

# Atomic physics with attosecond pulses



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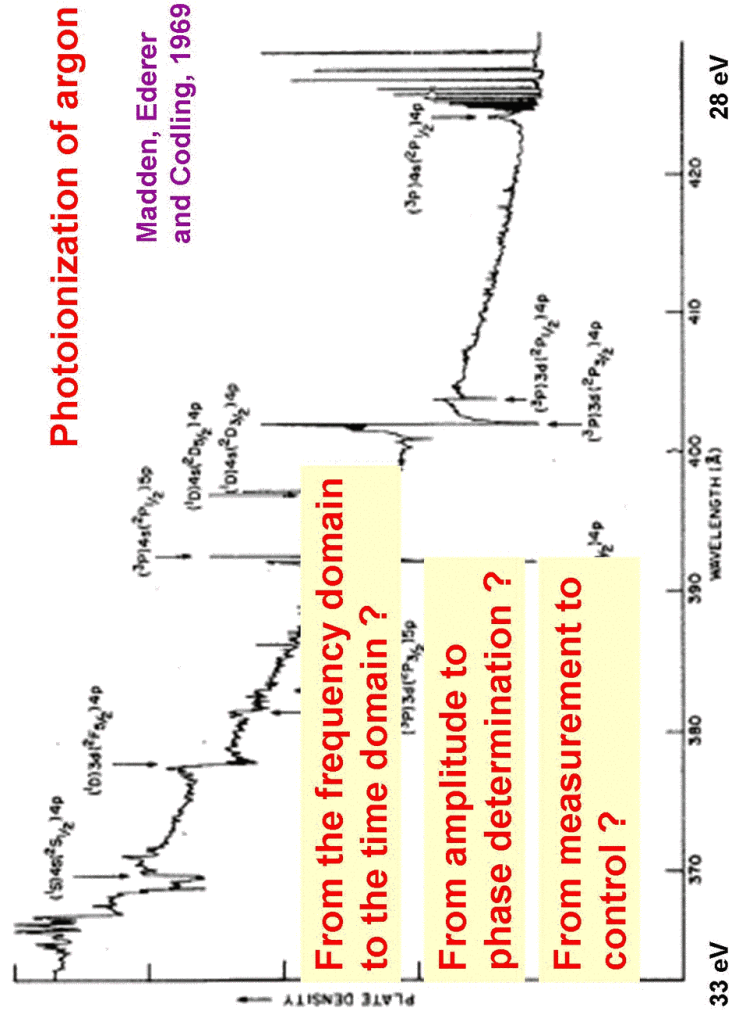
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## Photoionization of atoms



## Attosecond tools

### TOOL 1

#### Returning electron wavepacket

Tomography Itatani, 2004  
 Structure dynamics Kanai, 2005  
 ISRS Baker, 2006

### TOOL 2

#### Single attosecond pulses

Inner-shell ionization Henstchell, 2001  
 Auger decay Kienberger, 2002, 2004  
 Drescher, 2002

### TOOL 3

#### Trains of attosecond pulses

Paul, 2001, Mairesse, 2003  
 López-Martens, 2005

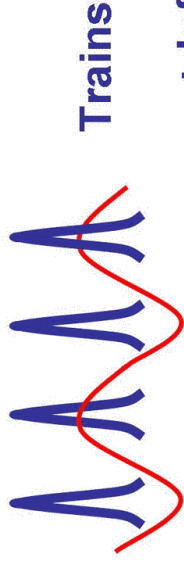
### TOOL 3'

#### Trains of attosecond pulses with one pulse per cycle

Mauritsson et al. PRL (2006)

# Outline

## 1. Attosecond Technology

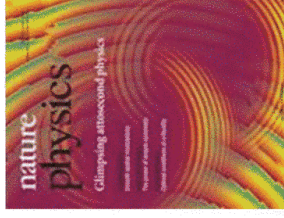


+ Infrared field

## 2. Applications

Electron Wave Packet Interferometry

Ionization dynamics



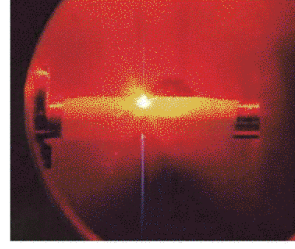
## Generation of high-order harmonics

Laser



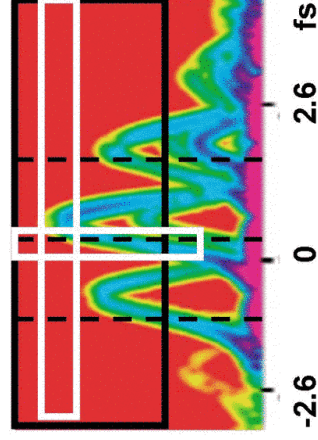
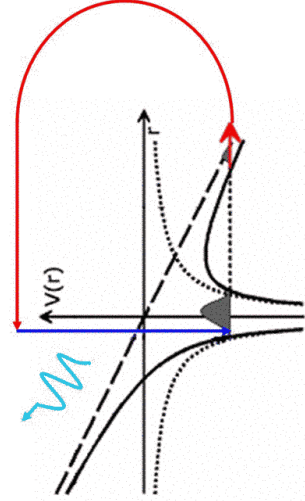
Titanium-Sapphire, 800 nm  
1 kHz, 2 mJ, 35 fs pulses

