Catching Electrons with Light

Julien Bertrand

Paul.Corkum@nrc.ca

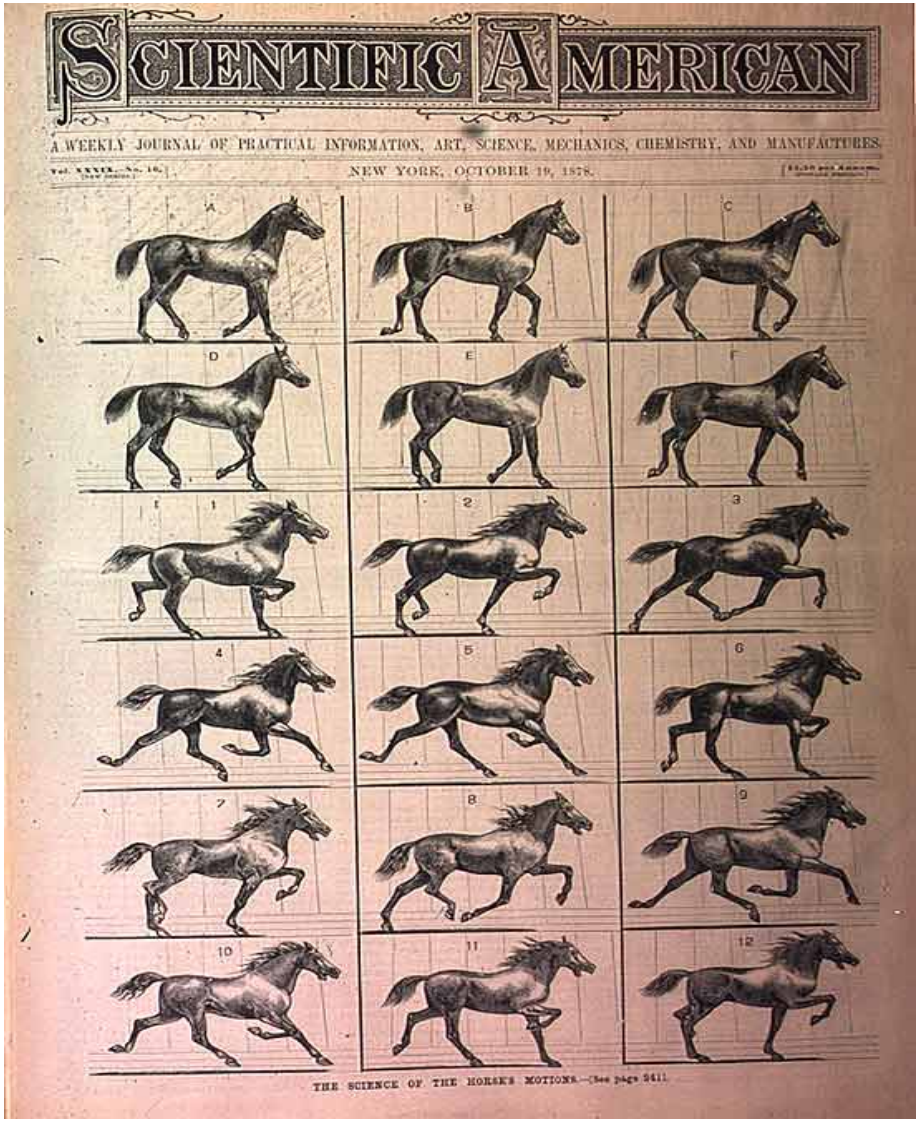
Sarah Golin

uOttawa

“Milli”-Science – Catching a horse in mid-trot

Eadward Muybridge

The first movies


SCIENTIFIC AMERICAN

A WEEKLY JOURNAL OF PRACTICAL INFORMATION, ART, SCIENCE, MECHANICS, CHEMISTRY, AND MANUFACTURES.

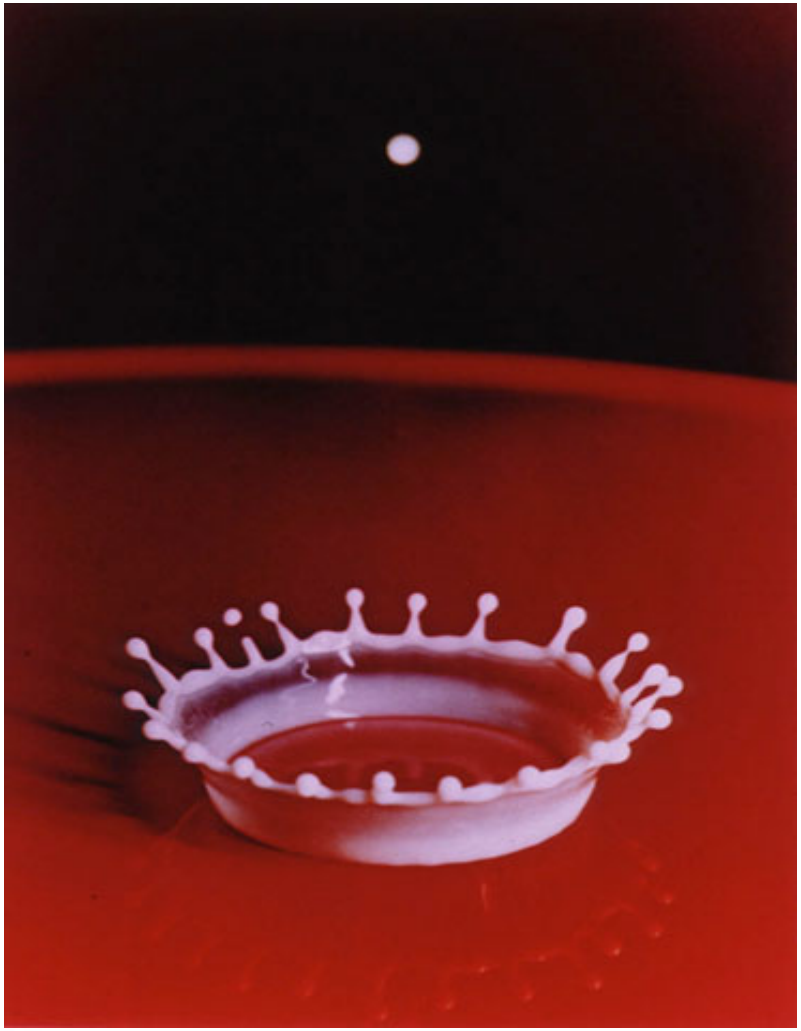
NEW YORK, OCTOBER 19, 1878.

THE SCIENCE OF THE HORSE'S MOTIONS.—(See page 241.)

An important technical question of 1878

uOttawa

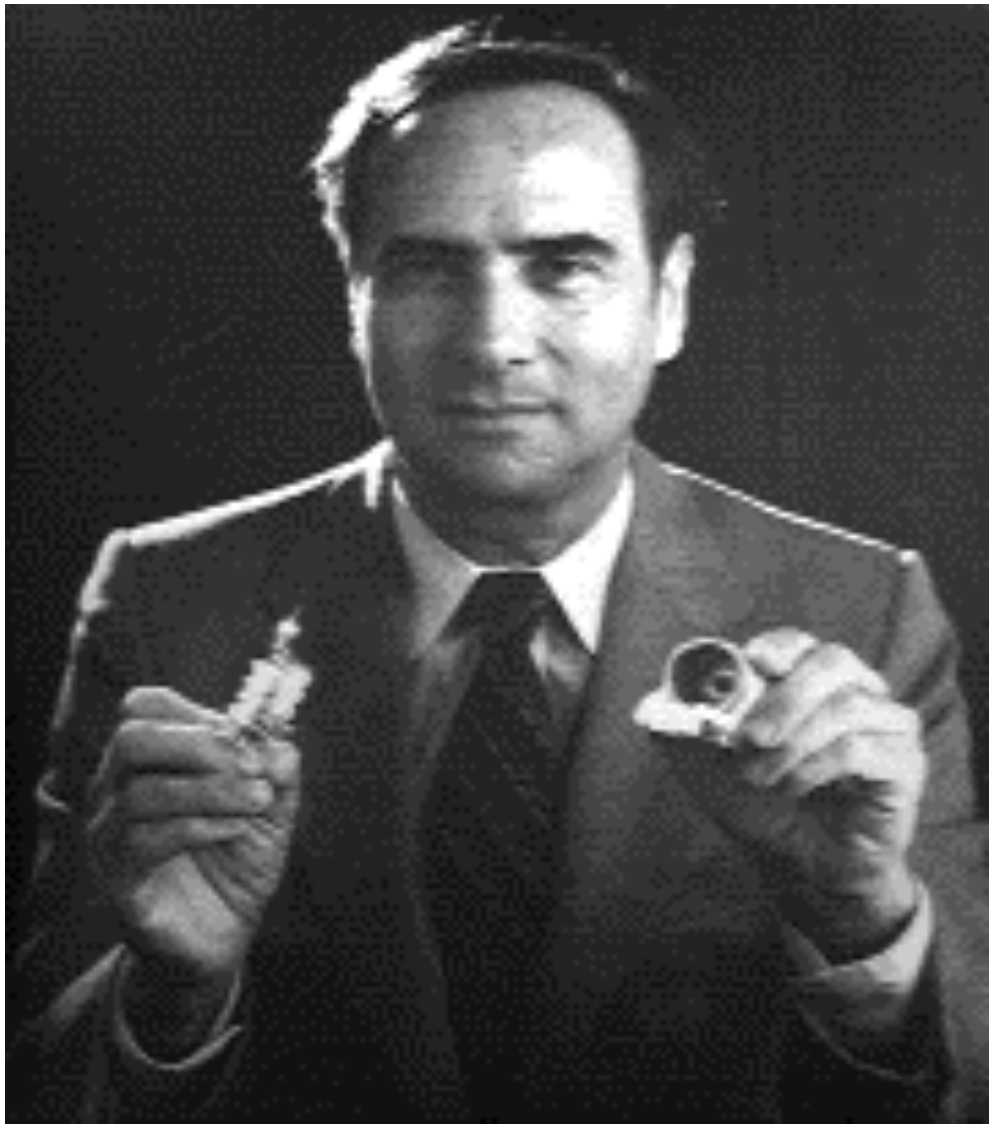
“Micro”-science: Art and Science are one



Harold E. Edgerton

1938

And then came the laser



The laser changed everything!

