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ATTOSECOND PHYSICS

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UNIT XIX LASER ASSISTED PHOTOIONIZATION EMISSION

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1st Semester 2024, Buenos Aires, Argentina

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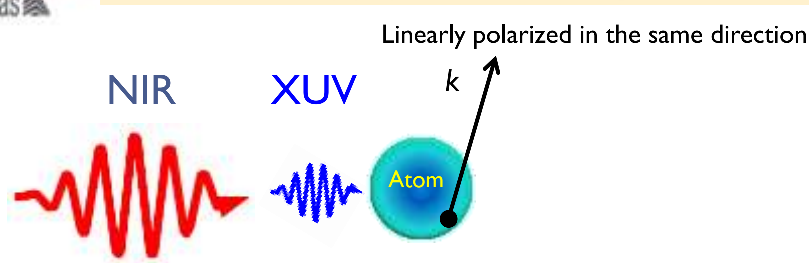

SEMICLASSICAL MODEL

$$T_{\mathrm{if}} = -\mathrm{i} \int_{-\infty}^{+\infty} \mathrm{d}t \, \langle \chi_f^-(\mathbf{r}, t) | H_{\mathrm{int}}(\mathbf{r}, t) | \phi_i(\mathbf{r}, t) \rangle$$

$$\mathbf{F}(t) = \mathbf{F}_X(t) + \mathbf{F}_L(t)$$

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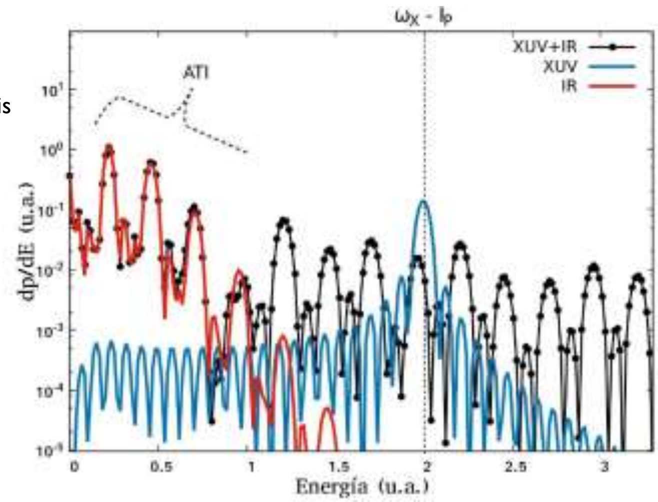
NIR ionization yields photoelectrons near threshold, whereas XUV ionization is about $E = n\omega_X - I_P$. Thus, we can separate XUV and NIR ionization in the energy domain easily. Therefore we exclude NIR ionization.

Gramajo's thesis



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$$\mathbf{A}(t) = -\int_0^t dt'[\mathbf{F}_X(t') + \mathbf{F}_L(t')]$$

$$\mathbf{A}(t) = \mathbf{A}_L(t) + \underbrace{\mathbf{A}_X(t)}_{\ll 1} \simeq \mathbf{A}_L(t)$$

$$\mathbf{F}_X(t) = F_{X0}(t)\cos(\omega_X t)\boldsymbol{\epsilon}_X$$

$$\cos(\omega_X t) = [\exp(i\omega_X t) + \exp(-i\omega_X t)]/2$$

$$S(t) = -\int_t^\infty dt' \left[\frac{(\mathbf{k} + \mathbf{A}(t'))^2}{2} + I_p - \omega_X\right]$$

$$T_{if}^{SFA-} \simeq -\frac{i}{2}\int_{-\infty}^{+\infty} dt\ d_X(\mathbf{k} + \mathbf{A}_L(t))\,F_{X0}(t)\,\exp[iS(t)]$$

