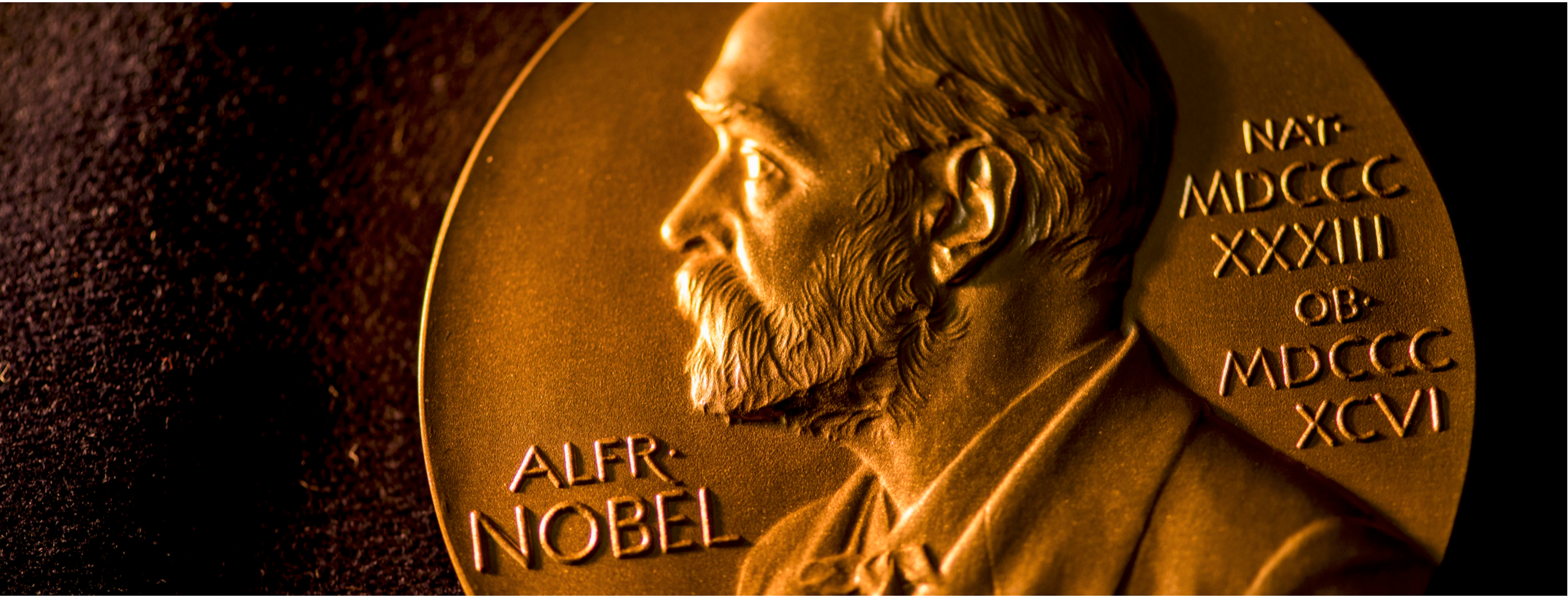
Nobel Prize in Physics 2023



Awarded for the greatest benefit to mankind

Nobel Prize in Physics 2023

Pierre Agostini

The Ohio State University, USA

Anne L'Huillier

Lund University, Sweden

Ferenc Krausz

Max Planck Institute of Quantum Optics
Ludwig-Maximilians-Universität München
Germany

"for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter"

Birth of attosecond science

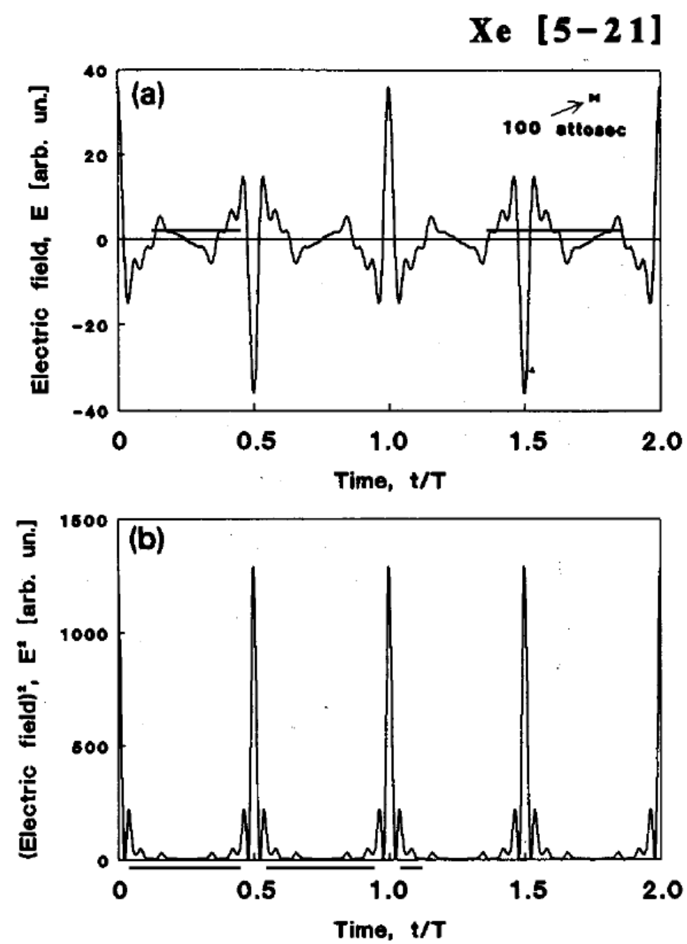
- High-order harmonic generation has led to the development of a new field – **attoscience**.

Proposal for attosecond light pulse generation using laser induced multiple-harmonic conversion processes in rare gases

Gy. Farkas and Cs. Tóth
Research Institute for Solid State Physics, Central Research Institute for Physics, P.O. Box 49, H-1525 Budapest, Hungary

Received 11 June 1992; accepted for publication 13 July 1992
Communicated by V.M. Agranovich

A new principle of attosecond light pulse generation is suggested. The method is based on a Fourier synthesis of laser induced multiple harmonics, which all are oscillating with the same fixed phase as predicted and observed recently in rare gases. According to our calculation using published experimental data, the production of a regular sequence of ~30–70 as duration light pulses is expected to be realizable.



$$E(t) = \sum_{n=n_p}^{n_c} E_n \cos(n\omega_0 t)$$

$$I(t) = \frac{1}{T} \int E^2(t)\, \mathrm{d}t$$

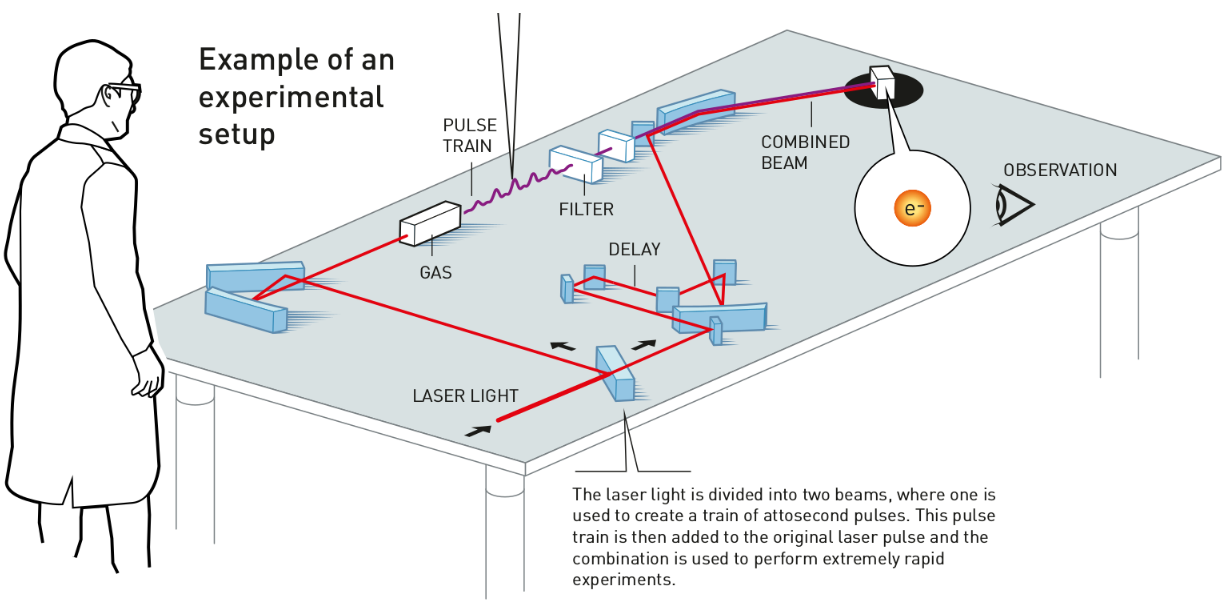
Farkas and Tóth, Phys. Lett. A **168**, 447 (1992)

What can we use attosecond pulses for?

Attosecond pulses can be used for:

- to directly observe the wave oscillations of light
- to directly observe electron dynamics in matter
- to watch quantum interference build up in real time
- to measure the time it takes for an electron to be stripped away from the atom
- petahertz electronics
- preventive medicine

etc.