Atomic Medium



Gas cell with rare gas  
Pressure: ~20 mbar

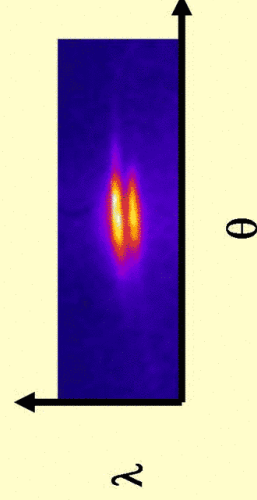
## Physics of high-order harmonics



**Chirp compensation**  
**No second trajectory**

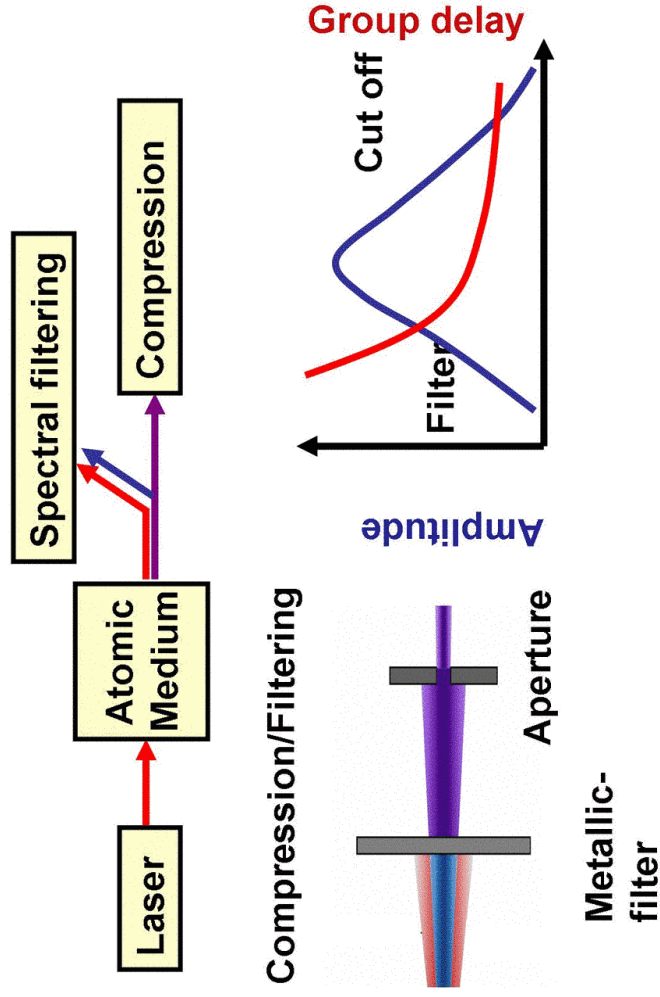
A. Pukhov, 2005

**Can we make a train with  
 the second trajectory?**



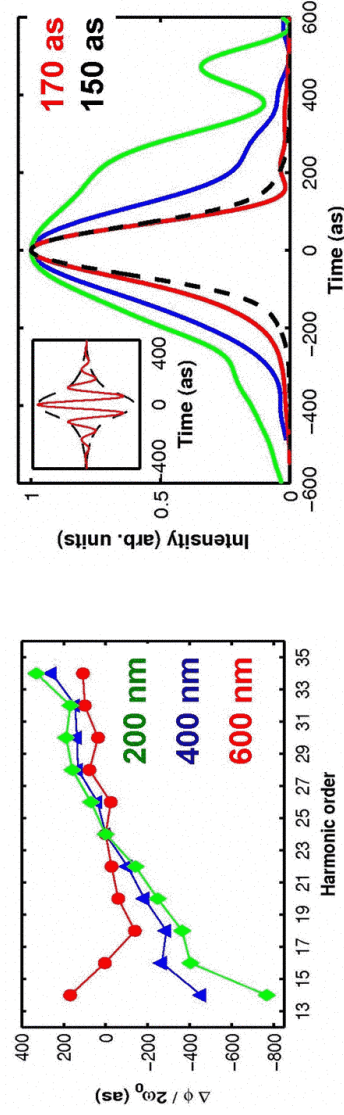
O. Guilbaud, B. Schütte, E. Georgiadou

## Amplitude and phase control

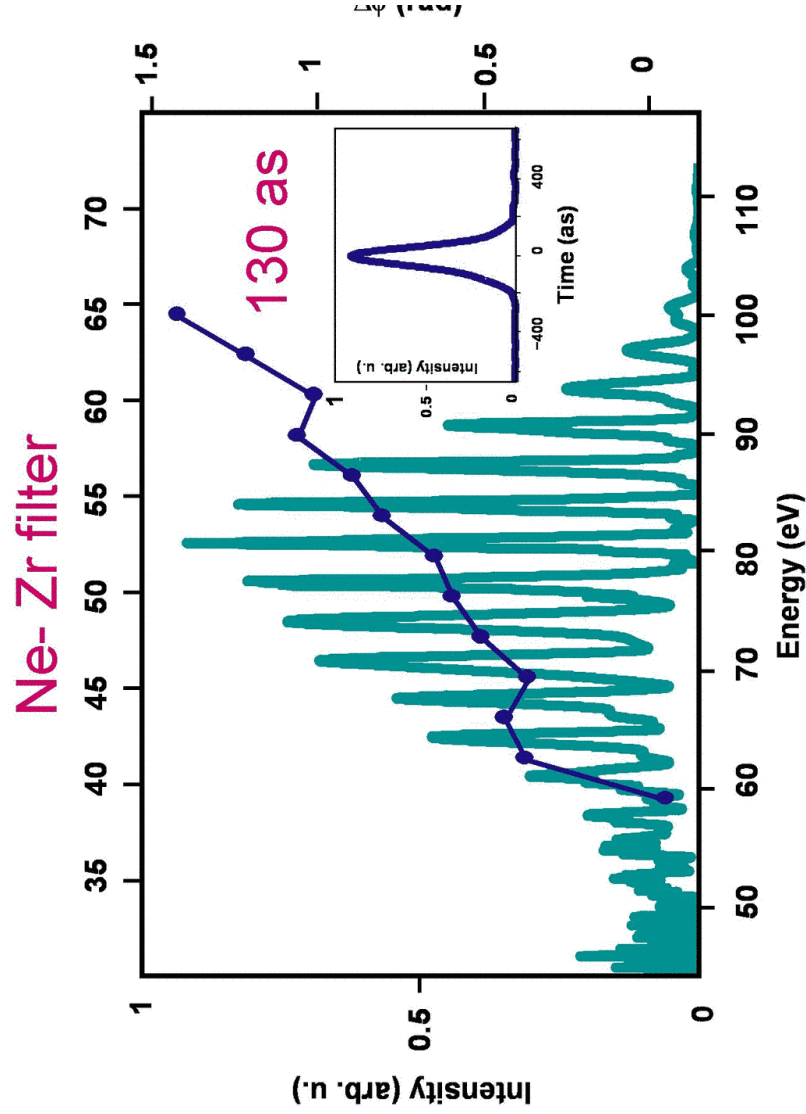


