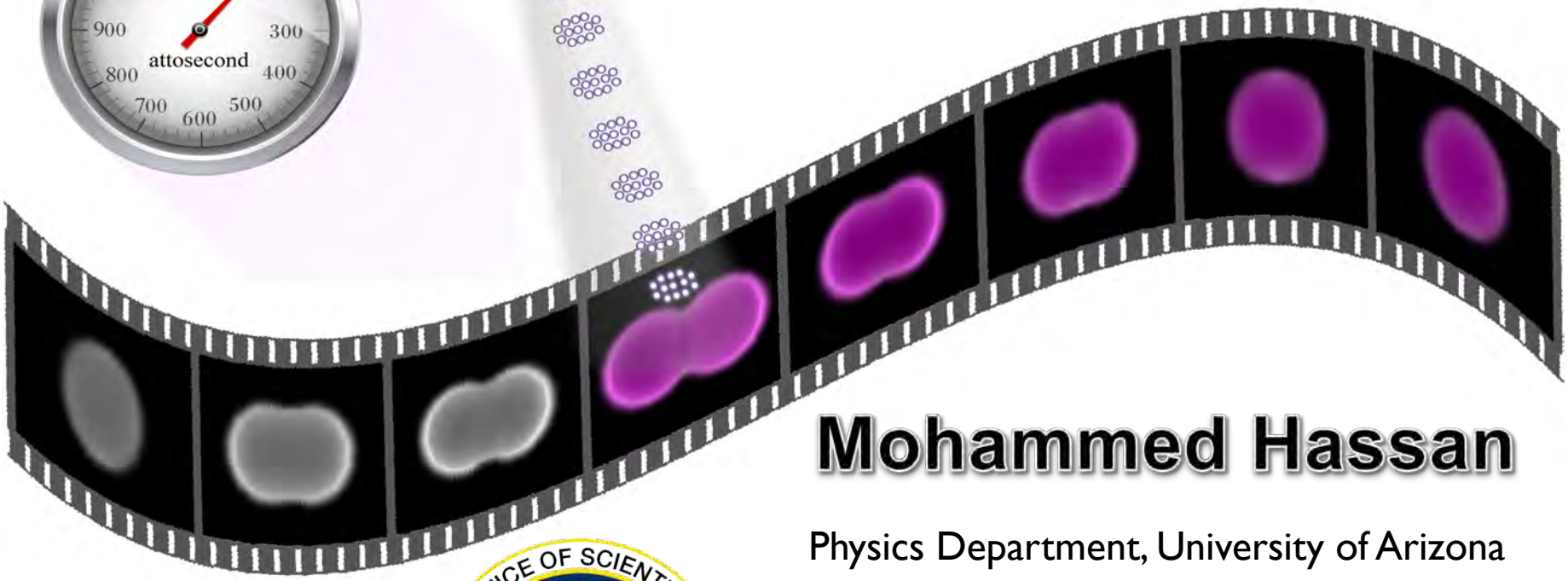
Seeing Electron in Action



Mohammed Hassan

Physics Department, University of Arizona

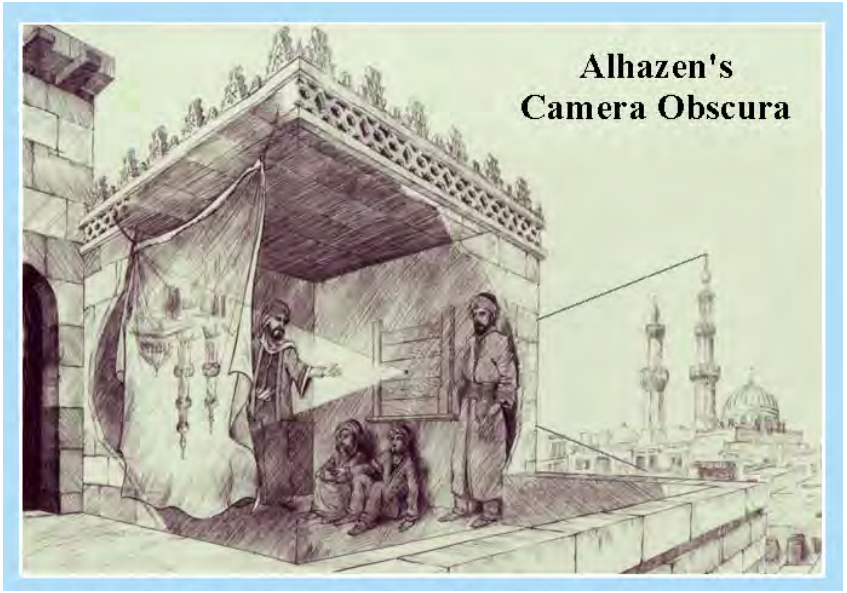
YIP Grant AWARD
NO. FA9550-19-1-0025

Seeing is believing: era of imaging

Attomicroscopy

First imaging experiment in history

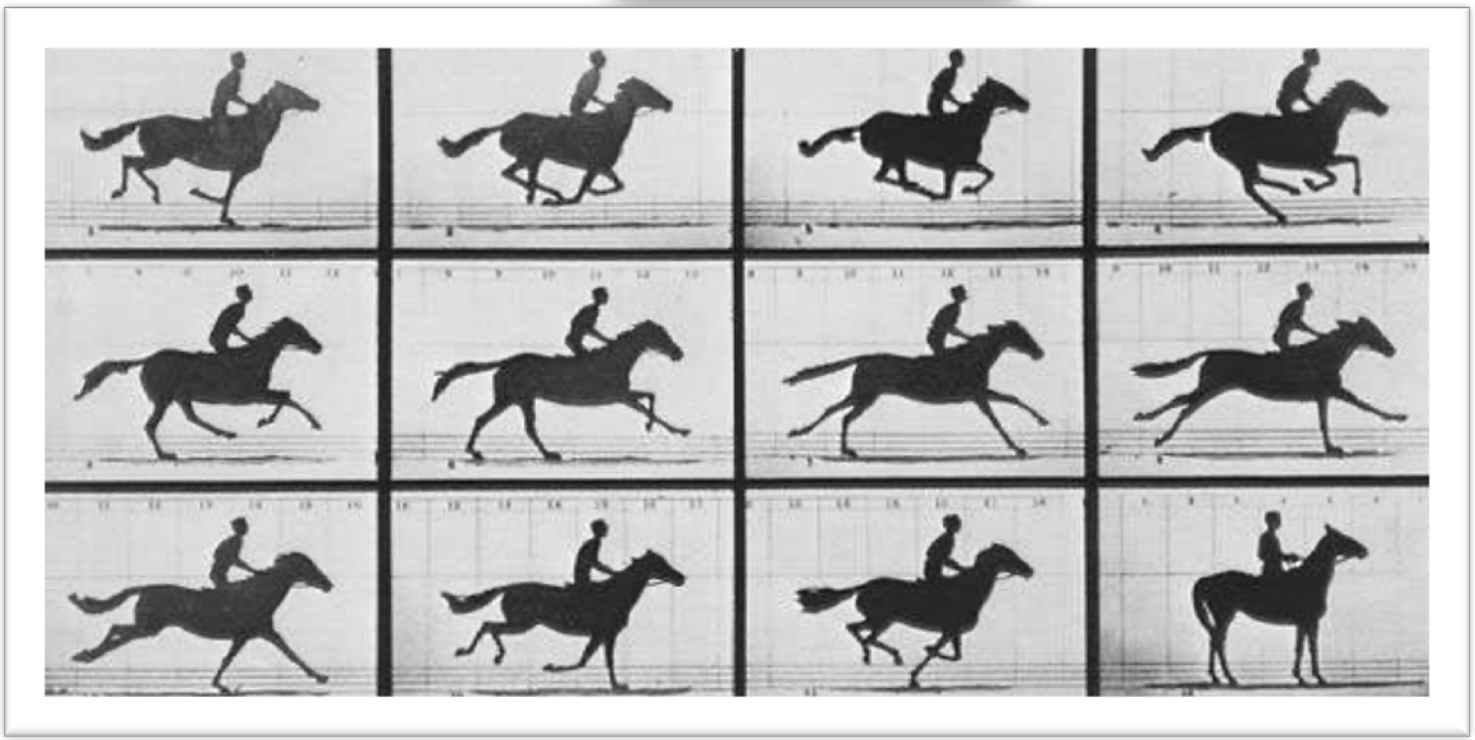
Hassan Ibn al-Haytham



Ibn al-Haytham's seven-volume Book of Optics, published in 1015, greatly influenced the field of optics. However, some aspects of Ibn al-Haytham's work have also been the subject of controversy for historians of science.

Stephen R. Wilk, "Ibn al-Haytham: 1,000 Years after the Kitāb al-Manāẓir," Optics & Photonics News 26(10), 42-48 (2015)

Horse in motion



Muybridge, J. "The horse in motion." *Nature* 25.652 (1882): 605-605.

Attomicroscopy

Ultrafast Science

space (m)

10^{-9}

electrons in

nanostructures

molecules

atoms

atoms in

molecules & solids

$\Delta W_{electron/hole}$ ~ sub-eV

$\Delta W_{valence}$ > 1eV

ΔW_{vibr} ~ milli-eV

nuclear distance

10^{-12}

ΔW_{core} >> 10 eV

nuclear structure & dynamics

10^{-18}

~ 100 fs

10^{-12} time (s)

Ahmed Zewail
NP in 1999

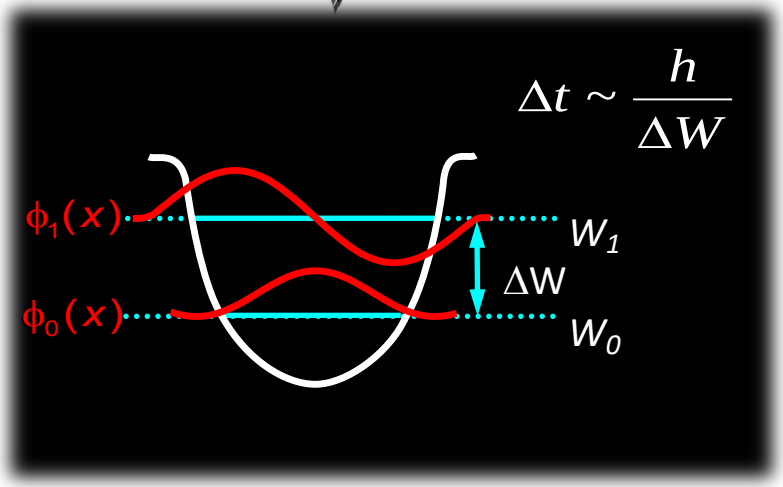
10^{-15}

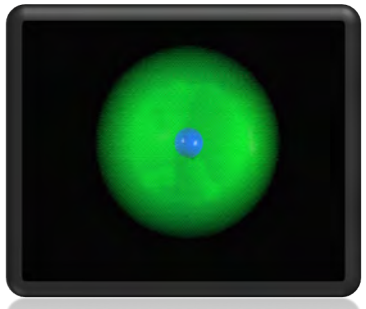
attophysics

femtochemistry

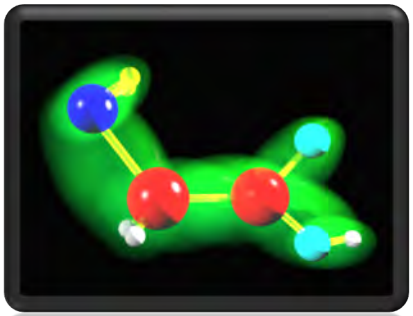
Attomicroscopy

Time scale of electron motion





1S-2S quantum H atom (300 as)



Charge migration in peptides (0.4-10 fs)

How brief are attoseconds??

1 second (s) = 10^0 s = 1 s
1 miliesecond (s) = 10^{-3} s = 0.001 s
1 microsecond (s) = 10^{-6} s = 0.000001 s
1 nanosecond (s) = 10^{-9} s = 0.000000001 s
1 picosecond (s) = 10^{-12} s = 0.000000000001 s
1 femtosecond (s) = 10^{-15} s = 0.000000000000001 s
1 attosecond (s) = 10^{-18} s = 0.0000000000000000001 s

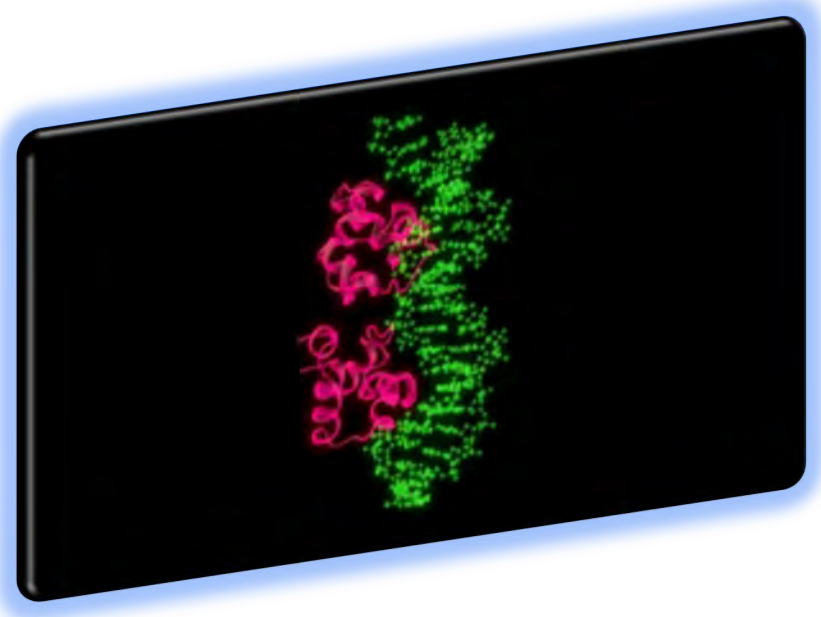
One attosecond is to one second as

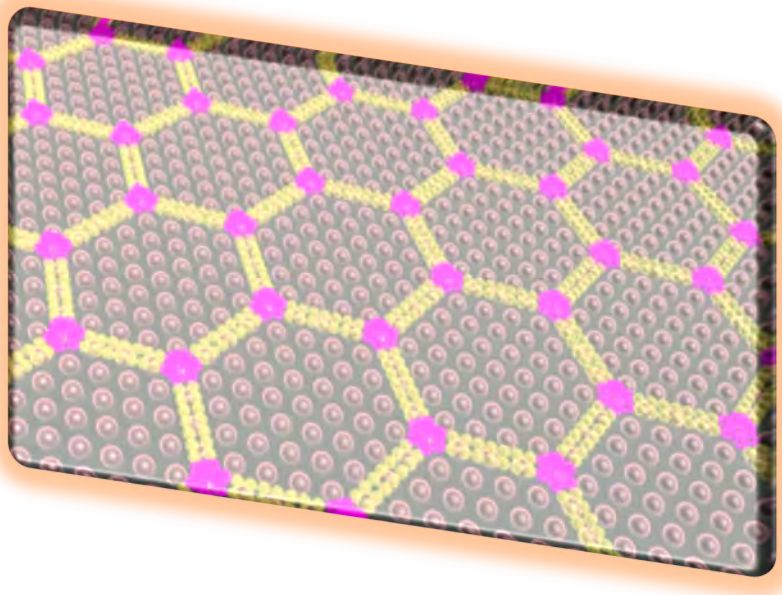
one second is to the age of the universe

00:01

Attomicroscopy

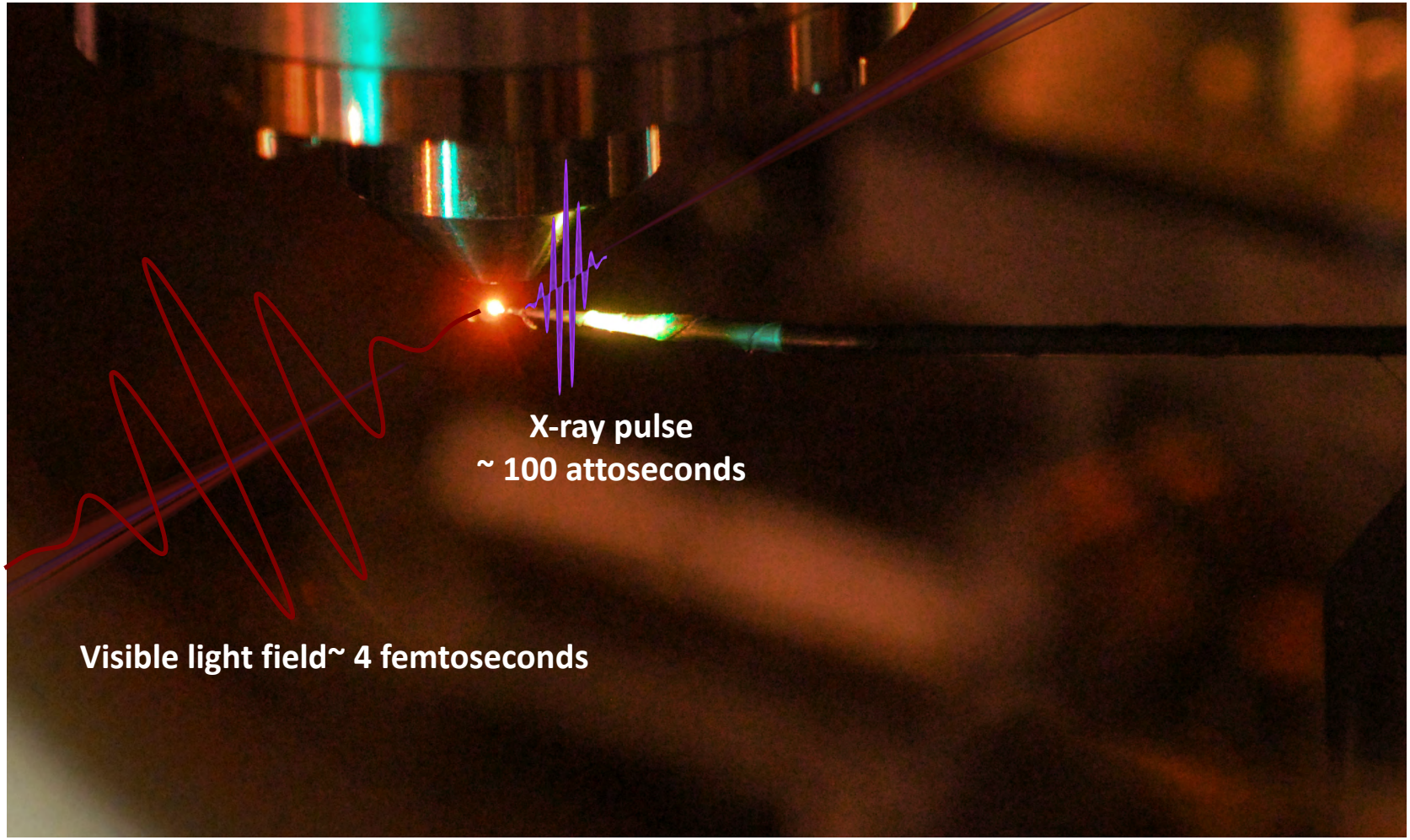
Electron motion in our life!





www.Attoworld.com

20 years of Attosecond Science



P. B. Corkum & Ferenc Krausz *Nature Physics* **volume 3**, (2007)

20 years of Attosecond Science

Scientific Background on the Nobel Prize in Physics 2018

GROUNDBREAKING INVENTIONS IN LASER PHYSICS

OPTICAL TWEEZERS AND GENERATION OF HIGH-INTENSITY, ULTRA-SHORT OPTICAL PULSES

The Nobel Committee for Physics

However beautiful, the femtosecond laser technology developed during the 1960s, 1970s and 1980s was unable to break the 1-fs-pulse–duration limit. Shortly after the first experimental realisations of high harmonics, it was suggested that, in analogy with mode locking, high-order harmonics could lead to pulses shorter than 1 fs [73]. A decade later, after building on many improvements and insights into HHG by means of CPA-based lasers, the first attosecond pulses were experimentally observed [74, 75]. This was the birth of a new research field – attosecond science. For the first time, the electron dynamics inside atoms, molecules and matter in the condensed phase could be probed [76].

20 years of Attosecond Science

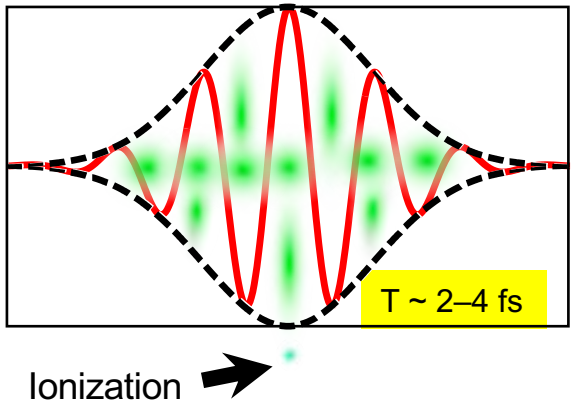
Attosecond tools gives an access to the electron dynamics in matter

- Few-cycle pulses provide the attosecond resolution to trigger electron dynamics in strong-field interaction and ionized systems.
- EUV pulses probe the electron dynamics in time-resolved spectroscopic measurements.

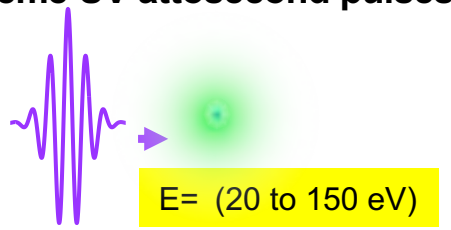
Limitations of the current tools;

1. Neutral systems
2. Molecular systems
3. Complex electronic systems
4. The dynamics in Space and time domains together
5. Limited electron motion control

- **Few-cycle to single-cycle pulses**

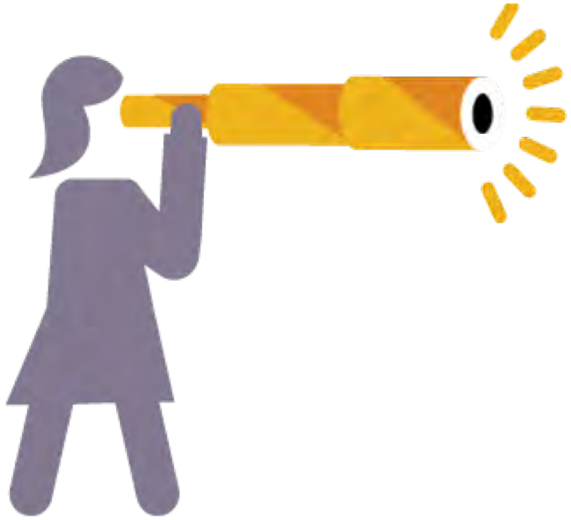


- **Extreme UV attosecond pulses**



- The field calls for a *paradigm shift* tools to trigger, control and image the electron dynamics in matter;

- **Synthesized Attosecond Laser Pulse (ALP)**
- **Attosecond Electron Pulse (AEP)**



We can *only* control what we can see

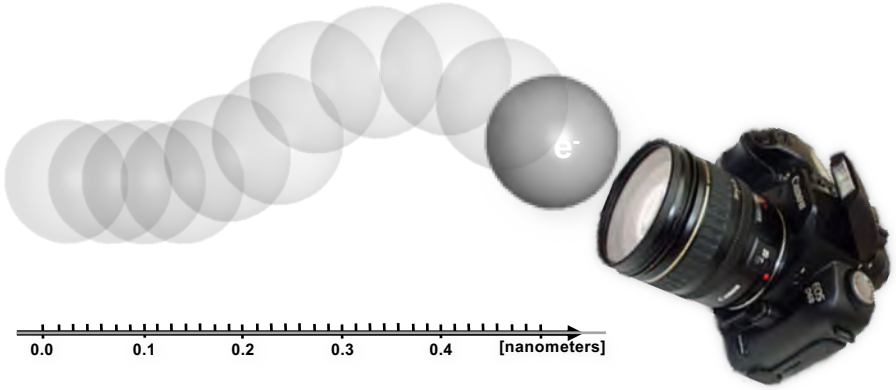
These tools will allow to develop:

- **Attosecond Electron Diffraction** and
- **Attosecond Electron Microscopy "Attomicroscopy"**
- **fine control the electron motion in its native time scale.**

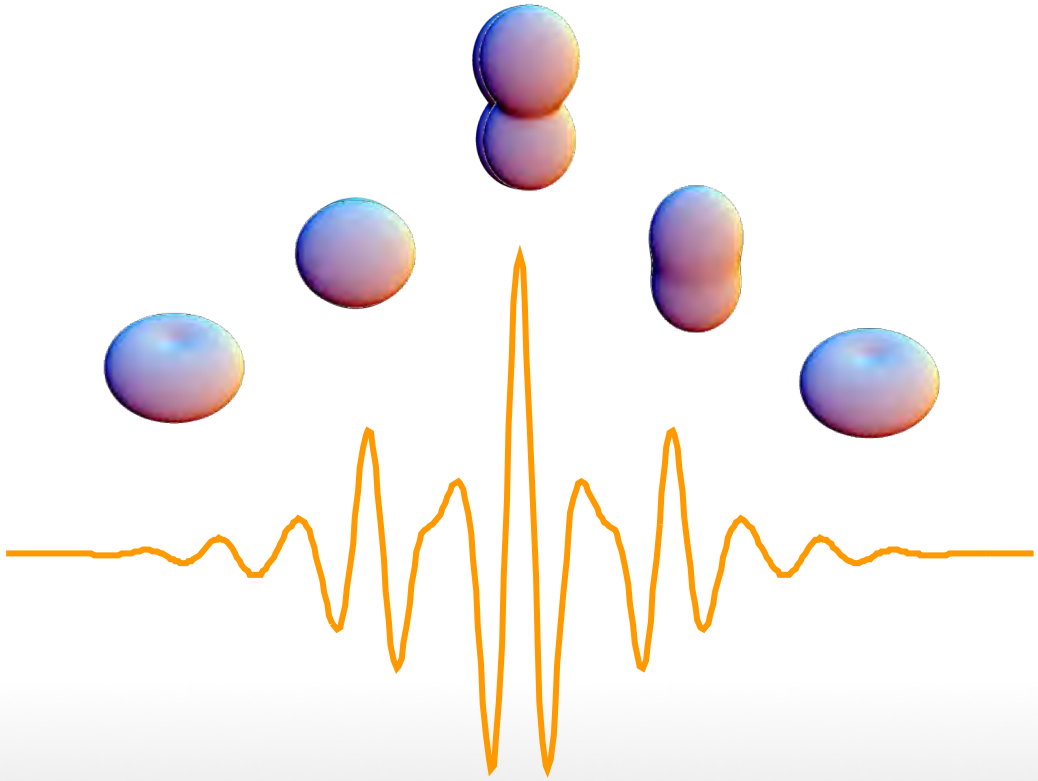
which will take the whole field to the next level by permit, for the first time, directly image and record "movies" the electron motion in action.

