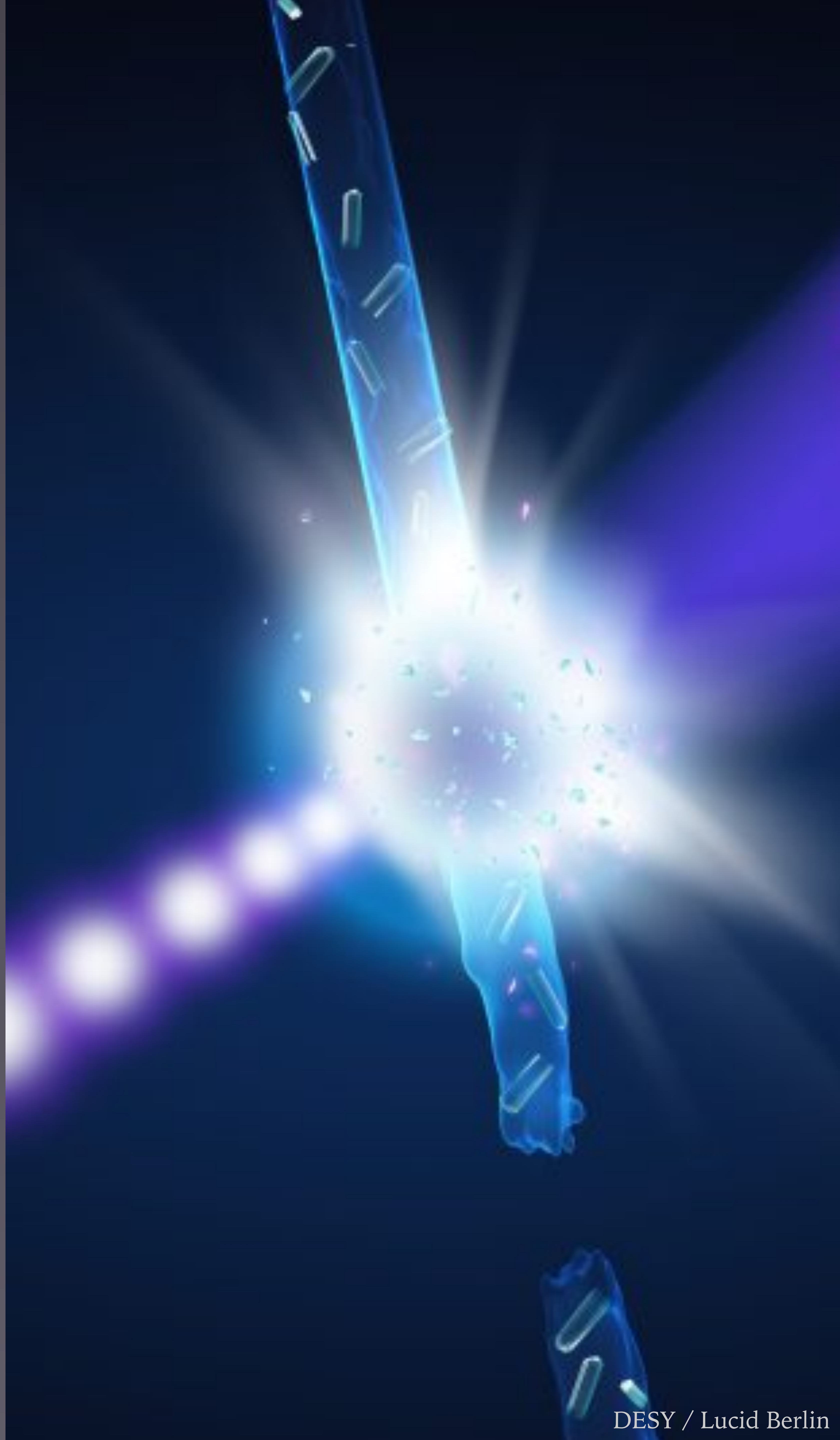
AN ULTRASHORT HISTORY OF ULTRAFAST IMAGING

Caroline Arnold



DESY / Lucid Berlin

About Me

- Physicist at Deutsches Elektronen-Synchrotron DESY
- PhD in ultrafast molecular physics
- Pronouns: she/her

What Is the Goal of Ultrafast Imaging?

Long exposure time: blurry image 1 s

Short exposure time: clear image 1/100 s

Take clear pictures of moving objects

Movies

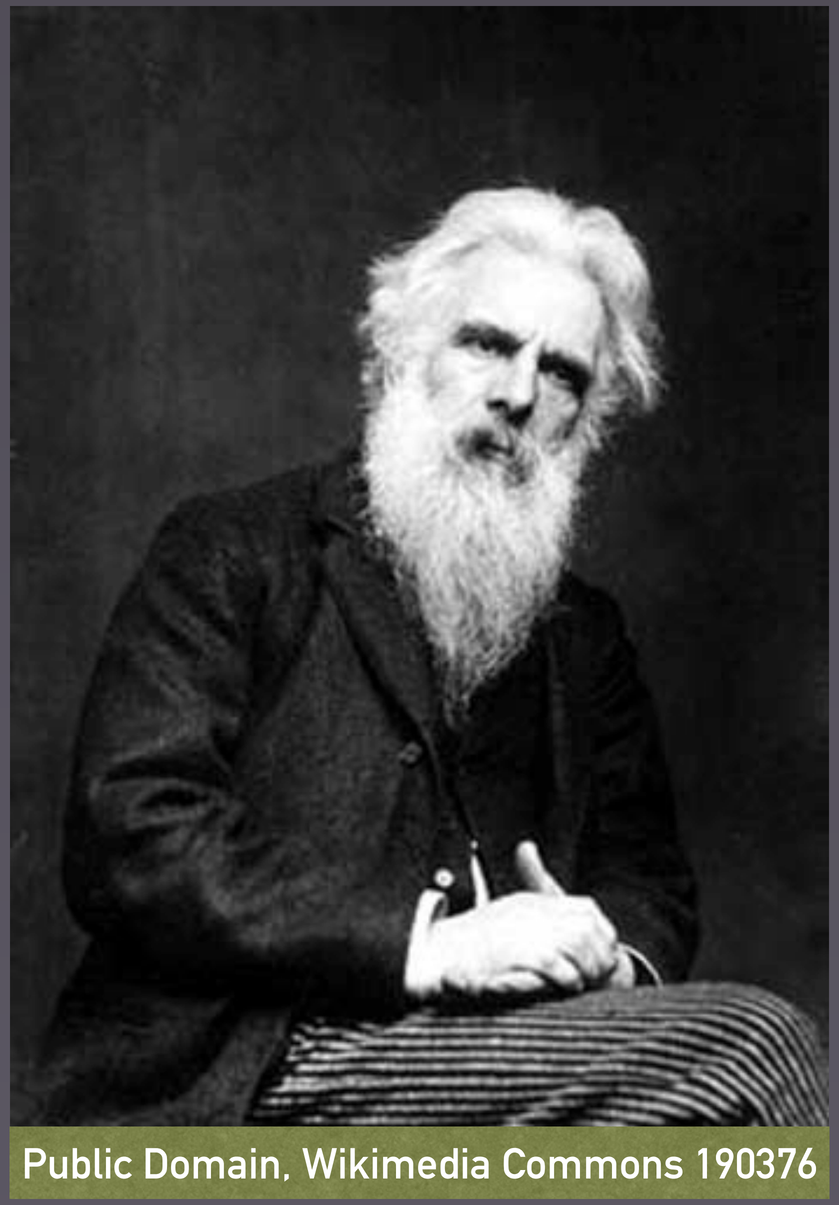
- Most processes in nature are not static
- More insight from time-resolved images

http://thebiglead.com/2014/02/11/cross-country-skiing-crash-gifts-emil-joensson-a-bronze-medal/

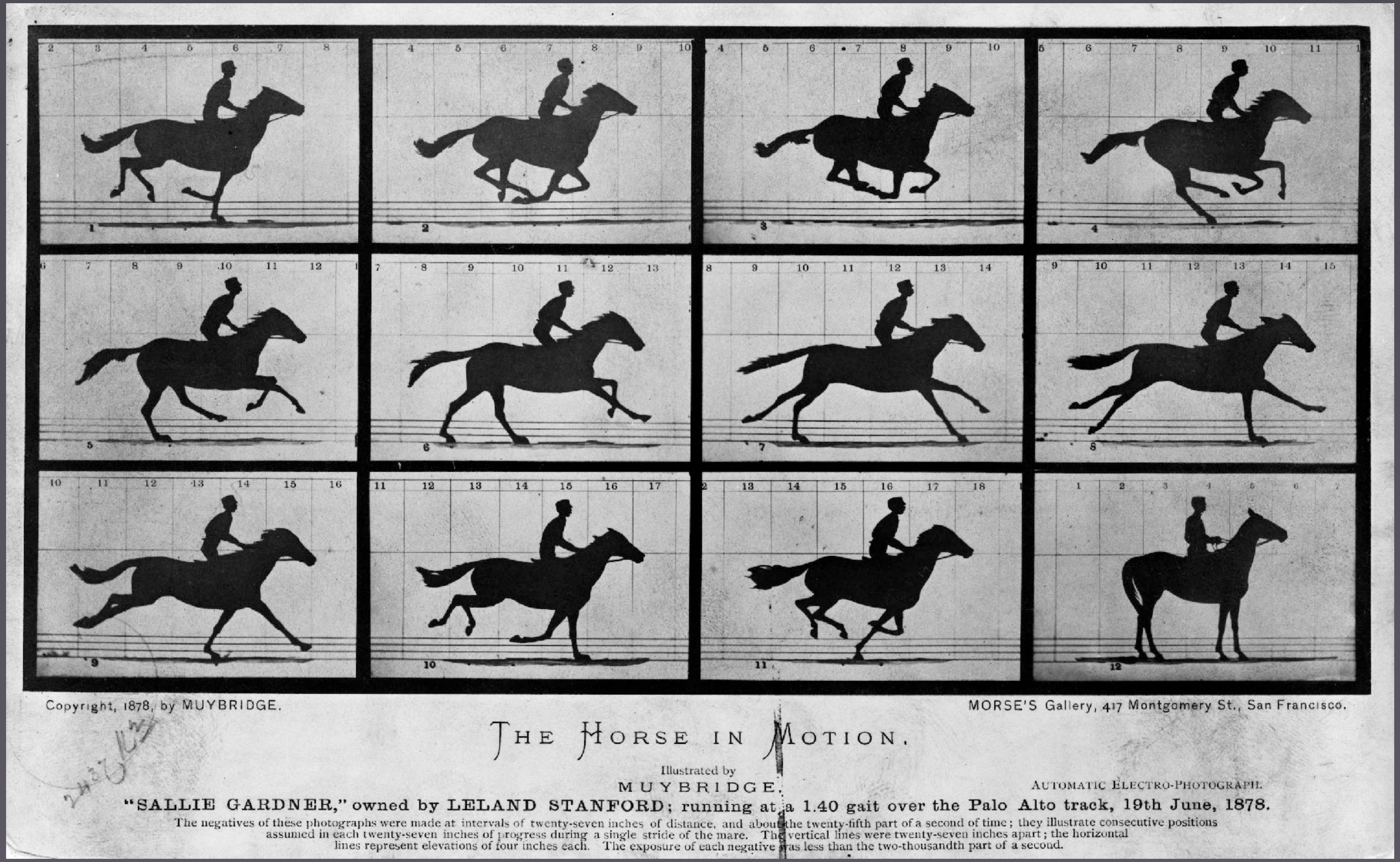
The First Ultrafast Movie

Does a galloping horse ever lift all its legs off the ground?

Eadweard Muybridge (1830 - 1904)



- Stop-motion technique



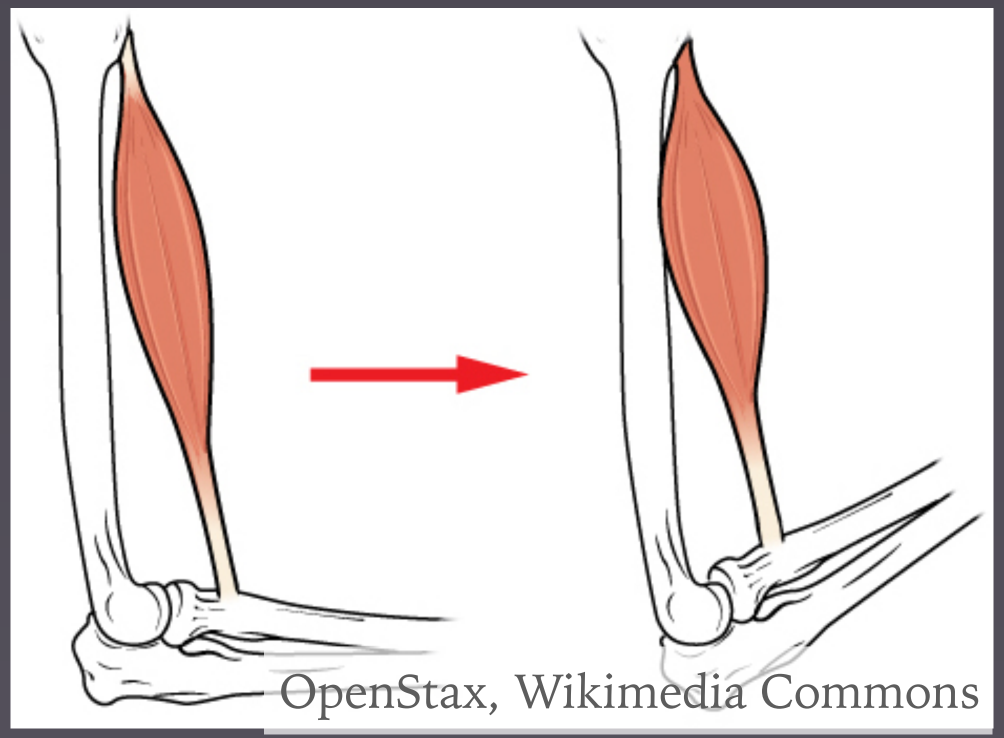
The Horse in Motion, Stanford 1878

What Is Ultrafast?


Malene Thyssen, Wikimedia Commons

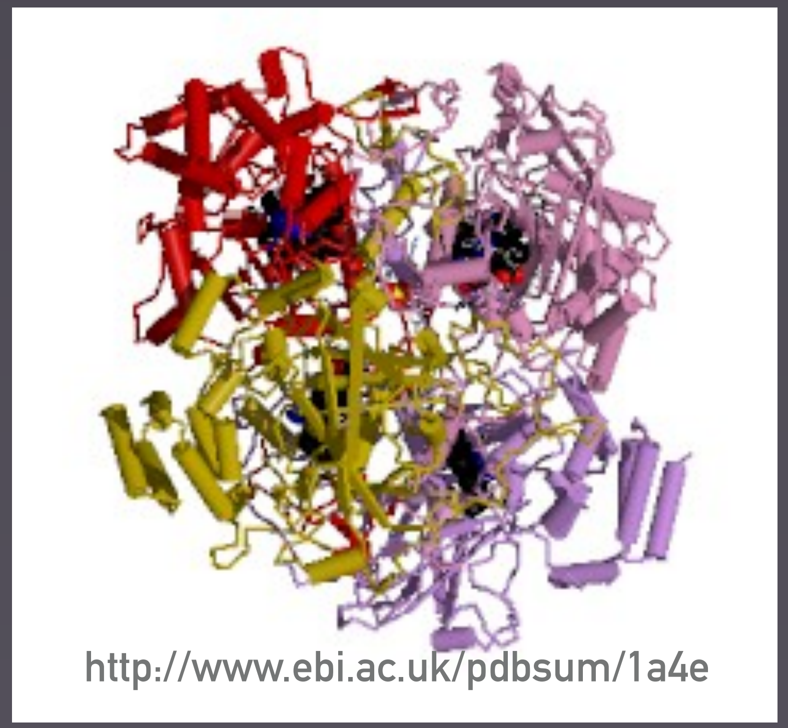
second

1 s


OpenStax, Wikimedia Commons

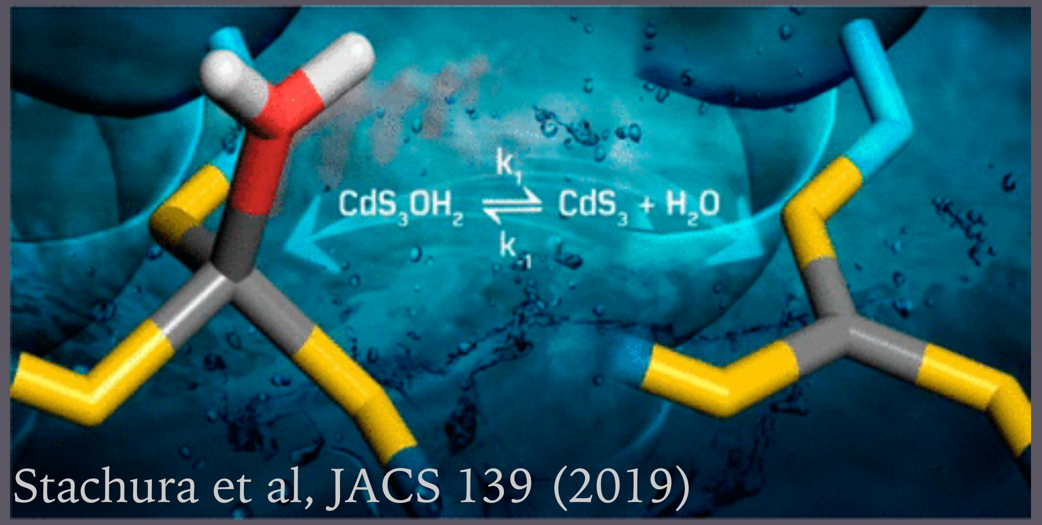
millisecond

$1 \text{ ms} = 0.001 \text{ s} = 10^{-3} \text{ s}$


http://www.ebi.ac.uk/pdbsum/1a4e

microsecond

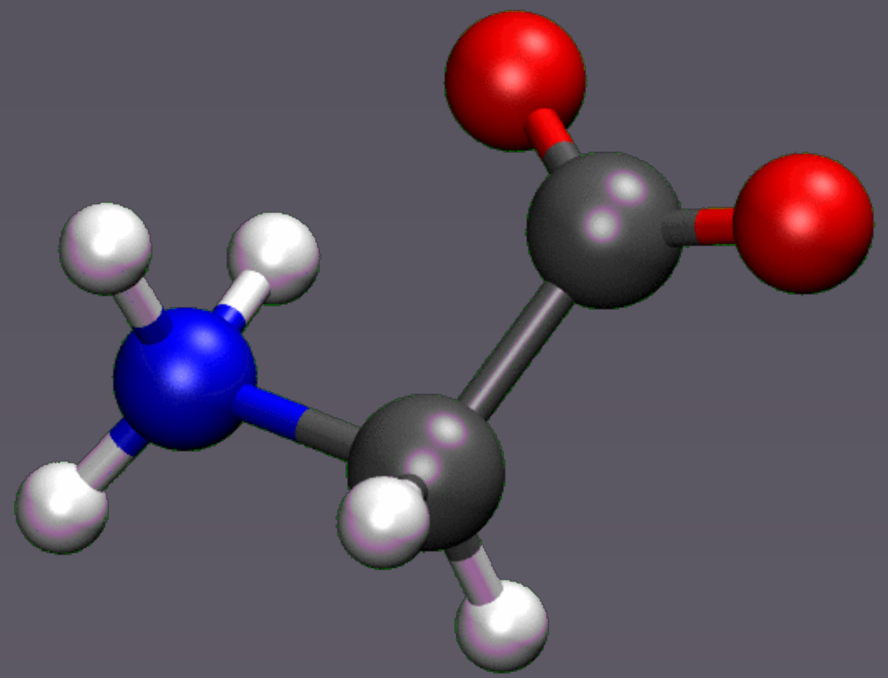
$1\ \mu\text{s} = 0.000001 \text{ s} = 10^{-6} \text{ s}$



