Week 3: Light

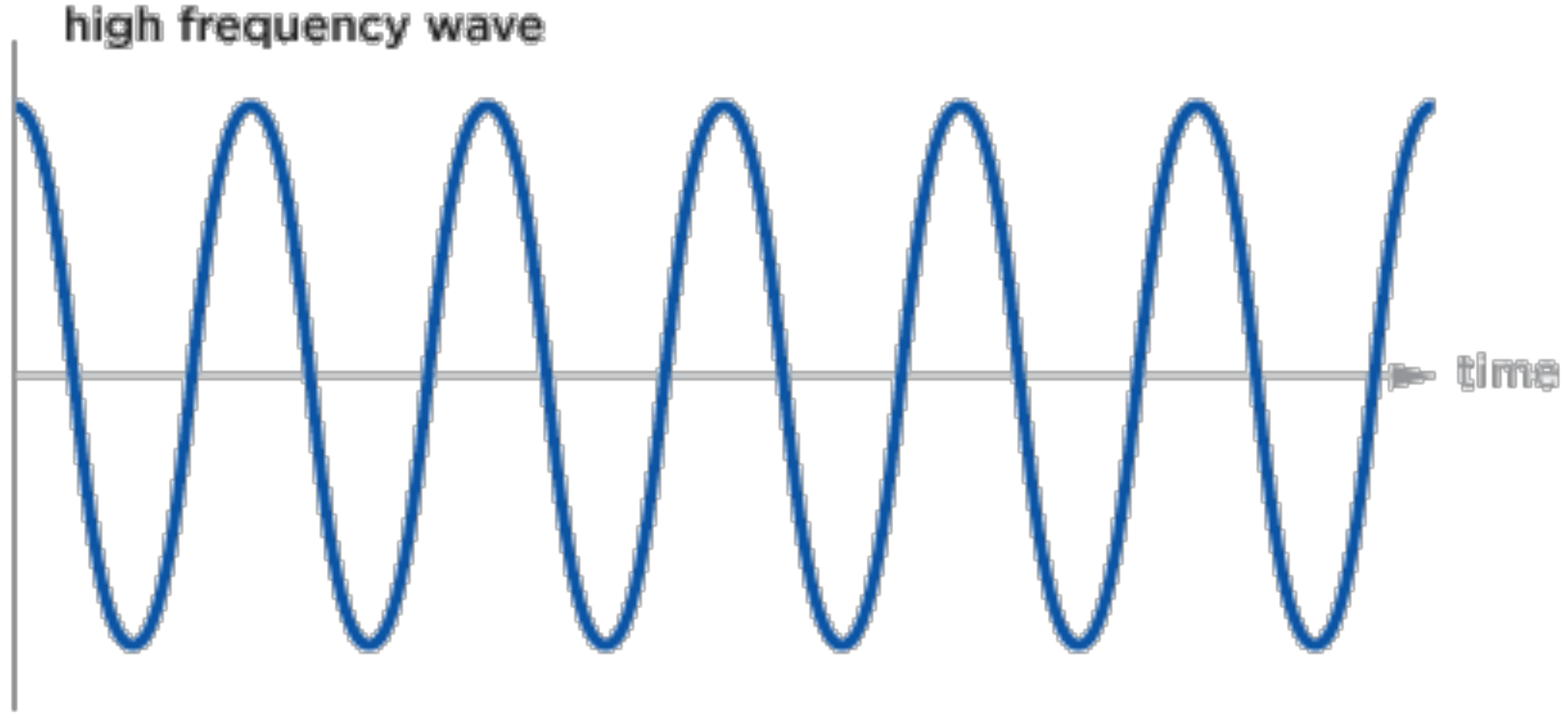
HW2 due on Thursday

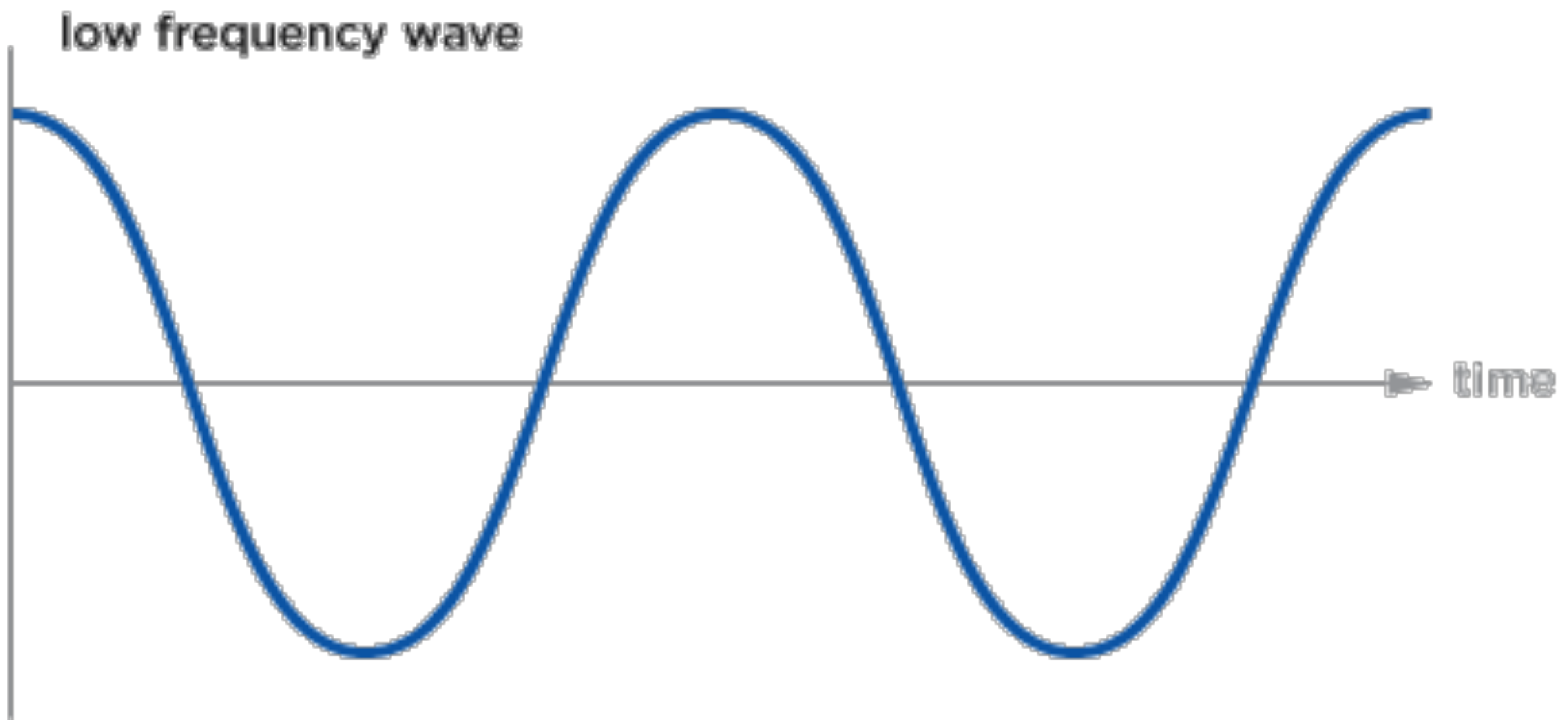
Read Ch. 5 (can skip 5.5)

Let there be *LIGHT!*

- Review of atomic structure, energy exchange processes, and spectroscopy
- Radiative transfer
- Thermodynamic equilibrium
- Blackbody radiation
- Wien’s Law

"Light" is electromagnetic radiation of any wavelength/frequency, not just what eyes see





Classically, can be thought of a wave traveling down an electric field line like an induced transverse wave down a rope.

In QM, quanta of the wave are called photons, which have energy and momenta determined by wavelength/frequency.

