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Exploring quantum theory with ultrafast science

100 Years of Quantum Physics

21st Recontres du Vietnam

07th October 2025

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Part 1: What is ultrafast science?

Observation

Visual observation

Route 1

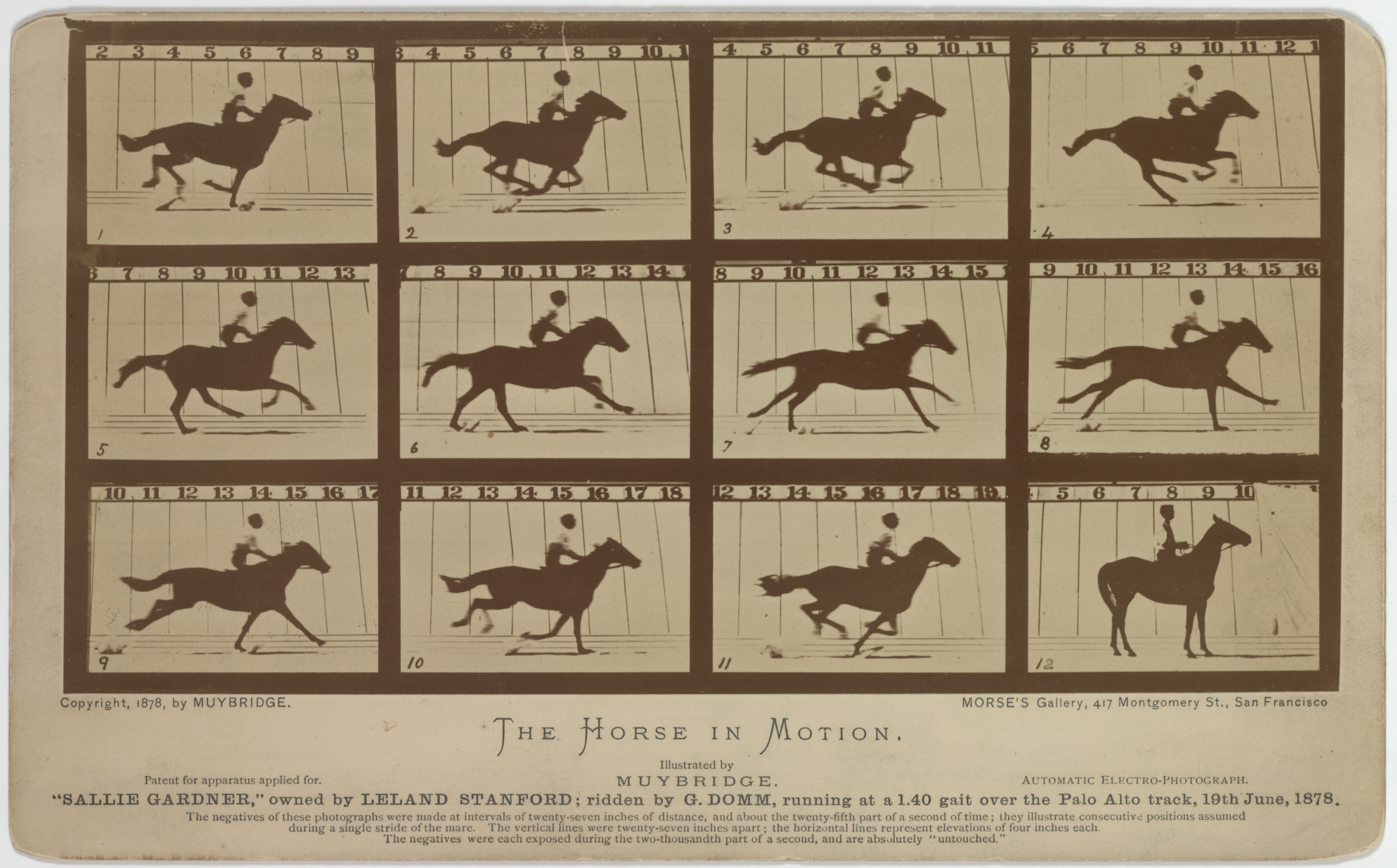
Object

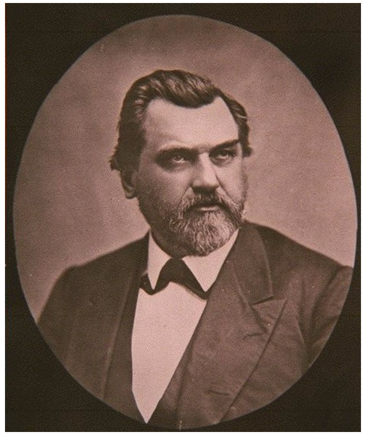
- Lens → Retina → Brain → Visualized in our brain
- Lens → Sensor → CPU → Print out on the screen/photo

Route 2

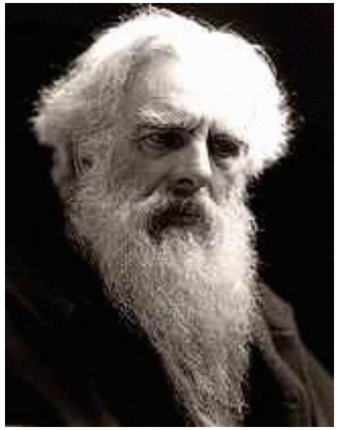
The birth of ultrafast technology

Do all four hooves of a trotting horse ever simultaneously leave the ground?





