ATTO PHYSICS: Observing Matter on Its Natural Time Scale

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General Reference:

- http://www.attoworld.de/Home/attoworld/

Outline

- ***Motivation, Terminology, and Time Scales***
- ***Background: Lasers and Laser Light Intensity***
- ***Ultrafast Processes: The Realm of Attosecond Physics***
- ***Current Achievements and Future Prospects***

Motivation

Motivation

What is Attosecond Physics?: It is the use of ultrashort pulses of laser light to understand, control, and image ultrafast atomic and molecular processes.

Why is it important?: It is a means to follow chemical reactions (as well as other atomic-scale transformations) in real time as they occur.

What are the key problems?:

- Laser pulses must be ultrashort, i.e., shorter than the timescale of atomic and molecular processes
  - *Key Problem*: Typical laser pulses are much longer than most ultrafast electronic processes.
  - *Solution*: Employ ultrashort bursts of radiation emitted by laser-driven electrons.
- 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)

Scientific Terminology

Names for Various Powers of Ten

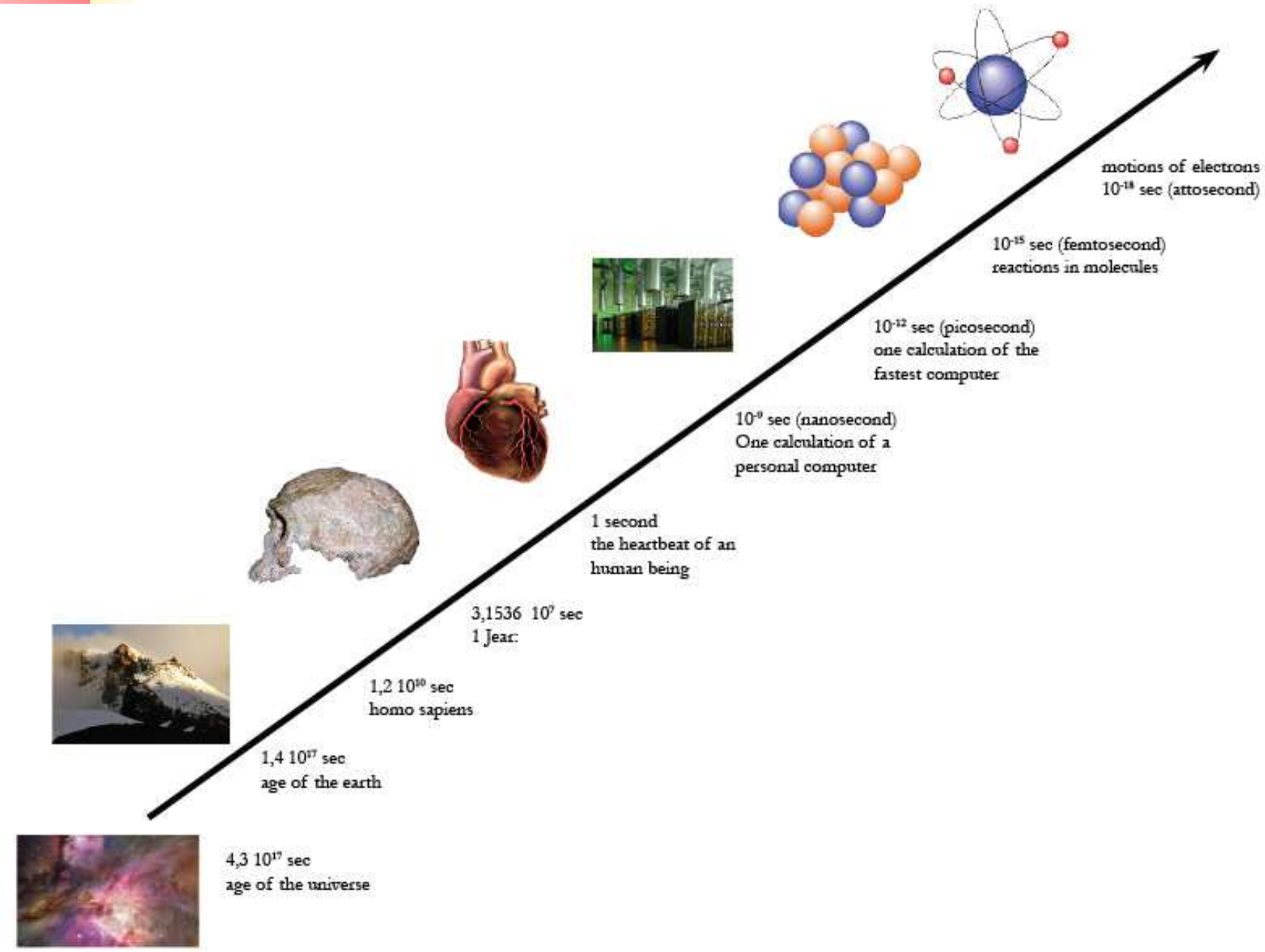
10^n	Prefix
10^{24}	yotta
10^{21}	zetta
10^{18}	exa
10^{15}	peta
10^{12}	tera
10^{9}	giga
10^{6}	mega
10^{3}	kilo
10^{2}	hecto
10^{1}	deca, deka
10^{0}	*(none)*

10^{0}	*(none)*
10^{-1}	deci
10^{-2}	centi
10^{-3}	milli
10^{-6}	micro
10^{-9}	nano
10^{-12}	pico
10^{-15}	femto
10^{-18}	atto
10^{-21}	zepto
10^{-24}	yocto

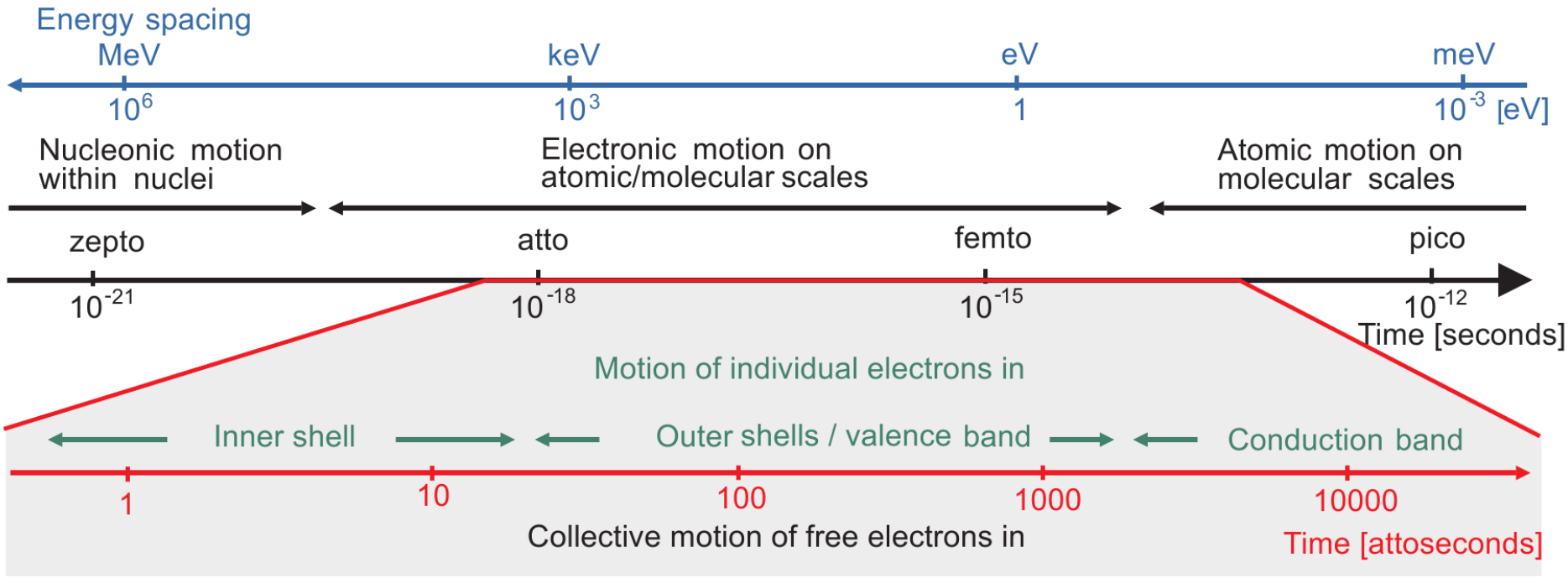
Time Scales


WEEKLY | NEWS IDEAS INNOVATION | THE BEST JOBS IN SCIENCE
NewScientist
6 November 2004
WELCOME TO
ATTOWORLD
Where a second lasts the age of the universe

