In the quest for a real-life tricorder akin to those in Star Trek, our Project aims to establish new standards in the research on handheld devices for scanning, analyzing, and recording various data from the world that surrounds us. Inspired by the iconic moments in science fiction and motivated by the failures and successes in past attempts, our scientific goal is to harness the power of mode-locked lasers that would be suitable for a universal “probe”: a sniffing nose, a sensitive ear and a watchful eye; that would unlock the key component of an all-purpose "multimeter." Our journey starts with acknowledging the remarkable achievements in femtosecond photochemistry by Professor Ahmed Zewail and the optical frequency combs demonstrated by Professors John Hall and Theodor Hänsch – a trio of Nobel Prize winners from around the break of the XX and XXI century. The common thread in these breakthroughs, enabling various measurements with unprecedented precession, is laser mode-locking, a very special technique exploiting an area of physical sciences known as “nonlinear optics”. This technique enables generation of light pulses so short, that their duration compared to one second is like comparing the duration of one second to the age of the universe. With such short and fast “light bullets” nothing can hide: even the motion of an electron around a nucleus can be detected.

Currently, mode-locking is predominantly achieved in the bulk, using lasers built with crystals like the titanium-doped sapphire. Lasers built with optical fibers also show promise here, but even this technology has reached limitations in miniaturization. Our project boldly explores a new frontier – two-dimensional Boron Nitride (2D BN) crystals – to overcome these challenges. Exactly: two-dimensional – this means co thin, that one of the three dimensions, be it the thickness, for example, is so small, that it can be neglected when compared with the other two dimensions. Because of this special feature, a 2D BN-based “photonic chip” can exceed the existing and mature technologies in the field of ultrafast lasers, because the one “negligible” dimension forces the material to have such properties, which are unachievable with the traditional, “three dimensional” materials. This means working out a new class of practical devices with a potential to access the shorter wavelengths, i.e. colors of laser light, including those colors which already extend beyond our vision’s sensitivity - the ultraviolet; and the UV is essential for applications in many modern methods of measurement for molecular identification (essential when new medicine is discovered), environmental analysis (when the air that we breath or the plants that we feed to our live stock is verified), and in materials science (when our cloths, trains or smartphones are designed and made).

The significance of our project firstly resides in advancing the knowledge and understanding of nonlinear optics in 2D BN, paving the way for the development of integrated mode-locked lasers. By fabricating the 2D BN-based “photonic chips” and exploring their nonlinear properties, we aim to answer fundamental questions related to nonlinear absorption, emission gain bandwidths, and chromatic dispersion shaping. Our focus on the BN's potential for self-mode-locked on-chip short-wavelength lasers is to enable transformative applications in ultrafast and compact sources not easily achievable even at a lab bench by using other experimental techniques or technologies. Secondly, the Project's impact extends beyond scientific curiosity; it addresses the practical challenges of making mode-locked lasers more compact, cost-efficient, and applicable in diverse fields. The real-world impact includes advancements in spectroscopy, sensing and imaging, or more generally: in the democratization of sophisticated photonics tools for non-specialists. Our hypothesis is that 2D BN can serve as an ideal material for mode-locking in integrated ultrafast lasers. Recent achievements in engineering of the luminescent properties in 2D BN heterostructures (that is the “photonic chips”) provide a solid foundation. The proposed research aims to understand the relationship between material properties of the BN and its various modifications and their controllability for nonlinear optics performance.

In essence, our work takes inspiration from science fiction, leverages real-life, foundational achievements in physics, and focuses on harnessing the unique properties of special stacks of very thin, “two-dimensional” crystals to unlock the path towards handheld, integrated lasers that can be used to “sniff”, “hear” or “see” what eludes our natural senses in our surrounding.