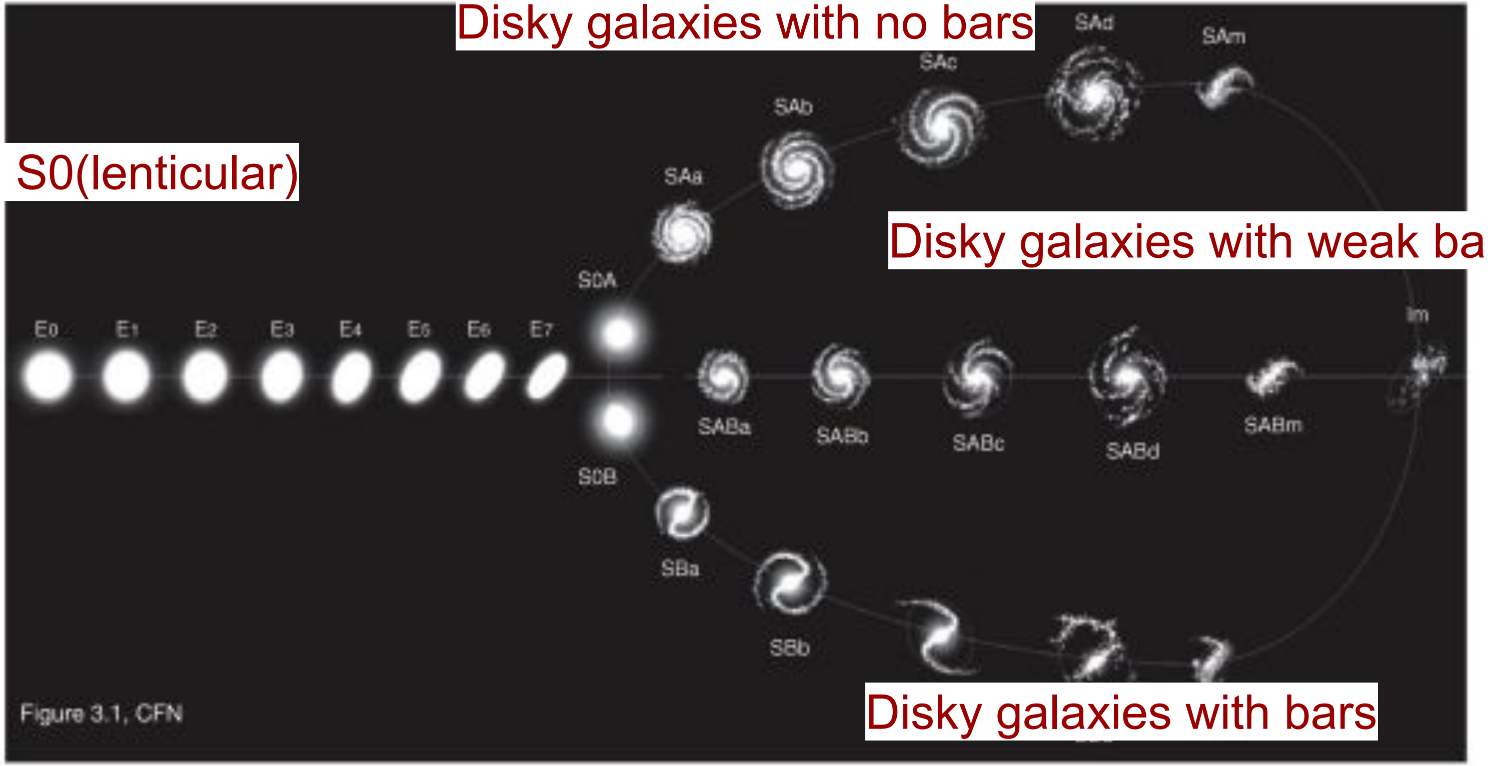
Galaxies Lec 4

Present-Day Galaxies:

Ellipticals + S0(lenticular)

Disky galaxies with no bars

Disky galaxies with weak bars



Disky galaxies with bars

Left -> right disk/bulge ratio get smaller (based on lumin.)

Ellipticals + S0 are called early type galaxies. If evolves it goes from spirals to then ellipticals and hence they are formed pretty late but they are old still.

Surface Brightness

The galaxy light profile is typically characterized by a Sersic profile.

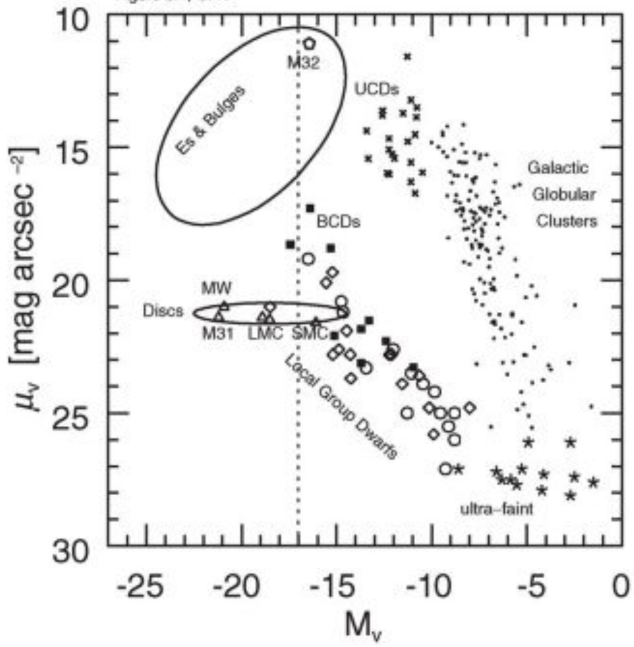
$$I_\lambda(R) = I_{\lambda,e} \exp\left\{-b(n)\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right\},$$

Here $I_{\lambda,e}$ is the surface brightness at a given wavelength λ at effective radius R_e

n = **Sersic index**

b(n) = 2n - 1/3 + 4/(405n)

Figure 3.4, CFN

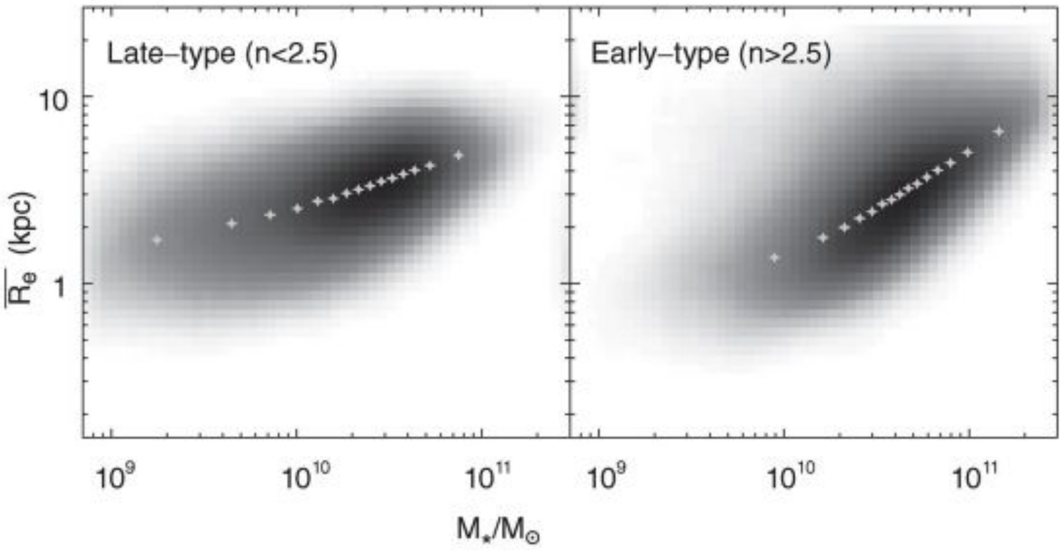


Sersic index: steepness of curve ~ low means disky and flat, while high means bulgy and sharp

Central surface brightness is not random; it segregates "Early Type" morphology (Ellipticals/Bulges) from "Late Type" disks and dwarfs. Early types approach a "maximum" stellar density limit that disks never reach.

Size

Figure 3.5, CFN



Spirals etc

Ellipticals/S0

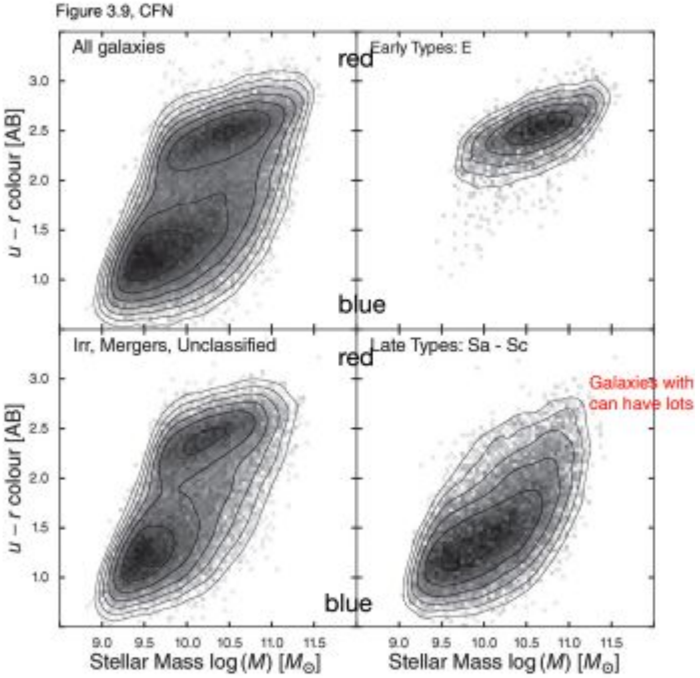
Steeper trend in radius and mass in ellipticals =>

Early types grow by mergers. The energy of the collision can puff up the outer layers, making the resulting galaxy physically large relative to the mass it gained.