Time Scales

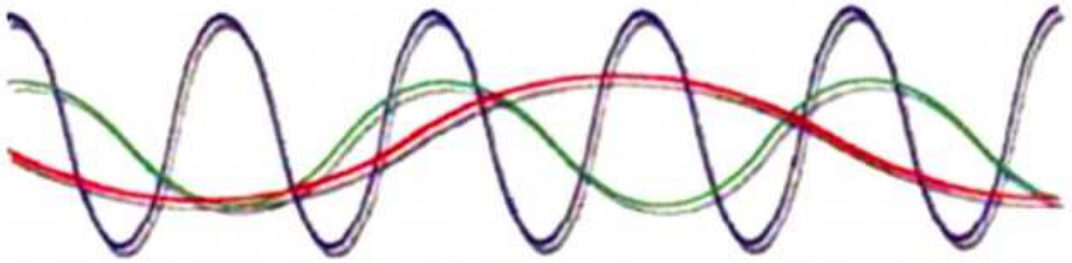

motions of electrons
10^{-18} sec (attosecond)
10^{-15} sec (femtosecond)
reactions in molecules
10^{-12} sec (picosecond)
one calculation of the
fastest computer
10^{-9} sec (nanosecond)
One calculation of a
personal computer
1 second
the heartbeat of an
human being
3,1536 10^{7} sec
1 Jear:
1,2 10^{10}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

Background: The Development of Intense Laser Fields

Incoherent versus Coherent Light

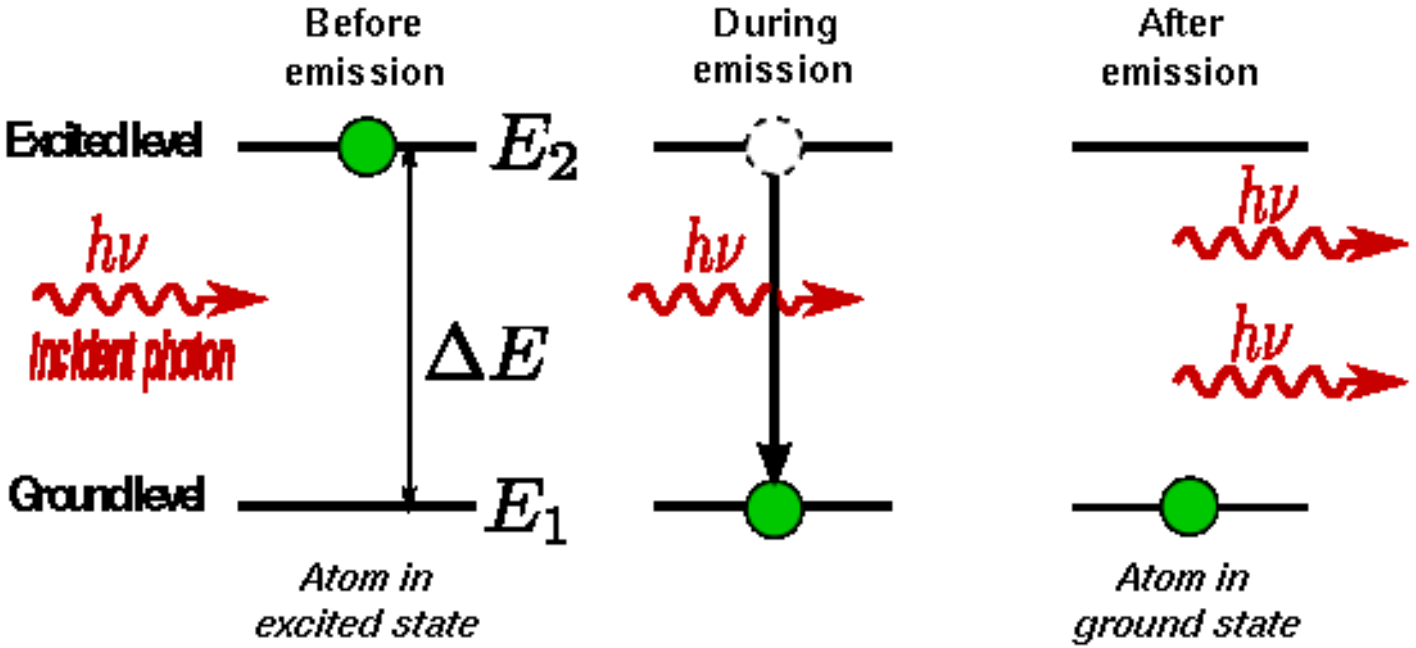


Sunlight (many different colors)

LED: one color (monochromatic) and waves not in phase (non-coherent)

LASER: One color (monochromatic) and waves in phase (coherent)

