

The ASPECS Survey: An ALMA Large Programme Targeting the Hubble Ultra-Deep Field

Manuel Aravena¹
 Chris Carilli²
 Roberto Decarli³
 Fabian Walter⁴
 on behalf of the ASPECS collaboration^a

¹ Universidad Diego Portales, Santiago, Chile

² National Radio Astronomy Observatory, Socorro, USA

³ INAF Bologna, Italy

⁴ Max Planck Institute for Astronomy, Heidelberg, Germany

The ALMA Large Programme ASPECS (The ALMA SPECTroscopic Survey in the UDF) set out to measure the dust and molecular gas content in distant galaxies in the best-studied cosmological deep field, the Hubble Ultra-Deep Field (UDF). Thanks to a unique observing technique, the survey resulted in a full census of gas-rich galaxies in the UDF, yielding dozens of detections in dust continuum and molecular gas emission. Their physical properties could be accurately constrained thanks to the unparalleled wealth of ancillary data, including the most sensitive Hubble Space Telescope (HST) and VLT/MUSE observations. The data confirm that, on average, the gas mass fractions of distant galaxies decreased by an order of magnitude since redshift 2, and that the gas depletion times are ~ 1 Gyr, in approximate agreement with the local value. The ASPECS deep Band 6 continuum map of the field shows that more than 90% of the dust continuum emission in the field has been resolved in individual galaxies. The total CO emission in this well defined cosmological volume is used to constrain the evolution of the cosmic molecular gas density. Together with previous measurements of the evolution of the cosmic densities of stellar mass, star formation rate and atomic gas, these measurements provide quantitative constraints of the gas accretion rate onto the central discs of galaxies.

ASPECS motivation and survey strategy

It has been well established that stars form from molecular gas. In order to

characterise the evolution of galaxies through cosmic time, a measurement of their molecular gas content, and its evolution over cosmic time, is therefore indispensable. Such a measurement was one of the three prime directives driving the ALMA project from its conception. With this goal in mind, the ALMA Large Programme ASPECS, the first extragalactic large programme approved for ALMA, was designed to make an unbiased, three-dimensional survey of the molecular gas content of galaxies in the best studied extragalactic deep field, the iconic Hubble Ultra-Deep Field (UDF).

Choice of field

Choosing the UDF as the prime target for this survey (Figure 1) was straightforward. The UDF has the highest quality of observations in depth and resolution across the electromagnetic spectrum, extending beyond traditional continuum imaging, and is ideally situated for ALMA observations. Any additional observations, for example, under ASPECS but also other ALMA initiatives, add to the legacy value of this deep field. Besides ASPECS, recent key observations of the field include major Guaranteed Time Observation (GTO) initiatives with the Multi Unit Spectroscopic Explorer (MUSE) on ESO's VLT — the most sophisticated wide-field optical integral field unit available (Bacon et al., 2017). The availability of the MUSE data, from which over a thousand spectroscopic redshifts have been derived, enables significant gains in line stacking in 3D space. Furthermore, the UDF has also been selected as the primary deep field for James Webb Space Telescope (JWST) guaranteed time programmes, and observations are expected early in JWST's mission (at the end of 2021). In summary, the UDF will maintain its status as the state-of-the-art deep survey field for the foreseeable future.

Observational strategy

The observational approach of ASPECS to studying the molecular gas and dust in distant galaxies is unique as it does not preselect galaxies from other multi-wavelength data (for example, through measurements of their stellar mass or

star formation rate). Instead, imaging a significant region on the sky with ALMA mosaics, as well as scanning in frequency space, yields an unbiased measurement of molecular gas in a well defined cosmic volume. This is due to the fact that the key tracer of molecular gas, the carbon monoxide molecule (CO), emits radiation at distinct frequencies that approximately correspond to multiples of the frequency of the CO(1–0) ground transition at 115 GHz (corresponding to a wavelength of ~ 2.7 mm). These emission lines are then redshifted by the change in the cosmic scale factor for distant sources (Figure 2). For example, the CO(3–2) line at ~ 345 GHz will be redshifted to an observed frequency of ~ 100 GHz for a galaxy at redshift $z = 2.5$.

The net observational results of the ASPECS observations are 3D data cubes, the three axes being right ascension, declination and frequency, where frequency equates to the line-of-sight distance via the redshift. The areal coverage of the ASPECS observations is shown in Figure 1, and the frequency coverage in Figure 2. ASPECS covers two frequency regimes, the 3-mm band and the 1-mm band. This approach was chosen so as to maximise the cosmic volume for redshifted CO lines, as well as to obtain millimetre continuum images of the UDF to unprecedented depths.

