Introduction

Welcome to PHYS 644, Galaxies + Cosmology! In this course we'll study astrophysics on the scales of galaxies and above.

$\boxed{\text{Intro slides.}}$

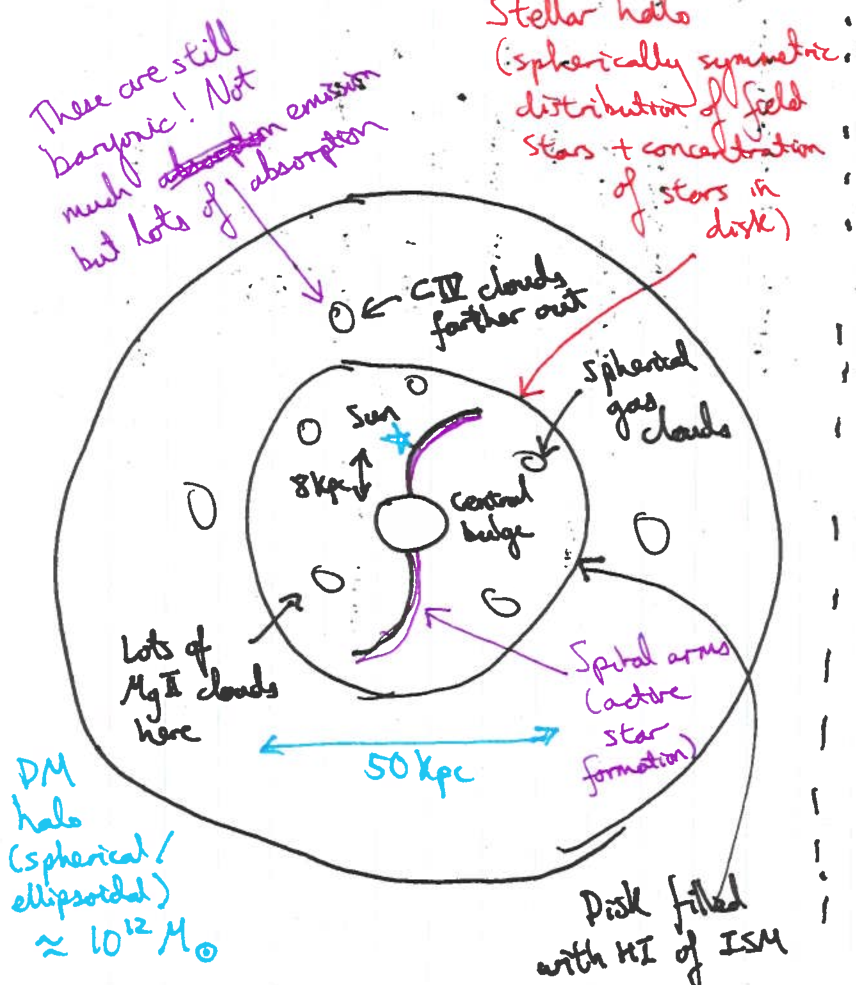
The goal here is to impart some basic tools and principles, not to cover everything in mind-numbing detail.

Galaxy Observations

What are the various parts of a typical galaxy? Rotate page....

Top view

(Recall: $1pc \simeq 3 \times 10^{18}$ cm $\simeq 3.26$ ly)

