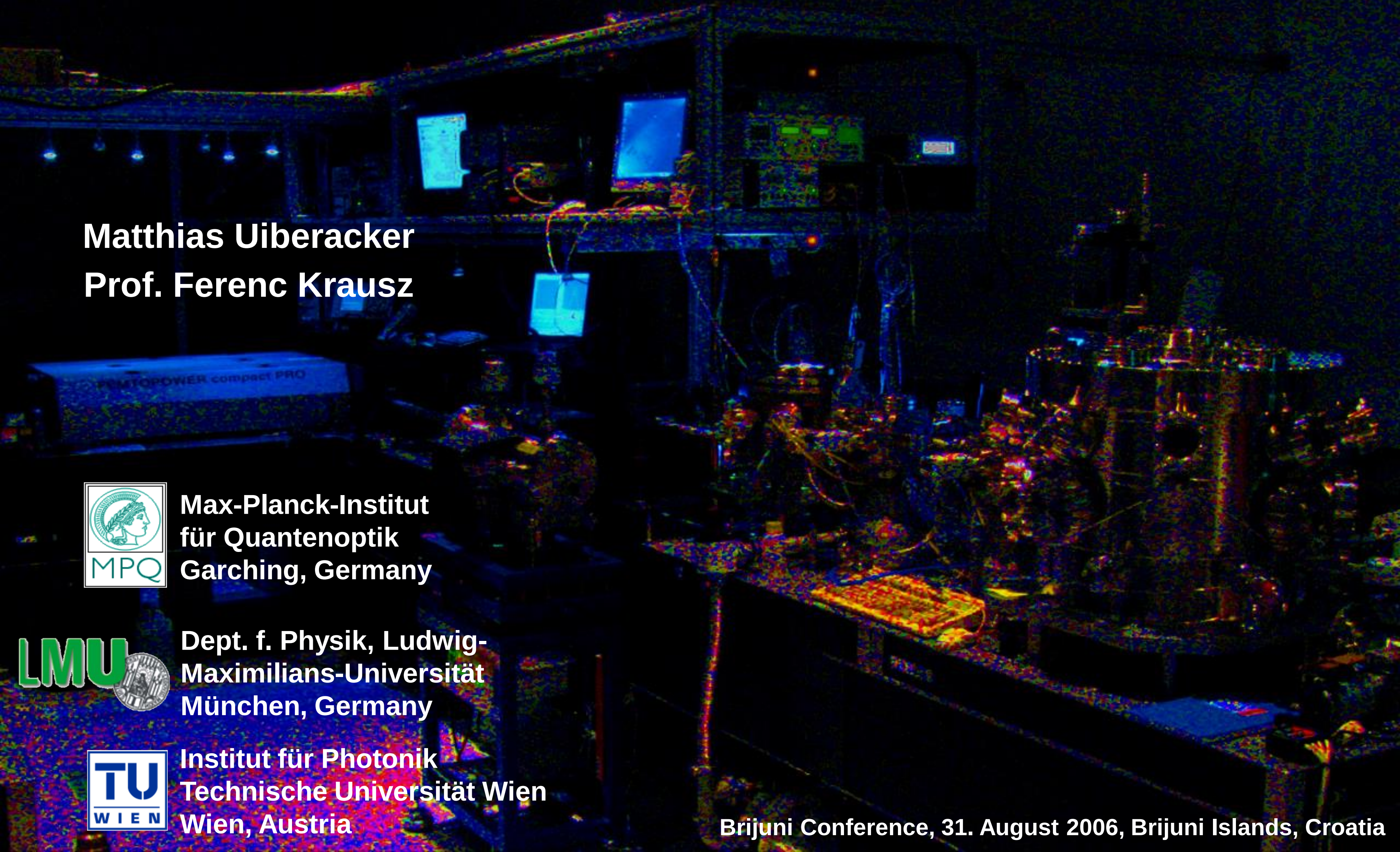
# Sampling electron dynamics in atoms in real time with sub-femtosecond resolution

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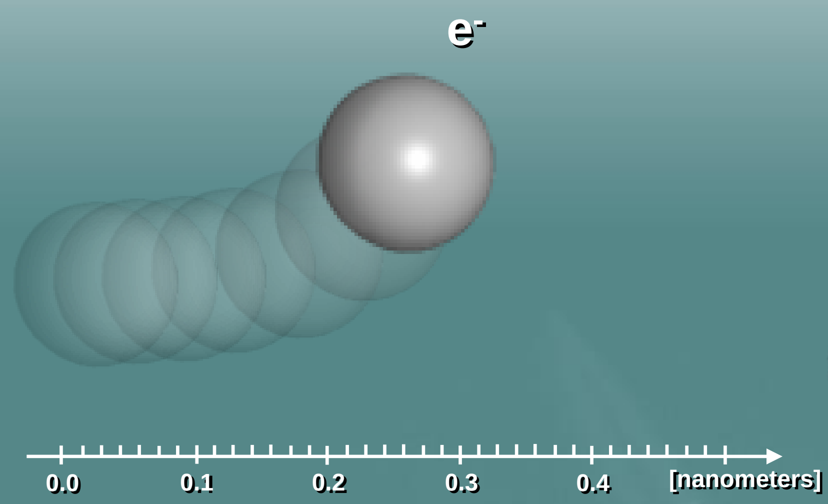
Technische Universität Wien
Wien, Austria


Brijuni Conference, 31. August 2006, Brijuni Islands, Croatia

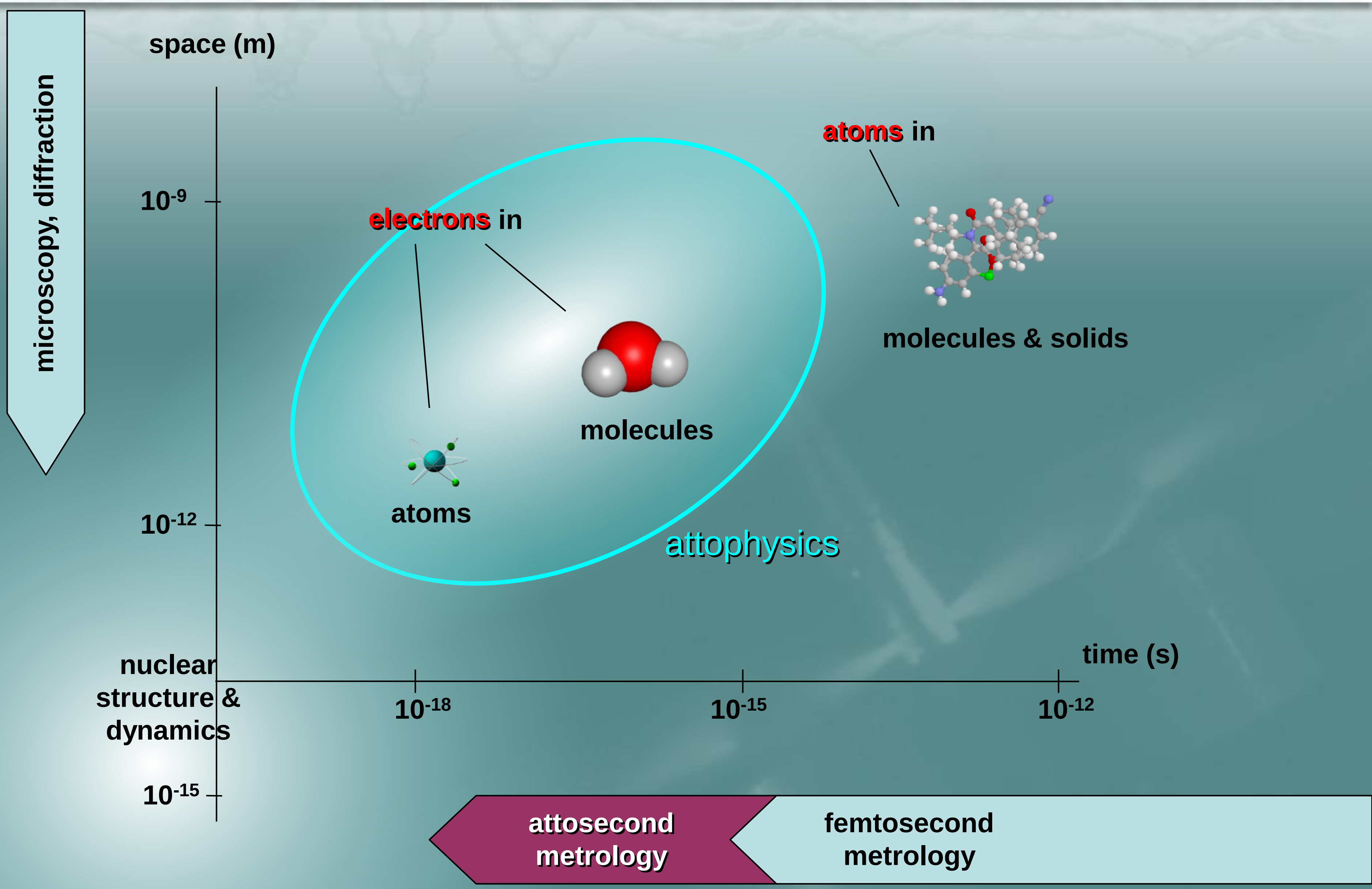
# attosecond physics aims at gaining insight into the motion of electrons on atomic scales




**direct control & real-time observation**

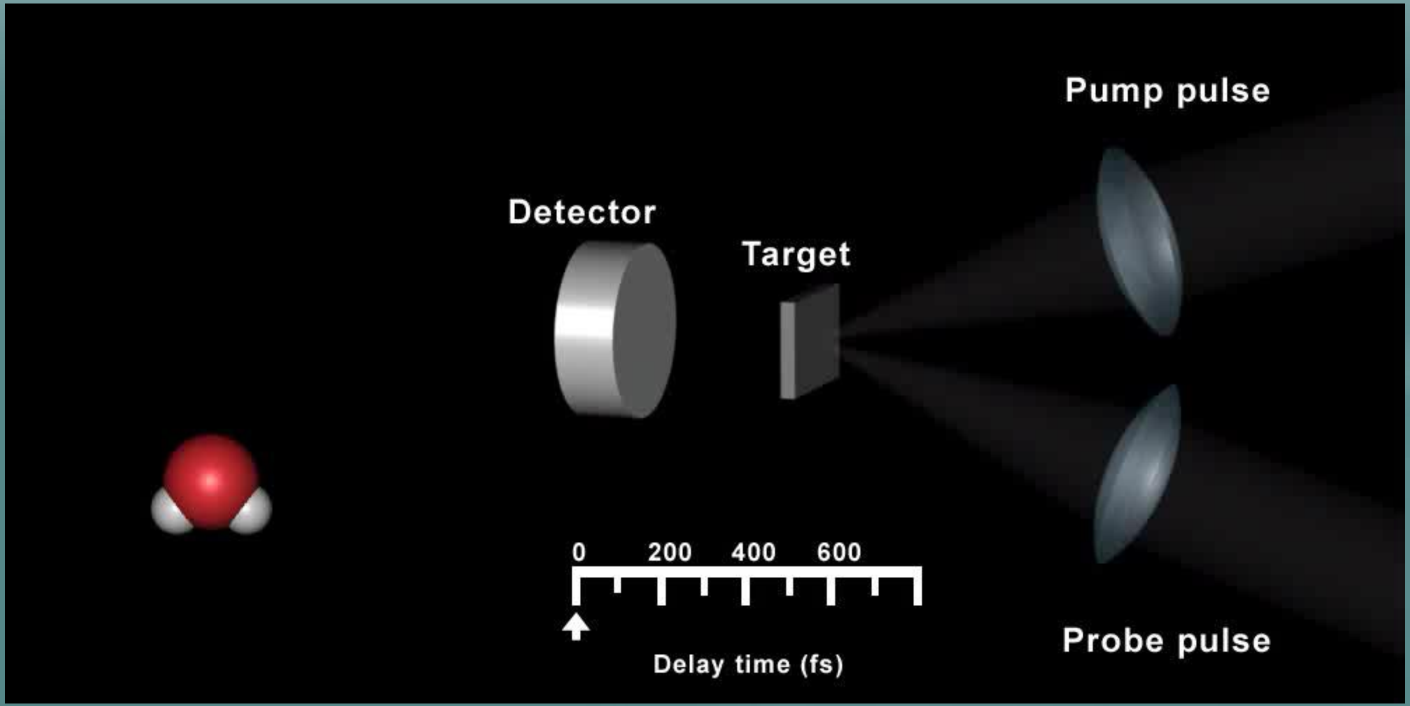
**of electronic motion in atoms, molecules, solids and plasmas**

