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Galaxy formation and reionisation

Eduard Salvador Solé[*†]
Institut de Ciències del Cosmos. Universitat de Barcelona (UB-IEEC), E-08028 Barcelona, Spain
E-mail: e.salvador@ub.edu

Alberto Manrique and David Canales
Institut de Ciències del Cosmos. Universitat de Barcelona (UB-IEEC), E-08028 Barcelona, Spain
E-mail: a.manrique@ub.edu

I review the present knowledge of two fundamental processes in cosmology: galaxy formation and reionisation. After a brief description of the observations informing on reionisation, I then focus on the theoretical modelling of galaxy formation and the evolution of the intergalactic medium. I show that all the information we currently have on cosmic evolution at high-z combined with the preceding one on reionisation allows us to severely constrain the reionisation process. Special attention is paid to the possible implications on that scheme of some recent unexpected observations.

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1. INTRODUCTION

Galaxy formation and reionisation are two intertwined fundamental issues in modern cosmology. Indeed, it is nowadays believed that the reionisation of the cosmic gas outside galaxies after it became essentially neutral at a redshift of $z \sim 1100$ is the result of the ionising emission from luminous sources, which also reheated it and enriched it with metals and left as remnants the seeds of supermassive black holes (SMBHs) and reheated it. Conversely, the evolution of the intergalactic medium (IGM) also plaid a crucial role in galaxy formation, as the temperature, metallicity and ionisation state of the IGM determined at a great extent the possibility that it were trapped by haloes of different masses, cooled within them and fed galaxy growth. However, that general scheme is still to be confirmed and the details of the process to be determined.

In this contribution I give a brief review of the observational information we currently have on reionisation and explain the big progress expected to be achieved on that line in the near future. On the other hand I describe the connection between reionisation and galaxy formation from a theoretical viewpoint and show how the information we also have on the global cosmic evolution since very high-z, combined with the information on reionisation, can be used to severely constrain the epoch of reionisation (EoR), i.e. the way galaxies formed and evolved and their effects on the IGM, in particular on reionisation.

2. Observational basis of reionisation

As of today, all the information we have on reionisation is partial. It comes from the light of distant sources and the CMB radiation. However, there is founded hope that we will soon be able to directly probe the EoR by means of 21 cm line observations.

2.1 Distant luminous sources

Distant sources allow us to determine the ending redshift of reionisation. Indeed, the absence of global absorption shortwards of the rest-frame Lyman-α (Lyα) emission line seen in the spectra of quasars at $z < 3$ made [60] realise that the hydrogen present in the nearby intergalactic medium (IGM) was ionised ($x_{\rm HI} < 10^{-4}$) except for small intervening systems yielding discrete absorption lines, the so-called Lyα forest. The Gunn-Peterson trough caused by neutral intergalactic hydrogen was finally found by [5] and [42] in the spectra of quasars at $z \sim 6$, suggesting that value for the redshift $z_{\rm ion,H}$ of ionisation completion.

Several subsequent studies using: (a) the mean opacity of the Lyα forest [49]; (b) the size of the proximity zone around quasars [170, 49, 10, 86, 93]; (c) the detection of damping wing absorption by neutral IGM in quasar spectra [102, 103, 113]; (d) its non-detection in the spectra of gamma ray bursts [159, 97]; (e) the abundance of Lyα emitters (LAEs) [90, 61, 55, 97, 101, 123, 80]; and (f) the covering fraction of dark pixels in the Lyα and Lyβ forests [95] confirmed a value of $z_{\rm ion,H}$ of $6.0^{+0.3}_{-0.5}$.

The fact that the number of LAEs decreases very steeply beyond $z = 6$ is particularly illustrative. The number density of LAEs at $z = 7$ seems indeed to be only 18-36 per cent of the density at $z = 6.6$ [75], there being no spectroscopically confirmed LAE at $z > 7$ ([122], but see the end of this talk). The fact that we still see LAEs at $z > 6$ is well understood. Lyα photons are somewhat redshifted in origin due to the velocity of the emitting gas clouds and, more importantly, due to the fact they are also redshifted when leaving the ionised bubbles around galaxies. As the higher z, the smaller ionised bubbles, such an effect, which is notable at z near 6, becomes negligible at $z \sim 7$ where the volume filling factor of ionised regions, $Q_{\rm HII}(z)$, has greatly decreased.

