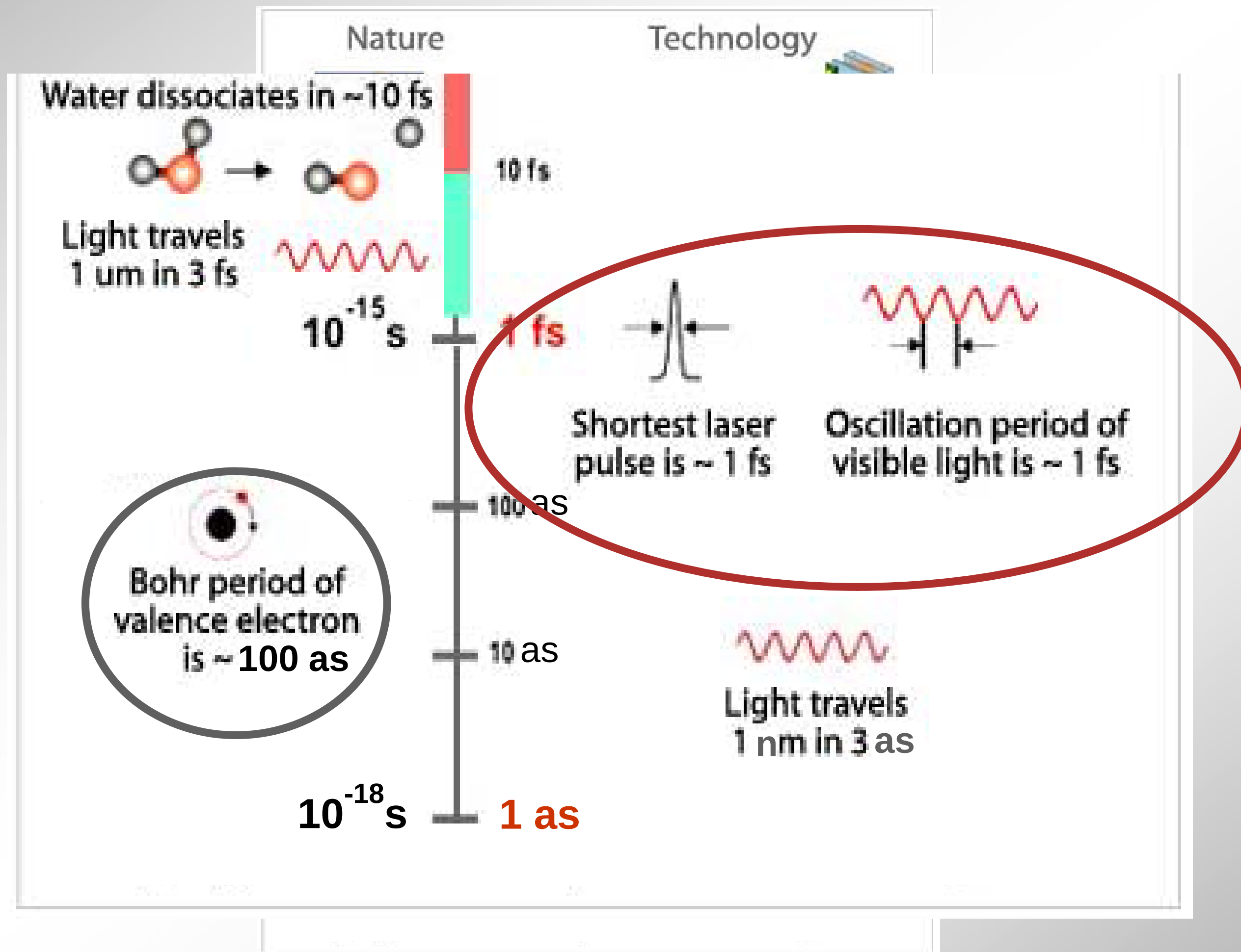
