



LUND  
UNIVERSITY

A close-up photograph of a magnolia flower with large, pinkish-white petals and a yellow center, set against a blurred background of a white building with blue-framed windows and a clear blue sky.

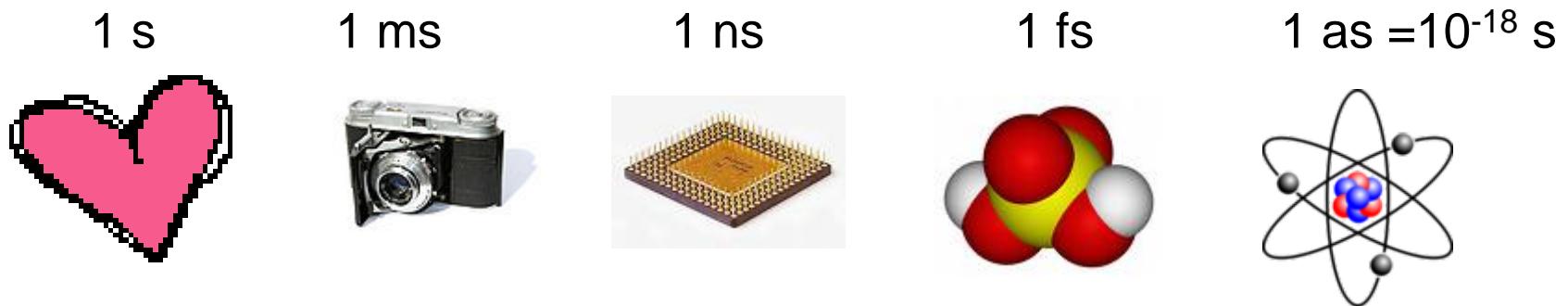
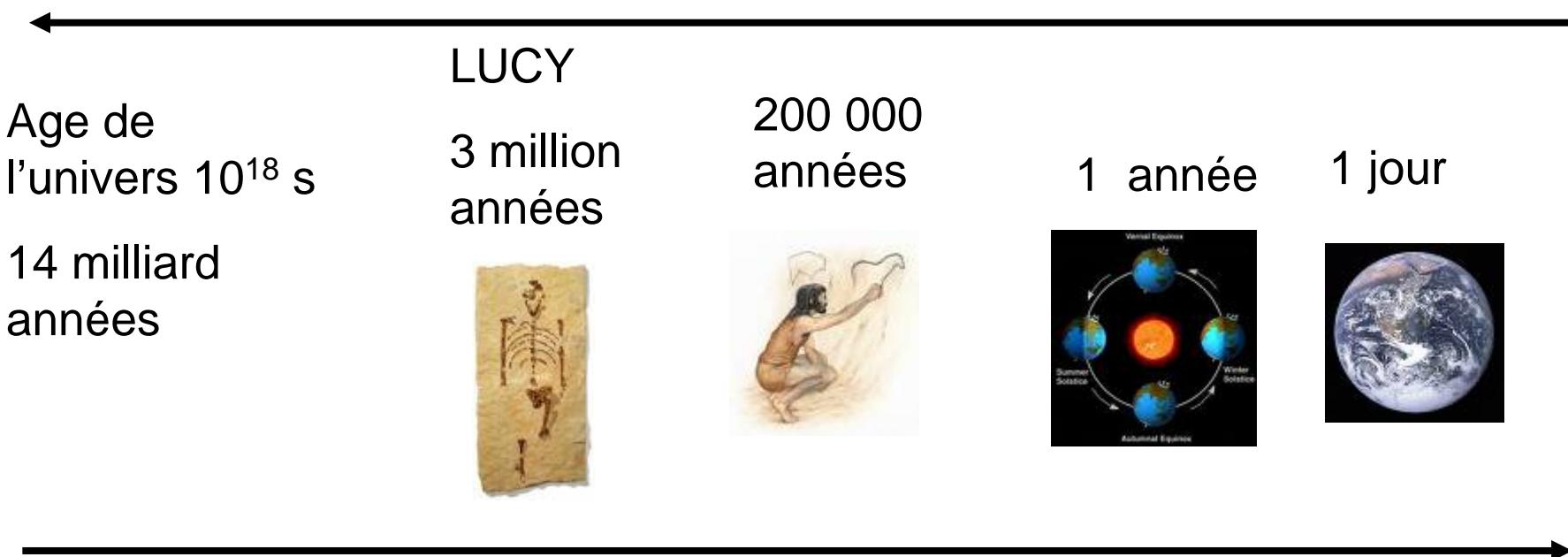
# Que se passe t'il en un milliardième de milliardième de seconde ?

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ANNE L'HUILIER PHYSICS DEPARTMENT



**Une attoseconde = 0.000 000 000 000 000 001 =  $10^{-18}$  s**



# Plan

- Caméras ultrarapides
- Impulsions ultracourtes
- Impulsions attosecondes
- Comment suivre le mouvement des électrons  
dans les atomes



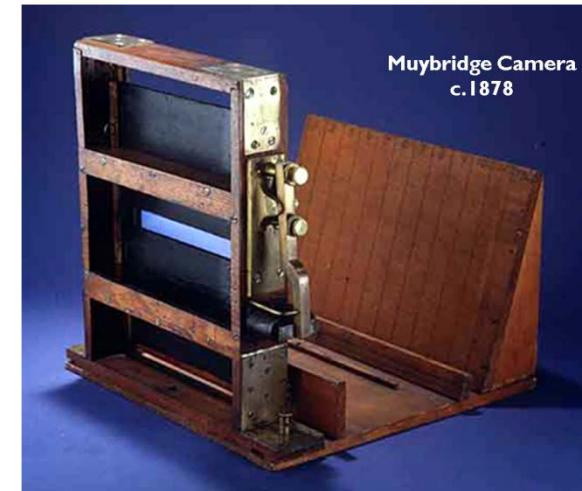
# La première caméra



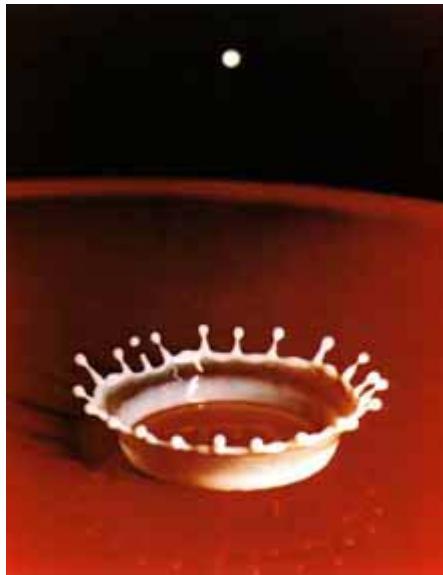
*Wikipedia*



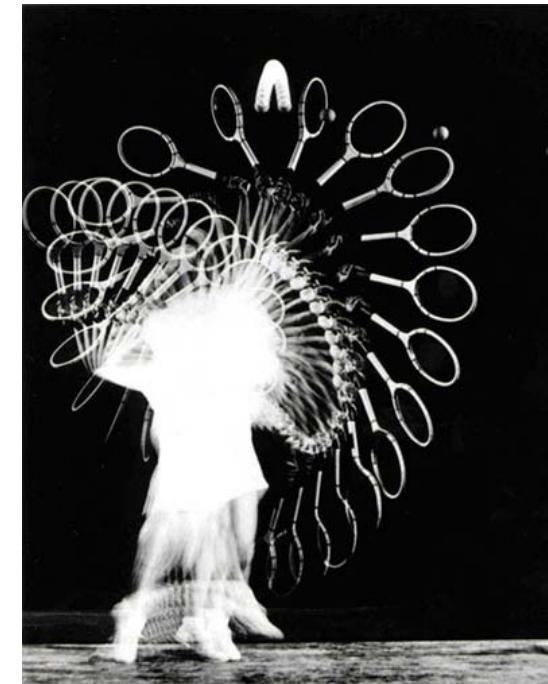
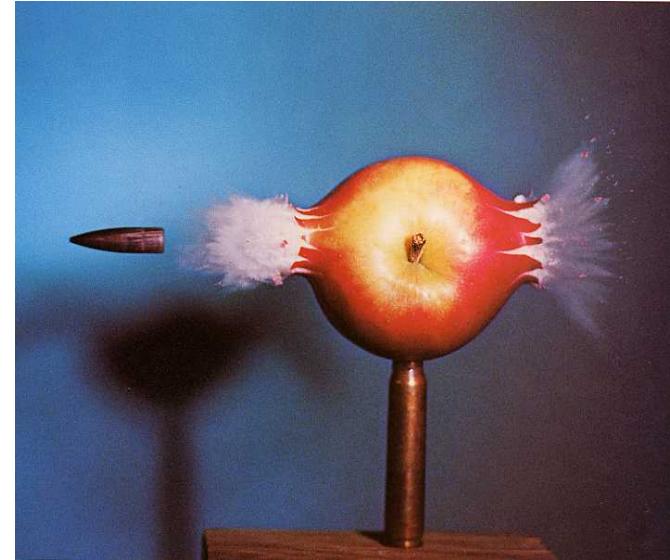
Muybridge, 1877  
Obturateur mécanique  
ms



# Le premier flash

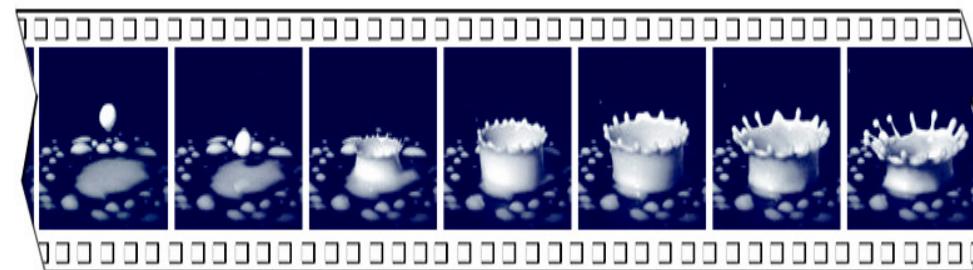


*Wikipedia*

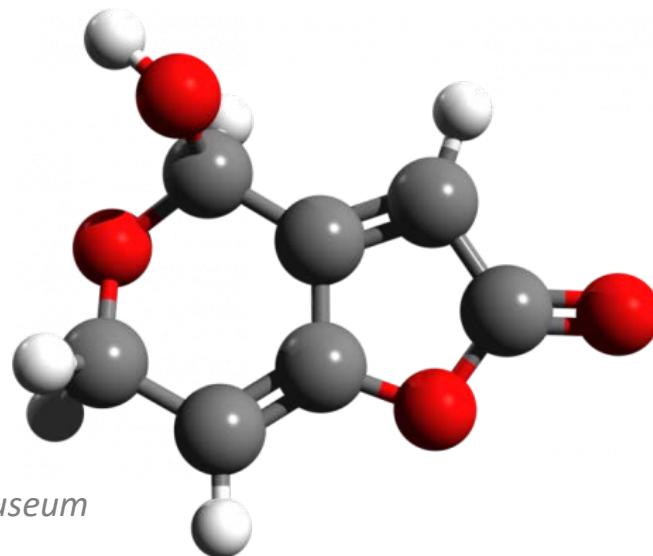


Edgerton, 1957

Flash       $\mu\text{s}$

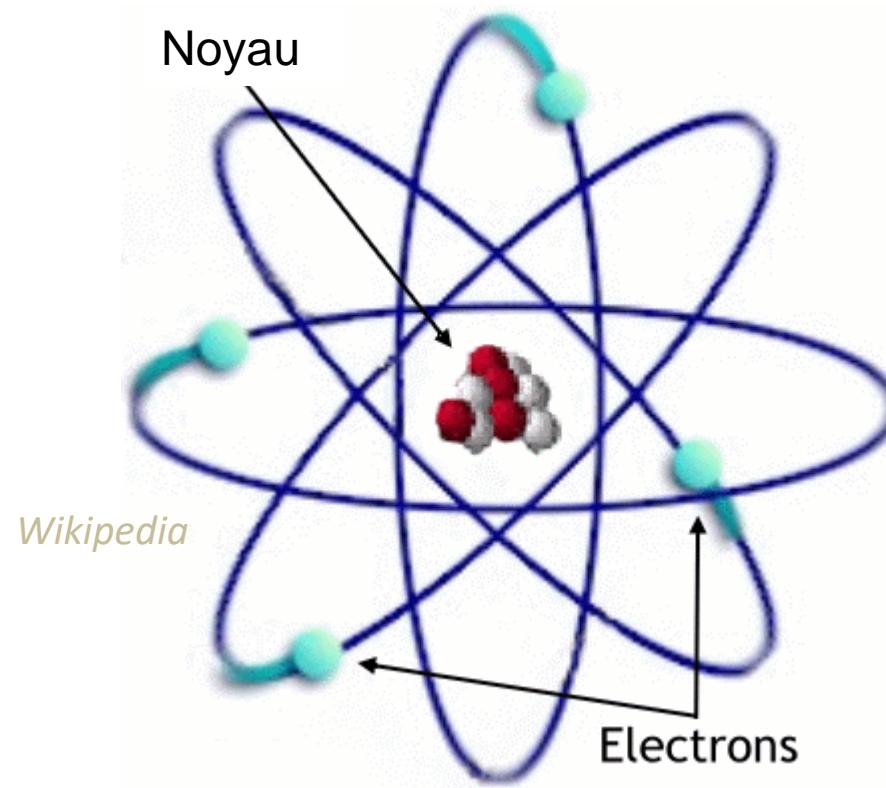


# Plus les particules sont légères, plus elles vont vite!



Mouvement des atomes  
impulsions femtosecondes  
 $1 \text{ fs} = 10^{-15} \text{ s}$   
 $= 0.000000000000001$

