

# Evolution of Cosmic Structure

## Lecture 11 -Physical model of galaxy formation

Suhail Dhawan



UNIVERSITY OF  
BIRMINGHAM

[s.dhawan@bham.ac.uk](mailto:s.dhawan@bham.ac.uk)

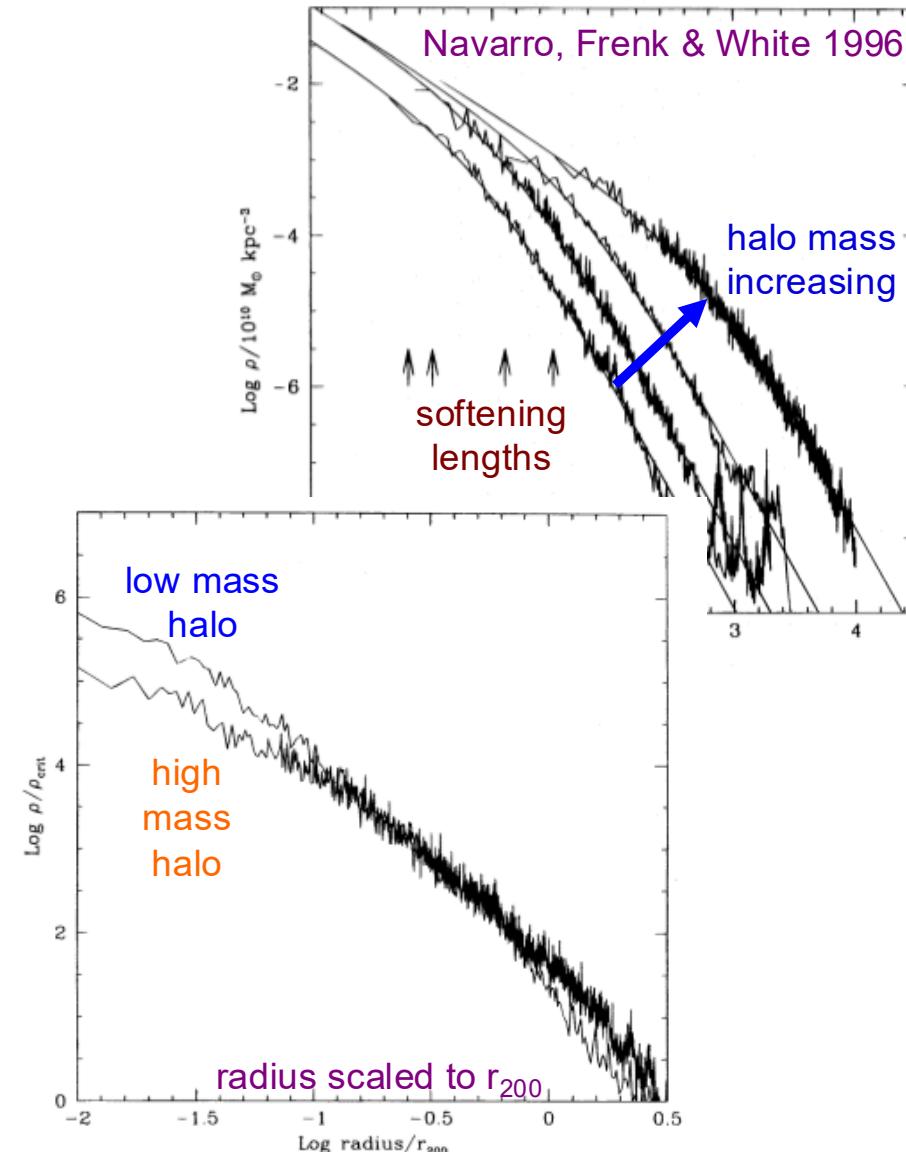
# Dark matter halos

Navarro, Frenk & White (1996) studied a large sample of dark matter haloes and found the profiles of most halos were well fitted by the functional form:

$$\rho(r) = \frac{4\rho_s}{(r/r_s)(1+r/r_s)^2}$$

where  $\rho_s$  is the density at the scale radius  $r_s$ . This has consequently become known as an **NFW profile**.

They also found that when these profiles are almost **self-similar** when scaled to a characteristic overdensity radius



# Incorporating baryon physics - examples

## Cosmic feedback – Supernova, AGN, etc.

- In the absence of heating processes, it is found that most of the gas in cosmological simulations cools at high  $z$ , when the Universe is dense, and would form stars. In practice, only 10-15% of the baryonic matter is found in stellar form.
- In reality, this is prevented by *cosmic feedback* – the process whereby stars and AGN pump energy back into gas which surrounds them, preventing it from cooling.

