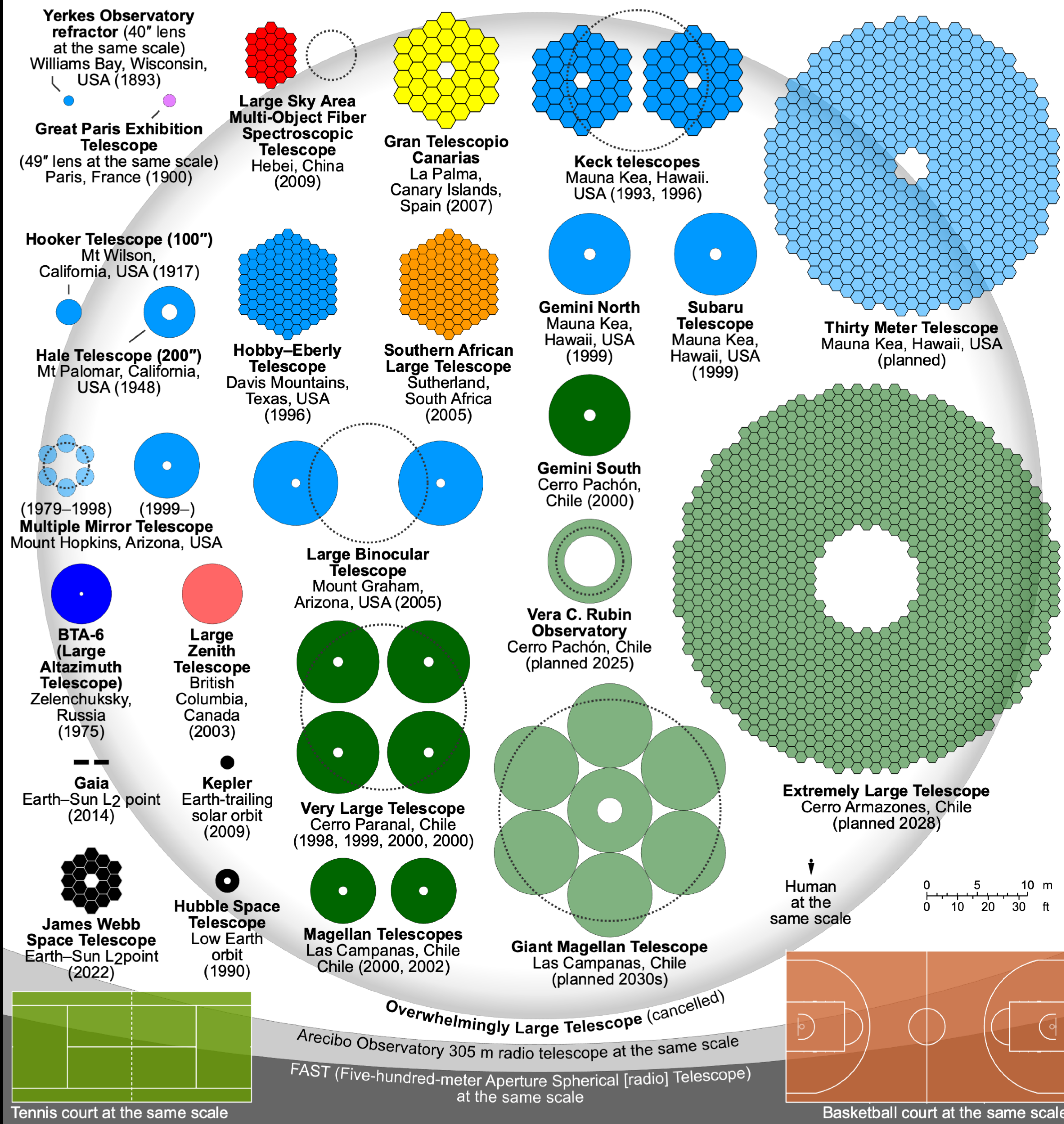
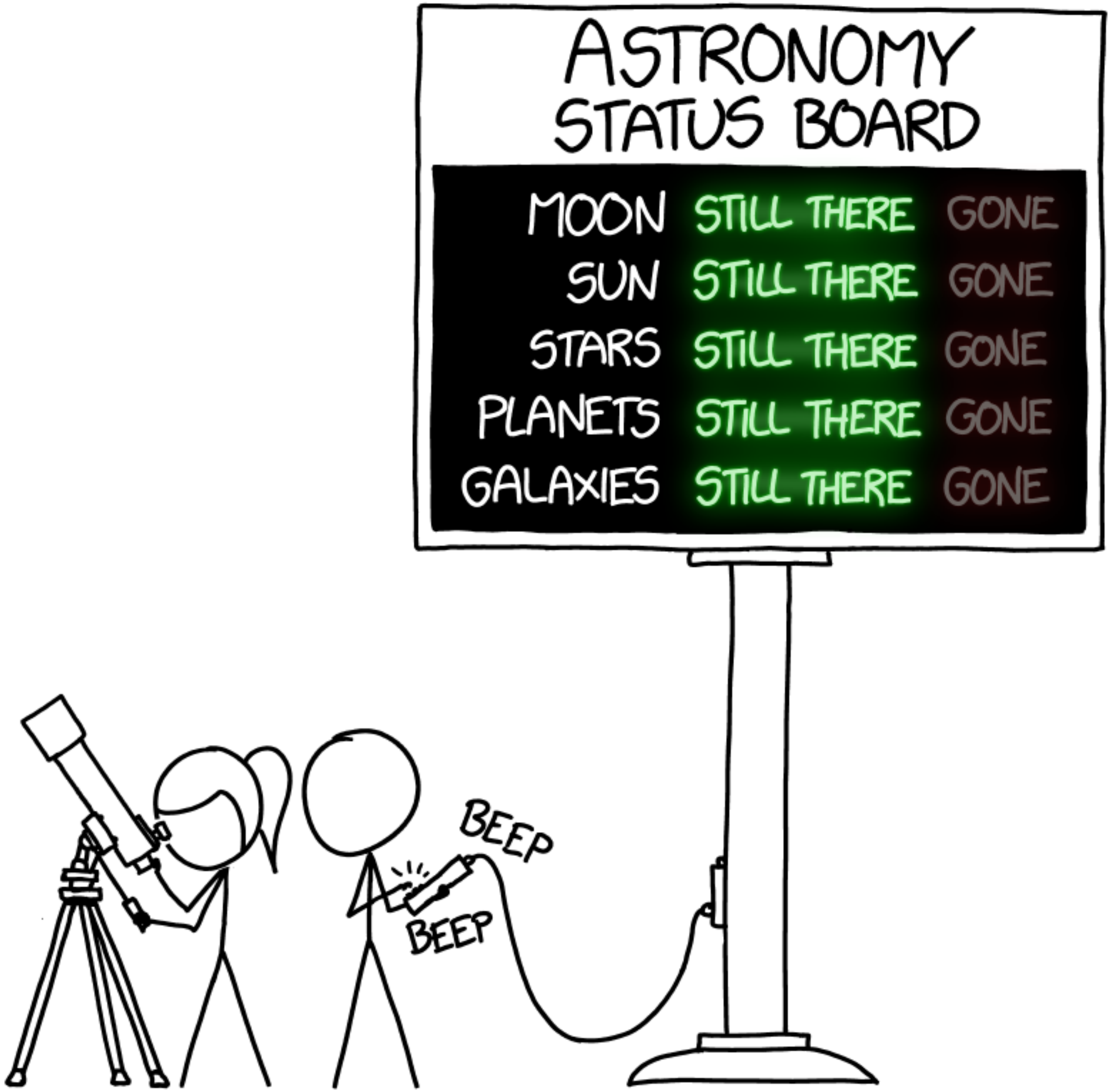
ASTR20A:
Introduction to Astrophysics I

Dr. Devontae Baxter
Lecture 8
Tuesday, October 21, 2025



Announcements

- **Homework #3 due Tuesday, 10/21 by 11:59 pm via Gradescope.**
- Midterm Exam I will take place on **Thursday, 10/23 from 2:00-2:50pm**
- **Homework #4 will be available on Canvas tomorrow morning.**

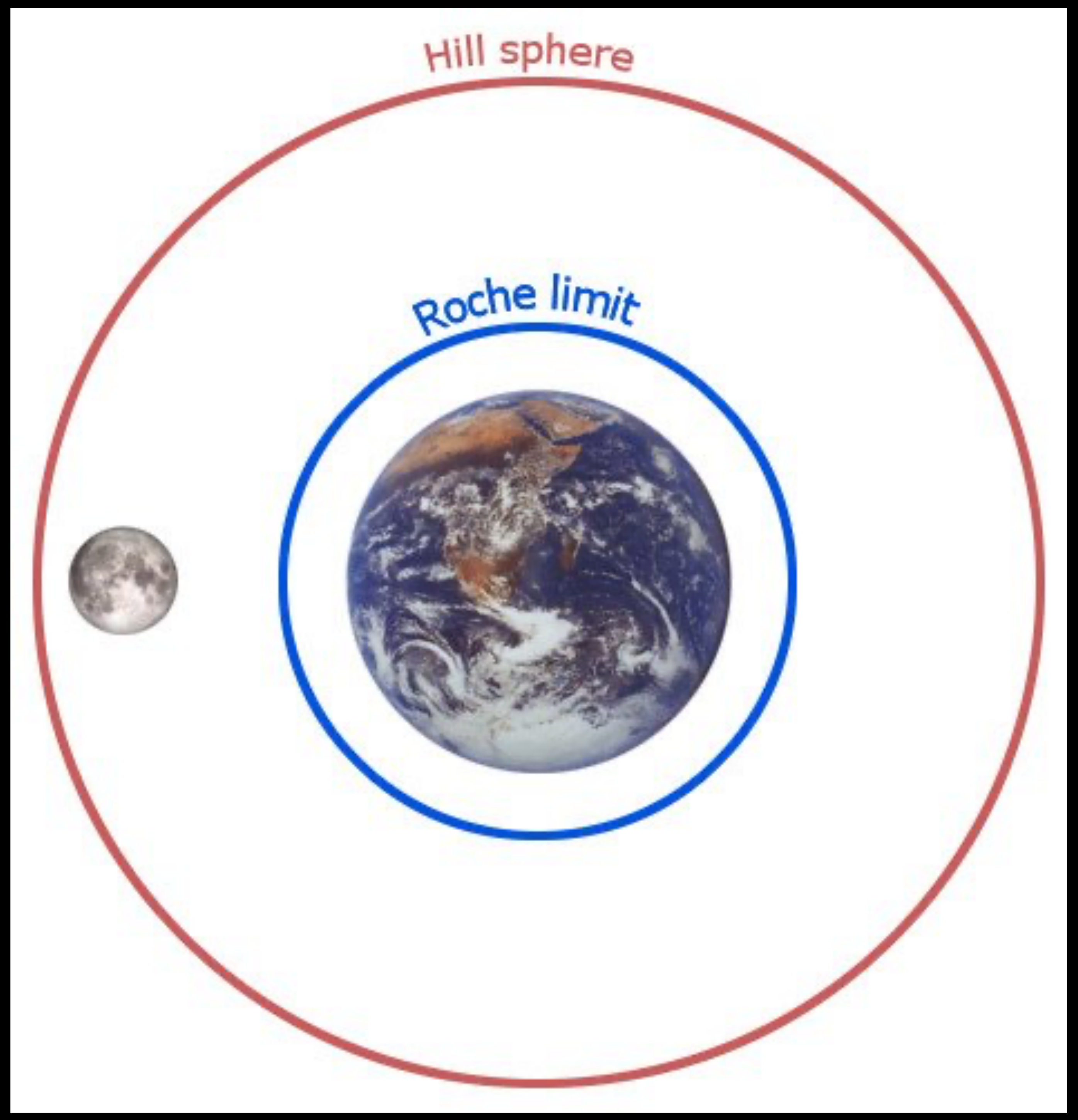



Questions?

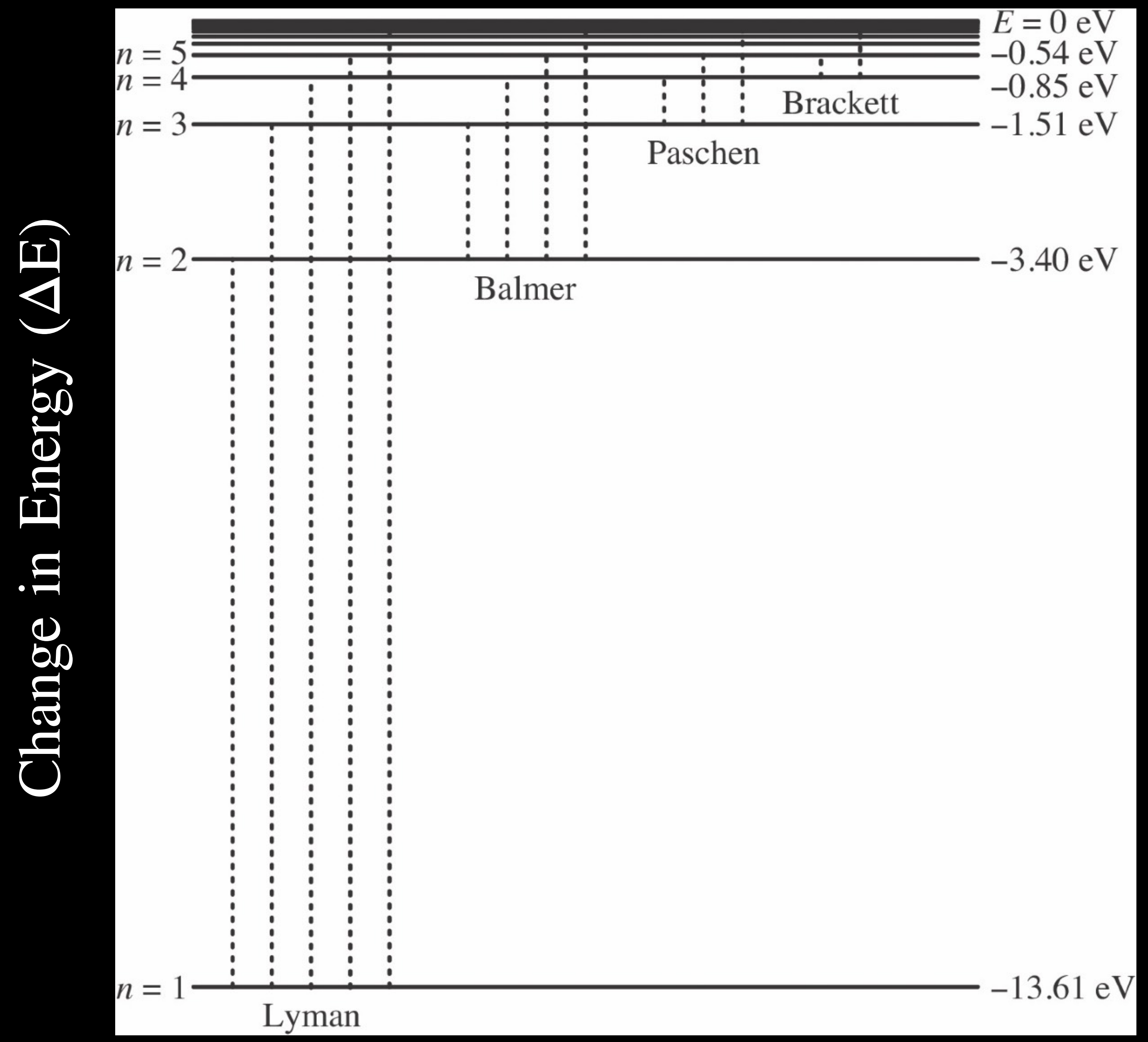
Recap of Lecture 6

In the previous lecture, we discussed the **Earth-Moon system** and **interactions between light and matter.** The key concepts that we discussed were:

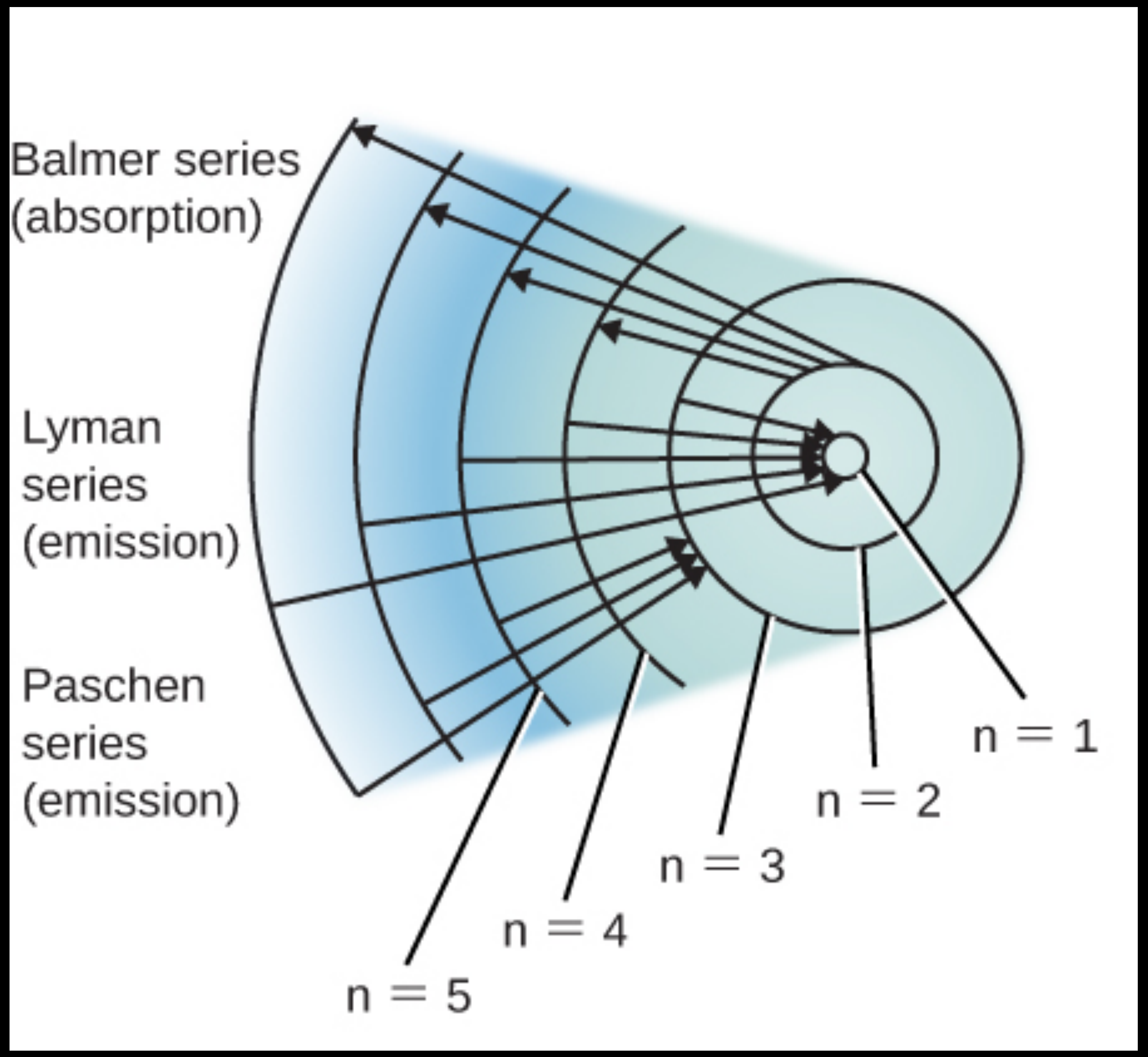
The Moon is unbound beyond Earth's Hill radius and torn apart within the Roche radius.



