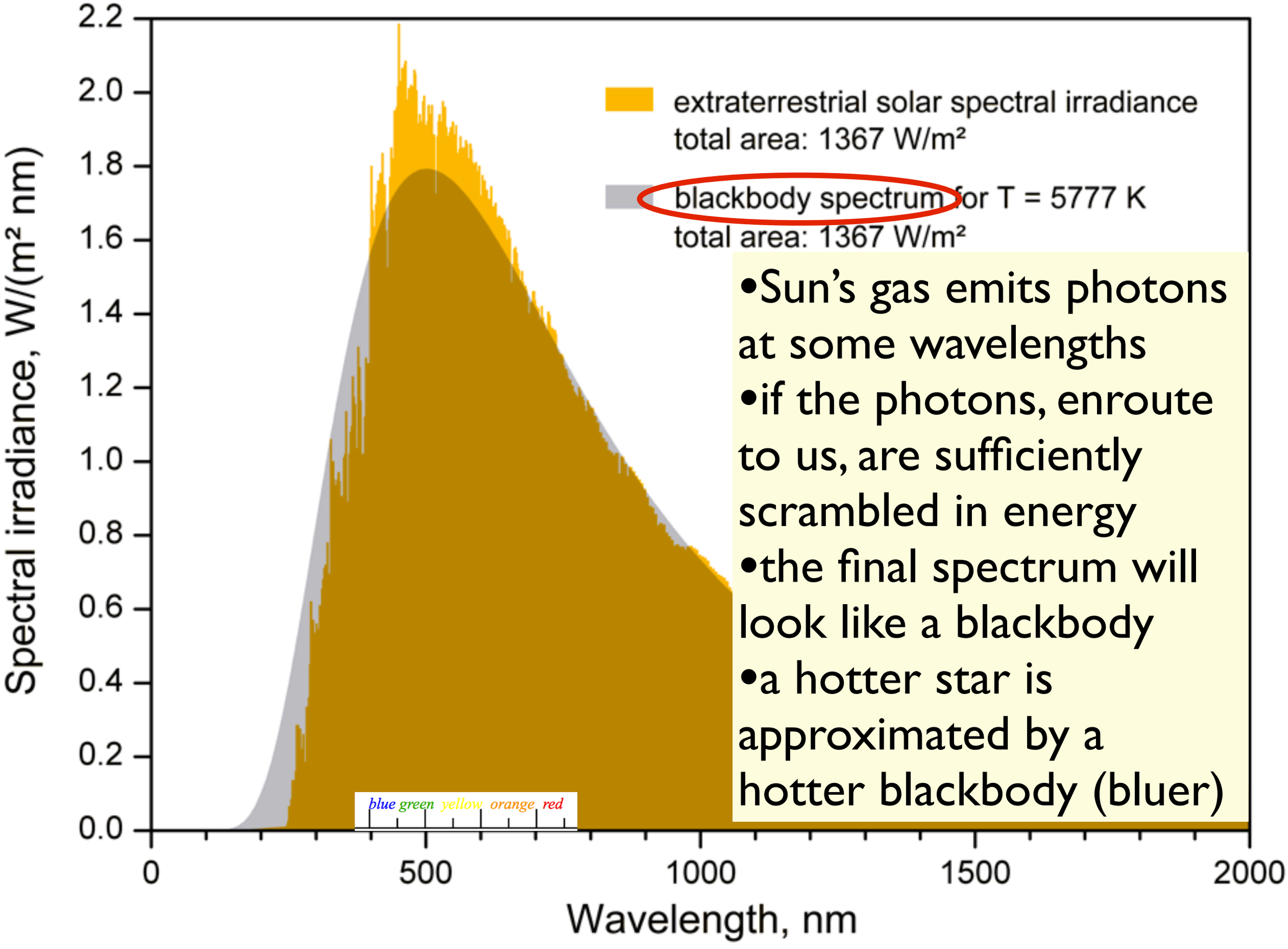
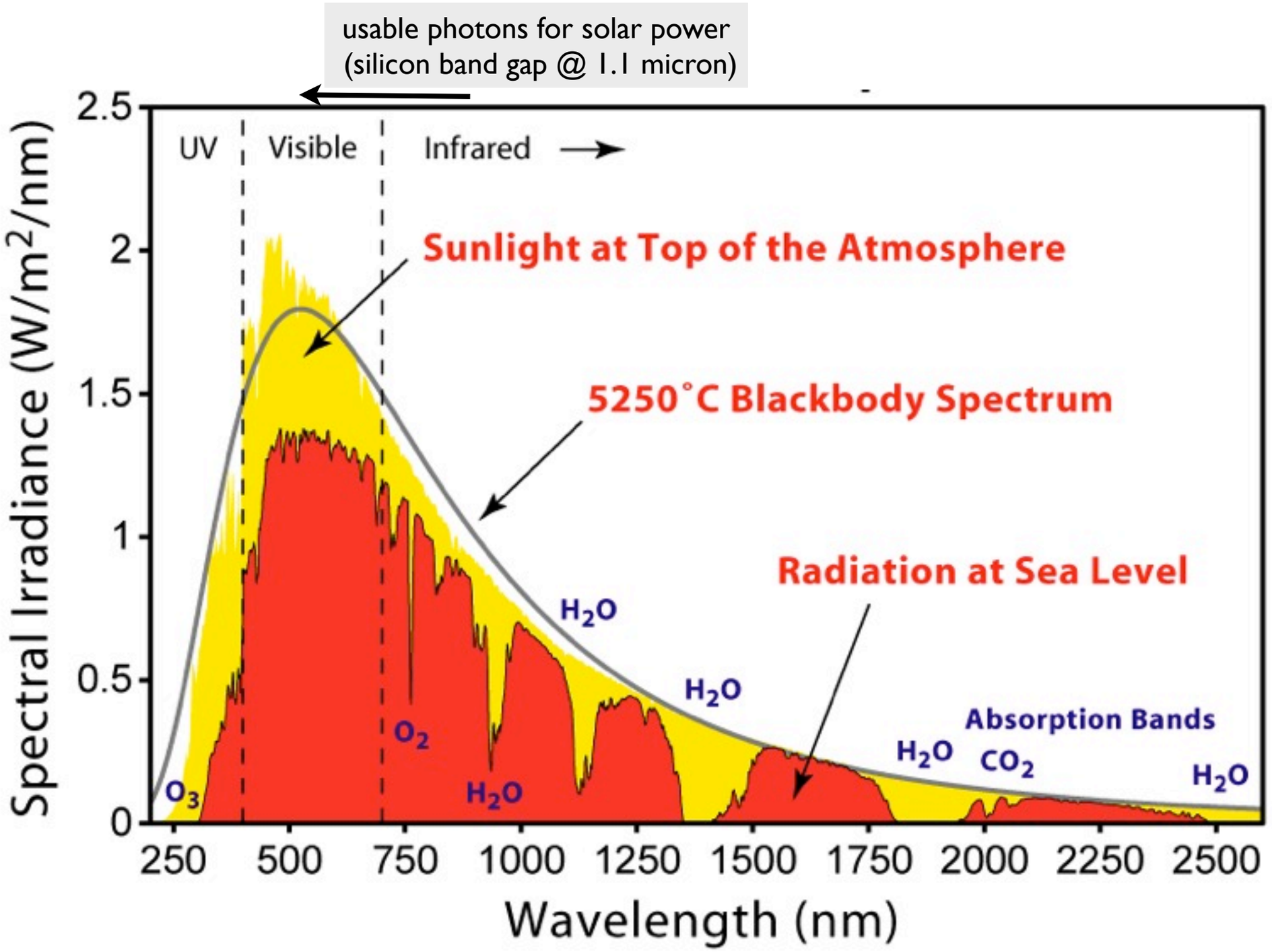
the "blackbody" spectrum is an approximation

