ASTR20A:
Introduction to Astrophysics I

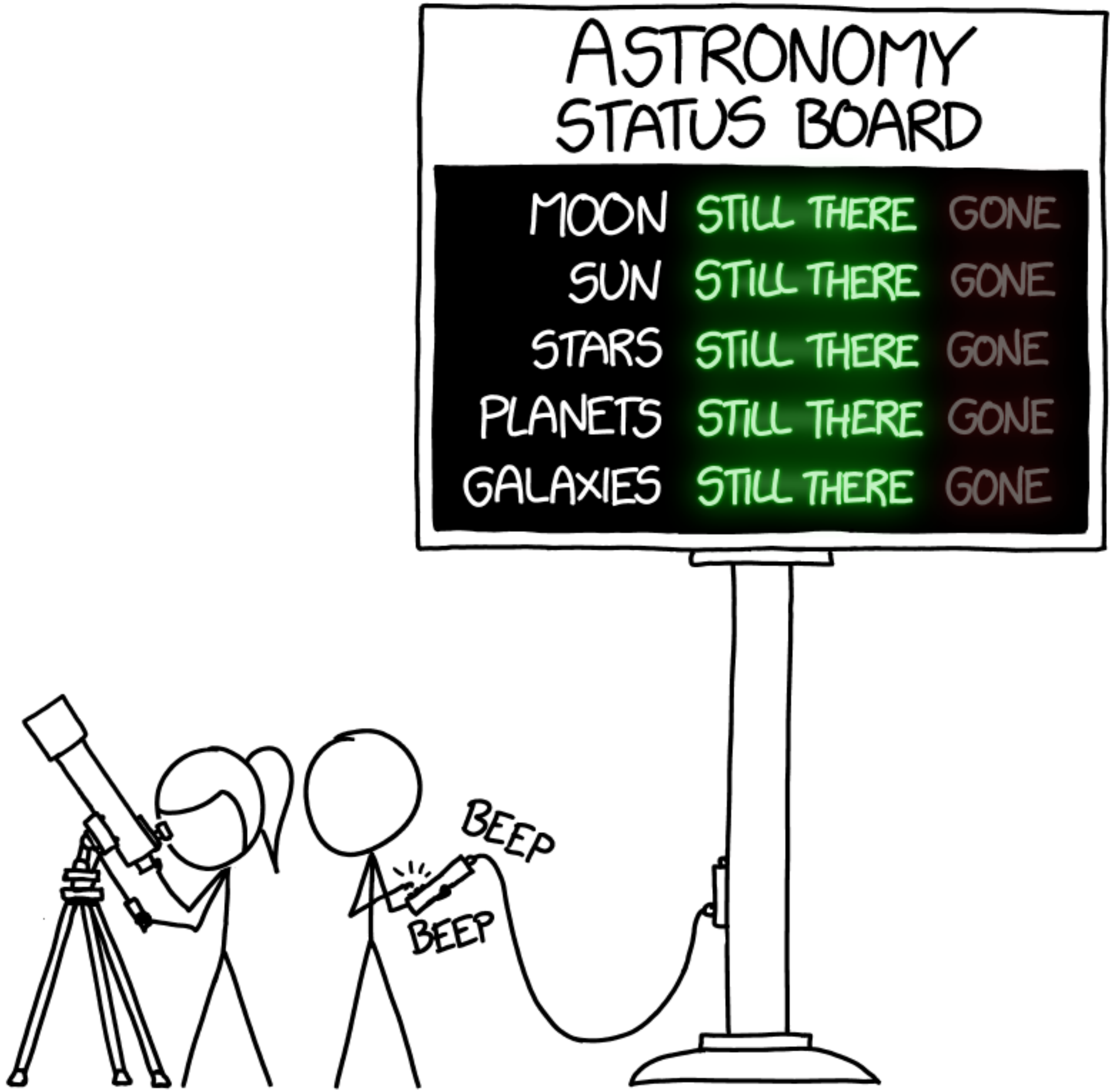
Dr. Devontae Baxter

Lecture 6

Thursday, October 16, 2025

Announcements

- Coding exercise #2 due **Sunday, 10/19 by 11:59 pm via Datahub** (this one is a little more involved).
- A Midterm review will take place on Monday during the discussion.
- The study guide form Midterm I is in the Week 4 Module on Canvas.
- **Homework #3 due Tuesday, 10/21 by 11:59 pm via Gradescope.**
- Remember that **SERF 329** is reserved for ASTR 20A study session on Mondays from 4-6pm.
- I *highly recommend* that you use this space to work together on the homework.




Questions?

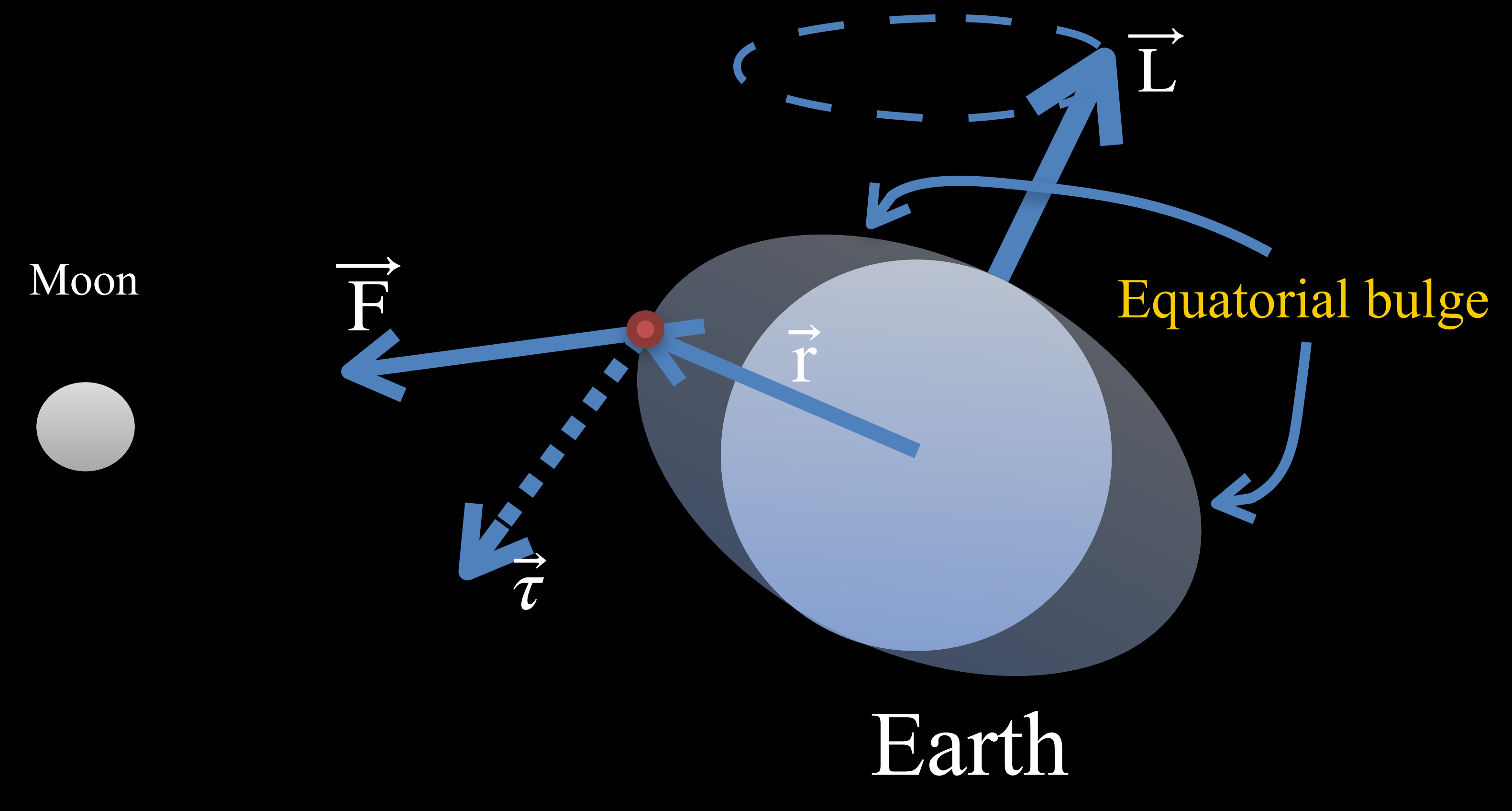
Recap of Lecture 6

In the previous lecture, we discussed orbital energies, orbital speed, and the dynamics of the Earth-Moon system. The key concepts that we discussed were:

Conservation of energy in a two-body isolated system + relationship between total orbital energy and orbit shape.

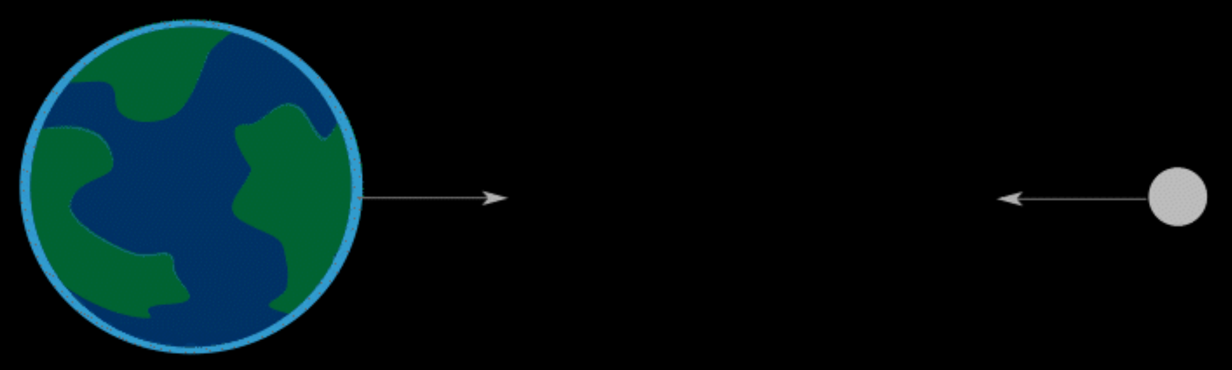
Eccentricity	Energy	Orbit shape
$e = 0$	$E < 0$	circular
$0 < e < 1$	$E < 0$	elliptical
$e = 1$	$E = 0$	parabolic
$e > 1$	$E > 0$	hyperbolic

The role of the Moon in driving the precession of the Earth.



The impact of tidal forces in the Earth-Moon system.

$$\Delta F_{\mathrm{Moon}}(r_1) = -\frac{2GM_{\mathrm{Moon}}mR_{\oplus}}{r_0^3}$$

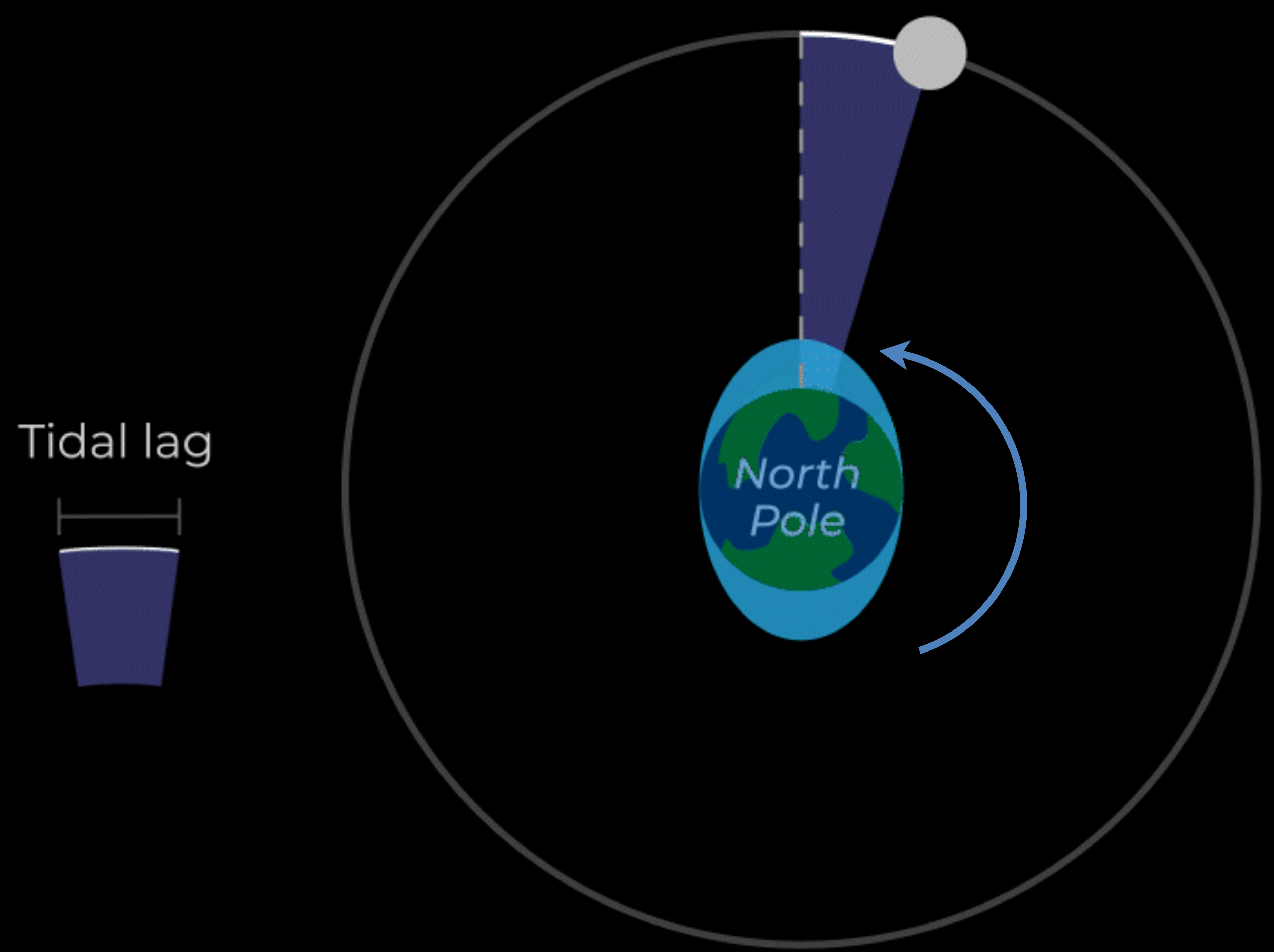


$$\Delta F_{\mathrm{Moon}}(r_2) = \frac{2GM_{\mathrm{Moon}}mR_{\oplus}}{r_0^3}$$

Today, we will discuss conclude our discussion of the Earth-Moon system and dive into the interaction of matter and radiation!

Tides lead the Moon's upper transit

Due to friction between the slowly rotating tidal bulges and the more rapidly rotating Earth, the bulges are dragged forward by ~10 degrees.

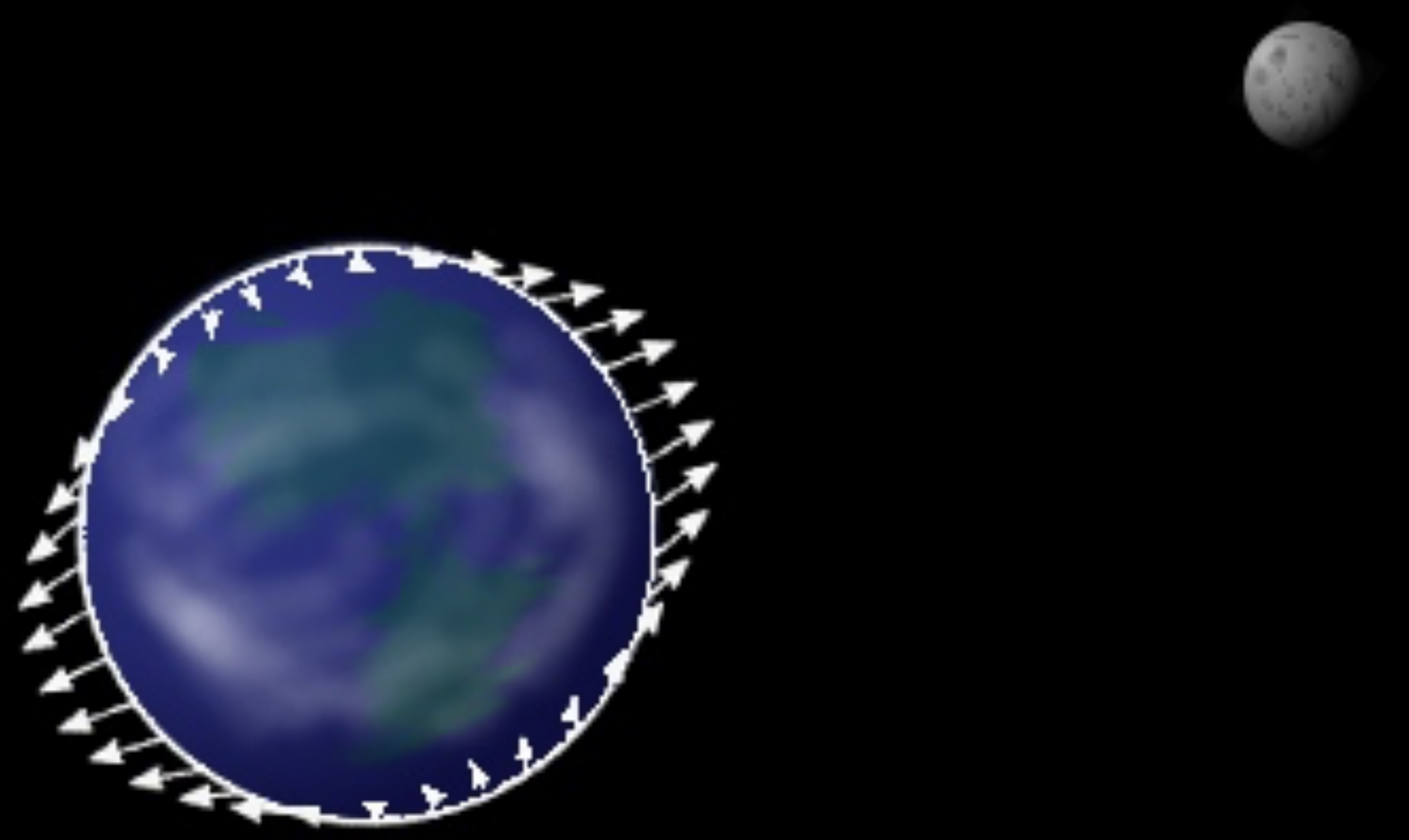


This misalignment causes observers on Earth will see the Moon make an upper transit about 40 minutes *before* ***high tide.***

Since the Earth's tidal bulges aren't aligned with the Moon's position, the high tide bulges are never directly lined up with the Moon, but a little ahead of it.

The Moon is slowing down the Earth

In the past the Moon was much closer to the Earth. It is slowing down since the Moon is pulling slightly strongly on the nearer side of the tidal bulge, causing a net torque on the Earth.

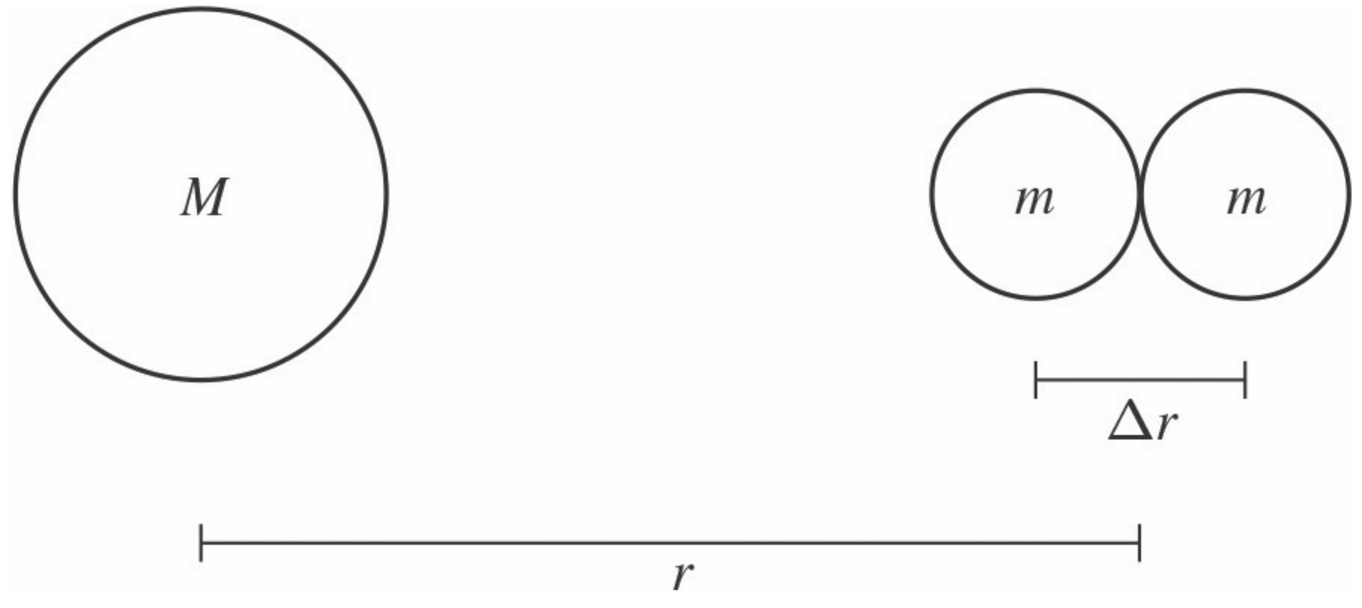


This torque slows the rotation of the Earth, and is referred to as “**tidal braking**”.

