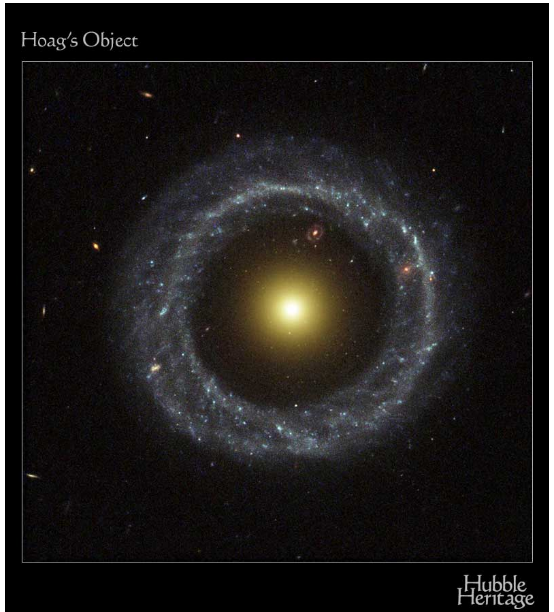
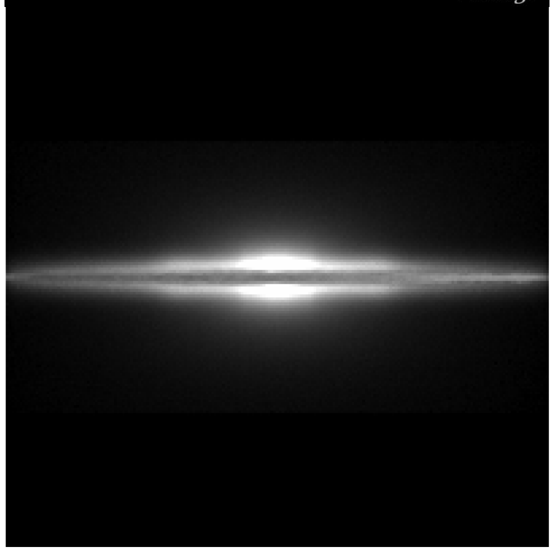
Galaxy Spectra

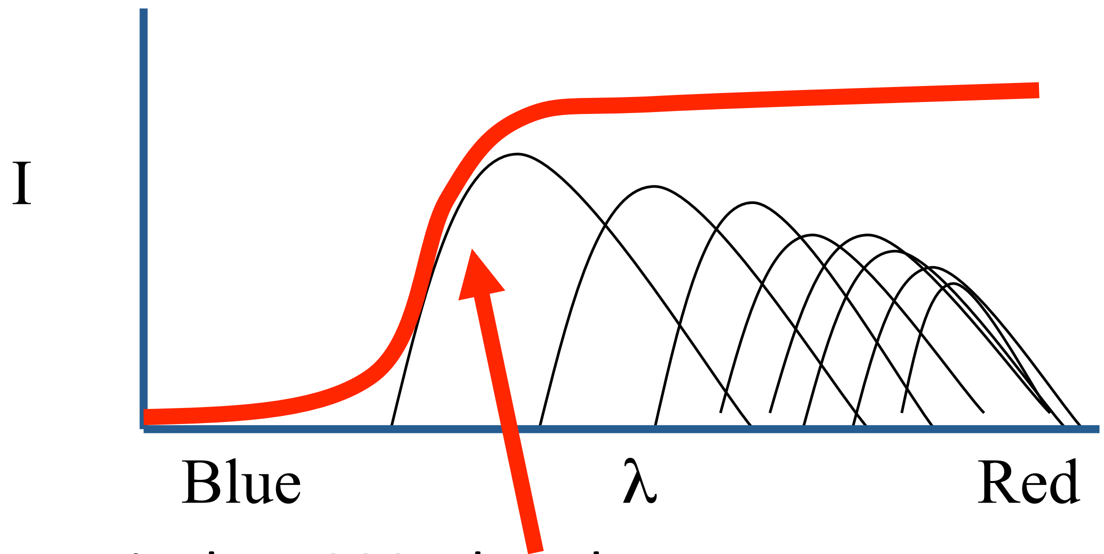
- Galaxy spectra
  - Continuum
  - Absorption Lines
  - Emission Lines
  - Typical Spectra
    - Elliptical
    - Spiral
    - Irregular
- Galaxy motion
  - Radial velocity
  - Redshift
  - Redshift → distance
  - Peculiar velocities
- Galaxy inclination
- Gas, dust and stars





Continuum

- The combination of many Black-Body spectra spanning a range in temperatures
- This produces a fairly flat overall spectrum



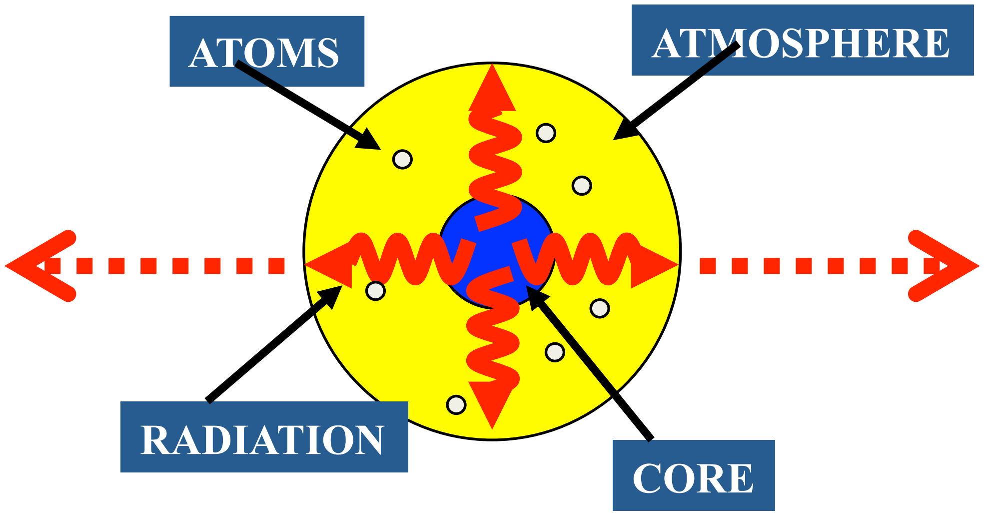
- The main feature is the 4000A-break

The 4000A-break

- Caused by:
  - blanket absorption of high energy radiation from metals in the stellar atmospheres
  - the lack of hot blue stars
- Hence:
  - Ellipticals => A strong 4000A-Break
  - Spirals => A weak 4000A-Break
  - Irregulars => No 4000A-Break

Absorption Lines

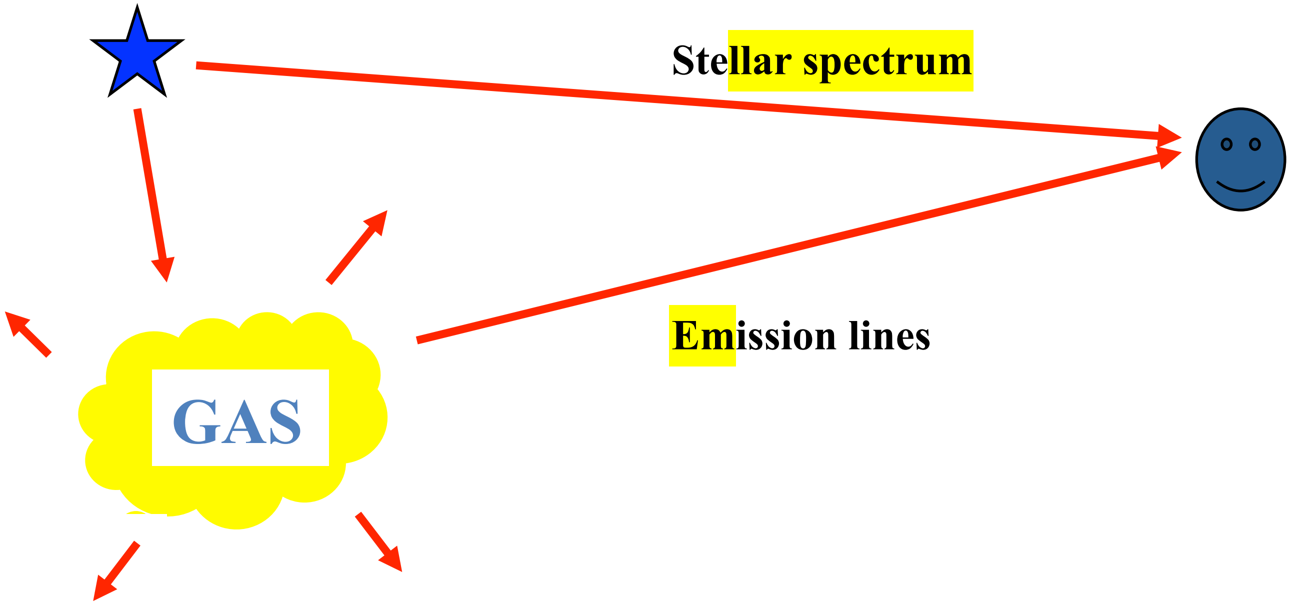
- Mainly caused by Atoms/Molecules in a star's atmosphere that absorb specific wavelengths



- Can also be due to COLD gas in the interstellar medium which can EXTRACT energy from the passing radiation

Emission Lines

- Caused by gas being ionized and heated and then re-radiating at specific allowed wavelengths



- Stars form from gas so are often embedded
- Young stars ionise gas which releases radiation at a specific wavelength as it recombines

