



*Time lingers long enough for those  
who want to utilize it.*  
**Leonardo da Vinci** (1452 till 1519)

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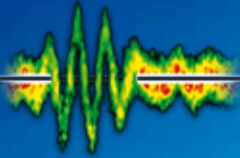
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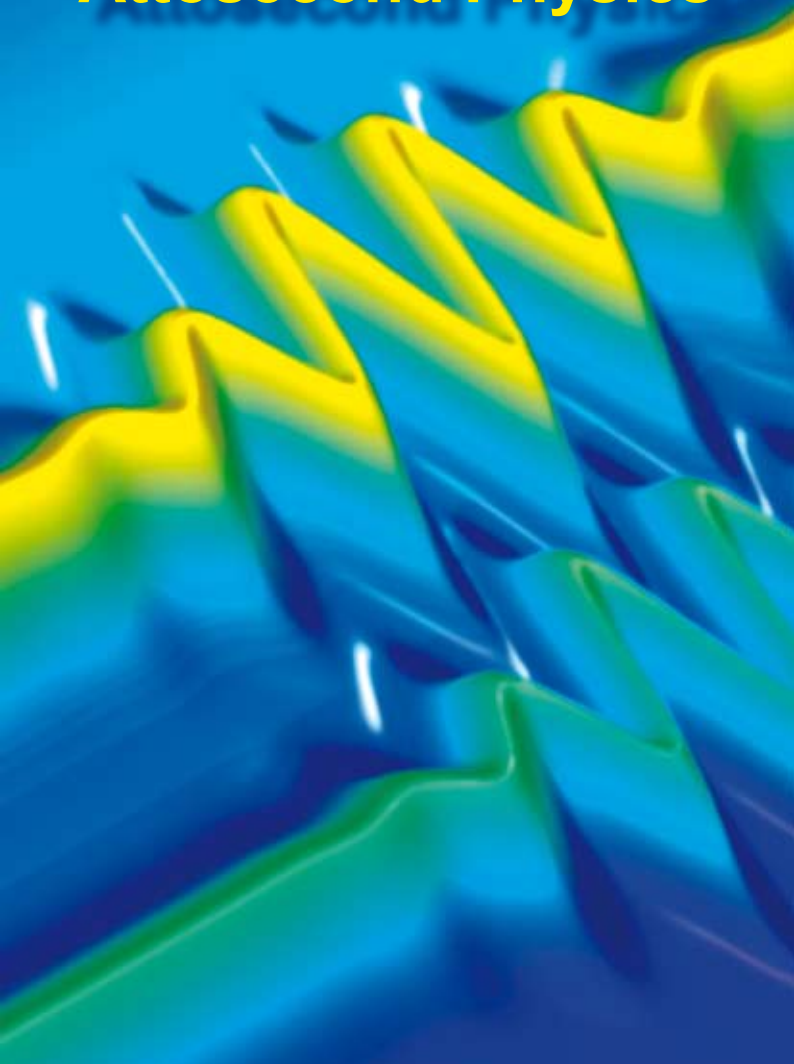


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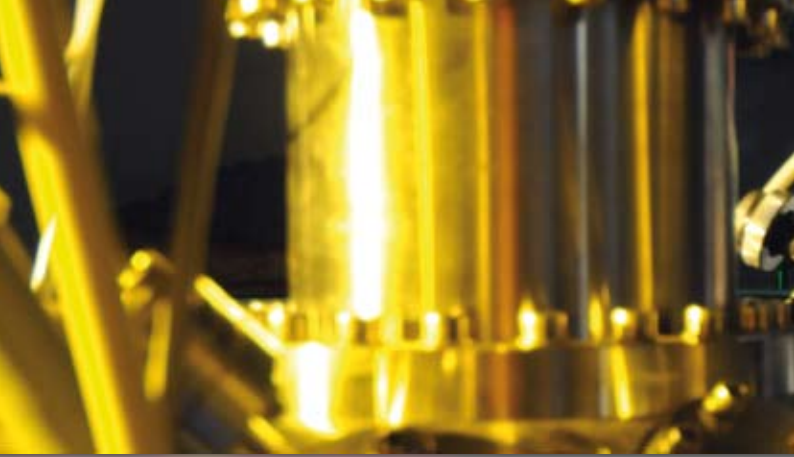
**LMU**



