Misurare il tempo: un viaggio alla scoperta della materia su scale di tempo ultrabrevi

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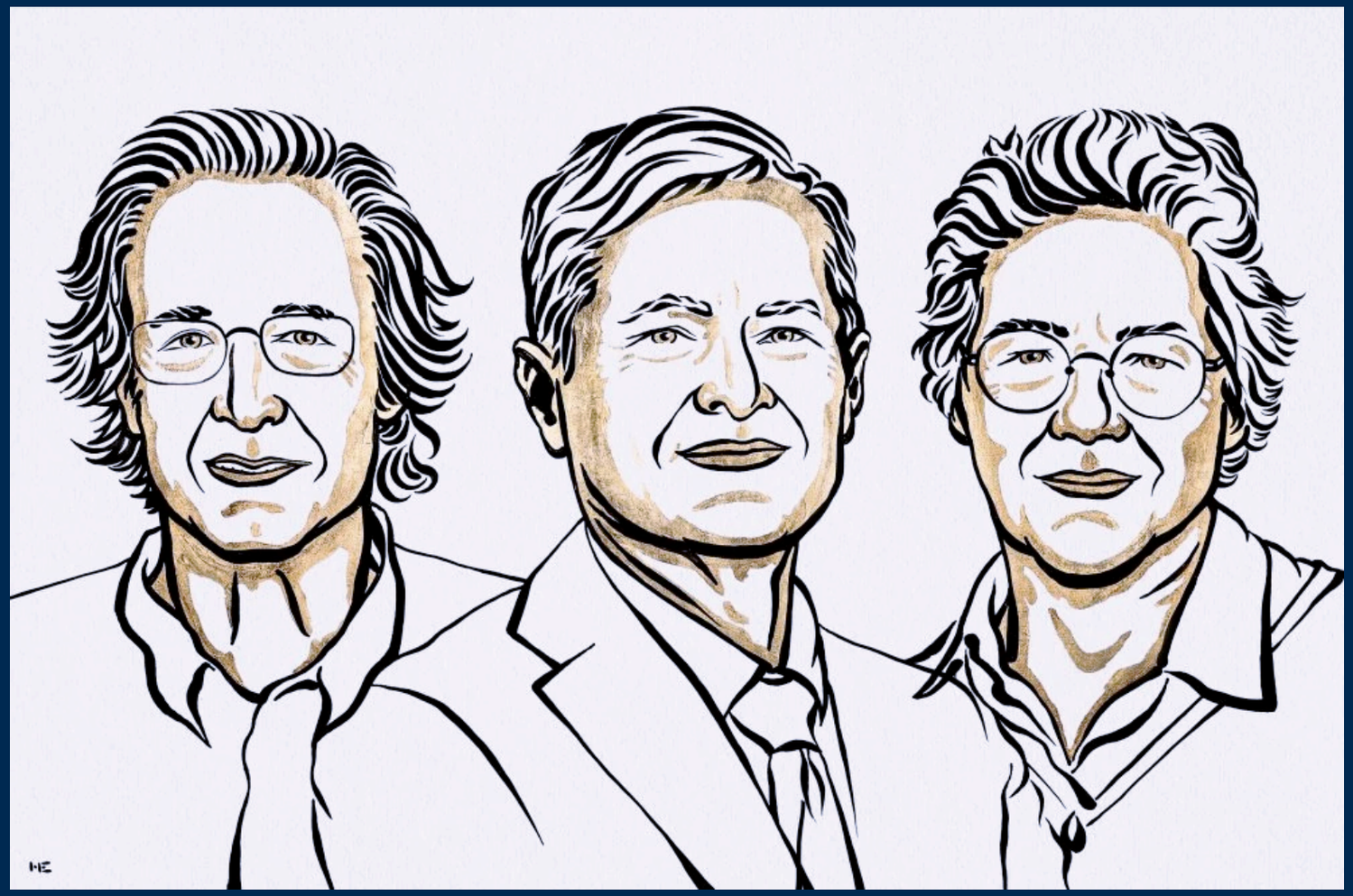
UNIVERSITÀ CATTOLICA del Sacro Cuore

STRUTTURA, NUMERO E MOVIMENTO Il tempo nella matematica e nella fisica
Milano 6 ottobre 2023

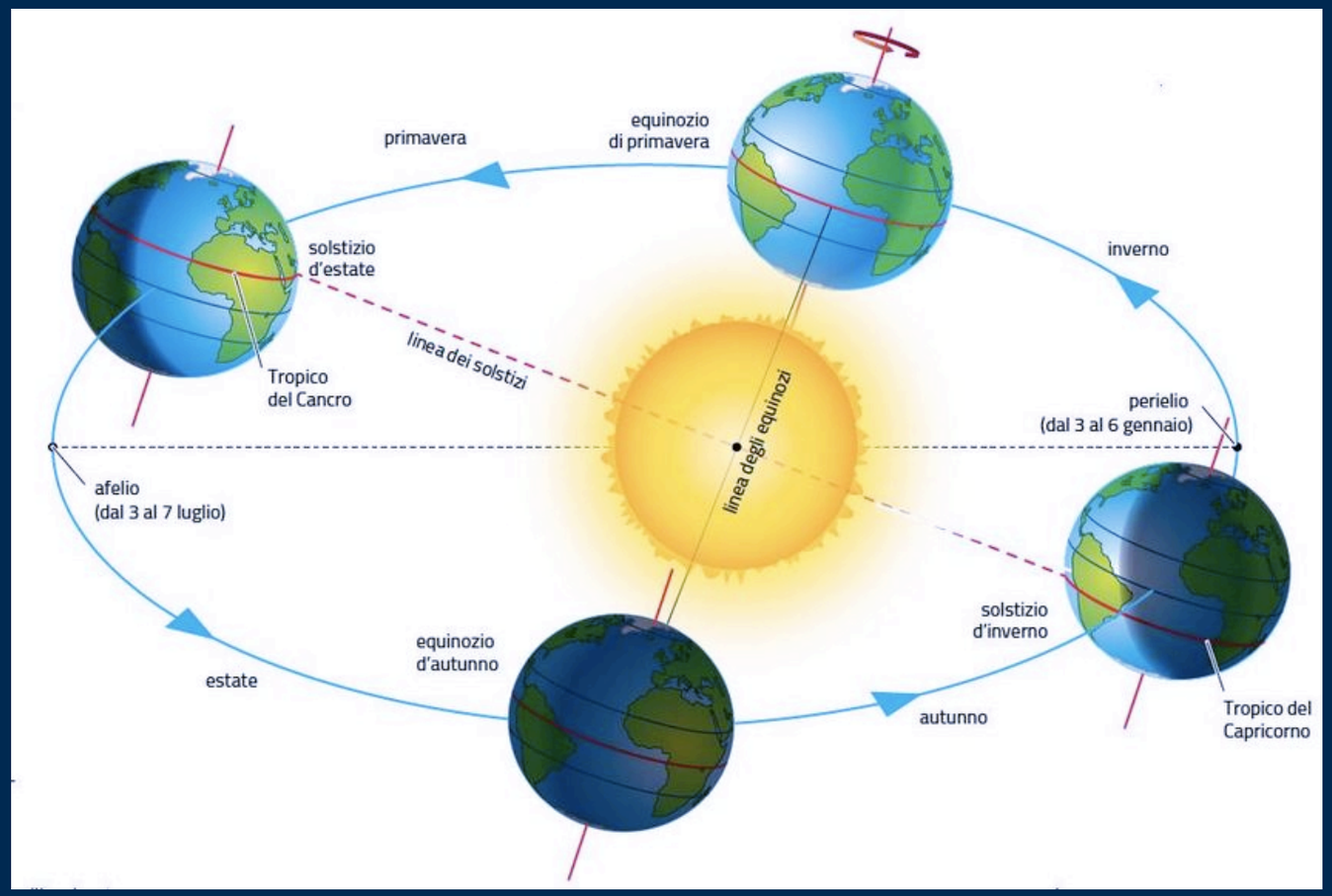
The Nobel Prize in Physics 2023



The Nobel Prize in Physics 2023 was awarded jointly to Pierre Agostini, Ferenc Krausz and Anne L'Huillier "*for experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter*"