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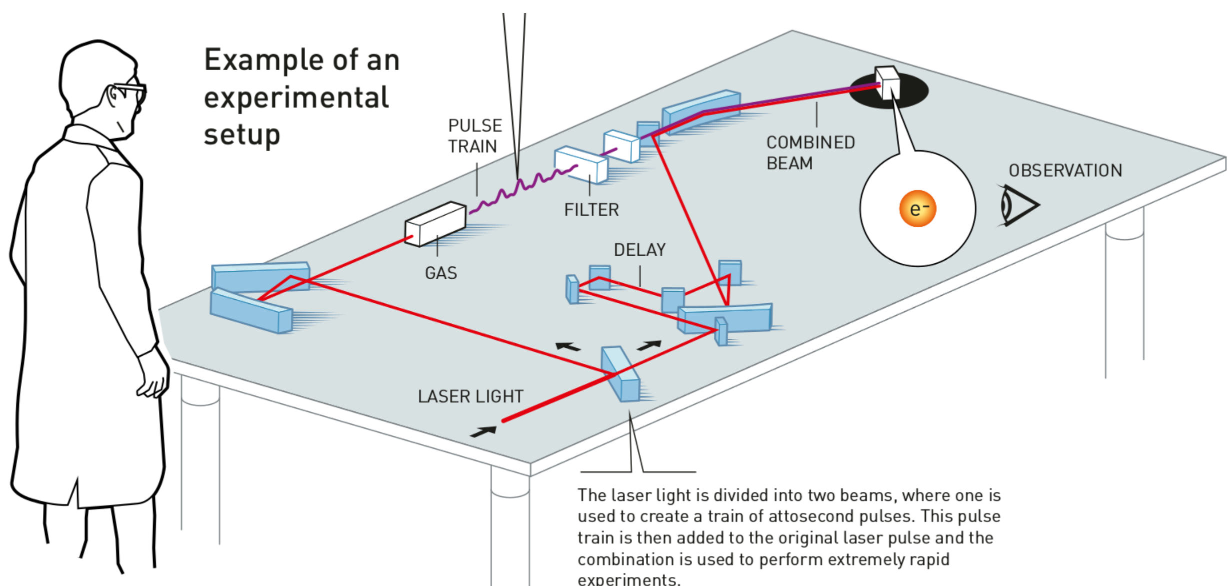
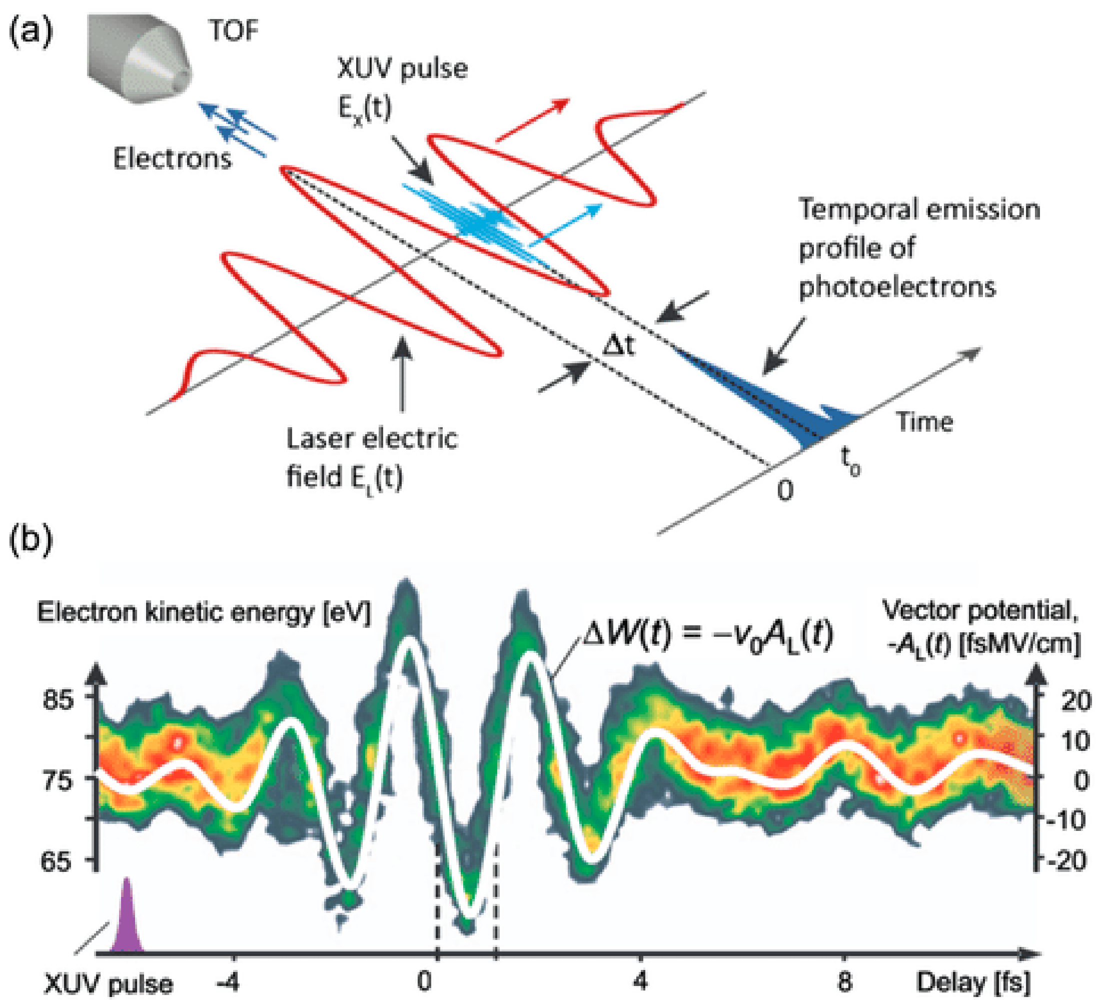


Direct measurement of light wave

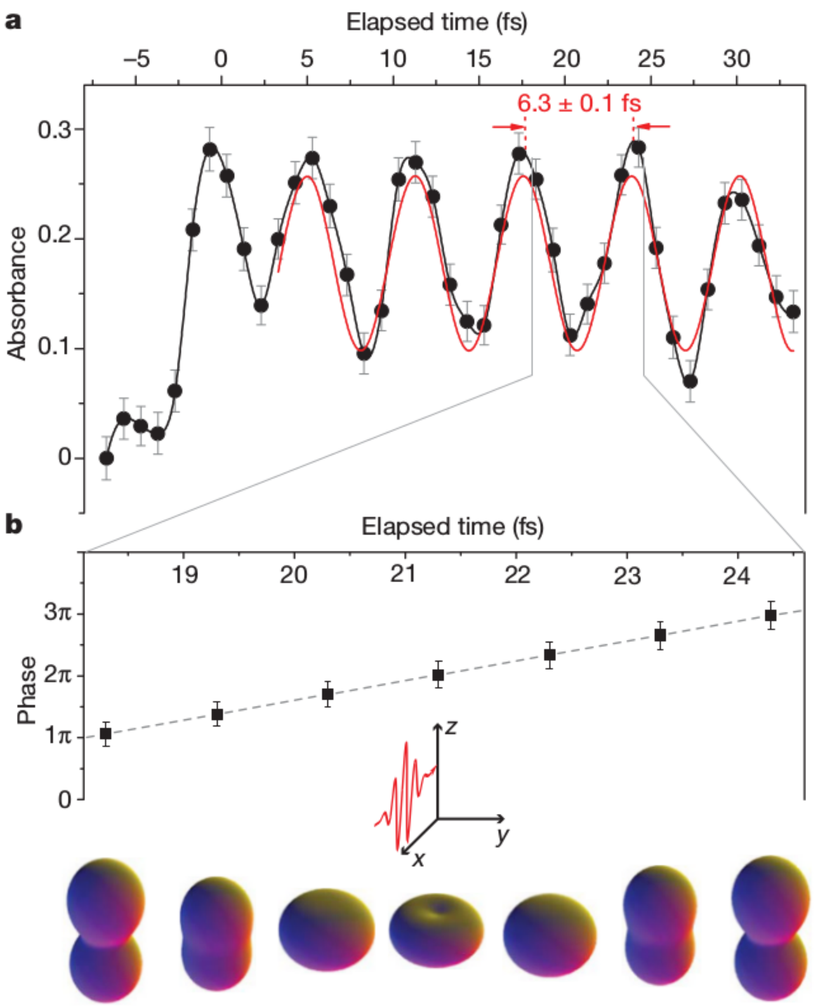
Attosecond streaking

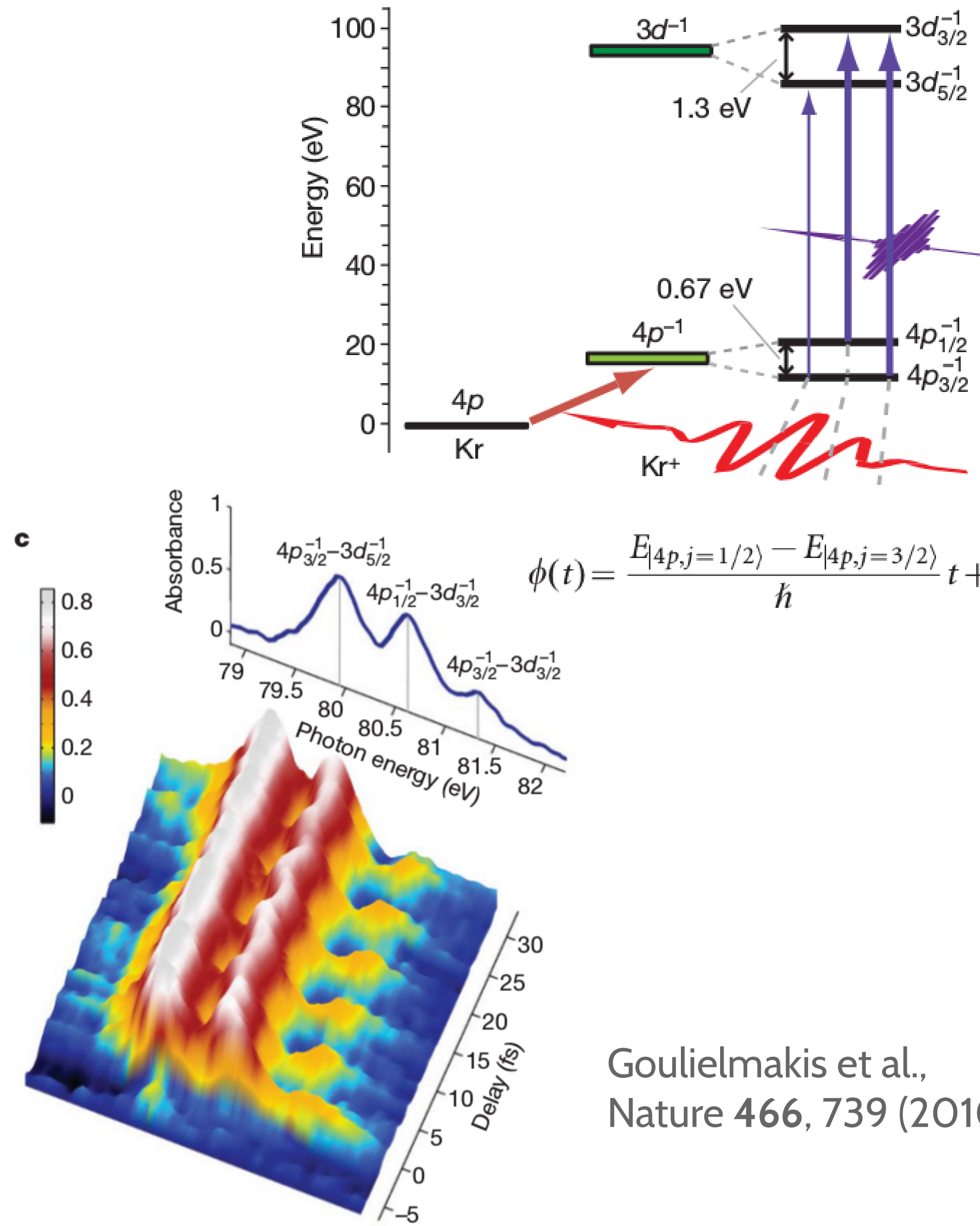


Gaulielmakis et al., Science **305**, 1267 (2004)