# The Laboratory for Attosecond Physics



Professor Ferenc Krausz



## The Laboratory for Attosecond Physics

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The beat of a fly's wings lasts an eternity as compared with the time dimensions with which the scientists at the Laboratory for Attosecond Physics (LAP) are concerned. LAP is a joint project of Max-Planck-Institut für Quantenoptik (MPQ) at Garching and Ludwig Maximilians Universität München (LMU). The attosecond physicists involved are investigating the fastest processes hitherto known in nature outside the atomic nucleus. These processes last just very few attoseconds. An attosecond is a billionth of a billionth of a second.

### **In the world of quanta**

The scientists' research immerses them in the world of quanta, where the classical laws formulated by Sir Isaac Newton more than 350 years ago lose their validity. The position and motion of elementary particles can no longer be exactly determined simultaneously. The particles are often mysteriously bound together and have either wave or particle properties.

LAP's laser physicists are primarily interested in the behaviour of electrons in atomic dimensions in every form of matter: atoms, molecules, solids and also plasmas. Atoms consist of a nuc-



*Time is what prevents everything from  
happening at once.*

**John A. Wheeler**, US physicist (b. 1911)

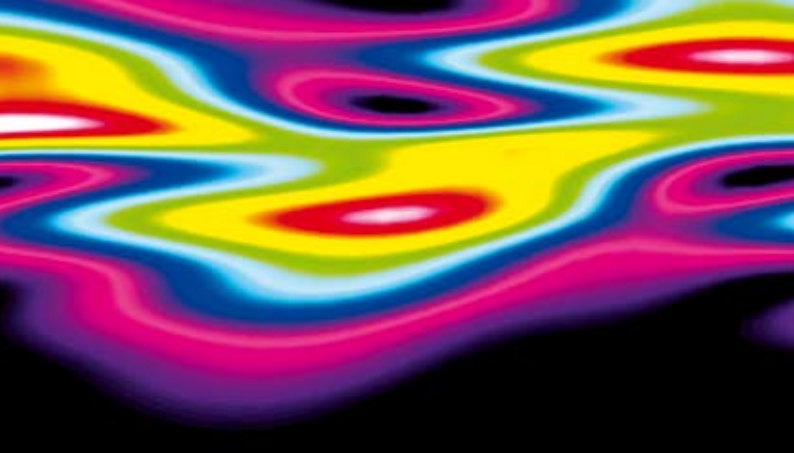
leus comprising protons and neutrons and of a shell of electrons. Electrons are quantum particles – they cannot be divided any more. When light impinges on electrons in atoms, they gain additional energy and jump between energy states. Their motion is ultrafast, lasting just a few tens to a few thousand attoseconds.

### **Ultrashort light pulses**

To investigate such motion, the physicists have to be just as fast as the electrons. They achieve this with light flashes which themselves last just a few tens of attoseconds. The light flashes are fired at the samples, two at a time. The first one excites the electrons in the atoms to set them in motion; the second one then observes the reaction of the particles. The physicists thus “photograph” the electrons in motion inside atoms. The shorter these light pulses are - like the shutter speed of an ordinary camera - the more details of the motion of the speeding elementary particles become discernible.

*View inside an experimental chamber: two light flashes (blue and red) examining a sample.*

