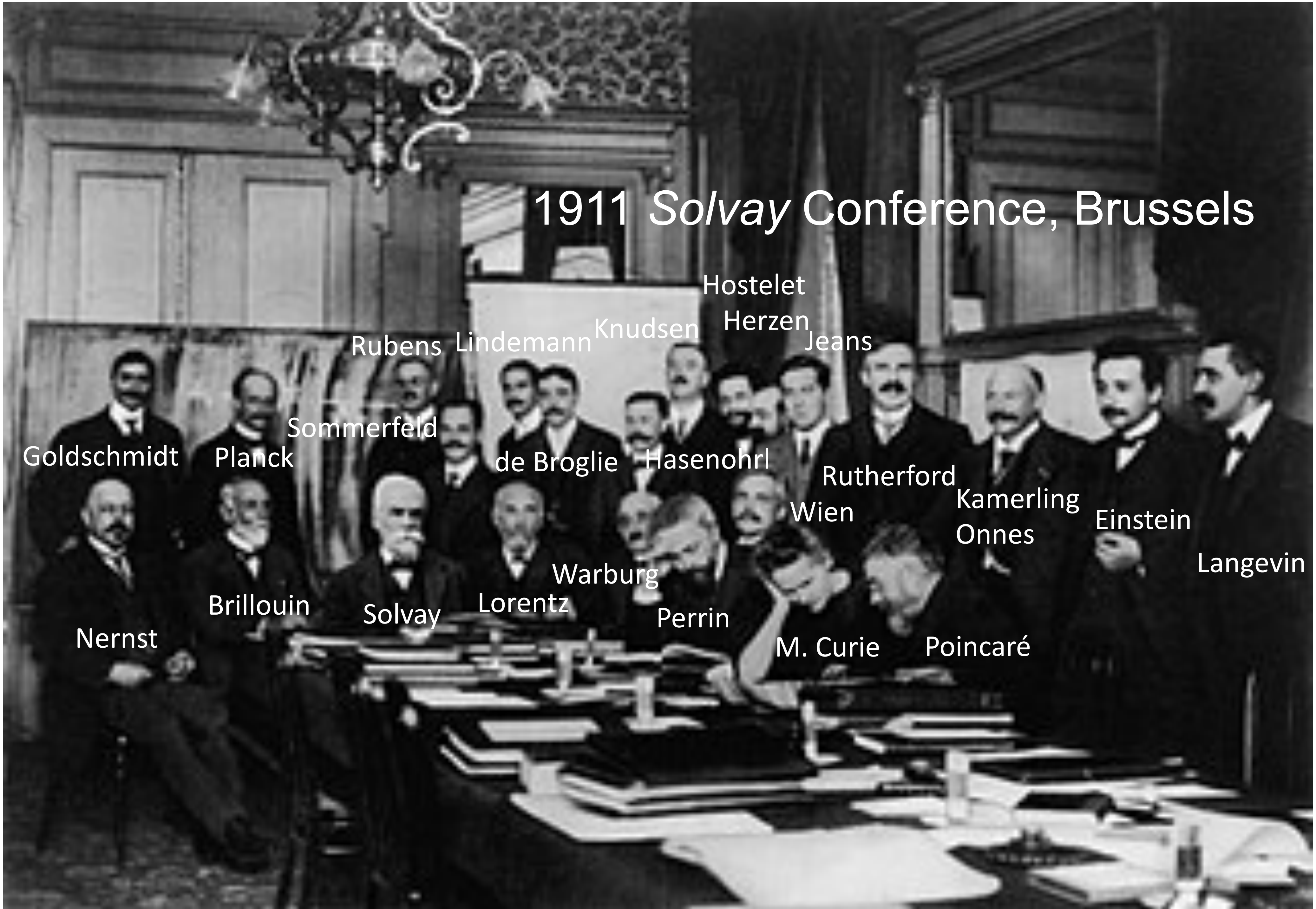
LABORATORIO DI FISICA MODERNA

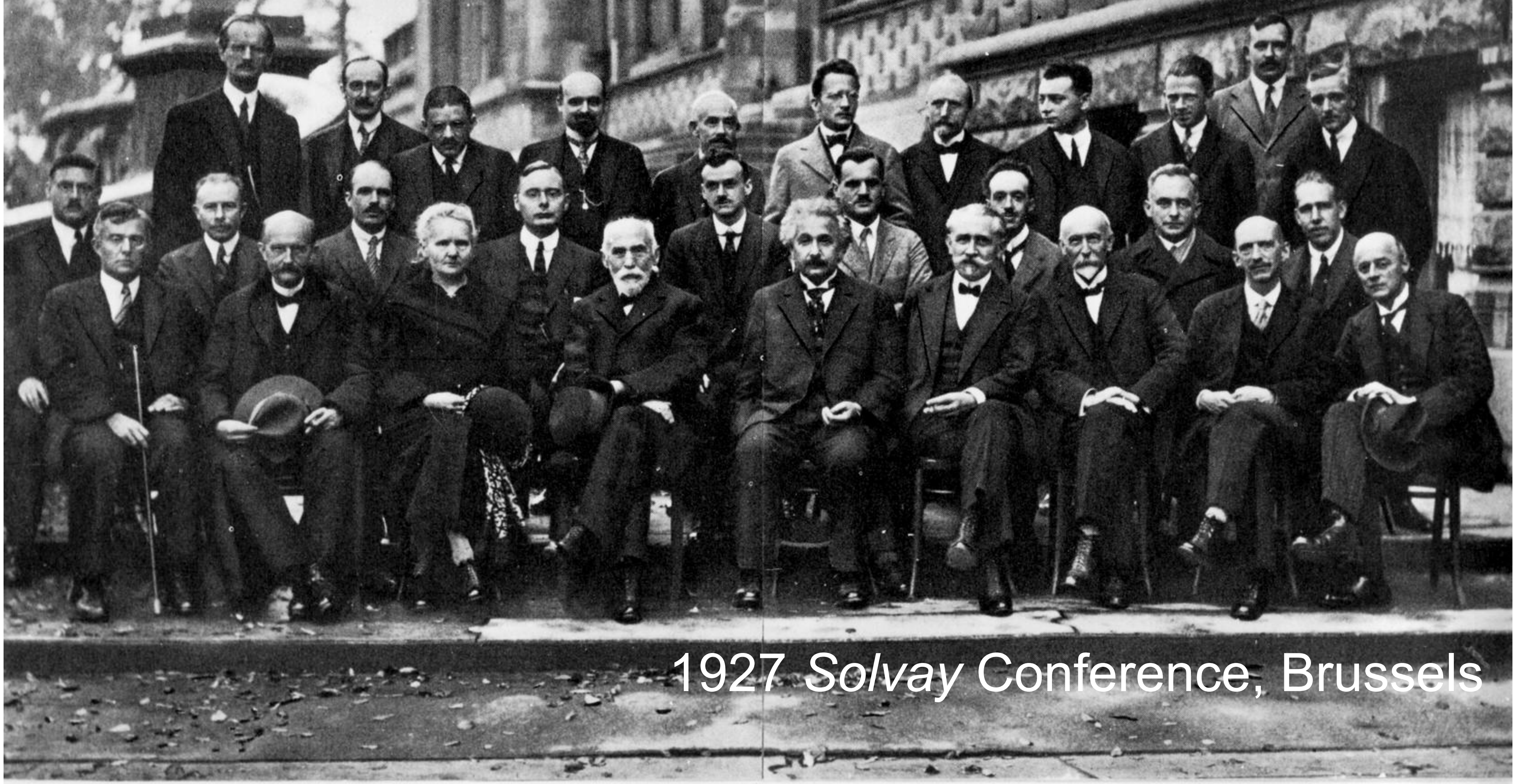
PLS - 2018-19 -1

L. Martina

Dipartimento di Fisica
Università del Salento
Sezione INFN - Lecce

1911 *Solvay* Conference, Brussels


Hostelet
Herzen
Knudsen
Jeans
Rubens
Lindemann
Sommerfeld
Goldschmidt
Planck
de Broglie
Hasenohrl
Rutherford
Wien
Kamerling
Onnes
Einstein
Langevin
Warburg
Brillouin
Solvay
Lorentz
Perrin
Nernst
M. Curie
Poincaré



1927 *Solvay* Conference, Brussels

Photographie Benjamin Couprie

