Galaxy Formation Part 1

Where are we in the course so far?

- Galaxies consist of a puffy dark matter halo + a collection of stars + gas clouds that aren't quite as extended.
- Concerned mostly with gravitational effects in steady state, rather than how ~~eg how~~ the stars were born in the first place. In fact, we showed that stars were collisionless and thus we could treat them as mere tools for tracing the gravitational potential.

This changes today. We are going to start paying attention to the stars and gas, and how it all came to be.

For the purposes of the next few lectures on galaxy formation, we will define a galaxy as

> A gravitationally-bound system of stars embedded in a dark matter halo and exhibiting sustained star formation over cosmological time periods.

We'll think about galaxies in yet another different way when we do cosmology; galaxies will just be point tracers of the mass distribution then!

How do we get to something like this? It will necessarily be a story that goes beyond treating galaxies in steady state.

$\Rightarrow$ Show Illustris movie

We're going to start telling this story today, but be warned — galaxy formation is an inexact science. Luckily, there are some general principles that we can use as a guide.

Baryons vs Dark Matter

Astro ppl use "baryons" as a synonym for "ordinary matter" including things like the leptons (eg electrons) that particle physicists wouldn't consider "baryons"

One of the most important things to bear in mind is the different way in which baryons behave compared to DM. Stars and gas are made of baryons, so we need to understand this.

Suppose you were given some DM and some baryonic gas and you wanted to make a galaxy. You need this stuff to collapse to ignite nuclear fusion and start fusion.

Gravity starts this process off and doesn't care whether you're dealing with baryons or DM. It treats everything the same (this is the equivalence principle from general relativity!).

But as things start to collapse, the baryons behave differently because they feel the electromagnetic force. This means that there are two baryonic effects we need to worry about:

(1) Baryons feel $\boxed{\text{pressure}}$

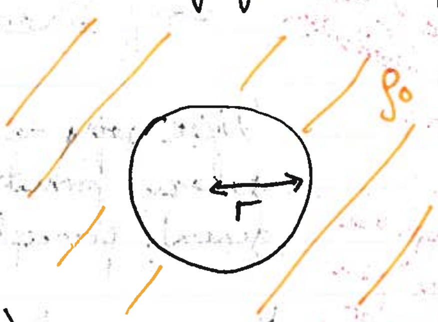
Last lecture we saw that when we had a swarm of collisionless particles like DM, the collective gravitational effect causes the velocity dispersions to act like a type of pressure. Baryons will have this too, but far more important for a gas cloud is the actual gas pressure.

A real pressure that you would normally think of as "the pressure of an ideal gas."

Recall from last time the condition for a blob of gas to collapse is

$$t_{sound} > t_{freefall}$$

$$t_{sound} \sim \frac{r}{c_s} \quad \text{(sound crossing time)} \qquad t_{freefall} \sim \frac{1}{\sqrt{G\rho_0}} \quad \text{(free fall time)}$$



If $\frac{r}{c_s} \gtrsim \frac{1}{\sqrt{G\rho_0}}$ then the sound waves can't act quickly enough to stabilize the cloud against collapse.

For a DM blob, the effective sound speed is due to the effective pressure from the velocity dispersion
For baryons a far more important contribution is the real gas pressure:

Eg $\quad c_s \sim \sqrt{\frac{k_B T}{m}}$ ← Temperature of gas
← Typical mass of gas atom/molecule

So for collapse, we need

$$r \gtrsim \frac{c_s}{\sqrt{G\rho_0}} \Longrightarrow r \gtrsim \sqrt{\frac{k_B T}{G m \rho_0}}$$

(Hot gas cloud harder to collapse than a cold one)

Important: In the early universe, before conditions were cool enough for atoms to form, there were ions + photons flying around... scattering between ions + e^- actually more important source of pressure than thermal pressure back then (see later discussion + graph)

A baryonic cloud, with its extra thermal pressure, is harder to collapse than a blob of DM. Isn't this the wrong way around? Doesn't this give rise to something like this?

This is the opposite of what we see in a galaxy, where the DM is more diffuse and the baryons are more concentrated.
What we are missing is the fact that...

② Baryons can $\boxed{\text{radiate}}$

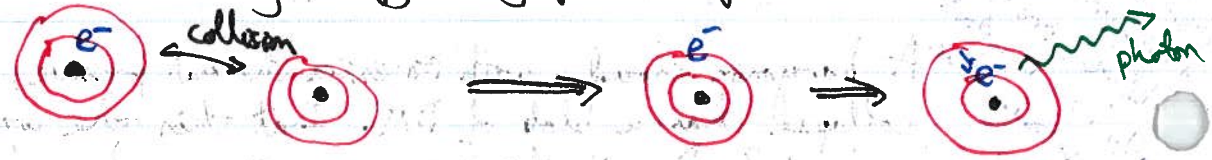
Unlike DM, baryons feel electromagnetism, so they can lose energy by giving off photons, & they can cool and reduce their pressure support. This then lets them collapse further.

