Computational Study of Strong-Field Ionization in Bicircular Laser Fields

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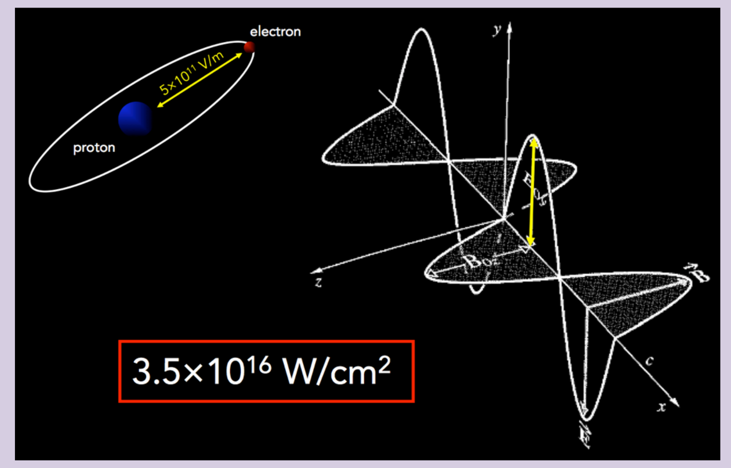
Abstract

Since the discovery of multiphoton, multiply charged ionization 35 years ago, the study of double ionization in intense laser fields has been foundational in the development of strong-field physics. In the rescattering model, the Coulomb potential of the atom is distorted by the laser field, leading to liberation of an electron through tunneling. This electron gains energy from the laser field and is driven back to the ion, where it can help free a second electron via impact ionization. Since this process relies on trajectories that bring the first electron back to the ion, it is most effective with linear polarization, and is reduced significantly with increased ellipticity. But it has been shown that a bicircular laser pulse, generated by combining two counter-rotating circular polarization, can also lead to effective double ionization. We recently investigated the dynamics of these processes with a computational study utilizing a classical ensemble [Physical Review Letters 116, 143005 (2016)]. Here, we present new results generated with a high-performance computational cluster, uncovering novel patterns in recollision timing, identifying classes of complex trajectories that contribute to double ionization, and demonstrating that rescattering can occur even in co-rotating fields.

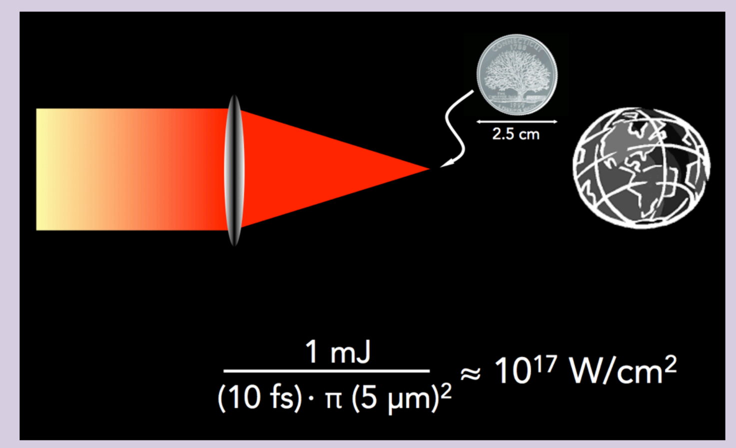
We gratefully acknowledge support from the Office of Research and Sponsored Programs - Summer Support Initiative.

High-Intensity Lasers



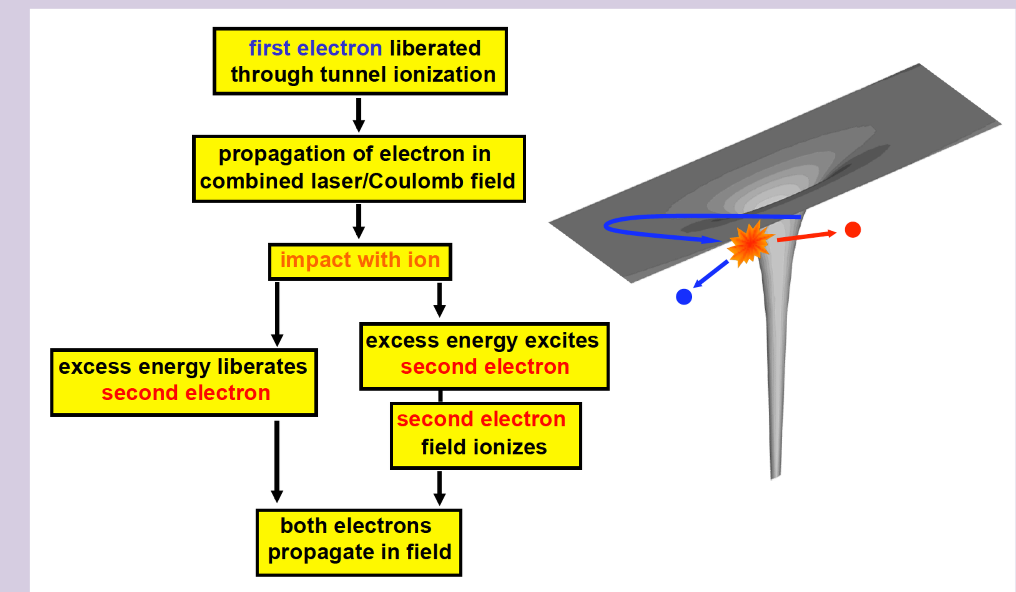
The atomic unit of intensity is determined by setting the amplitude of the electric field in a pulse of light equal to the electric field magnitude that binds the electron to the proton in a hydrogen atom. At these high intensities, atoms can be ionized even for low photon energies, in defiance of Einstein's description of the photoelectric effect.