Direct observation of valence electron dynamics

Krypton ion (Kr^{+})



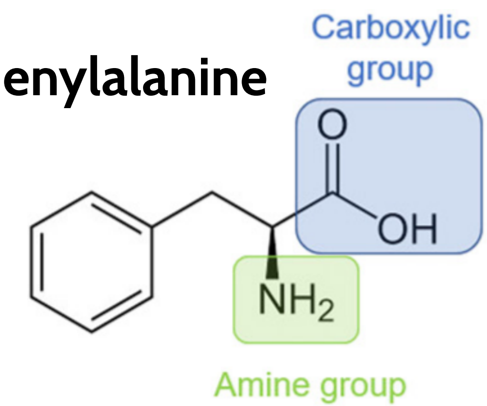


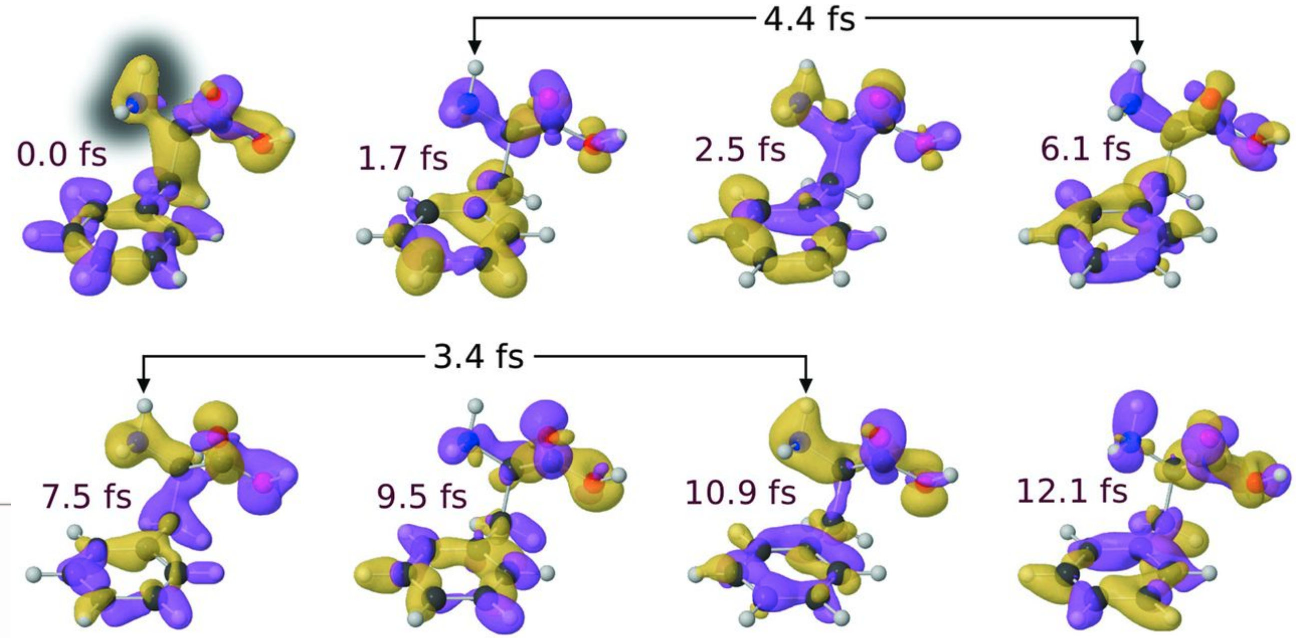
$$\phi(t) = \frac{E_{|4p,j=1/2\rangle} - E_{|4p,j=3/2\rangle}}{\hbar} t + \phi_0$$

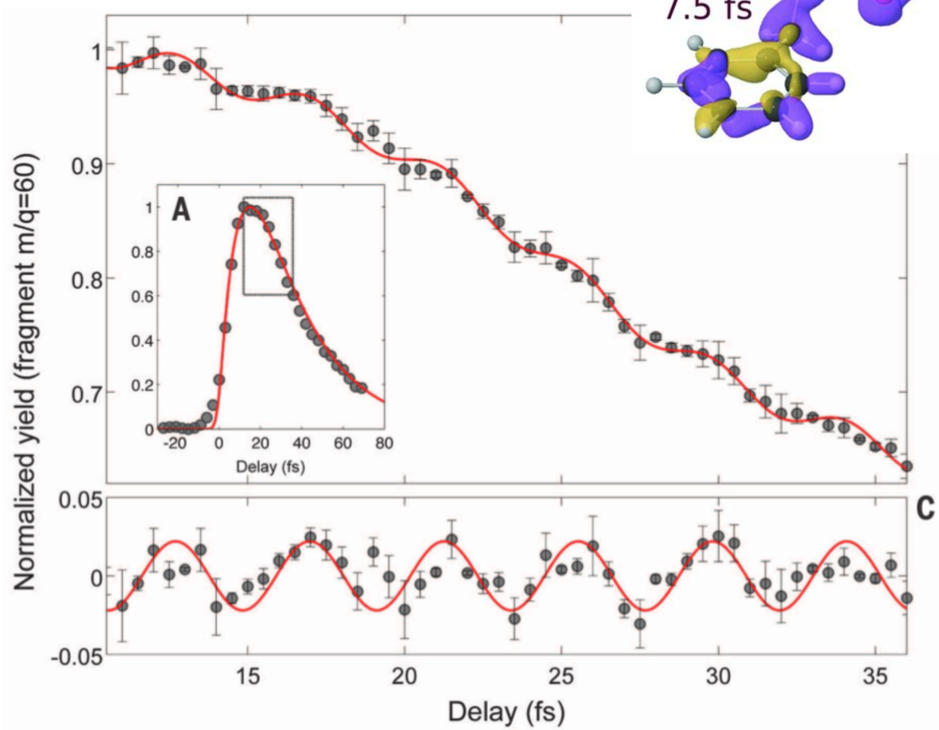
Goulielmakis et al., Nature **466**, 739 (2010)

Direct observation of charge migration

Phenylalanine







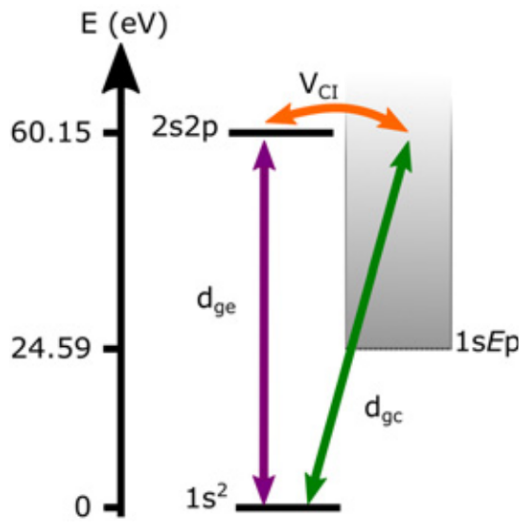
Charge migration mostly between the amine and carboxylic groups in 4 fs

