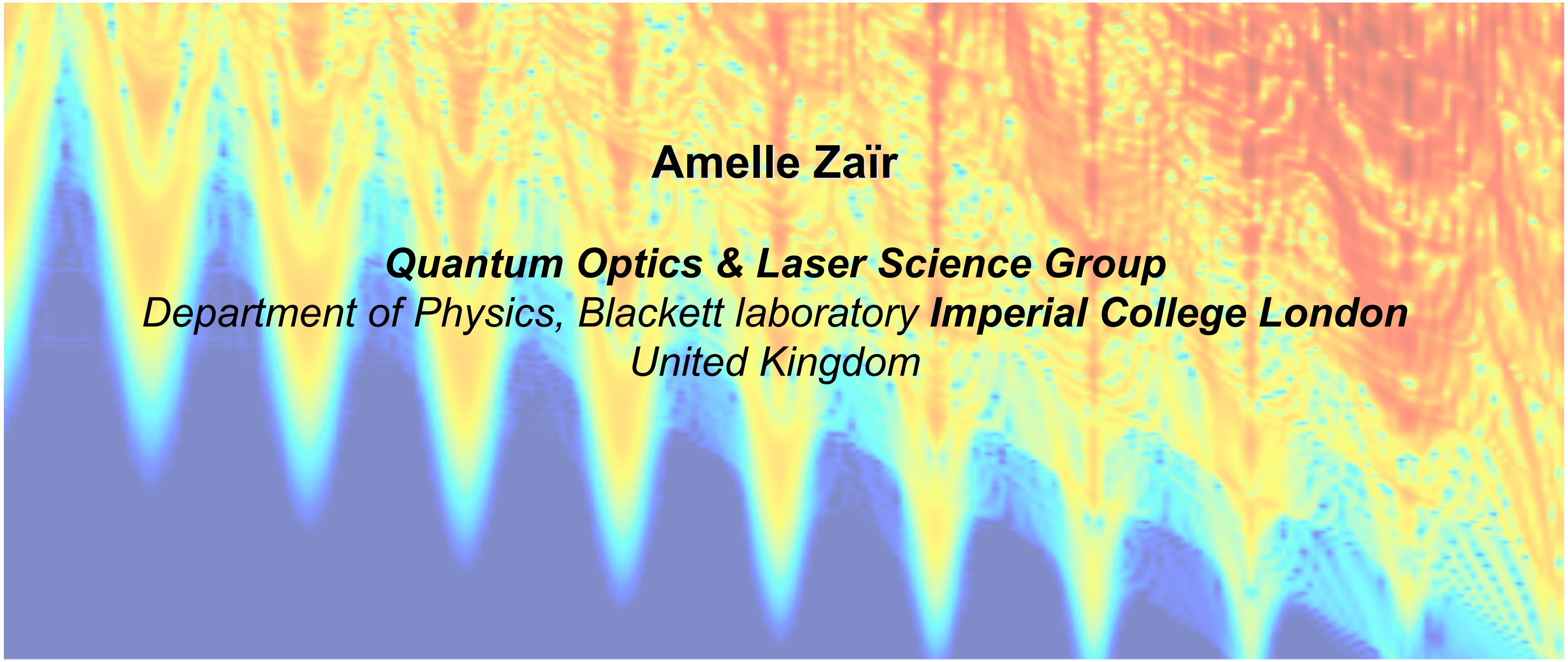
Quantum path interferences in atomic High order harmonic generation



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KITP-Santa Barbara May 2009

HHG XUV source

Spectral range	1-100's eV => keV	HHG at µm	OPCPA Fiber laser OPA
Efficiency	10^{-6} => 10^{-4}	Long focal Phase matching quasi-phase matching	Optic design cells target contra-propagation

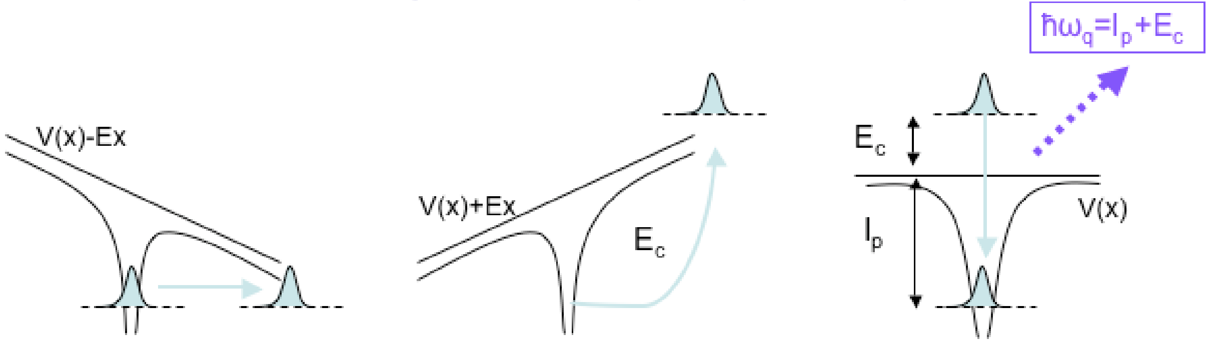
Spatial and temporal coherences/ small divergence mrad