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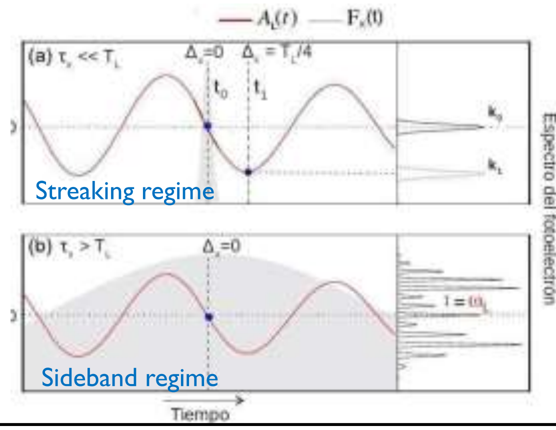
We solve using the Saddle point approximation: $dS(t_s)/dt = 0$

$$\frac{[\mathbf{k} + \mathbf{A}_L(t_s)]^2}{2} = \omega_X - I_P$$

The emission velocity to the continuum is different from zero.



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INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. 38 (2005) S727–S740 doi:10.1088/0953-4075/38/9/019

Attosecond physics: facing the wave–particle duality

Markus Drescher[1,2] and Ferenc Krausz

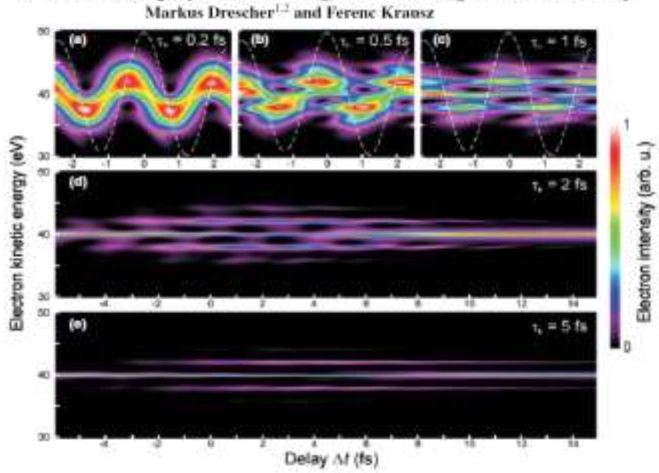

Figure 11. Simulation of time-resolved electron spectra for hypothetical Auger decay at various time constants for the atomic relaxation. An initial kinetic energy centred around 40 eV is assumed. The figure visualizes the gradual transition from a particle-like character of the electrons for very short electron wave packets, revealed by an oscillatory dependence of the spectra on the temporal delay, to a clear signature of wave-like behaviour in the form of spectral sidebands.

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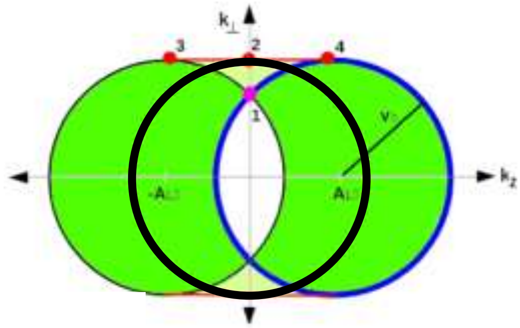
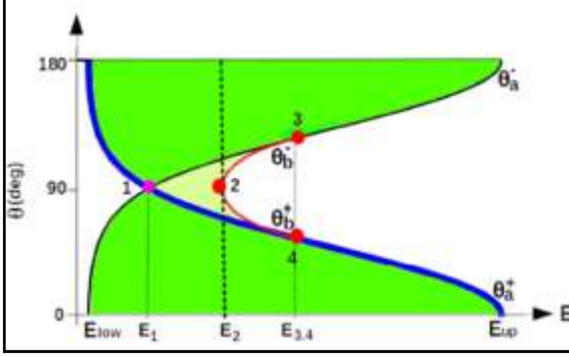
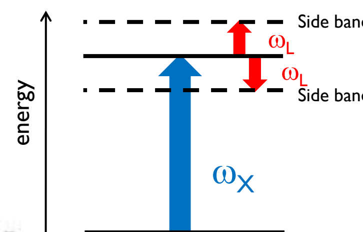
classically forbidden

two ionization times

four ionization times







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Exercise 16: Considering the relation between the measured angle θ and the ejection angle without IR, θ_i: $\tan\theta = \dfrac{v(t)\sin\theta_i}{v(t)\cos\theta_i + A(t)}$

