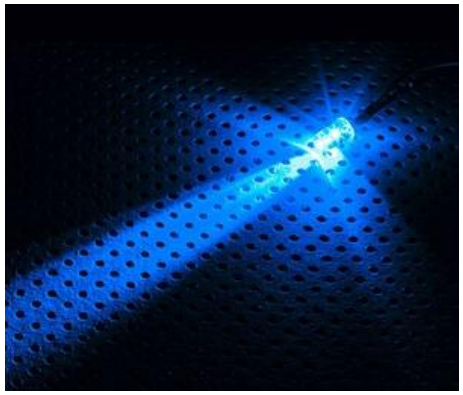
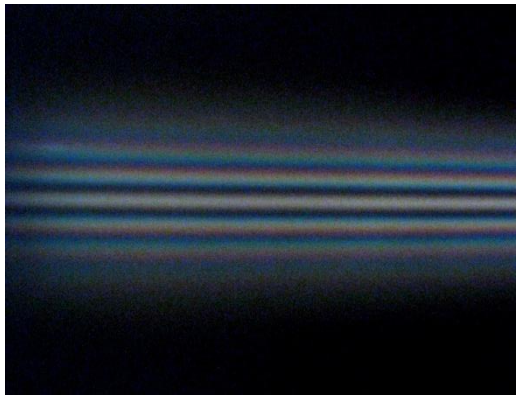
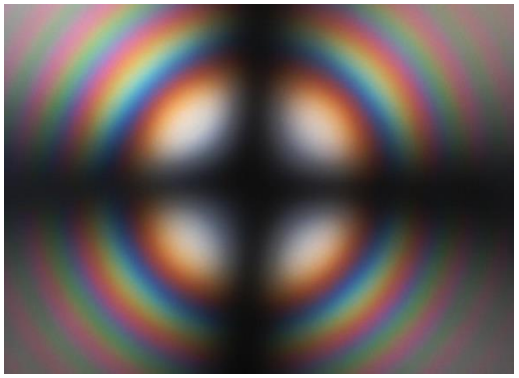
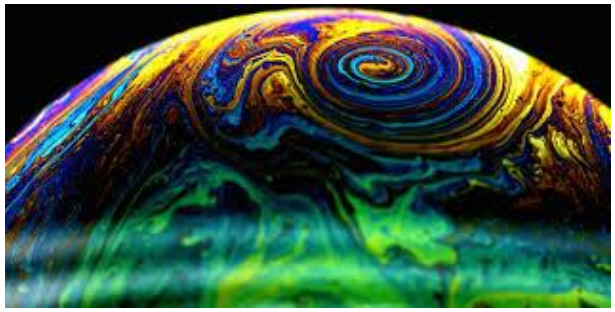
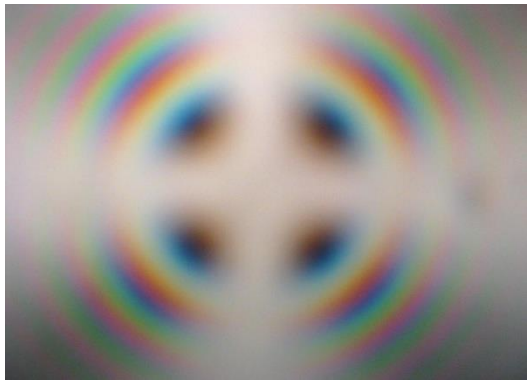




cycle « Lumière et couleurs »

Renaud Mathevet

Université Paul Sabatier

LNCMI

UNIVERSITÉ TOULOUSE III PAUL SABATIER Université de Toulouse

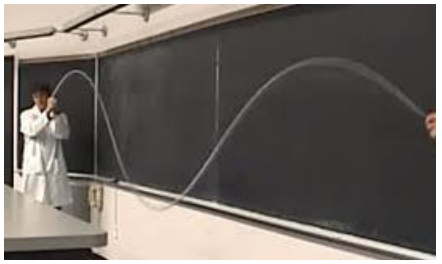
Plan

Du modèle corpusculaire au modèle ondulatoire

De la spectroscopie au modèle quantique de l'atome…

… jusqu'à la LED bleue

et au-delà…



Plan

Du modèle corpusculaire au modèle ondulatoire

De la spectroscopie au modèle quantique de l'atome…

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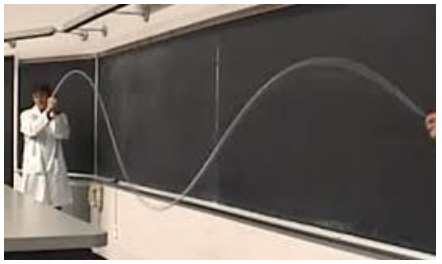
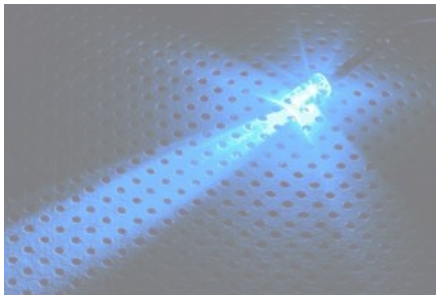
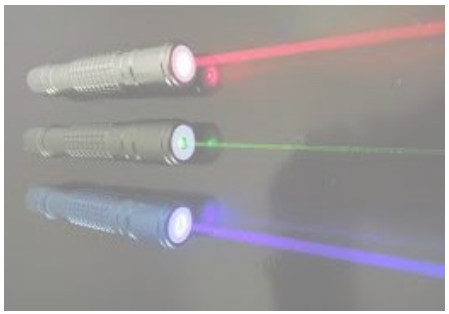
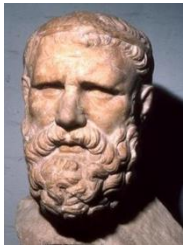




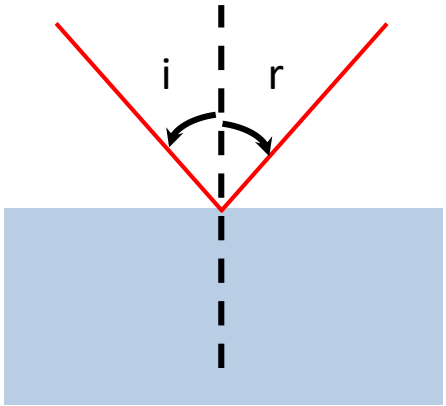


Conceptions antiques

ombres portées:
- rayon lumineux
- propagation rectiligne



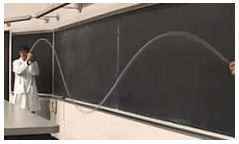
Eratosthène
≈ 230 av. JC

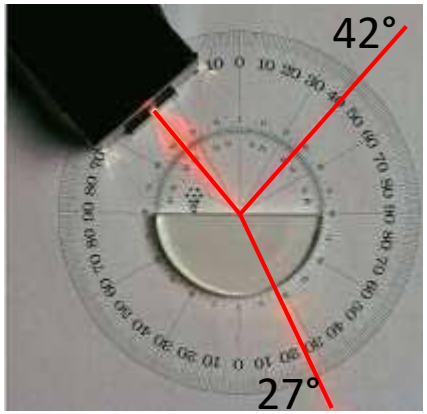


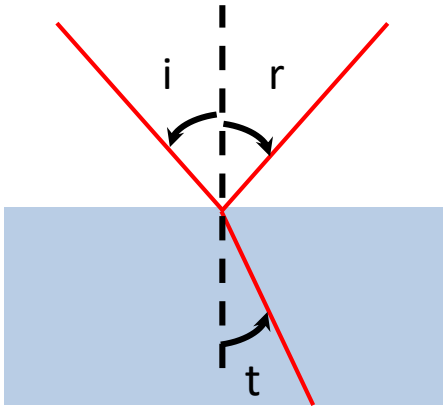
r = -i

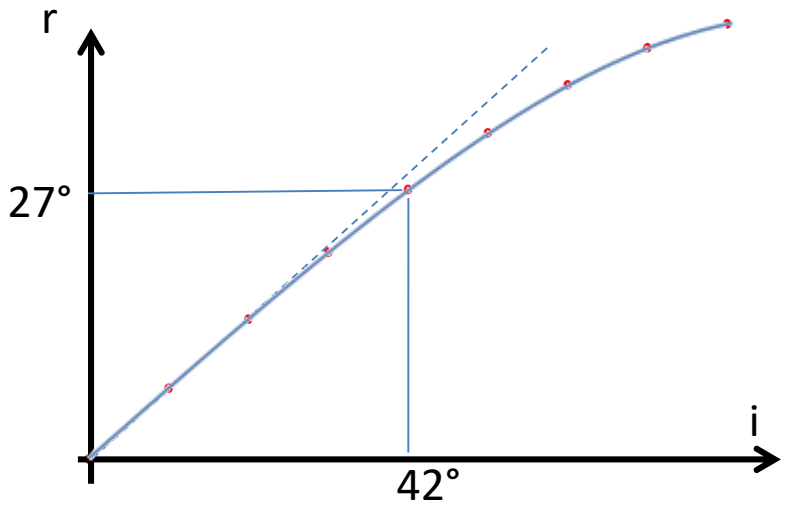
Euclide
≈ 300 av. JC

Lois de Snell et Descartes





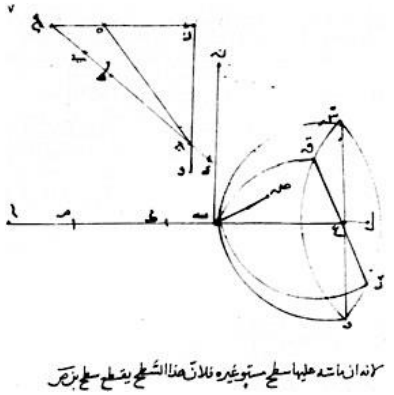




Willebrord Snell
1580-1626

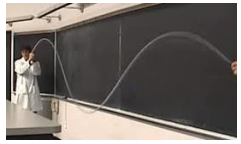
René Descartes
1596-1650

$$\sin r = n \sin i$$



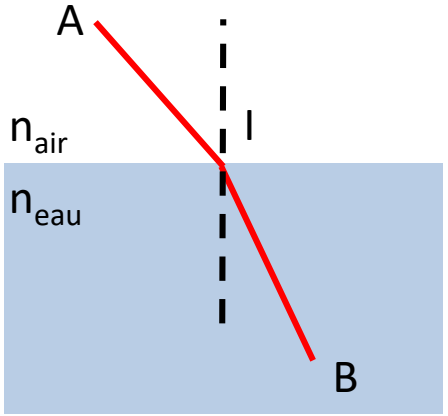
Abou Saʿd al-ʿAlaʾ ibn Sahl
vers 984

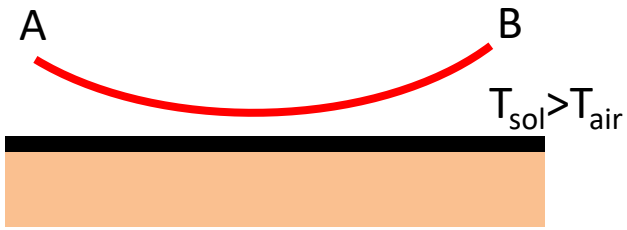
Principe de Fermat (1657)



Pierre de Fermat
(vers 1605-1665)

« La nature agit toujours par les voies les plus courtes et les plus simples. »

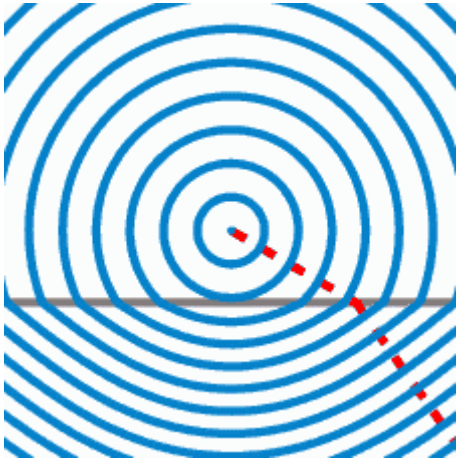




$T_{mer}<T_{air}$

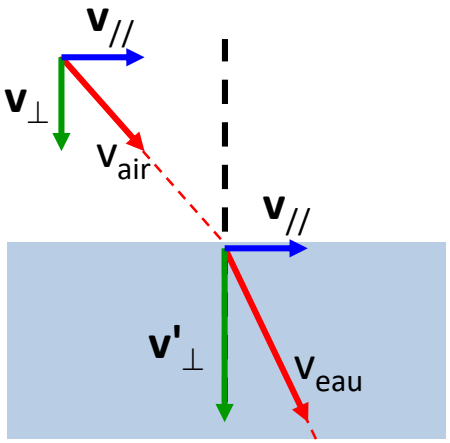
Interprétations

Christian Huygens
1629 -1695



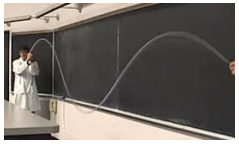
$v_{eau} < v_{air}$

René Descartes
1596-1650

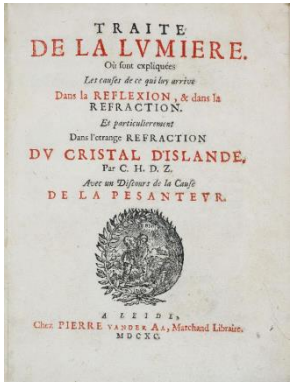


$v_{eau} > v_{air}$

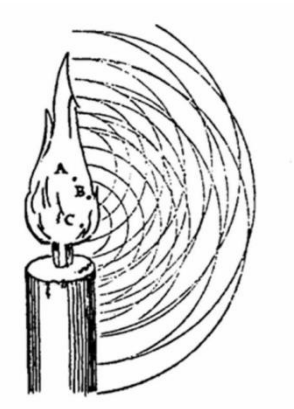
Newton vs Huygens



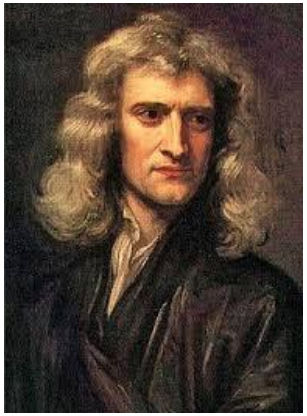
Christian Huygens
1629 -1695



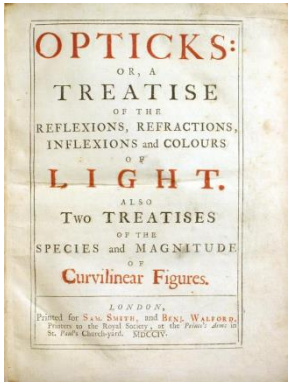
traité de la lumière
1690



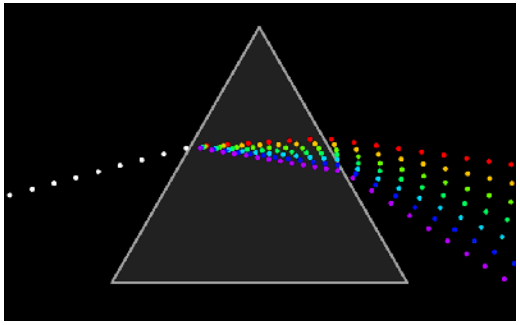
ondes



Isaac Newton
(1642 – 1727)