Such high intensities could in principle be reached by focusing all of the sunlight striking the Earth onto a spot the size of a quarter. Fortunately, such extreme measures are not required, as it is possible to generate laser pulses with modest energies but with very short pulse widths. By focusing to small spot sizes, impressive intensities can be reached in the laboratory.

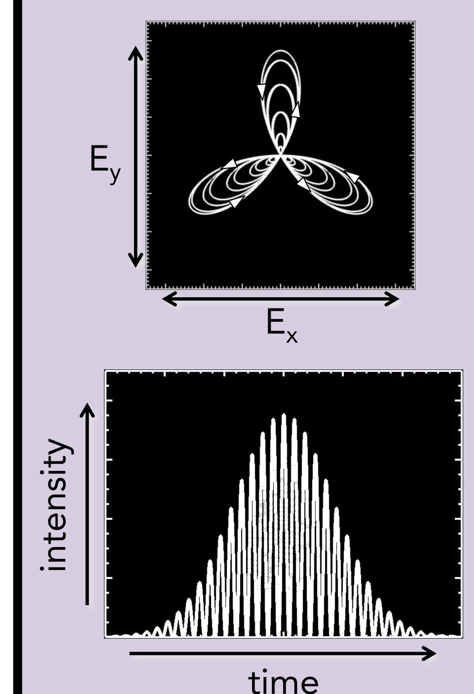


The technique of chirped-pulse amplification was developed by Gérard Mourou and Donna Strickland at the University of Rochester in the 1980s. This scheme is now widely used worldwide to generate intense ultrashort laser pulses, and earned the pair the 2018 Nobel Prize in Physics.