Envelope duration	fs	
Pulses	as	train or isolated
Control	nm/fs-as	quantum path (QPI)/HHG at µm
Characterisation	fs-as	FROG-CRAB RABBITT XUV-SPIDER
	Spatial and temporal coherences small divergence mrad phase front	XUV-SEASPIDER

Outline

- Classical and quantum approach for HHG description
- Control: Quantum-paths interference QPI
- Experimental set-up
- Analysis through SFA model
- What ‘s next: QPI molecules

HHG in atoms

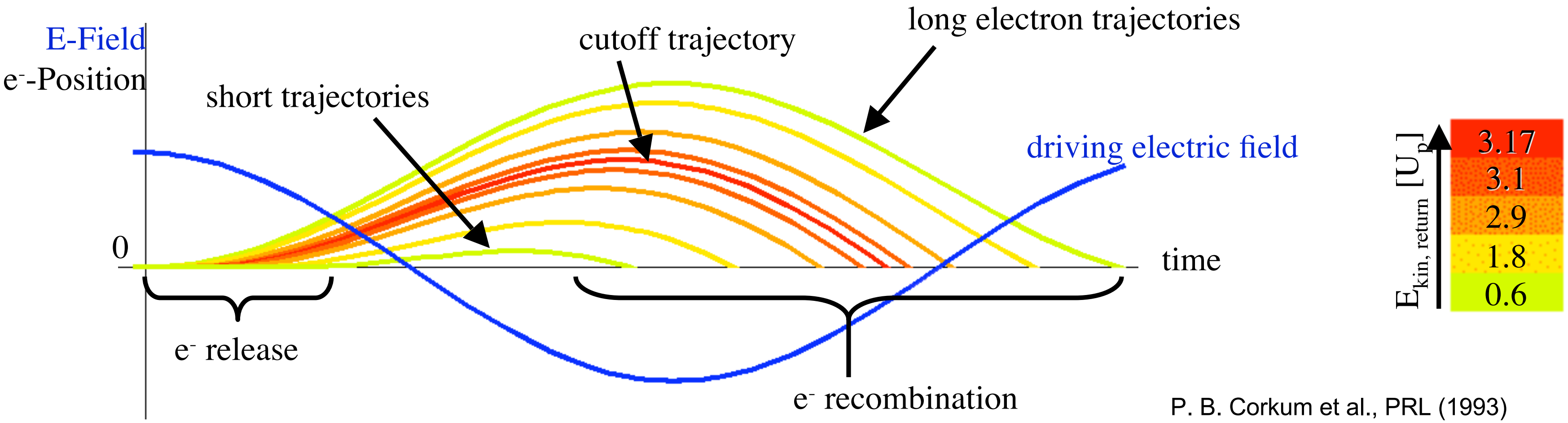


Atomic potential I_p 1: tunnel ionisation 2: propagation 3: radiative recombination

$$\hbar\nu_q = I_p + E_c \le I_p + 3.17U_p$$

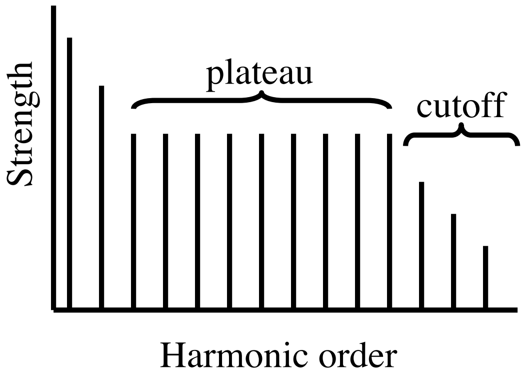
Electronic trajectories

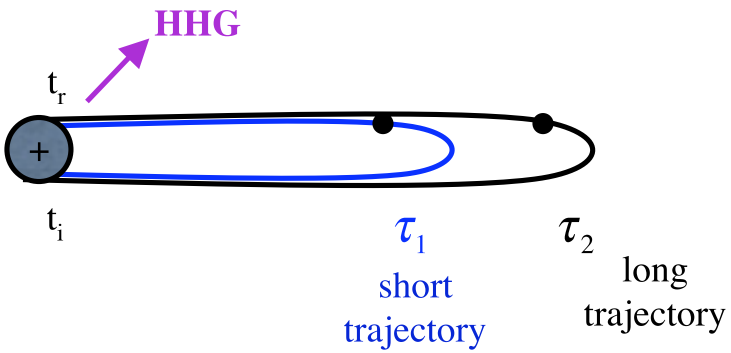
→ Several trajectories for the same kenetic energy



P. B. Corkum et al., PRL (1993)

Quantum paths





$$x_q(t) = \overset{\text{short}}{\left|x_q^{(1)}\right| e^{i\Phi_q^{(1)}}} + \overset{\text{long}}{\left|x_q^{(2)}\right| e^{i\Phi_q^{(2)}}} + \underset{\text{Weak contribution}}{\ldots}$$

