

# *Attosecond Science*



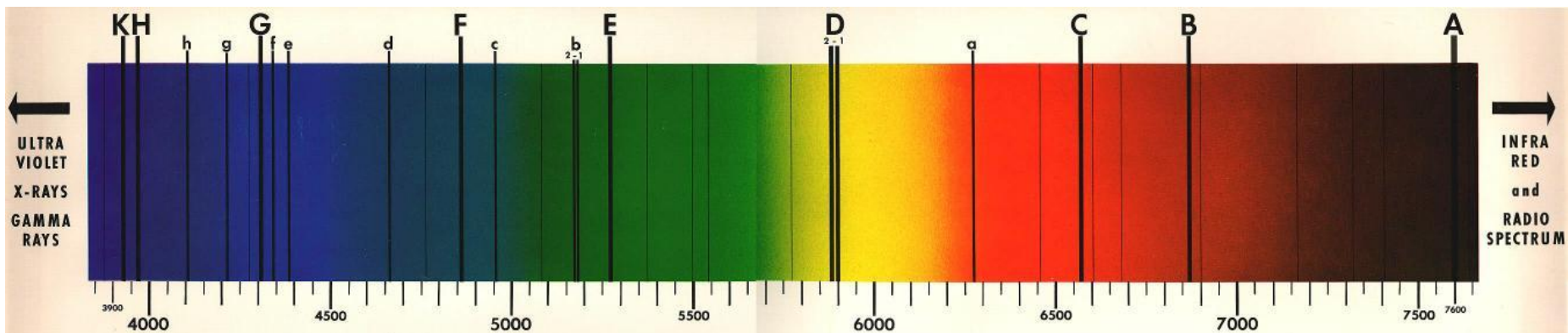
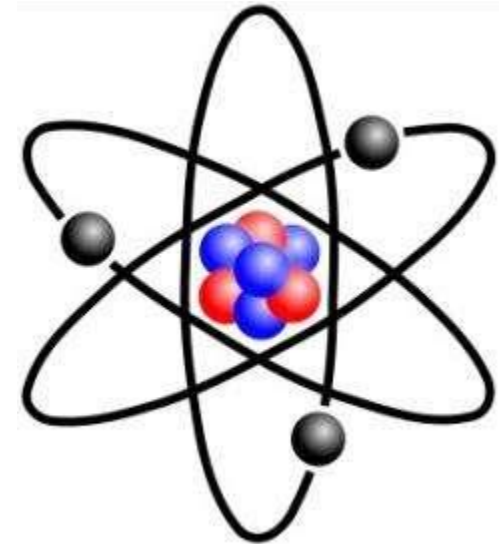
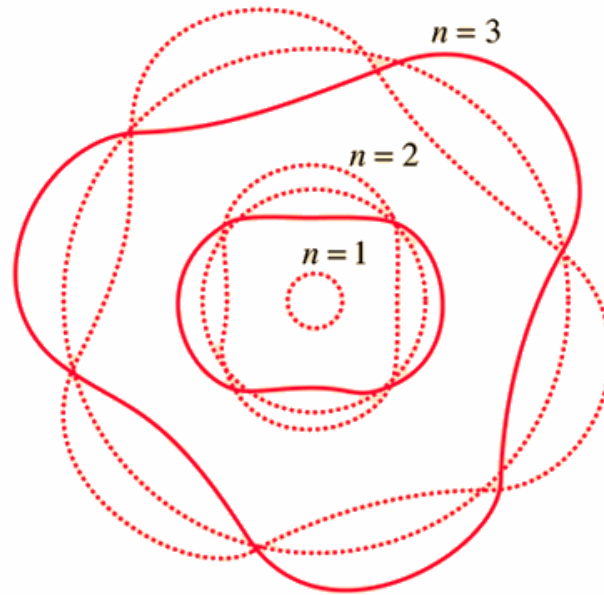
Marc Vrakking

Outreach Symposium on 'Accelerators for Science and Society'

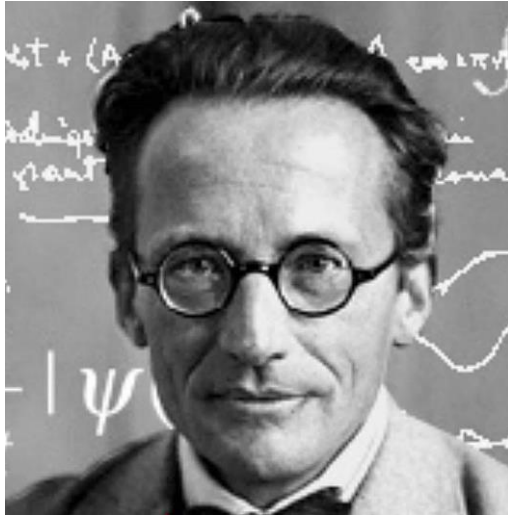
# Our story starts 100 years ago....



