Galaxy Formation Part 2

Few-sentence summary of where we were last time — baryons feel pressure but they can radiate, so they behave differently from DM as both try to collapse. As baryons fall into grav. potential wells supersonically they are shock heated — ironically, this unlocks various cooling mechanisms (more on this today!) that allow the baryonic gas clouds to eventually collapse to much more compact configurations than the DM.

Let's now talk about the qualitative history of what's going on:

⇒ $\boxed{\text{Return to Qualitative Story from last set of notes}}$

This is a nice story, but before we get into more of the qualitative details I want to mention some of the observables used to test models of galaxy formation.

A couple of key observables.

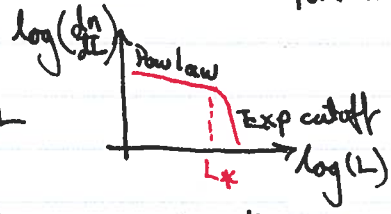
(1) Luminosity Functions.

This is a probability distribution function that quantifies how many galaxies exist in different luminosity bins, ie it's essentially a histogram of galaxy luminosities.

⇒ $\boxed{\text{Show SDSS luminosity function}}$ ← Note: need to correct for selection effects ∵ we are talking intrinsic luminosities (eg dust corrections important).

Well-fit by Schechter Function:

$$\phi(L)\,dL \equiv \underbrace{\frac{dn}{dL}}_{\text{\# of galaxies/volume between } L \text{ and } L+dL} dL = \left(\frac{\phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} e^{-(L/L^*)}\,dL$$



$\alpha \simeq -1.3$ @ $z=0$ "faint end slope"

$L^* \sim 10^{10} L_\odot$

Trying to constrain (observationally) this function at high redshifts is a huge industry these days!

$\Rightarrow$ $\boxed{\text{Show high-z UVLF}}$

Notes: - In UV!
- Plotting magnitudes.
- Data gets sparse!

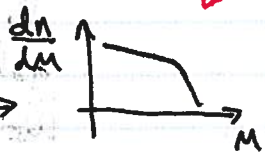
Why do people care about this? Notice that the faint end slope evolves with redshift. Even though the faint end is where all the faint galaxies are, they are very numerous, so during reionization they contribute a ton of ionizing photons. Whether our story of reionization hangs together or not depends a lot on the details of the faint-end slope (which is the hardest bit to measure!)

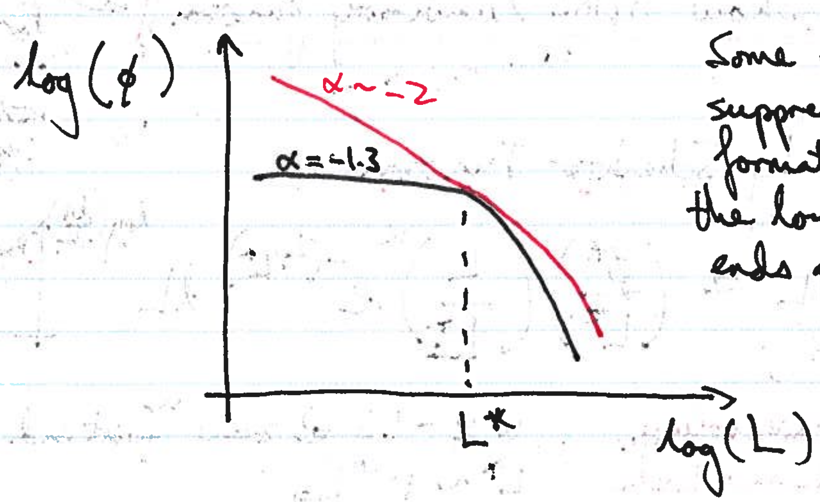
Even at lower redshifts the luminosity function is of a lot of interest in constructing galaxy formation models. So far, I have painted this picture where every ~~halo~~ DM halo has a gas cloud that eventually collapses and forms stars.

$\hookrightarrow$ If this is true, then the shape of the halo mass function should look like the luminosity function and I can translate one into the other.

Histogram of halo masses

Indeed, it looks qualitatively similar $\longrightarrow$ but in detail:





Some mechanisms for suppressing star formation @ both the lower and upper ends are needed!

(Preview: feedback!)