Spirals are more regulated.

Colour

Ellipticals/S0



Spirals etc

Quenching. Disky are forming stars and are blue while ellipticals are quenched, red and dead.

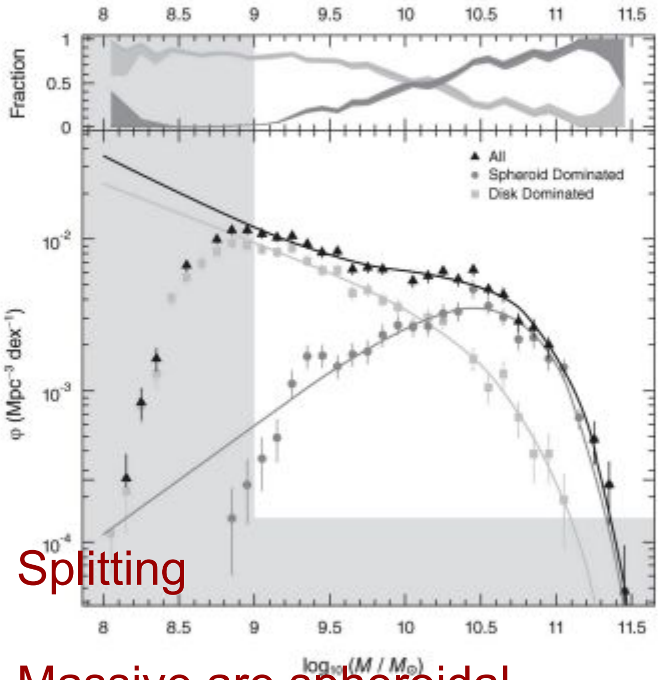
Very little stars that are green (green valley) meaning the process is very abrupt going from star forming to quenched.

Galaxy Luminosity Function

$$\Phi(L)\mathrm{d}L = \Phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \mathrm{d}\left(\frac{L}{L^*}\right),$$

ϕ^* is characteristic density
L^* is characteristic luminosity
α is the faint-end slope

Figure 3.11, CFN



Splitting

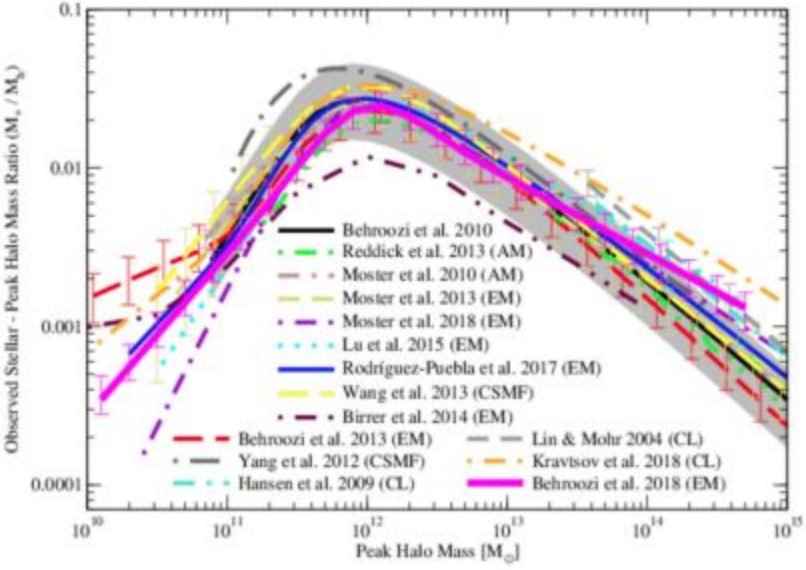
Massive are spheroidal while the disk are low mass dominating split

This **Schechter Function** tells us there is a physical limit to how big galaxies can get. Something prevents galaxies from growing infinitely large, causing that exponential drop-off at the high-mass end (often attributed to AGN feedback preventing gas cooling).

Stellar-to-Halo Mass Relation

Behroozi+2018

Stellar mass to halo mass



Halo mass

For a dark matter halo of a certain size, how efficient is it at forming stars?

This specific mass is the "sweet spot" for galaxy formation. Halos of this size are the most efficient at turning gas into stars.

Left side drops due to shallow pot wells

Right side drops due to shock heating accretion > gas sound speed converting bulk motion to thermal quench star formation

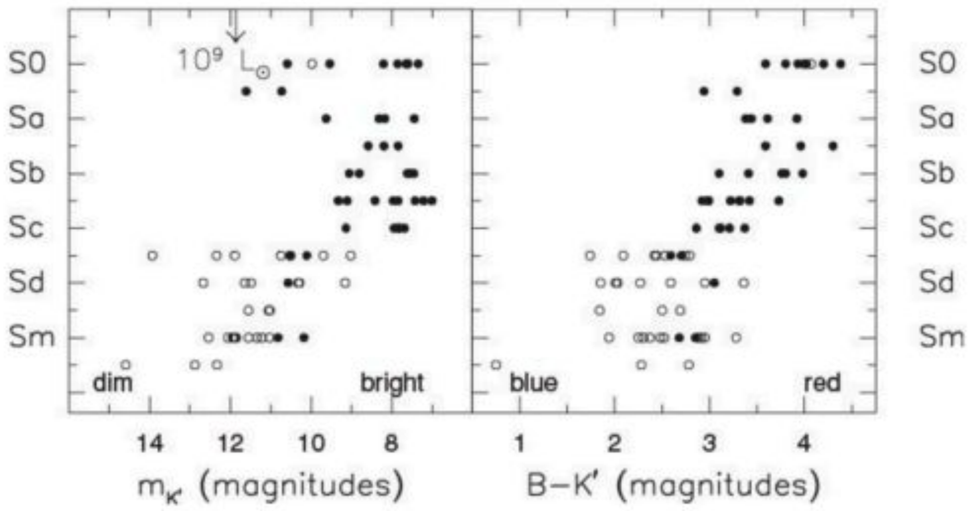
Galaxies Lec 4.1

Disky- Star Forming Galaxies

Stars

Sparke & Gallagher Figure 5.6

Galaxy types



Late

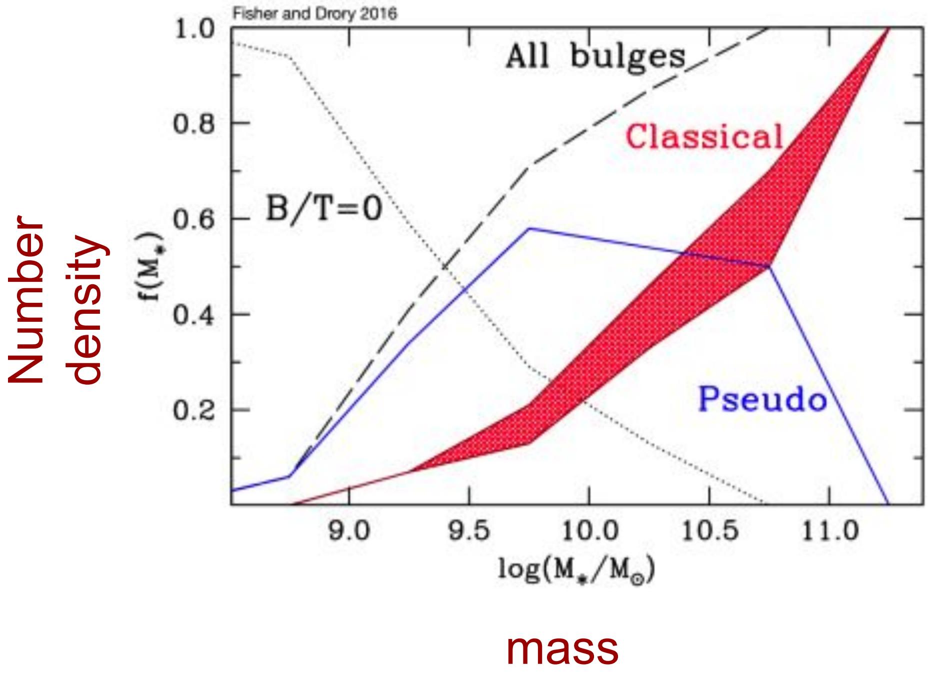
Early

More red the more you move to the redder

Apparent mag
(but distance all the same so tracks lum)

K-band tracks mass
(infared - old,
low-mass stars)

Right side drops due to shock heating accretion > gas sound speed converting bulk motion to thermal quench star formation

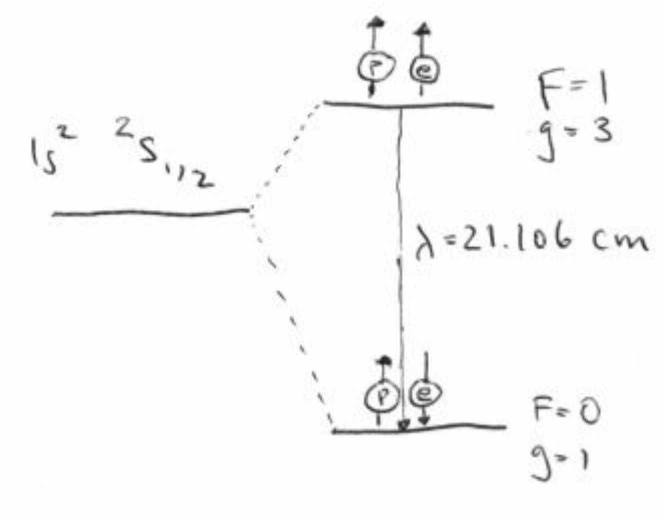


if you are small, you likely won't form one (staying a pure disk).