Niels Bohr



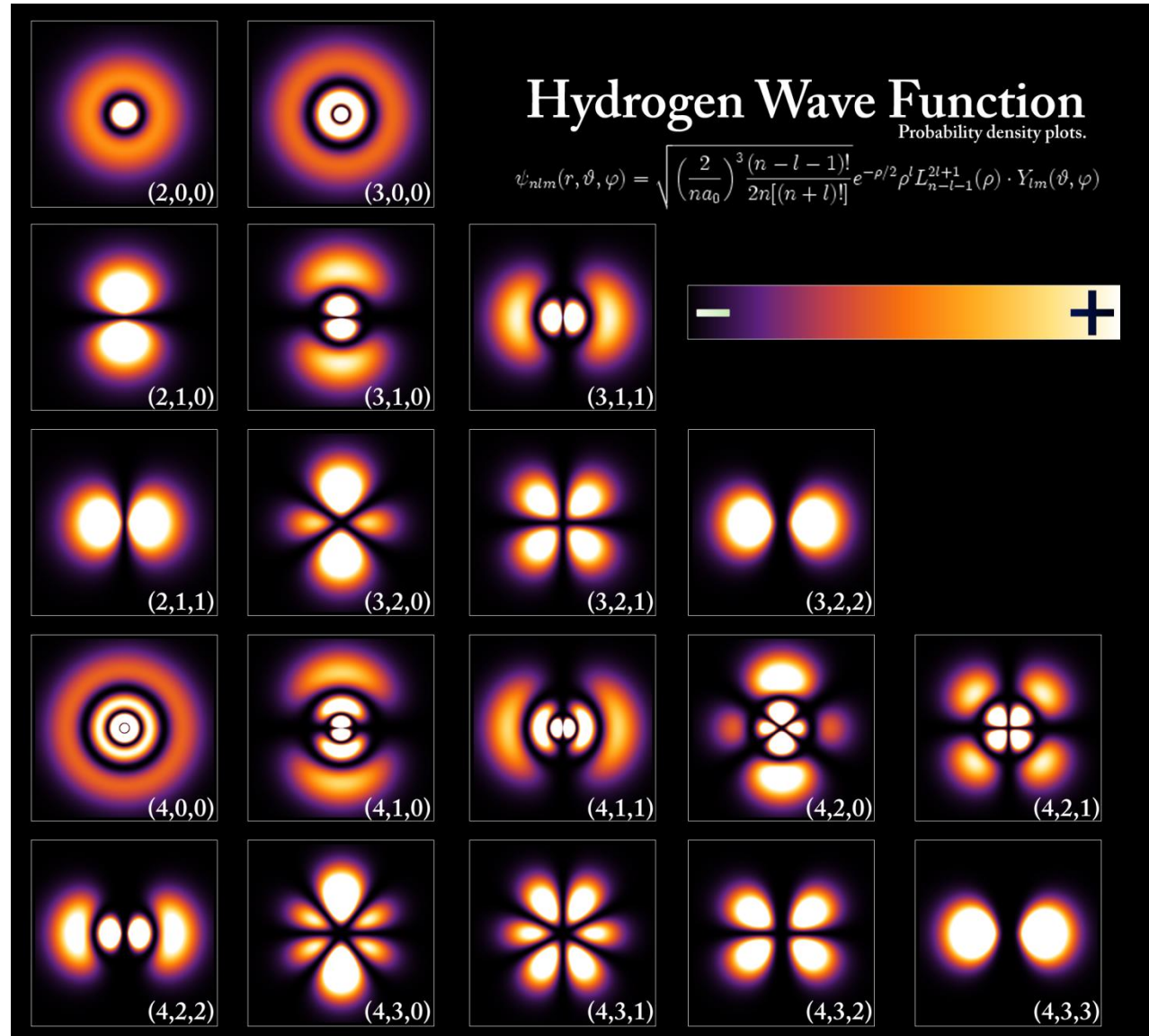
# ... leading to quantum mechanics



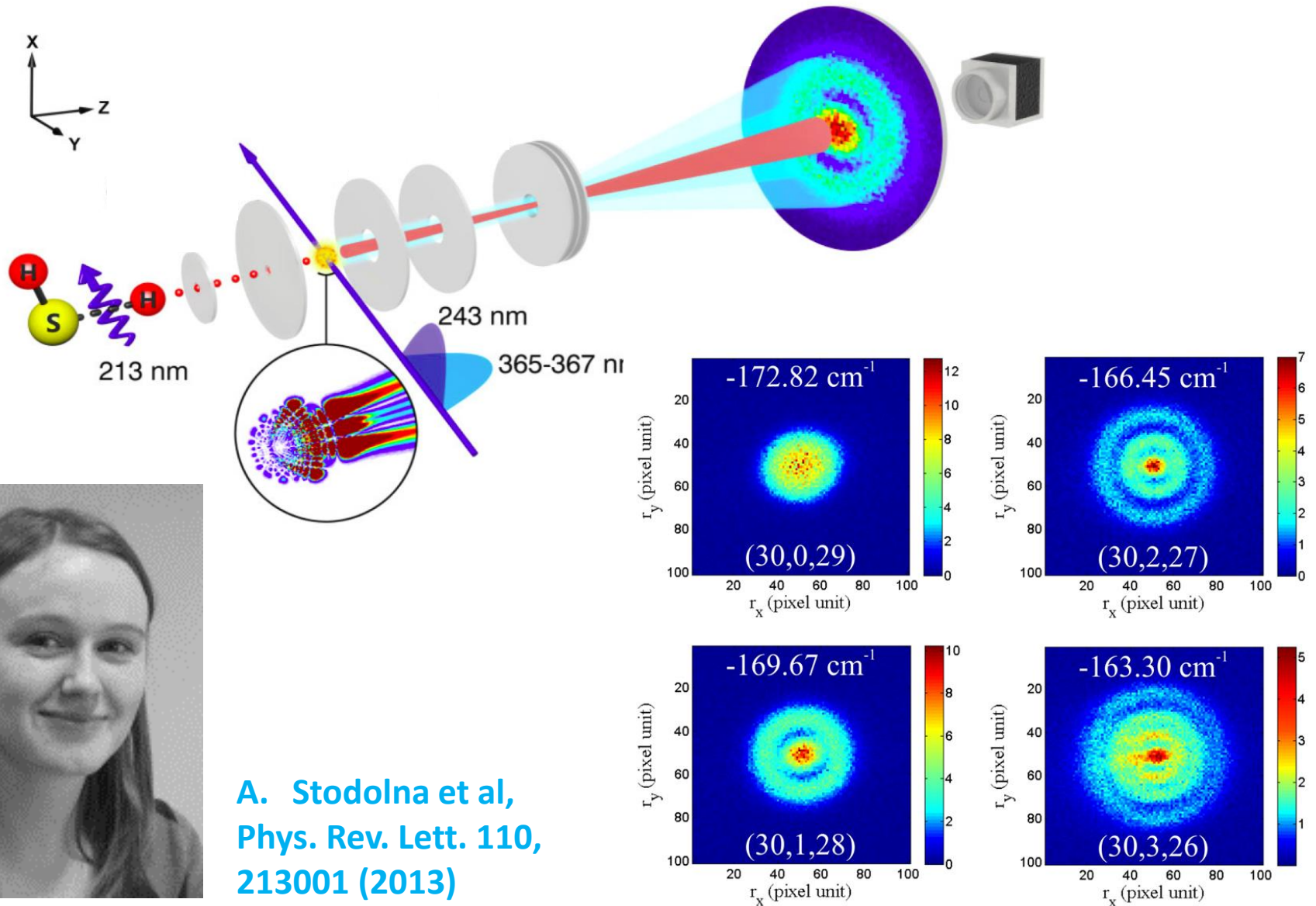
Erwin Schrödinger



Werner Heisenberg

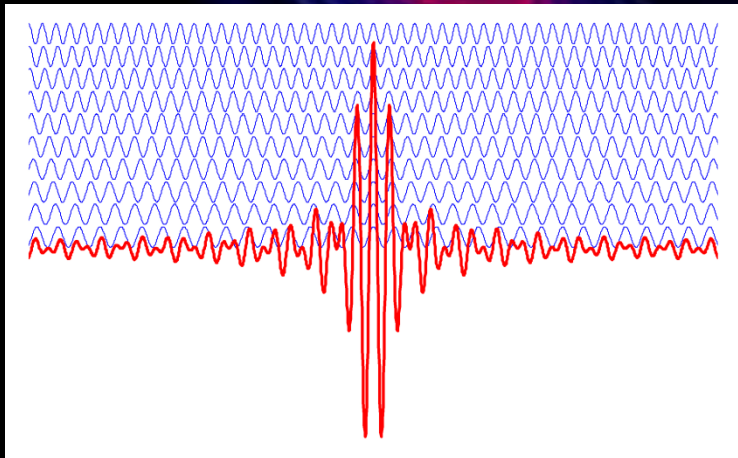
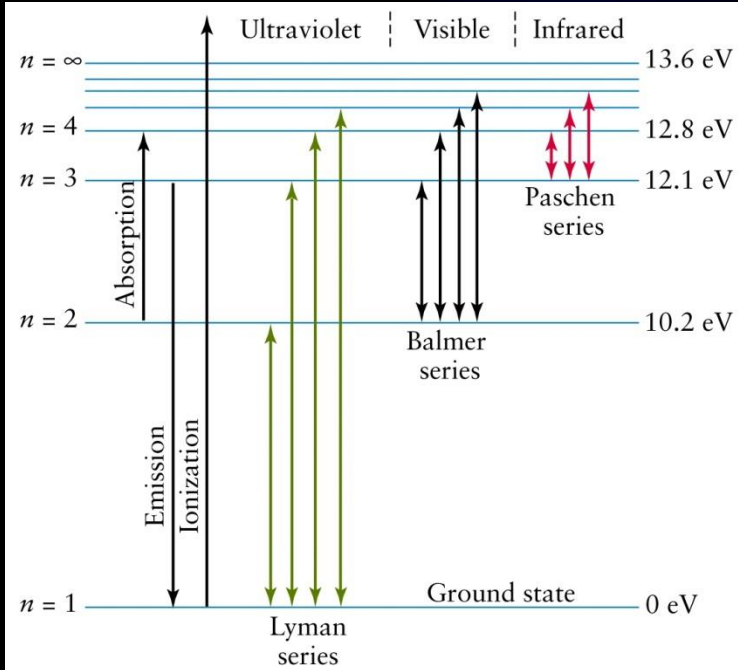