Harmonic phase

$$\phi_q^{(i)}(t) \approx -U_p \tau_q^{(i)} \approx -\alpha_q^{(i)} I_{Laser}(t)$$

Phase dependence on the laser Intensity

Harmonic chirp

$$\Delta\omega_q^{(i)}(t) = -\frac{\partial \phi_q^{(i)}(t)}{\partial t} \approx \alpha_q^{(i)} \frac{\partial I(t)}{\partial t}$$

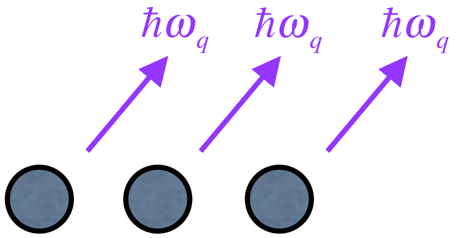
Spectral bandwidth dependence on the intensity gradient

M. Lewenstein et al., PRA (1994)

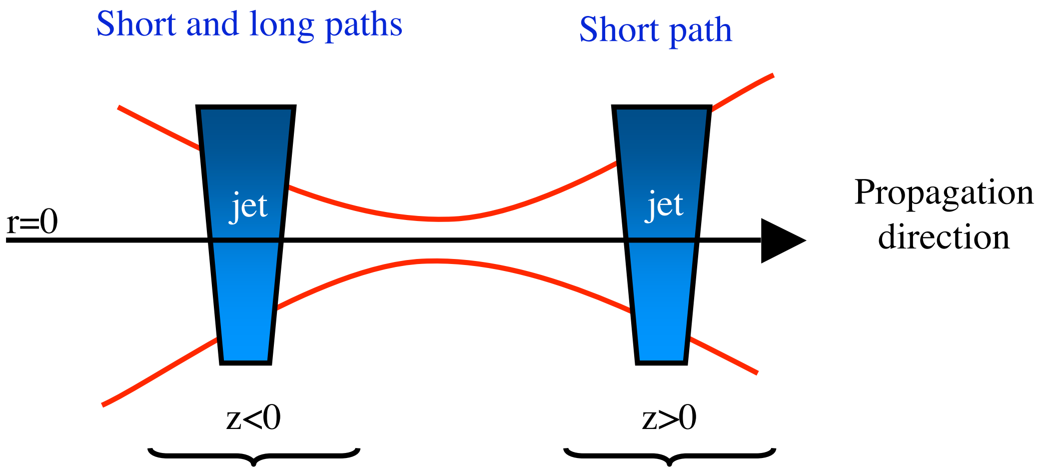
Macroscopic response

Phase matching

$$\vec{k}_q = q\vec{k}_L(r,z) + \vec{\nabla}\phi_q^{(i)}(r,z,t)$$



Macroscopic
HHG emission

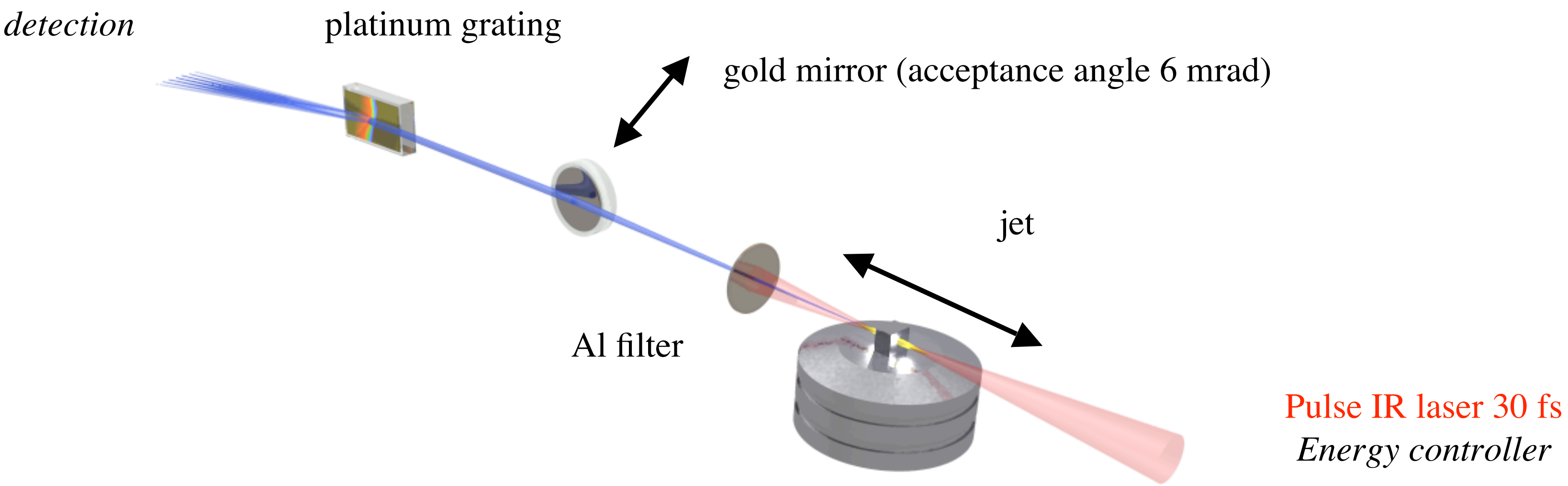


Jet position: Control on quantum-paths and phase matching

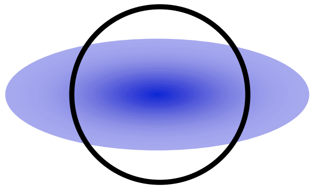
Different divergence short/long
→ Spatial selection: Control on path contribution to the detection