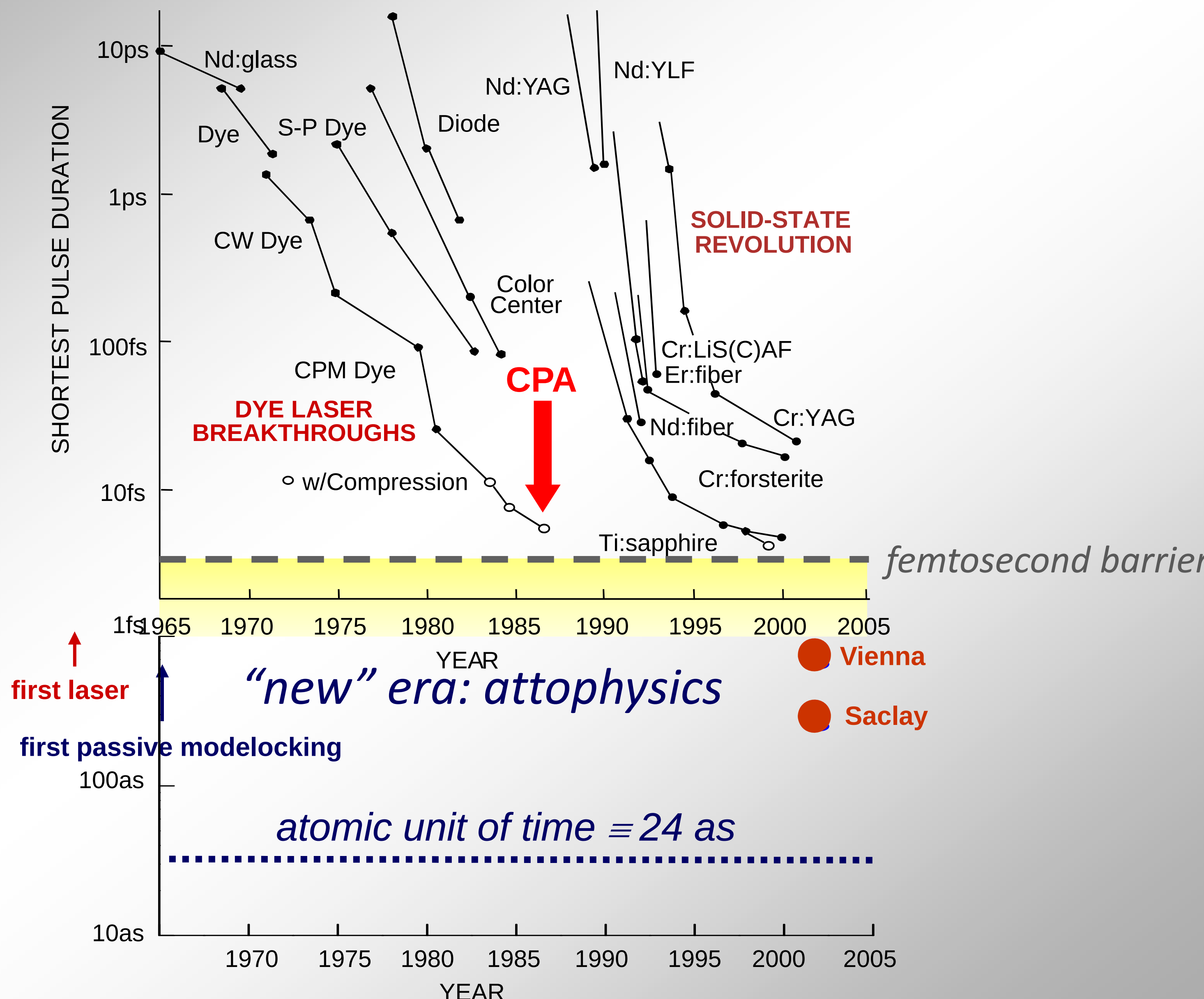
Louis F. DiMauro



