



Molecular hydrogen in absorption at high redshifts

Science cases for CUBES

S. A. Balashev¹ · P. Noterdaeme^{2,3}

Received: 2 October 2021 / Accepted: 17 February 2022

© The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract

Absorption lines from molecular hydrogen (H_2) in the spectra of background sources are a powerful probe of the physical conditions in intervening cold neutral medium. At high redshift, $z > 2$, H_2 lines are conveniently shifted in the optical domain, allowing the use of ground-based telescopes to perform high-resolution spectroscopy, which is essential for a proper analysis of the cold gas. We describe recent observational progress, based on the development of efficient pre-selection techniques in low-resolution spectroscopic surveys such as the Sloan Digital Sky Survey (SDSS). The next generation of spectrographs with high blue-throughput, such as CUBES, will certainly significantly boost the efficiency and outcome of follow-up observations. In this paper, we discuss high priority science cases for CUBES, building on recent H_2 observations at high- z : probing the physical conditions in the cold phase of regular galaxies and outflowing gas from active galactic nucleus.

Keywords Molecular hydrogen · Quasar absorption lines · Active galactic nuclei

1 Introduction

Molecular hydrogen (H_2) – the most abundant molecule in the Universe – traces the cold ($T \sim 100$ K) phase of the neutral gas. Since this phase is inclined to gravitational collapse through Jeans instability, understanding its physical and chemical properties is fundamental for a complete theory of star-formation throughout the

✉ S. A. Balashev
s.balashev@gmail.com

P. Noterdaeme
noterdaeme@iap.fr

¹ Ioffe Institute, Politekhnikeskaya 26, 194021 Saint Petersburg, Russia

² Franco-Chilean Laboratory for Astronomy, Camino El Observatorio 1515, Las Condes, 75014 Santiago, Chile

³ Institut d'Astrophysique de Paris, CNRS-SU, UMR\7095, 98bis bd Arago, 75014 Paris, France

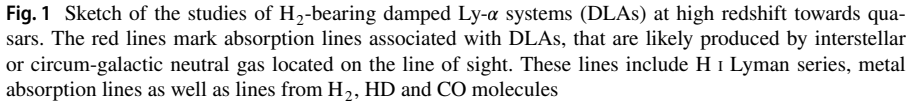
Universe's history. Molecular hydrogen can be detected directly through electronic absorption lines in the Lyman and Werner bands ($\sim 91 - 110$ nm rest-frame) [11, 62]. At high redshift ($z > 2$), H_2 lines are conveniently shifted into optical domain and become accessible for the ground telescopes. Because of their brightness, quasars are generally used as background sources, although there is growing interest in the use of gamma-ray burst afterglows as well [10, 28, 53]. The large collecting area of ground-based telescopes, combined with high-resolution spectrographs, permits to resolve narrow H_2 lines that typically arise from several rotational levels in the cold ~ 100 K neutral medium (see e.g. [5]). The ability to detect rotational levels is key to probe the physical conditions in the gas by modelling the relative population of H_2 levels (e.g. [25]).

In this paper, we briefly describe an historical perspective and recent progress in studying diffuse molecular and translucent gas at high- z , through H_2 absorption lines, mostly with Ultraviolet-Visual Echelle Spectrograph (UVES, [15]) and X-shooter [71] instruments on the Very Large Telescope (VLT) in Paranal. We discuss the tremendous boost in this field that would be enabled by Cassegrain U-Band Efficient Spectrograph (CUBES, [74]), in particular thanks to its efficient coverage of $\sim 300 - 400$ nm wavelengths. Key benefits will be: (i) an increase of the sample sizes of reachable systems by an order of magnitude. The corresponding systems are already available from pre-selection in the Sloan Digital Sky Survey (SDSS, [73]) but other surveys will also contribute to discover new ones; (ii) the access to more extreme and elusive environments (e.g. more dusty/molecular rich). This will allow us not only to access the thermal state of the cold phase of the neutral medium of the overall population of high- z galaxies but also to investigate the active galactic nuclei (AGN) feedback and quasar environment as probed by a recently discovered population of proximate H_2 absorption systems.¹

2 Observations of H_2 absorption

Molecular hydrogen being a homonuclear molecule, it has no dipole moment in the ground electronic state. Therefore, in emission, H_2 can be observed only under specific conditions in the interstellar medium (ISM) – mainly in photo-dissociated regions, which represent dense and warm gas, with temperatures $\gtrsim 500$ K – the typical distances between rotational energy levels of ortho- or para- H_2 . In turn, the electronic Lyman ($B^1\Sigma_u^+ - X^1\Sigma_g^+$) and Werner ($C^1\Pi_u - X^1\Sigma_g^+$) bands transition of H_2 are permitted. These transitions were first detected in space via rocket flight observations by [11] and then extensively analysed using the Copernicus satellite [62], mostly towards bright nearby stars. These, as well as following observations by the Far Ultraviolet Spectroscopic Explorer (FUSE, [58]) satellite, concerned the local

¹ “Proximate” here refers to absorption systems with redshift z_{abs} similar to that of the quasar emission, z_{em} , typically with $\Delta v \approx c \cdot |z_{\text{abs}} - z_{\text{em}}| / (1 + z_{\text{em}}) < \text{few} \times 1000 \text{ km s}^{-1}$, where c is the speed of light. Such absorption systems can be physically associated with the quasar and/or its host galaxy.



2.1 High redshifts

² Corresponding to full width half maximum (FWHM) of the instrument function, $\text{FWHM} = c/R \approx 6 \text{ km s}^{-1}$, where c is the speed of light.

 Springer

with $\log N(\text{HI}) \geq 20.3$, or to strong sub-DLAs with $19 \leq \log N(\text{HI}) < 20.3$. A third sub-class has recently been introduced for the highest column densities, with $\log N(\text{HI}) > 21.7$ and dubbed extremely strong DLAs (ESDLAs, [44]).

The first H_2 absorption system at high z was detected serendipitously by [31] towards PKS 0528 – 250 using only 2 Å resolution spectrum obtained by Anglo-Australian 3.9m telescope [33]. The second high- z H_2 absorption system was detected only a decade later [16] using the Multiple Mirror Telescope, indicating a very slow progress in this field in pre-VLT/Keck era.

2.2 VLT/Keck era

A new epoch of high- z H_2 absorption studies began with the advent of high-resolution spectrographs, High Resolution Echelle Spectrometer (HIRES, [72]) and UVES on the 8-m class telescopes Keck and VLT, respectively. This resulted in a increase of the number of detected molecular hydrogen absorption systems, with the most important contribution arising from the VLT, thanks to dedicated and regular science programs to search for H_2 [30, 50, 64]. The UVES database for H_2 systems comprised thirteen H_2 systems [39]. On Keck telescope, in spite of a large observational program focusing on DLAs ($\gtrsim 100$ DLA were studied at $z \gtrsim 2$ [52]), H_2 was reported in only a handful of systems [23, 52], mostly due a wavelength coverage not optimised for H_2 during observations. The semi-blind surveys on these telescopes (and also Magellan, see [21]) indicated that the incidence rate of H_2 in DLAs is pretty low $\sim 10\%$ for H_2 column densities above 10^{17} cm^{-2} [39]. An independent estimate of the incidence rate in the overall population of DLAs, $\sim 4.0 \pm 0.5(\text{stat.}) \pm 1.0(\text{syst.})\%$ for saturated H_2 absorption systems ($\log N(\text{H}_2) > 18$) was later obtained from the detection of H_2 lines in the composite DLA spectrum [7] constructed with SDSS.