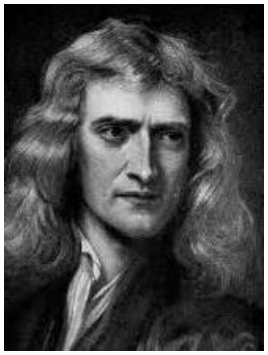


Optiks – 1704

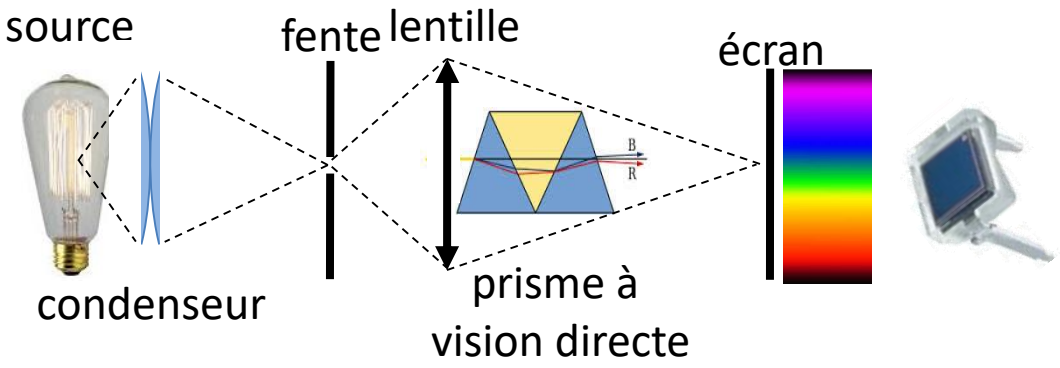


corpuscules

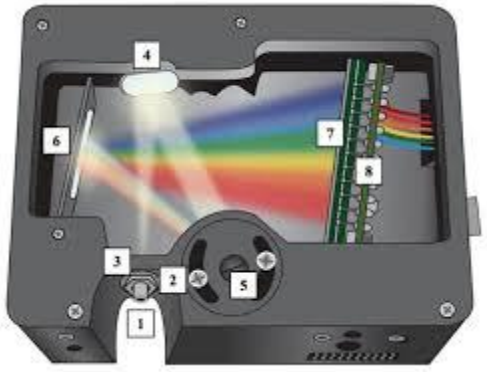
Les couleurs (1666)



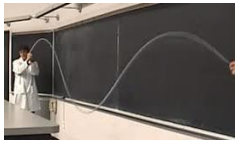
Isaac Newton
1642-1726



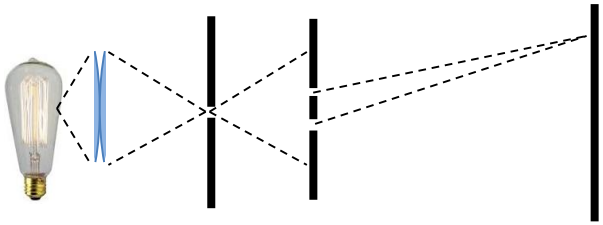
spectromètre
USB

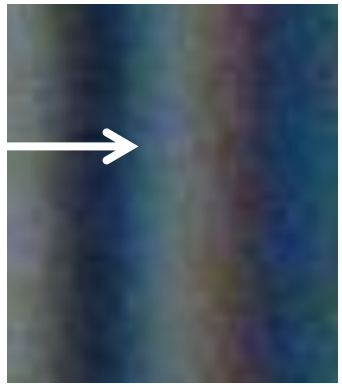


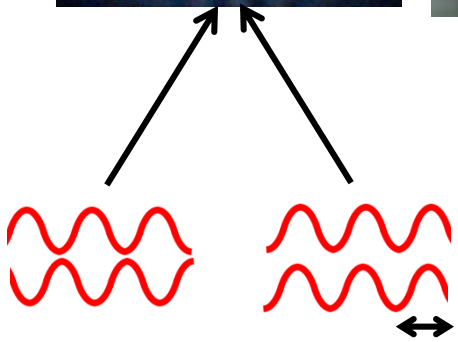
Interférences (1802)

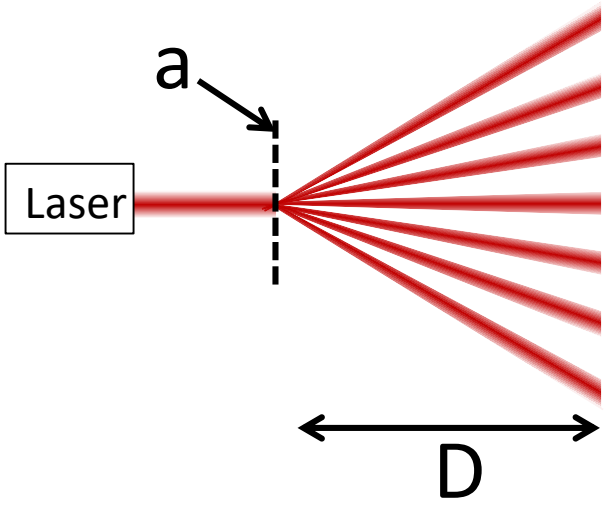


Thomas Young
1773-1829





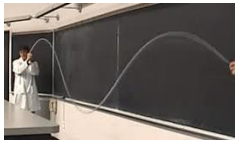


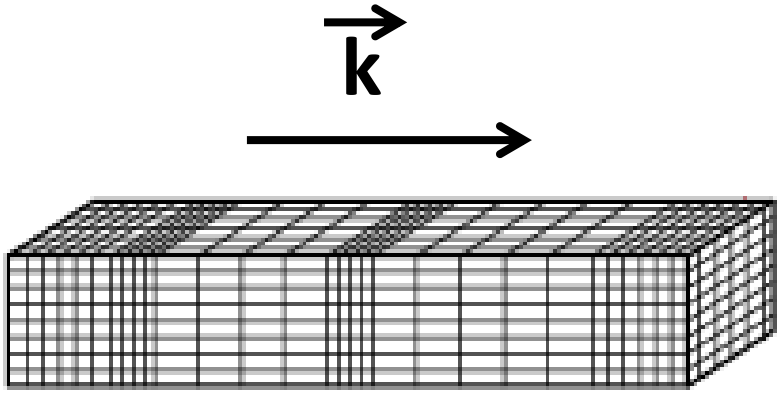


↕ $i=\lambda D/a$

$\lambda_{typ.}=0.65\ \mu m$

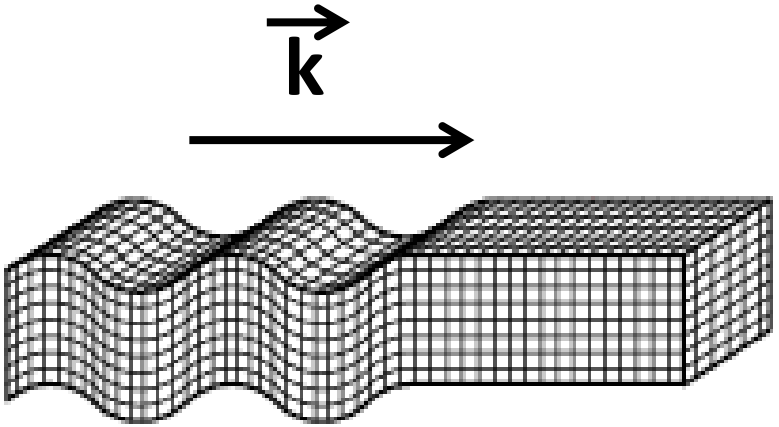
Deux types d'ondes





$\vec{v} \parallel \vec{k}$

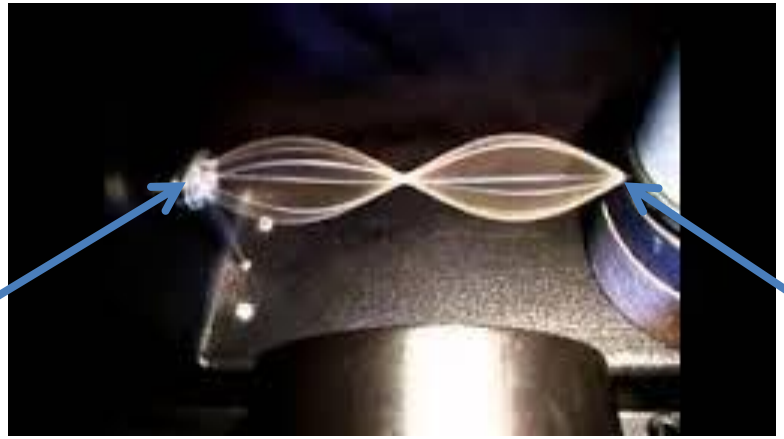
longitudinale

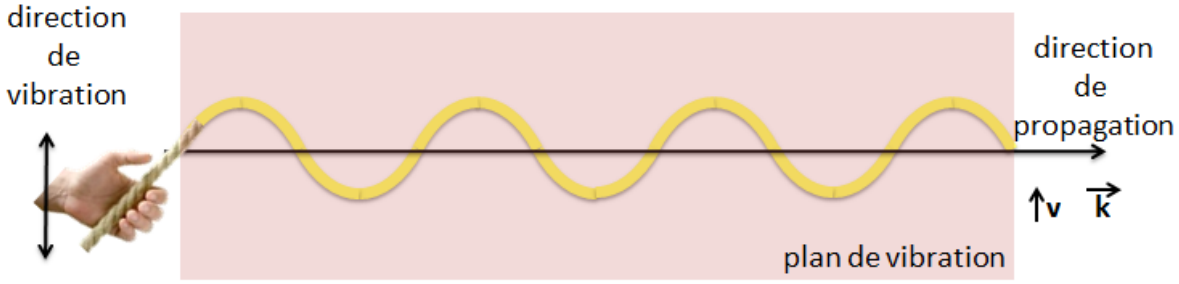


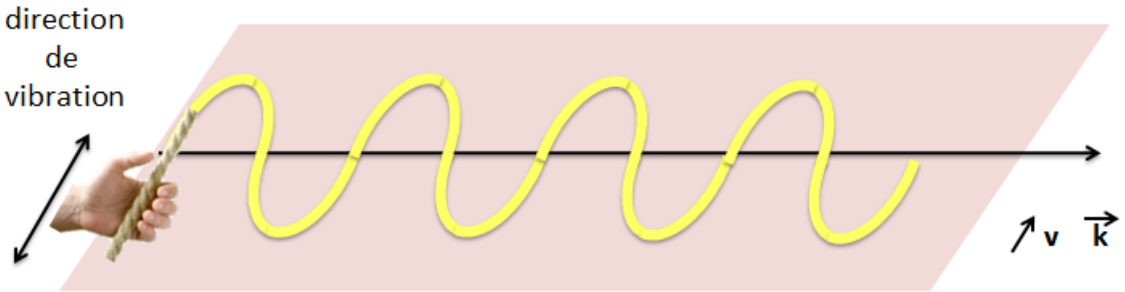
$\vec{v} \perp \vec{k}$

transverse

Corde de Melde

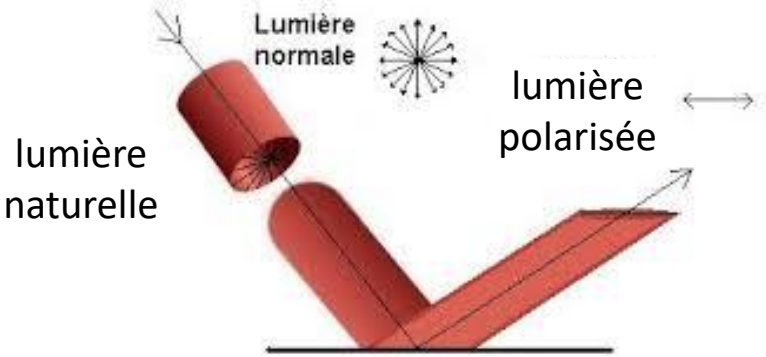


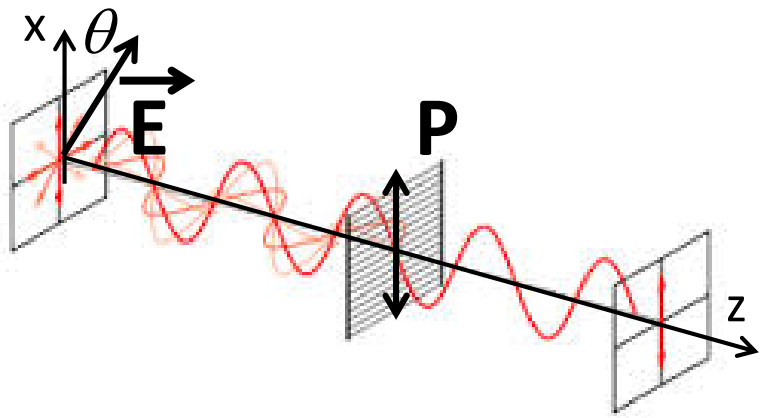




Polarisation (1809)

