# attosecond physics:

## basic tools & first applications

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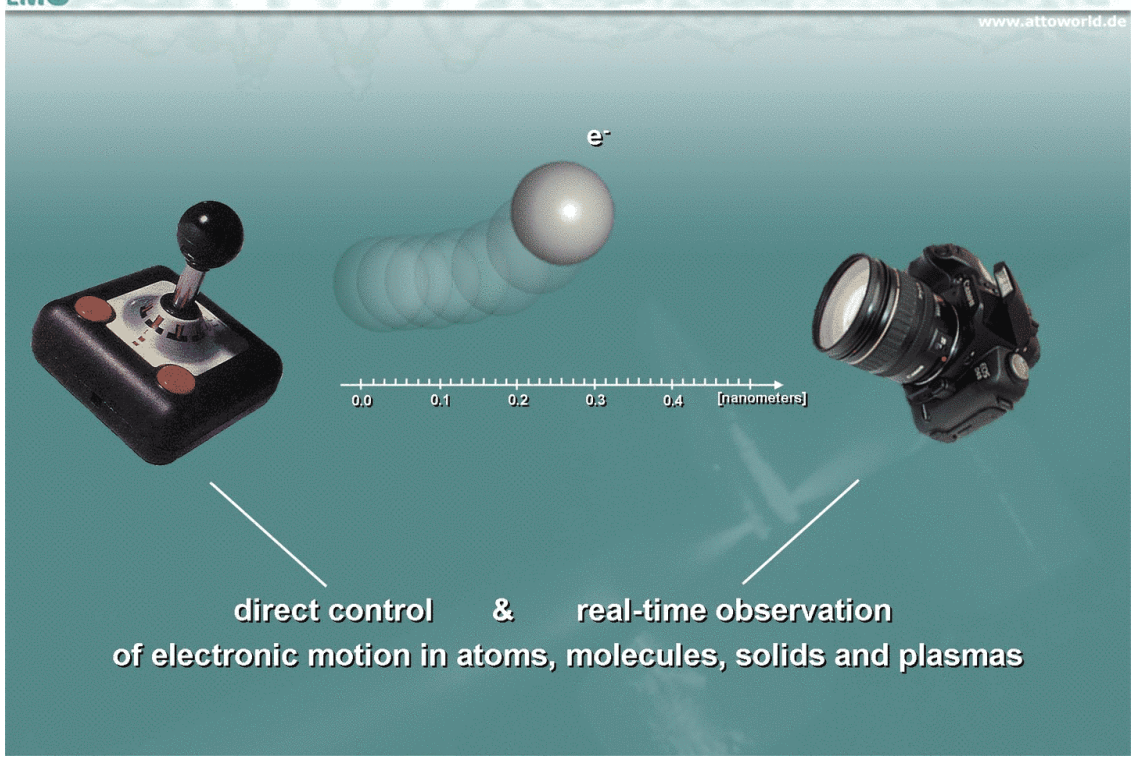
Technische Universität Wien
Wien, Austria

Attosecond Science Conference
Kavli Inst. of Theoretical Physics, UC Santa Barbara, 1 August, 2006

## 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

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„ ... the greater the detail in which we can pursue Nature on any path, the richer and more durable will be the gain that can be derived from our perceptiveness...“

Max Planck

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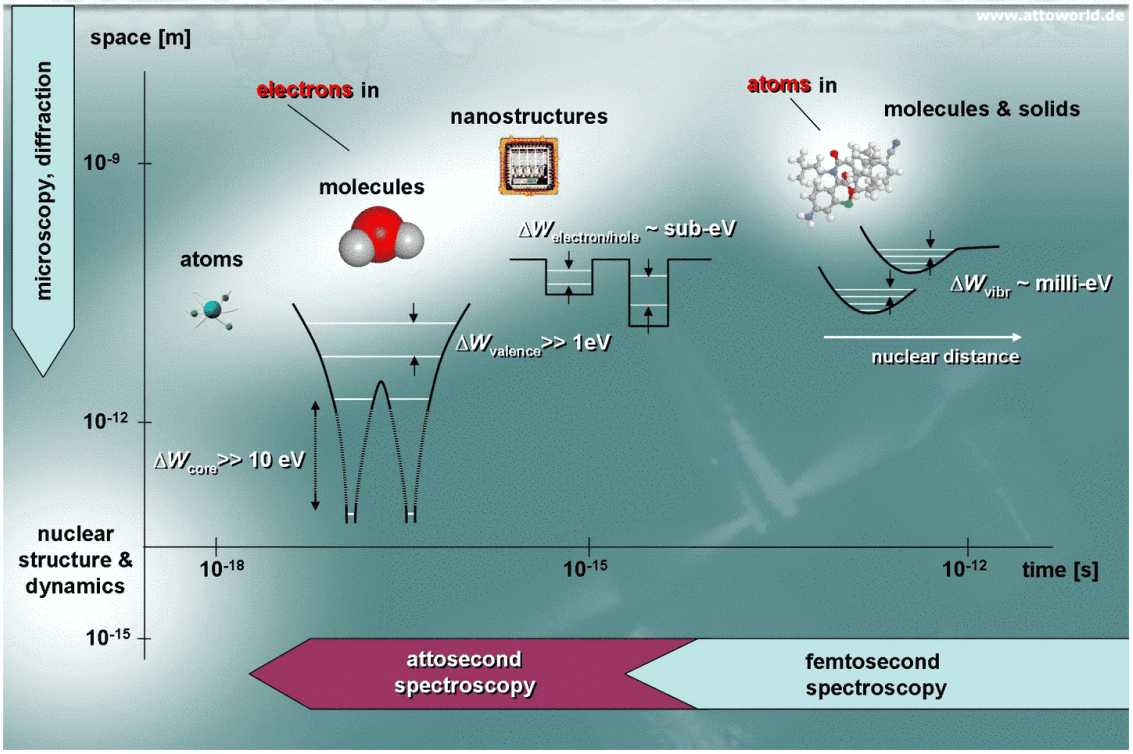
## structure and dynamics in the microcosm



## evolution of ultrafast science

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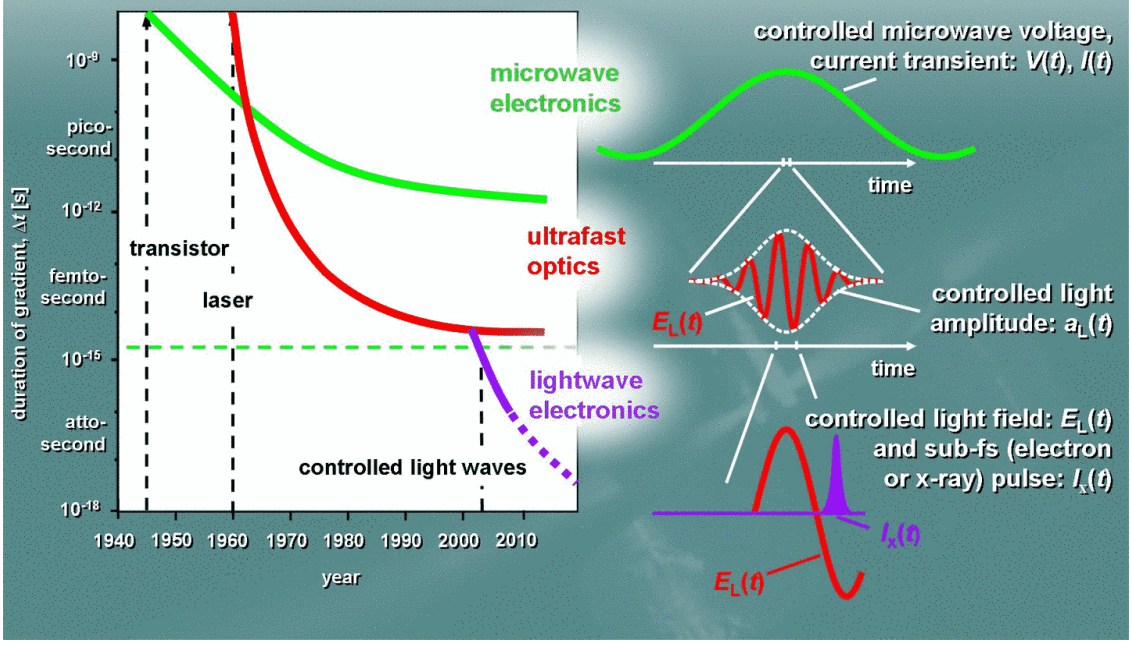
**ultrafast control & metrology relies on a signal with a controlled, steep temporal gradient**