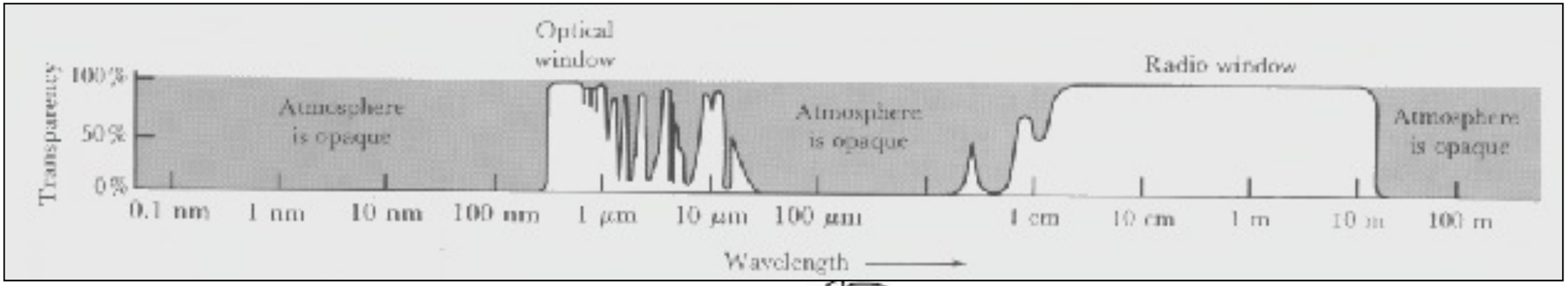


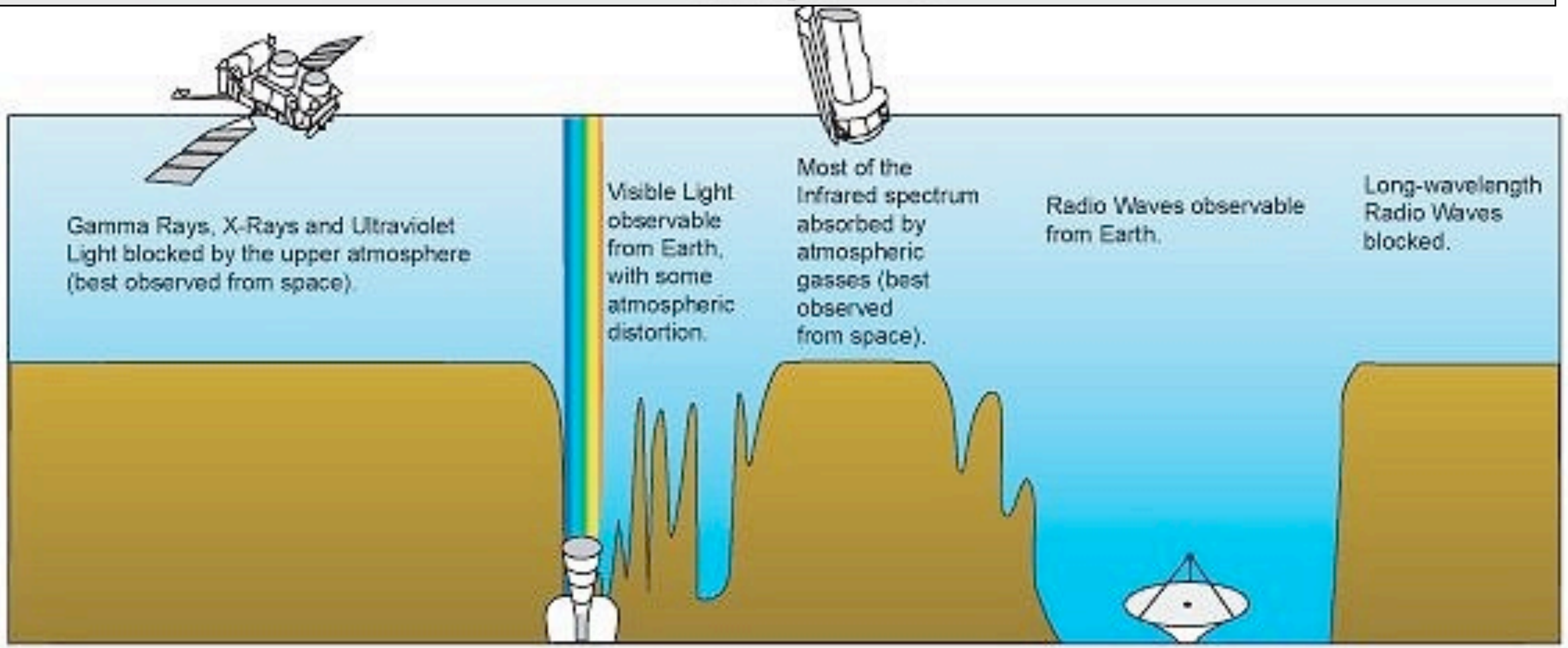
- Sun's gas emits photons at some wavelengths
- if the photons, enroute to us, are sufficiently scrambled in energy
- the final spectrum will look like a blackbody
- a hotter star is approximated by a hotter blackbody (bluer)

- Molecules in the Earth atmosphere absorb in certain wavelengths (filtering)
- Ozone (O_3) absorbs in UV
- H_2O, CO_2 absorbs in infrared, "the Greenhouse effect"



Due to these absorptions, our atmosphere is transparent only in optical & radio.





Atoms/molecules absorb or emit at specific wavelengths.

This allows us to study the make-up of celestial bodies as if they are on our table-top.

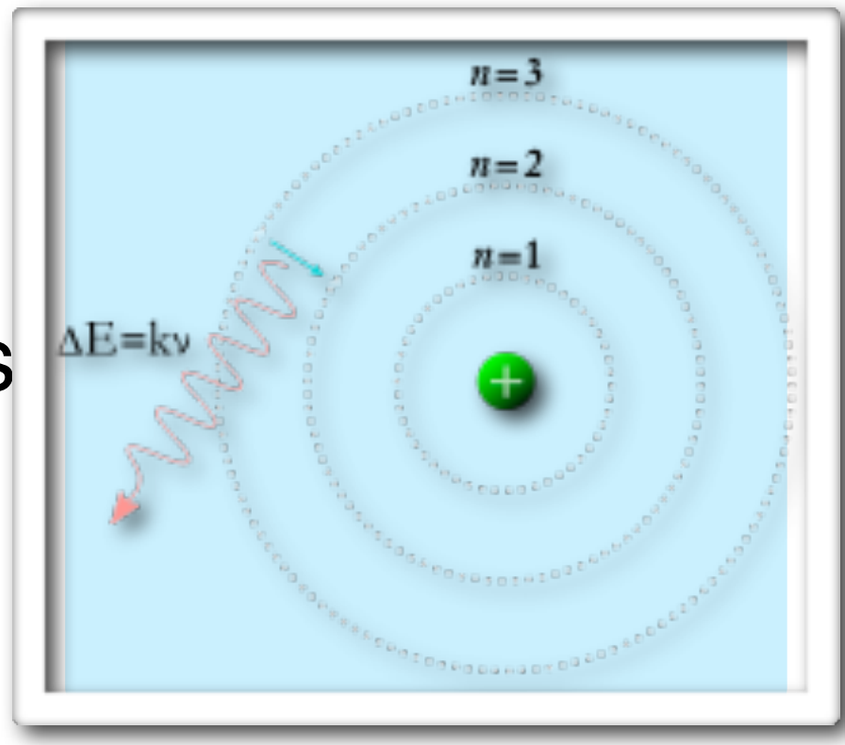
The mechanism behind this was first revealed by Niels Bohr in the 1920s.

Quantum mechanical behaviour of matter
-- Niels Bohr's hydrogen atom (1913)

•classical orbits, e.g., planetary orbits around the Sun, can be of any shape/size.

•electron is both a wave and a particle. inside an atom, its wave-like nature determines that it can only have some special orbits.

•Electrons can only move between these allowed orbits, by interacting with photons Otherwise they remain stable.



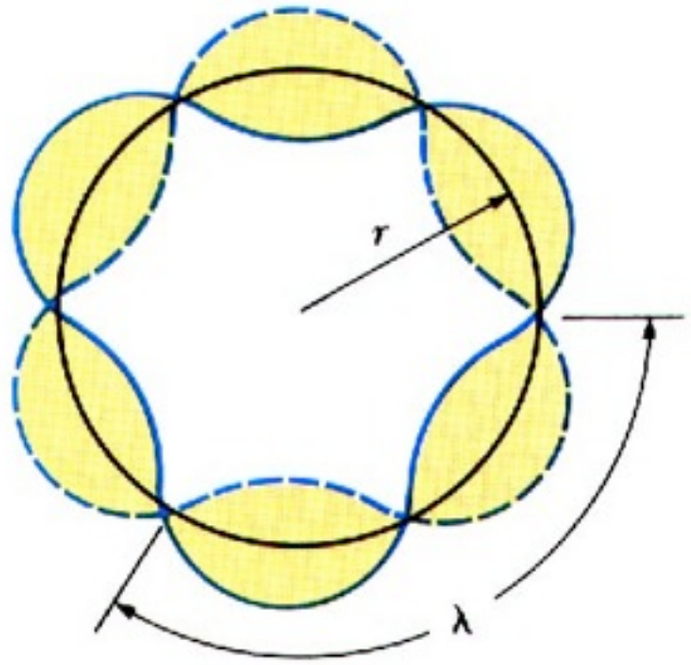
What are these special orbits?

- electrons are particles as well as waves, with wavelength (the de Broglie wavelength)

$$\lambda = h/p = h/(m\ v)$$

- **assume**: the circumference of the orbit has to be an integer number times the wavelength (standing wave)

$$2\ \pi\ r = n\ \lambda = n\ h/(m\ v)$$



- r and v are related: electrostatic attraction between the nucleus and the electron has to be balanced by the centrifugal force

$$\frac{k_e e^2}{r^2} = \frac{m_e v^2}{r}$$

Energy of an orbit with quantum number n

- size of the orbit is quantized as

$$r = n^2 \left(\frac{h}{2\pi}\right)^2 \frac{1}{m_e k_e e^2} = n^2 \frac{\hbar^2}{m_e k_e e^2} = n^2 \times (0.5\mathring{A})$$

- and the energy is quantized as

$$E = \frac{1}{2} m_e v^2 + \left(-\frac{k_e e^2}{r}\right) = -\frac{1}{n^2}\left(\frac{k_e^2 e^4 m_e}{2\hbar^2}\right) \approx -\frac{1}{n^2} \times (13.6\text{ev})$$

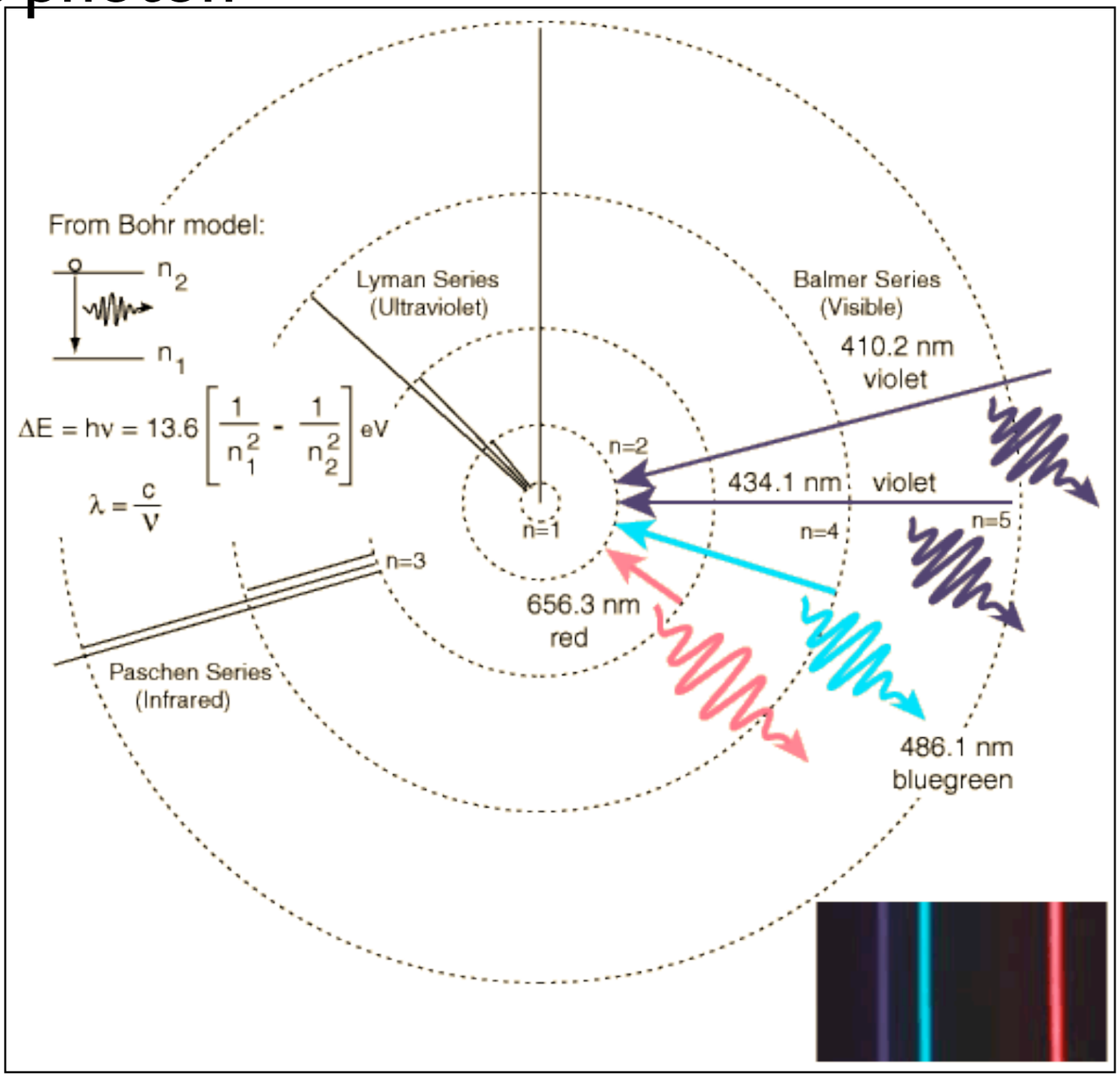
- this is a semi-classical theory that gives the right result. Modern quantum mechanics posits that electrons are spherical clouds of probabilities.