**Chimie femtoseconde**

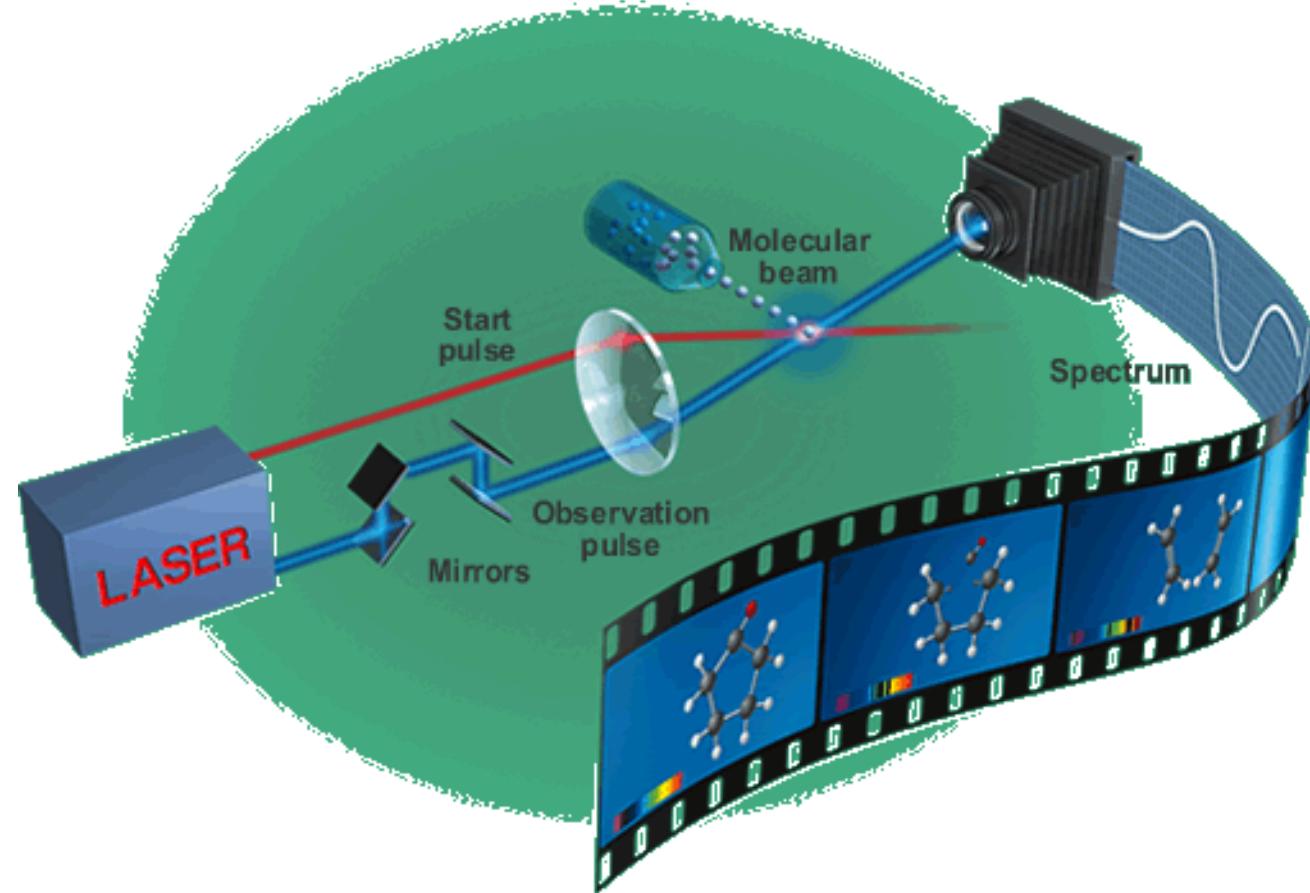


Mouvement des électrons  
impulsions attosecondes  
 $1 \text{ as} = 10^{-18} \text{ s}$

**Physique attoseconde**



# Chimie femtoseconde: mouvement des atomes dans les molécules



Zewail, 1987

*Nobel foundation*



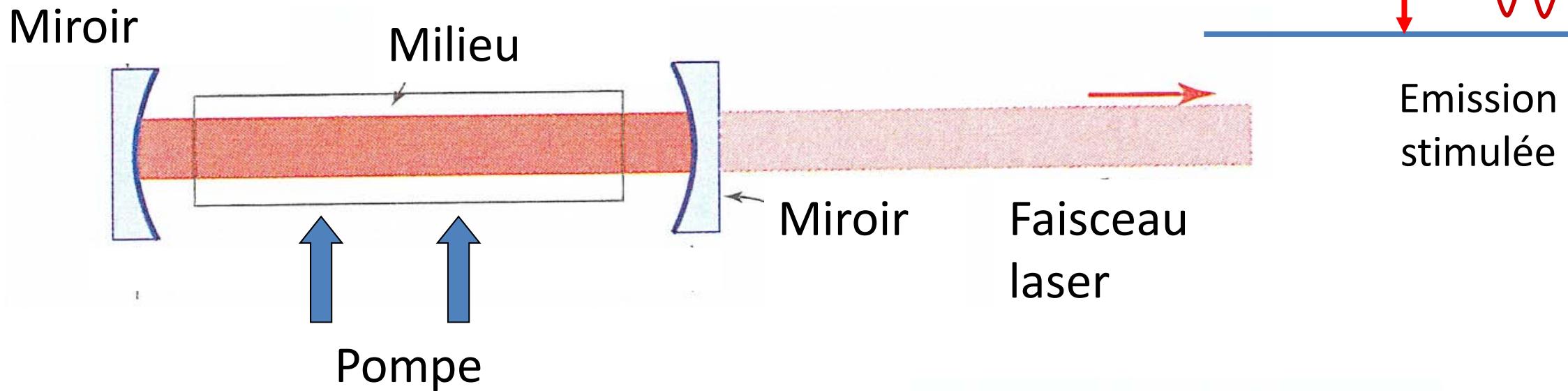
1999



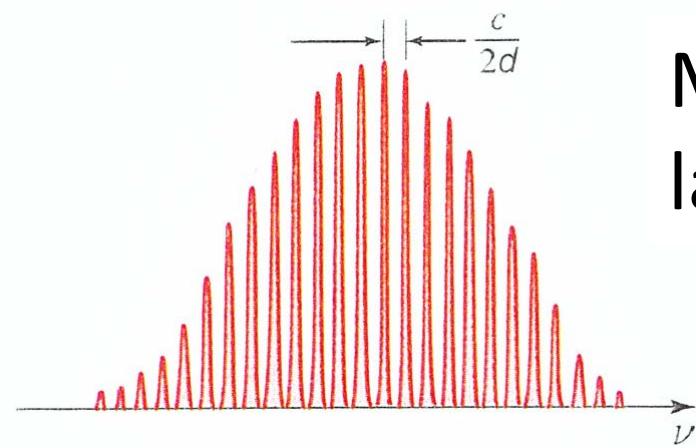
# Plan

- Caméras ultrarapides
- Impulsions ultracourtes: impulsions laser femtosecondes
- Impulsions attosecondes
- Comment suivre le mouvement des électrons dans les atomes