Leland Stanford



Eadweard Muybridge

Time Resolution:
1/25th of a second

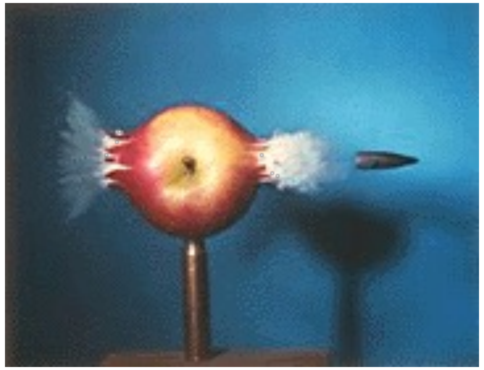
(Adapted from Rick Trebino's slides)

Past ultrafast technology

Strobe photography

Harold
Edgerton
MIT, 1942

"How to Make
Apple sauce
at MIT"
1964



"Splash on a Glass"
Junior High School
student
1996

Time resolution: a few microseconds

(Copied from Rick Trebino's slides)

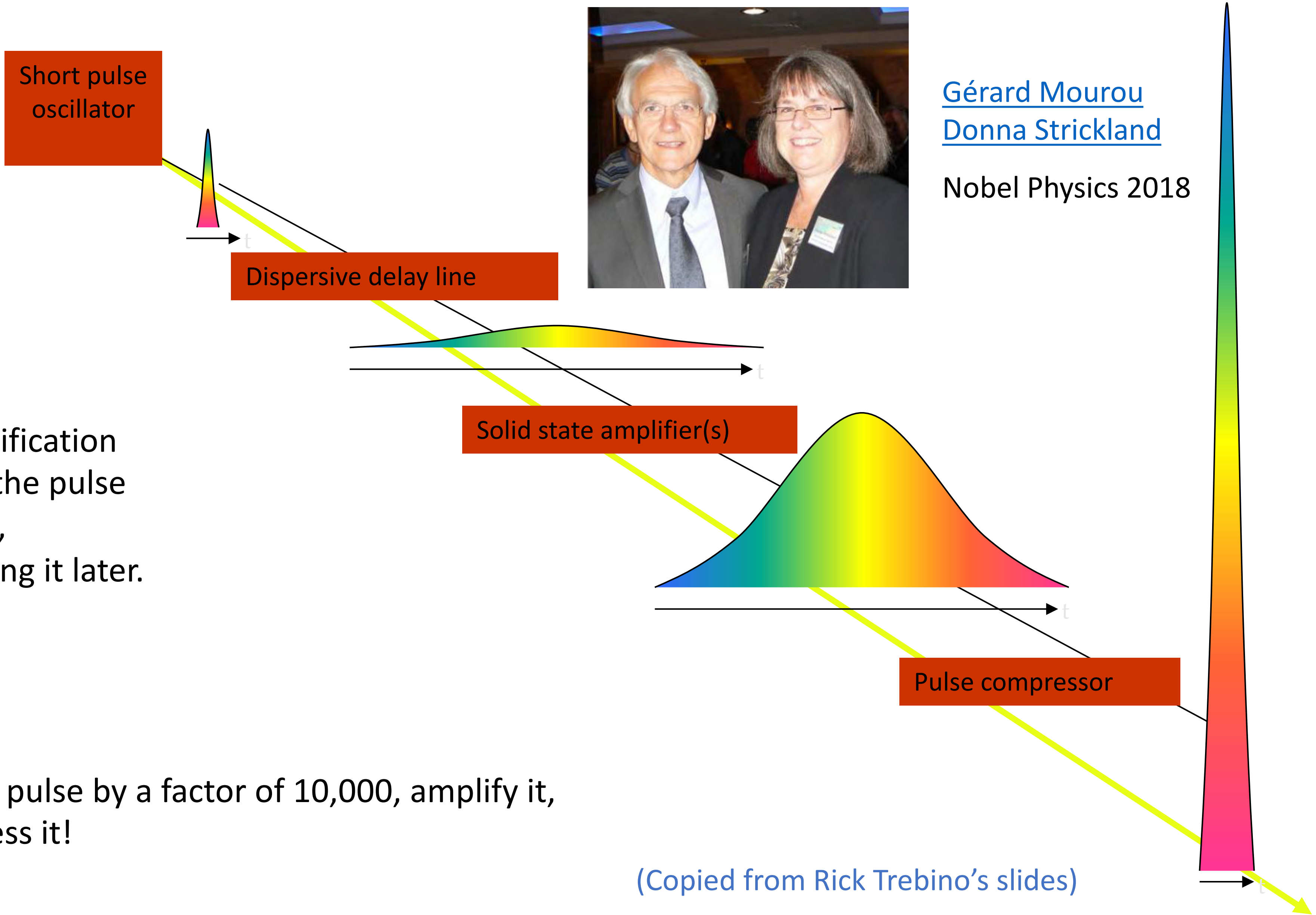
Modern digital camera

Shutter	SHUTTER TYPE	Mechanical shutter / Electronic shutter
