Attosecond laser systems and applications

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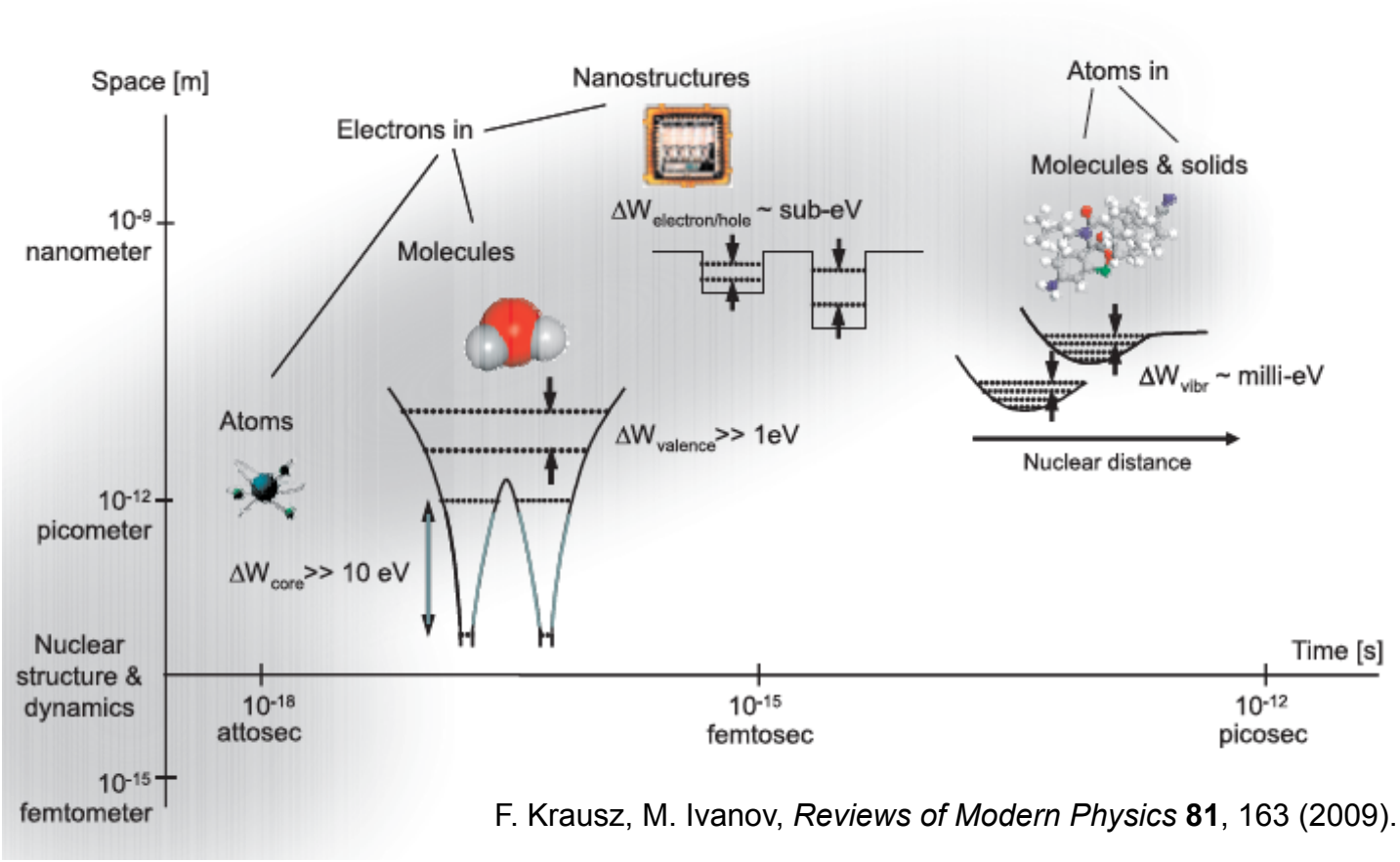
8th Annual Laser Safety Officer Workshop

September 11, 2012

Characteristic length and time scales



F. Krausz, M. Ivanov, *Reviews of Modern Physics* **81**, 163 (2009).

Atomic unit of time: 24 as

Electron orbit time around the nucleus in the first Bohr orbit: 150 as

Outline

Motivation for research on the attosecond timescale

Attosecond pulse generation

- Femtosecond pulse generation
- High harmonic generation
- Isolating attosecond pulses

A few experiments

- Inner-shell spectroscopy
- Attoclock measurements
- Valence electron motion

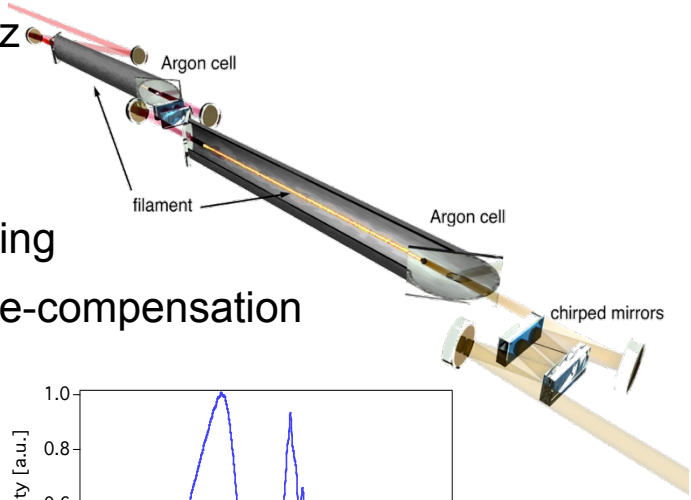
Conclusion

Femtosecond pulse generation

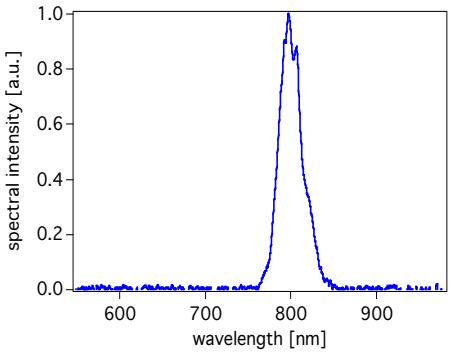
- Laser: Ti:Sapphire: 30 fs, 1 mJ, 800 nm, 1 kHz
- 2-stage filament compressor in Argon:

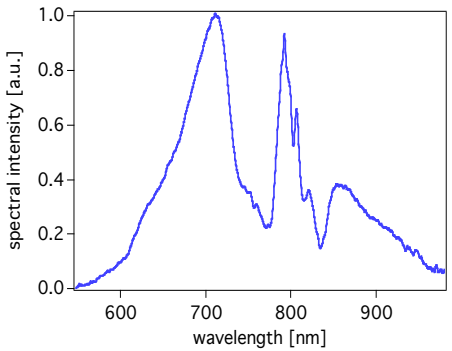
  Self guiding in a noble gas - spectral broadening