28, Avenue Louise, Bruxelles

R. H. FOWLER

A. PICCARD E. HENRIOT ED. HERZEN TH. DE DONDER E. SCHROEDINGER W. PAULI W. HEISENBERG L. BRILLOUIN

P. EHRENFEST E. VERSCHAFFELT

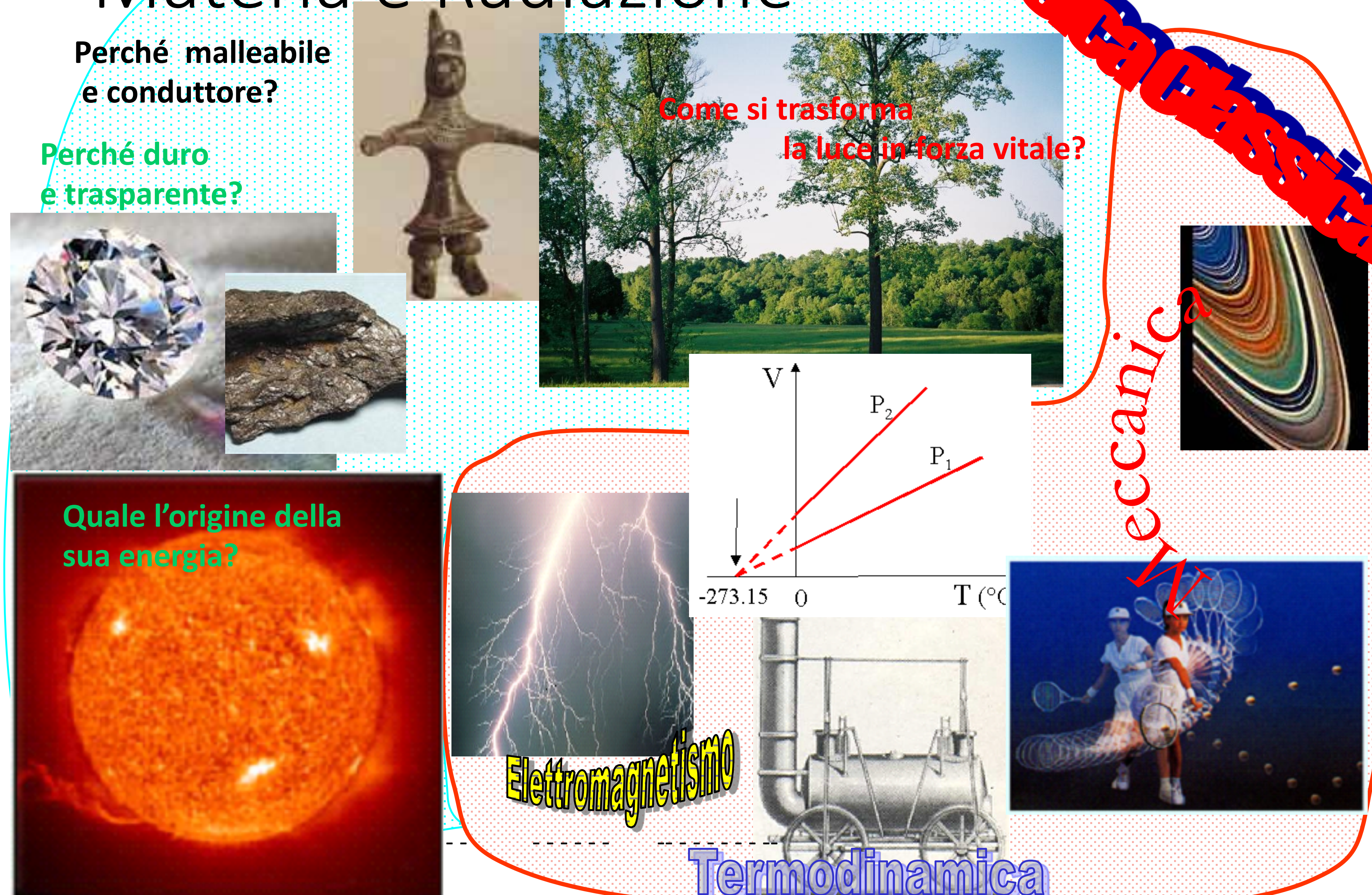
P. DEBYE M. KNUDSEN W. L. BRAGG H. A. KRAMERS P. A. M. DIRAC A. H. COMPTON L.V. DE BROGLIE M. BORN N. BOHR

I. LANGMEIR M. PLANCK MADAME CURIE H. A. LORENTZ A. EINSTEIN P. LANGEVIN CH. E. GUYE C.T.R. WILSON

O.W. RICHARDSON

Materia e Radiazione

Fisica Classica



Perché malleabile e conduttore?