# the microcosm: imaging in space and time



# high–speed photography of microscopic processes:

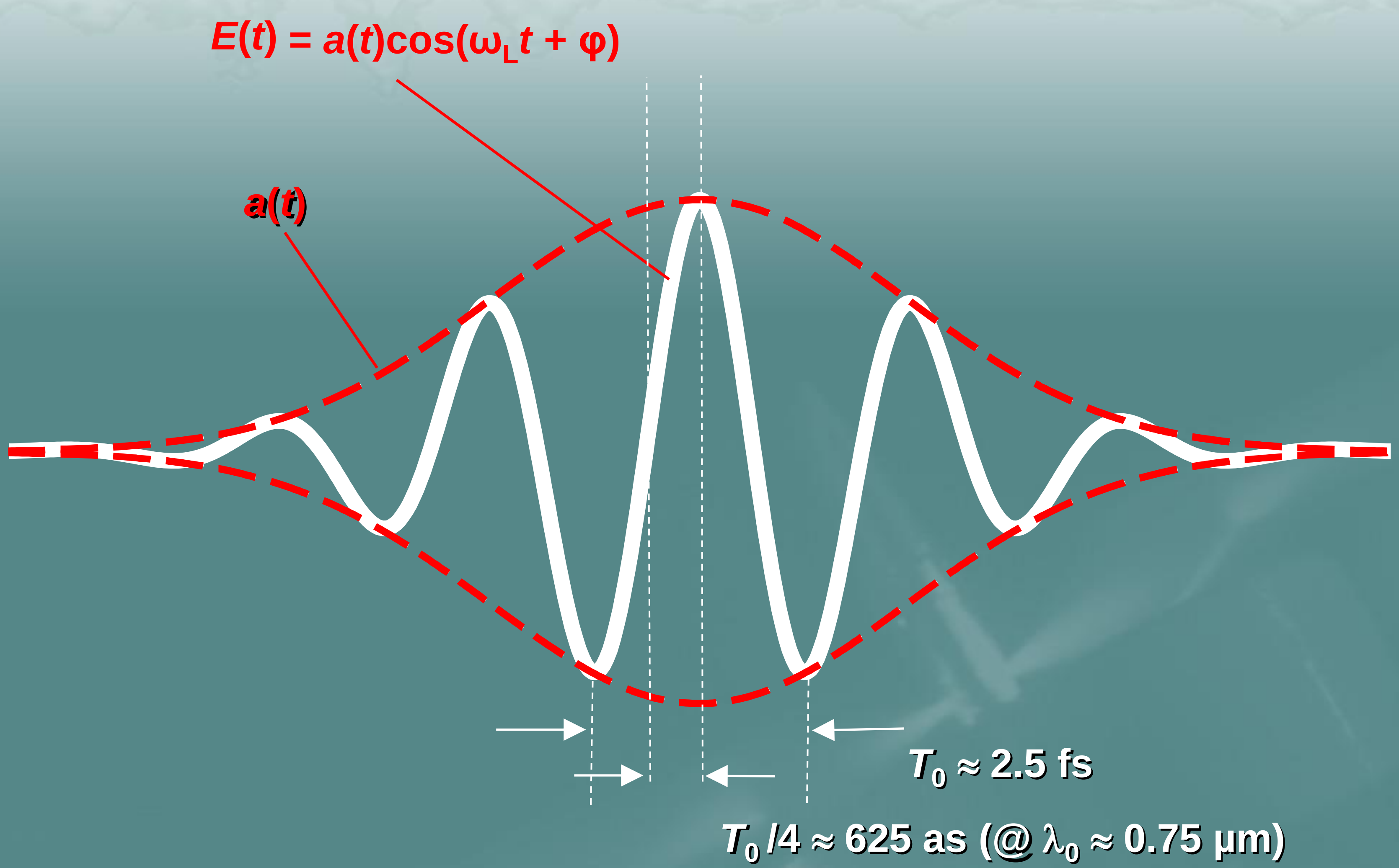
## time–resolved pump-probe spectroscopy



# a sampling system with sub-fs resolution

- utilizing pump/probe techniques
- pump pulse and probe pulse need to be short enough to freeze the motion of electrons
- ultrashort visible laser pulses are close to the wavecycle-limit of pulse duration (1-3fs).
- ..but, can be used to produce shorter (sub-fs) xuv pulses (high harmonic generation)
- efficiency for 2 sub-fs xuv pulses is not sufficient yet
- what to do?

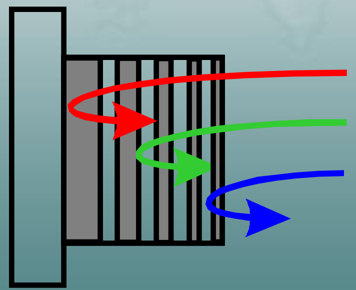
# using the electric field of laser pulses for probing with sub-fs resolution




- requires stabilization and control of carrier-envelope phase
- in combination with a weak sub-fs xuv pulse -> pump/probe measurements with sub-fs resolution!

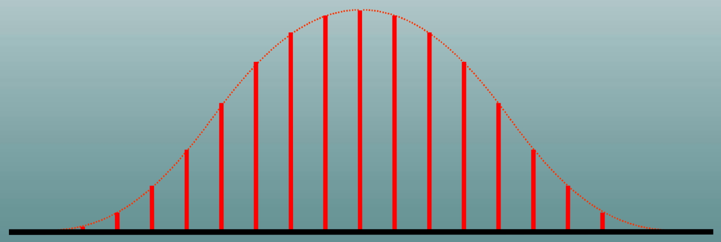
# waveform-controlled few-cycle light opens the door to steering & capturing electrons on an attosecond timescale

**ultrabroadband dispersion control with chirped multilayers**

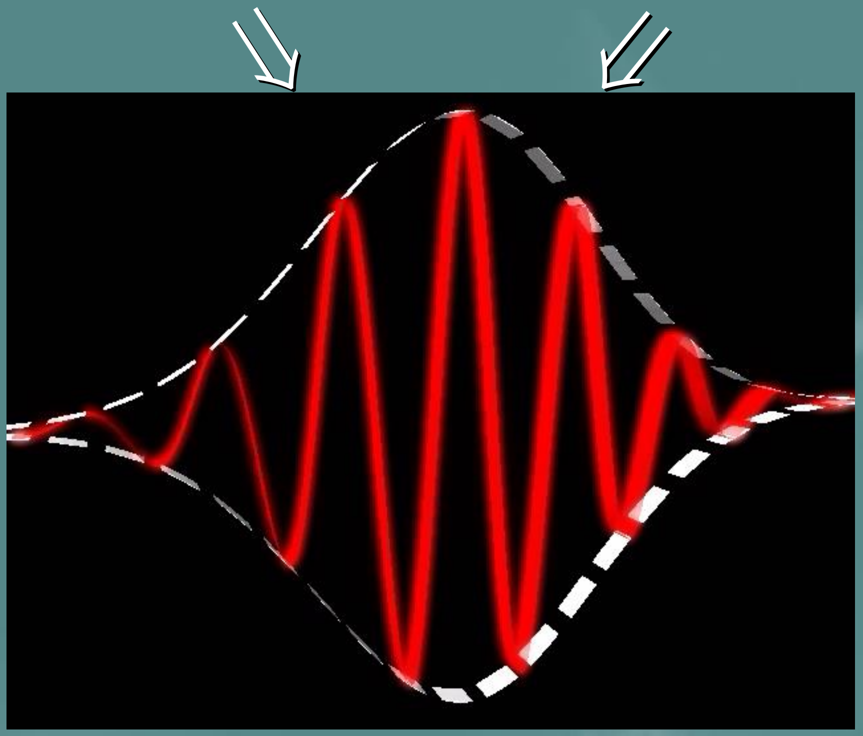


R. Szipöcs, K. Ferencz, Ch. Spielmann, F. Krausz
*Opt. Lett.* **19**, 201 (1994)

**stabilization of the frequency comb of a mode-locked laser**

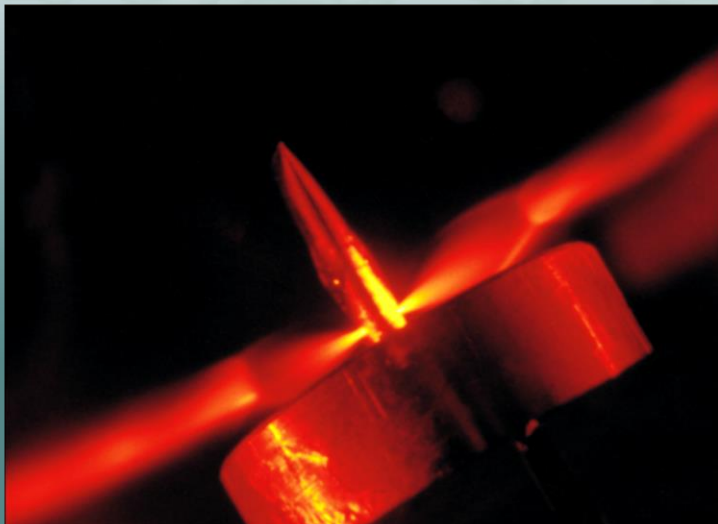


T. W. Hänsch et al., 1997, 1999
H. Telle et al. *Appl. Phys. B* 69, 327 (1999)
D. Jones et al., *Science* **288**, 635 (2000)

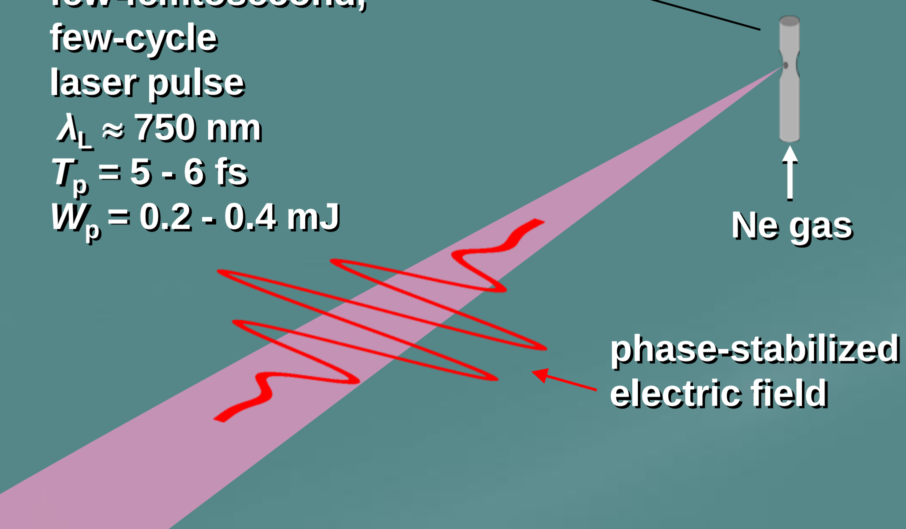


A. Baltuska, T. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, V. Yakovlev, A. Scrinzi, T. W. Hänsch, F. Krausz, *Nature* **421**, 611 (2003)

# xuv/x-ray radiation from strongly driven atoms



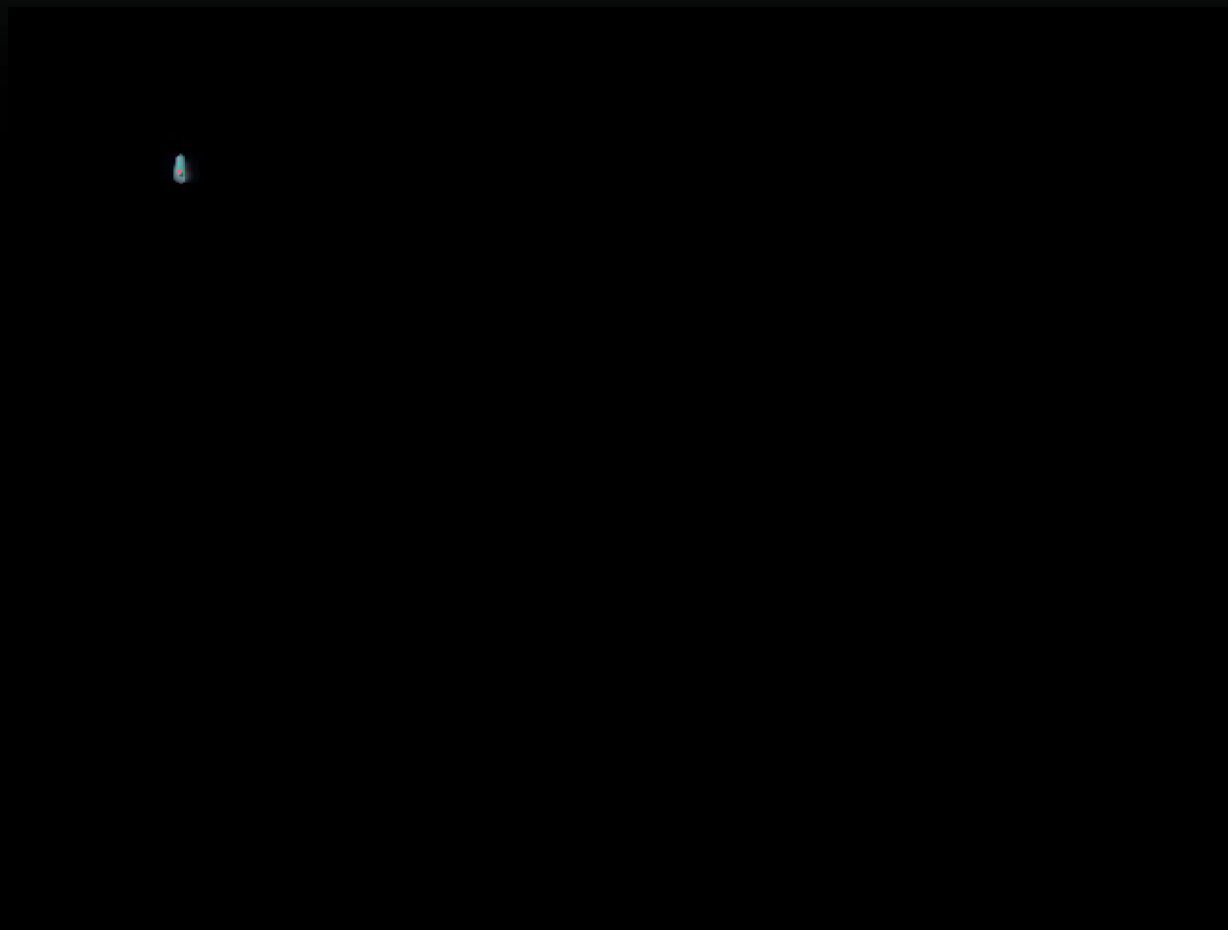
**few-femtosecond, few-cycle laser pulse**
**$\lambda_L \approx 750$ nm**
**$T_p = 5 - 6$ fs**
**$W_p = 0.2 - 0.4$ mJ**