Imaging and control of the electron motion in action

Imaging and record movies of electron motion in action and its control on its native time scale promises to break new ground in science and technology

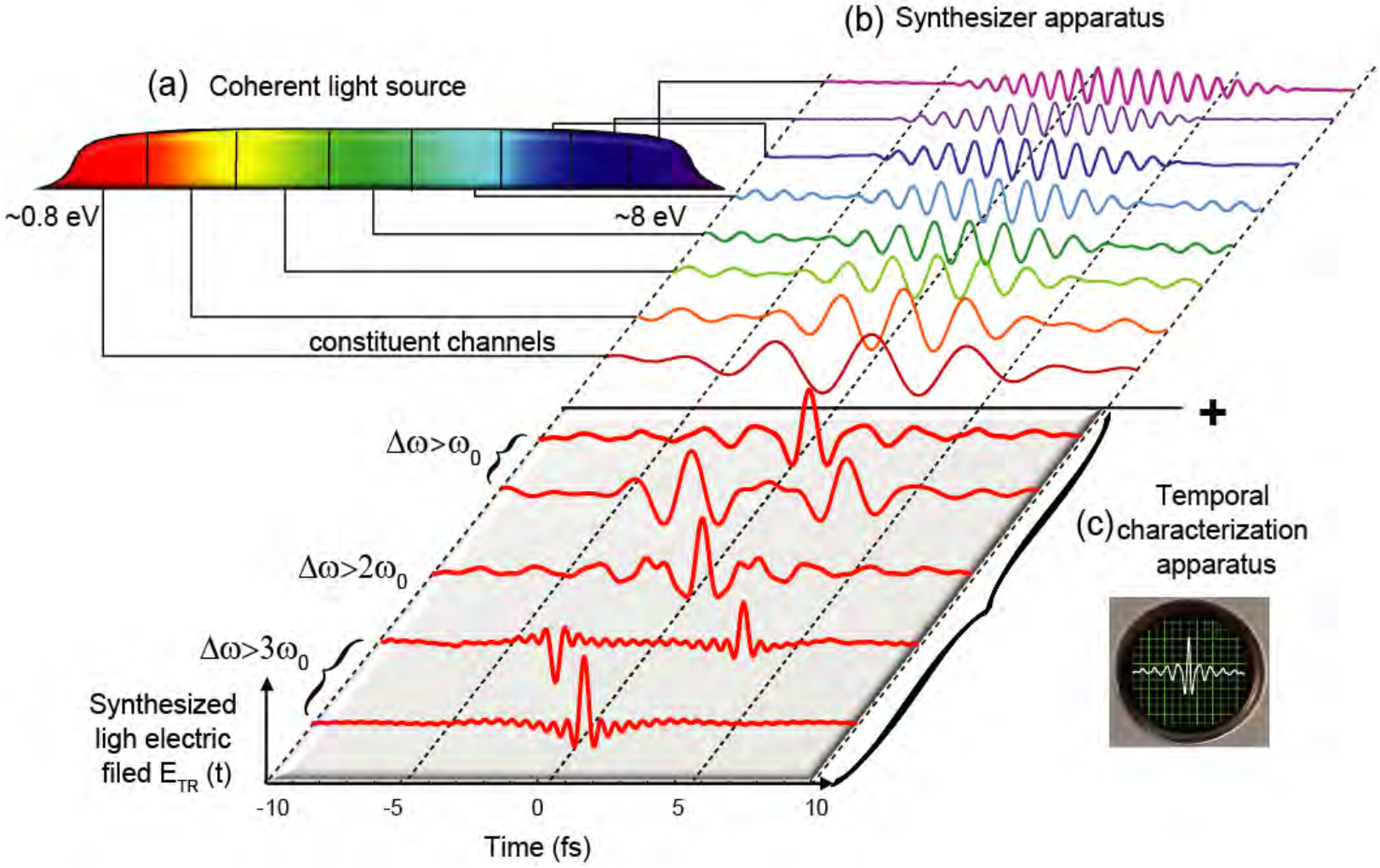


I- Attosecond electron motion control



Light Field Synthesis: The concept

M. Hassan *et. al.*, Rev. Sci. Instr. 83,11, (2012).

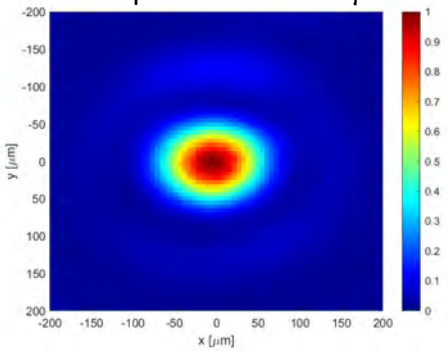


Generation of the broadest supercontinuum spans more than 2-octves

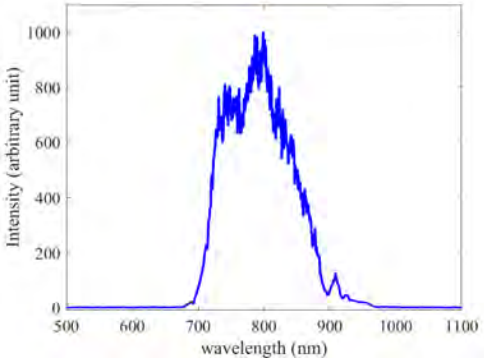
15 fs, 800 nm,
Power=13 W

Beam profile

Beam profile- 150x150 μm

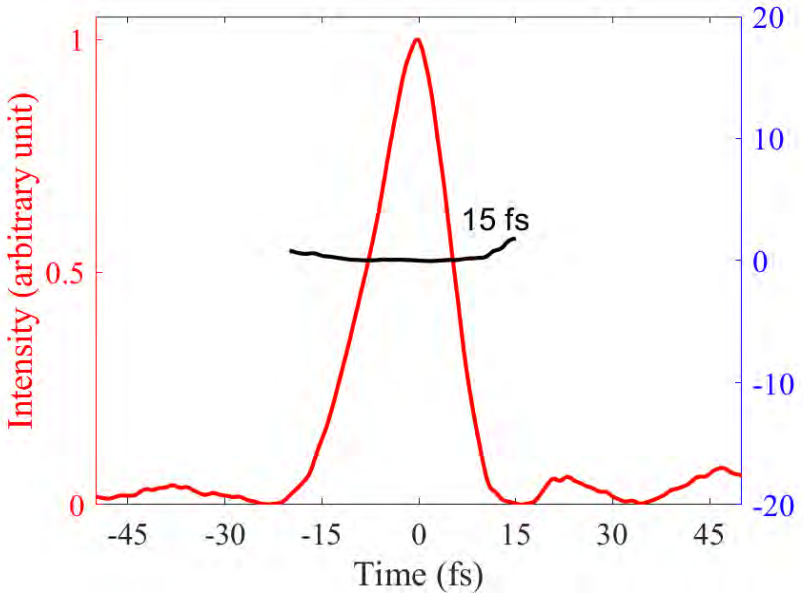


Spectrum spans from 700-900 nm

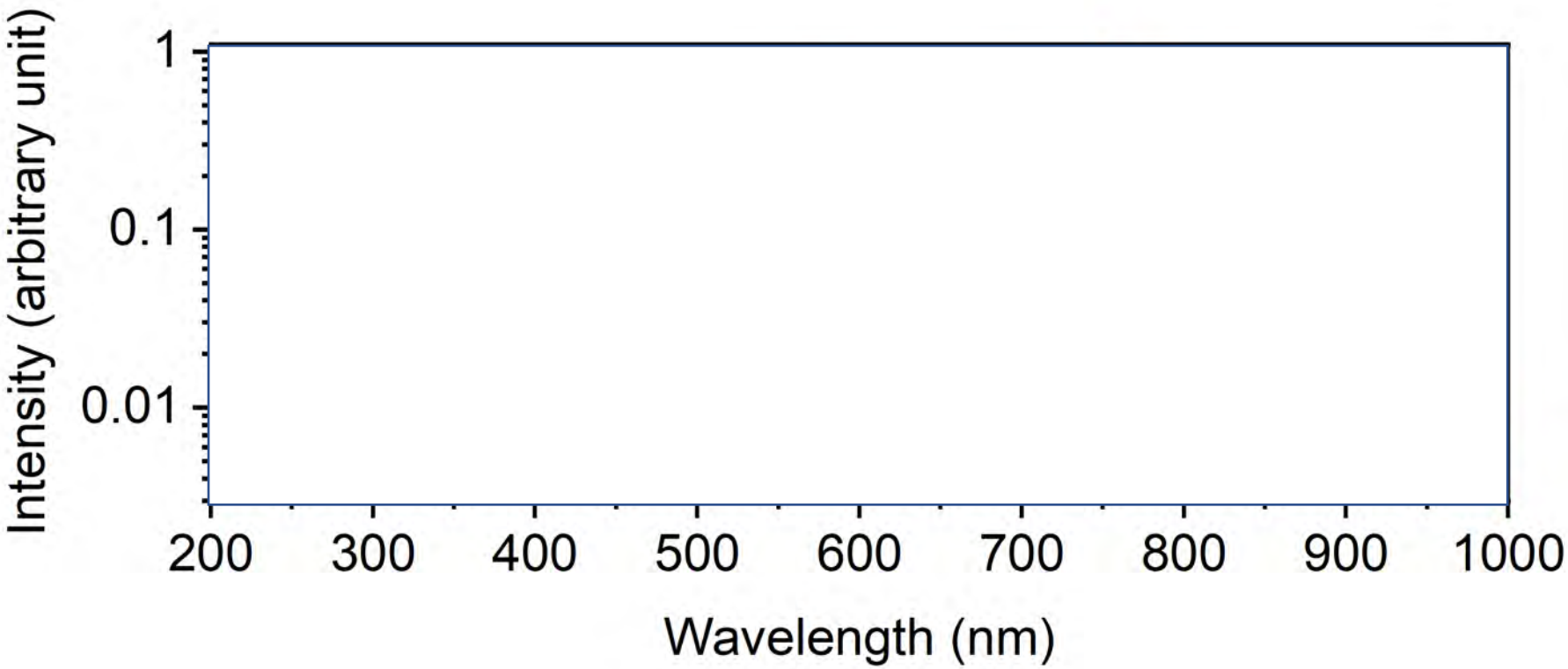


Power= 6 W

Pulse duration=15 fs

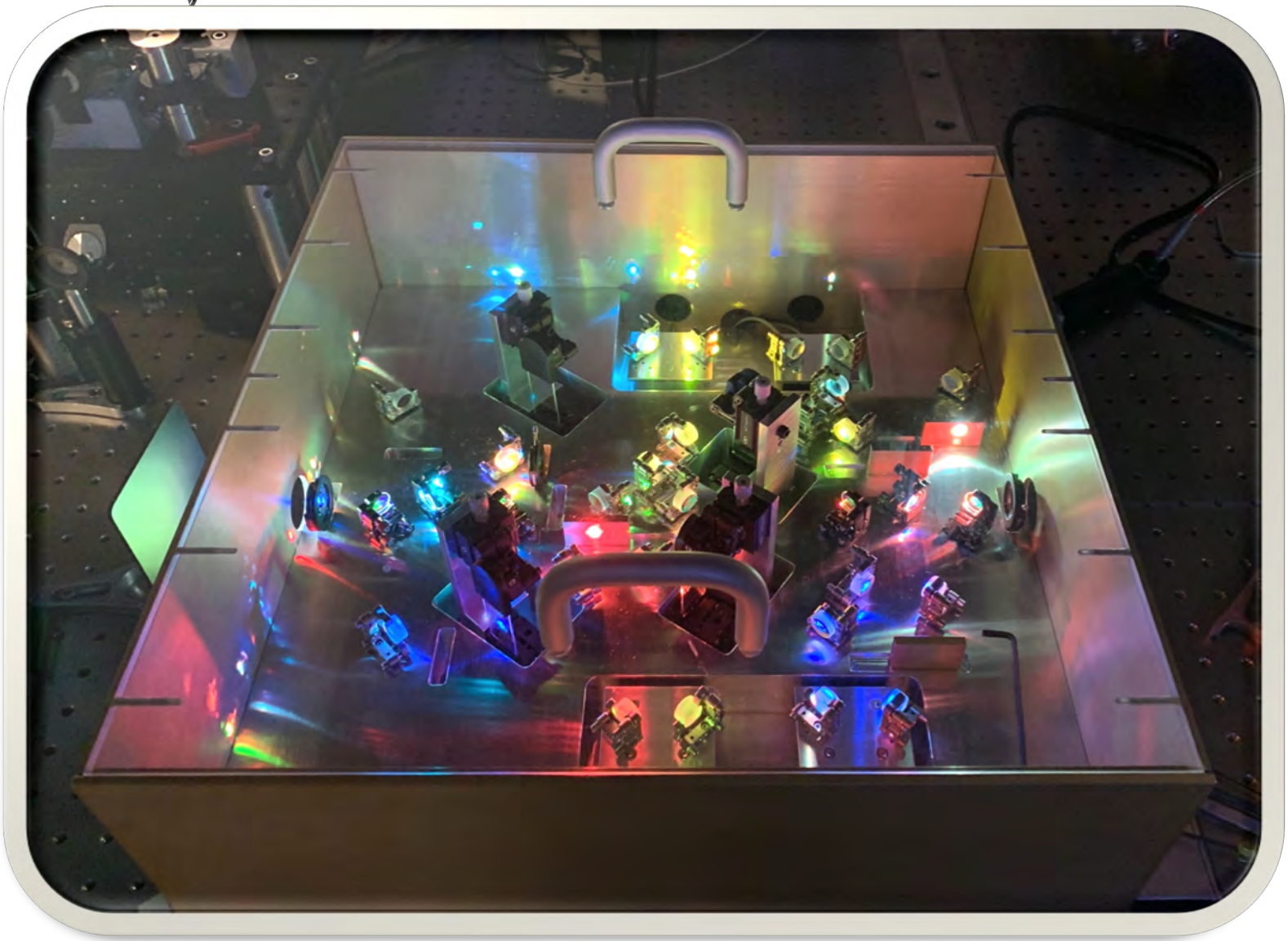


Generation 2-octves broadest supercontinuum



Attomicroscopy

Light Field Synthesizer in action

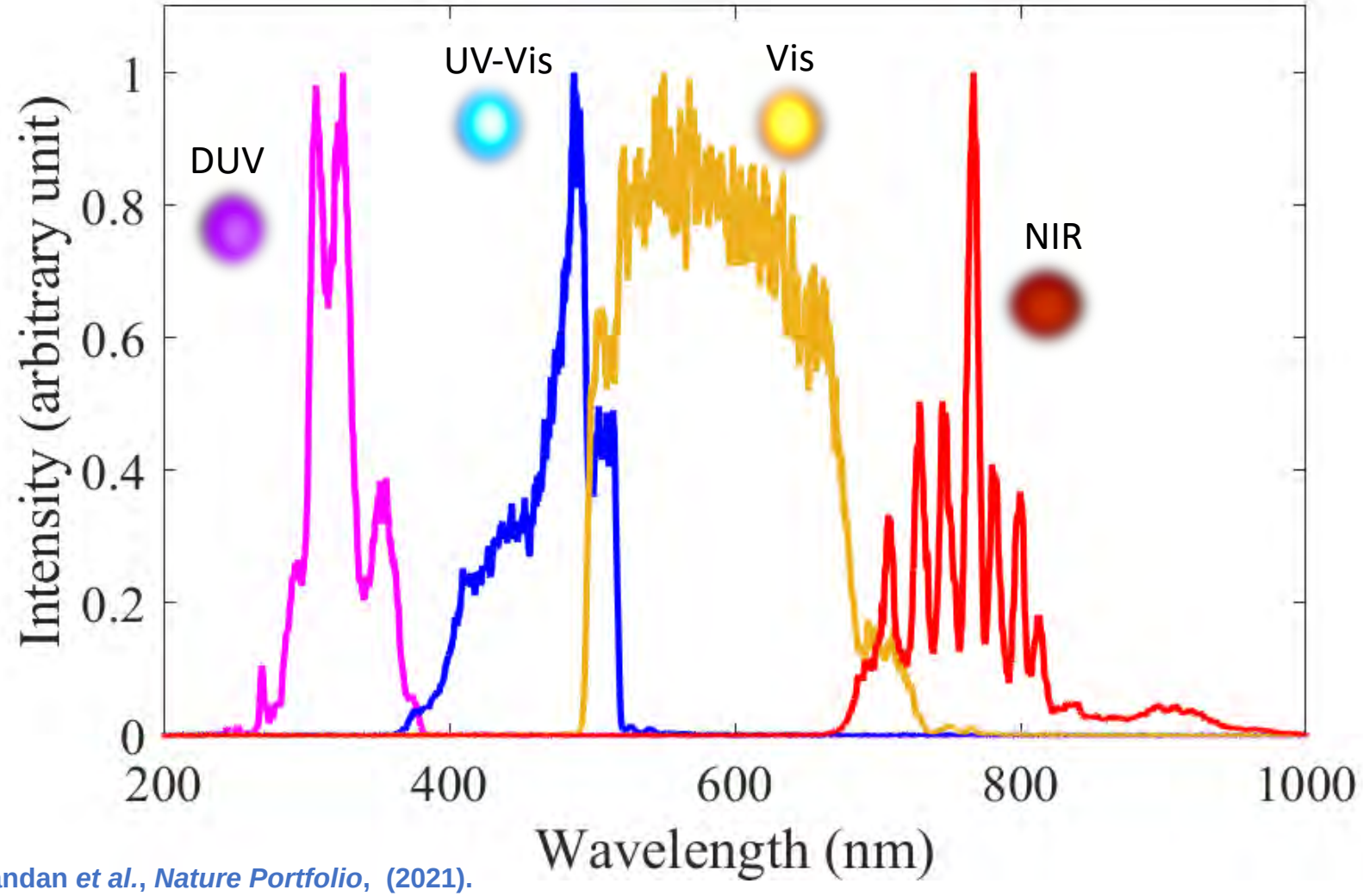


Attomicroscopy

Light Field synthesizer in action

M. Th. Hassan et al., **Nature,** 2016. **530** (7588)

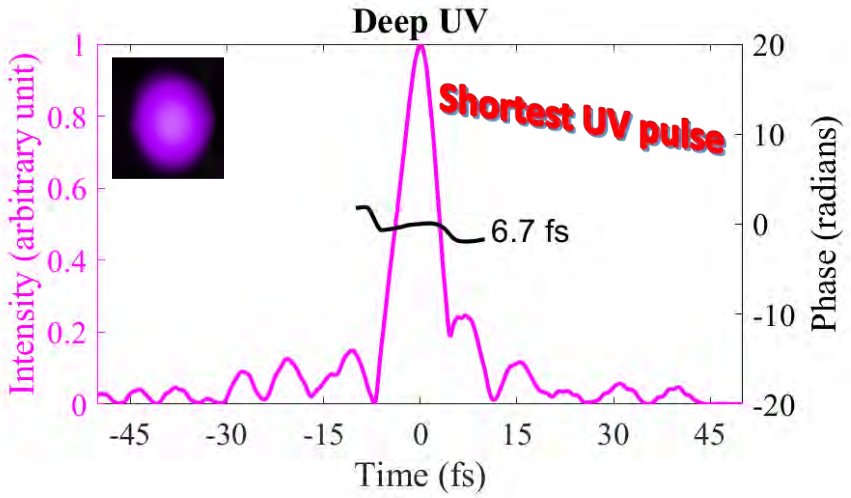
Light Field Synthesizer channels spectra

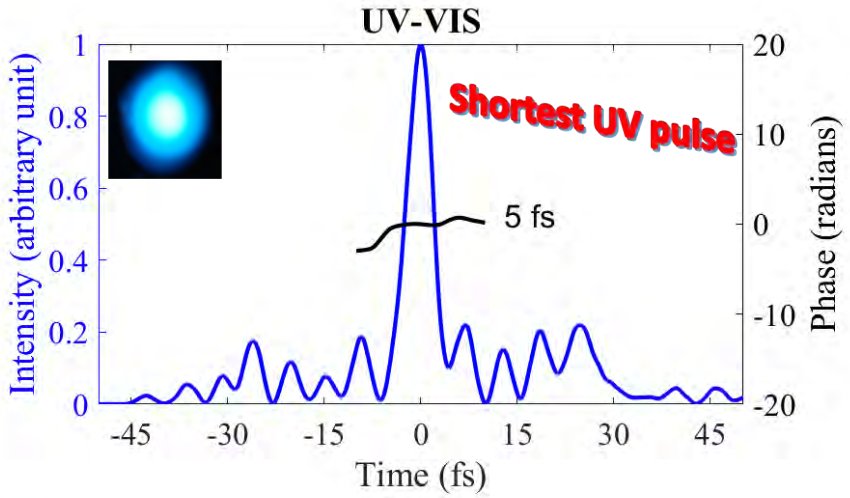


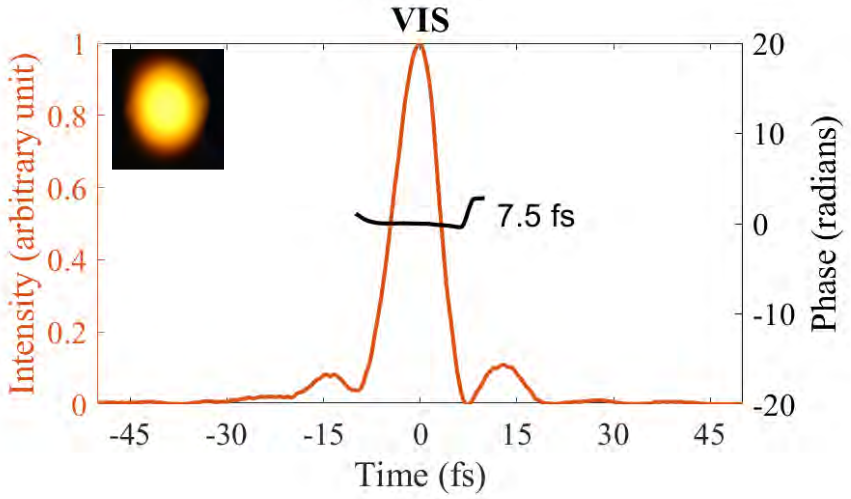
H. Dandan *et al.*, *Nature Portfolio*, (2021).

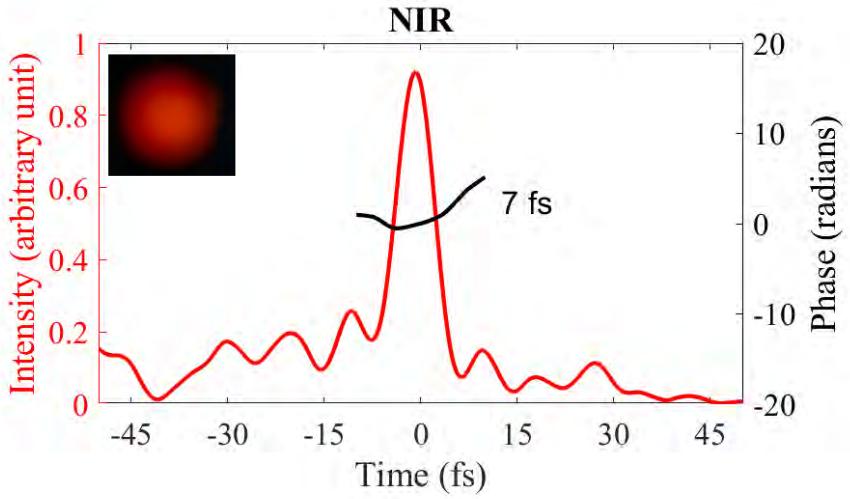
Attomicroscopy

Light Field Synthesizer channels pulse duration



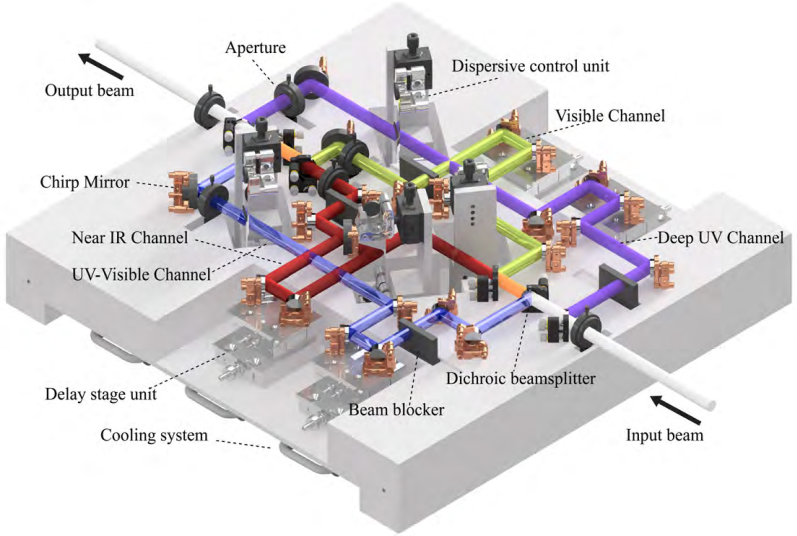


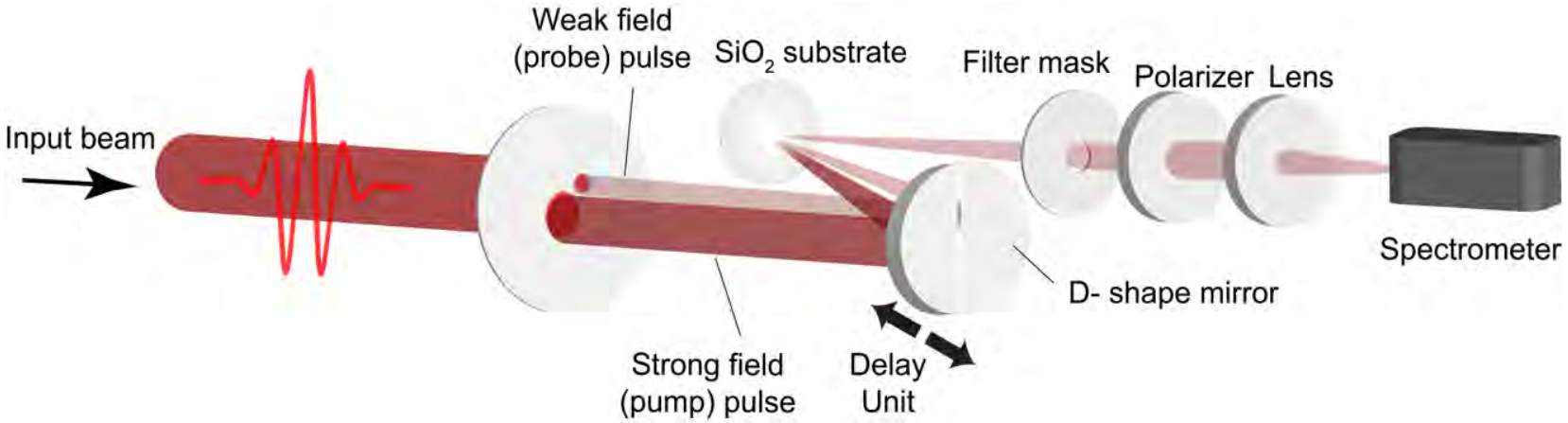




Attomicroscopy

All-Optical light field sampling



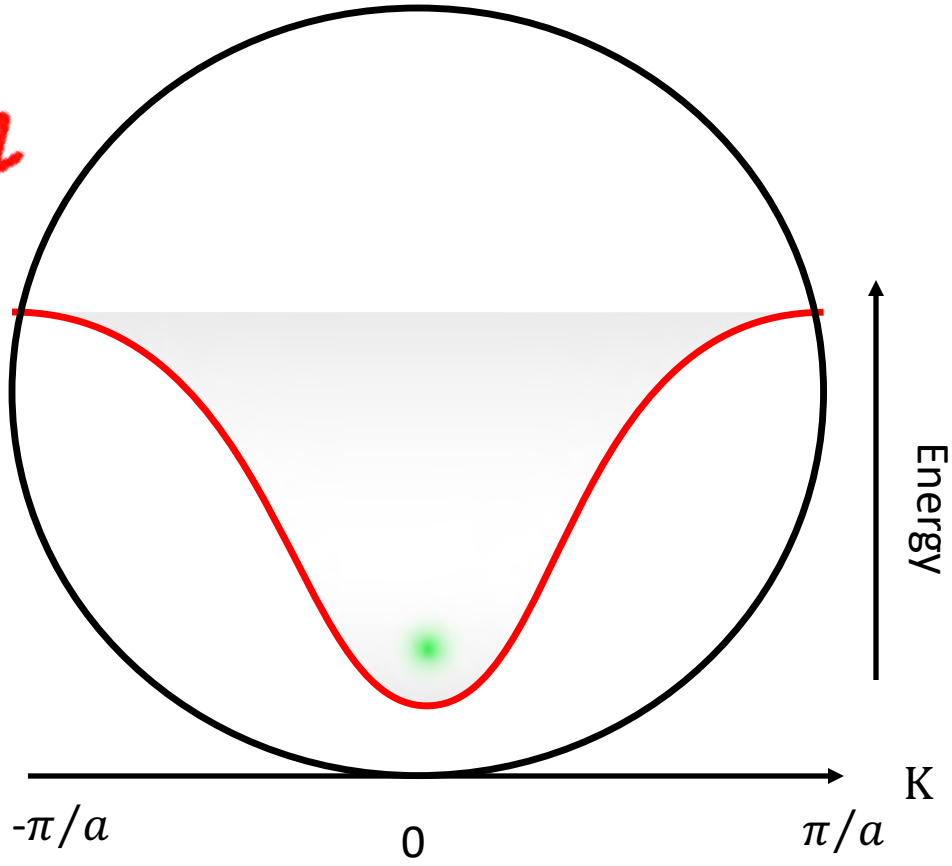


H. Dandan *et al.*, *Nature Portfolio*, (2021).

Dielectric in Strong Ultrafast Optical Field

For more details please read Apalkov V & Stockman MI (2012) Theory of dielectric nanofilms in strong ultrafast optical fields. Physical Review B 86(16):165118.