	SHUTTER SPEED	Still images (Mechanical shutter): 1/4000 to 30 s, Bulb, Still images (Electronic shutter): 1/8000 to 30 s, Movies: 1/8000 to 1 s
	FLASH SYNC. SPEED	1/160 s (35mm full frame), 1/200 s (APS-C) [5]
	ELECTRONIC FRONT CURTAIN SHUTTER	Yes

1/8000s = 125 μs

Part 2: Key contributions

Development of intense laser pulses
Chirped Pulse Amplification technique



Gérard Mourou
Donna Strickland

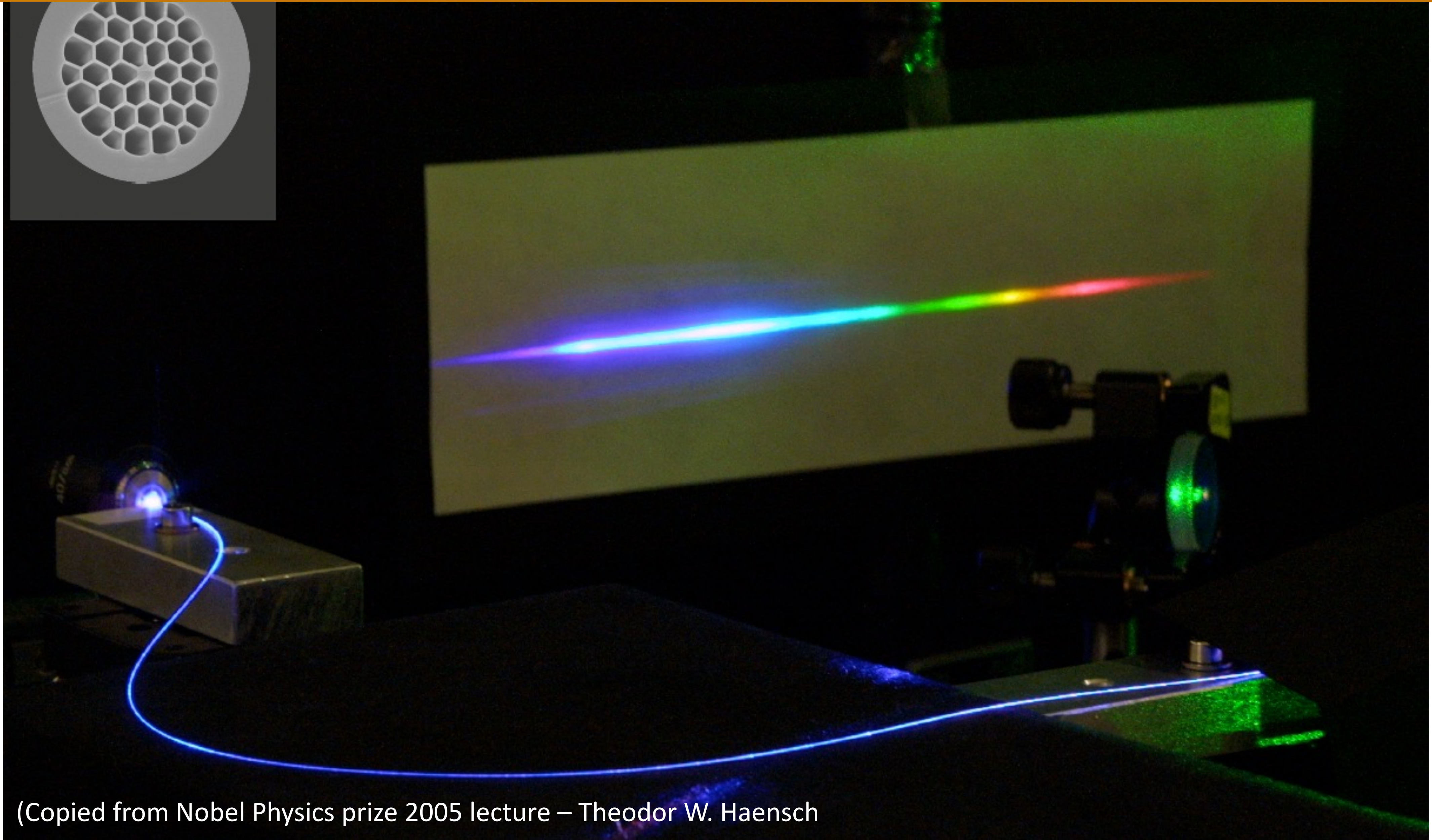
Nobel Physics 2018

Chirped-Pulse Amplification involves stretching the pulse before amplifying it, and then compressing it later.