Energy levels in atoms are quantized.



Atoms absorb photons when excited and emit them upon de-excitation.



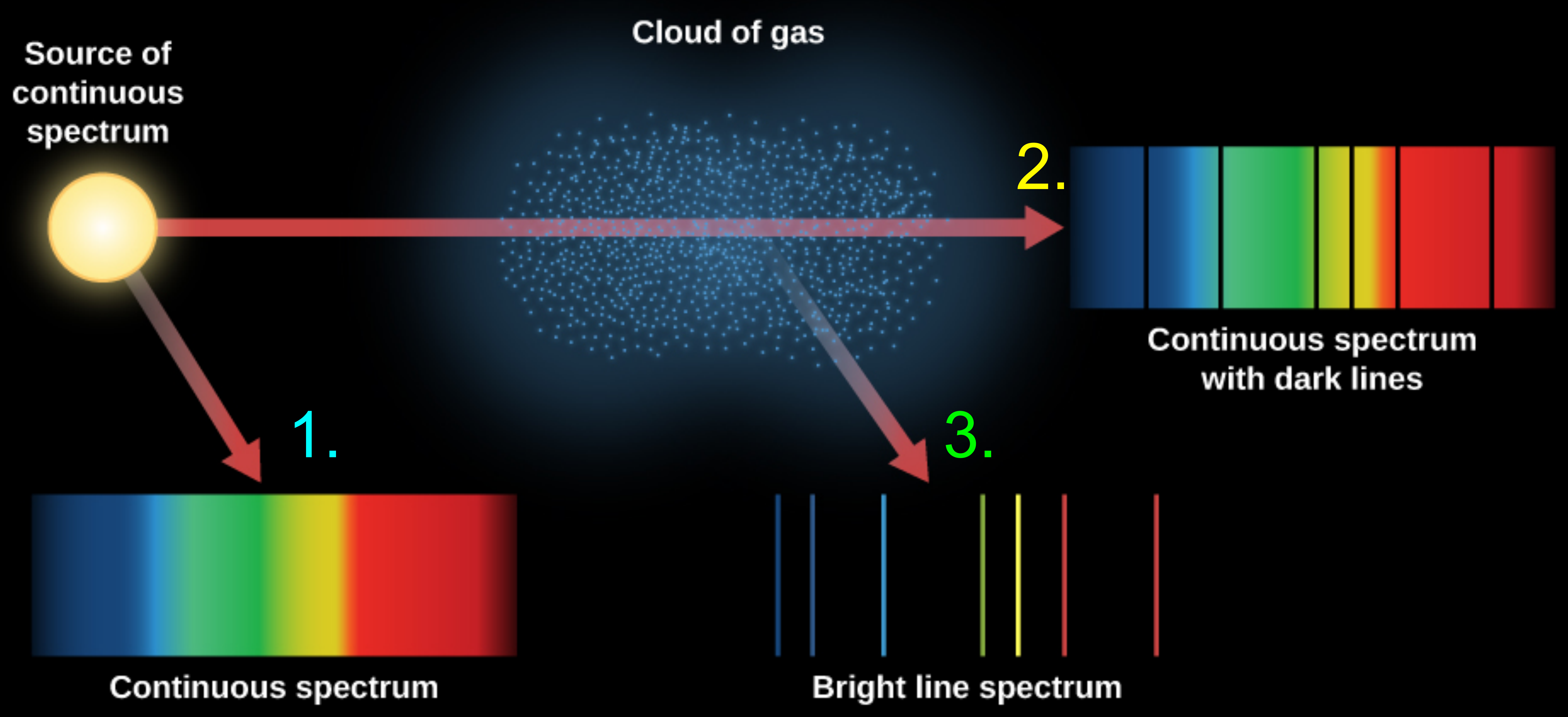
Today, we will discuss conclude our discussion of the **interaction of matter and radiation** and begin our discussion on the **astronomical detection of light.**

Kirchoff's Laws

1. A solid, liquid, or dense gas emits light at all wavelengths

2. A low density, cool gas in front of a hotter source of a continuous spectrum creates a DARK LINE or ABSORPTION LINE spectrum.

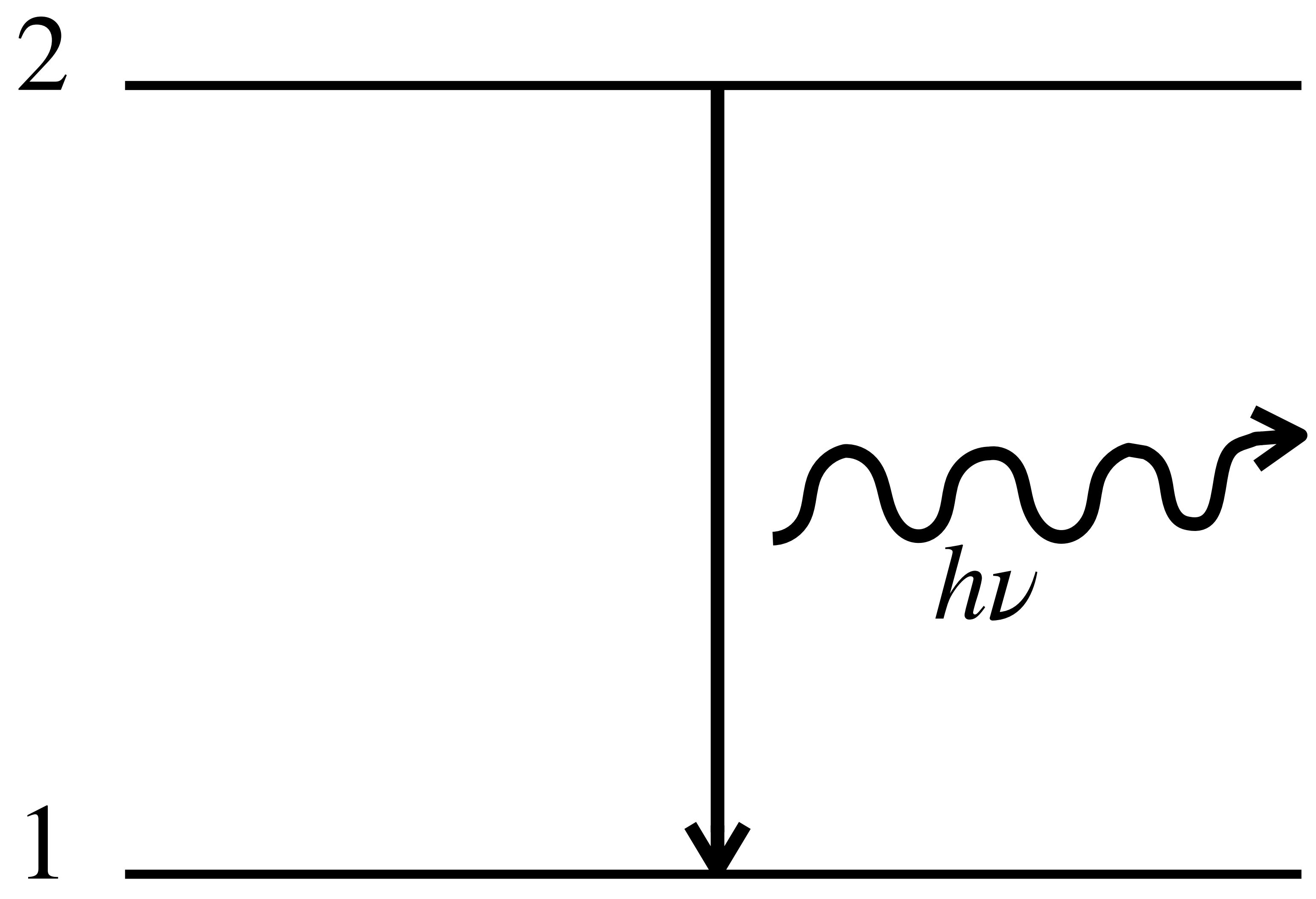
3. A low density, hot gas seen against a cooler background emits a BRIGHT LINE or EMISSION LINE spectrum.



The Width of Emission and Absorption Lines

In reality, emission and absorption lines have a finite width in wavelength ($\Delta\lambda$) about their central wavelength (λ).

Spontaneous emission: an atom moves from an excited state to a lower energy state:



$$X^* \rightarrow X + h\nu$$

To determine this width, let's consider the case of *spontaneous emission* in which an electron in an excited state has a finite lifetime (τ) before it suddenly undergoes a transition to a lower energy state.

The probability, per second, that this transition will occur can be determined quantum mechanically and is known as the **Einstein A coefficient**.

The Width of Emission and Absorption Lines

If there are n_2 atoms per unit volume in the the $n = 2$ (first excited) state, the number of photons emitted per second per unit volume from *spontaneous emission* will be:

$$\frac{dN_{\mathrm{phot}}}{dt} = n_2 A_{21}$$

The numerical value of A depends strongly on whether a transition in question is “permitted” or “forbidden” with typical values given as:

$A \sim 10^8\ \mathrm{s}^{-1} \rightarrow$ permitted lines
$A \sim 1\ \mathrm{s}^{-1} \rightarrow$ “forbidden” lines

“Forbidden” lines aren’t truly forbidden, they are simply much less likely to occur.

A_{21} is the Einstein coefficient for transitions from the n = 2 state to the n = 1 state.

The Width of Emission and Absorption Lines

An electron making a “forbidden” transition will spend $\tau \sim 1$ second in the higher energy level before dropping to a lower energy level.

Conversely, an electron making a “permitted” transition will only spend $\tau \sim 10$ nanoseconds in the higher energy level before leaping to the lower energy level!

Since the Einstein coefficient simply give transition probabilities, the lifetime of an excited state is uncertain!

The Width of Emission and Absorption Lines

In quantum mechanics, this is interpreted in terms of the **Heisenberg Uncertainty Principle**, which states that the position x and momentum p of a particle has uncertainties Δx and Δp that satisfy the inequality:

$$\Delta x \cdot \Delta p \gtrsim \hbar$$

This equation can also be written as,

$$\Delta t \cdot \Delta E \gtrsim \hbar$$

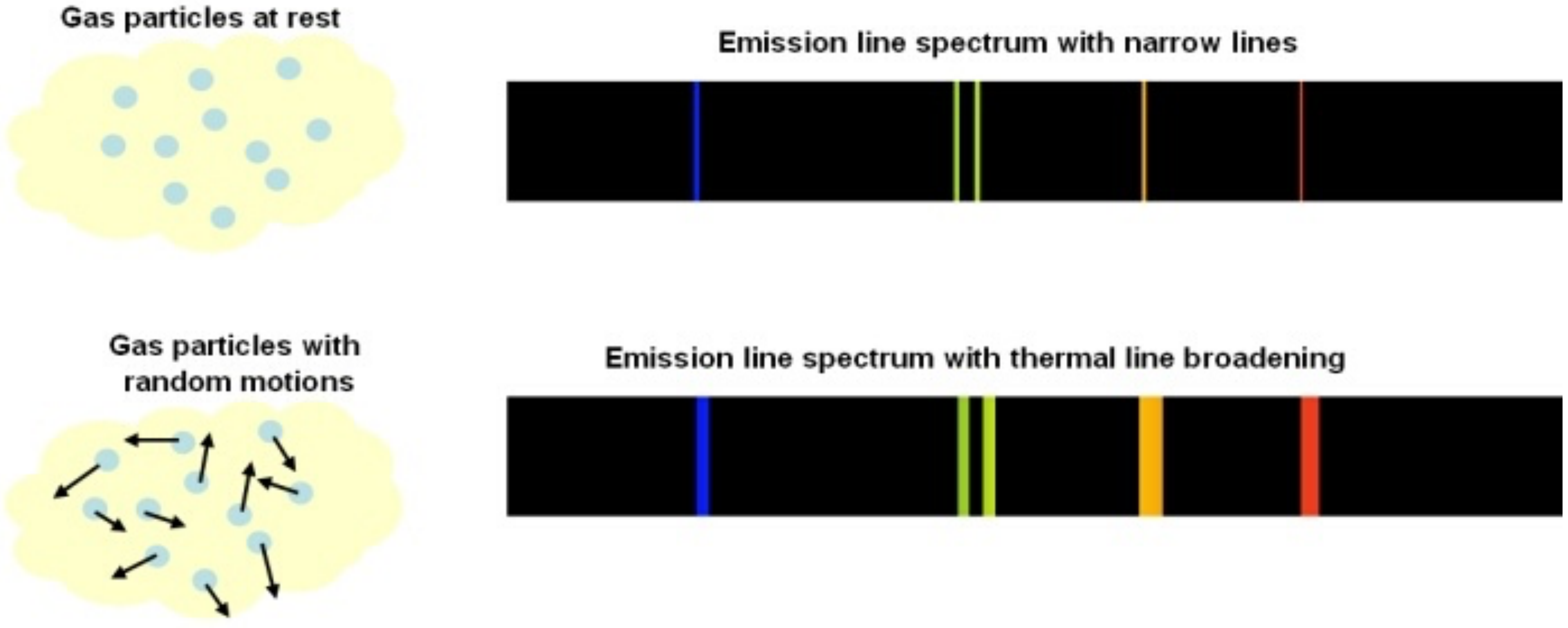
where ΔE can be interpreted as the uncertainty in the photon energy and Δt is the uncertainty in its time of creation.

Therefore, small values of Δt require large values of ΔE such that permitted transitions give rise to *broader* of emission/absorption lines — a phenomenon known as as “natural broadening”.

Thermal Broadening

Temperature, which reflects the random motion of particles in a gas, leads to **thermal broadening of spectral lines.**

As the temperature of the gas increases, particles move faster, producing a spread in observed wavelengths due to the Doppler effect.



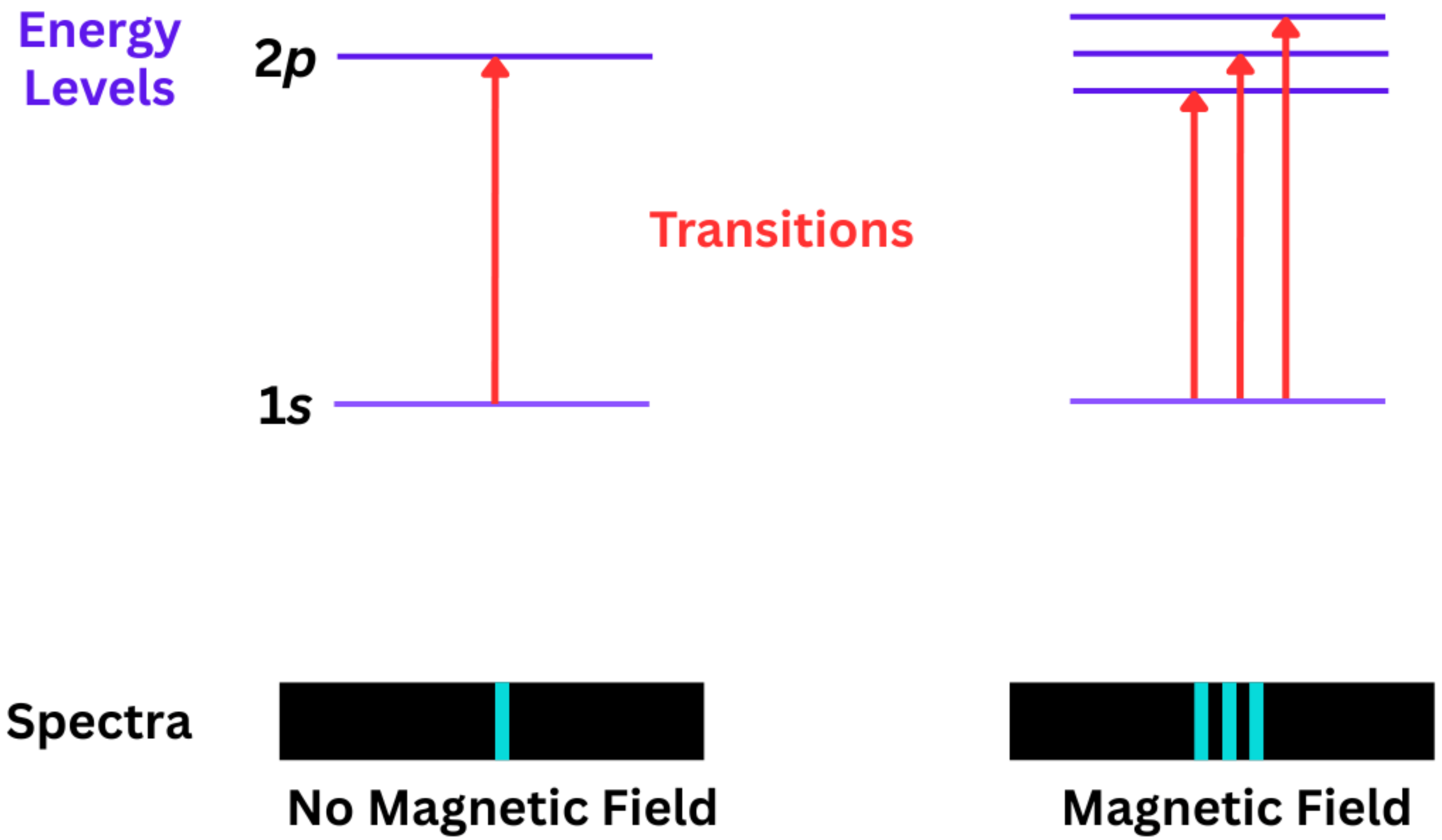
The amount of line broadening is given by:

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\sqrt{\frac{kT}{m}}}{c}$$

where T is the kinetic temperature, m is the mass of the particle, k is the Boltzmann constant, and c is the speed of light.