Perché duro e trasparente?

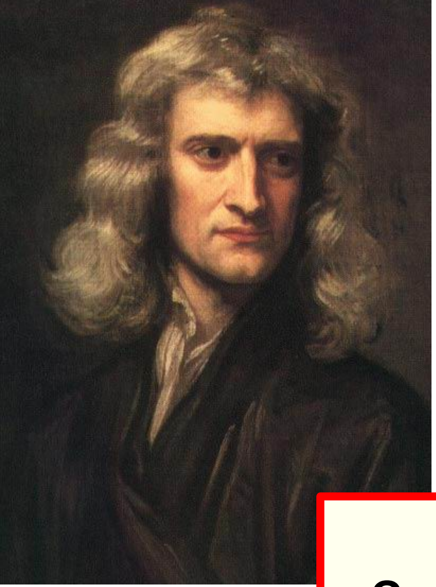
Come si trasforma la luce in forza vitale?

Quale l'origine della sua energia?

Meccanica

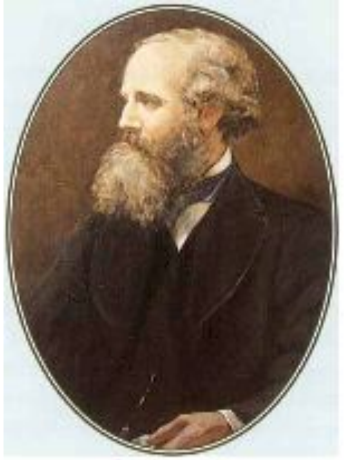
Elettromagnetismo

Termodinamica



I. Newton

Fisica Classica



James Clerk Maxwell
1831 - 1879

Particelle

Ogni corpo persevera nello stato di quiete o di moto rettilineo uniforme, a meno che Φnon sia costretto a cambiarlo a causa di FORZE ad esso impresse (principio d'inerzia)

Il cambiamento dello stato di moto è proporzionale alla forza impressa lungo la linea retta di applicazione

$$\vec{F} = m\,\vec{a}$$

Ad ogni azione corrisponde una reazione uguale in intensità e contraria in verso

$$\vec{F}_{12} = -\vec{F}_{21}$$

Campi

$$\Phi_{S_{chiusa}}(\vec{E}) = \frac{Q_{Tot.in\,S_{chiusa}}}{\epsilon_0}$$

L. Gauss per E

$$\Phi_{S_{chiusa}}(\vec{B}) = 0$$

L. Gauss per B

$$\oint_{\gamma_1} \vec{E}\cdot d\vec{l} = -\frac{d\,\Phi_{S_{\gamma 1}}(\vec{B})}{dt}$$

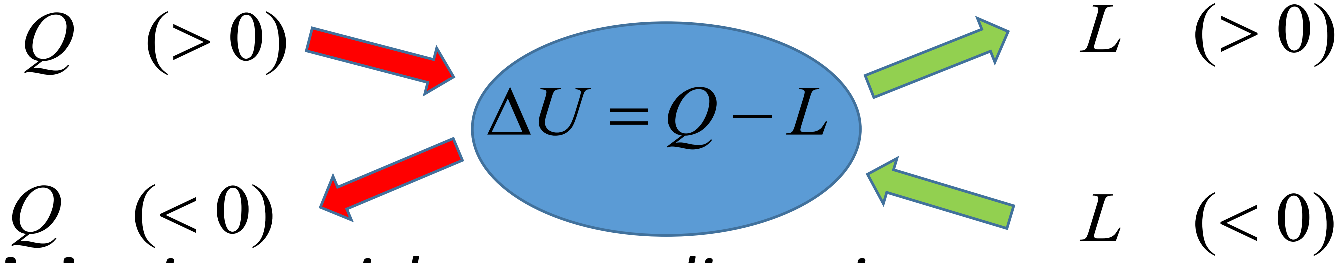
L. Faraday - Neuman - Lenz

$$\oint_{\gamma_2} \vec{B}\cdot d\vec{l} = \mu_0\, I_{S_{\gamma 2}} + \varepsilon_0 \frac{d}{dt}\Phi_{S_{\gamma 2}}(\vec{E})$$

L. Ampére - Maxwell

Termodinamica

- **Principio zero:** *se i corpi A e B sono entrambi in equilibrio termico con un terzo corpo C, allora lo sono anche fra loro.*
- **Primo principio** (conservazione dell'energia) : *la variazione di energia interna di un sistema e' la somma algebrica del calore e del lavoro scambiati con l'ambiente*



$Q \quad (>0)$

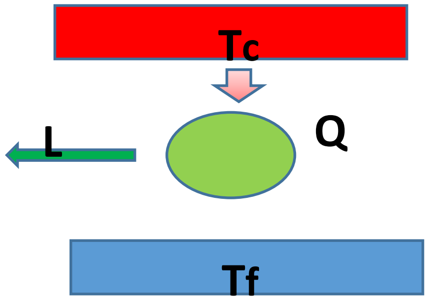
$L \quad (>0)$

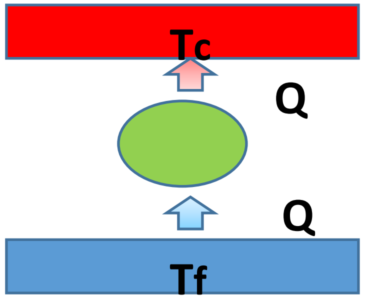
$$\Delta U = Q - L$$

$Q \quad (<0)$

$L \quad (<0)$

- **Secondo Principio:** *in un ciclo termodinamico*
  - (Kelvin - Planck) *e' **impossibile** convertire **completamente** in lavoro il calore assorbito dal serbatoio "caldo"*
  - (Clausius) *e' **impossibile** far passare **unicamente** del calore dal serbatoio "freddo" a quello "caldo"*





“pro-” vs ”contro-” atomismo

PRO

Congr. dei Chimici, Karlsruhe (1860) : definizione di molecola e di atomo (disaccordo)

J.C. Maxwell: *“Benche’ nel corso dei tempi si siano verivicate catastrofi … le molecole… continuano ad esistere oggi esattamente come vennero create: perfette in numero, misura e peso “* (1873)

