# Natural quenching of stellar formation

Author: Víctor Alfaro Rudilla
*Facultat de Física, Universitat de Barcelona, Diagonal 645, 08028 Barcelona, Spain.*[*]

Advisor: Eduard Salvador Solé

**Abstract:** Observation shows that, over cosmic history, star formation increased until $z = 2$. After that it suffered a strong quenching. Various internal and external causes have been postulated to explain this phenomenon. In this paper, we investigate a third more fundamental possibility, which we call "natural quenching". This quenching would simply arise as the consequence of the growth of halos. According to numerical simulations, the more massive halos, the less concentrated they are so that the gas trapped within them cools at a lower rate. Consequently, over cosmic evolution, the accretion of gas onto galaxies slows down, which translates into a lower star formation rate. The aim of this study is to find the characteristic time at which this natural quenching becomes effective and check whether it coincides with a redshift of about 2.

## I. INTRODUCTION

Observation (see e.g. [1]) shows that the star formation rate density, which was monotonously increasing since the formation of the first stars at a redshift ($z$) of 20, begins to steeply decline when $z$ reaches a value around 2. The reason of such an apparent quenching of star formation is still a matter of debate.

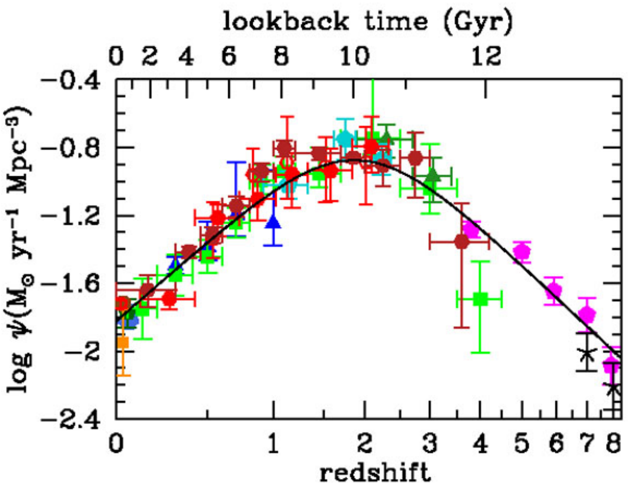


FIG. 1: Madau diagram for the star formation ratio density.

A variety of causes have been proposed which are classified in two big cathegories, namely internal and external causes.

Internal causes are all feedback mechanisms taking place inside galaxies that yield the ejection of their interstellar gas back into the halo. That gas loss thus diminishes or even exhausts the gas available for galaxies to form stars. The main mechanisms of this kind are the winds due to the energy ejection from supernovae accompanying star formation itself [2] and the super-winds or radio jets from active galactic nuclei (AGN) powered by super-massive black holes (SMBH) accreting part of the gas present in galaxies [3].

External causes are not due to the internal physics of galaxies but to their interaction with their surroundings. The main mechanisms of this kind are tidal stripping due to the gravitational interaction of the galaxy with their neighbours [4] and ram-pressure stripping due to the interaction of the galaxy orbiting inside the halo with the intra-halo gas (or inter-galactic medium) which sweeps its inter-stellar gas off. In both cases, the galaxy loses at least part of its inner gas, which automatically quenches the going-on star formation.

However, there is still a third mechanism, which despite being fundamental in the sense that it is directly linked to the growth of galactic halos and the cooling of gas within them fuelling galaxies with new gas is usually forgotten. Quantifying how this process can affect the star formation rate over cosmic time to see whether or not it can play an important role in the quenching of star formation at a redshift of about 2 is the main objective of this work. We insist in that this mechanism which is hereafter referred as "natural quenching" is neither internal nor external as those mentioned before. Of course, even if we find that the characteristic time of natural quenching corresponds to a redshift of about 2 this will not prove that it is the dominant quenching mechanism. But this result would demonstrate that such an additional contribution to quenching must be seriously taken into account.

The aim of this study is thus to estimate the redshift at which this natural quenching will typically begin to operate, neglecting any other possible quenching mechanism. Whether the typical redshift of natural quenching is close to $z = 2$ or not will allow us to assess its possible importance in the general quenching of star formation in

*Electronic address: valfarru7.alumnes@ub.edu

galaxies.

## II. MOTIVATION

To understand how natural quenching takes place, we need to describe how galactic halos grow, how their central density evolves and how this effects the cooling rate of the hot gas trapped within.