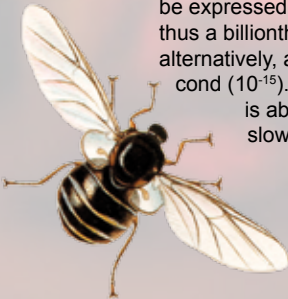




## The dimension of an attosecond

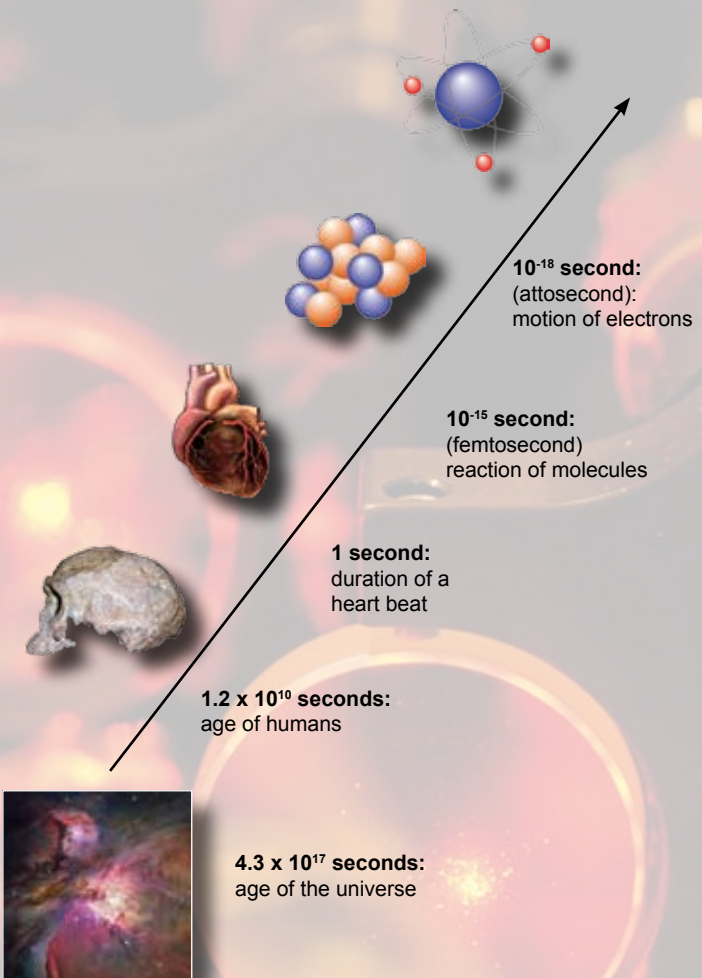
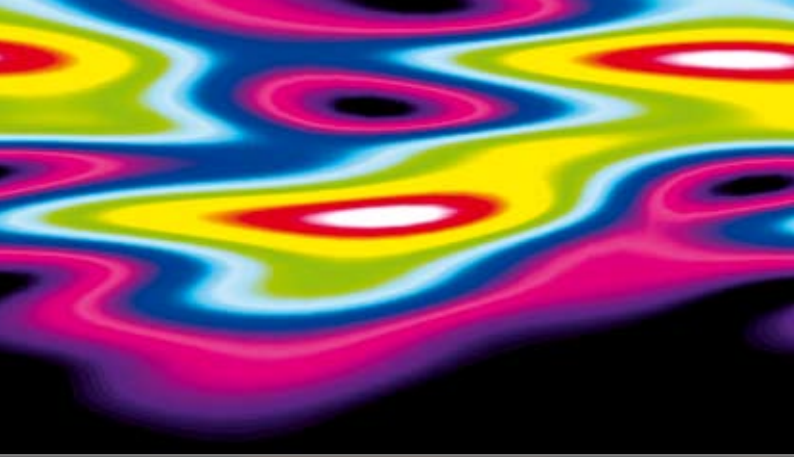
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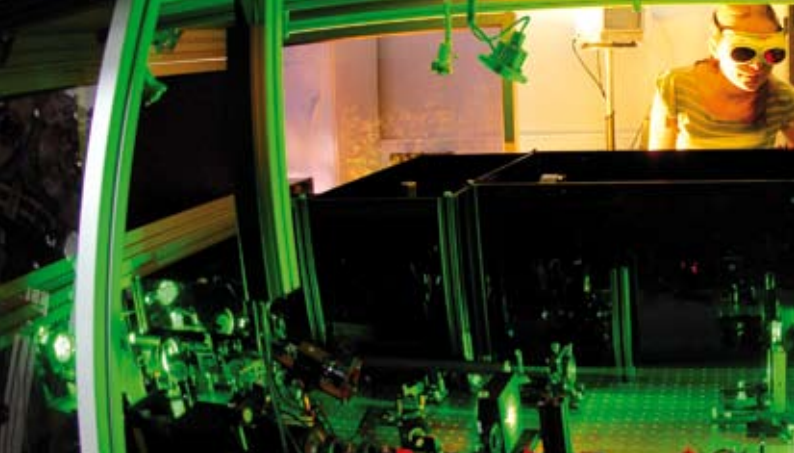
For a change, it was not the Greeks but the Scandinavians who were responsible for the origin of the term “atto”, which comes from Danish “atten” for eighteen. In the decimal system the word “atto” is used as prefix for a number with 17 zeros after the decimal point; the 18th decimal place following is then a number above zero. In short, this can also be expressed as  $10^{-18}$ . An attosecond is thus a billionth of a billionth of a second; alternatively, a thousandth of a femtosecond ( $10^{-15}$ ). The beat of a fly’s wings is about a million billion times slower.