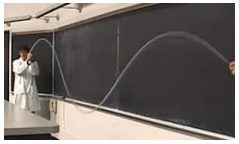
Etienne Malus
1775-1812



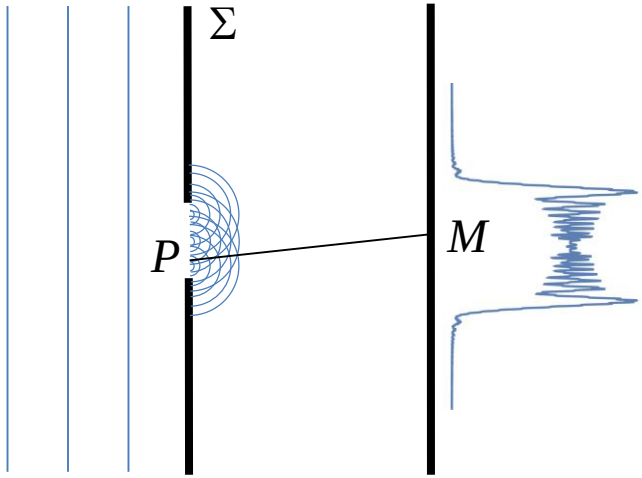


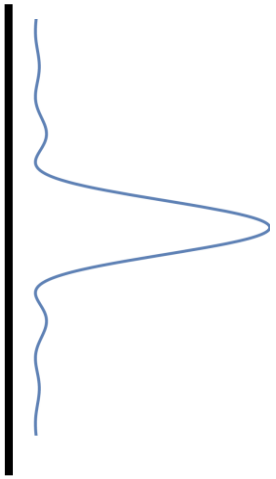
onde *transverse*

Diffraction (1815)

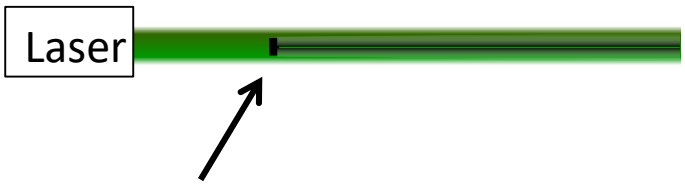


Augustin Fresnel
1788-1827

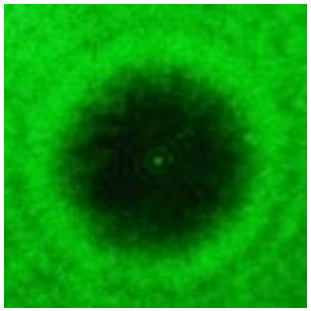




$$\Psi(M) = -\frac{i}{\lambda}\iint_{\Sigma} Q(P;M)\Psi_i(P)\frac{e^{ikPM}}{PM}d^2P$$



écran circulaire

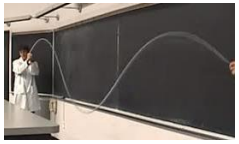


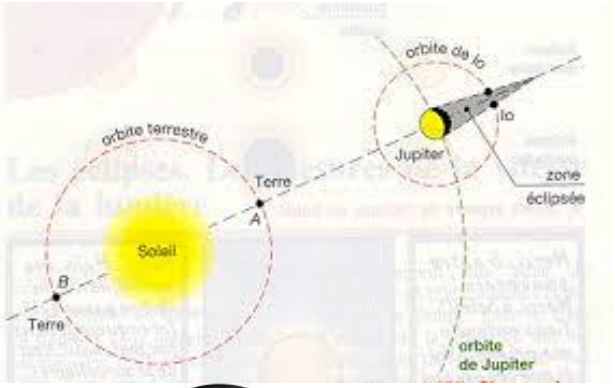
point de Poisson
1818

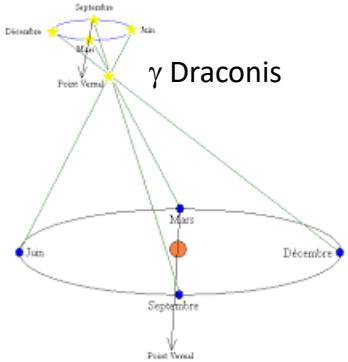
Denis Poisson
1781-1840

François Arago
1786–1853

Vitesse de la lumière







1676

Ole Christensen Rømer
1644-1710

1725

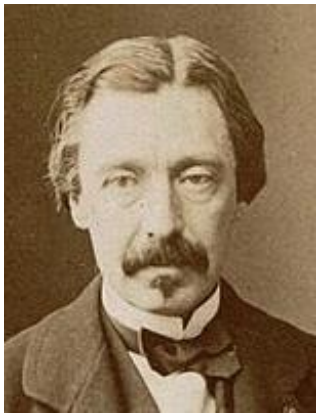
James Bradley
1693-1762

1849

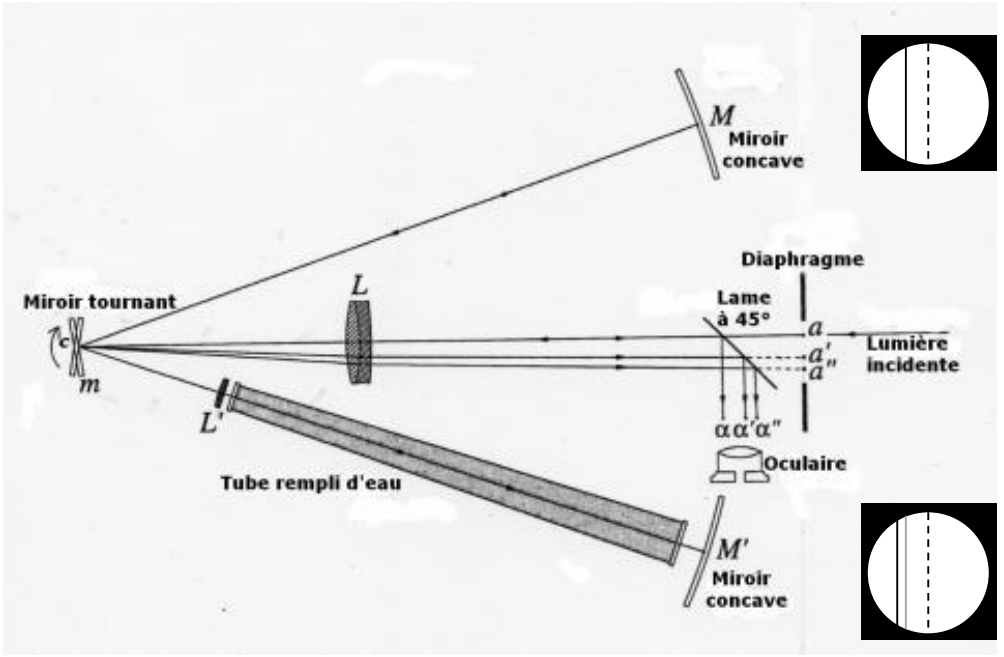
Hippolyte Fizeau
1819-1896

$$c \approx 3 \times 10^8 \, m.s^{-1}$$

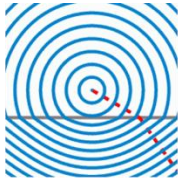
Foucault – Fizeau (1850)



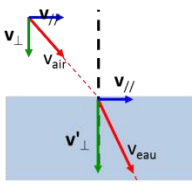
Léon Foucault
(1819-1868)



$v_{eau}<v_{air}$



$v_{eau}<v_{air}$



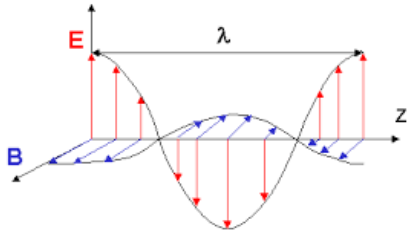
$v_{eau}>v_{air}$

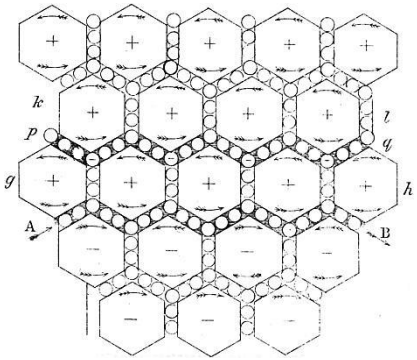
Electromagnétisme (1865)

James Clerck Maxwell
1831-1879

$$\left.\begin{aligned}\nabla.\mathbf{E} &= 0\\ \nabla.\mathbf{B} &= 0\end{aligned}\right\}$$

$$\left.\begin{aligned}\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} &= \mathbf{0}\\ \nabla \times \mathbf{B} - \epsilon_0\mu_0\frac{\partial \mathbf{E}}{\partial t} &= \mathbf{0}\end{aligned}\right\} \quad \lambda = c/\nu$$





"A Dynamical Theory of the Electromagnetic Field"
Phil. Trans. R. Soc. Lond. **155**, 459–512 (1865)

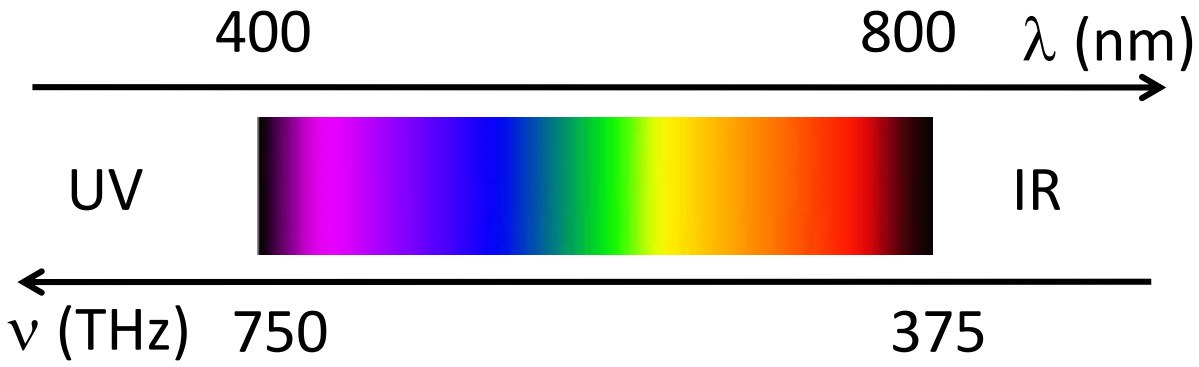
$$\frac{\partial^2 \mathbf{E}}{\partial t^2} - \frac{1}{\epsilon_0\mu_0}\frac{\partial^2 \mathbf{E}}{\partial z^2} = 0 \qquad c \approx 3 \times 10^8\, m.s^{-1}$$

« Nous pouvons difficilement éviter la conclusion que la lumière consiste en des ondulations du même milieu que celui qui est la cause des phénomènes électriques et magnétiques »

La lumière fin XIX^{ème} siècle

Onde électromagnétique transverse

$$c \approx 3 \times 10^8 \, m.s^{-1}$$



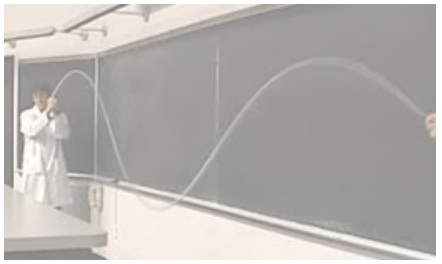
Plan

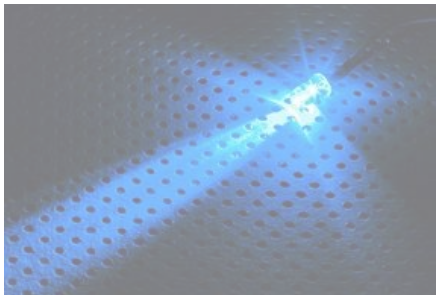
Du modèle corpusculaire au modèle ondulatoire

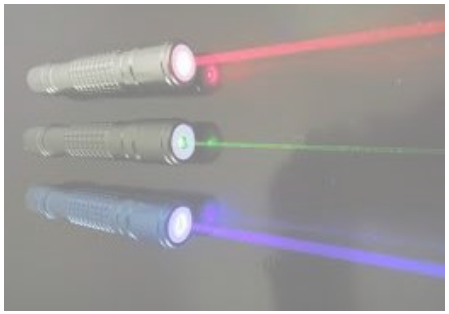
De la spectroscopie au modèle quantique de l'atome…

… jusqu'à la LED bleue

et au-delà…

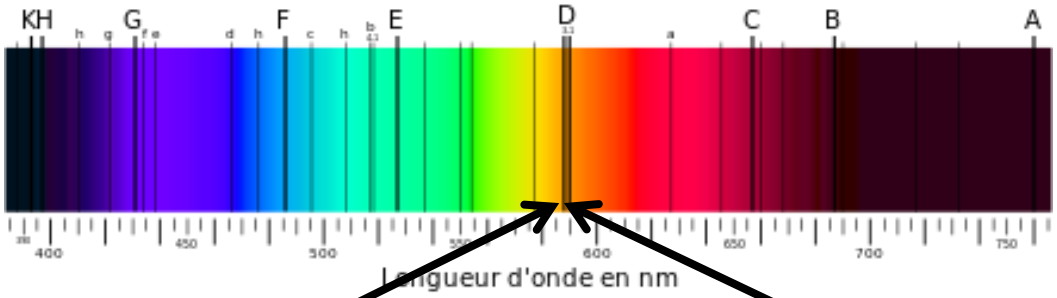






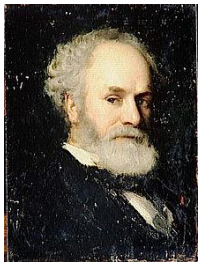
Un formidable outil…

Joseph von Fraunhofer (1814)



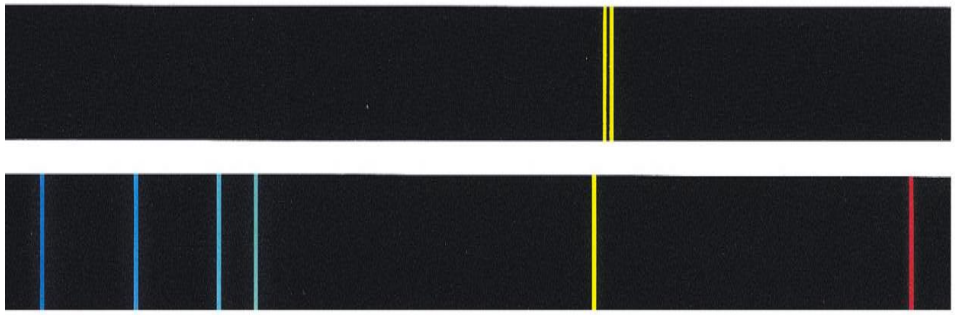
587,5nm ?