Zeeman Broadening

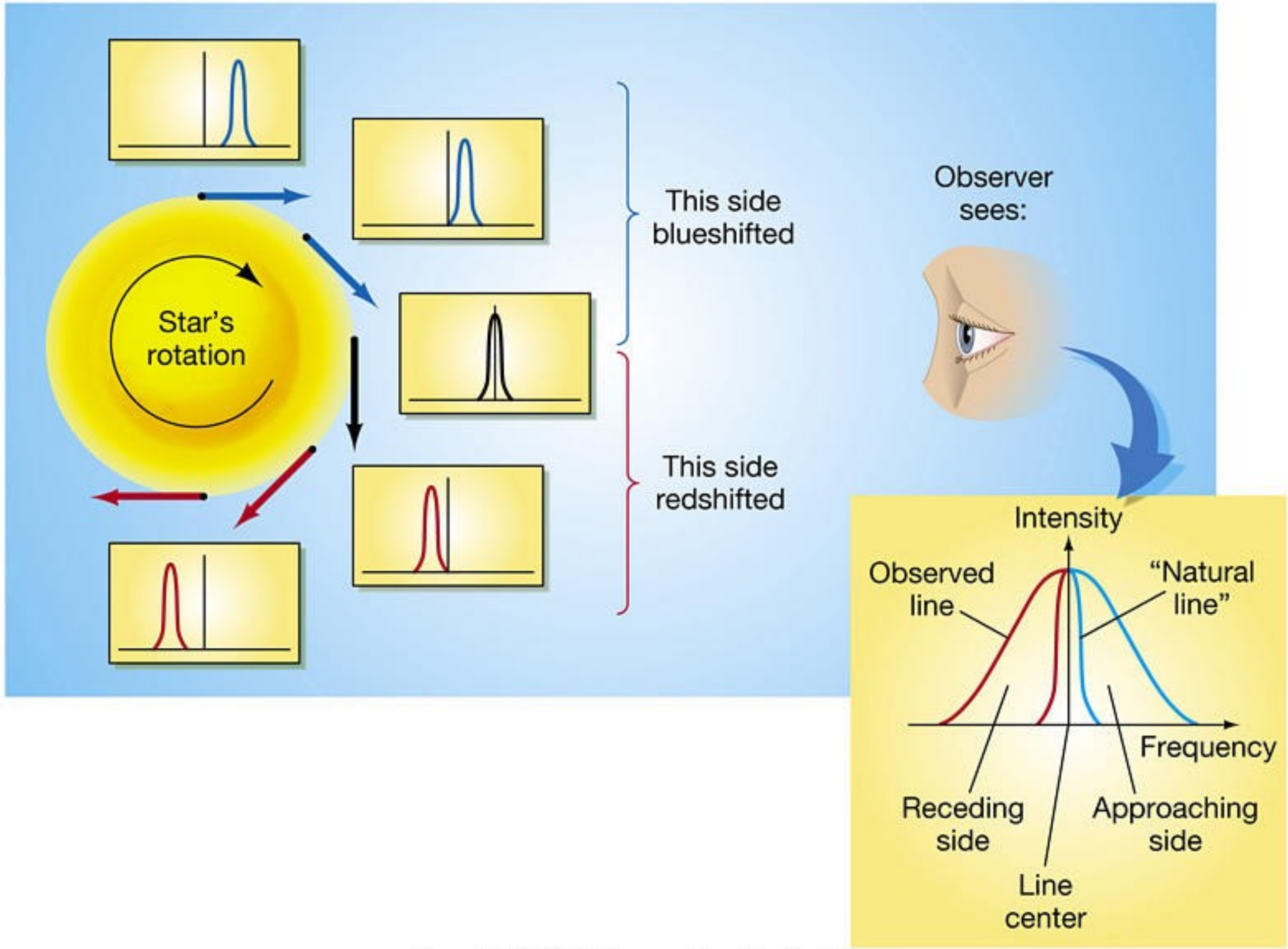
When an atom is placed in a magnetic field, spectral lines that normally appear as a single line can split into multiple closely spaced lines. This splitting of spectral lines is known a the Zeeman effect.



The Bohr model could not explain the Zeeman effect, as it treated each energy level as a single fixed energy rather than allowing for multiple sub-states.

Rotational Broadening

When a star (or galaxy) rotates, parts of it move **toward** us (blue-shifted) and parts move **away** from us (red-shifted). These Doppler shifts cause the spectral lines to appear **broadened** in the observed spectrum.

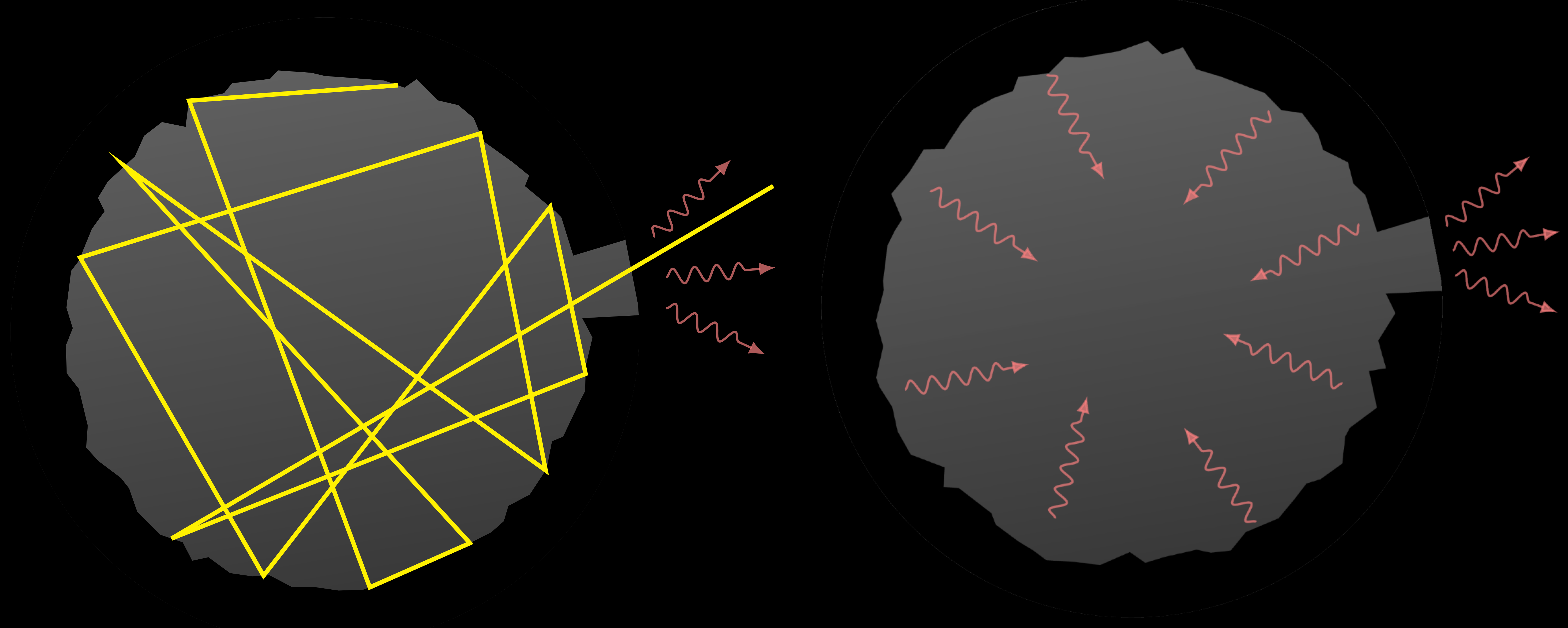


Black Body Radiation

Objects made of dense gas, or of opaque liquid or solid material, produce radiation that is, to a first approximation, *blackbody radiation*.

A blackbody radiator is an *idealized object* that absorbs all incident electromagnetic radiation, reflects none, and emits the maximum possible thermal radiation for its temperature.

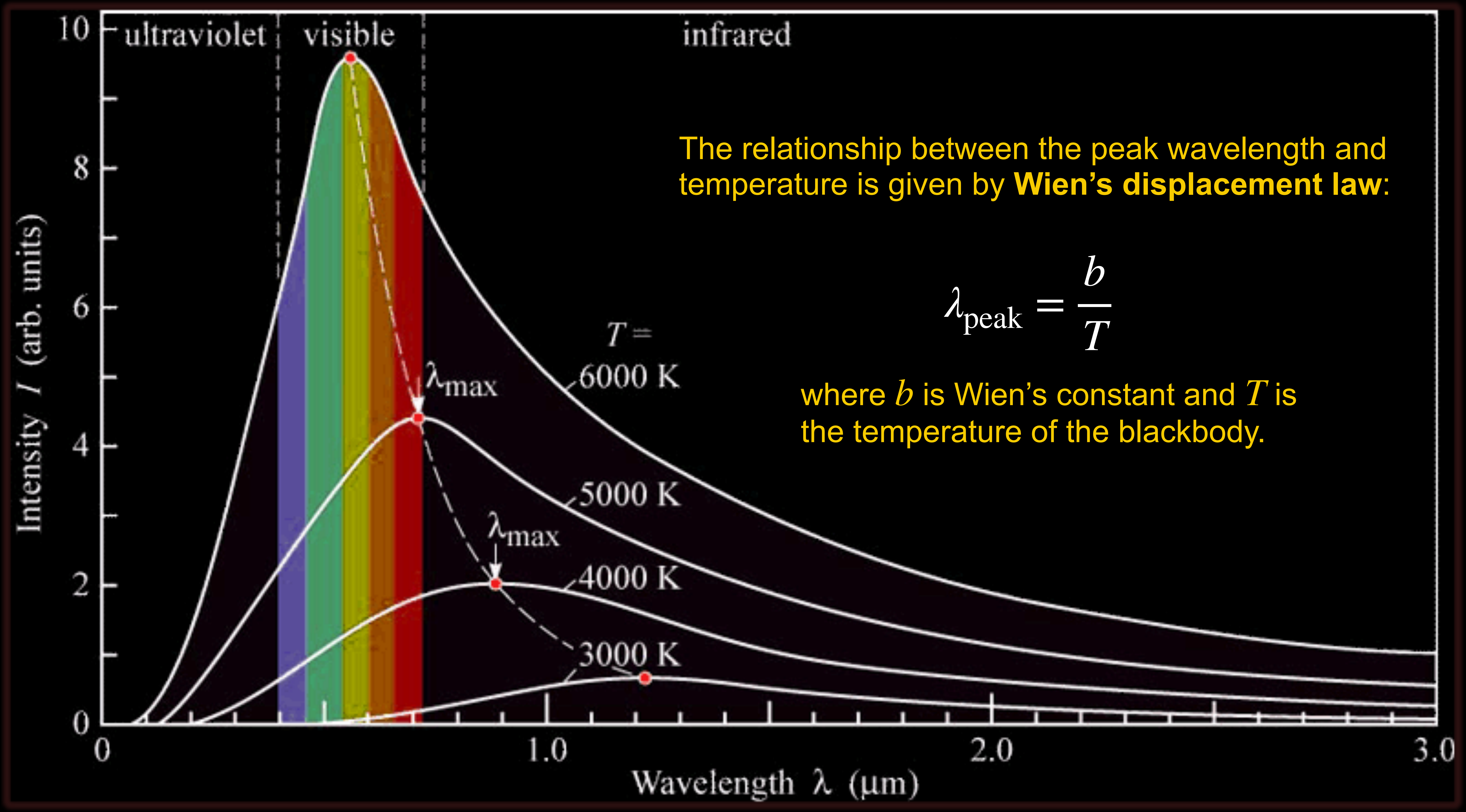
Model of an ideal black body (a cavity with a hole)



Everyday examples of approximate blackbodies include the Sun and hot stoves.

Black Body Radiation - Wien Law

A blackbody has a distribution of intensities vs. wavelength depends on its temperature. Higher temperatures correspond to shorter peak wavelengths (bluer light).



The relationship between the peak wavelength and temperature is given by **Wien's displacement law**:

$$\lambda_{\text{peak}} = \frac{b}{T}$$

where b is Wien's constant and T is the temperature of the blackbody.

Luminosity

If a star is approximated as a blackbody with temp *T* and radius *R*, then the total **luminosity** (total energy output) is:

$$L = 4\pi R^2 \sigma T^4$$

$\sigma = 5.67 \times 10^{-8}\ \mathrm{J\ s^{-1} m^{-2} K^{-4}}$ (Stefan-Boltzmann constant)

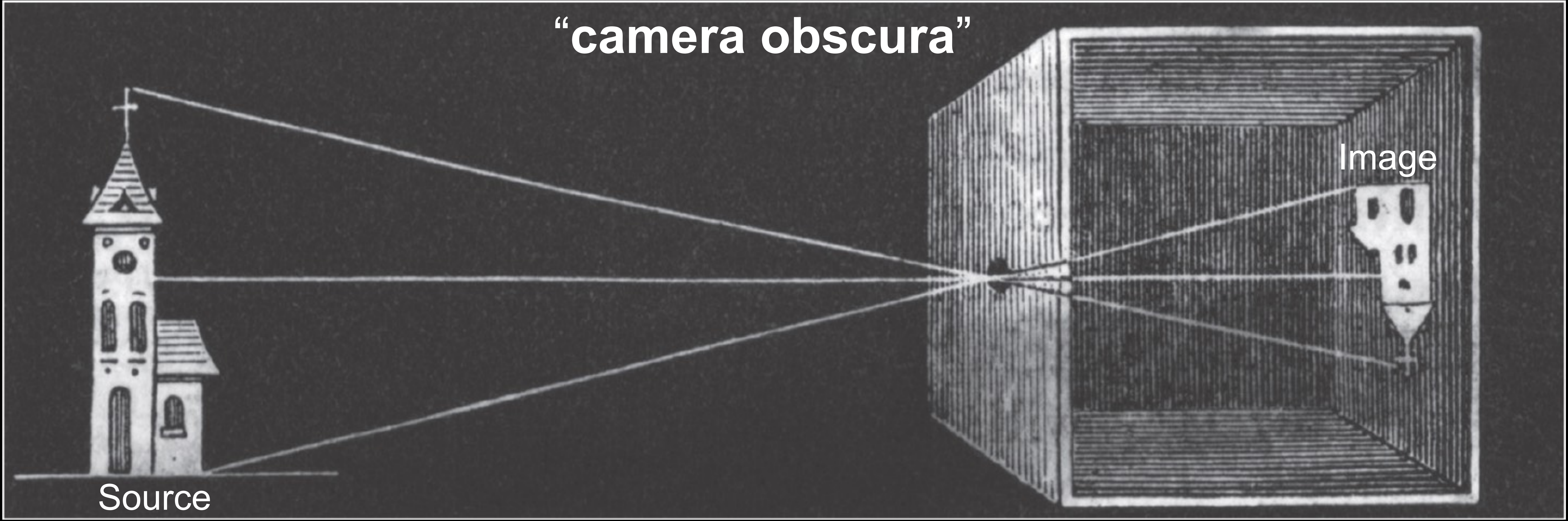
For the Sun, $R_\odot = 6.96 \times 10^8\ \mathrm{m}$ and $T_\odot \approx 5780\ \mathrm{K}$

$$L_\odot = 3.8 \times 10^{26}\ \mathrm{J\ s^{-1}} = 3.8 \times 10^{26}\ \mathrm{W}$$

Questions?

