Highlights of Spanish Astrophysics VIII, Proceedings of the XI Scientific Meeting of the Spanish Astronomical Society held on September 8–12, 2014, in Teruel, Spain. A. J. Cenarro, F. Figueras, C. Hernández-Monteagudo, J. Trujillo Bueno, and L. Valdivielso (eds.)

Constraints on Reionization from the Observed Properties of the High-z Universe.

Eduard Salvador-Solé

Institut de Ciències del Cosmos. Universitat de Barcelona. Avda. Martí Franquès 1, E-08028, Barcelona, Spain

Abstract

Reionization and galaxy formation are two central issues of modern cosmology. In the present talk, I review the current theoretical and observational status of this subject and present a new powerful approach, based on a very complete and detailed Analytic Model of Intergalactic and GAlaxy evolution (AMIGA), that allows one to simultaneously constrain the reionization and galaxy formation processes through the observed properties of the high-z Universe.

1 Introduction

Reionization and galaxy formation are two central issues of modern cosmology. These are complex non-linear processes involving meny different phases and a very wide range of scales, so they are hard to study both analytically and numerically. Moreover, they are tightly coupled, so there is little hope to comprehend any of them without the other.

There has been a lot of work on this topic since the nineties of last century. Without pretending to be exhaustive, I can say many authors have focussed on the evolution of the IGM by the action of luminous sources treated in a non-fully consistent way [82, 65, 71, 55, 24, 72, 56, 38, 57, 39, 19, 8, 88], while others have concentrated in the formation and evolution of galaxies, with the intergalactic medium (IGM) properties again treated in a non-fully consistent way [2, 35, 80, 18, 20, 30, 15, 40, 79, 27, 86, 28, 1, 3, 74, 44]. No work has hitherto addressed both coupled aspects self-consistently.

In the present talk, I give a brief overview of the present theoretical and observational status of this subject and present a new powerful approach atempting to constrain the coupled evolution of galaxies and IGM from the observed properties of the Universe at $z \geq 2$. This approach makes use of a very complete and detailed Analytic Model of Igm and GAlaxy evolution (AMIGA), developed at the Institute of Cosmos Sciences in Barcelona, that monitors for the first time the coupled evolution of those two conponents self-consistently.

The outline of the talk is the following. In Sect. 2, I give a brief review on the state of affairs about reionization, both from the observational and theoretical points of view. In Sect. 3, I focus on the new approach we put forward. Conclusions are drawn in Sect. 4.

2 Current Status of Reionization

According to the current paradigm of hierarchical galaxy formation in the flat Λ cold dark matter (CDM) corsmology, things must have happened like this. Dark matter halos began to grow at matter-radiation equality, but baryon fluctuations did not grow at that moment because they were supported by radiation pressure. After recombination, neutral gas began to evolve freely and, at a redshift z of about 20 or 30, it began to fall into mini halos where it underwent molecular cooling, giving rise to the first, metal-free, Population III (Pop III) stars. These stars ionized small bubbles and polluted them with metals. When the metallicity in those ionized bubbles reached a critical metallicity of about 10^4 $Z_\odot$, atomic cooling began to proceed inside halos and normal galaxies formed, causing ionizing bubbles to keep on growing. These bubbles progressively overlapped until the whole Universe became fully ionized.

This is the general story. But we would like to have a much more accurate picture of galaxy formation and the epoch of reionization (EoR).

2.1 Observations on reionization

What do observations tell us about reionization? One important piece of information comes from the light of distant objects. As noticed by Gunn & Peterson [33], the light of nearby quasars indicates that nearby IGM is ionized. Indeed, their spectra show hydrogen Lya absorption lines caused by intervening neutral filaments embedded in the ionized IGM. The higher z, the more abundant those Lya lines, giving rise to the so-called Lya forest. Becker et al. [5] and Gjorgowsky et al. [22] found the first evidence of neutral hydrogen in the IGM at a z of about 6. The spectra of quasars at that redshift or greater ones show no Lya forest because all the radiation emitted by quasars shortwards of the rest-frame Lya line is absorbed by H I along the line-of-sight, giving rise to the so-called Gunn-Peterson trough.

Nowadays, many other observations dealing with the opacity of the Lya forest and Lya emitters (e.g. [54, 34, 84, 26, 11, 52, 53, 61, 59, 43] support this conclusion and allow one to put upper and lower bounds on the redshift of hydrogen reionization around 6. Moreover, similar observations point to a redshift of full He reionization between 2 and 3 [21, 6].

