Comment la lumière joue avec la matière ?
Avec l'optique non linéaire !

Benoît BOULANGER

Auditorium BU Sciences UJF - Mardi 17 novembre 2015

The nature of light : a wave - a particle

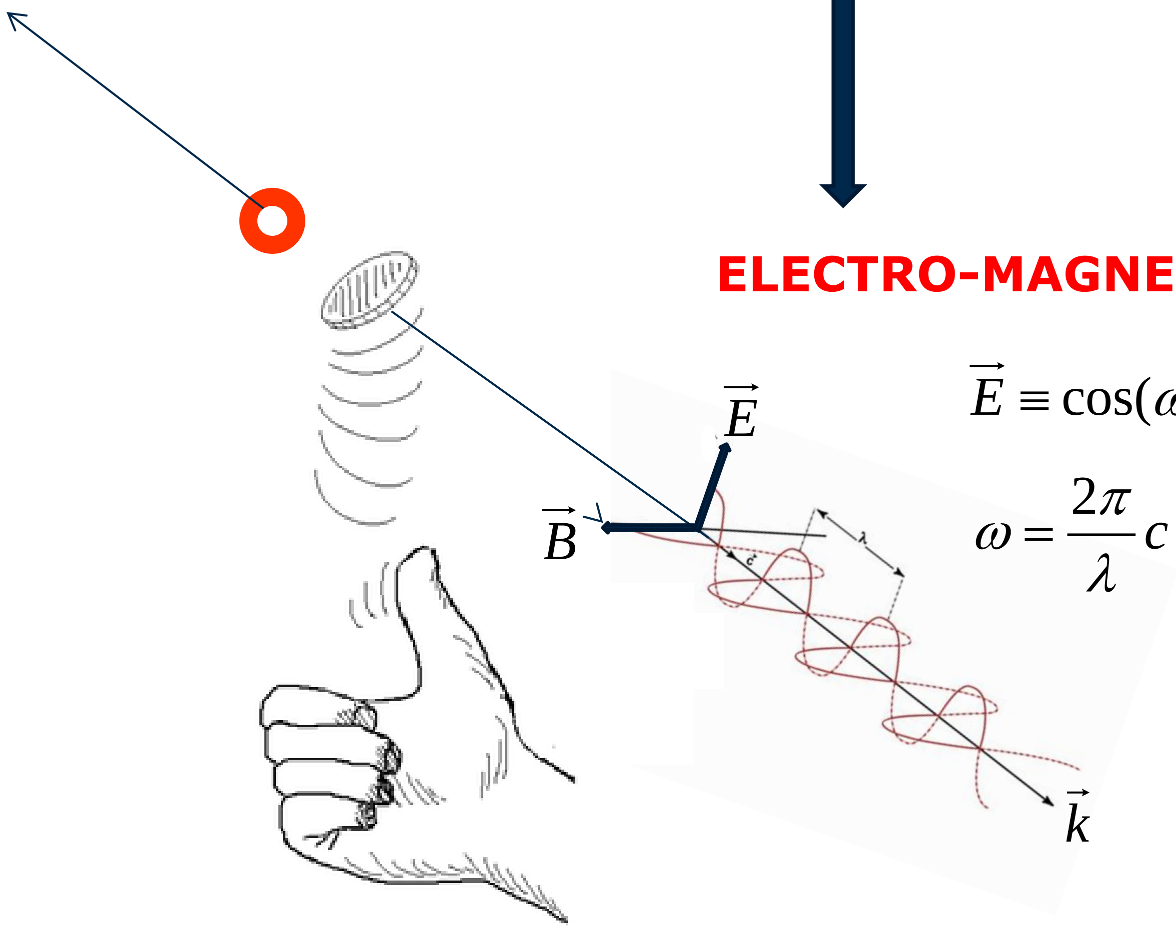
PHOTON

- Energy $= \hbar\omega$
- Momentum $= \hbar\vec{k}$
- Polarization $\vec{E}$

$(\omega, \vec{k}, \vec{E})$

Connection between classical and quantum

ELECTRO-MAGNETIC WAVE



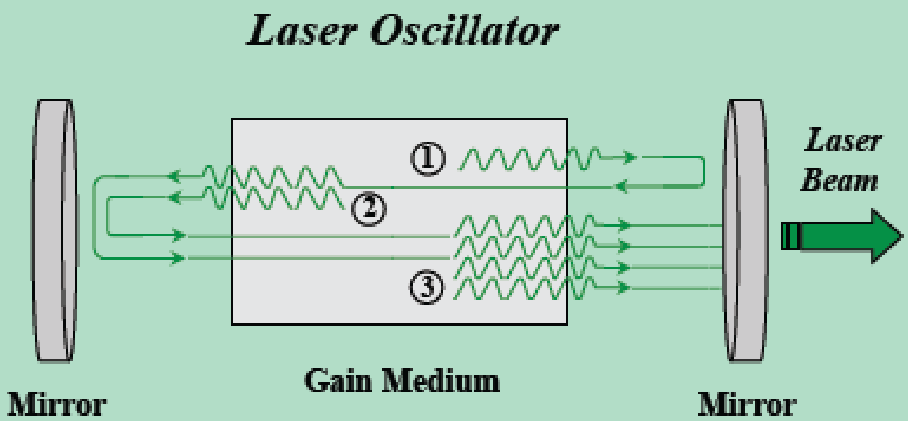
$$\vec{E} \equiv \cos(\omega t - \vec{k}.\vec{r})$$

$$\omega = \frac{2\pi}{\lambda} c$$

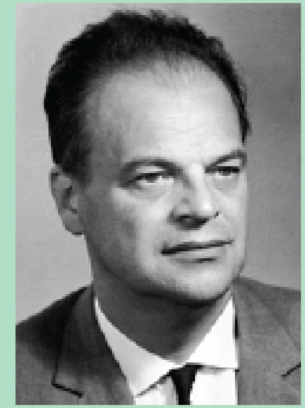
1960, The invention of LASER

Charles Townes
1915-2015
(Nobel Prize, 1964)

Arthur Schawlow
1921-1999
(Nobel Prize, 1981)



- *Coherent*
- *High Intensity*
- *Directional*
- *Monochromatic*

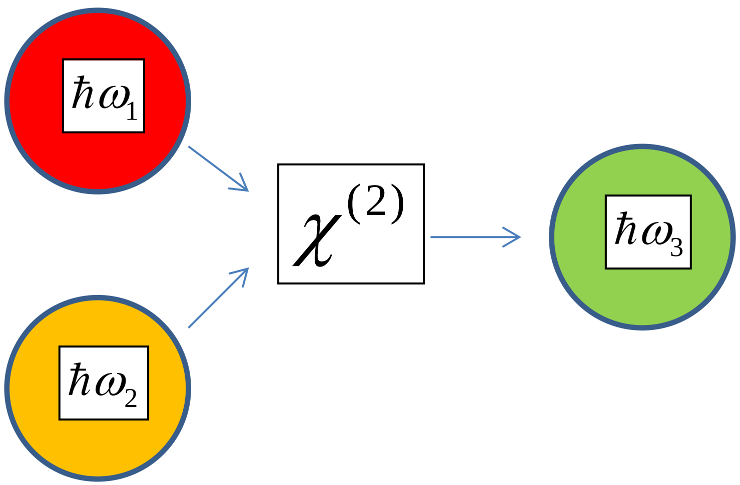


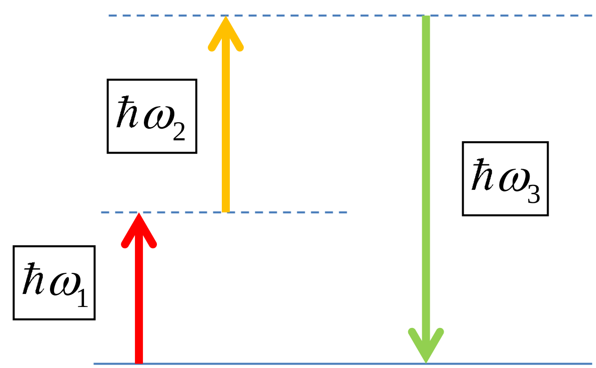
Nicolay Basov
1922-2001
(Nobel Prize, 1964)