Early Imaging Science

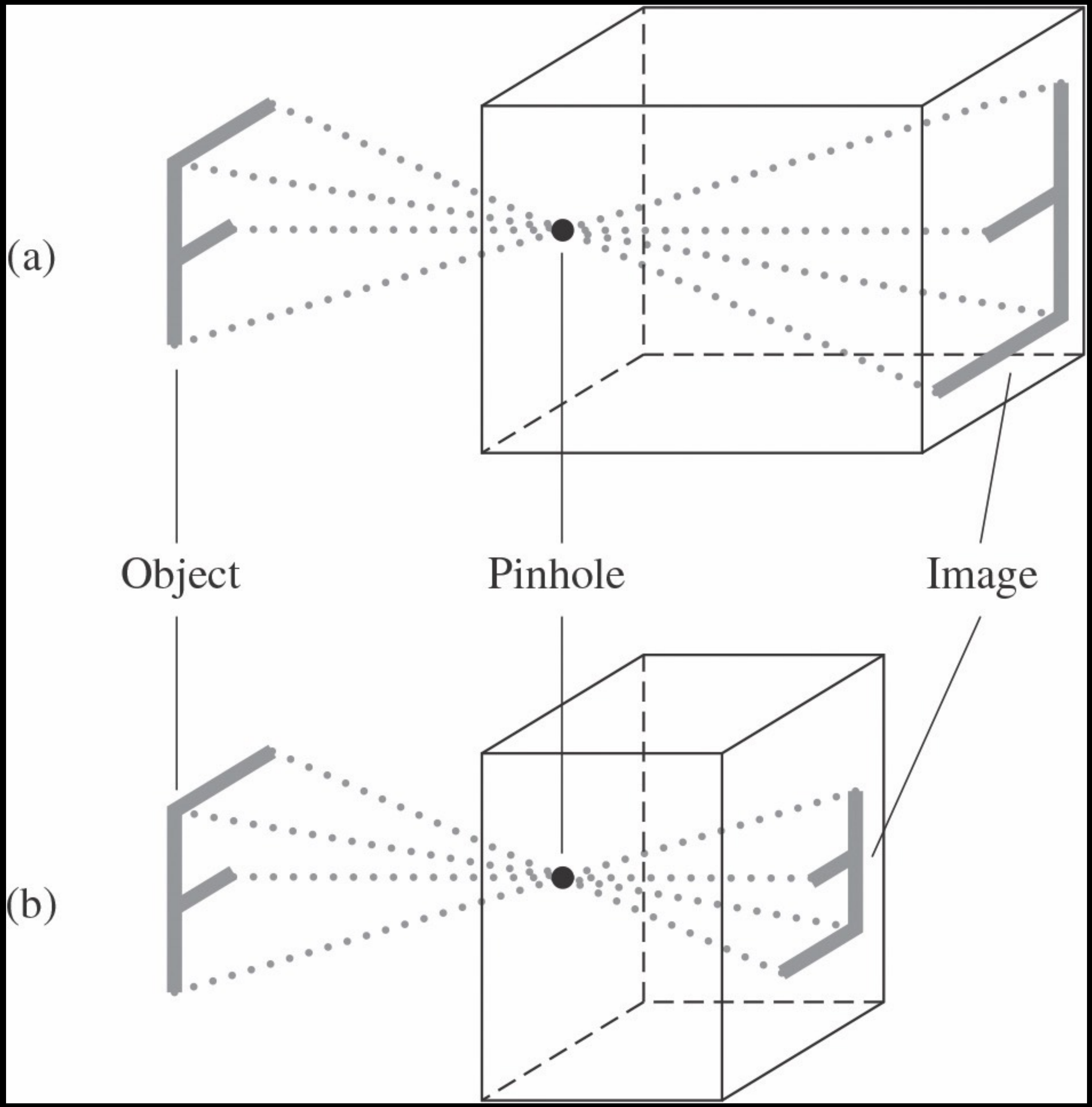
A telescope can be thought of as a camera, so understanding how cameras work is important for learning the basics of imaging science.



A small hole in a wall projects an image into a darkened room.

- Only light rays traveling in specific directions pass through the hole and reach the far wall.
- The setup has very low sensitivity — only a few photons enter at a time.

Early Imaging Science



- Because the pinhole is small, only a limited number of photons pass through.
- As a result, a long exposure time is needed to record a detectable image.
- For a fixed pinhole size, the exposure time (t) scales with the image area:

$$t \propto F^2$$

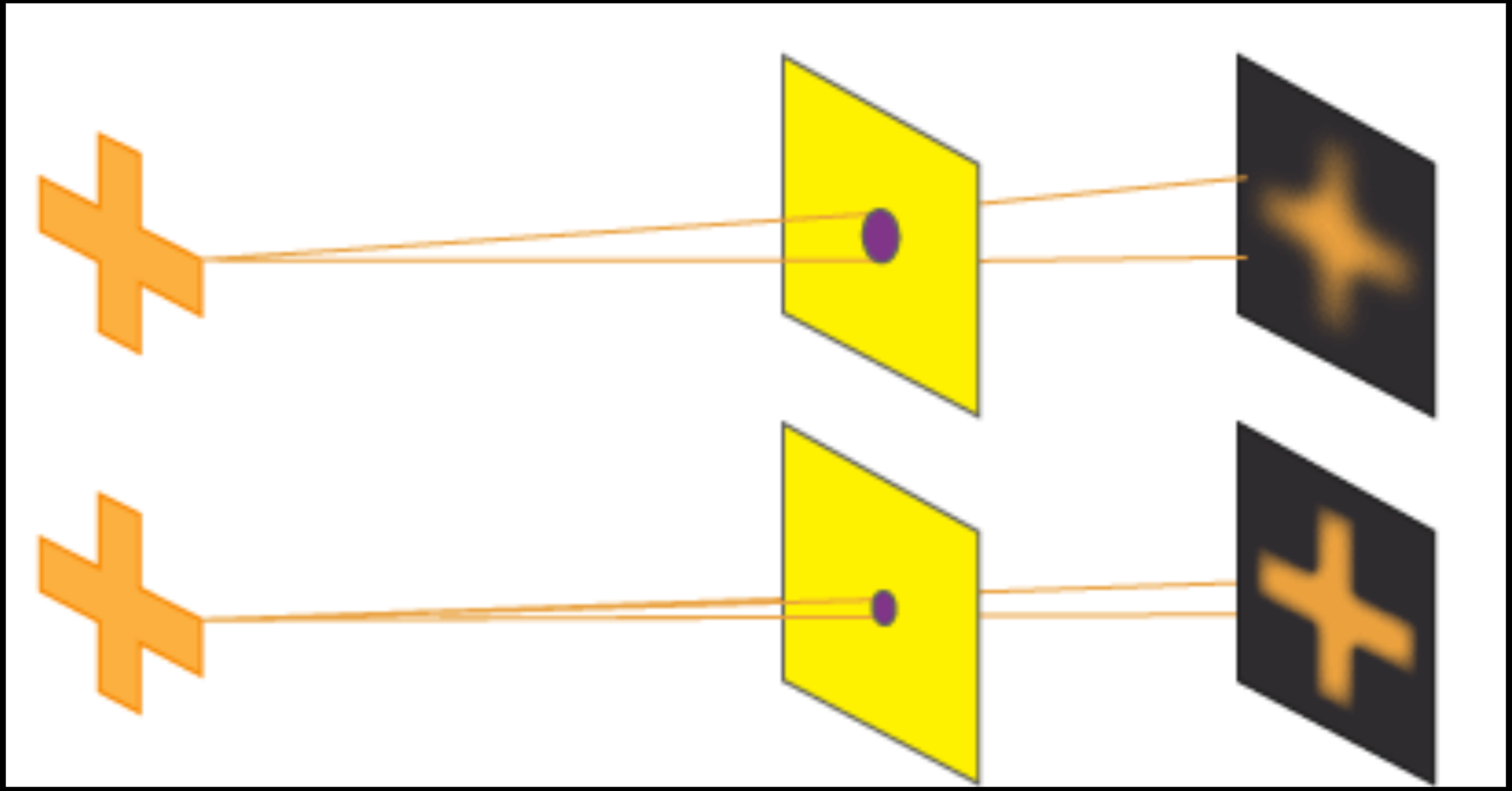
Where F is the distance between the pinhole and the image plane, which we refer as the "**focal length"**

- We call a camera with a short focal length a *fast* system (and vice versa)

Early Imaging Science

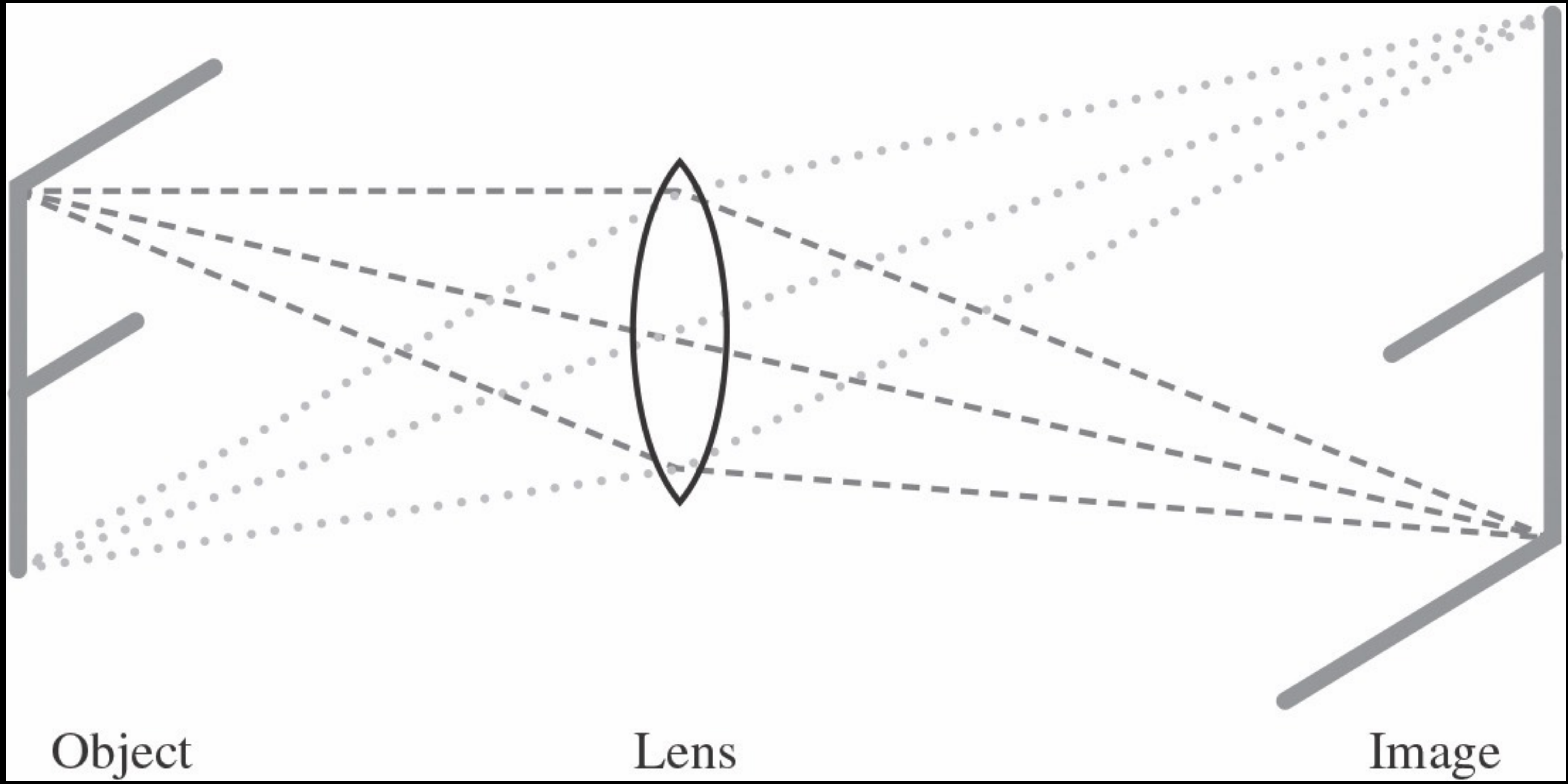
To reduce the exposure time while keeping the image large, **we need to collect more photons per unit time.**

- One way is to increase the size of the pinhole, allowing more light through.
- However, this breaks the **1-to-1 mapping** between points on the object and the image.
- Light rays from different parts of the object now overlap on the image plane, resulting in a **blurry image**.



Optics: Convex Lens

If we replace the pinhole with a *convex* **lens** we can focus light rays at specific locations on the image.



Review: The refractive index of a material is $n \equiv c/v_m$, where c is the speed of light in a vacuum and v_m is the speed of light in the material. For air, $n = 1.0003$

Optics: f-number

In a fixed lens setup, the image will be in focus only at a fixed distance F from the lens. The distance F to the **focal plane** depends on the shape of the lens and refractive index.

We often refer to the "f-number" when talking about lenses, defined as $f = F/D$, where D is the diameter of the lens.

$f/1.4$

Large diameter / shorter exposure time

$f/16$

Small diameter / longer exposure time

Optics: Plate Scale

When light from two stars separated by some angular distance (θ) on the sky pass through a telescope, their images form on the detector a distance (d) apart.

The **plate scale** (s) relates the angular separation to the physical separation on the image plane:

$$\theta[\mathrm{arcsec}] = s\left[\frac{\mathrm{arcsec}}{\mathrm{mm}}\right] \cdot d[\mathrm{mm}]$$

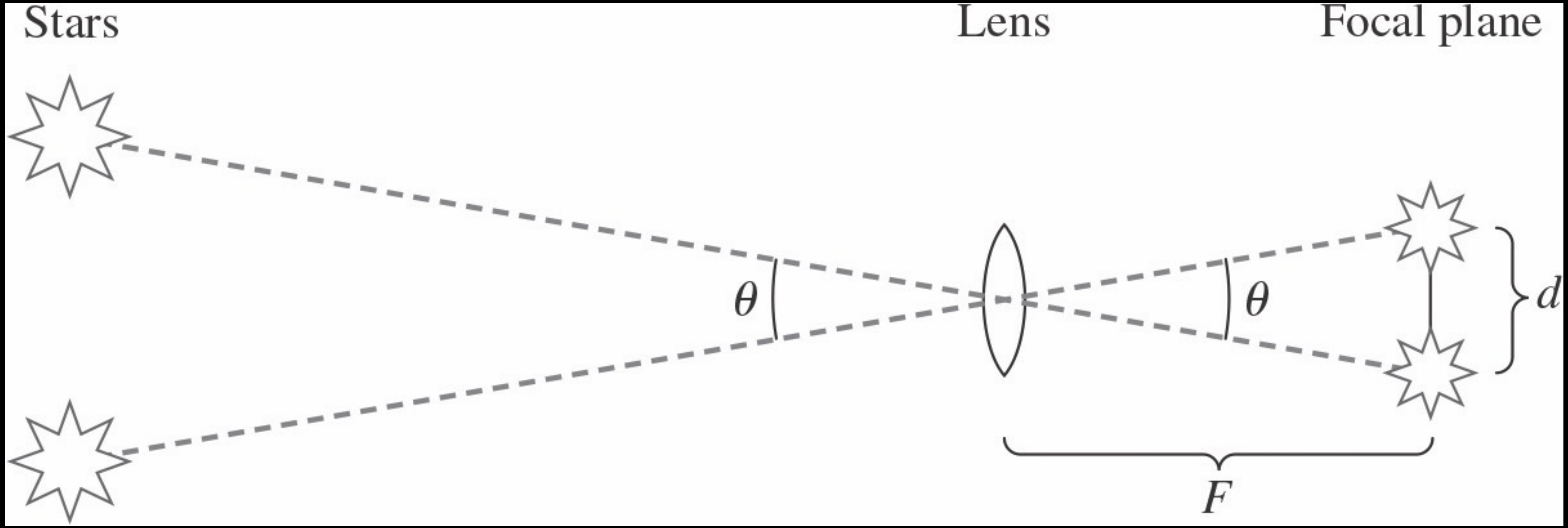
Historically, s converted sky angles to distances on photographic plates; today, it tells us how many arcseconds correspond to one detector pixel.

Annie Jump Cannon examines a photographic plates of the night sky. She created the stellar classification system still used today.

Image credit: Harvard-Smithsonian Center for Astrophysics

Optics: Plate Scale

Consider two stars separated on the sky by an angle θ. On the detector, their images appear a distance d apart.