② Colour – luminosity diagrams

⇒ $\boxed{\text{Show colour vs. stellar mass}}$

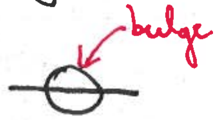
Interesting trends come up! People who do these sorts of galaxy observations find, for example, that from $z \sim 2$ to 0, the # of "red and dead" galaxies ~~decreases~~ increases, but the # of blue starforming galaxies goes down — something quenching star formation.

③ Scaling relations

Often we can study various properties in detail and to see if there are any correlations. One very famous example (among many!) is the "$M - \sigma$ relation"

Mass of supermassive BH.

velocity dispersion (ie r.m.s velocity) of stars in a bulge



A very tight correlation! ⇒ $\boxed{\text{Show } M\text{-}\sigma \text{ from Kormendy + Ho}}$

Why is it so tight? Sometimes people's knee-jerk reaction when they see this is that they say "isn't this obvious? The more massive the mass in the middle, the faster the orbits!" Careful! Even though the BH's mass is big, it is not the dominant contributor to the grav. potential.

So what happens? These big bulgy galaxies / ellipticals grew via mergers. ∴ which means I can think of more massive galaxies ⇒ having gone through more mergers. Even if the galaxy mass (related to σ) is initially uncorrelated with the BH mass, as I average a large # of mergers, the central limit theorem tightens up the correlation.

So it's not that the BH mass causes higher velocity dispersions. It's that there's a co-evolution.

This also tells us that our mental model of galaxy formation shouldn't just think of a one-time collapse of a gas cloud — we need to worry about accretion and mergers as well.

To summarize ~~out~~ our galaxy formation ingredients so far:

- Gravity $\rightarrow$ collapse, $\rightarrow$ accretion, $\rightarrow$ mergers
- Cooling
- Star formation
- Feedback.

We'll now examine these in a little more detail.

Cooling

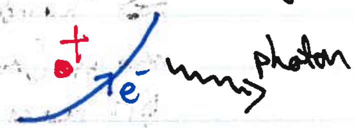
Let's work through a number of cooling mechanisms.

(1) Compton cooling

This is where e^-'s in a gas cloud can scatter off CMB photons, transferring energy to CMB photons via inverse Compton scattering.

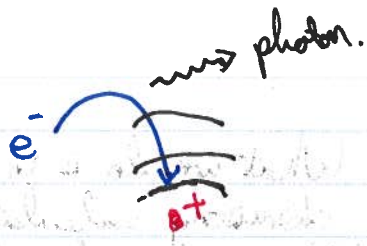
Unimportant except @ high redshifts ($z > 5$) $\therefore$ has a greater effect when universe was denser $\Rightarrow$ photon density higher.

(2) Free-free (bremsstrahlung)



Electrons + ions accelerate each other $\Rightarrow$ photon emitted. Most important when temperatures are high.

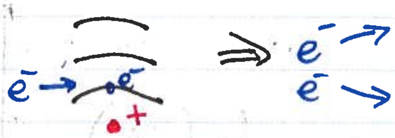
(3) Free - bound (recombination)



Electron falls back into atom ⇒ photon emitted that carries away energy

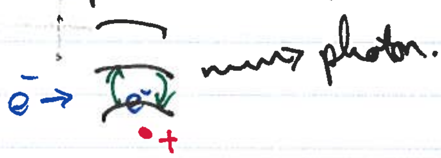
(4) Bound - free (collisional ionization)

Free Electron kicks a bound electron off.



(5) Bound - bound (collisional excitation)

Electron hits atom, excites electron in atom to higher energy level but doesn't ionize. When electron drops back down, emits photon that carries energy away



As you can imagine, taking all this into account is hard! We need to do thermodynamics + chemistry!

Fortunately, there is a neat way to parametrize all of this and essentially have someone else do the work for us.

