Attosecond Physics: A “Spin-Off” of Strong Field (Intense Laser) Physics

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General References:

- F. Krausz and M. Ivanov, Rev. Mod. Phys. **81**, 163 (2009)
- http://www.attoworld.de/Home/attoworld/

Map of the U.S.A.

University of Nebraska Campus: Summer Evening

University of Nebraska Campus: Fall Morning

University of Nebraska Campus: Winter Scene

University of Nebraska Campus: Spring Scene

Outline

- ***Motivation***
- ***Background: The Development of Intense Laser Fields***
- ***Key Results of Strong Field Physics***
- ***Ultrafast Processes: The Realm of Attosecond Physics***
- ***Few-Cycle, Intense Attosecond Pulses: Nonlinear Attosecond Physics***
- ***Concluding Remarks***

Motivation

Motivation

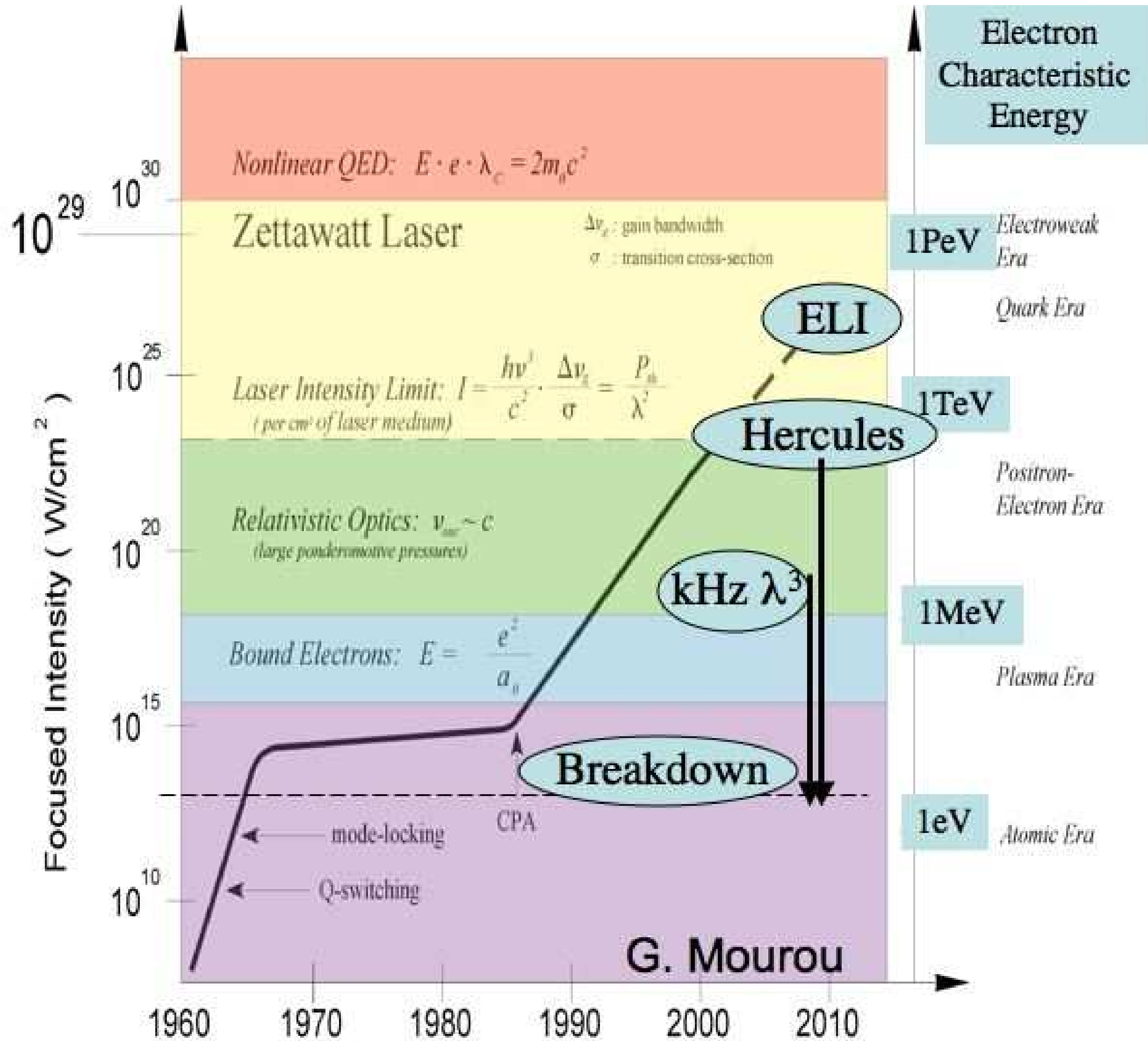
Key Goals of Attosecond Physics: Understand and control ultrafast atomic and molecular processes.

Key requirements:

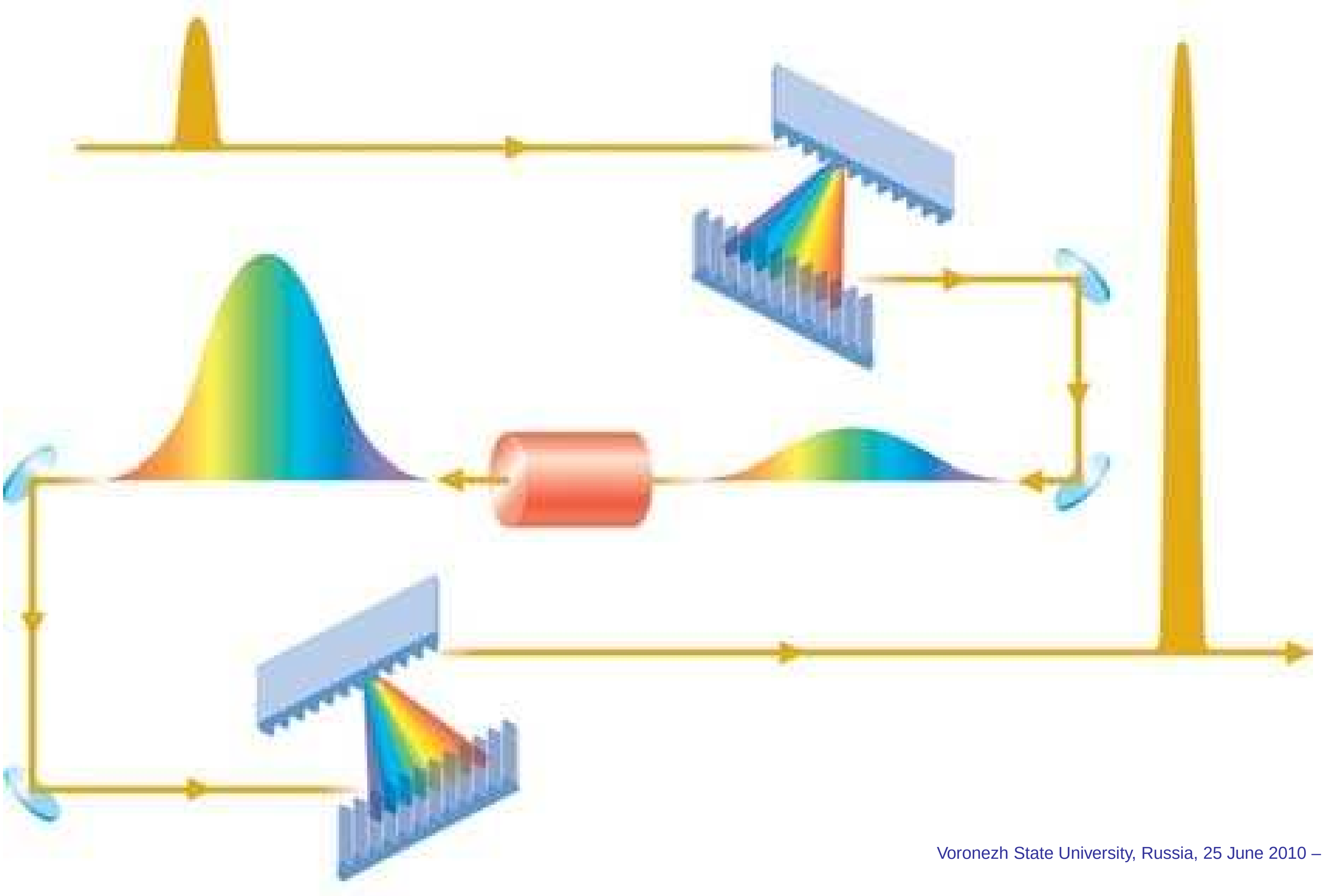
- Laser pulses must be ultrashort, i.e., shorter than the timescale of atomic and molecular processes
  - *Partial Solution*: optically compress the laser pulses
  - *Key Limitation*: Ti:sapphire lasers (800 nm) have a period of 2.7 fs
- Laser electric fields must be comparable in strength to those within atoms and molecules, i.e., so that such processes can be controlled
  - *Key problem*: intense laser fields can destroy optical components!
  - *Solution*: chirped pulse amplification (CPA)