Theodore H. Maiman,

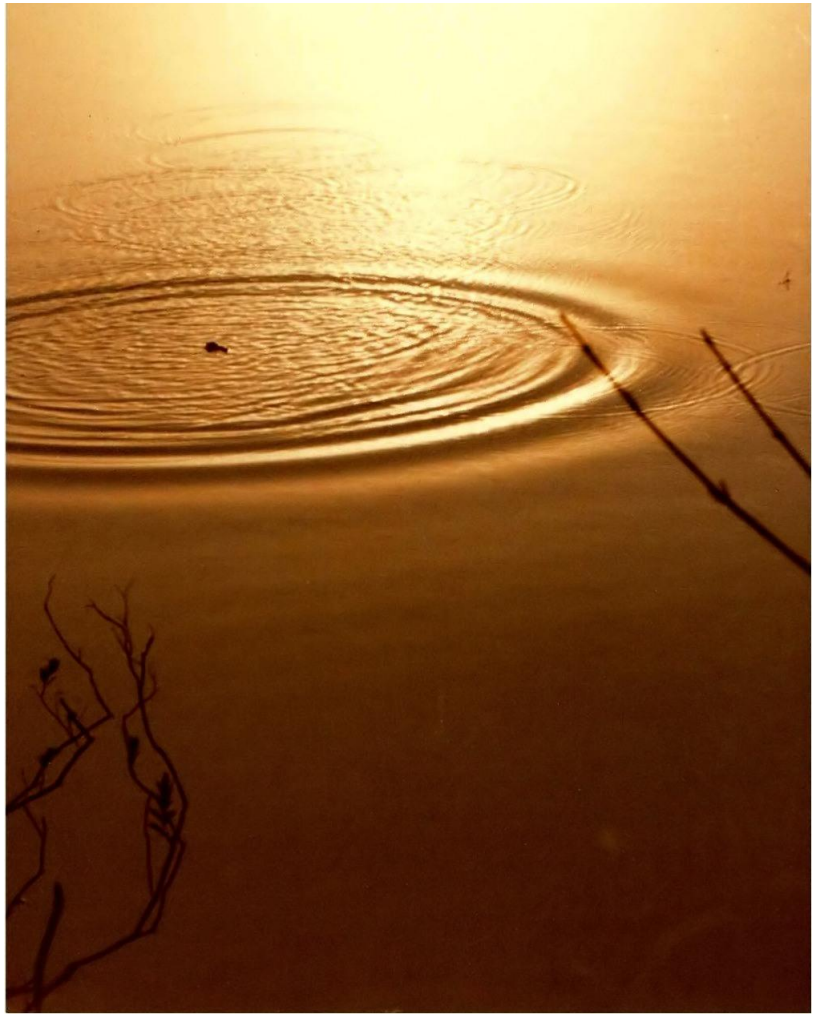
May 1960

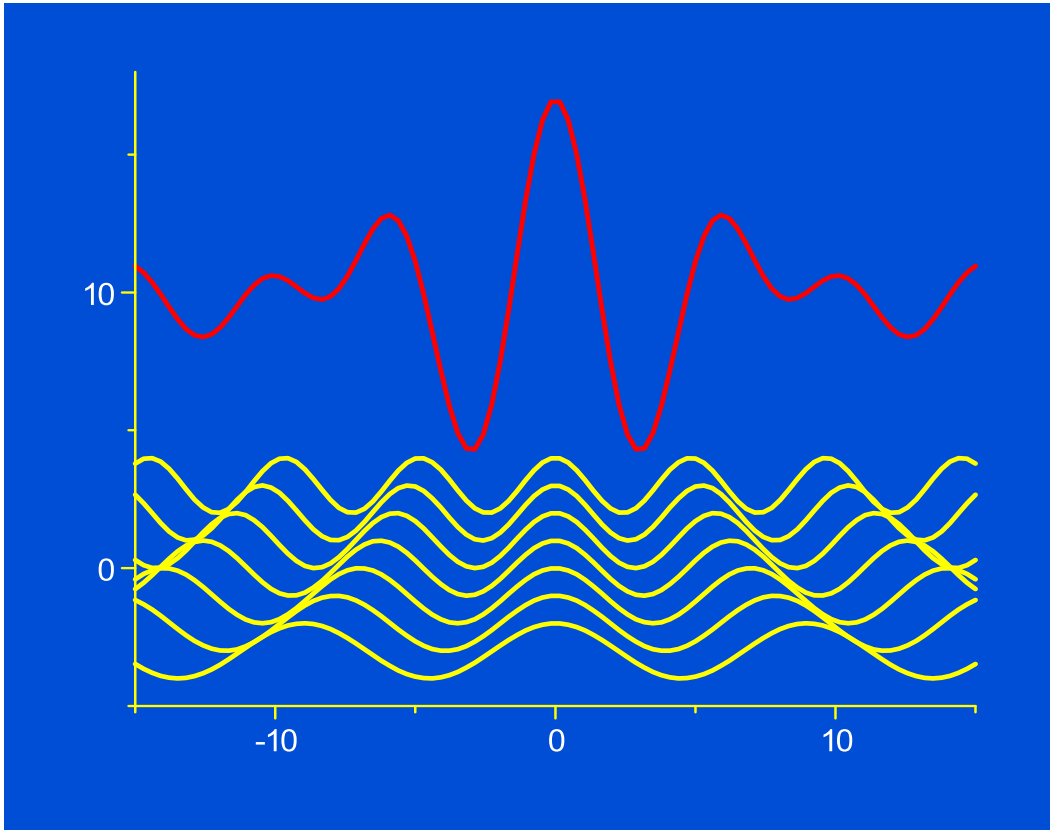
Did you know that the first laser has been here, in Vancouver, since 1999?

Lasers control light

uOttawa

How to make a short flash of light

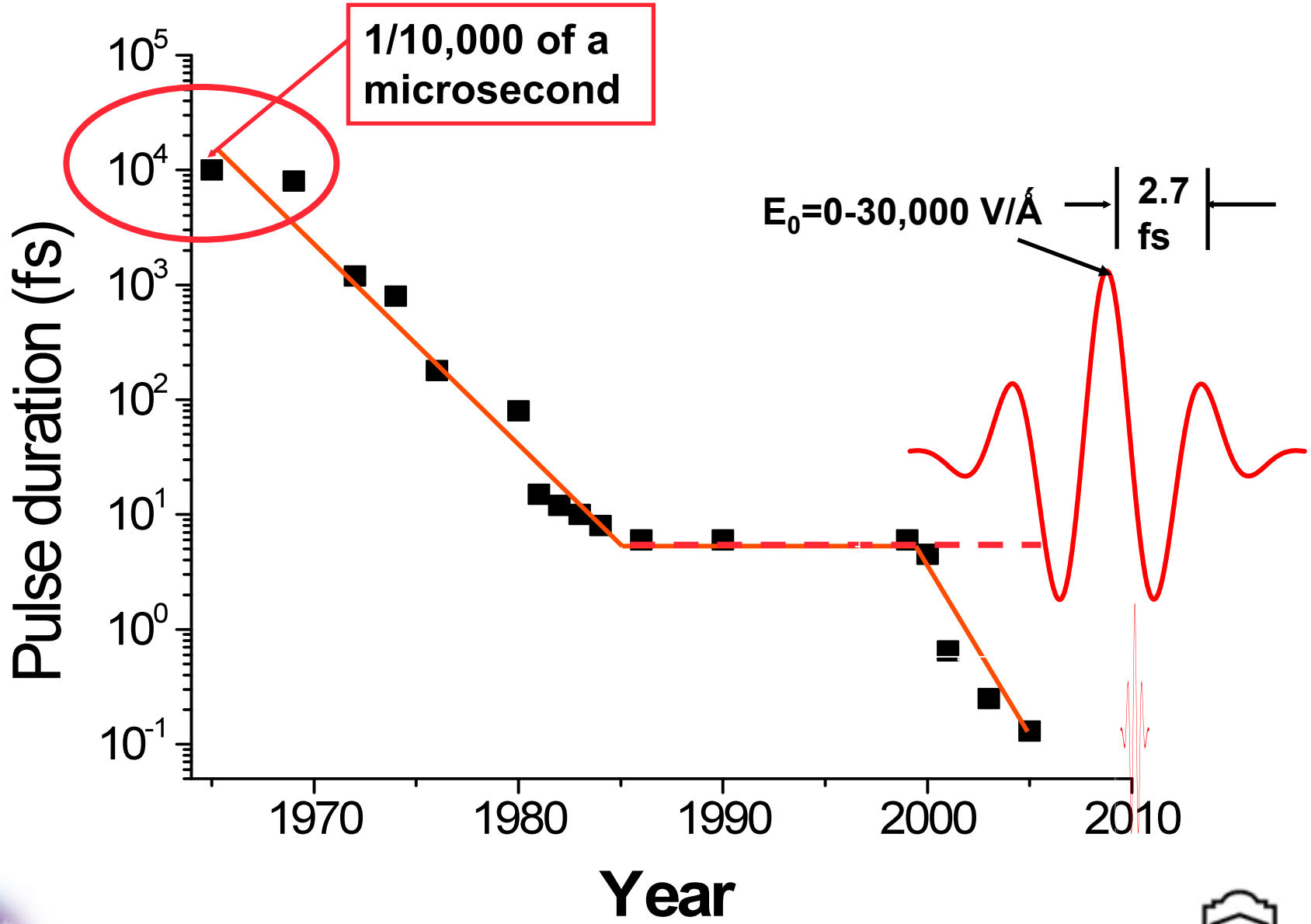




What is the new technology?

