Assessing tunneling-multiphoton dichotomy in photoionization:

Keldysh parameter γ versus scaled frequency Ω

Turker Topcu *and* Francis Robicheaux
Department of Physics, Auburn University, Alabama 36849-5311, USA

Motivation and previous work

- Keldysh parameter $\gamma = \omega\sqrt{2I_p}/F$ is commonly used for referring to the dominant ionization regime in atoms: $\gamma<1$ for tunneling and $\gamma>1$ for multiphoton ionization.
  [L. V. Keldysh, Zh. Eksp. Theor. Fiz. 47, 1945 (1964)]
- There are several shortcomings of this approach when laser frequencies are considered outside the usual strong field process driven by 800 nm laser pulses, *e.g.* HHG and ATI.
  [H. R. Reiss, Prog. Quant. Electr. 16, 1 (1992).]
- For a fixed laser frequency, laser intensity can be varied so that **any** value for γ can be attained.
- We map out a landscape in (γ,Ω) space, which shows regions with features commonly attributed to tunneling or multiphoton processes.
- Expressing γ in terms of the scaled parameters $\Omega=\omega n^3$ and F/n^4 gives $\gamma=\Omega/F$, which takes dynamics inside the Coulomb potential into account in addition to the laser induced dynamics.
- We perform two sets of calculations for ionization rates and probabilities of a H atom out of $1s$, $2s$, $8s$ and $16s$ states for a large set of (γ,Ω) pairs.

Numerical Simulations

We solve the time-dependent Schrödinger equation with a linearly polarized laser field on a (ℓ,r)-grid using an implicit split split operator technique.

Ionization Rate Calculations

We express the total wave function as a superposition $\psi(r,l,t)=\psi_0(r,l)+\psi_1(r,l,t)$, and solve

$$\left[\mathrm{i}\frac{\partial}{\partial t}-H(r,l,t)\right]\psi_1(r,l,t)=H_{\mathrm{L}}\psi_0$$

Given that $\psi(t)=\psi_0+\psi_1(t)$, and that ψ_0 is an eigenstate, this equation is exact and allows for atomic processes of all orders.

Ionization Probability Calculations

We solve the full time-dependent Schrödinger equation starting from the initial states $1s$, $4s$, and $8s$ for a laser pulse with width of 160 classical periods.