Background: The Development of Intense Laser Fields

Historical Overview of Increases in Laser Intensities

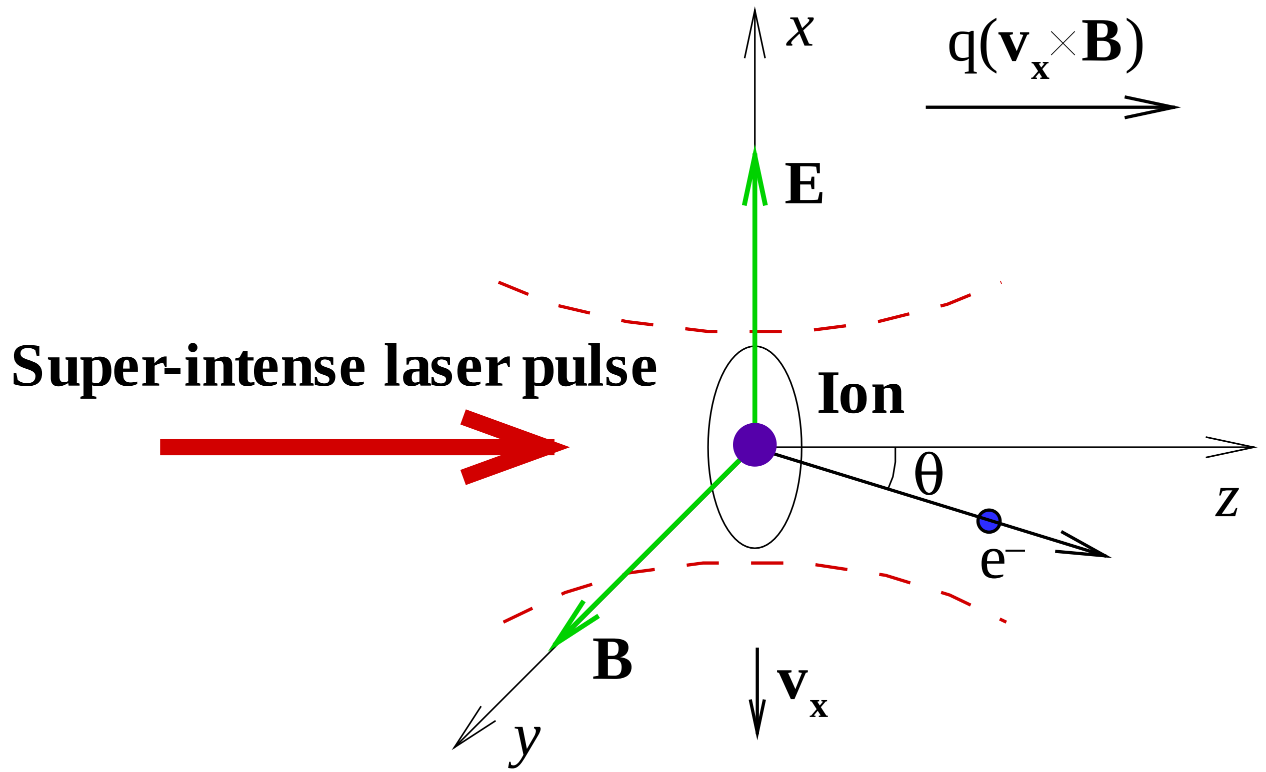


Chirped Pulse Amplification (CPA)



Geometry of Intense Laser Ionization of a Highly Charged Ion Target

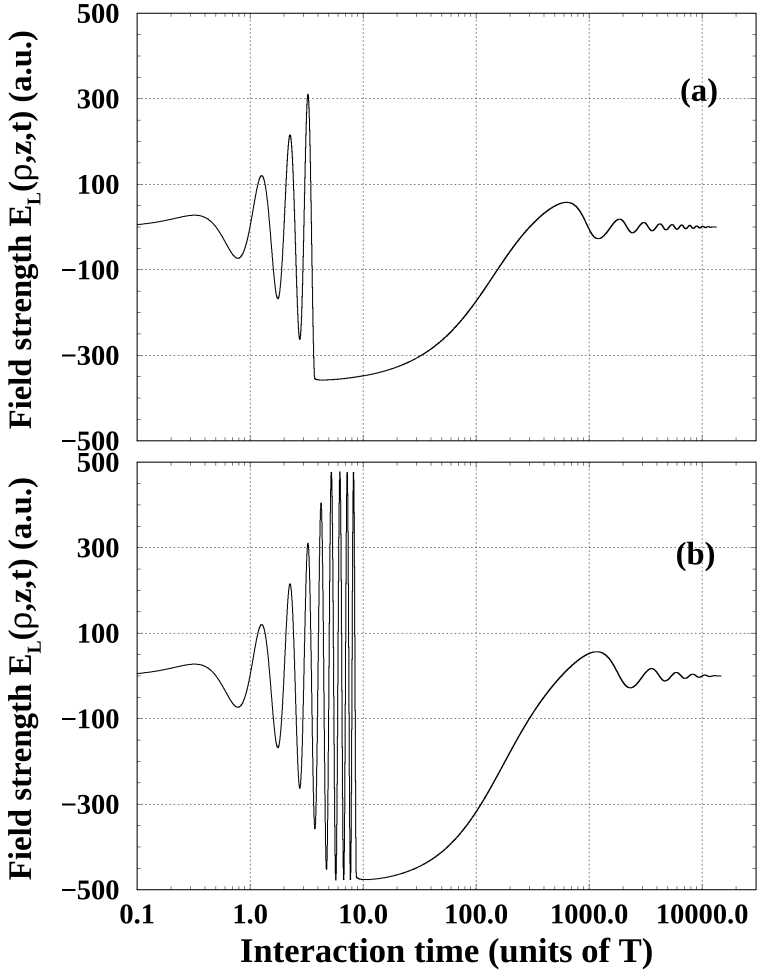
[S.X. Hu and A.F. Starace, Phys. Rev. Lett. **88**, 245003 (2002)]

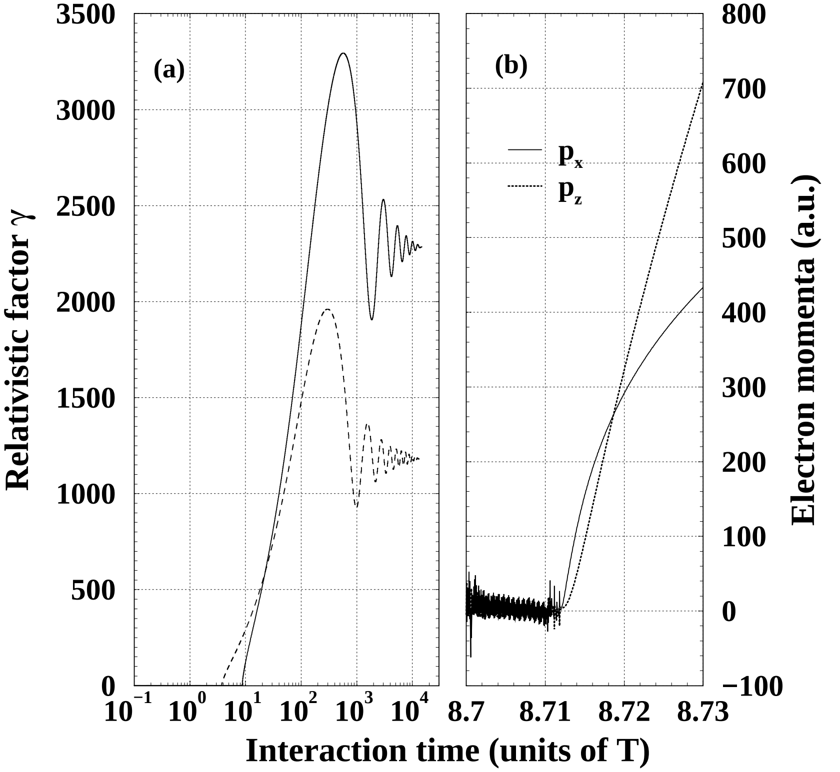


J.D. Gillaspy, JPB **34**, R93 (2001): "Any charge state of any ion can be produced."