# 2013: first orbital observations

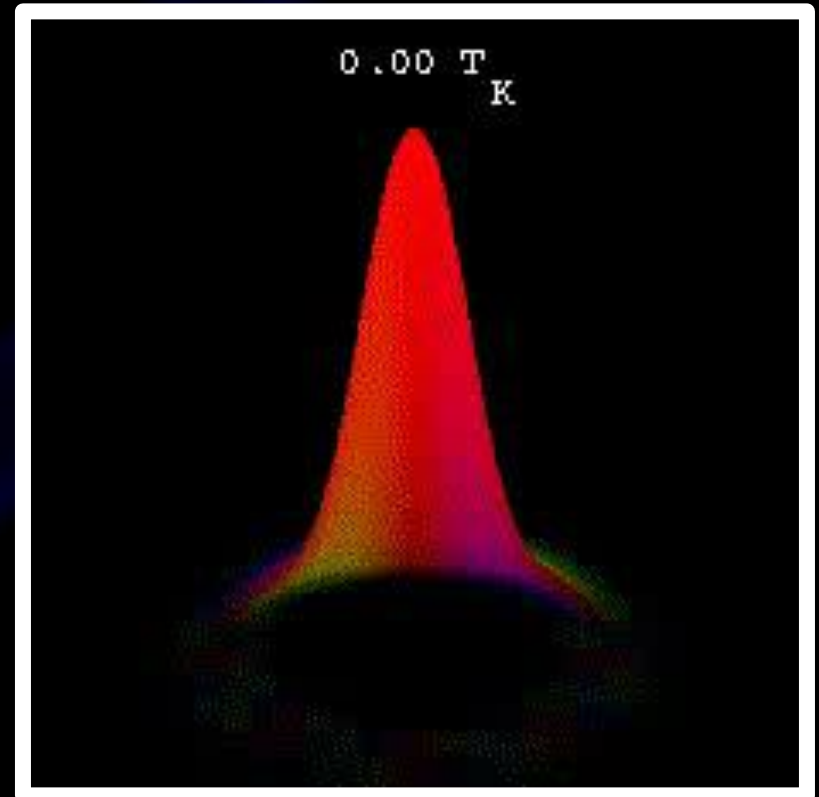


A. Stodolna et al,  
Phys. Rev. Lett. 110,  
213001 (2013)

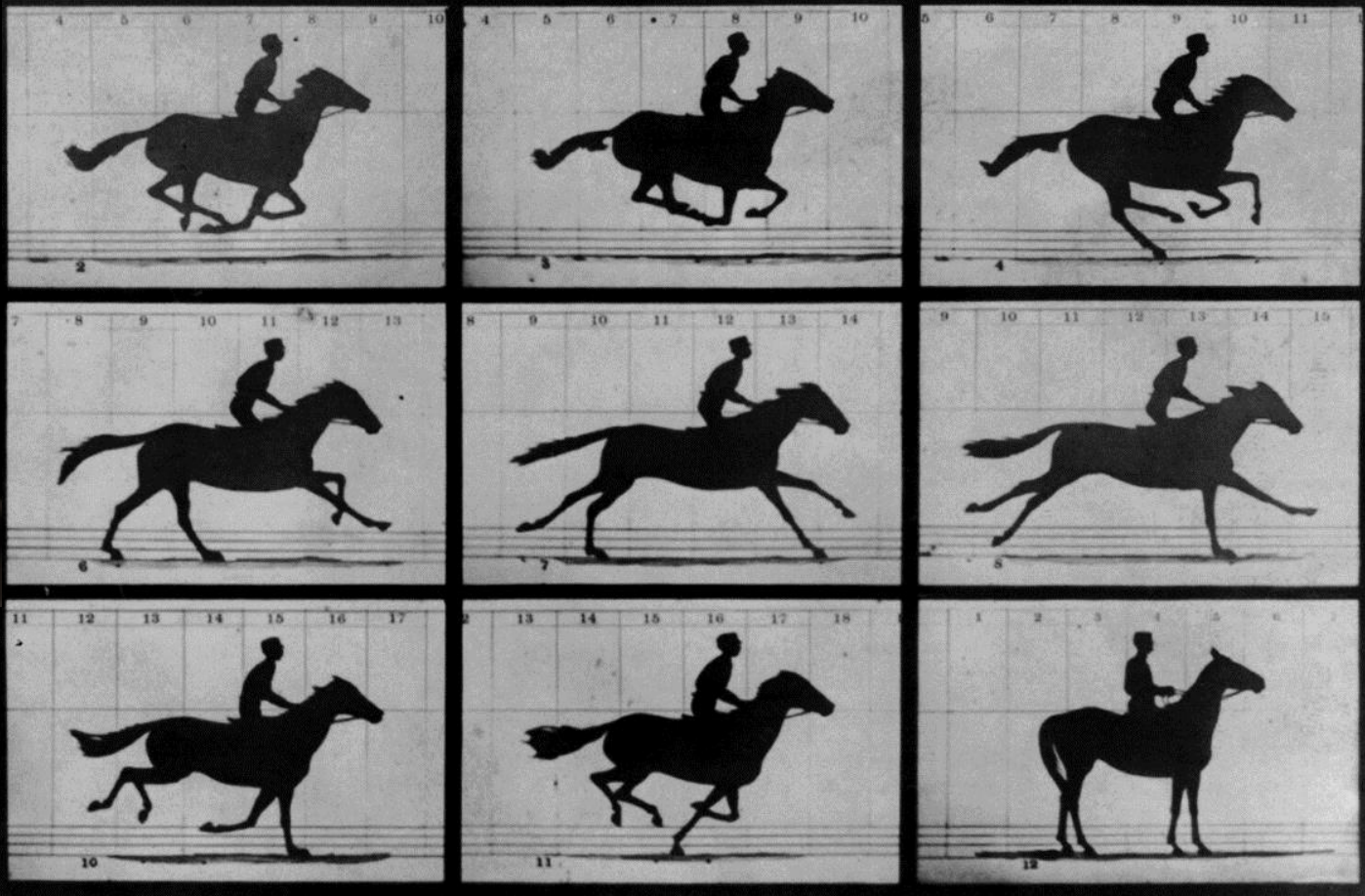
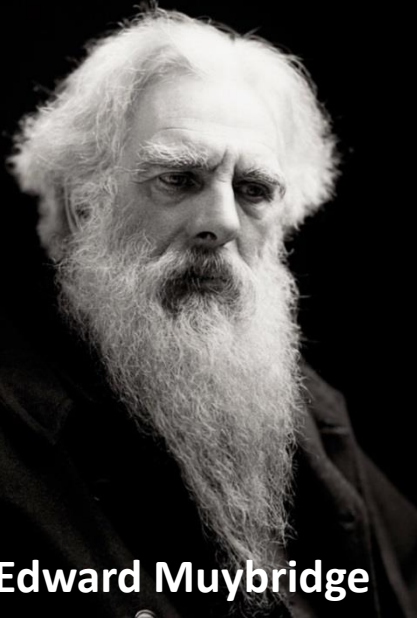
# Recovering the planetary model



*Exciting several electronic levels at the same time leads to the creation of a particle-like wave packet*



# Going back to 1886...



Edward Muybridge

Copyright, 1878, by MUYBRIDGE.

MORSE'S Gallery, 417 Montgomery St., San Francisco.

## THE HORSE IN MOTION.

Illustrated by  
MUYBRIDGE.

AUTOMATIC ELECTRO-PHOTOGRAPH.