. electron orbits have discreet energies

.an electron at the n=2 orbit, decays to the n=1 orbit: emits a photon

.to go backward: absorbs a photon

. .....

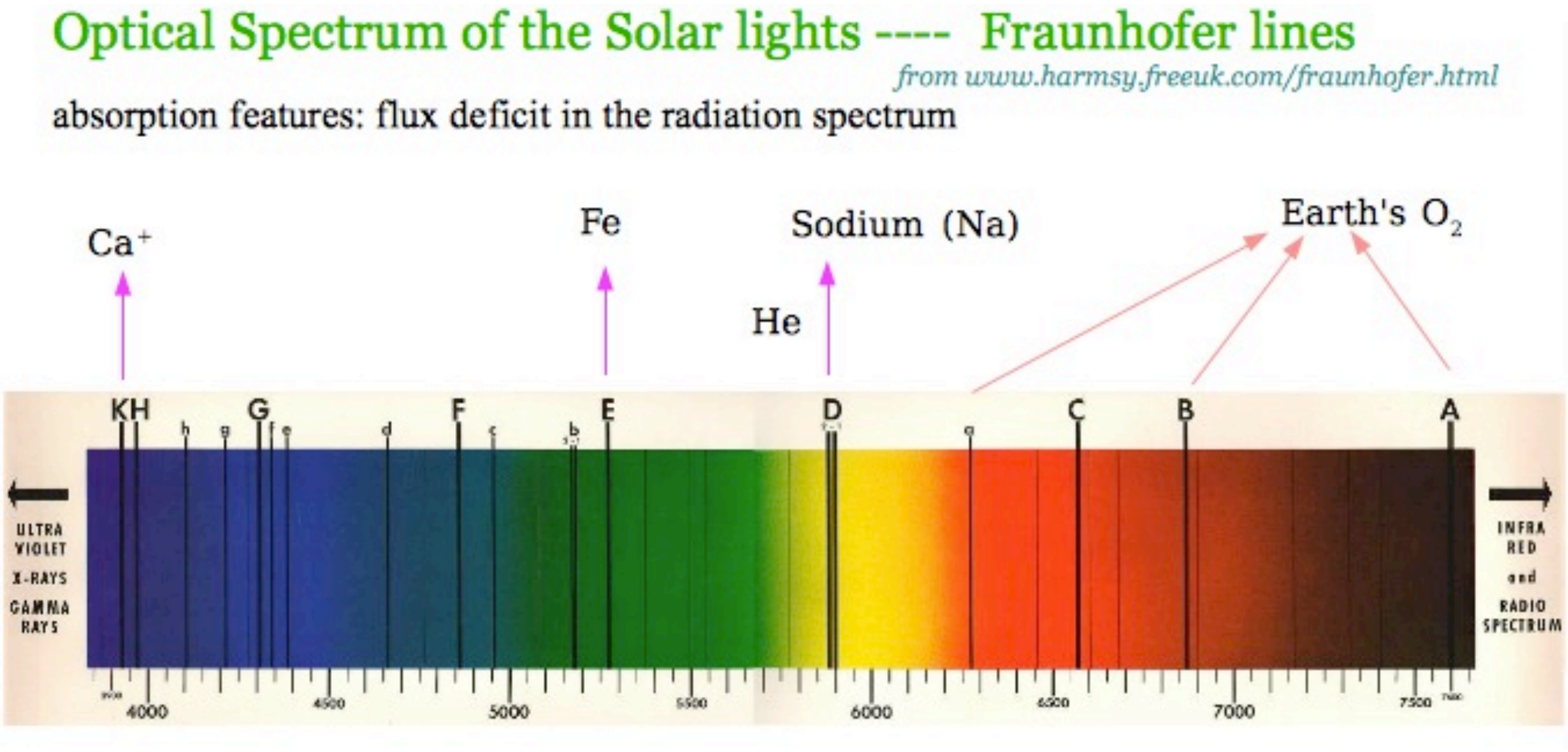


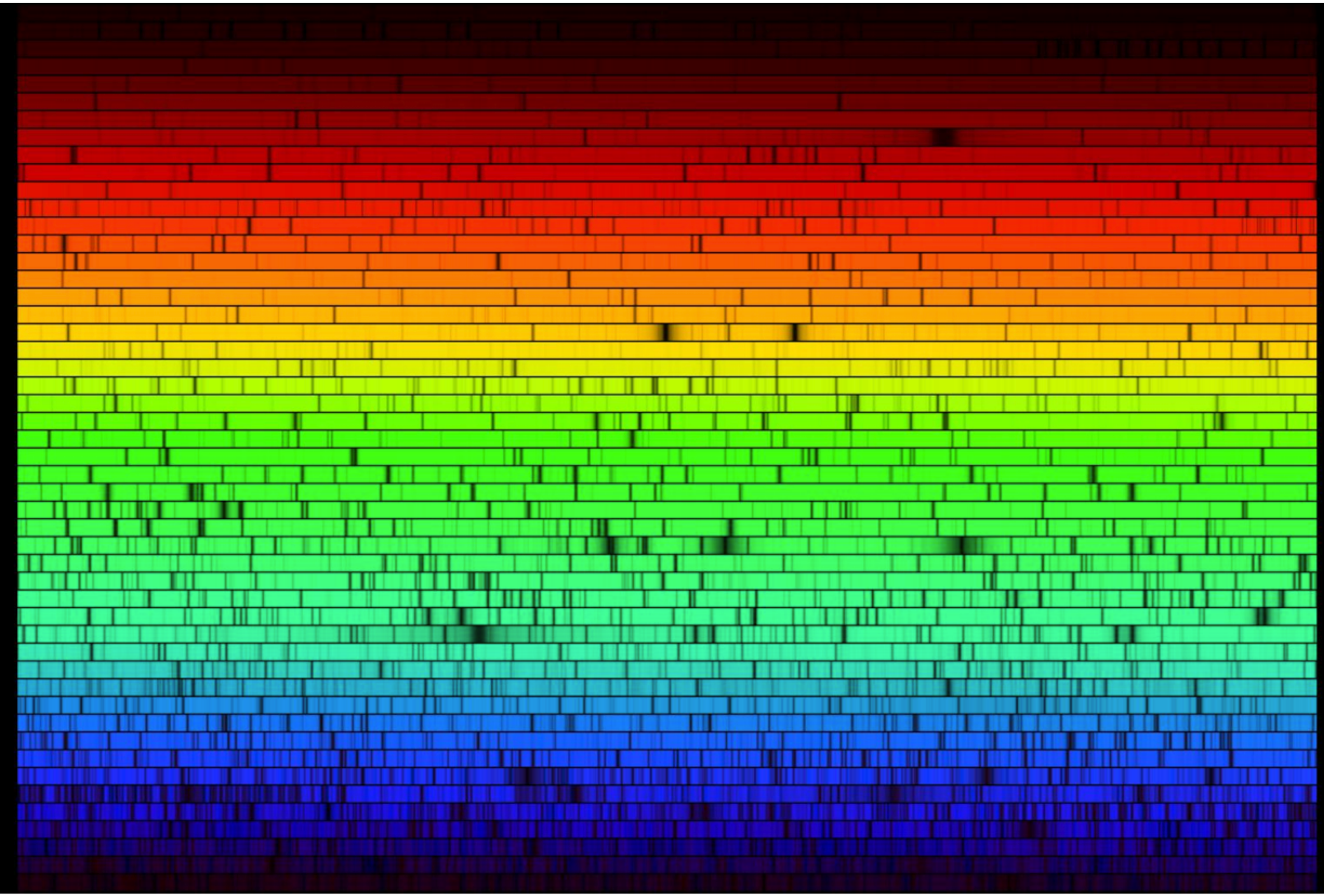
Lyman, Balmer, Paschen...series

"Of all objects, the [stars and] planets are those which appear to us under the least varied aspect. We see how we may determine their forms, their distances, their bulk, and their motions. Be we can never know anything of their chemical or mineralogical structure.