3 Pre-selection with SDSS

The low detection rate of H_2 among DLAs, together with the $\sim 15\%$ incidence rate of high- z DLA in quasar spectra results in a very low efficiency of blind searches, making this approach time-costly and impractical on highly over-subscribed telescopes. Fortunately, the availability of the SDSS, that collected several 10^5 quasar spectra with $R \approx 2000$, not only permitted the detection of many thousands high- z DLAs/sub-DLAs [42, 48], but also triggered the development of efficient techniques for pre-selecting H_2 -bearing systems. Indeed, it was shown that strong H_2 absorption systems (with $\log N(\text{H}_2) \gtrsim 18$) can be either detected directly via their characteristic Lyman-Werner band signature in SDSS spectra (provided their quality is high enough and the Lyman- α forest not too dense) [4, 36] or using C I as a good tracer of H_2 [41, 63], in particular at high metallicity. Several C I lines are generally located redwards of the Lyman- α emission, allowing their automated detection in SDSS [29]. An example of the H_2 -bearing DLA that has been initially found in SDSS and lately followed-up with both X-shooter and UVES is shown in Fig. 2. Finally,

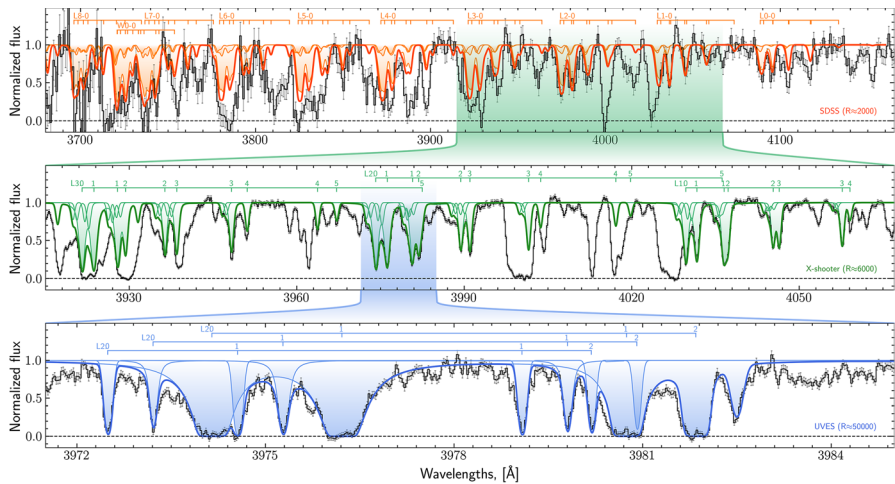


Fig. 2 Portions of spectra of J 1237 + 0647 featuring H_2 absorption lines from a system at $z = 2.625$, see [43]. The top, middle and bottom panels correspond to the spectrum obtained using SDSS ($R \approx 2000$), X-shooter ($R \approx 6000$) and UVES ($R \approx 50000$), respectively. The black and colored thick lines show the observed spectrum and total model profile of H_2 absorption system, respectively. The colored lines and regions in each panel show the profiles of individual velocity components, that are resolved and fitted using the UVES spectrum [43]. The horizontal line with marks show the positions of H_2 absorption lines of the Lyman (denoted as L) and Werner (denoted as W) bands from different rotational levels, with the number above each tick indicate the rotational level

it was found that the incidence rate of H_2 significantly increases (up to $\sim 50\%$) in the ESDLA sub-sample from QSO [7, 47, 56] as well as GRB afterglows sightlines [10]. This is most likely due to the corresponding lines of sight intercepting galaxies at small galacto-centric distances [1, 32, 55, 56], where the prevailing physical conditions, and in particular the gas pressure, favour the existence of the cold phase and the $H\ I/H_2$ conversion [8, 10, 18, 47].

A comparative study of these three pre-selection techniques [5] indicates that they have different selection function in terms of the properties (such as metallicity, $N(H\ I)$, $N(H_2)$, presence of CO, etc.) and therefore should complement each other. For example, regarding the metallicity, the CI-selected systems have on average an order of magnitude higher metallicities than ESDLA-selected ones, while direct search for H_2 lines pick up absorption systems in between [5]. It is also important to note, that these pre-selections were obtained based solely on SDSS owing to its statistical power. Current samples therefore inherit from the quasar selection functions of the different SDSS spectroscopic surveys [27]. In particular, optical selection tends to exclude highly reddened quasars and hence dusty and large H_2 column systems. This, together with the small cross-section of dense molecular clouds implies that the H_2 absorption systems currently probe mostly diffuse molecular gas (with exception of a few cases, see [8, 43]).

Notwithstanding, these techniques allowed us to significantly increase the number of confirmed H_2 absorption systems from ~ 15 to ≈ 50 in the last decade, with an extremely efficient use of the observational time on the largest optical telescopes.

This also permitted the study of systems spanning a very large range of properties of the underlying galaxy population. Among them, we can note the detection of: (i) Perseus-like cloud at $z \approx 2$ [37]; (ii) CO and 2175Å dust bump in high-metallicity H₂-bearing DLAs [40, 46, 63]; (iii) large H₂ column density and low-metallicity absorbers, representing CO-dark molecular clouds [8, 55]; (iv) low impact parameter ESDLA with large H₂ column [55]. In short, the study of H₂ absorbers at high- z towards quasars and GRB afterglows opened a unique window to the understanding of the ISM properties in the overall galaxy population, similar to what has been done in the local ISM towards bright nearby stars.

4 CUBES science case

In spite of significant progress in recent years, the observations are now reaching a bottleneck, mostly due to the limiting instrumental capabilities to follow-up faint targets (typically $m_G \gtrsim 19$) that make the bulk of the new and most promising candidates. In fact, while observations were first obtained with UVES (since high resolution has a high priority for H₂ studies), the preference has then shifted to X-shooter to optimize the observing time for $m_G \gtrsim 19$ targets. The drawback for choosing X-shooter is the loss in spectral resolution $R \sim 6000$,⁴ which quite complicates the analysis and limits the derivation of physical quantities from the data (see e.g. [5, 37] and comparison of the spectra in Fig. 2). Currently, most of the bright targets accessible from VLT have already been observed, and available candidates in SDSS are already out of reach for UVES and at the limit for X-shooter within reasonable observing time, see Fig. 5.

CUBES [74] will exactly fill this gap, with a high efficiency in the blue, while keeping a high-resolution to maximise the scientific outcome. This is essential to continue investigating the cold neutral phase in and around galaxies at high redshifts. Indeed the efficiency of CUBES is about an order of magnitude higher than UVES, and the declared resolution ($R \sim 20000$) is enough to resolve the H₂ lines much better than X-shooter currently can do. Using CUBES exposure time calculator [17], we estimate that for a QSO with G-band magnitude around 20, $S/N \approx 10$ can be reached in only one hour of observing time. This will allow one to increase the available samples by several fold, as needed for the relevant science goals. Additionally, the wavelength coverage of CUBES is already optimized for H₂ identified in SDSS (see Fig. 5). In the following three subsections, we will briefly describe the most important CUBES science goals to our eyes, dealing with intervening and proximate H₂-bearing DLAs, i.e. cold gas in, respectively, the overall population (hence mostly faint) galaxies and the environment of massive active galaxies.

⁴ H₂ absorption lines mostly falls in UVB arm of X-shooter

4.1 Intervening DLAs: probing galaxies at high- z

While the first detected H_2 absorption system at high- z was found at the quasar redshift (see recent re-analysis by [6]), studies of H_2 initially focused on intervening systems – absorption systems at cosmological remote distances from the quasar, i.e. that are not physically associated with the later. Typically, these are securely chosen by a velocity difference $\Delta v \approx (z_{\text{abs}} - z_{\text{qso}})/(1 + z_{\text{qso}})c > f_{\text{ew}} \times 1000 \text{ km s}^{-1}$. This permits a large redshift path to be probed and therefore, such systems were preferentially selected in the first blind surveys.⁵

The determination of the physical conditions was one of the primary goal of studies of intervening H_2 absorption systems [3, 38, 64], since excitation of H_2 rotational levels (e.g. [5, 45]), as well as associated C I fine-structure (e.g. [8, 22]), and rotational levels of HD (e.g. [3]) and CO molecules [46, 63] provide a straight way to do it. The later two molecules were found in a handful of H_2 -bearing DLAs systems, but provide valuable independent constraints on the physical conditions for molecular gas with high column, thanks to different sensitivities of the molecules on the various excitation processes. Indeed, the rotational levels of molecules as well as fine-structure levels of atomic species are populated by a competition between collisional excitation, radiative pumping (following the electronic UV transitions) and direct radiative excitation. Therefore the measured populations on these levels are sensitive to the rates of these processes and provide the way to constrain the kinetic temperature, number density, UV flux and Cosmic Microwave Background (CMB) temperature (mostly using CO, [46]).

