PHAS 1102 – Physics of the Universe

An astrophysics course in TWO parts:

1)**Stellar Astrophysics -- Prof. Raman Prinja**

....3 October → 2 November 2011

(i.e. Up to 'Reading Week' : 7-11 Nov)

2) **Cosmology – Prof. Ian Howarth**

...14 Nov. → 14 Dec. 2011

PHAS 1102 -- Physics of the Universe

- **3 hours** of lectures per week (up to Reading Week).

“Reading week” (Nov 7-11)

Mon. 11:00-13:00 at Roberts G06 (Fleming LT)

Wed. 10 (sharp!)-11 at Harrie Massey LT
(We will mostly **not** use the 9—10 am slot on Wed.!!)

+ ‘Problem solving tutorials’ → online timetable

check any change of schedule on moodle → course website…

Attendance record → programme tutors

Assessment:

(i)In-course assessments (2 ‘tests’) – see timetable

The assessments wil be based on PRIOR DISCLOSED questions from (a) problem sheets – (not marked)
(b) Problem solving tutorials (PSTs)

In-course asessments → 15%

(ii) Written exam in ~ May (don’t panic!!) → 85%

- **Course Website** for **Stellar astrophysics (Part 1)**:
  http://www.ucl.ac.uk/~ucaprkp/phas1102/

(linked from Moodle...)

- **Notes** -- Lecture slides of first half of the course will be GRADUALLY handed out and/or posted at the website

  ……BUT

  there'll be additional goodies during the lectures!

  ...make notes!

Moodle

- PHAS1102 site on Moodle → links to website above!

(https://moodle.ucl.ac.uk/login/index.php)

PHAS 1102 -- Physics of the Universe

Topics covered:

Part 1 **Stellar Astrophysics** (Prof. Raman Prinja)

- Radiation, luminosity, effective temperature
- Atomic structure and stellar spectra
- Classification of stars
- Energy generation, nuclear fusion, solar neutrinos
- Stellar evolution
- End-states of stars

- Part 2 -**Cosmology** Prof. Howarth (Nov – Dec. 2010)
- Extragalactic distance scales
- Universe composition, galaxies and clusters
- Dark matter, dynamical mass, gravitational lensing
- Hubble’s law, extragalactic distance scale
- ‘World models’, density parameter
- The ‘concordance model’

Reading list

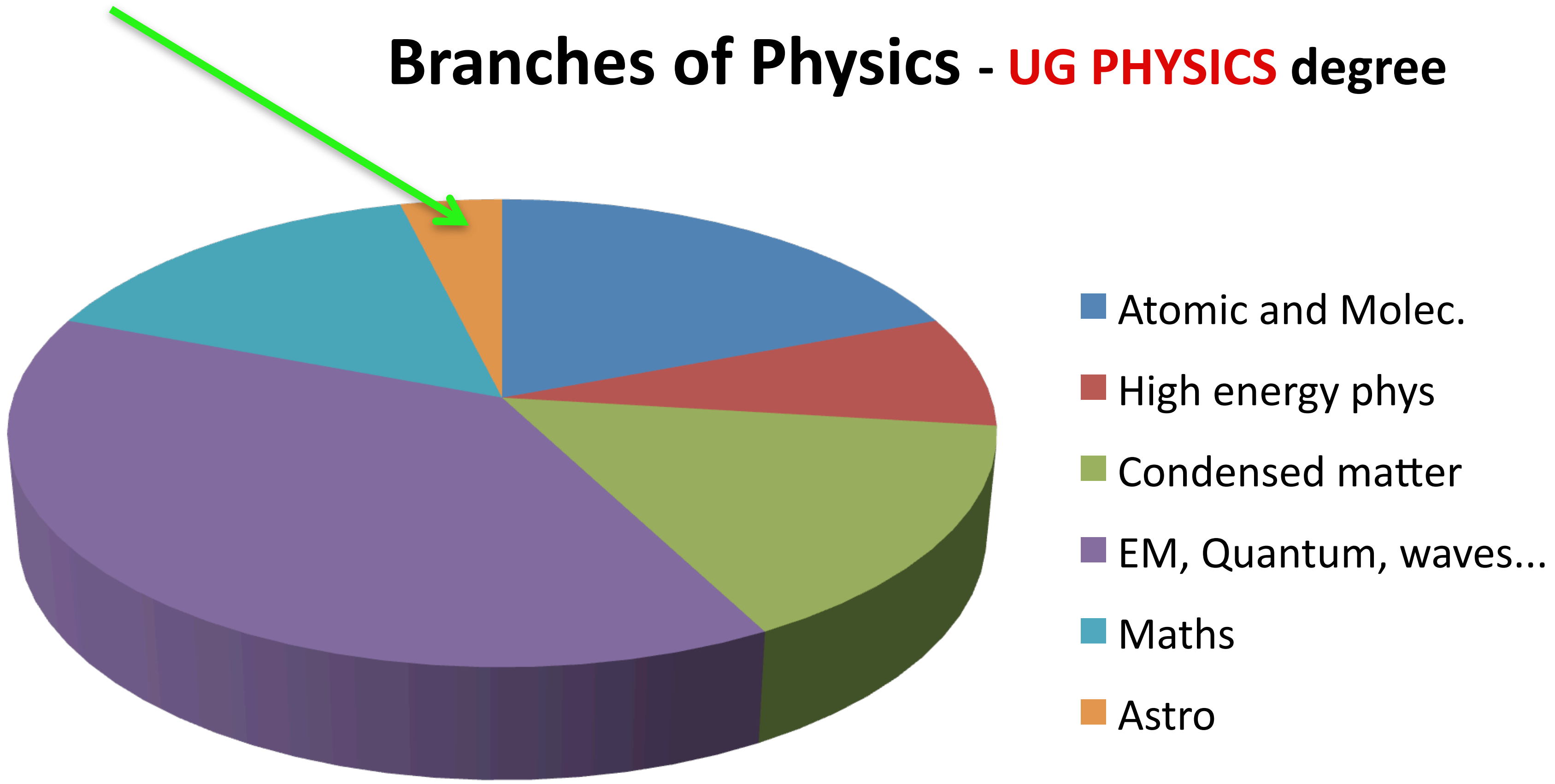
- Zeilik & Gregory, “Introductory Astronomy and Astrophysics (4th ed., Thomson Learning, 1998)
- Freedman & Kaufmann, “Universe” (8th ed., Freeman, 2008)

Contact details:

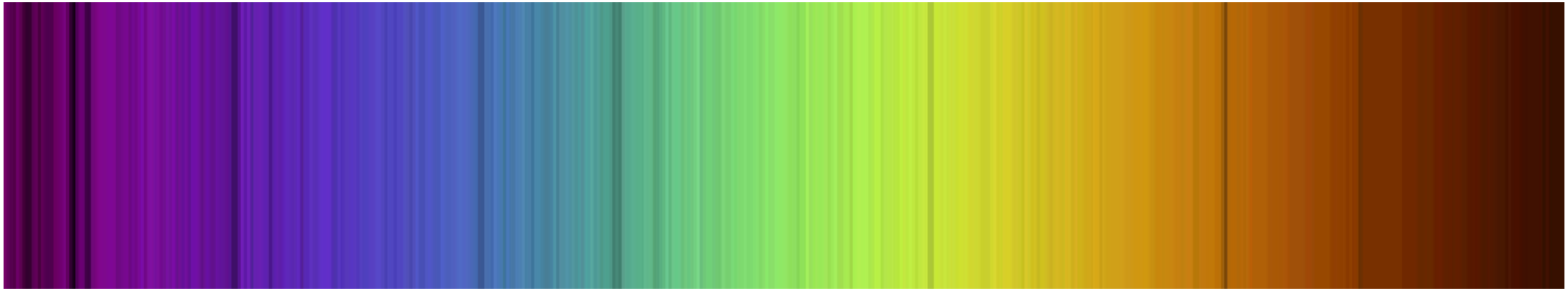
- Prof. Raman Prinja
  Kathleen Lonsdale Building (Astrophysics)
  Ground floor - Room G03

- **Best to use e-mail first:**
  rkp AT star.ucl.ac.uk (AT = @)

Astrophysics course.....why!



PHAS 1102



1) Introduction to stars and **RADIATION**

Key conceptual topics:

- Why are stars not eternal?
- Why is there such a rich diversity of stars?
- How do we know about stellar evolution (over billions of yrs)?

- What are the different stellar life paths?
- What factors do the life paths depend on?

- What are the end-states of evolution?
- What is cosmic recycling?

…tremendous variety of stars

… E.g. **Massive stars →**

- 20 – 100 times more massive than the Sun
- 20 – 100 larger than the Sun
- up to a million times more luminous

Stellar properties

	Sun	**stars**
Mass	$1 M_\odot = 2 \times 10^{30}\,\mathrm{kg}$	$\sim 0.1 - 40\, M_\odot$
Radius	$1 R_\odot = 7 \times 10^{8}\,\mathrm{m}$	$\sim 0.1 - 20\, R_\odot$
Temperature	$5800\,\mathrm{K}$	$\sim 2500 - 45000\,\mathrm{K}$
Chemical composition	$70\%\,\mathrm{H}, 28\%\,\mathrm{He}, 2\%\,\mathrm{Metals}$	
Magnetic field	$\sim 0.1\,\mathrm{T}$ in spots	$\sim 0.5\,\mathrm{T}$
Rotational velocity	$20\,\mathrm{km\,s^{-1}}$	$\lesssim 500\,\mathrm{km\,s^{-1}}$
Age	$\sim 4.5 \times 10^{9}$ years	$\lesssim 13 \times 10^{9}$ years

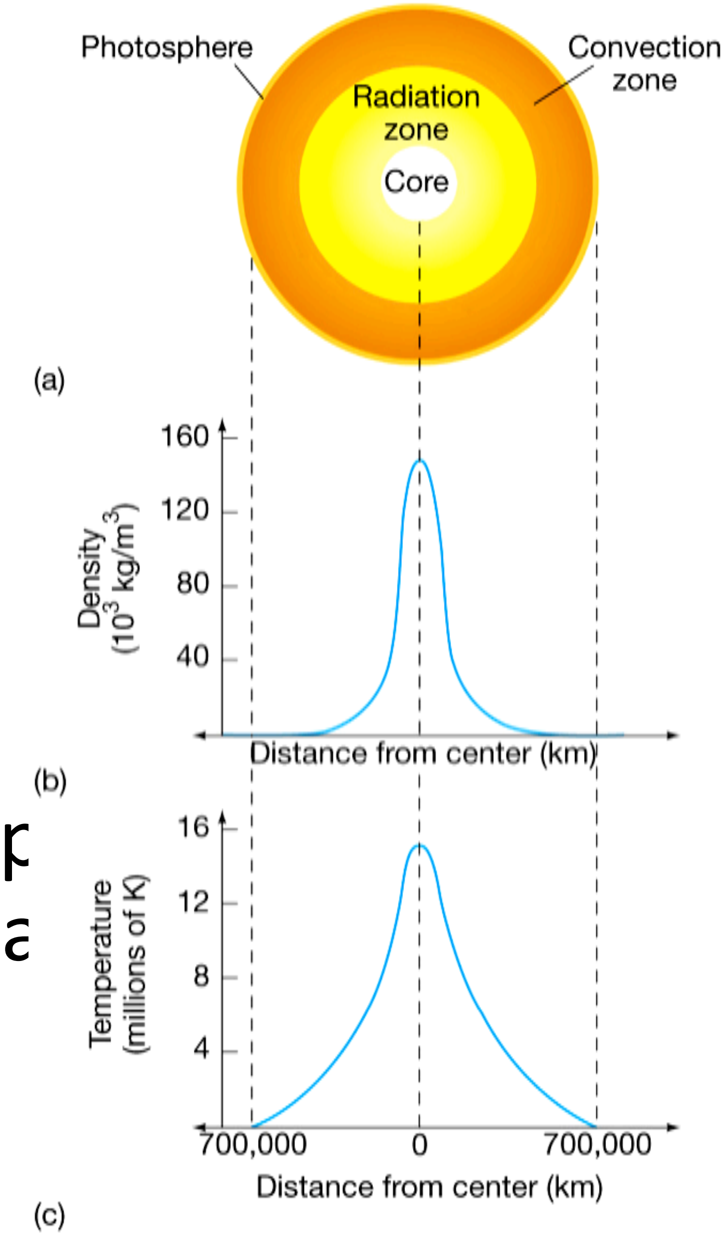
Main body of the Sun is defined by the dominant transport process

$0 <$ core $< R_o/4$

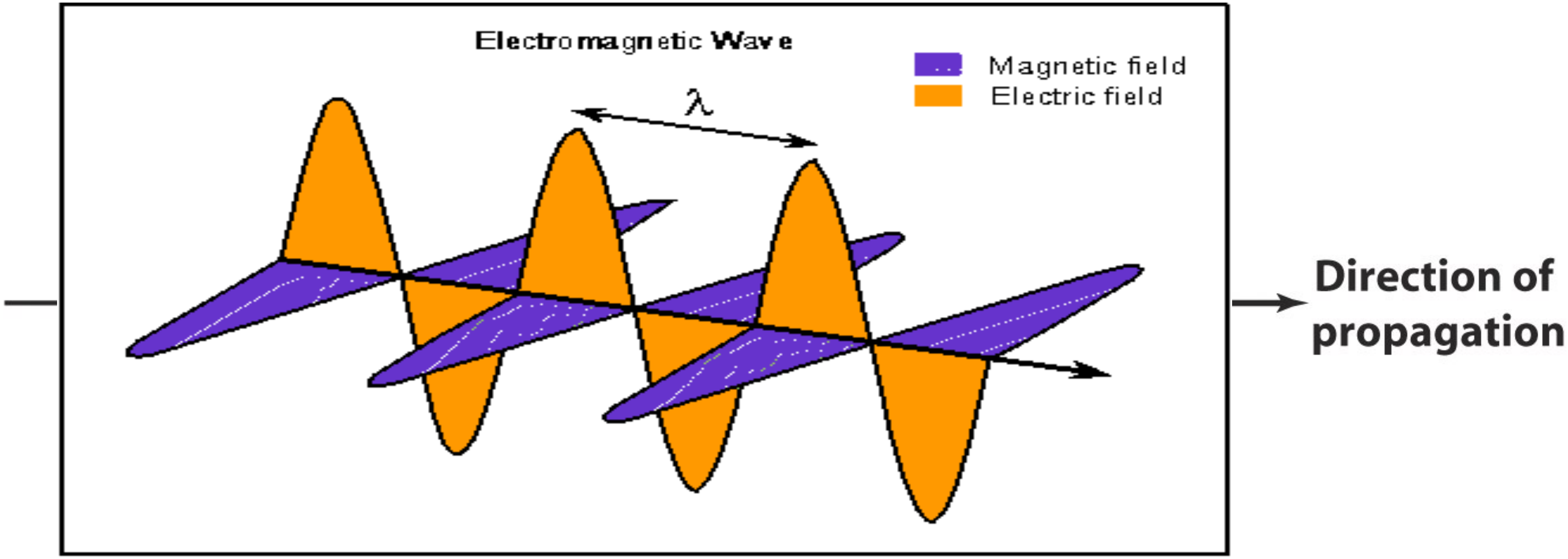
$R_o/4 <$ radiative $< 0.8\ R_o$

$0.8\ R_o <$ convective $< R_o$

Solar atmosphere = photosp
+ chromosphere + corona



Light is Electromagnetic Radiation



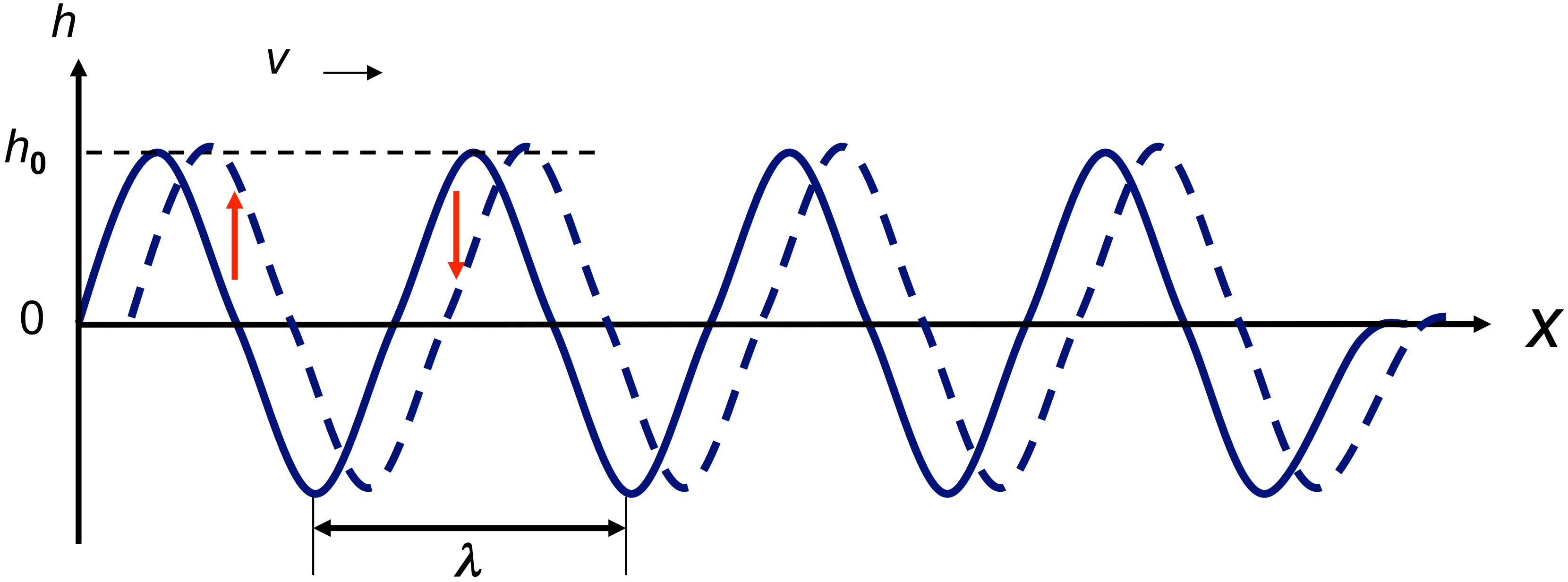
- **The nature of light is electromagnetic radiation**
- In the 1860s, James Clerk **Maxwell** succeeded in describing all the basic properties of electricity and magnetism in four equations: the Maxwell equations of **electromagnetism.**
- Maxwell showed that electric and magnetic field should travel space in z/.z,

Electromagnetic waves

General equation, for e.m., acoustic, seismic, etc. waves:

$$\boxed{h = h_0 \sin\left[\frac{2\pi}{\lambda}(x - vt)\right]}$$

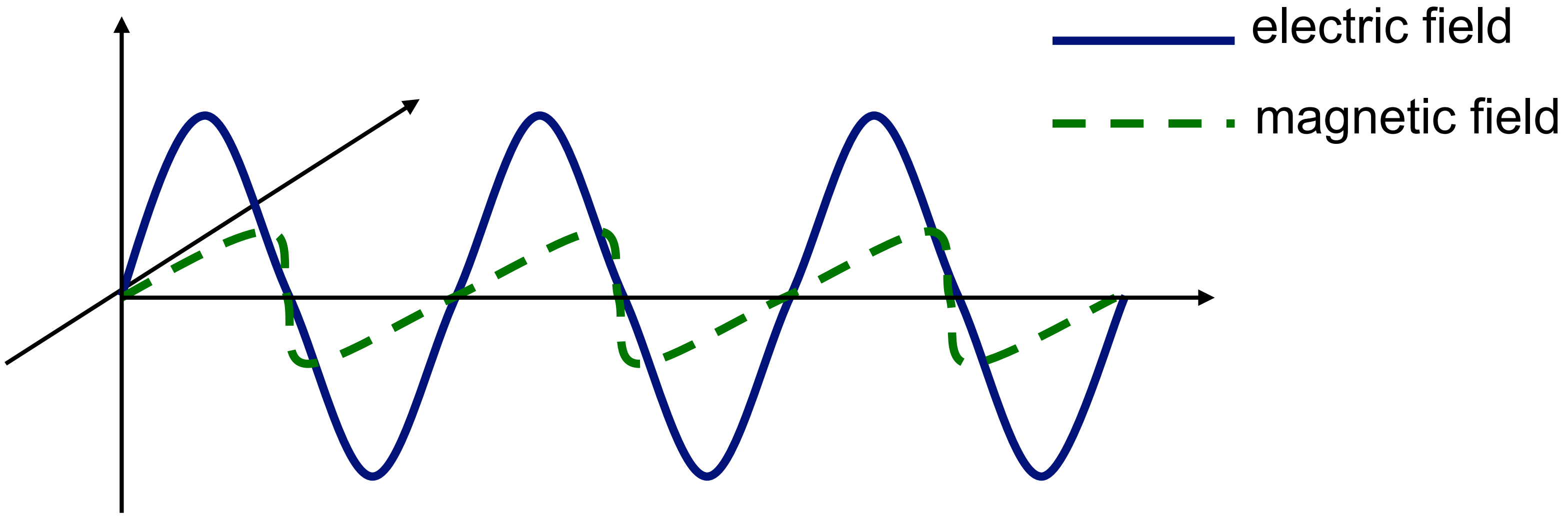
λ = wavelength v = propagation speed t = time



Two things happening: local oscillations and wave propagation

Electromagnetic waves

Time varying electric field produces perpendicular time-varying magnetic field (Maxwell's equations).