589,0 et 589,6nm



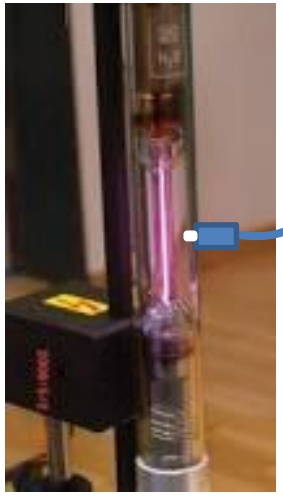
Jules Janssen

Norman Lockyer



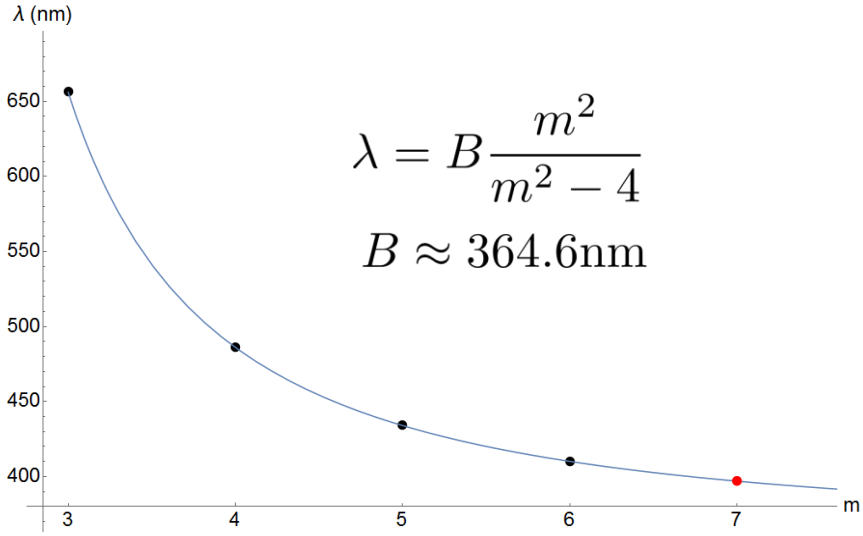
découverte de l'Hélium (1848)

Spectre de raies (1885)



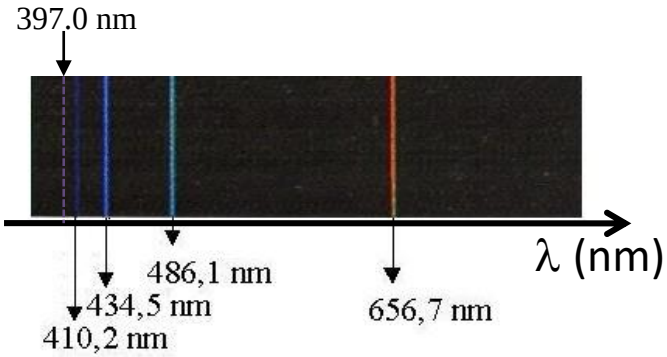
lampe H_2O

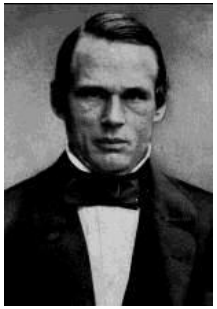
spectromètre USB



$$\lambda = B\frac{m^2}{m^2-4}$$

$$B \approx 364.6\text{nm}$$



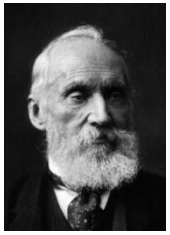


Anders Ångström
1814-1874

m=7

Johann Balmer
1825-1898

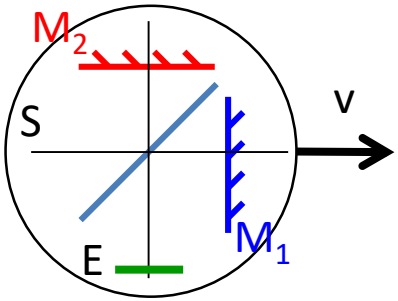
Michelson-Morley (1887)



Lord Kelvin
(1824-1907)

« La connaissance en physique est semblable à un grand ciel bleu, à l'horizon duquel subsistent seulement deux petits nuages d'incompréhension. »

Albert Michelson
(1852-1931)

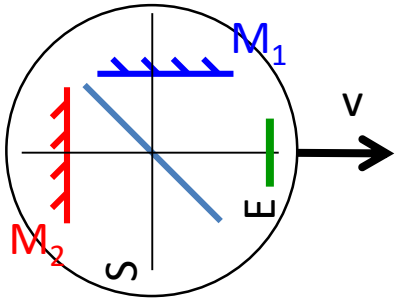


c: lumière / éther
v: terre / éther

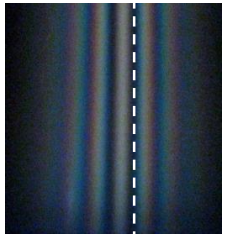
$$t_{\parallel} \approx \frac{2L}{c}(1 + v^2/c^2) \qquad t_{\perp} \approx \frac{2L}{c}(1 + v^2/2c^2)$$

$$\delta t_0 = t_1 - t_2 = t_{\parallel} - t_{\perp} \approx + \frac{2L}{c}(v^2/2c^2)$$

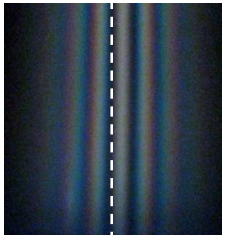
Edward Morley
(1838-1923)



$$\delta t_{90} = t_1 - t_2 = t_{\perp} - t_{\parallel} \approx - \frac{2L}{c}(v^2/2c^2)$$

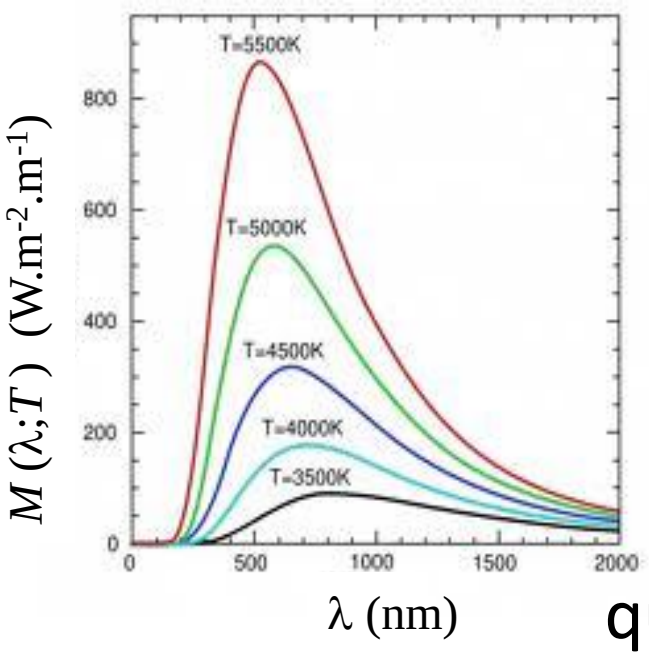


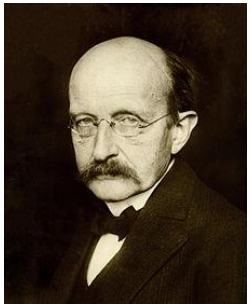
0°



90°

Corps noir (1900)





Max Planck
(1858-1947)

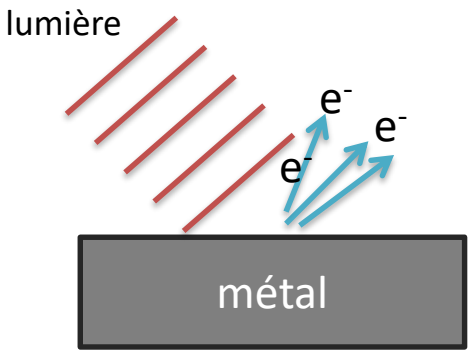
$$E = h\nu$$

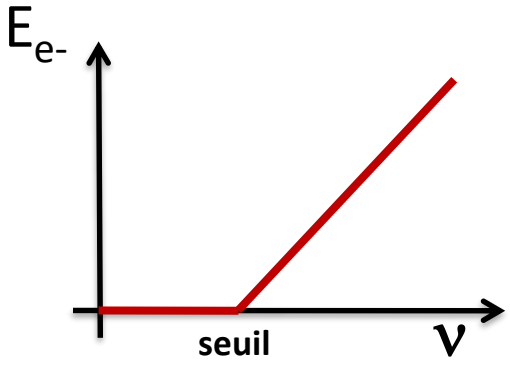
quantification des échanges d'énergie

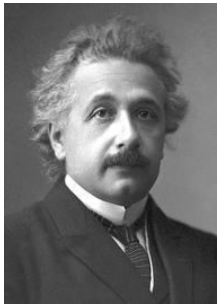
Effet Photoélectrique

Heinrich Hertz
1857-1894

1887

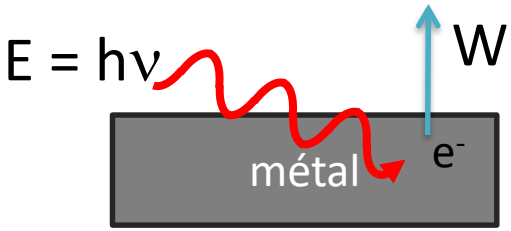






Albert Einstein
1879-1955

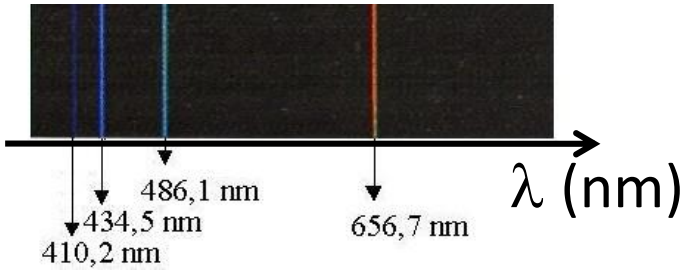
1905



$E_{e^-} = h\nu - W$

Photon

Quantification de l'énergie

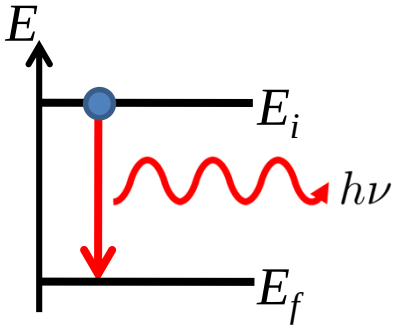


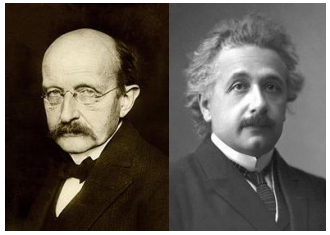
$$\lambda = B\frac{m^2}{m^2-4}$$

Johannes Rydberg
1854-1919

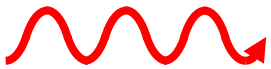
Walther Ritz
1878-1909

$$\frac{1}{\lambda} = R_y\left(\frac{1}{m^2} - \frac{1}{n^2}\right)$$





$$E = h\nu = hc/\lambda$$



$$h\nu = R_H\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

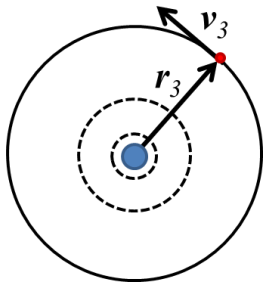
$E_f \quad E_i$

Synthèse quantique

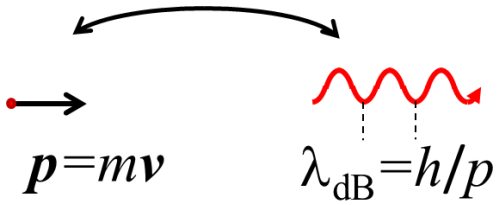
Niels Bohr
1885-1962

Louis de Broglie
(1892-1987)

Erwin Schrödinger
(1887-1961)

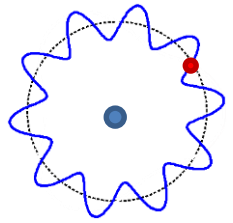


(1913)



(1924)

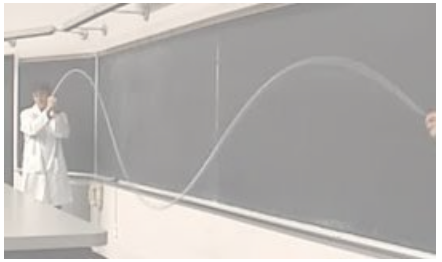
$$i\hbar\frac{\partial\psi}{\partial t} = \left[-\frac{\hbar^2}{2m}\Delta + V\right]\psi$$