A fully independent piece of information on reionization comes from the cosmic microwave background (CMB) radiation, more specifically, from the CMB temperature and polarization anisotropies mainly from data obtained by *WMAP* [37] and *Planck* [63] satellites. Indeed, at large angular angles (or low multipole numbers l), the temperature power spectrum follow remarkably well the theoretical predictions on the primary fluctuations produced at recombination in the post inflationary flat CDM 'concordant' cosmology. But at wavenumbers $l \sim 2500$ corresponding to arcmin scales, the spectra obtained by the *Atacama Cosmology Telescope* (ACT) and the *South Pole Telescope* (SPT) begin to deviate from the

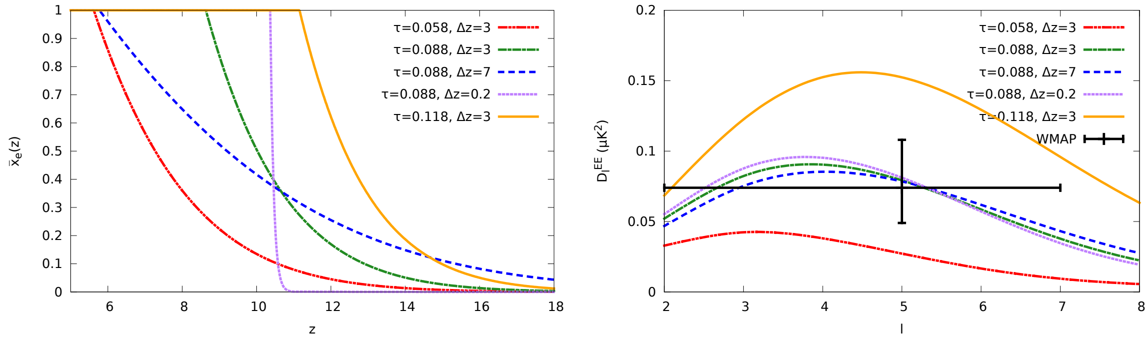

Figure 1: Different smooth reionization histories (left) and their effects in the polarization spectra on large angular scales (right). The error bar corresponds to the measurement obtained with WMAP data.

theoretical predictions due to the fact that what is observed is the secondary anisotropies due to the so-called kinetic Sunyaev-Zel'dovich (kSZ) effect caused by the Thomson scattering of CMB photons by free electrons in small ionized patches with non-null bulk motions and dust emission from nearby galaxies as the Milky Way that dominates the signal at those scales. Such a deviation thus harbors valuable information on the EoR.

And this is not all. Thomson scattering of CMB photons by free electrons also produces polarization anisotropies of the E-mode. We can thus also draw information on the EoR from such fluctuations. Actually, the polarization spectrum, so far known only at large angles, does not give any accurate answer. Many different smooth reionization histories are compatible with data (see Fig. 1). Moreover, reionization is not smooth but patchy, which increases the freedom to be fixed before been able to adjust the cosmological parameters by fitting the temperature spectrum. The way to circumvent this problem is to chose as a reasonable approximation, the solution corresponding to instantaneous reionization with no need to specify the evolution of ionized bubbles. But this does not solve the problem.

The best we can do is trying to simulate the kSZ effect arising from many different plausible reionization histories, pollute the predicted temperature spectrum according to some model of dust emission by galaxies and try to fit the observed one (together with the constraint on the polarization spectrum at large scales). Following this procedure, it has been possible to establish 95% confidence bounds on the evolution of ionized fractions [87] (see Fig. 4), although the correction for dust emission carried out is not very reliable.

2.2 Open questions

The different values of the redshift of reionization obtained from the two previous independent approaches suggest that reionization was not instantaneous. But the uncertainty on ther EoR is large. Moreover, not only is the timing of reionization, as mentioned, poorly constrained, but the mechanism that causes it is equally uncertain.

Nowadays, it is widely accepted that reionization is due to photoionization. But the source of the ionizing UV photons is largely unknown. It is not even excluded that they can be produced by decaying or self-annihilating dark-matter particles, although the scenario usually adopted and hereafter assumed is the simplest one that they are mainly produced by luminous sources. However, even in this most favorable scenario, the precise contribution coming from AGN, bright and dwarf normal galaxies and Pop III stars is unknown. Clearly, a more direct probe on the EoR would be welcome.