Illustration of Electron Energy Gain Following Ionization of V^{22+}

[S.X. Hu and A.F. Starace, Phys. Rev. Lett. **88**, 245003 (2002)]

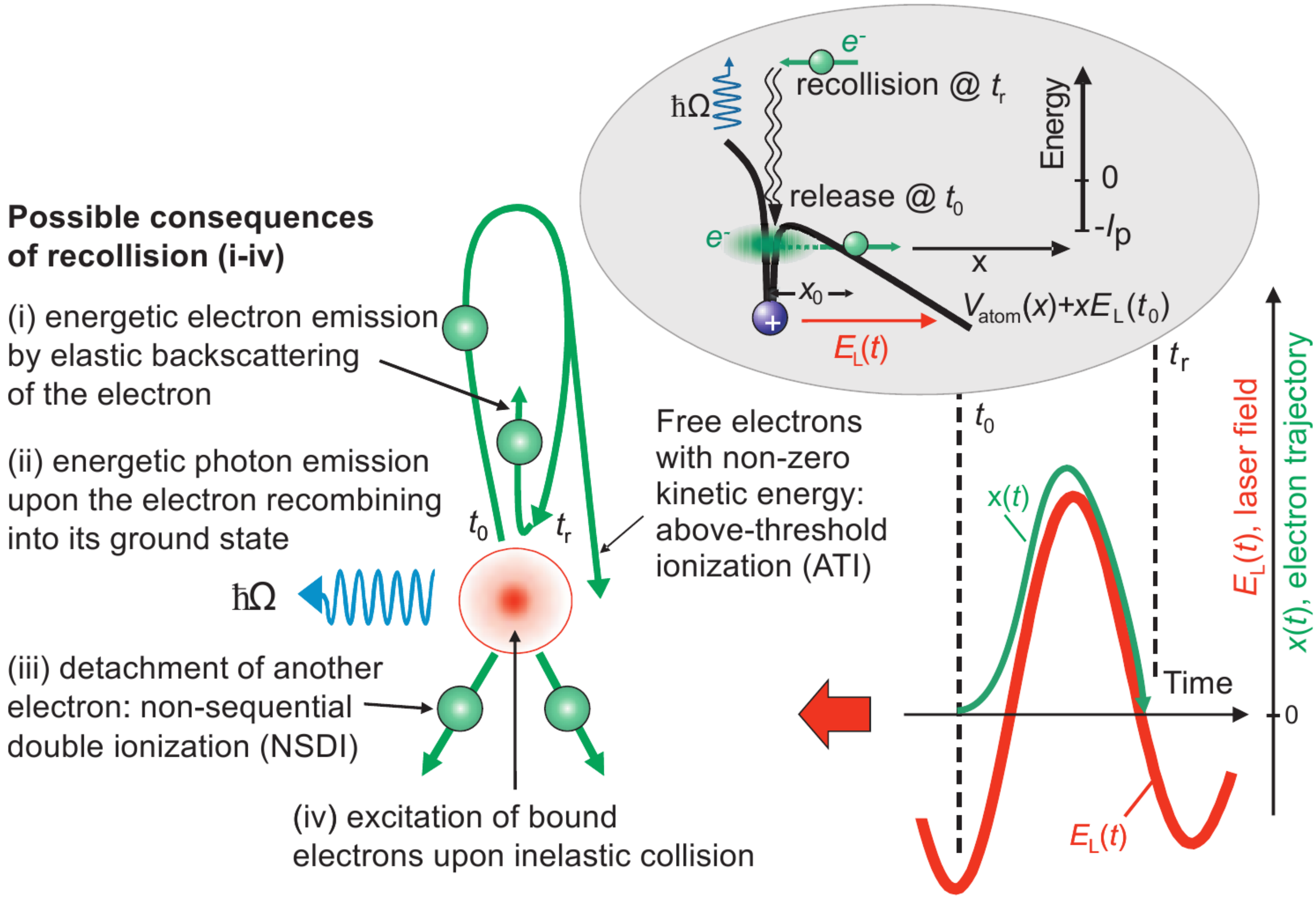




$I = 8 \times 10^{21}$ W/cm^2, $\lambda = 1054$ nm, 15-cycle laser pulse, $w_0 = 10\,\mu$m.

Key Results of Strong Field Physics

3 Step Scenario



Non-Perturbative Plateau Features

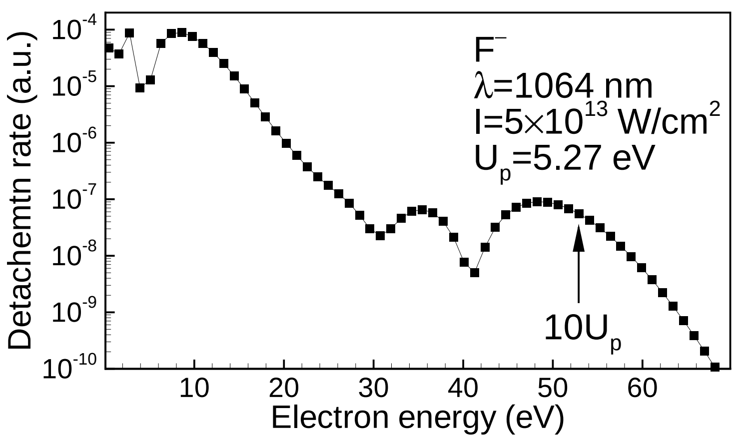
- **Key laser-atom processes: above threshold ionization (ATI) and high-order harmonic generation (HHG)**

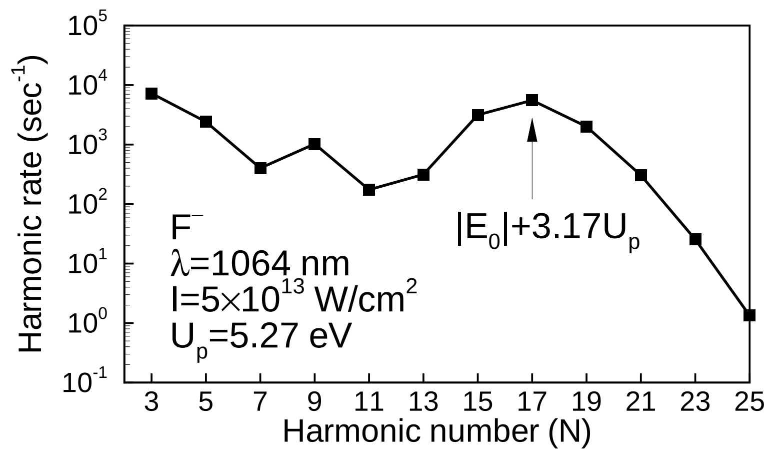
[M.V. Frolov, A.V. Flegel, N.L. Manakov, and A.F. Starace, J. Phys. B **38**, L375 (2005)]

  - *Plateau structure in ATI/ATD spectra, with cutoff near* $E_c \approx 10U_p$
  - *Plateau structure in HHG spectra, with cutoff near*

$$N_c\hbar\omega \approx |E_0| + 3.17U_p,\ U_p = \frac{e^2F^2}{4m\omega^2}, \quad E_0 = -\frac{\hbar^2\kappa^2}{2m} =$$

