Spectroscopy is a powerful tool to achieve a deep insight into the microscopic world physics. Precise studies of the internal structure of molecules and of fundamental molecular interactions play an important role in a variety of applications. Atmospheric studies such as the determination of cloud-top heights or of greenhouse gases concentration strongly rely on spectroscopic data. In clinical studies the presence in human breath of certain molecules (carbon monoxide, ethane, acetone, ...) beyond given concentration levels are recognized as biomarkers of a variety of diseases such as asthma, diabetes, or nephritis. In astrophysics our understanding of the atmospheric composition of exoplanets as well as the identification of regions where stars have been formed again relies on spectroscopic data. In the industrial sector, besides the monitoring of pollutants from manufacturing plants, the knowledge of water vapor concentration plays a key role, especially for semiconductors. In telecommunications several molecular transitions are commonly used as a wavelength references for fiber communication links. At a more fundamental level spectroscopy is used to determine physical constants and to assess whether they experience changes over cosmological times, as argued by some theories on the evolution of the universe. Spectroscopy is also used in metrology where selected transitions serves as the standards of physical quantities like meter and second. For all such goals being reached, accurate spectroscopic instruments and proper data analysis techniques are required.

In this project we aim to take advantage of the most recent advances in laser-based spectrometers, which have experienced over recent years a tremendous boost with respect to performance metrics such as sensitivity, spectral resolution, and frequency stability, and create an opportunity to determine the frequencies of weak molecular transitions of $O_2$, CO, $CO_2$, and $H_2$ with unprecedented sub-kHz accuracy and precision. We plan to combine the saturation spectroscopy, that provides the best so far data on line positions, with the cavity-enhanced techniques characterized by very high sensitivity and to push the limits of their applicability to a new ultimate level. The spectrometer will be linked to the optical atomic clock which nowadays can reach the frequency stability of even $10^{-18}$. Three ultra-sensitive spectroscopic techniques which provide access to both absorption and dispersion spectra will be used. It will allow to eliminate the instrumental errors present in all of these techniques and increase the metrological capabilities of the spectrometer. In the project we will also develop a new line-shape model describing the saturation dips which is needed to extract the line positions with rarely achieved sub-kHz uncertainties. The model will go much beyond the commonly used Lorentzian profile by taking into account e.g. the speed-dependent collisional effects.

The project results will allow to compare theory and experiment at a new ultimate level. The tests of quantum electrodynamics for molecules at an unprecedented level of accuracy will directly contribute to the development of science. Such extremely precise and accurate measurements can be used to solve some of the fundamental quantum mechanical problems like searching of new physics beyond the Standard Model or searching of space-time variations of physical constants. Since the targeted molecular species play a key role in atmospheric, clinical, environmental as well as astrophysical studies, the project can have impact on these fields. The list of line positions generated within the project will be incorporated into the most popular spectroscopic databases thus making the results of the project accessible to a broad scientific community.