We can stretch the pulse by a factor of 10,000, amplify it, and then recompress it!

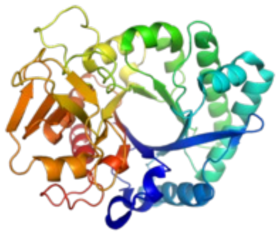
(Copied from Rick Trebino’s slides)

Development of nonlinear optics
Supercontinuum generation as an example

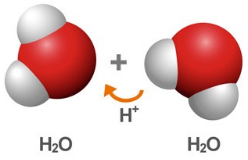


(Copied from Nobel Physics prize 2005 lecture – Theodor W. Haensch

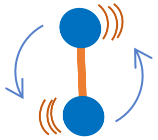
Femtosecond / Attosecond



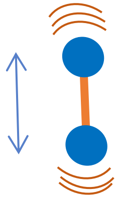
protein motions



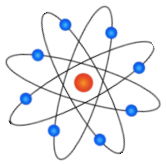
proton transfer



rotations



vibrations



electron motion

1 millisec. 10^{-3} s

1 microsec. 10^{-6} s

1 nanosec. 10^{-9} s

1 picosec. 10^{-12} s

1 femtosec. 10^{-15} s

1 attosec. 10^{-18} s

Ahmed Zewail

Facts

Photo from the Nobel Foundation archive.

Ahmed H. Zewail
Nobel Prize in Chemistry 1999

Born: 26 February 1946, Damanhur, Egypt

Died: 2 August 2016, Pasadena, CA, USA

Affiliation at the time of the award: California Institute of Technology (Caltech), Pasadena, CA, USA

Prize motivation: "for his studies of the transition states of chemical reactions using femtosecond spectroscopy"

Prize share: 1/1

Nobel Prize in Physics 2005

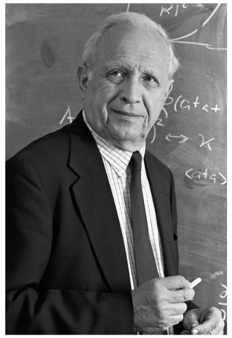


Photo: J.Reed
Roy J. Glauber
Prize share: 1/2

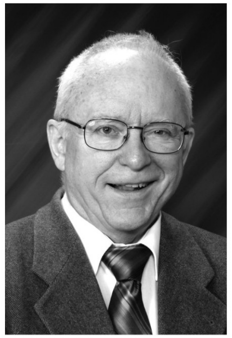
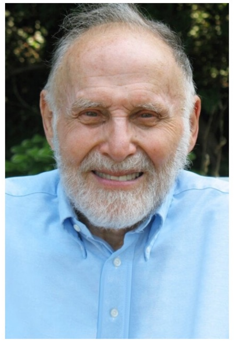


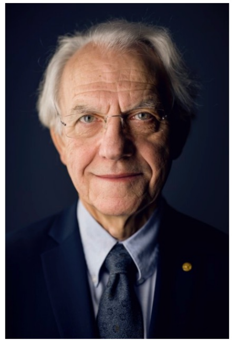
Photo: Sears.P.Studio
John L. Hall
Prize share: 1/4

Photo: F.M. Schmidt
Theodor W. Hänsch
Prize share: 1/4

Nobel Prize in Physics 2018



© Arthur Ashkin
Arthur Ashkin
Prize share: 1/2



© Nobel Prize Outreach. Photo: A. Mahmoud
Gérard Mourou
Prize share: 1/4

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Donna Strickland
Prize share: 1/4