time is defined by physical processes

modified from LCLS/SLAC website

a history of ultra-fast: breaking the fs barrier



challenges of breaking the fs barrier

- sub-femtosecond $\Rightarrow$ short wavelengths (XUV, x-rays)

  single-cycle 25 *as* pulse $\Rightarrow$ 7.5 nm (~165 eV photon energy)

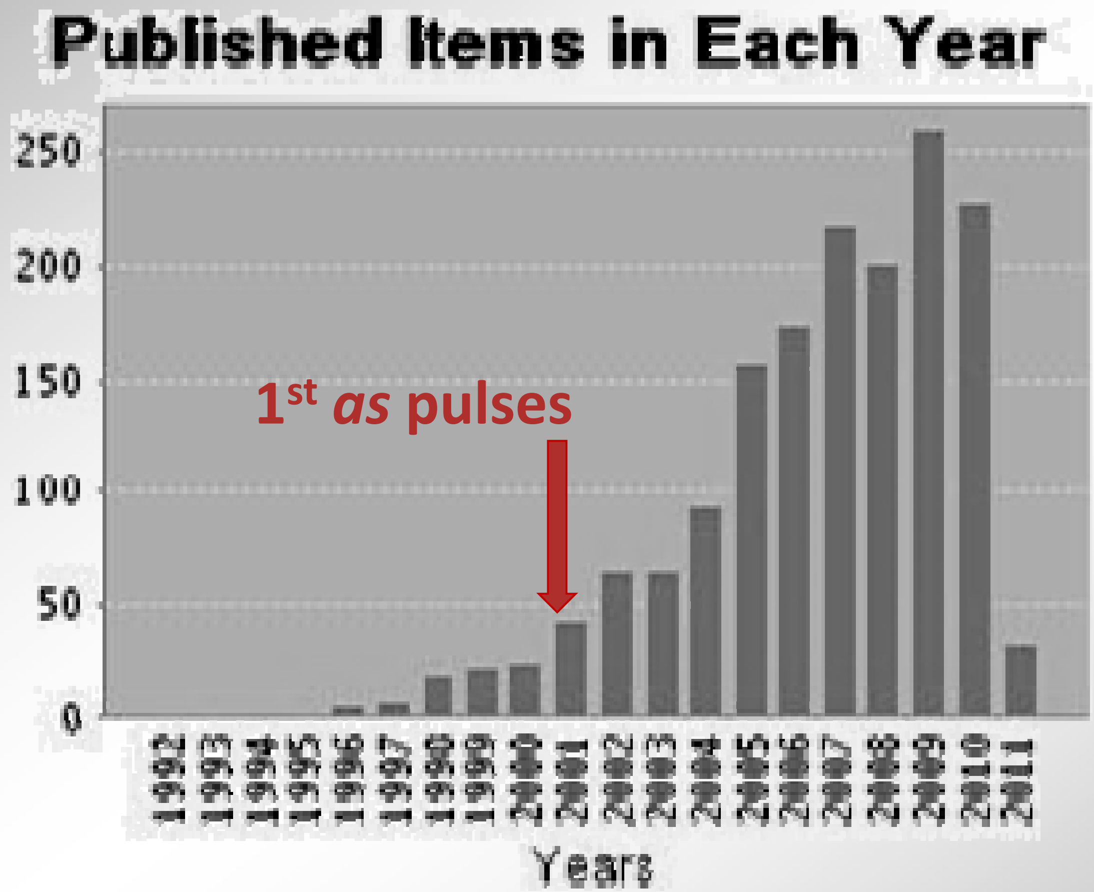
- uncertainty principle: $\Delta\nu * \Delta t \cong 1$ $\Rightarrow$ need bandwidth!!

  single-cycle 25 *as* pulse $\Rightarrow$ 20×10^{15} Hz frequency spread

- control the phases of the field, i.e. mode-locking

- attosecond metrology

the growth of attosecond science



- **attosecond science can address a broad range of interdisciplinary problems specifically, electron correlation and strongly damped systems**

from ISI Web of Knowledge

attosecond production approaches

- coherent or cascade stimulated Raman scattering

  Kaplan, Harris, Sokolov….

- solid target interactions, non-relativistic/relativistic

  Kaplan, Mourou, Naumova….

- 4th generation light sources: XFELs & ERLs

- high harmonic generation from gases

  Farkas, Toth, L'Huillier….