W. Thomson: “ *E’ un fatto assodato che un gas consista di molecole in movimento …. Il diametro di una molecola di gas non puo’ essere inferiore a* 2 x 10^{-9} cm .” (1870)

L. Boltzmann : *“…dare una dimostrazione del tutto generale della II legge della teoria del calore, come scoprire il teorema meccanico ad essa corrispondente*.” (1866)

“*I problemi della teoria meccanica del calore sono … problemi di teoria della probabilita’* .” (1871)

CONTRO

M. Planck : “ *La piena validita’ del II principio … e’ incompatibile con l’ipotesi di atomi finiti*” (1883)

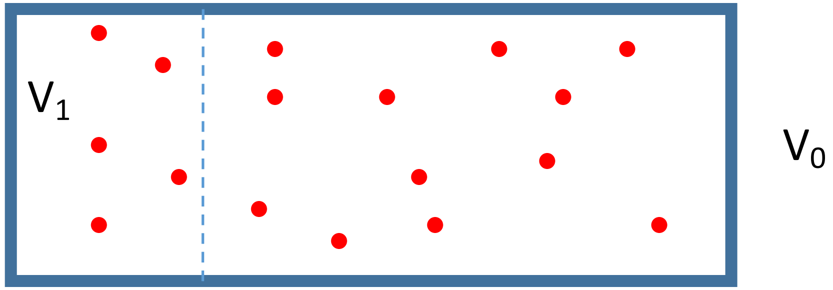
W. Ostwald: *” L’asserzione che tutti i fenomeni … sono riducibili a fenomeni meccanici …e’ sbagliata. …. Tutte le equazioni della meccanica ammettono l’inversione temporale … Quindi … un albero potrebbe diventare di nuovo germoglio e seme, una farfalla bruco e un vecchio bambino*. ”

E. Mach : “ *Non e’ confacente alla fisica considerare mutevoli strumenti , quali molecole e atomi, alla stregua di realta’ sottostanti ai fenomeni.”* (1895)

Termodinamica e Statistica

L. Boltzmann

Gas ideale costituito da N
molecole all'equilibrio termico



Probabilita' per la singola molecola
di trovarsi in V_1

$$p=\frac{V_1}{V_0},\qquad q=\frac{V_0-V_1}{V_0}$$

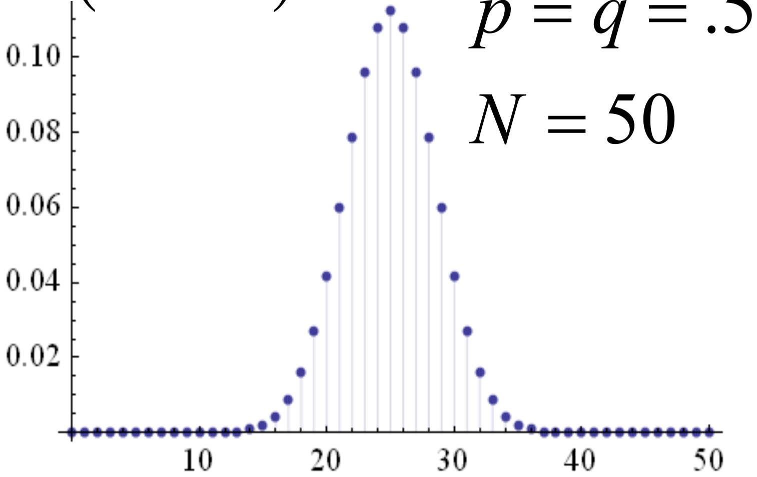
Probabilita' per n molecole
di trovarsi in V_1 e N-n all'esterno

$$P(n)=\frac{N!}{n!(N-n)!}p^n q^{N-n}$$

$$\boxed{S=k\ln P+c}$$

Principio
di Boltzmann

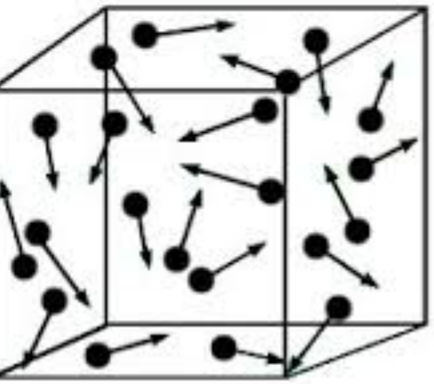
Il sistema **tende** al macrostato di massima entropia,
cioe' a quello che possiede il numero massimo di
microstati



$$p=q=.5,$$
$$N=50$$

Molecole e
Moto Browniano

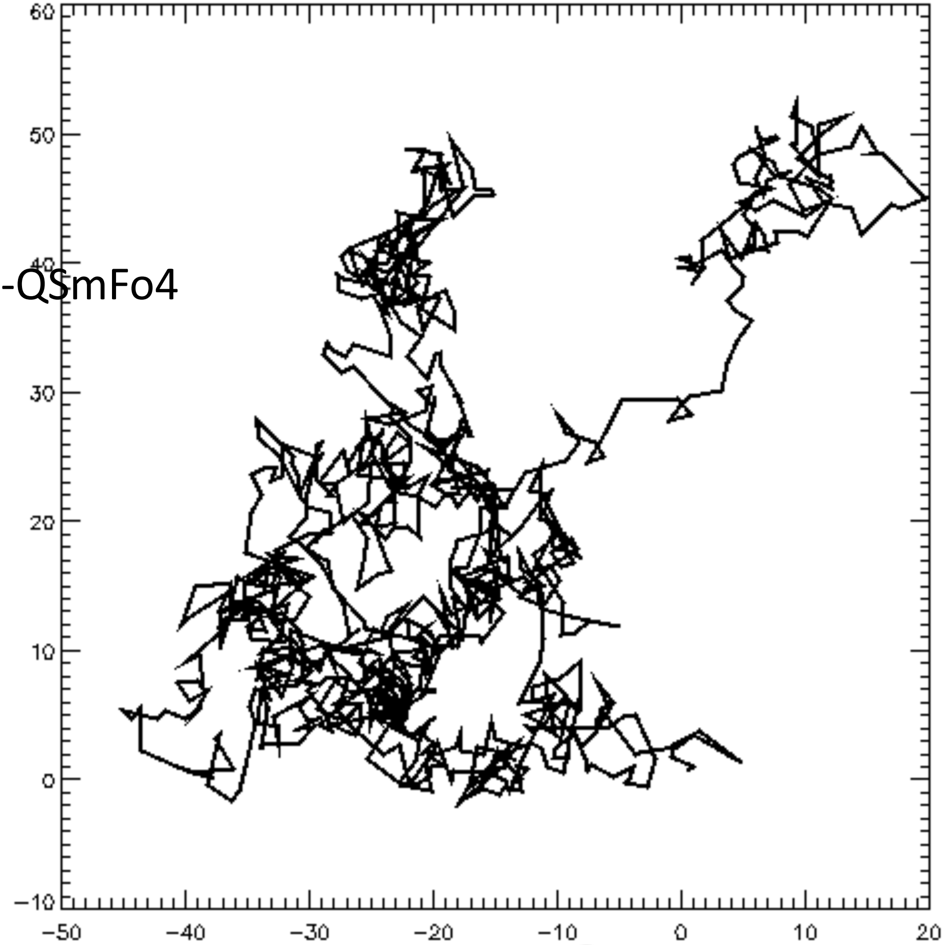
https://www.youtube.com/watch?v=Xscn-QSmFo4