Notice that all of these are two-body processes, so the rate of cooling must scale like n^2 ← $n \equiv$ number density of particles

This means we can write:

temperature

$$\boxed{\mathcal{E} \equiv n_H^2 \, \Lambda(T, Z)}$$

metallicity

(Some books/papers use a different ~~conditio~~ convention and call ~~use~~ the LHS Λ)

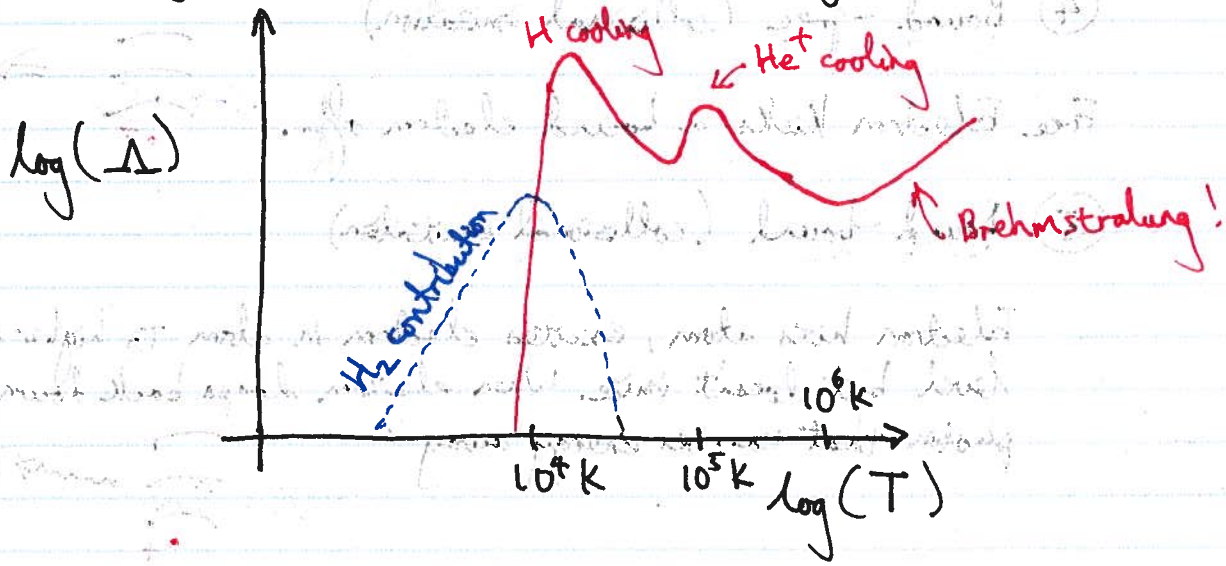
Cooling rate $\left[\frac{\text{energy}}{\text{time}}\right]$

$n_H \equiv$ # density of H

"Cooling function"

What we do is to essentially outsource all the complicated chemistry calculations to someone else and just ask them for the cooling fct.!

Generally looks like this for a primordial gas with H and He



Above 10^4 K, atomic line cooling via H becomes efficient. Below this, need molecules like H_2 — but the right conditions for this aren't always present! (Eg Lyman-Werner background from before).
At high temperatures, Bremsstralung: $n^2 V \propto n^2 T^{1/2}$.

When we have a metal-enriched gas there are even more channels for cooling $\Rightarrow$ Show cooling curve with metals

Important! Sorry it's so squished

Where we are going with this — remember that the temperature of a gas is determined by the shock heating as it falls into the grav. potential well and converts kinetic energy to ~~tee~~ thermal motions. But as a gas free falls into a well, $v \sim \sqrt{\frac{GM}{R}}$

$\Rightarrow$ $\cancel{\frac{1}{2}mv^2 \sim \frac{GM}{R}}$ $k_B T \sim \frac{1}{2} m v^2 \sim \frac{GM}{R}$ $\Rightarrow$ Different ~~galaxy~~ masses hit different parts of cooling curve and we can figure out whether they can cool and form a galaxy

Galaxy Formation Part 3

Where we are right now is we've decided that the cooling of baryons is a critical process as gas needs to lose energy to collapse and start forming stars.

We also saw that since most of the cooling processes require the interactions of two particles, we can write

$$\boxed{\mathcal{E} \equiv n_H^2 \, \Lambda(T, Z)}$$

Cooling rate

density of H

Cooling fct.

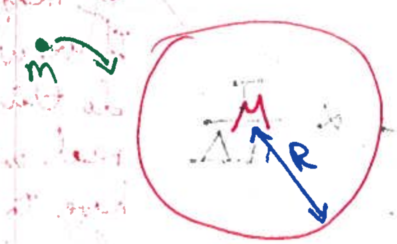
All of the subtle chemistry, stat. mech, etc. is encoded in the cooling fct. $\Rightarrow$ $\boxed{\text{Show example}}$

I say "might" because these analyses come with caveats! We'll mention some of them as we go along

Today we're going to sketch out how we can use this info to work out the masses of galaxies that might be able to form.