Moon gains angular momentum → Earth rotates slower.

How small can an orbit be?

Objects are held together by their own self-gravity. **What if a small mass is close to a bigger mass, how close can they get before the small mass is pulled apart?**



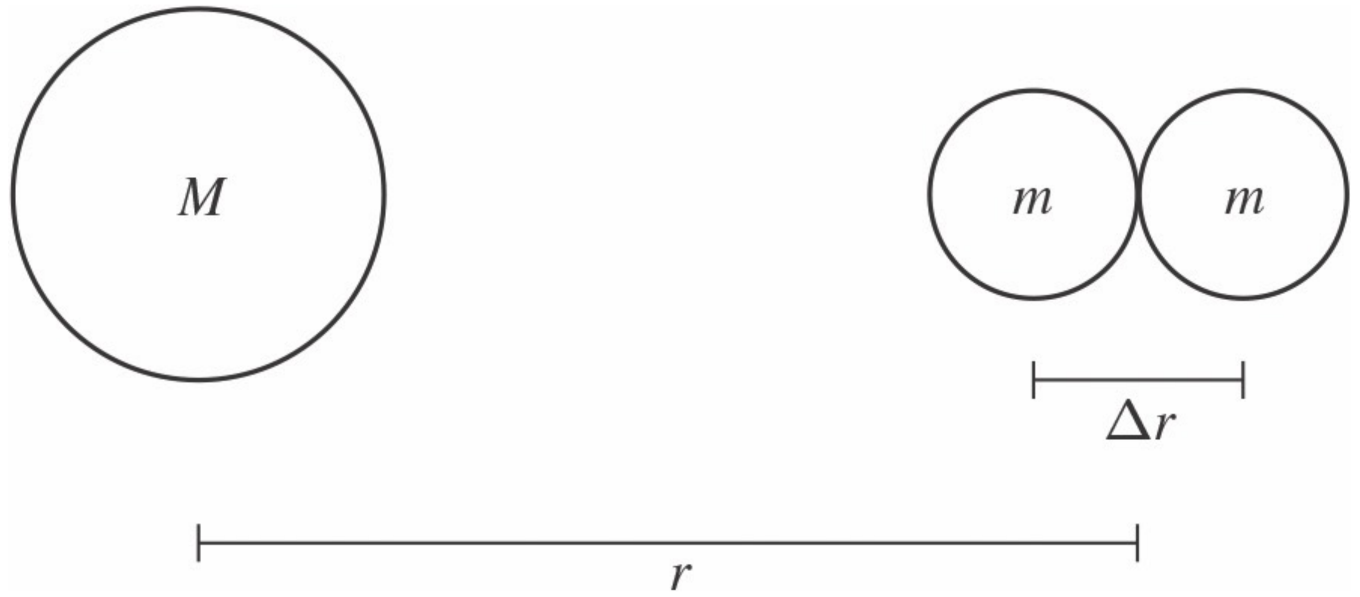
Need to know the differential force from the 2 masses

$$\Delta F = \frac{dF}{dr}\Delta r = \frac{2GMm}{r^3}\Delta r$$

The self-gravity holding the two masses together

$$F = -\frac{Gmm}{(\Delta r)^2}$$

How small can an orbit be?



We can keep decreasing the distance r until we reach a critical distance called the "**Roche limit**" (***r*$_\mathbf{R}$**), where the **tidal forces from the larger body become stronger than the self-gravity** holding the smaller object together, causing it to be pulled apart.

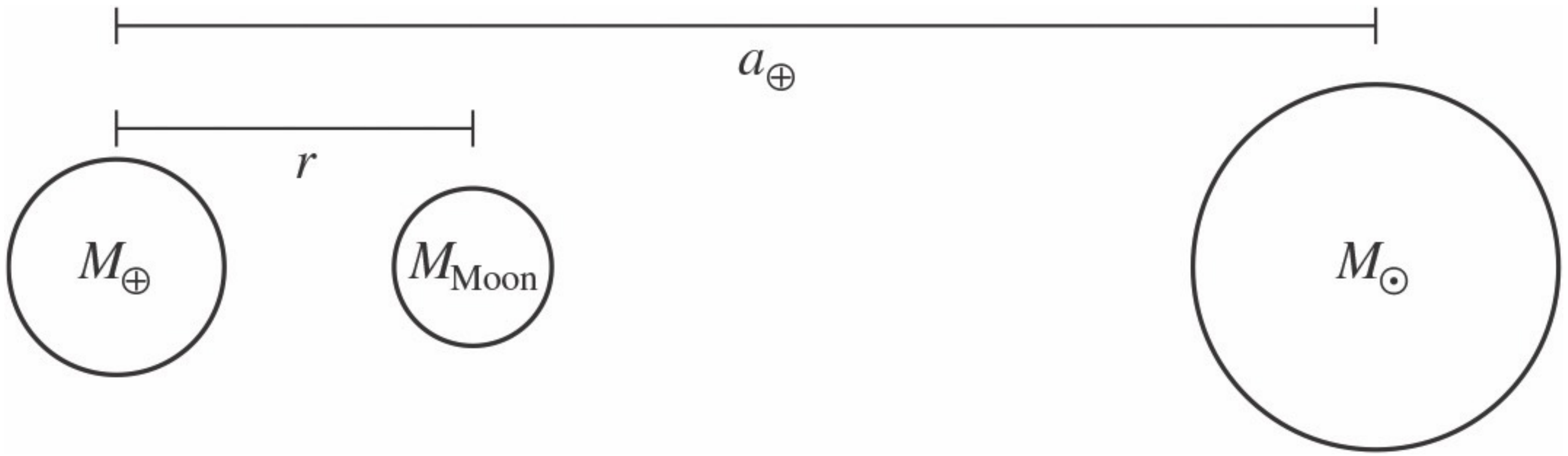
$$\frac{2\mathrm{GMm}}{r_{\mathrm{R}}^3}\Delta r = \frac{Gmm}{(\Delta r)^2}$$

$$r_R = \left(\frac{2M}{m}\right)^{\frac{1}{3}} \Delta r$$

How big can an orbit be?

There is a region around an object where its **own gravity dominates** over the gravitational influence of a more massive body — this defines its **Hill radius**.

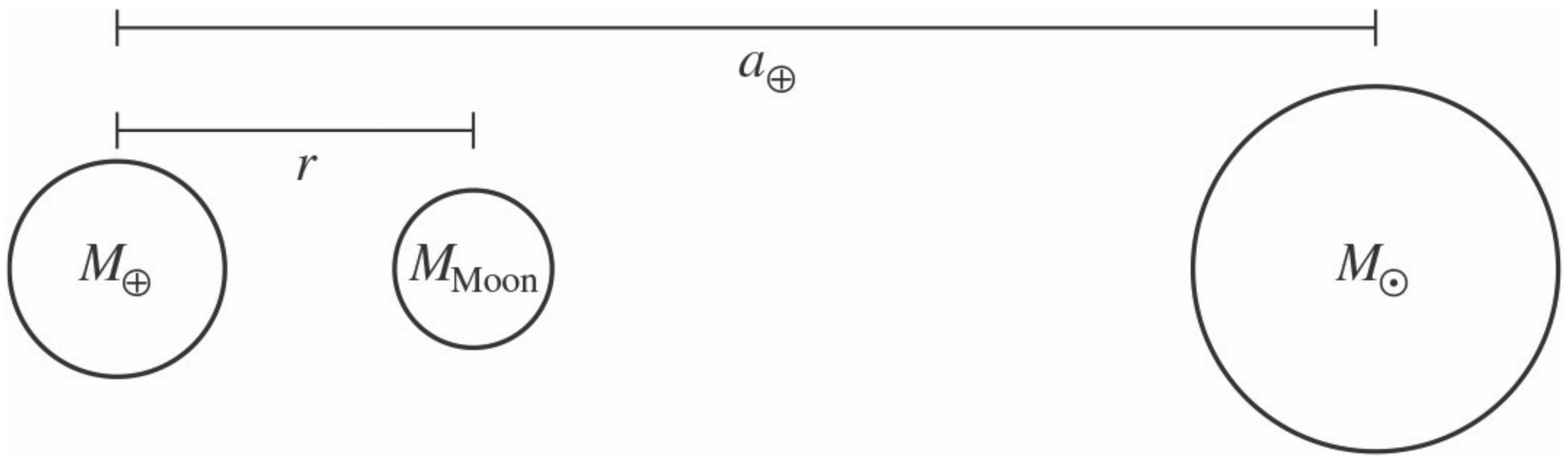
For example, in the Earth–Moon–Sun system, we can compare:



Consider the Earth's acceleration due to the Sun and the Moon's acceleration due to the Sun.

$$\Delta g = g_{Moon} - g_\oplus = \frac{GM_\odot}{\left(a_\oplus - r\right)^2} - \frac{GM_\odot}{a_\oplus^2}$$

How big can an orbit be?



Since $r \ll a_\oplus$ we can make approximations and arrive at

$$\Delta g \approx \frac{GM_\odot}{a_\oplus^2}\left(1 - \frac{2r}{a_\oplus}\right) - \frac{GM_\odot}{a_\oplus^2} \approx \frac{2GM_\odot r}{a_\oplus^3}$$

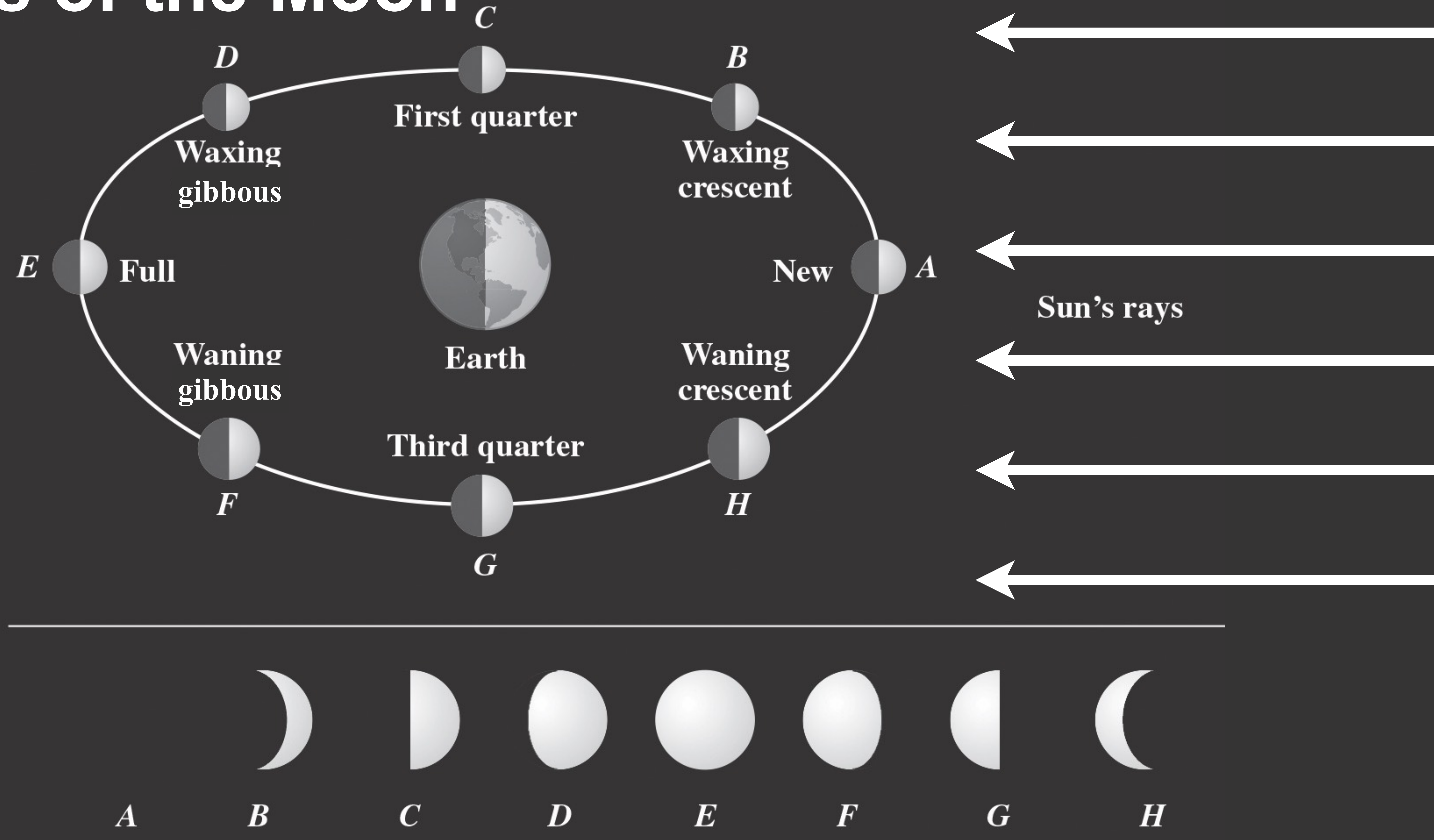
As r increases, so does Δg. Once we get to where Δg is equal to the Moon's acceleration due to Earth we have

$$\frac{2GM_\odot r_H}{a_\oplus^3} = \frac{GM_\oplus}{r_H^2} \xrightarrow{\textbf{Hill Radius}} r_H = \left(\frac{M_\oplus}{2M_\odot}\right)^{\frac{1}{3}} a_\oplus$$

Inside this radius**, satellites or moons can remain gravitationally bound** to the smaller body despite the pull of the larger

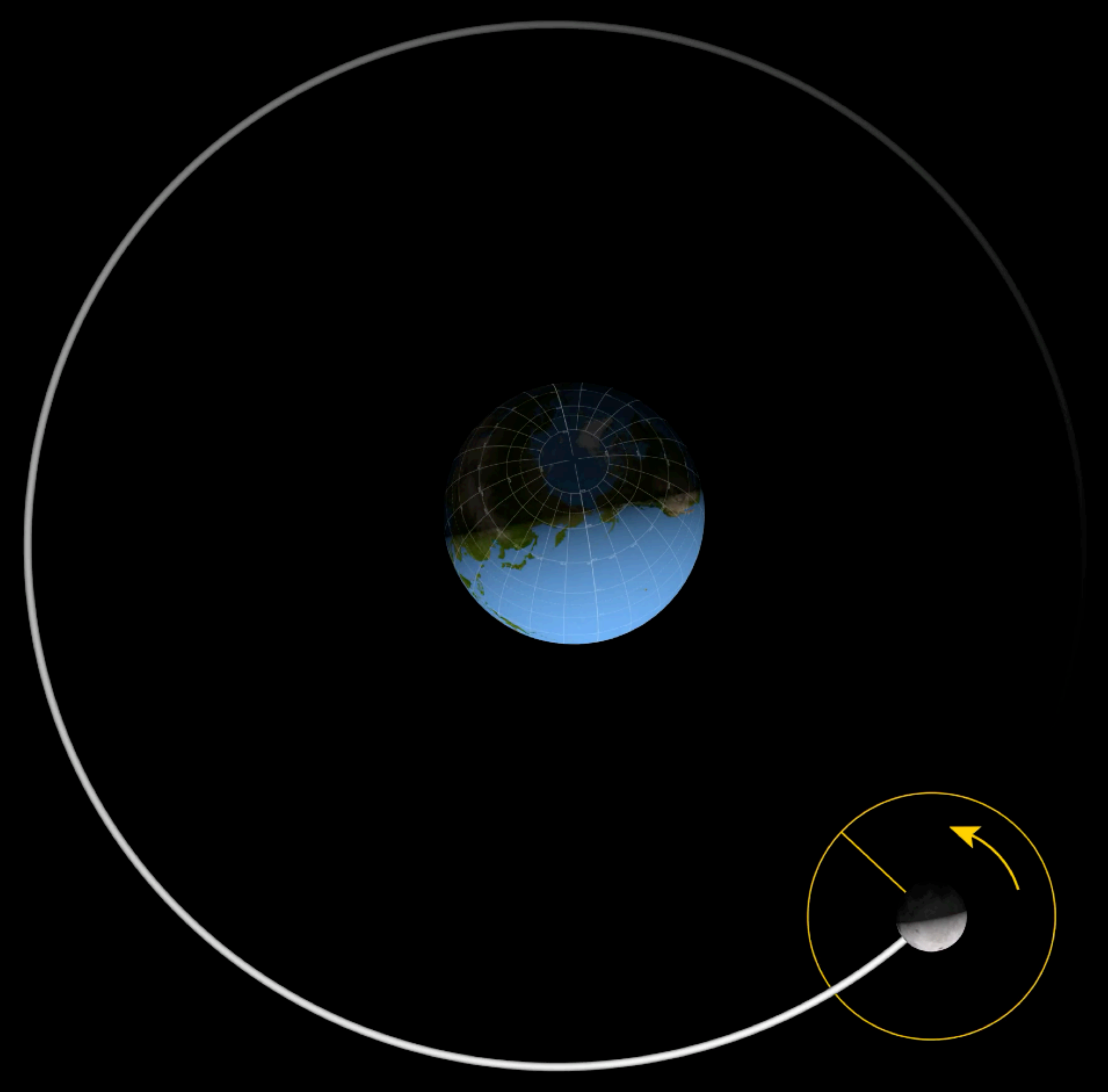

Questions?

Phases of the Moon



Synchronous Rotation

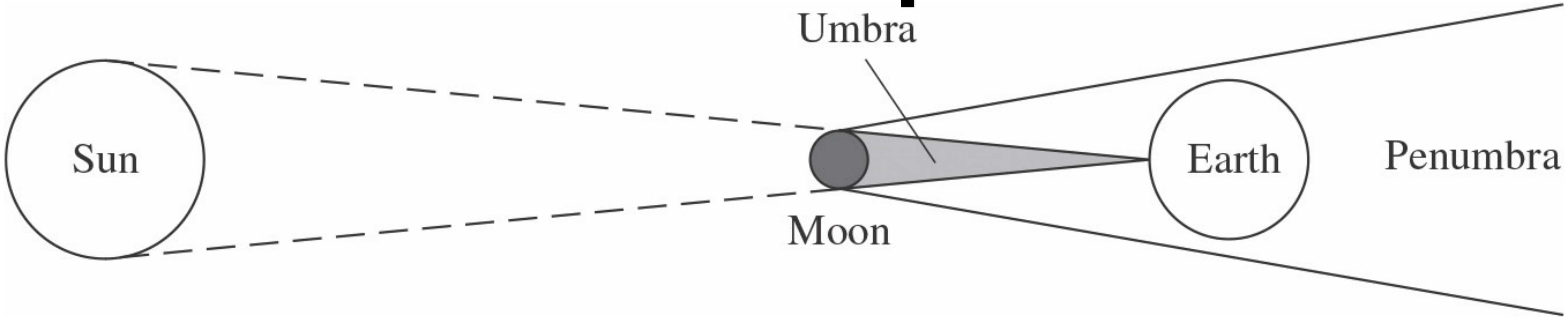
The Earth's gravity pulls on the Moon's tidal bulges, creating a torque that gradually slows the Moon's rotation. Over time, this process *synchronizes* the Moon's **rotation with its orbit,** so the same side always faces Earth.



In short, tidal forces from Earth have slowed the Moon's rotation until its rotation period matches its orbital period.

Questions?