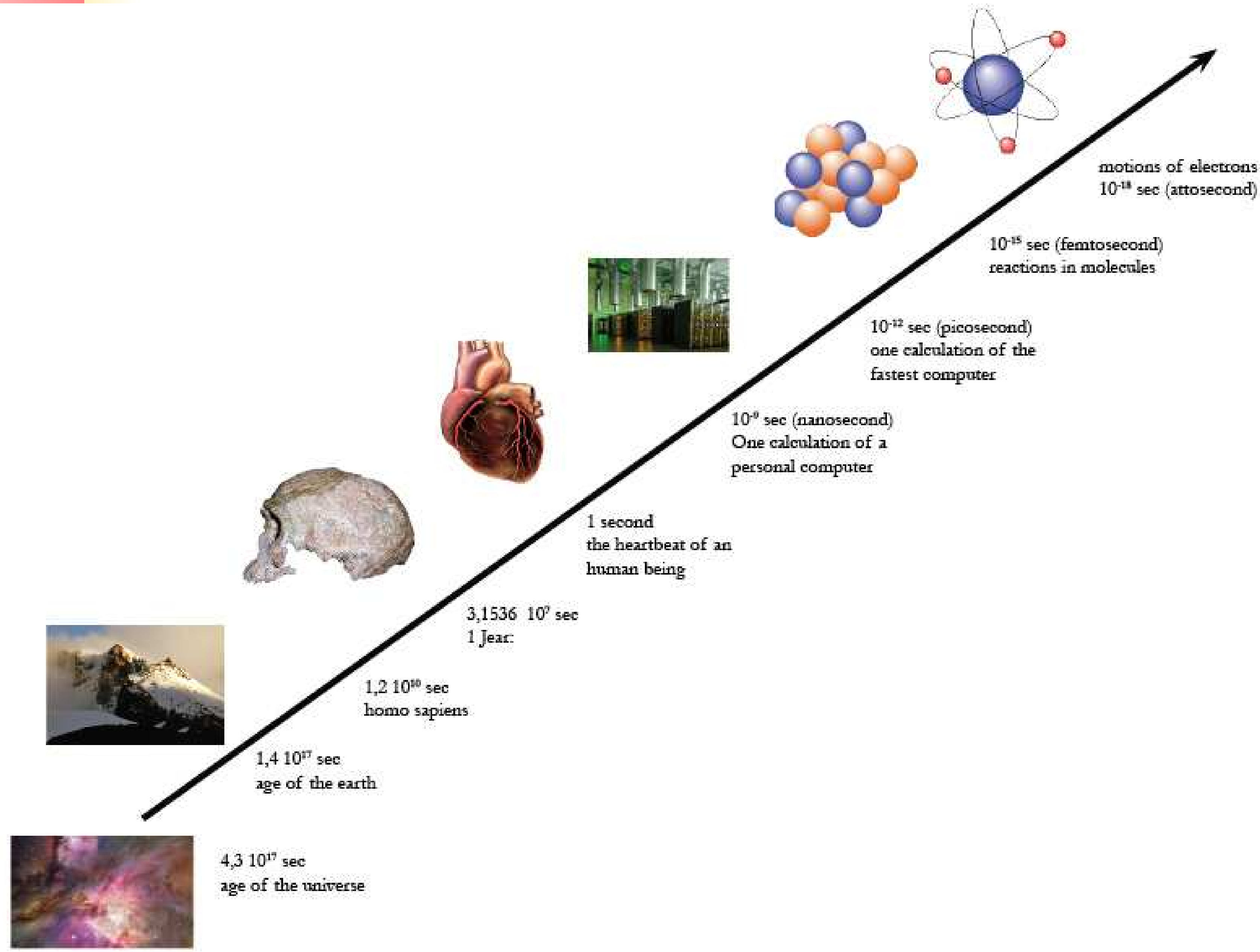
binding energy of the initial state



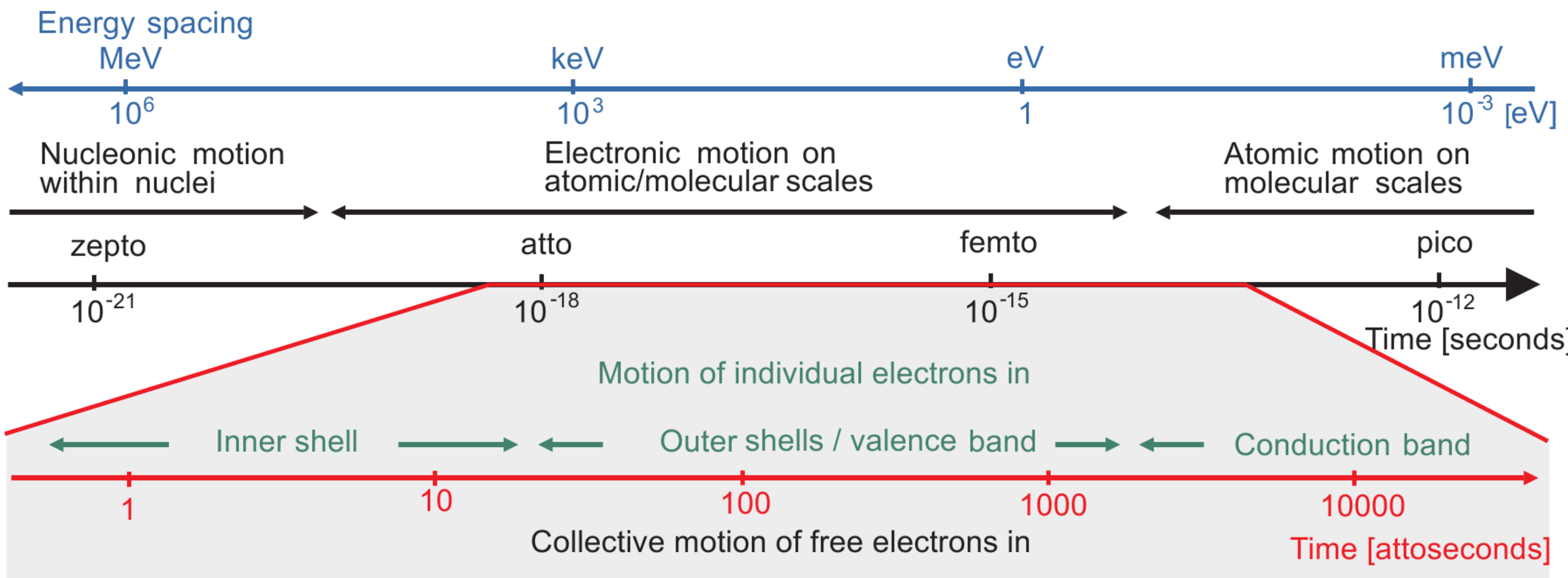


Ultrafast Processes: The Realm of Attosecond Physics

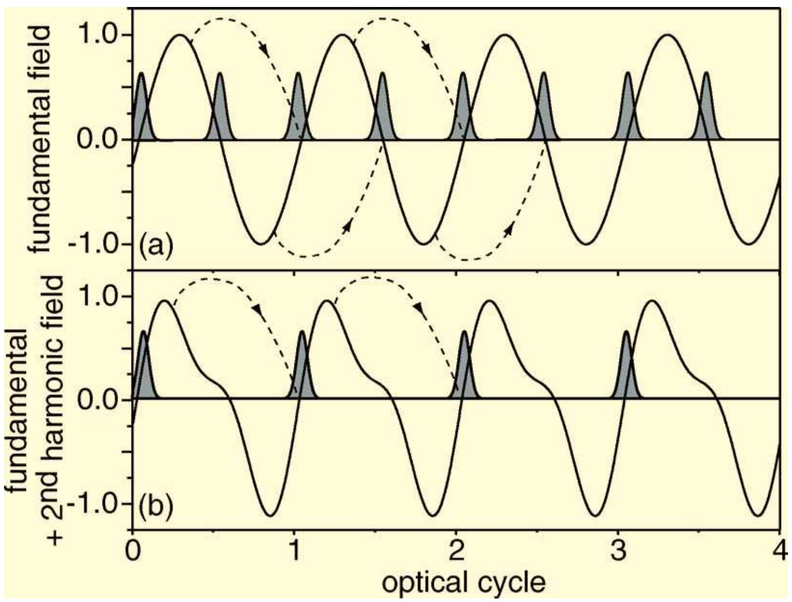
Time Scales

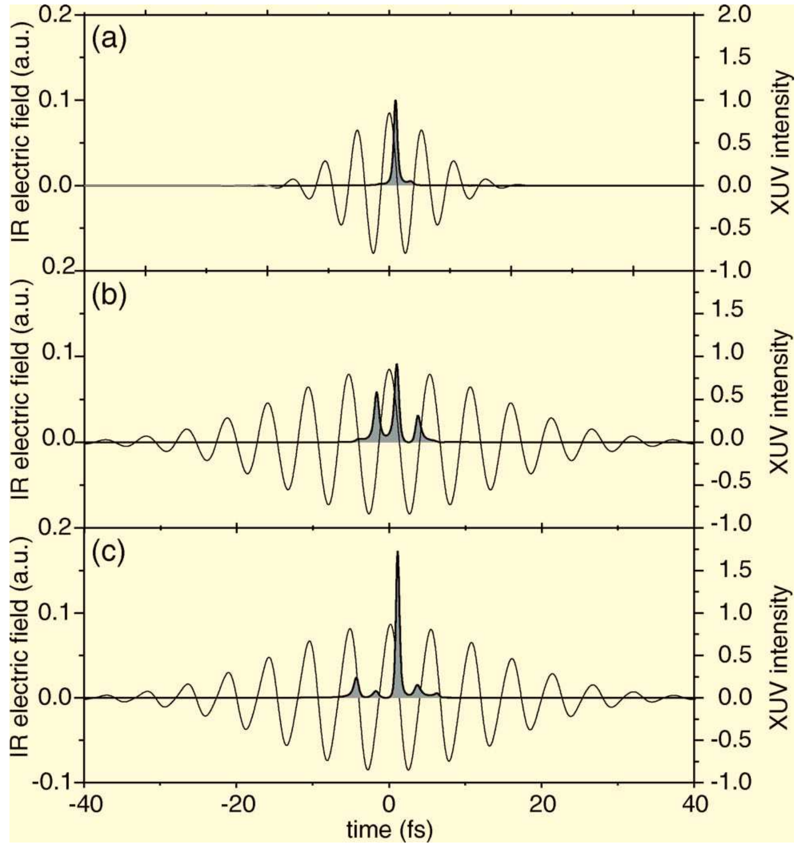

motions of electrons
10^{-18} sec (attosecond)
10^{-15} sec (femtosecond)
reactions in molecules
10^{-12} sec (picosecond)
one calculation of the
fastest computer
10^{-9} sec (nanosecond)
One calculation of a
personal computer
1 second
the heartbeat of an
human being
3,1536 10^{7} sec
1 Jear:
1,2 10^{10} sec
homo sapiens
1,4 10^{17} sec
age of the earth
4,3 10^{17} sec
age of the universe

Time Scales


Energy spacing
MeV
keV
eV
meV
10^6
10^3
1
10^-3 [eV]
Nucleonic motion within nuclei
Electronic motion on atomic/molecular scales
Atomic motion on molecular scales
zepto
atto
femto
pico
10^-21
10^-18
10^-15
10^-12
Time [seconds]
Motion of individual electrons in
Inner shell
Outer shells / valence band
Conduction band
1
10
100
1000
10000
Collective motion of free electrons in
Time [attoseconds]