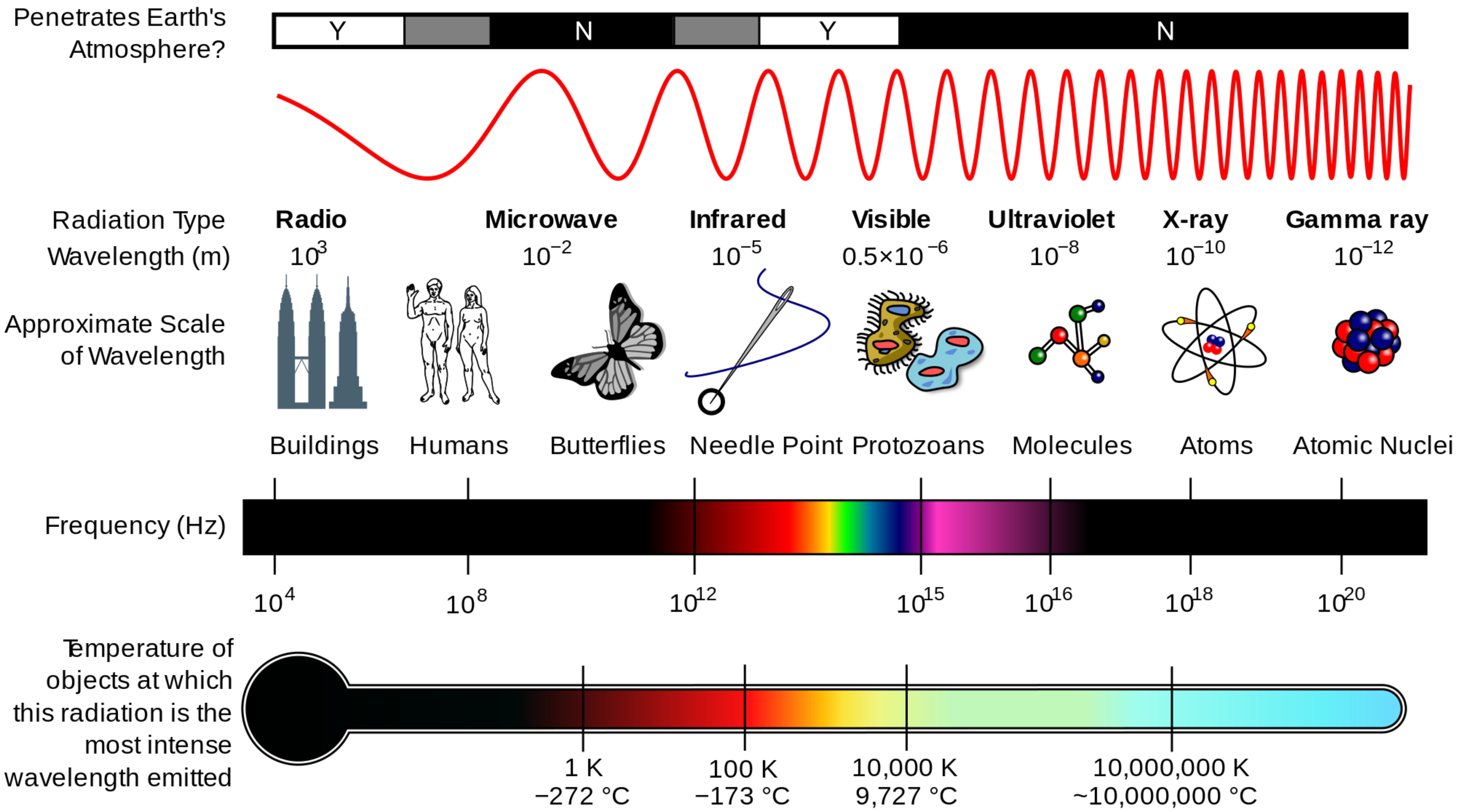
$$E = h\nu = \frac{hc}{\lambda}$$

$$h = 6.626 \times 10^{-34} \text{ J s} = 4.135 \times 10^{-15} \text{ eV s}$$

$$c = 2.998 \times 10^{8} \text{ m s}^{-1}$$

$$\hbar = \frac{h}{2\pi}$$

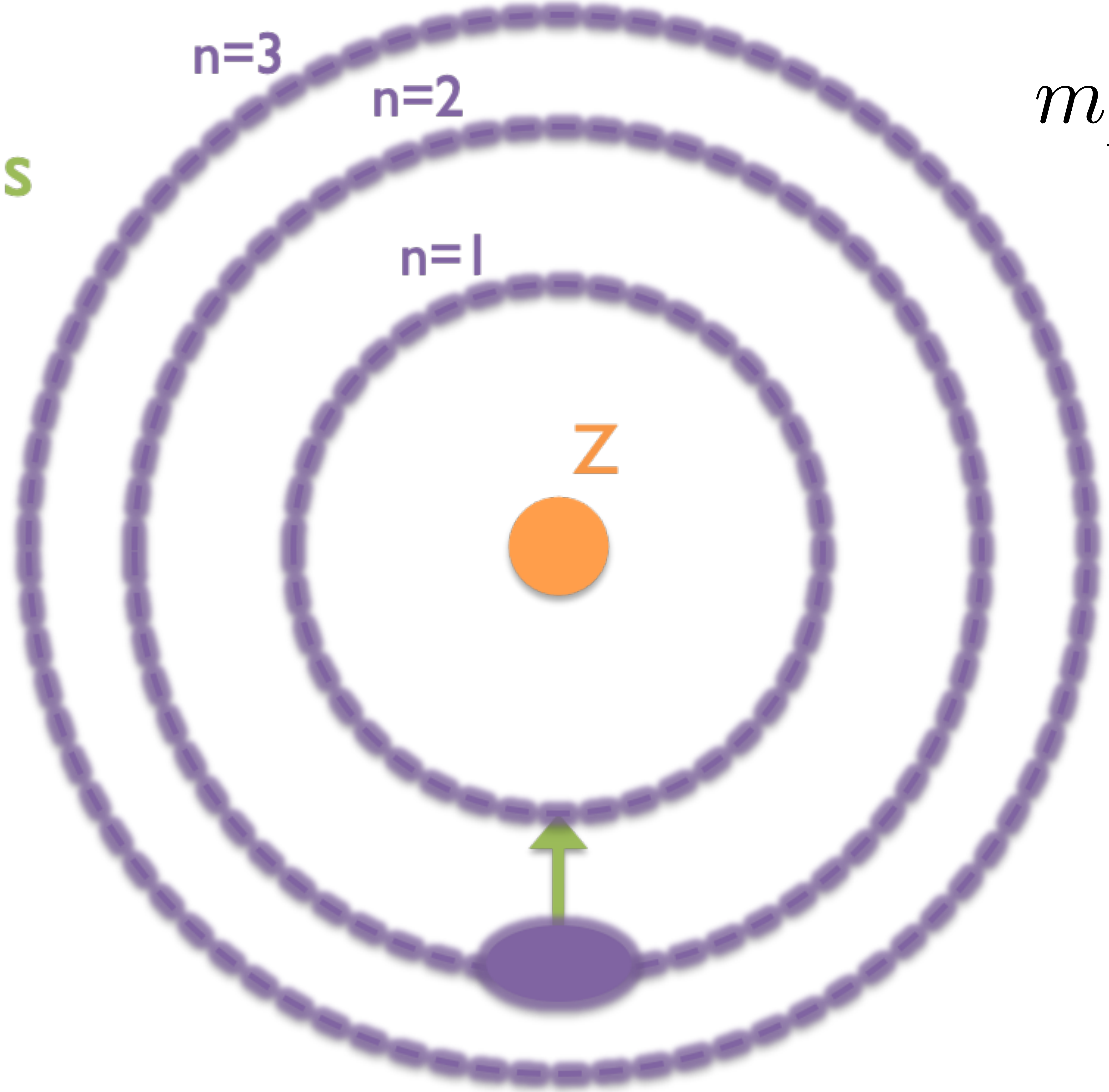
$$1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$$



Penetrates Earth's Atmosphere?
Y
N
Y
N
Radiation Type
Wavelength (m)
Radio
10^{3}
Microwave
10^{-2}
Infrared
10^{-5}
Visible
0.5×10^{-6}
Ultraviolet
10^{-8}
X-ray
10^{-10}
Gamma ray
10^{-12}
Approximate Scale of Wavelength
Buildings
Humans
Butterflies
Needle Point
Protozoans
Molecules
Atoms
Atomic Nuclei
Frequency (Hz)
10^{4}
10^{8}
10^{12}
10^{15}
10^{16}
10^{18}
10^{20}
Temperature of objects at which this radiation is the most intense wavelength emitted
1 K
−272 °C
100 K
−173 °C
10,000 K
9,727 °C
10,000,000 K
~10,000,000 °C

Atomic Structure (quantized energy levels)

Z protons
A−Z neutrons



$$m_p = 1.673 \times 10^{-27}\ \mathrm{kg}$$

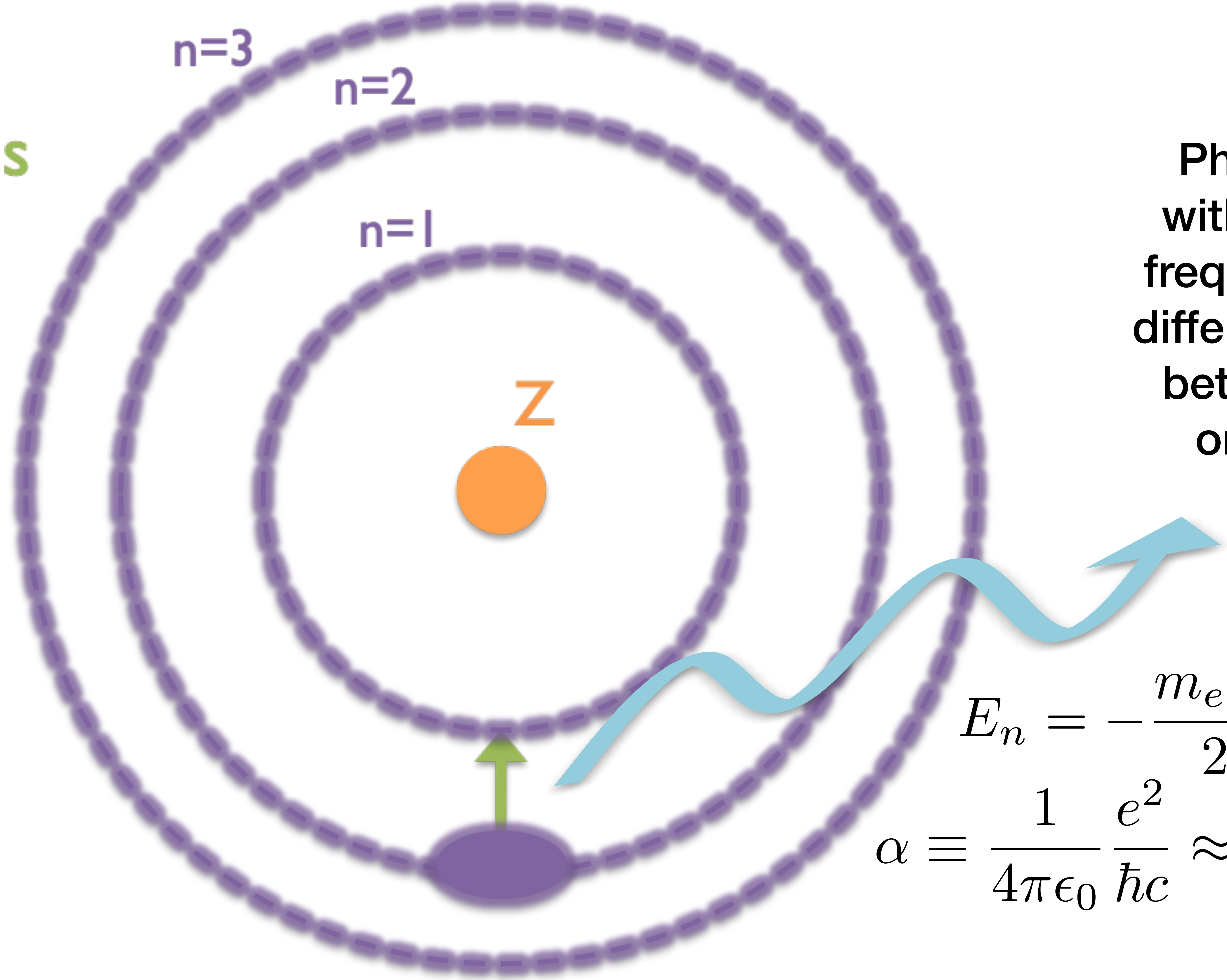
$$m_e \approx m_p/1836$$

$$m_n \sim m_p$$

Atomic Structure (quantized energy levels)

Z protons

A−Z neutrons



Photon emitted with wavelength/ frequency equal to difference in energy between allowed orbits (energy levels)

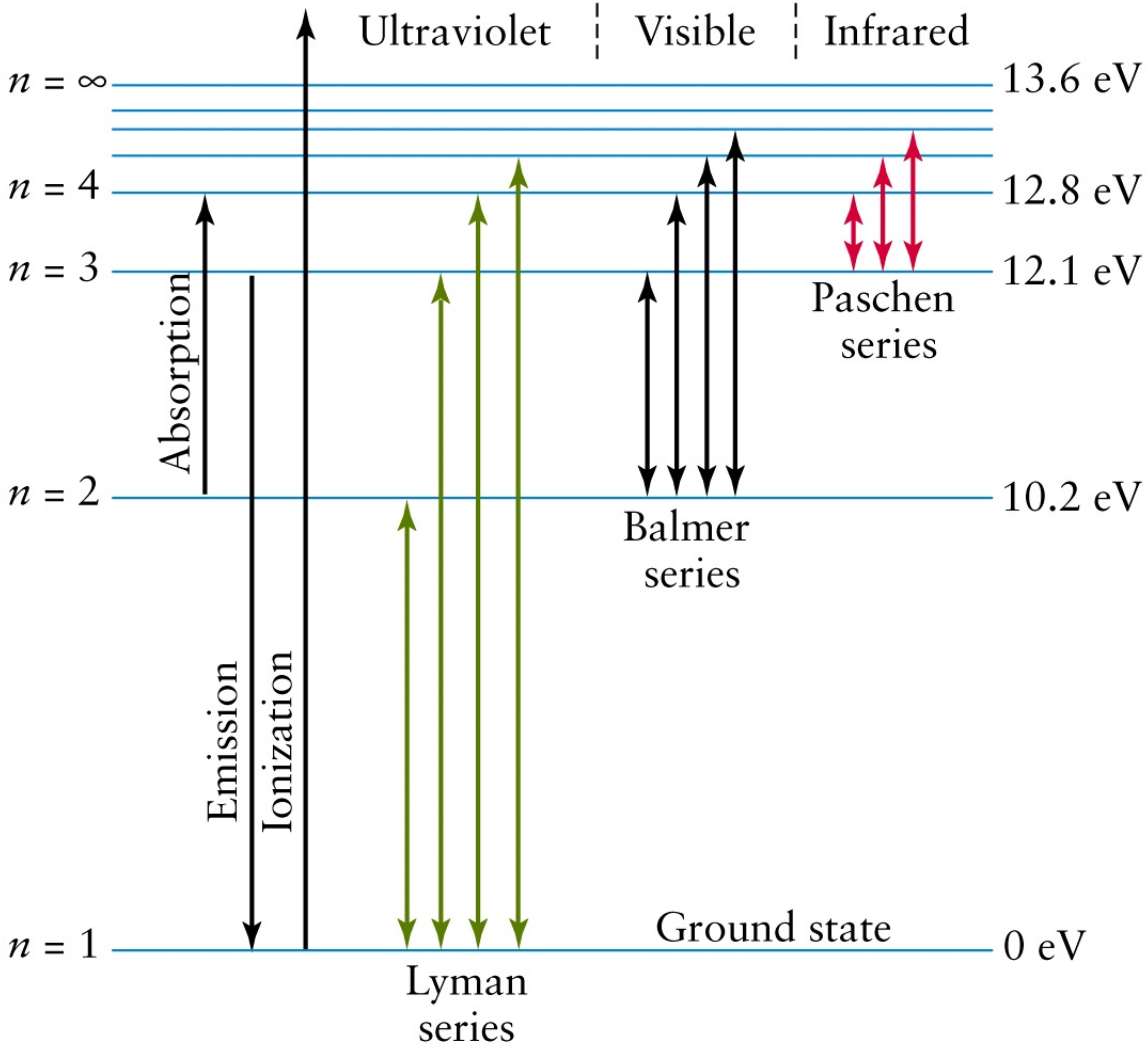
$$E_n = -\frac{m_e c^2}{2}\alpha^2 \frac{Z}{n^2}$$

$$\alpha \equiv \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} \approx 7.30 \times 10^{-3} \approx \frac{1}{137}$$