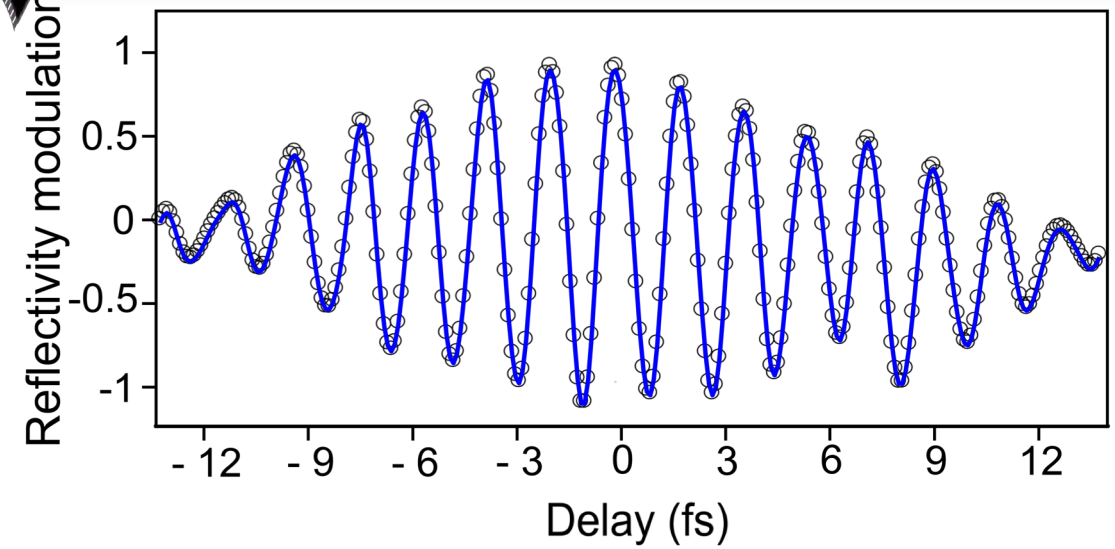
The motion of an electron with 1D wave vector *k*, pointing along the direction of electric field, is described by the following equation



Schiffrin, A. *et al*. *Nature* **493**, 70, (2013).

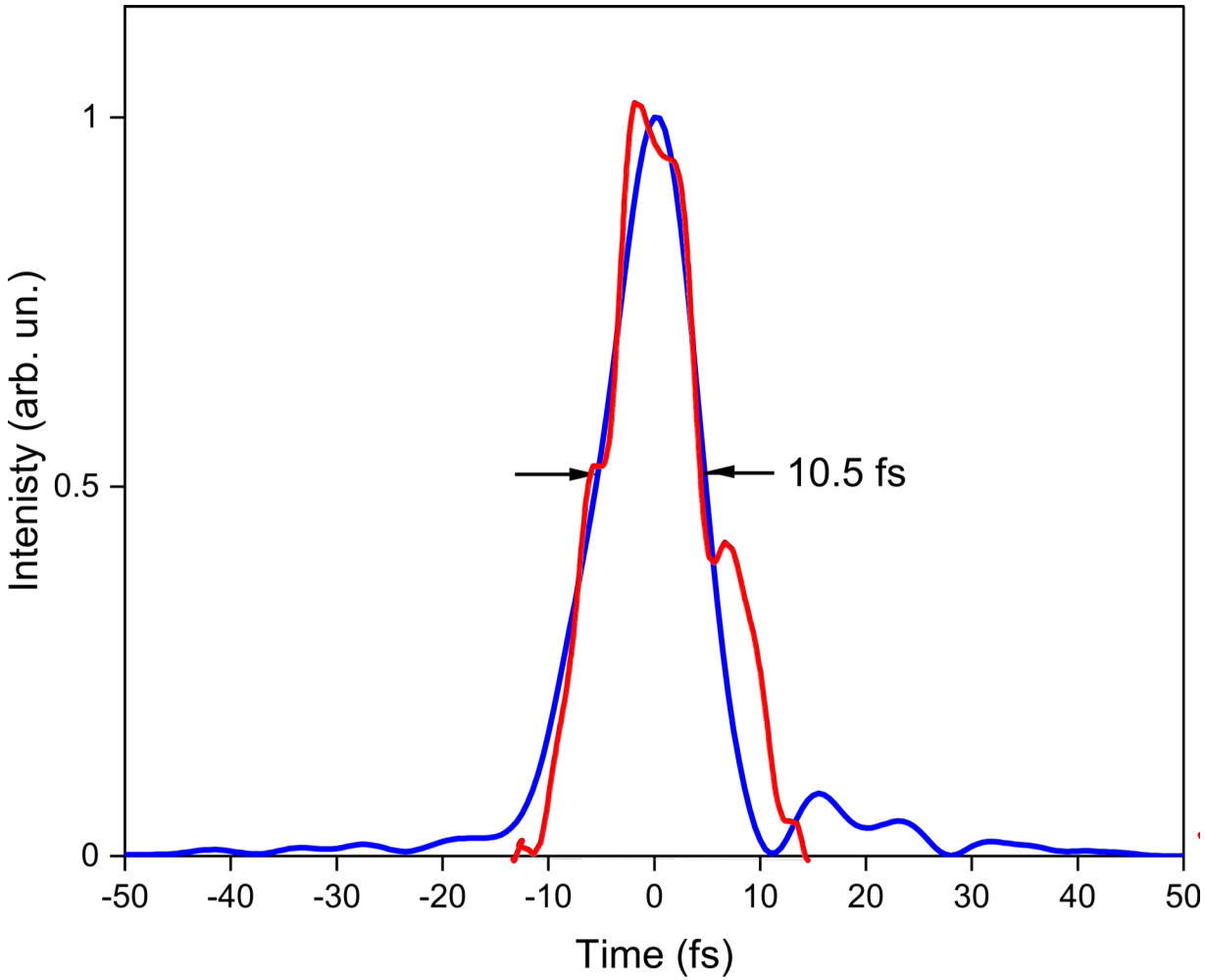
Attomicroscopy

All-Optical light field sampling



H. Dandan *et al.*, *Nature Portfolio*, (2021).

All-Optical light field sampling



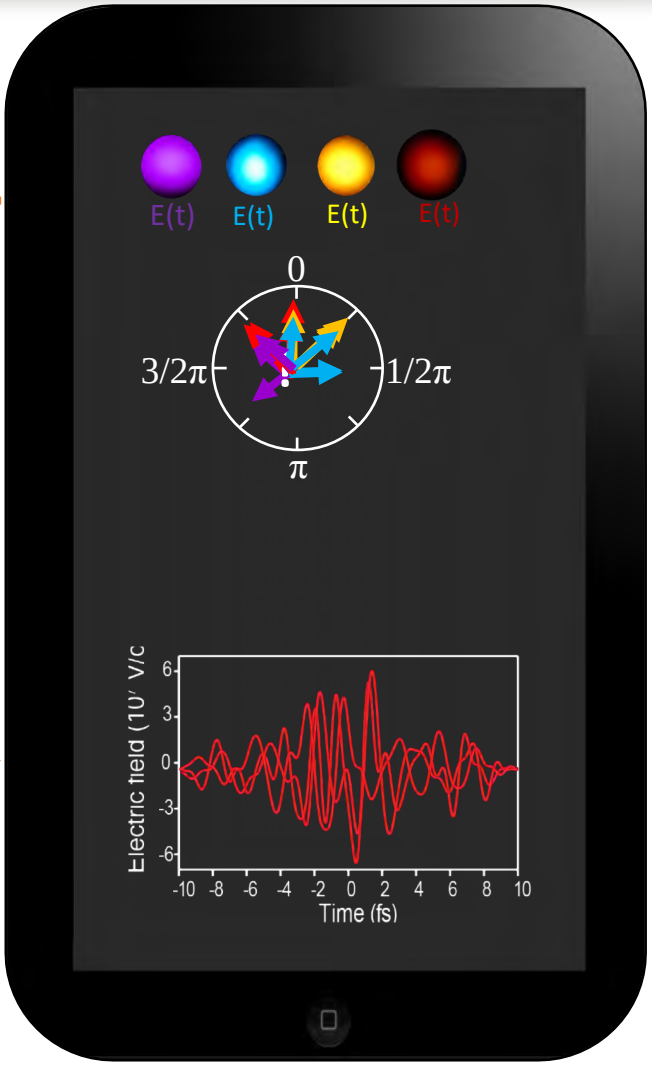
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Attomicroscopy

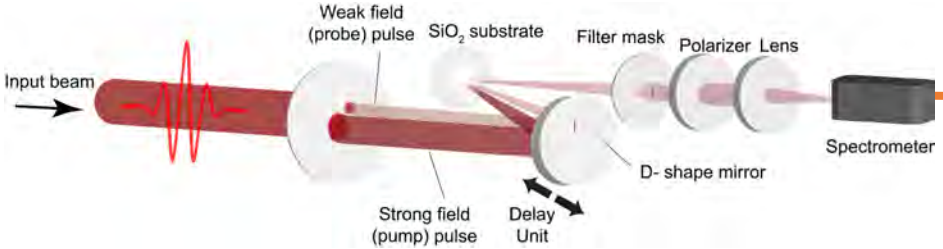
Attosecond Synthesis of Light Fields

Field Synthesis

Feedback



Measurement



Analysis

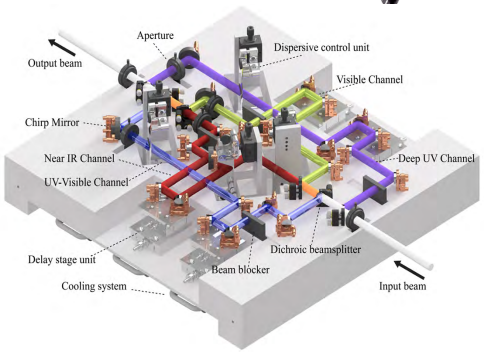
M. Th. Hassan et al.,Rev. Sci. Instrum. 83, 111301 (2012).

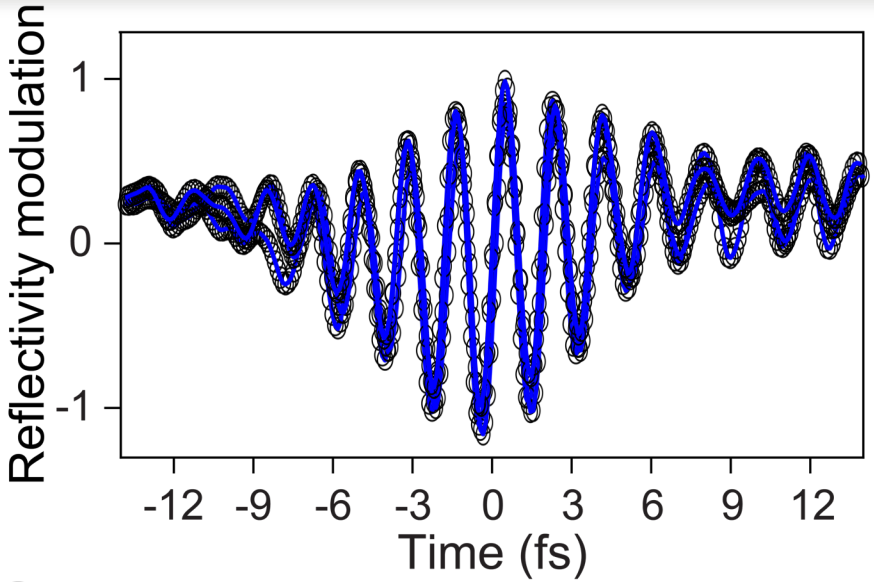
M. Th. Hassan et al., Nature 530 (7588): 66-70 (2016)

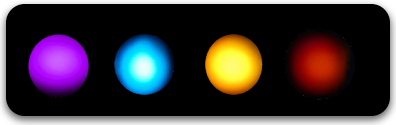
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Attomicroscopy

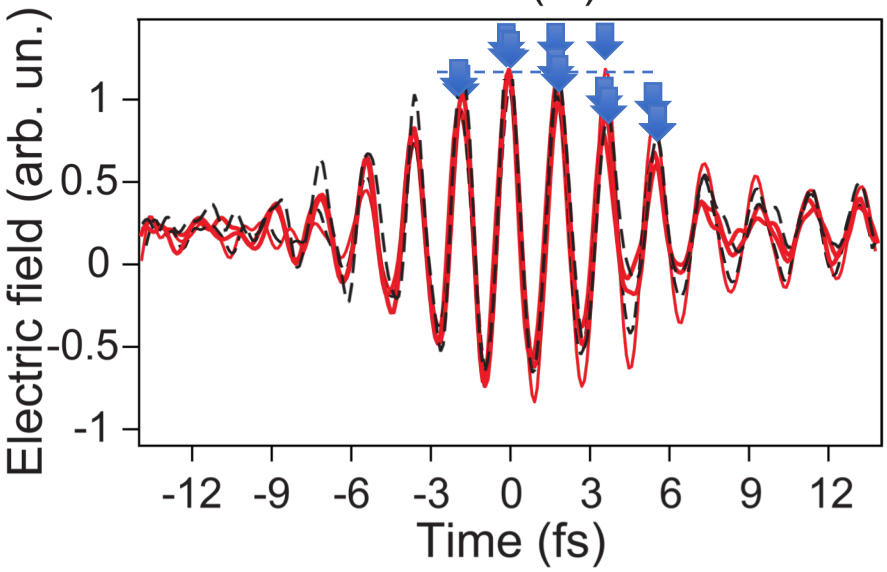
All-Optical light field sampling





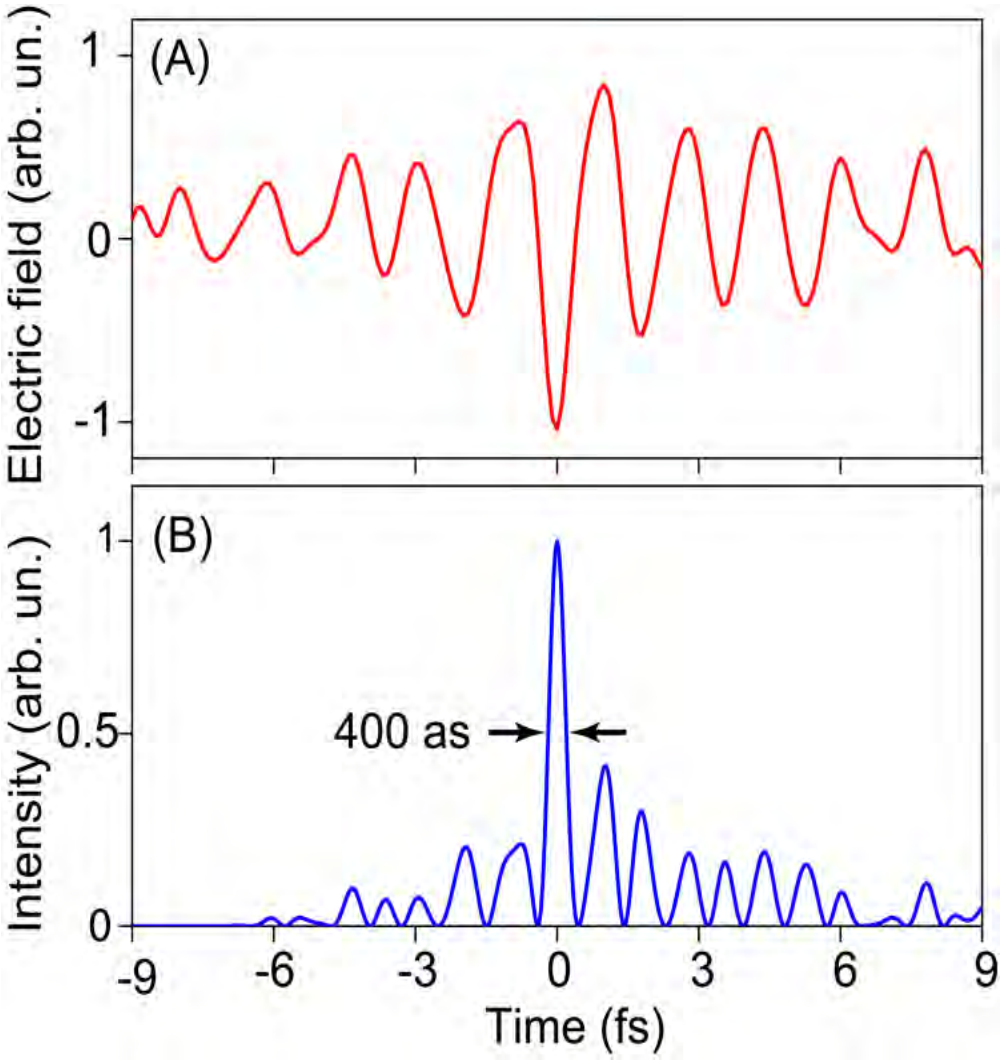


-2fs -2fs



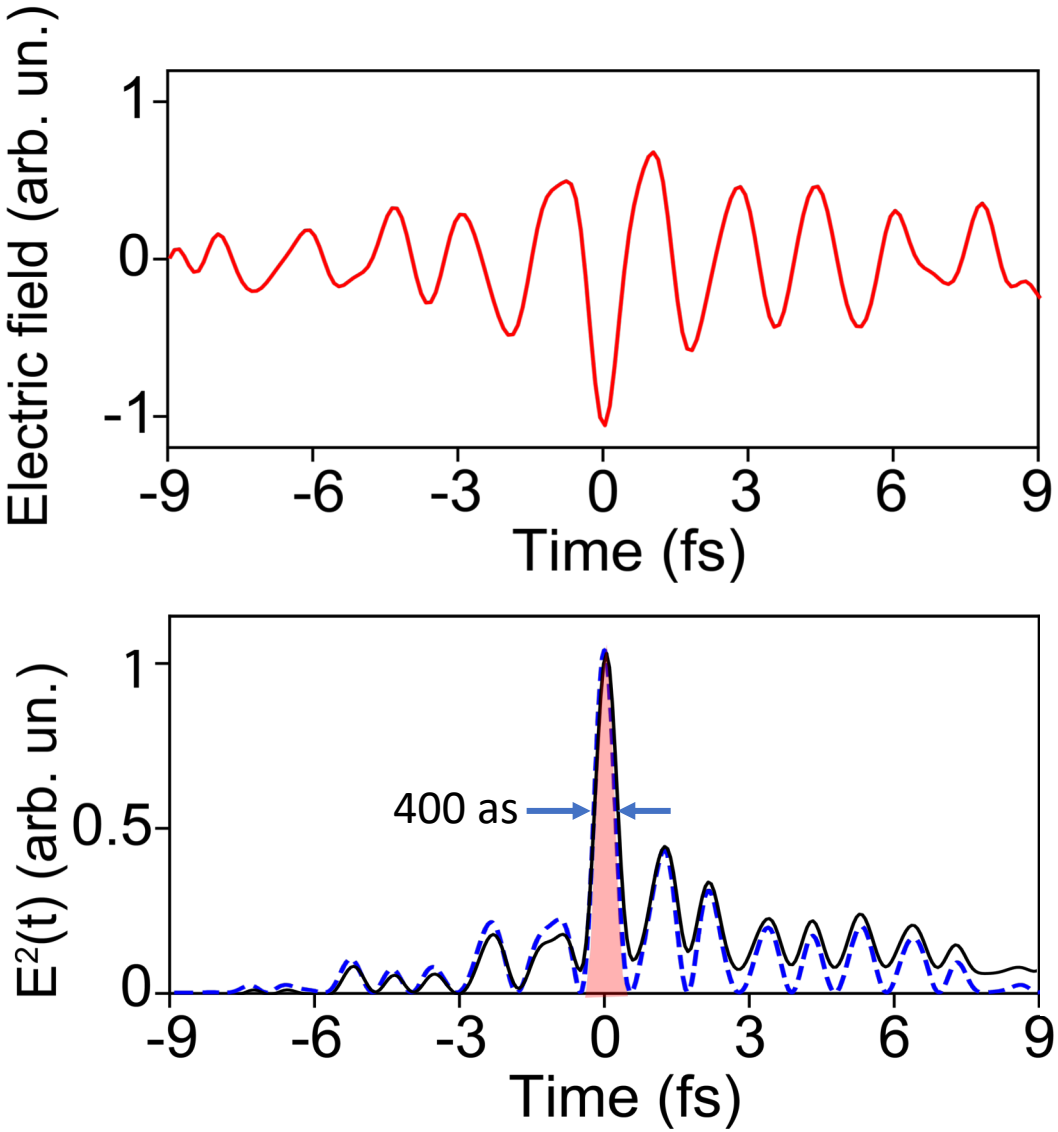
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Optical attosecond pulses



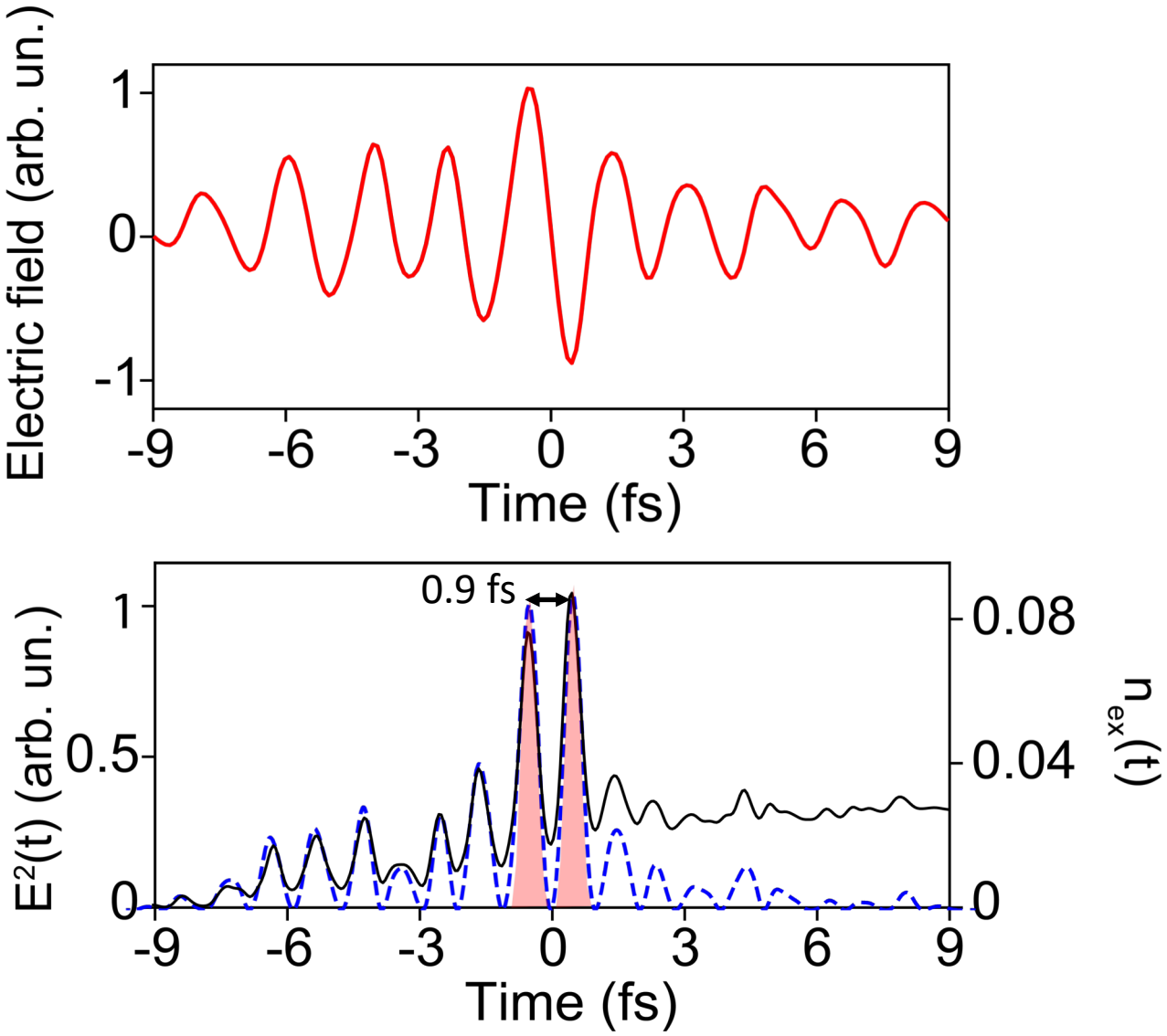
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Quantum control of electron motion in dielectric



