The Intergalactic Medium: Overview and Selected Aspects

Draft Version

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June 18, 2018

Contents

Attention: Weird figure placement, missing captions and typos ahead!

1 Introduction

- Currently most baryonic matter and roughly half of the dark matter reside in the IGM, even more at earlier times (90% of all primordial baryons at $z \geq 1.5$ and 95% of all dark matter at $z = 6$) [1, 2]
- Relevant for the understanding of galaxy formation and testing of cosmological theories
- As the baryons in the IGM are detected only though their absorption signatures, the physical structures that give rise to the features must be modeled [1]
- Structure of this work: chronologically examining aspects (that I find interesting or relevant...) of the IGM, starting with a very brief overview of the early universe, followed by an analysis of the IGM at progressively lower redshifts up to $z \sim 0$ where the IGM meets the CGM (Circumgalactic Medium)

2 The IGM at high redshifts (z > 5)

2.1 Early Universe and Reionization

- After Big Bang: H and He are ionized [2, 1]
- Early universe (at around $z \approx 1100$ or $t \approx 400000\,\mathrm{a}$): Recombination of cosmic gas (known through CMB observations), H became neutral [2]
- Around $z \sim 20$: Galaxies begin to form
- End of the dark age: Start of (H-) reionization around $z \sim 12$, completion of reionization estimated to be at $z \sim 6$ [3, 4, 5]
- Supposed primary source for the reionization is high energy radiation from galaxies [2] (mostly stars, but SNe contribute too [6]), exact mechanisms poorly understood

2.2 Dark Matter implications from IGM measurements

- From the metal enrichment of the IGM, constraints on Dark Matter particles can be found using a semi-analytic model called Delphi (**D**ark Matter and the **e**mergence of ga**l**axies in the e**p**oc**h** of re**i**onization) [7]
- The model tracks the Dark Matter and baryonic assembly of galaxies at $z \simeq 4 - 20$ and can incorporate different assumptions on the nature of Dark Matter, such as Cold Dark Matter (CDM) , 1.5 keV and 3 keV Warm Dark Matter (WDM)
- Result so far: WDM models can confidently be ruled out, e.g. 1.5 keV WDM calculations result in substantially less bound DM in low mass halos than observed, while fiducial CDM calculations are in accordance with measurements so far

3 The IGM at intermediate redshifts (2 < z < 5)

3.1 Ly α forest

3.1.1 Hydrogen (H I)

- Ly α transitions occure in neutral hydrogen between the ground state and the first excited state; the rest wavelength of the Ly α spectral line is 1216 $\AA$ [8]