EM waves are self-propagating, i.e. they need no medium.

c = speed of light in m s^{-1}
λ = wavelength in m
ν = frequency in Hz

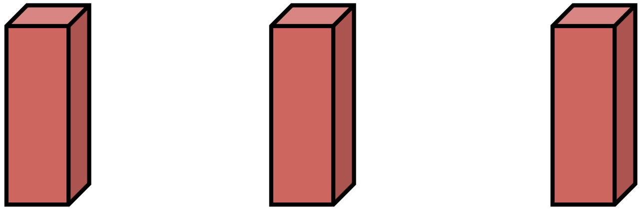
$$\boxed{c = \lambda \nu}$$

c = 2.998 x 10^8 m s^{-1}

Note difference: ***c*** (speed of light) ↔ v (source velocity)!

Quantum nature of light

Alternatively, light can be thought of as packets (or ‘quanta’) of energy called ***photons***. Photon energy, *E*:



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

ν = frequency (Hz) h = Planck’s constant (= 6.63 x 10^{-34} J s)

high frequency

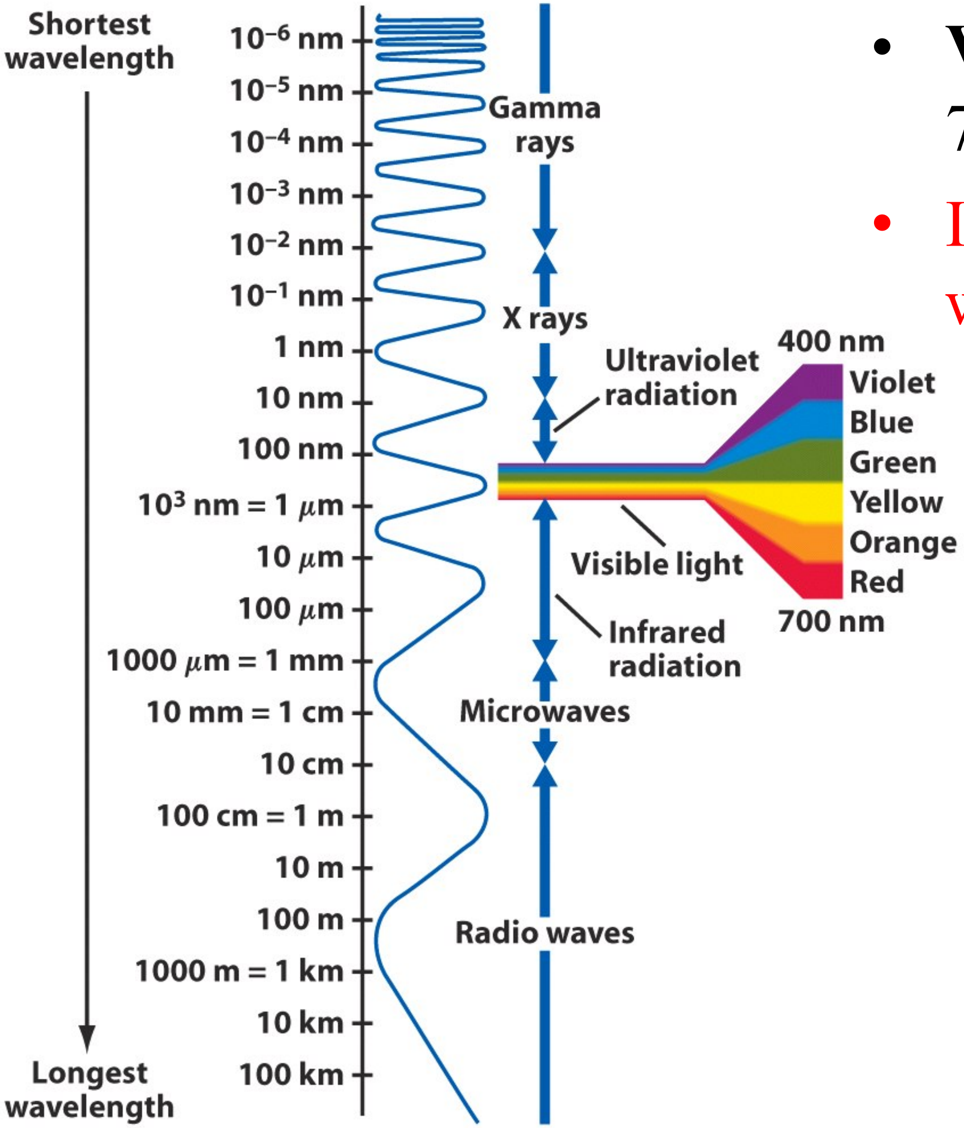
⇒ short wavelength

⇒ high energy

Examples of particle nature of light can be seen in:

- Photo-electric effect
- Atomic spectra

Electromagnetic Spectrum



- **Visible light** falls in the 400 to 700 nm range
- In the order of decreasing wavelength
  - Radio waves: 1 m
  - Microwave: 1 mm
  - Infrared radiation: 1 μm
  - Visible light: 500 nm
  - Ultraviolet radiation: 100 nm
  - X-rays: 1 nm
  - Gamma rays: 10^{-3} nm

Units

Wavelength: SI units – metre, m

Optical/UV: **Angstrom, A** 1A = 10^{-10} m = 10^{-8} cm = 0.1nm

nanometre, nm 1nm = 10^{-9} m

Infrared: **micron, μm** 1μm = 10^{-6} m

Frequency: SI units – Hertz, Hz

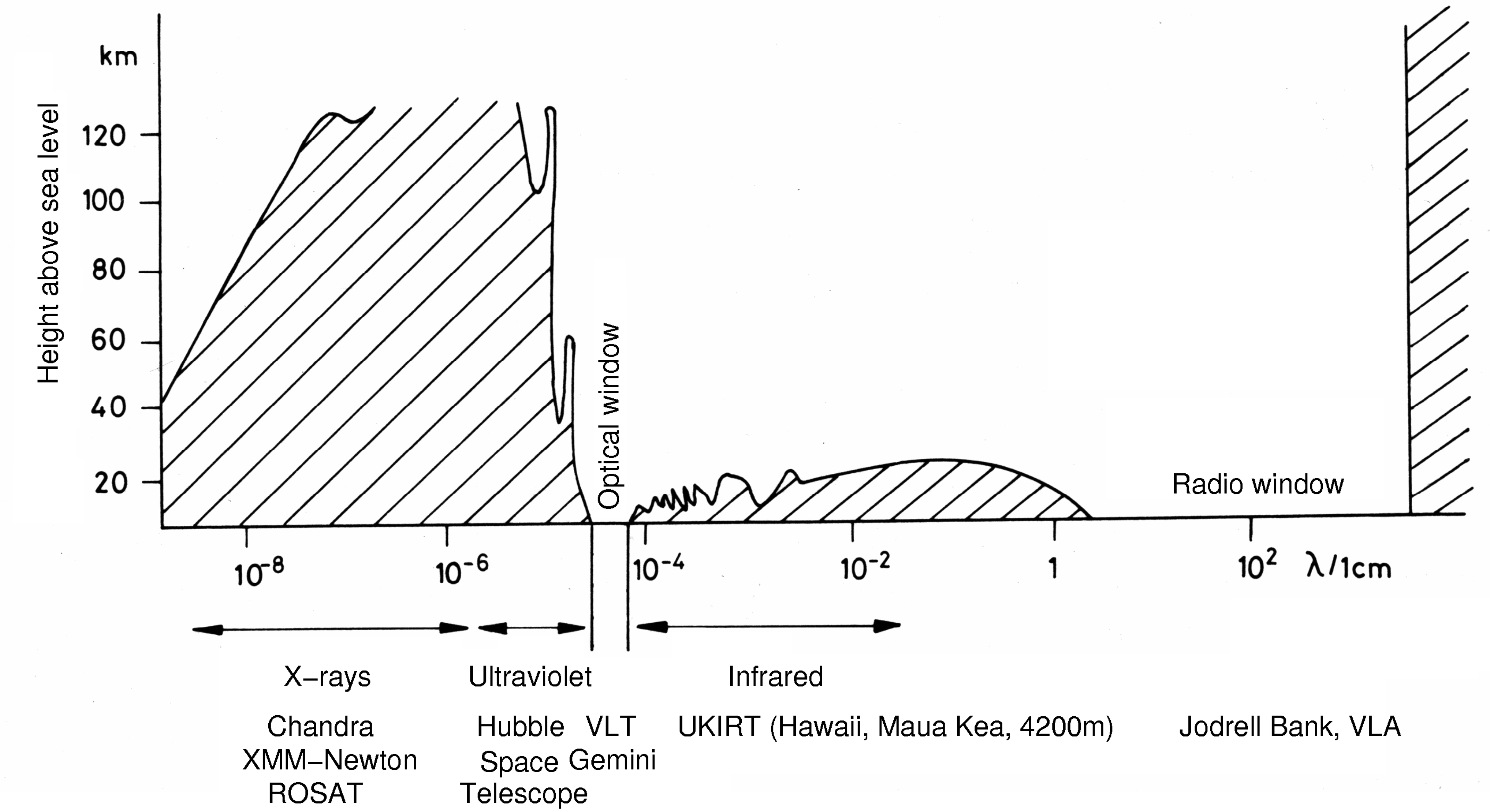
Radio: **Gigahertz, GHz** 1GHz = 10^{9} Hz

Energy: SI units – Joules, J

X-ray: **electron volts, eV** 1eV = 1.6×10^{-19} J

1keV = 1.6×10^{-16} J

Penetration depths through the Earth atmosphere



Doppler effect

The **Doppler effect** is of fundamental importance in astrophysics.

The observed wavelength, λ, is different from the emitted wavelength, λ_0, due to the radial velocity of the emitter with respect to the observer:

$$\boxed{\frac{(\lambda - \lambda_0)}{\lambda_0} \equiv \frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}}$$

λ = observed wavelength
λ_0= 'rest' wavelength
v = source's radial velocity

$\lambda > \lambda_0$ implies a 'redshift' of the light, $v > 0$, the emitter is moving away from the observer

$\lambda < \lambda_0$ implies a 'blueshift' of the light, $v < 0$, the emitter is moving towards the observer

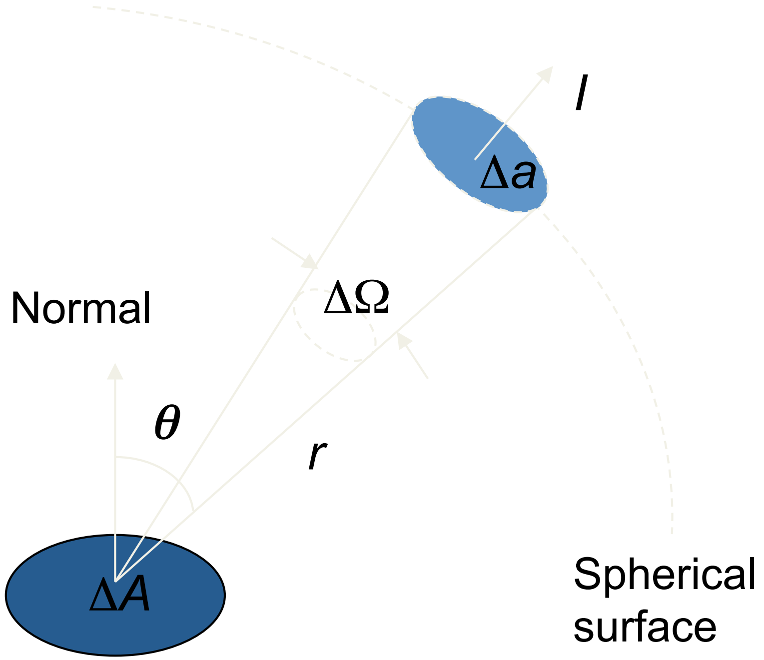
'Astronomical redshift'

$$\boxed{z \sim \frac{v}{c}}$$

Intensity, Luminosity and Flux (1)

Intensity I : Amount of energy **emitted** per unit time Δt,
per source unit area ΔA,
per unit frequency interval $\Delta\nu$,
per unit solid angle $\Delta\Omega$ in a given direction

(depends on direction!)



$$\boxed{\Delta\Omega = \frac{\Delta a}{r^2}}$$

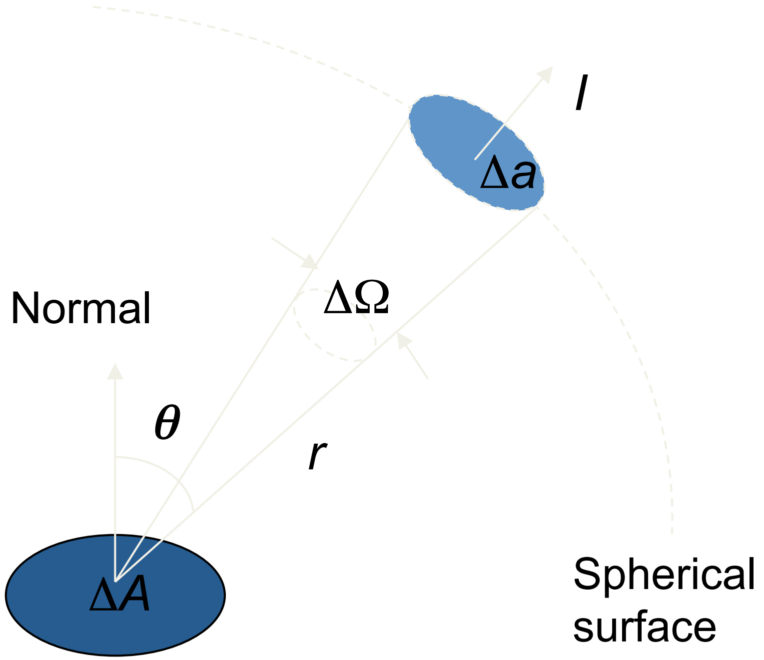
Steradian (sr):
Unit of solid angle
(entire spherical surface:
➔ 4π sr)

$$\Delta a = 4\pi r^2$$

Intensity units (e.g.): Joule s^{-1} m^{-2} Hz^{-1} sr^{-1}

Intensity, Luminosity and Flux (2)

Luminosity L : Total energy emitted per unit time (second) from a spherical star of total surface *A*, over all frequencies and in all directions



$$L = 4\pi \int_0^\infty A\, I(\nu)\, d\nu$$

I(ν): Monochromatic intensity (i.e. intensity emitted at specific frequency *ν*)

Unit of luminosity:
Watt = Joule s^{-1}

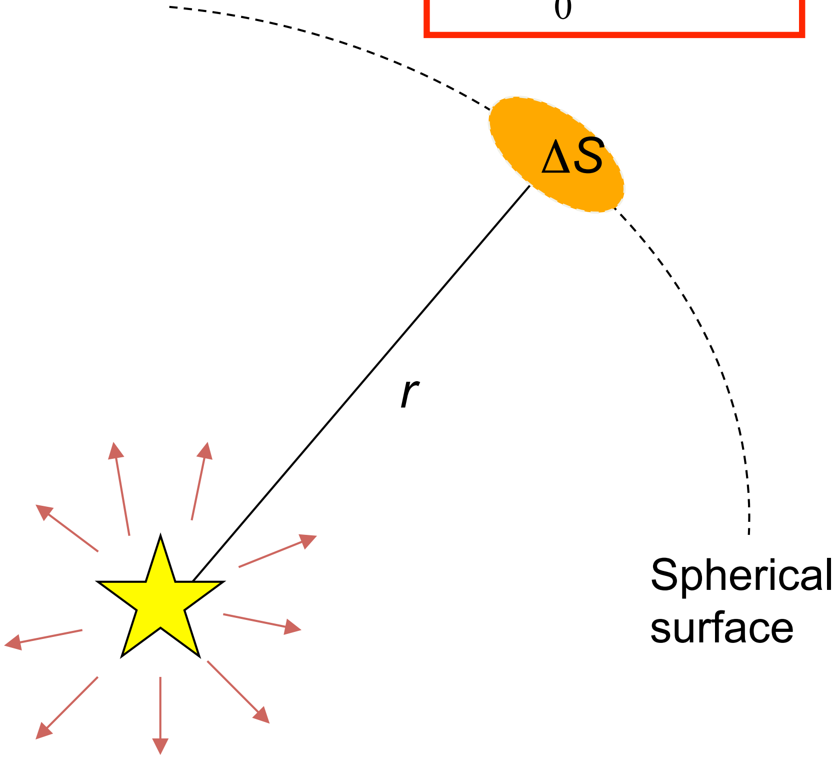
Intensity, Luminosity and Flux (3)

