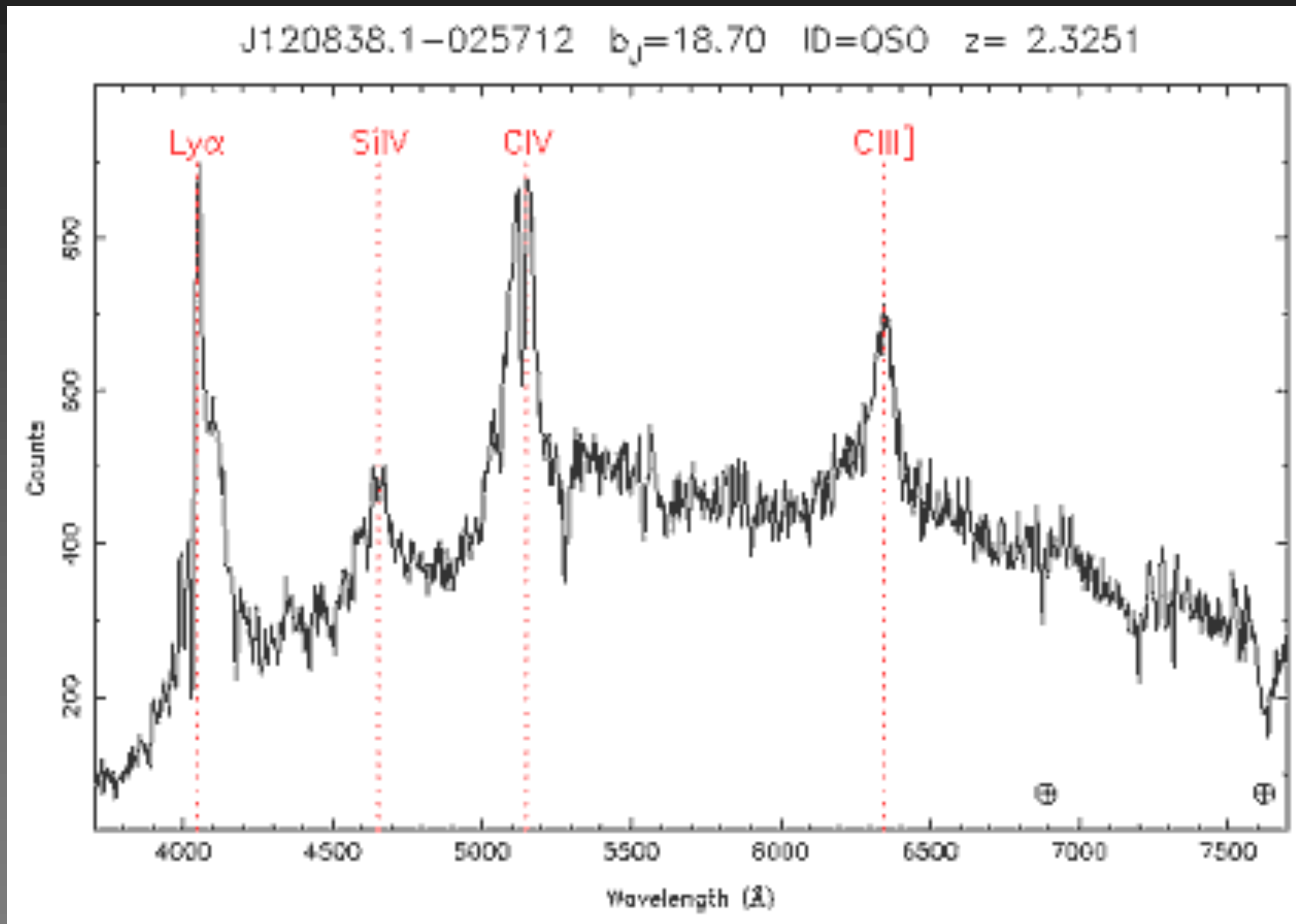
ASTR 2115

Spectroscopy, Imaging and Telescopes

Announcements

- HW#1 is due on my desk in class on Thursday Aug 29 at the START of CLASS
- Last day to drop with refund is Sept 6
- Keep Saturday, September 28 open for Telescope Tour

Spectrum of a “quasar” – what kind of spectrum is this?



How are these spectra produced?

By photons interacting with matter!

Recall: we are interpreting the light collected by our telescopes.

$$E = hc/\lambda = h\nu$$

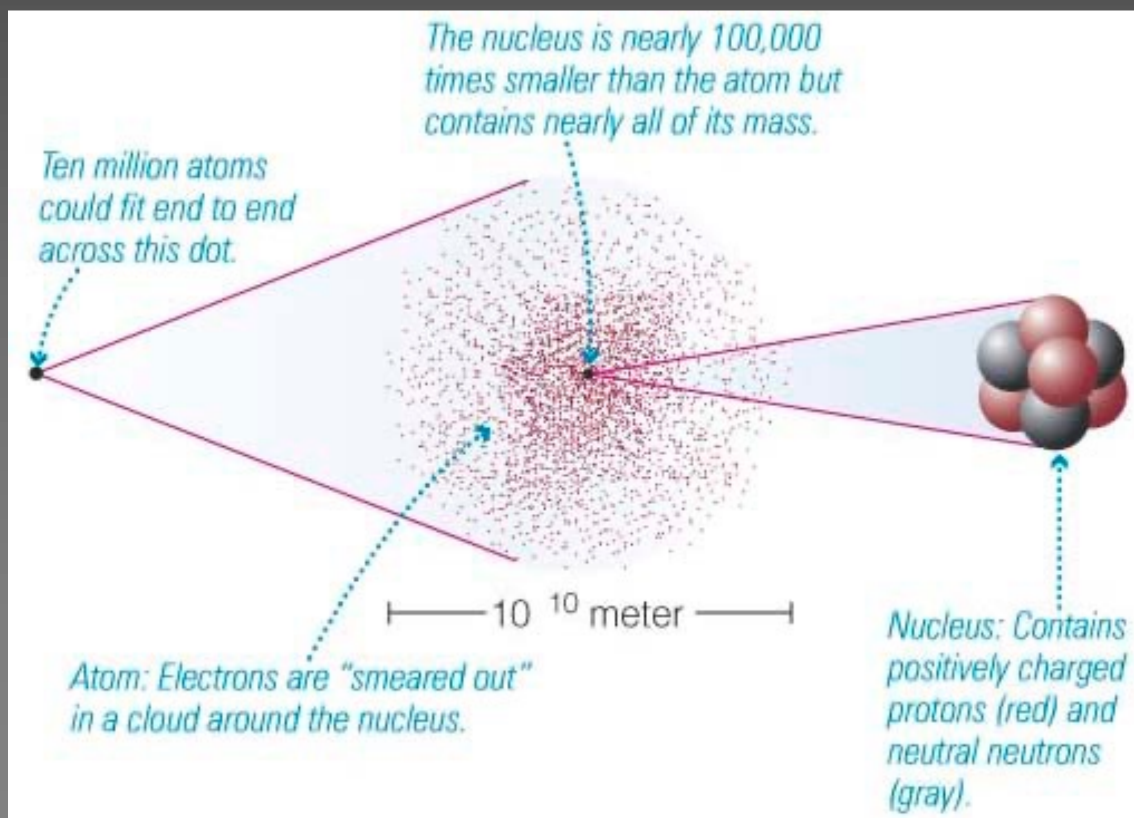
Let's look into how these interactions take place.

Atomic structure

Nucleus contains heavy, subatomic particles:

- Protons (positively charged)
- Neutrons (uncharged)

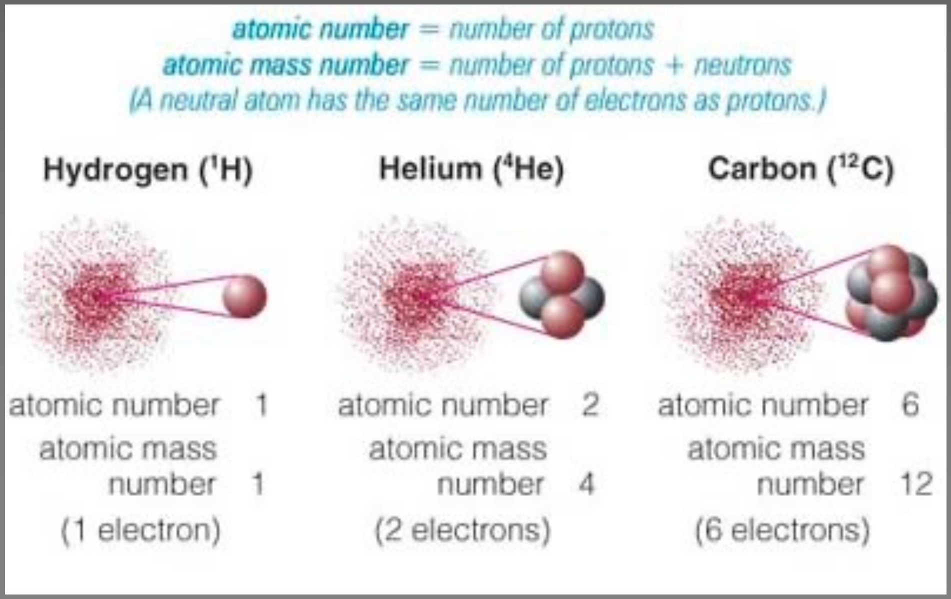
Electrons in a cloud orbiting the nucleus (negatively charged)



Chemical elements

- Atoms are distinguished into *elements* by the total number of protons in the nucleus.

- This is called the atomic number:
  - 1 proton: Hydrogen
  - 2 protons: Helium
  - 3 protons: Lithium and so on.



How is energy stored in atoms?

Atoms can contain energy in three ways:

- Mass energy $E=mc^2$ (because of their mass)
- Kinetic energy (because of their motion)
- Electric potential energy (because of arrangement of electrons)

The last one is important here, because the electric potential energy is altered by EM radiation.

To understand how the atom reacts to EM radiation (and to interpret the results!) we need to know how atoms gain and release electrical potential energy.