Aleksander Prokhorov
1916-2002
(Nobel Prize, 1964)

Nonlinear three-photon processes

Fusion of two photons ⟺ Sum-Frequency Generation (SFG) (Up conversion)





Energy conservation $\hbar\omega_1 + \hbar\omega_2 = \hbar\omega_3$

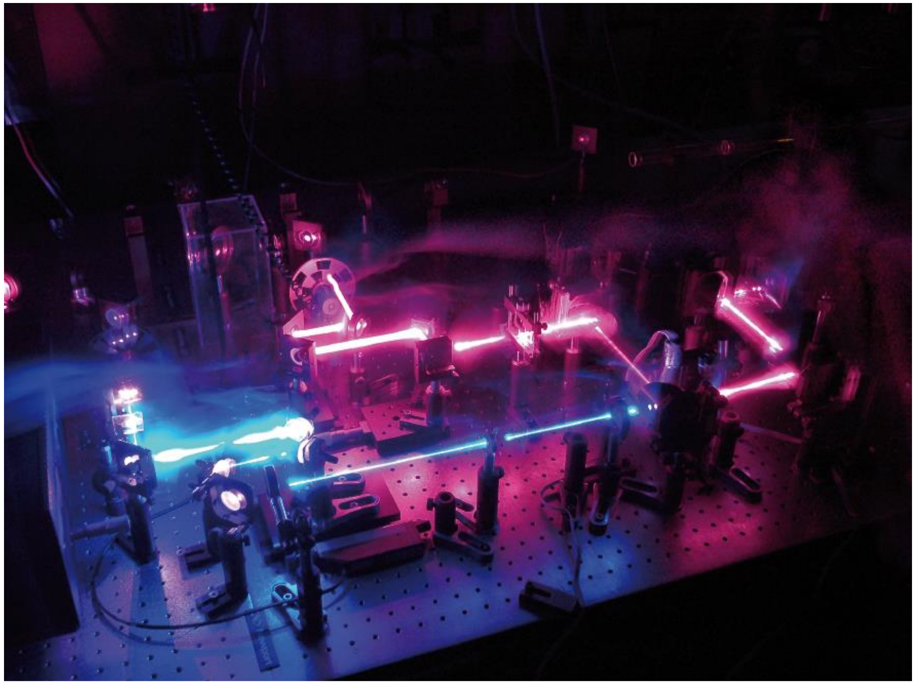
Momentum conservation $\hbar k_1 + \hbar k_2 = \hbar k_3$

$\omega_1 = \omega_2$ in the case of Second Harmonic Generation (SHG)

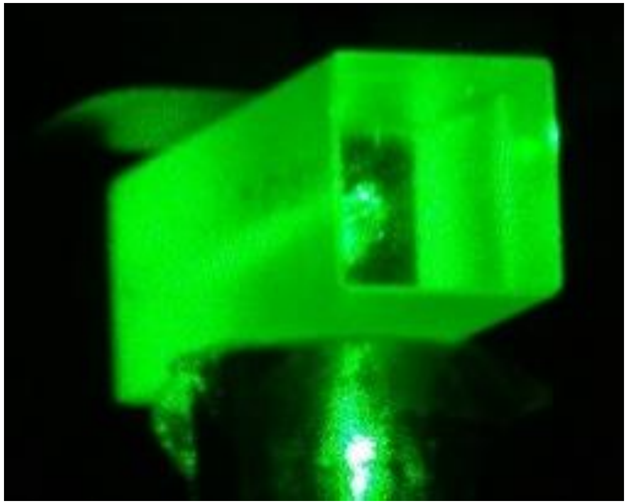
Second harmonic generation experiments

From red to blue

$$\omega + \omega = 2\omega$$

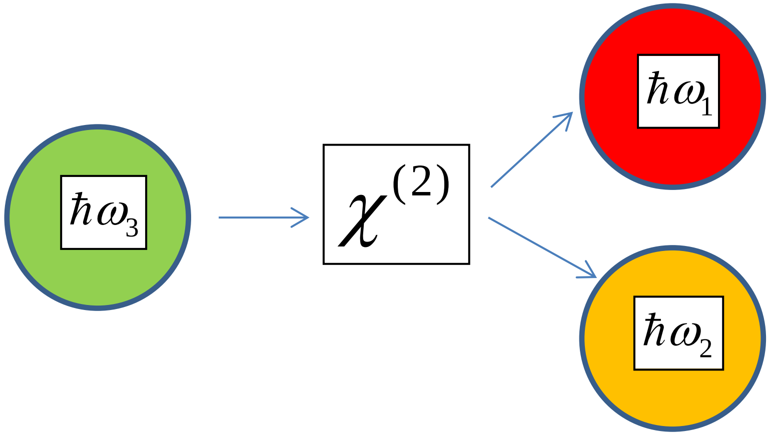


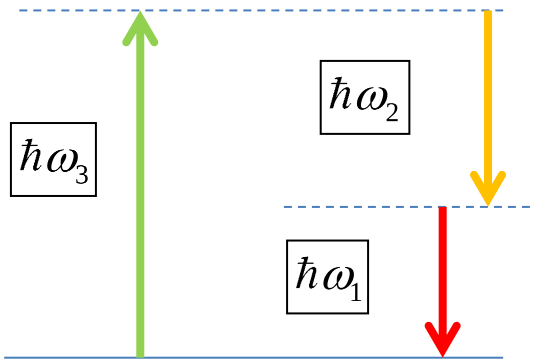
From invisible to visible



A revolution in medicine : ophtalmology, dermatology, etc.

Spontaneous splitting of one photon into two ⟺ Parametric Fluorescence (Down conversion)



