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# Transform our Understanding of the Baryon Cycle with High-Resolution Quasar Spectroscopy (ByCycle)

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**The term baryons refers to the normal matter of the Universe. Surprisingly, only a minority of this normal matter (< 10%) can be probed by observations of starlight from galaxies. The ByCycle project aims to study the remaining majority of the baryons traced by the intergalactic gas. To this end, ByCycle will use the powerful synergy of absorption and emission diagnostics by observing a large sample of background quasars to probe the circumgalactic medium of foreground objects in the same sky regions. The objective of the 2.8-million fibre-hour ByCycle project is ultimately to characterise the physical processes by which gas changes phases and travels into, through, and out of galaxies. Such a study is essential to our understanding of the growth of structure in the Universe.**

## Scientific context

Astronomers now know the basic constituents of the present Universe: 73% dark energy, 23% dark matter, and 4% baryons. The term baryons is used to refer to the normal matter of the Universe. One of the great successes of the last decades is the excellent agreement between estimates of the total comoving baryon density from Cosmic Microwave Background (CMB) anisotropies (Planck Collaboration et al., 2016), primordial nucleosynthesis (Cooke, Pettini & Steidel, 2018) and fast radio burst dispersion measures (Macquart et al., 2020). However unlocking the physics of the normal matter continues to represent a most intriguing enigma in astrophysics and cosmology. Indeed, although the amount of matter bound in stars grows with time, only a minority of the baryonic material is found there; even today, > 90% of the baryons are found in the gaseous phase of the Universe. Notably, progress in determining the baryons' location and physical state will have an impact beyond understanding the evolution of star formation and galaxies. Indeed, the survival of satellite sub-halos in cosmological hydrodynamical simulations generating orders of magnitude more dwarf galaxies than observed — the 'missing satellites problem' — relates to our capacity to accurately model galactic feedback. Furthermore, baryonic effects impact the dark matter distribution and thus the inference of cosmological parameters from weak lensing surveys (Semboloni et al., 2011; Chisari et al., 2018; Foreman et al., 2020).

From the Big Bang onwards, the baryons collapse with dark matter to form the cosmic web, galaxies, stars and, ultimately, the planets that we observe. Baryons from the cosmic web accrete onto galaxies and cool into a phase which fuels star formation, which in turn expels material in powerful outflows. The result is a multiphase medium of pristine and enriched material that lies in the immediate surroundings of galaxies, the so-called circumgalactic medium. More globally, the cosmic baryon cycle describes these processes of motion and phase transformation of the baryons (Tacconi, Genzel & Sternberg, 2020; Peroux & Howk, 2020; Walter et al., 2020).

## Specific scientific goals

### Baryons as a function of time: a census of the cosmic metals

Characterising the relationship between stars, gas and metals is a critical component of understanding the cosmic baryon cycle. Observations of the evolution of metals are key to constraining this global picture of the evolution of the Universe. The early accounting of the total metal budget by Pettini (1999) found an order of magnitude shortfall in the comoving density of observed metals compared with those expected to be produced by the stellar content of the Universe (Madau & Dickinson, 2014; Bouwens et al., 2020; Zavala et al., 2021). The ByCycle project will observe hundreds of thousands of high-redshift quasar spectra with 4MOST at high resolution, providing a robust picture of the metal content of the baryons in the Universe over much of its history.

### Baryons as a function of space: characterising the circumgalactic medium

Ultimately, a detailed map of the cool gas component around galaxies will characterise the dominant baryon reservoir associated with forming galaxies, as well as providing constraints on gas flows that are an essential part of the current galaxy formation paradigm (Chen et al., 2021). Recent findings indicate that the circumgalactic medium is a major reservoir of heavy elements with a mass rivaling, and possibly exceeding, that of the galaxies themselves (Peeples et al., 2014). Hence, the gas around galaxies holds valuable