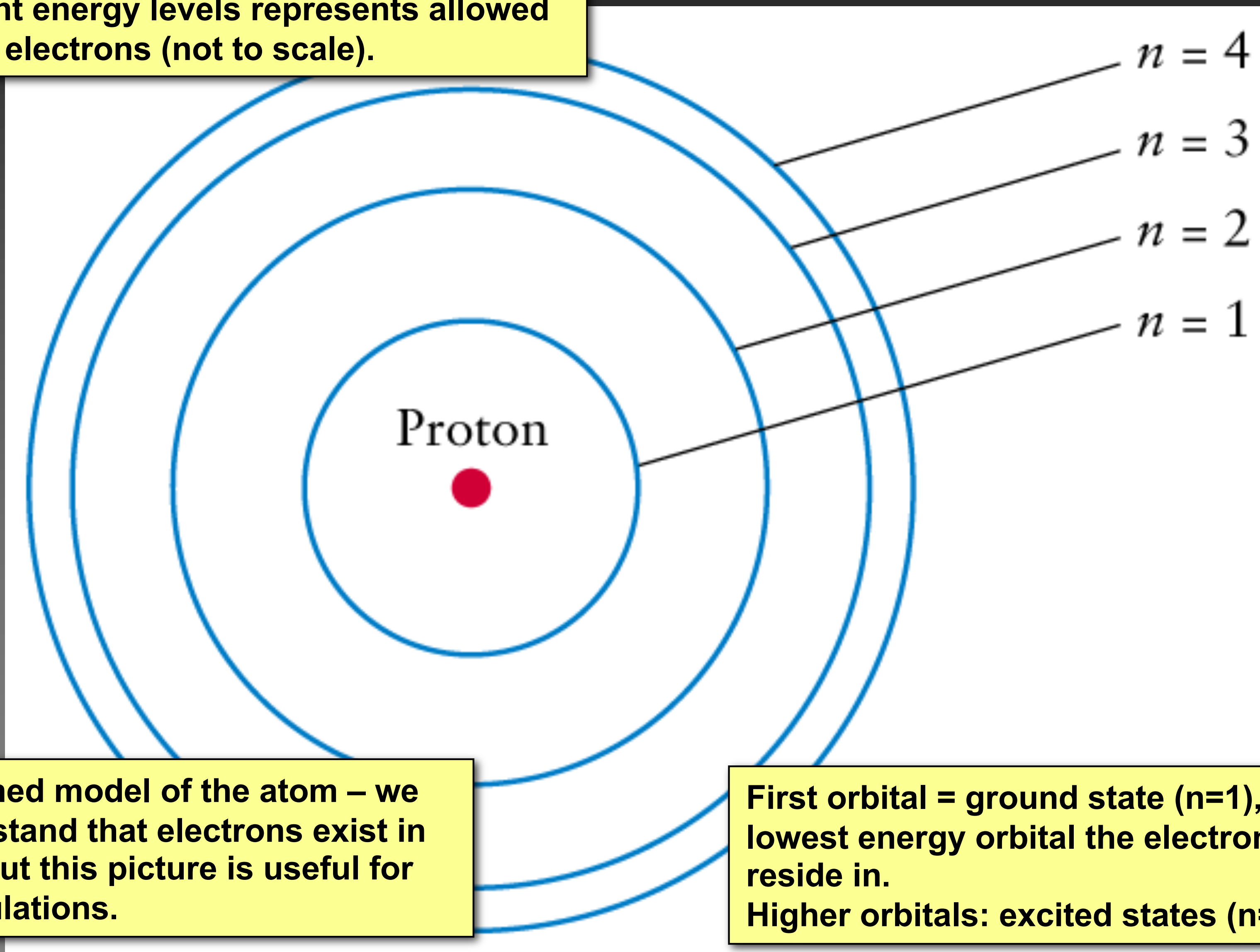
Inside the atom

Quantum mechanics determines the details:

- Electrons can only orbit the nucleus in discrete orbitals
- Each orbital corresponds to a particular energy of the orbiting electron
- The electron must have exactly the right energy - otherwise it cannot be in that orbital

The simple Bohr model for the hydrogen atom: a single electron orbiting a single proton (the nucleus).

The different energy levels represents allowed orbitals for electrons (not to scale).

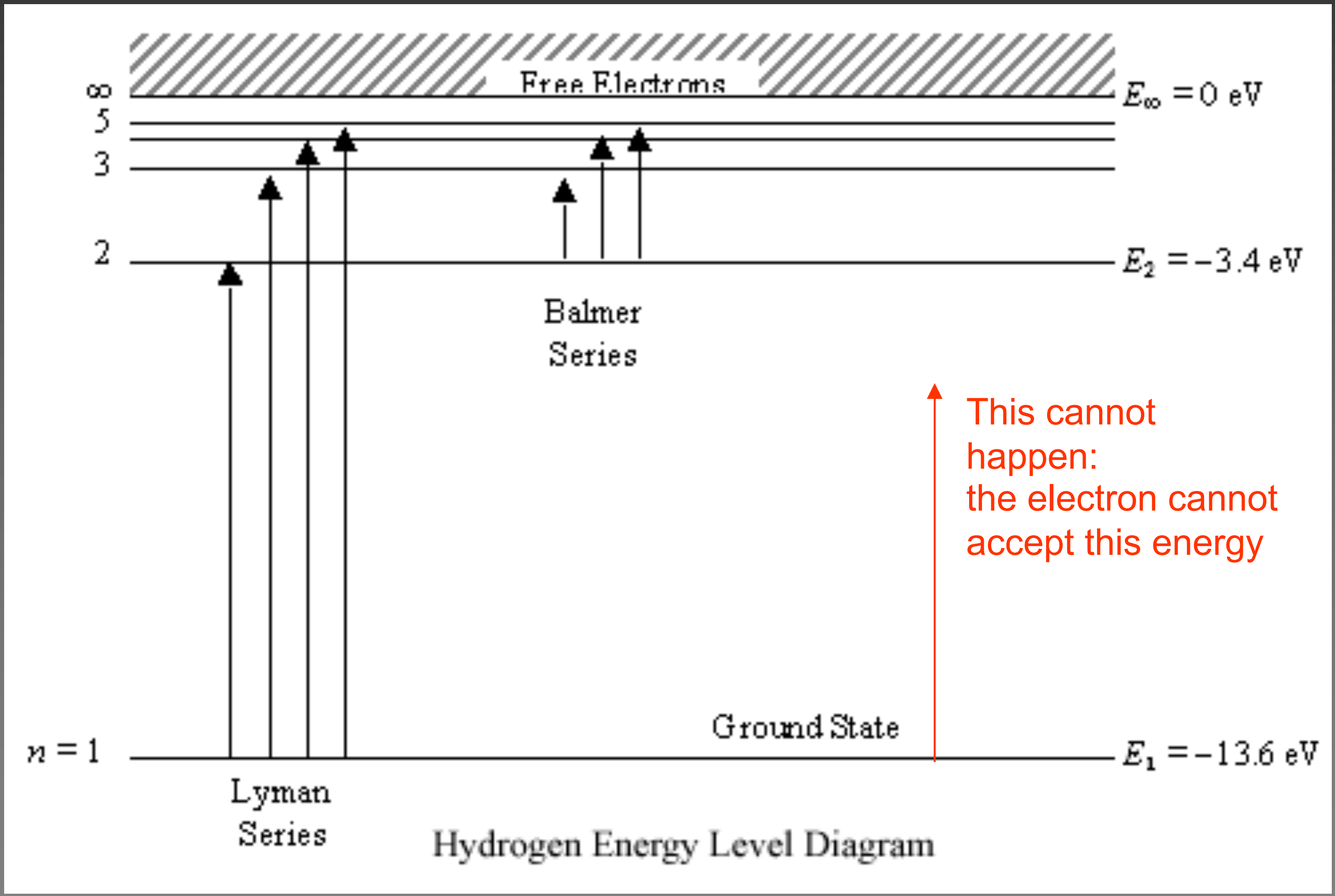


Old-fashioned model of the atom – we now understand that electrons exist in "clouds", but this picture is useful for some calculations.

First orbital = ground state (n=1), the lowest energy orbital the electron can reside in.
Higher orbitals: excited states (n=2,3,4…)

Energy level diagram of H

Orbitals come in specific and exact energies



Emission and Absorption

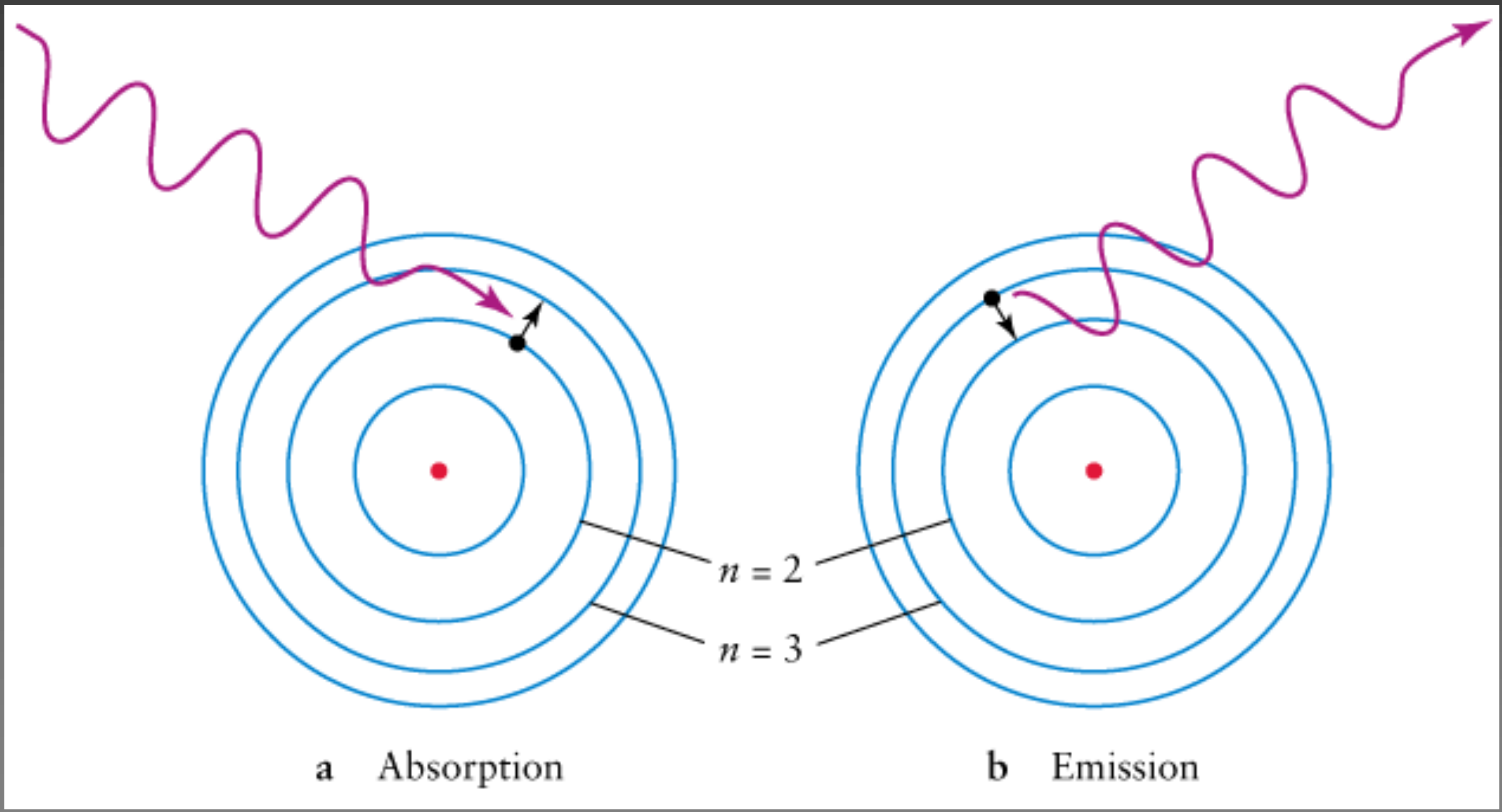
- Atoms can get into excited states by either
  - Colliding (other atoms or free electrons, higher T => higher E)
  - Absorbing photons (of specific energy)

- Absorption: only photons with exact excitation energy are absorbed, ALL others pass through unaffected.

- Atoms get out of excited states by emitting photons in random directions.

- Recall: $E = h\nu$ (a transition between energy levels correspond to a photon of a specific frequency).