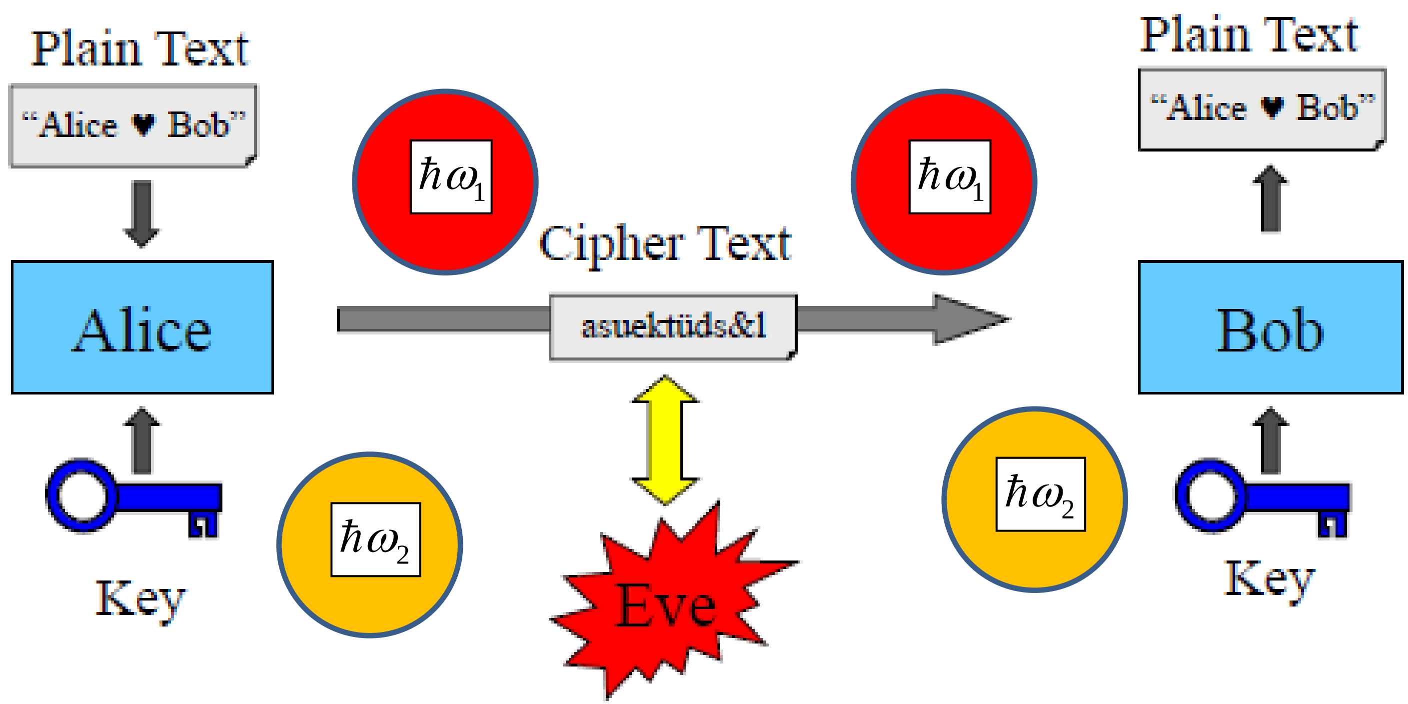


Energy conservation $\hbar\omega_3 = \hbar\omega_1 + \hbar\omega_2$

Momentum conservation $\hbar k_3 = \hbar k_1 + \hbar k_2$

The exact reverse of two-photon fusion

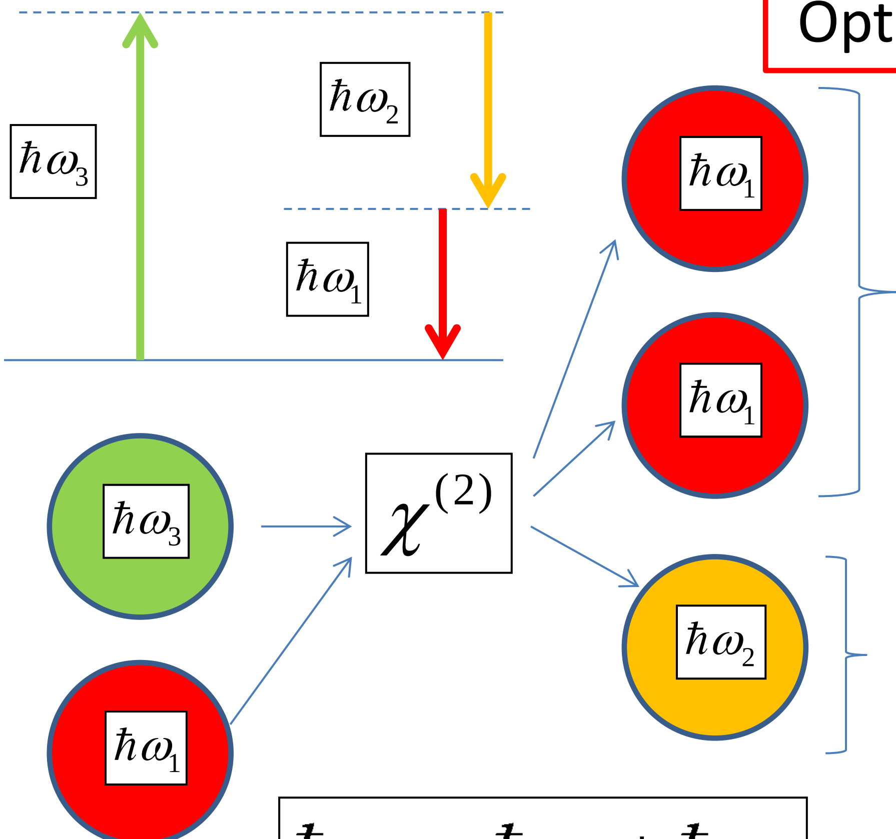
Example of quantum cryptography using photon pairs



- Secure communication between Alice and Bob
- The spy, Eve, tries to read the encoded message

Stimulated splitting of one photon into two ⟷

Difference-Frequency Generation (DFG)
(Down conversion)
Optical Parametric Amplification (OPA)



Optical Parametric Amplification (OPA)
@ ω_1

Difference-Frequency Generation (DFG)
@ ω_2

$$\hbar\omega_3 = \hbar\omega_1 + \hbar\omega_2$$

$$\hbar k_3 = \hbar k_1 + \hbar k_2$$

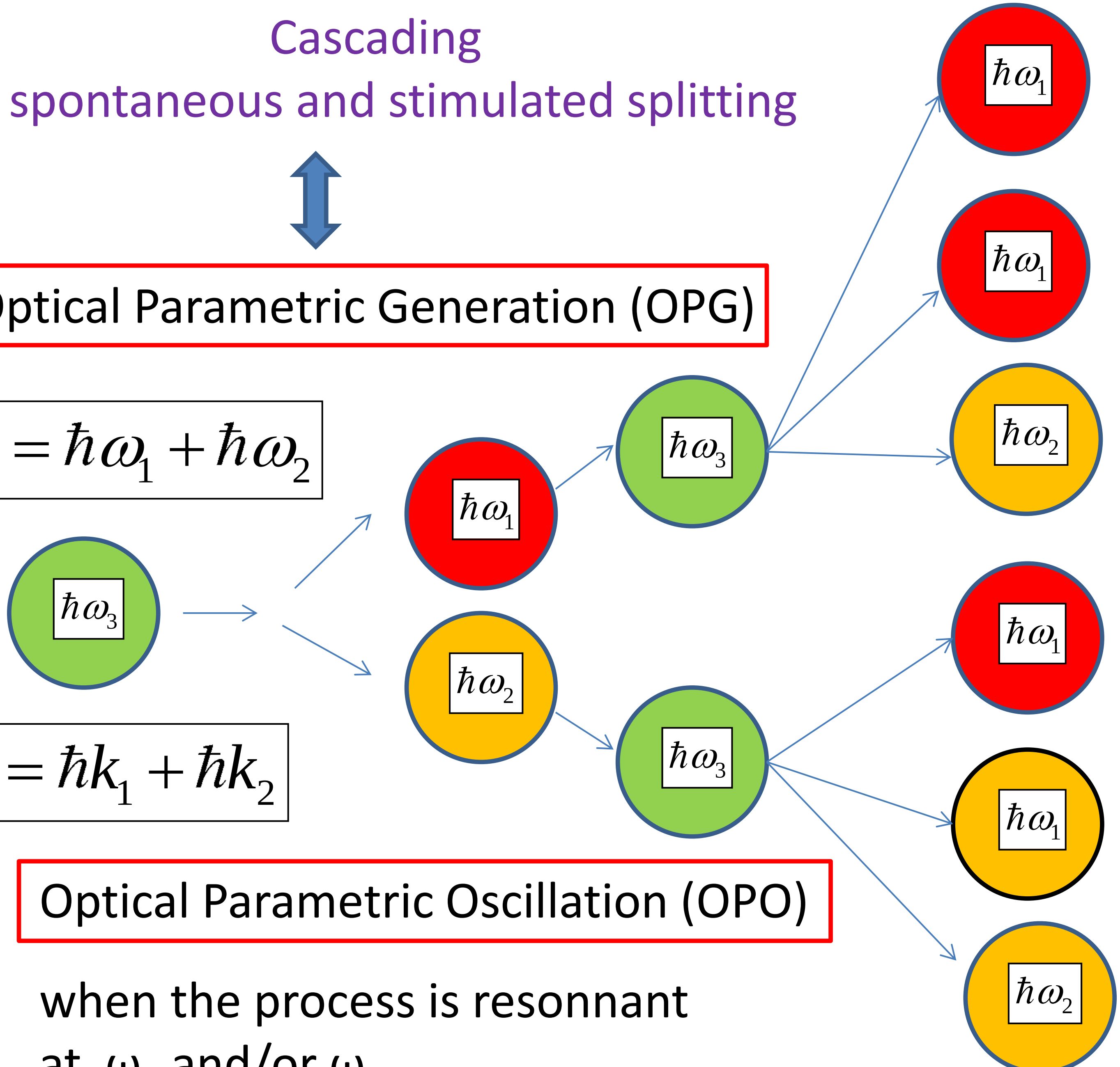
Idem for a stimulation
@ ω_2

Cascading
of spontaneous and stimulated splitting

⇕

Optical Parametric Generation (OPG)