(1926)

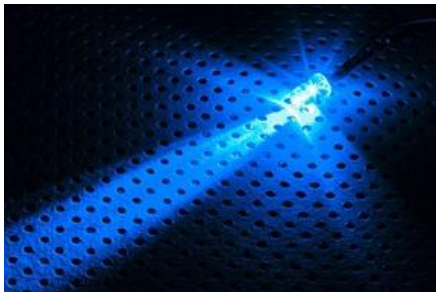
Plan

La lumière

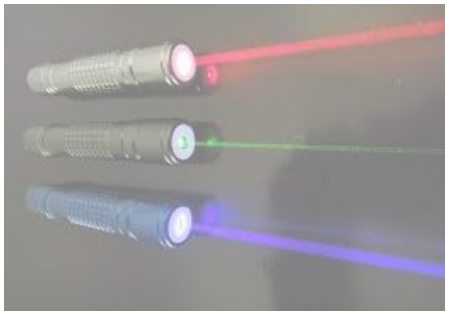


De la spectroscopie au modèle quantique de l'atome…

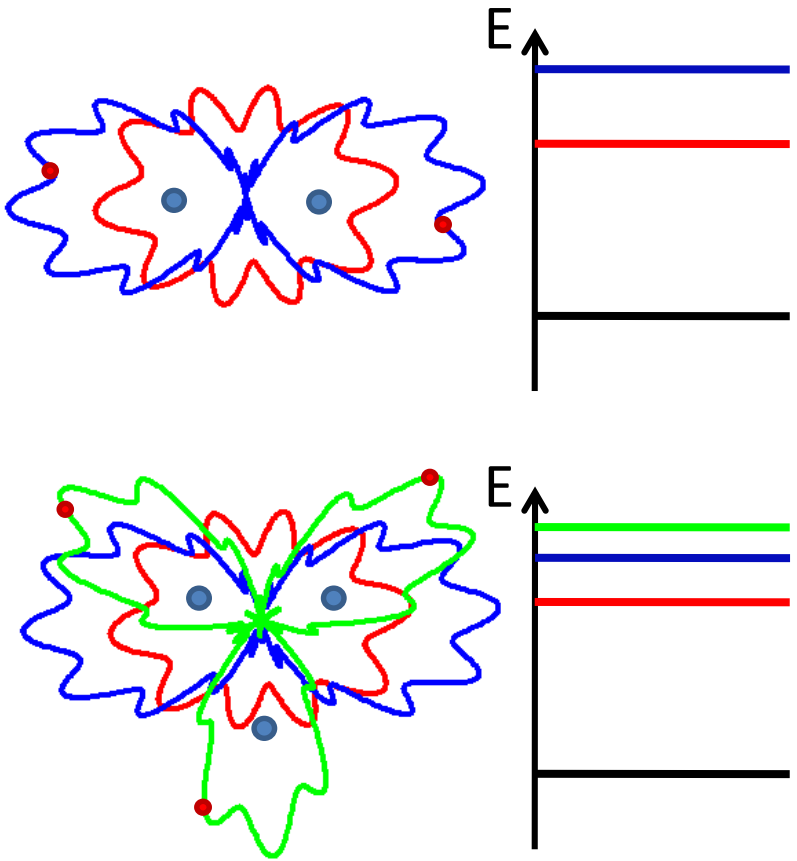
… jusqu'à la LED bleue

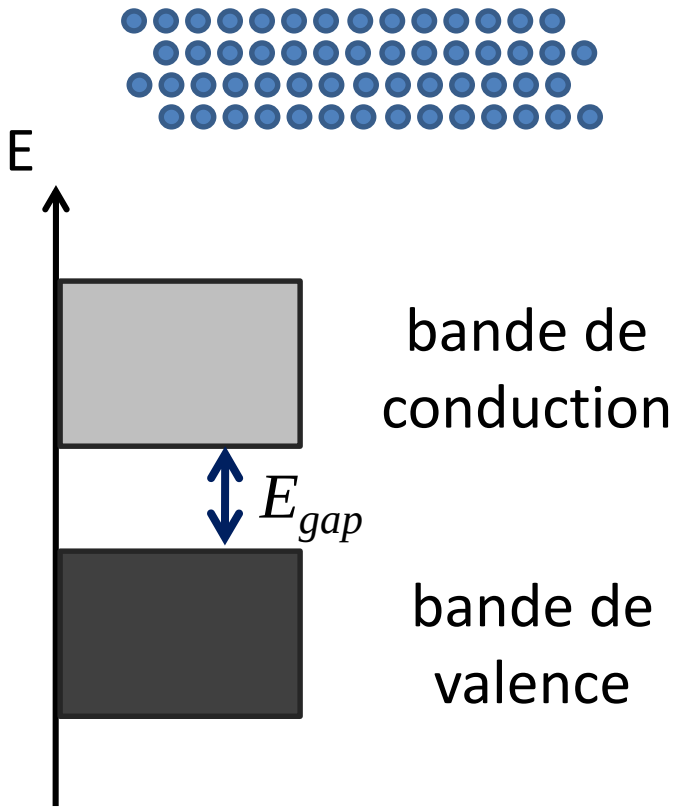


et au-delà…

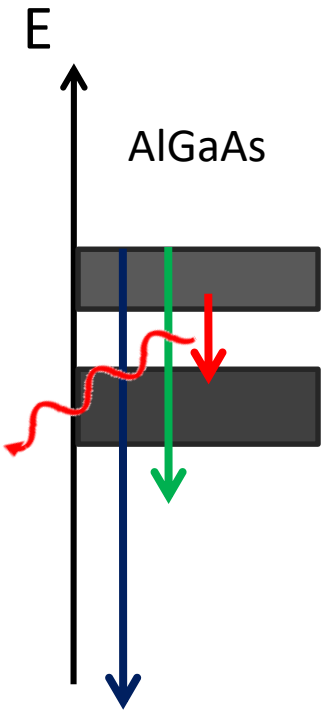


De l'atome au cristal

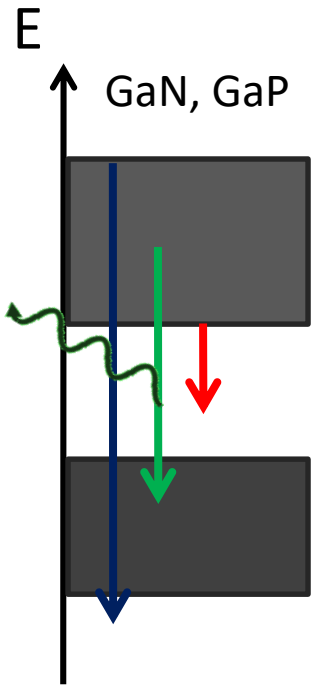




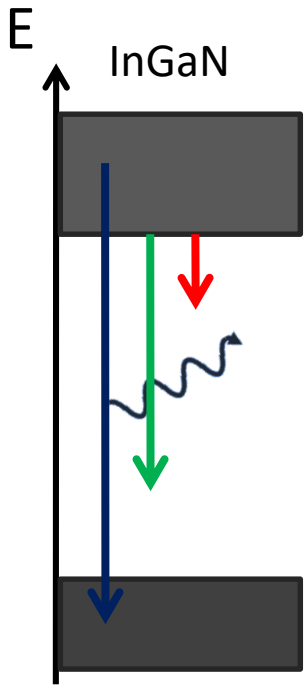
Spectre de bandes



faible gap
rouge



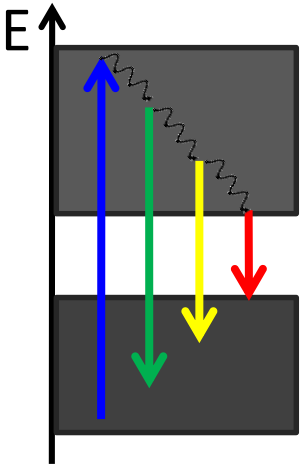
gap moyen
vert

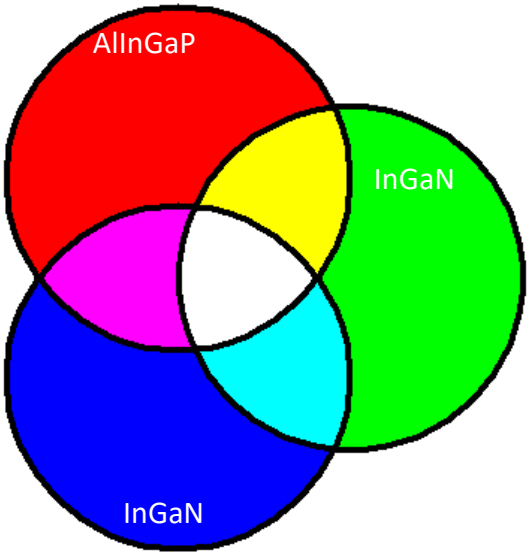


grand gap
bleu

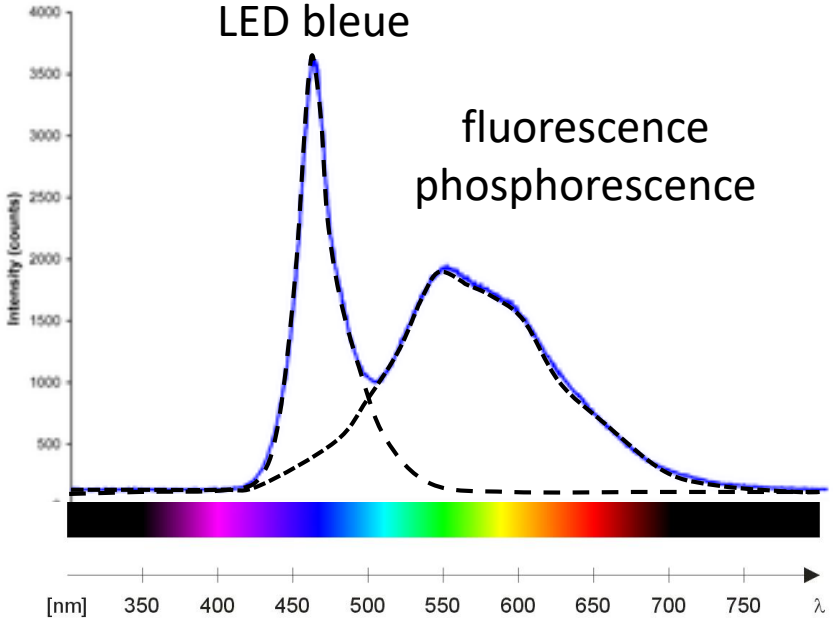
LED Blanche

$Y_3Al_5O_{12}$: Ce

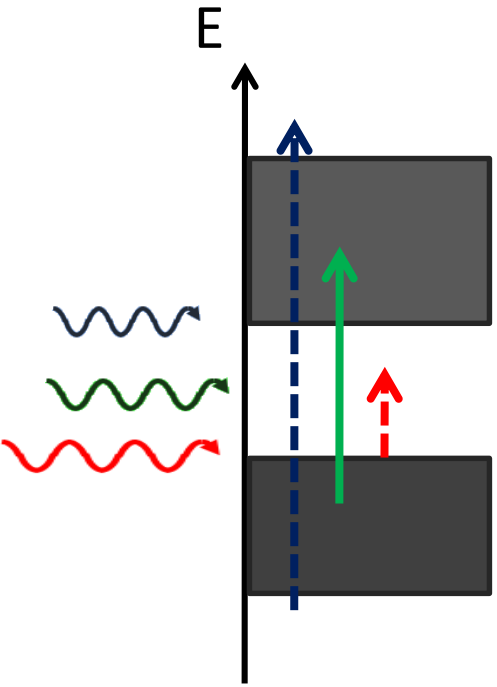


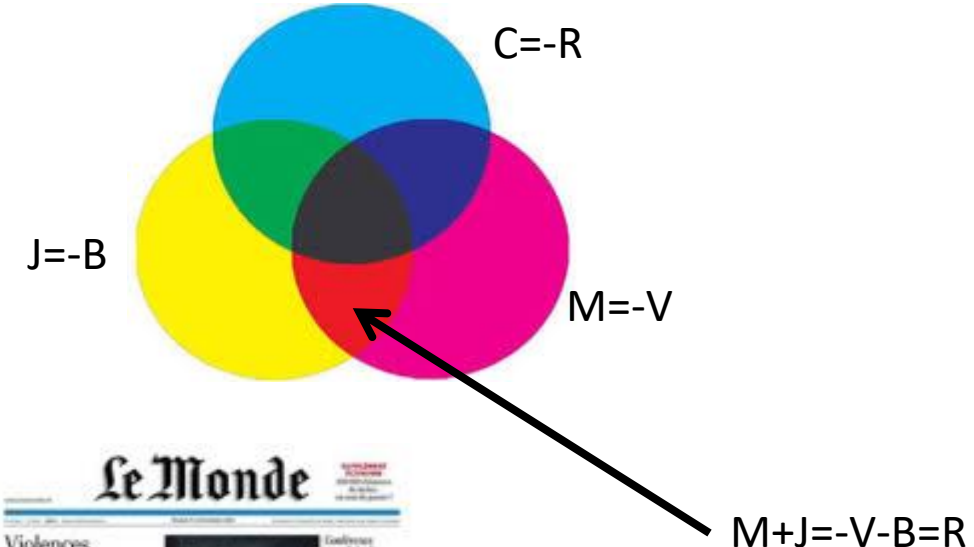


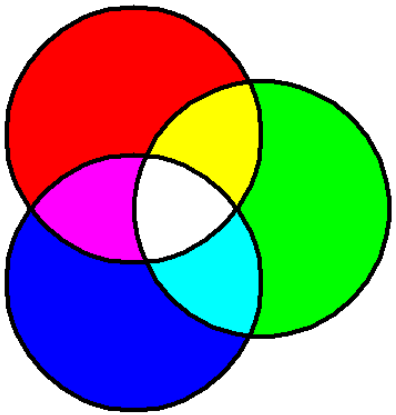
synthèse additive



Synthèse soustractive







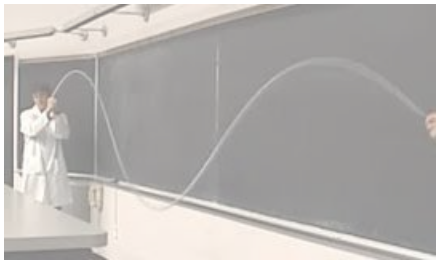
Plan

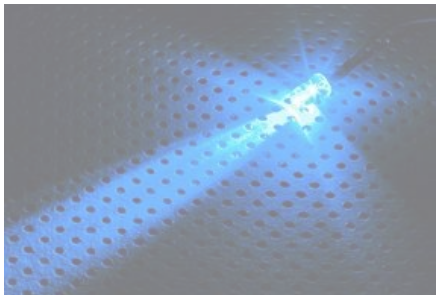
Du modèle corpusculaire au modèle ondulatoire