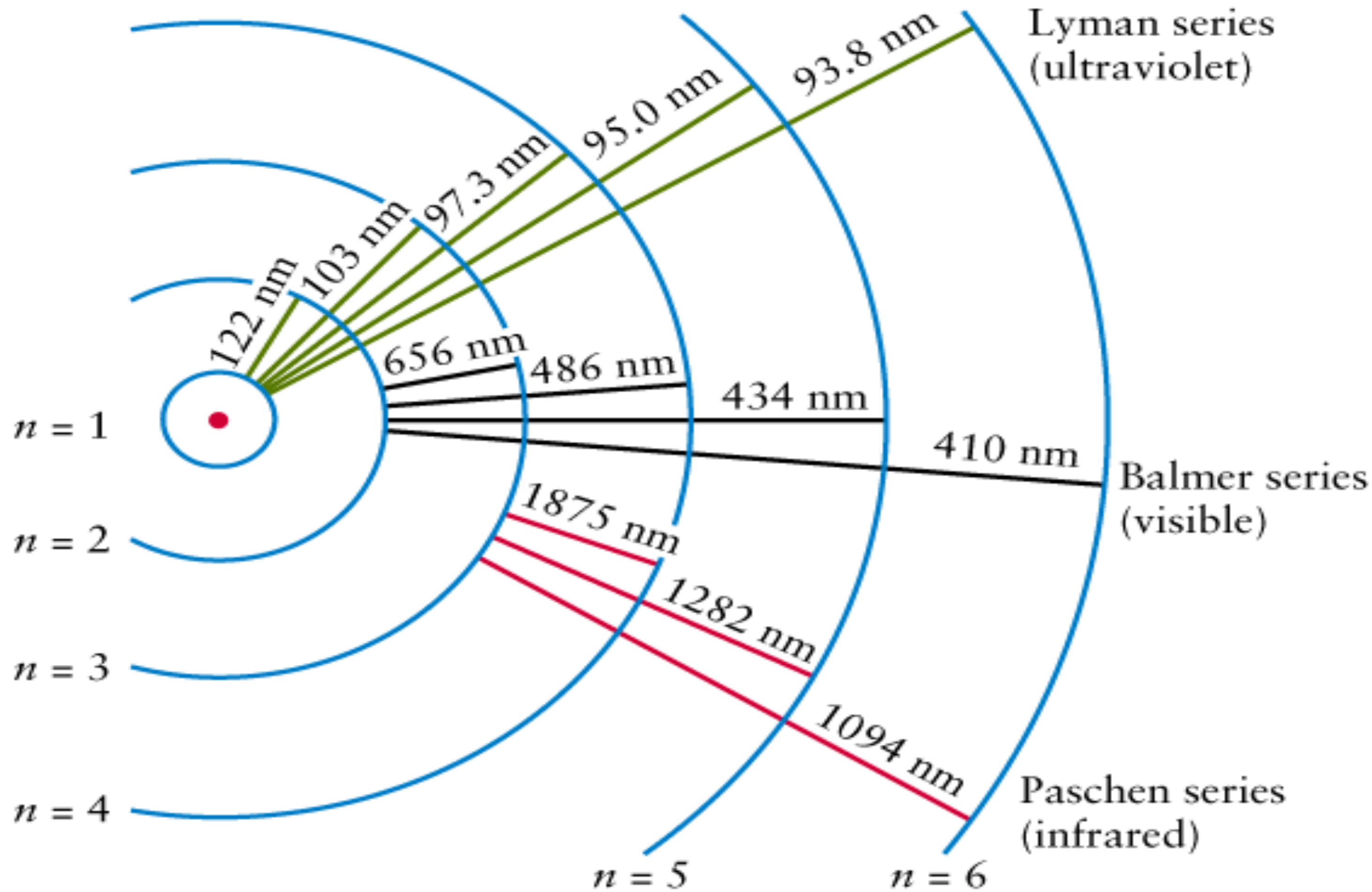
- An atom can *absorb* a photon, causing electron to jump up to a higher energy level.
- An atom can *emit* a photon, as an electron falls down to a lower energy level.



Emission and absorption line spectra

- Hot, low density gas where atoms are isolated will cause emission lines
  - Lines at specific wavelengths, dark between lines

- Light from continuous spectrum through cooler gas cause absorption lines
  - Dark regions corresponding to wavelengths of emission lines seen when the gas is hot, bright between lines



Bohr formula for hydrogen wavelengths

$$\frac{1}{\lambda} = R\left(\frac{1}{N^2} - \frac{1}{n^2}\right)$$

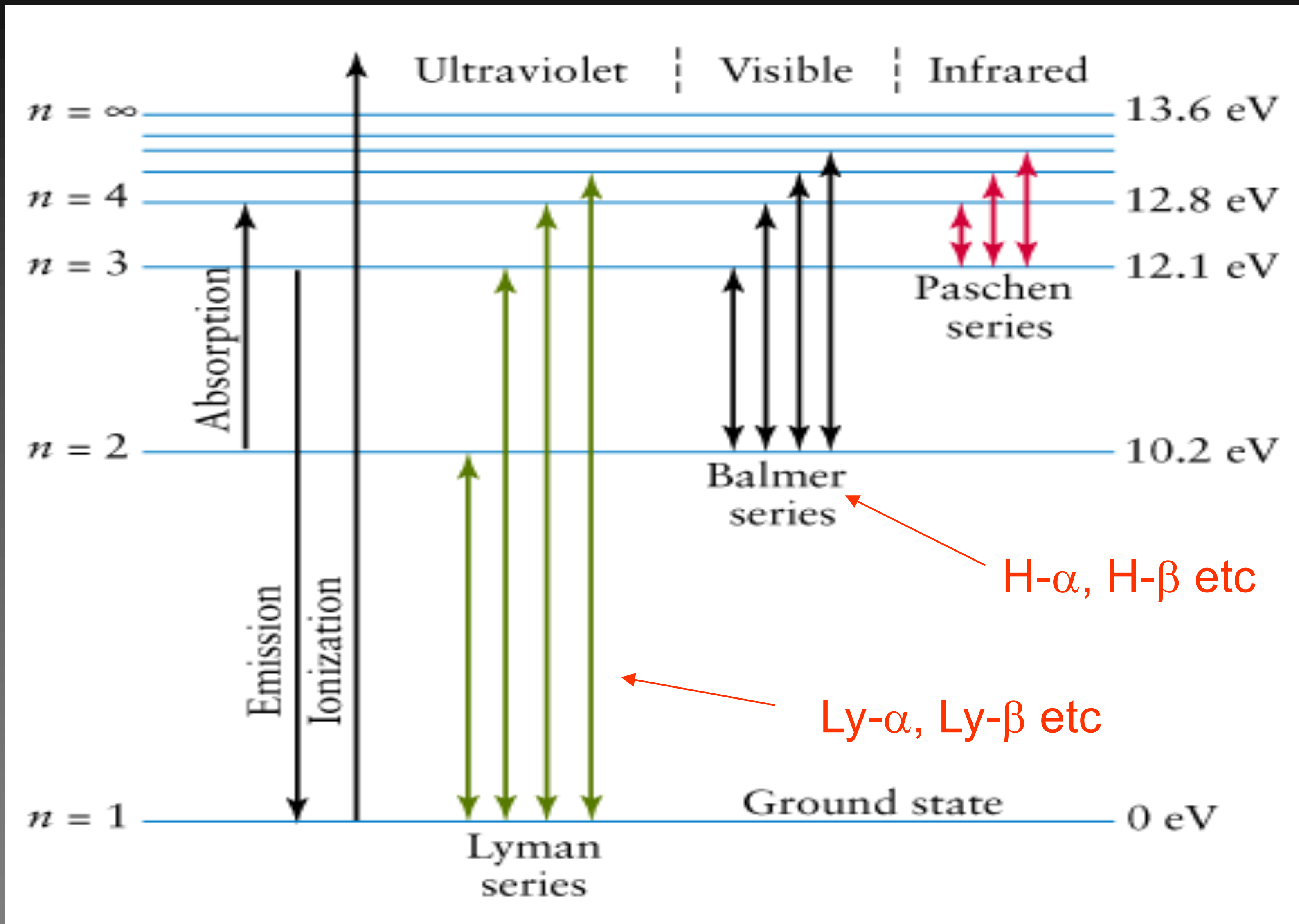
N = number of inner orbit

n = number of outer orbit

R = Rydberg constant = $1.097 \times 10^{7}\ \mathrm{m}^{-1}$

λ = wavelength (in meters) of emitted or absorbed photon

Energy level diagram for hydrogen:



Excited, low-density hydrogen gas. Red due to “H-alpha” emission line, n = 3 to n = 2.

Fingerprints of matter

- H has an easy orbital structure, but more complex atoms (several electrons) will have more difficult structure
- This cause more energy levels and a more complex line spectra
- Each element has a unique spectrum, reflecting the unique electron orbital structure.
- Isotopes has same lines, but slightly shifted in wavelength.