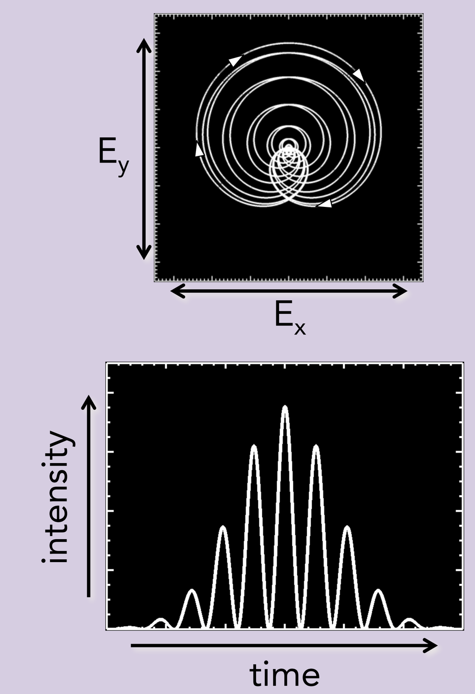
Atoms in Strong Fields



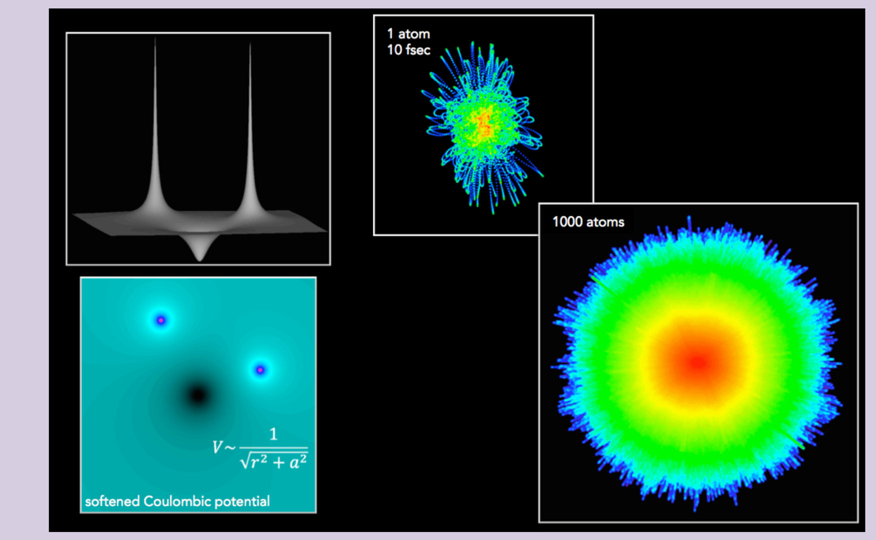
The fundamental physical process in strong-field laser science is the non-sequential double ionization of atoms via a strongly correlated electron-electron mechanism known as "rescattering". This phenomena relies crucially on a laser-driven electron returning to the ion, which is efficient for linear polarization and impossible for circular polarization. But a laser pulse composed of two colors (typically at ω and 2ω) of circularly polarized light can also lead to rescattering. We study this process computationally for counter- and co-rotating fields.



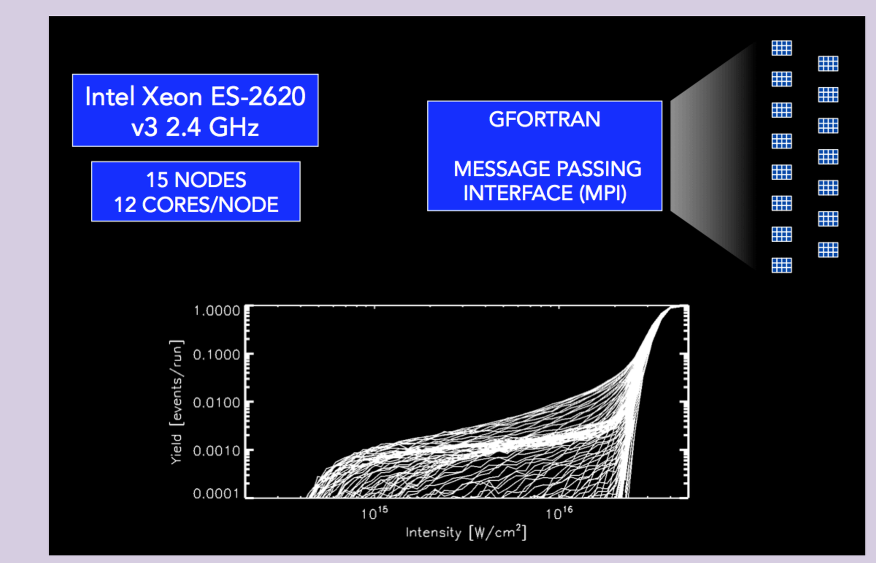
Bicircular 2ω-ω laser pulses trace out unique electric field amplitudes as a function of time. For counter-rotating fields (left), patterns with a three-fold symmetry are observed, while co-rotating fields (right) generate cycloid shapes. Here, the 2ω:ω amplitude ratio is set to 1:1, but by varying this ratio the patterns can be significantly altered. This allows for the ability to dramatically tune the rescattering dynamics by simply changing the relative intensity of the two colors.



