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

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

Cooling rate

\# density of H

Cooling fct.

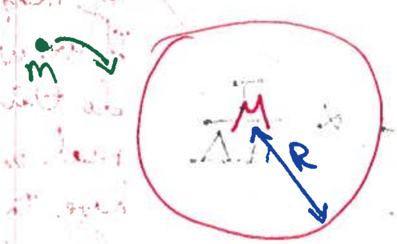
All of the subtle chemistry, stat. mech, etc. is encoded in the cooling fct. $\Rightarrow$ $\boxed{\text{Show example}}$

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.

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

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

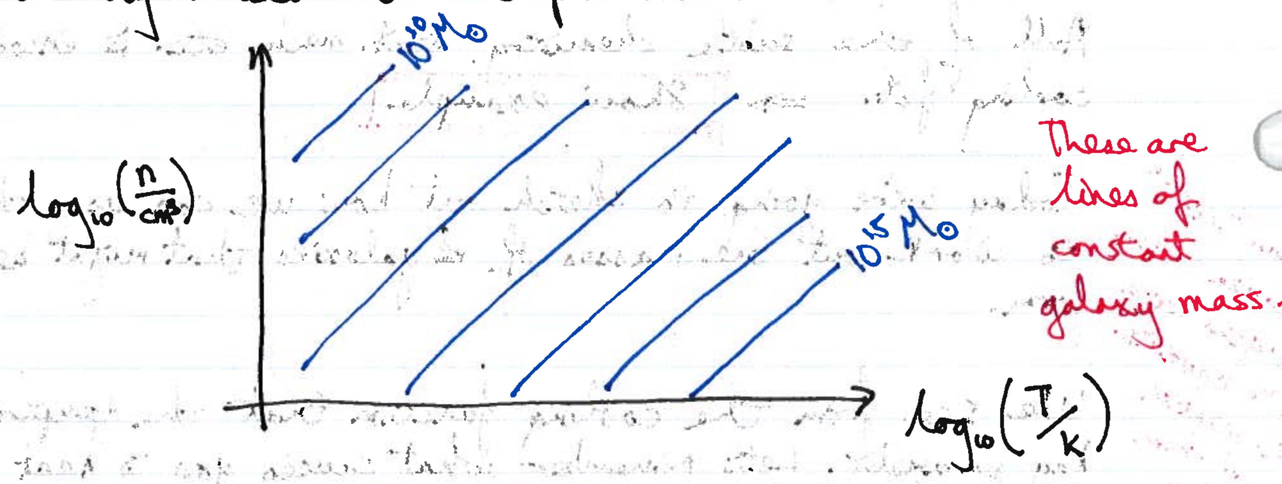
$$\tfrac{1}{2} m v^2 \sim k_B T. \quad \Rightarrow \quad M \propto RT$$

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 ~~rate~~ 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.



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:

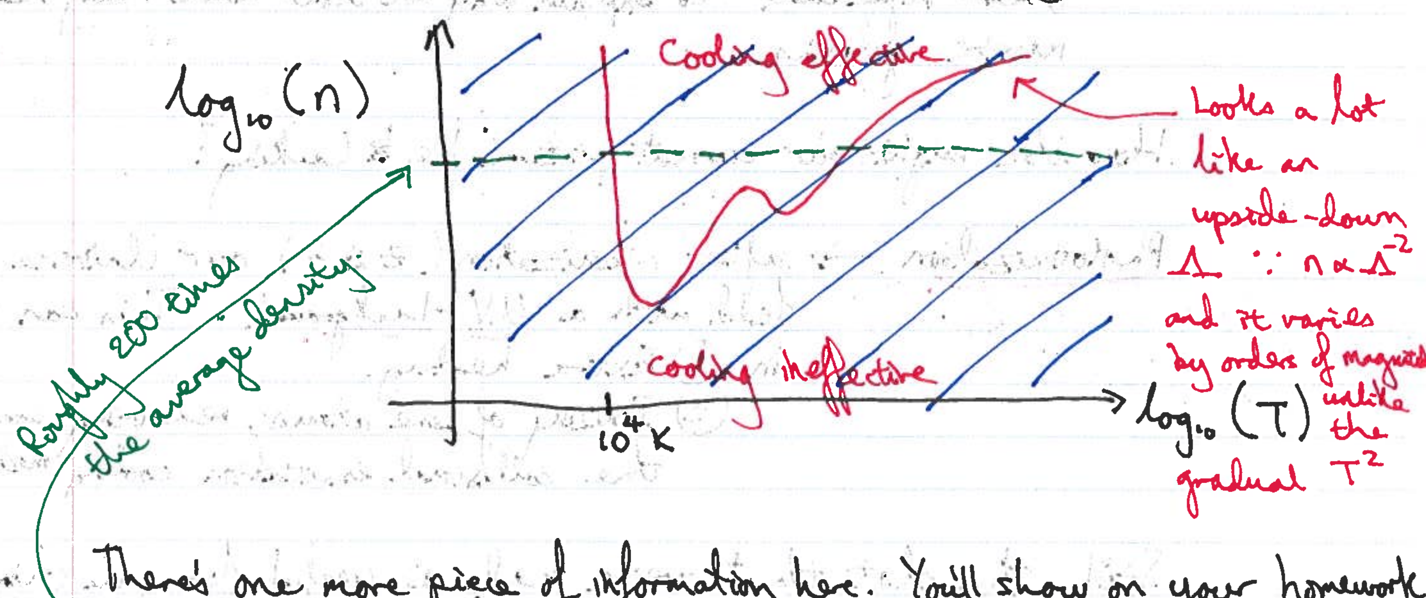
$$t_{ff} \propto \frac{1}{\sqrt{G\rho}} \propto n^{-1/2}.$$

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 ⇒ $\boxed{\text{Show picture}}$

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 of galaxies and have a mass of up to even $10^{15} M_\odot$. Our picture suggests that any extra gas falling into a galaxy cannot cool properly, so it should remain hot. And indeed this is the case! Galaxy clusters have hot gas that's so hot we see them in X-rays!

⇒ $\boxed{\text{Show Abell 1689}}$

Star Formation

At this point we've talked about the general conditions under which gas can collapse. Let's now talk in a little more detail about how this gas might eventually form stars.

Some gas falls in. If it is @ $T \gtrsim 10^4$ K, then it'll start cooling, but once it gets to $T \sim 10^4$ K, it'll need molecules like H_2 to cool further + form stars. The gas needs to wait for this to happen.

Eventually we get star formation in Giant Molecular Clouds. These are clouds of 10^5 to $10^6 M_\odot$ and 10s of pc across.

⇒ $\boxed{\text{Show some pictures}}$

Notice the dark patches — this is obscuration due to dust. Dust is important because it serves as a catalyst for H_2 formation.

In addition — dust can help absorb some of the UV background to "protect" H_2 molecules from dissociation.
— the gas can also be dense enough to self-shield. This is where the outer layers can protect the innards of a ~~cl~~ clump.

⇒ $\boxed{\text{Show penguin picture}}$

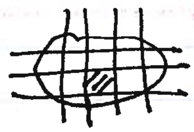
OK! So we've got some nice conditions for star formation. How much ~~star~~ star formation do we get?

Kennicutt – Schmidt Law : $$\boxed{\dot{\Sigma}_* \propto \Sigma_{gas}^{\,n}}$$

$n \gtrsim 2$ globally.
$n \approx 1.4 \pm 0.15$ for star-forming galaxies

Surface star formation rate density in $M_\odot\, yr^{-1}\, kpc^{-2}$

density of gas.



How do we know this? The H_2 gas is actually hard to see directly, because it doesn't have super accessible emission lines. Fortunately, for every $\sim 10^4$ H_2 molecules there tends to be 1 CO molecule, which has spectral lines that can be seen in radio. There's then a known conversion factor, $X_{CO} = \dfrac{n(H_2)}{I_{CO}}$.