$$\hbar\omega_3 = \hbar\omega_1 + \hbar\omega_2$$



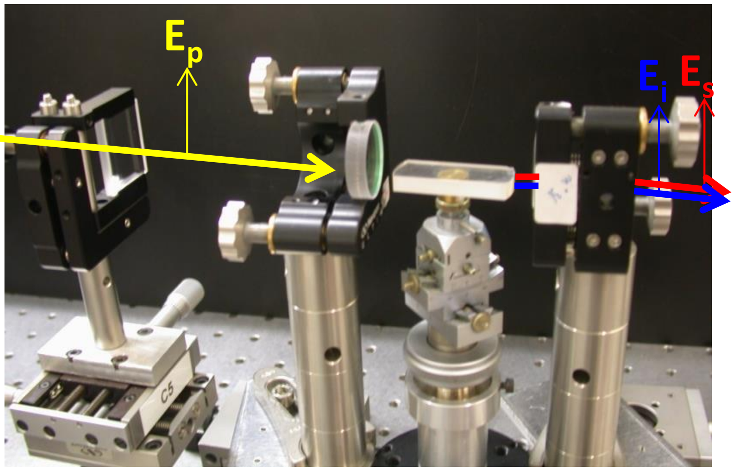
$$\hbar k_3 = \hbar k_1 + \hbar k_2$$

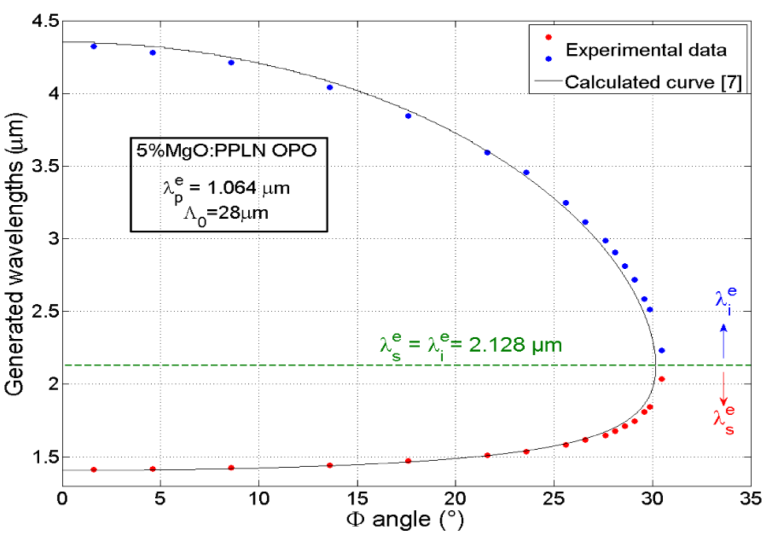
Optical Parametric Oscillation (OPO)

when the process is resonnant
at ω_1 and/or ω_2

Examples of Optical Parametric Oscillators (OPO)

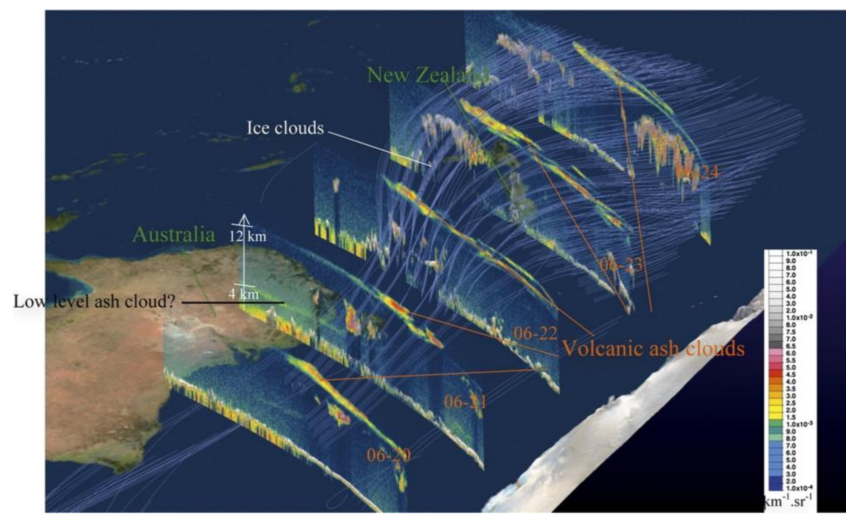
A new tunable OPO





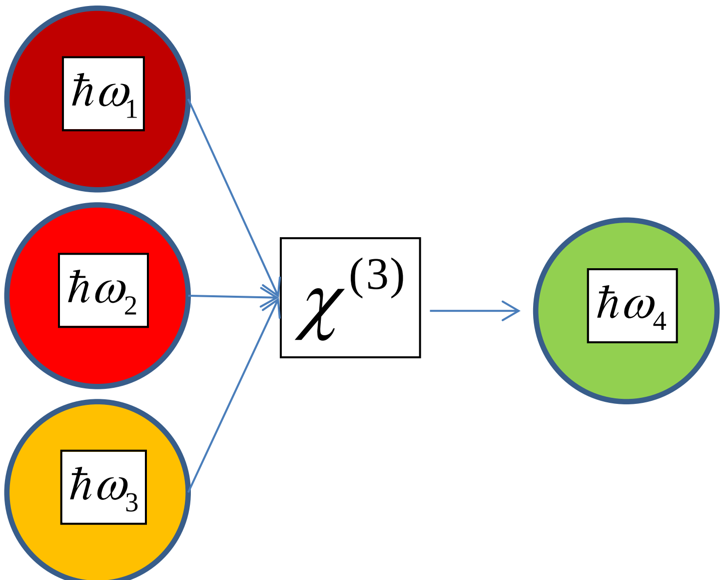
Kemlin, Jegouso, Debray, Segonds, Boulanger, Menaert, Ishizuki, Taira, Opt. Lett. (2013)

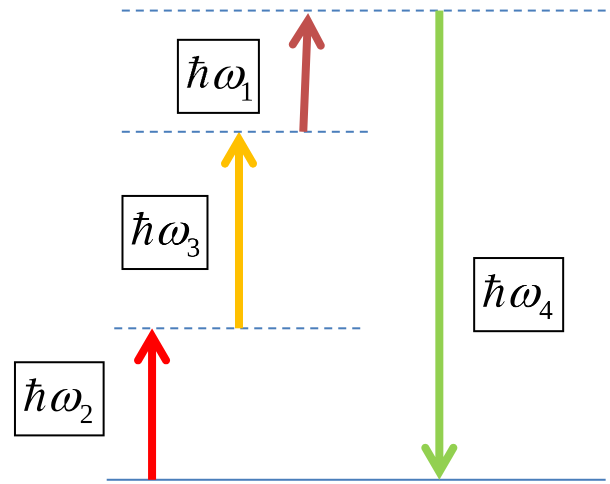
The LIDAR : an eye in the atmosphere



Nonlinear four-photon processes

Fusion of three photons ⟺ Sum-Frequency Generation (Up conversion)





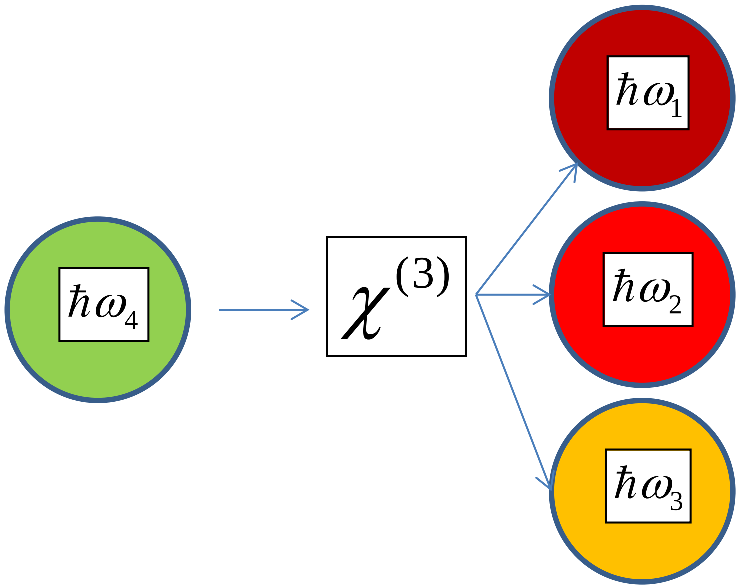
$$\hbar\omega_1 + \hbar\omega_2 + \hbar\omega_3 = \hbar\omega_4$$