# Laser

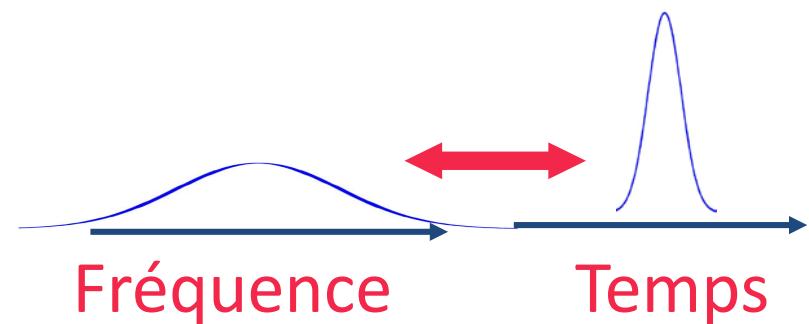


Modes  
laser

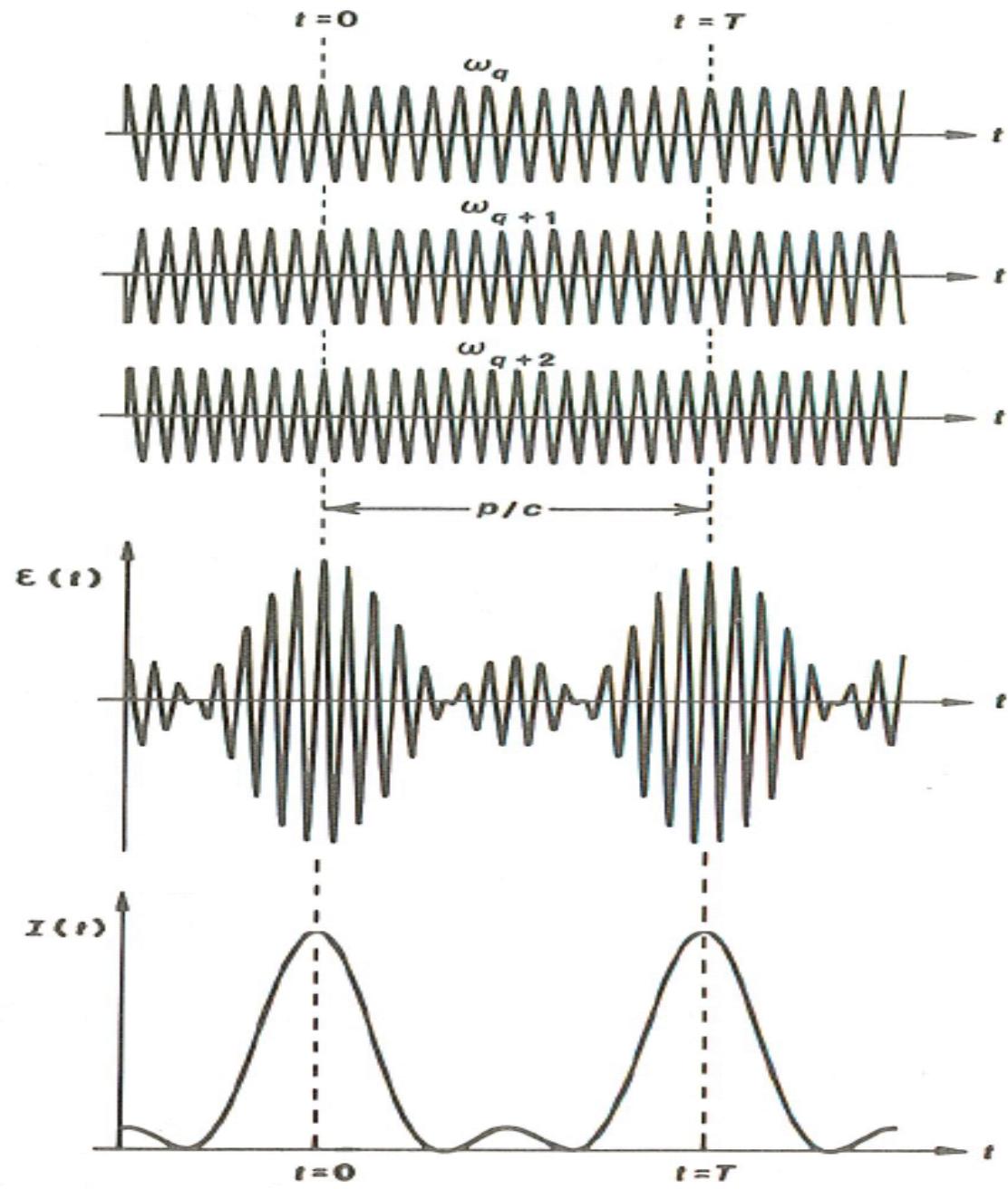


# Blocage de modes

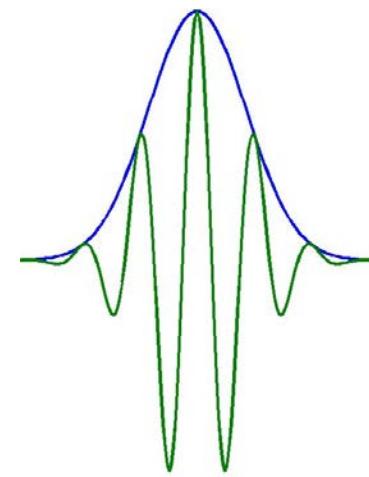
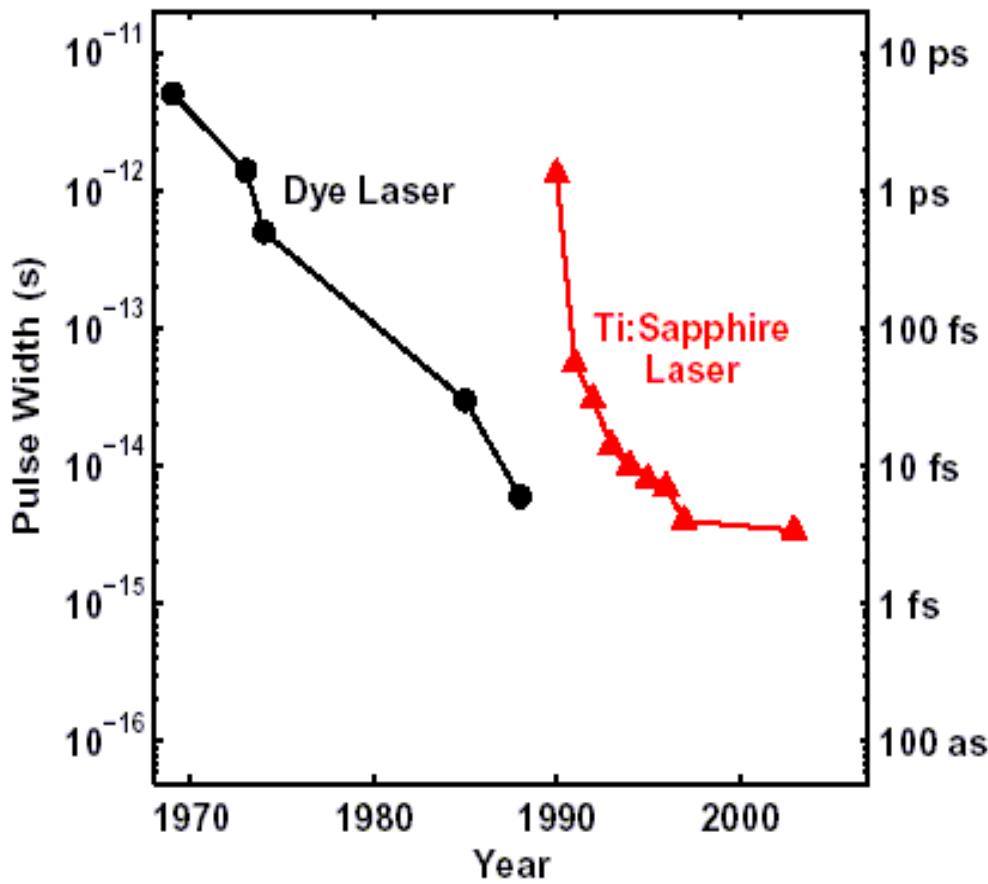
$$\Delta\tau\Delta\nu \approx 1$$



Bandé spectrale  
large



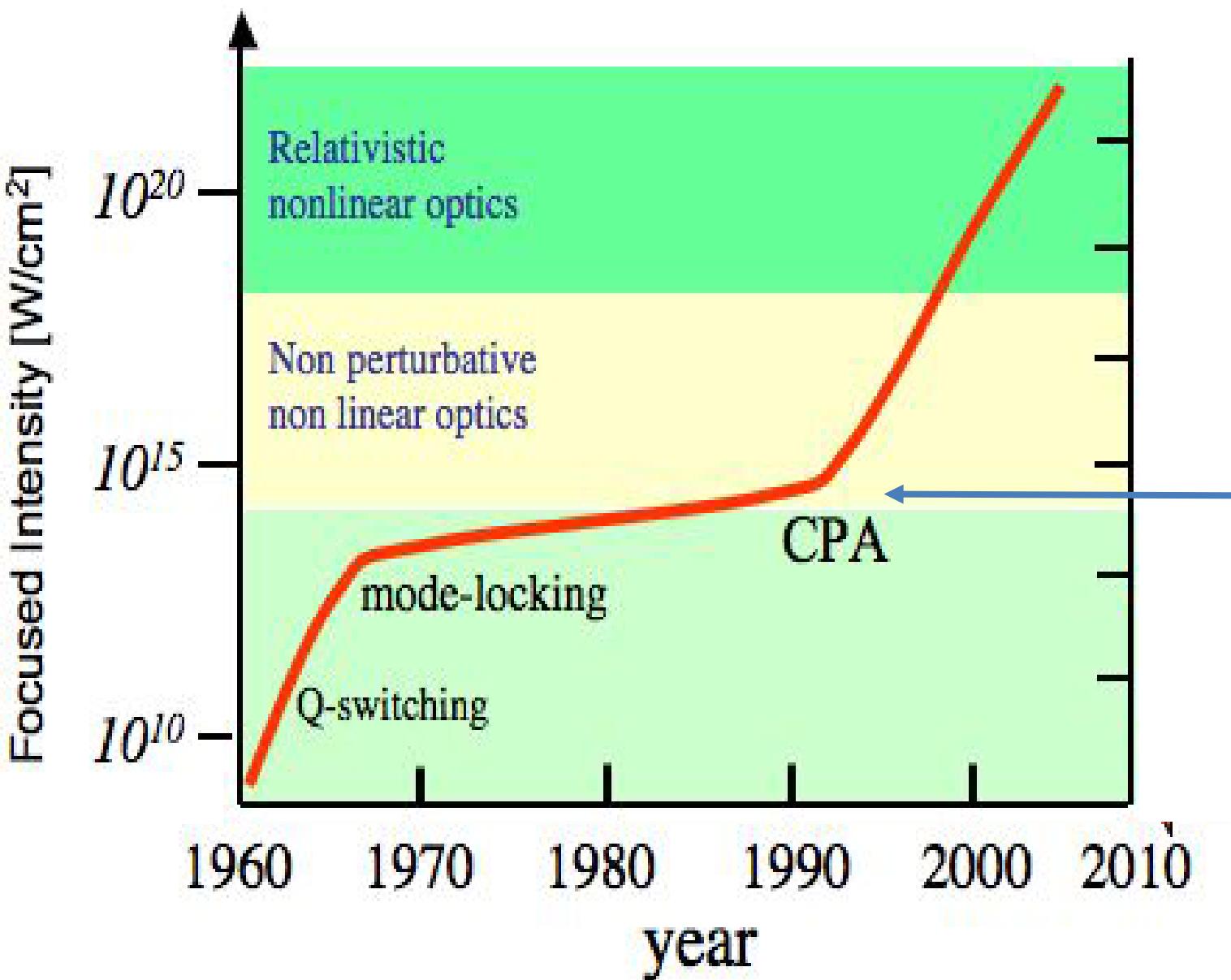
# Impulsions laser ultracourtes



1 cycle = 2.7 fs  
@ 800 nm

Limitation due à la largeur de bande disponible et à la longueur d'onde centrale

# Impulsions laser intenses

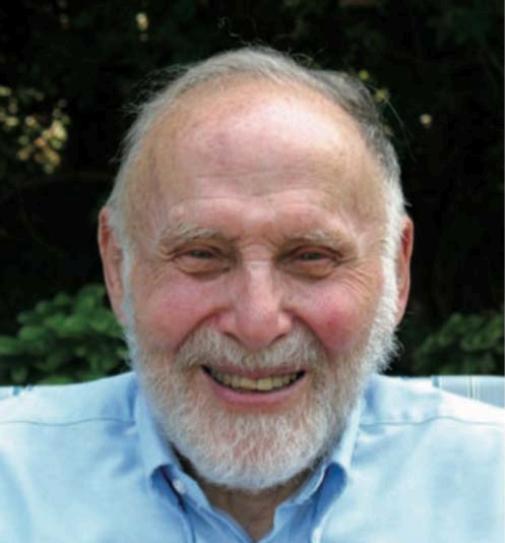


Limitation due aux effets non-linéaires conduisant au dommage du matériau laser.



# NOBEL PRIZE IN PHYSICS 2018

*for groundbreaking inventions in the field of laser physics*



Arthur Ashkin (USA)

*for the optical tweezers and  
their application to  
biological systems*

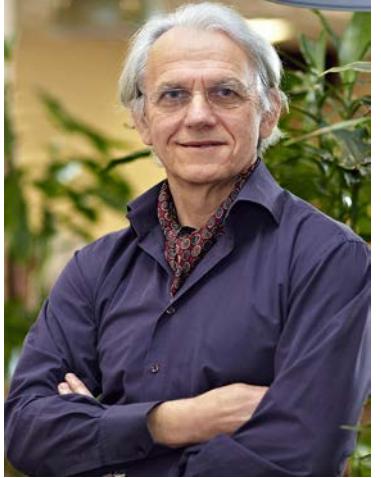


Gérard Mourou (France/USA)  
Donna Strickland (Canada)

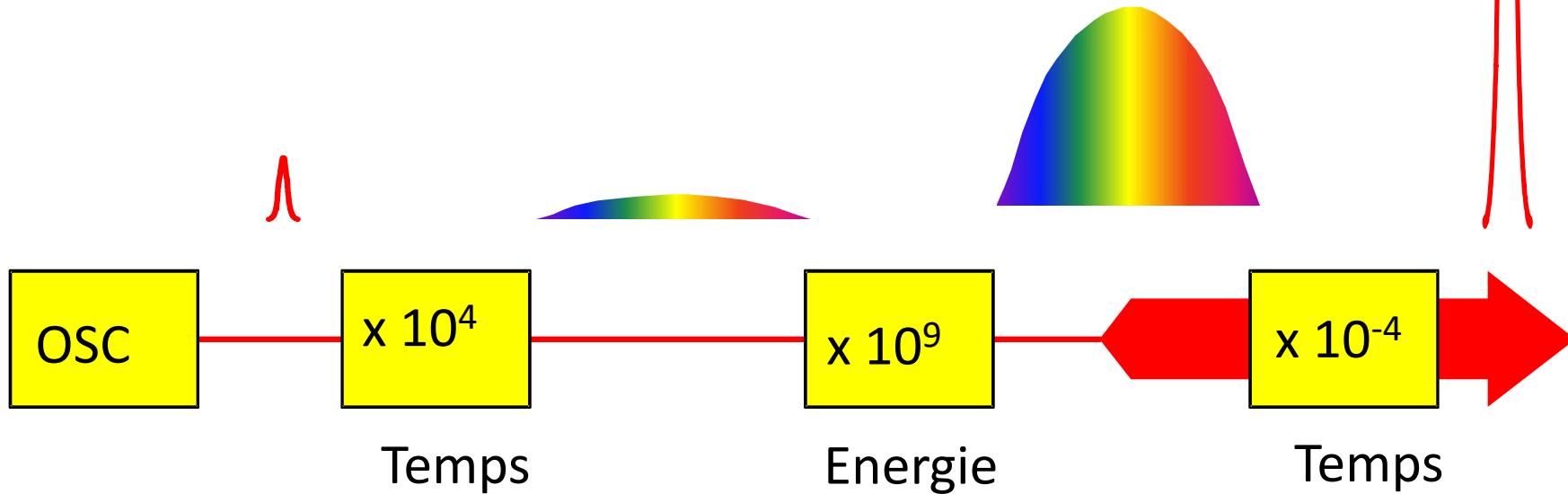
*for their method of generating  
high-intensity, ultra-short optical  
pulses*



