Part IV: Simplest baryonic behaviour and galaxies

What happens to the baryons?

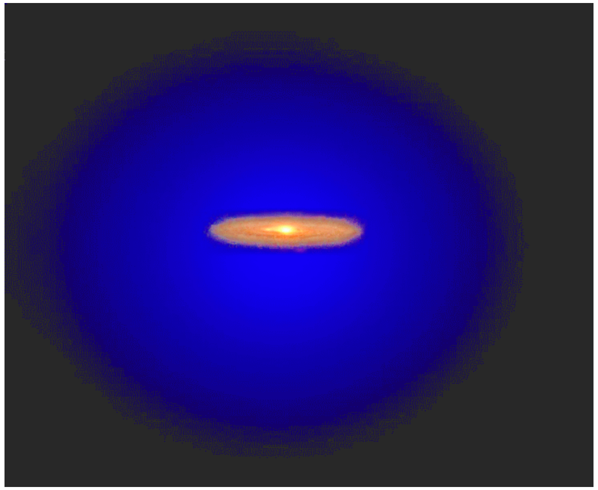
At $z \sim 1000$, (CMB last scattering surface) we have Δ_k for baryon fluctuations $<< \Delta_k$ for DM, because of the lost growth during acoustic oscillations of the former.

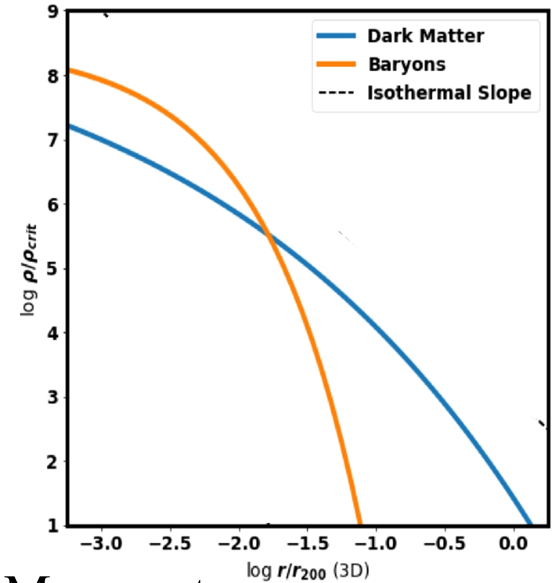
When baryons become neutral atoms, interactions between photons and baryons effectively cease:

- The Universe becomes "transparent" rather than "opaque"
- the pressure of the matter (provided by photons) is substantially reduced. The baryons quickly fall into the gravitational potential wells of the DM fluctuations, so the Δ_k become the same again, and baryons and DM become well mixed.
- thermal coupling between baryons and photons is lost and the baryons cool as R^{-2} (the heat capacity had previously been provided by the photons cooling as R^{-1}) until they become reheated during non-linear structure collapse (see later).

Certainly by the time the first DM haloes form, we would expect the (cool) baryons and DM to be well mixed.

Yet, we know that a "galaxy" represents a concentration of baryons at the center of a DM halo. Question: What causes the baryons to concentrate at the bottom of the potential well?





Answer: Baryons can lose energy by radiative cooling. DM cannot.

First, baryons heat up as their bulk kinetic energy is converted to thermal energy (= individual random kinetic energy) through virialisation and particle-particle collisions.

Energy per particle (= temperature) set by mass and size of the halo (via the virial condition). Typically 10^5K for galaxy mass haloes, up to 10^8K for 10^{15} $M_\odot$ haloes.

$$\frac{3kT}{2m} = \frac{1}{2}v^2 \sim \frac{GM}{R}$$

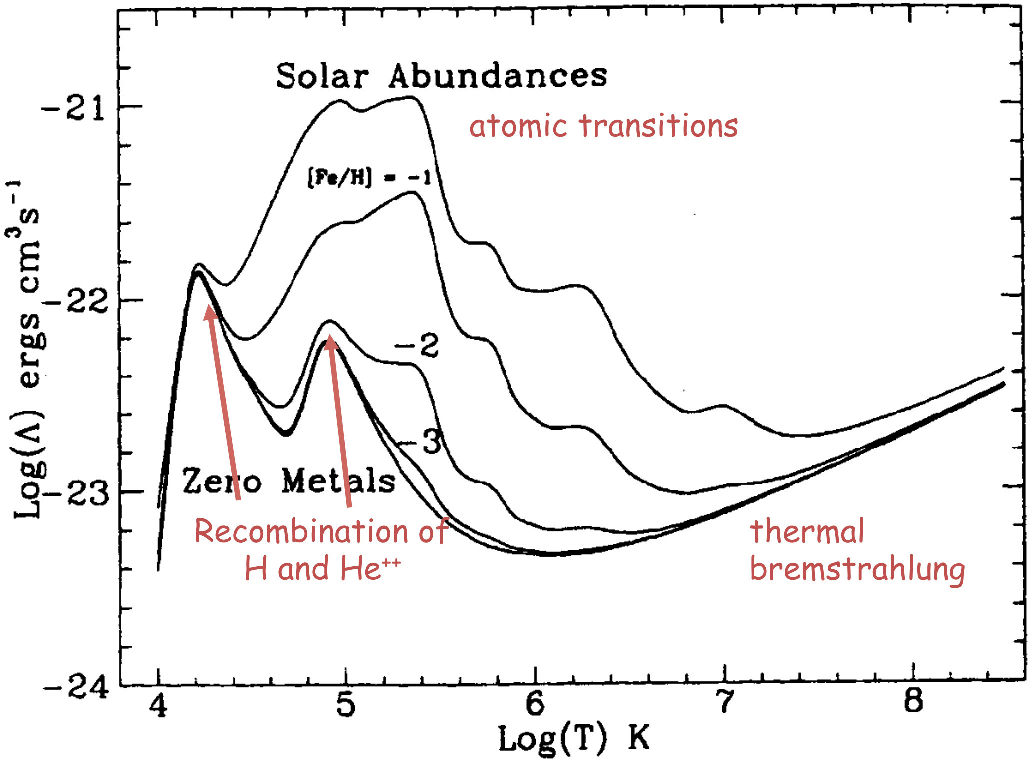
Cooling (dissipation):