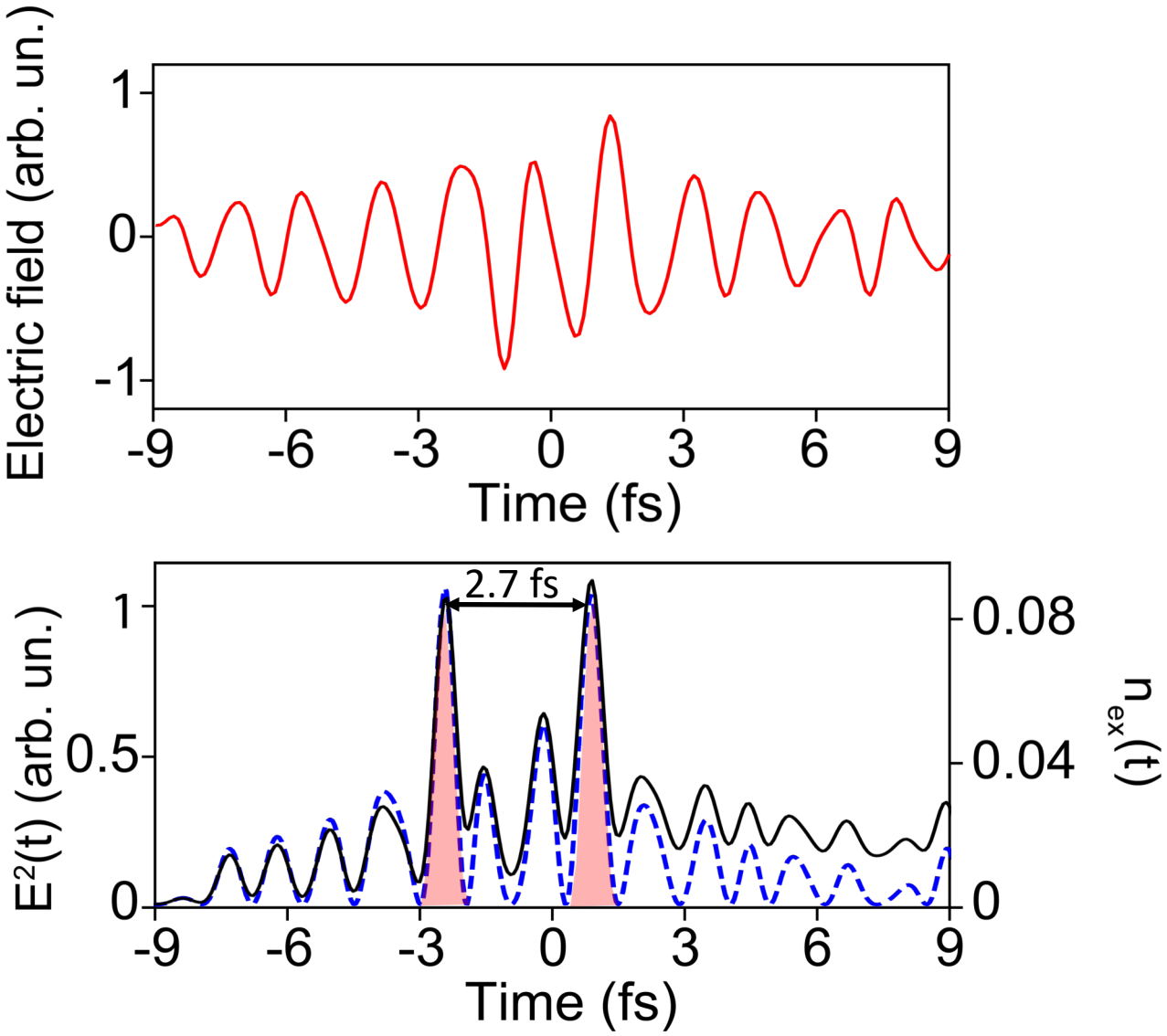
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Quantum control of electron motion in dielectric



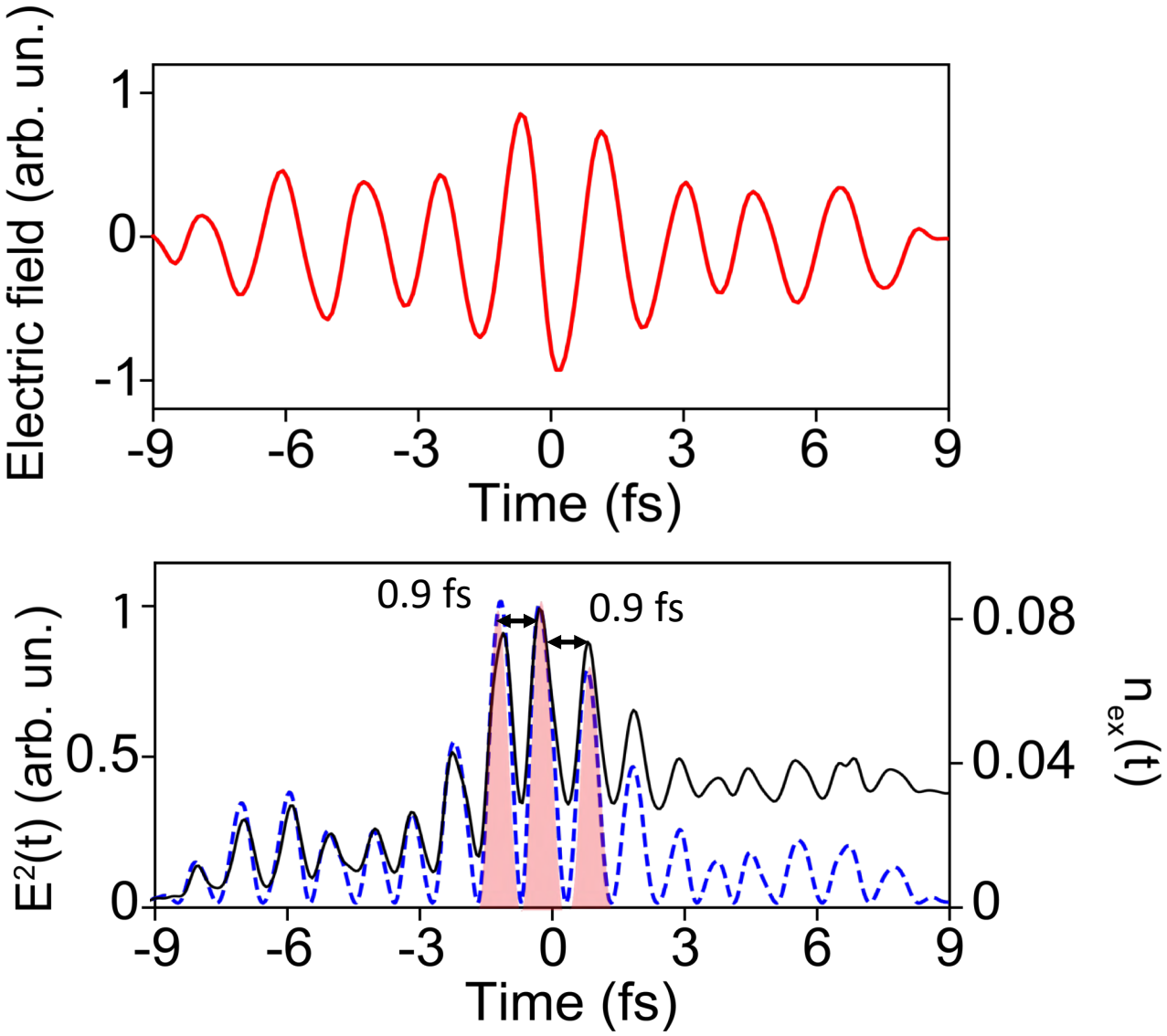
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Quantum control of electron motion in dielectric



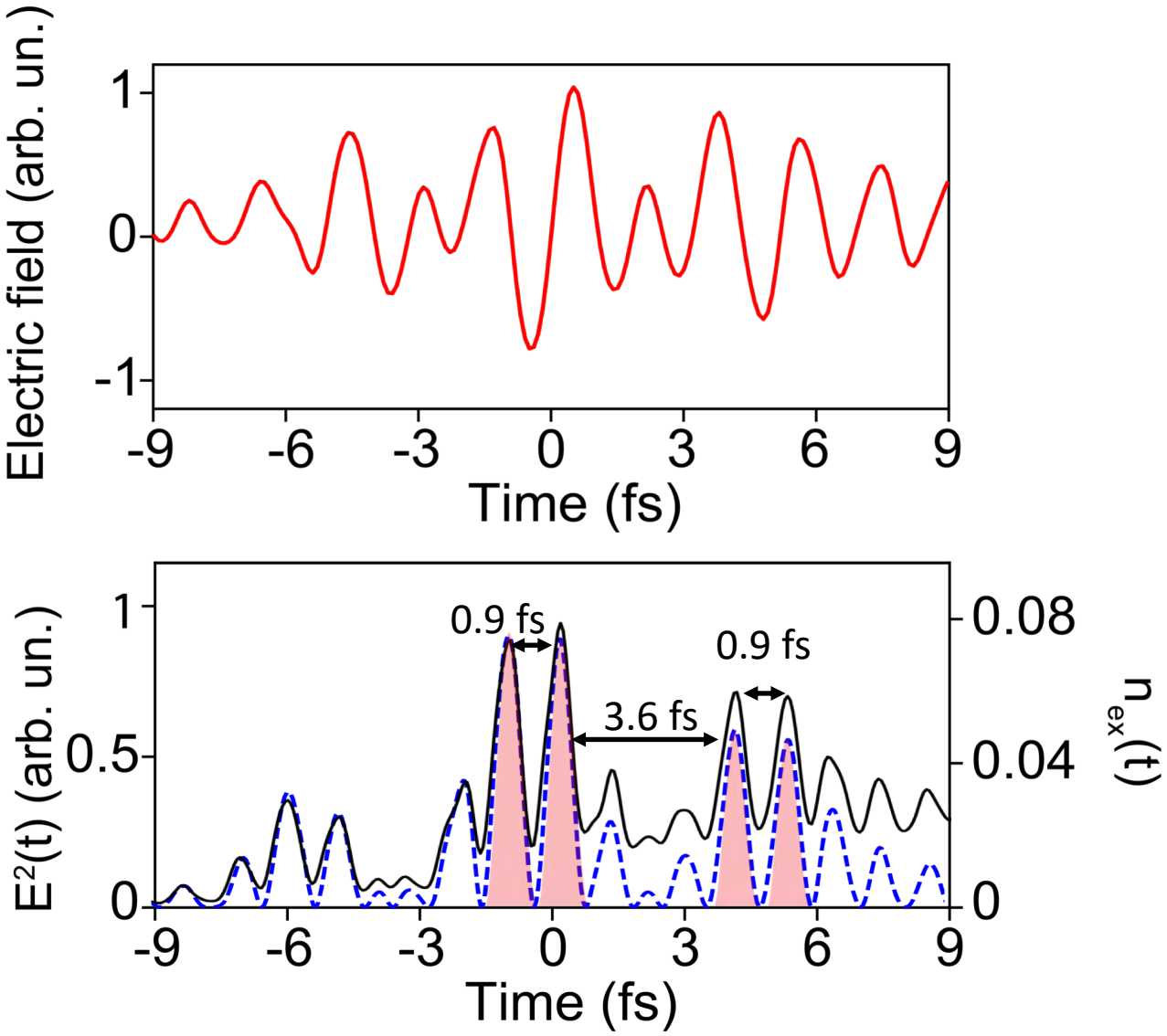
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Quantum control of electron motion in dielectric



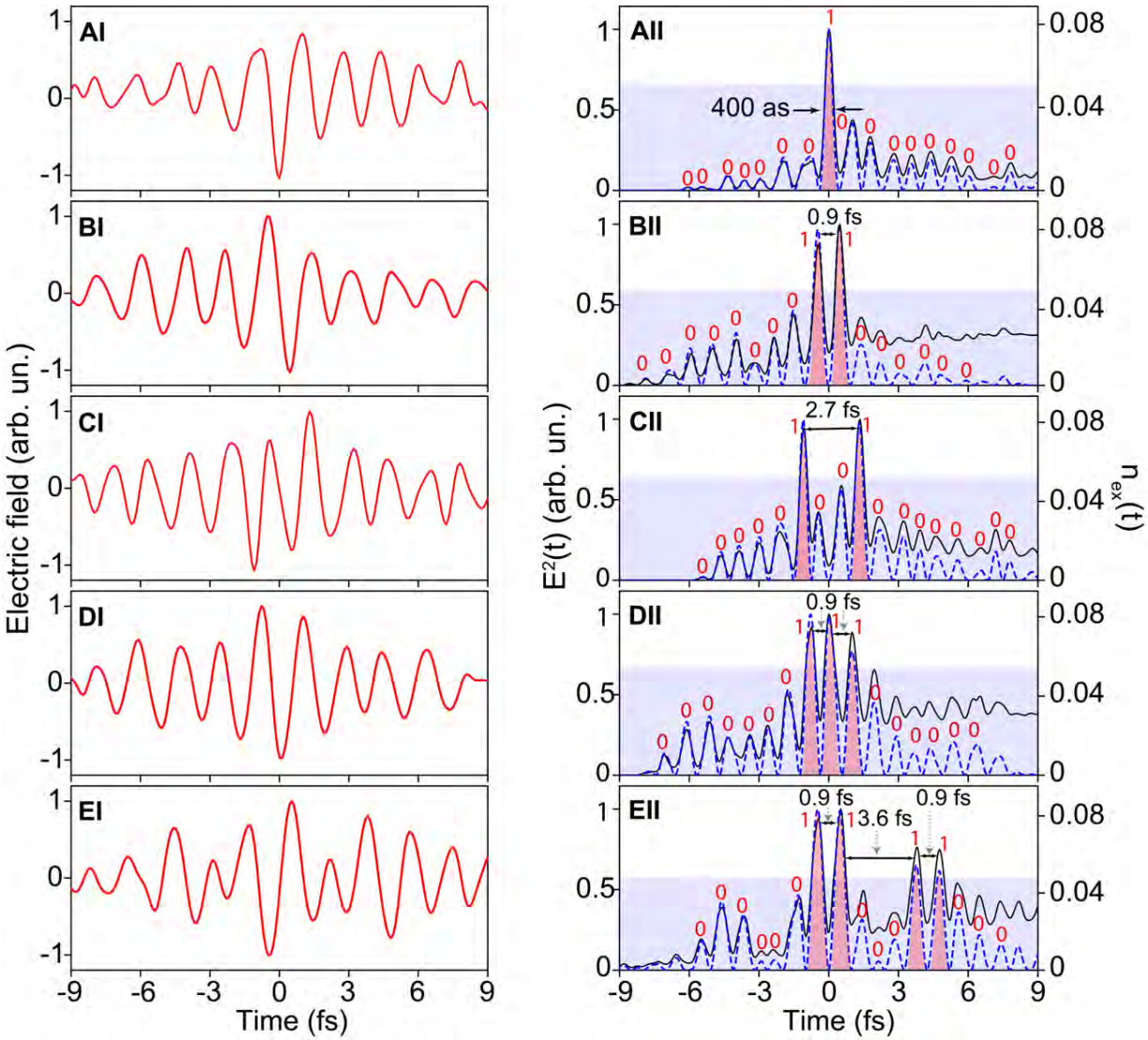
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Quantum control of electron motion in dielectric



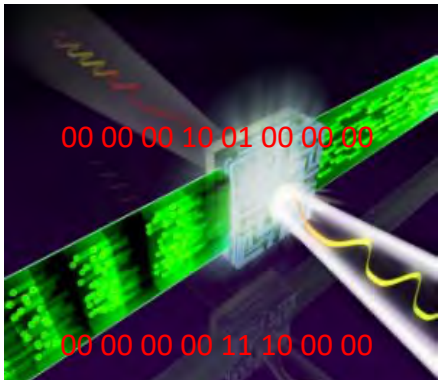
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Quantum electronics
Petahertz Optical Switch and Transistor



00 00 00 01 00 00 00 00

00 00 00 00 11 00 00 00

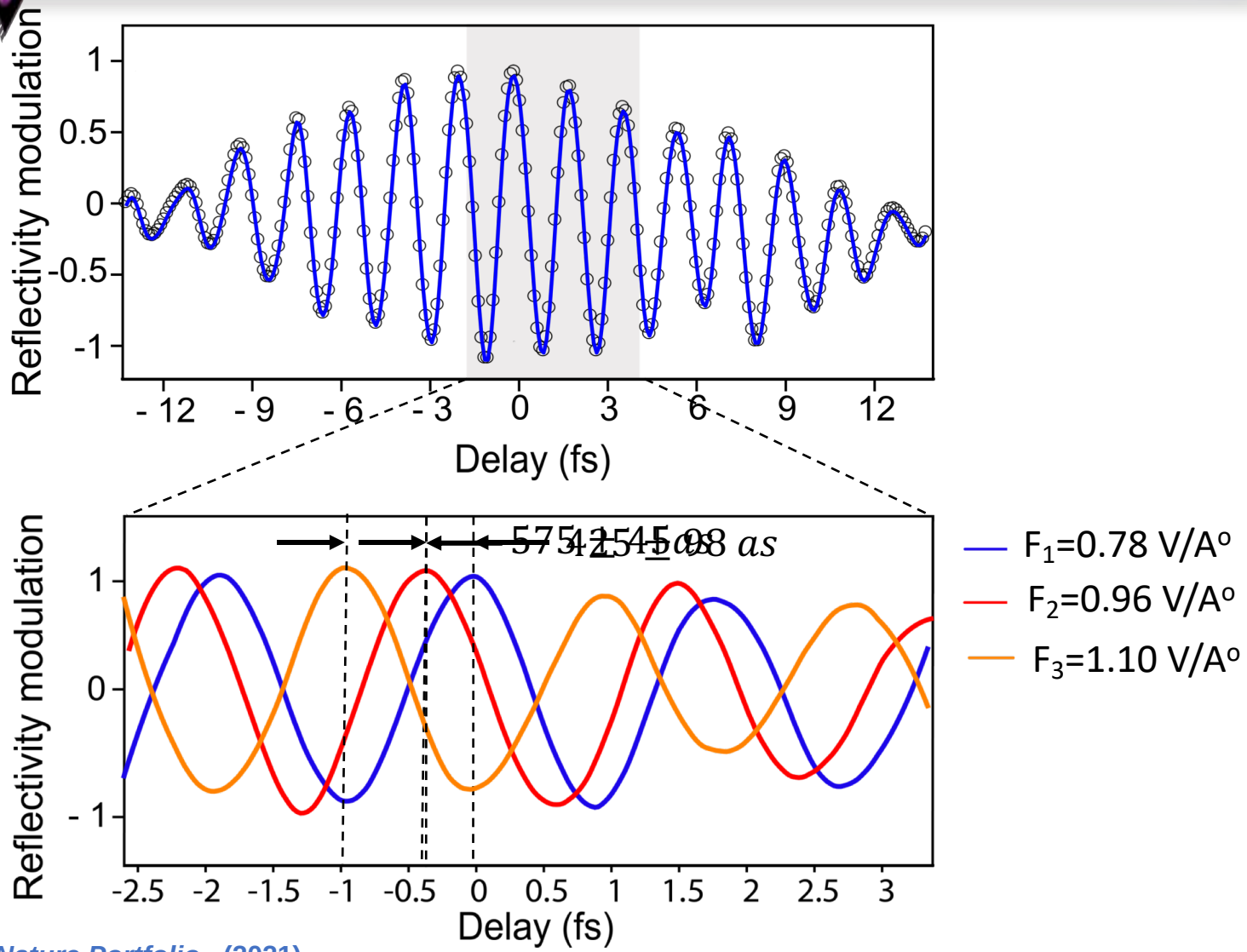


Nature Photon **8,** 214–218 (2014)

00 00 00 11 00 01 10 00

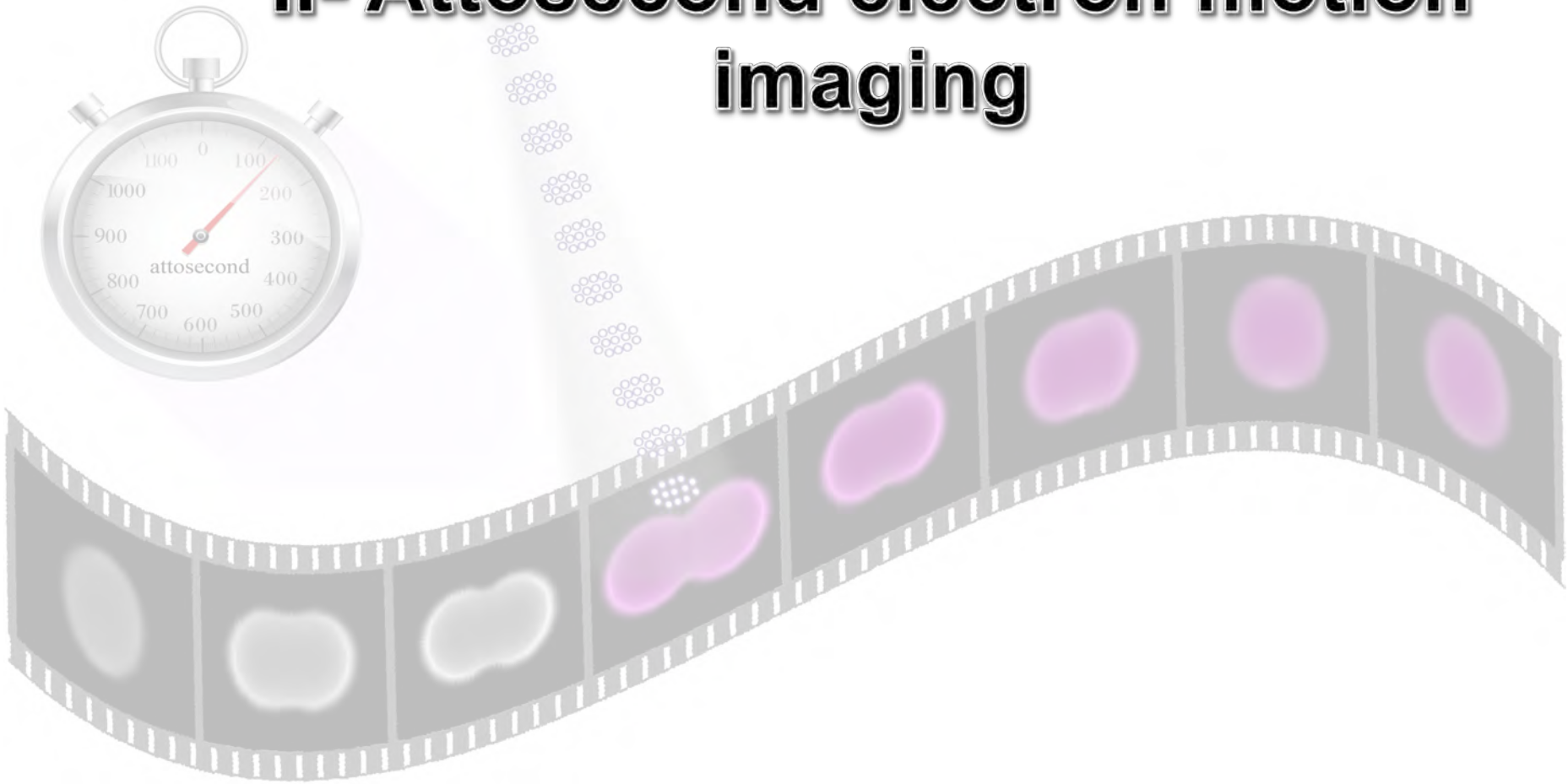
H. Dandan *et al.*, *Nature Portfolio*, (2021).

Attosecond electronic delay response in dielectric



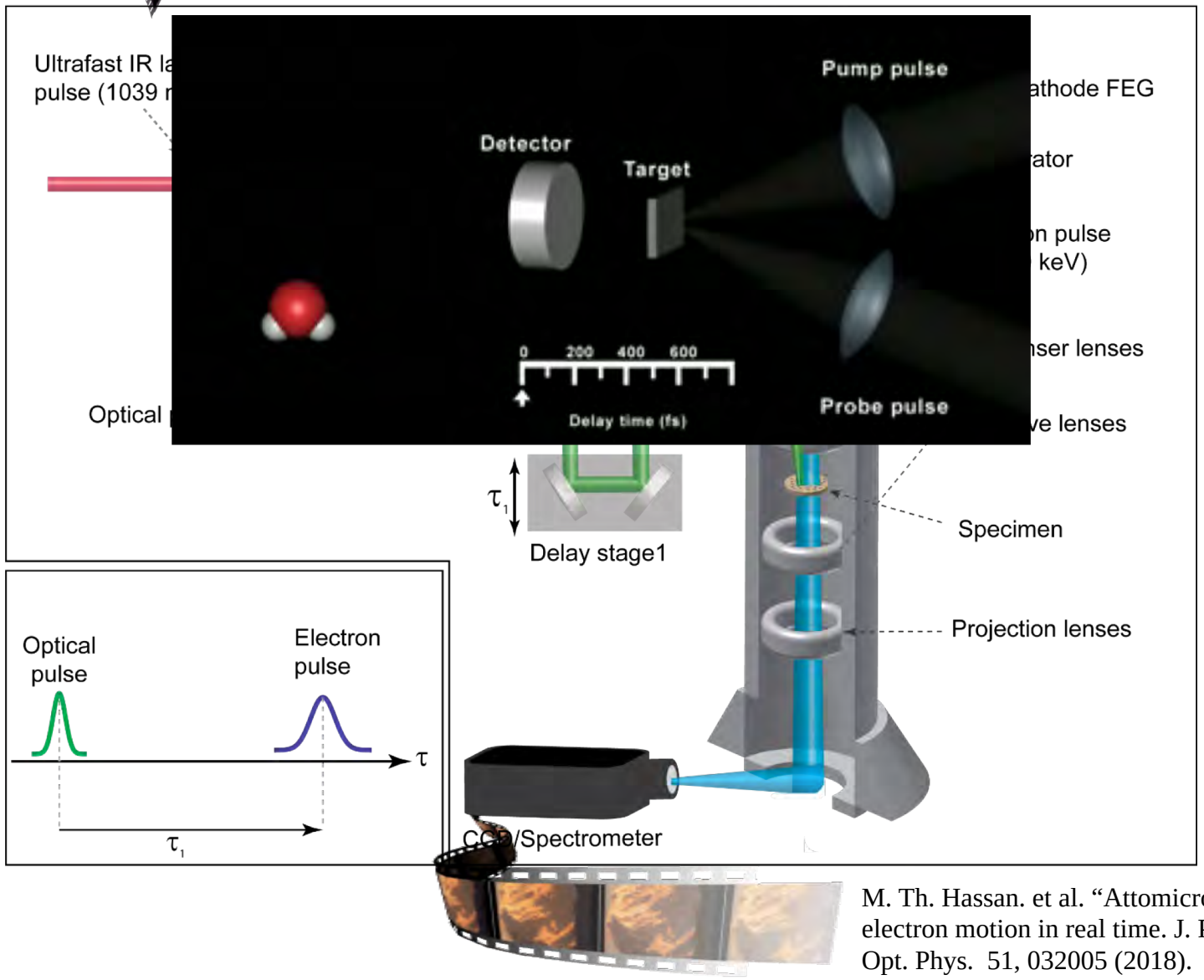
H. Dandan *et al.*, *Nature Portfolio*, (2021).