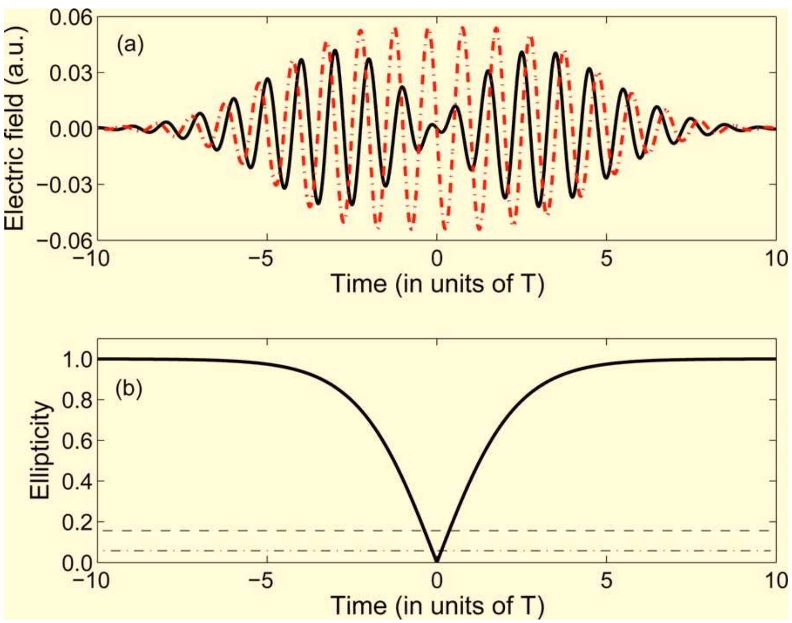
Generation of a Single Atto Pulse

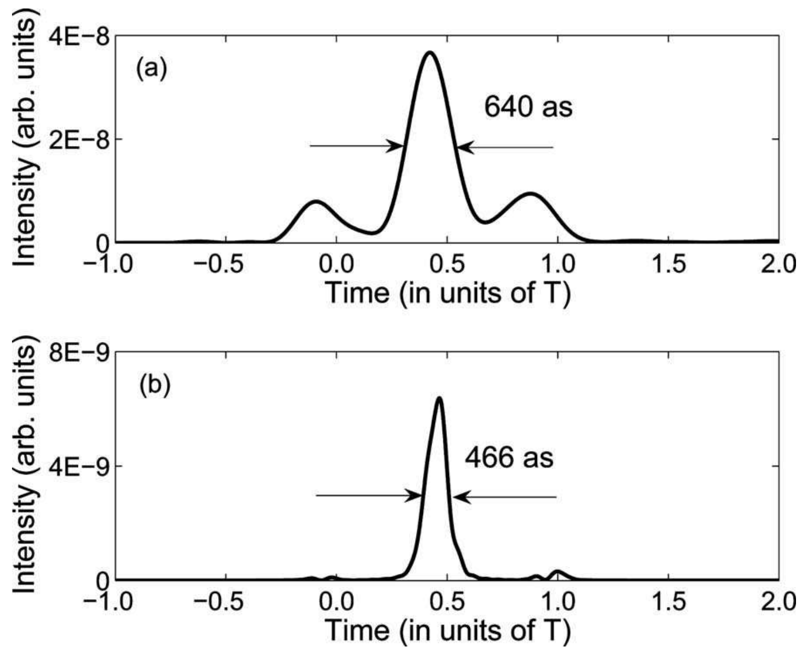




T. Pfeifer et al, *Optics Letters* **31**, 975 (2006)

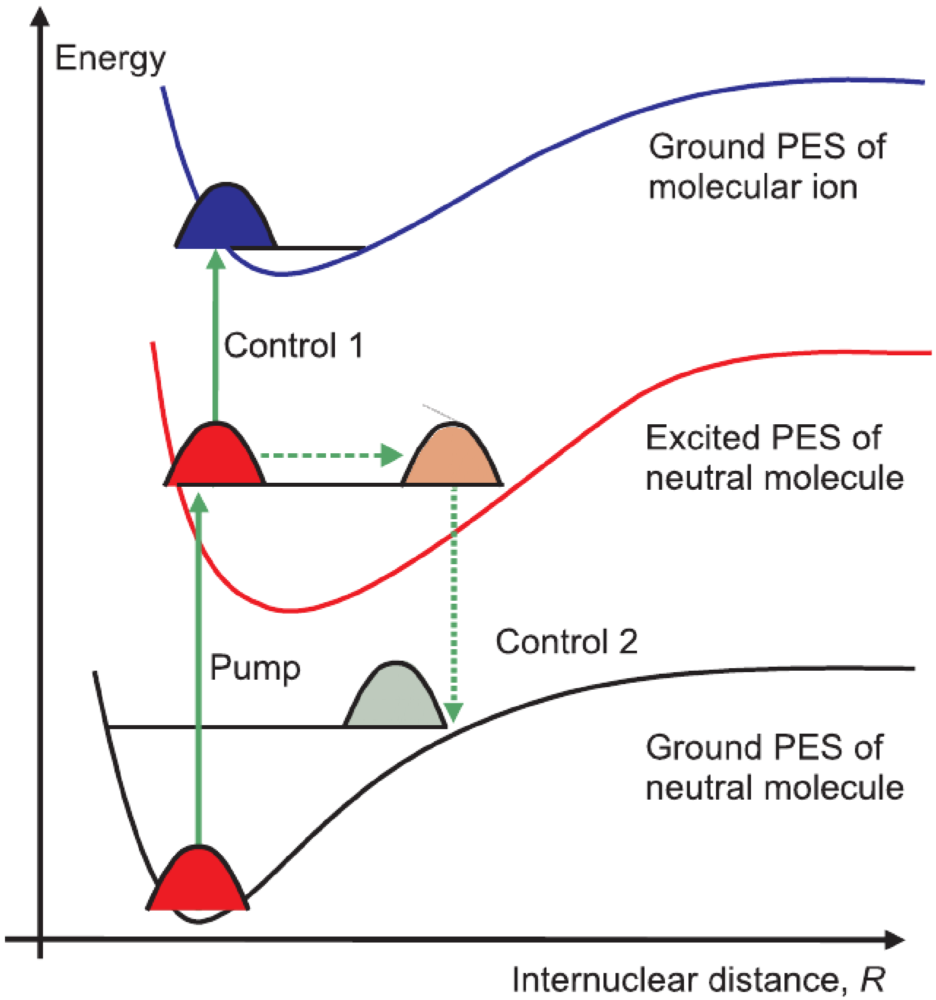
Two counter-propagating, circularly-polarized laser pulses



