# Neutral outflows in high-redshift dusty galaxies

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# 1 | Introduction



## 1.1 The Baryon Cycle

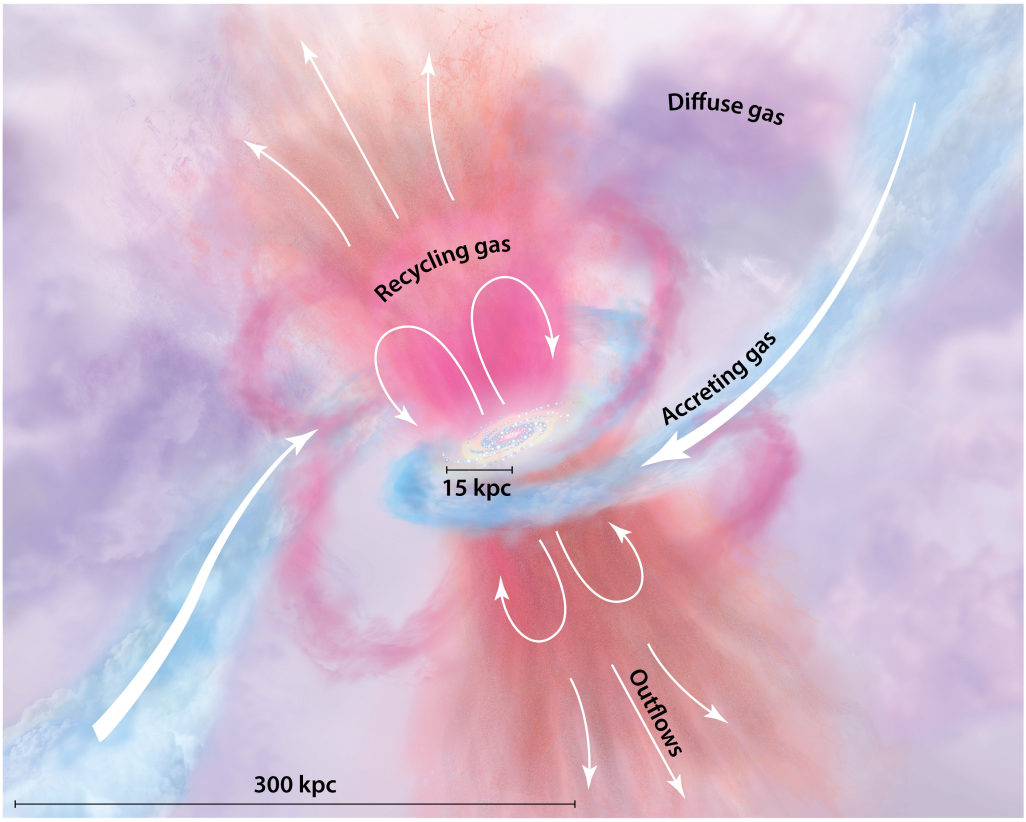
The life of a galaxy from birth until death is a continuous and complex interplay between it and the wider cosmic web from which it forms.

The infant universe was a highly homogenous, isotropic mixture of hot ionised gas and cool, non-baryonic matter incapable of or very weakly interacting electromagnetically, called cold dark matter (CDM) (White et al., 1994; Scott et al., 1995). Imprinted on the initial matter distribution were subtle density fluctuations which, over time, gravitationally attracted the weakly-interacting CDM. Eventually, the overdense regions collapsed to form large structures called dark matter halos (Peacock, 1999) and even larger filamentary and sheet-like structures formed in between, creating a web-like structure across the cosmos. As the universe continued to expand, the hot baryonic matter cooled and began to gravitate towards and flow along these structures, accreting onto the growing dark matter halos. Dissipation of energy and angular momentum allowed gas within the halos to fall to their centers and collapse to form molecular clouds (Rees & Ostriker, 1977; White & Rees, 1978) or accrete onto primordial black holes. It is from these clouds that the first stars and the first galaxies were formed. Easy, right?