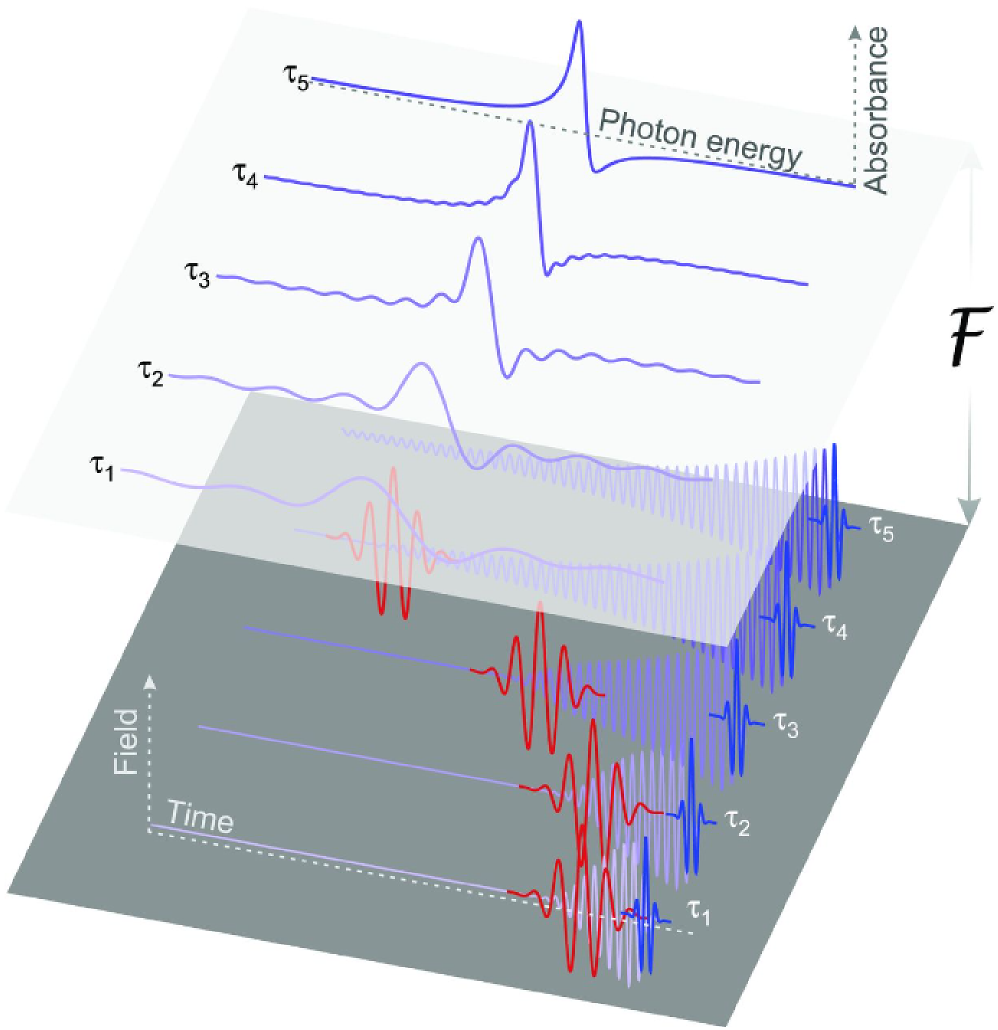
The probe pulse is most likely absorbed by the amine group

Calegari et al., Science **346**, 336 (2014)

Watching interference build up in real time

Fano resonance in helium (He)

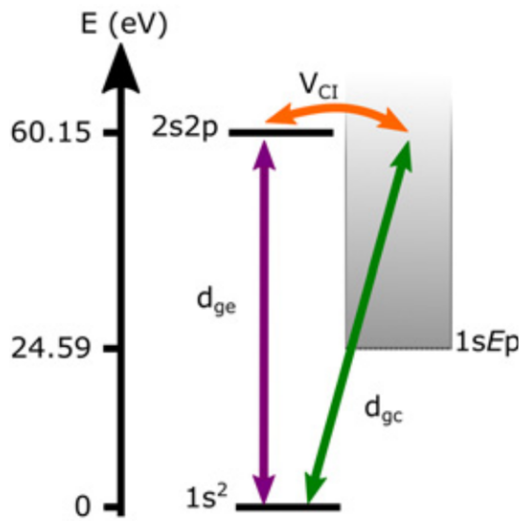


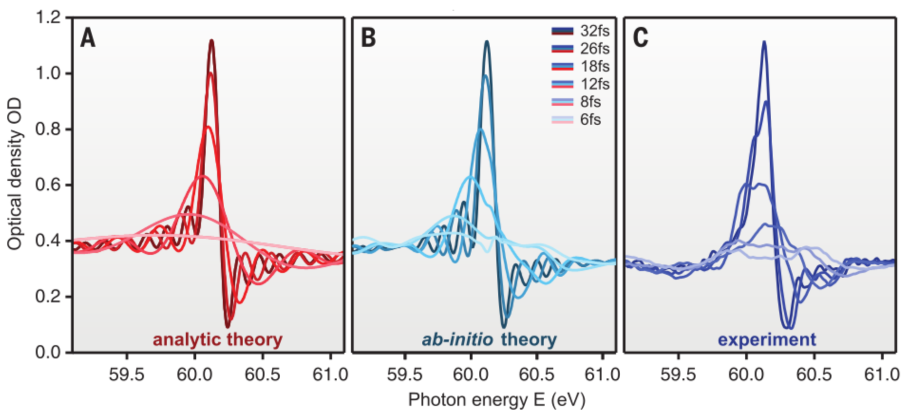


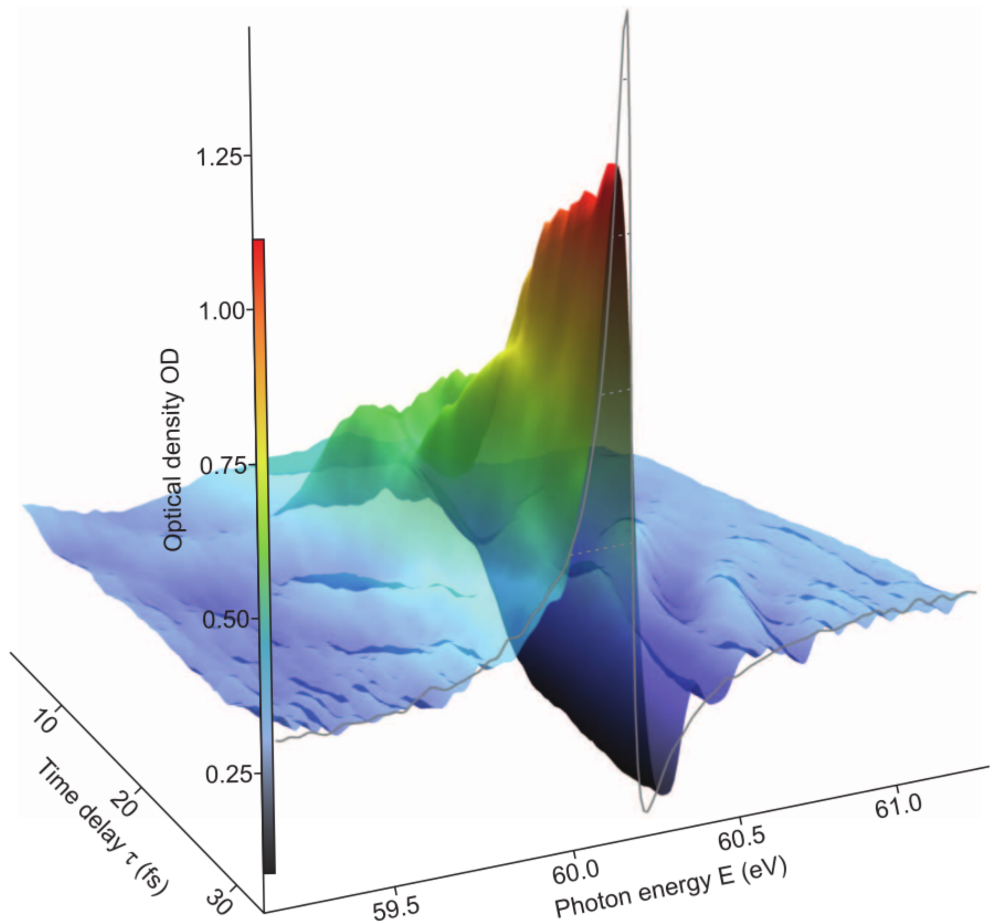
Kaldun et al. Science **354**, 738 (2016)

Watching interference build up in real time

Fano resonance in helium (He)



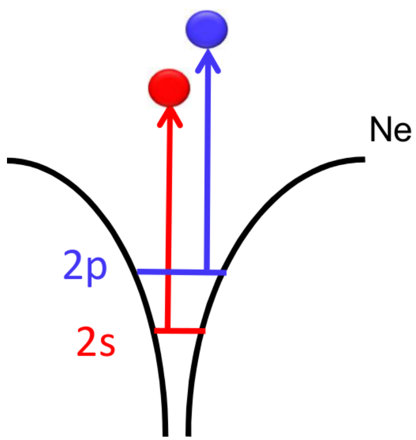




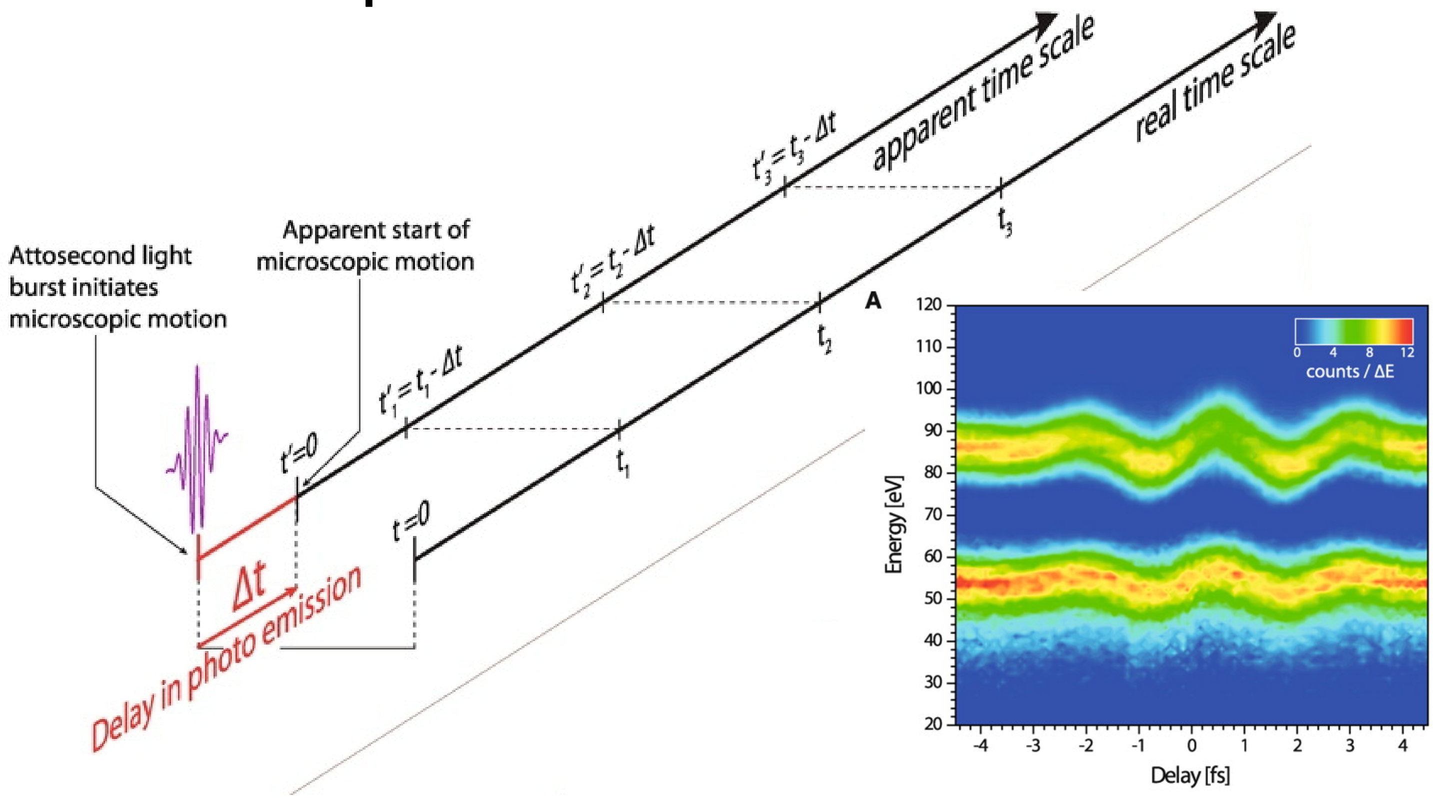
Kaldun et al. Science **354**, 738 (2016)