2.2 The CMB radiation

Another partial information on reionisation arises from the analysis of the large-scale cosmic microwave background (CMB) anisotropies. Thomson scattering of free electrons by CMB photons yields an absorption and polarisation of that radiation which remains imprinted in the temperature power spectrum and the E-mode polarisation power spectrum, both on large angular scales. Unfortunately, such imprints are integral effects so that different reionisation histories yield identical results. The usual way to leave that degeneracy is to assume instantaneous reionisation and adjust the values of $z_{\rm ion,H}$ and the optical depth, τ.

The 9-year data gathered from the *Wilkinson Microwave Anisotropy Probe* (WMAP9, [67]) led to $\tau = 0.089 \pm 0.014$, while the three-years temperature *Planck* data combined with the polarisation WMAP data yielded $\tau = 0.078 \pm 0.014$ [125], and the most recent data inferred from the own large-scale polarisation anisotropies have further decreased it to $\tau = 0.058 \pm 0.012$ [126].

The corresponding values of $z_{\rm ion,H}$ are 10.6 ± 1.2, $9.9^{+1.8}_{-1.6}$ and $8.8^{+0.9}_{-0.8}$. The marked difference from the previous value of $z_{\rm ion,H} \sim 6$ indicates that reionisation, far from being instantaneous, ought to be extended, and possibly non-monotonous [173, 30, 32, 69, 62, 149, 115, 57, 53, 172, 11].

The small-scale temperature power spectrum can also inform on the duration Δz of reionisation through the kinetic Sunyaev-Zel'dovich effect. However, this piece of information is greatly disturbed by dust emission whose correction is hard to achieve.

Another integral quantity that constrains the EoR, similar to τ but more sensitive to low redshifts, is the weak comptonisation distortion of the CMB radiation spectrum. Although its measured upper limit of $y < 1.5 \times 10^{-5}$ [94] is a rather loose constraint, it has the advantage with respect to τ of being inferred with no modelling.

2.3 The 21 cm line

The hyperfine 21 cm line is a powerful tool to directly probe the EoR (see [111] for a comprehensive review). Neutral hydrogen is seen in absorption or emission over the CMB continuum depending on whether the spin temperature, $T_{\rm S}$, is lower or higher than the CMB temperature, respectively. This line is optically thin, so by varying the frequency in the observer frame one can have a tomography of the cosmic H I content over redshift. Specifically, the brightness temperature of the 21 cm line at the redshift z depends on the density of neutral hydrogen and the spin and CMB temperatures at that z through the expression

$$\delta T(z) \approx 0.14K \times x_{\rm HI}(z)\Omega_{\rm b}h\left(\frac{1+z}{\Omega_{\rm m}}\right)^{1/2}\left[1-\frac{T_\gamma(z)}{T_{\rm S}(z)}\right] \tag{2.1}$$

where $x_{\rm HI}$ is the neutral hydrogen fraction, $\Omega_{\rm m}$ and $\Omega_{\rm b}$ are the matter and baryon density parameters in the flat Λ Universe and h is the Hubble constant in units of 100 Km s^{-1} Mpc^{-1}. Therefore, as $T_\gamma(z)$ is known from the current value of the CMB temperature, by measuring $T_{\rm S}(z)$ we can estimate $x_{\rm HI}(z)$.

T_S can be obtained from the kinetic temperature T_K of the gas. Indeed, at $z > 30$ the gas density is so large that collisions warrant $T_S = T_K$, with T_K decaying adiabatically since $z \sim 150$ (until then the gas was coupled to the CMB radiation through Compton scattering with residual electrons). At lower z T_S tends to meet T_γ. But, at a redshift of about 20, stars begin to form and Lyα photons couple again T_S to T_K (the Wouthuysen-Field effect), which begins to rapidly increase heated through X-rays mainly produced in supernovae and the Lyα photons themselves.