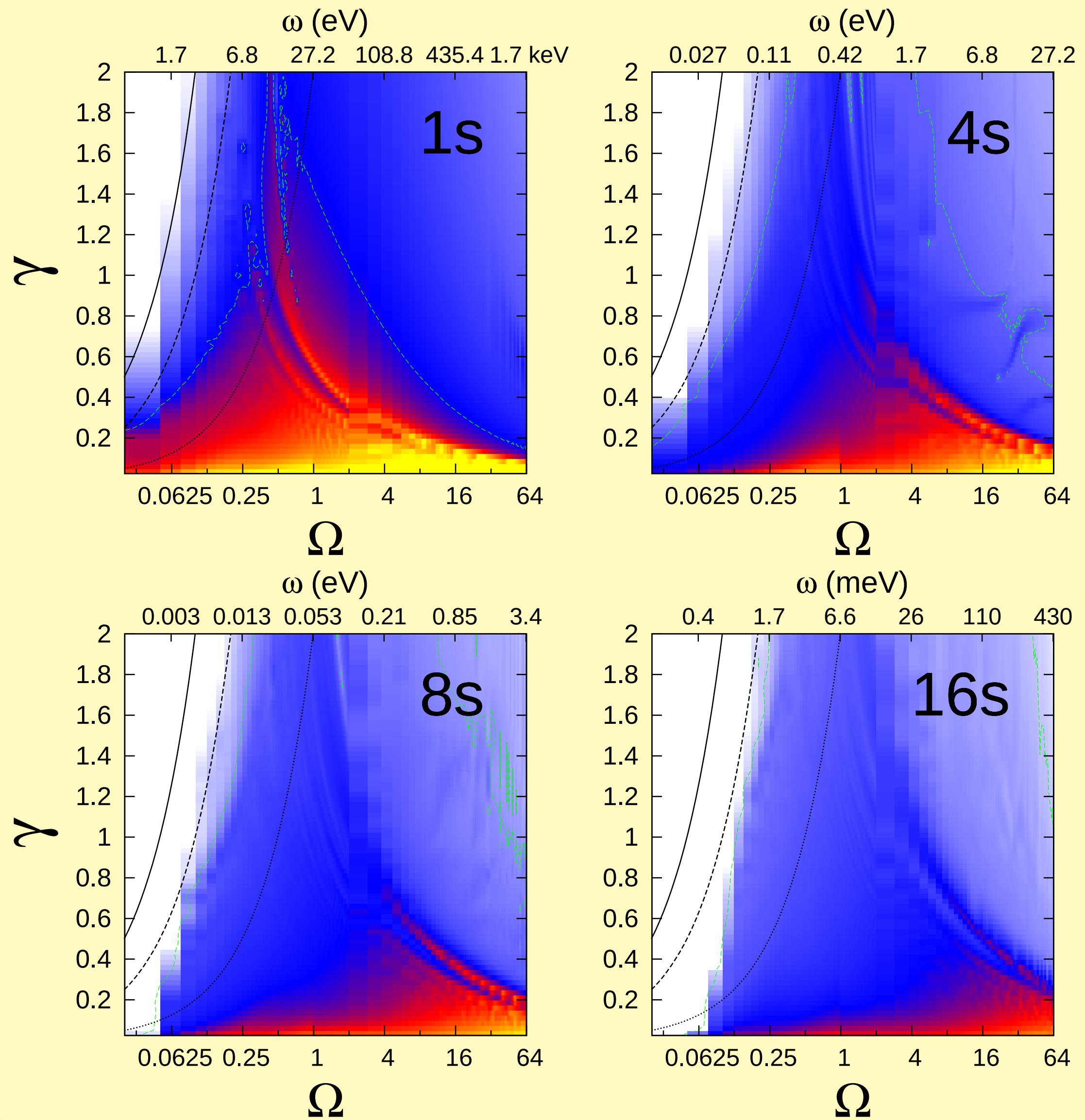
$$\left[\mathrm{i}\frac{\partial}{\partial t}-H(r,l,t)\right]\psi(r,l,t)=0$$

Ionization Rates in (γ,Ω)-space

Ionization rates Γ from initial states $1s$, $4s$, $8s$, and $16s$. The Ω and Γ axes are in $\log_2$ and $\log_{10}$ scale. The **ridge** structures correspond to the N-photon ionization thresholds at