  Chirped mirrors for pulse compression and pre-compensation

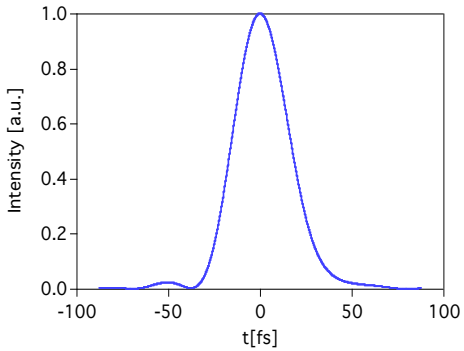


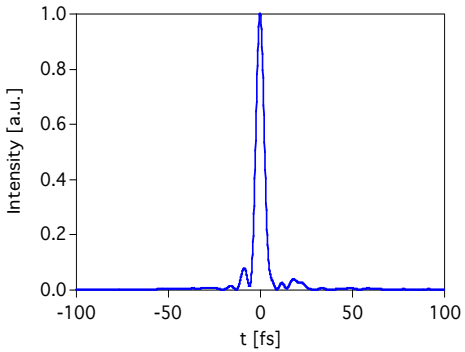
Spectrum





Pulse duration

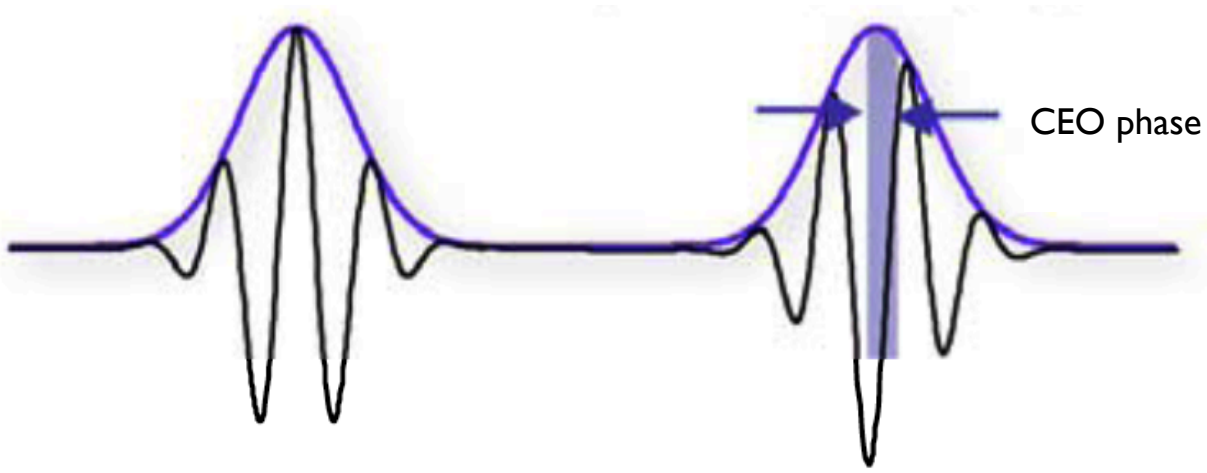




C. P. Hauri *et al.*, *Appl. Phys. B* **79**, 673 (2004).

Carrier Envelope Phase

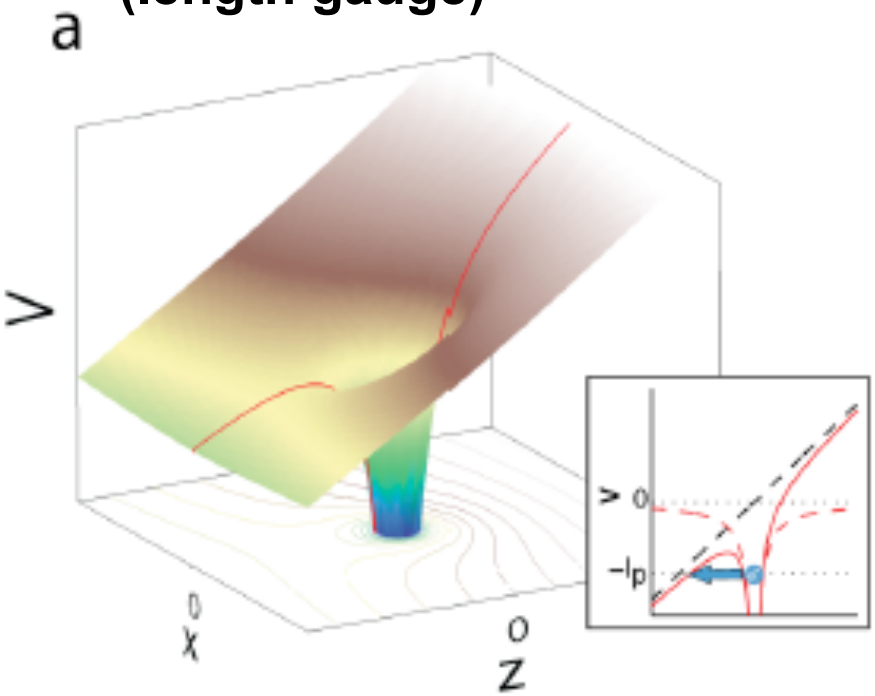
$$E_y = E_{0y}(t)\sin(\omega t + \phi_{CEO})$$



H.R. Telle, G. Steinmeyer, A. E. Dunlop, J. Stenger, D. H. Sutter, U. Keller, *Appl. Phys. B* **69**, 327 (1999)

Strong field ionization

Atomic potential in a strong laser field (length gauge)



A. N. Pfeiffer *et al.*, *Nat. Phys.* **8**, 76 (2012)

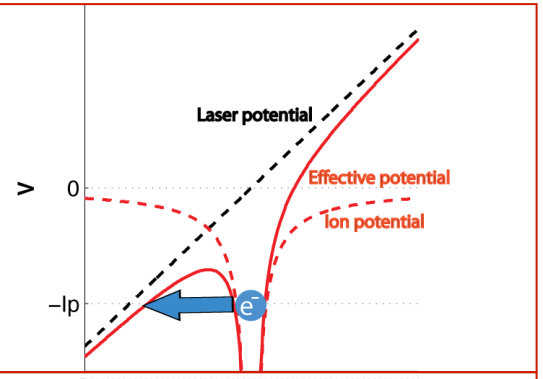
Standard model for strong field ionization:

Semi-classical model

P. B. Corkum, *Phys. Rev. Lett.* 71, 1994 (1993).

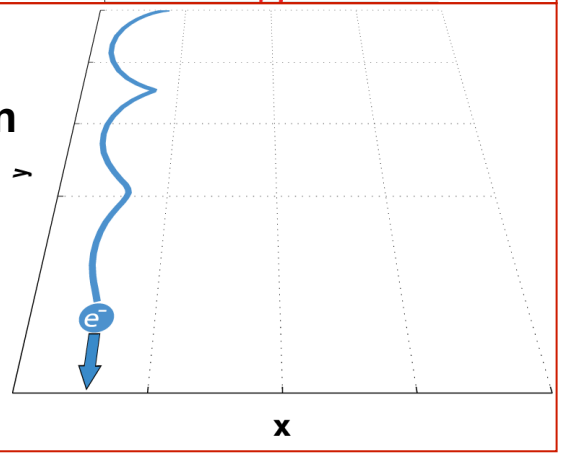
1st step:

Tunneling
Quantum picture

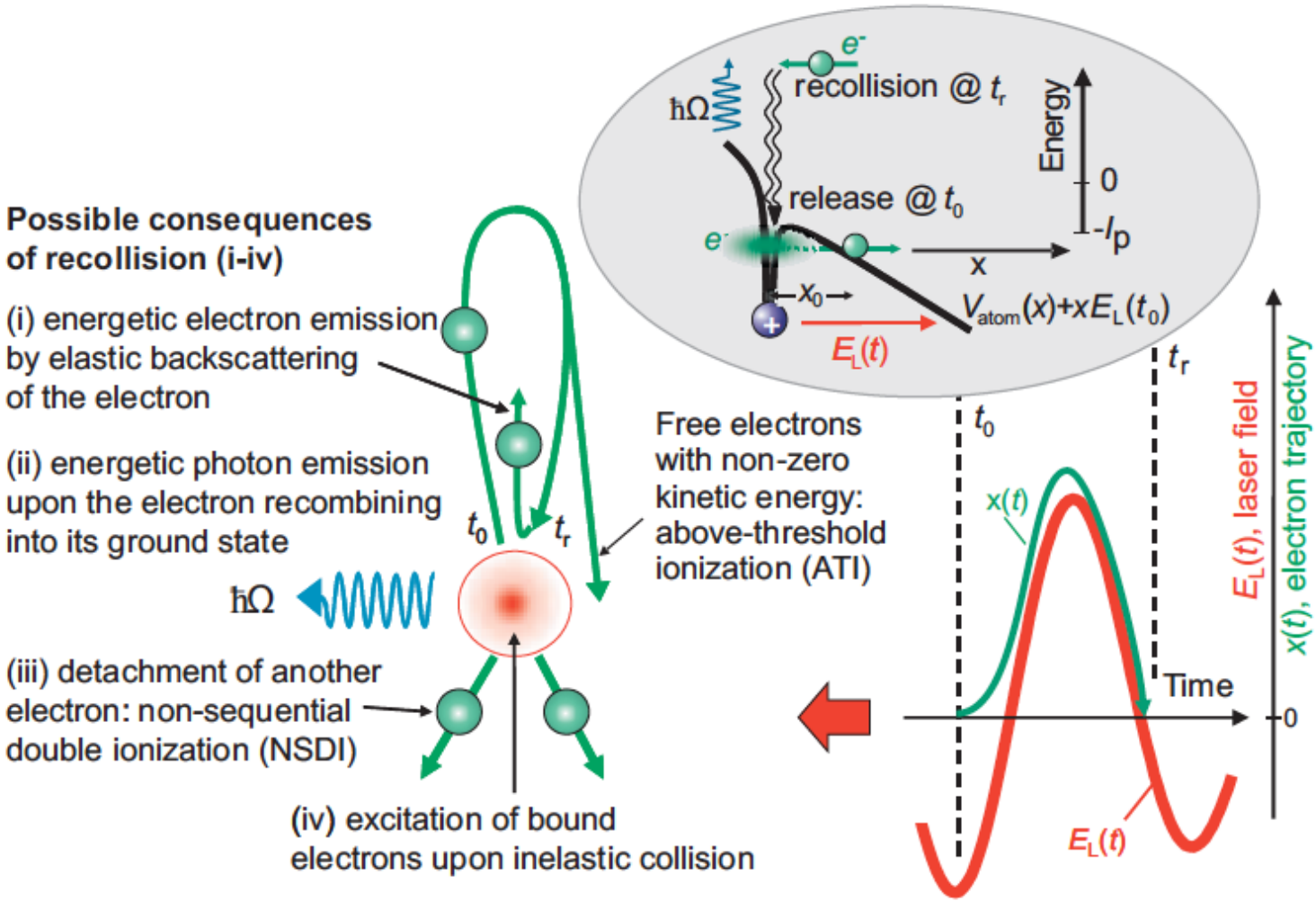


2nd step:

Newtonian motion
Classical picture

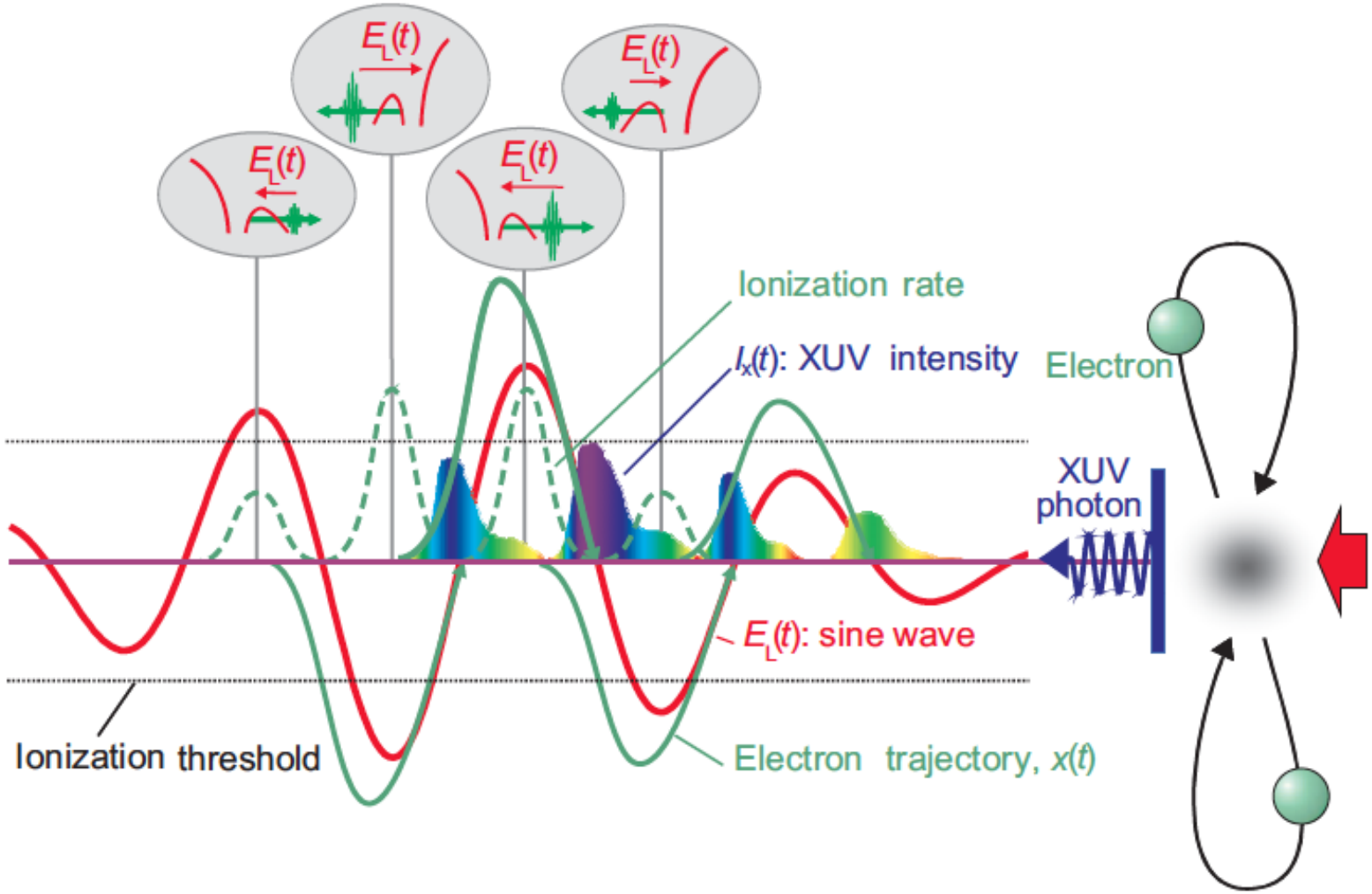


Electron recollision



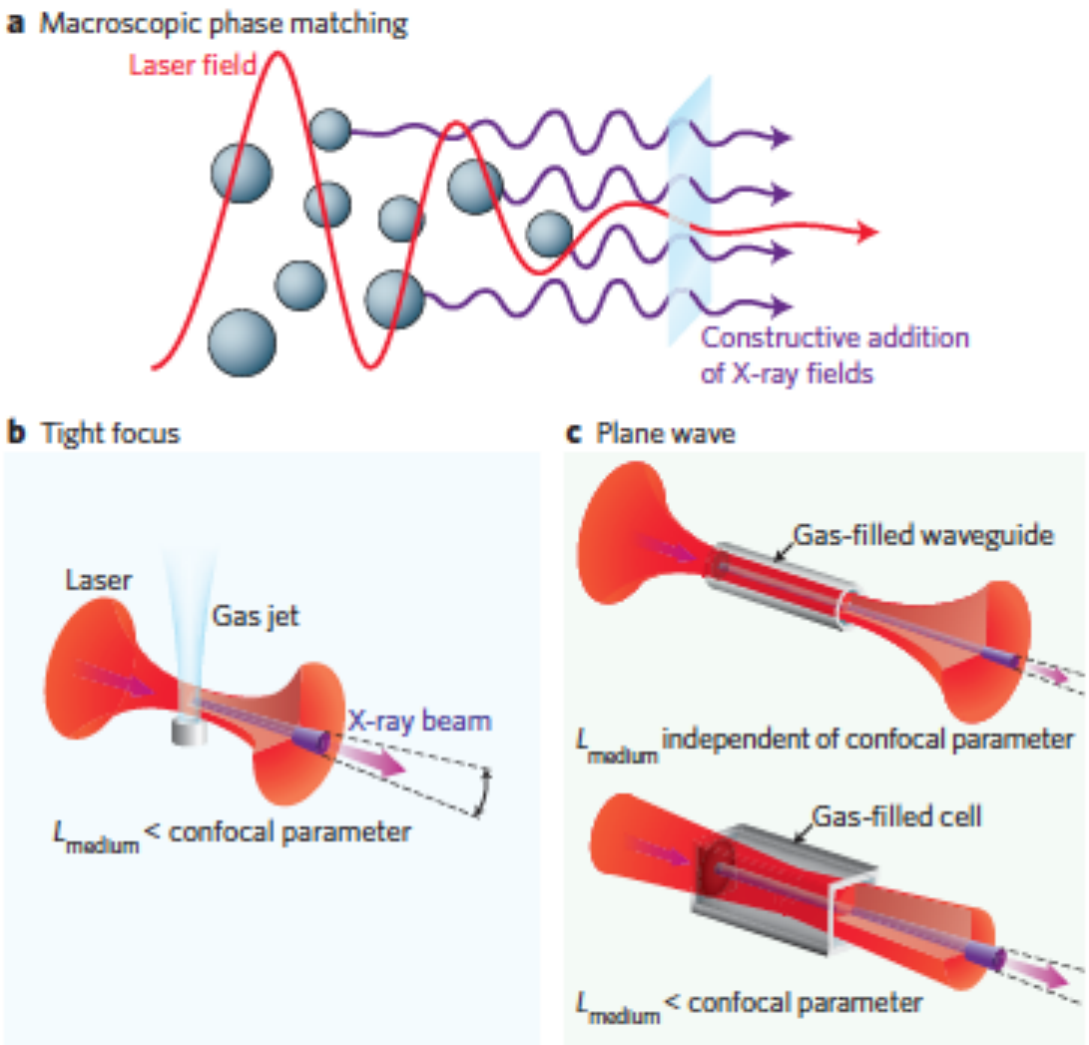
F. Krausz, M. Ivanov, *Reviews of Modern Physics* **81**, 163 (2009).

High Harmonic Generation



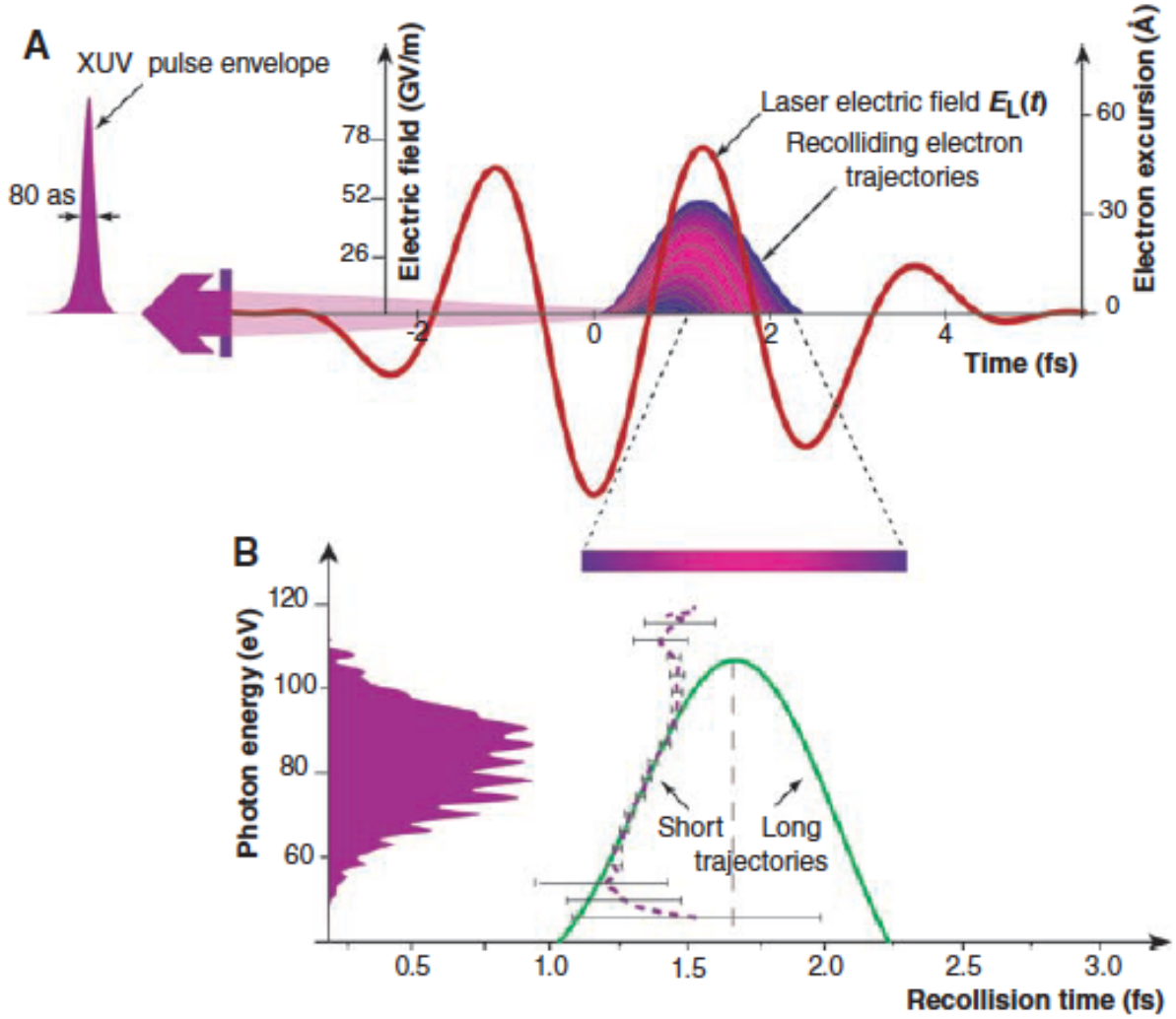
F. Krausz, M. Ivanov, *Reviews of Modern Physics* **81**, 163 (2009).

Phase matching



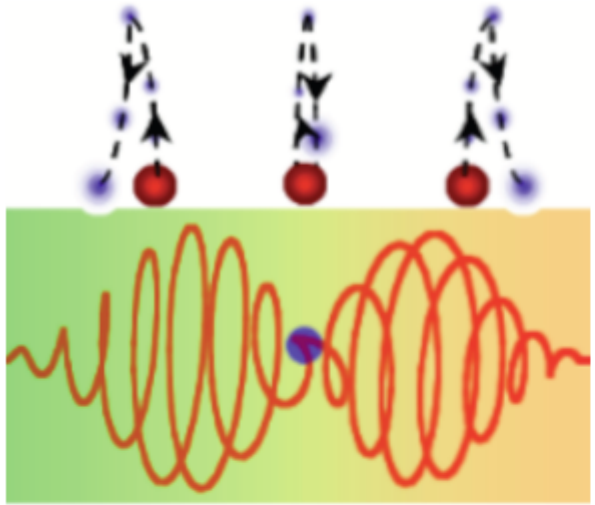
T. Popmintchev, M. C. Chen, P. Arpin, M. M. Murnane, H. C. Kapteyn, *Nature Photonics* **4**, 822 (2010)