uOttawa

A discontinuity in technology



- Divide one second into 1,000,000,000 pieces

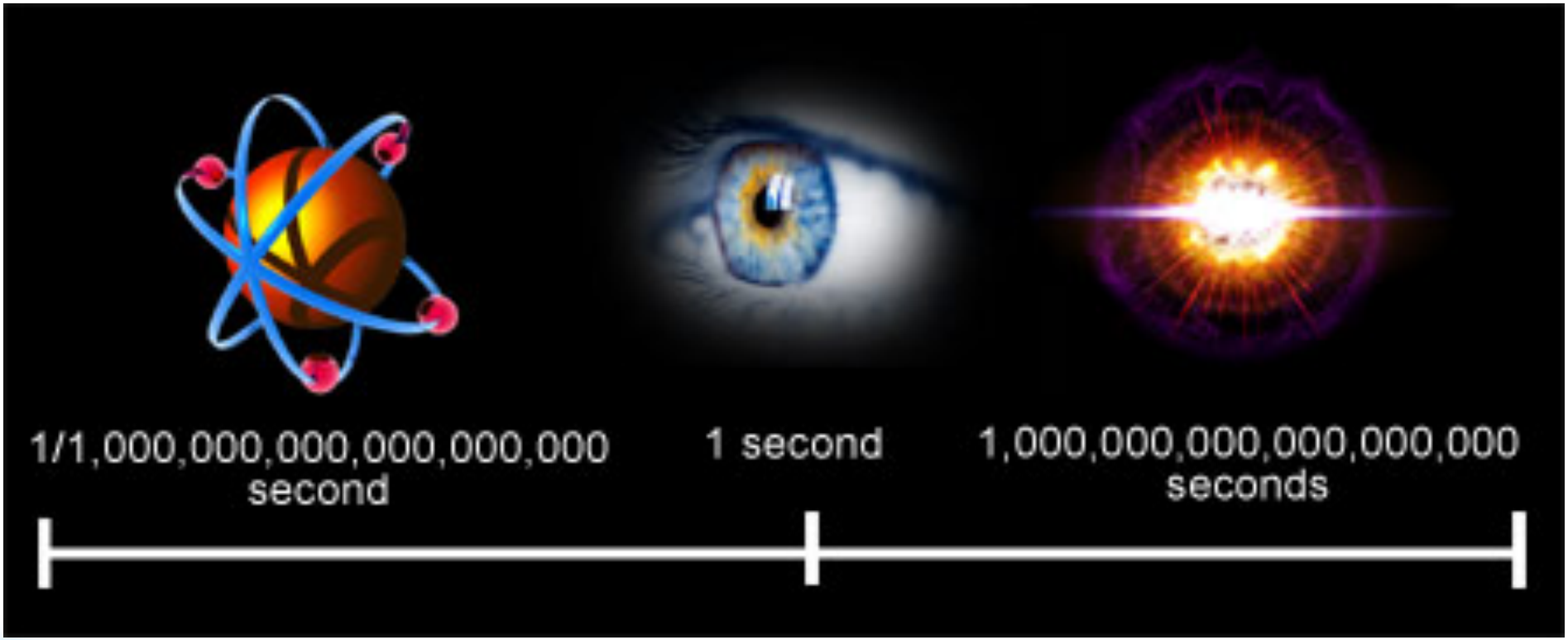
Nanosecond

- Take one nanosecond and divide it into 1,000,000,000 more pieces

That's an attosecond

Second Way to visualize an attosecond

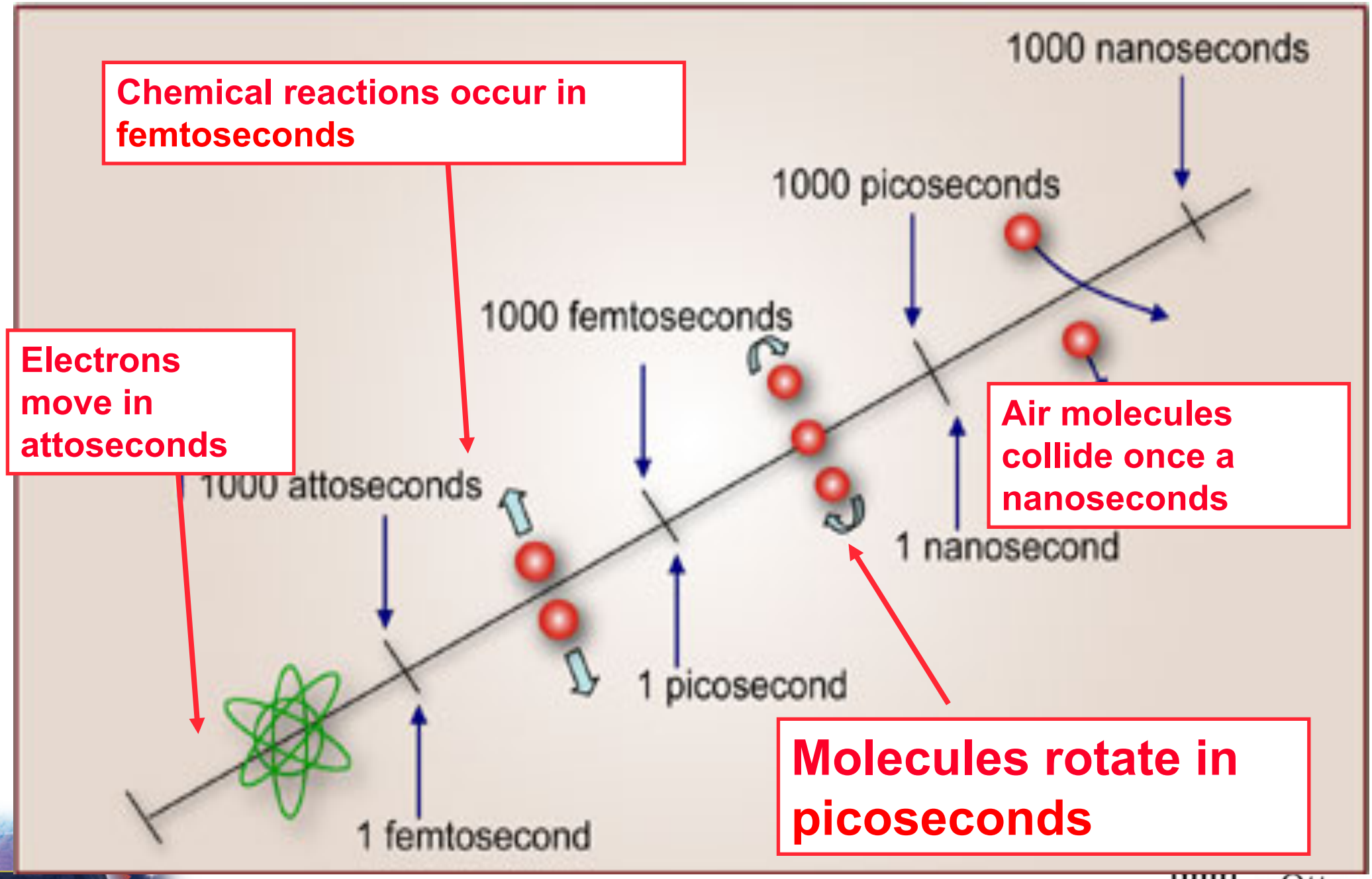
1 attoseconds is to 1/2 second as 1/2 second is to the age of the universe.



How? -- Why?

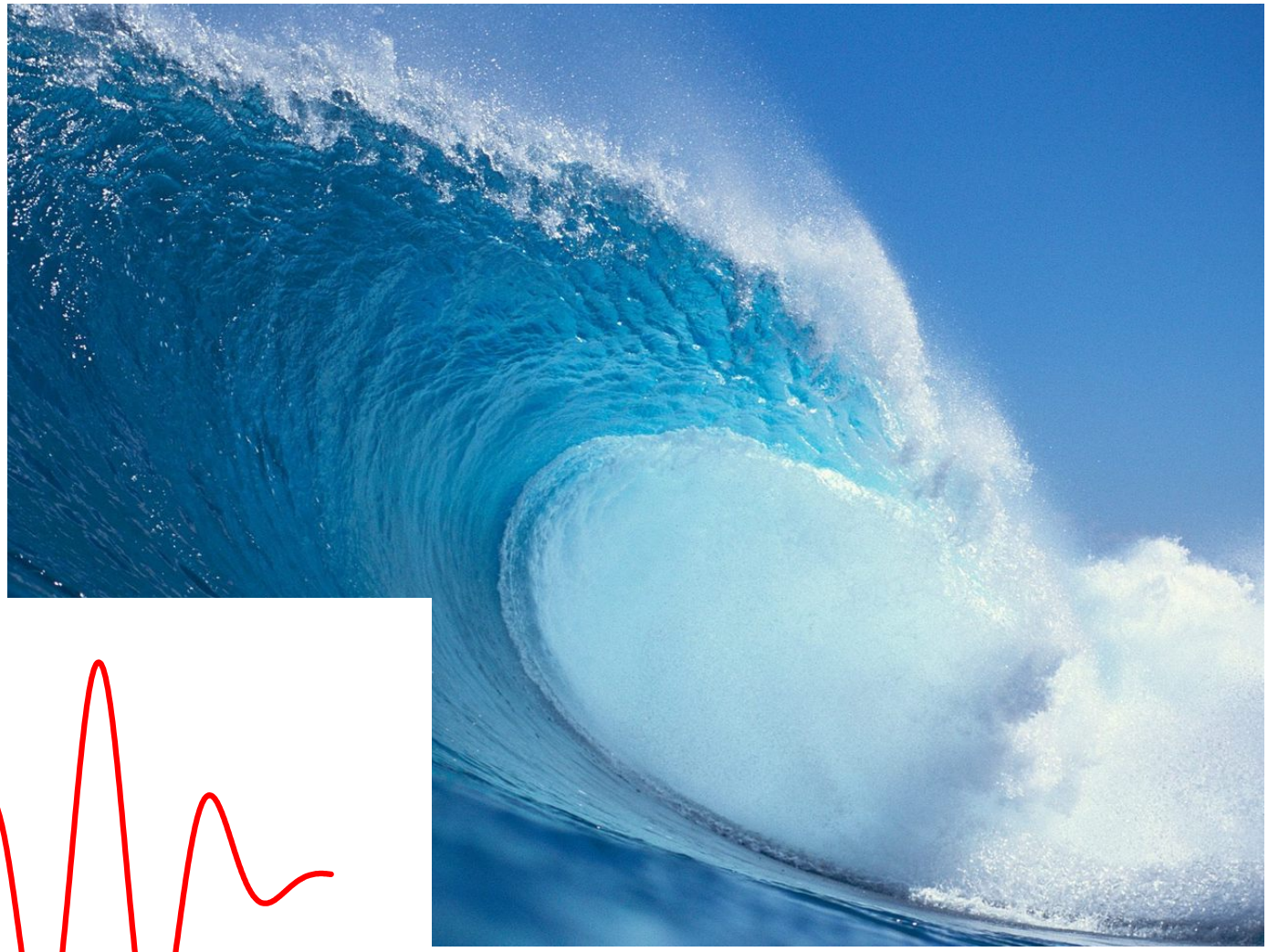
uOttawa

Less than a microsecond, we lose the image



Everything that fast is too small to see with visible light.

Why? Because the wavelength of laser light is 10,000 times larger than an atom.



Imagine trying to "see" a grain of sand by looking for its effect on a large wave.

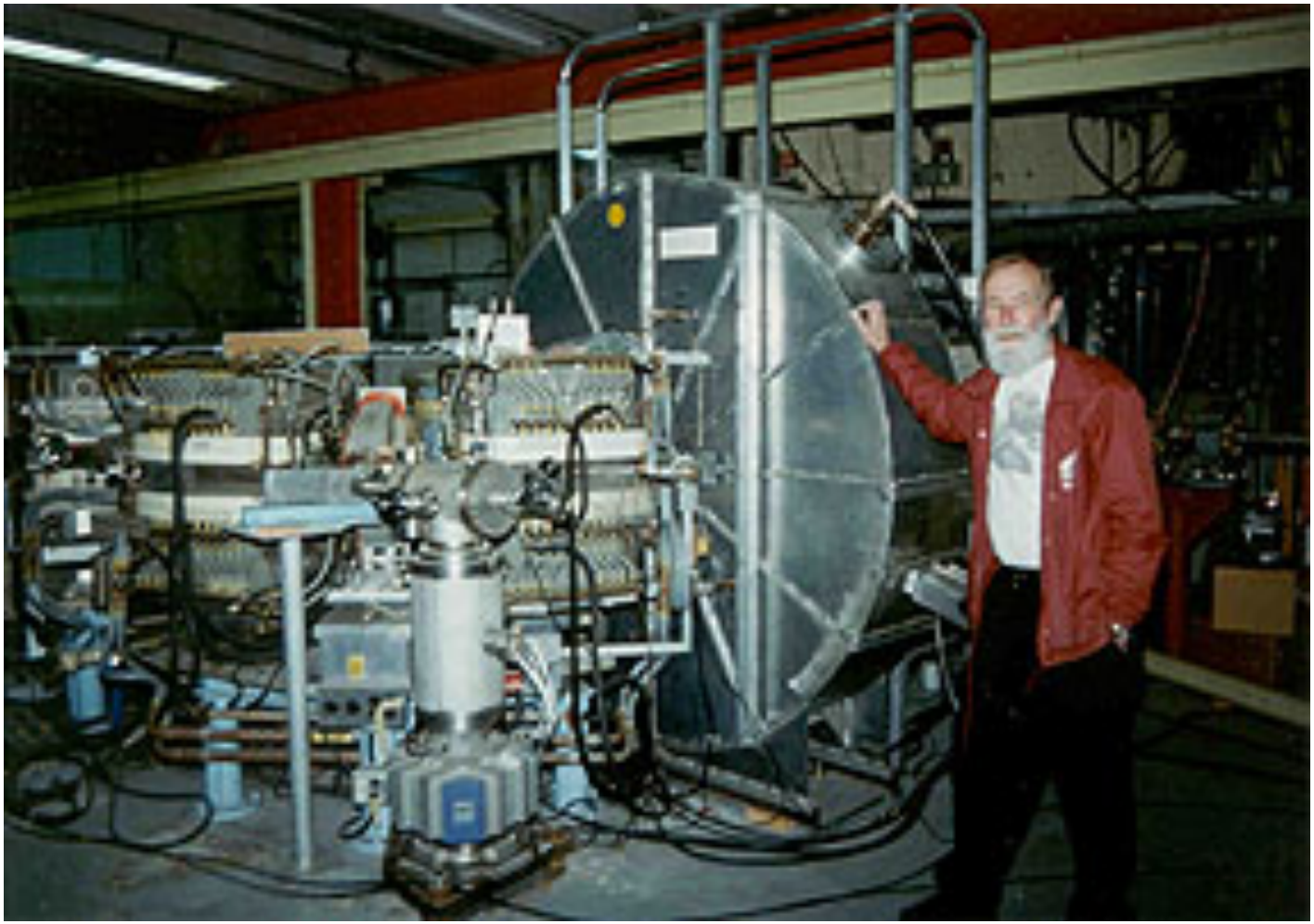
uOttawa

Still, lasers have had a *huge impact*.

Most of what we know about fast *solid state or molecular processes*, we know from lasers.