Therefore, the problem with this method is not only the difficulty to measure the cosmological 21 cm signal, which is 5 orders of magnitude smaller than the synchroton emission from the Galaxy, but also that it relies on the accurate modelling of galaxy formation and the evolution of the IGM temperature (see below).

Last week [18] reported the detection of a weak absorption line on the CMB continuum which is believed to correspond to the wanted 21 cm line signal. However, the shape of that absorption feature is quite unexpected. We will comback to this point at the end of the talk.

3. Theoretical insight

Among the various mechanisms that might cause reionisation (see e.g. [31]), the most simple and natural one is photo-ionisation by luminous sources, namely active galactic nuclei (AGN), normal galaxies with ordinary Population II (Pop II) stars, and first generation metal-free Population III (Pop III) stars. The X-ray background demonstrates that AGN emit typically one order of magnitude less UV photons than needed at $z \sim 6$ [169, 29, 99]. This implies that either massive SMBHs are too scarce [167], or their associated AGN are too obscured by dust [161], while more abundant mini-quasars associated with stellar black holes would have too short duty cycles [2, 105]. Likewise, the star formation rate (SFR) densities derived from the rest-frame UV luminosity functions (LFs) of normal bright galaxies [96, 88, 14, 15] show that these objects are insufficient to ionise the IGM by $z \sim 6$. Therefore, ionisation should be achieved either as the result of a substantial abundance of faint star-forming galaxies [136, 74, 17] or of the still undetected Pop III stars [149, 144].

The situation is even more uncertain regarding He II reionisation. The He II mean opacity inferred from the Lyα forest suggests that the redshift of complete He II reionisation, $z_{\rm ion,He}$, should be less than or approximately equal to 3 [135, 142, 43, 98, 6], and probably no smaller than 2 as the AGN emission begins to decline at that redshift [29]. AGN are indeed the most plausible ionising sources responsible of He II reionisation as they emit more energetic photons than normal galaxies and Pop III stars, the other sources of energetic photons, do not form at $z < 6$.

Therefore, the full characterisation of the EoR from the CMB anisotropies or the 21 cm line observations relies on the theoretical modelling of galaxy formation.

3.1 Galaxy formation

The modelling of galaxy formation has been a subject of intense work since the pioneer work by [133], [145], [166], [21] and [165]. This has been carried out by means of hydrodynamic simulations (e.g. [158, 156, 153, 114, 154, 140, 46, 41, 168, 121, 141, 117] as well as semi-analytic models (SAMs) (e.g. [77, 26, 150, 76, 34, 66, 9, 104, 19, 110, 134, 52]).

SAMs are more practical and inform more easily on the typical properties of objects. They have the bad reputation of describing the baryon physics by means of simple recipes with a very large number of free parameters. But simulations, which are believed to be based on first principles only and to provide more accurate and detailed information, involve the same recipes and parameters as SAMs at subresolution scales. On the other hand, they are more CPU expensive and hard to deal with.

A general problem with all those models is that they are not complete as they do not include molecular cooling at the base of the first generation zero-metallicity Population III (Pop III) stars, which caused the initial reheating and metal-enrichement of IGM and released the seeds of SMBHs that evolved into active galactic nuclei (AGN). What is worse, the feedback on IGM is not self-consistently modelled, but it is dealt with in a rather arbitrary way through some parameters to be adjusted.

3.1.1 Feedback on IGM

The impact of galaxy formation on the IGM began to be addressed in a series of papers studying mechanical heating by active galactic nuclei [19, 35], radiative heating through X-rays produced in supernovae [166, 40, 28, 165, 83, 119] and ionisation from young stars [72, 132, 143, 108, 106, 47].

The IGM evolution is described by a couple of differential equations for its ionisation state and temperature with some source functions provided by a galaxy model. It is in this latter part where most approximations and simplifying assumptions are made, depending on the particular approach followed, namely hydrodynamic simulations [129, 164, 116, 27, 173, 73, 120, 160, 4, 147], numerical and semi-numerical simulations [177, 50, 176, 148], pure analytic models [63, 157, 44, 54, 1, 78], and semi-analytic models [3, 47, 100, 52, 171], each of them with its pros and cons.