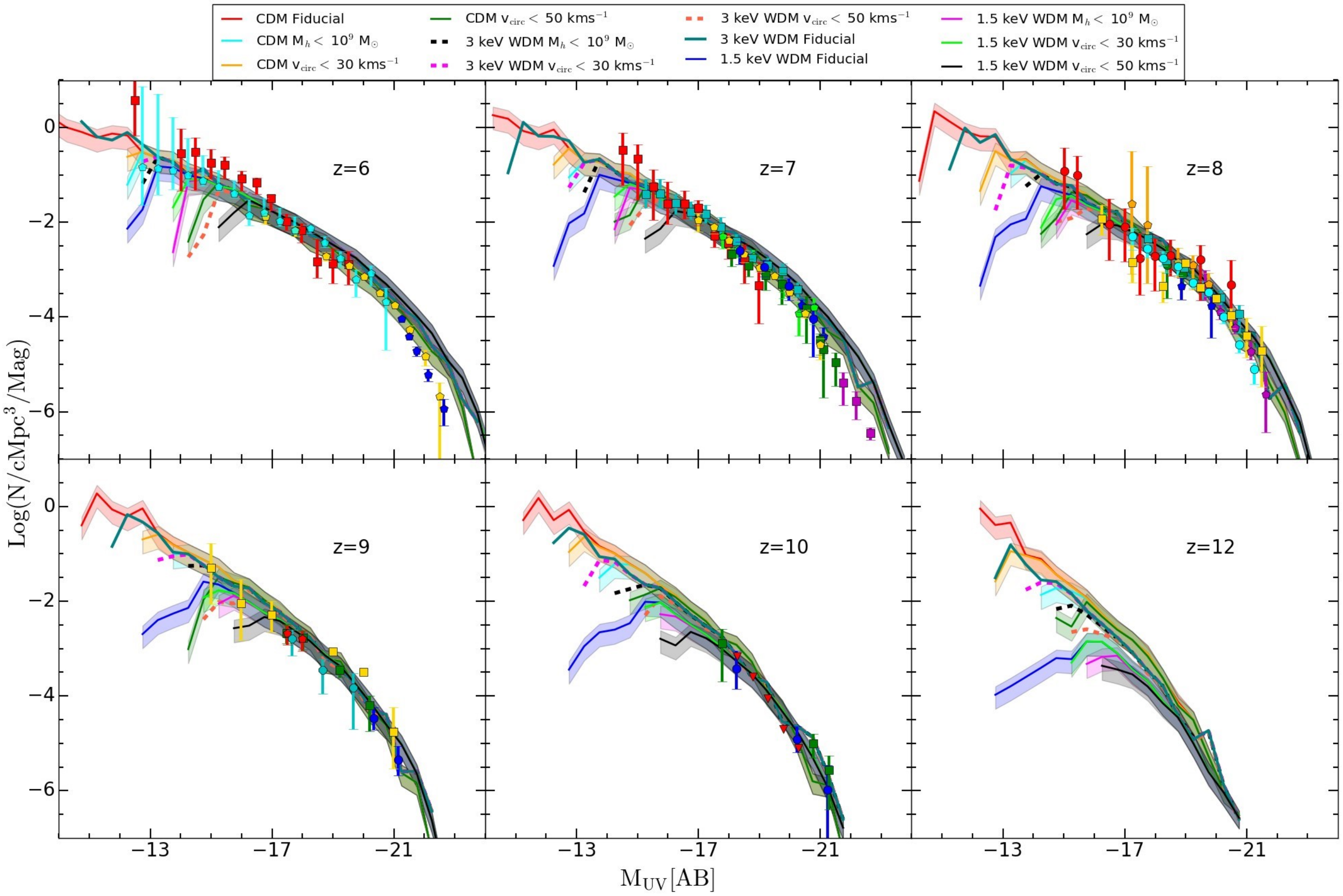

Figure 1: UV Luminosity Functions [7]

- The “forest” in the spectrum is a result of the light (from a quasar) passing through intergalactic neutral hydrogen clouds at different redshifts, thereby creating several distinct absorbtion lines
- Provides one of the most important sources for the study of the IGM [9]

- The Lyα forest is especially distinctive in the intermediate redshift region ($z \sim 2-5$), getting more transmissive at lower redshifts until only a small portion ($30\pm10\,\%$) of the gas is seen in Lyα absorbtion at $z \sim 0$, therefore making it less useful as a tool for lower redshifts (see chapter 4)
- Likewise, the number of lines increases with redshift up to $z \sim 6$, where the forest then turns into the Gunn-Peterson trough (i.e. regions with no detected transmission)

3.1.2 Helium (He II)

- He II Ly α sprectral line at 304 $\mathring{A}$(in the rest frame of the absorbing gas), also forms a Ly α forest [2]
- Harder to observe, because of foreground absorbtion of neutral hydrogen; only a few (1% at $z \sim 3$) quasars have enough transmission in the He II Ly α forest [2]
- Aparrently there was also a He II reionization (He II → He III), as with the H I Ly α forest