2.3 Waiting for a direct probe

21 cm line observations can fill the gap. 21 cm line is produced when the spin of the electron in a hydrogen atom changes its orientation relative to that of the proton. By absorbing one CMB photon, the atom reaches the excited isospin state and by emitting one photon it returns to the ground state. The abundance of atoms in the excited state is related to the spin temperature, T_{spin}, of the gas. Depending on whether this temperature is higher or lower than the CMB temperature, $T_{\rm CMB}$, we will see the 21 cm line either in emission or absorption. And looking at different frequencies we can have a tomography of the neutral hydrogen content in the Universe at different z's. A very complete and detailed theoretical review on the use of 21 cm line as a cosmological probe for reionization is available at [58].

But the complications found in the practical implementation of this technique are huge. The signal is 10^{-5} times that produced in foreground sources (there is of course neutral hydrogen in essentially all galaxies including our own). In addition, the processes entering the game are numerous and their relative importance hard to establish. Indeed, depending on the epoch, T_{spin} is more or less different not only from $T_{\rm CMB}$ but also from the gas temperature, T_{gas}. More importantly, not all IGM is in phase regarding the ionization state. Consequently, some a priori idea of the expected signal is needed in order to know where and how to look for. For this reason, this approach also requires modeling or performing simulations of the spectrum of brightness temperature, accounting for the evolution of ionized bubbles.

Despite all those complications, the goal is so appealing that there are nowadays numerous teams all over the world working in this line of research.

3 A new approach from the properties of the high-z Universe

In this Section, I will show that the observed properties of the high-z Universe can also be used to simultaneously constrain the EoR and galaxy formation. Indeed, as reionization and galaxy formation are tightly coupled, reionization should influence the properties of the Universe. The nearby Universe is probably too distant from the end of reonization for the imprints of that process to be detectable. The most marked signal should be found at redshifts of about 6 or higher, but data on the Universe at those zs are still scarce. Thus, a good compromise to start with is to look at the properties of the Universe at z higher than or equal to 2.

3.1 Data on the high-z Universe

What do we know about the Universe at $z \geq 2$? Nowadays there are reliable data on at least 9 independent cosmic histories: the stellar mass density (e.g. [85, 66, 78, 31, 46, 47]), the cold gas mass density [62, 64], the mass density locked in MBHs [45, 83, 7], the SFR density [12, 66, 49, 13, 14, 60, 25], the size of galaxies [17, 16], the metallicity of galaxies, that is of their stars and the cold gas or ISM [75, 36], the IGM metallicity in the form of carbon abundance [76, 67, 73, 23], the metagalactic ionizing background [77, 13, 4], and the IGM temperature [48, 10, 9] (panels from top to bottom and from left to right in Fig. 3). In addition, we have information on the mass function (MF) of galaxies [78, 32] and MBHs [81, 83] at several z's in the desired redshift interval.

3.2 AMIGA: a model of galaxy formation

And what about the model to be used? Since we want to fix the EoR by comparing the predictions of the model with data on galaxies and IGM, we need to do better than ever and build a realistic, self-consistent model of the coupled evolution of galaxies and IGM. This is provided by the new Analytic Model of Igm and GAlaxy evolution (AMIGA) developed by our team [50]. But before going into the novelties of AMIGA, I will briefly describe the basic concepts of galaxy formation.

The physics of CDM is very simple and we can trace its clustering since inflation where density fluctuations had well-known properties. Similarly, the inner properties of virialized halos are also well-known thanks to N-body simulations (see the review [29]) and easy to accurately model analytically [68, 69, 41, 42].

The physics of baryons is on the contrary much more complex due, as mentioned, to the feedback of luminous sources. As mentioned, at some moment after recombination, baryons begin to fall in massive halos (with virial temperature, T_{vir}, higher than the actual IGM temperature, $T_{\rm IGM}$). The hot gas in halos cools and falls to the halo centre where it forms a rotationally supported disk. There, stars form giving rise to Pop III star clusters or normal galaxies. As halos keep on merging, galaxies accumulate in halos, where they suffer dynamical friction with dark matter particles and orbital decay. This causes them to be accreted by or to merge with the central most massive galaxy.

Stars radiate, explode, and leave BH remnants. UV photons ionize the surrounding IGM and photoheat it, while X-rays produced in SNe Compton-heat the IGM on larger scales. Stars also liberate metals which may return to the hot gas in the halo through SN- and AGN-driven winds or even escape from the halo and retun to the IGM. Thus, stellar feedback is partly positive and partly negative for the subsequent galaxy formation. As mentioned, reionization proceeds through singly ionized bubbles, harbouring doubly ionized subbubbles, embedded in the neutral IGM. This means that those three phases evolve separately.