The velocity of light is near 300.000 kilometres per second. In one attosecond light travels a distance not longer than a few billionths of a metre. This is equivalent to a string of three hydrogen atoms. The duration of an attosecond in relation to that of a second is as a second in relation to the age of the universe, which is about 13,7 billion years old.

$$1 \text{ as} = 0.000\ 000\ 000\ 000\ 000\ 001 \text{ s}$$





## The birth of an attosecond light pulse

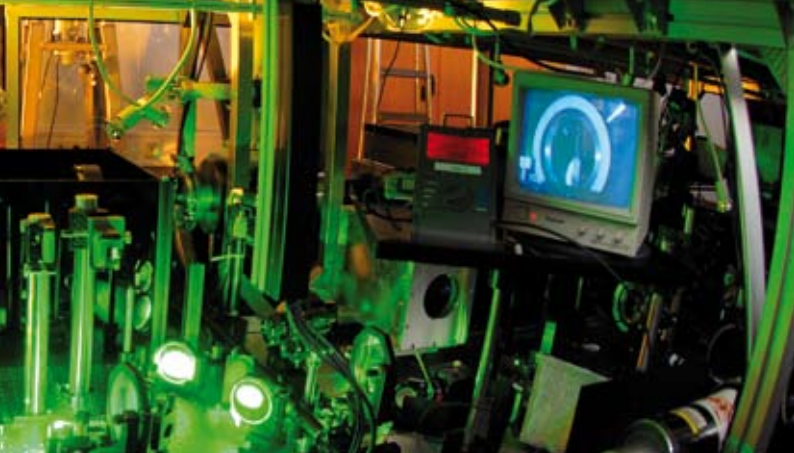
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Attosecond light flashes are generated with lasers whose pulses are in the femtosecond range. For this purpose the laser physicists fire femtosecond light pulses at a small nozzle in a vacuum chamber. This nozzle emits neon atoms (see back cover), in which the strong electric field of the laser pulses first an electron away from the nucleus and then (due to its oscillating nature) smashes it back, where the electron releases its energy as an attosecond flash of light. This light is invisible to the naked eye because emitted in the extreme ultraviolet and X-ray region, with wavelengths of about ten nanometres.

The world's first attosecond pulses were demonstrated by Prof. Ferenc Krausz's research team in 2001. At that time the flashes lasted as much as 650 attoseconds. In 2008 the LAP physicists reduced this to less than 100 attoseconds. This success was primarily due to the increasing degree of control of the laser light waves.

*Guinness certificate for the shortest light flash.*





## Light pulses with high power

Besides utilizing the ultrashort duration of their light flashes the LAP team is also working to generate laser pulses affording enormous power. These light pulses last a few femtoseconds ( $10^{-15}$  second). In this brief length of time a light pulse can be provided with a power equivalent to that generated by all of the world's nuclear power plants together.



*View inside  
the high-  
field laser  
laboratory*

Concentrated in a single light flash, this power produces extremely strong electric and magnetic fields. The huge forces exerted release, for example, electrons and accelerate them to almost the velocity of light. This in turn allows the elementary particles to serve as a radiation source and help, for example, to produce powerful, laser-driven X-radiation.

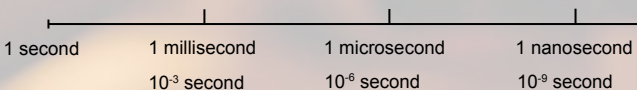
This radiation might provide unprecedented image quality for biological or medical applications and help to make minute structures visible.



