FÍSICA

Real Sociedad Española de Física

R.S.E.F.

VNiVERSiDAD D SALAMANCA

CAMPUS DE EXCELENCIA INTERNACIONAL

Attociencia, herramientas para controlar los procesos más breves

Miércoles, 16 de noviembre, 13:00 h.
Aula III (edificio Trilingüe)

Carlos Hernández García

Área de Óptica
Departamento de Física Aplicada

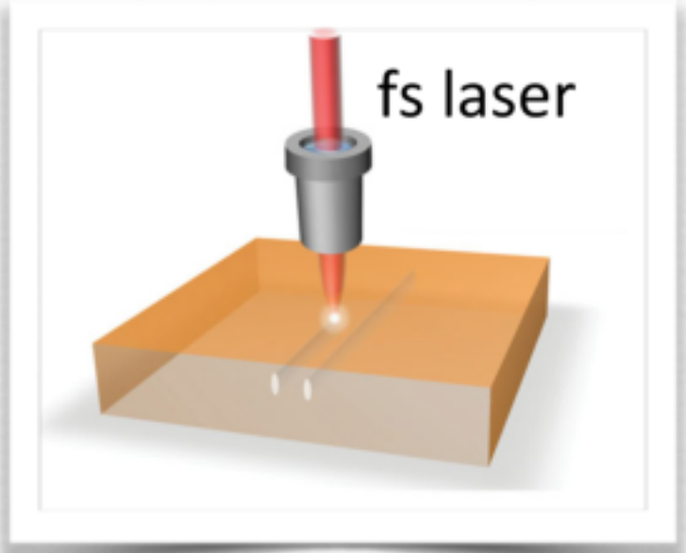
ALF USAL

Grupo de Investigación en

Aplicaciones del Láser y Fotónica

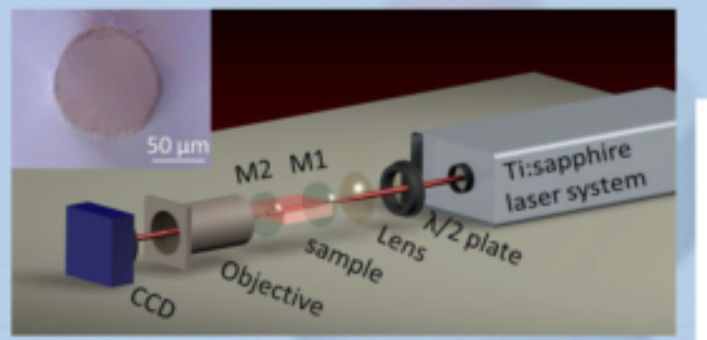
Gabriel Castillo
Enrique Conejero
Helder Crespo
Ana García González
Irene Heras
Carlos Hernández García
Marta Morales
Pablo Moreno
Luis Plaja
René Rodriguez Beltrán
Javier Rodriguez Vázquez de Aldana
Carolina Romero
Julio San Román
Íñigo Sola

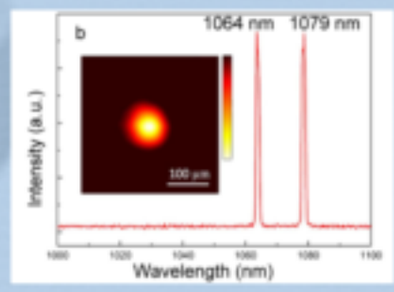
Fabrication of integrated photonics devices in transparent dielectrics



ACTIVE PHOTONIC DEVICES

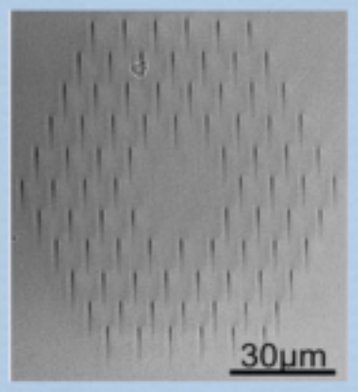
Fabrication of compact high-performance devices as waveguide lasers and frequency converters

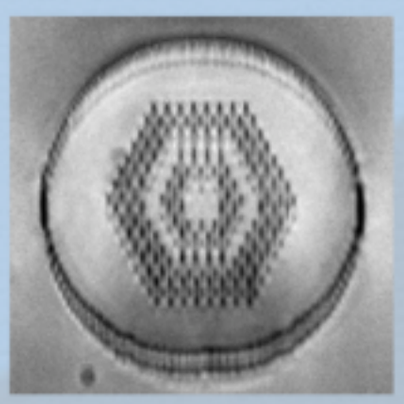




NEW FABRICATION STRATEGIES

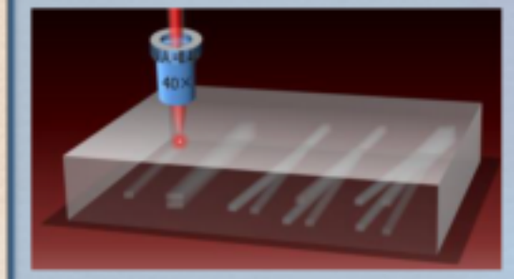
Design of novel approaches for engineering the optical properties of waveguides





FUNCTIONAL 3D DEVICES

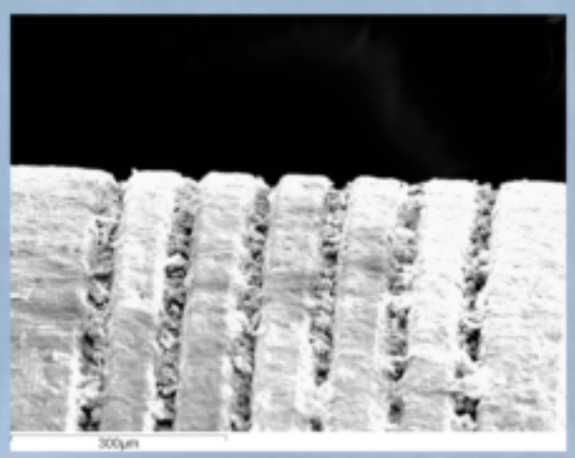
Implementation of 3D photonic circuits with complex geometry

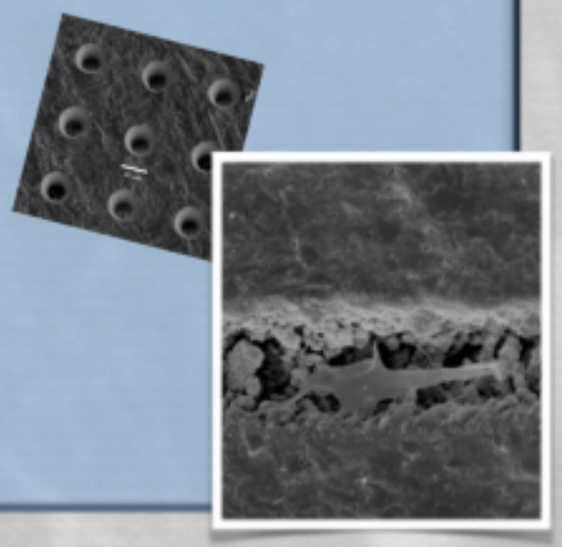


Surface engineering with ultrashort laser pulses.

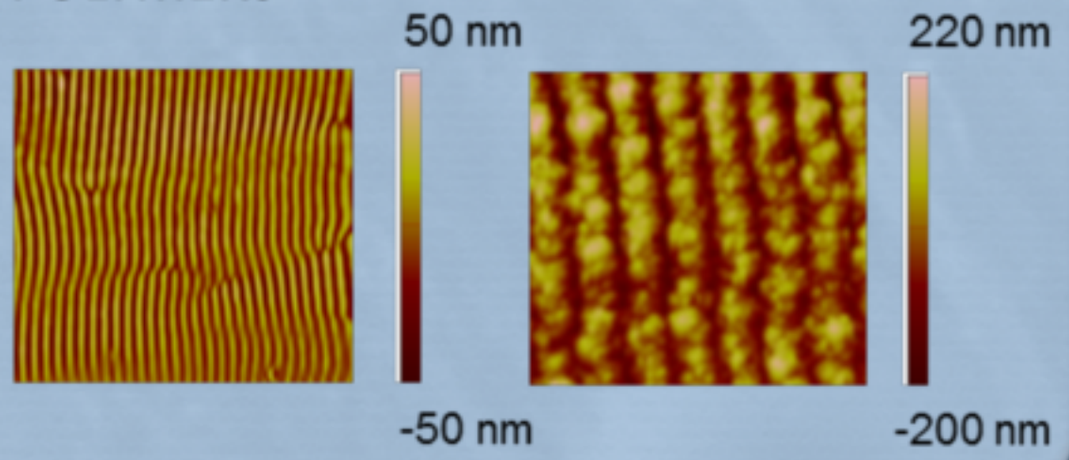
LANAMAP-CSIC

IMPLANT SURFACE MICROSTRUCTURING FOR IMPROVING TISSUE GROWTH





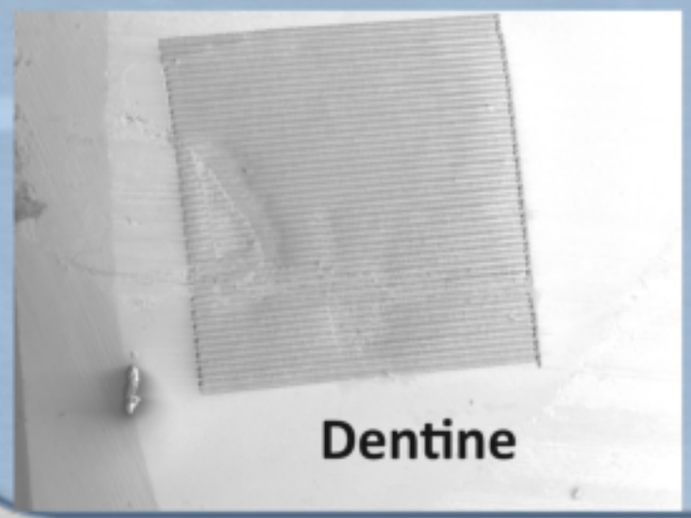
FEMTOSECOND LIPSS IN POLYMERS

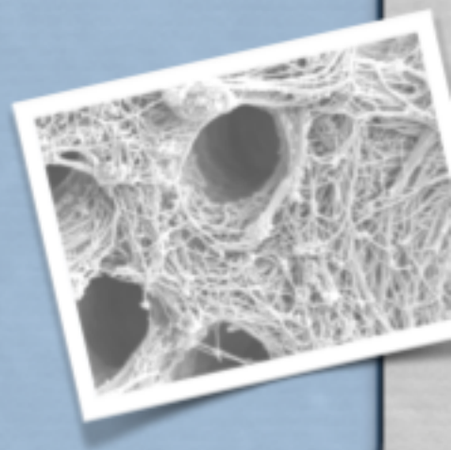


TAILOR-MADE MICROFABRICATION

Hard & brittle materials

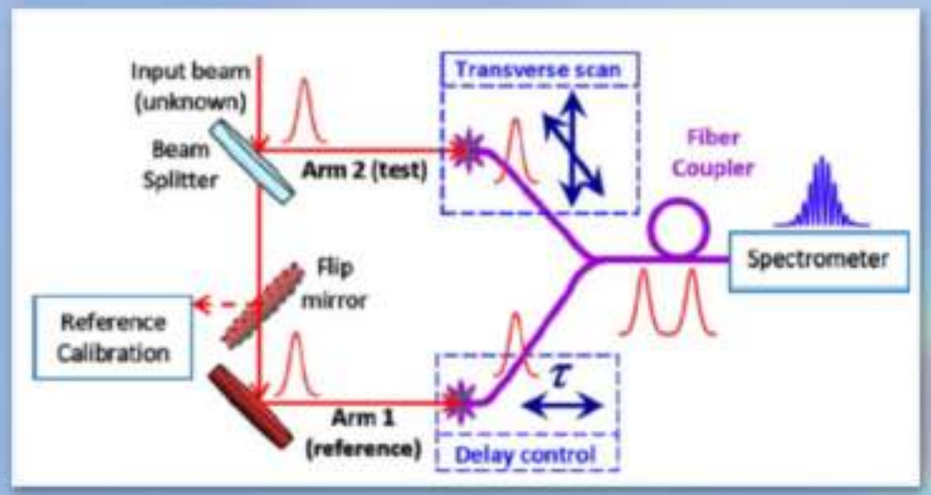
DENTAL TISSUE CONDITIONING FOR ORTHODONTICS



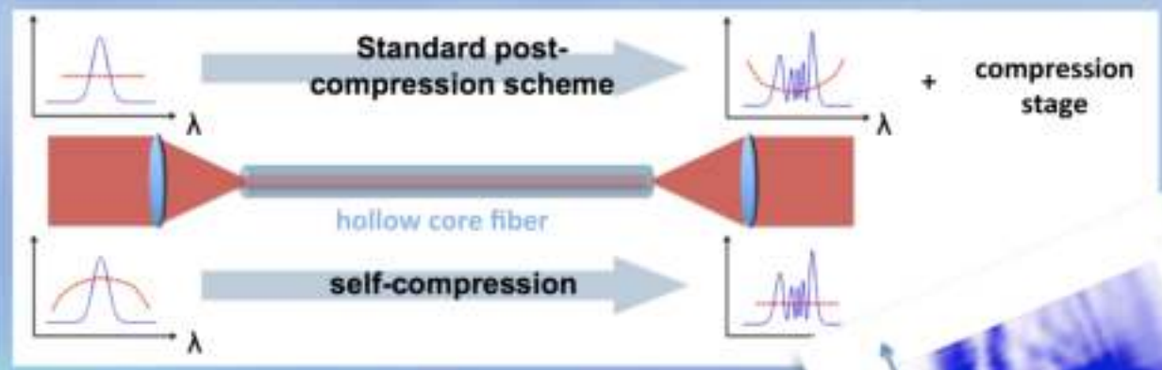


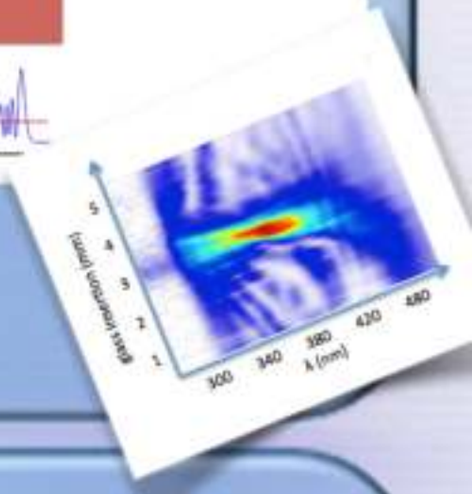
Pulse diagnostics and non-linear propagation

SPATIO-TEMPORAL RECONSTRUCTION (STARFISH)

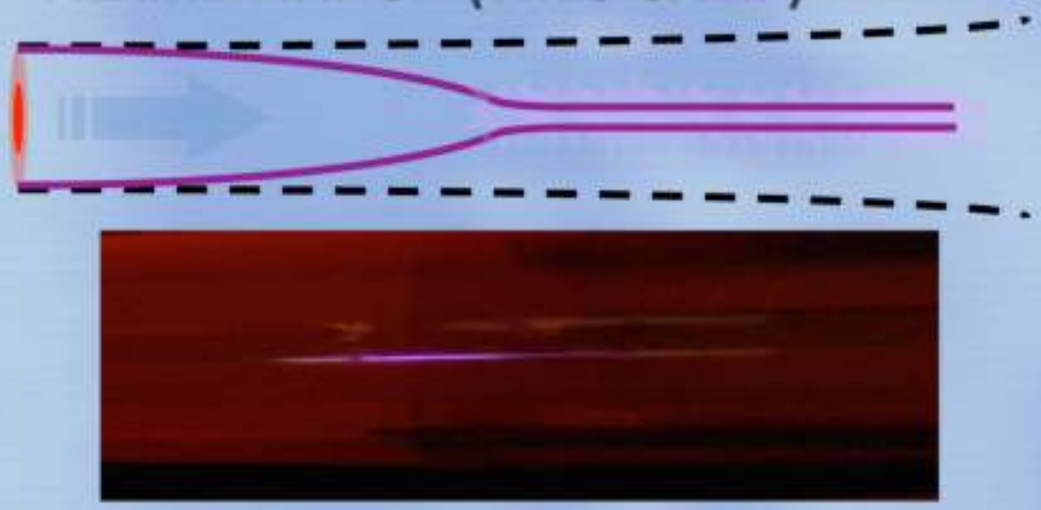


PULSE COMPRESSION

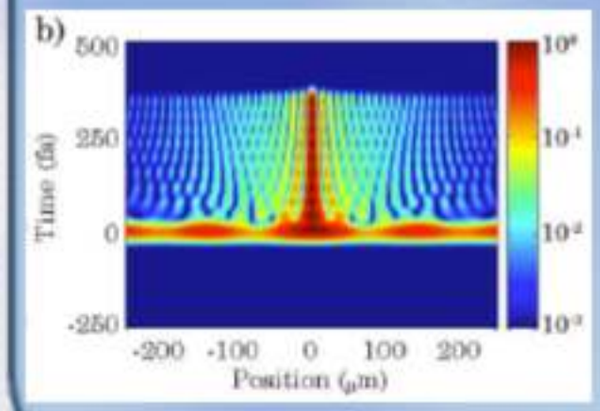




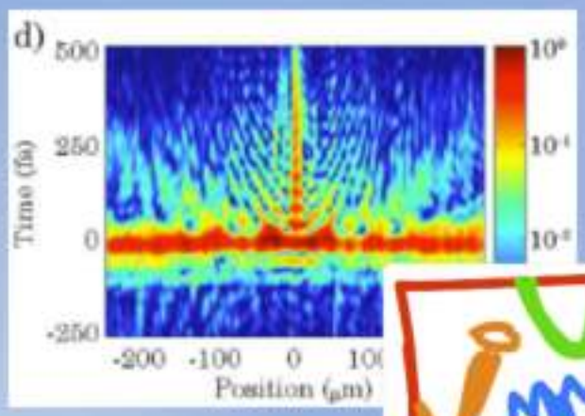
FILAMENTATION (THEO & EXP)



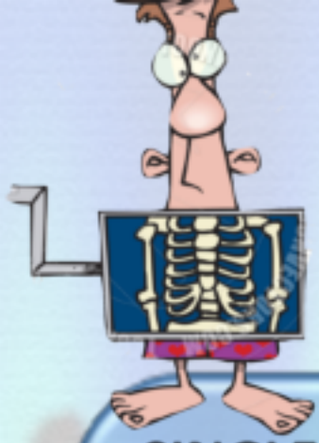
DIAGNOSTICS OF PULSED COMPLEX BEAMS



THEO

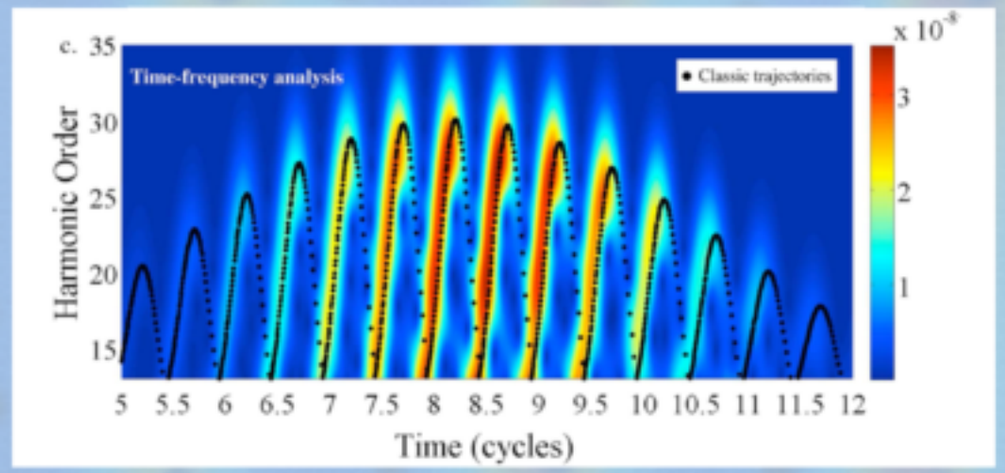


EXP

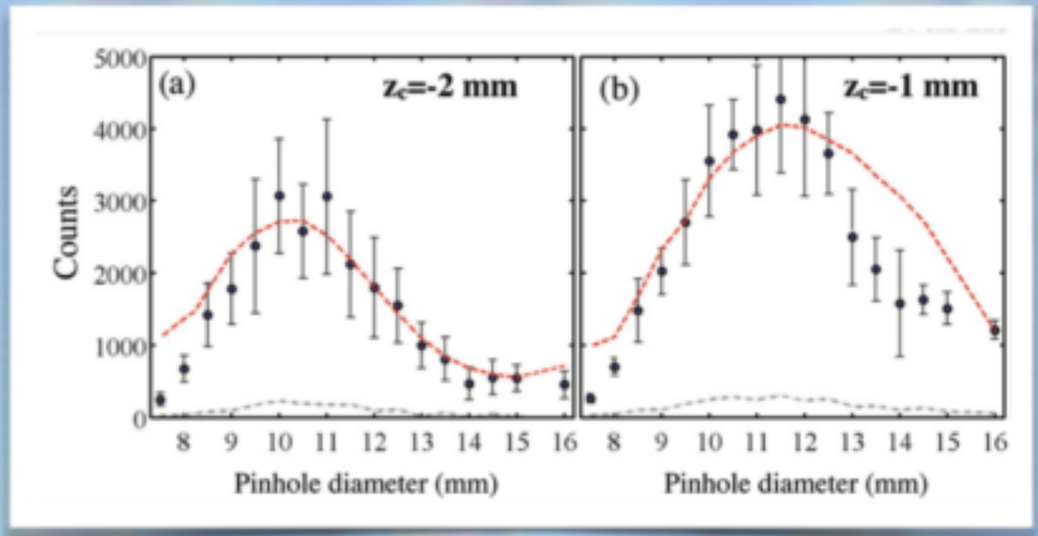


High-order harmonics and Attosecond Science (Theo & Exp)