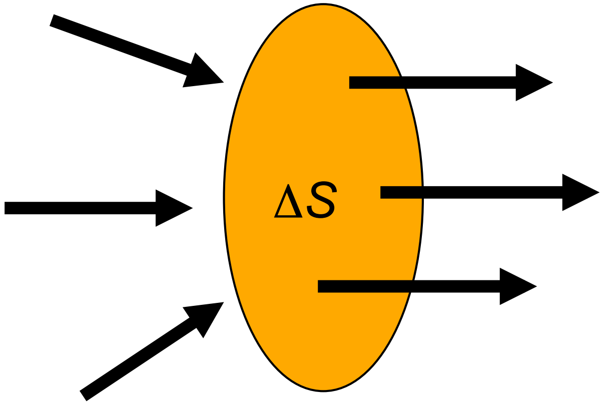
Monochromatic flux $F(\nu)$: Amount of energy at frequency ν received per unit time Δt, passing through a unit surface ΔS of the detector, per unit frequency interval $\Delta\nu$

Total flux:

$$\boxed{F = \int_0^\infty F(\nu)\,d\nu}$$

Unit of flux $F(\nu)$: Joule s^{-1} m^{-2} Hz^{-1}





Energy flux from a star through concentric sphere at distance r:

$$\boxed{F = \frac{L}{4\pi r^2}}$$ in Joule s^{-1} m^{-2}

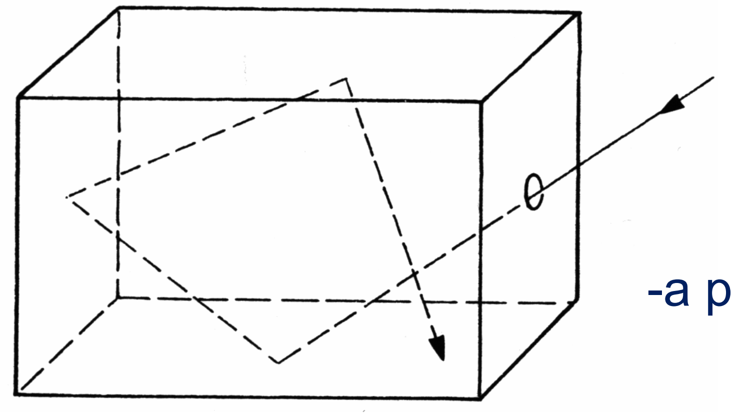
‘Thermal’ spectrum of radiation: Blackbody (1)

: A body which absorbs all radiation incident upon it.
To be in perfect thermal equilibrium, it must also emit radiation at the same rate it absorbs it
➔ its temperature is maintained

Example: Perfectly insulated enclosure within which radiation is in equilibrium with the enclosure walls
➔ observe blackbody radiation through a pinhole

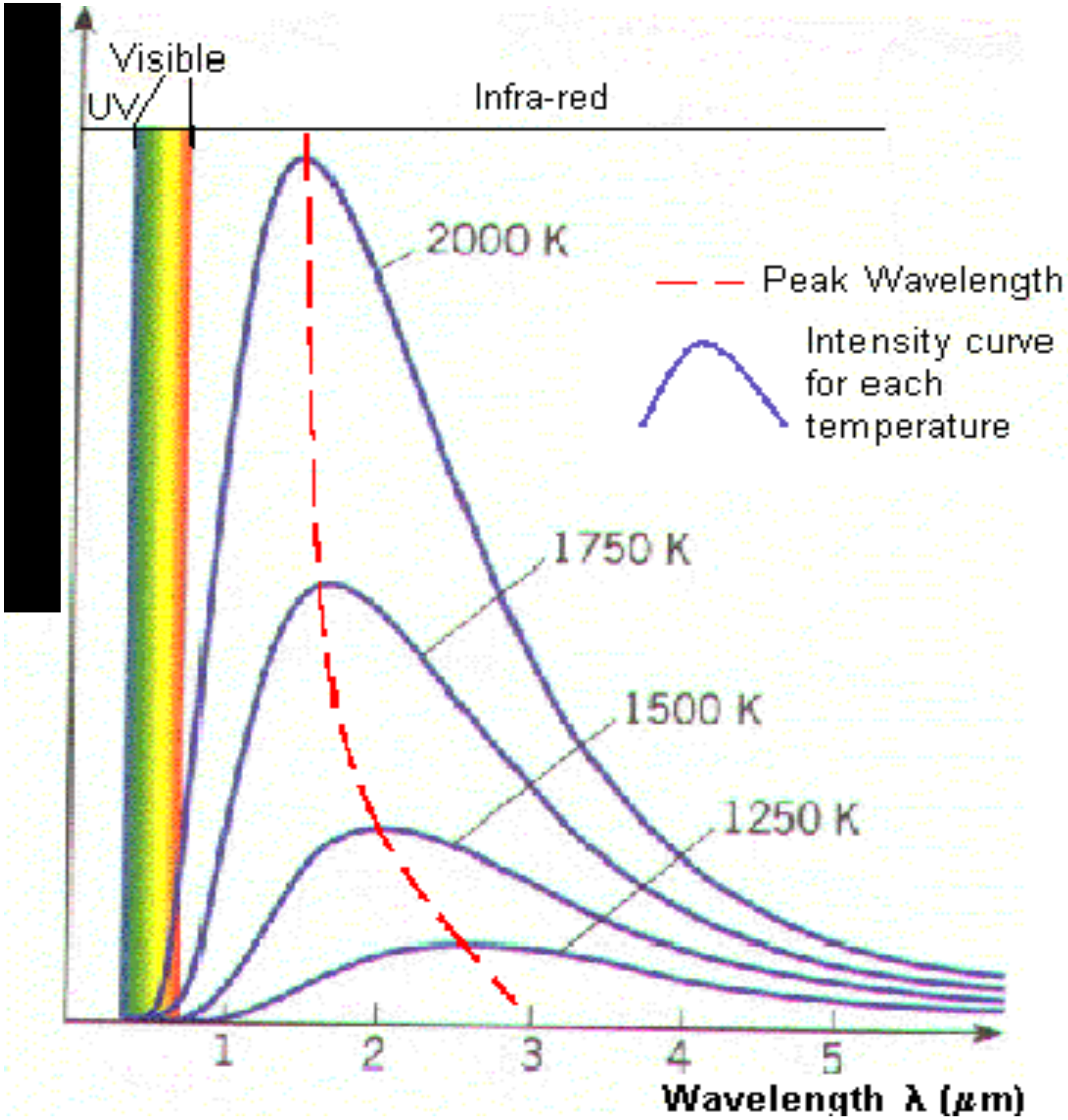
Gases in the interior of stars are opaque to all radiation

➔ Surfaces of stars emit very closely to a *blackbody spectrum*



-a perfect absorber/emitter, absorbs all intercepted photons

‘Thermal’ spectrum of radiation: Blackbody (2)



In 1900 Planck postulated e.m. energy propagates in quanta, and derived the blackbody radiation law:

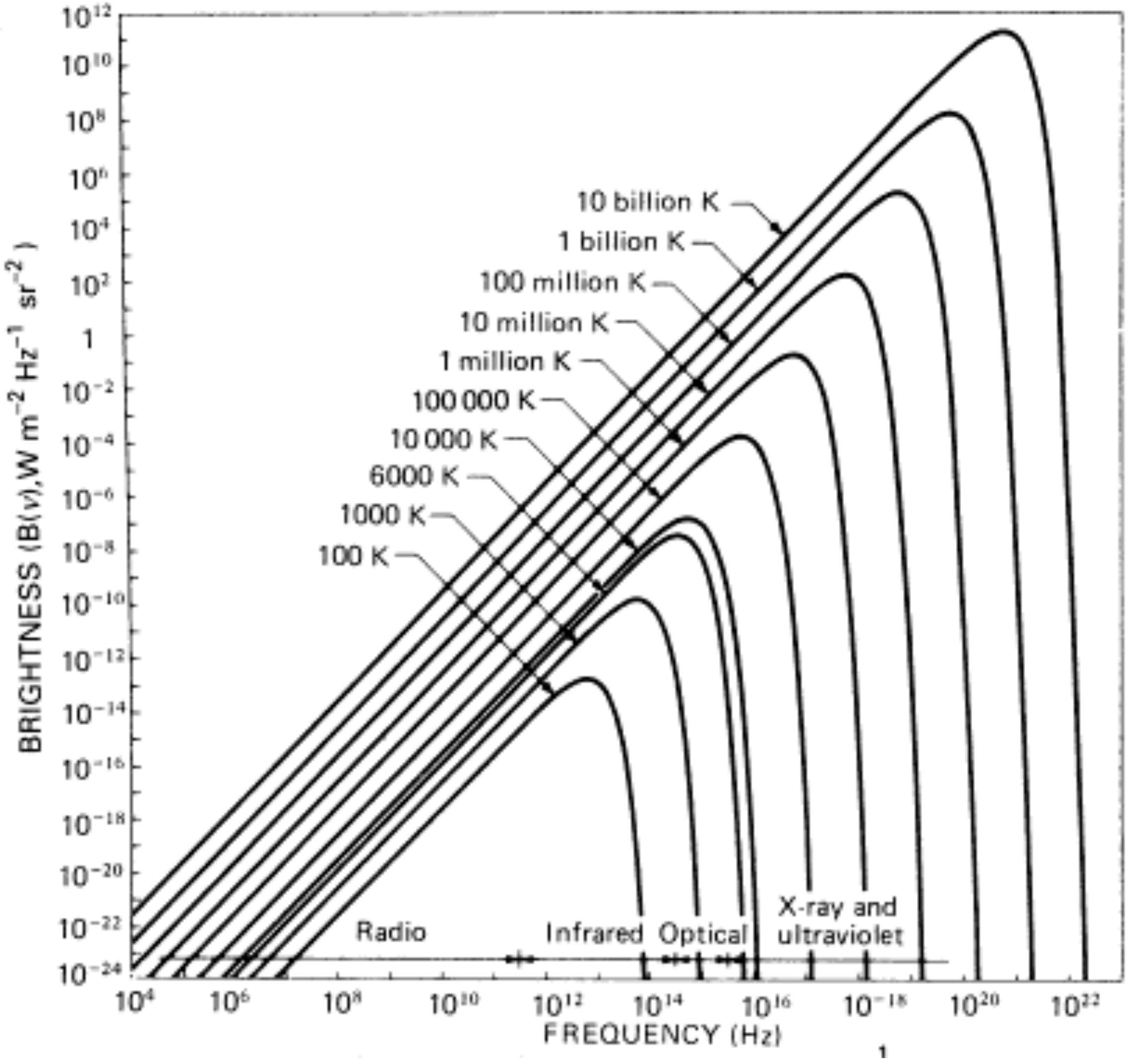
$$I(\lambda)\,\Delta\lambda = \frac{2hc^2}{\lambda^5}\left[\frac{1}{e^{hc/\lambda kT}-1}\right]\Delta\lambda$$

where $I(\lambda)$ is the intensity emitted by a blackbody at temperature T in the range of wavelength λ and $\lambda+\Delta\lambda$

h: Planck’s constant
c: speed of light
k: Boltzmann’s constant
T: temperature in Kelvin

‘Thermal’ spectrum of radiation: Blackbody (3)

Alternatively, we can express the blackbody radiation law (also called Planck’s function) in terms of frequency:



$$I(\nu)\Delta\nu = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{h\nu/kT}-1}\right]\Delta\nu$$

where $I(\nu)$ is the intensity emitted by a blackbody at temperature T in the range of frequency ν and $\nu + \Delta\nu$

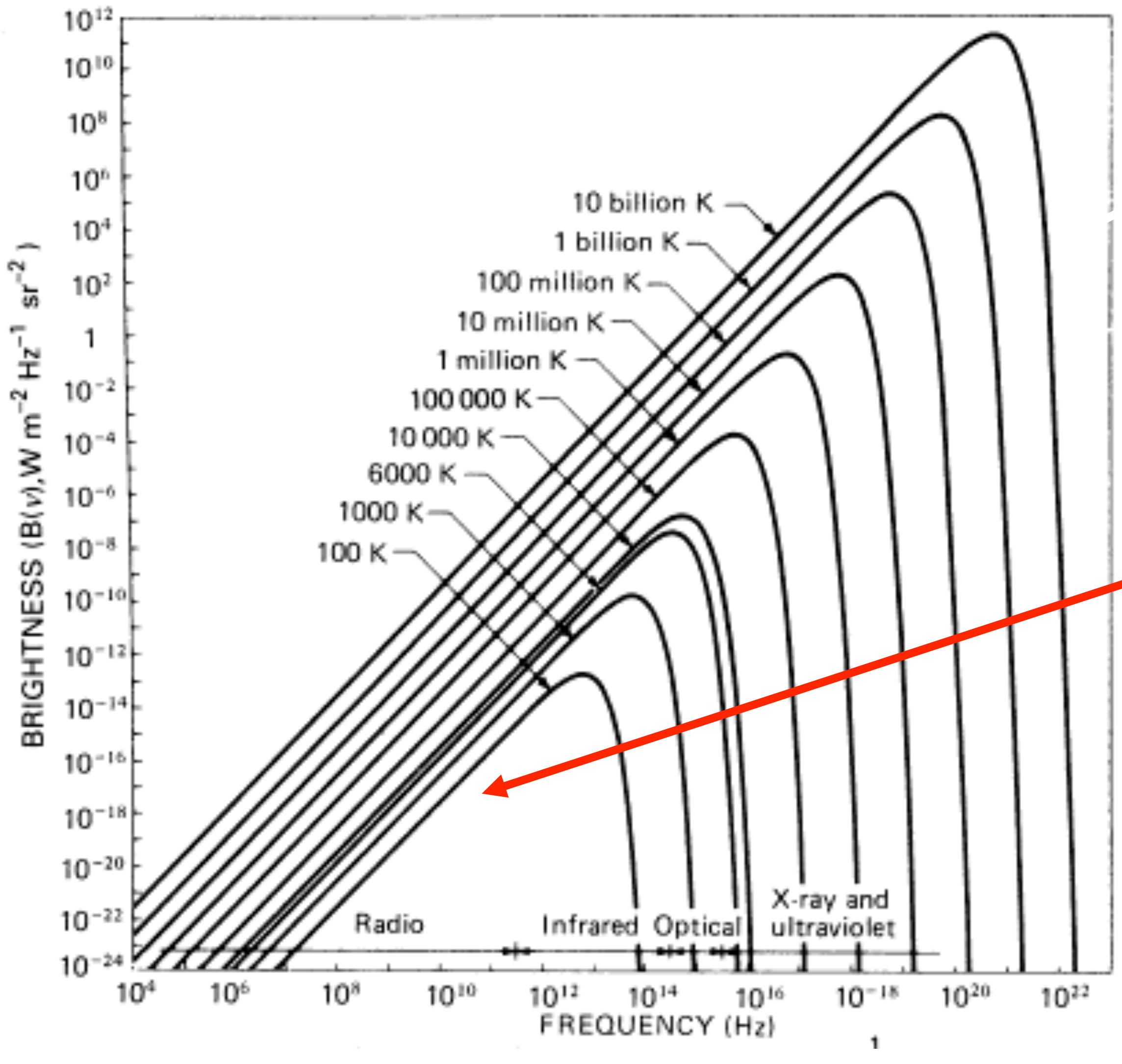
h: Planck’s constant
c: speed of light
k: Boltzmann’s constant
T: temperature in Kelvin

‘Thermal’ spectrum of radiation: Blackbody (4)

Useful approximations - At high frequencies, Wien distribution:

$$I(\nu) = \frac{2h\nu^3}{c^2} e^{-h\nu/kT}$$

$$I(\lambda) = \frac{2hc^2}{\lambda^5} e^{-hc/\lambda kT}$$

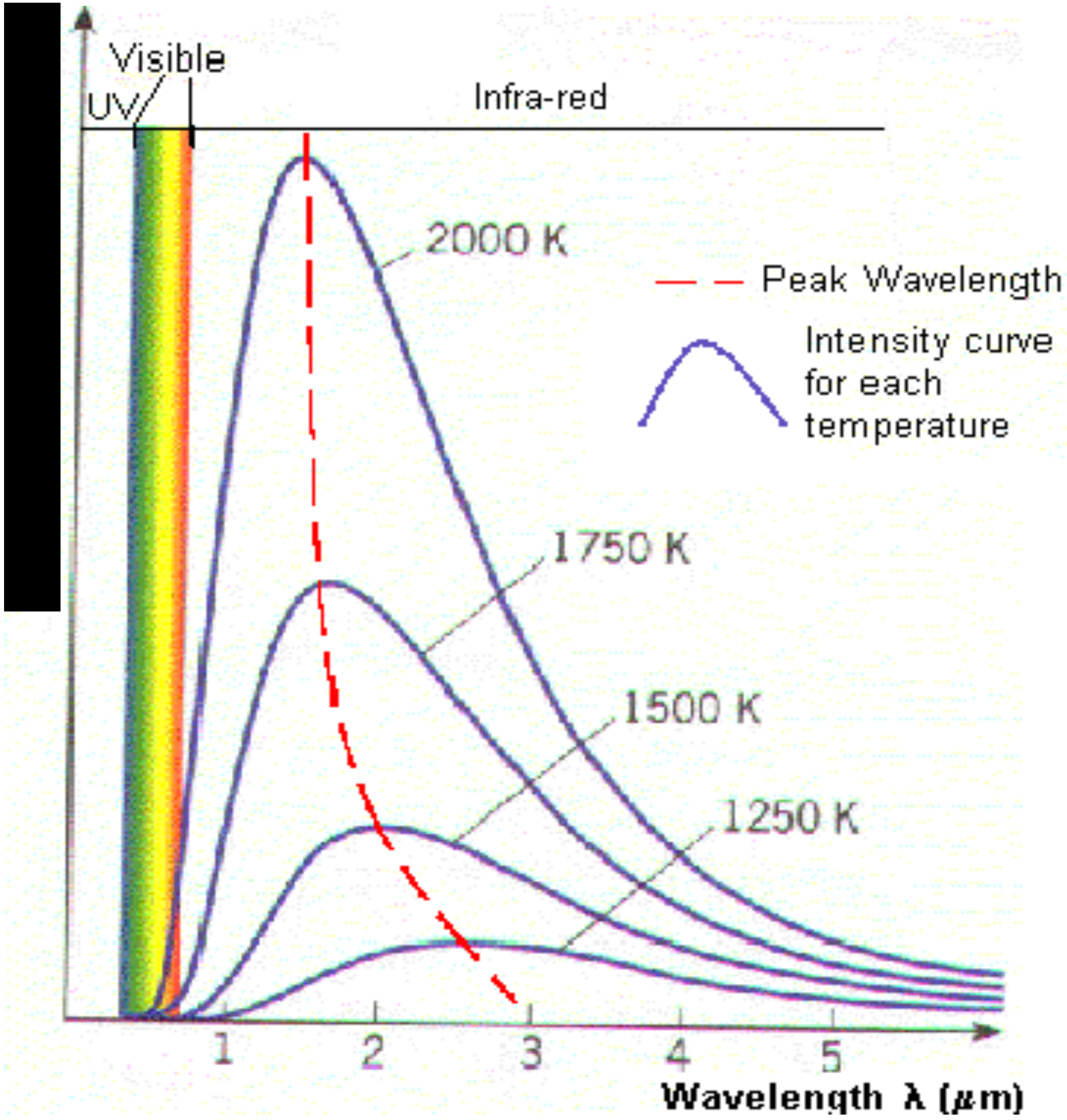


At low frequencies, the Rayleigh-Jeans distribution applies:

$$\boxed{I(\nu) = \frac{2\nu^2 kT}{c^2}}$$

$$\boxed{I(\lambda) = \frac{2ckT}{\lambda^4}}$$

‘Thermal’ spectrum of radiation: Blackbody (5)