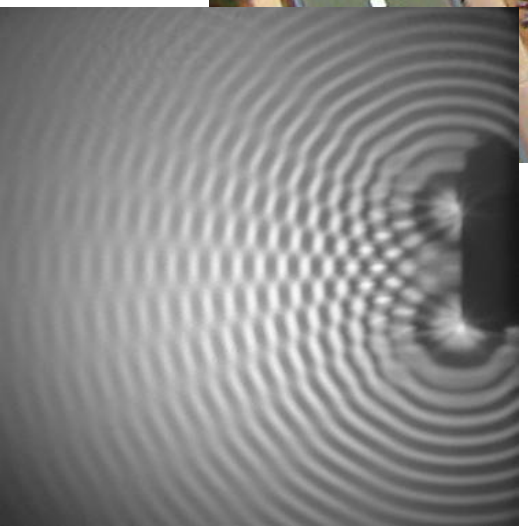
However, most interesting dynamics are *accompanied by structural changes which must be simulated or left to "chemical intuition."*

And then, in 1968, came a new light source -- the synchrotron

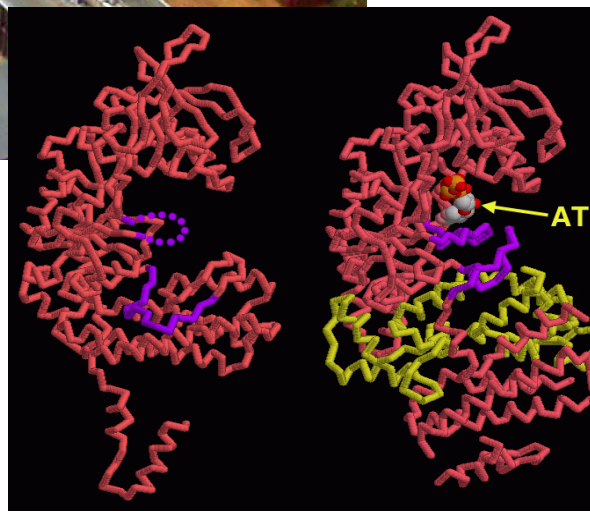


With wavelength 1/10,000 of the light wavelength – the size of the atom

A modern synchrotron



We know the structure of biological molecules from X-ray diffraction.



You will have noticed that this conference is called VUVX

VUV means vacuum ultraviolet – light whose wavelength is too short to travel through the atmosphere

X stands for X-ray.

Synchrotrons produce VUV and X-ray radiation.

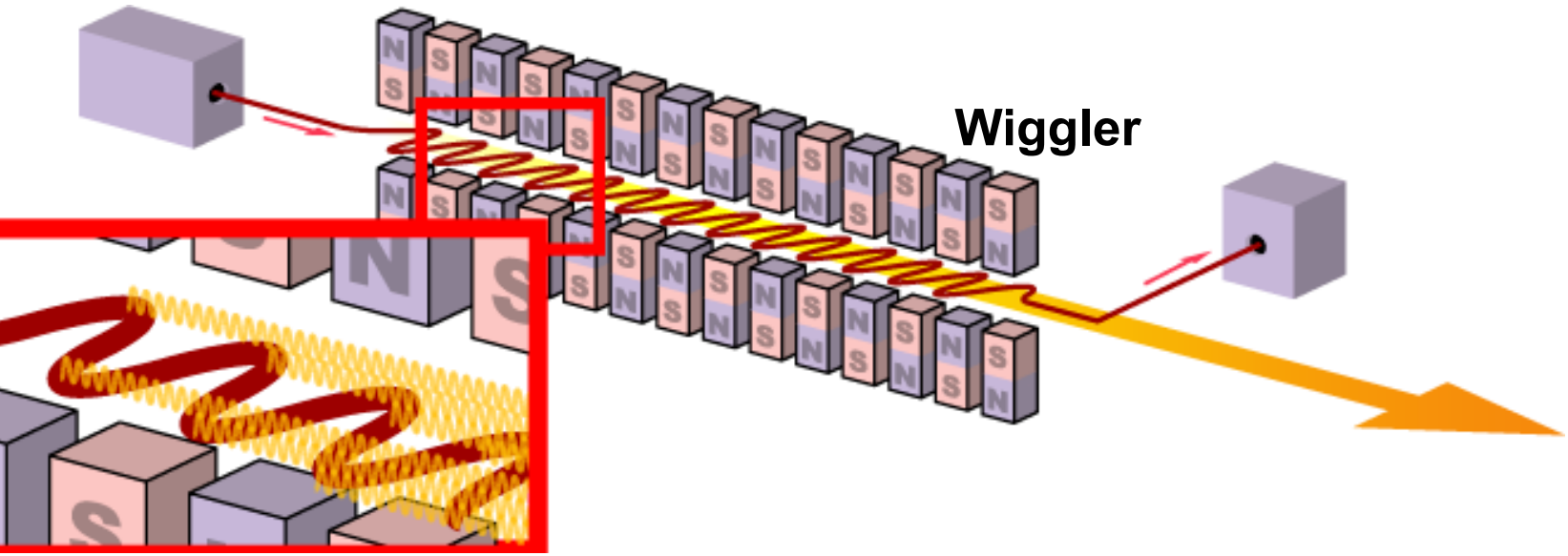
A theme of VUVX is the convergence of synchrotron and laser science

After 50 years, both technologies have reached this stage.

Art and science are being united once more.

That is the subject of the reminder of my talk.

Approach #1: Transform a "synchrotron" into a laser.



The first X-ray "free electron laser" operated this year at Stanford University.

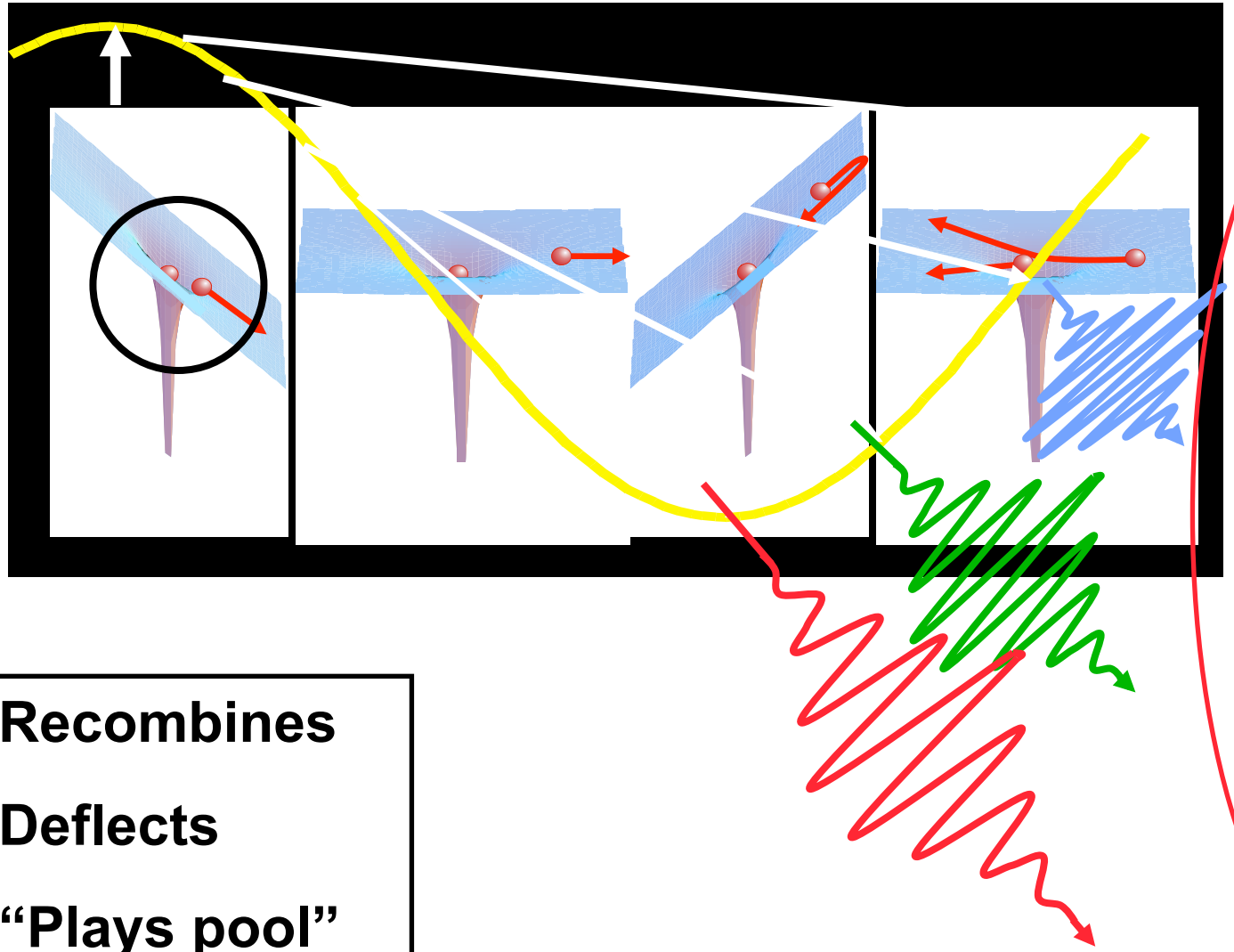
Approach #2: Transform a laser beam into a "synchrotron" – to create attosecond pulses and to make molecular movies.

Light is an oscillating voltage

A very high voltage can rip electrons from the molecules in the air.

The key idea: F=ma

Light → electron → light



VUVX

From soft X-rays

↑

To extreme ultraviolet

↑

To ultraviolet

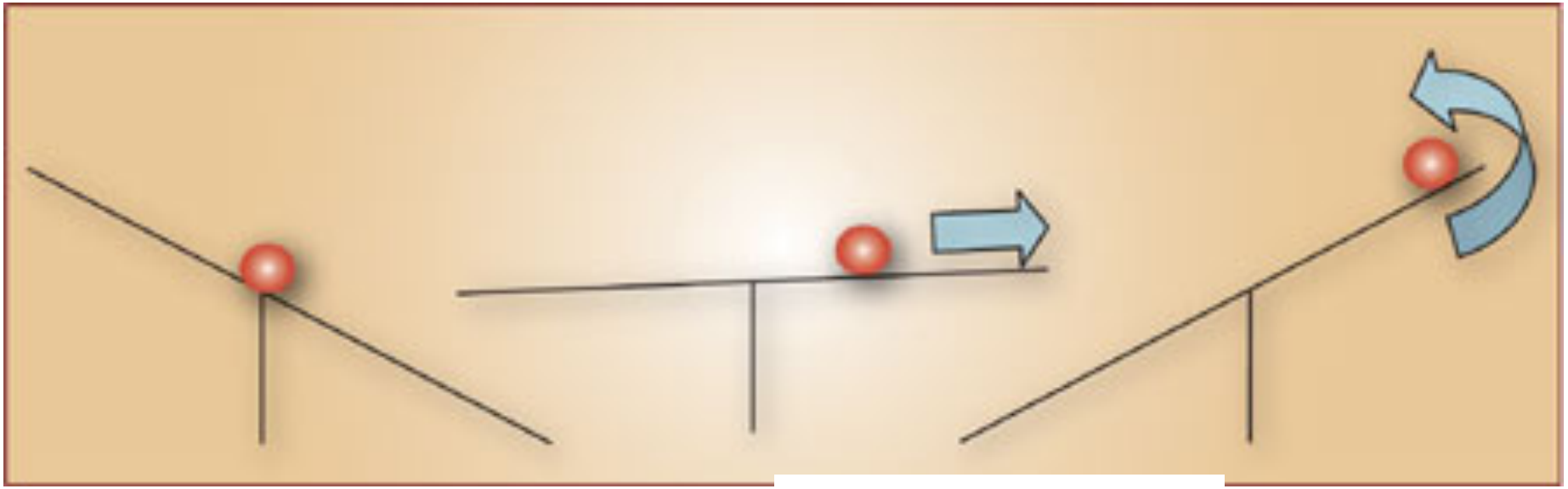
Recombines

Deflects

"Plays pool"