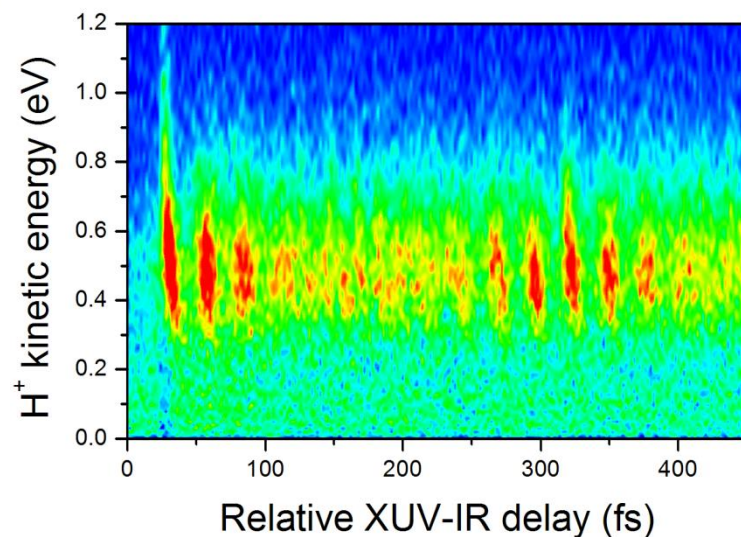
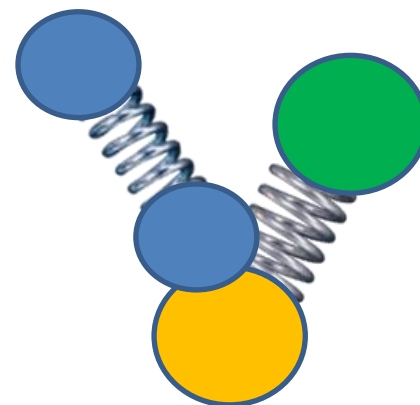
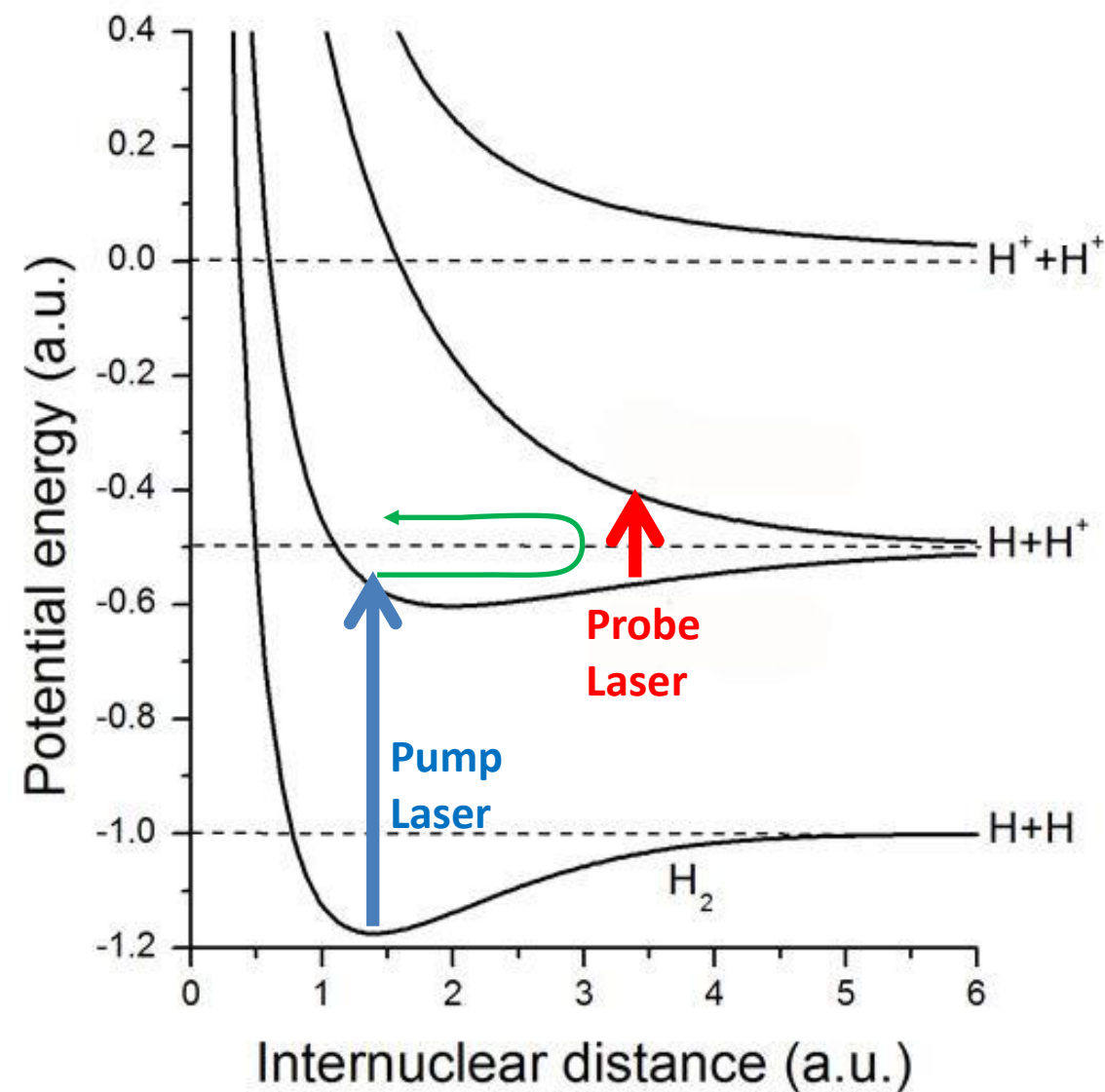
"SALLIE GARDNER," owned by LELAND STANFORD; running at a 1.40 gait over the Palo Alto track, 19th June, 1878.

The negatives of these photographs were made at intervals of twenty-seven inches of distance, and about the twenty-fifth part of a second of time; they illustrate consecutive positions assumed in each twenty-seven inches of progress during a single stride of the mare. The vertical lines were twenty-seven inches apart; the horizontal lines represent elevations of four inches each. The exposure of each negative was less than the two-thousandth part of a second.

# ***Time-Resolved Measurements***



# Snapshots with lasers





***Time Scales:  
From Nano- to Attosecond  
Physical, Chemical and  
Biological Changes***

**Atomic Resolution  
Single Molecule Motion**

**Transition States &  
Reaction Intermediates**

**Femto-  
chemistry**

**IVR & Reaction Products**



**Nano**

**Pico**

**Femto**

Radiative  
Decay

Rotational motion

Vibrational motion

**Fundamentals**

Internal Conversion & Intersystem Crossing

Vibrational  
Relaxation

Collisions in  
Liquids

**Physical**

Predissociation  
Reactions

Harpoon  
Reactions

Norrish  
Reactions

Dissociation  
Reactions

**Chemical**

Proton  
Transfer

Abstraction, Exchange  
& Elimination

Diels-Alder Reactions

Cage Recombination

Protein Motions

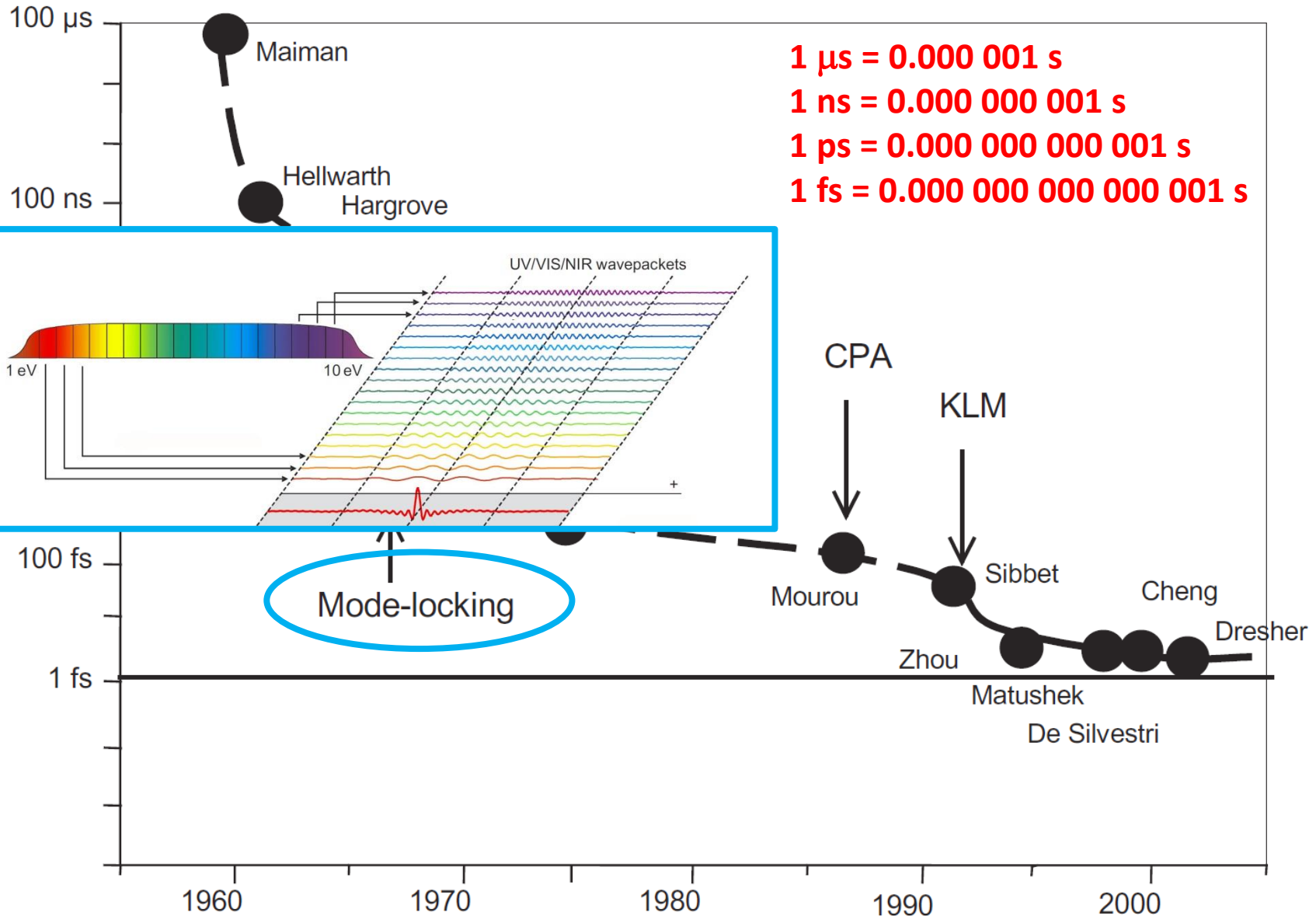
Photosynthesis (ET)  
Vision (isomerization)