Stachura et al, JACS 139 (2019)

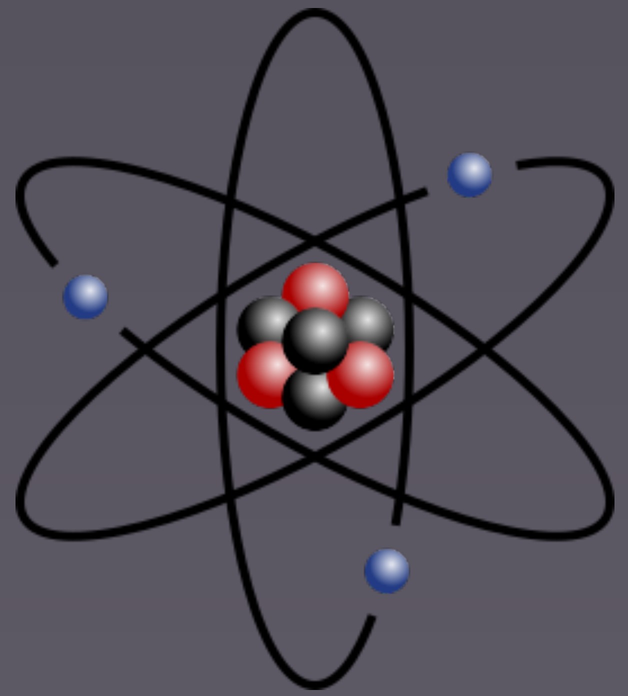
nanosecond

$1 \text{ ns} = 10^{-9} \text{ s}$



femtosecond

$1 \text{ fs} = 0.000000000000001 \text{ s} = 10^{-15} \text{ s}$

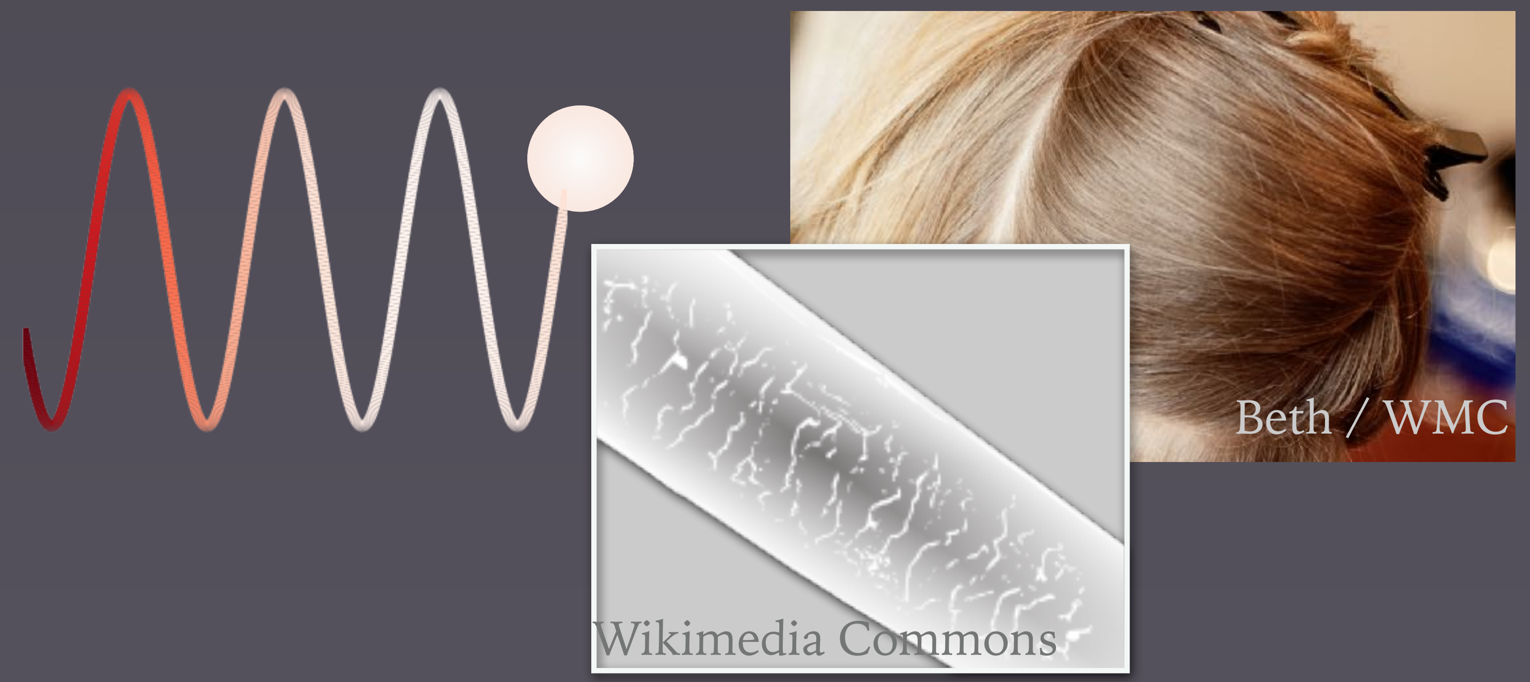


attosecond

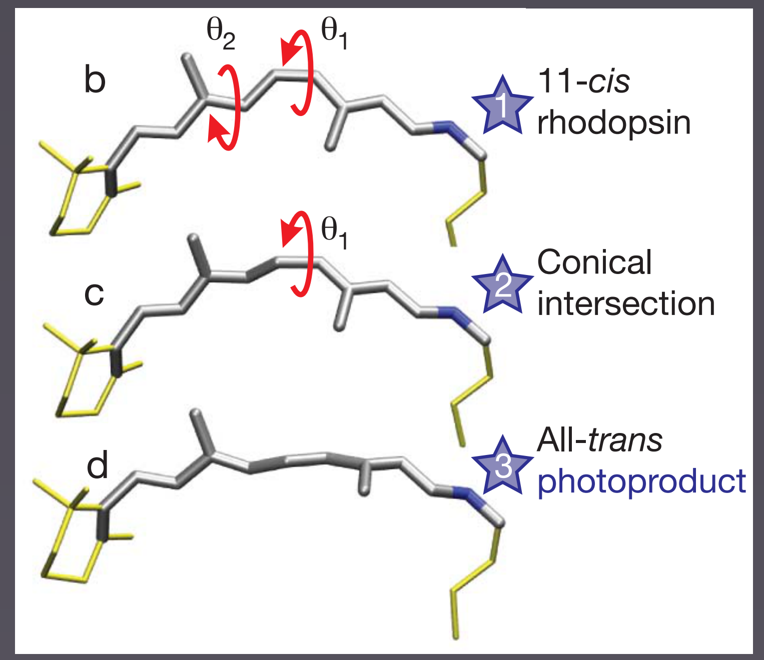
$1 \text{ as} = 10^{-18} \text{ s}$

The Femtosecond Time Scale

Light crosses hair in 30 fs

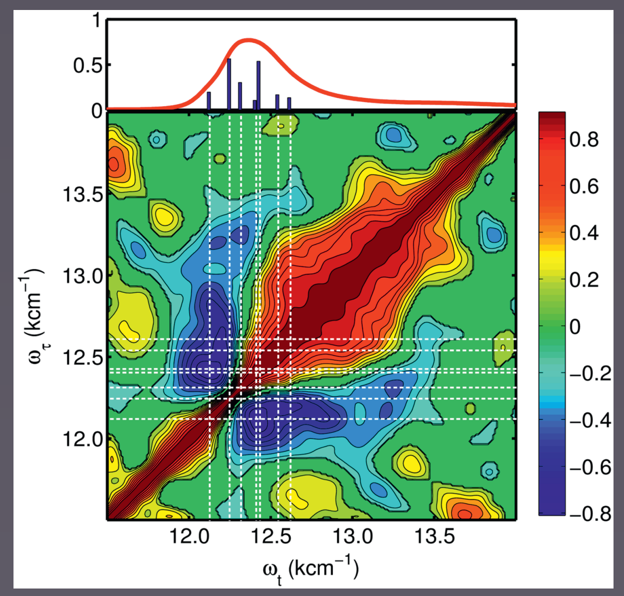


First steps of vision in 200 fs

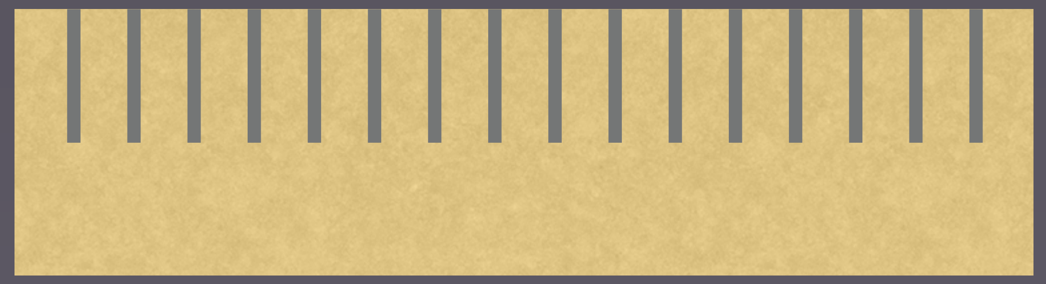


Polli et al, Nature 467 (2010) Polli et al, Nature 467, 440 (2010)

Photosynthesis sets off in 100 fs



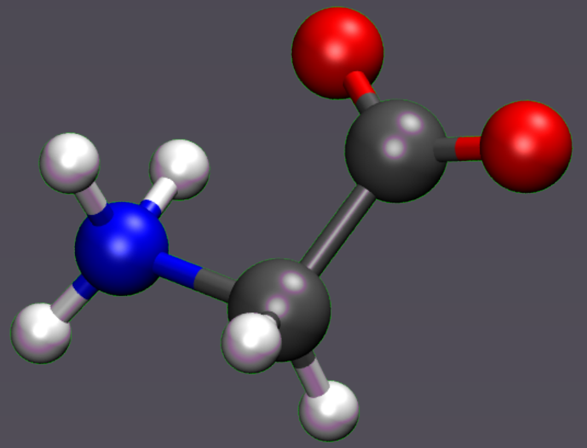
Duan et al, PNAS 114 (2017)



Atomic to nanometer scale

Time Resolution

Choose the right exposure time

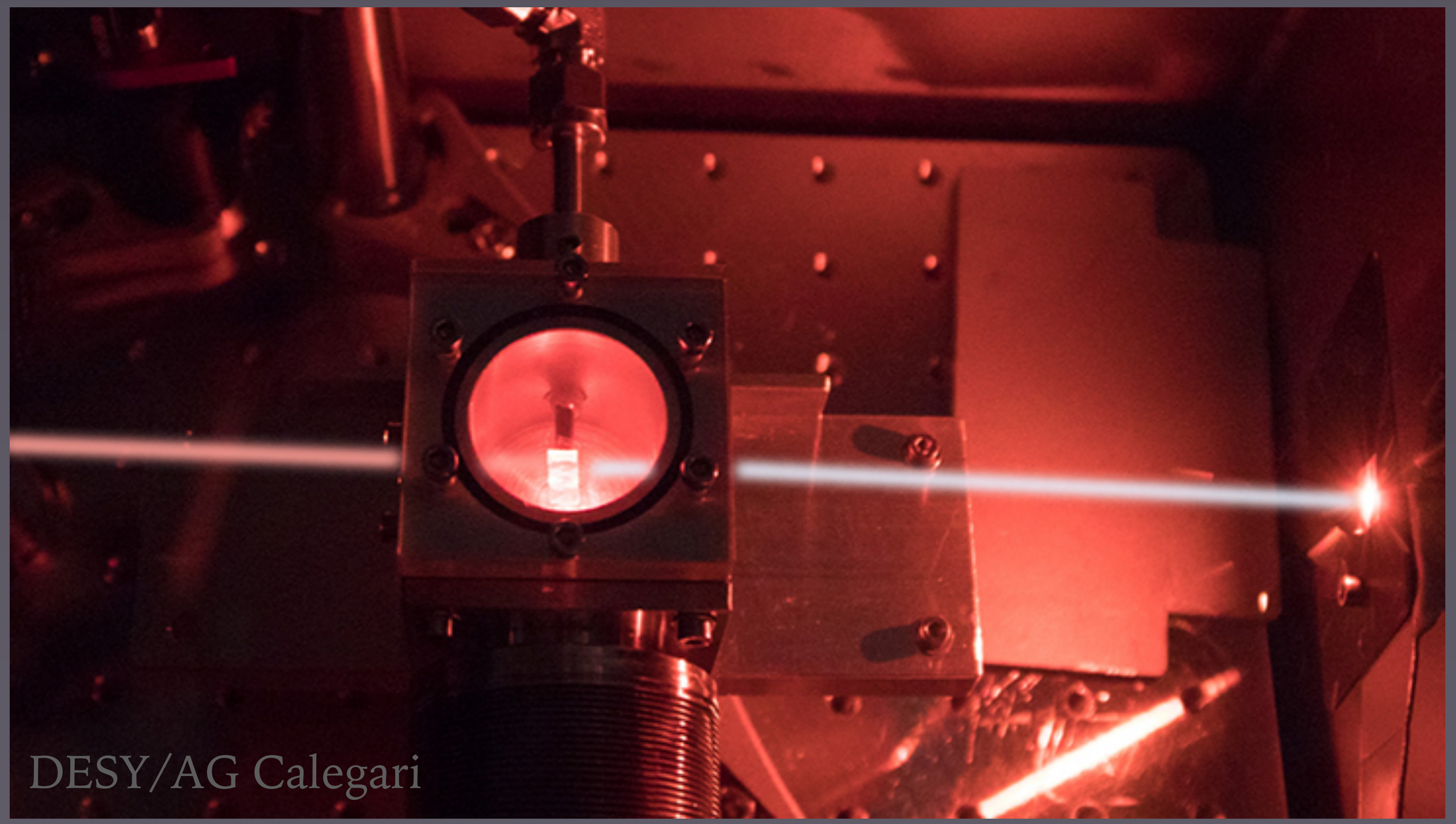


second → millisecond → microsecond → nanosecond → picosecond → femtosecond

Petr Novak, Wikipedia

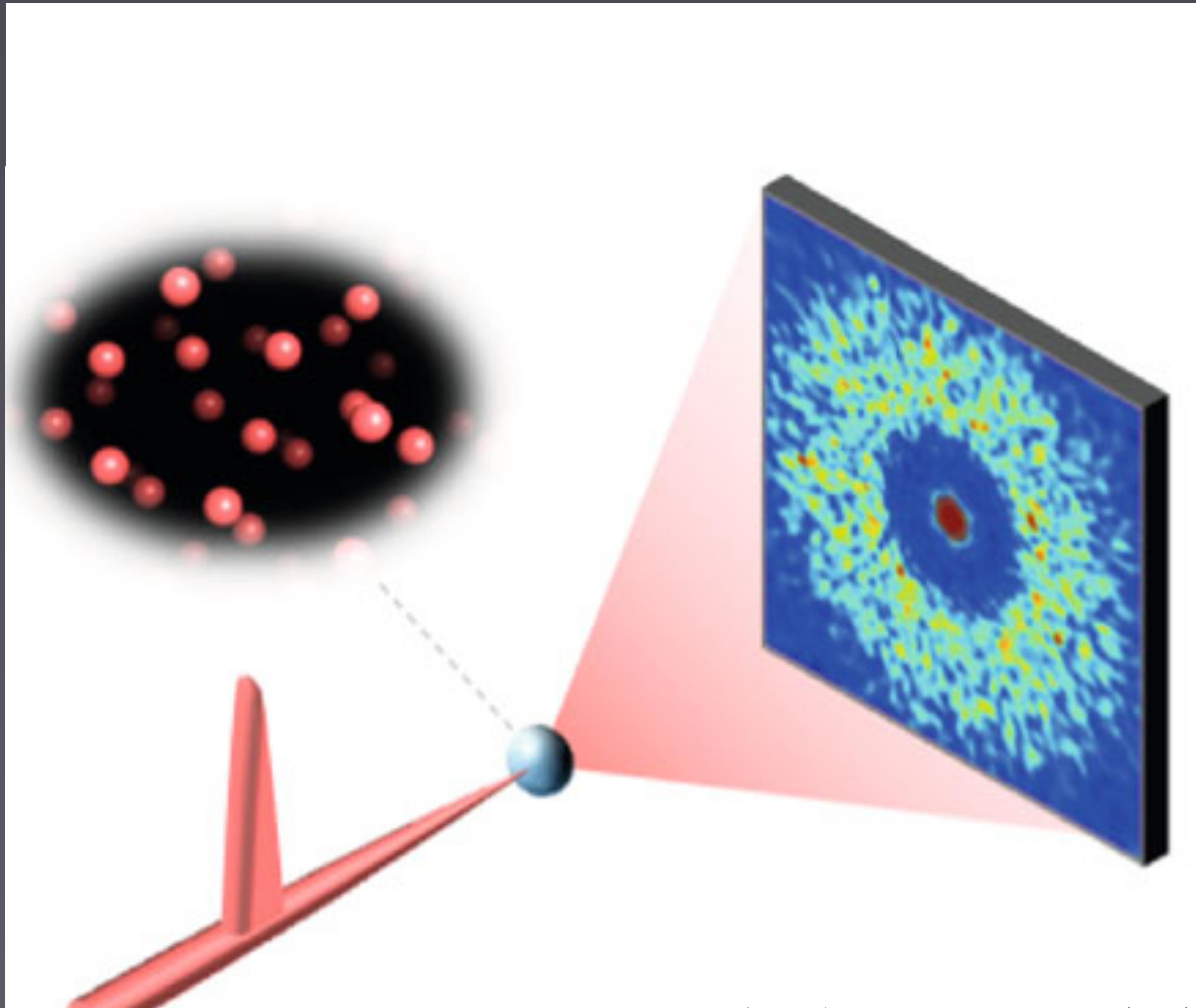
Dmitry Makeev

Garanin et al, Quantum Electronics 44 (2014)