## Amplitude and phase control

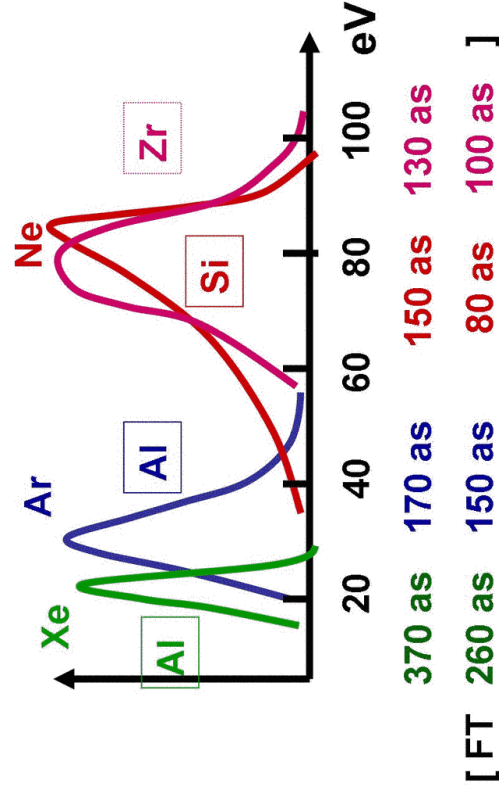
### Ar- Al filter



1.2 optical cycles  
30 eV



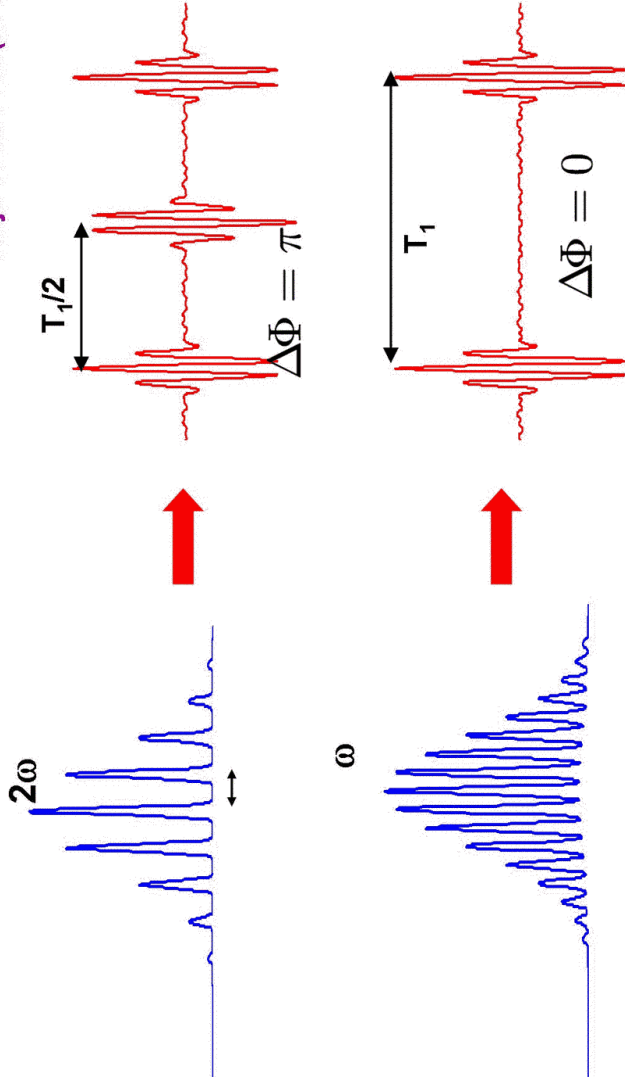
### Amplitude and phase control



Other technique: broadband  
chirped mirrors

## Trains of attosecond pulses

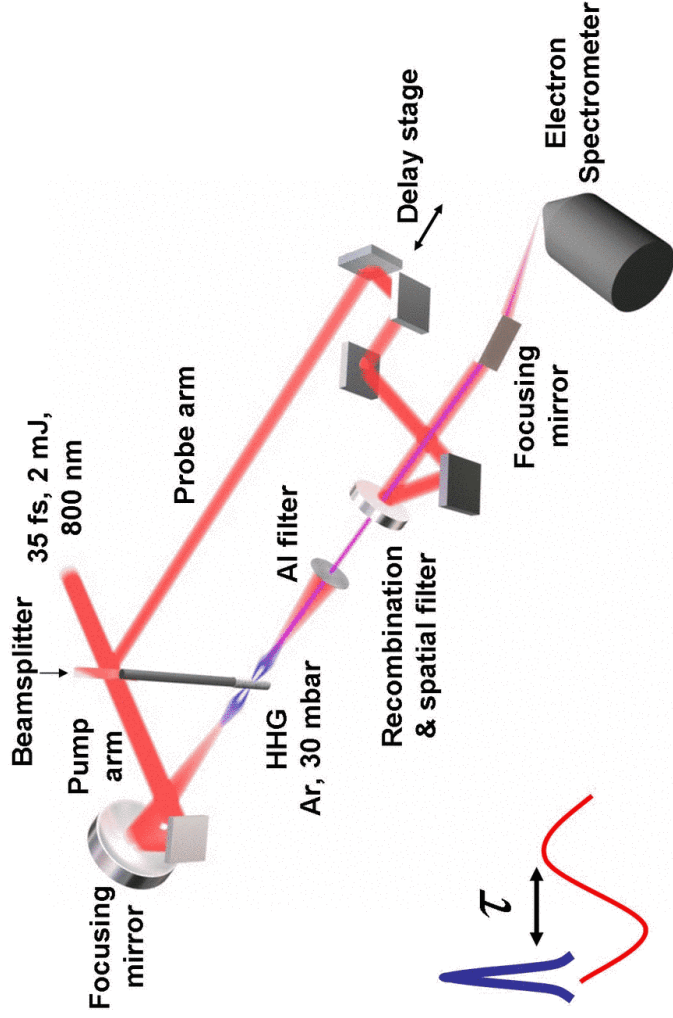
Varjú et al. *PRL* (2005)



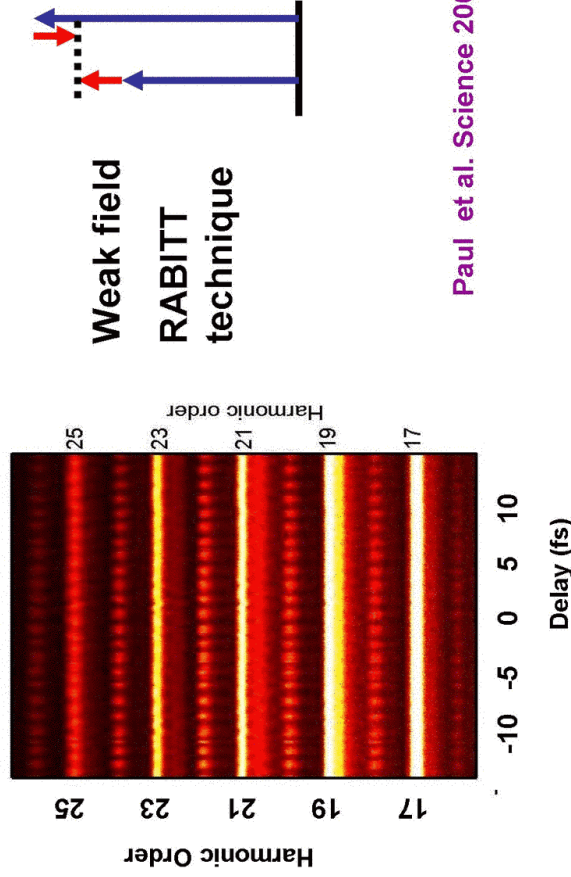
Using a combination of fundamental field and second harmonic

Mauritsson et al. *PRL* (2006)