prove that:

$$v(t)\cos\theta_i = -A(t)\sin^2\theta \pm v(t)\cos\theta$$

Saddle point approximation:

$$T_{if} = \sum_{t_s} \frac{\sqrt{2\pi}\, F_{X0}(t_s)\, d_z(\mathbf{k}+\mathbf{A}_L(t_s))}{|\ddot{S}(t_s)|^{1/2}} \exp\left[iS(t_s) + i\frac{\pi}{4}\,\mathrm{sgn}[\ddot{S}(t_s)] \right]$$

$$\left.\frac{dS(t)}{dt}\right|_{t=t_s} = 0 \quad \Rightarrow \quad \frac{[k_z + A(t)]^2}{2} + \frac{k_\perp^2}{2} = \omega_X - I_p = \frac{v_0^2}{2}$$

$$\ddot{S}(t_s) = \frac{d^2S(t)}{dt^2}\Big|_{t_s} = -[\mathbf{k} + \mathbf{A}_L(t_s)] \cdot \mathbf{F}_L(t_s)$$

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$$\frac{dP}{d\vec{k}} = \left|T_{if}\right|^2 = 4\Gamma(k_\perp) F(\vec{k}) B(k)$$

Diffraction grating in the time domain

intercycle: $B(k)$ $\varepsilon_n = \hbar\,\omega_X + n\hbar\,\omega_L - I_p - U_p$ position of sidebands

intracycle: $F(\vec{k}) = \cos^2\left(\frac{\Delta S}{2}\right)$ along the forward direction

A. Gramajo *et al*, J. Physics B **51**, 055603 (2018).

ΔS : accumulated action between $t_r^{(1)}$ and $t_r^{(2)}$

$$\Delta S = \left(\frac{k_z^2}{2} + I_p + U_p - \omega_X\right)\frac{1}{\omega_L}\left\{\pi - 2\sin^{-1}\left[\frac{\omega_L}{F_{L0}}\left|k_z - v_0\right|\right]\right\} - \mathrm{sgn}(k_z - v_0)\frac{F_{L0}}{2\omega_L^2}(3k_z + v_0)\sqrt{1 - \frac{\omega_L^2}{F_{L0}^2}(k_z - v_0)^2},$$

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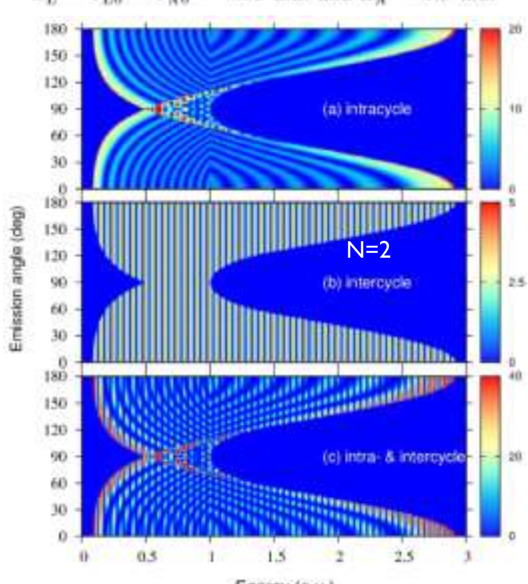
Hydrogen atom

$\omega_L = F_{L0} = F_{X0} = 0.05$ a.u. and $\omega_X = 1.5$ a.u.