The growth of the halo masses, $M_h$, is given by the evolution over time of the halo mass function. Numerical simulations show that such a mass function takes the form given by Press-Schechter [5], which takes the form [6]

$$\frac{\partial n_{PS}(M_h,t)}{\partial M_h} = \frac{\bar{\rho}(t)}{M_h}\frac{\partial V(M_h,t)}{\partial M_h} \tag{1}$$

where

$$V(M_h,t) = \frac{1}{2}erfc\Big[\frac{1}{\sqrt{2}}\frac{\delta_{ci}(t)}{{\sigma_0}^{th}(M_h,t)}\Big], \tag{2}$$

The previous expressions make use of the following functions

$$\delta_{ci}(t) = 1.69/a(t)$$
$${\sigma_0}^{th}(M_h,t) = C{M_h}^{-\frac{n+3}{6}}$$

where $a(t)$ is the cosmic scale factor solution of the Friedman equation, equal to one at the current time $t_0$, index $n$ is equal to $-1.5$, and constant $C$ can be readily derived from the empirical value of the current r.m.s. density fluctuation, ${\sigma_0}^{th}(M_0) = 0.831$, at the scale $M_0 = \frac{4\pi}{3}\bar{\rho}_0 \times (8Mpc)^3$, where $\bar{\rho}_0$ is the mean density of the universe, $\bar{\rho}(t) = \bar{\rho}_0 a^{-3}(t)$.

The halo mass profile is according to the NFW profile [7], which leads to the mass profile [8]

$$M(r) = M_h f(r_s)\Big[\ln\Big(1+\frac{r}{r_s}\Big) - \frac{r}{r+r_s}\Big] \tag{3}$$

where we have introduced the function

$$f(r_s) = \frac{1}{\ln\Big(1+\frac{R_h}{r_s}\Big) - \frac{R_h}{R_h+r_s}}$$

in terms of the total halo radius $R_h$, given at the time $t$ by the virial relation

$$R_h = \Big(\frac{3M_h}{4\pi\bar{\rho}(t)200}\Big)^{1/3} \tag{4}$$

and of the halo core radius $r_s$, which is related to the mass $M_s$ inside it, through the relation [8]:

$$r_s = KM_s^{\alpha} \tag{5}$$

In equation (4), $\alpha$ is equal to 0.308 and $k = r_0/(M_0)^{\alpha}$ (see [8] for the values of $r_0$ and $M_0$ in the WMAP7 cosmology used here).

Finally, the rate density at which the hot gas trapped within halos cools and fuels the central galaxy giving rise to star formation takes the form (see [9] and references therein)

$$\dot{\epsilon} = \Lambda n_e^2 = A\rho_s^2 \tag{6}$$

where $\Lambda$ is the Dopita-Sutherland gas emissivity, equal to $5\times10^{-23}ergs^{-1}cm^3$, and $\rho_s$ is the halo density at the core radius $r_s$, so that constant $A$ is given by $f_b^2\Lambda/(4m_p^2)$, where $m_p$ is the proton mass (for simplicity, we assume a purely fully ionized hydrogenic gas), and $f_b$ is the well-known cosmic baryonic mass fraction $\Omega_b/\Omega_m = 0.65$ .

From the previous equations, we can infer some conclusions. According to the evolution of halo mass function, eqs. (1) and (2), since the typical mass of halos increases with time, so does also the mass of gas trapped in halos (the mass ratio $f_b$ is constant). But the gas cooling rate, eq. (6) is proportional to the square of the central halo density $\rho_s$, which diminishes with increasing halo mass as indicated by the dependence of $r_s$ on halo mass, eqs. (3) to (5) the halo concentration $c \equiv R_h/r_s$ decreases with increasing halo mass). Consequently, we expect the total amount of gas being accreted onto galaxies to have a maximum at some moment between the time of first star formation ($z\sim30$) and the current time ($z=0$).

The existence of that maximum makes us expect the fuelling of gas into galaxies, which increases at the beginning more rapidly than the rate at which the Universe expands, to eventually become smaller. In other words, there should be a redshift $z_q$ at which star formation stops increasing with increasing time and begins to decrease. This redshift will thus mark the redshift of natural quenching we are interested in.

## III. MODELING NATURAL QUENCHING

According to the preceding reasoning, in order to derive $z_q$ we need to equal the typical characteristic time of gas cooling inside halos with the characteristic time of cosmic expansion or, equivalently, their respective inverse values

$$\frac{\dot{\epsilon}}{\epsilon} = \frac{\dot{a}}{a} \tag{7}$$

The right-hand member of eq. (7) can be readily obtained from the solution of the Friedmann equations for a flat Universe (neglecting the dark energy)

$$a(t) = t^{2/3} \tag{8}$$

with $t$ in units of the current age of the universe $t_0 = 13.8$ Gyr, from which we can readily obtain its time derivative $\dot{a}$.