**Biological**

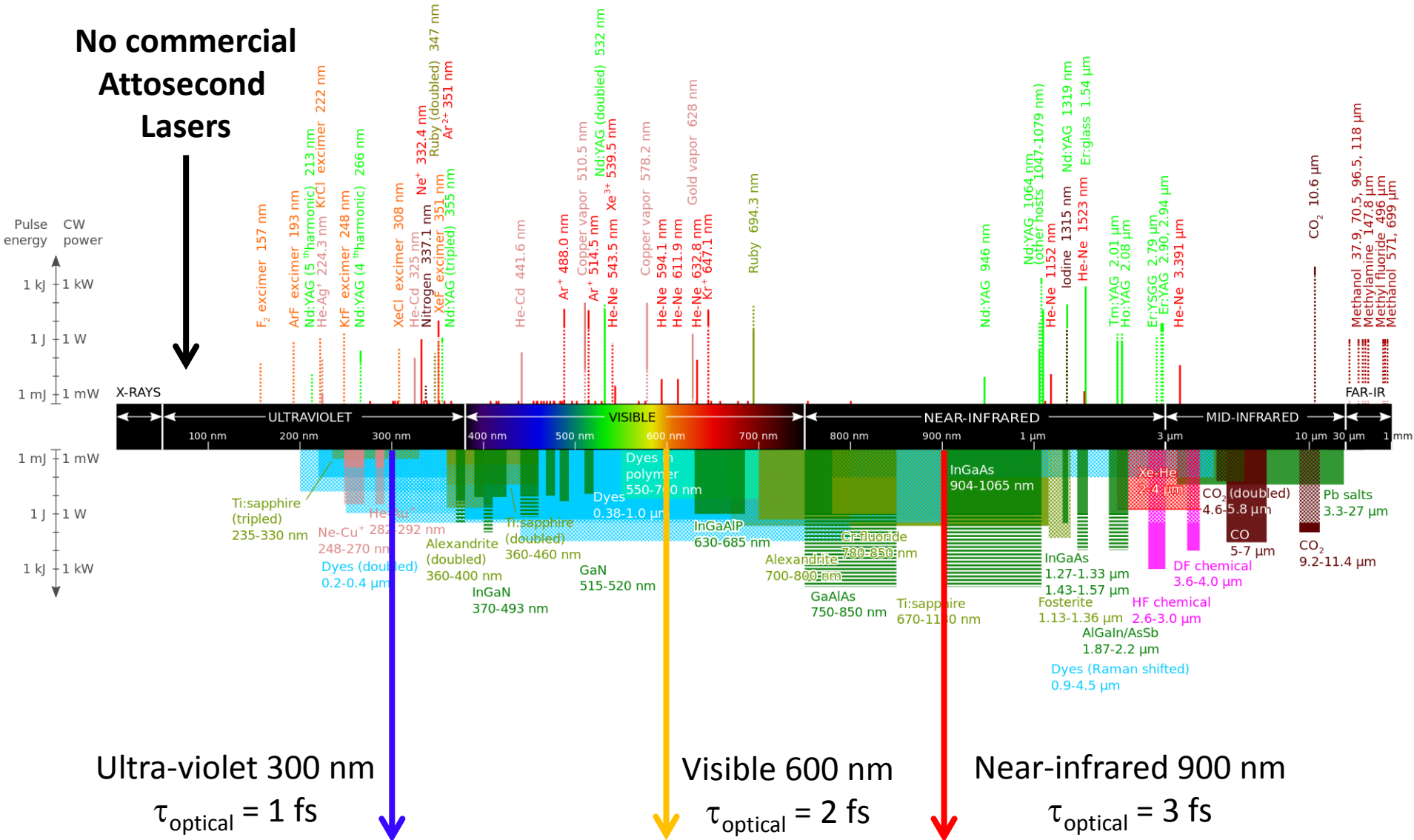
Conical intersections

**After A.H. Zewail, JPC 2000**

# Laser pulse duration

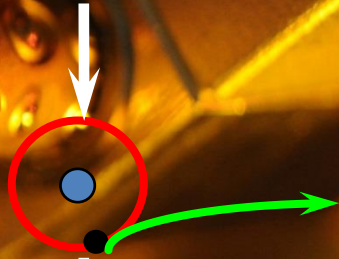


# Lasers cover many wavelengths

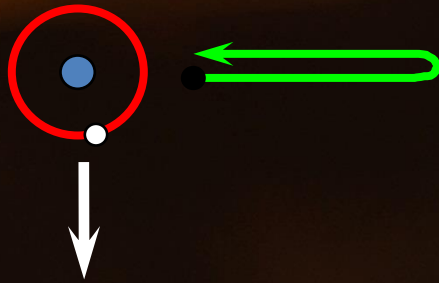


# Generation of attosecond pulses

Intense near-infrared femtosecond laser



Step 1: ionization and removal of an electron from the positive ion core



Step 2: acceleration of the electron in the oscillatory laser field

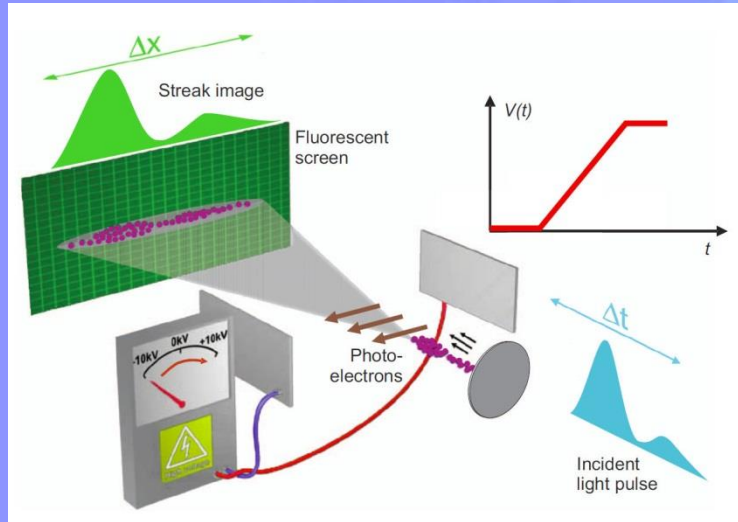


Step 3: recombination, accompanied by the emission of an XUV photon

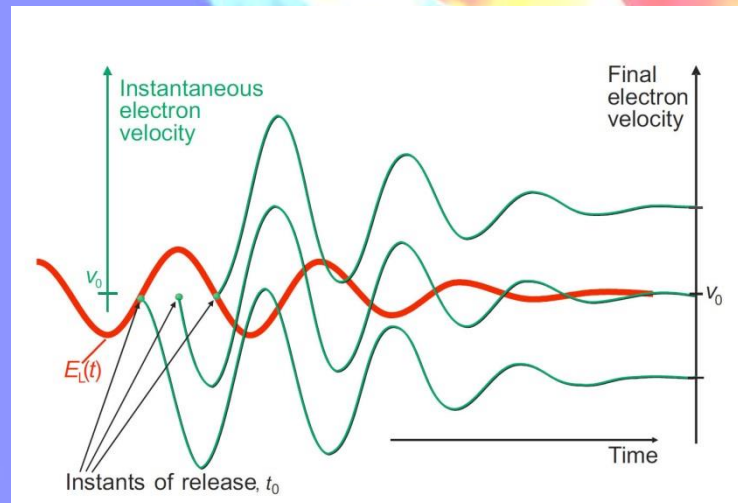
Intense near-infrared femtosecond laser  
+ XUV radiation