uOttawa

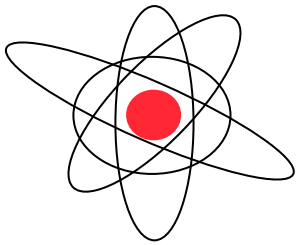
Just to make sure it is clear



It’s child’s play

uOttawa

Just like light, electrons and even atoms are waves



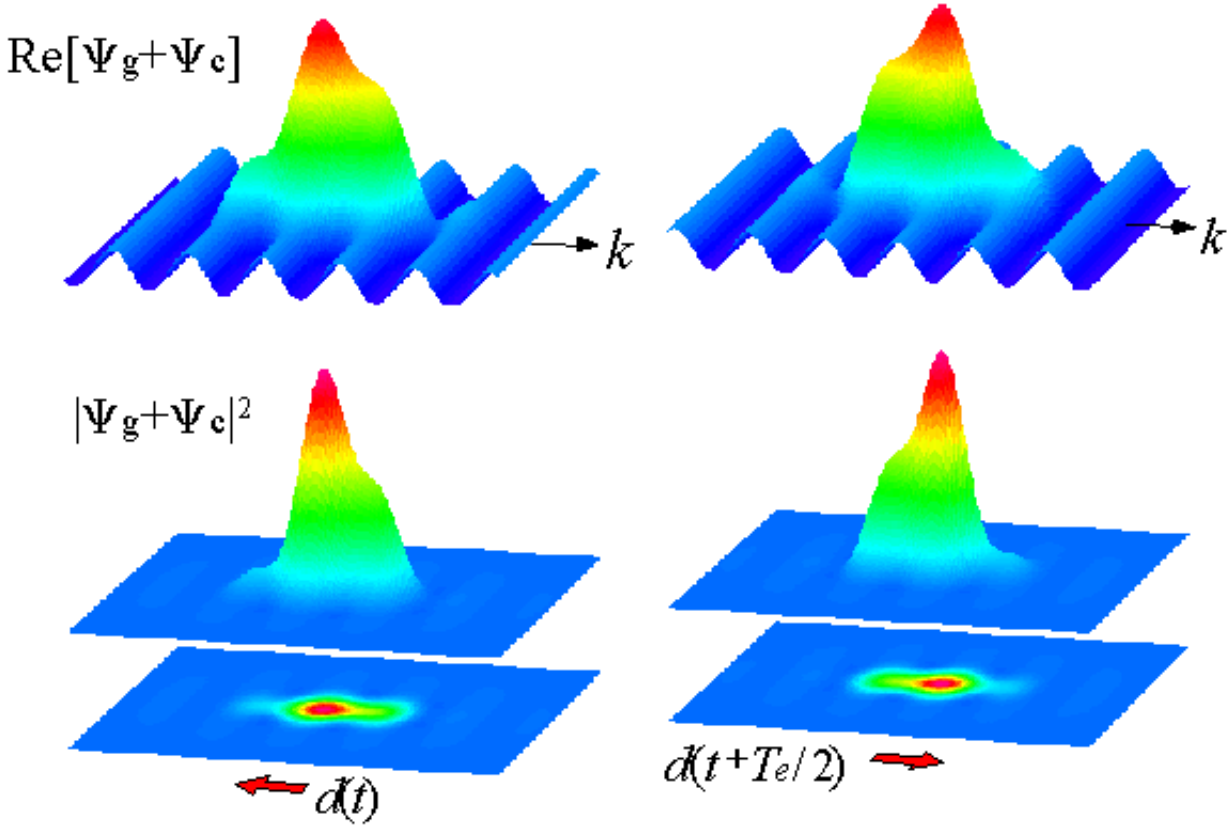
We often represent electrons like little planets -- or marbles

but

electrons are wave too.

Their wavelength is smaller than light

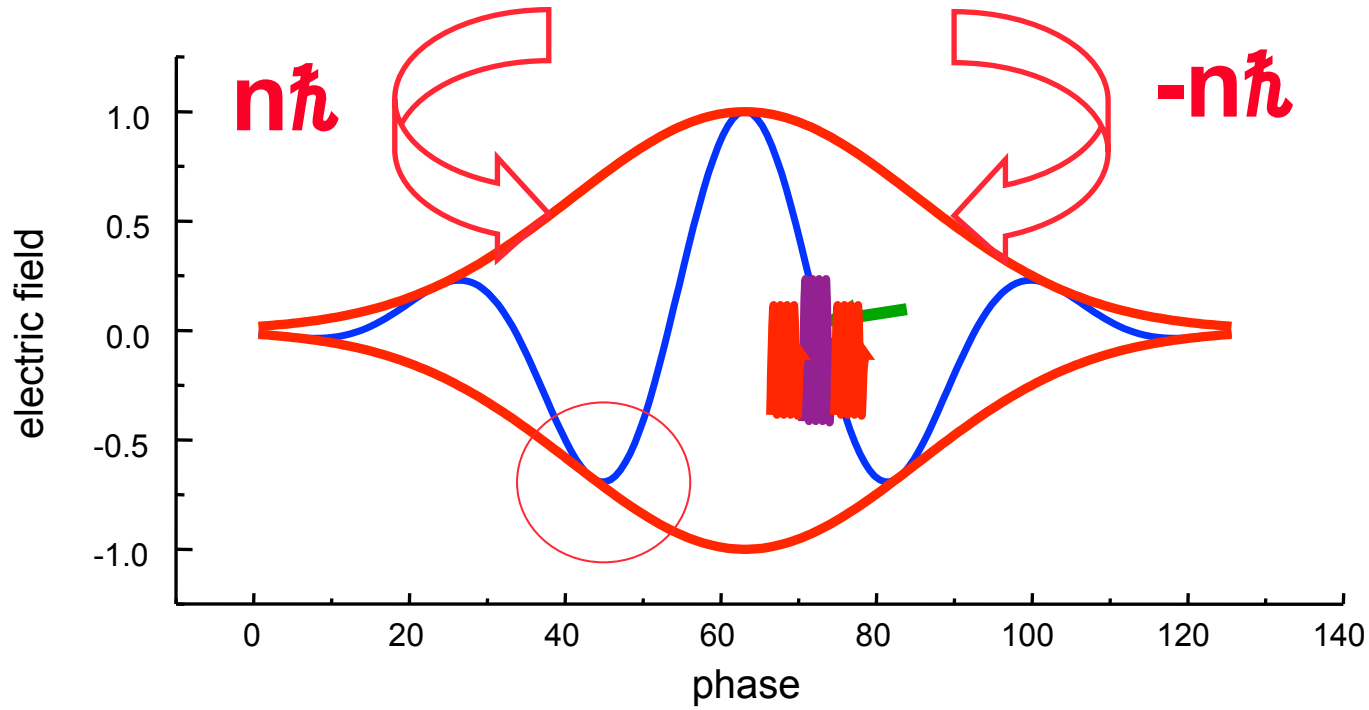
The single atom "wiggler" – quantum interference

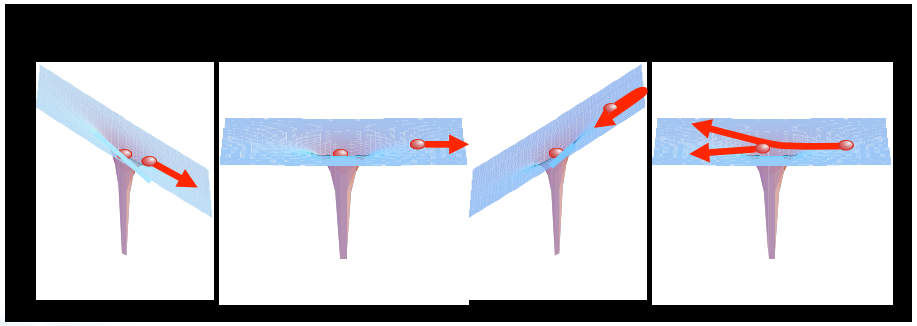


Amplitude and phase of the re-collision electron are transferred to light *through d (t).*

$$d(t)=\{\int \Psi er\, a(k) e^{ikx}\, d^3r\} e^{\underbrace{(IP+KE)}_{\omega}t}$$

How to make the shortest pulse on earth



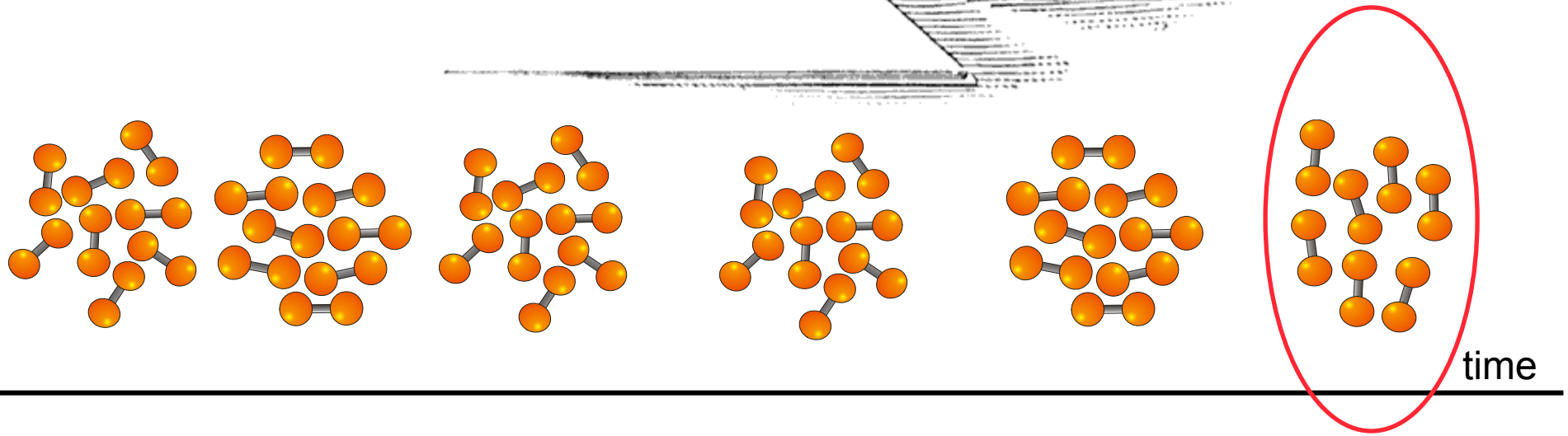


control the laser field

80 attoseconds

uOttawa

50 years of laser science has taught us how to control molecules – almost as well as you control a pen with your hand



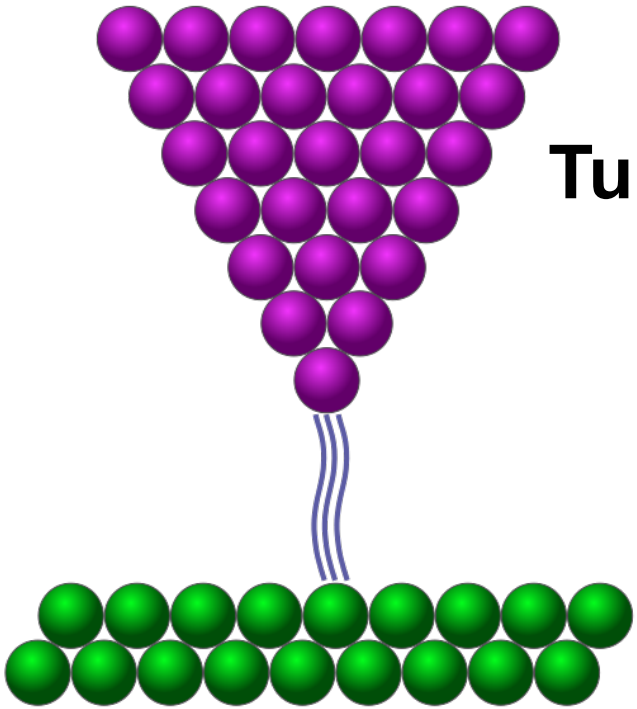
Three new ways to take single frames

1 **Tunneling** (to characterize orbitals)