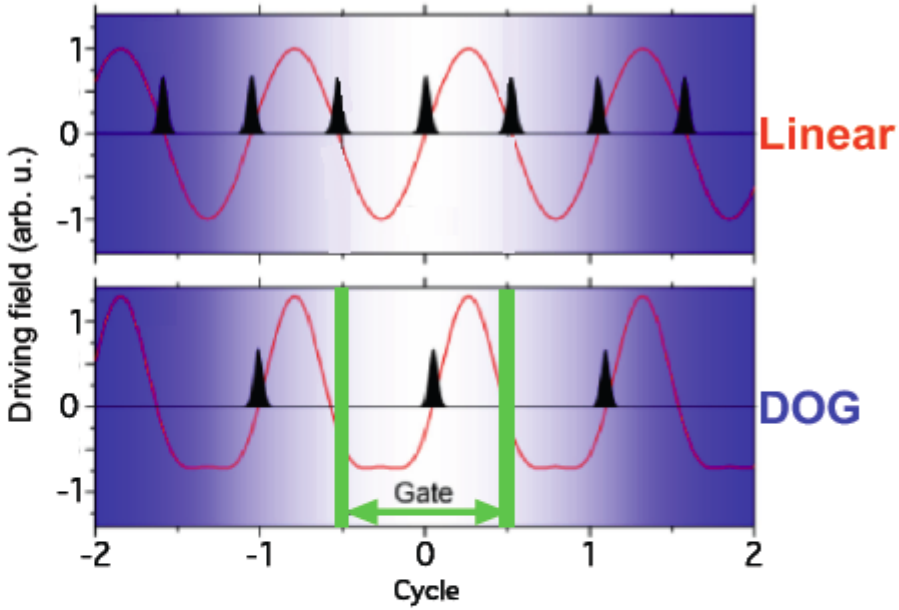
Isolating attosecond pulses I: Amplitude Gating

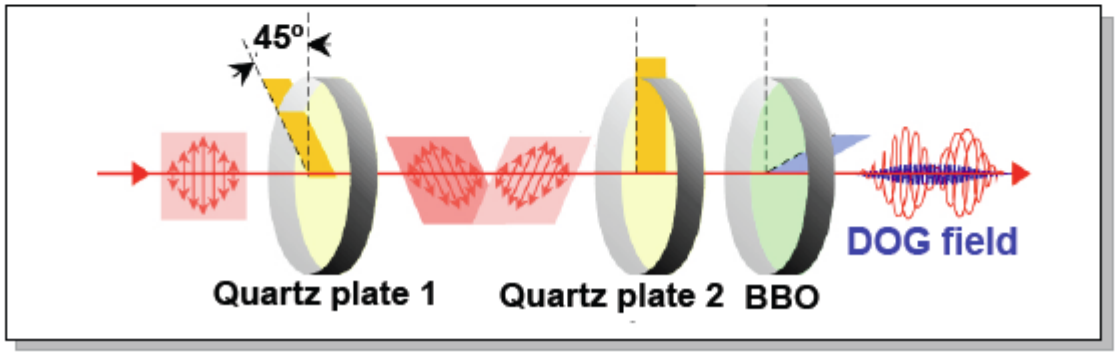


E. Goulielmakis *et al.*, *Science* **320**, 1614 (2008)

Isolating attosecond pulses II: Double Optical Gating







H. Mashiko et. al., Phys. Rev. Lett. 100, 103906 (2008).

New record

NEWS & ANALYSIS

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Florida team sets new ultrashort pulse record

04 Sep 2012

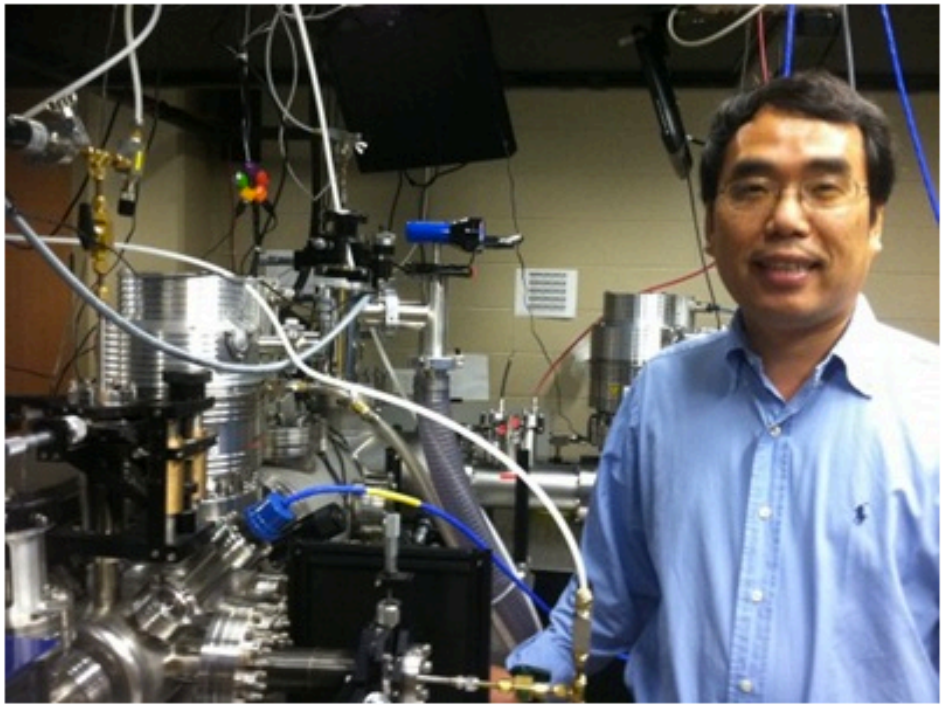
Laser pulse lasting just 67 attoseconds improves on previous best of 80 attoseconds set by German team in 2008.

A new tool to watch quantum effects such as the movement of electrons in chemical reactions is closer to being realized, after a Florida research team set a new record for the world's shortest laser pulse.

Measured at just 67 attoseconds, the mark set by Zenghu Chang and colleagues at the University of Central Florida improves on the previous best of 80 attoseconds, and gets closer to what is regarded as the crucial figure required to "see" electron dynamics and chemical reactions in action.

Chang told *optics.org* that, based on research published in 2005, it is believed that when an electron is suddenly removed, the universal response of molecular and atomic systems lasts for approximately 50 attoseconds. "67 attoseconds is a step closer to meeting the requirement of observing the 50 attoseconds universal response," he pointed out.

Chang and colleagues have been able to improve on the previous record, which was set by a group at the Max-Planck Institute for Quantum Optics in Garching that included the **ultrashort-pulse pioneer Ferenc Krausz**, thanks in part to the use of a new optical technique.



Ultrafast worker: UCF's Zenghu Chang

Outline

Motivation for research on the attosecond timescale

Attosecond pulse generation

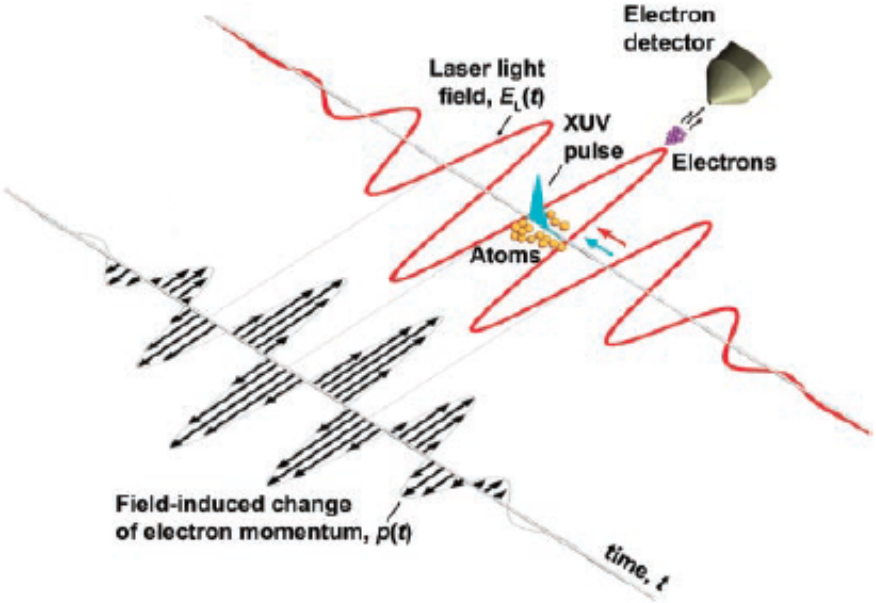
- Femtosecond pulse generation
- High harmonic generation
- Isolating attosecond pulses