Do we have an explanation? Sort of, but not really.

Try this: $\dot{\rho}_* \propto \dfrac{\rho_{gas}}{t_{ff}} \propto \rho_{gas}^{1.5}$. Then I just do an integral to project down to a surface density.

$t_{ff} \sim \dfrac{1}{\sqrt{G\rho}}$

Maybe reasonable if we're envisioning a collapsing cloud? Maybe not?

This looks promising, but the problem is that if I write the proportionality constant,

$$\dot{\rho}_* = \varepsilon_{SF} \frac{\rho_{gas}}{t_{ff}}, \text{ we find that } \varepsilon_{SF} \approx 1\%.$$

As physicists we don't like factors far from unity without explanation

Star formation is generically quite inefficient.

What else do we know about ~~star~~ of star formation? The Kennicutt-Schmidt Law tells us about the total star formation rate. But it doesn't tell us how many low vs high mass stars are formed.

The initial mass function (IMF) is a probability distribution function telling us exactly this.

$$\frac{dN_*}{d\log m_*} \propto m_*^{-\alpha}$$

In the present universe where we form Pop I stars, $\alpha \simeq 1.35$. This is called a Salpeter IMF.

For Pop III, we don't know! Huge open research question.

Quick advertisement

On the problem set, you will bring together some of these ideas in a model known as the bathtub model

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

Galaxy Formation Part 4

Today we're going to aim to bring a bunch of pieces together. We've talked about cooling and star formation. One of the last pieces we have to discuss is feedback.

Motivation

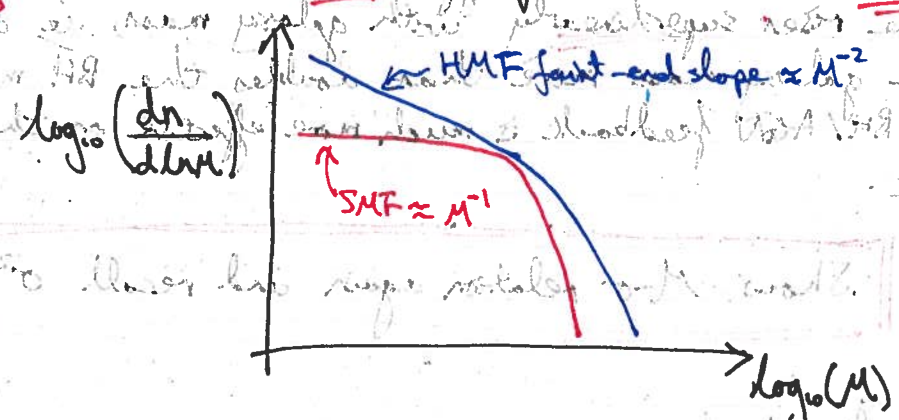
Recall two facts we've mentioned previously:

1. Star formation is generically inefficient — gas turns into stars very slowly.
2. We see fewer low-mass and high-mass galaxies than we might expect from just from counting halos

Remember I'm not counting it as a galaxy unless it's forming stars!

For ~~the~~ second point, we previously pointed to comparisons between the luminosity function's shape and the halo mass function. We can also phrase this as a difference in shape between the halo mass function and the stellar mass fct.

Obtainable from theory or N-body simulations



This is even clearer if I ~~divide these curves and plot their ratios~~ show you the stellar-mass-to-halo-mass ratios

$\Rightarrow$ $\boxed{\text{Show Weschler + Tinker plot}}$

One sees several things:

- The overall normalization is fairly low. Last time we talked about how only $\approx 1\%$ of gas is converted into stars per free fall time t_{ff}. But here we see that even in steady state,

it's not much better.
- We need something to really suppress star formation at low and high masses.

The prevailing wisdom is that the feedback mechanisms responsible for this are different at different masses.