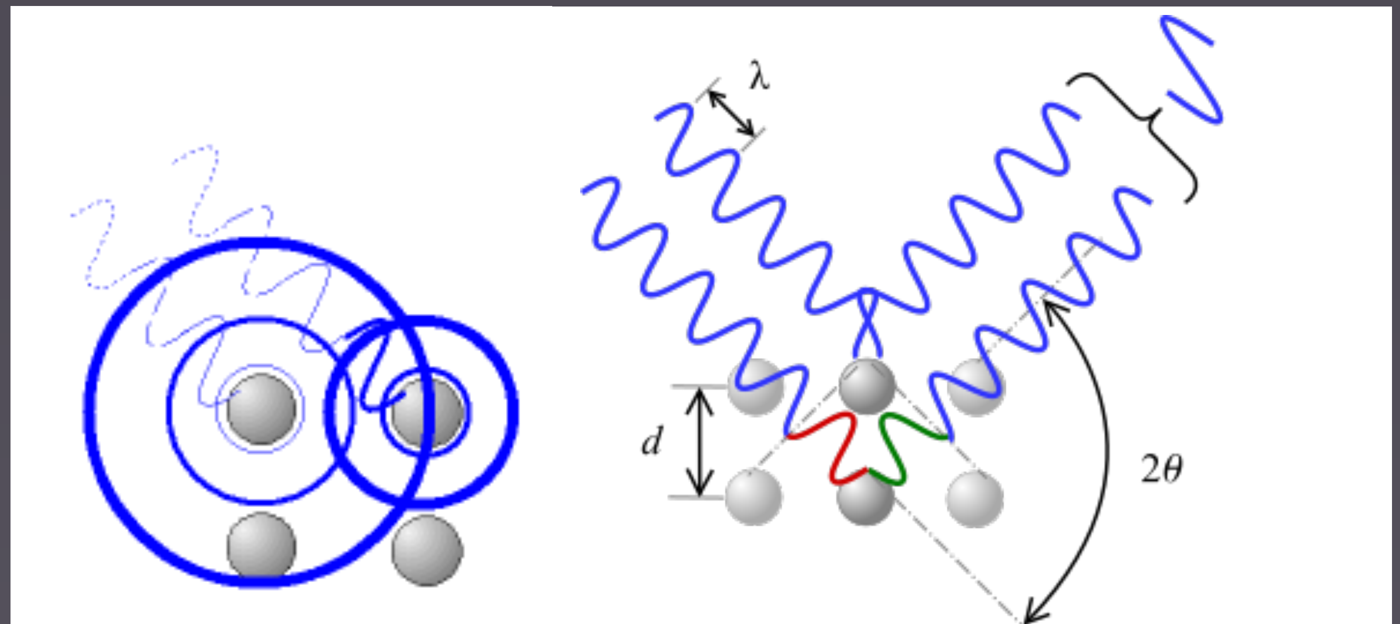
DESY/AG Calegari

X-Ray Diffraction



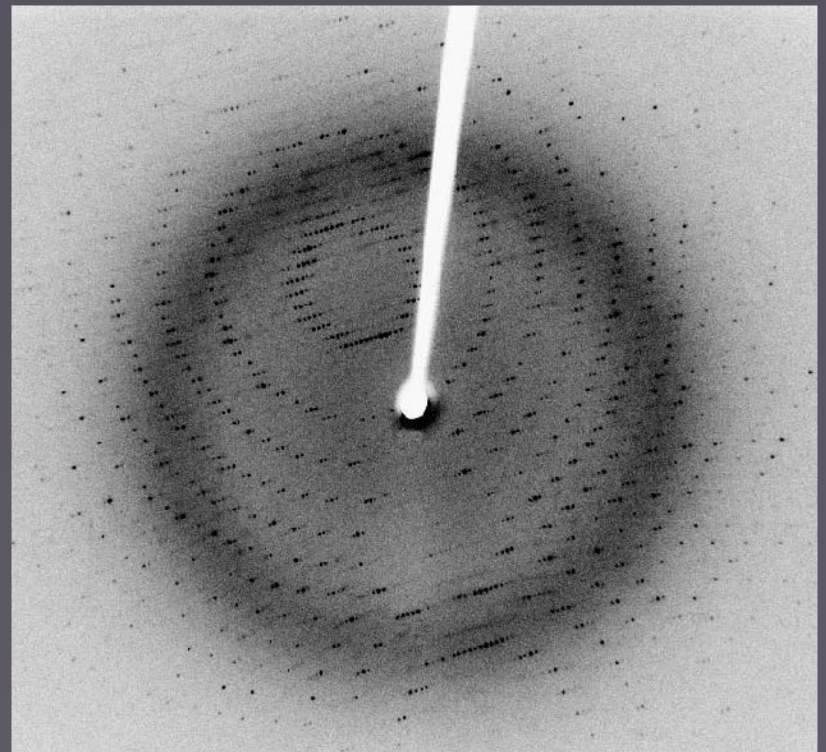
Perakis et al, Nature Communications (2018)