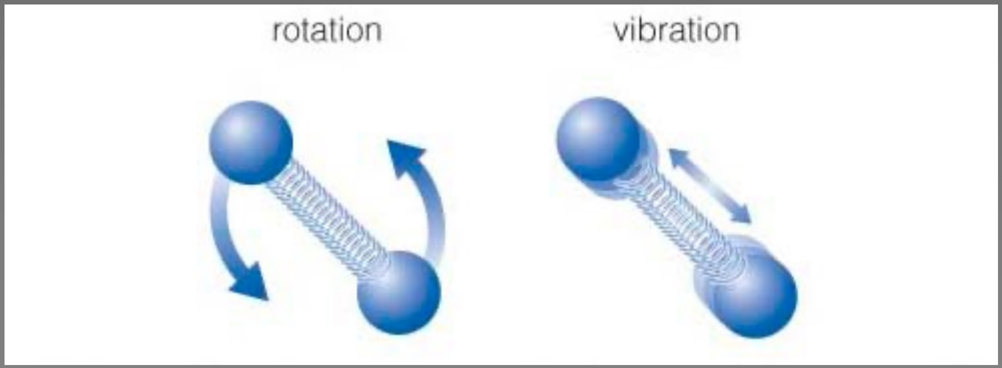
Molecules

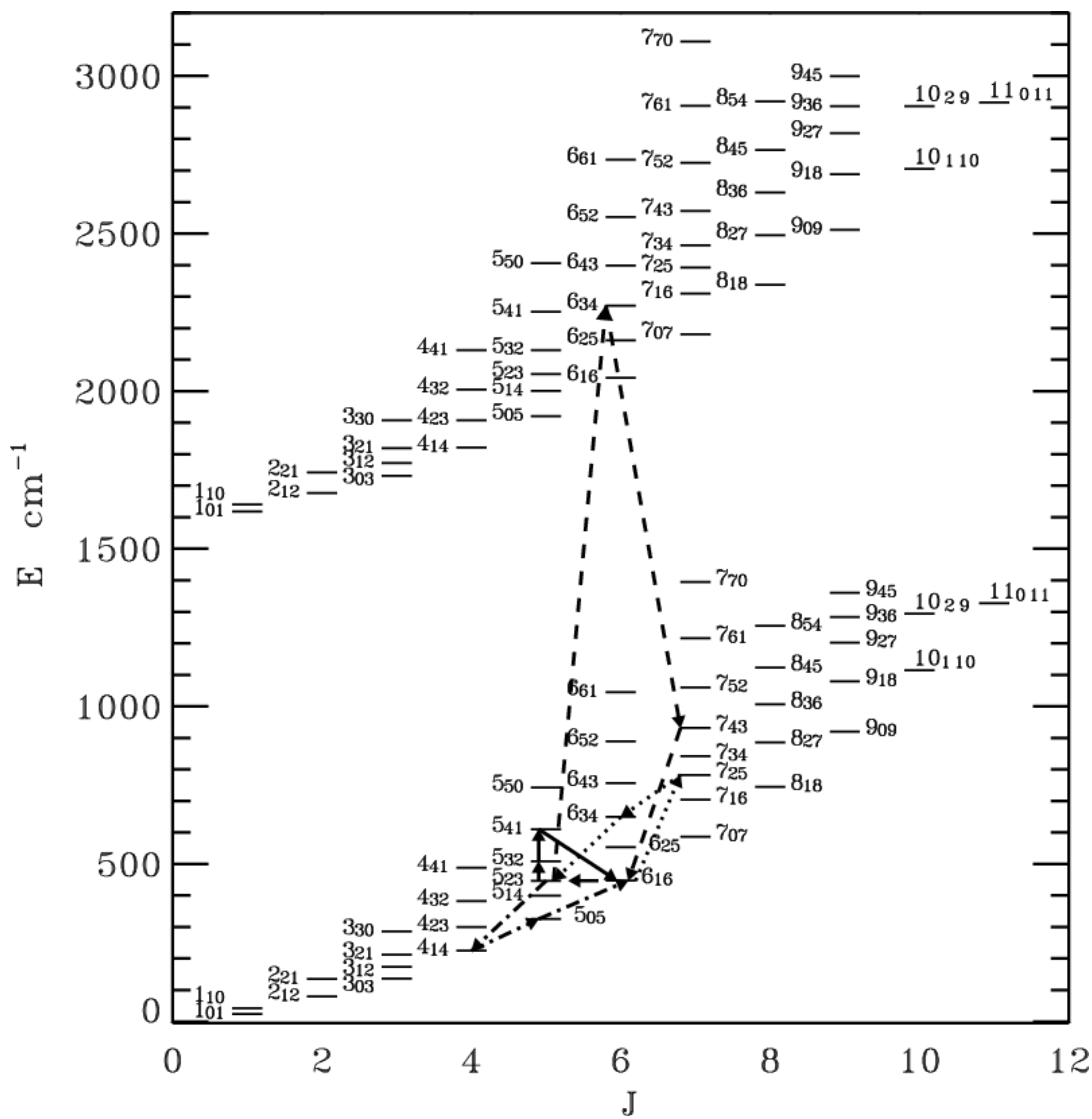
- Even more complex, compounds of two or more atoms of same or different elements

- Share some electrons in common orbitals

- Have vibrational and rotational energy levels as well (IR, microwave, radio)

=> Very complex spectra!





E cm^{-1}
J
0
500
1000
1500
2000
2500
3000
0
2
4
6
8
10
12
1_{01} 1_{10} 2_{12} 2_{21} 3_{03} 3_{12} 3_{21} 3_{30}
4_{14} 4_{23} 4_{32} 4_{41} 5_{05} 5_{14} 5_{23} 5_{32} 5_{41} 5_{50}
6_{16} 6_{25} 6_{34} 6_{43} 6_{52} 6_{61}
7_{07} 7_{16} 7_{25} 7_{34} 7_{43} 7_{52} 7_{61} 7_{70}
8_{18} 8_{27} 8_{36} 8_{45} 8_{54}
9_{09} 9_{18} 9_{27} 9_{36} 9_{45}
$10_{1\,10}$ $10_{2\,9}$ $11_{0\,11}$

Ionization

- If an atom or a molecule absorbs enough energy from a photon or a collision, an electron can escape the force field => positive ion

- By adding electrons, you can get a negative ion

- Ions differ from the neutral atoms/molecules: different spectral line signatures, and different chemical properties

Spectroscopy

The spectrum of an objects tells us:

- Which atoms and molecules are present, and in which proportions
- Which atoms are ionized, and in which proportions
- How excited the atoms are, which tells us about the physical state (cold, hot)

=> Spectroscopy is a very important tool of the astronomer.

Doppler shifts: information about motion

- Happens for all wave phenomena:

  sound => change of pitch

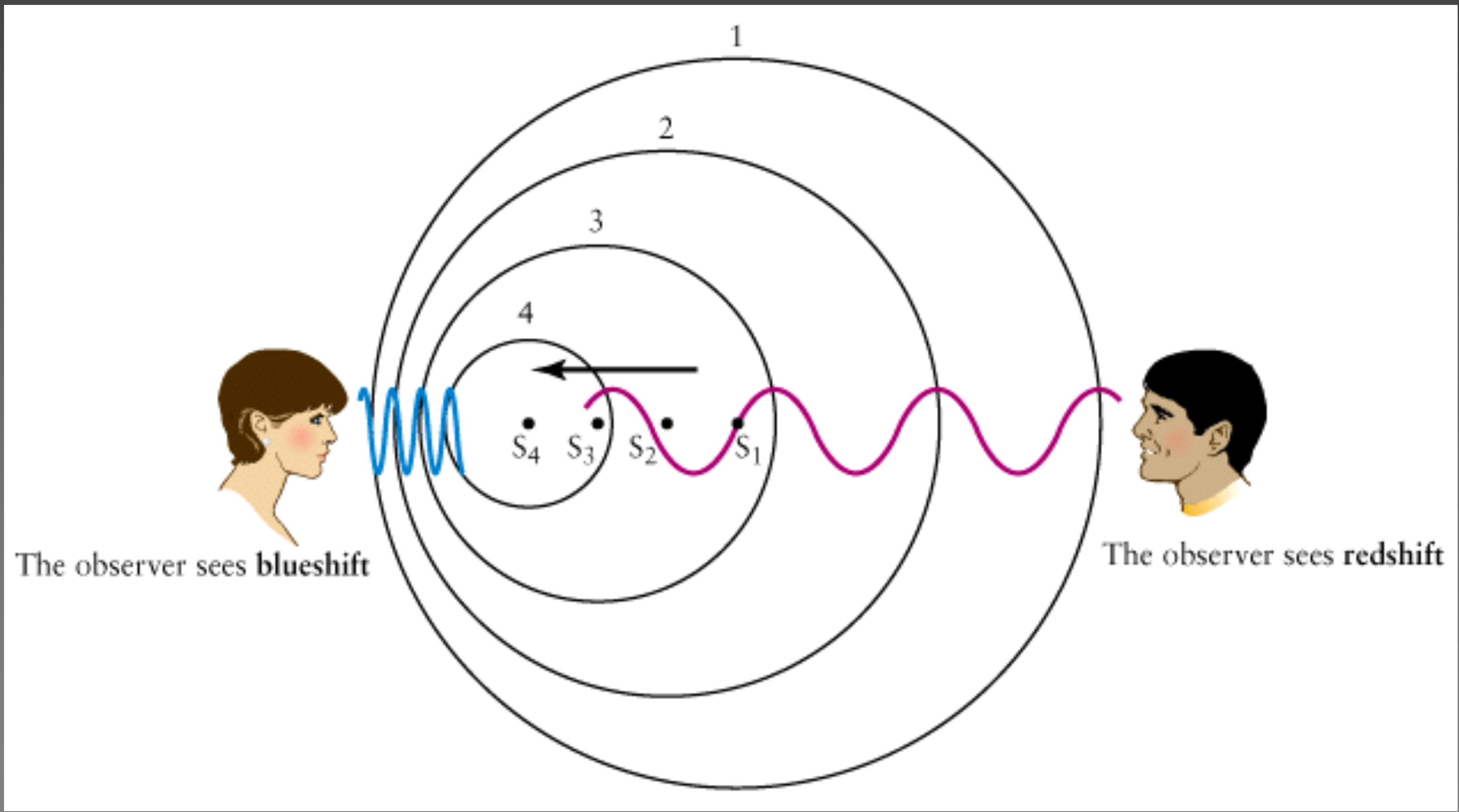
  light => change of wavelength (or color)

$$V_{rad} = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} c = \frac{\Delta\lambda}{\lambda_{emitted}} c$$

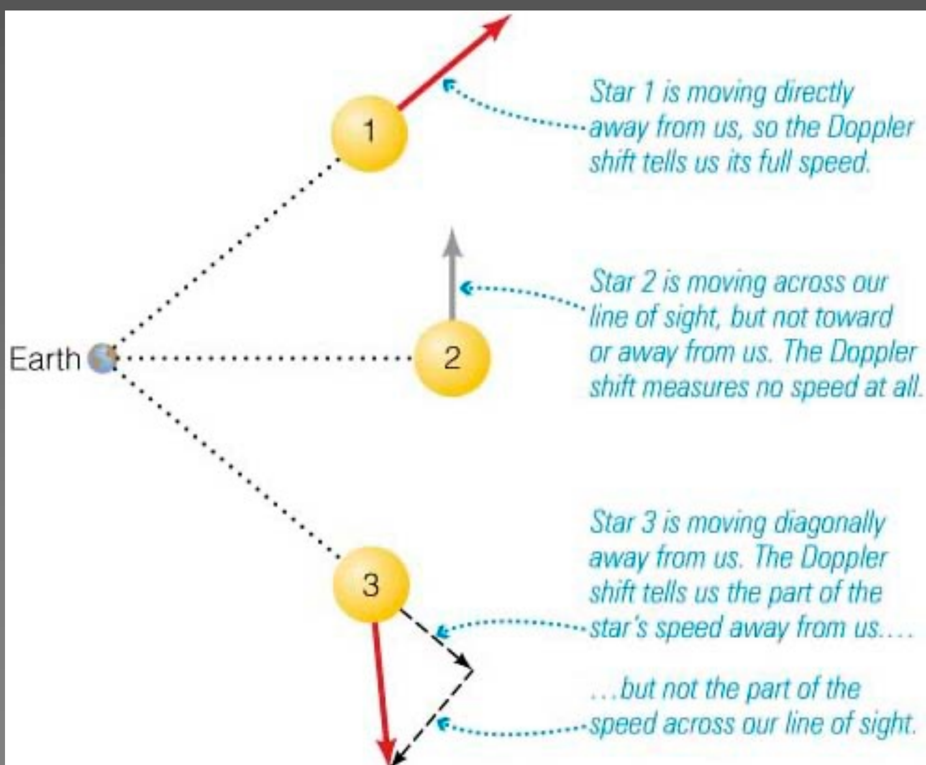
where V_{rad} is the velocity of the emitting source (m/s), c is the speed of light (m/s).

$$V_{rad} = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} c = \frac{\Delta\lambda}{\lambda_{emitted}} c$$