In questo articolo dovremo mostrare che, …., particelle di dimensioni visibili al microscopio sospese in un fluido**, in seguito al moto molecolare del calore** possono descrivere moti osservabili.

A. Einstein, *Ann. d. Phys.*, 17 (1905) 549

$$D = \frac{RT}{\underline{N_A}} \frac{1}{6\pi\eta \underline{d}}$$



$$D = \frac{1}{2} \lim_{t\to\infty} \frac{\langle \vec{r}^{\,2}(t) \rangle}{t}$$

Coefficiente di diffusione

N_A = **Numero di Avogadro**
d = raggio della particella
η = coeff. di viscosita’

Realta’ delle molecole

J. Perrin

J. Perrin: Nobel 1926

N_A	
68×10^{22}	per mezzo di emulsioni analoghe a gas;
62×10^{22}	“ emulsioni analoghe a liquidi;
60×10^{22}	“ fluttuazioni emulsioni concentrate;
64×10^{22}	“ moto Browniano traslazionale;
65×10^{22}	“ moto Browniano rotazionale;
75×10^{22}	“ opalescenza critica;
65×10^{22}	“ azzurro del cielo;
64×10^{22}	“ radiazione di corpo nero;
61×10^{22}	“ goccioline ionizzate secondo Millikan;
62×10^{22}	“ decadimento radioattivo

> *“La teoria atomica ha trionfato. Ancora poco tempo fa assai numerosi,*
> *i suoi avversari, alfine conquistati, rinunciano uno dopo l’altro a sfide che furono*
> *a lungo legittime e senz’altro utili”* J. Perrin “ Les Atomes“, (Paris, 1913)

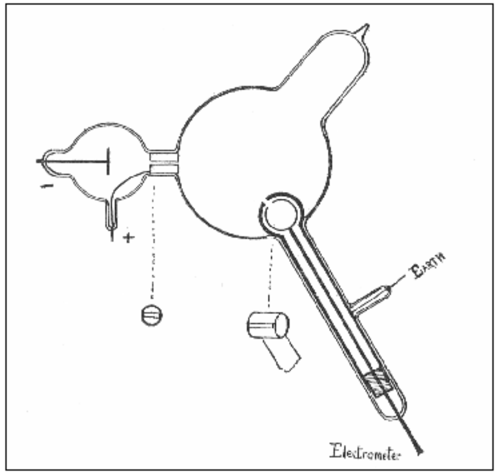
Fundamental Physical Constants

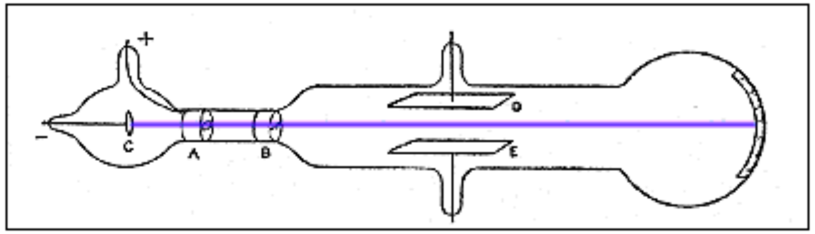
$N_A = 6.022\,141\,79 \times 10^{23}$ mol^{-1}

$$l_{atomo} \approx \sqrt[3]{\frac{M_{atomo}}{N_A\ \delta_{atomo}}} \approx 10^{-10} m = 1\ \hat{A}$$

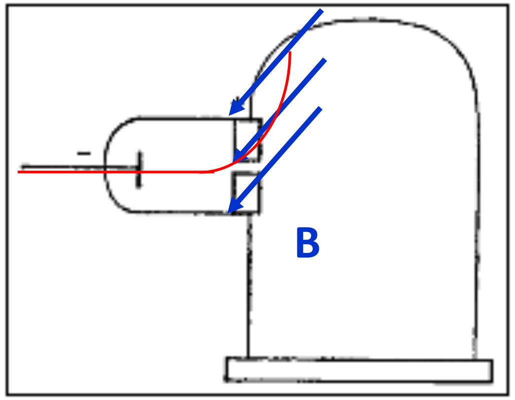
La scoperta dell’elettrone

J.J. Thomson





$$\boxed{\frac{e}{m} = \frac{2V}{B^2 r^2}}$$



> “We have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state: a state in which all matter... is of one and the same kind; this matter being the substance from which all the chemical elements are built up."

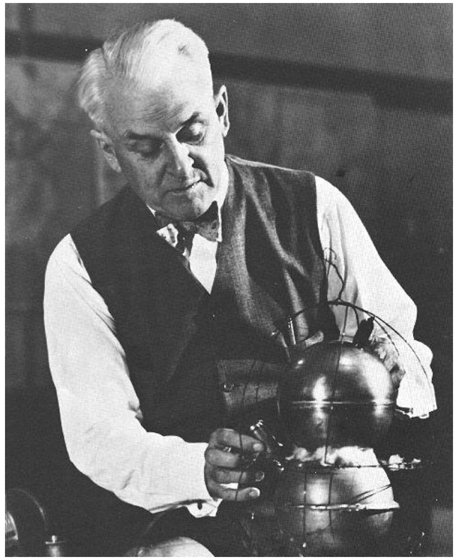
(J.J. Thomson, *"Cathode Rays,"* The London Phil. Mag. J. Science, V, Oct.1897)

