# EOR in alternative cosmological scenarios

**D.Crociani[1], L. Moscardini[1], M. Viel[2], M. Bartelmann[3] and M. Meneghetti[4]**

[1]Università di Bologna (IT), [2]INAF-Osservatorio Astronomico di Trieste (IT), [3]Universität Heidelberg (DE), [4]INAF-Ossevatorio Astronomico di Bologna (IT)

## INTRODUCTION

Reionization marks a crucial point for the history of the universe, since at this epoch the first sources of light ionize the neutral intergalactic medium (IGM) and affect the following formation of the structures.

This quite complex scenario, not so far well understood, has been investigated through many theoretical approaches that relate the statistical properties of the ionized regions to those of the ionizing sources, making assumptions on how the galaxies ionize the IGM and on how the IGM recombines. Then it is important to well describe the hierarchical evolution of the first structures in order to build a good picture of the reionization process.

The aim of our work is to investigate how reionization proceeds in non-standard universes and to obtain some observational quantities which can allow to constrain the structure formation scenarios.

## METHOD

We use the analytic methods proposed by Furlanetto & Oh (2005) and Avelino & Liddle (2006) to achieve the statistical properties of the ionized bubbles.

In these approaches, reionization is an "inside-out" phenomenon and the distributions of the HII regions and the ionizing sources are related by some hypotheses as:

- $M_{HII}=\zeta M_{gal}$ with $\zeta$=ionising efficiency
- 1:1 correspondence between galaxies and HII regions
- the clumping factor of the inhomogeneous IGM

Then, assuming a statistical description for the distribution of ionizing sources allows to obtain the mass function of the ionized bubbles and other quantities (typical size, IGM optical depth, etc) that could be constrained by the future observations.

Given the theoretical problems related to the cosmological constant in the standard cosmological framework (ΛCDM), we investigate how reionization occurs in a quintessence universe, characterized by a time-evolving dark energy component. We assume the models proposed by Ratra & Peebles (2003) (RP) and Brax & Martin (2000) (SUGRA), that show a quite different evolution of the $w(z)$ equation-of-state parameter with respect to the ΛCDM case ($w$=-1) mostly at high redshifts, i.e. when reionization begins (Fig.1).

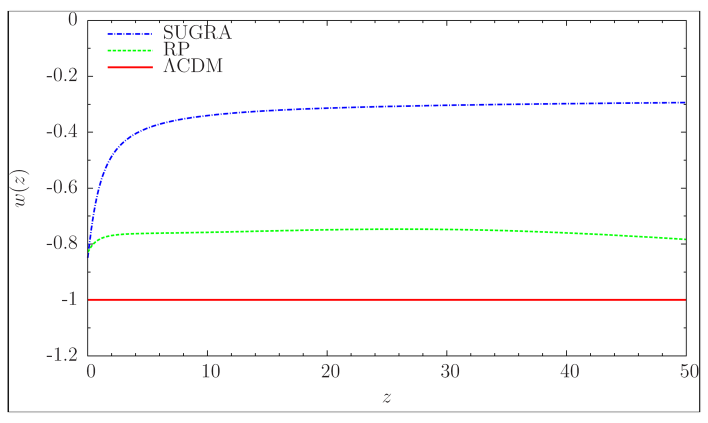

**Fig 1.** *Time-evolution of the w parameter in the three considered cosmological cases.*

The main effect of the quintessence component is an earlier growth of matter fluctuations, then larger halos form at the same cosmological epoch, as shown in Fig. 2.

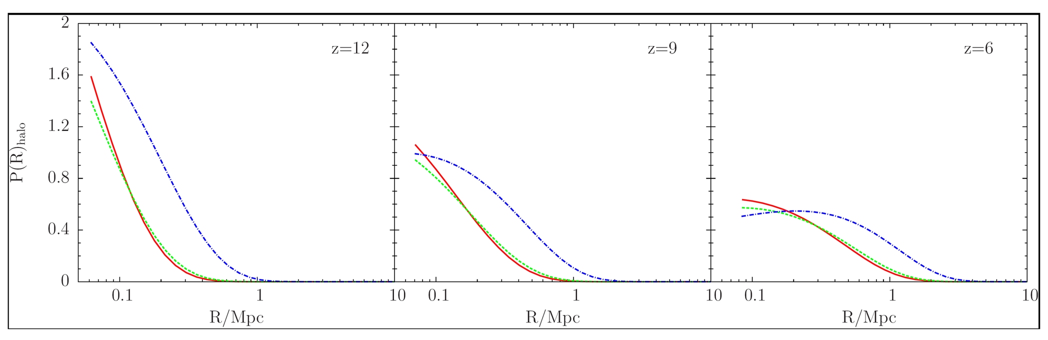

**Fig 2.** *Halo probability distributions at z=6, 9 and 12 for the ΛCDM (red solid line), RP (green dotted line) and SUGRA (blue dot-dashed line) universes.*