# Amplification à derive de fréquence CPA

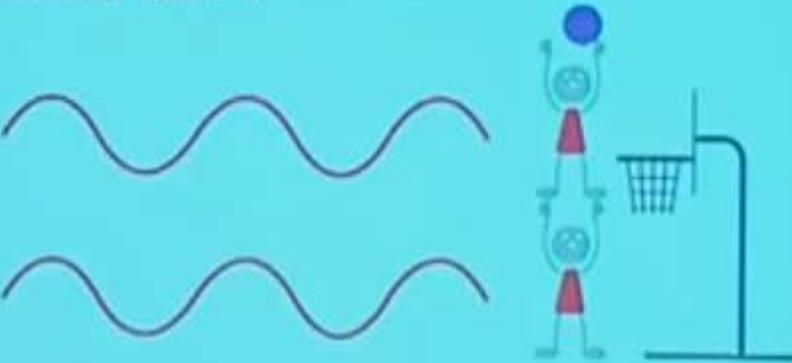


$$P = \frac{E}{\tau}$$



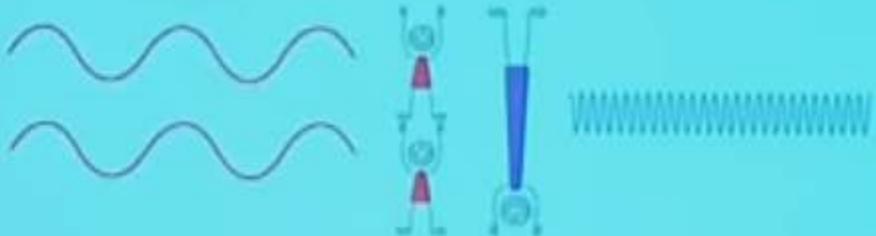
## MULTIPHOTON PHYSICS

Two Red Photons  
Working Together = One Violet Photon



MARIA GOEPPERT  
MAYER  
1963

## NONLINEAR INTERACTION



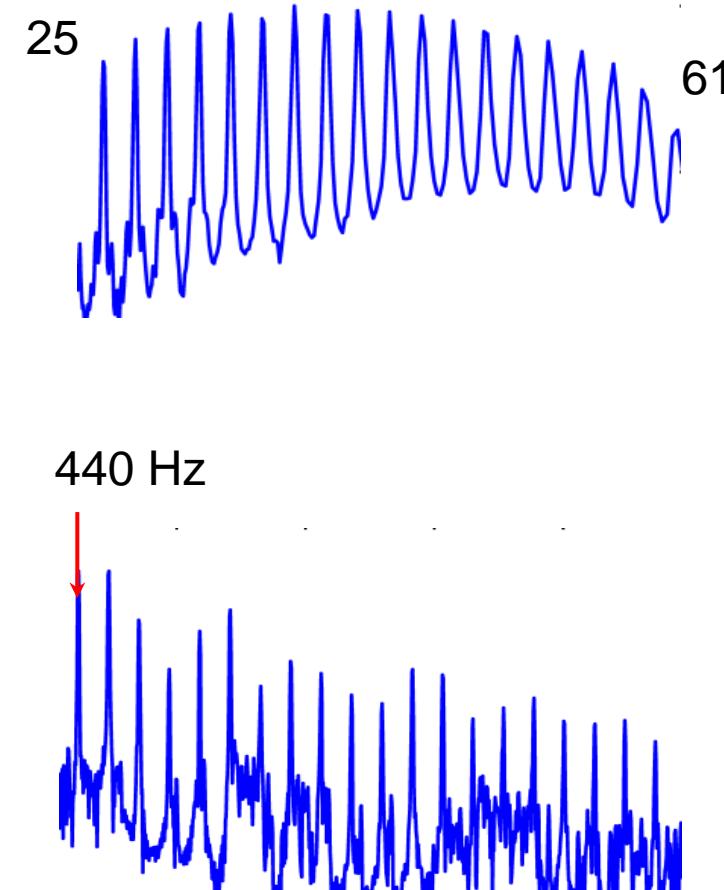
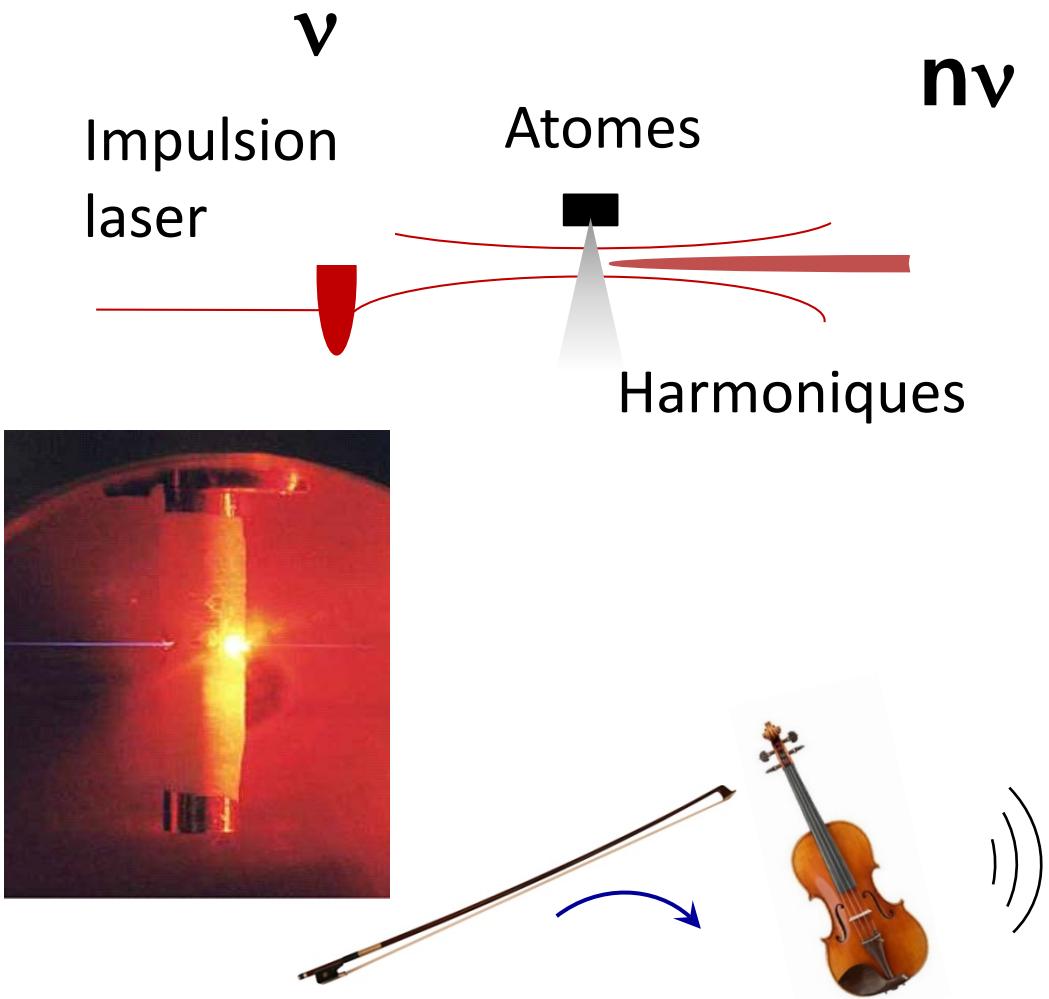
PETER A. FRANKEN  
1985



# Plan

- Caméras ultrarapides
- Impulsions ultracourtes
- Impulsions attosecondes
- Comment suivre le mouvement des électrons dans les atomes

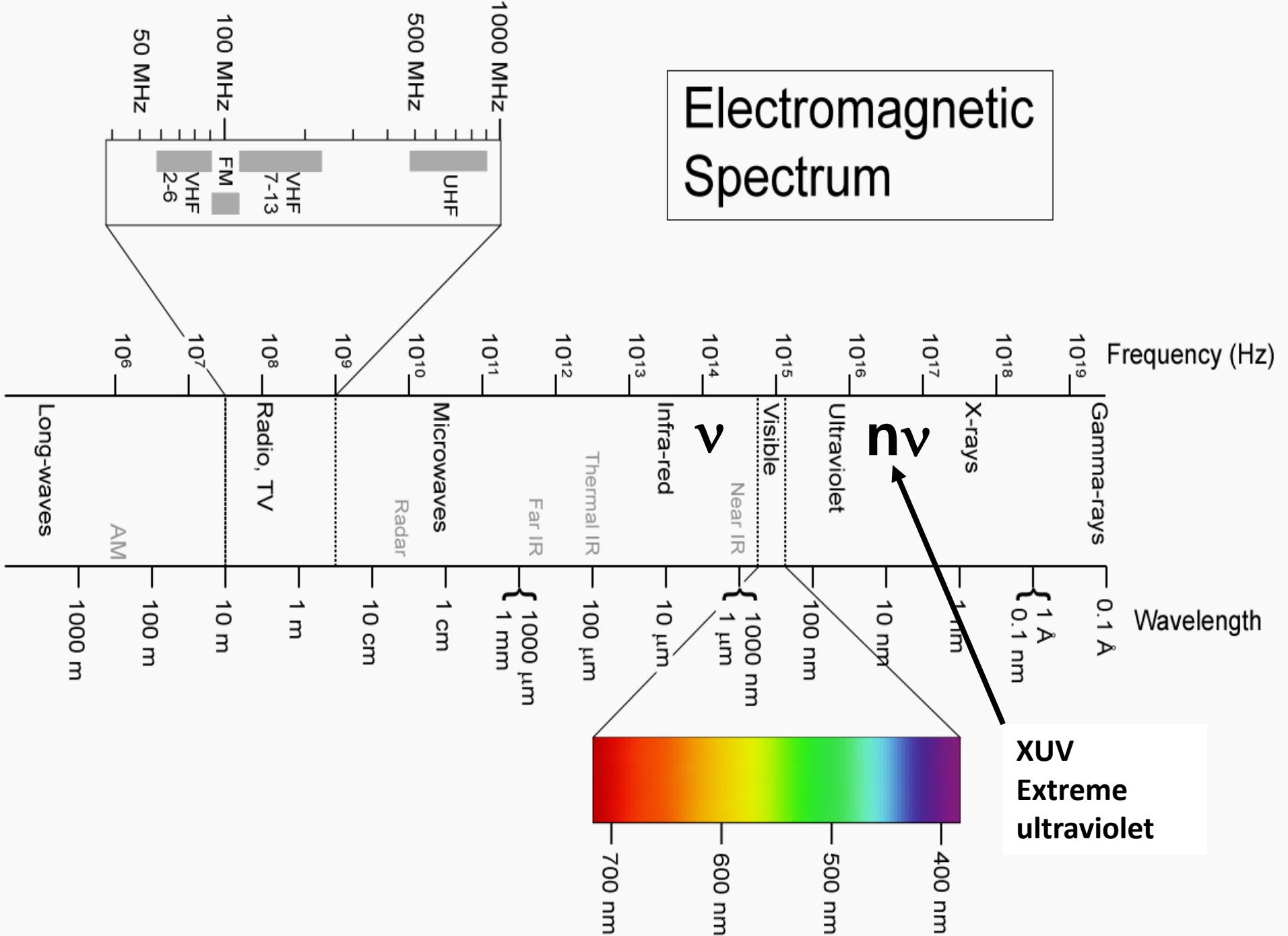
# Génération d'harmoniques d'ordre élevé