M101

Emission nebulae (HII regions) in spiral arms

Absorption / Emission Lines

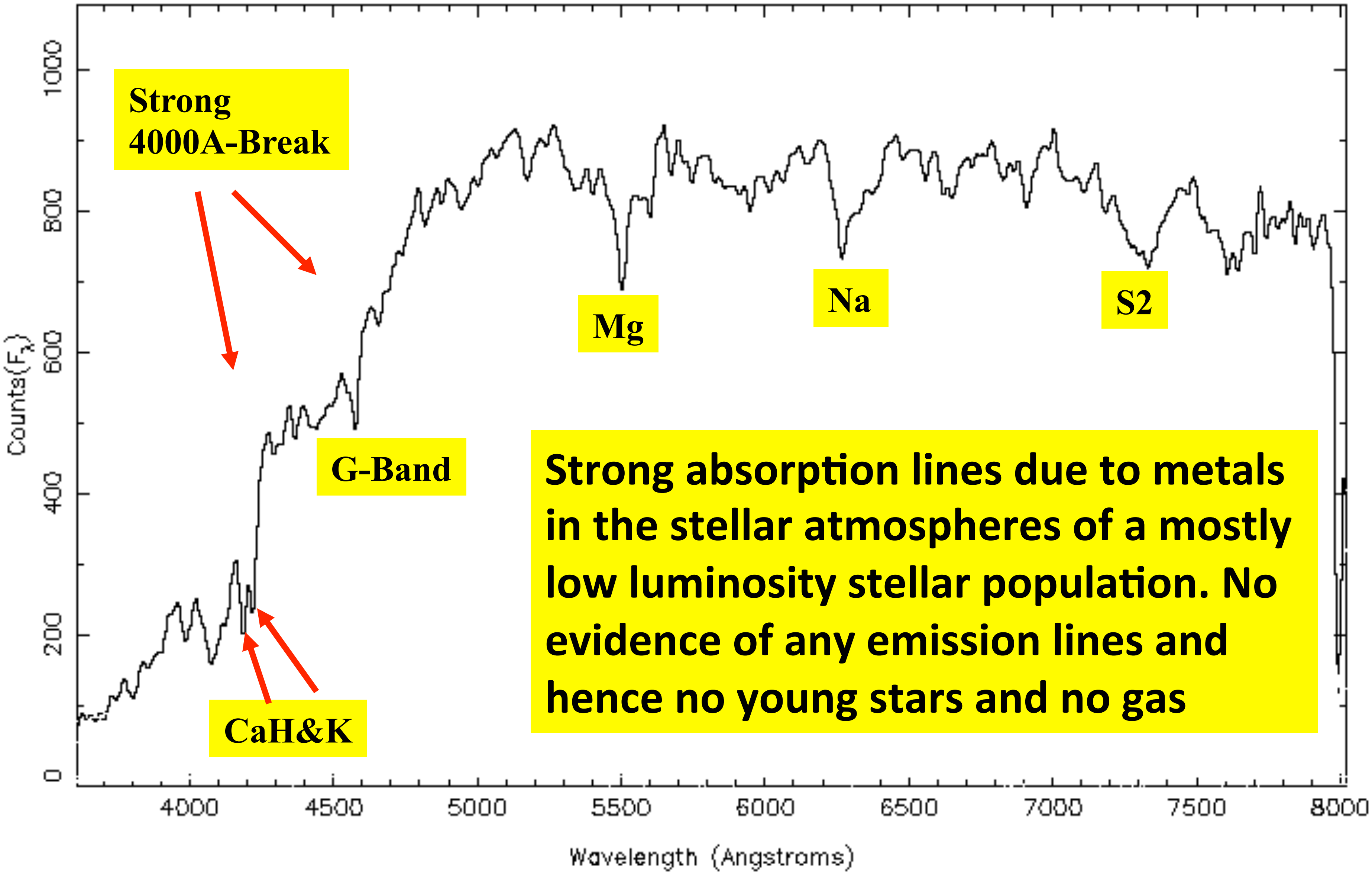
- Absorption Lines
  - Need metals in stellar atmospheres or cold gas in the interstellar medium
- Implies
  - Old stellar population = old galaxy
- From
  - Ellipticals
  - Spiral Bulges

- Emission Lines
  - Need very hot gas and O and B type stars
- Implies
  - Newly formed stars = star-forming/young galaxy
- From
  - Spiral Disks
  - Irregulars

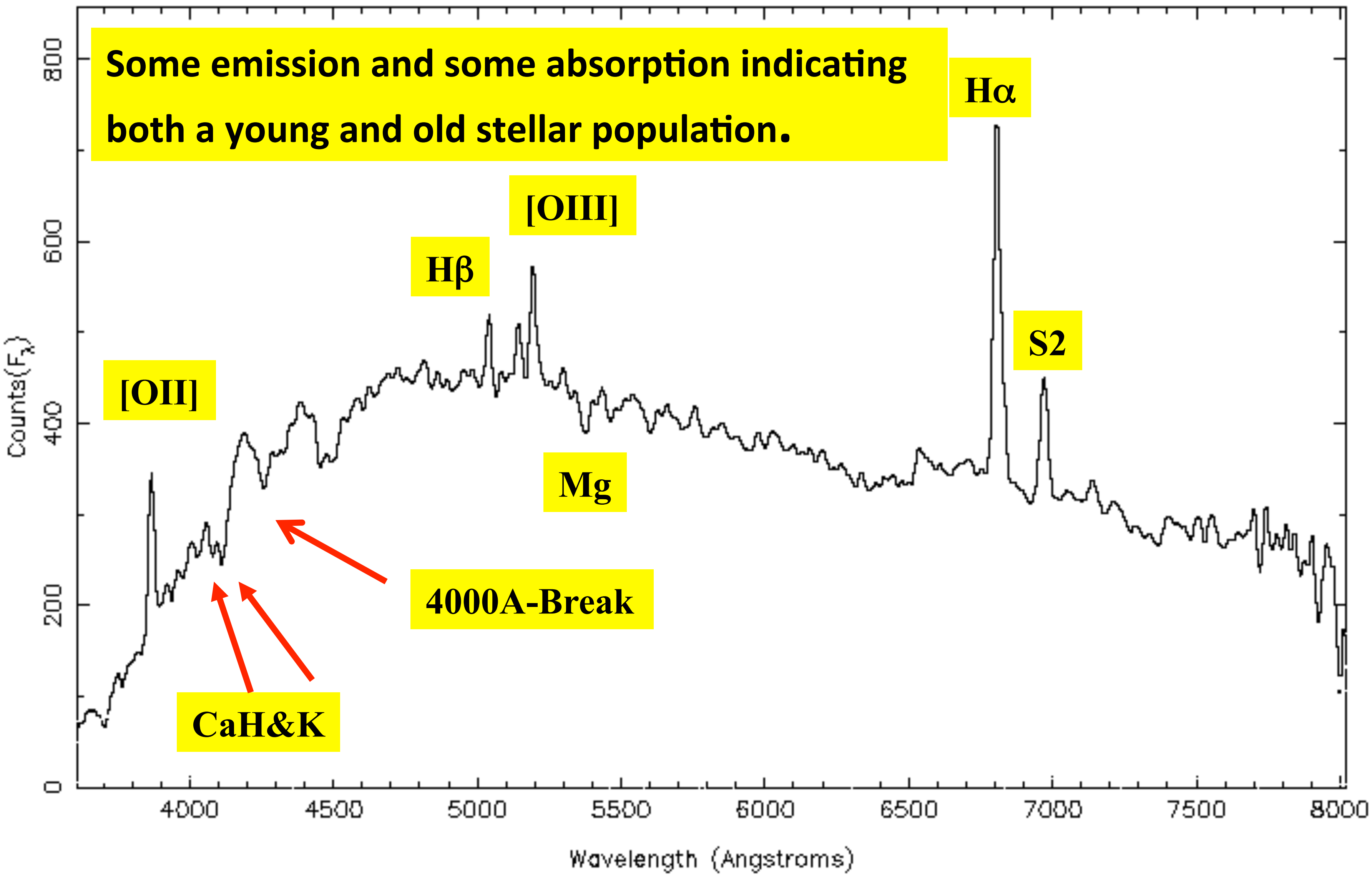
Typical Spectral features

- Absorption
  - Ca(H) = 3933.7A
  - Ca(K) = 3968.5A
  - G-band = 4304.4A
  - Mg = 5175.3A
  - Na = 5894.0 A
- Emission
  - [OII] = 3727.3A
  - $H\delta$ = 4102.8A
  - $H\gamma$ = 4340.0A
  - $H\beta$ = 4861.3A
  - [OIII] = 4959.0A
  - [OIII] = 5006.8A
  - $H\alpha$ = 6562.8A
  - S_2 = 6716.0A