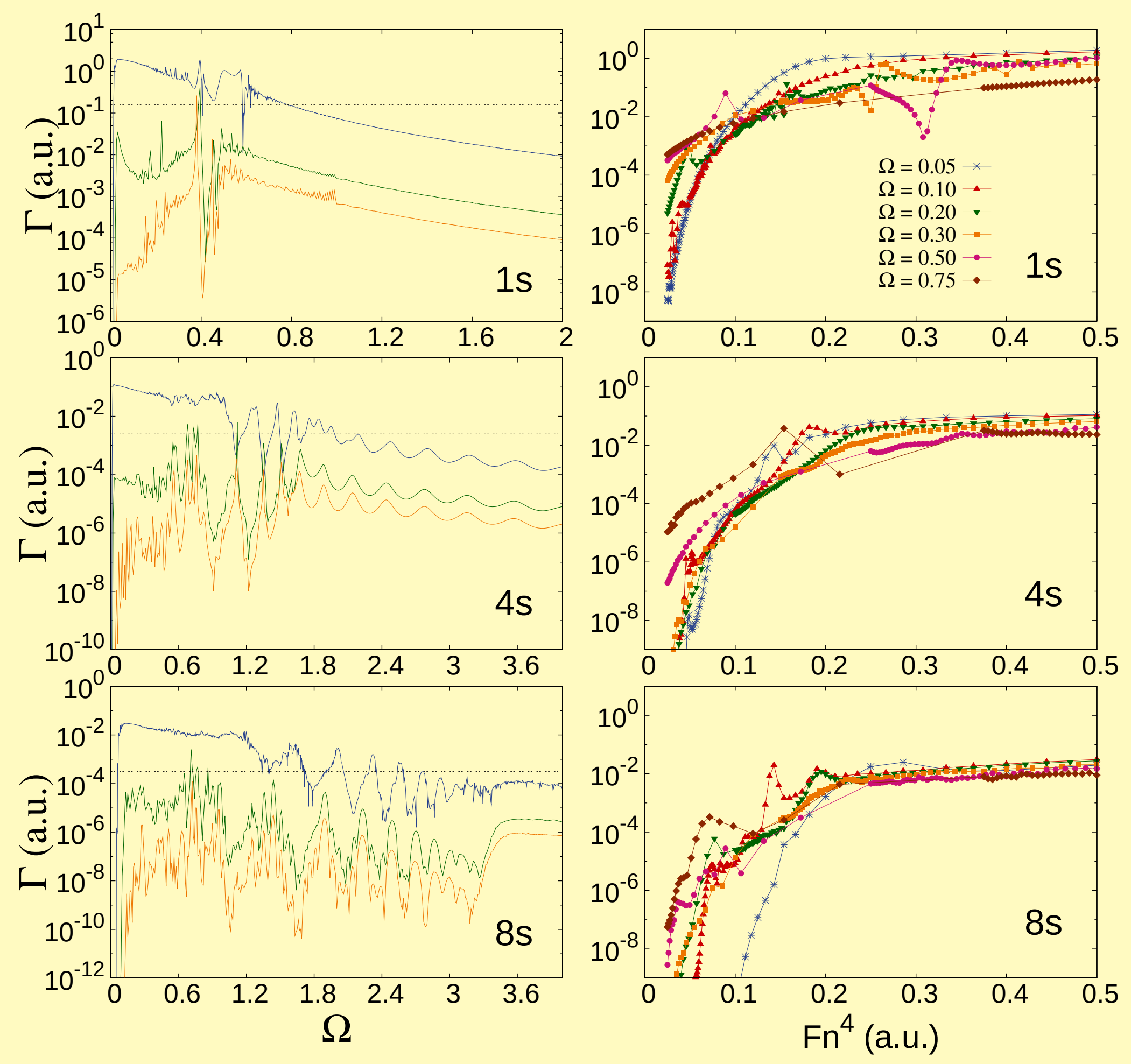
$$\Omega_N=\omega_N/\omega_K=n/(2N)$$

Ionization is suppressed beyond the $\Omega>n/2$ limit.