On the low mass end, supernovae provide this feedback.

On the high mass end, active galactic nuclei (ie supermassive black holes) are responsible.

One can put together some plausibility arguments for why these different mechanisms are important in different regimes of halo mass.

Eg The M-σ relation suggests that the mass of a black hole rises superlinearly with galaxy mass, ie doubling the galaxy mass more than doubles the BH mass, so BH/AGN feedback is much more effective on the high-mass end.

$\Rightarrow$ $\boxed{\text{Show } M\text{-}\sigma \text{ relation again and recall } \sigma^2 \sim \frac{GM}{R}}$

Feedback Mechanisms

Feedback can operate in several ways to suppress star formation:
- It can change the conditions of the gas that is trying to form stars.
- It can prevent gas from accreting and collapsing in the first place
- It can eject gas already in a galaxy.

"Detailed" mechanisms:

① Reionization feedback. ~~After reionization~~ There are two parts to this. Remember that what happens during reionization is that UV photons from the first galaxies ionize the neutral hydrogen in the IGM.

- Any energy in excess of the 13.6 eV (binding energy of H) in the photon ends up in the free e^-, which can bash into other things and heat them up. This makes it hard for gas clouds in small halos to collapse.

Sometimes also called "squelching"

- After reionization, there's very little neutral hydrogen to absorb UV photons, so there's a UV background that roams free, heating gas and preventing collapse.

② Supernova feedback.

Massive stars go supernovae. This can have two effects. First, the energy ~~ejection~~ injection can push gas out of a halo. Another mechanism is that the energy injection can heat up the gas, making it hard to collapse.

One tricky thing: sometimes the heated gas just cools off quickly, making it hard to maintain pressure needed for outflows. (All sorts of ad hoc prescriptions used in simulations to "save" this)

③ AGN / Supermassive BH feedback

The BH gets all the attention, but there's a lot going on!

$\Rightarrow$ $\boxed{\text{Show unified AGN pic}}$

AGNs can heat up gas & push winds out, and ionize or photodissociate gas.

Massive amounts of energy are output by AGN — open question is how this energy couples to ISM to affect the gas there, and how efficient this is.

At this point, we've discussed some of the main pillars of galaxy formation — gravity, cooling, feedback, and star formation.

How does one bring this all together in a galaxy formation model?

Galaxy Formation Models

There are lots of different ways to put together a coherent model of galaxy formation. Three example classes:

1. Hydrodynamical simulations.

- Solve equations of gravity and hydrodynamics in a cosmological context.
- Can't resolve all relevant scales for galaxy formation, so rely on subgrid prescriptions to capture what can't be resolved.