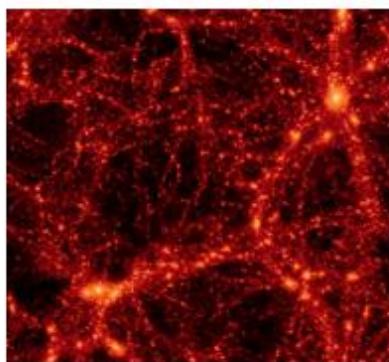
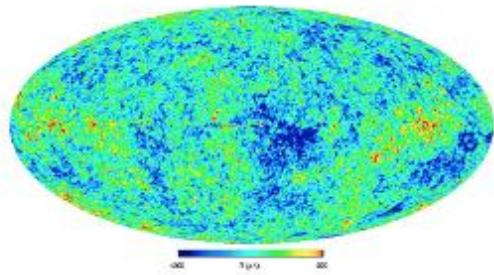
# Incorporating baryon physics - examples

## Cosmic feedback – Supernova, AGN, etc.

- Since stellar evolution is fairly well understood, we can predict how many supernovae should follow after star formation with a given IMF.
- The total energy released from each supernova is believed to be about  $10^{44}\text{J}$ , but it is very uncertain how this couples with surrounding gas.
- For example, heating dense gas will simply cause it to radiate profusely, so that the supernova energy escapes from the galaxy with little effect.

**What techniques are used to simulate the development of cosmic structure? How can complex baryon physics be incorporated? What light do the results cast on the evolution of structure?**

- The role of simulations
- N-body simulations and dark matter halos
- Adding gas – hydrodynamics
- Incorporating baryon physics
- A physical model of galaxy formation – cooling, feedback



Cosmological model  
 $(\Omega_m, \Omega_\Lambda, h)$ ; dark matter

Primordial fluctuations  
 $\delta\rho/\rho(M, t)$

Dark matter halos  
(N-body simulations)

Gas processes  
(cooling, star formation, feedback)

Gasdynamic simulations

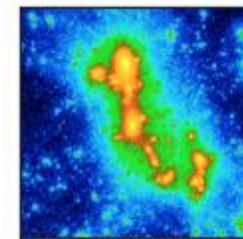
Semi-analytics

Galaxy formation/evolution

Well established

Well understood

**DIFFICULT!**



# Semi-analytic models

Incorporating sub-grid physics into dark matter + hydro simulations is complex and leads to slow computations. So Cole et al (2000) introduced an alternative approach.

Rather than attempting to solve the hydrodynamic equations, **semi-analytic models** use approximate prescriptions to calculate the rate at which gas cools within dark halos, and then forms stars, producing supernovae etc.

# Semi-analytic models

Subsequently, the evolution of the resulting galaxy is followed, as its halo grows through accretion and mergers, and the properties of the galaxy (e.g. optical colours, star formation rate etc.) can be tracked within the code.

This approach makes for much quicker computations, and allows a wide range of prescriptions to be tried out.

However, it does not allow the behaviour of the gas to be studied in any detail, and says little about the Universe outside of galaxies.

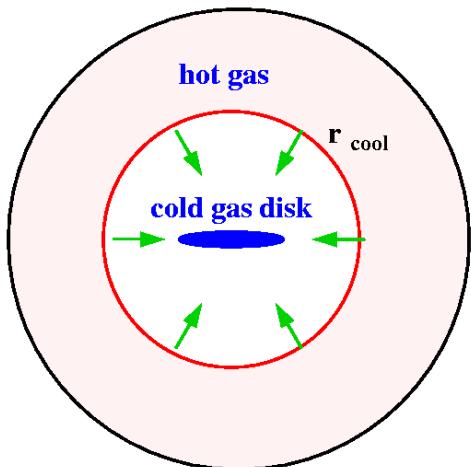
# Semi-analytic models

- infalling gas **shock-heated** to

$$T_{vir} = \frac{1}{2} \frac{\mu m_p}{k} \left( \frac{GM}{r_{vir}} \right)$$

- gas **cools radiatively** out to radius  $r_{cool}$  where

$$t_{cool}(r_{cool}) = T_{halo}$$



- cold gas **collapses to rotationally supported disk**
- **conservation of angular momentum**

$$\rightarrow r_{disk} \sim \lambda_H r_{cool}$$

The basic approach works like this:

- Dark halos are taken either from an N-body simulation, or from Press-Schechter theory
- The gas is assumed to heat to the virial temperature within each halo