high harmonic generation in gases

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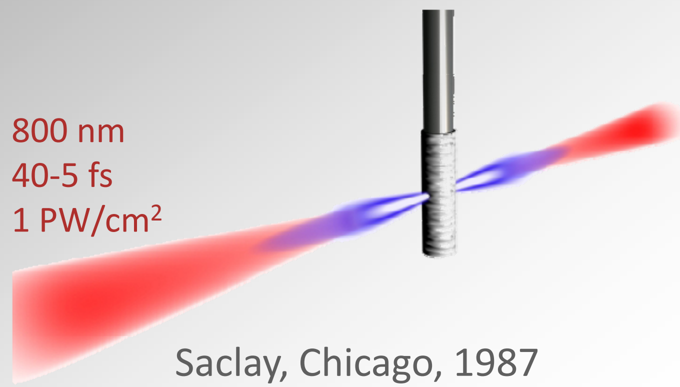
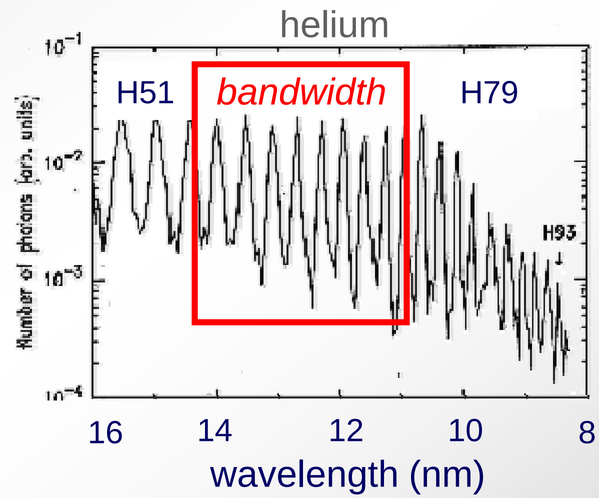
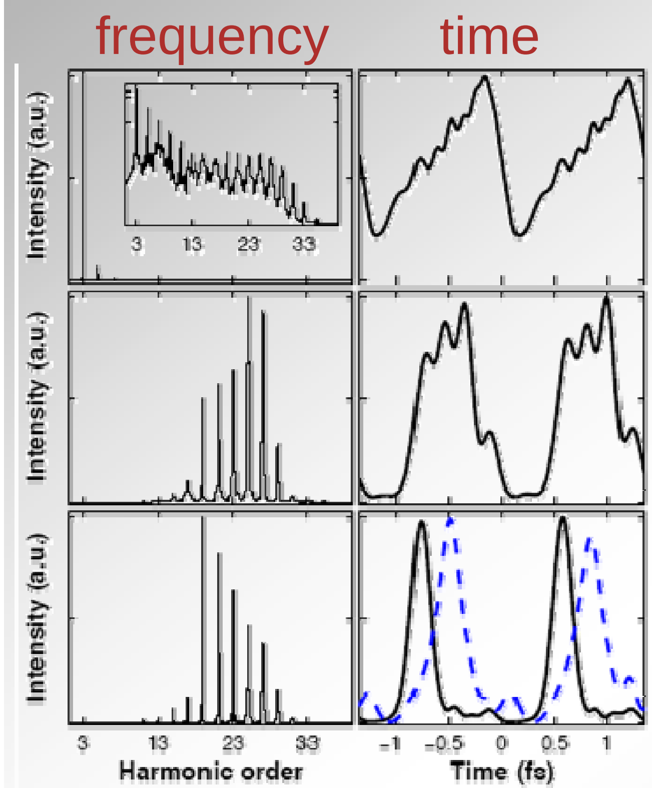
nonlinear frequency conversion: $\omega_q = q\omega_{800}$