## Characterization of attosecond pulses

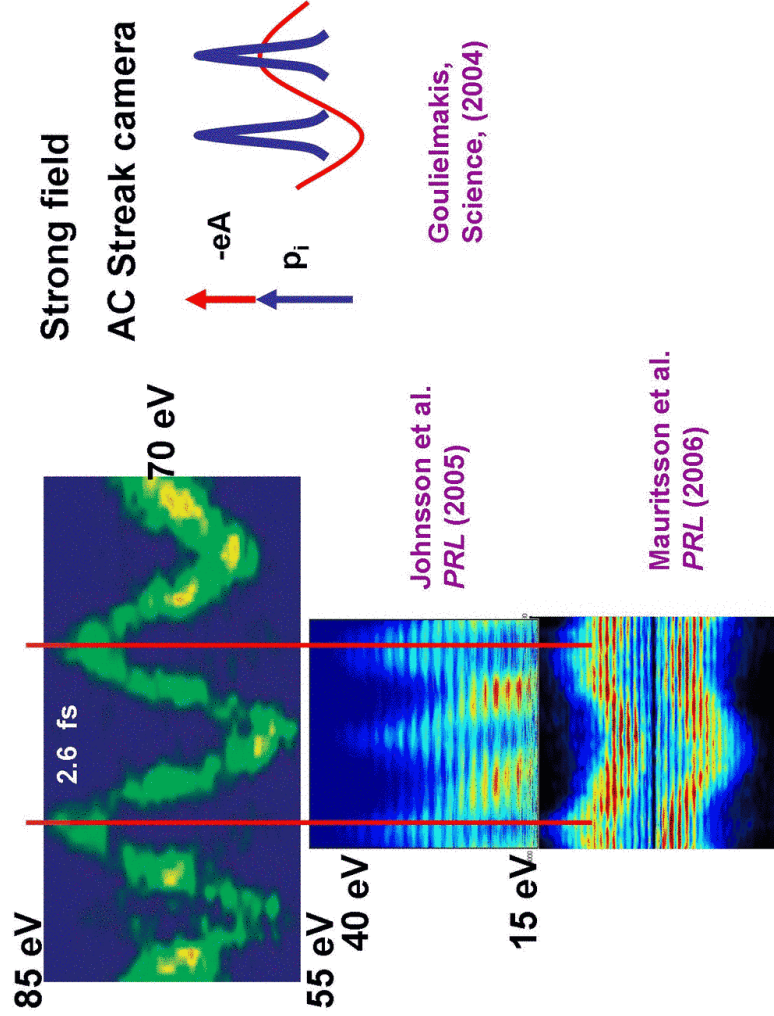


# Characterization of attosecond pulses in a train



Paul et al. Science 2001

# Characterization of attosecond pulses



Johnson et al. PRL (2005)

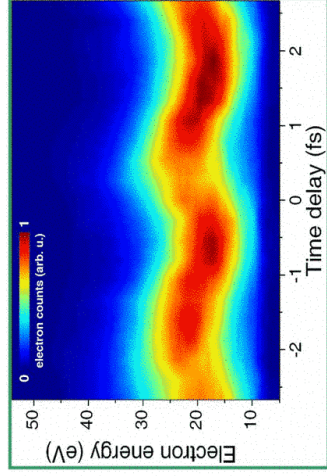
Goulielmakis, Science, (2004)

Mauritsson et al. PRL (2006)

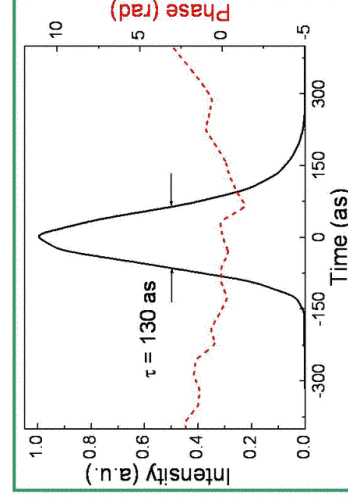
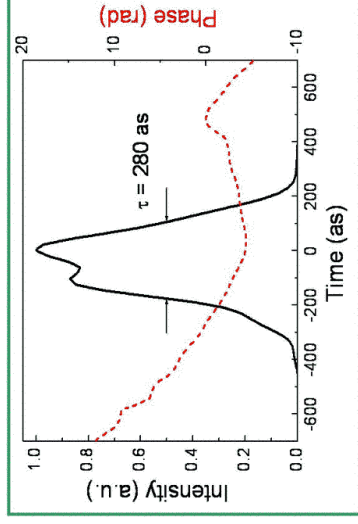
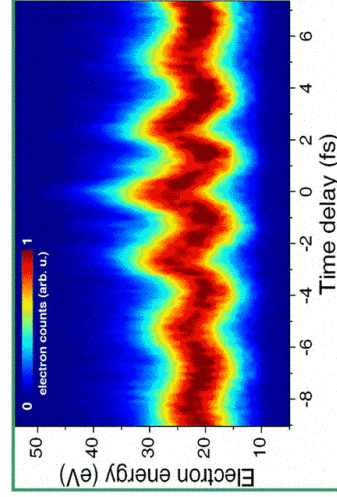


Milan, Nisoli et al.