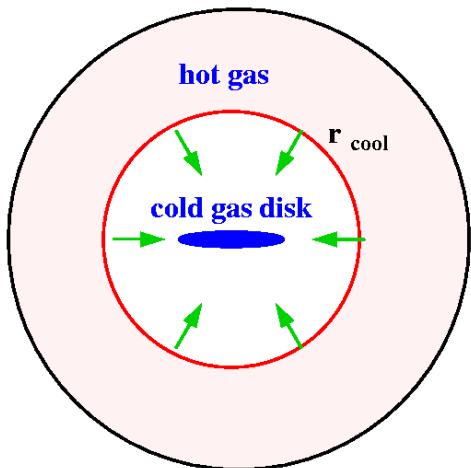
# Semi-analytic models

- infalling gas **shock-heated** to

$$T_{vir} = \frac{1}{2} \frac{\mu m_p}{k} \left( \frac{GM}{r_{vir}} \right)$$

- gas **cools radiatively** out to radius  $r_{cool}$  where

$$t_{cool}(r_{cool}) = T_{halo}$$



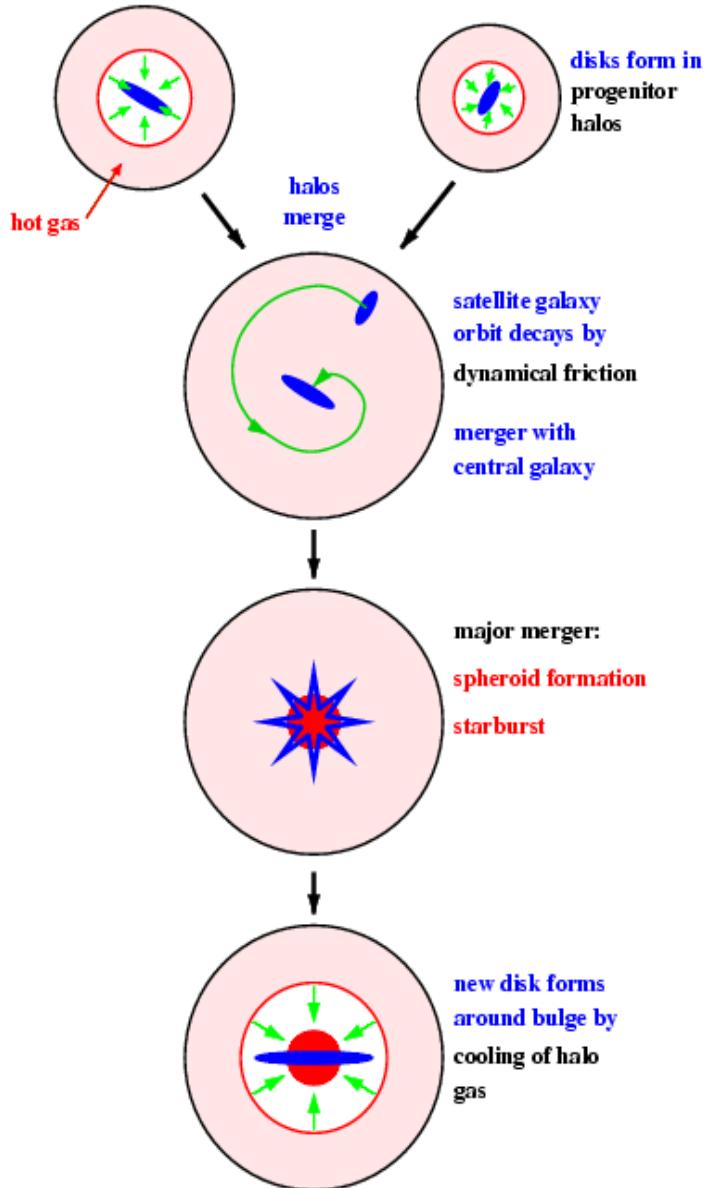
- cold gas **collapses to rotationally supported disk**
- **conservation of angular momentum**

$$\rightarrow r_{disk} \sim \lambda_H r_{cool}$$

- Some of it then cools (using an assumed gas density profile and cooling function) and forms a rotationally supported disc

- Star formation then takes place within this disc according to the K-S law, producing a galaxy

# Semi-analytic models



- When such halos merge (these events are derived from merger trees) the larger galaxy is assumed to assume a central position in the new halo, whilst the smaller one spirals in due to *dynamical friction*
- When it reaches the centre, the two galaxies merge, and if they contain cool gas then this may be used up in a *starburst*
- Spiral structure is assumed to be destroyed in the merger, and the stars form a central *bulge*
- Further cooling of hot gas can then build a new disc around this bulge
- Other processes such as growth of a central black hole, can be incorporated into semi-analytic models

# Baryon heating

As the baryonic material is concentrated into collapsing halos, it will be compressed and heated. A rich variety of extra physics now comes into play.

If the halo contains gas, then new gas falling in will hit this supersonically and will shock, converting its kinetic energy into thermal energy. Its temperature will therefore be raised to the “virial temperature”  $T_v$ , derived from the equation

$$\frac{3}{2}kT_v = \frac{GM\mu m_H}{r_v}$$

where  $r_v$  is the “virial radius” out to which the system is virialised.

# Baryon heating

We have already seen that from the top-hat model the mean density of a newly virialised halo is 178 times the critical density of the Universe. It is therefore customary to round this up to 200, and estimate the radius out to which a halo is virialised as  $r_{200}$ , the radius within which the mean density is 200x the critical density – i.e. for an object of mass  $M$ , we have

$$M = \frac{4\pi}{3}r_{200}^3 \times 200\rho_c$$

Putting in some relevant numbers, the halo masses of typical large galaxies are  $\sim 10^{12} M_\odot$  and we find

$$T_{200} \propto M^{2/3} = (M/10^{12} M_\odot)^{2/3} 1.0 \times 10^6 \text{K}$$

where we have taken  $\mu=0.6$ .

# Radiative Gas Cooling

Let  $H$  and  $C$  be the volumetric heating and cooling rate of gas from radiative processes (measured, for instance, in units of ergs/s/cm<sup>3</sup>) In most of galaxy formation situations,  $H = 0$ . That is, there is no heating of the gas from radiative processes – the gas is said to be **optically thin**.

The cooling will be a function of temperature and metallicity, so it is useful to define a **cooling function**  $\Lambda(T, Z) \equiv \frac{C}{n_H^2}$

# Radiative Gas Cooling

The **cooling time**, is then the time it takes to radiate away this energy:

$$t_{cool} \equiv \frac{\rho\epsilon}{C} = \frac{\rho\epsilon}{n_H^2 \Lambda(T, Z)}$$

Remembering that the energy of an ideal gas is

$$\epsilon = \frac{1}{\gamma - 1} \frac{k_B T}{\mu m_p}$$

where  $\gamma = 5/3$  for a monotonic gas.