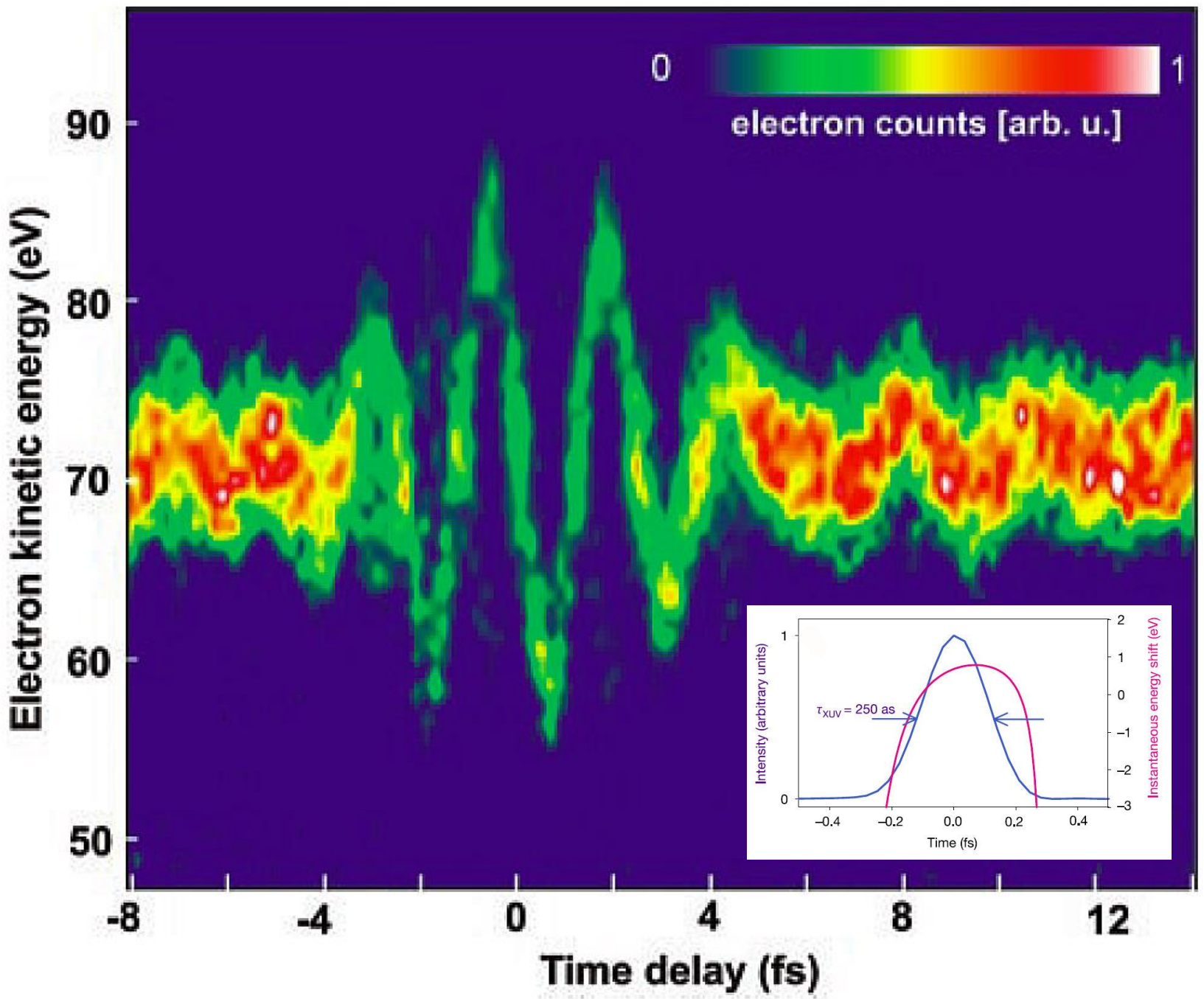
# Measuring attosecond pulses



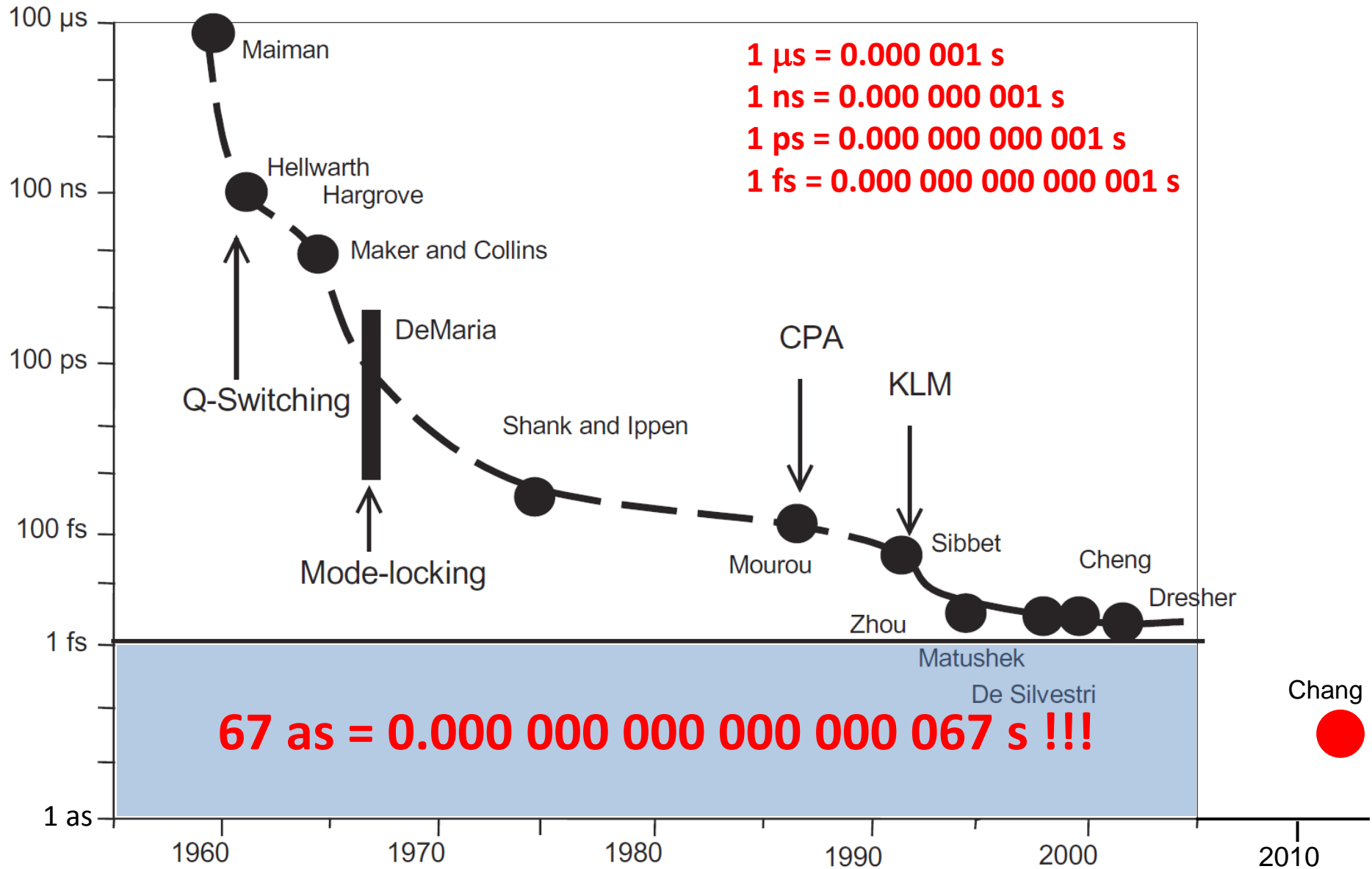
Attosecond pulses cannot be measured by conventional detectors (oscilloscopes) or sophisticated streak cameras



Use an “attosecond streak camera” where the streaking field is itself a laser!!!