Using the small-angle approximation $\tan\theta \approx \theta$ (in radians), we can relate the two separations as:

$$\theta[\text{radians}] \approx \frac{d}{F}$$

Optics: Plate Scale

Converting from radian s to arcseconds, we arrive at:

$$\theta[\text{arcsec}] = \theta[\text{radians}]\left(\frac{180^\circ}{\pi\ \text{radians}}\right)\left(\frac{3600\ \text{arcsec}}{1^\circ}\right) = 206265\left(\frac{d}{F}\right)$$

Thus, the relationship between the plate scale and focal length is given by:

$$s[\text{arcsec/mm}] = \frac{206265}{F[\text{mm}]} = \frac{206265}{f D[\text{m}]}$$

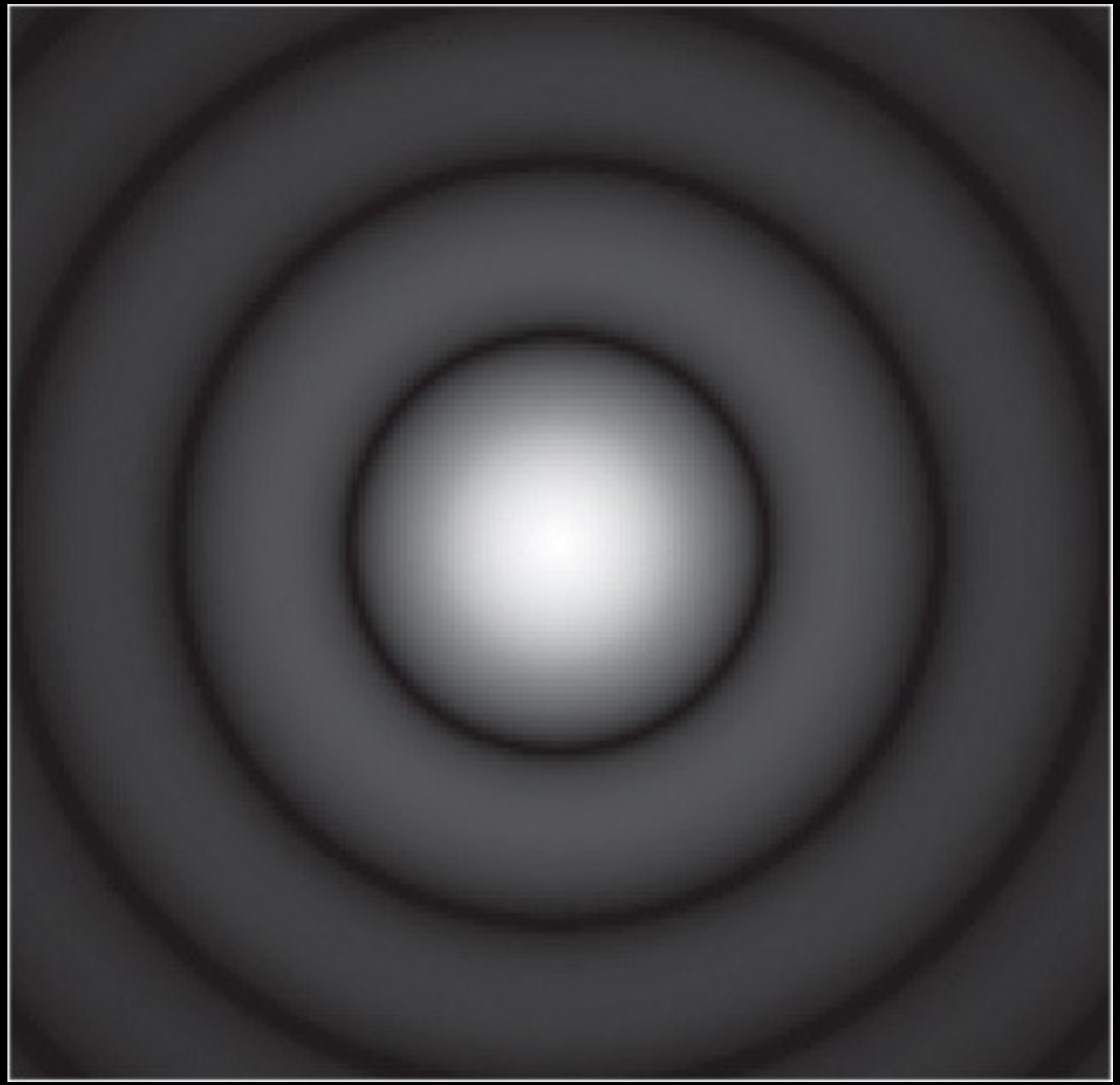
The human eye has $F \approx 17$ mm, therefore our “plate scale” is $s \approx 12{,}100$ arcsec/mm, or $s \approx 3.4^\circ/\text{mm}$; when you look at the full Moon, its image covers an area of your retina less than 0.15mm across.

Optics: Diffraction

You might conclude that for a telescope of diameter D, images will become larger (and therefore more detailed) by increasing the focal ratio f/D.

However, simply increasing f/D doesn't result in more detailed images.

- This is because at the level of fundamental physics, the quality of images is limited by *diffraction*.
- When light from a point source passes through a circular aperture of finite size, it does not form a perfect point.
- Instead, it produces a "diffraction pattern" characterized by a bright central spot surrounded by concentric rings !



Airy Disk

The diameter of the central bright region (known as the *Airy disk,* named after its discoverer, George Airy) is determined by the telescope's aperture size D and the wavelength of observed light λ.

To *resolve* two nearby objects as distinct, the light from one object must fall within the first dark ri of the other. The minimum angular distance you can resolve two objects is:

$$\theta_{\mathrm{min}}[\mathrm{rad}] = 1.22\frac{\lambda}{D}$$

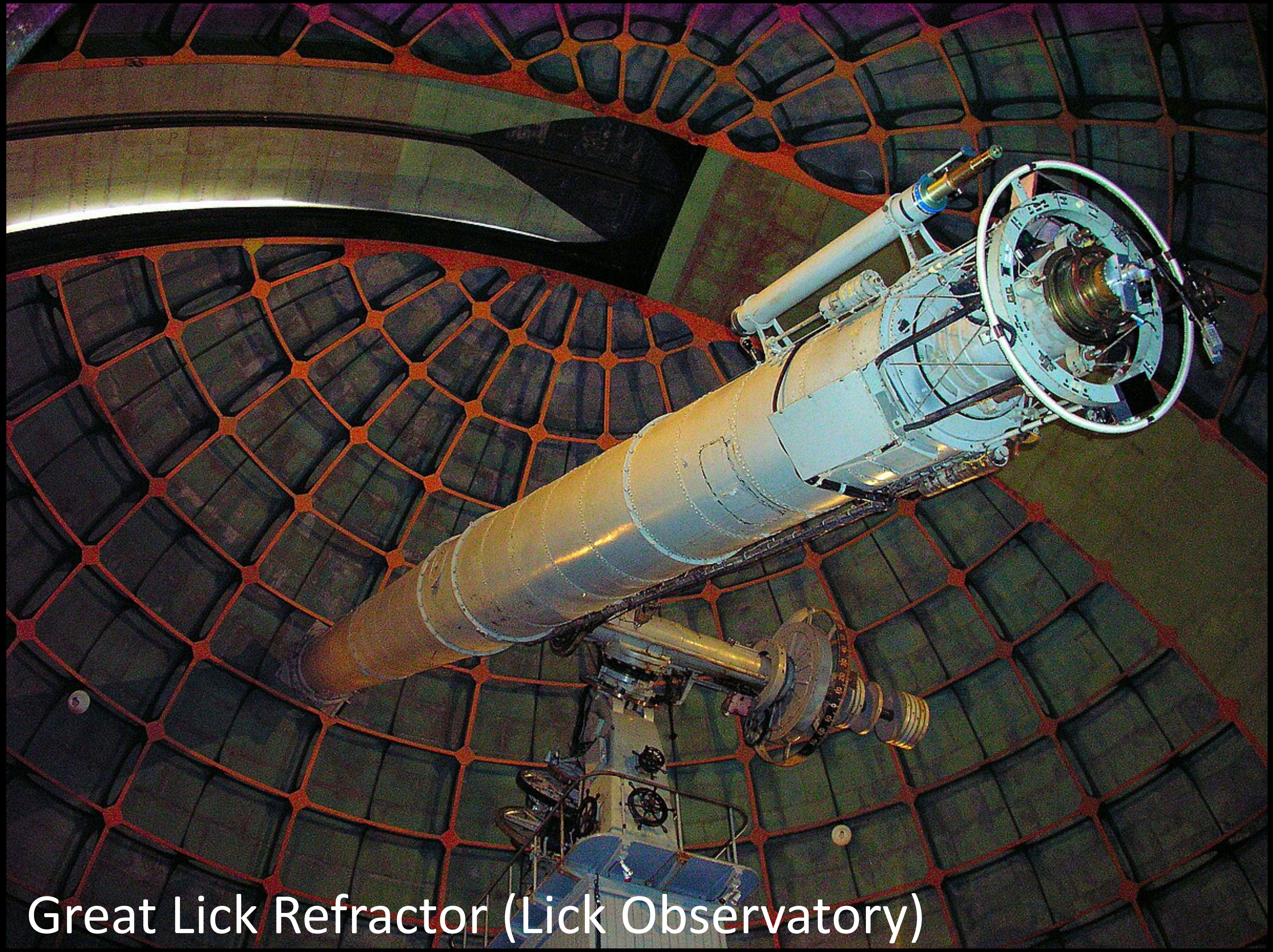
Caveat: In practice, the Earth's atmosphere blurs astronomical images due to turbulence—this is what causes stars to appear to twinkle. We call this effect **seeing**, and even at the best observing sites on Earth where turbulence and air flow is minimized, the typical seeing limit is about $\sim 0.25''$.

No matter how large a ground-based telescope you build, atmospheric seeing sets a practical limit on resolution.

(A) 2 radii separation
(B) 1 radius separation
(C) 0.8 disk separation
(D) 0.5 disk separation
1.5
1.0
0.5
0.0
−2
0
2
Disk radii


Questions?

Refracting Telescopes



Great Lick Refractor (Lick Observatory)


Astronomers included to demonstrate size

Telescopes with lenses used as the **primary** light-gathering element are called "**refracting**" telescopes (**refractors**)

These were developed a long time ago, but not ideal.

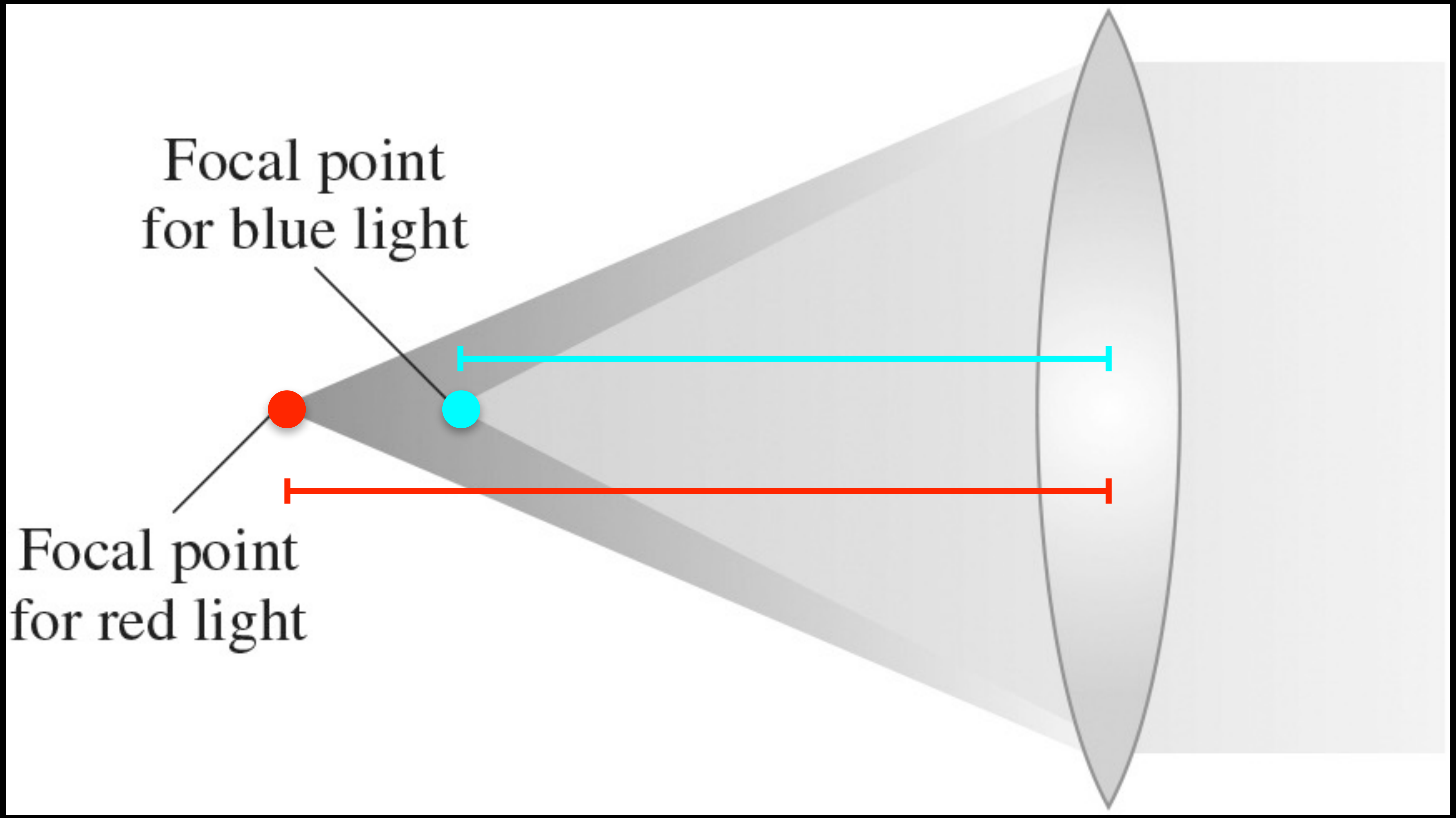
1. Lenses weigh a ton!
2. Hard to keep a long tube stable as you move it around

Chromatic Aberration

Refractive index decreases with wavelength. Short wavelengths are bent through a greater angle than long wavelengths.

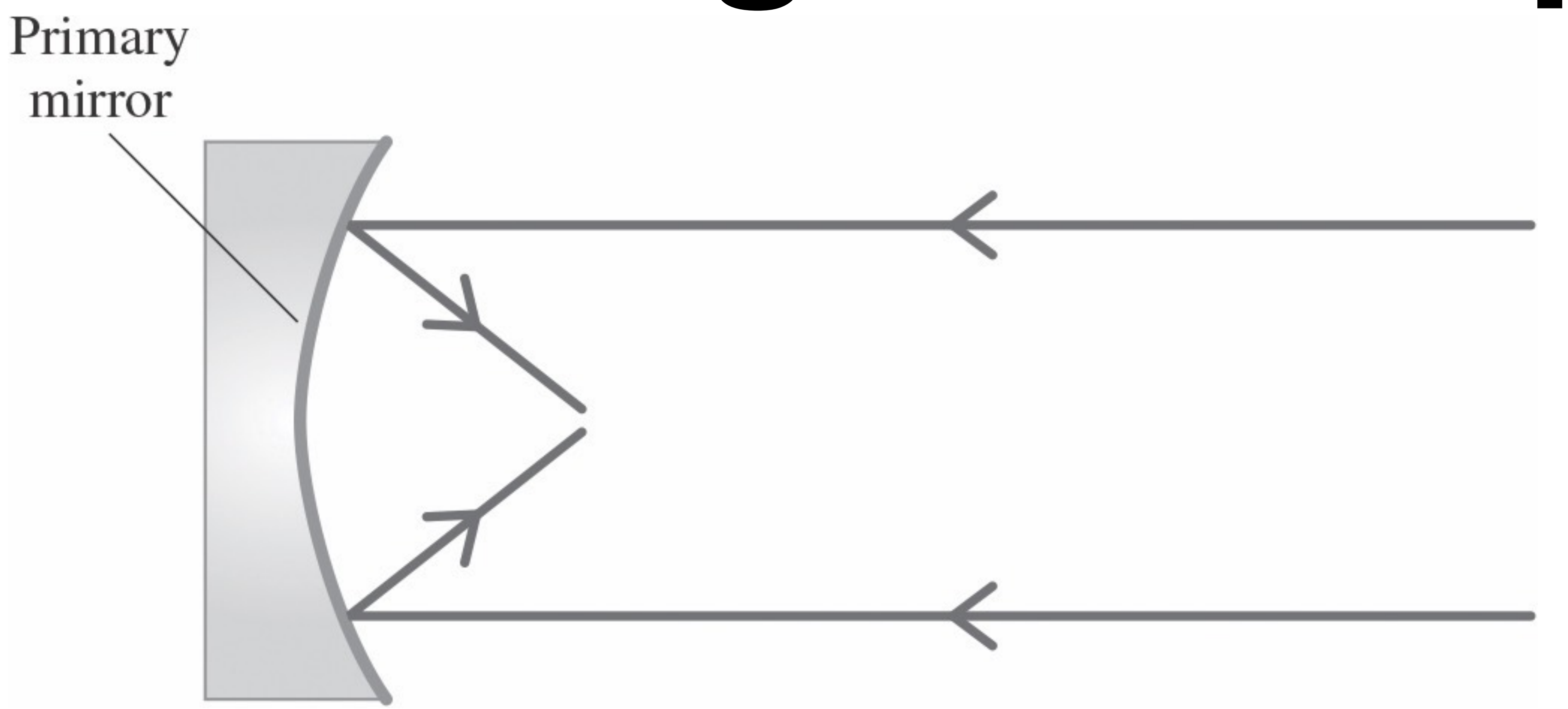
With refracting telescopes, it is not possible to focus all wavelengths of light for the object you are observing at the same spot on the detector.

Consequently, some wavelengths will be blurred.



Chromatic aberration in a refraction; the focal length for blue light is *shorter* than for red light.

Reflecting Telescopes



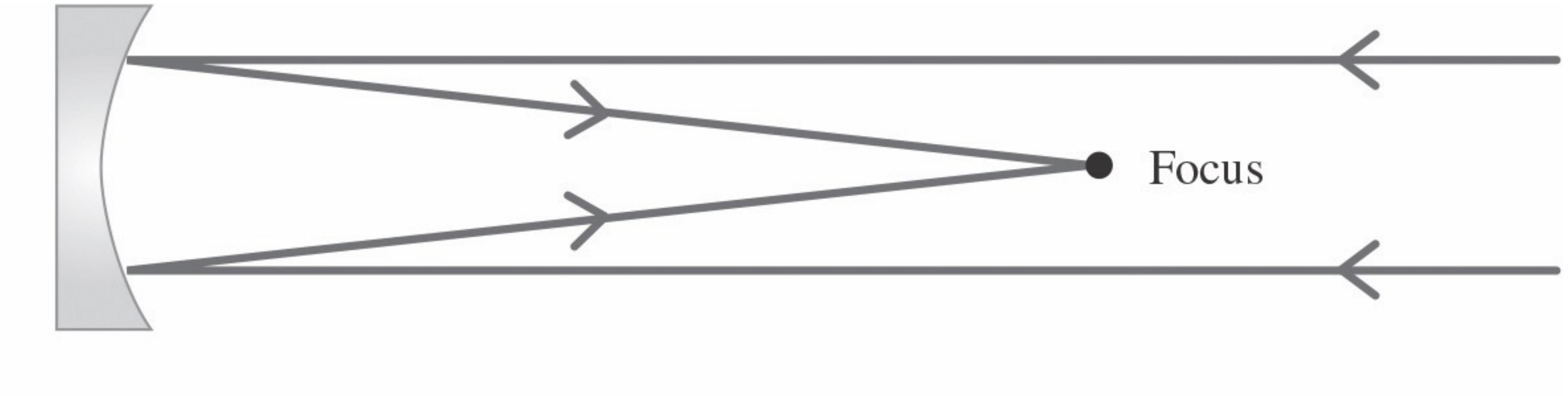
Telescopes that use a mirror as the **primary** light-gathering element are called “**reflecting**” telescopes (**reflectors**).