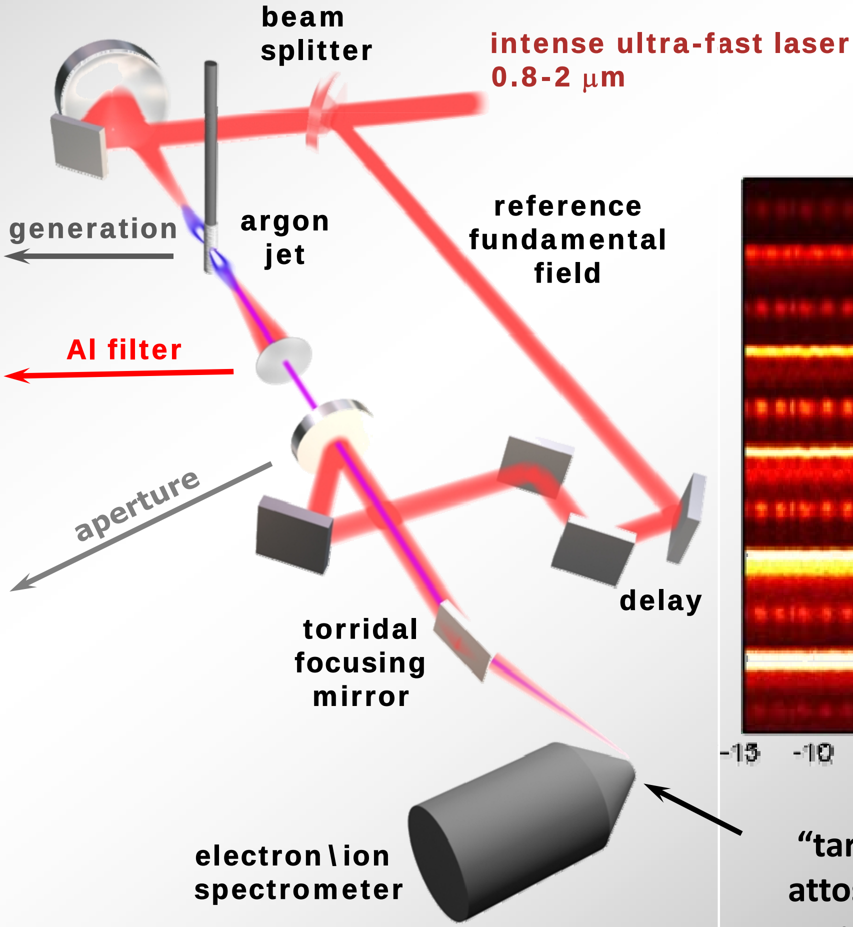


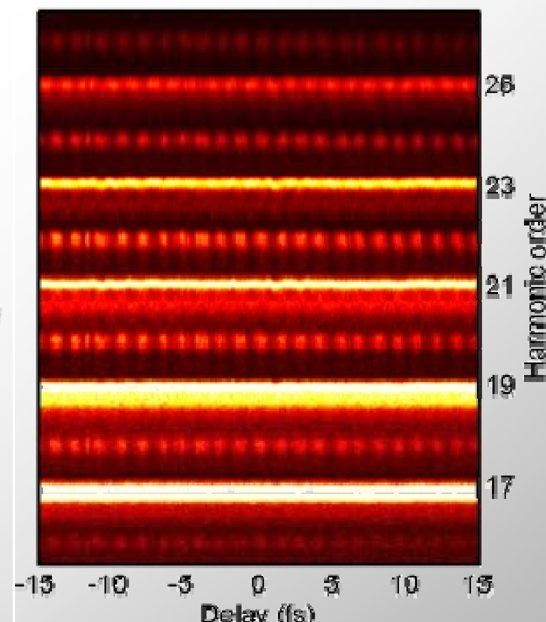
- intense laser-atom interaction produces a comb of odd harmonic
- harmonics result from the physics of a field-driven electron
- attosecond pulses are formed by Fourier synthesis
- physics needs Schrödinger’s and Maxwell’s equations
- hhg sources are table-top

attosecond beamline and end-station



selection in argon:
harmonic order 13 to 31





“target spectrogram”
attosecond pulse train
+ reference field

world-wide attosecond light sources

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- attosecond laboratories are developing world-wide
  US (4), Europe (13), Canada (1), Japan (2), Korea (1)