Data products

The primary data products of the ASPECS observations are the Band 3 and Band 6 data cubes. In Figure 3 we show 2D renderings of the 3D cubes. Spectral lines of individual galaxies show up as point sources in the 3D cubes, corresponding to CO emission from a galaxy at a given position and redshift. In the 1-mm cube some linear features in frequency are also apparent: these features arise from dust continuum emission from the highest star formation rate galaxies in the field. Consequently, these spectral scans also deliver the deepest dust continuum maps of the Universe. Taken together, these methods enable a full characterisation of the molecular gas and dust in the cosmological volume probed by the UDF, down to galaxy masses that encompass the bulk of the

luminosity and mass out to redshifts ~ 4 , when the Universe was only 1.6 billion years old, i.e., 1/8th of today's age.

The validity of the observational approach for the ASPECS Large Programme was demonstrated by a number of pilot programmes, both with the IRAM (Institut de Radio Astronomie Millimétrique) Plateau de Bure Interferometer (now called NOEMA; Walter et al., 2014; Decarli et al., 2014) and ALMA observations in earlier cycles (Walter et al., 2016; Aravena et al., 2016a,b; Decarli et al., 2016a,b; Bouwens et al., 2016; Carilli et al., 2016). Our frequency scans of a contiguous deep field are complementary to targeted studies of high-redshift galaxies, most notably under the IRAM Plateau de Bure High-z Blue Sequence Survey projects (PHIBSS1/2; Tacconi et al., 2010, 2013, 2018; Genzel et al., 2015).

The evolution of dust and molecular gas in the UDF

One of the core results of ASPECS is to pinpoint which of the many hundreds of galaxies visible in the HST observations of the UDF are rich in molecular gas and dust, i.e., the material that is essential for star formation to proceed. The ASPECS survey (including its pilot programme) is reaching completion, and will eventually result in a total of 17 publications in international refereed journals¹. We highlight some of the key results here.

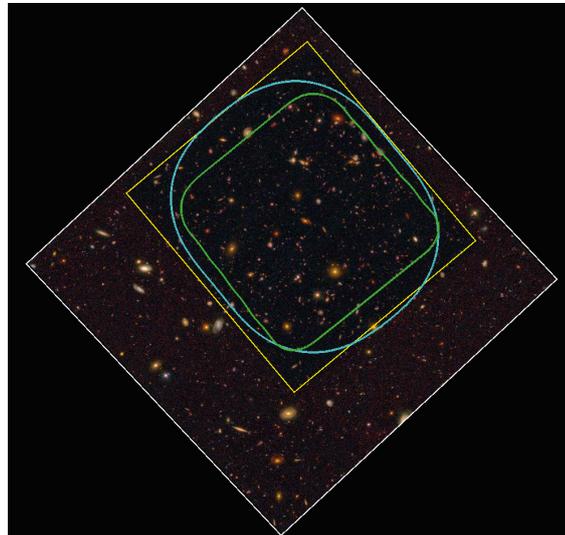


Figure 1. Spatial coverage of ASPECS within the Hubble Ultra-Deep Field (UDF) in Band 3 (region indicated in blue) and Band 6 (in green). A 17-pointing mosaic was needed for the Band 3 observations, and 85 pointings were used for the Band 6 observations. The deepest part of the UDF, also referred to the XDF, is shown in yellow. The colours represent a multi-band HST image.

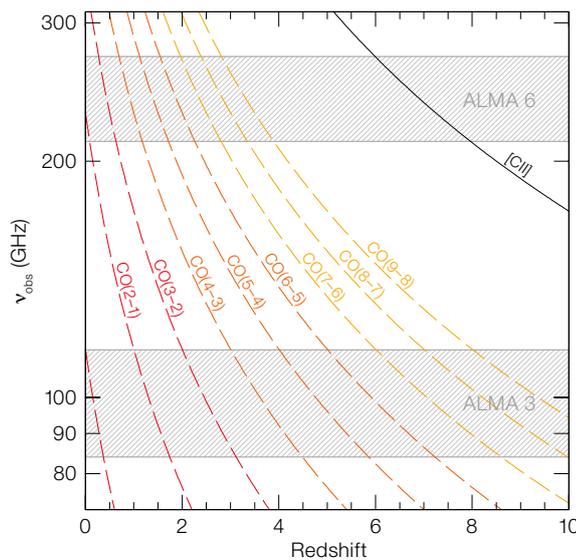


Figure 2. Frequency coverage of the ALMA Bands 3 and 6 with ASPECS (grey regions). Five separate tunings were required to cover the full ALMA Band 3 and eight tunings were needed for Band 6. The different bands cover the different rotational transitions of CO as a function of redshift, as indicated by the coloured dashed lines. The [CII] line is also covered for galaxies at redshift $z < 8$ in Band 6. The data can also be used to construct continuum maps in Band 3 and 6. Figure taken from Walter et al. (2016).