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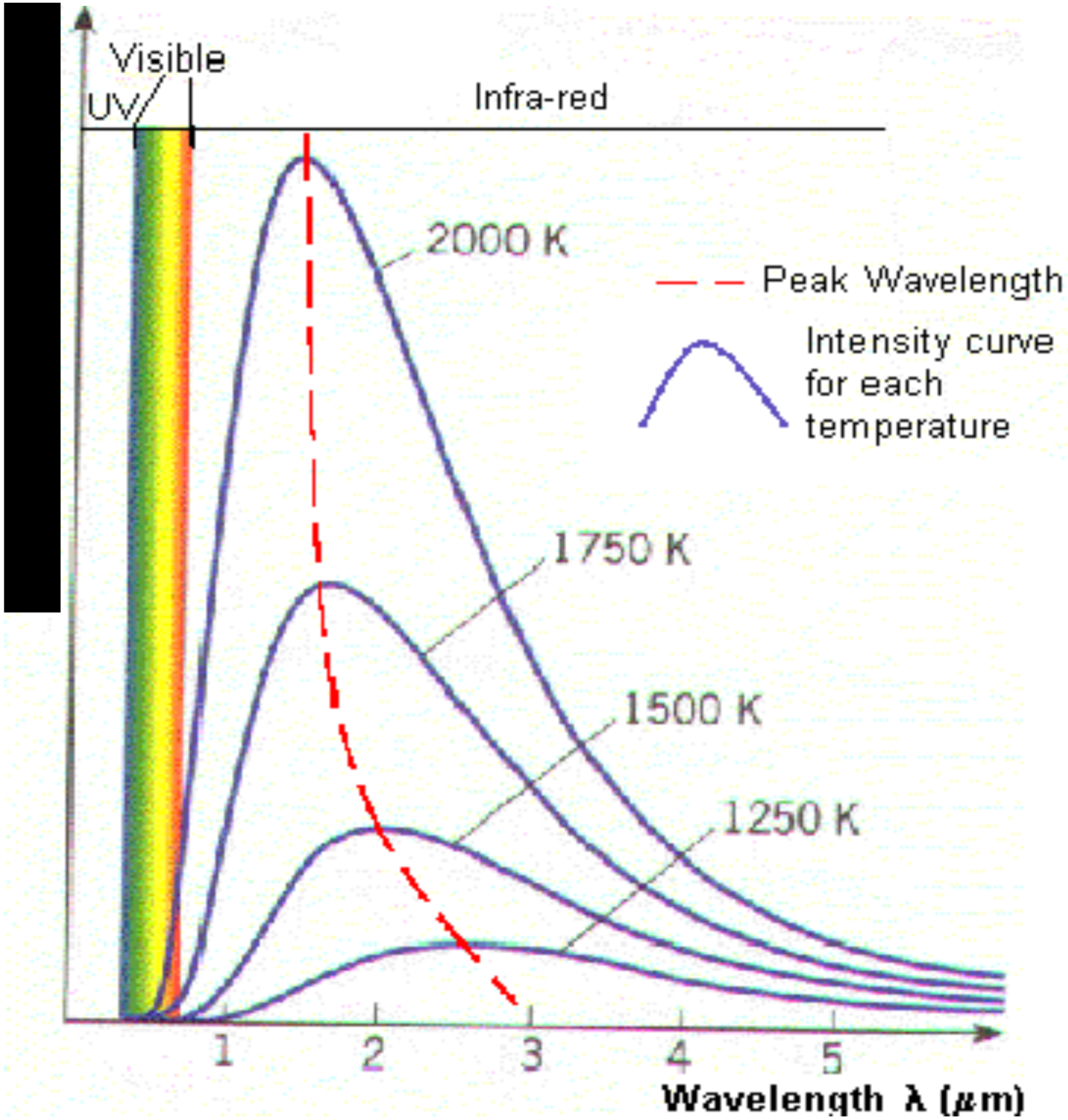
Wien displacement law expresses <u>wavelength at which maximum intensity of blackbody radiation is emitted as a function of temperature</u>; it is obtained by setting

$$\frac{dI(\lambda)}{d\lambda} = 0$$

$$\rightarrow \quad \boxed{\lambda_{\max} \approx \frac{3\times 10^{-3}}{T}}$$

where $\lambda_{\max}$ in m
T in Kelvin

‘Thermal’ spectrum of radiation: Blackbody (7)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Stefan-Boltzmann law

Area under Planck’s curve (by integrating Planck’s function over wavelength and all solid angles) is the <u>total power emitted per unit area</u>:

W m^{-2}

$$\boxed{F(T) = \sigma T^4}$$

σ= 5.67 x 10^{-8} W m^{-2} K^{-4}

σ = Stefan-Boltzmann’s constant

Luminosity of star of radius *R* (emitting as a blackbody)

W

$$\boxed{L = 4\pi R^2 \sigma T^4}$$

PHAS 1102 Physics of the Universe

2 – Spectra and stellar classification

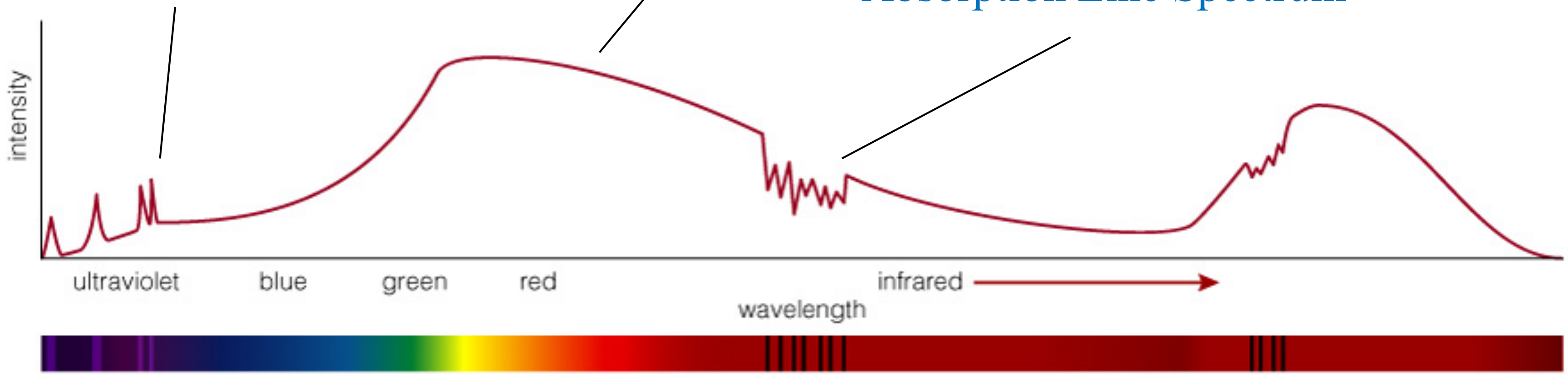
Wave nature of light

$$\boxed{\lambda = \frac{c}{\nu}}$$

Quantum nature of light - Photons (or quanta)

$$\boxed{E = h\nu}$$

What are the three basic types of spectra?



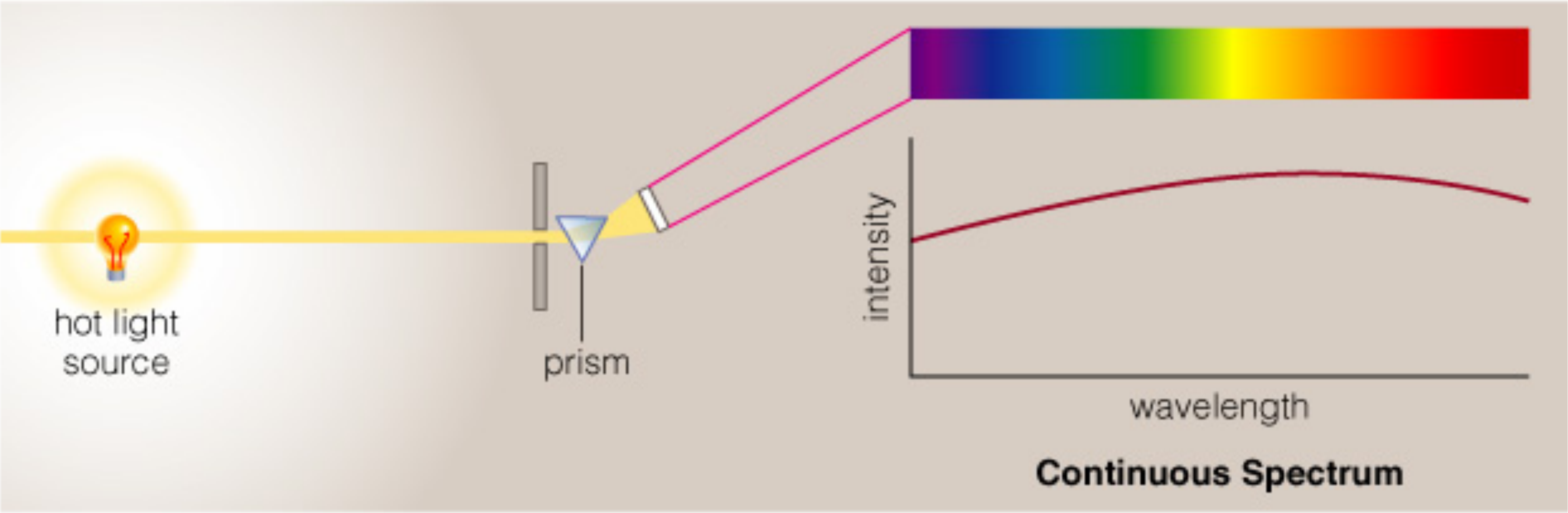
Continuous Spectrum

Emission Line Spectrum

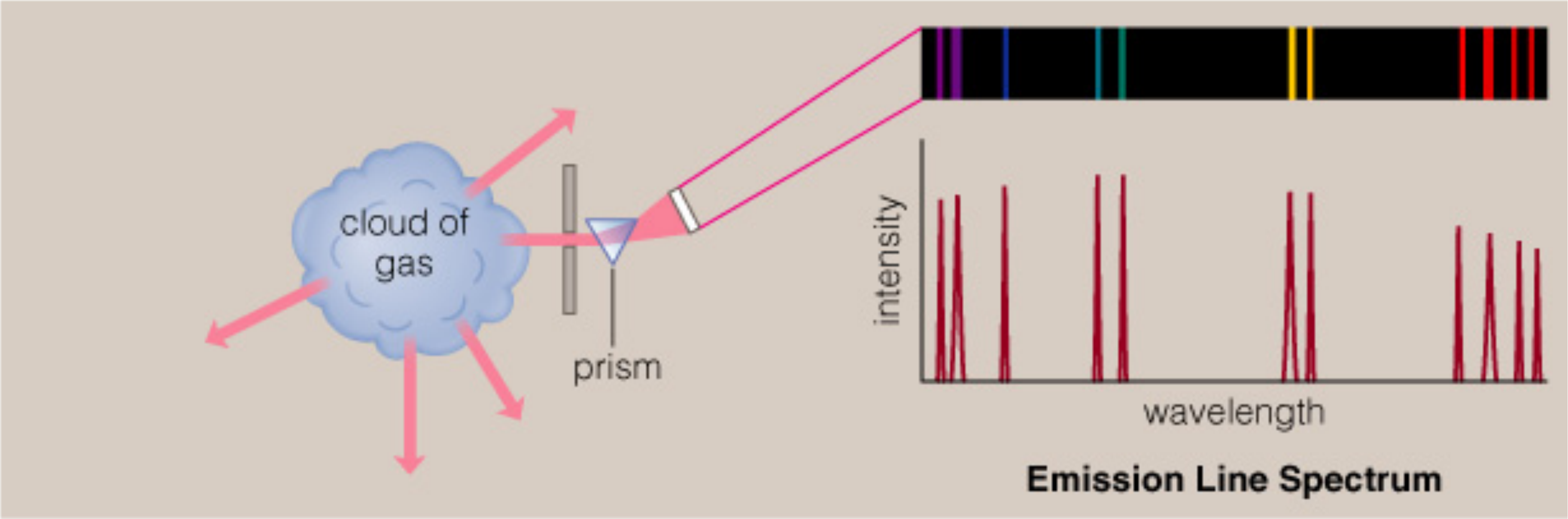
Absorption Line Spectrum

Spectra of astrophysical objects are usually combinations of these three basic types: how they arise is described by Gustav Kirchhof’s Laws.

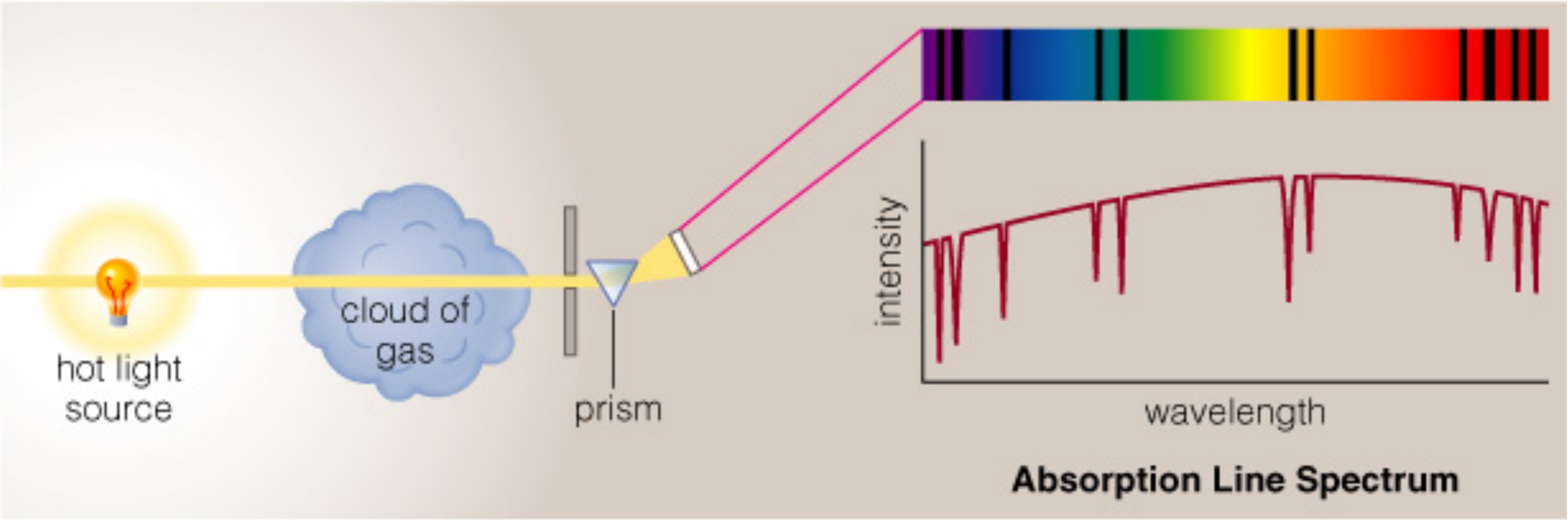
Continuous Spectrum



Emission Line Spectrum



Absorption Line Spectrum



Absorption and emission lines - Atoms

Where do absorption and emission lines come from?

From the absorption or production of energy when an electron in an atom changes its energy level (orbit).

An atom can be described as a very small nucleus, consisting of *neutrons* and *protons*, surrounded by a cloud of *electrons* (out to a radius of ~10^{-10}m) – *neutrons*, *protons* and *electrons* are elementary particles, building blocks of matter.

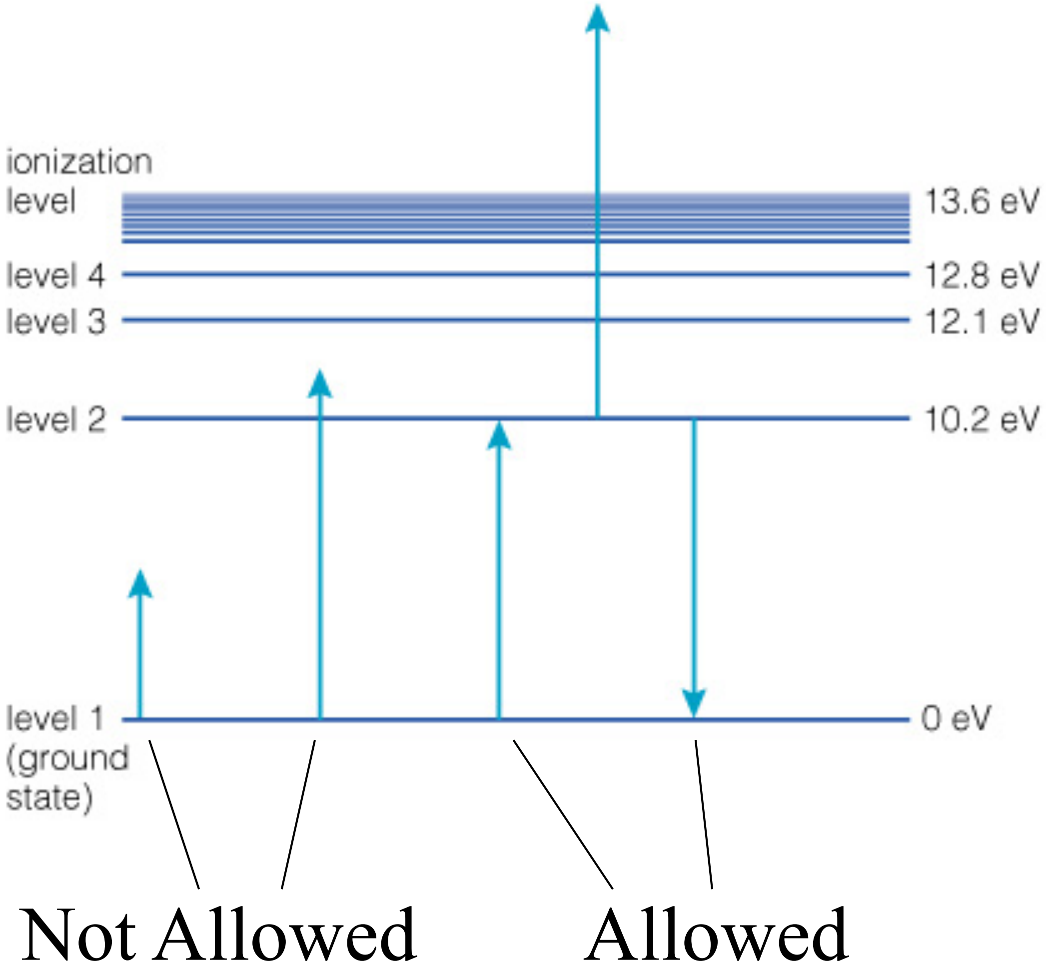
Proton mass = 1.6725×10^{-27} kg charge = $+e$