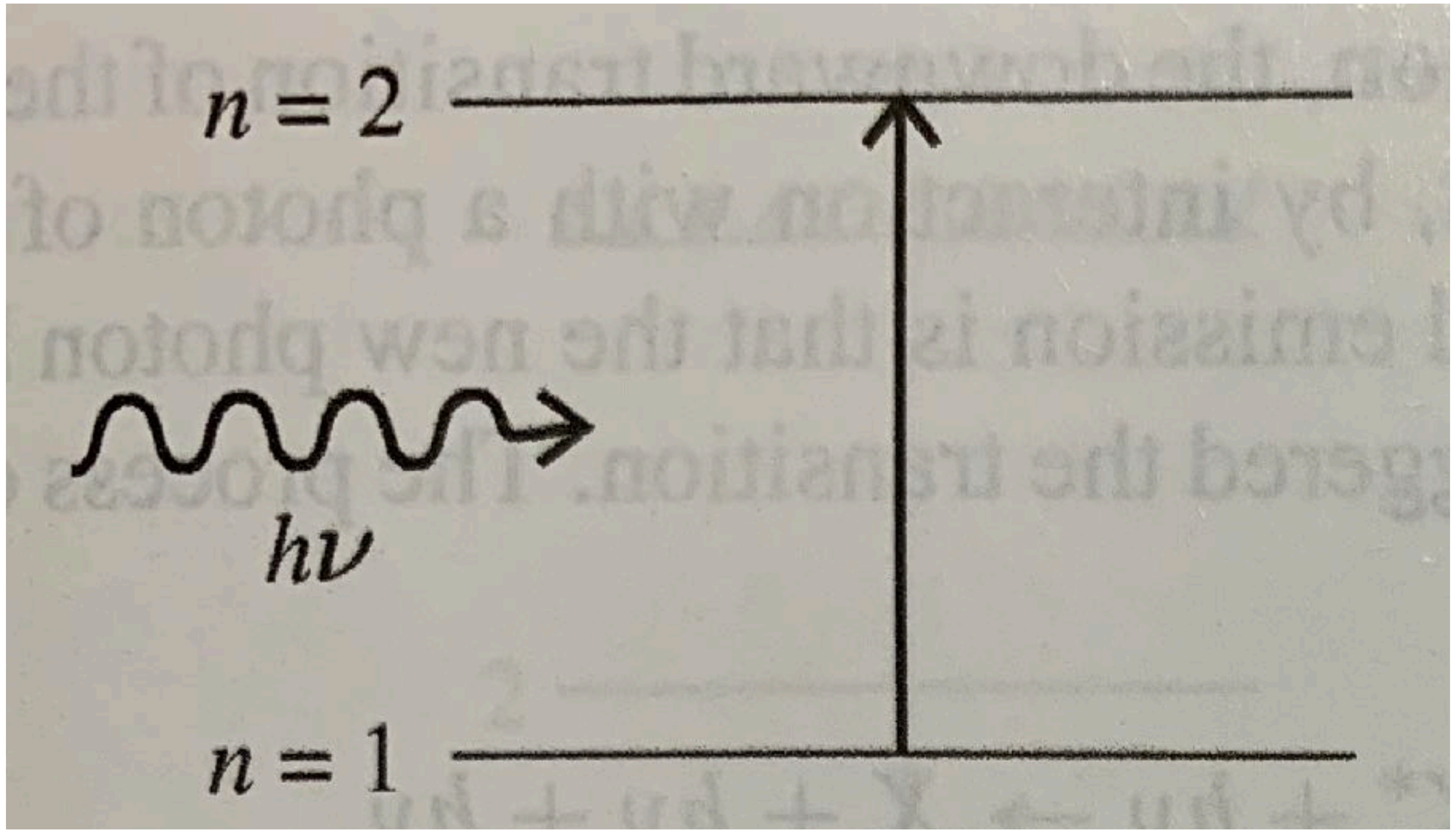
Energy Levels

$$\Delta E = E_n - E_{n'} = (13.6\ \text{eV})\ Z^2 \left[\frac{1}{(n')^2} - \frac{1}{n^2}\right]$$

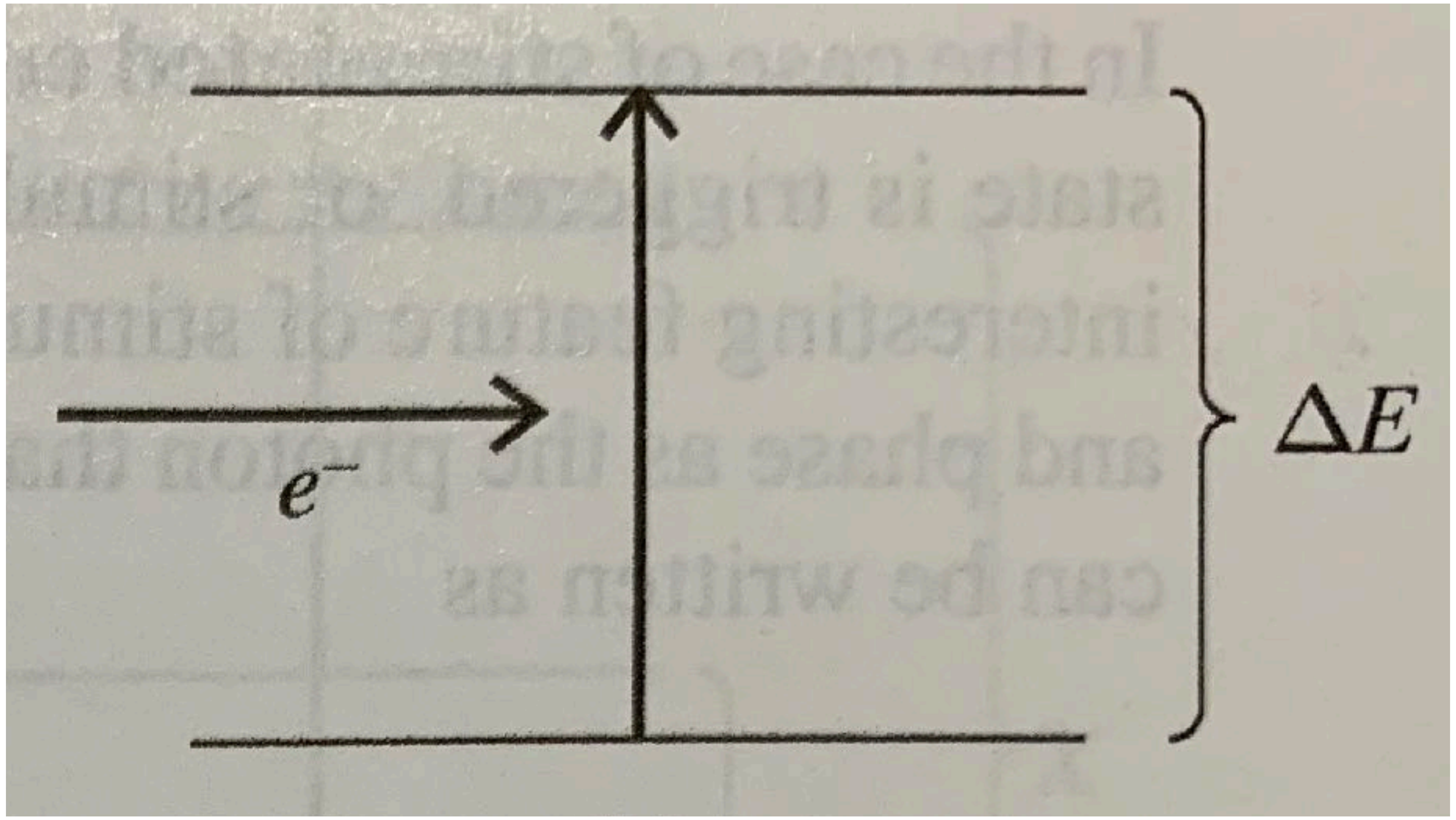
(Energies correspond to neutral hydrogen)