$$\frac{e}{m} = \mathbf{-1.758\ 820\ 12(15) \times 10^{11}\ C\ kg^{-1}}$$

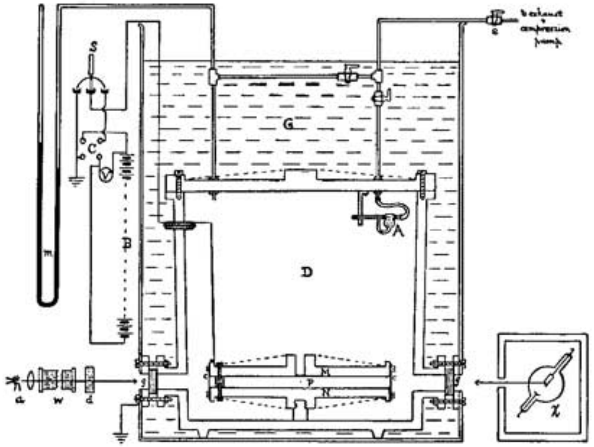
http://www.aip.org/history/electron/jjhome.htm

The NIST Reference on
Constants, Units, and Uncertainty

L’esperienza di Millikan

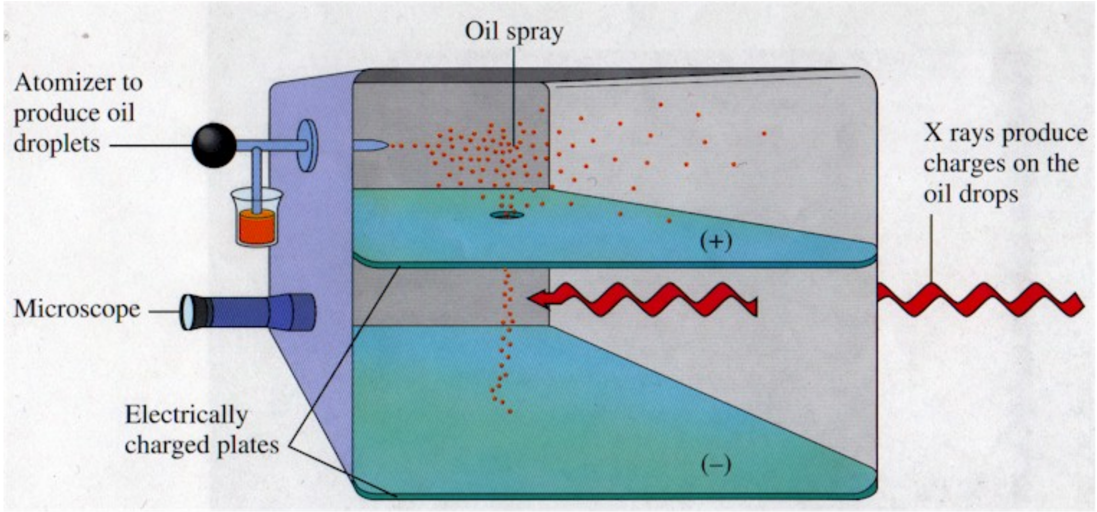


R. Millikan



e = 1.602 176 53(14) x 10^{-19} C

The NIST Reference on Constants, Units, and Uncertainty


Oil spray
Atomizer to produce oil droplets
X rays produce charges on the oil drops
Microscope
(+)
Electrically charged plates
(−)

$$F_{visc} = 6\pi r \eta v \text{ velocità limite } v$$

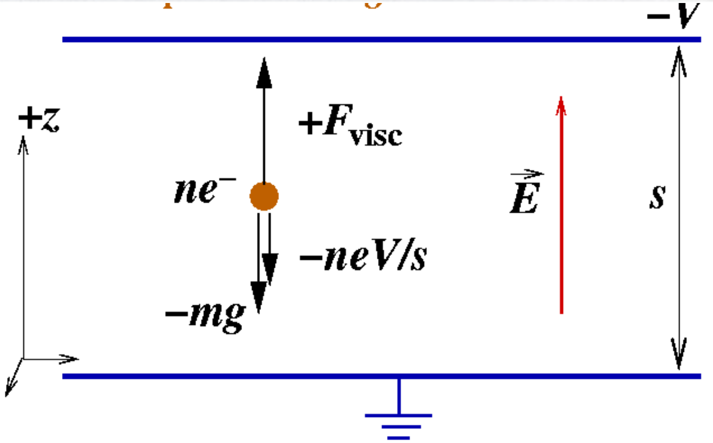
$$\frac{4}{3}\pi r^3 \rho g = 6\pi r \eta v$$

$$r = \sqrt{\frac{9\eta v}{2\rho g}}$$

$$qE = mg$$

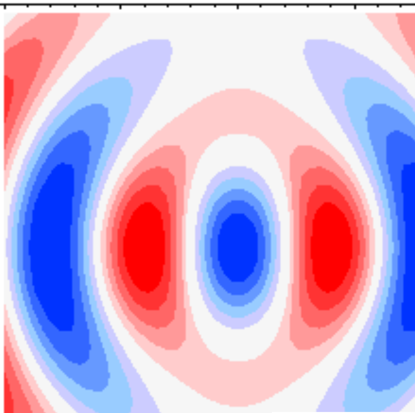
$$E = \frac{V}{d}$$

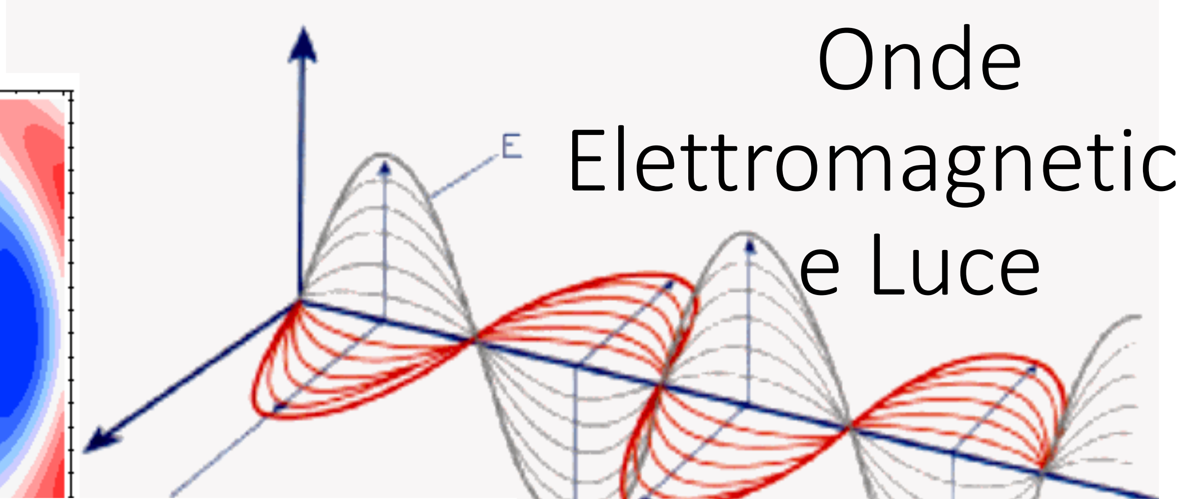
$$\boxed{q = \frac{18\pi d}{V}\sqrt{\frac{\eta^3 v^3}{2\rho g}}}$$