– August Comte (1842)
Famous French Philosopher

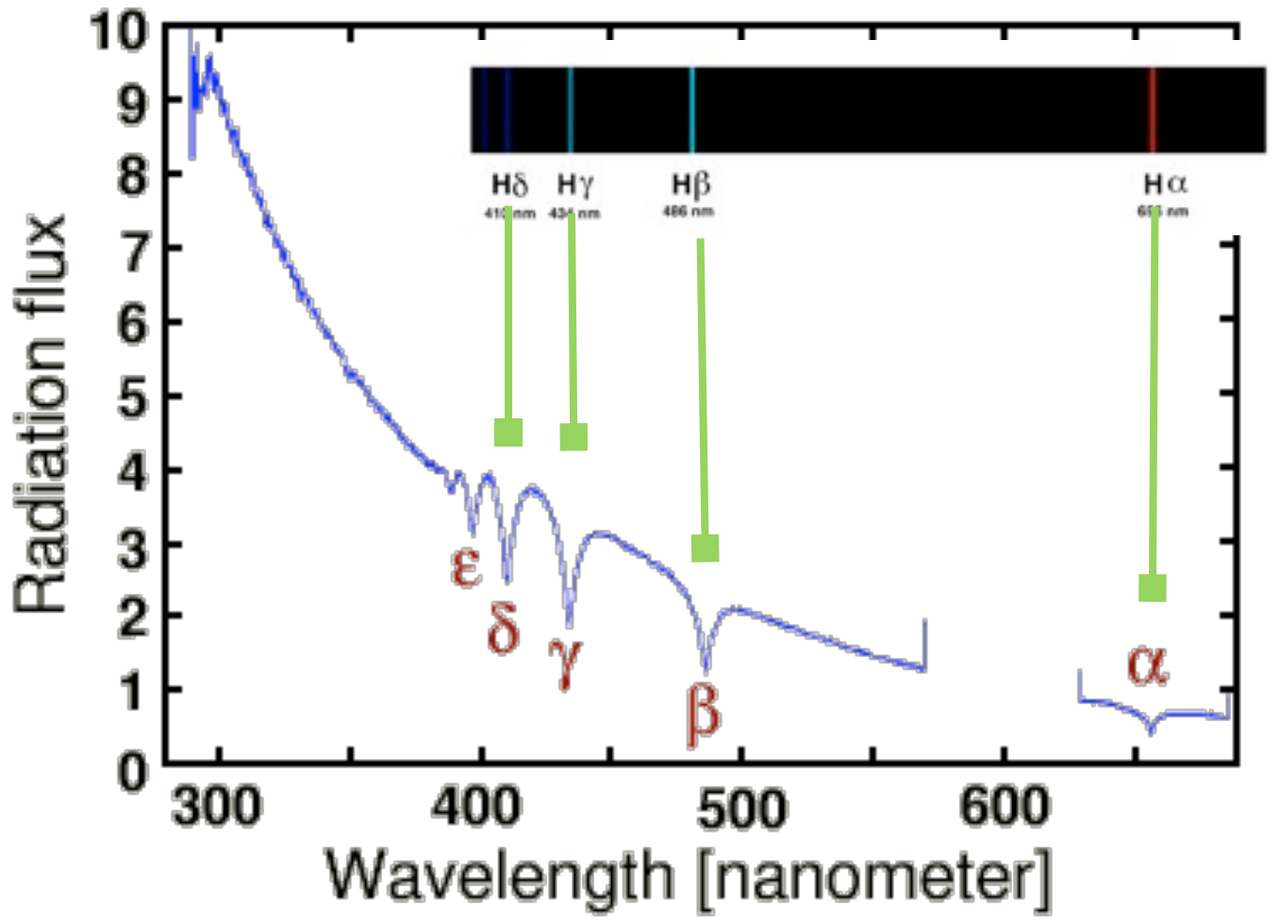
Eight years later (1850), Fraunhofer found this when looking at the Sun through a prism (don't do this at home):

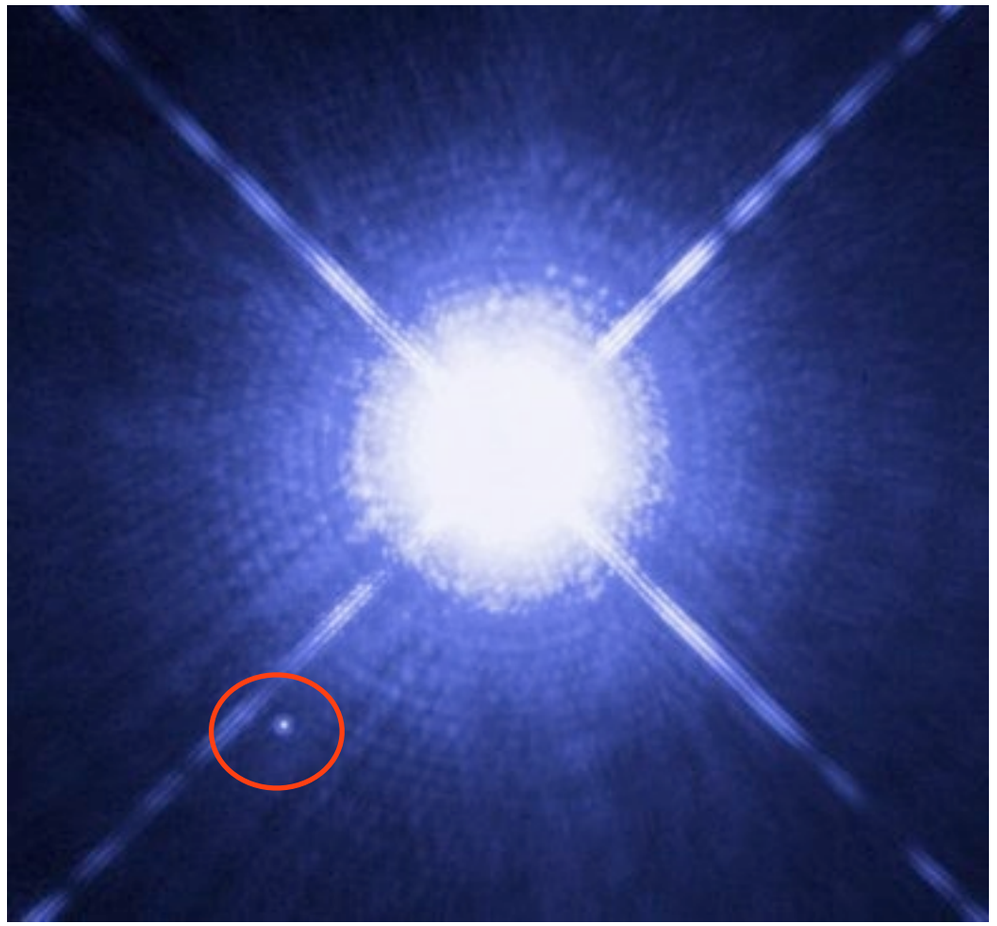




a very high resolution spectrum of the Sun

Spectrum of Sirius B (a white dwarf)

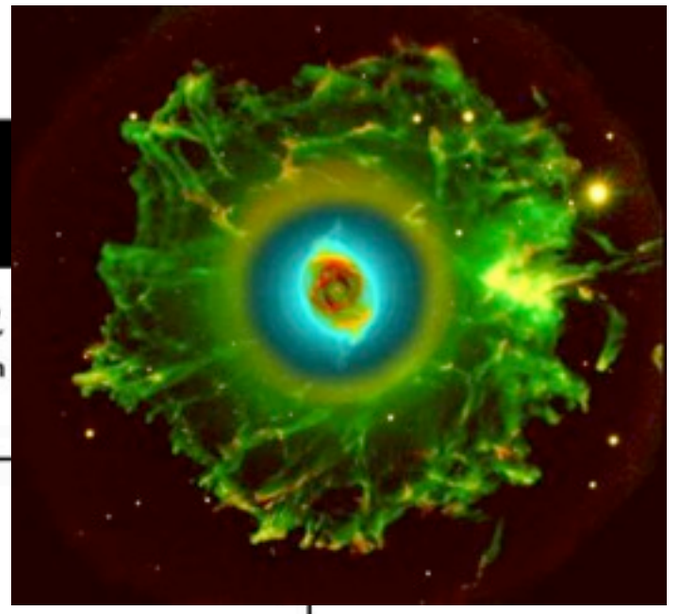




Hydrogen gas is in absorption

blackbody radiation from deeper, hotter layers of the star is absorbed by the cooler outer layer of gas at specific wavelengths, producing an **absorption spectrum**.

hot hydrogen gas in lab

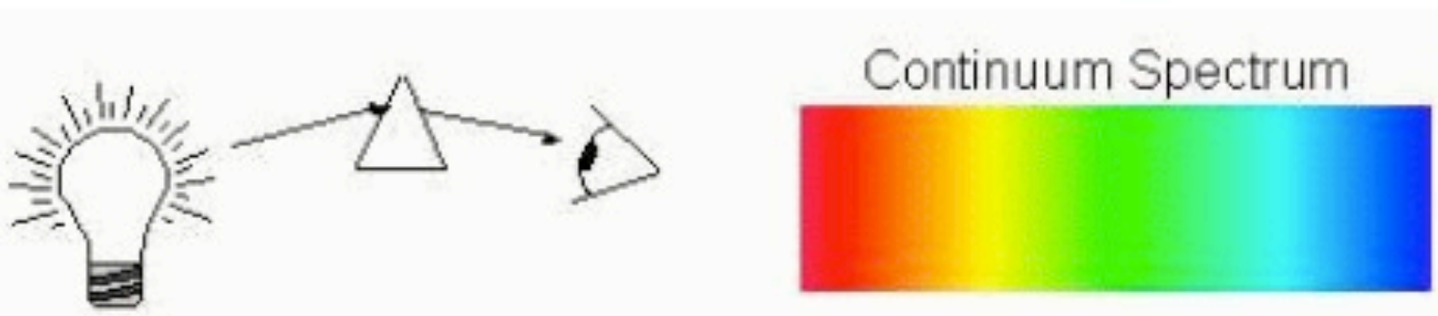


spectrum of a planetary nebula (gas around a dead star)