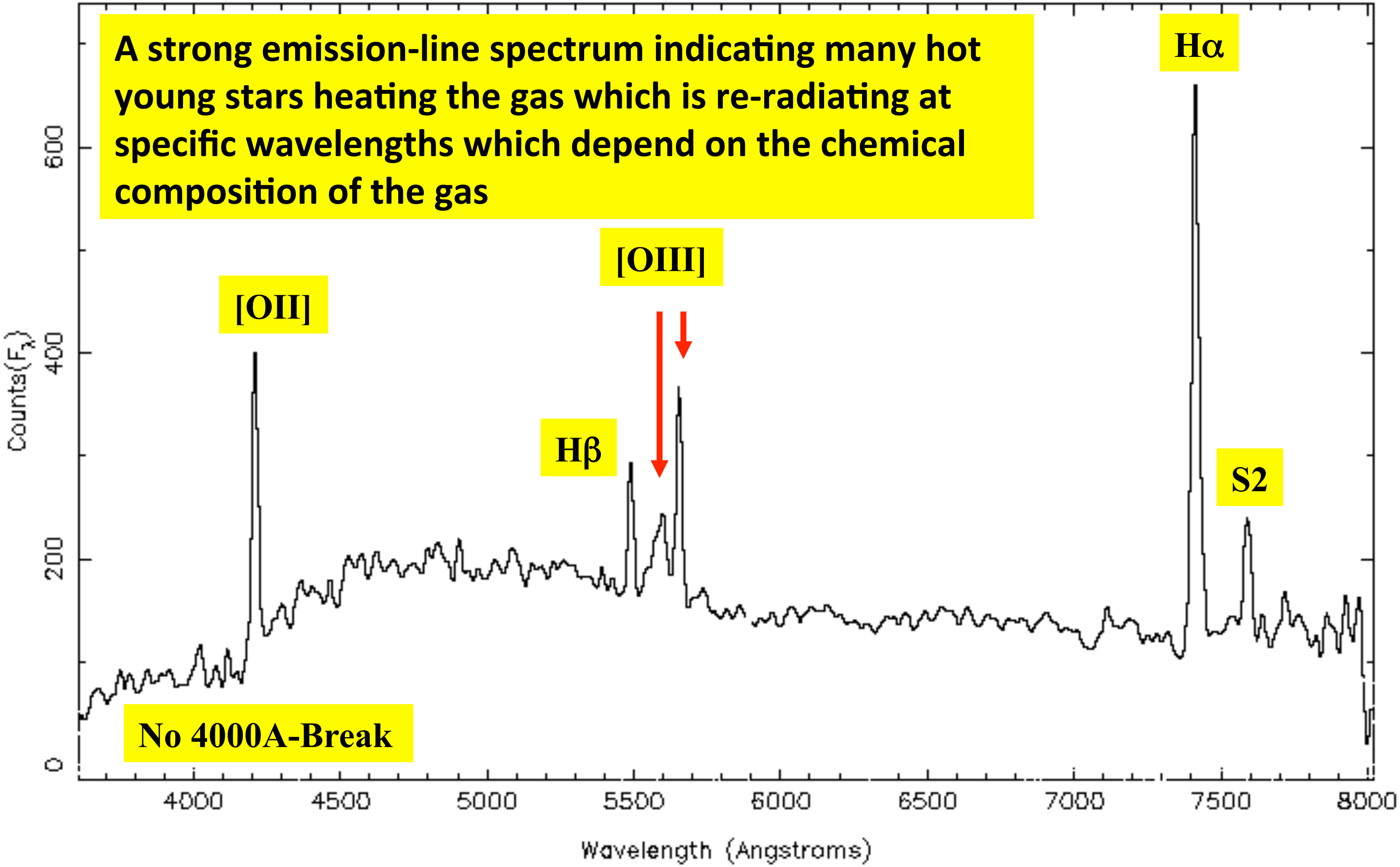
Example Spectrum: Elliptical



Example Spectrum: Spiral



Example Spectrum: Irregular



Radial Velocities

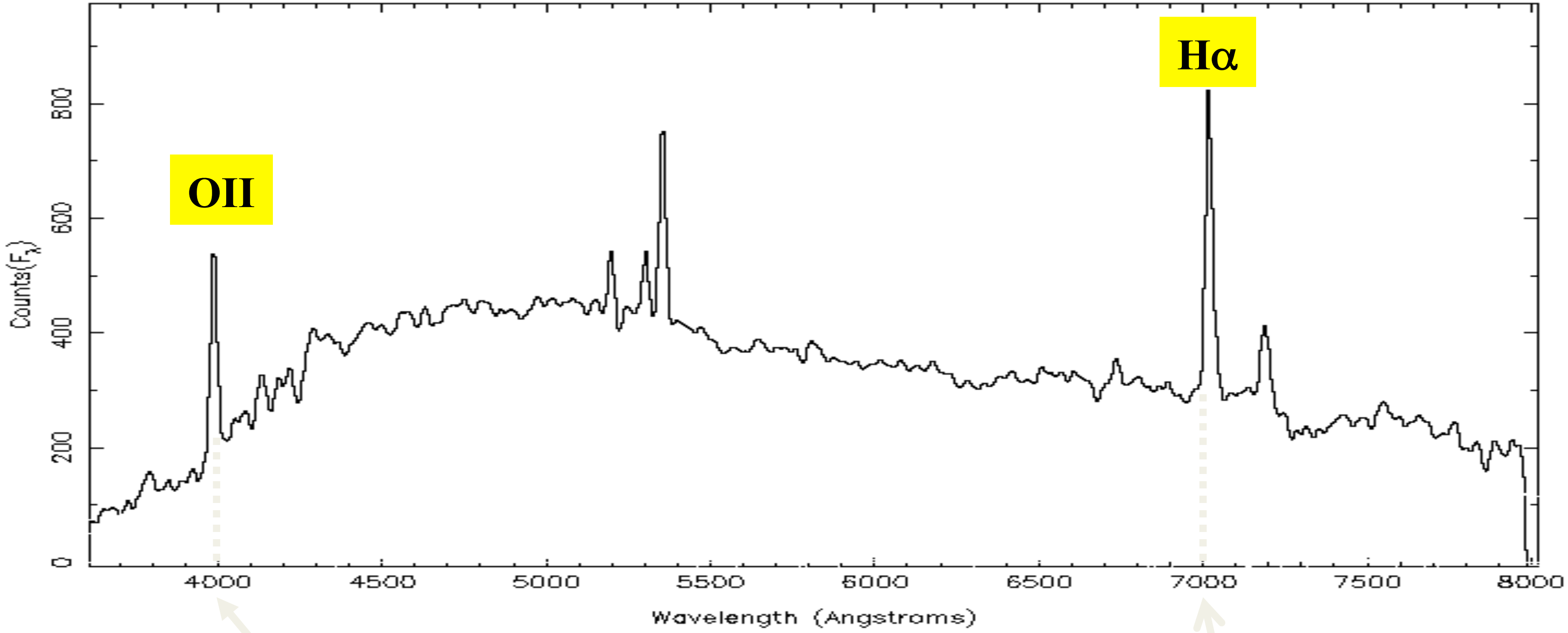
- Most galaxy spectra are REDSHIFTED, which means their spectral features are offset compared to those measured for gasses in the lab
- i.e., characteristic combinations of lines are systematically offset to longer wavelengths
- This is interpreted as a DOPPLER shift and implies that galaxies are moving away
- Positive velocities: RECEEDING
- Negative velocities: APPROACHING

$$\boxed{\frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{c}}$$

or

$$\boxed{\frac{\lambda_{\mathrm{OBSERVED}}}{\lambda_{\mathrm{CALIBRATION}}} = \frac{v + c}{c}}$$