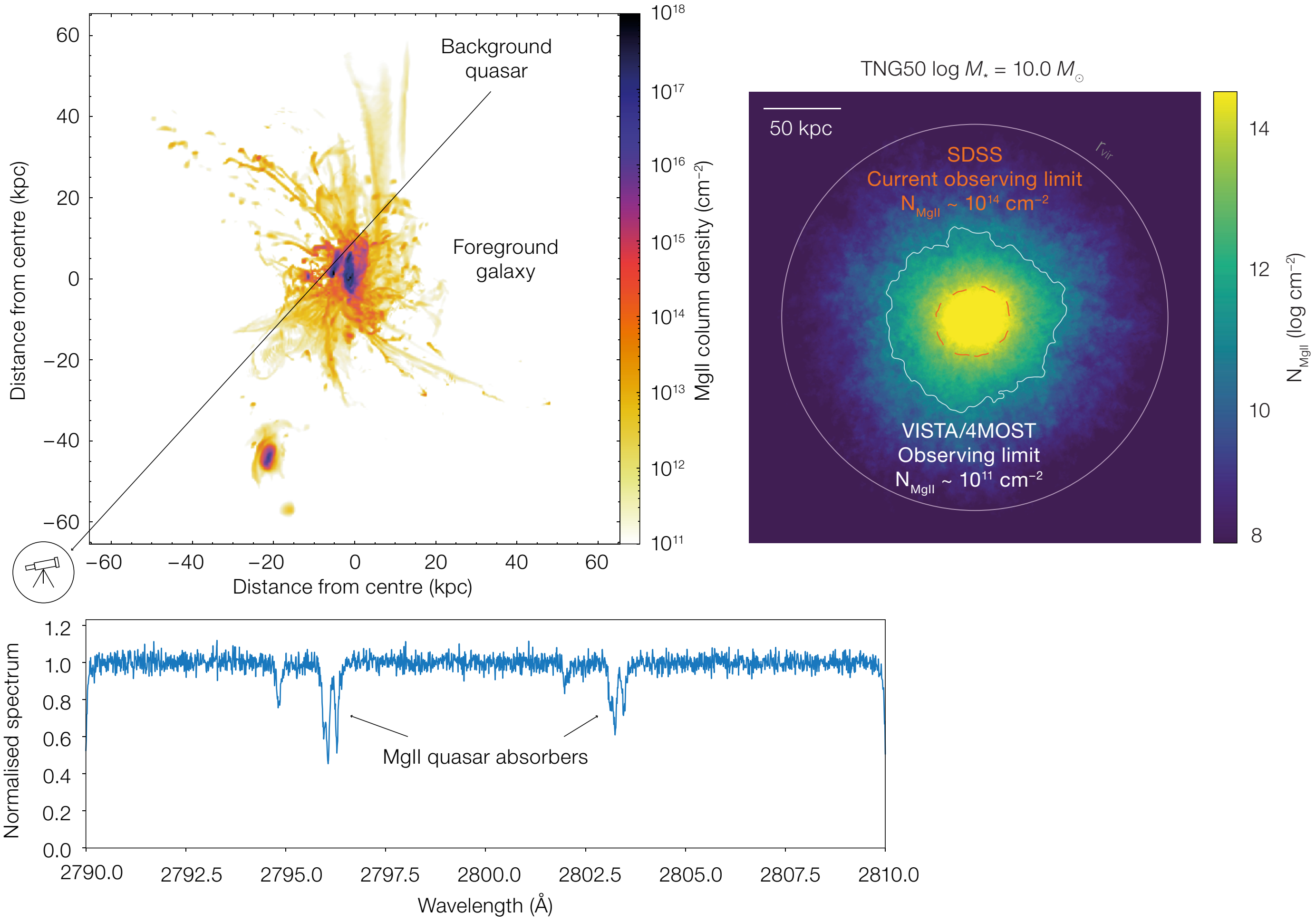

**Figure 1.** Top left panel: Schematic view of the observational setup. Absorption lines detected against bright background quasars observed with 4MOST high-resolution fibres offer a unique opportunity to study the distribution and chemical properties of the circumgalactic medium gas of foreground galaxies observed with 4MOST low-resolution fibres. The top panel shows results from zoom-in FOGGIE[2] simulations with exquisite resolution (~ 0.1 kpc scales) in the circumgalactic medium of galaxies (Peeples et al., 2019; Augustin et al., 2021). The ByCycle project is designed to probe the whole range of MgII column densities displayed. The bottom left panel presents a 4MOST normalised mock quasar spectrum with typical rest-frame MgII doublet lines. Right panel: Illustris TNG50[3] simulations of the circumgalactic metal distribution (Szakacs et al., 2023). This is a 2D stack of 200 $z$ = 0.5 galaxies like the ones probed by ByCycle. The red contour illustrates the current MgII column density detection limit from SDSS (Anand, Nelson & Kauffmann, 2021), while the white contours correspond to the MgII column density limit of ByCycle. The white circle shows the $r_{200}$ radius, the Virial radius assuming a critical overdensity constant of 200. The ByCycle project will provide an improvement of three orders of magnitude in the MgII column density probed in the extended circumgalactic medium of galaxies, thanks to its large multiplexing capability and spectral resolution of $R$ = 20 000.

clues to the fueling of star formation and feedback processes. The ByCycle project[1] aims to characterise the circumgalactic medium gas and metals of 1.5 million galaxies, active galactic nuclei, groups and clusters.