We also investigate reionization in models with primordial non-Gaussianity. Even if standard inflationary models predict almost Gaussian fluctuations, present-day observations do not exclude the presence of a small amount of non-Gaussianity (see Komatsu et al. 2008), parametrized by the $f_{nl}$ parameter: $|f_{nl}|\leq 300$. The effect of the primordial non-Gaussian overdensity distribution is an enhanced larger halos formation at high $z$ than in the standard case, for $f_{nl} > 0$ (Fig. 3).

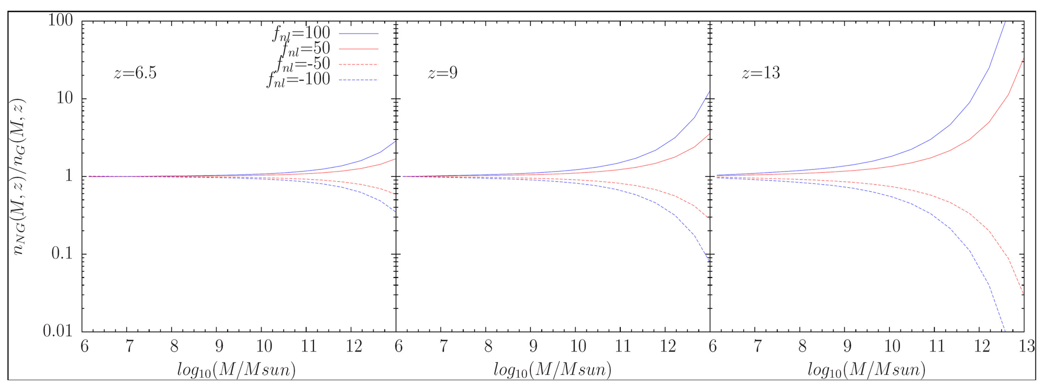

**Fig 3.** *Halos mass function ratios for the scale-independent non-Gaussian and the Gaussian cases, at redshift 6.5, 9 and 13 from left to right. Solid and dashed lines show a positive and negative non-Gaussianity case, assuming $f_{nl}=\pm 100$ (blue lines) and $\pm 50$ (red lines), respectively.*

Given the relation between bubbles and halo formation, a non-standard cosmology can affect the reionization scenario.

## RESULTS

Assuming a quintessence cosmology and neglecting the IGM recombination, through the Furlanetto and Oh (2005) model we obtain an enchanced formation of the larger bubbles (Fig. 4) at the same $z$ and larger characteristic radius of the HII regions at the same reionization phase $\bar{x}_i$ (Fig. 5, left panel).

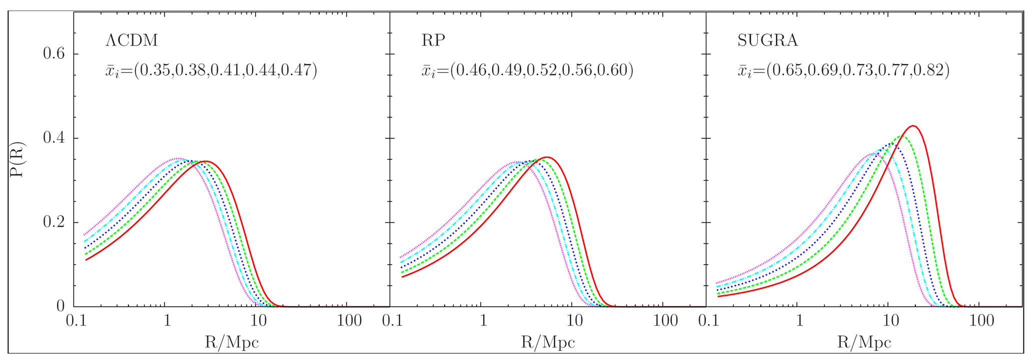

**Fig 4.** *The HII regions probability distributions at z=8.8 (magenta dotted line), 8.6 (cyan dot-dashed line), 8.4 (blue short dashed line),8.2 (green long dashed line) and 8 (red solid line) assuming ζ=6 for the three considered universes.*

This effect is smoothed by the IGM recombination rate, then the typical size of the HII regions is smaller (Fig. 5, right panel) and the bubble distribution piles up at the maximum radius (Fig. 6, thick lines) at the same reionization phase.