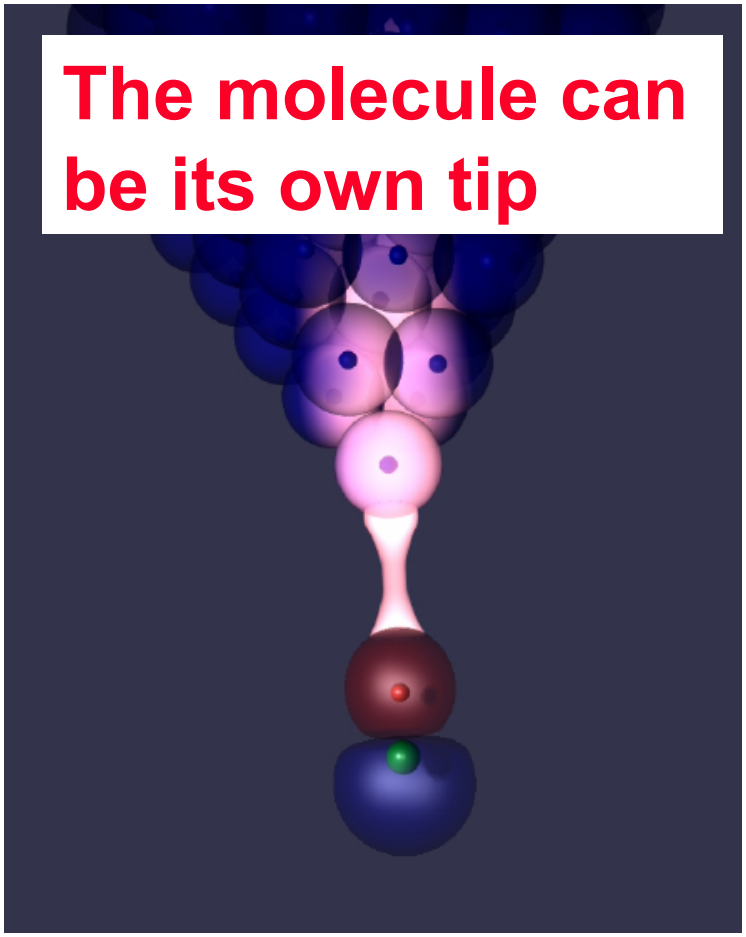
2 **Elastic scattering** or Laser Induced Electron Diffraction (to determine nuclear positions)

3 **Interferometry** (to image orbitals -- *photoelectron spectroscopy in reverse*)

Tunneling has transformed surface science.



Tunneling is one of the simplest quantum mechanical process

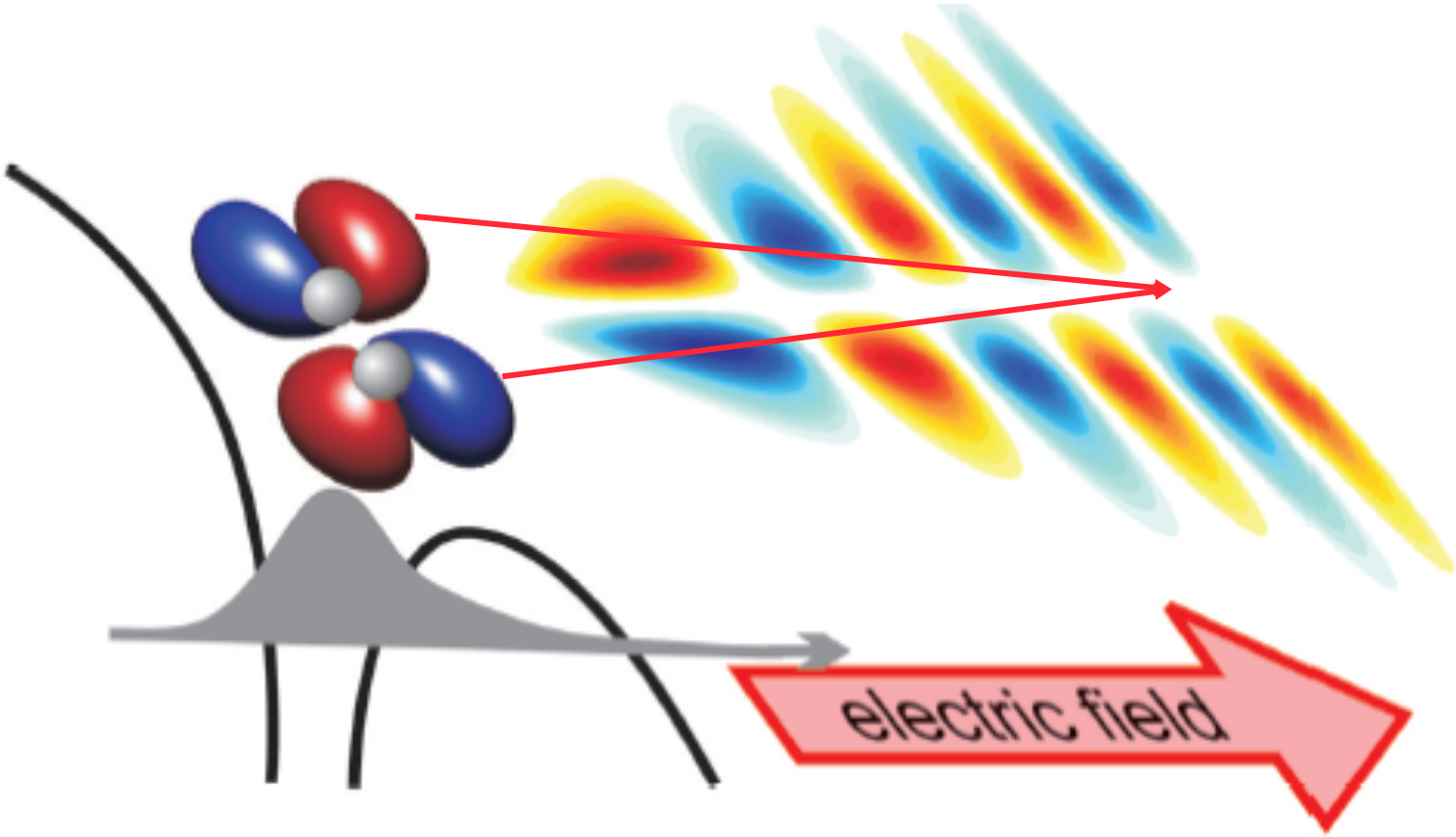


An STM

Measures I(r)

If we could rotate the molecule we would have a molecular STM

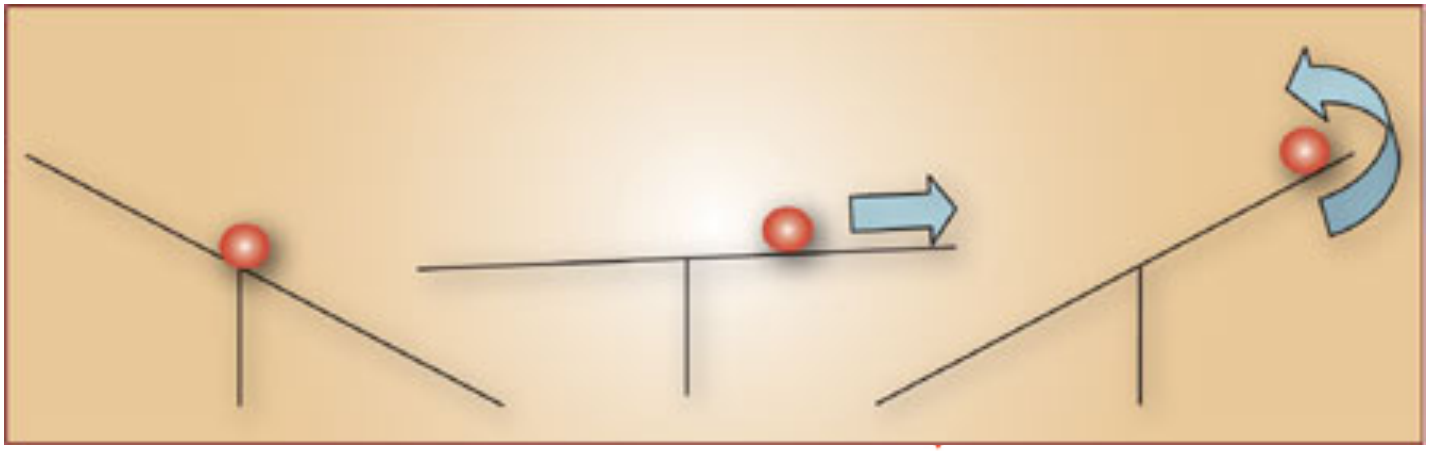
But a molecular STM has much more information

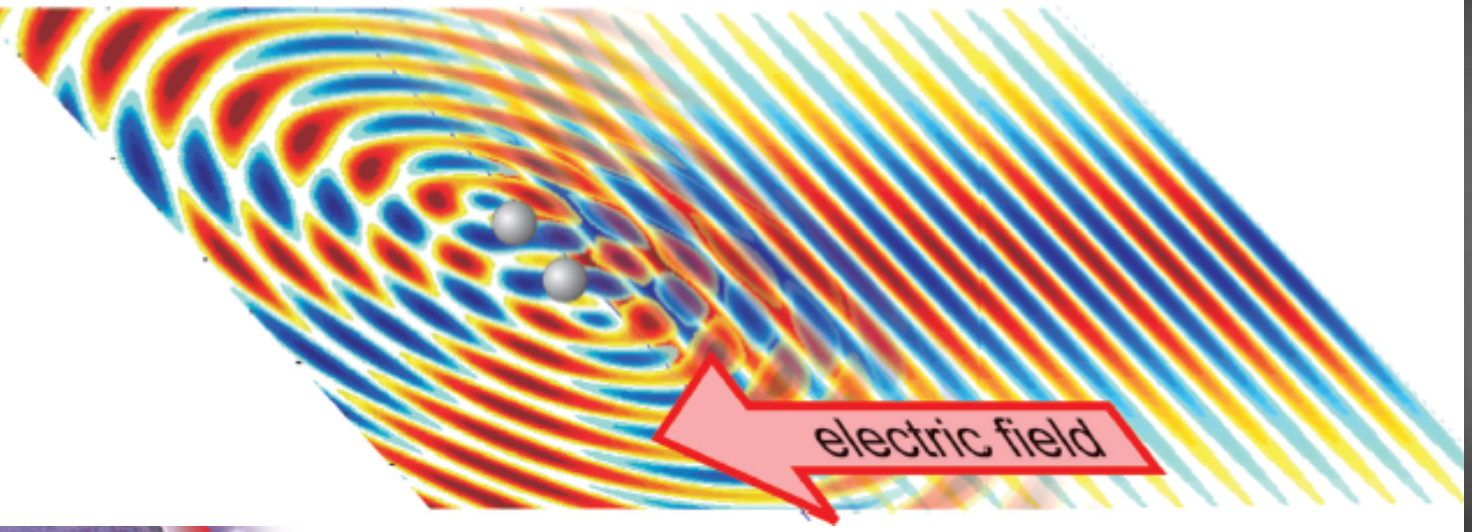


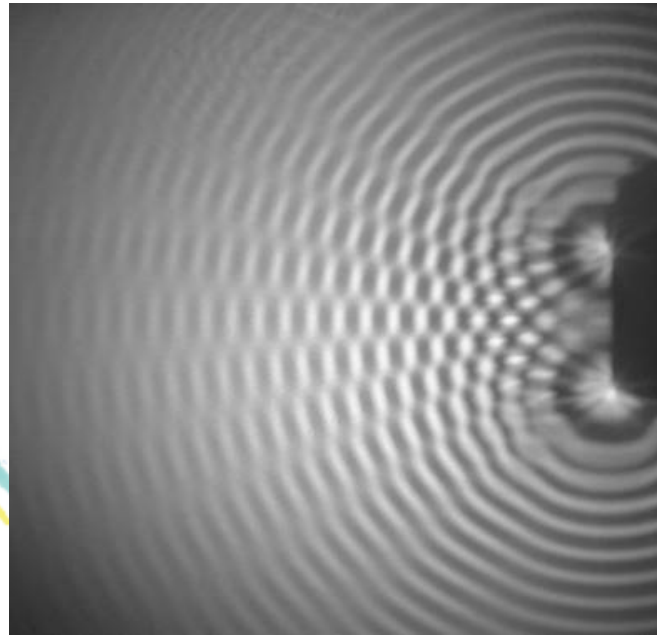
$$\Psi_c(\theta) = \langle p_\perp | \Psi \rangle \exp\left[-\frac{p_\perp^2 \sqrt{IP}}{E\sqrt{2}} \right] \omega(t)$$