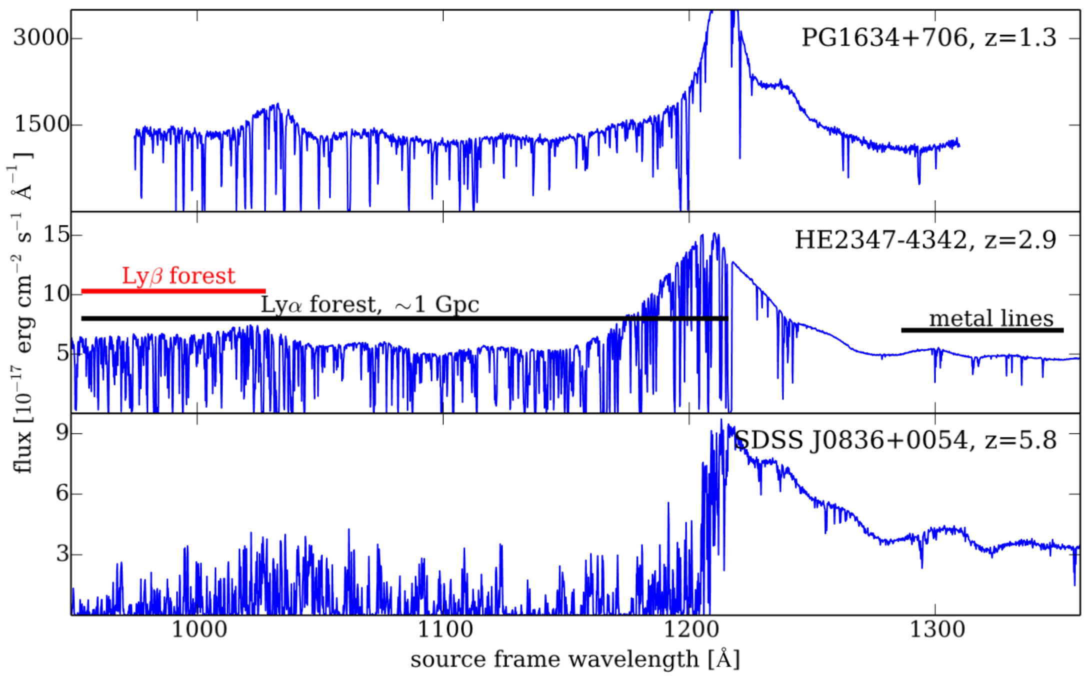

Figure 2: Ly α forest spectral region of quasars [2]

- The very high transition strength means a very small amount of singly ionized helium can lead to total absorption of the incoming radiation; typically, neutral fractions of $f_{\mathrm{HeII}} \gtrsim 10^{-3}$ can produce a Gunn-Peterson trough, making detection of the early stages of helium II reionization difficult [10]

3.2 λCMD simulations

- λCMD models predict a qualitatively similar Lyα forest (seen in figure 4)

- Main parameters of simulation are the density structures, the photoionization rates and the gas temperatures [2]
- The statistical properties of the gas density field are assumed to be those expected from evolving (via the equations of hydrodynamics and gravity) the cosmological initial conditions subject to a uniform ionizing background that turns on at $z \sim 10$; This posits that galactic feedback processes – which are known to blow baryons out of galaxies – do not significantly impact the low density gas seen in the Ly α forest
- The H I photoionization rate Γ (and hence the ionizing background) is assumed to be spatially uniform, which is motivated by the much longer mean free path of ionizing photons relative to the mean distance between sources – a scenario that suppresses fluctuations
- The temperature is assumed to be a power-law function of density, often this power-law is parameterized in terms of the density in units of the cosmic mean, Δ_b, as $T(\Delta_b) = T_0 \Delta_0^{\gamma-1}$ with T_0 and $\gamma - 1$ being parameters that are varied to fit the observations
- It is assumed that the Lyα forest absorption can be extracted sufficiently well that metal line contamination, errors in the estimate of the quasar's intrinsic continuum, and damping wing absorption do not bias inference