Neutron mass = 1.6748×10^{-27} kg charge = 0

Electron mass = 9.1091×10^{-31} kg charge = $-e$

($e = 1.6 \times 10^{-19}$ Coulomb)

Energy Level Transitions

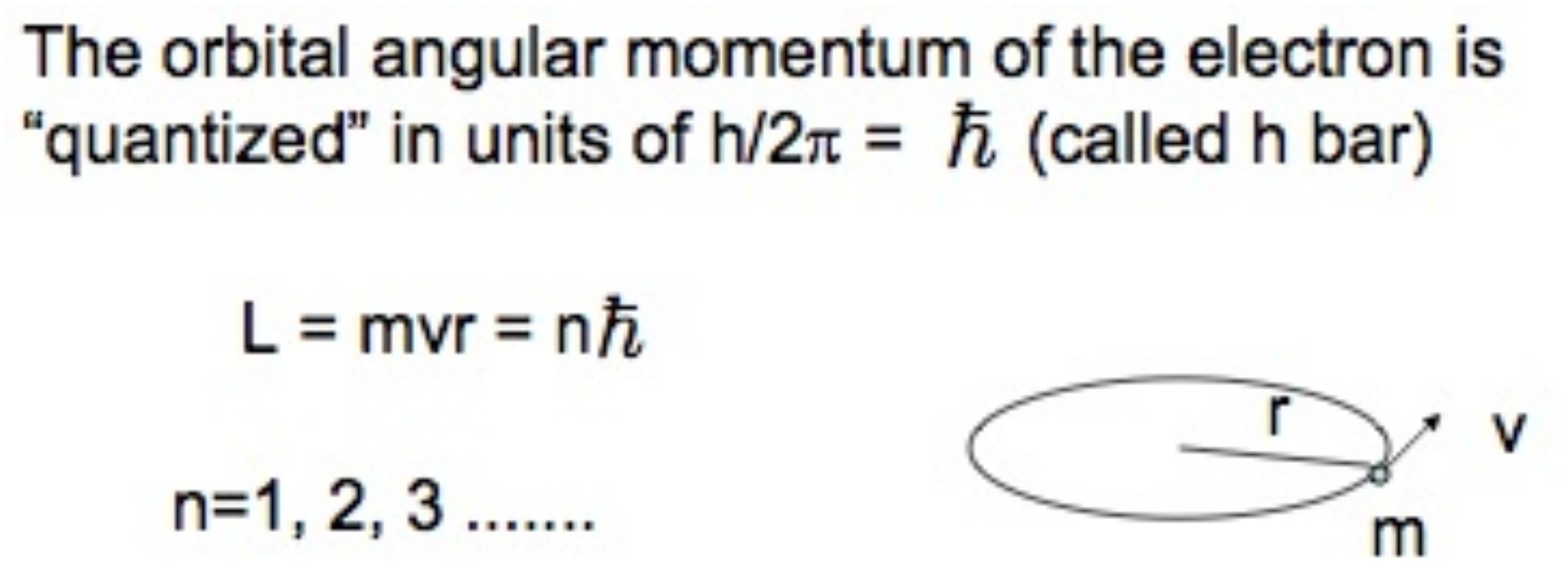


- The only allowed changes in energy are those corresponding to a transition between energy levels (here, Hydrogen)

Bohr’s atom ➔ Quantum mechanics

In 1911 Rutherford put forward the nuclear theory of the atom with electrons orbiting the nucleus

To explain the stability of this model, in 1913 Niels Bohr postulated that only a discrete number of orbits are allowed, and that in them the electron cannot radiate



The orbital angular momentum of the electron is “quantized” in units of $h/2\pi = \hbar$ (called h bar)

$$L = mvr = n\hbar$$

$n=1, 2, 3 \ldots\ldots$

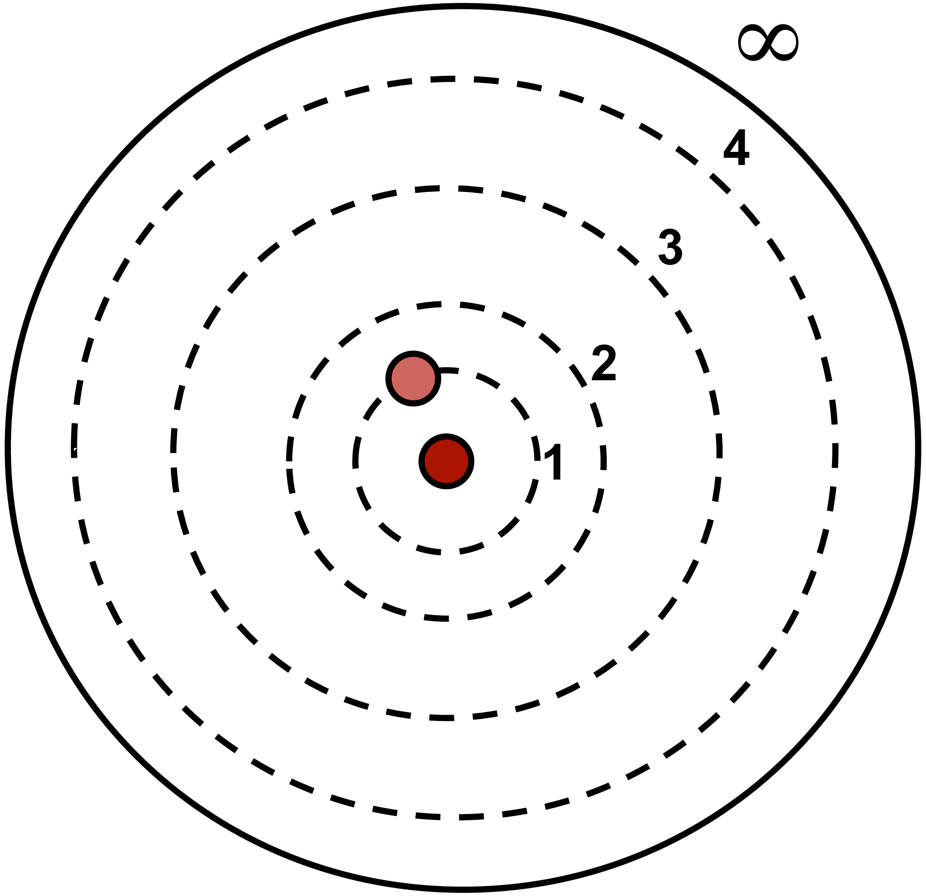
Bohr's atom ➔ Quantum mechanics...

Permitted orbits: those where the electron's orbital angular momentum is an integer multiple of $\frac{h}{2\pi}$ where h is Planck's constant

➔Principal quantum number n = 1, 2, 3, …

Bohr also postulated that - a single discrete quantum of radiation is emitted or absorbed as the electron jumps from an orbit to another, and - the energy of the radiation equals the orbits' energy difference

The hydrogen atom



Take the simple case of Bohr's hydrogen atom.

It has one proton in the nucleus and one orbiting electron.

In its stable state, the electron orbits in the energy level defined by n = 1 (the ground state). There are an infinite number of discrete energy levels, converging to n = , the ionization potential.

∞

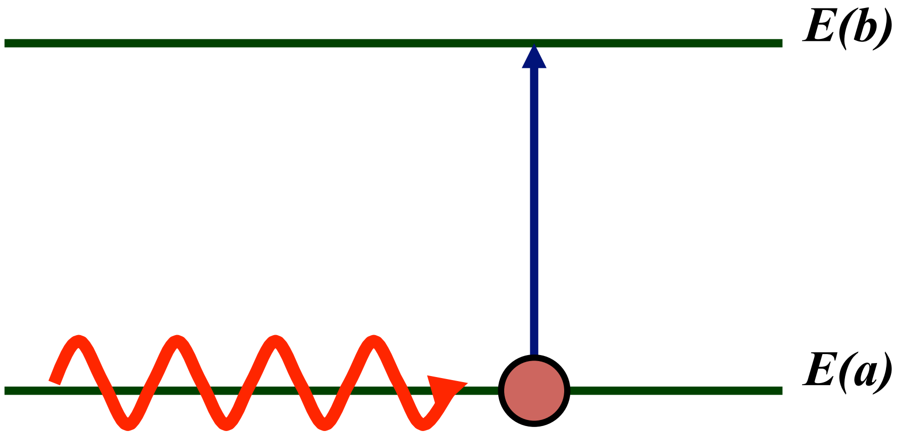
Quantum numbers

Only certain discrete energy levels are allowed for electrons in atoms. The levels are defined by quantum numbers, of which n is the 'principal' (but there are several others …).

The electron energy levels are negative (orbits are 'bound'):

$$\boxed{E(n) \propto -\frac{1}{n^2}}$$

Quantum mechanics



Photon energy, $h\nu = E(b) - E(a)$

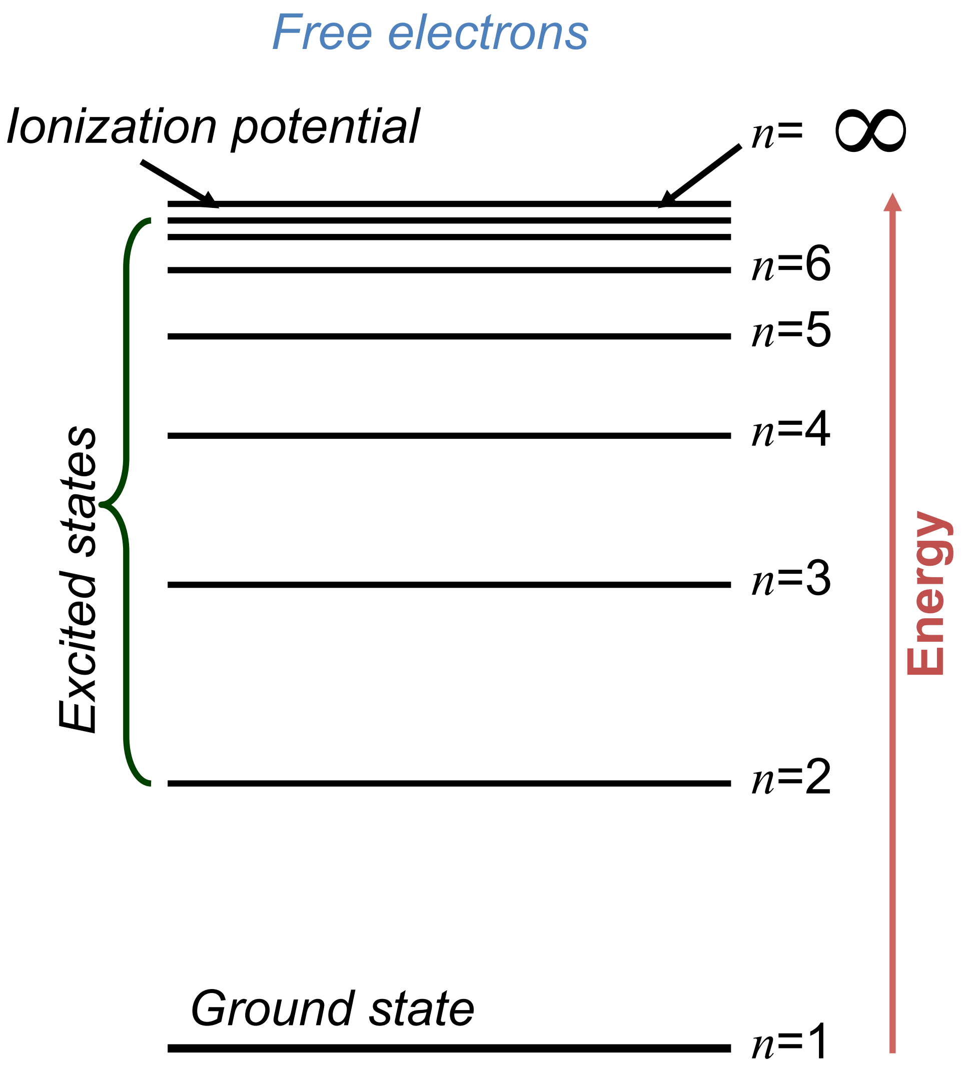
$E(a)$ more negative than $E(b)$

Energy levels: ionization potential

Atoms have an infinite number of energy levels, converging to a finite energy value (the ionization potential).

If an electron gains more energy than the ionization potential, then it is no longer bound to the atom.

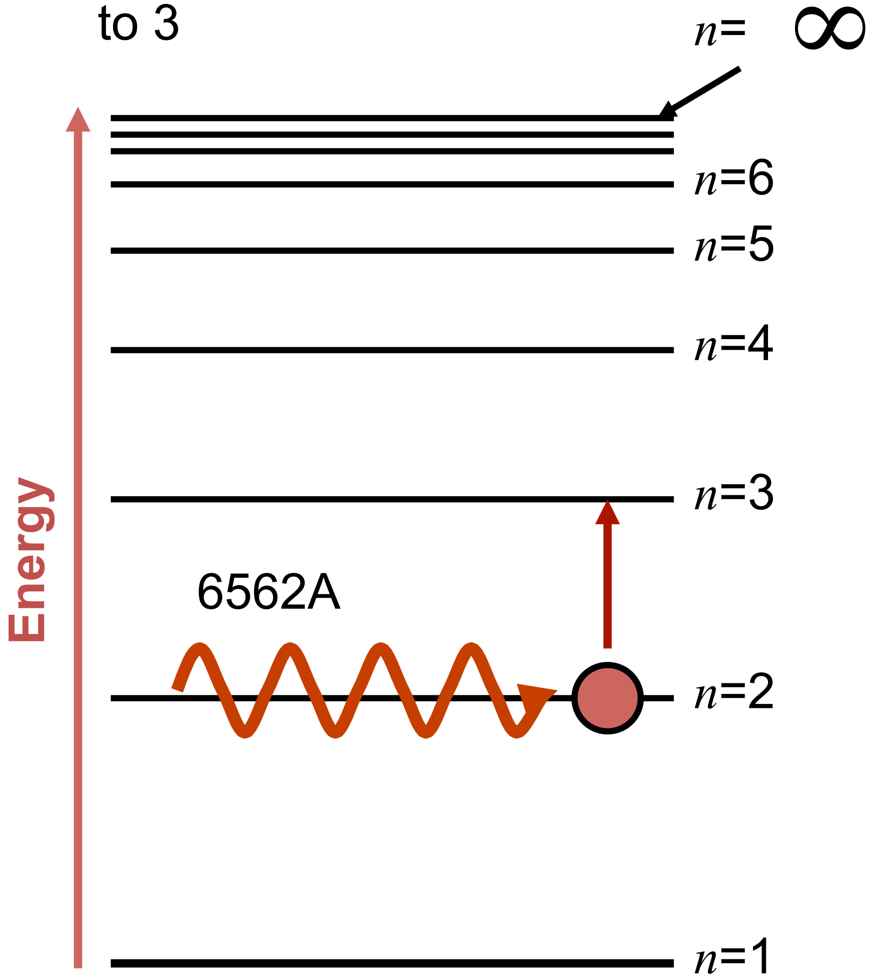
Only the lowest level (the ground state) is generally stable. Excited states (when an electron is in level n = 2 or higher) have lifetimes of ~10^{-8}s



Levels structure complex, especially for atoms heavier than H: more quantum numbers exist, and many more energy levels too ...