Drescher *et al.*, *Science* **291**, 1923 (2001)
Hentschel *et al.*, *Nature* **414**, 509 (2001)
Kienberger *et al.*, *Science* **297**, 1144 (2002)

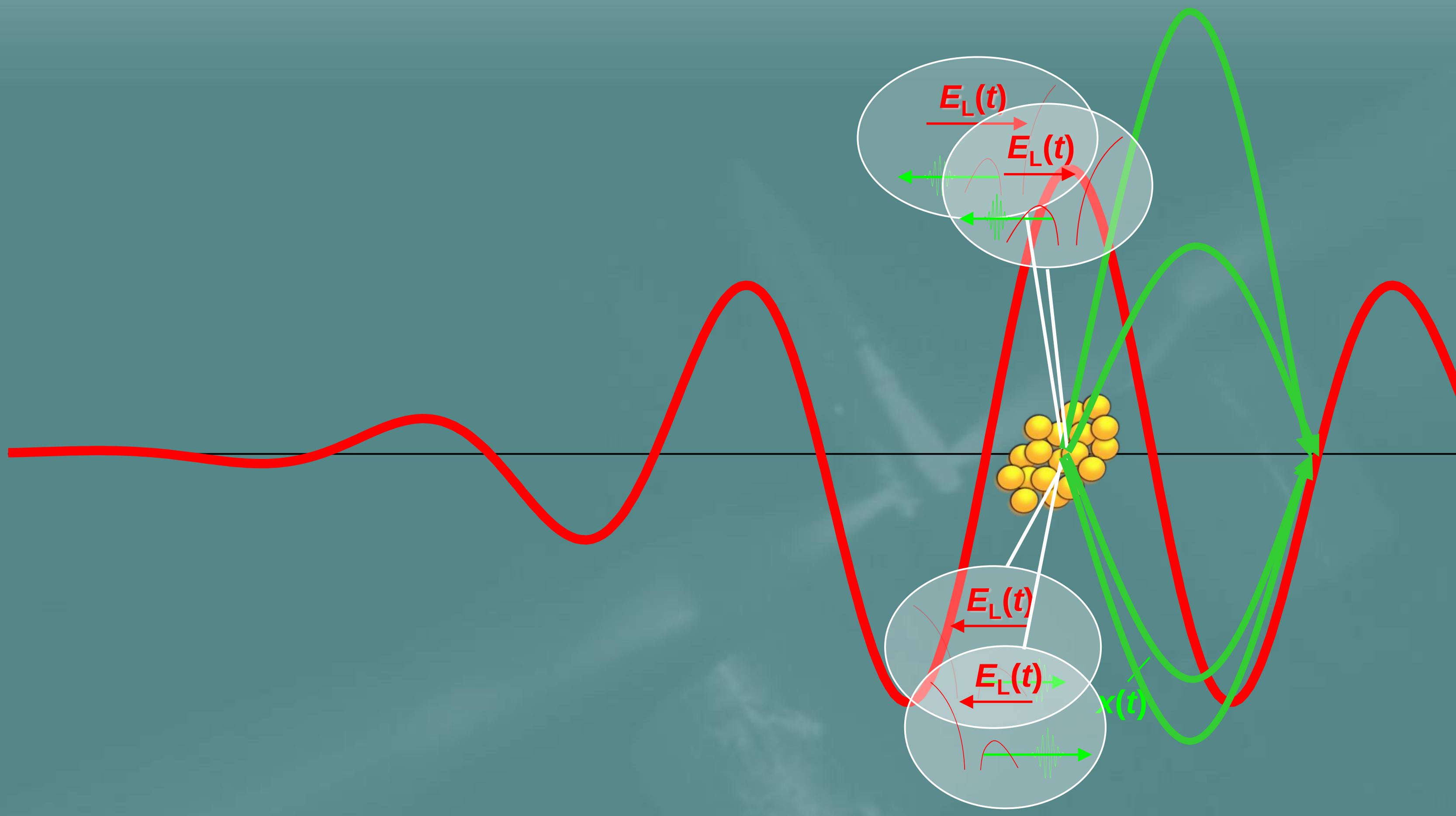
# steering bound electrons with controlled light fields: the generation of a sub-femtosecond pulse





3D-solution of the Schrödinger equation for hydrogen: Armin Scrinzi (TU Vienna)

# xuv/x-ray radiation from strongly driven atoms



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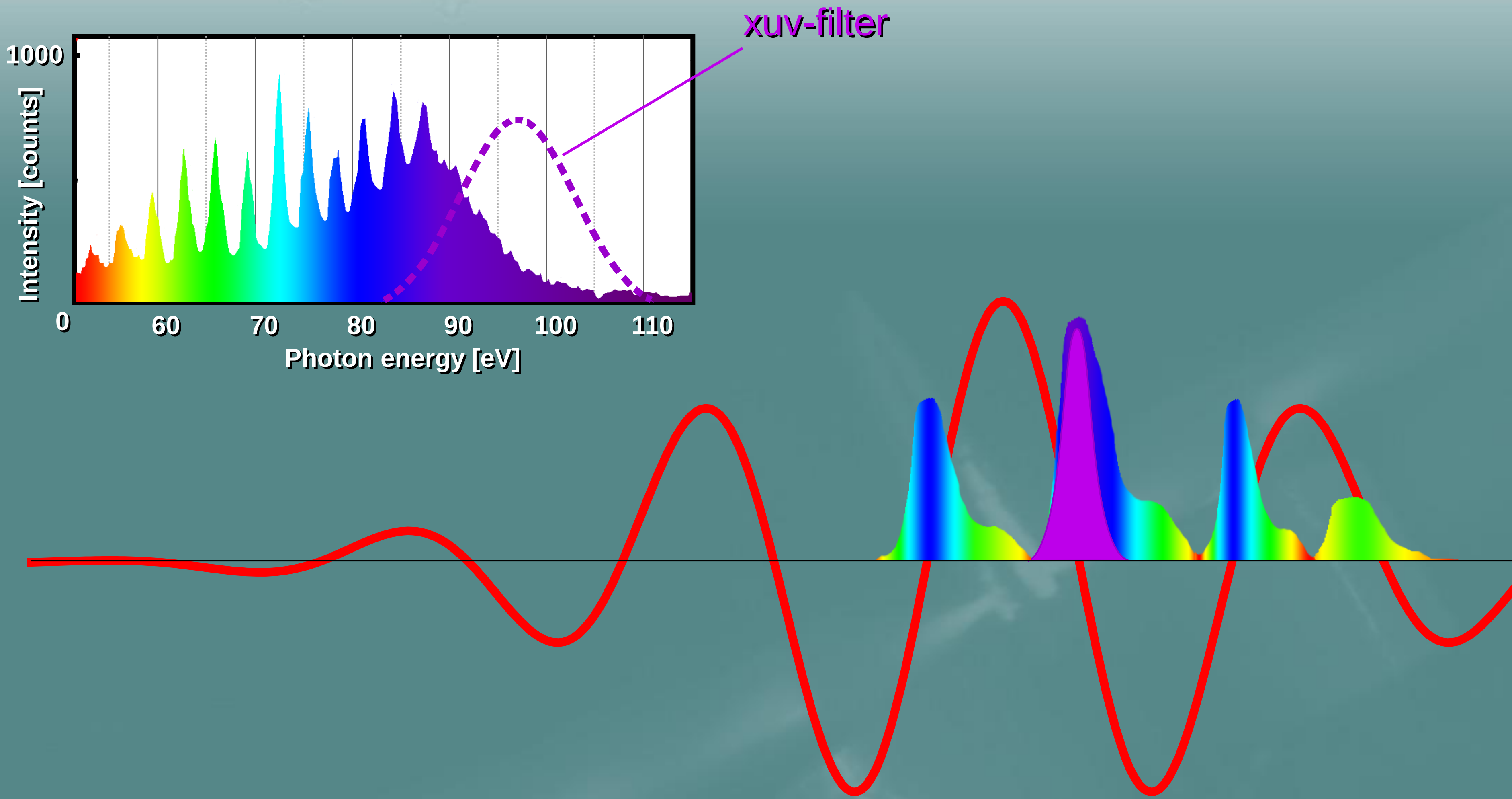
Ludwig-Maximilians
Universität München

# sub-femtosecond xuv/x-ray pulse generation



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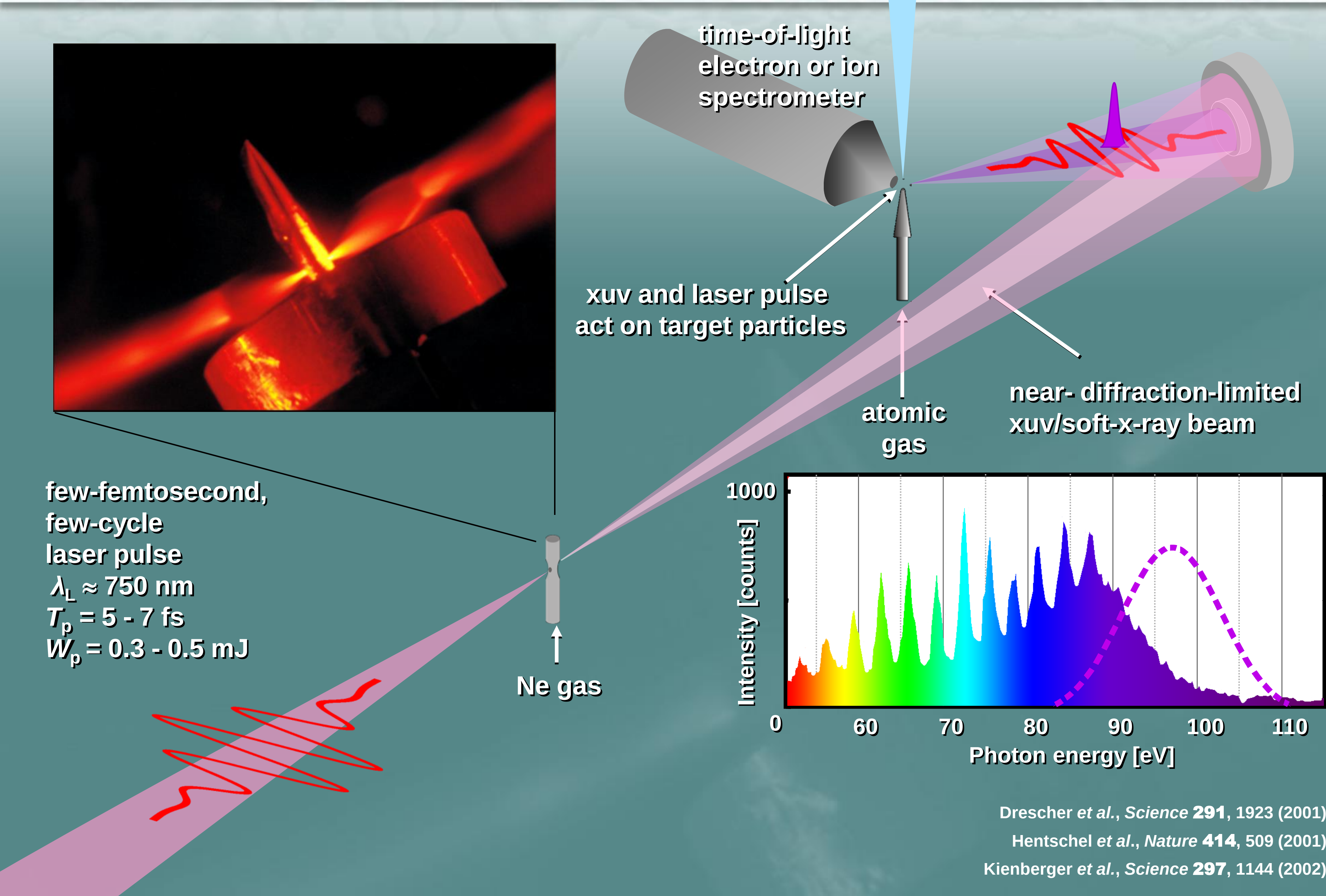
MPQ
Ludwig-Maximilians Universität München LMU