Redshifted if receding, blueshifted (negative sign) if approaching



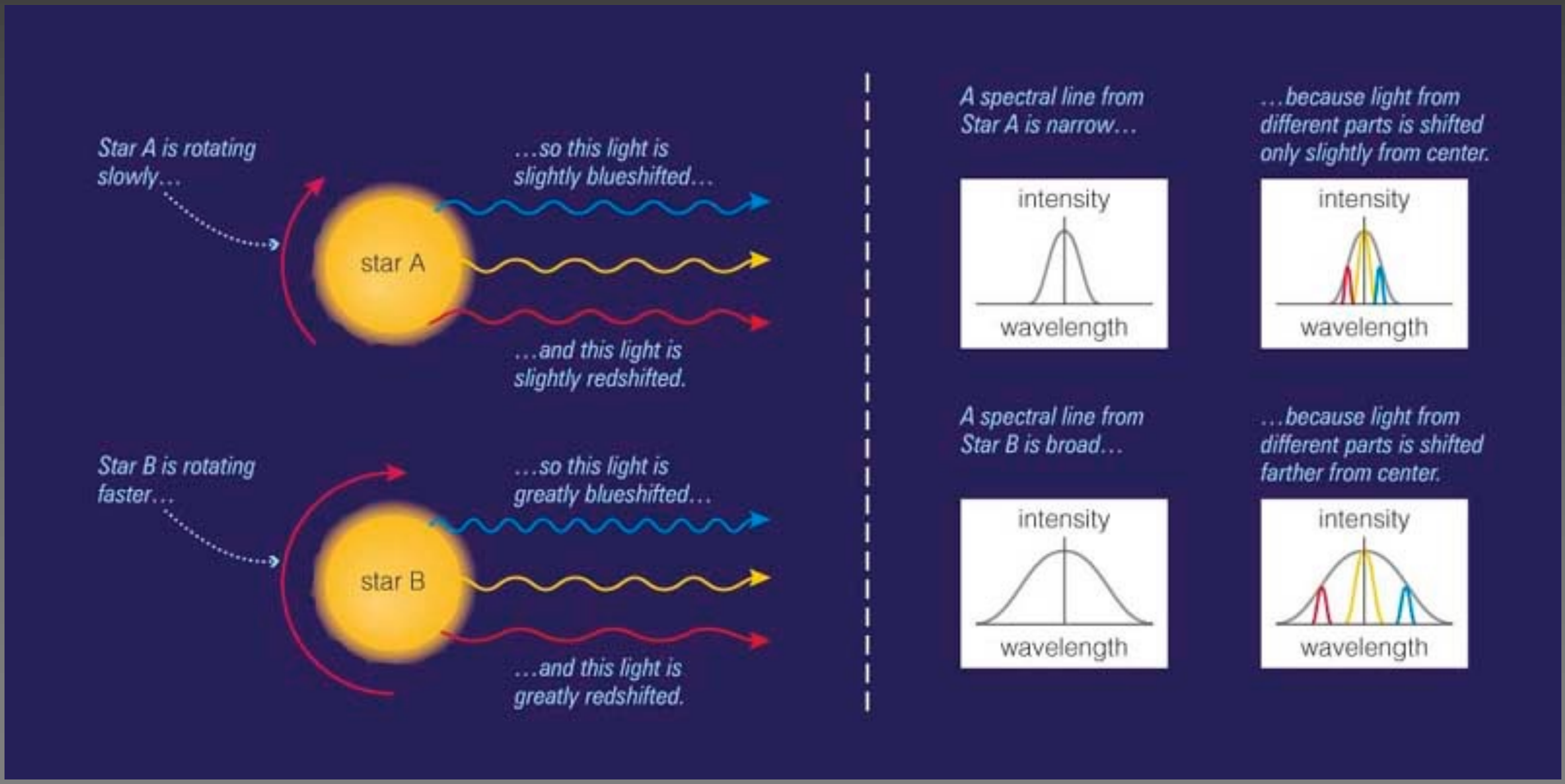
- Spectral lines provides the reference points for measuring Doppler shift



- The velocity measured is a *radial* velocity, the *tangential* part has to be measured with *proper motions*.

- Doppler shift can also measure rotation, and it does effect the widths of spectral lines.

- The more 'motion' you have in an object, the broader the spectral line



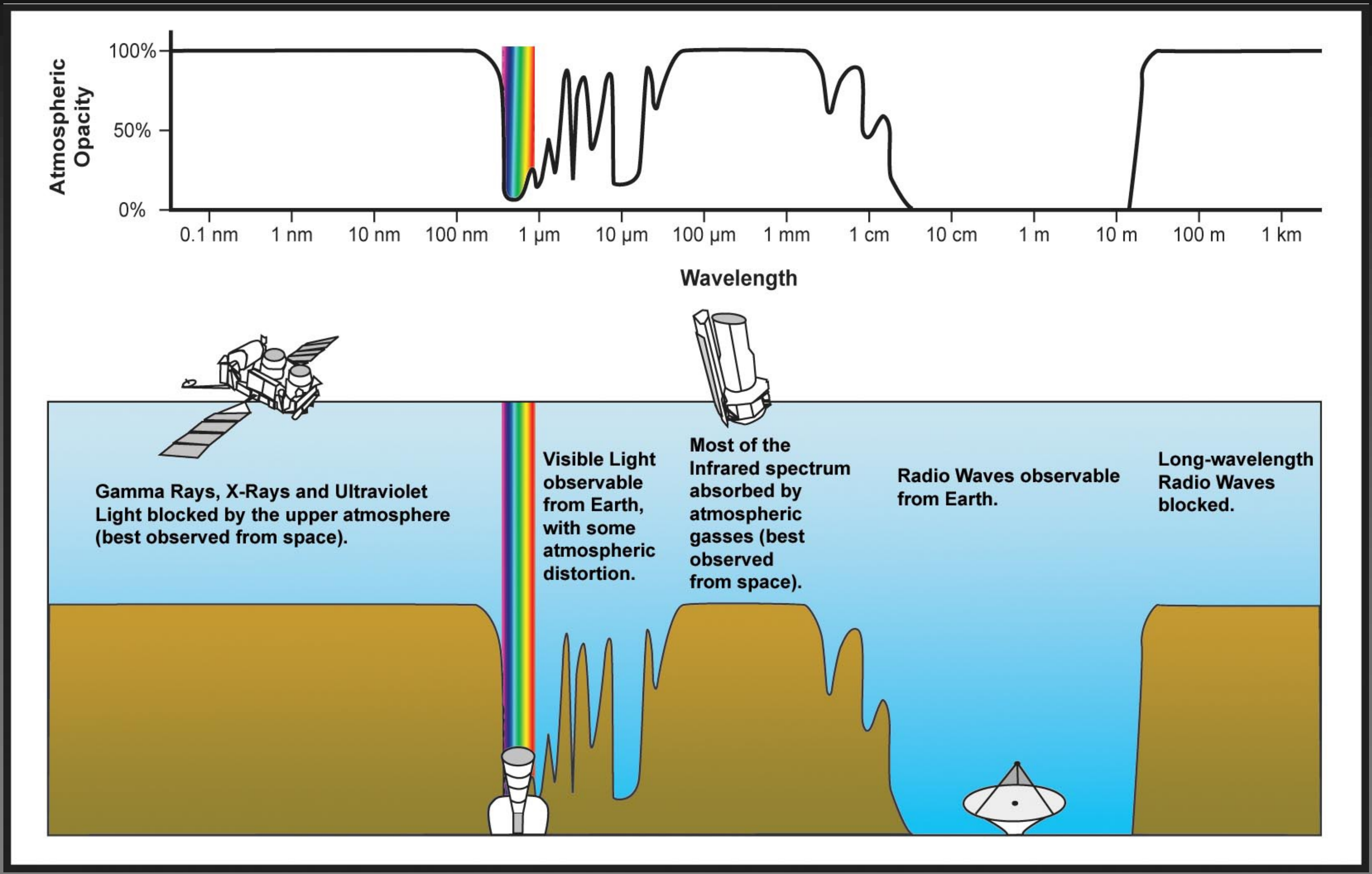
Worksheet Problem

- You observe the Hα absorption line in Barnard's star (intrinsic wavelength 656.28 nm), a spectral type M4 red dwarf, at 656.04 nm, and a proper motion of 10.4 arcseconds/year. Barnard's star is one of the closest stars to us at just 1.833 pc. Calculate the true space velocity of Barnard's star with respect to Earth.

  Is it approaching or receding?

  What is the velocity of the star?