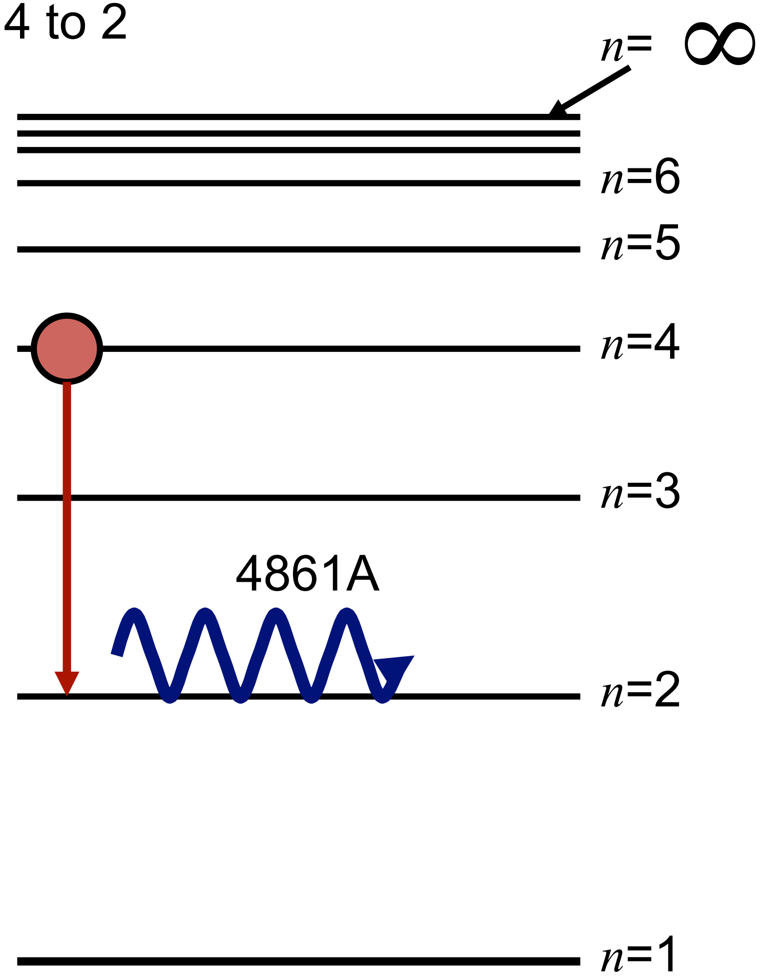
Transitions of the hydrogen atom

Electron moves up from 2 to 3



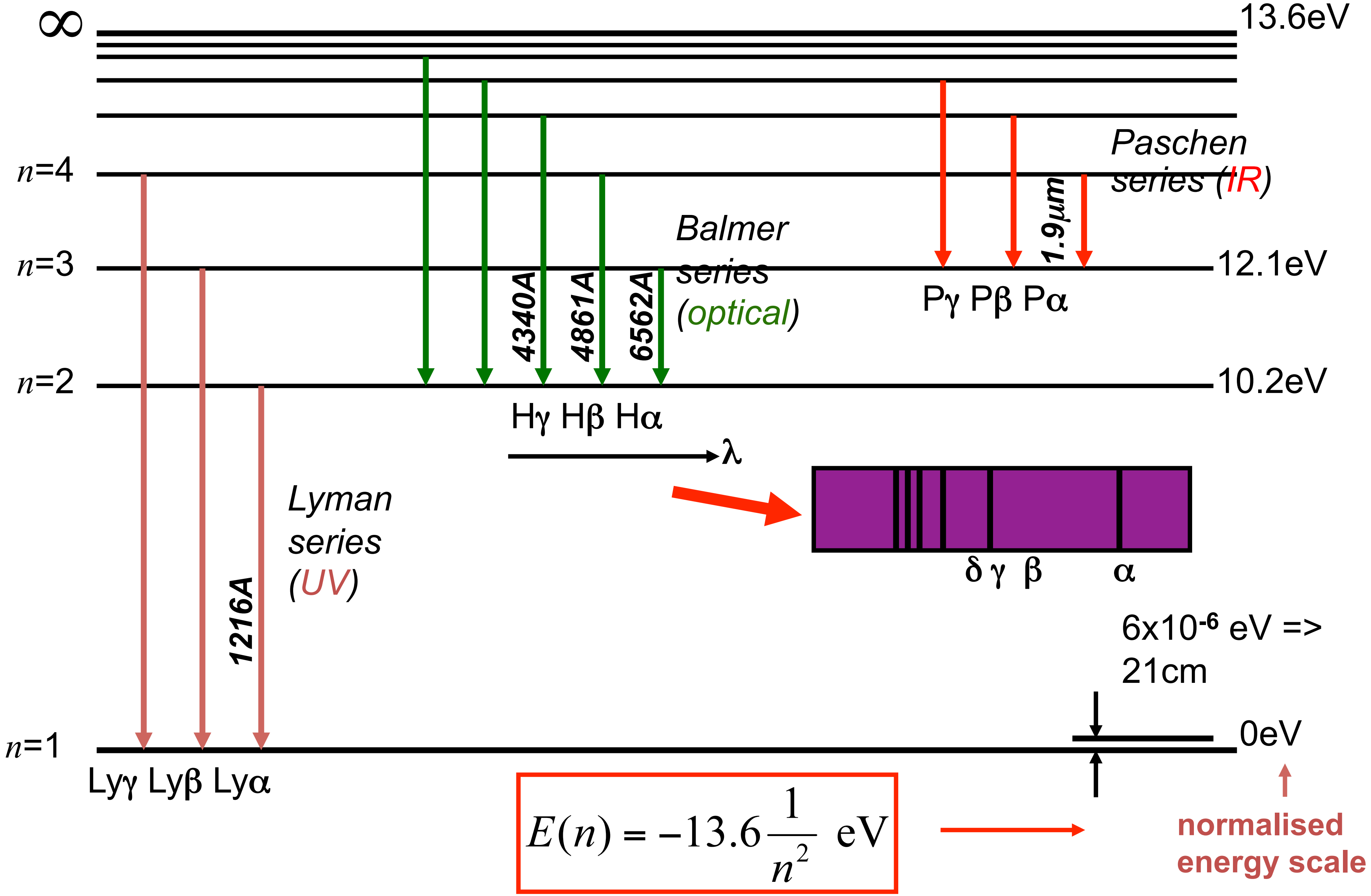
Absorption line at 6562A

Electron moves down from 4 to 2



Emission line at 4861A

Spectrum of the hydrogen atom



$$\boxed{E(n) = -13.6\frac{1}{n^2}\ \mathrm{eV}}$$

Emission lines

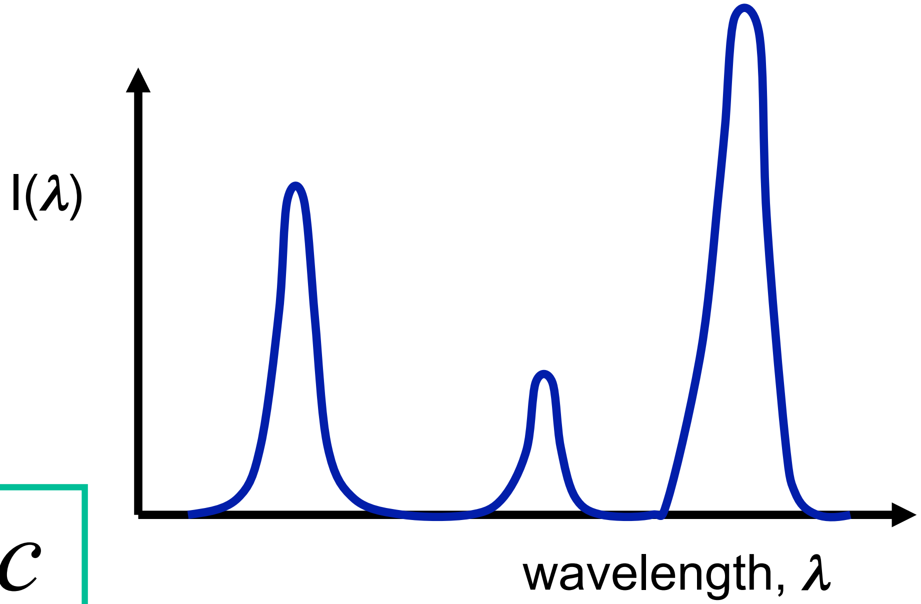
To produce emission lines, an excited state must first be populated – when the electron in an excited state falls by one or more levels, an emission line is produced.

To populate the excited levels:

(a) Collisional excitation

(b) Photo-excitation

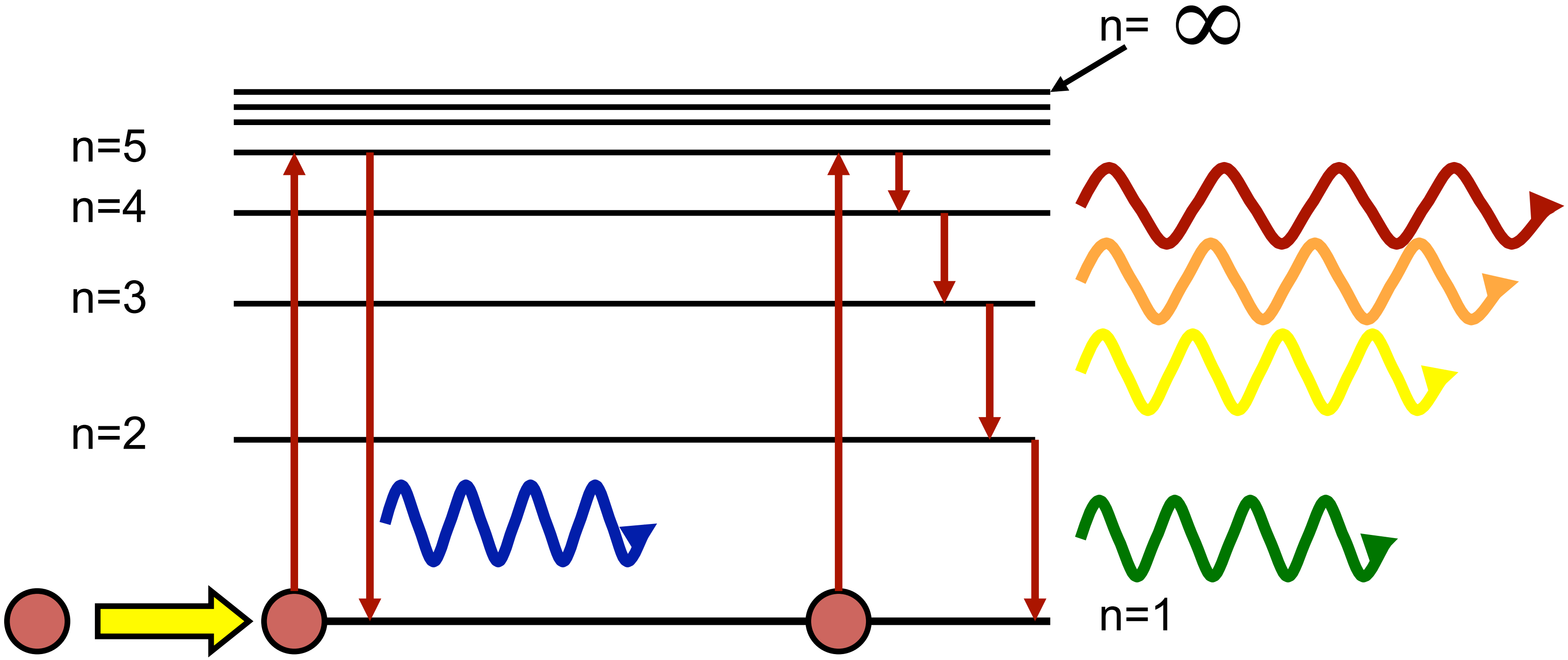
(c) Recombination



These all produce emission lines...

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

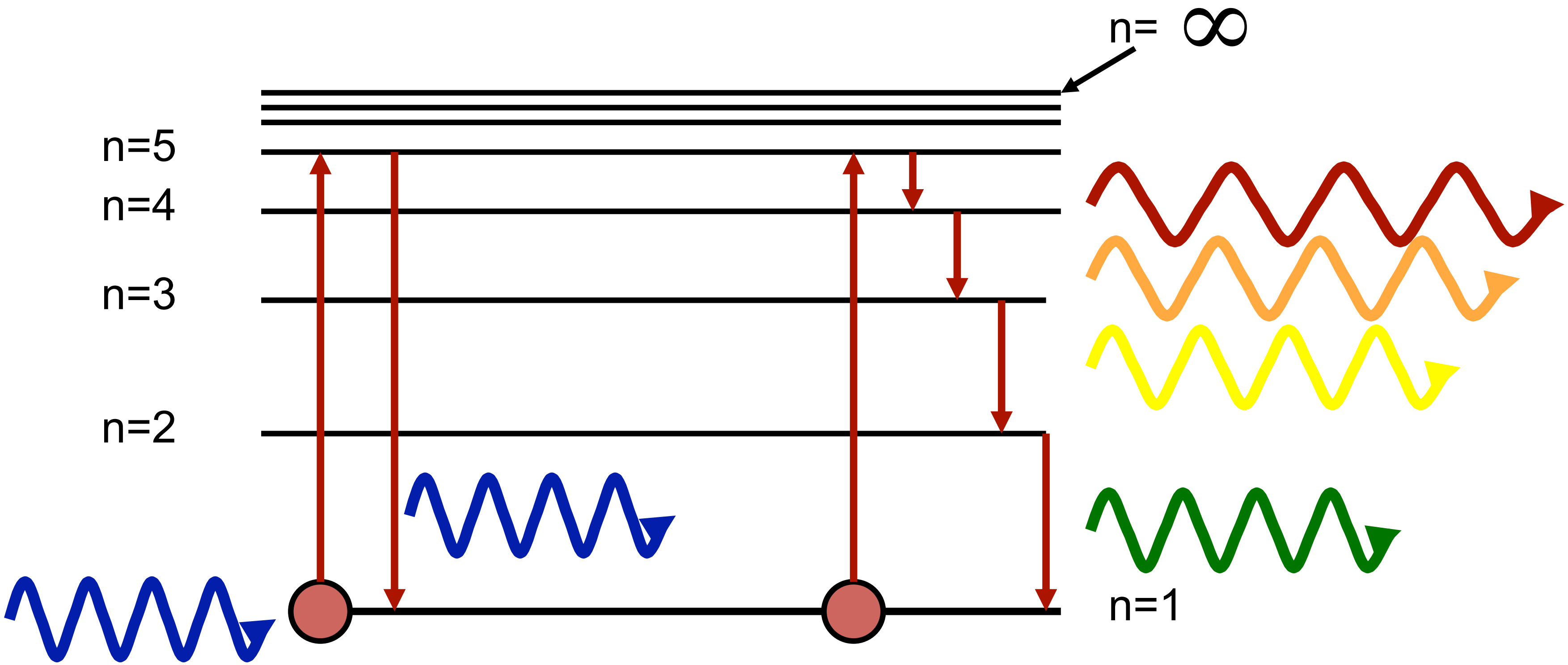
Collisional excitation



Collisions with electrons/ions/atoms can knock bound electrons into higher energy levels. The energy comes from the kinetic energy of the colliding particle.

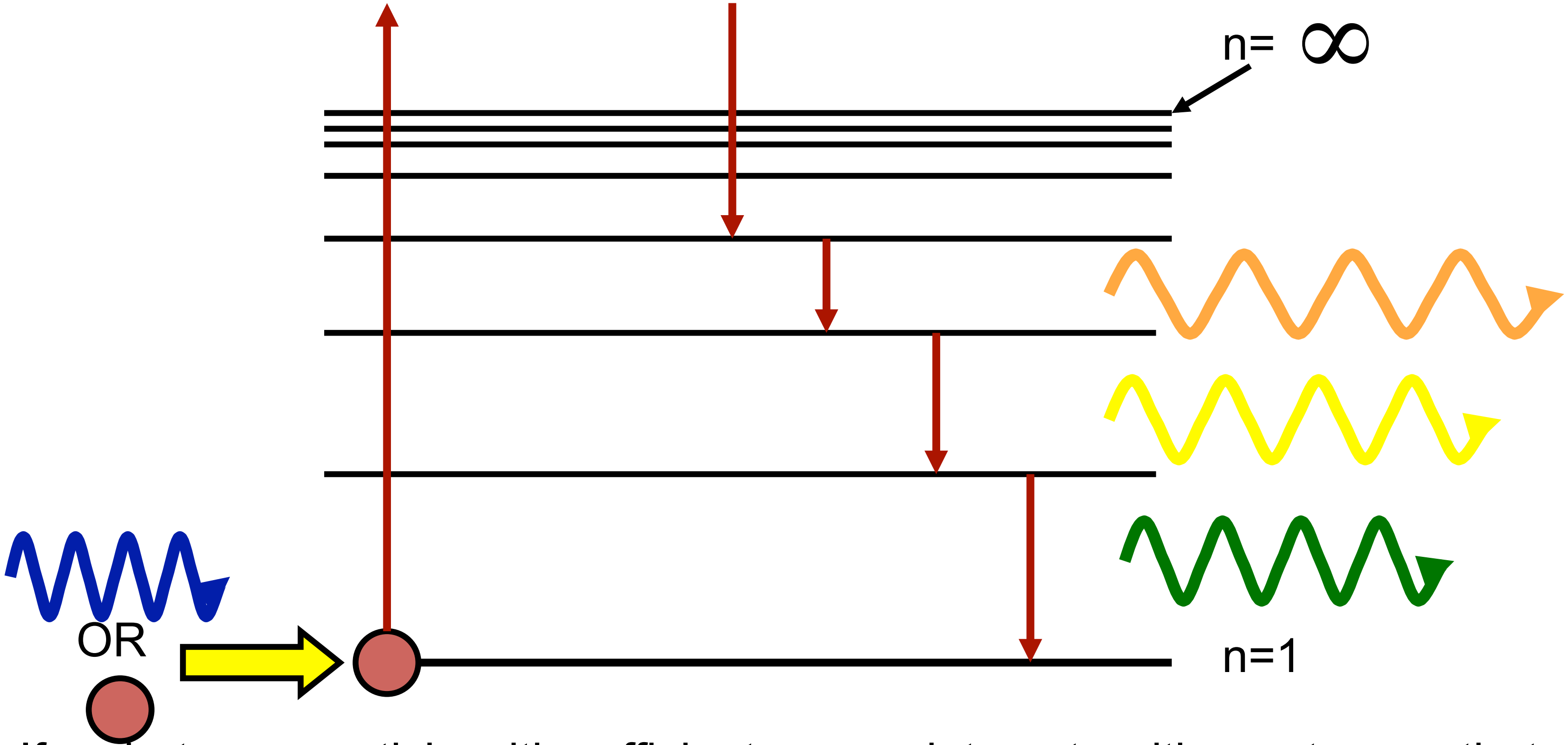
The electron falls back to lower levels and this energy is radiated away.

Photo-excitation



If a photon with the right energy interacts with an atom or ion, an electron can be moved up to a higher level for a short while, before it falls back down to the ground state.

Recombination, following ionization



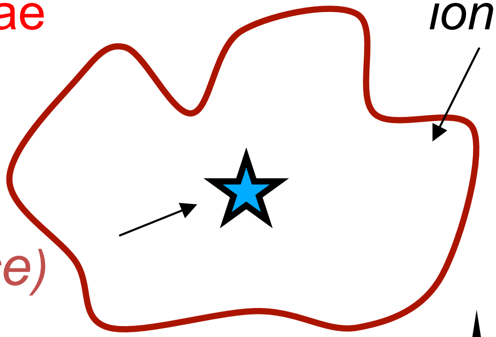
If a photon or particle with sufficient energy interacts with an atom so that an electron is stripped away, the atom is said to have been ionized.

A free electron can recombine with an ion, finishing up into an excited state – it will then cascade down to ground level producing line emission (radiative cascade).