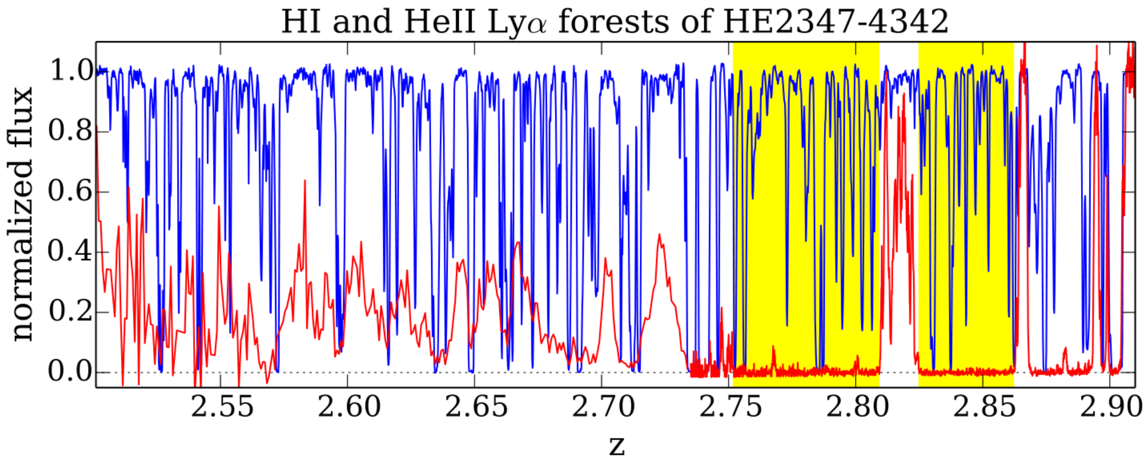

Figure 3: [2]

3.3 Metal enrichment

- Stars did not only ionize the IGM, but the radiation pressure, combined with SNe, powered winds that enriched the IGM with metals [2]
- Metal-line absorption is fundamentally different from its primordial big brother, the Lyα forest, owing to its much greater sensitivity to the processes of galaxy formation and evolution (while galactic outflows suppress star formation and therefore metal production, they concurrently distribute metals into haloes and the IGM) [11]
- Metallicity of IGM at $z \sim 2-3$ between $10^{-3.5}$ and $10^{-2.0}\,M_{\odot}$ [11]
- Main results of simulations: 20% of the metals reside outside of halos at $z \sim 2$ and only 4% at $z \sim 0$ $\Rightarrow$the majority of metals today reside within galaxies, in contrast to the bulk of baryons that reside outside haloes
- The exact process of the metal enrichment depends on many parameters (such as different phases of the IGM, the strength of galactic winds etc.); several simulations are compatible with current measurements, so no particular model sticks out

4 The IGM at low redshifts ($0 < z < 2$)

4.1 The missing baryons problem

- As already stated: at lower redshifts, the Ly α forest becomes progressively more transmissive as the Universe is further diluted by cosmological expansion, with an average transmission of $\exp[-\tau_{\mathrm{eff}}]$ with $\tau_{\mathrm{eff}} = 0.016(1+z)^{1.1}$ over $0 < z < 1.2$, compared to $\tau_{\mathrm{eff}} = 0.36$ at z = 3 [2]
- Estimates find that only $30 \pm 10\%$ of the $z \sim 0$ gas is seen in Lyα absorption and that $\sim 10\%$ of the baryons lie within galaxies or reside as hot gas inside galaxy clusters; this accounting leaves a large fraction that are "missing", the inability to observe most of the baryons at $z \sim 0$ is referred to as the "missing baryon problem" [2]
- The key here is to understand how galactic feedback redistributes gas around galaxies (and how this redistribution in turn affects how the IGM feeds galaxies) [2]