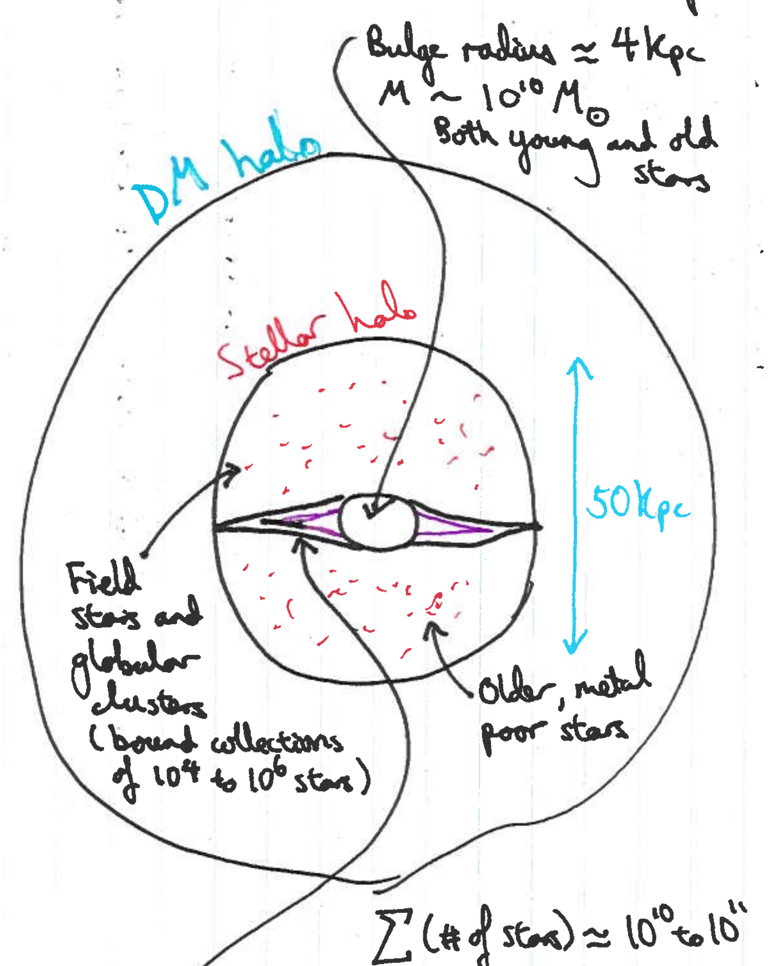


$\simeq 200$ kpc

(No defined edge, but this is good @ order-of-magnitude level)

Side view

(Age of MW $\simeq 10^{10}$ yr
$T_{orb} \simeq 3 \times 10^{8}$ yr)



$\sum$(# of stars) $\simeq 10^{10}$ to 10^{11}

Thin disk: $h \sim 0.3$ kpc (youngest, most active star formation)

Thick disk: $h \sim 1$ kpc

Lots of gas, dust in disk

Those are the pieces of a galaxy. But what sorts of observations give us this picture?

We'll go through a few in this lecture:

- Morphology (shape)
- Surface brightness
- Rotation curves

} Can only be done for nearby ("low redshift") galaxies

- Flux (how bright)
- Spectra (flux as fct. of wavelength)
- Redshift

} Can still be done for distant ("high redshift") galaxies as well as nearby ones.

Morphology

Today's galaxies can be broadly classified into two classes: spirals and ellipticals ⇒ $\boxed{\text{show pictures}}$

Spiral Galaxies	Elliptical Galaxies
– Younger, bluer stars	– Older, redder stars

(High mass stars are bluer ∵ their blackbody temps are higher, but they burn out their fuel sooner ⇒ old stellar populations don't have high mass stars ⇒ redder)

Spiral Galaxies	Elliptical Galaxies
– Active star formation esp. in spiral arms.	
– Lots of gas	– Little gas
– "Cold": little dispersion in velocities. Motion of stars dominated by bulk motion	– "Hot": little bulk motion. Motion dominated by random velocity dispersions

(I don't mean this literally! We're talking about the "temperature" of a "gas" where each particle is a star)

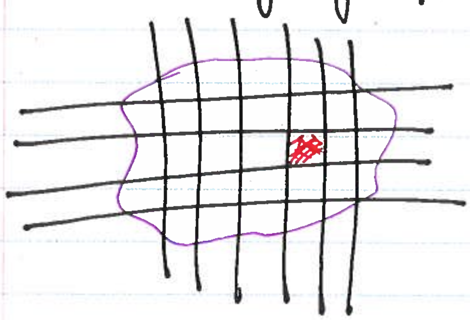
- Held up by rotation	- Held up by "thermal" motion

⇒ $\boxed{\text{Slide Q on Density-Morphology relation}}$

- Less likely in dense, cluster environment	- More likely to be found in clusters
- Exponential surface brightness profile (sersic index $n=1$)	- deVaucoleurs profile (sersic index $n=4$)