These have many advantages over refractors:

1. No chromatic aberration
2. You can support a mirror from its back (not just edges)
3. Easier to make very large mirrors (weight loss tricks)

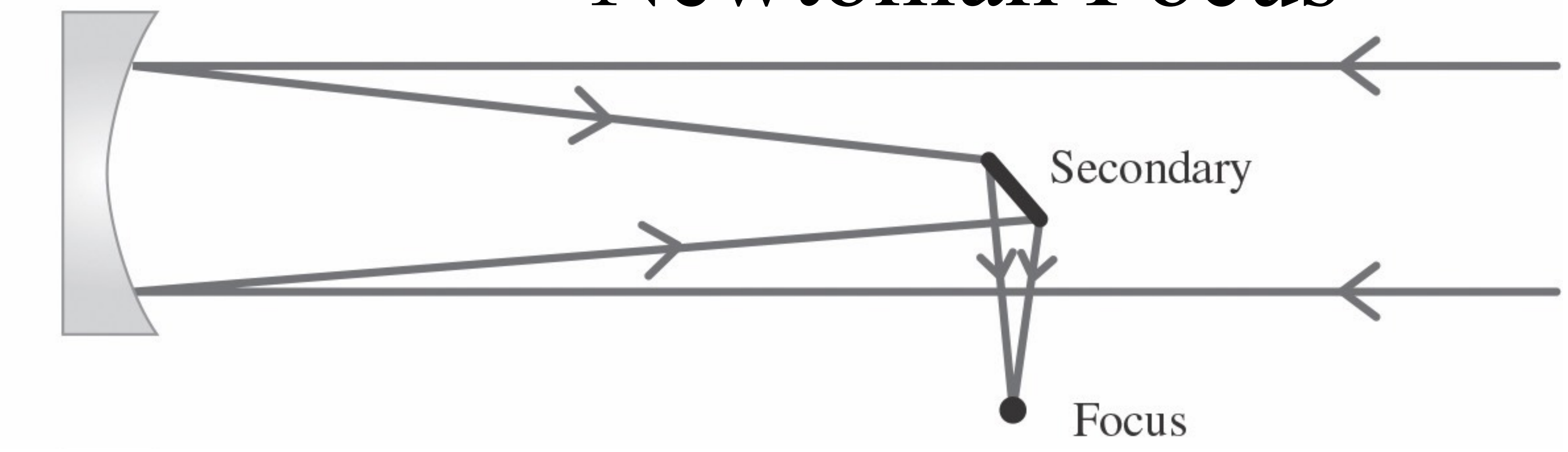
Types of Reflectors

Prime Focus



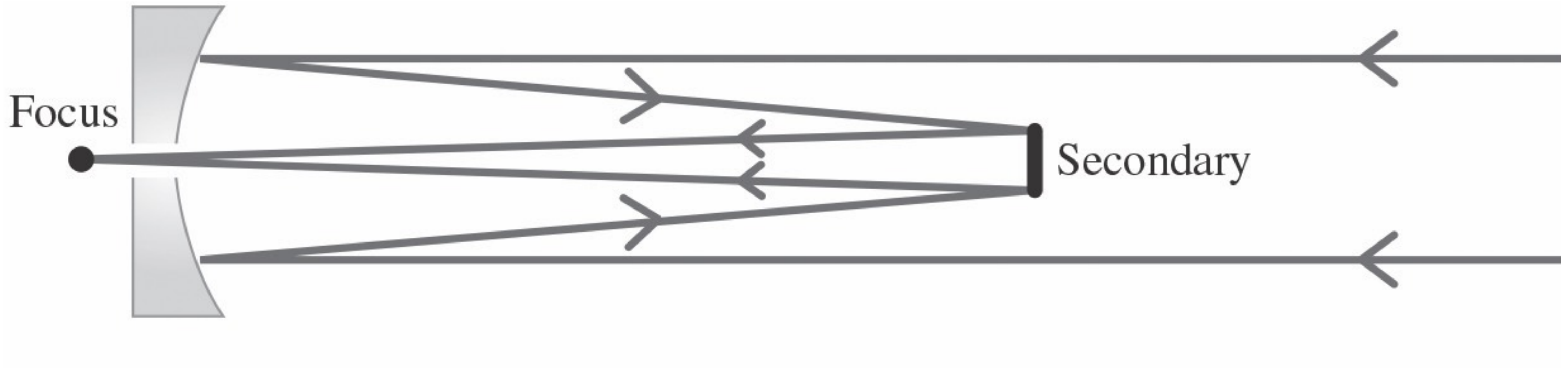
Not ideal for large detectors as they must be placed between incoming light and mirror

Newtonian Focus



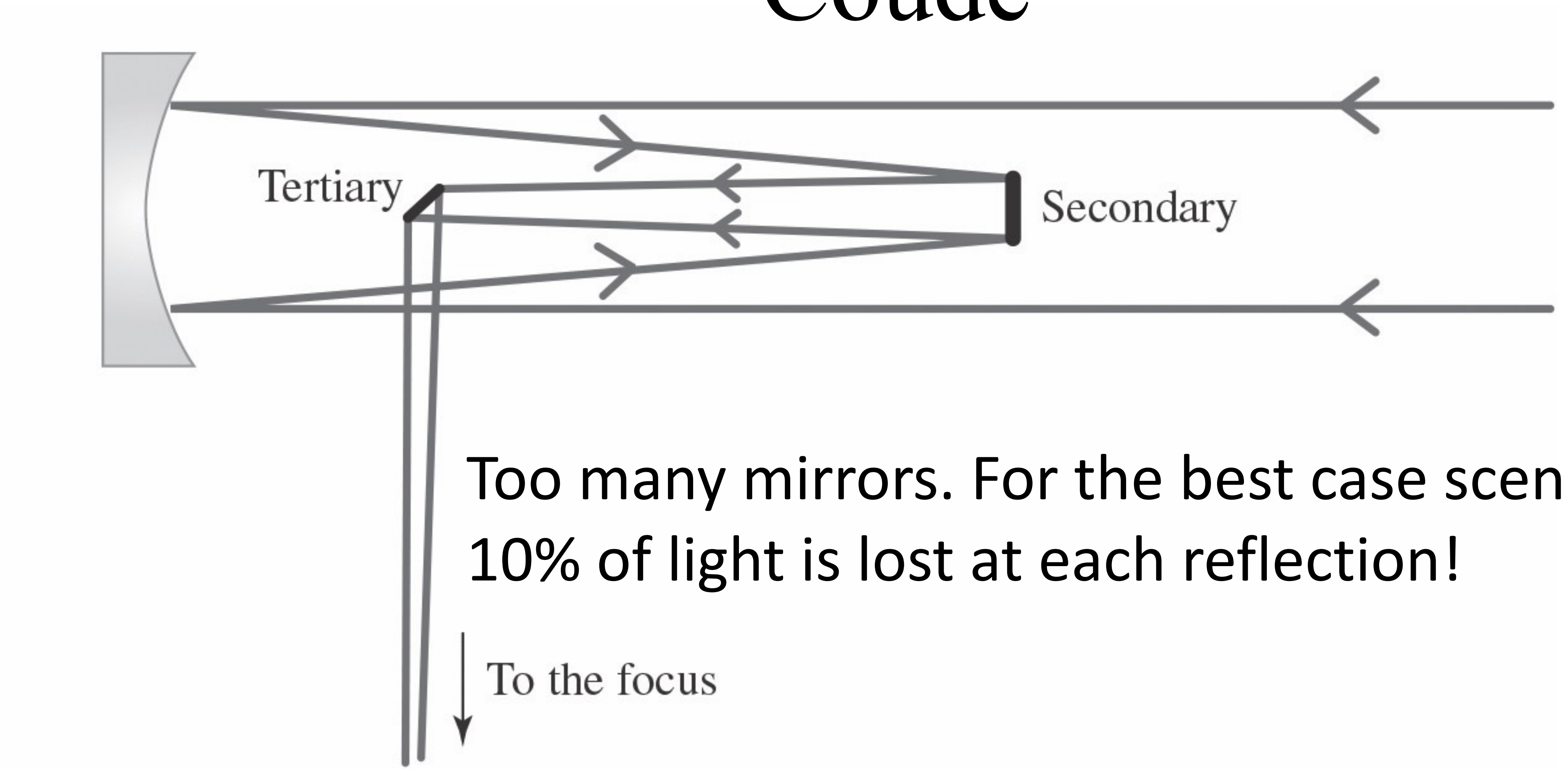
Not ideal for heavy detectors as they must be attached to the side of the telescope tube.

Cassegrain



Ideal scenario: allows for long focal length while remaining compact, heavy instruments can be placed at the base of telescope

Coudé



Too many mirrors. For the best case scenario, 10% of light is lost at each reflection!

Brain Break – Think-pair-share

The idea of building a telescope on the Moon has been floated around for many years.

What are some of the potential benefits of putting a telescope on the Moon?

What type of telescope should it be?

What are some of the potential drawbacks?

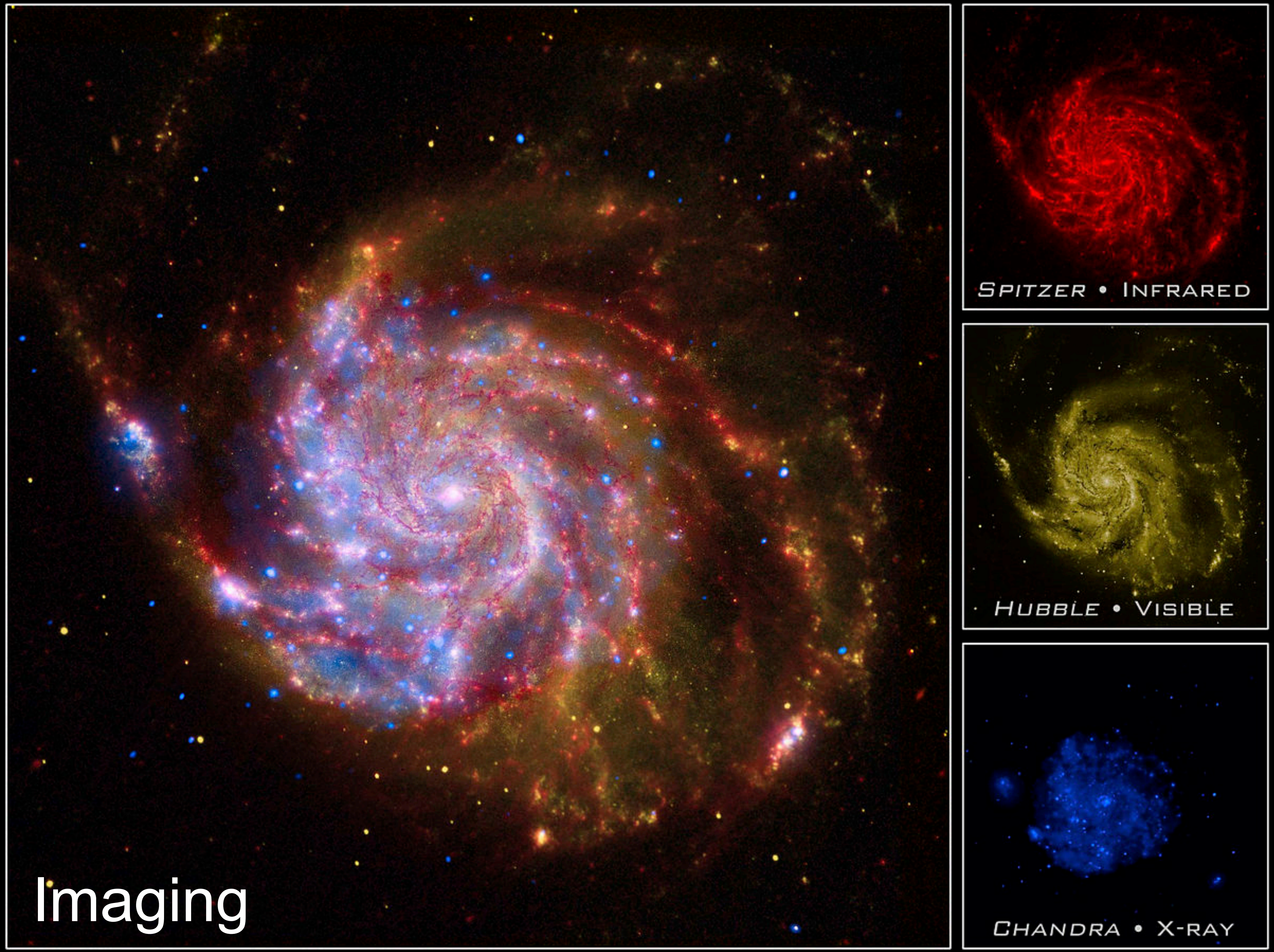
Do you think there will be a telescope on the Moon in your lifetime?

Imaging & Spectroscoy

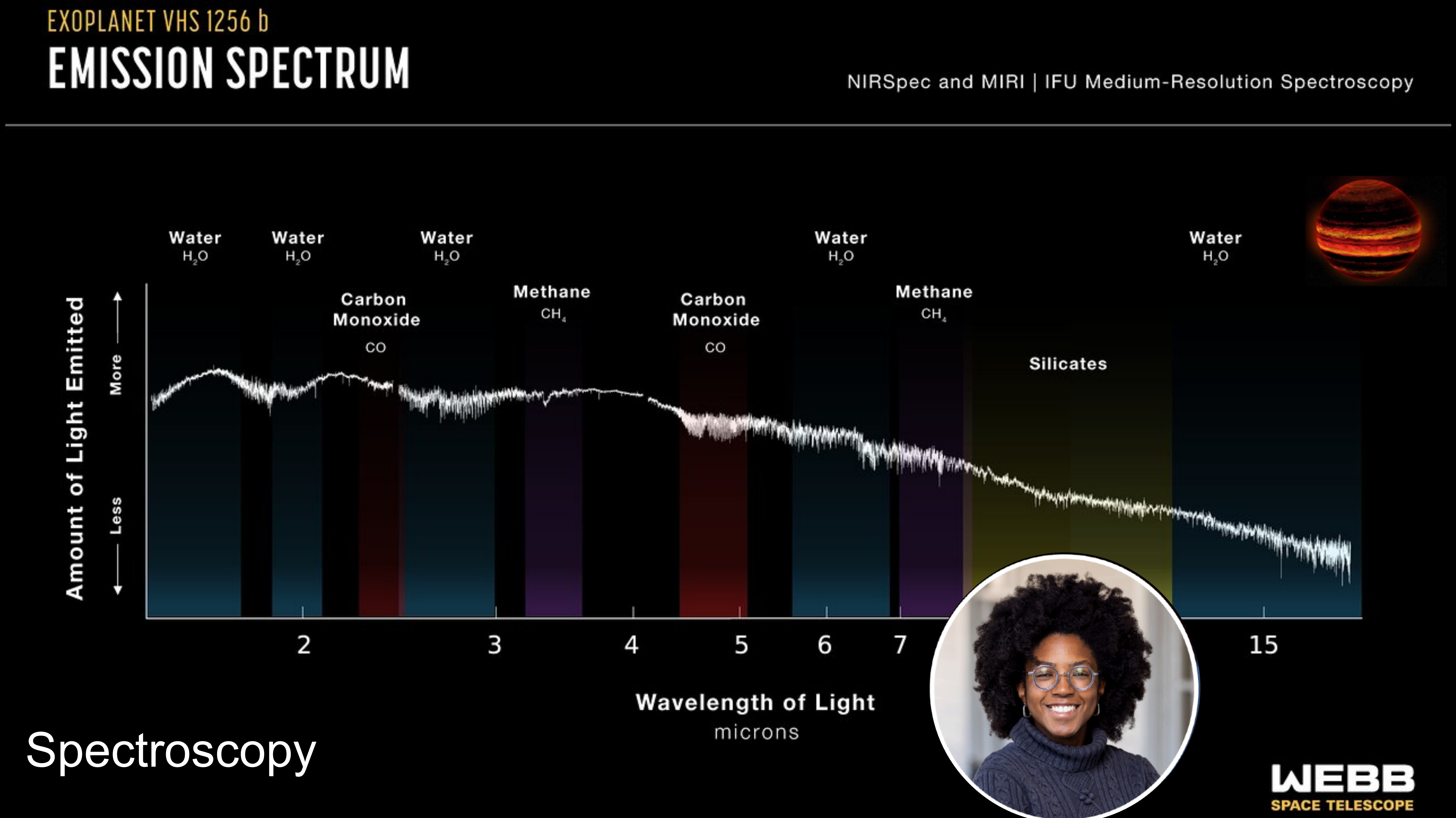
Two Main Types of Astronomical Instruments

Imagers: Measure the brightness of objects and use filters to limit the range of wavelengths reaching the detector.