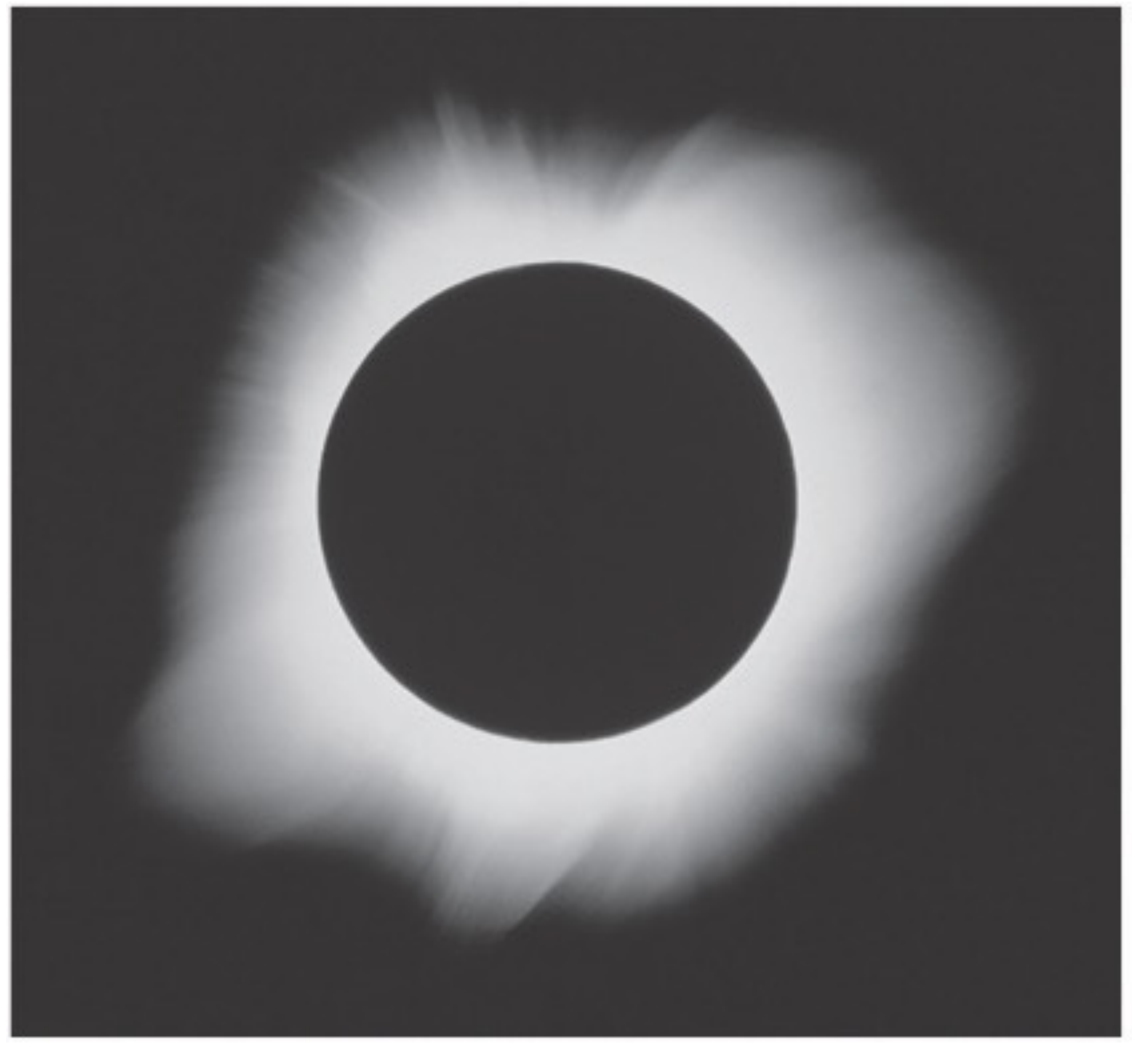
Solar Eclipses



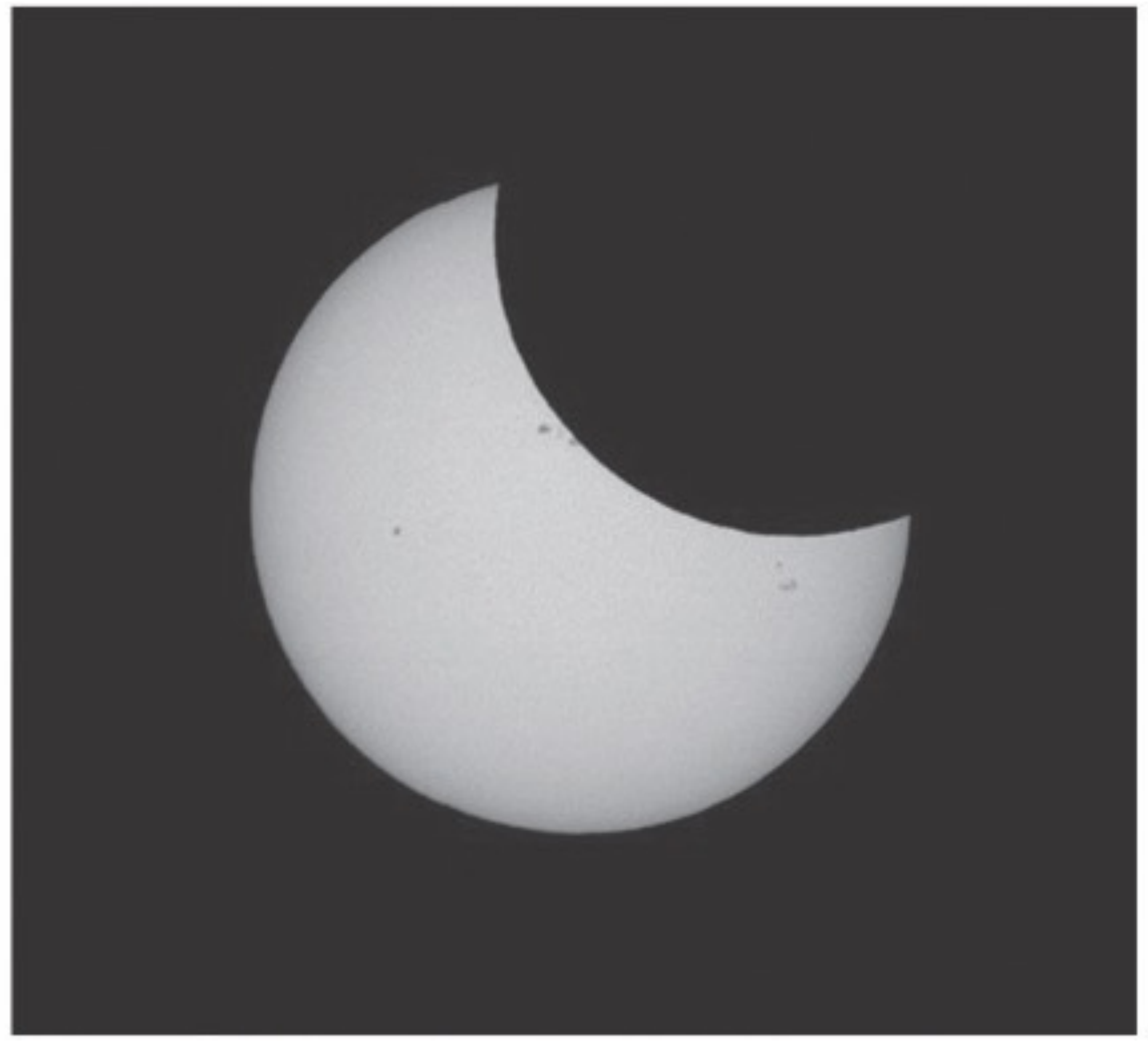
Occurs when the Moon goes between Earth and the Sun.

Umbra: Inner region of the shadow.

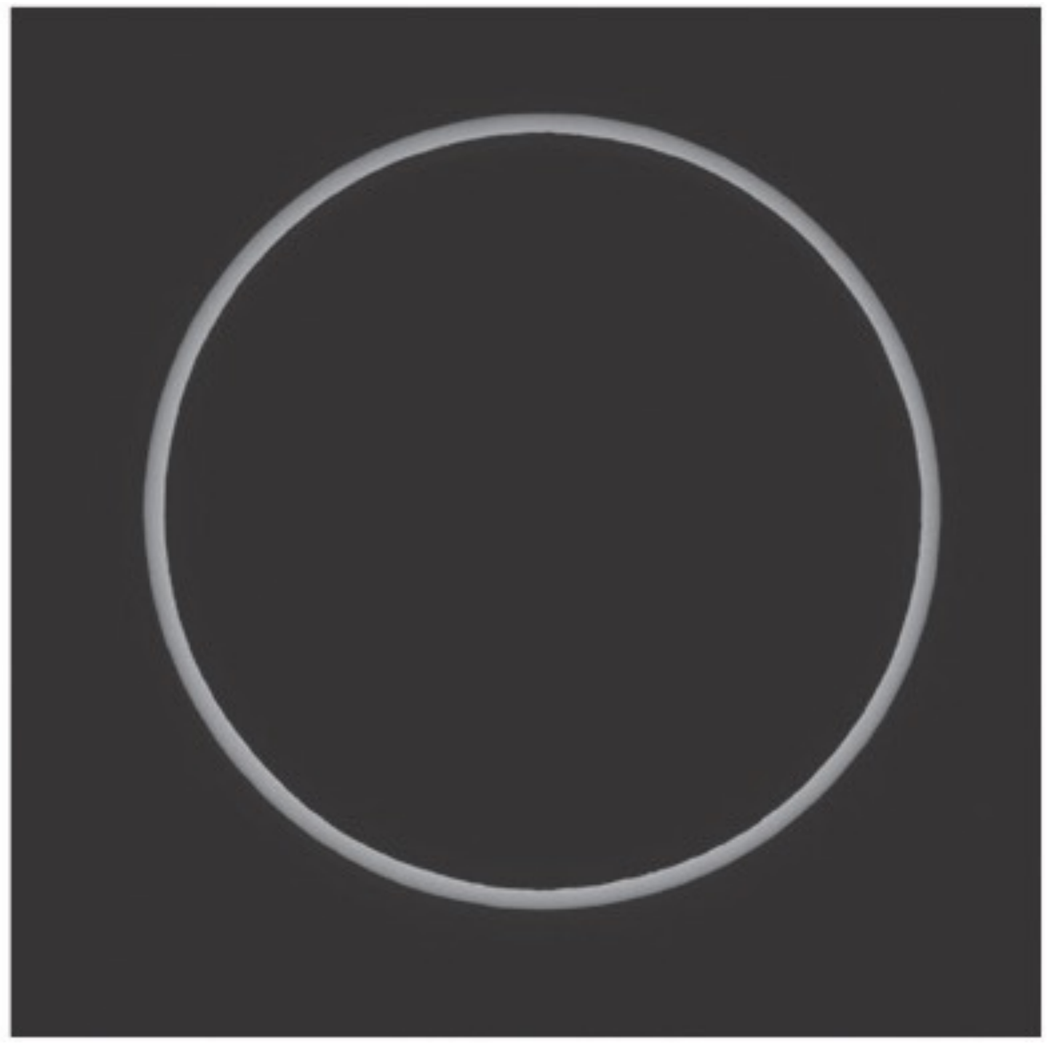
Penumbra: Outer region of the shadow.



Total Solar Eclipse

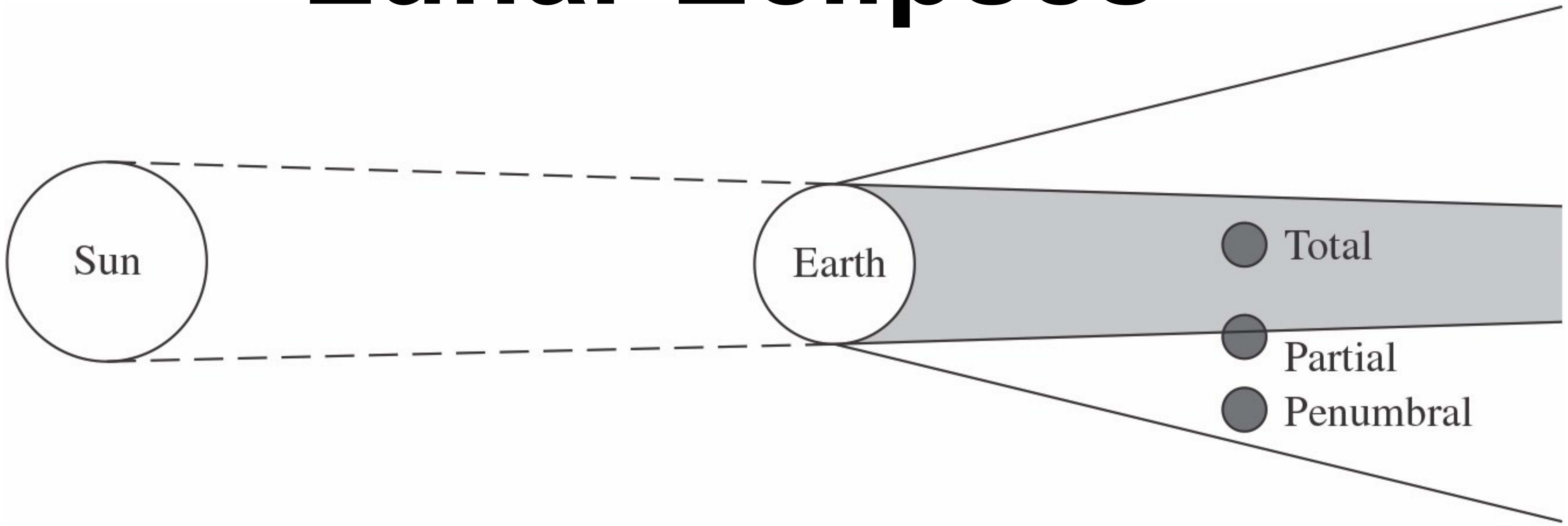


Partial Solar Eclipse



Annular Eclipse

Lunar Eclipses



Occurs when <u>the Moon pass through Earth's shadow</u>

Total Lunar Eclipse

Partial Lunar Eclipse

Penumbral Lunar Eclipse

2026 Aug 12
2021 Jun 10
2021 Jun 10
2030 Jun 01
2024 Apr 08
2023 Oct 14
2024 Apr 08
2023 Oct 14
2027 Aug 02
2028 Jan 26
2028 Jul 22
2024 Oct 02
2027 Feb 06
2023 Apr 20
2030 Nov 25
2026 Feb 17
2021 Dec 04
Total Eclipse
Annular Eclipse
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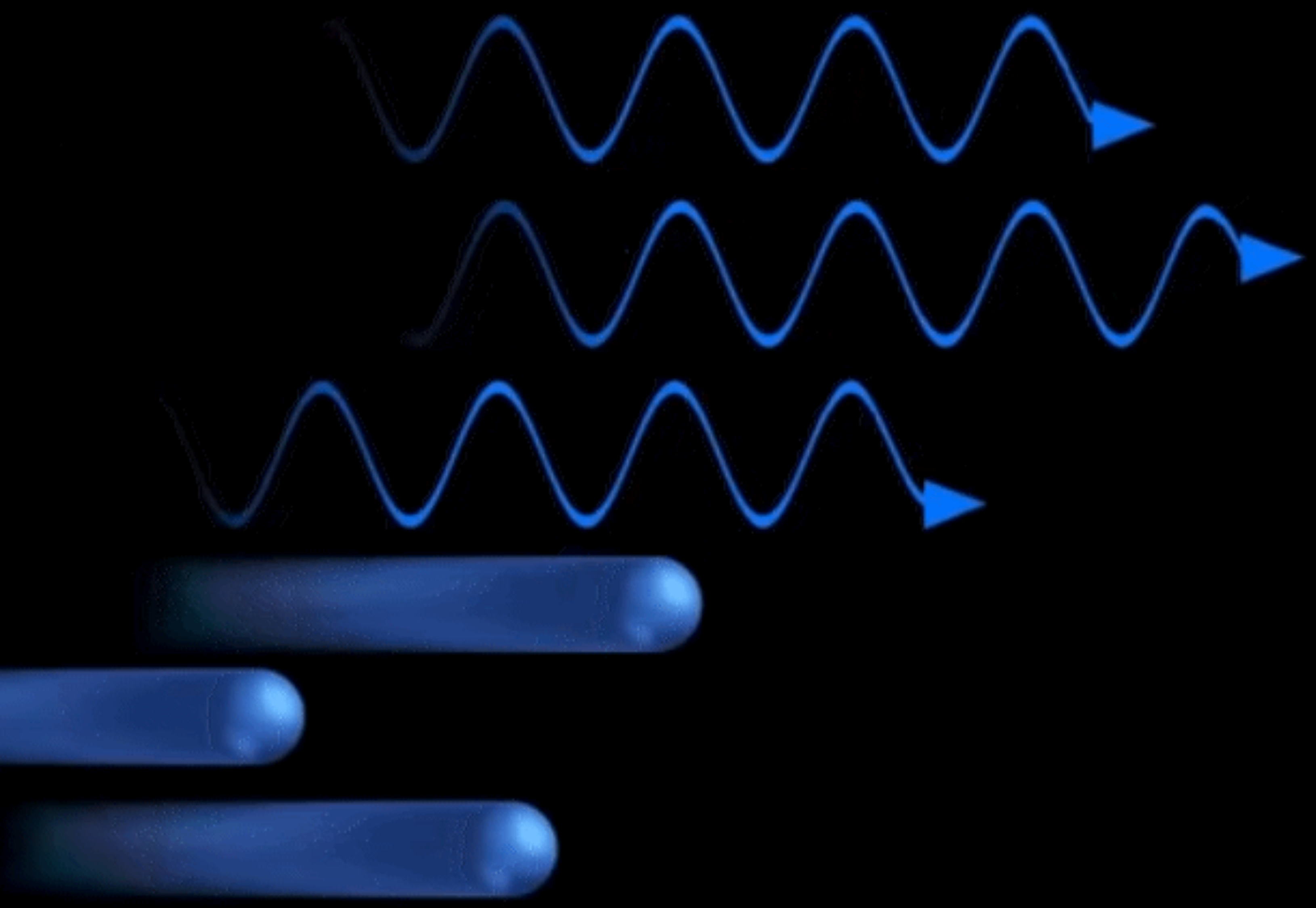
Questions?

Interaction of Matter & Radiation

Our understanding of the cosmos is *almost entirely* derived from capturing and analyzing light!

Light exhibits a fascinating property in which it can be described as being made of electromagnetic waves *and* a stream of massless particles known as photons.