Stimulated Emission



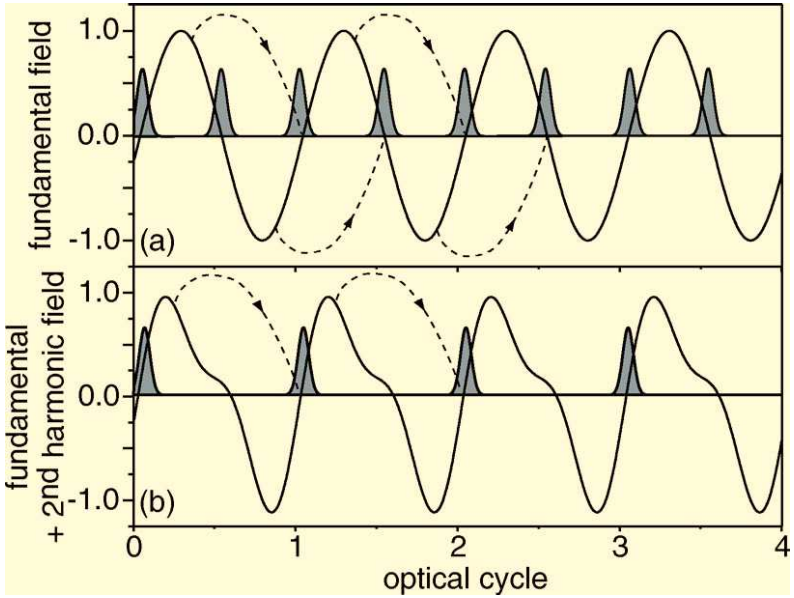
$$E_2 - E_1 = \Delta E = h\nu$$

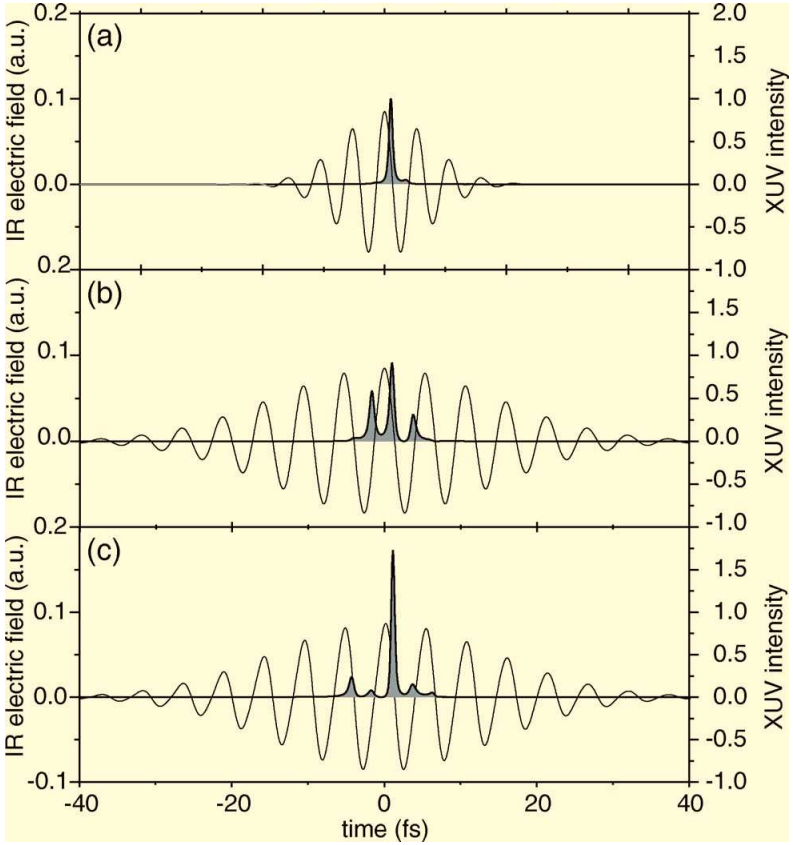
Light is comprised of "photons," each with energy $h\nu = hc/\lambda$ where $\nu\lambda = c$.

An aside: The human eye can detect single photons!

Generation of Atto Pulses

Attosecond Pulse Train vs. *Single Attosecond Pulse*





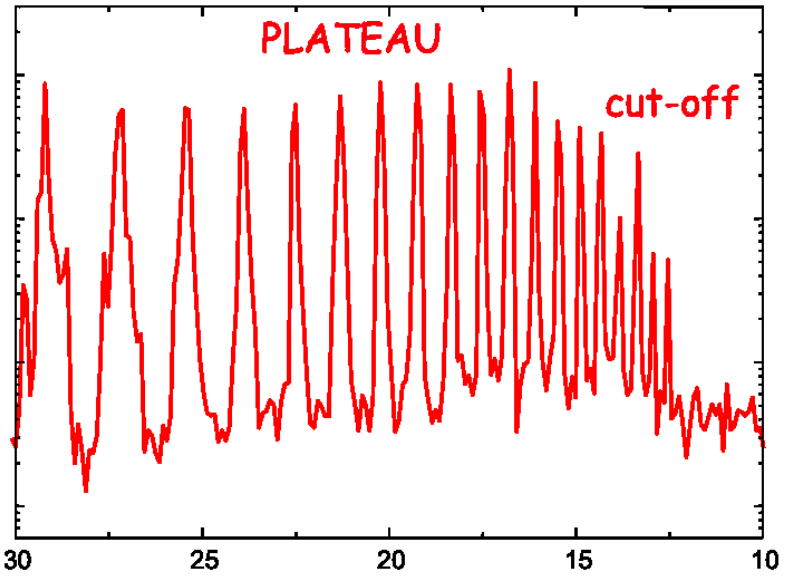
Solid lines: Driving Laser Field

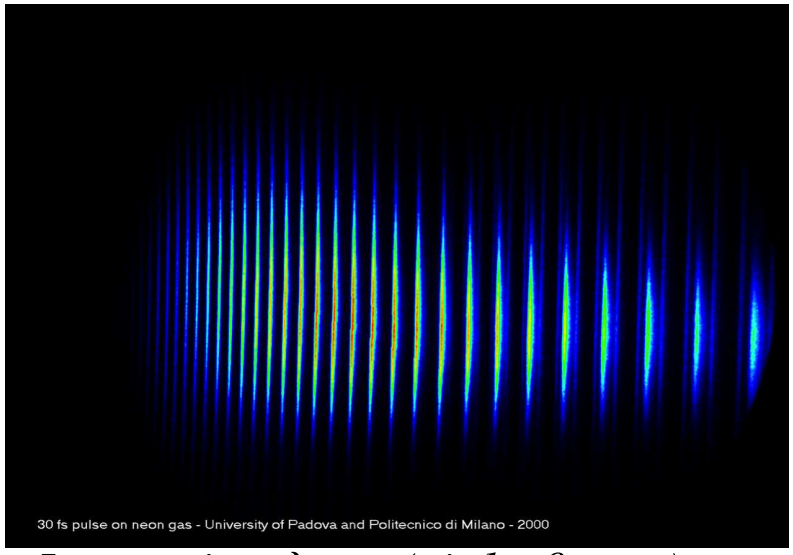
Dotted Lines: Ionized electron trajectories

Shaded Pulses: Attosecond pulses

Spectrum of Atto Pulses

Harmonic Spectrum Plotted vs. Wavelength $\lambda(nm)$





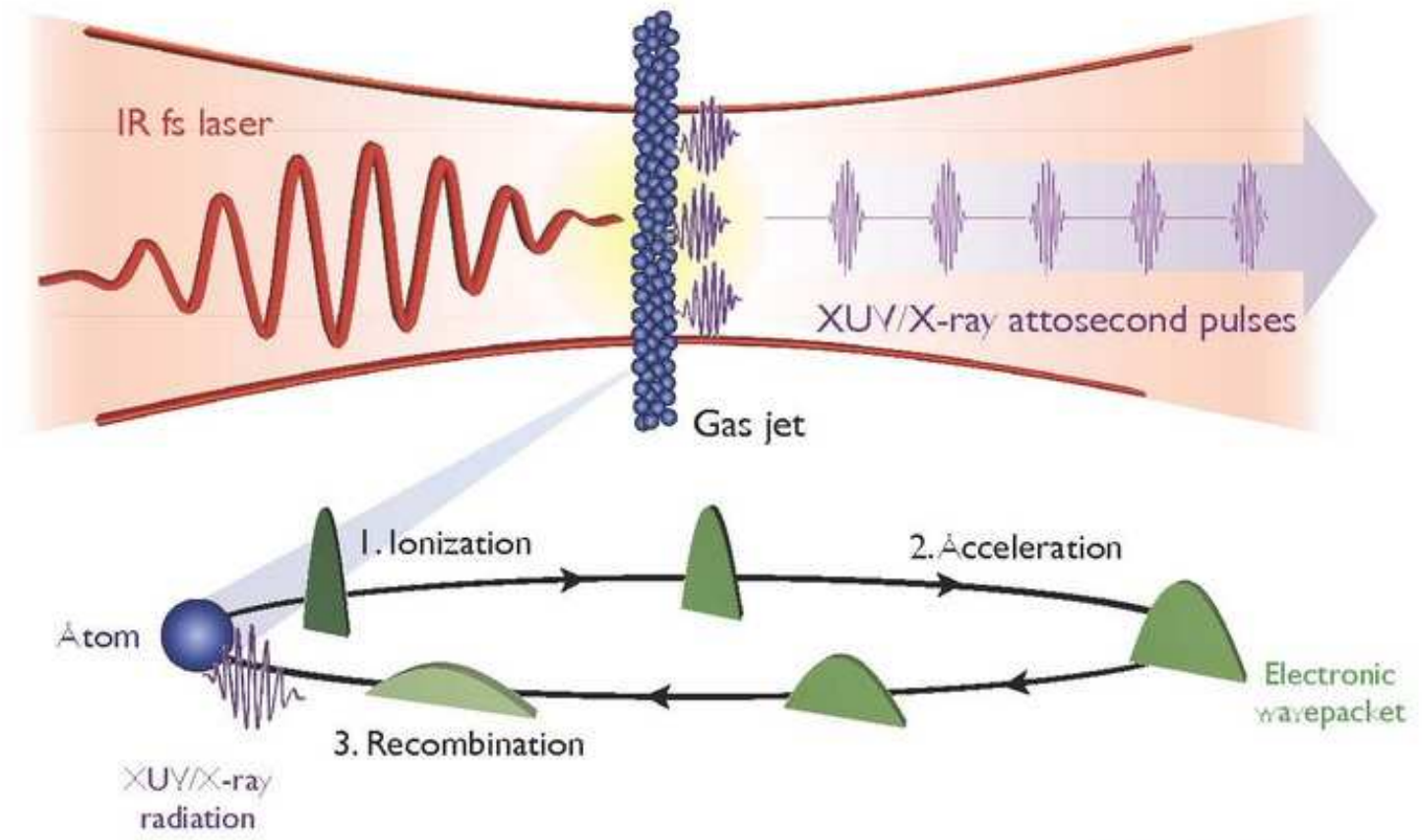
Decreasing $\lambda \rightarrow$ (left figure); *Increasing $\lambda \rightarrow$ (right figure)*