Radiative cooling rate of a gas is described by cooling function Λ(T)

$$\frac{dE}{dT} = -n^2\Lambda(T)$$

n^2 because always two-particle processes

Radiative cooling rate of a gas is described by cooling function L(T). The physical processes depend on T: atomic transitions (will depend on composition, free-free Bremstrahlung etc.



Galaxy-mass haloes (10^{12} $M_\odot$) have n and T that should lead to efficient cooling**.

$10^{15}M_\odot$ haloes (forming later, lower n) do not.

**** what do we mean by "efficient cooling"?**

$$t_{cool} \sim \frac{E}{dE/dt} \sim \frac{3kT}{2n\Lambda(T)} << t_H$$

What happens as the gas cools and loses energy

$$\frac{3kT}{2m} = \frac{1}{2}v^2 \sim \frac{GM}{R}$$

As an aside: initially, n increases but T remains the same because it is set by the (fixed) potential (-GM/R) of the DM halo. But. after this isothermal collapse, T starts to increase once the baryons dominate the central potential.

More important: what halts dissipation?

- Either (but probably not relevant) the material becomes non-dissipational (e.g. it is made into stars)
- More important: if the matter is rotationally supported, so that the relative velocities become small in a uniformly rotating disk, the transfer of energy from potential to kinetic to thermal to radiative will cease.

How does the contracting material spin up?

It is convenient to consider a dimensionless angular momentum parameter, λ. This could be constructed in terms of angular momentum J, total energy E, and mass M as follows (Peebles** 1969).

$$\lambda = J E^{1/2} G^{-1} M^{-5/2}$$

For our purposes, matter contracting within a fixed DM halo, a simpler form (Bullock+ 2001) is more useful,, with $j = J/M$ the specific angular momentum of some particular component and V_c the (roughly constant) circular velocity of the halo potential it is moving in.

$$\lambda' = \frac{j}{\sqrt{2}\, V_c r}$$

In this latter form, it is easy to see that

(a) circular orbits imply $\lambda = 2^{-1/2}$, since $j = V_c r$

(b) λ should increase as r^{-1} during contraction. Therefore, contraction will stop when λ reaches

$$\lambda \sim \lambda_0 \left(\frac{r_0}{r} \right)$$

$$r_{\lambda=0.7} \sim \sqrt{2}\, r_0 \lambda_0$$

** Peebles got the Nobel Prize yesterday for "theoretical contributions to cosmology"

What sets λ_0: the origin of angular momentum

Numerical simulations give the initial λ_0 for typical haloes to be of order 0.05, with some scatter, implying $r_{\lambda=0.5} \sim 0.07\, r_0$, i.e. contraction by a factor of ten or more.

This in turn implies that the baryonic density in galaxies is enhanced by ~ 1000 over that in the initial halo, i.e. that it will be of order 10^6 x that of the universe as a whole.

Important point: Uniformly rotating disks of matter, which represent the minimum kinetic energy E for a given J, are the natural consequence of the dissipation of energy in a cooling gas.

Where does the initial $\lambda \sim 0.05$ of the halo come from (since the vorticity in Universe should be zero?
Asymmetric density enhancements produce torques on collapsing structures, transfering angular momentum, especially near the time of turn-around.

Important points (Part IV)

- Soon after recombination, the baryons will be well-mixed with the DM, despite different behaviour during acoustic oscillations phase.

- Baryons can separate from the DM in a halo if the cooling time is short compared with the age of the Universe. This is true for galaxy-mass haloes (around 10^{12} $M_{\odot}$) but not for larger haloes (e.g. 10^{15} $M_{\odot}$) that form later at lower density and higher temperature.

- Cooling gas will naturally form a rotating disk with the gas particles in circular orbits, at which point the rate of loss of energy will be very low.

- Haloes initially form with some small specific angular momentum, due to tidal torques from surrounding asymmetrically distributed material.

- This implies collapse factors of the baryons of order a factor of ten, producing a further factor of 1000 increase in the density relative to the Universe as a whole.