state-of-the-art attosecond generation

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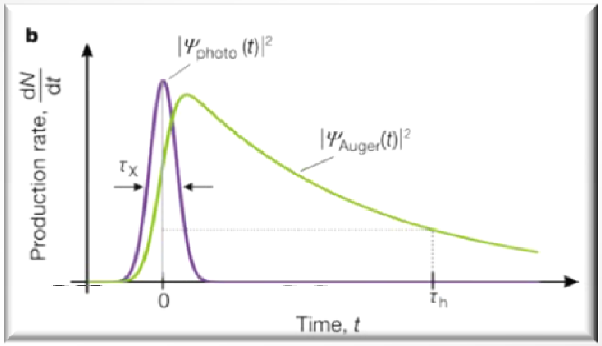
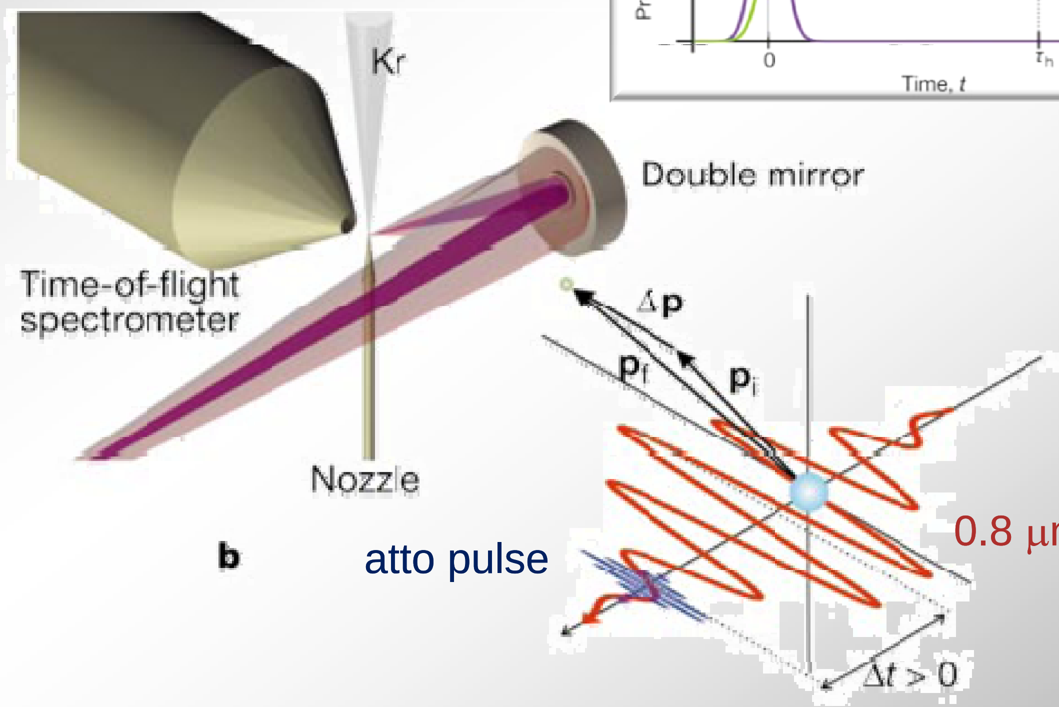
- **attosecond pulse train**
  - ✓dispersion compensation (*Lund group)*
    130 as, 35 eV
  - ✓long-wavelength fundamental field (*Ohio group*)
    120 as, 200 eV
- **isolated attosecond pulse**
  - ✓polarization gate, dispersion compensation, CEP
    130 as, 35 eV, 0.5 nJ (*Milano group)*
  - ✓1.4-cycle driver, dispersion compensation
    80 as, 120 eV, 0.5 nJ (MPQ-Garching group)

MPQ atto-streaking for time-resolving Auger decay

detected electron energy (classical result):

$$W_f = W_i + 2U_p \sin(\omega_f t)^2 \cos 2\theta + [8W_i U_p]^{1/2} \sin(\omega_f t) \cos\theta$$





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

MPQ Auger decay measurement: Nature 419, 803 (2002)