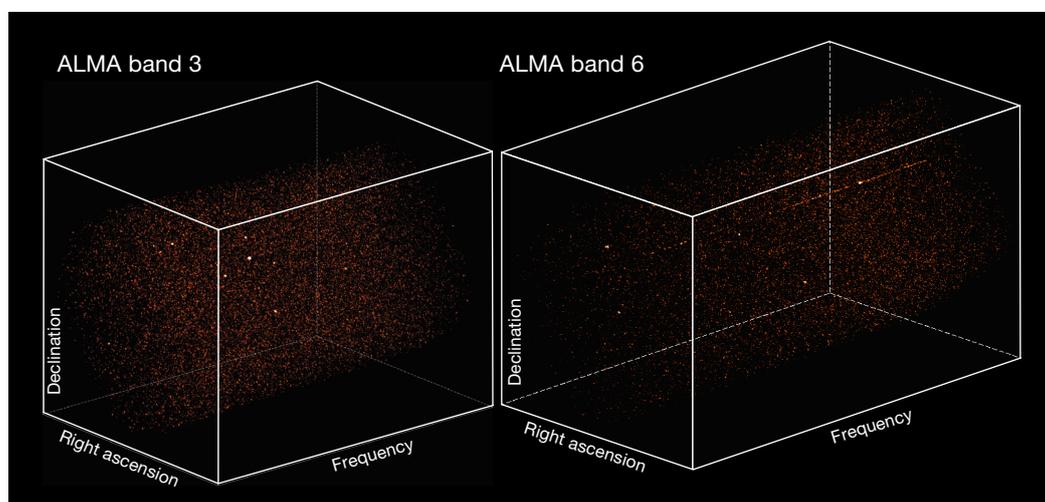


Figure 3. ASPECS delivers two 3D data cubes, one for Band 3 and one for Band 6, with the following axes: right ascension, declination, and frequency. These figures show 2D renderings of the cubes. Individual line detections of galaxies in the UDF are clearly visible in the data cube. In most cases these correspond to emission from rotational transitions of carbon monoxide. Linear features (most prominently seen in the Band 6 observations) correspond to continuum detections.

Continuum observations

The unprecedented depth of the ALMA 1-mm continuum map of $< 10 \mu\text{Jy}$ (shown in Figure 4) obtained by ASPECS over the UDF region puts critical constraints on the abundance of dust reservoirs in the early Universe. Gonzalez-López et al. (2020) report the detection of 32 unambiguous dusty galaxies. The cumulative number of sources reveals a dearth of dusty galaxies at decreasing 1-mm flux densities compared to extrapolations from previous surveys. A direct consequence of this result is that deeper observations will not yield many more new dusty galaxies, i.e., any future, deeper observations at these wavelengths will not substantially alter the budget of dust emission in the UDF as unveiled by ASPECS. Thus, ASPECS was able to pinpoint as individual galaxies the population responsible for almost all of the Extragalactic Background Light (EBL) at 1 mm in the UDF.

The comparison of 1-mm dust continuum number counts shown in Figure 5 with models (Popping et al., 2020) shows excellent agreement between model and data, even when splitting the sample into bins of basic galaxy properties (redshift, stellar and dust masses, star formation rate [SFR]). These number counts are dominated by galaxies in the redshift range $1 < z < 3$, and show a lack of dust reservoirs for less massive galaxies. The absence of major dust reservoirs in low-mass galaxies implies that dust obscuration is unlikely to be a major concern for the many low-mass (dwarf) galaxies seen in the UDF, with important implications for calculating the evolution of cosmic star formation rate density from rest-frame ultraviolet observations out to the highest redshifts (Bouwens et al., 2016; in preparation).

Gas-mass selected galaxies in the UDF

The most significant ASPECS CO detections in the UDF are shown in Figure 6, both as CO spectra and as contours on top of the HST multi-band imaging. It is clearly evident from Figure 6 that the gas-selected galaxy sample uncovered by ASPECS consists of galaxies of different types and environments.

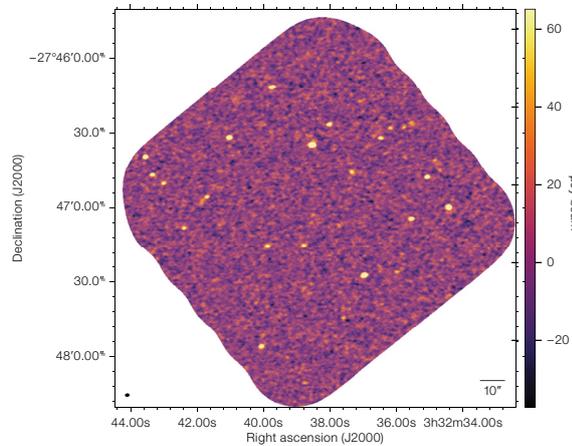


Figure 4. ASPECS Band 6 continuum map of the UDF (Gonzalez-López et al., 2020). The noise reached in this map is $\sim 9.5 \mu\text{Jy/beam}$, making this the deepest ALMA continuum map of a cosmological deep field obtained to date. There are 32 unambiguously detected dusty galaxies in the field.