misurare il tempo

fenomeni periodici come riferimento per definire l'unità di tempo

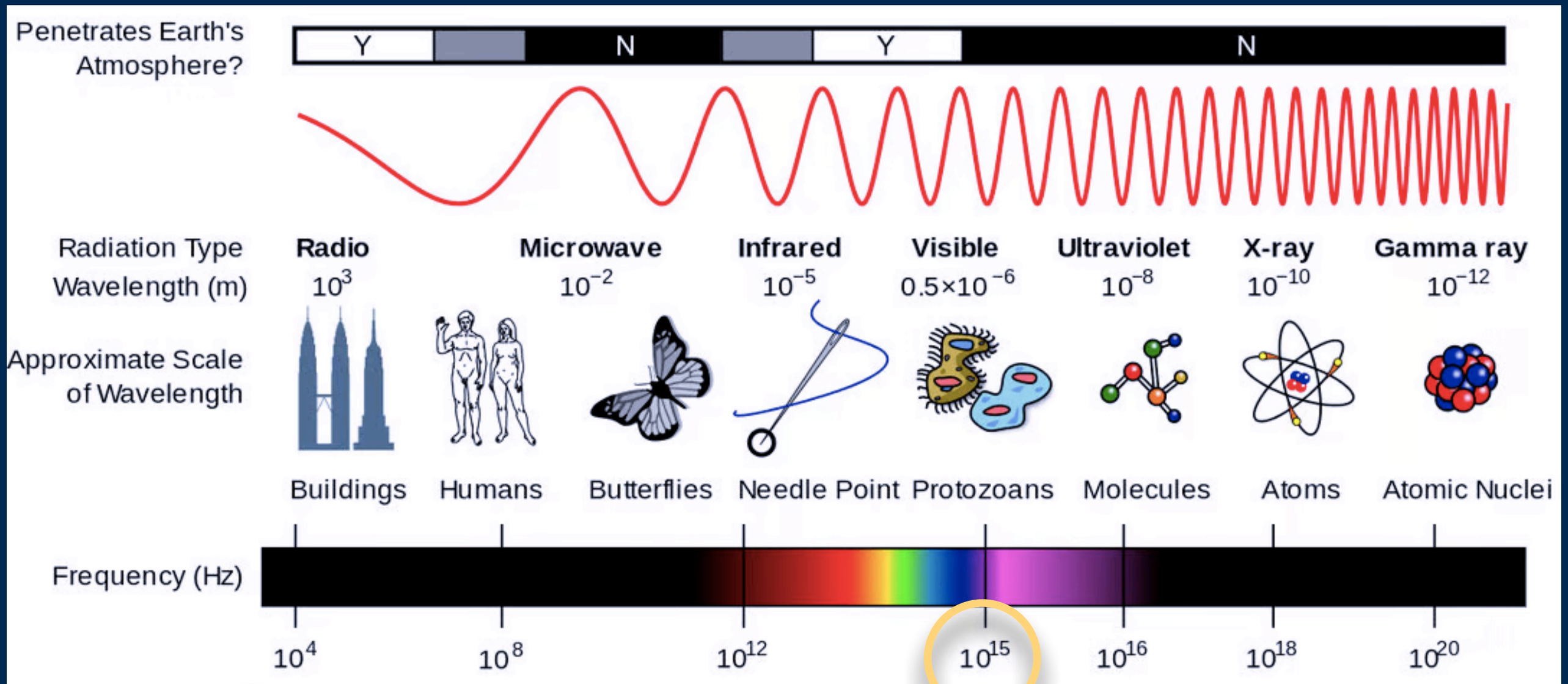


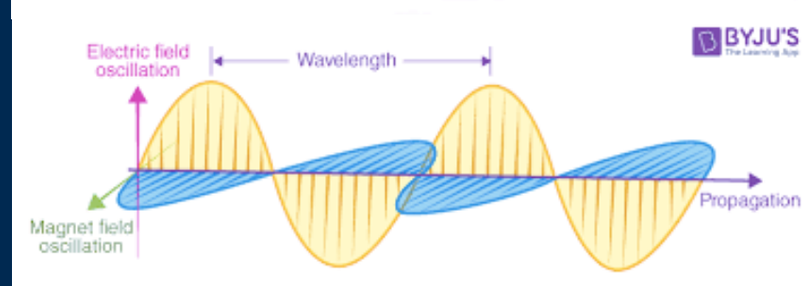
- stagioni
- giorno/notte
- ecc…

misurare il tempo è equivalente a misurare una frequenza!

lo spettro elettromagnetico

il campo elettromagnetico è l'evento più periodico che conosciamo!

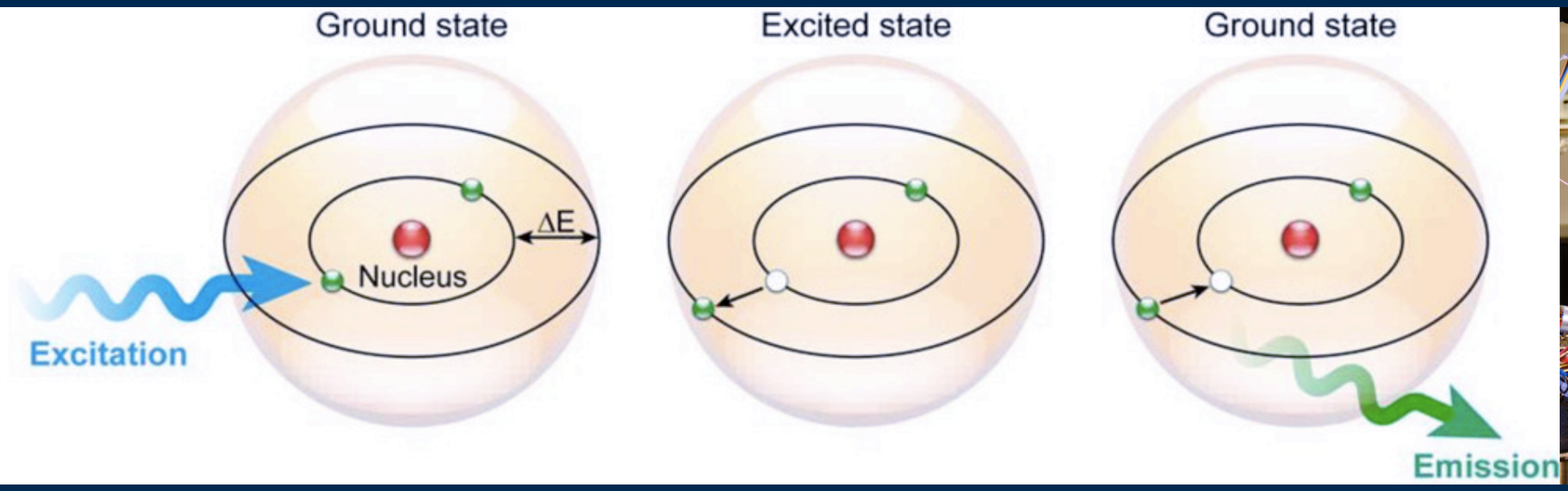


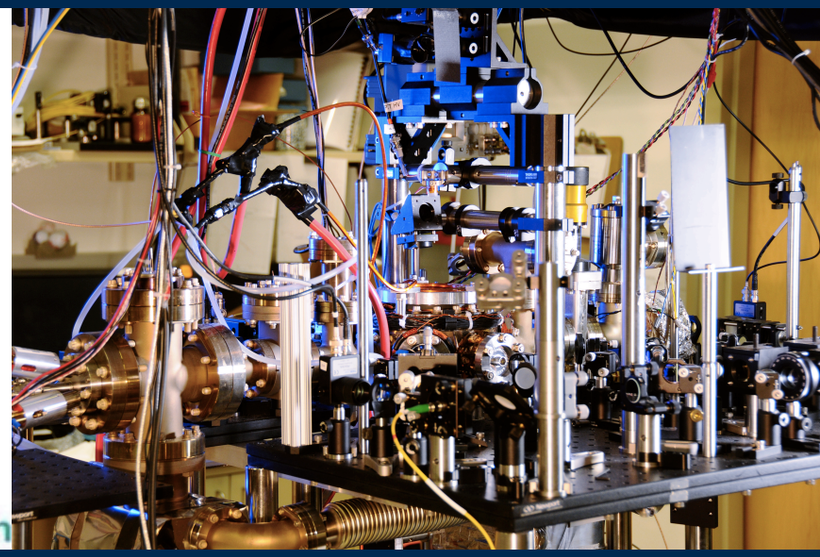


la frequenza della luce visibile è 10^{15} Hz
(un milione di miliardi di ripetizioni al secondo!)

orologi atomici

$f = 10^{15}$ Hz con una precisione di 10^{-3} Hz



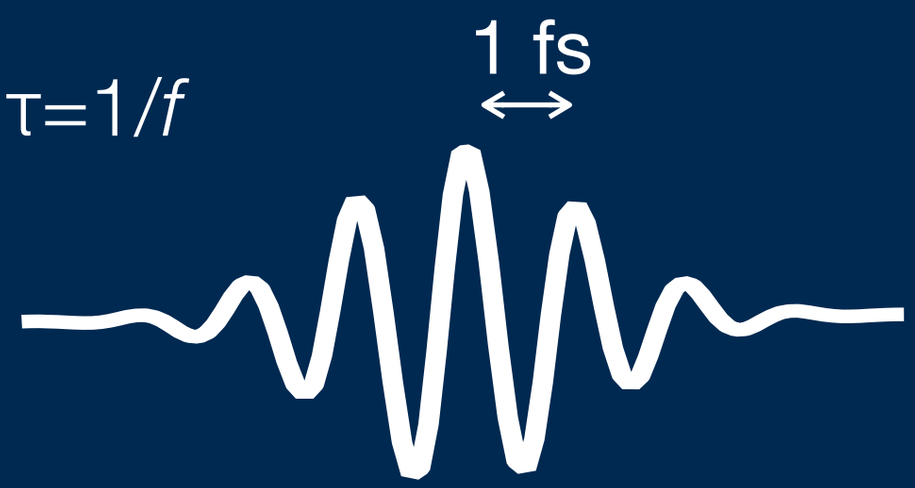


One of these clocks, the strontium atomic clock, is accurate to within 1/15,000,000,000 of a second per year. This is so accurate that it would not have gained or lost a second if the clock had started running at the dawn of the universe.

www.nist.gov

luce per misurare fenomeni velocissimi

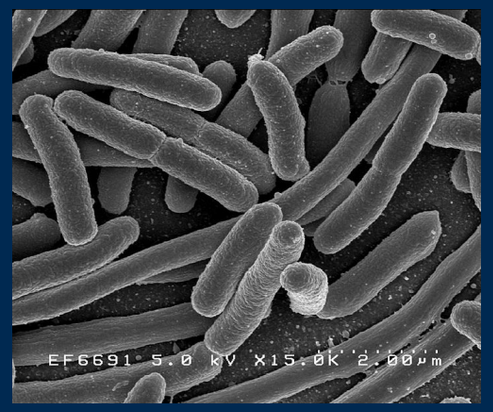
periodo $\tau = 1/f$



electromagnetic field visible light

1 femtosecond = 10^{-15} s = 0.000000000000001 s

like the ratio between:

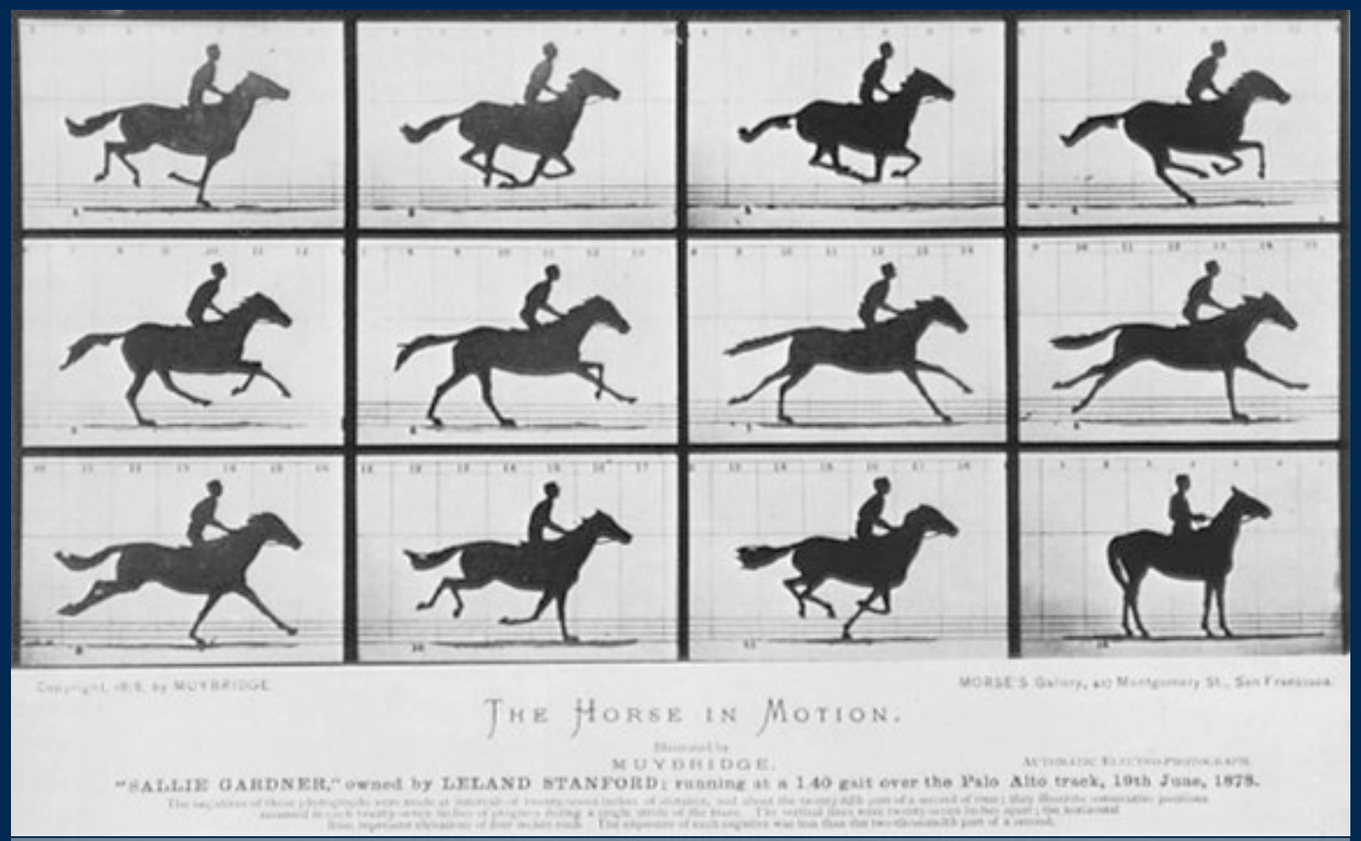


bacteria

earth-moon distance

fotografia veloce

High-speed photography by E. Muybridge
(1872, San Francisco)



ultrafast shutter?

Nobel Lecture by A. Zewail (1999)
(femtochemistry)

fotografia veloce

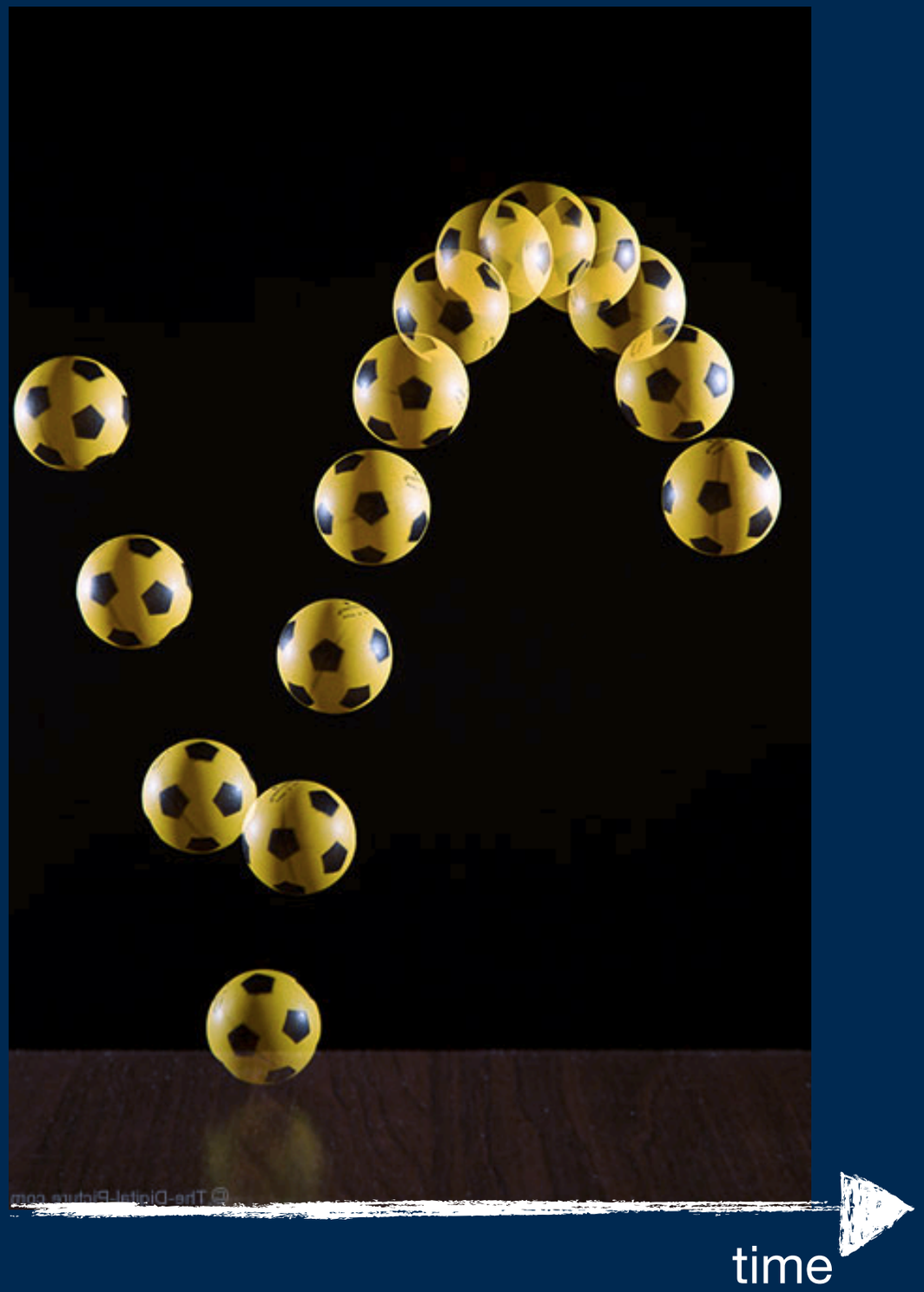
quanto veloce può essere l'otturatore di una macchina fotografica?

$1\ \mu s = 10^{-6}\ s$

immagini stroboscopiche

stroboscopic light

1 ms

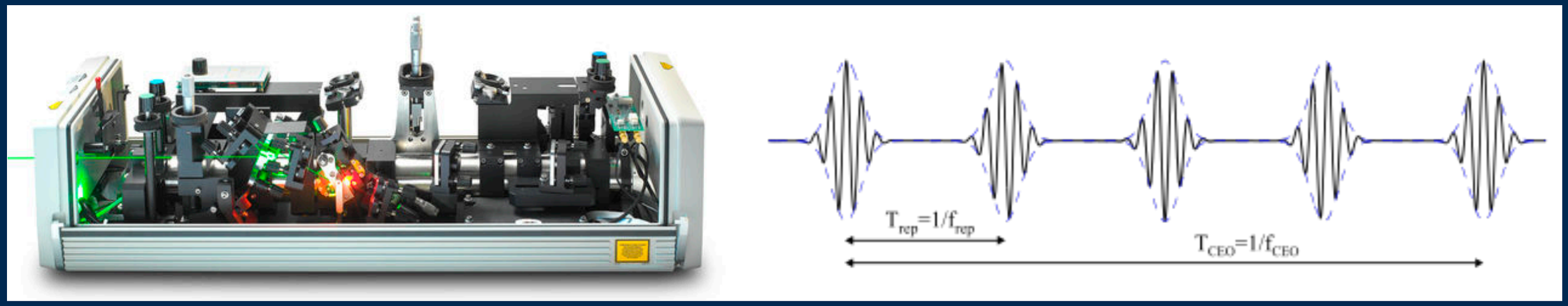


⇒impulsi di luce più brevi della dinamica di un sistema fisico

ultrafast lasers

⇒ femtosecond flashes of lights

Nobel prize to Gérard Mourou and Donna Strickland (2018), "for their method of generating high-intensity, ultra-short optical pulses”



10 fs

electromagnetic field

1 femtosecond = 10^{-15} s = 0.000000000000001 s

optical cycle: 2 fs @ 600 nm

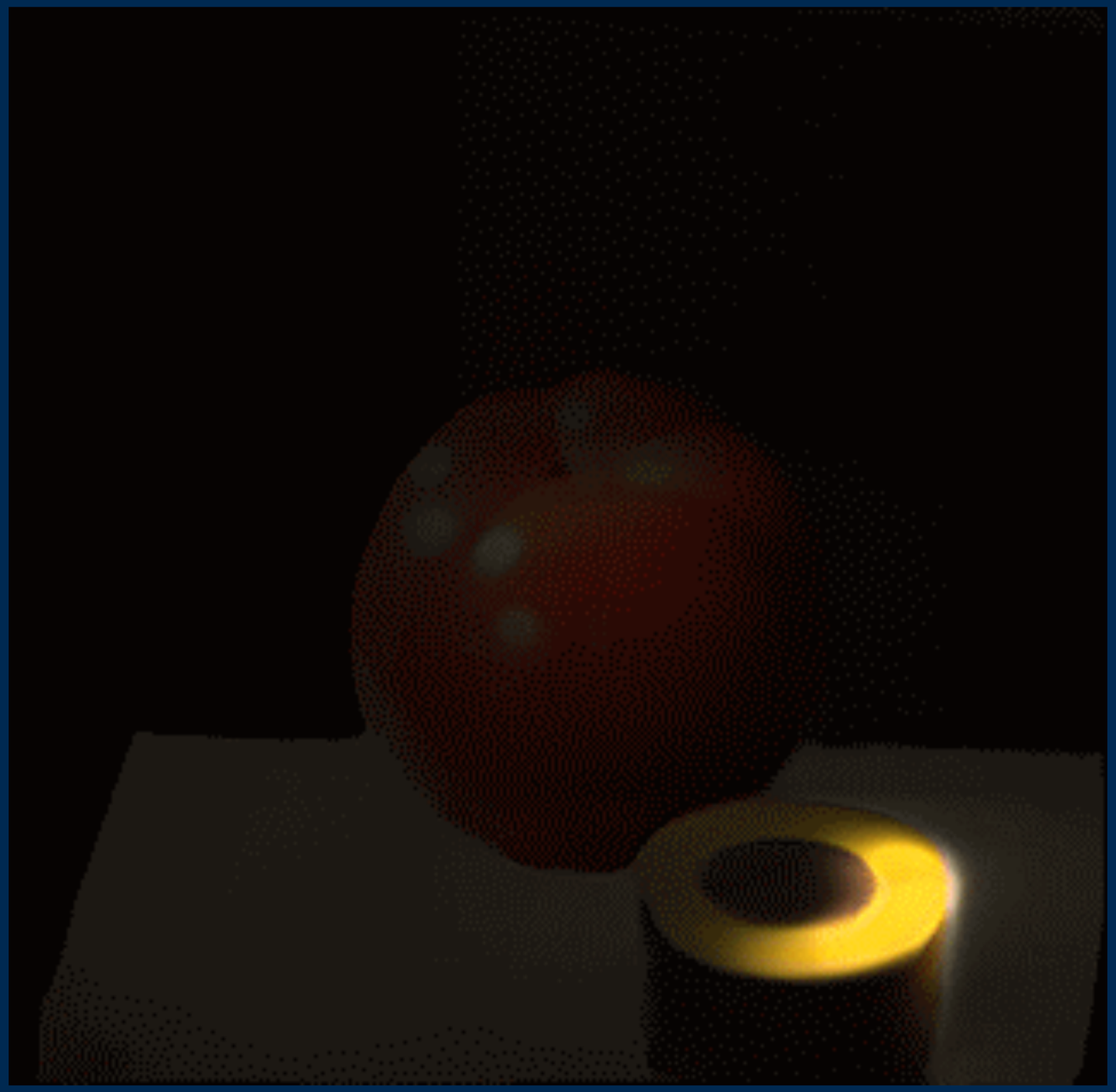
femto-photography

10 cm ⇒ 100 picoseconds @ speed velocity ($3 \cdot 10^8$ m/s)