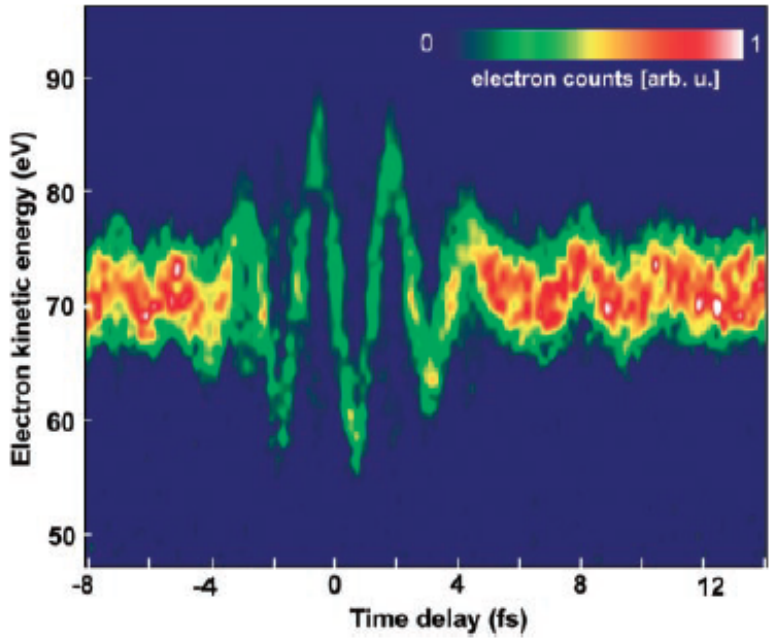
Applications

- Inner-shell spectroscopy
- Attoclock measurements
- Valence electron motion

Conclusion

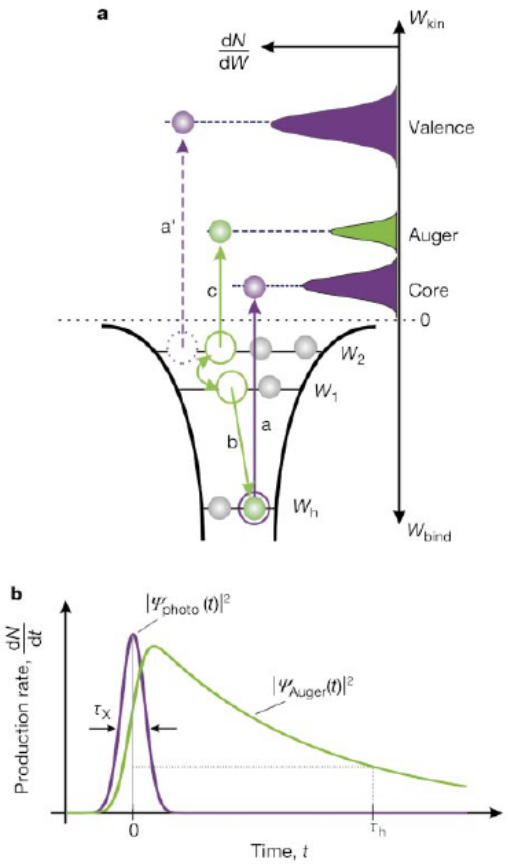
Linear electron streaking

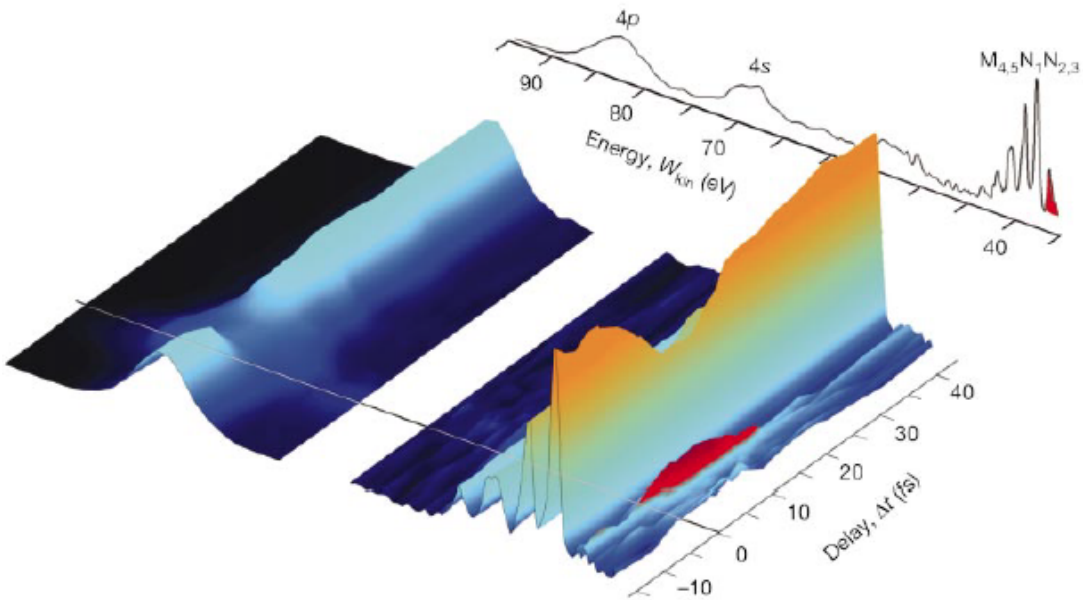




E. Goulielmakis *et al.*, *Science* **305**, 1267 (2004)

Atomic inner-shell spectroscopy



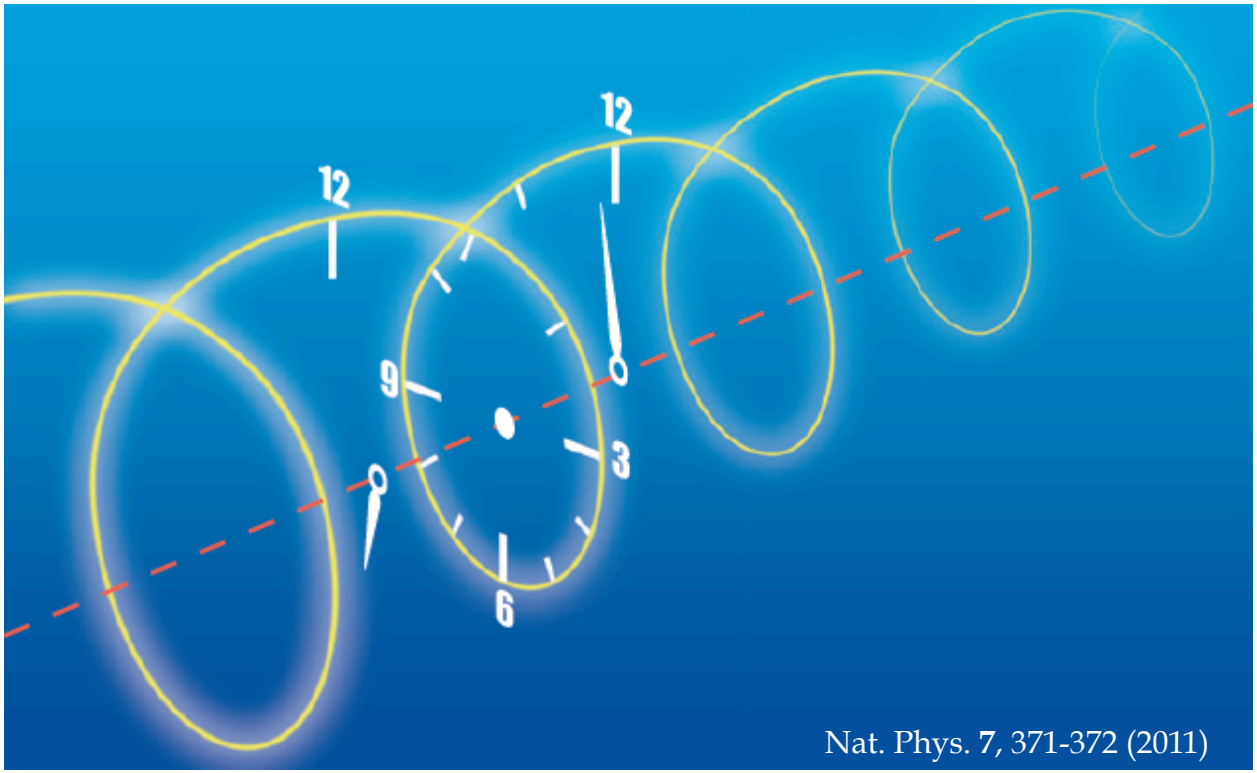


Time domain measurement of the M-shell vacancy lifetime in krypton: 7.9 fs

M. Drescher *et al.*, *Nature* **419**, 803 (2002)

Angular electron streaking: Attoclock

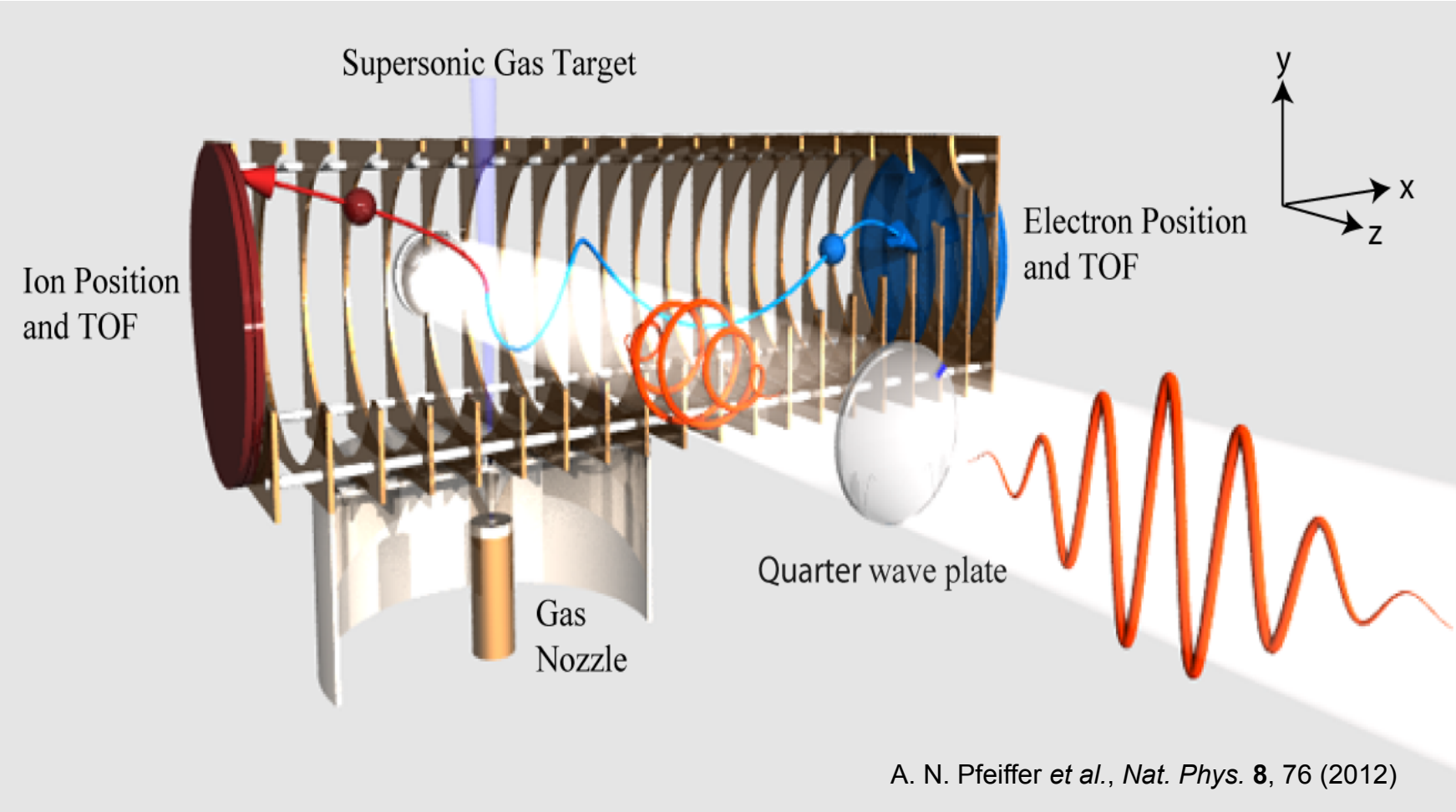
Infrared electric field rotates around 360° within one optical cycle



Magnitude of electron momentum (envelope of the electric field) → Hour hand of the "Attoclock"

Emission angle of electrons (rotating electric field vector) → Minute hand of the "Attoclock"