Originally, H_2 -bearing DLAs were analysed mostly on a case-by-case basis. The main outcome of these studies were: (i) The measurement of the gas kinetic temperature, estimated using the ortho-to-para ratio⁶ of H_2 molecules, and giving $T_k \sim 100 \text{ K}$, i.e. H_2 probe the cold phase of ISM; (ii) The measurement of the number densities, found in the range $n \approx 10 - 300 \text{ cm}^{-3}$, i.e. also consistent with what is expected for the cold neutral ISM; (iii) The derivation of the strength of the UV field, found to span a large range from slightly lower than the Draine field up to two orders of magnitude higher. Recently performed systematic analyses of the emergent samples of H_2 -bearing DLAs [25, 26] start to show interesting dependencies between estimated physical conditions. For example: (i) The thermal pressure measured in the cold phase of the ISM increases with increasing neutral gas column density [5, 8]. This is quite expected from analogy with local measurements as well as simulations, which shows that the high column density systems probe galaxies at the smallest impact parameters, and hence expected to have enhanced pressures; (ii) The ratio of UV field to number density correlates with the gas temperature [25]. This correlation is also metallicity-dependent but it seems not to contradict with heating-cooling balance of the neutral ISM (see Fig. 3). (iii) The cosmic ray ionization rate estimated using HD/ H_2 ratio is found to depend quadratically on the strength of the

⁵ However, since the cross section of associated systems are found to be much larger, as was found later, the incidence rate of intervening and proximate systems are not much different, see Section 4.2

⁶ In the case of H_2 , this corresponds to the ratio of $J=1$ and $J=0$ rotational levels.

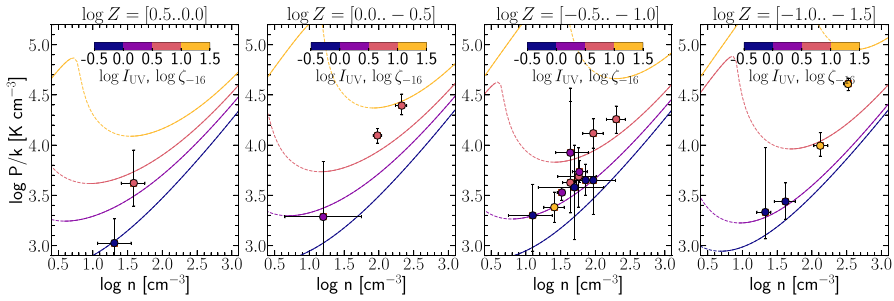


Fig. 3 The measured thermal pressure versus number density in intervening H_2 absorption systems at high redshifts. The panels from left to right correspond to three samples of selected metallicities in $\log Z = 0.5, 0.0, -0.5, -1.0, -1.5$ bins, shown on the top of each panel. The curves on each plot show the calculation of the phase diagram at median metallicity of the bin. The color of the lines and symbols indicate a measured (and assumed) UV field (in Draine field units). For calculations we also co-scaled cosmic ray ionization rate with UV field (assuming that they are both associated with star formation), which is indicated by the color bar at the top of each panel

UV field [26]. Since cosmic ray ionization ray also determine the thermal balance especially at low metallicities [9], this should also be take into account for future studies. To summarize, we anticipate many progresses in our understanding of the physics of the cold diffuse gas at high- z , and hence in our understanding of how star-formation occurs, when larger samples (probing wider ranges of the physical conditions and chemical enrichment) will get observed with CUBES.

4.2 Proximate DLAs: probing AGNs outflowing gas

A recent study of the SDSS quasar database by [36] uncovered a population of proximate (i.e. at sensibly the quasar redshift) H_2 absorption systems. It was found that the incidence rate of proximate H_2 is actually up to a factor of 10 higher than what is expected from the statistics of intervening ones. This is opposite to naive expectations that the strong radiation field of quasar should suppress the presence of H_2 in its vicinity, due to efficient photo-dissociation of the molecules. However, the observed strong excess hypothetically can be explained by either clustering of the matter and satellite galaxies around quasars or the presence of galactic-scale outflows, which, as current local observations indicate, frequently contains a large amount of molecular gas [12, 70]. The detection of leaking $\text{Ly-}\alpha$ emission (seen as $\text{Ly-}\alpha$ emission inside the damped $\text{Ly-}\alpha$ absorption) in a roughly half of the candidates from SDSS [36], as well as follow-up observations [35] indicate that substantial fraction of proximate H_2 absorption systems may indeed arise from outflowing gas. In that sense, molecular hydrogen served as the species that allow the pre-selection of these systems in low-resolution spectra, but also provides a key diagnostic of the physical conditions in the diffuse molecular gas associated with outflow. For example, in the first and only one system of such class studied in details so far, J 0015 + 1842 at $z = 2.631$, it was found, using the excitation of H_2 rotational levels, that the number density is $n \sim 10^4 \text{ cm}^{-3}$ and that the UV field is $\sim 10^3$ times higher than the Draine field. This is significantly higher than what is typically measured in intervening DLAs.

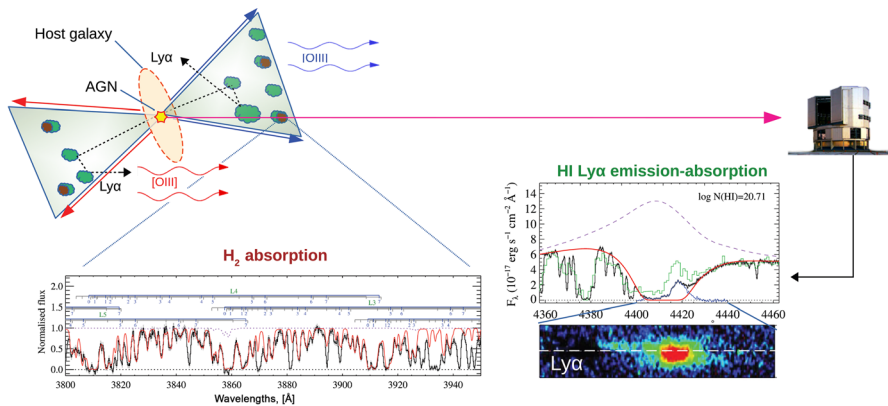


Fig. 4 Sketch representing studies of AGN outflowing gas using VLT/X-shooter observations (reproduced from [35]). The left and right bottom panels show portions of J 0015 + 1842 spectrum covering H_2 absorption lines and $Ly-\alpha$ emission/absorption line, respectively. The detection of extended [O III] and $Ly-\alpha$ emission (shown in 2d spectrum in the bottom panel) and surprisingly high excitation of H_2 rotational levels, indicate that this absorption system is associated with outflowing gas