Example Radial Velocity



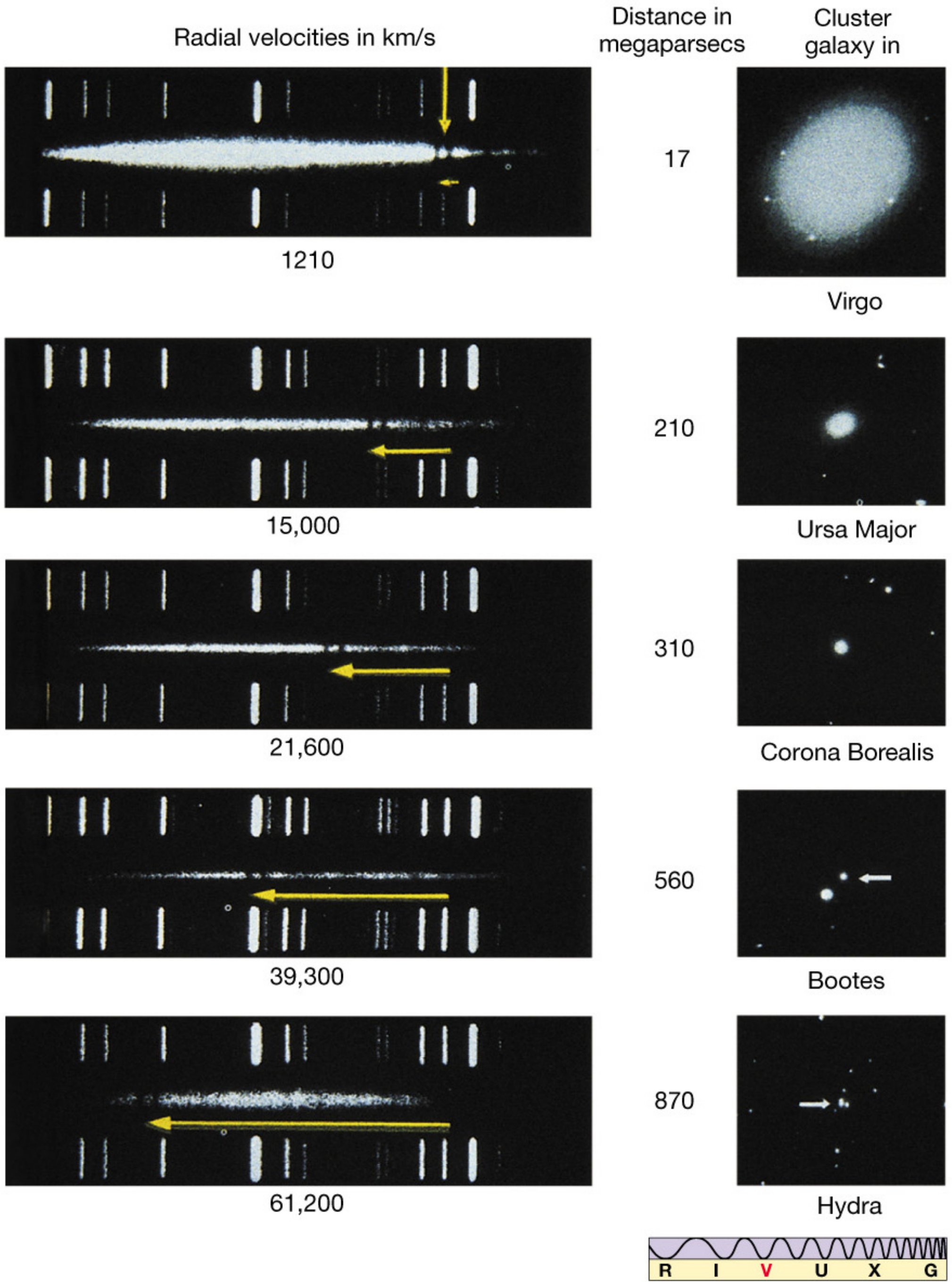
OII is at 4000A

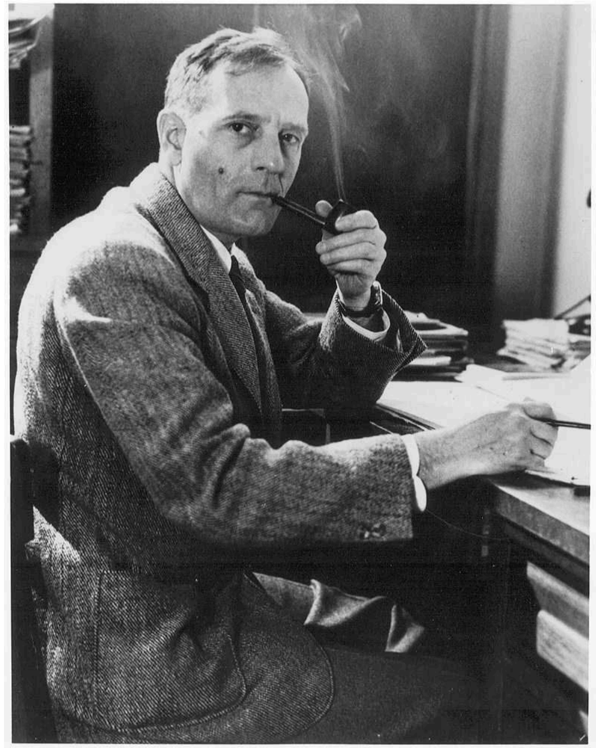
Hα is at 7030A

$$v = c\left(\frac{\lambda_{OBS} - \lambda_{CAL}}{\lambda_{CAL}}\right) = c\left(\frac{4000 - 3727}{3727}\right) = 21{,}974\,\mathrm{km/s}$$

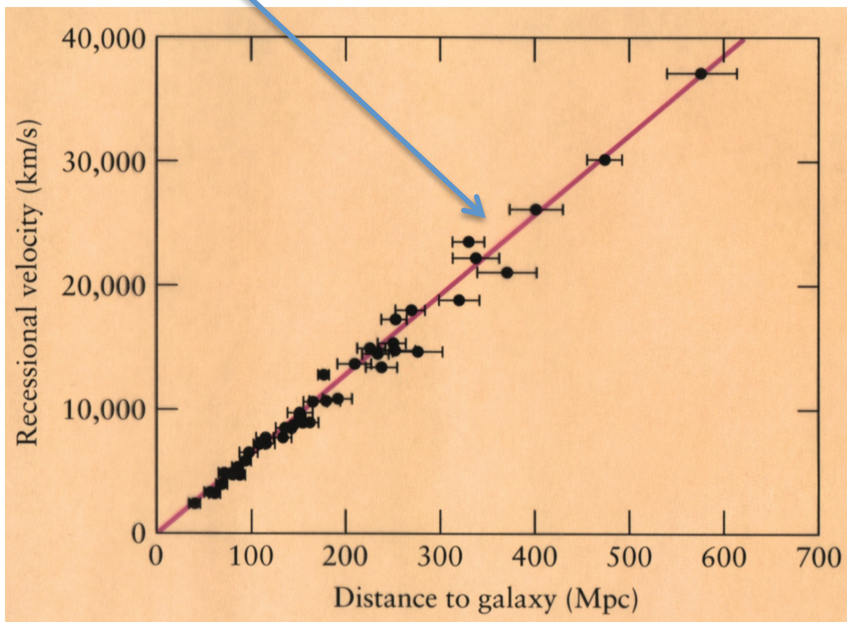
$$v = c\left(\frac{467}{6563}\right) = 21{,}500\,\mathrm{km/s}$$

GALAXY IS MOVING AWAY AT ABOUT 21,750 km/s

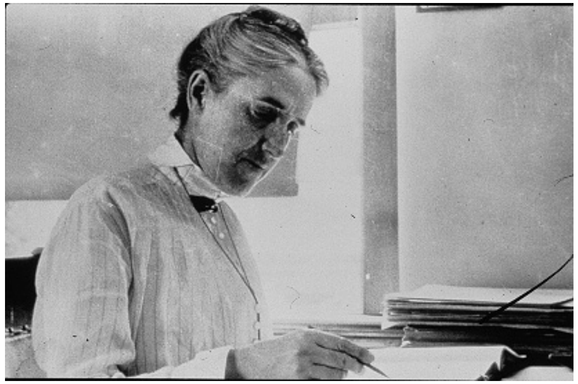

Radial velocities in km/s
Distance in megaparsecs
Cluster galaxy in
1210
17
Virgo
15,000
210
Ursa Major
21,600
310
Corona Borealis
39,300
560
Bootes
61,200
870
Hydra
R I V U X G



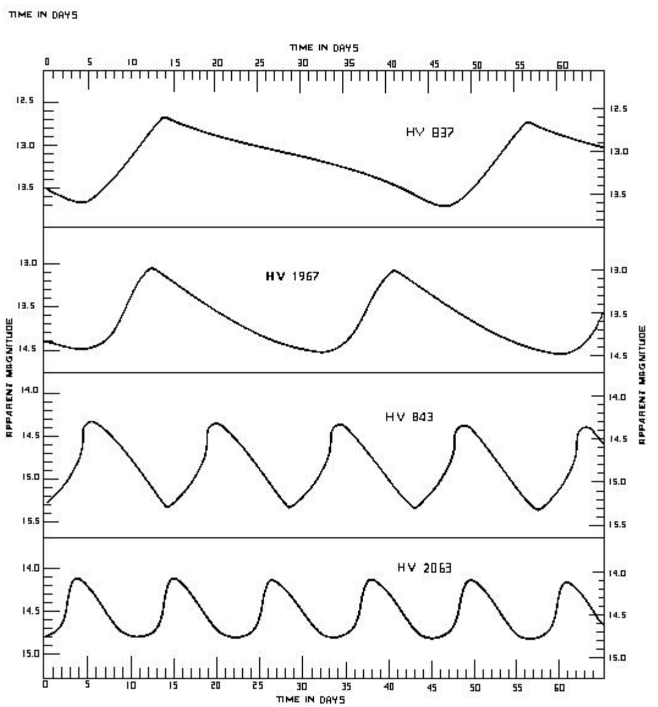
$$d = \frac{v}{H_o}$$

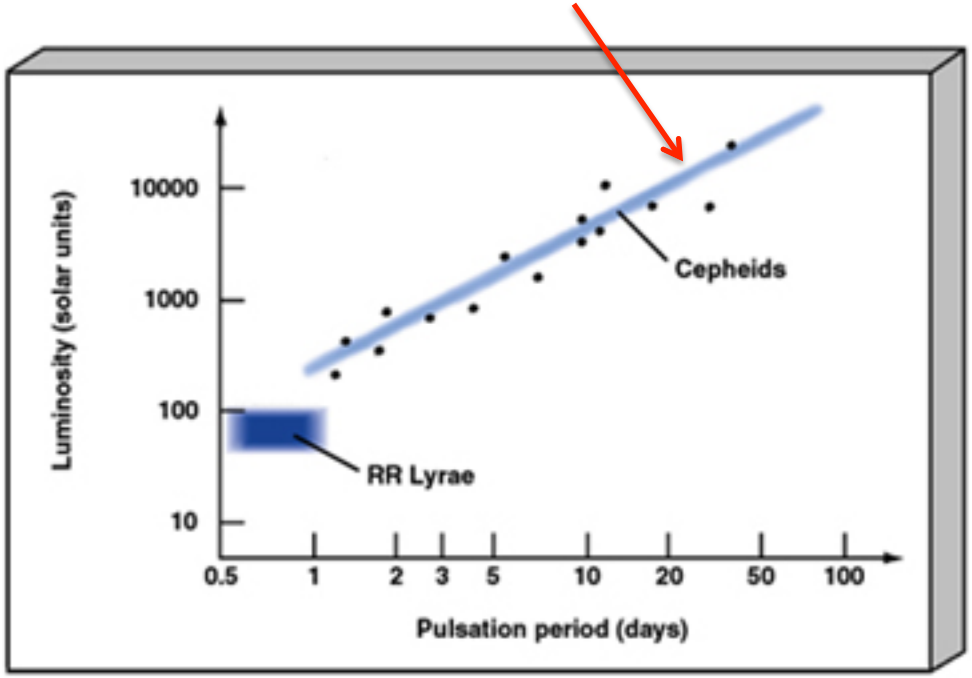

Recessional velocity (km/s)
40,000
30,000
20,000
10,000
0
0
100
200
300
400
500
600
700
Distance to galaxy (Mpc)