The master equations for the evolution of the H II and He III volume filling factors, $Q_{\rm HII}$ and $Q_{\rm HeIII}$, coupled to the evolution of the IGM temperatures in the three separate phases,

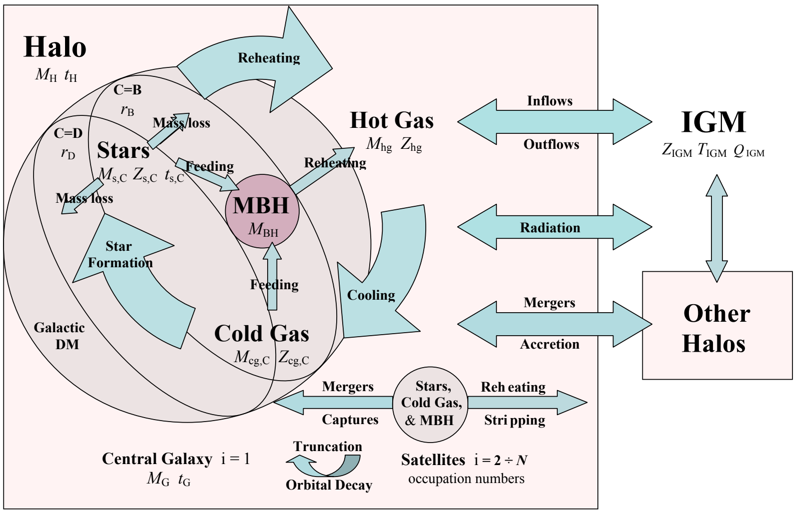

Figure 2: Main processes included in AMIGA causing changes in the different baryonic phases and properties that are monitored (densities, temperatures and metallicities) inside and outside halos. The notation used is self-explanatory.

are [50]

$$\frac{\mathrm{d}Q_{\mathrm{SII}}}{\mathrm{d}t} = \frac{\langle \dot{N}_{\mathrm{SII}}\rangle}{\langle n_{\mathrm{S}}\rangle} - \left[\left\langle \frac{\alpha_{\mathrm{SI}}(T_{\mathrm{IGM}})}{\mu^{\mathrm{e}}}\right\rangle_{\mathrm{SII}} \frac{C\,\langle n_{\mathrm{b}}\rangle}{a^3(t)} + \frac{\mathrm{d}\ln\langle n_{\mathrm{S}}\rangle}{\mathrm{d}t}\right] Q_{\mathrm{SII}}\,, \tag{1}$$

$$\frac{\mathrm{d}T}{\mathrm{d}\ln(1+z)} = T\Big[2 + \frac{2}{3}\frac{\mathrm{d}\ln(n/\langle n\rangle_{\mathrm{i}})}{\mathrm{d}\ln(1+z)} + \frac{\mathrm{d}\ln\mu}{\mathrm{d}\ln(1+z)} + \frac{\mathrm{d}\ln\varepsilon}{\mathrm{d}\ln(1+z)} - \frac{\mathrm{d}\ln n}{\mathrm{d}\ln(1+z)}\Big], \tag{2}$$

where subscripts S, SI, and SII stand for H, H I, and H II, or He I, He II, and He III, and angular brackets mean averages over the regions denoted by subscript (in the lack of any subscript the average is over the whole IGM). The average of a function $f(T_{\mathrm{IGM}})$ of the IGM temperature in the region j is taken equal to $f(T_{\mathrm{j}}) + (\mathrm{d}^2 f/\mathrm{d}T^2)\sigma^2_{T\mathrm{j}}/2$, with T_{j} equal to the mean temperature in that region and $\sigma^2_{T\mathrm{j}}$ the corresponding variance. In Eq. (1), $\langle n_{\mathrm{b}}\rangle$ is the comoving cosmic baryon density, $a(t)$ is the cosmic scale factor, μ^{e} is the electronic contribution to the mean molecular weight, $\dot{N}_{\mathrm{SII}}$ is the comoving metagalactic ionizing photon rate density due to luminous sources and recombinations to He II and He I ground states for H I-ionizing photons, α_{SI} is the recombination coefficient to the SI species, and C is the ionized clumping factor.