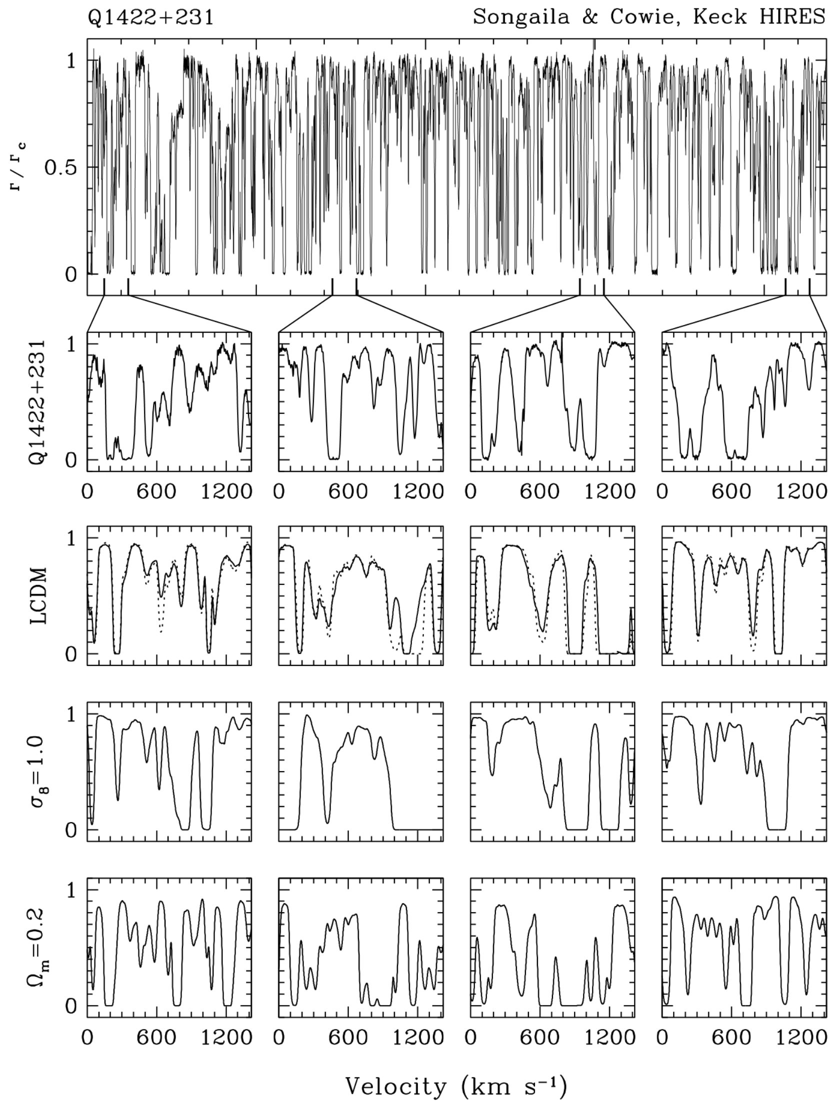

Figure 4: [2]

- Hypothesis: missing baryons in galaxy groups are contained in the WHIM (Warm-Hot Intergalactic Medium) with temperatures between 100,000 and one million Kelvin, a view supported by recent measurements and modeling (using the kinetic Sunyaev-Zel'dovich effect) [12]

4.2 IGM-galaxy connection

- From: [13]
- Galaxies of all luminosity ($L > 0.01\,L^*$) and spectral-type show strong, associated Ly α absorption to impact parameter $\rho = 300\,\mathrm{kpc}$ with a very high covering fraction ($\approx 90\%$)
- Galaxies with luminosities ($L > 0.1\,L^*$) exhibit a high covering fraction ($> 80\%$) for significant O VI absorption to $\rho = 200\,\mathrm{kpc}$ and to $200\,\mathrm{kpc}$ for sub-L^* galaxies
- Dwarf galaxies ($L < 0.1\,L^*$) exhibit a low covering fraction for $\rho > 50\,\mathrm{kpc}$