De la spectroscopie au modèle quantique de l'atome…

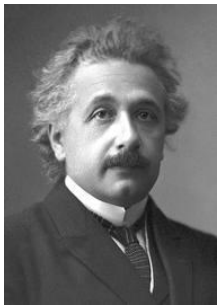
… jusqu'à la LED bleue

et au-delà…

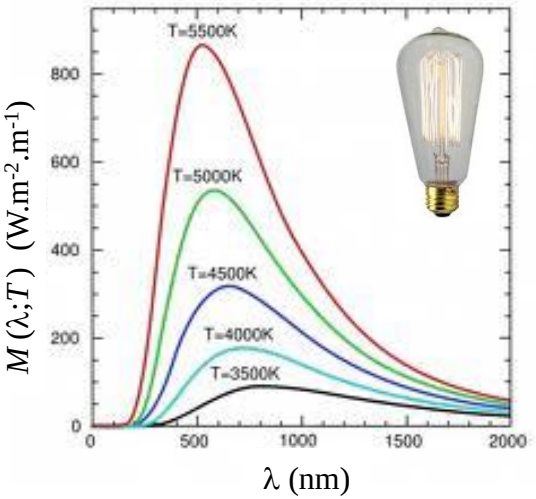




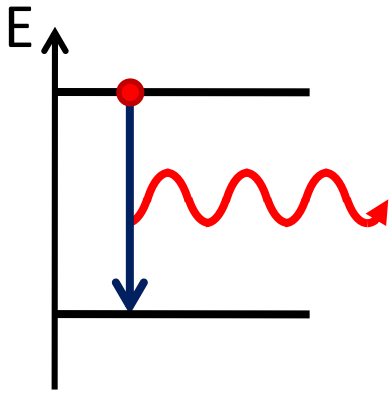
Théorie quantique du rayonnement



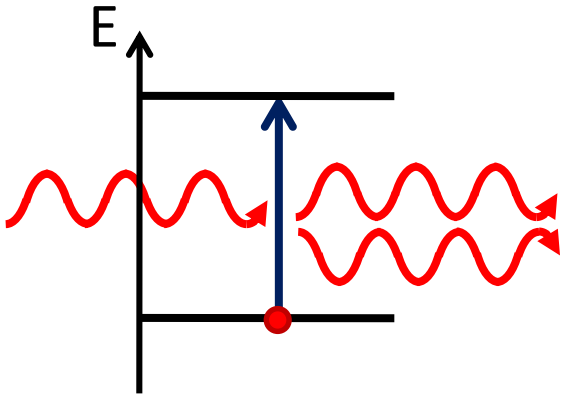
Albert Einstein
(1917)



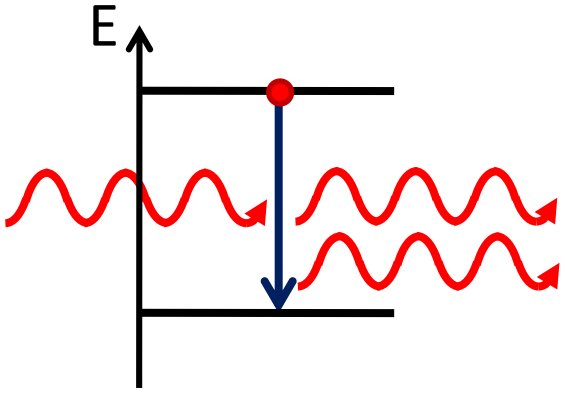
corps noir



émission spontanée



absorption



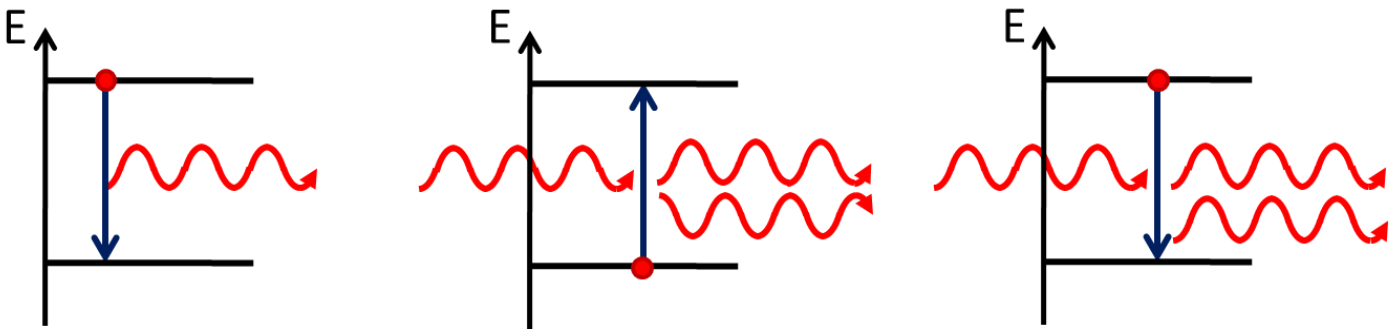
émission stimulée

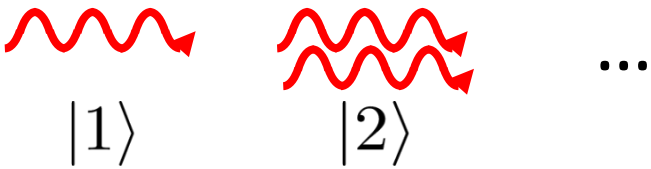
Tout quantique (1927)

Pascual Jordan
(1902-1980)

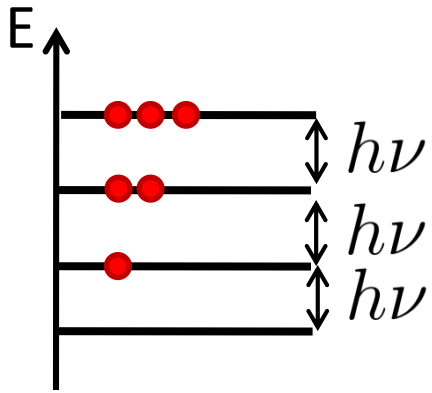
Paul Dirac
(1902-1984)

Wolfgang Pauli
(1900-1958)





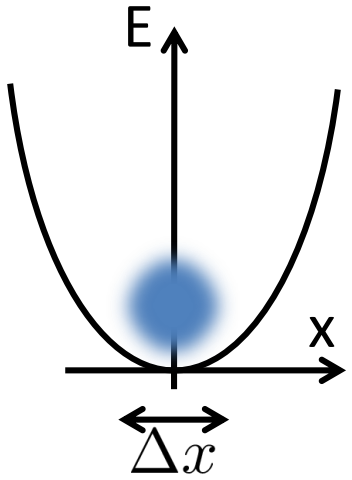
$|0\rangle$: vide quantique

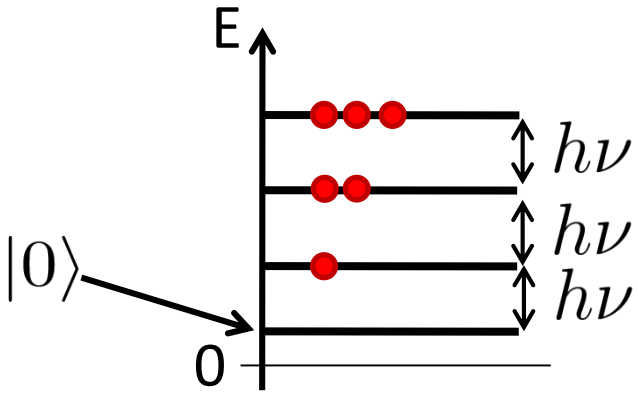


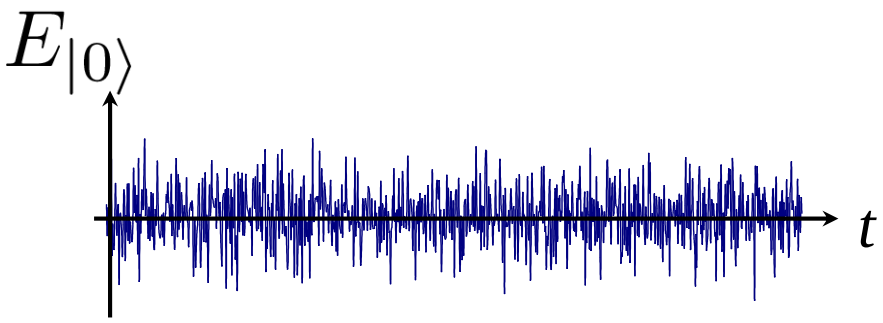
Fluctuations du vide

Werner Heisenberg
(1901-1976)

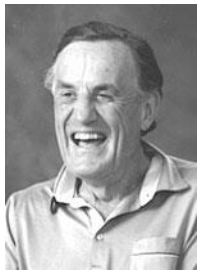
$$\Delta x \Delta p \geq \hbar/2$$







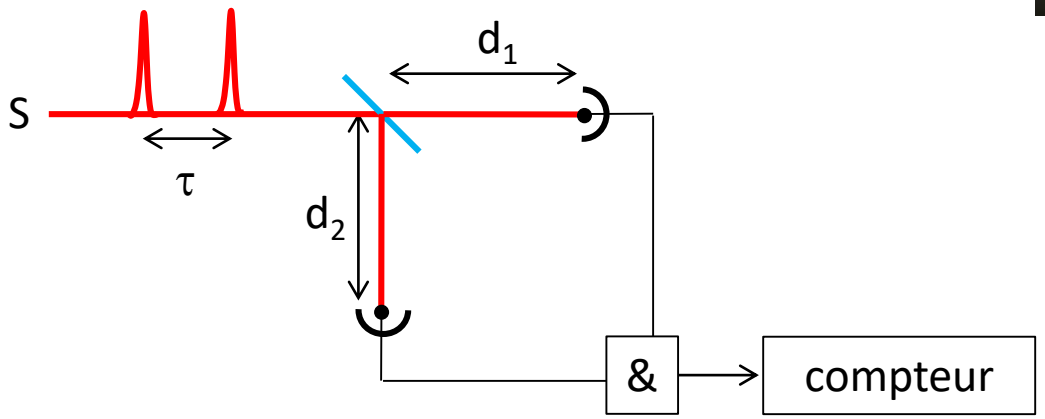
Corrélations d'intensité (1950's)

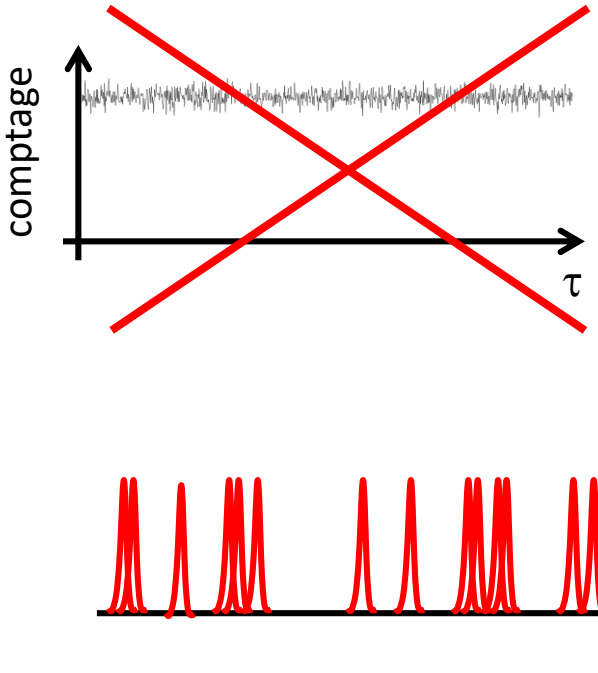


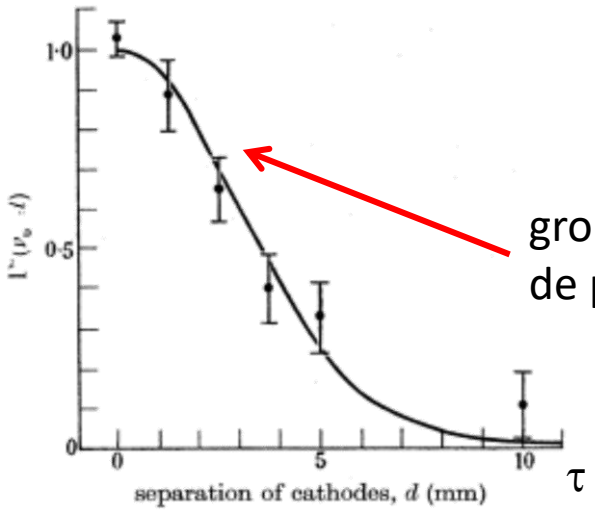
Robert Hanbury-Brown

Richard Twiss

Roy Glauber
(1925-)