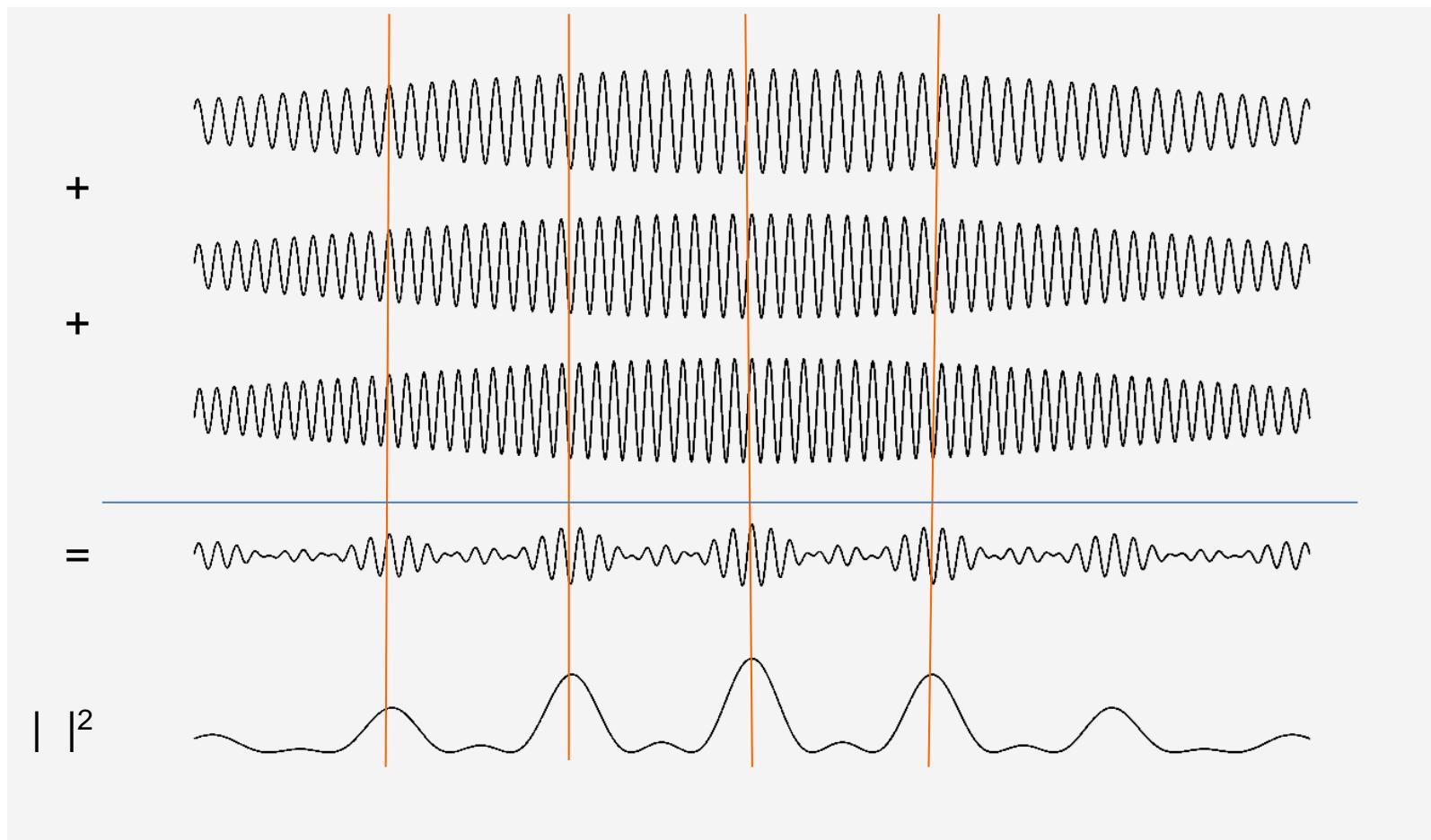
Ferray et al., J Phys B, 1988

McPherson et al., JOSA B 1987

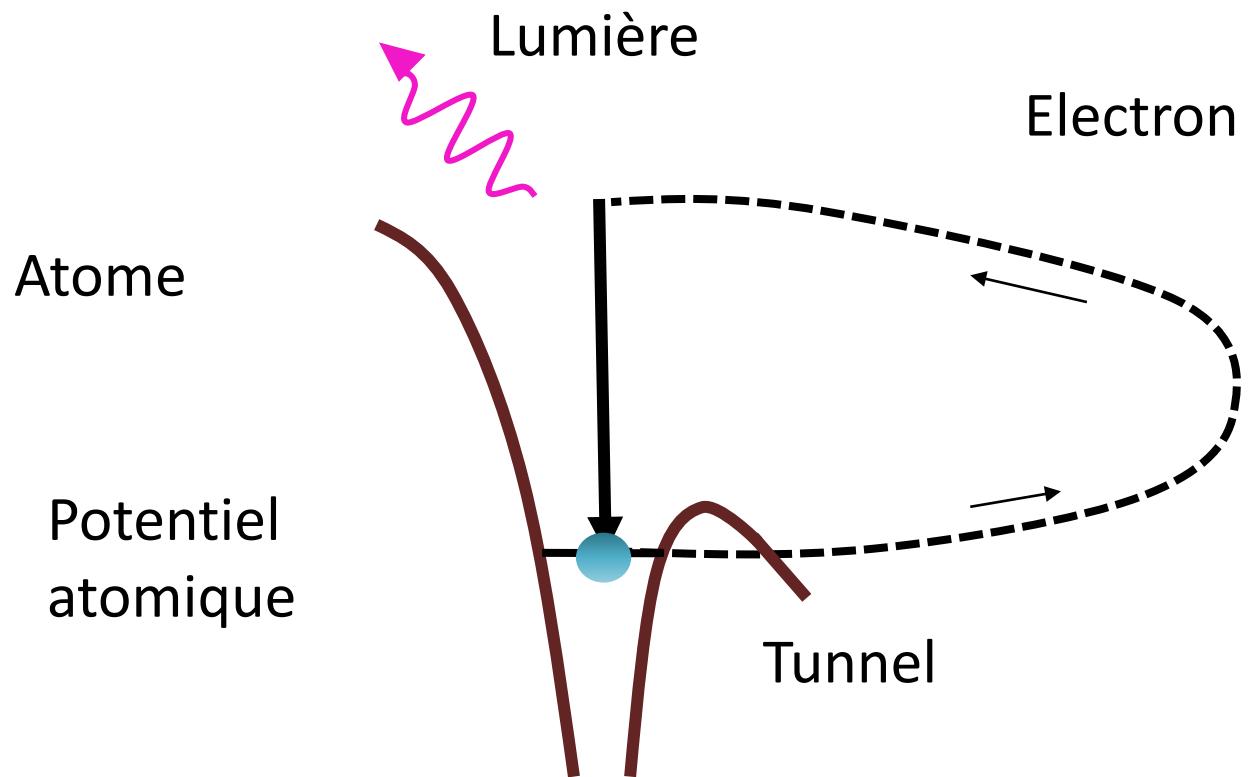
# Electromagnetic Spectrum



# Impulsions attosecondes ?

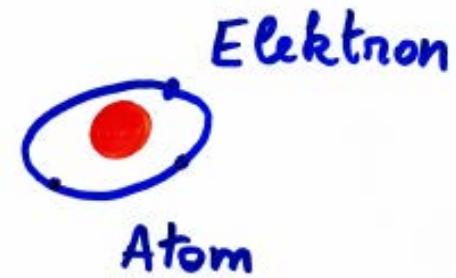
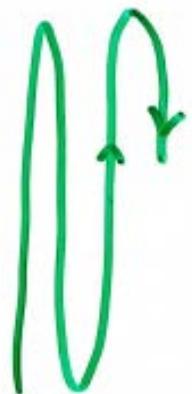


# Atome en champ laser intense

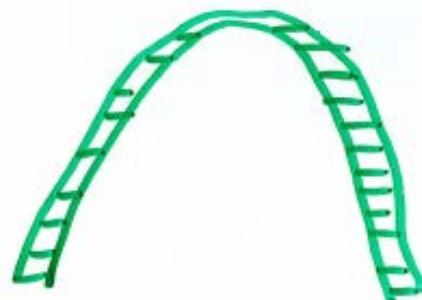
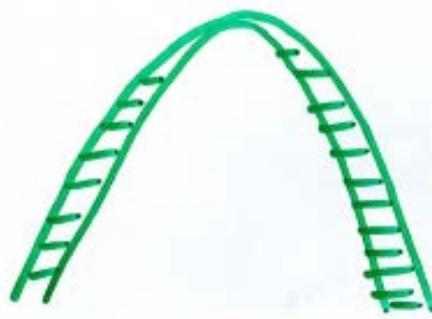


$$i\hbar \frac{\partial \Psi}{\partial t} = H\Psi = -\frac{\hbar^2}{2m} \nabla^2 \Psi + [V(r) + e\mathbf{E}(t) \cdot \mathbf{r}] \Psi$$

L'aventure d'un  
électron dans  
un champ laser  
(Ph. Balcou)

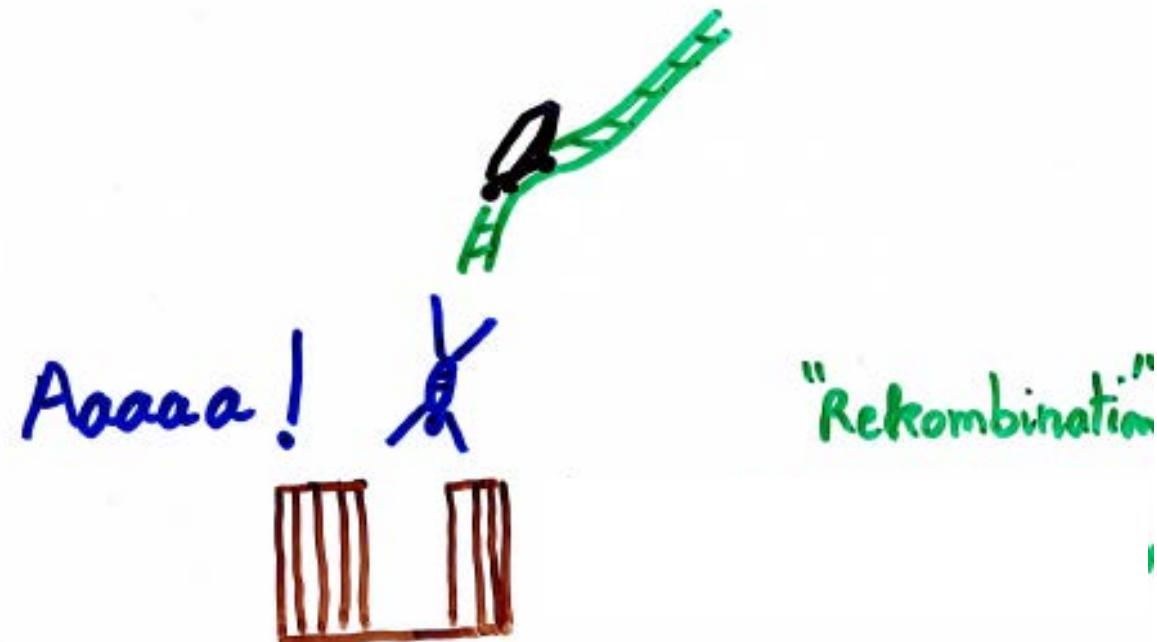
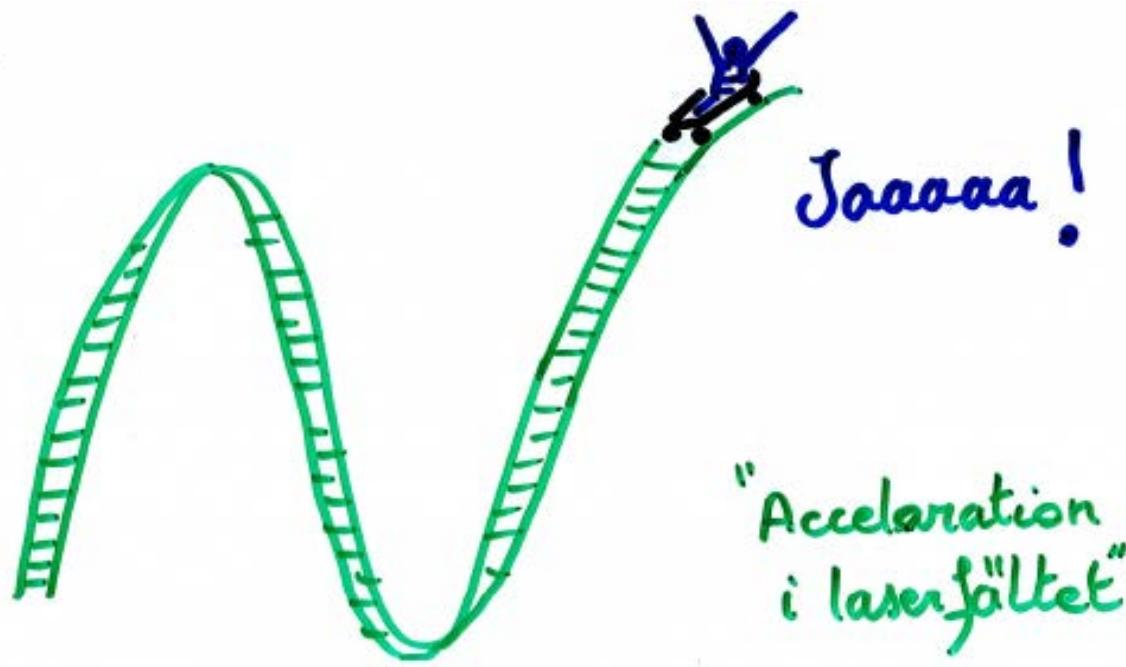


Laser

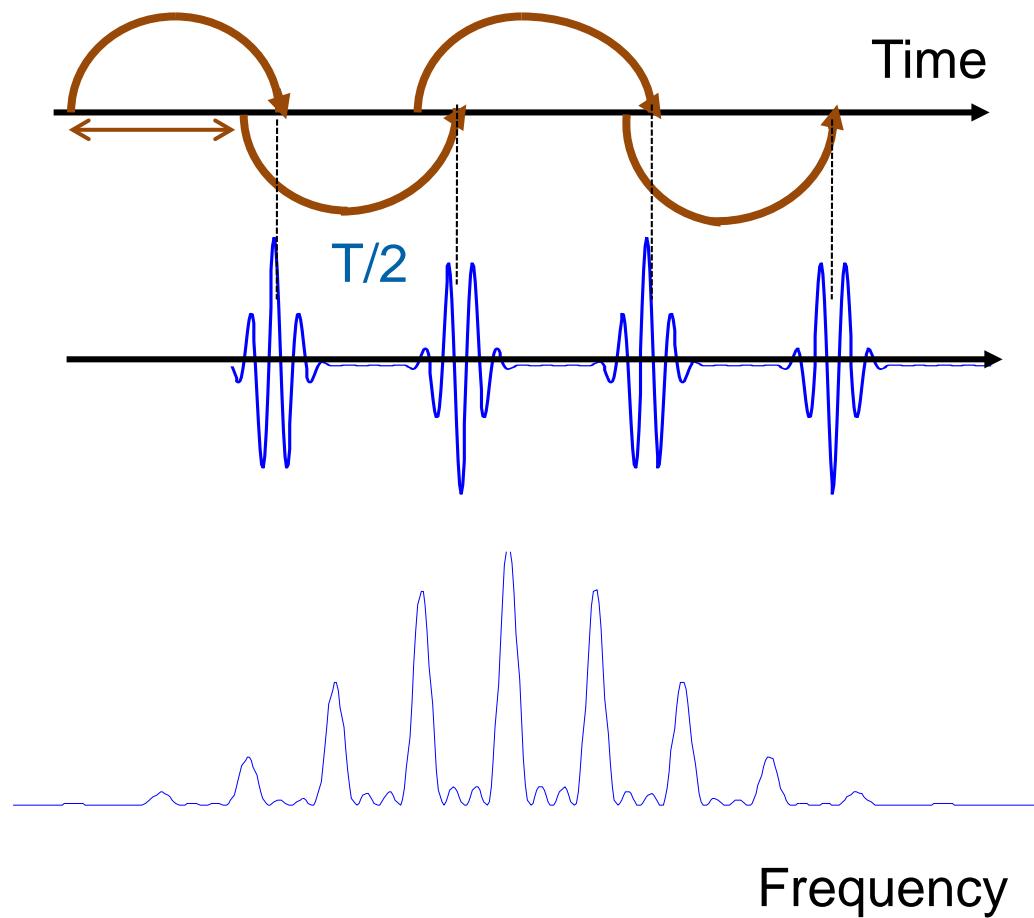


"Tunnel  
Ionisation"