femtocamera.info (MIT)

https://www.youtube.com/watch?v=EtsXgODHMWk

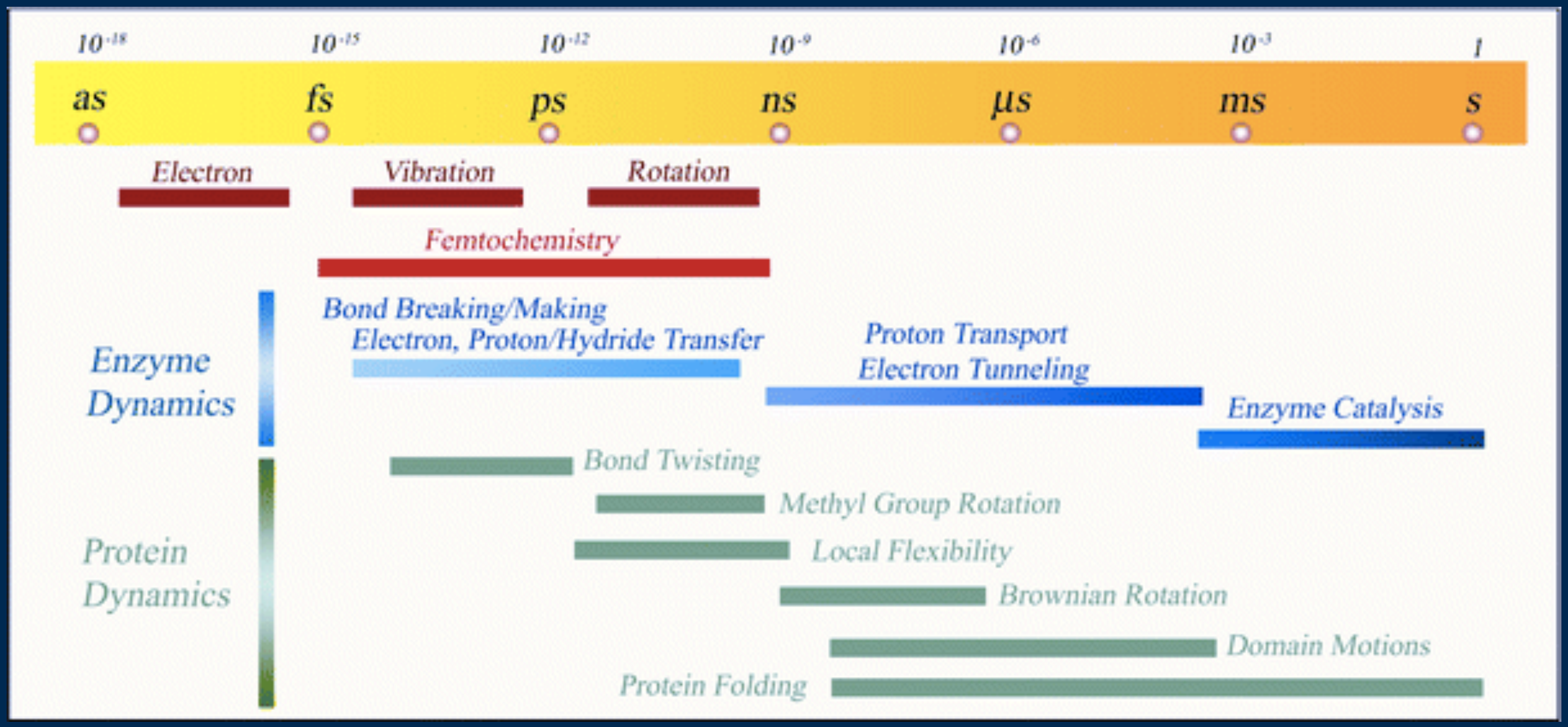
Femto-photography



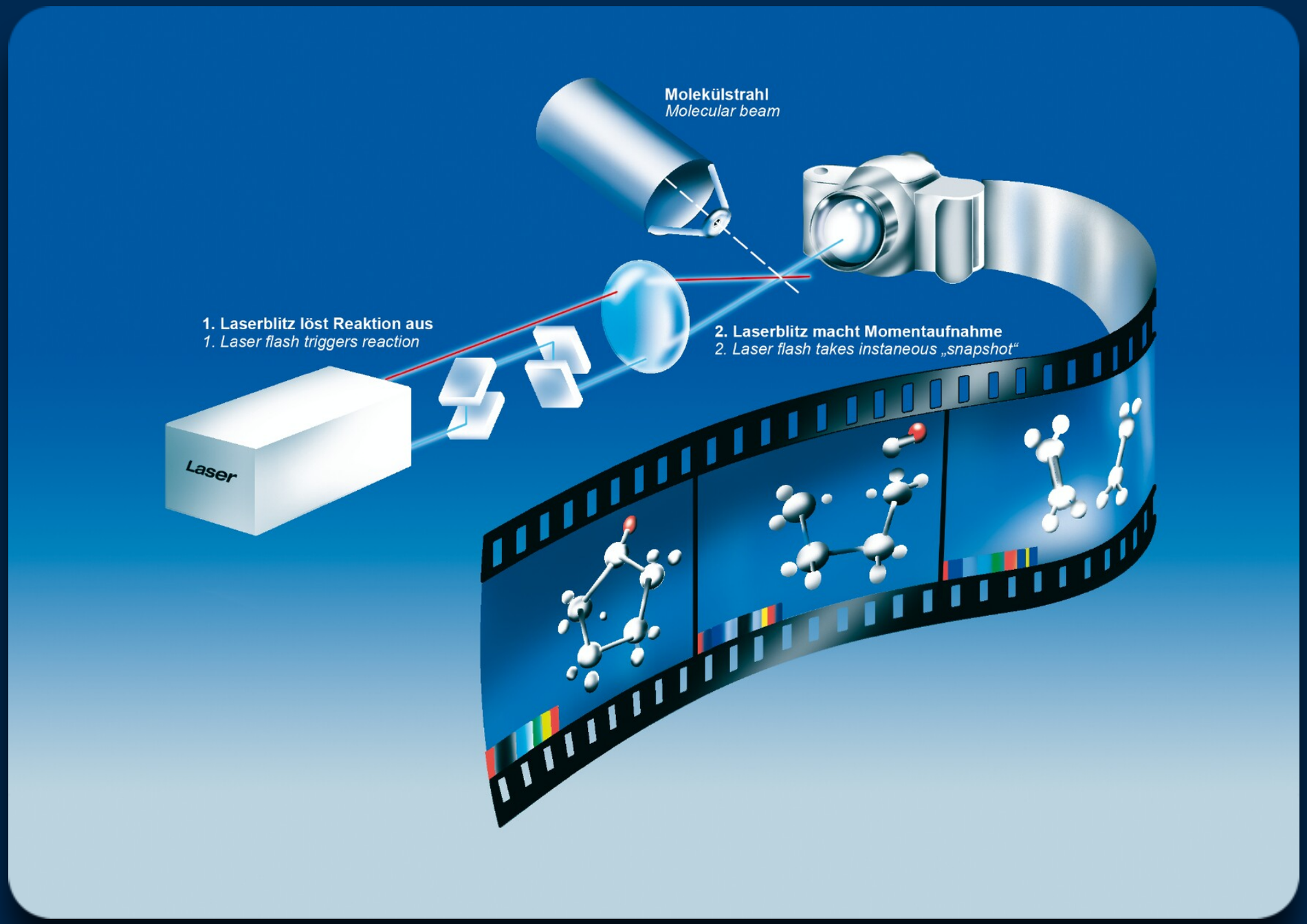
femtocamera.info (MIT)