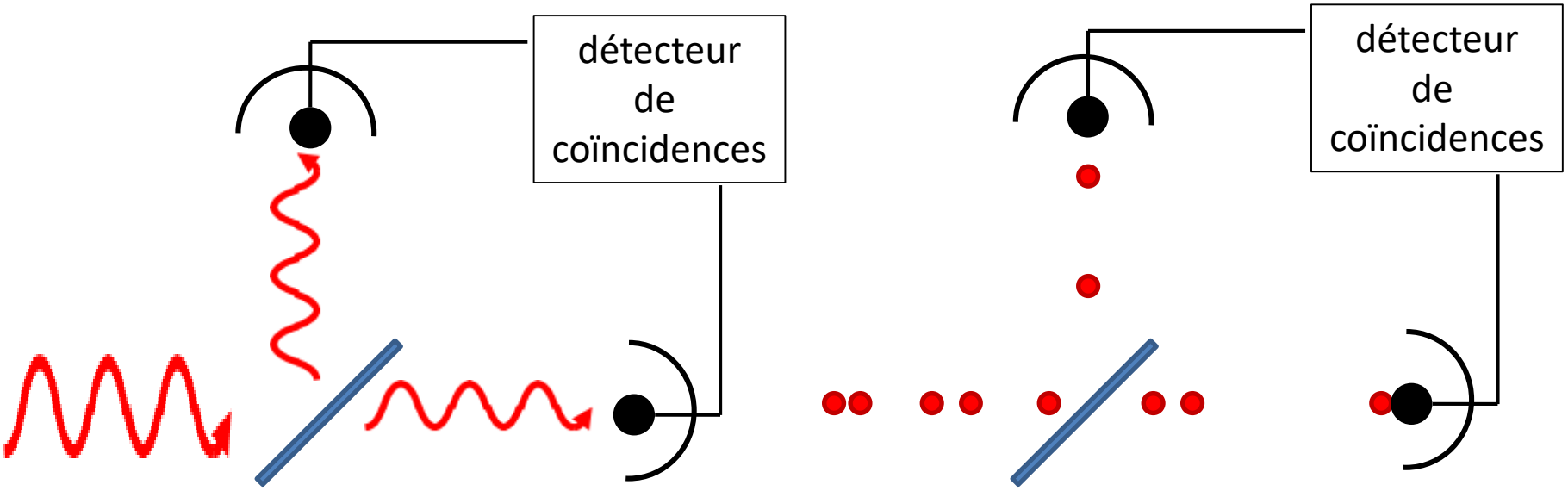






groupement
de photons

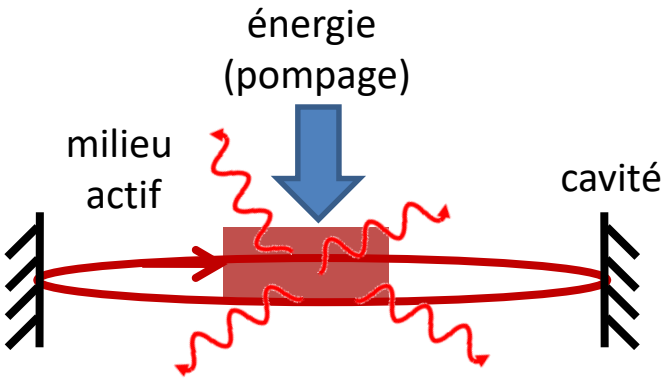
La séparatrice…

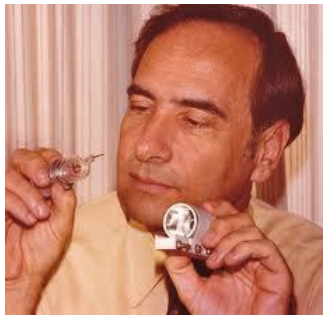


coïncidences fortuites

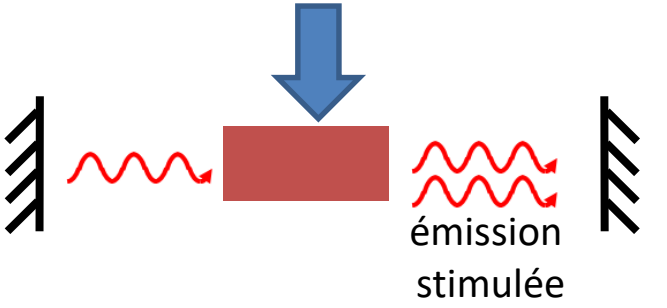
pas de coïncidences

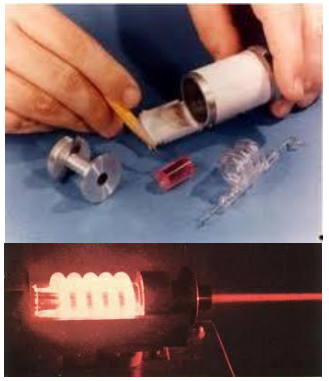
Laser (1960)

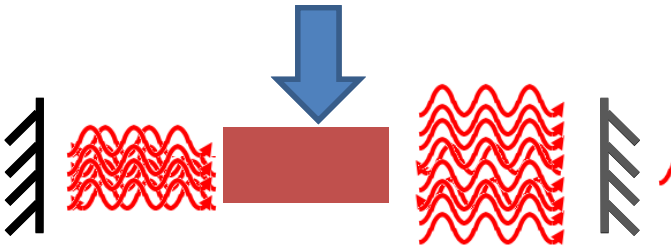




Theodore Maiman
(1927 - 2007)







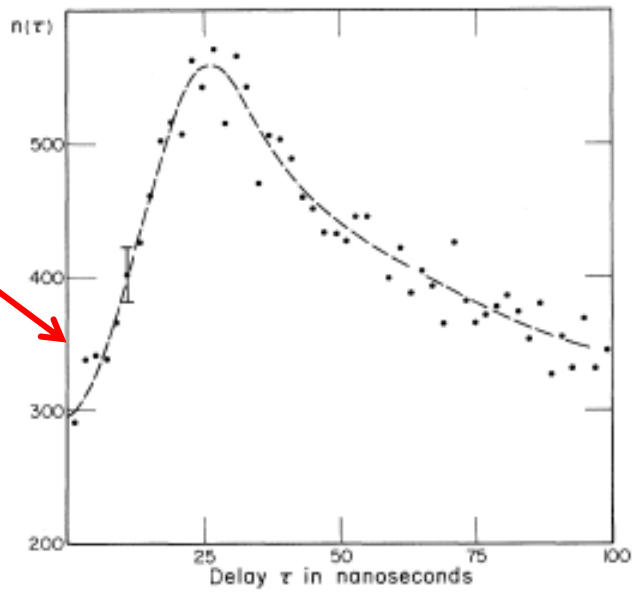
$$|N \gg 1\rangle$$

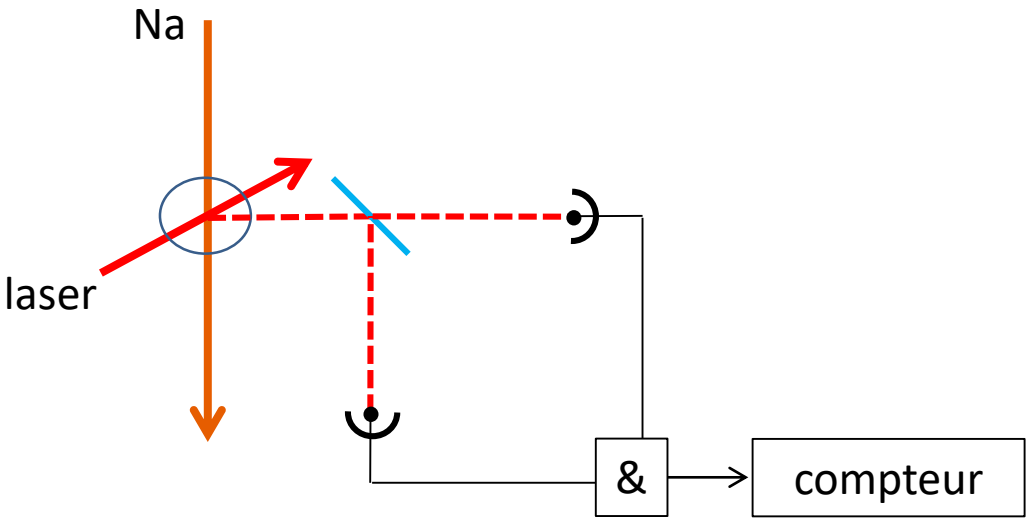
Couper un photon? (1977)

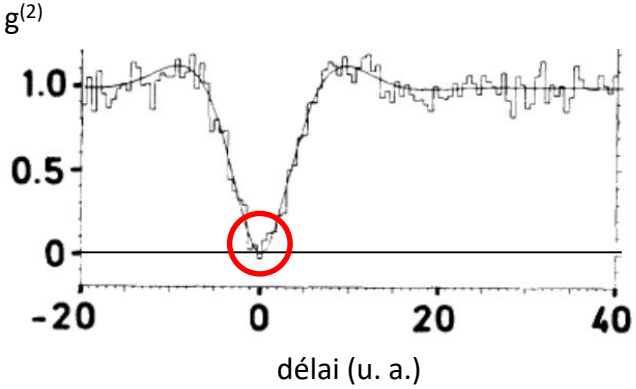


Kimble – Dagenais – Mandel (1977)

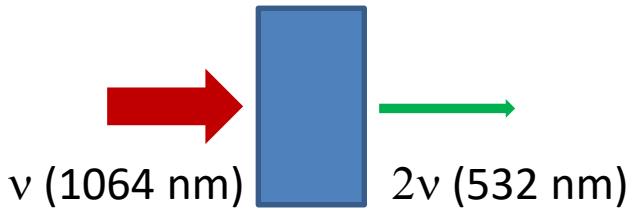
dégroupement
de photons

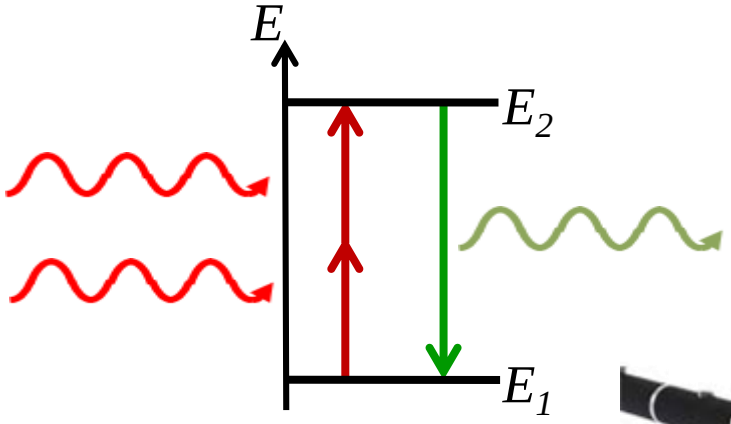




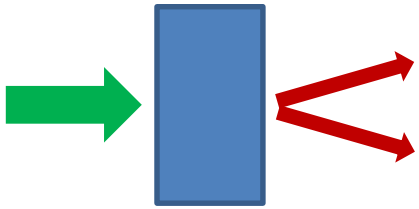


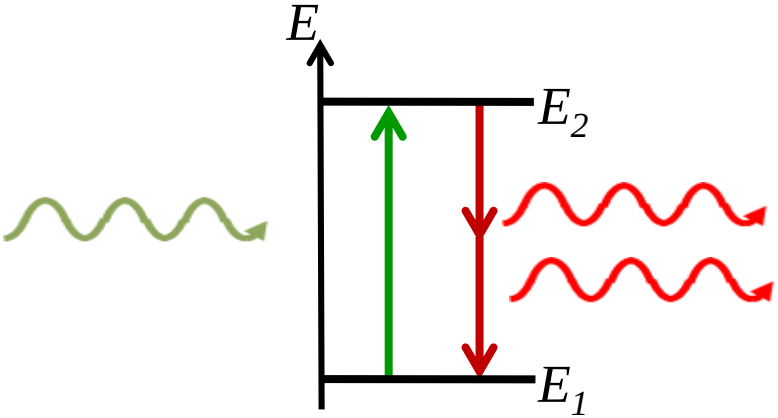
Lasers et optique non linéaire (70's)



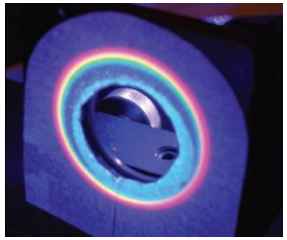


doublage de fréquence



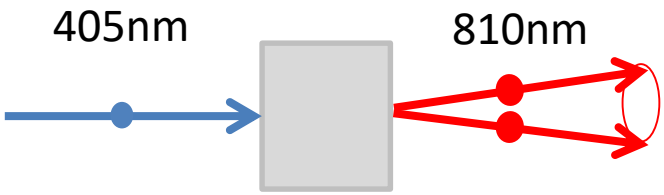


génération paramétrique

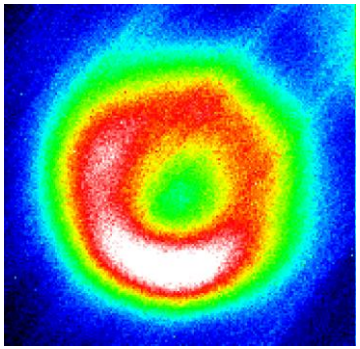


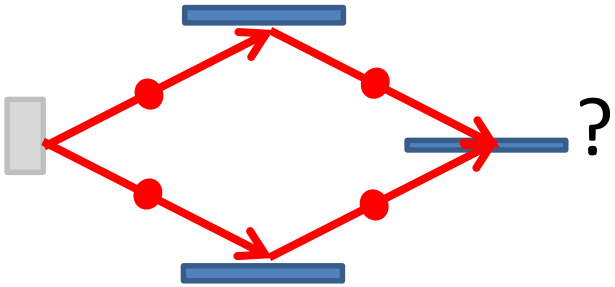
2 photons uniques (1986)