Reminder: Cepheid P-L relation



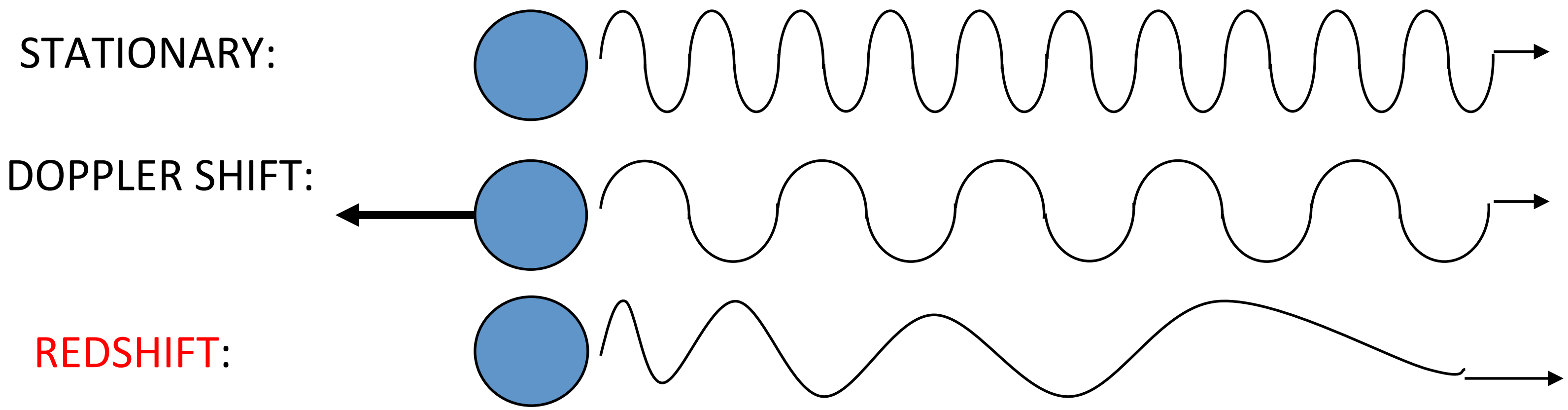
- Well studied stellar objects
- Very bright ($M_v \sim -2$)
- Pulsate regularly (~ few days)
- Pulsation period depends on luminosity
- P-L relation calibrated to 220 stars via Hipparcos parallax distances (1997)
- Measuring the pulsation and apparent magnitude for a distant Cepheid provides a direct distance measurement given a known P-L relation.





Redshift

- We now know the Universe is expanding (see later lectures)
- An expansion implies a stretching of space-time.
- The more space-time there is between you and an object the faster it will appear to be moving away.
- It is the expansion which causes a galaxy's spectrum to be REDSHIFTED:



REDSHIFT IS NOT THE SAME AS DOPPLER SHIFT

Redshift

- A useful parameter for cosmology is the redshift:

$$\boxed{z = \frac{\lambda - \lambda_o}{\lambda_o} = \frac{\Delta\lambda}{\lambda_o}}$$

- This is analogous to the definition of Doppler shift such that: from which follows:

$$\boxed{z \equiv \frac{\mathrm{v}}{c}}$$

$$\boxed{d = \frac{zc}{H_o}}$$

Hubble constant

- Although this is the wrong interpretation of redshift it is a good approximation for low-*z* ($z < 0.1$)

- Hubble constant = rate of expansion in units of (km/s)/Mpc
  - Current value ~75 km/s/Mpc

Calculating distances

- Using Hubble's Law (which we'll discuss more later) we can easily estimate distances from a galaxy's measured redshift.

  e.g., If H_0 = 75 km/s/Mpc and the redshift is measured to be 0.1 what is its distance ?

$$\boxed{d = \frac{zc}{H_o} = \frac{0.1 \times 3 \times 10^5}{75} = 400 Mpc}$$

  This implies that for example its [OII] line, normally at 3727A, occurred at 4100A

Peculiar Velocities

- Gravitational attraction between galaxies and larger objects (clusters, groups, superclusters, filaments)
- Velocity we measure is not just the expansion of the universe

$$\boxed{V_{RADIAL} = V_{RECESSIONAL} \pm V_{PECULIAR}}$$

- For example the MW is falling into Virgo which in turn is falling into The Great Attractor.
- *If we know a galaxy's peculiar velocity we can correct for this additional velocity component.*

Peculiar Velocities

- What we measure from spectra:

  V_{RADIAL} or $V_{LINE\ OF\ SIGHT}$

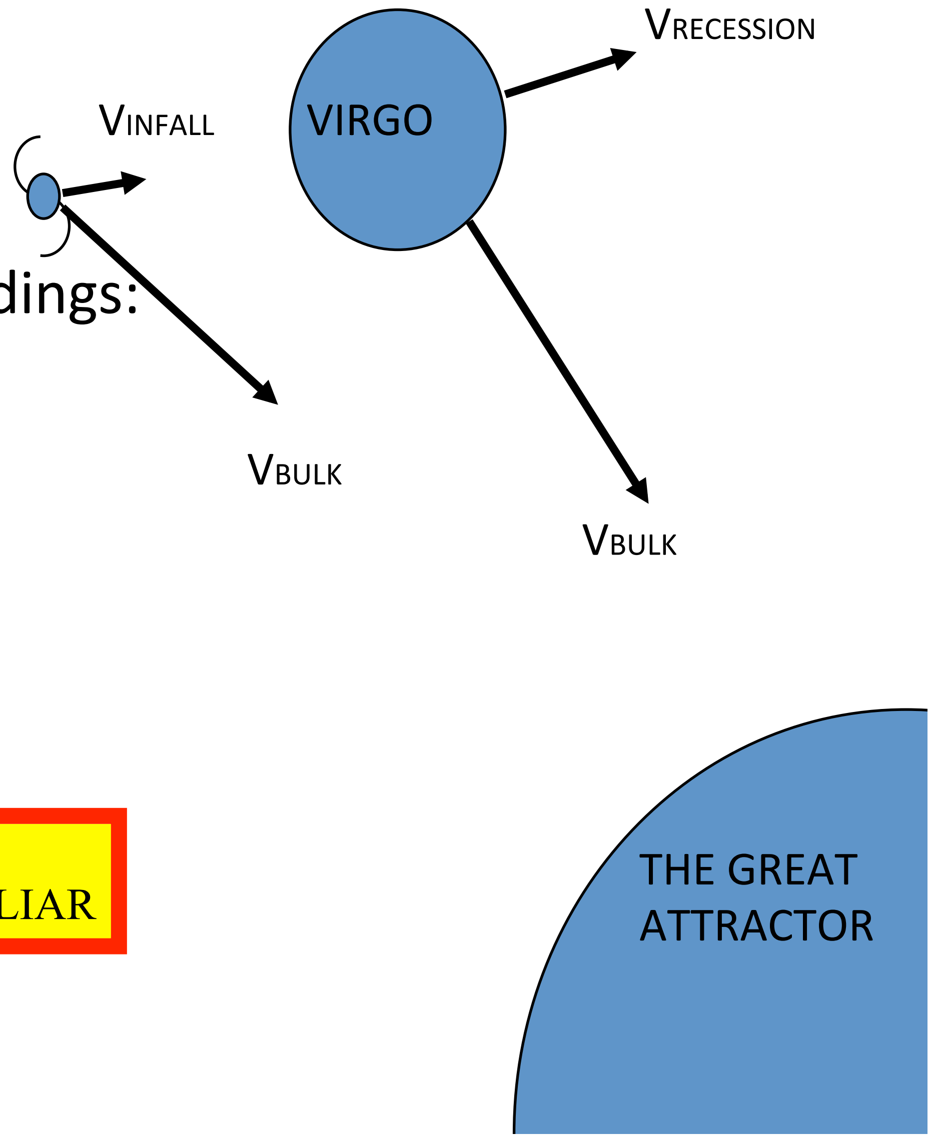
- Objects velocity w.r.t. our surroundings:

  $V_{PECULIAR}$ or V_{INFALL}

- Velocity due to expansion:

  $V_{RECESSION}$ or $V_{EXPANSION}$

$$\boxed{V_{RADIAL} = V_{RECESSIONAL} \pm V_{PECULIAR}}$$



Example

- The MW is falling *towards* Coma at V_{infall} =1000km/s.
- Distance is 50 Mpc (from Cepheids)
- If the redshift, z = 0.01, what is H_0 ?

$$z = \frac{V_{RADIAL}}{c} = \frac{V_{RECESSION} - V_{INFALL}}{c}$$

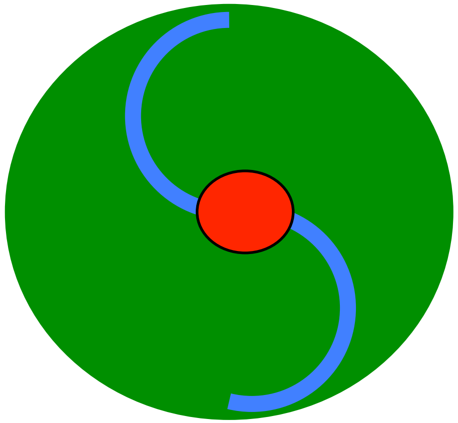
$$H_o = \frac{V_{RECESSION}}{d} = \frac{cz + V_{INFALL}}{d} = \frac{3000 + 1000}{50}$$