The "wave-particle duality"

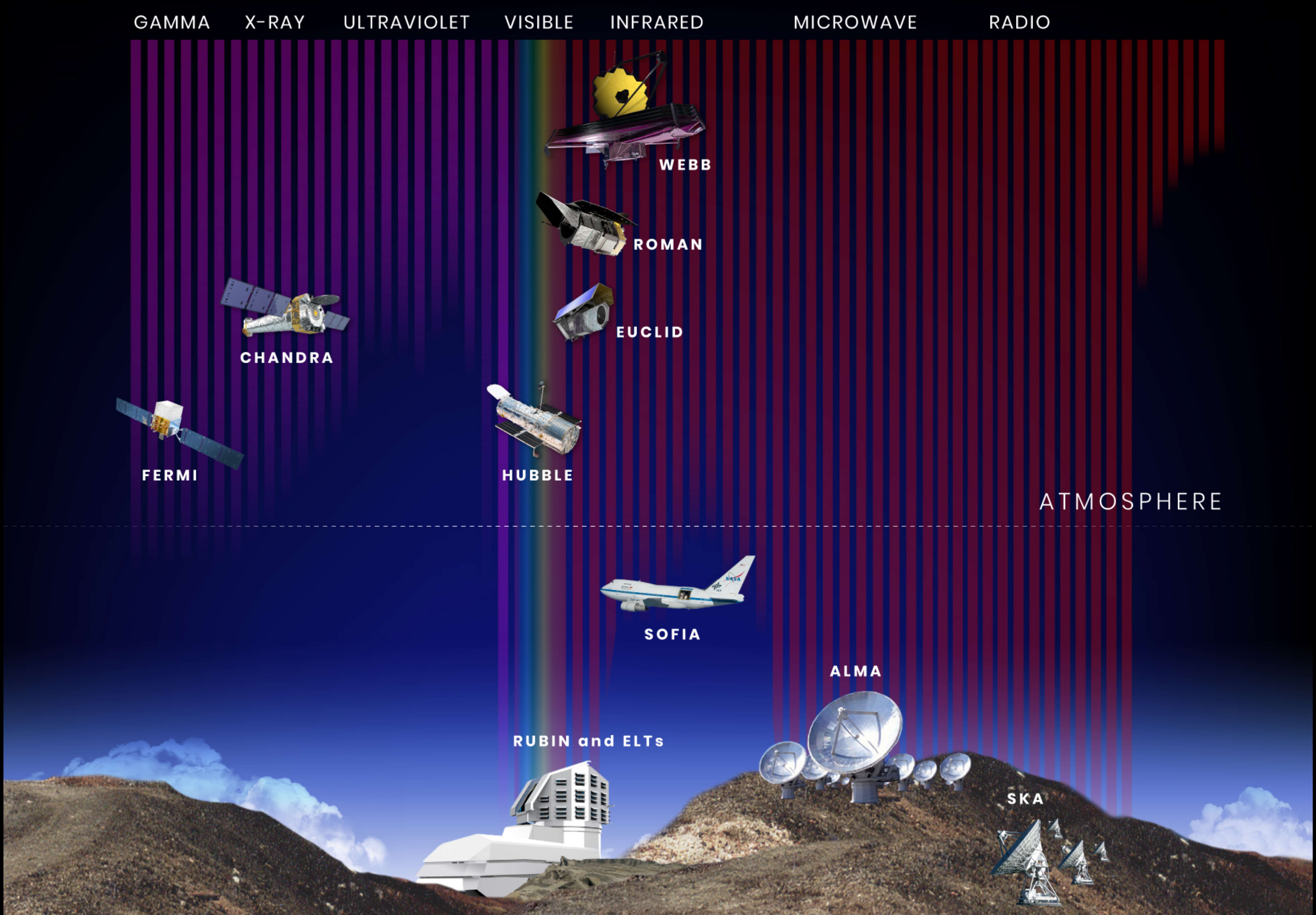


Electromagnetic waves are characterized by their wavelength λ, or frequency $\nu = \dfrac{c}{\lambda}$

Photons are characterized by their energy $E = h\nu$, where $h = 6.626 \times 10^{-34}\ \mathrm{J\ s} = 4.135 \times 10^{-15}\ \mathrm{eV\ s}$

$1\ \mathrm{eV} = 1.602 \times 10^{-19}\ \mathrm{Joules}$

Swift
Fermi
Chandra
NuSTAR
GALEX
Kepler
Euclid
Hubble
JWST
Spitzer
Roman
Herschel
Planck
Spektr-R
gamma ray
X-ray
ultraviolet
visible
infrared
microwave
radio
SOFIA
Keck
SALT
Gemini
HESS
CARMA
Greenbank
VLA



GAMMA
X-RAY
ULTRAVIOLET
VISIBLE
INFRARED
MICROWAVE
RADIO
WEBB
ROMAN
EUCLID
CHANDRA
FERMI
HUBBLE
ATMOSPHERE
SOFIA
ALMA
RUBIN and ELTs
SKA

Atomic Structure (Bohr Model)

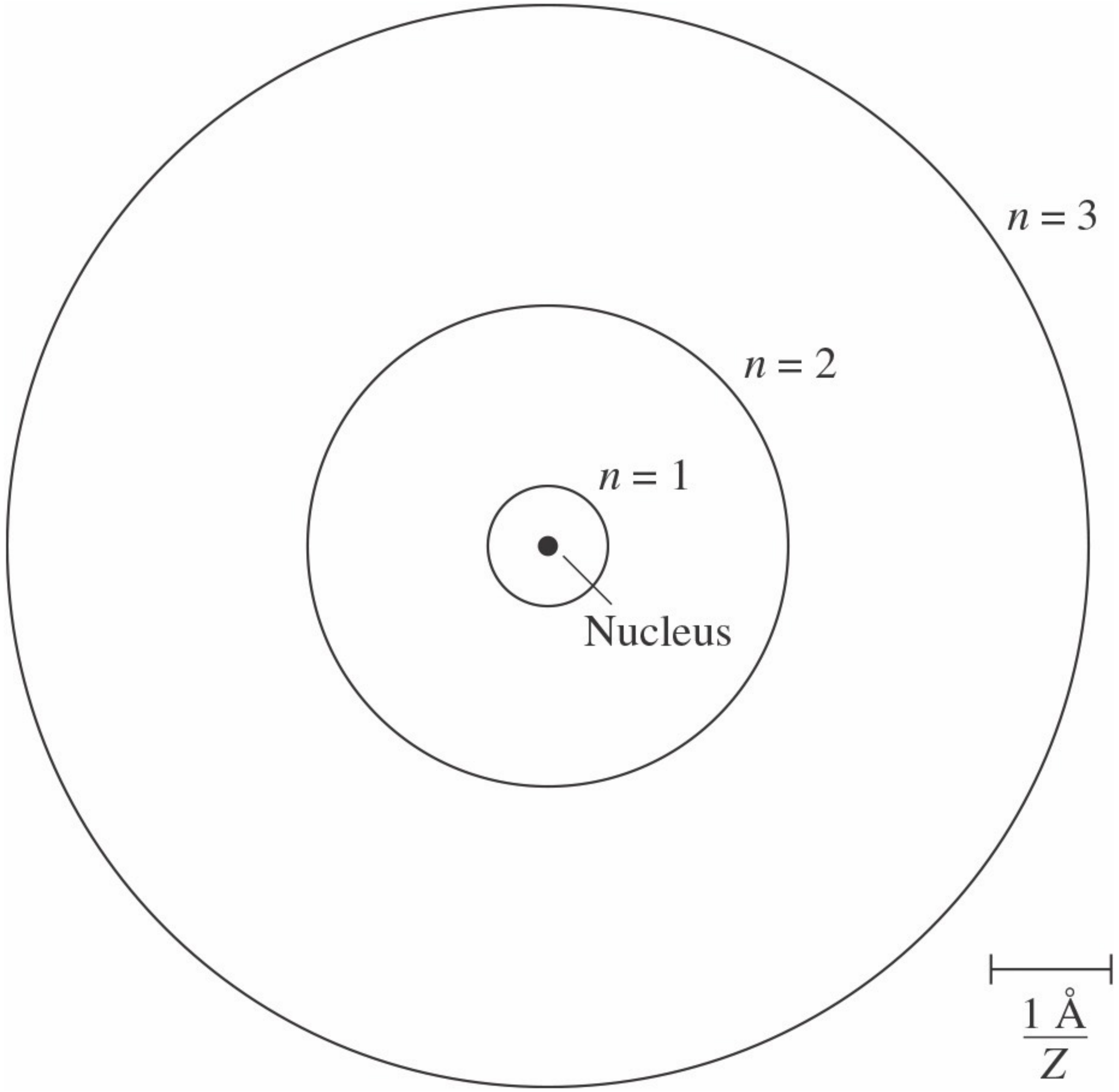
The Bohr model of the atom is characterized by negatively charged electrons of mass m_e orbiting a nucleus composed of Z positively charged protons of mass m_e and some number of neutrally charged neutrons of mass m_n.

In Bohr's model, the electron travels on a circular orbit and experiences a centripetal force given by:

$$F_{\text{centripetal}} = -\frac{m_e v^2}{r}$$

It also feels a coulomb force given by:

$$F_{\text{coulomb}} = -\frac{(Ze)e}{4\pi\epsilon_0 r^2}$$



Atomic Structure (Bohr Model)

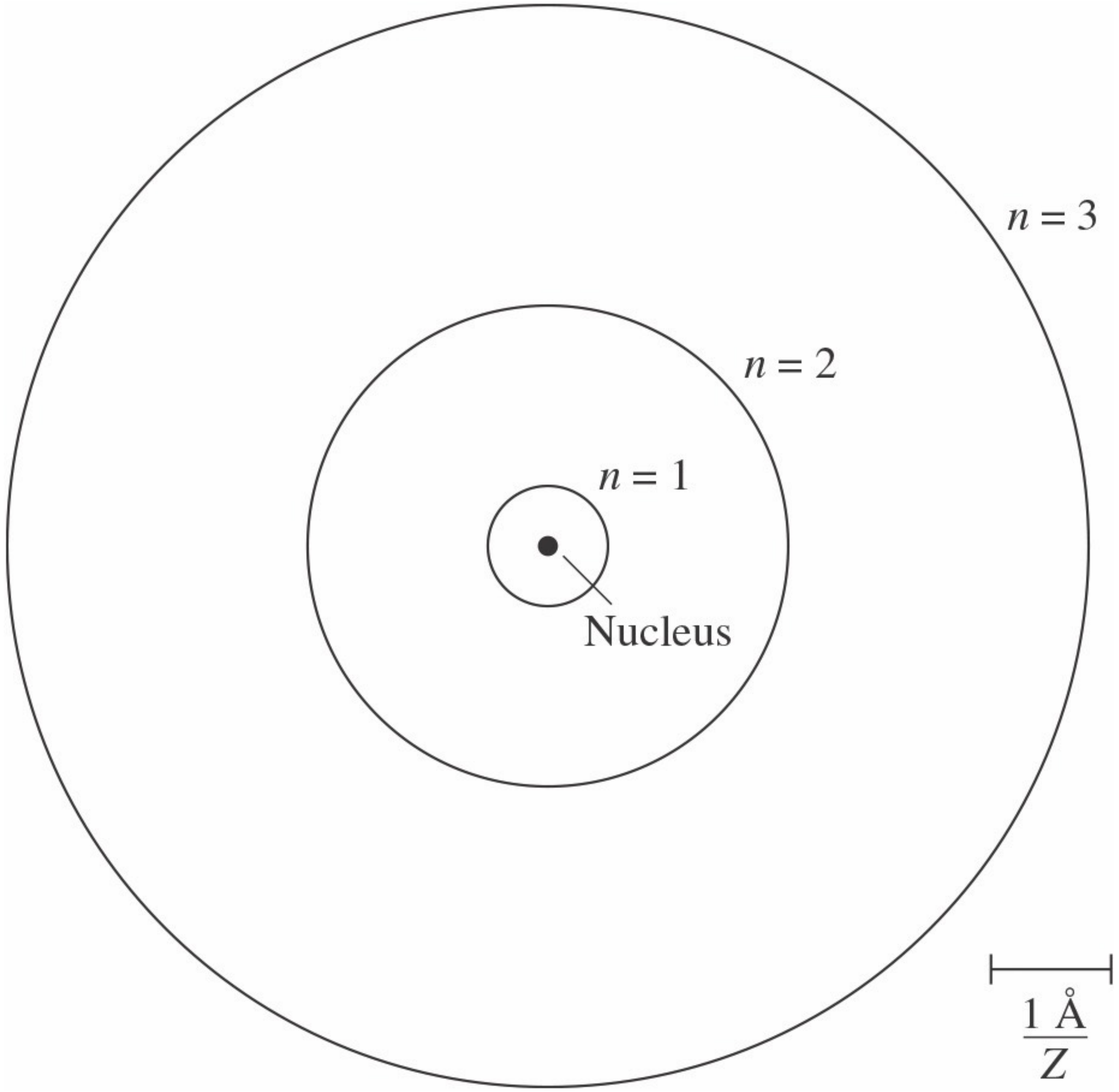
Balancing the centripetal and Coulomb forces and solving for the velocity:

$$-\frac{Ze^2}{4\pi\epsilon_0 r^2} = -\frac{m_e v^2}{r} \longrightarrow v^2 = \frac{Ze^2}{4\pi\epsilon_0 m_e r}$$

$$K = \frac{1}{2}m_e v^2 = \frac{Ze^2}{8\pi\epsilon_0 r} \text{ (Kinetic energy)}$$

$$U = -\frac{Ze^2}{4\pi\epsilon_0 r} \text{ (Potential energy)}$$

$$E = K + U = \frac{Ze^2}{8\pi\epsilon_0 r} - \frac{Ze^2}{4\pi\epsilon_0 r} = -\frac{Ze^2}{8\pi\epsilon_0 r}$$



Energy is quantized!

Atomic Structure (Bohr Model)

Recall,

$$m_e v^2 = \frac{Ze^2}{4\pi\epsilon_0 r}$$

Angular momentum for the e^-:

$$L = m_e v r = \frac{nh}{2\pi} = n\hbar \quad \text{(quantized!)}$$

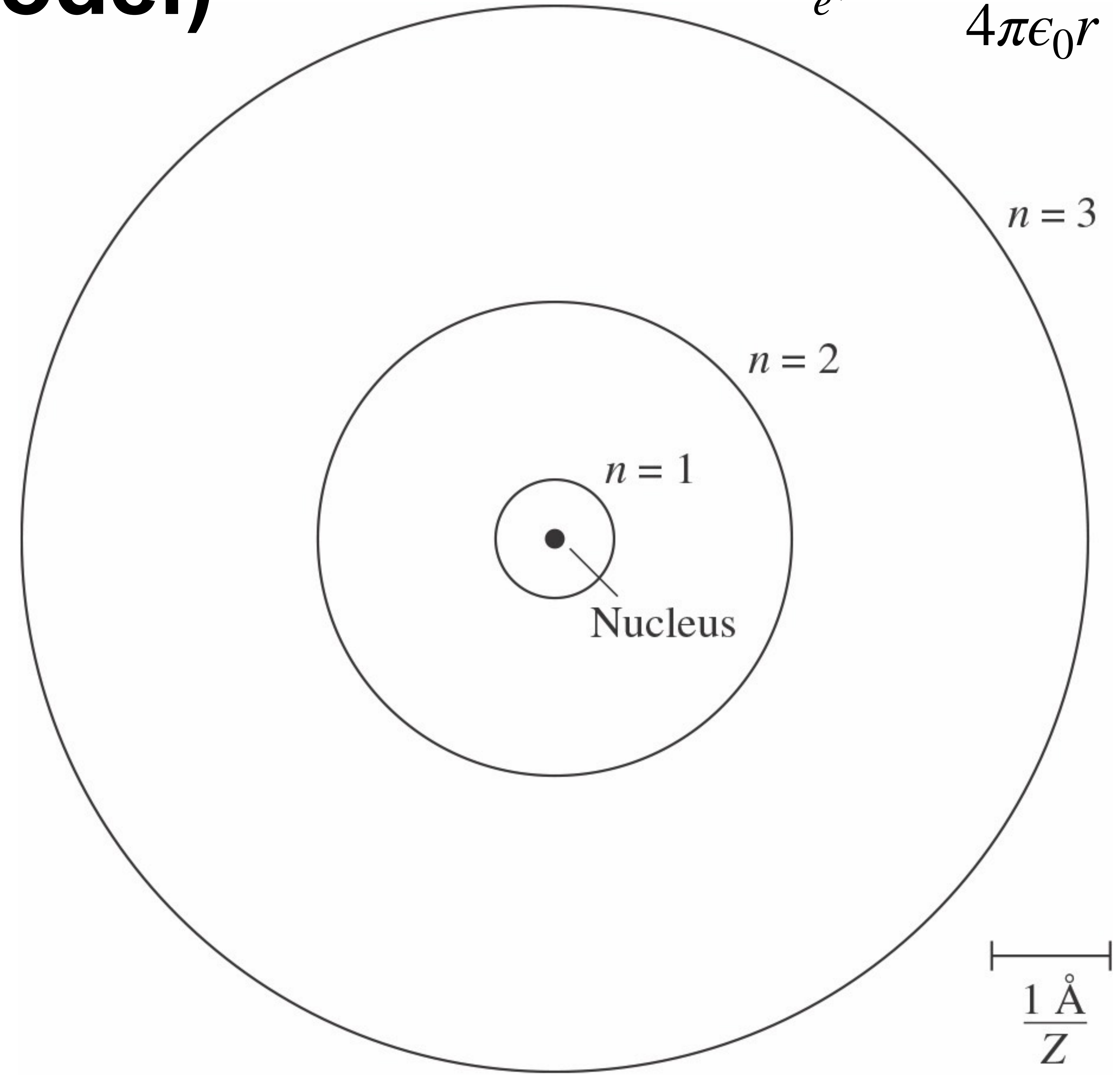
Squaring both sides:

$$m_e^2 v^2 r^2 = n^2\hbar^2$$

Substituting & solving for the orbital radius r:

$$r_n = \frac{4\pi\epsilon_0\hbar^2}{Ze^2 m_e} n^2 \quad \text{(quantized)}$$

$$r_n = \frac{5.29\times 10^{-11}\ \text{m}}{Z} n^2 = \frac{0.529\ \text{Å}}{Z} n^2$$



$$1\ \text{Å} \equiv 1\times 10^{-10}\ \text{m}$$

Atomic Structure (Bohr Model)

Recall, $r_n = \dfrac{4\pi\epsilon_0\hbar^2}{Ze^2m_e}n^2$

Substituting the expression for r_n, we see that the quantized energy level for the e^- is:

$$E_n = -\frac{Ze^2}{8\pi\epsilon_0 r_n} = -\frac{Z^2e^4m_e}{32\pi^2\epsilon_0^2\hbar^2n^2}$$

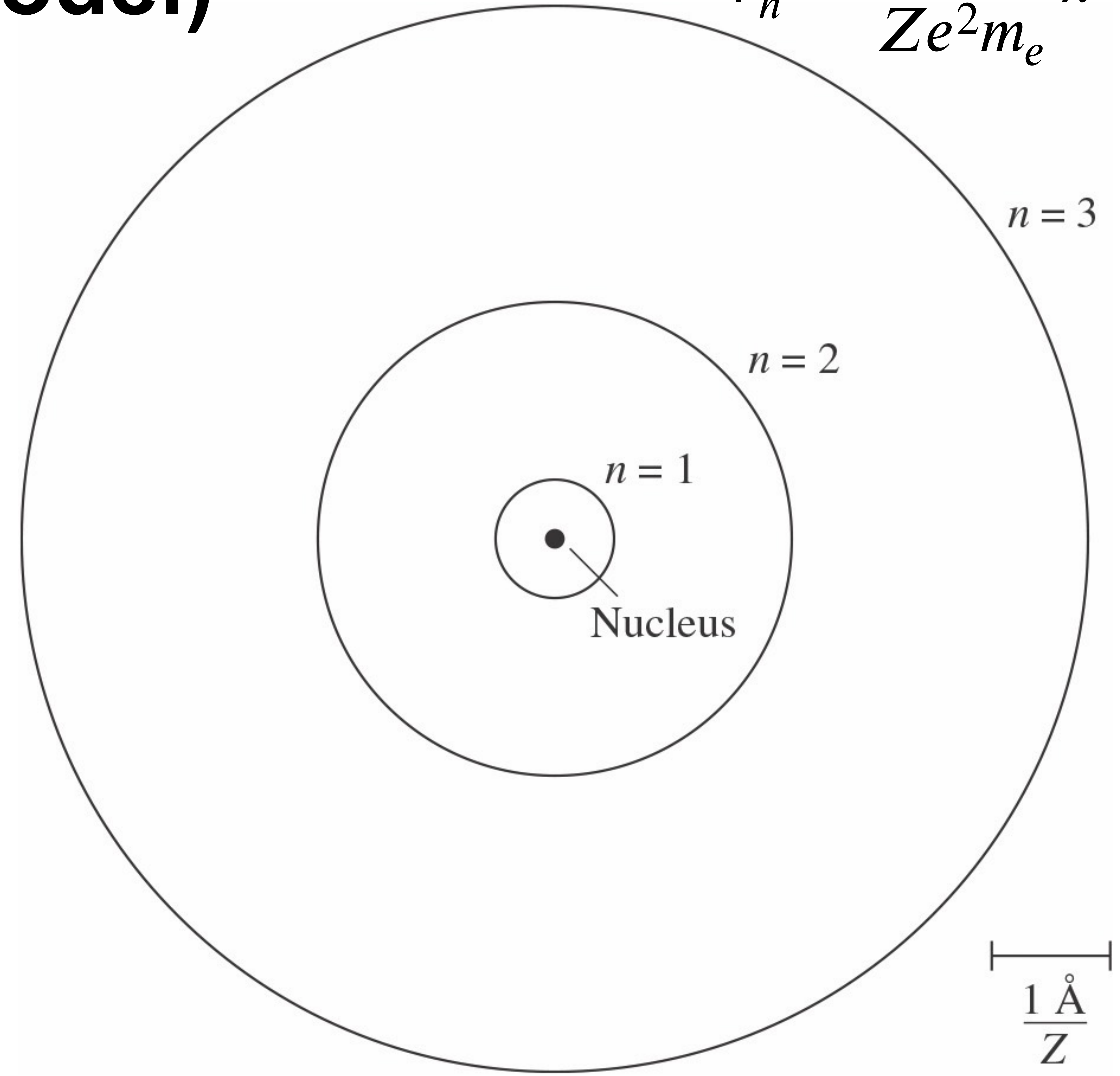
$$E_n \approx = -13.6\ \text{eV}\ \frac{Z^2}{n^2}$$

In the case of Hydrogen Z = 1

Since the electron is moving in a circle, it is also accelerating, which means it is radiating at a rate:

$$P = \frac{2}{3}\frac{e^2}{4\pi\epsilon_0}\frac{a^2}{c^3} = \frac{2}{3}\hbar\alpha\frac{a^2}{c^2}$$

Where α is is the fine-structure constant



Atomic Structure (Bohr Model)

The acceleration of the e^- is:

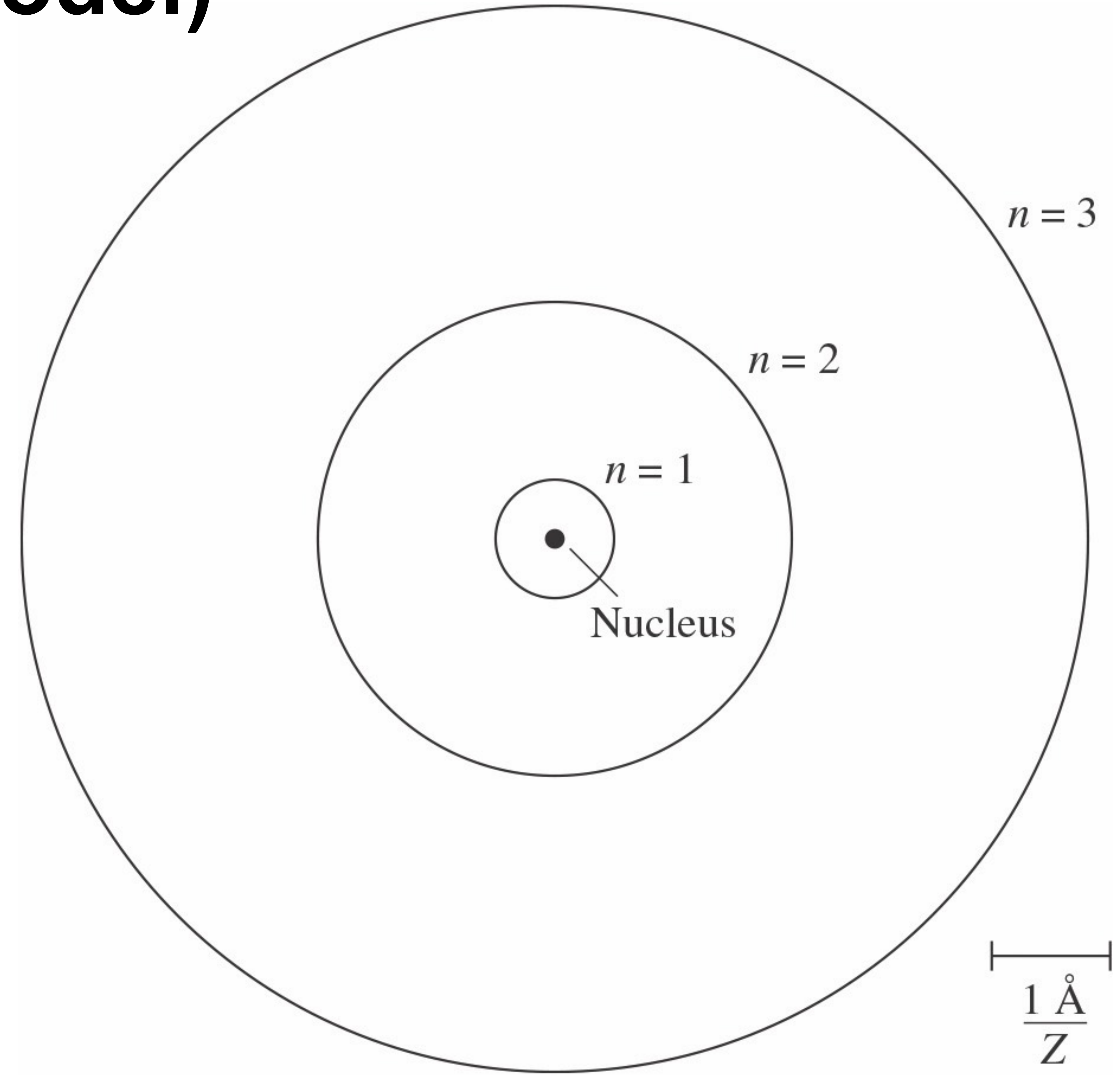
$$a = \frac{v^2}{r} = \frac{Ze^2}{4\pi\epsilon_0}\frac{1}{m_e r^2} = \frac{Z\alpha\hbar c}{m_e r^2}$$

Plugging in r_n gives us:

$$a = \frac{Z\alpha\hbar c}{m_e}\frac{m_e^2 c^2 \alpha^2 Z^2}{\hbar^2 n^4} = \frac{Z^3\alpha^3 m_e c^3}{\hbar n^4}$$

And the power radiated becomes

$$P = \frac{2}{3}\alpha^7 \frac{\left(m_e c^2\right)^2}{\hbar}\frac{Z^6}{n^8}$$



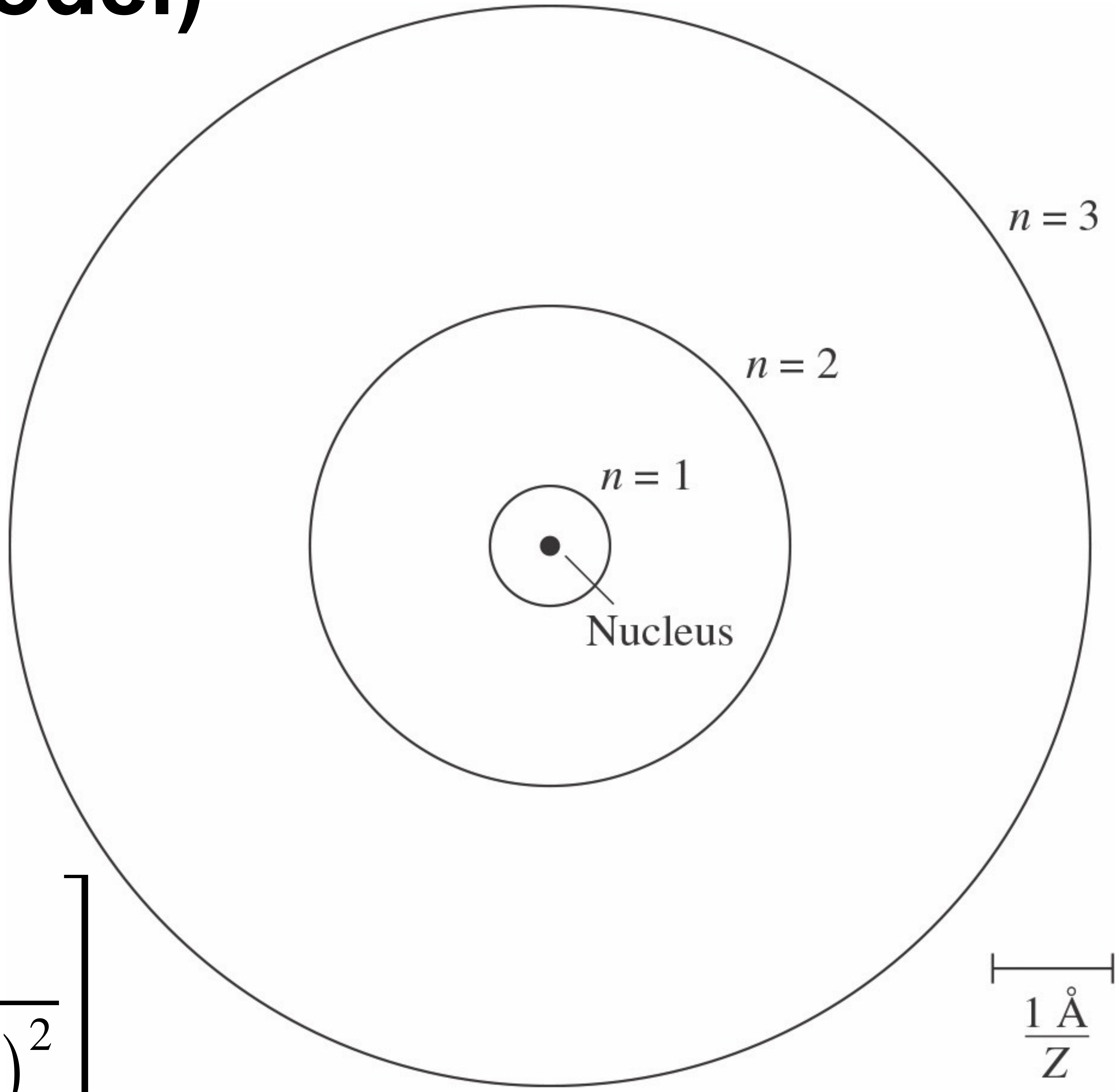
Atomic Structure (Bohr Model)

In higher energy states ($n > 1$) the lifetime of the orbit (τ) is:

$$\tau \approx \frac{E}{\left(\frac{dE}{dt}\right)} = \frac{E_n}{P} = \frac{3}{4}\frac{1}{\alpha^5}\frac{\hbar}{m_e c^2}\frac{n^6}{Z^4}$$

We can calculate the change in energy from state n_1 to n_2 ($n_1 > n_2$)

$$\Delta E = E_{n_1} - E_{n_2} = \frac{\overset{13.6\text{ eV}}{\boxed{m_e c^2}}}{2}\alpha^2 Z^2\left[\frac{1}{(n_2)^2} - \frac{1}{(n_1)^2}\right]$$



Atomic Structure (Bohr Model)

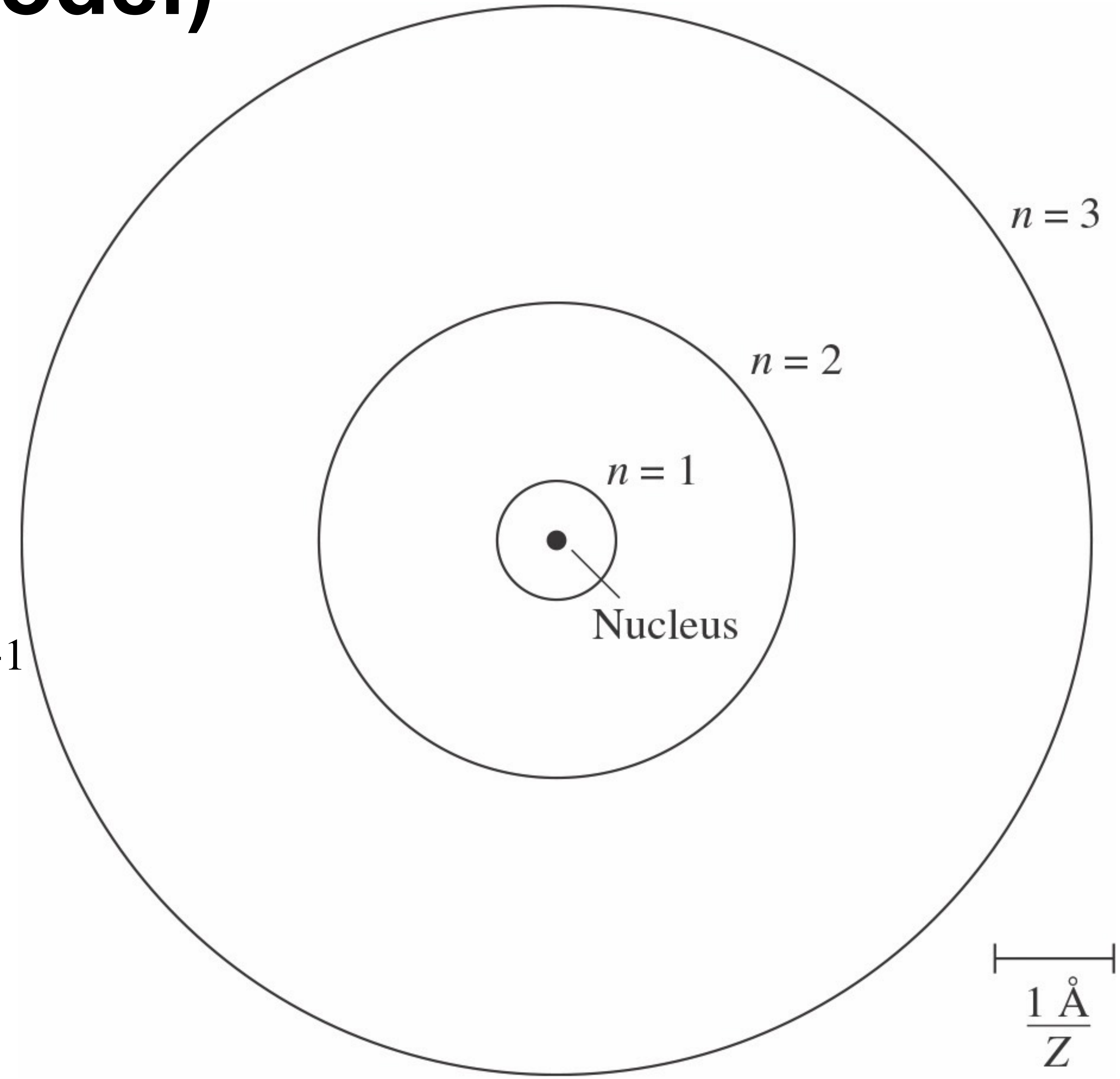
The energy of the photon that is absorbed or emitted is:

$$\Delta E = h\nu = \frac{hc}{\lambda}$$

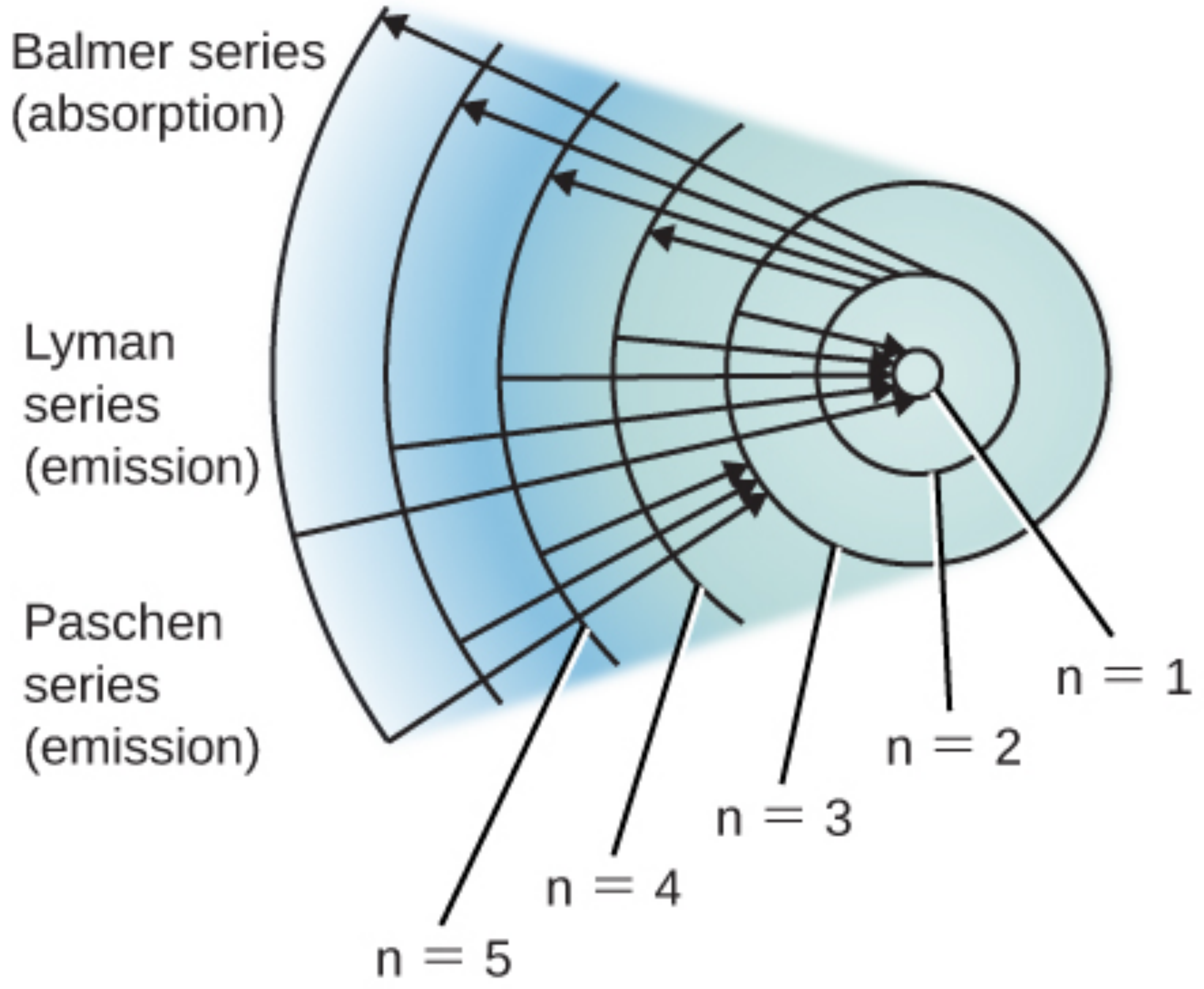
We can solve for wavelength of photon emitted as

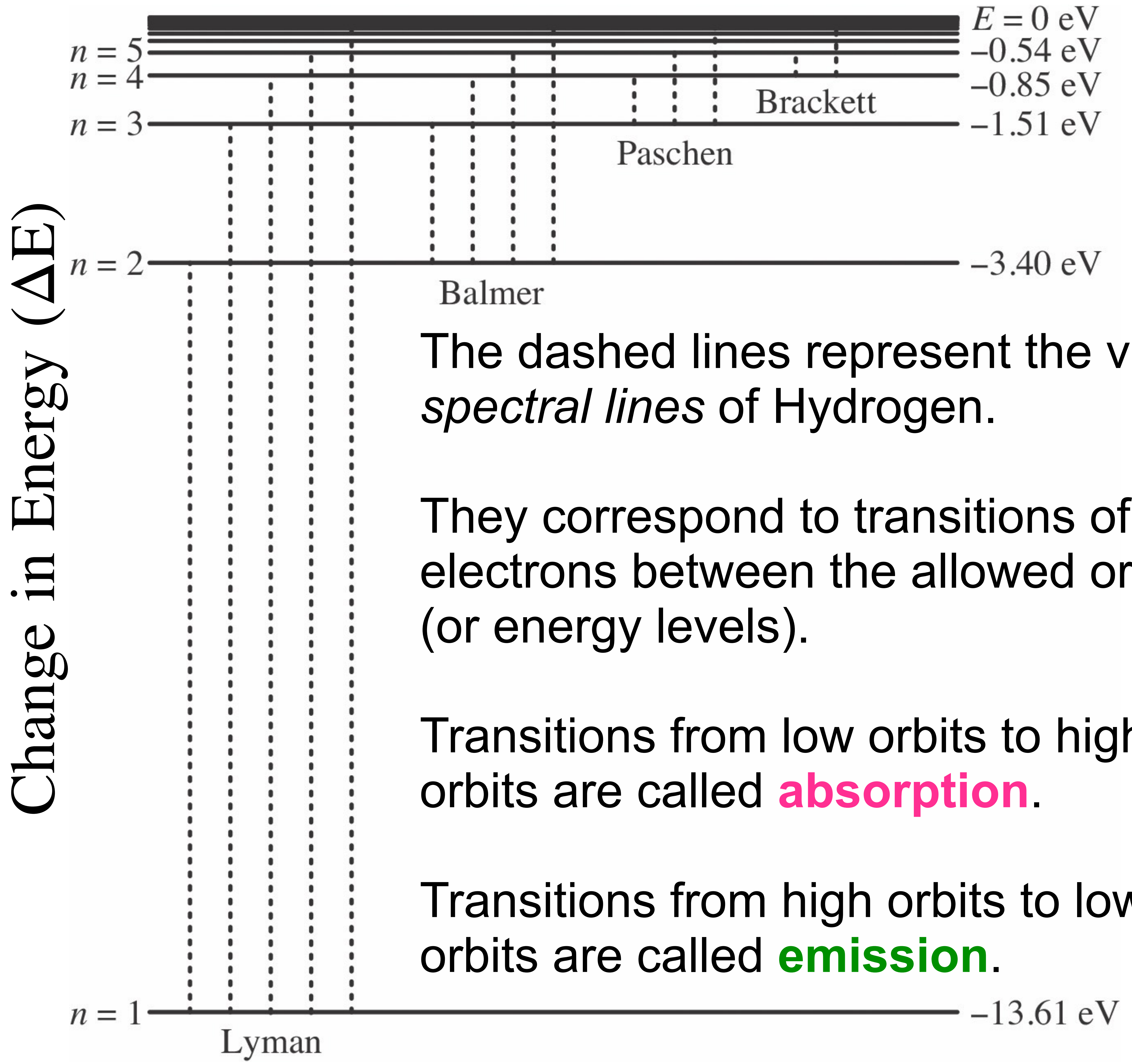
$$\lambda = \frac{hc}{\Delta E} = \left(\frac{2h}{m_e c \alpha^2 Z^2}\right)\left[\frac{1}{(n_2)^2} - \frac{1}{(n_1)^2}\right]^{-1}$$

$$\lambda = \frac{911.6\ \text{Å}}{Z^2}\left[\frac{1}{n_2^2} - \frac{1}{n_1^2}\right]^{-1}$$



Energy-Level Diagrams for Hydrogen





The dashed lines represent the various *spectral lines* of Hydrogen.