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

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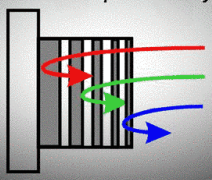
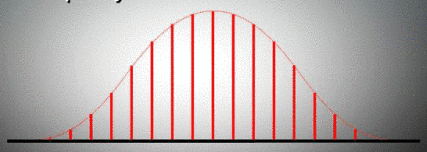
ultrabroadband dispersion control with chirped multilayers



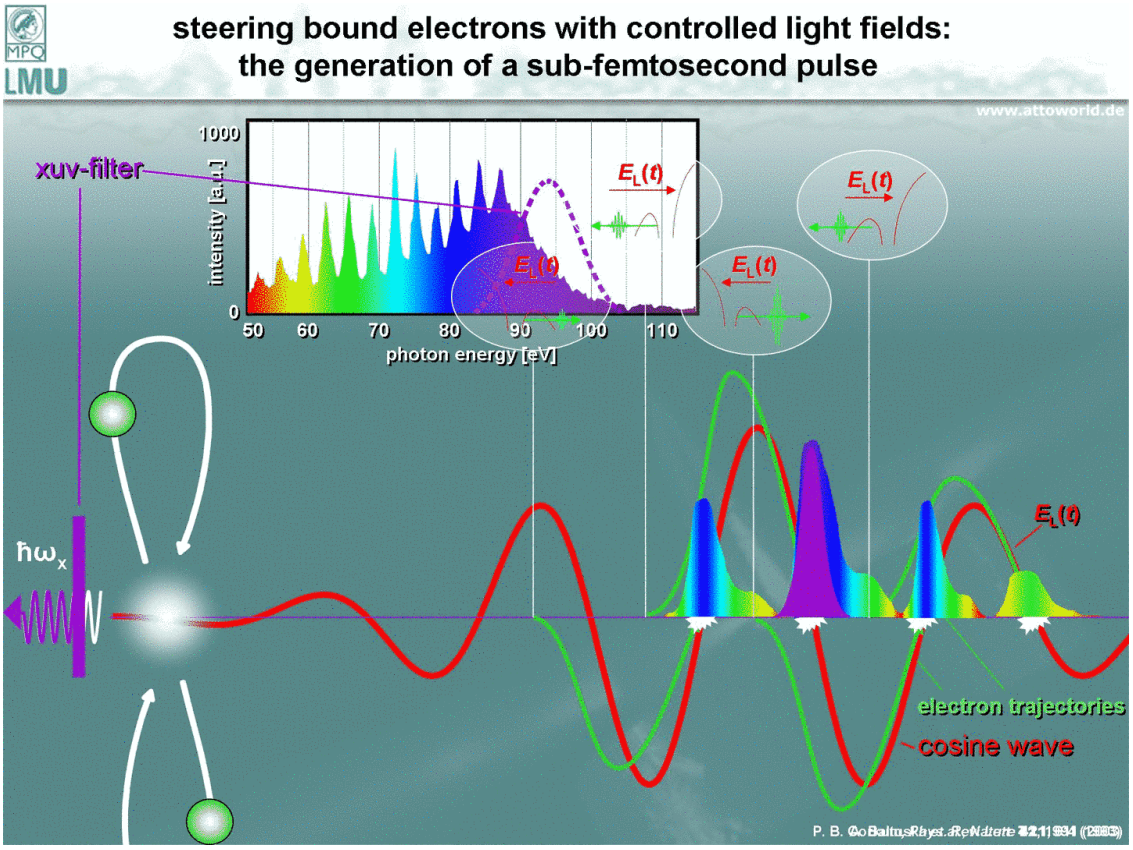
R. Szipöcs, K. Ferencz, Ch. Spielmann, F. Krausz
*Opt. Lett.* **19**, 201 (1994)

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)


steering bound electrons with controlled light fields:
the generation of a sub-femtosecond pulse
MPQ
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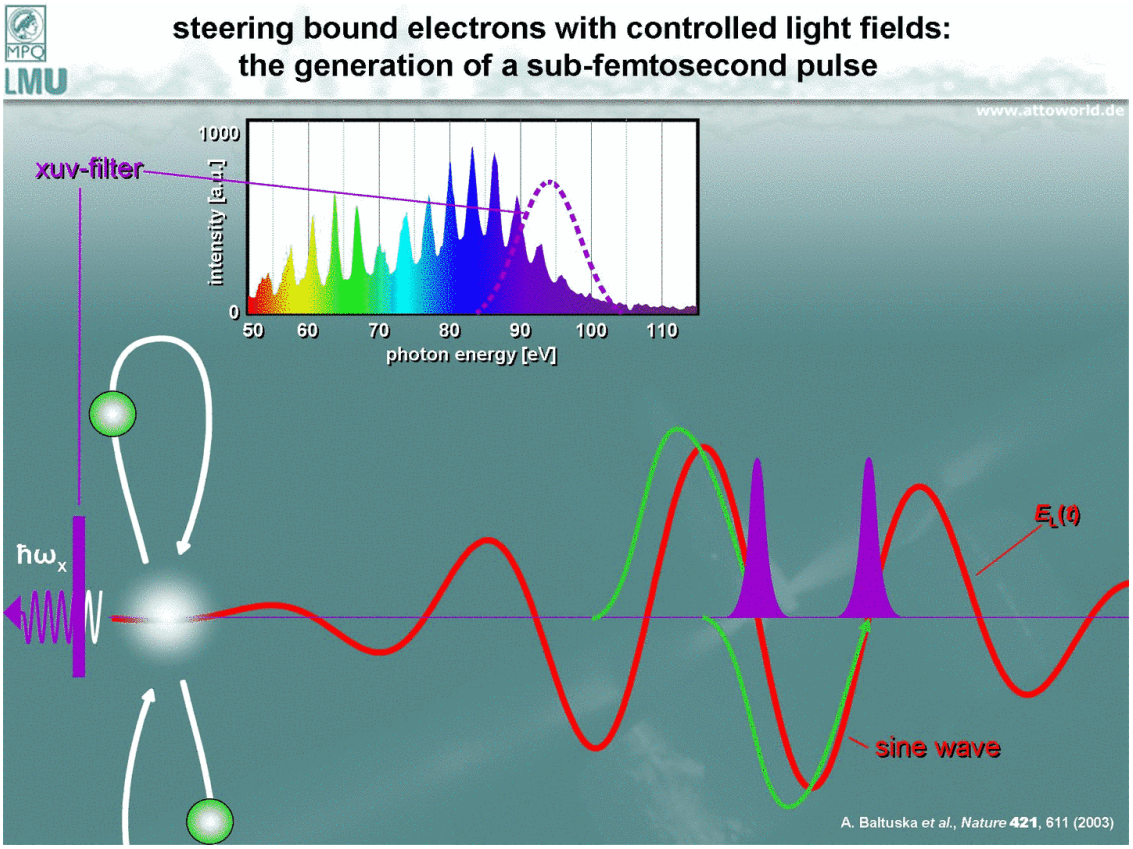
xuv-filter
1000
intensity [a.u.]
0
50
60
70
80
90
100
110
photon energy [eV]
$E_L(t)$
$\hbar\omega_x$
electron trajectories
cosine wave
P. B. Corkum, Phys. Rev. Lett. 71, 1994 (1993)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MPQ
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xuv-filter
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intensity [a.u.]
0
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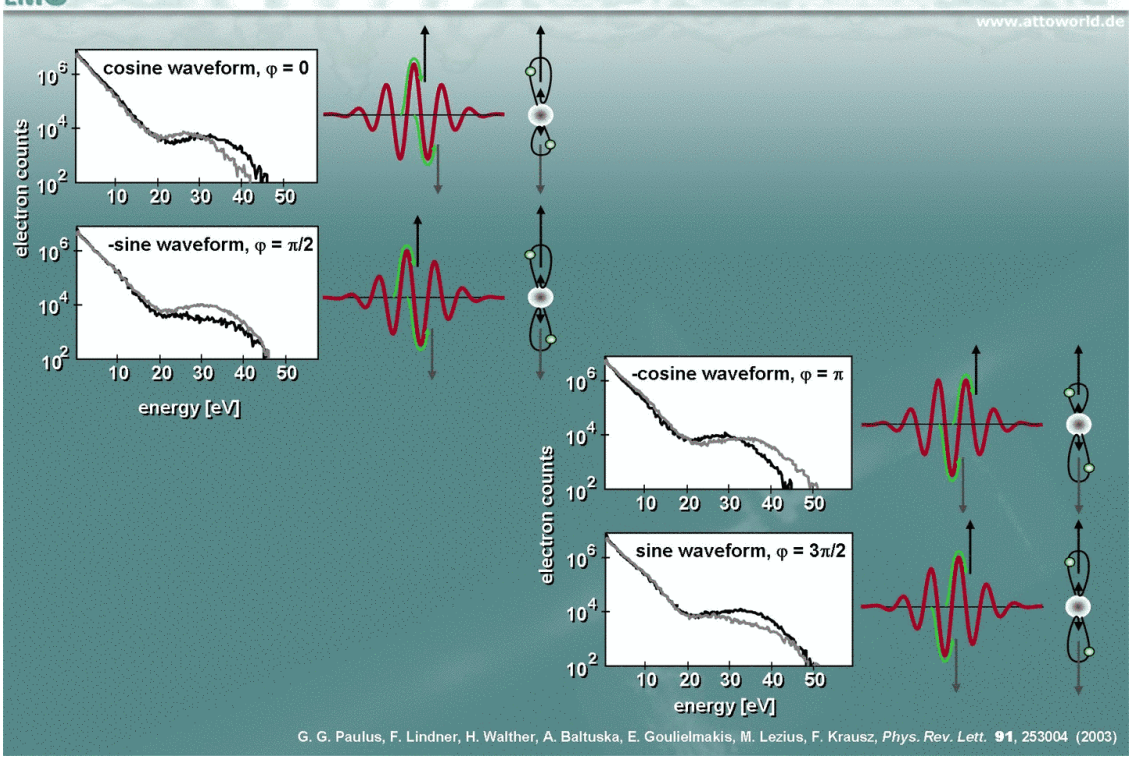
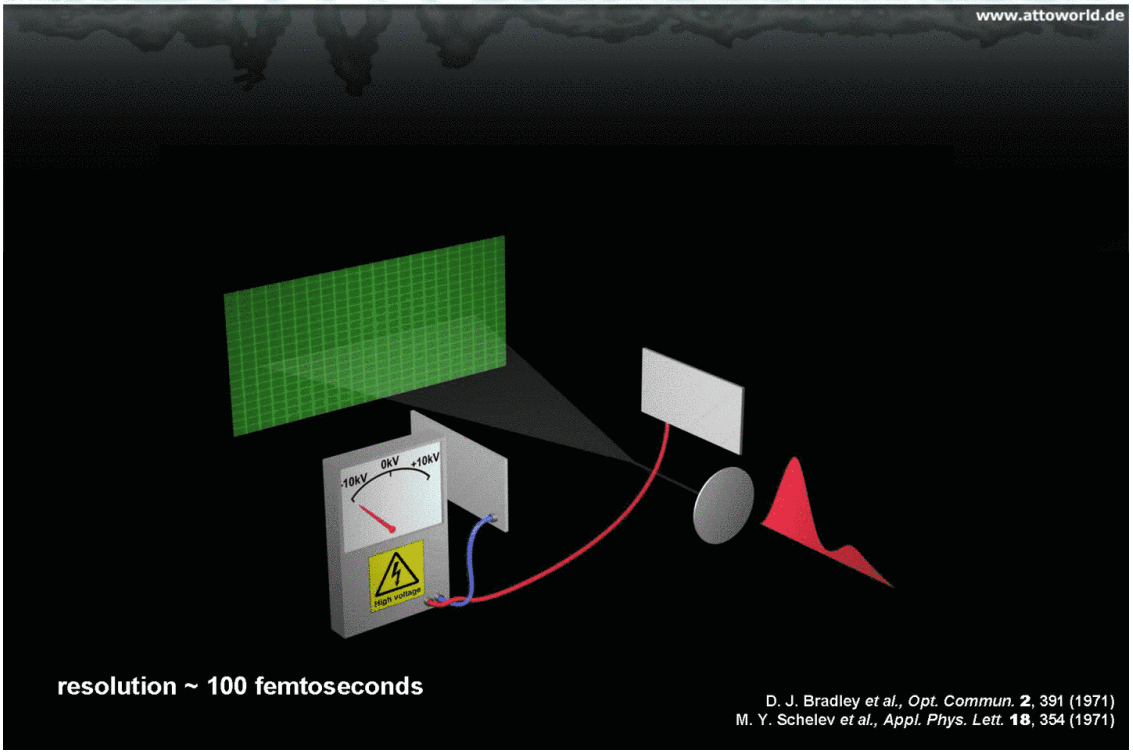
70
80
90
100
110
photon energy [eV]
$E_L(t)$
$\hbar\omega_x$
sine wave
A. Baltuska et al., Nature 421, 611 (2003)