The first term in claudators on the right of Eq. (2), equal to 2, gives the cosmological adiabatic cooling of the gas element; the second term gives its adiabatic heating–cooling by gravitational compression–expansion for the baryon density n_{b} around the mean value $\langle n_{\mathrm{b}}\rangle_{\mathrm{j}}$ in region j; the third term gives the cooling due to the increase in mean molecular weight, μ, caused by ionization and outflows from halos; the fourth term gives the Compton cooling from CMB photons, and the gain–loss of energy density, ε, due to photo-ionization–recombination, Compton heating from X-rays, the achievement of energy equipartition by newly ionized–recombined fraction of gas plus mechanical heating accompanying outflows

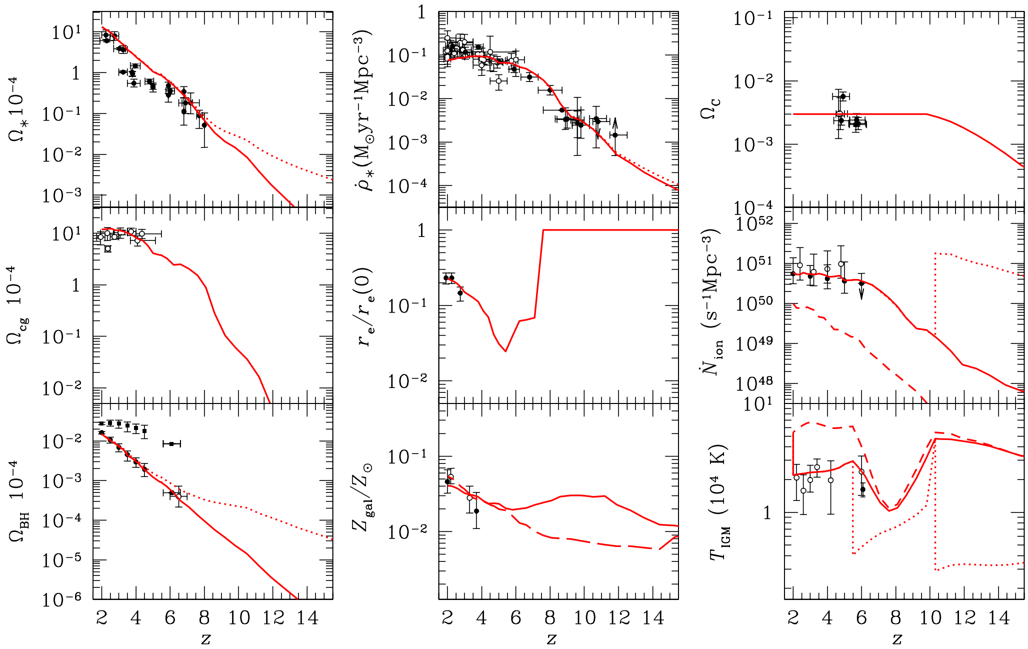

Figure 3: Best solution of the galaxy formation model and its fits to the data on the 9 cosmic histories at high-z (see text for the history plot in each panel and the origin of the data in filled and empty circles with error bars.)

from halos; and the fifth term gives the cooling–heating by the gain–loss of baryon density, $n_{\rm b}$, due to outflows–inflows.

The source functions in those equations, namely $\dot{N}_{\rm SII}$, μ, ε and n, are provided by that part of the model dealing with luminous sources, which monitors in detail all relevant processes taking place inside and outside halos (Fig. 2).

In particular, it includes molecular cooling, taking into account the different channels producing H_2 molecules, and Pop III stars, taking into account their different evolution, SED, yield and BH remnants according to their mass. BHs produced in each Pop III star cluster coalesce in a big BHs of about 500 $M_\odot$. These BHs are the seeds of MBHs.

AMIGA minimizes the total number of free parameters. There are only 8 of them, so the problem is well-constrained. Note that there are only two describing Pop III stars: the yield of massive Pop III stars and the total mass fraction locked into mini-MBH or, equivalently, the mass fractions in each of the three main mass ranges defining the Pop III star initial mass function (IMF).

3.3 Results

The proposed approach works. Indeed, on the one hand, the internal consistency of some of the data fixes 3 parameters. On the other hand, the parameters fixing the properties of

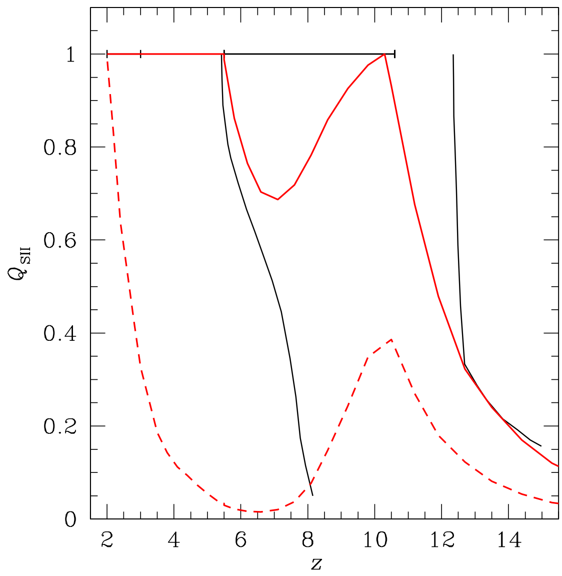

Figure 4: Predicted hydrogen (solid orange line) reionization history, with a first ionization at $z = 10.3$ and a second and definite one at $z = 5.5$, separated by a small recombination period. Helium reionization (dashed orange line) and 95% confidence limits on hydrogen reionization (black lines) drawn from WMAP data.