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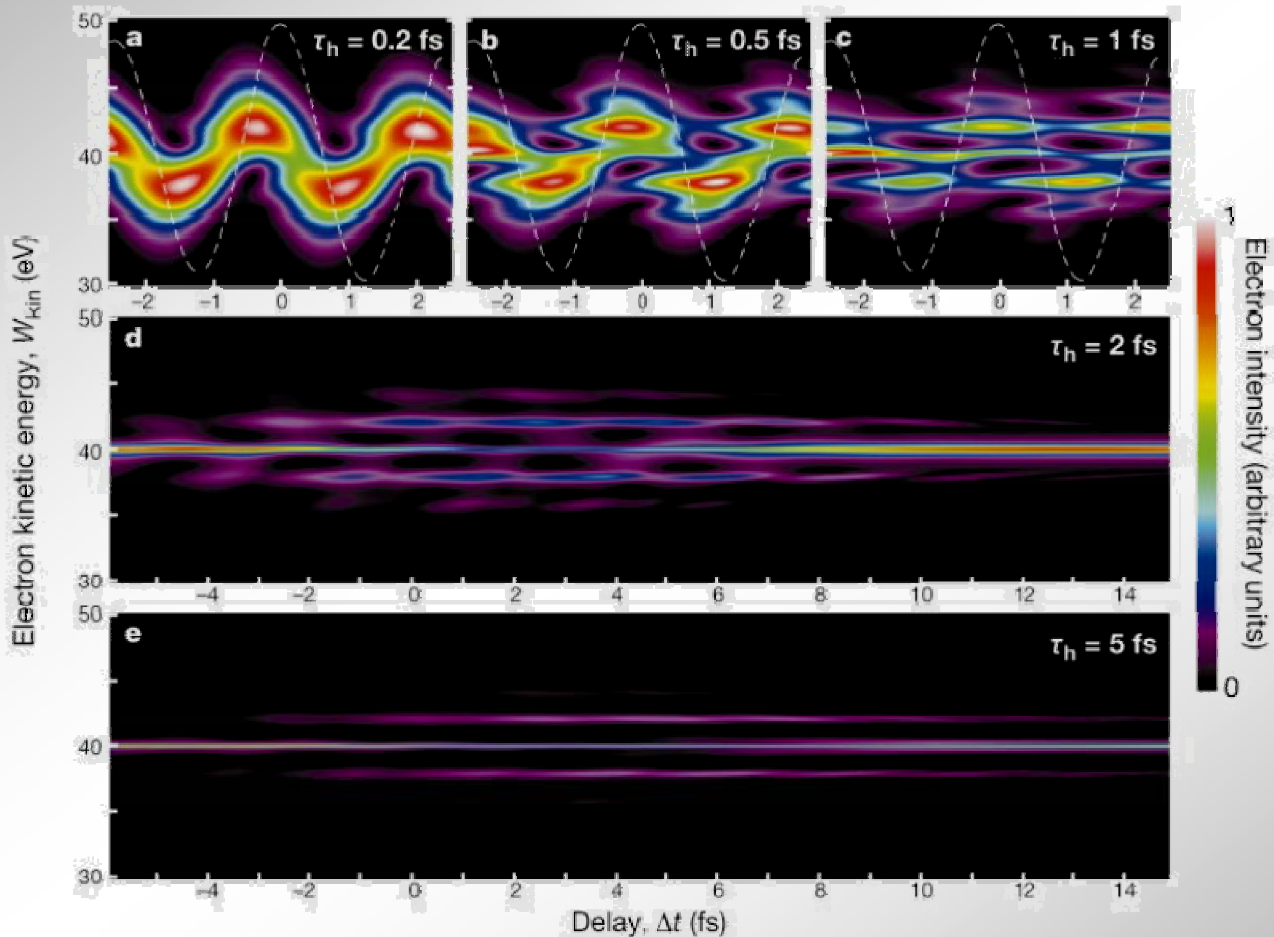
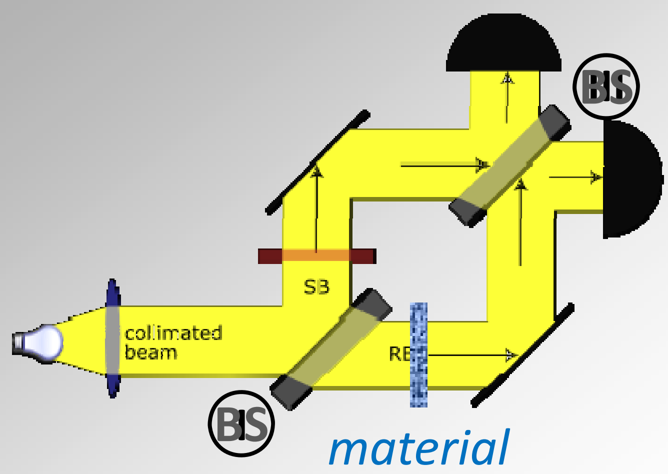
- the 90 eV attosecond pulse excites a core electron (3d) in Kr
- the ir-field streaks the energy of the photoelectron & Auger
- energy streak is proportional to the phase (time)