Absorption of Energy

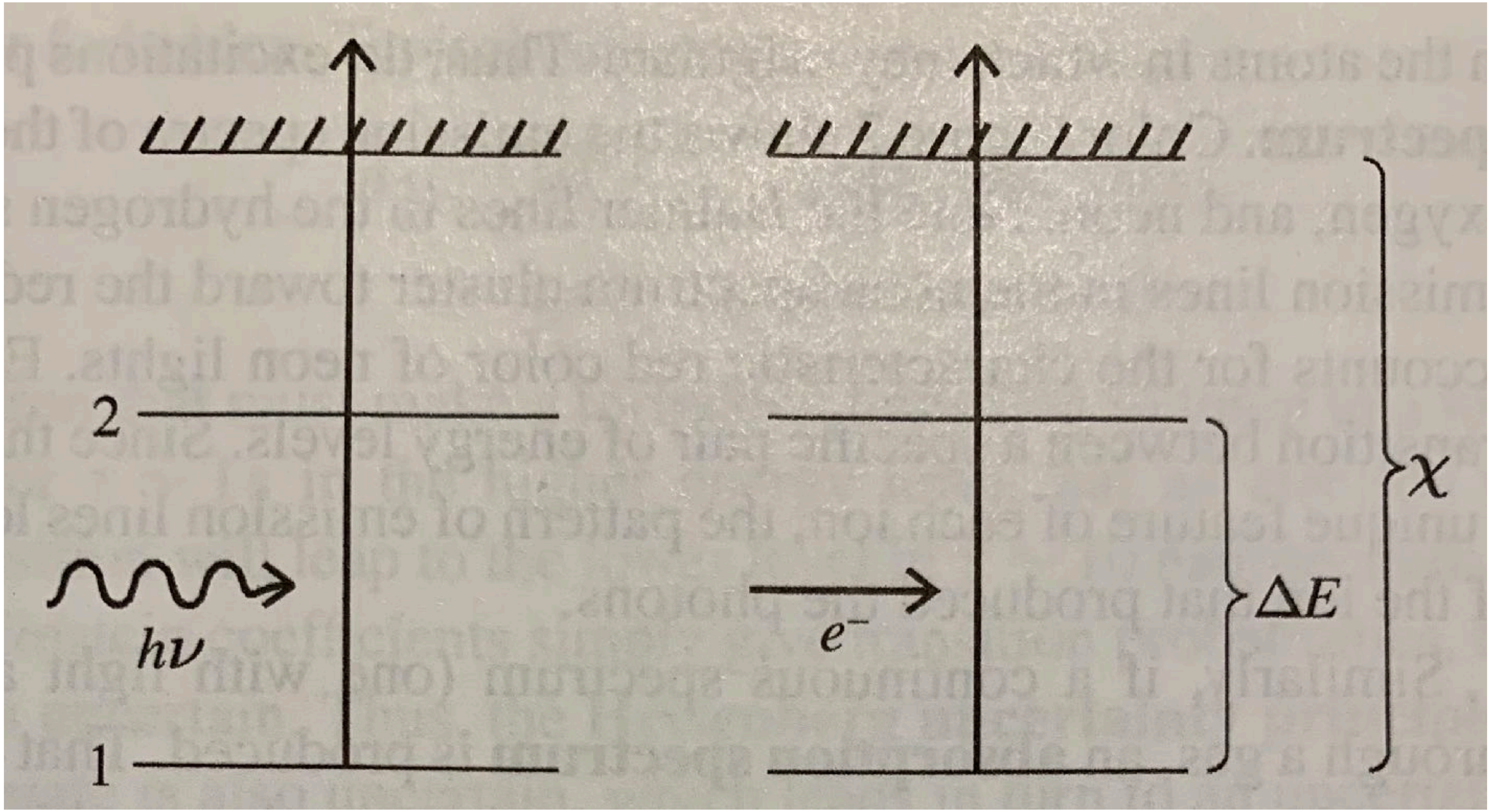


Photoexcitation



Collisional Excitation

Absorption of Energy



Photoionization

Collisional Ionization

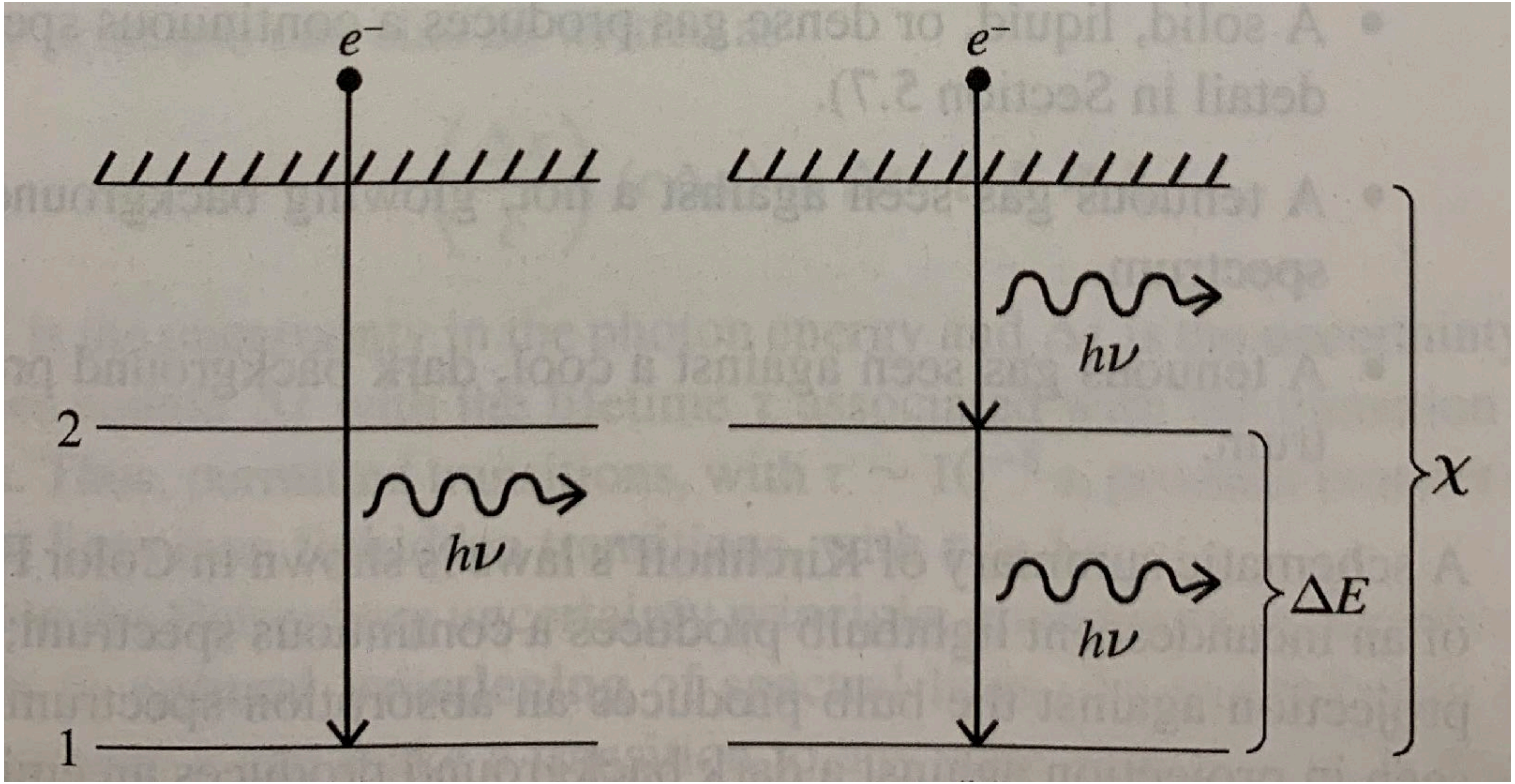
Emission of Energy

Stimulated Emission

Spontaneous Emission

Collisional De-excitation

Emission of Energy

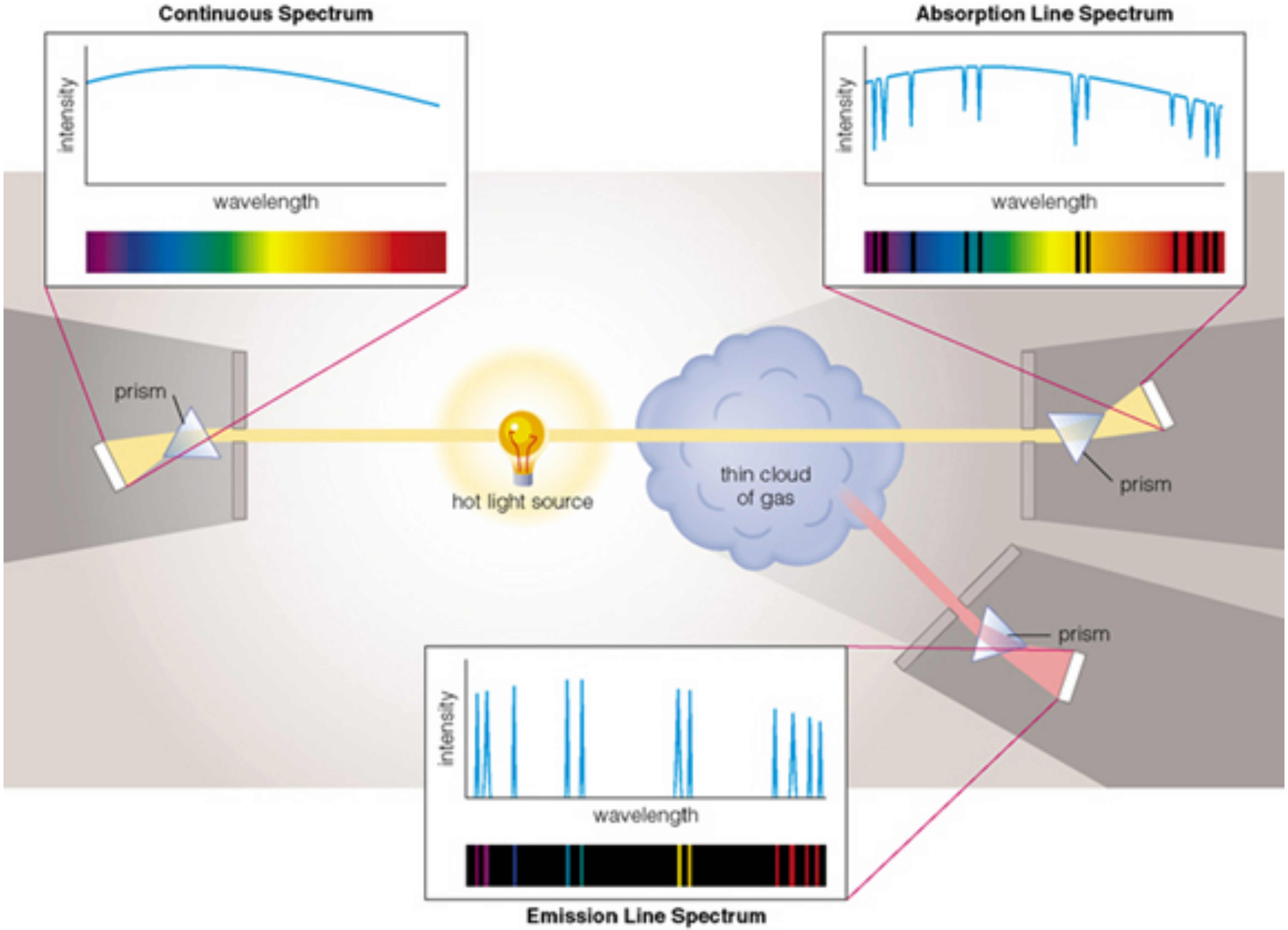


Radiative Recombination

Kirchoff’s Laws

- A solid, liquid, or dense gas produces a continuous spectrum.
- A tenuous gas in front of a hot background produces an absorption spectrum.
- A tenuous gas in front of a cool background produces an emission spectrum.