Attoclock setup



A. N. Pfeiffer *et al.*, *Nat. Phys.* **8**, 76 (2012)

COLTRIMS

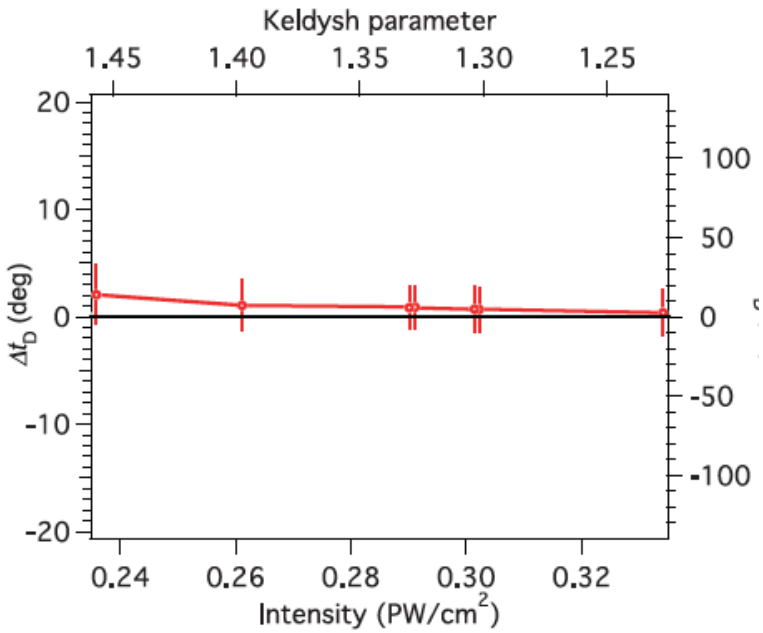
(Cold Target Recoil Ion Momentum Spectroscopy)

R. Dörner *et al.*, *Phys. Rep.* **330**, 95 (2000)

Attoclock measurements

Tunneling delay time

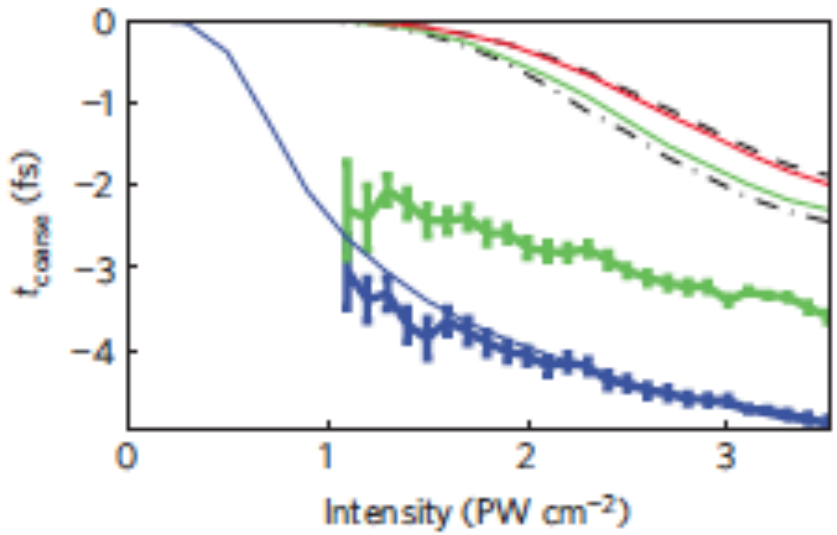
(He, single ionization)