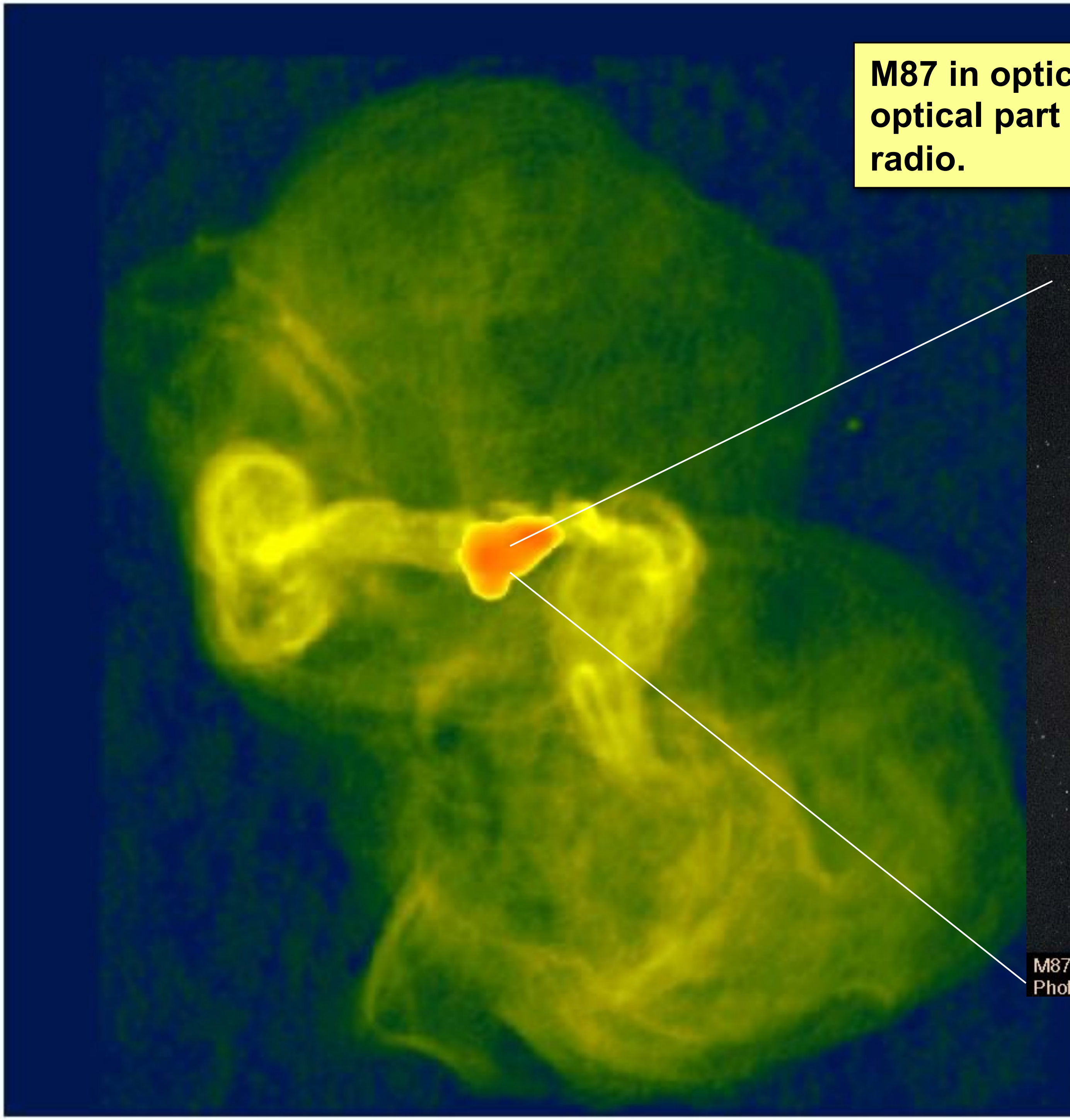
Radio Astronomy

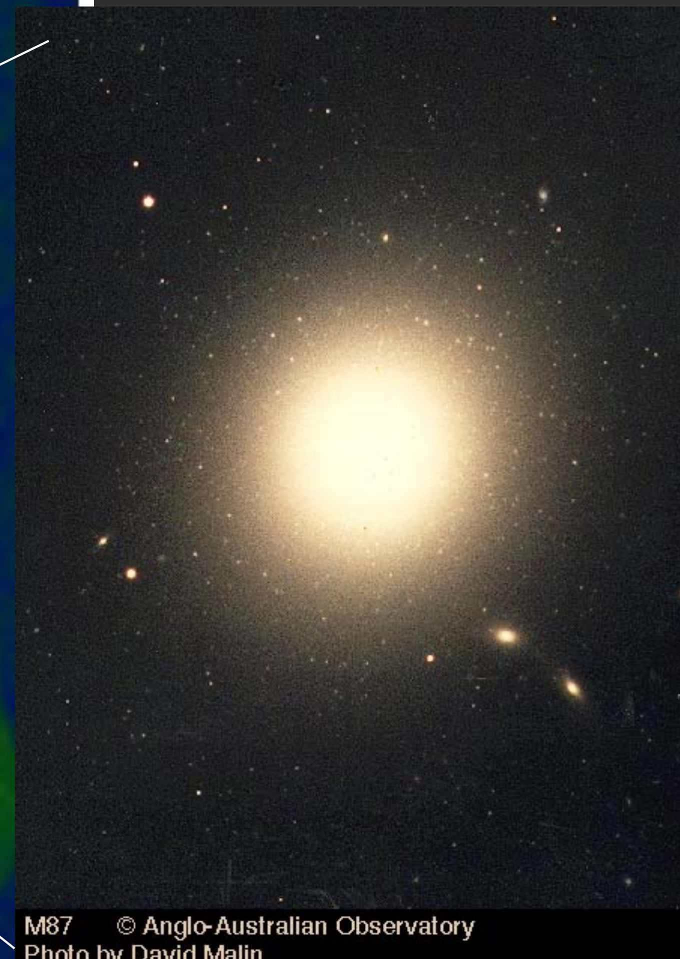


'Non-visible' wavelengths (but probing 'visible' matter).

Visible matter is matter that produces EM radiation.

M87 in optical and radio. Note optical part is tiny compared to radio.





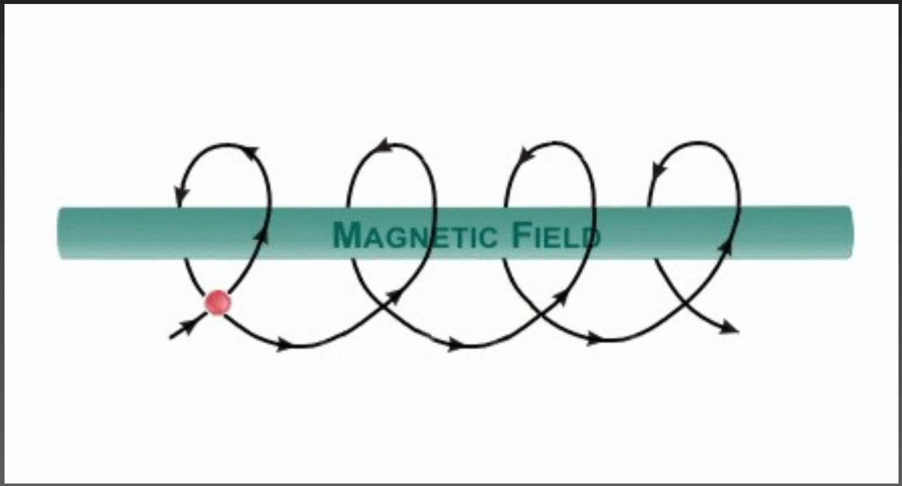
Synchrotron emission

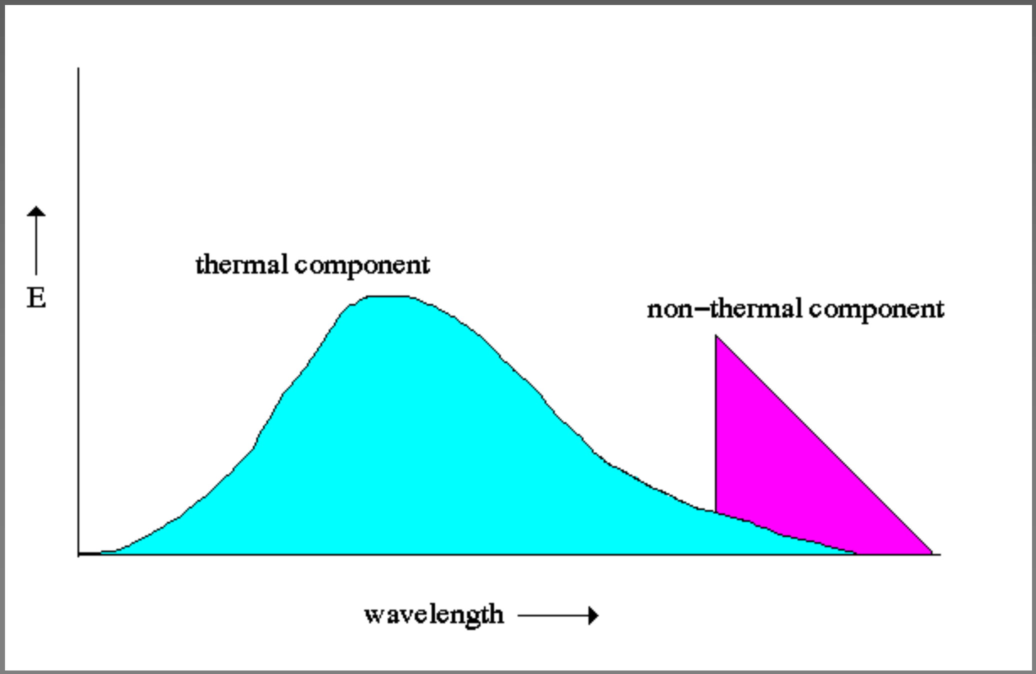
- Electrons spiraling in B-field
- Change of direction

  => change of acceleration

  => change in energy

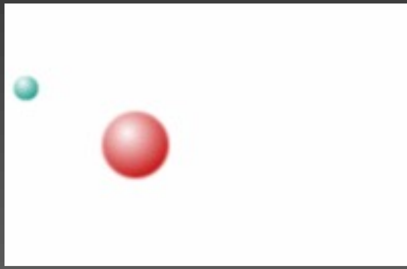
  => emission of a photon





Other emission mechanisms

- Bremsstrahlung (photons deflected by charged particles)

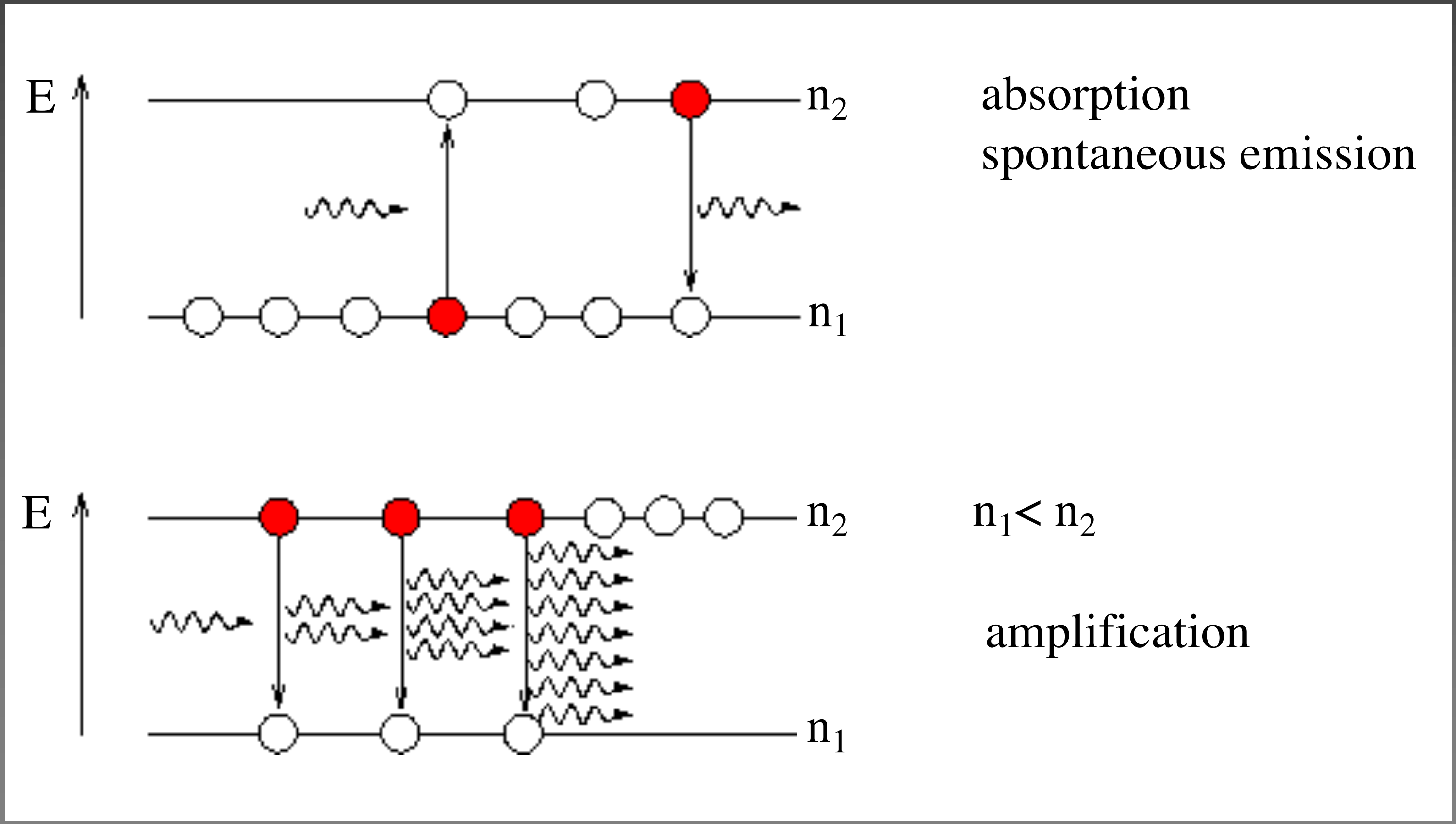


- Atomic and molecular spectral line emission
- Thermal (blackbody) radiation from e.g. planets, stars.
- Stimulated emission of radiation (Masers)

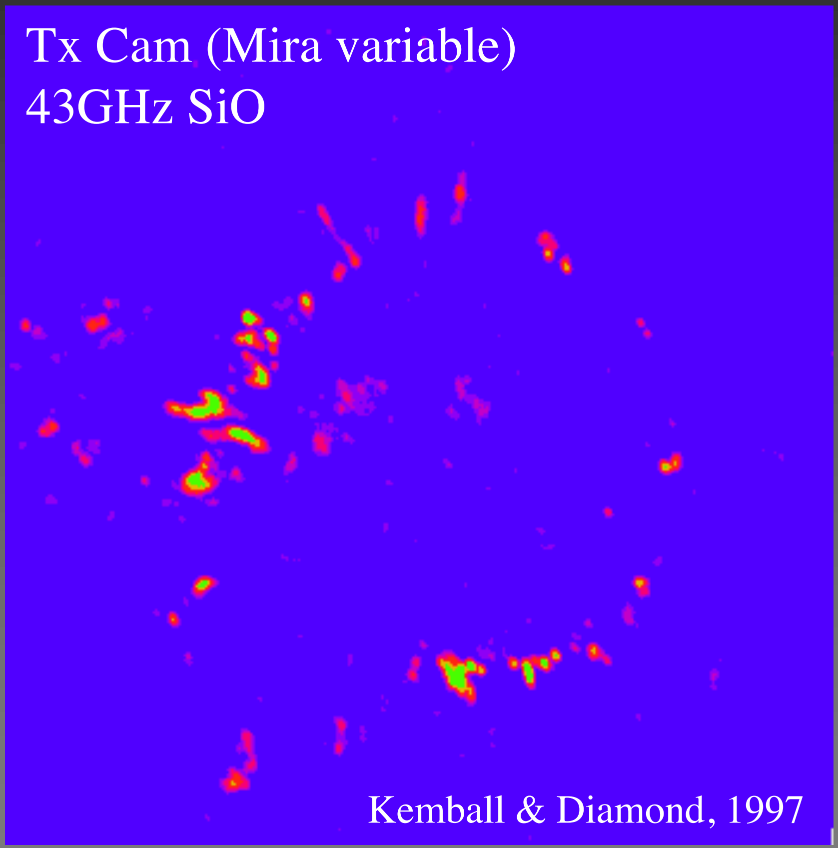
Different emission processes occur under different physical conditions!