# Laser pulse duration



**Time Scales:  
From Nano- to Attosecond  
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Biological Changes**

**Atomic Resolution  
Single Molecule Motion**

**Electron Dynamics**

**Transition States &  
Reaction Intermediates**

**Femto-  
chemistry**

**Atto-  
physics**

**IVR & Reaction Products**



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**Pico**

**Femto**

**Atto**

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Decay

Rotational motion

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**Fundamentals**

Photoabsorption

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Vibrational  
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Collisions in  
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**Physical**

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Auger excitation

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Harpoon  
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(e,e) coupling

Proton  
Transfer

Abstraction, Exchange  
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**Chemical**

(e,atom) coupling

Cage Recombination

Protein Motions

Photosynthesis (ET)  
Vision (isomerization)

**Biological**

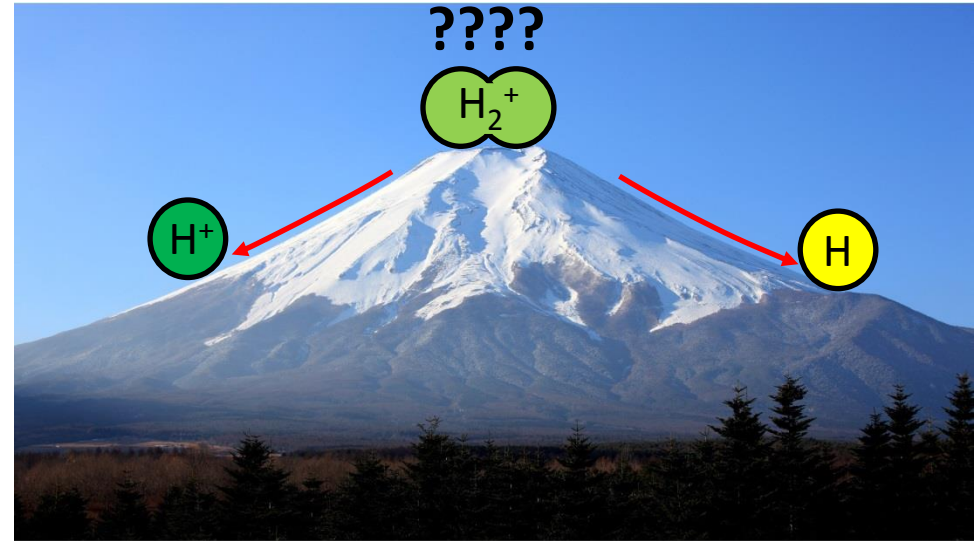
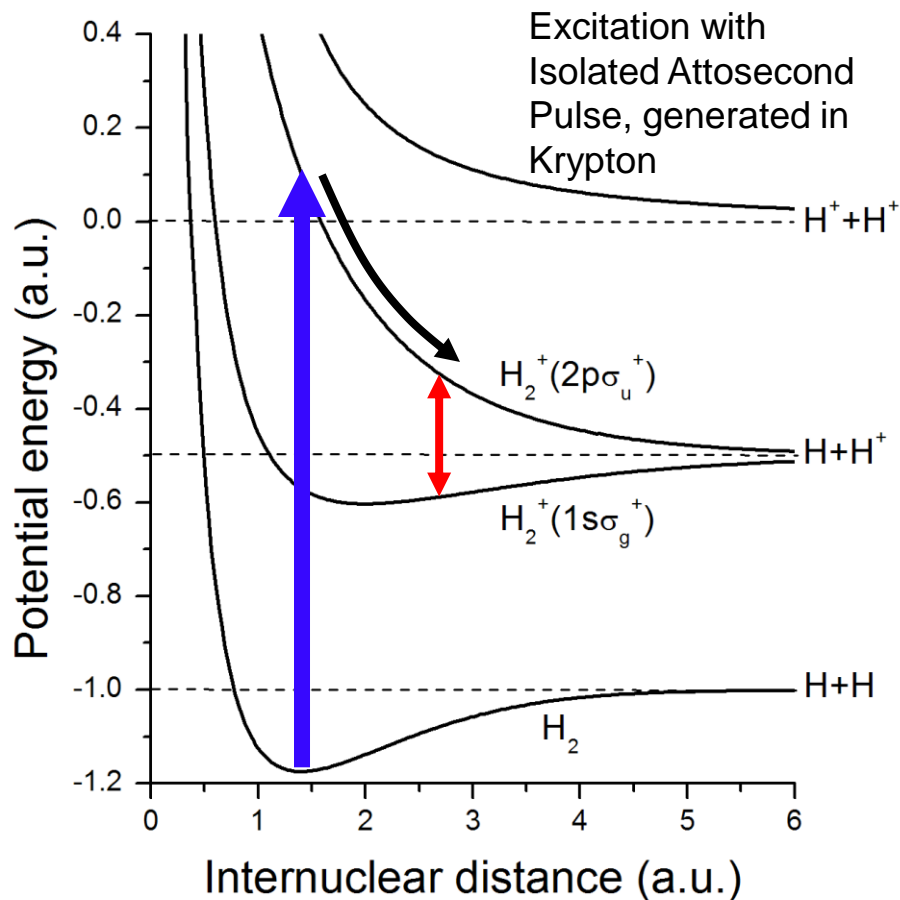
electron migration