X-rays diffract at crystalline structures

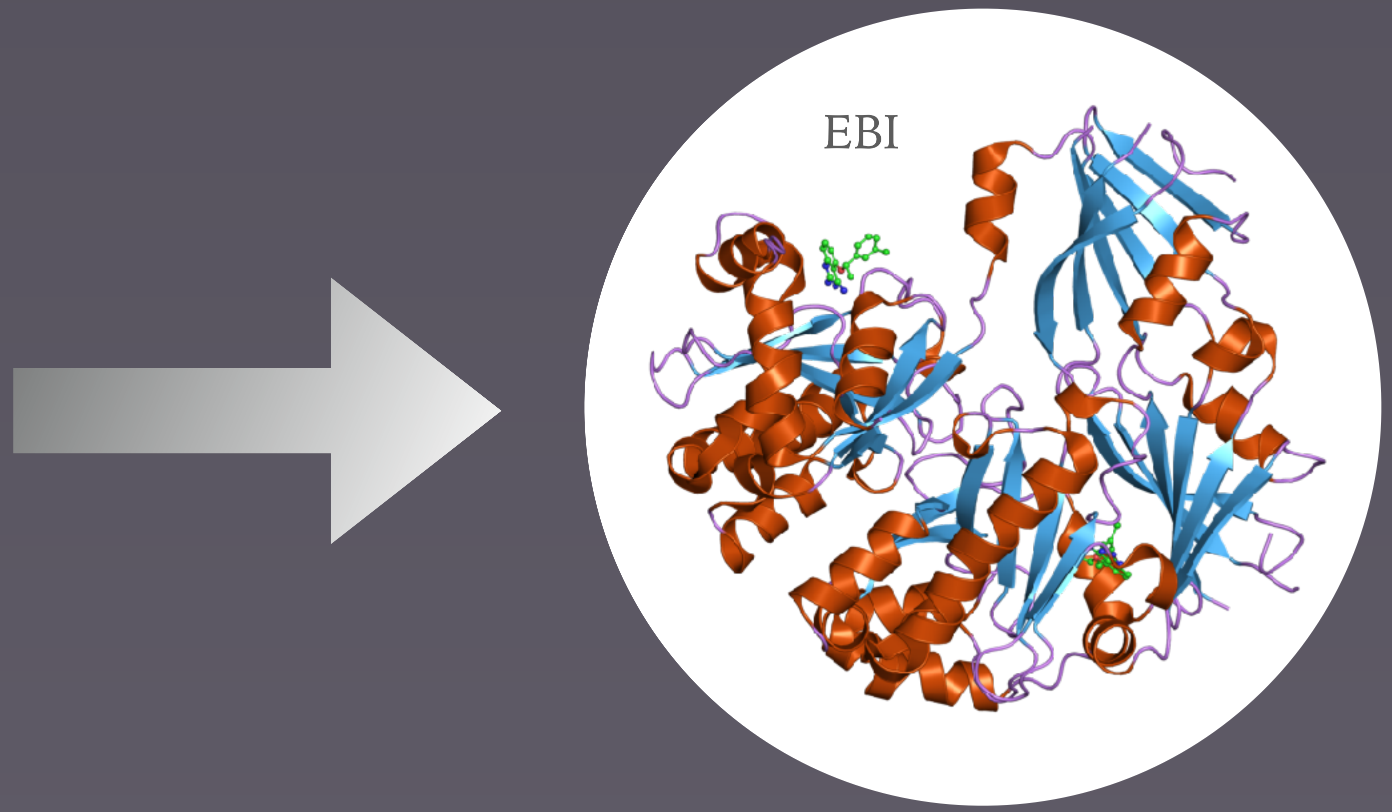


Christophe Dang Ngoc Chan

Reconstruction



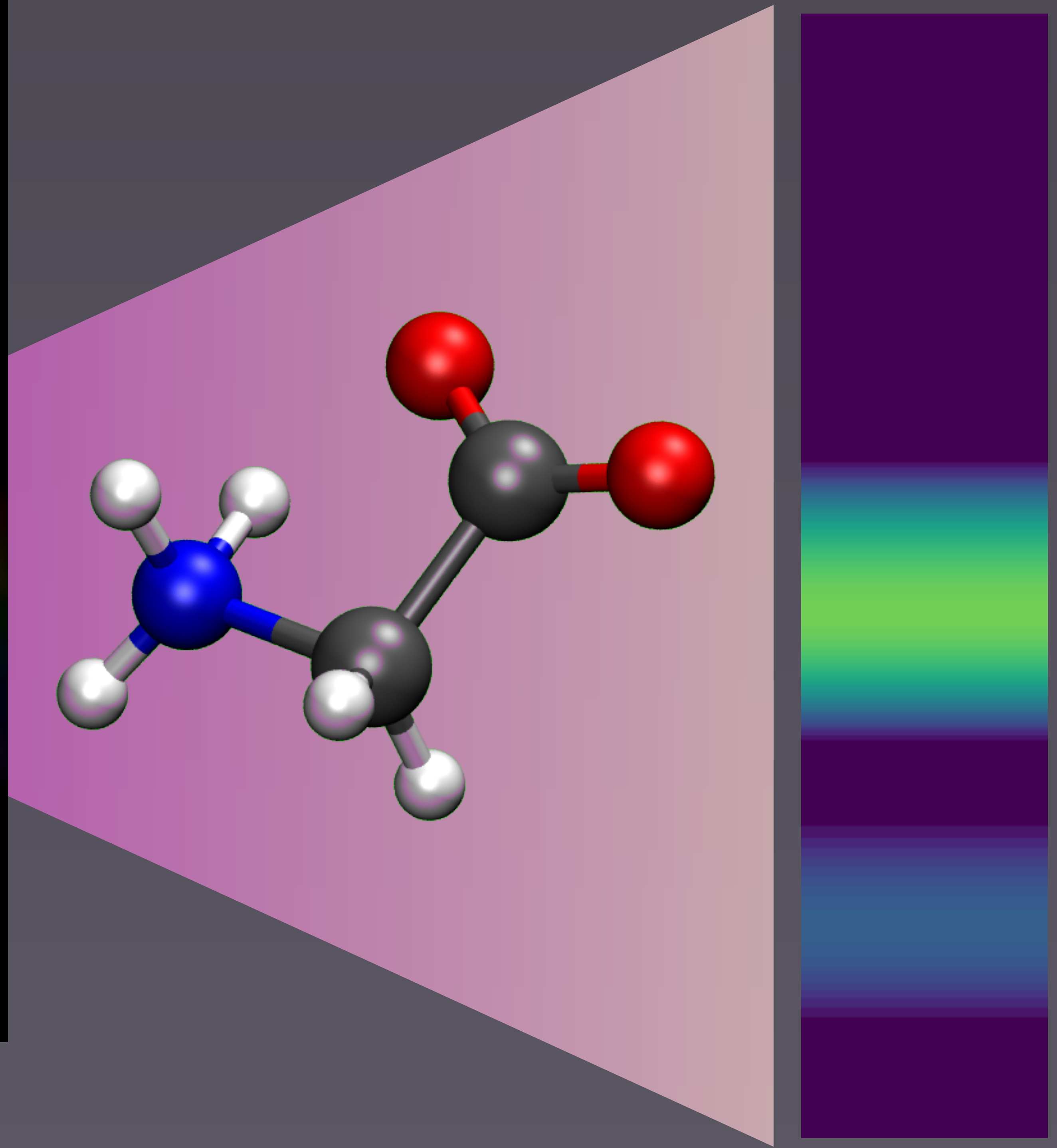
Jeff Dahl, Wikimedia

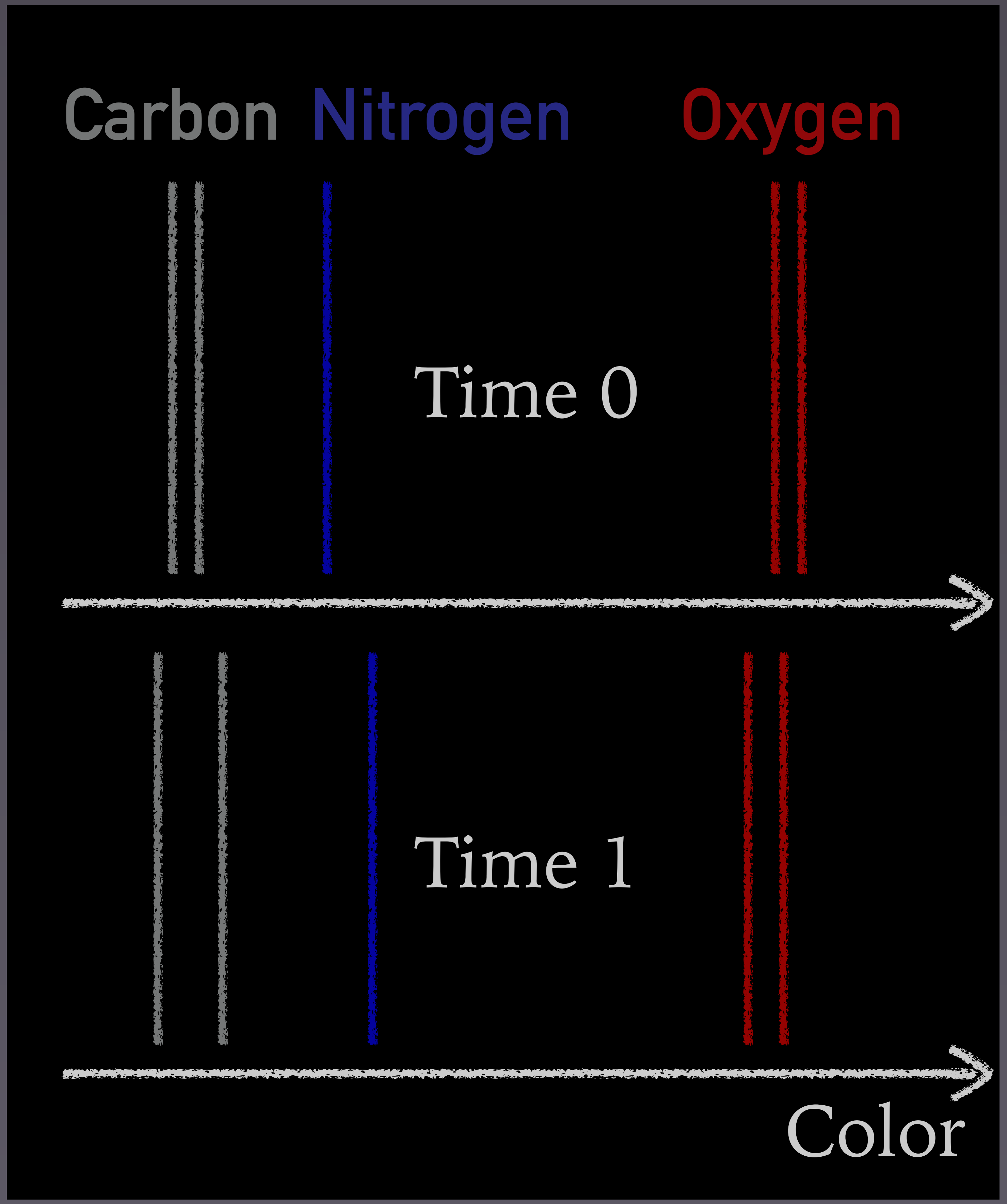


EBI

Absorption Spectroscopy


Sceptre, Wikimedia Commons

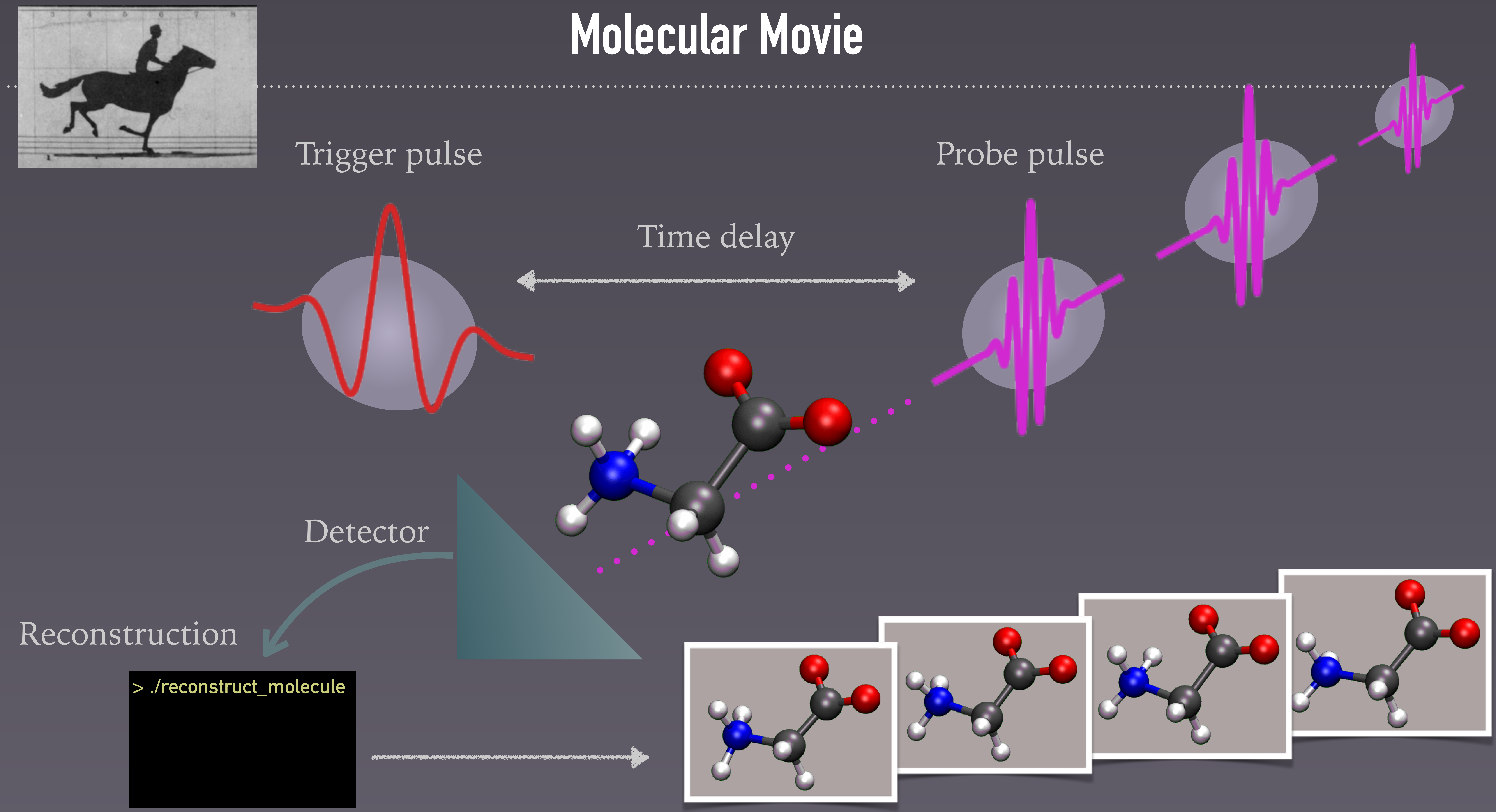




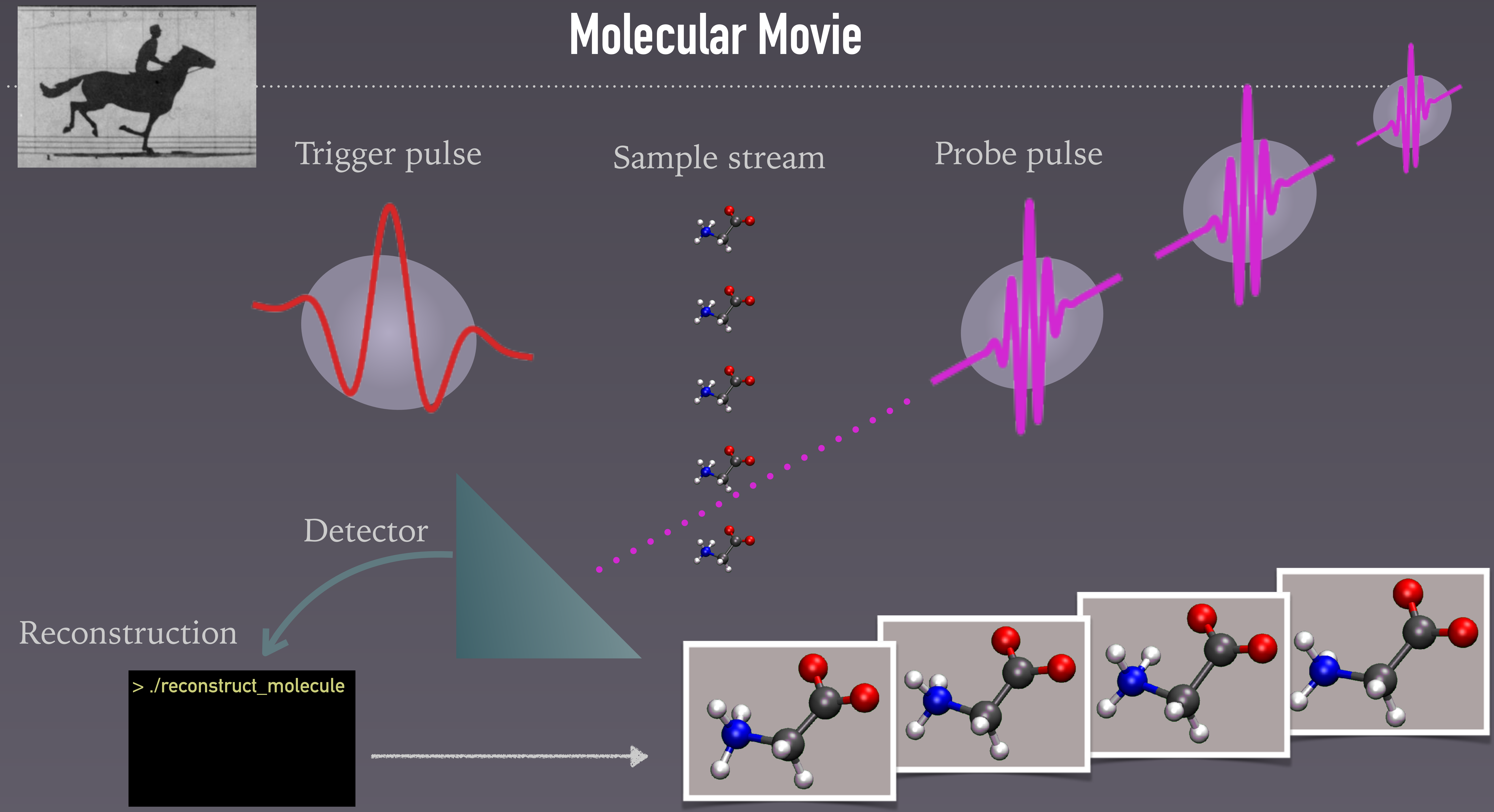
- Molecule blocks certain colors

It's quantum!

- Characteristic of chemical elements and time-dependent changes
- More probe signals: photoelectrons, fragmentation, …


Molecular Movie
Trigger pulse
Probe pulse
Time delay
Detector
Reconstruction
> ./reconstruct_molecule

Molecular Movie



Requirements for Light Sources

Ultrashort pulses

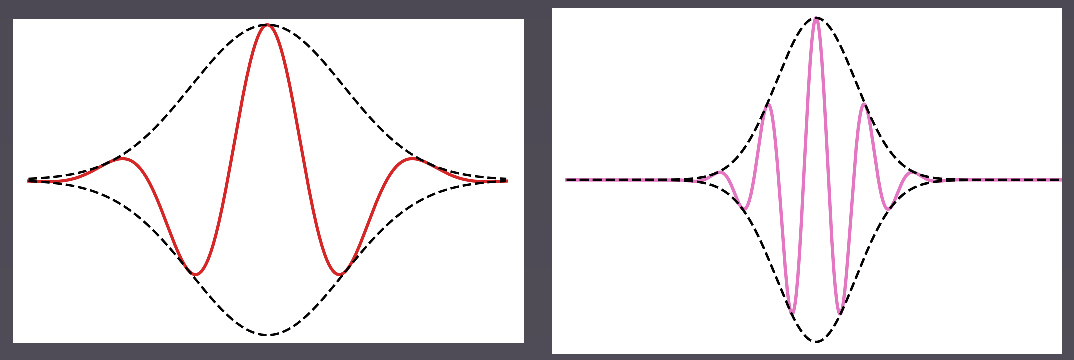
High brilliance

Small wavelength

Coherent laser light

Center wavelength

Ultrashort pulse

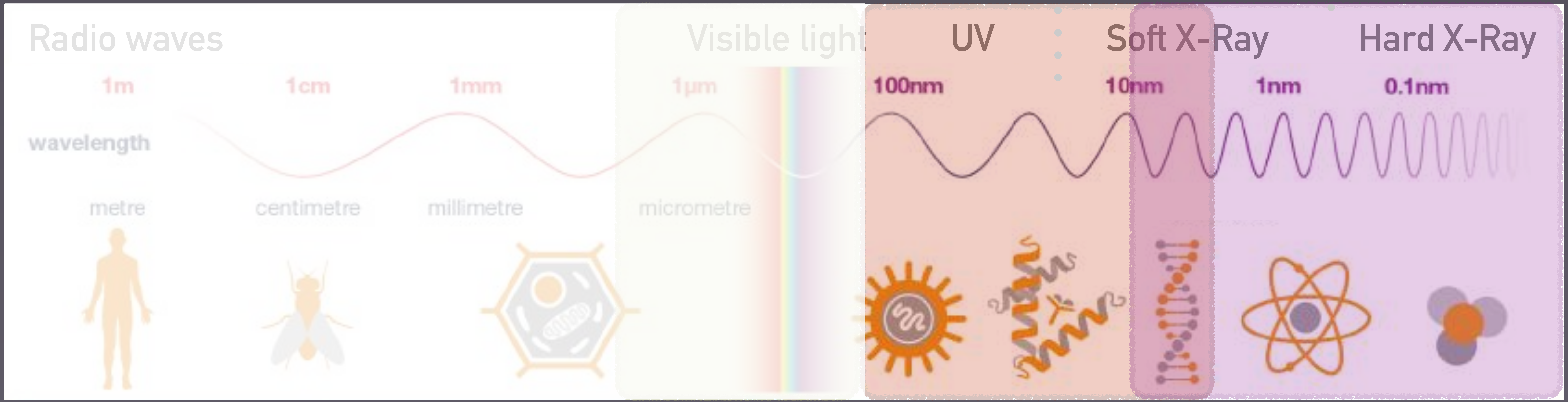


Diffraction limit

Conventional laser

Laboratory

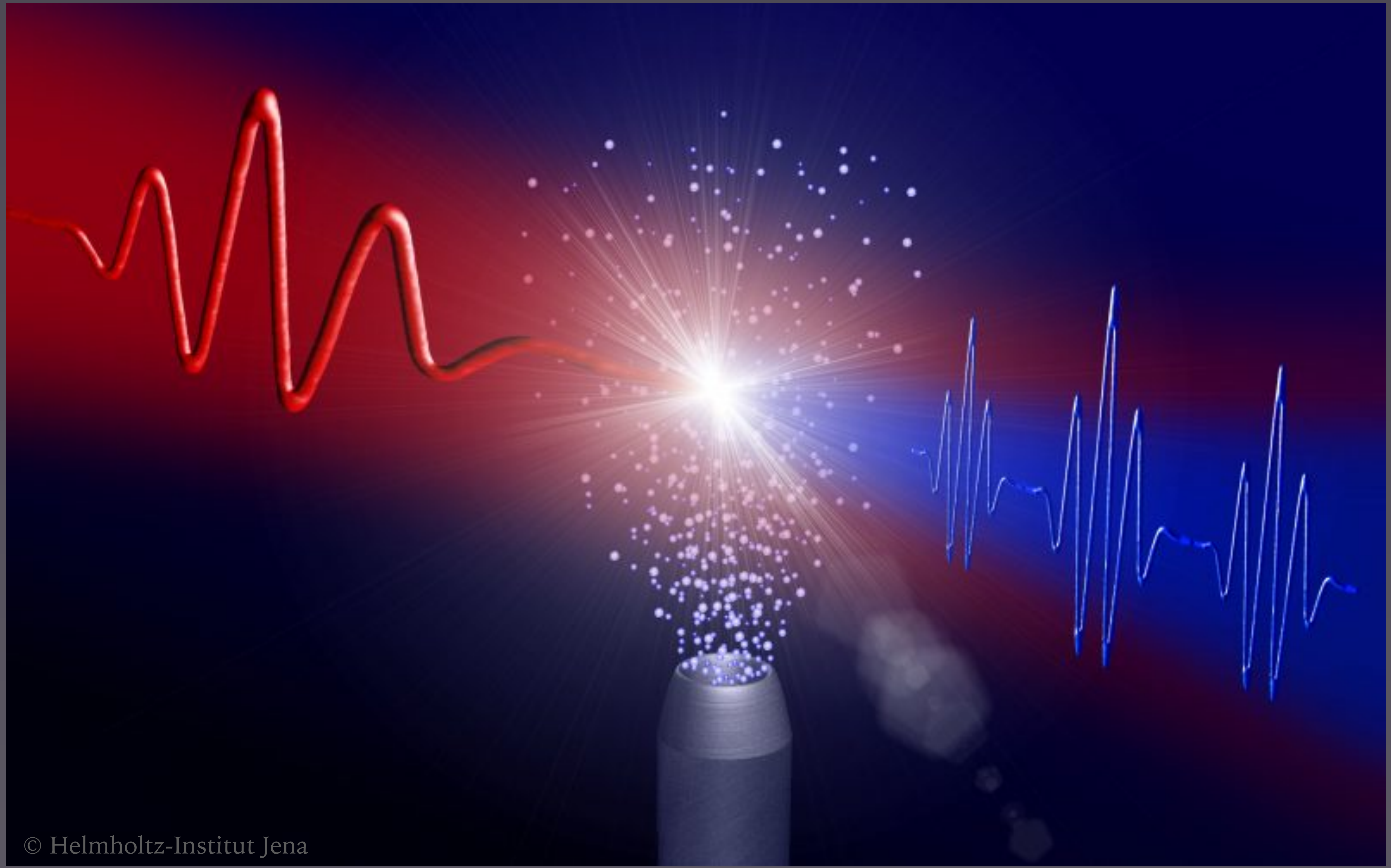
Free-Electron Laser



Ultrashort Laser Pulses in the Laboratory

High-harmonic generation (HHG)

- ➤ High-intensity red laser pulse
- ➤ Focused in gas cell
- ➤ Generates new frequencies of light

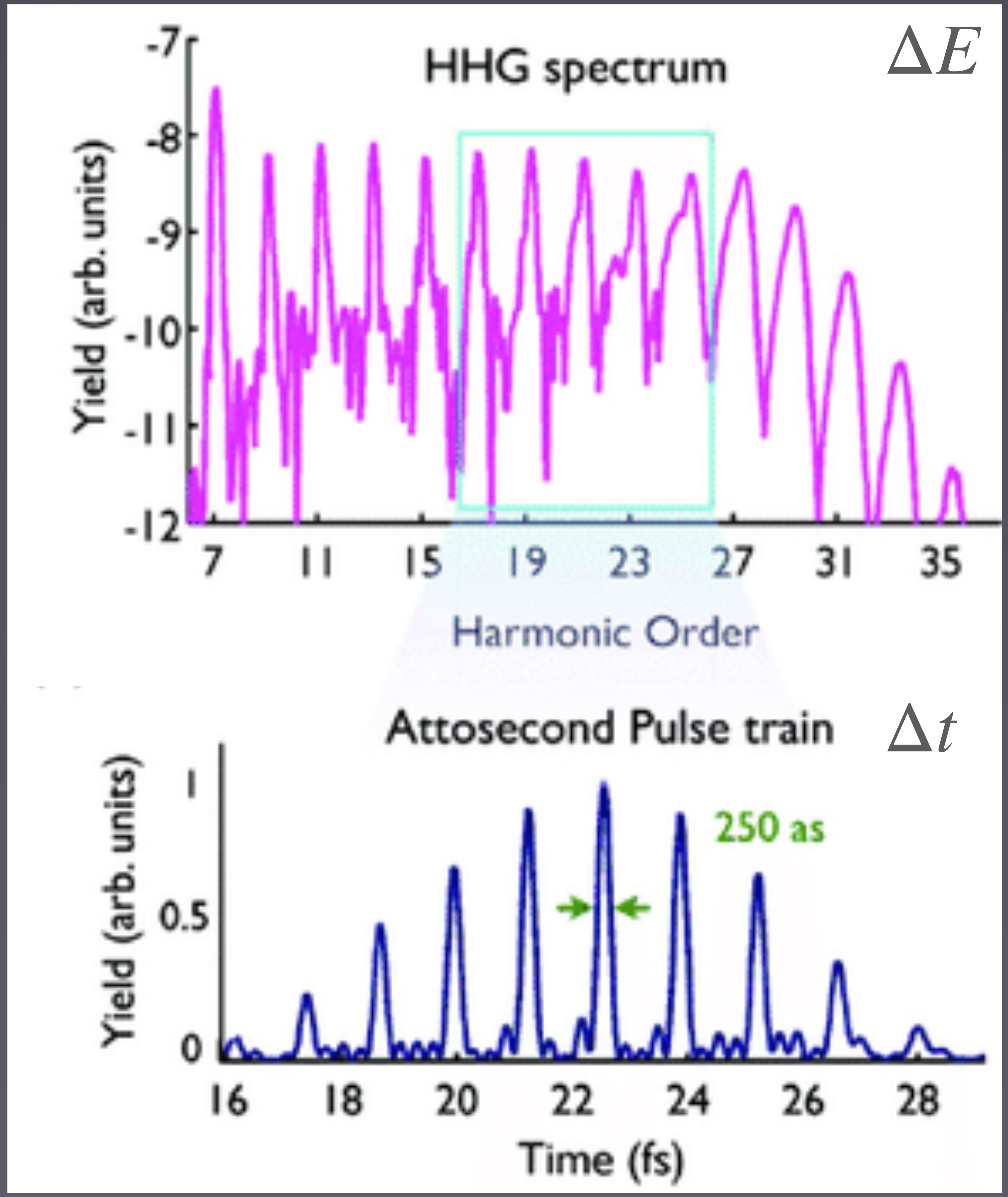


Donna Strickland

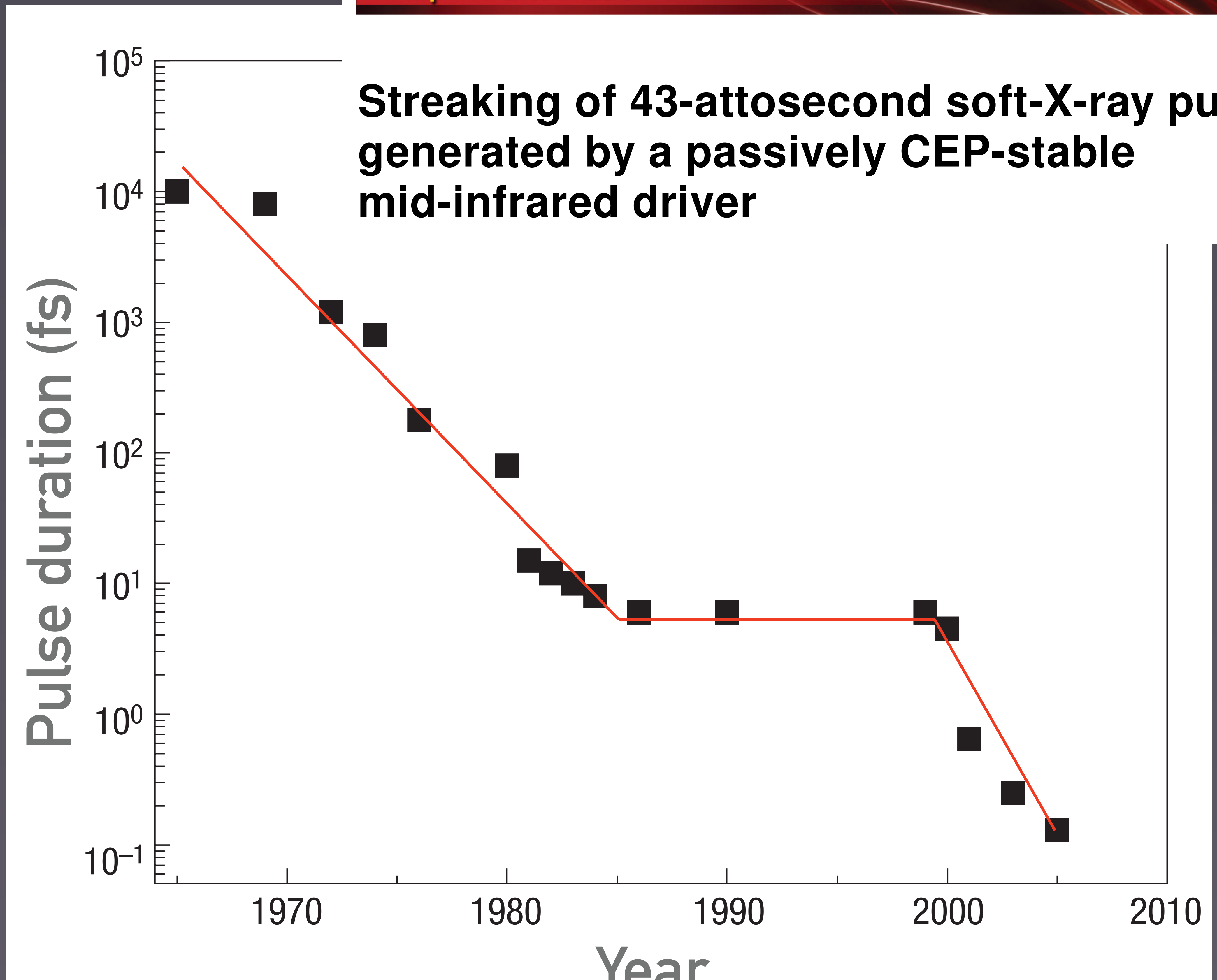
Gérard Mourou

Ultrashort Laser Pulses in the Laboratory

Fourier limit $\Delta E \cdot \Delta t = 0.442$



Ultrashort Extreme Ultraviolet Vortices. 10.5772/64908



Corkum and Krausz, Nature Physics 6 (2007)