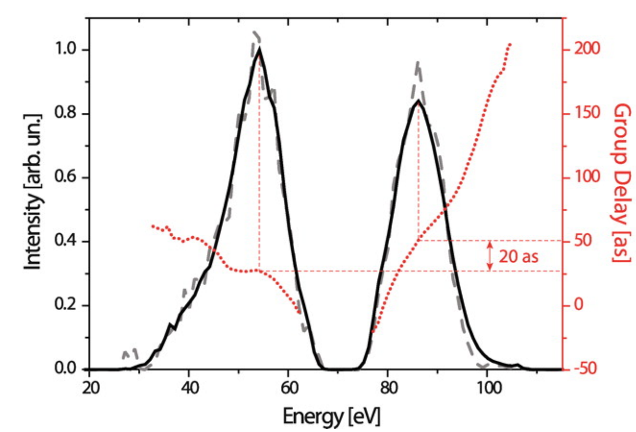
Photoemission time delays

Single ionization of Ne from 2s and 2p shells



Ne $1s^2 2s^2 2p^6$





$$\langle \varepsilon | \psi(t) \rangle = \chi(\varepsilon) e^{-i\varepsilon t/\hbar} = |\chi(\varepsilon)| e^{-i\phi(\varepsilon)}$$

$$\phi(\varepsilon) = \arg[\chi(\varepsilon)] - \varepsilon t/\hbar$$

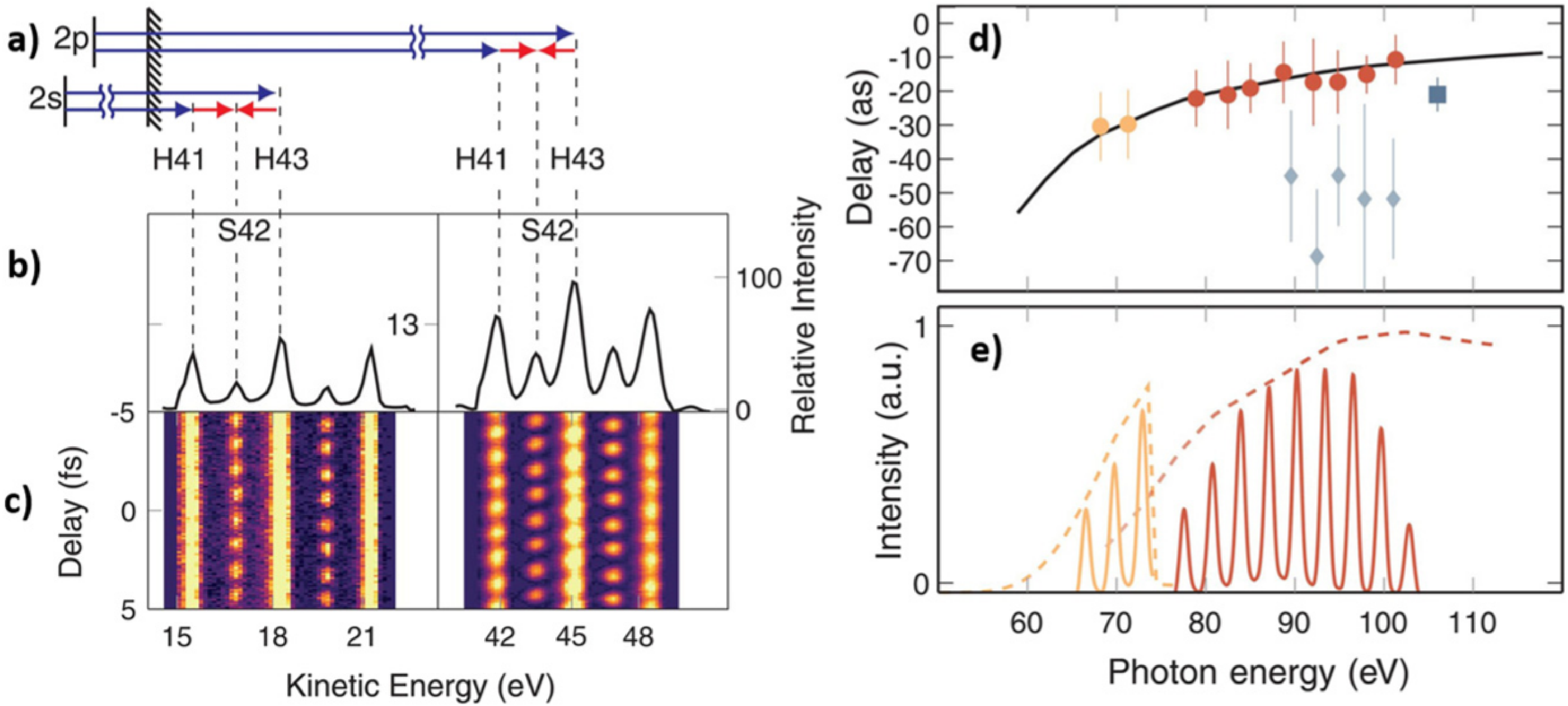
$$\Delta t = \frac{\partial \phi}{\partial \varepsilon} = \hbar \frac{\partial}{\partial \varepsilon} \arg[\chi(\varepsilon)]$$

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

Photoemission time delays

Single ionization of Ne from 2s and 2p shells

High temporal (20 as) and spectral (200 meV) accuracy!



Isinger et al. Science **358**, 893 (2017)