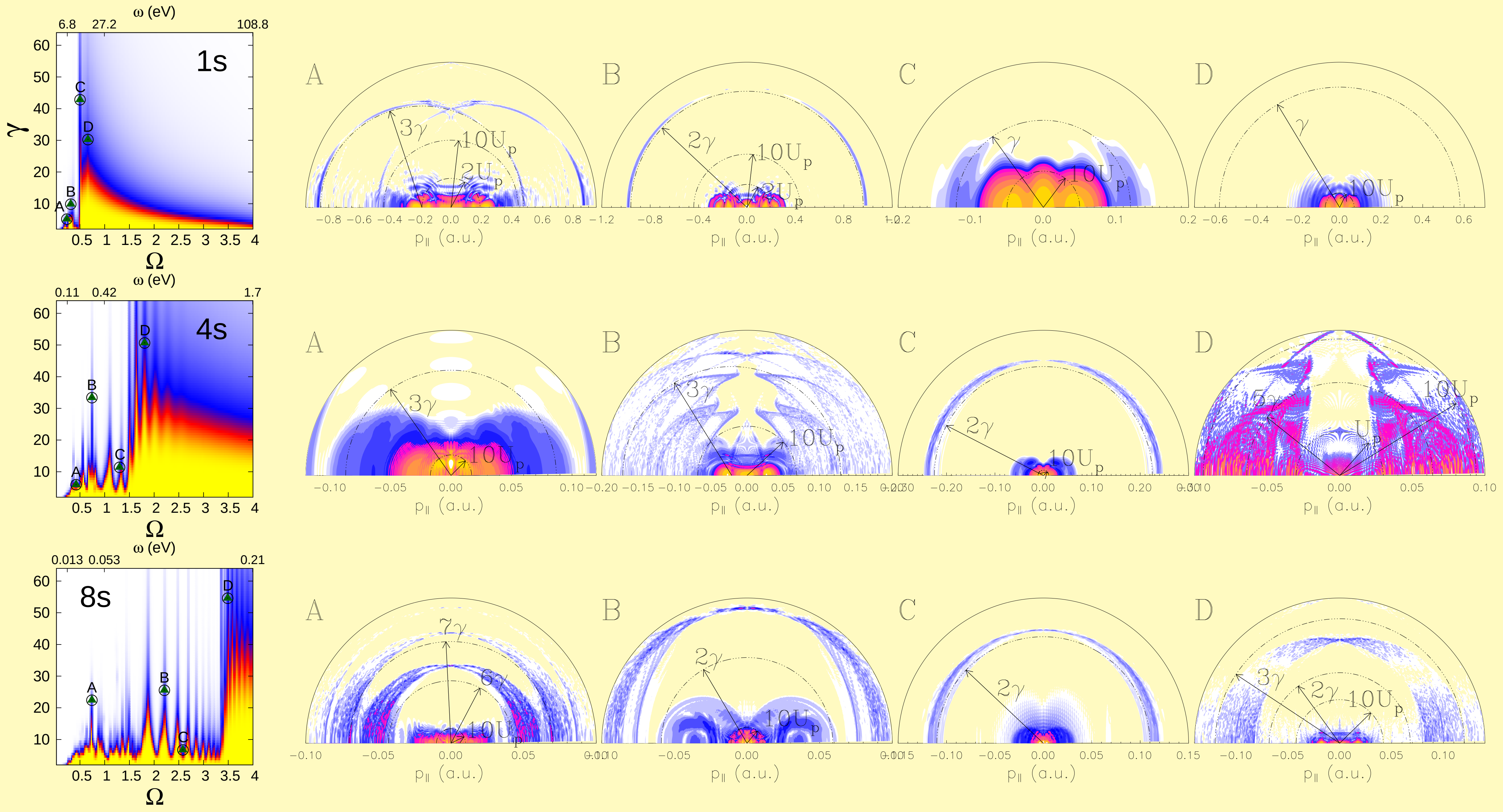
Constant F and Ω slices

Slices along constant F and Ω lines in the (γ,Ω) landscape yield the rates as function of Ω (spectroscopic viewpoint) and F (strong field viewpoint).