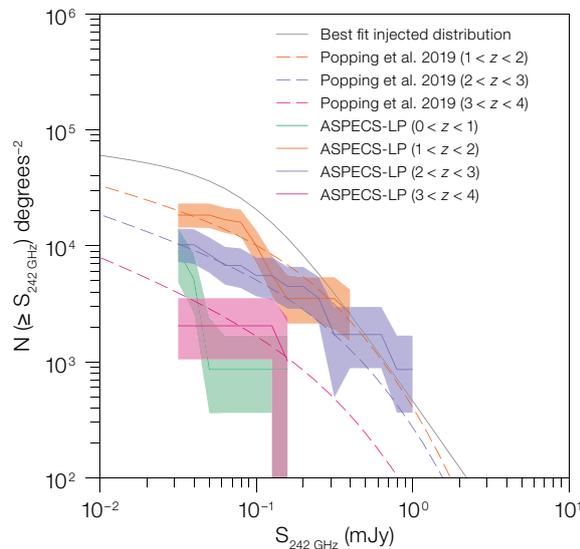


Figure 5. The solid grey line shows the ASPECS 1-mm continuum number counts recovered in the Band 6 continuum map. The coloured solid lines show the number counts as a function of redshift. The dashed lines are from the theoretical models by Popping et al. (2020). There is good agreement between the models and the observations. Most of the galaxies that are detected in dust continuum in the UDF are located at redshifts $1 < z < 3$. Figure taken from Gonzalez-López et al. (2020).

Aside from just pinpointing the galaxies that contain most of the cold dust reservoirs in the UDF, the wealth of multi-wavelength data available for the ASPECS/UDF field, which includes deep HST imaging and MUSE spectroscopy, enables a full characterisation of the physical properties of the ASPECS galaxies. We find that almost all CO emitters have 1-mm dust detections, indicating an obvious connection between molecular gas and dust, yet with varying interstellar medium properties. Interestingly, most ASPECS galaxies appear relatively bright in the HST optical/near-infrared images ($m_{F160W} < 25$ magnitudes), suggesting less obscuration than that observed in prototypical massive, dusty star-forming galaxies (“submillimetre galaxies”), and implying a lack of “optically/near-infrared dark” galaxies within the ASPECS sample.

Many of the ASPECS galaxies are found to be on the so-called galaxy main-sequence (for example, Brinchmann et al., 2004; Elbaz et al., 2007), but others are classified as starbursts or quiescent galaxies. A significant number of galaxies are found in crowded regions, the result of either the presence of companions, or chance superpositions. The deep optical spectroscopy from VLT/MUSE (hundreds of galaxy spectra in the UDF; Inami et al., 2017), has been used, in some cases, to unambiguously constrain the CO transition and hence the redshift of a galaxy (Boogaard et al., 2019). In most of the ALMA-detected galaxies more than one rotational transition of the CO molecule is detected. These multi-line observations are used to put first constraints on the physical properties of the interstellar medium (for example, density,