Spectrographs: Split light into its constituent wavelengths using a **dispersing element** to produce a **spectrum**



Spiral Galaxy M101 Spitzer Space Telescope • Hubble Space Telescope • Chandra X-Ray Observatory
NASA / JPL-Caltech / ESA / CXC / STScI ssc2009-03a

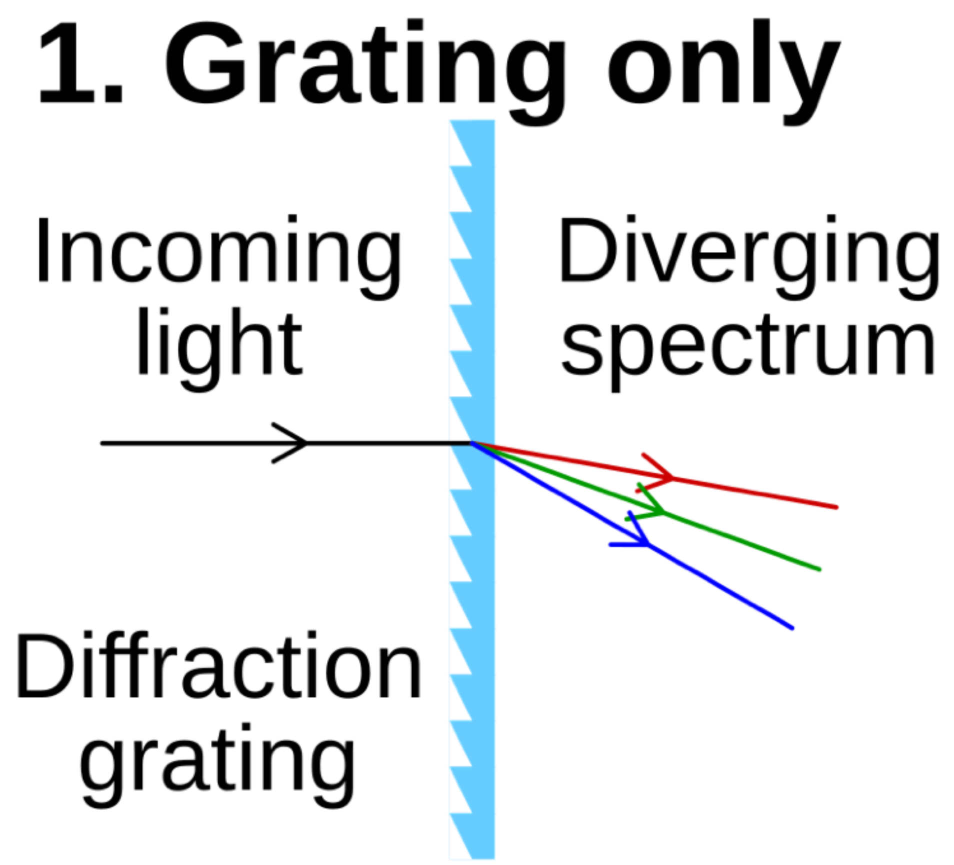


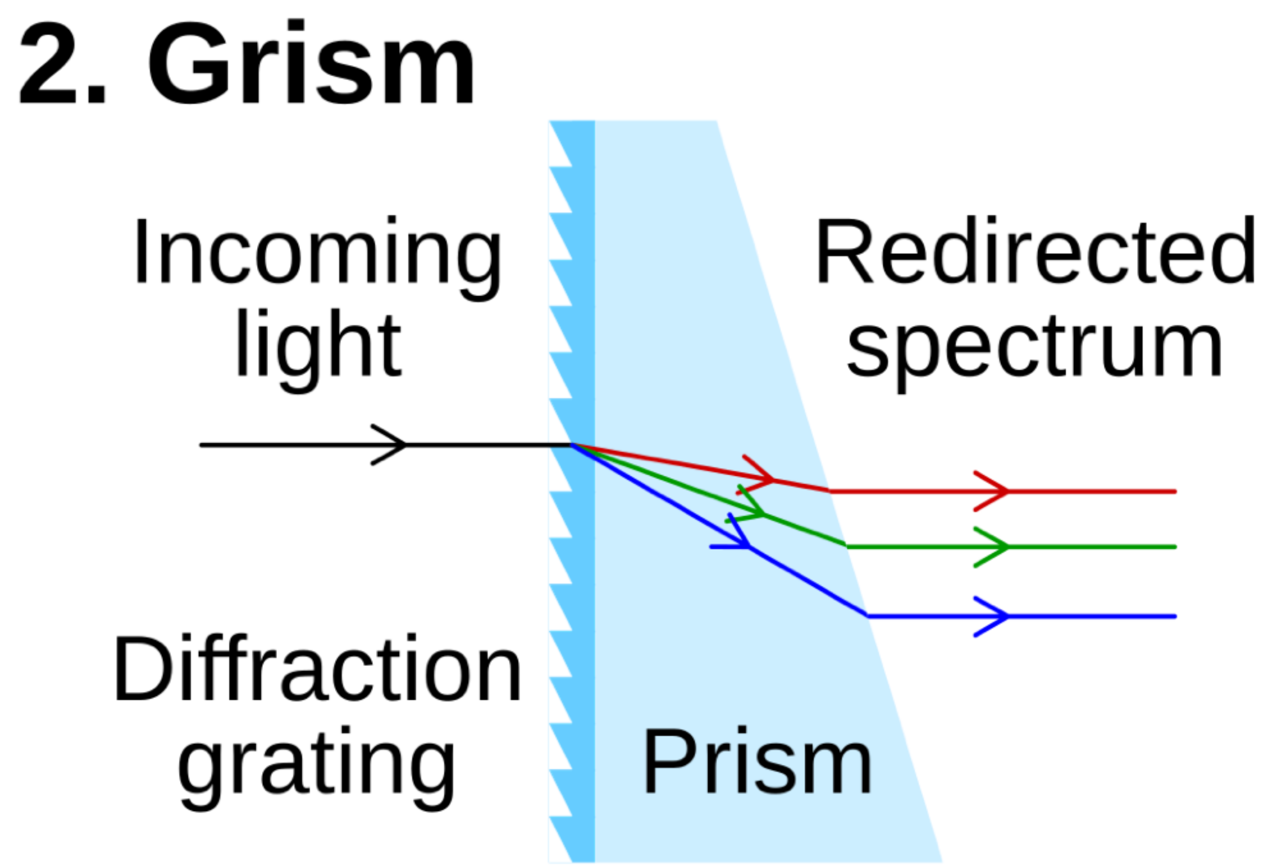
Spectroscopy

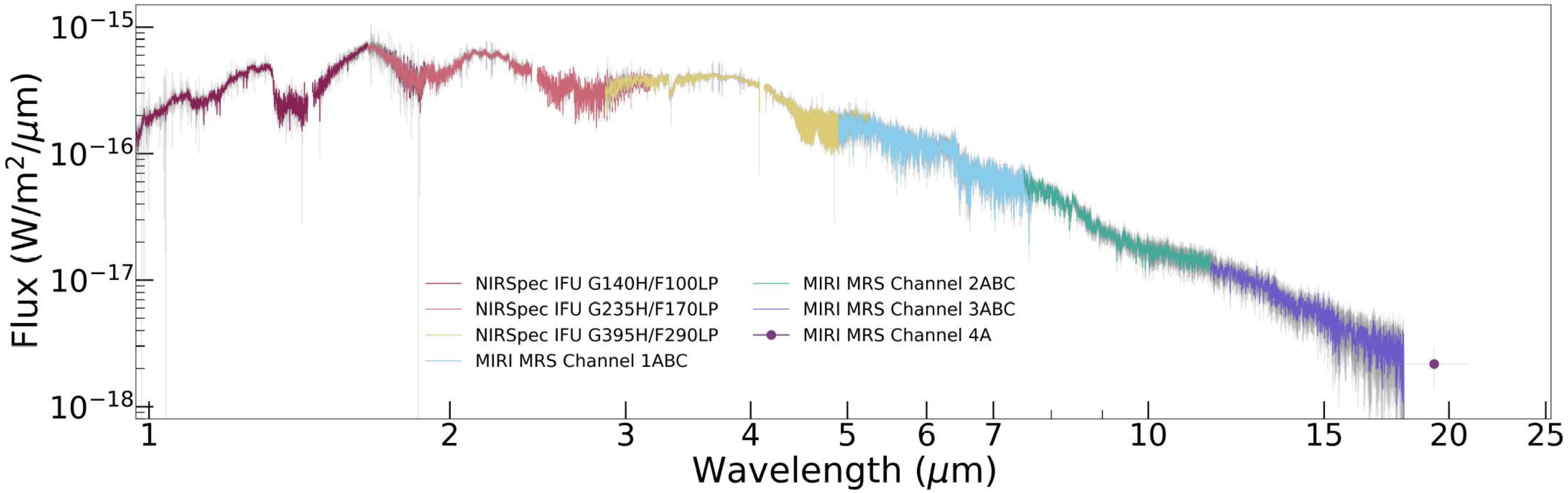
Miles et al. 2023 found evidence of “clouds of sand” on a distant “Super Jupiter”

Spectrographs in a Nutshell

- A **spectrograph** disperses incoming light into its component wavelengths.
- This is done using a **diffraction grating**, **prism**, or a combination (***grism***).
- The resulting **spectrum** can be recorded on a detector for analysis.



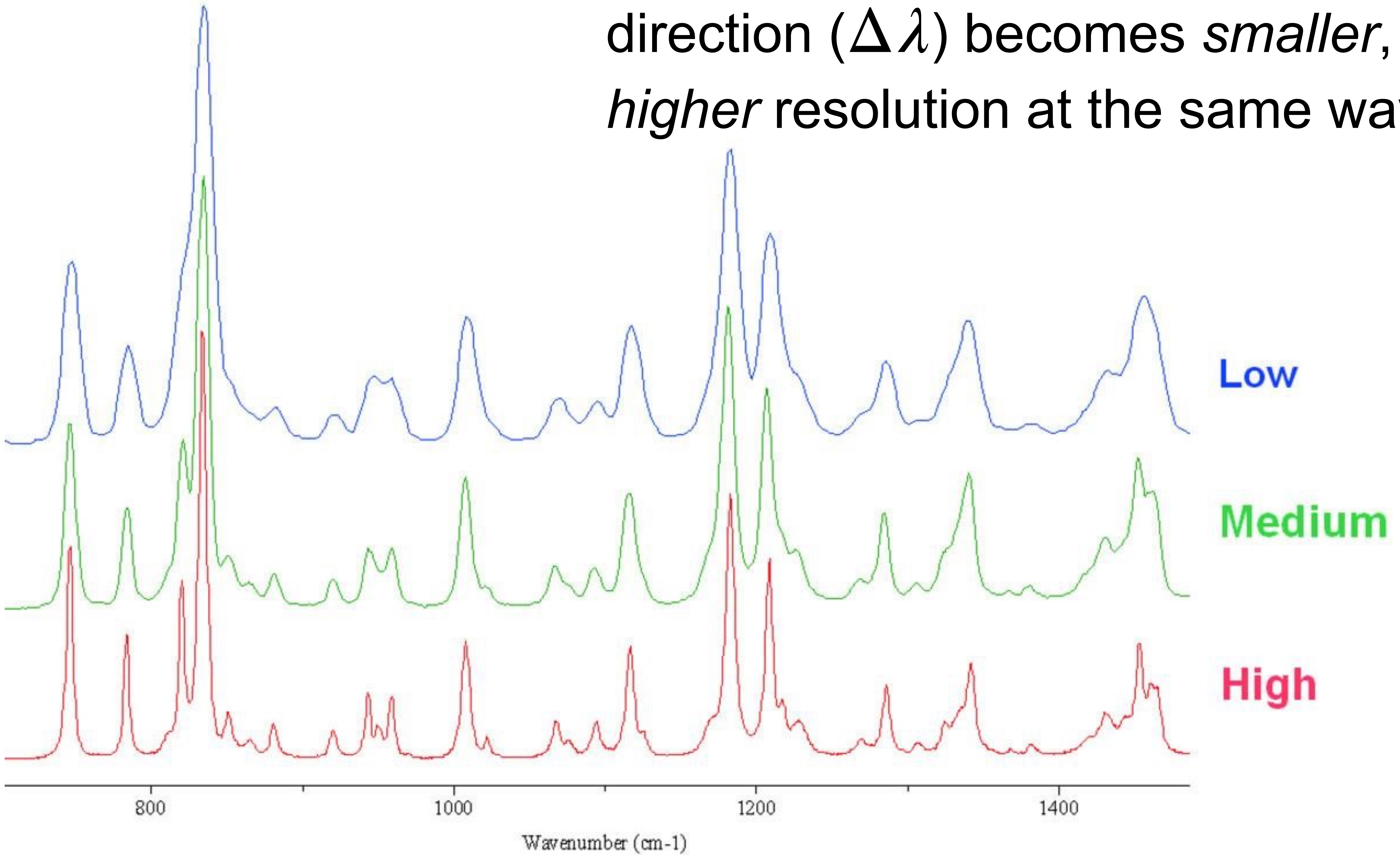




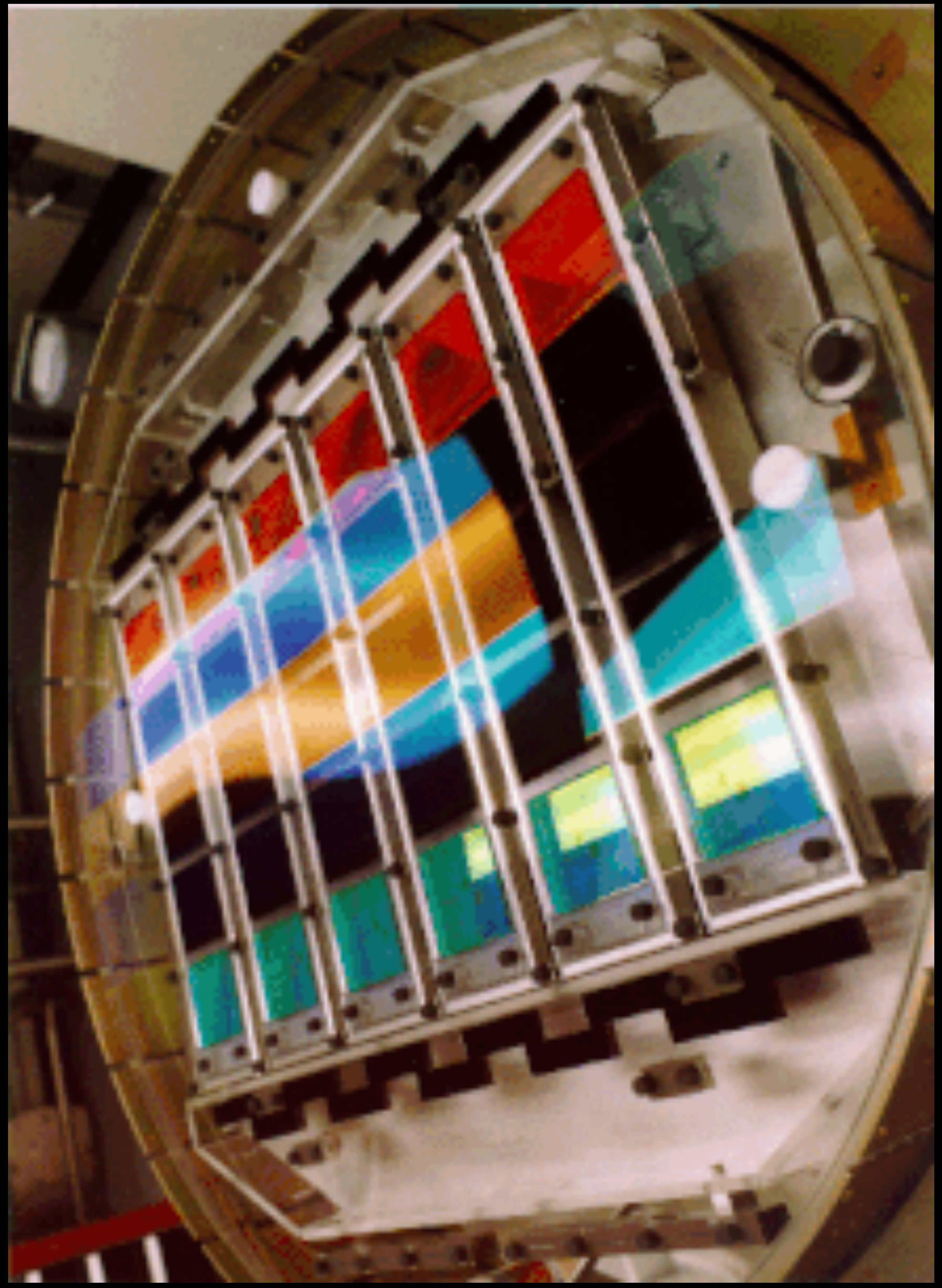
Spectrograph Resolution

A spectrographs is characterized by its ***spectral resolution***.
This is defined as $R = \lambda / \Delta\lambda$.

As the width of a pixel in the spectral direction ($\Delta\lambda$) becomes *smaller*, we get a *higher* resolution at the same wavelength (λ).