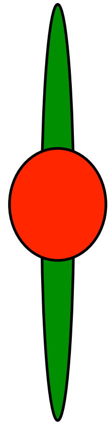
$$H_o = 80 km / s / Mpc$$

Note: Be very careful with the sign of V_{INFALL} & $V_{PECULIAR}$, it is intuitive

Typically V_{INFALL} is subtracted but for $V_{PECULIAR}$ it will depend on the direction of the peculiar velocity (towards us= -ve, away= +ve)

Galaxy Inclination





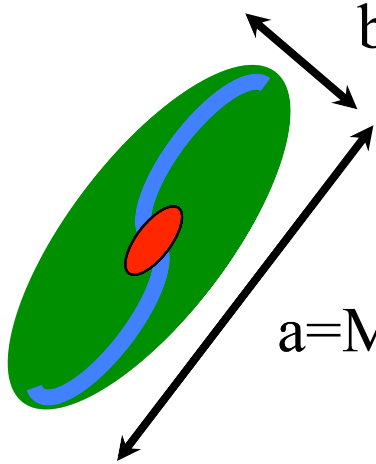
FACE-ON

Inclination=0^o

EDGE-ON

Inclination=90^o

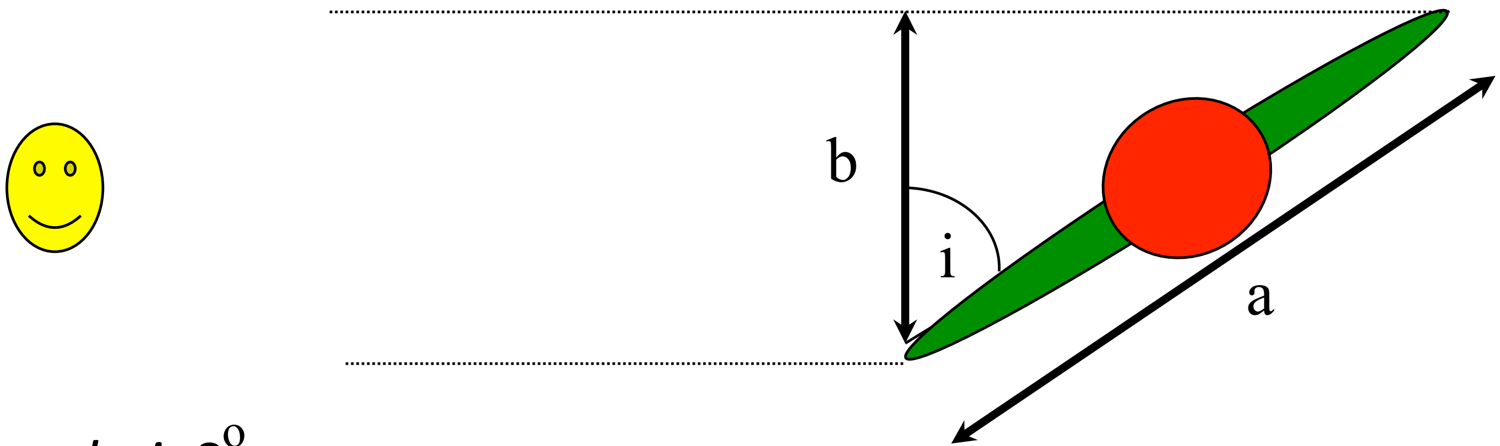
Majority of galaxies are somewhere in between



Calculating the Inclination

- Assuming galaxies are circular:
- Inclination, *i*, is given by:

$$\boxed{\cos(i) = \frac{b}{a}}$$

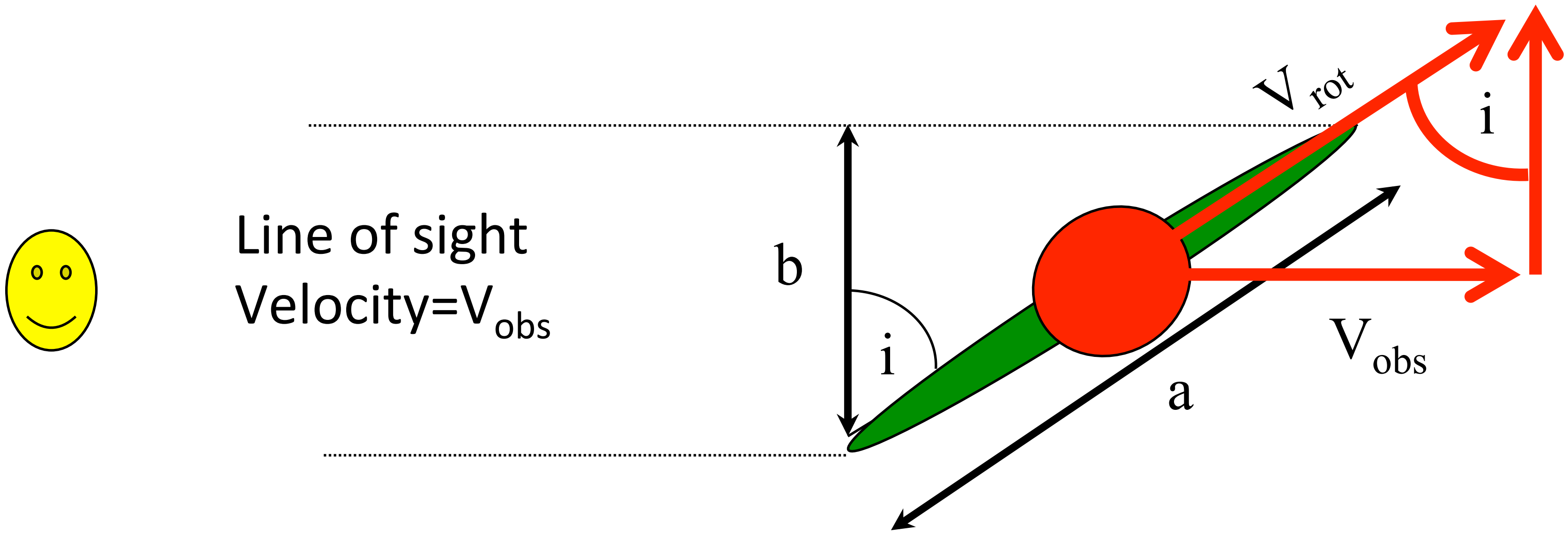


- $a=b$, $i=0^{o}$
- $b=0$, $i=90^{o}$

NB: *a* is always measurable

Line of sight velocity

- When we measure the rotational velocity from a spectral line we need to correct for inclination.



Hence if,

i=90 , V_{obs} = V_{rot}

i=0 , V_{obs} = 0

$$\boxed{V_{ROT} = \frac{V_{OBS}}{\sin(i)}}$$

Example

A long slit spectrum aligned along a galaxy's major axis indicates a variation in the [OII] line of 5A, The midpoint of the [OII] line is observed to be at 3900A and the major-to-minor axis ratio is 3. What is the rotational velocity of the outermost stars ?

$$i = \cos^{-1}(1/3) = 70.5^0$$

Note: 5/2 A

$$V_{OBS} = \frac{\Delta\lambda}{\lambda} c = \frac{2.5}{3900} \times 3 \times 10^5 = 192 km/s$$

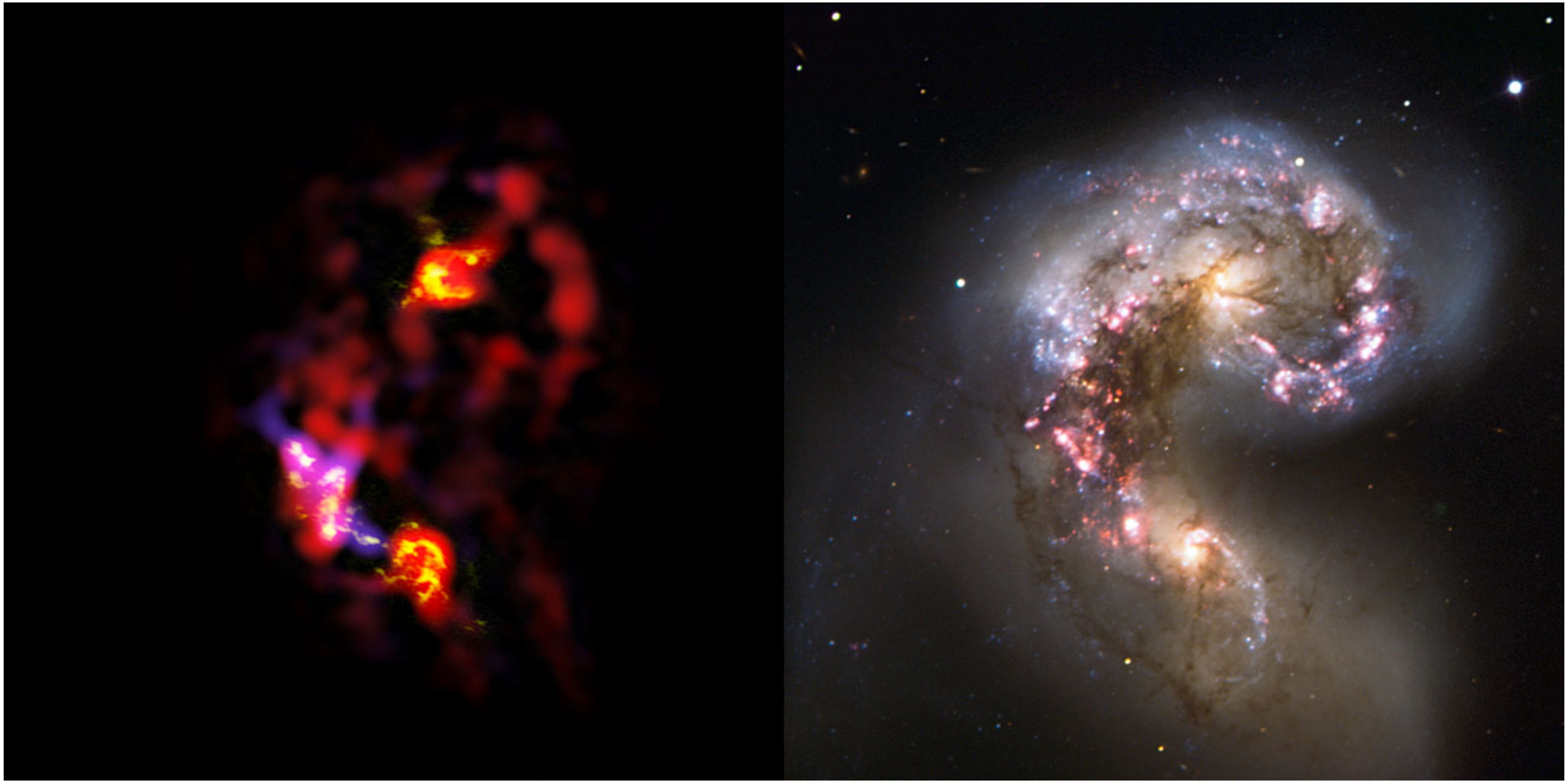
$$V_{ROT} = \frac{V_{OBS}}{\sin(i)} = 204 km/s$$