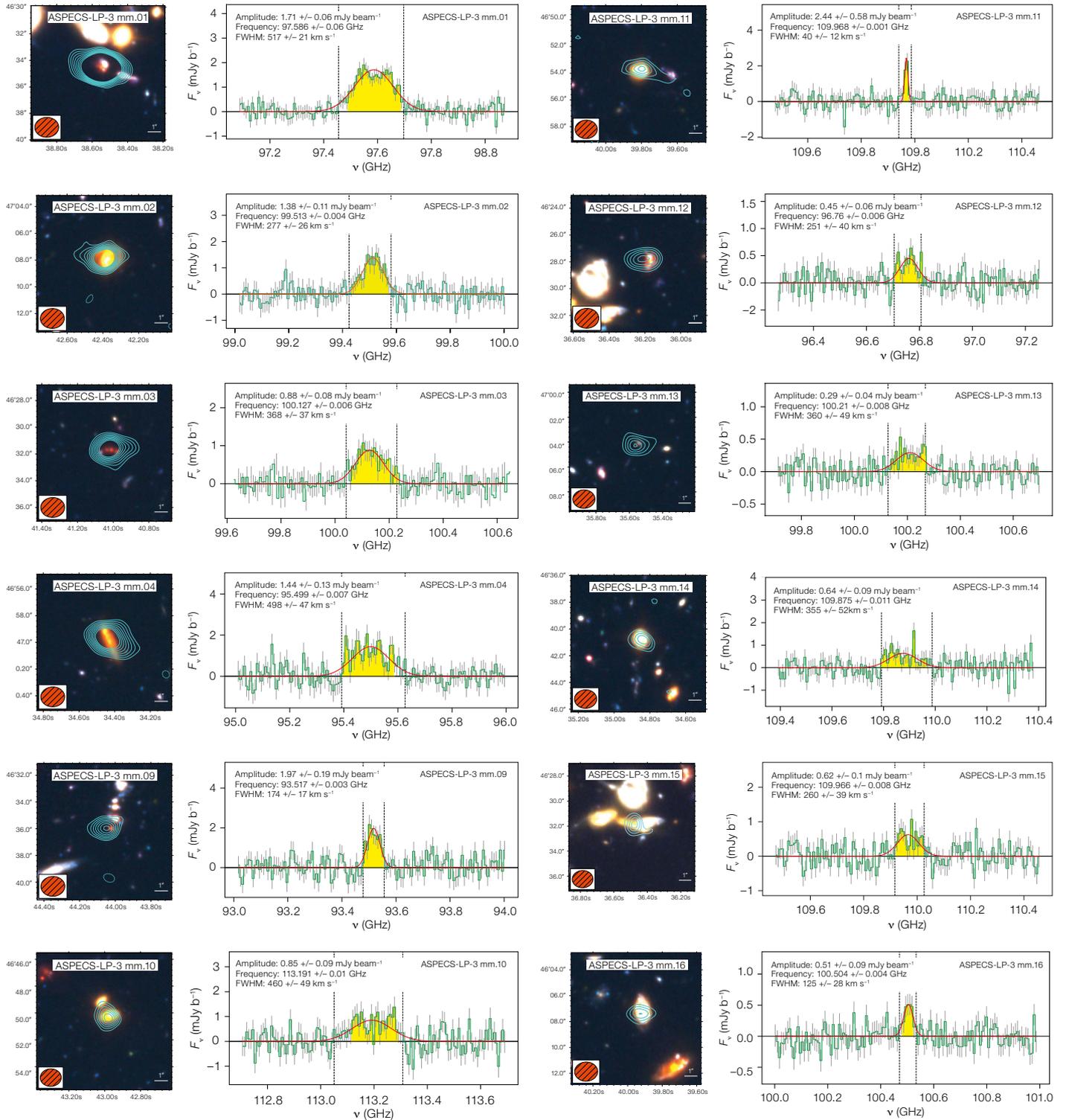


Figure 6. Collection of detected CO lines (spectra) and the corresponding CO emission overplotted as contours on the HST multi-band images of the UDF. Our dust/gas-selected sample of galaxies in the UDF covers a large variety of galaxies in different environments. Figure taken from Gonzalez-López et al. (2019).