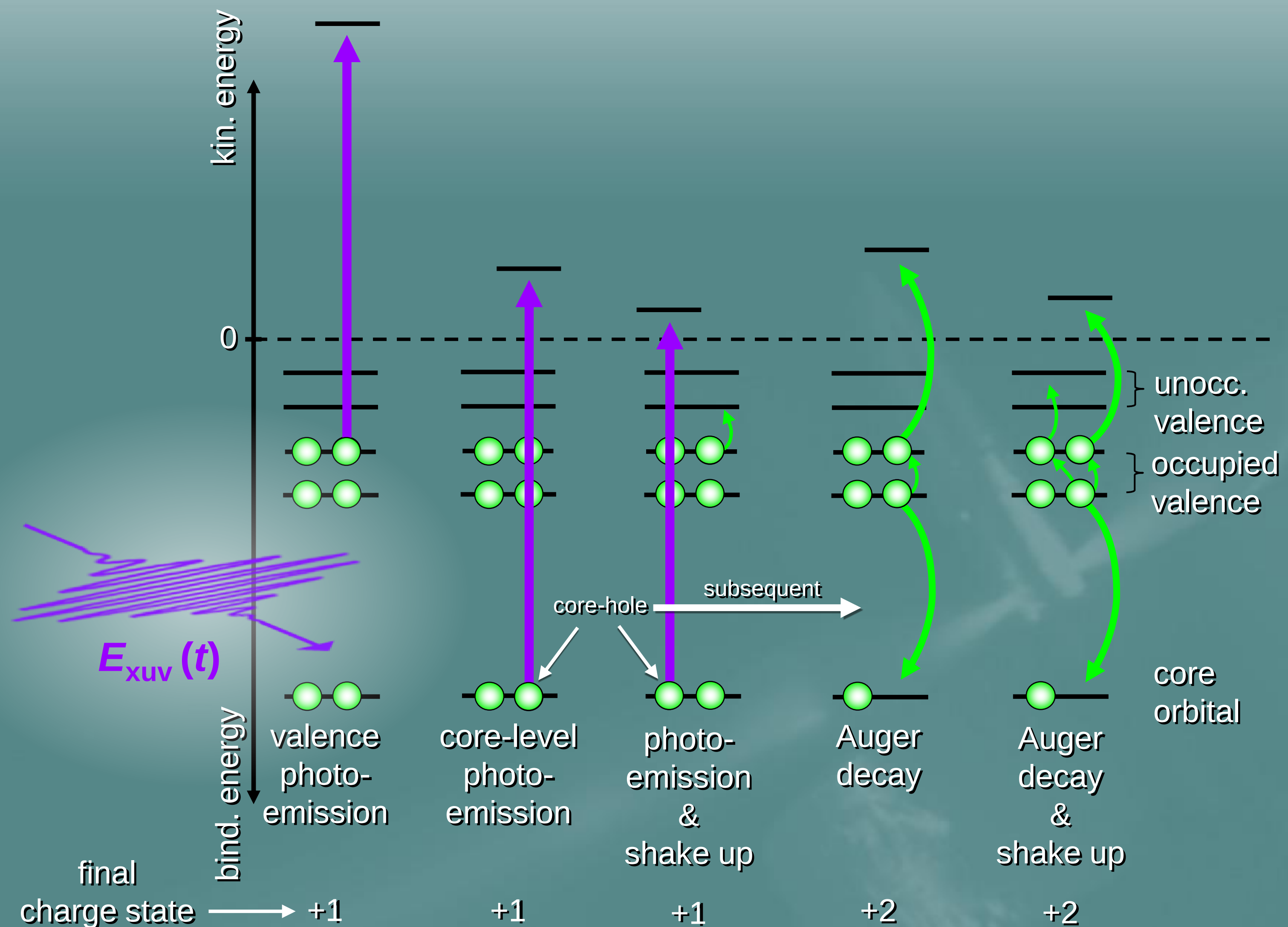
# attosecond pulse generation and detection




Drescher *et al.*, *Science* **291**, 1923 (2001)
Hentschel *et al.*, *Nature* **414**, 509 (2001)
Kienberger *et al.*, *Science* **297**, 1144 (2002)

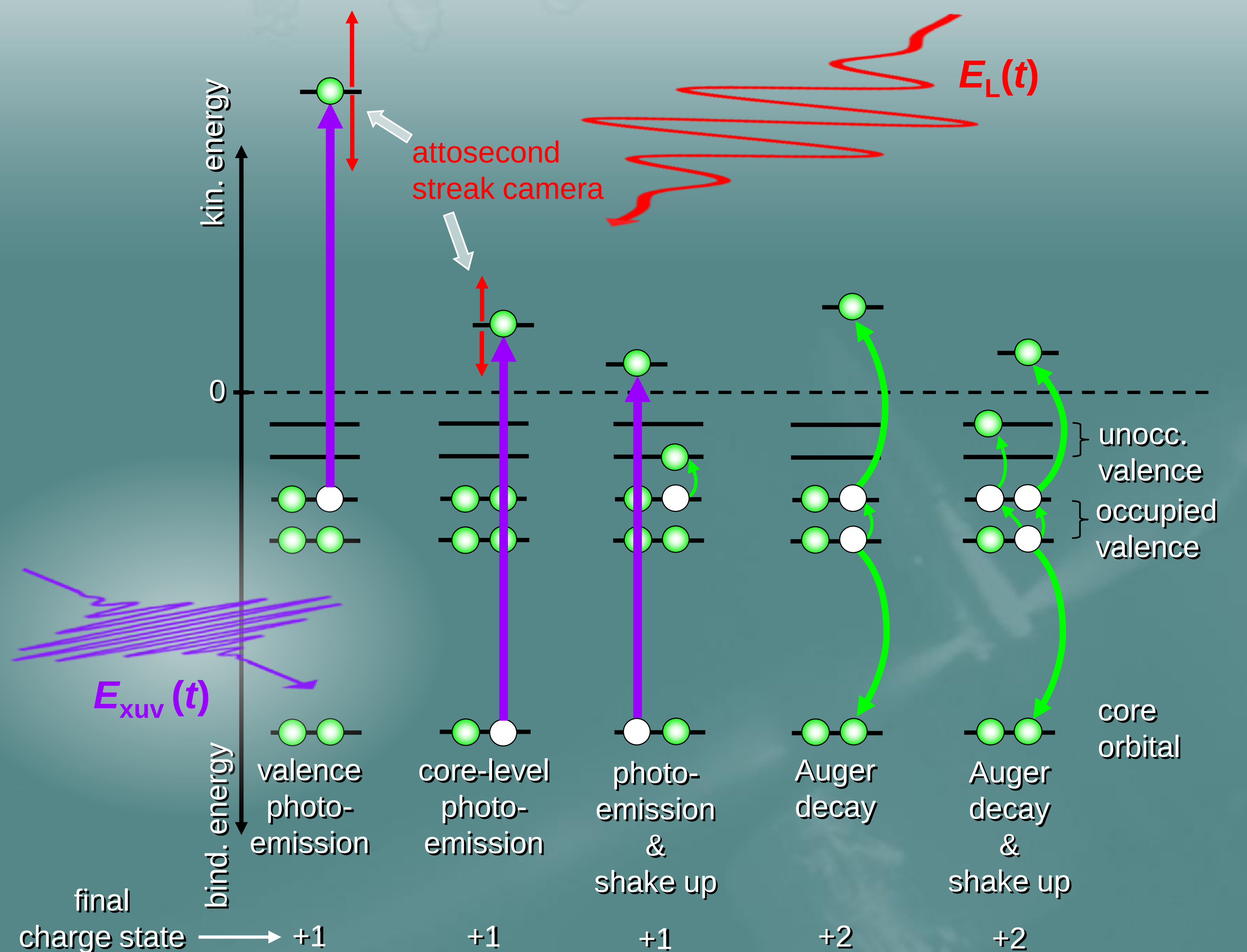
# triggering electronic transitions inside atoms

## by irradiation with xuv-light pulses



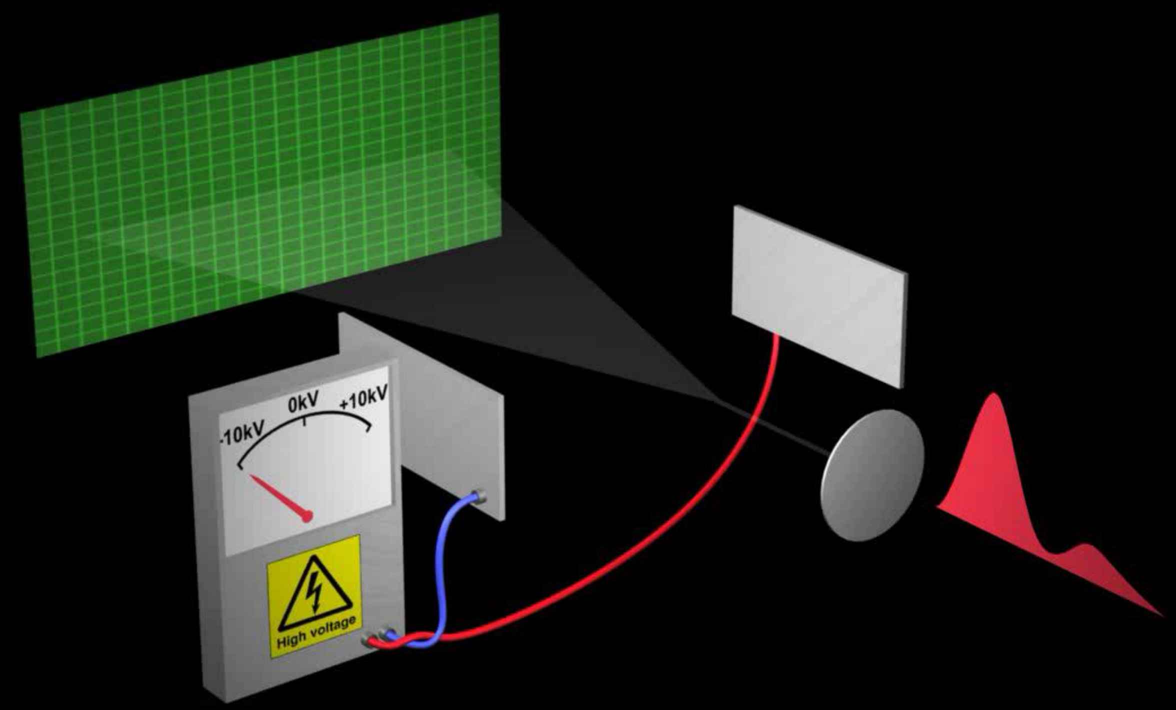
# probing electronic transitions inside atoms