Sources of emission lines

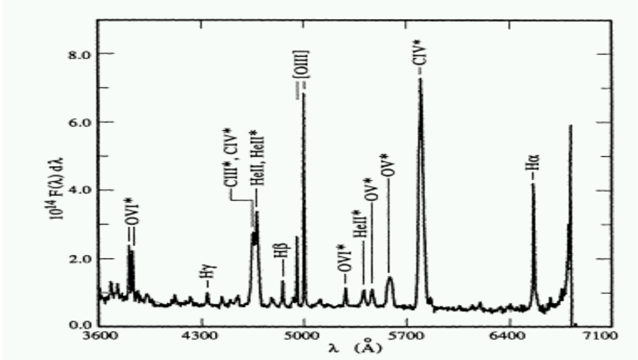
Photoionization → ***Recombination***

Hot ionized nebulae
(e.g. HII regions)

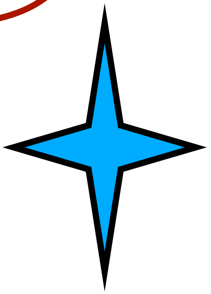


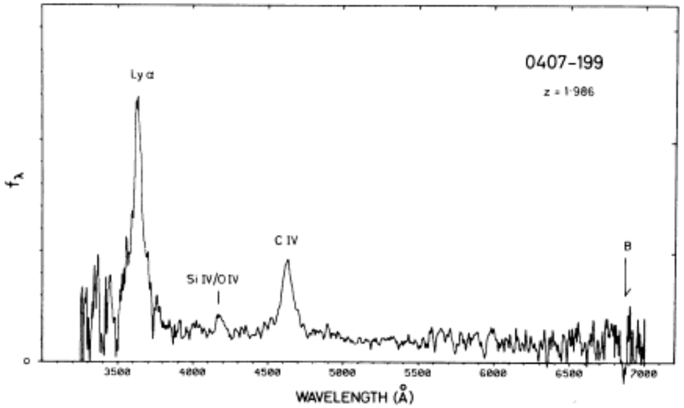
ionized gas

hot star (UV source)



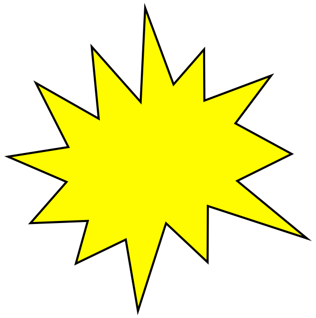
Active galactic
nuclei (e.g. quasar)

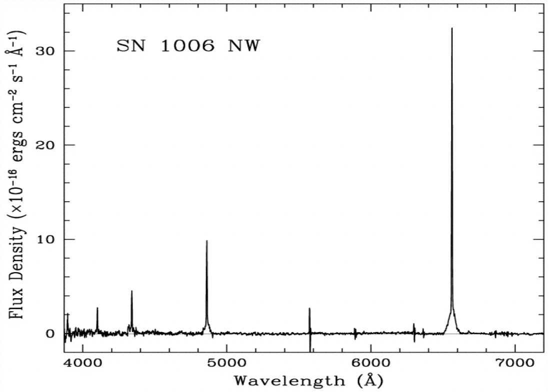




Collisional ionization → ***Recombination***

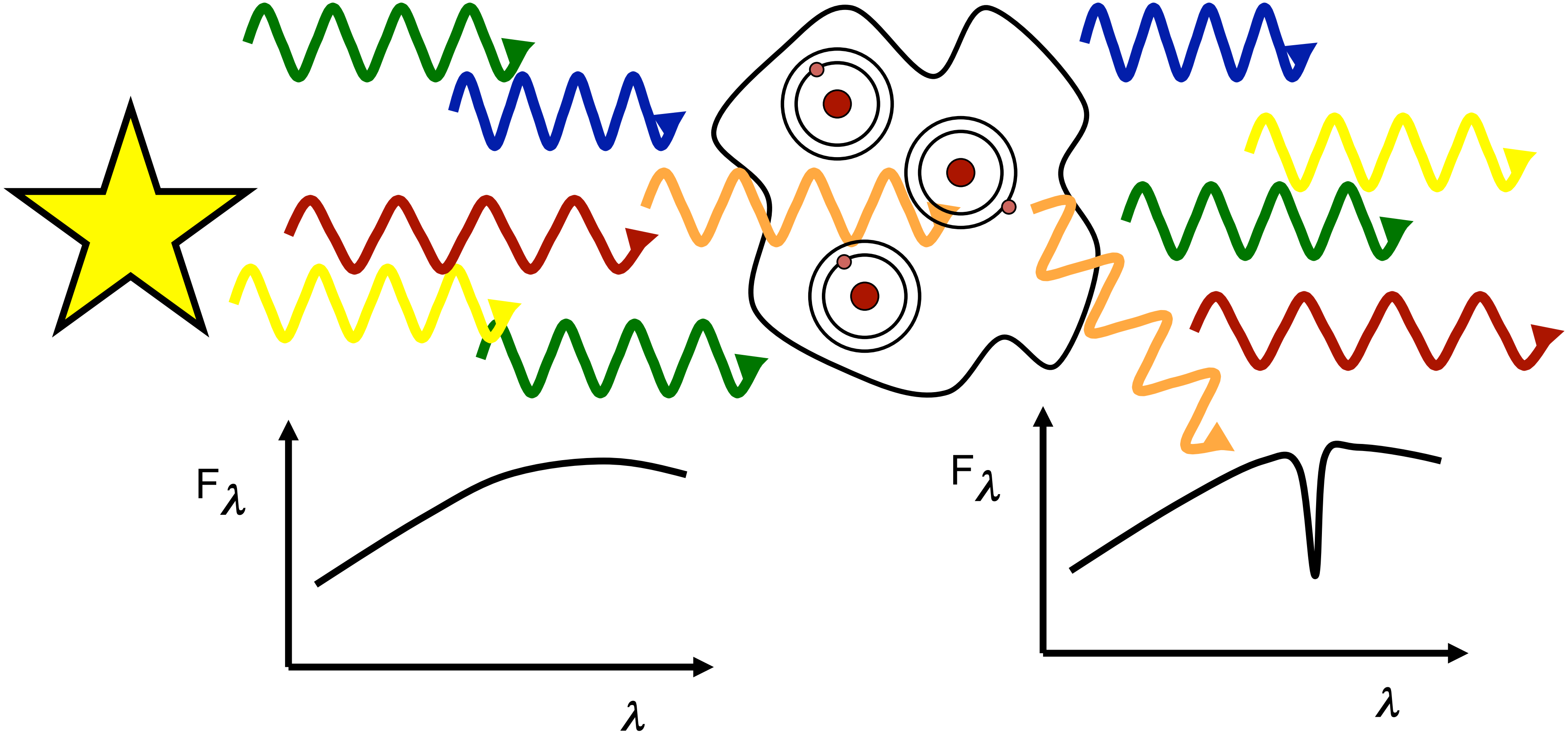
Supernova
Remnant



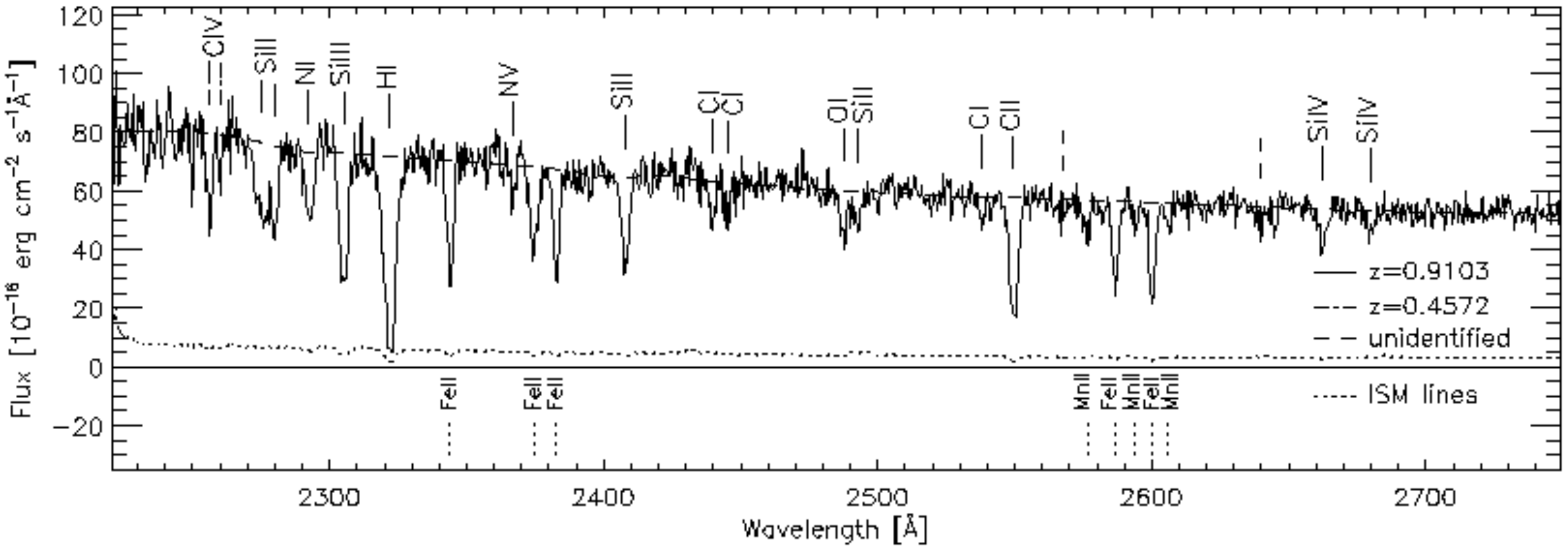


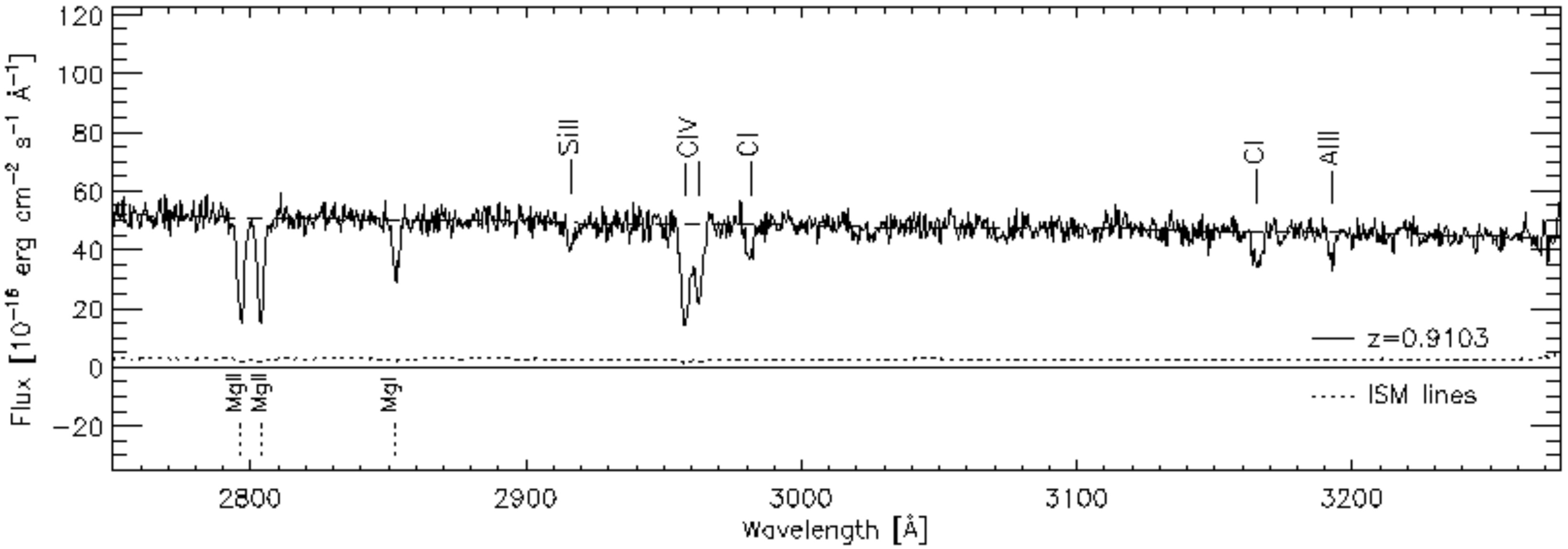
Absorption lines formation

When atoms/ions in a gas are illuminated, they will absorb photons at those wavelengths which will move electrons in the atoms/ions from one level to another.



QSO Spectrum with IGM Absorption





Absorption lines formation (cont.)

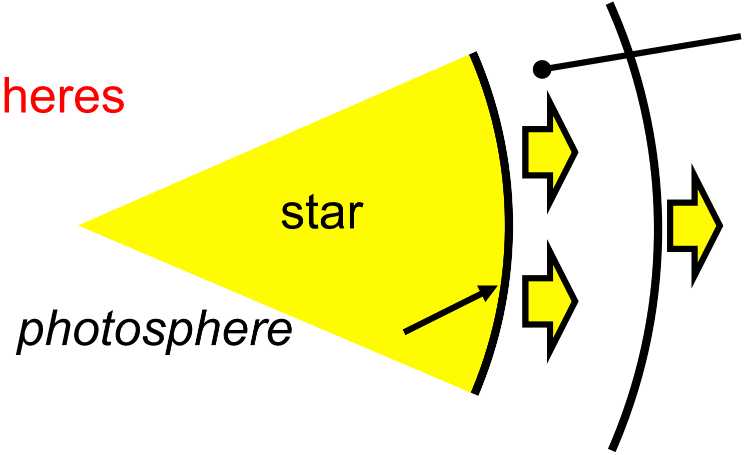
Atoms or ions in a gas will absorb photons whose energy corresponds exactly to the energy that an electron in that atom/ion needs to move into a higher level.

After about 10^{-8} seconds, the electron will fall back down to the most stable state, emitting a photon with an energy corresponding to the difference between the levels, but in a random direction.

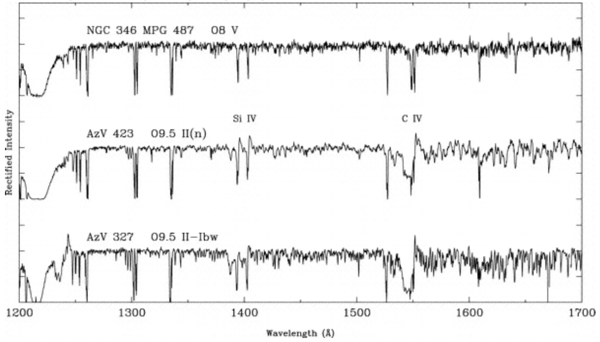
So if you look through the gas at a source, you will see very few photons at that energy because these are being absorbed and re-emitted in random directions. This produces an absorption line.

Sources of absorption lines

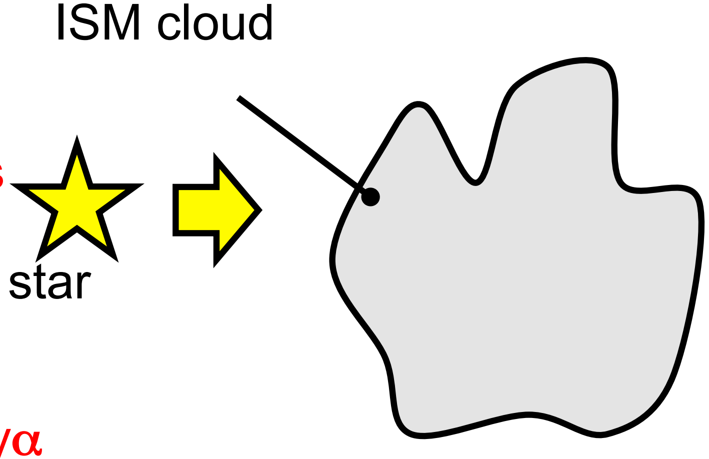
Stellar atmospheres

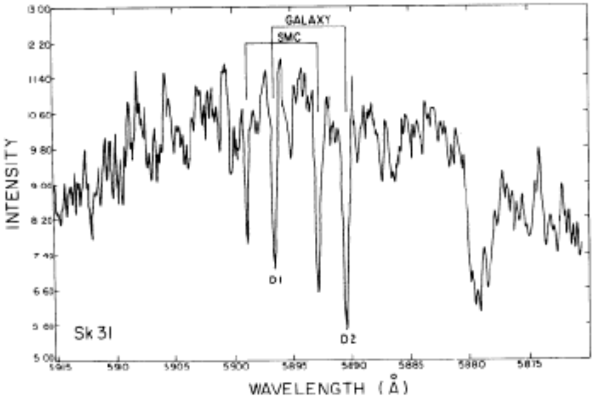


outer layers absorb blackbody emission from the star

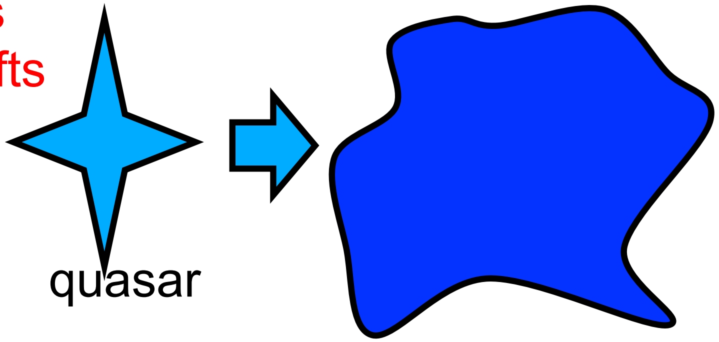


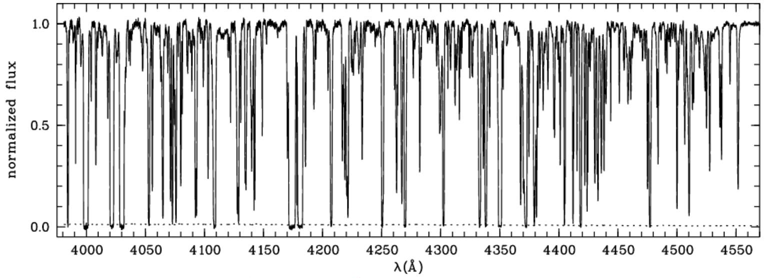
Interstellar gas





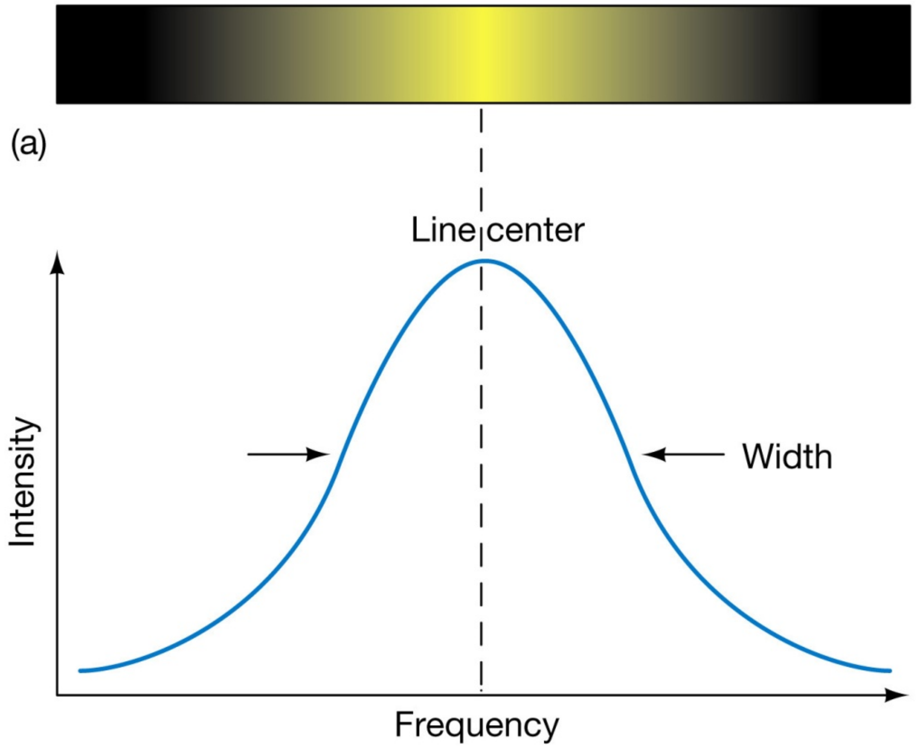
Intergalactic Lyα
systems of clouds
at different redshifts





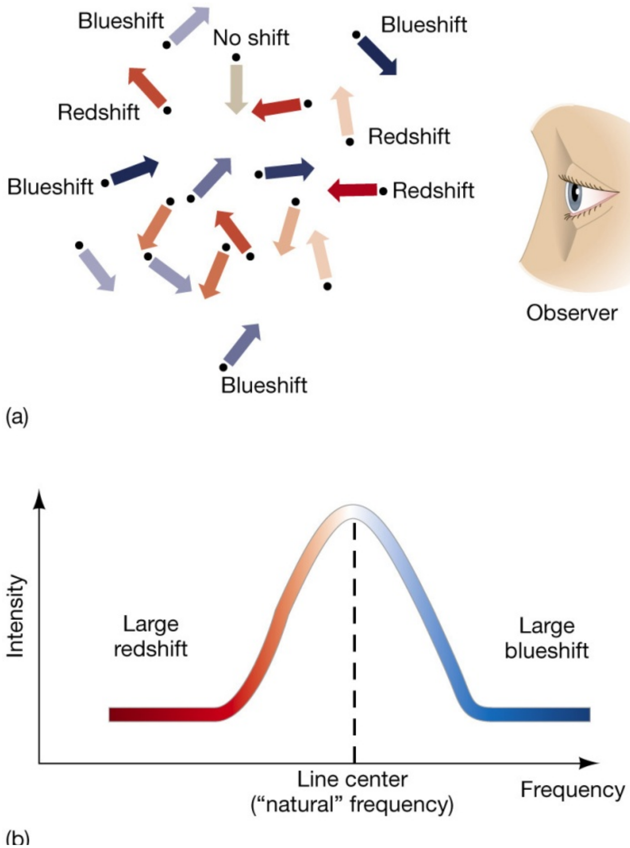
'Lyα forest'