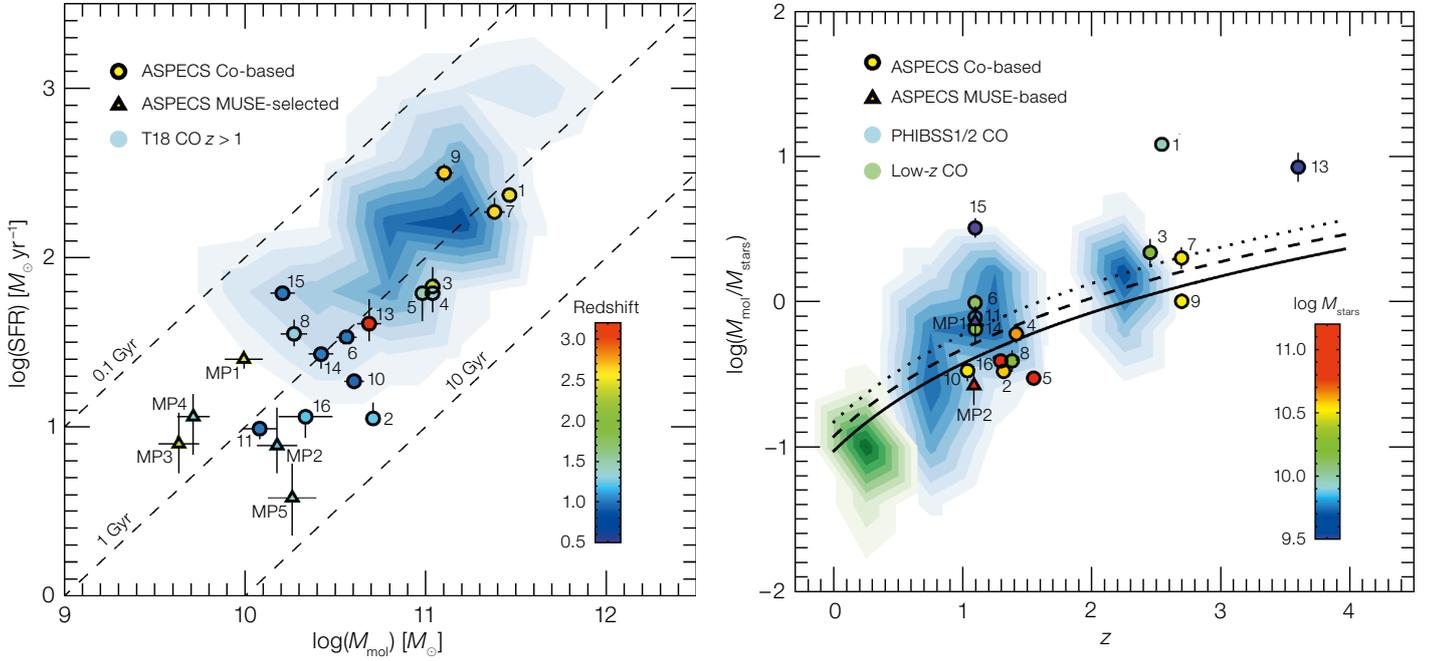


Figure 7. Left: Star formation rate (SFR) vs. molecular gas content of the galaxies in the UDF — the ASPECS CO detections are indicated as coloured symbols. The blue-shaded area is from the CO measurements obtained by the PHIBSS1/2 surveys (Tacconi et al. 2013; 2018). Overall, the gas-selected galaxies in the UDF show properties similar to those of galaxies in previous, targeted studies. The gas depletion times, defined as $M_{\text{mol}}/\text{SFR}$, are shown as dashed lines. Values are typically ~ 1 Gyr, irrespective of redshift, similar to what is found in the local universe. Right: Gas mass fraction, defined as $M_{\text{mol}}/M_{\text{stars}}$, as a function of redshift. The gas-selected galaxies in the UDF again show behaviour similar to that found in previous, targeted studies, albeit with significant scatter. Overall the gas mass fraction decreases by about an order of magnitude from redshift 2 to today’s Universe. Figures taken from Aravena et al. (2019).

temperature). In addition to CO, atomic carbon (C I) is also detected in many sources (Boogaard et al., in preparation). Together with the dust continuum emission, these data provide a number of different ways of estimating molecular gas masses, corresponding to the fuel for star formation in galaxies (Aravena et al., 2020).

In Figure 7 we present some of the properties of the ASPECS-selected galaxies in context with other studies. In the left panel of Figure 7 we plot the star formation rate (SFR) of a galaxy as a function of gas mass (M_{mol}). In such a plot, diagonal lines (indicated as dashed lines) are lines of constant gas depletion time. The gas-mass selected ASPECS galaxies in the

UDF cover a similar parameter space as do earlier targeted studies (Tacconi et al., 2013, 2018), albeit with a somewhat larger scatter. On average, their depletion time is ~ 1 Gyr irrespective of redshift, which is similar to the value derived for star-forming galaxies in the local Universe. In the right panel of Figure 7 the gas mass fraction, defined as $M_{\text{mol}}/M_{\text{stars}}$, is plotted as a function of lookback time. Our gas-selected galaxy sample confirms the conclusion based on targeted samples, that there is a fundamental change in the properties of star forming galaxy over time, namely, that the gas mass fraction decreases by an order of magnitude from redshifts $z \sim 2$ to today (Aravena et al., 2019).

The cosmic evolution of the molecular gas density

The CO emission in the data cubes can be used to derive CO luminosity functions for the different CO transitions (i.e., redshifts) covered by ASPECS. By assuming empirical relations for the CO excitation in galaxies, the expected emission in the rotational ground transition of CO(1–0) can be derived. From that, a molecular gas mass can be assigned to a galaxy by employing the so-called CO-to- H_2 conversion factor (Bolatto, Wolfire & Leroy, 2013). This conversion fac-

tor is known to be metallicity-dependent. Fortunately, many of the UDF galaxies have metallicity estimates from the deep MUSE UDF initiative. These measurements indicate that most of the galaxies under consideration are consistent with solar metallicities (Boogaard et al., 2019). Ultimately, the combined information can be used to derive molecular gas (H_2) mass functions for the different redshift bins covered by the observations. In an additional step, the total molecular gas mass can be summed in a specific redshift bin. As the cosmic volume is well defined for each redshift bin through the ASPECS setup, the cosmic density of the molecular gas can be derived by dividing the total H_2 mass by the volume, as discussed below.