Think about this like the story of the Tortoise and the Hare.
DM ≡ the hare : quick to collapse initially ∵ no thermal pressure support, but it stops eventually ∵ can't radiate away energy.

Plus early on, the Thomson scattering when universe was still ionized

Baryonic gas = the tortoise : slow to collapse initially ∵ thermal pressure support* but can catch up and collapse further ∵ can radiate and lose energy.

Side note : we will revisit this later ∵ it is a very important point, but for now, just note that the rate of cooling will depend on many factors, including the current temperature of the cloud. For example, one way for a gas cloud to cool is for collisions between the atoms / molecules to excite electrons to higher energy levels, and then for the electrons to fall back down and emit a photon to carry energy away from the gas cloud.

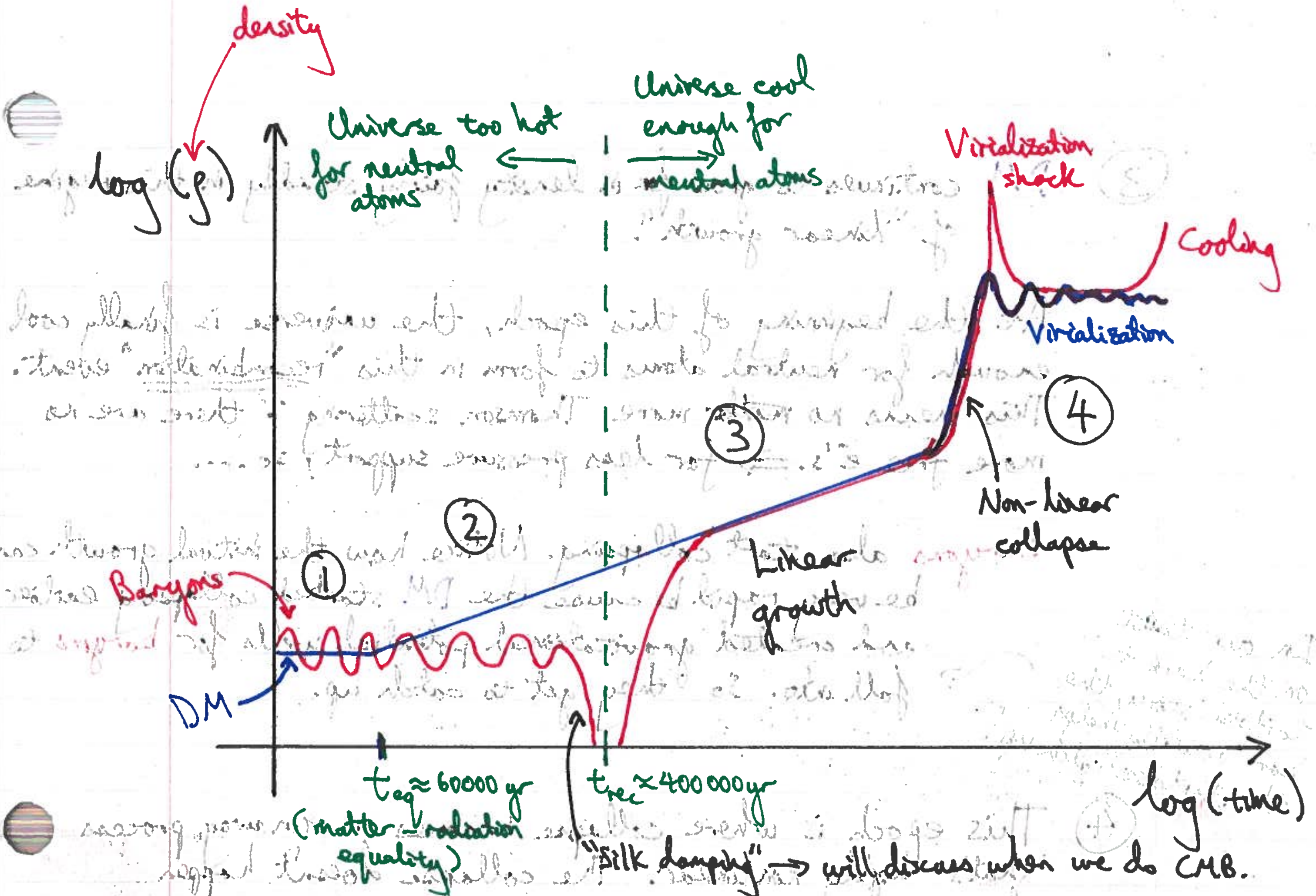


The temperature changes the effectiveness of this mechanism ∵ higher T ⇒ more frequent + more violent collisions that can excite different energy levels. And the chemical composition affects what energy levels there are.