No. After all this cooling and collapsing the formation of stars and accretion disks around supermassive black holes injected energy and momentum back into the interstellar medium (ISM). Winds, radiation pressure and supernovae heat and disturb the surrounding gas, delaying its collapse into new stars and in the most extreme circumstances gas is pushed back out of the galaxy in the form of outflows. This not only removes mass, angular momentum and fuel for future star formation but enriches the circum– (CMG: Tumlinson et al., 2017) and inter–galactic (IGM: Oppenheimer et al., 2019; Davies et al., 2019; Keller et al., 2019) medium with metals. Outflows travelling below the escape velocity of their potential wells remain gravitationally bound to the galaxy and can eventually cool and reaccrete back onto the galaxy via fountain flows, if not subjected to additional feedback in the CGM. And thus the baryonic cycle of the universe is set in motion (Fig. 1.1). Galaxies continue to grow by accreting gas from the CGM and IGM or by merging with other halos until the supply of gas is shut off or the CGM becomes too hot for gas to accrete onto the galaxy. Eventually, star formation, black hole accretion and outflows will either use up or remove all the gas, ceasing star formation and quenching the galaxy. This thesis tackles the question of how and how much the removal of gas in massive galaxy outflows impacts the evolution and the eventual demise of their host galaxies.

## 1.2 The Multiphase Nature of Galaxy Outflows

Observational evidence of galaxy outflows first came from metal absorption in quasar sightlines through the circum-galactic medium of other galaxies (Meyer & York, 1987; Simcoe et al., 2004). This showed that some of the gas enriched within the galaxy must have been ejected into its surroundings. The first direct evidence of galaxy outflows came from optical and X-ray observations of the ionised gas phase (Heckman et al., 1990; Strickland et al., 2004). Following




Tumlinson J, et al. 2017.
*Annu. Rev. Astron. Astrophys.* 55:389–432

Figure 1.1: *Cartoon from Tumlinson et al. (2017), detailing the complex inflow, outflow and recycling of gas through the circum-galactic medium.*

this discovery, observations in the IR and submillimeter wavelengths soon uncovered the atomic and molecular phases associated with outflowing cool gas (e.g., Walter et al., 2002), revealing the multiphase nature of galaxy outflows.

A few decades later and outflows have been shown to be ubiquitous in the universe, ejected from dwarf galaxies, and massive star-forming galaxies alike. The bright emission and absorption lines associated with the ionised gas phase allowed extensive observations across a wide range of outflow and galaxy properties, revealing that galaxies with high star formation rates (SFRs), stellar masses and SFR surface densities drive more extreme outflows (faster, larger outflow rates) (Lehnert & Heckman, 1996; Rupke et al., 2005; Martin, 2005; Westmoquette et al., 2012; Rubin et al., 2014; Chisholm et al., 2016; Heckman & Borthakur, 2016). Soon after, the advent of Herschel SPIRE, and the IRAM PdBI allowed observations of the cold gas outflow phase in a large number of nearby galaxies (Sturm et al., 2011; Spoon et al., 2013; Veilleux et al., 2013; Cicone et al., 2014; Veilleux et al., 2020). Mass outflow rates (MOFRs) in the cold gas have been found to rival or even exceed the SFRs of local Luminous and Ultra Luminous Infra

Red Galaxies (LIRGs; $L_{IR} > 10^{11}L_{\odot}$ and ULIRGs; $L_{IR} > 10^{12}L_{\odot}$). As in the ionised gas, the presence and luminosity of an AGN appears to significantly boost the outflow velocity (Sturm et al., 2011; Spoon et al., 2013; Stone et al., 2016) and MOFR (Cicone et al., 2014) and decrease the gas depletion time (Sturm et al., 2011; Cicone et al., 2014; González-Alfonso et al., 2017) of local luminous galaxies. Whilst intense star formation is found to be effective in powering massive molecular outflows, these studies showed that when present, AGNs were the dominant influence of outflow properties. Regardless, it has become clear that massive outflows driven by star formation and AGN are not just closely connected with their host galaxy properties, but are a key ingredient in their evolution.

With observations of outflowing gas across all wavelengths, studies comparing the relative impact of each outflow phase became possible. Ionised gas tracing the fastest and hottest phase of the outflow was found to dominate the kinetic energy budget whilst the slower neutral and molecular phases are responsible for carrying out the bulk of the mass and momentum (Walter et al., 2002; Rupke et al., 2005; Feruglio et al., 2010; Herrera-Camus et al., 2020; Fluetsch et al., 2021). Gas ejected from the galaxy in the neutral and molecular phases had the added influence of removing the direct fuel for star formation. The impact of this phase on the evolution of the galaxy is therefore of great interest.

