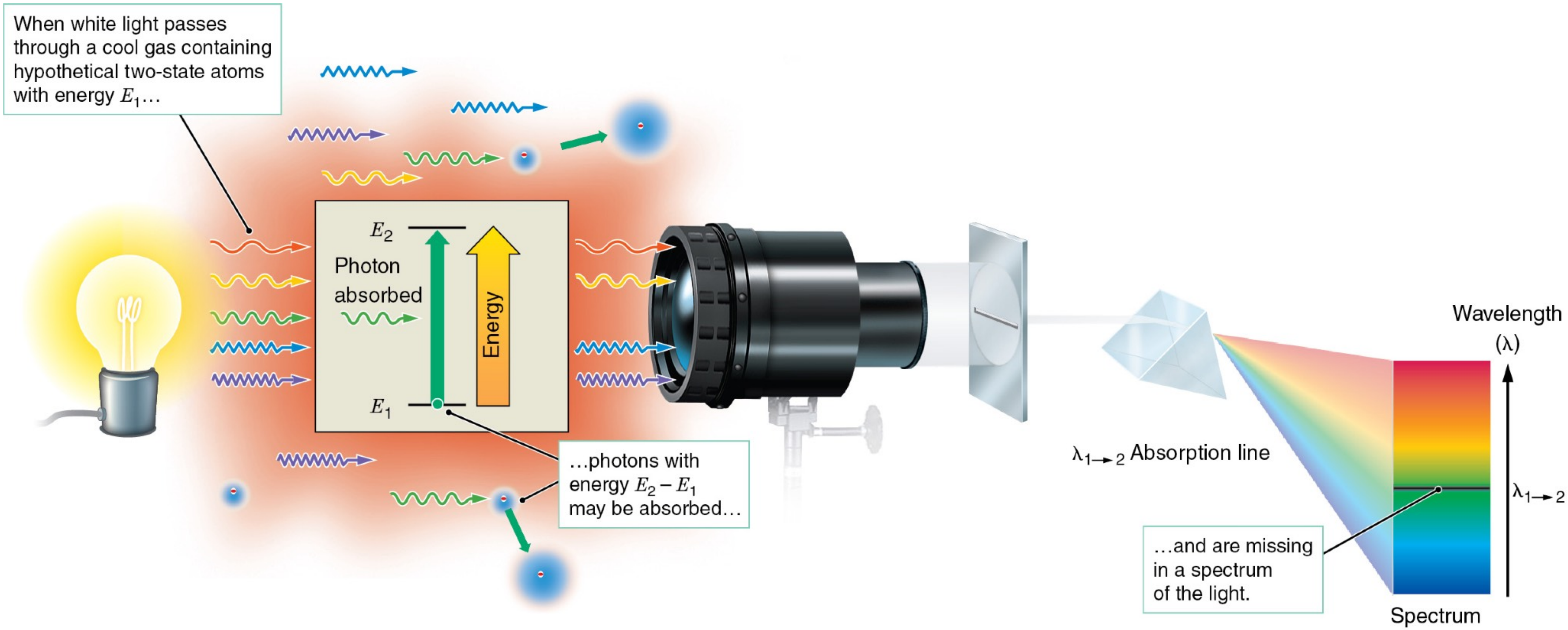
- Electrons can have certain quantized energies; other energies are not allowed.
- Each type of atom has a unique set of energies.
- When electrons change energy levels, they absorb or emit light.
- Electrons not in the ground state are said to be in **excited states**.

Absorption Spectra

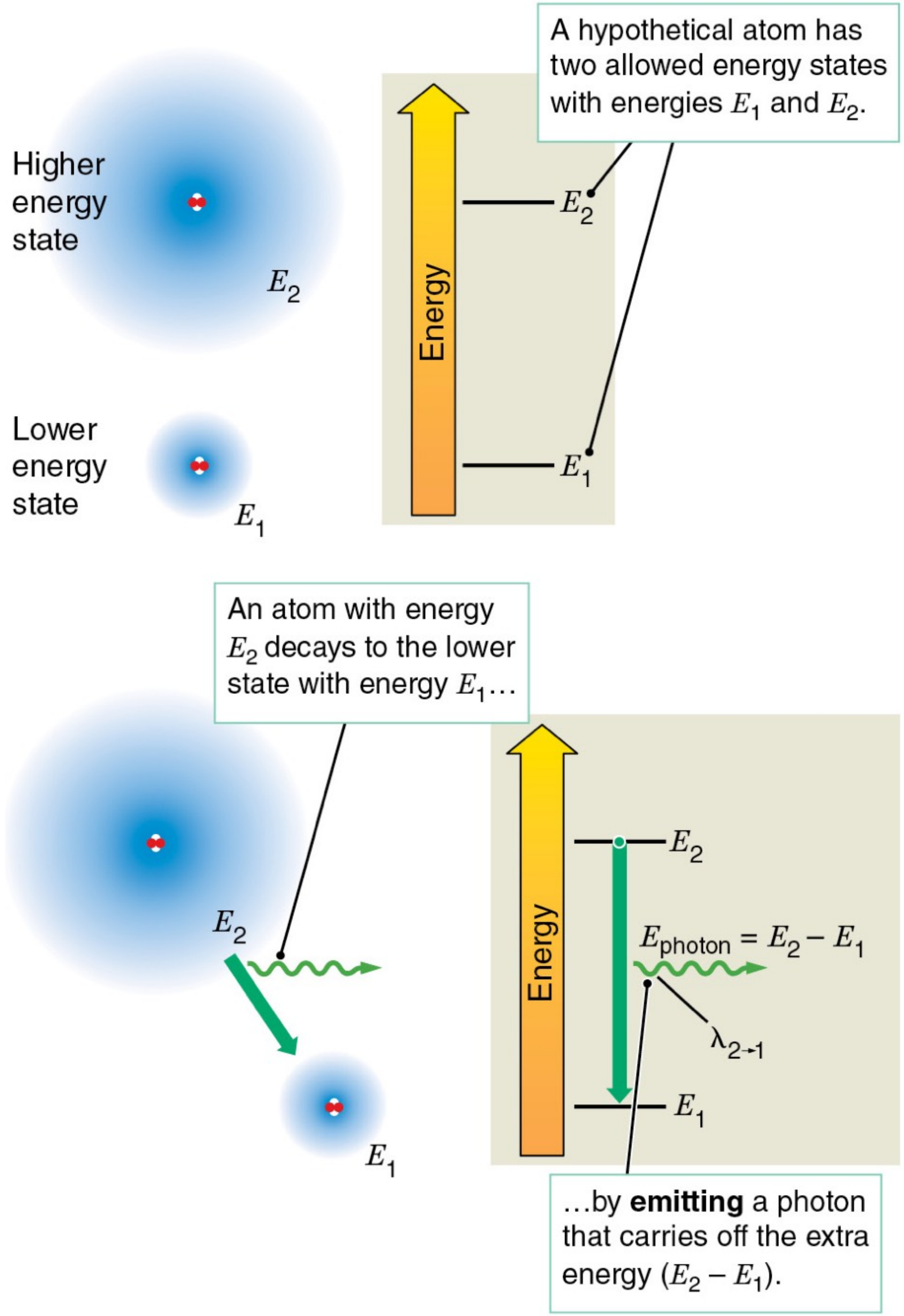
- **Absorption**: An electron absorbs the energy of a photon, moving the electron to a higher energy level.
- The photon's energy has to be equal to the energy difference.
- This will absorb a photon with a specific wavelength



Absorption Spectra

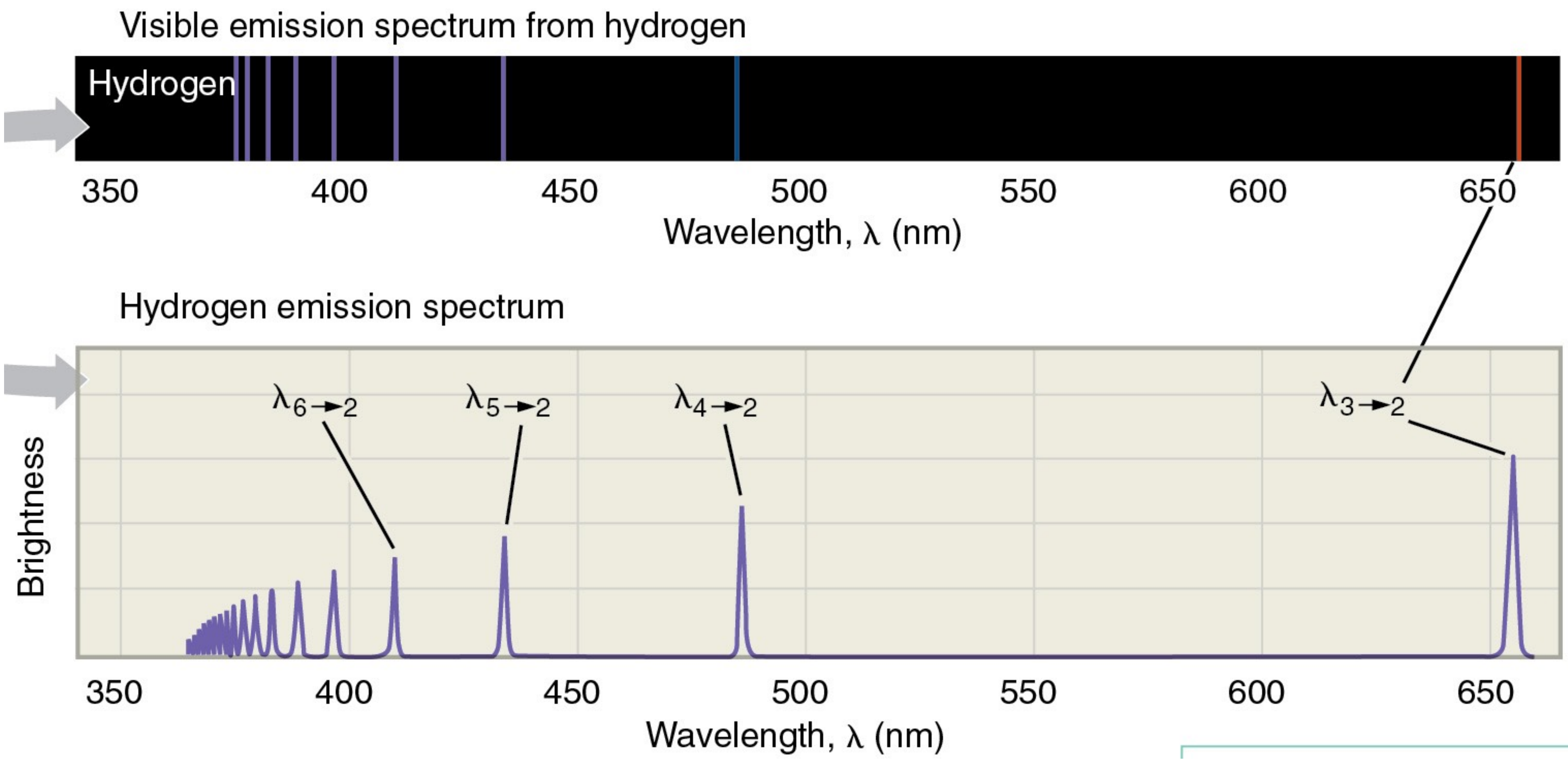


Emission Spectra

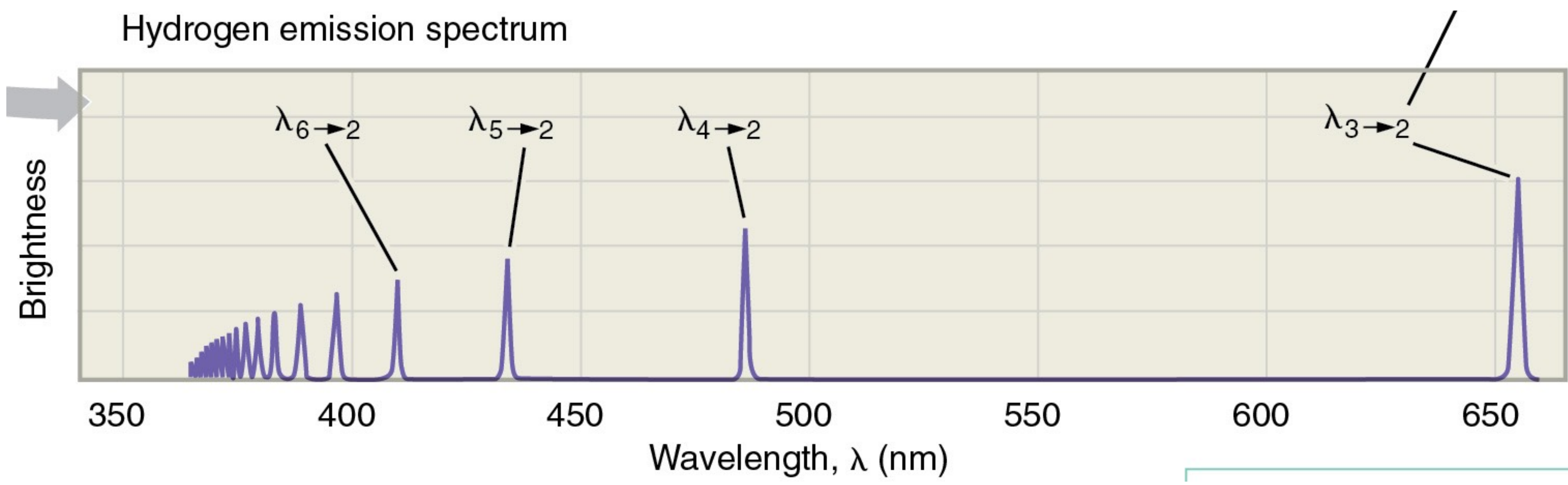


- **Emission**: An electron in an excited state emits a photon and drops to a lower energy state, losing energy.
- The photon's energy is equal to the energy difference between the two levels.
- This produces a photon with a specific wavelength (color).

The Emission-Line Spectrum of Hydrogen



Bohr's model predicts wavelengths of hydrogen lines



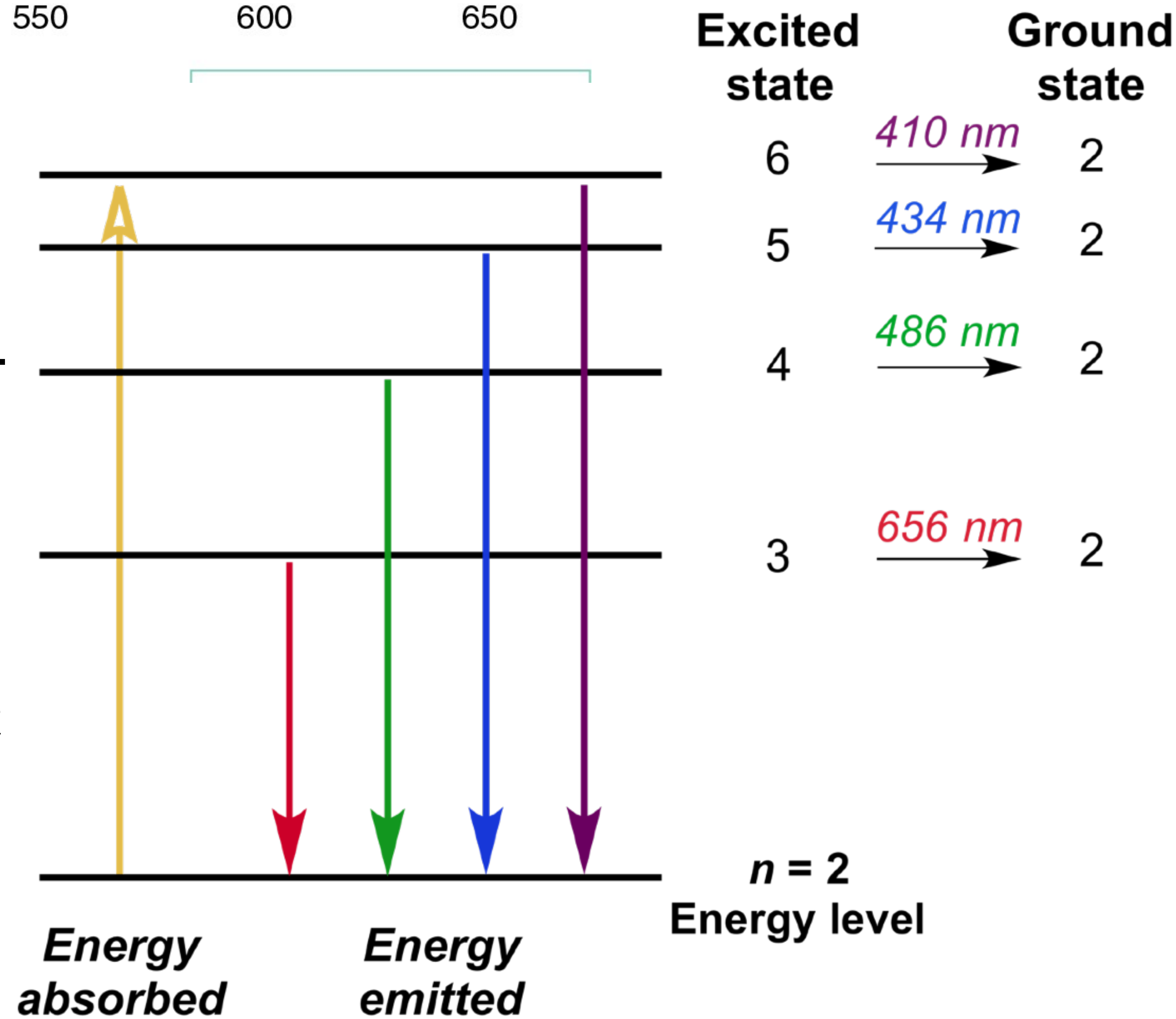
$$E_n = -\frac{13.6\ \text{eV}}{n^2}$$

$$\frac{1}{\lambda} = \left(\frac{1}{n_{\text{low}}^2} - \frac{1}{n_{\text{high}}^2}\right)\frac{13.6\text{eV}}{hc}$$

n_{low} = quantum number of lower orbit

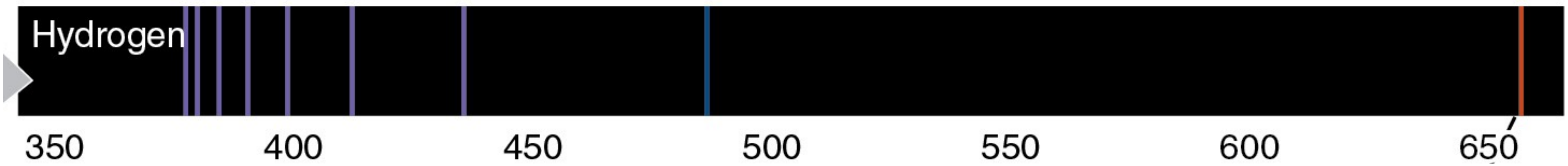
n_{high} = quantum number of higher orbit

λ = wavelength of emitted photon



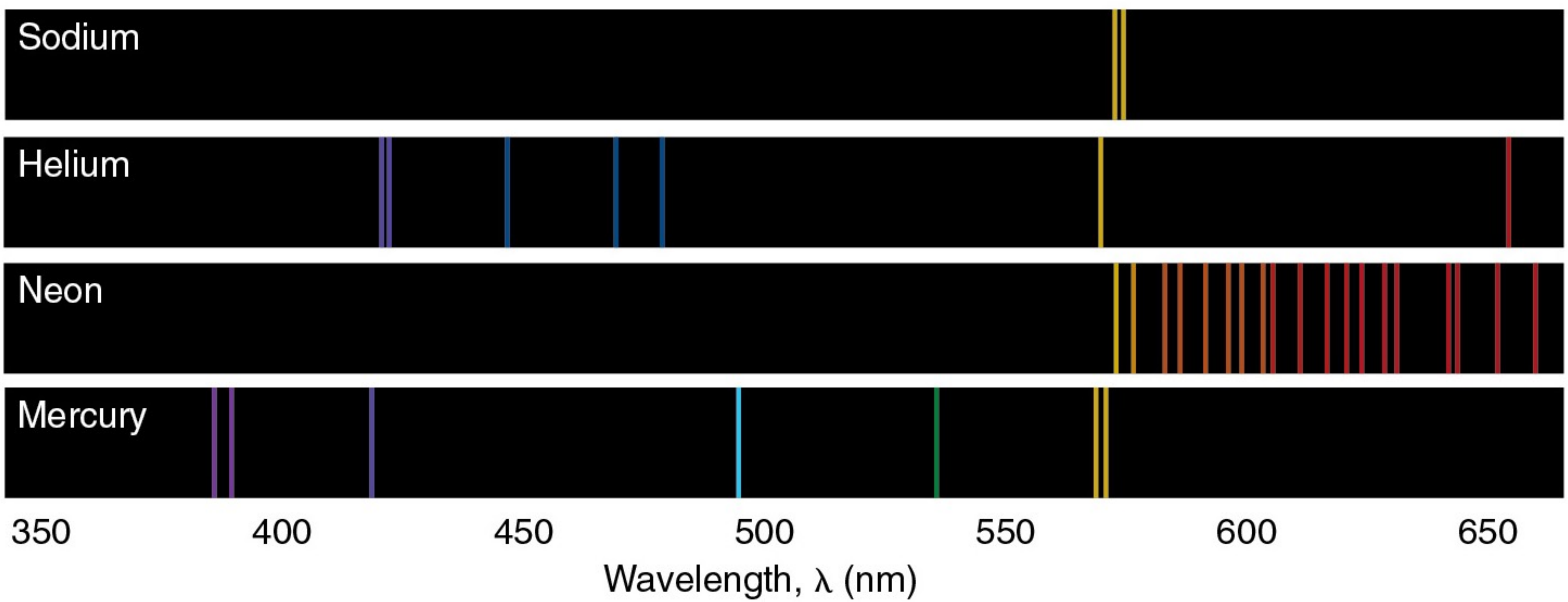
Emission Line Spectra from Different Elements Can Be Calculated

Visible emission spectrum from hydrogen

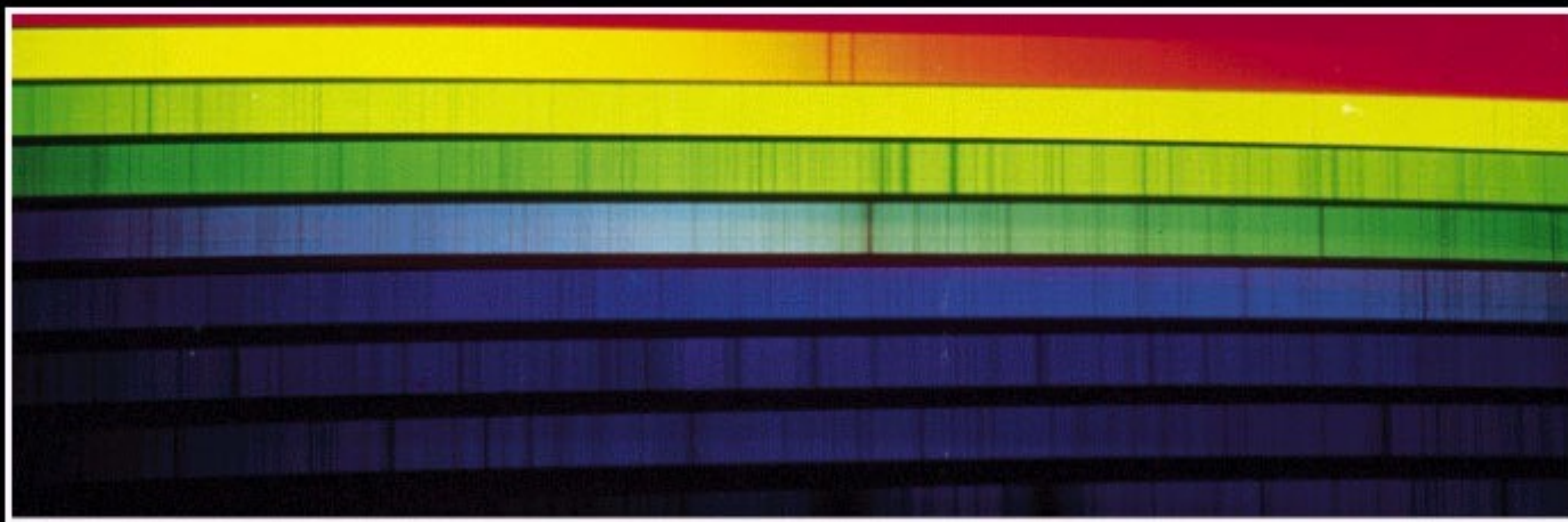


Each type of atom has a unique spectral fingerprint.

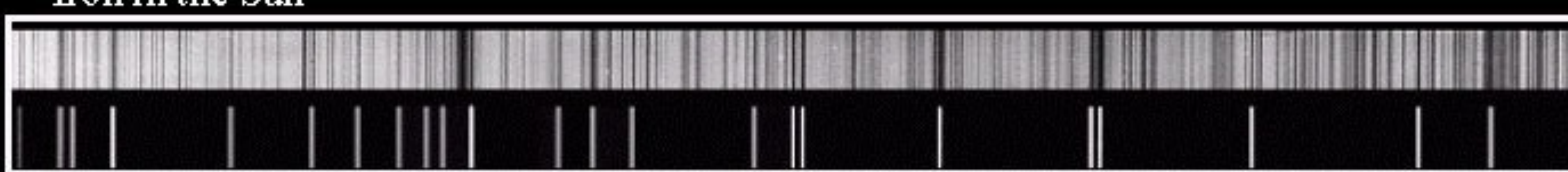
Emission spectra for sodium, helium, neon, and mercury



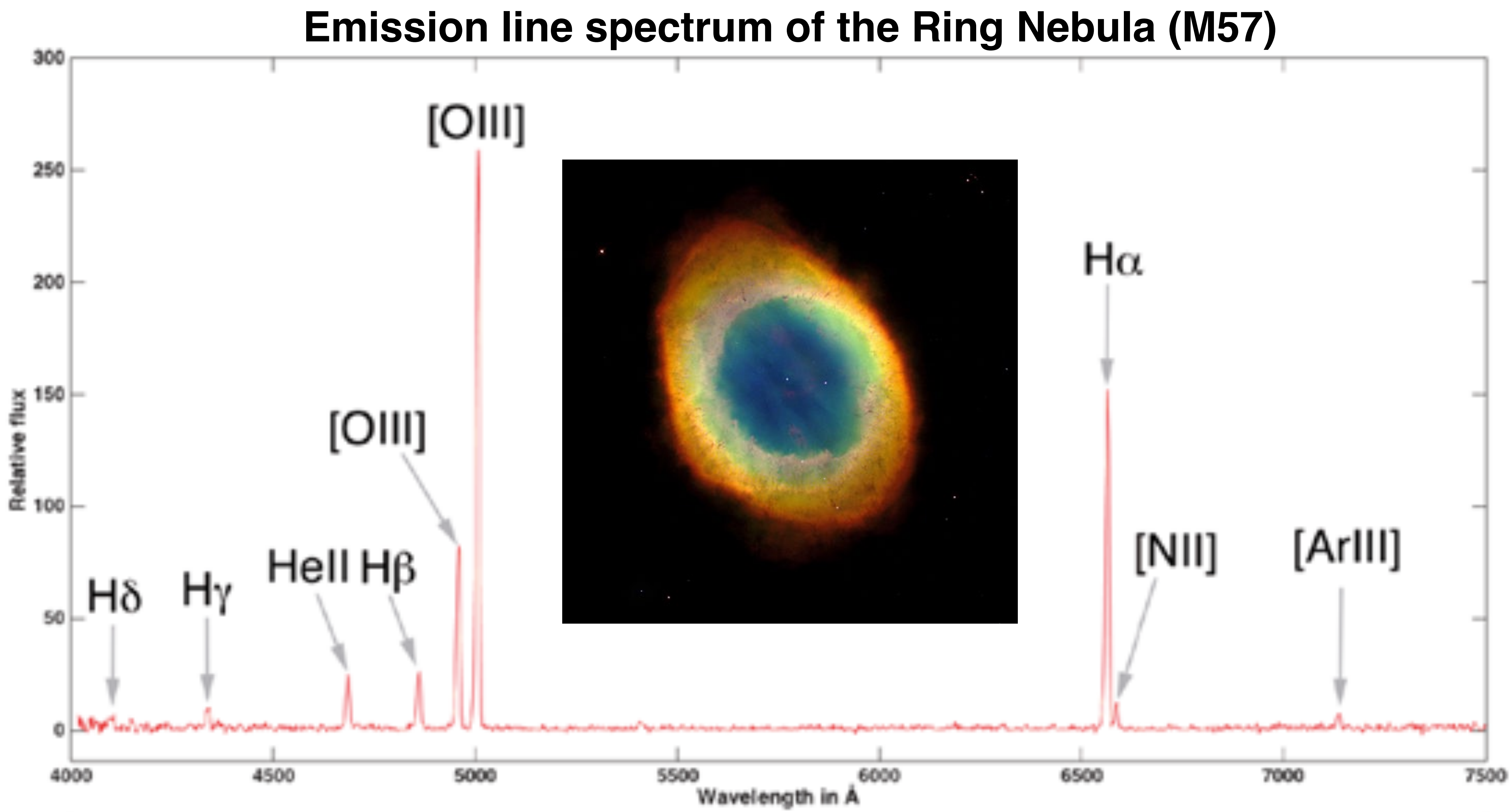
Absorption lines in the Solar spectrum indicate the presence of ionized iron (Fe II)



Iron in the Sun

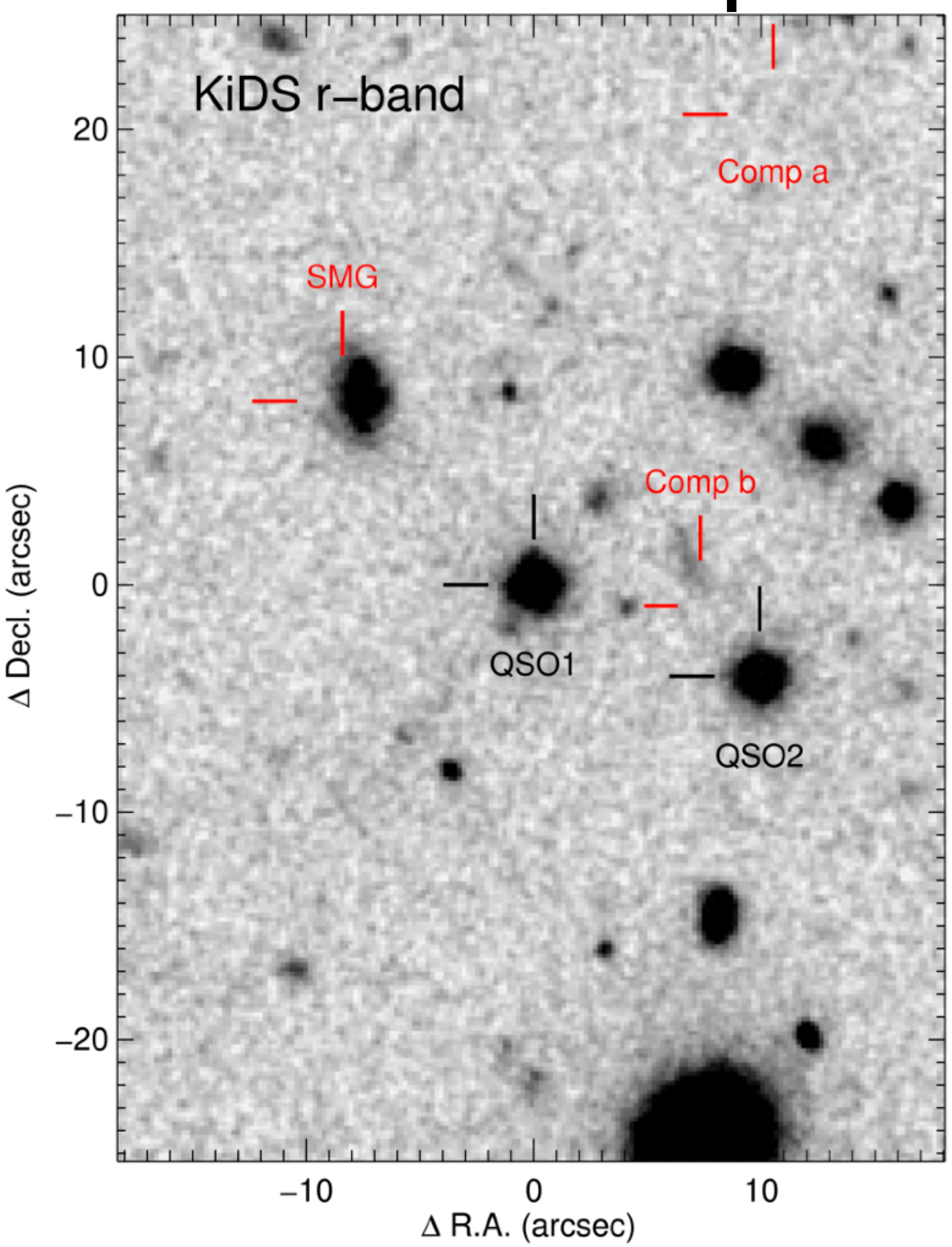


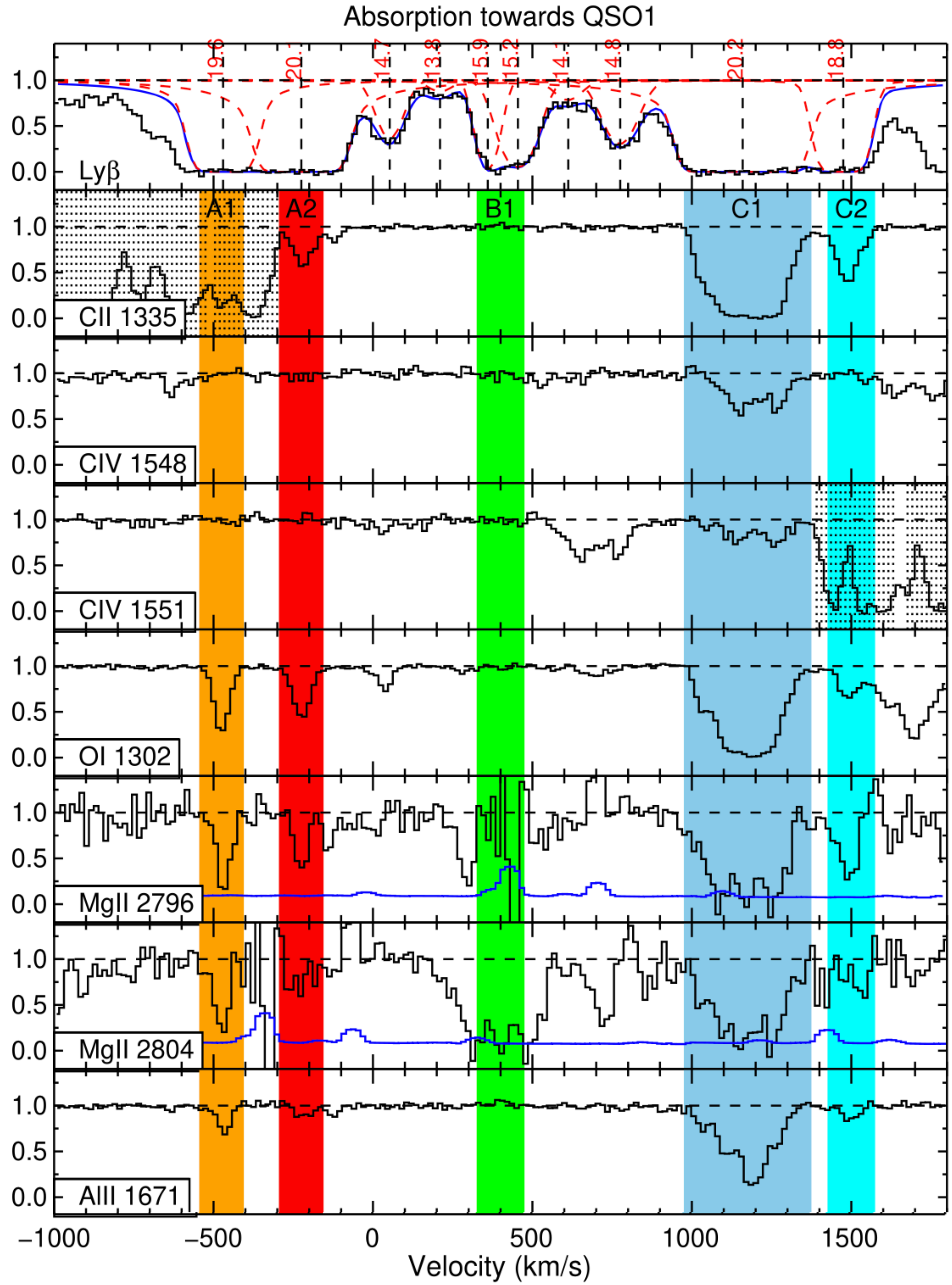
Identification of chemical elements in emission lines