Research Article Vol. 25, No. 22 | 30 Oct 2017 | OPTICS EXPRESS 27506

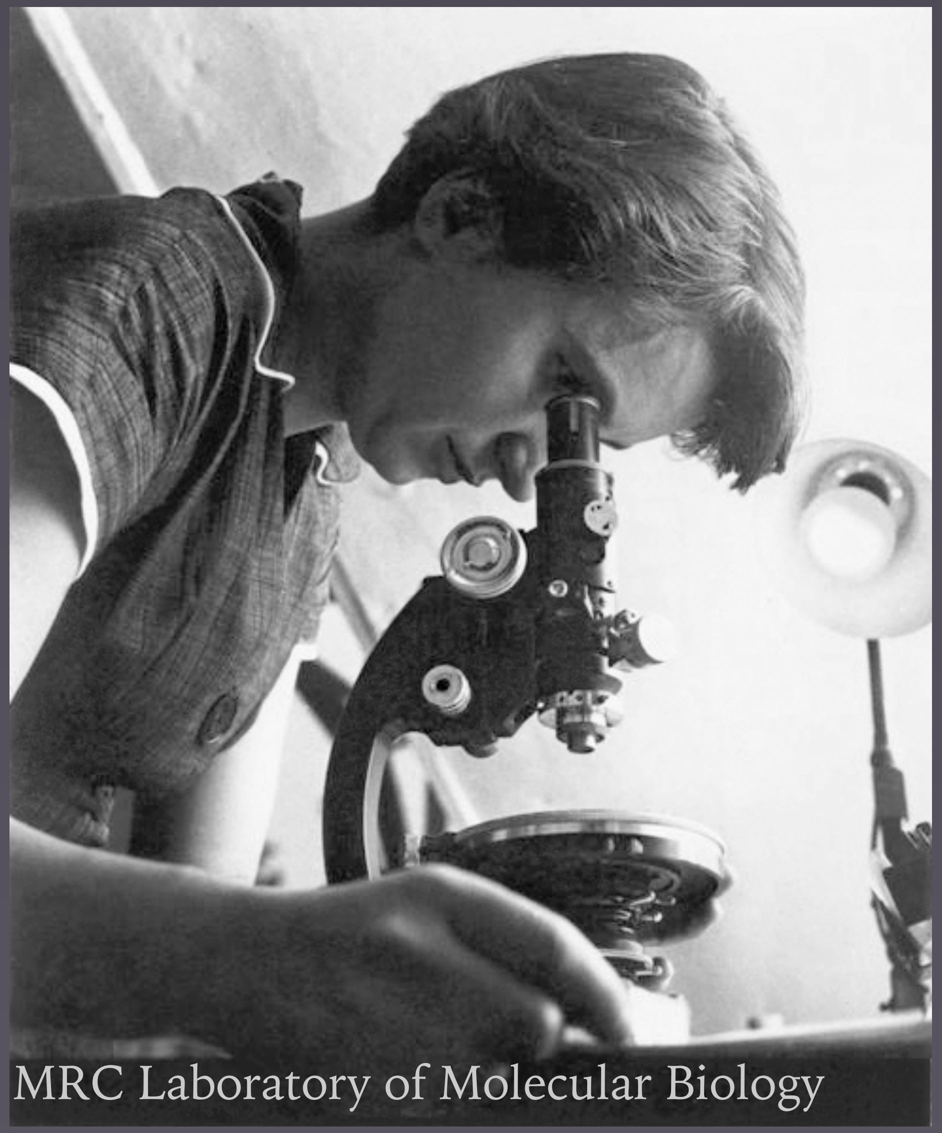
Optics EXPRESS

Streaking of 43-attosecond soft-X-ray pulses generated by a passively CEP-stable mid-infrared driver

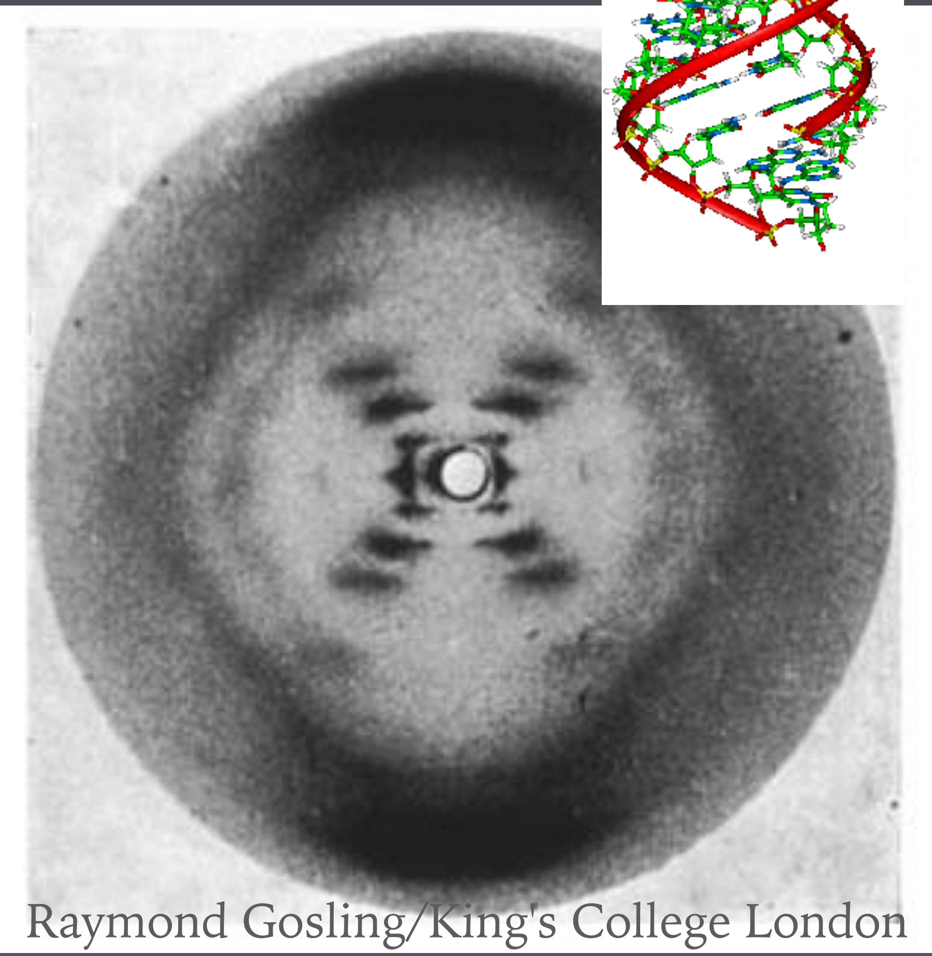
Cannot go to hard x-rays

Light Source for X-Ray Diffraction

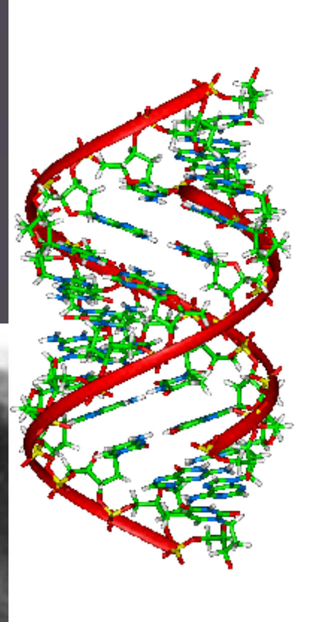
Rosalind Franklin (1920 - 1958)

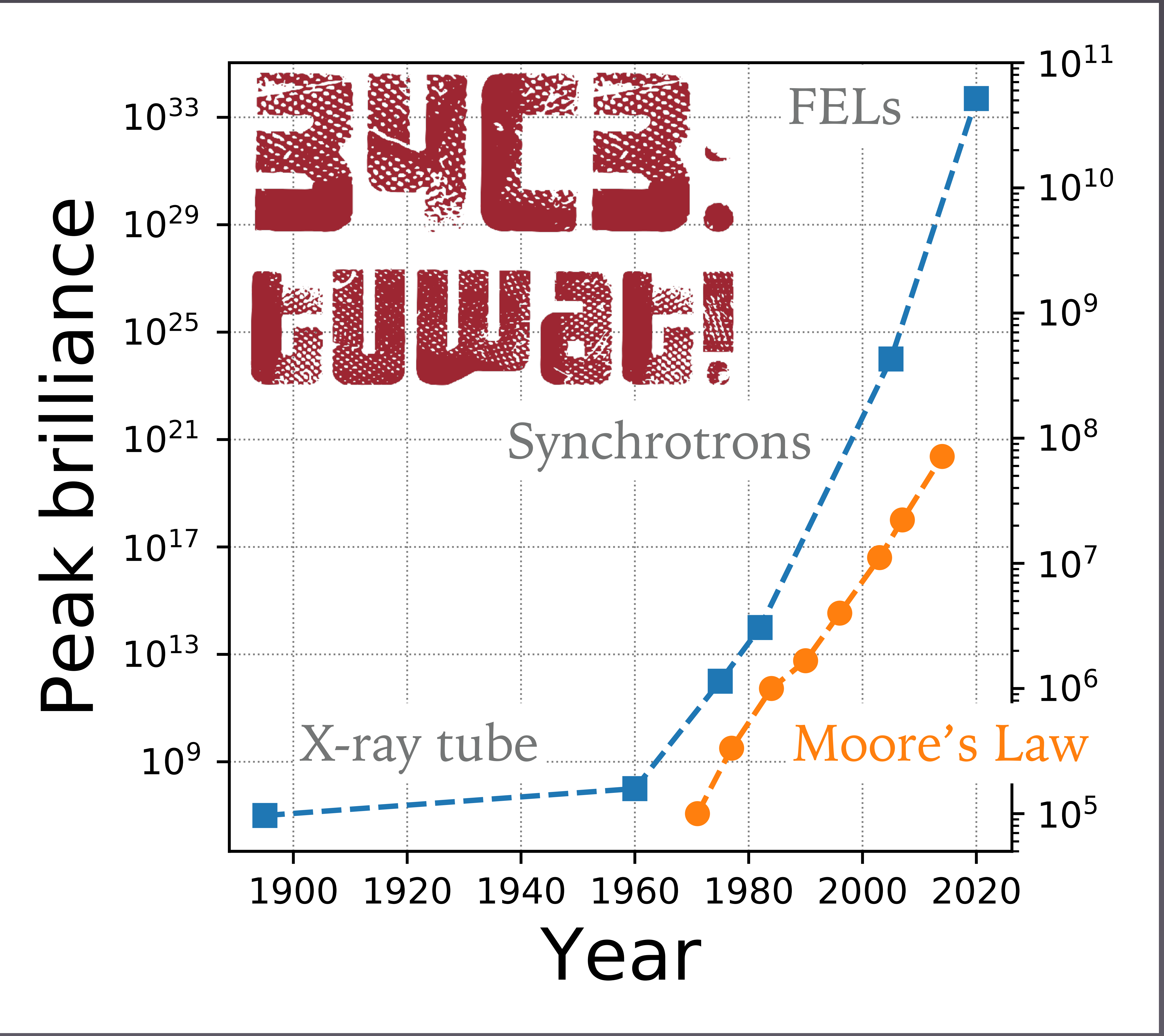


MRC Laboratory of Molecular Biology



Raymond Gosling/King's College London



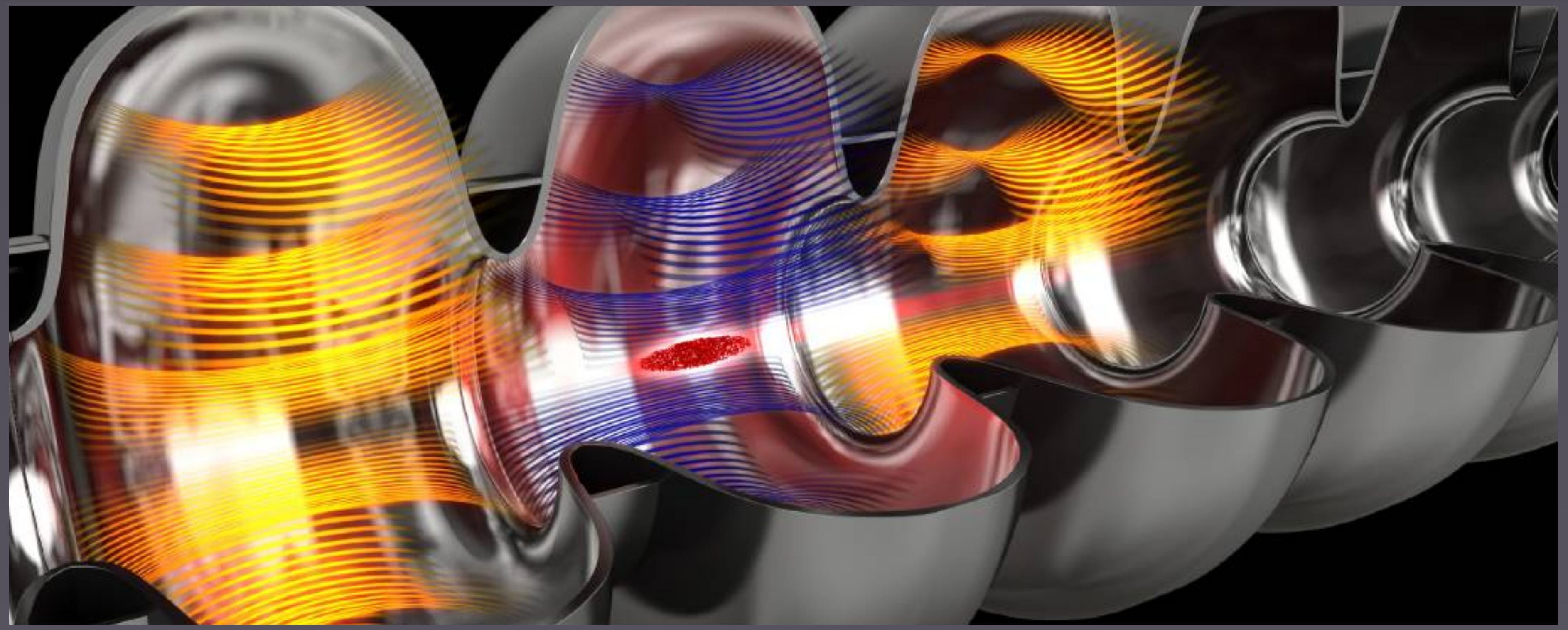


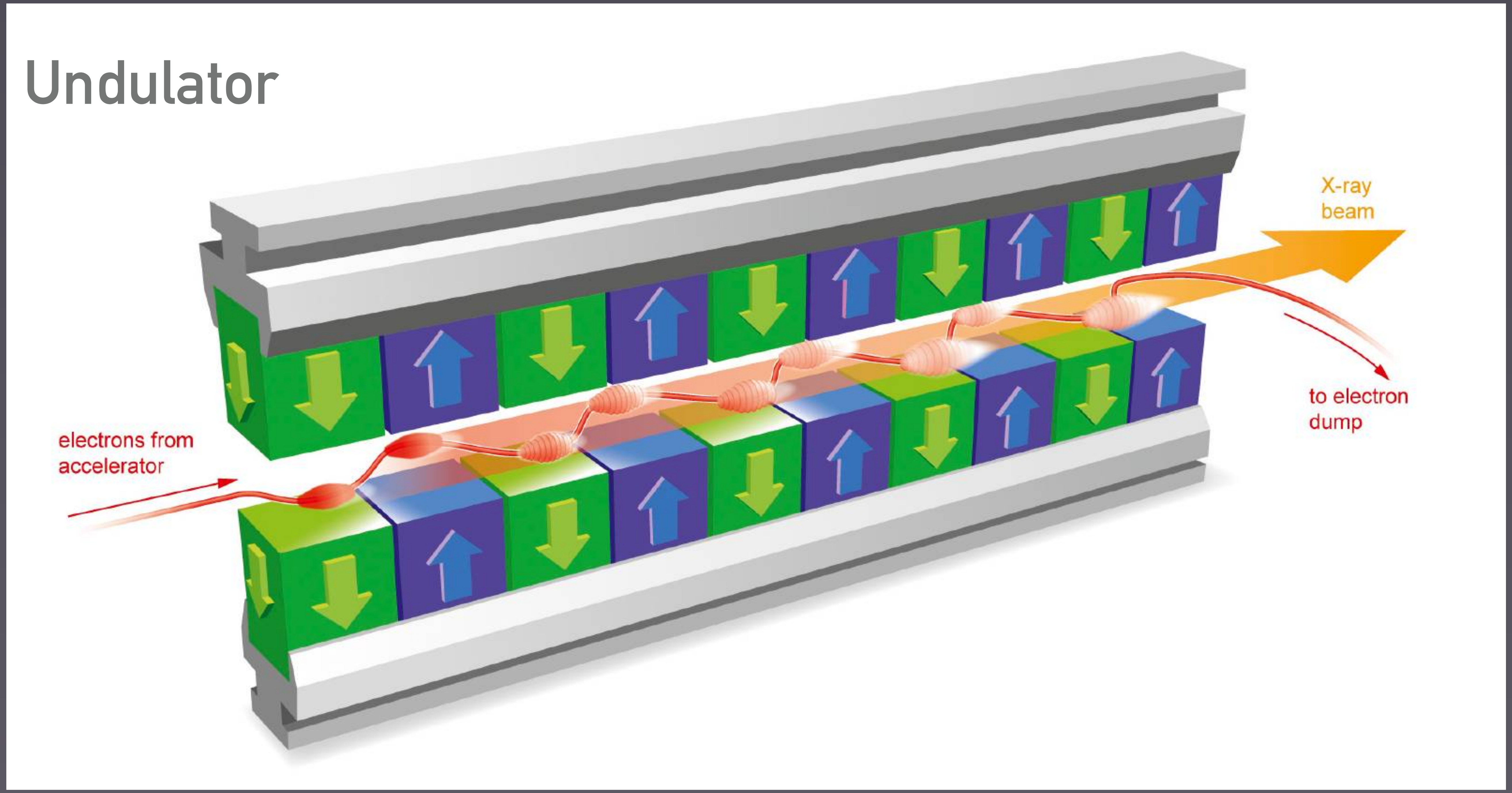
- X-ray diffraction revealed DNA structure
- Shorter pulses require high brilliance

  (Photons in the beam per second)