Note: peaks are equally spaced in the laser photon energy $h\nu_L = hc/\lambda_L$ of the driving laser.

The energy of the Nth harmonic is $h\upsilon_N = Nh\nu_L$.

Three-Step Model

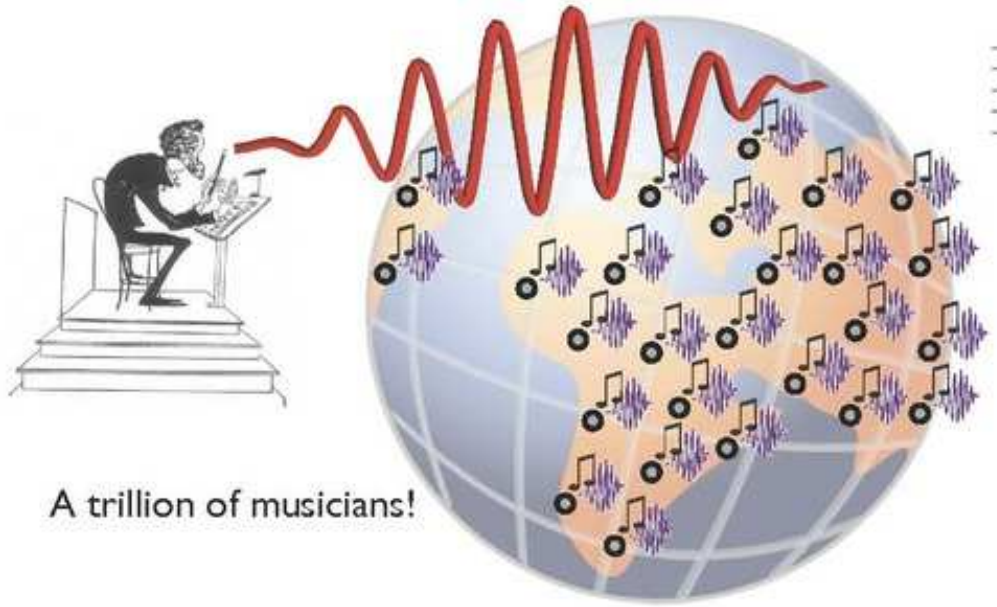
High-order Harmonic Generation (HHG)



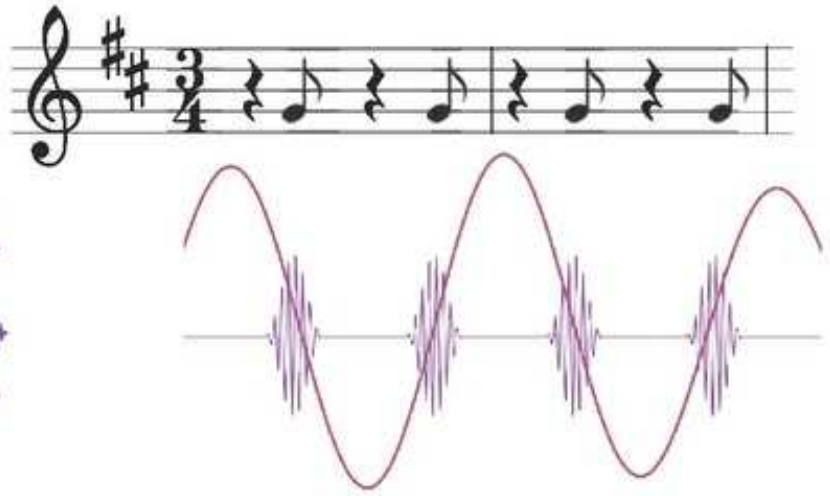
Corkum PRL 71, 1994 (1993)
Schafer et al. PRL 70 1599 (1993)

The harmonic orchestra

Laser as the orchestra director...