The Nobel Prize in Physics 2023

Ill. Niklas Elmehed © Nobel Prize Outreach
Pierre Agostini

Ill. Niklas Elmehed © Nobel Prize Outreach
Ferenc Krausz

Ill. Niklas Elmehed © Nobel Prize Outreach
Anne L'Huillier

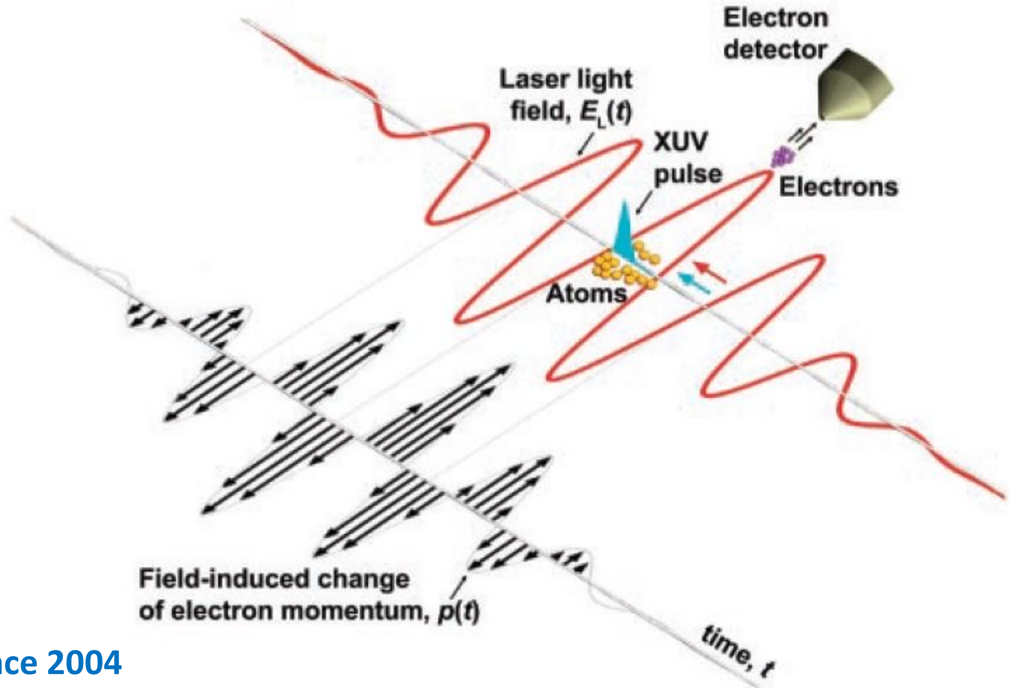
now comes train/isolated attosecond pulses …

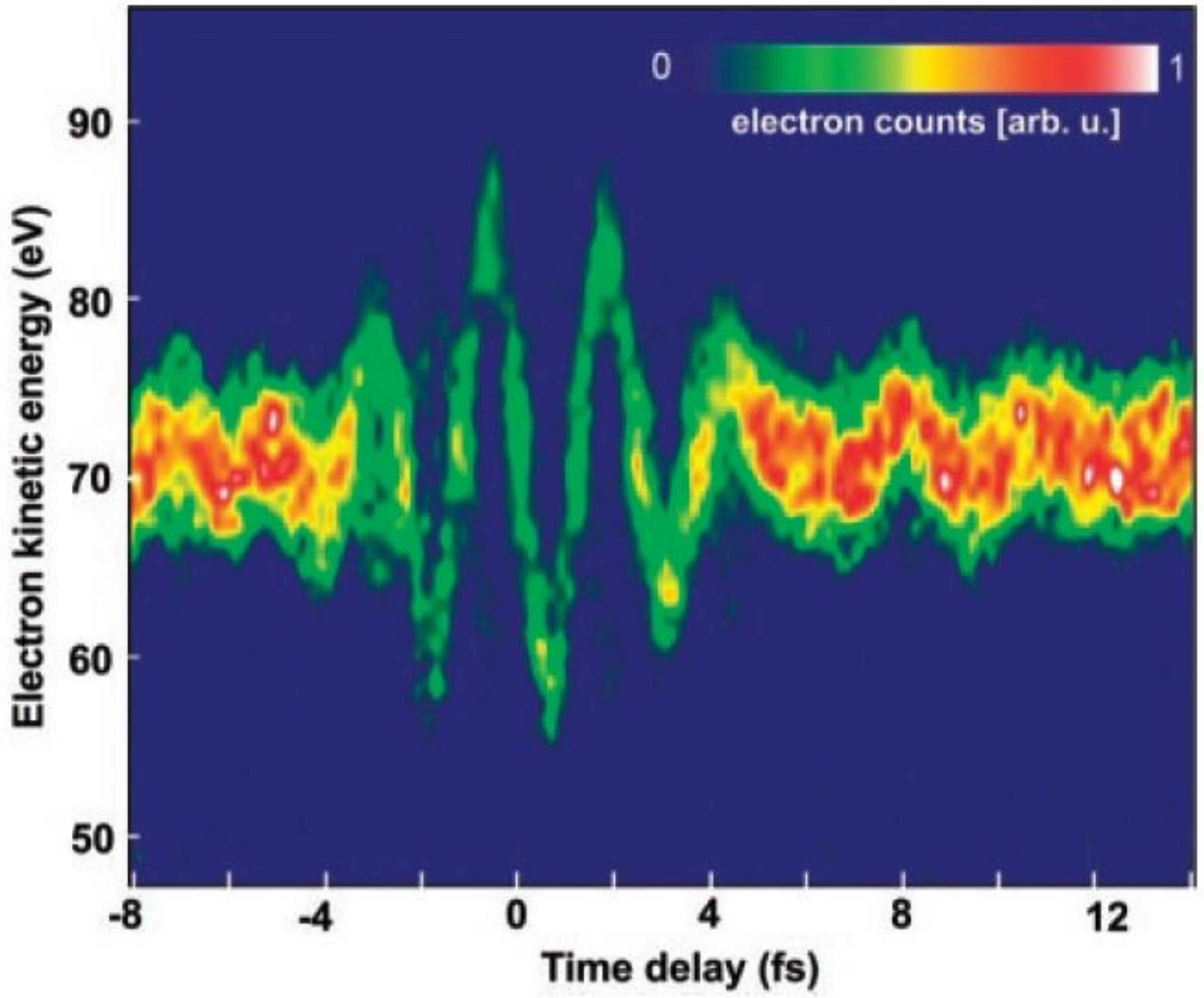
Key papers

Direct Measurement of Light Waves

E. Goulielmakis,[1]* M. Uiberacker,[1]* R. Kienberger,[1] A. Baltuska,[1] V. Yakovlev,[1] A. Scrinzi,[1] Th. Westerwalbesloh,[2] U. Kleineberg,[2] U. Heinzmann,[2] M. Drescher,[2] F. Krausz[1,3]†