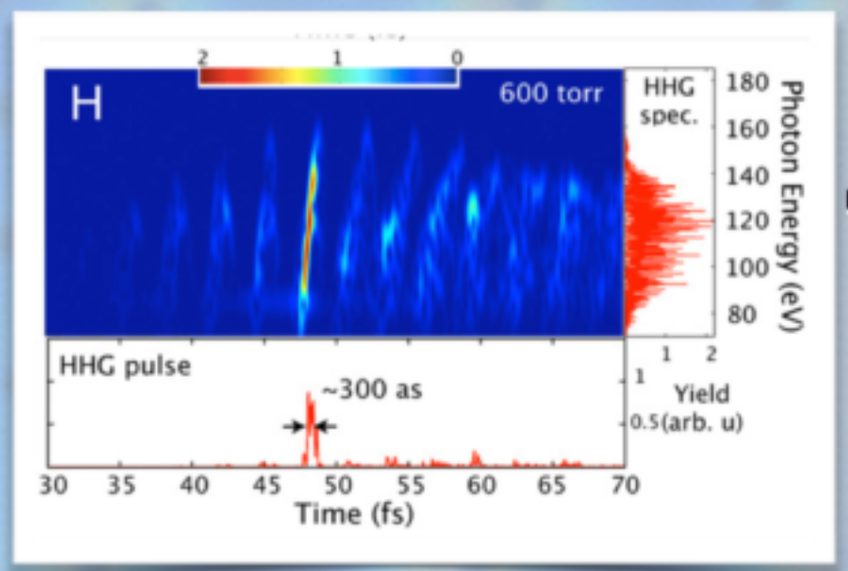
SINGLE ATOM: SFA+
PROPAGATION: DDA



BENCHMARKING WITH EXPERIMENTS



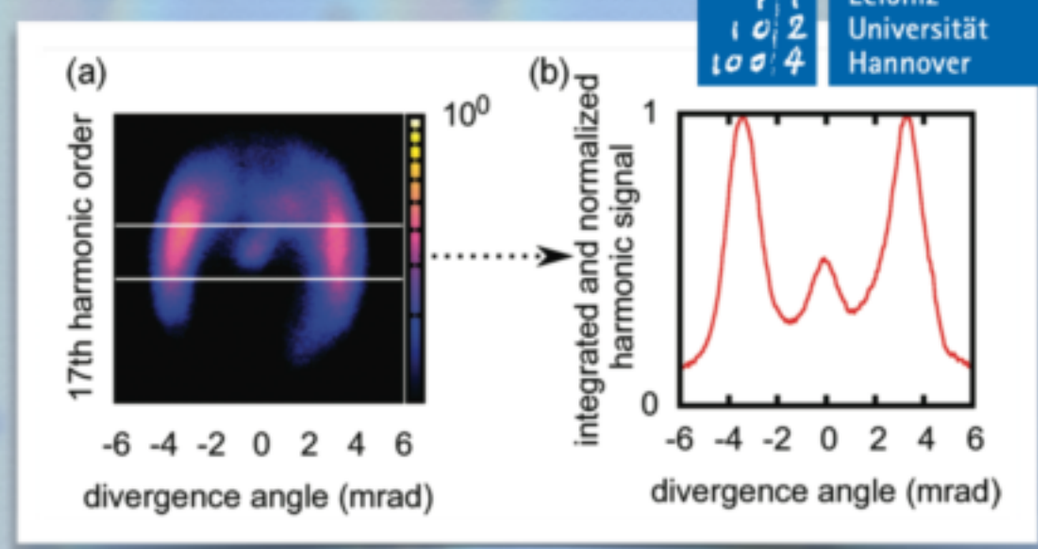
Role of transversal phase-matching



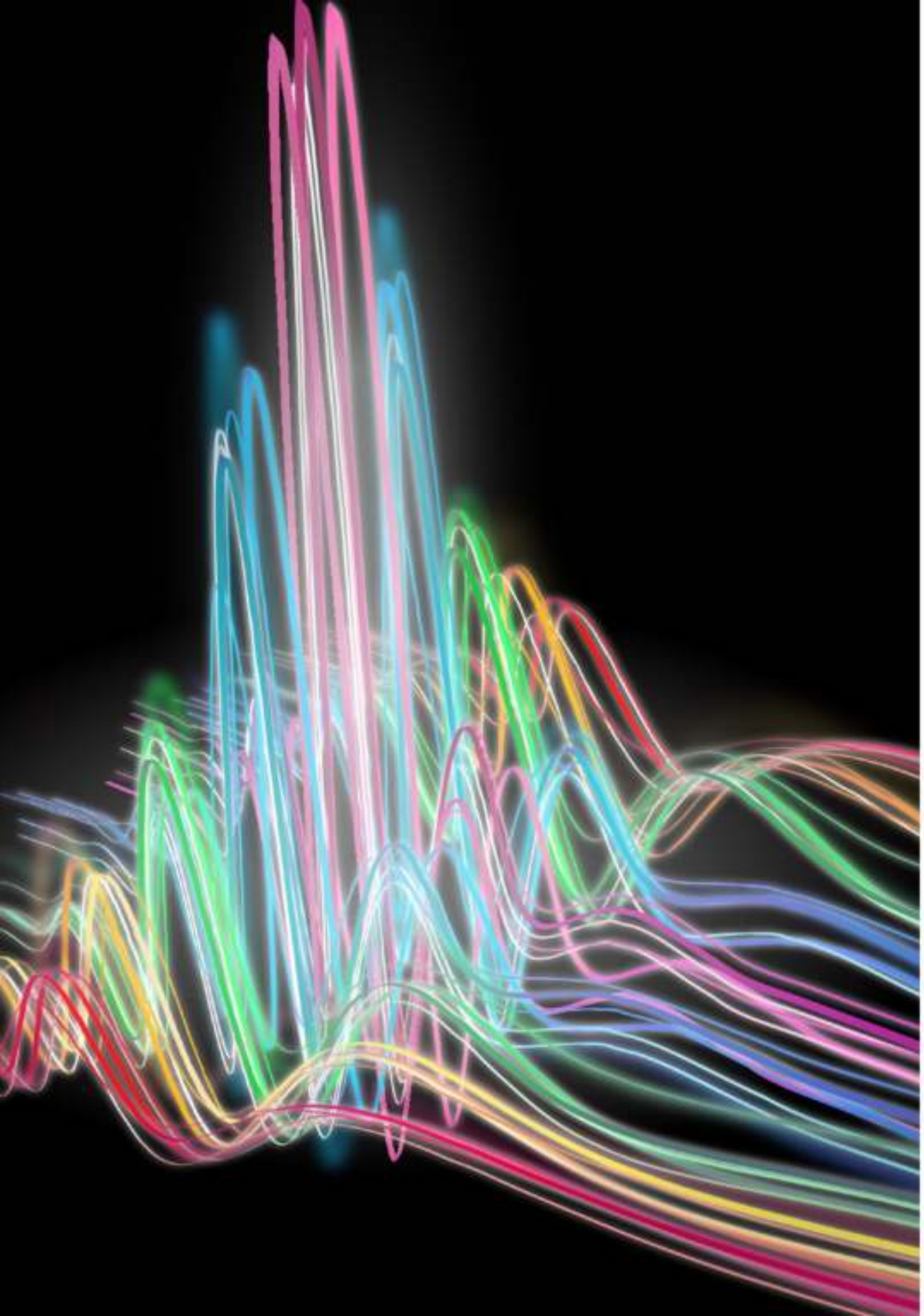
JILA

Isolated X-ray attosecond pulses

Leibniz Universität Hannover



XUV harmonics in gas cell



ÍNDICE

- **Introducción a la Attociencia**
- **¿Cómo generamos pulsos de attosegundo?**
- **¿Cómo controlamos sus propiedades?**

ALF USAL
Aplicaciones del Láser y Fotónica

Foto: J. R. Vázquez de Aldana

1 segundo

1/1000 **mili**segundo

1/1000000 **micro**segundo

1/1000000000 **nano**segundo

1/1000000000000 **pico**segundo

1/1000000000000000 **femto**segundo

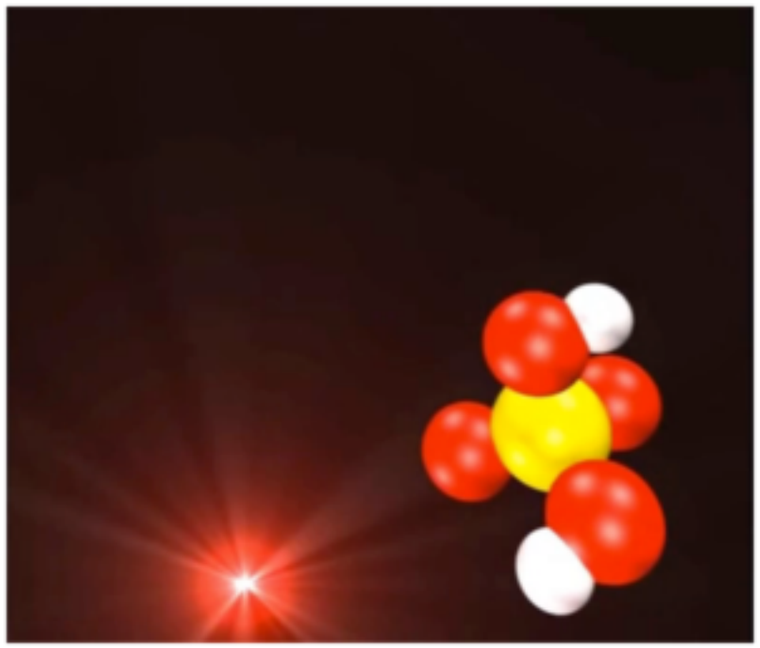
1/1000000000000000000 **atto**segundo

Picosegundos 10^{-12} s.

Reacciones Químicas

Disociación del ácido sulfúrico

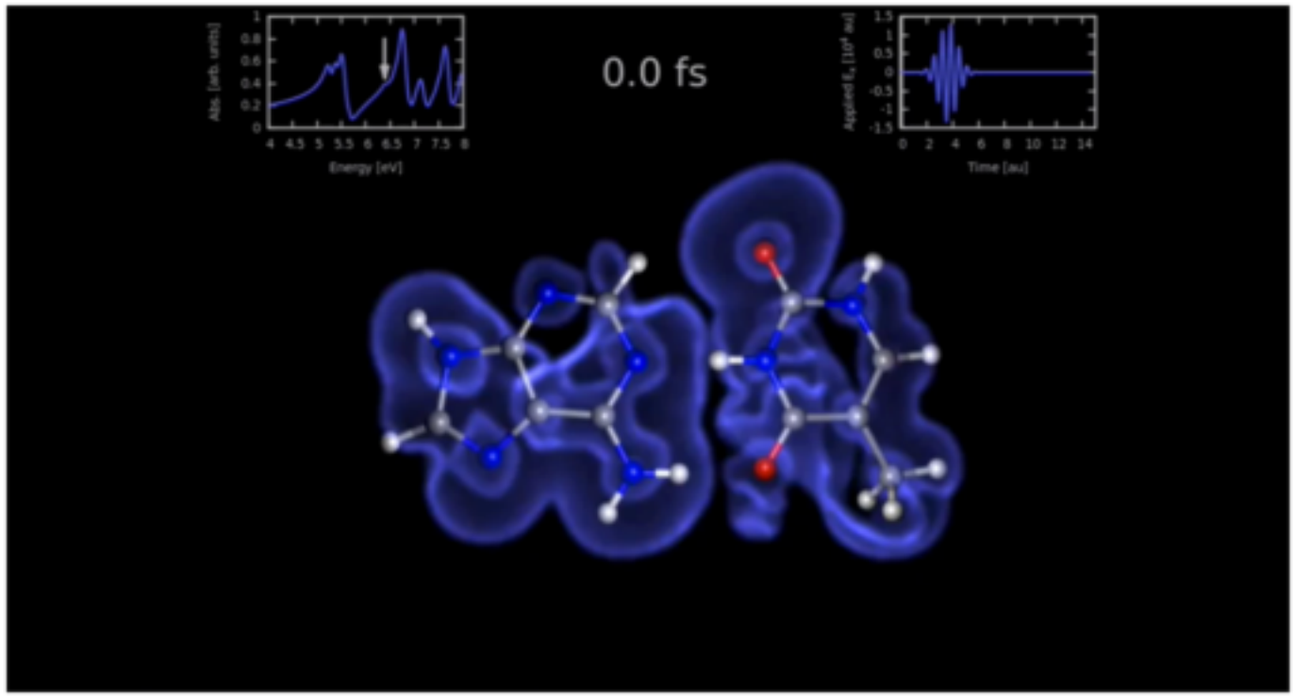
$$H_2SO_4 \rightarrow H_2O + SO_3$$



Femtosegundos 10^{-15} s.

Física-Química:

El movimiento de electrones en moléculas



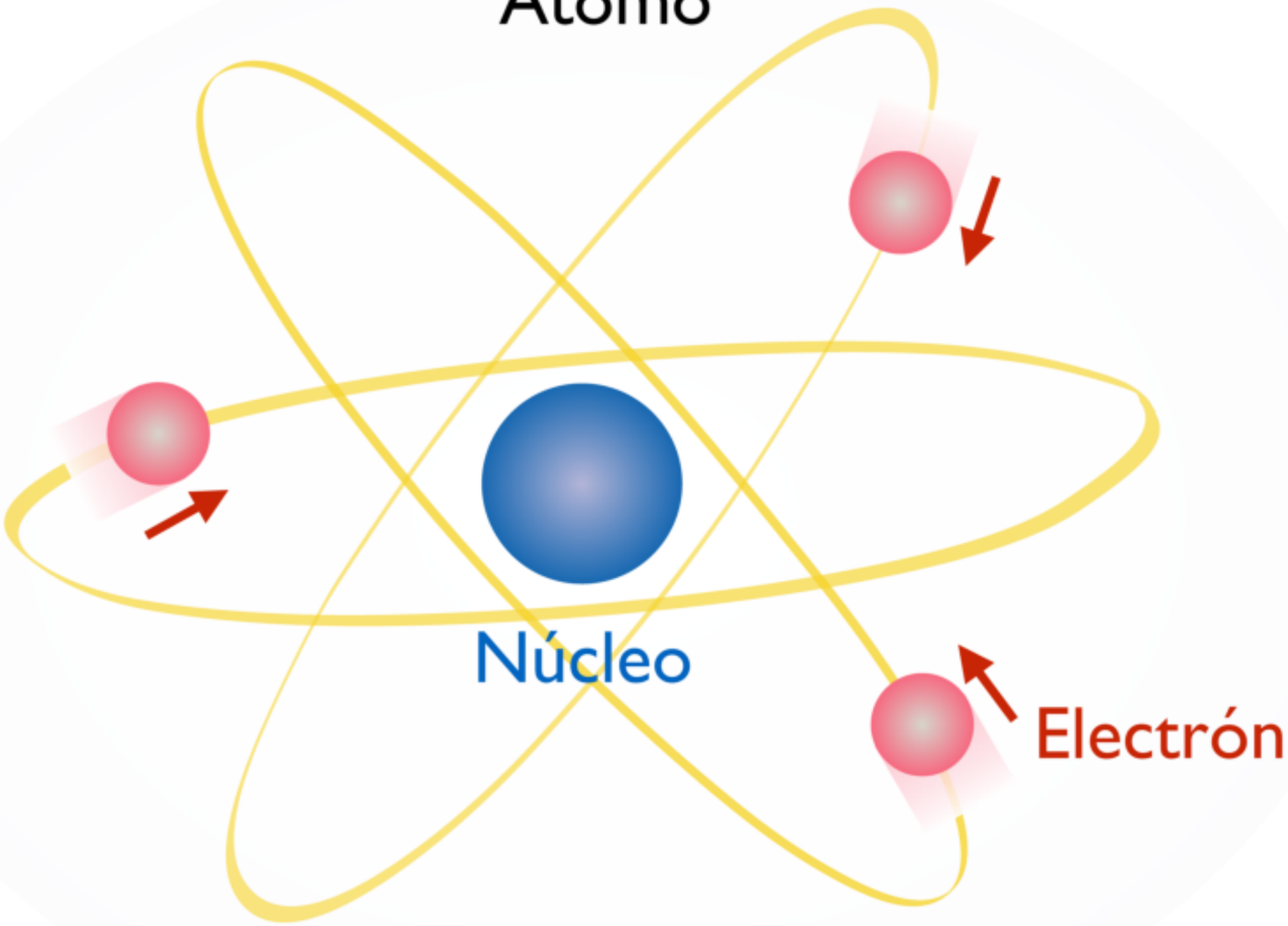
Charge transfer excitation between adenine and thymine

Attosegundos 10^{-18} s.

1/1000000000

000000000

Átomo



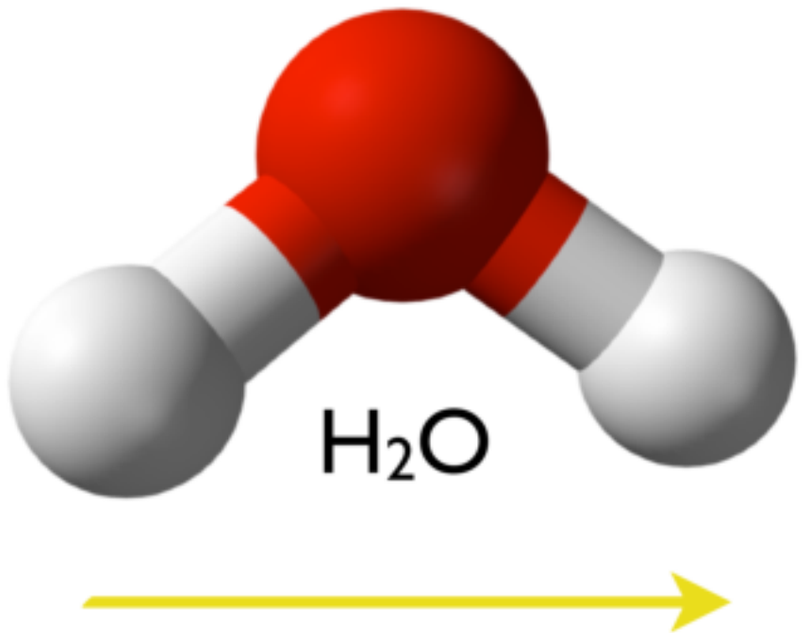
100 attosegundos

1 segundo

1 attosegundo = 10^{-18} segundo

La luz recorre...

¡7.5 vueltas a la Tierra
en un **segundo**!



¡una molécula de agua
en un **attosegundo**!