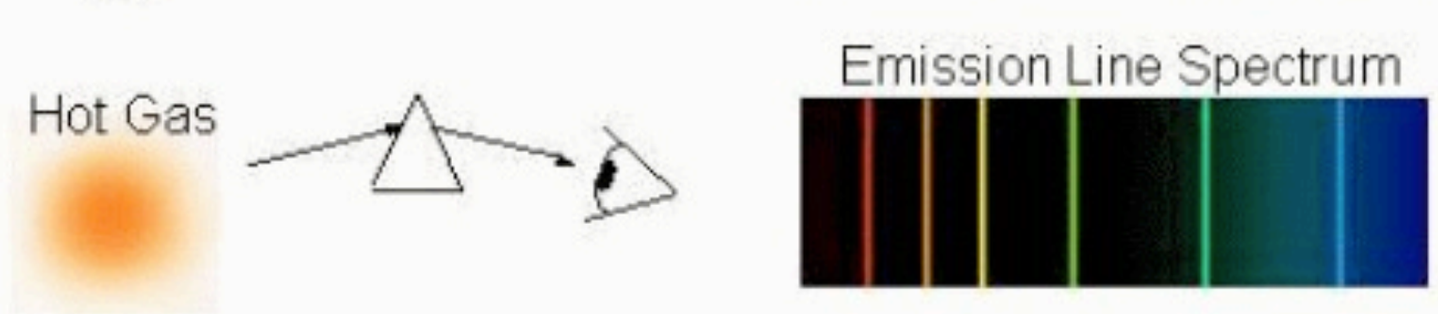
hot gas producing an **emission spectrum**

3 Types of astronomical spectra

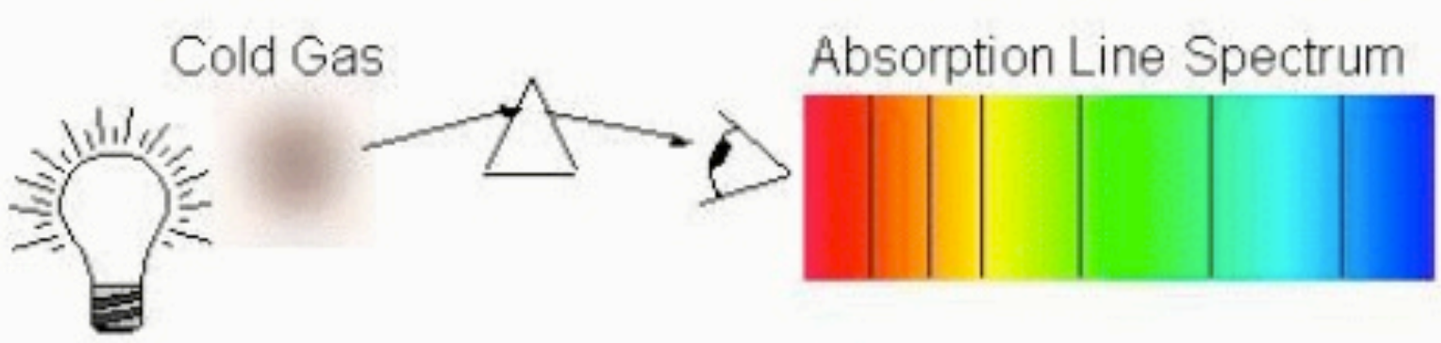
Continuum



Emission lines



Absorption lines

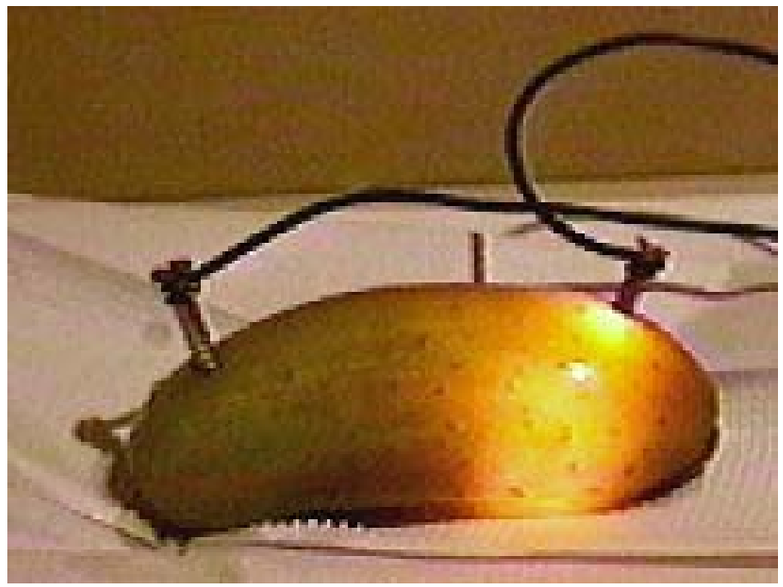


continuum spectrum: e.g., blackbody

emission spectrum: a hot gas that radiates only in spectral lines

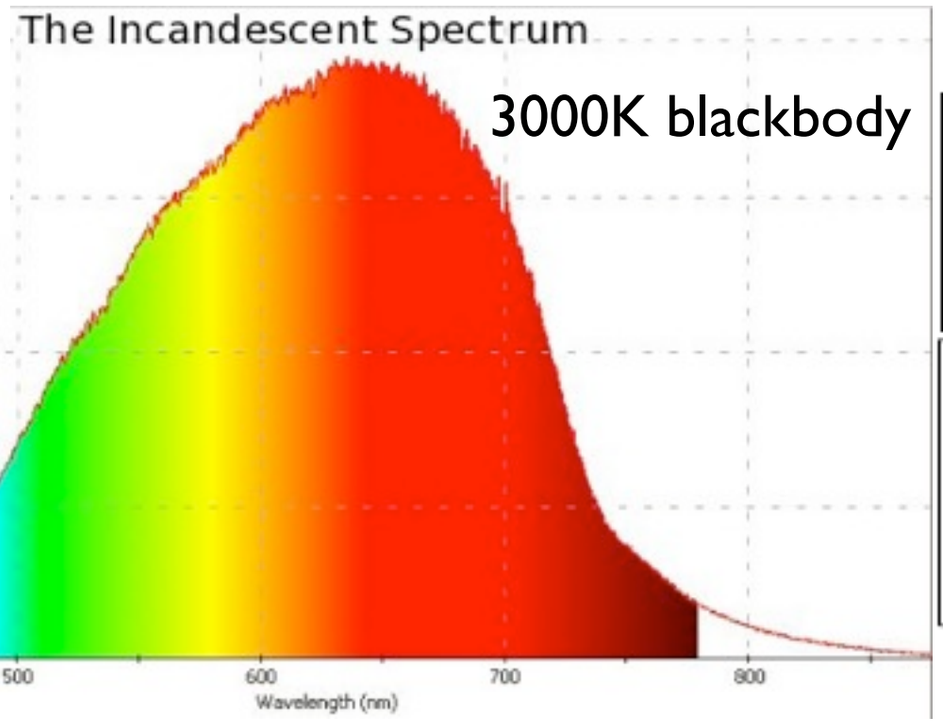
absorption spectrum: continuum radiation being partially absorbed by intervening colder gas

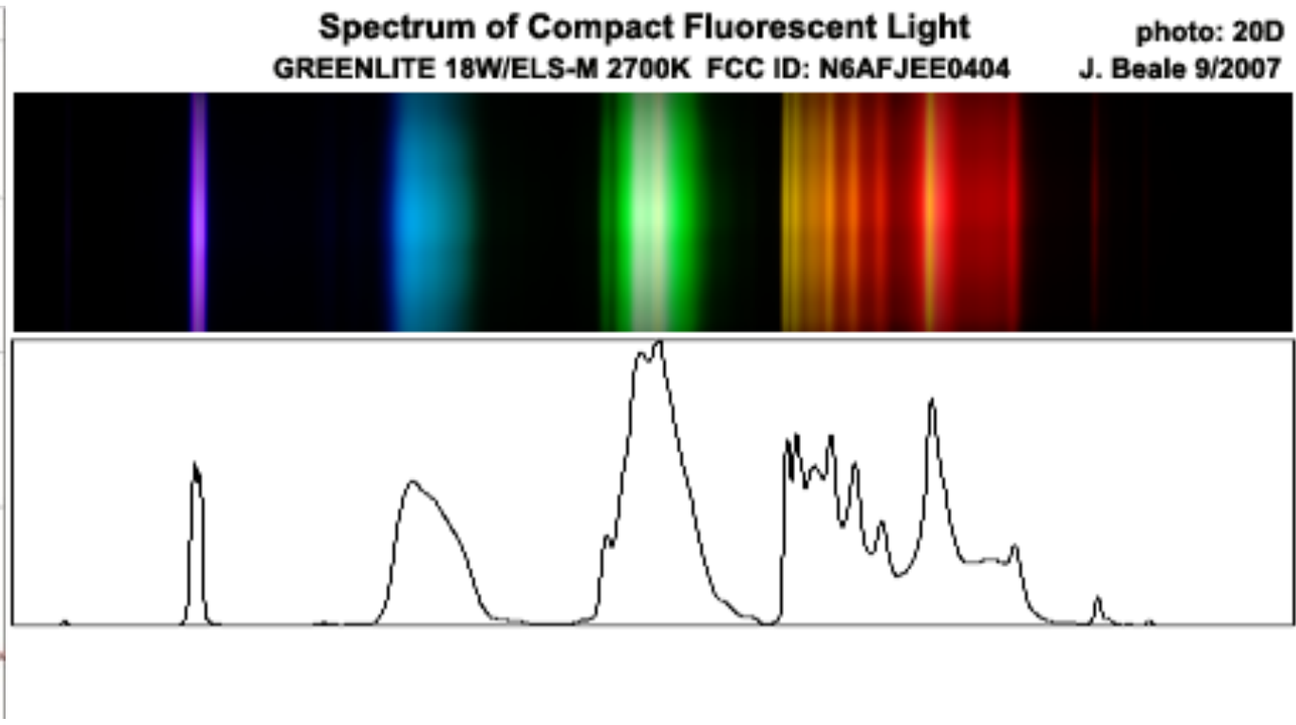
emission spectrum



Real World Applications:

why do compact fluorescent bulbs cut your monthly energy bills?





Energy efficient lights work by emitting in only a narrow range of wavelength (emission lines), and fool our brains into thinking the light is a broad spectrum.