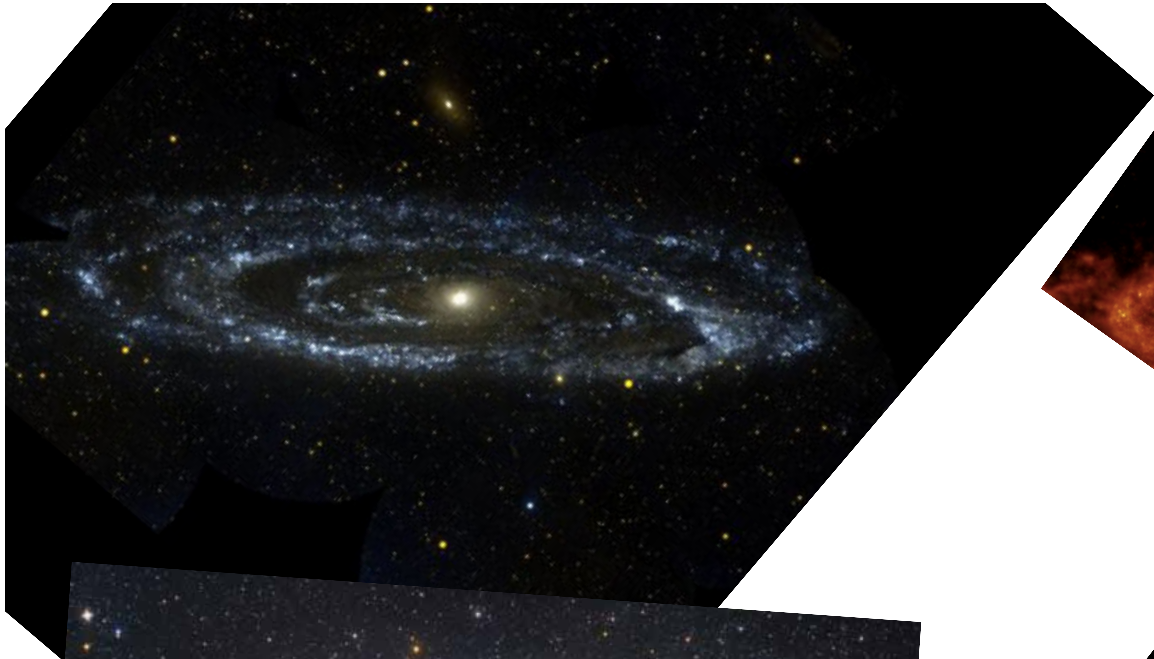
Note: λ=3900 and not 3727 (as reference is to the galaxy centre)

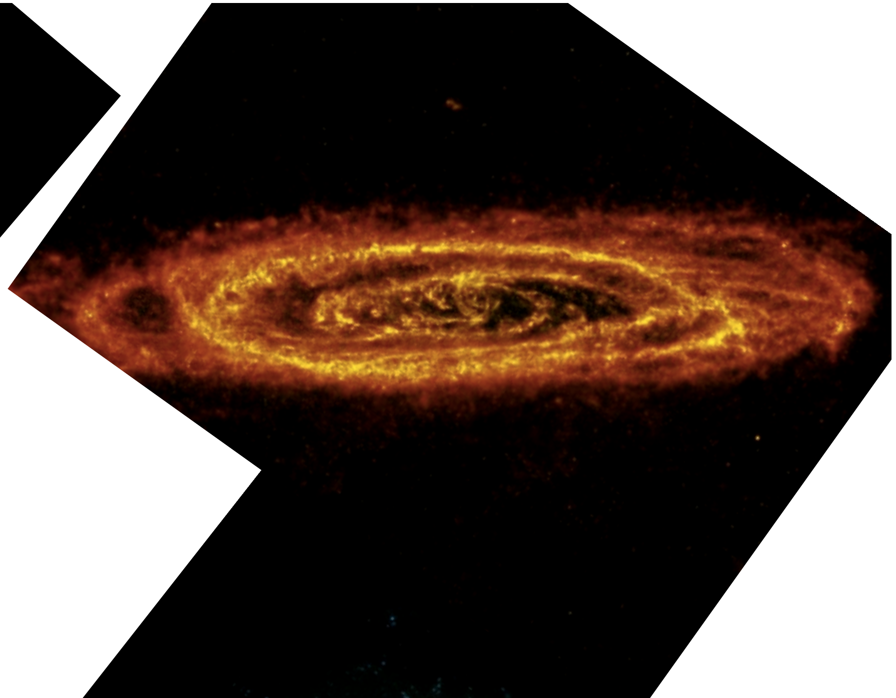
Stars, Dust and Gas in Galaxies

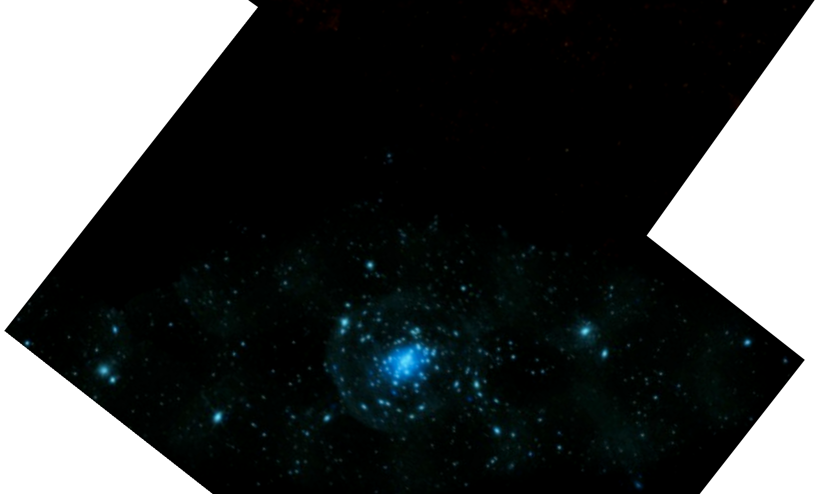
- Dust mass is negligible but can block up to 90% of the light and provides a good indication of where the fresh stars are
- Stars form from gas in galaxy
- In the high-density regions the gas is converted into Stars
  - Elliptical: very little gas content
    - ~ all gas converted into stars => $$\frac{M_{HI}}{M_{STARS}} = 0.01 - 0.1$$
  - Spiral: some gas content
    - most gas converted => $$\frac{M_{HI}}{M_{STARS}} = 0.1 - 1.0$$
  - Irregular: lots of gas
    - little gas converted => $$\frac{M_{HI}}{M_{STARS}} \geq 1.0$$

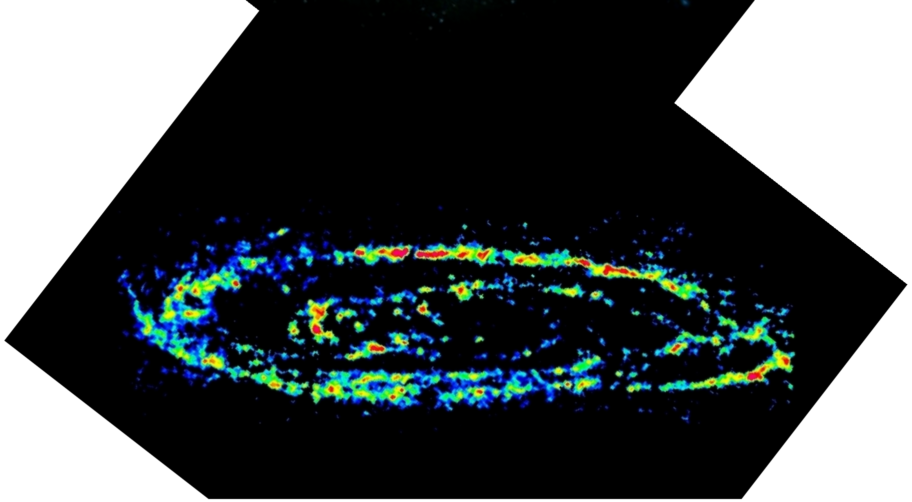
Warm dust and starlight in Antenae galaxy