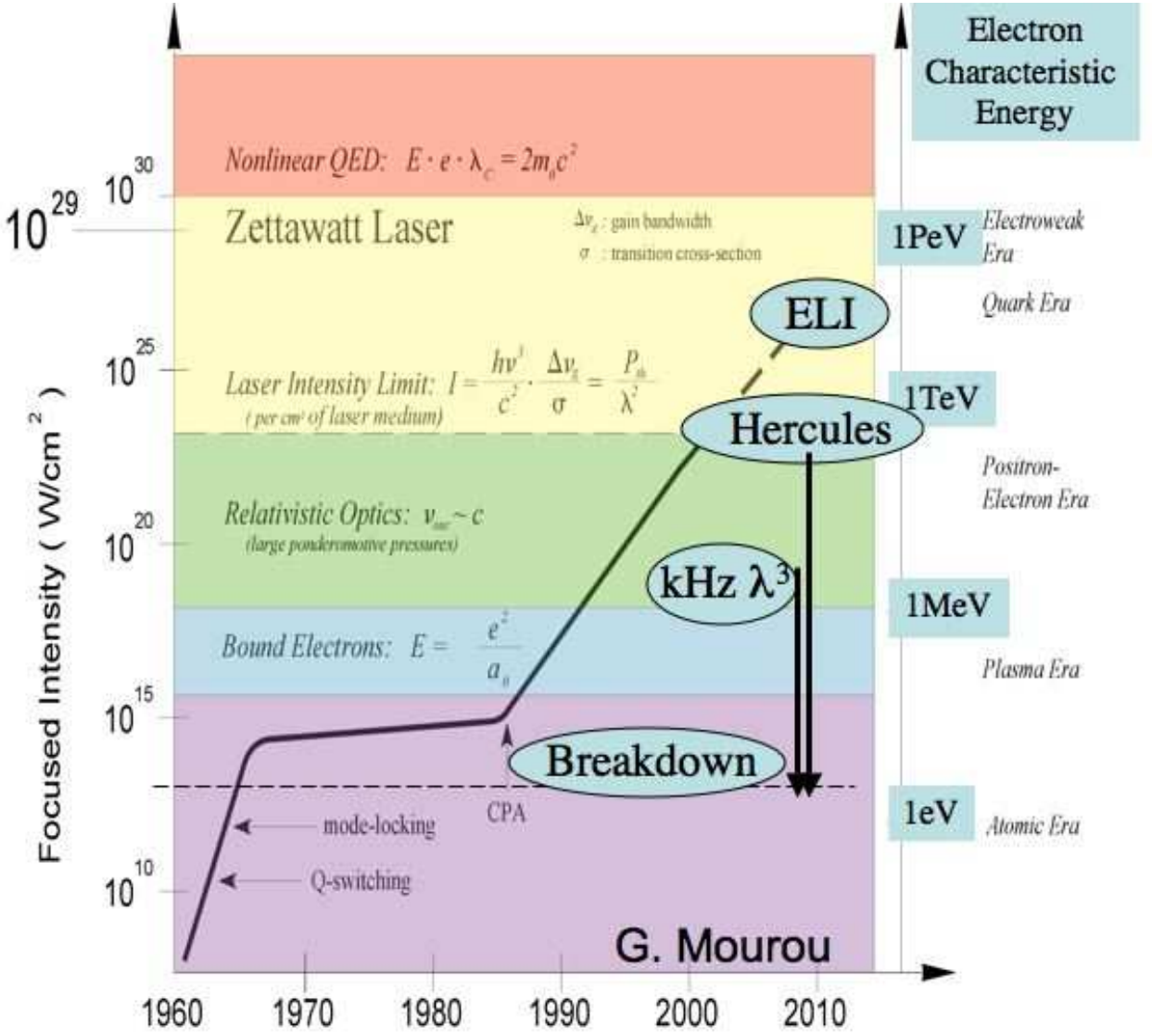
A trillion of musicians!



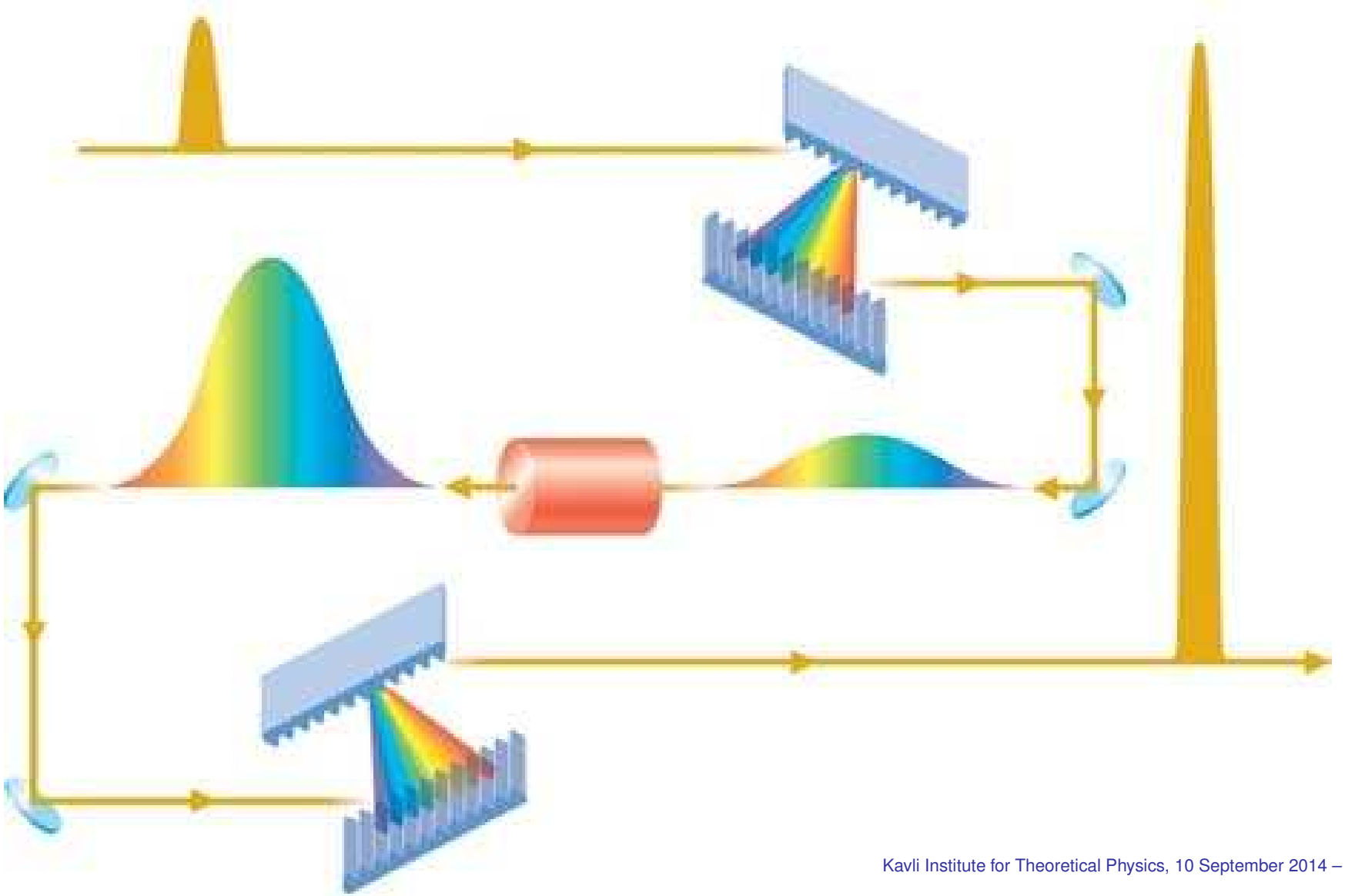
As a result, a *melody* of attosecond pulses is emitted coherently.

... and each atom of the gas as a musician, emitting attosecond pulses synchronized with the rhythm dictated by the laser