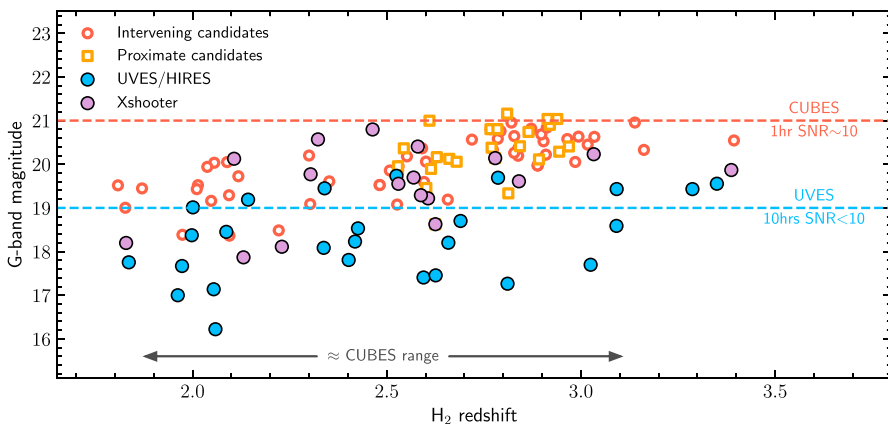


Fig. 5 G-band magnitude and redshifts of H_2 absorption systems at high redshift. The blue and violet circles represent systems already confirmed and analysed using UVES/HIRES and X-shooter, respectively. The red and orange squares represent respectively the intervening and proximate H_2 candidates, pre-selected in the SDSS. The blue and red dashed lines indicate the typical magnitudes of the quasars that can be reached with UVES 10 hrs and CUBES 1hr exposure time, respectively, to achieve $SNR \sim 10$ in the spectrum. The redshift range accessible with CUBES is marked by the black horizontal solid lines with arrows

Assuming that the quasar produces most of the UV radiation, this permitted to constrain the distance between the AGN central engine and H_2 -bearing medium to be $\sim 10 - 15$ kpc, see Fig. 4. The analysis of J 0015 + 1842 urges for observing a sample to enable statistical studies and address open questions about the nature of these systems, constraining key parameters of AGN outflows, such as the mass rate, fraction of active AGNs, opening angles etc. Additionally, the detection of such kind

of systems opens wide opportunities for the multi-wavelength observations of AGN outflows at high- z , including near IR (to study H_2 in emission), sub-mm (to study cold molecular phase by CO emission [34] as well as other molecules) and makes valuable quantitative input for the modelling of outflowing gas.

4.3 Probing dense gas

As we already mentioned above, SDSS has, by construction, significant selection bias against dusty and red quasars [27]. Indeed, if dust is present anywhere along the line of sight, then the background quasar will appear fainter and redder than it intrinsically is (e.g. [49, 51]). Quasars with such dusty systems are therefore more likely to fall outside the color-selection and/or below the flux-limit of spectroscopic surveys. Since, as local measurements indicate, the amount of dust obscuration scales with the H_2 column density (e.g. [57, 59, 60]), this implies a bias against absorption systems with high H_2 column densities. These elusive systems correspond to translucent or dense molecular gas and therefore their detailed study is very important for a complete theory of the baryon cycle in the ISM over a wide range of metallicities. The next generation spectroscopic survey telescopes (such as 4-m Multi-Object Spectroscopic Telescope (4MOST), Dark Energy Spectroscopic Instrument, Mauna Kea Spectroscopic Explorer, William Herschel Telescope Enhanced Area Velocity Explorer, etc) will likely push further the quasar selection parameter space and obtain samples with significantly less selection bias against dusty absorbers. Follow-up observations of reddened quasars in the blue will naturally require a very good efficiency as can be brought by CUBES.

4.4 Astrophysical probes of fundamental physics

Molecular hydrogen absorption systems also provide unique probes of fundamental physics and cosmology. By comparing the observed relative wavelengths of the numerous absorption lines from H_2 with those measured in the laboratory, it is possible to constrain the variation of the electron-to-proton mass ratio, μ , over cosmological time scales [2, 65, 69], which gives typical limits of $|\Delta\mu/\mu| < 5 \times 10^{-6}$ [67]. This value is limited by systematics (including instrumental ones, [54]), the sensitivity of H_2 transitions to variation of μ , as well as a lack of systems with suitable characteristics. While it was found that some molecules (e.g. CH_3OH , NH_3 and HC_3N) are much more sensitive to variation of μ [19, 24], these are very rarely detected in the distant Universe⁷. Therefore, H_2 will remain a main probe for variations of μ . By surveying H_2 , CUBES will bring new targets at different redshifts, which are essential to decrease statistical errors as well as alleviating a number of possible systematics related to the systems characteristics. Additionally, accompanying detections

⁷ This is due to combination of two factors: (i) the cross-section of dense molecular gas (that is needed to detect aforementioned complex molecules) is much smaller than that of H_2 -bearing gas (associated mostly with more diffuse cold medium) (ii) the small fraction of radio bright QSOs, which are needed for the analysis sensitive transition

of HD and CO molecules in H_2 absorption systems can also provide independent constrain on μ [13, 14, 20, 68]. Moreover, as we mentioned above, the detection of CO associated with H_2 [63] provides a direct measurement of the CMB temperature at high redshift [46], a fundamental test for the adiabatic cooling of the Universe predicted by standard Big-Bang theory.

In short, while CUBES's design will not permit direct use of these astrophysical probes (because of a relatively short wavelength range and because it is not intended to have exquisite wavelength calibration), CUBES will be extremely effective in characterizing a large number of appropriate H_2 -bearing DLAs, very much easing the selection for follow-up studies with higher resolution and stable spectrographs.

4.5 Candidates

Figure 5 shows the G-band magnitude - redshift diagram for the confirmed (already followed-up) and candidates H_2 absorption systems (preselected in SDSS and that can be observed from Paranal). The intervening candidates were compiled based on DR14 using the direct- H_2 and C I pre-selection techniques (for descriptions of techniques, see [4, 29]) and proximate candidates were taken from [36]. The improved efficiency of the CUBES in comparison with UVES will allow to collect $\text{S/N} \sim 10$ spectra for all available candidates in less than one hour per object, when UVES requires already 10h for 2 magnitude fainter objects. In addition, the wavelength range of CUBES corresponds to redshifts for H_2 lines that almost perfectly match the redshift distribution of the candidates. This shows that we already have a substantial number of the targets that can be straightforwardly follow-up with CUBES with high efficiency to multiply the available samples of intervening and proximate H_2 -bearing DLAs.

5 Conclusions

Investigating molecular hydrogen absorption systems at high- z provides an extremely powerful probe of the physical conditions of the cold phase of the interstellar medium in the overall population of remote galaxies. The stepped-like progress in these studies has always been determined by observational capabilities, where two evident boosts were associated with (i) the advent of 8-m class telescopes (KECK and VLT) and (ii) the development of efficient pre-selection techniques in massive spectroscopic surveys (SDSS). We are now facing a bottleneck since follow-up studies of the many targets identified in the SDSS are faint and already reach the capabilities of current instruments. This issue can be overcome with CUBES - the next generation efficient blue spectrograph that is planned to be mounted on the VLT. We briefly discussed three H_2 -related top-priority science cases for CUBES in our opinion: (i) Studies of the thermal state of the cold ISM in the wide range of the environments sampled by intervening DLAs, (ii) Detailed investigations of the molecular gas in AGN outflows at high redshifts (iii) Probes of translucent and dark molecular gas in absorption via hunting for the dusty and high-column H_2 -bearing

DLAs that can be exclusively be reached with CUBES. This, together with the forthcoming generation of spectroscopic surveys, such as 4MOST (which will provide better exploration of the sky accessible from Paranal) will definitely provide the next boost in understanding the small-scale physics in the gas over a wide range of redshifts and environments.

Acknowledgements SB is supported by Russian Science Foundation grant 18-12-00301. PN is supported by the French *Agence Nationale de la Recherche* under grant ANR-17-CE31-0011 (“HIH2”).