# Cooling time

Thus, the **cooling time**, is:

$$t_{cool} = \frac{3 n k_b T}{2 n_H^2 \Lambda(T, Z)} \propto n^{-1} \propto \rho^{-1}$$

(The 3/2 is the common way of writing this, but in reality, factors of order 1 don't matter.)

This means gas cools more quickly in dense regions. It is useful to compare this cooling time to two other timescales in the universe: **the age of the universe** and the **free-fall time**.

Very roughly, the age of the Universe is the Hubble time:

$$t_H = \frac{1}{H(z)} \propto \frac{1}{(G\rho)^{1/2}}$$

The free-fall time (or dynamical time) is the timescale on which a gas cloud collapses in absence of pressure and timescale on which the system restores hydrodynamic equilibrium

$$t_{ff} = \left( \frac{3\pi}{32 G \rho_{sys}} \right)^{1/2} \propto \frac{1}{(G \rho_{sys})^{1/2}}$$

Given that typical  $\rho_{sys}$  is 200  $\rho_{critical}$ , that is roughly  $t_{ff} \approx \frac{t_H}{10}$ .

# Cooling regimes:

We can distinguish three regimes depending on those relative timescales:

1.  $t_{cool} > t_H$  - In this phase, cooling is not important. The gas will be in hydrostatic equilibrium unless recently disturbed, and will be stable against collapse.

# Cooling regimes:

We can distinguish three regimes depending on those relative timescales:

1.  $t_{cool} > t_H$  - In this phase, cooling is not important. The gas will be in hydrostatic equilibrium unless recently disturbed, and will be stable against collapse.
2.  $t_{ff} < t_{cool} < t_H$  - This system is in 'quasi-hydrostatic equilibrium'. It evolves on the cooling timescale. The gas contracts slowly as it cools, but the system has sufficient time to continue to re-establish hydrostatic equilibrium.

# Cooling regimes:

We can distinguish three regimes depending on those relative timescales:

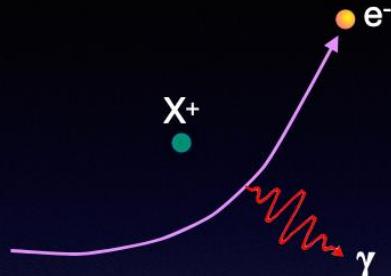
1.  $t_{cool} > t_H$  - In this phase, cooling is not important. The gas will be in hydrostatic equilibrium unless recently disturbed, and will be stable against collapse.
2.  $t_{ff} < t_{cool} < t_H$  - This system is in 'quasi-hydrostatic equilibrium'. It evolves on the cooling timescale. The gas contracts slowly as it cools, but the system has sufficient time to continue to re-establish hydrostatic equilibrium.
3.  $t_{cool} < t_{ff}$  - Cooling of the gas is catastrophic. The gas cannot respond fast enough to the loss of pressure. Since the cooling time decreases with increasing density, the cooling proceeds faster and faster. The gas falls to the center of the dynamic system on a free-fall time.

Note that the cooling and free-fall time can change as a function of redshift, as they typical densities change.

# Types of radiative cooling

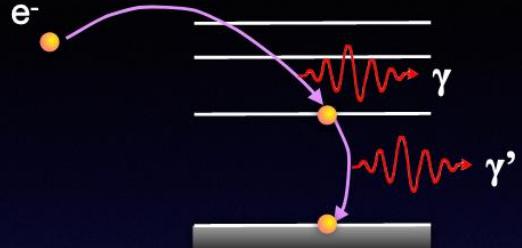
The main cooling processes in galaxy formation are two-body radiative processes in which the gas loses energy through the emission of photons because of two-body interactions. There are four processes that can be important:

## 1) free-free (bremsstrahlung)



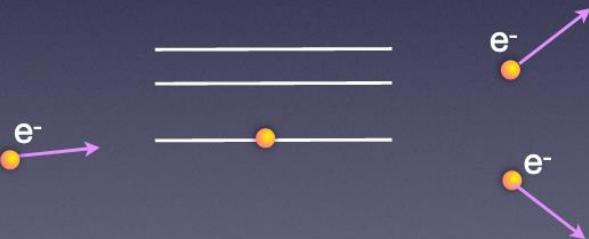
Free electron is accelerated by ion. Accelerated charges emit photons, resulting in cooling. For bremsstrahlung,  $\Lambda \propto T^{1/2}$

## 2) free-bound (recombination)



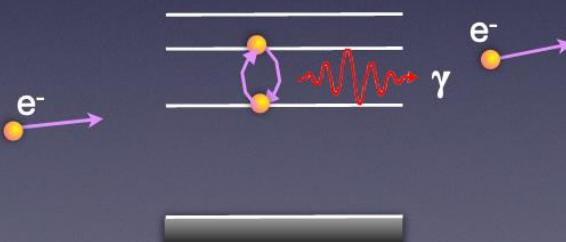
Free electron recombines with ion. Binding energy plus free electron's kinetic energy are radiated away. If capture into an excited state, subsequent (line) emission may result as electron cascades down to ground level.