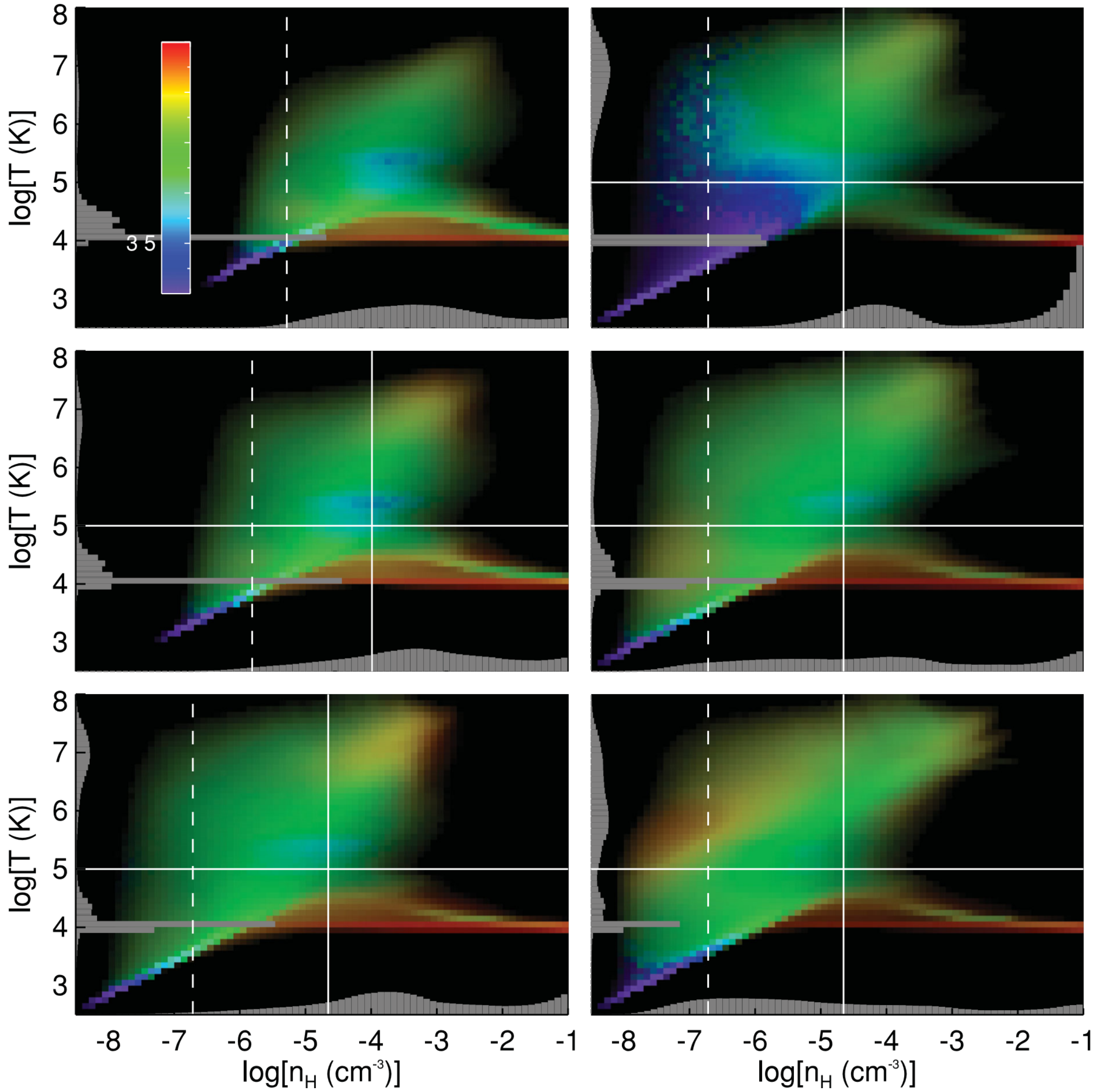

Figure 5: [11]

- Despite these high covering fractions of Ly α and O VI absorption, there are examples of nondetections to very sensitive limits, even at very low impact parameters ($\rho \lesssim 50\,\mathrm{kpc}$)
- Few, if any, of the weak Lyα absorbers ($W^{\mathrm{Ly}\alpha} < 100\,\mathrm{m\AA}$) from the low-z IGM arise in the virialized halos of $z \sim 0$ galaxies, or their surrounding CGM (Circumgalactic Medium); the majority of strong Lyα absorbers ($W^{\mathrm{Ly}\alpha} > 300\,\mathrm{m\AA}$), however, does arise in these environments
- The strongest O VI absorbers ($W^{1031} > 100\,\mathrm{m\AA}$; $N_{\mathrm{OVI}} > 10^{14}\,\mathrm{cm}^{-2}$) arise preferentially in the galactic halos of $L > 0.01\,L^*$ galaxies
- Weaker O VI absorbers are associated with the extended CGM of sub-L^* galaxies
- Current predictions for models where O VI gas arises in a collisionally ionized WHIM are ruled out at high confidence, it is suggested that O VI gas is primarily associated with a photoionized CGM with $n_H \approx 10^{-5}\,\mathrm{cm}^{-3}$and typical dimension $d \sim 300\,\mathrm{kpc}$

5 Conclusion

- Very few observables, mostly spectral line analysis
- The information gained is largely dependant on models and simulations (Yes Thorben, I don't like it either, but that's just how it is ☺)
- ...

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