Data availability The data underlying this article will be shared on reasonable request to the corresponding author.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

References

1. Arabsalmani, M., Møller, P., Fynbo, J.P.U., Christensen, L., Freudling, W., Savaglio, S., Zafar, T.: On the mass-metallicity relation, velocity dispersion, and gravitational well depth of GRB host galaxies. *MNRAS* **446**(1), 990–999 (2015). <https://doi.org/10.1093/mnras/stu2138>
2. Bagdonaite, J., Murphy, M.T., Kaper, L., Ubachs, W.: Constraint on a variation of the proton-to-electron mass ratio from H₂ absorption towards quasar Q2348–011. *MNRAS* **421**(1), 419–425 (2012). <https://doi.org/10.1111/j.1365-2966.2011.20319.x>
3. Balashev, S.A., Ivanchik, A.V., Varshalovich, D.A.: HD/H₂ molecular clouds in the early Universe: The problem of primordial deuterium. *Astronomy Letters* **36**(11), 761–772 (2010). <https://doi.org/10.1134/S1063773710110010>
4. Balashev, S.A., Klimenko, V.V., Ivanchik, A.V., Varshalovich, D.A., Petitjean, P., Noterdaeme, P.: Molecular hydrogen absorption systems in Sloan Digital Sky Survey. *MNRAS* **440**(1), 225–239 (2014). <https://doi.org/10.1093/mnras/stu275>
5. Balashev, S.A., Klimenko, V.V., Noterdaeme, P., Krogager, J.K., Varshalovich, D.A., Ivanchik, A.V., Petitjean, P., Srianand, R., Ledoux, C.: X-shooter observations of strong H₂-bearing DLAs at high redshift. *MNRAS* **490**(2), 2668–2678 (2019). <https://doi.org/10.1093/mnras/stz2707>
6. Balashev, S.A., Ledoux, C., Noterdaeme, P., Srianand, R., Petitjean, P., Gupta, N.: Nature of the DLA towards Q 0528–250: High pressure and strong UV field revealed by excitation of C I, H₂, and Si II. *MNRAS* **497**(2), 1946–1956 (2020). <https://doi.org/10.1093/mnras/staa2108>
7. Balashev, S.A., Noterdaeme, P.: Constraining the H₂ column density distribution at $z \sim 3$ from composite DLA spectra. *MNRAS* **478**(1), L7–L11 (2018). <https://doi.org/10.1093/mnrasl/sly067>
8. Balashev, S.A., Noterdaeme, P., Rahmani, H., Klimenko, V.V., Ledoux, C., Petitjean, P., Srianand, R., Ivanchik, A.V., Varshalovich, D.A.: CO-dark molecular gas at high redshift: very large H₂ content and high pressure in a low-metallicity damped Lyman alpha system. *MNRAS* **470**(3), 2890–2910 (2017). <https://doi.org/10.1093/mnras/stx1339>
9. Bialy, S., Sternberg, A.: Thermal phases of the neutral atomic interstellar medium from solar metallicity to primordial gas. *ApJ* **881**(2), 160 (2019). <https://doi.org/10.3847/1538-4357/ab2fd1>
10. Bolmer, J., Ledoux, C., Wiseman, P., De Cia, A., Selsing, J., Schady, P., Greiner, J., Savaglio, S., Burgess, J.M., D’Elia, V., Fynbo, J.P.U., Goldoni, P., Hartmann, D.H., Heintz, K.E., Jakobsson, P., Japelj, J., Kaper, L., Tanvir, N.R., Vreeswijk, P.M., Zafar, T.: Evidence for diffuse molecular gas and dust in the hearts of gamma-ray burst host galaxies. Unveiling the nature of high-redshift damped Lyman- α systems. *A&A* **623**, A43 (2019). <https://doi.org/10.1051/0004-6361/201834422>
11. Carruthers, G.R.: Rocket observation of interstellar molecular hydrogen. *ApJ* **161**, L81 (1970). <https://doi.org/10.1086/180575>
12. Cicone, C., Maiolino, R., Sturm, E., Graciá-Carpio, J., Feruglio, C., Neri, R., Aalto, S., Davies, R., Fiore, F., Fischer, J., García-Burillo, S., González-Alfonso, E., Hailey-Dunsheath, S., Piconcelli, E.,

- Veilleux, S.: Massive molecular outflows and evidence for AGN feedback from CO observations. *A&A* **562**, A21 (2014). <https://doi.org/10.1051/0004-6361/201322464>
13. Daprà, M., Niu, M.L., Salumbides, E.J., Murphy, M.T., Ubachs, W.: Constraint on a cosmological variation in the proton-to-electron mass ratio from electronic CO absorption. *ApJ* **826**(2), 192 (2016). <https://doi.org/10.3847/0004-637X/826/2/192>
 14. Daprà, M., Noterdaeme, P., Vonk, M., Murphy, M.T., Ubachs, W.: Analysis of carbon monoxide absorption at $z_{\text{abs}} = 2.5$ to constrain variation of the proton-to-electron mass ratio. *MNRAS* **467**(4), 3848–3855 (2017). <https://doi.org/10.1093/mnras/stx331>
 15. Dekker, H., D’Odorico, S., Kaufer, A., Delabre, B., Kotzlowski, H.: Design, construction, and performance of UVES, the echelle spectrograph for the UT2 Kueyen Telescope at the ESO Paranal Observatory. In: Iye, M., Moorwood, A.F. (eds.) *Optical and IR Telescope Instrumentation and Detectors*, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 4008, pp. 534–545 (2000). <https://doi.org/10.1117/12.395512>
 16. Ge, J., Bechtold, J.: Molecular hydrogen absorption in the $z = 1.97$ Damped Ly α absorption system toward quasi-stellar object Q0013-004. *ApJ* **477**(2), L73–L77 (1997). <https://doi.org/10.1086/310527>
 17. Genoni, A., Landoni, M., Cupani, G., et al.: The CUBES Instrument model and simulation tools. *ExA* in press as part of the CUBES Special Issue (2021)
 18. Guimarães, R., Noterdaeme, P., Petitjean, P., Ledoux, C., Srianand, R., López, S., Rahmani, H.: Metallicities, dust, and molecular content of a QSO-damped Ly α system reaching $\log N(\text{H I}) = 22$: An Analog to GRB-DLAs. *AJ* **143**(6), 147 (2012). <https://doi.org/10.1088/0004-6256/143/6/147>
 19. Henkel, C., Menten, K.M., Murphy, M.T., Jethava, N., Flambaum, V.V., Braatz, J.A., Muller, S., Ott, J., Mao, R.Q.: The density, the cosmic microwave background, and the proton-to-electron mass ratio in a cloud at redshift 0.9. *A&A* **500**(2), 725–734 (2009). <https://doi.org/10.1051/0004-6361/200811475>
 20. Ivanov, T.I., Roudjane, M., Vieitez, M.O., de Lange, C.A., Tchang-Brillet, W.Ü.L., Ubachs, W.: HD as a probe for detecting mass variation on a cosmological time scale. *Phys. Rev. Lett.* **100**(9), 093007 (2008). <https://doi.org/10.1103/PhysRevLett.100.093007>
 21. Jorgenson, R.A., Murphy, M.T., Thompson, R., Carswell, R.F.: The Magellan uniform survey of damped Lyman α systems - II. Paucity of strong molecular hydrogen absorption. *MNRAS* **443**(3), 2783–2800 (2014). <https://doi.org/10.1093/mnras/stu1314>
 22. Jorgenson, R.A., Wolfe, A.M., Prochaska, J.X.: Understanding physical conditions in high-redshift Galaxies through C I fine structure lines: data and methodology. *ApJ* **722**(1), 460–490 (2010). <https://doi.org/10.1088/0004-637X/722/1/460>
 23. Jorgenson, R.A., Wolfe, A.M., Prochaska, J.X., Carswell, R.F.: Direct evidence of cold gas in DLA 0812+32B. *ApJ* **704**(1), 247–254 (2009). <https://doi.org/10.1088/0004-637X/704/1/247>
 24. Kanekar, N., Ubachs, W., Menten, K.M., Bagdonaitė, J., Brunthaler, A., Henkel, C., Muller, S., Bethlehem, H.L., Daprà, M.: Constraints on changes in the proton-electron mass ratio using methanol lines. *MNRAS* **448**, L104–L108 (2015). <https://doi.org/10.1093/mnras/ltu206>
 25. Klimenko, V.V., Balashev, S.A.: Physical conditions in the diffuse interstellar medium of local and high-redshift galaxies: measurements based on the excitation of H₂ rotational and C I fine-structure levels. *MNRAS* **498**(2), 1531–1549 (2020). <https://doi.org/10.1093/mnras/staa2134>
 26. Kosenko, D.N., Balashev, S.A., Noterdaeme, P., Krogager, J.K., Srianand, R., Ledoux, C.: HD molecules at high redshift: cosmic ray ionization rate in the diffuse interstellar medium. *MNRAS* **505**(3), 3810–3822 (2021). <https://doi.org/10.1093/mnras/stab1535>
 27. Krogager, J.K., Fynbo, J.P.U., Møller, P., Noterdaeme, P., Heintz, K.E., Pettini, M.: The effect of dust bias on the census of neutral gas and metals in the high-redshift Universe due to SDSS-II quasar colour selection. *MNRAS* **486**(3), 4377–4397 (2019). <https://doi.org/10.1093/mnras/stz1120>
 28. Krühler, T., Ledoux, C., Fynbo, J.P.U., Vreeswijk, P.M., Schmid, S., Malesani, D., Christensen, L., De Cia, A., Hjorth, J., Jakobsson, P., Kann, D.A., Kaper, L., Vergani, S.D., Afonso, P.M.J., Covino, S., de Ugarte Postigo, A., D’Elia, V., Filgas, R., Goldoni, P., Greiner, J., Hartoog, O.E., Milvang-Jensen, B., Nardini, M., Piranomonte, S., Rossi, A., Sánchez-Ramírez, R., Schady, P., Schulze, S., Sudilovsky, V., Tanvir, N.R., Tagliaferri, G., Watson, D.J., Wiersema, K., Wijers, R.A.M.J., Xu, D.: Molecular hydrogen in the damped Lyman α system towards GRB 120815A at $z = 2.36$. *A&A* **557**, A18 (2013). <https://doi.org/10.1051/0004-6361/201321772>
 29. Ledoux, C., Noterdaeme, P., Petitjean, P., Srianand, R.: Neutral atomic-carbon quasar absorption-line systems at $z > 1.5$. Sample selection, H I content, reddening, and 2175 Å extinction feature. *A&A* **580**, A8 (2015). <https://doi.org/10.1051/0004-6361/201424122>