Figure 8 shows the cosmic molecular gas density as a function of redshift. The key result here is that the H_2 gas density peaks at around $z = 2$ and then declines by almost an order of magnitude to the value measured in the local Universe. This behaviour was suggested in previous CO deep fields, including the ASPECS pilot programme, but the error bars now enable us to firmly conclude that there is an increase and then a decline in the gas density with cosmic time. The results are also consistent with gas masses derived from dust continuum measurements, including those using the ASPECS

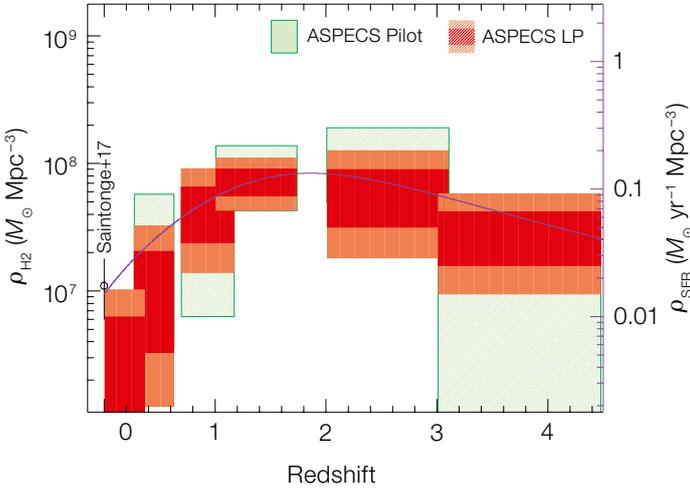


Figure 8. The cosmic evolution of the density of the molecular gas mass as a function of lookback time. The results derived from ASPECS are shown as red boxes (Decarli et al., in preparation). The measurements are anchored at $z = 0$ through the measurement by Saintonge et al. (2017). There is an unambiguous decline of the molecular gas density from redshifts $z \sim 2$ to today by about an order of magnitude. For comparison, we also show the evolution of the star formation rate density in purple (see units on the right y-axis, Madau & Dickinson [2014]) that shows a similar decline from the peak of the “epoch of galaxy assembly” at $z \sim 2$ to today.

continuum map (Scoville et al., 2017; Liu et al., 2019; Magnelli et al., 2020). This peak of H_2 density corresponds to the peak in the star formation history (“the epoch of galaxy assembly”). We next discuss the implications of the ASPECS results for galaxy formation.

The cosmic baryon cycle

The ASPECS survey allows the determination — from an unbiased selection — of the evolution of the cosmic molecular gas density from low redshift out to within 2 Gyr of the Big Bang. This behaviour can now be put in context with other key estimates of galaxy properties, in particular the evolution of the cosmic density of star formation rate and the build-up of stellar mass. In Figure 9 we compare our ASPECS results for molecular gas with other baryonic phases that are associated with galaxies, most notably the stellar mass and the atomic gas (HI). The stellar mass, which is characterised with multi-band optical/near-infrared imaging, constantly builds up over cosmic time, to first order following the time

integral of the cosmic star formation rate density (Madau & Dickinson, 2014). The density of atomic hydrogen, on the other hand, shows little variation as a function of lookback time. The behaviour of the atomic gas is in stark contrast to the rise and fall of the molecular gas density, as derived by ASPECS. It should be noted that at a cosmic age of about 4 Gyr the H_2 density reached that of the HI, but stays below the HI at all other times. At around the same age of the Universe, the stellar mass density surpasses that of the total (cold) gas, as seen in HI + H_2 .

The masses/densities of the molecular and atomic gas seen at high redshift imply that their masses are insufficient to account for the stellar mass budget seen in today’s Universe. Together with other measurements, the ASPECS results constrain the accretion rates of gas from the circum- and inter-galactic medium — the accretion that is necessary to explain the stellar mass growth. As such, it provides constraints on a key component in the cosmic baryon cycle in galaxies (Walter et al., 2020).

The current age of the Universe is indicated by a vertical line at a cosmic age of 13.7 Gyr in Figure 9. Under the assumption of continuity we can use empirical fitting functions to forecast the evolution of the baryon content associated with galaxies over the next few Gyr. Assuming that our fits can indeed be extrapolated into the future, the molecular density will decrease by a factor of two over the next 5 Gyr, whereas the HI and stellar mass densities will remain