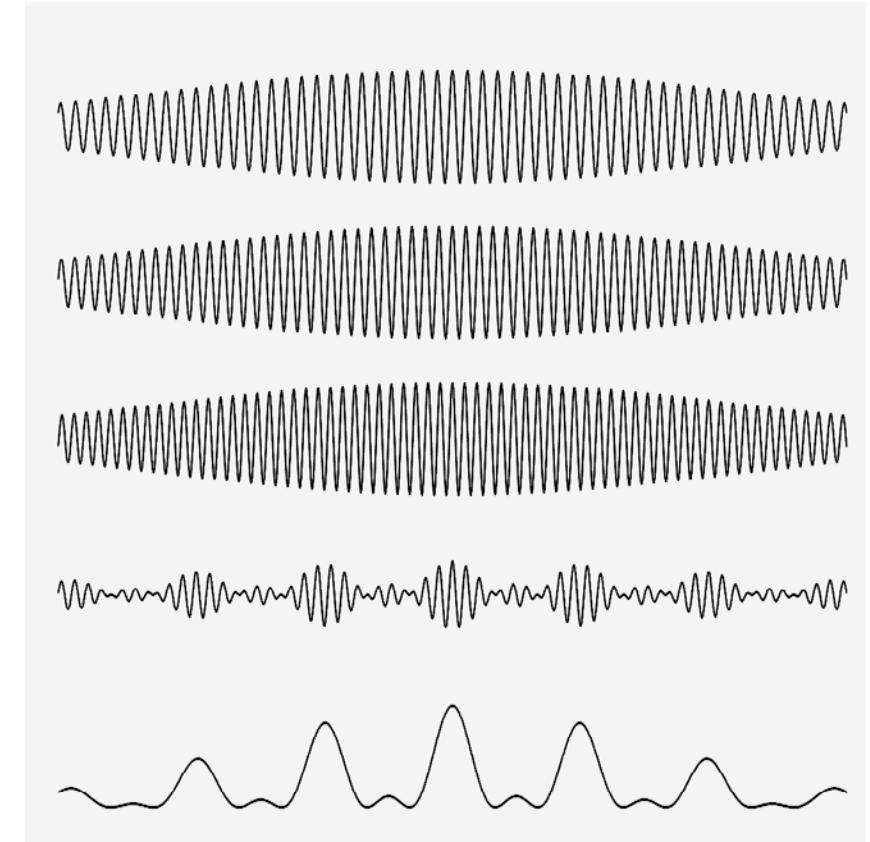
L'aventure d'un  
électron dans  
un champ laser  
(Suite)



# Temps et fréquence

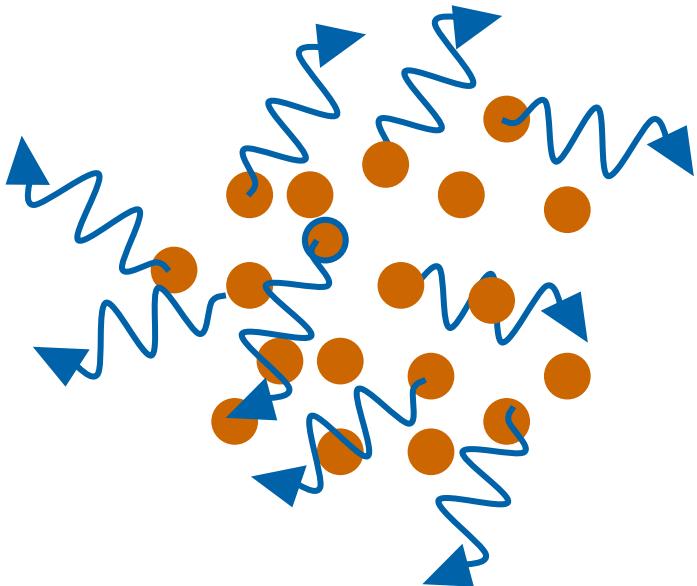


Interférence d'impulsions attosecondes

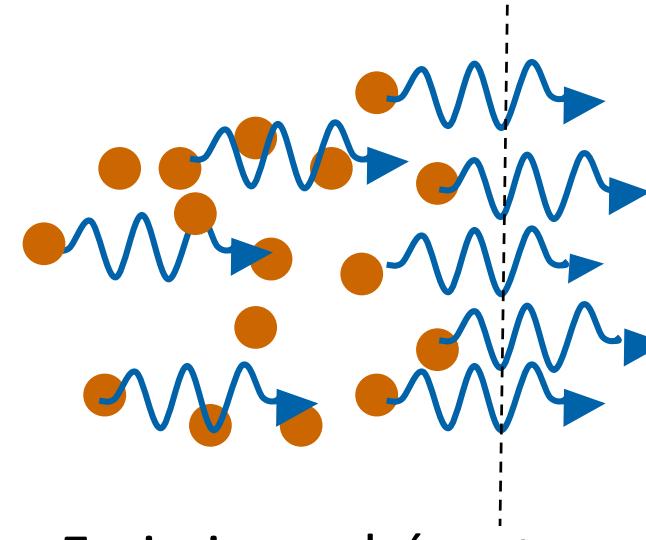


Interférences d'ondes bloquées en phase

# Phénomène d'optique non-linéaire



Emission incohérente



Emission cohérente

Vitesse de phase du fondamental =  
Vitesse de phase du champ harmonique

# Impulsions attosecondes

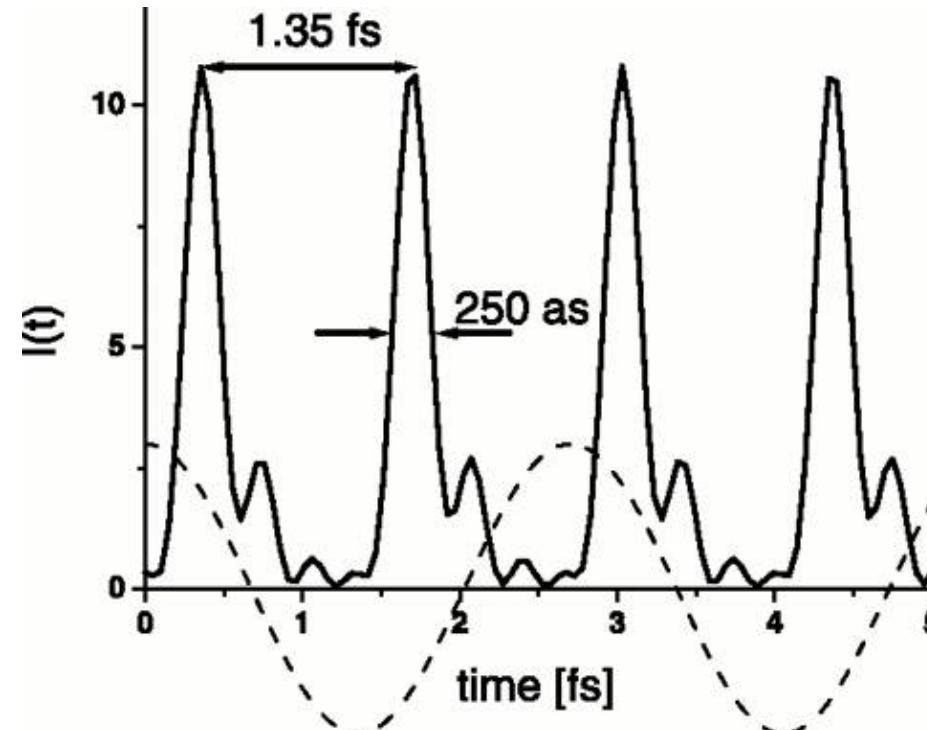
Paris, 2001, 250 as

Vienne, 2001, 450 as

Lund, 2004, 170 as

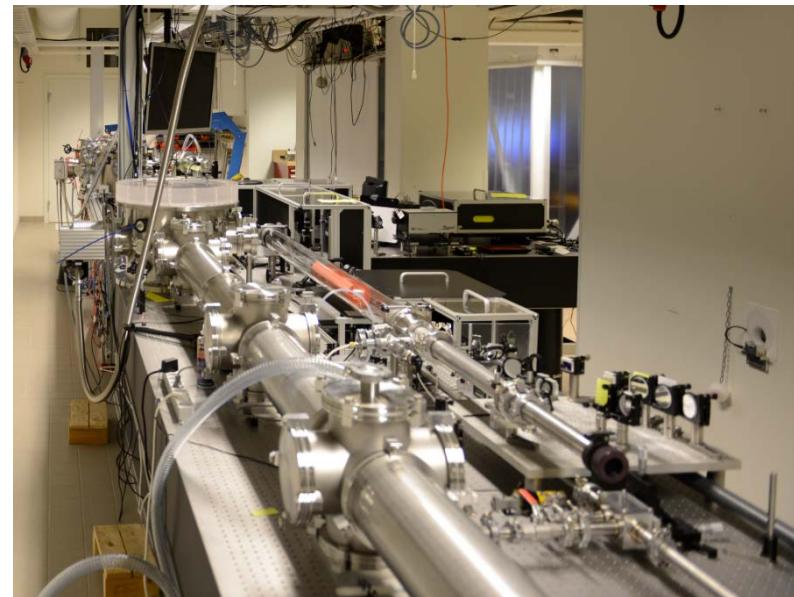
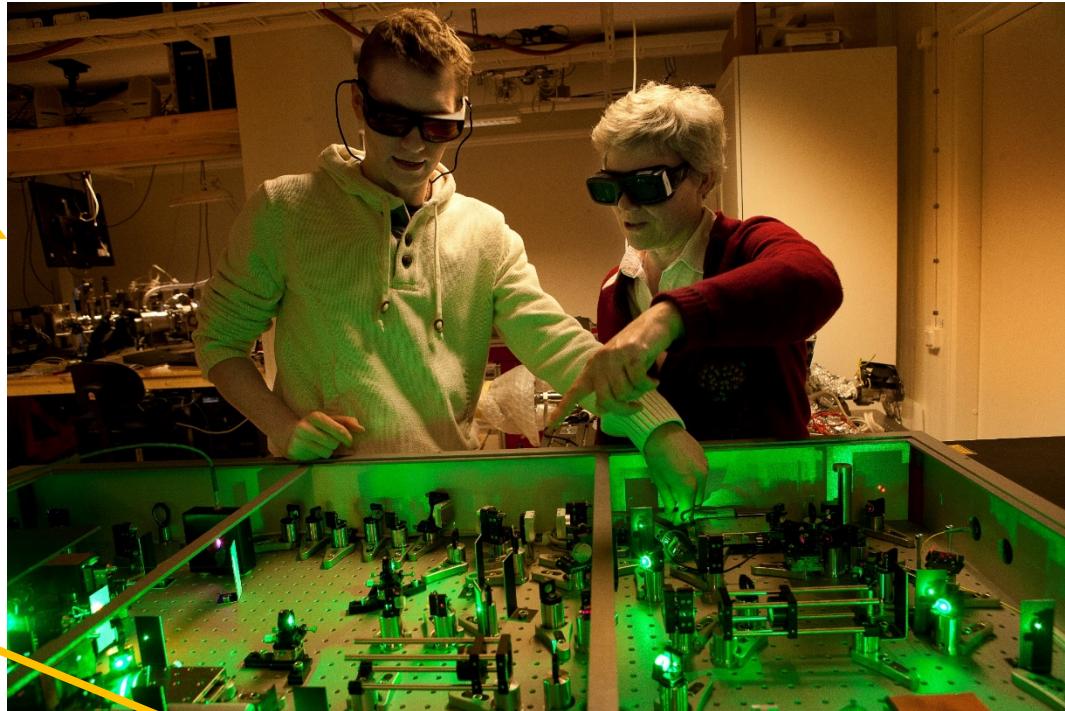
Milan, 2006, 130 as