30. Ledoux, C., Petitjean, P., Srianand, R.: The very large telescope ultraviolet and visible Echelle spectrograph survey for molecular hydrogen in high-redshift damped Lyman α systems. *MNRAS* **346**(1), 209–228 (2003). <https://doi.org/10.1046/j.1365-2966.2003.07082.x>
31. Levshakov, S.A., Varshalovich, D.A.: Molecular hydrogen in the $z=2.811$ absorbing material toward the quasar PKS 0528–250. *MNRAS* **212**, 517–521 (1985). <https://doi.org/10.1093/mnras/212.3.517>
32. Lyman, J.D., Levan, A.J., Tanvir, N.R., Fynbo, J.P.U., McGuire, J.T.W., Perley, D.A., Angus, C.R., Bloom, J.S., Conselice, C.J., Fruchter, A.S., Hjorth, J., Jakobsson, P., Starling, R.L.C.: The host galaxies and explosion sites of long-duration gamma ray bursts: Hubble Space Telescope near-infrared imaging. *MNRAS* **467**(2), 1795–1817 (2017). <https://doi.org/10.1093/mnras/stx220>
33. Morton, D.C., Jian-Sheng, C., Wright, A.E., Peterson, B.A., Jauncey, D.L.: Absorption lines and ion abundances in the QSO PKS 0528–250. *MNRAS* **193**, 399–413 (1980). <https://doi.org/10.1093/mnras/193.2.399>
34. Noterdaeme, P., Balashev, S., Combes, F., Gupta, N., Srianand, R., Krogager, J.K., Laursen, P., Omont, A.: Remarkably high mass and velocity dispersion of molecular gas associated with a regular, absorption-selected type I quasar. *A&A* **651**, A17 (2021). <https://doi.org/10.1051/0004-6361/202140745>
35. Noterdaeme, P., Balashev, S., Krogager, J.K., Laursen, P., Srianand, R., Gupta, N., Petitjean, P., Fynbo, J.P.U.: Down-the-barrel observations of a multi-phase quasar outflow at high redshift. VLT/X-shooter spectroscopy of the proximate molecular absorber at $z = 2.631$ towards SDSS J001514+184212. *A&A* **646**, A108 (2021). <https://doi.org/10.1051/0004-6361/202038877>
36. Noterdaeme, P., Balashev, S., Krogager, J.K., Srianand, R., Fathivavsari, H., Petitjean, P., Ledoux, C.: Proximate molecular quasar absorbers. Excess of damped H_2 systems at $z_{abs} \approx z_{QSO}$ in SDSS DR14. *A&A* **627**, A32 (2019). <https://doi.org/10.1051/0004-6361/201935371>
37. Noterdaeme, P., Krogager, J.K., Balashev, S., Ge, J., Gupta, N., Krühler, T., Ledoux, C., Murphy, M.T., Pâris, I., Petitjean, P., Rahmani, H., Srianand, R., Ubachs, W.: Discovery of a Perseus-like cloud in the early Universe. H I-to- H_2 transition, carbon monoxide and small dust grains at $z_{abs} \approx 2.53$ towards the quasar J0000+0048. *A&A* **597**, A82 (2017). <https://doi.org/10.1051/0004-6361/201629173>
38. Noterdaeme, P., Ledoux, C., Petitjean, P., Le Petit, F., Srianand, R., Smette, A.: Excitation mechanisms in newly discovered H₂-bearing damped Lyman- α clouds: systems with low molecular fractions. *A&A* **474**(2), 393–407 (2007). <https://doi.org/10.1051/0004-6361:20078021>
39. Noterdaeme, P., Ledoux, C., Petitjean, P., Srianand, R.: Molecular hydrogen in high-redshift damped Lyman- α systems: the VLT/UVES database. *A&A* **481**(2), 327–336 (2008). <https://doi.org/10.1051/0004-6361:20078780>
40. Noterdaeme, P., Ledoux, C., Srianand, R., Petitjean, P., Lopez, S.: Diffuse molecular gas at high redshift. Detection of CO molecules and the 2175 Å dust feature at $z = 1.64$. *A&A* **503**(3), 765–770 (2009). <https://doi.org/10.1051/0004-6361/200912330>
41. Noterdaeme, P., Ledoux, C., Zou, S., Petitjean, P., Srianand, R., Balashev, S., López, S.: Spotting high- z molecular absorbers using neutral carbon. Results from a complete spectroscopic survey with the VLT. *A&A* **612**, A58 (2018). <https://doi.org/10.1051/0004-6361/201732266>
42. Noterdaeme, P., Petitjean, P., Carithers, W.C., Pâris, I., Font-Ribera, A., Bailey, S., Aubourg, E., Bizyaev, D., Ebelke, G., Finley, H., Ge, J., Malanushenko, E., Malanushenko, V., Miralda-Escudé, J., Myers, A.D., Oravetz, D., Pan, K., Pieri, M.M., Ross, N.P., Schneider, D.P., Simmons, A., York, D.G.: Column density distribution and cosmological mass density of neutral gas: Sloan Digital Sky Survey-III Data Release 9. *A&A* **547**, L1 (2012). <https://doi.org/10.1051/0004-6361/201220259>
43. Noterdaeme, P., Petitjean, P., Ledoux, C., López, S., Srianand, R., Vergani, S.D.: A translucent interstellar cloud at $z = 2.69$. CO, H_2 , and HD in the line-of-sight to SDSS J123714.60+064759.5. *A&A* **523**, A80 (2010). <https://doi.org/10.1051/0004-6361/201015147>
44. Noterdaeme, P., Petitjean, P., Pâris, I., Cai, Z., Finley, H., Ge, J., Pieri, M.M., York, D.G.: A connection between extremely strong damped Lyman- α systems and Lyman- α emitting galaxies at small impact parameters. *A&A* **566**, A24 (2014). <https://doi.org/10.1051/0004-6361/201322809>
45. Noterdaeme, P., Petitjean, P., Srianand, R., Ledoux, C., Le Petit, F.: Physical conditions in the neutral interstellar medium at $z = 2.43$ toward Q 2348–011. *A&A* **469**(2), 425–436 (2007). <https://doi.org/10.1051/0004-6361:20066897>
46. Noterdaeme, P., Petitjean, P., Srianand, R., Ledoux, C., López, S.: The evolution of the cosmic microwave background temperature. Measurements of T_{CMB} at high redshift from carbon monoxide excitation. *A&A* **526**, L7 (2011). <https://doi.org/10.1051/0004-6361/201016140>