10^{-12} s 10^{-15} s 10^{-18} s

1 ps 1 fs 1 as time

e⁻

Rotation Vibration Electron motion


12
329
State Farm
12

10^{-12} s 10^{-15} s 10^{-18} s

1 ps 1 fs 1 as time

e⁻

Rotation Vibration Electron motion

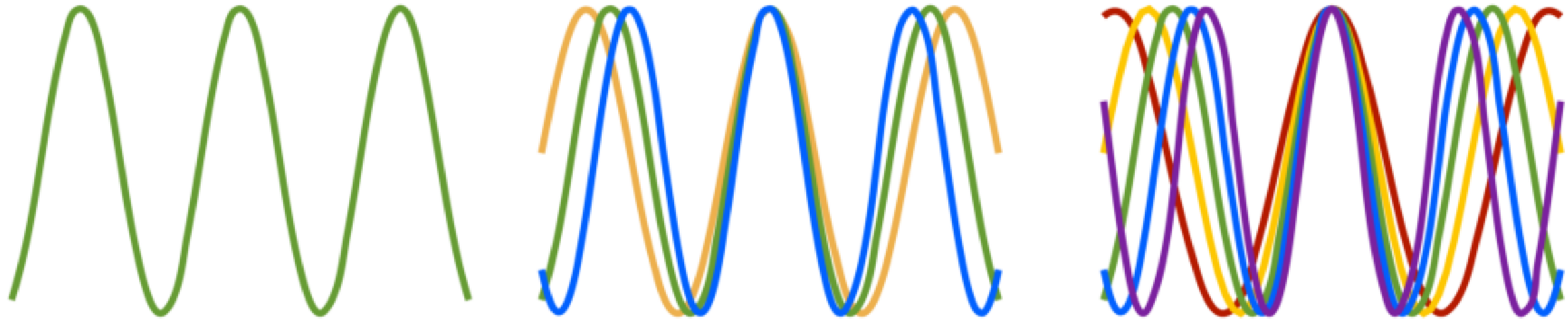
Foto: J. R. Vázquez de Aldana

Construyendo un pulso de luz ultracorto

Una sola frecuencia

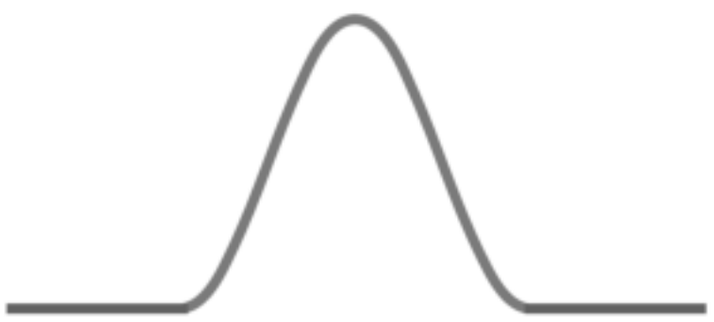
Algunas frecuencias

Muchas frecuencias

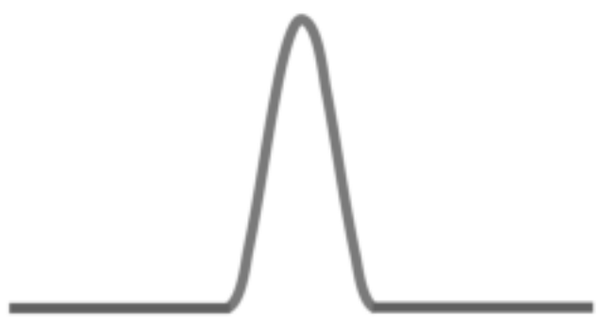


Emisión continua

Pulso corto

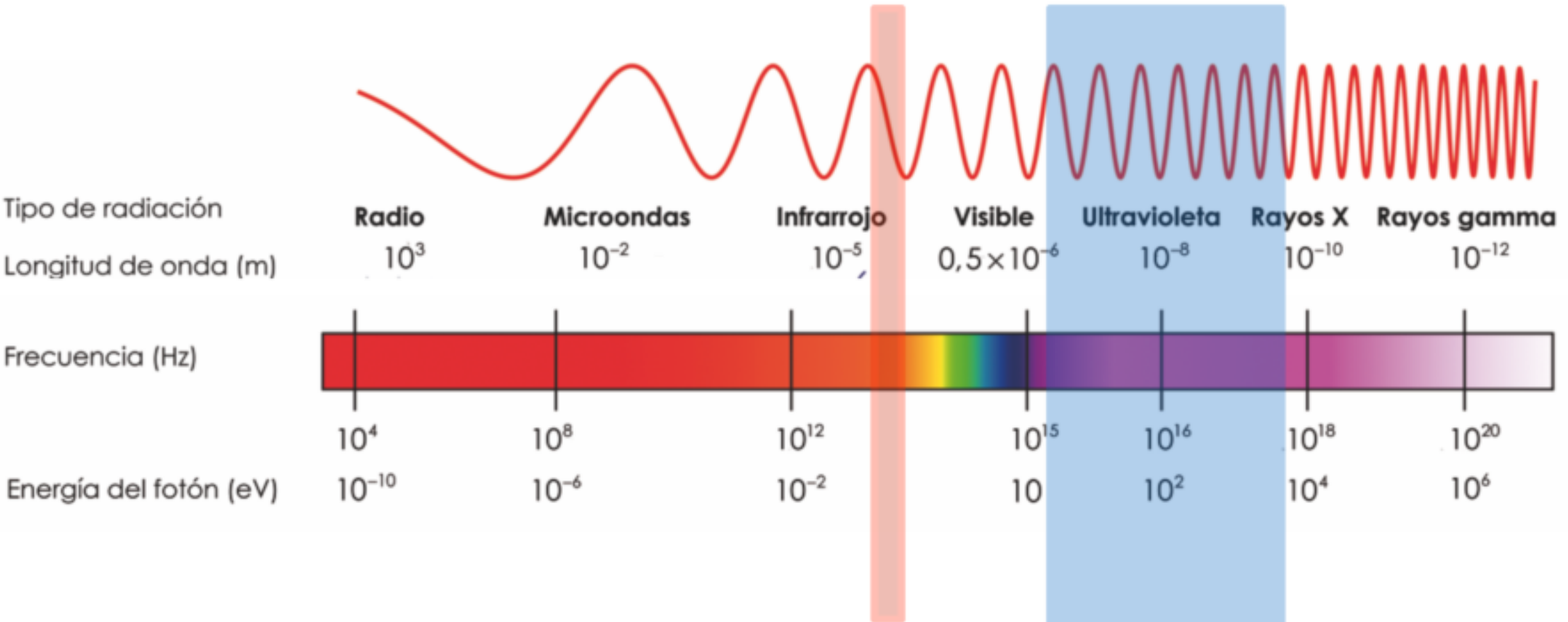


Pulso ultracorto



tiempo

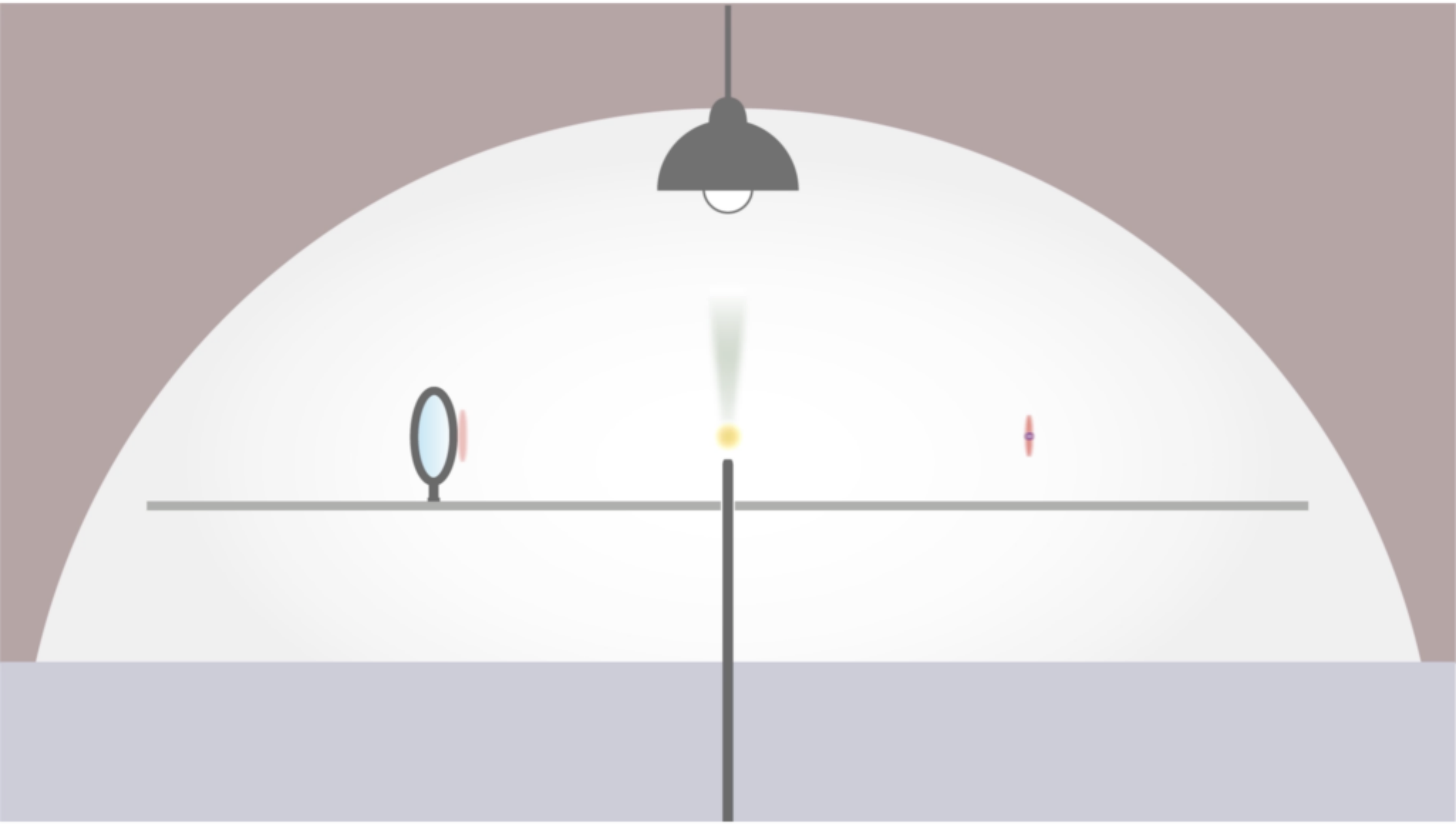
Pulso Largo vs Pulso Corto



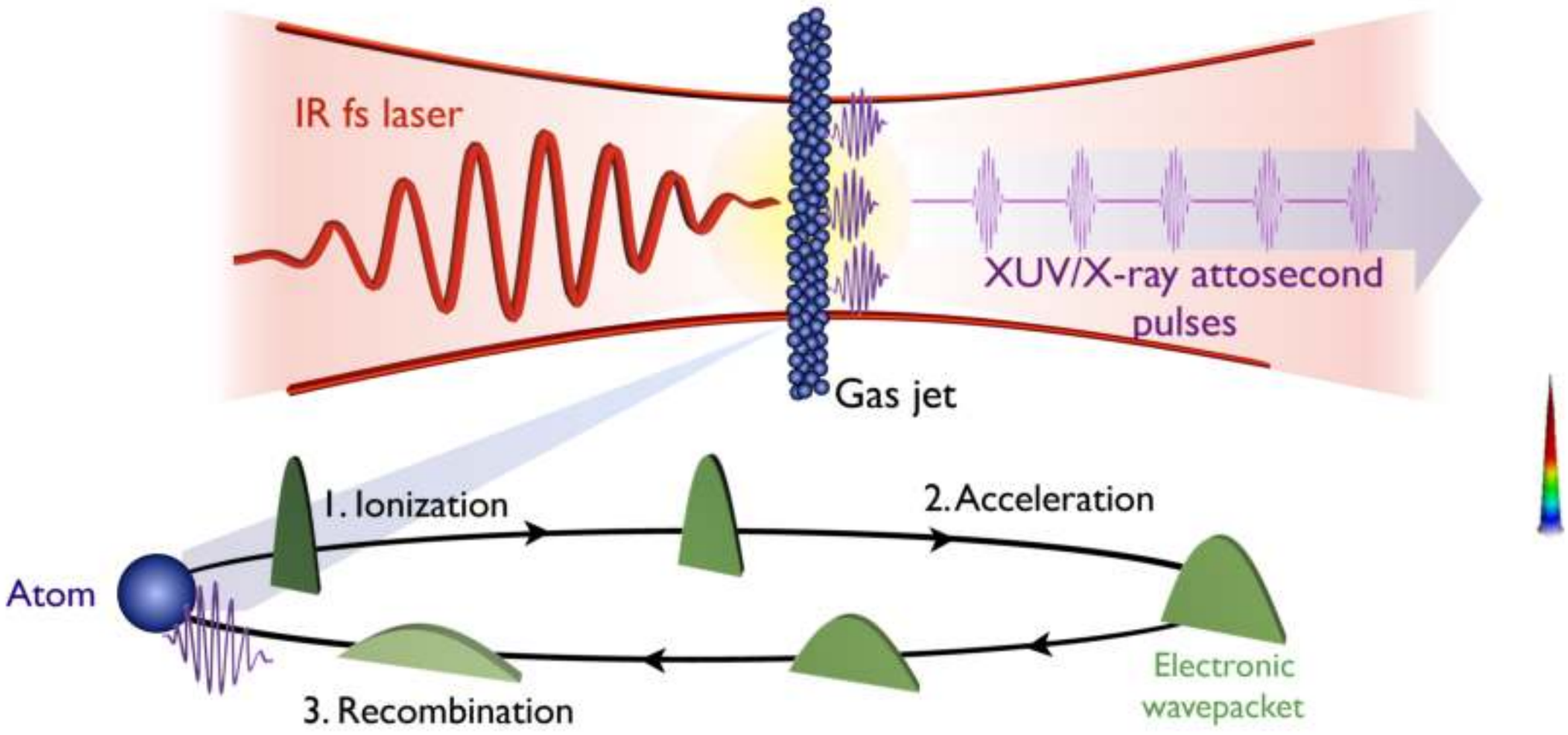
Pulsos de pocos **femtosegundos**
Anchura espectral (0.25 eV)
centrados en 800 nm, 1.5 eV
(1 ciclo=2.7 fs)

Pulsos de pocos **attosegundos**
Anchura espectral (700 eV)
centrados en 1.5 nm, 800 eV
(1 ciclo= 5 as)

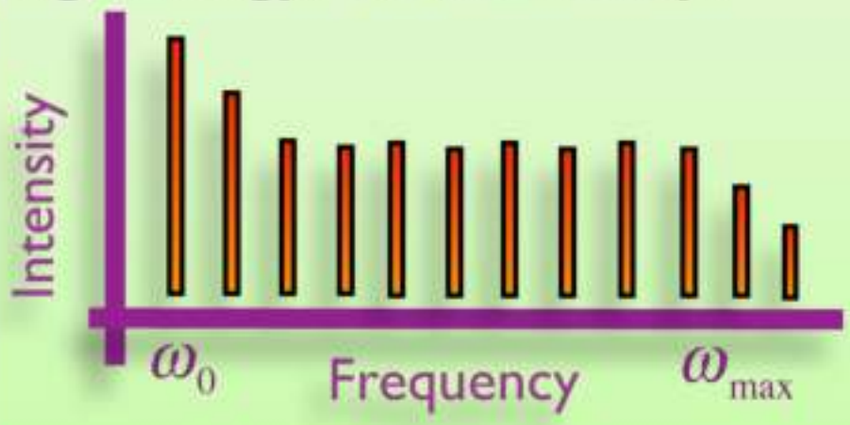
High-order harmonic generation



High-order harmonic generation

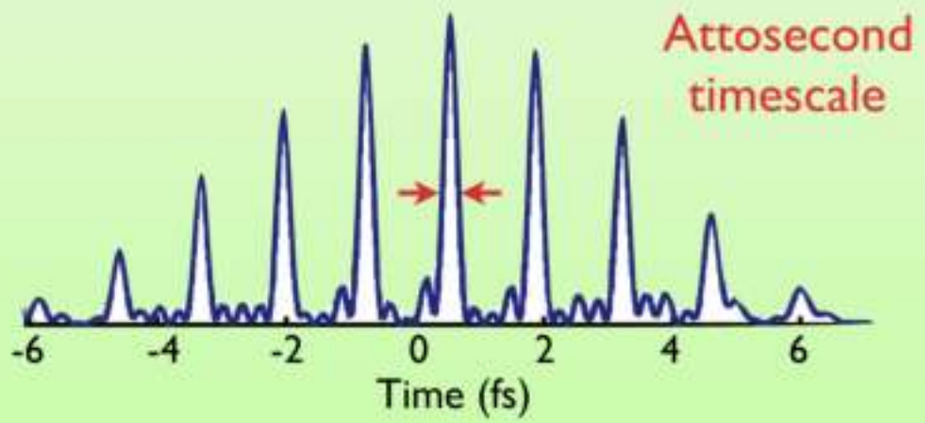


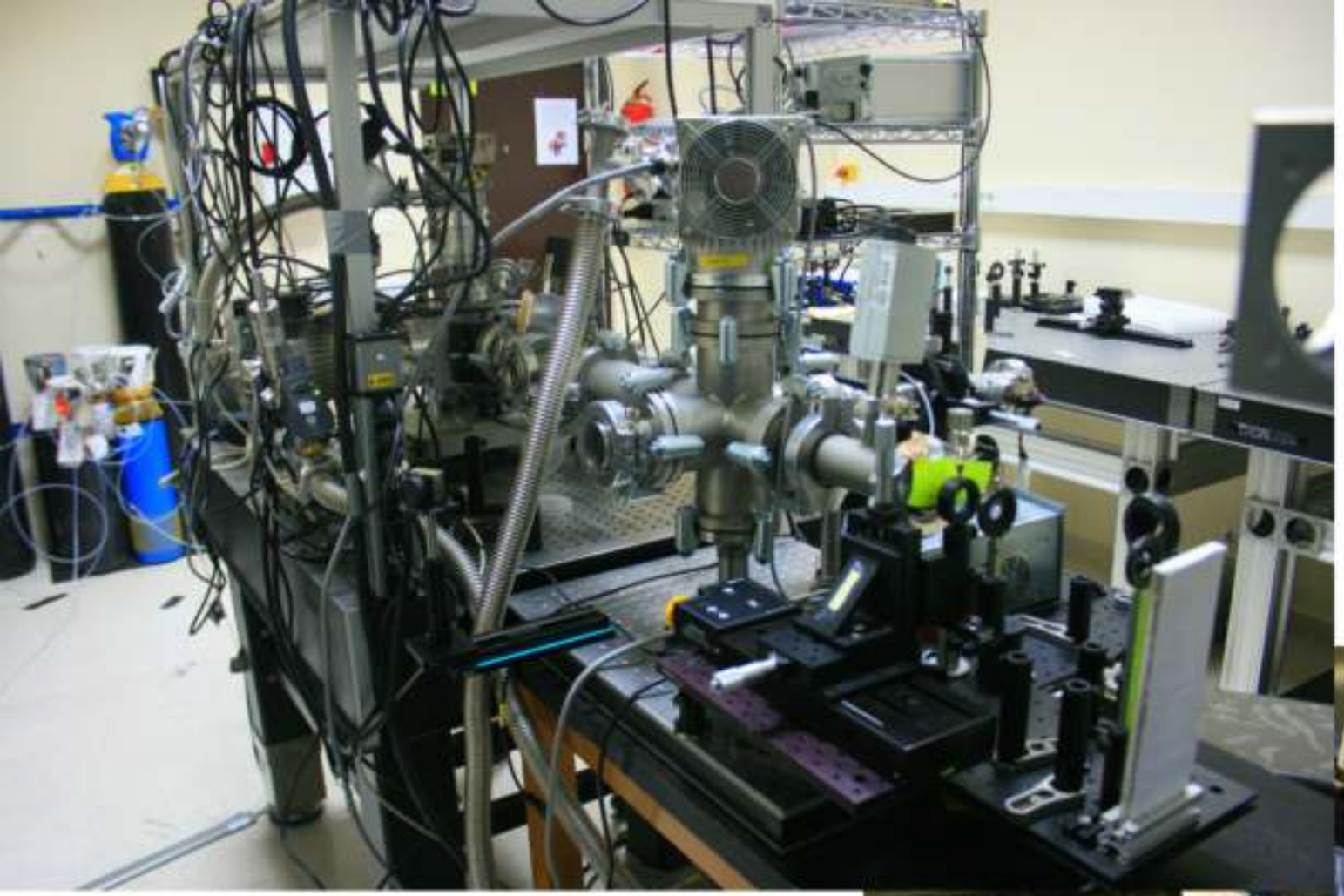
1. High Energy: VUV to X-rays

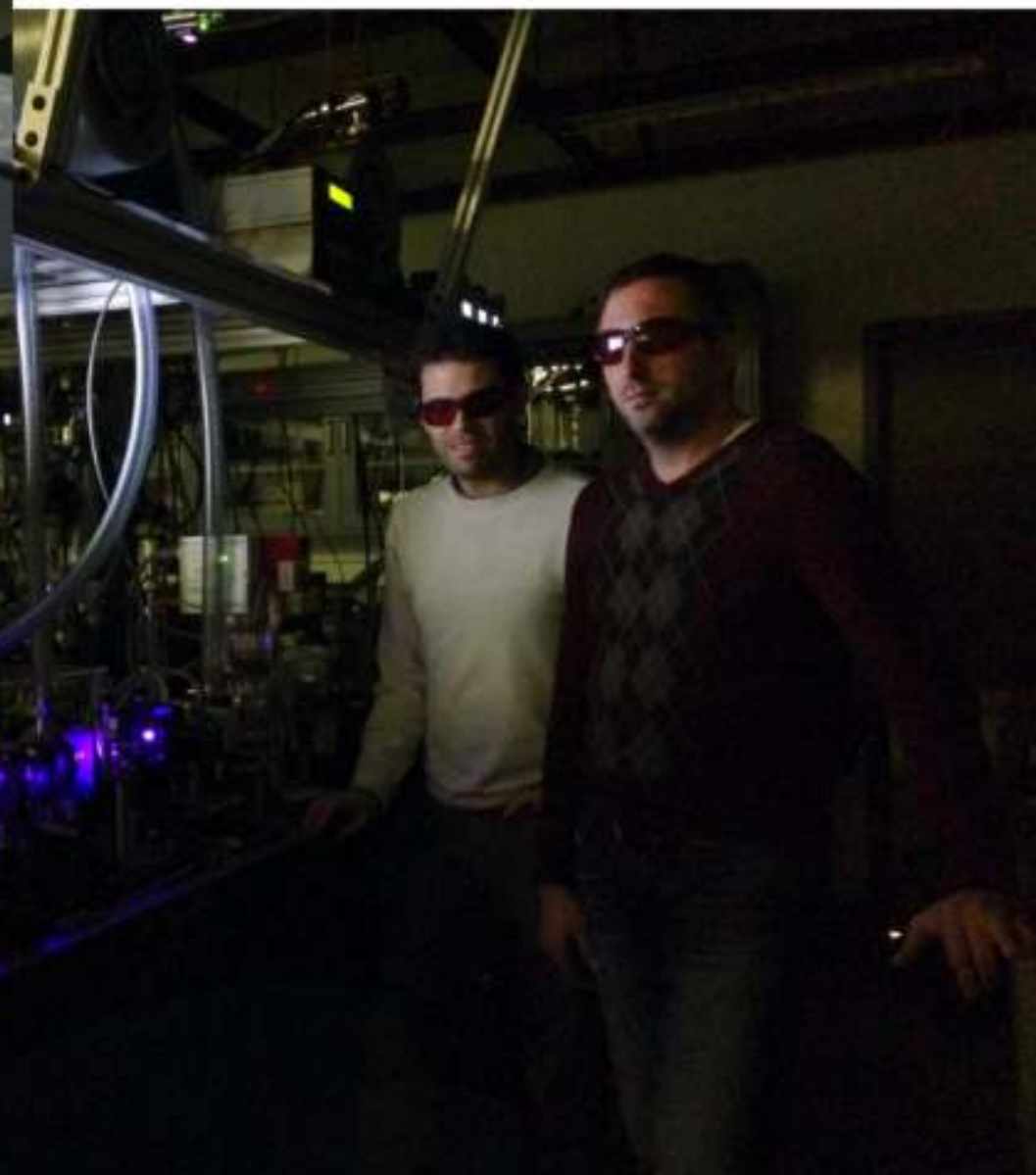


Fourier Transform

2. Ultrashort pulses: Attosecond (1







Theoretical challenges

At typical laser intensities (10^{13} – 10^{15} W/cm^2) the interaction between atoms and the laser field is nonperturbative.

$$i\hbar\frac{\partial}{\partial t}\left|\psi(t)\right\rangle = H(t)\left|\psi(t)\right\rangle \qquad H = \frac{\vec{p}^{\,2}}{2m} + V + e\vec{E}\cdot\vec{r}$$

Exact solution: Time Dependent Schrödinger Equation (TDSE).

Microscopic Challenge

3D calculations require huge patio-temporal grids, and thus are very slow.