## Building a sizeable legacy sample

Today, the circumgalactic medium is best probed by the powerful technique of examining the gas in absorption against background sources (such as quasars or gamma-ray bursts) whose lines of sight pass through an identified foreground galaxy's halo. The absorption lines offer the most compelling way to study the distribution, chemical properties and mass budget of the mixed halo gas by probing matter at different densities, metallicities and temperatures (Figure 1, left panels). In these quasar absorbers, the minimum column density, which is tightly correlated to the volumetric gas density that can be detected (Rahmati et al., 2013), is set by the apparent brightness of the background sources and thus the detection efficiency is independent of the redshift of the foreground host galaxy. Figure 1 (right panel) illustrates the three orders of magnitude gain in magnesium (MgII) column density that will be reached with the ByCycle survey compared to what is available today. We will use the powerful synergy of absorption and traditional emission diagnostics by observing one million background quasars and 1.5 million foreground objects in the same sky regions with 4MOST.

The high-redshift element of ByCycle focuses on several dozen thousand strong Lyman-α absorbers tracing both neutral and ionised gas observed over a large area. The ByCycle high-redshift quasars will be used to probe the

Lyman-$\alpha$ absorbers tracing the neutral gas phase and its metal content with the goal of providing a modern metal census. The metal content of gas traced by Lyman-$\alpha$ absorbers will be modelled with the column density of metal ions through Voigt-profile fitting (for example, Quiret et al., 2016). We will determine the dust-corrected and ionised-gas metallicity by performing a full photoionisation modelling (Hamanowicz et al., 2020) informed by the presence of elements with various degrees of ionisation. By counting the number of detected systems of various strengths, we will provide a robust estimate of the number density per unit redshift of strong Lyman-$\alpha$ absorbers which will allow us to calculate their gas mass content, $\Omega_{gas}$. This quantity is also critical for estimates of the meta-galactic ultraviolet background used in radiative transfer models of the high-redshift Universe (Kollmeier et al., 2014; Fumagalli et al., 2017). With the measurements of the metallicity and gas mass, we will directly test whether the strong Lyman-$\alpha$ quasar absorbers at intermediate redshifts do indeed contain the reservoir of missing metals. This novel census of the metal mass density will provide a new perspective on the missing metals problem and existing tensions with models (Yates, Peroux & Nelson, 2021).

With the low-redshift part of the ByCycle project, we will crosscorrelate quasar absorbers with galaxies detected in emission in the same fields. The primary targets are magnesium (MgII) quasar absorbers, that trace cooler gas at $10^4$ K and whose doublet nature makes their signature in quasar spectra unambiguous. The strong complementarity of absorption and emission diagnostics will be used to characterise the low-density gas which is key to our understanding of galaxy formation and evolution. We will gather a sample of 1 million $z > 0.55$ quasar spectra, exploring the low-density gas traced by 250 000 MgII absorbers. The physical properties of the metal absorbers will be crosscorrelated with up to a million foreground galaxy spectra observed in the same fields (Driver et al., 2019; Richard et al., 2019). An additional 600 000 active galactic nuclei and 20 000 groups and clusters are ideally suited to probing the rarer, denser foreground objects (Merloni et al., 2019; Finoguenov et al., 2019). These observations will be stacked to measure the radial profile of both Lyman-$\alpha$ gas and metals as a function of galactocentric radii (see left panels of Figure 1 and Turner et al., 2017; Chen et al., 2021). Specifically, we will quantify the covering fraction of the neutral gas and numerous ion species (including MgII and CIV) as a function of impact parameter. We will compute the number density of metal absorbers down to small rest-frame equivalent width, thus probing the most diffuse and extended gas. Together these measurements will put direct limits on the clumpiness of the medium and provide new constraints on the scales of metal mixing in the circumgalactic medium (Nelson et al., 2020; Augustin et al., 2021). These quantities relate directly to the missing satellites problem (Byrohl et al., 2021; Mitchell & Schaye, 2022). Furthermore, these findings will put new constraints on state-of-the-art cosmological hydrodynamic simulations with increased spatial resolution in the circumgalactic medium regions that aim to characterise the physical properties of the gas (van de Voort et al., 2019; Peeples et al., 2019). We will further assess the strength of the absorbers by computing the optical depth of the metal doublets for different phases of the gas from cold, at temperature $T = 10^4$ K (MgII), to warm, at $T = 10^5$ K (CIV). We will locate the gas spatially and in velocity space with respect to the associated foreground galaxies (Turner et al., 2014; Chen et al., 2021). In so doing, we will probe the net effect of inflow and outflow interactions, revealing recycled gas and the history of circumgalactic medium metal enrichment. We will constrain the source of ionisation, the dynamical state of the circumgalactic medium gas and hence the total baryonic content of galaxy halos. We stress that baryonic effects have a significant impact on the distribution of matter, which needs to be incorporated into ongoing and future weak lensing experiments.