They are more efficient because the bulbs don't have to be heated up to high temperature, unlike conventional bulbs (and wasting energy in infrared lights)

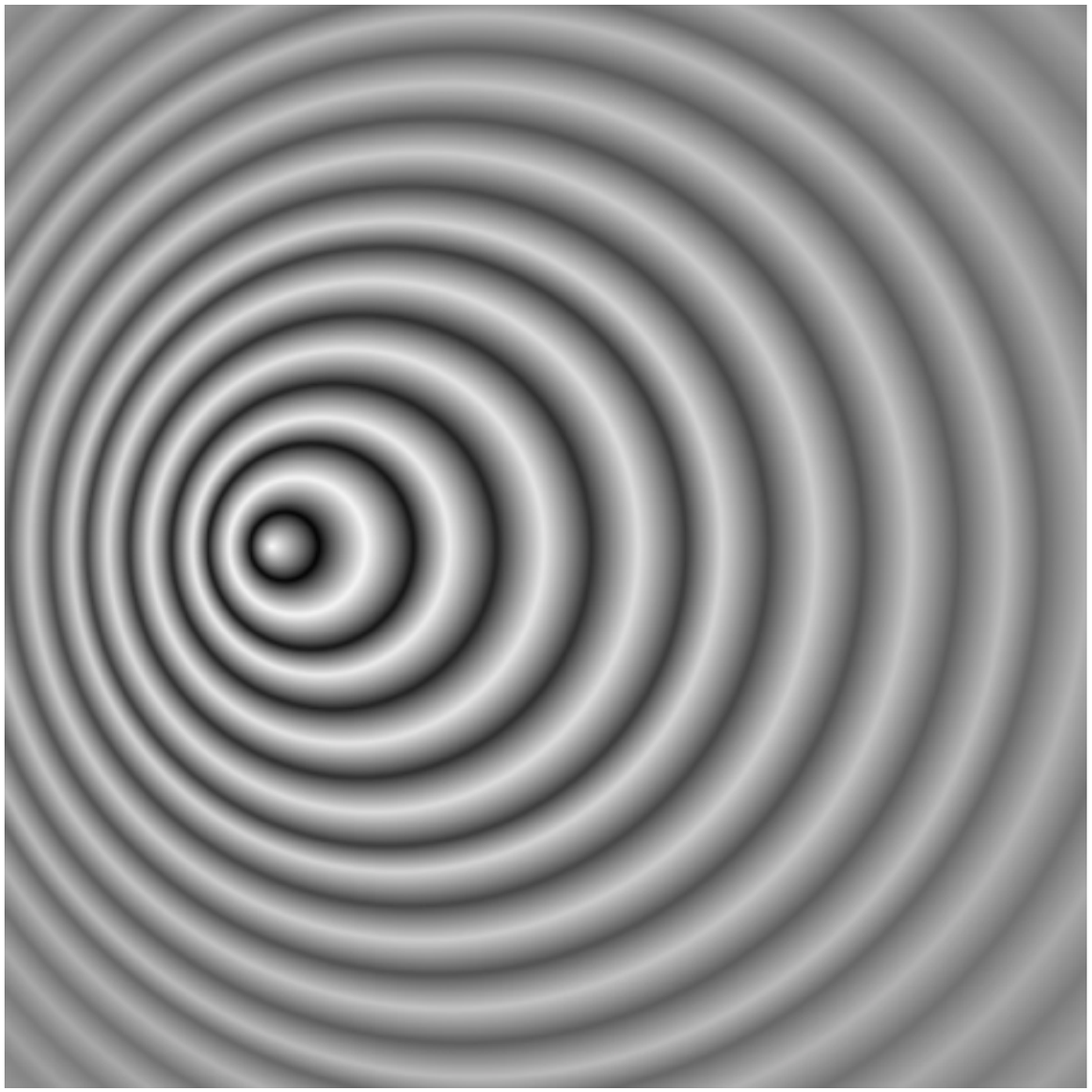
The (Classical) Doppler effect

Light is a wave, just like sound wave, or water wave.

light source moving toward you

$\lambda = \lambda_0 * (1 - v/c)$

light blue-shifted



moving away from you

$\lambda = \lambda_0 * (1 + v/c)$

light red-shifted

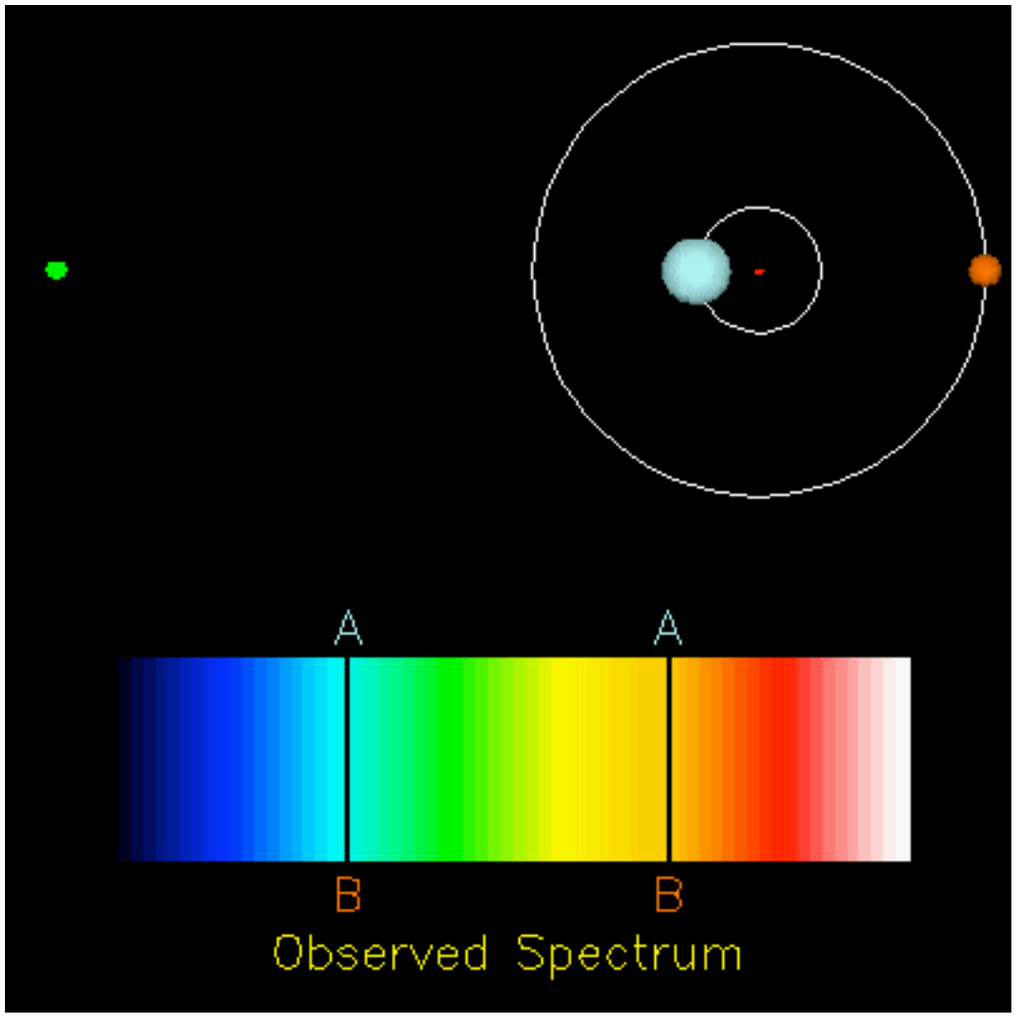
perpendicular direction

$\lambda = \lambda_0$ (rest wavelength)