We have to use approximations at the microscopic level:
The Strong Field Approximation

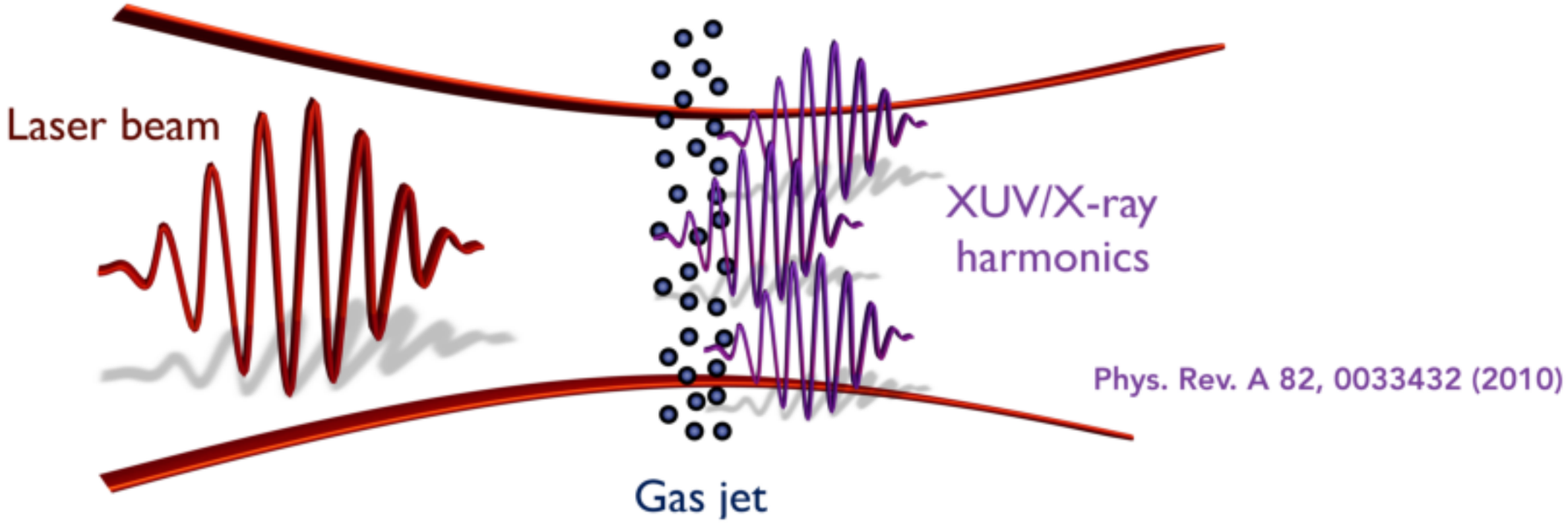
J.A. Pérez-Hernández, et al. Opt. Exp. 17, 9891 (2009)

Theoretical challenges

Macroscopic Challenge

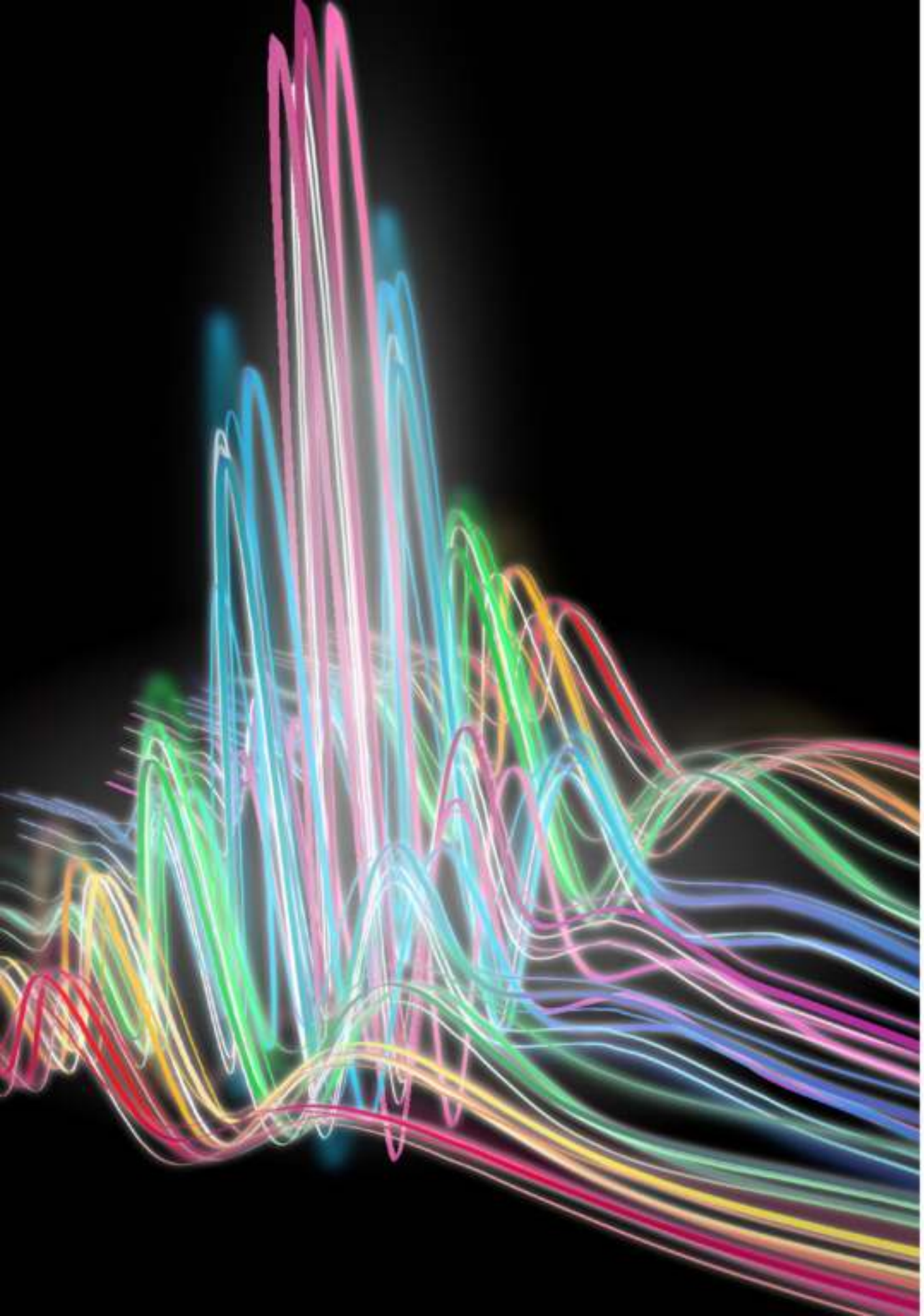
Phase-matching (involves lot of single-atom calculations, and coupling with the Maxwell equations)

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial}{\partial t^2}\vec{E} = \frac{4\pi}{c^2}\frac{\partial}{\partial t}\vec{J}$$



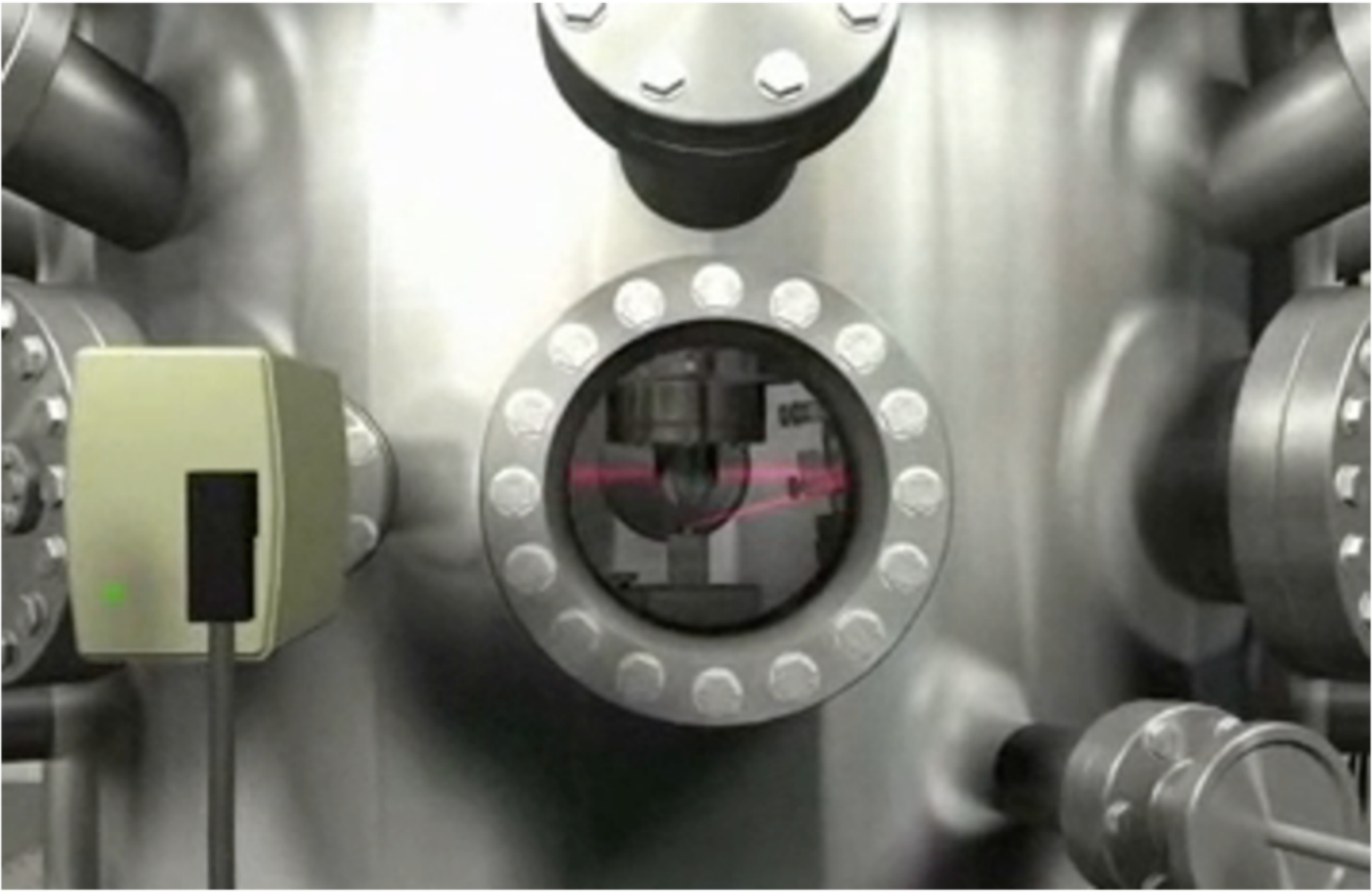
Phys. Rev. A 82, 0033432 (2010)

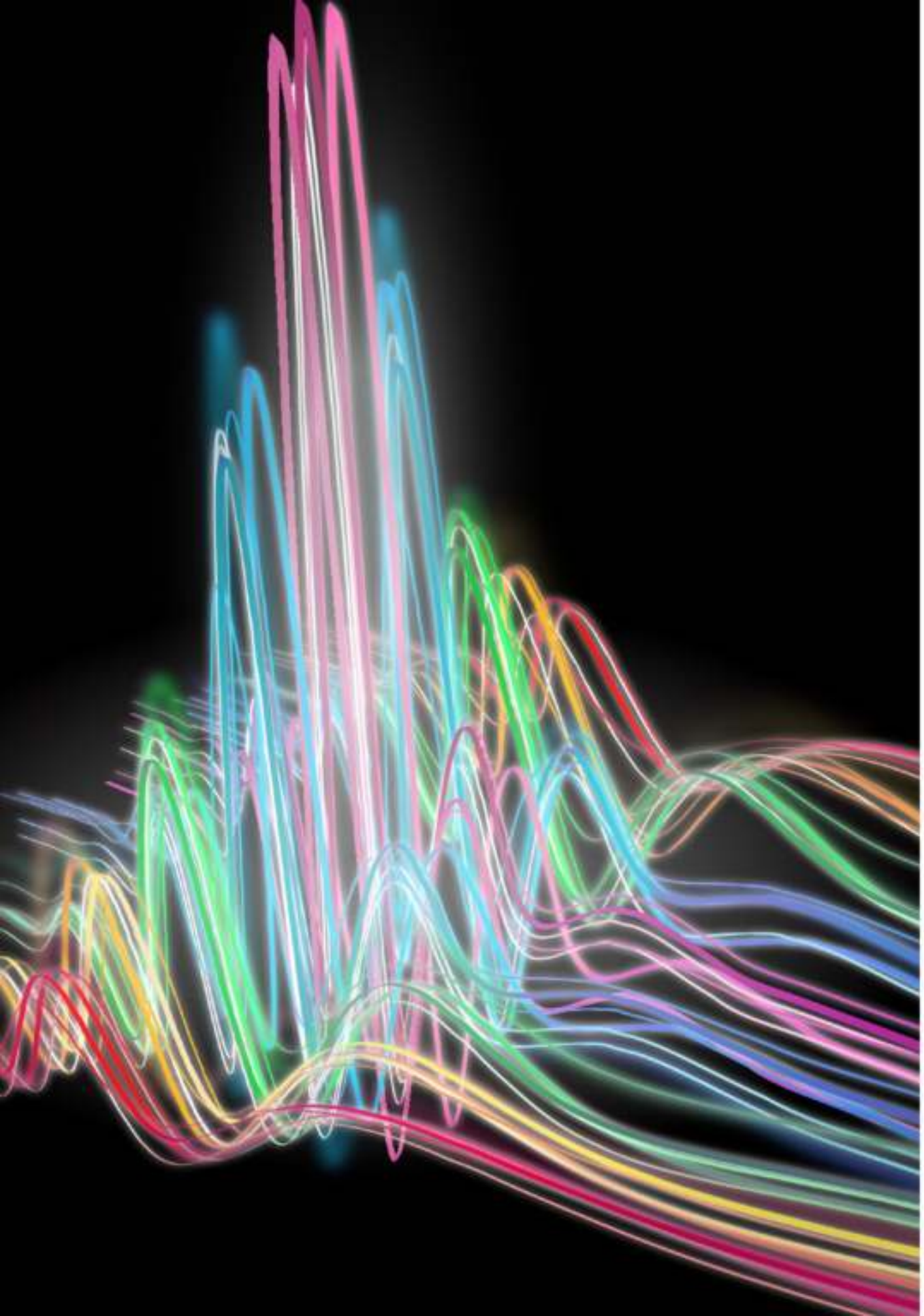
We have to use approximations at the macroscopic level.



- **How do we measure such pulses?**

ALF USAL
Aplicaciones del Láser y Fotónica

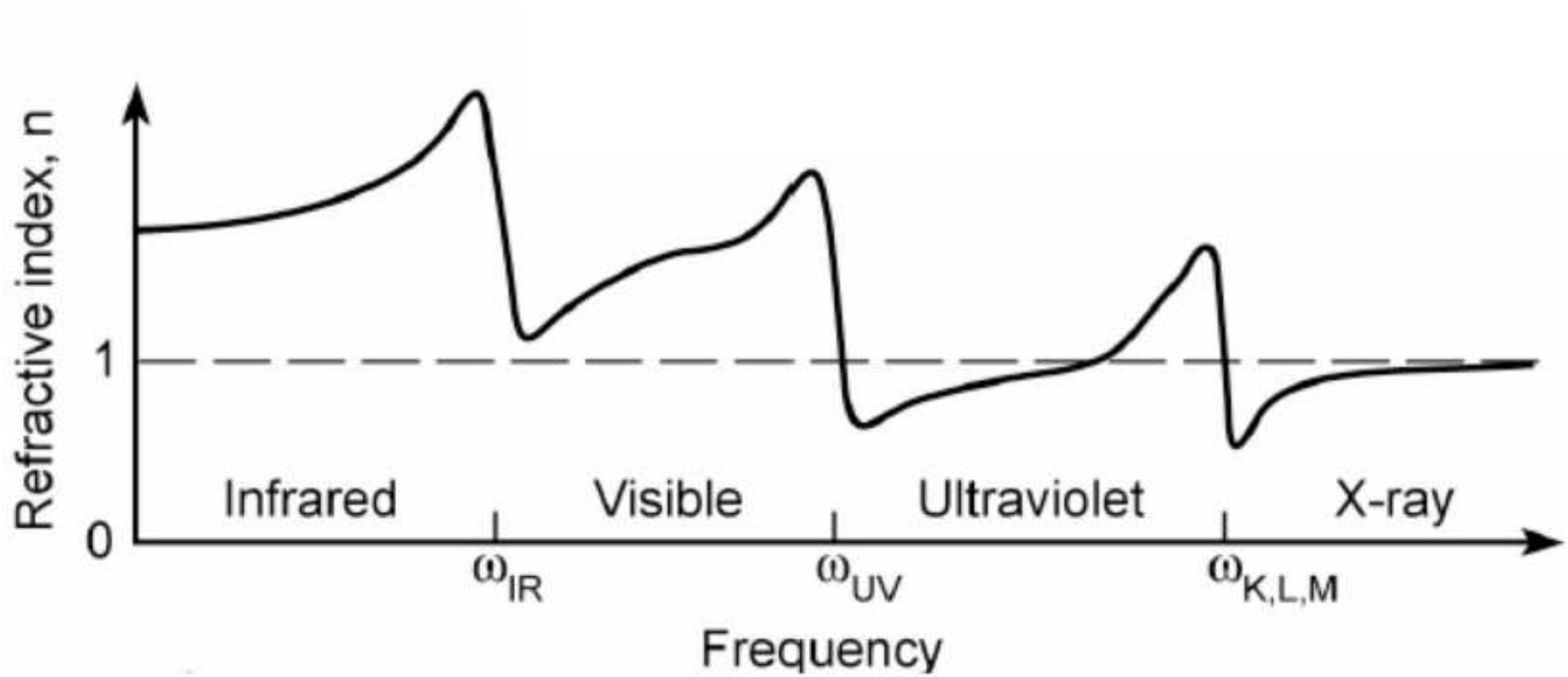




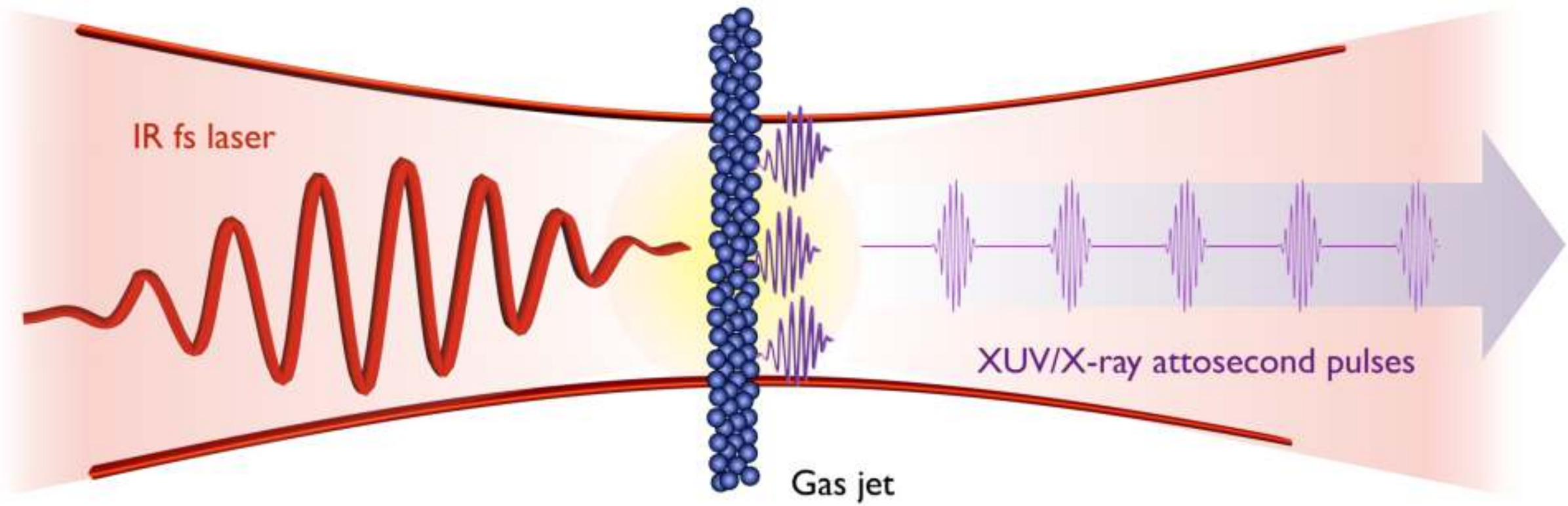
- **How do we control their properties?**
  - **Energy and pulse duration**
  - **Angular momentum**
    - **Spin: Polarization**
    - **Orbital**

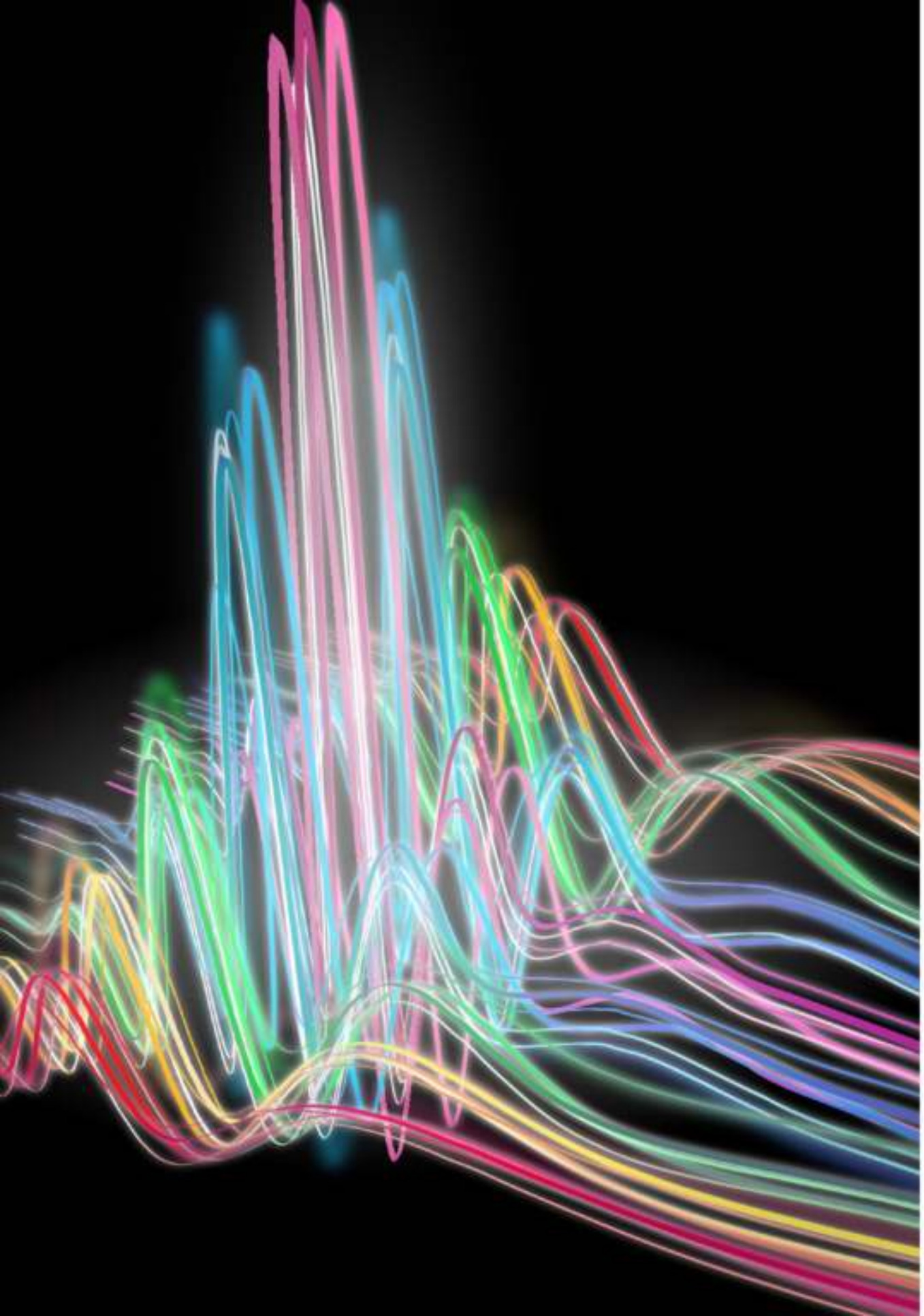
ALF USAL
Aplicaciones del Láser y Fotónica

The problem…


Refractive index, n
1
0
Infrared
Visible
Ultraviolet
X-ray
ω_{IR}
ω_{UV}
$\omega_{K,L,M}$
Frequency