## 3) bound-free (collisional ionization)



Impact of free electron ionizes a formerly bound electron, taking (kinetic) energy from the free electron

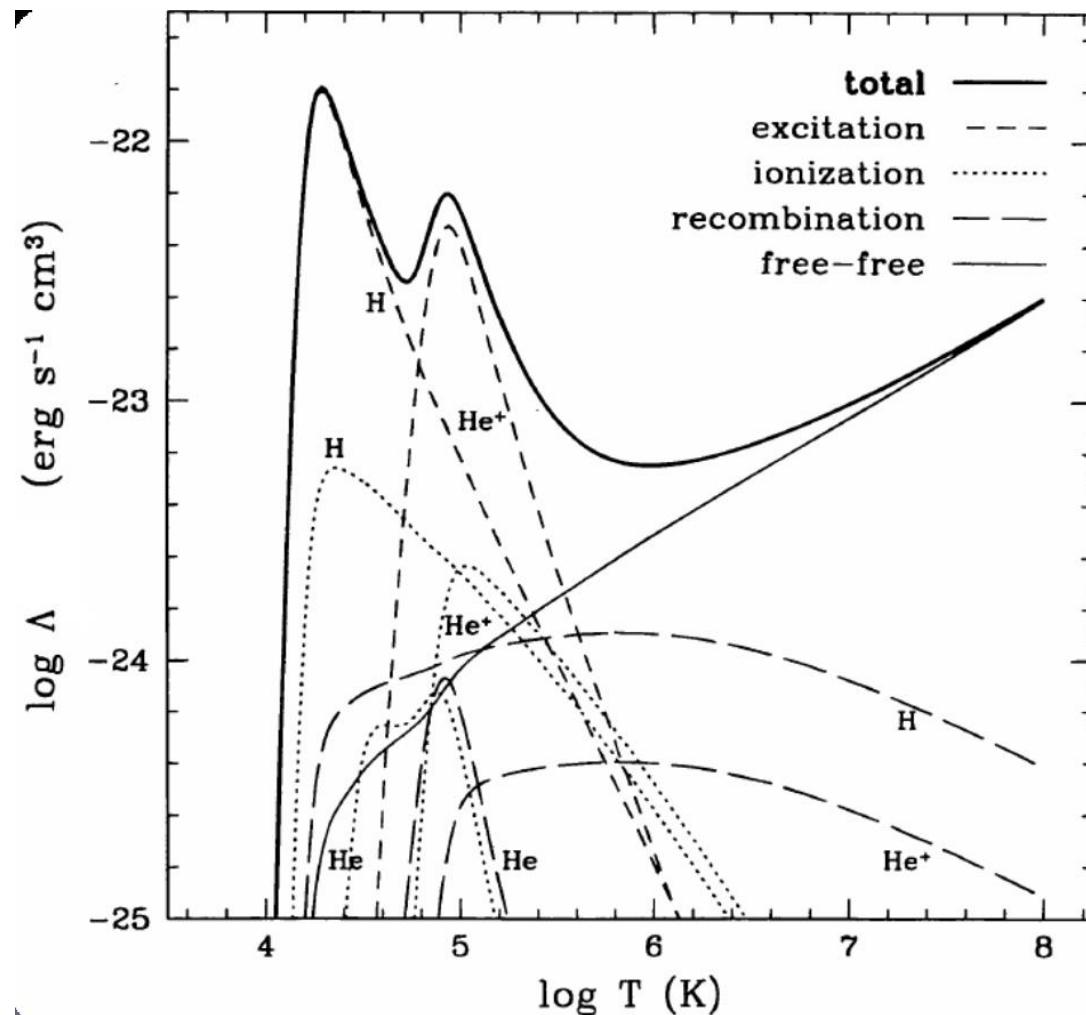
## 4) bound-bound (collisional excitation)



Impact of free electron knocks bound electron to excited state. As it decays, it emits a photon. Note, in case of collisional de-excitation, no photon is emitted (no net cooling)

# Cooling equilibrium and cooling function

The cooling rates depend on the detailed ionic species for each of the atomic species. For instance,  $n_e$ ,  $n_{H_0}$ ,  $n_{H^+}$  for hydrogen. The creation and destruction of those species is short compared to the hydrodynamics, so ionization equilibrium is usually assumed (either photoionization or collisional).