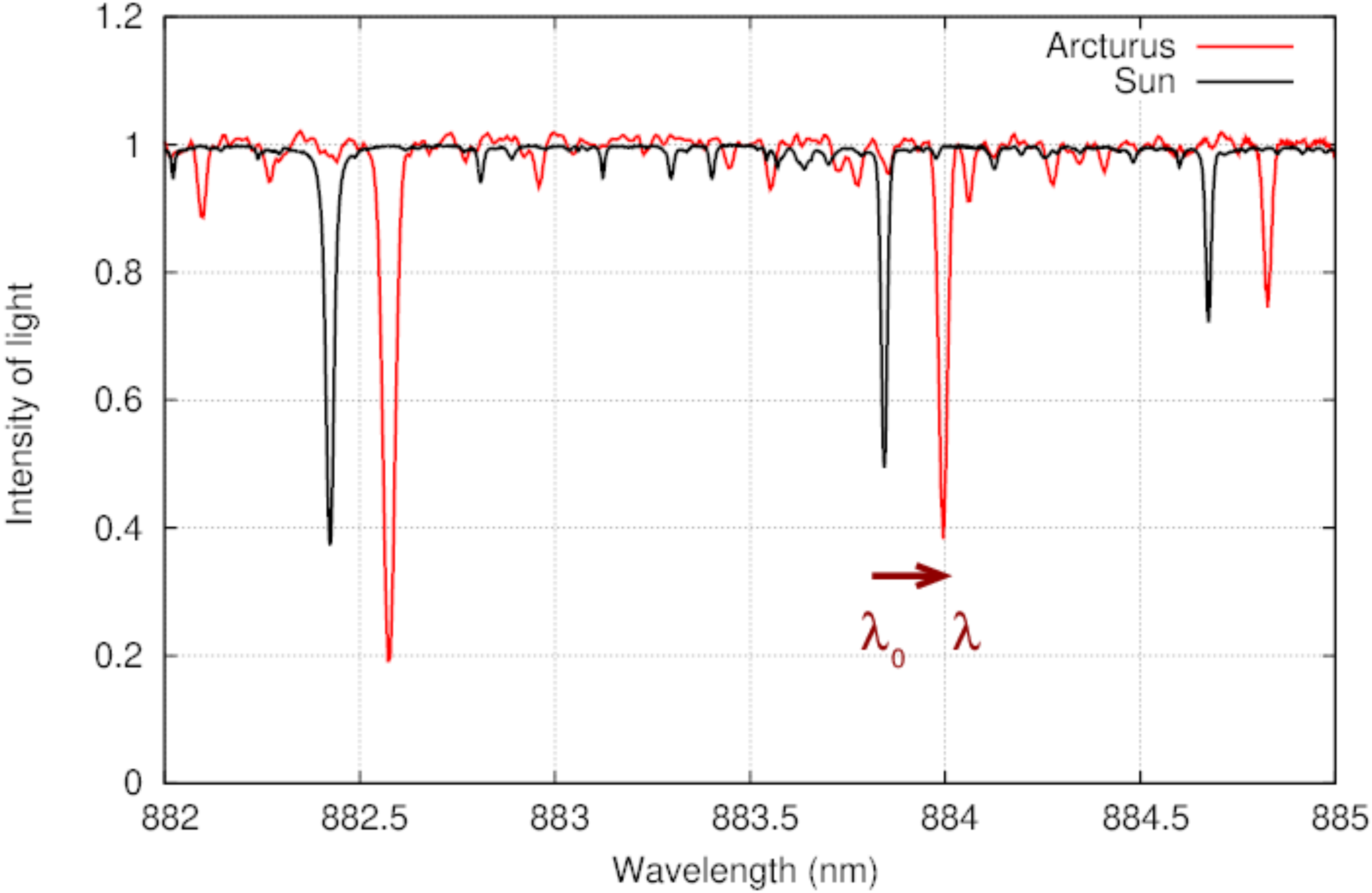
Absorption line spectra reveal chemical composition of intervening gas towards the Quasar

Fu et al. 2021 ApJ





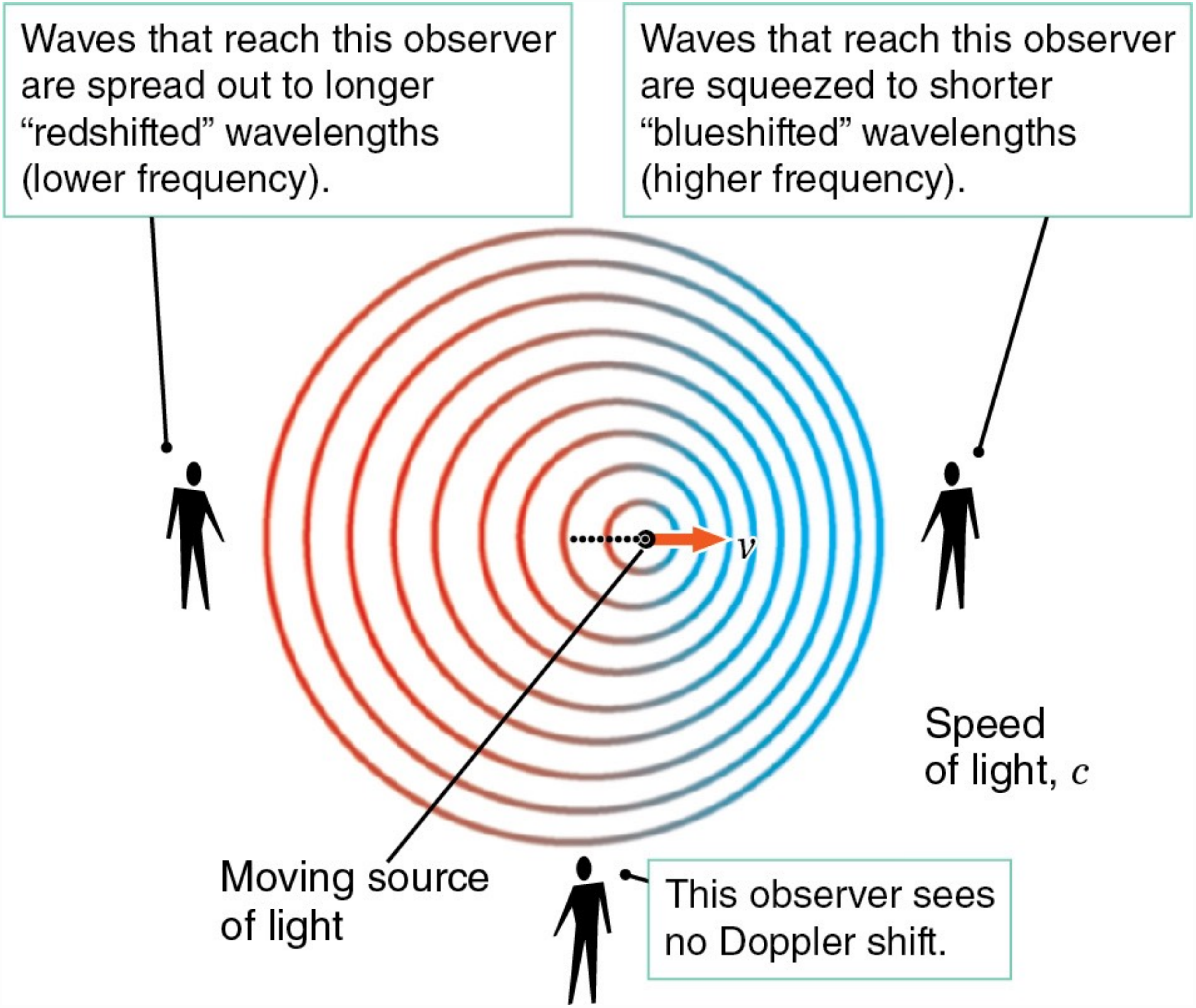
Part II: Doppler Shifts of Spectral Lines



Doppler Shift

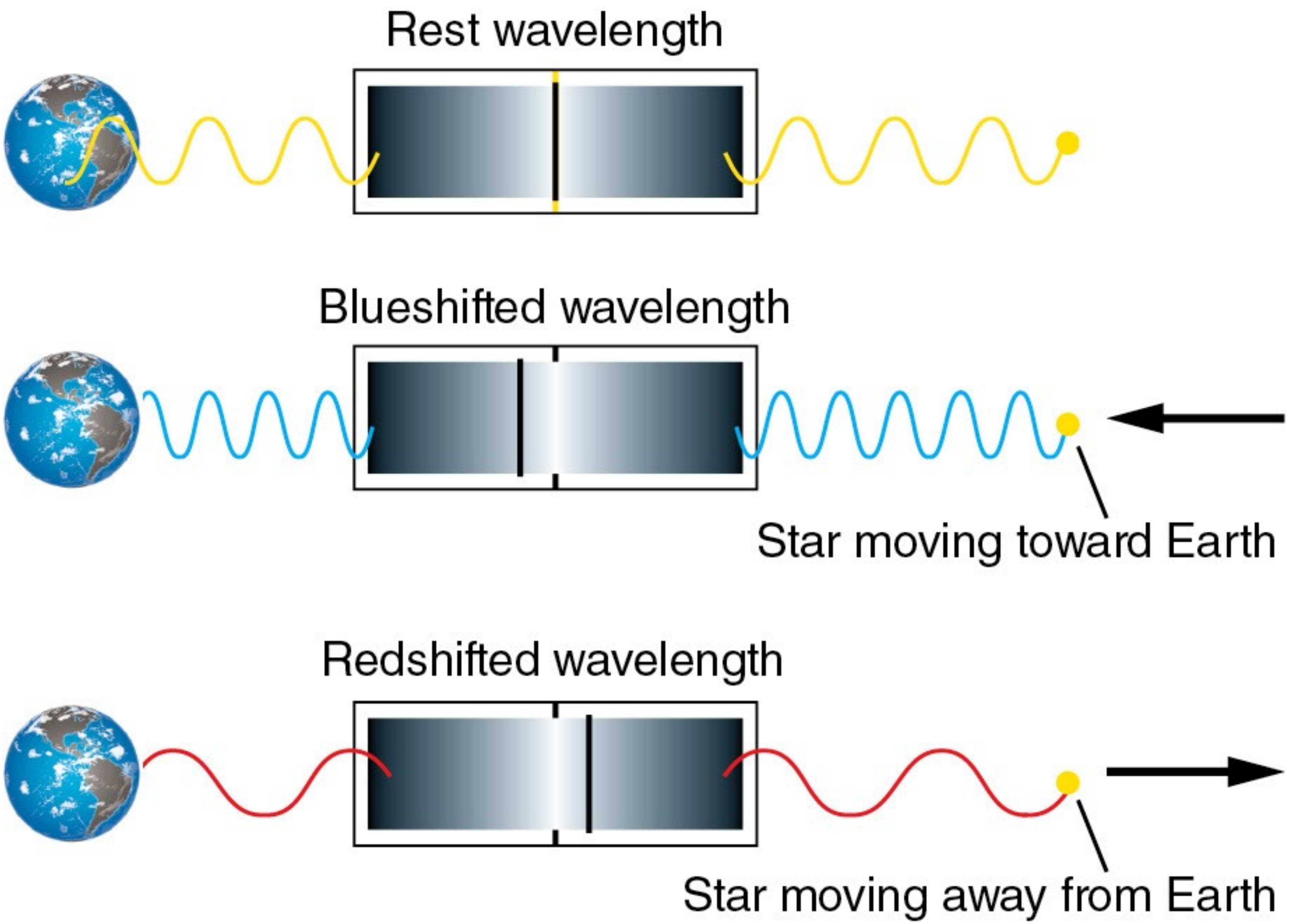
How to measure radial velocity

- **Doppler shift:** The motion of a light source toward or away from us changes our perception of the wavelength of the waves reaching us.

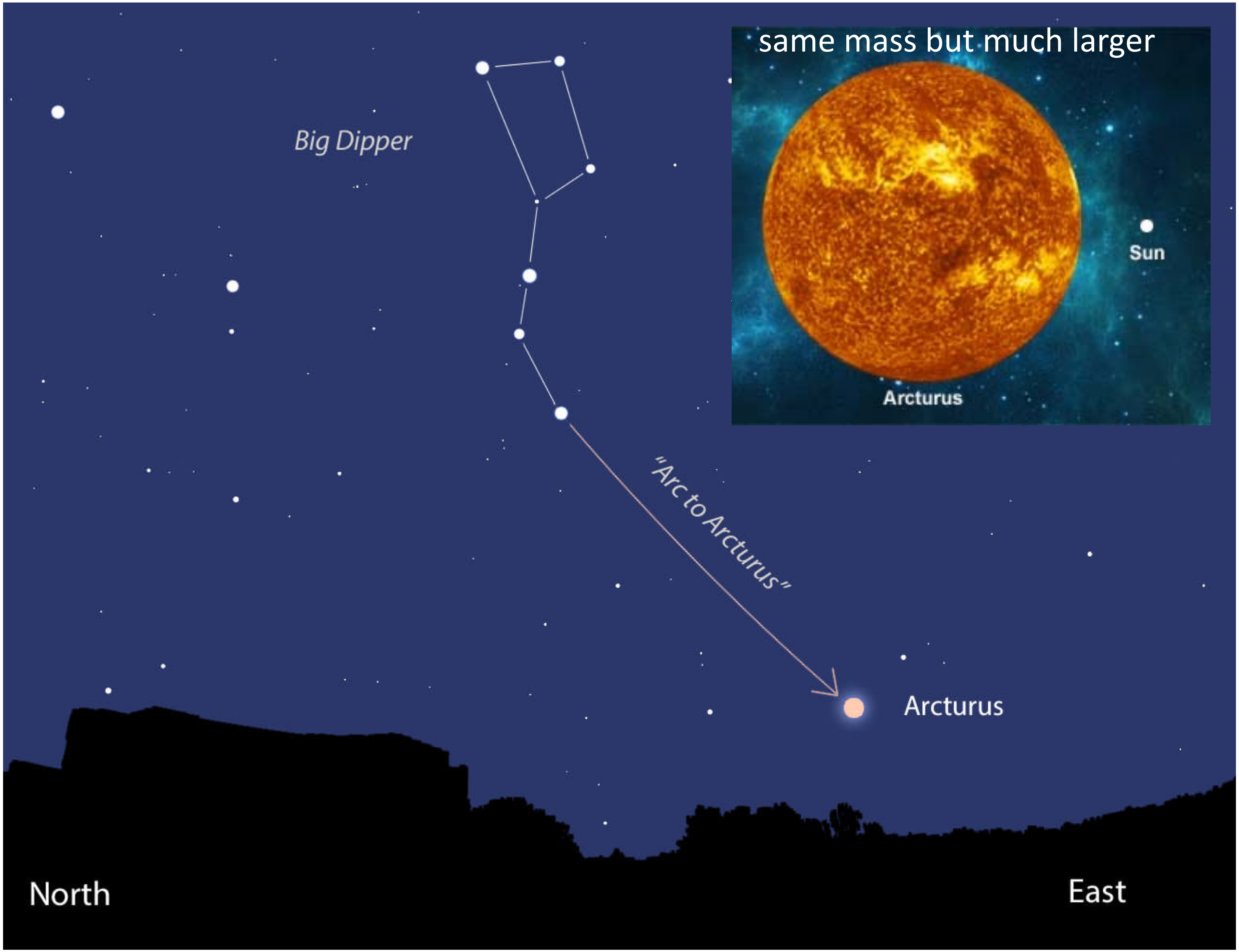


Doppler shifts of EM waves - blueshift vs. redshift

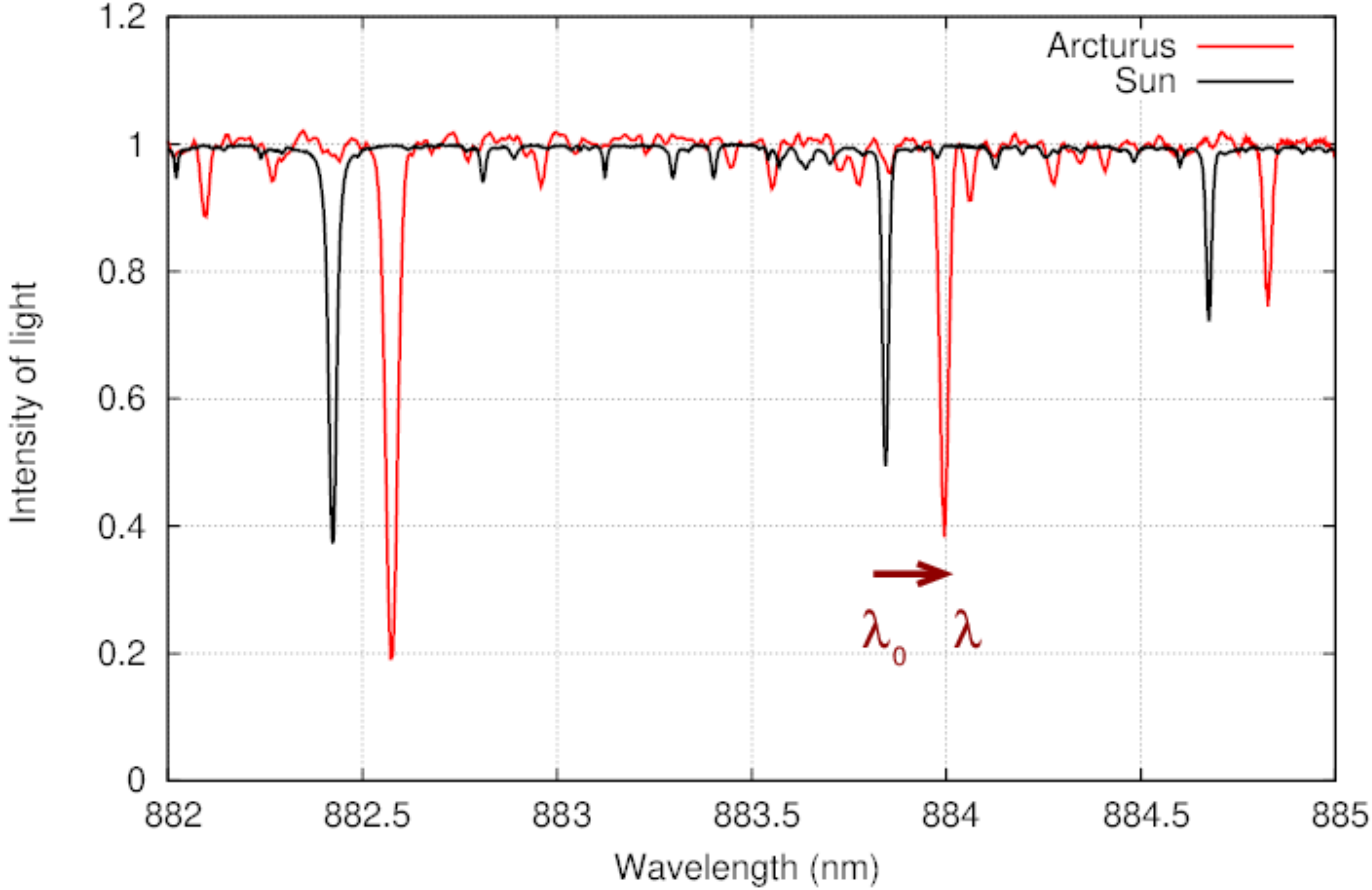
- Light from approaching objects is **blueshifted**; the waves crowd together.
- Light from receding objects is **redshifted**; the waves are spaced farther apart.



Doppler shift measured by comparing spectra (e.g., Arcturus)



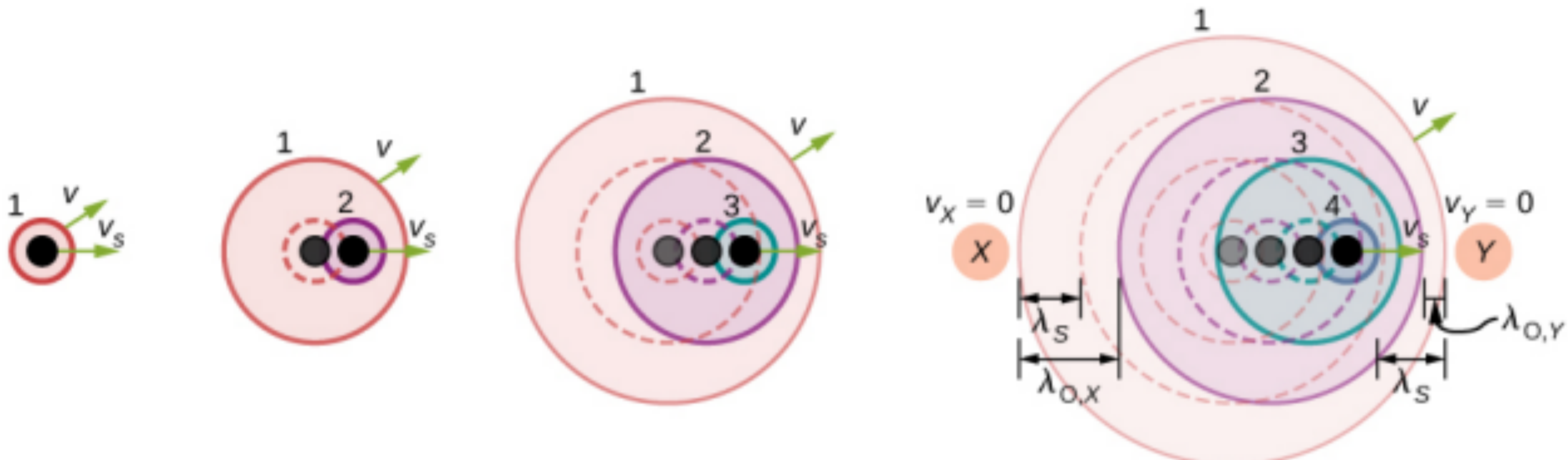
Doppler shift measured by comparing spectra of Arcturus & Sun



Doppler shift equation derivation

$$\frac{V_r}{c} = \frac{\lambda_{\rm obs} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\rm obs}}{\nu_{\rm obs}}$$

V_r - **radial velocity (along line-of-sight)**, c - speed of light, $\lambda_{\rm obs}$- observed wavelength, λ_0 - rest-frame wavelength



$$\lambda_{\rm obs} = \lambda_0 + v_r \delta t = \lambda_0 + v_r/\nu_0 = \lambda_0 + v_r(\lambda_0/c)$$

only the **radial v component** matters,
the ***transverse v component*** has no Doppler effect

Definition of the sign of radial velocities

- **Redshift**: The distance between the observer and the source is ***increasing (positive velocity)***
- **Blueshift**: The distance between the observer and the source is ***decreasing (negative velocity)***

$$\frac{V_r}{c} = \frac{\lambda_{\mathrm{obs}} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\mathrm{obs}}}{\nu_{\mathrm{obs}}}$$

λ_o = wavelength at rest frame

λ_{obs} = wavelength seen by observer

V_r = radial velocity is the velocity component along the line-of-sight

c = speed of light

Practice: Wavelength shift to velocity

- In the lab room, you measure the wavelength of a strong Hydrogen line at 656.3 nm; at telescope, you detect the same Hydrogen line from a nebula and its wavelength has been shifted to 659.0 nm. What is the velocity of the nebula relative to us along the line-of-sight?

$$\frac{V_r}{c} = \frac{\lambda_{obs} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{obs}}{\nu_{obs}}$$

$$v_r = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}} \times c = \frac{659.0\text{ nm} - 656.3\text{ nm}}{656.3\text{ nm}} \times (3 \times 10^8\text{ m/s})$$

$$= 1.2 \times 10^6\text{ m/s}$$

Practice: Frequency shift to velocity

- A spacecraft transmits a signal at 98.75 MHz. It is received on Earth at 98.76 MHz. How fast is the spacecraft moving relative to Earth and in which direction (away or towards us)?

$$\frac{V_r}{c} = \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\text{obs}}}{\nu_{\text{obs}}}$$

Answer: Vr = (98.75-98.76)/98.76 * c = -30 km/s

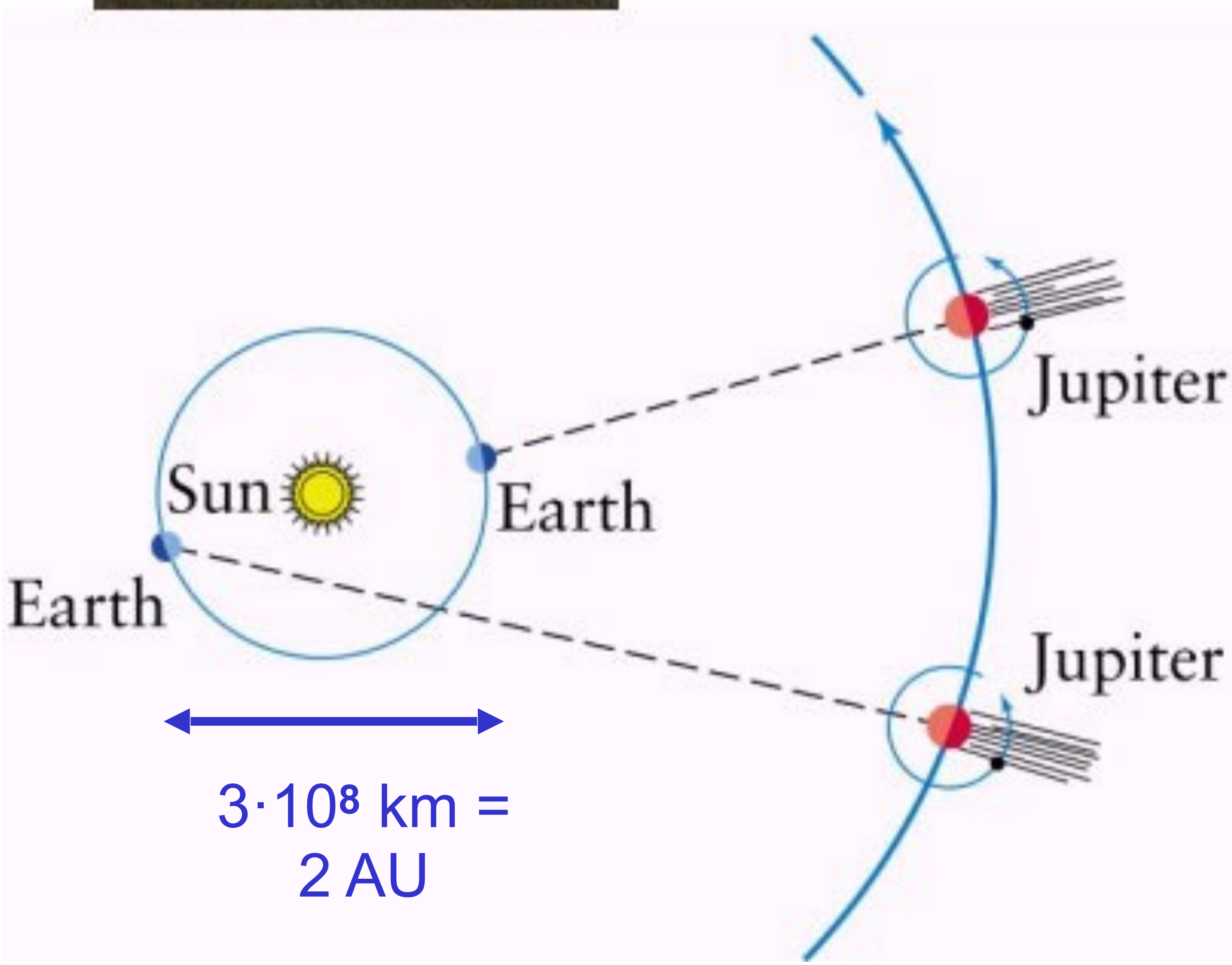
Application: speed of light measurement

- If we know the radial velocity V_r, the wavelength shift, and the rest-frame wavelength, we can use these measurements to infer speed of light:

$$\frac{V_r}{c} = \frac{\lambda_{\text{obs}} - \lambda_0}{\lambda_0}$$

$$\Rightarrow c = V_r \frac{\lambda_0}{\lambda_{\text{obs}} - \lambda_0}$$

Roemer's Speed-of-Light Measurement (1676)



In 1676, Danish astronomer Olaus Røemer discovered that the exact time of **eclipses of Jupiter's moon** varied as the distance to Jupiter varied.

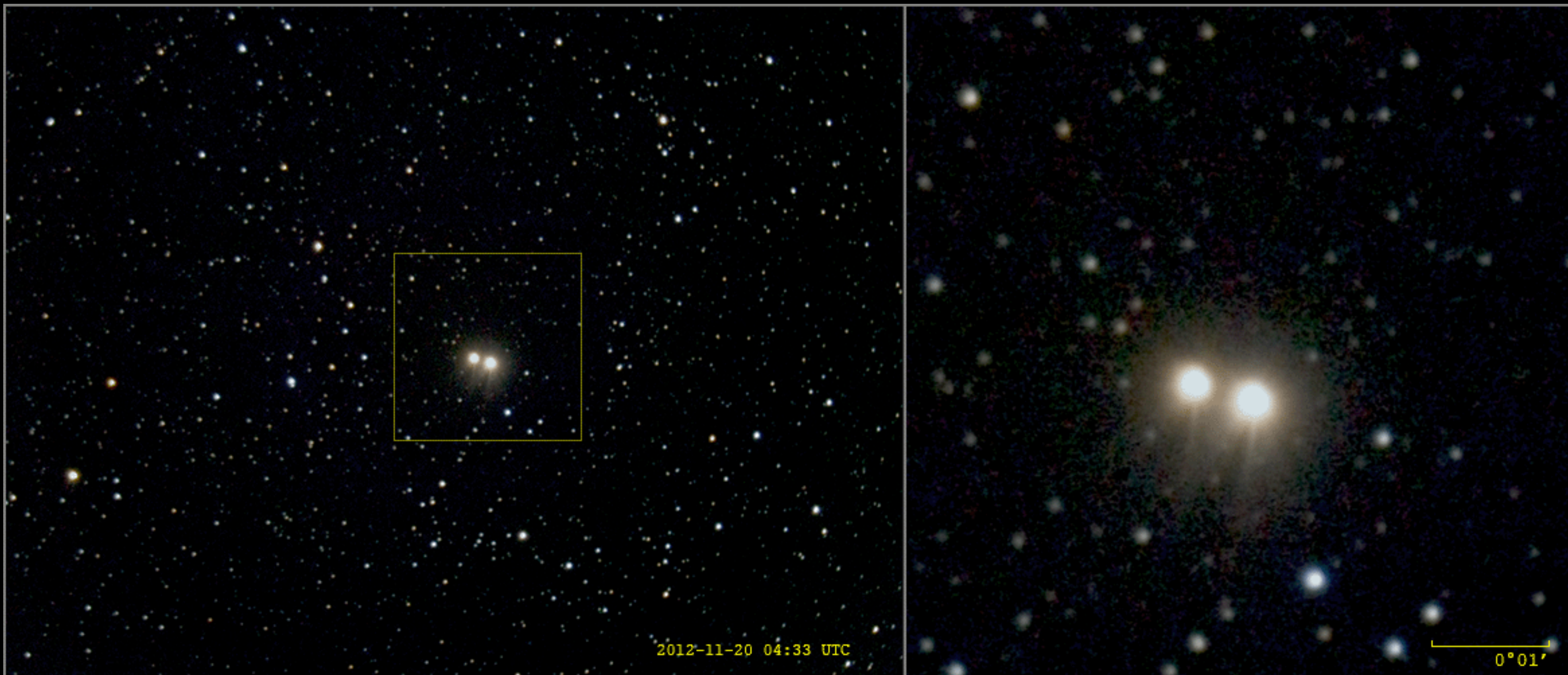
He explained that this occurs because it takes varying amounts of time for light to travel the varying distance between Earth and Jupiter. This realization enabled him to measure the speed of light for the first time.

Alternatively, the varying eclipsing period as Earth moves relative to Jupiter can be understood as a **Doppler effect,** and the moon's orbital motion makes it a regular oscillator with a fixed rest-frame frequency ($\nu_0 = 1/P_{\mathrm{orbit}}$).