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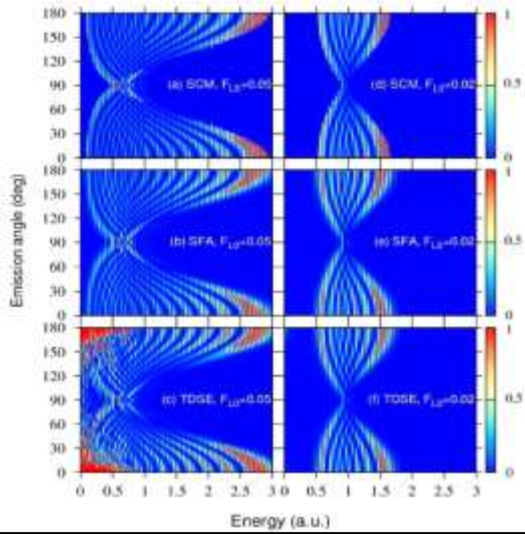
Comparisson of semiclassical model with quantum results

Hydrogen atom, $\omega_X = 1.5, \omega_L = 0.057, N = 2$



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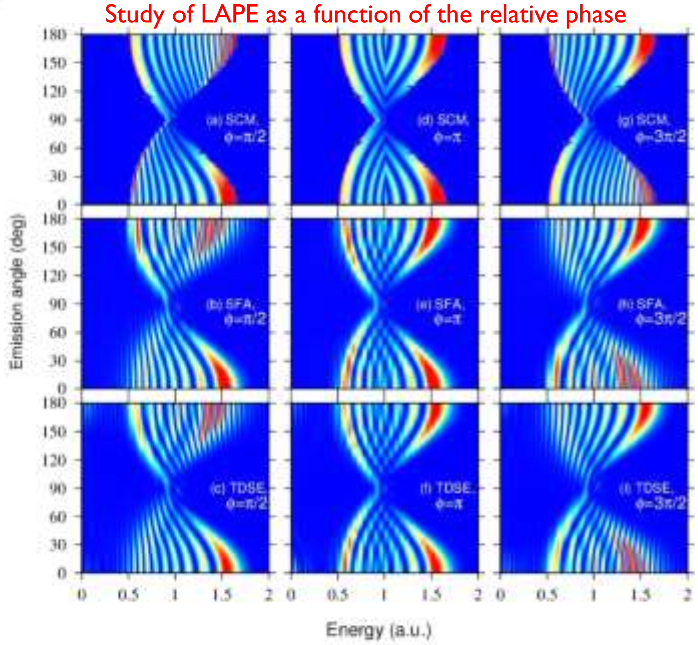
Study of LAPE as a function of the relative phase



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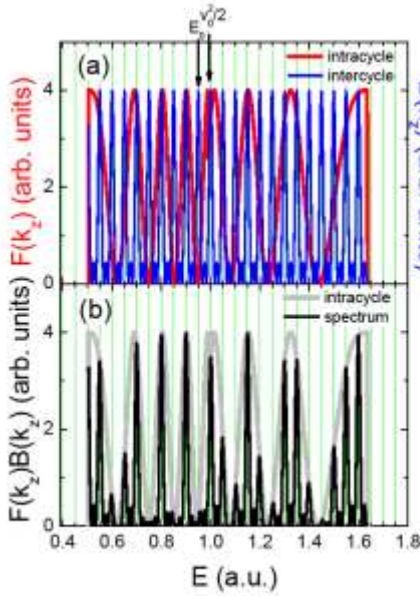
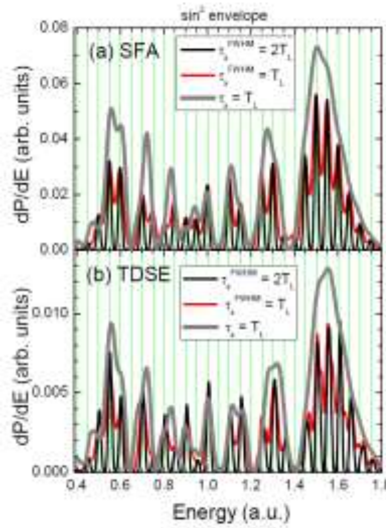
Emission along the polarization axis