light unchanged

Doppler effect revealing motion in a binary star system

observer

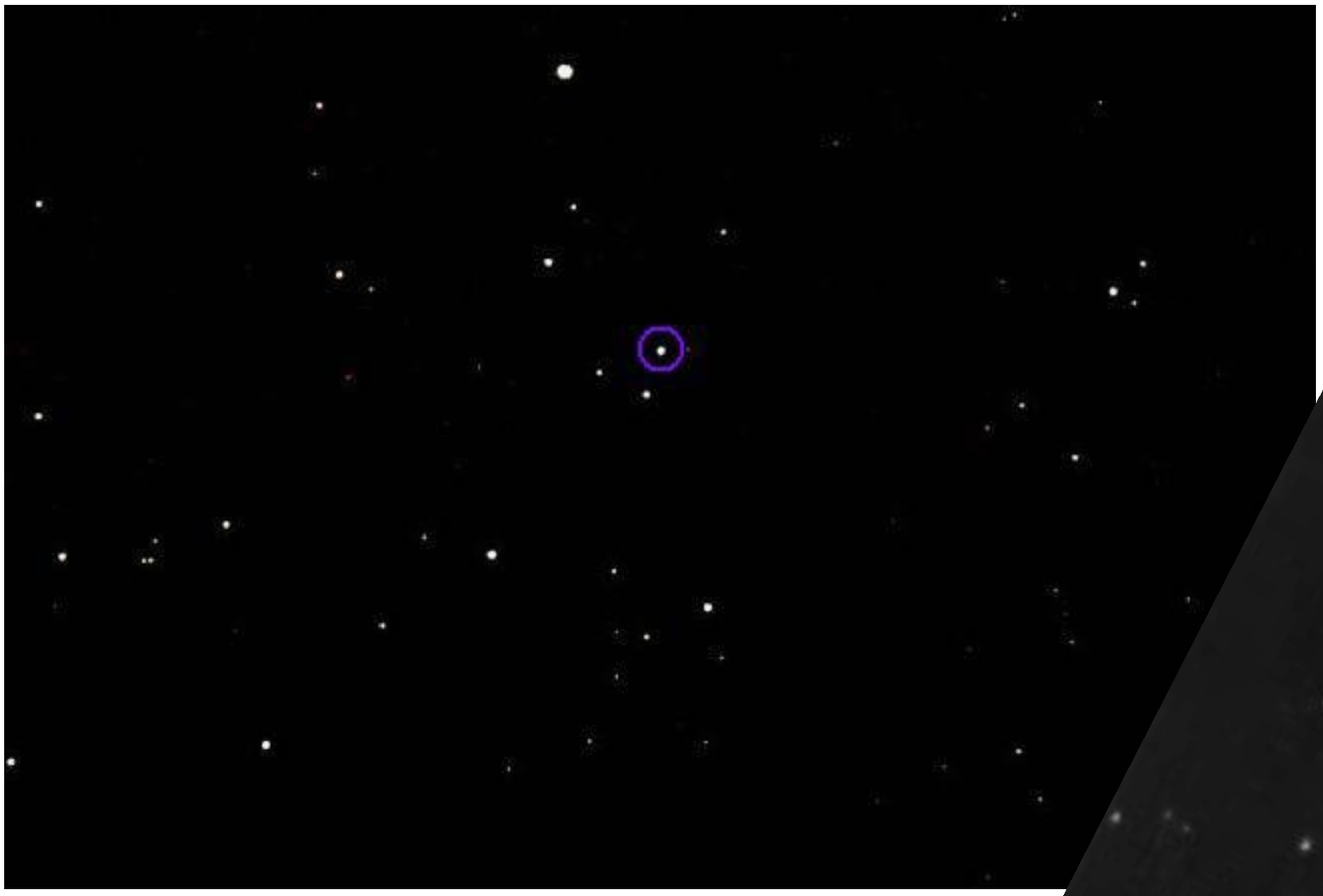


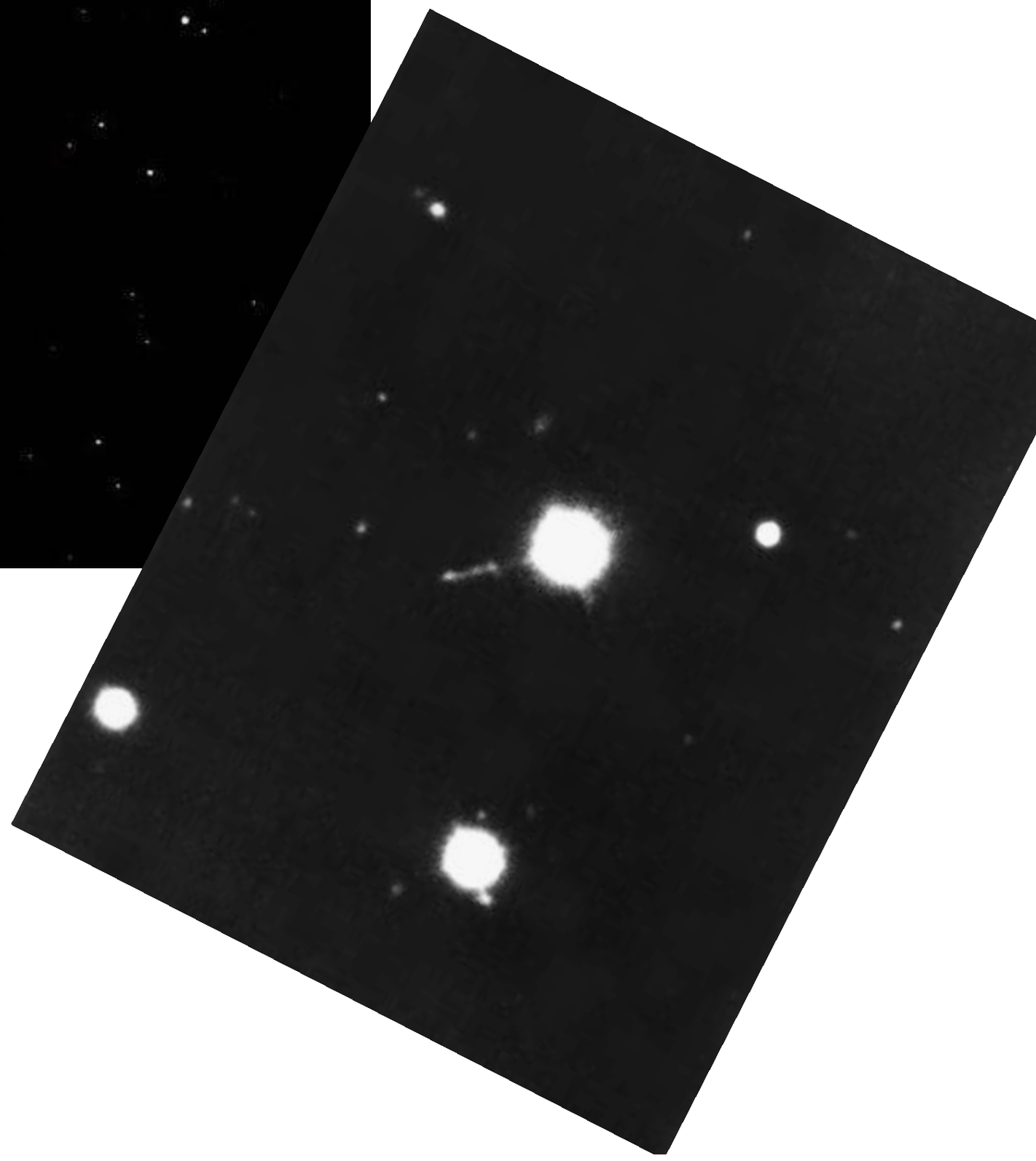
only line-of-sight
velocity matters

moving away from
you

$\lambda = \lambda_0 * (1 + v/c)$
light red-shifted

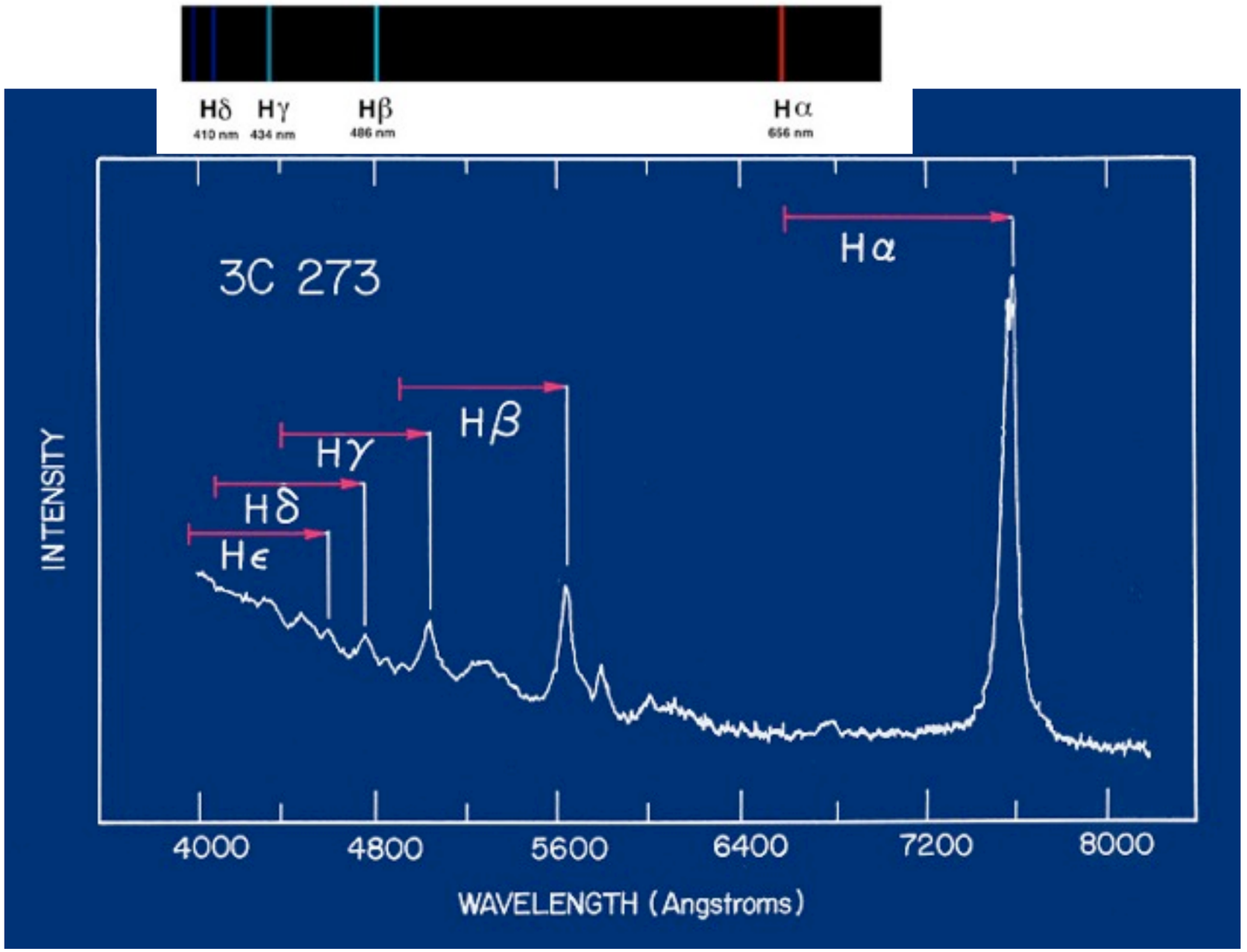
Quasar 3C 273





quasar (quasi-stellar object): star-like point sources but at cosmological distances. Their extremely high intrinsic luminosities are powered by massive blackholes.