Proper Motion

How to measure transverse velocity

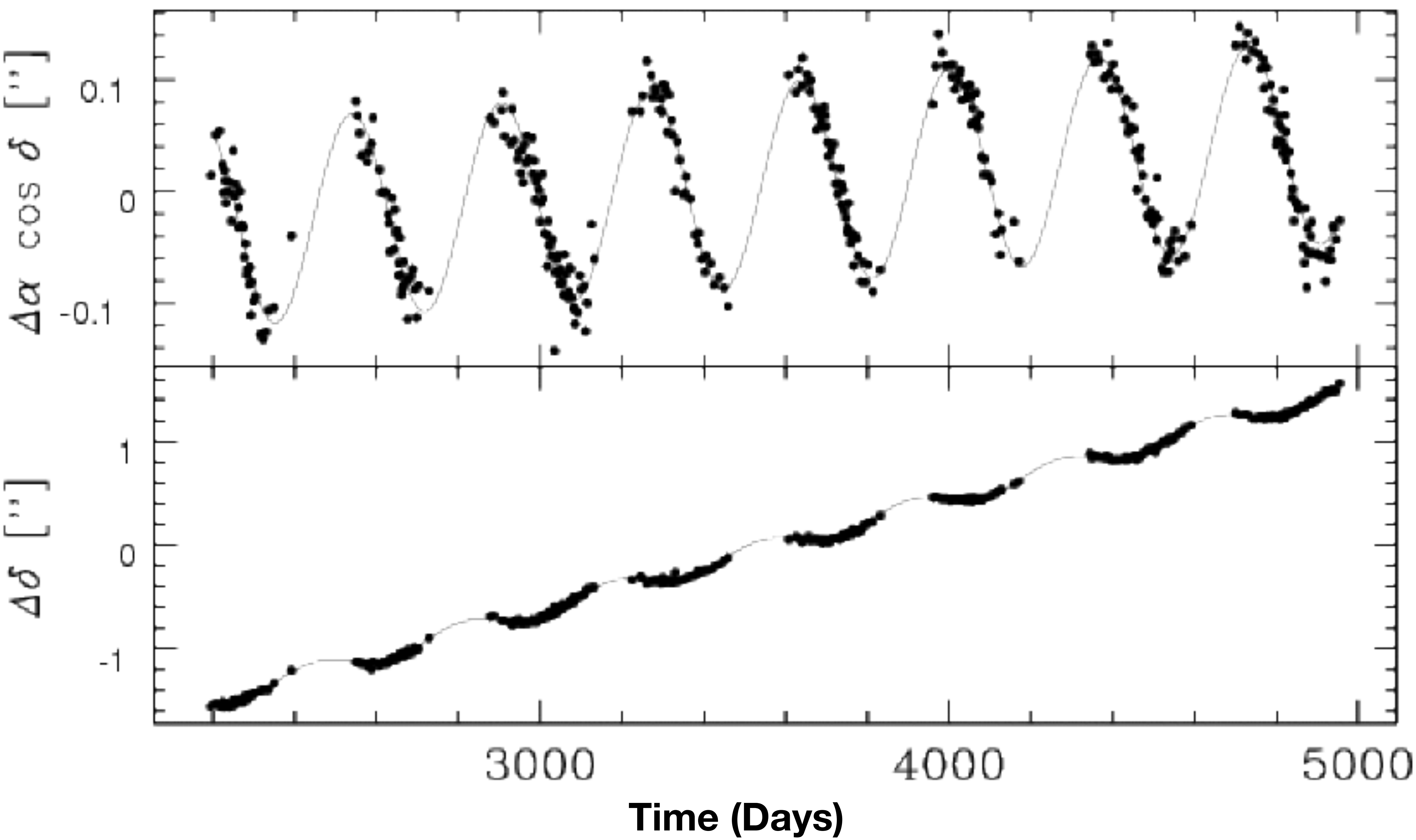
61 Cygni A+B proper motion



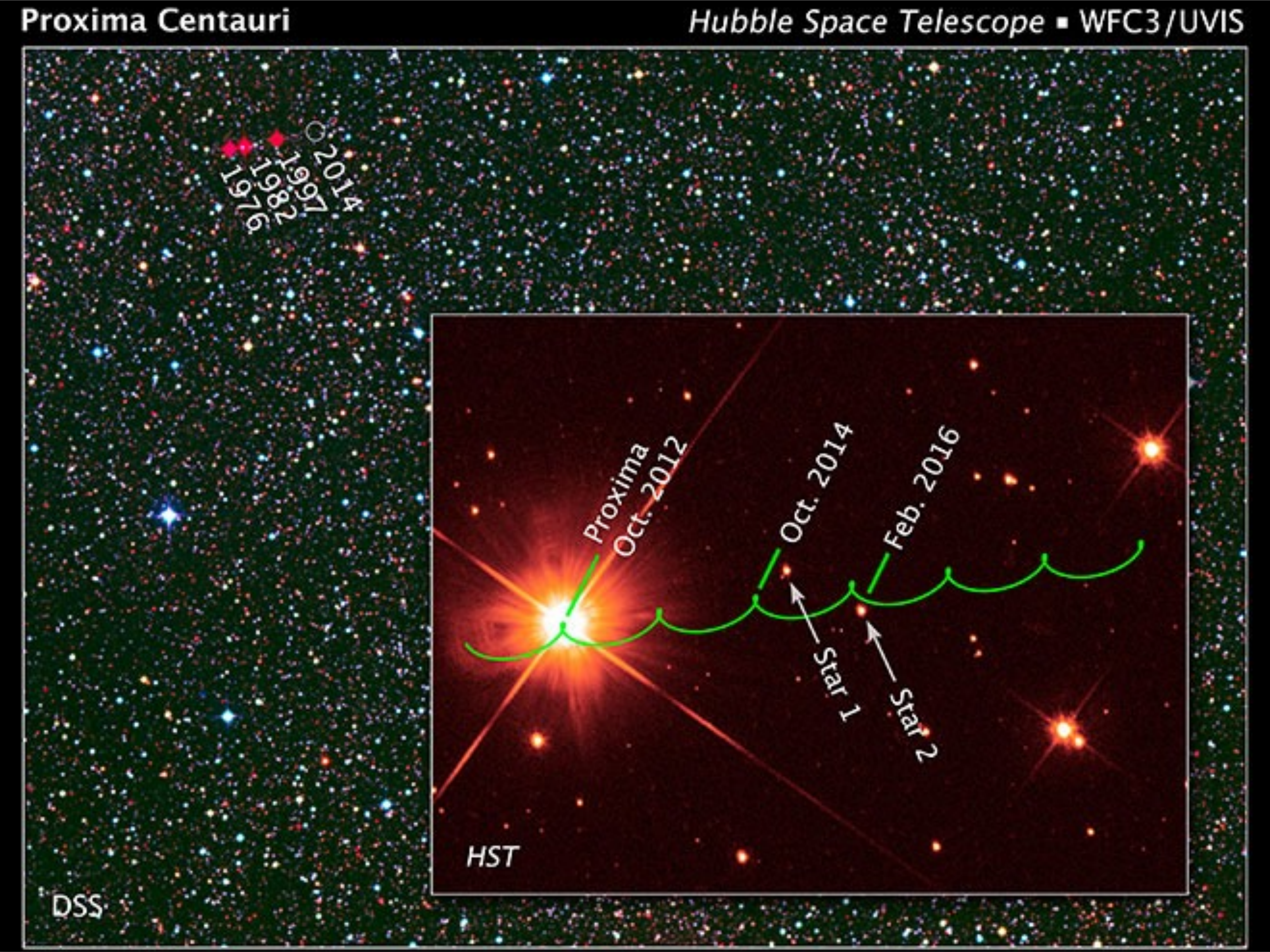
2 million stars’ motion 5 million years into the future

RA offset vs. time & Dec offset vs. time

Proper motion (Linear) + Parallax (Periodic)



Poleski *et al.*, 2011, *Acta Astron.,* 61, 199 (arXiv:1110.2178)


Proxima Centauri
Hubble Space Telescope ▪ WFC3/UVIS
2014
1997
1982
1976
Proxima
Oct. 2012
Oct. 2014
Feb. 2016
Star 1
Star 2
HST
DSS

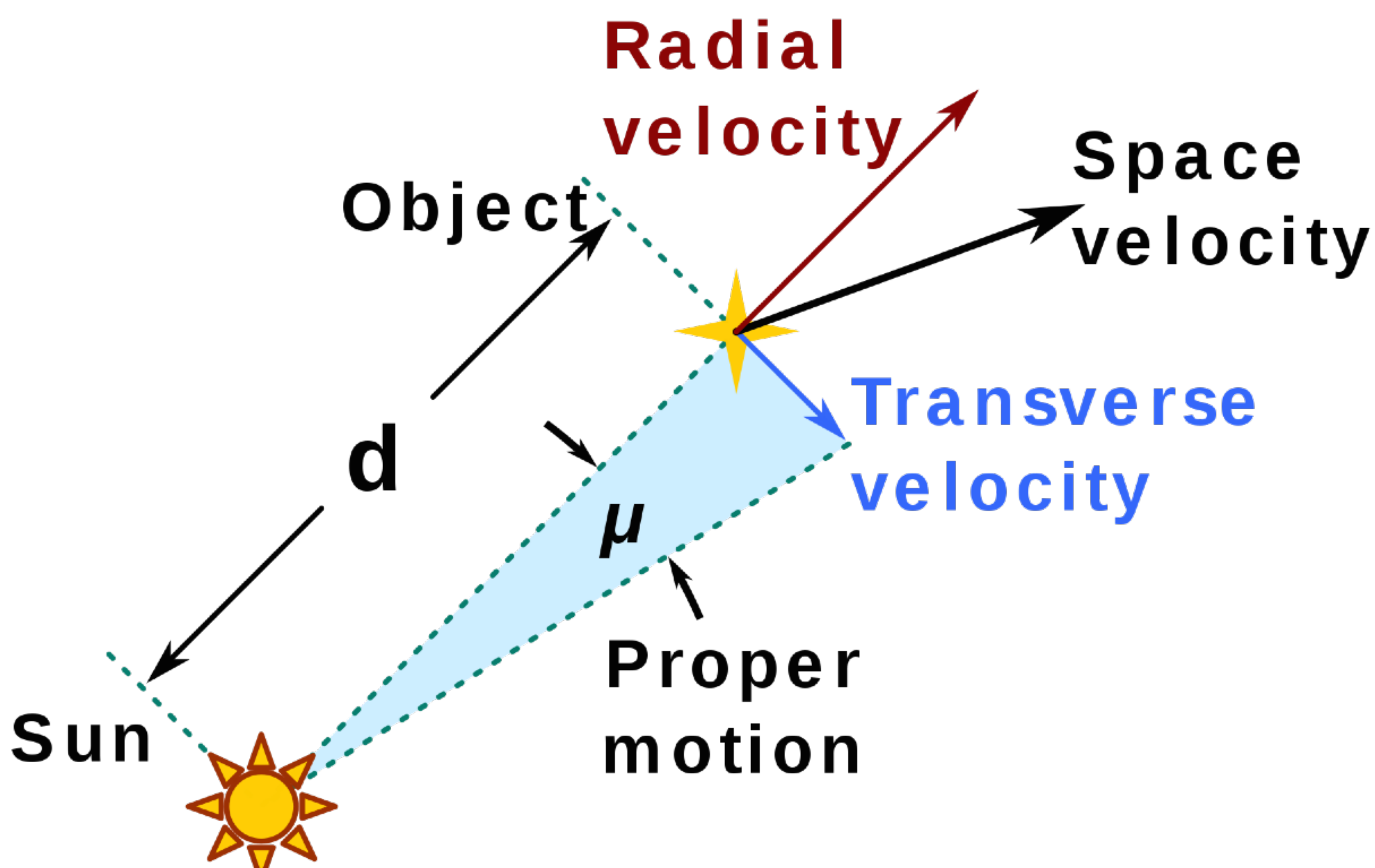
Transverse velocity from proper motion (μ) and parallax (p)

distance from parallax: $d = 1 \text{ parsec}\left(\frac{1''}{p}\right)$

transverse velocity from proper motion & parallax:

$$V_t = \mu d = 4.74\,\text{km/s}\left(\frac{\mu}{1''/\text{yr}}\right)\left(\frac{1''}{p}\right)$$

note: 4.74 km/s = 1 AU/yr



Part III: Telescope & Camera

- Choosing Telescopes
  - Optical design
  - Light gathering power
  - Diffraction limit
- Choosing Cameras
  - Plate scale
  - Field of view
  - Quantum efficiency

Telescope optical design

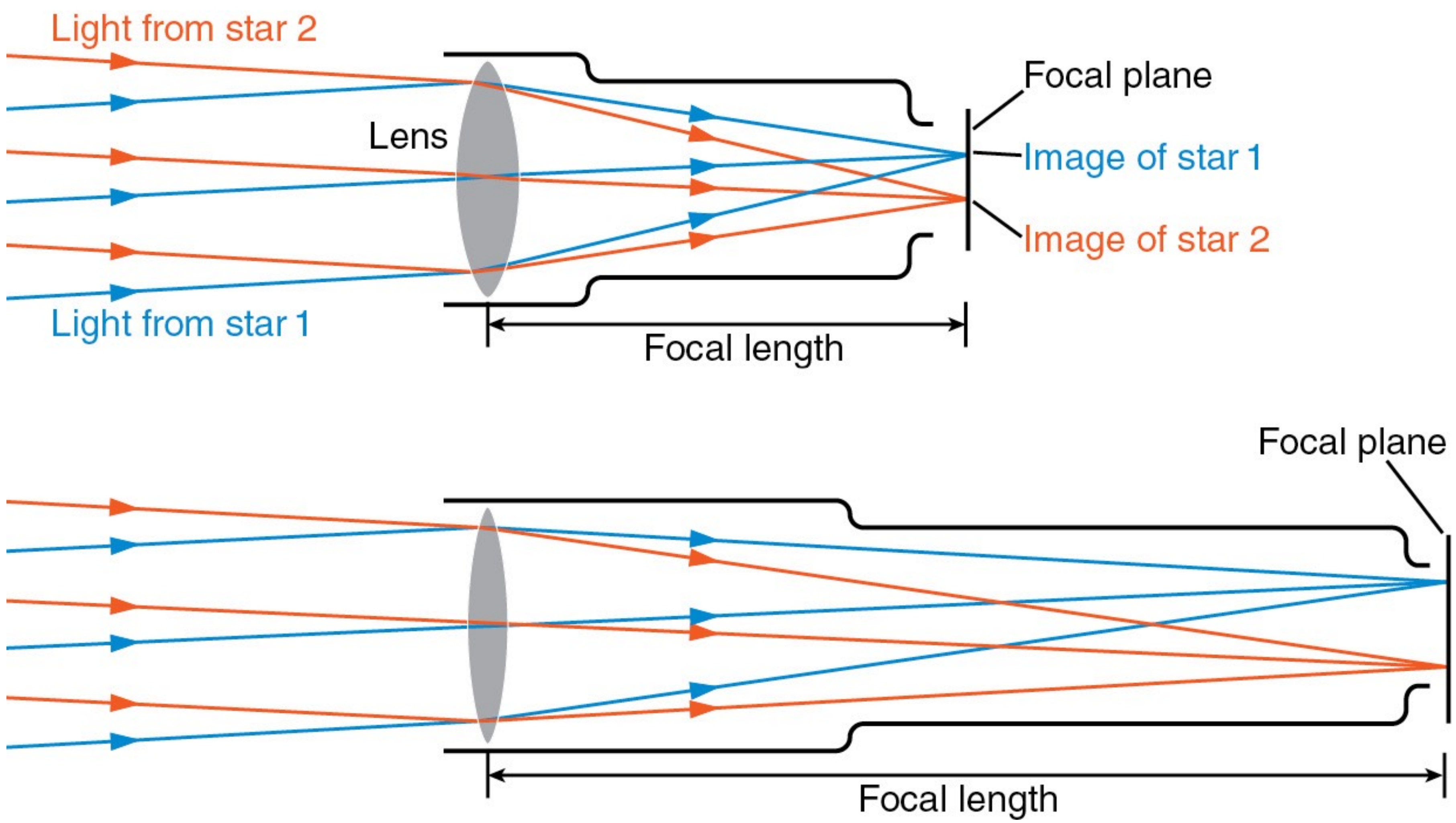
Refractors vs. Reflectors

Two Basic Types of Telescopes

- Refractors
  - Use lenses to concentrate incoming light at a focus.
- Reflectors
  - Use mirrors to concentrate incoming light at a focus.

The goal is always the same – gather as much light as possible and form an image at a focus.

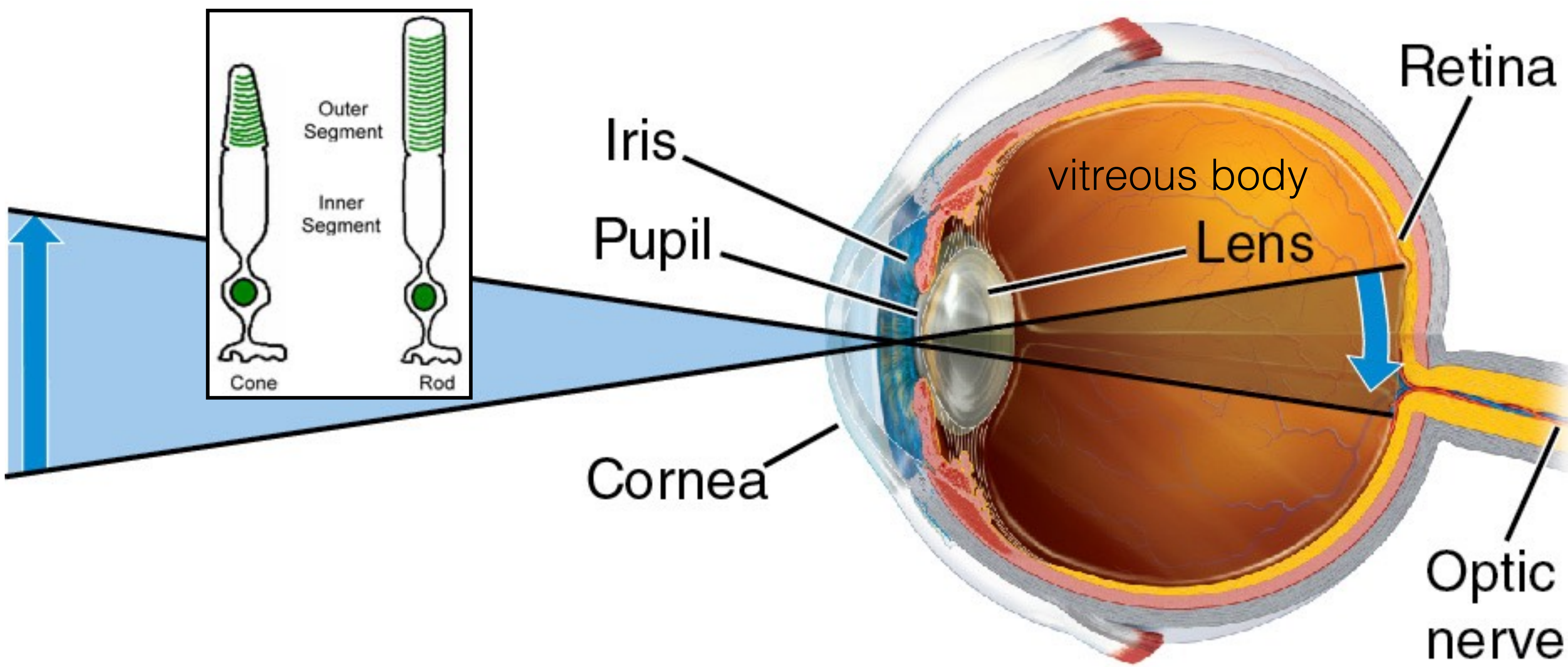
Refractors – Reversed Image, Focal Length, & Focal Ratio



- The **focal length** is the distance between lens and the focal plane.
- The **focal length** determines the **image size** (and the **plate scale)**
- The **aperture** is the diameter of the objective lens (D).
- Optics are geometry, and geometry is scalable. So we define a convenient scalable parameter called **Focal Ratio**, $f = F/D$, as the ratio between the focal length and the aperture of the lens

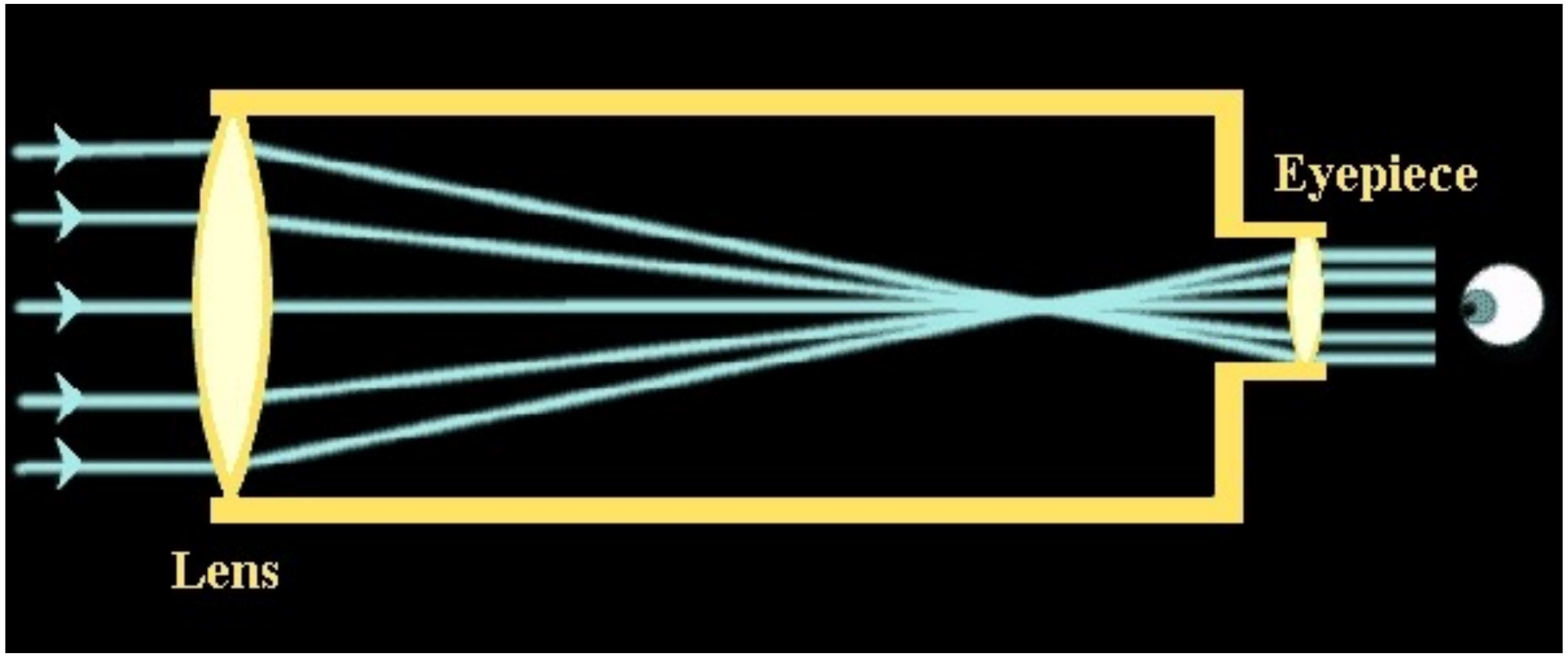
The Eye as a Refracting Telescope

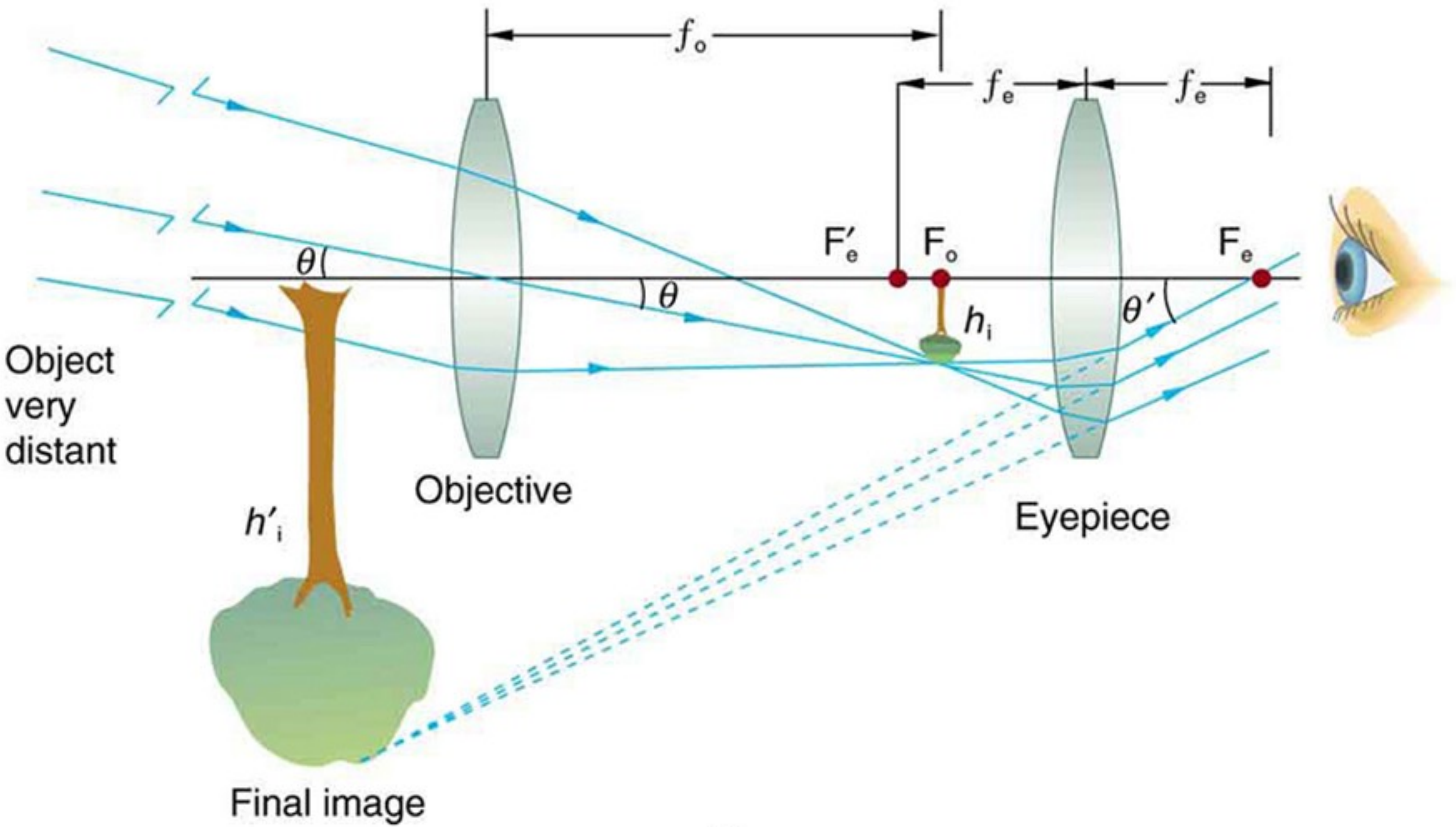
- It collects light and focuses an image with a lens.
- It collects a limited amount of light because of the small pupil.
- The eye has a very large field of view, but suffers from relatively poor angular resolution (an arcmin or so)
- Cone and rod photoreceptor cells have diameters between 2 um and 10 um. There are 6 million of cones and 120 million rods.



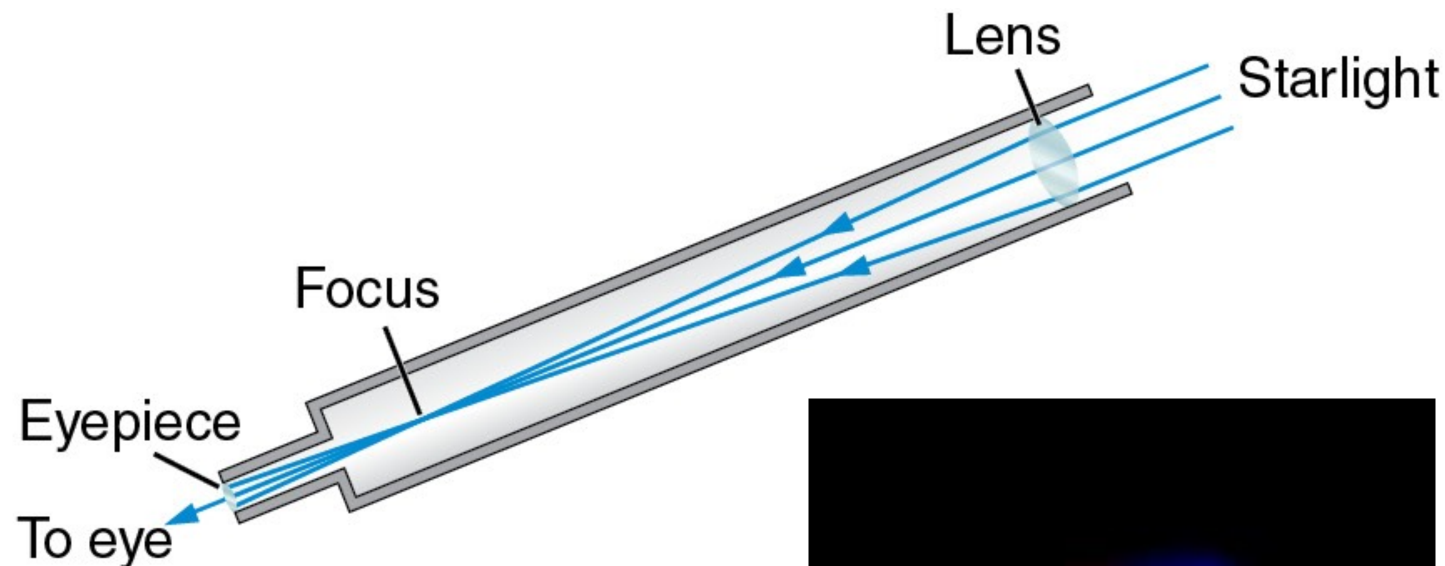
Refractors – Why do we need eyepieces?

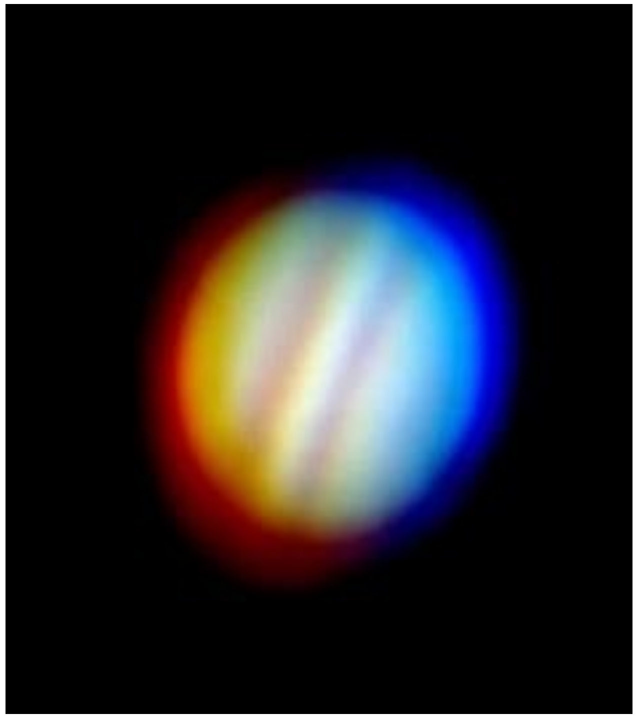
- Refracting telescopes use a concave **objective lens** to refract the light to focus it.
- In addition to the objective lens, another lens is needed for eye observations, it's called **eyepiece**.
- Eyepiece is needed because our eye has a lens in it.



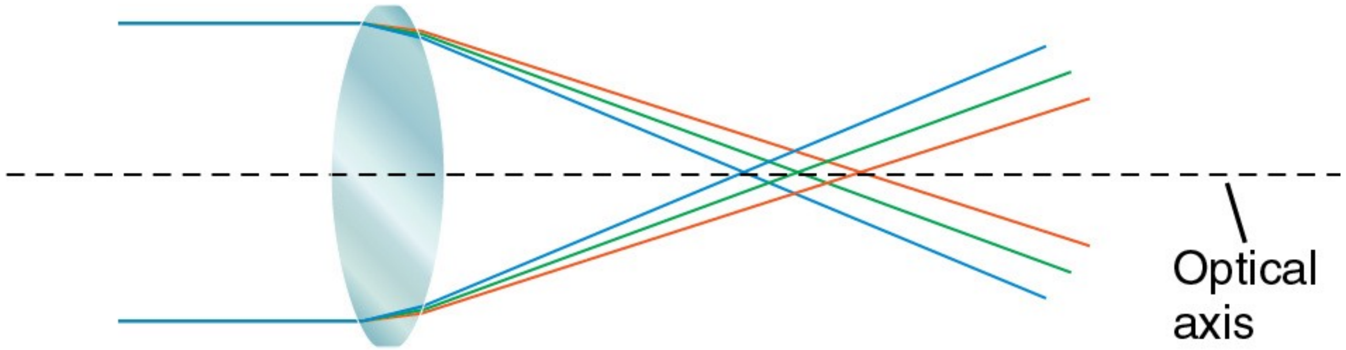


Problems with Refractors - why modern telescopes are mostly reflectors?