Historical Overview of Increases in Laser Intensities

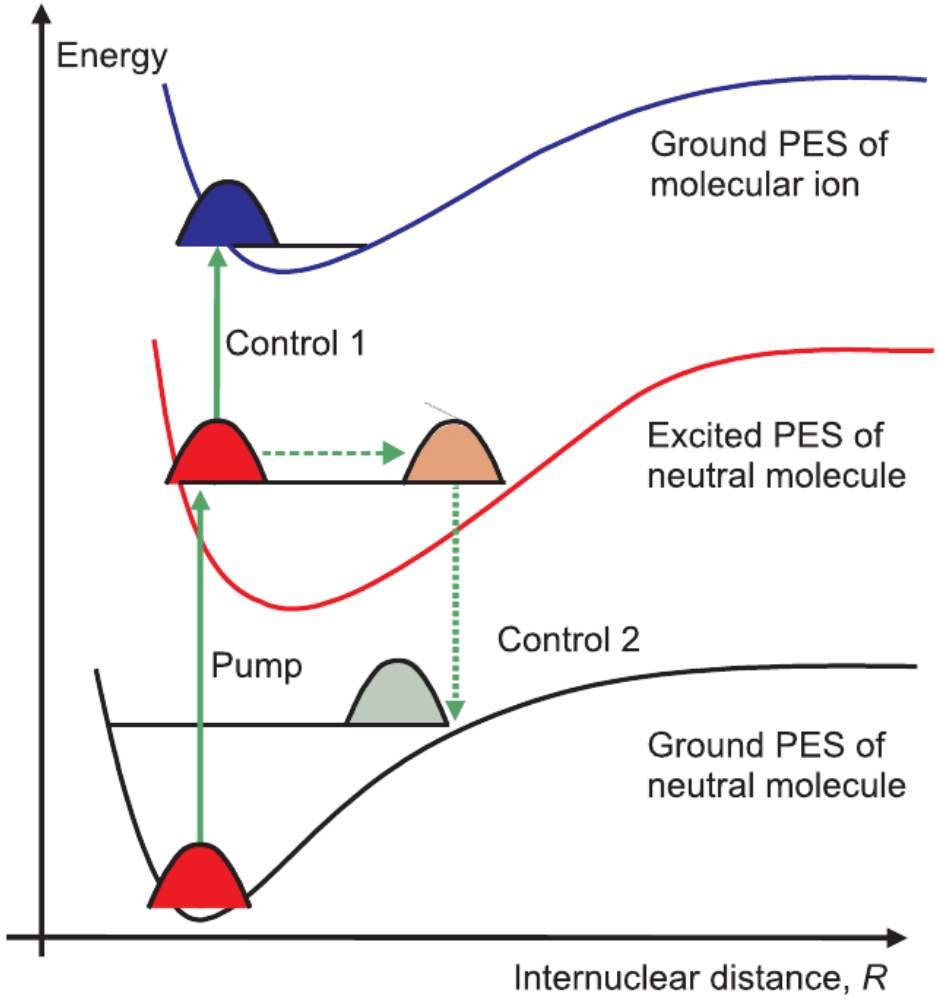


Chirped Pulse Amplification (CPA)



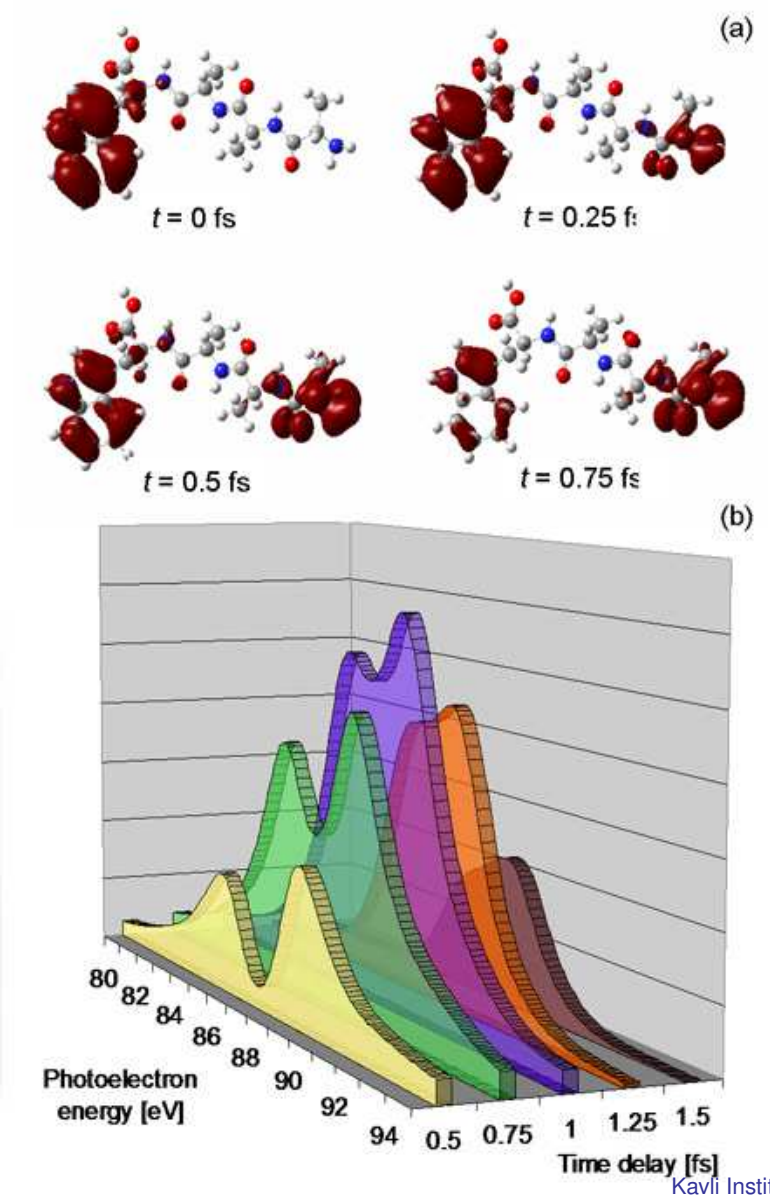
Ultrafast Processes: The Realm of Attosecond Physics