# Cooling equilibrium and cooling function

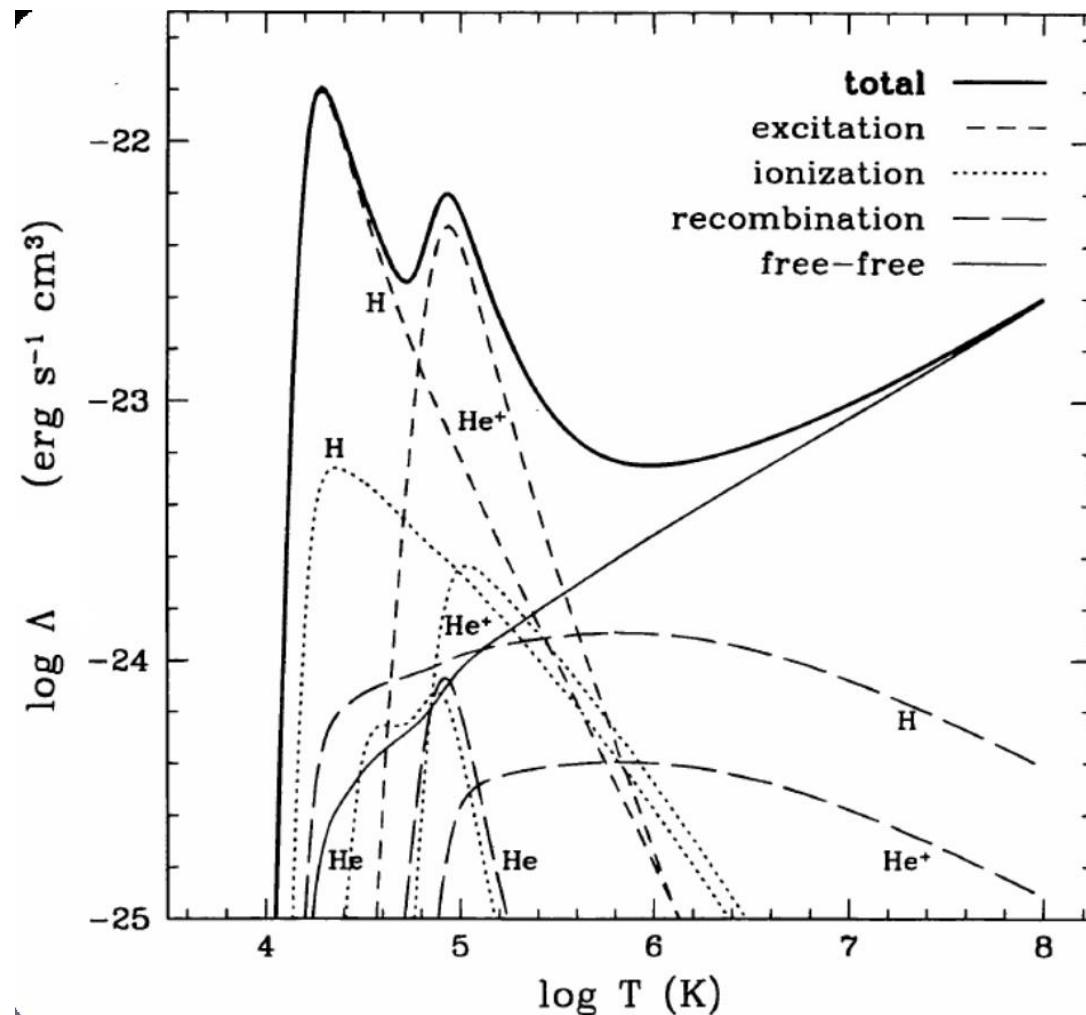
At high T, gas is fully ionized, - only  
bremsstrahlung

At  $T < 10^4$  K, all gas is neutral – no cooling

At  $t \sim 10^4$  K, all H is ionized – cooling peak

At  $t \sim 10^5$  K, He is ionized – second peak.

Other metals contribute depending on their  
structure and abundance



# Cooling equilibrium and cooling function

The cooling rates depend on the detailed ionic species for each of the atomic species. For instance,  $n_e$ ,  $n_{H_0}$ ,  $n_{H^+}$  for hydrogen. The creation and destruction of those species is short compared to the hydrodynamics, so ionization equilibrium is usually assumed (either photoionization or collisional).