II- Attosecond electron motion imaging



Attosecond Electron Diffraction and Microscopy “Attomicroscopy”

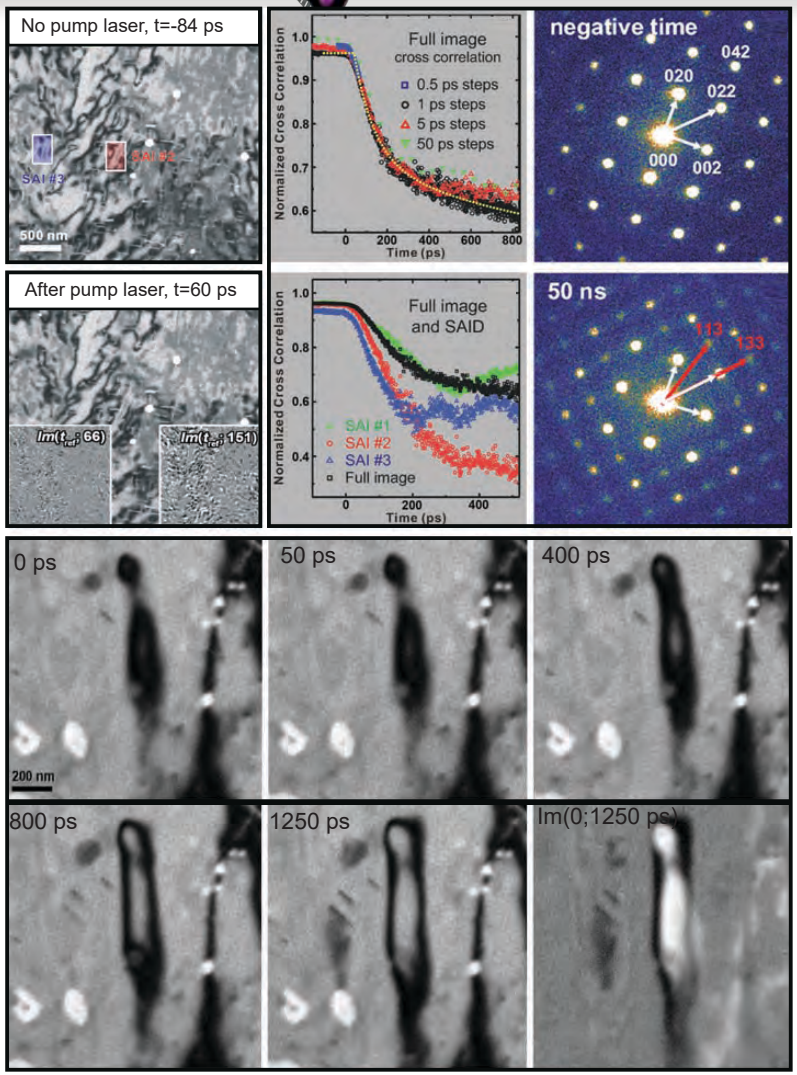
Ultrafast Electron Microscopy

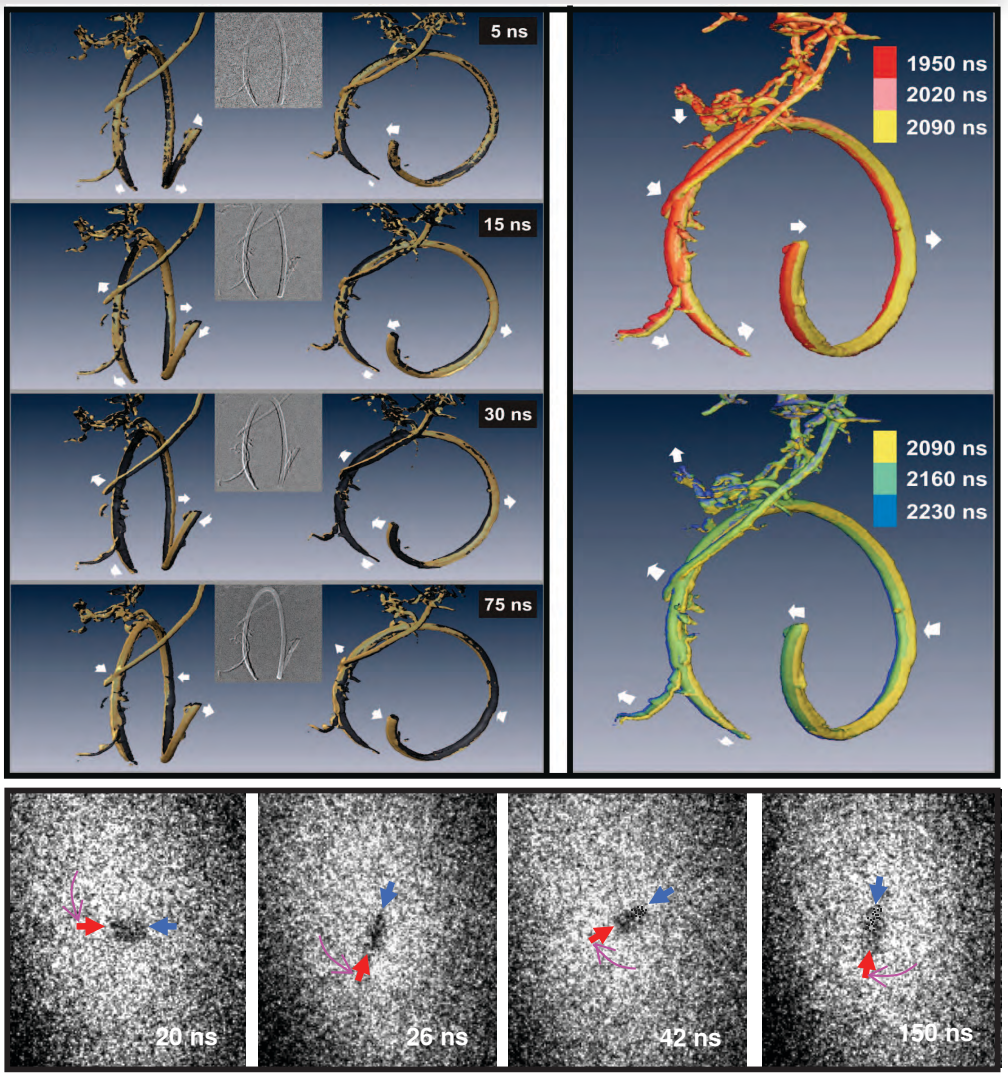


M. Th. Hassan. et al. "Attomicroscopy: imaging the electron motion in real time. J. Phys. B: At. Mol. Opt. Phys. 51, 032005 (2018).

Attomicroscopy

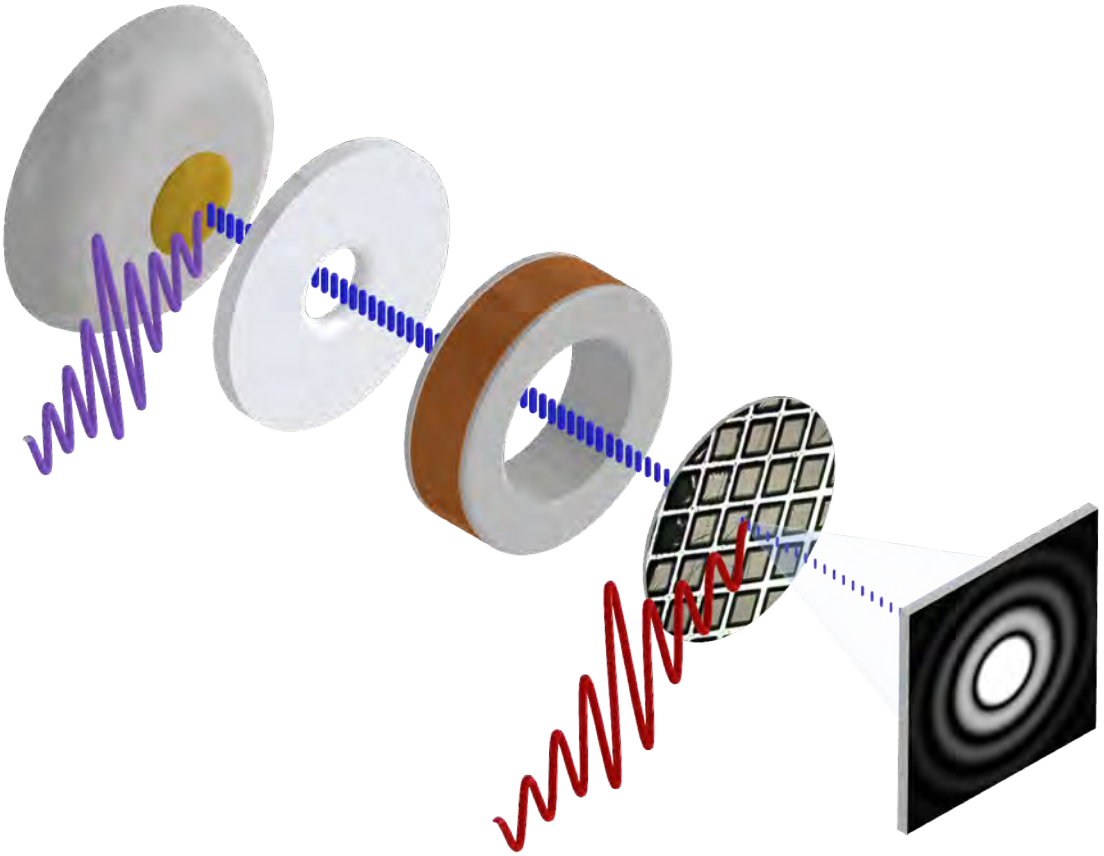
Ultrafast Electron Microscopy (UEM) Applications





M. T. Hassan, Attomicroscopy: from femtosecond to attosecond electron microscopy. *J. Phys. B: At. Mol. Opt. Phys.* 51, 032005 (2018).

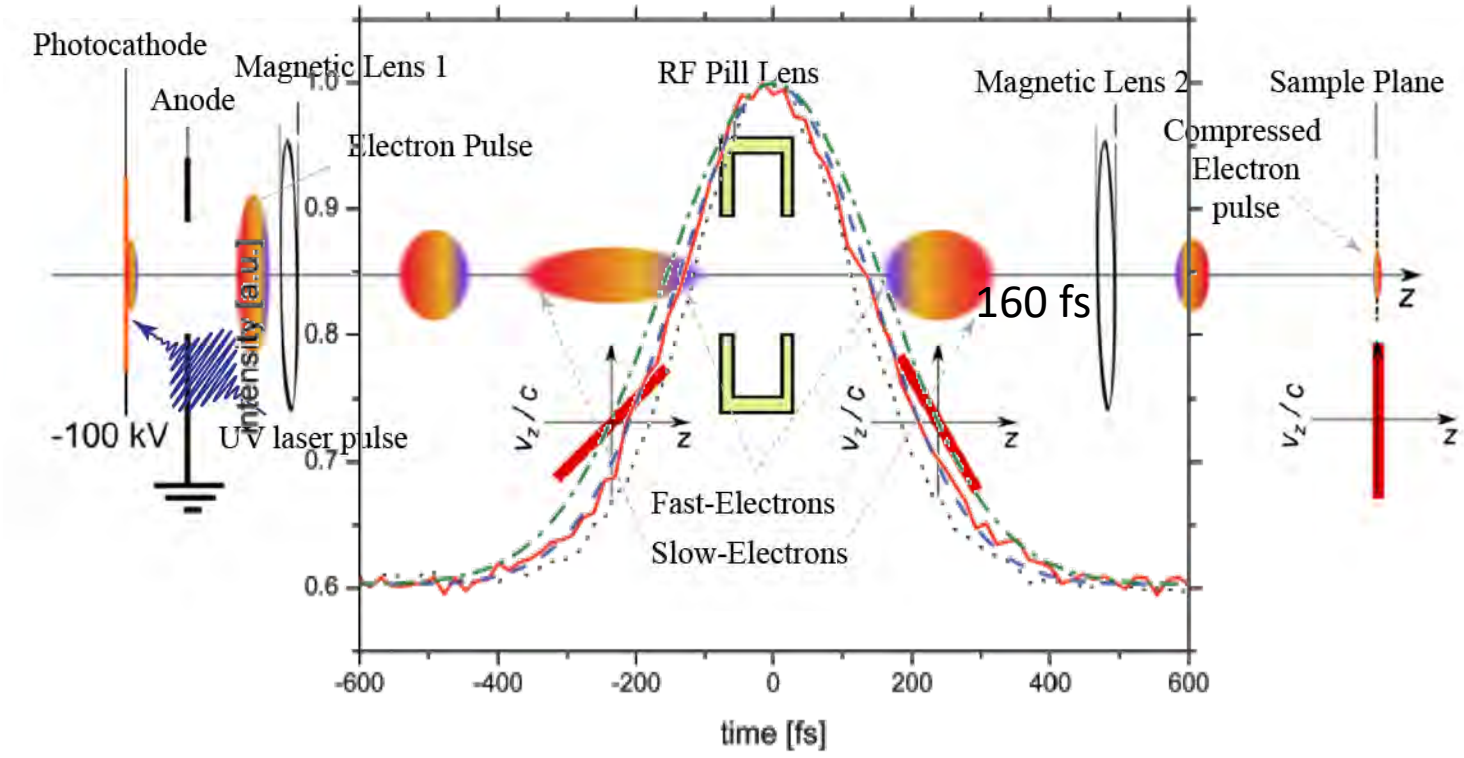
Ultrafast Electron Diffraction (UED)



M. T. Hassan, Attomicroscopy: from femtosecond to attosecond electron microscopy. *J. Phys. B: At. Mol. Opt. Phys.* 51, 032005 (2018).

Electron Pulse compression in Ultrafast Electron Diffraction

RF compression scheme of ultrafast electron pulse



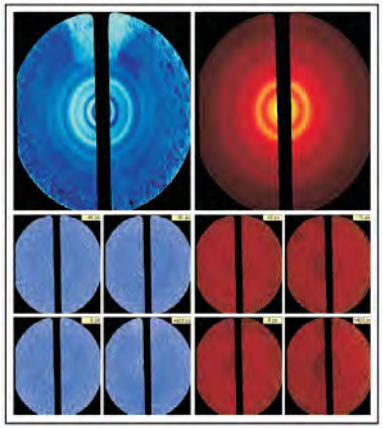
PRL 105, 264801 (2010)

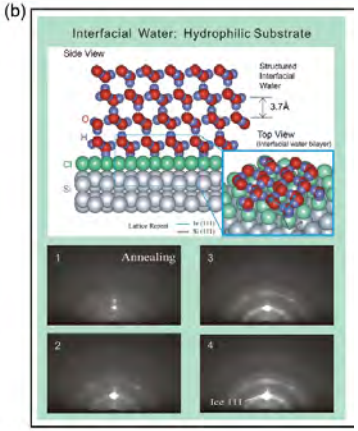
Sciaini G and Miller R D 2011, Rep. Prog. Phys. 74 096101

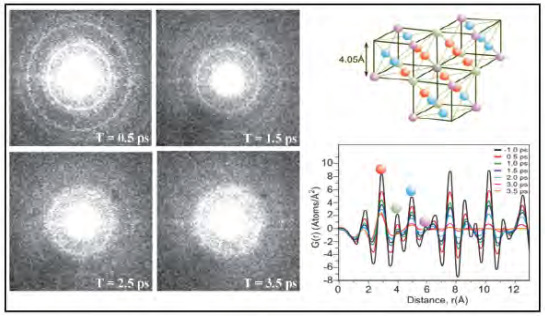
M. T. Hassan, Attomicroscopy: from femtosecond to attosecond electron microscopy. *J. Phys. B: At. Mol. Opt. Phys.* 51, 032005 (2018).

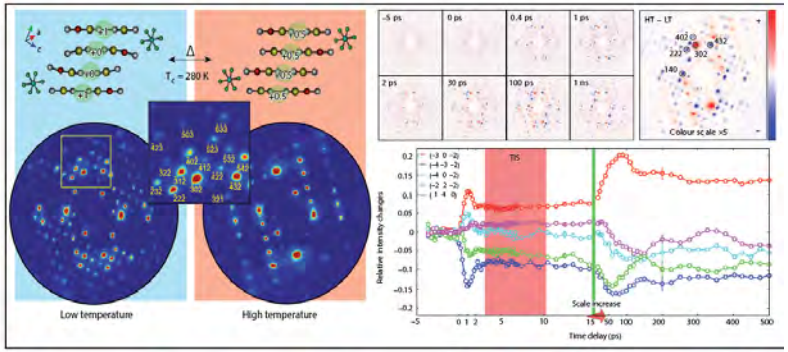
Attomicroscopy

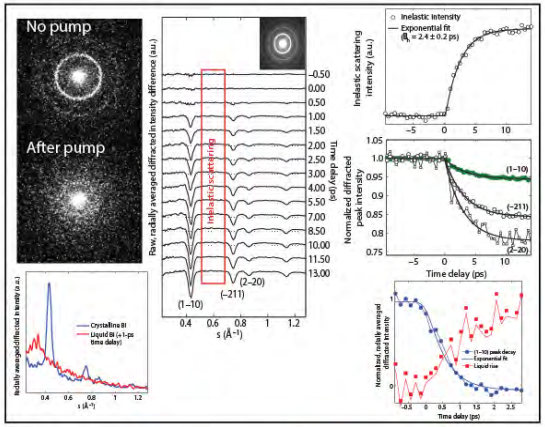
Ultrafast Electron Diffraction applications

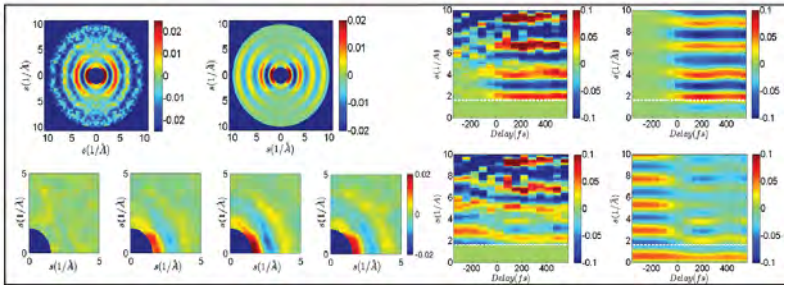


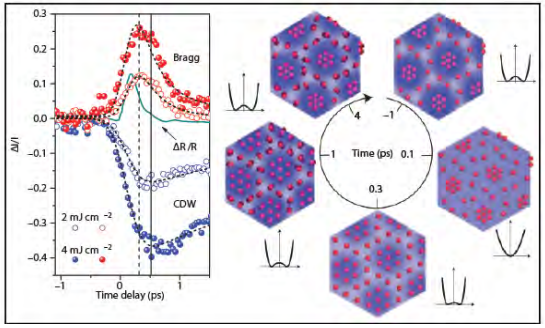


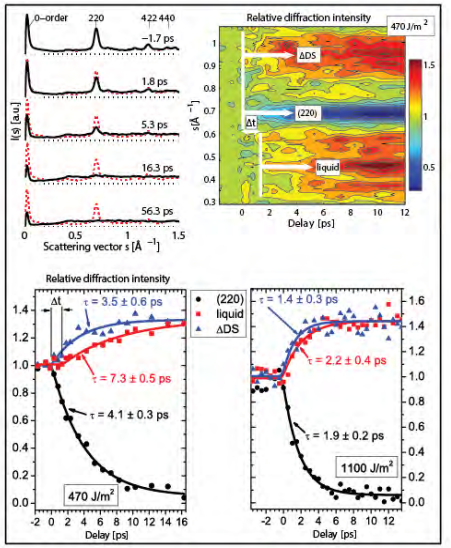


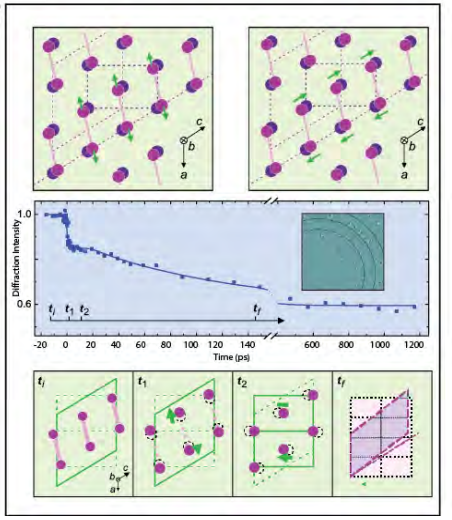






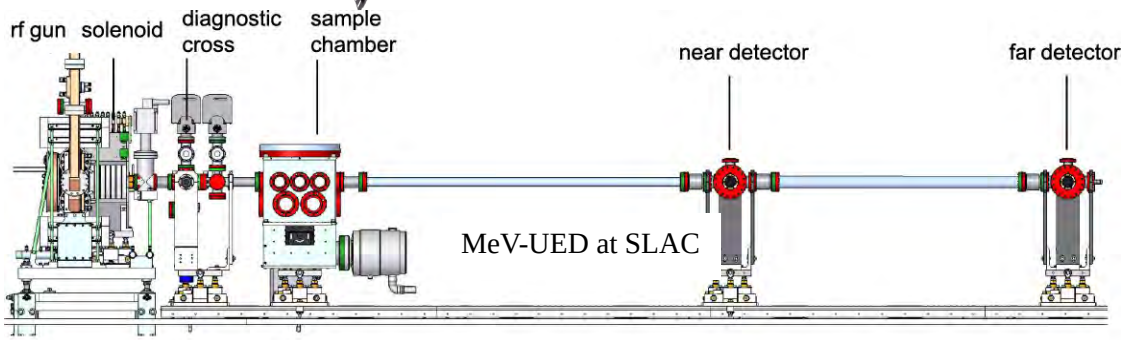


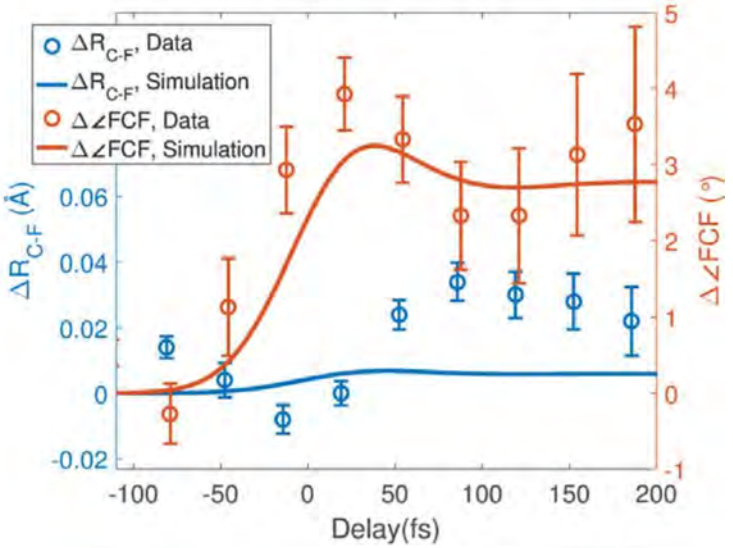


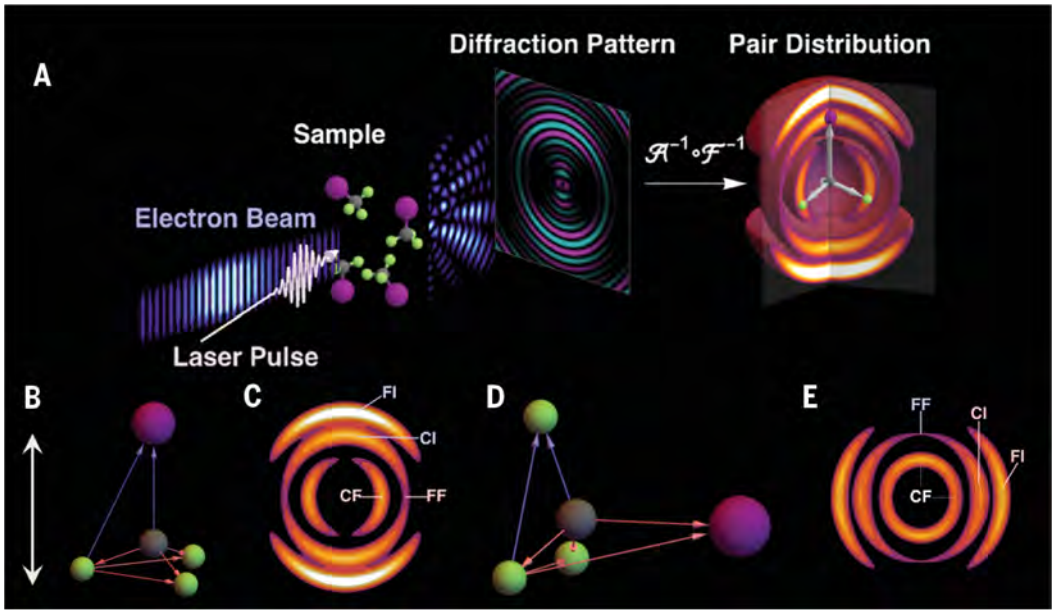


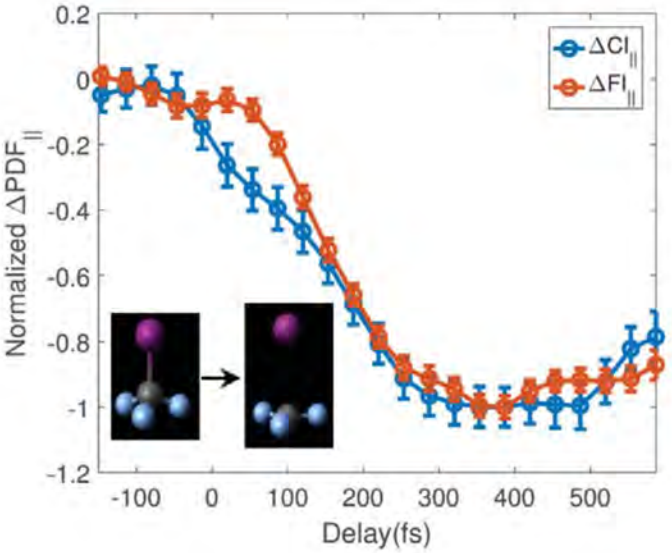
M. T. Hassan, Attomicroscopy: from femtosecond to attosecond electron microscopy. *J. Phys. B: At. Mol. Opt. Phys.* 51, 032005 (2018).