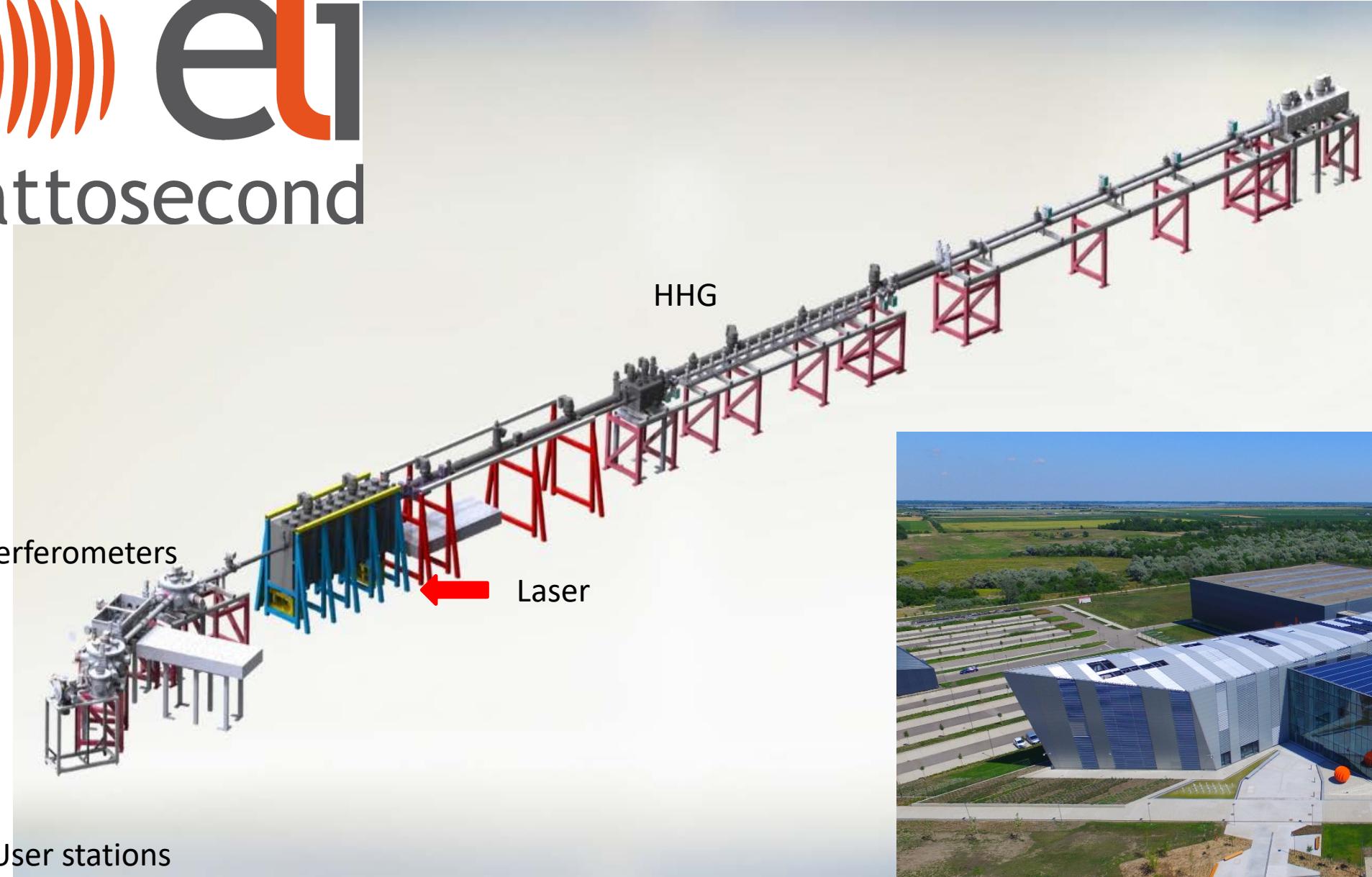
Munich, 2008, 80 as



**Sources  
attosecondes**

**Laser**





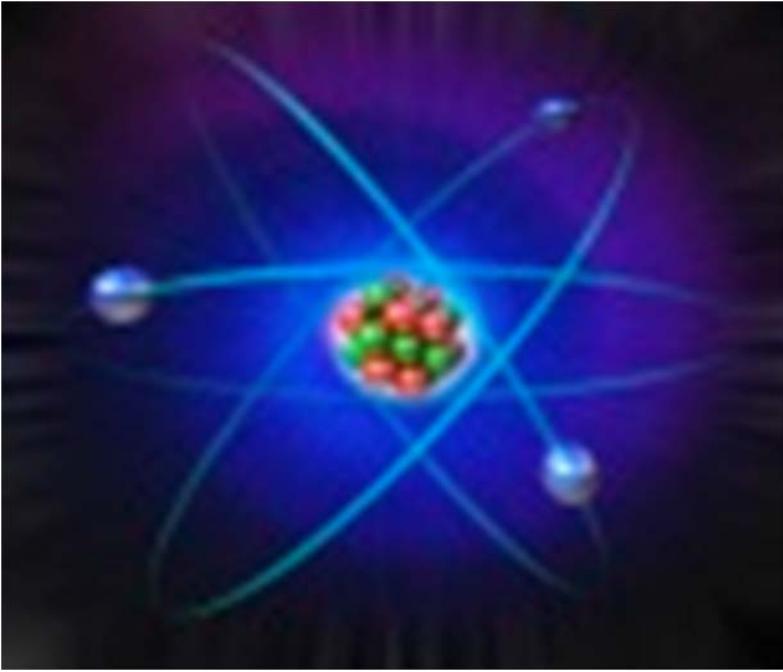
Szeged, Hongrie



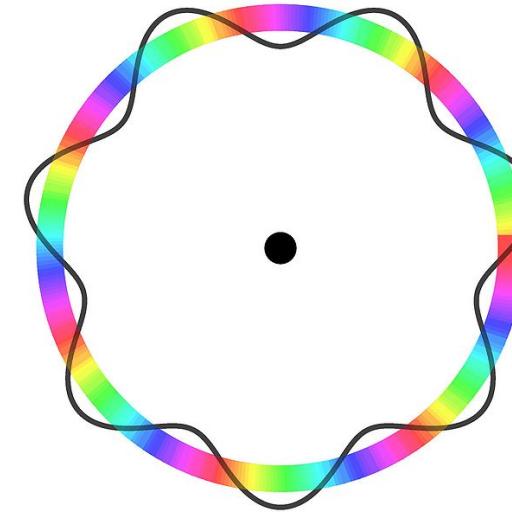
# Plan

- Caméras ultrarapides
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dans les atomes

# Mouvement des électrons dans les atomes



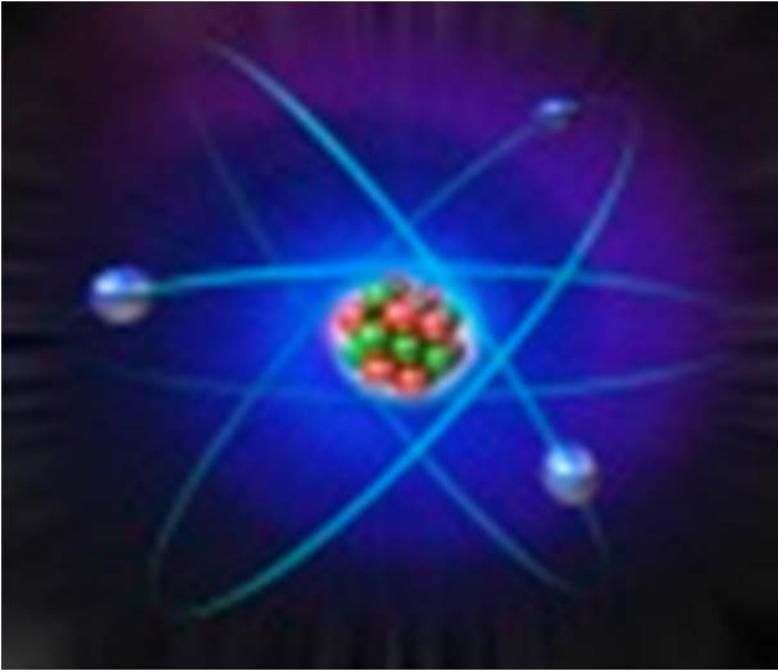
1s electron T=150 as  
Bohr 1913



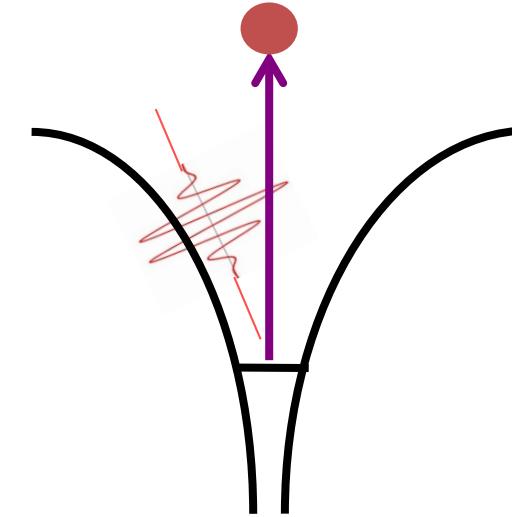
DeBroglie  
1924



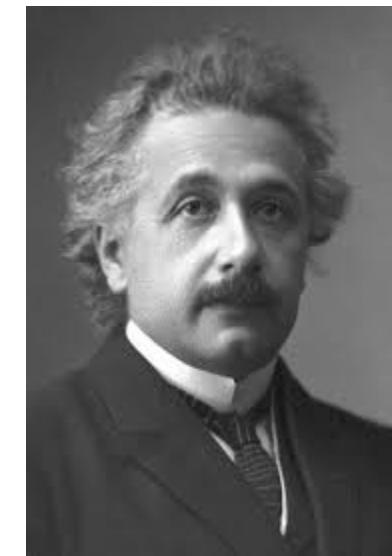
# Mouvement des électrons dans les atomes



1s electron T=150 as  
Bohr 1913



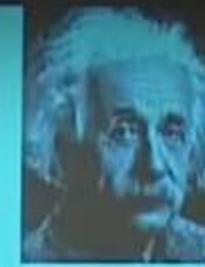
L'effet photoélectrique  
(Einstein) 1905



## PHOTOELECTRIC EFFECT

Violet Light

Electron ejected at high speed



ALBERT EINSTEIN

Photoelectric Effect

1905

Combien de temps  
faut-il à un électron  
pour être ionisé ?



spela upp (k)

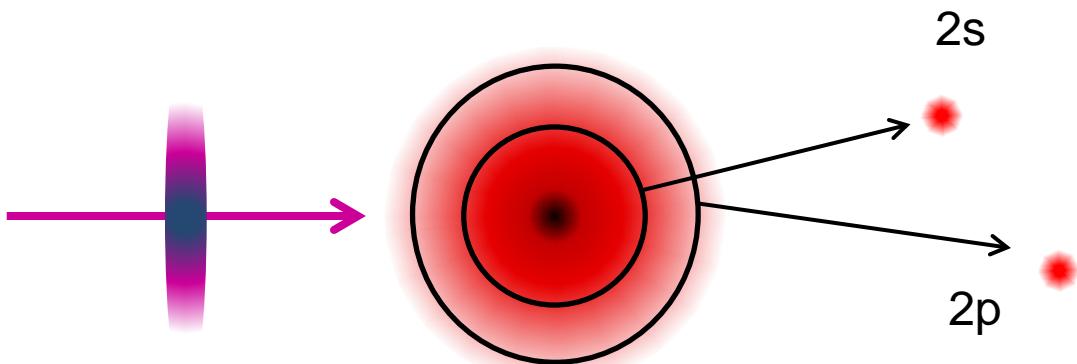
nobeiprize

7:35 / 32:13

Rulla för mer information

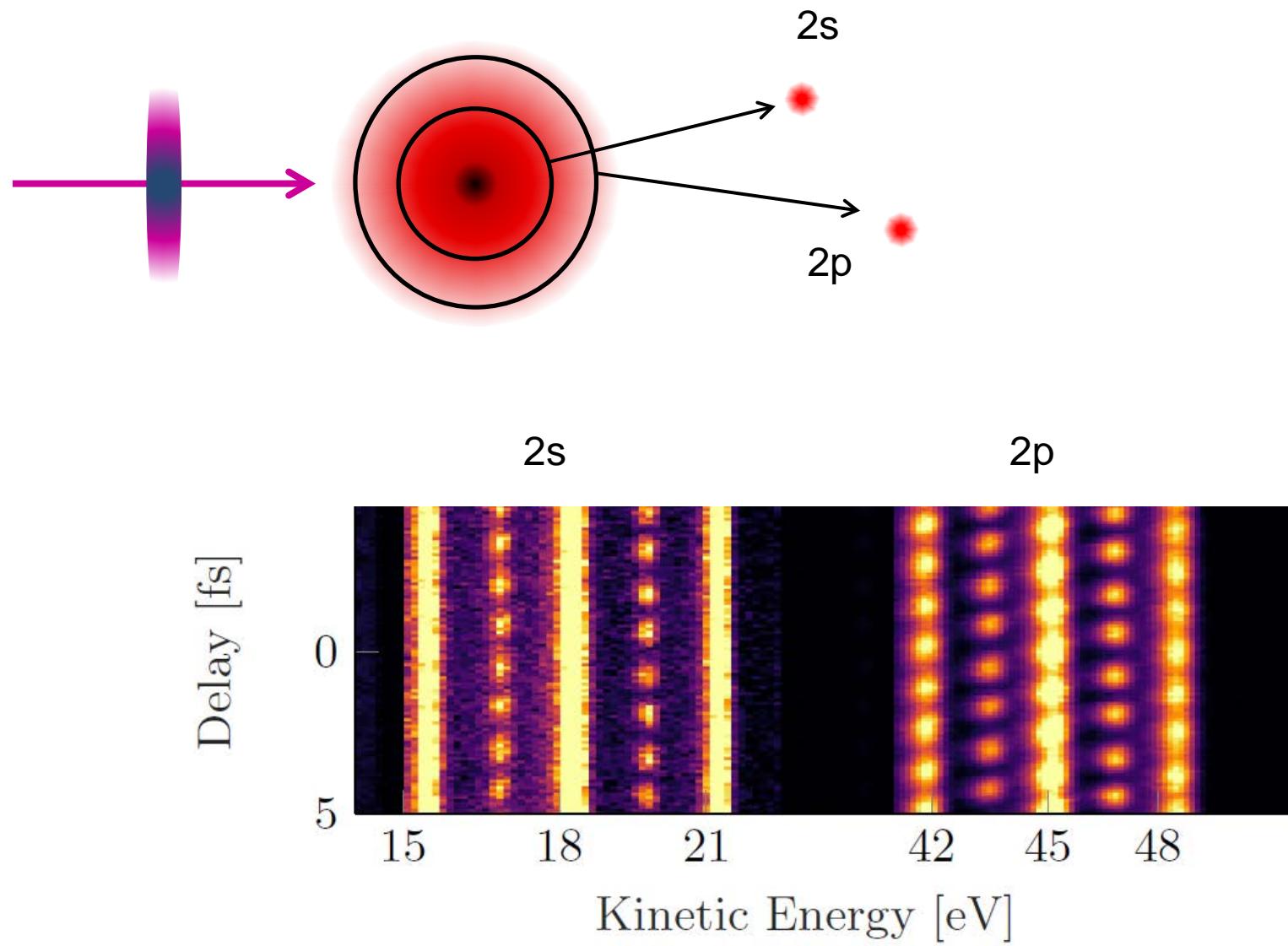
# Lequel arrive le premier ?