Femto-photography

biochemistry clock



immagini della formazione di legami chimici

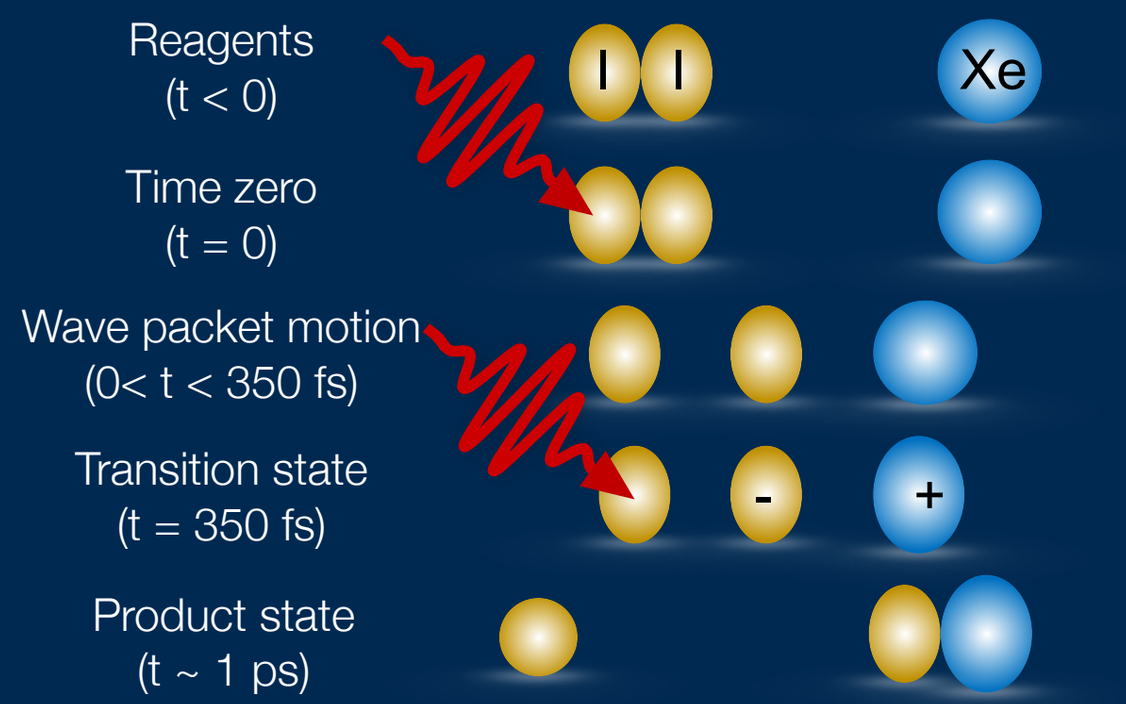


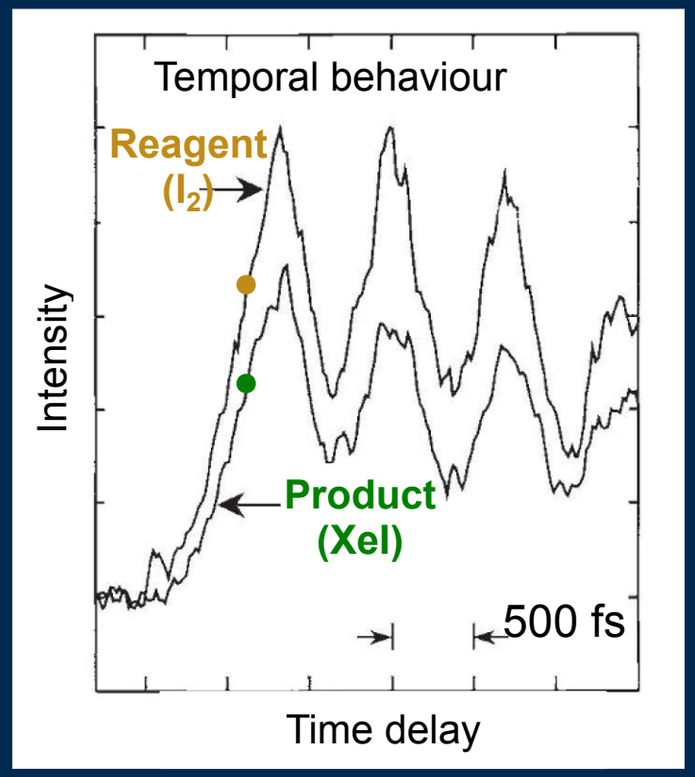
movies of chemical reactions and
electronic interactions in materials

Femto-chemistry

Atom-molecule reaction: rare gas atoms (Xe) and halogen molecules (I_2)

$$I_2 + Xe + h\nu \rightarrow [\,Xe\ldots I\ldots I\,]^* \rightarrow XeI + I$$

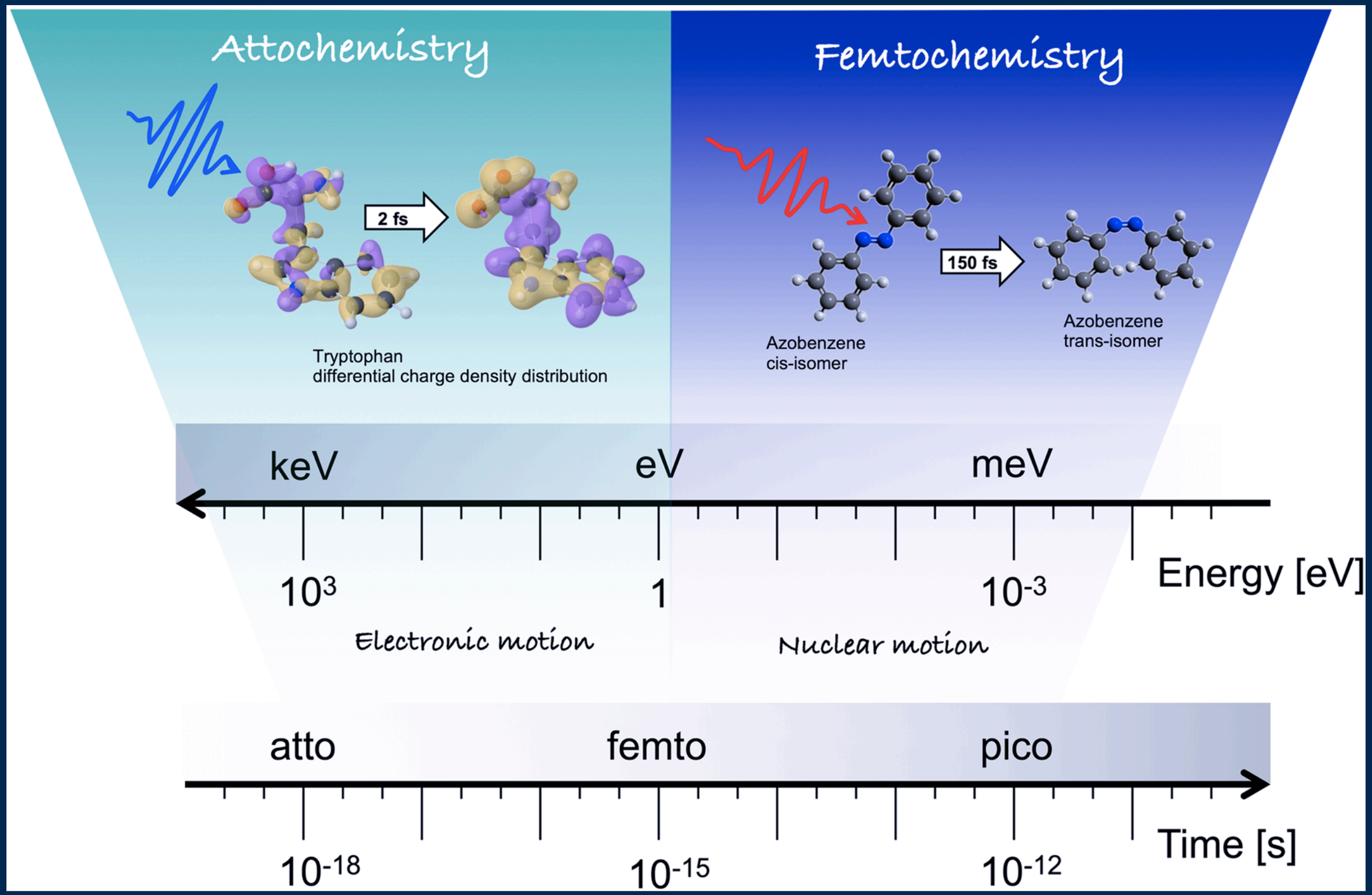




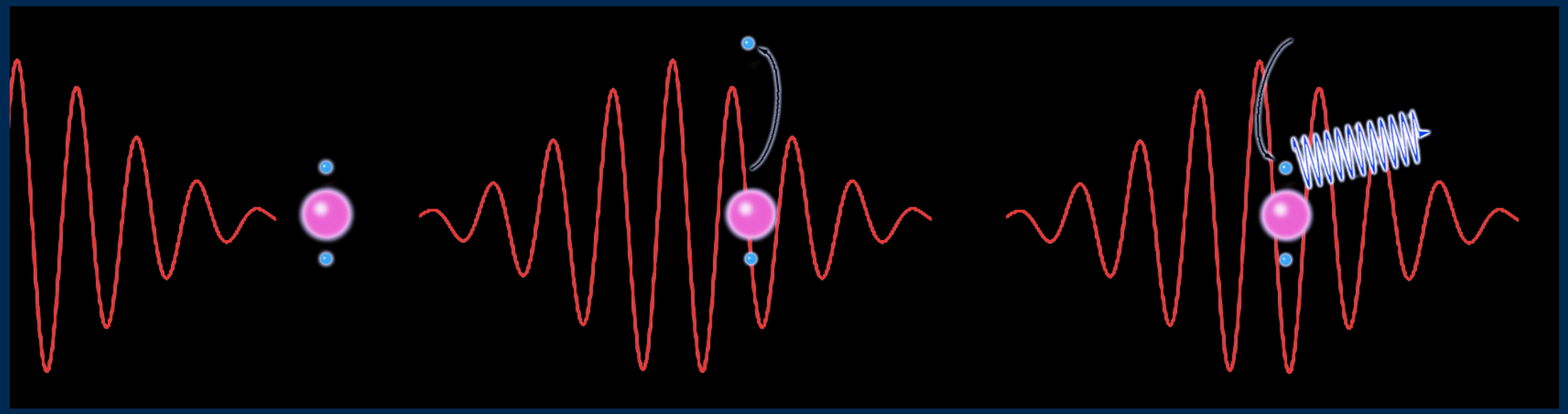
Potter & Zewail, Nature 355, 66 (1992)

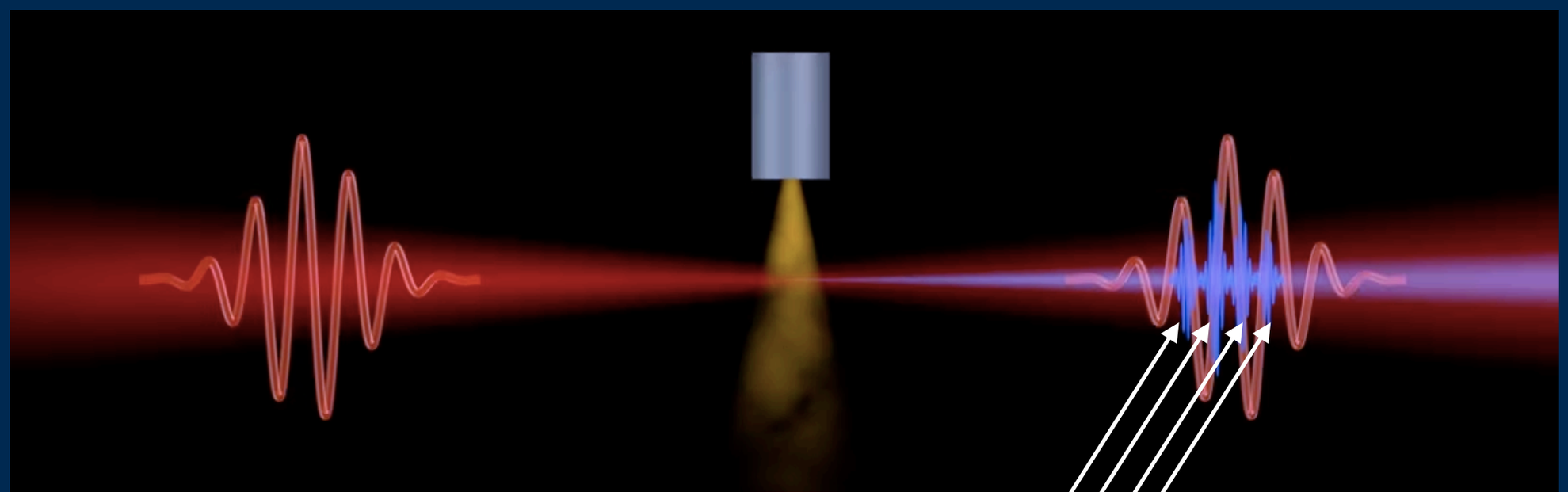
The Nobel Prize in Chemistry 1999 was awarded to Ahmed H. Zewail "for his studies of the transition states of chemical reactions using femtosecond spectroscopy"