## 1.3 Outflows at High-z

A consequence of self-regulated galaxy growth is that the most vigorous growth periods in a galaxy's life are accompanied by the most aggressive feedback and consequently the most extreme outflows (Schaye et al., 2015; Nelson et al., 2019; Pillepich et al., 2019; Henriques et al., 2020). Therefore, in the interest of studying and quantifying the impact of outflows on the formation and evolution of their galaxies, it is imperative to target the most rapid phases of galaxy assembly.

Madau & Dickinson (2014) showed that the star formation rate density and black hole accretion of the universe peaks at redshifts between $z = 2 - 4$. At this epoch, outflows are believed to be ubiquitous. At $z > 4$, however, massive quiescent galaxies are already present in the universe (Straatman et al., 2014; Guarnieri et al., 2019; Carnall et al., 2020; Valentino et al., 2020). The short lifespans of these galaxies imply intense star formation and black hole activity capable of depleting their massive gas reservoirs in a short time. Thus, feedback and outflows in the most heavily starforming and active galaxies at $z > 6$ are of particular interest in deciphering the evolution of these systems Carnall et al. (2020).

Detecting outflows at high-z, however, is observationally a difficult task. Low-z observations of high-velocity line wings in molecular emission lines (e.g, in CO lines Feruglio et al., 2010, Fig.1.2) have shown that the outflowing component typically contributes only a few per cent of the total line flux. The bright [CII] line has successfully detected outflows in a handful of individual sources at high-z (Fan et al., 2018; Herrera-Camus et al., 2021; Tripodi et al., 2022) but has proven to be an inefficient (Bischetti et al., 2019; Novak et al., 2020) and unreliable outflow tracer (Spilker et al., 2020a). Fortunately, in sources with a bright dust continuum molecular absorption lines provide a powerful alternative tracer of the cool gas intervening between the observer and the host galaxy. An absorption line blue-shifted with respect to the systemic velocity of the host galaxy thus provides unambiguous evidence of outflowing gas. Low-z Herschel SPIRE spectra of the OH 119 $\mu m$ and $OH^+$ lines have successfully uncovered numerous neutral outflows in local (U)LIRGs (e.g., Fischer et al., 2010; Sturm et al., 2011; Spoon et al., 2013; Stone et al., 2016; van der Werf et al., 2010; Rangwala et al., 2011, Fig. 1.2). More recently, improvements in millimetre wave facilities, such as the Atacama Large Millimeter Array (ALMA) and the Northern Extended Millimeter Array (NOEMA), have produced observations of high-z dusty sources reliably demonstrating with multiple different molecular absorption lines (e.g., $OH^+$, $CH^+$, OH, $H_2O$) this efficient and sensitive method of tracing neutral outflows in the distant universe (Falgarone et al., 2017; Spilker et al., 2018; Jones et al., 2019; Spilker et al., 2020b,a; Riechers et al., 2021; Shao et al., 2022). Despite this promising start, observations of cool neutral gas outflows are still severely limited at high-z in both sample size and quality. Observations with high S/N capable of reliably disentangling outflow signatures from gas at systemic velocities, with high spatial resolution capable of determining geometrical properties and samples including active galaxies are in particular lacking at this epoch. This brings us to this thesis.