## controlling recollision with the electric field of light: back-scattered electrons measure the waveform




G. G. Paulus, F. Lindner, H. Walther, A. Baltuska, E. Goulielmakis, M. Lezius, F. Krausz, *Phys. Rev. Lett.* **91**, 253004 (2003)

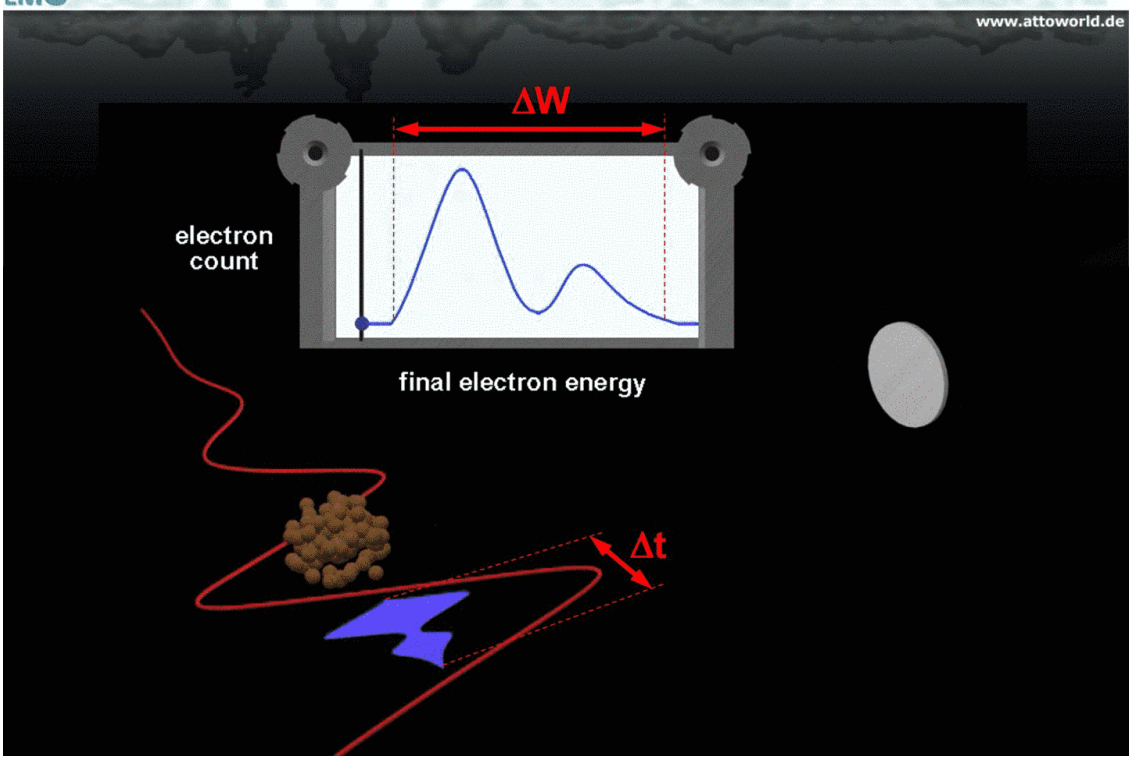
## electron-optical streak camera



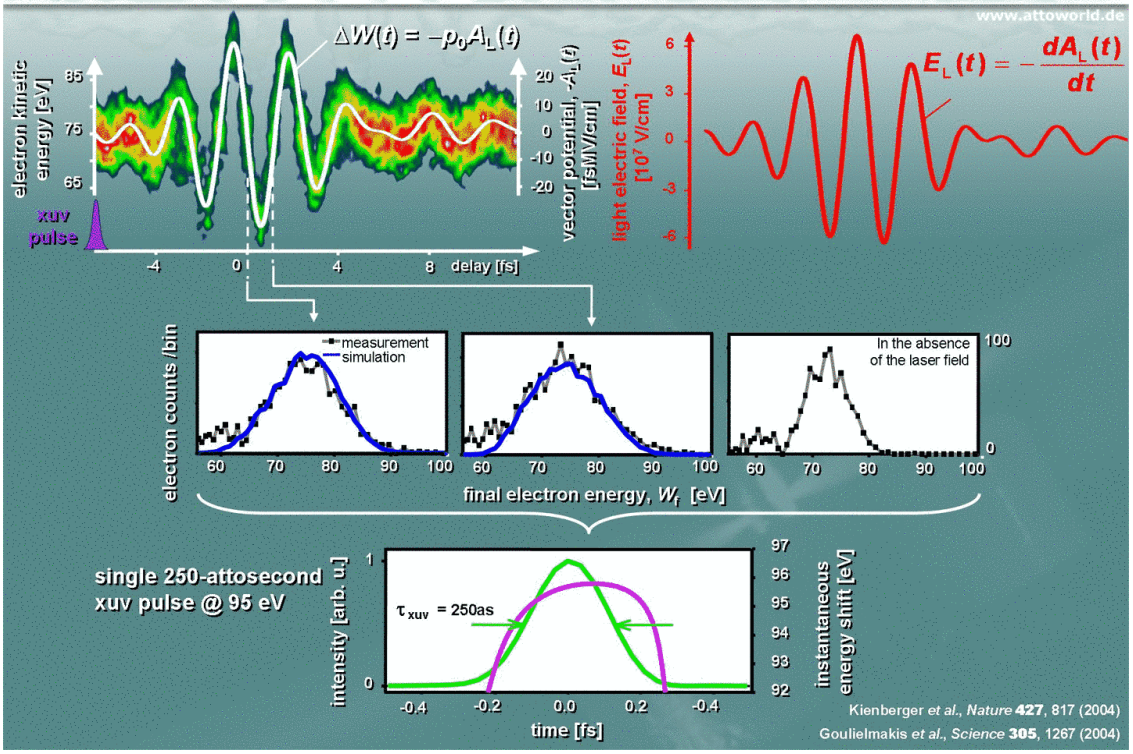

resolution ~ 100 femtoseconds

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

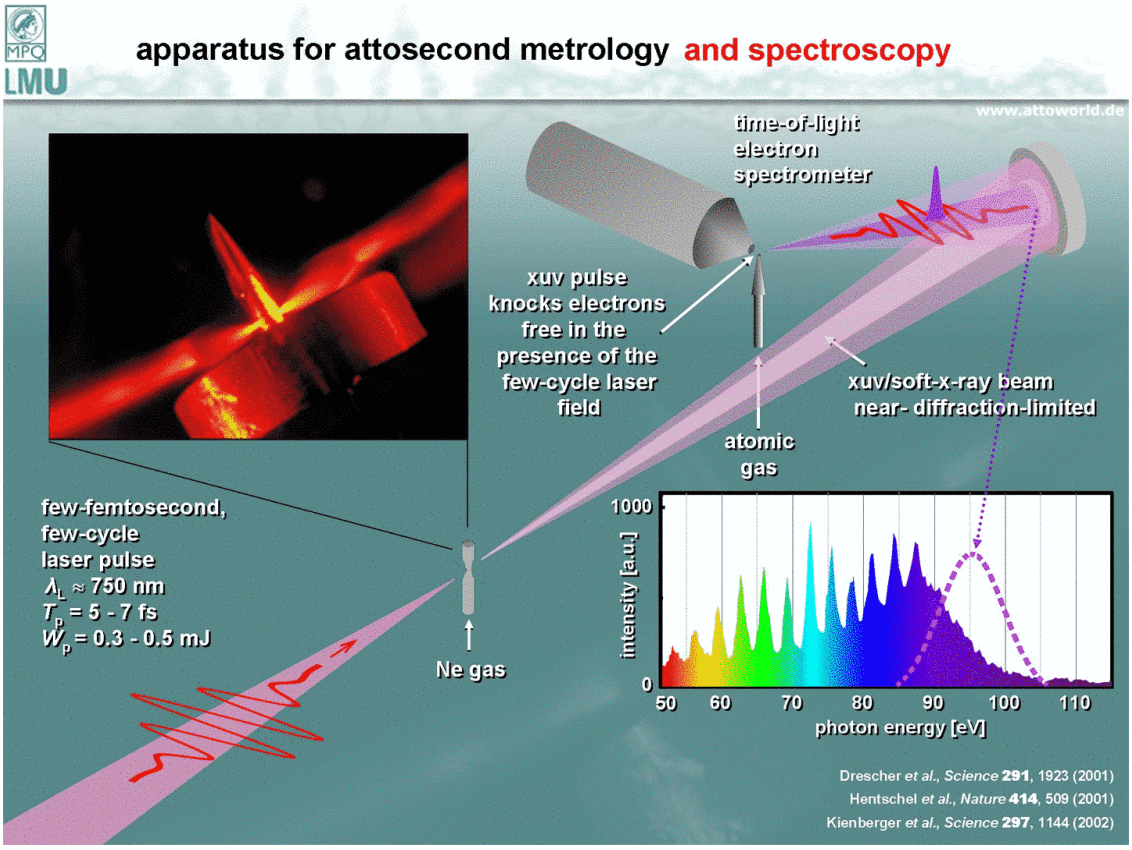
## optical-field-driven streak camera




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




Kienberger *et al.*, *Nature* **427**, 817 (2004)
Goulielmakis *et al.*, *Science* **305**, 1267 (2004)


MPQ