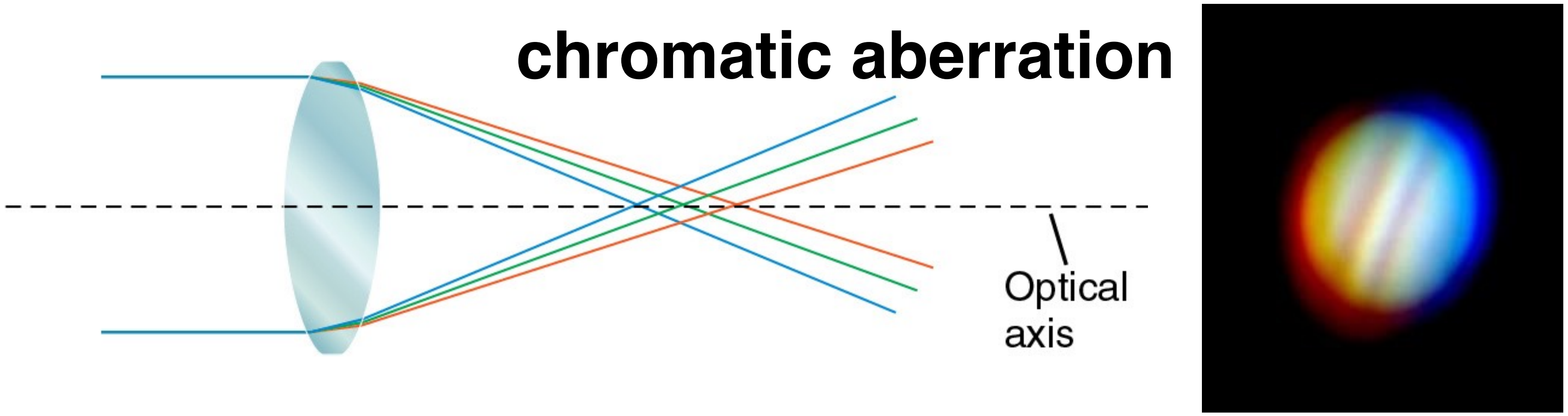


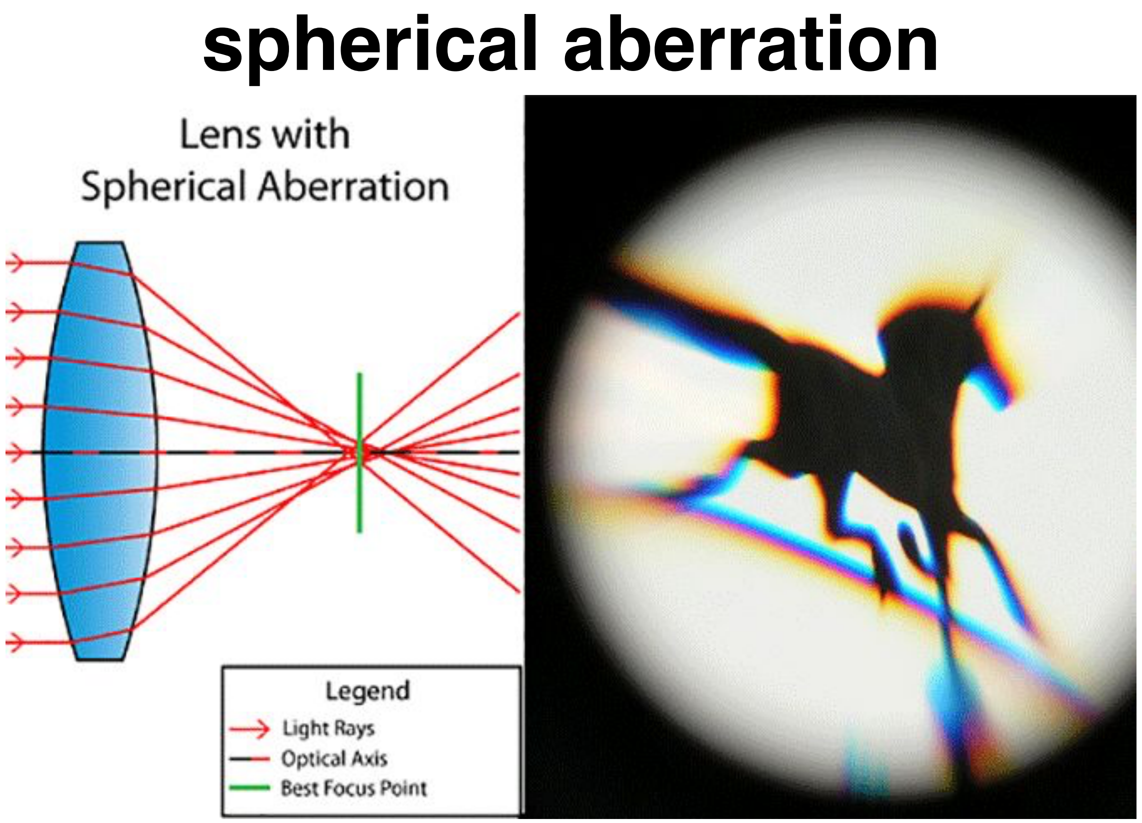


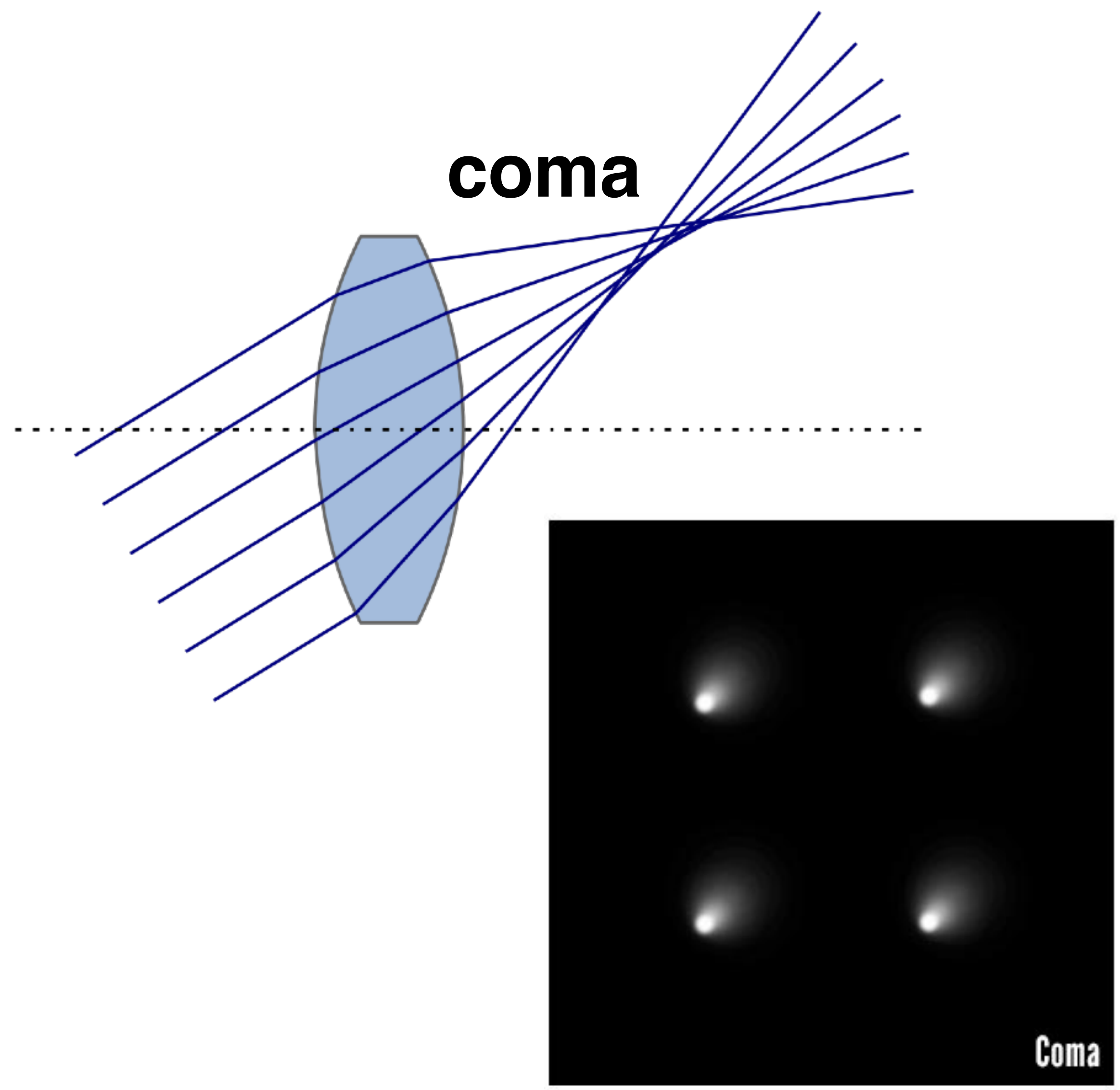
- Problems with refractors:
  - need **large structures** because of long focal lengths
  - **difficult** to make lenses
  - lenses suffer from **chromatic aberration**
- The largest refracting telescope has a 1-meter aperture and a focal length of 20 meters: it's built in 1897 (Yerkes Observatory)



Optical Aberrations: Chromatic aberration, Spherical aberration, & Coma

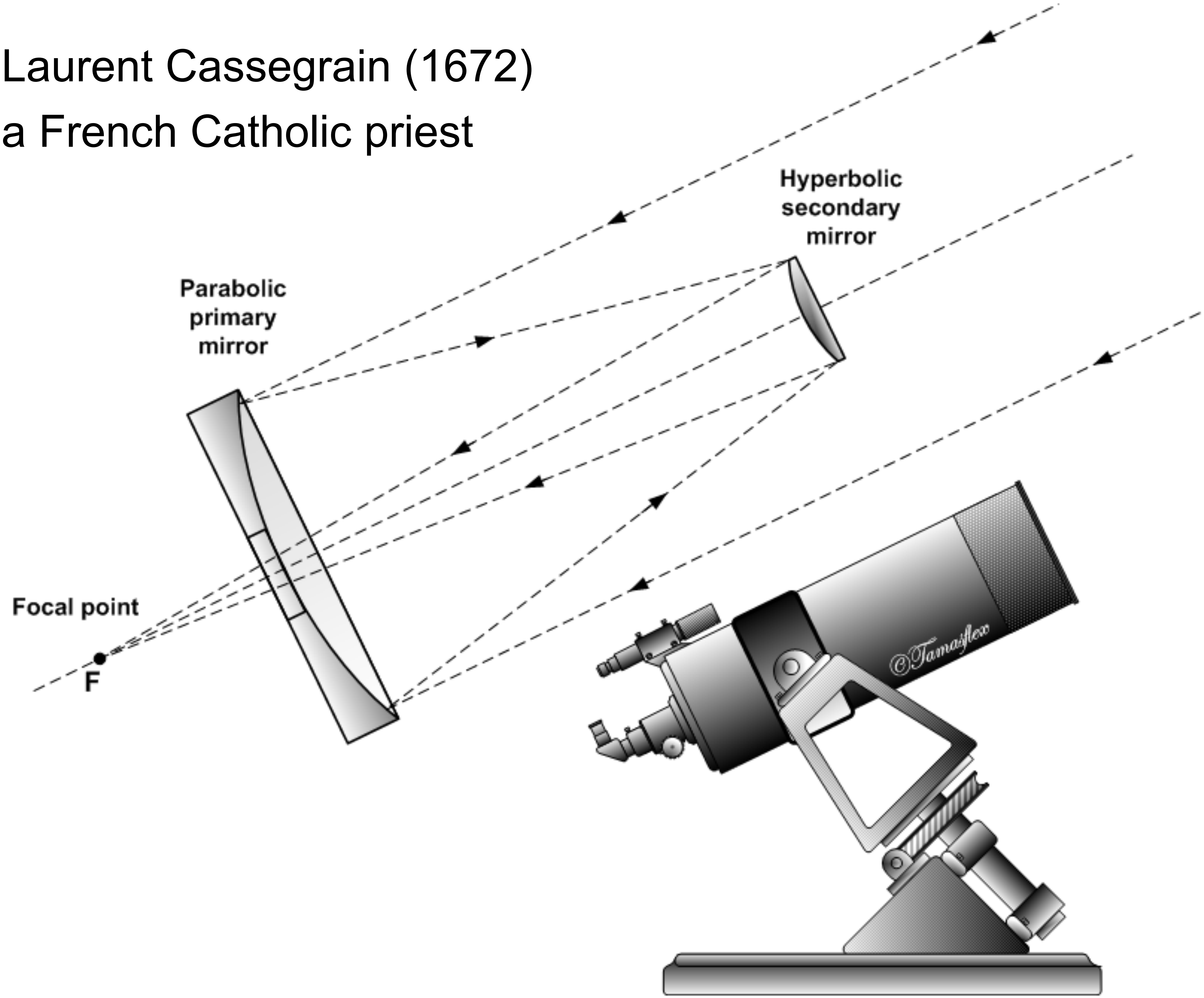






The most successful reflector design: Cassegrain

- Laurent Cassegrain (1672)
- a French Catholic priest



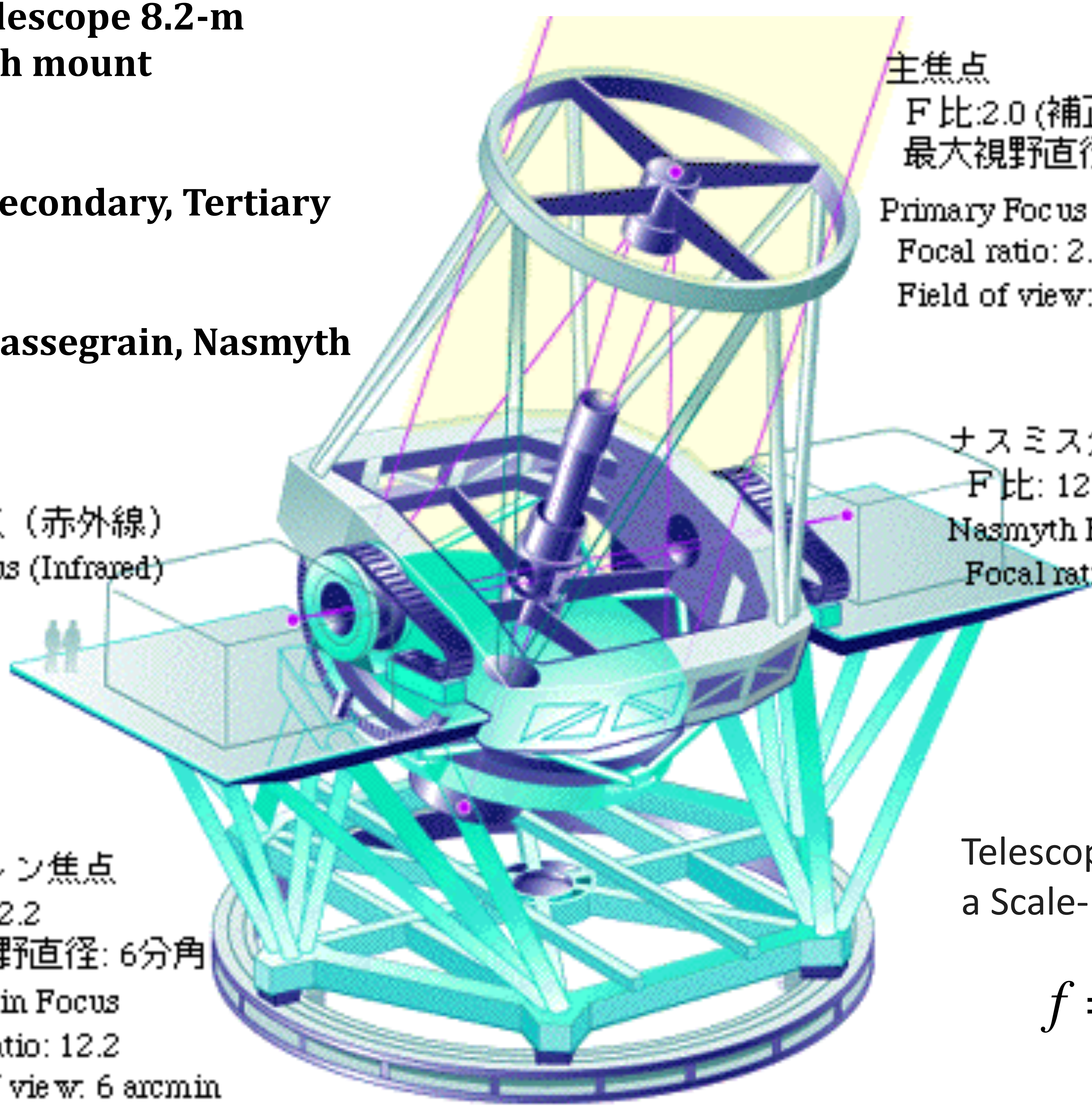
Cassegrain Reflectors Examples

Cassegrain Reflectors: The 8-meter Subaru Telescope

Subaru Telescope 8.2-m
alt-azimuth mount

Mirrors:
Primary, Secondary, Tertiary

Focuses:
Primary, Cassegrain, Nasmyth

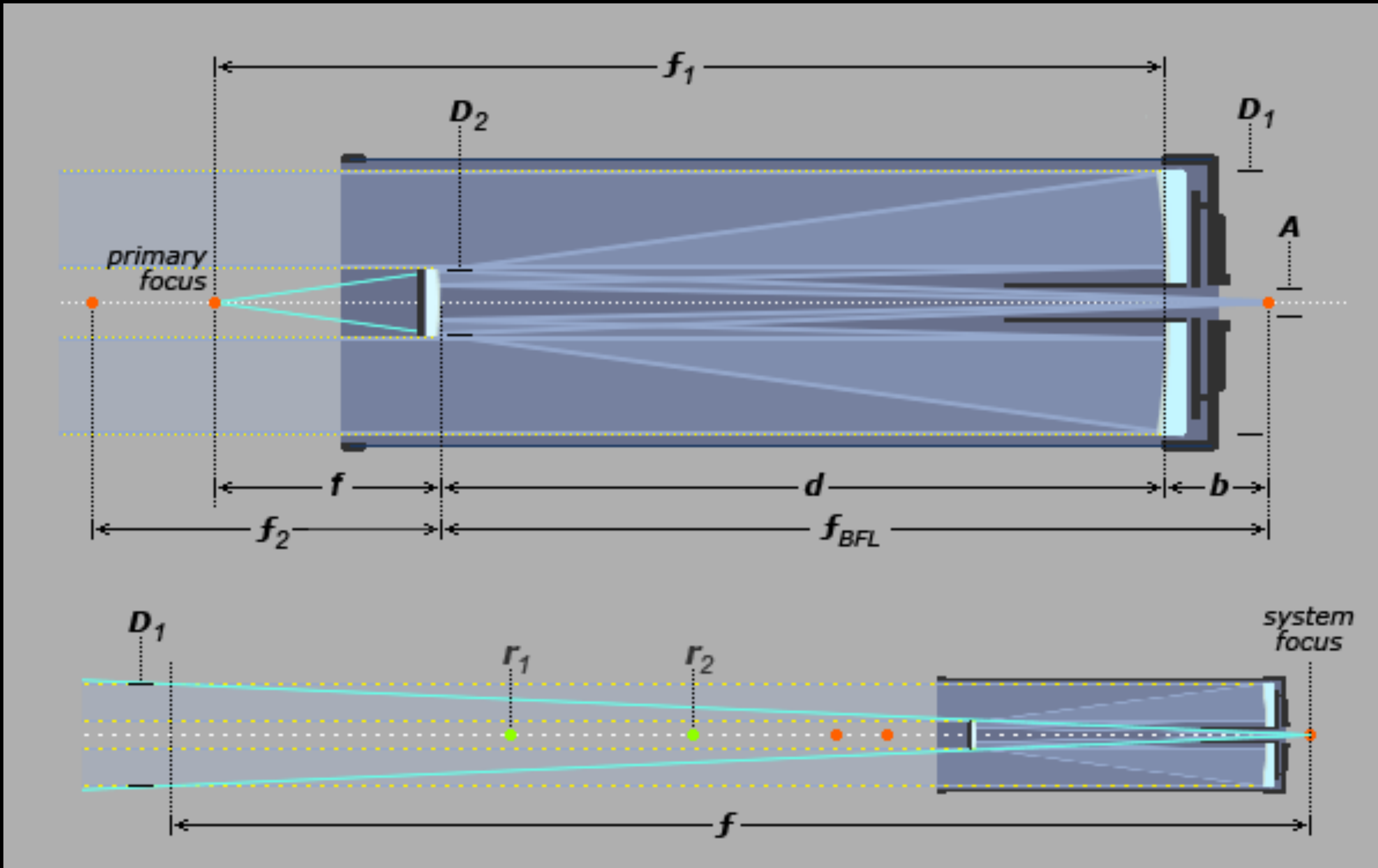


Telescope Focal Ratio:
a Scale-Free Parameter

$$f = F/D$$

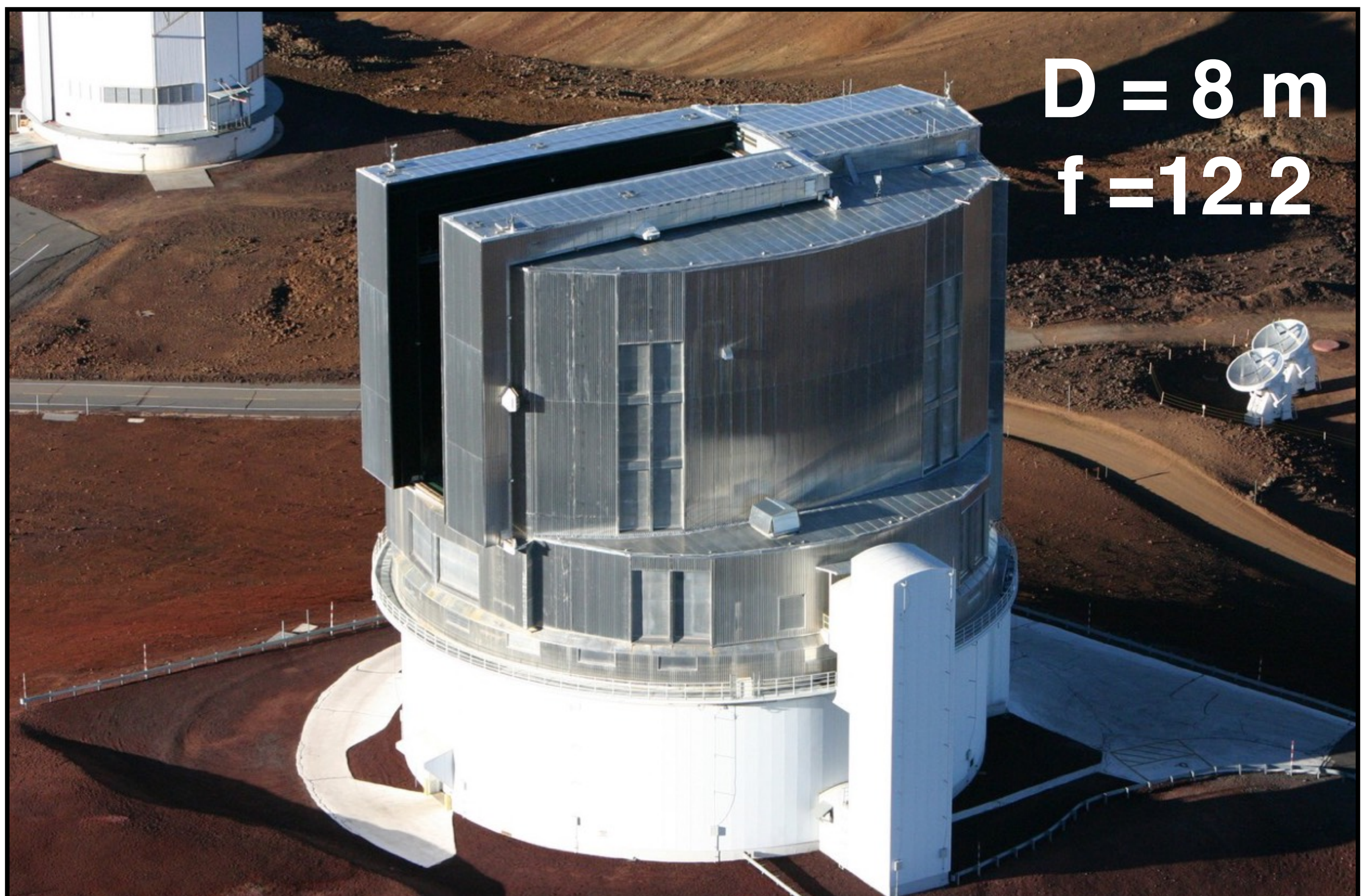
遠藤孝悦・画　日経サイエンス1996年2月号より
Illustration by Takaetsu Endo, taken from Nikkei Science 1996

THE FOCAL LENGTH OF A CASSEGRAIN REFLECTOR CAN BE MUCH LONGER THAN THE LENGTH OF THE TELESCOPE



A telescope can be described by just two parameters: Diameter of the Primary Mirror (D), and Focal Ratio (f = F/D)

- Why larger **D** is always desired?
  - **Greater light gathering power** => higher sensitivity (see fainter sources)
  - **Smaller diffraction pattern** => higher angular resolution (*when equipped with adaptive optics or launched to space*)
  - **Longer focal length** => smaller plate scale (higher definition [HD] images), because plate scale should be smaller than diffraction limit to take advantage of the high angular resolution offered by the large aperture

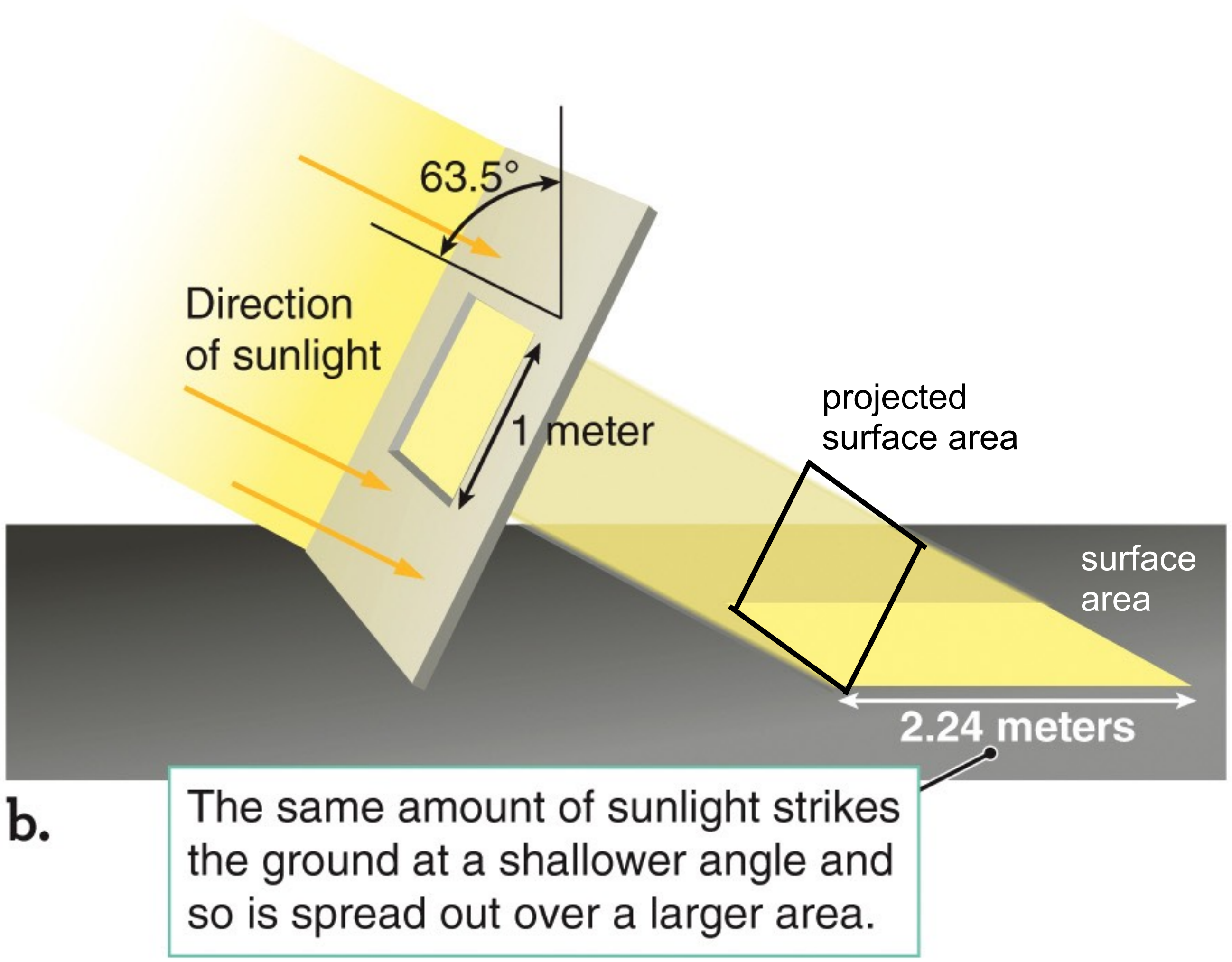


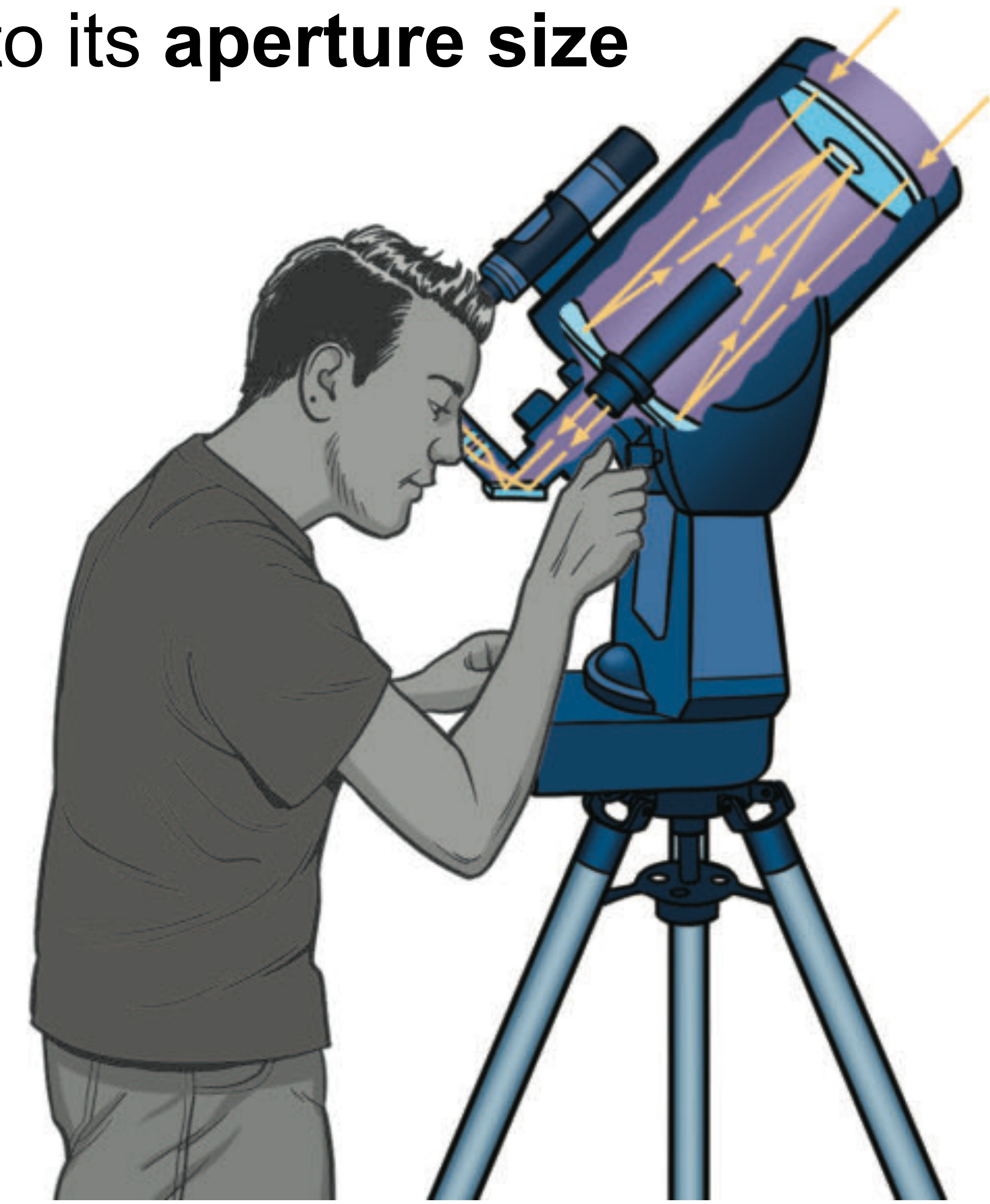
Telescope:
Light gathering power

Received Power (P) from Received Flux (F)

$$P = F \times \text{Projected Area}$$

- Because **most** telescopes are designed to be pointed at the source, its **projected area** equals to its **aperture size**

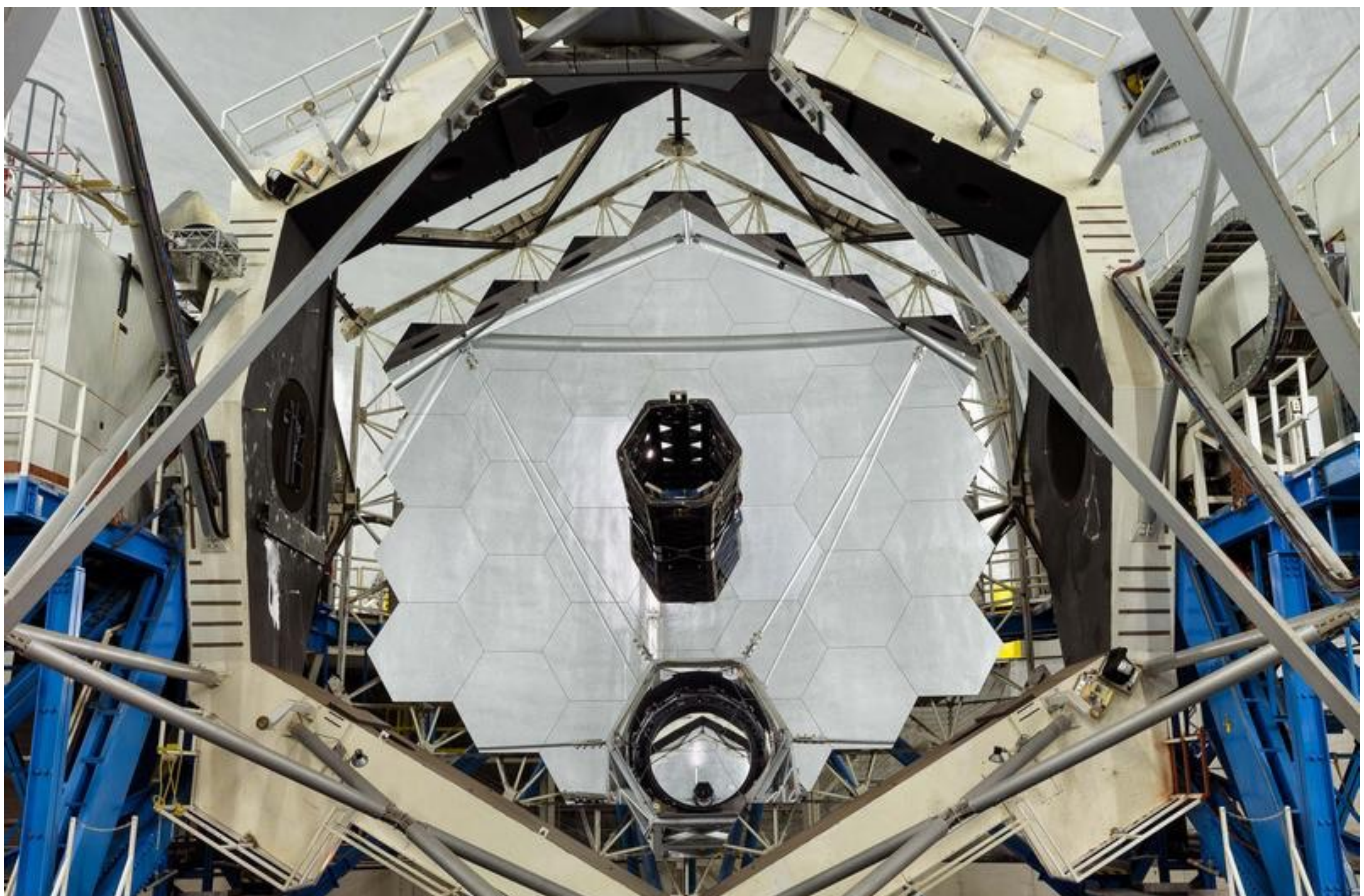




Practice: Light Gathering Power

- The **light-gathering power** of a telescope is proportional to the **square of the aperture ($\propto D^2$)**.

$$\frac{\text{Light-gathering power of Keck}}{\text{Light-gathering power of 8-inch telescope}} = \frac{(10\text{ m})^2}{(0.2\text{ m})^2} = \left(\frac{10}{0.2}\right)^2 = 2{,}500$$

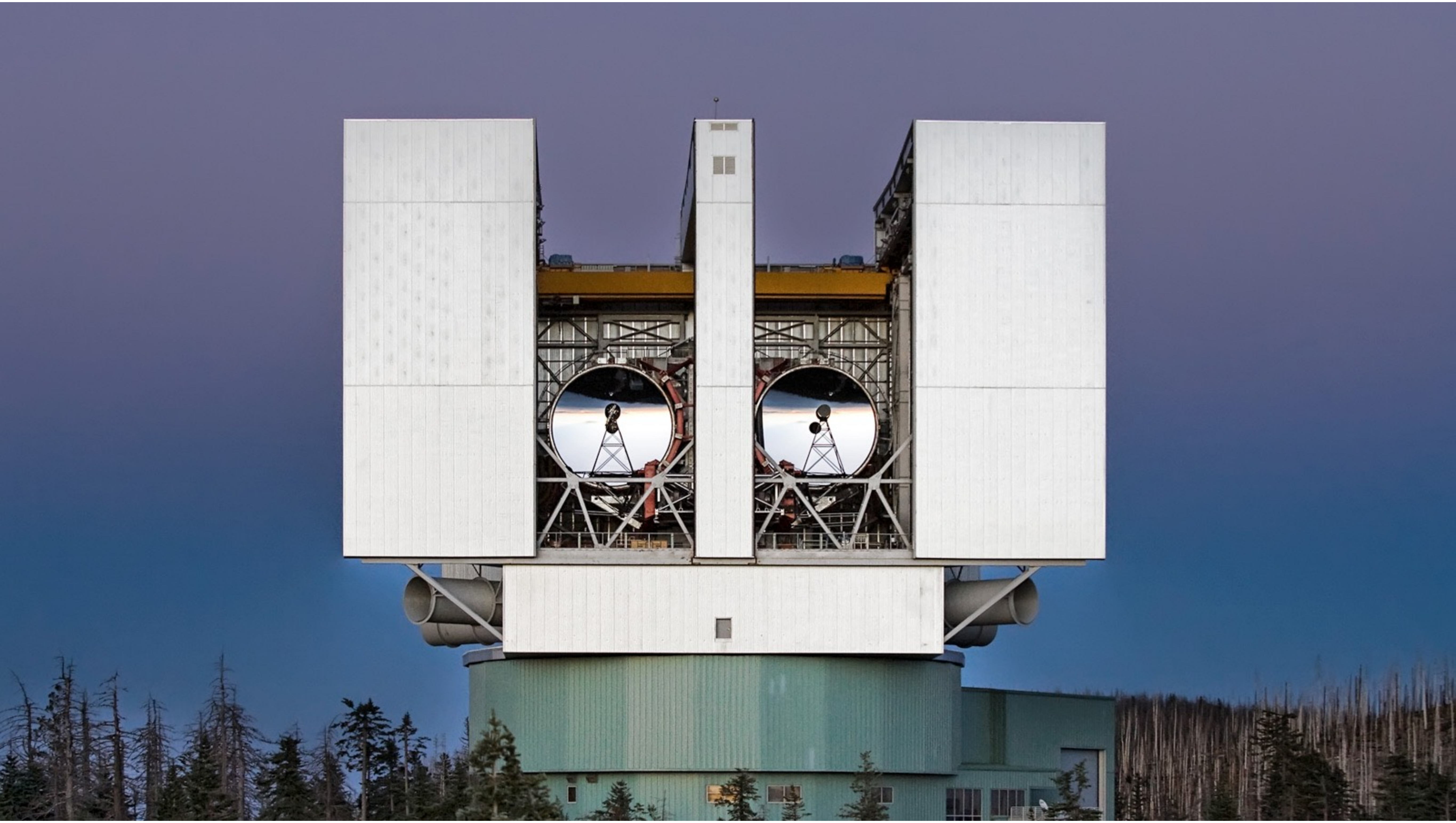


Each 10-m primary mirror is comprised of **36 hexagonal segments**. Each segment is 1.8 meters in diameter, weighs 880 pounds or roughly 0.4 metric tons and is covered with a thin, reflective layer of aluminum.