Ionization of hydrogen

$F_{X0} = 0.01; \omega_X = 1.5; F_{L0} = 0.02; \omega_L = 0.05$



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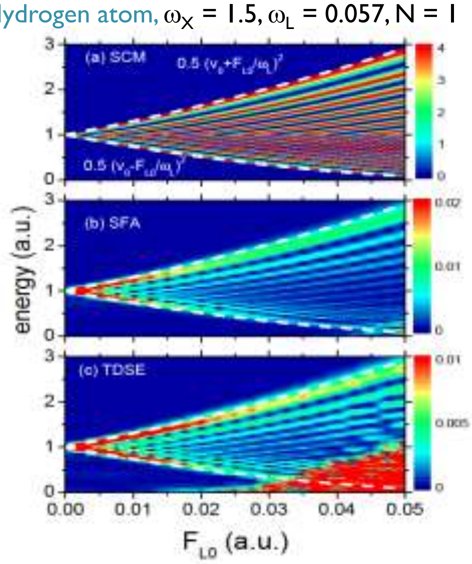
Intracycle pattern

Energy distribution vs. laser intensity

Hydrogen atom, ω_X = 1.5, ω_L = 0.057, N = 1



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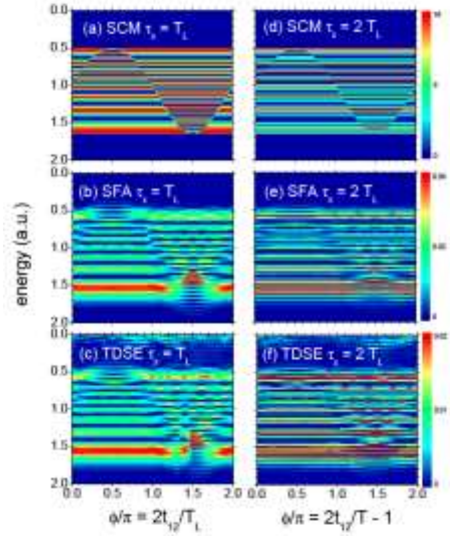
Energy distribution vs. delay time



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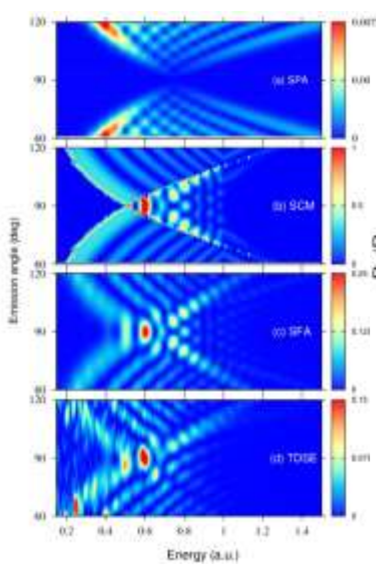
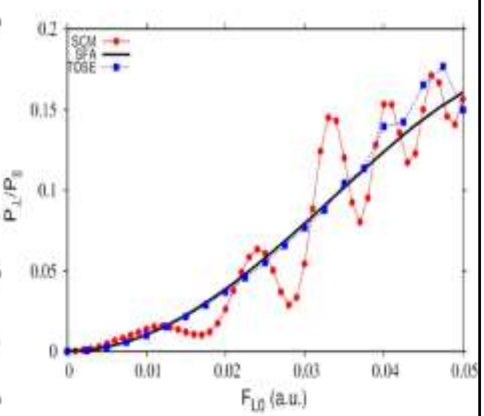
Hydrogen atom, $\omega_X = 1.5$, $\omega_L = 0.057$, $N = 1$





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Perpendicular emission

$$|T_{if}^{-}|^2 = \underbrace{4\Gamma(k_\perp)\frac{4}{\sqrt{1-(\beta/A_{L0})^2}}\cos^2\left(\frac{\Delta S}{2}+\frac{\pi}{4}\right)\sin^2\left(\frac{\tilde{S}}{4}\right)}_{F(k_\perp)}\underbrace{\left[\frac{\sin(N\tilde{S}/2)}{\sin(\tilde{S}/2)}\right]^2}_{B(k_\perp)}$$

$$|T_{if}^{-}|^2 = 4\Gamma'(k_\perp)\underbrace{\cos^2\left(\frac{\Delta S}{2}+\frac{\pi}{4}\right)}_{G(k_\perp)}\underbrace{\left[\frac{\sin(N\tilde{S}/2)}{\cos(\tilde{S}/4)}\right]^2}_{H(k_\perp)}$$