Hot blackbody
Cloud of
cooler gas
Prism
Prism
b
Absorption line spectrum
a
Continuous spectrum
c
Emission line spectrum

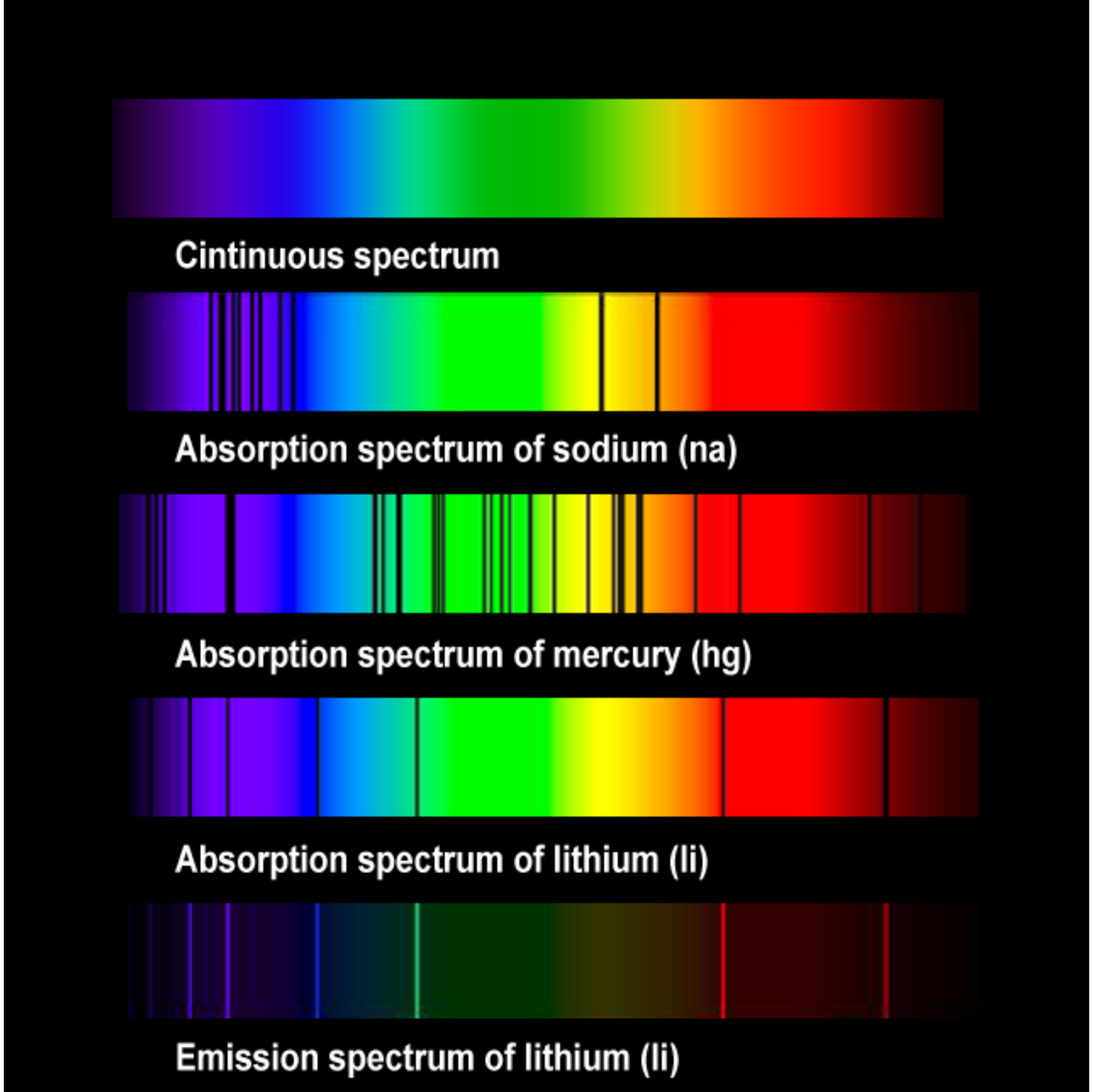

Continuous Spectrum
intensity
wavelength
Absorption Line Spectrum
intensity
wavelength
prism
hot light source
thin cloud
of gas
prism
prism
intensity
wavelength
Emission Line Spectrum

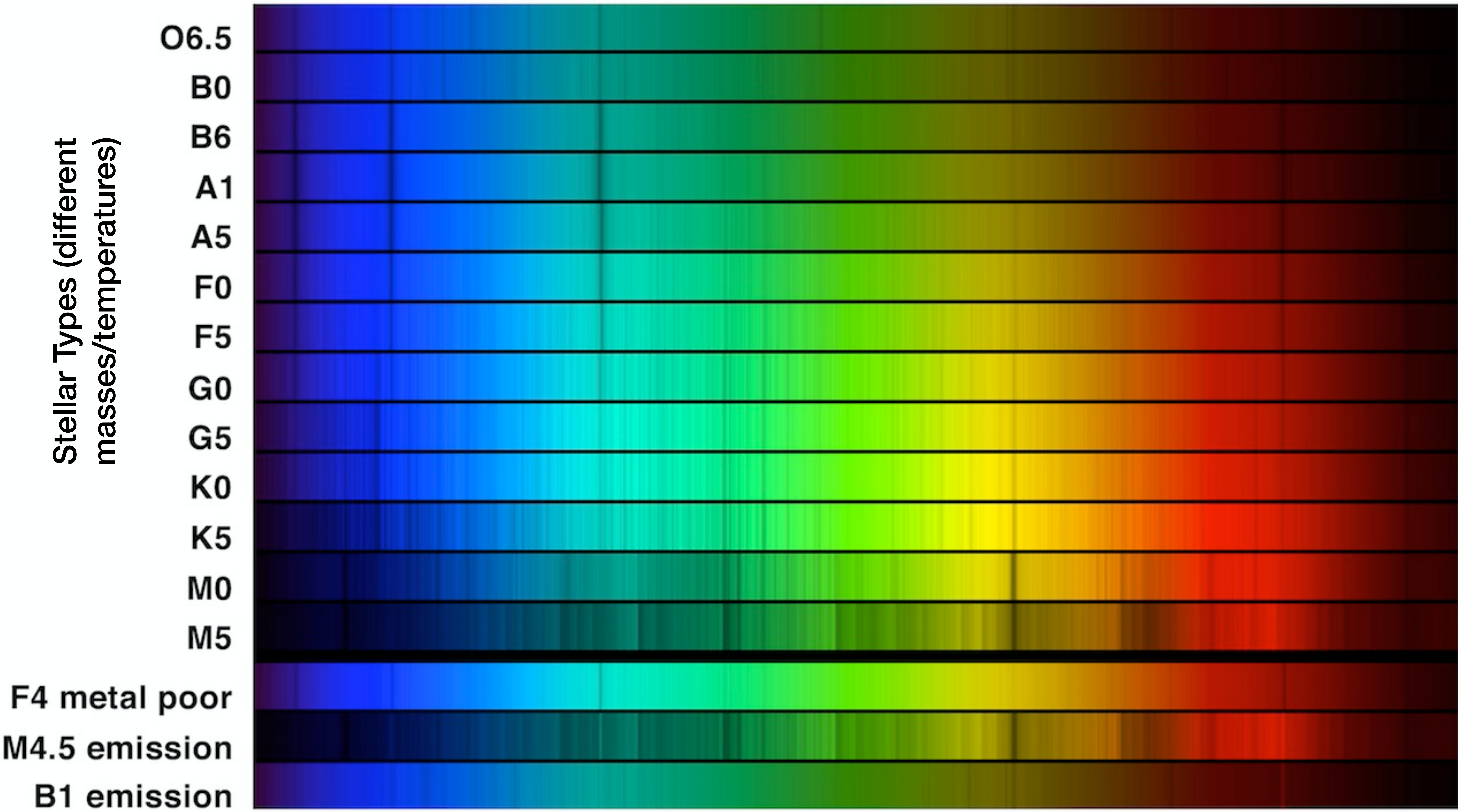
Spectra are like Fingerprints

They encode what and how much of an element is present in a gas (of a cloud, star, etc.), how hot it is, and whether it's being excited by something else

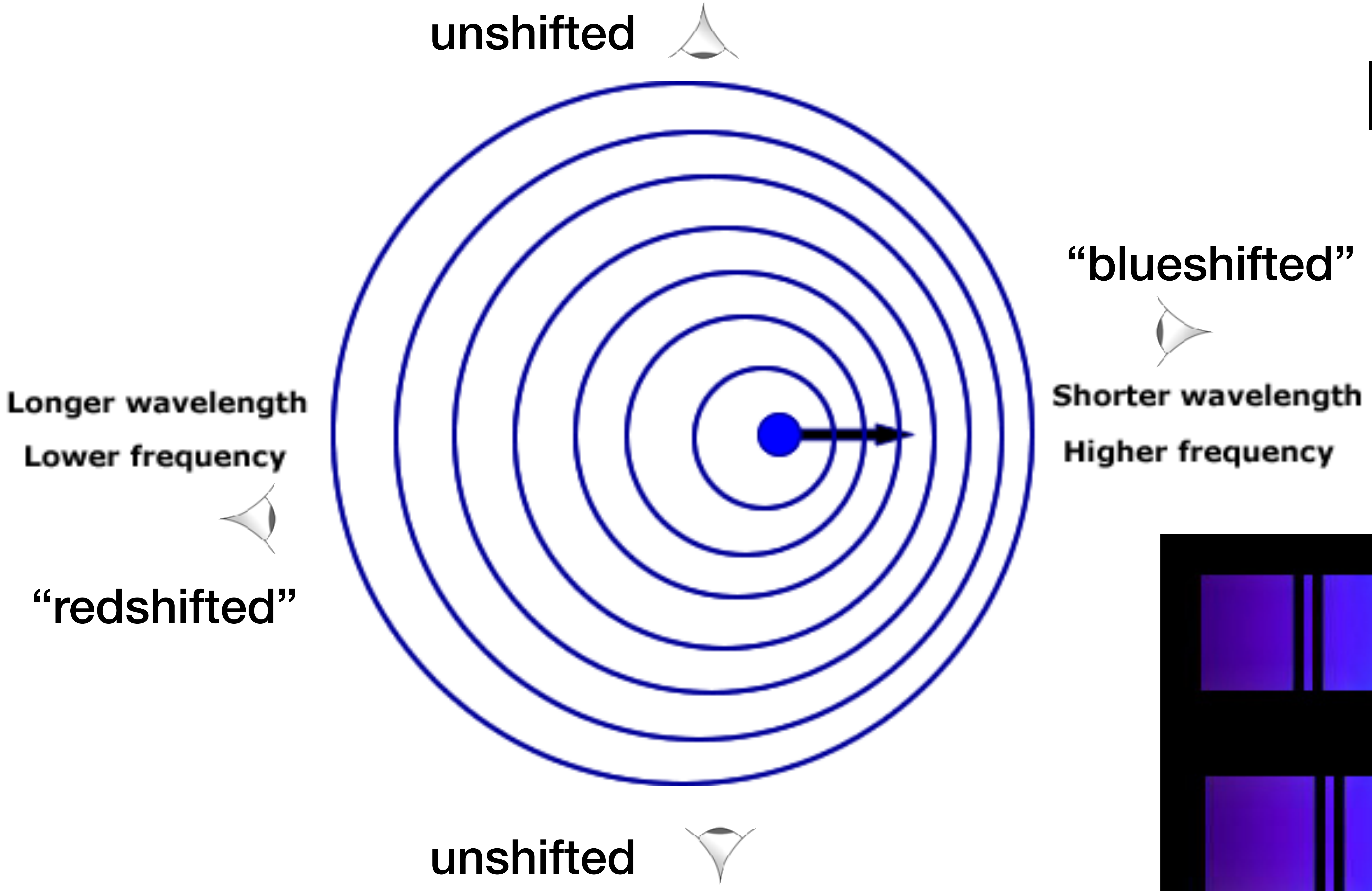
Each element has a unique pattern of lines, which can be seen in absorption or emission

$$\Delta E = E_n - E_{n'} = (13.6\ \mathrm{eV})\ Z^2 \left[\frac{1}{(n')^2} - \frac{1}{n^2}\right]$$