$$A = \frac{3\sqrt{3}}{2} a^2$$

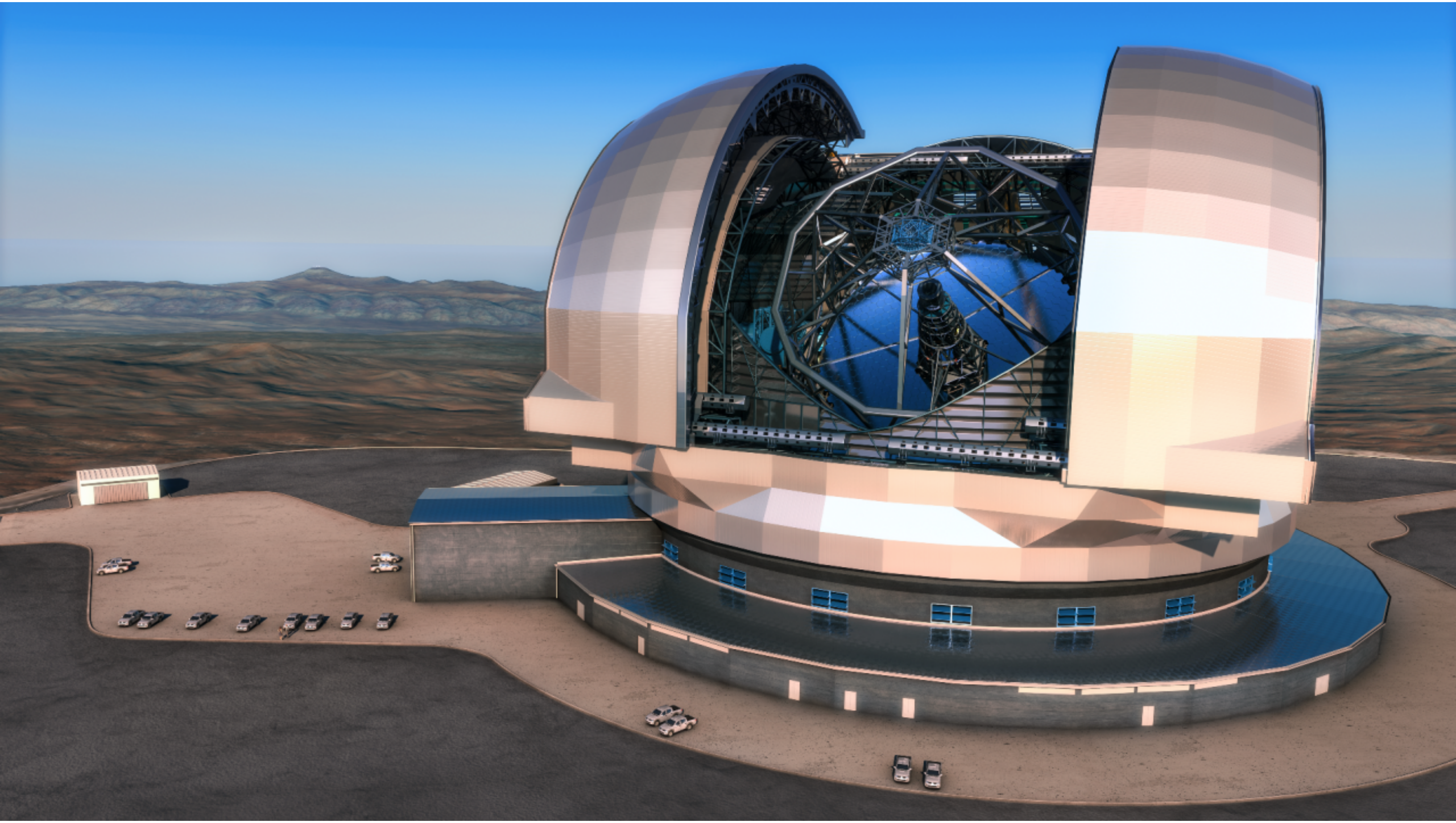
LBT (Large Binocular Telescope)

Two 8.4 m wide mirrors

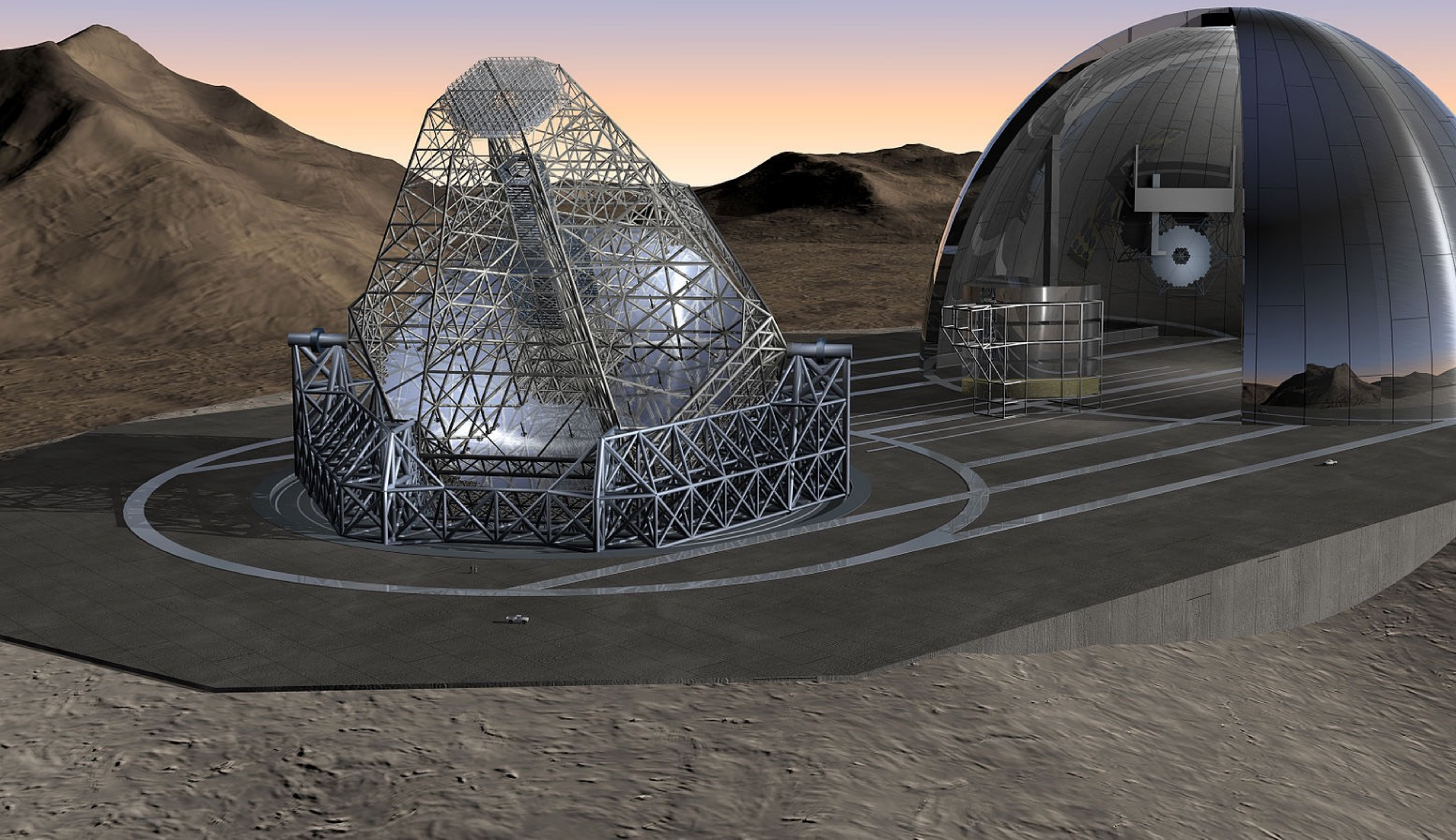



VLT (Very Large Telescope)

ELT (Extremely Large Telescope) [future project]



OLT (Overwhelmingly Large Telescope) [future project]

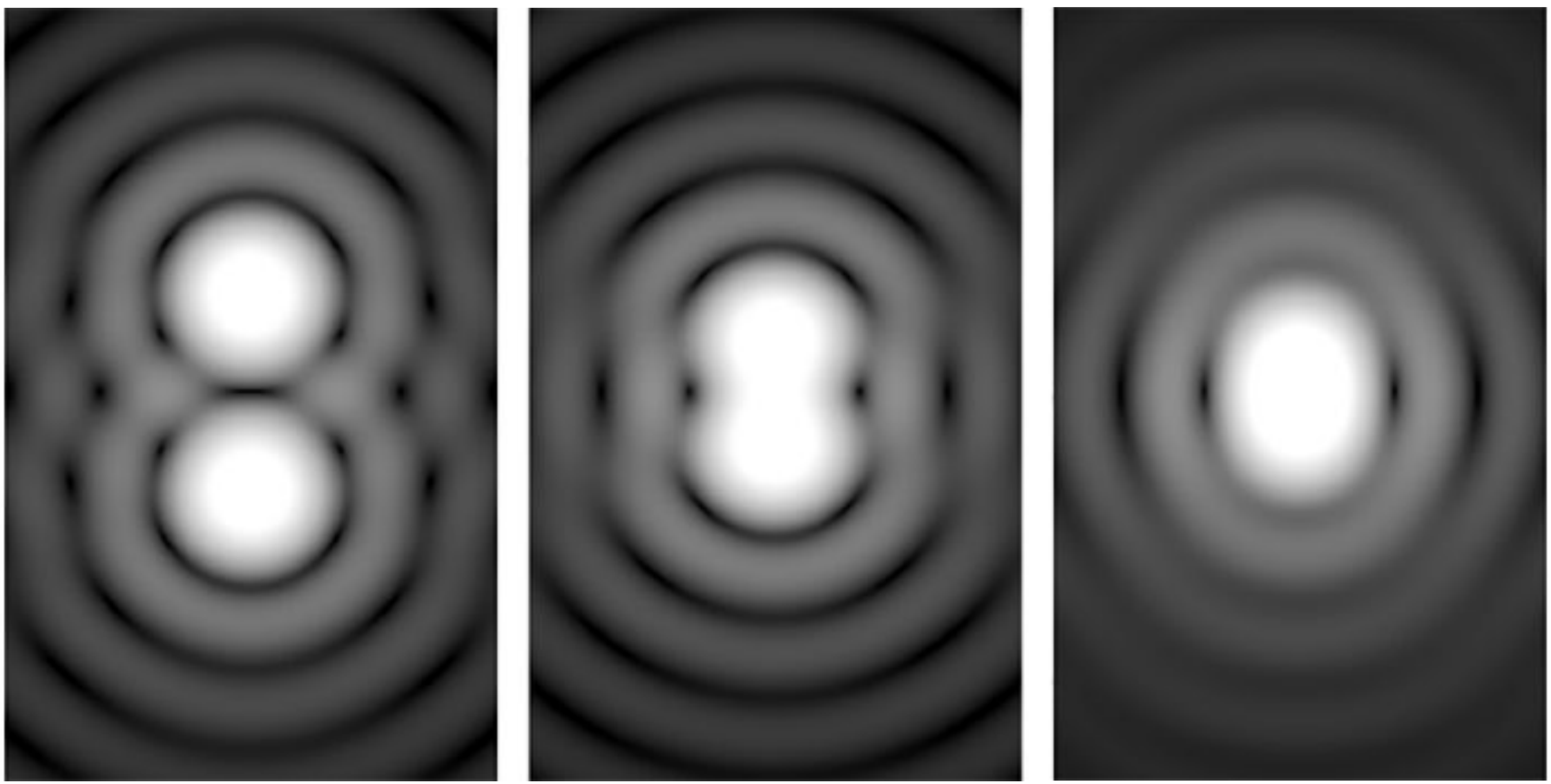


Best Possible Angular Resolution

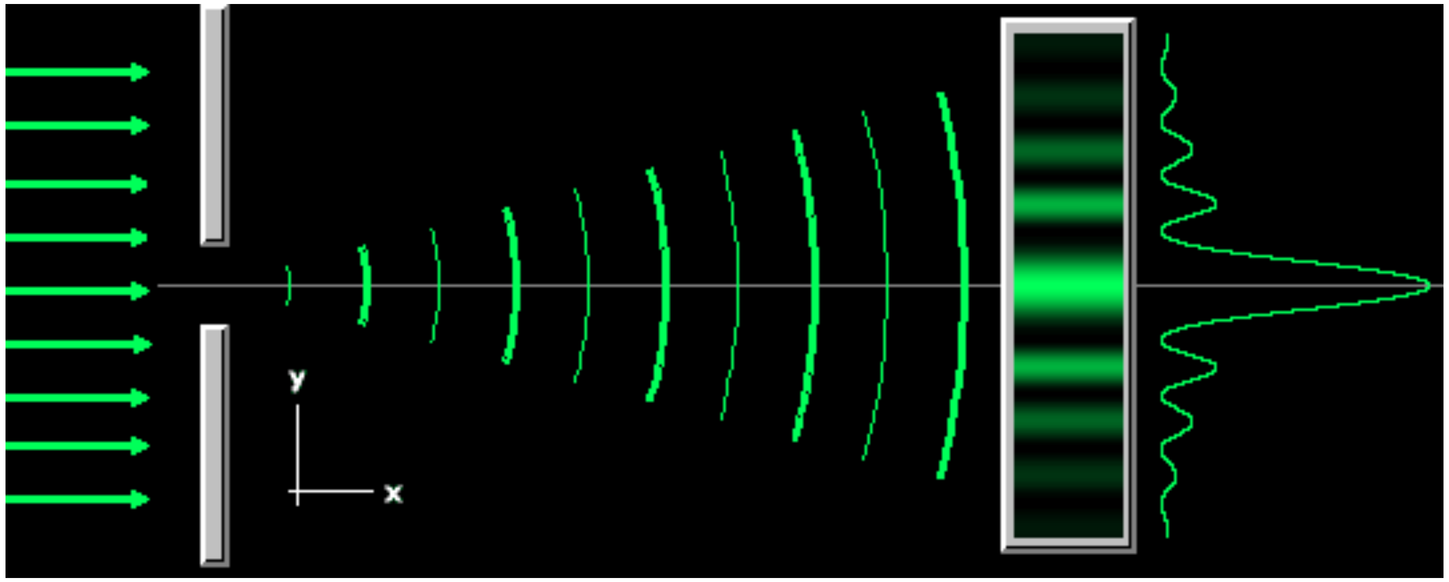
diffraction limit $\theta = \lambda/D$

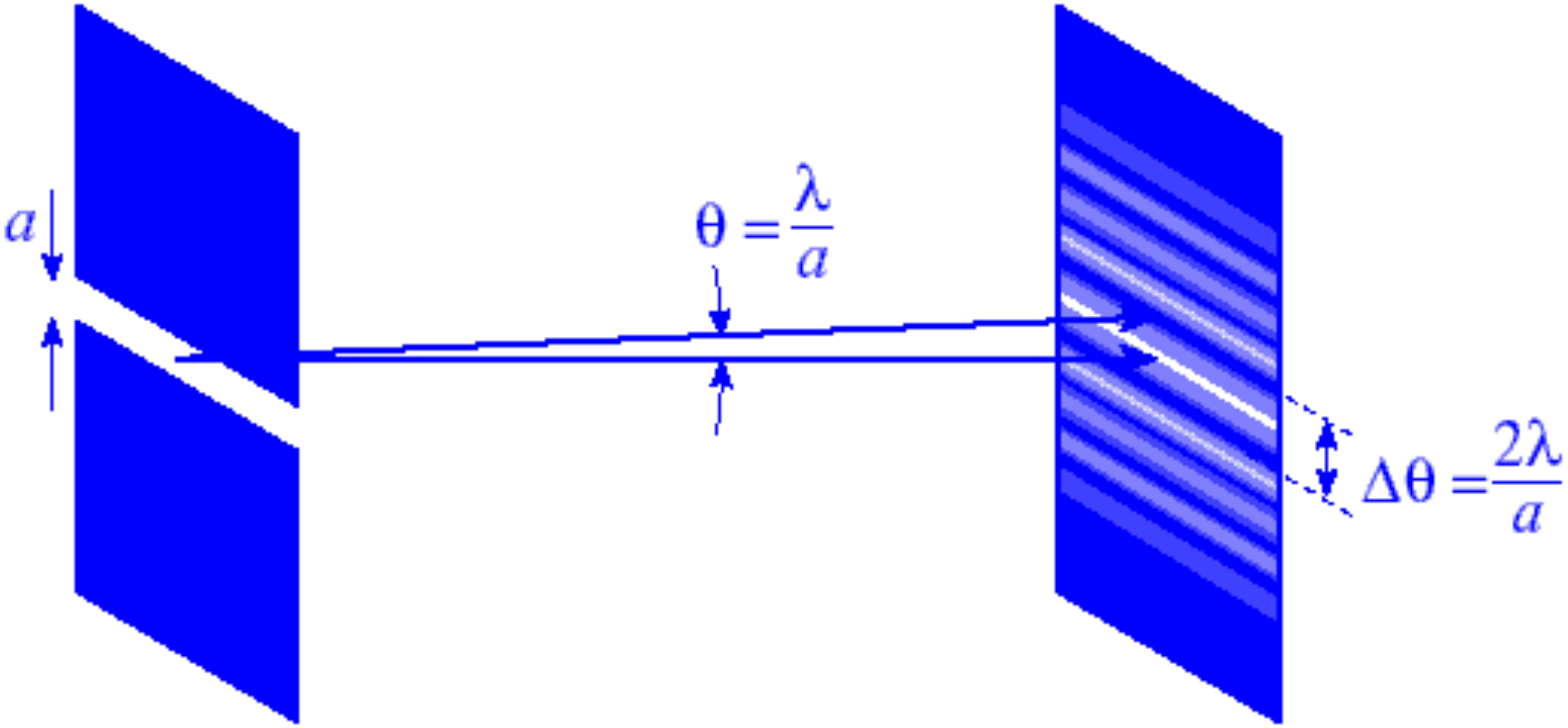
The **diffraction limit** determines the closest **angular separation** between two point sources that is resolvable by *perfect optics with no atmospheric turbulence*

well resolved | just resolved | not resolved

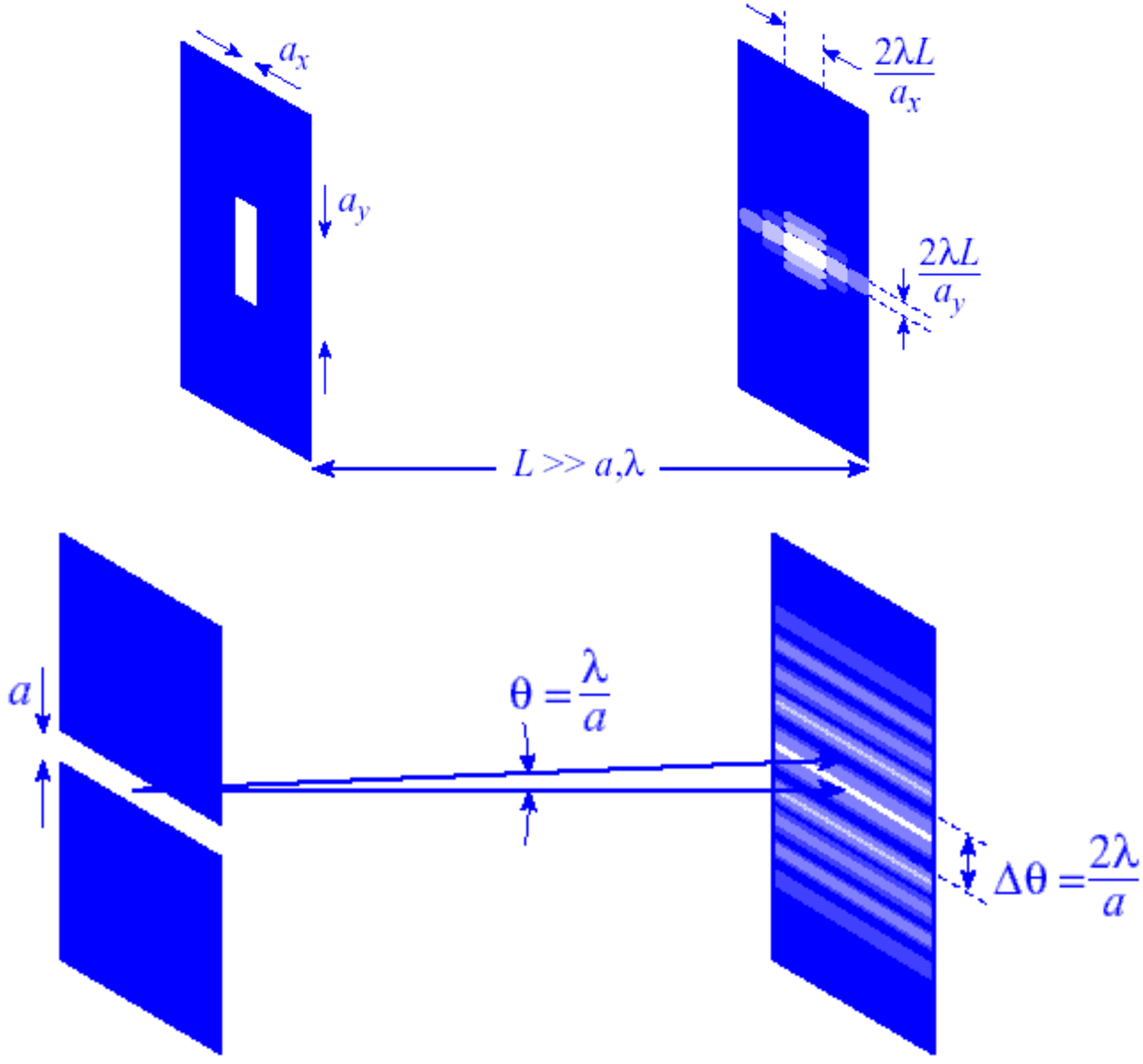


Diffraction pattern of a long slit

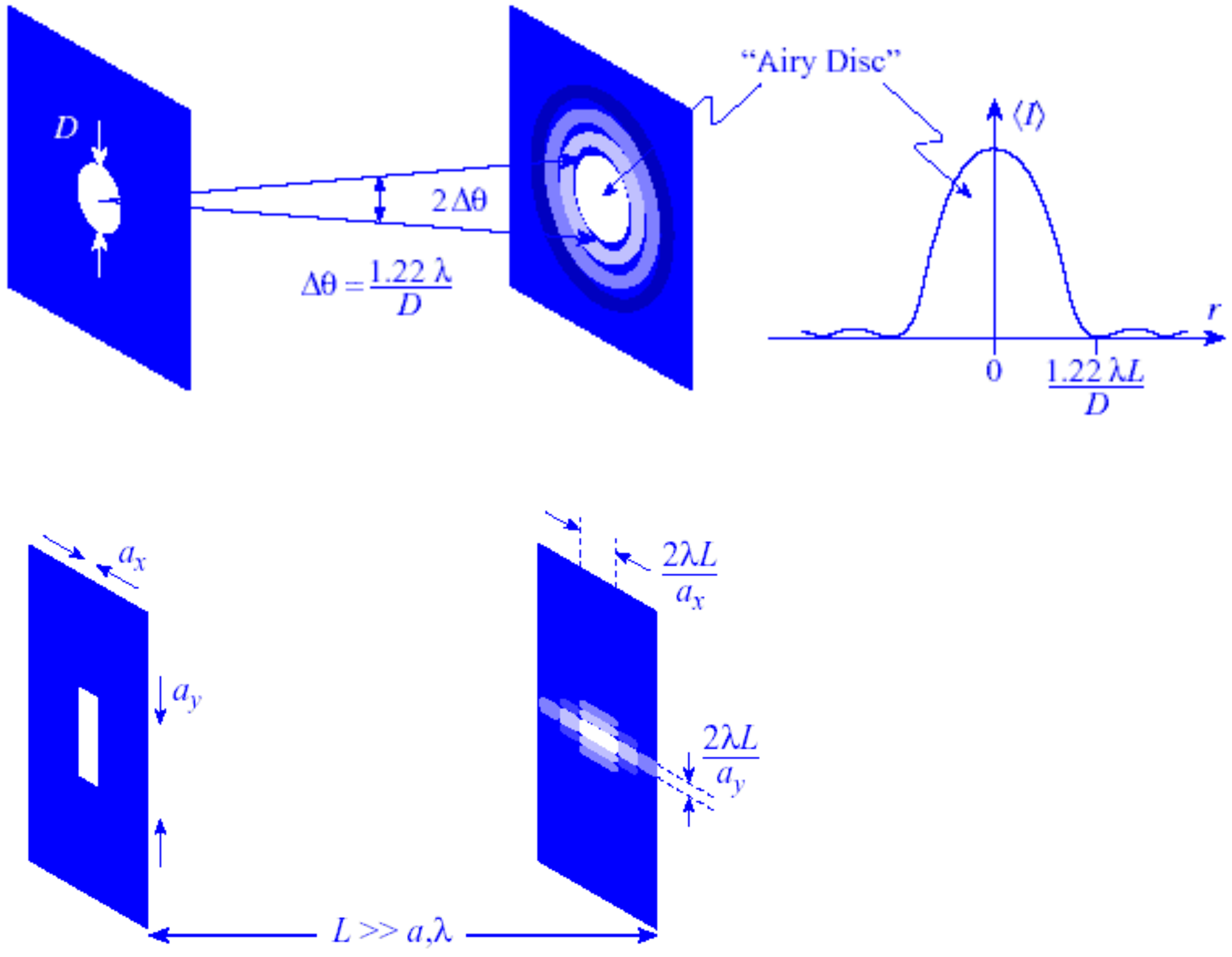




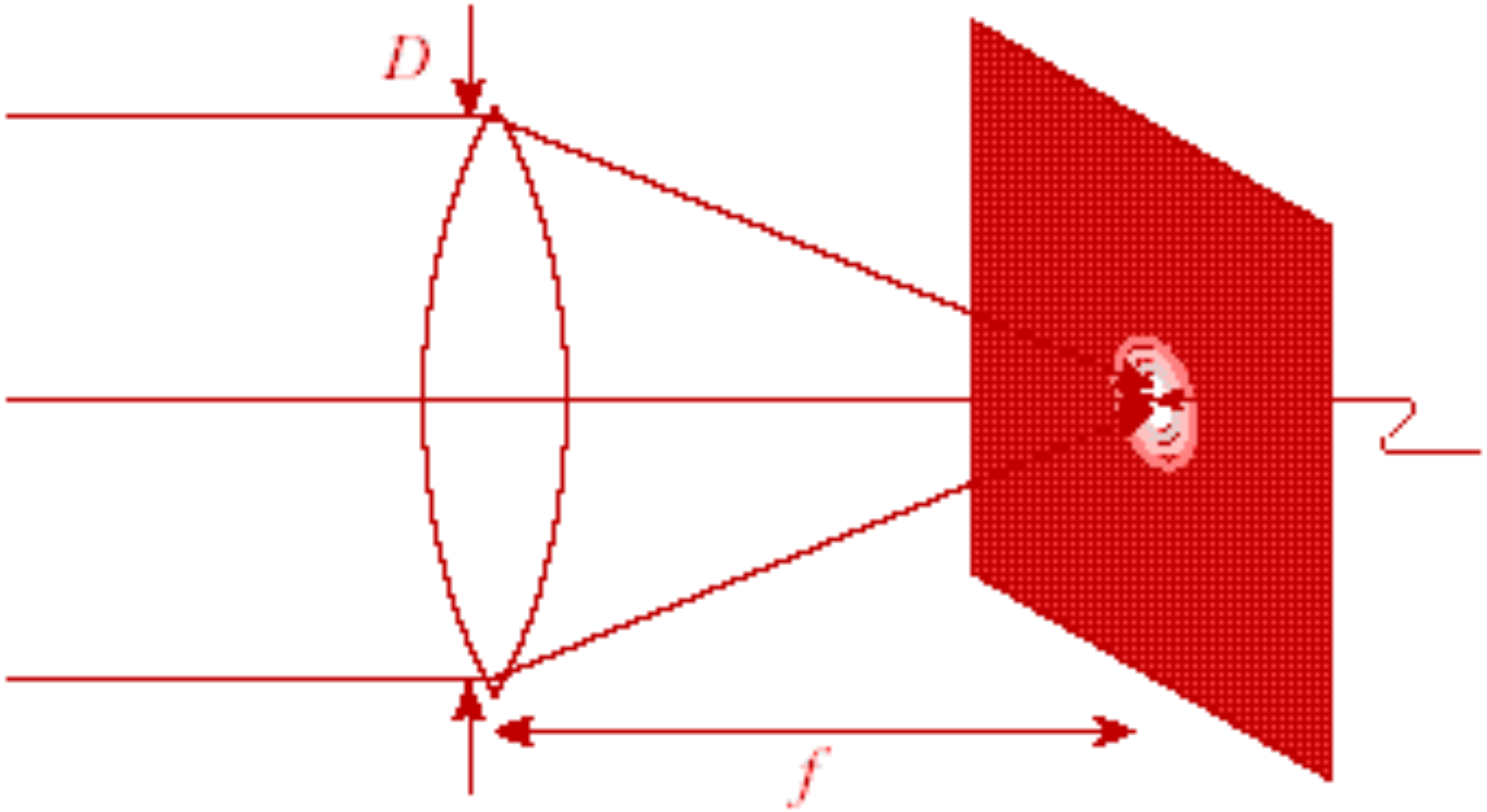
Diffraction pattern of a narrow slit



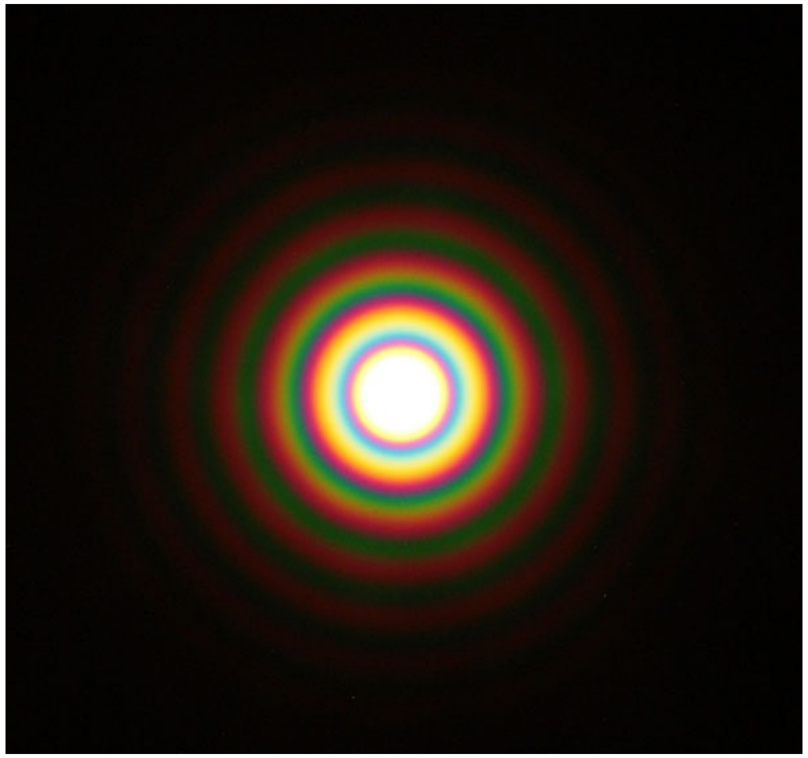
Diffraction pattern of a circular aperture

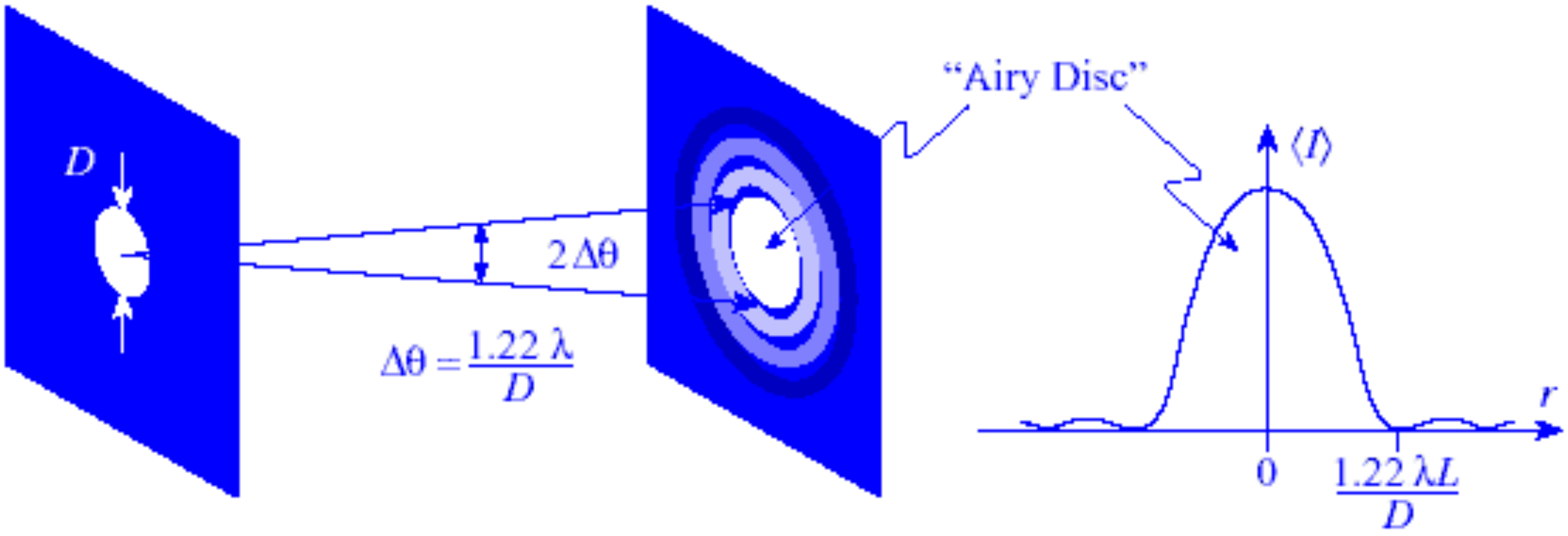


Diffraction pattern of a circular aperture that focuses light



The Airy Disk



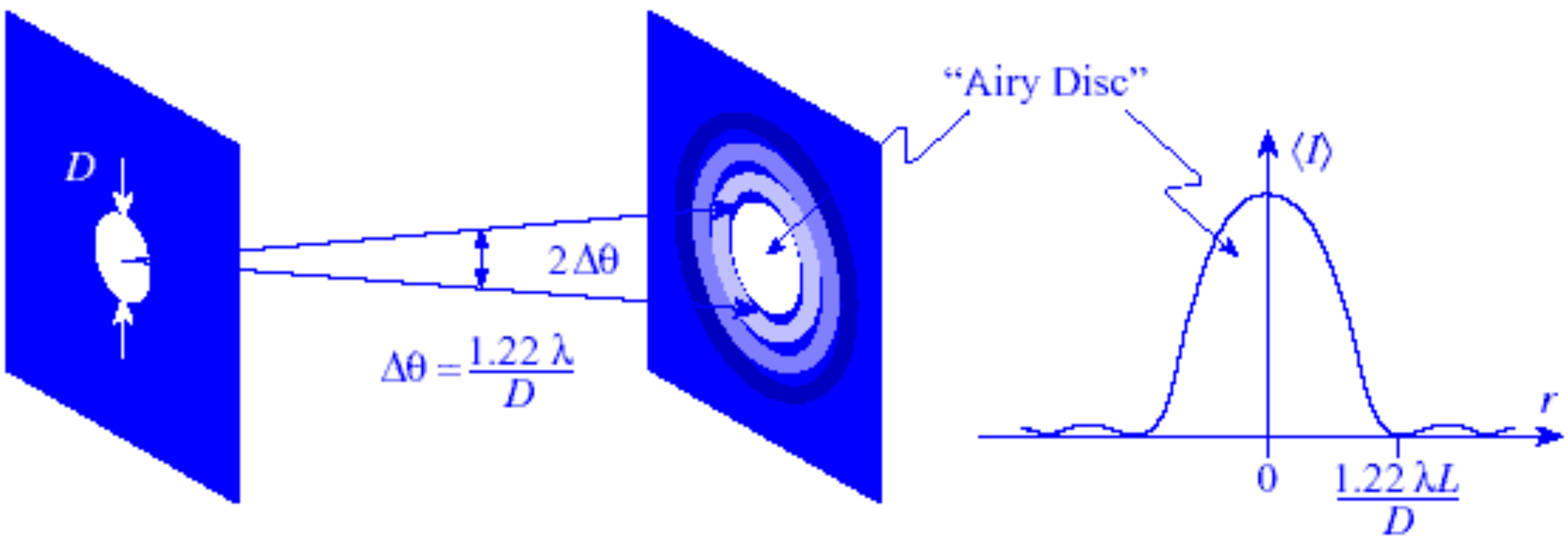


The Diffraction Limit of A Circular Lens/Mirror

The **diffraction limit** is defined as the ***radius*** of the Airy disk:

$$\theta = 1.22\frac{\lambda}{D} \text{ radian} = 206265 \times 1.22\frac{\lambda}{D} \text{ arcsec}$$