Most of the previous works assume simple hydrogenic composition and a constant, uniform temperature, equal to that of photoionised hydrogenic gas ($\sim 10^4$ K). The first coupled equations for the IGM ionisation state and temperature after reionisation taking into account the dependence of the latter on the hydrogen and helium abundances and local density of the gas [107] were derived by [70]. And [71] and [69] extended them to the EoR itself. [24] derived the equations taking into account the full composite, inhomogeneous, and multiphase nature of IGM (i.e., singly and doubly ionised regions embedded within a neutral background; [109]).

On the other hand, the source functions are calculated assuming an evolving *universal* halo mass function (MF), while the halo MF is different in ionised and neutral regions because as the mass of haloes able to trap gas and form stars depends on the temperature and ionisation state of the IGM. [92] derived for the first time the equations governing the IGM evolution, taking into account all these effects.

3.2 Coupled evolution of galaxies and IGM

But, as mentioned in the introduction, to model in a fully self-consistent way galaxy formation and reionisation one must account for the coupled effects of one on each other.

In the last few years a big effort has been done along this line in the hydrodynamic cosmological simulations of last generation, such as the so-called Horizon-AGN project [8], First Billion Year project [37], the Technicolor Dawn project [51], and the SPHINX [138] project.

However, the goal has been only partially accomplished as none of these cosmological simulations is complete enough. For instance they include the parallel growth of SMBHs and AGN feedback, but the seeds of SMBHs are put in an adhoc way and the same is true for the origin of metals. Indeed, none of these simulations include molecular cooling and Pop III star formation and feedback.

Another important limitation of all these models is, as mentioned, the large number of free parameters they harbour. Such a freedom facilitates, of course, the recovery of the data one is interested in, but at the cost of making the result less reliable. This is particularly true because these models are usually used to explain very specific phenomena only, whereas the model capabilities to recover other observables is not checked.

4. Observations on cosmic evolution

There is nowadays numerous observational data on the evolution of Universe since the Dark Ages.

The most representative datasets of each kind (and their references) are the following:

(a) The cold gas mass density history [124, 128, 130, 84, 175, 22, 39].

(b) The stellar mass density history [131, 155, 58, 59, 81, 82, 112, 25].

(c) The SMBH mass density history (following [85], taking into account the universal SMBH to spheroid mass ratio [79] times the spheroid to total stellar mass ratio [56]).

(d) The hot gas metallicity history [152, 137, 146, 45, 38].

(e) The cold gas metallicity history ([89, 151, 36, 174]).

(f) The stellar metallicity history ([64, 151]).

(g) The IGM metallicity history (based on estimates by [137, 146, 45]).

(h) The galaxy morphology history (specifically, the fraction of spheroid-dominated galaxies with masses $> 10^{11}$ M$_\odot$, [23, 20, 162, 127]).

(i) The galaxy size history (specifically, the median effective radii of spheroid-dominated galaxies, [23, 163]).

(j) The SFR density history [131, 88, 16, 118, 33, 48, 68].

(k) The H I-ionising emissivity history (from galaxies [7], and from AGN [29])

(l) The IGM temperature history [87, 12, 13].

Moreover, we have a few differential properties at discrete redshifts:

(m) the galaxy stellar MFs (or UV LFs),

(n) the SMBH MFs (or AGN optical and X-ray LFs)

and SFR vs. galaxy stellar mass or galaxy star-forming main sequences.

All this information should be taken into account by any model of galaxy formation and IGM evolution such as AMIGA pretending to be trusted.