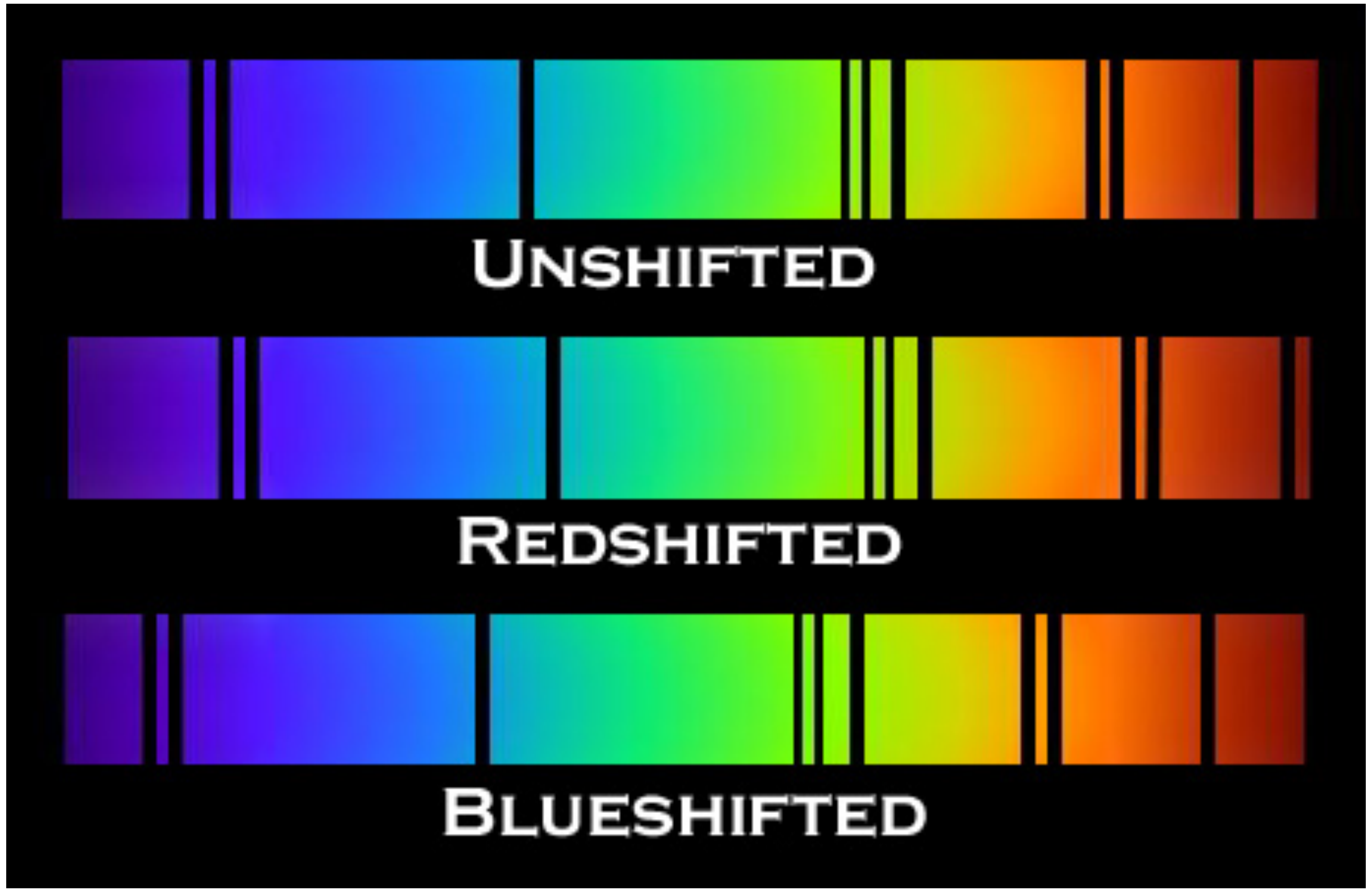



Stellar Types (different masses/temperatures)
O6.5
B0
B6
A1
A5
F0
F5
G0
G5
K0
K5
M0
M5
F4 metal poor
M4.5 emission
B1 emission

Doppler Shift



$$z = \frac{\Delta\lambda}{\lambda} = \frac{\Delta\nu}{\nu}$$



Allows us to infer motions
along the "line of sight"

Lines are not delta functions!

i.e., the difference b/t energy levels is NOT exact

Motion-induced Broadening (small Doppler shifts cause lines to appear more broad)

- Thermal Broadening
- Rotational Broadening
- Turbulent Broadening

Other Types of Broadening

- Natural Broadening
- Pressure Broadening
- Zeeman Broadening

Natural Broadening

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

$$A_{21} \sim 10^8 \text{ s}^{-1}$$ (permitted)

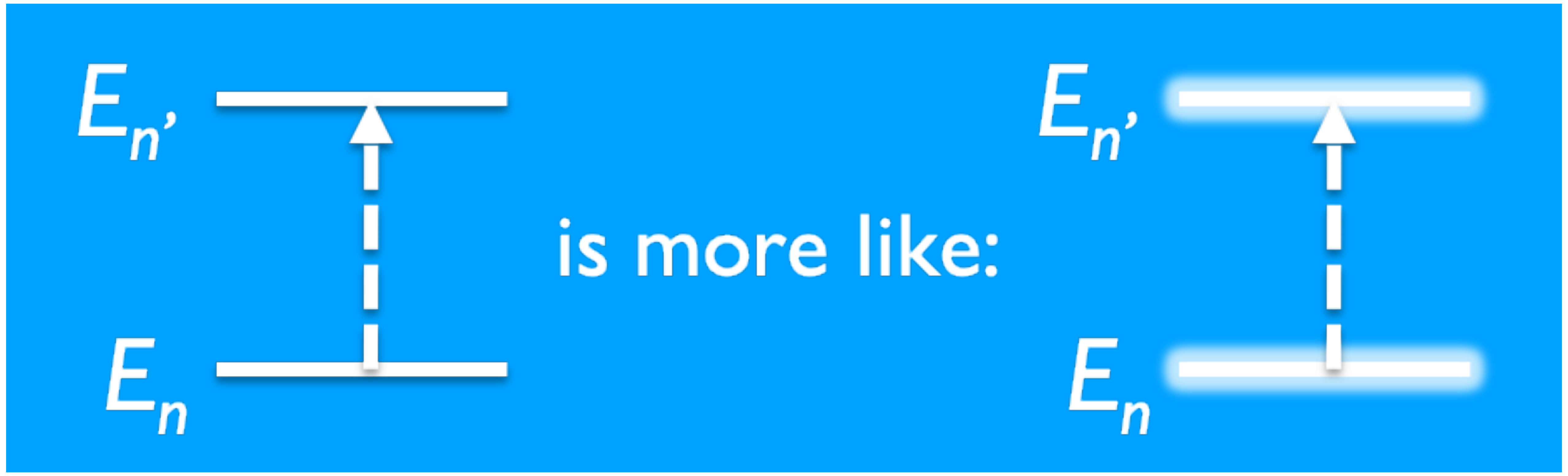
$$\sim 1 \text{ s}^{-1}$$ (forbidden)

Heisenberg uncertainty principle

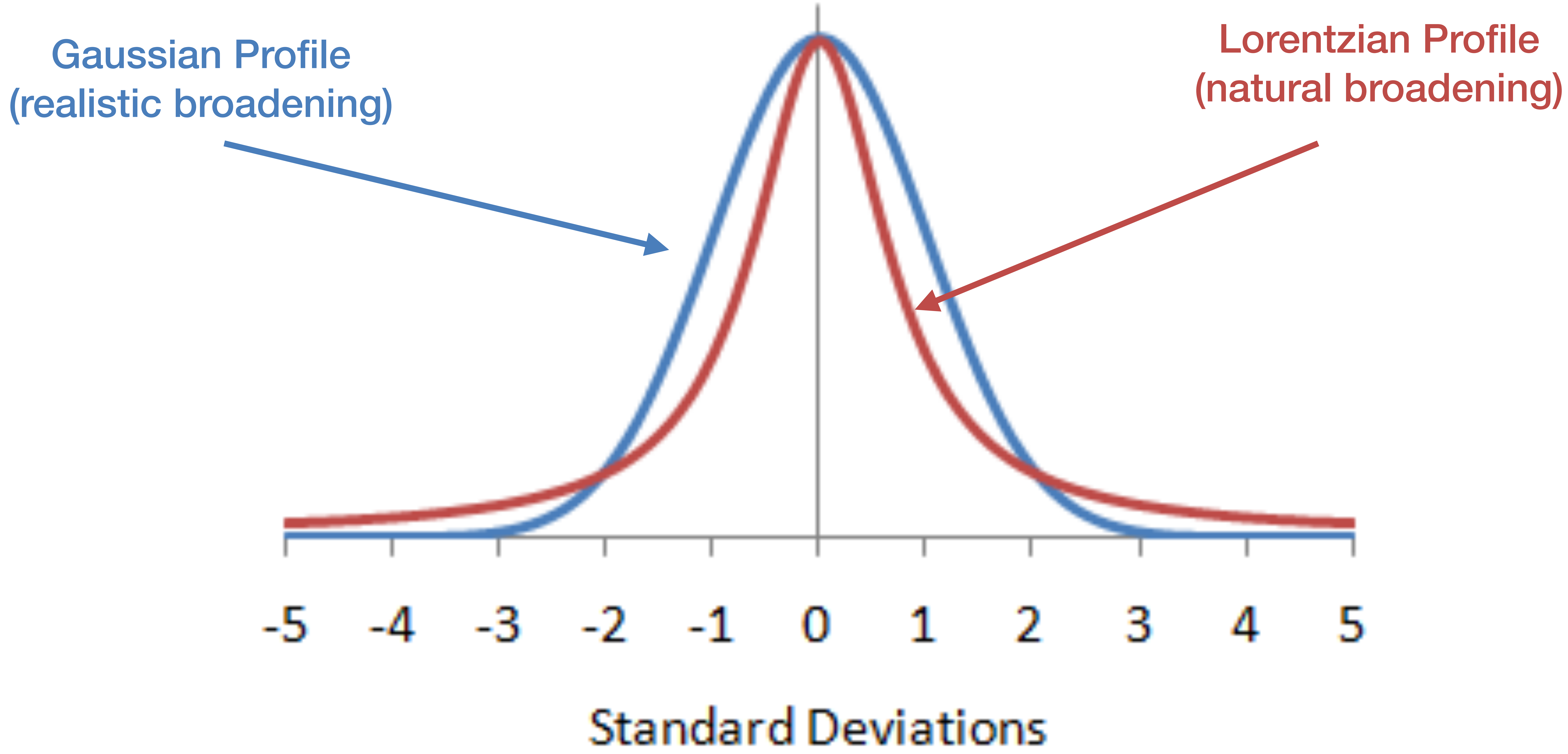
$$\Delta x \cdot \Delta p \gtrsim \hbar$$