If you are medium, you likely grow one slowly from your own disk (Pseudobulge).

If you are huge, you likely formed one violently through mergers long ago (Classical Bulge).

Gas



We want to weigh the mass of the gas. How?

Most of the mass in the Interstellar Medium (ISM) is neutral hydrogen.

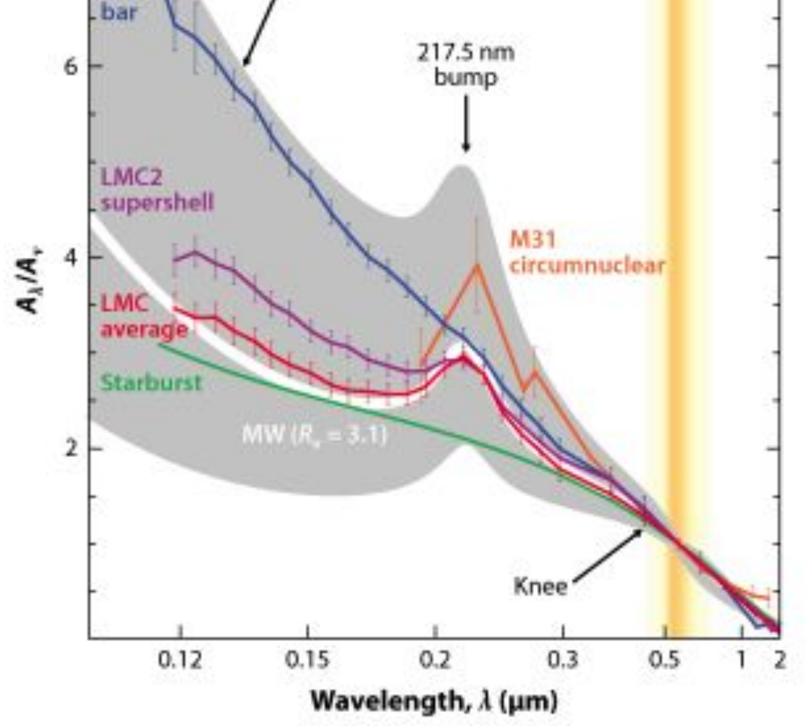
Measure 21cm
Total Flux (F_{HI}) - gives column density (assume optically thin)

Measure the distance
Get mass

$$\mathcal{M}_{\rm HI} \simeq 2.343 \times 10^5 (1+z)^{-1} \left(\frac{d_L}{1\,\rm Mpc}\right)^2 \left(\frac{F_{\rm HI}}{\rm Jy\,km\,s^{-1}}\right) \mathcal{M}_\odot,$$

z=redshift, d_L= luminosity distance
for our purposes, we can assume z=0

Dust - get SF



Dust extinction curve:

Find Twins: You identify two stars that have the exact same Spectral Type by looking a lines dust dims everything not abundance

The "Control" Star: Pick one star that is nearby and thus unreddened.

Compare difference in color or brightness in the "test" star is purely due to the dust extinction.

Blue Light is Blocked More. The "Bump" due to PAHs. Those are important because they are responsible for up to 50% of the heating in the neutral ISM. Without them, the gas in galaxies would be much colder. ~ done so by photoelectric knocking out electrons which then thermally heat up surrounding. Important because without heating sources, gravity would win too easily.

Table 9.5 Gas-Phase Abundances Relative to H of Selected Elements (ppm) in H I Regions

Element	Solar[a]	WIM $F_\star = -0.1$	WNM $F_\star = 0.1$	CNM $F_\star = 0.4$	Diffuse H_2 $F_\star = 0.8$
C[b]	295.	114.	111.	109.	93.
N	74.	62.	62.	62.	62.
O	537.	592.	534.	457.	372.
Na	2.04	(2.)	(2.)	(2.)	(2.)
Mg	43.7	28.1	17.8	8.9	3.6
Al	2.95	(0.54)	(0.27)	(0.097)	(0.025)
Si	35.5	31.6	18.7	8.5	3.0
S	14.5	14.5	14.5	11.8	5.3
Ca	2.14	(0.39)	(0.20)	(0.070)	(0.018)
Ti	0.089	0.013	0.0052	0.0013	0.0002
Fe	34.7	5.2	2.9	1.19	0.36
Ni	1.74	0.32	0.16	0.057	0.015
M^+ [c]	432.	197.	168.	142.	107.

[a] From Table 1.4.
[b] Gas-phase C abundance from Jenkins (2009) reduced by factor 2 (see text).
[c] Photoionizable "metals": $M = C + Na + Mg + Si + S + Fe + 3.9 \times Ni$.

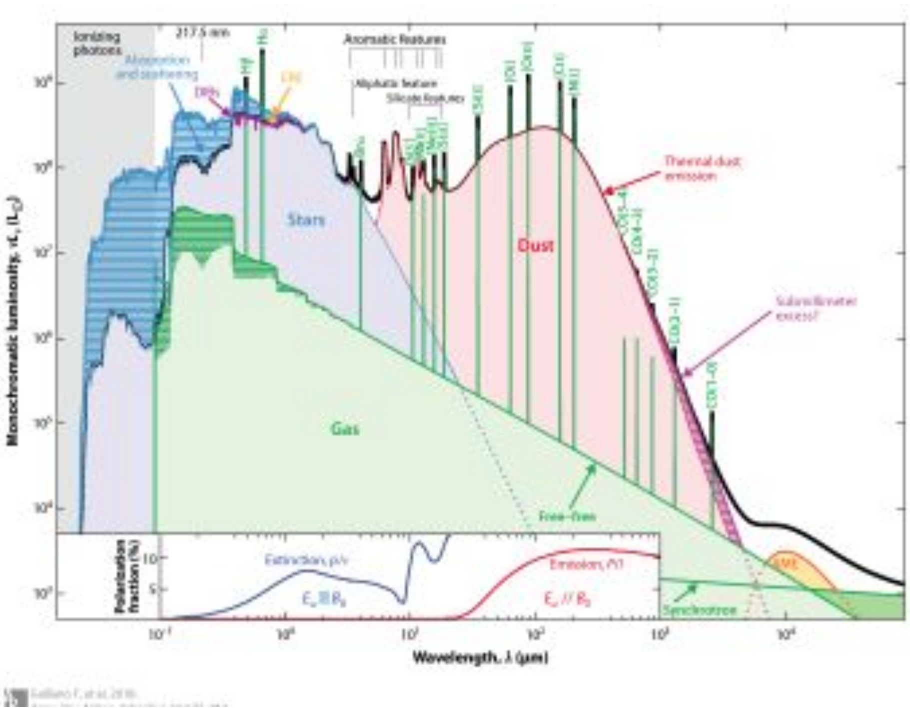
Table 9.5, Draine

How to determine what dust is made of.

If an element is abundant in the Sun but missing from the gas, it must be locked up in solid dust grains!

As the gas gets colder and denser (CNM), more atoms "freeze out" of the gas and stick to the dust grains. It is just like water vapor condensing into dew on a cold morning—the gas phase loses atoms to the solid phase.

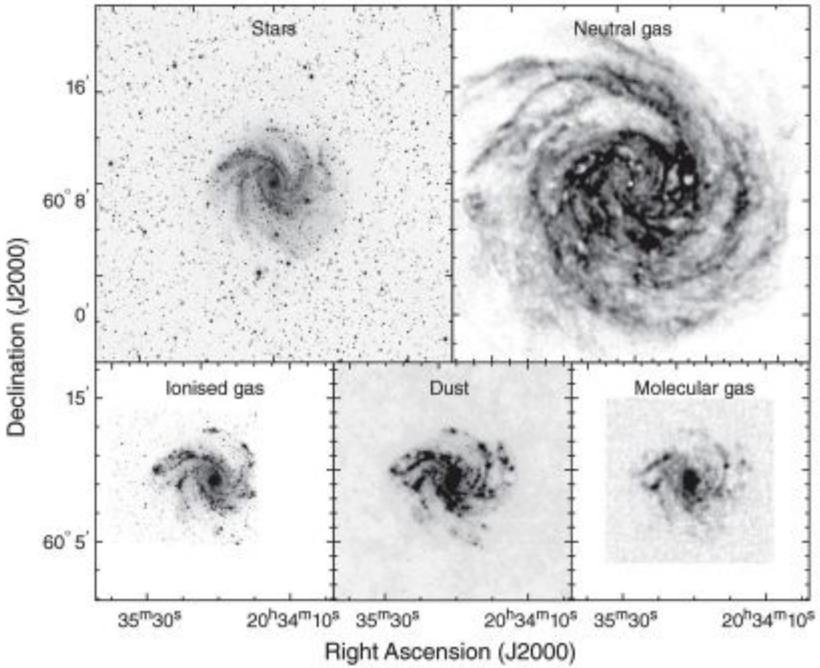
Dust extinction curve depends on the dust SIZE. Processes that change dust sizes are **sputtering** (high speed collisions), **shattering**, **sublimation** and **astration** (consumption by newly-formed stars)



JWST PAH Tracing Star Formation: Since PAHs need UV light to get excited, and **UV light** comes from massive young stars, seeing these bright lines is a "smoking gun" for active star formation.

Bang for your Buck: while PAHs only make up ~3% of the total dust mass, they dominate the mid-IR spectrum. They are incredibly efficient at converting UV light into IR light, making them visible across the universe even when other dust features are too faint to see.