High-order harmonic generation

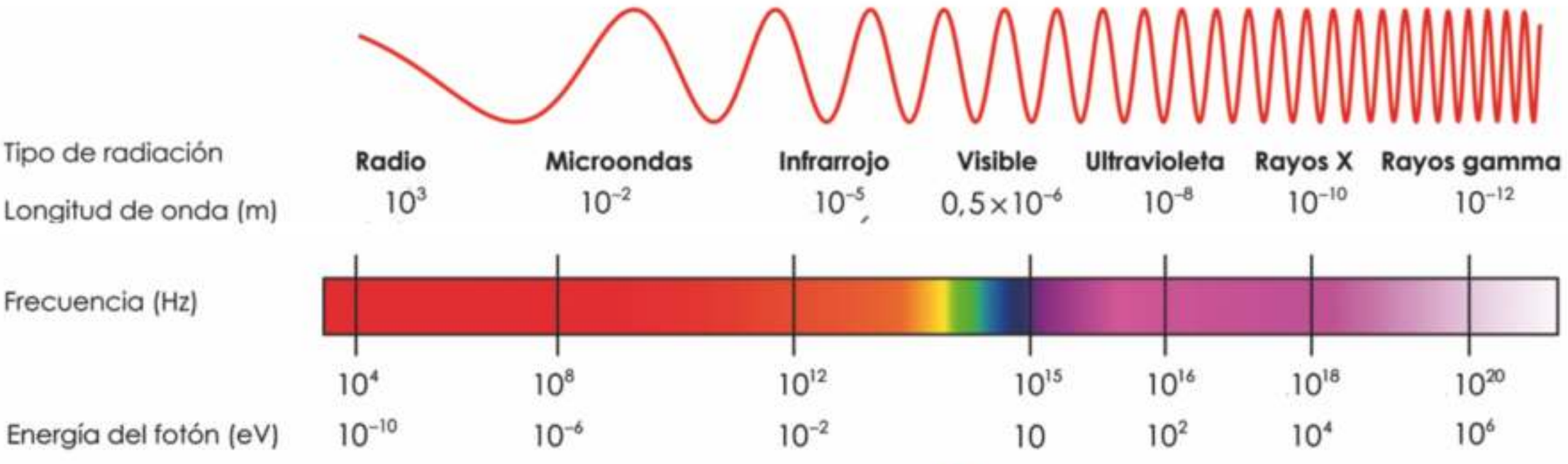


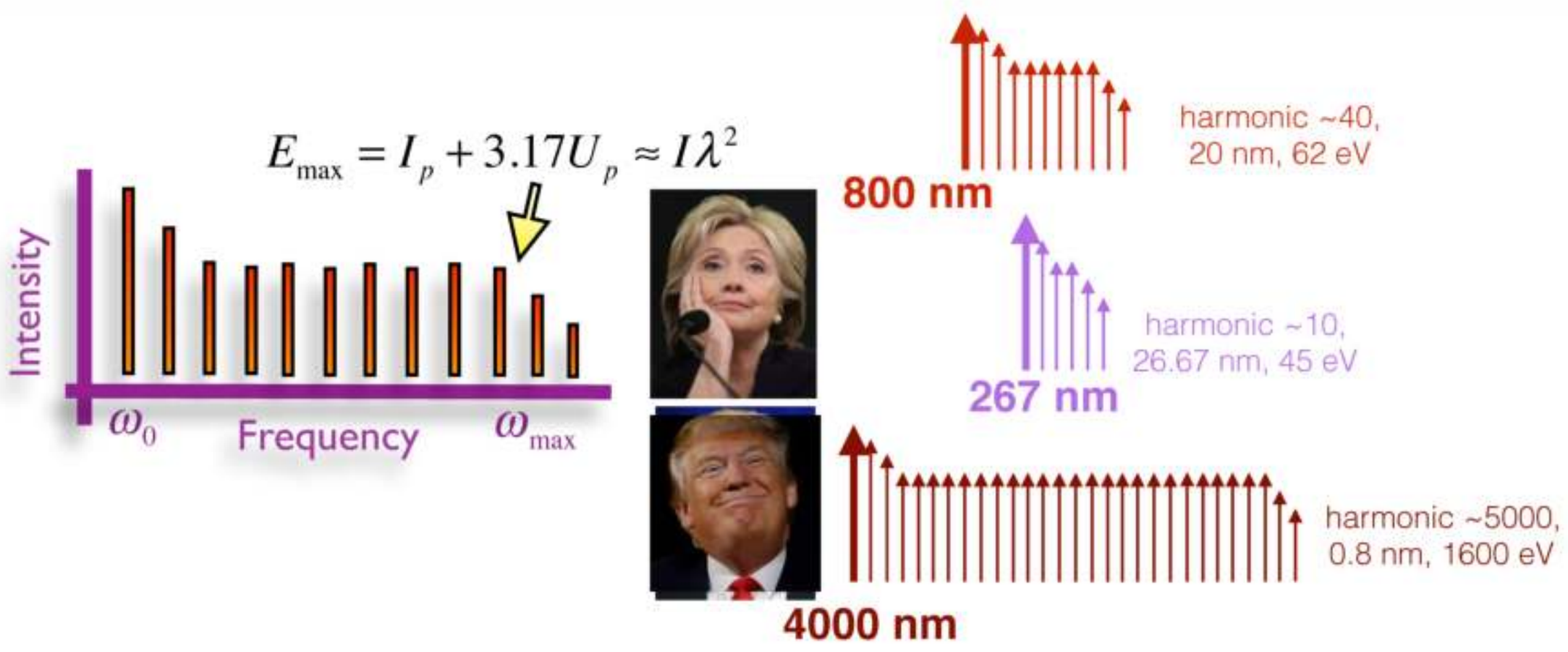


- **How do we control their properties?**
  - **Energy and pulse duration**
  - **Angular momentum**
    - **Spin: Polarization**
    - **Orbital**

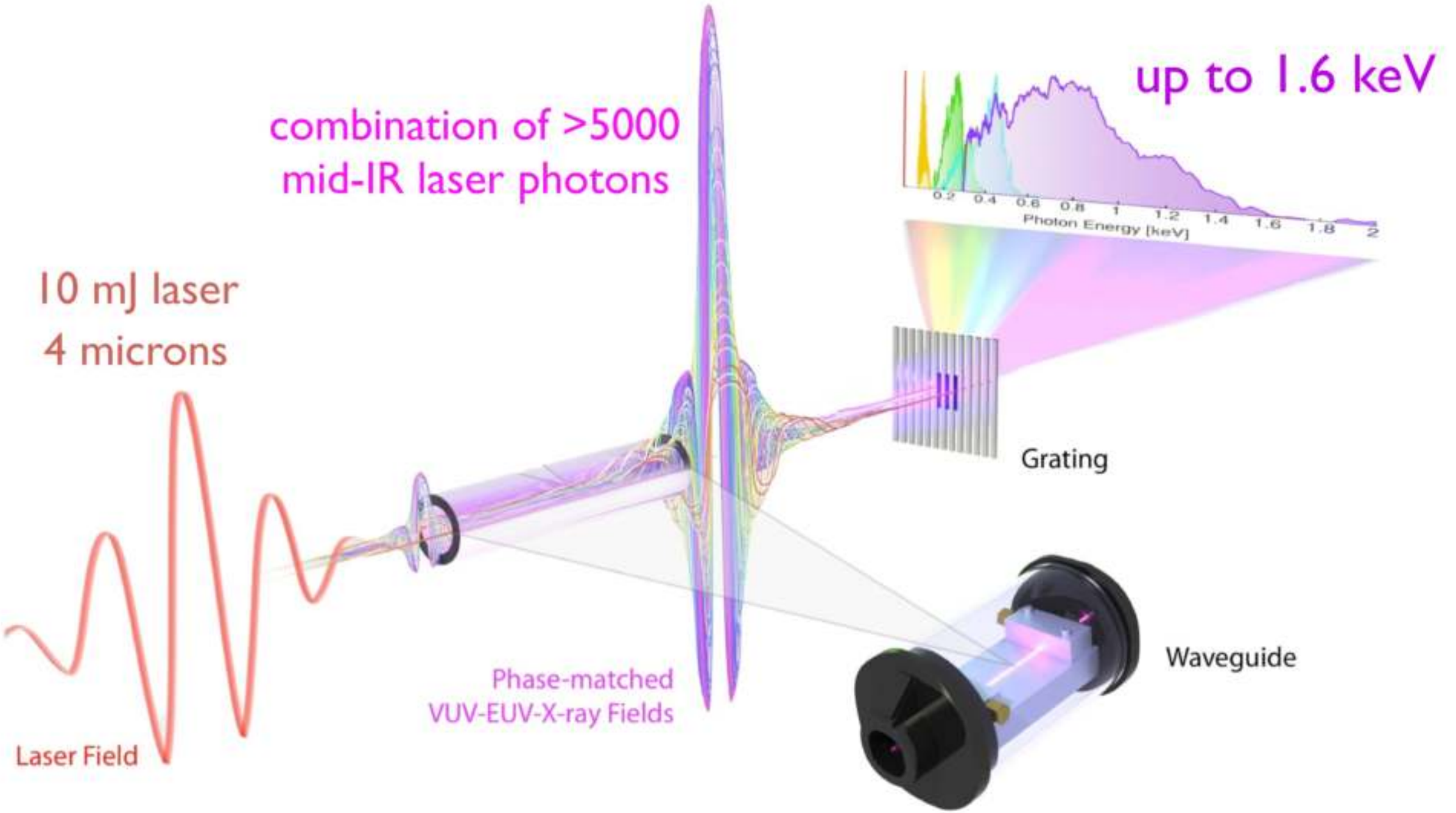
ALF USAL
Aplicaciones del Láser y Fotónica

Increasing the energy of attosecond pulses



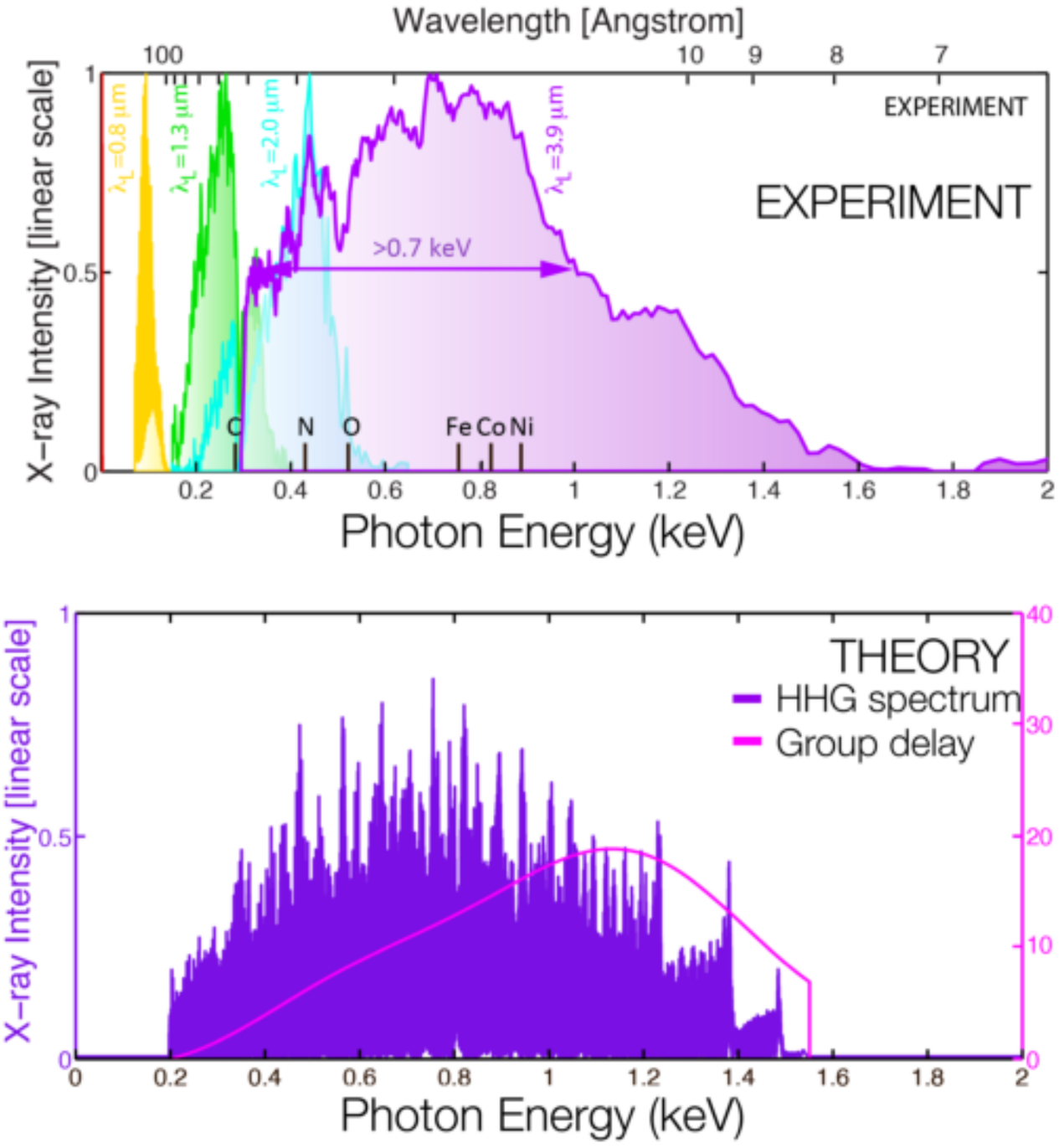


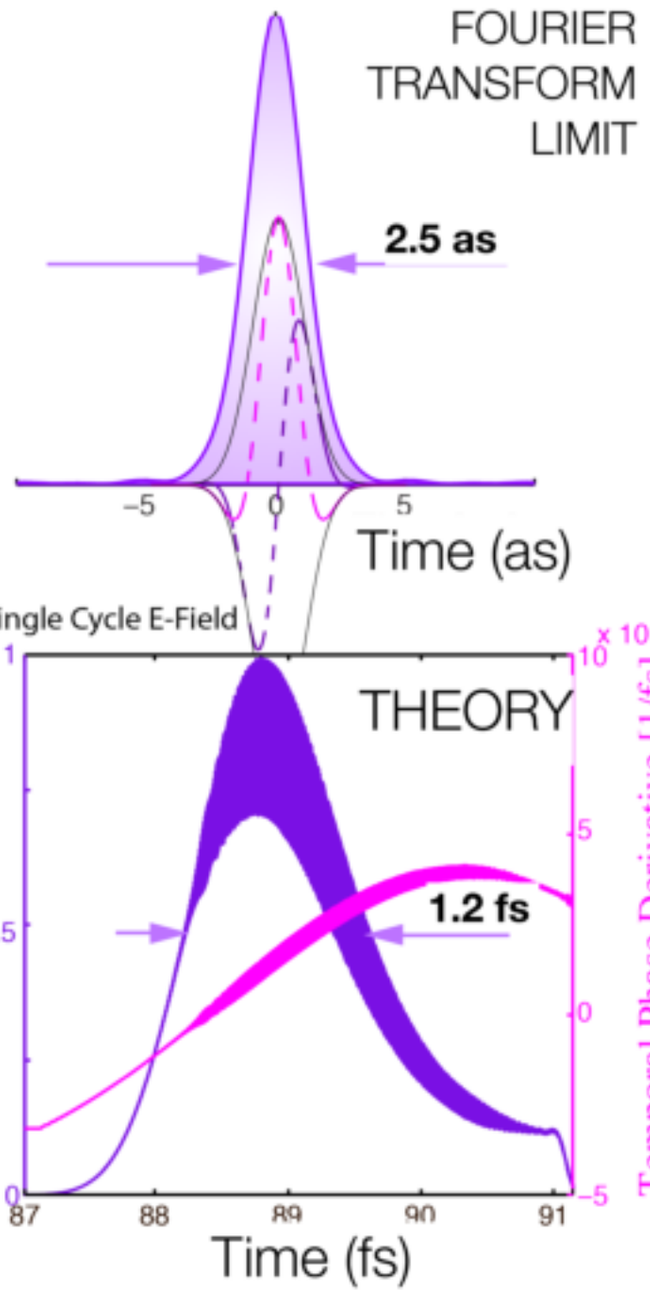
Coherent X Rays



Science 336, 1287 (2012)

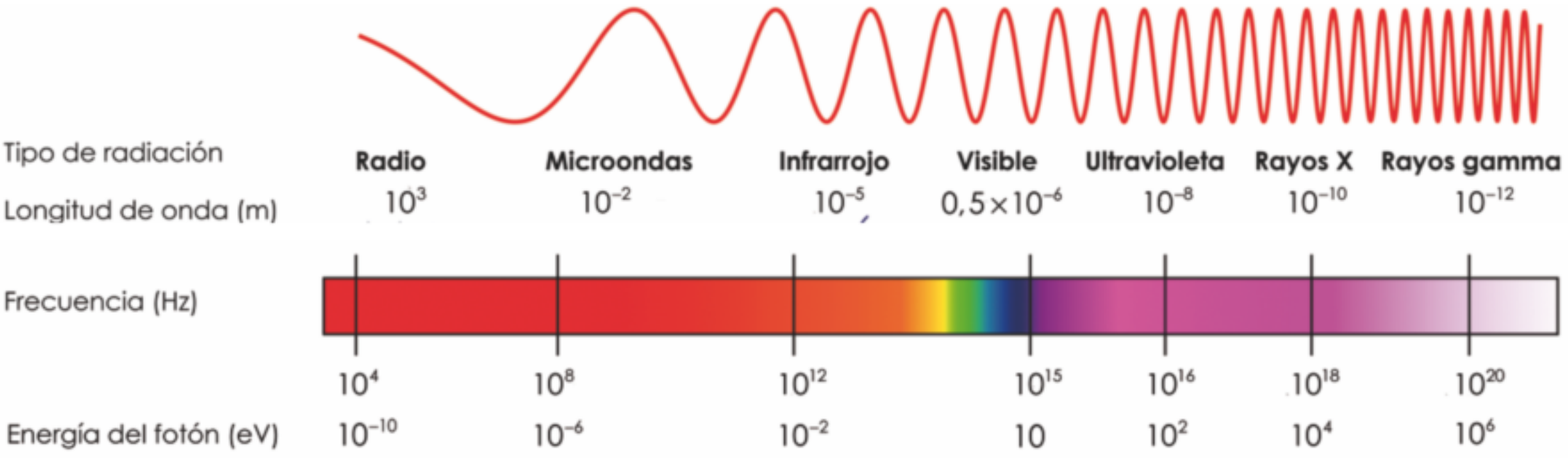
Coherent X Rays

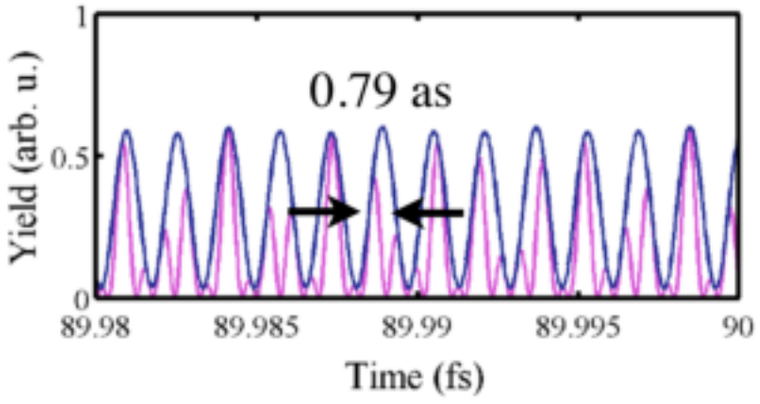




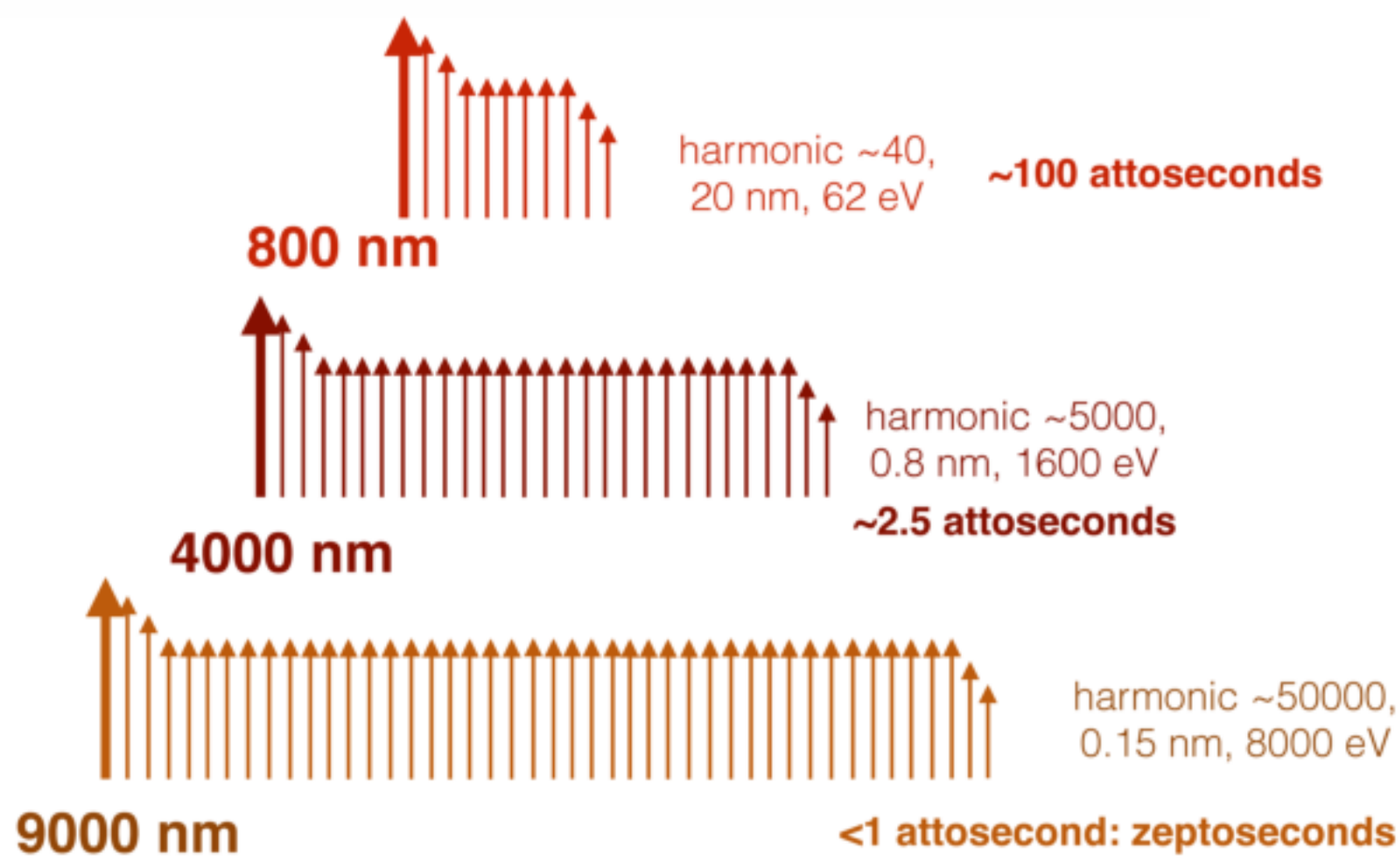
Science 336, 1287 (2012)

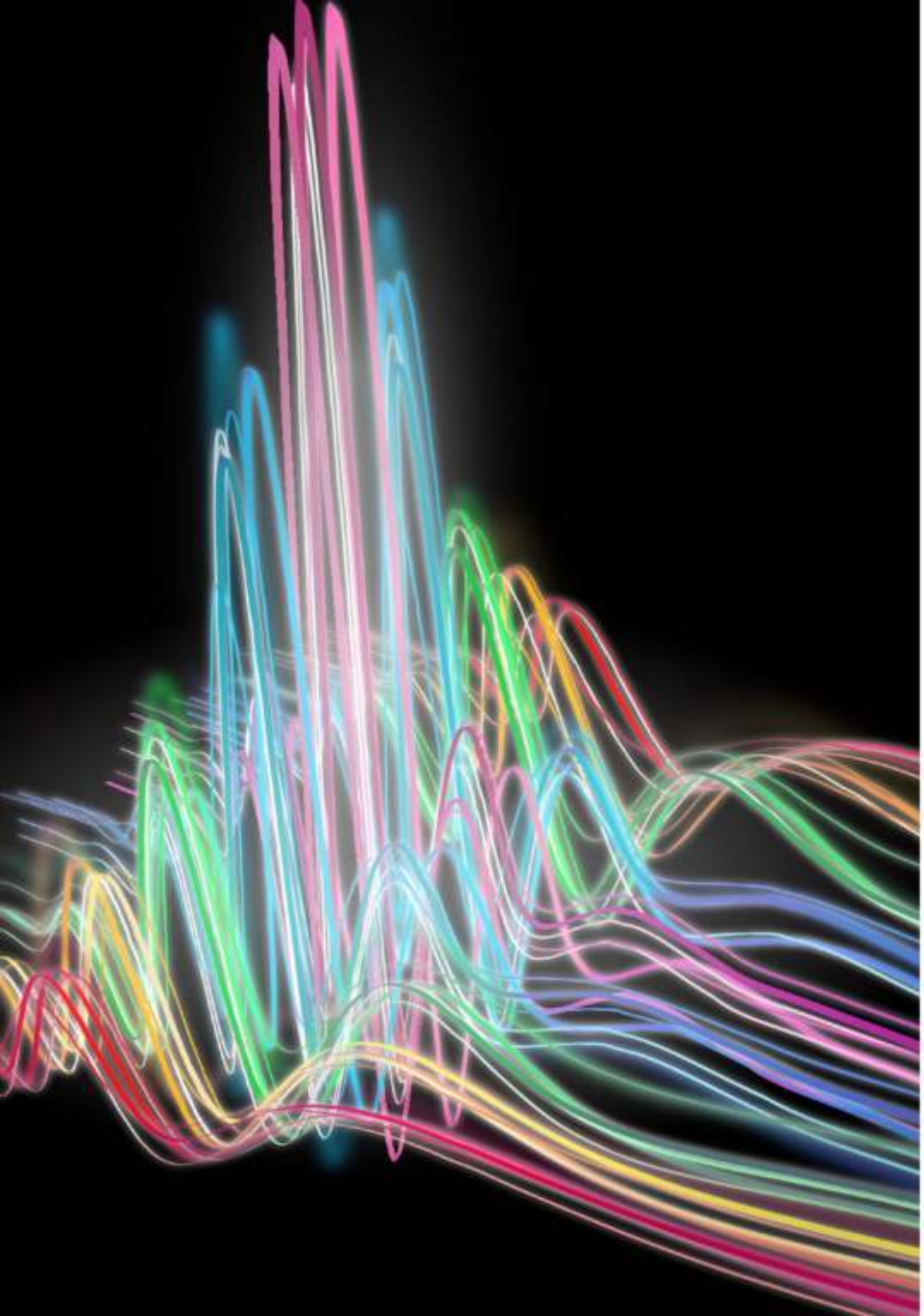
Where is the limit?