■ 100-nm Aluminum filter

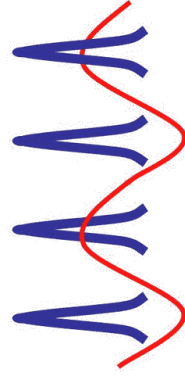


➔ 300-nm Aluminum filter



## Outline

### 1. Attosecond Technology



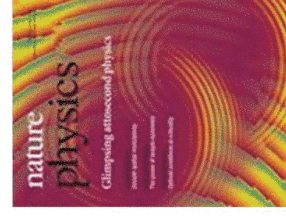
Trains

+ Infrared field

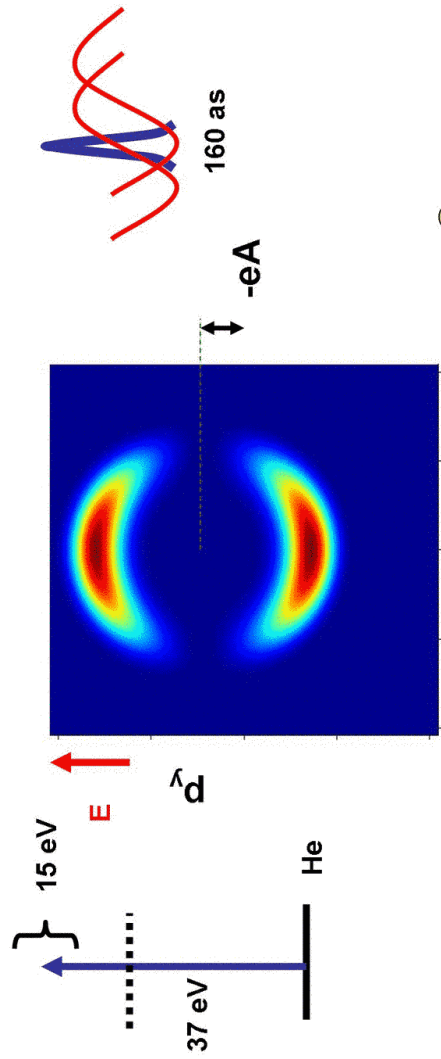
### 2. Application

Electron Wave Packet Interferometry

Ionization dynamics

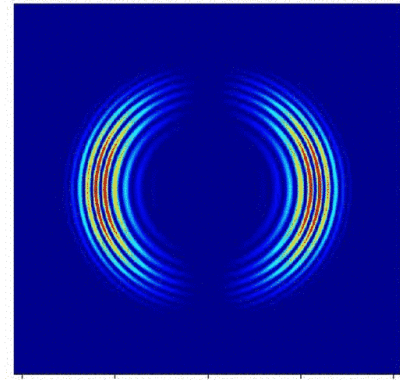
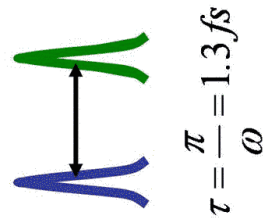


**Ionization of an atom by a single attosecond pulse  
in presence of an infrared field**



**Strong or weak field?**

**Ionization of an atom by two attosecond pulses**



$$W = \frac{p_x^2}{2m} + \frac{p_y^2}{2m} + I_p$$



Circles

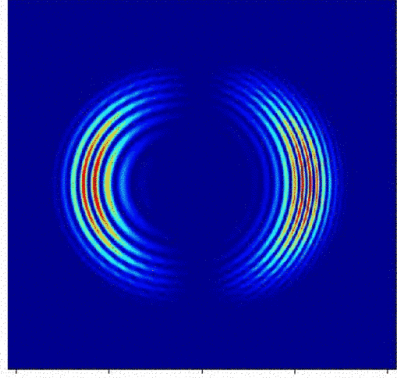
$$a \approx d_1 e^{i\psi_1} + d_2 e^{i\psi_2} e^{i\pi}$$

$$\Delta\Psi = \pi + \frac{W\pi}{\hbar\omega}$$



$$W = (2n+1)\hbar\omega$$

Ionization of an atom by two attosecond pulses  
in presence of an infrared field

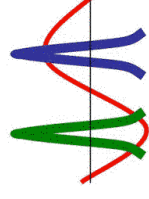
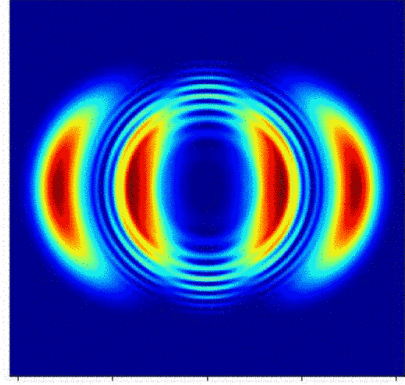


Off-centered  
circles

No momentum  
transfer

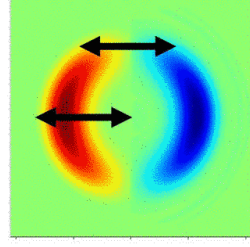
$$a \approx d_1 e^{i\psi_1} + d_2 e^{i\psi_2} e^{i\pi} \left( \pi + \frac{W\pi}{\hbar\omega} + \frac{2eE p_y}{m\hbar} \right)$$

Ionization of an atom by two attosecond pulses  
in presence of an infrared field