We see from the cooling function that the temperature is a key parameter. Let's remember what causes gas to heat up. Gas falls in from "infinity" and speeds up gaining kinetic energy. Then it shock heats and converts the bulk kinetic energy into thermal motions.

If I have a halo of mass M, then the velocity of the gas as it free-falls to radius R is



$$v \sim \sqrt{\frac{GM}{R}}$$

If this is converted into thermal motions, then

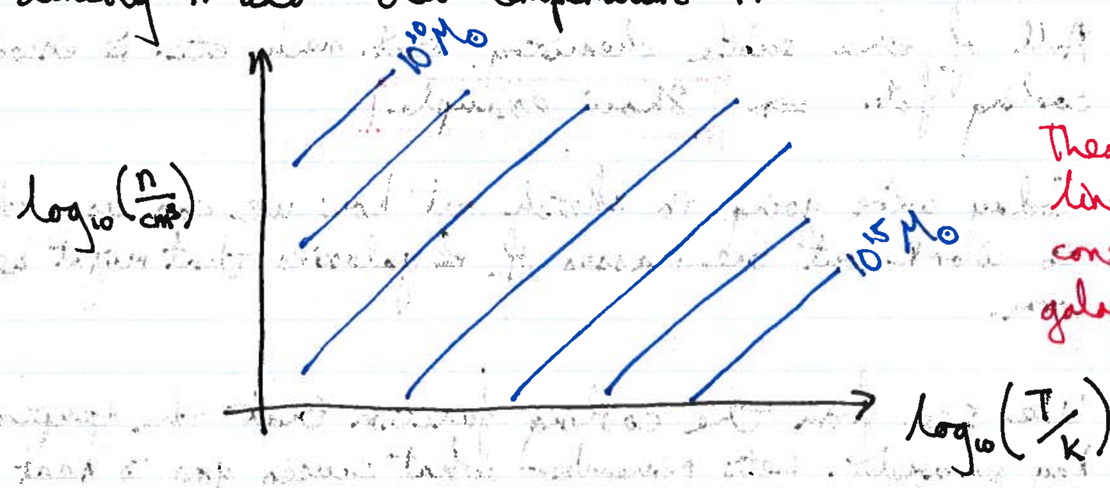
$$\frac{1}{2} m v^2 \sim k_B T. \quad \Rightarrow \quad M \propto R T$$

It turns out that what is more convenient is to express things in terms of the density rather than the radius (after all, the cooling ~~xxxx~~ rate depends on density).

So $\rho \sim \frac{M}{R^3} \Rightarrow R \propto \left(\frac{M}{n}\right)^{1/3}$ number density $n = \frac{\rho}{m}$

and $M \propto M^{1/3} n^{-1/3} T$ and $\boxed{M \sim T^{3/2} n^{-1/2}}$

What I'm going to do is to describe galaxies based on their density n and their temperature T.



These are lines of constant galaxy mass.

Now, what we could do is to go to every point on this plane, read off n and T, and plug it into our formula for the cooling rate. But we'd just get some number without context.

Define the cooling timescale t_{cool} as

$$t_{cool} \sim \frac{\text{Thermal energy}}{\text{Cooling rate}} \sim \frac{n k_B T}{n^2 \Lambda} \propto \frac{T}{n\Lambda}$$

This is just order of magnitude! If we wanted to do this for real we'd have to solve a differential eqn.

To figure out if a gas cloud's ~~cool~~ cooling time, we should compare this to the free fall time t_{ff}. On your problem set you showed that:

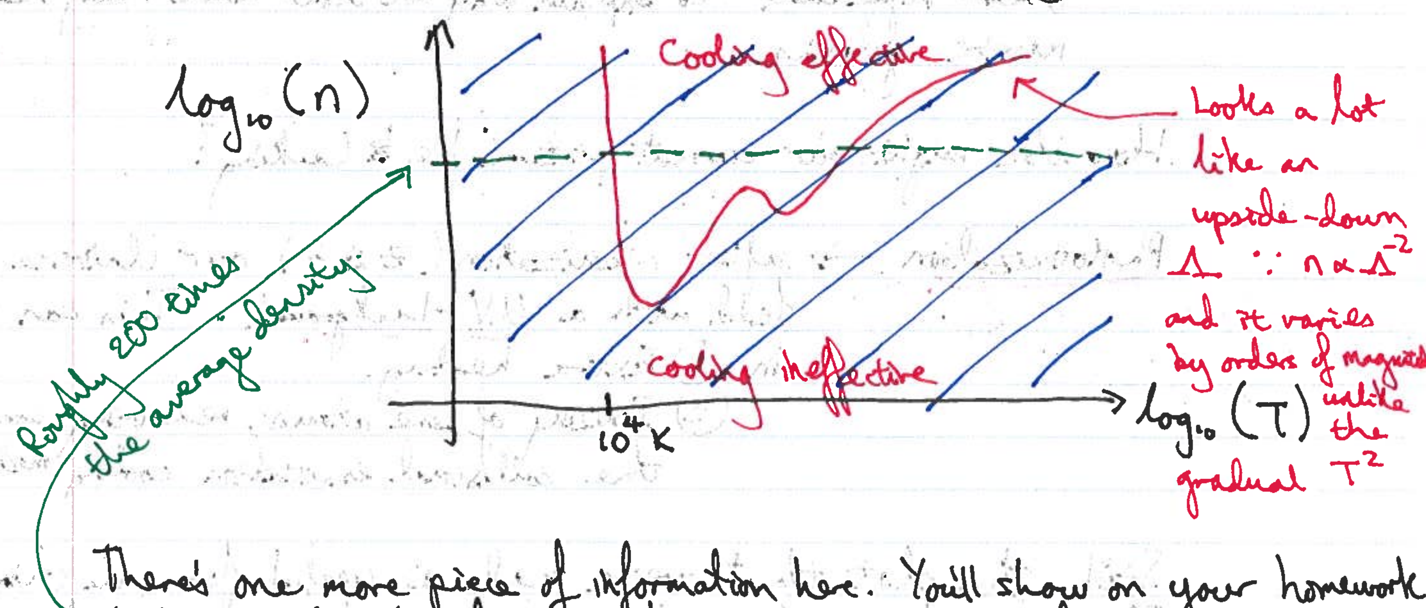
$$t_{ff} \propto \frac{1}{\sqrt{G\rho}} \propto n^{-1/2}.$$

Whether a gas cloud cools or not (or rather, quickly enough to collapse) depends on whether t_{cool} is bigger or smaller than t_{ff}. If t_{cool} is bigger than t_{ff}, then cooling happens too slowly in the timescales over which the cloud would want to collapse, so it doesn't.

The dividing line is when $t_{ff} = t_{cool}$:

$$t_{ff} = t_{cool} \Rightarrow \frac{T}{n\Lambda(T,Z)} \propto n^{-1/2} \Rightarrow \boxed{n \propto \frac{T^2}{\Lambda(T,Z)^2}}.$$

If I know the shape of $\Lambda(T,Z)$, then this is just an equation on the T-n plane that I can plot to serve as a boundary between "cooling is effective" vs "cooling is ineffective".



There's one more piece of information here. You'll show on your homework that a good rule of thumb for a virialized halo's density is approximately 200 times the average matter density of the universe.

This means we can look @ where the red and green curves intersect and then just read off what range of blue curves are permissible!

Let's see an actual picture with numbers $\Rightarrow$ $\boxed{\text{Show picture}}$

This can help guide us regarding what sorts of galaxies might form.

Notice how it's really hard to get objects with $M \gtrsim 10^{12} M_\odot$! In the early days, it was thought that maybe this could explain why there are very few galaxies this massive (remember the exponential cut-off?)

Turns out this is not enough, because of hierarchical structure formation.

↳ This is the idea that smaller structures form first and then merge to form larger ones. Our calculations here assume some of monolithic collapse. We still need some other ingredient to explain why we don't have really really massive galaxies.

How else might our current picture be lacking?

Photoionization → after reionization ($z \lesssim 6$) our Universe is filled with a UV-background. This can result in ① Extra heating.
② Ionizing of some atoms, removing some of the collisional excitation cooling mechanisms.

Still, the plot that we've made is useful for some things! For example, consider galaxy clusters, which consist of 1000s