uOttawa

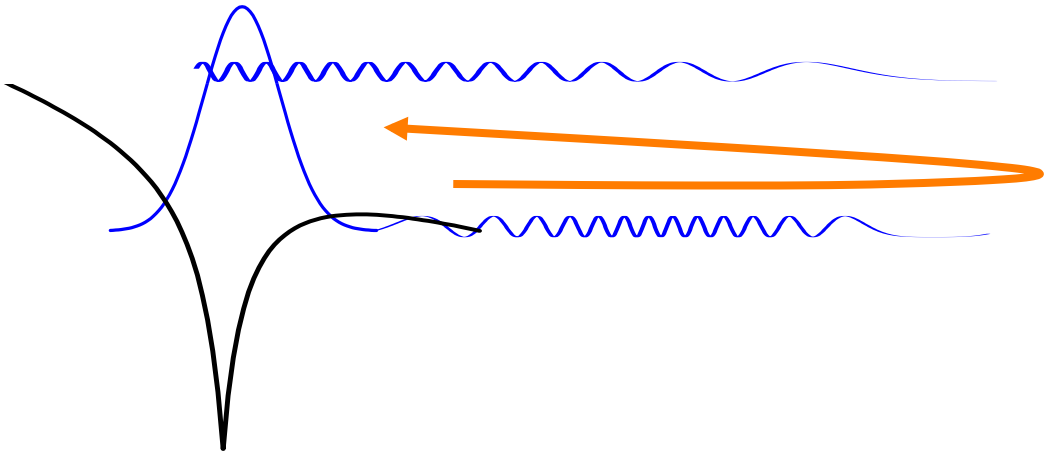
In linearly polarized light Tunnelling and Diffraction occur together

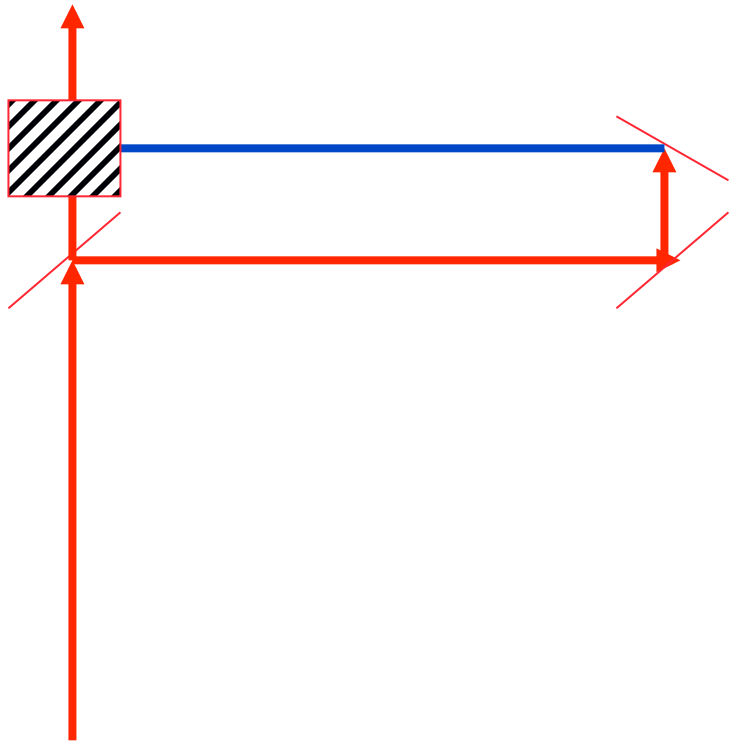






Attosecond pulse generation as electron interferometry





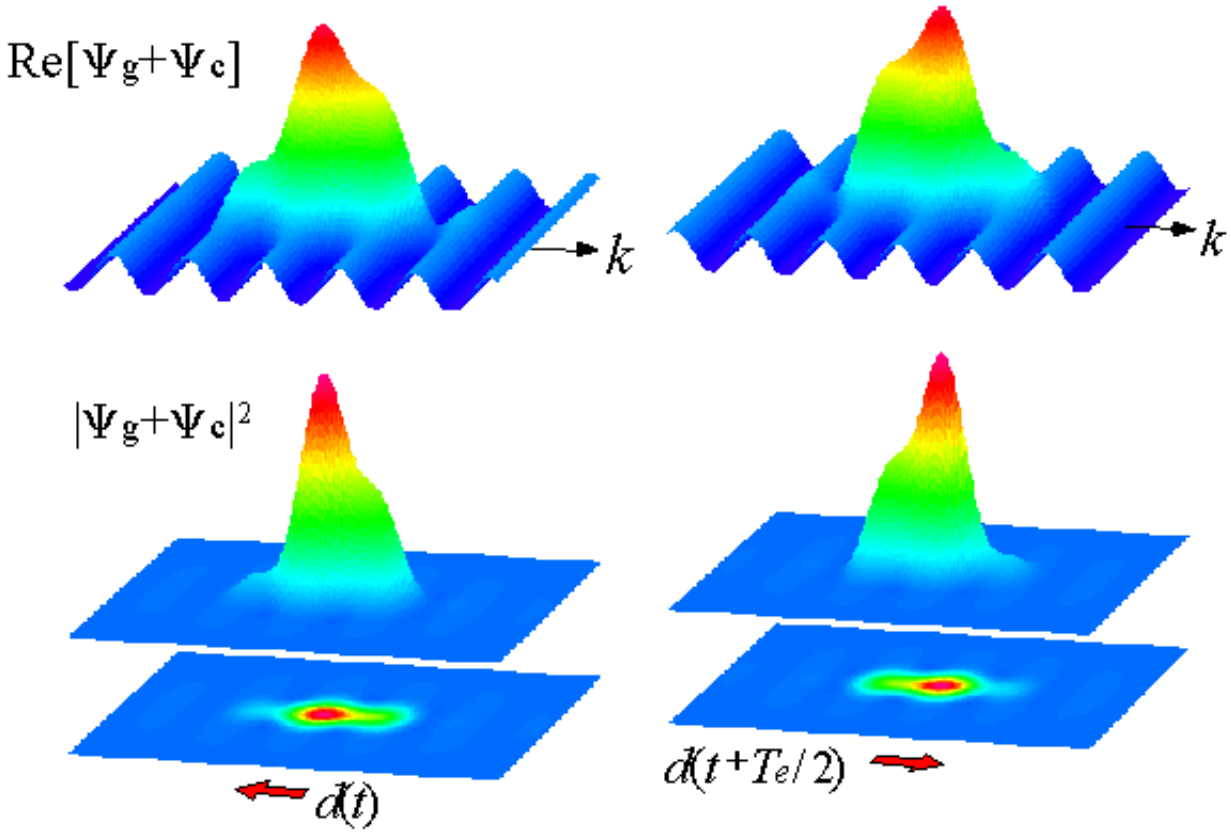
Molecular interferometer

Optical interferometer

Interferometers allow us to determine everything about the waves involved.

uOttawa

Reading the interferometer
High Harmonics/Attoseconds pulses



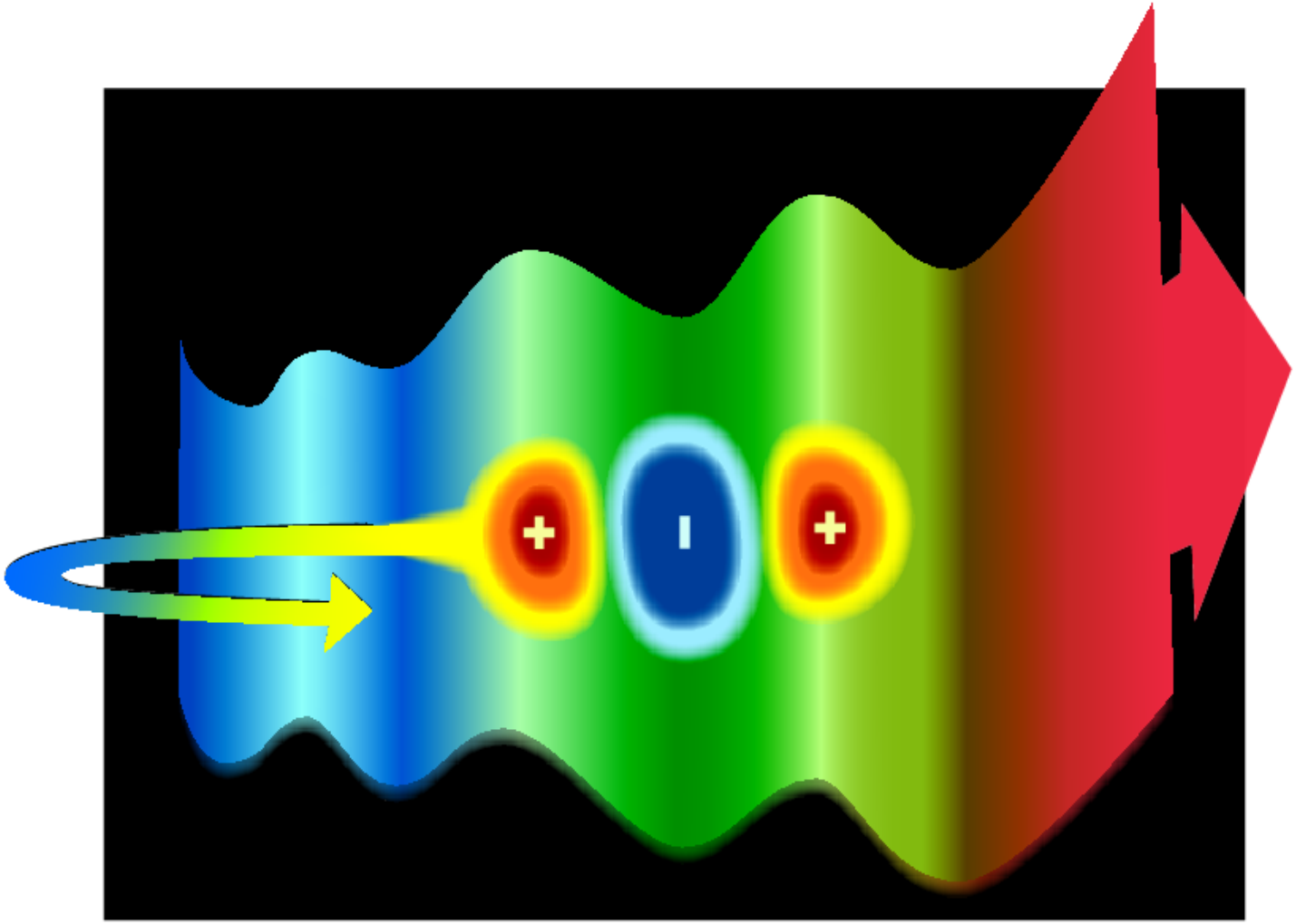
Amplitude and phase of the re-collision electron are transferred to light *through d (t).*

$$d(t)=\{\int \Psi_{er}\, a(k)\, e^{ikx}\, d^3r\}\, e^{\underbrace{(IP+KE)}_{\omega}t}$$