Phys. Rev. Lett. 111, 033002 (2013)



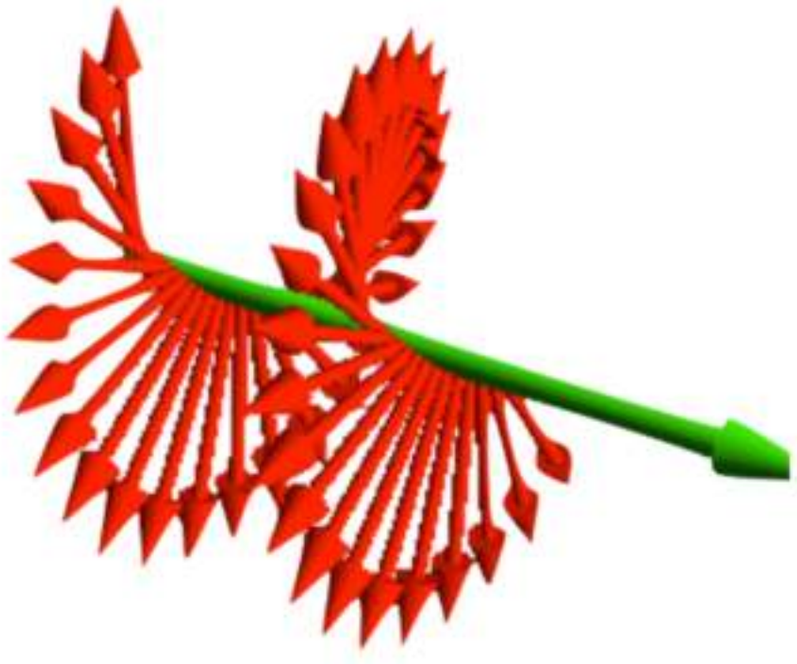


- **How do we control their properties?**
  - **Energy and pulse duration**
  - **Angular momentum**
    - **Spin: Polarization**
    - **Orbital**

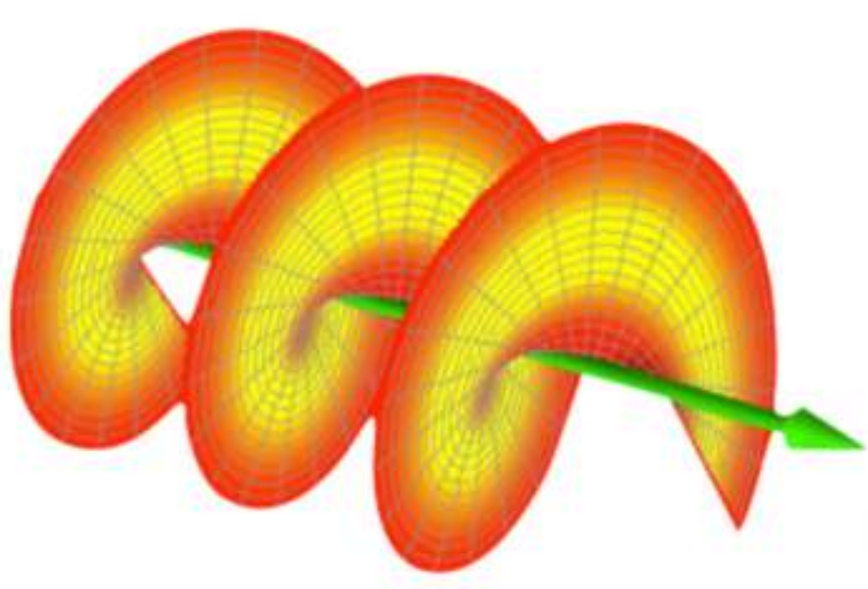
ALF USAL
Aplicaciones del Láser y Fotónica

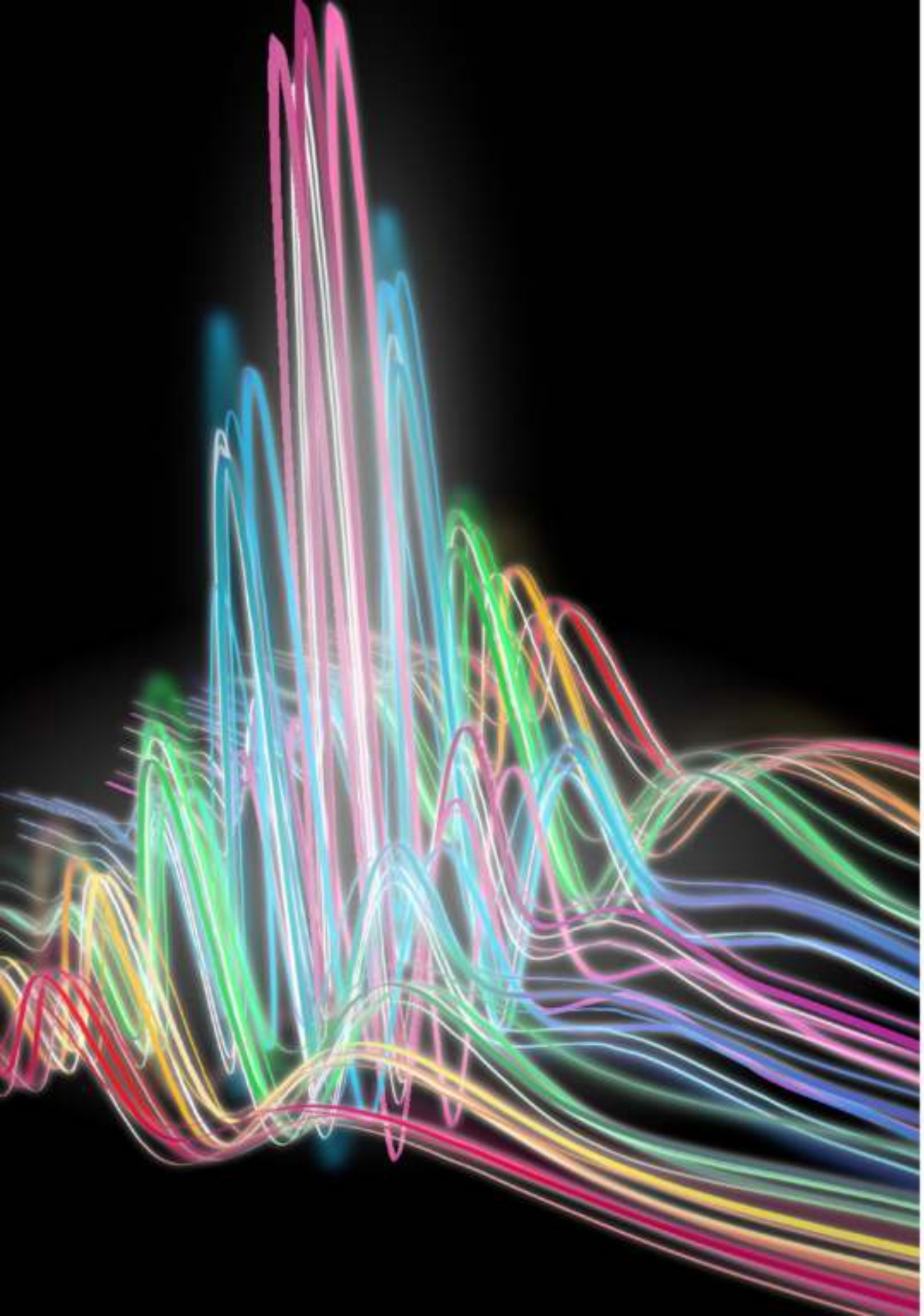
Light angular momentum

Spin angular momentum
(Polarization)



Orbital angular momentum
(Vortex)



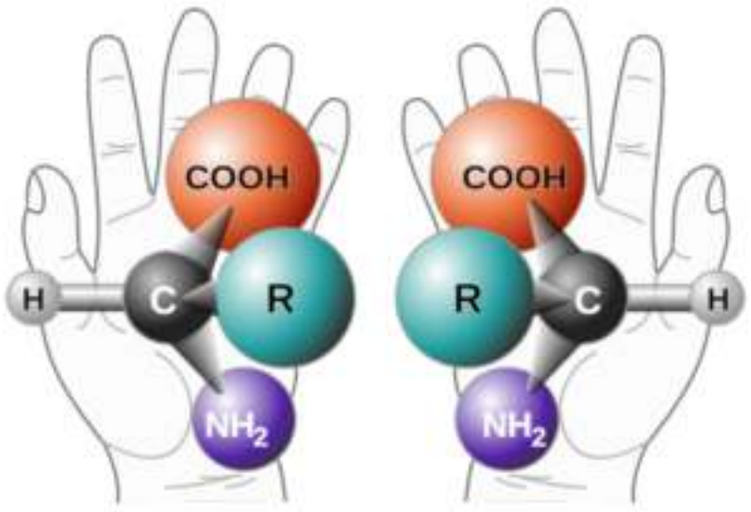


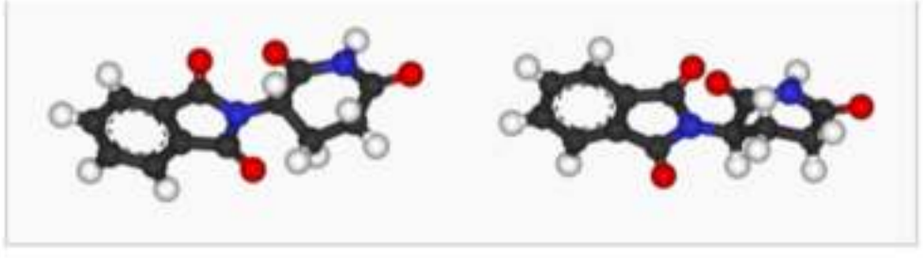
- **How do we control their properties?**
  - **Energy and pulse duration**
  - **Angular momentum**
    - **Spin: Polarization**
    - **Orbital**

ALF USAL
Aplicaciones del Láser y Fotónica

Circularly polarized ultrafast sources enables ultrafast circular dichroism measurements

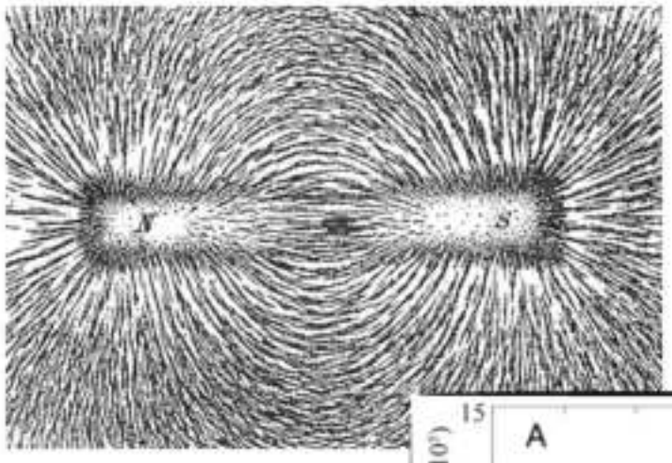
Chiral molecules

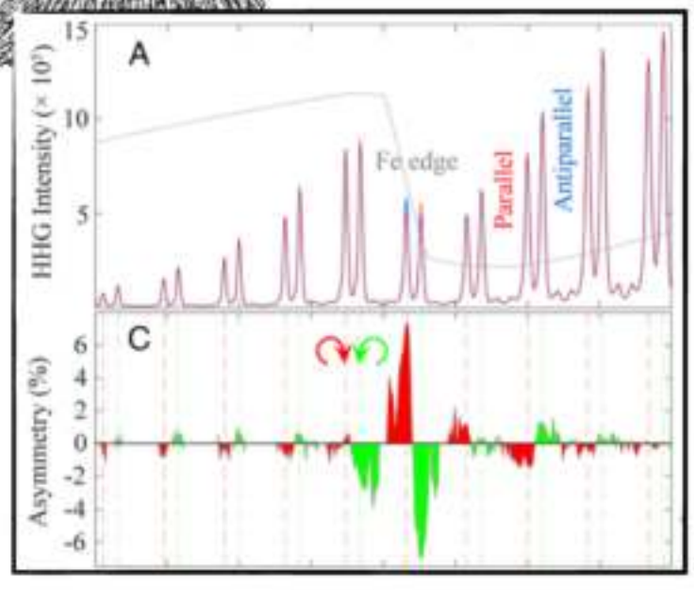




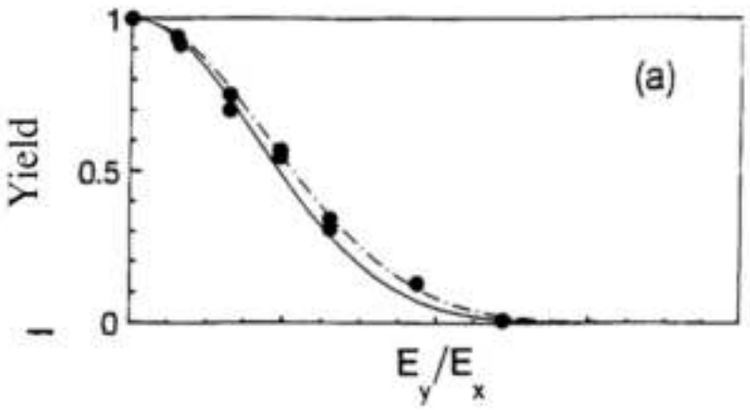
Magnetic materials

X-ray magnetic circular dichroism (XMCD)





Polarization control of harmonics



The yield decreases dramatically with ellipticity

P. Dietrich, N. H. Burnett, M. Ivanov, and P. B. Corkum,
Phys. Rev. A 50, R3585(R) (1994)

Linearly Polarized

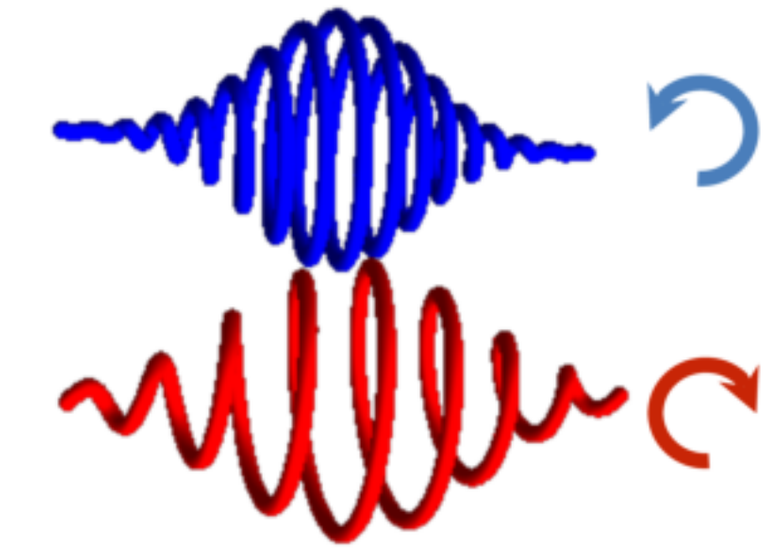
Elliptically Polarized

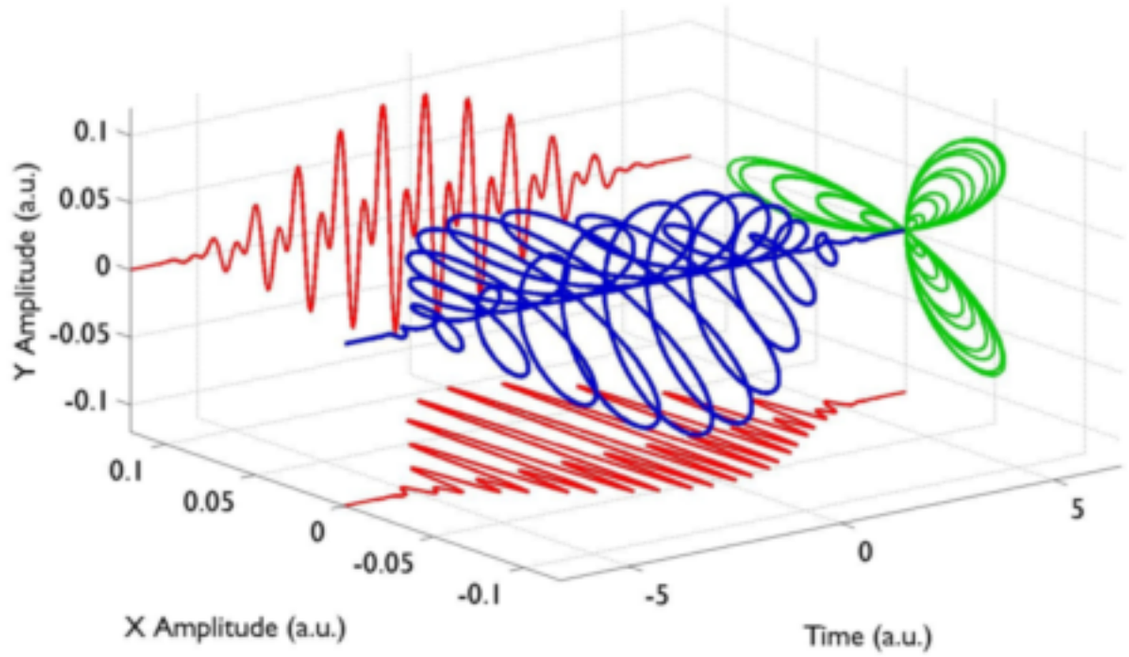
Circularly Polarized

HHG driven by two-color counter-rotating fields

$\omega + 2\omega$

800 nm + 400 nm

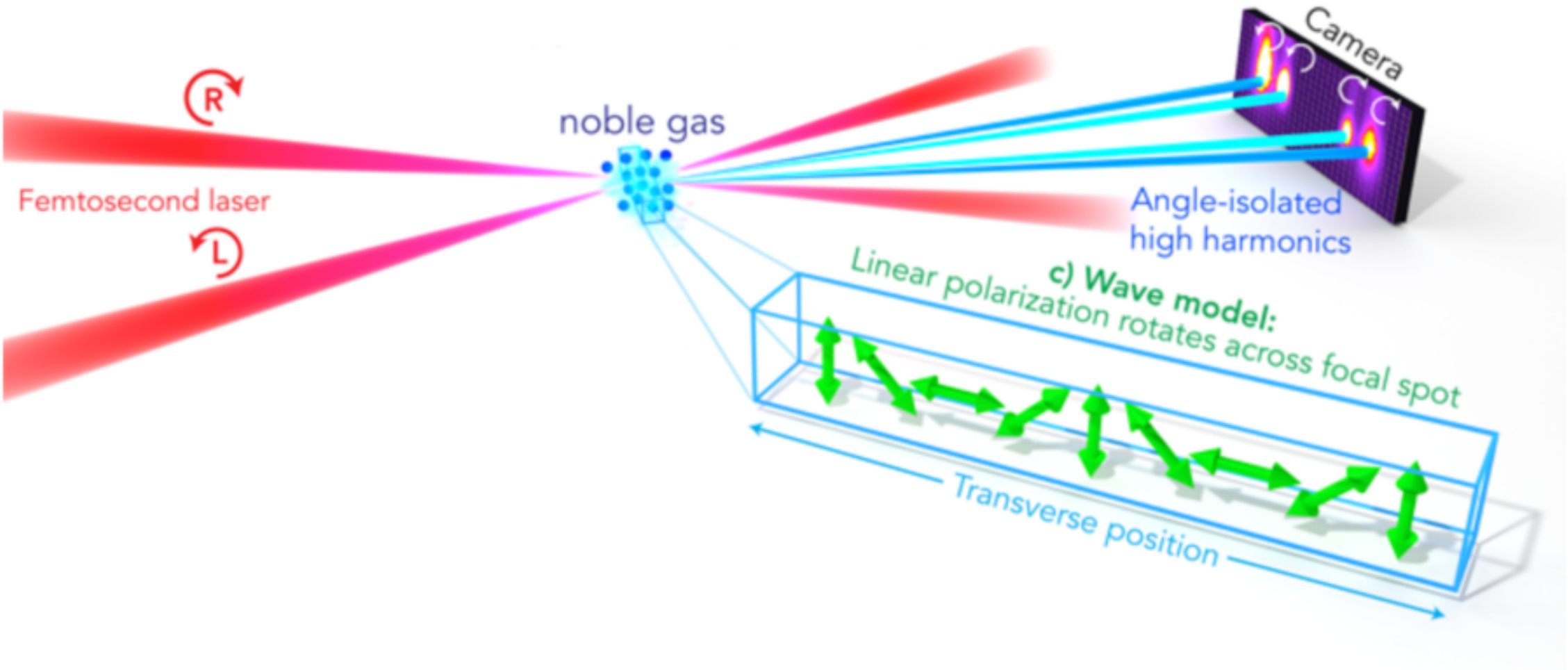




H. Eichmann, et al. Phys. Rev. A, 51, R3414 (1995)
S. Long, et al. *Phys. Rev. A* 52 2262 (1995)
D. Milosevic, et al. *Phys. Rev. A* 61 063403 (2000)

O. Kfir, et al. *Nat. Photon.* 9, 99–105 (2015)
A. Fleischer, et al. *Nat. Photon.* 8, 543–549 (2014)

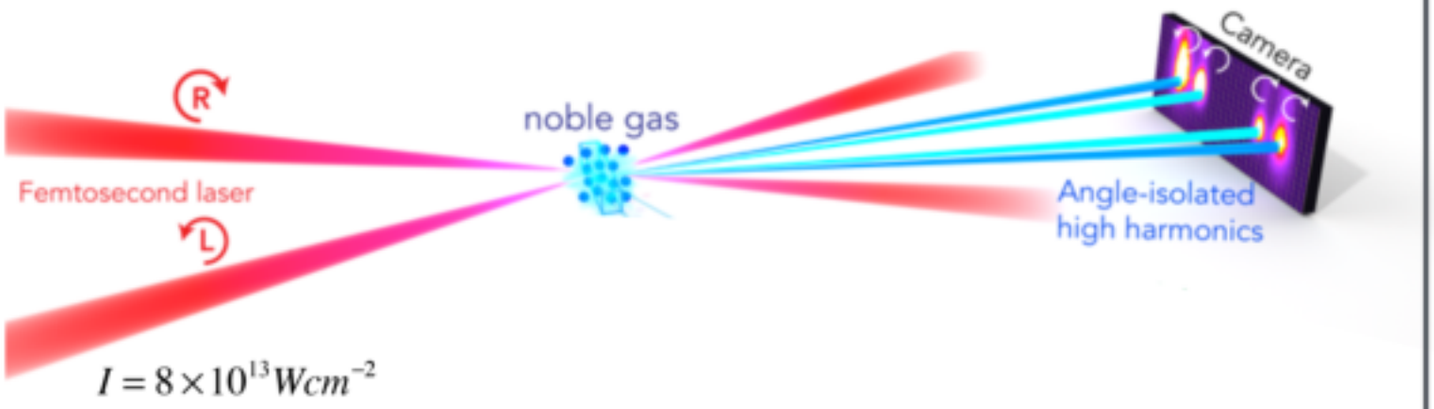
Macroscopic: Non collinear circularly polarized HHG



Nature Photonics 9, 743 (2015).
Physical Rev. A 93, 043855 (2016).