The electromagnetic field of visible light performs $\sim 10^{15}$ oscillations per second. Although many instruments are sensitive to the amplitude and frequency (or wavelength) of these oscillations, they cannot access the light field itself. We directly observed how the field built up and disappeared in a short, few-cycle pulse of visible laser light by probing the variation of the field strength with a 250-attosecond electron burst. Our apparatus allows complete characterization of few-cycle waves of visible, ultraviolet, and/or infrared light, thereby providing the possibility for controlled and reproducible synthesis of ultrabroadband light waveforms.





Science 2004


nature
Attosecond physics
Snapshots of an excited atom
LaserFocusWorld
Producing attosecond pulses
PHYSICS TODAY
Science
Attosecond
nature
SEE HOW THEY RUN
www.attoworld.de

Part 3: Applications

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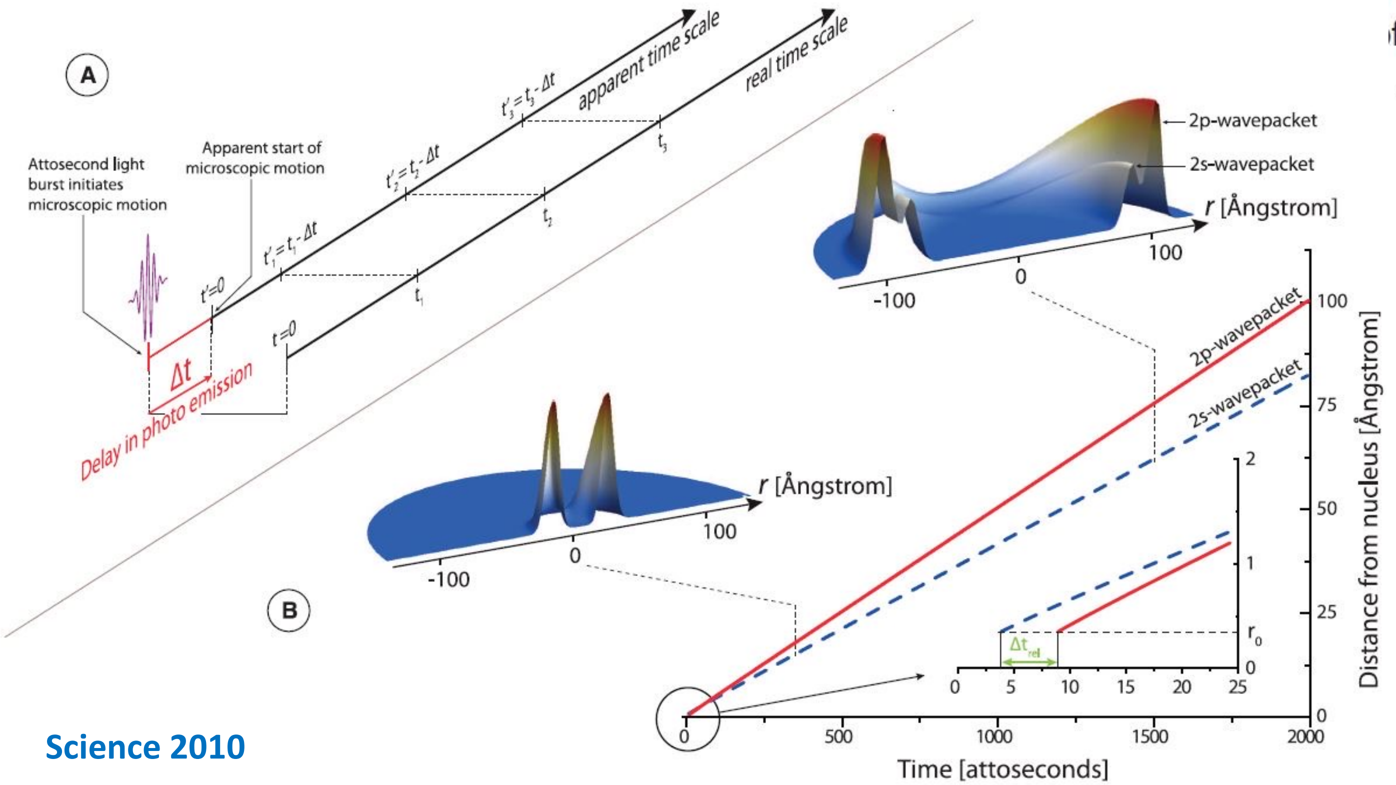
Delay in Photoemission