2. Semi-analytic Models

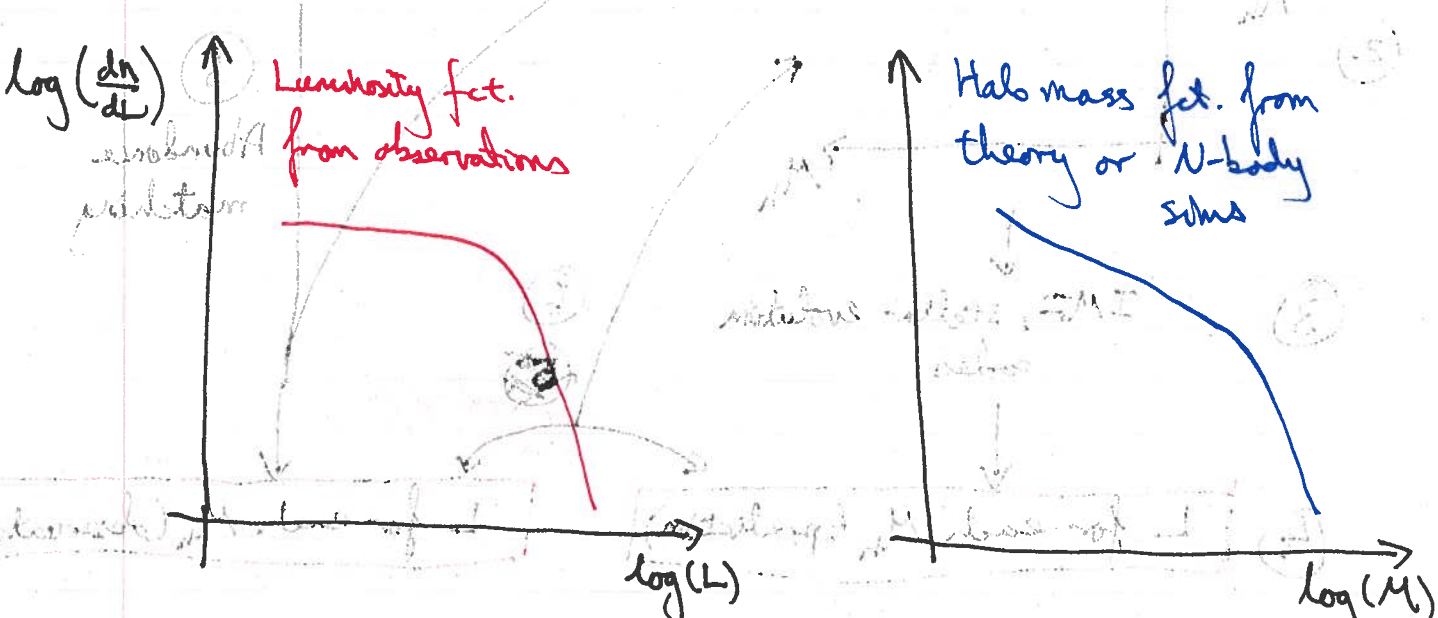
- Run N-body simulation, keeping track of merger trees of halos. ⇒ Show picture
- Keep track of key properties for halos using analytic prescriptions.

③ Semi-empirical Models

These are where we really tune things directly to observations. For example, there is the technique of abundance matching.

Here, the assumption is that the most massive halo hosts the most luminous galaxy, the 2nd most massive halo hosts the 2nd most luminous galaxy etc.