$2eA$

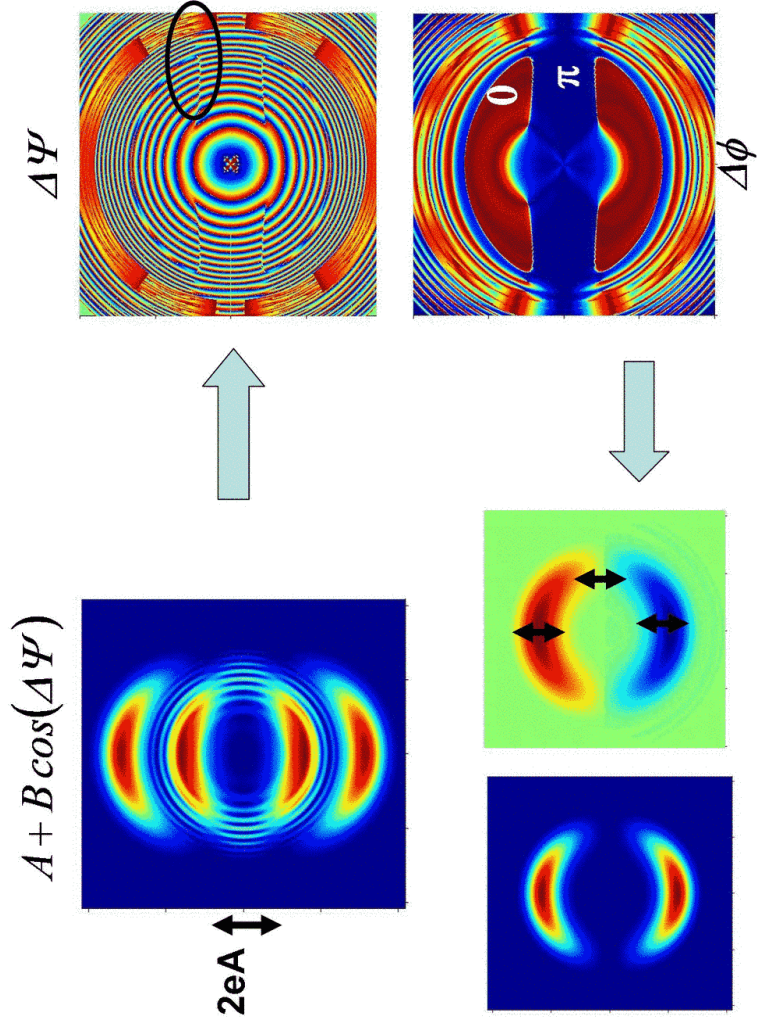
Momentum  
shear



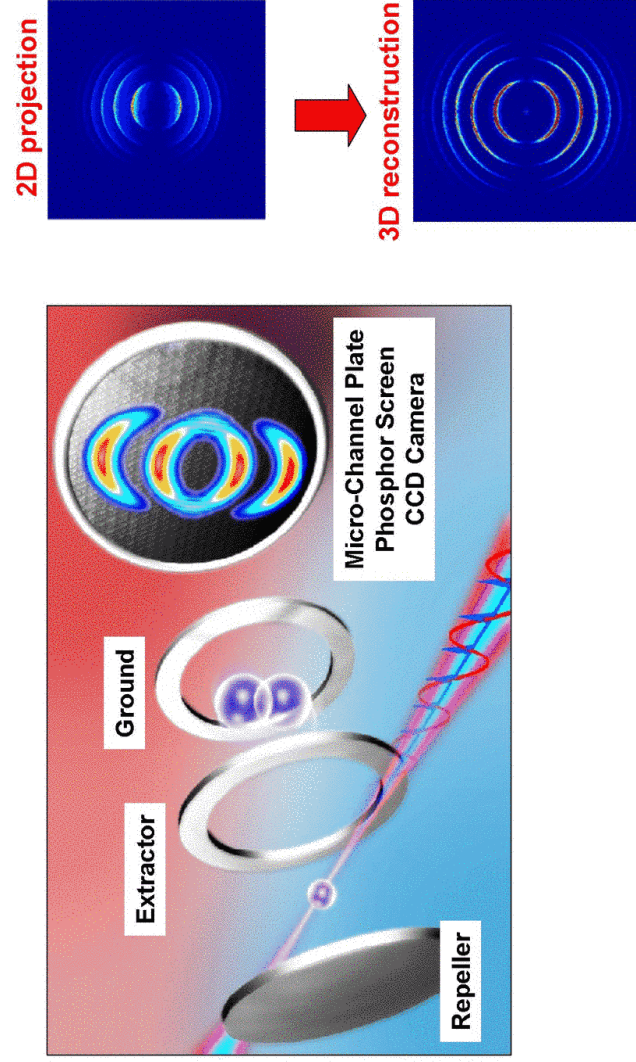
$$a \approx d_1 e^{i\psi_1} + d_2 e^{i\psi_2} e^{i\pi}$$

$$\left( \pi + \frac{W\pi}{\hbar\omega} + \phi(p_x, p_y + eA) - \phi(p_x, p_y - eA) \right)$$

### Analysis of the interferogram

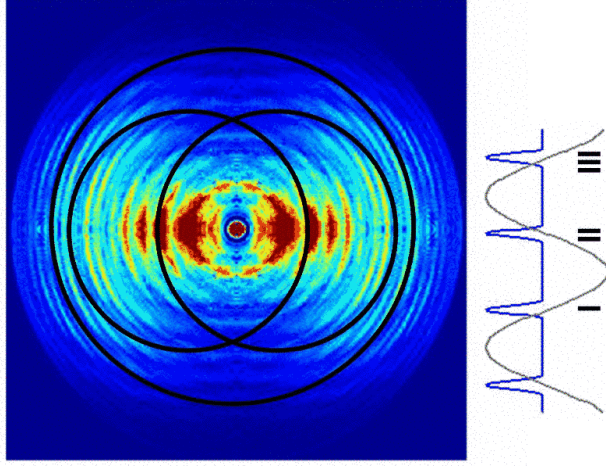
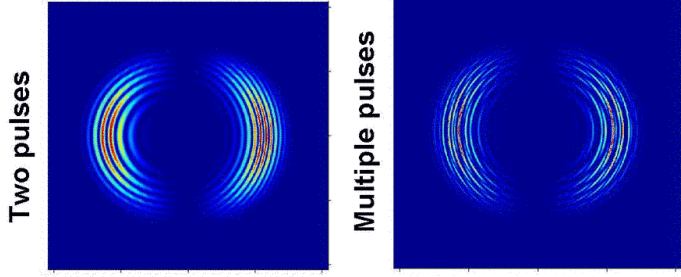


### Experimental set up



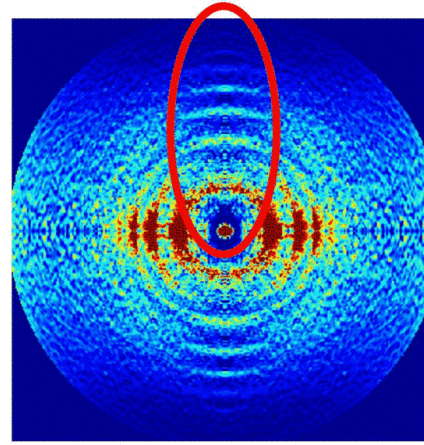
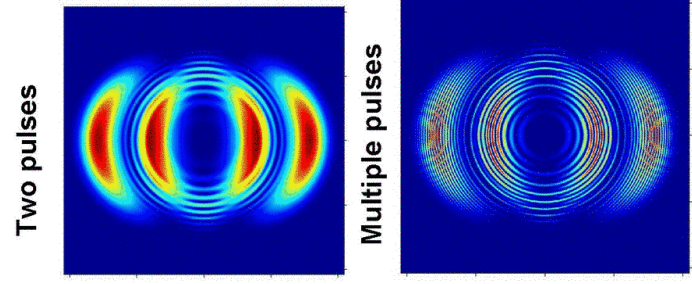
Eppink and Parker, *Rev. Sci. Instr.* (1997)  
Vrakking, *Rev. Sci. Instr.* (2001)

### No momentum shear

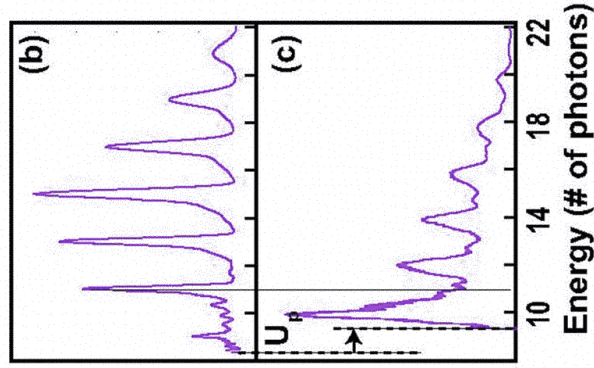


Remetter et al., *Nature Phys*, 2006.