Molecular Hydrogen - Get SF

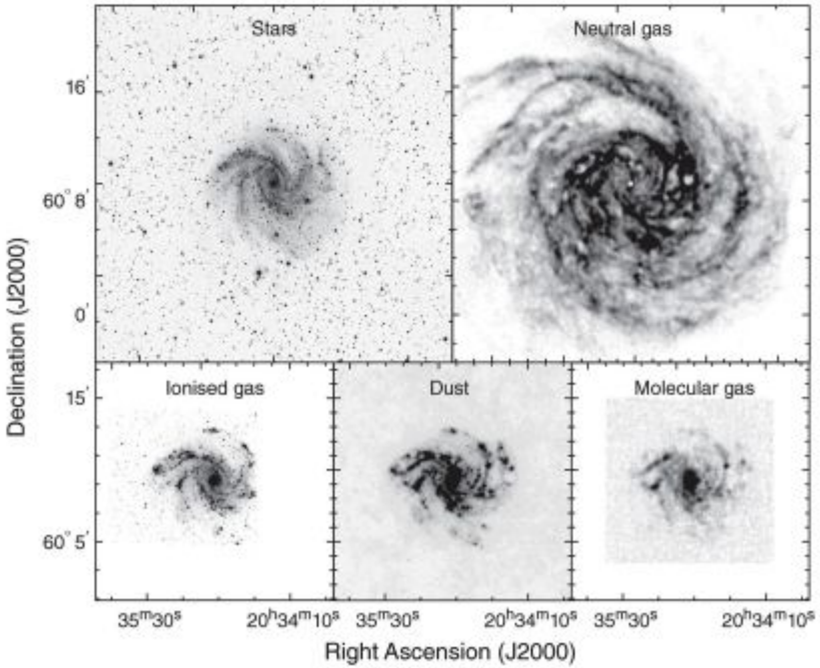


ALMA allows us to overlay these maps perfectly to see exactly where gas turns into stars pixel-by-pixel. By producing resolved H2 maps

Ionized Gas (Bottom Left): This traces hot, massive young stars (active star formation).

Molecular Gas (Bottom Right): This traces the cold, dense fuel.

They look nearly identical. This proves that star formation requires high-density cold molecular gas. You don't just need hydrogen (HI); you need it to be crushed into dense molecular clouds (H_2) to collapse into stars.

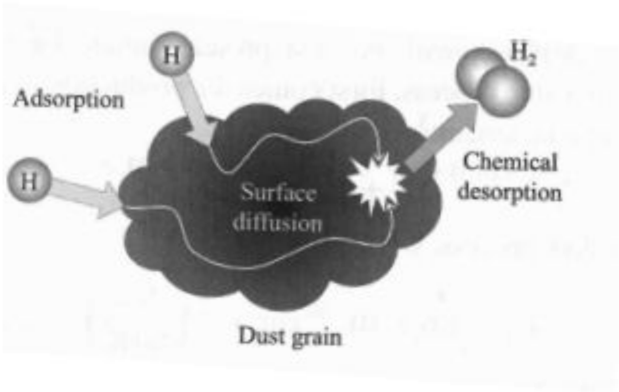


Note we don't actually look at H2 since they dont have dipole. We measure instead **CO** rotational transition lines and relate a ratio on CO/H connection to get the mappings.

$$X_{CO} \equiv \left(\frac{N_{H_2}}{\mathrm{cm}^{-2}}\right)\left(\frac{\int T_b(v)\mathrm{d}v}{\mathrm{K\,km\,s^{-1}}}\right)^{-1} \approx 2 \times 10^{20},$$

for example, can be derived assuming clouds are in virial equilibrium to get total mass

challenge: usually only derived for Milky Way. work underway to measure for more galaxies



Molecular hydrogen forms on dust grains. Cannot form in empty space because after reaction they have too much energy and no way to get rid of it and end up disassociating

However, the survivability of the newly formed H2 depends sensitively on density. If they are not dense enough not enough self shielding will prevent the UV from breaking it apart which is produced by the newly formed stars.

Mass of the molecular clouds can be estimated from CO to get number densities and then getting mass after connecting with the hydrogen

In Class Problem — Dust Growth

- 1. Consider a simple model of dust grain growth via collisions. Assume a grain of element X has number density n_X, mass m_X, radius a, and rms thermal velocity v_x. The probability that a grain collision leads to sticking is given by p_x. The mass density of the grains is ρ_{gr}.
  - (a) write an equation for mass growth of grains dMg/dt.
  - (b) derive an equation for da/dt in terms of n_X, v_x, ρ_{gr}, m_X, p_x.
    - Note: for CNM properties and assuming p=1, we get

$$\frac{da}{dt} \approx 0.3\,\mu m\ Gyr^{-1} \left(\frac{n_C/n_H}{2.7 \times 10^{-4}} \right)$$

      - So you can get grains in ~Gyr timescales in CNM, but growth is much faster in AGB atmospheres!
  - (c) A typical mass loss rate for an AGB stars is 10^{-6} $M_\odot$/yr. How much dust will this deliver to the ISM in its ~10^6 yr lifetime? You may assume the galaxy has a similar metallicity as the Milky Way.

Star Formation Rate indicators

Aside: other star formation rate indicators?

1. **UV continuum (with dust correction)**

Far-UV continuum (at ~1500 Å) is powered primarily by O and B stars. Measurement of UV luminosity density can be linked to a star formation rate (using stellar population synthesis models, assuming IMF, metallicity, star formation history), provided you correct for effects of dust attenuation! This in turns relies on knowledge of how much attenuation is present in the galaxy.

$$\mathrm{SFR}\ (M_\odot\ yr^{-1}) = 1.4 \times 10^{-28}\ L_\nu\ (\mathrm{ergs\ s^{-1}\ Hz^{-1}}).$$

(from Kennicutt 1999, updated conversions available!)

Important: UV continuum is sensitive to star formation over 100 Myr previous to observation (since also sensitive to B stars), whereas Hα sensitive to star formation in previous 10 Myr.

2. **FIR (dust) continuum emission**

The dust continuum emission is reprocessed light from young stars!

For dusty starburst galaxies, essentially all UV light is obscured by dust, the integral of the dust thermal emission (LIR) gives the total UV luminosity — in turn can be converted to an SFR using stellar population models.

$$\mathrm{SFR}\ (M_\odot\ yr^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s^{-1}}) \quad (starbursts),$$

Kennicutt 1999

More **modern methods** use energy balance, simultaneously fitting the UV emission (unobscured star formation) and FIR emission from dust (obscured star formation) with stellar population models (i.e., CIGALE, MAGPHYS) to get the total SFR of a galaxy.

3. **Radio continuum emission**

Free-free emission (HII regions) + synchrotron (cosmic rays accelerated by supernovae) — can be calibrated to give SFR.

Densities

To get densities of measuring ratios of forbidden lines. Where collisional de-excitation and spontaneous emission are balanced. The two lines come from two slightly different energy states and their intensity ratios tells us about the density.

We need to measure these things so that we can count the atoms. And measure **metallicity**.

Helps link O abundance to H abundance.

Temprature

To get a temperature we can get the ratios of the nebular lines. Or the cut off at xray from free free emission.

Mass Profiles

Goal: find the **stellar mass-to-light ratio** appropriate for the galaxy, then multiple by the observed luminosity to get **total MASS**

Do multiple Stellar Pop synthesis and which model SED shape best reproduces observed galaxy spectrum (or colors).

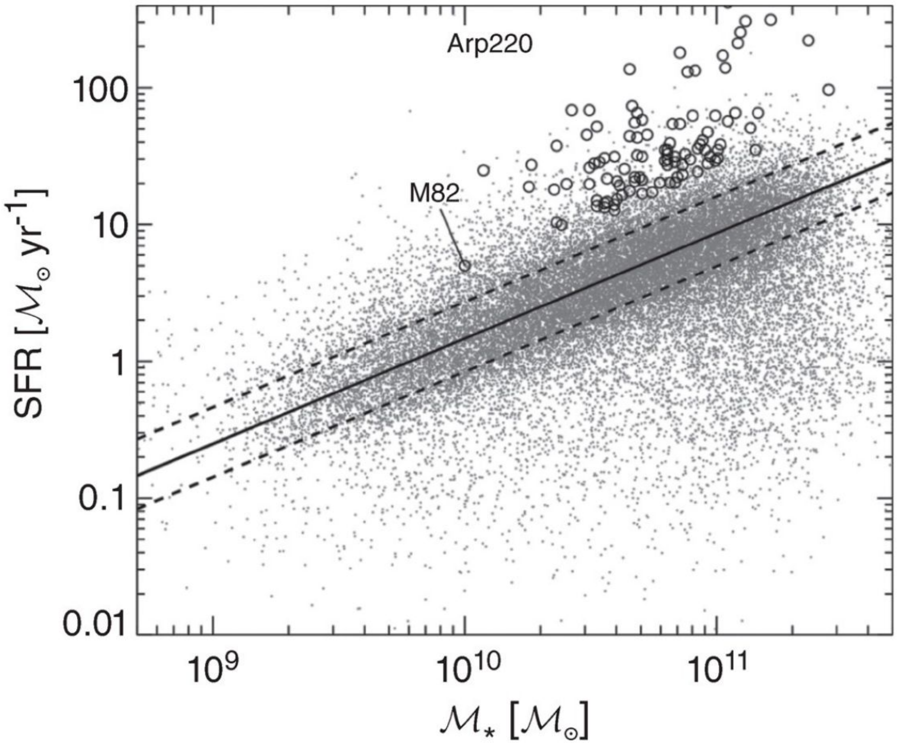
This identified the demographics of the stars in that galaxy.

We know the luminosity of those stars and we now also know their mass from the models and thus derive a mass-to-light ratio.