Conical intersections

**After A.H. Zewail, JPC 2000**



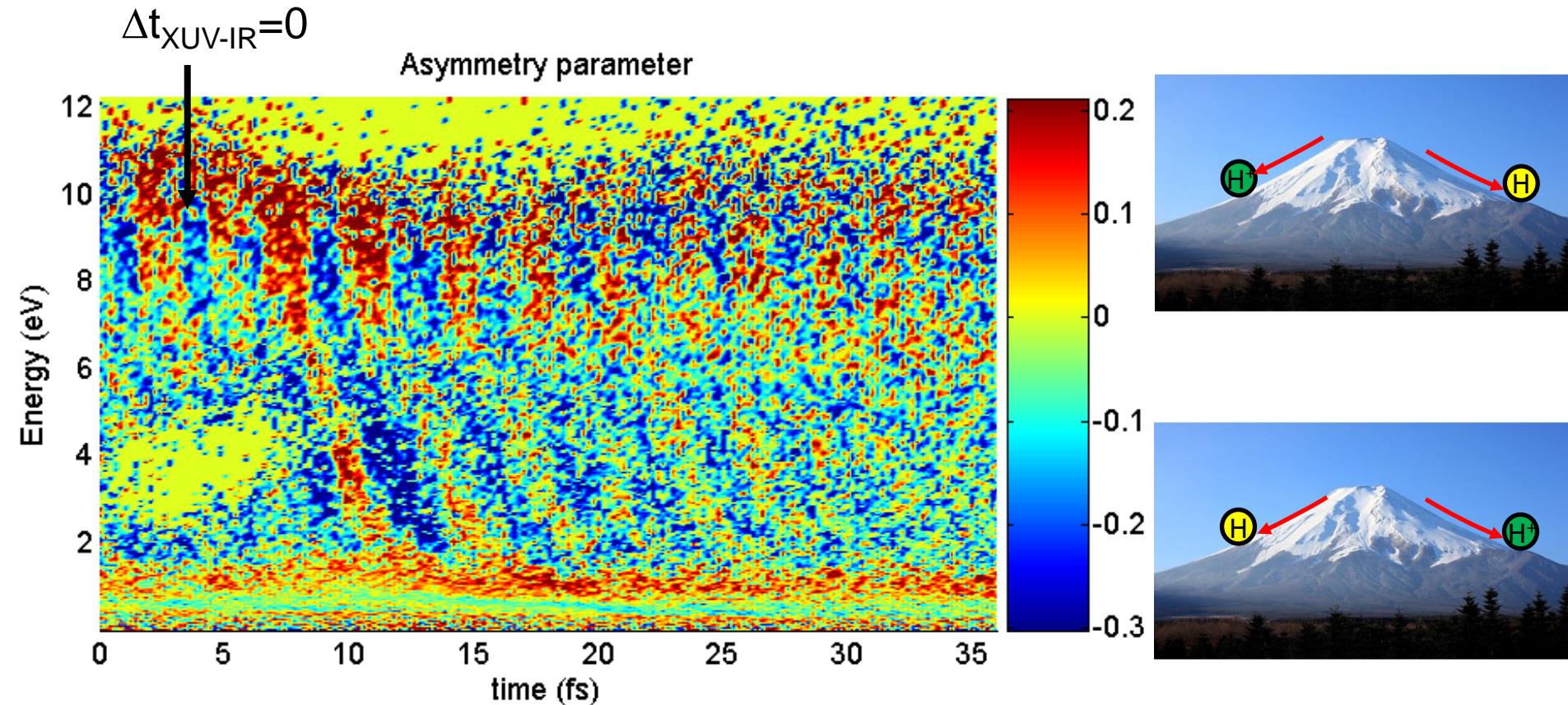
# Measurements with attosecond pulses



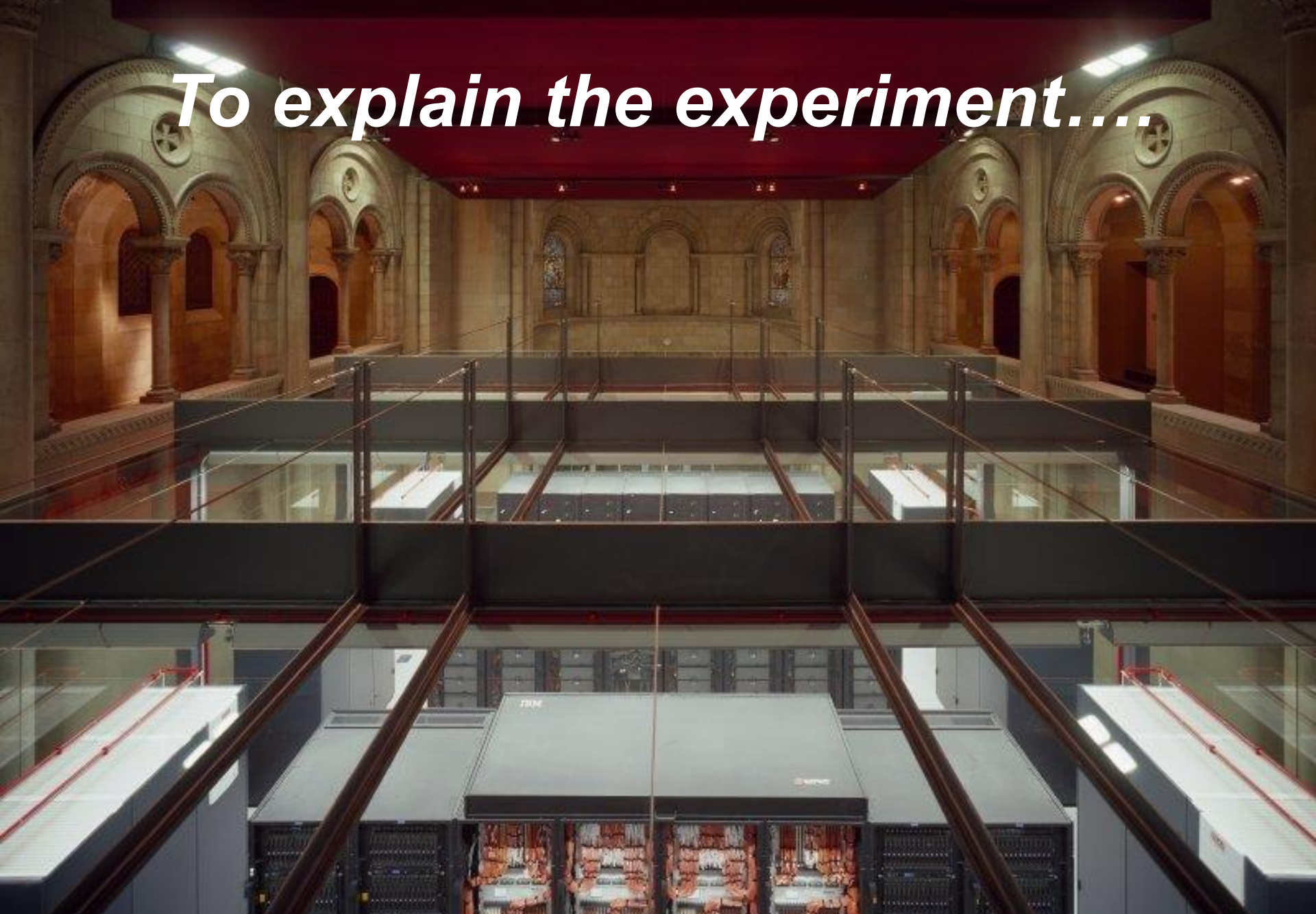
Does the H atom (containing one electron) go the left or the right?

Does the  $H^+$  ion (not containing an electron) go to the right or left?

# *Electron localization in XUV-IR dissociative ionization of $H_2$ and $D_2$*

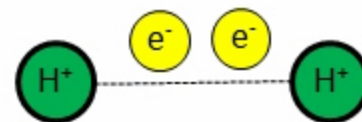
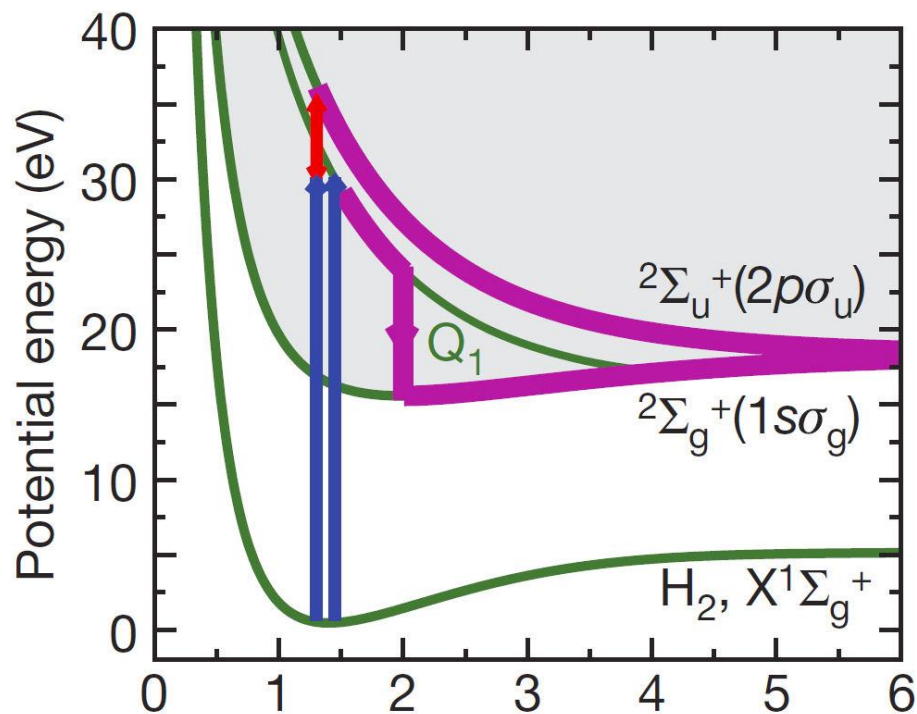


*To explain the experiment....*

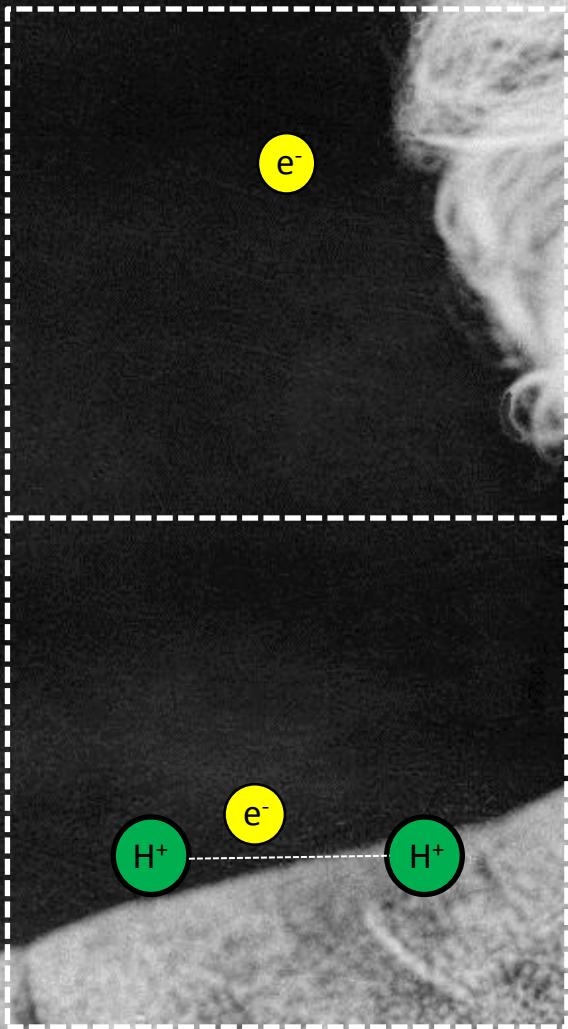


**Collaboration with F. Martin and co-workers (Madrid)**

# Scenarios for Electron Localization



# Quantum Entanglement



*Hmmm...  
spooky  
action at a  
distance*



***Thanks for your  
attention***

**Marc Vrakking**

Outreach Symposium on 'Accelerators for Science and Society'