## by means of strong-field-induced free-free transitions: streaking



# electron-optical streak camera

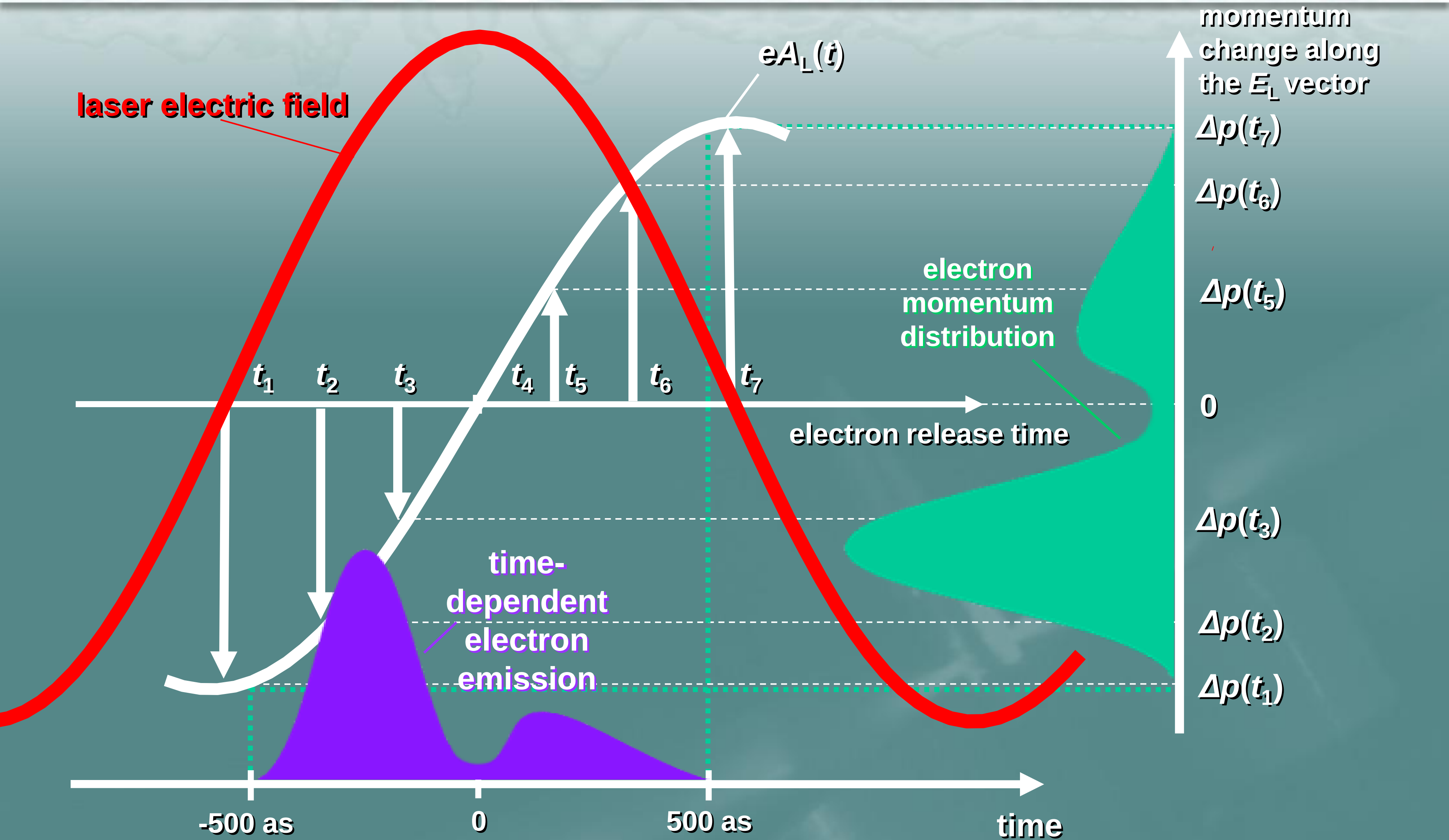





**resolution ~ 100 femtoseconds**

D. J. Bradley *et al., Opt. Commun.* **2**, 391 (1971)
M. Y. Schelev *et al., Appl. Phys. Lett.* **18**, 354 (1971)

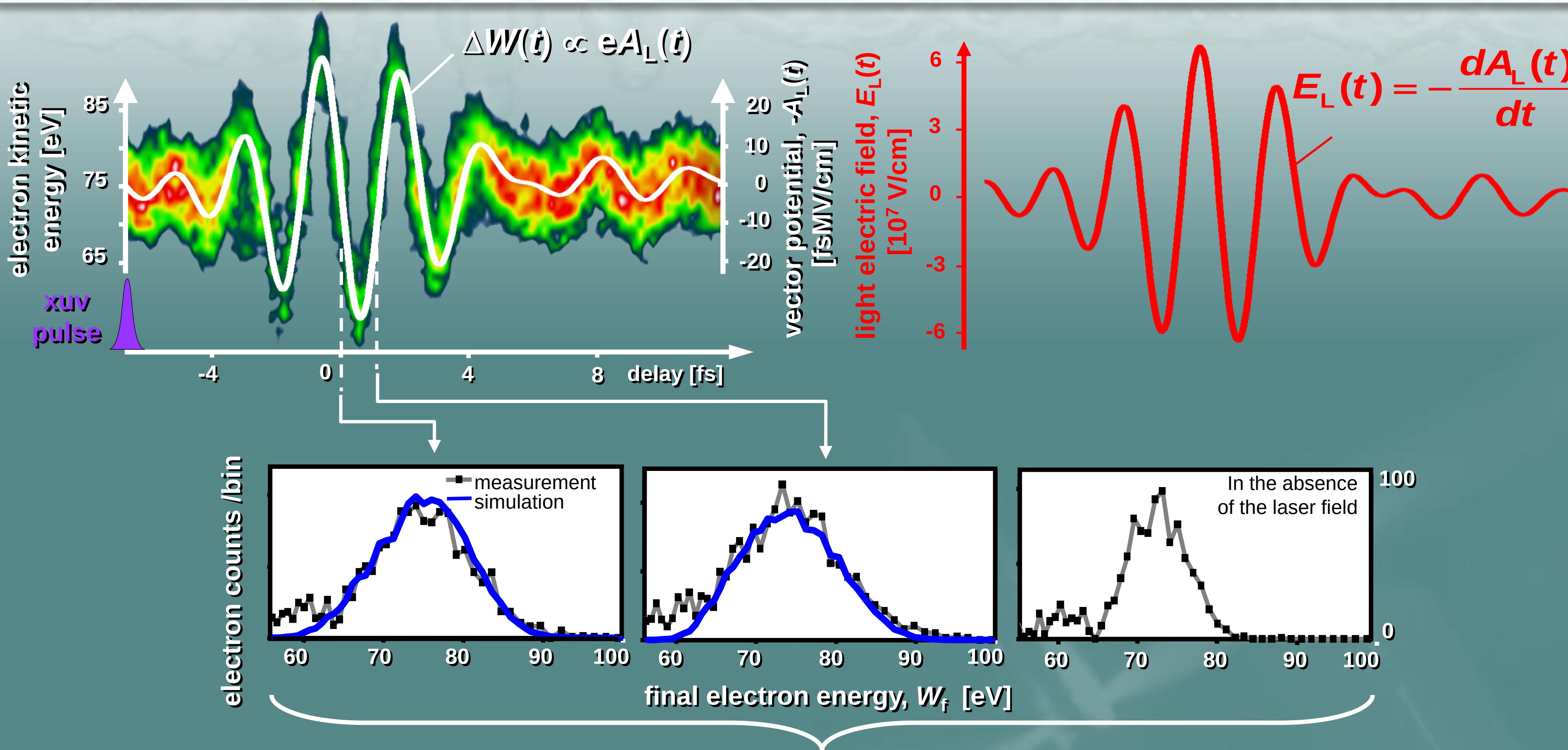
# mapping time to momentum



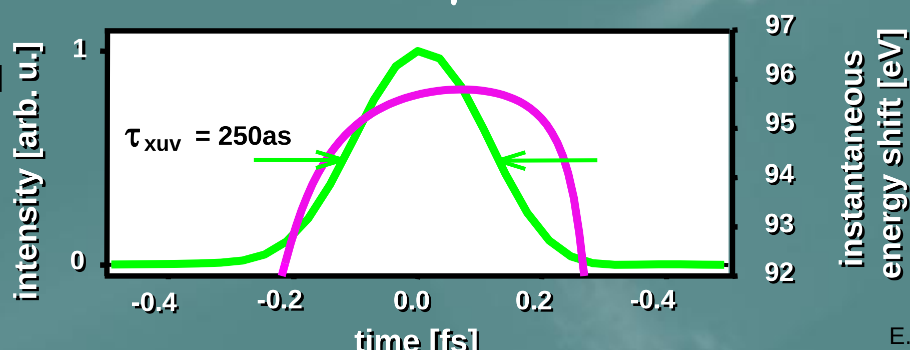

## optical-field-driven streak camera

J. Itatani *et al., Phys. Rev. Lett.* **88**, 173903 (2002)
M. Kitzler *et al., Phys. Rev. Lett.* **88**, 173904 (2002)

# attosecond streak camera: complete measurement of a few-cycle light wave *and* a sub-fs xuv pulse



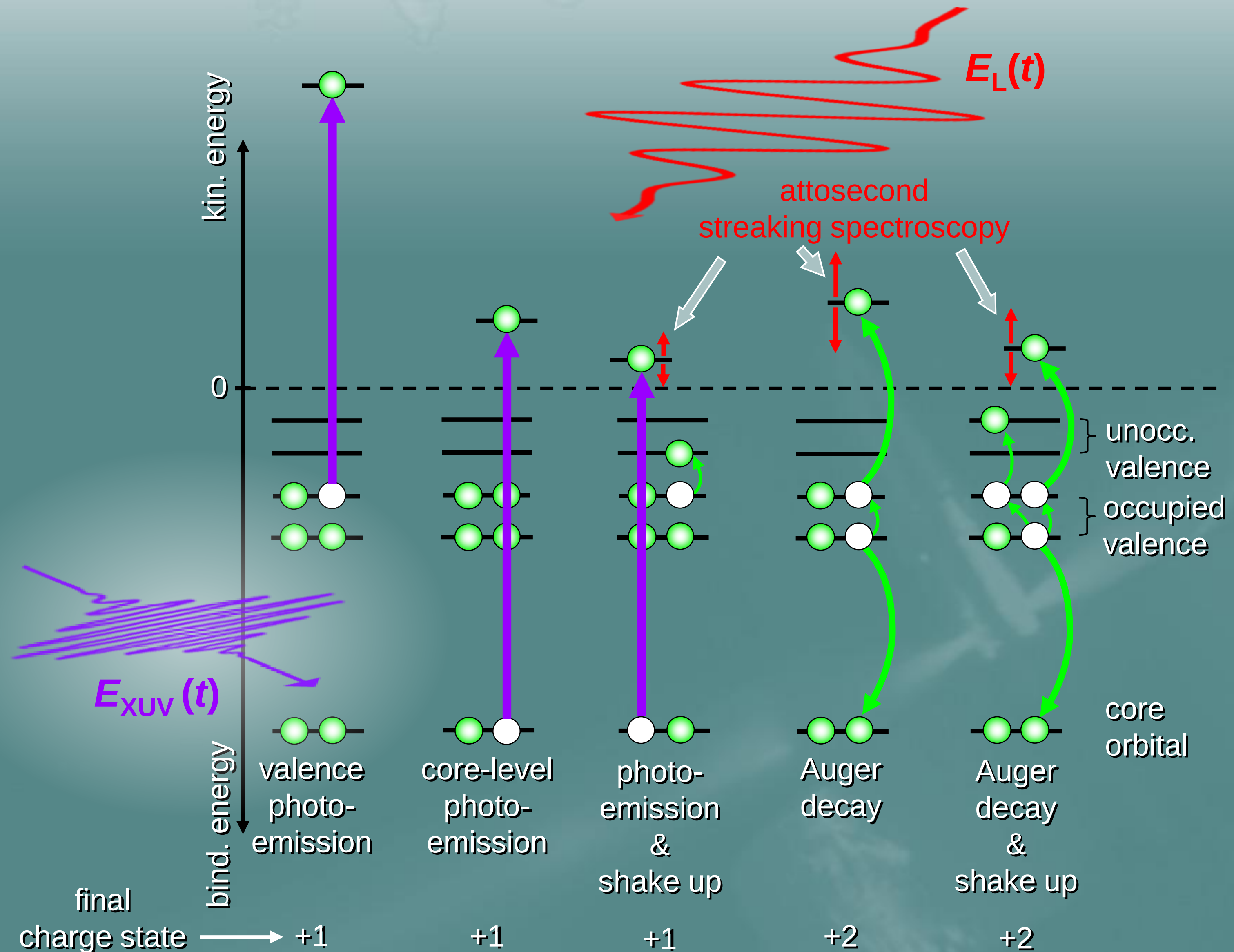

**single 250-attosecond xuv pulse @ 95 eV**



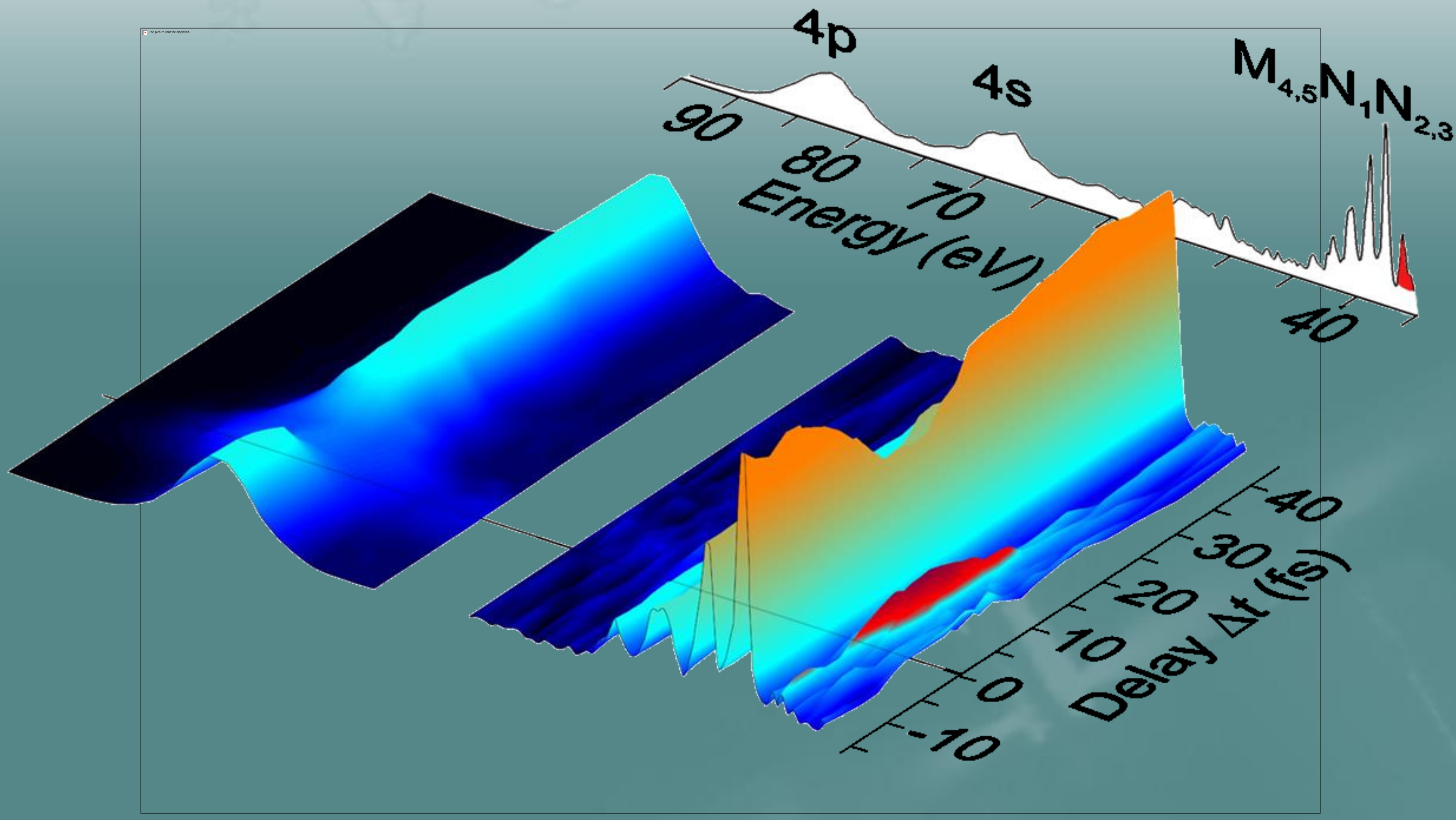

E. Goulielmakis *et al*., *Science* **305**, (2004)