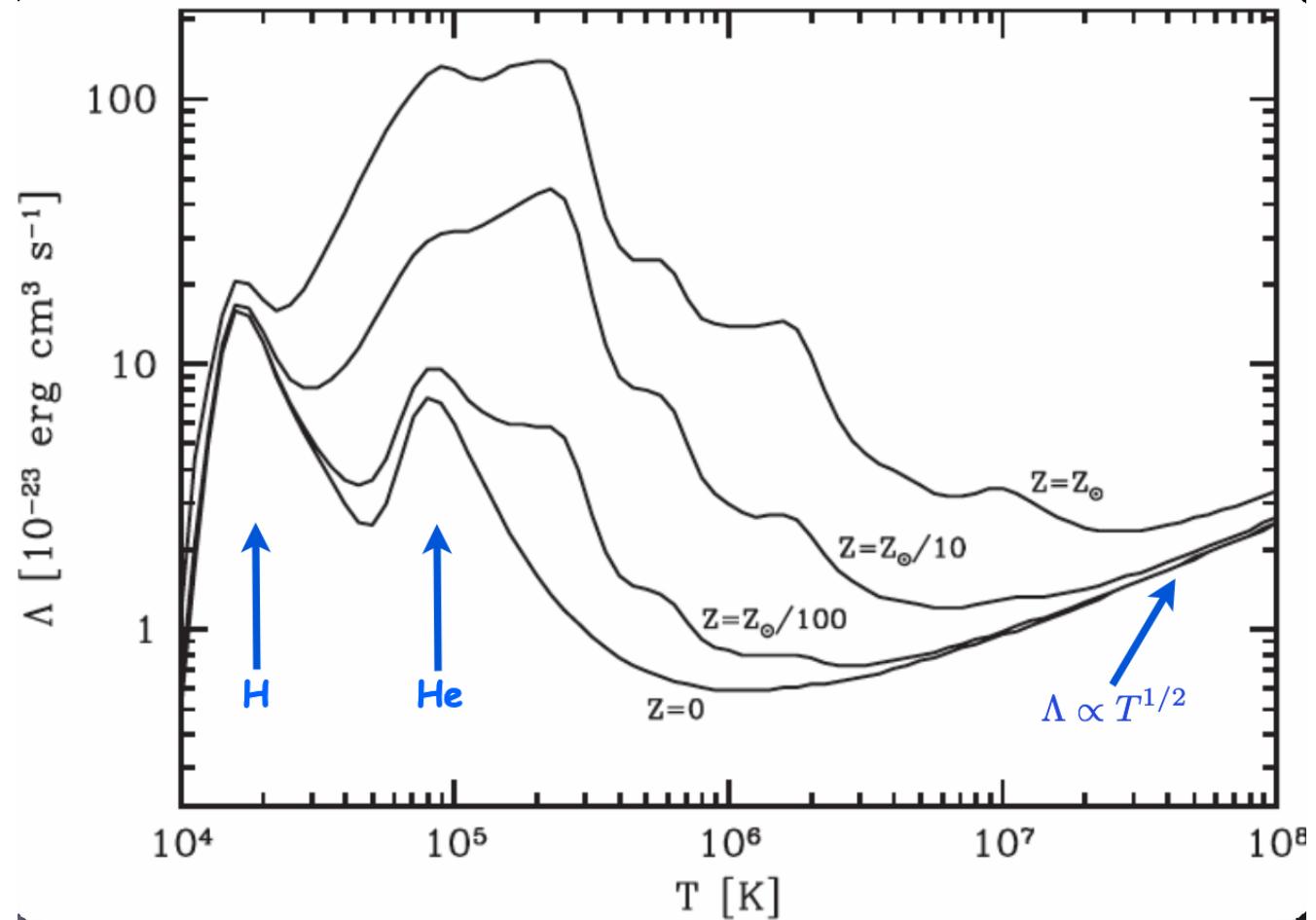
At high T, gas is fully ionized, - only bremmstrahlung

At  $T < 10^4$  K, all gas is neutral – no cooling

At  $t \sim 10^4$  K, all H is ionized – cooling peak

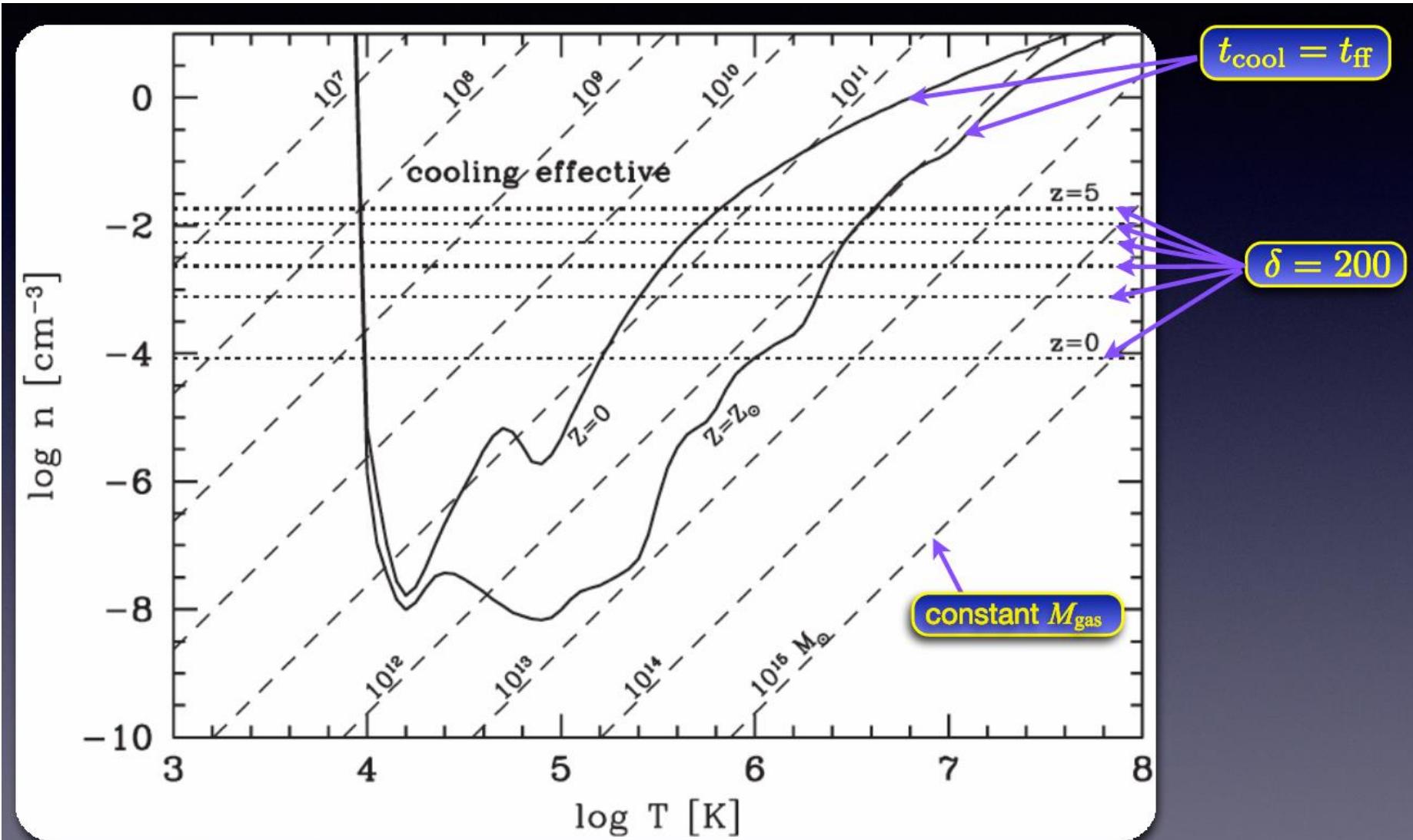
At  $t \sim 10^5$  K, He is ionized – second peak.