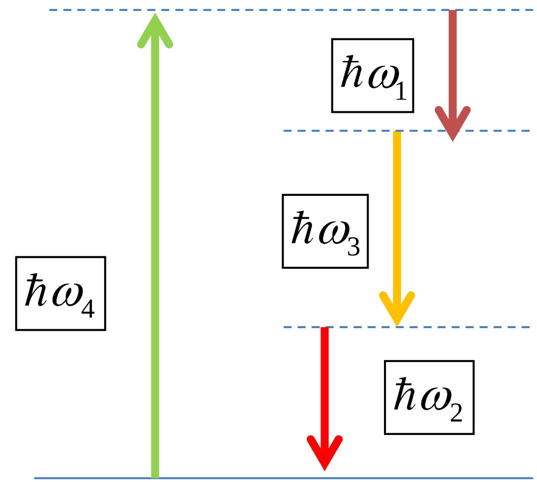
$$\hbar k_1 + \hbar k_2 + \hbar k_3 = \hbar k_4$$

$\omega_1 = \omega_2 = \omega_3$ in the case of Third Harmonic Generation (THG)

Spontaneous splitting of one photon into three

Parametric Fluorescence (Down conversion)





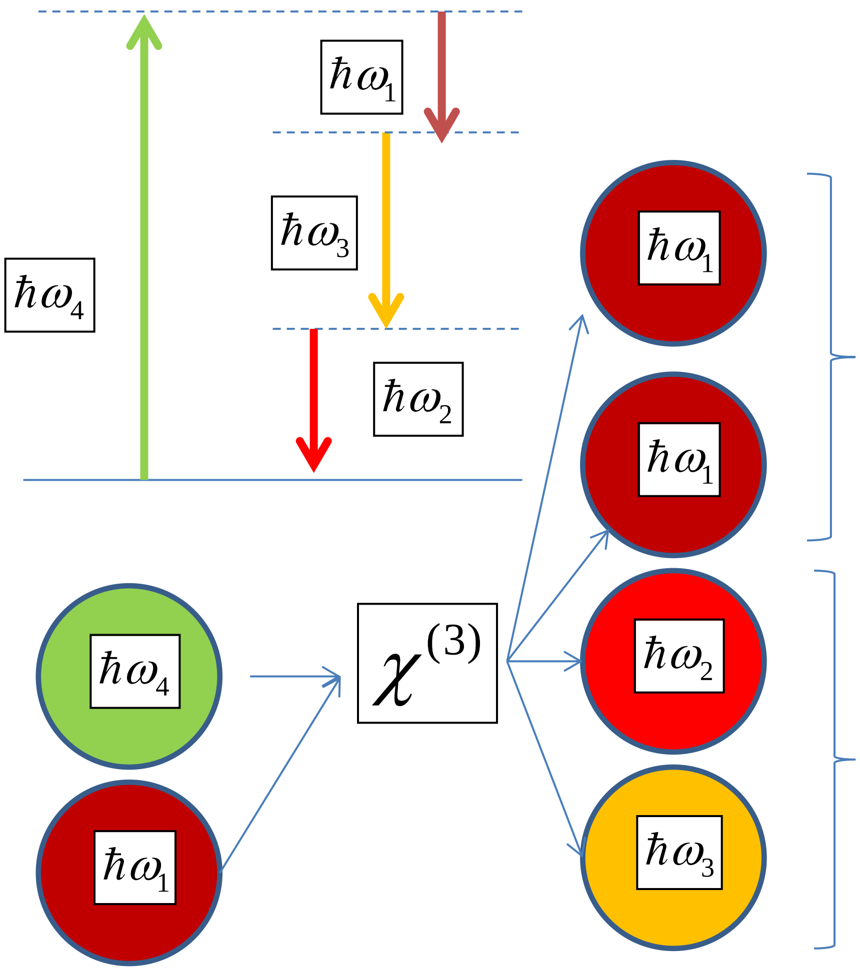
$$\hbar\omega_4 = \hbar\omega_1 + \hbar\omega_2 + \hbar\omega_3$$

$$\hbar k_4 = \hbar k_1 + \hbar k_2 + \hbar k_3$$

The exact reverse of three-photon fusion

Single-Stimulated splitting of one photon into three ⟺

Difference-Frequency Generation
Optical Parametric Amplification
(Down conversion)



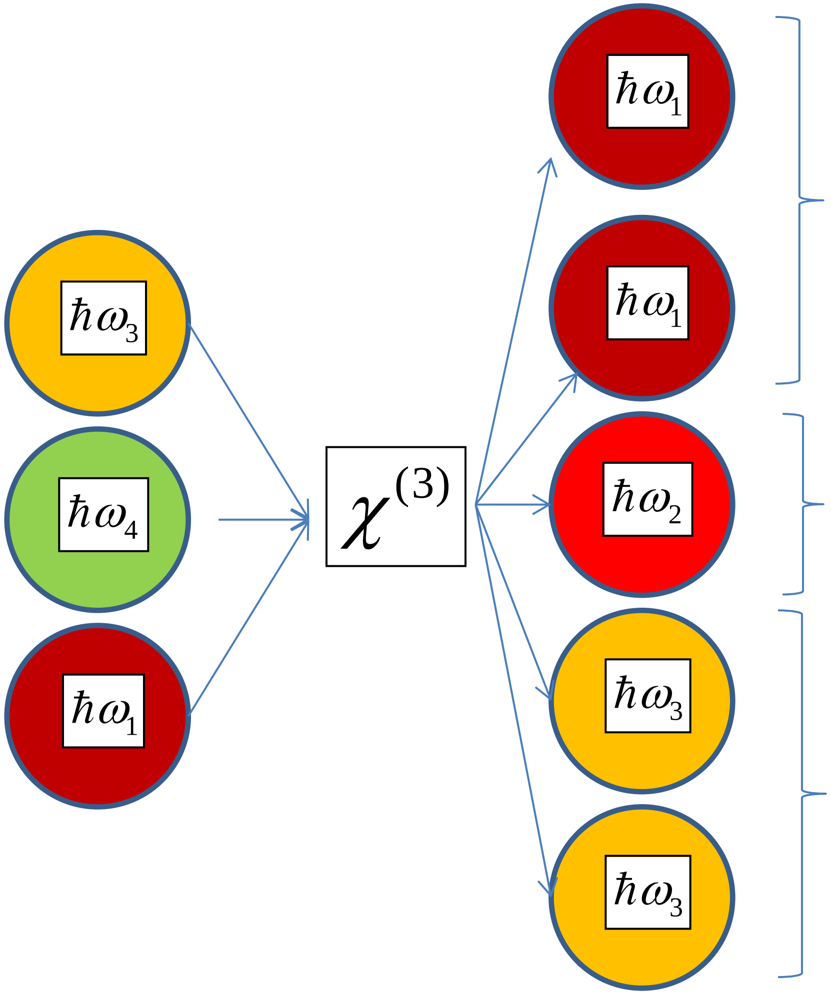
Optical Parametric Amplification (OPA) @ ω_1

Difference-Frequency Generation (DFG) @ ω_2 & ω_3

Idem for a stimulation @ ω_2 or ω_3

Double-Stimulated splitting of one photon into three

Difference-Frequency Generation
Optical Parametric Amplification
(Down conversion)