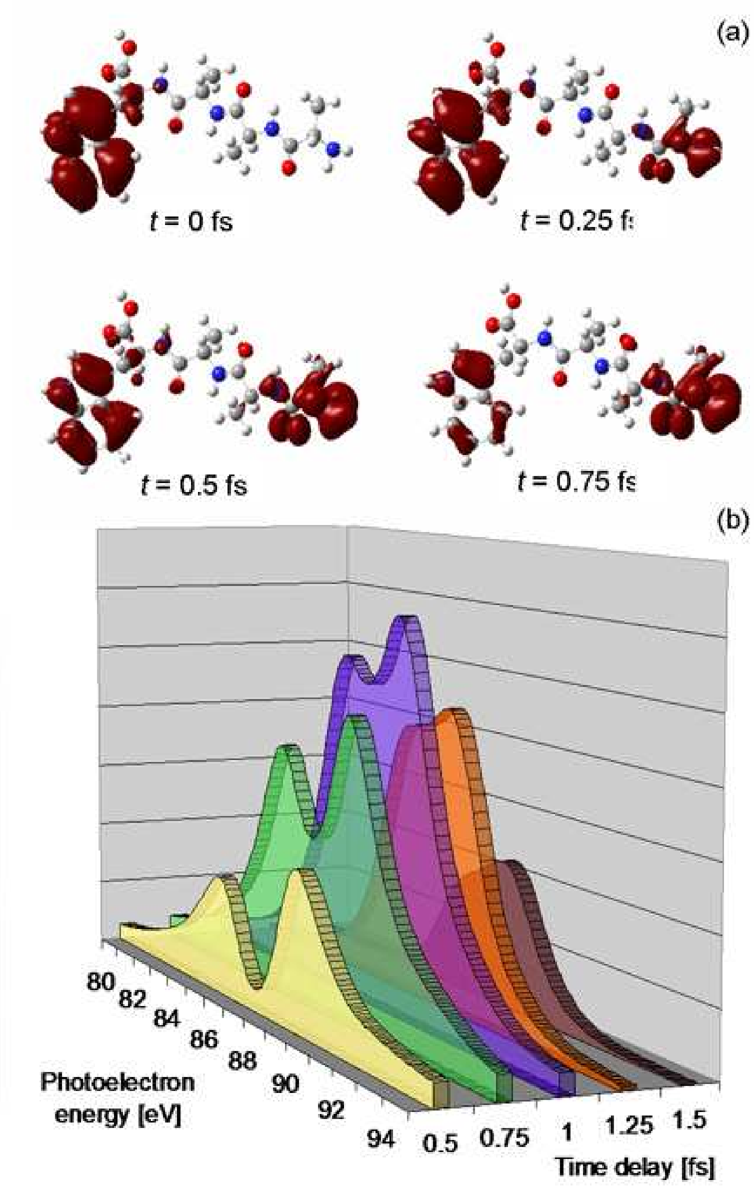


F. He, C. Ruiz, and A. Becker, *Optics Letters* **32**, 3224 (2007)

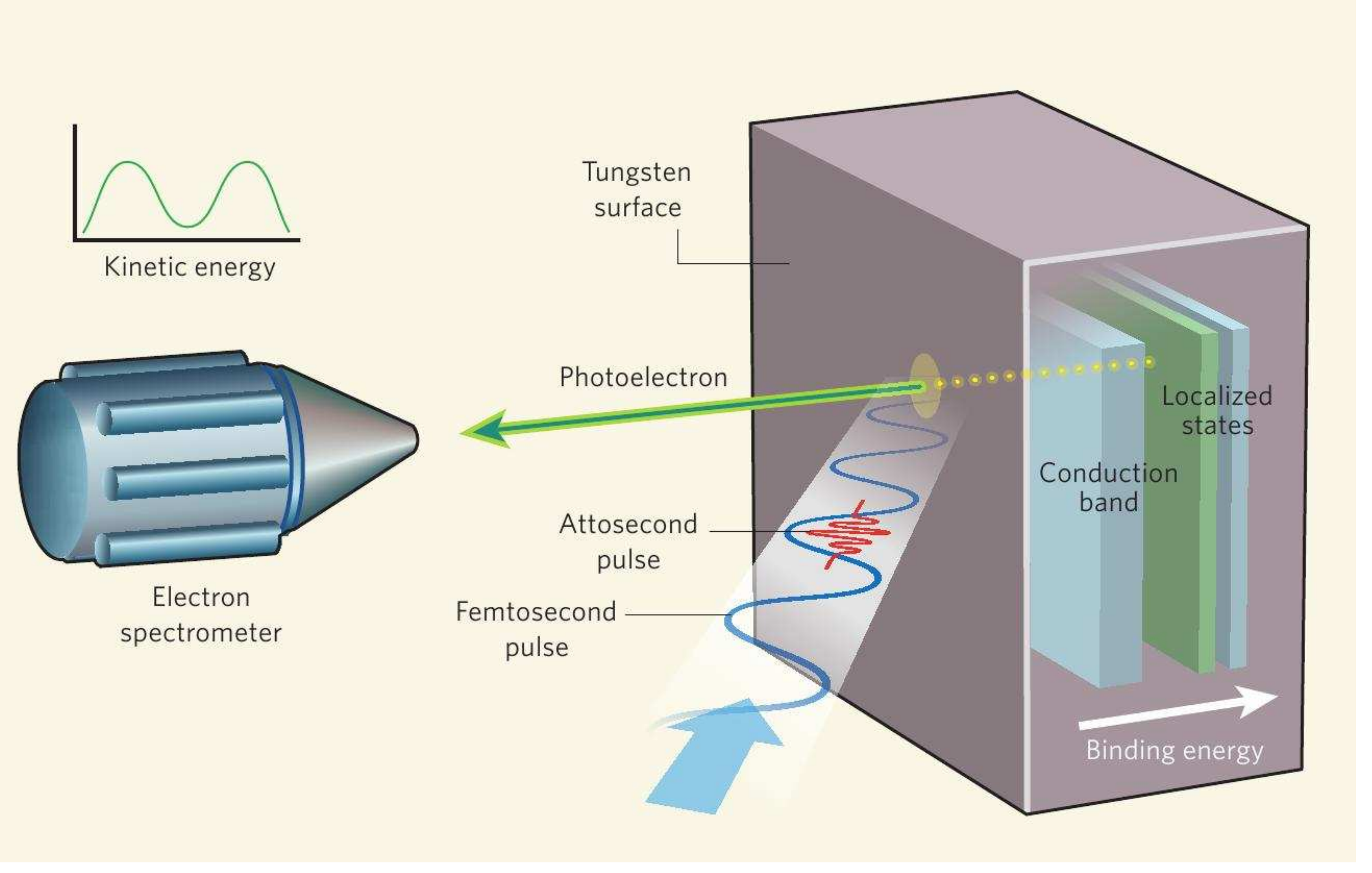
Pump-Probe Control of Molecular Processes



Electronic Excitation Transport in a Biomolecule *(R.D. Levine and J.-F. Remacle)*

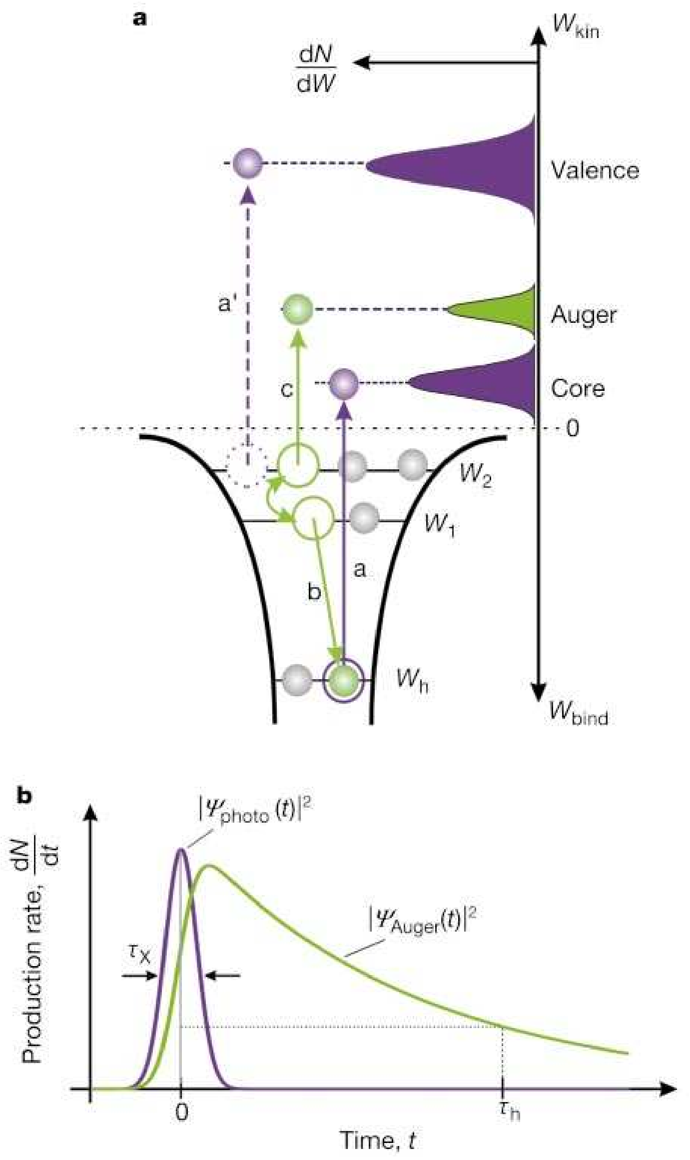


Atomic Scale Transport in Solids



D. M. Villeneuve, *Nature* **449**, 997 (2007)

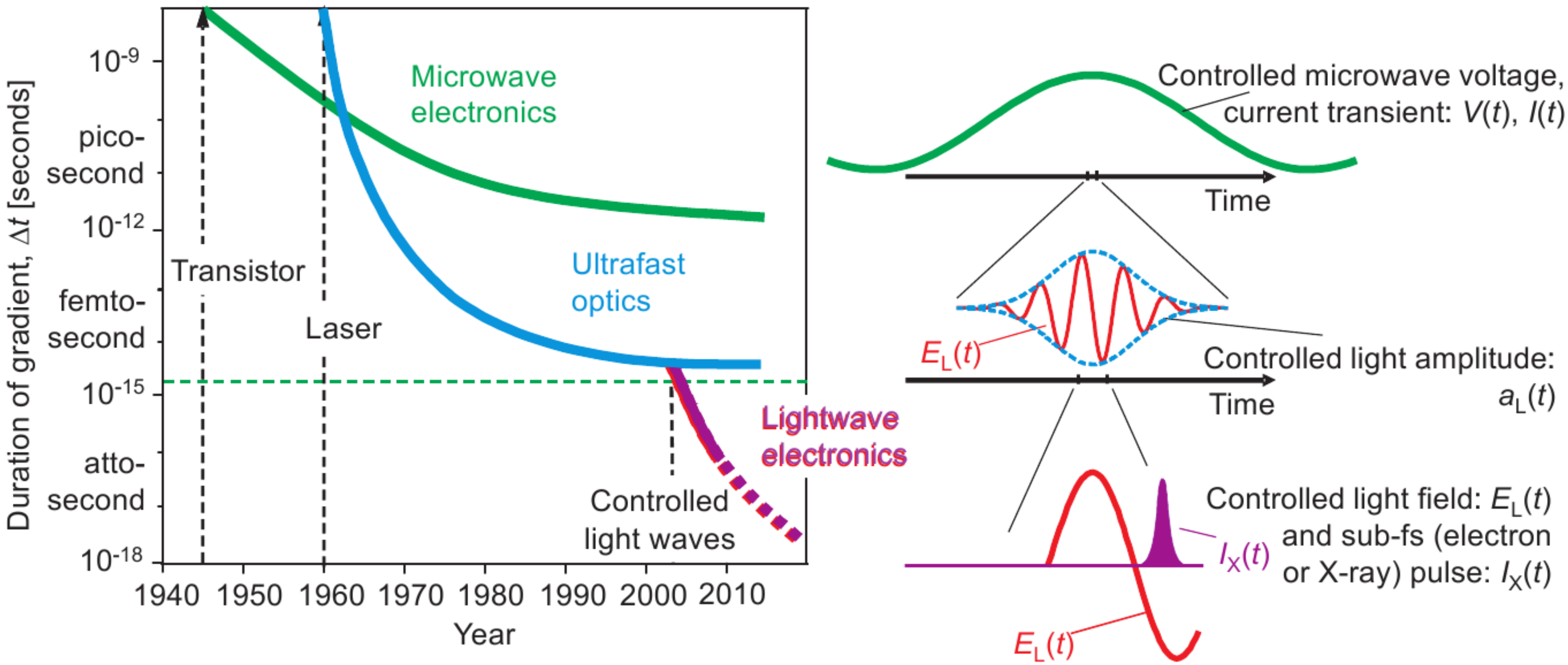
Temporal Development of an Auger Process