## A brief history of time measurement

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Whoever wants to determine intervals of short duration has to be able to measure time. Priests in Mesopotamia and Egypt were among the first to succeed about 4,000 years ago in measuring time intervals. As far back as that scholars enlisted light for the purpose. To do this they developed the Gnomon. By observing the shadow cast by this rod-shaped body they determined astronomical quantities and thus were able to compile the first annual calendars. In Egyptian cities obelisks serving as sundials were also erected. The invention of the laser in 1960 heralded a completely new era of short-time laser pulses to observe in real time the motion of whole atoms in molecules and solids. For this achievement professor Ahmed Zewail at California Institute of Technology (CALTECH) was awarded the Nobel Prize in Chemistry in 1999. The attosecond pulses of the LAP scientists then opened the way to direct observation of the thousand times faster motion of electrons.



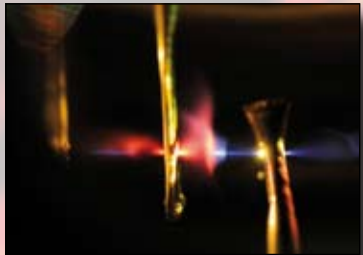


*It is not that we have too little time,  
but we fail to use much of it.*  
**Seneca, Roman philosopher (1st. cent. A.D.)**

### **Control via light**

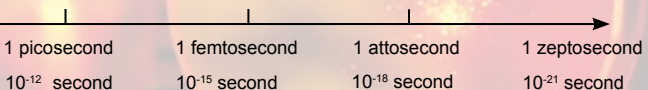
The way to the attosecond range proceeded via control of the oscillations of laser light.

The LAP scientists with Prof. Ferenc Krausz utilised Prof. Theodor Hänsch's frequency comb technique, for which he was awarded the Nobel



Prize, to “subdue” light waves for the first time. This created the condition for controlled generation of attosecond flashes and their precise measurement. Attosecond measurement thus owes its existence to a previous technical development. This is a good example of how scientists enhance scientific progress by enlisting know-how from other colleagues.

*Attosecond metrology*





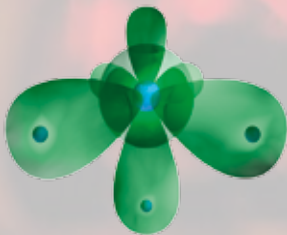
## Tool for the 21<sup>st</sup> century

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Only with the help of light can one identify and control the fastest processes in nature. For light provides the only force that can vary its intensity and direction just as fast as electrons change position. This makes light the 21st century's tool for medicine, biology and information technology.

Both in nature and technology it is primarily the motion of electrons that plays a fundamental role. They initiate chemical reactions; they bind atoms to molecules; or help with transmission of information and stimuli in organisms. In metals electrons move in the crystal lattice. This makes the metals electrically conductive and also enables them to transport heat. Information technology uses electrons for transmitting data. No computer chip will ever calculate faster than electrons move.

*Quantum mechanical view of a molecule composed of atoms: Around the atomic nuclei (blue) are the electrons. Their flight paths are not classical. Within the regions marked (green), the particles are to be found with a certain probability.*





## Technologies for the future

Till today most phenomena in the world of electrons are still unknown. The question how electrons behave and interact in atoms presents laser physics with major challenges. Another focus of interest is the development of technologies by which electron motion can be controlled with light. Besides researching the fundamental processes of life, this new knowledge of electron phenomena will contribute in medicine to developing innovative technologies, such as for the diagnosis and therapy of diseases some of which are still incurable. Attosecond metrology also affords the possibility of accelerating information processing to its ultimate limit. Once approached, calculations become feasible with the enormous frequency of light oscillations.

### Captions for the front and back covers:

**Front cover:** Spectrum of the energy distribution of electrons accelerated by attosecond light flashes. The two curves are displaced in time by 110 attoseconds and thus provide information on the flight time of the elementary particles.

**Back cover:** A nozzle emits a rare gas that converts laser pulses, coming from the right, into attosecond light flashes (see p. 6).