−V
+z
$+F_{visc}$
ne^-
$\vec{E}$
s
$-neV/s$
$-mg$

http://www.aip.org/history/gap/Millikan/Millikan.html

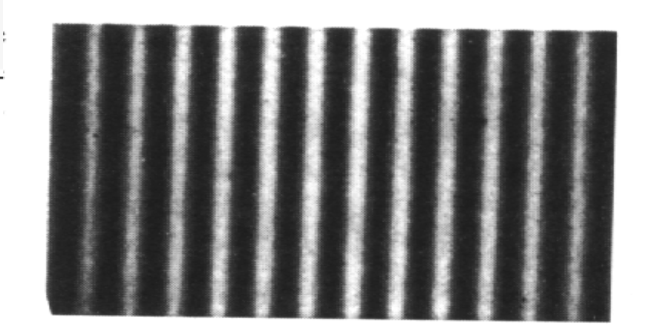
PSSC: FISICA, vol. 2, Cap. 28-4



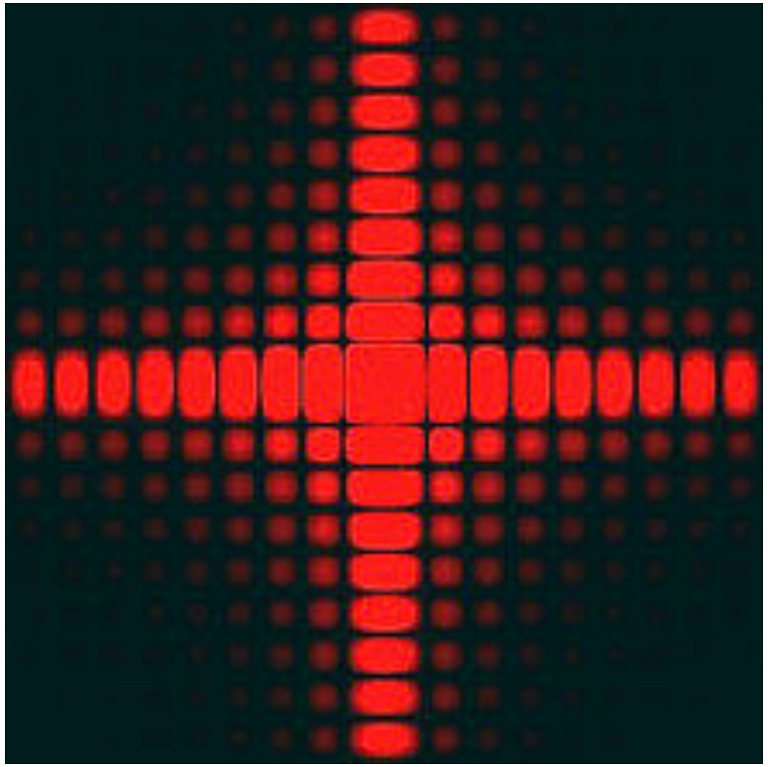


Onde Elettromagnetiche e Luce

R. Hertz



Onde Hertziane (1887)



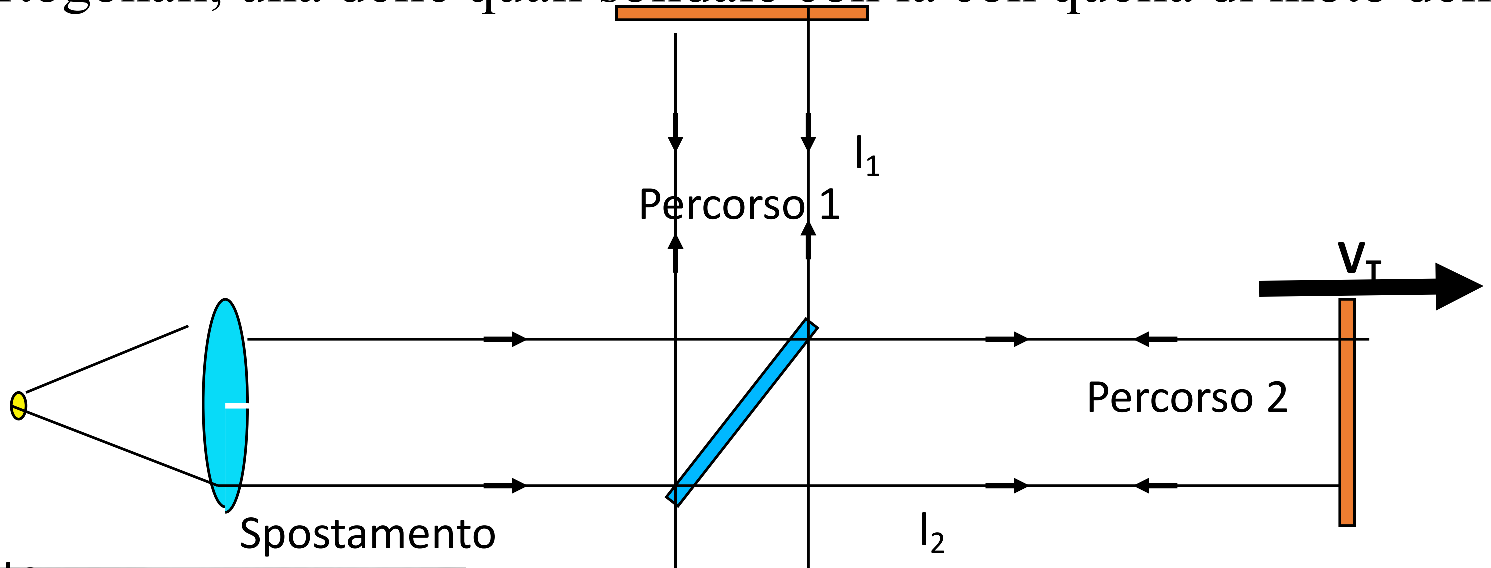
G. Marconi

$$\nabla^2 f - \frac{1}{c^2}\frac{\partial^2 f}{\partial^2 t} = 0$$

NON INVARIANTE SOTTO TRASFORMAZIONI DI GALILEI

Esperienza di Michelson e Morley

Misurare le *ipotetiche* proprietà dell’Etere confrontando la velocità della luce lungo due direzioni ortogonali, una delle quali solidale con la con quella di moto della Terra