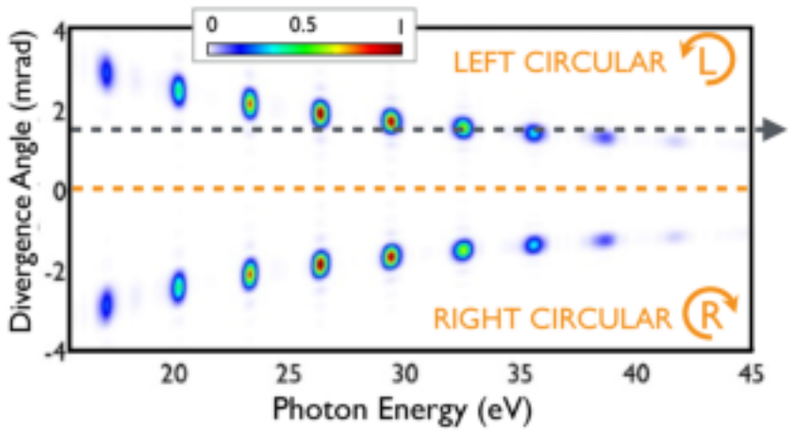
Circularly polarized attosecond pulses

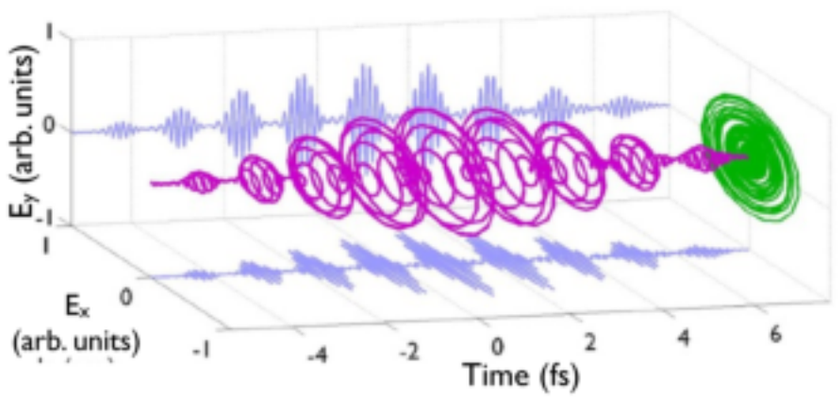
NON-COLLINEAR ONE-COLOR



$I = 8 \times 10^{13} Wcm^{-2}$

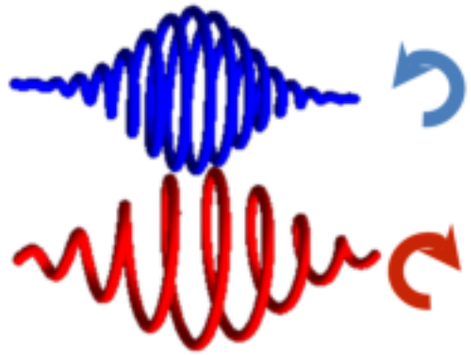
Long (15 fs) driving pulse: Circularly polarized attosecond pulse train



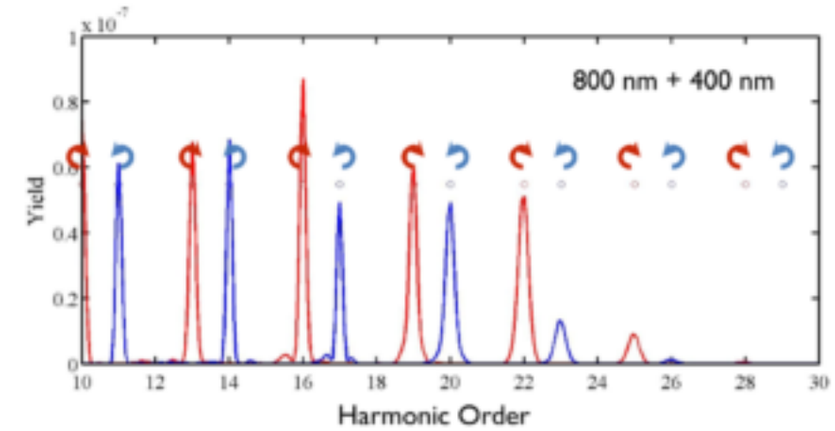


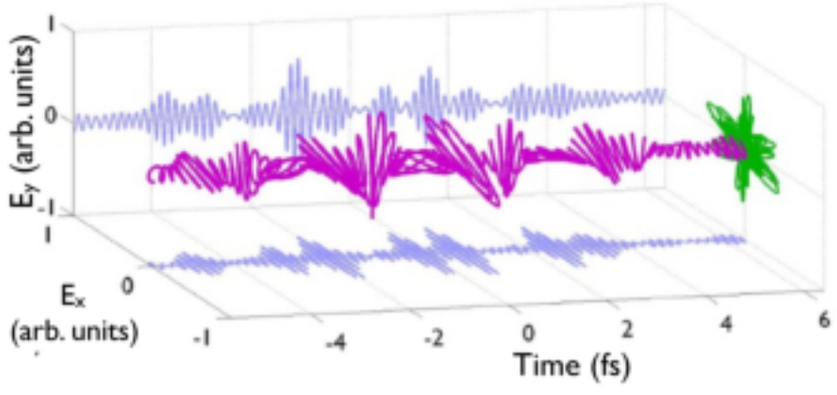
Nature Photonics 9, 743 (2015).
Physical Rev. A 93, 043855 (2016).

COLLINEAR TWO-COLOR HHG

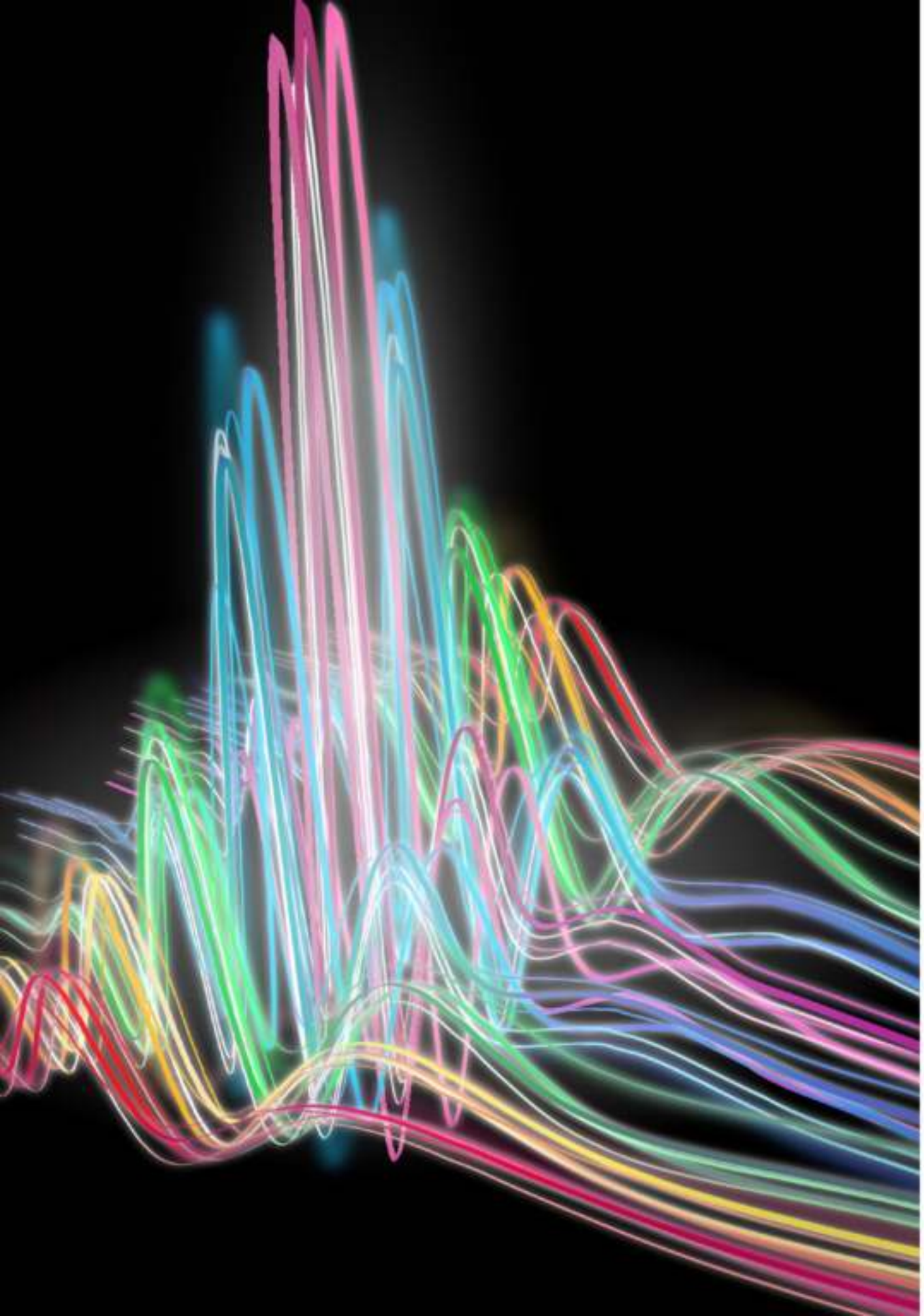


Long driving pulse:
Linearly polarized attosecond pulse train





Science Advances 2, e1501333 (2016).
PNAS 112, 14206 (2015).

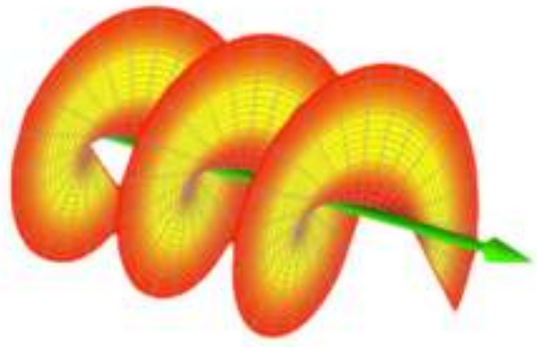


- **How do we control their properties?**
  - **Energy and pulse duration**
  - **Angular momentum**
    - **Spin: Polarization**
    - **Orbital**

ALF USAL
Aplicaciones del Láser y Fotónica

Optical vortices

Optical vortex: field structure with a spiral phase ramp about a point-phase-singularity.



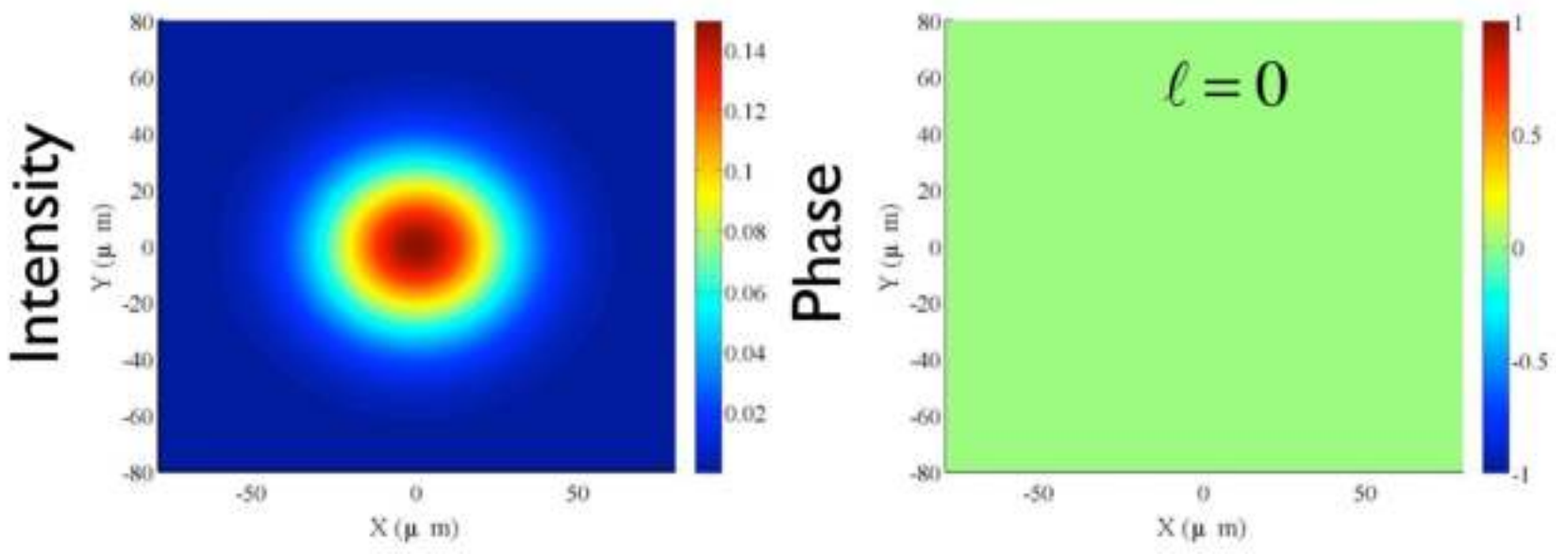
OAM beams described by Laguerre-Gauss modes:

$$LG_{\ell,p}(\rho,\phi,z) = E_0 \frac{W_0}{W(z)}\left(\frac{\rho}{W(z)}\right)^{|\ell|} L_p^{|\ell|}\left[\frac{2\rho^2}{W^2(z)}\right]\exp\left(-\frac{\rho^2}{W^2(z)}\right)\exp\left(ik\frac{\rho^2}{2R(z)} + i\zeta(z) + i\ell\phi\right)$$

ℓ Topological charge

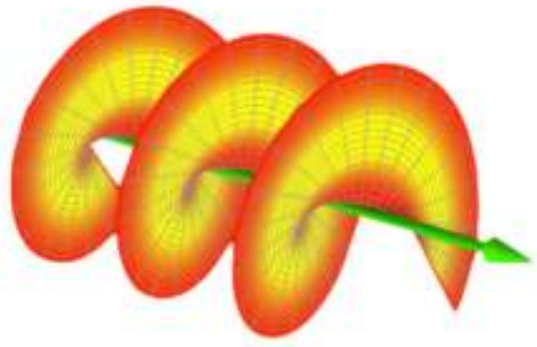
p Radial nodes

$LG_{0,0}$



Optical vortices

Optical vortex: field structure with a spiral phase ramp about a point-phase-singularity.



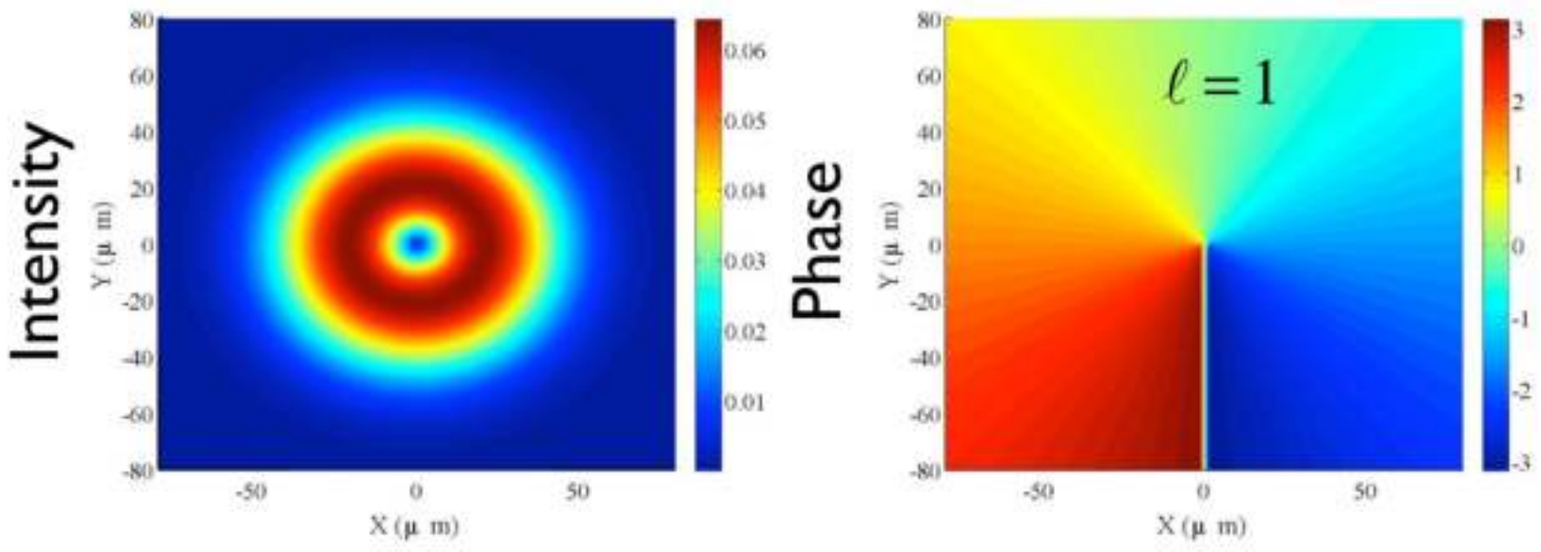
OAM beams described by Laguerre-Gauss modes:

$$LG_{\ell,p}(\rho,\phi,z) = E_0 \frac{W_0}{W(z)}\left(\frac{\rho}{W(z)}\right)^{|\ell|} L_p^{|\ell|}\left[\frac{2\rho^2}{W^2(z)}\right]\exp\left(-\frac{\rho^2}{W^2(z)}\right)\exp\left(ik\frac{\rho^2}{2R(z)} + i\zeta(z) + i\ell\phi\right)$$

ℓ Topological charge

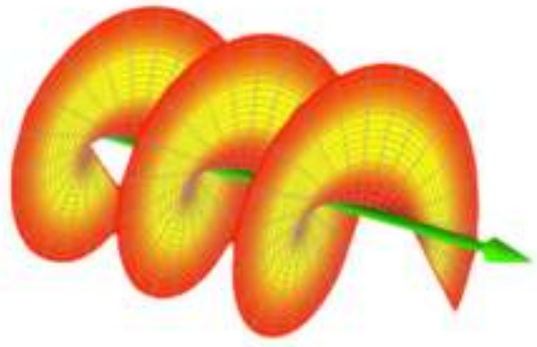
p Radial nodes

$LG_{1,0}$



Optical vortices

Optical vortex: field structure with a spiral phase ramp about a point-phase-singularity.



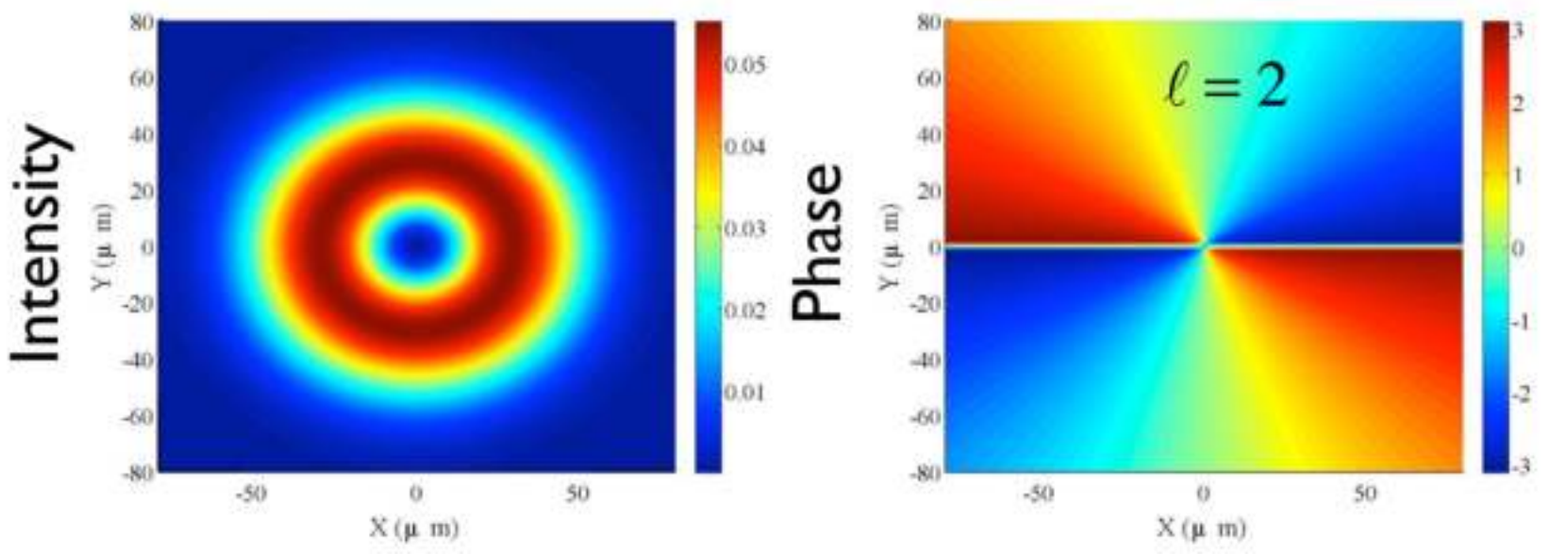
OAM beams described by Laguerre-Gauss modes:

$$LG_{\ell,p}(\rho,\phi,z) = E_0 \frac{W_0}{W(z)}\left(\frac{\rho}{W(z)}\right)^{|\ell|} L_p^{|\ell|}\left[\frac{2\rho^2}{W^2(z)}\right]\exp\left(-\frac{\rho^2}{W^2(z)}\right)\exp\left(ik\frac{\rho^2}{2R(z)} + i\zeta(z) + i\ell\phi\right)$$

ℓ Topological charge

p Radial nodes

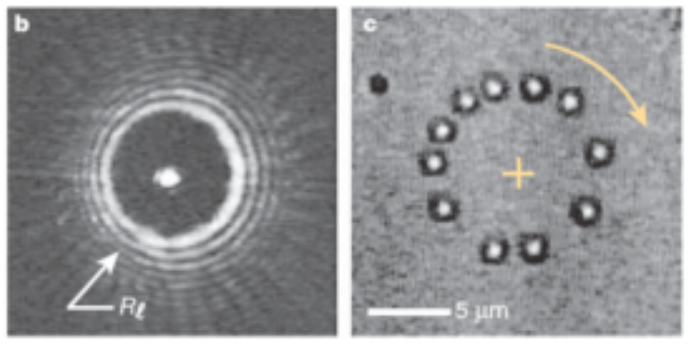
$LG_{2,0}$



Why are OAM beams interesting?