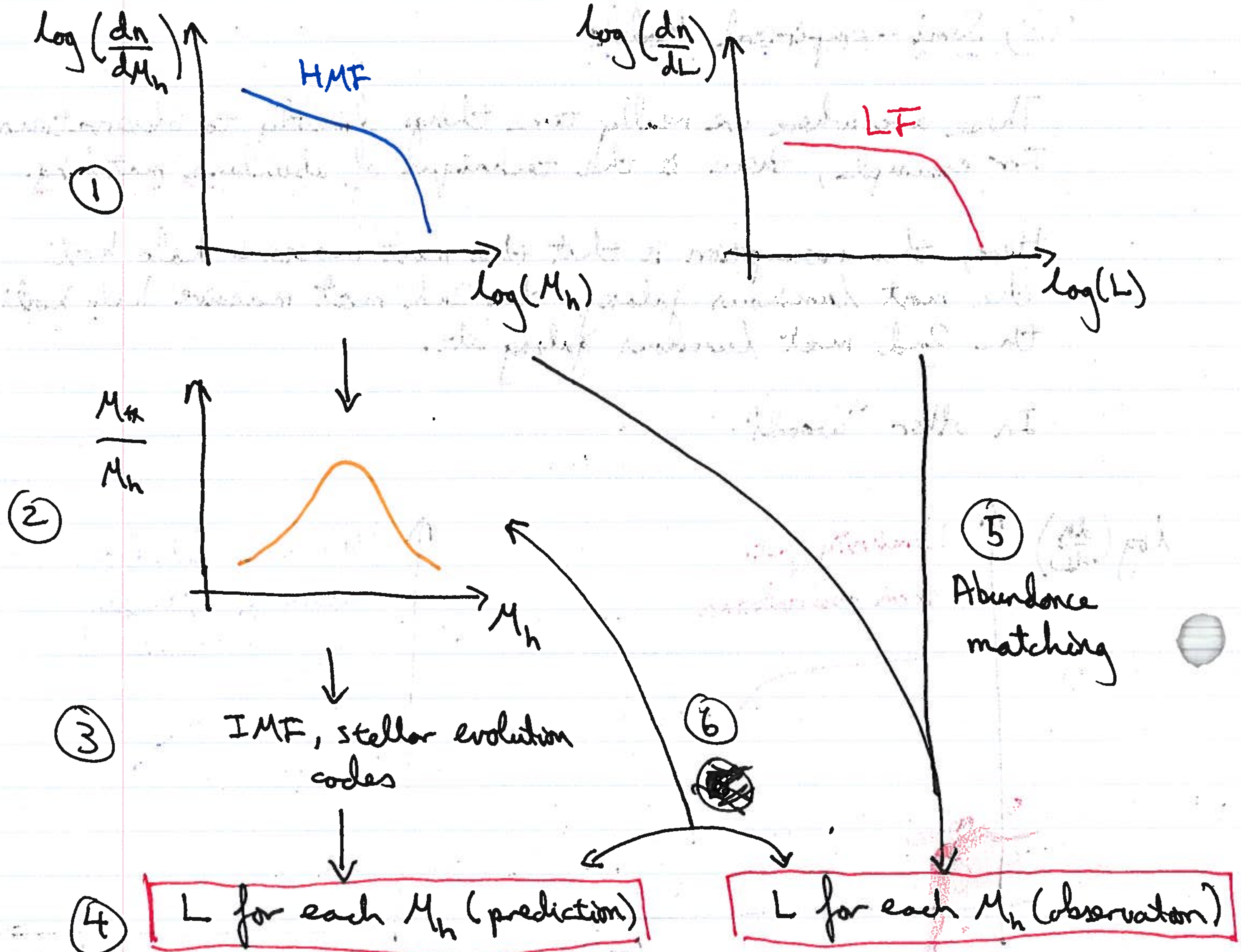
In other "words"



I draw a population of galaxies from each and rank order them

$(L_1, L_2, L_3, \ldots)$ $(M_1, M_2, M_3, \ldots)$

This can be incorporated into a more detailed framework.



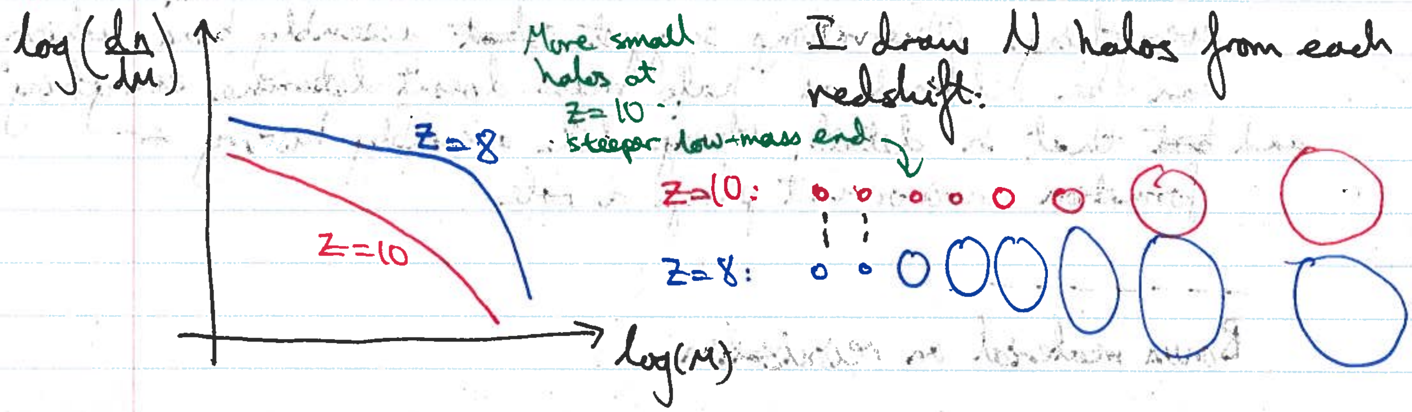
1. Start with HMF and draw a random population of halos M_h
2. Use an assumed $M_* - M_h$ connection to assign stellar masses M_* to each halo.
3. Use IMF and knowledge of stellar evolution to simulate a population of stars for each halo.
4. Predict L for each halo by integrating over whole population.
5. Figure out the same thing by applying abundance matching to observations.
6. Compare and adjust $M_* - M_h$ relation until the fit is good.