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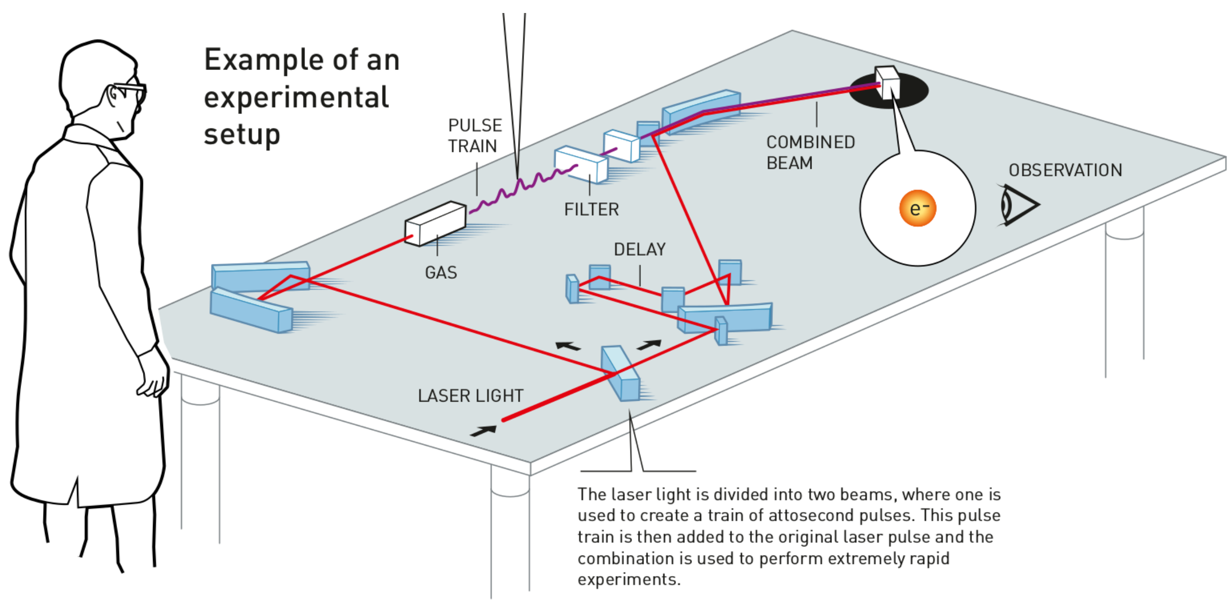
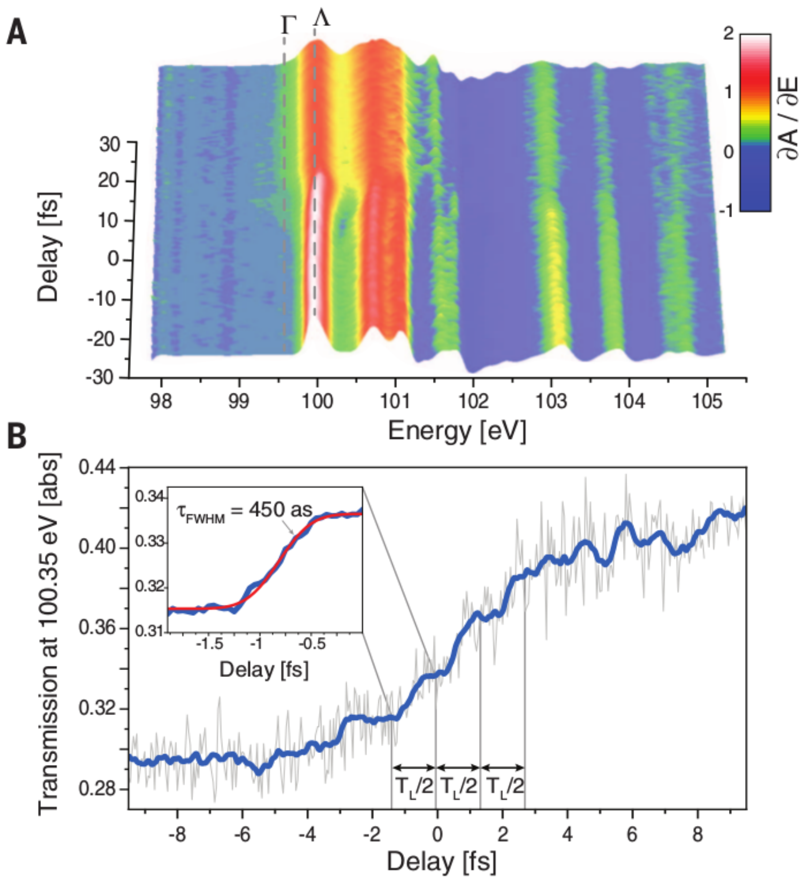
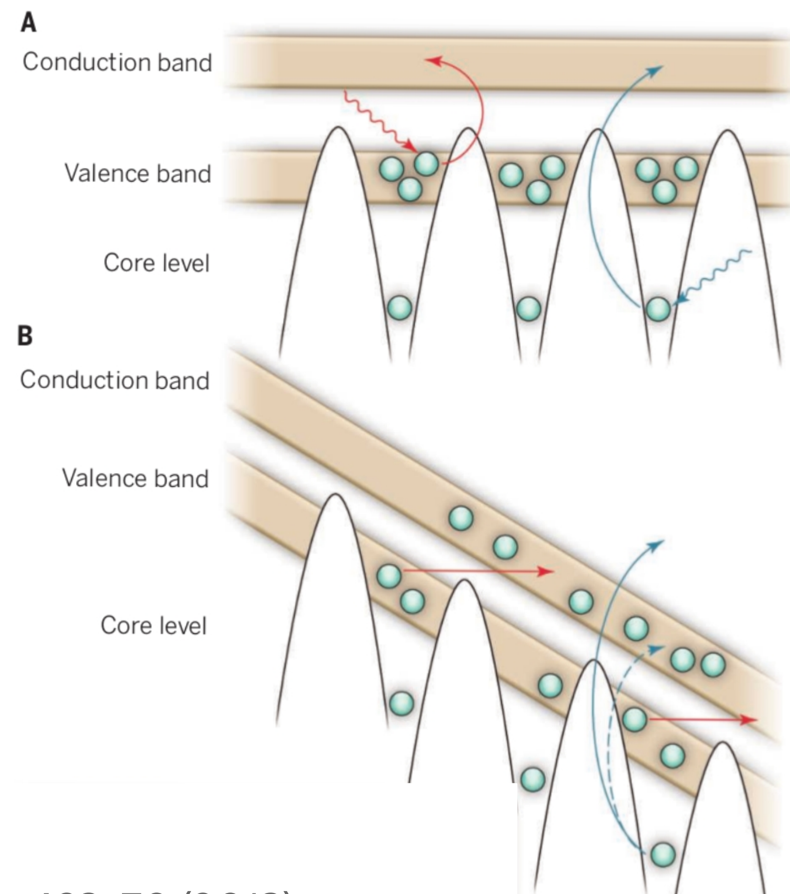


Towards petahertz electronics

Silicon dioxide (SiO_2)

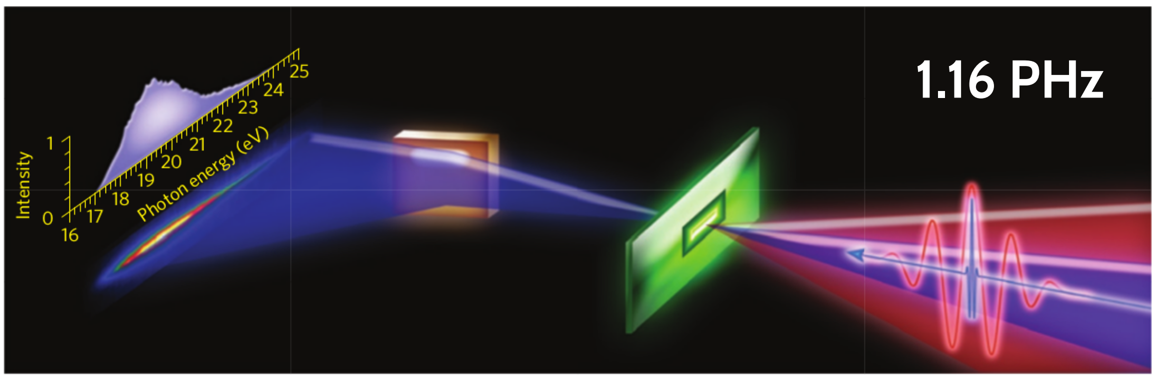


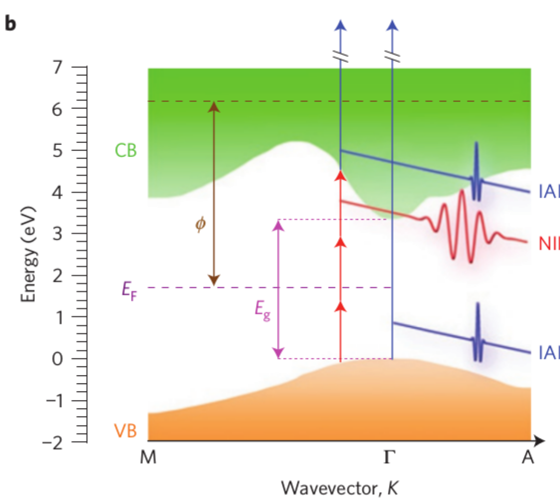


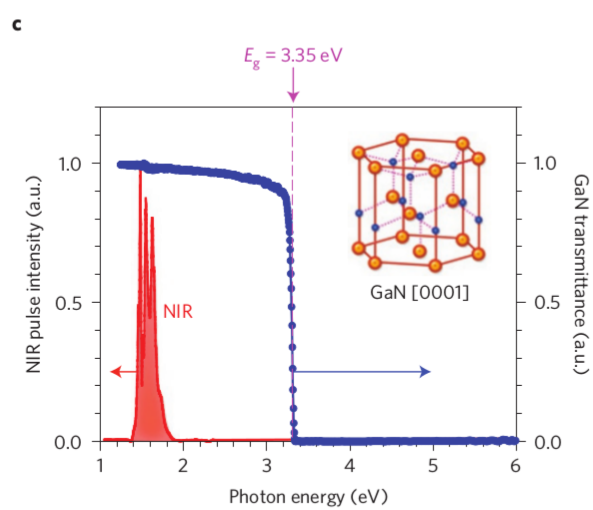
Schiffrin et al., Nature **493**, 70 (2013)
Schultze et al., Nature **346**, 1348 (2014)
Sommer et al., Nature **534**, 86 (2016)

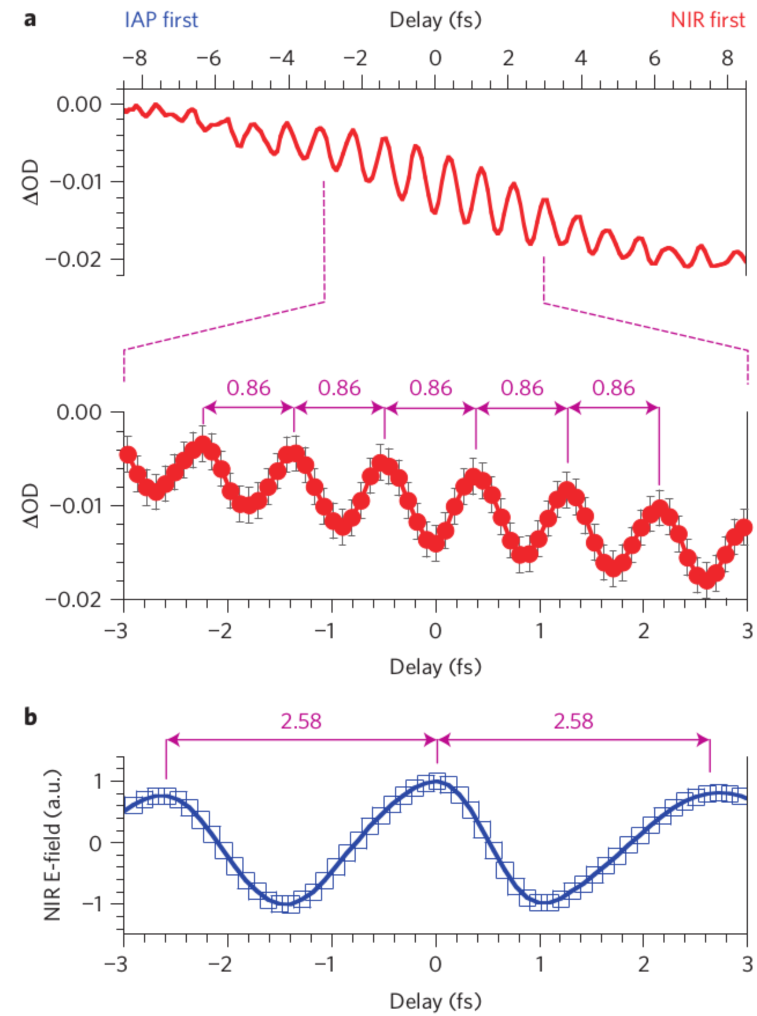
Towards petahertz electronics

Gallium Nitride (GaN)