They correspond to transitions of electrons between the allowed orbits (or energy levels).

Transitions from low orbits to high orbits are called **absorption**.

Transitions from high orbits to low orbits are called **emission**.

Energy-Level Diagrams for Hydrogen

Hydrogen Spectral Lines Series:

Lyman Series (**absorption**): electron transitions from $n = 1 \to n \geq 2$.

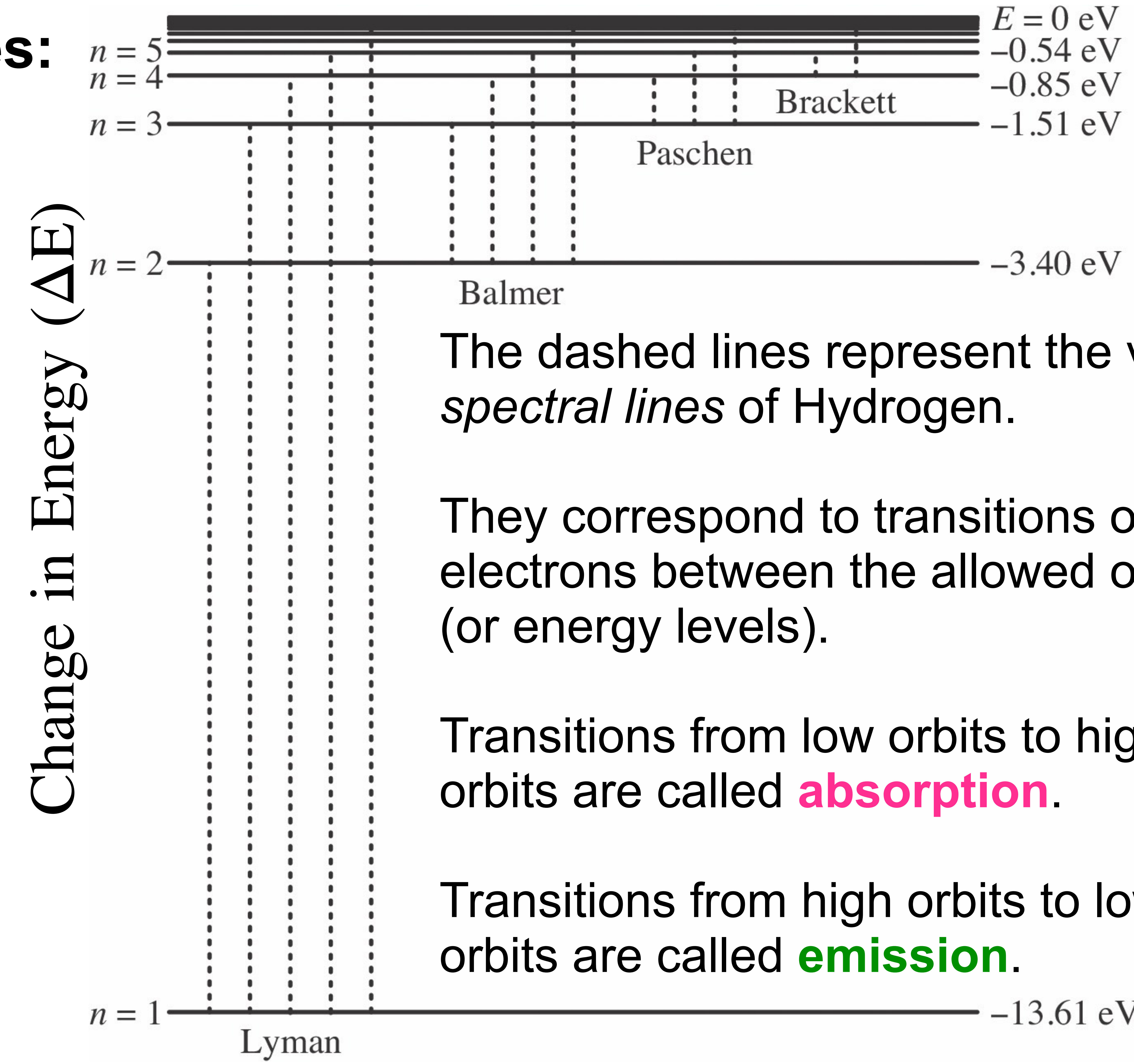
Lyman Series (**emission**): electron transitions from $n \geq 2 \to n = 1$.

Balmer Series (**absorption**): electron transitions from $n = 2 \to n \geq 3$.

Balmer Series (**emission**): electron transitions from $n \geq 3 \to n = 2$.

Paschen Series (**absorption**): electron transitions from $n = 3 \to n \geq 4$.

Paschen Series (**emission**): electron transitions from $n \geq 4 \to n = 3$.



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Transitions from low orbits to high orbits are called **absorption**.

Transitions from high orbits to low orbits are called **emission**.

Review of Electrons and Atomic Transitions

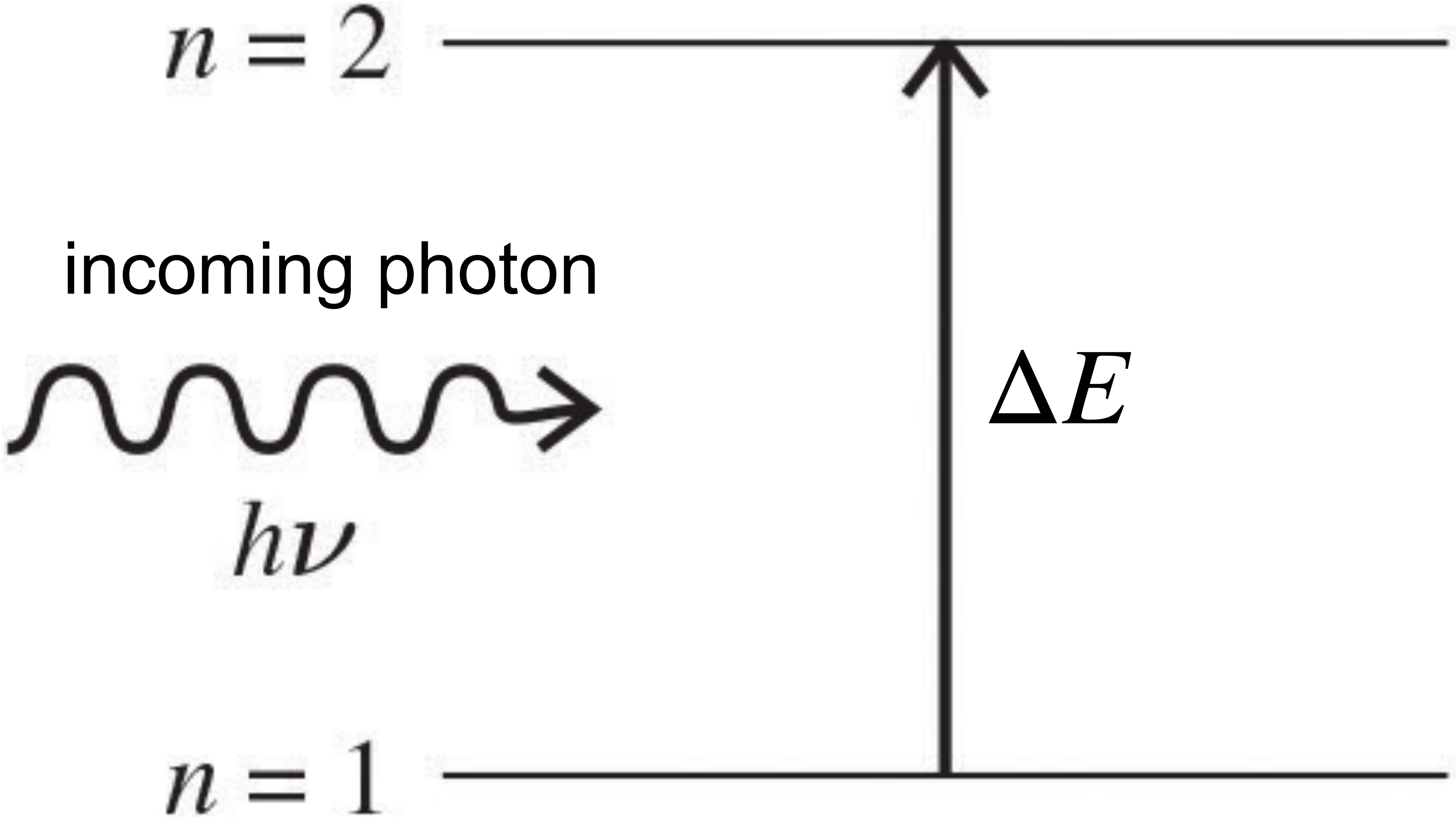
- Electrons are **fermions** (particles with half-integer spin).
- They obey the **Pauli exclusion principle**, which states that *no two electrons can occupy the same quantum state.*
- Atoms naturally evolve toward the lowest possible energy state, which is the most stable configuration.
- When an electron transitions from a higher to a lower energy level, it can do so through several possible paths (e.g., $n = 4 \longrightarrow 3,\ 2,\ 1$)
- These transitions are governed by **selection rules**, which define **permitted** and **forbidden** transitions


Questions?

Photoexcitation

A photon can excite an electron to a higher energy state. The electron **absorbs** the photon's energy, which is exactly equal to the difference between the two energy levels, $\Delta E = h\nu$.

This process can be written symbolically as:



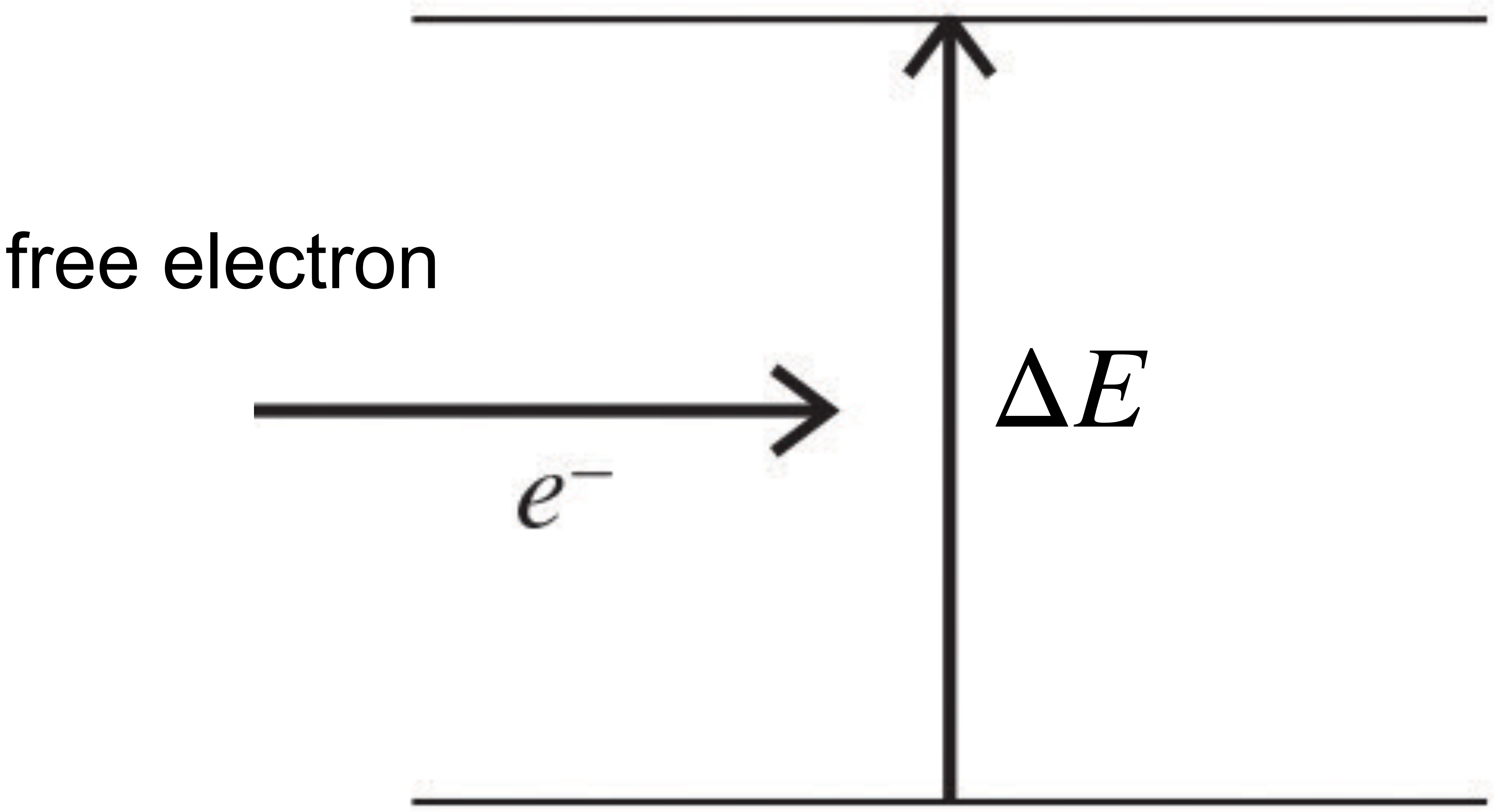
$$X + h\nu \rightarrow X^*$$

where

- X: atom in its **ground state.**
- X^*: atom in an **excited state.**

Collisional excitation

An electron in an atom can be excited to a higher energy level **when it collides with a free electron.** In this case, some of the free electron's kinetic energy is transferred to the internal energy of the atom through **collisional excitation.**



This process can be written symbolically as:

$$X + \frac{1}{2}m_e v^2 \rightarrow X^* + \frac{1}{2}m_e v'^2$$

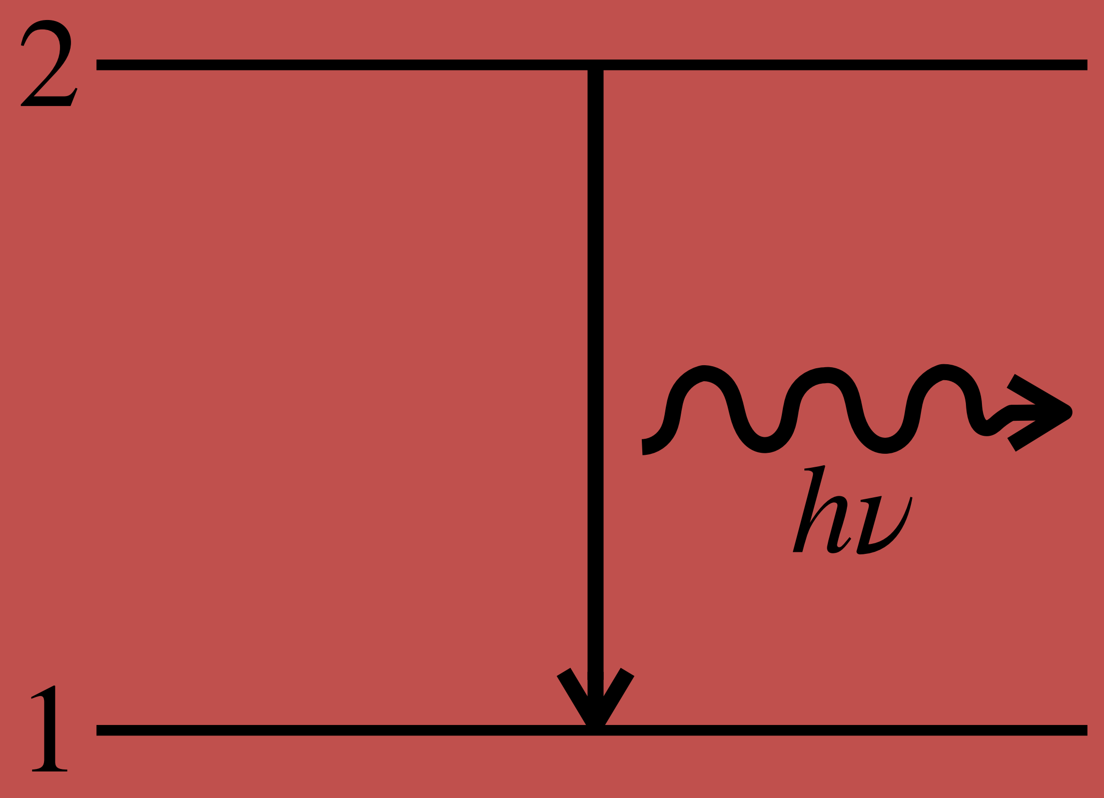
The outgoing (free) electron has kinetic energy:

$$E' = \tfrac{1}{2}m_e v'^2 = \frac{1}{2}m_e v^2 - \Delta E$$

If the collision transfers enough energy to the bound electron, it can move to a higher energy level or become ionized!

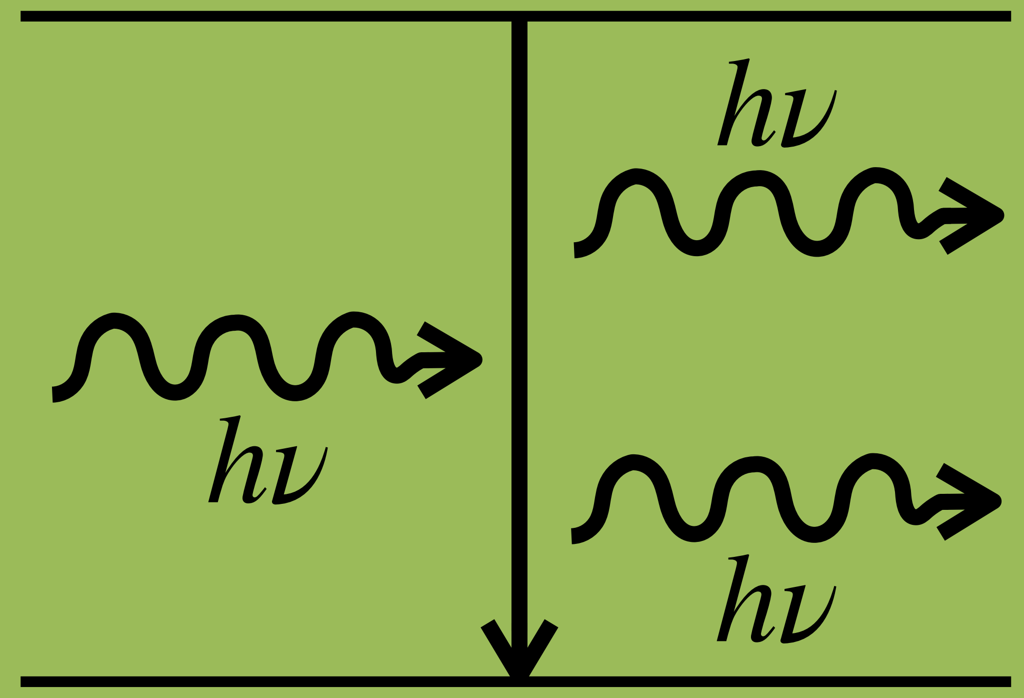
Emission Mechanisms

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



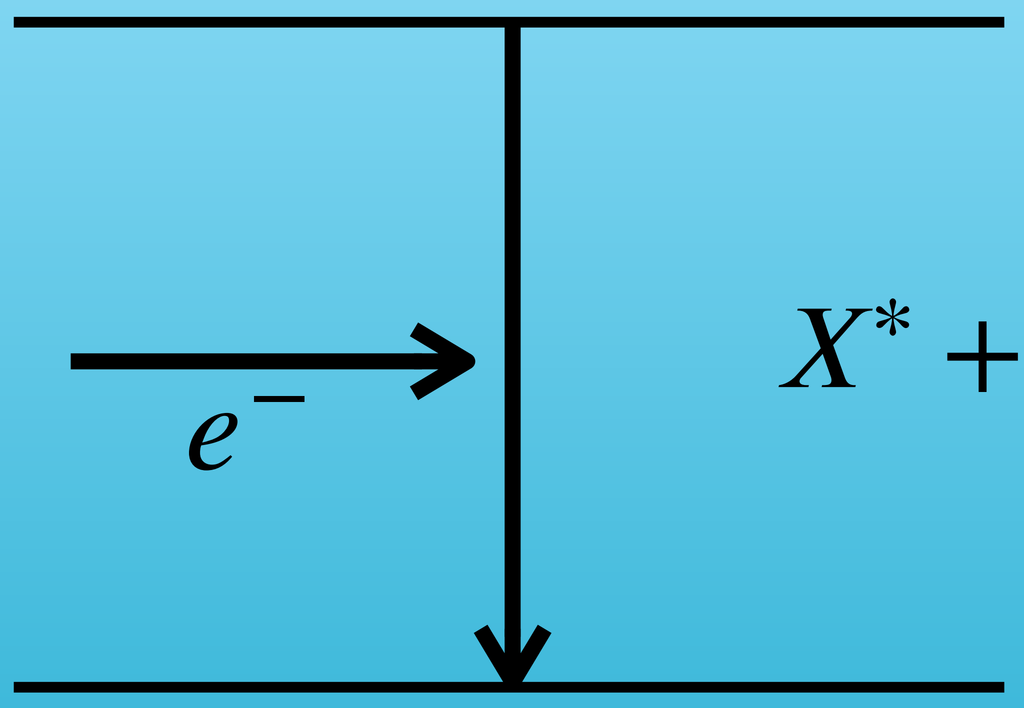
$$X^* \rightarrow X + h\nu$$

Stimulated emission: photon triggers downward transition:



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

Collisional de-excitation: free e^- takes energy away in a collision:

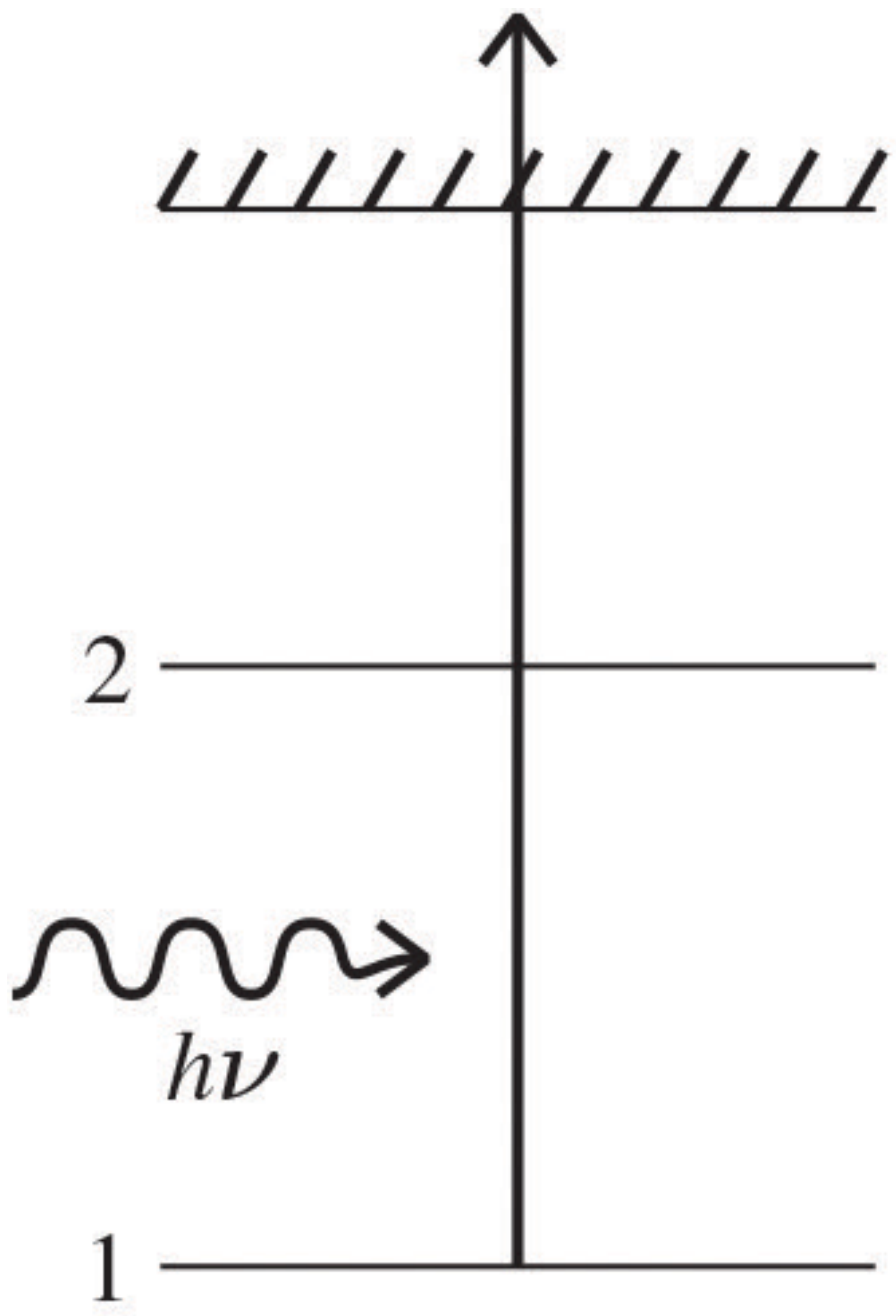


$$X^* + \frac{1}{2}m_e v^2 \rightarrow X + \frac{1}{2}m_e (v')^2$$

Photoionization

An atom is "photo-ionized" when a photon with energy greater than the ionization potential ($h\nu > \chi$) is absorbed by a bound *e*–.
The bound *e*– can become unbound.

$$X + h\nu \rightarrow X^{+} + \frac{1}{2} m_e \upsilon^2$$

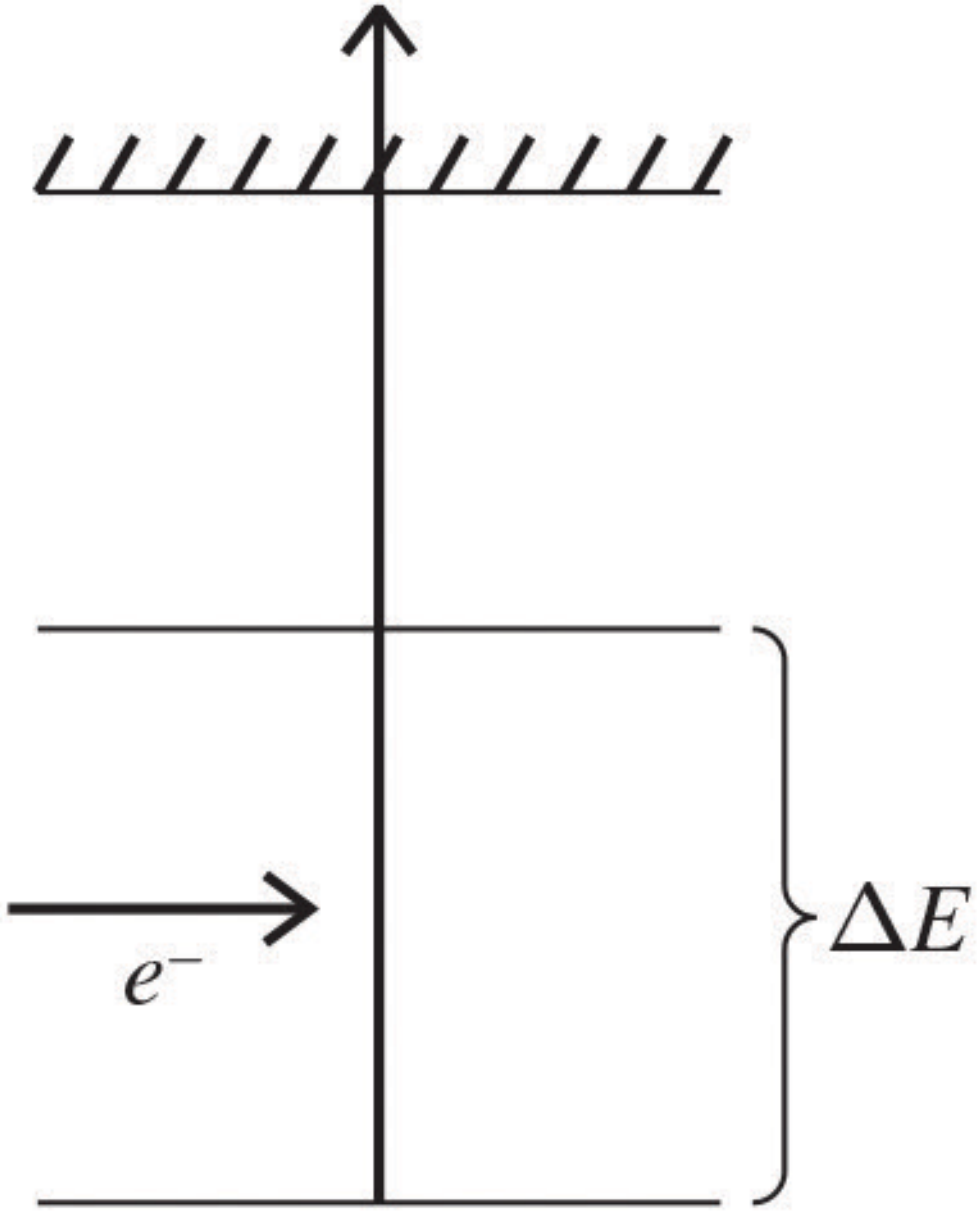


Collisional Ionization

Atoms are **collisionally ionized** when a free *e*– with kinetic energy greater than the ionization potential χ collides with the atom:

$$X + \frac{1}{2}m_e v^2 \rightarrow X^+ + \frac{1}{2}m_e (v')^2 + \frac{1}{2}m_e (v'')^2$$

Two free *e*– created in the end.

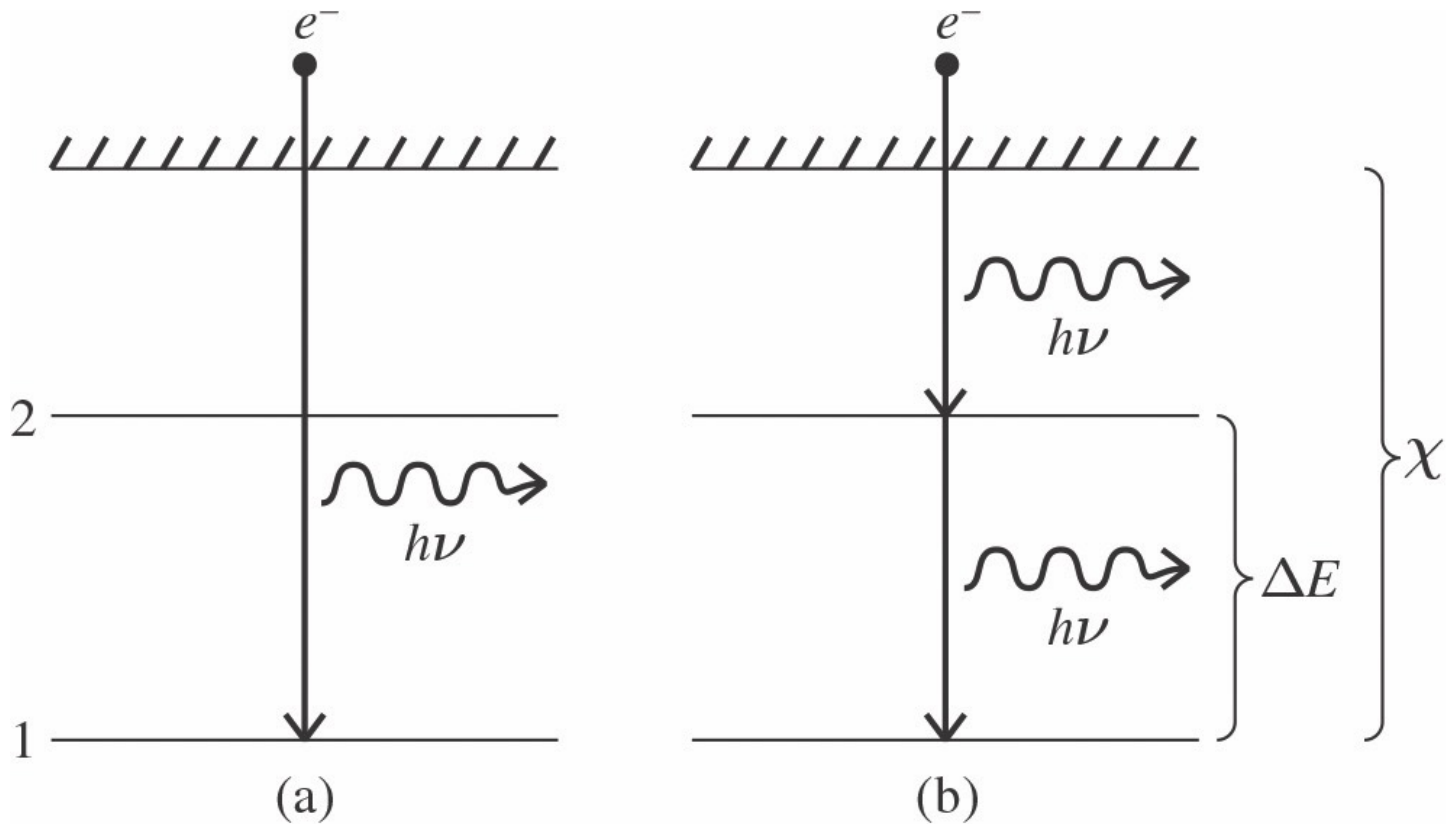


Recombination

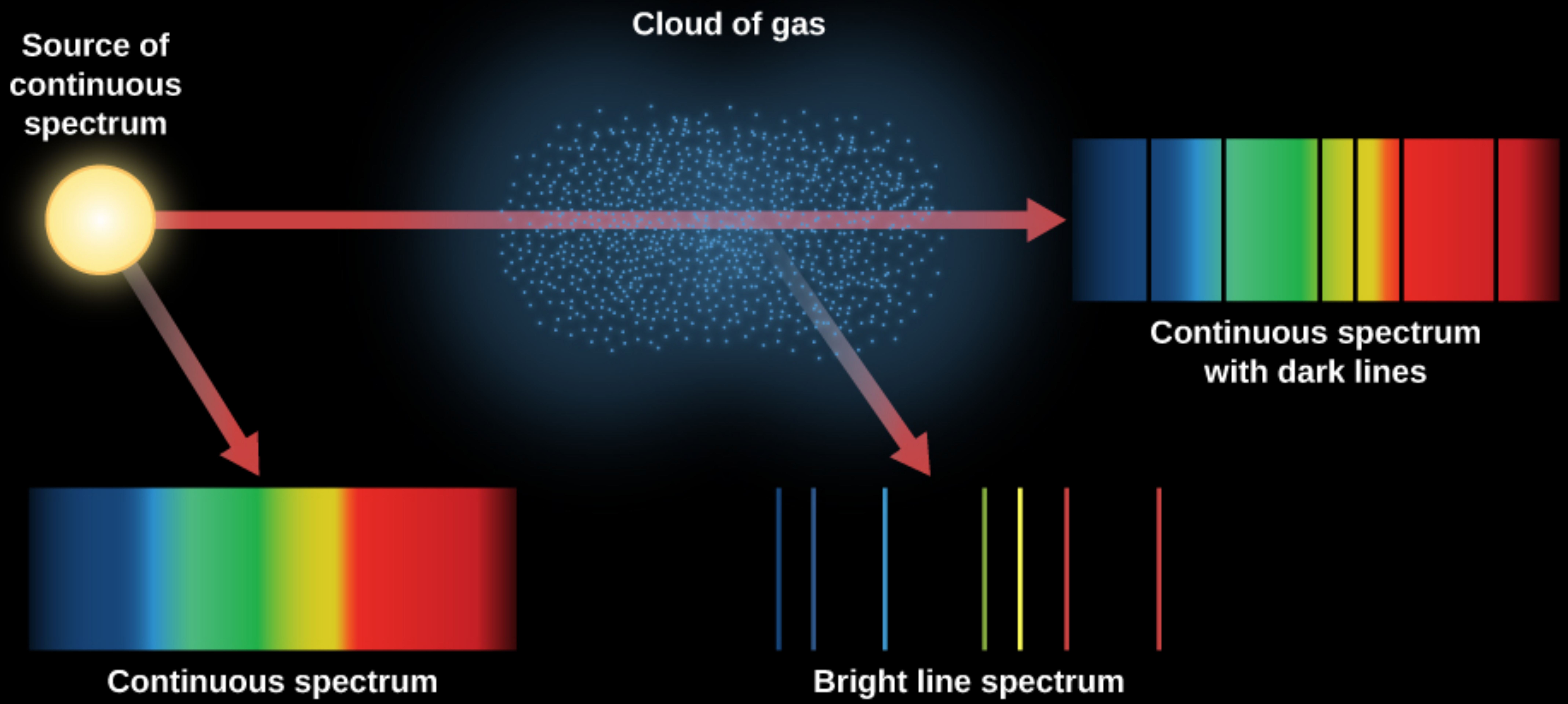
Atoms that have been ionized (i.e., ions) can capture free electrons. This process is called “recombination”

$$X^+ + \frac{1}{2}m_e v^2 \rightarrow X + h\nu$$

Can produce one or multiple photons (cascade).



Emission and Absorption Spectra



Questions?

Brain Break – Think-pair-share

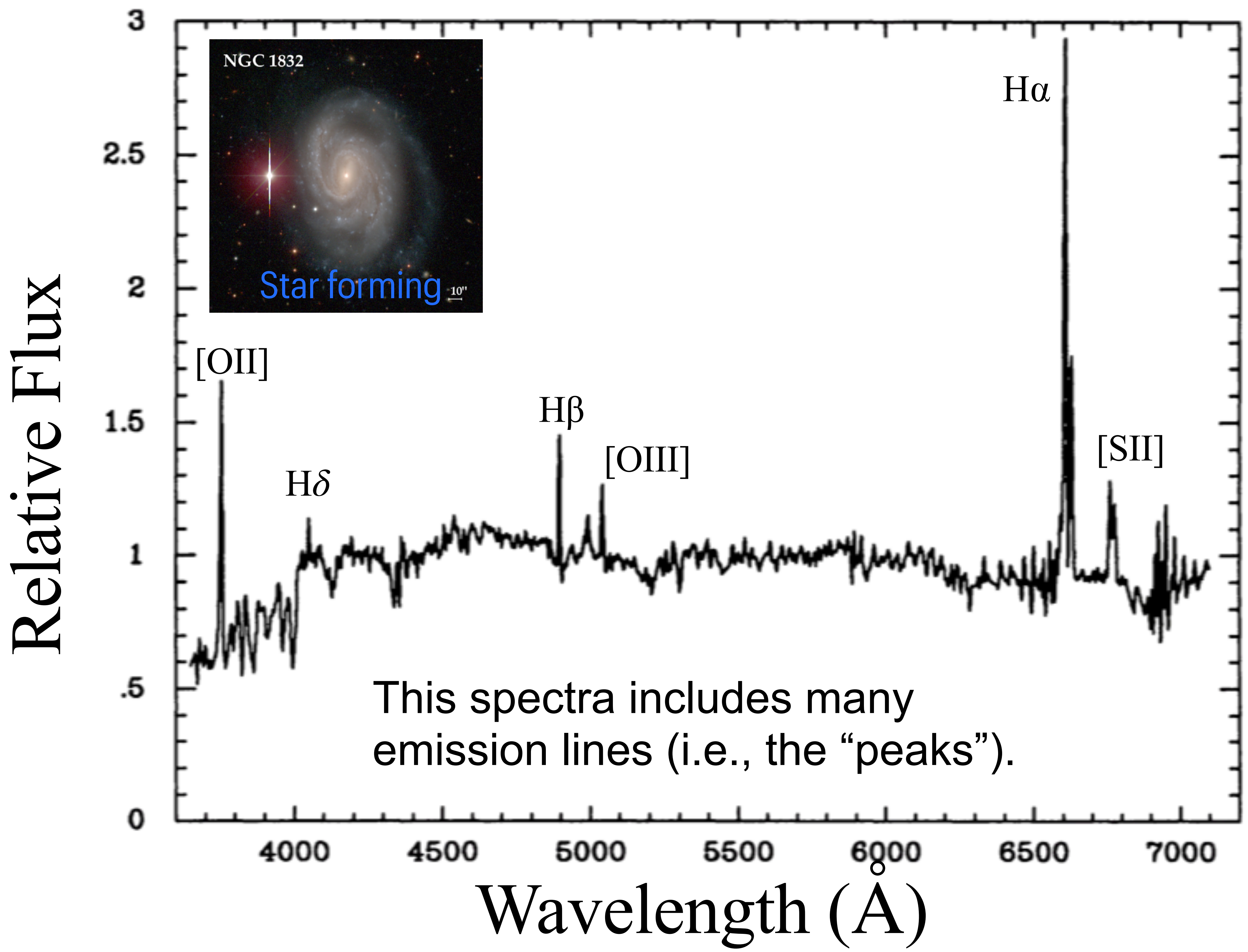
What is *ionization energy,* and how does it differ from the energy required to excite an electron within an atom?