P. Salières et al., Science (2001)

Experimental set-up

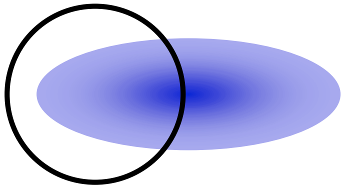


On-axis spatial selection
Weak divergence



Detection of the short path contribution

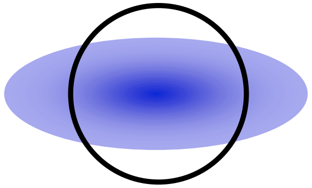
<u>Off-axis</u> spatial selection
All divergence



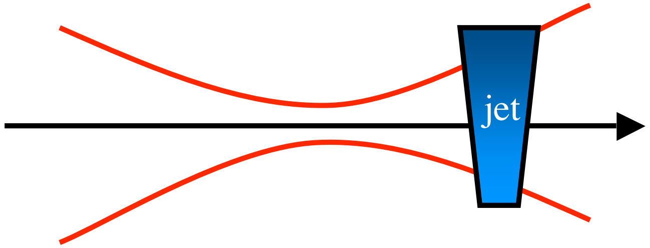
Detection of both path contributions
Position of the filter= control on the contrast

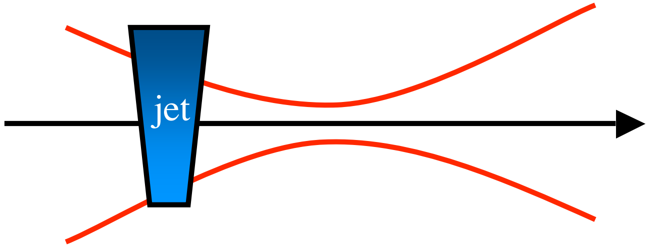
Intensity dependence

ON-AXIS