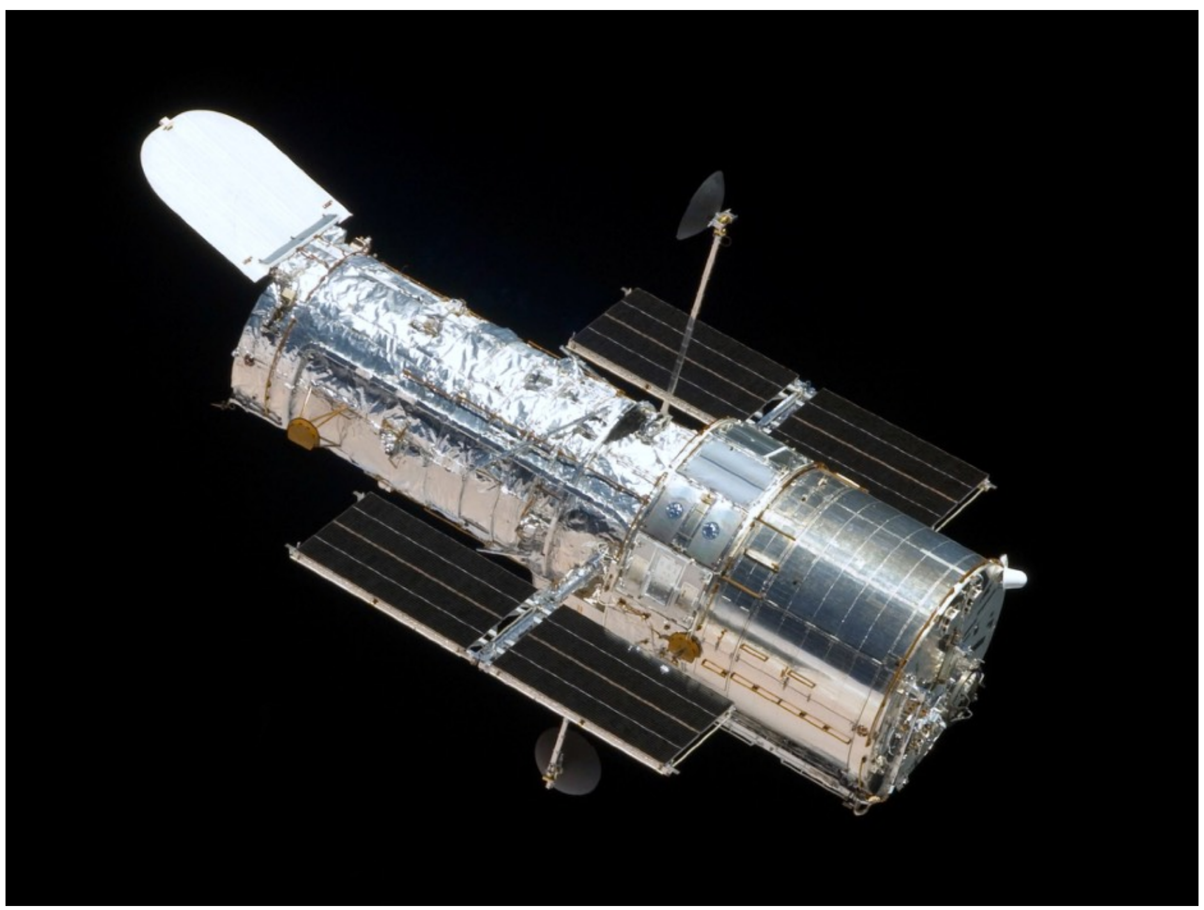
where ***λ*** is the wavelength and ***D*** is the lens/mirror diameter



Practice: Calculating Diffraction Limit

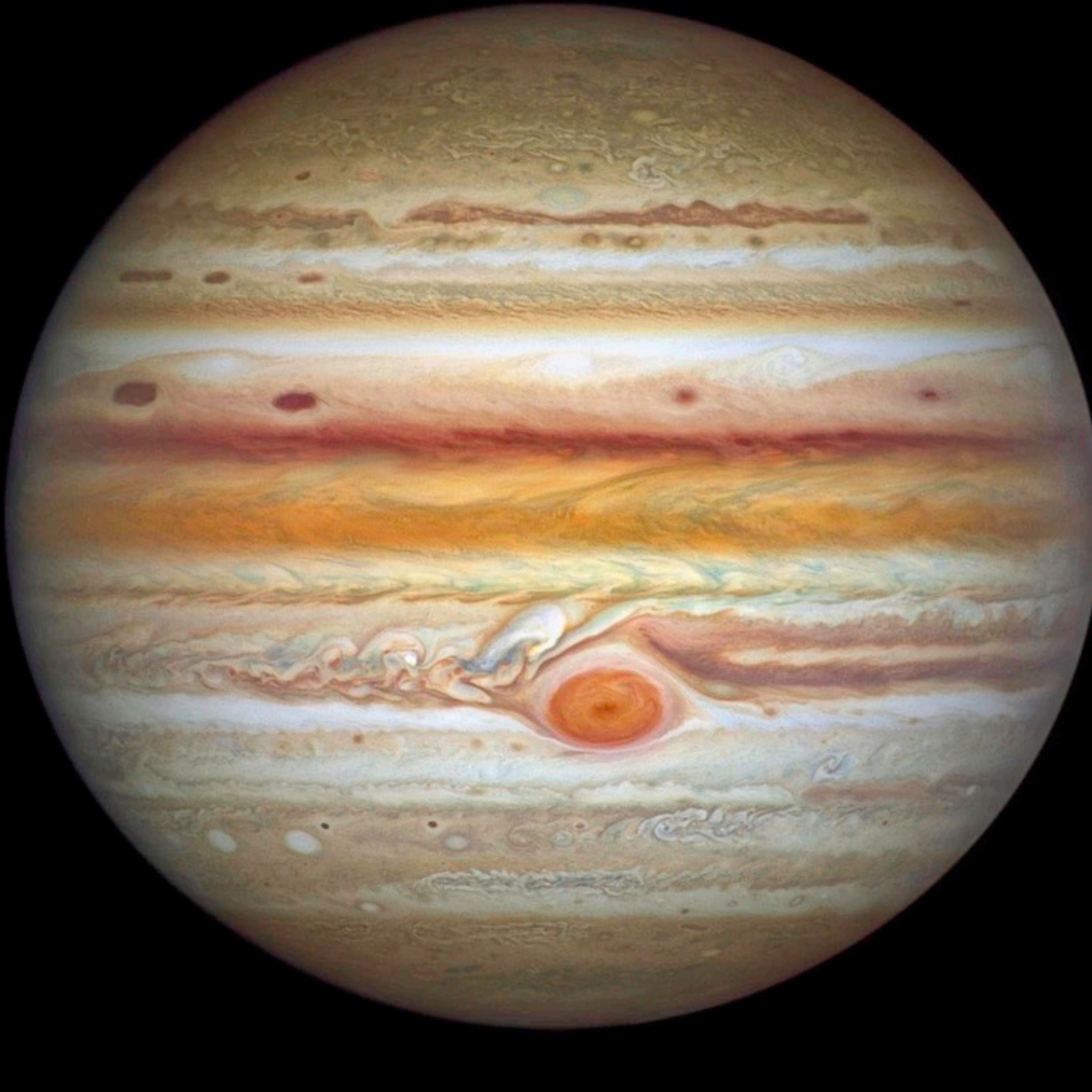
$$\theta = 1.22\frac{\lambda}{D}\ \text{radian} = 206265 \times 1.22\frac{\lambda}{D}\ \text{arcsec}$$

Practice: Hubble Space Telescope



What is the diffraction limit of the HST at a wavelength of 500 nm? The diameter of HST's primary mirror is 2.4 meter.

Answer: 0.052 arcsec

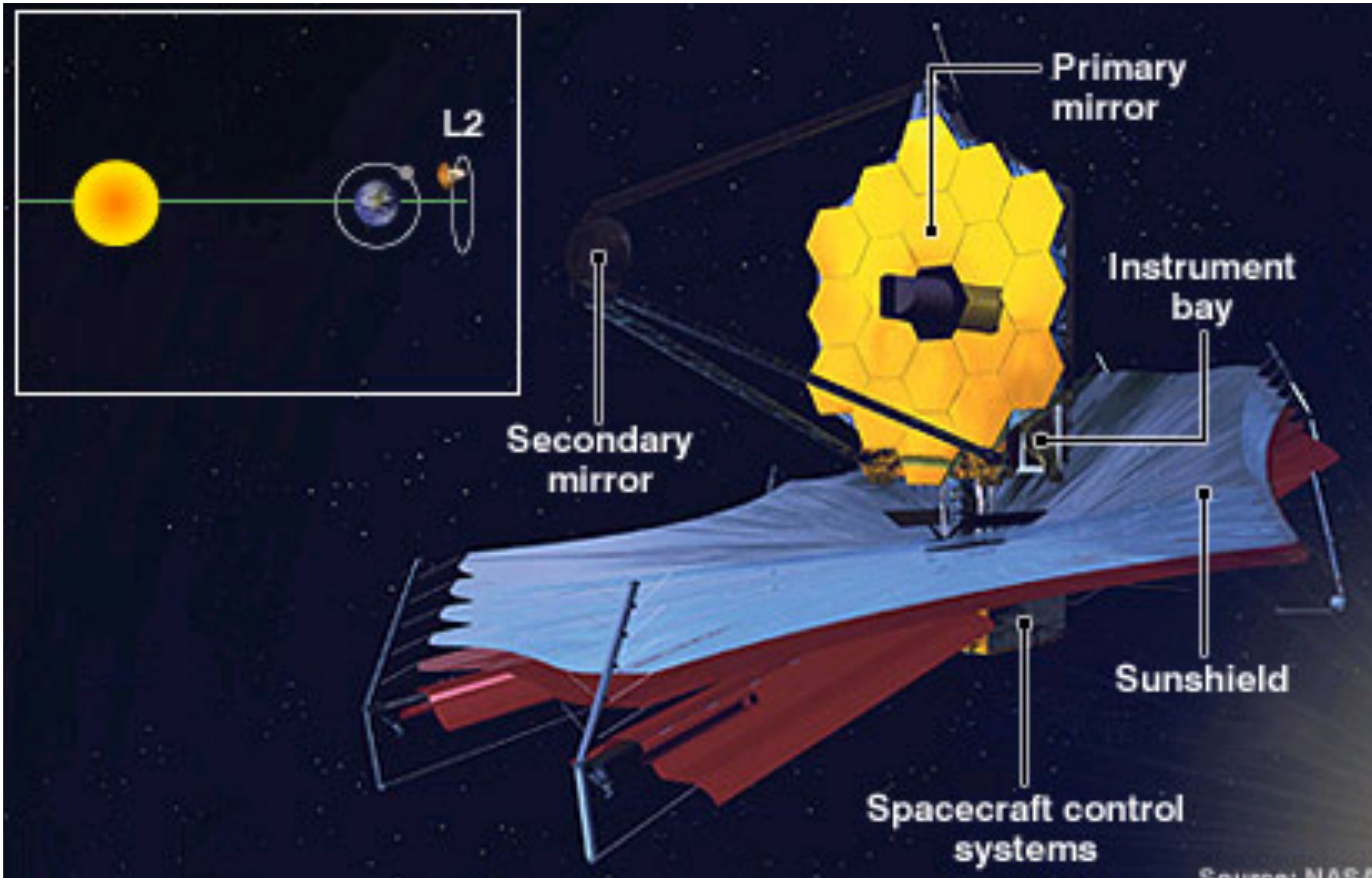



NGC 2174, the Monkey Head Nebula

Interferometers

maximizing resolution by synthesizing multiple apertures

If segmented mirrors can work together as one,
do we really need to fill the aperture with mirrors?

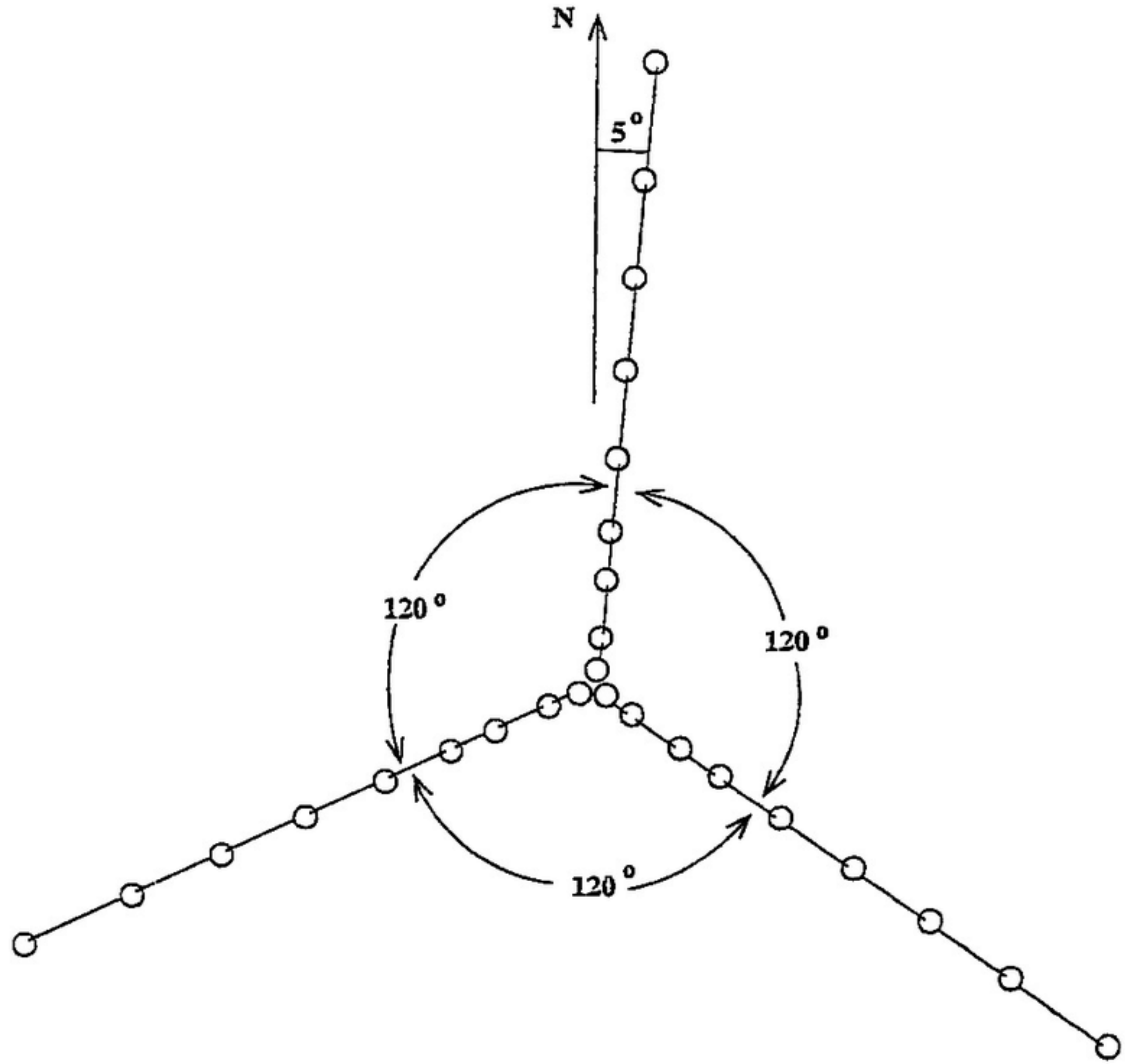


VLA (Very Large Array)

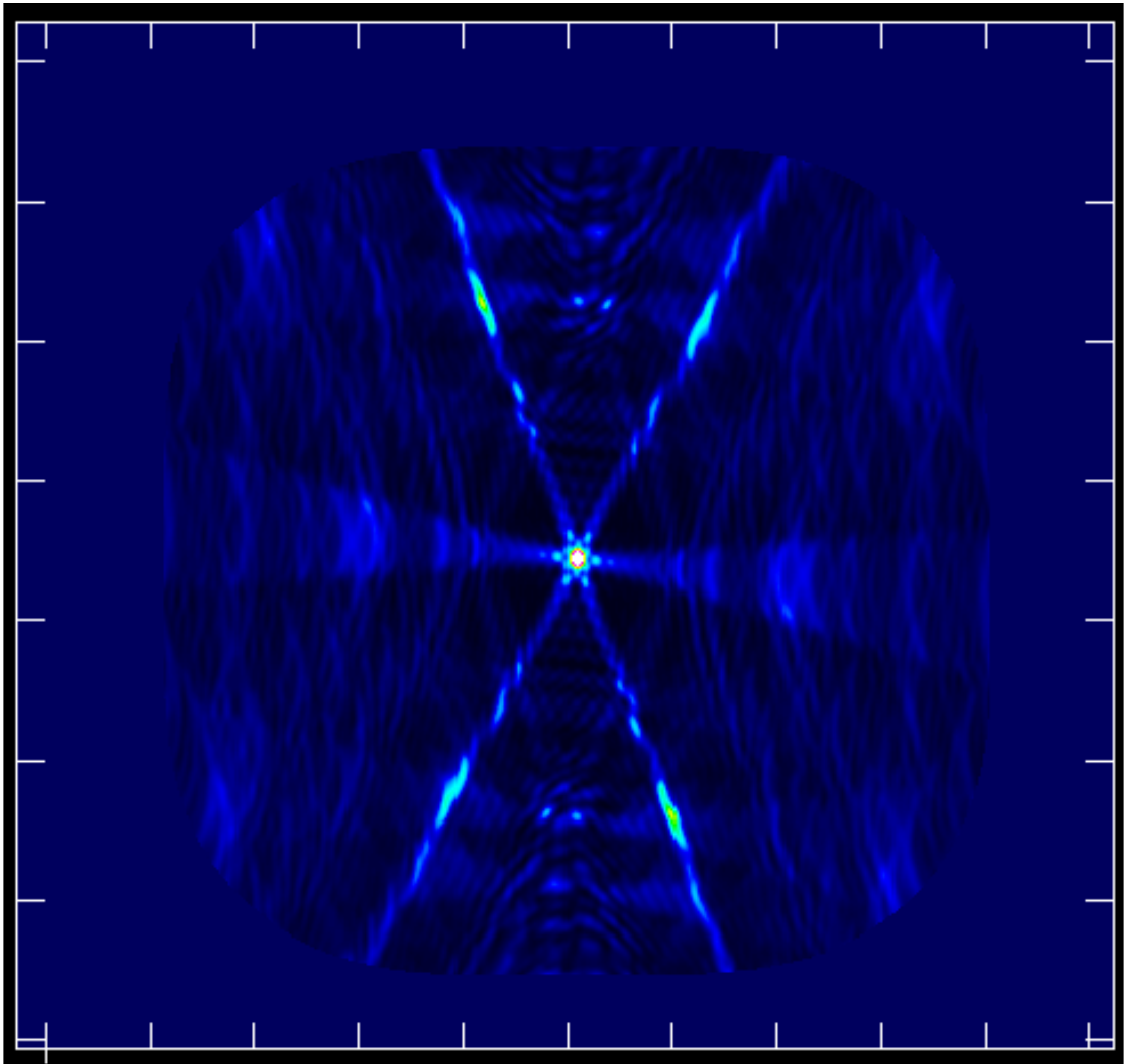
27 parabolic dishes, each **25 meters (82 feet) in diameter**.

A Single VLA Dish (25 m in diameter)

We can calculate the diffraction patterns of differently shaped apertures, even for the **fragmented aperture** of the **VLA**



diffraction pattern of the VLA interferometer this is what a radio star’s image look like

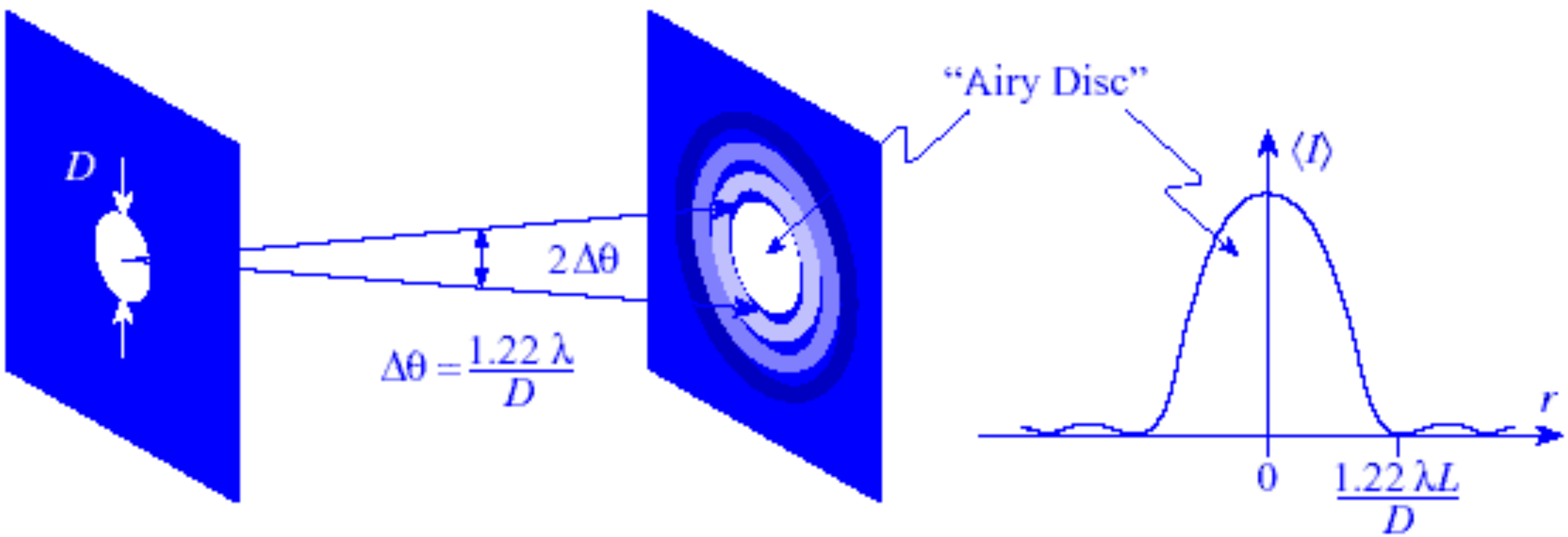


The Diffraction Limit of an Interferometer

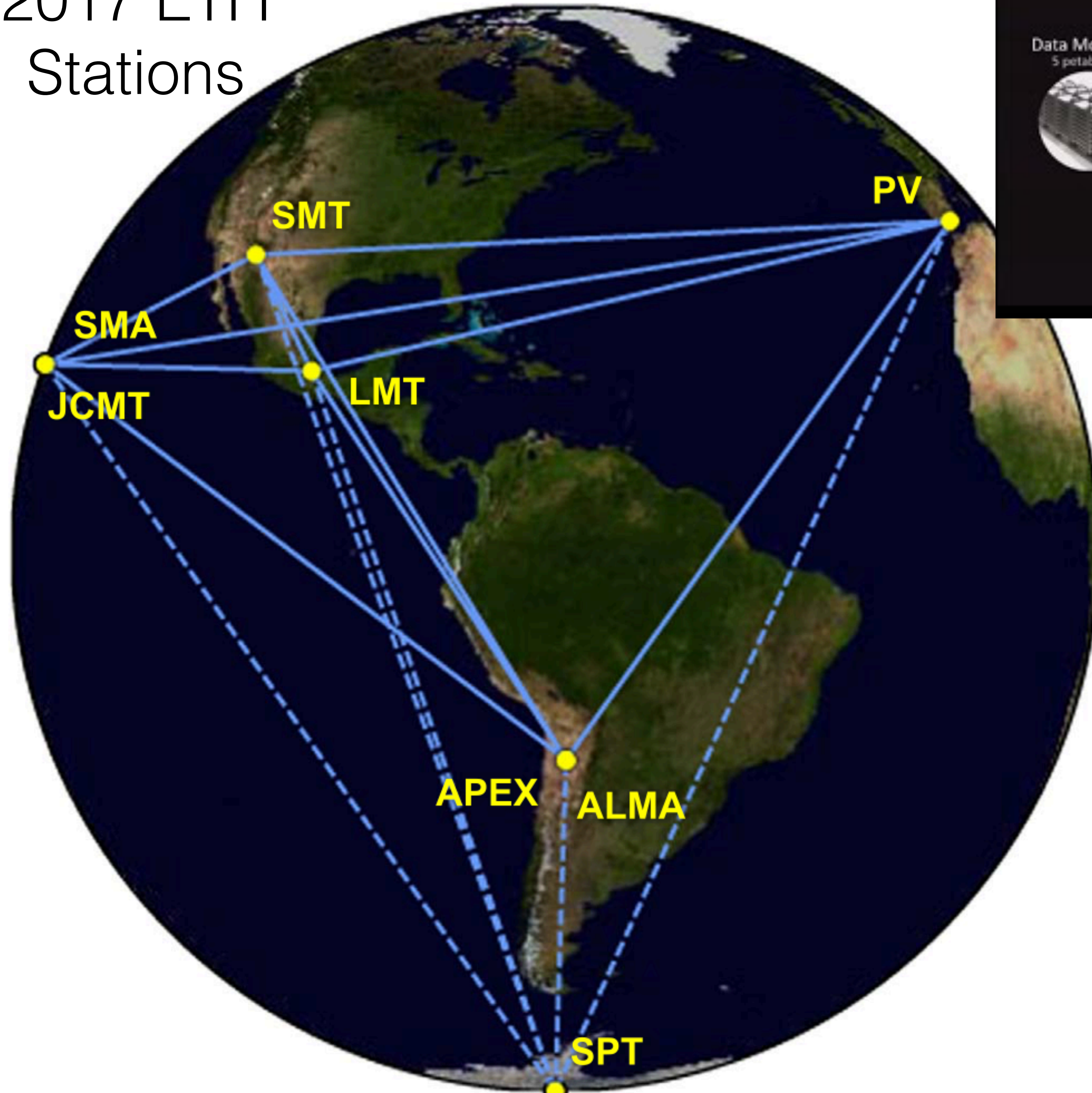
The diffraction limit is the ***radius*** of the ***central*** disk:

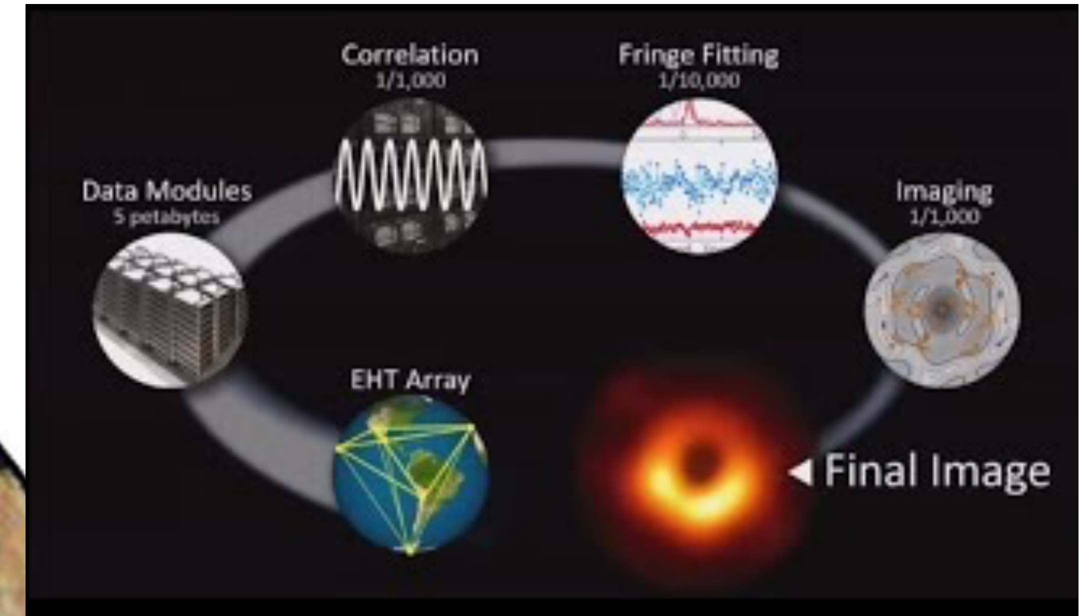
$$\theta = 1.22\frac{\lambda}{D}\ \text{radian} = 206265 \times 1.22\frac{\lambda}{D}\ \text{arcsec}$$

where ***λ*** is the wavelength and ***D*** is the **widest separation** between two elements in the interferometer

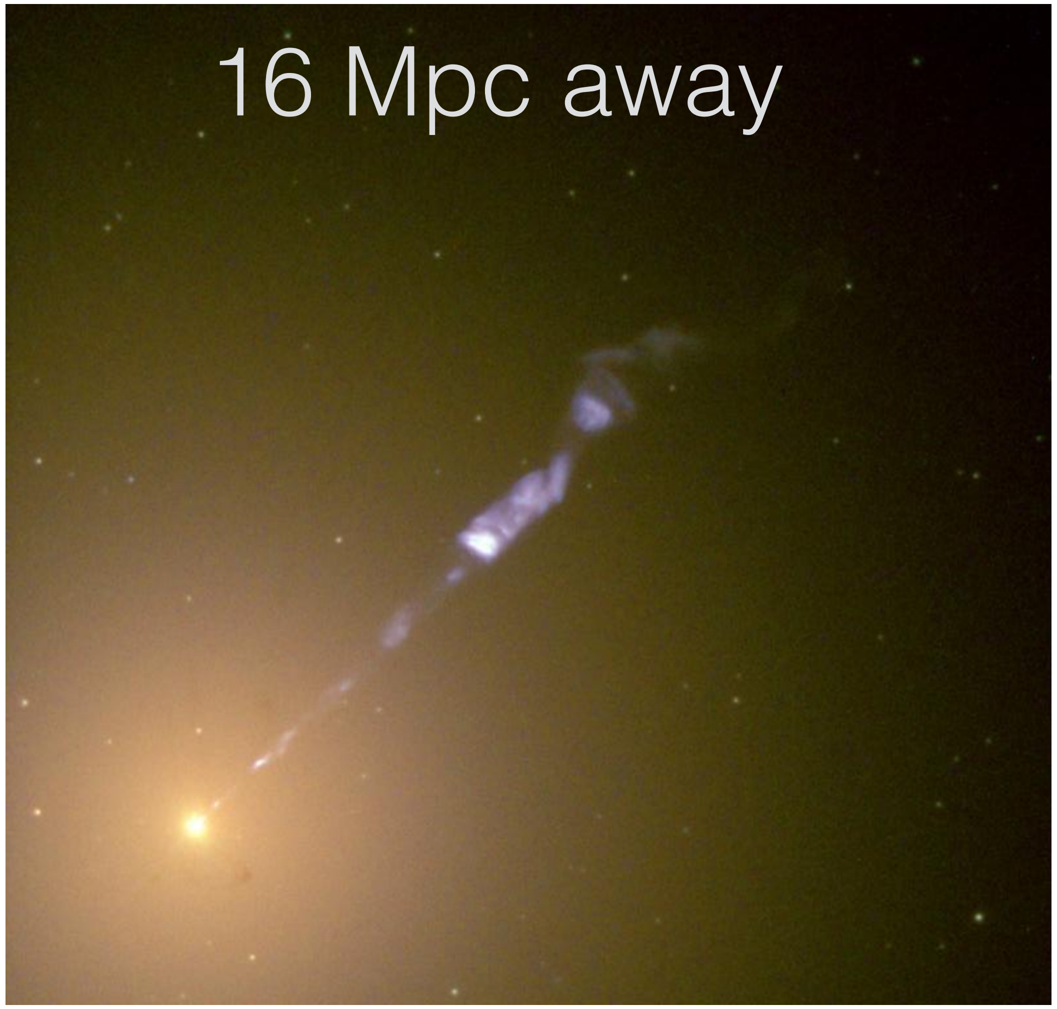


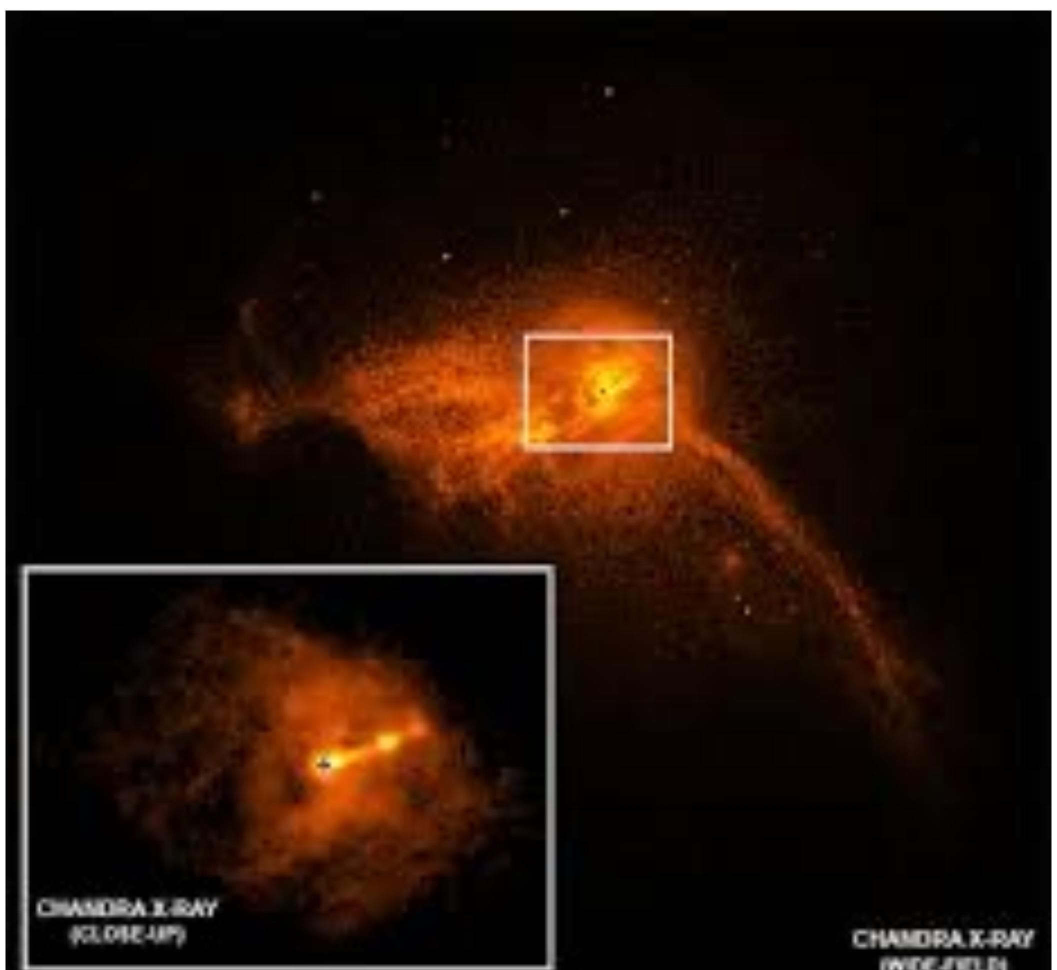
2017 ETH Stations

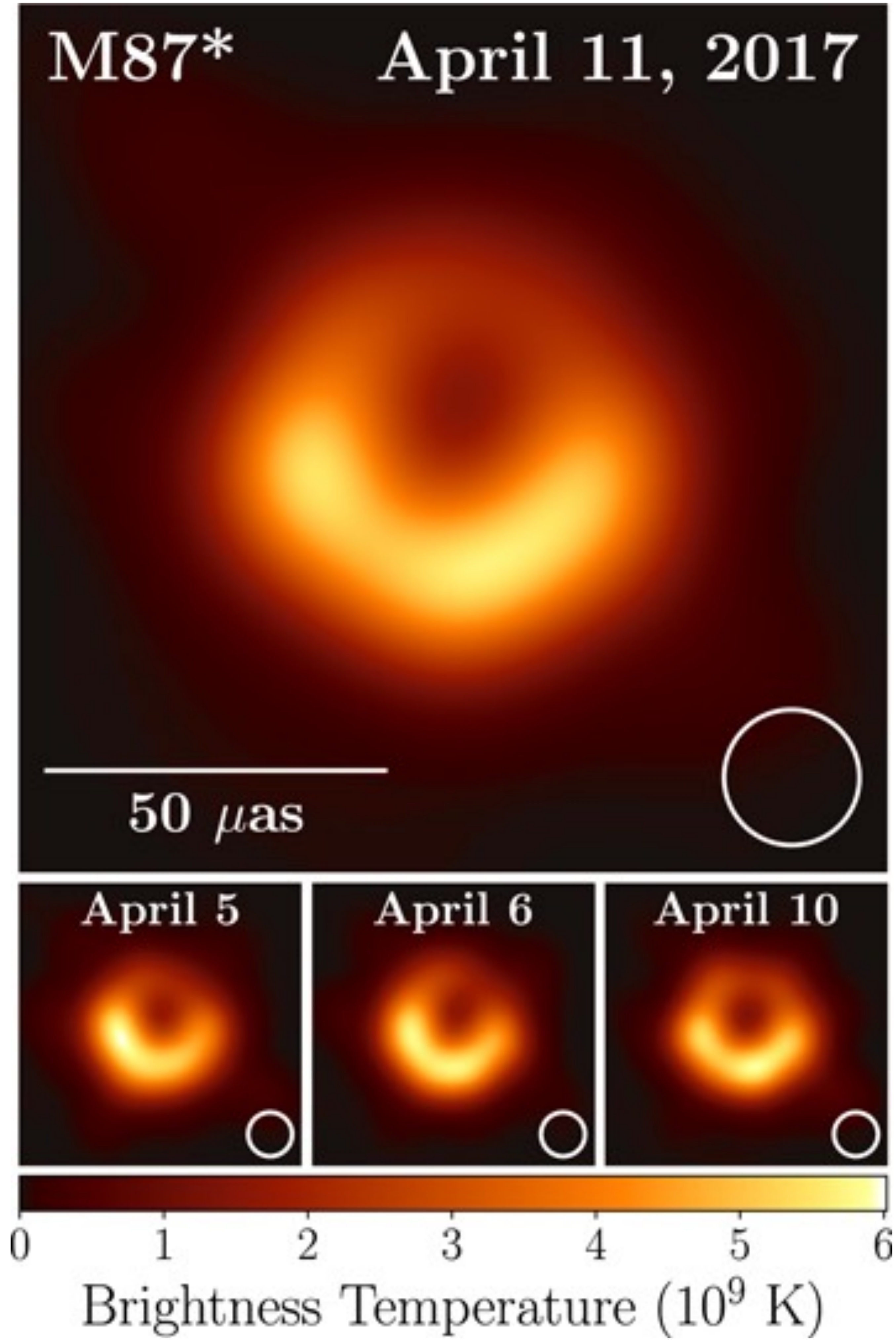




https://iopscience.iop.org/journal/2041-8205/page/Focus_on_EHT


16 Mpc away


CHANDRA X-RAY
(CLOSE-UP)
CHANDRA X-RAY
(WIDE-FIELD)