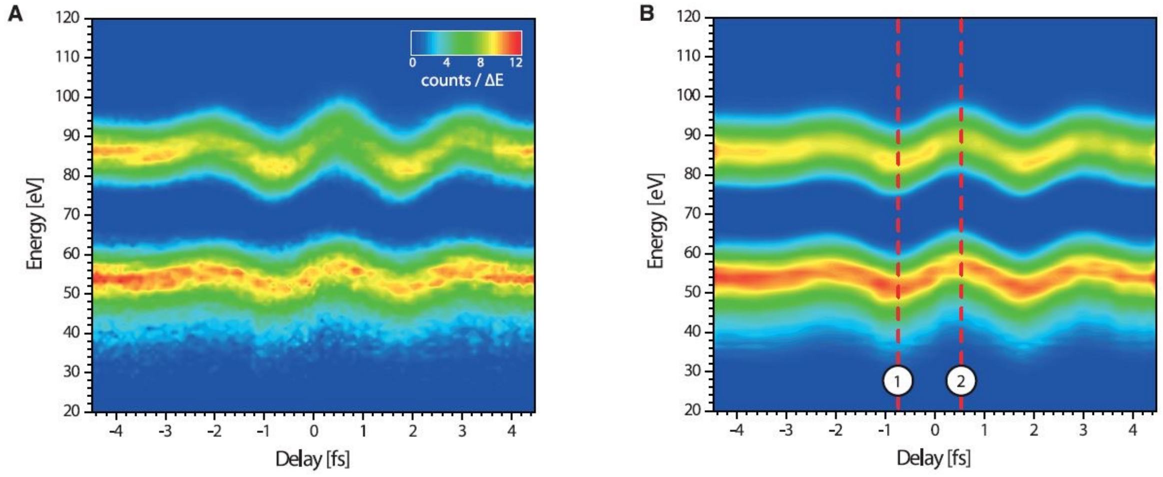
M. Schultze,[1,2]* M. Fieß,[2] N. Karpowicz,[2] J. Gagnon,[1,2] M. Korbman,[2] M. Hofstetter,[1] S. Neppl,[3] A. L. Cavalieri,[2] Y. Komninos,[4] Th. Mercouris,[4] C. A. Nicolaides,[4] R. Pazourek,[5] S. Nagele,[5] J. Feist,[5,6] J. Burgdörfer,[5] A. M. Azzeer,[7] R. Ernstorfer,[3] R. Kienberger,[2,3] U. Kleineberg,[2] E. Goulielmakis,[2] F. Krausz,[1,2] V. S. Yakovlev[1,2]*

Benchmarking fundamentals of quantum mechanics

Extreme temporal resolution is available!

Photoemission from atoms is assumed to occur instantly in response to incident radiation and provides the basis for setting the zero of time in clocking atomic-scale electron motion. We used attosecond metrology to reveal a delay of 21 ± 5 attoseconds in the emission of electrons liberated from the 2*p* orbitals of neon atoms with respect to those released from the 2*s* orbital by the same 100–electron volt light pulse. Small differences in the timing of photoemission from different quantum states provide a probe for modeling many-electron dynamics. Theoretical models
attosecond timing metrology may provide insight into electron correlations
f the zero of time in atomic-scale chronoscopy with a precision of a





Photoemission is instantaneous in QM

Our observation of photoemission is NOT instantaneous

Science 2010

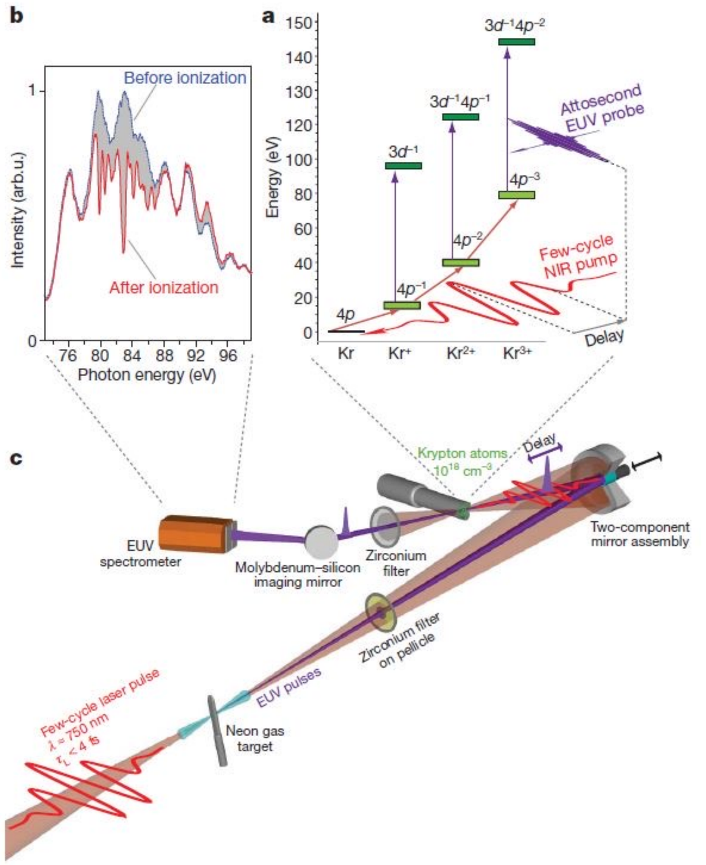

nature
Attosecond physics
Snapshots of an excited atom
LaserFocusWorld
Producing attosecond pulses
PHYSICS TODAY
Science
Attosecond SPECTROSCOPY
nature
SEE HOW THEY RUN
www.attoworld.de