Mass Profile: obtained via rotation curves. Rotation curves can be measured via H1 21cm lines? Since it is rotating we can just use Centrifugal Balance to get the profile. Only in Early types do we need jeans equations

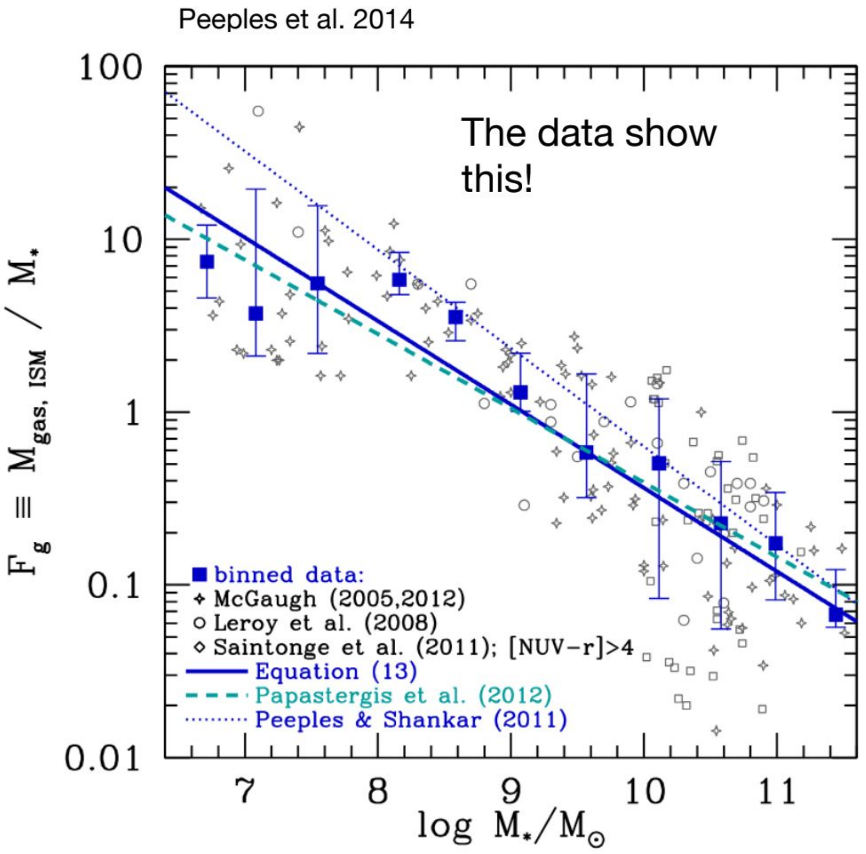
Scaling Relations

Adapted from Elbaz+2007



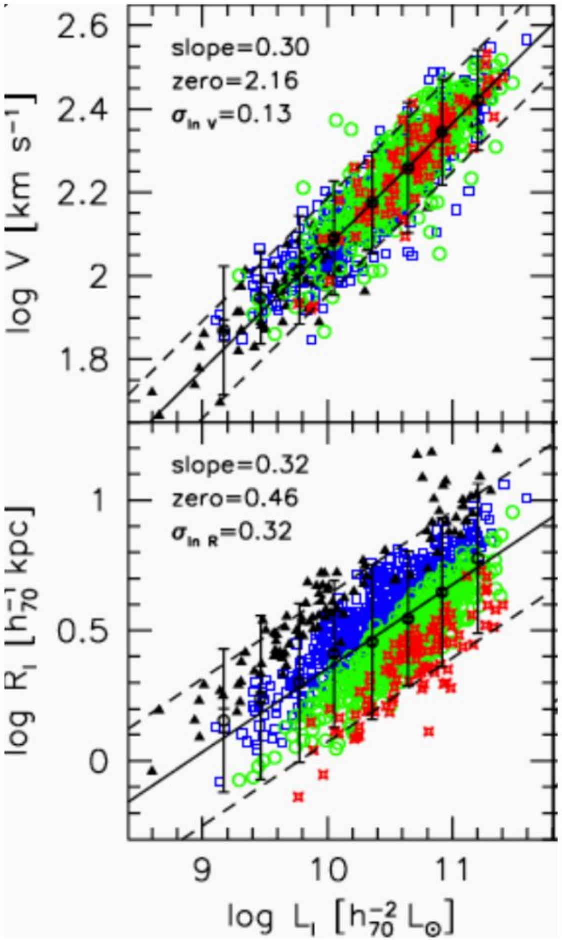
Plotting **mass** and **SFR** together gives us a trend

Tells us about Growth rates



Plotting **mass** and **Metallicity** together gives us a trend

Describes how leaky the system is in the leaky box model



Plotting luminosity and velocity gives us a trend

Tully-Fisher Relation

L = V^4

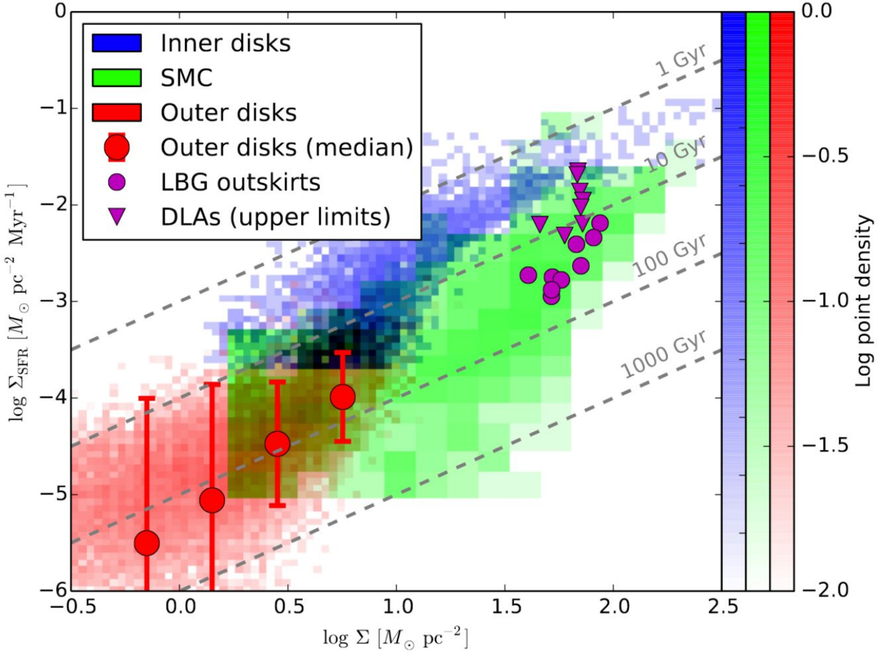
Can be used as candles

Can provide DM Halo connection

Tully-Fisher: Tells us the container size (Halo Mass).

Mass - SFR: Tells us how fast the container is filling up with stars (Growth Rate).

Mass-Metallicity: Tells us how "leaky" the container is (Outflows/Feedback).



Star formation density

Total Gas Density

Kennicutt-Schmidt Law ~

Gives a rule to describe the rate at which one turns into the other!