M87*
April 11, 2017
50 μas
April 5
April 6
April 10
0
1
2
3
4
5
6
Brightness Temperature (10^9 K)

Telescope + Camera:

detector, plate scale, & field of view

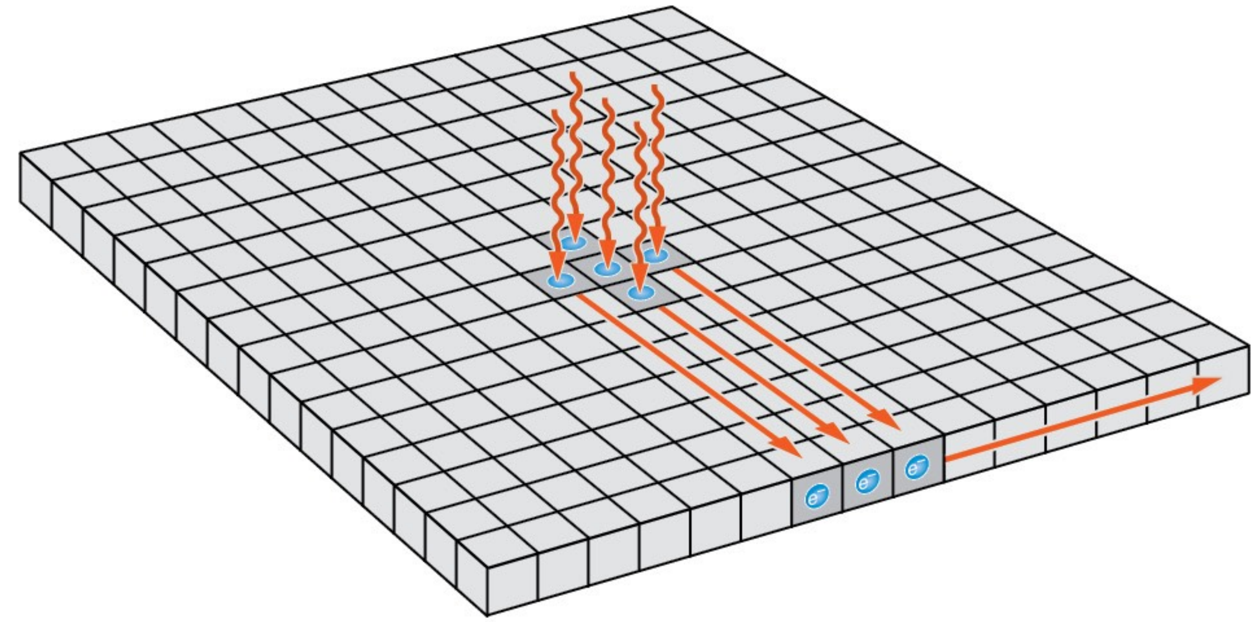
2009 NOBEL PRIZE IN PHYSICS

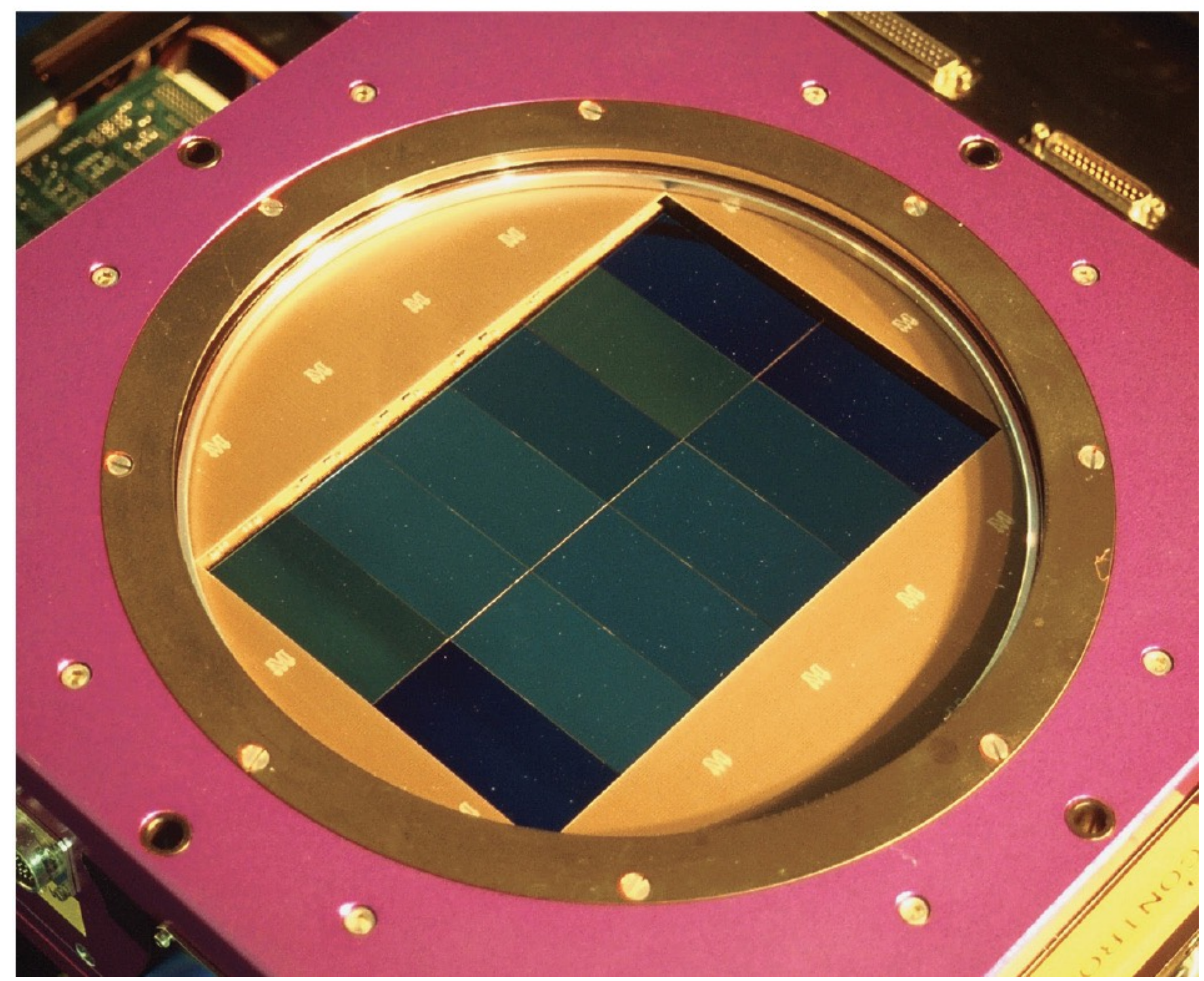
Willard S Boyle and George E Smith (1969 invention at Bell Labs)

The charge-coupled device (CCD) provided the first way for a light-sensitive silicon chip to store an image and then digitize it, opening the door to the creation of digital images.

Silicon-based Detectors: e.g., CCD and CMOS

- **CCDs: charge-coupled devices** (such as digital cameras)
- Electronic detectors record photons on **pixels**.
- Photons create a signal in the array.
- The electronically recorded images can greatly exceed photographs in quality.
- CCDs are the astronomer's detector of choice.





How to calculate how large an area this image covers?

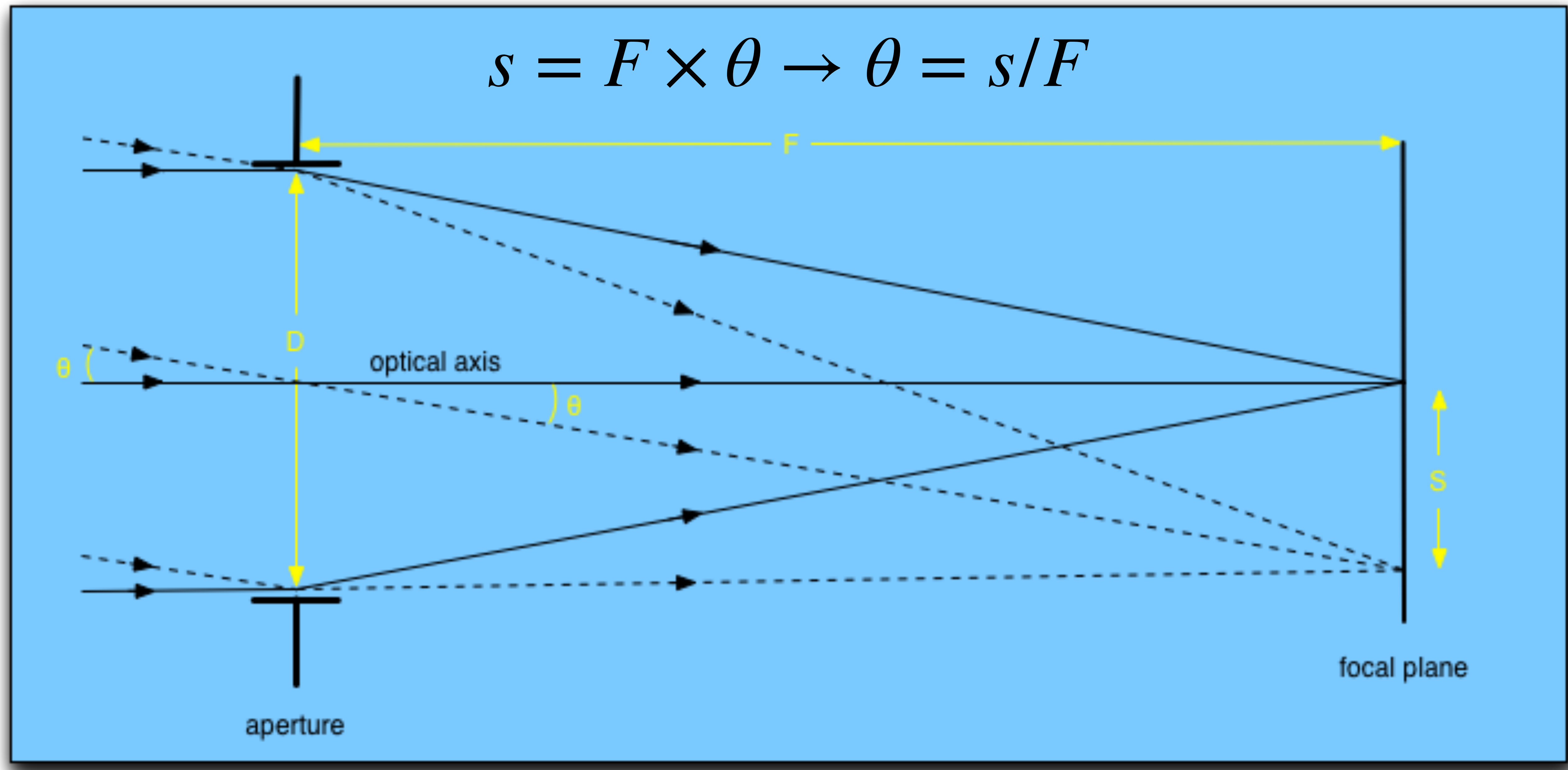
We need to know (1) the angular size of each pixel and
(2) the number of pixels on each side

Plate Scale is defined as the angular size of a pixel, it has a unit of arcsec/pixel

$$\text{plate scale} = \frac{\text{pixel size}}{\text{focal length}} \Rightarrow \text{plate scale}(''/\text{pixel}) = 206265''/\text{radian} \times \frac{\text{pixel size}(\mu\text{m}/\text{pixel})}{\text{focal length(m)} \times 10^6}$$

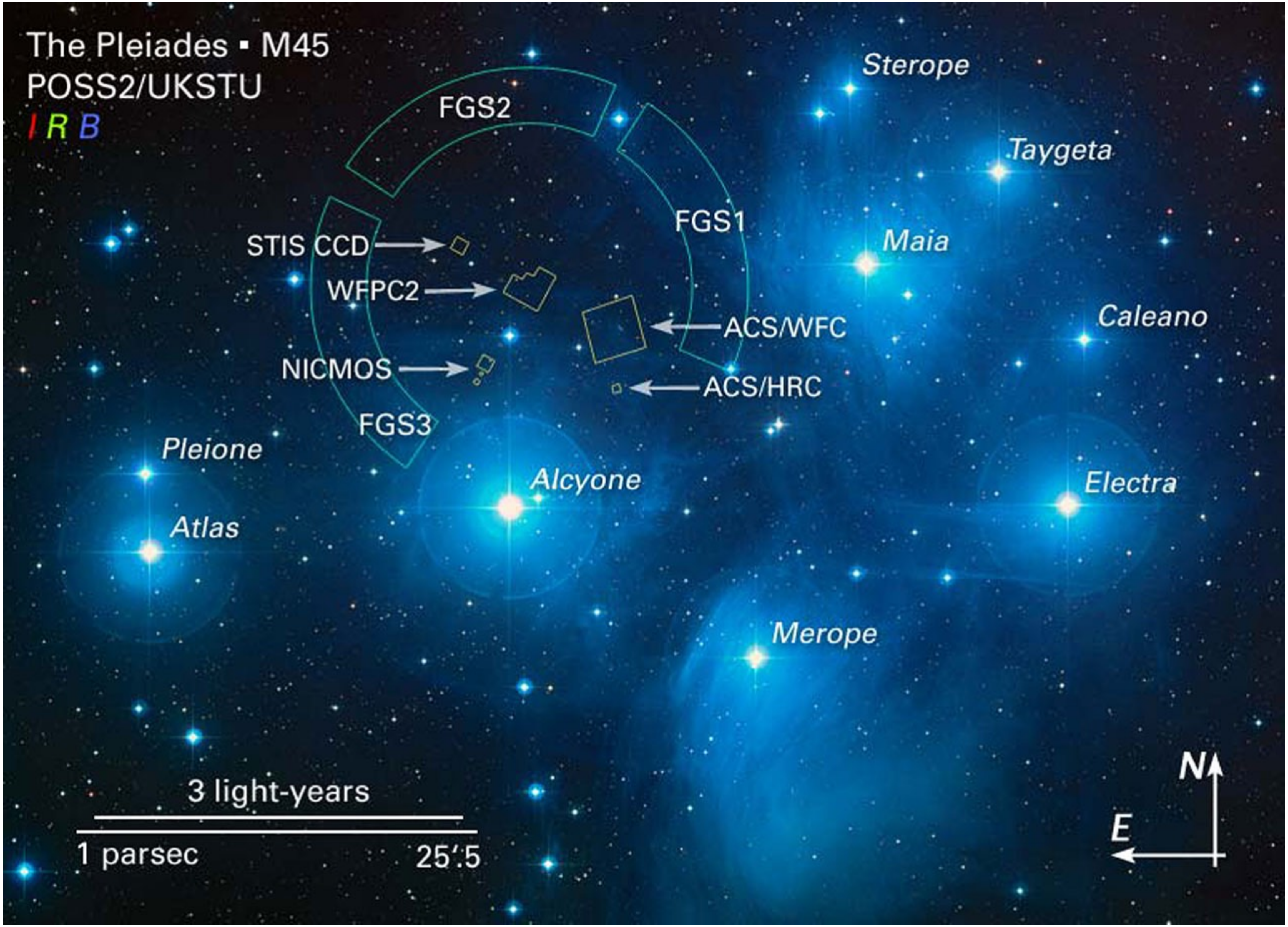
often the focal length is not provided, but the focal ratio is:

Focal Ratio = Focal Length / Aperture Diameter



The Field of View of a camera is defined as the angular dimension of the full detector:

FoV = Plate Scale x [Nx, Ny]



Practice: Meade Scope

$$\text{plate scale}(''/\text{pixel}) = 206265'' \times \frac{\text{pixel size}(\mu\text{m}/\text{pixel})}{\text{focal length}(\text{m}) \times 10^6}$$

- The Meade LX200GPS in the small dome has an aperture diameter of 10 inch (25.4 cm) and a focal ratio of F/10 (which is defined as the ratio between focal length and aperture diameter).
- The Panasonic GF2 digital camera that you'll mount on it has a sensor with a dimension of 17.3mm x 13mm and 4000 x 3000 pixels (12 Megapixels).
- What is the pixel size in μm/pixel?
- What is the plate scale in arcsec/pixel?
- What is the field of view in arcmin?

Chap 6: Equations

Doppler Shift

$$\frac{V_r}{c} = \frac{\lambda_{\rm obs} - \lambda_0}{\lambda_0} = \frac{\nu_0 - \nu_{\rm obs}}{\nu_{\rm obs}}$$

Telescope Focal Ratio (optics are scalable)

$$f = F/D$$

Diffraction Limit (angular resolution limit of perfect optics)

$$\theta = 1.22\frac{\lambda}{D}\ \text{radian} = 206265'' \times 1.22\frac{\lambda}{D}$$

CCD Plate Scale & Field of View

$$\text{plate scale}(''/\text{pixel}) = 206265'' \times \frac{\text{pixel size}(\mu\text{m}/\text{pixel})}{\text{focal length}(\text{m}) \times 10^6}$$

$$\text{FoV} = \text{plate scale} \times (N_X, N_Y)$$

where N_X and N_Y are the number of pixels along each axis on the detector

Part IV: Observational Sites

- Atmospheric Seeing (turbulence)
- Atmospheric Transmission

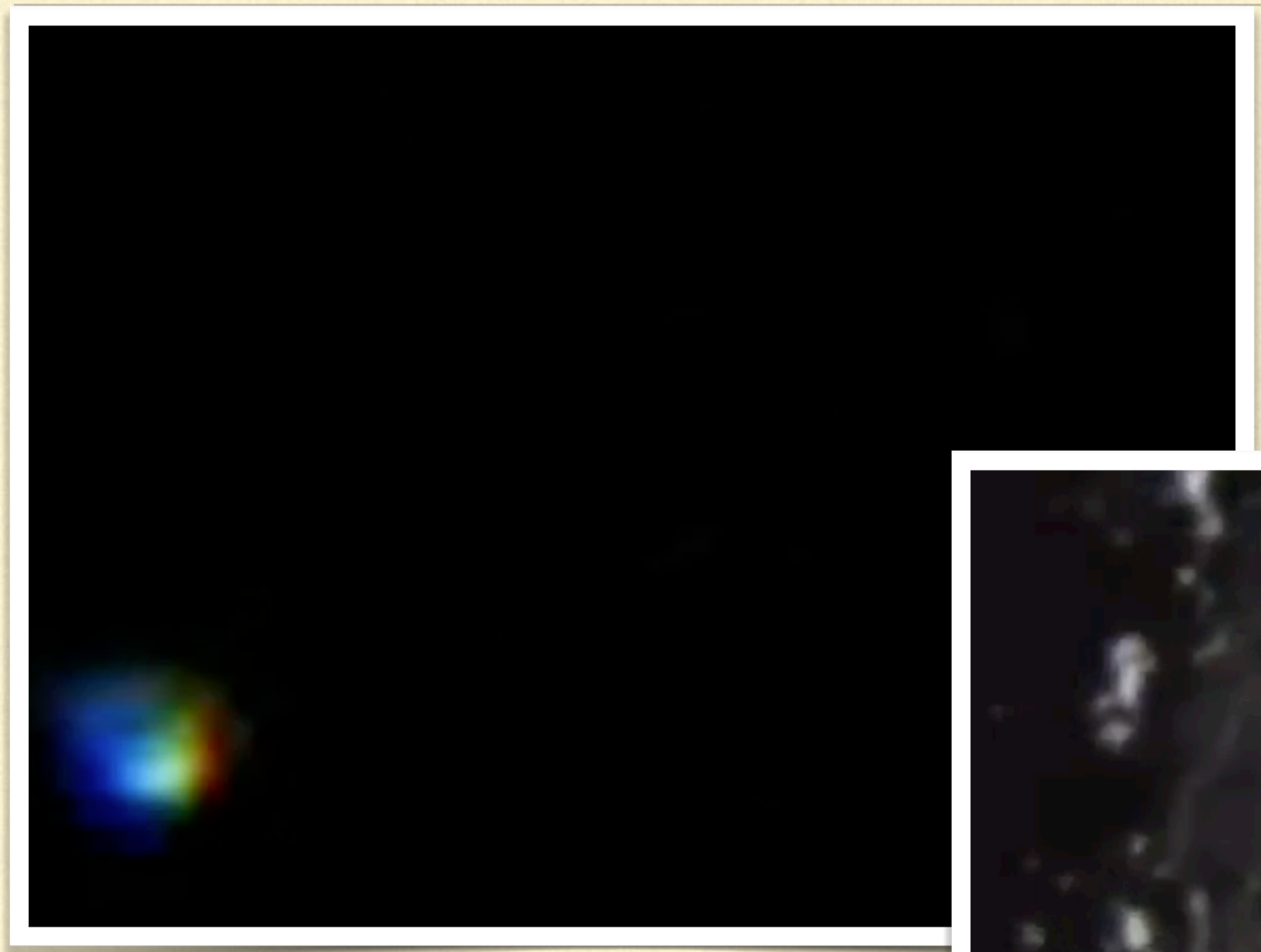
Atmospheric Seeing

Ground-based optical and IR observations need Adaptive Optics to achieve Diffraction Limit

The relatively thin atmosphere of the Earth

stratosphere at altitude of 20-50 km, which is less than 1% of R_{Earth}

GROUND-BASED OPTICAL AND INFRARED OBSERVATIONS ARE LIMITED BY **ATMOSPHERIC TURBULENCE (SEEING)**



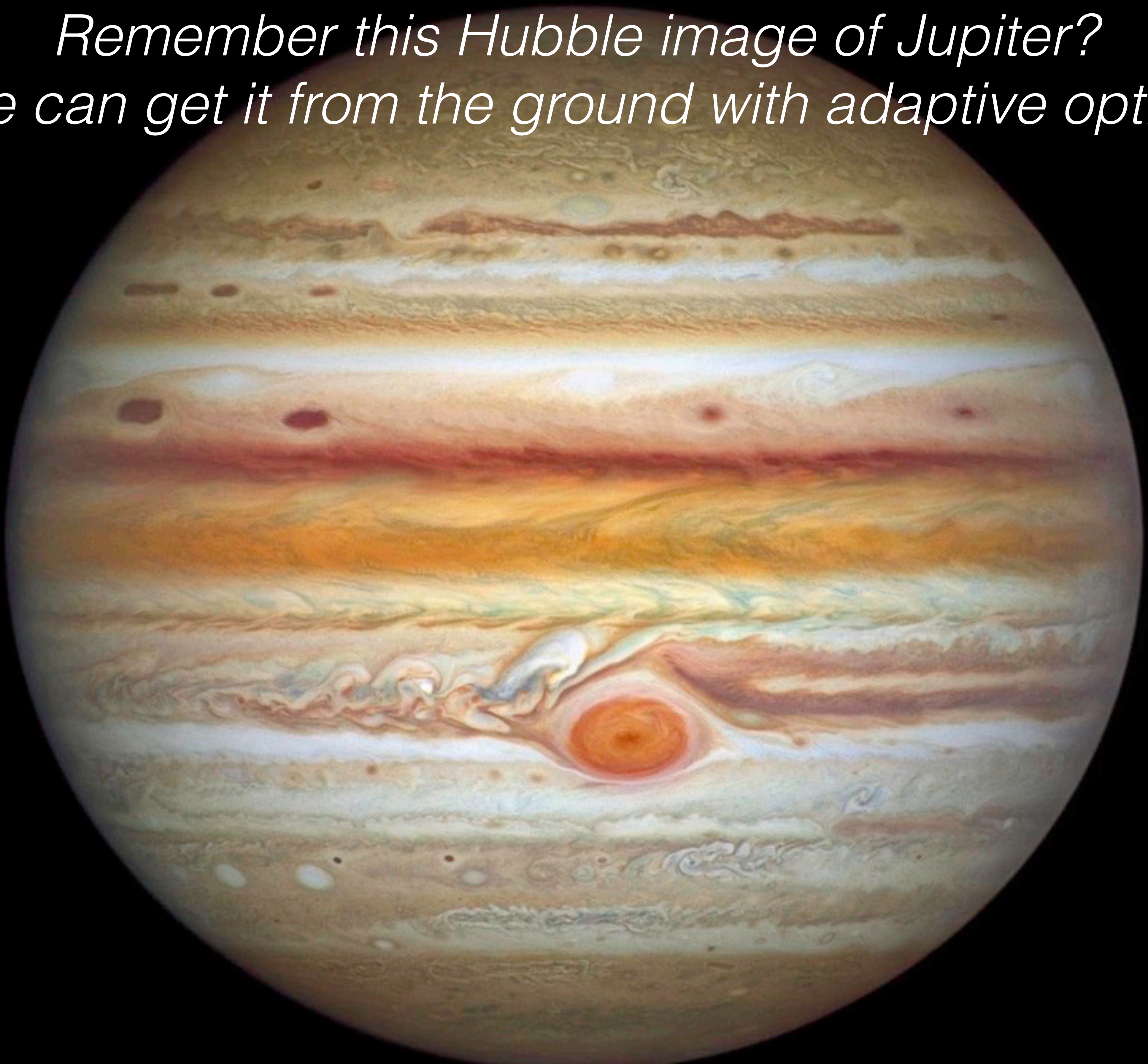
Twinkling of stars and the moon caused by pockets of air at different densities

Seeing quantifies the amount of aberrations from atmosphere turbulence

- Large-scale T gradients trigger subsonic turbulences. The T differences between **turbulent eddies** then cause variations of density and refractive index
- Most of the turbulence that blurs your image originate from the lowest and most massive atmosphere layer: the **troposphere** at altitudes < 15 km
- Typical seeing blurs the **Airy** pattern to a **Gaussian** with a FWHM of ~**2 arcsec**

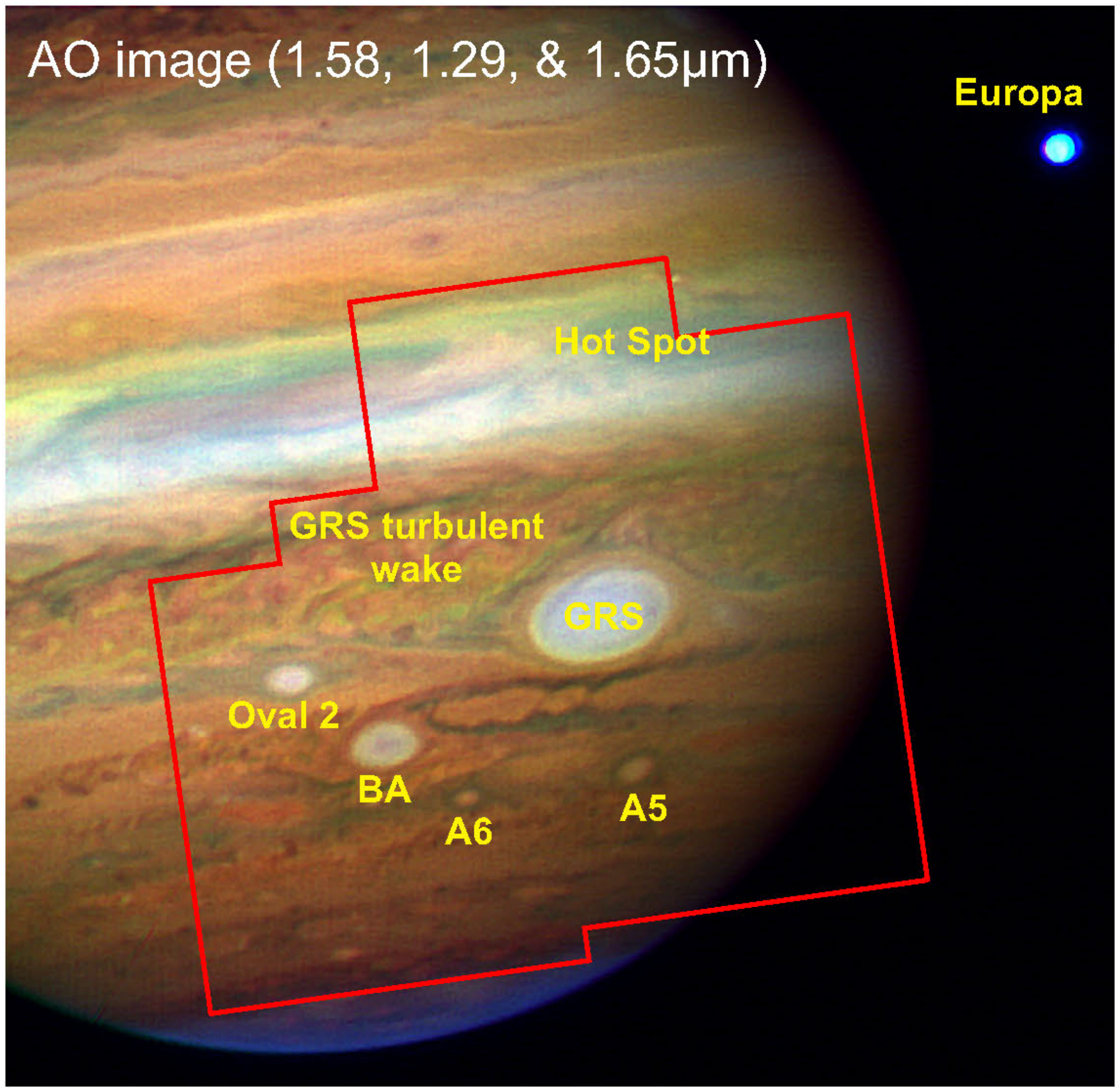
THE GOAL OF OPTICAL ASTRONOMERS: **REACHING DIFFRACTION LIMIT ON THE GROUND**

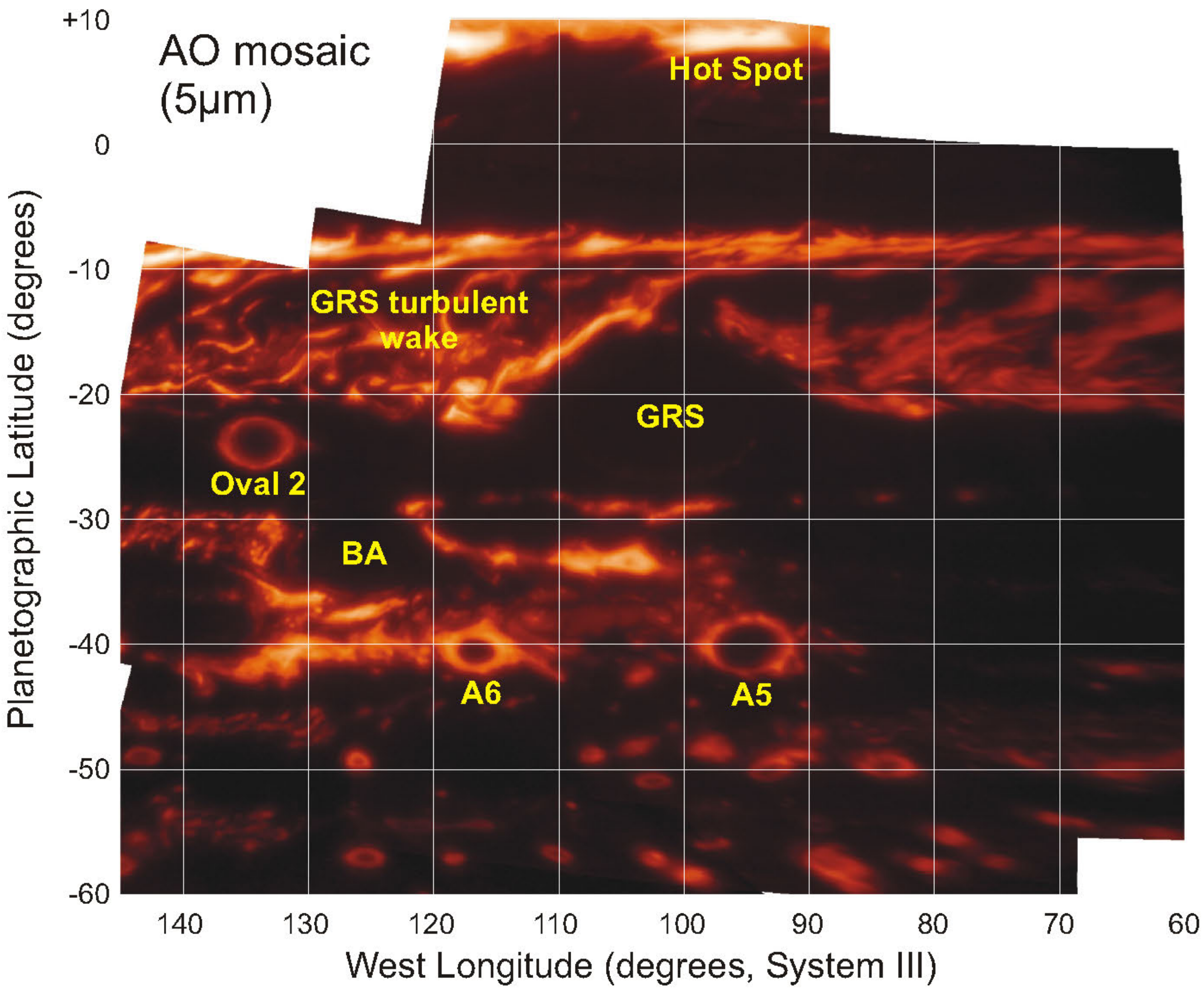
Remember this Hubble image of Jupiter?
We can get it from the ground with adaptive optics