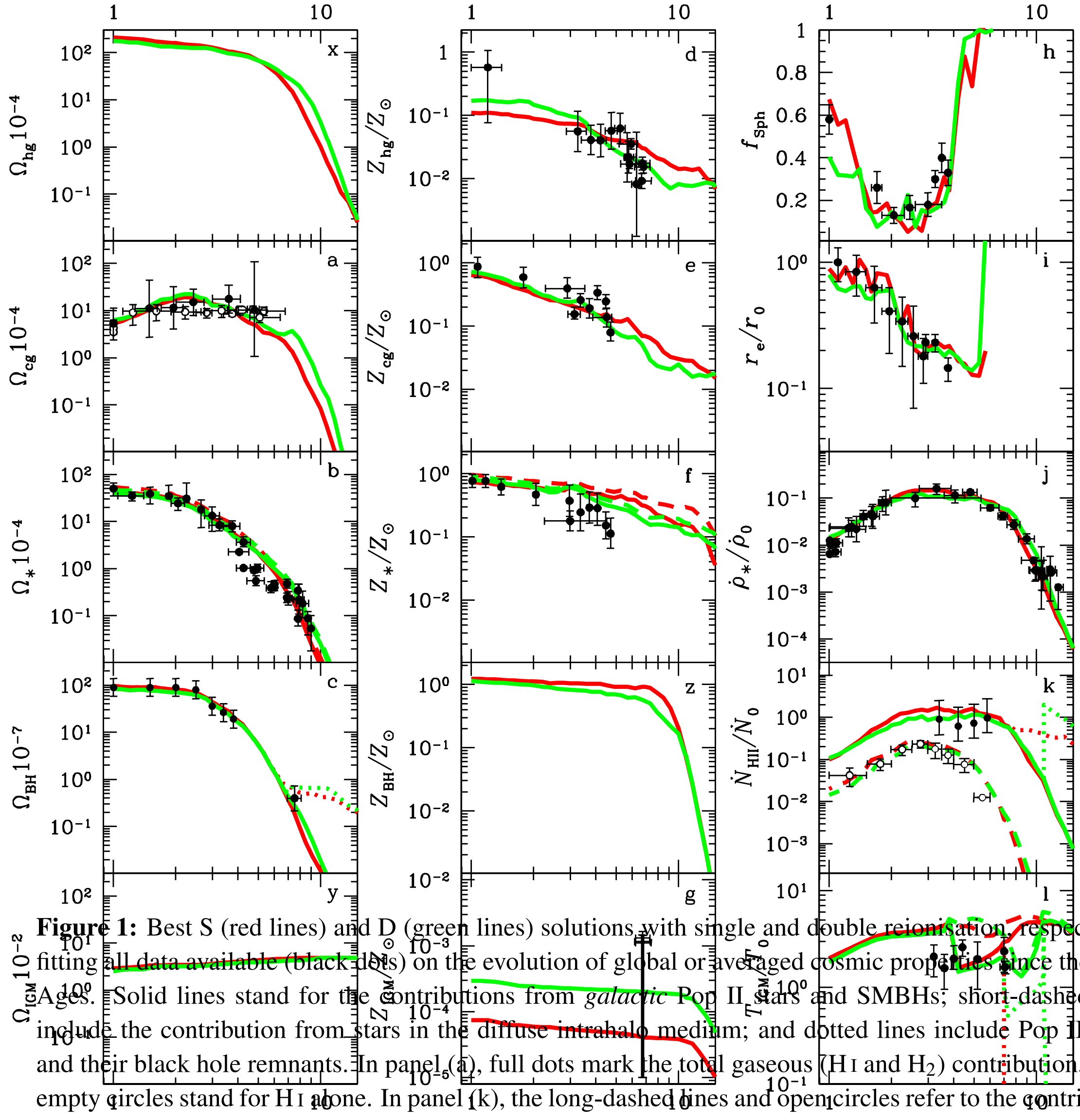

Figure 1: Best S (red lines) and D (green lines) solutions with single and double reionisation, respectively, fitting all data available (black dots) on the evolution of global or averaged cosmic properties since the Dark Ages. Solid lines stand for the contributions from *galactic* Pop II stars and SMBHs; short-dashed lines include the contribution from stars in the diffuse intrahalo medium; and dotted lines include Pop III stars and their black hole remnants. In panel (a), full dots mark the total gaseous (H I and H_2) contribution, while empty circles stand for H I alone. In panel (k), the long-dashed lines and open circles refer to the contribution from AGN, and in panel (l), solid, dashed, and dotted lines show the predictions for singly ionised, doubly ionised, and neutral regions, respectively (the dotted lines are shifted a factor 500 upwards at z higher than the redshift of first or unique ionisation). No observational data are available for the intrahalo gas mass density (x), IGM mass density (y), and metallicity of the matter fallen into SMBHs (z), whose predictions are plotted here for completeness. Density parameters are scaled to the critical cosmic density $\bar{\rho}_0$ at $z = 0$. The remaining scaling factors are: $r_0 = r_e(z = 0)$, $\dot{\rho}_0 = 1$ M$_\odot$ yr^{-1} Mpc^{-3}, $\dot{N}_0 = 10^{51}$ photons s^{-1} Mpc^{-3}, and $T_0 = 10^4$ K.

5. The AMIGA model

AMIGA (Analytical Model of IGM and GAlaxy evolution) [91] is the most complete, fully consistent model of galaxy formation model built so far.

It includes all the theoretical developments in the monitoring of luminous sources and IGM mentioned above as well as other technical improvements which make it particularly accurate. Indeed, the properties of dark matter haloes and their baryon content are dealt with by interpolating them in grids of masses and redshifts that are progressively built from trivial boundary conditions as haloes merge and accrete. This procedure is less computer memory-demanding than the usual method based on Monte-Carlo or N-body realisations of halo merger trees, and enables one to reach redshifts as high as wanted and halo masses as low as needed while maintaining a good sampling over the entire redshift and mass ranges. In this way one can integrate at every z the feedback of luminous sources for the halo MF (in ionised and neutral regions separately) and accurately evolve the IGM.