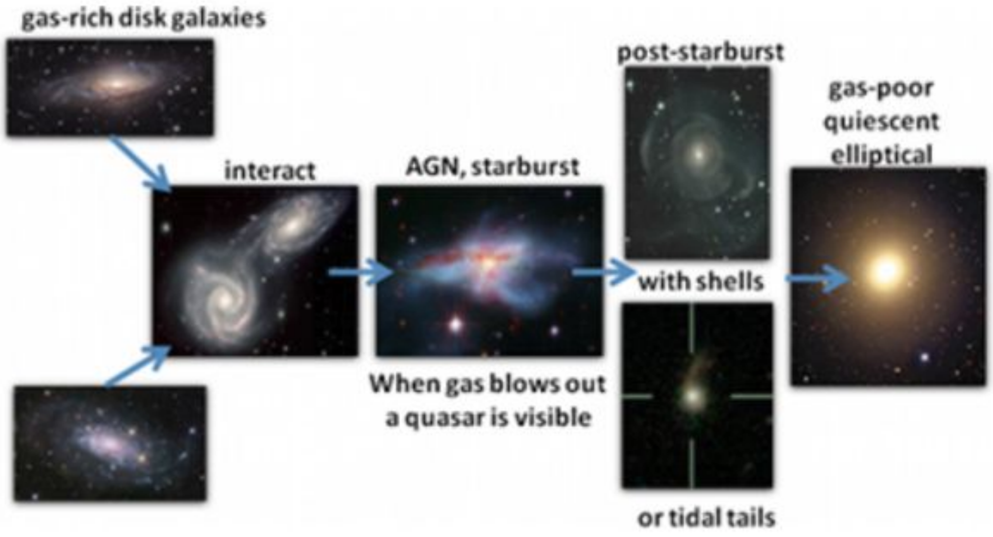
Gives us a depletion timescale

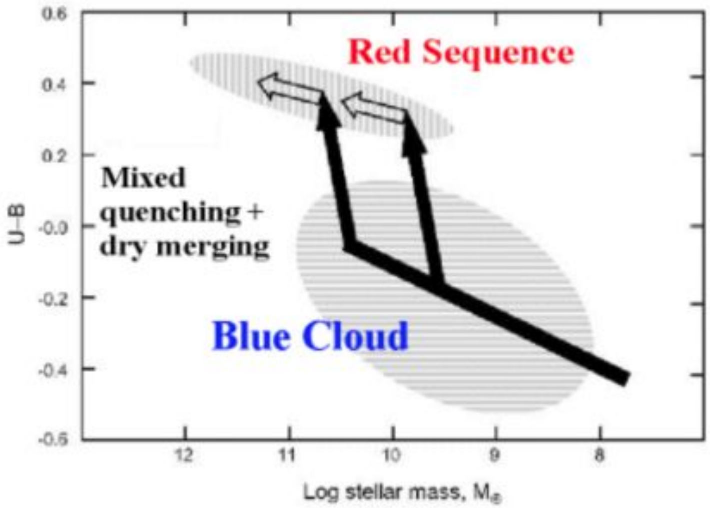
Star Formation

Galaxies Lec 4.1

Elliptical Galaxies

Formation

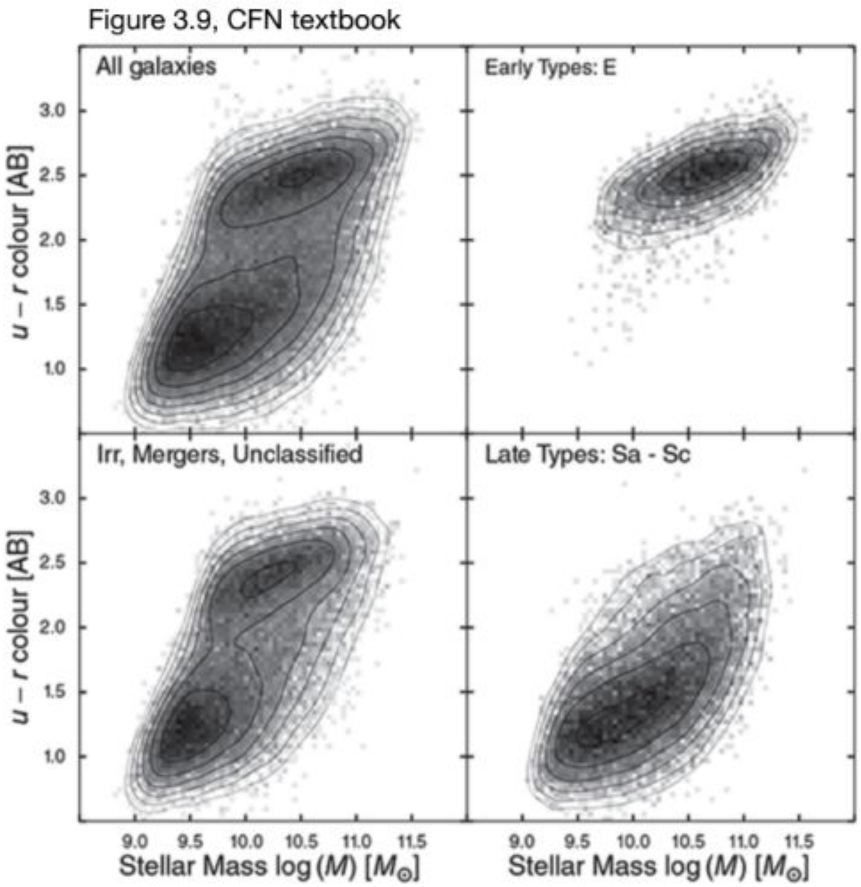




Starts off with lots of mergers and are WET mergers with lots of gas. Creates stars and becomes very blue

Then evolves on red sequence after quenching and merging dry

Formation



There is a sequence of early types being mostly red sequence and blue types being mostly disky

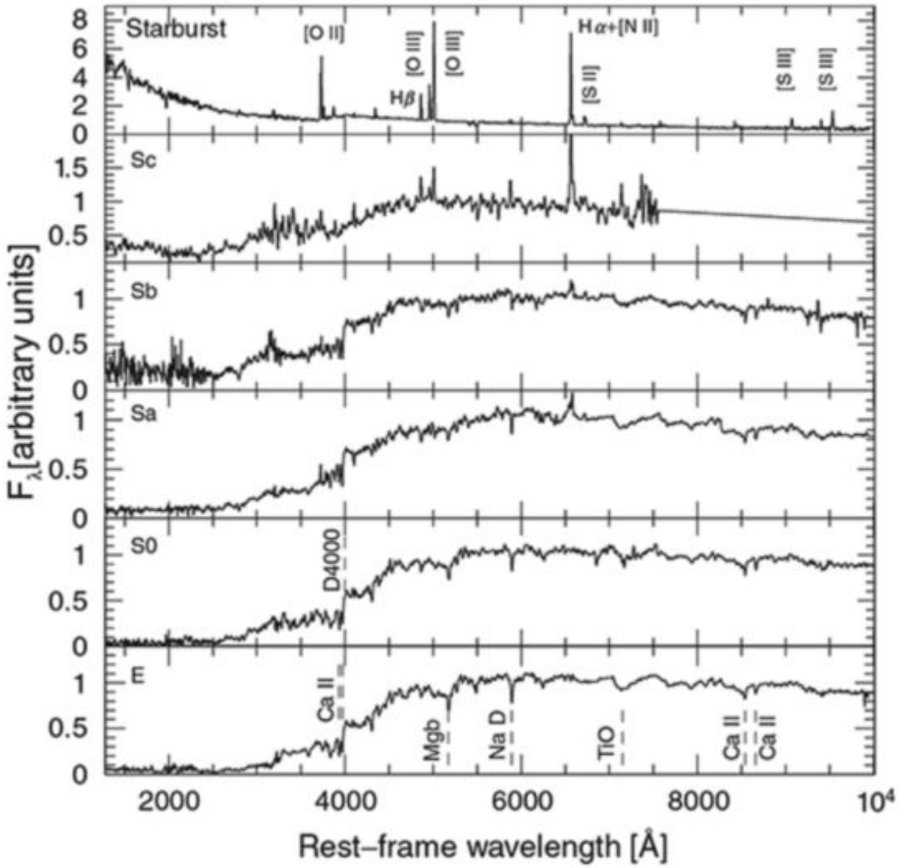
Spectra

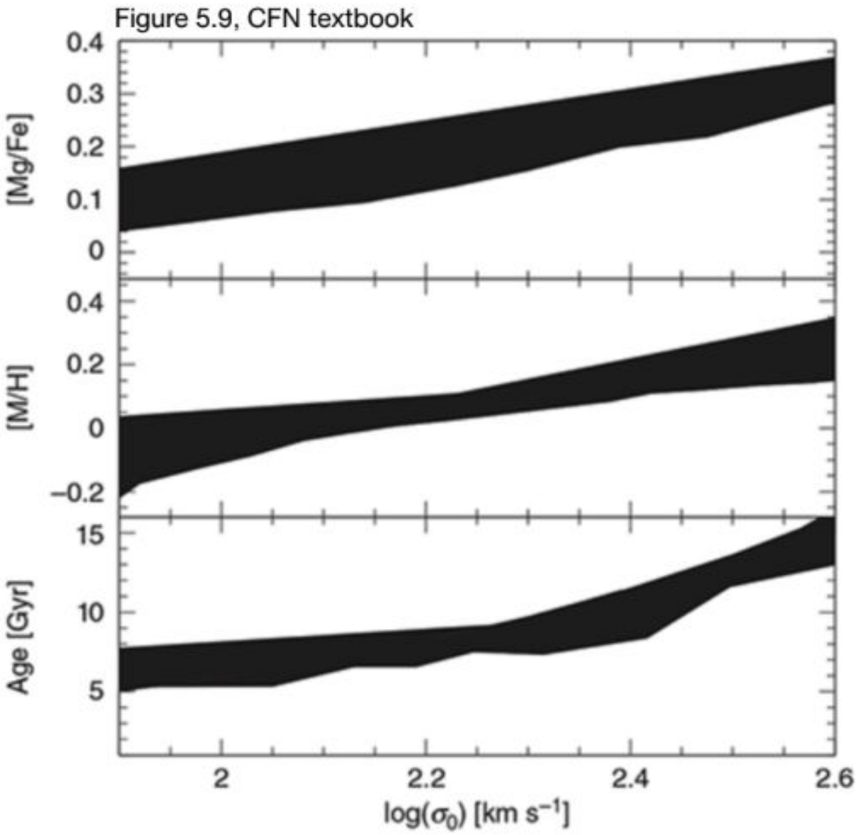
There is an important D4000 Break in their spectra

The Cause: sudden onset of absorption features in stellar types cooler than G0.

Indicates age and that they have evolved populations since no younger stars

Figure 3.7, CFN textbook





We see increased alpha enhancement the older the ones are!

This effect is called **downsizing**: most **massive** ETGs seem to form their stars first and **fastest**.

UV Upturn: We sometimes see in spectra that they have upturns in UV but its due to AGB Stars rather than younger ones!