Pump-Probe Control of Molecular Processes

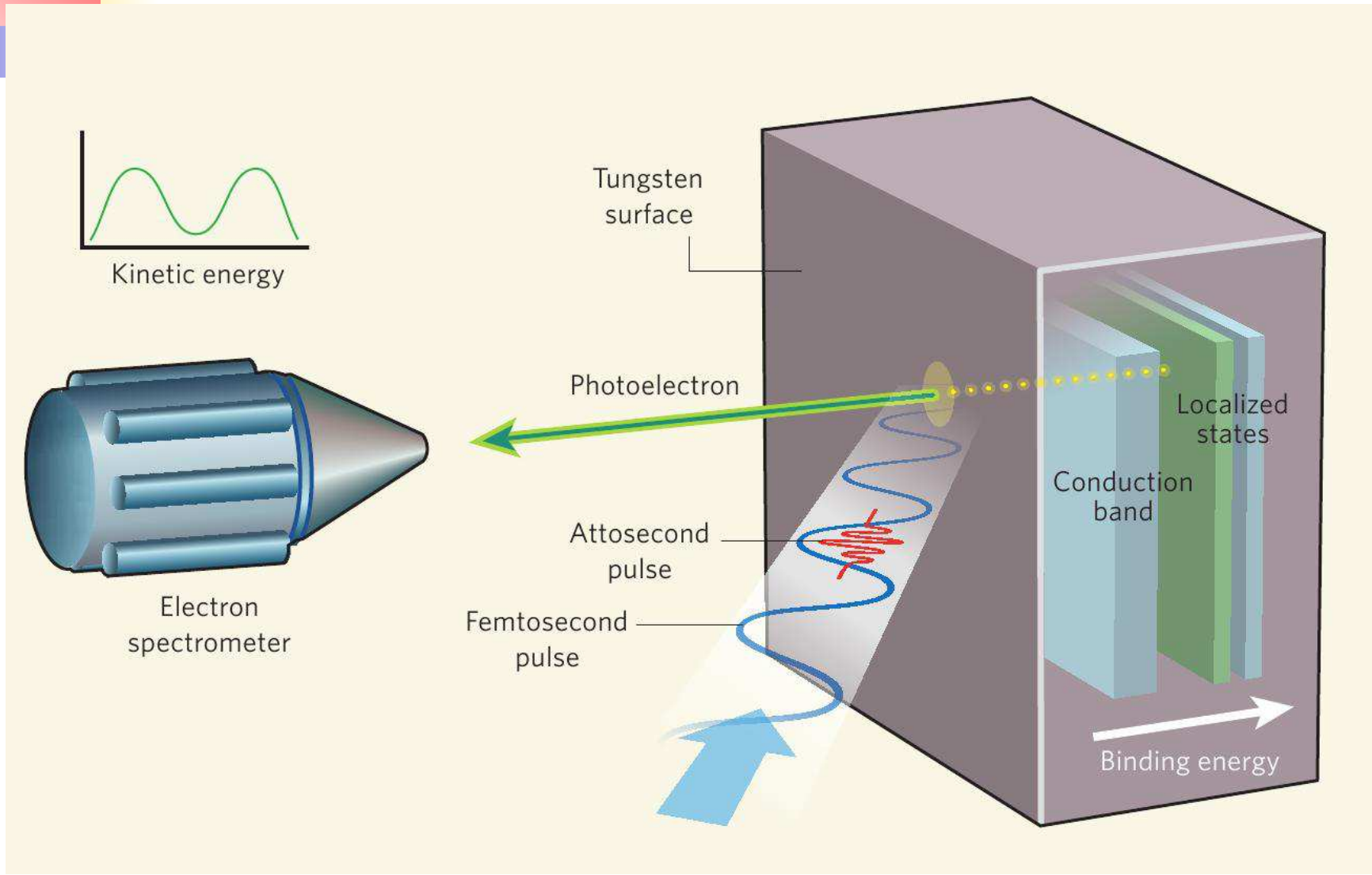


Electronic Excitation Transport in a Biomolecule (Tyrosine-terminated tetrapeptide)

cf. F. Remacle and R.D. Levine, PNAS **103**, 6793 (2006)

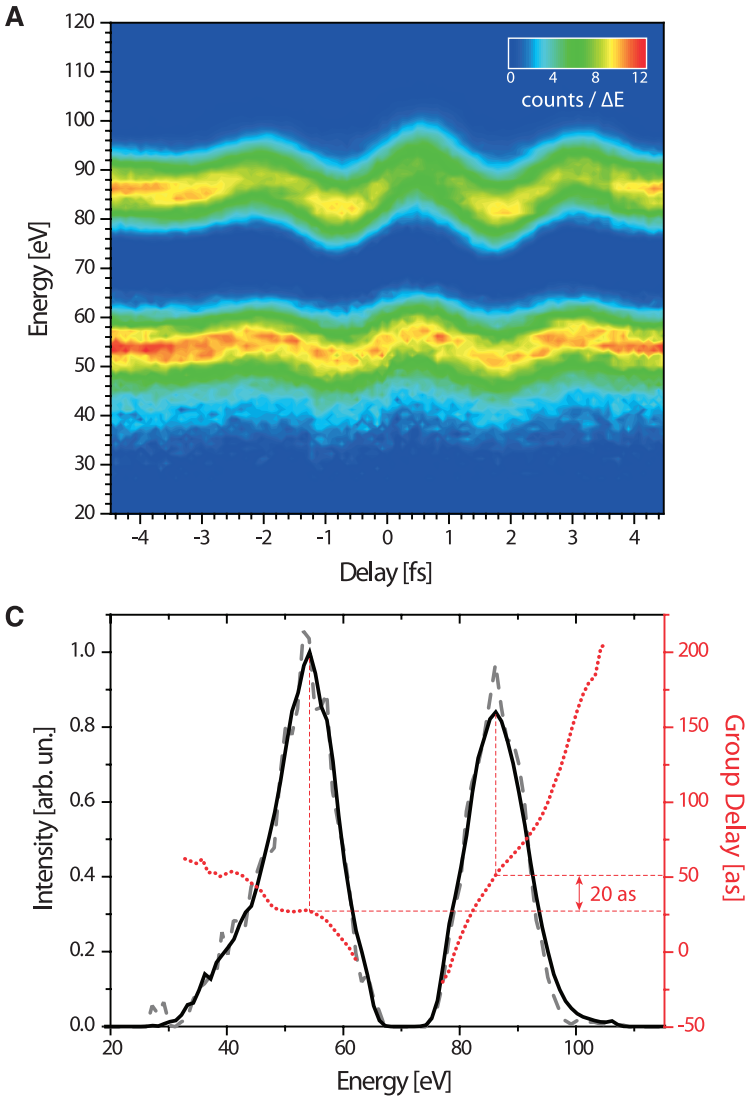


Electron Transport in Single Crystal W



D. M. Villeneuve, *Nature* **449**, 997 (2007); A.L. Cavalieri *et al.*, *ibid.* p. 1029.

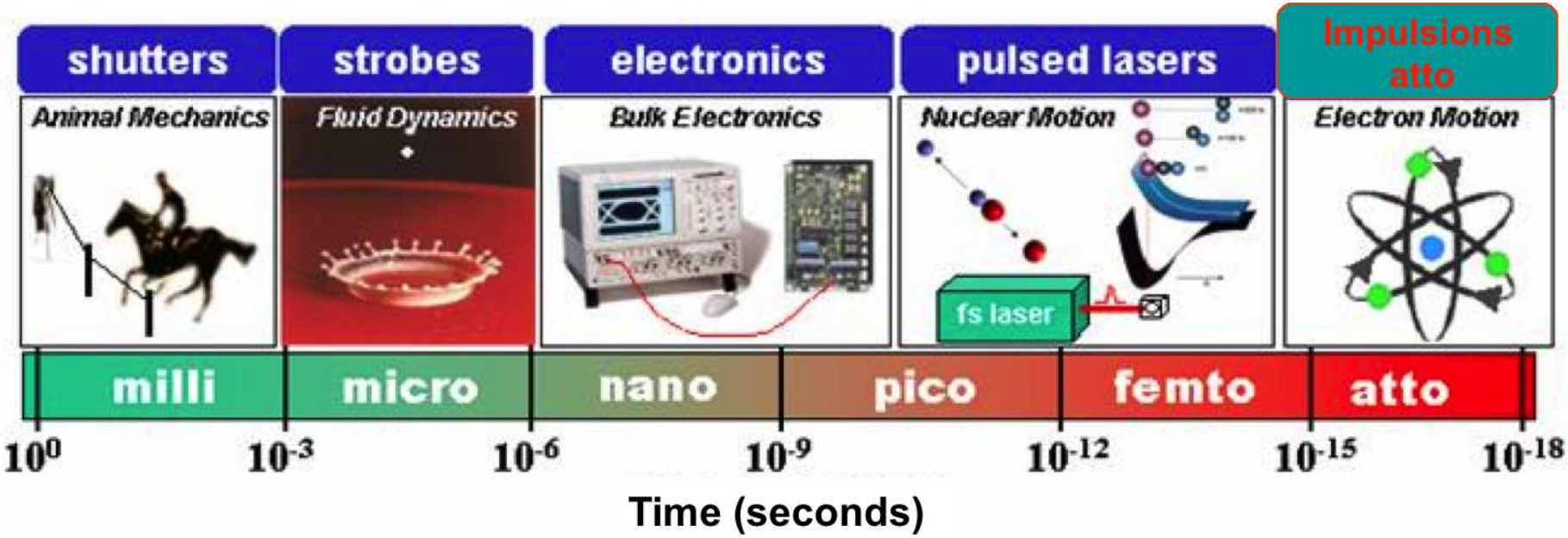
Photoemission Delay - Ne 2s, 2p Electrons