Surface Brightness

↳ "Amount of light per angular area (Eg per arcsec^2)"



$$I(r) = I_0 \exp\left[-\left(\frac{r}{r_0}\right)^{1/n}\right]$$

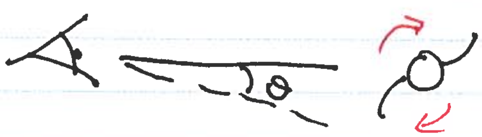
"sersic index"

Surface brightness averaged in azimuthal direction

Rotation Curves

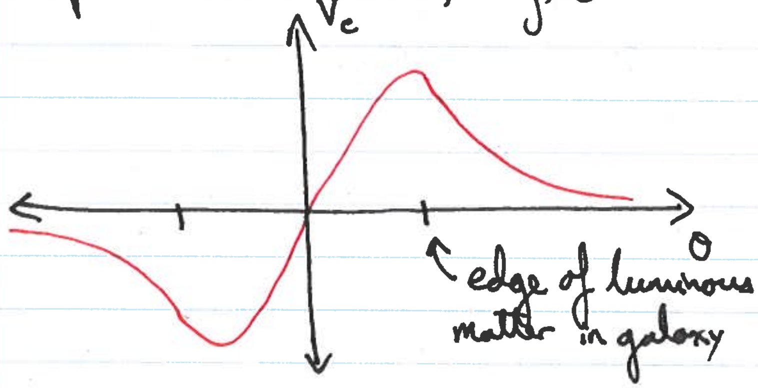
↳ "Speeds of objects (Eg stars or gas clouds) as a fct. of distance from the centre of a galaxy"

Measure using the Doppler shift of a known spectral line to get line-of-sight velocity



$$\frac{\Delta\lambda}{\lambda} = \frac{V_{LOS}}{c}.$$

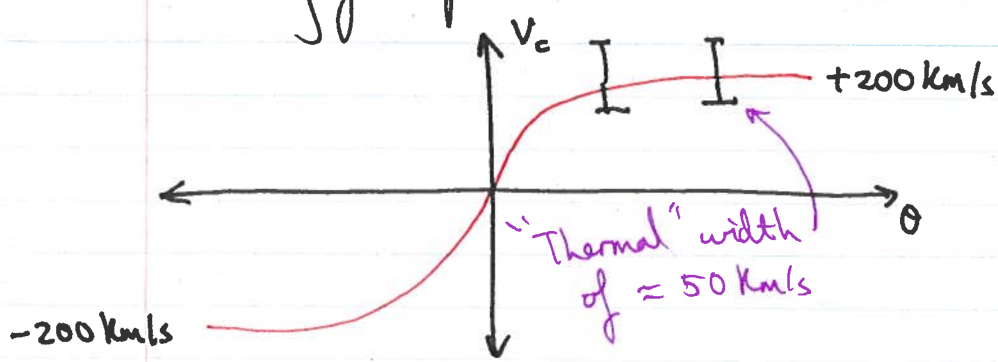
Expectation (back in, say, the 1970s):



$$\frac{V_c^2}{r} \sim \frac{GM_{gal}}{r^2}$$

$$\Rightarrow V_c \sim r^{-1/2}$$

Reality for spirals:

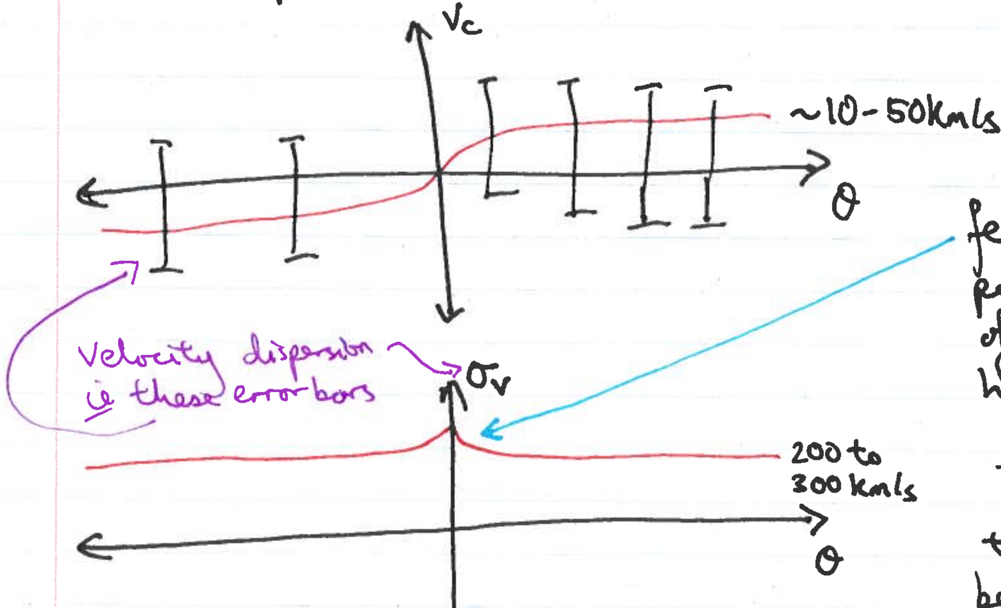


(Although these days there are even stronger pieces of evidence)

Evidence for dark matter!

(Vera Rubin, 1980s)

For ellipticals:



For some ellipticals we see this feature: a Keplerian point mass $\sim r^{-1/2}$ of the central black hole!

This feature is hard to observe for spirals because Doppler is only sensitive to LOS velocities $\Rightarrow$ need edge-on spiral. But most dust in disk $\Rightarrow$ greatest dust extinction

⇒ $\boxed{\text{Slide discussion question about wavelengths}}$

Observation	Band	Why
Intracluster medium (ICM)	X-rays	Very hot gas / plasma thermal bremsstrahlung ⇒ energetic photons (1)
Galaxy mergers	UV	Mergers induce star formation ⇒ young stars still present and haven't died ⇒ lots of UV (2)
Spiral arms	UV, visible	Sites of star formation ⇒ young stars
Dust	IR	Emission lines from molecular band structures
Galactic centre	IR / radio	Less extinction (dust scatters short λ preferentially)
Rotation curves	Visible / Radio (Hα) (21cm)	Other things relatively transparent to these lines
Stars	Visible	Peak in blackbody spectrum (3)
Galaxy counts	Visible (also IR these days)	" (4)

(1) Intracluster medium

Why so hot? Resides in the deep gravitational potential wells of galaxy cluster dark matter halos. When things fall into a deep well they gain lots of kinetic energy!

Estimate temperature:

$$v^2 \sim \frac{GM}{R} \Rightarrow \frac{1}{2} m_H v^2 \sim \frac{GMm_H}{R}$$

$$\approx$$

$$k_B T \sim \frac{GMm_H}{R}$$

Take Coma, a typical rich cluster with ≈ 1000 bright galaxies ($\sim 10^4$ including dim ones) about 100 Mpc away and ≈ 2 Mpc across. $M_{coma} \sim 10^{15} M_\odot$

$$k_B T \sim \frac{GM_{coma} m_H}{R_{coma}} \sim 20 \text{ keV} \quad (\text{X-rays})$$

$T \sim 3 \times 10^8$ K, a little high (should be $\sim 10^7$ K, but ok)

(The fact that the stars don't collide might be surprising. Stay tuned! We'll see why soon)

(2) Galaxy mergers

Why do galaxy mergers induce star formation? When two ~~of the~~ galaxies collide, the stars and DM basically go through one another, but the gas doesn't $\Rightarrow$ $\boxed{\text{Bullet cluster picture}}$

The gas gets more dense. Now, the cooling rate of gas goes like n_{gas}^2. Why? Because one of the dominant ISM cooling mechanisms is collisional excitations followed by photon emission de-excitation. Photons leave the system and the gas ends up cooler. The gas cooling becomes efficient, allowing gas clouds to clump and form stars.

③ Optical observations of stars

Optical observations do more than just give us pretty pictures.