EXAMPLE AO IMAGES

Persistent rings in and around Jupiter's anticyclones

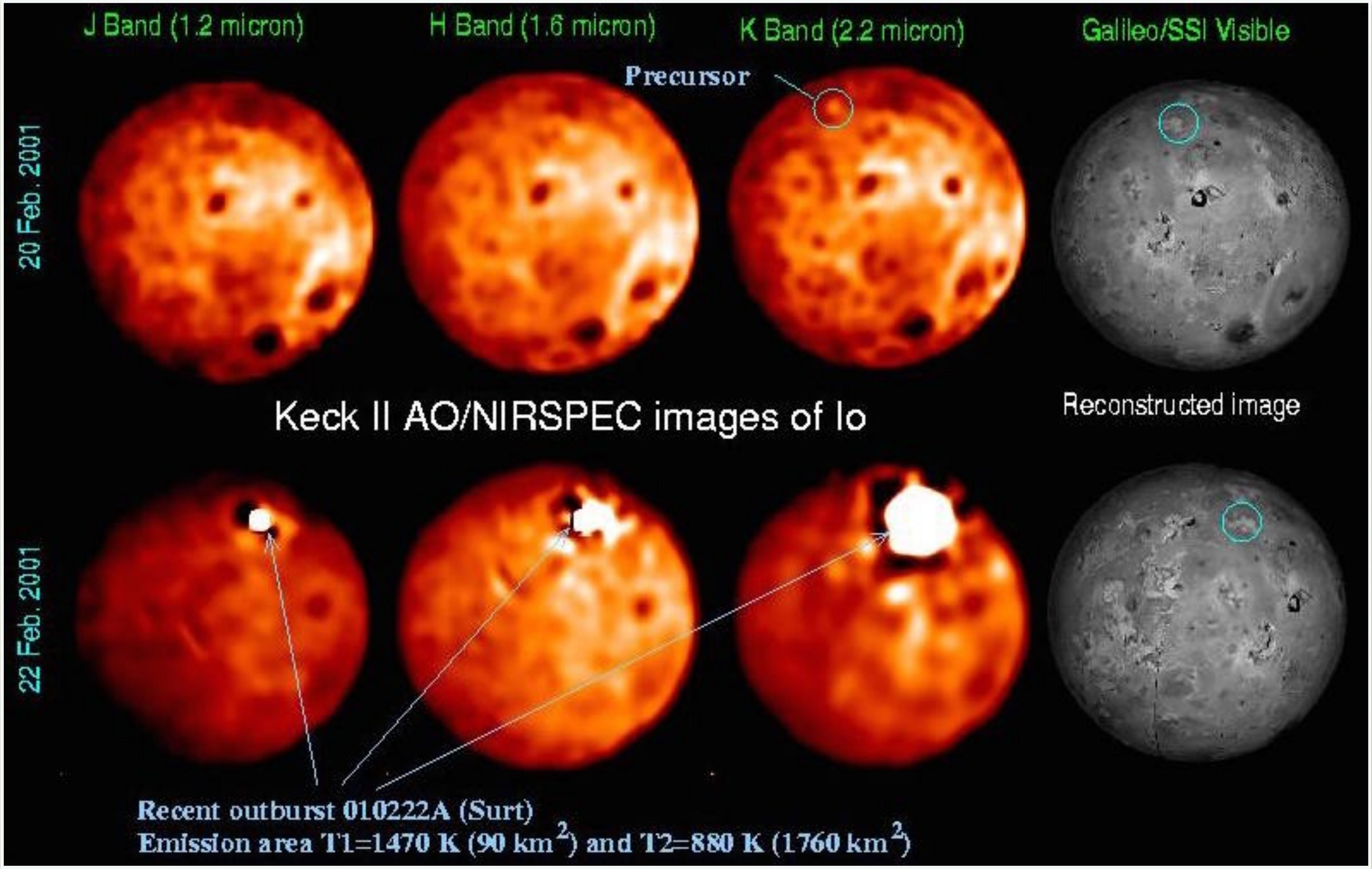




de Pater+(2010)

EXAMPLE AO IMAGES

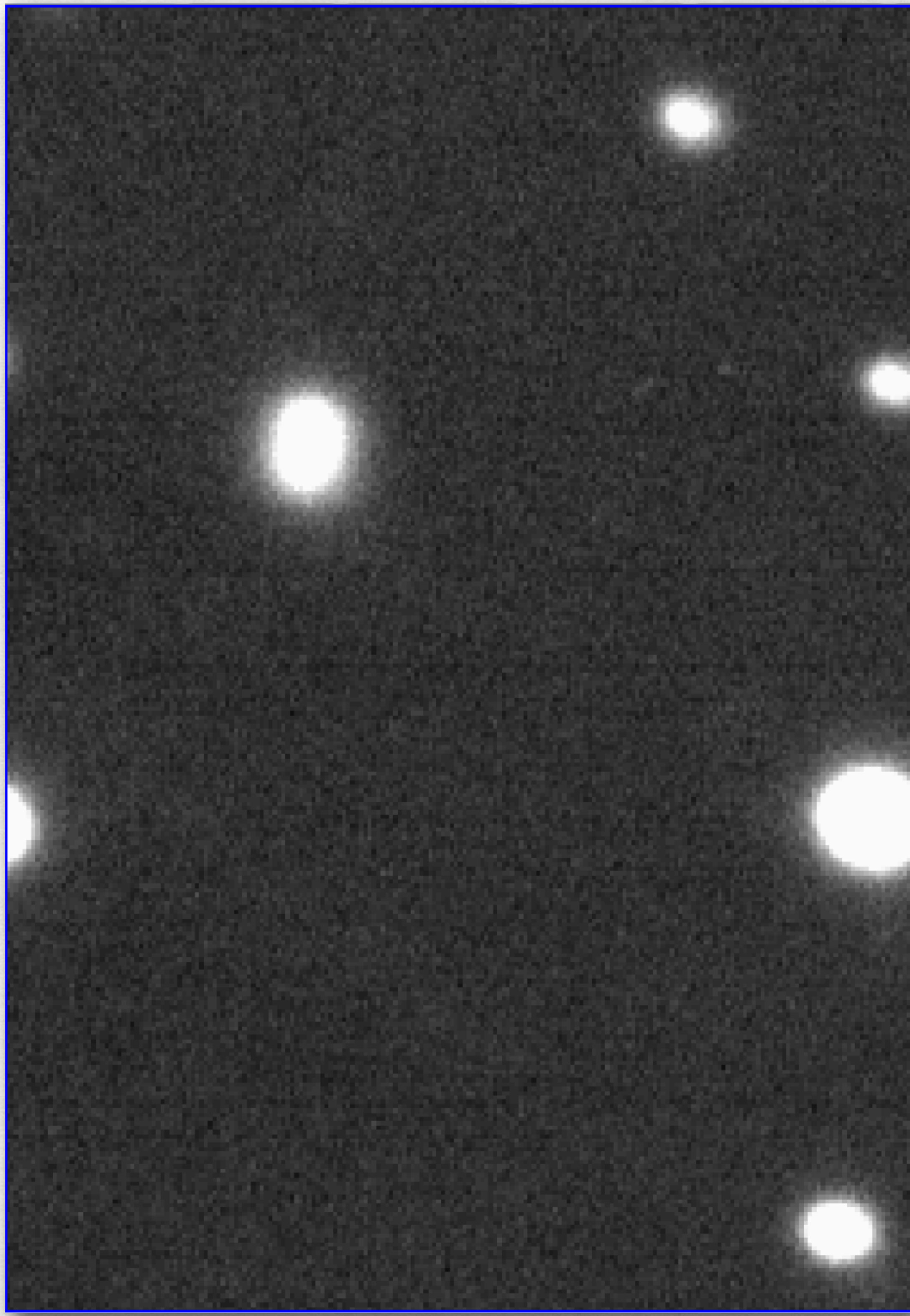
Volcanic eruptions on Jupiter's moon Io



Marchis+2002, see also de Pater+2014

An AO images I took with the 10-m Keck Telescope

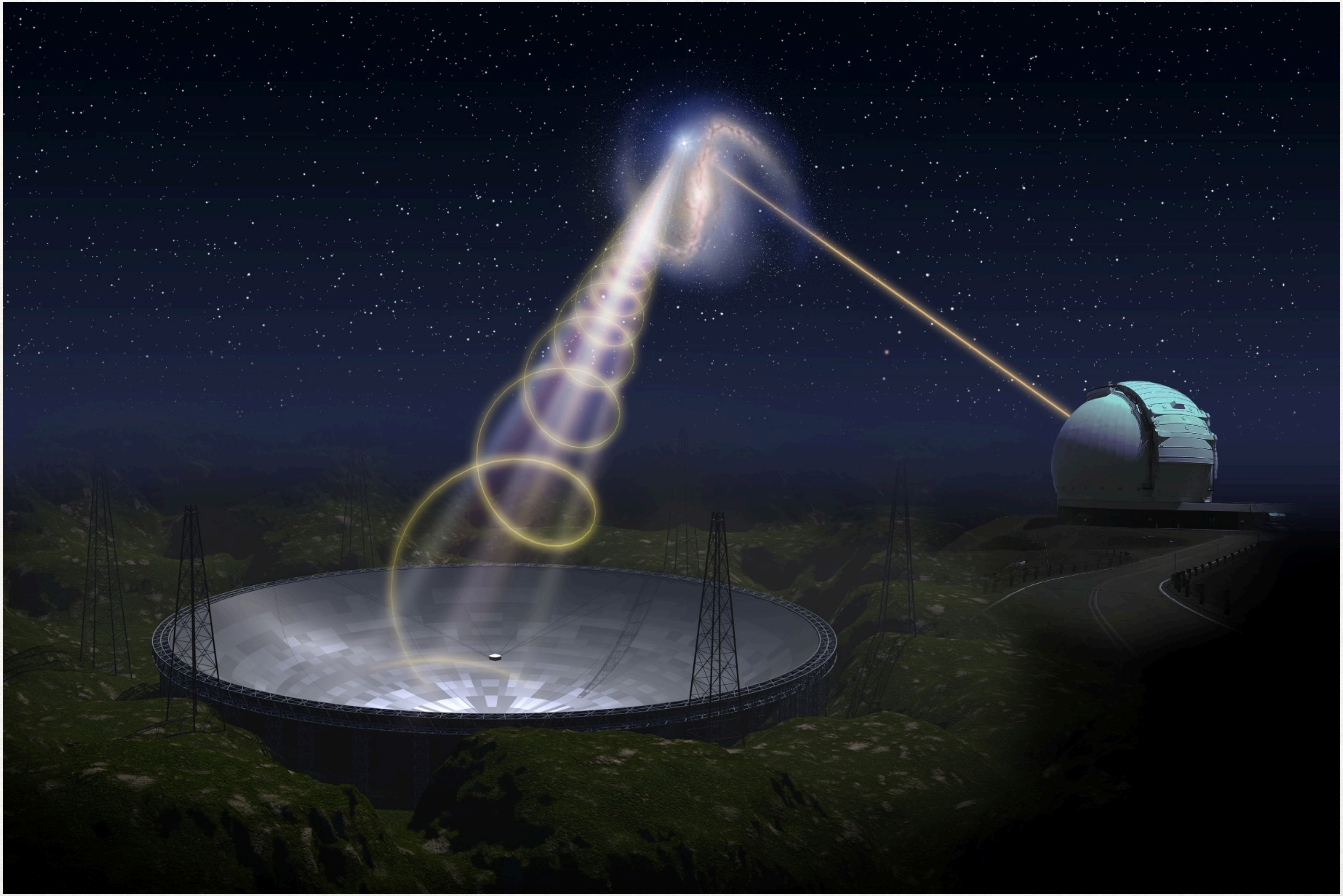
Seeing-limited observation



Adaptive optics observation

Astrophysics: Assessing the origins of an active fast radio burst

Nature, September 22, 2022

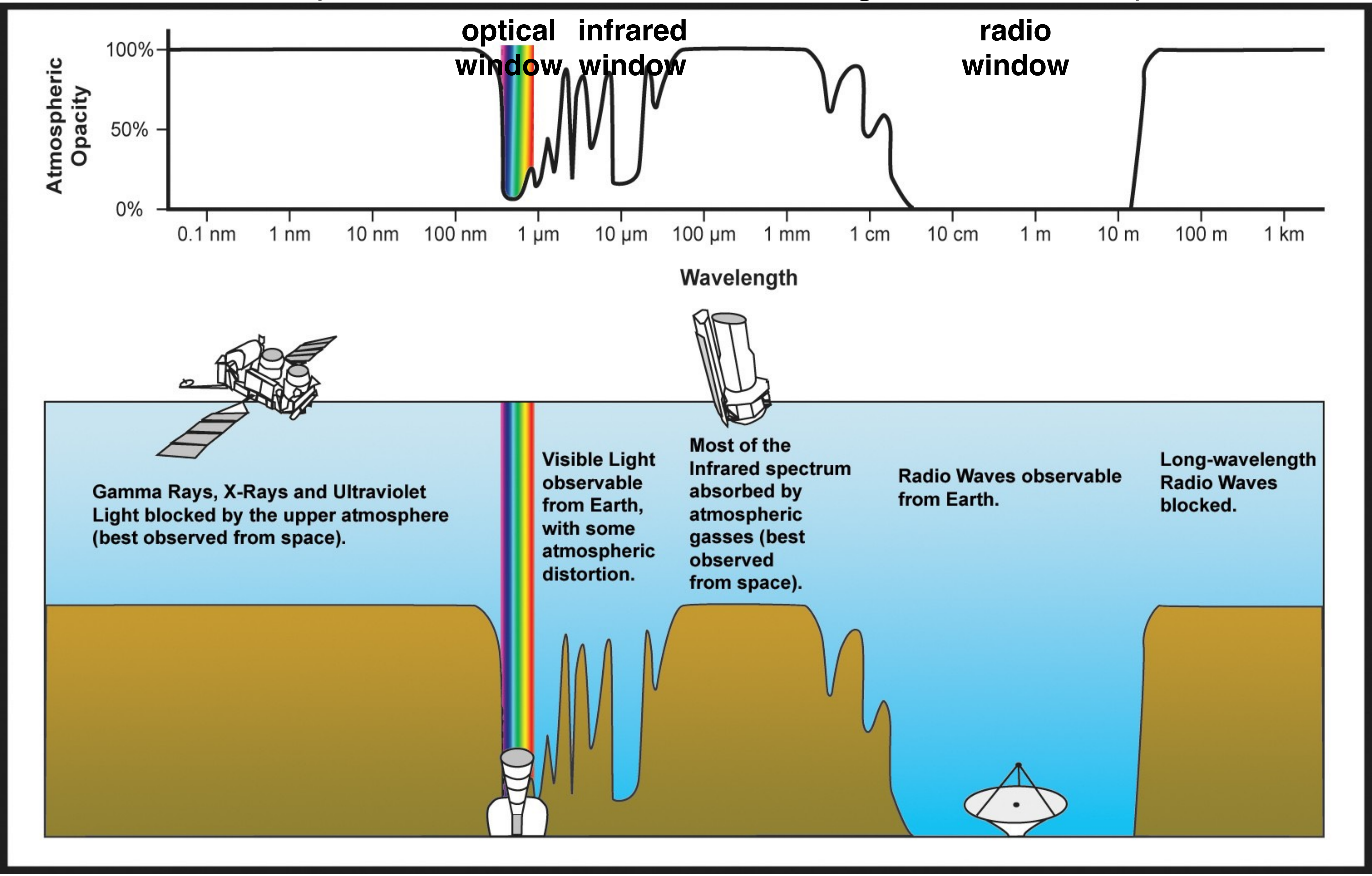


Atmospheric Transmission

the windows of EM waves

Atmospheric opacity, here defined as $1 - \exp(-\tau)$

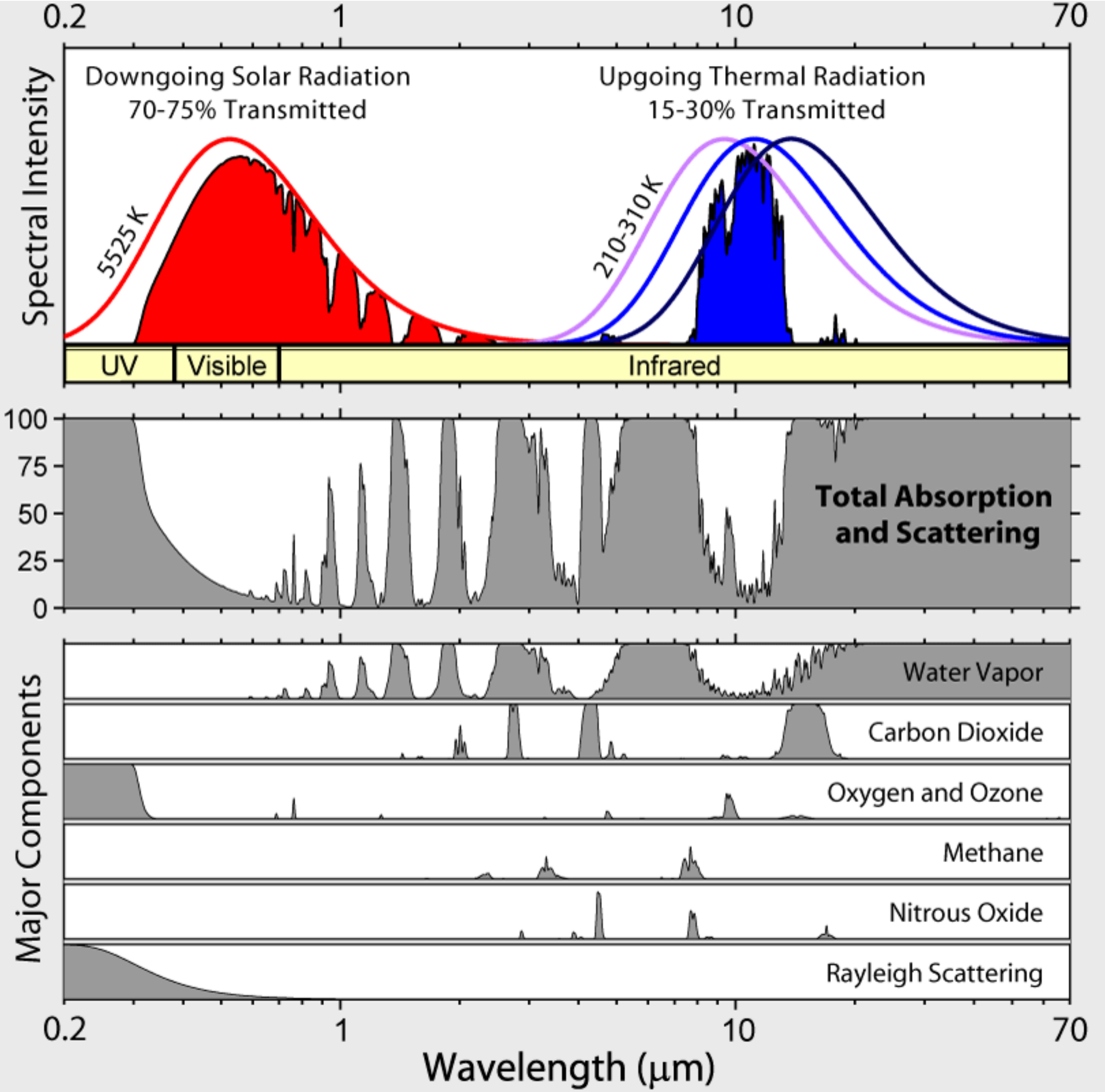
Three major windows to look through the atmosphere



Atmosphere opacity

Greenhouse effect

absorption from various molecules



Main Considerations of Ground Site Selection

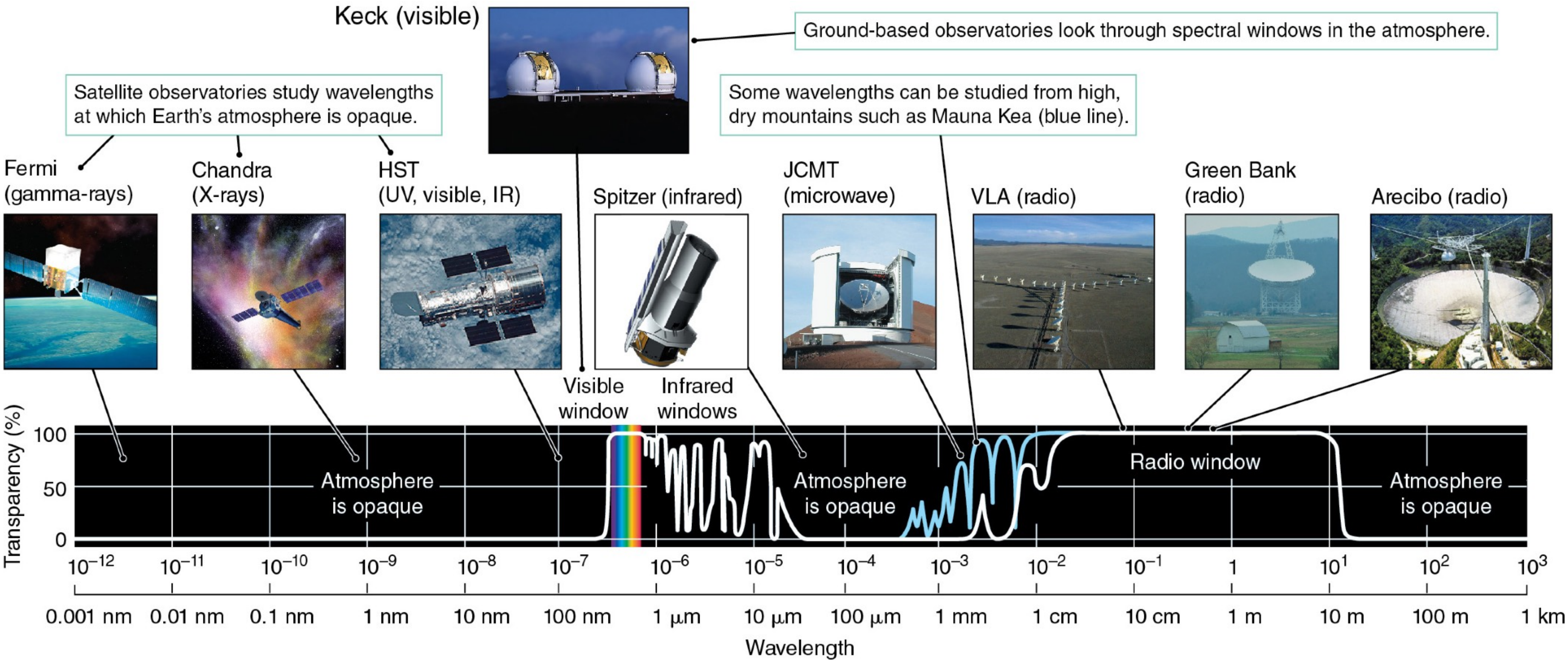
- Atmospheric transparency
- Atmospheric seeing
- Number of clear nights per year
- Visible fraction of the celestial sphere
- Light pollution

Winners:
Mauna Kea (Hawaii, USA)
Las Campanas, Cerro Paranal, Cerro Tololo (Chile)
Antarctica


Mauna Kea, Hawaii
4207 m

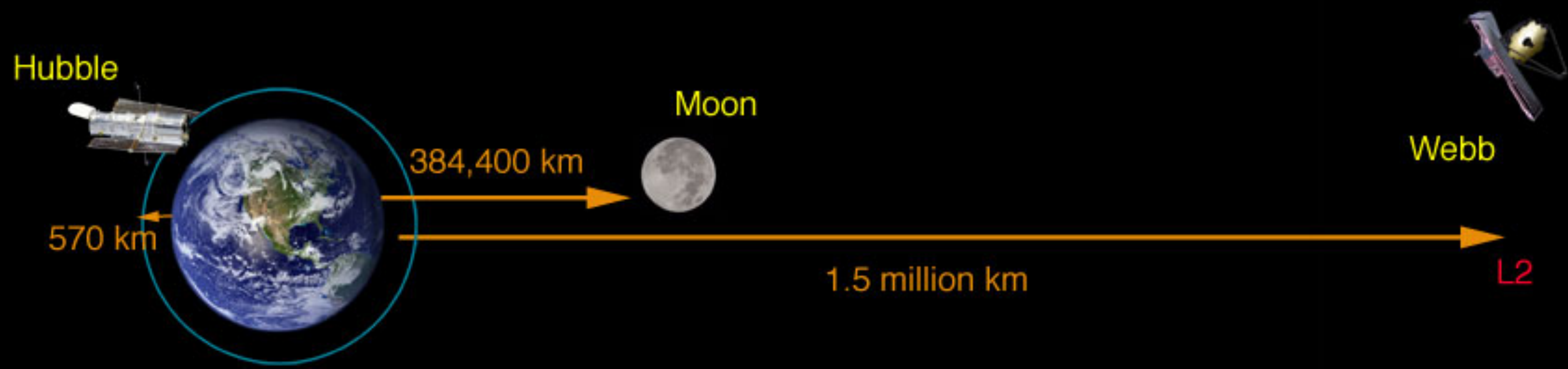

Cerro Paranal, Northern Chile, Alt: 2635m

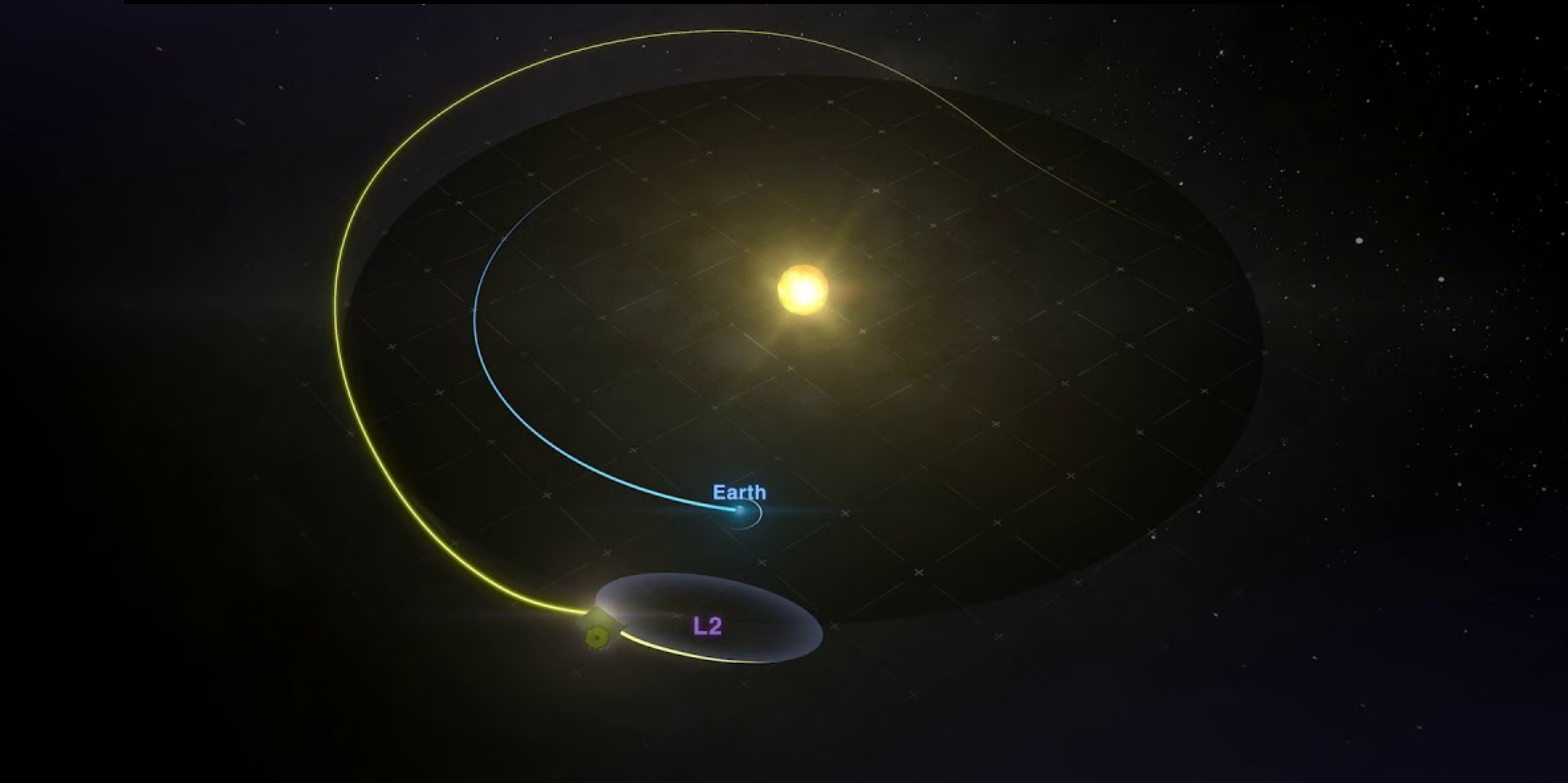
Atmospheric Transmission, here defined as $\exp(-\tau)$



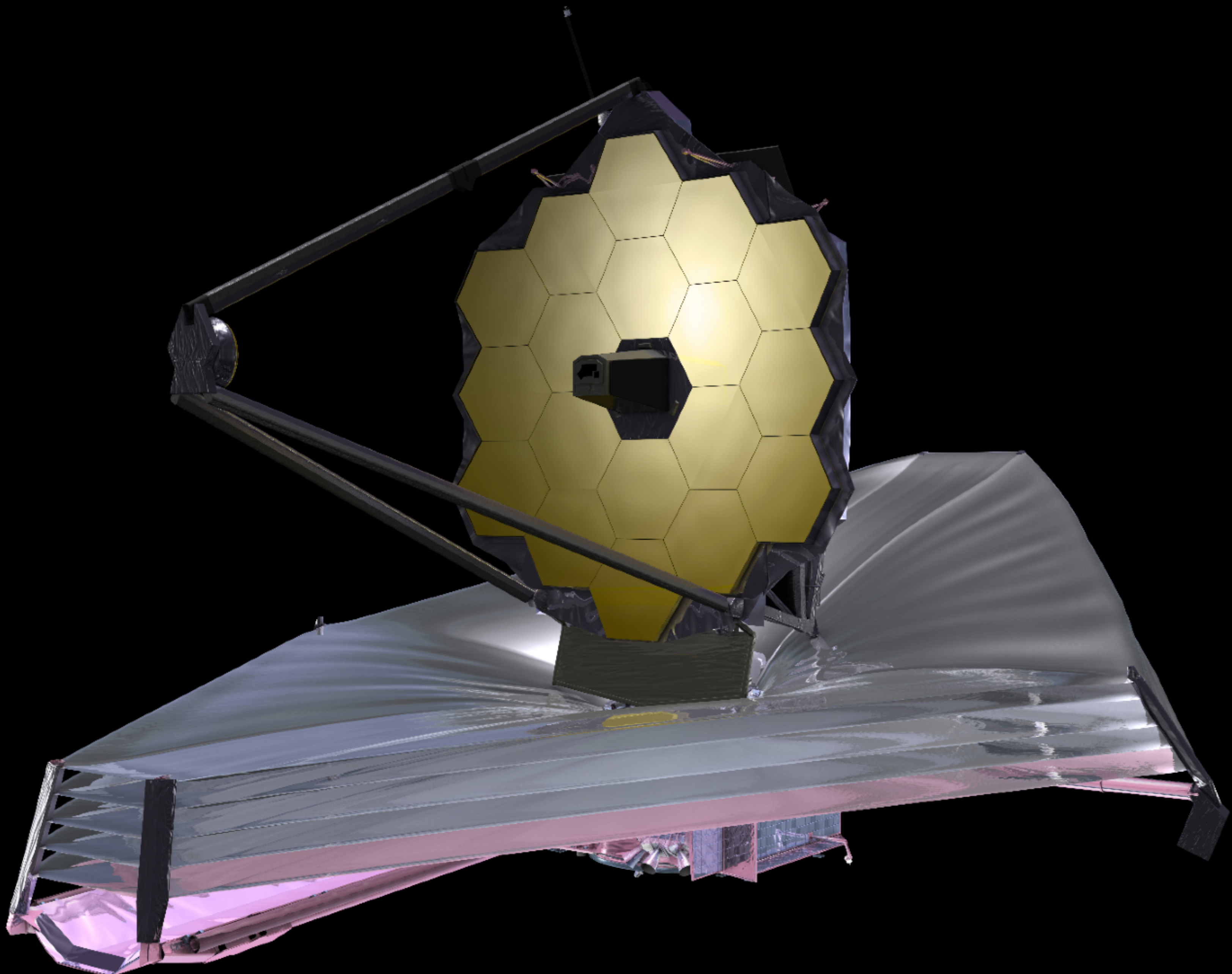
- Nearly all **X-ray, ultraviolet, and mid-to-far infrared** wavelengths are blocked by the atmosphere.
- To detect these photons, we need space-based telescopes.

JWST launch & deployment (Dec 25, 2021) - a Christmas Gift to Astronomers


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


Earth
L2

James Webb Space Telescope



Primary: 6 meter diameter segmented mirror

Operates at mainly IR wavelengths (0.6μm-28μm)

Location: Earth-Sun Lagrangian 2 Point

Mirrors are cooled to 40-50 K

Chapter 6: Astronomical Instruments

- Spectroscopy
  - Kirchhoff's laws of spectroscopy:
    - continuum, absorption lines, emission lines
  - Atomic models and energy levels
  - Identification of species
  - Doppler shift
- Telescope & Camera
  - Optical design
  - Light gathering power
  - Diffraction limit
  - Plate Scale
  - Field of View
- Observing Site
  - Atmospheric seeing
  - Atmospheric transmission