Addressing the fundamental discrepancy observed in sub-Doppler molecular spectra of the hydrogen molecule – development of new optical metrology technologies for testing quantum theory in molecules

The hydrogen molecule and its isotopologues serve as a crucial benchmark for precision tests of fundamental physics. Being the simplest neutral molecule, molecular hydrogen is comparatively straightforward for theoretical calculations and possesses long-lived energy states that can be measured with exceptional precision. This combination of theoretical tractability and experimental accessibility makes the hydrogen molecule an ideal system for testing **quantum electrodynamics (QED)** for molecules at unprecedented levels of accuracy, and for revealing tiny discrepancies that could signal **new physics beyond the Standard Model**. At the same time, ultra-precise measurements of hydrogen's spectral lines can potentially refine fundamental physical constants, such as the proton–electron mass ratio, thereby improving the accuracy of the basic parameters underlying many physical laws.

Recent advances in laser spectroscopy and quantum theory have pushed the precision of hydrogen molecule measurements to extraordinary levels, approaching uncertainties of just one part in ten billion. However, reaching beyond this point has proven challenging due to certain experimental obstacles. The major and still unresolved obstacle to improving frequency precision in Doppler-free saturation spectroscopy of the Lamb dip in molecular hydrogen is the unexpected appearance of dispersive line shapes that **contradict all previous theoretical predictions** and are, remarkably, absent in any other known molecular system. Some of the most compelling hypotheses attribute the unexpected line shapes to mechanisms that are inherently linked to the presence of a standing wave in the optical cavity.

To address these challenges, the project aims to develop an advanced optical spectroscopy system tailored to hydrogen molecule spectroscopy. The central feature of this system will be a novel high-finesse optical cavity that enables switching between standing and traveling-wave configurations in molecular saturation spectroscopy. This capability will allow us to test those hypotheses and presents an opportunity to resolve the puzzle of the Lamb dip line shape in the hydrogen molecule — with strong potential to improve the precision of hydrogen molecule line position measurements by **one to two orders of magnitude**. In addition, the apparatus will incorporate the ultra-precise cavity ring-down spectroscopy (CRDS) technique, which offers high sensitivity, resolution, and excellent baseline stability. Finally, to ensure absolute accuracy, all frequency measurements will be referenced to the optical frequency comb and a primary time standard.

With this state-of-the-art instrumentation, the project will measure selected rovibrational transitions in the hydrogen molecule with unprecedented precision. Comparing these measurements with the most precise theoretical calculations will provide a stringent test of QED in a molecular system. Any deviation between the observed and predicted frequencies would signal the presence of new physics beyond the current Standard Model, while close agreement would further validate QED accuracy at this scale and place tighter limits on possible new forces. In either case, the resulting data will sharpen the values of fundamental constants and set a new benchmark for precision spectroscopy, with broad implications for other fields such as precision metrology and astrophysics.