Ne  $1s^2 2s^2 2p^6$

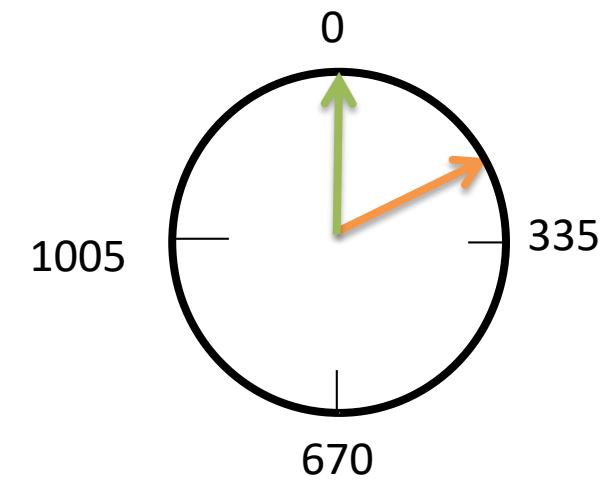
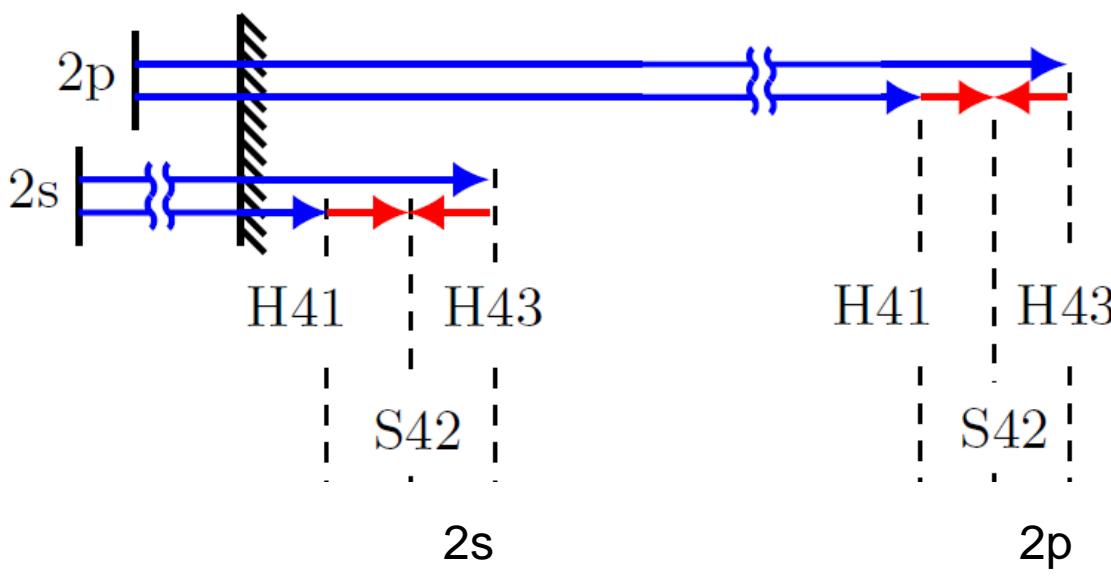


Courtesy: Mathieu Gisselbrecht

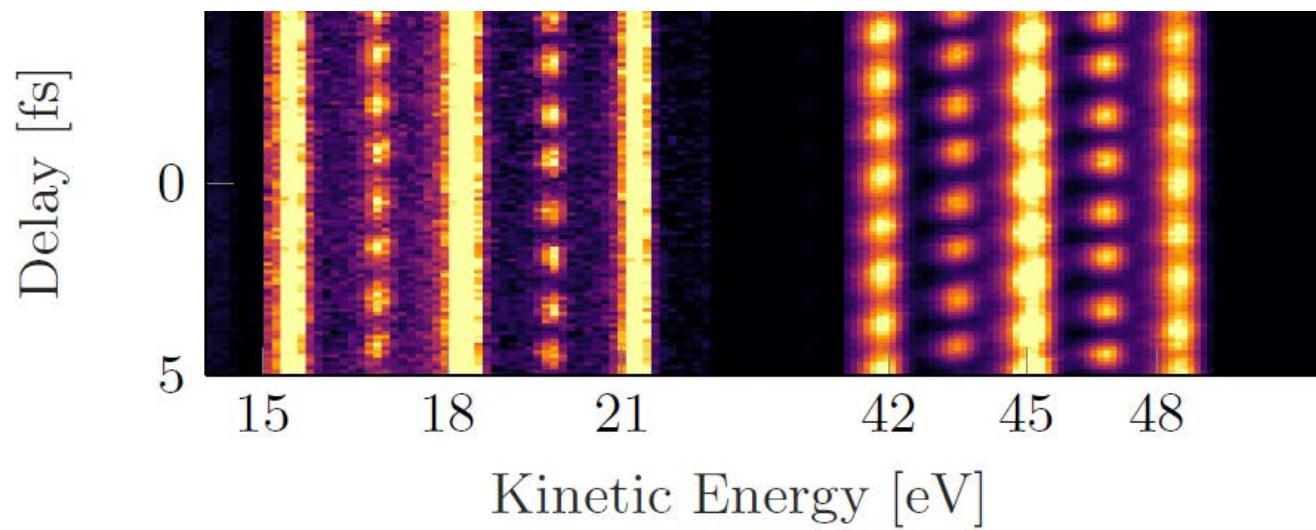
# Mesure d'un intervalle de temps



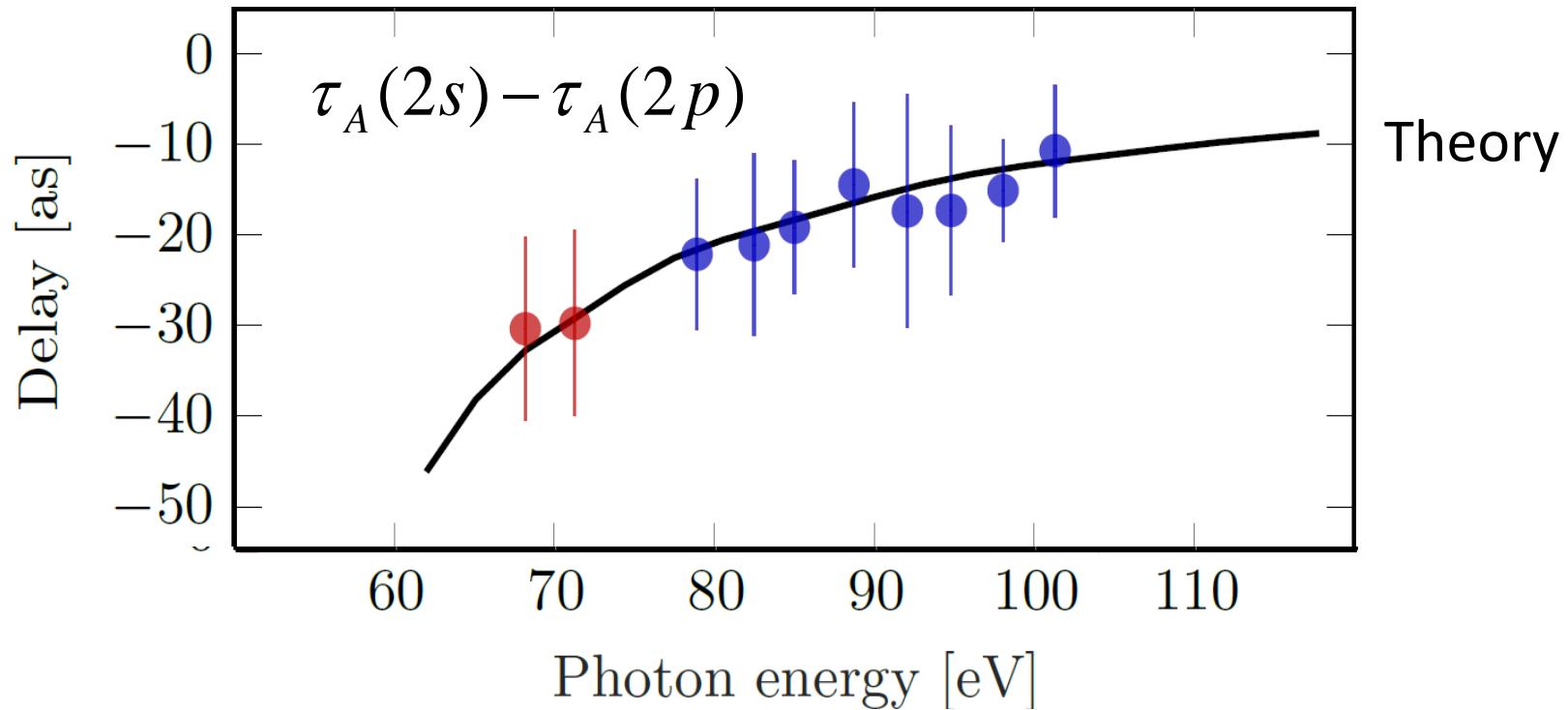
# Mesure d'un intervalle de temps



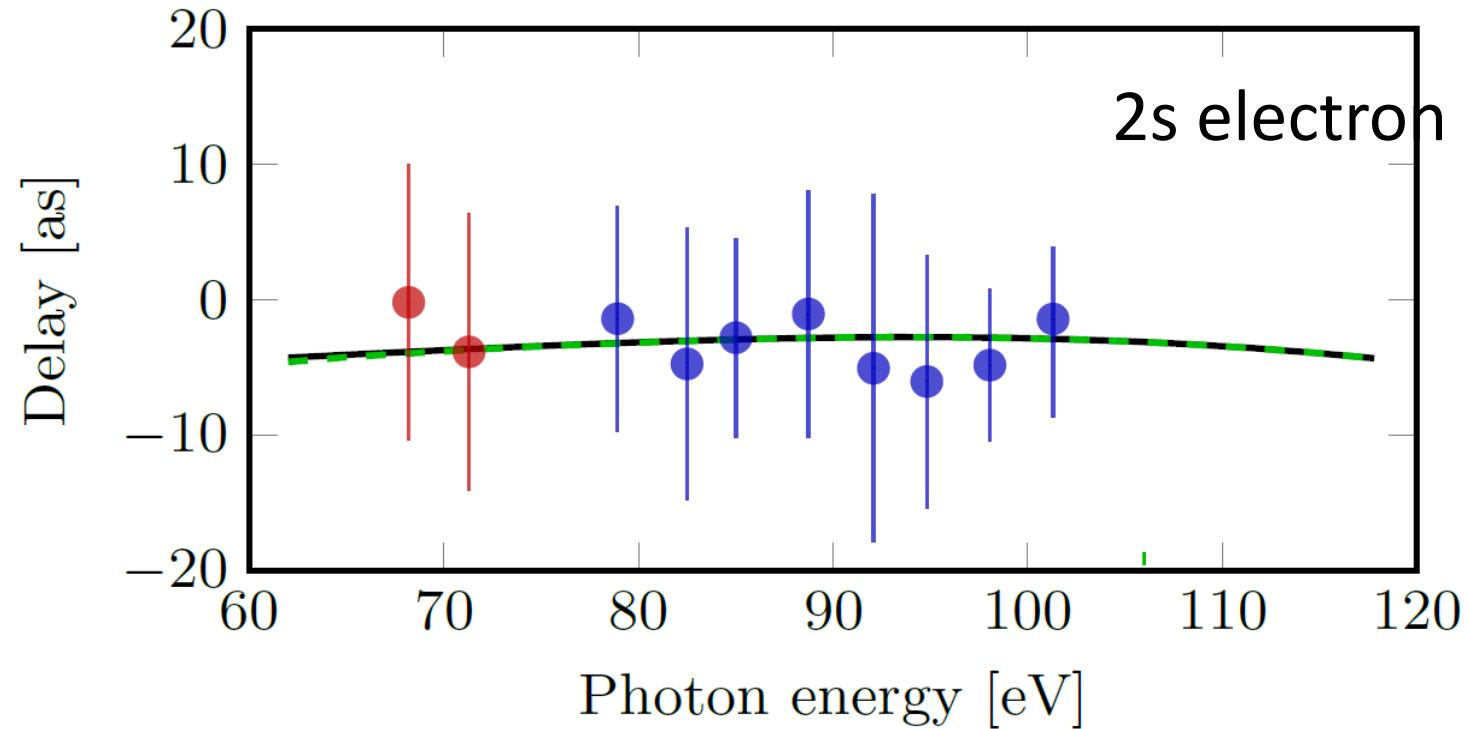
$$\tau_A(2s) - \tau_A(2p)$$



# Ionisation du néon en couche 2s et 2p



# Combien de temps faut-il à un électron pour être ionisé ?



SUEDE



# Merci !