MeV Ultrafast Electron Diffraction





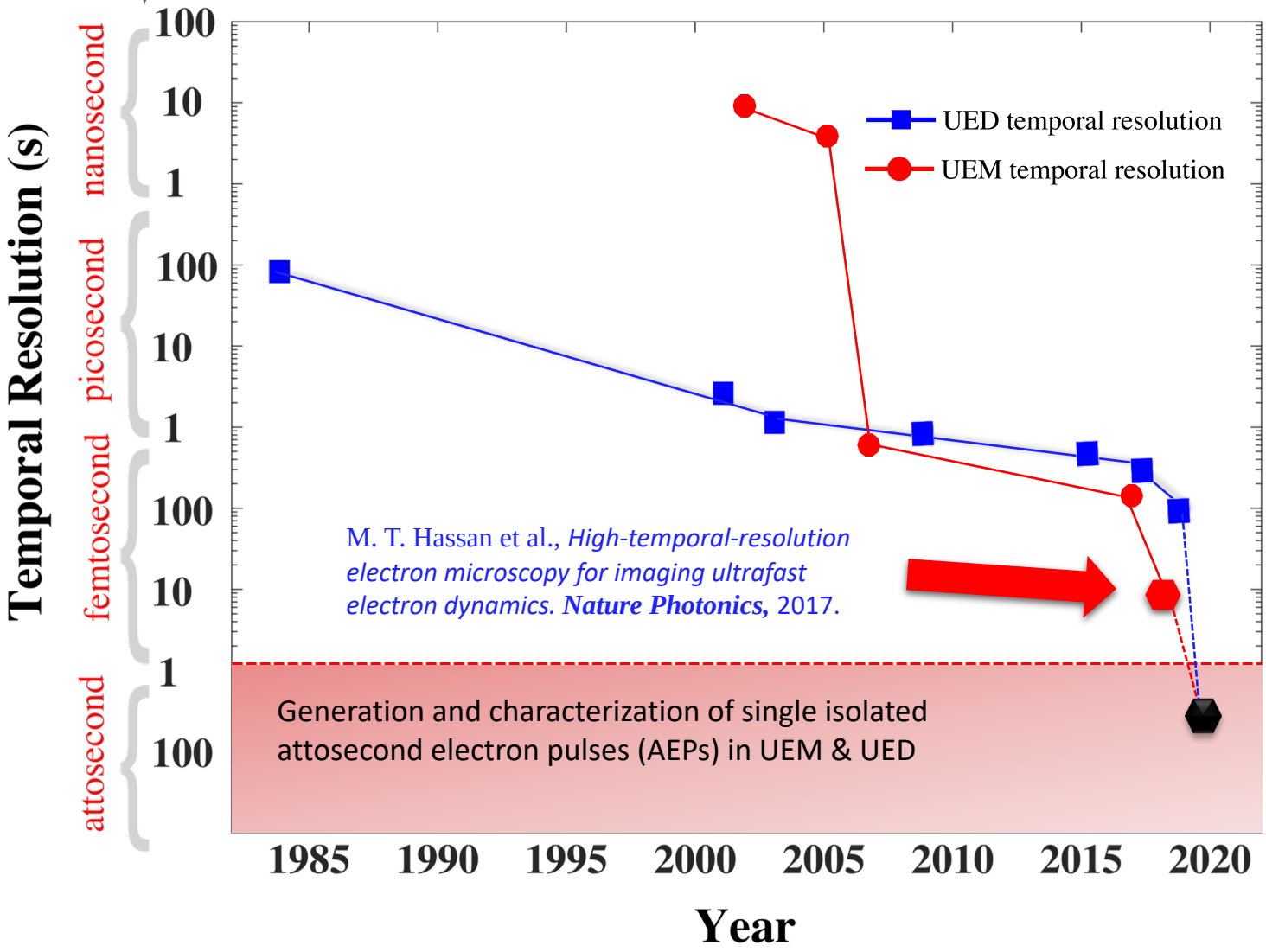




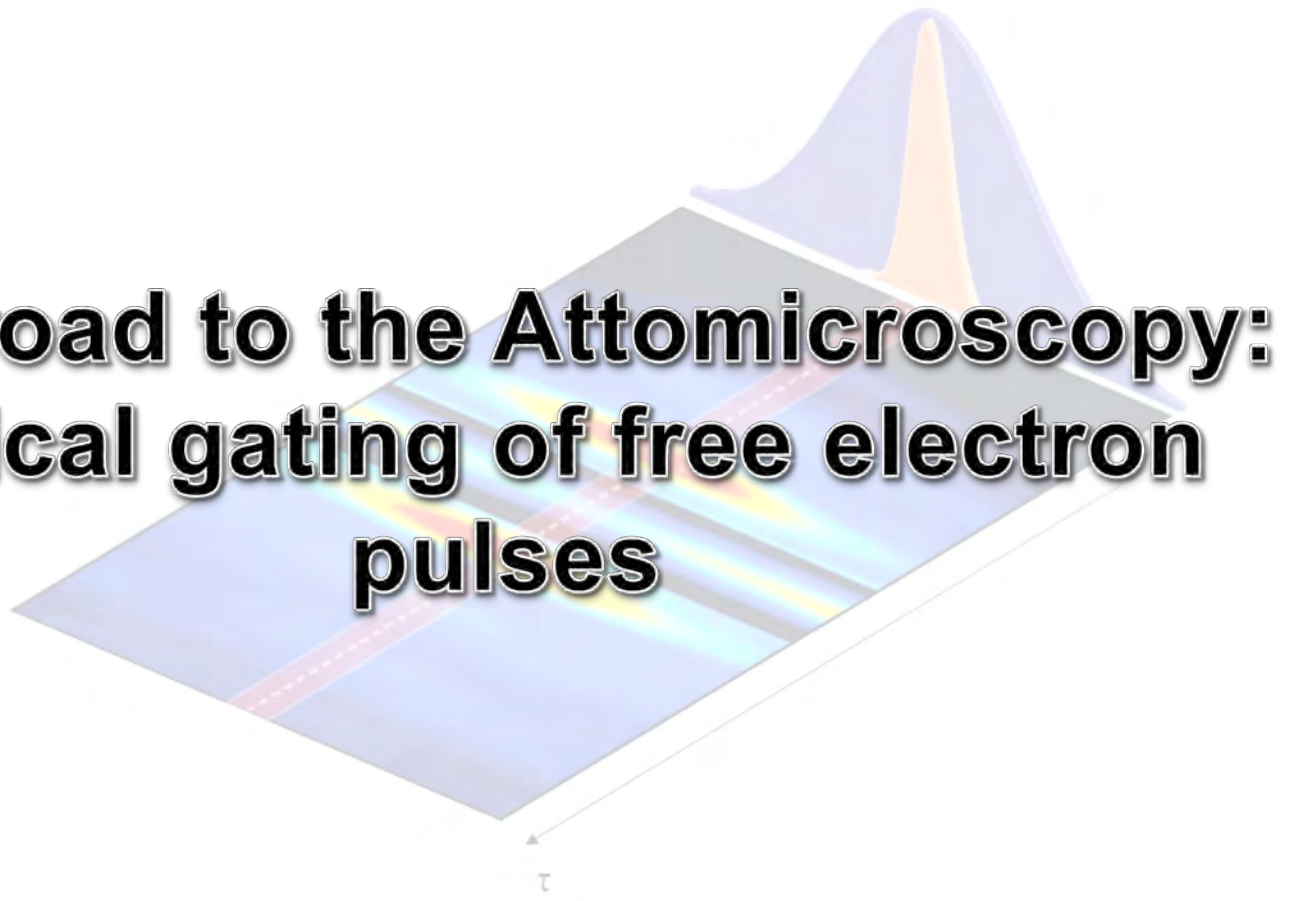
Jie Yang et. al. Science 361, 2020 (6397), 64-67.

Attomicroscopy

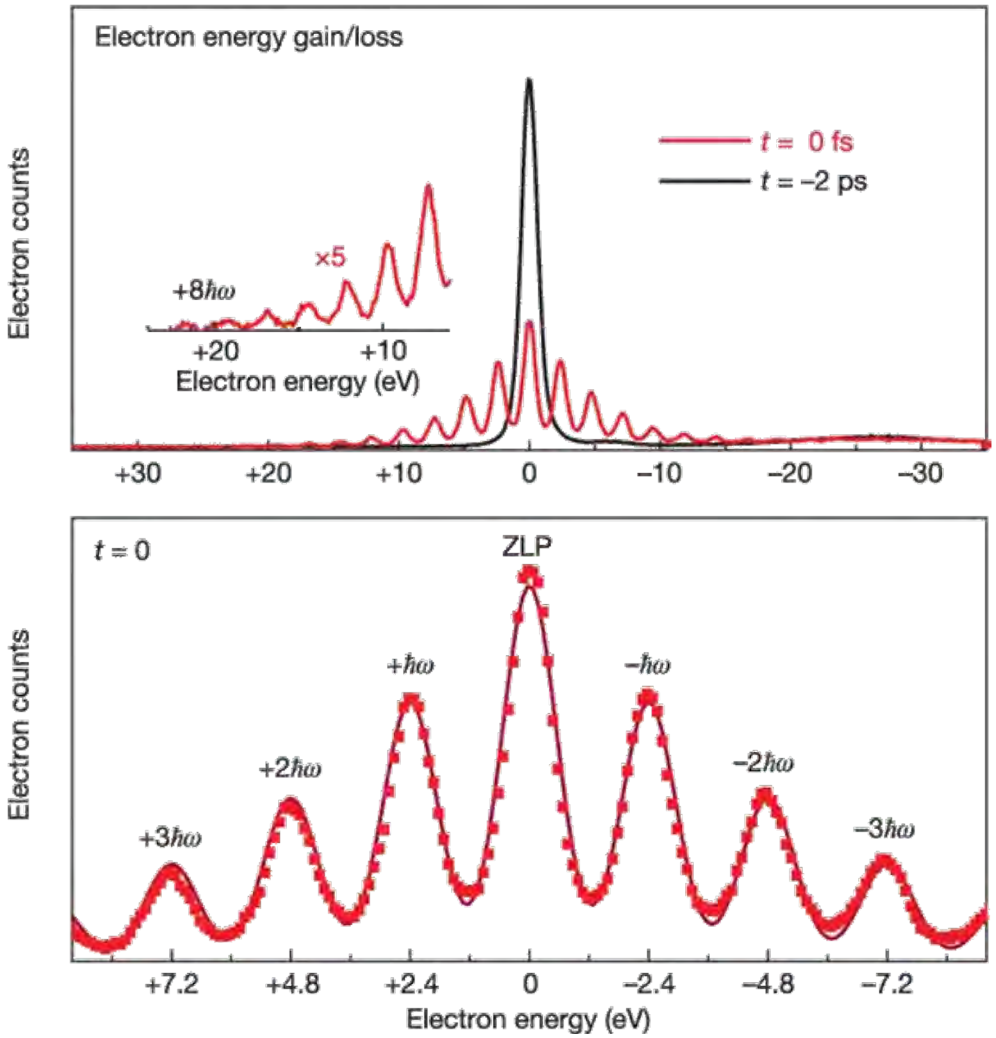
Temporal resolution of Ultrafast Electron Diffraction & Microscopy



The road to the Attomicroscopy: Optical gating of free electron pulses

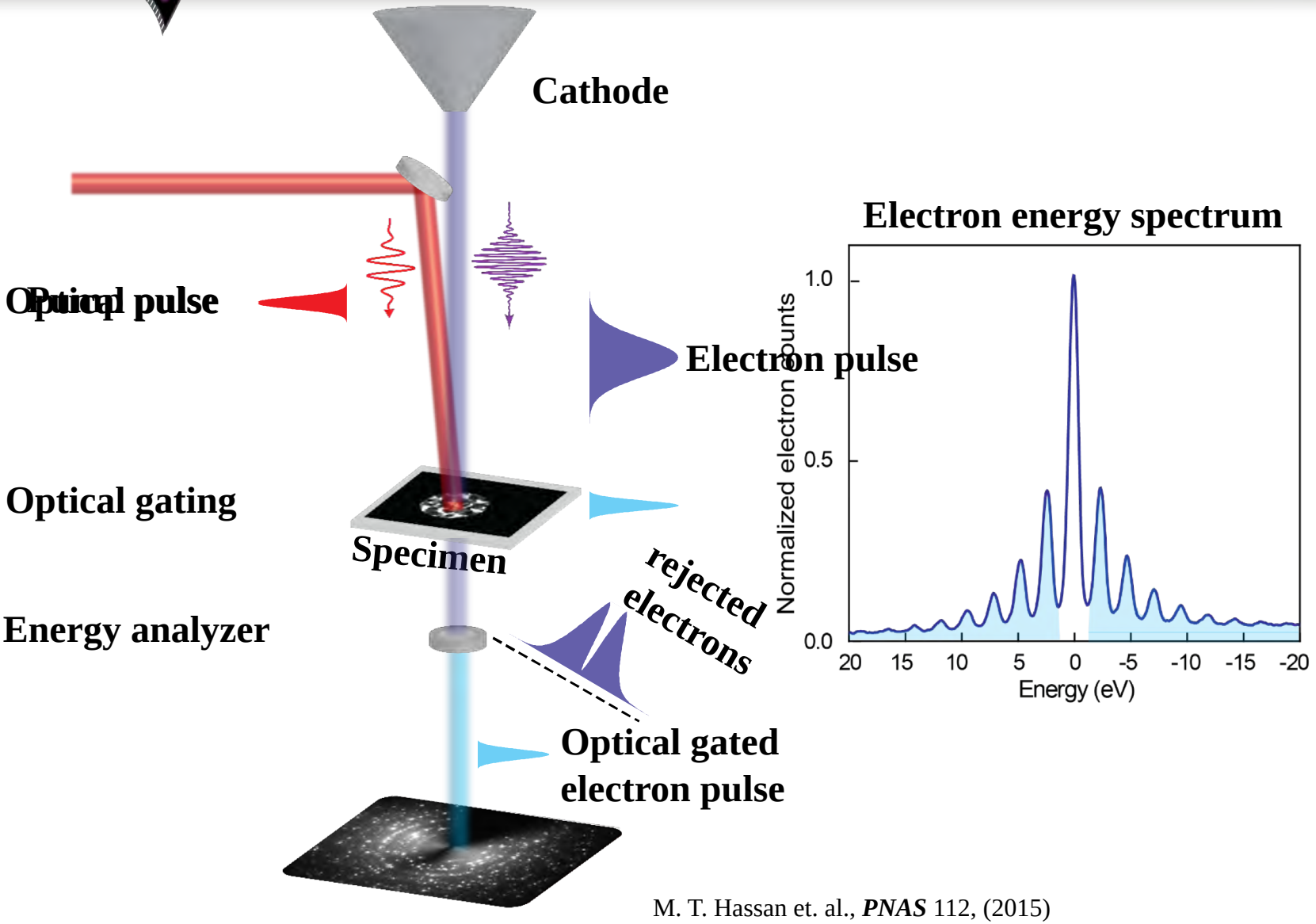


Photon Induced Near-field Electron Microscope (PINEM)



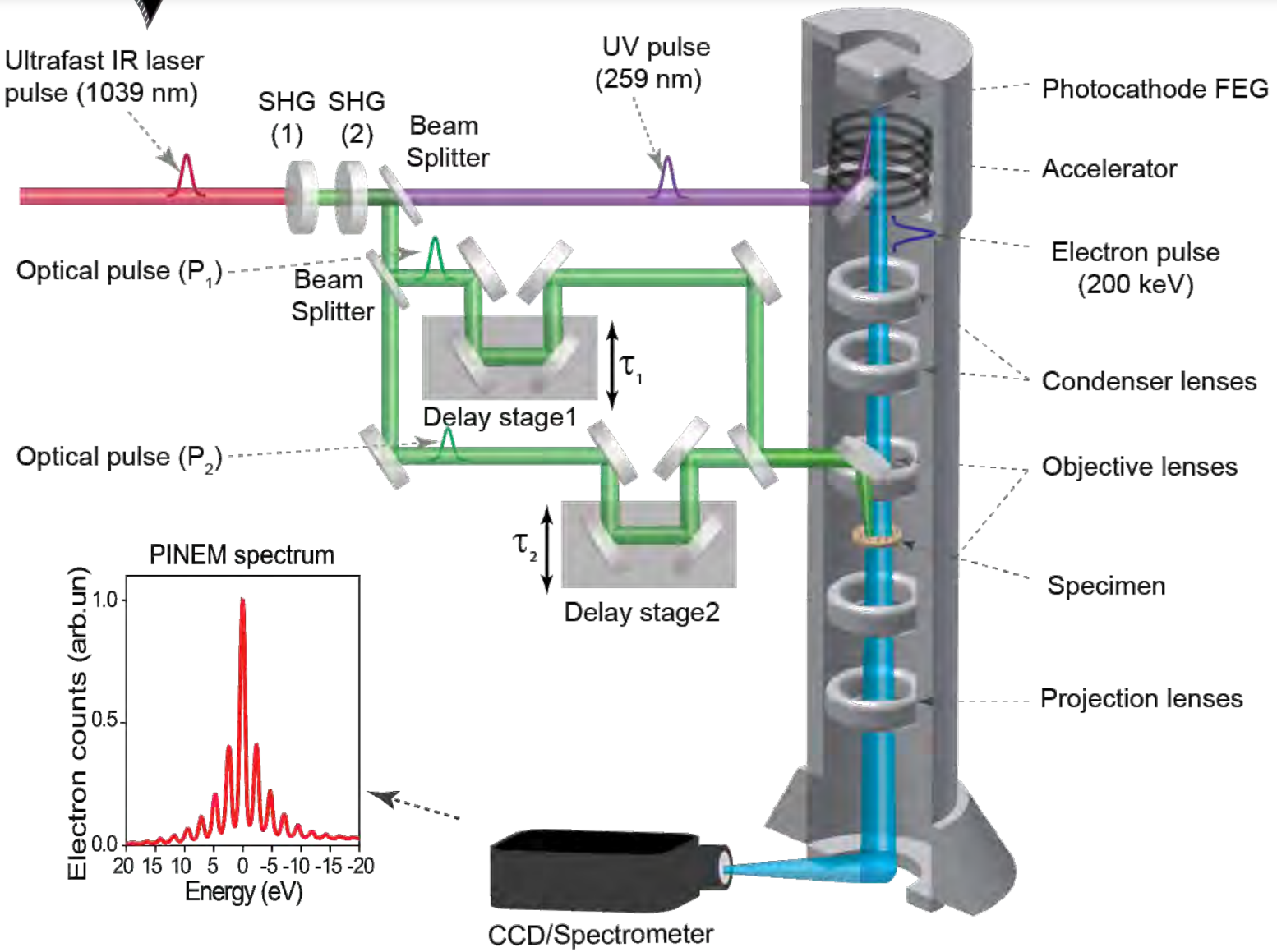
B. Barwick, D. J. Flannigan, A. H. Zewail**, Nature** 462, (2009).

Optical gating of ultrafast electron pulse



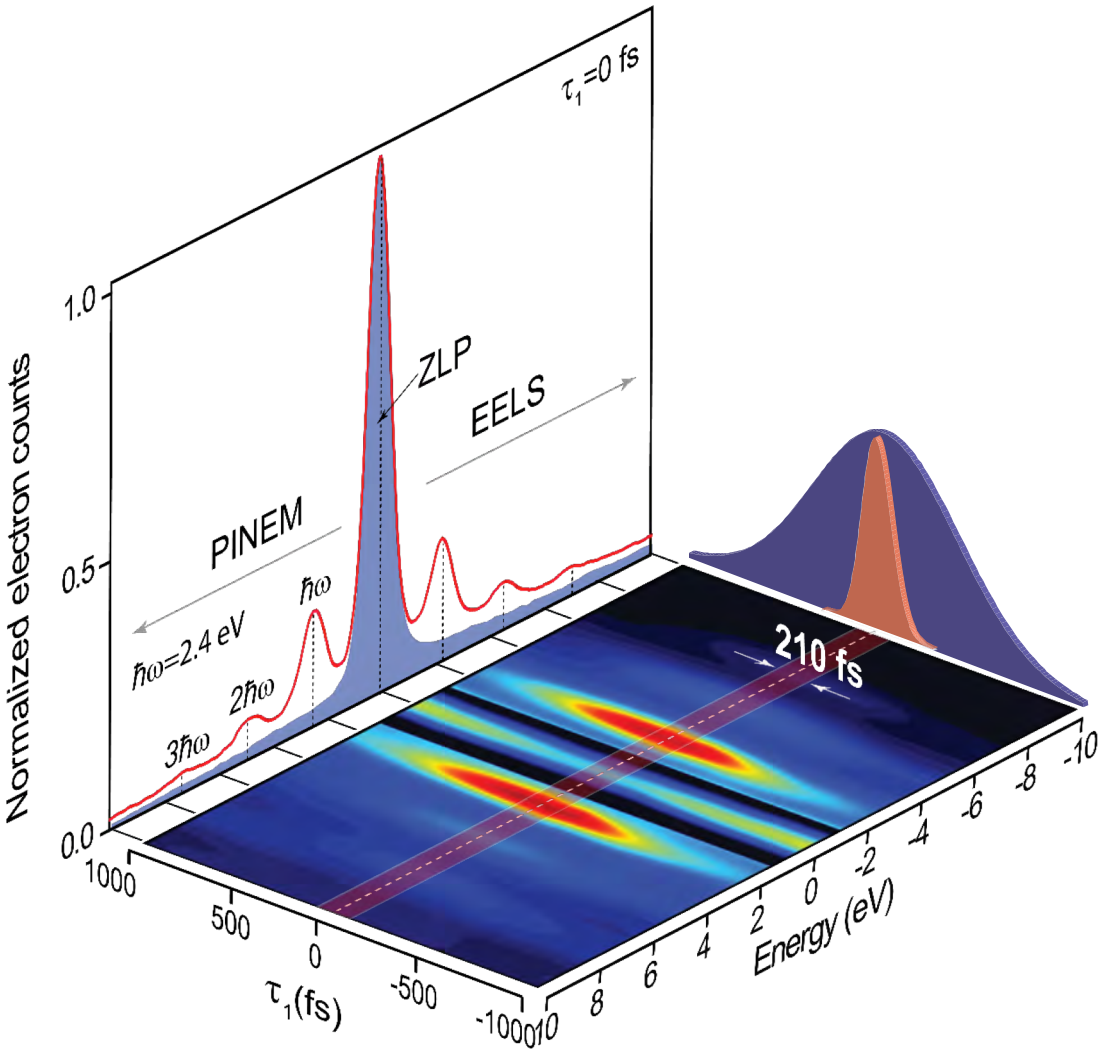
M. T. Hassan et. al., ***PNAS*** 112, (2015)

Optical gating experiment setup



M. T. Hassan et. al., ***PNAS*** 112, (2015)

Optical gating of 200 fs electron pulse



M. T. Hassan et. al., ***PNAS*** 112, (2015)

Ultrafast phase transition in VO_2 nanoparticle

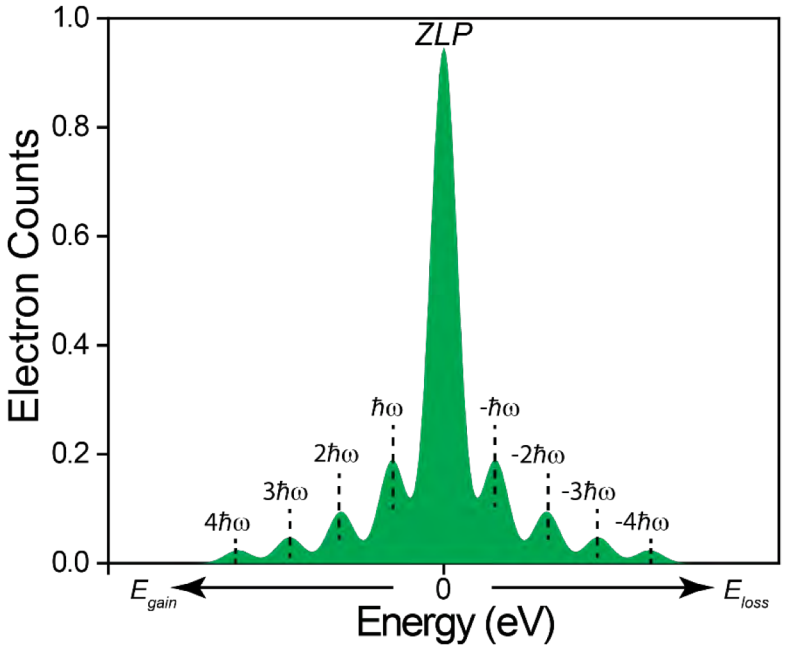
For a nanoparticles, the field integral at point (x,y) is given by

$$\tilde{F}_0 \approx -i\tilde{E}_0 \cos\phi \chi_s \frac{2}{3} a^3 (\Delta k)^2 K[\Delta k b]$$

$\tilde{E}_0$ the electric field amplitude of the incident light,
ϕ the light polarization,
a the radius of the cylinder,
$b = \sqrt{x^2 + y^2}$ the impact parameter,
Δk the momentum change of the electron,
K the modified Bessel function of the second type, and

$$\chi_s = 3(\varepsilon - 1)/(\varepsilon + 2)$$

Where is χ_s and ε are the susceptibility and the dielectric constant of the material

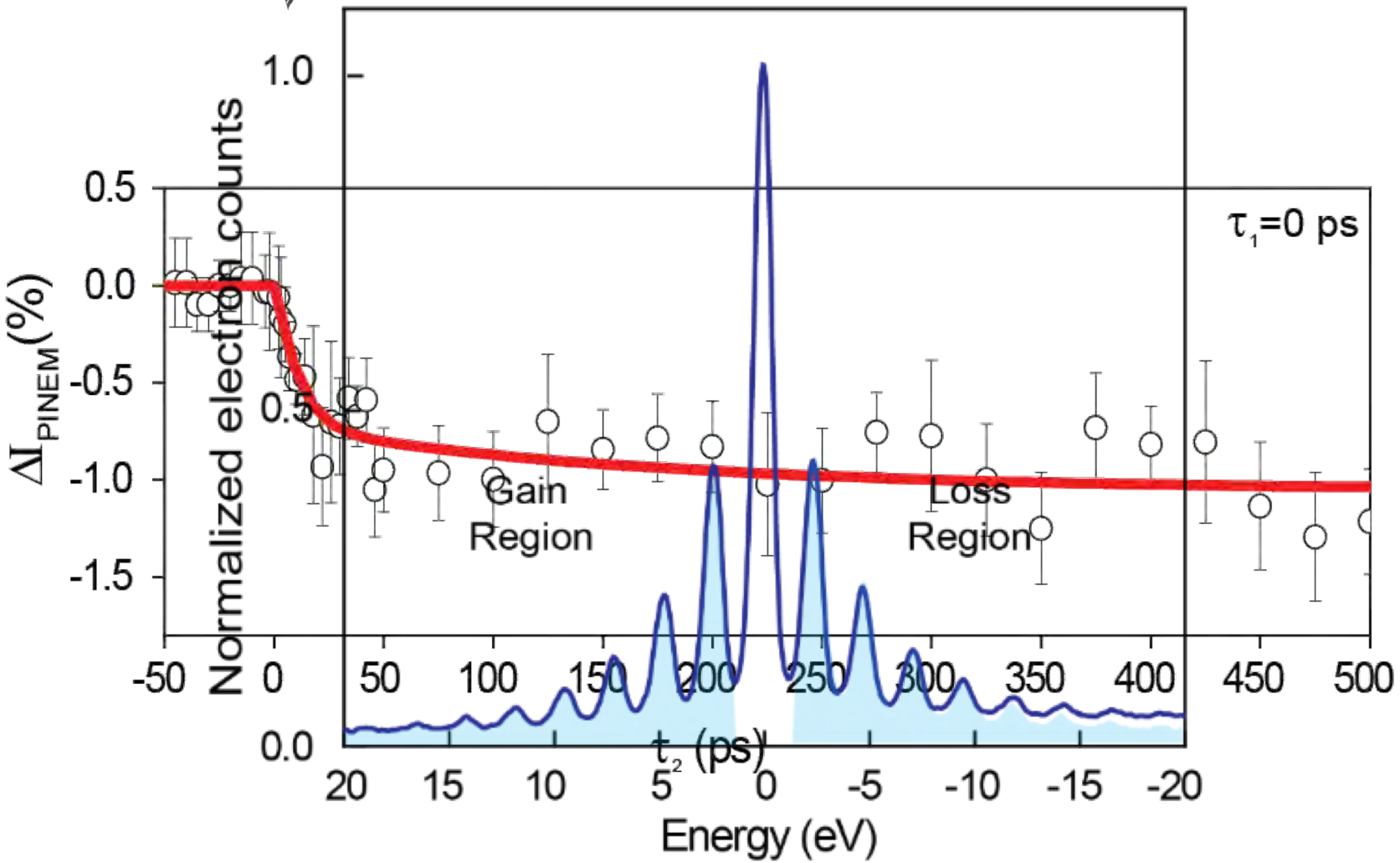


B. Barwick, D. J. Flannigan, A. H. Zewail, Nature 462, (2009).

S. T. Park, A. H. Zewail, Physical Review A 89, (2014).

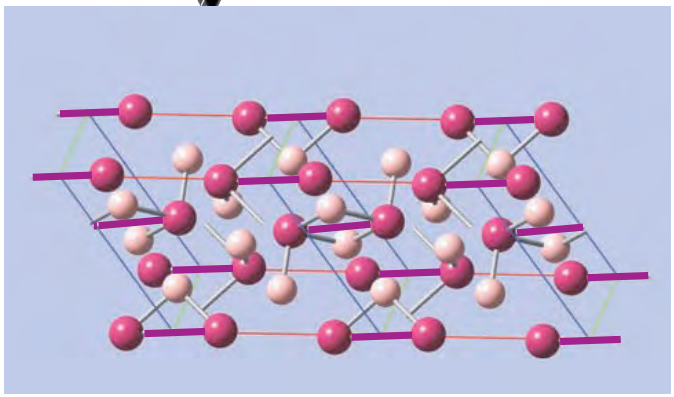
M. T. Hassan et. al., *PNAS* 112, (2015)