### With momentum shear



## Experimental results

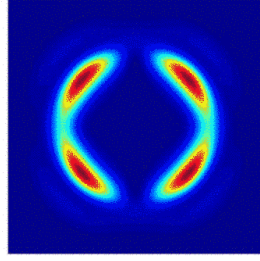
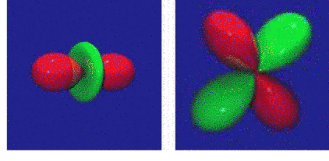


$$\pi + \frac{W\pi}{\hbar\omega} + \Delta\phi = 2n\pi$$

$$W = 2n\hbar\omega \quad \uparrow \quad \Delta\phi = \pi$$

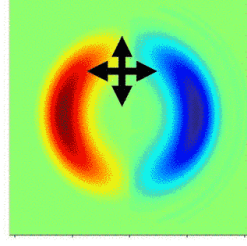
$$3p, m=0 \quad \uparrow \quad s, d, m=0$$

$$3p, m=\pm 1 \quad \uparrow \quad d, m=\pm 1$$



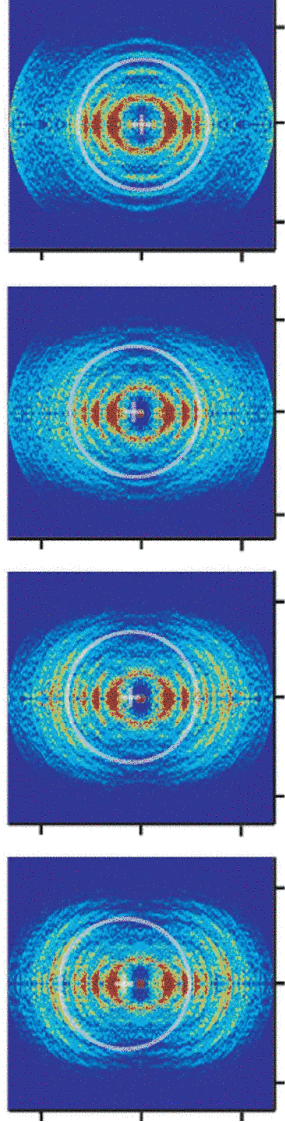
## Improvements

- Increase/vary the overlap
- Two pulses instead of a train
- Crossed polarizations

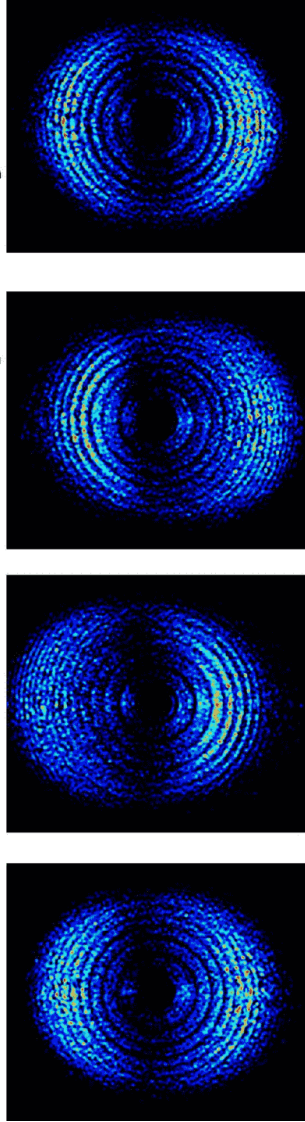


Can we learn something useful  
about atoms or molecules?  
What?

**Attosecond movie with two pulses /cycle**



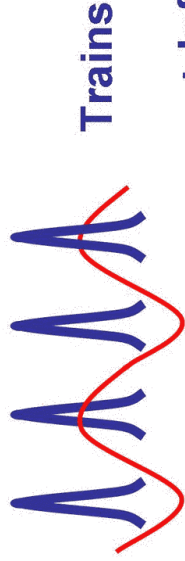
**Attosecond movie with one pulse /cycle**