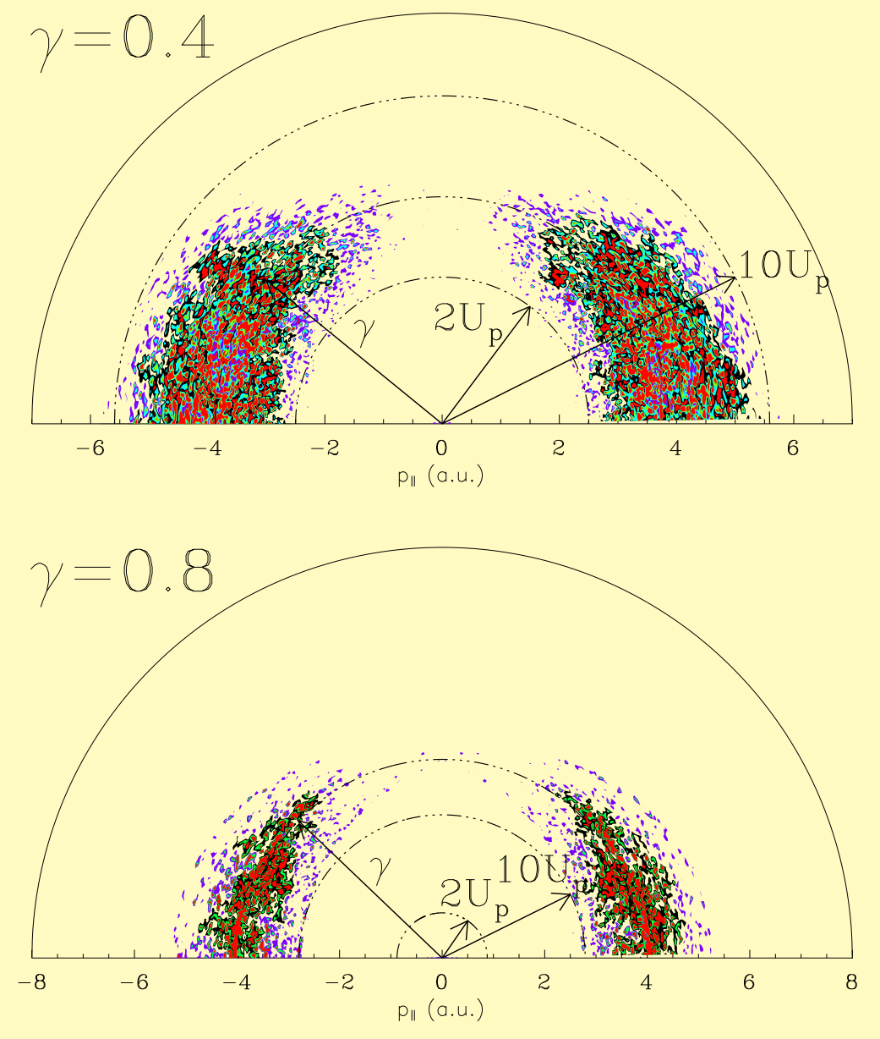
Ionization Probability and Momentum Distributions

(Left column) Ionization probabilities out of $1s$. $4s$, and $8s$ states for large $\gamma\gg1$ and Ω up to 4 using a laser pulse with a fixed width of 160τ_{Ryd}. $\gamma\gg1$ implies tunneling is predominant in all three maps. The multiphoton peaks and suppression of ionization are clearly visible in the $\Omega<n/2$ and $\Omega>n/2$ regions. (Right columns) Momentum maps at select few points. Momenta corresponding to lowest order (direct) multiphoton ionization, the $2U_p$ and $10U_p$ limits are indicated by dashed semicircles. The plots are in $\log_2$ (for $1s$) and $\log_4$ scales (for $4s$ and $8s$). Multiphoton rings and tunneling (small p) regions are visible along with some well known structures, like back rescattering rings.



The common feature in all of the momentum maps is that they are dominated by the low energy electrons - a distinct sign of tunneling. Despite the high values of the Keldysh parameter, tunneling and multiphoton processes coexist in this regime.

Small γ and large Ω



Momentum distributions for $\Omega=8$. Although Keldysh theory predicts tunneling to dominate the ionization dynamics in these cases ($\gamma<1$), momentum distribution is concentrated on the circular ridge with the radius suggesting single-photon ionization. The ridge is sharp for the higher γ (lower intensity), and dispersed for the lower γ (higher intensity).

No electrons inside the $10U_p$ limit for $\gamma=0.8$ meaning no ionized electrons are due to tunneling. Also no electrons for $E<2U_p$ for $\gamma=0.4$.

Acknowledgements

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