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apparatus for attosecond metrology and spectroscopy
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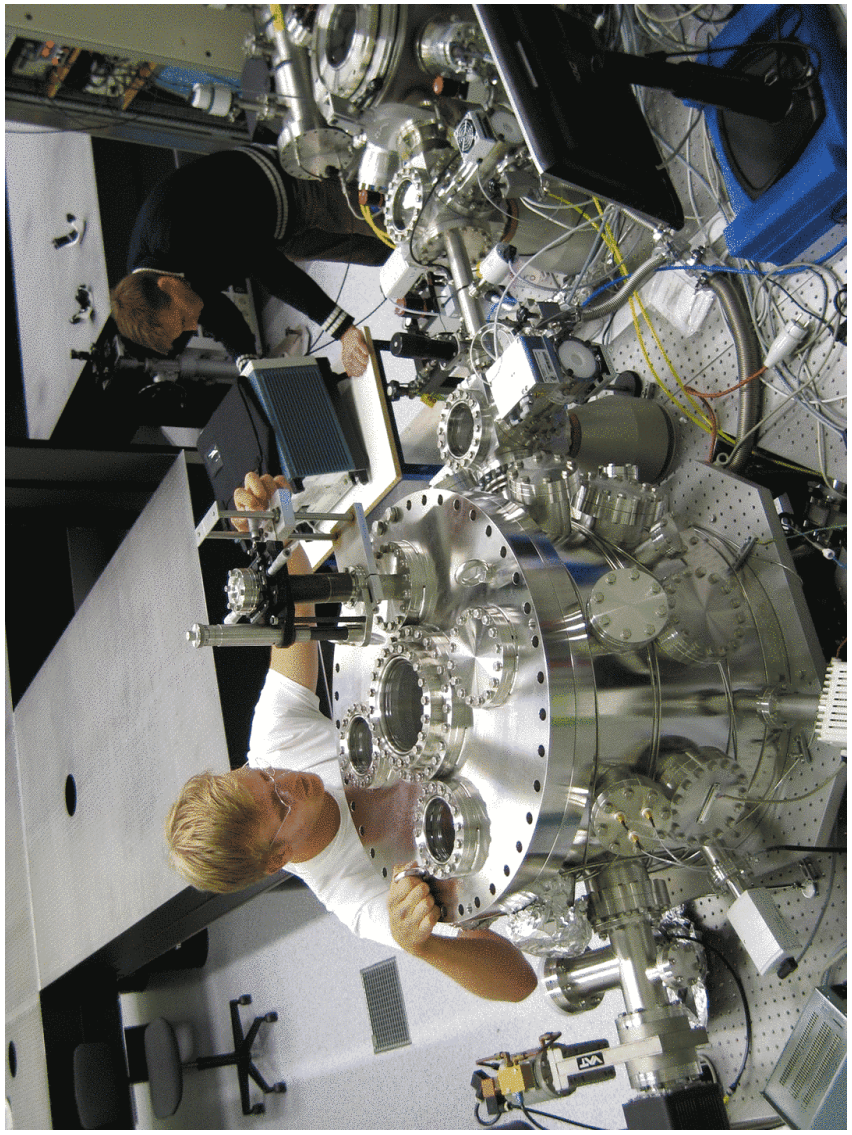
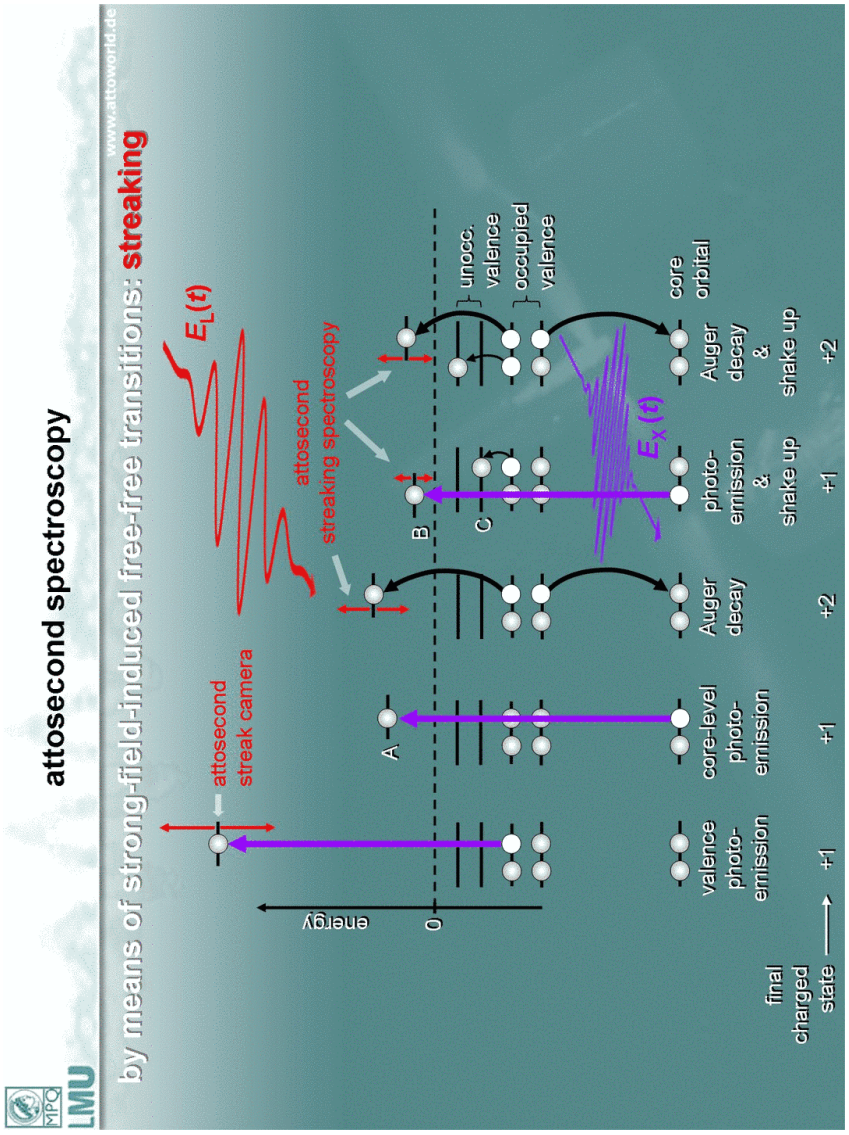
time-of-light
electron
spectrometer
xuv pulse
knocks electrons
free in the
presence of the
few-cycle laser
field
xuv/soft-x-ray beam
near- diffraction-limited
atomic
gas
few-femtosecond,
few-cycle
laser pulse
$\lambda_L \approx 750$ nm
$T_p = 5 - 7$ fs
$W_p = 0.3 - 0.5$ mJ
Ne gas
1000
0
intensity [a.u.]
50
60
70
80
90
100
110
photon energy [eV]
Drescher et al., Science 291, 1923 (2001)
Hentschel et al., Nature 414, 509 (2001)
Kienberger et al., Science 297, 1144 (2002)