47. Noterdaeme, P., Srianand, R., Rahmani, H., Petitjean, P., Pâris, I., Ledoux, C., Gupta, N., López, S.: VLT/UVES observations of extremely strong intervening damped Lyman- α systems. Molecular hydrogen and excited carbon, oxygen, and silicon at $\log N(\text{H I}) = 22.4$. *A&A* **577**, A24 (2015). <https://doi.org/10.1051/0004-6361/201425376>
48. Parks, D., Prochaska, J.X., Dong, S., Cai, Z.: Deep learning of quasar spectra to discover and characterize damped Ly α systems. *MNRAS* **476**(1), 1151–1168 (2018). <https://doi.org/10.1093/mnras/sty196>
49. Pei, Y.C., Fall, S.M., Bechtold, J.: Confirmation of dust in damped Lyman-alpha systems. *ApJ* **378**, 6 (1991). <https://doi.org/10.1086/170401>
50. Petitjean, P., Srianand, R., Ledoux, C.: Molecular hydrogen and the nature of damped Lyman-alpha systems. *A&A* **364**, L26–L30 (2000)
51. Pontzen, A., Pettini, M.: Dust biasing of damped Lyman alpha systems: a Bayesian analysis. *MNRAS* **393**(2), 557–568 (2009). <https://doi.org/10.1111/j.1365-2966.2008.14193.x>
52. Prochaska, J.X., Howk, J.C., Wolfe, A.M.: The elemental abundance pattern in a galaxy at $z = 2.626$. *Nature* **423**(6935), 57–59 (2003). <https://doi.org/10.1038/nature01524>
53. Prochaska, J.X., Sheffer, Y., Perley, D.A., Bloom, J.S., Lopez, L.A., Dessauges-Zavadsky, M., Chen, H.W., Filippenko, A.V., Ganeshalingam, M., Li, W., Miller, A.A., Starr, D.: The first positive detection of molecular gas in a GRB host galaxy. *ApJ* **691**(1), L27–L32 (2009). <https://doi.org/10.1088/0004-637X/691/1/L27>
54. Rahmani, H., Wendt, M., Srianand, R., Noterdaeme, P., Petitjean, P., Molaro, P., Whitmore, J.B., Murphy, M.T., Centurion, M., Fathivavari, H., D’Odorico, S., Evans, T.M., Levshakov, S.A., Lopez, S., Martins, C.J.A.P., Reimers, D., Vladilo, G.: The UVES large program for testing fundamental physics - II. Constraints on a change in μ towards quasar HE 0027-1836. *MNRAS* **435**(1), 861–878 (2013). <https://doi.org/10.1093/mnras/stt1356>
55. Ranjan, A., Noterdaeme, P., Krogager, J.K., Petitjean, P., Balashev, S.A., Bialy, S., Srianand, R., Gupta, N., Fynbo, J.P.U., Ledoux, C., Laursen, P.: Molecular gas and star formation in an absorption-selected galaxy: Hitting the bull’s eye at $z = 2.46$. *A&A* **618**, A184 (2018). <https://doi.org/10.1051/0004-6361/201833446>
56. Ranjan, A., Noterdaeme, P., Krogager, J.K., Petitjean, P., Srianand, R., Balashev, S.A., Gupta, N., Ledoux, C.: Chemical enrichment and host galaxies of extremely strong intervening DLAs towards quasars. Do they probe the same galactic environments as DLAs associated with γ -ray burst afterglows? *A&A* **633**, A125 (2020). <https://doi.org/10.1051/0004-6361/201936078>
57. Roman-Duval, J., Israel, F.P., Bolatto, A., Hughes, A., Leroy, A., Meixner, M., Gordon, K., Maden, S.C., Paradis, D., Kawamura, A., Li, A., Sauvage, M., Wong, T., Bernard, J.P., Engelbracht, C., Hony, S., Kim, S., Misselt, K., Okumura, K., Ott, J., Panuzzo, P., Pineda, J.L., Reach, W.T., Rubio, M.: Dust/gas correlations from Herschel observations. *A&A* **518**, L74 (2010). <https://doi.org/10.1051/0004-6361/201014575>
58. Sahnou, D.J., Friedman, S.D., Oegerle, W.R., Moos, H.W., Green, J.C., Siegmund, O.H.: Design and predicted performance of the far ultraviolet spectroscopic explorer. In: Bely, P.Y., Breckinridge J.B. (eds.) *Space Telescopes and Instruments IV*, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, vol. 2807, pp. 2–10 (1996). <https://doi.org/10.1117/12.255092>
59. Savage, B.D., Bohlin, R.C., Drake, J.F., Budich, W.: A survey of interstellar molecular hydrogen. I. *ApJ* **216**, 291–307 (1977). <https://doi.org/10.1086/155471>
60. Shull, J.M., Danforth, C.W., Anderson, K.L.: A far ultraviolet spectroscopic explorer survey of interstellar molecular hydrogen in the galactic disk. *ApJ* **911**(1), 55 (2021). <https://doi.org/10.3847/1538-4357/abe707>
61. Shull, J.M., Giroux, M.L., Penton, S.V., Tumlinson, J., Stocke, J.T., Jenkins, E.B., Moos, H.W., Oegerle, W.R., Savage, B.D., Sembach, K.R., York, D.G., Green, J.C., Woodgate, B.E.: Far ultraviolet spectroscopic explorer observations of the low-redshift Ly β Forest. *ApJ* **538**(1), L13–L16 (2000). <https://doi.org/10.1086/312781>
62. Spitzer, I., Cochran, J., Hirshfeld, W.D.A.: Column densities of interstellar molecular hydrogen. *ApJS* **28**, 373–389 (1974). <https://doi.org/10.1086/190323>
63. Srianand, R., Noterdaeme, P., Ledoux, C., Petitjean, P.: First detection of CO in a high-redshift damped Lyman- α system. *A&A* **482**(3), L39–L42 (2008). <https://doi.org/10.1051/0004-6361/200809727>
64. Srianand, R., Petitjean, P., Ledoux, C., Ferland, G., Shaw, G.: The VLT-UVES survey for molecular hydrogen in high-redshift damped Lyman α systems: physical conditions in the neutral gas. *MNRAS* **362**(2), 549–568 (2005). <https://doi.org/10.1111/j.1365-2966.2005.09324.x>