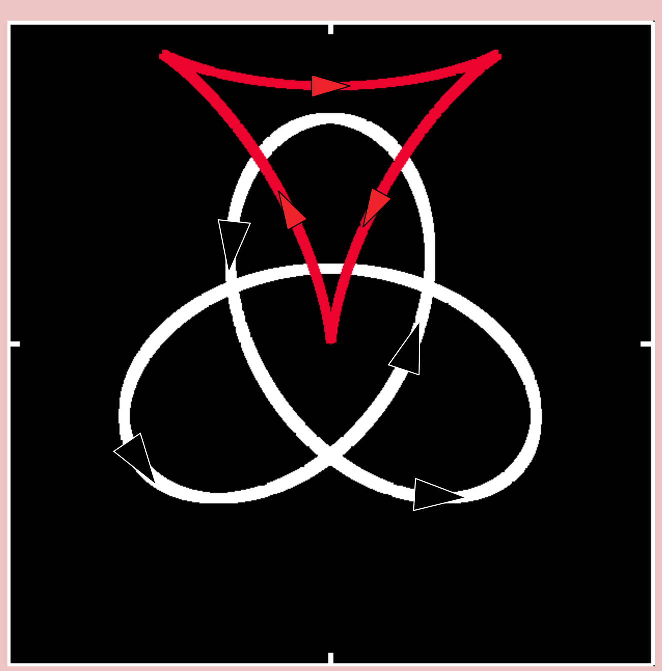
Computational Method



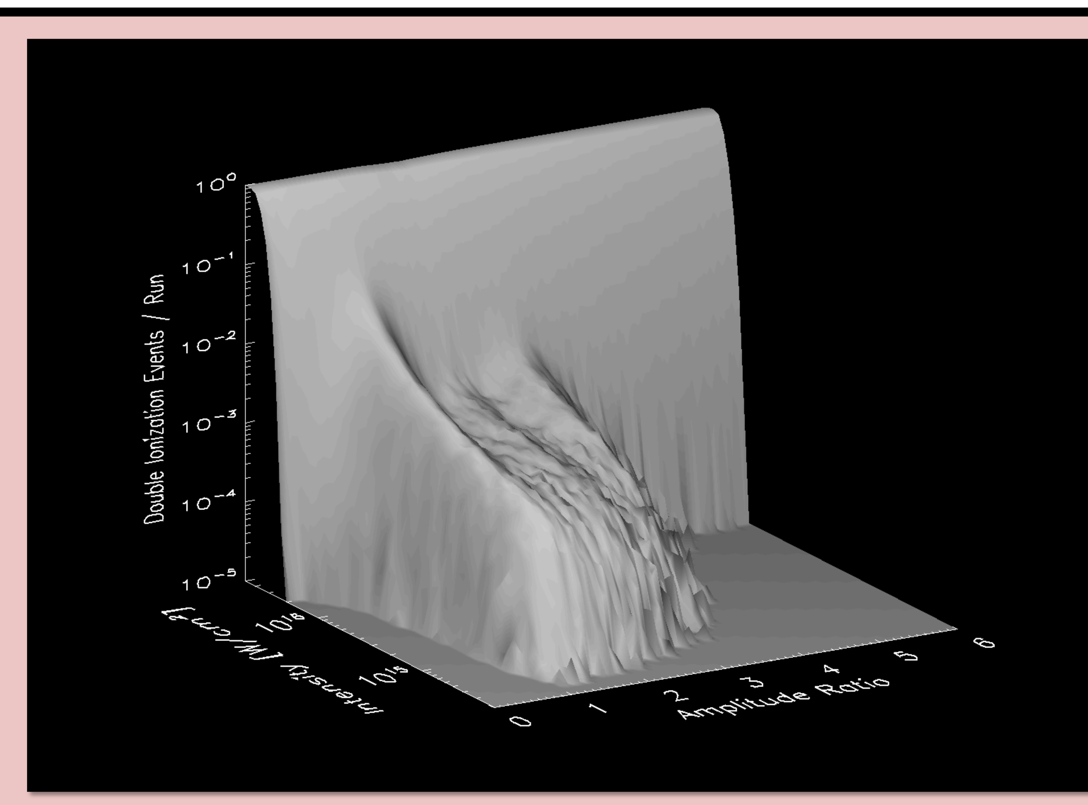
Classical model atoms are used to study the intense laser-atom interaction. By using a "softened" Coulombic potential, stable atoms are generated (above). Their interaction with the laser pulse can be analyzed with a large ensemble, giving insight into the overall behavior, or individually, allowing for the development of an intuitive physical picture of returning electron trajectories. The UNC High Performance Computational Cluster (below) is used to generate massive data sets, allowing for high-resolution analysis and investigation of very low probability events.