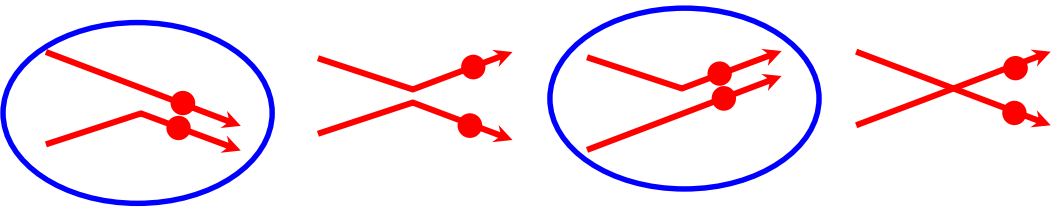
Hong - Ou - Mandel



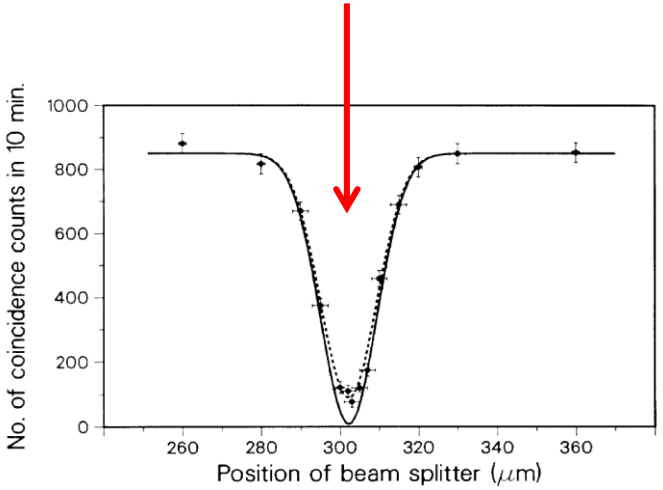
photons jumeaux







0 coïncidences



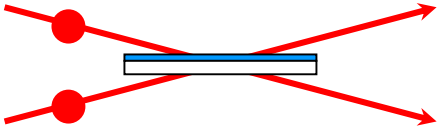
Incroyable mais vrai

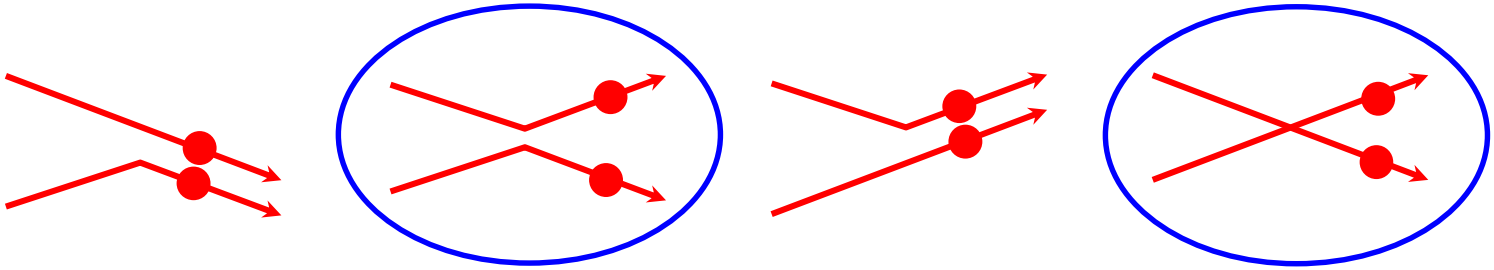
Voir film…

Interprétation

onde classique : toujours des coïncidences

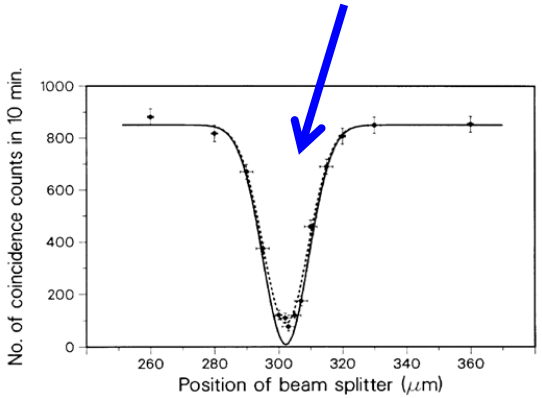
photons, particules classiques :





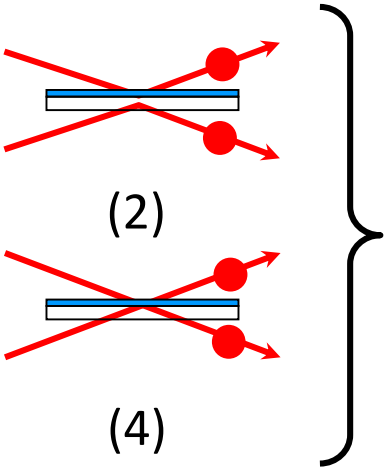
(1) (2) (3) (4)

toujours des coïncidences



(document original: Claude Fabre)

Interférences

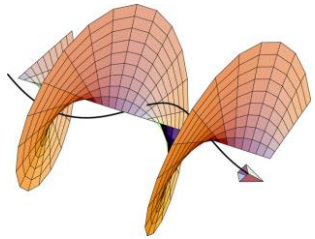


indistinguables $\quad |t,t\rangle + |r,r\rangle = 0$

dans le monde quantique,
de la probabilité plus de la probabilité
peut donner une probabilité nulle !!

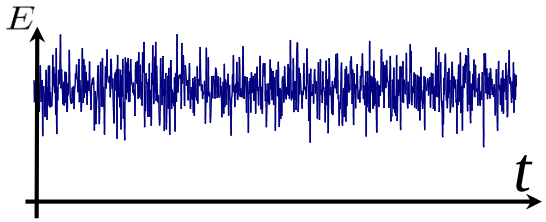
Au-delà de la dualité

la particule de lumière n'est pas un « fort petit corpuscule »
c'est l'excitation élémentaire d'un mode classique du champ
dont il hérite des propriétés

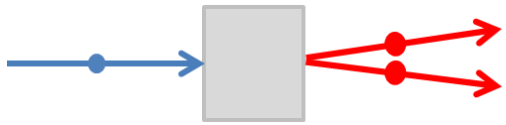


l'onde lumineuse n'est pas une onde de Maxwell classique

- fluctuations quantiques

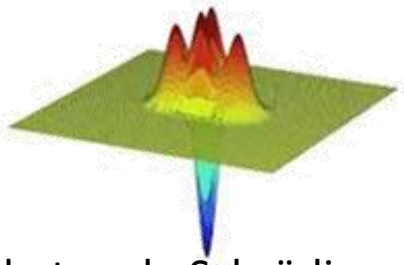


- corrélations quantiques non-locales
  (violation de l'inégalité de Bell)



le vide $|0\rangle$ n'est pas rien $|0\rangle + |1\rangle \neq |1\rangle$

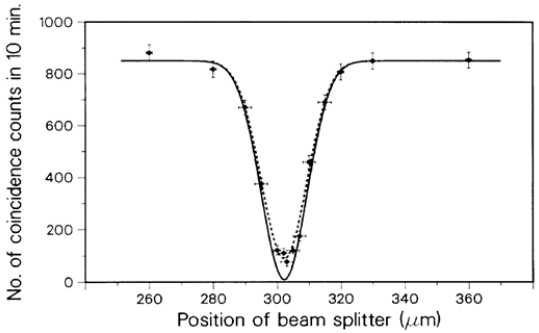
états cohérents "quasi-classiques" $|\alpha = +2\rangle$ $|\alpha = -2\rangle$ mais $|\alpha = +2\rangle + |\alpha = -2\rangle$



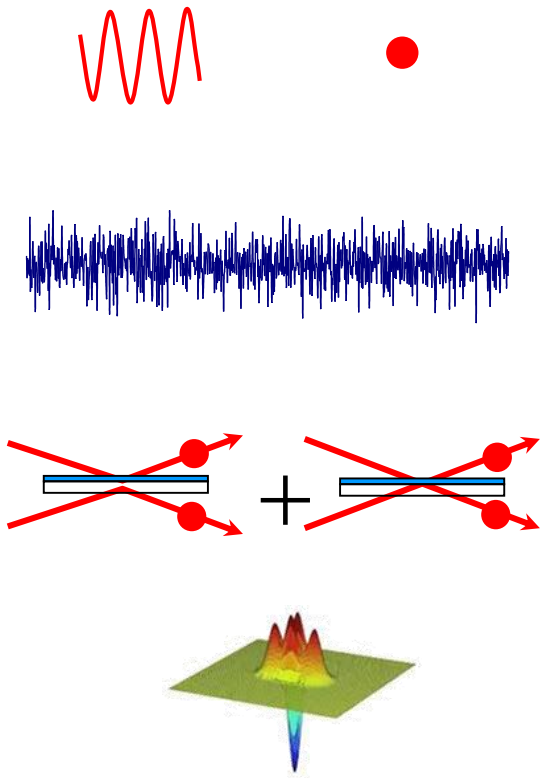
chaton de Schrödinger

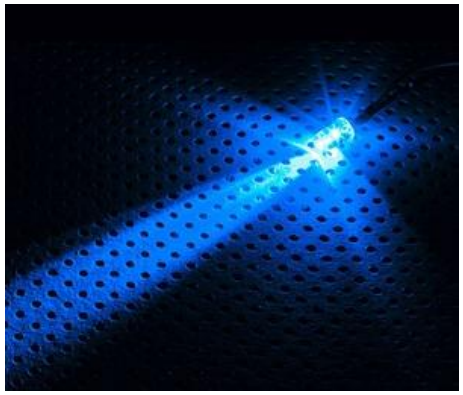
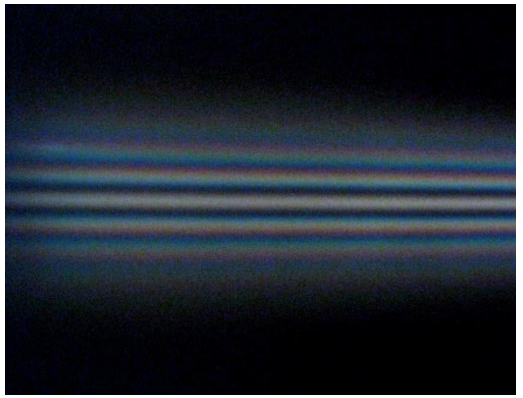
Une autre dualité

$$\mathrm{H}_n(a)\,\mathrm{H}_m(a^\dagger) = \frac{\mathrm{d}^n}{\mathrm{d}t^n} \mathrm{e}^{2ta-t^2}\Big|_{t=0} \frac{\mathrm{d}^m}{\mathrm{d}\tau^m} \mathrm{e}^{2\tau a^\dagger-\tau^2}\Big|_{\tau=0}$$
$$= \frac{\mathrm{d}^n \mathrm{d}^m}{\mathrm{d}t^n \mathrm{d}\tau^m} : \mathrm{e}^{-t^2-\tau^2+2ta+2\tau a^\dagger+4t\tau} :\Big|_{t=\tau=0}$$
$$= : \frac{\mathrm{d}^n}{\mathrm{d}t^n} [\mathrm{e}^{-t^2+2ta} \mathrm{H}_m(2t+a^\dagger)] :\Big|_{t=0}$$
$$= : \sum_{l=0}^{n} \binom{n}{l} \frac{\mathrm{d}^{n-l}}{\mathrm{d}t^{n-l}} \mathrm{e}^{-t^2+2ta} \frac{\mathrm{d}^l}{\mathrm{d}t^l} \mathrm{H}_m(2t+a^\dagger)\Big|_{t=0} :$$

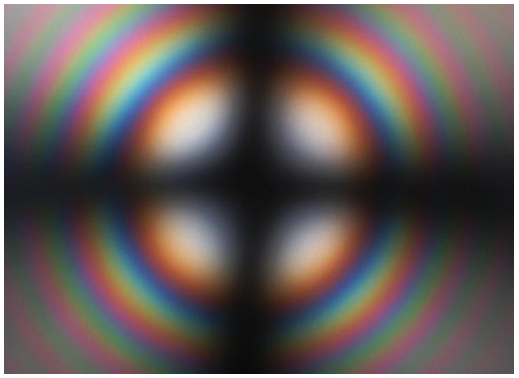
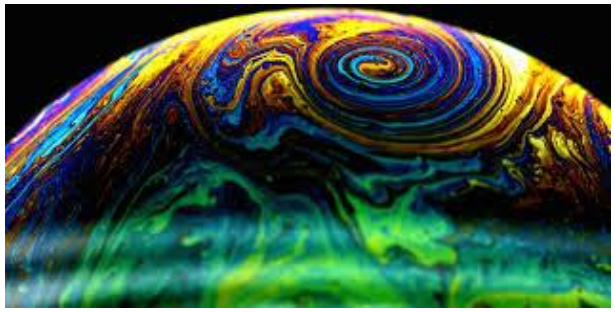
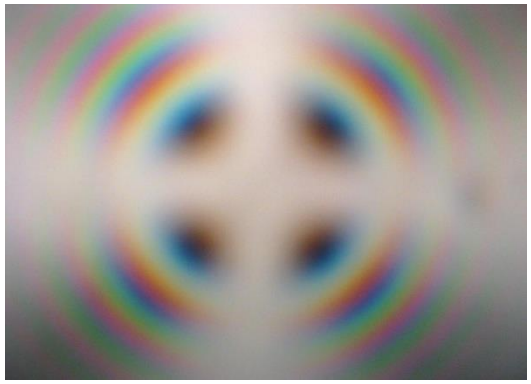


$$G^{(2)}(0) = \langle 1,1|\hat{E}_1^\dagger \hat{E}_2^\dagger \hat{E}_1 \hat{E}_2|1,1\rangle = 0$$



cycle « Lumière et couleurs »

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