65. Thompson, R.I.: The determination of the electron to proton inertial mass ratio via molecular transitions. *Astrophys. Lett.* **16**(3) (1975)
66. Tumlinson, J., Shull, J.M., Rachford, B.L., Browning, M.K., Snow, T.P., Fullerton, A.W., Jenkins, E.B., Savage, B.D., Crowther, P.A., Moos, H.W., Sembach, K.R., Sonneborn, G., York, D.G.: A far ultraviolet spectroscopic explorer survey of interstellar molecular hydrogen in the small and large magellanic clouds. *ApJ* **566**(2), 857–879 (2002). <https://doi.org/10.1086/338112>
67. Ubachs, W., Bagdonaite, J., Salumbides, E.J., Murphy, M.T., Kaper, L.: Colloquium: Search for a drifting proton-electron mass ratio from H₂. *Reviews of Modern Physics* **88**(2), 021003 (2016). <https://doi.org/10.1103/RevModPhys.88.021003>
68. Ubachs, W., Salumbides, E.J., Murphy, M.T., Abgrall, H., Roueff, E.: H₂/HD molecular data for analysis of quasar spectra in search of varying constants. *A&A* **622**, A127 (2019). <https://doi.org/10.1051/0004-6361/201834782>
69. Varshalovich, D.A., Levshakov, S.A.: On a time dependence of physical constants. *Soviet Journal of Experimental and Theoretical Physics Letters* **58**(4), 237–240 (1993)
70. Veilleux, S., Meléndez, M., Sturm, E., Gracia-Carpio, J., Fischer, J., González-Alfonso, E., Contursi, A., Lutz, D., Poglitsch, A., Davies, R., Genzel, R., Tacconi, L., de Jong, J.A., Sternberg, A., Netzer, H., Hailey-Dunsheath, S., Verma, A., Rupke, D.S.N., Maiolino, R., Teng, S.H., Polisensky, E.: Fast molecular outflows in luminous galaxy mergers: evidence for quasar feedback from Herschel. *ApJ* **776**(1), 27 (2013). <https://doi.org/10.1088/0004-637X/776/1/27>
71. Vernet, J., Dekker, H., D'Odorico, S., Kaper, L., Kjaergaard, P., Hammer, F., Randich, S., Zerbi, F., Groot, P.J., Hjorth, J., Guinouard, I., Navarro, R., Adolfse, T., Albers, P.W., Amans, J.P., Andersen, J.J., Andersen, M.I., Binetruy, P., Bristow, P., Castillo, R., Chemla, F., Christensen, L., Conconi, P., Conzelmann, R., Dam, J., de Caprio, V., de Ugarte Postigo, A., Delabre, B., di Marcantonio, P., Downing, M., Elswijk, E., Finger, G., Fischer, G., Flores, H., François, P., Goldoni, P., Guglielmi, L., Haigron, R., Hanenburg, H., Hendriks, I., Horrobin, M., Horville, D., Jessen, N.C., Kerber, F., Kern, L., Kiekebusch, M., Kleszcz, P., Klougart, J., Kragt, J., Larsen, H.H., Lizon, J.L., Lucuix, C., Mainieri, V., Manuputy, R., Martayan, C., Mason, E., Mazzoleni, R., Michaelsen, N., Modigliani, A., Moehler, S., Møller, P., Norup Sørensen, A., Nørregaard, P., Péroux, C., Patat, F., Pena, E., Pragt, J., Reinero, C., Rigal, F., Riva, M., Roelfsema, R., Royer, F., Sacco, G., Santin, P., Schoenmaker, T., Spano, P., Sweers, E., Ter Horst, R., Tintori, M., Tromp, N., van Dael, P., van der Vliet, H., Venema, L., Vidali, M., Vinther, J., Vola, P., Winters, R., Wistisen, D., Wulterkens, G., Zacchei, A.: X-shooter, the new wide band intermediate resolution spectrograph at the ESO Very Large Telescope. *A&A* **536**, A105 (2011). <https://doi.org/10.1051/0004-6361/201117752>
72. Vogt, S.S., Allen, S.L., Bigelow, B.C., Bresee, L., Brown, B., Cantrall, T., Conrad, A., Couture, M., Delaney, C., Epps, H.W., Hilyard, D., Hilyard, D.F., Horn, E., Jern, N., Kanto, D., Keane, M.J., Kibrick, R.I., Lewis, J.W., Osborne, J., Pardeilhan, G.H., Pfister, T., Ricketts, T., Robinson, L.B., Stover, R.J., Tucker, D., Ward, J., Wei, M.Z.: HIRES: the high-resolution echelle spectrometer on the Keck 10-m Telescope. In: Crawford, D.L., Craine, E.R. (eds.) *Instrumentation in Astronomy VIII, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 2198, p. 362 (1994). <https://doi.org/10.1117/12.176725>
73. ...York, D.G., Adelman, J., Anderson John, E.J., Anderson, S.F., Annis, J., Bahcall, N.A., Bakken, J.A., Barkhouser, R., Bastian, S., Berman, E., Boroski, W.N., Bracker, S., Briegel, C., Briggs, J.W., Brinkmann, J., Brunner, R., Burles, S., Carey, L., Carr, M.A., Castander, F.J., Chen, B., Colestock, P.L., Connolly, A.J., Crocker, J.H., Csabai, I., Czarapata, P.C., Davis, J.E., Doi, M., Dombeck, T., Eisenstein, D., Ellman, N., Elms, B.R., Evans, M.L., Fan, X., Federwitz, G.R., Fiscelli, L., Friedman, S., Frieman, J.A., Fukugita, M., Gillespie, B., Gunn, J.E., Gurbani, V.K., de Haas, E., Halderman, M., Harris, F.H., Hayes, J., Heckman, T.M., Hennessy, G.S., Hindsley, R.B., Holm, S., Holmgren, D.J., Huang, C.H., Hull, C., Husby, D., Ichikawa, S.I., Ichikawa, T., Ivezić, Ž, Kent, S., Kim, R.S.J., Kinney, E., Klaene, M., Kleinman, A.N., Kleinman, S., Knapp, G.R., Korienek, J., Kron, R.G., Kunszt, P.Z., Lamb, D.Q., Lee, B., Leger, R.F., Limmongkol, S., Lindenmeyer, C., Long, D.C., Loomis, C., Loveday, J., Lucinio, R., Lupton, R.H., MacKinnon, B., Mannery, E.J., Mantsch, P.M., Margon, B., McGehee, P., McKay, T.A., Meiksin, A., Merelli, A., Monet, D.G., Munn, J.A., Narayanan, V.K., Nash, T., Neilsen, E., Neswold, R., Newberg, H.J., Nichol, R.C., Nicinski, T., Nonino, M., Okada, N., Okamura, S., Ostriker, J.P., Owen, R., Pauls, A.G., Peoples, J., Peterson, R.L., Petravick, D., Pier, J.R., Pope, A., Pordes, R., Prosapio, A., Rechenmacher, R., Quinn, T.R., Richards, G.T., Richmond, M.W., Rivetta, C.H., Rockosi, C.M., Ruthmansdorfer, K., Sandford, D., Schlegel, D.J., Schneider, D.P., Sekiguchi, M., Sergey, G., Shimasaku, K., Siegmund, W.A., Smee, S., Smith, J.A., Snedden, S., Stone, R., Stoughton, C., Strauss, M.A., Stubbs, C., SubbaRao, M.,

- Szalay, A.S., Szapudi, I., Szokoly, G.P., Thakar, A.R., Tremonti, C., Tucker, D.L., Uomoto, A., Vanden Berk, D., Vogeley, M.S., Waddell, P., Wang, S.I., Watanabe, M., Weinberg, D.H., Yanny, B., Yasuda, N.: SDSS Collaboration: The sloan figital sky survey: technical summary. *AJ* **120**(3), 1579–1587 (2000). <https://doi.org/10.1086/301513>
74. Zanutta, A., Atkinson, D., Baldini, V., et al.: CUBES Phase-A design overview. *ExA* in press as part of the CUBES Special Issue(2021)

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.