attosecond spectroscopy
by means of strong-field-induced free-free transitions: streaking
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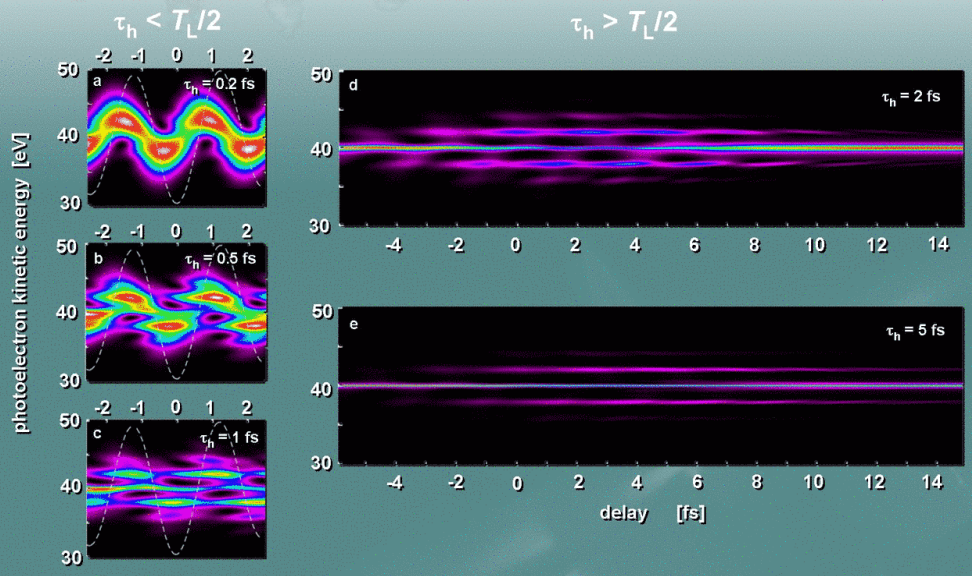
LMU
MPQ
attosecond streak camera
$E_L(t)$
attosecond streaking spectroscopy
energy
A
B
C
0
unocc. valence
occupied valence
$E_X(t)$
valence photo-emission
core-level photo-emission
Auger decay
photo-emission & shake up
Auger decay & shake up
core orbital
final charged state
+1
+1
+2
+1
+2

## attosecond streaking spectroscopy: simulated spectrograms of Auger decay for different lifetimes, $\tau_h$, of inner-shell vacancy