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

Few-Cycle, Intense Attosecond Pulses: Nonlinear Attosecond Physics

Ultrafast Science



Free Electron in a Laser Field

$$\ddot{x} = -E_L(t),$$

$$E_L(t) = -\frac{dA_L(t)}{dt},$$

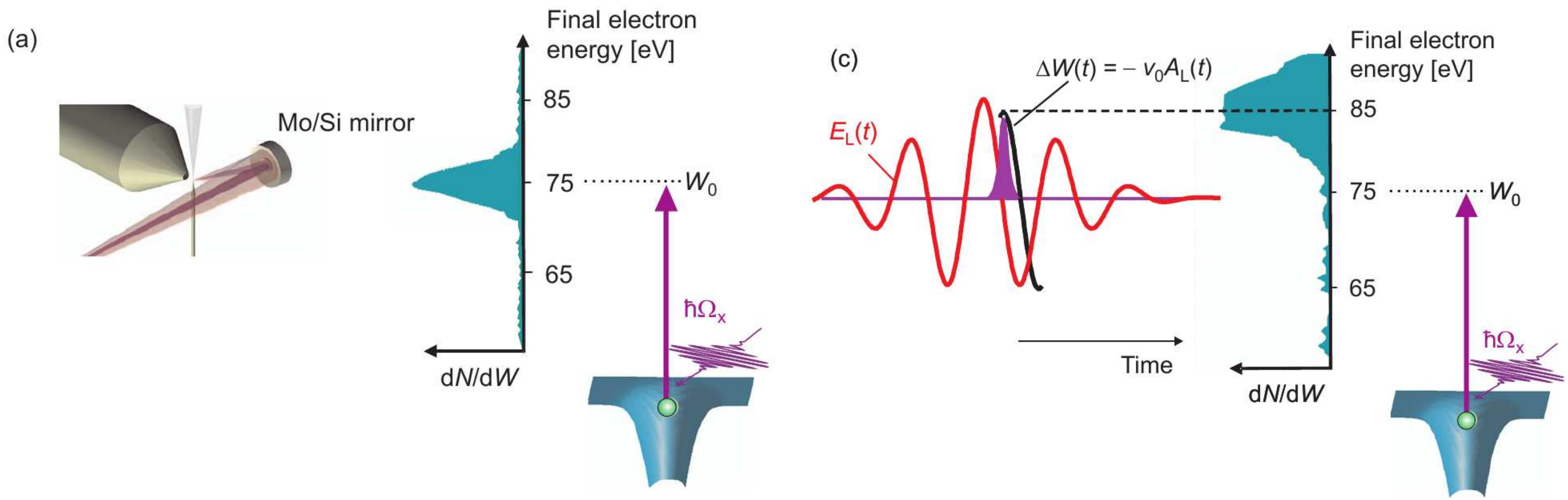
$$v(\infty) = v(t_0) + A_L(\infty) - A_L(t_0) = v_0 - A_L(t_0),$$