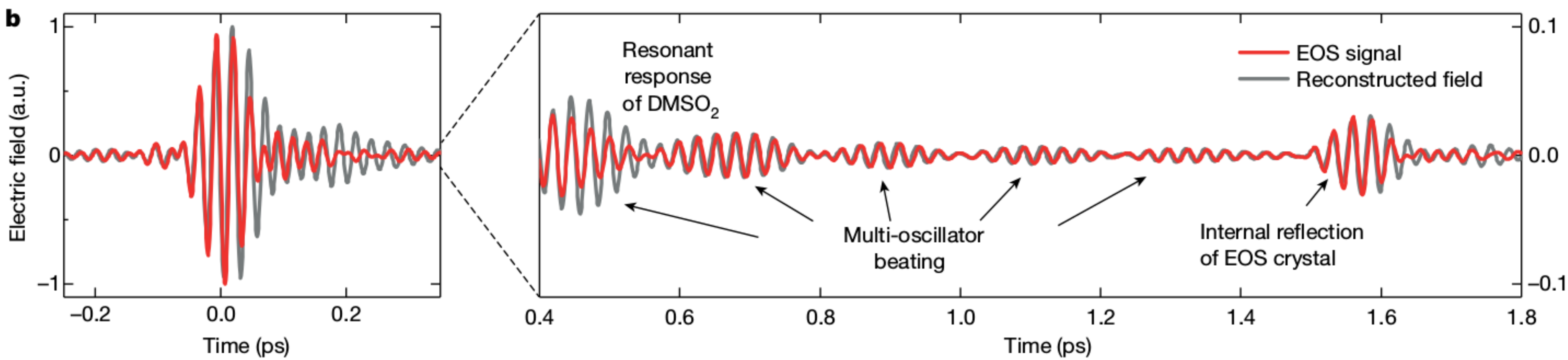


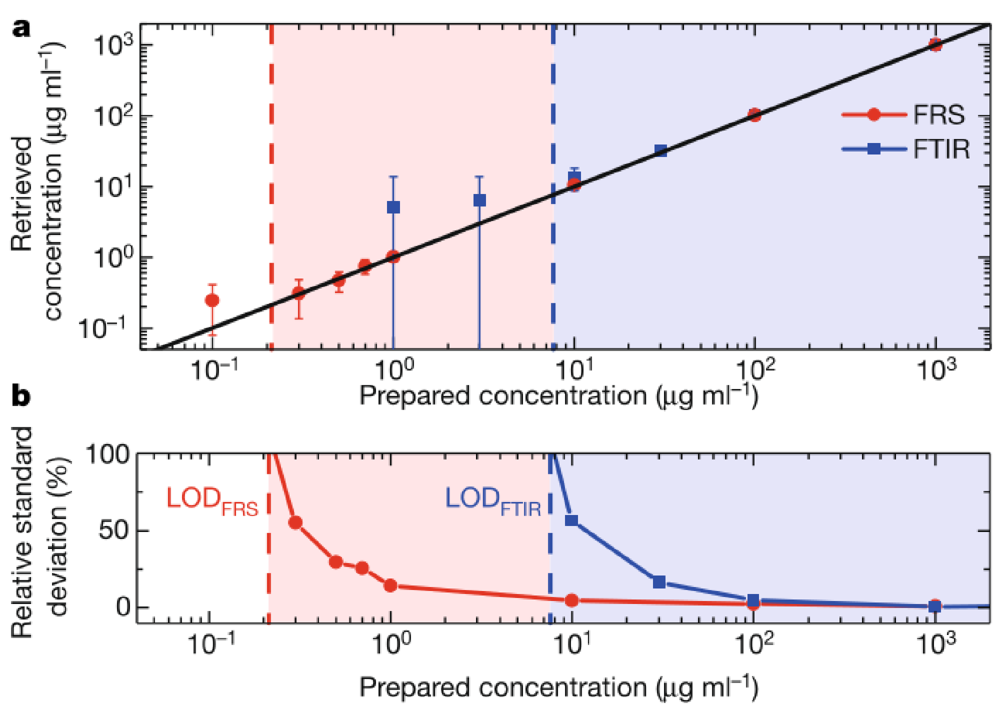


Mashiko et al, Nature Physics **12**, 741 (2016)

Electric-field-resolved molecular fingerprinting

Methylsulfonylmethane ($DMSO_2$) in water

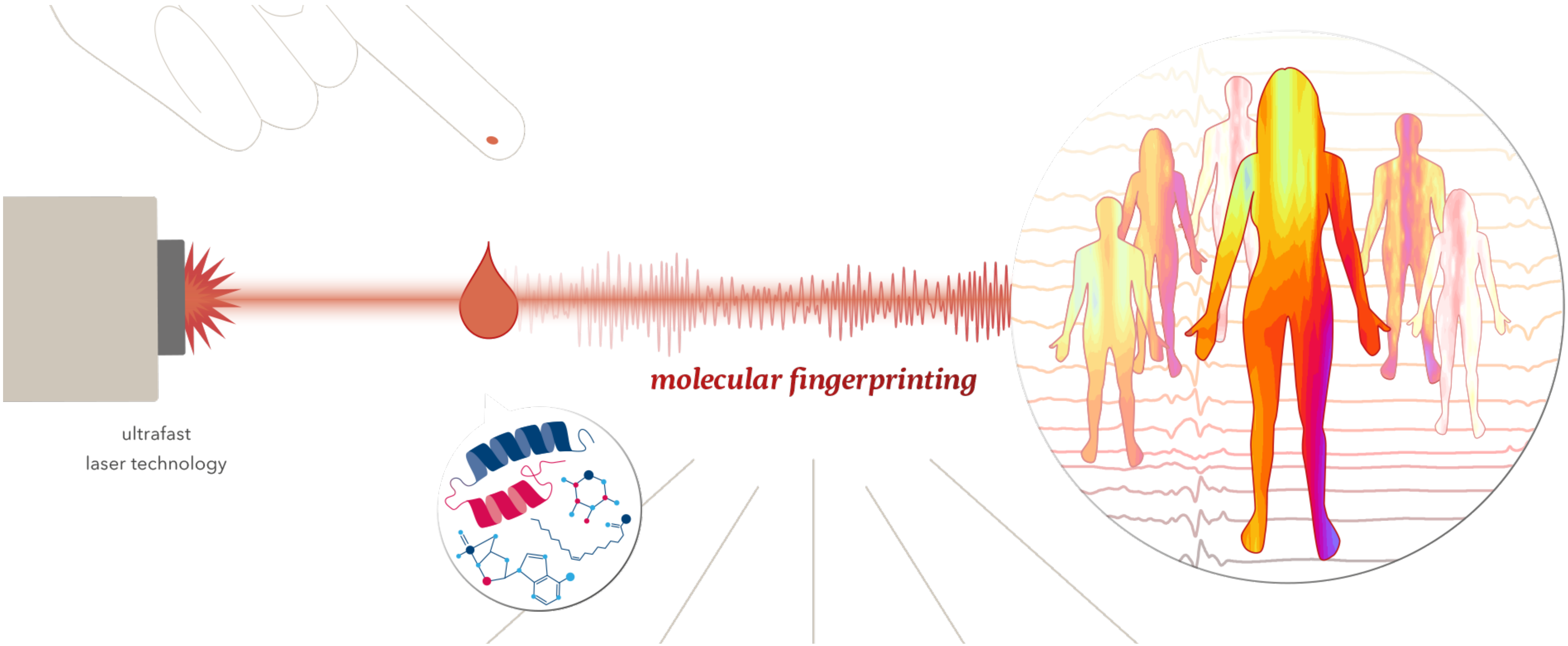




Pupeza et al, Nature **577**, 52 (2020)

