Summary

The standard model (SM) of particle physics is a theory with remarkable predictive power. One great example of its success is the recent discovery of the Higgs boson. However, at the same time the SM is incompatible with general relativity – a theory tested and trusted just as much. Furthermore, certain ad hoc features maintained by the SM indicate that its explanatory insights are not as broad and exhaustive as one would hope. One of the features that looks arbitrary is the number and the values of the free parameters of the SM or so-called fundamental constants. These constants include the masses of elementary particles and the strengths of the forces of nature which combined govern the chemical complexity of our universe. What is probably most unsettling is that the values of constants can only be measured experimentally and any attempts to derive them from first principles have so far proven unsuccessful. Is it simply nature’s last word or does it mean that the particular principles are yet to be discovered? Driven by this question, various propositions have been made where in alternate universes constants would take different values.

In this thesis, we explore the most basic question one can ask about a constant: is it actually constant? In particular, the focus of the present work is on the proton–electron mass ratio $\mu$ whose constancy is probed via spectroscopic measurements of sensitive transitions in molecular hydrogen (H$_2$) and methanol (CH$_3$OH) found in distant galaxies and in white dwarf atmospheres.

Most of the thesis (Chapters 2–4, 6, and 7) is based on astronomical observations of molecular clouds at intermediate-to-high redshifts which correspond to lookback times of 7.5 to 12.4 billion years. Cold gaseous material in the sightlines to distant quasars will absorb light at specific wavelengths according to the redshift and the chemical species present. The overall redshift $z$ of a given absorption system is shared among all the transitions. Regarding the sensitive molecular species, individual transitions may show additional distinctive shifts due to a variation of $\mu$. Hence, we can uncover a relative constraint of $\Delta \mu/\mu$ by comparing a relative pattern of H$_2$ or CH$_3$OH transitions observed in the astronomical sources to a corresponding pattern found under local $\mu$.

At redshifts $z > 2$, the rovibronic H$_2$ transitions with rest-frame wavelengths in the ultraviolet range ($\lambda_0 < 115$ nm) are shifted into the optical win-
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dow accessible with the Ultraviolet and Visual Echelle Spectrograph mounted on the Very Large Telescope. Chapter 2 presents an analysis of an H$_2$ absorption system at $z_{\text{abs}} = 2.43$, observed toward the quasar Q2348–011. The H$_2$ absorption profile exhibits seven velocity features, which, for an H$_2$ absorber, is unusually complex. The selected 32 transitions were modeled simultaneously with the surrounding and overlapping Lyman-α forest which consists of multiple transitions arising in neutral hydrogen clouds in the same line of sight. A comprehensive fitting method was applied allowing for parameter tying based on known molecular physics. The profiles were modeled using the VPFIT software by fitting the data with multiple Voigt profiles. The study resulted in a $\Delta \mu/\mu$ limit of $(0.68 \pm 2.78) \times 10^{-5}$ which, although not as constraining, is in agreement with other $\Delta \mu/\mu$ limits obtained at that redshift range.

In Chapters 3 and 4, the same methodology as in Chapter 2 was applied to two different H$_2$ absorbers observed, respectively, at $z_{\text{abs}} = 2.66$ toward quasar B0642–5038, and at $z_{\text{abs}} = 4.22$ toward quasar J1443+2724. The B0642–5038 absorber exhibits a much simpler absorption profile with a single velocity feature. A relatively high number of transitions (111) was included in the analysis which resulted in a final constraint of $\Delta \mu/\mu = (12.7 \pm 6.2) \times 10^{-6}$. At the accuracy level of several parts per million, the result was found to be sensitive to a number of different systematic effects, most notably to the long range wavelength distortions discovered in the Ultraviolet and Visual Echelle Spectrograph. A correction of the wavelength scale was implemented based on spectral analysis of asteroids and solar twins. The correction reduced the significance of a 3-σ non-zero $\Delta \mu/\mu$ which was obtained initially and increased the systematic uncertainty.

Detected at $z_{\text{abs}} = 4.22$, the H$_2$ absorber toward J1443+2724 allowed us to obtain the highest redshift direct $\Delta \mu/\mu$ measurement so far. An analysis of 89 H$_2$ transitions, which are each seen in two velocity features, yielded a $\Delta \mu/\mu$ limit of $(9.5 \pm 7.6) \times 10^{-6}$. Altogether, the results presented in Chapters 2–4, which focus on high redshift H$_2$ absorbers, do not provide evidence for varying $\mu$.

Chapter 5 is based on Galactic observations of white dwarfs, which are the compact remnant cores of low-mass stars. Detection of H$_2$ in their atmospheres (observed with the Hubble Space Telescope/Cosmic Origins Spectrograph) allowed to test for a possible $\mu$ dependence on gravity. A much higher temperature than in cold intergalactic clouds prompted sensitivity coefficient calculations for transitions from higher vibrational levels. A novel fitting method was applied where all the observed lines (close to a thousand per spectrum) were modeled by invoking only five free parameters in total. The analysis of the white dwarf GD133 yielded a constraint of $\Delta \mu/\mu = (2.7 \pm 4.7) \times 10^{-5}$ for a gravitational potential ten thousand times stronger than that on the Earth. The white dwarf G29–38, with an even stronger gravitational poten-
tial, yielded $\Delta \mu / \mu = (-5.8 \pm 3.8) \times 10^{-5}$.

In Chapters 6 and 7, a galaxy at redshift $z = 0.89$ toward PKS1830−211 is investigated to put a $\Delta \mu / \mu$ constraint at a stringent $10^{-7}$ accuracy level. Although being less numerous compared to a typical $\text{H}_2$ spectrum, the detected methanol absorption lines offer a huge advantage of enhanced sensitivity to $\mu$ variation. The sensitive rotational CH$_3$OH transitions are redshifted into the radio range from 0.1 to 5.0 cm. They were initially observed with the Effelsberg telescope (Chapter 6), later adding more observations from the Institut de Radio Astronomie Millimétrique 30-m telescope and the Atacama Large Millimeter/submillimeter Array (Chapter 7). The combined results are presented in Chapter 7, where various systematic effects are explored such as chemical segregation, excitation temperature, frequency dependence and time-variability of the background source. The study resulted in a constraint of $\Delta \mu / \mu = (-1.0 \pm 0.8_{\text{stat}} \pm 1.0_{\text{sys}}) \times 10^{-7}$. In conclusion, the radio measurements of methanol transitions at a lookback time of 7.5 billion years show no indication of varying $\mu$. 