Phase-locked THz waveforms are uniquely suited to control and trace the quantum dynamics of electrons in solid-state systems on subcycle time scales. Here, I discuss distinct non-perturbative THz dynamics observed over many orders of magnitude of the field amplitude: from atomically strong THz fields to quantum vacuum fluctuations.

First, atomically strong multi-THz pulses drive all-coherent charge dynamics including dynamical Bloch oscillation in bulk semiconductors. This subcycle electron motion leads to the generation of high harmonics covering up to 13 optical octaves in the THz-to-UV spectral range. At center frequencies of 1 THz, strong THz transients drive ballistic Dirac currents in the surface bands of a three-dimensional topological insulator, which we observe by angle-resolved photoemission directly in the bandstructure, with subcycle resolution.

In the antiferromagnet TmFeO$_3$, we achieve a comparable level of control for the spin degree of freedom by exploiting a novel electric-dipole mediated mechanism. Here, strong THz pulses drive ballistic spin dynamics across the entire phase space and facilitate minimally dissipative spin control including switching. At field amplitudes of 10 kV/cm, resonant excitation of Landau electrons of two-dimensional electron gases leads to non-perturbative cyclotron dynamics beyond Kohn’s theorem, including up to six-wave mixing signatures.

Finally, even the faint fields of quantum vacuum fluctuations may drive non-perturbative subcycle polarization dynamics. In our ultrastrongly light-matter coupled structures, the vacuum Rabi frequency $\Omega_0$ exceeds the carrier frequency of light, leading to a population of the ground state with 0.37 virtual photon pairs. Subcycle switching of $\Omega_0$ is predicted to release these photons as quantum vacuum radiation.