Ultrafast phase transition in VO_2 nanoparticle

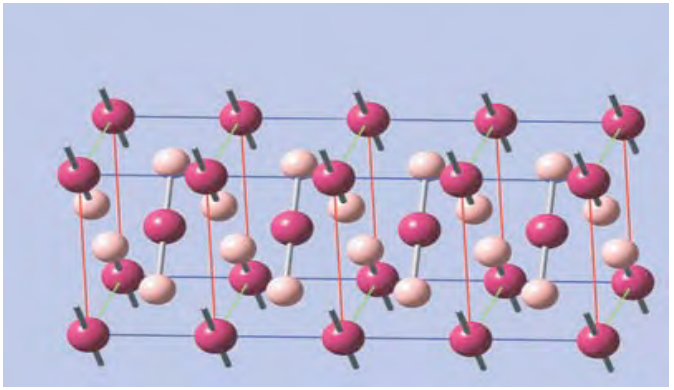


M. T. Hassan et. al., ***PNAS*** 112, (2015)

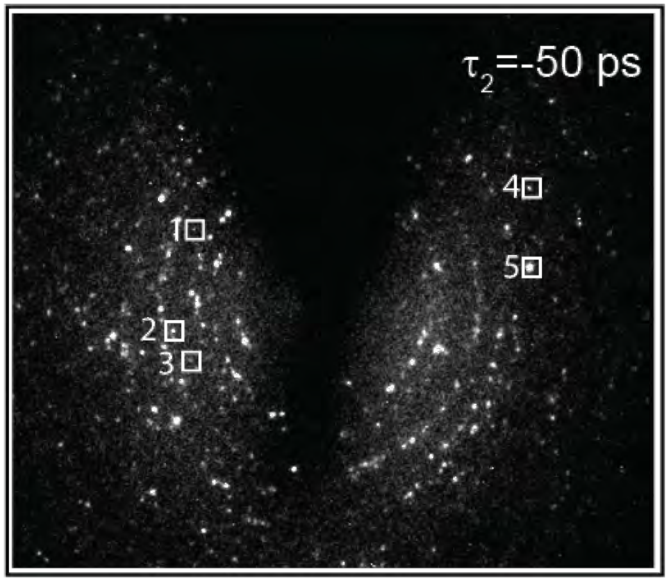
Ultrafast phase transition in VO_2 nanoparticle

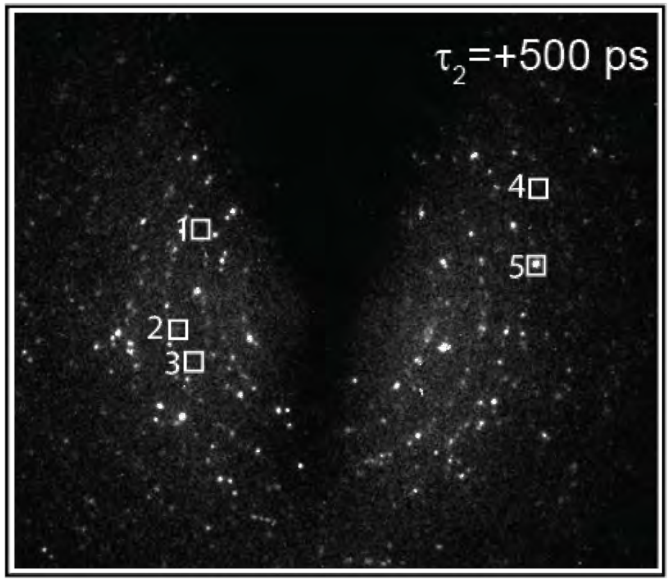


Monoclinic phase



Tetragonal (rutile) phase

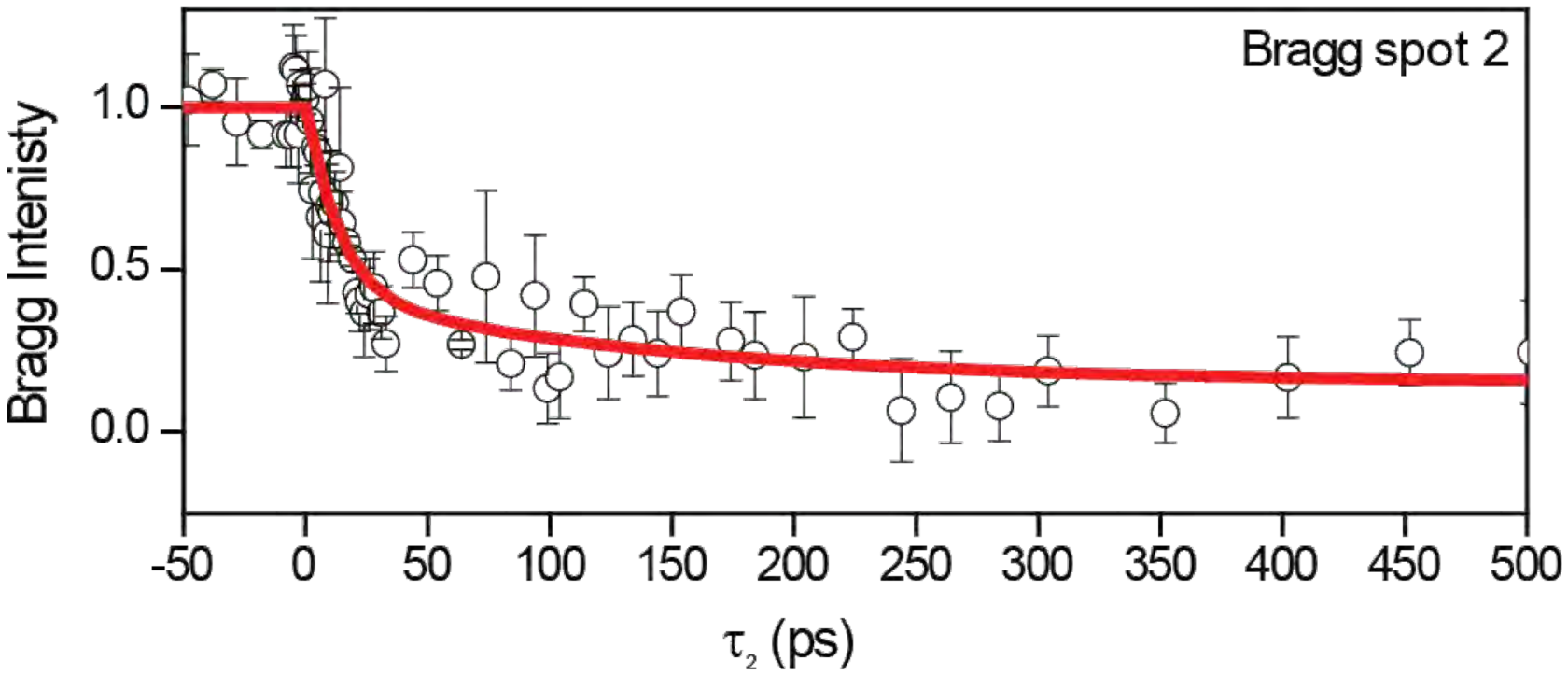




P. Baum et al., Science 318, (2007)788-792

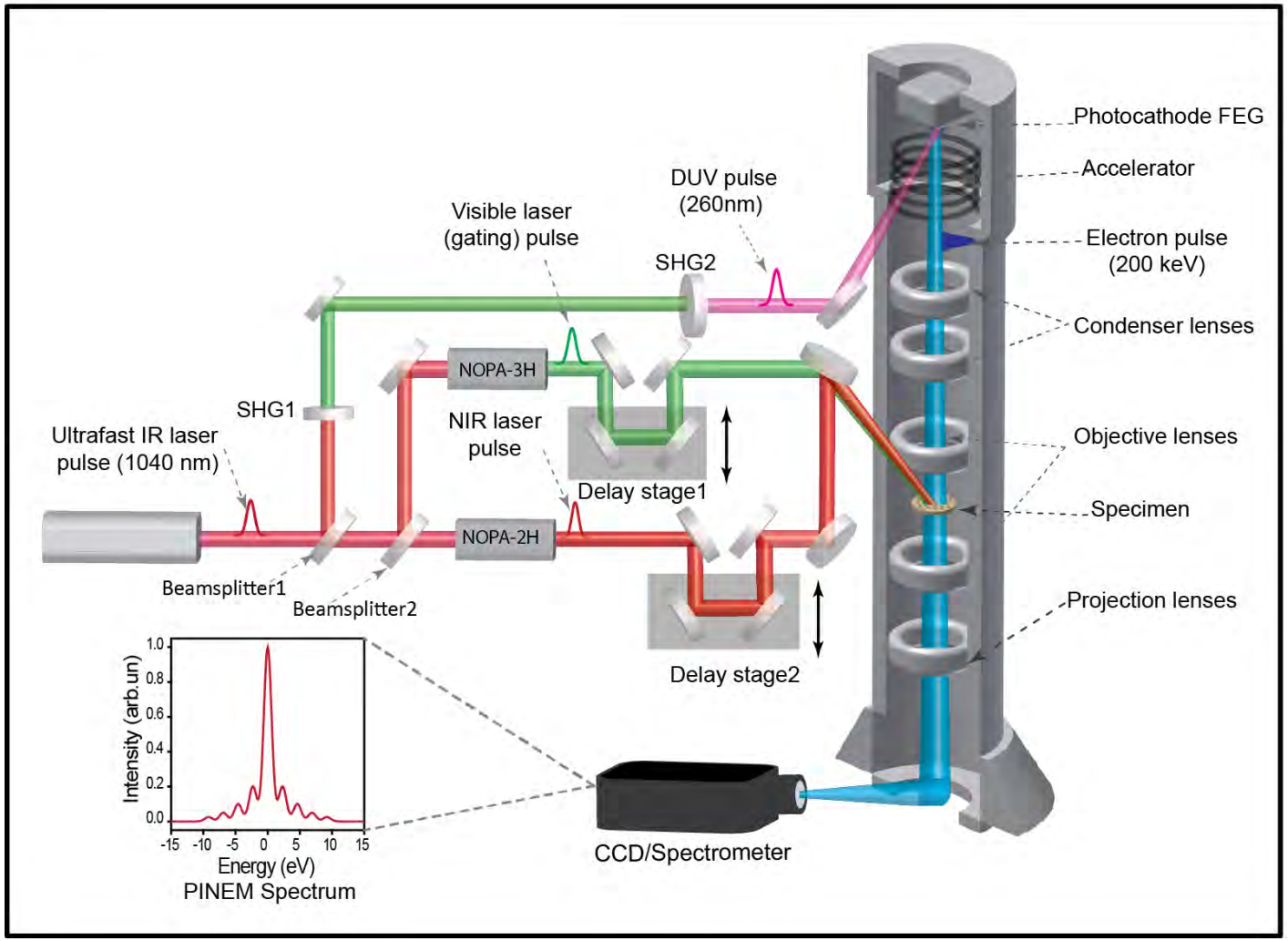
M. T. Hassan et. al., *PNAS* 112, (2015)

Ultrafast phase transition in VO_2 nanoparticle



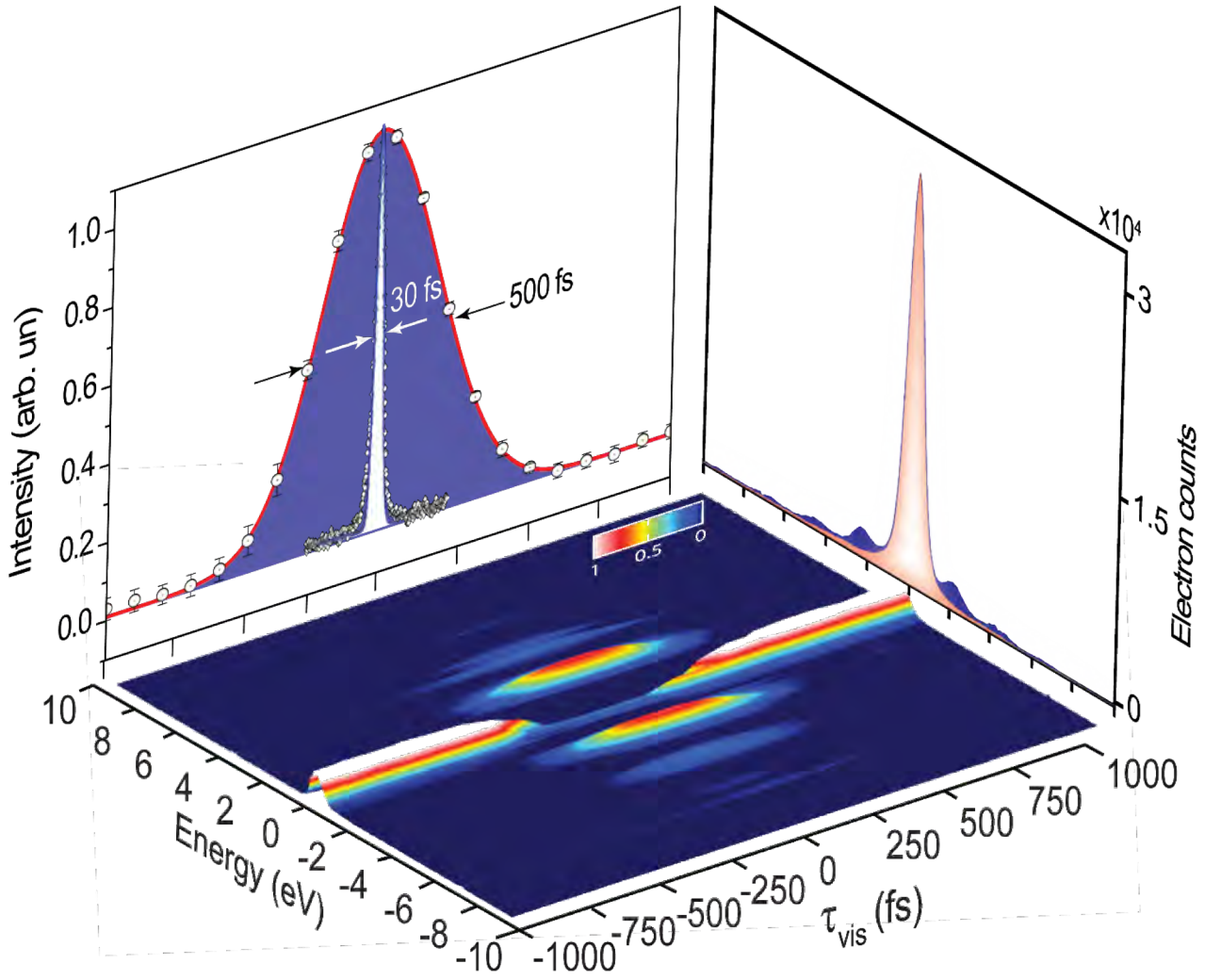
M. T. Hassan et. al., ***PNAS*** 112, (2015)

Realization of the electron dynamics temporal resolution in 4D Electron Microscopy



M. T. Hassan et al., *High-temporal-resolution electron microscopy for imaging ultrafast electron dynamics.* ***Nature Photonics,*** 2017. **11**(7)

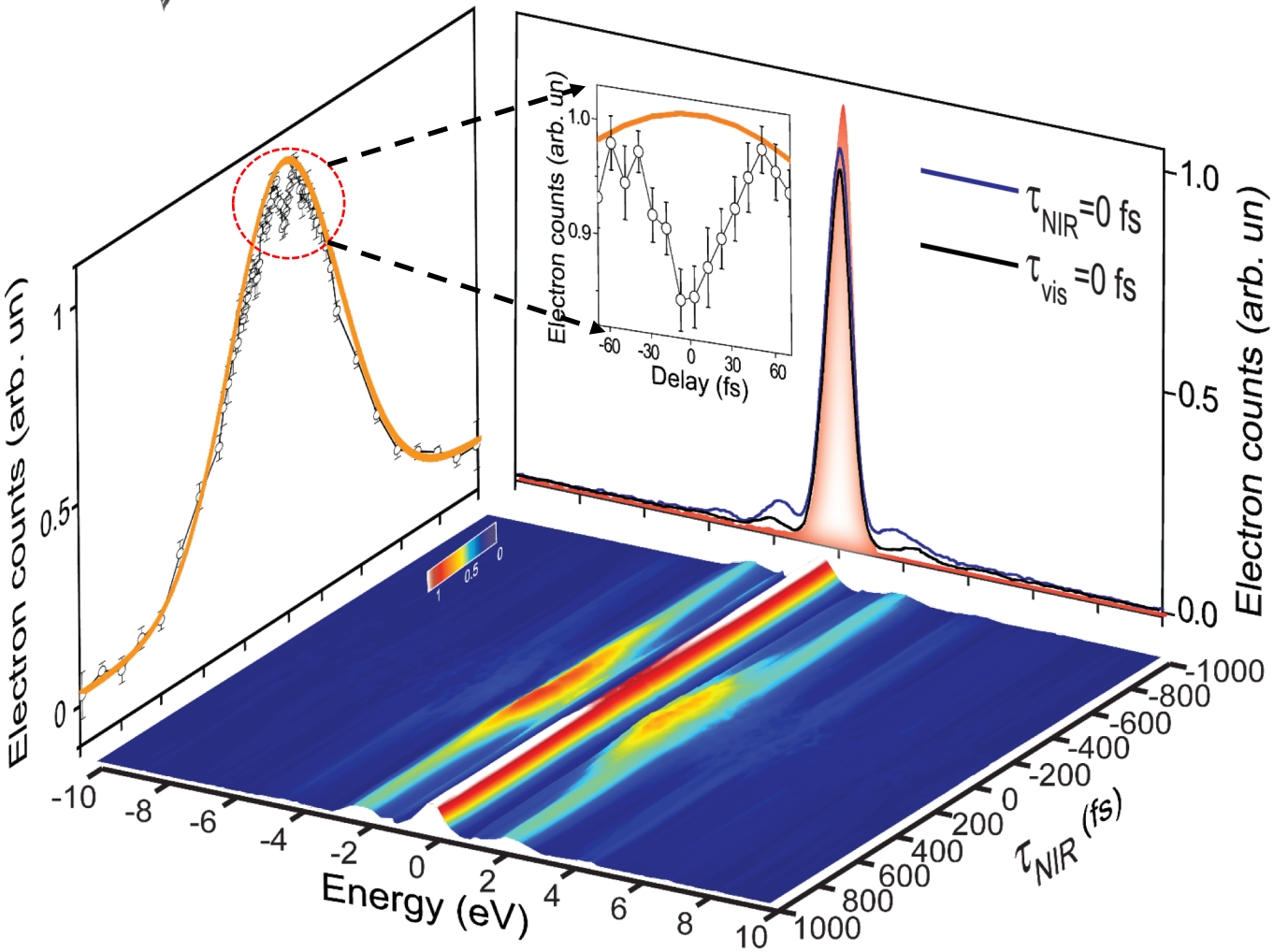
Shortest Electron Pulse in Electron Microscopy



M. T. Hassan et al., *High-temporal-resolution electron microscopy for imaging ultrafast electron dynamics.* ***Nature Photonics,*** 2017. **11**(7): p. 425-430

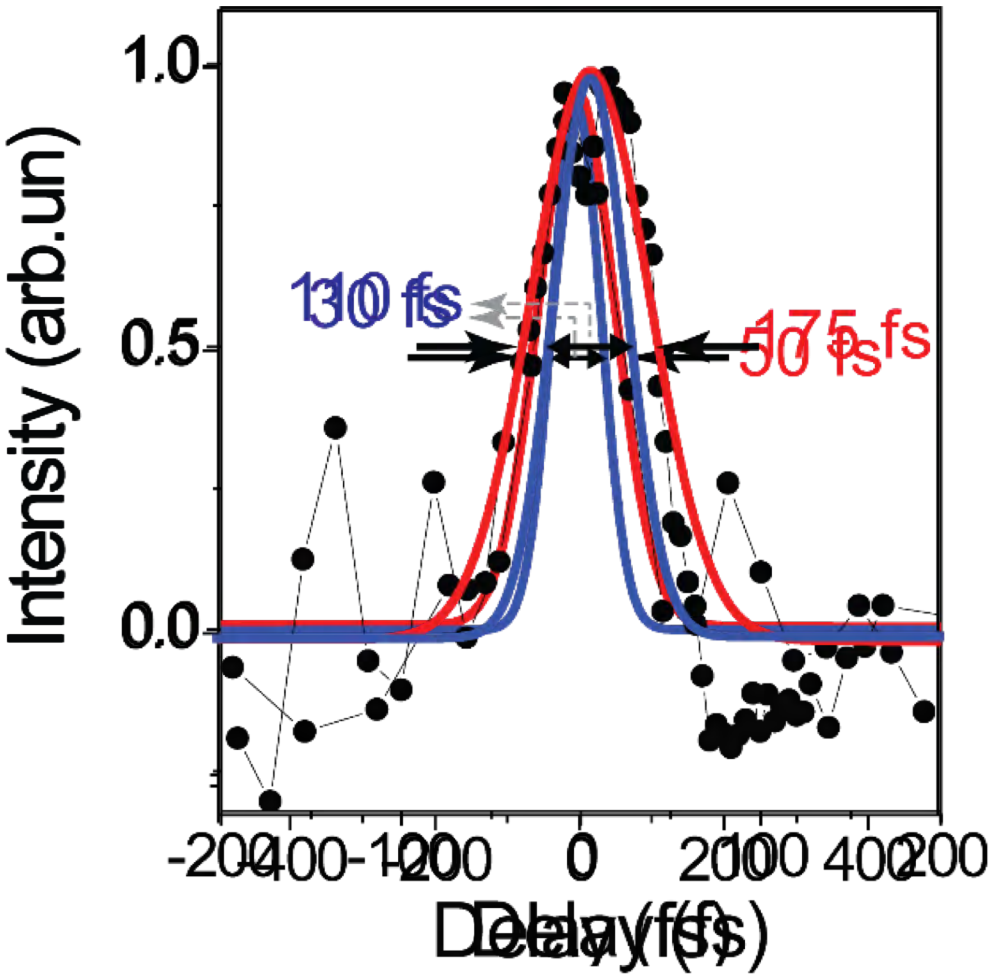
Attomicroscopy

Temporal characterization of 30 fs electron pulse



M. T. Hassan et al., *High-temporal-resolution electron microscopy for imaging ultrafast electron dynamics.* ***Nature Photonics,*** 2017. **11**(7): p. 425-430

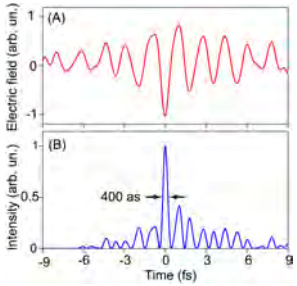
Realization of the electron-motion temporal resolution in 4D Electron Microscopy



M. T. Hassan et al., *High-temporal-resolution electron microscopy for imaging ultrafast electron dynamics.* ***Nature Photonics,*** 2017. **11**(7): p. 425-430

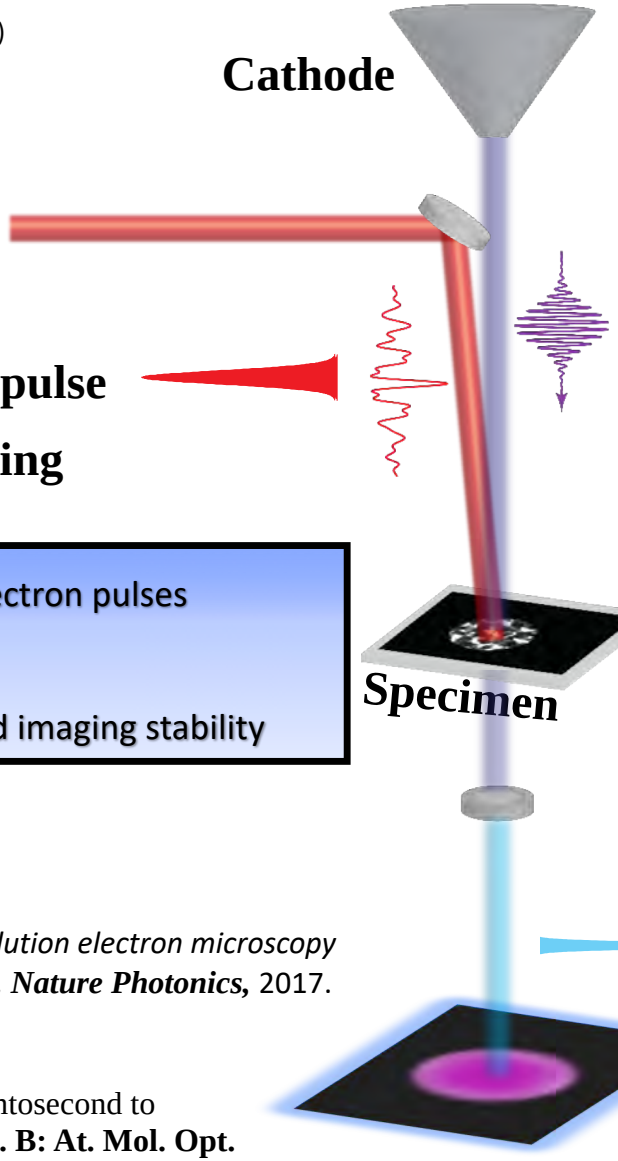
Attomicroscopy: Single isolated attosecond electron pulse

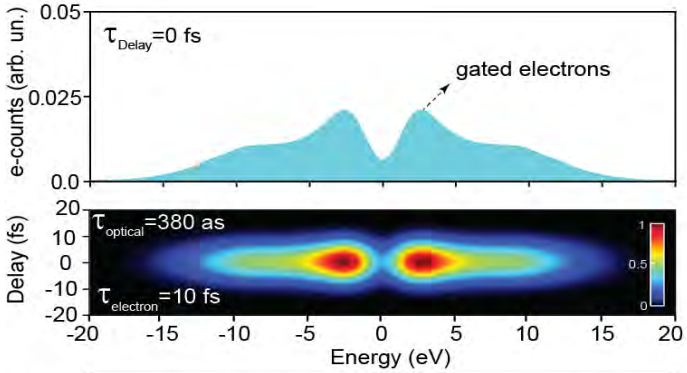
M. Th. Hassan et al., **Nature,** 2016. **530** (7588)



Optical attosecond pulse

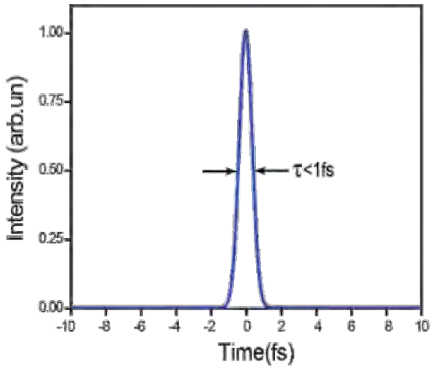
Attosecond optical gating





Electron pulse

- Single isolated attosecond electron pulses
- Attosecond pump pulses
- Attosecond phase stability and imaging stability