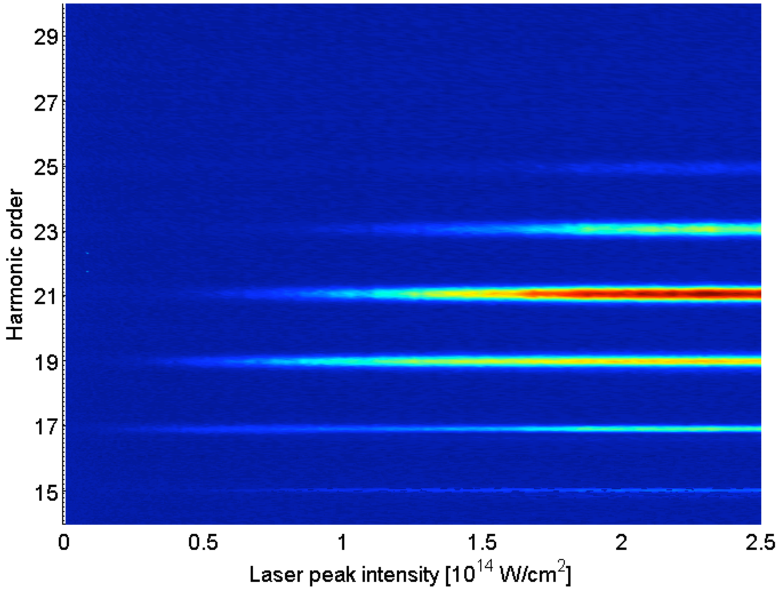


Argon

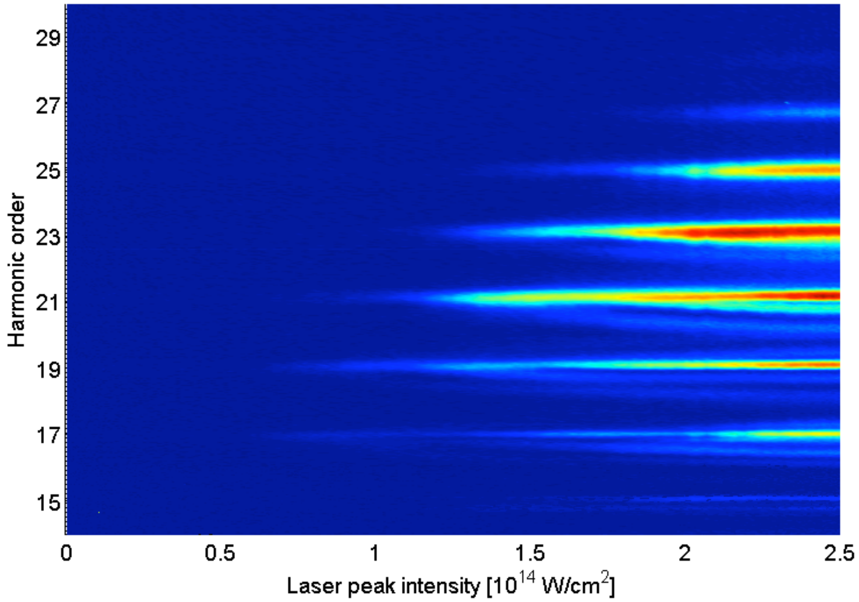




Short trajectory

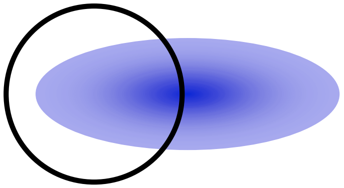


Short and long trajectories

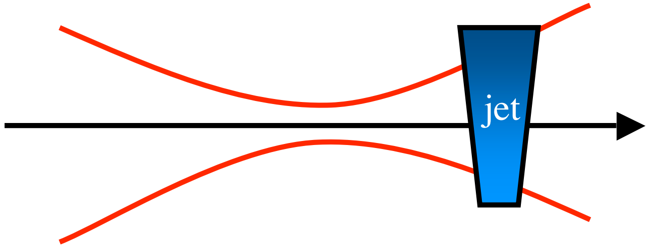


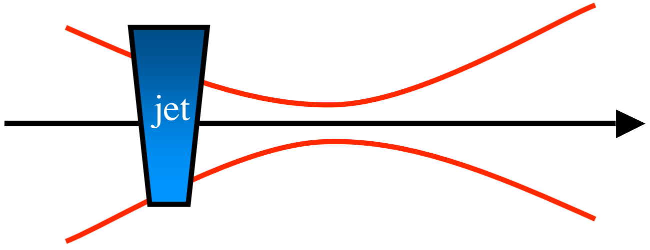
Intensity dependence

OFF-AXIS



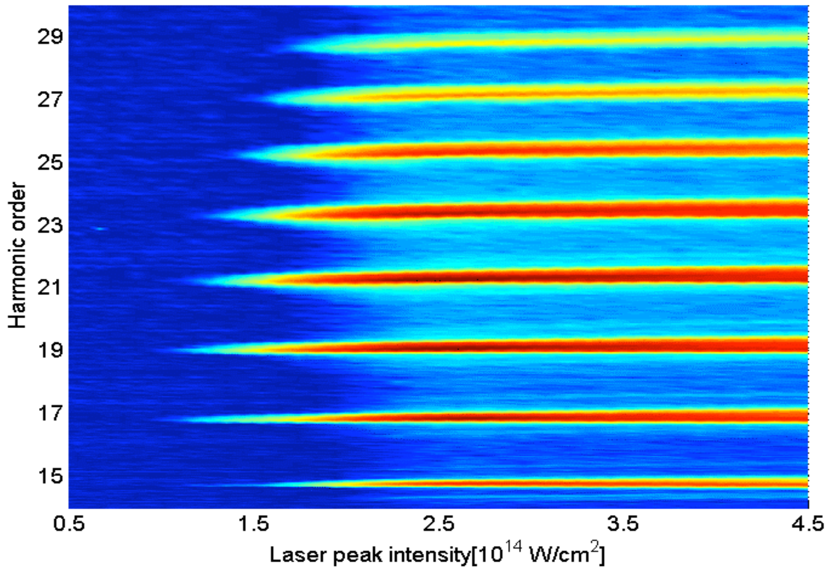
Argon

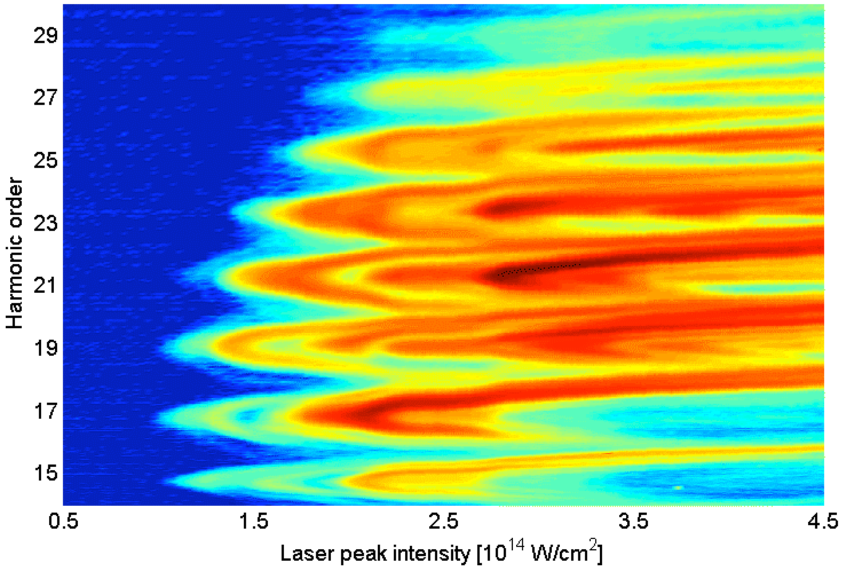




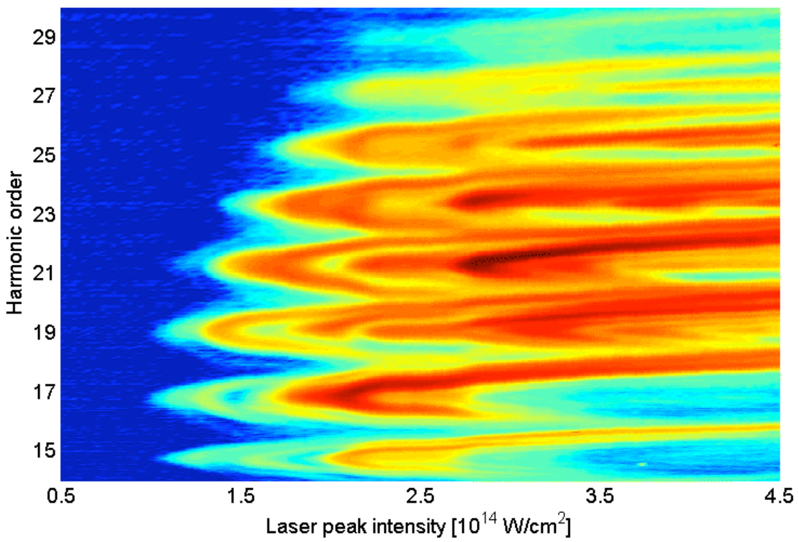
Short trajectory

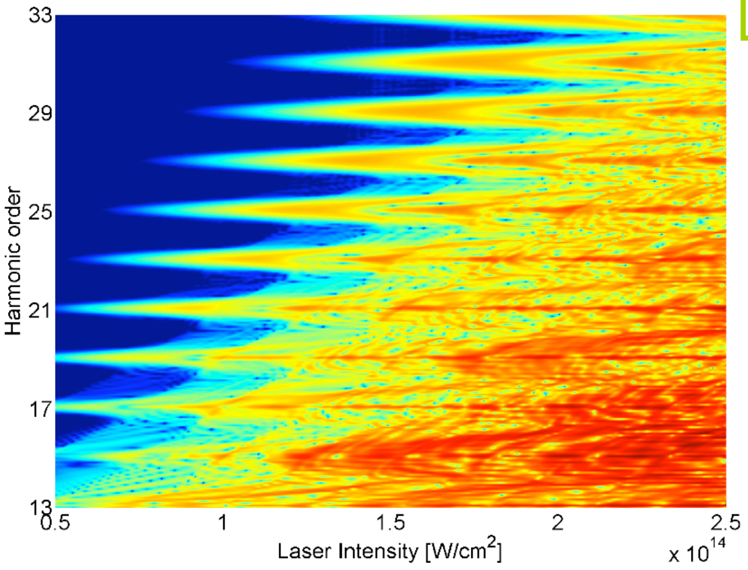