$$(\frac{\Delta x}{c})(\Delta p \cdot c) \gtrsim \hbar$$

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



Broadened Line Shapes



$$(\nu - \nu_0)/\sigma$$

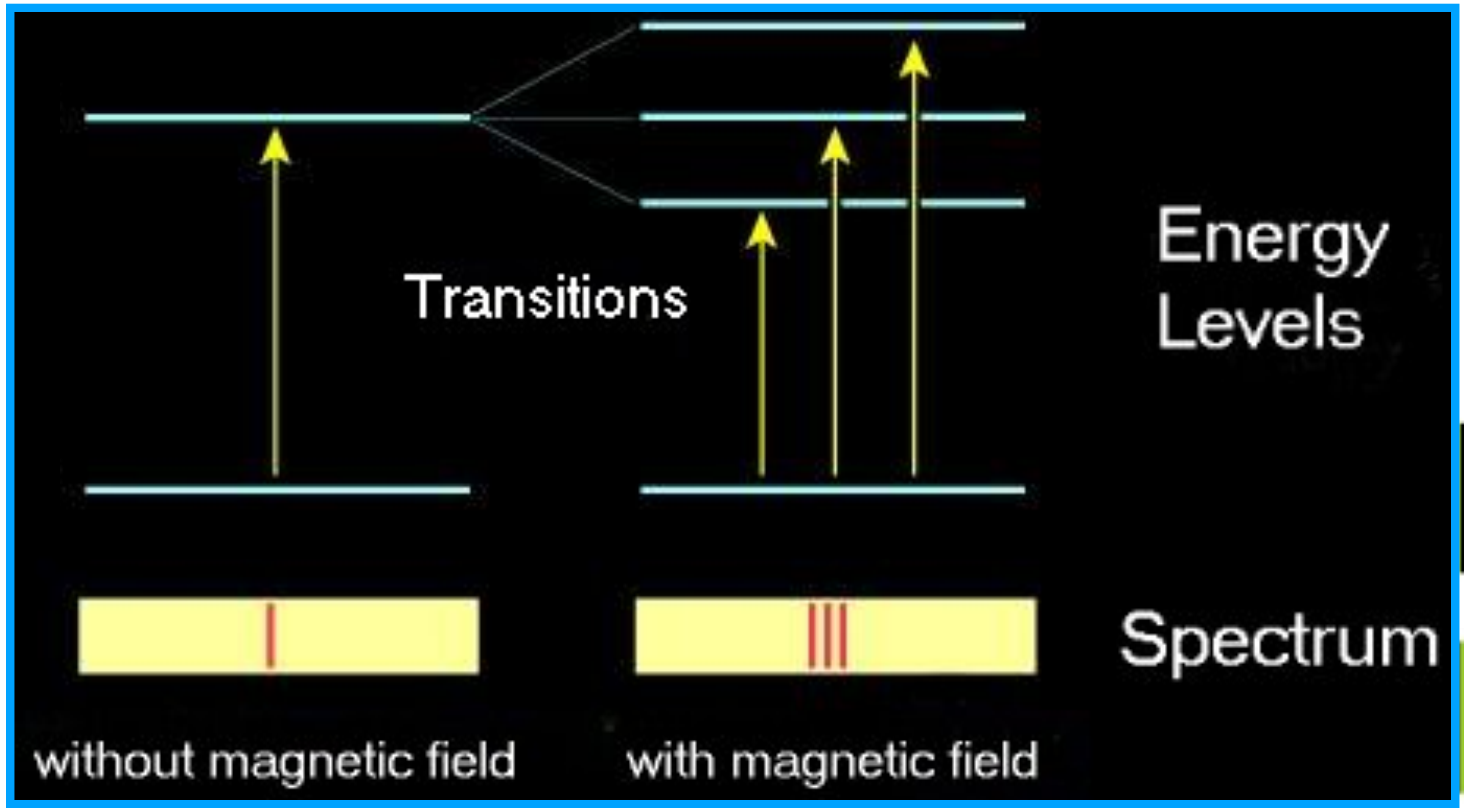
Lines are not delta functions!

i.e., the difference b/t energy levels is NOT exact

Dense environments, frequent collisions induce electric fields that modify energy levels

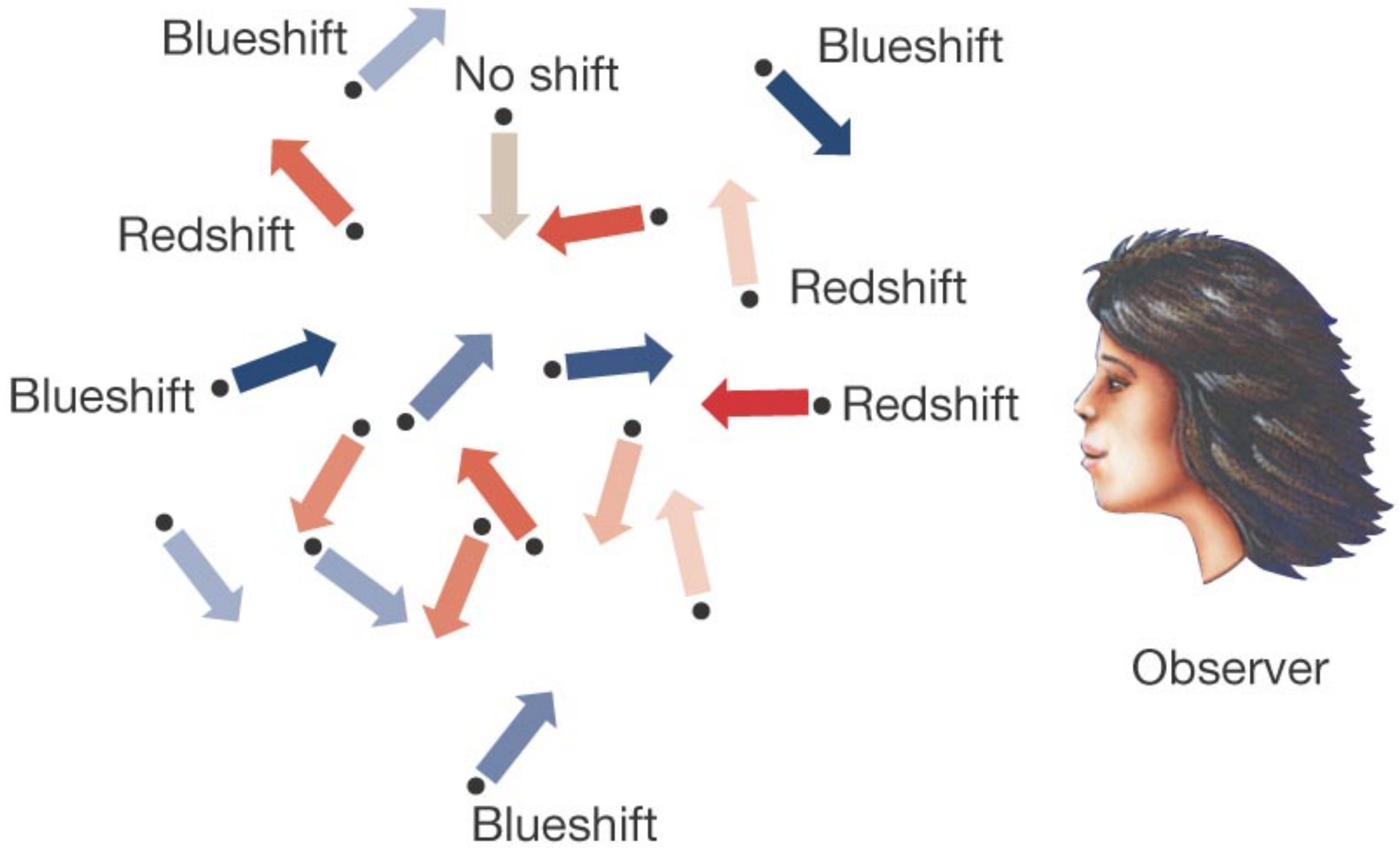
Other Types of Broadening

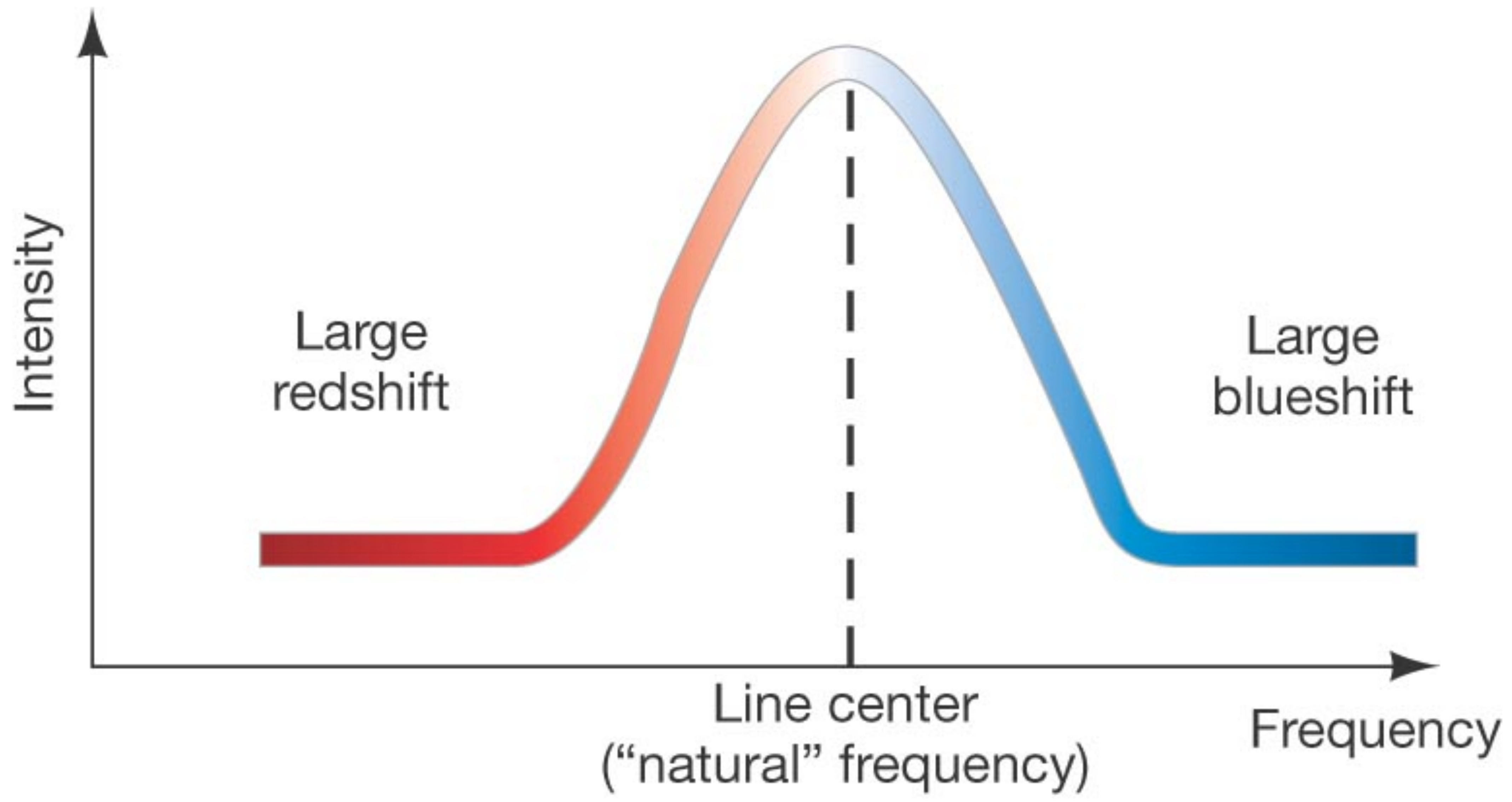
- Natural Broadening
- Pressure Broadening
- Zeeman Broadening