More velo disp -> more mass

Photometry

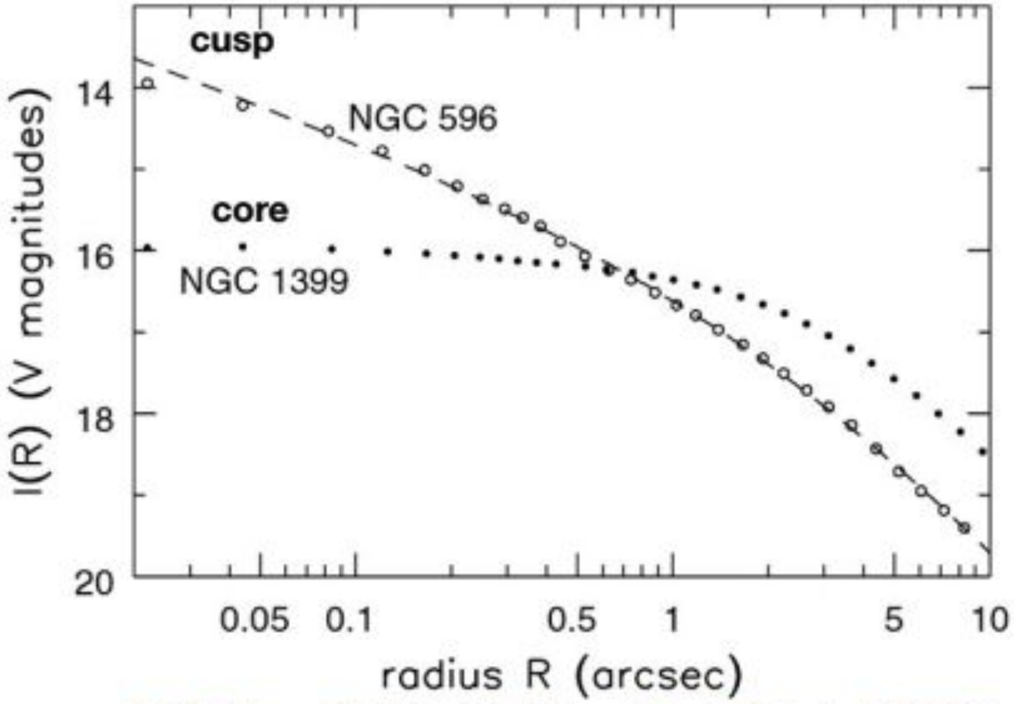
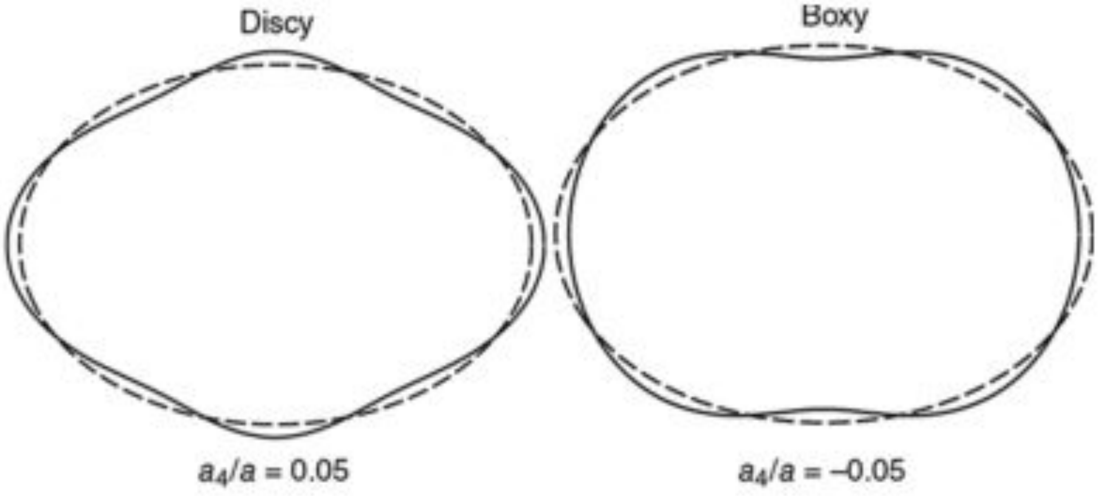


Fig 6.7 (T. Lauer) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

We see that

Midsize - cusp
Most luminous - cored

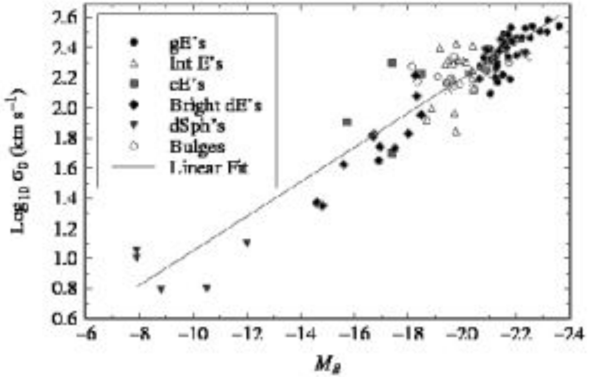
Boxy is supported by more random motions



UV Upturn: We sometimes see in spectra that they have upturns in UV but its due to AGB Stars rather than younger ones!

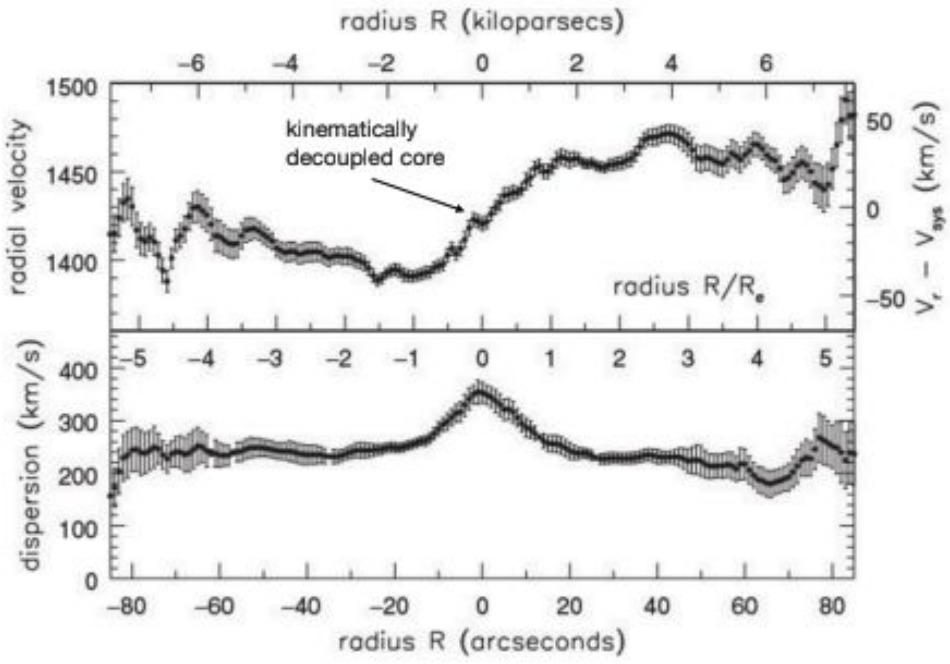
Disky often have significant rotation

Kinematics



$$\frac{L_V}{2\times10^{10}L_\odot}\approx\left(\frac{\sigma}{200\,\mathrm{km\,s^{-1}}}\right)^4.$$

Faber-Jackson relation: larger size the more random the spread!

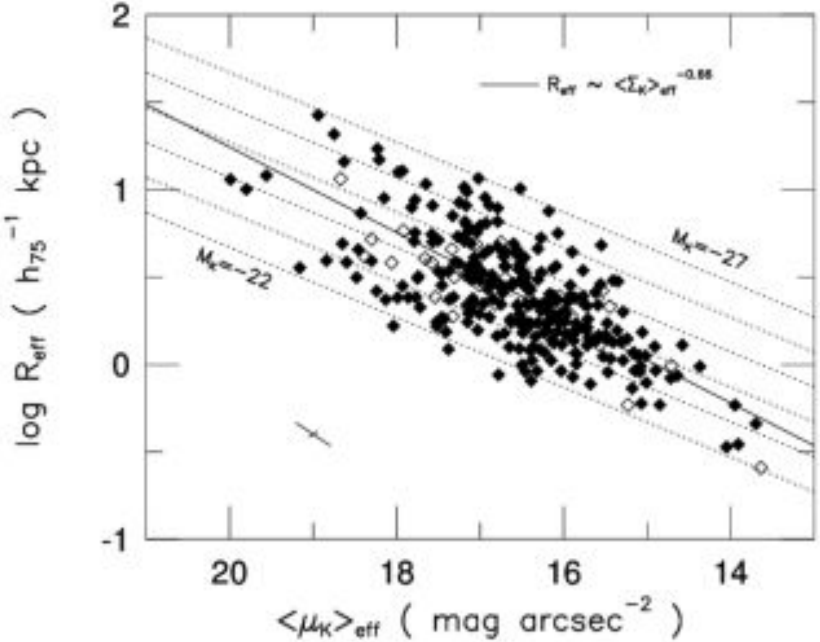


kinematically decoupled cores: inner few arcseconds rotate in opposite direction as the outer part of the galaxy! => **violent relaxation**

Violent relaxation is

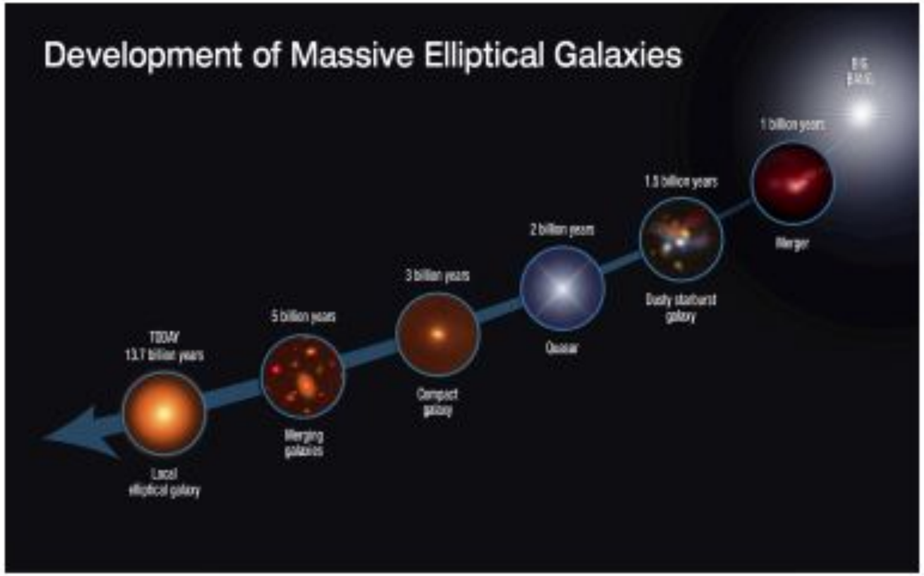
There are still disky isophotes indicating that they have not finished rotating.