## Target selection and survey area

The ByCycle survey strategy requires an *a priori* knowledge that the quasar's redshift is greater than $z = 0.55$ to ensure the detection of intervening absorbers along its line of sight within the 4MOST wavelength coverage. To assess both the nature and redshift of a large sample of targets we revert to a prior, likelihood, and posterior probability in a Bayesian analysis (see Yang & Shen, 2023). The selection algorithm assigns probabilities for quasars, galaxies and stars, and simultaneously calculates photometric redshifts (Salvato, Ilbert & Hoyle, 2019) for all extragalactic sources. We make use of the latest Gaia release (DR3) to classify known stars as well as the most recent DESI Legacy Imaging Survey[4] (DR10) in concert to estimate photometric redshifts. The comparison of the results with available quasar spectroscopic redshifts confirms that the resulting sample has both high completeness and high purity, securing the requirement of $z > 0.55$. This computation results in a total of 3.2 million quasars within the 4MOST project footprint (for example, with declination < +5 deg). To ease scheduling, the ByCycle survey provides targets to choose from a more extended catalogue of sources. In addition, the ByCycle survey has no requirement on completeness, cadence of observations or selection function. Instead, the strategy aims at maximising the number of low- and high-spectral-fibre pairs.

A key component of ByCycle is the sharing of the focal plane with other low-redshift extragalactic surveys. Indeed, ByCycle will combine high-resolution fibre observations of bright background quasars with low-resolution fibre observations of foreground galaxies, active galactic nuclei, groups and clusters that are in the same field. The ByCycle survey comprises both a deep and a wide component. The former is driven by the deep observations that will be carried out by low-resolution galaxy surveys in five distinct cosmological fields. The latter extends to an area designed in synergy with other efforts to cover > 15 000 deg$^2$.

In summary, the 2.8-million fibre-hour ByCycle survey will use the powerful synergy of absorption and emission diagnostics by observing a sizeable sample of background quasars and foreground galaxies in the same fields. At high redshift, we will build an unprecedented catalogue of Lyman-$\alpha$ absorbers, measuring their dust-free and ionisation-corrected metallicity to reappraise the missing metals problem. At late times, we will crosscorrelate high-resolution fibre observations of the quasars with low-resolution spectra of 1.5 million foreground objects (including galaxies) over the same area. From stacked observations, we will measure the radial profile, covering fraction and optical depth of the neutral hydrogen and metals in their circumgalactic medium. Together, these results will provide a robust census of the cosmic metals and refine our view of the circumgalactic medium. This long-lasting legacy dataset will bring high-resolution quasar spectroscopy to a new level — an increase of three orders of magnitude over currently available samples.

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## Links

[1] ByCycle project webpage: http://www.eso.org/~cperoux/ByCycle.html
[2] FOGGIE webpage: https://foggie.science/
[3] IllustrisTNG simulation project webpage: https://www.tng-project.org
[4] DESI Legacy Imaging Surveys: https://www.legacysurvey.org/

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C. Duran/ESO

This picture shows the grand skies of the Chajnantor plateau in the Chilean Atacama desert. The rare sight of clouds in this typically dry and arid region creates a dramatic display of reds and blues, as well as a sun pillar — an optical phenomenon caused by ice crystals in the atmosphere — that emanates from the Sun in line with a telescope. This large antenna is a part of the Atacama Large Millimeter/submillimeter Array (ALMA), which is co-owned by ESO.