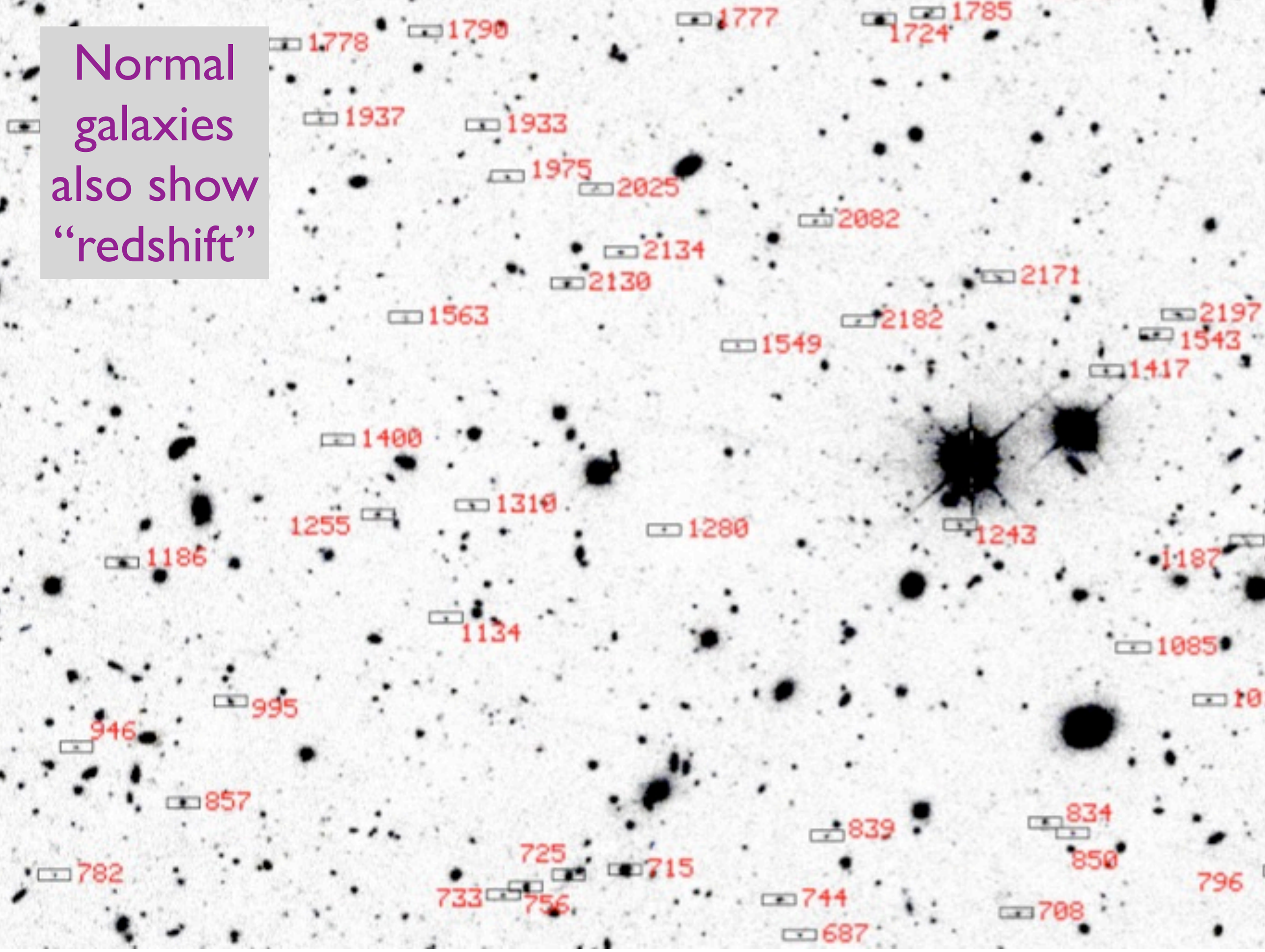
Spectrum of Quasar 3C 273



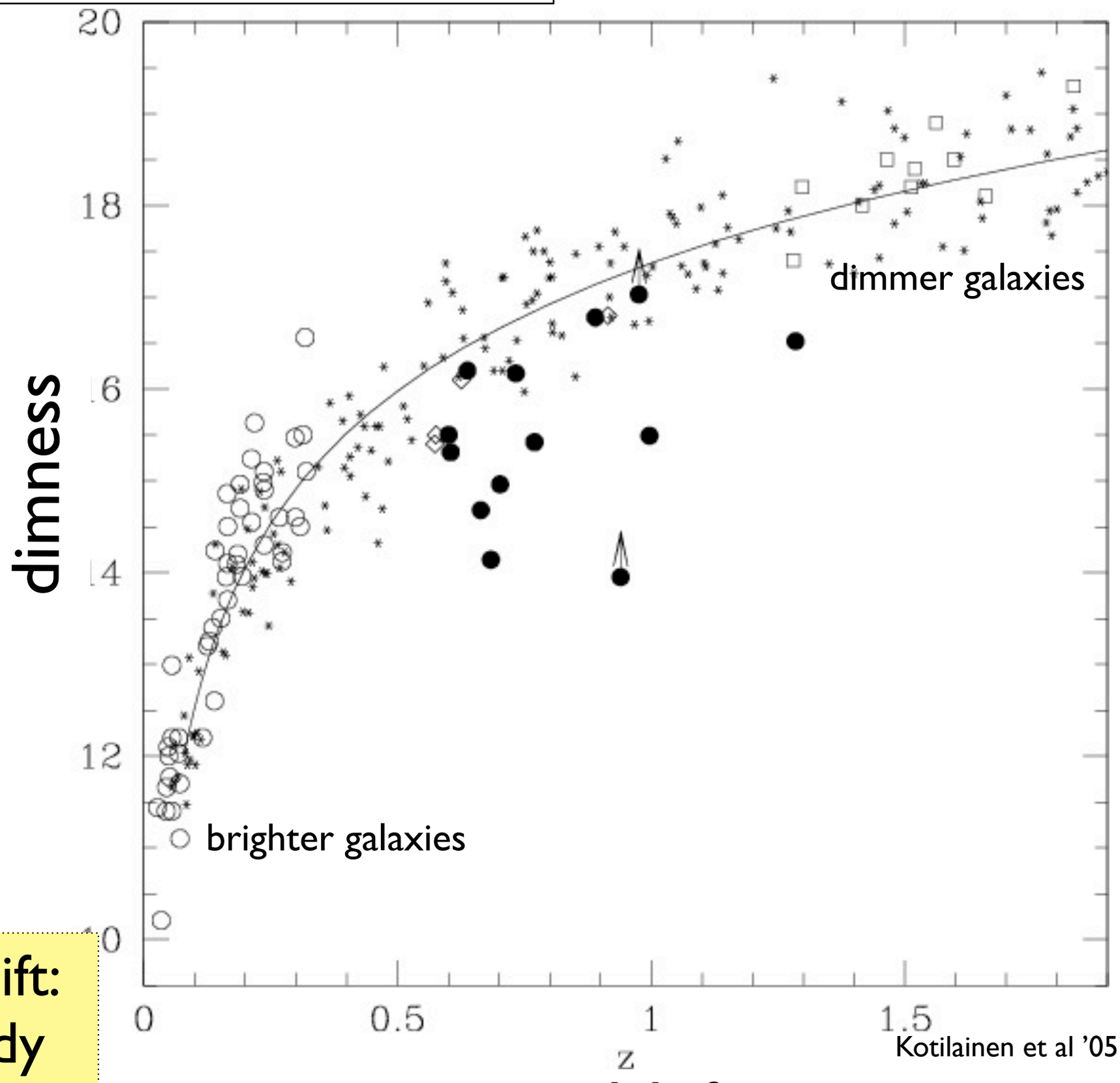
quasar discovered by Maarten Schmidt (1963)
in 3C 273: all hydrogen lines red-shifted by 15%:
$z = 0.15$

define redshift:
$z = \lambda/\lambda_0 - 1 = v/c$

Normal galaxies also show "redshift"



define redshift: $z = \lambda/\lambda_0 - 1$



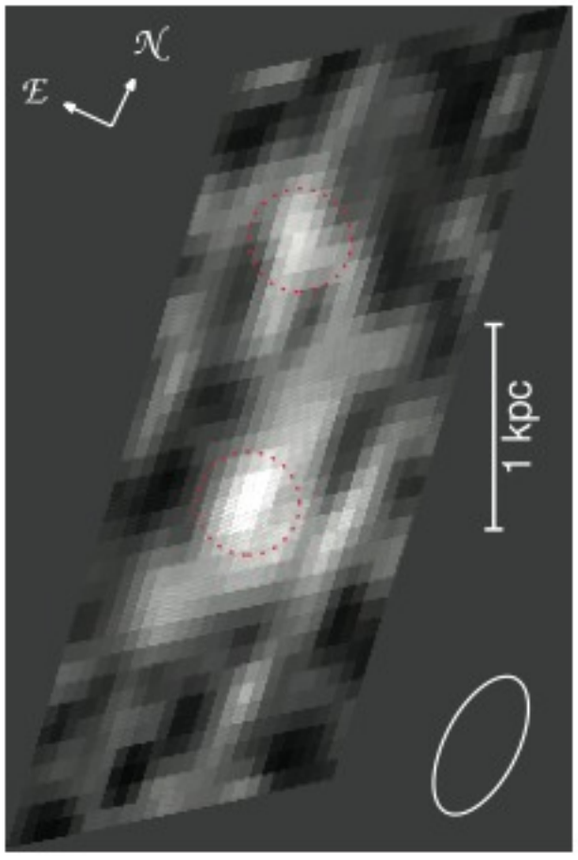
blueshift: nobody here!

galaxy holding the redshift record:

DISCOVERY OF A VERY BRIGHT STRONGLY LENSED GALAXY CANDIDATE AT $z \approx 7.6$[1]

L. D. Bradley,[2] R. J. Bouwens,[3] H. C. Ford,[2] G. D. Illingworth,[3] M. J. Jee,[4] N. Benítez,[5] T. J. Broadhurst,[6] M. Franx,[7] B. L. Frye,[8] L. Infante,[9] V. Motta,[10] P. Rosati,[11] R. L. White,[12] and W. Zheng[2]

Received 2007 September 21; accepted 2008 January 8



the Cosmic Microwave Background is at z~1100

cosmological redshift

$$z = \lambda/\lambda_0 - 1$$

. how fast are these objects receding from us? can it be faster than speed of light?

Classical Doppler Effect

$$\lambda = \lambda_0 (1 + v/c)$$

observed wavelength

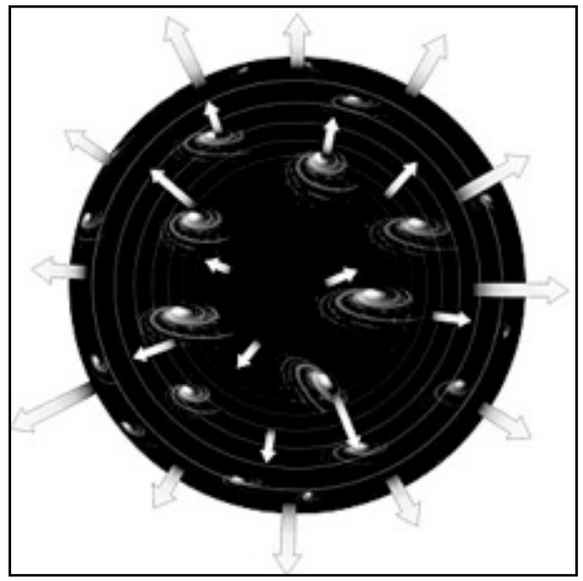
rest-wavelength

. why are we left in the middle?

we will discuss these in later lectures

All are redshifted.

The universe is expanding!



this was first pointed out by Edwin Hubble in the 1920s. It is one of the greatest scientific discoveries of the 20th century.