Photoelectron spectroscopy in reverse

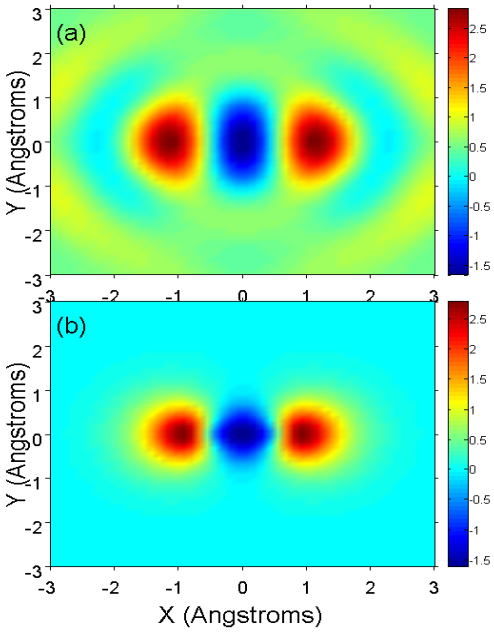
uOttawa

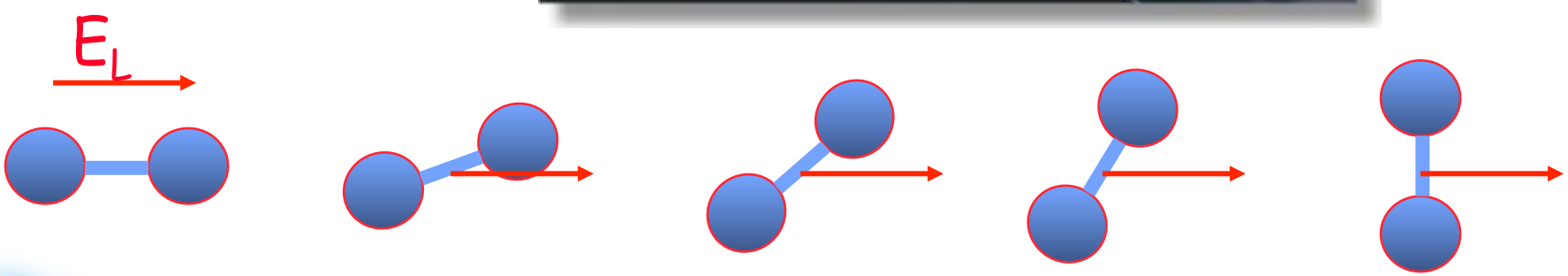
Tomographic Imaging (interference)



Nature 432, 867 (2004)

Machine for tomographic imaging of people (and molecules)





Why is this important (I)?

For centuries science has worked to measure faster and faster phenomena:

- **Now we have reached a time resolution of less than 10^{-16} sec.**

Conferees: Please see Krausz, 4PL1

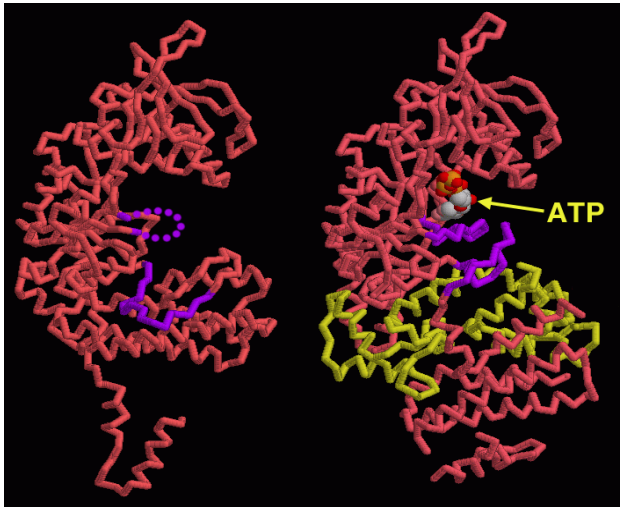
- **Developing the technology for measuring electrons and watching them move**

Conferees: Please see Niikura et al, SP012

Why is it important (II)?

For an entire century, science has worked to measure the structure of matter.

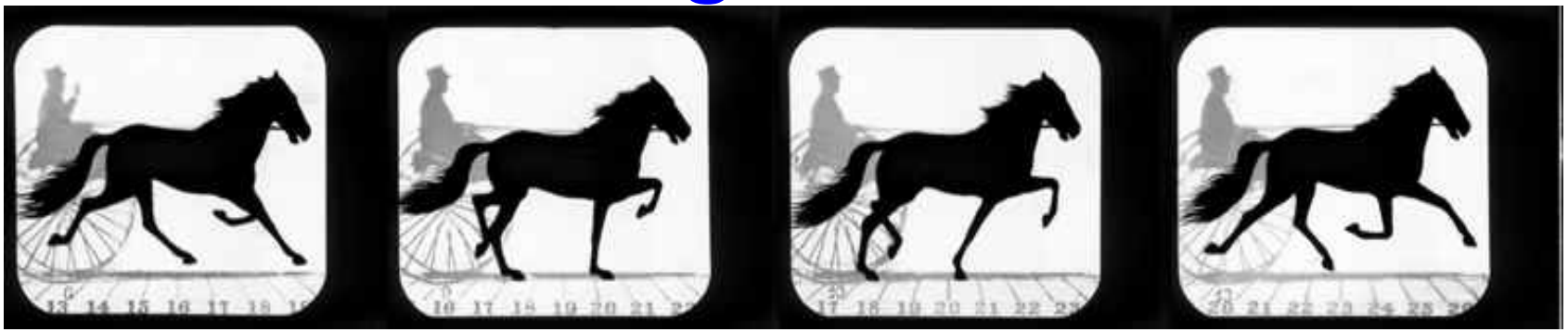
Once, this research was centered in Ottawa around G. Herzberg (who won a Nobel Prize)



Now synchrotrons dominate molecular imaging because the X-ray wavelength matches molecular dimensions.

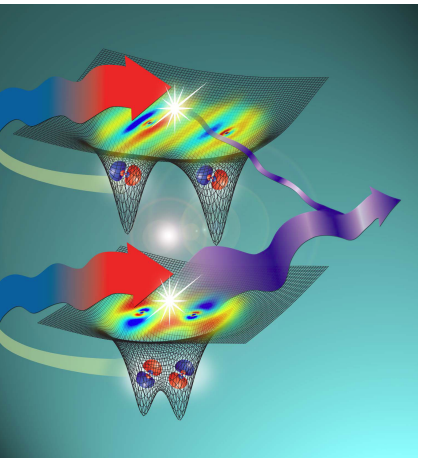
Synchrotrons image molecules without time resolution --- and not all molecules can be measured

Taking Stock: 130 years ago the first movies were being made



Eadward Muybridge,

The plot was poor, but the images were striking.



Now movies are being shot of atoms moving and bonds breaking. (The plot thickens)

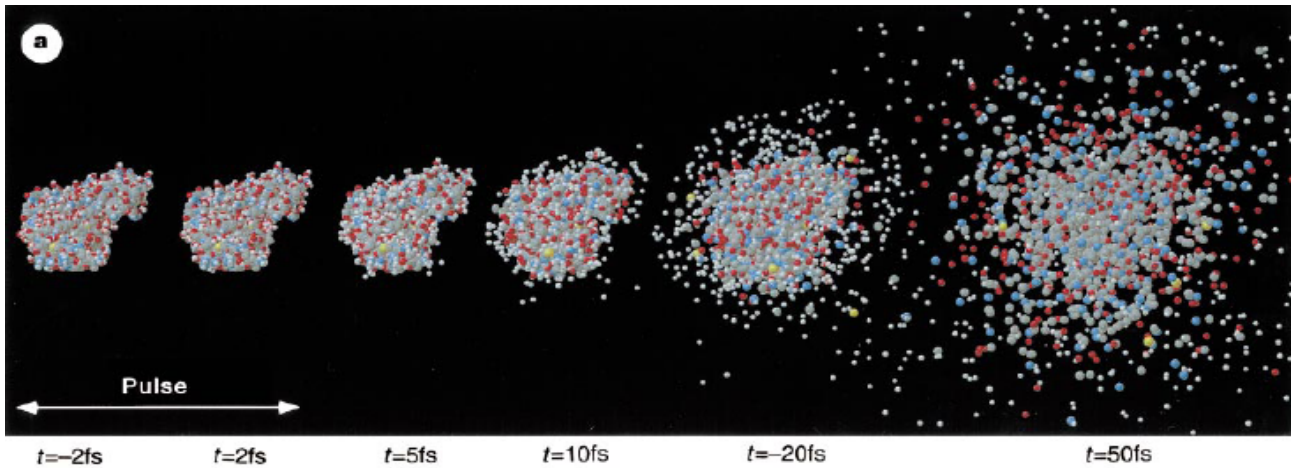
Conferees: Please see Villeneuve, 4PL2

uOttawa

Improving the plot?

Other advances are being made.

- X-ray Free Electron Lasers – LCLS, XFELS, SCSS



The world will invest billions over the next decade to produce intense 5-fs X-ray pulses for single molecule imaging.

- Femtosecond electrons from photo-cathodes – UofT, Cal Tech.

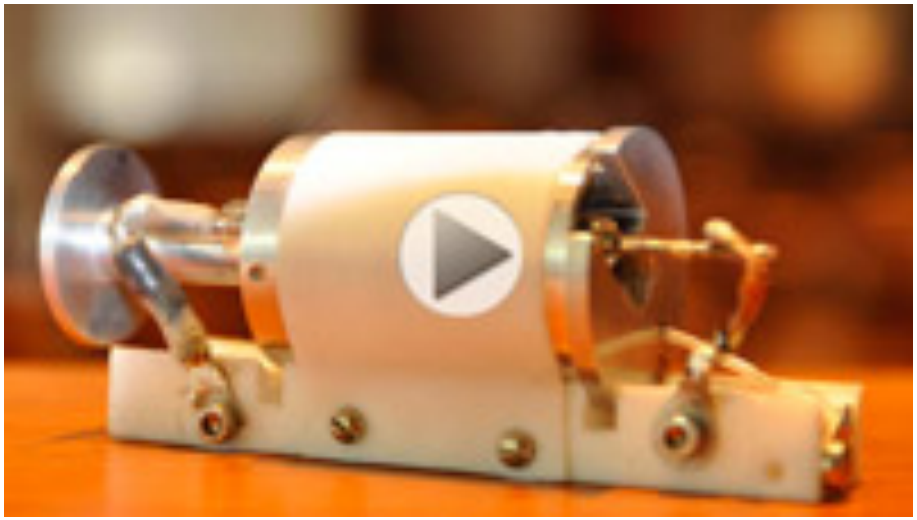
My prediction: Before 2018 Scientific American will have a front page "movie" of a dissociating molecule

Conferees: Please see Chapman, 5PL1

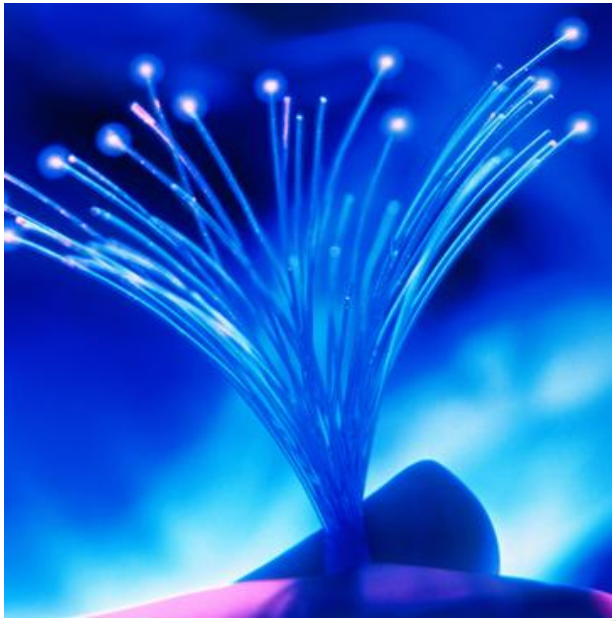
uOttawa

The laser is 50 years old

CD Player



The first Laser



Fibre Optic Communications

Who would have guessed?

uOttawa

Atto-researchers (2010)

Canada

China

Cuba

England

Germany

Iran

Israel

Italy

Japan *

Korea

Switzerland

* K. Ueda - an honorary member of the Atto-group

uOttawa

Laser system -- about pool table size