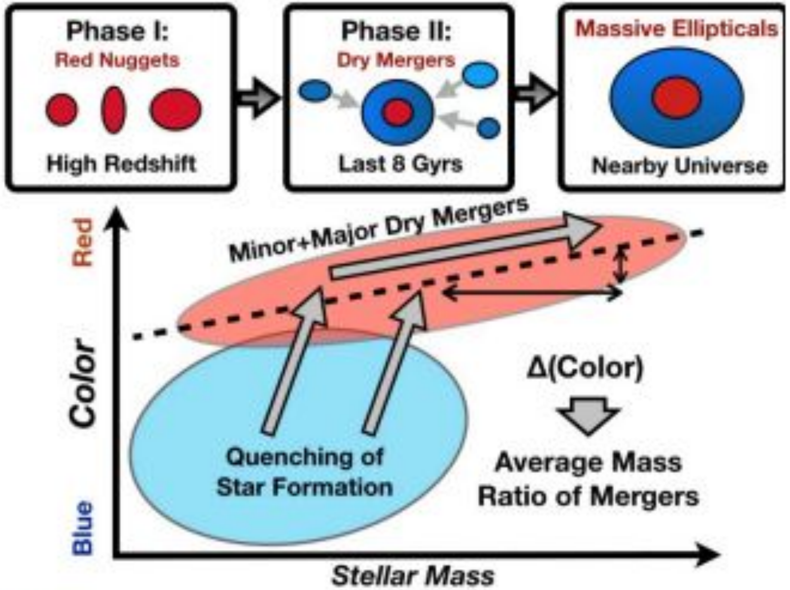
Scalings



- **Color - luminosity relation:** Luminous ellipticals are redder.
    - The luminous systems are older, with bulk of stars >10 Gyr.
- **Faber Jackson Relation:** the luminosity and velocity dispersion of ellipticals are related as $L \propto \sigma^4$.
- **Kormendy Relation:** the effective radius and effective surface brightness (i.e. average within R_e) of ellipticals are related as $R \propto \langle I_e \rangle^{-0.83}$
    - i.e. larger ellipticals are less dense.

Mergers





Major merger = merger between two galaxies of comparable mass.

- Gas-rich (dissipational) major mergers produce a central starburst. Star formation quenched — perhaps by AGN?
- Galaxy transitions from blue cloud to red sequence, forming compact elliptical (“red nugget”).
- Stellar kinematics and light profile similar to midsize ellipticals: high v/σ, central core, disky isophotes.
- Further evolution comes from dry (dissipationless) mergers. Size and mass increase, v/σ decreases, isophotes become boxy. End result is a massive elliptical galaxy at $z \sim 0$.

Getting Mass profile

Mass of Hot diffuse Gas

Step 1: Get temperature from free-free xray emission where it has a cuttof that has a temperature dependence

Step 2: get the plasma density from the emission and can be converted to gas density

Step 3: integrate to get mass

Hot diffuse gas dominate normal mass! And thus traces dark matter more than others

1. Virial theorem

→for best estimates, use tensor virial theorem (see below) including both rotation and random motions in KE tensor.

$$\frac{1}{2}\frac{d^2 I_{ij}}{dt^2} = 2K_{ij} + W_{ij}.$$

for order of magnitude estimate in luminous ellipticals, can use scalar virial theorem assuming $\sigma \gg v_{max}$

2. Dynamical modeling

→can use Jeans equations to get mass profile using tracer population (below spherical symmetry assumed, but can consider more complicated geometries)

$$\frac{d}{dr}(n_* \sigma_{rr}^2) + 2\beta \frac{n_* \sigma_{rr}^2}{r} = -n_* \frac{d\Phi}{dr}.$$

results depend on β, velocity anisotropy parameter (given known mass anisotropy degeneracy, discussed earlier in semester)

3. X-Ray gas

→assuming hydrostatic equilibrium, calculate total mass required to keep hot gas bound.

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\rho(r)\frac{G\mathcal{M}(<r)}{r^2}.$$

where

$$p = \frac{\rho}{\mu m_{\mathrm{p}}} k_{\mathrm{B}} T$$

4. Gravitational Lensing!

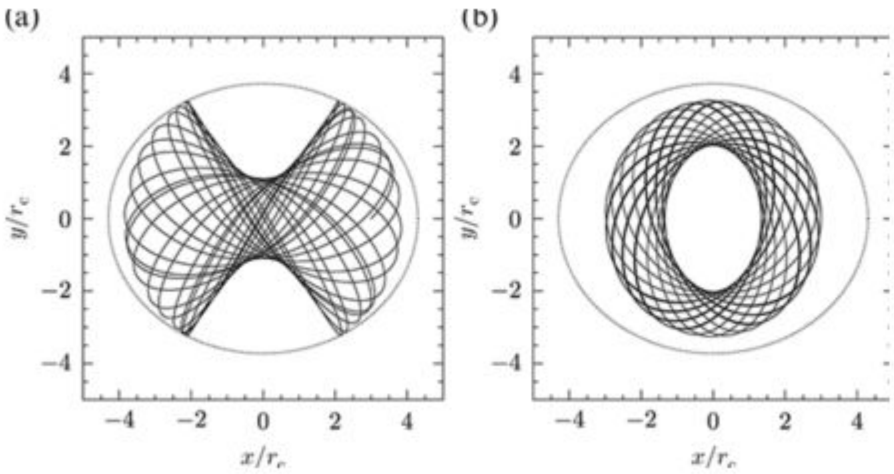
We can re-arrange to solve for the mass profile.

$$\mathcal{M}(<r) = \frac{k_{\mathrm{B}}}{\mu m_{\mathrm{p}}} \frac{r^2}{G\rho(r)} \frac{\mathrm{d}}{\mathrm{d}r}(-\rho T).$$

X-ray observations can provide constraints on the density and temperature gradient of hot gas, so we get total mass profile!

Box Orbits vs Tube Orbits

Boxy - random



Tube - it rotates fast

Secular and delivers mass to the central black hole and fuels the AGN

Star forming -> Ellipticals

Cluster	Groups
Larger ~ 1000	Smaller ~ 10-100
Early types	SF galaxies

Measure the masses

- **Virial theorem** for a rough estimate of the total mass, use radial velocity dispersion of member galaxies, assuming group is in steady state.

$$\frac{3\mathcal{M}\sigma_r^2}{2} = \mathcal{KE} = -\frac{\mathcal{PE}}{2} = \frac{3\pi}{64}\frac{G\mathcal{M}^2}{a_P},$$

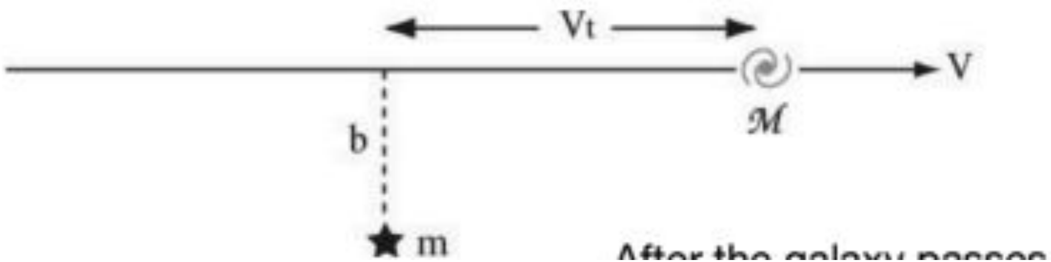
assume density profile described by Plummer sphere

- **X-rays+hydrostatic equilibrium.**

As with ETGs, find gravitational mass required to keep the hot gas bound. Observations of temperature and density gradient give mass profile.

$$\mathcal{M}(<r) = \frac{k_B}{\mu m_p}\frac{r^2}{G\rho(r)}\frac{d}{dr}(-\rho T).$$

Use SZ effects to measure the temperature and get the mass from the emission!



$$\Delta V_{\perp} = \frac{2Gm}{bV}$$

We call this deceleration **dynamical friction!** The motion of galaxy M is braked as it passes through a background of stars with density n.

→slower the velocity, more the dynamical friction.
→and larger mass objects lose the forward velocity faster.

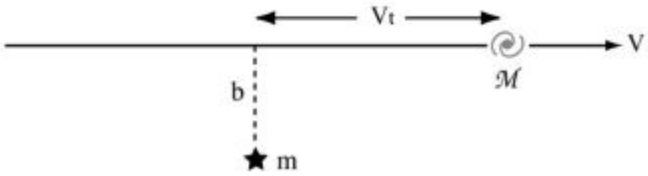
Dynamical friction is the "gravitational glue" that allows galaxies to merge.

Environmental Quenching

- **1. Galaxy Harassment**
  - Heating from high speed encounters.

- **2. Galactic Cannibalism**
  - Galaxies lose kinetic energy and angular momentum by dynamical friction.

$$-\frac{dV}{dt} = \frac{4\pi G^2(\mathcal{M}+m)}{V^2} nm \ln\Lambda$$



- **3. Ram Pressure Stripping**
  - Clusters have hot gas in the intracluster medium.
  - Galaxies will experience ram pressure as they traverse this extremely hot gas.
  - Can strip galaxy of its CGM, removing fuel for star formation ("**strangulation**").
  - Contributes to dearth of blue galaxies in central regions of clusters?