$$\frac{\sin(N\tilde{S}/2)}{\cos(\tilde{S}/4)} \xrightarrow{N\to\infty} \sum_{l}\delta(\tilde{S}/4+\pi/2-\ell\pi)$$

$$E_\ell = \omega_X + (2\ell+1)\omega_L - I_P - U_P$$

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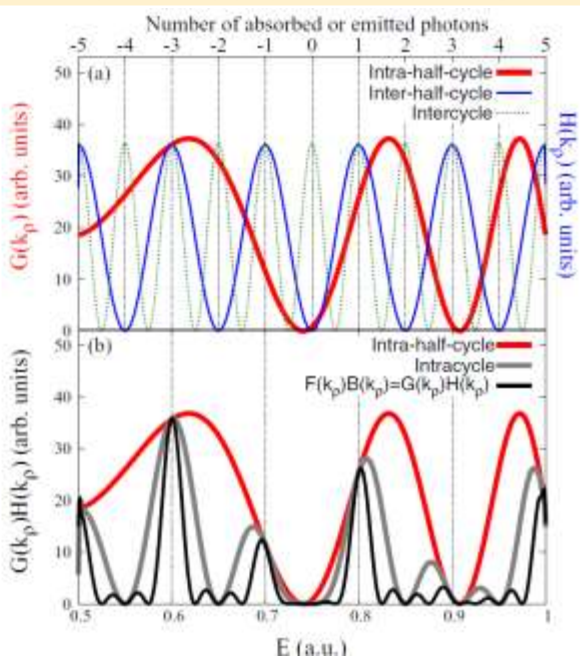

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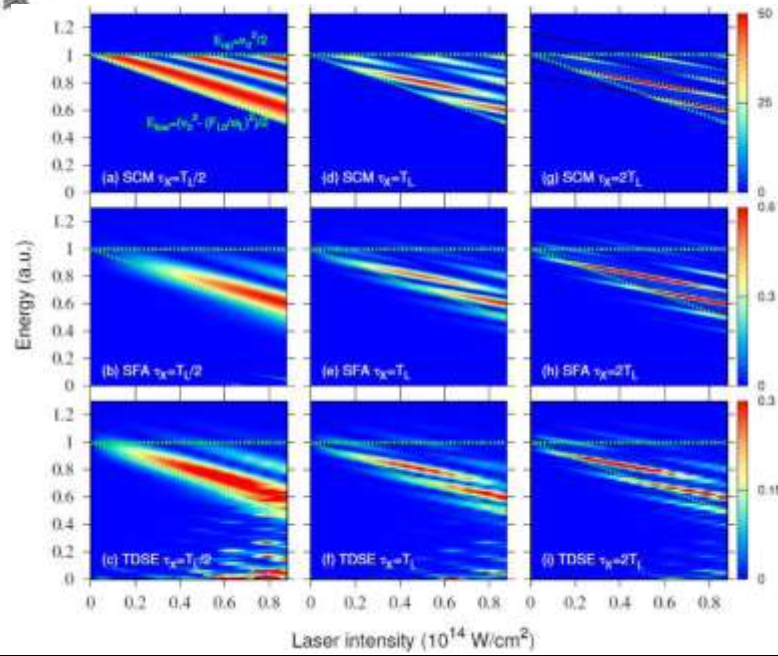

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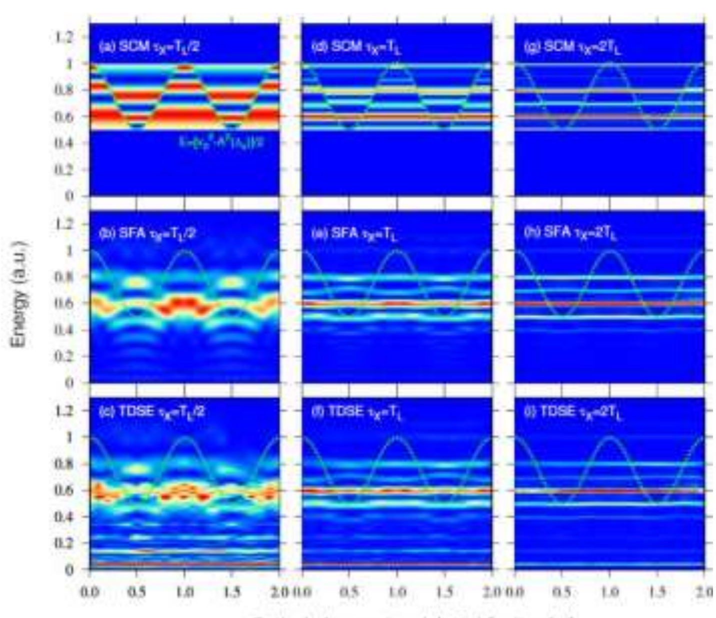