Pop III stars decouple from those fixing the properties of normal galaxies and, conviniently ordered, all these parameters can be fixed by adjusting one cosmic history each (see [70] for details). Therefore, we can easily determine the best values of all the parameters and all the data appear to be remarkably well fitted.

The model giving the best fits to the data on the cosmic histories observed is shown in Fig. 3. In addition, the galaxy MFs at different zs are also perfectly fitted. This is not the case for the MBH MFs, but the reason for this is that these MBH MFs are derived from optical AGN luminosity functions that seem to be contaminated by the light of their host galaxies. Such good fits are particularly remarkable given that there is essentially one parameter per cosmic history to adjust and that many of the cosmic histories show extremum points, hard to fit with such a little freedom. In this sense, the model allows one to understand the origin of all those features.

This best solution obtained predicts a double reionization (Fig. 4): a first ionization phase triggered by Pop III stars ending at $z = 10.3$, and a second one triggered by normals galaxies ending at $z = 5.5$. After the first reionization, all molecules are destroyed and all the IGM has got a metallicity higher than critical, so PopIII stars cannot form anymore and there is a recombination period until normal galaxies begin to ionize the IGM again.

Is single reionization definitely excluded? As the first ionization at $z = 10.3$ is due to Pop III stars, taking a less top-heavy Pop III star IMF and keeping all the remaining parameters unchanged, we can obtain one single ionization ending at $z = 5.5$. This solution gives automatically good fits to the data on galaxies because of the decoupling between of the properties of PopIII stars and normal galaxies. The only cosmic histories that depend on the Pop III star IMF are the IGM temperature and metallicity histories. The IGM temperature is not so badly fitted. The problem is in the predicted IGM metallicity, which is found to be clearly lower than observed.

4 Summary and conclusions

The points to retain from the first part (Sect. 2) are: i) there is hitherto no fully consistent model of the coupled evolution of galaxies and IGM, ii) the light from distant objects inform only on the redshift of complete reionization, ii) CMB temperature and polarization anisotropies and 21 cm line brightness temperature at different z's harbor valuable information of the EoR and iii) their fits require making lots of simulations of the EoR, which, in principle, do not need to be realistic, just to cover the right solution. But either because the information is integrated and the solution is not unique (CMB case) or because it is hard to infer (21 cm line case) some a priori idea of the EoR is necessary, which requires in turn some idea of galaxy formation and evolution.

The points to retain from the second part (Sect. 3) are: i) one can also try to simultaneously constrain the problem from the observed properties of the high-z Universe, ii) data on the Universe at $z \geq 2$ now begin to be numerous and accurate enough for that purpose and iii) for this purpose a complete and detailed model of galaxy and IGM evolution, AMIGA, consistently dealing with the coupling of those two elements has been developed that includes Pop III star and AGN feedbacks.

The main conclusion is that the new approach points towards a double reionization: with a first phase triggered by Pop III stars ending at $z = 10.3$, and a second one triggered by normals galaxies ending at $z = 5.5$, compatible with all previous constraints from distant luminous sources and CMB anisotropies.

Acknowledgments

This work was supported by the Spanish DGES AYA AYA2012-39168-C03-02 and the Catalan DIUE 2009SGR00217.

References

[1] Alvarez, M. A., Finlator, K., Trenti, M. 2012, ApJ Let., 759, L38

[2] Babul, A., & Rees, M. J. 1992, MNRAS, 255, 346

[3] Battaglia, N., Trac, H., Cen, R., Loeb, A. 2013, ApJ, 776, 81

[4] Becker, G. D., & Bolton, J. S. 2013, MNRAS, MNRAS, 436, 1023

[5] Becker, R. H., Fan, X., White, R. L. et al. 2001, AJ, 122, 2850

[6] Becker, G. D., Bolton, J. S., Haehnelt, M. G., Sargent, W. L. W. 2011, MNRAS, 410, 1096