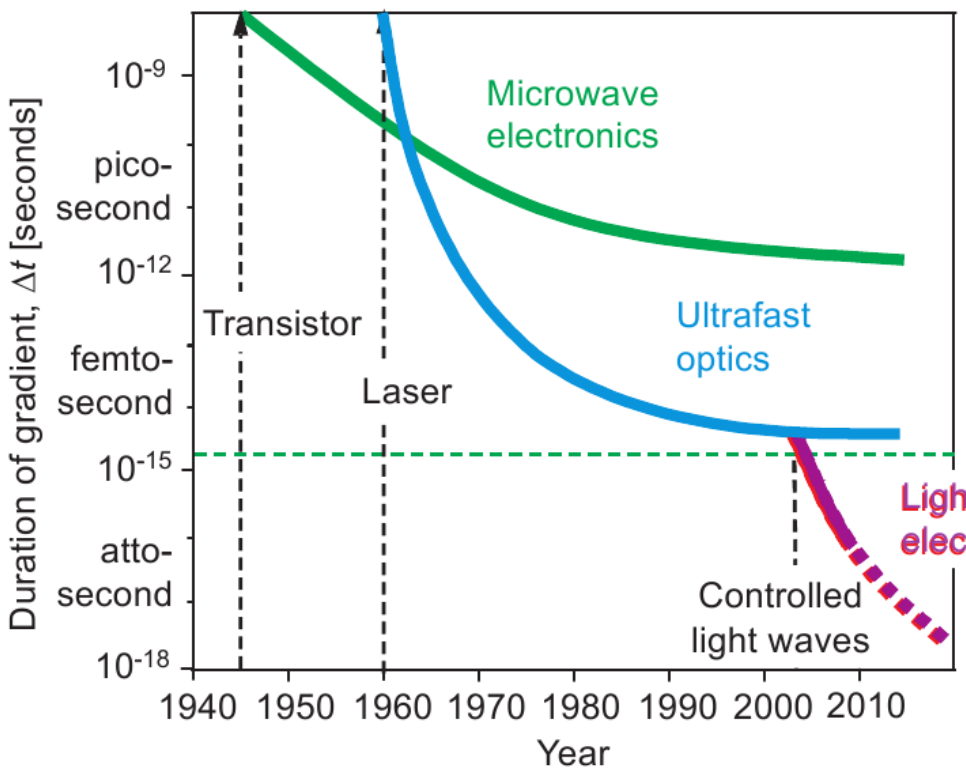
M. Schultze *et al.*, *Science* **328**, 1658 (2010)

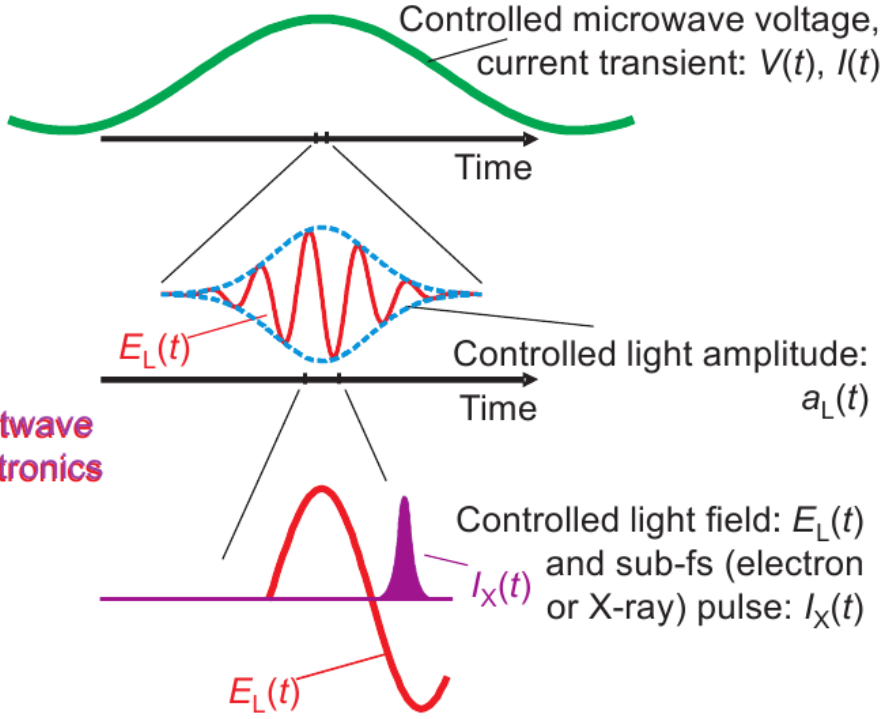
Current Achievements and Future Prospects

Ultrafast Science



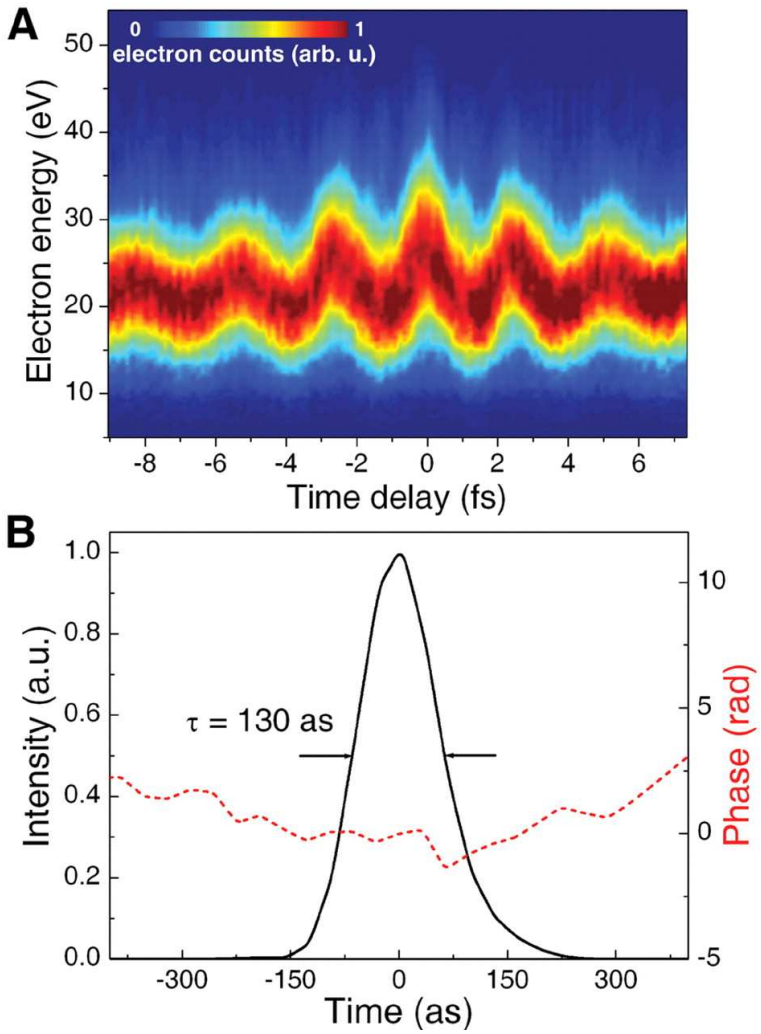
Ultrafast Science





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."

Current Achievements

- High-order harmonic generation has allowed the production of **isolated pulses of attosecond duration.**
- The **determination of the time scales of electronic motion** in atomic, molecular, and condensed matter processes is being achieved.
- **Control of such processes** is just beginning.

Future Prospects

- High-order harmonic generation may lead to **coherent laser light in the "water window" region**,
  i.e., $280\ \text{eV} \leq h\nu \leq 530\ \text{eV}$ or $4.4\ \text{nm} \geq \lambda \geq 2.34\ \text{nm}$.
- The **determination of nuclear time scales** will be achieved when zepto second laser light pulses are achieved.
- Production of **intense attosecond pulses** will permit:
  - *Attosecond pump - attosecond probe* experiments
  - *Control of electron angular distributions* by means of intense few-cycle pulses.