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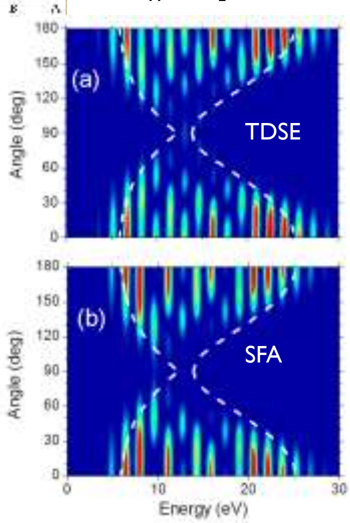
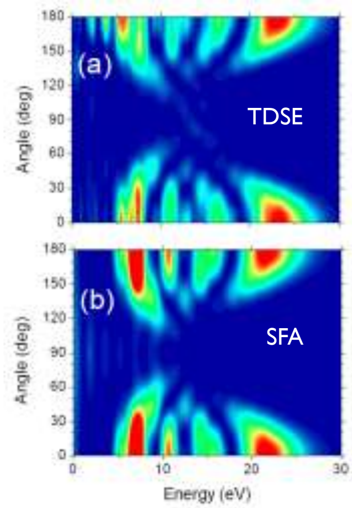
Laser assisted XUV ionization of Ar

NIR 800 nm, I_L = 14 TW/cm^2 and its 19th harmonic

$\tau_X = 5\,T_L$ $\tau_X = T_L$





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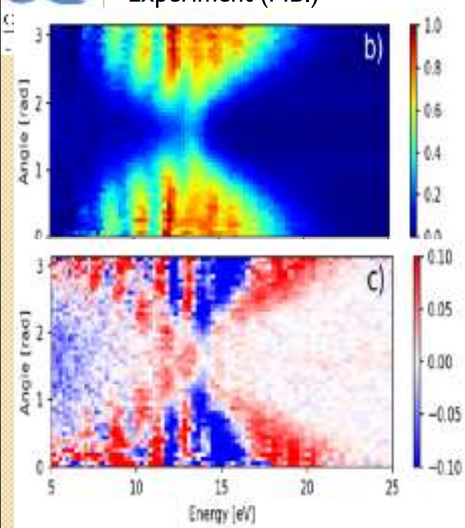
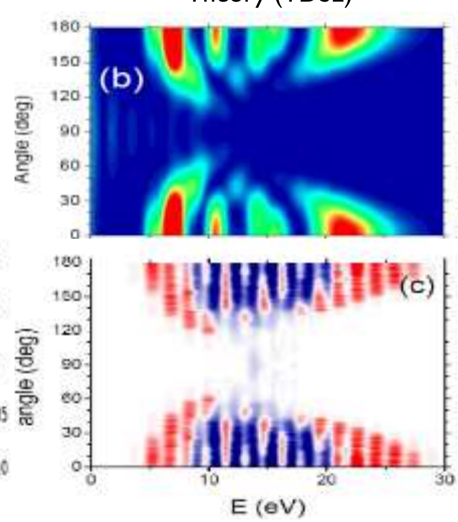
Average over the focal volume J. Hummert *et al*, Jour. Phys. B **53**, 154003 (2020)

Experiment (MBI) Theory (TDSE)





NIR 800 nm, I_L = 14 TW/cm^2 and its 19th harmonic