[7] Bennert, V. N., Auger, M. W., Treu, T., Woo, J.-H., Malkan, M. A. 2011, ApJ, 742, 107

[8] Benson, A. J., Sugiyama, N., Nusser, A., Lacey, C. G. 2006, MNRAS, 369, 1055

[9] Bolton, J. S., Becker, G. D., Raskutti, S., et al. 2012, MNRAS, 419, 2880

[10] Bolton, J. S., Becker, G. D., Wyithe, J. S. B., Haehnelt, M. G., Sargent, W. L. W. 2010, MNRAS, 406, 612

[11] Bolton, J. S., & Haehnelt, M. G. 2007a, MNRAS, 381, L35

[12] Bouwens, R. J., Illingworth, G. D., Franx, M., Ford, H. 2007, ApJ, 670, 928

[13] Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2011, ApJ, 737, 90

[14] Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2012, ApJ, 754, 83

[15] Bower, R. J., Benson, A. J., Malbon, R., Helly, J. C., Frenk, C. S., Baugh, C. M., Cole, S., Lacey, C. G. 2006, MNRAS, 370, 645

[16] Bruce, V. A., Dunlop, J. S., McLure, R. J., et al. 2014, MNRAS, 444, 1660

[17] Buitrago F., Trujillo I., Conselice C. J., Bouwens R. J., Dickinson M., Yan H., 2008, ApJ, 687, L61

[18] Ciardi, B., Ferrara, A., Governato, F., Jenkins, A. 2000, MNRAS, 314, 611

[19] Choudhury, T. R., & Ferrara, A. 2005, MNRAS, 361, 577

[20] Dijkstra, M., Haiman, Z., Rees, M. J., Weinberg, D. H. 2004, ApJ, 601, 666

[21] Dixon, K. L., Furlanetto, S. R. 2009, ApJ, 706, 970

[22] Djorgovski, S. G., Castro, S., Stern, D., Mahabal, A. A. 2001, ApJ, 560L, 5

[23] D'Odorico, V., et al. 2013, MNRAS, 435, 1198

[24] Efstathiou, G. 1992, MNRAS, 256, 43P

[25] Ellis, R. S., McLure, R. J., Dunlop, J. S., et al. 2013, ApJ Let., 763, L7

[26] Fan, X., et al. 2006, AJ, 132, 117

[27] Faucher-Giguère, C.-A., Lidz, A., Zaldarriaga, M., Hernquist, L. 2009, ApJ, 703, 1416

[28] Font, A. S., Benson, A. J., Bower, R. G., et al., 2011 MNRAS, 417, 1260

[29] Frenk C. S. & White S. D. M., 2012, Annalen der Physik, 524, 507

[30] Furlanetto, S. R., Zaldarriaga, M., Hernquist, L. 2004, ApJ, 613, 1

[31] González, V., Labbé, I., Bouwens, R. J., et al. 2010, ApJ, 713, 115

[32] González, V., Labbé, I., Bouwens, R. J., et al. 2011, ApJ, 735, L34

[33] Gunn, J. E., & Peterson, B. A. 1965, ApJ, 142, 1633

[34] Haiman, Z., & Cen, R. 2005, ApJ, 623, 627

[35] Haiman, Z., Thoul, A. A., Loeb, A. 1996, ApJ, 464, 523

[36] Halliday, C., Daddi, E., Cimatti, A., et al. 2008, A&Ap, 479, 41

[37] Hinshaw, G., Larson, D., Komatsu, E., et al. 2013, ApJ Sup. Ser., 208, 19

[38] Hui, L., & Gnedin, N. Y. 1997, MNRAS, 297, 27

[39] Hui, L., & Haiman, Z. 2003, ApJ, 596, 9

[40] Iliev, I. T., Mellema, G., Shapiro, P. R., Pen, U.-L. 2007, MNRAS, 376, 534

[41] Juan, E., Salvador-Solé, E., Domènec, G., Manrique, A. 2014, MNRAS, 439, 719

[42] Juan, E., Salvador-Solé, E., Domènech, G., Manrique, A., 2014, MNRAS, 439, 3156

[43] Jensen, H., Laursen, P., Mellema, G., et al. 2013a, MNRAS, 428, 1366

[44] Kaurov, A. A., & Gnedin, N. Y. 2013, ApJ, 771, 35

[45] Kelly, B. C., Vestergaard, M., Fan, X., et al. 2010, ApJ, 719, 1315

[46] Labbé, I., González, V., Bouwens, R. J., et al. 2010, ApJ, 708, L26

[47] Labbé, I., González, V., Bouwens, R. J., et al. 2010, ApJ, 716, L103

[48] Lidz, A., Faucher-Giguère, C.-A., Dall'Aglio, A., et al. 2010, ApJ, 718, 199