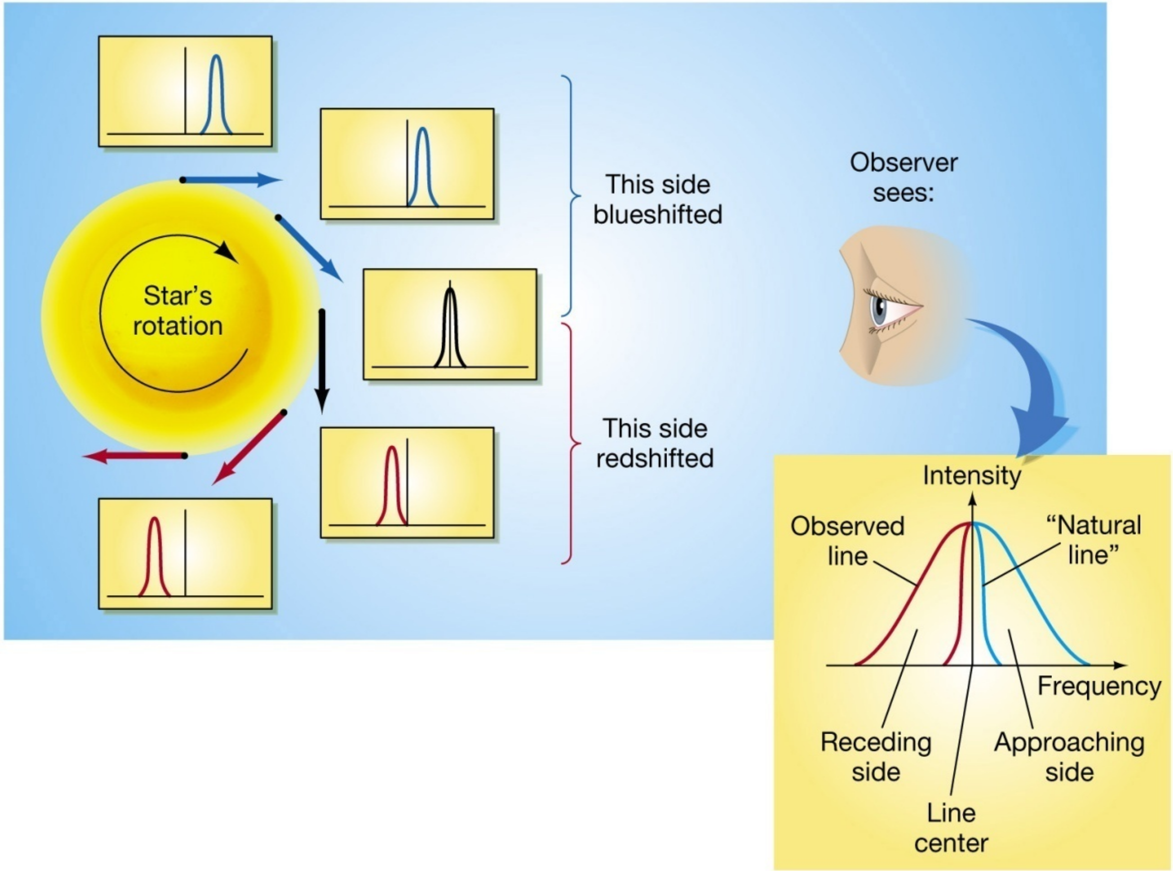
Spectral Line Shapes



- In reality, lines are not at exactly one frequency or wavelength
- All lines have widths, shown here for an emission line.
- Line shapes are an important tool in studying stars and gas in space

Thermal and Rotational Broadening





Stellar classification

A star is a hot, dense ball of gas. It emits approximately
a blackbody spectrum at a single temperature from its photosphere (lowest visible layers).

From Wien's law: Hotter a star is, the bluer. Cool stars look red and intermediate temperature stars appear yellow.

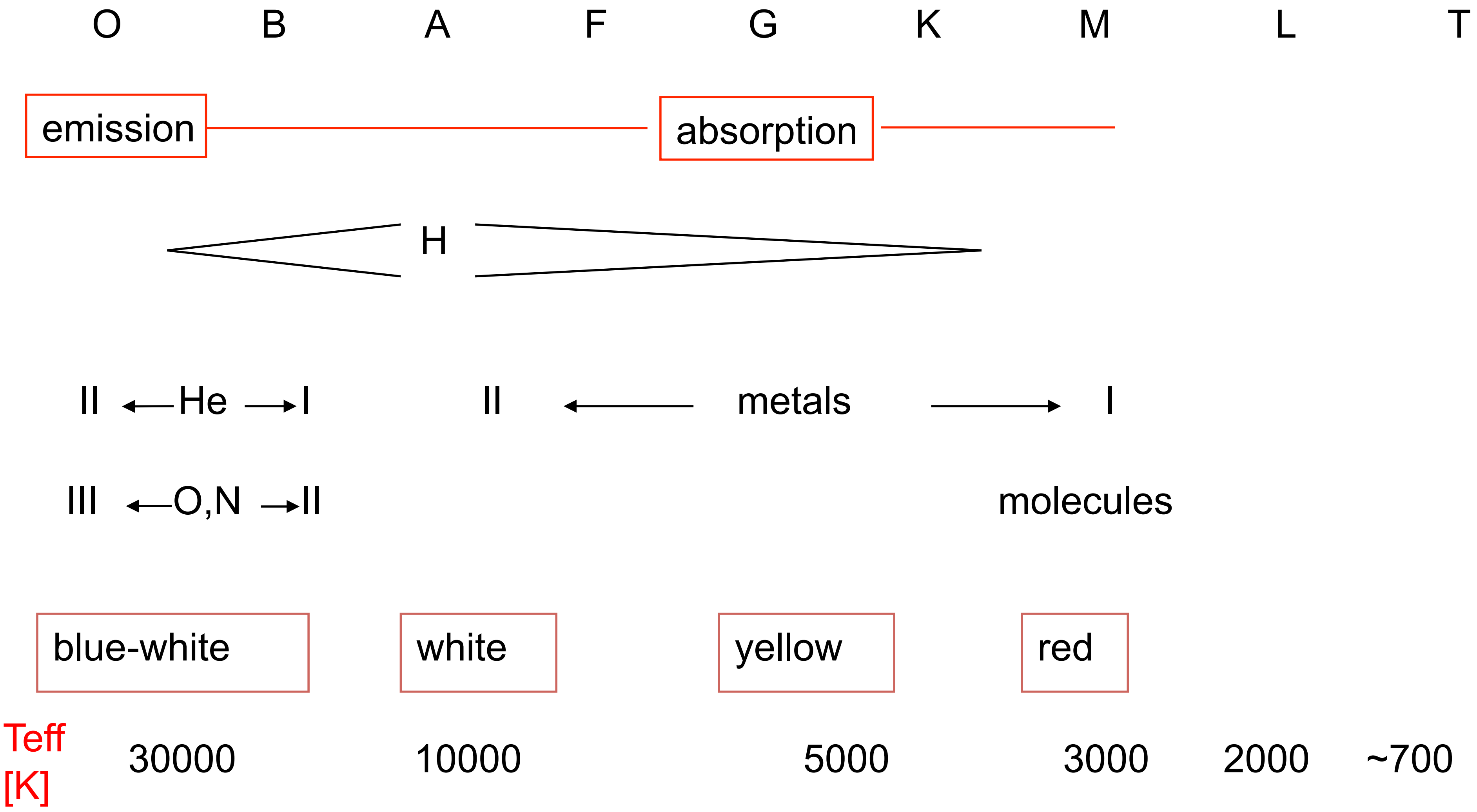
Photosphere is surrounded by thin, warm atmosphere which imprints absorption lines on the continuum.

Which ions do the absorption depends on the temperature
of the gas they are in …

Classification of Stars

- Based on spectral characteristics
- This gives information about temperature in an alternative way
- Absorption lines can be observed only for a certain range of temperatures
- The range involved shows atomic energy levels which have been populated

The Harvard classification



O B A F G K M L T

emission

absorption

H

II ← He → I

II ← metals → I

III ← O,N → II

molecules

blue-white

white

yellow

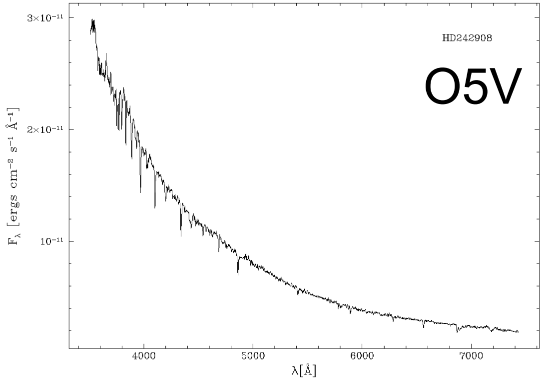
red

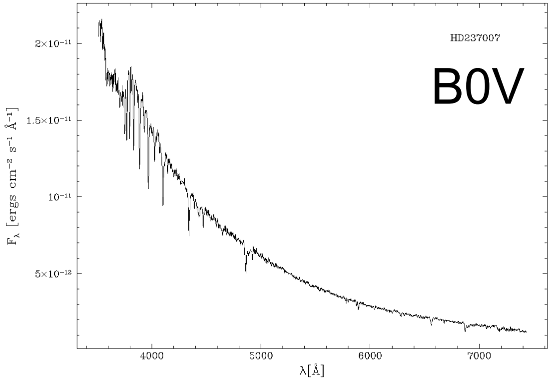
Teff [K] 30000 10000 5000 3000 2000 ~700

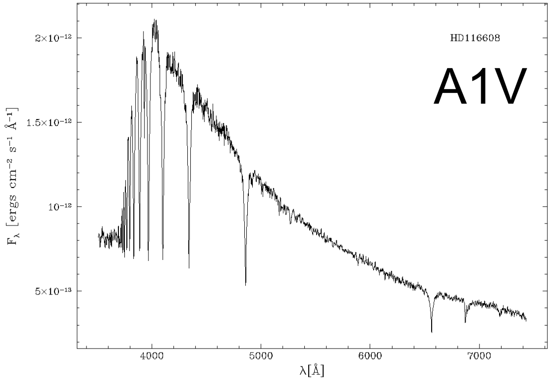
Divisions and subdivisions

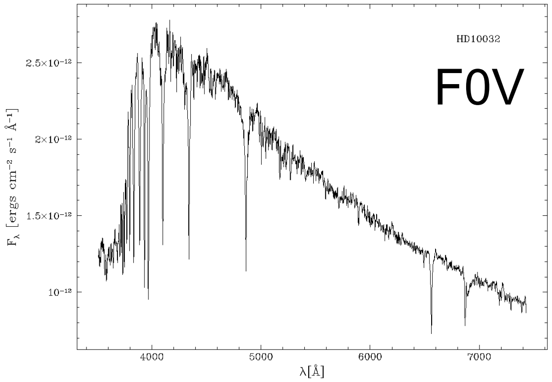
- …later …. discovered that the strength of the hydrogen line was connected with the surface temperature of the star.
- These classes are further subdivided by numbers (0-9)
- A0 denotes the hottest stars in the A class and A9 denotes the coolest ones
- The sun is classified as G2.

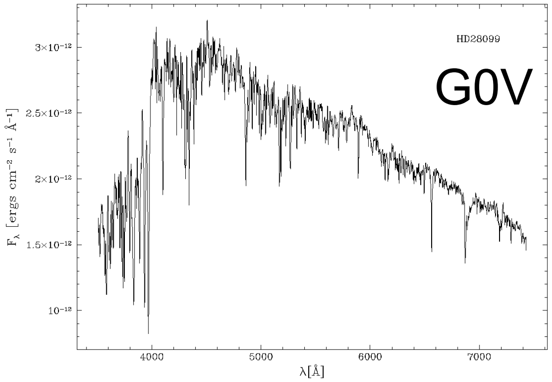
The Harvard spectral classification

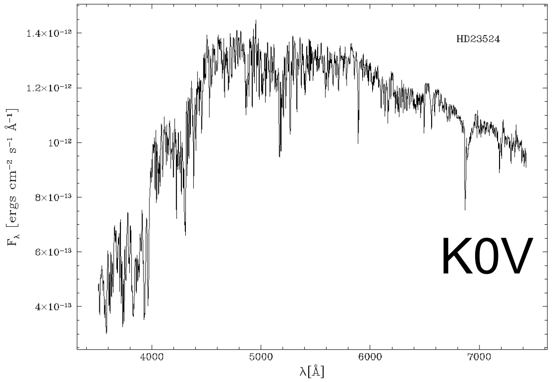


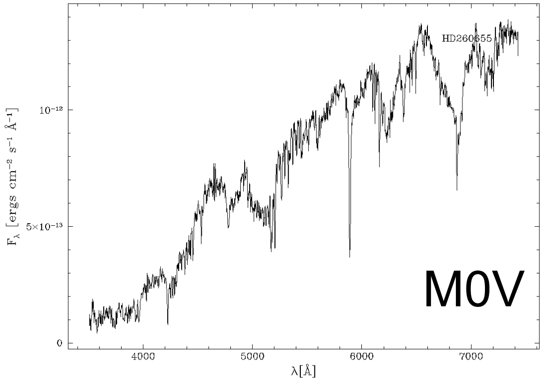


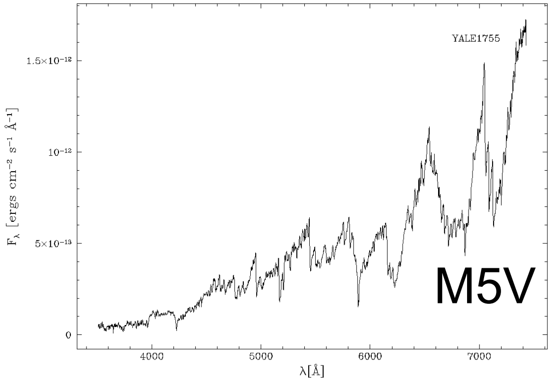












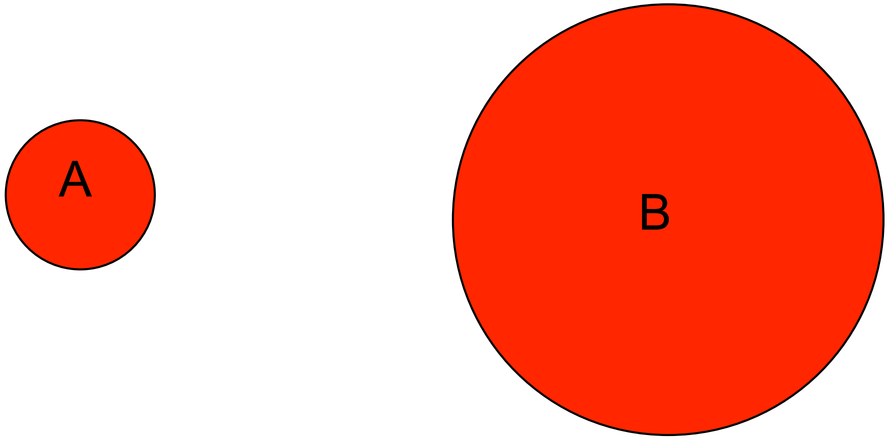
Stellar spectral types (4)

Spectral class	Colour	Surface temp (K)	Main lines	Example
O	Blue-violet	30000-50000	He II	Naos
B	Blue-white	11000-30000	He I	Rigel, Spica
A	White	7500-11000	H, Fe II, Si II, Mg II	Sirius, Vega
F	Yellow-white	6000-7500	Ca II	Canopus, Procyon
G	Yellow	5000-6000	Ca II, Fe I, CH	Sun, Capella
K	Orange	4000-5000	Ca II, Fe I	Arcturus, Aldebaran
M	Red-orange	<4000	Fe I, TiO	Betelgeuse, Antares

The Size (Radius) of a Star

We already know: flux increases with surface temperature (~ T^4); hotter stars are brighter.

But luminosity also increases with size:



Star B will be brighter than star A.

Luminosity is proportional to radius squared, L ~ R^2.

Quantitatively: $$\boxed{L = 4\,\underbrace{\pi R^2}\,\underbrace{\sigma T^4}}$$

Surface flux due to a blackbody spectrum

Surface area of the star

Stellar spectral types (5)

1943: Morgan & Keenan added **luminosity** as a second classification parameter ➔ 2-d scheme

Luminosity classes are designated by the Roman numerals I →V, in order of decreasing luminosity:

Ia = Most luminous supergiants
Ib = Supergiants
II = Luminous giants
III = Giants
IV = Subgiants
V = Main sequence stars (dwarfs)

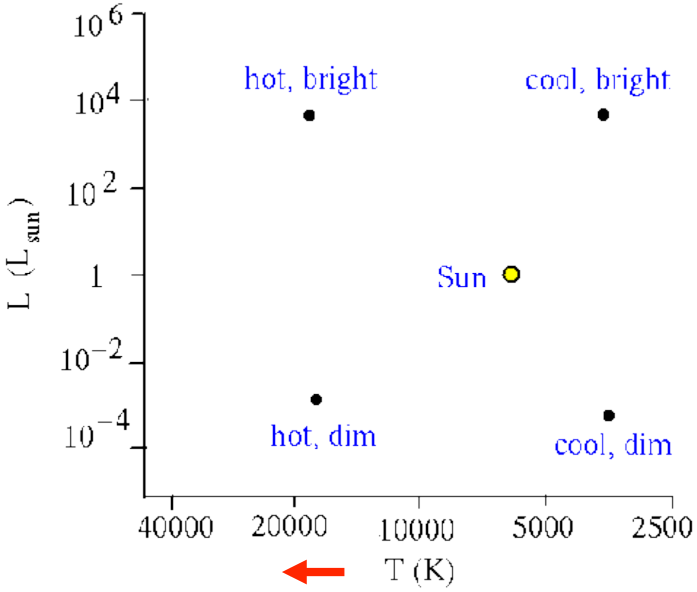
The Sun is a **G2V** star and has an effective (surface) temperature of ~6000 K.

Hertzsprung-Russell diagrams

1911-1913: Hertzsprung and Russell independently plotted stellar luminosity vs temperature (or spectral type).

Stars populate the diagram preferentially in certain regions. This may be partially understood in terms of luminosity of an object emitting thermal radiation:

$$L \sim R^2 T^4$$



H-R diagram for nearby+bright stars:

All stars visible to the naked eye + all stars within 25 pc