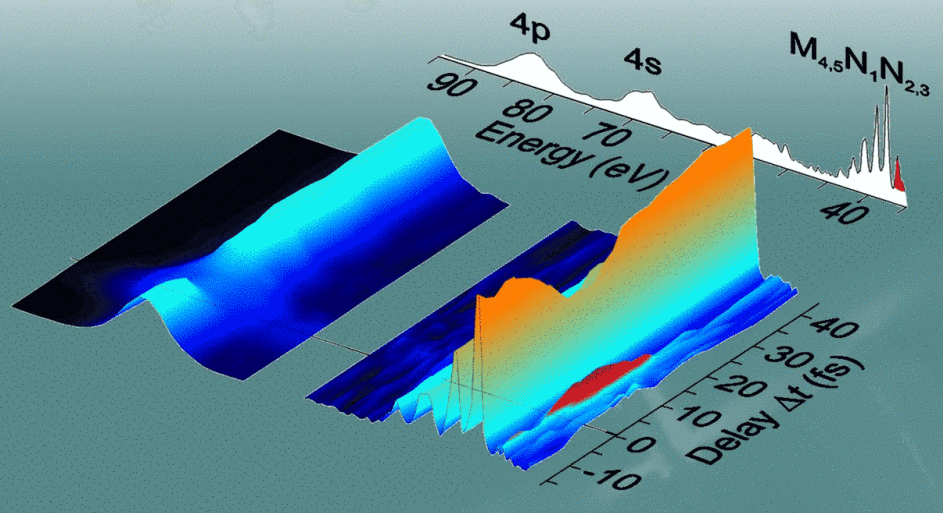

sampling by laser field
resolution ≈ 100 as

sampling by pulse envelope
resolution ≈ 1 fs

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

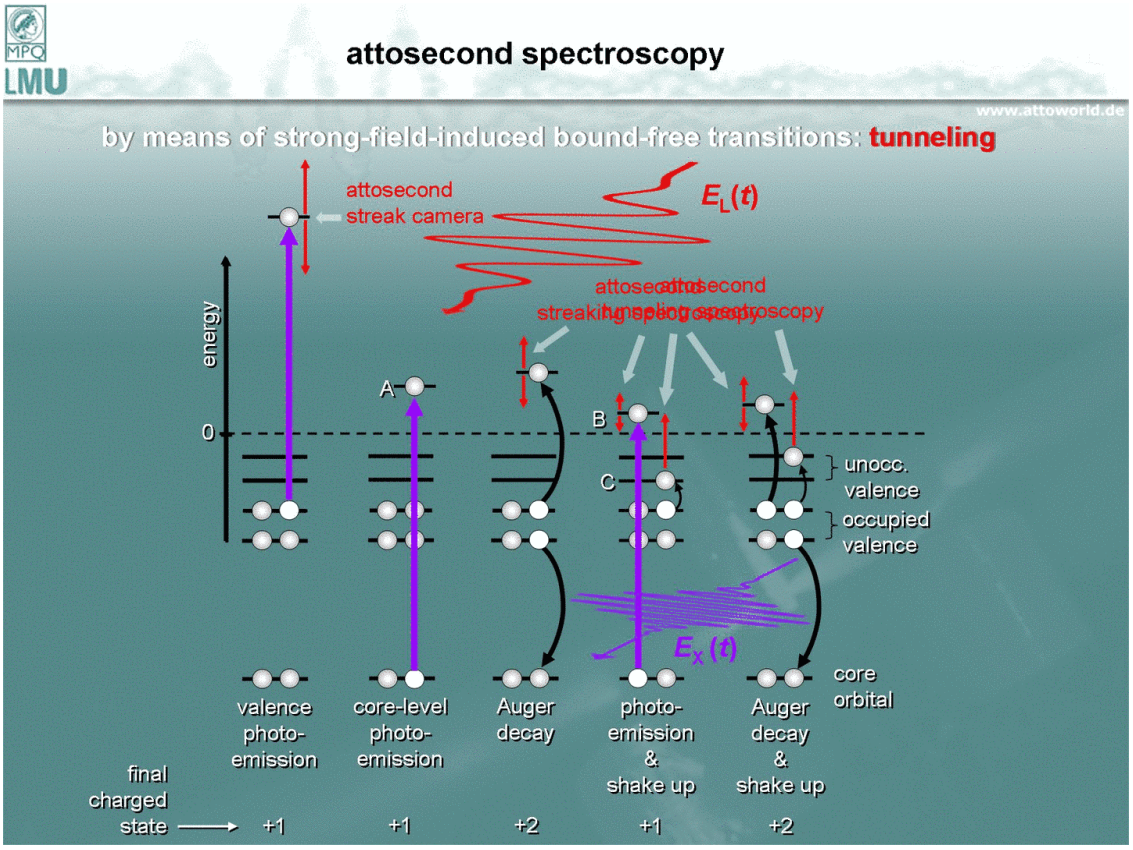
## streaked electron spectra following core-hole excitation in krypton by a sub-fs xuv pulse






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

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


attosecond spectroscopy
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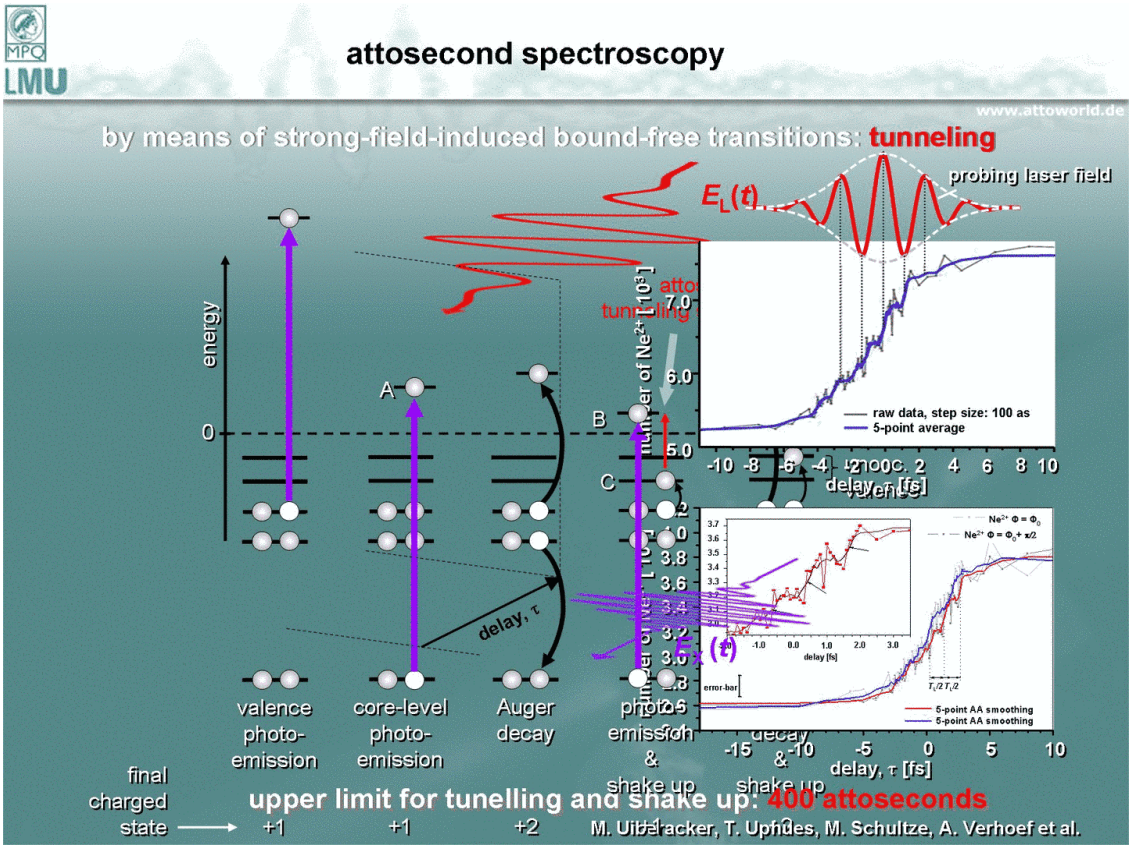
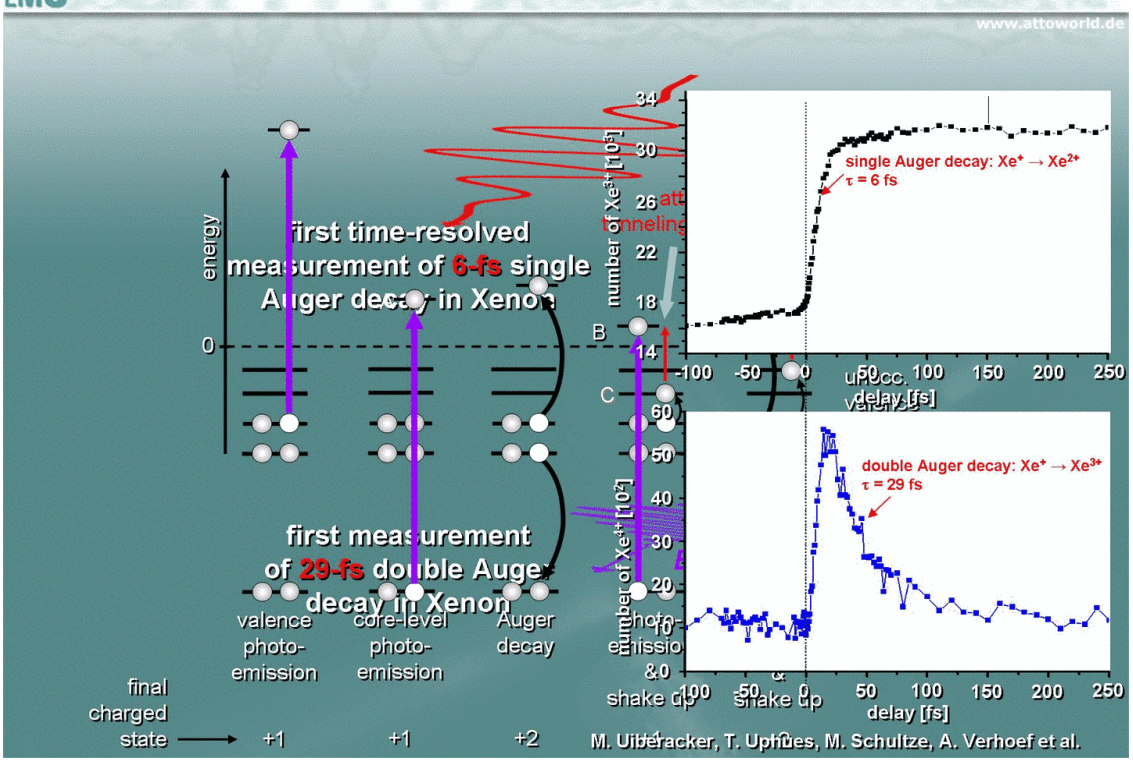
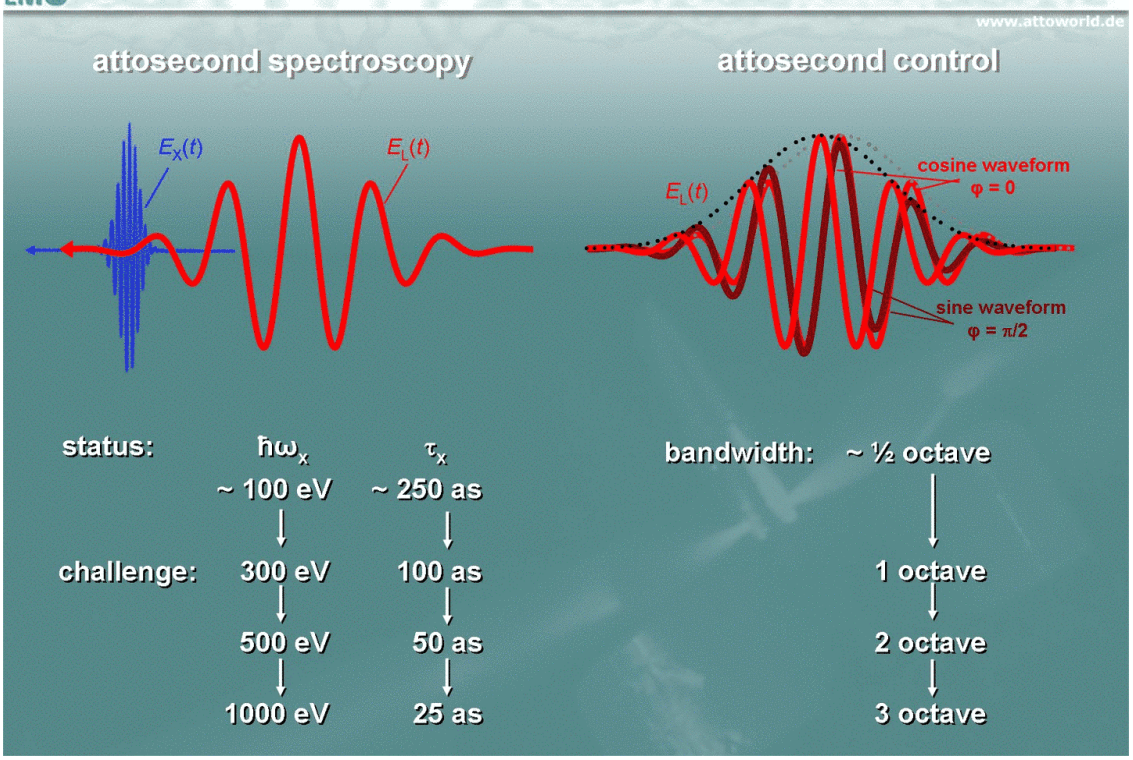
by means of strong-field-induced bound-free transitions: tunneling
attosecond streak camera
$E_L(t)$
energy
0
A
B
C
unocc. valence
occupied valence
$E_X(t)$
core orbital
valence photo-emission
core-level photo-emission
Auger decay
photo-emission & shake up
Auger decay & shake up
final charged state
+1
+1
+2
+1
+2