Principles of maser emission

Microwave **A**mplification by **S**timulated **E**mission of **R**adiation



Observing masers

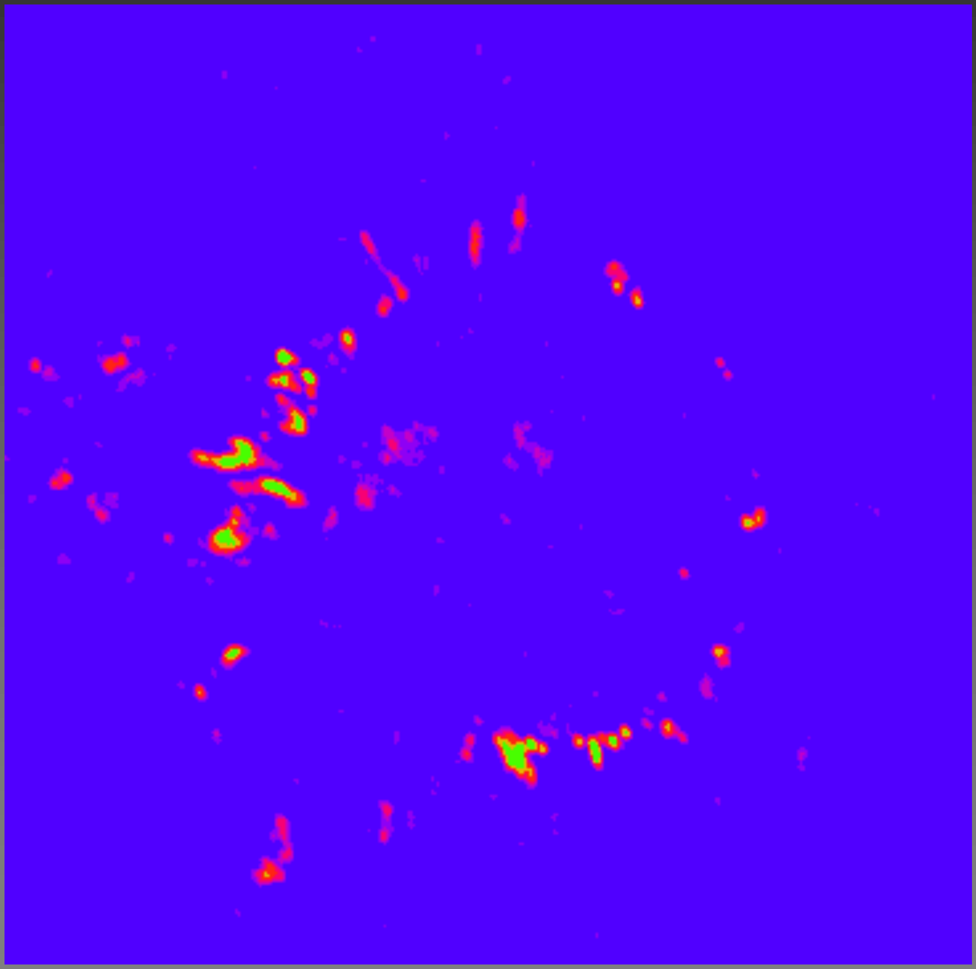


Masers are tracers of:

- Star forming regions
- Evolved stars
- Supernova remnants
- Outflows, jets

Maser emission is usually observed as very bright and compact regions.

Proper motion studies of TX Cam

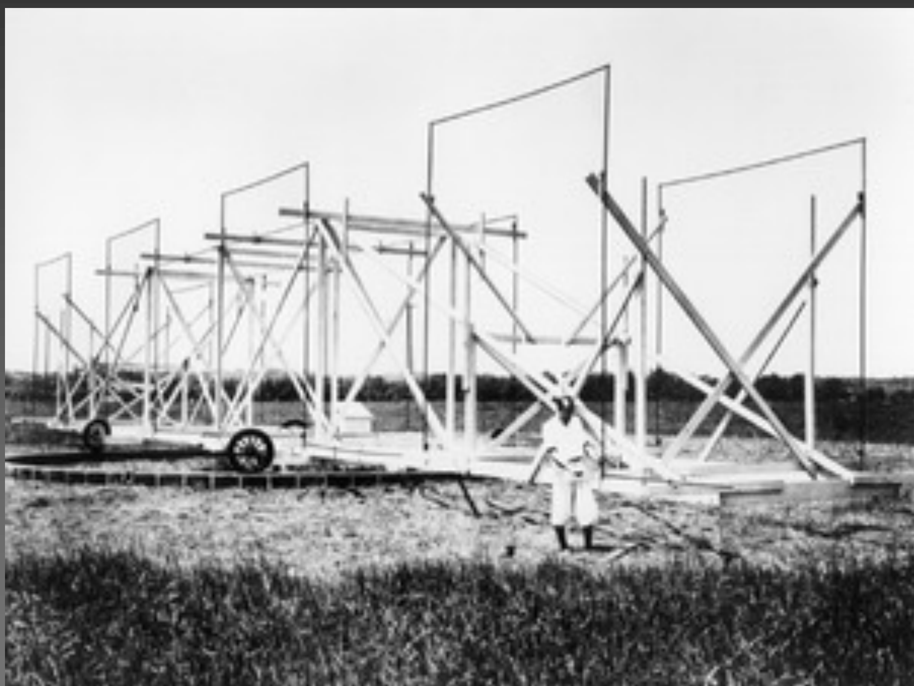


Diamond & Kemball 2003

Significance

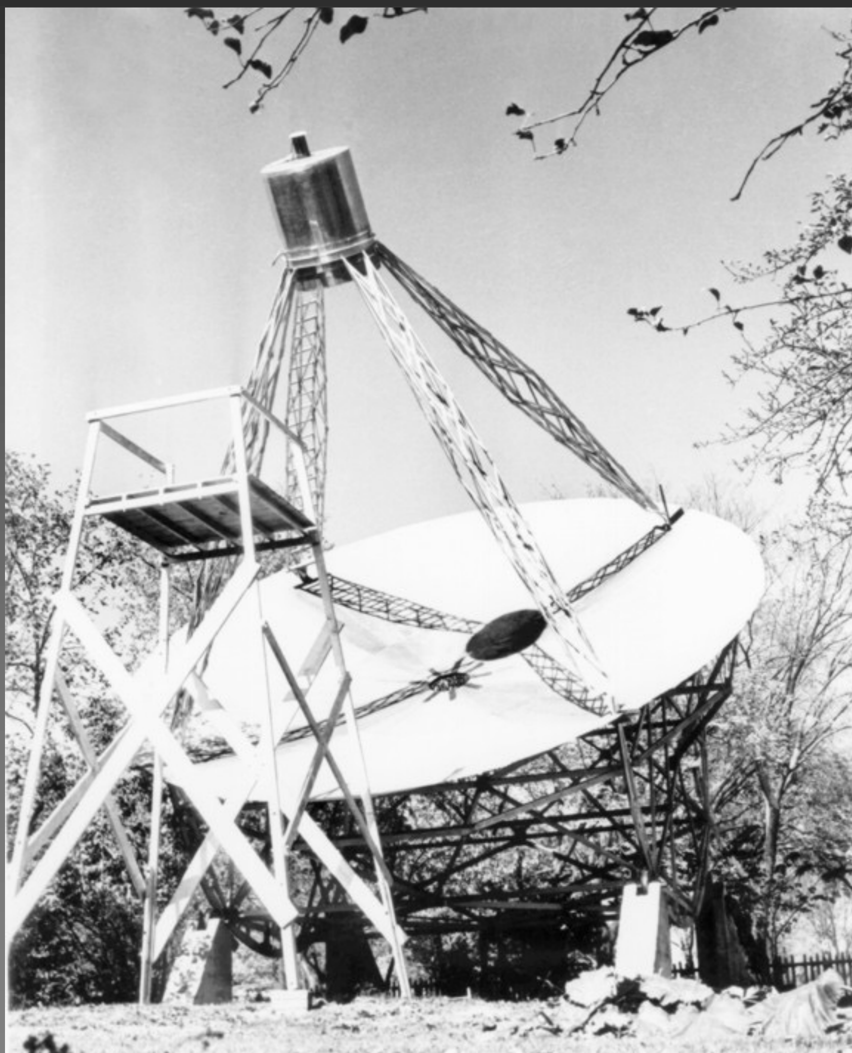
- Masers probe specific physical and chemical conditions.
- Amplified emission - we can study sources that are too weak in their thermal emission.
- Many transitions are in the rotational levels at frequencies in the radio regime.
- Radio: we can study regions obscured in the optical (like star forming regions).

Karl Jansky: Founder of radio astronomy



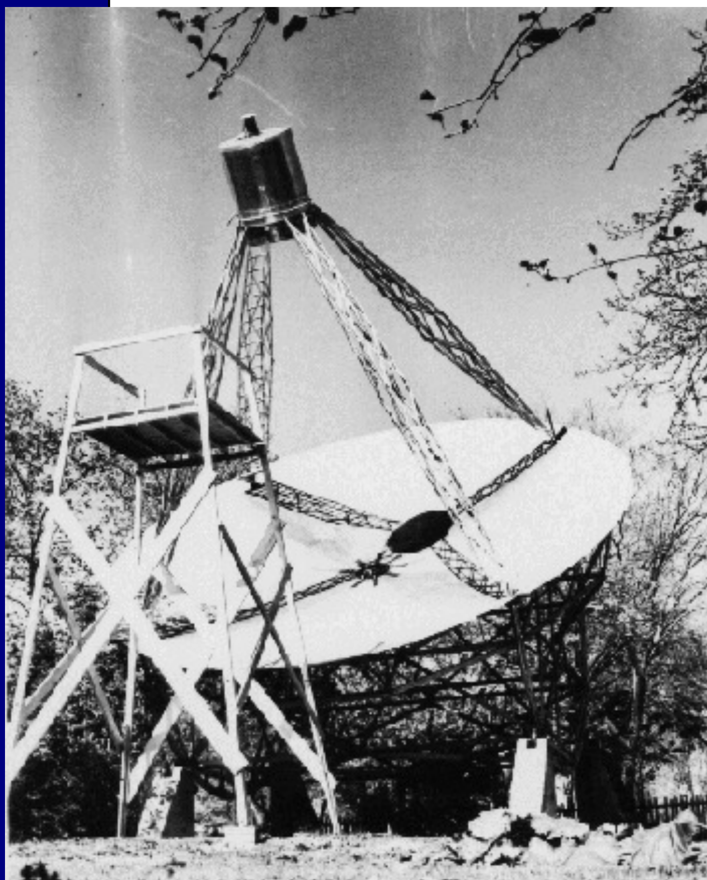
- 1931: built a telescope for Bell Labs working at 20 MHz
- Discovered three types of emission: (1) Nearby thunderstorms; (2) Distant thunderstorms; (3) Emission from the Milky Way
- Proposed to build a bigger telescope but Bell Labs wasn't interested.