[49] Lorenzoni, S., Bunker, A. J., Wilkins, S. M., et al. 2011, MNRAS, 414, 1455

[50] Manrique, A., & Salvador-Solé, E. 2014, accepted for publication in ApJ

[51] Manrique, A., Salvador-Solé, E., Juan, E., et al. 2014, accepted for publication in ApJSS, arXiv:1411.5288

[52] McQuinn, M., Hernquist, L., Zaldarriaga, M., Dutta, S. 2007, MNRAS, 381, 75

[53] Mesinger, A., & Furlanetto, S. R. 2008, MNRAS, 386, 1990

[54] Mesinger, A., & Haiman, Z. 2004, ApJ, 611, L69

[55] Miralda-Escudé, J., & Ostriker, J. P. 1990, ApJ, 350, 1

[56] Miralda-Escudé, J., & Rees, M. J. 1994, MNRAS, 266, 343

[57] Miralda-Escudé, J., Haehnelt, M., Rees, M. J. 2000, ApJ, 530, 1

[58] Morales, M. F., & Wyithe, J. S. B. 2010, Ann. Rev. A&Ap, 48, 127

[59] Mortlock, D. J., Warren, S. J., Venemans, B. P., et al. 2011b, Nature, 474, 616

[60] Oesch, P. A., Bouwens, R. J., Illingworth, G. D., et al. 2013, ApJ, 773, 75

[61] Ouchi, M., Shimasaku, K., Furusawa, H., et al. 2010, ApJ, 723, 869

[62] Péroux, C., McMahon, R. G., Storrie-Lombardi, L. J., Irwin, M. J. 2003, MNRAS, 346, 1103

[63] Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2013, arXiv:1303.5076

[64] Prochaska, J. X., Herbert-Fort, S., Wolfe, A. M. 2005, ApJ, 635, 123

[65] Rees, M. J. 1986, MNRAS, 218, 25P

[66] Reddy, N. A., & Steidel, C. C. 2009, ApJ, 692, 778

[67] Ryan-Weber, E. V., Pettini, M., Madau, P., Zych, B. J. 2009, MNRAS, 395, 1476

[68] Salvador-Solé, E., Viñas, J., Manrique, A., Serra, S. 2012a, MNRAS, 423, 2190

[69] Salvador-Solé, E., Serra, S., Manrique, A., González-Casado, G. 2012b, MNRAS, 424, 3129

[70] Salvador-Solé, E., & Manrique, A. 2015, in progress

[71] Shapiro, P. R., & Giroux, M. L. 1987, ApJ, 321, L07

[72] Shapiro, P. R., Giroux, M. L., Babul, A. 1994, ApJ, 427, 25

[73] Simcoe, R. A., Cooksey, K. L., Matejek, M., et al. 2011, ApJ, 743, 21

[74] Sobacchi, E., & Mesinger, A. 2013a, MNRAS, 432, 51

[75] Sommariva, V., Mannucci, F., Cresci, G., et al. 2012, A&Ap, 539, A136

[76] Songaila, A. 2001, ApJ, 561, 153

[77] Stark, D. P., Ellis, R. S., Richard, J., Kneib, J.-P., Smith, G. P., Santos, M. R. 2007, ApJ, 663, 10

[78] Stark, D. P., Ellis, R. S., Bunker, A., et al. 2009, ApJ, 697, 1493

[79] Trac, H., Cen, R., Loeb, A. 2008, ApJ Let., 689, L81

[80] Thoul, A. A., & Weibnberg, D. H. 1996, ApJ, 465, 608

[81] Vestergaard M., Fan X., Tremonti C. A., Osmer P. S., Richards G. T. 2008, ApJ, 674, L1

[82] White, S. D. M., & Rees, M. 1978, MNRAS, 183, 341

[83] Willott, C. J., Albert, L., Arzoumanian, D., et al. 2010, AJ, 140, 546

[84] Wyithe, J. S. B., Loeb, A., Carilli, C. 2005, ApJ, 654, 12

[85] Wilkins, S. M., Trentham, N., Hopkins, A. M. 2008, MNRAS, 385, 687

[86] Zahn, O., Mesinger, A., McQuinn, M, et al. 2011, MNRAS, 414, 727

[87] Zahn, O., et al. 2012, ApJ, 756, 65

[88] Zhang, J., Hui, L., Haiman, Z. 2007, MNRAS, 375, 324