attosecond spectroscopy
www.attoworld.de
by means of strong-field-induced bound-free transitions: tunneling
probing laser field
$E_L(t)$
energy
0
A
B
C
delay, τ
raw data, step size: 100 as
5-point average
delay, τ [fs]
5-point AA smoothing
$E_X(t)$
valence photo-emission
core-level photo-emission
Auger decay
photo-emission & shake up
Auger decay & shake up
final charged state
+1
+1
+2
upper limit for tunelling and shake up: 400 attoseconds
M. Uiberacker, T. Uphues, M. Schultze, A. Verhoef et al.

## attosecond tunneling spectroscopy



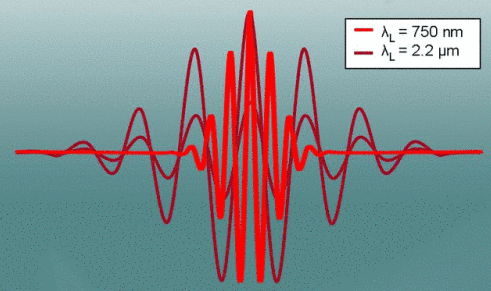

## attosecond technology: status – challenges

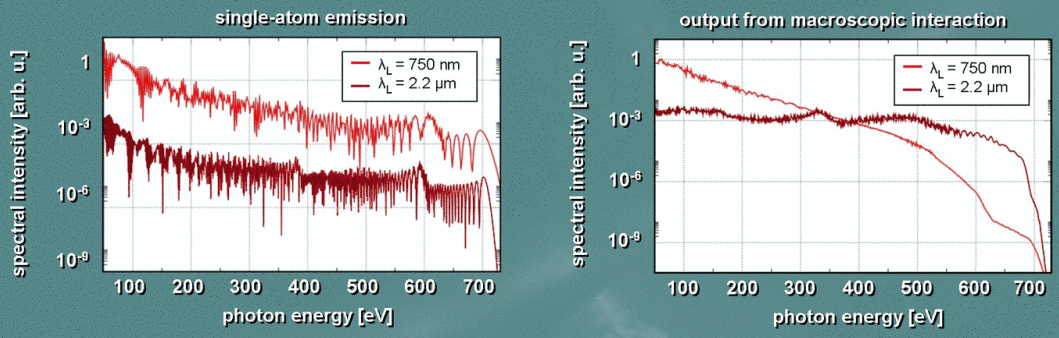


## scaling sub-fs pulses to higher photon energies: driving atoms with few-cycle infrared light



$(\hbar\omega_x)_{max} \sim E_L^2 \lambda_L^2$



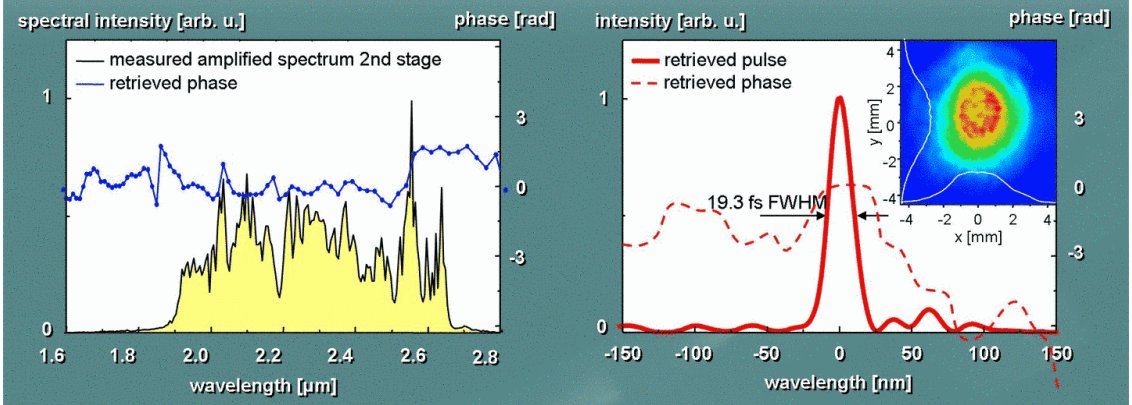




attosecond soft-x-ray ( → 1 keV) pulses with useful flux?

## towards a terawatt-scale, waveform-controlled, few-cycle IR source



proof of feasibility: ps-pumped OPCPA @ $\lambda_L$ = 2.2 μm




$\tau_L$ < 20 fs, $T_L \approx$ 7 fs, $W_L \approx$ 0.5 mJ, $f_r$ = 1 kHz, reproducible waveform

A. Baltuska, T. Fuji, X. Gu N. Ishii et al.

## 2-octave-spanning, intense uv/vis/nir supercontinuum

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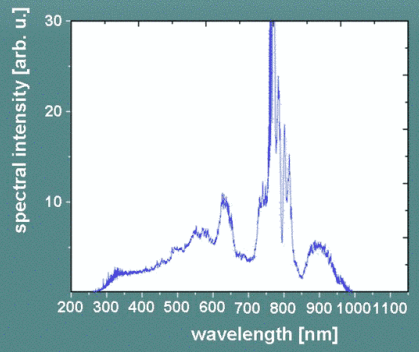
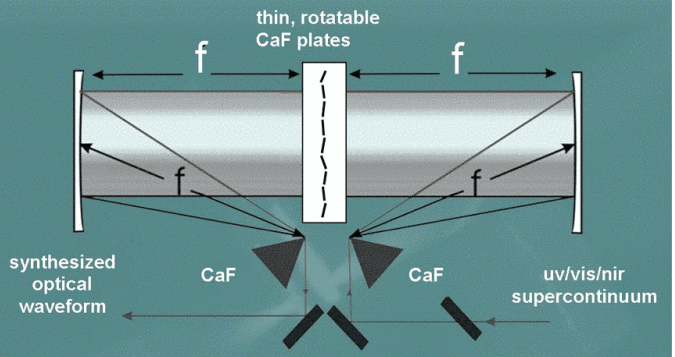
generation: self-phase modulation of 5-fs pulses in a plasma channel