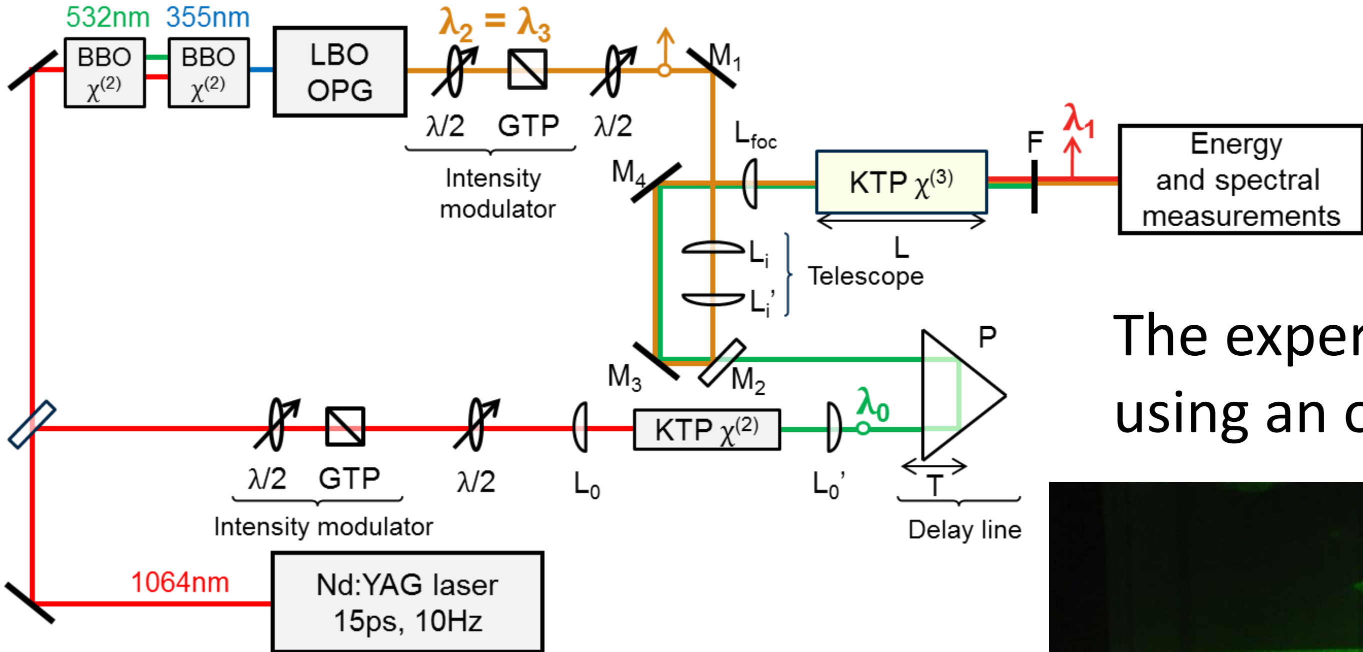
Optical Parametric Amplification (OPA)
@ ω_1

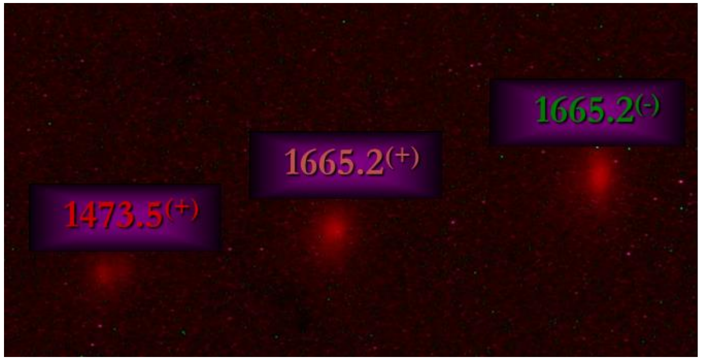
Difference-Frequency
Generation (DFG)
@ ω_2 & ω_3

Optical Parametric Amplification (OPA)
@ ω_3

The triplet of photons : a new state of light

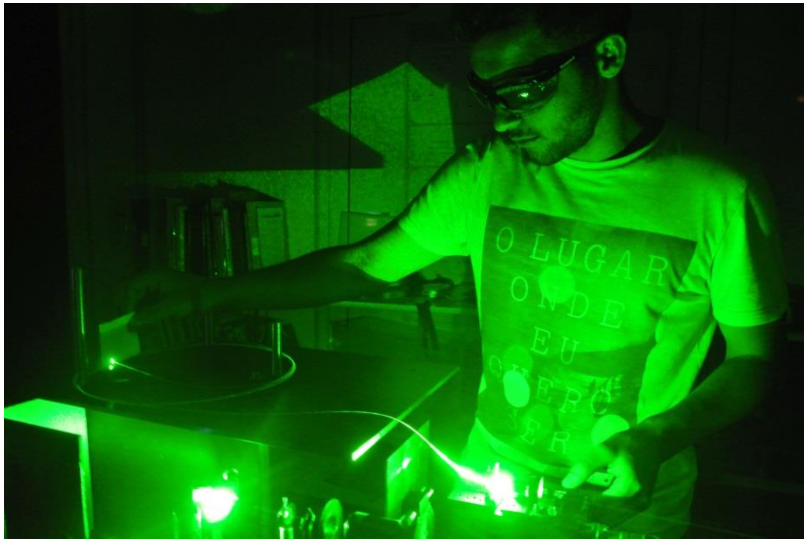
The pioneer experiment using a KTP crystal





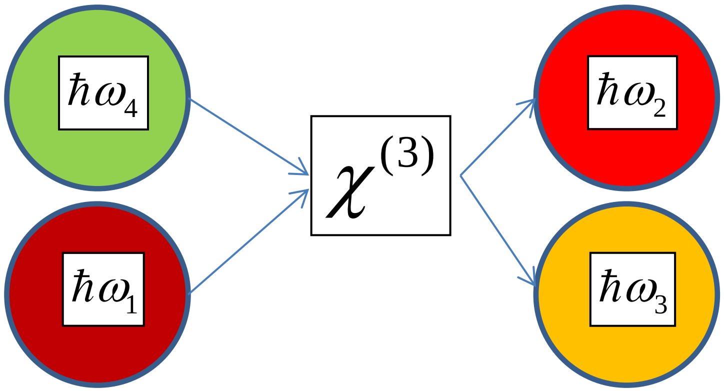
Douady & Boulanger
Optics Letters 29(23) (2004)

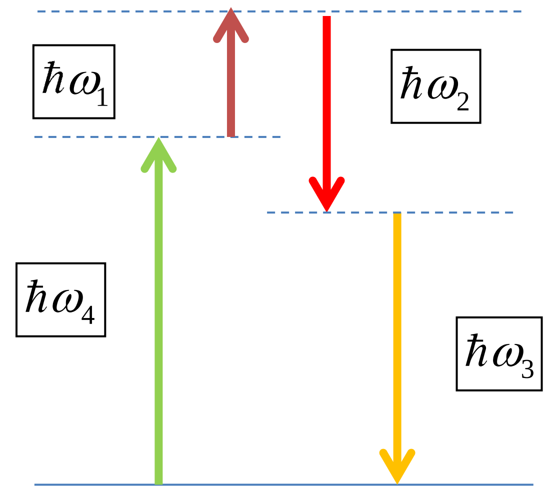
The experiment in progress using an optical fiber



Boulanger, Ducci, Gérard
La Recherche, Hors Série, N° 14 (2015)