Free-Electron Laser

Accelerate electrons to relativistic speed



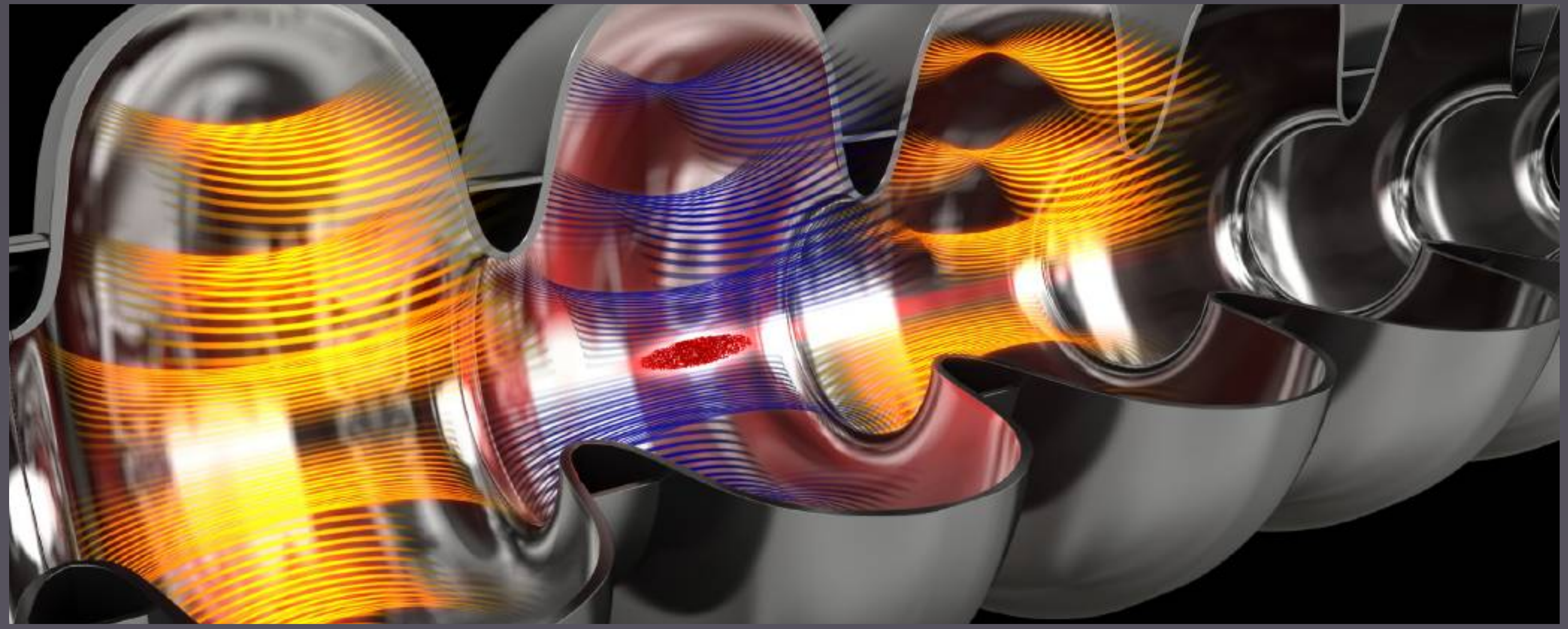


Electrons enter undulator

- Magnets force wiggling motion
- X-ray radiation emitted

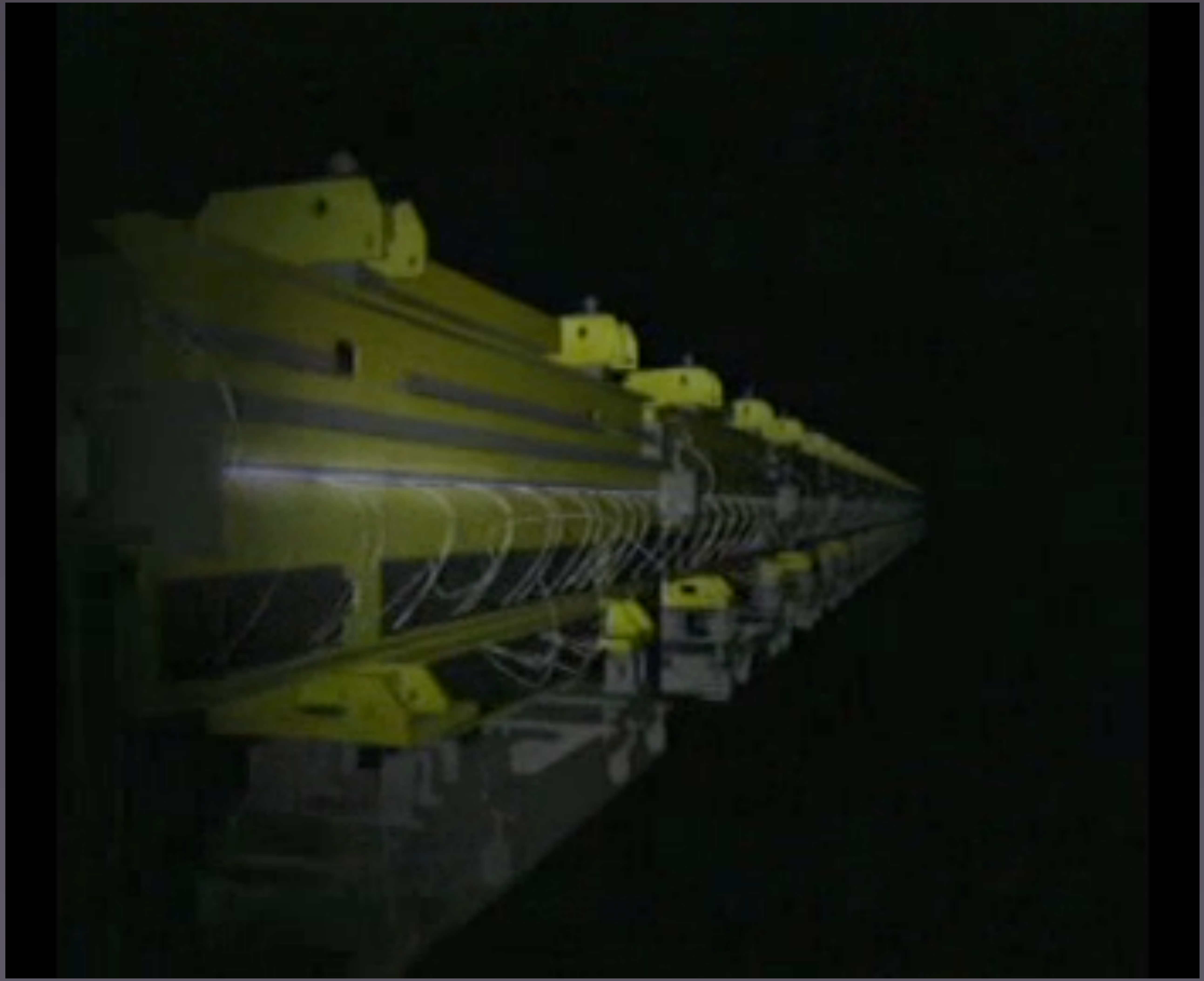
Free-Electron Laser

Accelerate electrons to relativistic speed

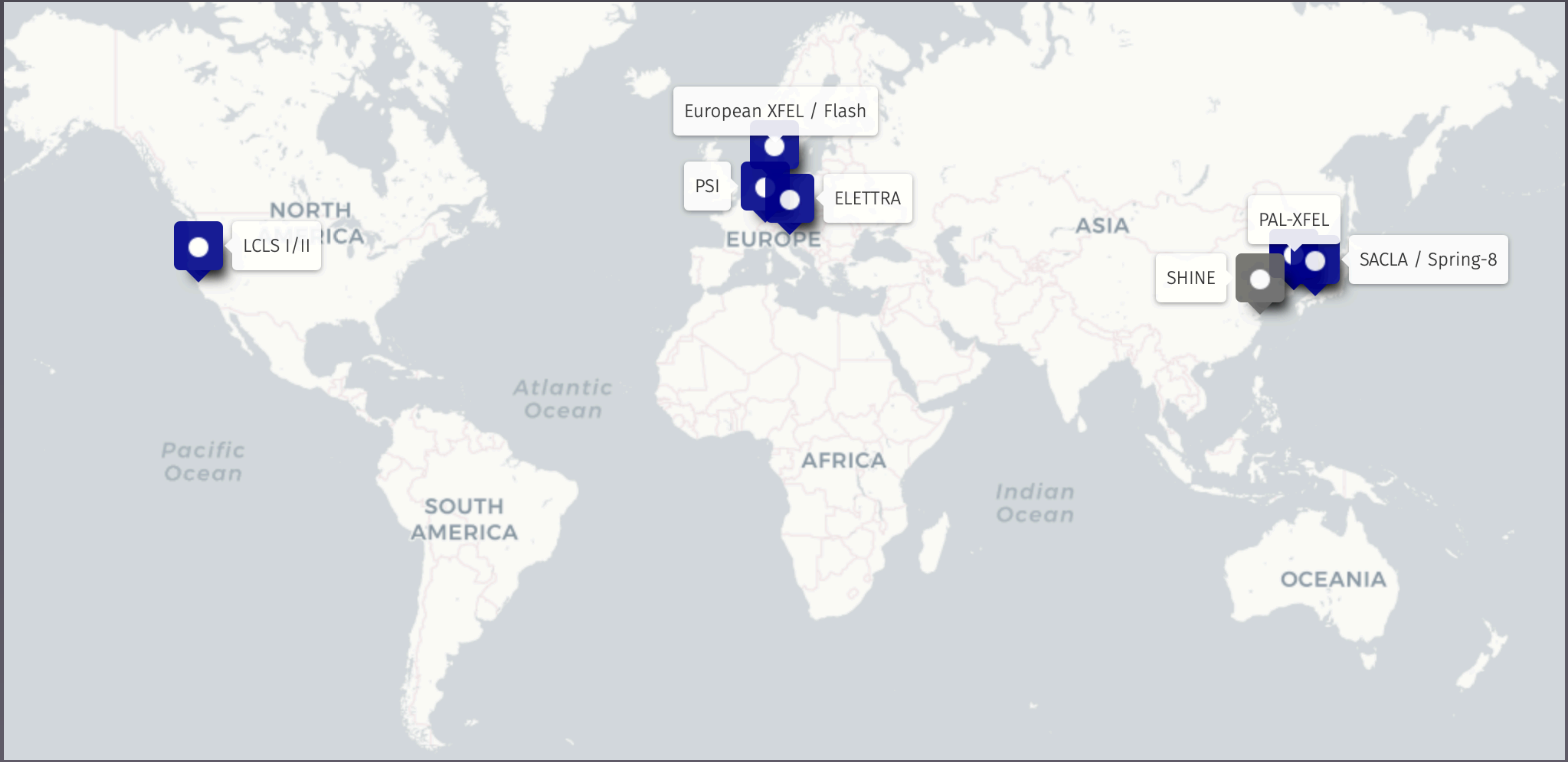


Electrons enter undulator

- ➤ Magnets force wiggling motion
- ➤ X-ray radiation emitted

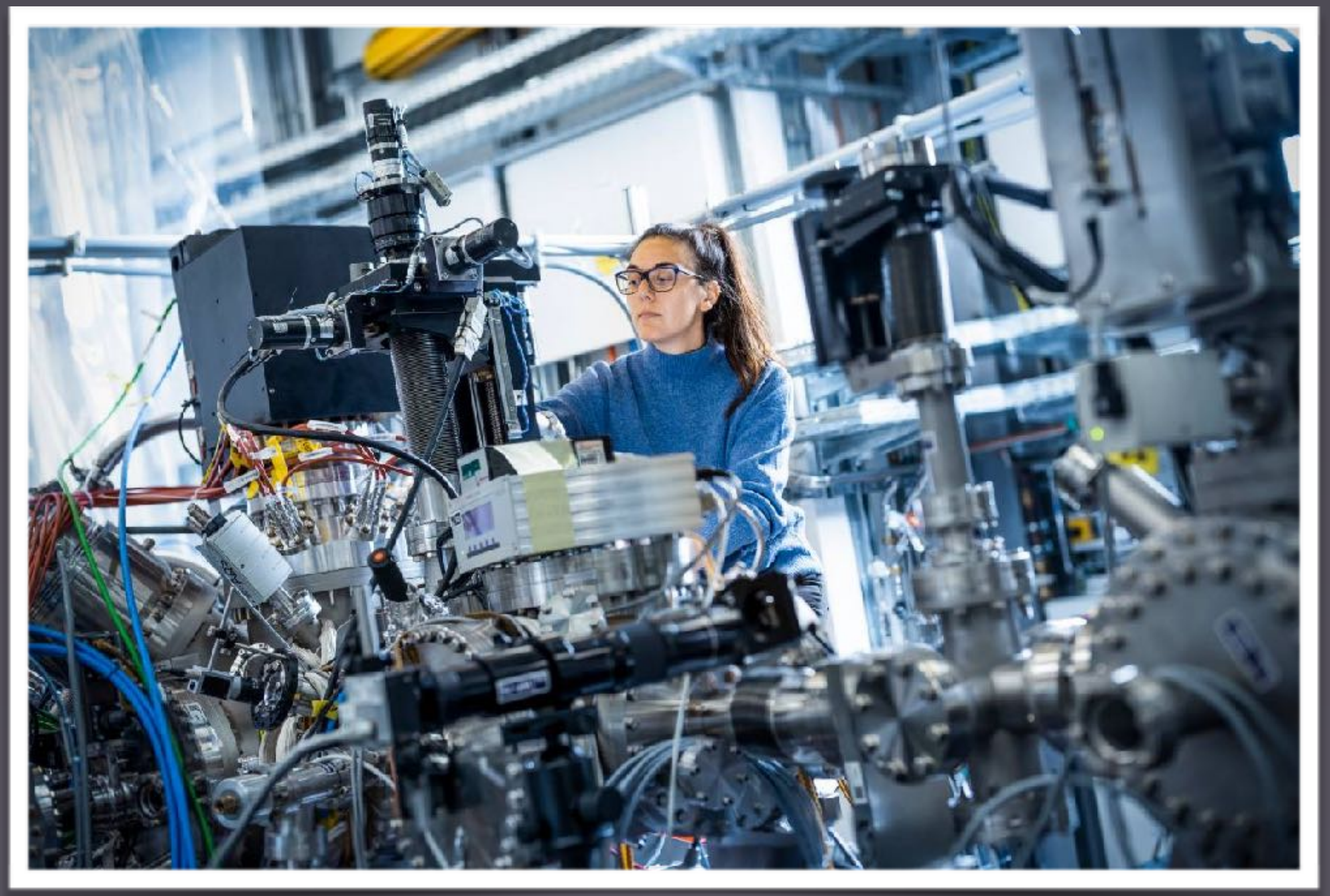


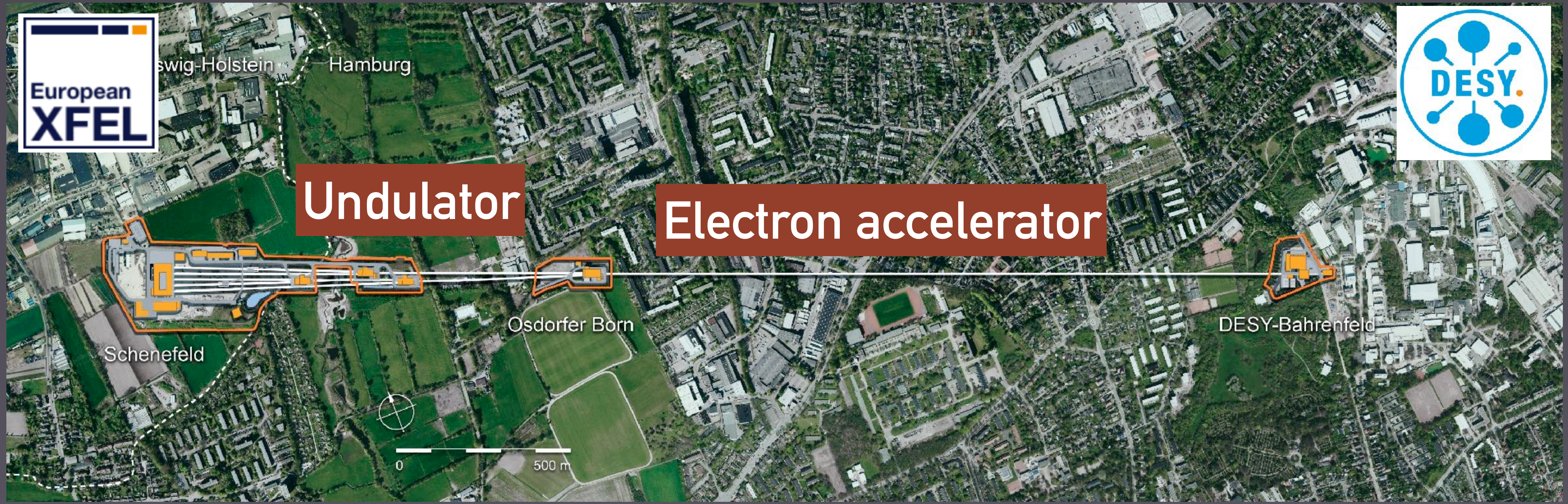
Free-Electron Lasers in the World



European X-Ray Free-Electron Laser

3.4 km long





- Six experimental end stations
- Material science, biomolecule imaging, chemistry, …
- 27,000 flashes / second

- Total construction costs

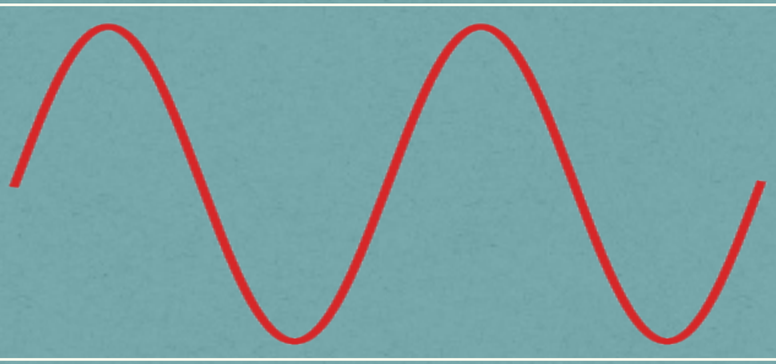
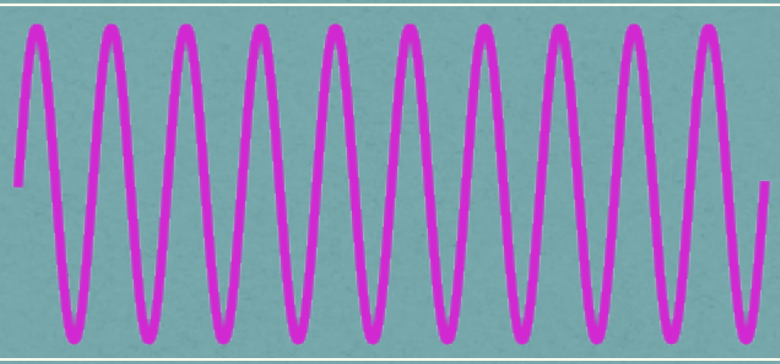
  8 years / 1.25 billion €