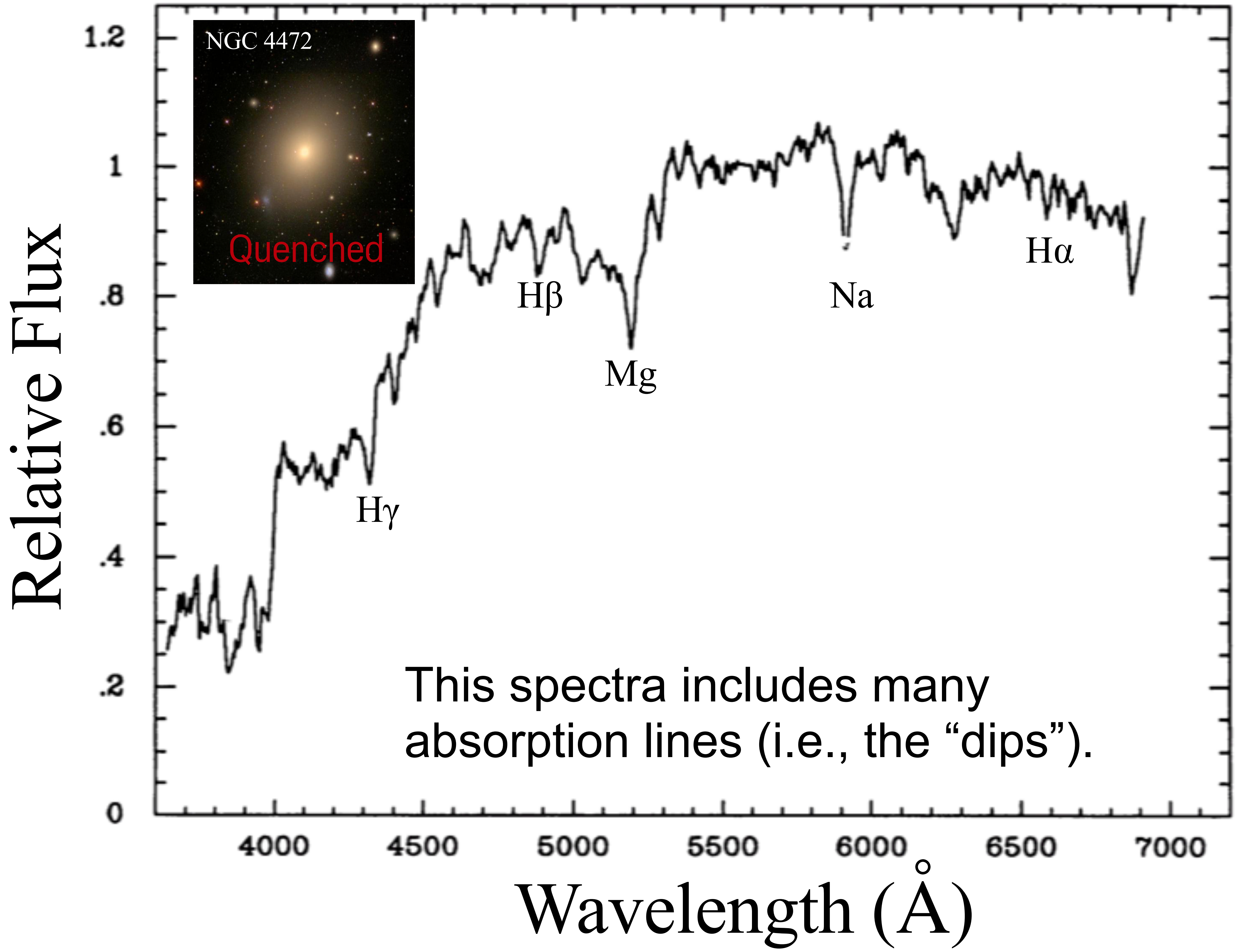
What signatures do you think ionization processes imprint on the light from stars and galaxies?

What are some physical properties that could be estimated by analyzing these signatures?

Image credit: Adapted from Figs. 3 & 4 of Kennicutt (1992)

A Tale of Two Galaxies



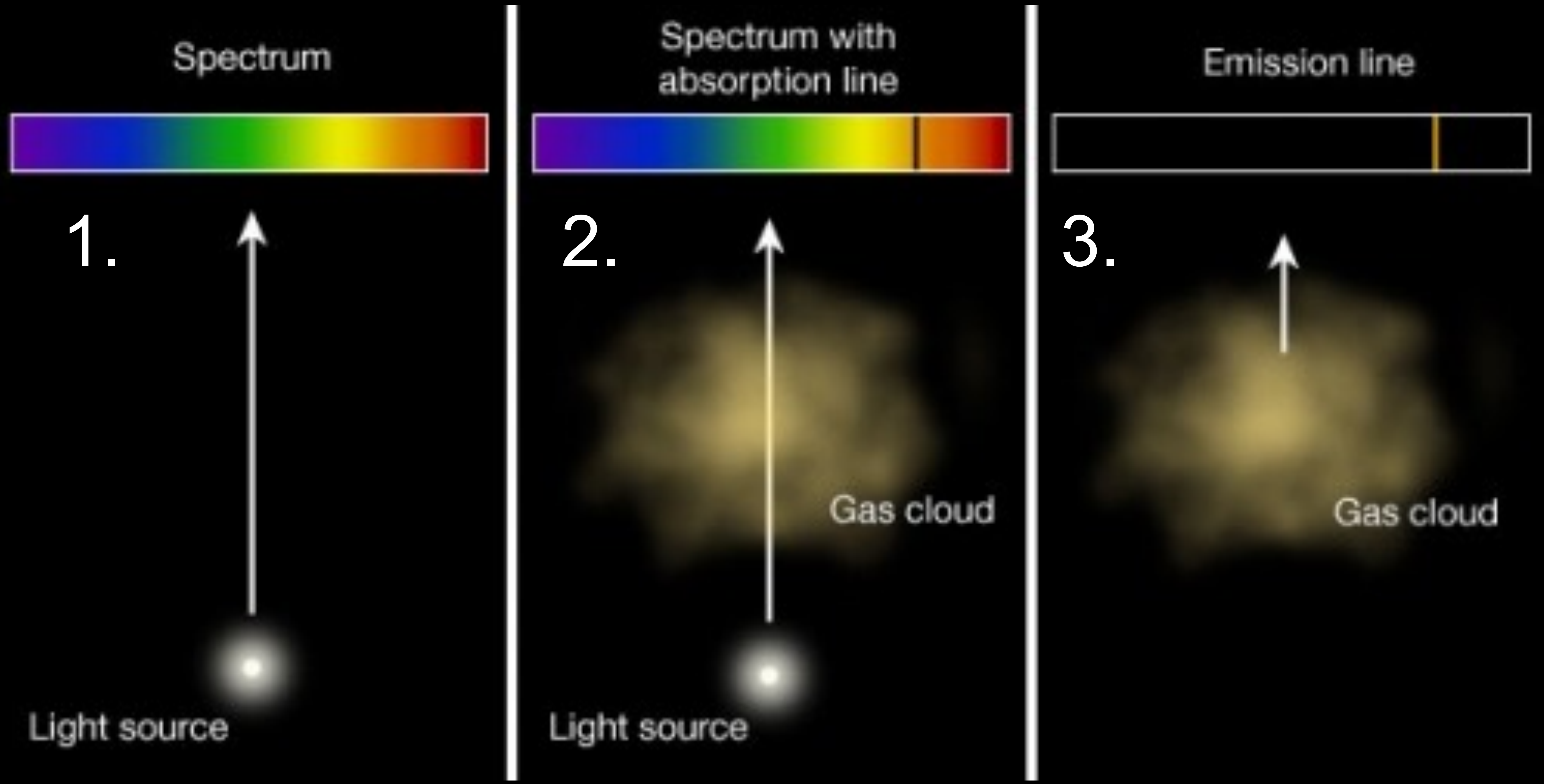


- The spectra includes Hydrogen alpha ($\lambda \sim 6563$ Å) emission ($n \geq 3 \rightarrow n = 2$).
- This is known as a “recombination line” caused by UV radiation from young, high-mass stars that ionize nearby hydrogen gas. After some time the free electrons “recombine” with the protons, forming neutral hydrogen and releasing a photon.
- **Takeaway:** This galaxy must be undergoing star formation!

- These dips are largely caused by absorption of photons in the atmospheres of low-mass stars.
- The lack of emission lines also informs us that there aren’t many sources of ionizing radiation —- e.g., young, massive stars.
- **Takeaway:** This galaxy must shut down star formation!

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.



Lines have widths

Remember there is a finite lifetime for the excited state before it undergoes a transition to a lower energy state.

The probability per second that this transition will occur can be determined quantum mechanically. We call it the **Einstein A coefficient**.

If there are n_2 ions per unit volume in the n = 2 excited state, the number of photons expected per second per unit volume from spontaneous emission will be:

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

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

Lines have widths

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

E can divide transitions base on their **Einstein A coefficients**.

$A_{21} \sim 10^8\ \mathrm{s}^{-1} \rightarrow$ permitted lines
$A_{21} \sim 1\ \mathrm{s}^{-1} \rightarrow$ “forbidden” lines

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

Thermal Broadening

Temperature can be thought of as a measure of the random motion (or speed) of particles in a gas. This is known as the *kinetic temperature.*

The distribution of these random particle speeds follows the *Maxwell–Boltzmann distribution:*

$$F(v) \propto v^2 \exp\left(-\frac{mv^2}{2kT}\right)$$

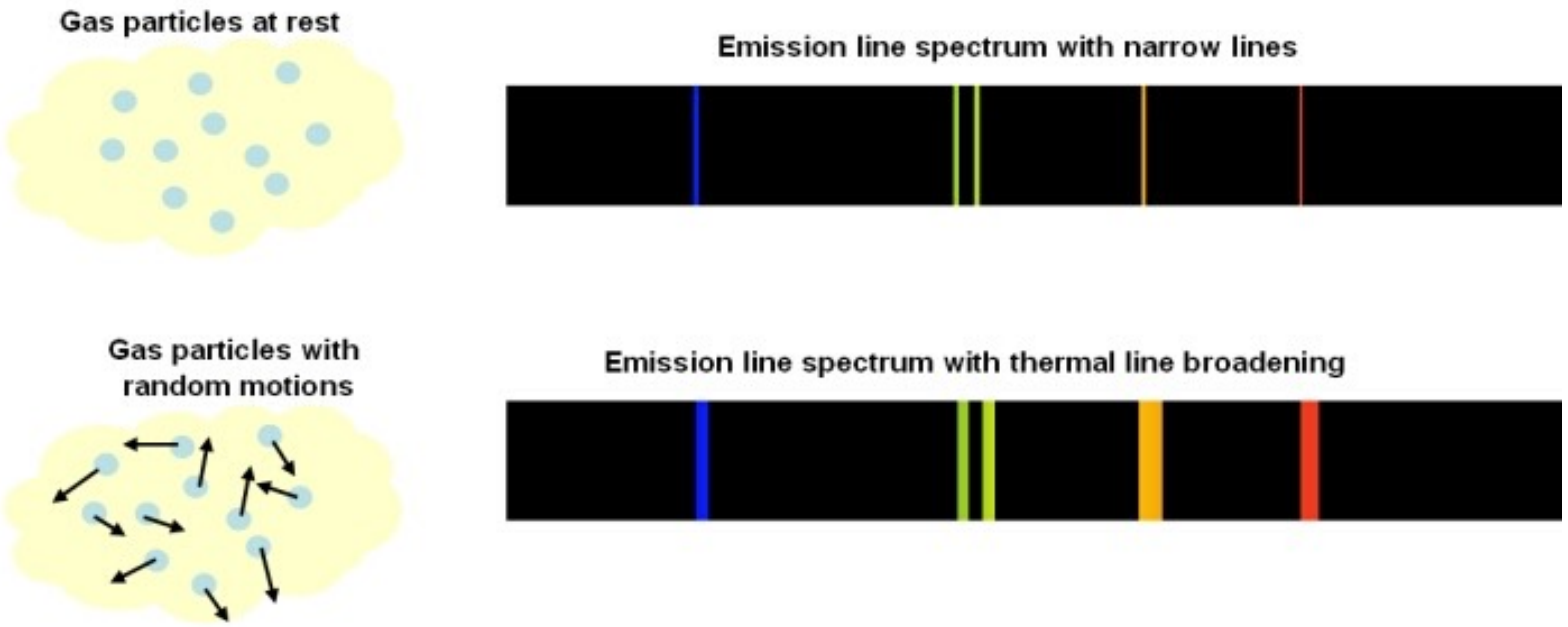
Where,

$k = 10^{-4}\ \mathrm{eV\ K}$ (Boltzmann constant)

v = “root mean square (rms)” velocity = typical speed of particles in a gas.

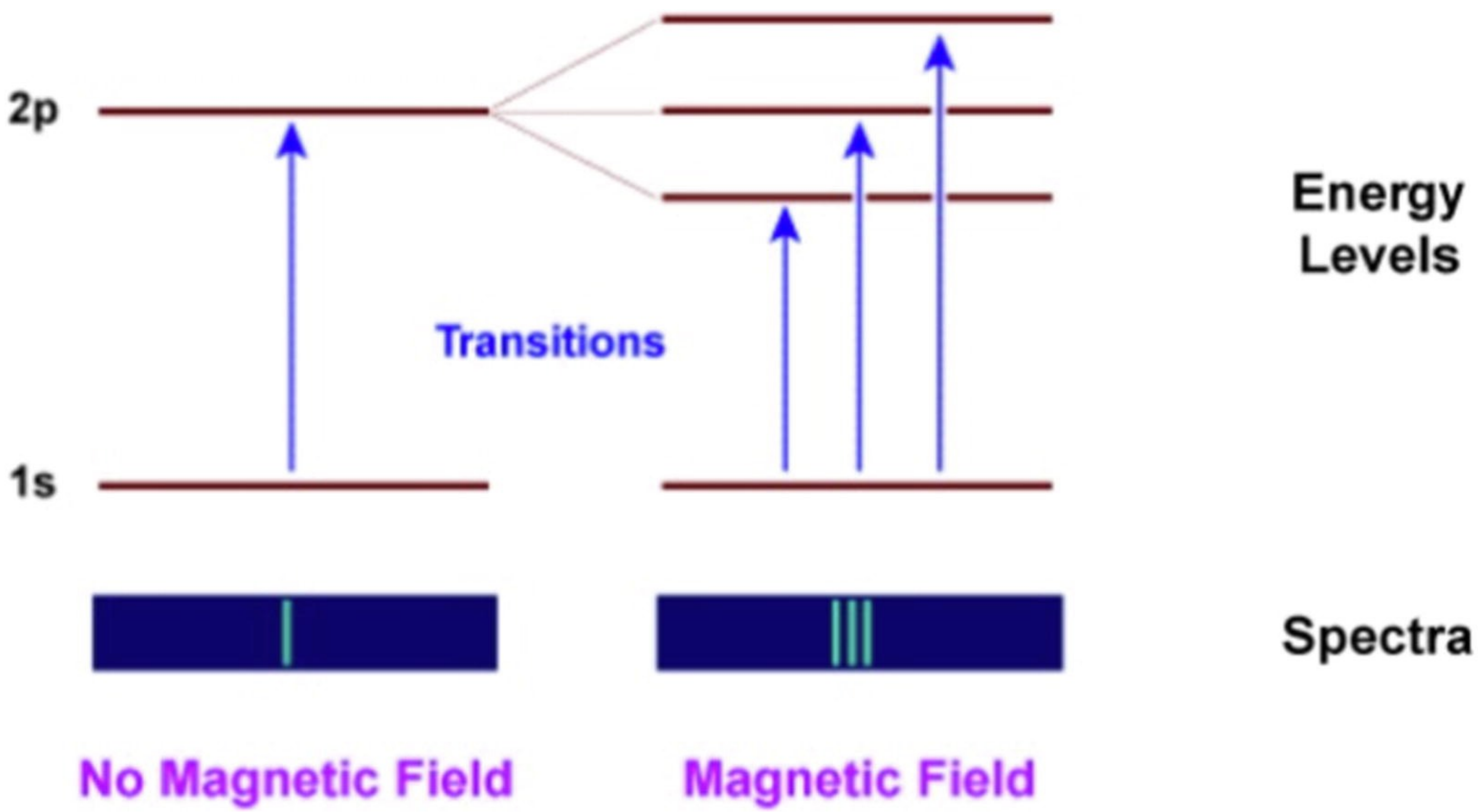
Relation between wavelength of light and temperature:

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



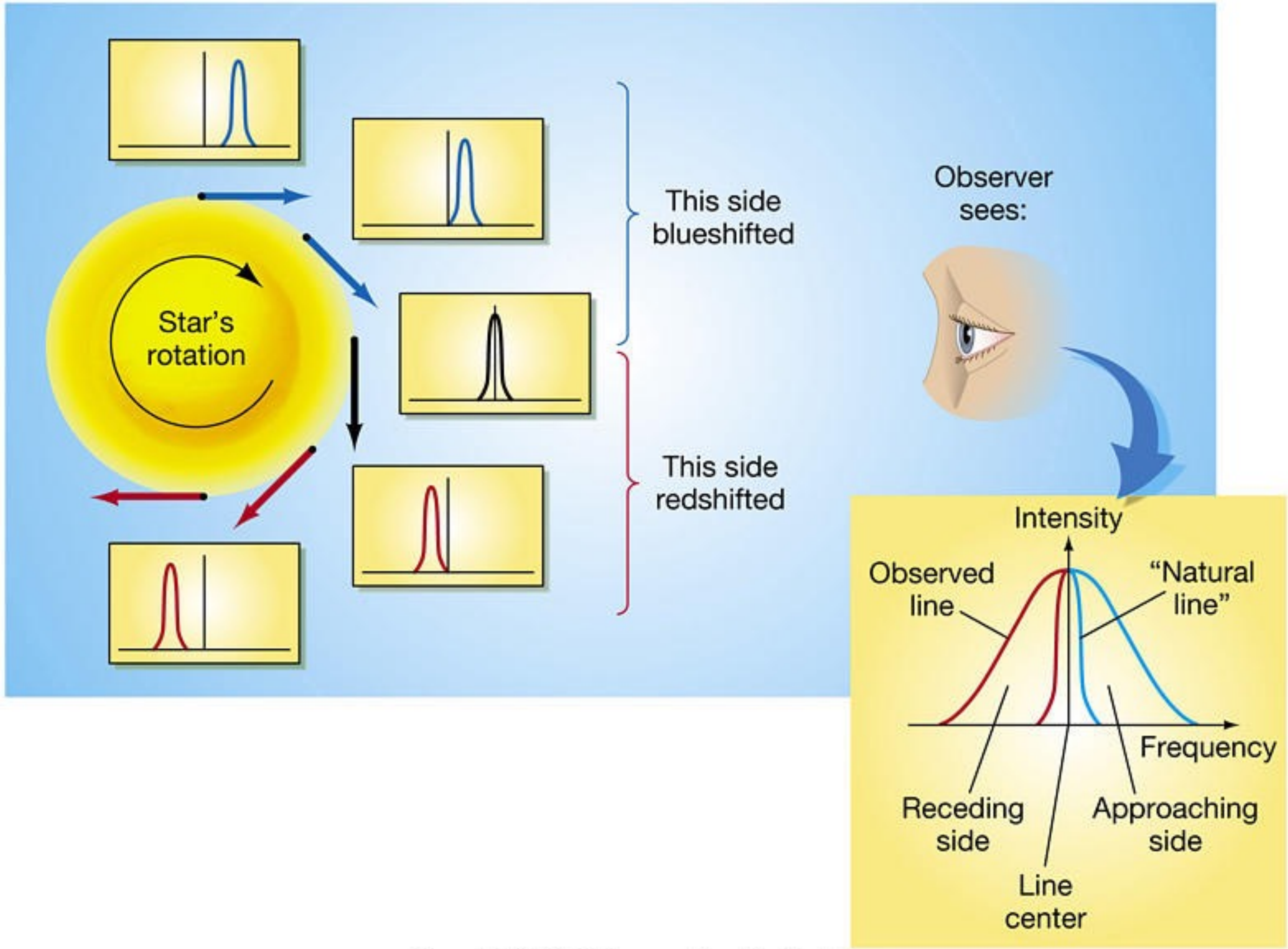
Zeeman Broadening

When a magnetic field is present, it can split energy levels that would normally be the same (degenerate) into slightly different energies.



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.




Questions?

Reminders

- Coding exercise #2 due **Sunday, 10/19 by 11:59 pm via Datahub** (this one is a little more involved).
- Attend the Midterm Study Session on Monday during discussion.
- **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.
- Remember that **SERF 329** is reserved for ASTR 20A study session on Mondays from 4-6pm.