P. Eckle *et al.*, *Science* **322**, 1525 (2008)

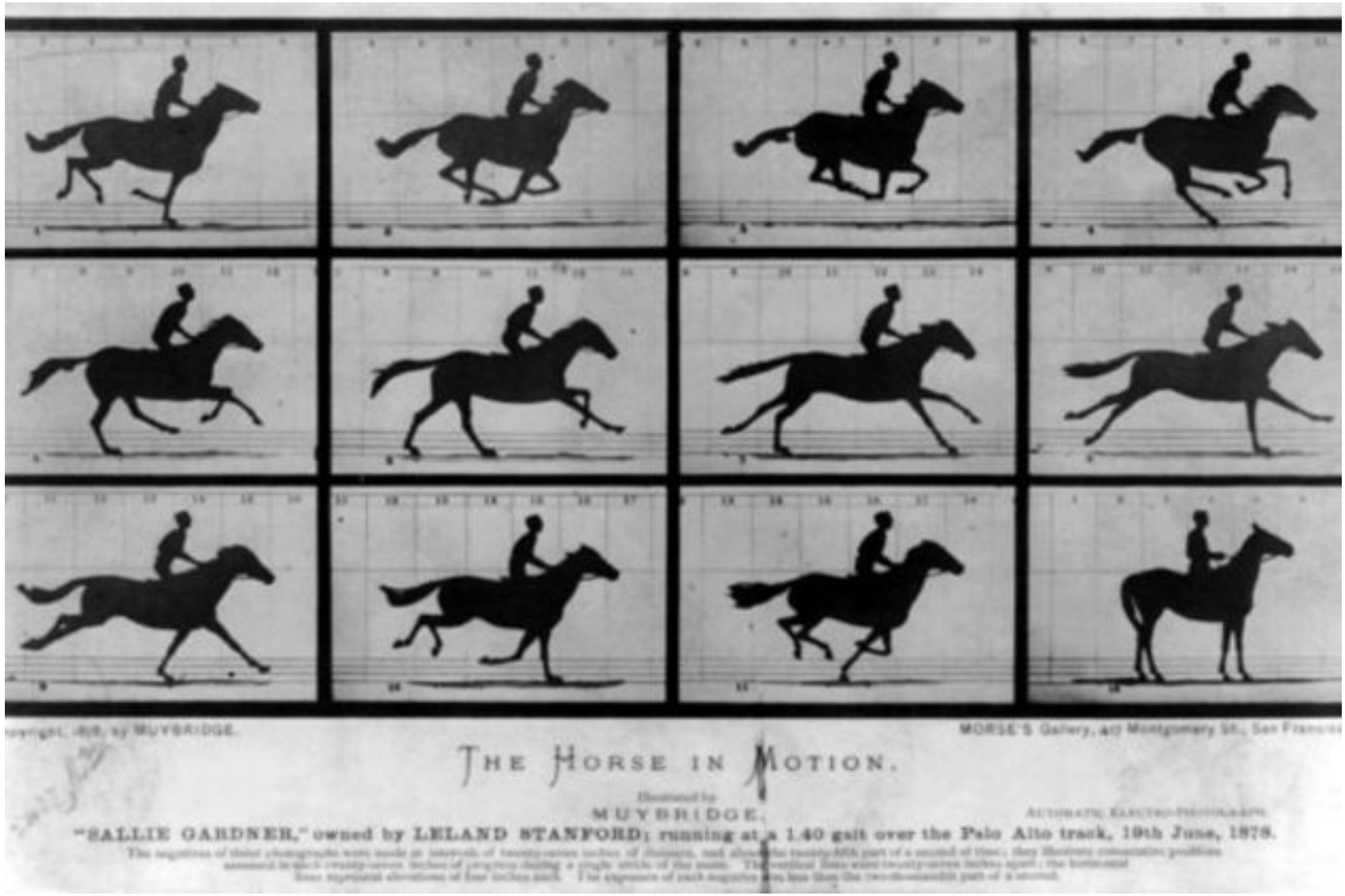
Ionization times

(Ar, double ionization

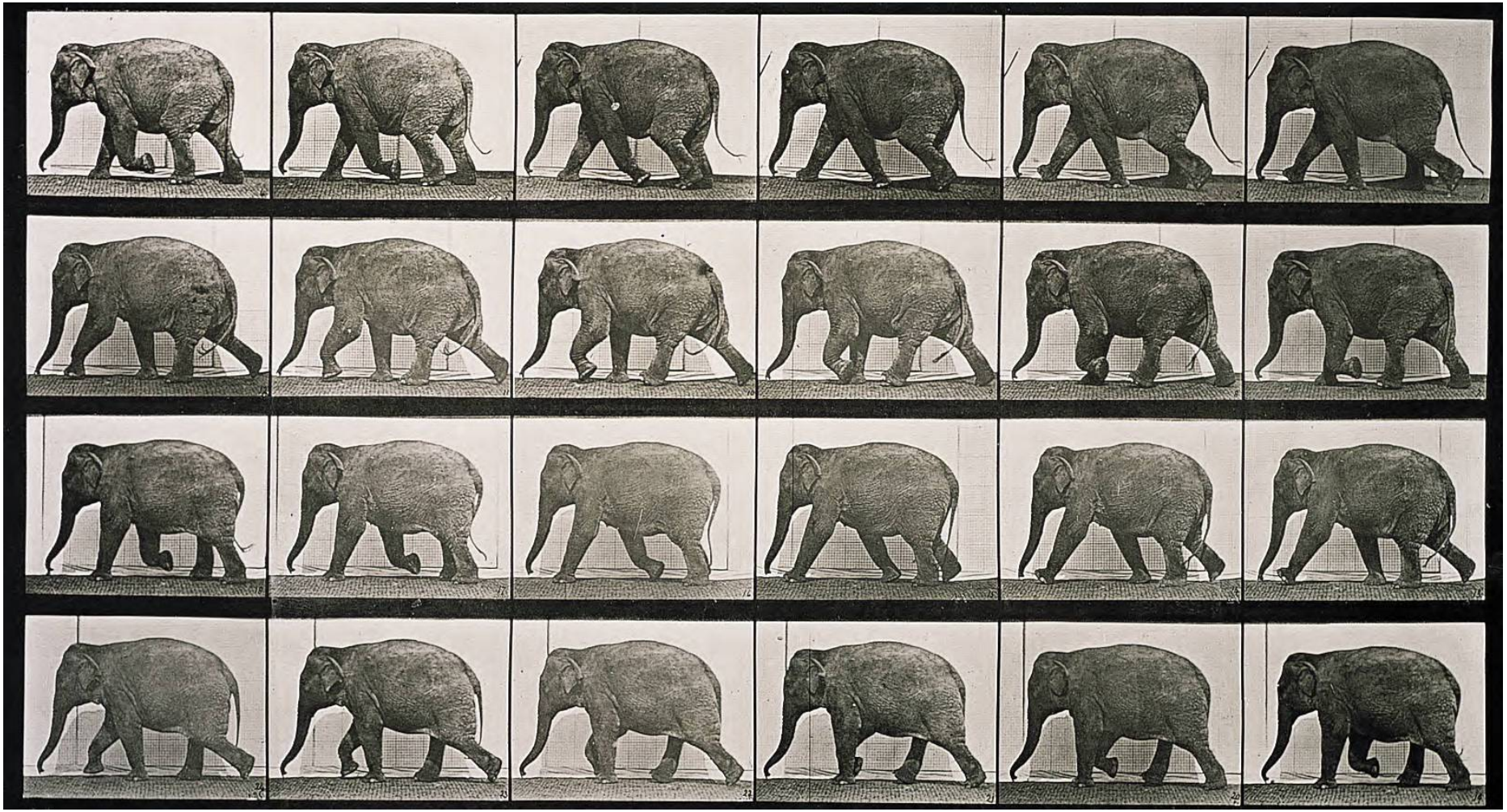


A. N. Pfeiffer, C. Cirelli, M. Smolarski, R. Dörner, U. Keller, *Nat. Phys.* **7**, 428 (2011)

Electro-Photography

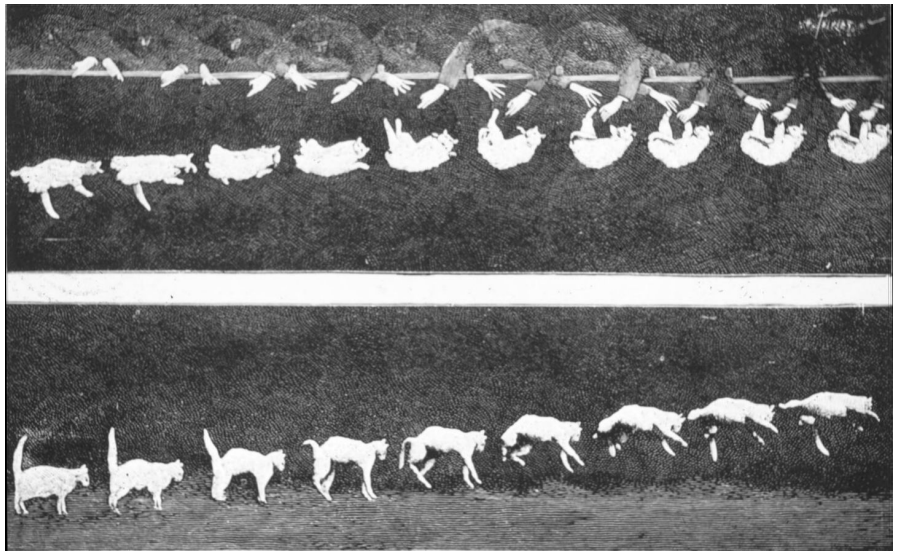


Electro-Photography: Slow Systems



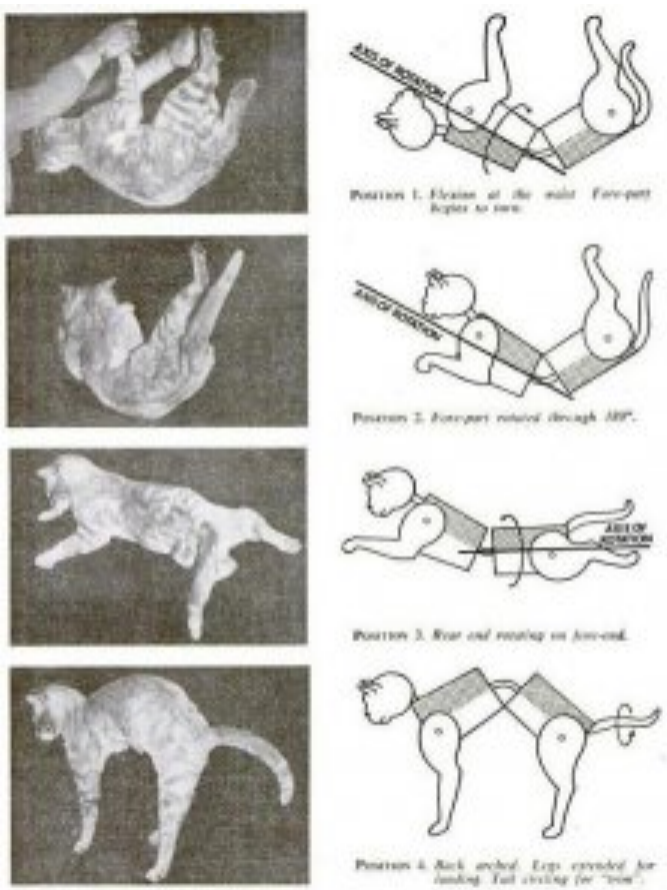
Electro-Photography: Fast Systems

Frame rate: 60 /s



Etienne Jules Marey, 1894

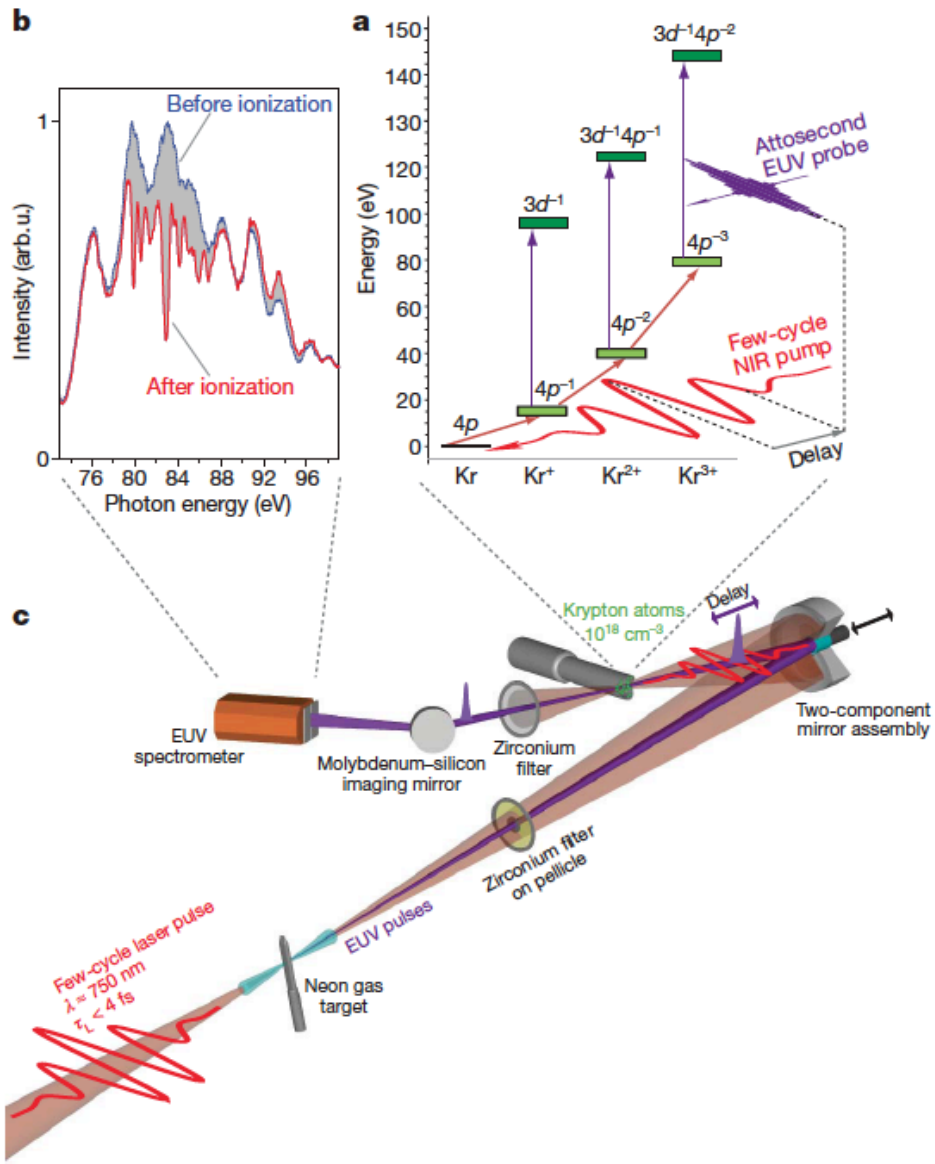
Frame rate: 1500 /s



1/8 s

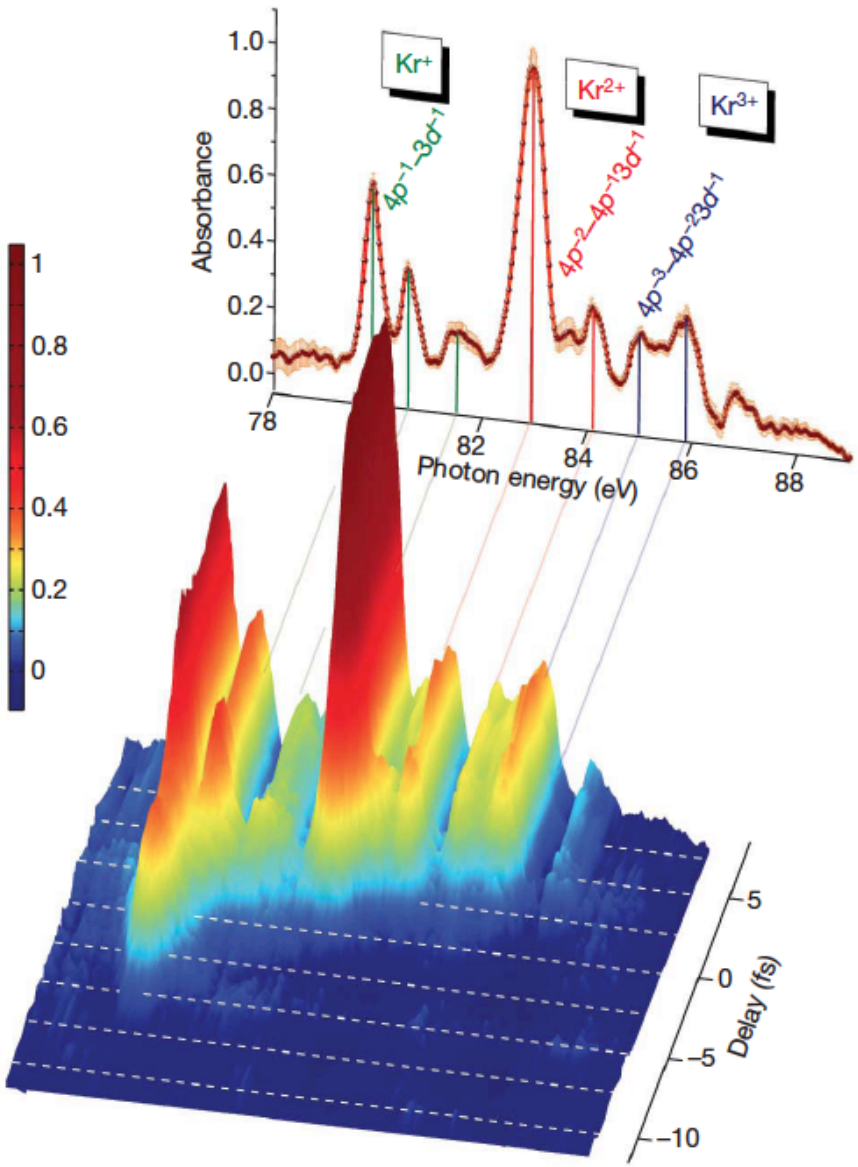
McDonald, “How does a cat fall on its feet?”, The New Scientist, **7**, no. 189, pp. 1647 (1960).