Regarding the left-hand member of eq. (7), the cooling rate density $\dot{\epsilon}$ is given by eq. (6), while the density of specific kinetic energy of the gas is

$$\epsilon = \frac{3}{2}\frac{M_g}{V_h}\frac{kT_g}{m_p} \tag{9}$$

where $M_g$ is the mass of gas contained in the halo, equal to $f_b M_h$, $V_h = 4\pi R_h^3$ is its volume, $T_g$ is the gas temperature and $k$ is the Boltzmann constant.

In order to find the quenching time $t_q$, we need to express all quantities appearing in the left-hand member of eq. (7) in terms of the halo mass $M_h$ and $t$, then find the typical halo mass $M_h^*$ as a function of time, $t$, and finally substitute such an expression into that equation.

### A. Cooling time as a function of halo mass

The density of kinetic energy of the gas, eq. (9) is related to the halo mass through the virial relation

$$3\frac{kT_g}{m_p} = \frac{GM_h}{R_h} \tag{10}$$

where $G$ is the Newton's gravitational constant, where the halo radius $R_h$ is also the function of $M_h$ and $t$ given by eq. (4).

This leads to

$$\epsilon(t) = \frac{f_b G}{4a(t)} {M_h}^{2/3} \Big(\frac{4\pi}{3}\Big)^{1/3} (\bar{\rho}_0 200)^{4/3} \tag{11}$$

On the other hand, we also need to write the cooling rate density, eq. (6), in terms of $M_h$. This is readily done, taking into account the relation

$$\rho_s = \frac{3M_s}{4\pi {r_s}^3} \tag{12}$$

which, given the relation (5) between $r_s$ and $M_s$, leads to

$$\dot{\epsilon} = \frac{f_b^2 \Lambda}{4m_p^2} \left( \frac{3M_s^{1-2\alpha}}{4\pi K} \right)^2. \tag{13}$$

Of course to accomplish our goal we still need to express the inner mass $M_s$ in terms of the total halo mass $M_h$. This is done by making use of eq. (7) for $r = r_s$, taking into account once again the relation (5) between $r_s$ and $M_s$. By doing this we arrive at

$$M_s(M_h, t) = \left\{ \frac{\dot{a}(t)}{a^4(t)} B {M_h}^{2/3} \right\}^{\frac{1}{2-6\alpha}} \tag{14}$$

where $B = 4\pi^2 f_b G K^6/(9A)(4\pi/3\bar{\rho}_0^4 200^4)^{1/3}$.

### B. Typical halo mass at a given cosmic time

But the previous expressions give the typical cooling time of halos of arbitrary mass $M_h$ at $t$, whereas what we actually need is the typical halo mass at that time, $M_h^*(t)$.

In order to find that, we will use the Press-Schechter mass function, eq. (1). We must differentiate it with respect to $M_h$ and equal it to zero. The result is the most abundant halo mass, given by

$${M_h}^*(t) = \left[ \frac{(n-9)a^2(t)}{2(n+3)E^2} \right]^{\frac{3}{n+3}} = Da^4(t) \tag{15}$$

where the constant $D$ is equal to $(3.5/E^2)^2$, being $E = 1.69/\sqrt{2}C$ (remember that index $n$ is equal to $-1.5$).

## IV. RESULT

Substituting the halo mass $M_h$ in the quenching condition, eq. (14), by the expression of the typical halo mass at $t$, $M_h^*(t)$, given by eq. (15), we are led to the wanted equation for the quenching time $t_q$.

Unfortunately this is an implicit equation for $t$ so that it must be solved numerically. The result we obtain is $t_q \approx 9 \times 10^{-2} t_0$.

Given the relation between cosmic time and redshift

$$1 + z = a^{-1}(t), \tag{16}$$

this leads to a quenching redshift of $z_q \approx 4$.

## V. CONCLUSIONS

The redshift of natural quenching we have obtained is not far from $z = 2$. Taking into account the number of approximations and simplifying assumptions we have used in our derivation, this result is very encouraging as it shows that natural quenching by itself could be enough to explain the observed behaviour of the cosmic evolution of the star formation rate density.

We should therefore re-calculate everything without making such approximations and simplifying assumptions and looking for the exact median cooling rate for halos of different masses given their distribution at any cosmic time instead of adopting the typical halo mass.

If the result were always very close to $z = 2$ it would be worth trying to assess whether natural quenching is really predominant in comparison to other internal and external quenching mechanisms. This latter calculation is however much harder to perform as all internal and external mechanisms are hard to estimate. The only practical way to do that is by means of a complete model of galaxy formation including all the different effects as the AMIGA model developed by the team led by Dr. Salvador-Solé.

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