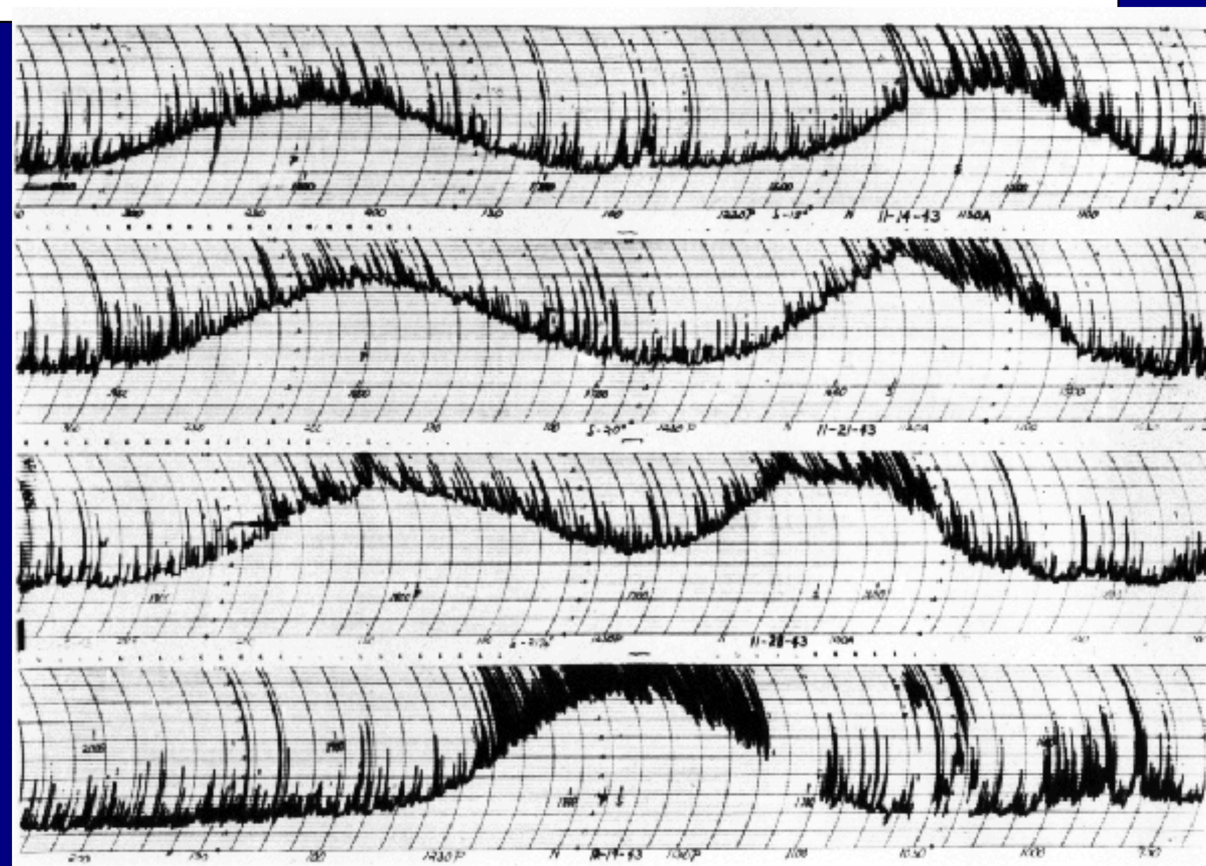
Grote Reber: Founder of radio astronomy



- 1937: built a telescope in his backyard in Wheaton, Illinois
- Radio amateur: but found emission from the Sun and other galaxies
- Technology improved dramatically during World War II.

Radio Frequency Interference



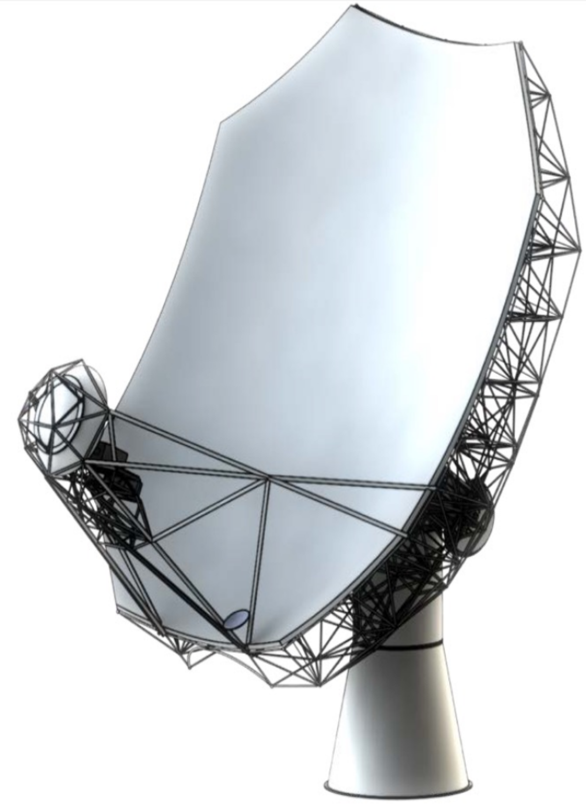


Grote Reber's telescope and Radio Frequency Interference in 1938

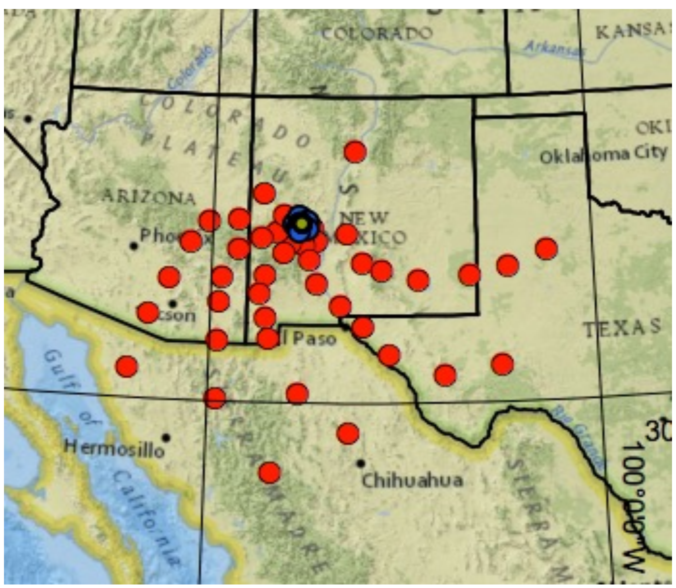
Eric J. Murphy – ngVLA Project Scientist

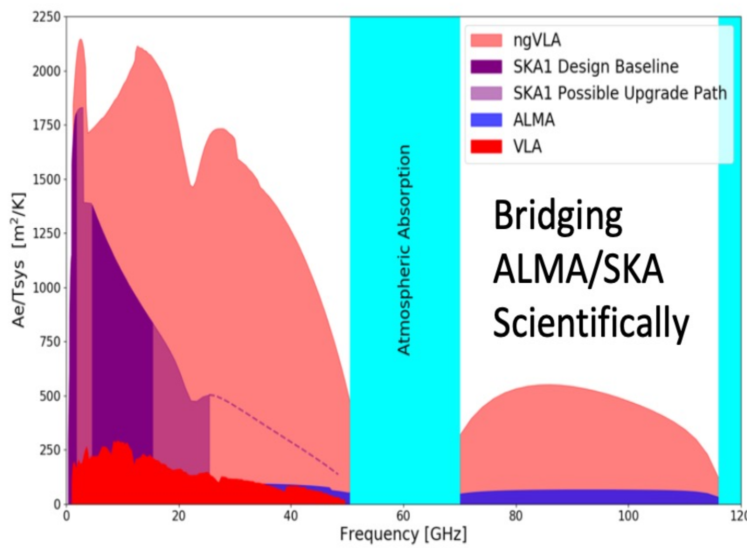
ngVLA.nrao.edu

A next-generation Very Large Array (ngVLA)



- Scientific Frontier: ***Thermal imaging at milli-arcsec resolution***
- Sensitivity/Resolution Goal: ***10x sensitivity & resolution of JVLA/ALMA***
- Frequency range: ***1.2 –116 GHz***
- Located in Southwest U.S. (NM, TX, AZ) & MX, centered on VLA
- Low technical risk (reasonable step beyond state of the art)





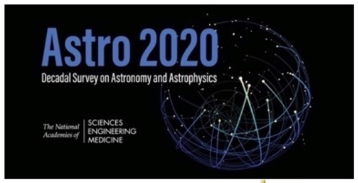
Bridging ALMA/SKA Scientifically

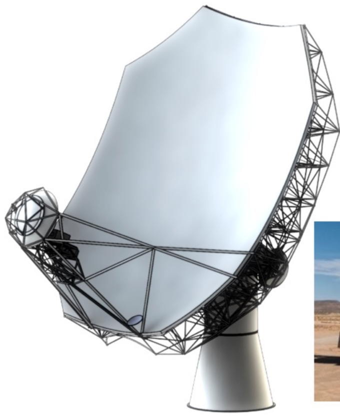
Complementary suite of meter-to-submm arrays for the mid-21st century

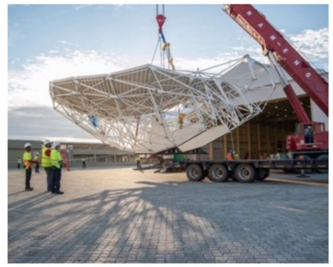
- **< 0.3 cm:** ALMA 2030
- **0.3 to 3 cm: ngVLA**
- **> 3 cm:** SKA

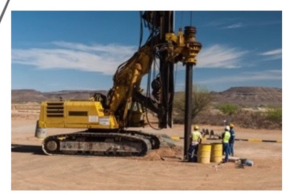
http://ngvla.nrao.edu

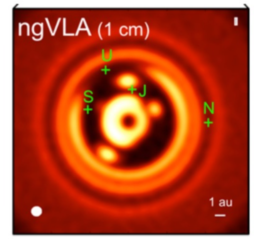
next generation Very Large Array

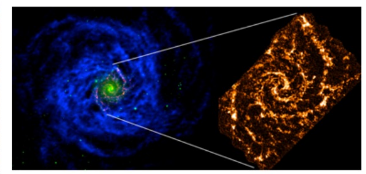


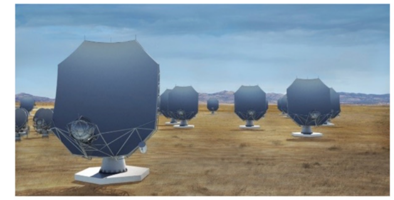












2019 — ngVLA Submission to Astro2020

2021 — Astro2020 Recommendation Published

Submit ngVLA Proposal to NSF/MREFC

2023 — Prototype Delivered to VLA Site

2025 — Complete NSF/MREFC FDR

2026 — ngVLA Construction →

2029 — Initiate ngVLA Early Science (> VLA capabilities)

2035 — Achieve Full Science Operations