# probing electronic transitions inside atoms

## by means of strong-field-induced free-free transitions: streaking



# streaked electron spectra following core-hole excitation in krypton by a sub-fs xuv pulse

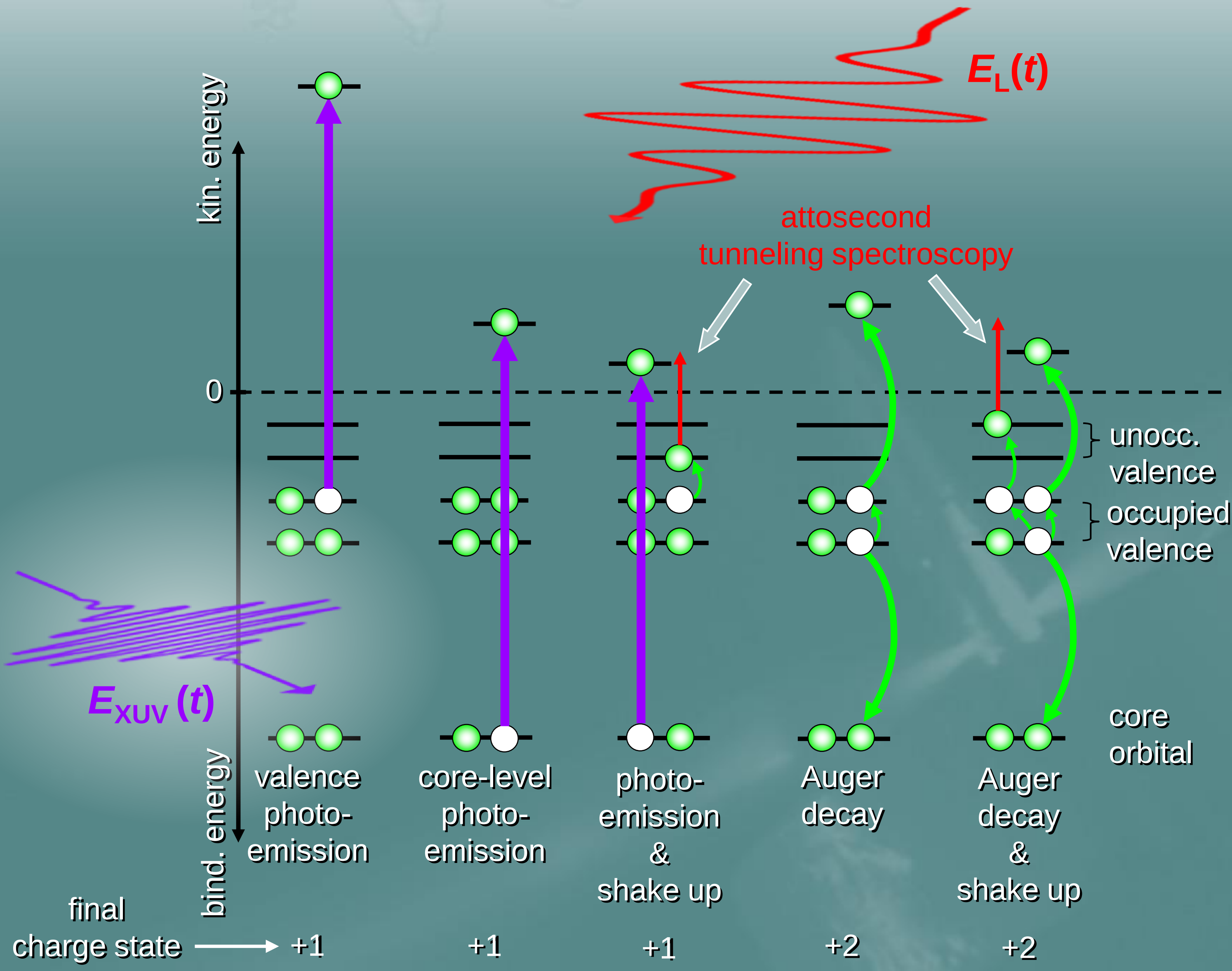



**tracing core-hole decay directly in time**
**lifetime of M-shell (3d) vacancy in Krypton: $\tau_h$ = 7.9±1 fs**

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

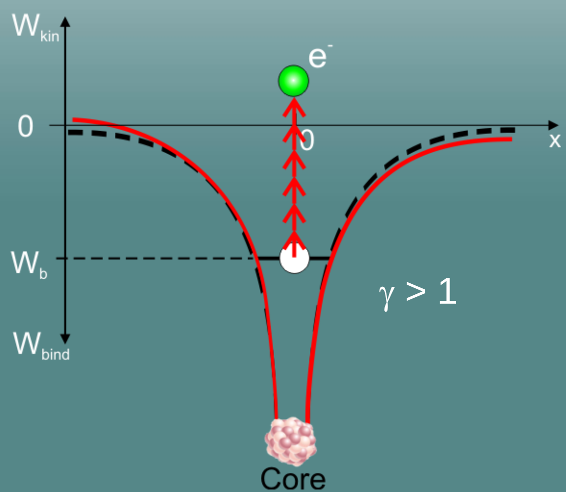
# probing electronic transitions inside atoms

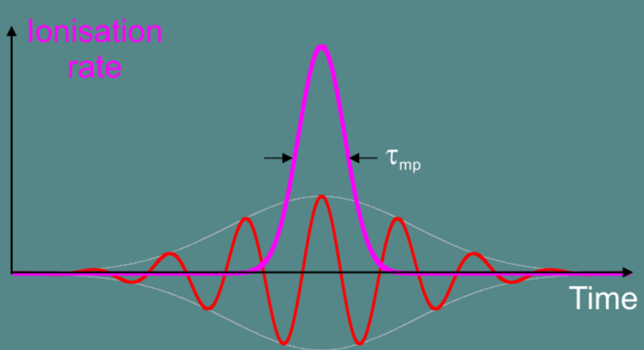
by means of strong-field-induced bound-free transitions: **tunneling**



# multiphoton versus tunneling ionization: the Keldysh theory

## multiphoton ionization:
due to absorption of many photons



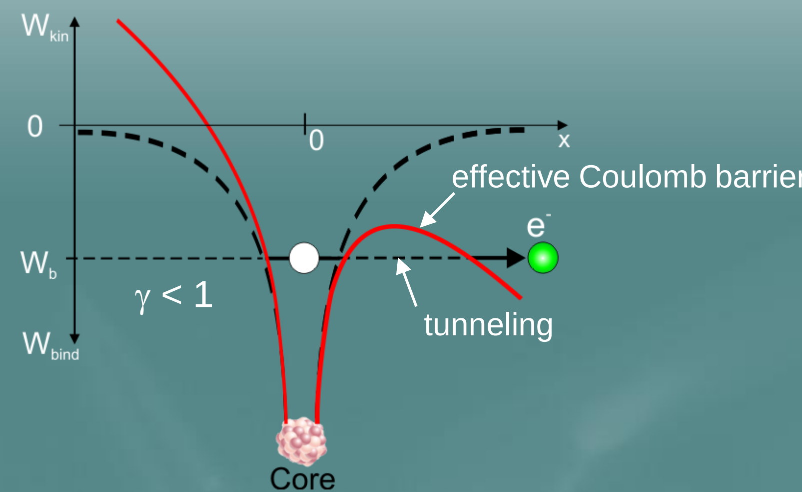



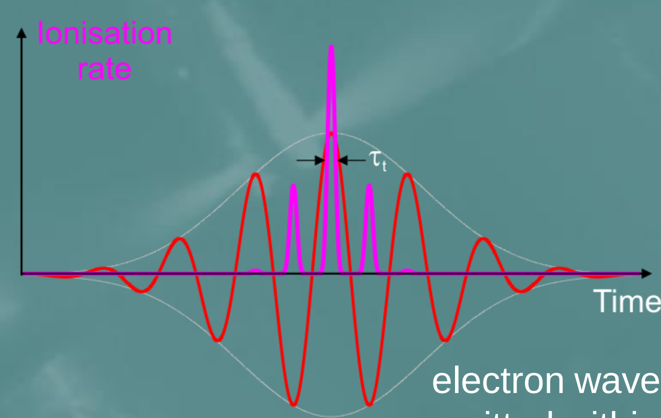

electron emission within a time $\tau_{mp}$ shorter than the pulse duration

Keldysh parameter:

$$\gamma = \frac{\omega_L \sqrt{2mW_b}}{eE_L}$$

## tunneling ionization:
due to suppression of Coulomb potential

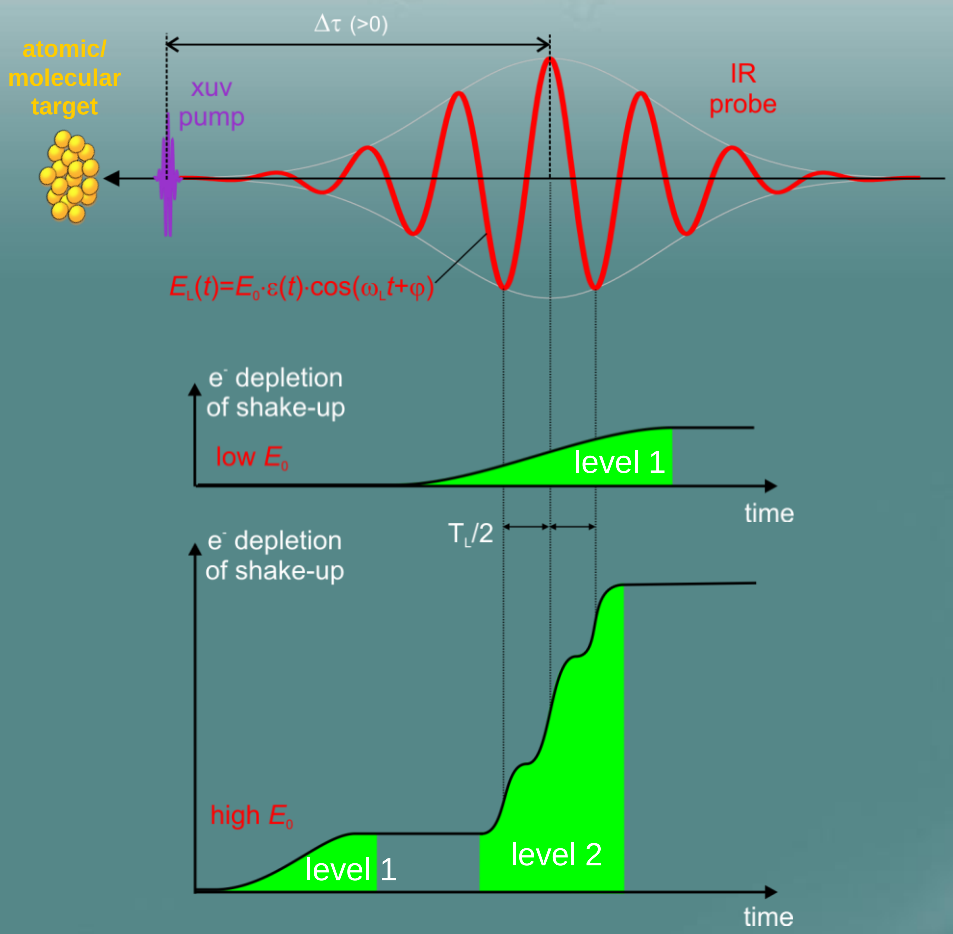


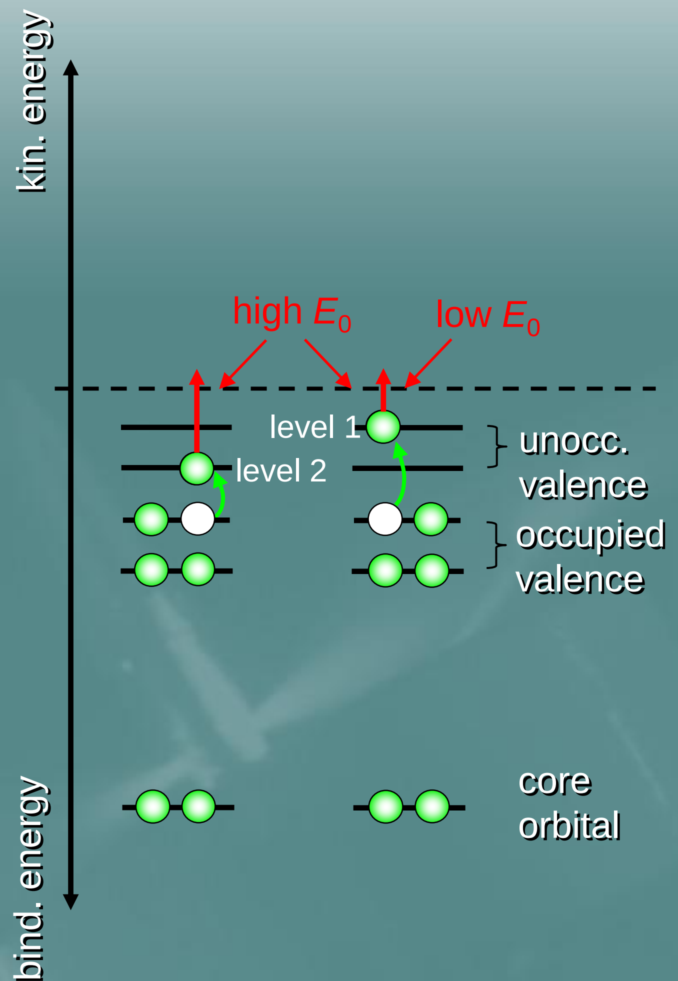




electron wave-packets emitted within a time $\tau_t$ shorter than the half-period of the laser

Keldysh, L.V., Sov. Phys. JETP **20**, 1307 (1965)

# time evolution of probing – ionization with a few-cycle pulse

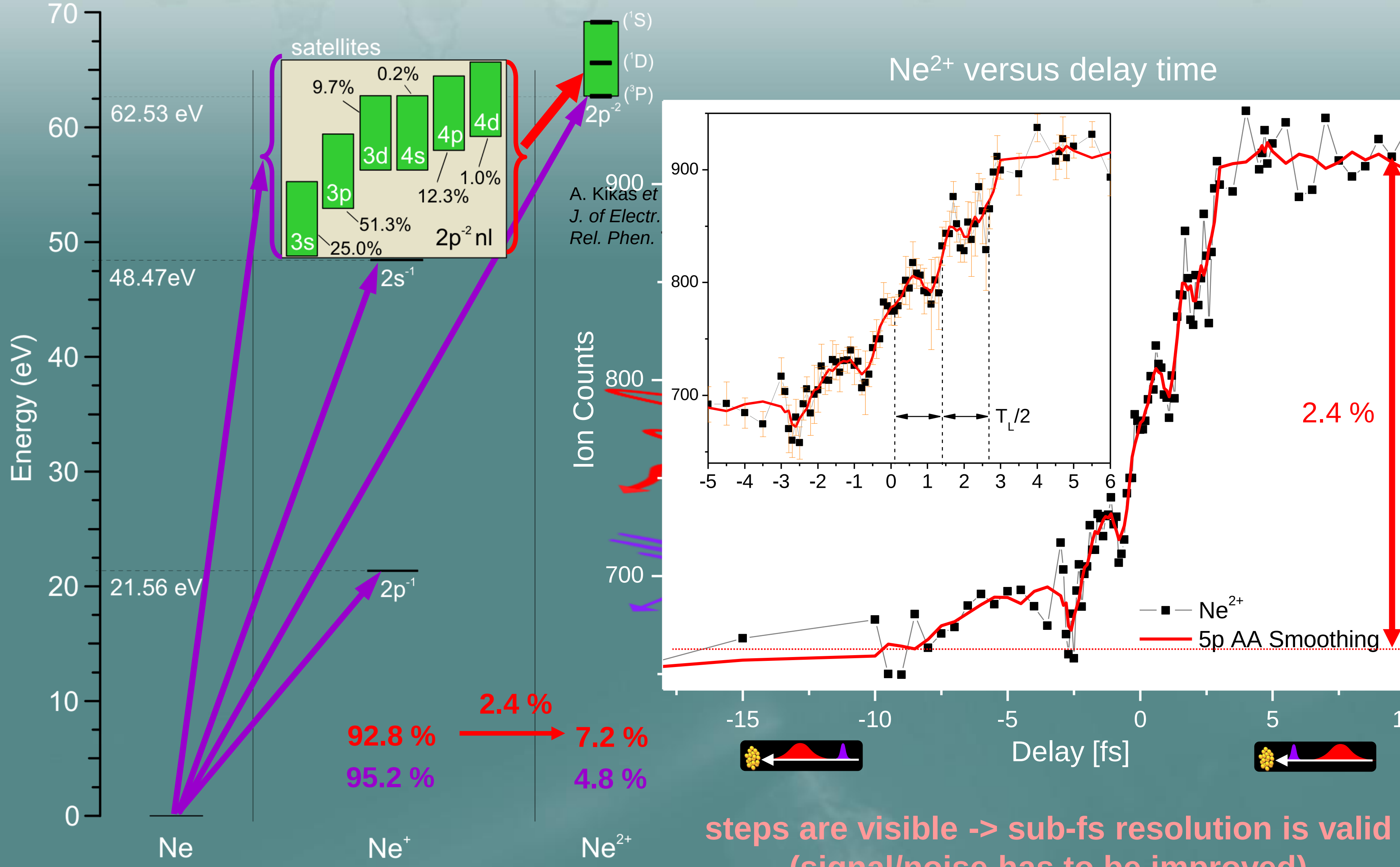


# attosecond tunneling spectroscopy

first experiments in neon and xenon

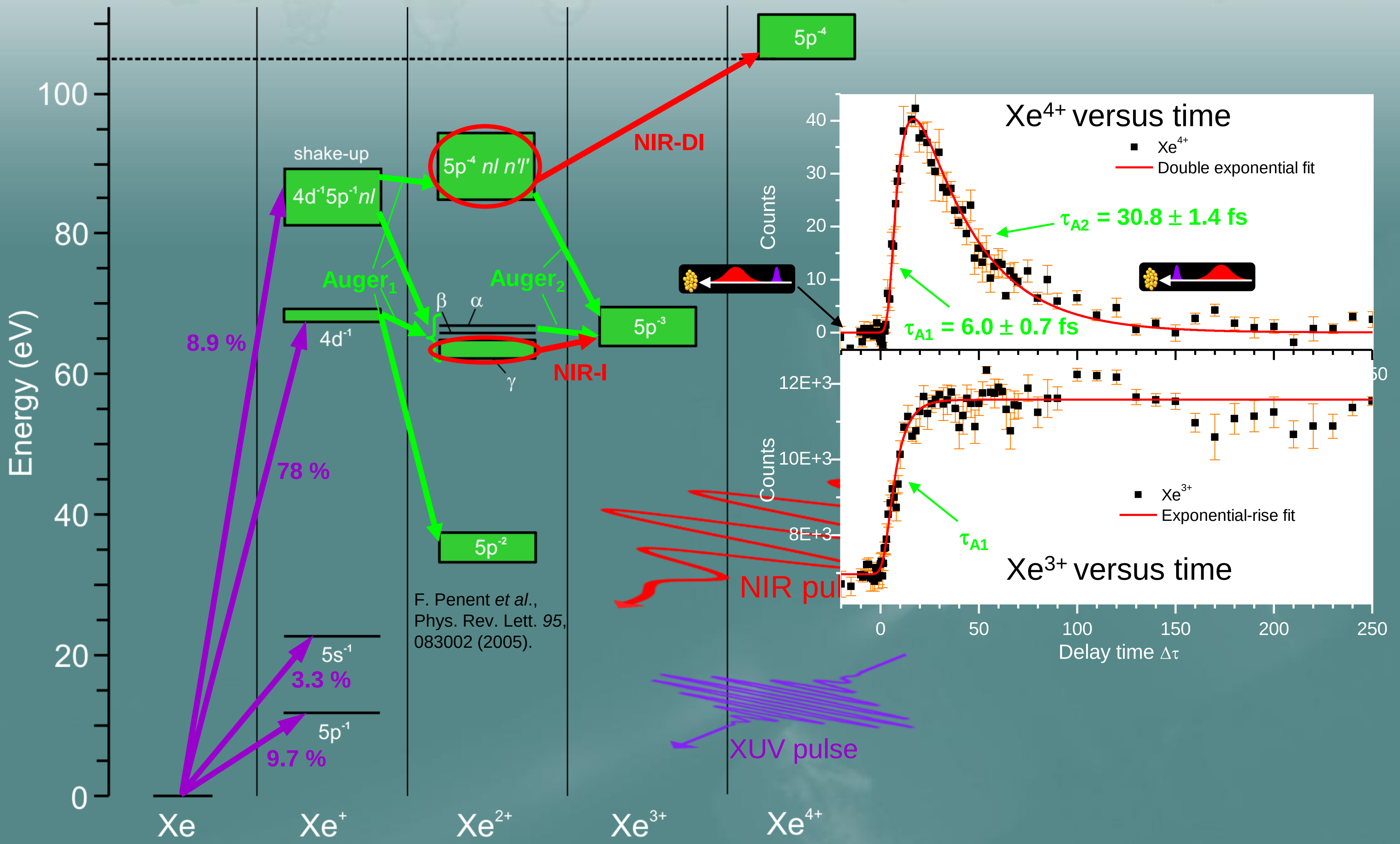
# testing the sub-fs resolution with neon




**steps are visible -> sub-fs resolution is valid**
**(signal/noise has to be improved)**

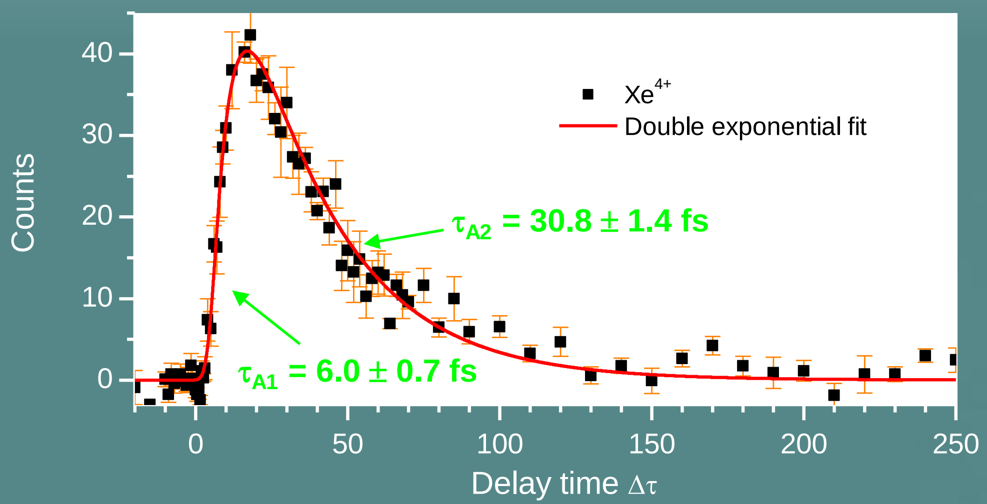
..to be published

# xenon energy levels – illustration of dynamics



# resolving electron dynamics in xenon

this experiment:




..to be published

time-integral frequency-resolved experiments:

$\tau_{A1}$ ($4d_{3/2}$) = 6.3 ± 0.2 fs
$\tau_{A1}$ ($4d_{5/2}$) = 5.9 ± 0.2 fs

$\tau_{A2}$ > 23 fs

F. Penent, Phys. Rev. Lett. 95, 083002 (2005).

# coworkers & collaborators

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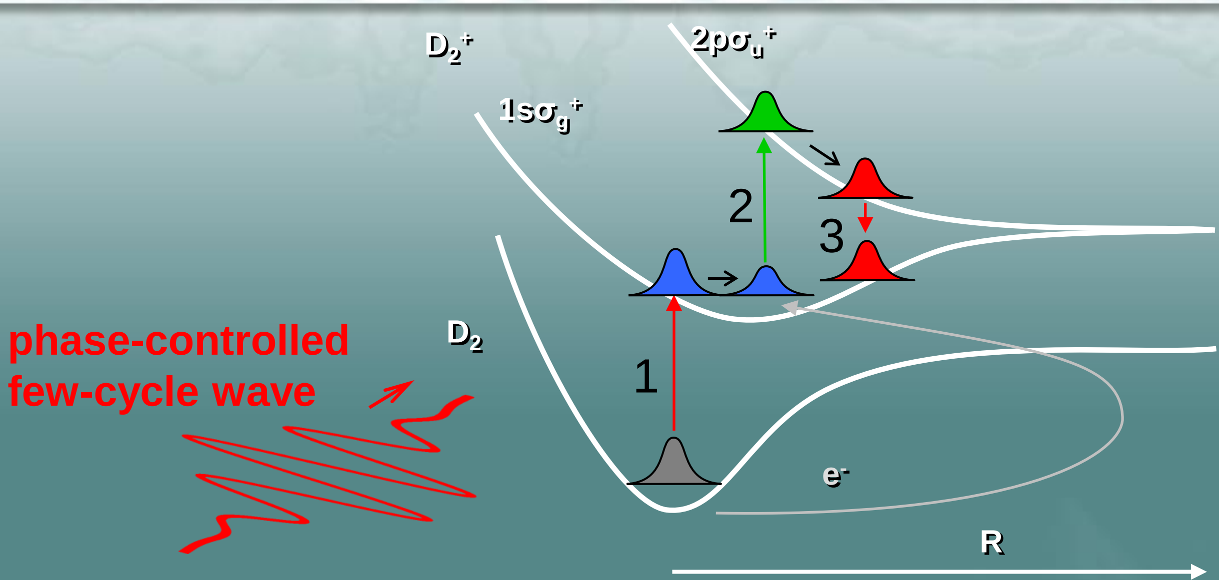
graphics: Barbara Ferus

# End

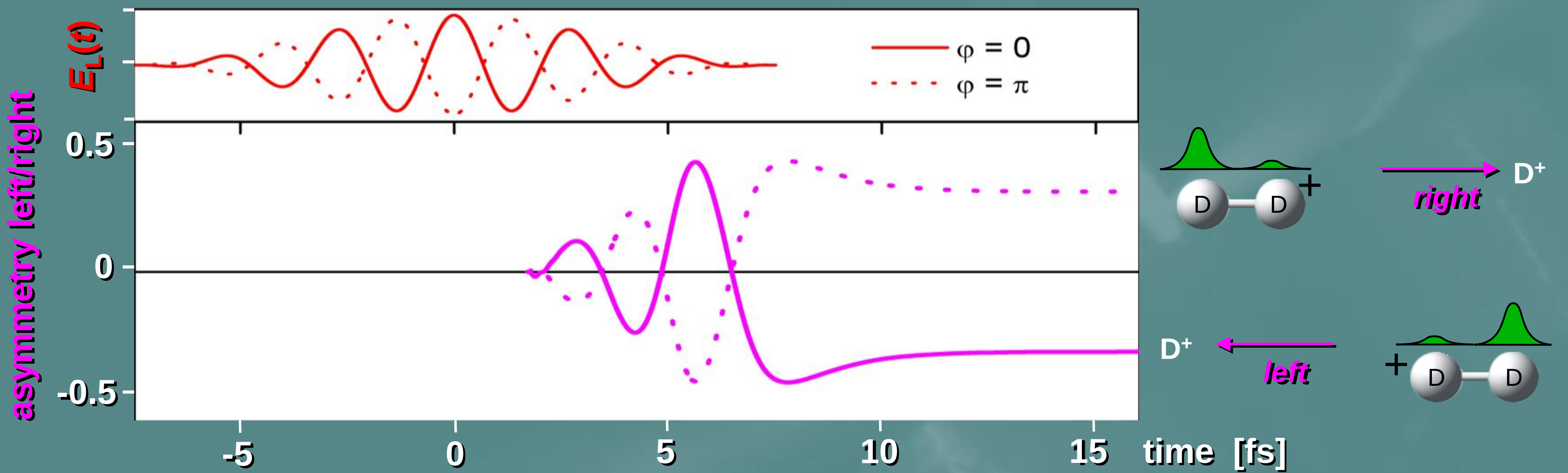
# may attosecond control of electronic motion in chemical bonds affect the outcome of molecular dynamics?




**1** ionization of $D_2$

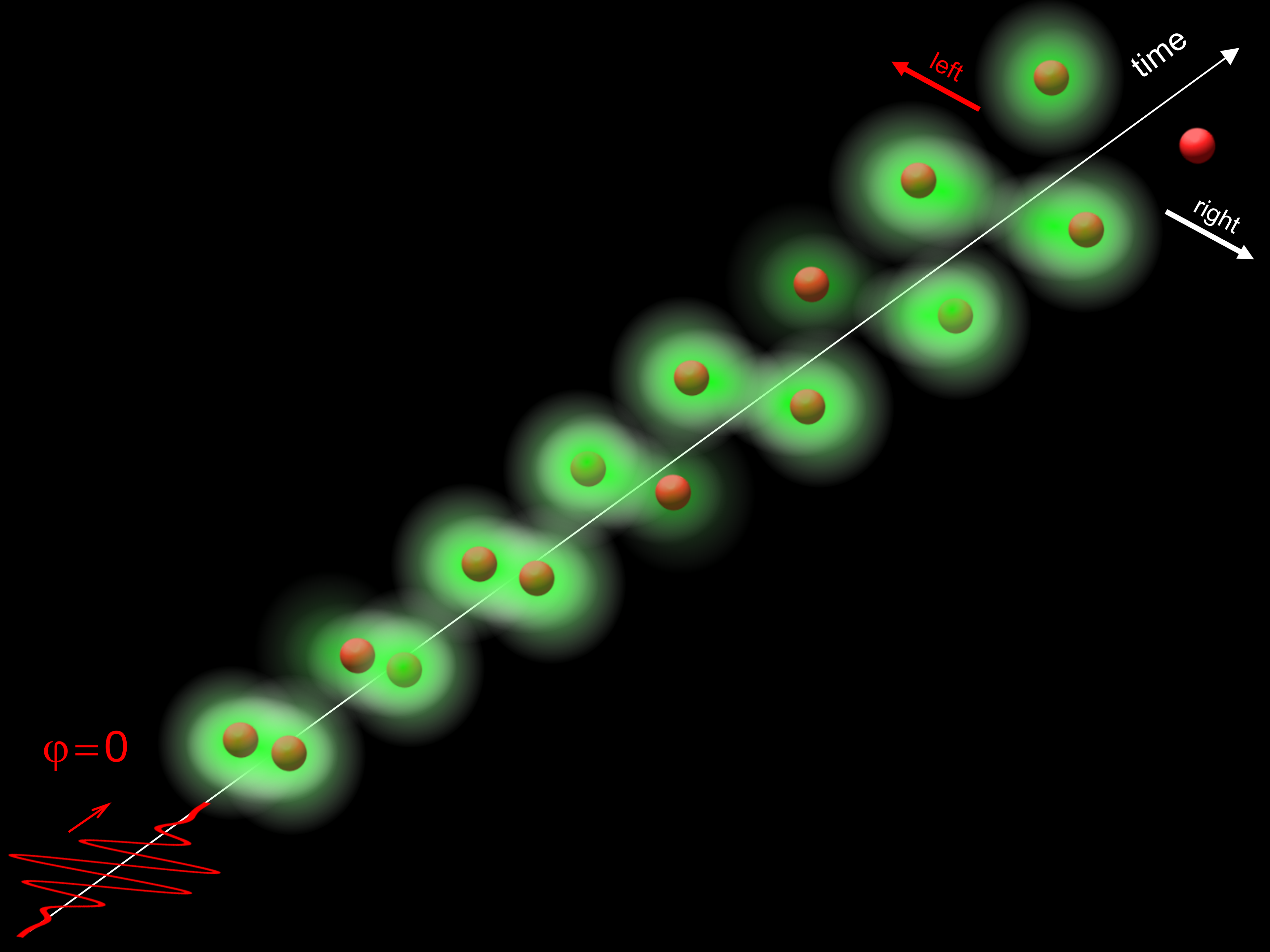
**2** recollisional excitation

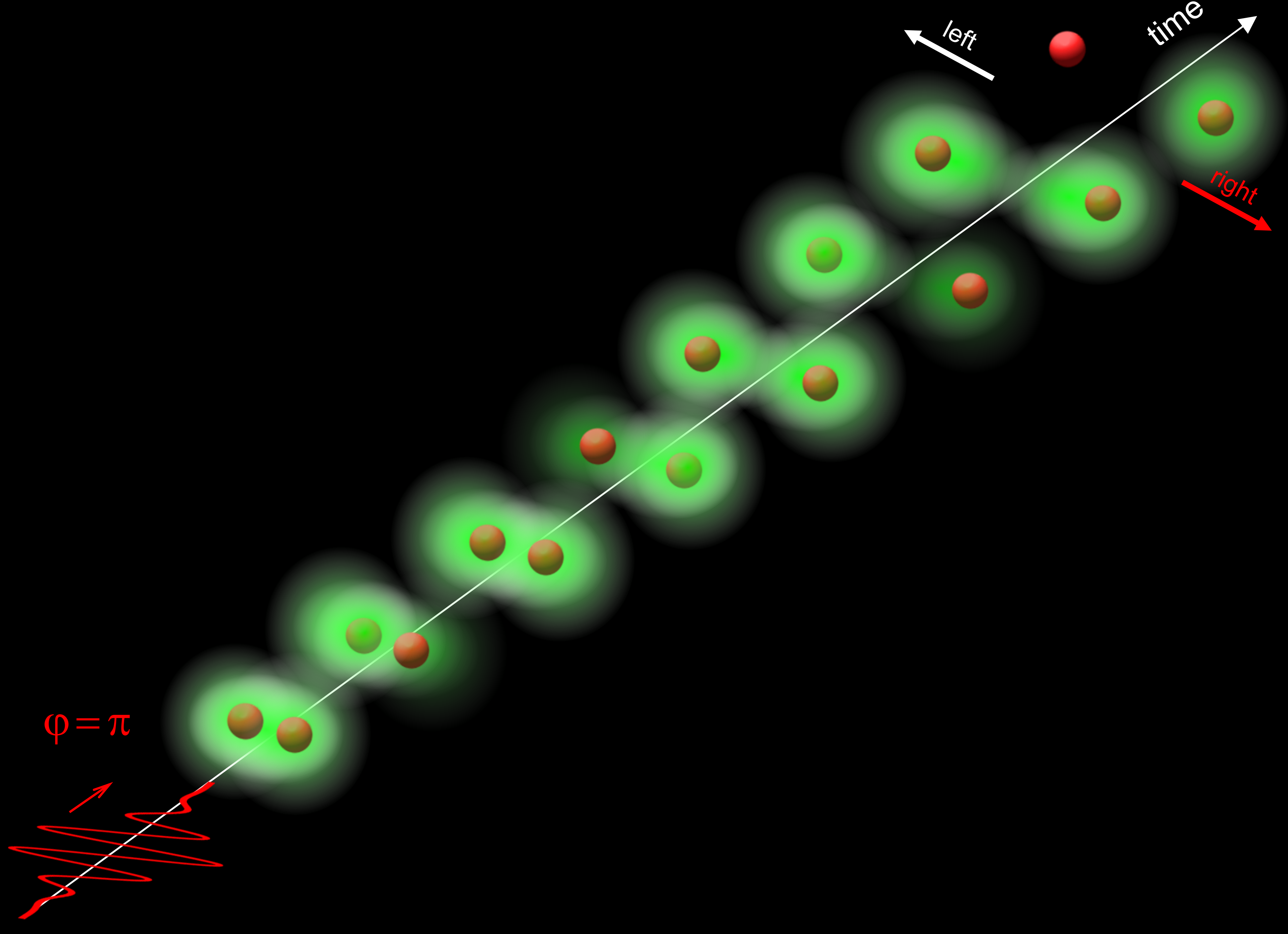
**3** formation of a coherent superposition ($1s\sigma_g^+$,$2p\sigma_u^+$) state in $D_2^+$




⇒ YES: direction of emission of $D^+$ is controlled by light waveform

M. Kling *et al.*, *Science* **312**, 246 (2006)


left
time
right
φ=0


left
time
right
φ = π