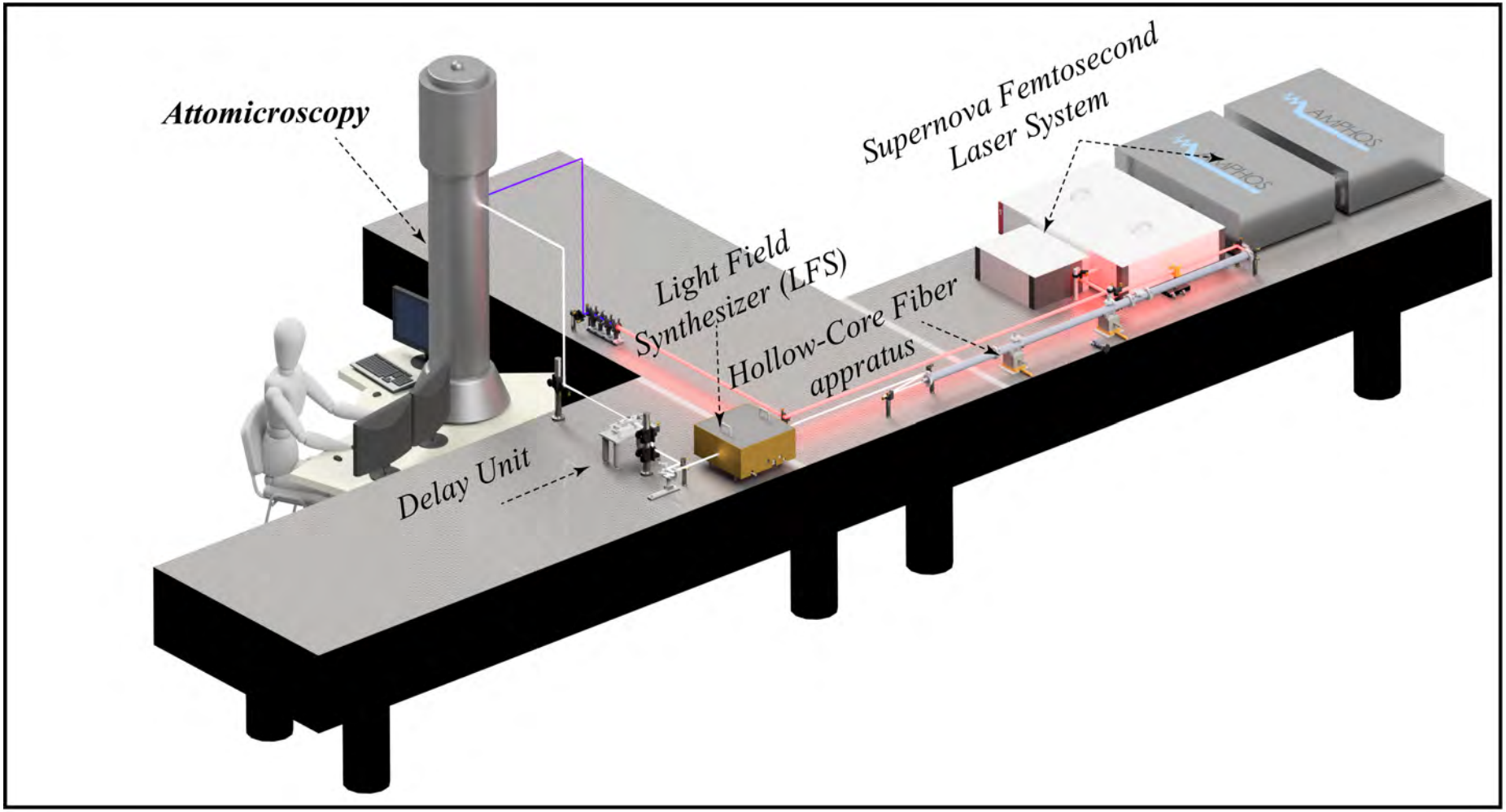


Attosecond optical gated electron pulse

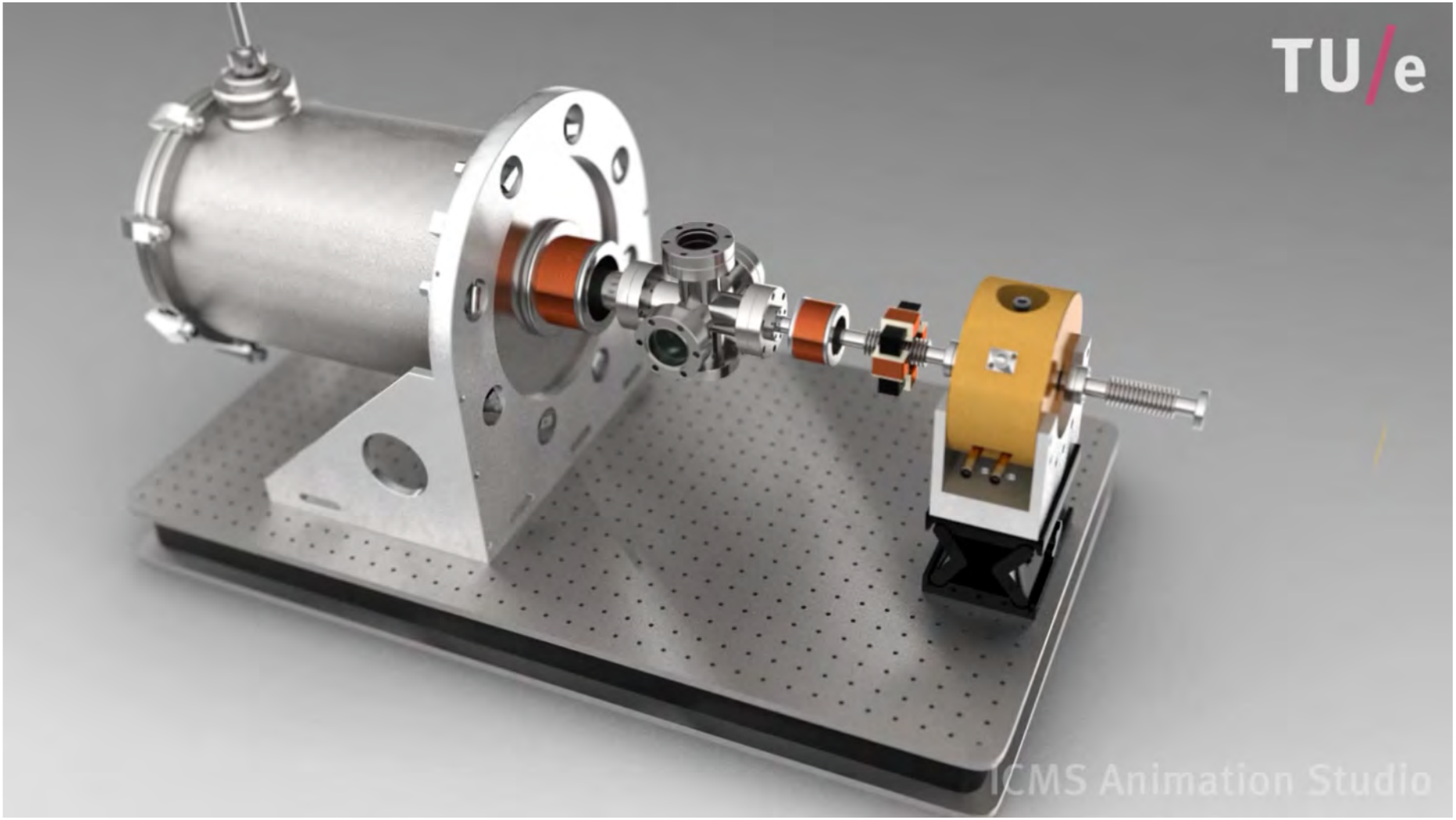
M. T. Hassan et al., *High-temporal-resolution electron microscopy for imaging ultrafast electron dynamics.* ***Nature Photonics,*** 2017. **11**(7): p. 425-430

M. T. Hassan, Attomicroscopy: from femtosecond to attosecond electron microscopy. **J. Phys. B: At. Mol. Opt. Phys**.51, 032005 (2018).

Attomicroscopy setup

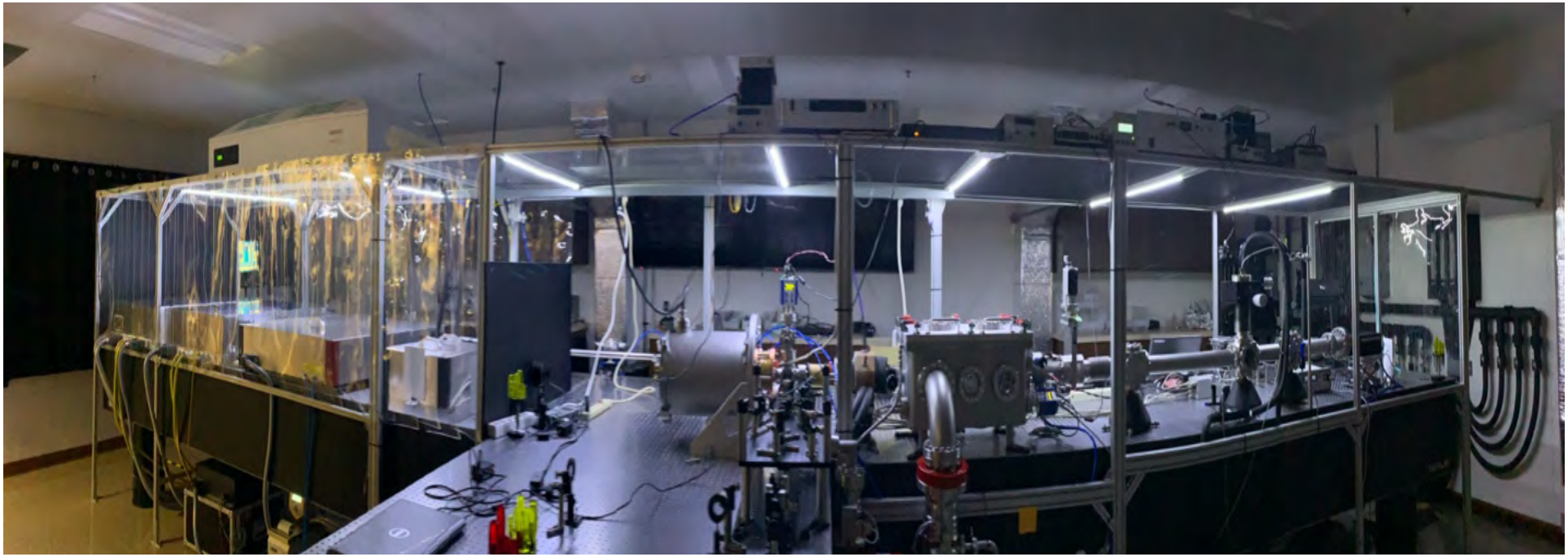


Attosecond Electron Diffraction setup



D. Hui et al., “Attosecond electron imaging” (in preparation).

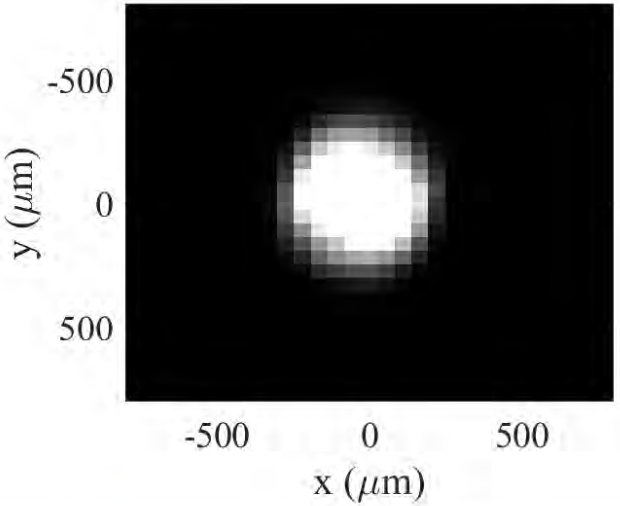
Attosecond Electron Diffraction setup in Hassan's Lab

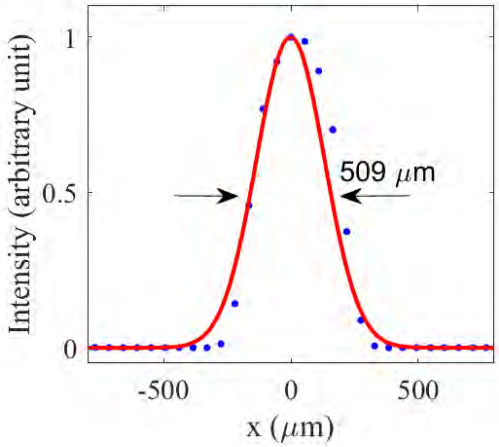


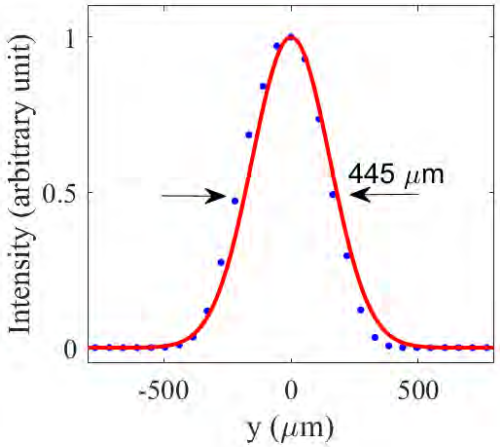
D. Hui et al., "Attosecond electron imaging" (in preparation).

Electron beam properties

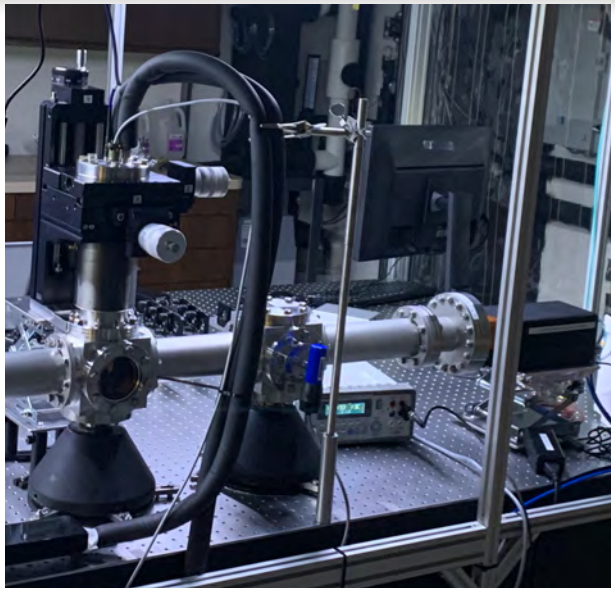
E= 90KeV,
The number of electrons =10^9/S

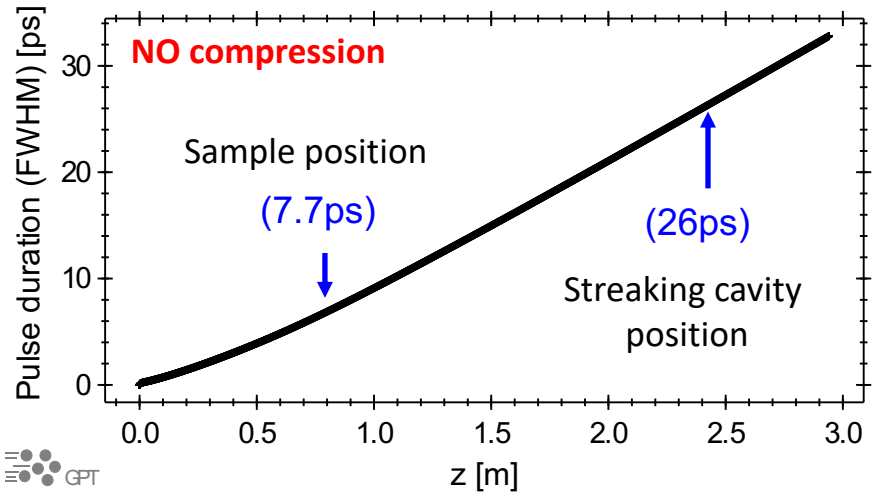


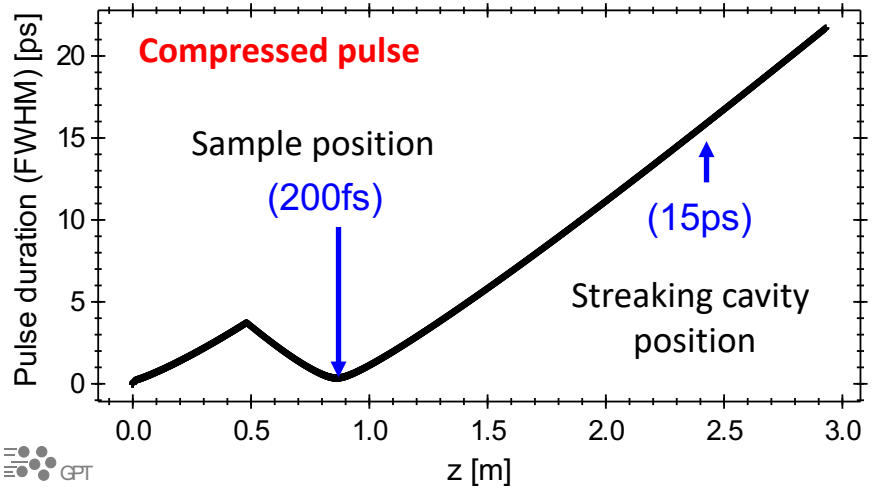




Electron pulse duration

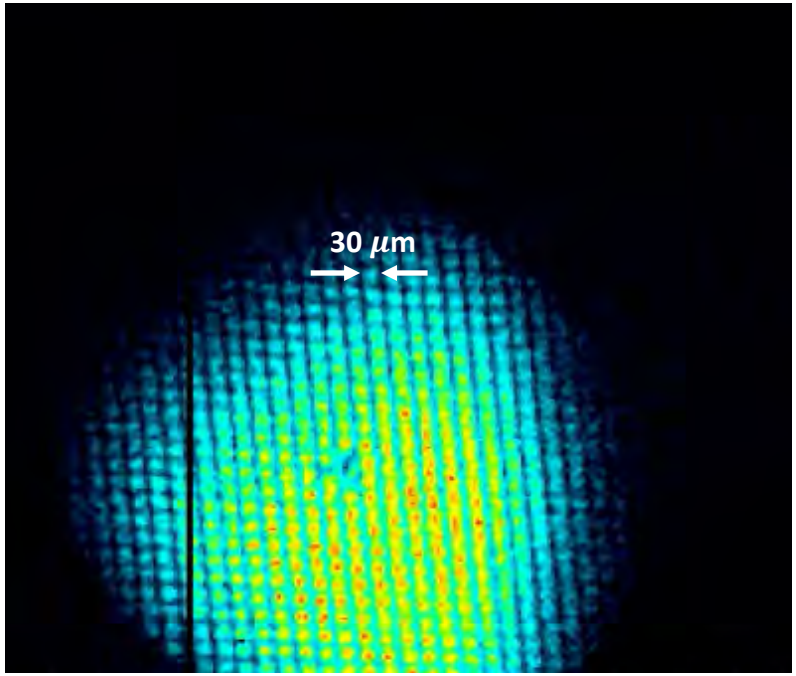






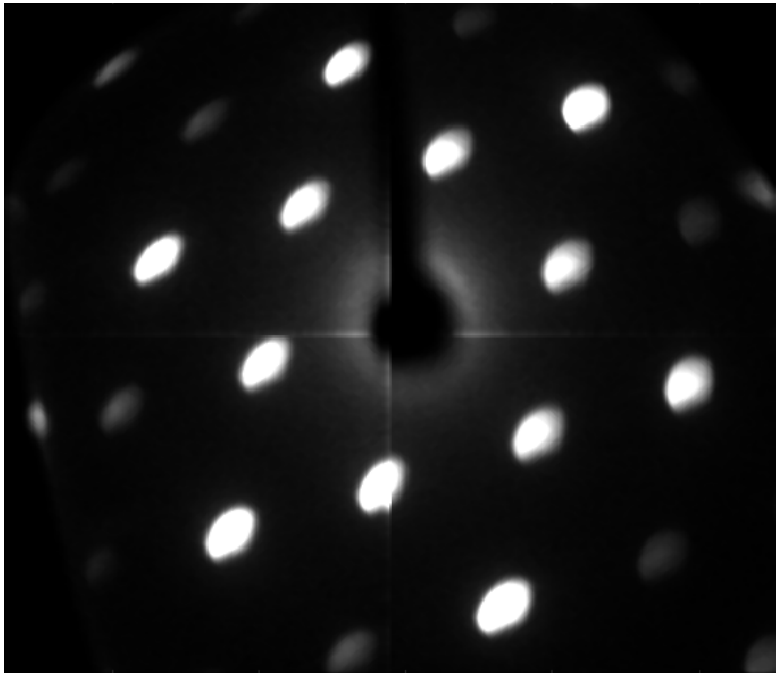
Electron diffraction setup resolution

Direct imagining resolution



Direct Imaging of Aluminum grid
Resolution< 30 μm

Diffraction imagining resolution



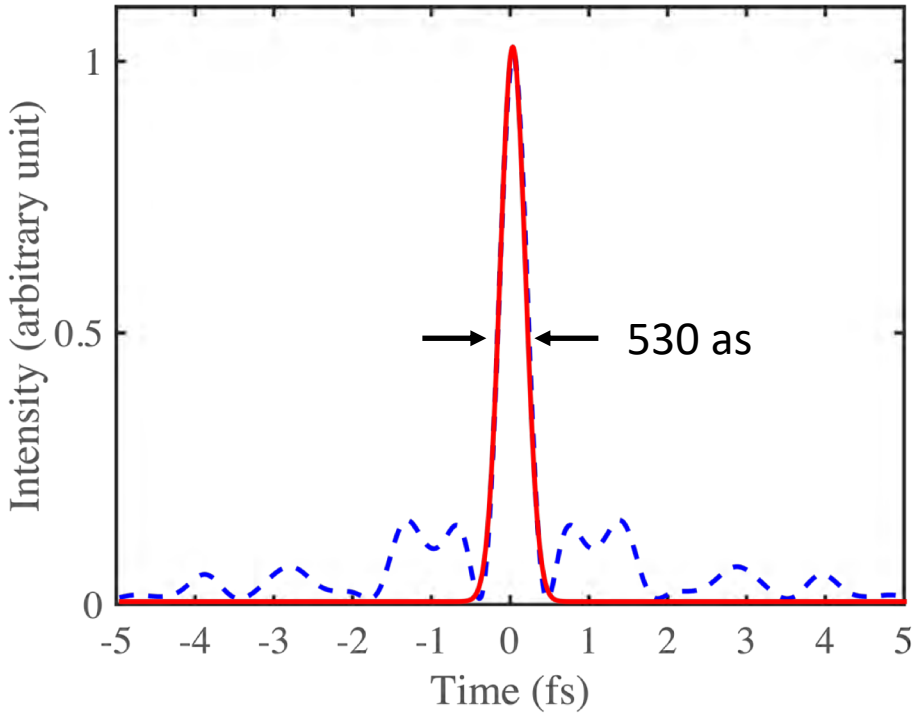
Diffraction pattern of graphene
Resolution= 1Pm

D. Hui et al., “Attosecond electron imaging” (in preparation).

Optical gating and the generation of attosecond electron pulses

gating attosecond laser pulse

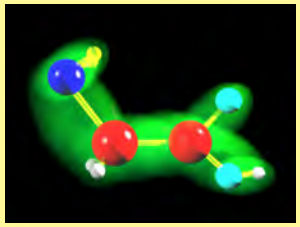
gated attosecond electron pulse

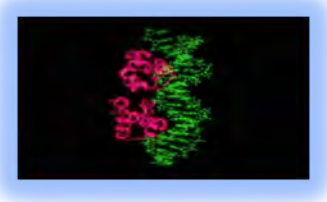


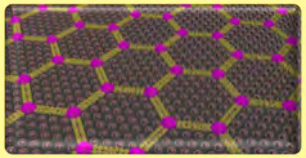
D. Hui et al., "Attosecond electron imaging" (in preparation).

Why Attosecond electron imaging is revolutionary

Attomicroscopy will be the **Rosetta Stone** for electron dynamics in complex and quantum systems







Science:

- Imaging electron motion to reveal the quantum physics of complicated systems—impossible to simulate even when using quantum computers
- Snapshots of electron motion to provide real-time access to electron dynamics and improve our understanding of chemical interactions
- The recent developments in Cryo-electron microcopy (Nobel prize-2017) and the liquid-cell technology in electron microscopy together with Attomicroscopy will enable studies of electron dynamics in biomolecules in their native environment

Information technology:

- Imaging electron dynamics in the solid-state in both real time and space.

Attomicroscopy

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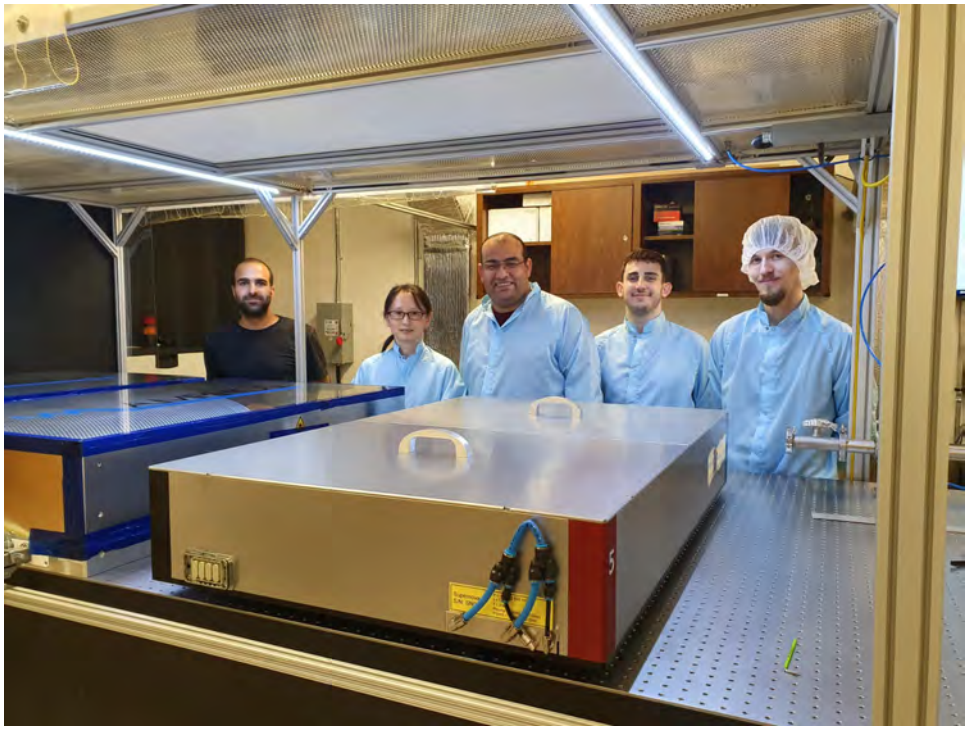

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