# Les Lumières: probing the cosmic Epoch of Reionization with high-redshift quasars

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# English summary

If I had to summarise the contents of this thesis in just two words, it would be its title: *Les Lumières*. Light is essential to us as astrophysicists, as we inevitably have to infer all information about the nature of our Universe from light[3] that we manage to detect with our telescopes on the ground or in space. Particularly suitable for our purposes is a specific type of astrophysical lights that we call *quasars*. These astrophysical objects are shining so extraordinarily bright that they came to be known as *quasi-stellar objects* or *quasars*, even though their distances are anything but comparable to those of stars in our own galaxy. On the contrary, powered by supermassive black holes in the centres of distant galaxies, quasars are so exceptionally powerful and bright that we are still able to detect them at *cosmological* distances, out to redshifts $z \sim 7.5$. Given the time it took until their light that we are currently observing had reached Earth, looking at such distant sources means nothing else but peering into our Universe's first billion years.

A landmark event has shaped the evolution of our Universe at these early times: the *Epoch of Reionisation*. Initiated by the first stars and galaxies that started forming in these years, this era marked the end of the cosmic *dark ages* where the Universe remained devoid of any visible light. However, once these first astrophysical sources had started forming, their light quite literally illuminated our Universe: *Les Lumières* – a cosmic *Age of Enlightenment*. This light even had an impact on the vast voids in between these galaxies that we call the *intergalactic medium* (IGM) – the regions where most cosmic matter actually resides. Being exposed to these new sources of light, the neutral hydrogen atoms in the intergalactic medium successively got *re*-ionised by their radiation. As such, bubbles of ionised hydrogen formed around these ionising sources, and grew and merged until the entire intergalactic medium was reionised.

The progression of this process is characterised in terms of the fraction of neutral (as opposed to ionised) hydrogen atoms in the intergalactic medium. Precisely measuring the evolution of this fraction as a function of cosmic time is a highly challenging task – and also the main subject of this thesis. Probing this progression brings us back to quasars, our astrophysical lights that are particularly useful exactly for these purposes. This is because substantial amounts of neutral hydrogen present in the foreground of a quasar imprint a characteristic absorption signature upon its spectrum, the so-called Lyman-$\alpha$ *damping wing*. The fact that its strength is highly sensitive to the exact amount of neutral hydrogen makes it an exquisite probe of reionisation.

[3] as well as particles such as cosmic rays and neutrinos, and, most recently, gravitational waves

At the same time, the quasar itself is a an exceptionally powerful source of ionising radiation which carves out an ionised bubble around itself whose size grows the longer the quasar has been shining. This reduction of neutral material due to the quasar's own ionising radiation weakens the intergalactic damping wing signature but also imprints a second characteristic signature upon its spectrum, the so-called *proximity zone*, whose size reflects the extent of the ionised region around the quasar. This, in return, informs us about its lifetime, a crucial quantity for understanding the growth and evolution of the supermassive black holes powering these quasars.

Breaking the degeneracy between the contribution from the global, cosmological reionisation process and the quasar's own impact as an astrophysical source is one of the fundamental tasks related to this problem and requires both adequate simulations and a sophisticated inference pipeline to relate these simulations to observational data. This thesis is concerned with one such framework that has recently been established for these purposes, trying to push its boundaries to extract even more information from the intergalactic damping wing signature than has been used thus far.

**Chapter 2** presents an inventory of the current state of the art of quasar damping wing analysis and quantifies the precision that such measurements are able to achieve when accounting for all relevant sources of uncertainty. We are demonstrating that, besides the uncertain lifetime of the quasar, two contributions are of comparable importance, both with a substantial impact on the overall error budget. First, the damping wing signature is not observable individually but imprinted upon the intrinsic spectrum of the quasar. Reconstructing this intrinsic spectrum and disentangling it from the IGM absorption imprint naturally affects the overall constraining power. Second, reionisation did not proceed uniformly but rather according to a "swiss-cheese" topology where individual ionised bubbles grew and merged until the Universe was reionised in its entirety. As such, the actual distribution of neutral and ionised patches along a given line of sight can vary substantially, even when the *average* fraction of neutral hydrogen is fixed. Sightline-to-sightline variations therefore further add to the error budget on this global average quantity.

This latter source of uncertainty is also the motivation for **Chapter 3**, a theoretical study where we establish two new summary statistics that are defined to be robust against cosmic variance in the IGM. Instead of constraining a global average, these parameters are defined locally, quantifying the neutral hydrogen content directly in front of a given source. As such, they open up the possibility of using the IGM damping wing imprint not only to constrain the global timing but also the local topology of reionisation. In addition, we show that these summary statistics do not require any assumptions about the underlying reionisation model and can thus be constrained in a model-independent fashion.

In **Chapter 4**, we proceed by incorporating our new parameterisation of IGM damping wings into our existing inference codebase. We also put forward a framework that allows us to tie these model-independent, local constraints to a specific reionisation model. This amounts to imposing a non-trivial prior on our local summary statistics and then also results in a model-dependent constraint on the global IGM neutral fraction. By testing our inference pipeline on a large set of mock spectra, we also quantify the precision with which we are able to constrain these new statistics.

The thesis ends with **Chapter 5** which presents the first practical application of our newly developed parameterisation. By analysing JWST/NIRSpec spectra of two of the most distant quasars known to date, J1007+2115 at $z = 7.51$ and J1342+0928 at $z = 7.54$, we obtain, for the first time, constraints on the local ionisation topology in front of these two objects. While the first sightline appears to be largely ionised, the second one shows clear evidence of a damping wing imprint, and thus a non-trivial amount of neutral material along the line of sight. With this analysis, we also take the first step towards the application of our framework to a statistical sample of high-redshift sources that will become available in the coming years, shedding bright new light on our understanding of the Epoch of Reionisation.