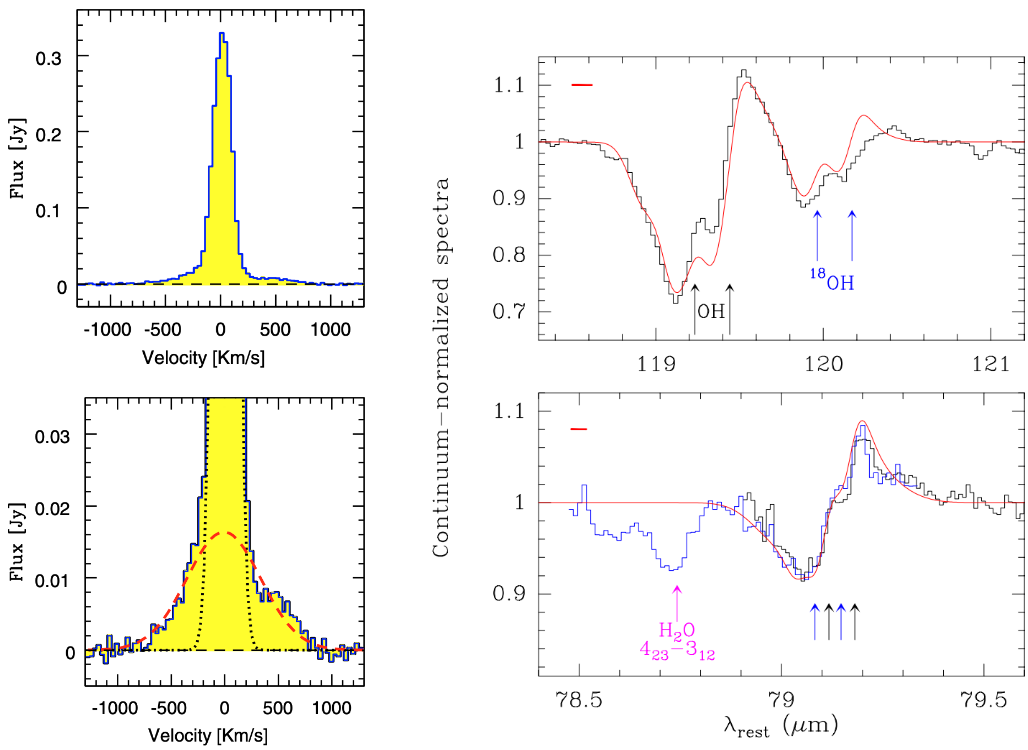



Figure 1.2: *Early detections of molecular outflows in local ULIRGs using left) high-velocity wings on CO emission lines (Feruglio et al., 2010), and right) blue-shifted OH absorption (Fischer et al., 2010).*

## 1.4 This Thesis



In this thesis, we target the cool neutral atomic and molecular outflow phases in the most heavily starforming and active galaxies during the epochs of greatest galaxy assembly, $z = 2{-}4$ and $z > 6$. In this way, we aim to study the maximum impact of massive galaxy outflows on the evolution and demise of their host galaxy and investigate the primary driving mechanisms responsible for the ejection. The chapters are as follows:

- **Chapter 2**
  This chapter takes a detailed look at the massive neutral outflow in the z=2.0924, gravitationally lensed Dusty Star-Forming Galaxy (DSFG), J085358.9+015537 (G09v1.40). We use spatially resolved observations of the blue–shifted $OH^+(1_1 - 1_0)$ absorption line, taken with ALMA to study the geometry and velocity field of the outflowing gas. Also detected in this data is the adjacent CO(9-8) emission line, tracing warm dense gas in the galaxy, and the underlying dust continuum. The high S/N and resolved dust continuum allows gravitational lens modelling of the system and thus a comparison of the intrinsic outflowing neutral gas and systemic molecular gas and dust properties in the source plane. This work showcases the detail in which we can study high-z massive galaxy outflows with the current facilities.

- **Chapter 3**
  The OH 119$\mu m$ absorption line has successfully revealed the high prevalence of massive molecular outflow in z>6 DSFGs (Spilker et al., 2020a). AGN, however, are expected to play a vital role in the quenching of these systems by z=4 but have comparatively few detections at this epoch. In this chapter, we present a pilot program of three $z > 6$ quasar hosts targeting the OH 119$\mu m$ line. We show that OH 119$\mu m$ absorption is effective in detecting molecular outflows in these systems, but that it is important to observe quasar hosts during their blow-out phase when the central AGN is coupled most strongly with the surrounding ISM.

- **Chapter 4**
  Similar to chapter 3, we identify a gap in observations targeting neutral gas outflows in quasar hosts at $z = 2-4$. We present a pilot program, targeting the $OH^+(1_1 - 1_0)$ transition in five $z = 2 - 4$ dusty quasar hosts, successfully show that $OH^+(1_1 - 1_0)$ absorption can be used to detect neutral outflows in these systems. Again we find that targeting active galaxies during their blow-out phase is vital in measuring the full role AGNs play in ejecting cool gas from their hosts.

- **Chapter 5**
  We end the thesis with a beautiful sample of high S/N spectra of the $OH^+(1_1 - 1_0)$ and CO(9-8) lines in 16 $z = 2 - 4$ DSFGs. This sample provides the highest quality sample of $OH^+(1_1 - 1_0)$ spectra currently available over this epoch, allowing us to successfully disentangle the outflowing gas from that at systemic values. Direct measurements of the outflowing gas properties are therefore possible, revealing a turbulent reservoir of neutral outflowing gas around high-z DSFGs.

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