The number of free parameters in AMIGA is greatly reduced in comparison to other galaxy formation models thanks to causally linking physical processes that are usually treated as independent from each other. In fact, the 9 free parameters left are fully constrained through the fit to the observational information on reionisation described in Section 2 and the information on the main cosmic properties given in Section 4.

All the acceptable solutions found [139] are tightly grouped in two narrow sets, one for moderately top-heavy Pop III star initial mass functions (IMFs) leading to single reionisation with $\tau = 0.072^{+0.004}_{-0.005}$, and another one for top-heavier Pop III star IMFs leading to double reionisation with $\tau = 0.102^{+0.001}_{-0.001}$ (see Fig. 2). The first ionisation phase in the latter solutions is driven by Pop III stars until $z \sim 10$, and after a short recombination period a second ionisation phase takes place, driven by normal bright and faint galaxies. While in the solutions with single reionisation, both kinds of sources compete in parallel.

Both kinds of solutions give excellent fits to all the 13 independent observed cosmic histories (Fig. 1), the galaxy stellar MFs and the galaxy star-forming main sequences at different redshifts, being the first time that a galaxy formation model fits all the information available on cosmic evolution.

The CMB Thomson optical depth found in double reionisation, though consistent with the observational estimates from the *WMAP* 9-year and *Planck* three-year data, is 3σ larger than the most recent estimate from the Planck data. While the CMB optical depth found in single reionisation is consistent with that estimate. Thus, τ favours the single reionisation scenario. However, double reionisation cannot be rejected yet. Indeed, the uncertainty in τ is still big and, what is more important, it has the following advantages. First, it can explain in a simple natural manner the Lyα-emitting galaxies recently observed at $z \sim 9$ [178, 65], together with the gap in their distribution between $z \sim 7$ and ~ 9. Second, the strange shape of the 21 cm line signal reported by [18] could also be naturally explained. Indeed, Lyα photons are only present in a thin shell around ionised bubbles, with an intermediate temperature between those in the ionised bubbles and in the deep neutral background, so in equation (1) we should replace $x_{\rm HI}(z)$ by the fraction of neutral hydrogen in those shells, $x_{\rm lya}(z)$, and $T_{\rm S}$ by the corresponding temperature, $T_{\rm lya}$. The fact that $T_{\rm lya}$ should increase in a much more moderate way (if not keep essentially constant) and that $x_{\rm lya}(z)$

should rapidly vanish with the growth of ionised bubbles in double reionisation could explain the poorly understood shape of that absorption feature.