L. Goulielmakis, S. Köhler *et al.*

possible implementation of multi-color optical waveform synthesis




T. Binhammer, E. Rittweger, R. Ell, F. X. Kärtner, and U. Morgner, *IEEE J. Quant. Electron.* **41**,1552 (2005)

## ultrawide-band optical waveform synthesis: attosecond shaping of light fields

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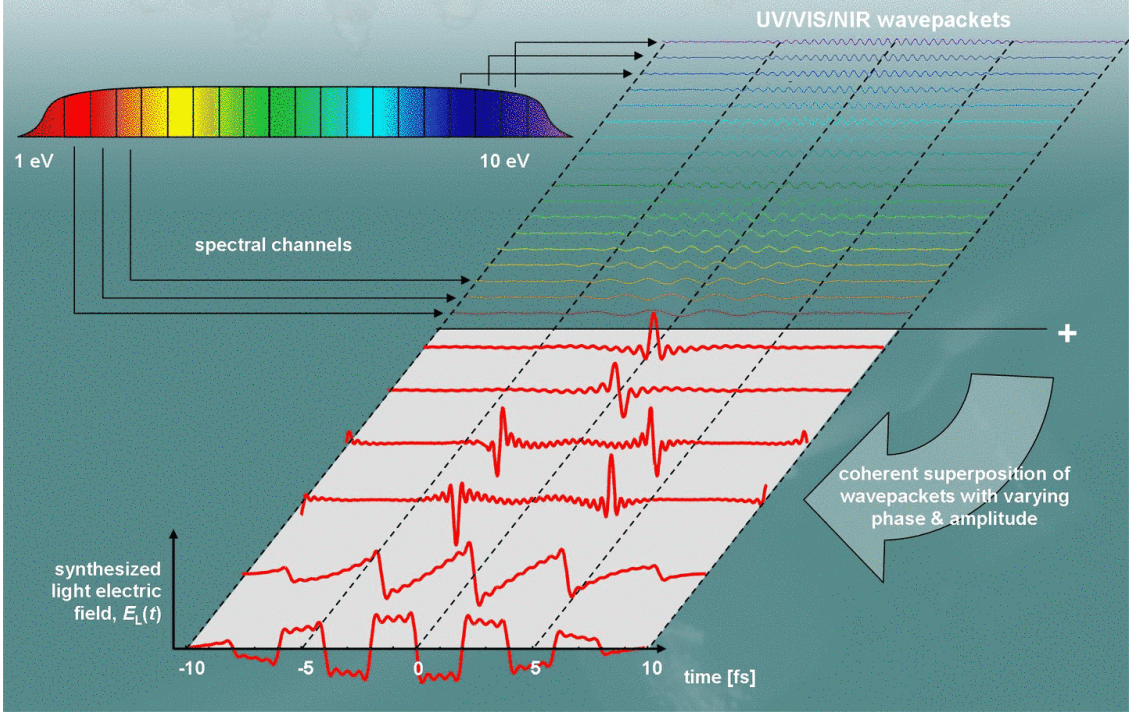
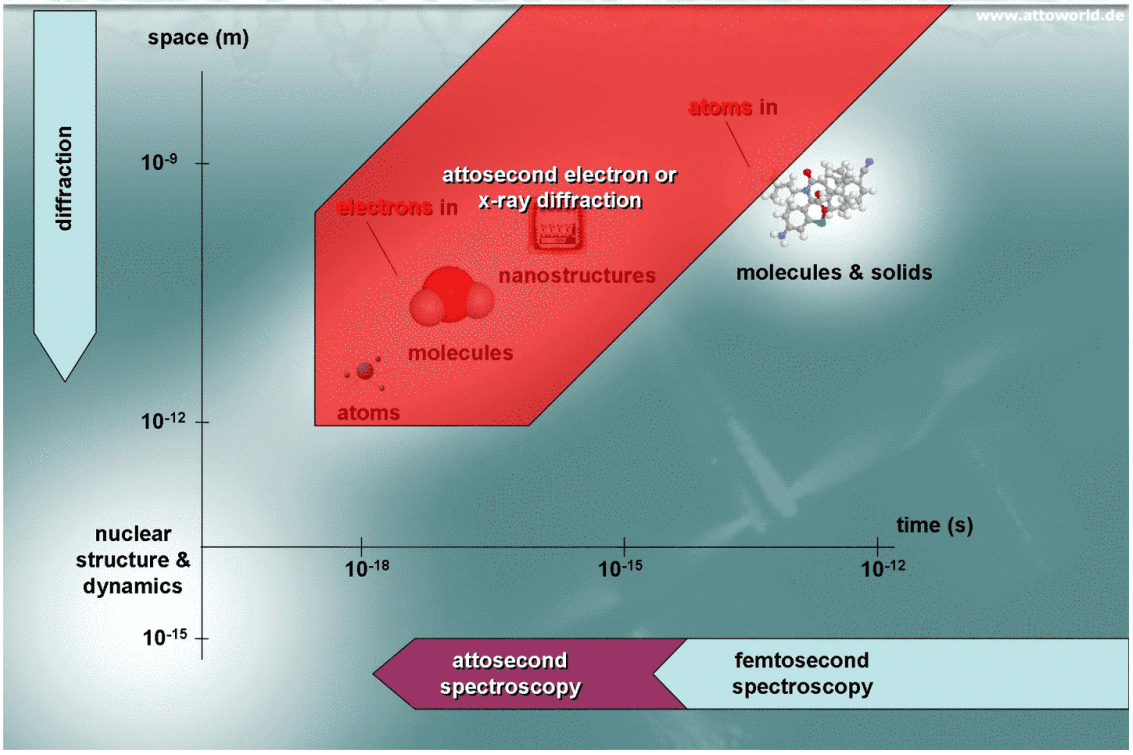
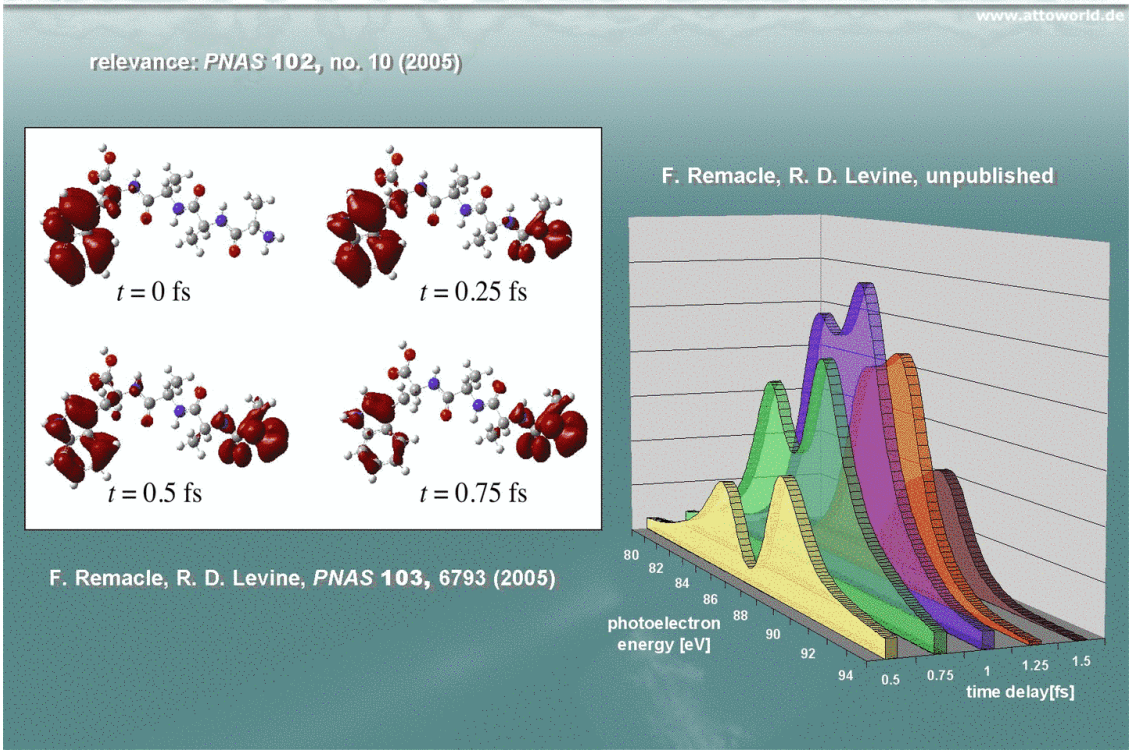


## 4-dimensional imaging with sub-atomic resolution in space and time?




## controlling and probing charge transfer in bio-molecules?



## coworkers & collaborators

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- A. Cavalieri
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- E. Goulielmakis
- X. Gu
- R. Kienberger
- A. Marcinkevicius
- M. Uiberacker
- V. Yakovlev

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- T. Metzger
- J. Rauschenberger
- M. Schultze
- F. Tavella
- C. Theisset
- A.-J. Verhoef

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A. Scrinzi
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M. Lezius, K. Kompa
MPQ Garching, Germany

presentation (ppt/www): Barbara Ferus