Tully-Fisher relation: $L \propto V^4$ (spirals)

Luminosity (intrinsic brightness) of galaxy — Speed of stars

$\approx 10\%$ scatter

Faber-Jackson relation: $L \propto \sigma_v^4$ (ellipticals)

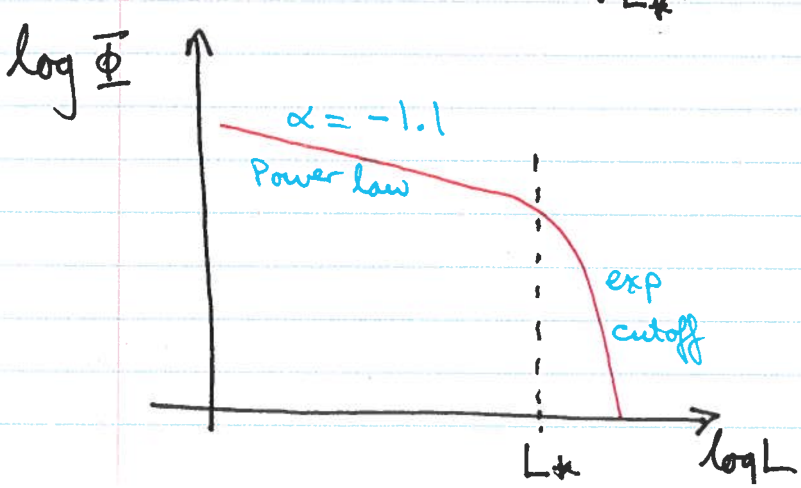
(Higher scatter than TF)

④ Schechter's Law

Schechter's Law is a luminosity function $\Phi(L)$

$\Phi(L)\,dL = \begin{pmatrix} \text{\# of galaxies per unit volume} \\ \text{with luminosity between } L \text{ and } L+dL \end{pmatrix}$

$$= \Phi^* \left(\frac{L}{L_*}\right)^{\alpha} \exp\left(\frac{-L}{L_*}\right) \frac{dL}{L_*}$$



$\alpha = -1.1$

$L_* = 3 \times 10^{10}\, L_\odot$ (typical bright galaxy)

$\Phi^* = 5 \times 10^{-3}\ \text{Mpc}^{-3}$

(Exact parameters depend on environment)

If we look @ the total # of galaxies:

$$N_{total} = \int_0^\infty \Phi(L)\, dL = \text{diverges!}$$

The faint end blows up. Unphysical, but does capture the fact that our Universe is dominated by faint objects as far as numbers go.

Total luminosity $L_{total} = \int_0^\infty L\,\Phi(L)\,dL$ = converges, dominated by L_*.

∴ Even though there are lots of faint things, the light of our Universe is dominated by relatively bright galaxies like ours.

Aside from the luminosity fct., a lot of the observations we've discussed so far require resolving the spatial structure of a galaxy.

For distant galaxies we often can't. But there are still things we can measure:

Flux

$$f_\nu = \frac{dE}{dA_\perp\, dt\, d\nu} \propto \frac{1}{r^2}$$

"Power per detector area in freq. bin"

("How bright something appears")

Apparent magnitude $m_\nu = -2.5 \log_{10}\left(\frac{f_\nu}{f_{\nu,ref}}\right)$

Historically taken to be Vega.

Absolute magnitude $M_\nu = m_\nu - 5 \log_{10}\left(\frac{\text{distance}}{10\,pc}\right)$
(m_ν @ 10 pc)

Spectra

We aren't completely helpless even when we can't spatially resolve a galaxy though. We can look @ the light as a function of wavelength or frequency, ie spectra

$\Rightarrow$ $\boxed{\text{Show examples}}$

Redshift

Spectra are particular important for using the Doppler effect to find the velocity of a galaxy as a whole:

$$\text{Redshift} \quad z = \frac{\Delta\lambda}{\lambda}$$

Why do we care? Universe is expanding, so the farther away a galaxy is, the more space between us and it, ~~so~~ which means if every bit of space stretches, then more distant = moving away faster.

$\Rightarrow$ Redshift gives us a distance, and since light from distant objects were emitted long ago, also tells us how far back in time we are looking.

Two types of redshift measurements:

i) ~~z~~ Spectroscopic redshift. Get a high frequency resolution spectrum, identify lines, measure z directly.
High ~~p~~ precision + accuracy but expensive.

ii) Photometric redshift. Look @ galaxy through a few coarse filters and fit to a template. Cheap but larger uncertainties

$\Rightarrow$ $\boxed{\text{JWST slides}}$