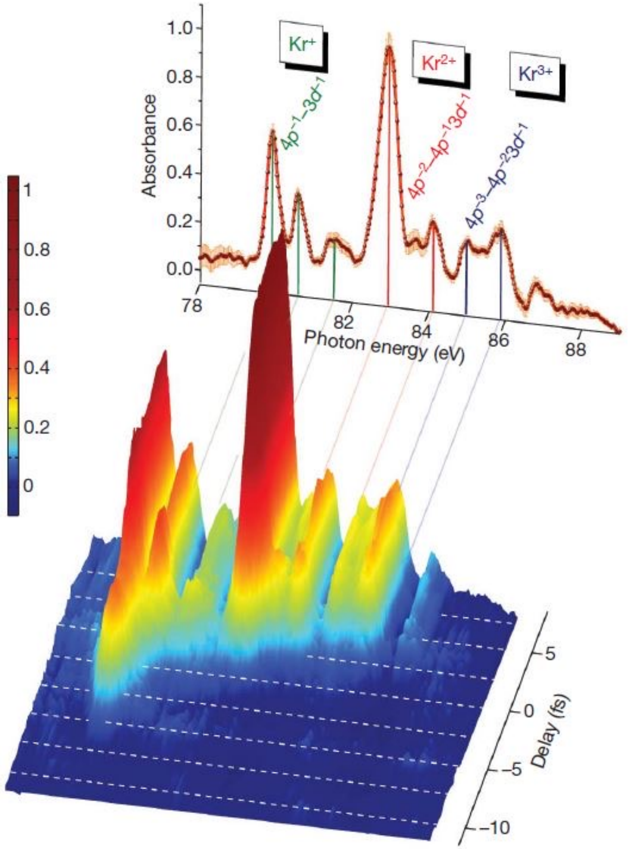
Vol 466 | 5 August 2010 | doi:10.1038/nature09212 nature

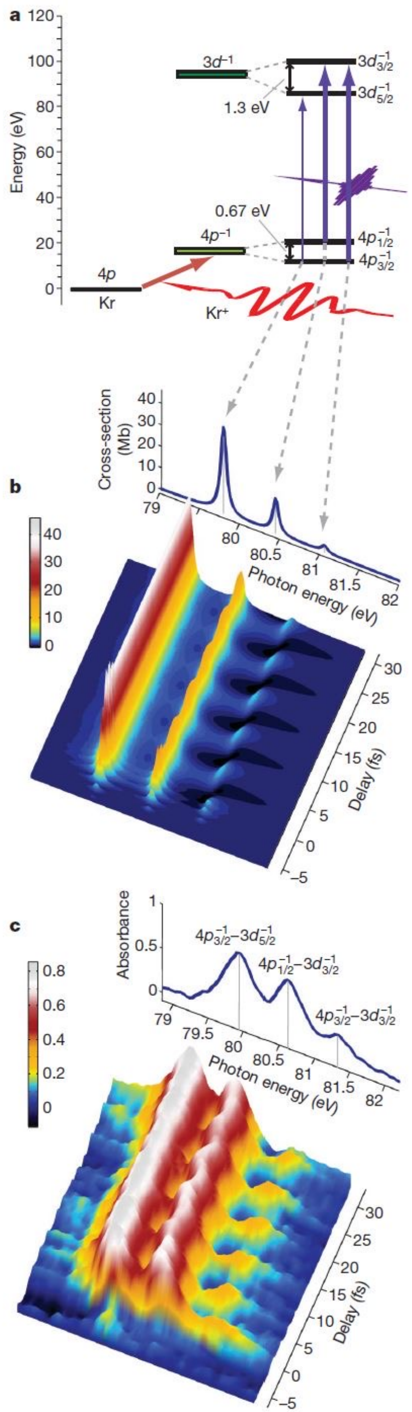
LETTERS

Real-time observation of valence electron motion

Eleftherios Goulielmakis[1]*, Zhi-Heng Loh[2,3]*, Adrian Wirth[1], Robin Santra[4,5], Nina Rohringer[6], Vladislav S. Yakovlev[1,7], Sergey Zherebtsov[1], Thomas Pfeifer[2,3]†, Abdallah M. Azzeer[8], Matthias F. Kling[1], Stephen R. Leone[2,3] & Ferenc Krausz[1,7]







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Thank you for your attention!