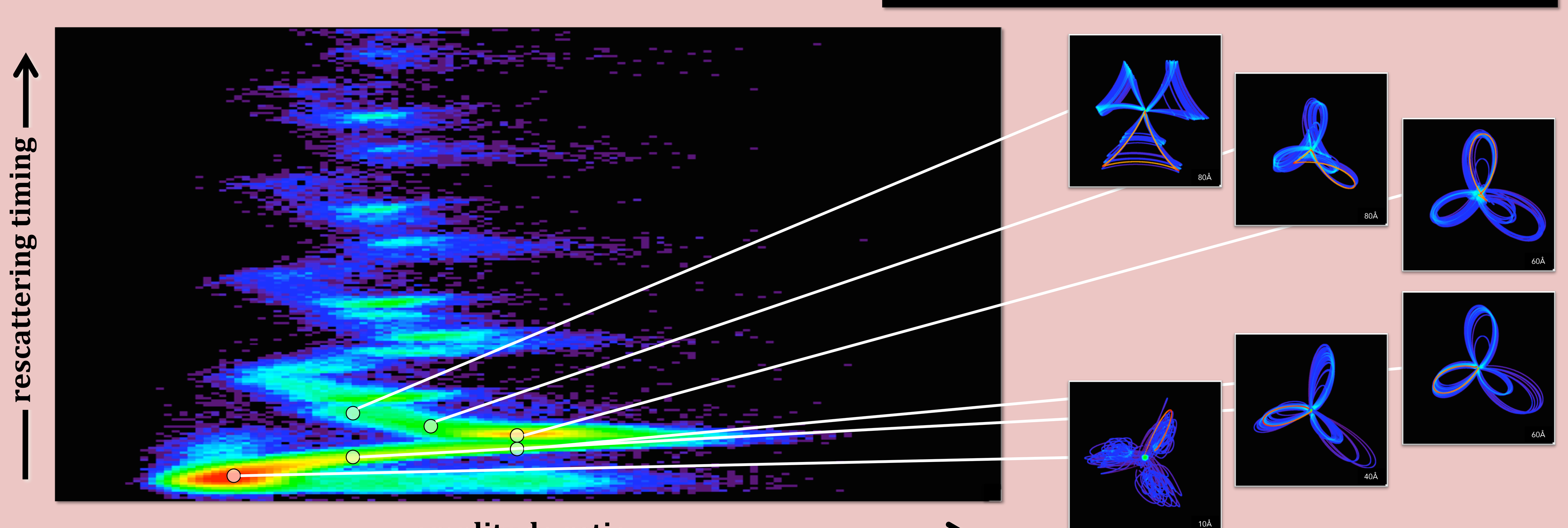


Double Ionization in Counter-Rotating Fields

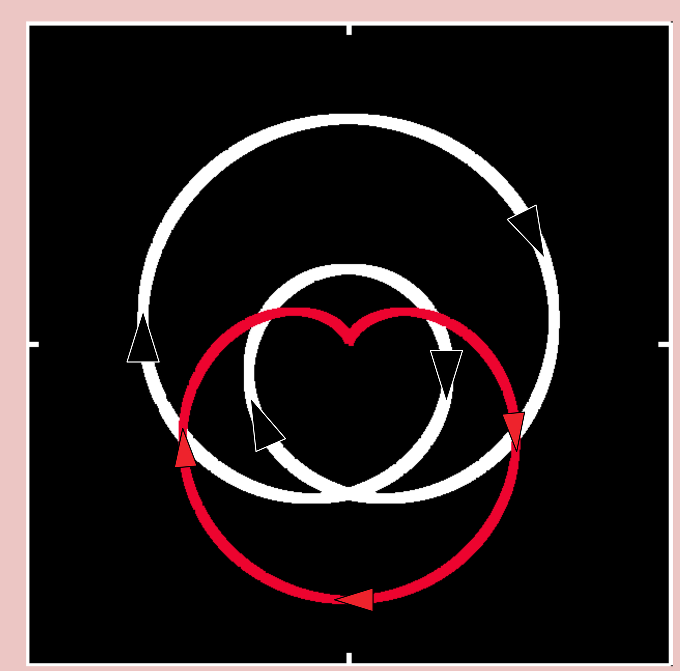


A counter-rotating 2ω:ω = 2:1 bicircular field (left) generates an electric field pattern (white) that can drive an electron in a triangular closed loop trajectory (red). This simple trajectory results from releasing the electron at the peak of the field and ignores the effects of the other electron or the ion. But the full simulation shows how rescattering occurs across a wide range of amplitude ratios, resulting in an impressive double ionization "knee" (right). The timing of the rescattering trajectories that lead to double ionization (below) varies significantly as a function of amplitude ratio, giving rise to looping, triangular, and even fish-shaped trajectories. The images of sample trajectories (below right) each show 100 events, with one event highlighted for each case (the width of each image is indicated).





Double Ionization in Co-Rotating Fields



A co-rotating 2ω:ω = 2:1 bicircular field (left) generates an electric field pattern (white) that can drive an electron in a looping closed loop trajectory (red). But in contrast to the counter-rotating case, this trajectory occurs for release of the electron at a <u>minimum</u> in the intensity. This is much less likely to occur, since the atomic Coulomb potential is barely suppressed at low intensities. Nevertheless, the full simulation shows how rescattering still occurs across a wide range of amplitude ratios, albeit at a much lower rate (right). The timing of the rescattering trajectories that lead to double ionization (below) varies significantly as a function of amplitude ratio, giving rise to a variety of looping trajectories.