- Elbphilharmonie

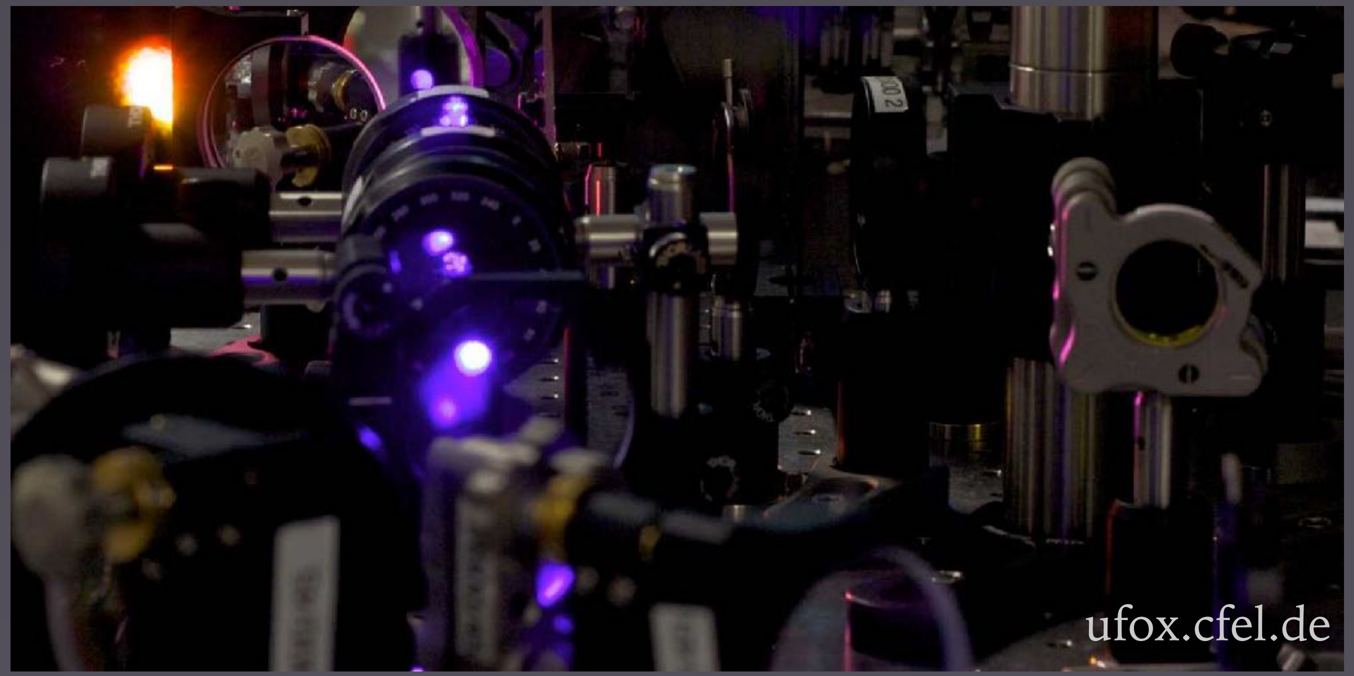
  9 yrs / 870 million €

European XFEL / Jan Hossan

Comparison of Light Sources

	Laboratory	XFEL
Min pulse duration	< 100 attoseconds	10 femtoseconds
Peak brilliance	💥	💥💥💥
Wavelength		
Control	😀	😕
Cost and availability	💰	💰💰💰

Laboratory setup

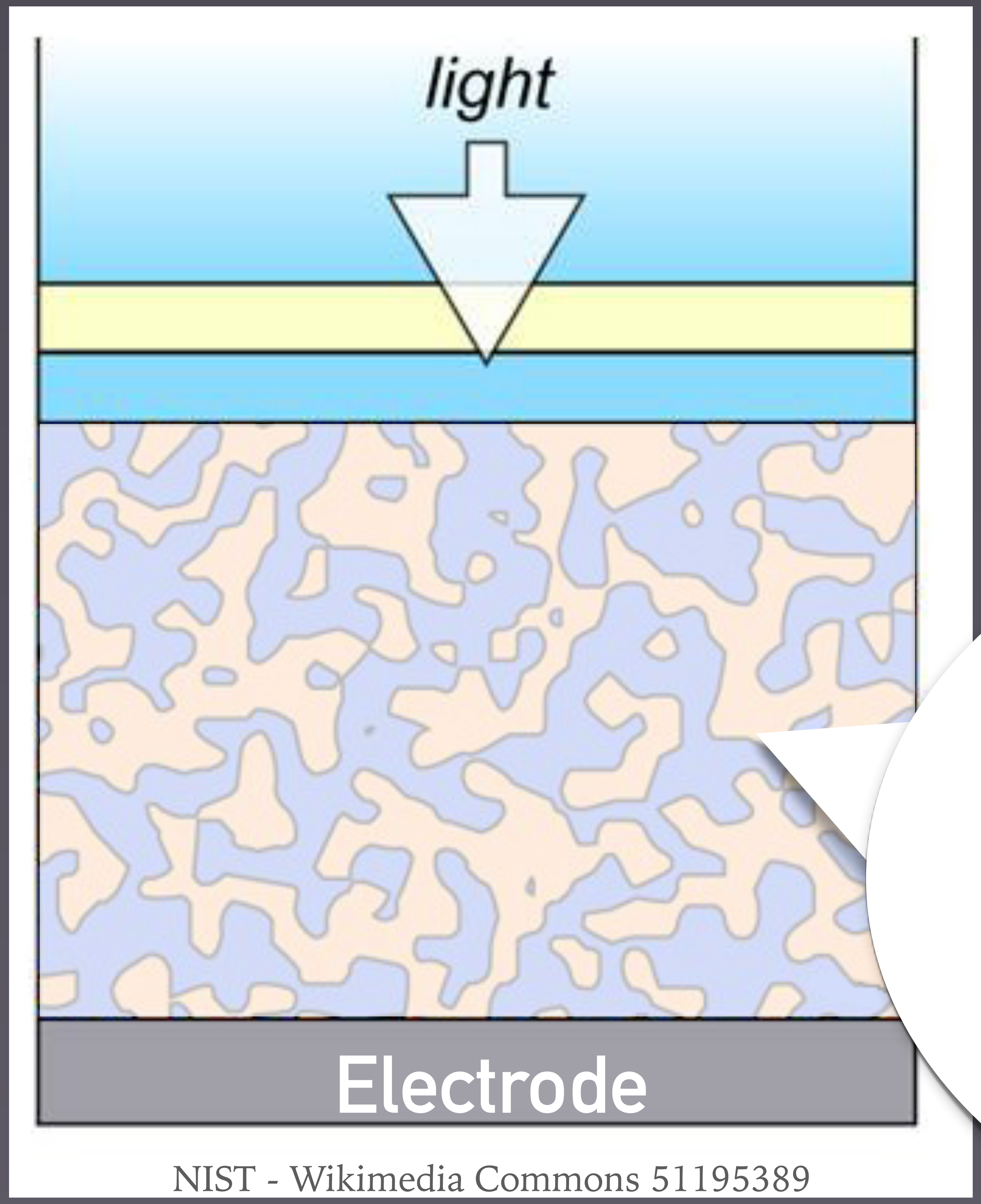


XFEL tunnel

Young et al, Roadmap of ultrafast x-ray atomic and molecular physics, J. Phys. B 51 (2018)

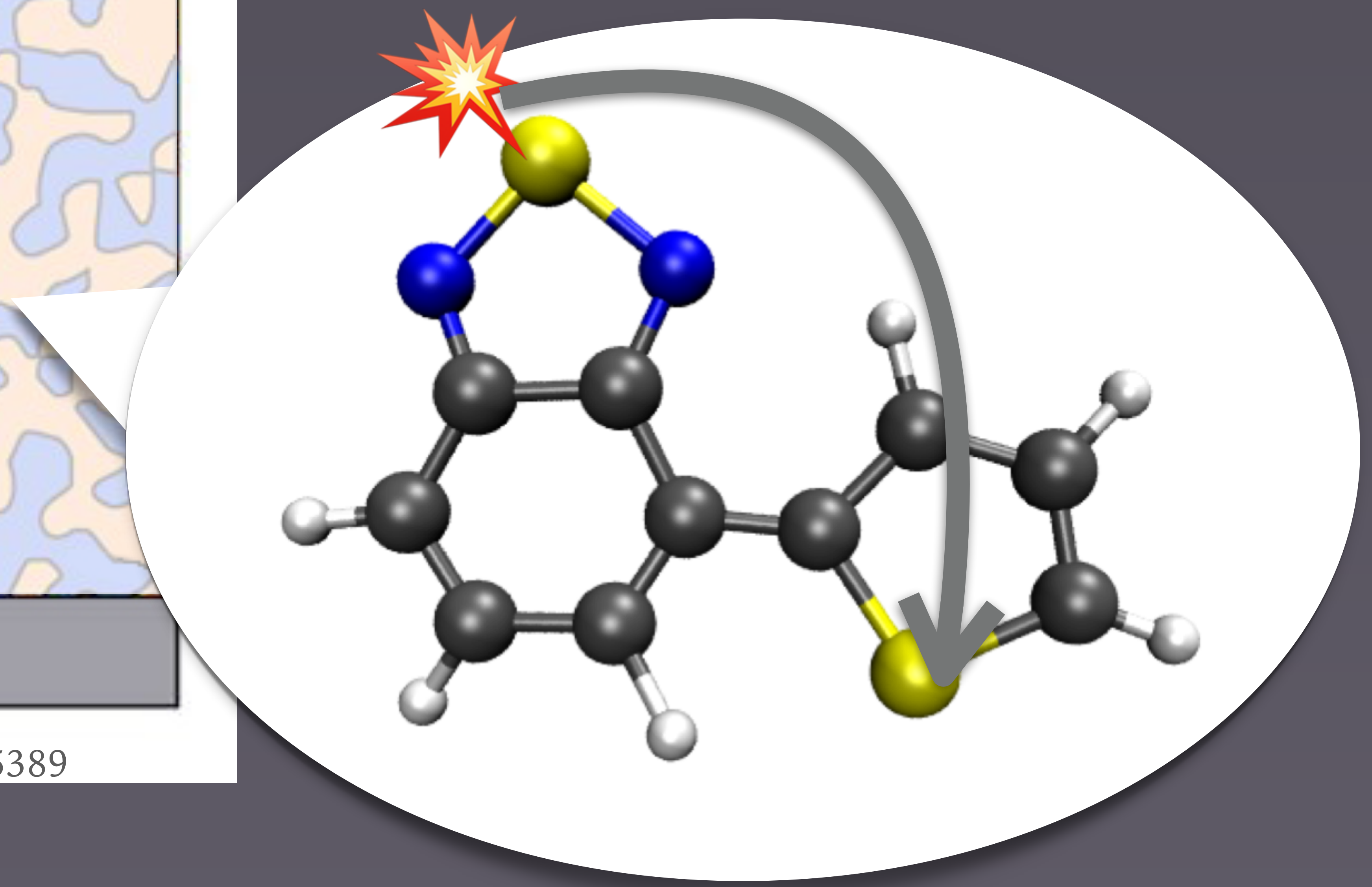
Organic Solar Cell

An example for insights from ultrafast science



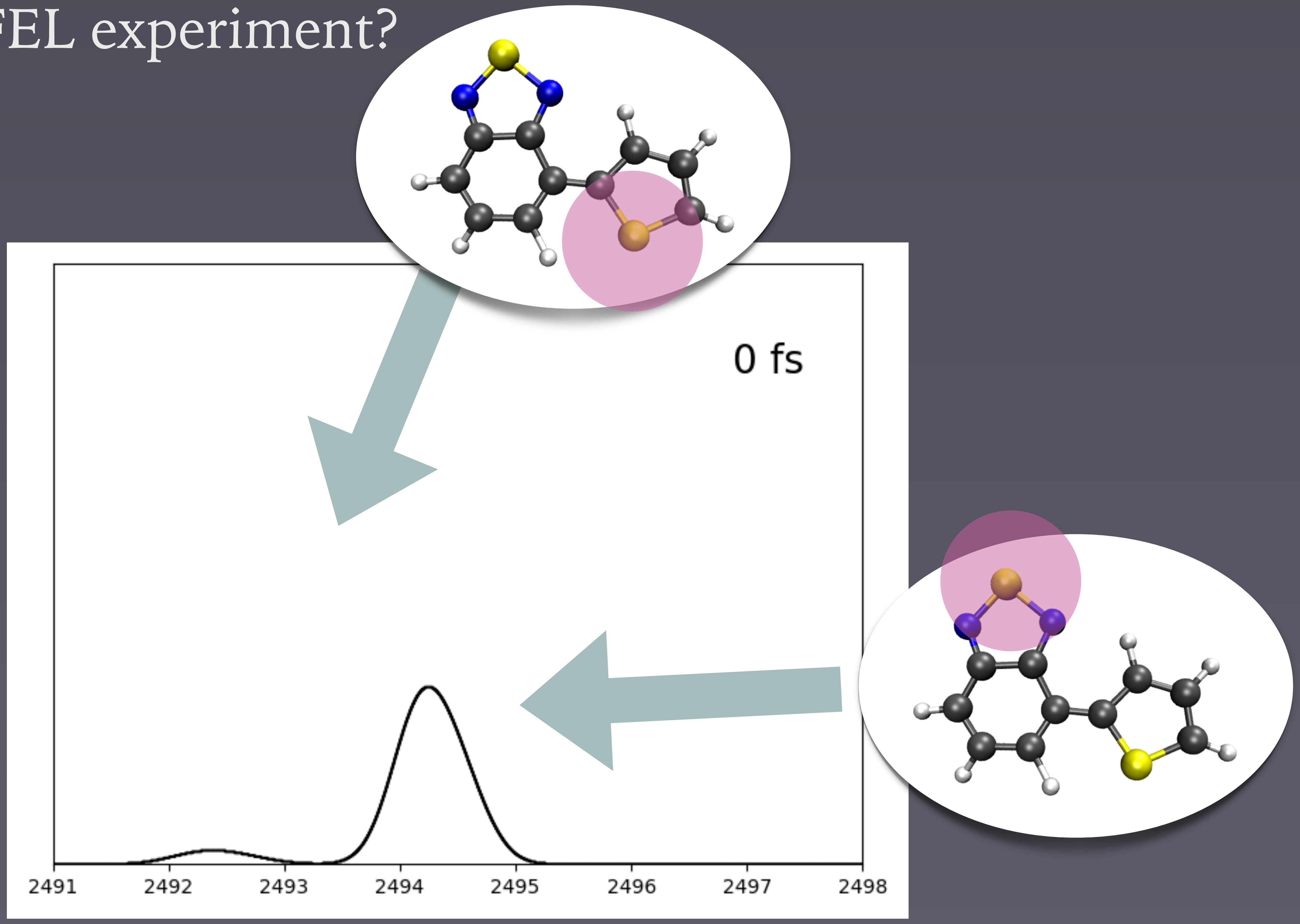
Need to transport the charges

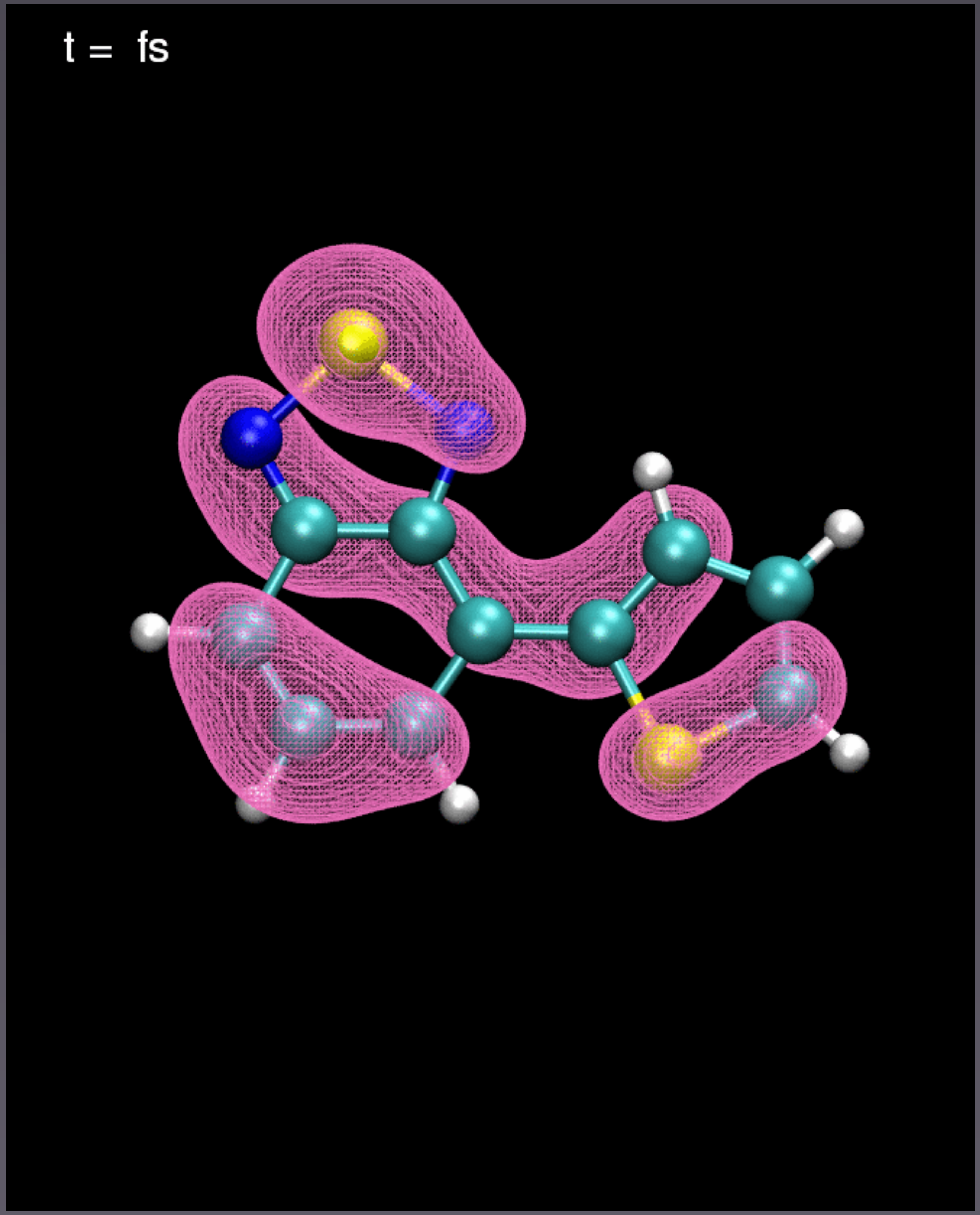
Polymer BT-1T



Observe Charge Migration

- Calculate the ultrafast charge migration in BT-1T
- Shows up in the x-ray absorption spectrum
- XFEL experiment?