broadened

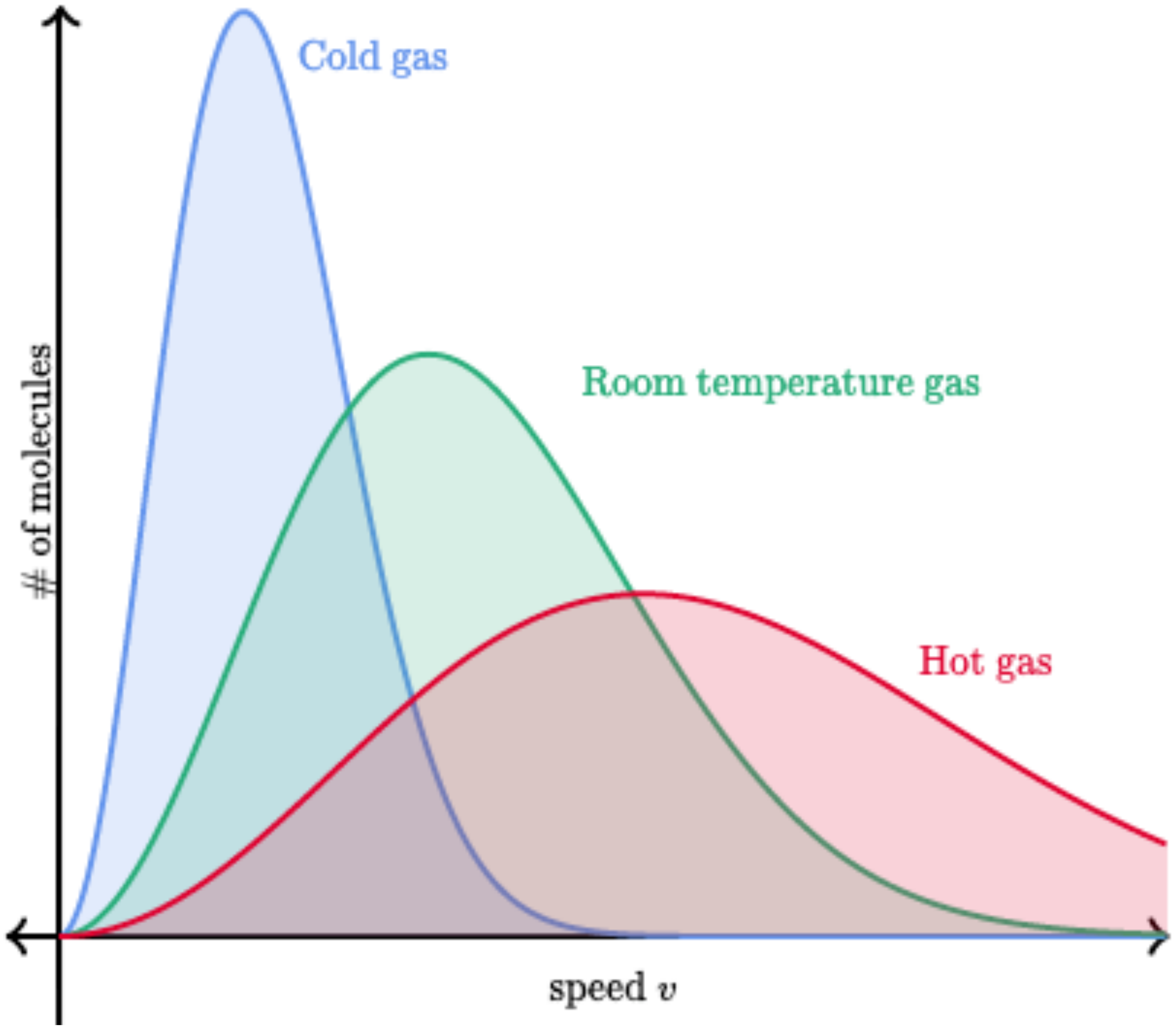
Doppler Broadening





Thermal Broadening

Velocity distribution of particles in thermal equilibrium have a Maxwell-Boltzmann distribution



$$F(v)dv = 4\pi \left(\frac{m}{2\pi kT}\right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2kT}\right) dv$$

$$F(E)dE = F(v)\frac{dv}{dE} = \frac{2}{\sqrt{\pi}kT}\left(\frac{E}{kT}\right)^{1/2} \exp\left(-\frac{E}{kT}\right)$$

$$\langle x \rangle = \int x f(x) dx$$

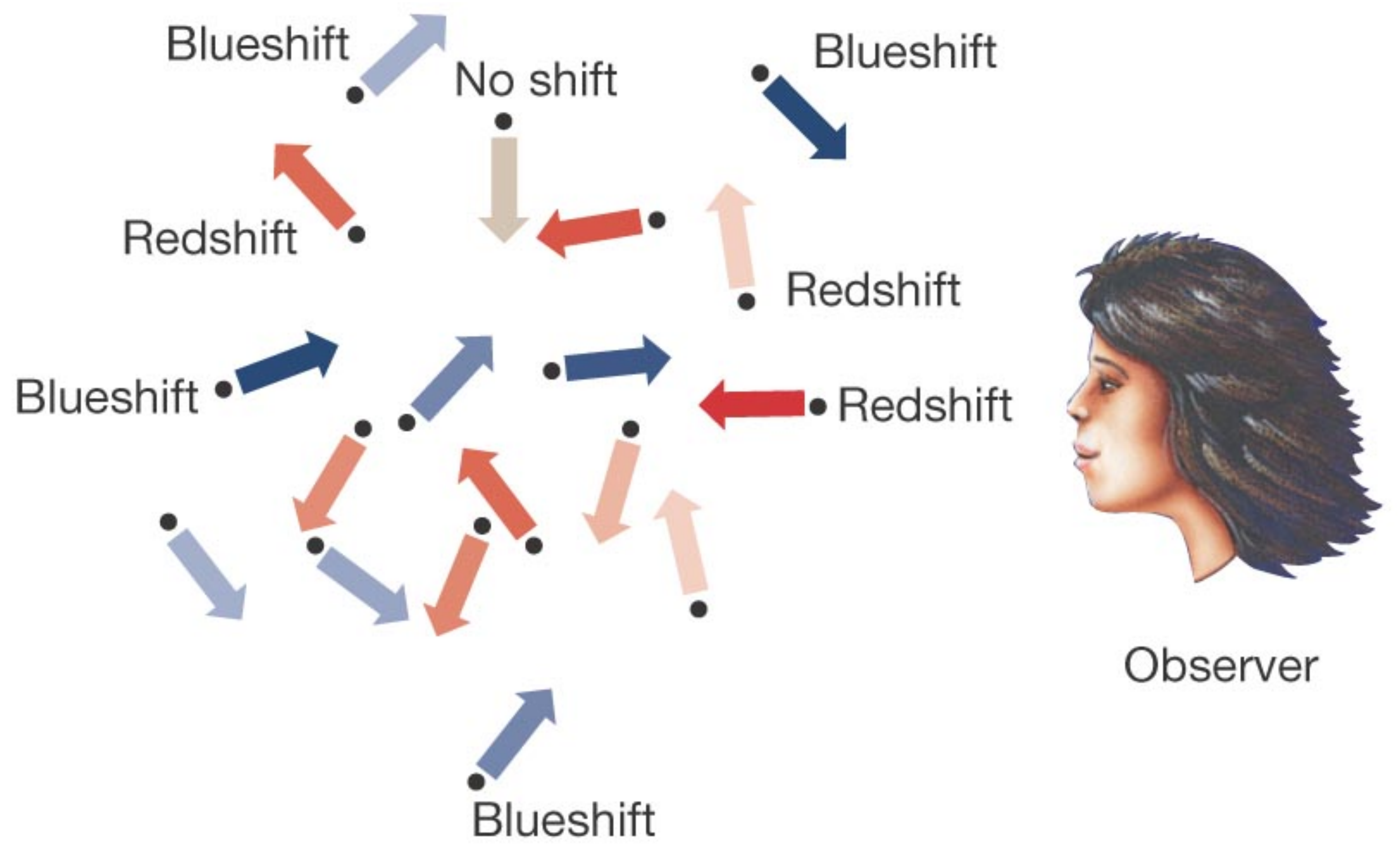
$$\langle v \rangle = \sqrt{\frac{8kT}{\pi m}}$$

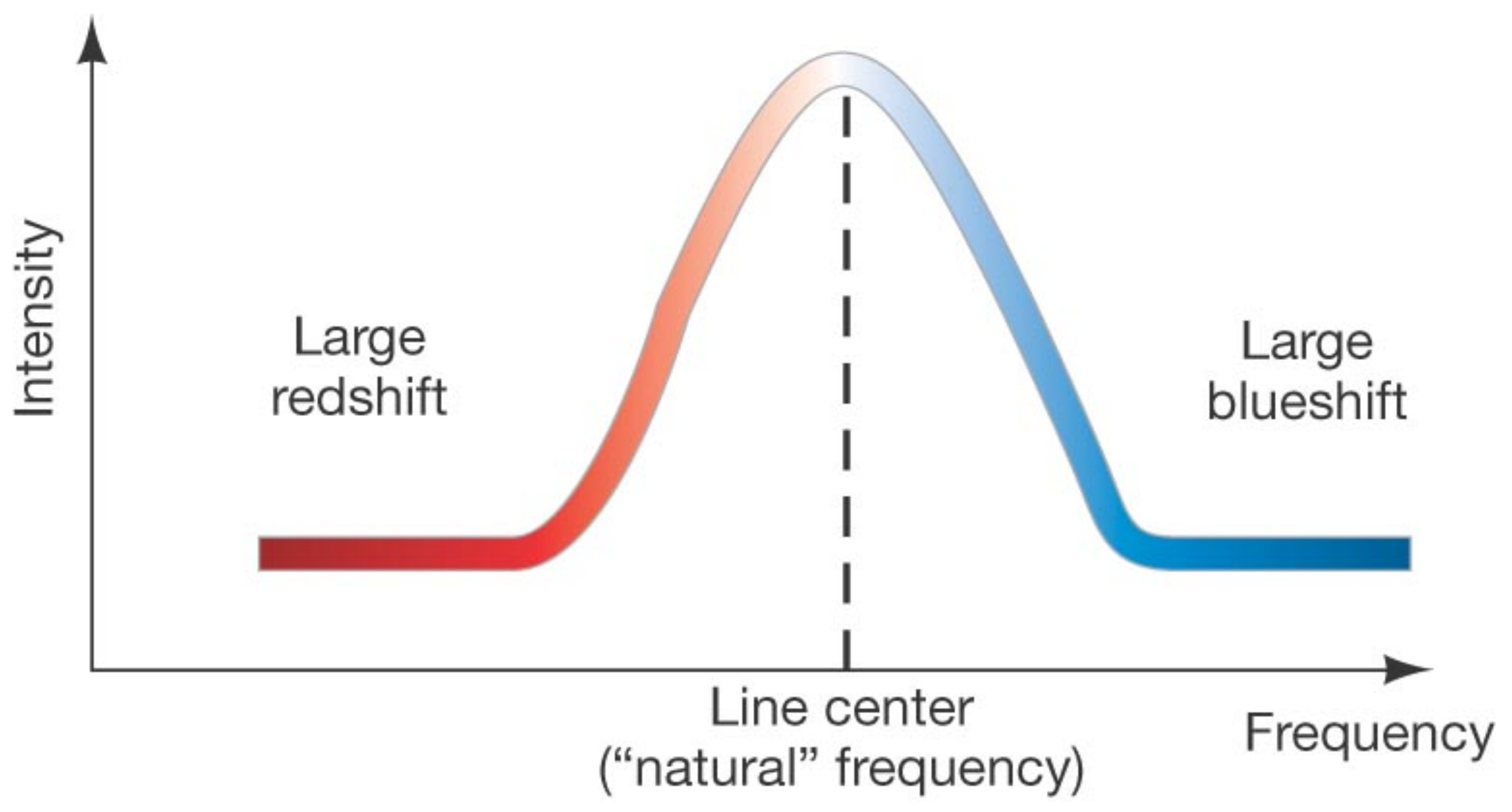
Avg. particle speed

$$\langle E \rangle = \frac{3}{2}kT$$

Avg. particle kinetic energy

Doppler Broadening





Thermal Broadening

line-of-sight "velocity dispersion"
(width of a Gaussian distribution)

$$\sigma_{\rm los} = \left(\frac{kT}{\mu m_p}\right)^{1/2} \approx 100 \text{ m s}^{-1} \left(\frac{T}{1\ K}\right)^{1/2} \mu^{-1/2} \longrightarrow \frac{\Delta\lambda}{\lambda} \approx \frac{\sigma_{\rm los}}{c}$$

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