One missing ingredient in what I just said was a connection between different redshifts. You would need to impose some extra conditions to ensure coherency.

I am describing a separate, but related model here

One possibility is an accretion based model. Suppose I had two HMFs @ different redshifts.

I draw N halos from each redshift.



Making a 1-to-1 correspondence between halos then allows me to compute their accretion rate.

We then say: $\dot{m}_* = f_* f_b \dot{m}_h$ ← accretion rate

SFR; M_*–M_h relation; baryon fraction

Then assume that UV emitted predominantly by massive stars that shine and die instantly (on cosmic timescales), so UV luminosity traces instantaneous star formation.

$$\Rightarrow L_{UV} \propto \dot{m}_*$$

and we have a prediction for UV luminosity functions that we can compare to observations!

What might be some limitations of this accretion-based model? One flaw is that it only models smooth accretion — mergers of two halos into one play no role.

Another potential problem for both of our semi-empirical models is that they don't account for assembly bias. ~~This is the~~ Our models assume that halo mass M_h determines everything. Observations suggest ~~that~~ assembly bias, which can be defined as "halo mass doesn't determine everything", and ~~but~~ that in detail, things like assembly history or formation environment plays a role.

Bonus material on reionization

These sorts of models can also be used to think about reionization.

A pivotal event in our Universe's history when first-gen galaxies systematically ionized the neutral hydrogen in the intergalactic medium (IGM)

$\Rightarrow$ $\boxed{\text{Show reionization movie.}}$

As a first stab at describing reionization, I might ask the very basic question of how we went from almost all neutral to almost all ionized.

Define $Q_{HII} \equiv$ Fraction of universe's volume that is ionized.

How did Q_{HII} go from $\simeq 0$ to $\simeq 1$ as a fct. of z (or time)?

The convenient thing here is that the easiest way to ionize a hydrogen atom is to send in a UV photon. And we've just built a model where we predict UV luminosities! We have everything we need.

Reionization is a competition between the ionization and recombinations. We can write this as a differential equation:

$$\frac{dQ_{HII}}{dt} = \underbrace{\frac{f_{esc} N_{ion} \dot{\rho}_*}{n_H}}_{\text{Ionizations}} - \underbrace{\alpha C n_e Q_{HII}}_{\text{Recombinations}}$$

The easiest way to understand this is to define the symbols!

$\dot{\rho}_*$: Cosmic star formation rate density

$$\int \dot{M}_* \underbrace{\frac{dn}{dM_h}}_{\text{halo mass fct.}} dM_h$$

Remember this is a fct. of M_h!

N_{ion} : # of ionizing photons emitted per unit stellar mass.

f_{esc} : Escape fraction — the fraction of ionizing photons that escape from the ISM to get to the IGM.

n_H : Number density of hydrogen

α: "Case A recombination coefficient".

n_e: Electron # density.

C: "Clumping factor" $\frac{\langle n_H^2 \rangle}{\langle n_H \rangle^2}$. A fudge factor to account for the fact that recombination is a 2-body process.

We can numerically integrate this and get $Q_{HII}(z)$.

$\Rightarrow$ $\boxed{\text{Brant Robertson figure}}$