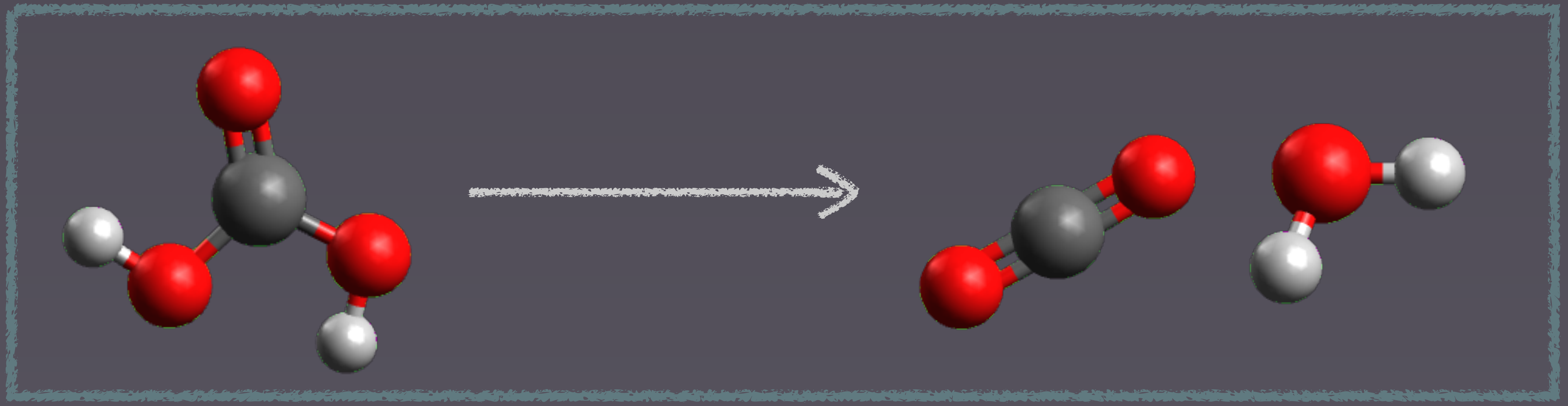




Khalili, Inhester, Arnold, Welsch, Andreasen, Santra. Journal of Structural Dynamics 6 (2019)

Beyond the Molecular Movie

Chemical reactions involve molecular dynamics

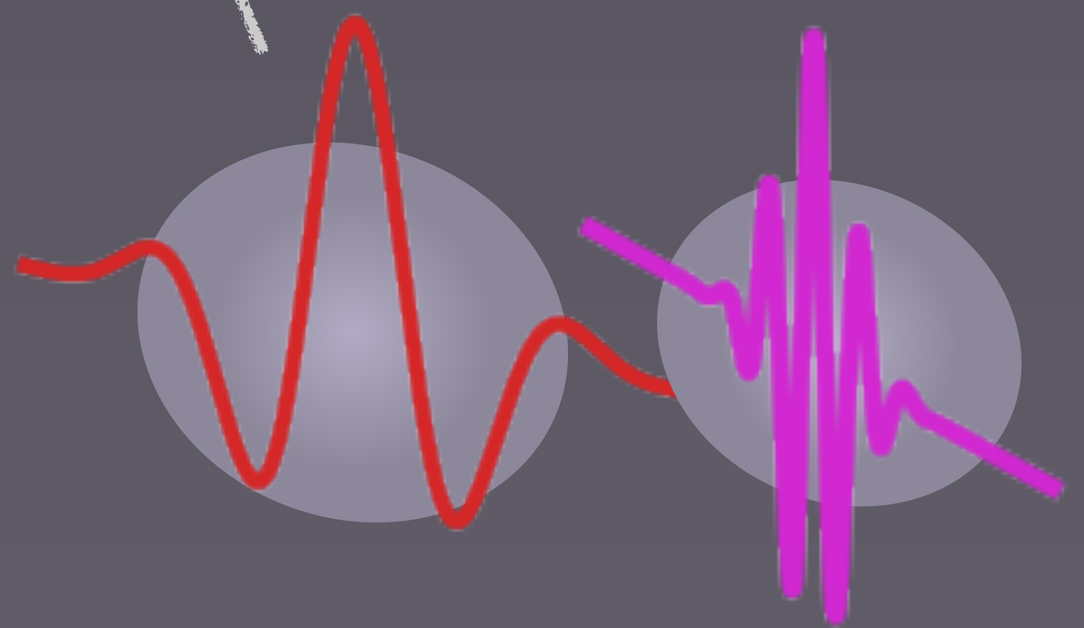


Trigger

Control reaction with light

Optimisation routine

```
> ./optimise_pulses
```

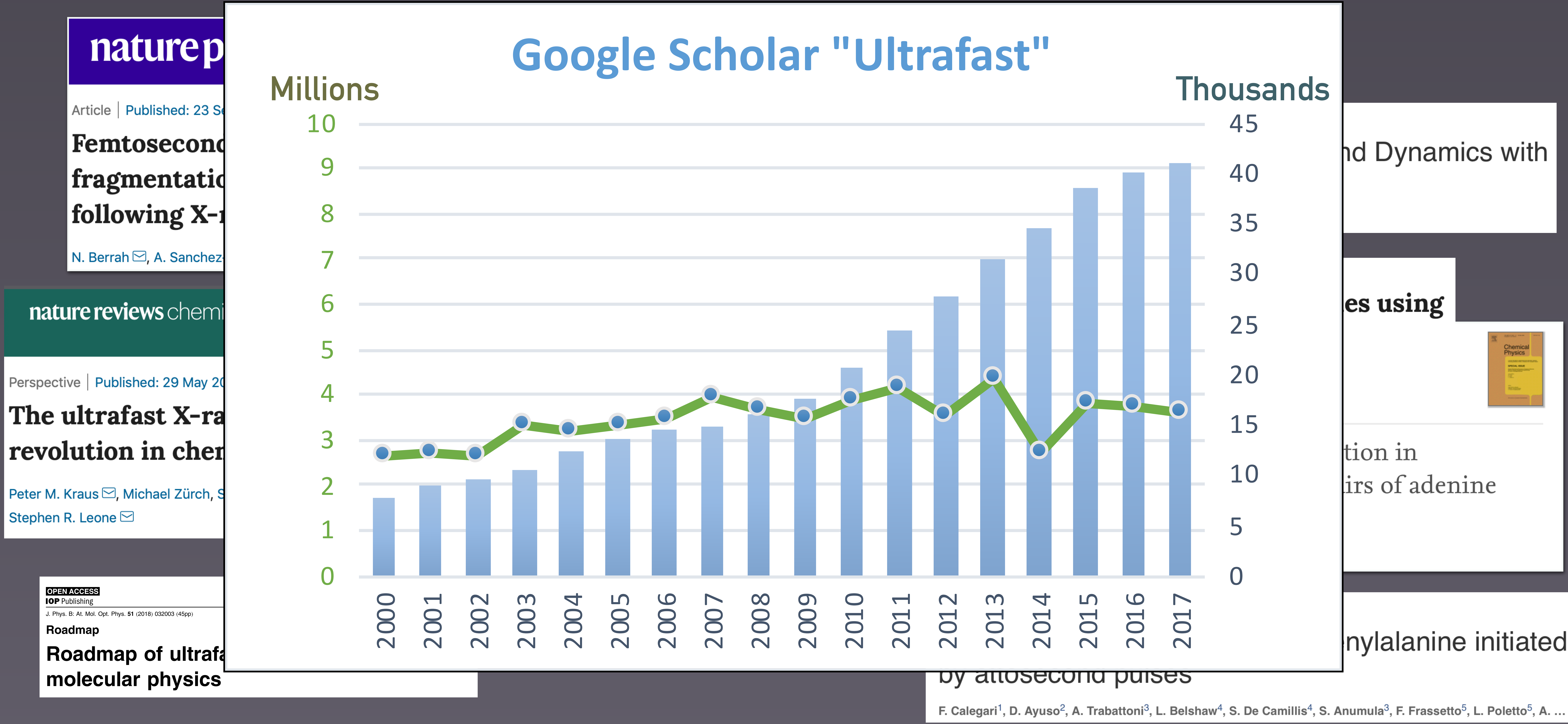


Generate sequence

<u>Ultrafast wish list</u>

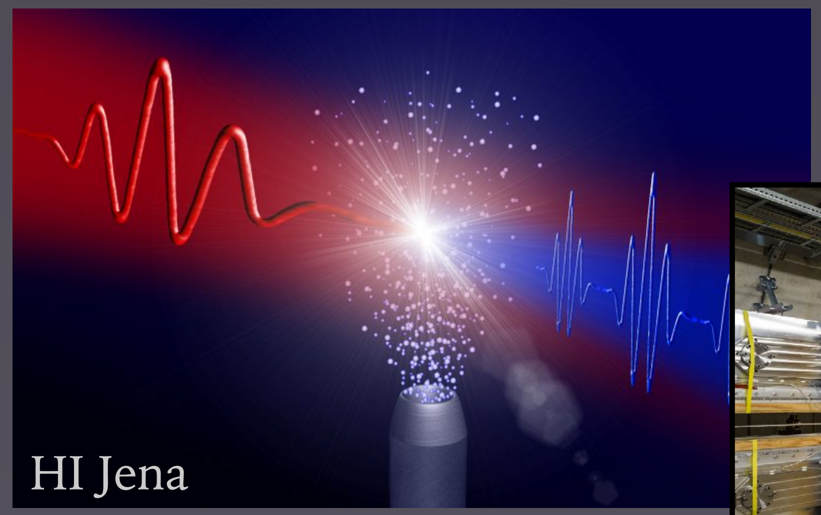
- ☑ Take the molecular movie
- ☐ Direct the molecular movie

An Ultrafast Developing Field

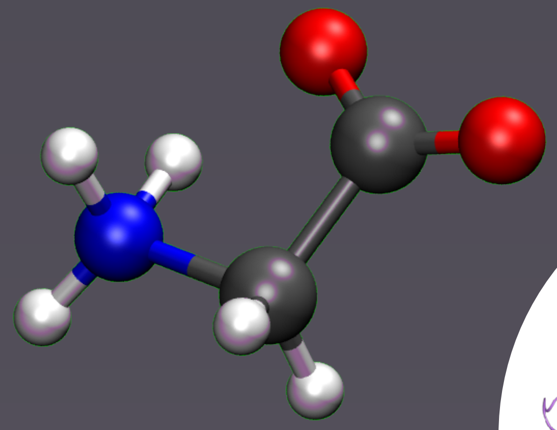


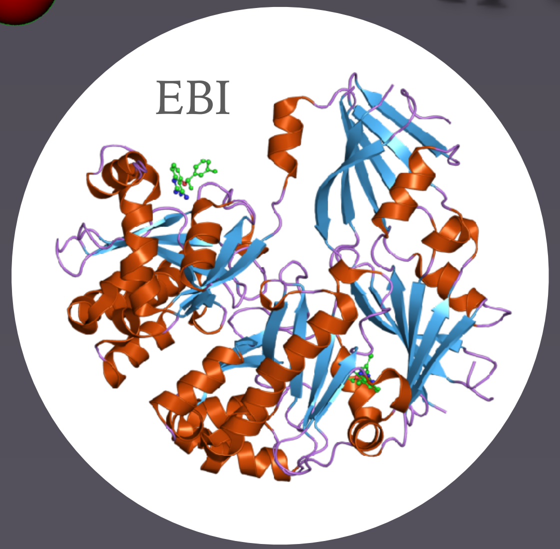
What's Next?

Develop light sources



Theoretical calculations

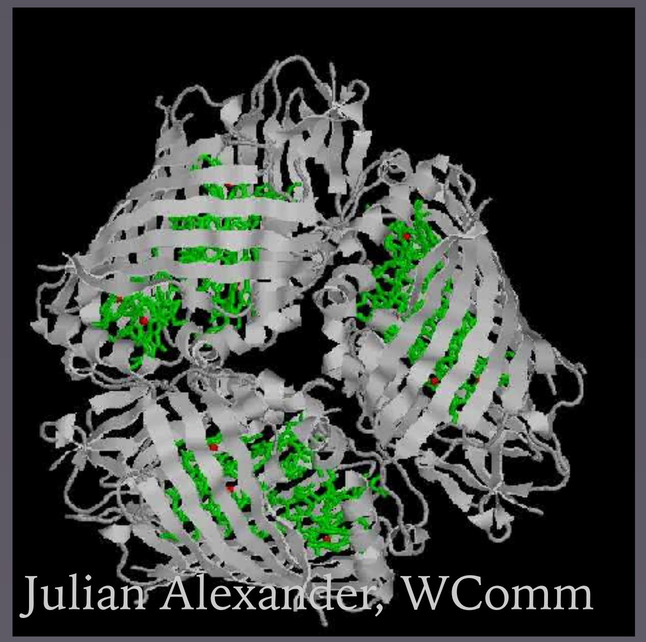


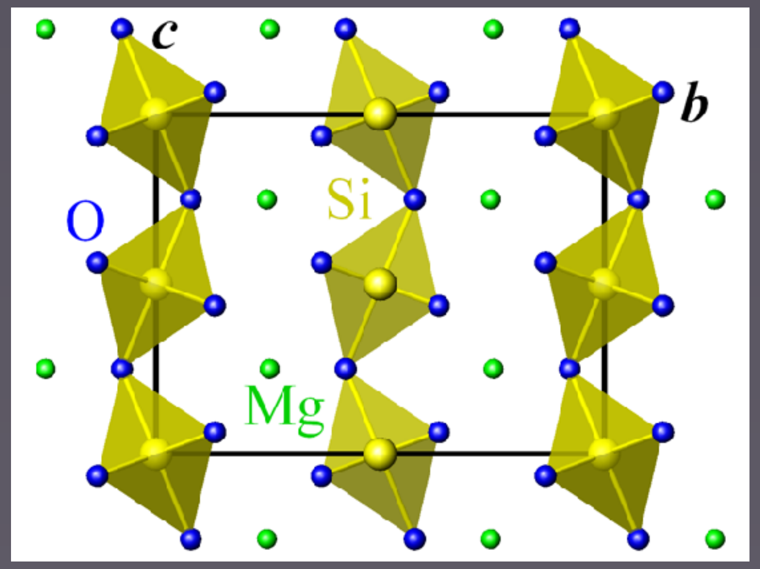


$$\hat{H} = \hat{H}_0 + \lambda \hat{H}_{\mathrm{int}}$$

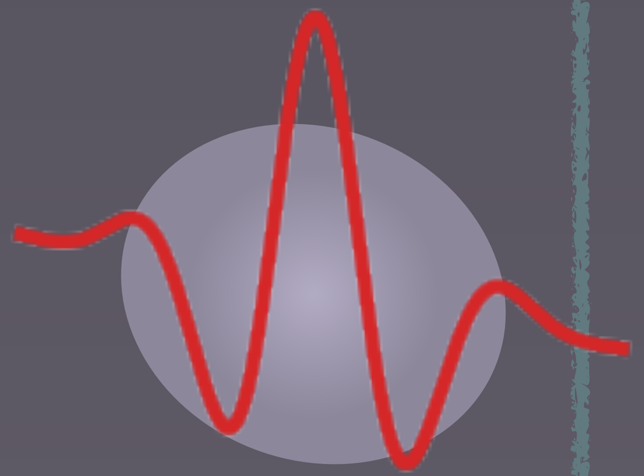
$$i \frac{\partial}{\partial t} \psi = \hat{H} \psi$$

Larger systems



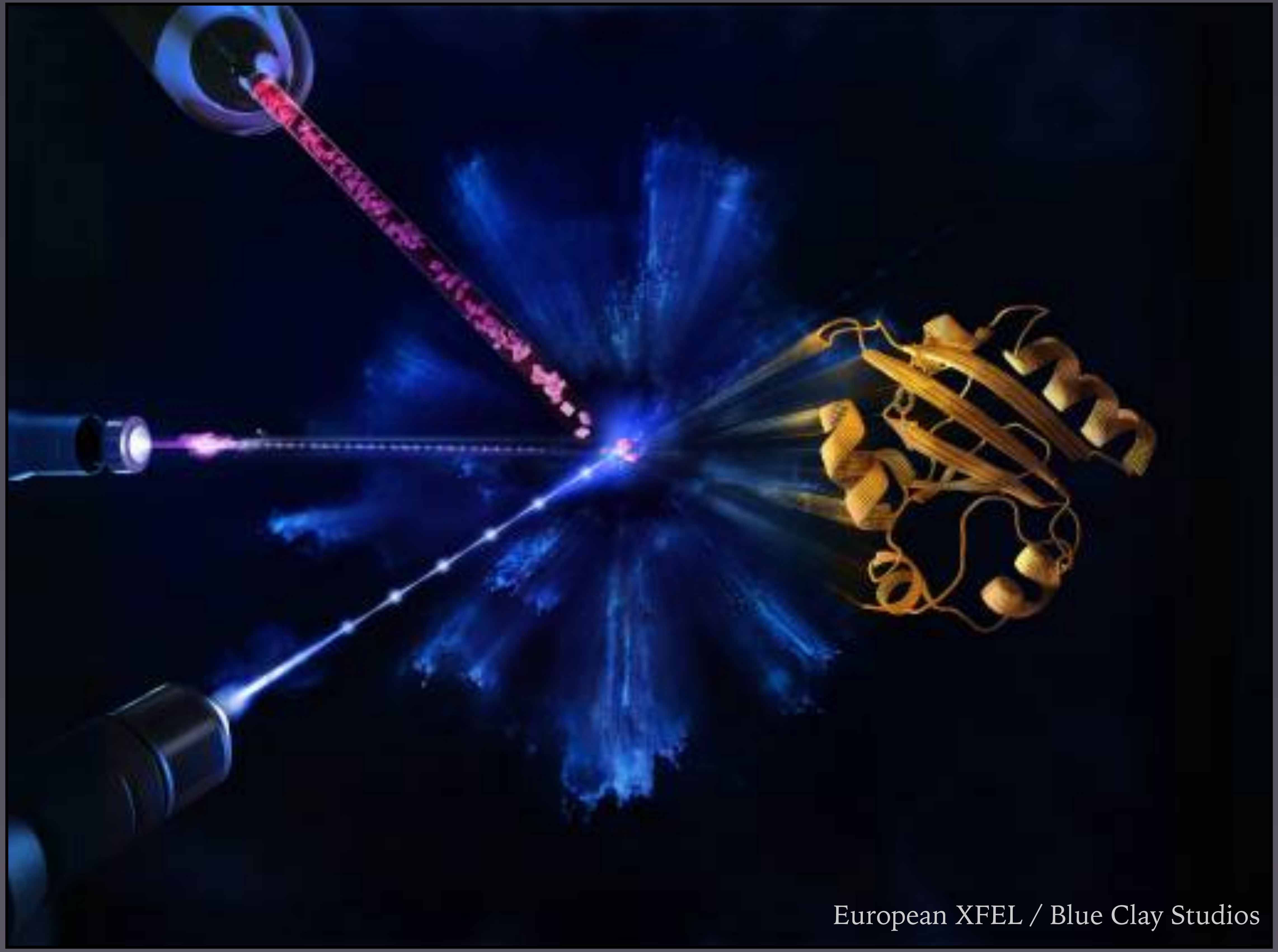


Control reactions with light



Thank You for Your Attention

- Femtosecond dynamics are fundamental for physics, chemistry, and biology
- Ultrashort laser pulses can take molecular movies
- Generated in the laboratory or at free-electron lasers
- Understanding a phenomenon gives us the possibility to control it!



European XFEL / Blue Clay Studios

Thanks to the supporting institutions

CUI THE HAMBURG CENTRE FOR ULTRAFAST IMAGING

CFEL SCIENCE

DESY.