Photon fusion/splitting ⟺ Four-wave mixing (FWM)





$$\hbar\omega_4 + \hbar\omega_1 = \hbar\omega_2 + \hbar\omega_3$$

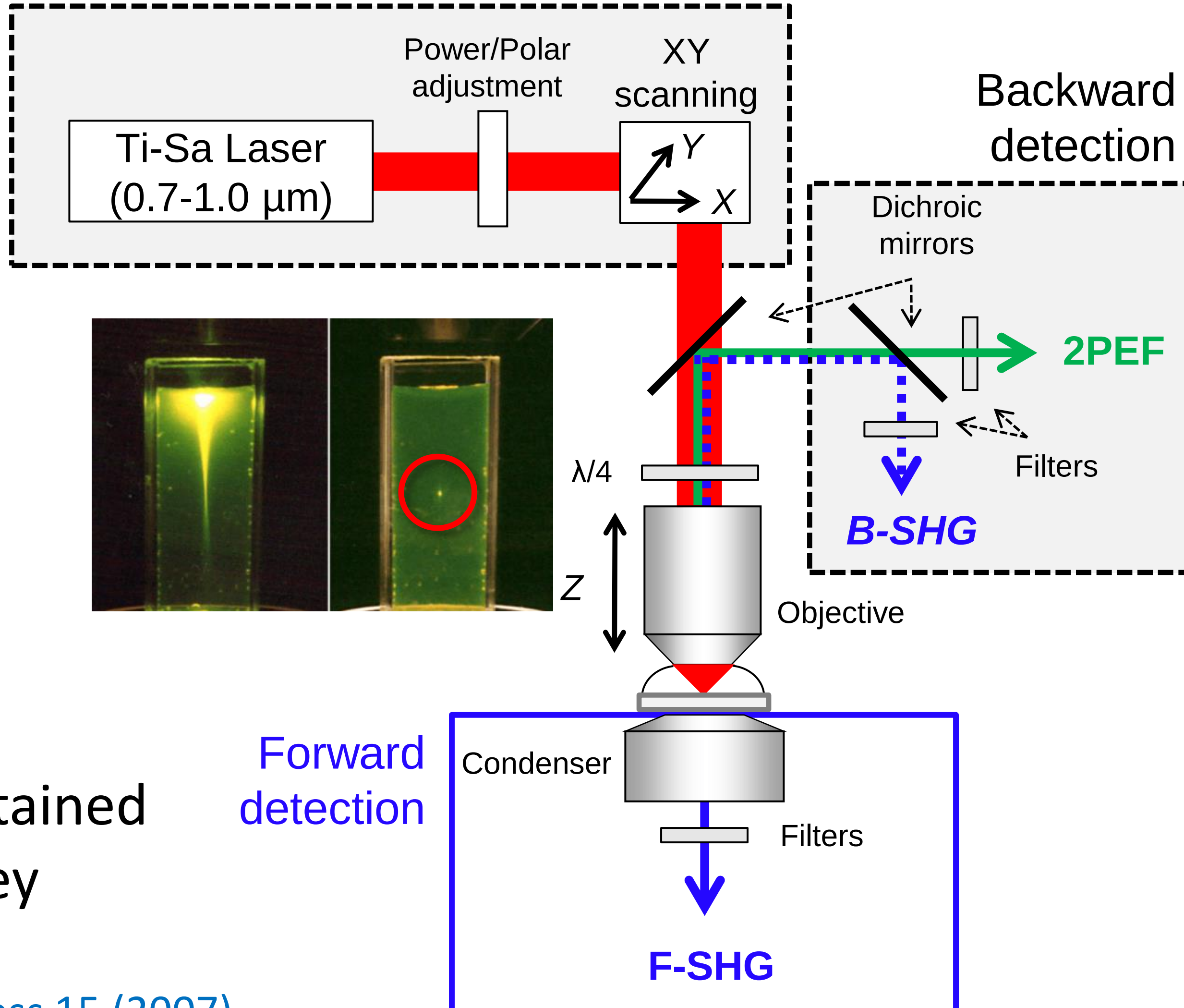
$$\hbar k_4 + \hbar k_1 = \hbar k_2 + \hbar k_3$$

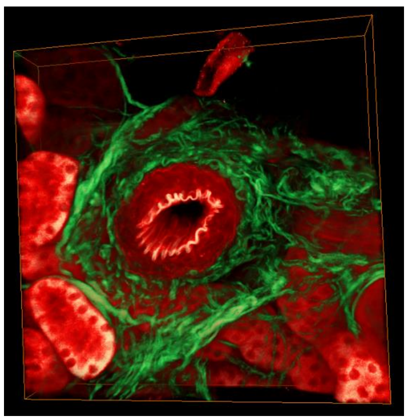
$\omega_1 = \omega_2 = \omega_3 = \omega_4$ in the case of

degeneracy

- Kerr effect $\mathrm{Re}\{\chi^{(3)}\}$
- Two-Photon Absorption $\mathrm{Im}\{\chi^{(3)}\}$