Other metals contribute depending on their structure and abundance



# Sites of galaxy formation

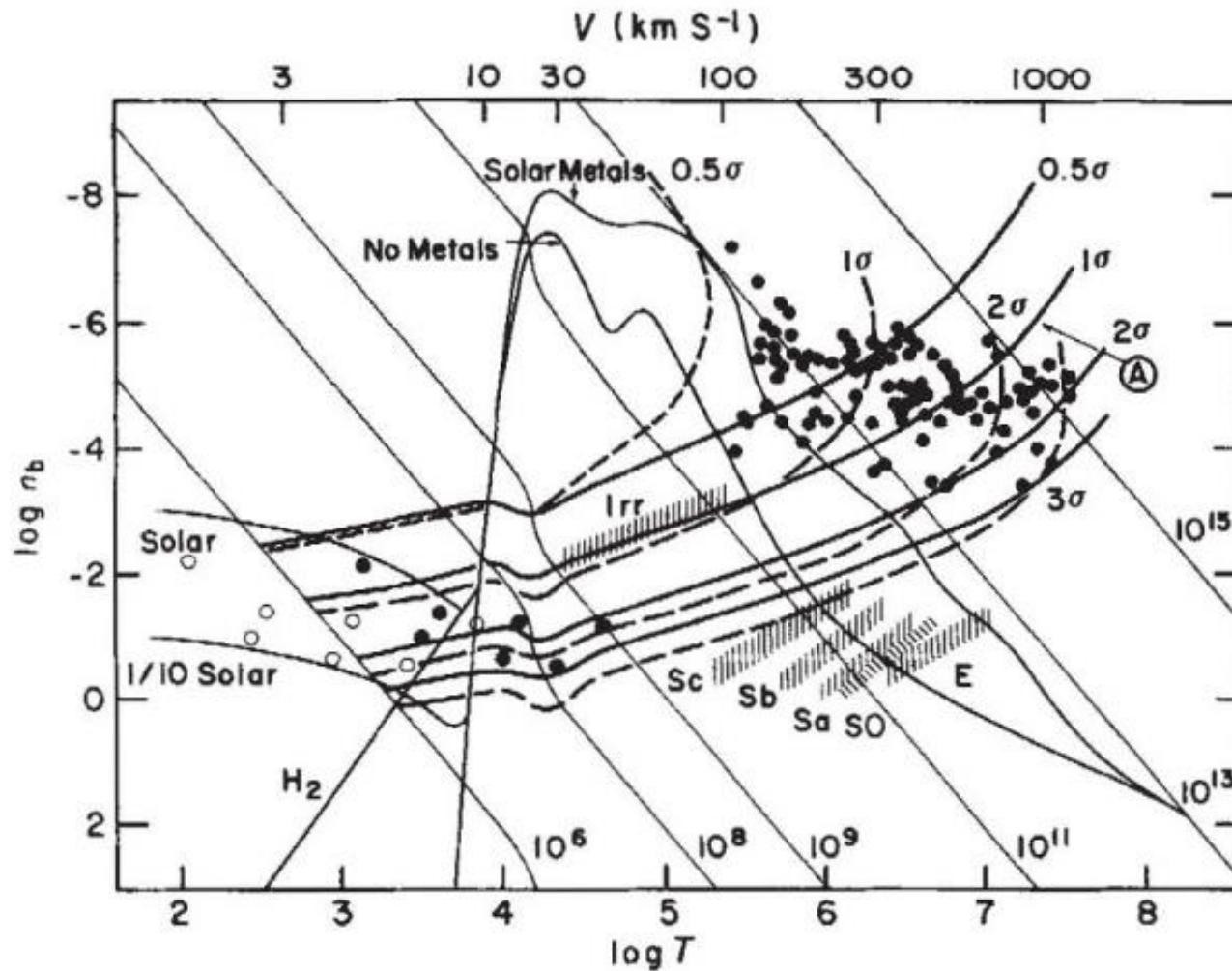
We can plot the location of the  $T_{\text{cool}} = t_{\text{ff}}$  lines in density - temperature space to see the locations of galaxy formation



Neither small or large mass halos can efficiently form

# Sites of galaxy formation

We can plot the location of the  $T_{\text{cool}} = t_{\text{ff}}$  lines in density - temperature space to see the locations of galaxy formation



Neither small or large mass halos can efficiently form

(Blumenthal, Faber, Primack, Rees (1984))