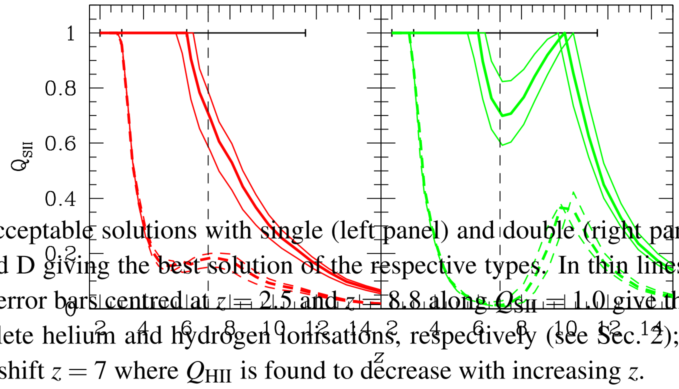

Figure 2: Only acceptable solutions with single (left panel) and double (right panel) reionisation. In thick lines models S and D giving the best solution of the respective types. In thin lines the solutions bracketing the two sets. The error bars centred at $z = 2.5$ and $z = 8.8$ along $Q_{SII} = 1.0$ give the estimated limits for the redshifts of complete helium and hydrogen ionisations, respectively (see Sec. 2); the vertical dotted black line marks the redshift $z = 7$ where Q_{HII} is found to decrease with increasing z.

6. Conclusions

In the last decades a big progress has been achieved in the modelling and observational characterisation of cosmic evolution since the Dark Ages. Thanks to these improvements it has nowadays become possible to severely constrain the intertwined complex processes of galaxy formation and reionisation.

Our ignorance on the Pop III star IMF still leads to a small degeneracy in the allowed solutions as two different solutions, one with single and the other with double reionisation, are still possible.

However, the rapidly growing observational data on the high-z Universe, coming from the CMB anisotropies and 21 cm line experiments as well as the observation of very distant LAEs could soon leave that degeneracy.

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DISCUSSION

W. KUNT QUESTION: As you apparently believe in the existence of SMBHs, how do you explain that in the Kormendy and Bender plot in Nature 469, 374-379 (2011), they all lose mass statistically?

E. SALVADOR-SOLE ANSWER: In the paper you mention it is shown that, *if* dark matter haloes predicted BH masses independent of their baryon content, then galaxy clusters should harbour very massive BHs that are not seen. However, the only observed correlation is that between the masses of SMBHs and (classical) bulges, not between SMBHs and disks as required by that premise. This means that bulges grow in parallel to SMBHs in galaxy mergers, but the growth of diks through gas accretion from haloes does not imply any BH growth. This is what our model considers and there is no problem about that.

G. AURIEMMA QUESTION: I have not seen in the list of free parameters the dark matter mass.

E. SALVADOR-SOLE ANSWER: The mass of dark matter particles is not needed in the model as we do not consider dark matter annihilation. We just need to know it is cold as the CDM power spectrum of density fluctuations determines the evolution of dark matter haloes.

G. M. BUCHER: What is the process that turns off the Population III stars after the initial burst in the double reionisation scenario?

E. SALVADOR-SOLE ANSWER: Population III stars form in neutral regions with primordial metallicity which are rapidly ionised. Metals are then ejected inside those ionised bubbles so that after the first ionisation phase is completed at $z = 10$ they are spread over the whole Universe. Consequently, during the subsequent recombination period, even though new neutral regions form, they are metal-rich so that Population III stars cannot form anymore.

D. PAOLETTI Comment: Current CMB experiments are sensitive to the optical depth, but future experiments will be able to constrain specific models of reionisation with constraints like the duration of the EoR and possibly be sensitive to the shape of the ionisation fraction which may be an interesting development for the model presented.

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