Used in multiphoton microscopy : spatial resolution

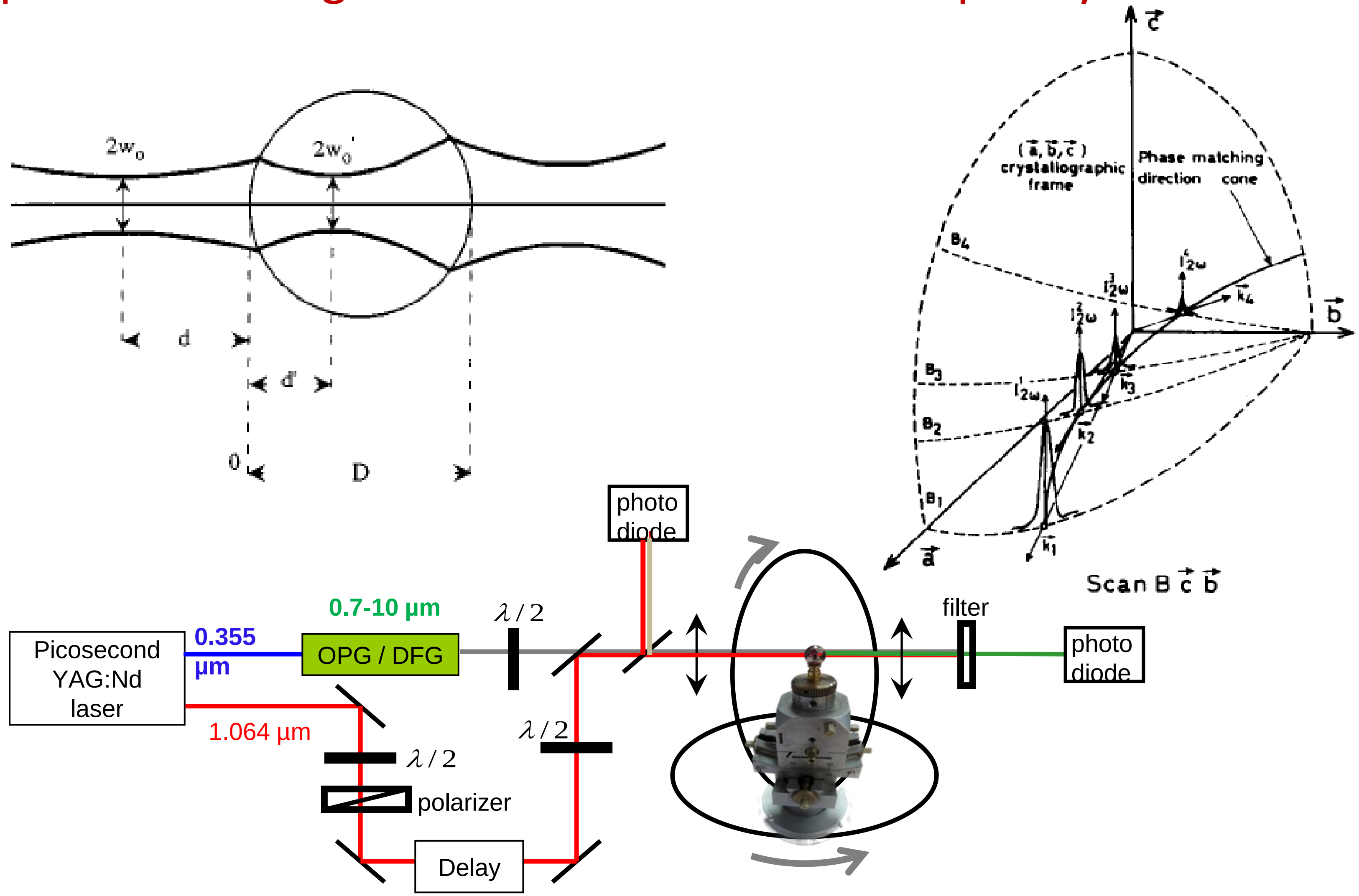




arcuate artery in unstained fibrotic murine kidney

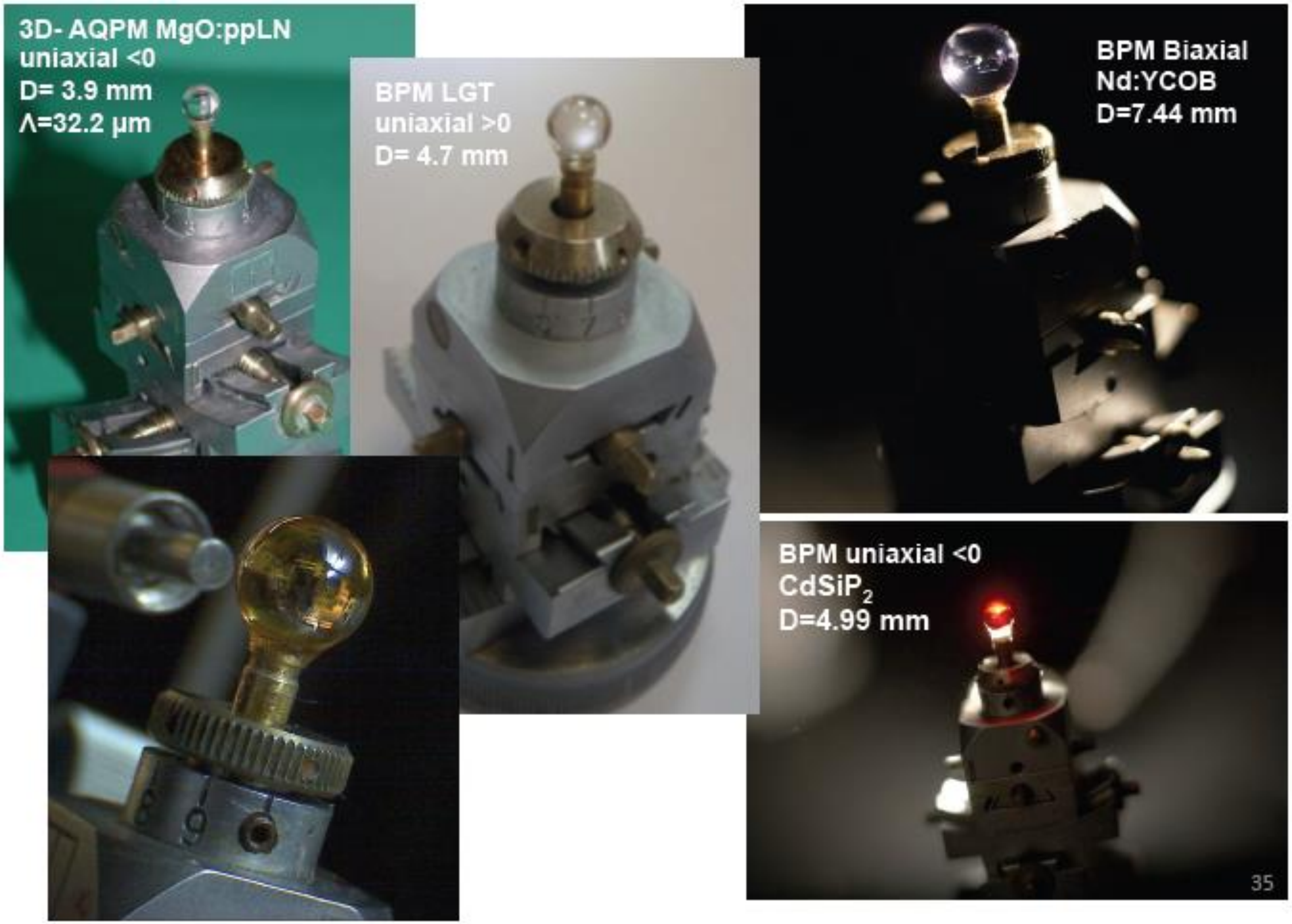
M. Strupler et al, Opt. Express 15 (2007)

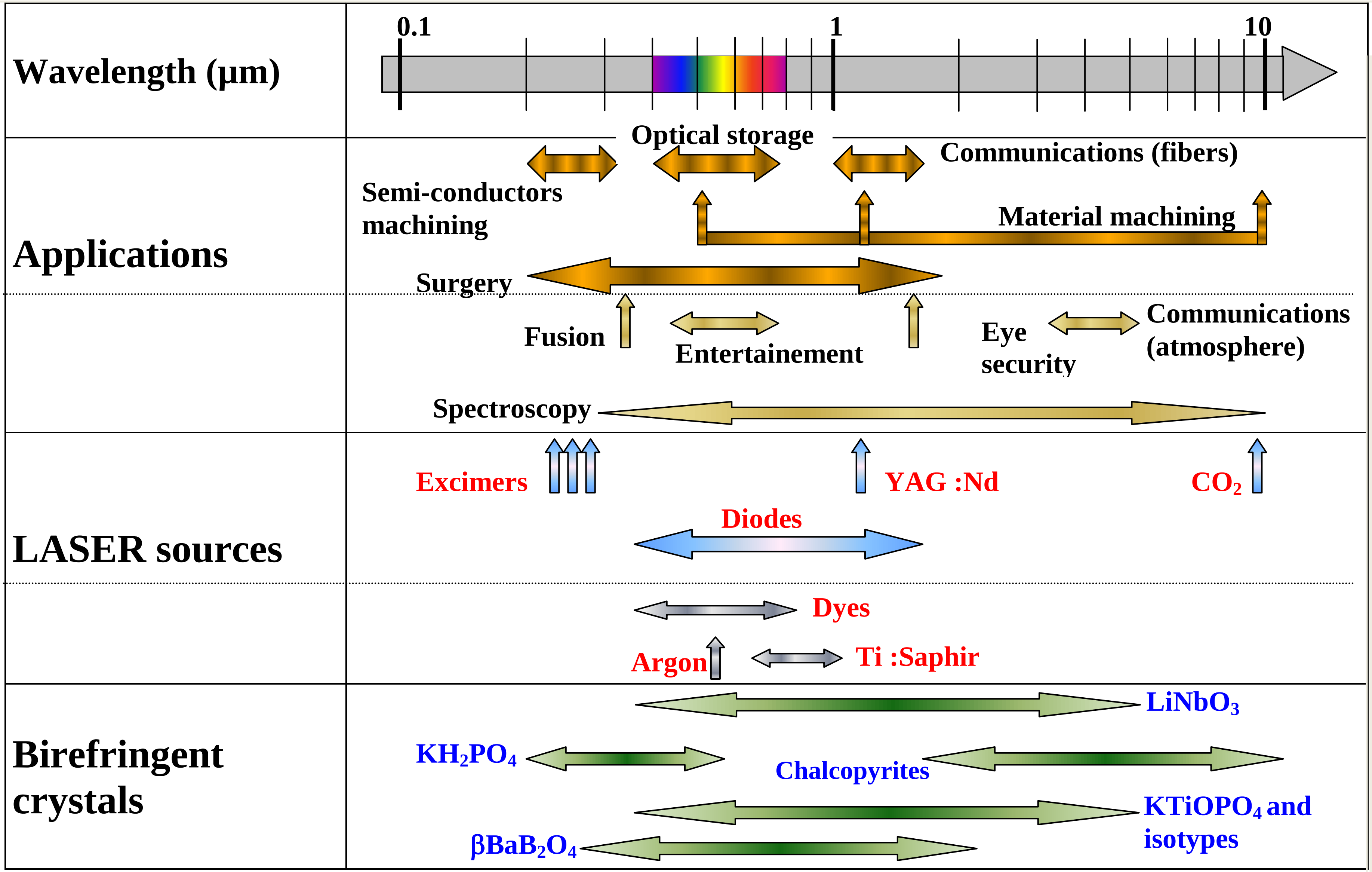
The sphere method : a unique tool for the direct measurement of phase-matching directions for nonlinear frequency conversion



Marnier & Boulanger, Opt. Com. 72 (1989) & Boulanger, Segonds, Ménaert, Zaccaro, Opt. Mat. 26 (2004)

Example of crystal spheres cyt and studied at Institut Néel





Boulanger and Fève, Encyclopedia of Electrical and Electronical Engineering, Vol 15, J.G. Webster Ed., Wiley, New York

THANK YOU VERY MUCH FOR YOUR ATTENTION