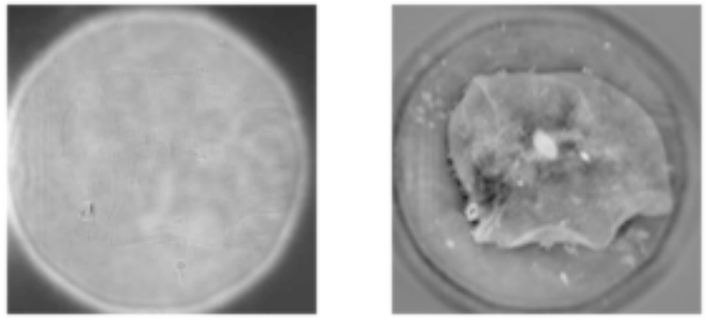
- Radiation-matter interaction implies *exchange* of energy and *momentum* (= mechanical forces)
  - Light torques on moving atoms M. Babiker et al, PRL 73, 1239 (1994)
- Fundamental processes can be modified by the presence of OAM
  - Modification of selection rules in atomic ionization.

    A. Picón et al, New. J. Phys 12, 083053 (2010)
- Technical applications
  - Optical communications J. Wang et al, Nat. Photonics 6, 488 (2012)
  - Micromachine actuators.



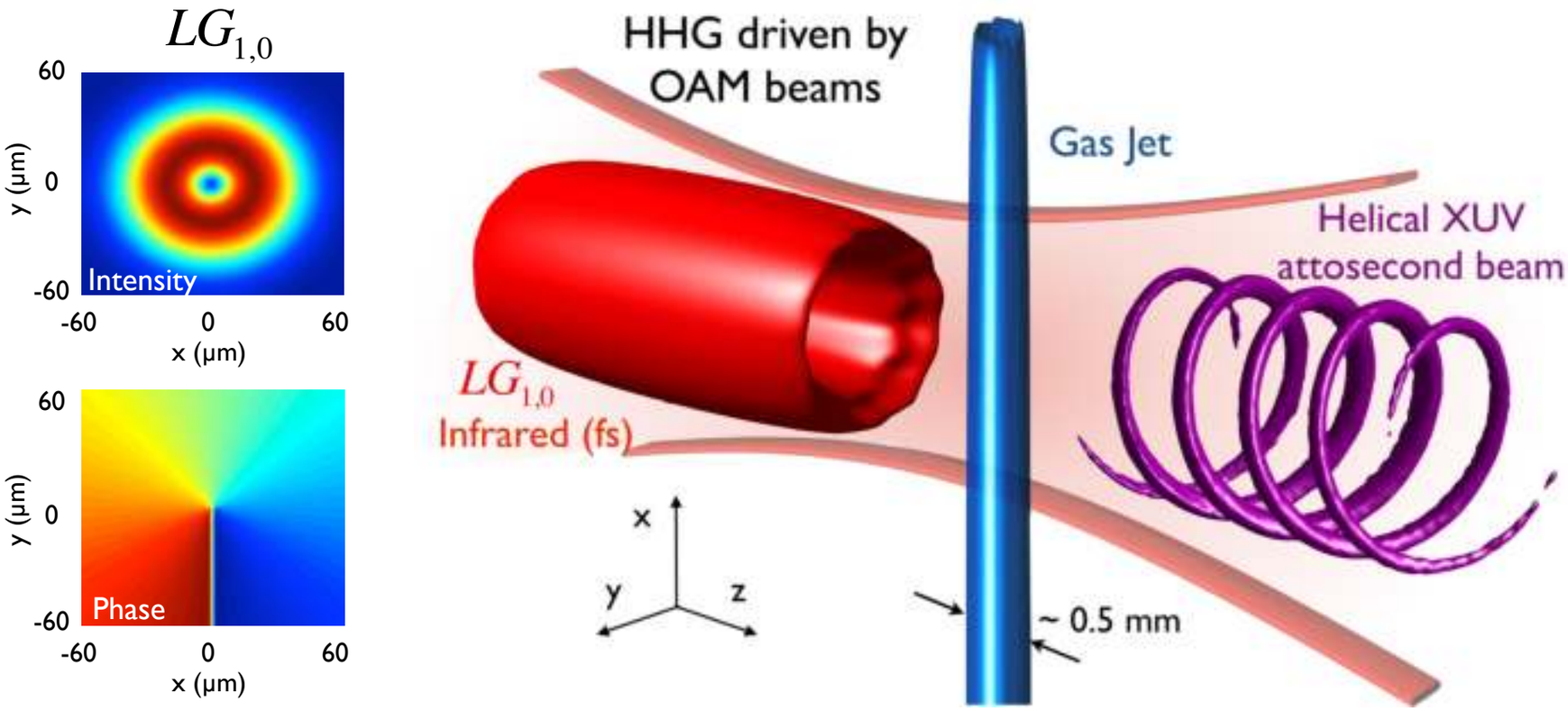
Reiew: D.G. Grier et al, Nature 424, 21 (2006)

  - Phase contrast microscopy



A. Jesacher et al, PRL 94, 233902 (2004)

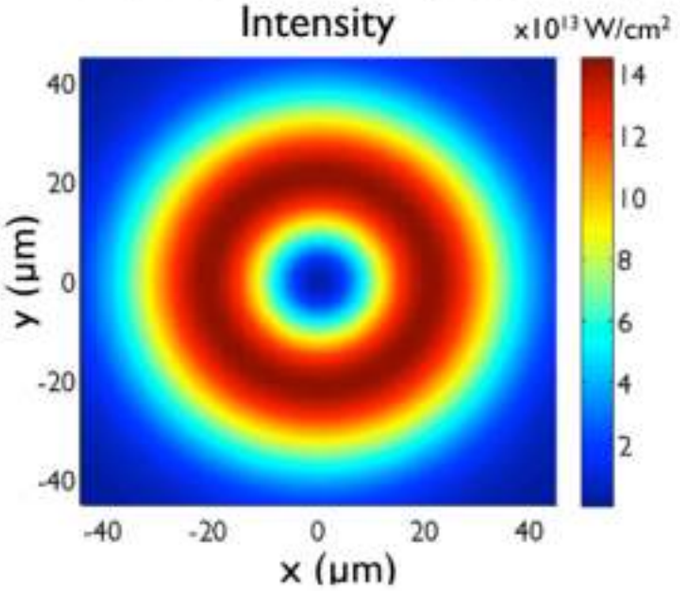
OAM-High Harmonic Generation

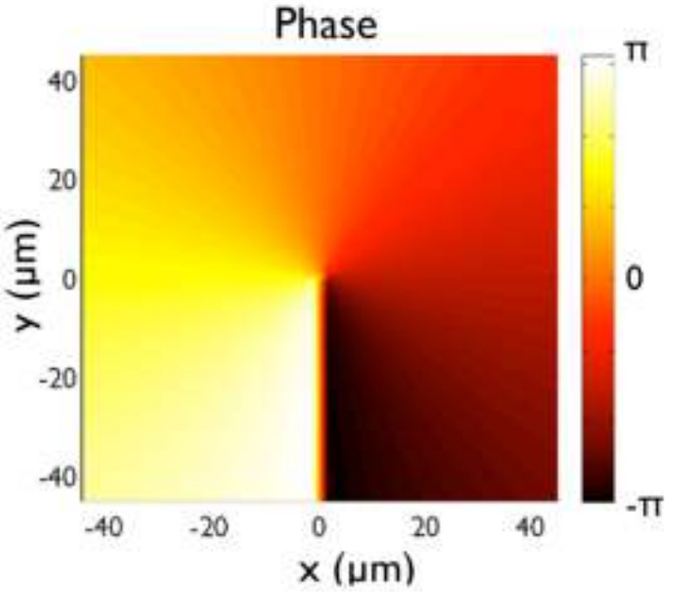


First experiment: M. Zürch, et al. Nature Physics 8, 743-746 (2012)

Harmonic vortices are emitted with the **same OAM as the fundamental beam.**

Fundamental (800 nm)

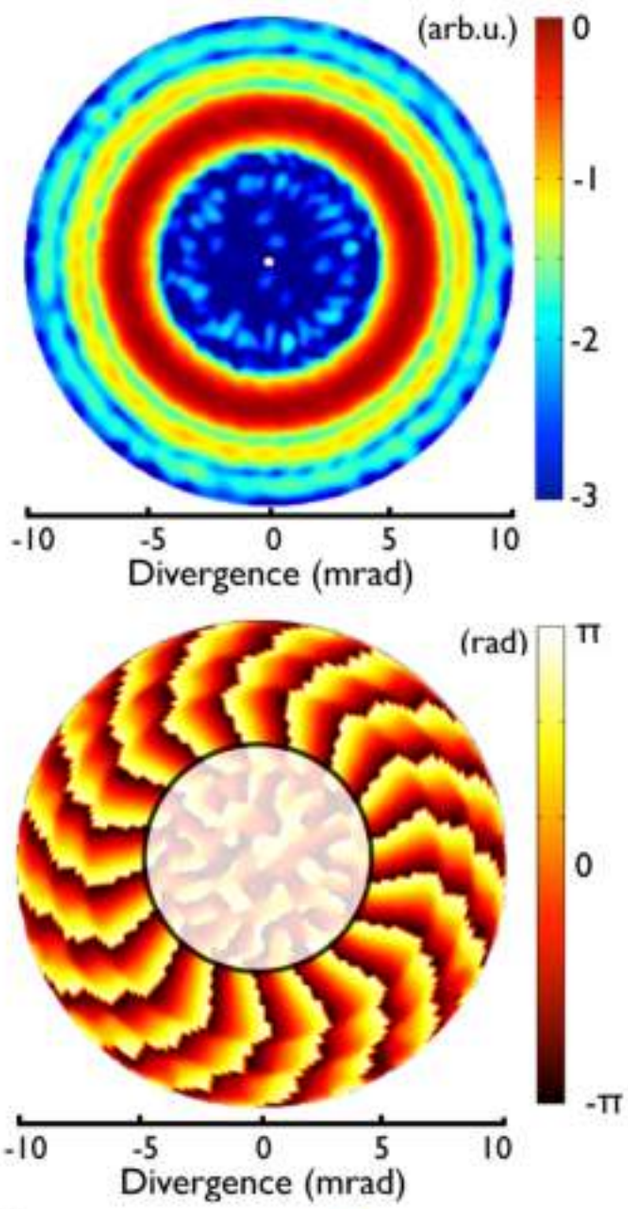


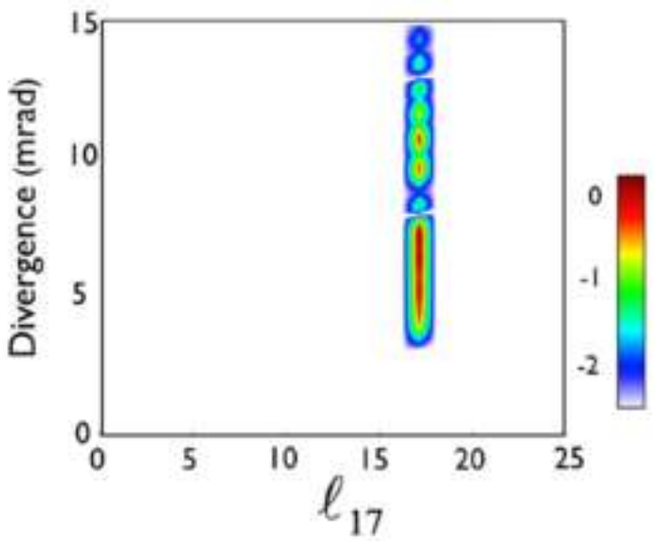


HHG

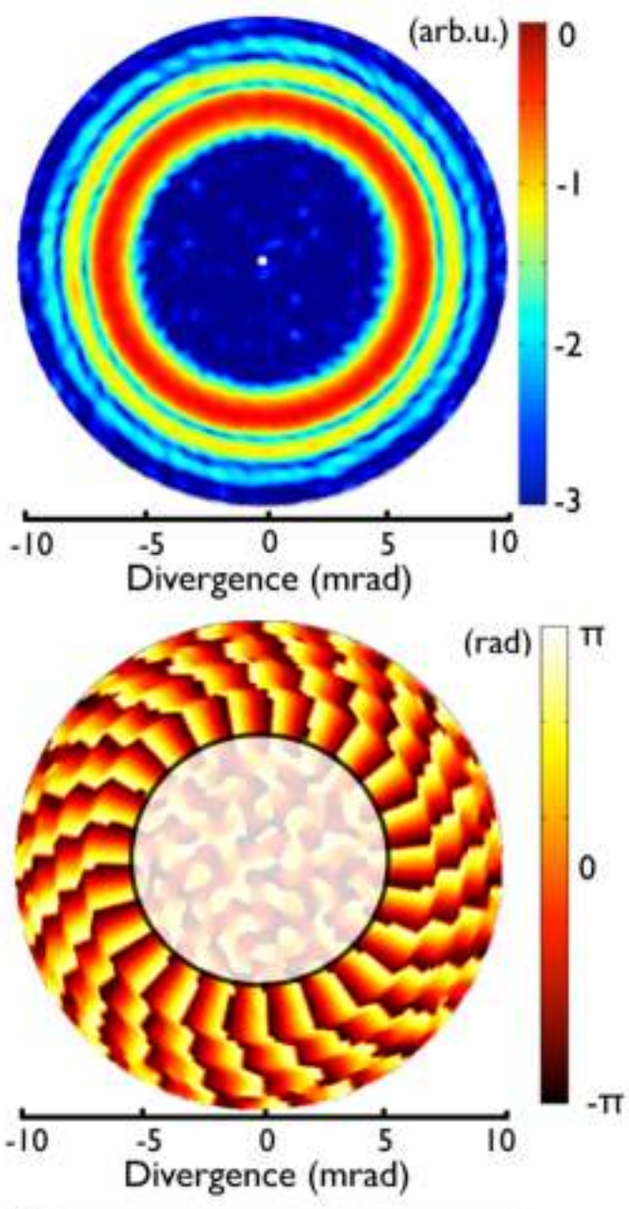
$q\ell\phi$

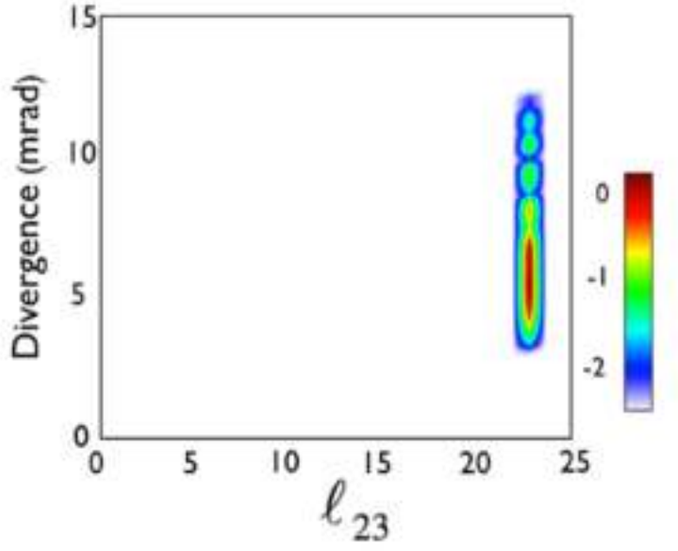
17th Harmonic, 47 nm, 26 eV





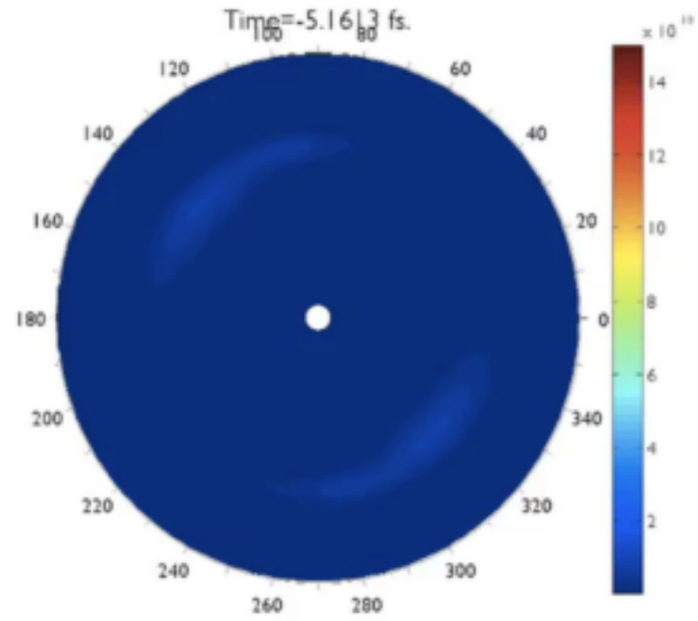
23rd Harmonic, 35 nm, 35 eV

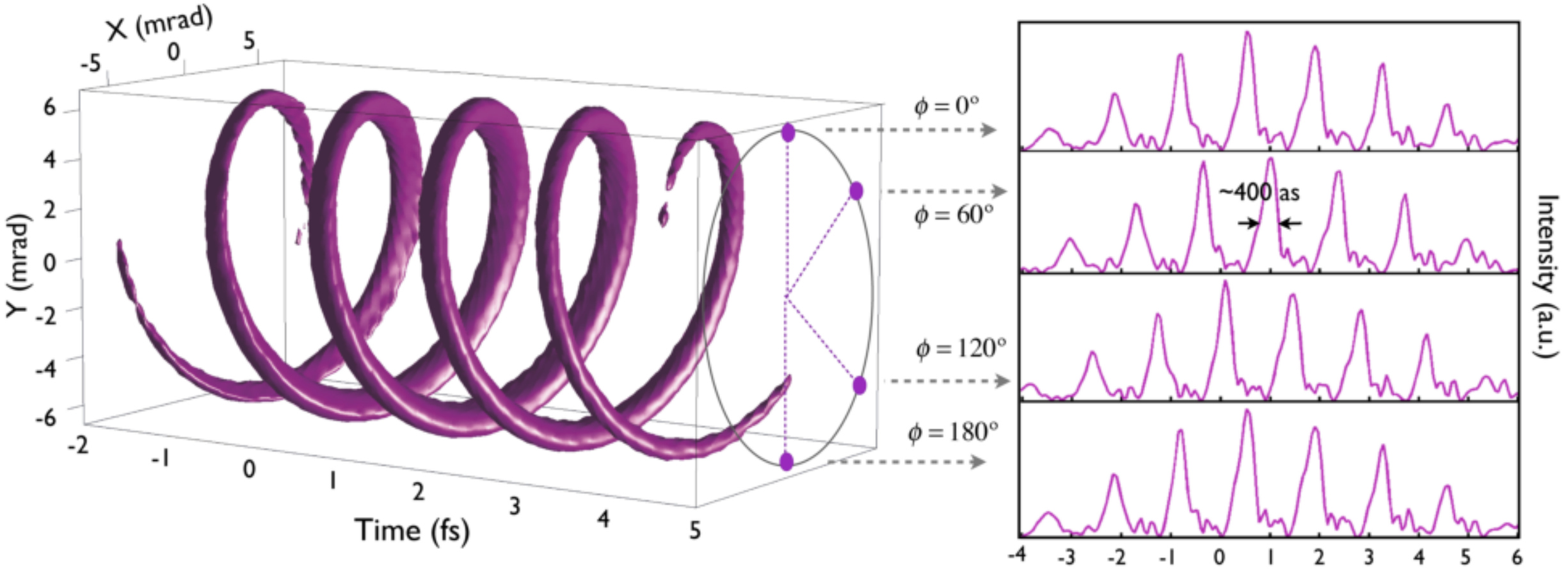




Phys. Rev. Lett. 111, 083602, (2013)
New J. Phys. 17, 093029 (2015)
Phys. Rev. Lett. 117, 163202 (2016)

Attosecond OAM beam





Phys. Rev. Lett. 111, 083602, (2013)
New J. Phys. 17, 093029 (2015)

CONCLUSIONES

Hoy en día podemos generar y medir pulsos de attosegu
controlando:

- **Su energía y duración**
- **Su momento angular:**
  - **Polarización**
  - **Momento angular orbital**

¿Límites?
Rayos X duros
Zeptosegundos

¿Interacción espín-órbita en la generación de pulsos de attosegundo?

Aplicaciones en:
Generación de corrientes magnéticas.
Estudio de transferencia de carga en moléculas.

ALF USAL
Aplicaciones del Láser y Fotónica

University of Salamanca (Spain)
Carlos Hernández-García, Laura Rego, Julio San Román, Íñigo Sola, Luis Plaja

JILA, Ultrafast AMO Theory group (USA)
Agnieszka Jaroń-Becker and Andreas Becker

JILA, Kapteyn-Murnane experimental group (USA)
Tenio Popmintchev, Dan Hickstein, Dimitar Popmintchev, Tingting Fan, Zhensheng Tao, Cong Chen, Patrik Grychtol, Franklin Dollar, Jennifer Ellis, Dimitriy Zusin, Ronny Knut,
Henry Kapteyn and Margaret Murnane

Argonne National Laboratory (USA)
Antonio Picón

Colorado School of Mines (USA)
Amanda Meier, Charles Durfee

National Tsing Hua University (Taiwan)
Ming-Chang Chen

Universitat Autònoma de Barcelona (Spain)
Alex Turpin, Jordi Mompart