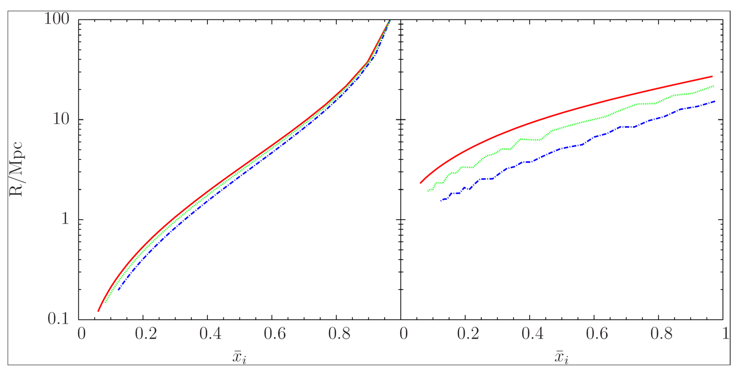

**Fig 5.** *$R_{char}$ (left panel) and $R_{max}$ (right panel) of the HII regions for the ΛCDM (red solid), RP (green dotted) and SUGRA (blue dot-dashed) cases.*

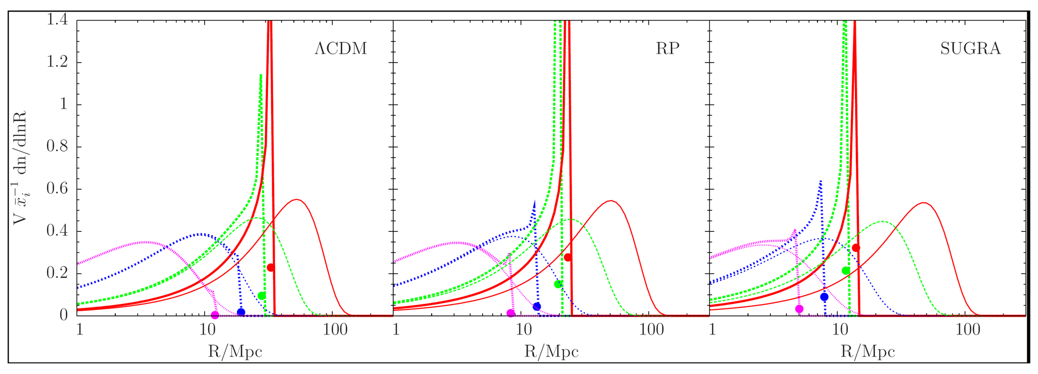

**Fig 6.** *HII regions probability distributions without (thin lines) and with (thick lines) IGM recombination, for $\bar{x}_i$ = 0.51 (magenta dotted line), 0.68 (blue short dashed line), 0.84 (green long dashed line) and 0.92 (red solid line). The filled points show the ionized volume in bubbles with $R=R_{max}$.*

The morphology of the bubbles affects the Ly-flux transmission, and in a quintessence universe we observe that the probability distribution for the IGM optical depth τ decreases at smaller τ (Fig. 7).

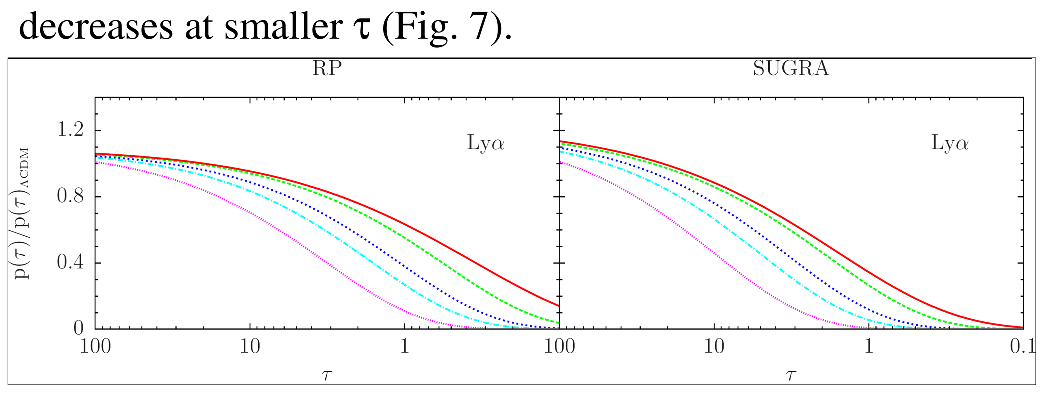

**Fig 7.** *The probability distributions of the IGM optical depth at z=6 and $\bar{x}_i$ = 0.95 for RP and SUGRA compared to the ΛCDM case, assuming $R_{max}$= 10 (magenta dotted line), 20 (cyan dot-dashed line), 30 (blue short dashed line), 60 (green long dashed line) and 600 (red solid line) Mpc.*