Short and long trajectories





First order QPI





Argon

SFA

Plateau harmonic (theory)

$$\alpha_q^{(1)} \approx 1-5\cdot 10^{-14}\,\frac{\text{rad cm}^2}{\text{W}}$$

$$\alpha_q^{(2)} \approx 20-25\cdot 10^{-14}\,\frac{\text{rad cm}^2}{\text{W}}$$

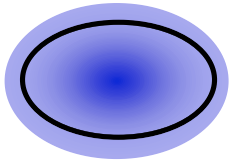
Periodicity of order 1:

$$\frac{2\pi}{\Delta\alpha} \approx 0.3-0.4\cdot 10^{14}\,\frac{\text{W}}{\text{cm}^2}$$

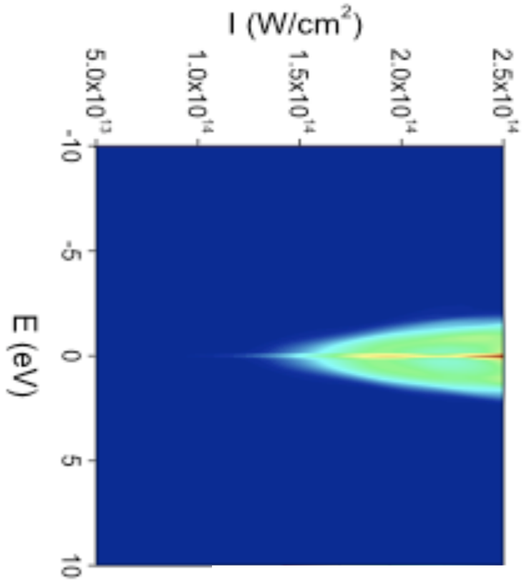
First order interferences 10's as control!!!