This is quite ironic, if you think about it — often to cool effectively you need to heat up first!

With these considerations in mind, let's trace the evolution of of a DM blob and a gas cloud that might form something like a galaxy.

[Need more space ⇒ diagram on next page]



① Early on, the universe is hot and ionized. A big soup of charged particles and photons.

Baryons feel a lot of pressure ∵ electrons can Thomson scatter off photons, and the electrons drag along the nuclei. It's a stiff photon-baryon fluid that can't collapse and just oscillates.

DM, interestingly enough, also can't collapse very well at early times! The universe is expanding very quickly and fighting against collapse.

② Eventually the universe's expansion has slowed down enough so that DM can start collapsing. Baryons are still trapped in a photon-baryon fluid and can't collapse.

(3) DM continues to grow ~~f~~ in density fairly steadily in this regime of "linear growth".

At the beginning of this epoch, the universe is finally cool enough for neutral atoms to form in this "recombination" event. This means no ~~matter~~ more Thomson scattering ∵ there are no more free $\bar{e}$'s. ⇒ far less pressure support, so....

Baryons also start collapsing. Notice how the initial growth can be very rapid because the DM started collapsing earlier and created gravitational potential wells for baryons to fall into. So they get to catch up.

In our twist on the hare + tortoise story, the hare actually helps the tortoise catch up!

(4) This epoch is where collapse becomes a runaway process that's highly nonlinear. The collapse doesn't happen forever because eventually the system comes into that delicate balance of virial equilibrium, where we have particles orbiting and with $U + 2T = 0$.

DM actually does this very slowly because it has no gas pressure and we saw that the two-body relaxation time is very slow (from an earlier lecture)

Look up things like "phase mixing" or "violent relaxation" to learn more

Baryons do something very interesting! Their density initially spikes! What's going on?

As the baryons fall into grav. potential wells, they're typically moving so quickly that they are supersonic i.e. the infall velocity of the gas is faster than the sound speed.

What happens then? You get pile ups of density called shocks

You've all seen shocks before. ⇒ Show pictures of hydraulic jumps and traffic jams.

The relatively slow sound speed means there is not much communication upstream and there is a density pile-up. What happens when baryons crash into each other like that? Coherent kinetic energy dissipates into heat. This raises the temperature and the cloud gets puffy again (so the density drops).

After this, you know the story — the baryons cool and lose energy so they get to collapse to higher densities than the DM.

This roughly completes our picture of how one DM blob and baryonic gas cloud might behave. Let's now stitch together a qualitative story of the sorts of events that this causes...

A Qualitative Story of Galaxy Formation

For reference only! Highly uncertain!

Cosmic Dawn ($t \sim 0.1$ Gyr; $z \sim 30$). The first stars (known as Pop III stars) form in small halos. These aren't very deep grav. pot. wells, so the gas wasn't that fast and wasn't shocked to super high temperatures. Luckily, molecular hydrogen can serve as a coolant because it has easily excitable lines in the IR. Pop III stars form. These are massive stars that burn through their fuel quickly and die.

Ironically, these stars tend ~~to~~ to choke off further star formation in these small halos:

Examples of feedback effects

- Supernovae push gas back out into the IGM
- Pop III stars produce photons in the Lyman–Werner band (11.2 to 13.6 eV), which are really good at dissociating molecular hydrogen.

Again, this irony of needing to heat up enough to cool effectively!

First Gen Galaxies / Second Gen Stars (Pop II) ($z \sim 20$ to 30; $t \sim 0.2$ Gyr). More massive halos exist, and shock-heated gas is hot enough to collisionally excite atomic hydrogen which then emits photons to cool. These are also massive enough to hold onto their gas in the presence of feedback.
$\Rightarrow$ First sustained star formation is first galaxies

Reionization ($z \sim 10$ to 6; $t \sim 0.5$ to 1 Gyr)

Enough star formation that UV photons can systematically ionize neutral hydrogen in the IGM. This is an example of feedback – the free electrons liberated by reionization can collide with atoms and heat up a gas cloud, fighting its collapse.

Star formation, feedback, accretion of more gas, and even mergers of galaxies continue ....

Cosmic high noon ($z \sim 2$; $t \sim 3$ Gyr)

Peak star formation rate. $\Rightarrow$ Show Madau plot

Something must quench star formation at late times.

Summary

Important ingredients for galaxy formation
- Gravity / accretion / collapse.
- Cooling.
- Star formation.
- Feedback.

In the next few lectures we will look @ these in more detail.