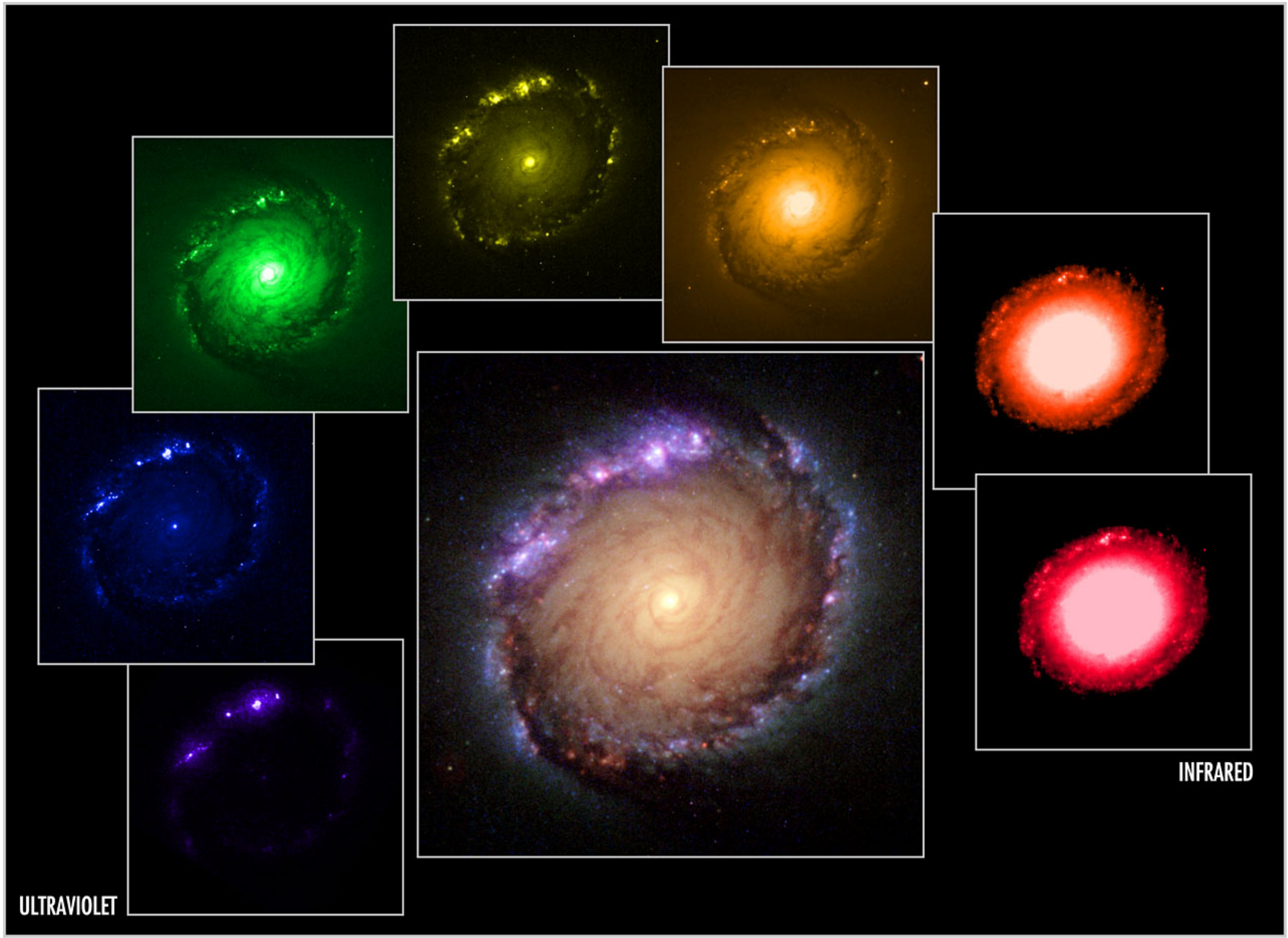








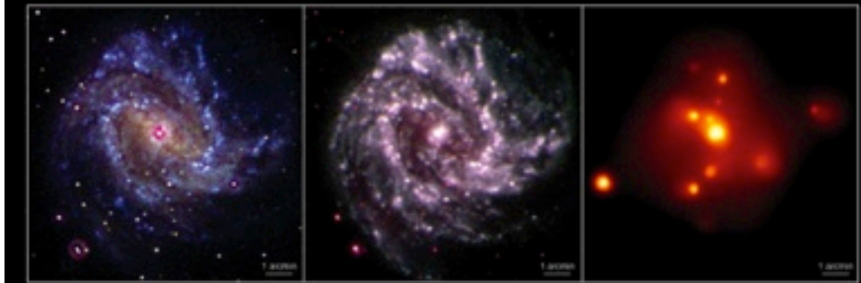




NGC1512

Visible | Ultraviolet | X-ray

M81

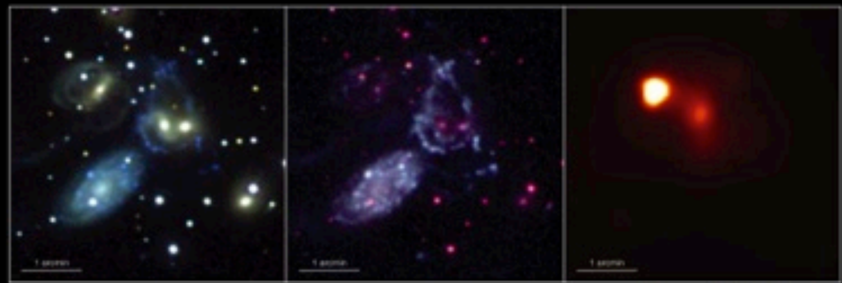


M83

M101

Visible | Ultraviolet | X-ray

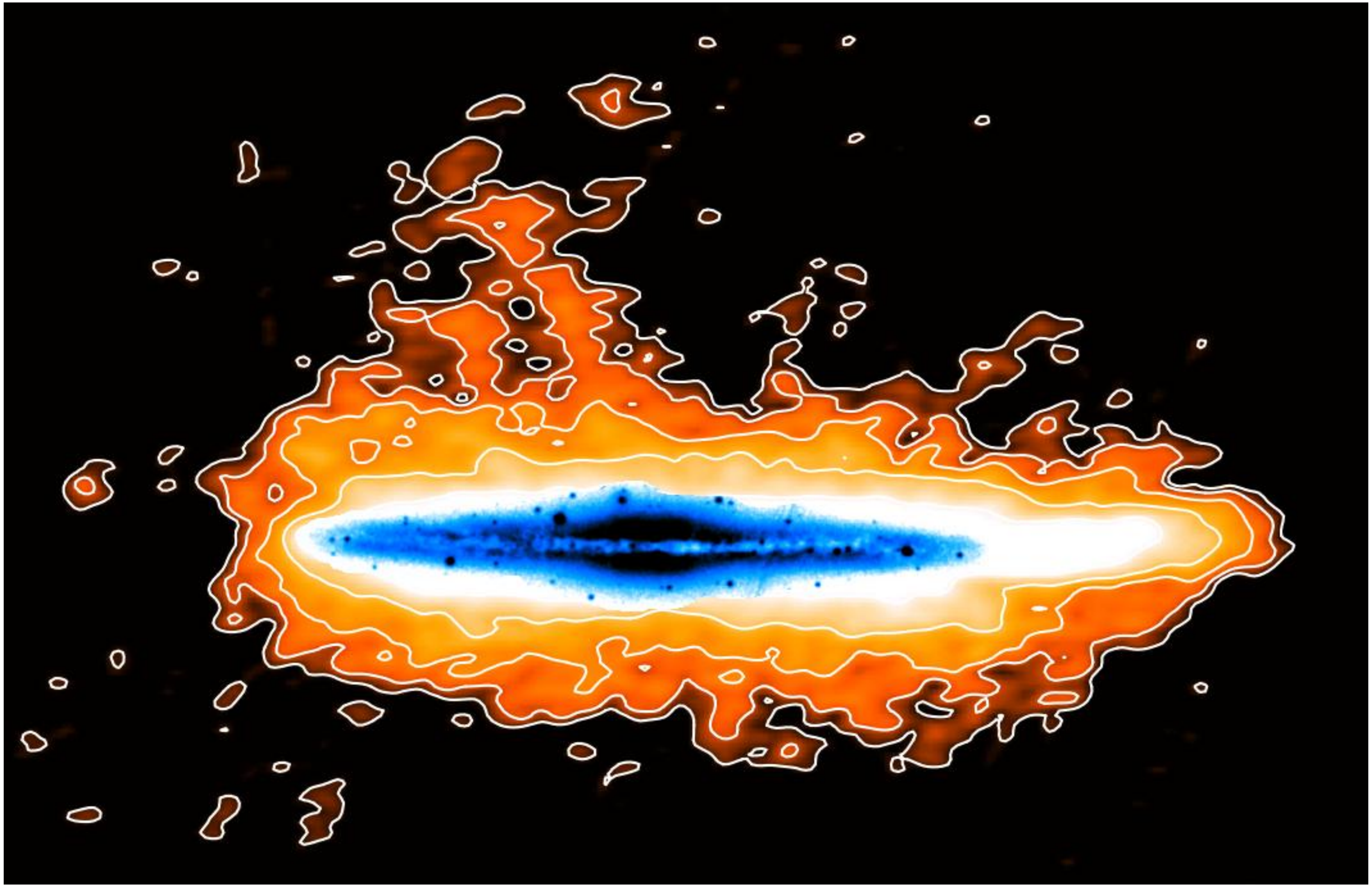
NGC 6946



Stefan's Quintet - Arp 319

Antennae - NGC 4038

Optical and radio image of NGC891



Distribution of Gas and Stars