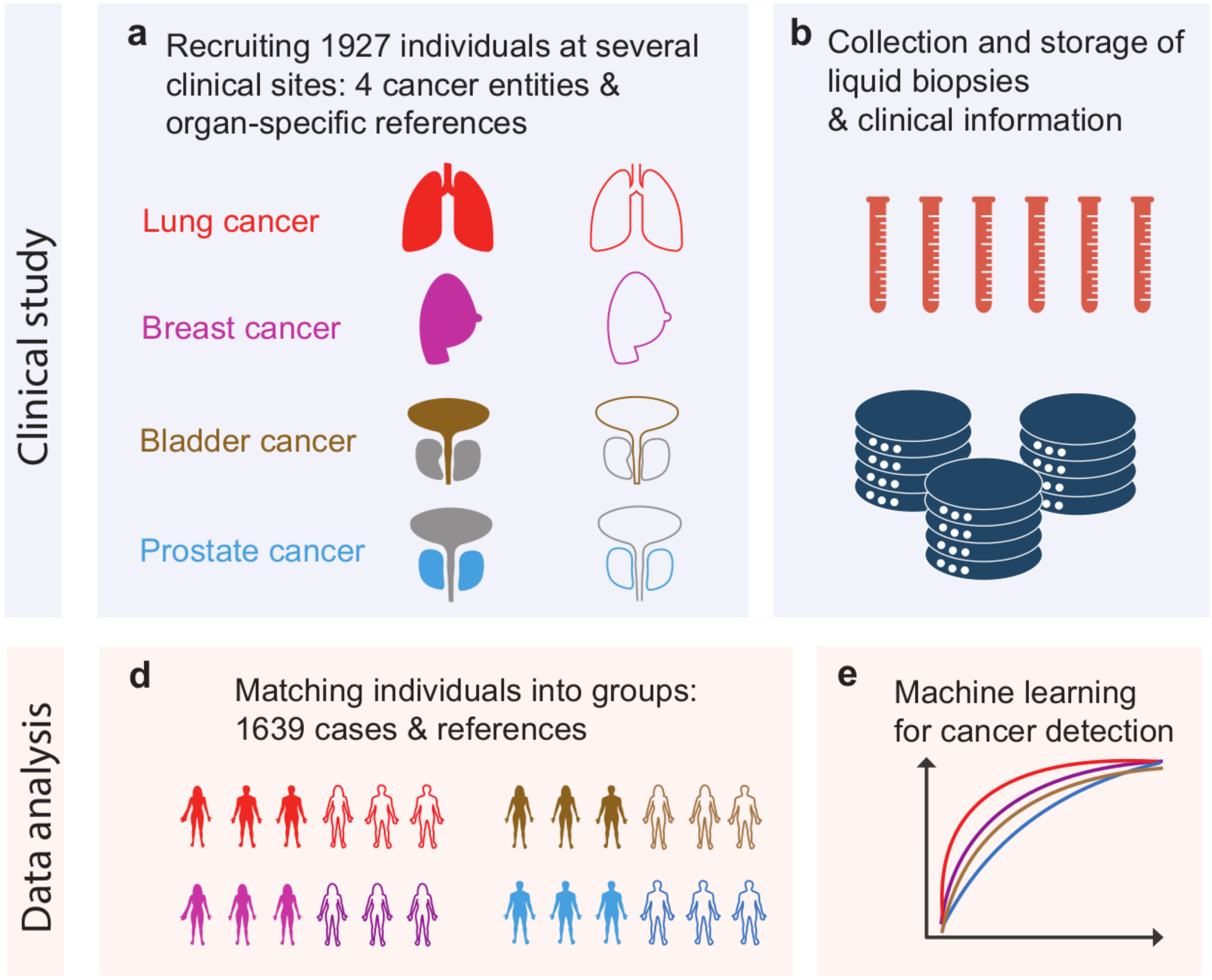
Towards preventive medicine

Blood samples



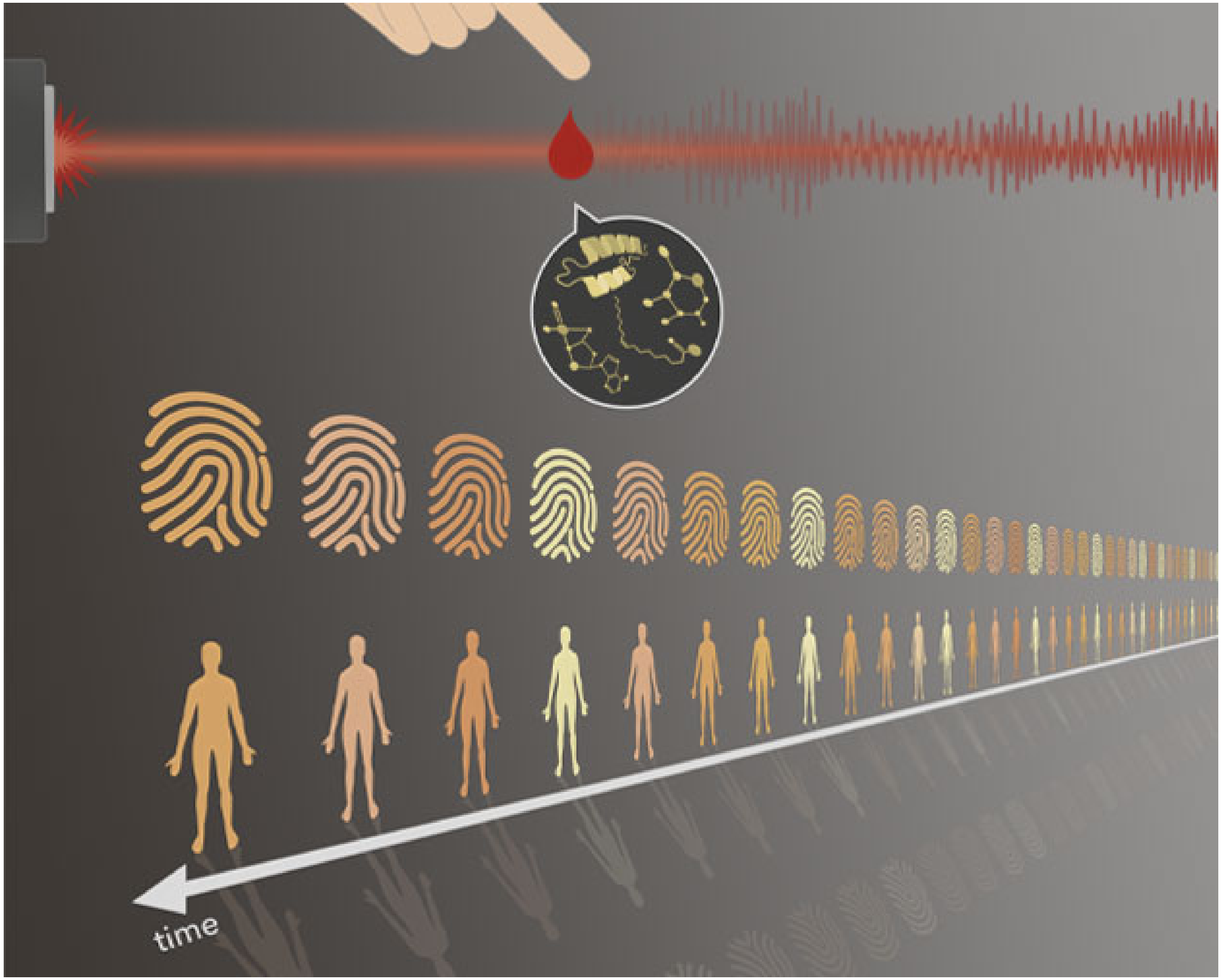
https://www.lasers4life.de/

Towards preventive medicine



Huber et al., eLife 10:e68758 (2021)

Towards preventive medicine



https://www.lasers4life.de/

PHYSICAL REVIEW A VOLUME 49, NUMBER 3 MARCH 1994

Theory of high-harmonic generation by low-frequency laser fields

M. Lewenstein,[1,*] Ph. Balcou,[2] M. Yu. Ivanov,[3,†] Anne L'Huillier,[2,4] and P. B. Corkum[3]
[1] *Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, Colorado 80309-0440*
[2] *Service des Photons, Atomes et Molécules, Centre d'Etudes de Saclay, 91191 Gif sur Yvette, France*
[3] *National Research Council of Canada, M-23A, Ottawa, Ontario, Canada K1A 0R6*
[4] *Lawrence Livermore National Laboratory, L-443, P.O. Box 5508, Livermore, California 94550*
(Received 19 August 1993)

PHYSICAL REVIEW A VOLUME 53, NUMBER 3 MARCH 1996

Theory of high-order harmonic generation by an elliptically polarized laser field

Philippe Antoine,[1,2] Anne L'Huillier,[1,3] Maciej Lewenstein,[1,4] Pascal Salières,[1] and Bertrand Carré[1]
[1] *Commissariat à l'Energie Atomique, DSM/DRECAM/SPAM, Centre d'Etudes de Saclay, 91191 Gif-sur-Yvette, France*
[2] *Laboratoire de Physique Atomique et Moléculaire, Université Catholique de Louvain, Chemin du Cyclotron, 2 B-1348 Louvain-la-Neuve, Belgique*
[3] *Department of Physics, Lund Institute of Technology, S-221 00 Lund, Sweden*
[4] *Centrum Fizyki Teoretycznej, Polska Akademia Nauk, 02-668 Warsaw, Poland*
(Received 10 August 1995)

VOLUME 77, NUMBER 7 PHYSICAL REVIEW LETTERS 12 AUGUST 1996

Attosecond Pulse Trains Using High–Order Harmonics

Philippe Antoine,[1,3] Anne L'Huillier,[2] and Maciej Lewenstein[1]
[1] *Commissariat à l'Energie Atomique, DSM/DRECAM/SPAM, Centre d'Etudes de Saclay, 91191 Gif-sur-Yvette, France*
[2] *Department of Physics, Lund Institute of Technology, S-221 00 Lund, Sweden*
[3] *Laboratoire de Physique Atomique et Moléculaire, Chemin du Cyclotron, Université Catholique de Louvain, 2 B-1348 Louvain-la-Neuve, Belgium*
(Received 8 March 1996)

We demonstrate that high-order harmonics generated by an atom in intense laser field form trains of ultrashort pulses corresponding to different trajectories of electrons that tunnel out of the atom and recombine. Propagation in an atomic jet allows us to select one of these trajectories, leading to a train of pulses of extremely short duration. [S0031-9007(96)00866-6]

PACS numbers: 32.80.Rm, 42.65.Ky

A. Zeilinger - Radek Łapkiewicz

ARTICLE

Received 24 Feb 2014 | Accepted 25 Jun 2014 | Published 30 Jul 2014

DOI: 10.1038/ncomms5502

Interface between path and orbital angular momentum entanglement for high-dimensional photonic quantum information

Robert Fickler[1,2], Radek Lapkiewicz[1,2], Marcus Huber[3,4], Martin P.J. Lavery[5], Miles J. Padgett[5] & Anton Zeilinger[1,2]

LETTER

doi:10.1038/nature13586

Quantum imaging with undetected photons

Gabriela Barreto Lemos[1,2], Victoria Borish[1,3], Garrett D. Cole[2,3], Sven Ramelow[1,3]†, Radek Lapkiewicz[1,3] & Anton Zeilinger[1,2,3]

F. Krausz

- Paweł Wnuk
- Maciej Kowalczyk

nature photonics ARTICLES
https://doi.org/10.1038/s41566-022-01001-2

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Single-cycle infrared waveform control

Philipp Steinleitner[1,6], Nathalie Nagl[1,2,6] ✉, Maciej Kowalczyk[1,2,3,6] ✉, Jinwei Zhang[1,4], Vladimir Pervak[2], Christina Hofer[1,2,3], Arkadiusz Hudzikowski[5], Jarosław Sotor[5], Alexander Weigel[1,3], Ferenc Krausz[1,2,3] and Ka Fai Mak[1] ✉

Research Article Vol. 10, No. 6 / June 2023 / *Optica* 801

OPTICA

Ultra-CEP-stable single-cycle pulses at 2.2 μm

Maciej Kowalczyk,[1,2,3,†] Nathalie Nagl,[1,3,5,†] Philipp Steinleitner,[3,6,†] Nicholas Karpowicz,[3] Vladimir Pervak,[1] Aleksander Głuszek,[4] Arkadiusz Hudzikowski,[4] Ferenc Krausz,[1,2,3] Ka Fai Mak,[3] and Alexander Weigel[2,3,*]

Nobel Prize in Physics 2023

"... the grater the detail in which we can pursue Nature on any path, the richer and more durable will be the gain that we can derive from our perceptiveness..."

Max Planck