See Mauritsson's talk

**Outline**

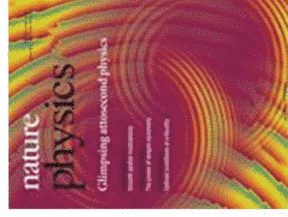
**1. Attosecond Technology**



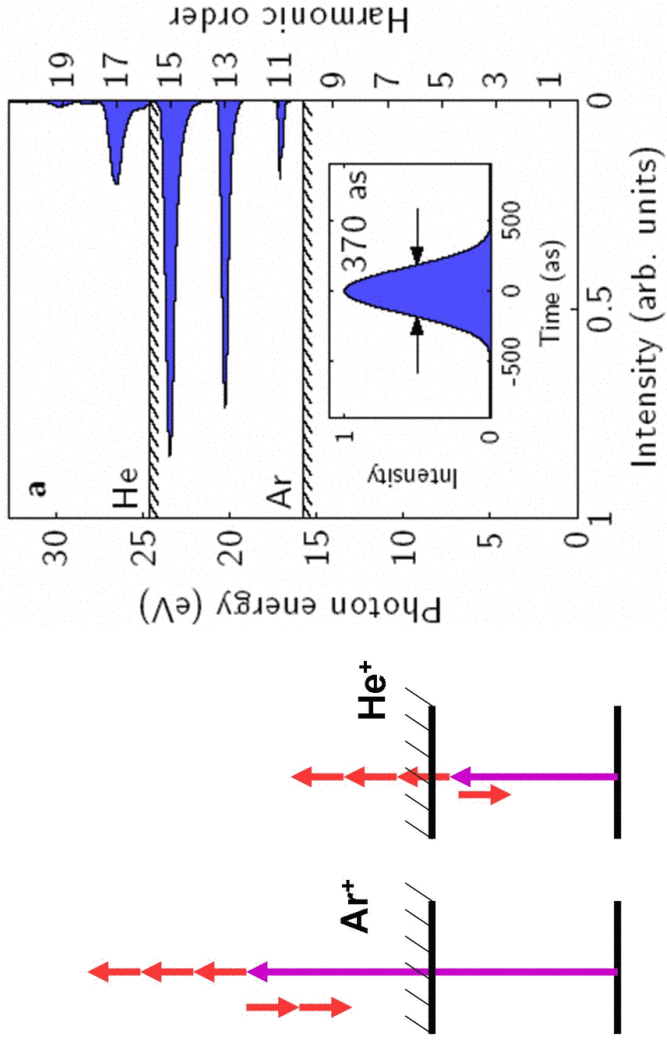
**2. Application**

**Electron Wave Packet  
Interferometry**

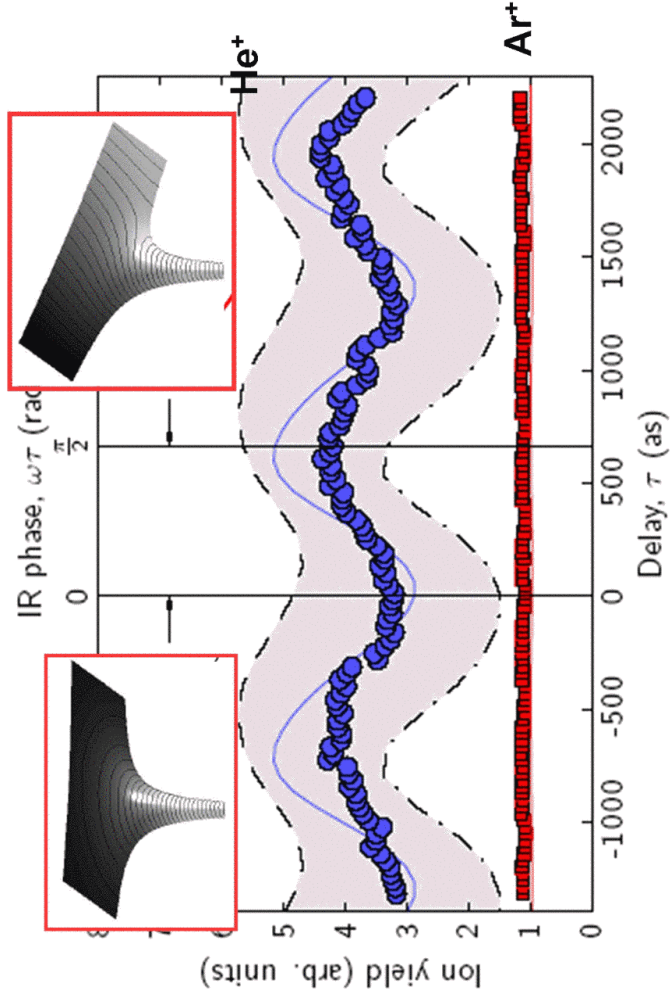
**Ionization dynamics**



### Below threshold wave packets

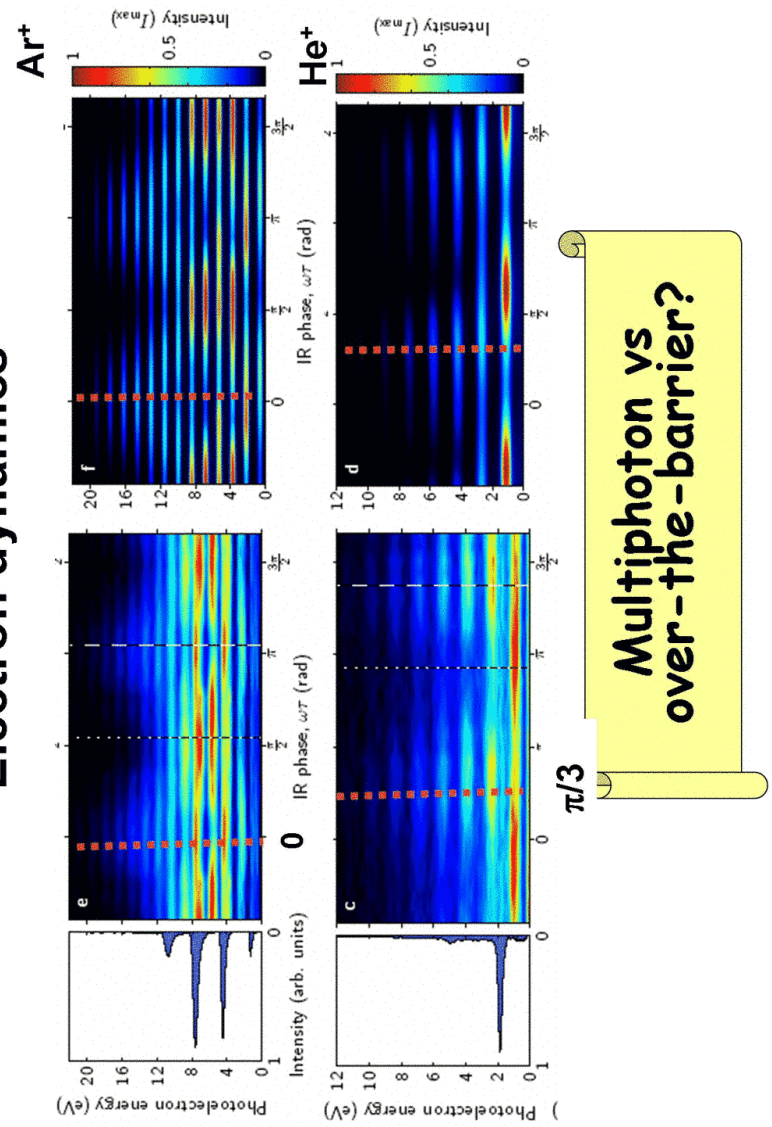


### Ion dynamics

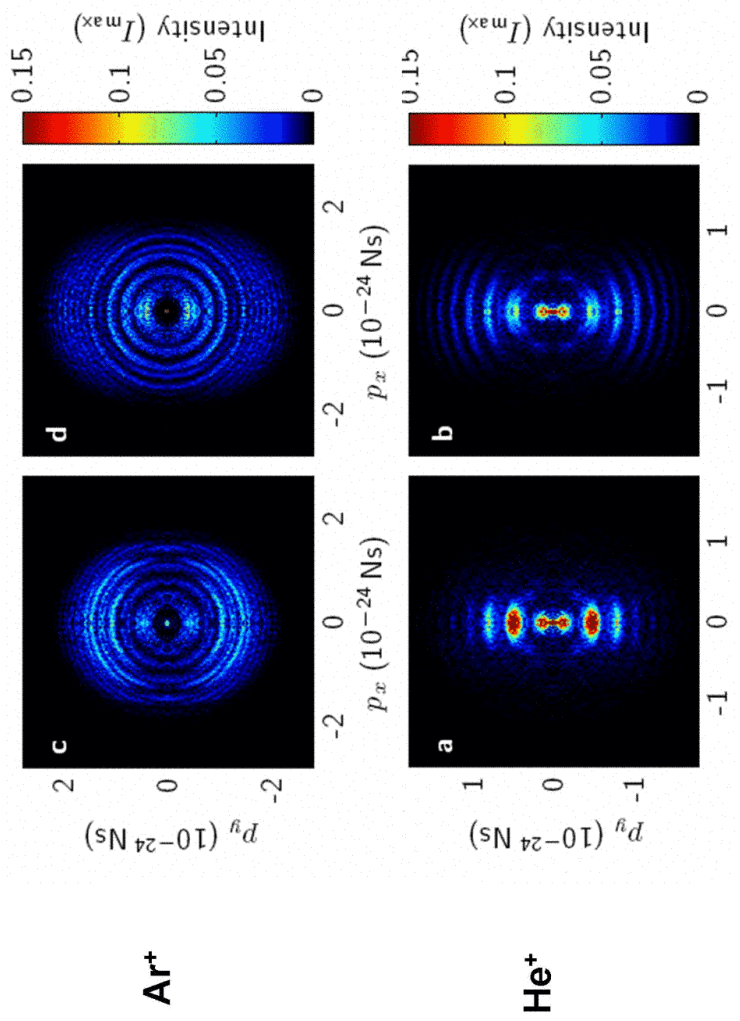




### Electron dynamics



### Momentum distributions



## **CONCLUSION**

### **Attosecond Technology**

**Trains of <200 as pulses at various energies  
with one or two pulses per cycle  
synchronized with an IR field**

### **Application:**

**Electron Wave Packet Interferometry  
Towards control of electronic waves  
Control of ionization dynamics**