To estimate the non-Gaussianity effects, we consider both the cases of a local scale-independent and an equilateral scale-dependent non-Gaussianity shape, assuming in the last case $f_{nl} \propto f_{nl}(k_{CMB})*(k)^{\alpha}$ (Loverde et al. 2008) and setting $f_{nl}(k_{CMB})$ in agreement with the WMAP5 results (Komatsu et al. 2008). Assuming the Avelino & Liddle (2006) model, we obtain a larger ionized fraction at high $z$ for both the local and the equilateral cases with high non-Gaussianity parameters (Fig. 8).

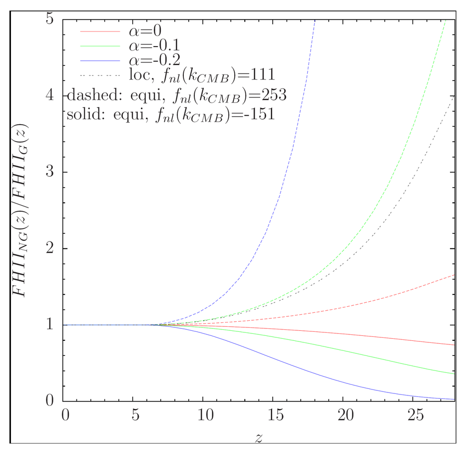

**Fig 8.** *Ionized fraction ratios between the non-Gaussian and Gaussian cases are shown for the local (black line) and the equilateral (colored lines) shapes. The equilateral curves are obtained for $f_{nl}(k_{CMB})$=-151 (solid line), 253 (dashed line) and assuming α=0 (red line), -0.1 (green line) and –0.2 (blue line).*

Thanks to the ionized fraction, we estimate the optical depth τ of the intergalactic medium for both the local and the equilateral shapes, as shown in Fig. 9. We obtain that τ is larger at high $z$, but the effect is smaller than 10% for both the non-Gaussian cases.

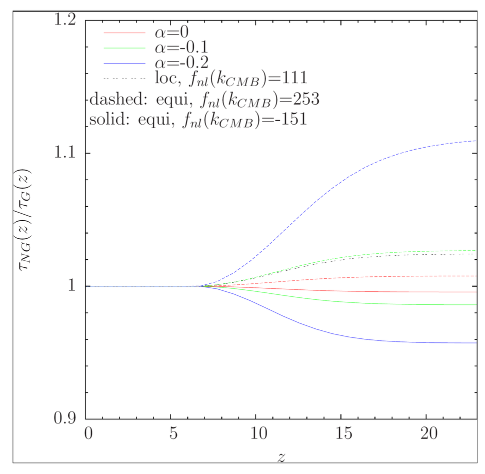

**Fig 9.** *Optical depth ratios between the non-Gaussian and Gaussian cases are shown for the local (black line) and the equilateral (colored lines) shapes. The equilateral curves are obtained for $f_{nl}(k_{CMB})$=-151 (solid line), 253 (dashed line) and assuming α=0 (red line), -0.1 (green line) and –0.2 (blue line).*

## CONCLUSIONS

Our main conclusions can be summarized as follows:

In a quintessence universe (Crociani et al. 2008),

- neglecting the IGM recombination, the formation of larger HII bubbles is enhanced and their typical size is higher at the same cosmological epoch;
- the recombination smooths this effect and at the same reionization phase the characteristic radius is smaller;
- the probability for the IGM optical depth decreases at smaller τ;

In models with primordial non-Gaussianity (Crociani et al. in prep.),

- the ionized fraction is larger at high redshifts when both the local and the equilateral shapes are assumed;
- the effect of non-Gaussianity on the IGM optical depth at high $z$ is small (<10%).

## REFERENCES

Avelino P. P., Liddle A. R., 2006, MNRAS, 371, 1755

Brax P., Martin J., 2000, Phys. Rev. D, 61, 103502

Crociani D., et al. 2008, MNRAS, 385, 728

Furlanetto S. R., Oh S. P., 2005, MNRAS, 363, 1031

Komatsu E., et al. 2008, Arxiv e-prints, 803

Loverde M., et al. 2008, Arxiv e-prints, 4

Peebles P. J., Ratra B., 2003, Review of Modern Physic, 75, 559

## CONTACTS

For further informations, please contact:

**Daniela Crociani**

Dipartimento di Astronomia, Università di Bologna (Italy)

Email: daniela.crociani5@unibo.it