Attosecond transient absorption



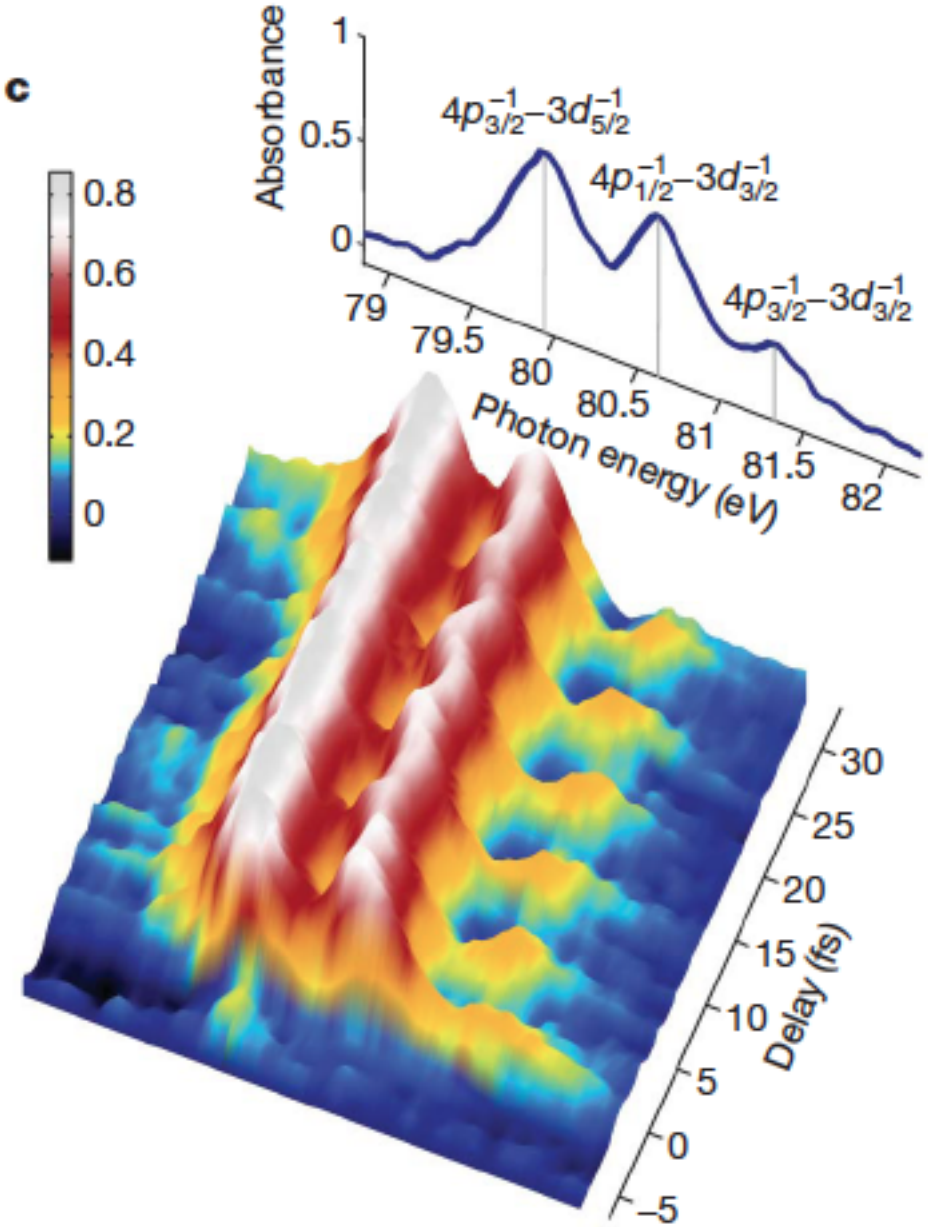
Goulielmakis, E. *et al.* Real-time observation of valence electron motion. *Nature* 466, 739 (2010)

Absorption of Kr^{2+} and Kr^{3+}



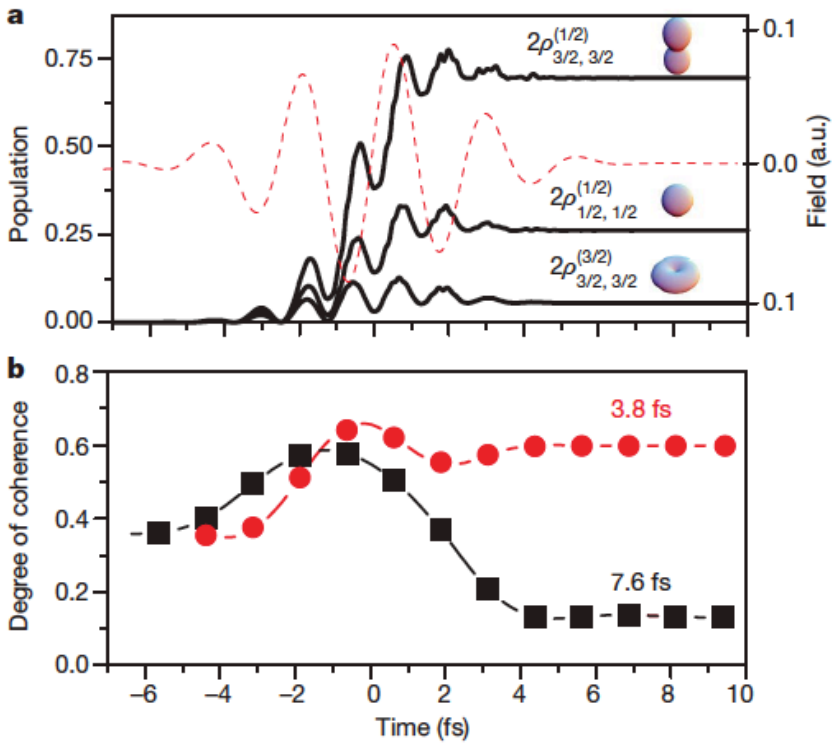
Goulielmakis, E. *et al.* Real-time observation of valence electron motion. *Nature* 466, 739 (2010)

Transient absorption

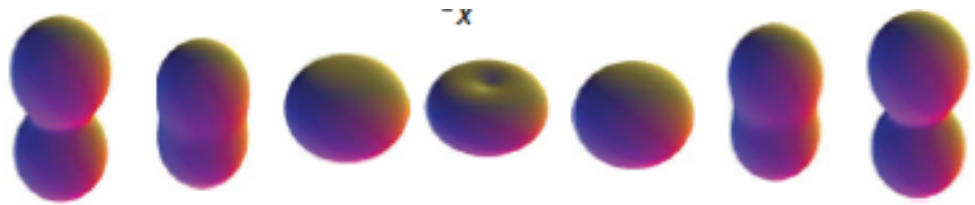


Goulielmakis, E. *et al.* Real-time observation of valence electron motion. *Nature* 466, 739 (2010)

Population dynamics of the density matrix



Reconstruction of valence-shell electron wave-packet motion

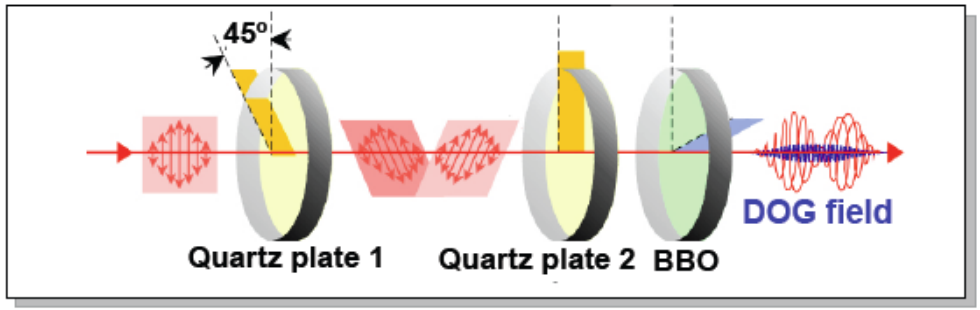


Goulielmakis, E. *et al.* Real-time observation of valence electron motion. *Nature* 466, 739 (2010)

Conclusion

Attosecond pulse generation

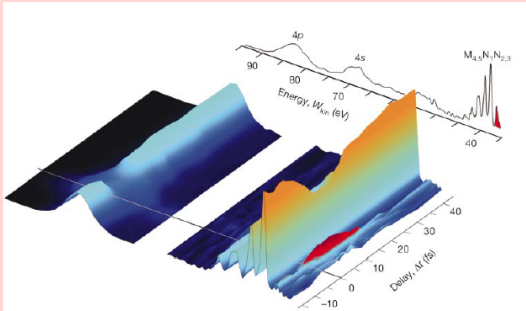
Double optical gating



H. Mashiko et. al., Phys. Rev. Lett. 100, 103906 (2008).

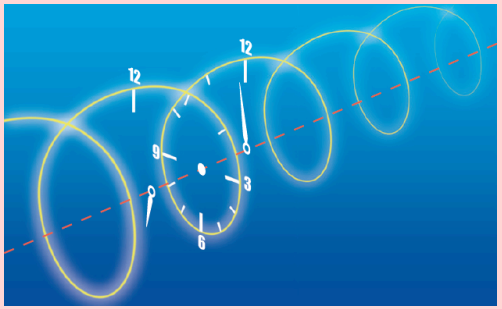
Attosecond experiments

Inner shell spectroscopy



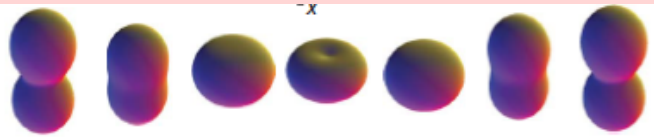
M. Drescher *et al.*, *Nature* **419**, 803 (2002)

Attoclock measurements



Nat. Phys. **7**, 371-372 (2011)

Valence electron motion



E. Goulielmakis *et al.*, *Nature* **466**, 739 (2010)