Atto-chemistry?



attosecond pulses generation

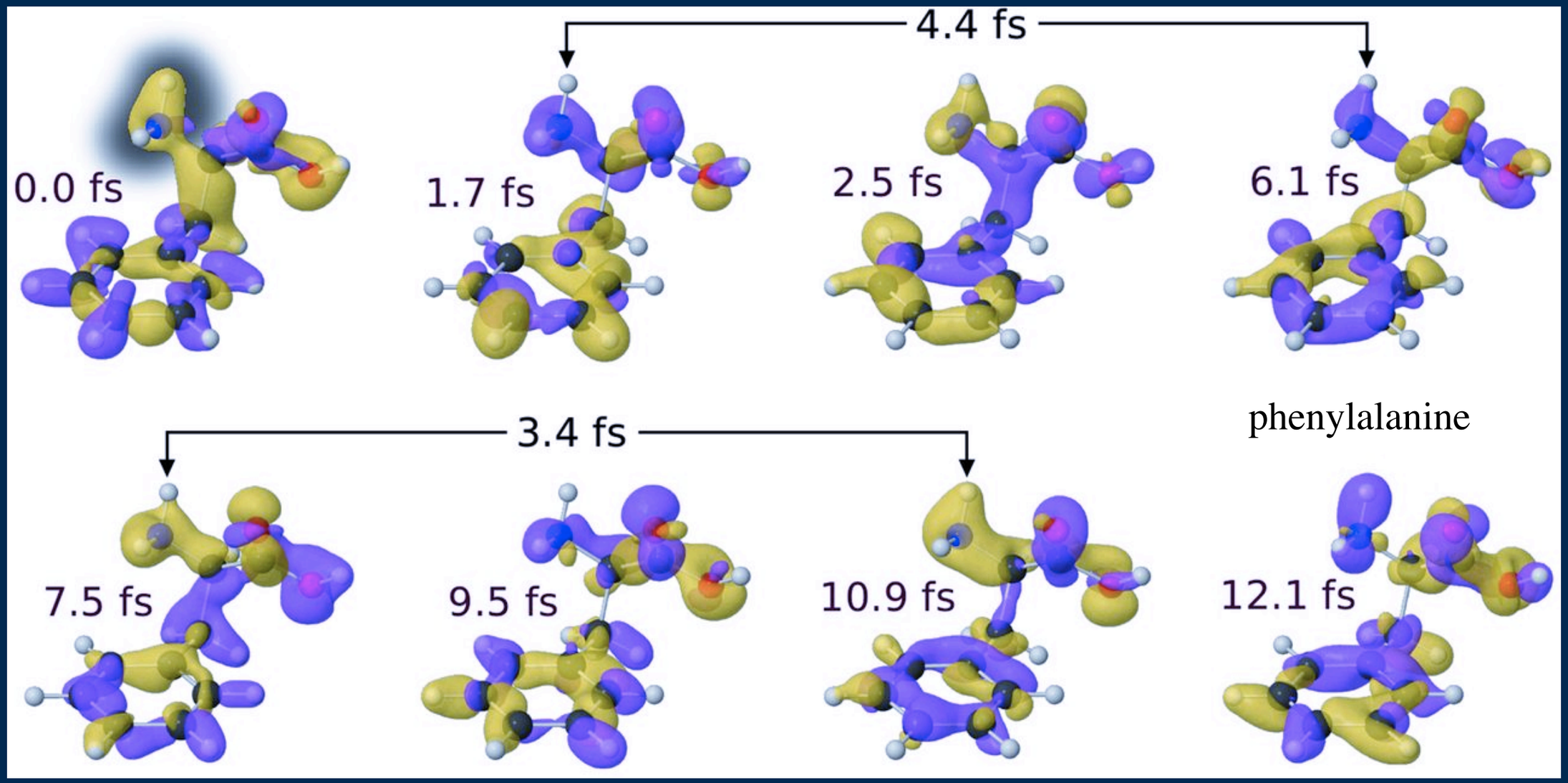




attosecond X-ray pulses

filmati della dinamica elettronica

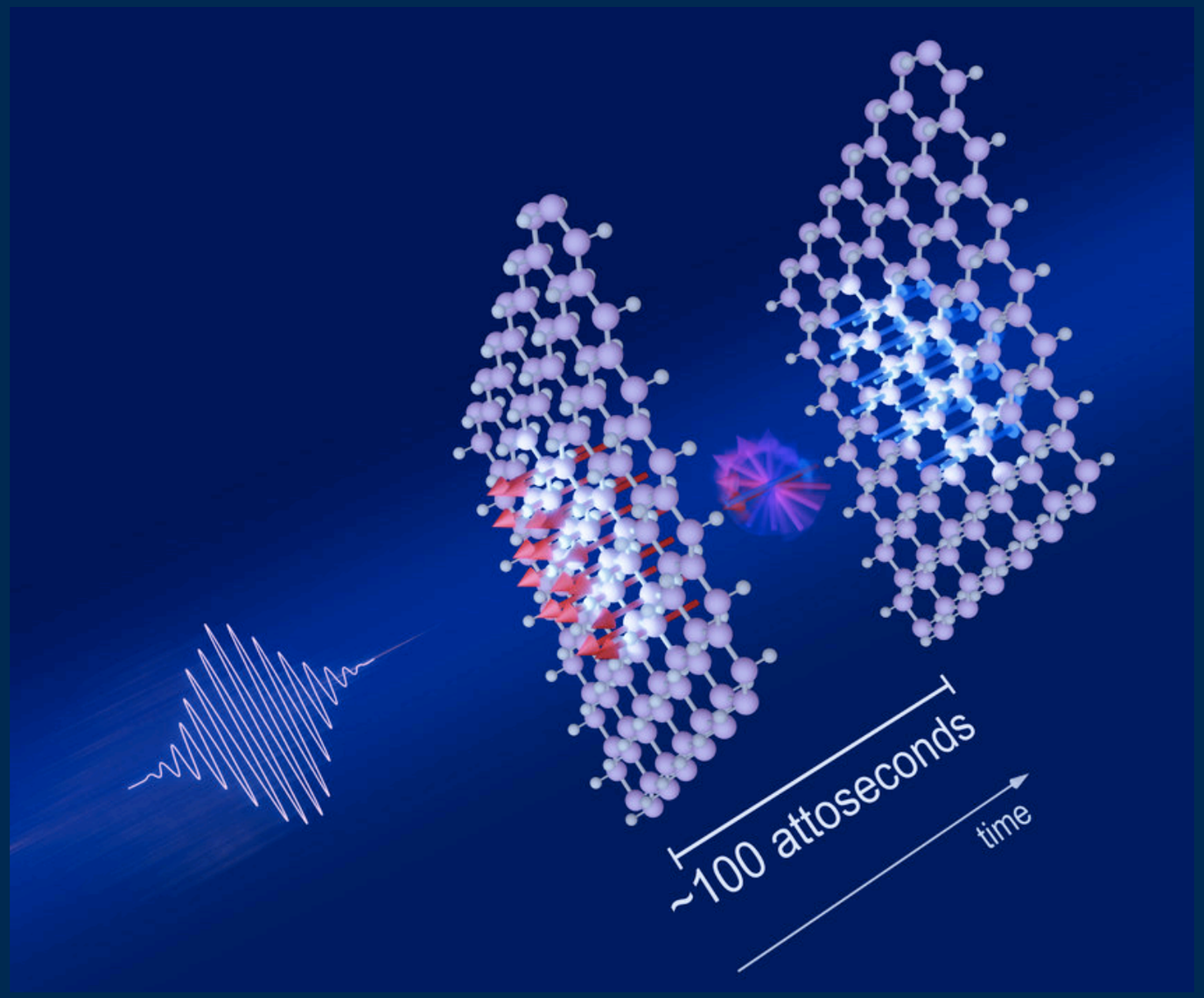
bio-relevant molecules



F. Calegari et al. J. Phys. B: At. Mol. Opt. Phys. 49 (2016) 142001

nuove frontiere

tempo di cambiamento della magnetizzazione in materiali bidimensionali

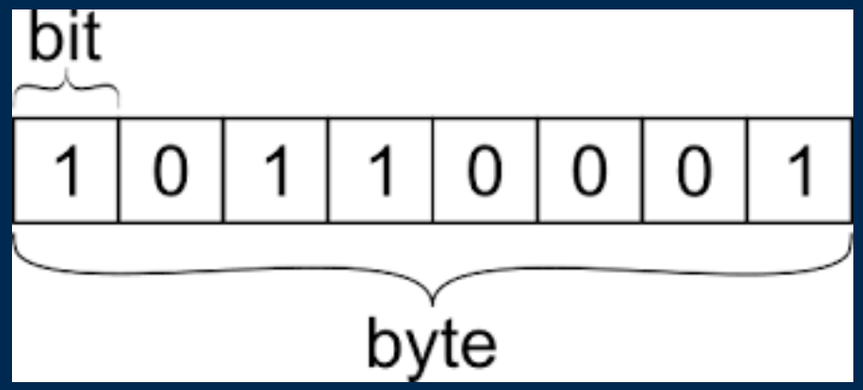


una finestra sui tempi di trasformazione della materia e i processi più veloci che possono avvenire in solidi, liquidi e gas

quantum computers

classical computing:

bit



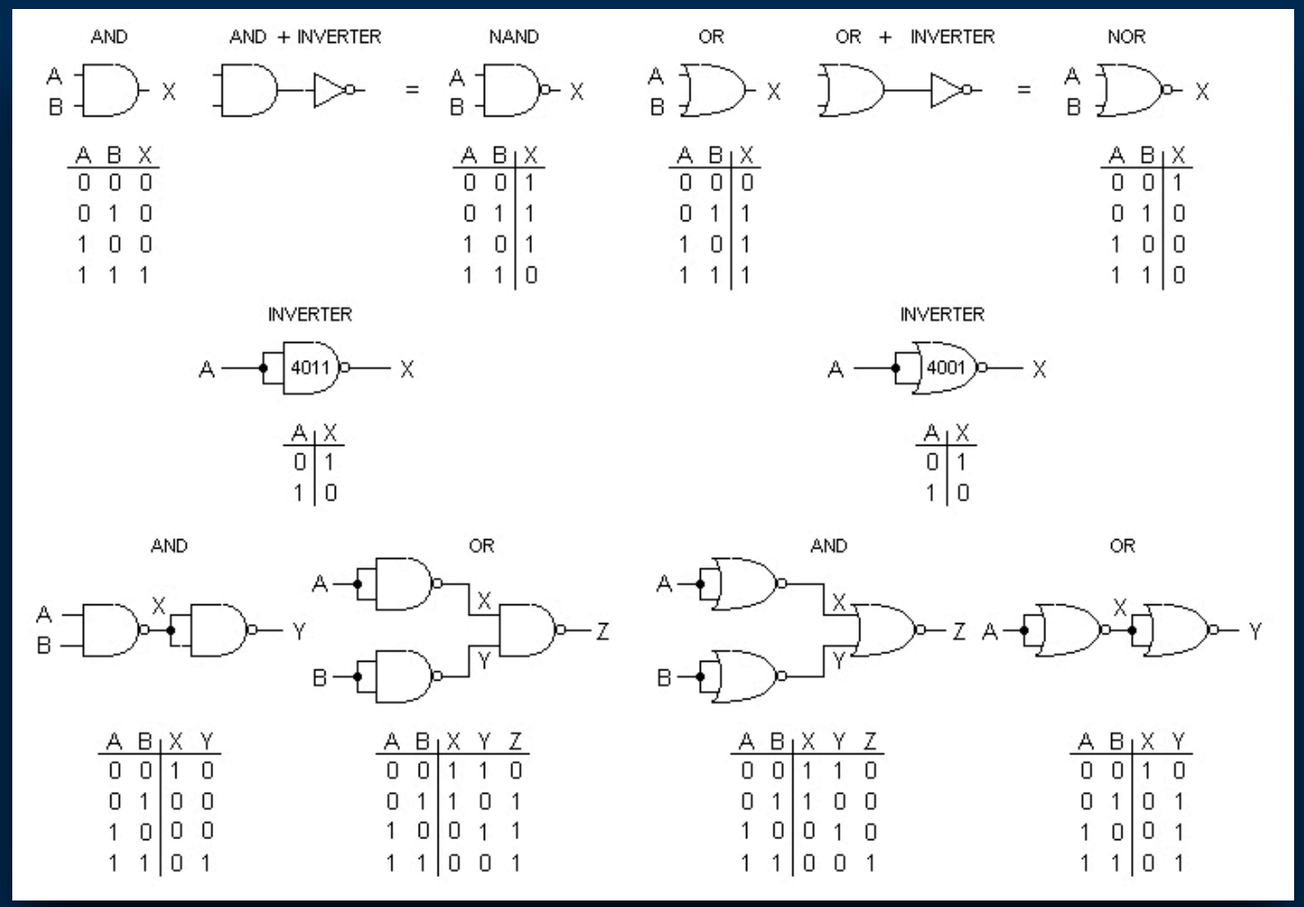
bit classico:

0 or **1**

linguaggio binario

Binary	decimal	Hexadecimal	Gray	2's complement
0000 0000	0	00	0	0
0000 0001	1	01	1	1

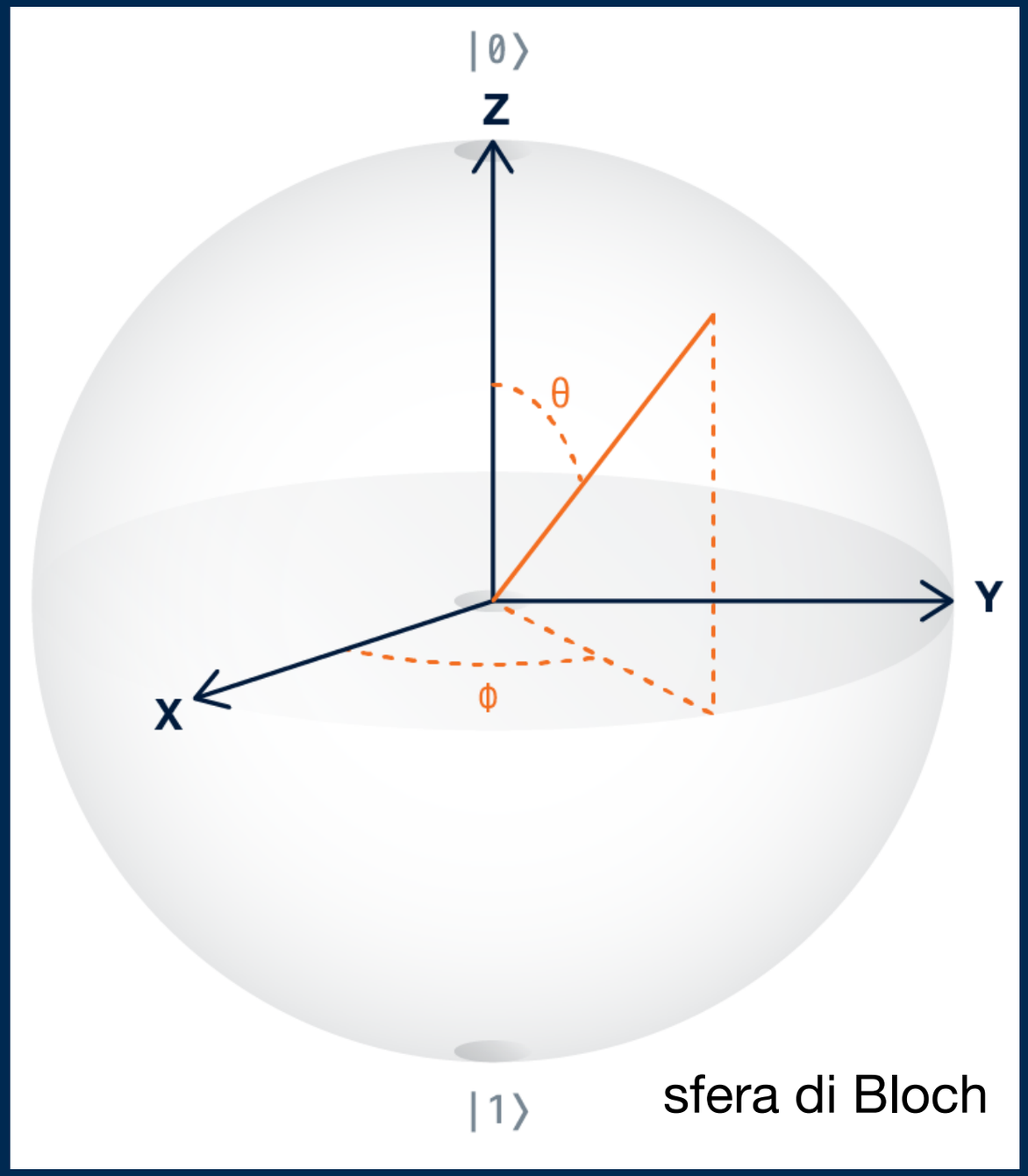
processing



operazioni logiche e circuiti digitali

quantum computers

il quantum bit può essere visto come un vettore in una sfera



sfera di Bloch

bit classico:

$|0\rangle$ o $|1\rangle$

solo vettori verticali

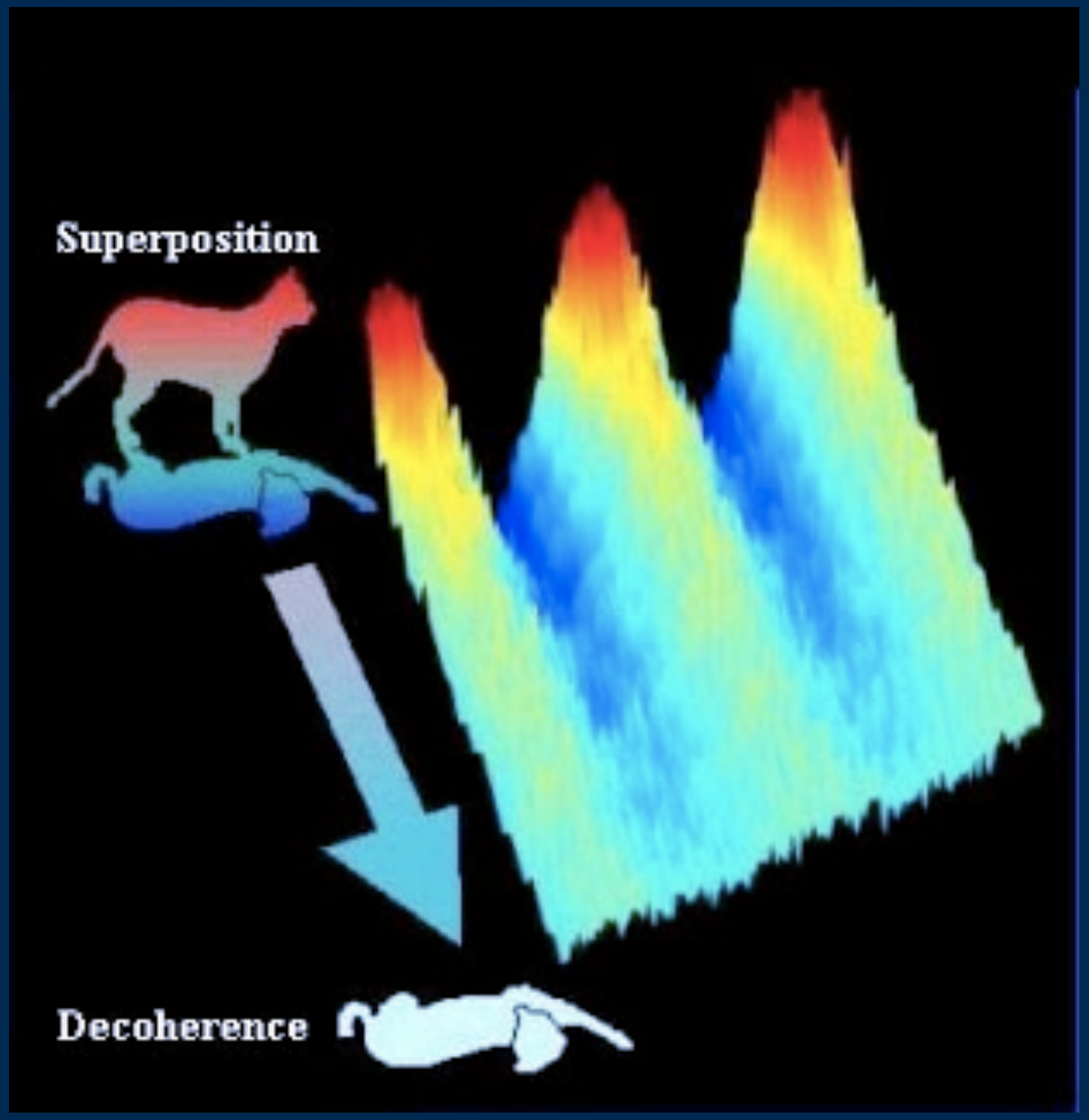
bit quantistico:

$c_0|0\rangle+c_1|1\rangle$

c sono coefficienti complessi

qualsiasi tipo di vettore!

decoerenza quantistica



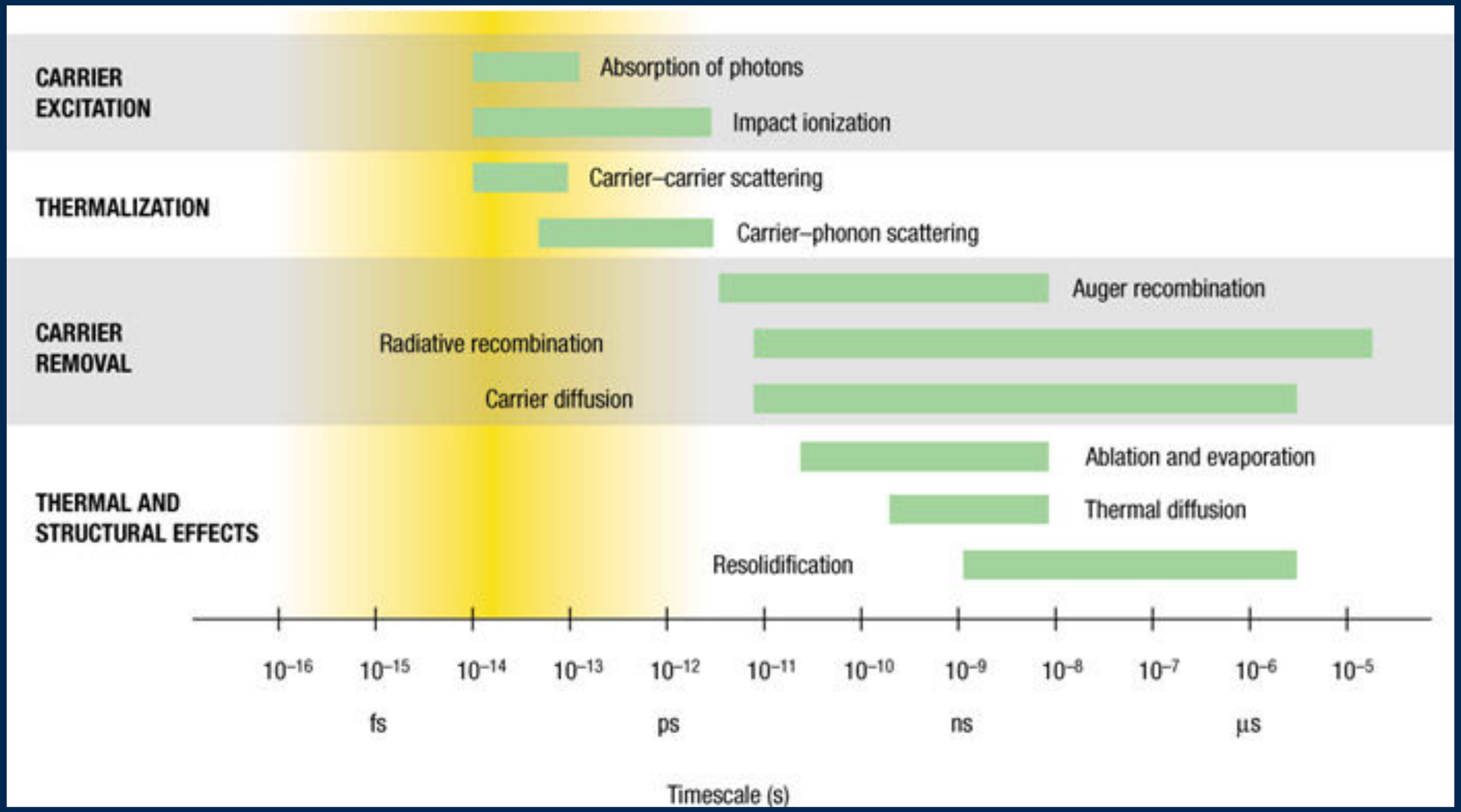
qualsiasi interazione con il mondo circostante provoca decoerenza

perdita della fase della funzione d'onda e della sovrapposizione di stati

$c_0|0\rangle + c_1|1\rangle$ → interazioni → $|0\rangle$ / $|1\rangle$

decoerenza quantistica

scale di tempo delle interazioni nella materia



S. K. Sundaram & E. Mazur. *Nature Materials* 1, 217-224 (2002)

quantum computers

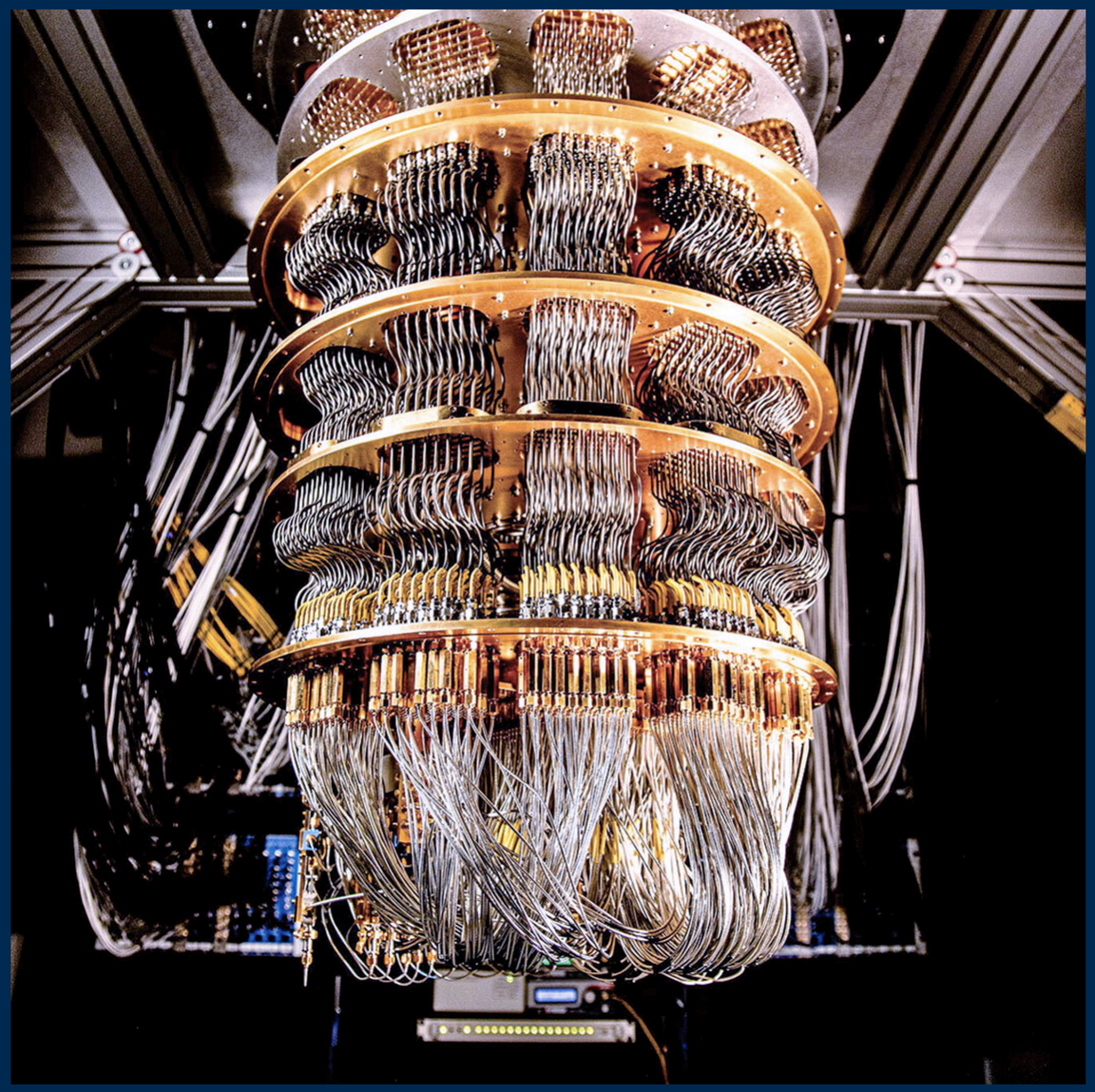
requisiti: effettuare operazioni più veloci del tempo di **decoerenza** (il tempo necessario per perdere la natura ondulatoria)

il numero di operazioni è dato dal rapporto tra il tempo necessario per una singola operazione (T_{op}) e il tempo di decoerenza (T_{dec})

system	T_{dec} (s)	T_{op} (s)	N_{op}
Nuclear spin	10^{4}	10^{-3}	10^{7}
Ion trap	10^{1}	10^{-6}	10^{7}
Excitons in Quantum dots	10^{-9}	10^{-12}	10^{3}
Spin in Quantum dots	10^{-7}	10^{-12}	10^{5}
Superconducting flux	10^{-8}	10^{-10}	10^{2}
superconducting +radiofrequency	**10^{-5}**	**10^{-10}**	**10^{5}**

$$N_{op} = \frac{T_{dec}}{T_{op}}$$

quantum computers



bassissime temperature
-273,13 °C!

impulsi agli atto e femtosecondi possono manipolare lo stato della materia ad alta temperatura prima che perda la coerenza quantistica

Thank you!