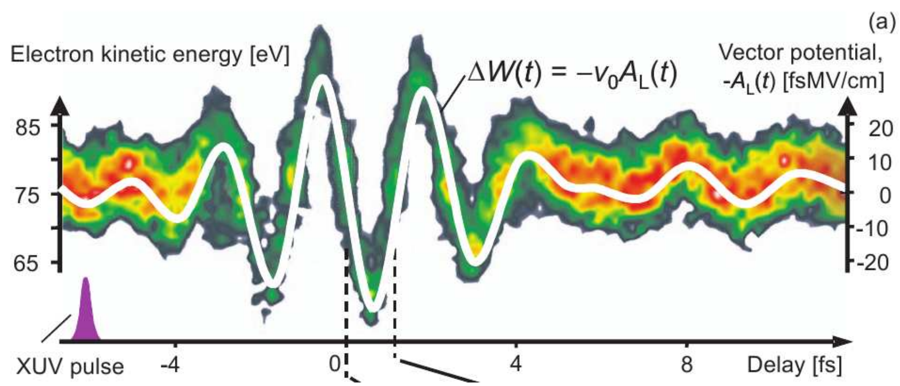
$$\Delta v = -A_L(t_0),$$

$$W(t) = \tfrac{1}{2}v^2(t),$$

$$\Delta W(t_0) \approx v_0 \Delta v = -v_0 A_L(t_0).$$

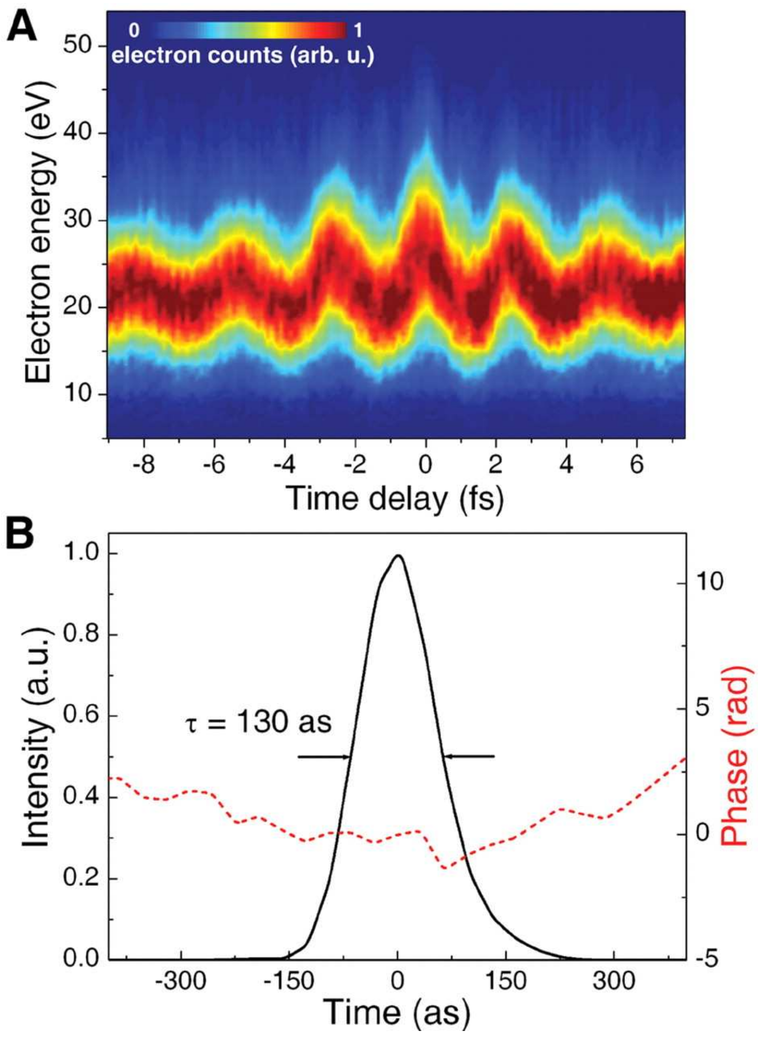
Attosecond streaking





Few-Cycle Attosecond Pulses

G. Sansone et al., *Science* **314**, 443 (2006).

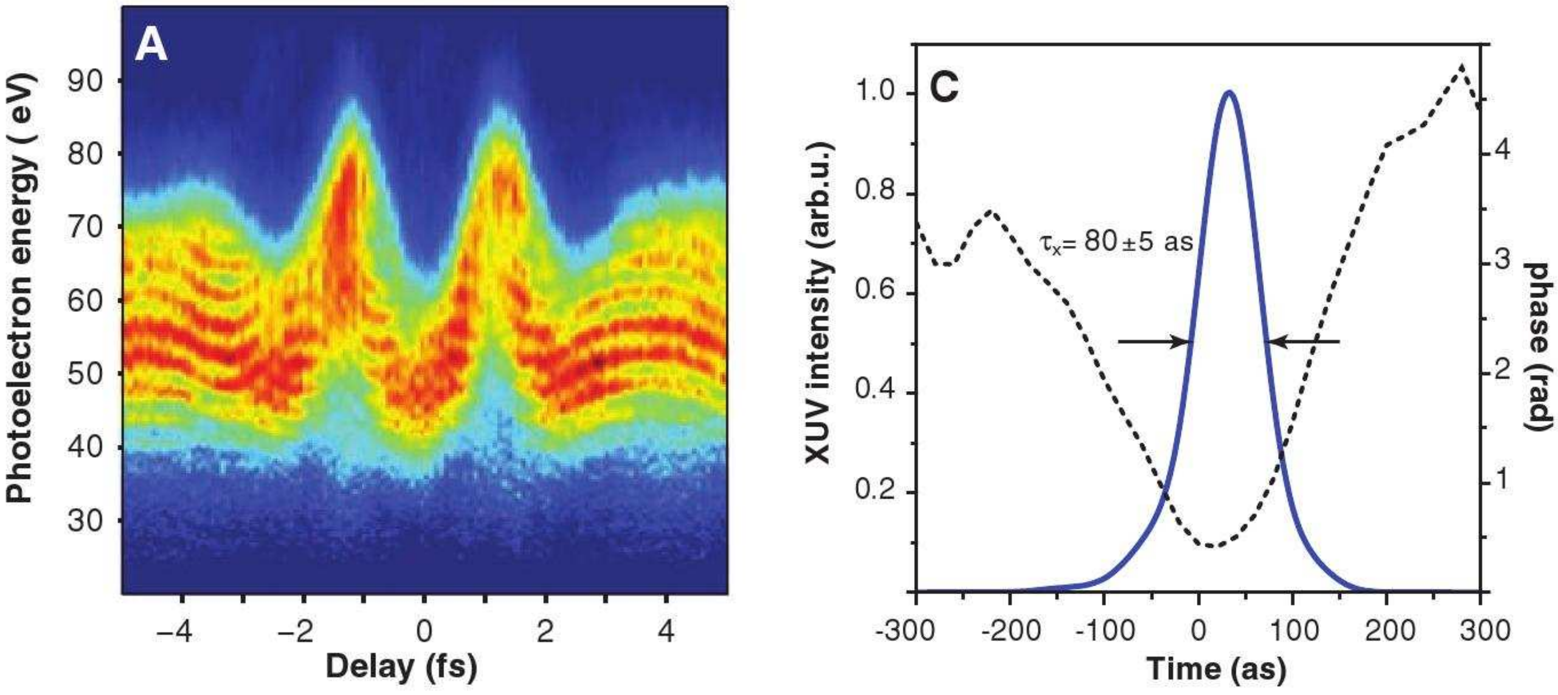


"The availability of **single-cycle isolated attosecond pulses** opens the way to **a new regime in ultrafast physics**, in which the strong-field **electron dynamics** in atoms and molecules **is driven by the electric field** of the attosecond pulses rather than by their intensity profile."

The CEP of the Attosecond Pulse Matters!

Few-Cycle Attosecond Pulses

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



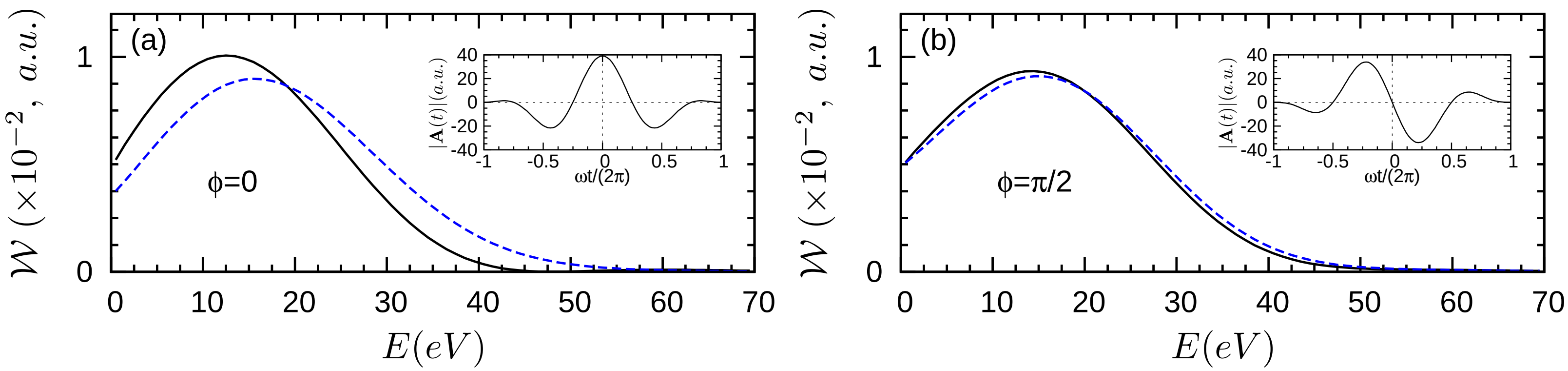
Dependence of Asymmetry on CEP

Ionization probability for the H atom by a linearly polarized pulse.

[E. A. Pronin, A. F. Starace, M. V. Frolov and N. L. Manakov, Phys. Rev. A **80**, 063403 (2009)]

Solid Line: $\alpha = 0$,

Dashed Line: $\alpha = \pi$, *Inset Panels:* Vector Potential $\mathbf{A}(t)$



$\hbar\omega = 36$ eV, *Pulse Shape:* $\cos^2$

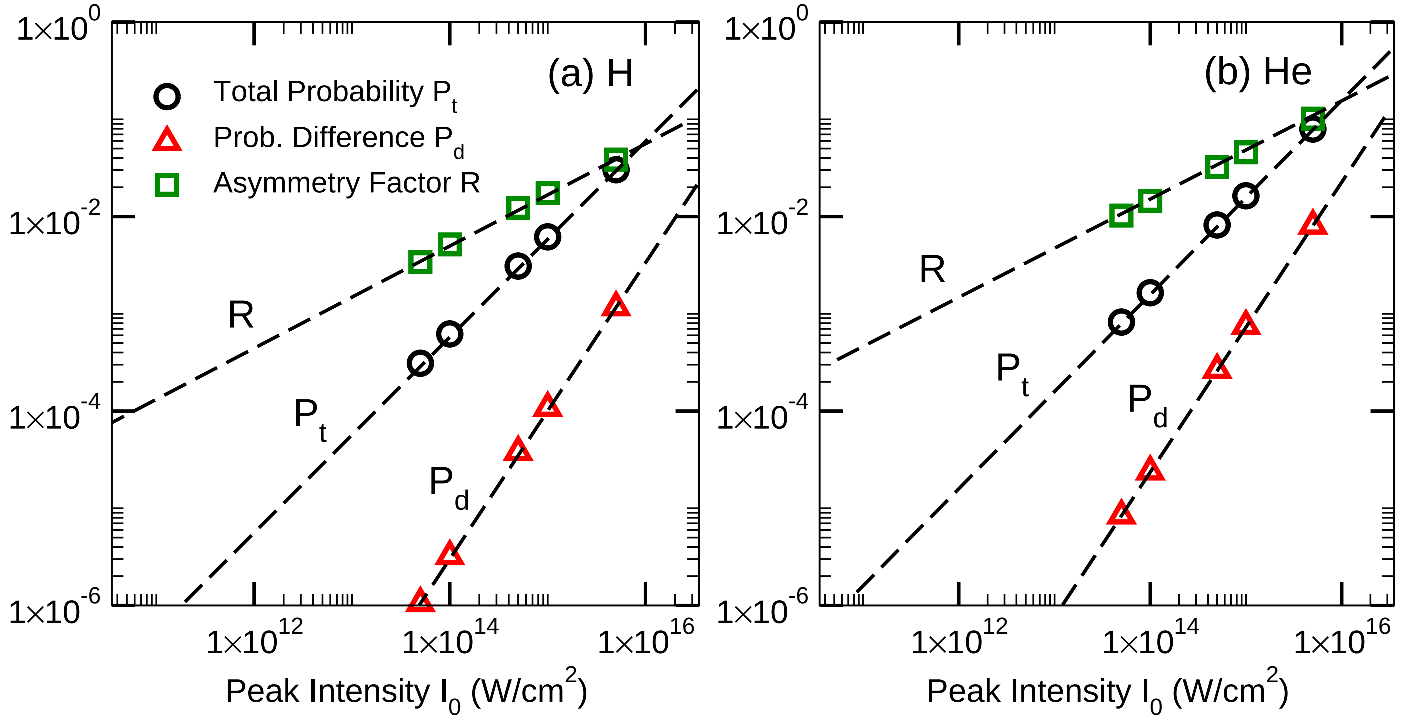
$I_0 = 5 \cdot 10^{15}$ W/cm^2, *Pulse Width:* 2 cycles

Intensity Dependence of the CEP-Induced Asymmetries

[L.Y. Peng, E.A. Pronin, and A.F.Starace, New J. Phys. **10**, 025030 (2008)]

$$P_t \equiv P_- + P_+ \propto I^{1.0}; \quad P_d \equiv P_- - P_+ \propto I^{1.5};$$

$$R \equiv P_d/P_t \propto I^{0.5}$$



Concluding Remarks

Summary and Conclusions

- The capability of intense laser physics to produce high-order harmonics has led to the ability to produce **single, few cycle pulses of attosecond duration.**
- The **determination of the time scales** of atomic, molecular, and condensed matter processes has been achieved.
- **Control of such processes** is just beginning.
- Production of **intense attosecond pulses** in the future will open up a new regime: **non-linear attosecond physics**.