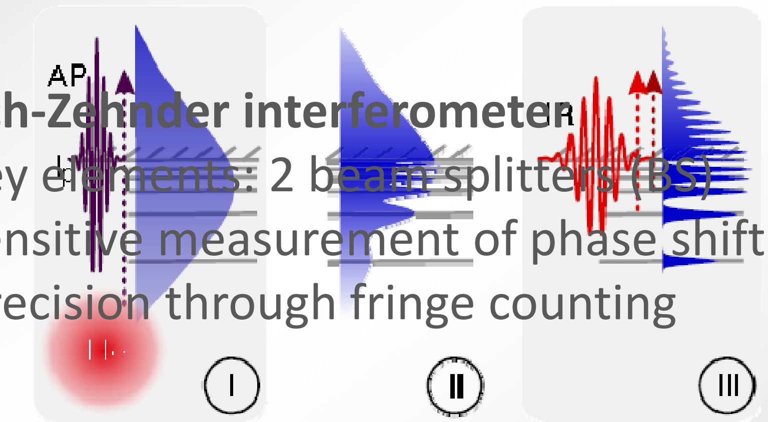
$$\tau_A = 7.9 \pm 0.9 \text{ fs}$$

precision in a time-domain electron interferometer

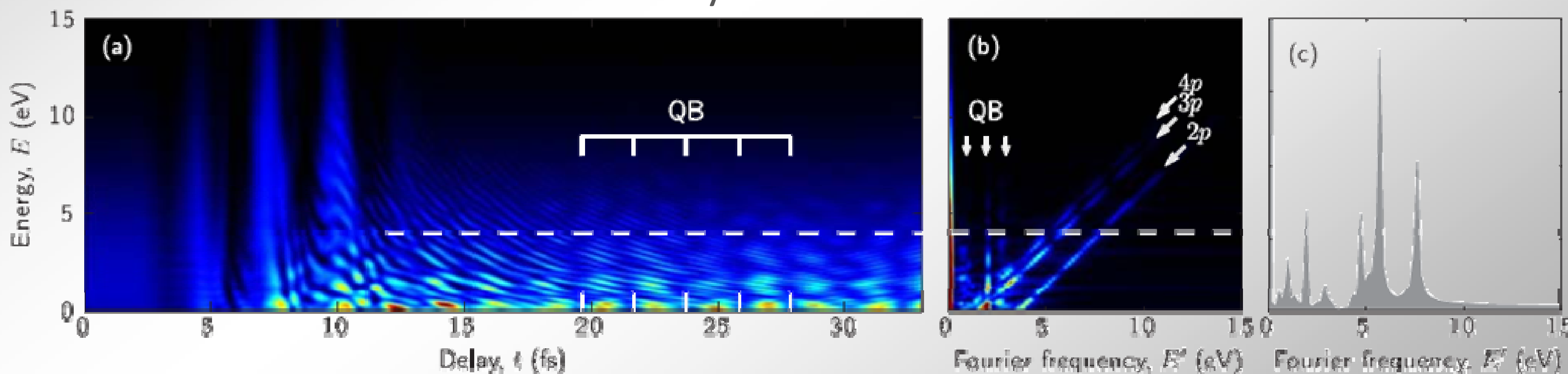


Mach-Zehnder interferometer

- key elements: 2 beam splitters (BS)
- sensitive measurement of phase shifts
- precision through fringe counting

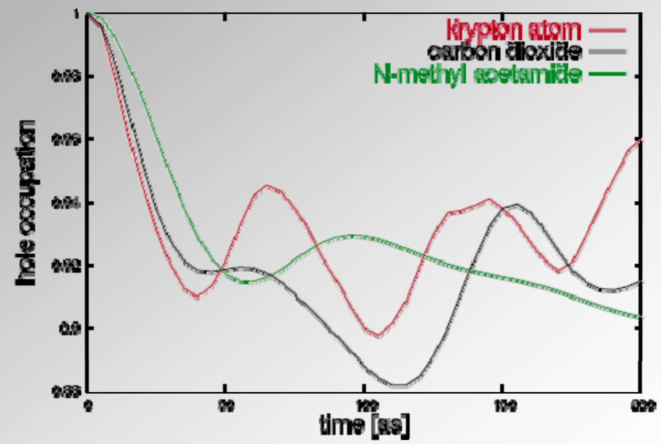


theory: Ken Schafer

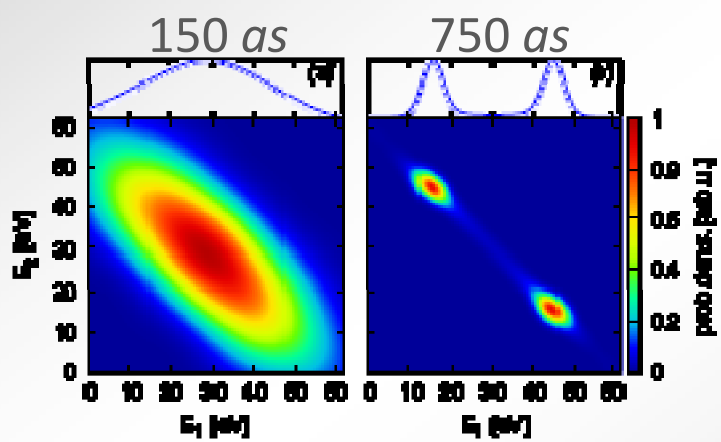


from Mauritsson et al. PRL **105**, 053001 (2010)

electronic response at early times



- universal attosecond response
  Breidbach & Cederbaum, PRL **94**, 033901 (2005)



- evolution of electron correlation
  Burgdorfer *et al.*, PRL **103**, 063002 (2009)
  2-photon double ionization of helium

these issues are uniquely addressed by attosecond science