Self-assembled ionic liquids are a remarkable class of materials that can spontaneously transform between two distinct liquid states while remaining a single substance. These are not ordinary liquids, but unique ionic compounds where carefully designed molecular architecture enables a rare and fascinating phenomenon called liquid-liquid transition (LLT). Unlike simple phase changes like melting or evaporation, LLT represents a fundamental shift in how the liquid organizes itself at the nanoscale, creating two versions of the same liquid with dramatically different properties. Recently, scientists made the groundbreaking discovery that certain phosphonium-based ionic liquids - salts that remain liquid at unusually low temperatures - exhibit this extraordinary behavior. What makes them truly special is their ability to self-assemble into intricate nanostructures, with charged and non-charged regions organizing themselves like a molecular mosaic. This hidden complexity, invisible to the naked eye, holds tremendous potential for engineering the next generation of smart materials that could revolutionize energy technologies and beyond.

This project aims to crack the code of how and why these liquid-liquid transitions happen. Using high-pressure experiments (up to 2GPa) and ultra-fast cooling techniques, we will study how these ionic liquids rearrange their molecular structures when transitioning between states. A key question is whether this change is purely driven by temperature and pressure or if it can be controlled by how quickly we compress or cool the liquid—like "freezing" it in an intermediate form.

The implications of this work extend far beyond fundamental scientific curiosity. Today’s batteries and energy storage devices rely on materials with fixed properties. If we can design ionic liquids that reversibly switch their conductivity or viscosity, we could create "smart electrolytes" that adapt to different conditions—improving efficiency and safety. Additionally, understanding LLTs could reveal new physics about how disordered materials behave under extreme conditions, which has implications e.g, in pharmaceutical formulations.

The most exciting outcomes we anticipate from this research include establishing the fundamental "design rules" for creating ionic liquids with switchable properties - understanding exactly which molecular features enable these transitions and how to control them. We expect to identify new ways to trigger these transitions using pressure or confinement. Perhaps most importantly, we're developing new experimental methods that will allow scientists to study these phenomena in a wide range of materials, opening up entirely new avenues of research. By combining cutting-edge experiments with custom-designed ionic liquids, this research could open doors to a new generation of adaptive materials where liquids don’t just flow—they transform.