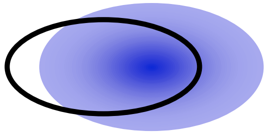
Macroscopic response

Propagation and macroscopic calculation SFA
Argon
H15

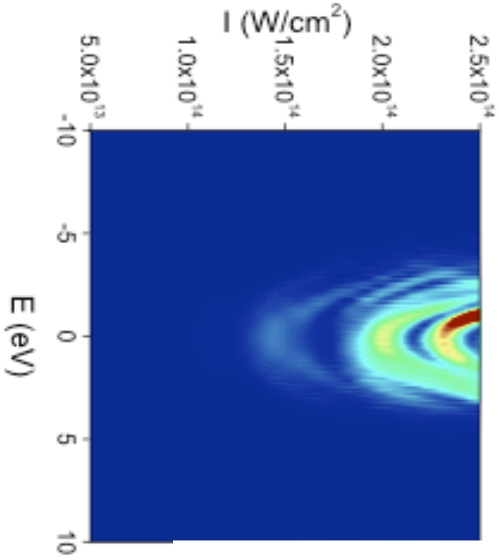


ON-AXIS
Short trajectory

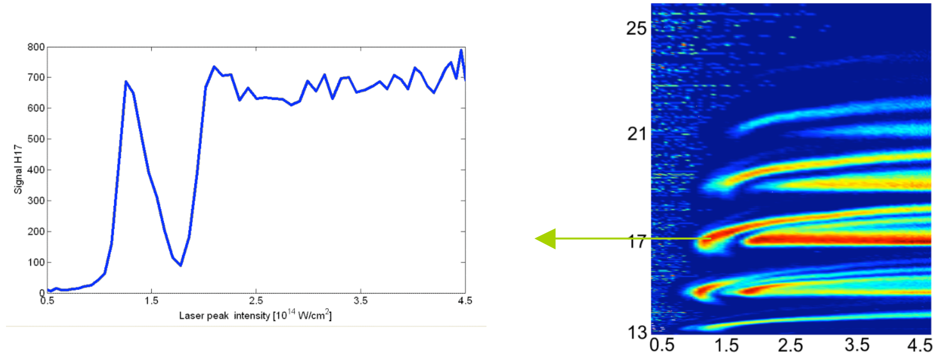




OFF-AXIS
short and long trajectories



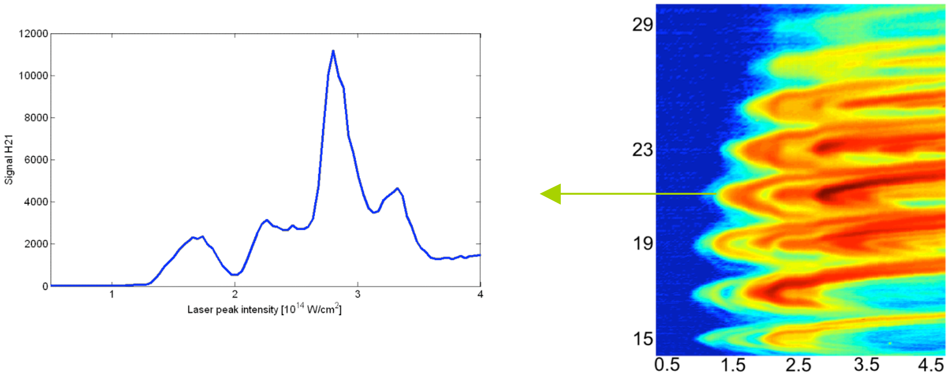
QPI: limitation



Xenon

Low I_p (12.1 eV)
(barrier supression at $8.7 \cdot 10^{13}$ W/cm^2)

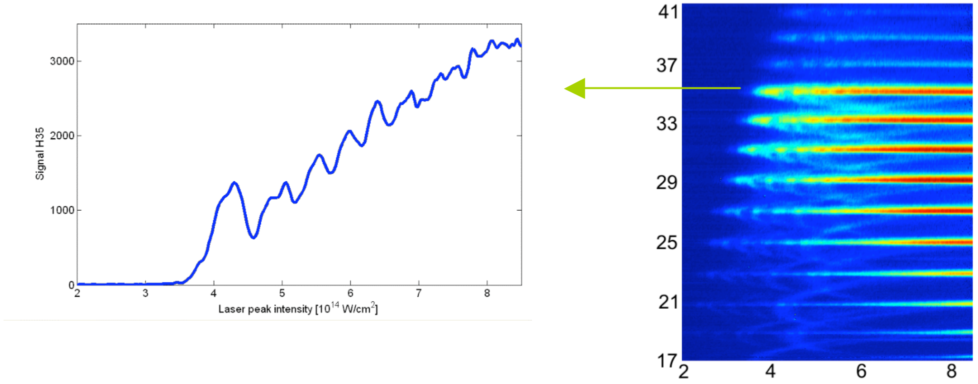
→ depletion
→ blue shifted



Argon

Mid I_p (15.8 eV)
(barrier suppression at $2.5 \cdot 10^{14}$ W/cm^2)