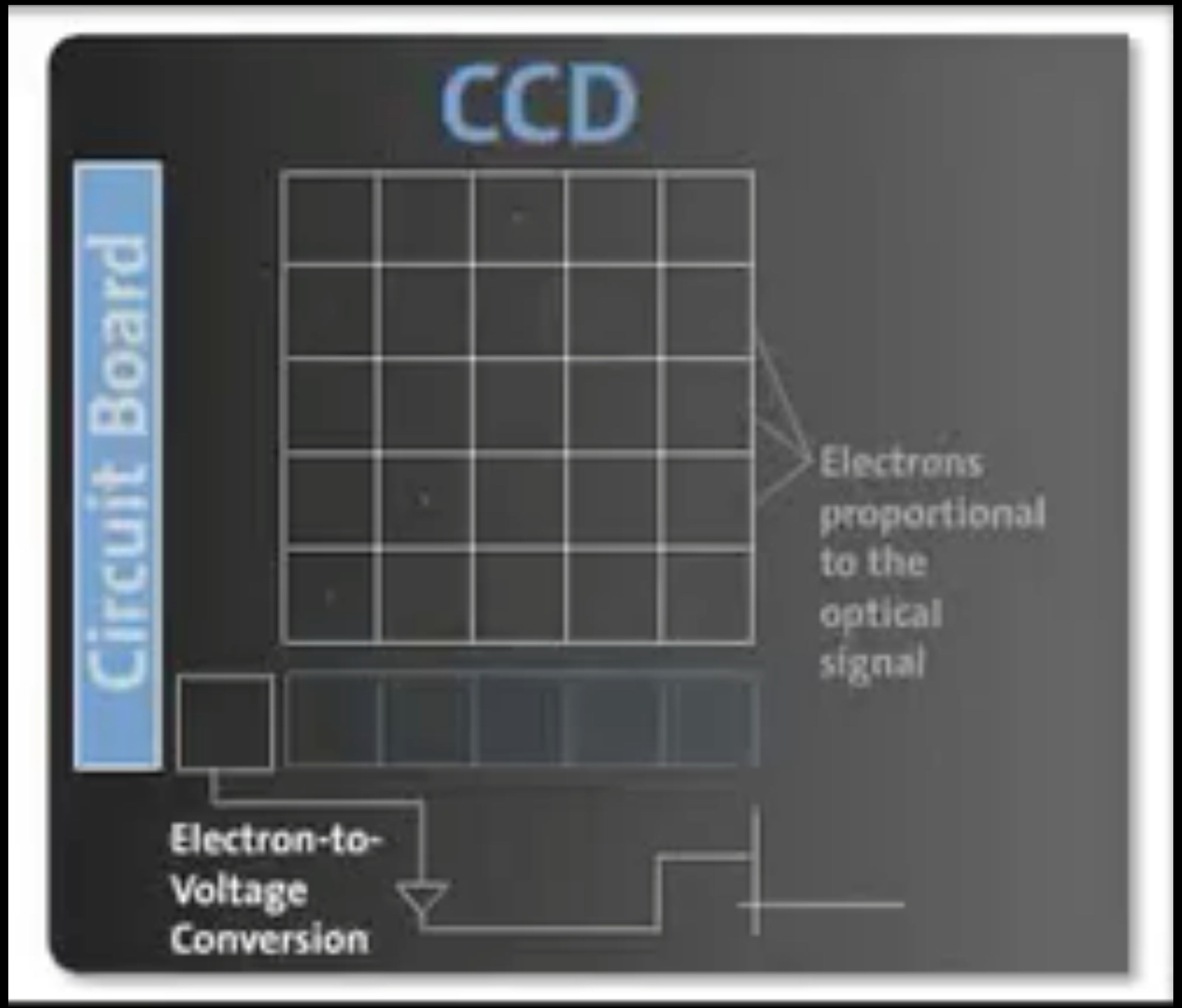


CCDs in a Nutshell



A charge-coupled device (CCD) accumulates local charges when hit by photons. These charges are then read off the CCD.

- Quantum efficiencies of ~80%
- Cosmic rays can deliver a lot of charge all at once
- Can make them very big (4k x 4k)



Signal-to-Noise

We often have to justify our telescope time with signal-to-noise (S/N or SNR) estimates, defined as,

$$\frac{S}{N} = \frac{\text{Measurement}}{\text{Uncertainty}}$$

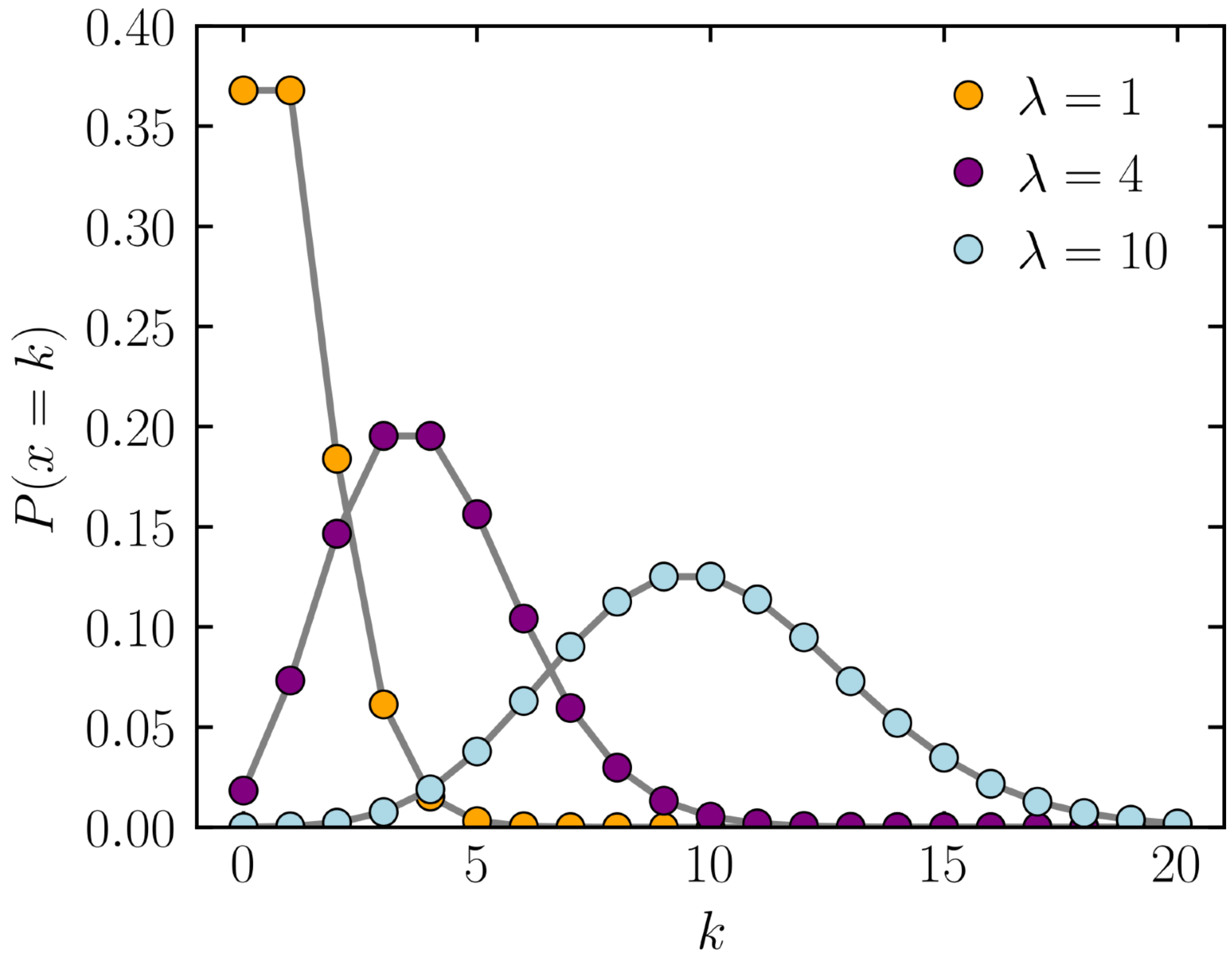
Photon counts are governed by Poisson statistics, so this simplifies to

$$\frac{S}{N} = \frac{\mu}{\sigma}$$

Counting Statistics (Poisson)

Probability of events occurring in a fixed interval of time.
Examples:

1. Number of large meteorites striking the Earth each year.
2. Machine malfunctions in a year at a warehouse
3. Number of customers arriving to a store in an hour
4. Number of photons hitting a detector in a time interval



Mean (μ) $= \lambda$

Variance (σ^2) $= \lambda$

λ = Expected number of photons

We will use μ instead of λ

Signal-to-Noise

For a Poisson distribution, $\sigma^2 = \mu$, therefore

$$\frac{S}{N} = \frac{\mu}{\sqrt{\mu}} = \sqrt{\mu}$$

This is valid if your object is much brighter than the background (think about a bright star that you can image with a short exposure time).

What if your object is faint and you need to take a long exposure?

Signal-to-Noise

In this case we need to compute the “noise” which is a combination of the noise from the source we are observing (e.g., star) and the noise of the background (e.g., sky everywhere including where the star is). Then,

$$\sigma^2_{\text{total}} = \sigma^2_{\text{source}} + \sigma^2_{\text{background}}$$

Therefore,

$$\frac{S}{N} = \frac{\mu_{\text{source}}}{\sigma_{\text{total}}} = \frac{\mu_{\text{source}}}{\sqrt{\sigma^2_{\text{source}} + \sigma^2_{\text{background}}}}$$

Signal-to-Noise

Since this is all Poisson statistics, we can use the fact that $\sigma^2 = \mu$ for all noise sources and we get

$$\frac{S}{N} = \frac{\mu_{\text{source}}}{\sqrt{\sigma^2_{\text{source}} + \sigma^2_{\text{background}}}} = \frac{\mu_{\text{s}}}{\sqrt{\mu^2_{\text{s}} + \mu^2_{\text{b}}}}$$

If $\mu_{\text{background}} > \mu_{\text{source}}$ (background limited)

$$\frac{S}{N} = \frac{\mu_{\text{s}}}{\sqrt{\mu^2_{\text{s}} + \mu^2_{\text{b}}}} \approx \frac{\mu_{\text{s}}}{\sqrt{\mu^2_{\text{b}}}}$$

Exposure times

The time we need to expose (or integrate) on a source is dependent on how S/N changes with time. Luckily, the numbers of photons received is linear with **exposure time**, *t* (for both source and background). This gives us two simple relationships

$$t \propto \left(\frac{\theta}{F_\lambda D}\right)^2 \propto \left(\frac{S}{N}\right)^2$$

$$\frac{S}{N} \propto \frac{t \cdot source\ photons}{\sqrt{t \cdot source\ photons\ +\ t \cdot background\ photons}} \propto \sqrt{t}$$

where θ is the seeing, F_λ is the flux from the source, and D is the diameter of the telescope. This provides a scaling relation that we can use to estimate exposure times against a well calibrated star.


Questions?

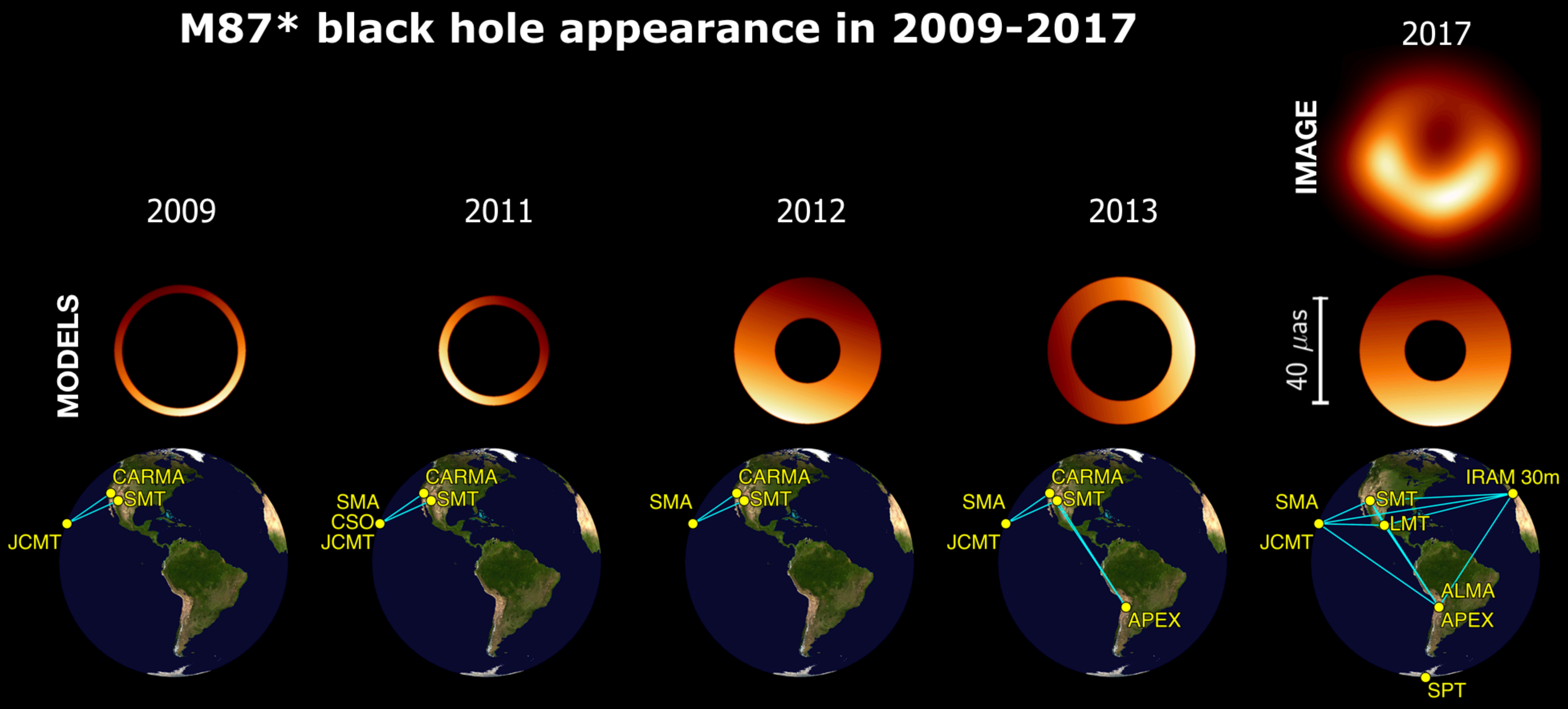
Interferometers

It's not reasonable to create an infinitely large telescope, but what if we could get increased angular resolution with small telescopes?

We can create an interferometer using two telescopes separated by a distance, which creates a telescope with a diameter the size of the baseline.

Event Horizon Telescope

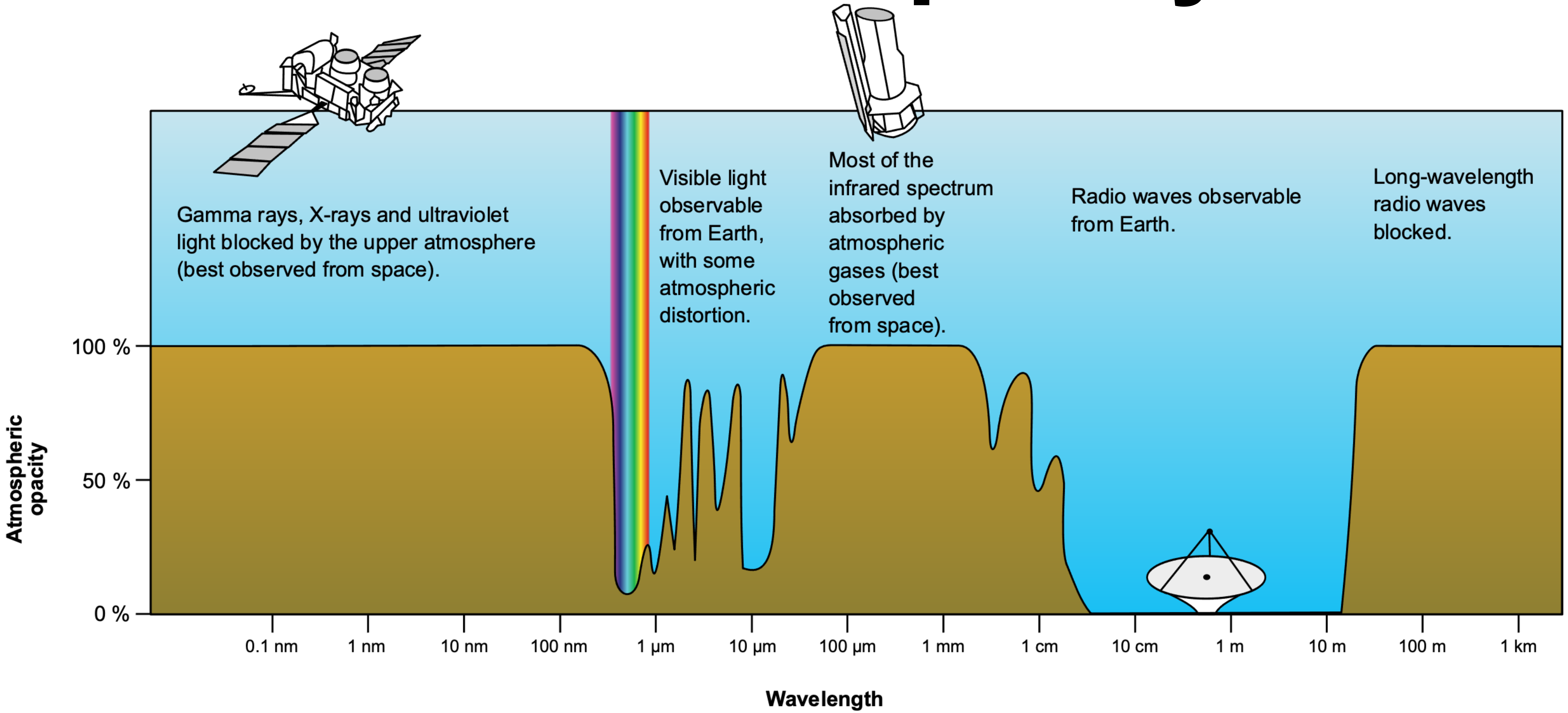
A telescope the size of the Earth!



Credit: M. Wielgus, D. Pesce

Event Horizon Telescope

Earth's Opacity



Earth is *mostly* transparent from $\lambda \approx$ 3100 Å–1.1 μm, and then again from $\lambda \approx$ 3 cm–1.1 μm


Questions?

Reminders

- **Homework #3 due Tuesday, 10/21 by 11:59 pm via Gradescope.**
- Midterm Exam I will take place next **Thursday, 10/23**
- Log into canvas and submit your answer to the discussion question by the end of the day to receive participation credit.