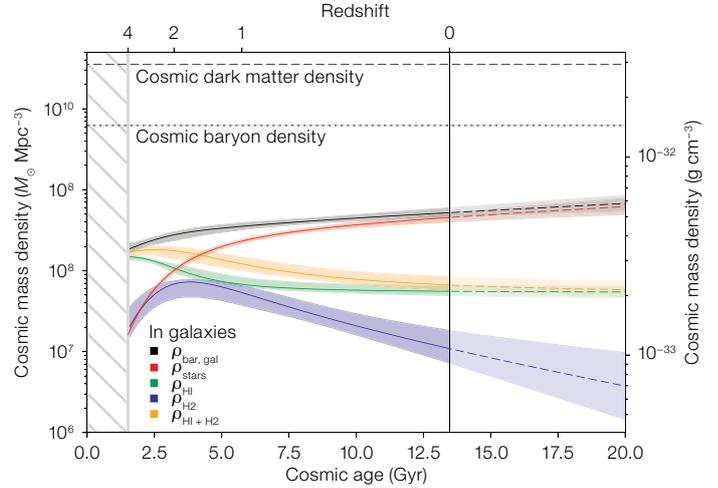


Figure 9. The ASPECS measurement of the evolution of the molecular gas content, ρ_{H_2} (blue line) is shown together with other baryonic components that are associated with galaxies. These are: the stellar mass (shown in red), and the atomic gas phase (HI, shown in green). The sum of atomic gas and molecular gas is also plotted (yellow line). For completeness, the cosmic baryon density and cosmic dark matter density are also shown. The vertical line at redshift $z = 0$ (top x-axis) indicates the current age of the Universe. A simple extrapolation of the curves shows that as the molecular gas density drops further in the future, the additional growth in stellar mass in galaxies will be marginal.

approximately constant. The star formation rate density will follow the decrease of H_2 . In this scenario, today’s Universe has entered “Cosmic Twilight”, during which the star formation activity in galaxies inexorably declines, as the gas inflow and accretion shut down.

Other topics addressed by ASPECS

For completeness, it should be mentioned that other investigations have been carried out using the ASPECS dataset. These studies include stacking experiments, both in the image plane and in redshift space (3D), capitalising on the rich spectroscopy from deep MUSE initiatives in the field (Bacon et al., 2017; Inami et al., 2017). These studies showed that most of the emission (both in the dust continuum and CO) in the field is accounted for by the detection of individual galaxies (Inami et al., in preparation). CO intensity mapping of the field also concluded that the majority of the CO emission in the field is detected by the current observations (Uzgil et al., 2019). We also compare results from ASPECS

to predictions from two cosmological galaxy formation models, the IllustrisTNG hydrodynamical simulations and the Santa Cruz semi-analytic model (Popping et al., 2019).

Next (observational) steps

The ASPECS observations were designed to maximise the sensitivity to molecular gas, which in turn did not result in spatially resolved observations. Now that ALMA has pinpointed which galaxies in the UDF are rich in dust and gas emission, the next step will be to spatially resolve the distribution of molecular gas and dust in individual galaxies with dedicated high-resolution ALMA observations. A particularly interesting goal is to determine the dynamics of the gas, including rotation, turbulence, infall, or outflow. Another goal is to obtain ALMA multi-band observations of these galaxies in order to further quantify the state of the molecular gas (for example, density, temperature). The galaxies in the UDF will also be the target of major observing campaigns with the upcoming James Webb Space Telescope (JWST). In this context ALMA will continue to play a key role in constraining the physical properties of galaxies near the peak of cosmic star formation ($z \sim 2$), and beyond.

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Notes

^a The ASPECS collaboration is led by PIs Manuel Aravena [UDP, Chile], Chris Carilli [NRAO, USA], Roberto Decarli [INAF, Italy] and Fabian Walter [MPIA, Germany], and consists of 40 scientists from 35 institutions in 9 countries, including: Roberto Assef (UDP, Chile), Roland Bacon (Univ. Lyon, France), Franz Bauer (PUC, Chile), Frank Bertoldi (AlfA, Germany), Leindert Boogaard (Leiden Obs., Netherlands), Rychard Bouwens (Leiden Obs., Netherlands), Thierry Contini (LATT, France), Paulo C. Cortes (JAO, Chile), Pierre Cox (IAP, France), Elisabete da Cunha (UWA, Australia), Emanuele Daddi (CEA Saclay, France), Tania Diaz-Santos (UDP, Chile), David Elbaz (CEA Saclay, France), Jorge Gonzalez-Lopez (UDP, Chile), Jacqueline Hodge (Leiden Obs., Netherlands), Hanae Inami (Univ. Hiroshima, Japan), Rob Ivison (ESO), Melanie Kaasinen (MPIA, Germany), Olivier Le Fèvre (LAM, France), Benjamin Magnelli (AlfA, Germany), Marcel Neeleman (MPIA, Germany), Mladen Novak (MPIA, Germany), Pascal Oesch (Geneva, Switzerland), Gergo Popping (ESO), Dominik Riechers (Cornell Univ., USA), Hans-Walter Rix (MPIA, Germany), Mark Sargent (Sussex Univ., UK), Ian Smail (Durham Univ., UK), Rachel Somerville (Flatiron Institute, USA), Mark Swinbank (Durham Univ., UK), Bade Uzgil (NRAO, USA), Paul van der Werf (Leiden Obs., Netherlands), Jeff Wagg (SKA, UK), Axel Weiss (MPIfR, Germany), Lutz Wisotzky (AIP, Germany).



ALMA, located in the Chilean Atacama desert, is the most powerful telescope for observing the cool Universe – molecular gas and dust.