→ depletion



Neon

high I_p (21.6 eV)
(barrier suppression at $8.6 \cdot 10^{14}$ W/cm^2)

→ no limitation

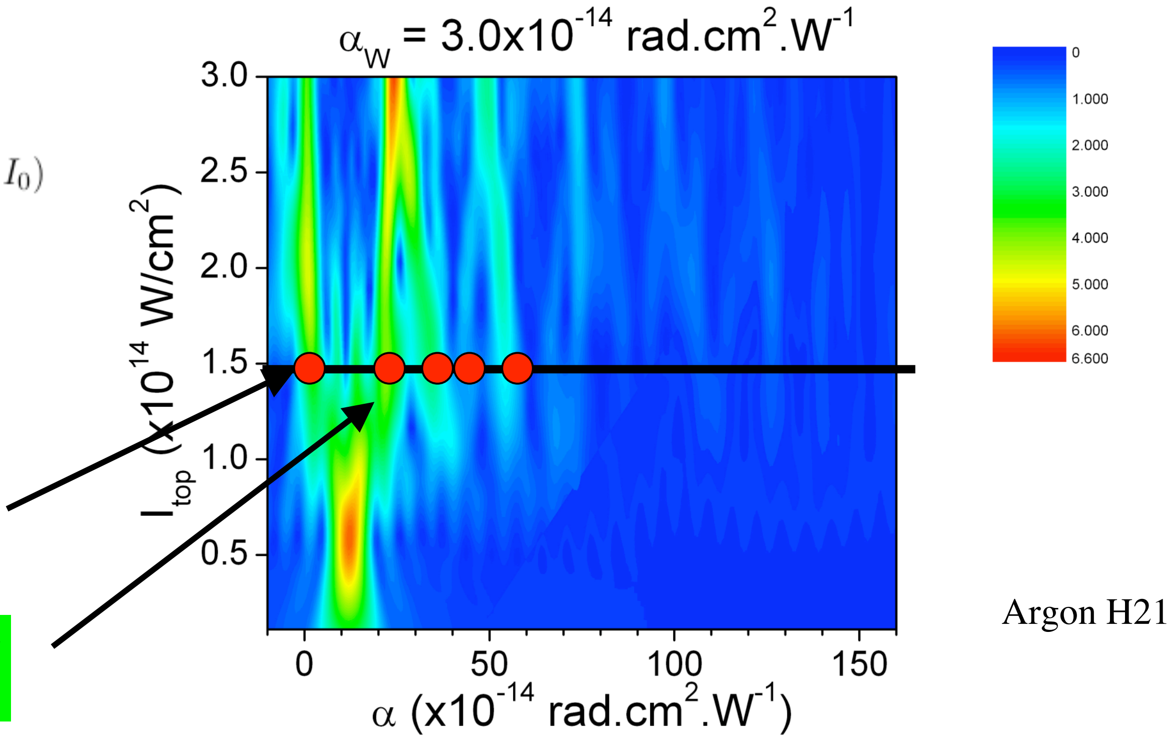
Distinction of QP

“Frequency- like analysis”

$$x_q(I) = \sum_j |x_q^{(j)}| e^{-\alpha_q^{(j)} I}$$

$$x_q(I, I_0) = \sum_j |x_q^{(j)}| e^{-\alpha_q^{(j)} I} \times W(I - I_0)$$

$$x_q(\alpha, I_0) = FT[x_q(I, I_0)]$$



$$\alpha_q^{(1)} = 5$$

$$\alpha_q^{(2)} = 25$$

Ph. Balcou et al., J. Phys B.(1998)

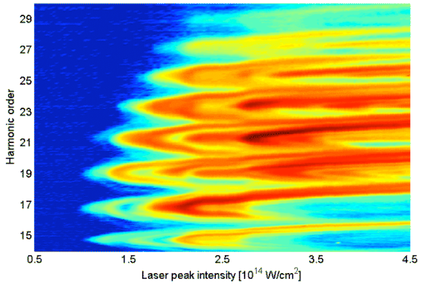
Conclusion

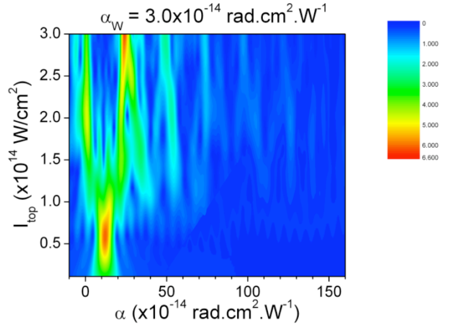
First order quantum path interferences observed experimentally

Study of the QPI as a technique -> atomic dipole phase extraction

High order interferences access through direct spectral measurements

Exploring more complicated target: diatomic molecules





A. Zaïr et al PRL 100, 143902 (2008)
M. Holler et al OE 17, 5716 (2009)

People

A. Zaïr, M. Holler, A. Guandalini, F. Schapper, J. Biegert, L. Gallmann and U. Keller

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SPAM

Thank you!!!