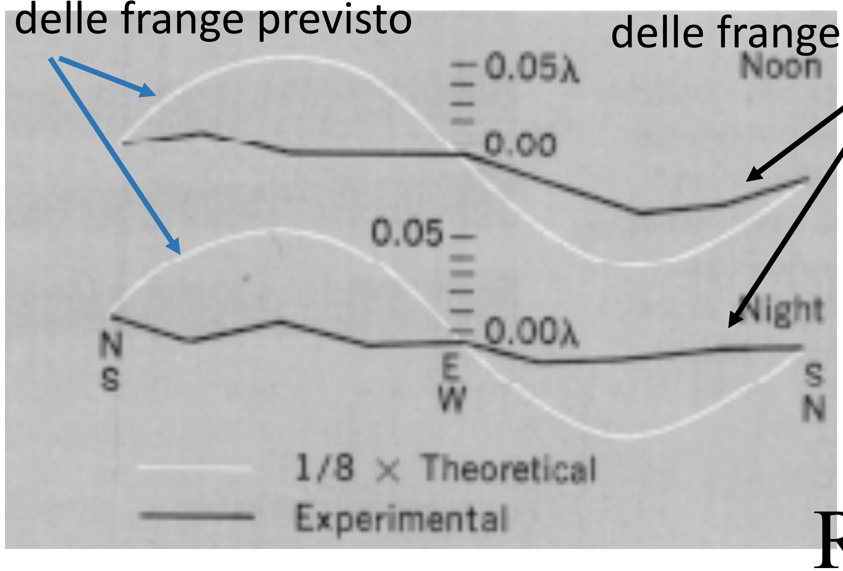

l_1
Percorso 1
V_T
Sorgente
Percorso 2
l_2

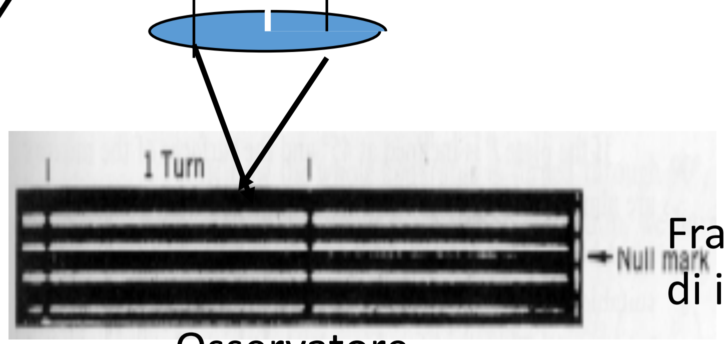
E.W. Morley

A.A. MIchelson

Spostamento delle frange previsto

Spostamento delle frange osservato



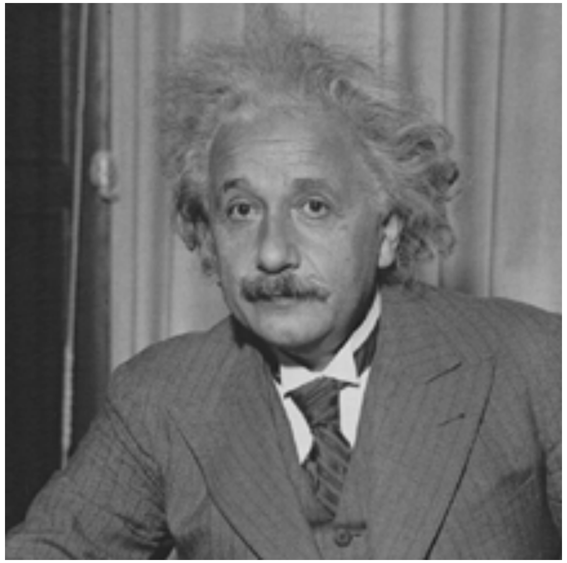

1 Turn
Null mark

Frange di interferenza

Osservatore

Risultato: Nessun vento di etere osservato!

I postulati della Relatività di Einstein



A. Einstein

1. **Postulato della relatività**

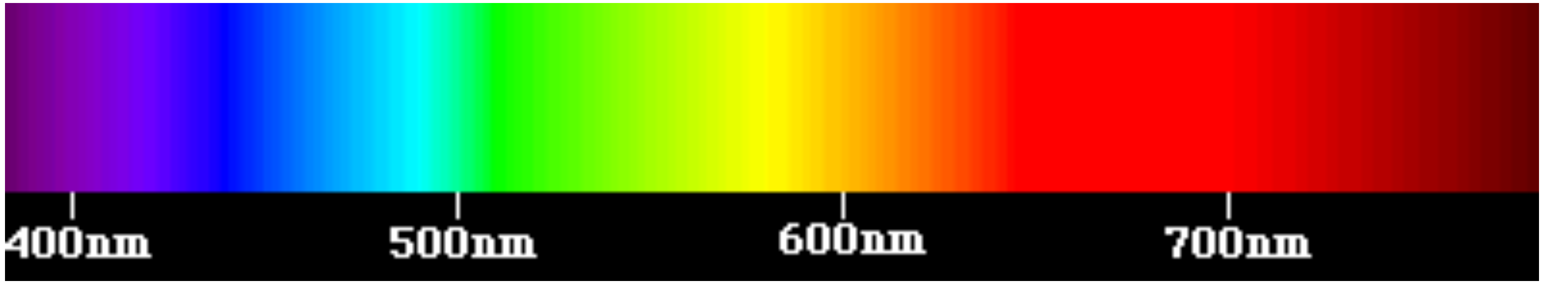
Le leggi della fisica sono le stesse in tutti i sistemi di riferimento inerziali. Non esiste un sistema di riferimento privilegiato

2. **Postulato della velocità della luce**

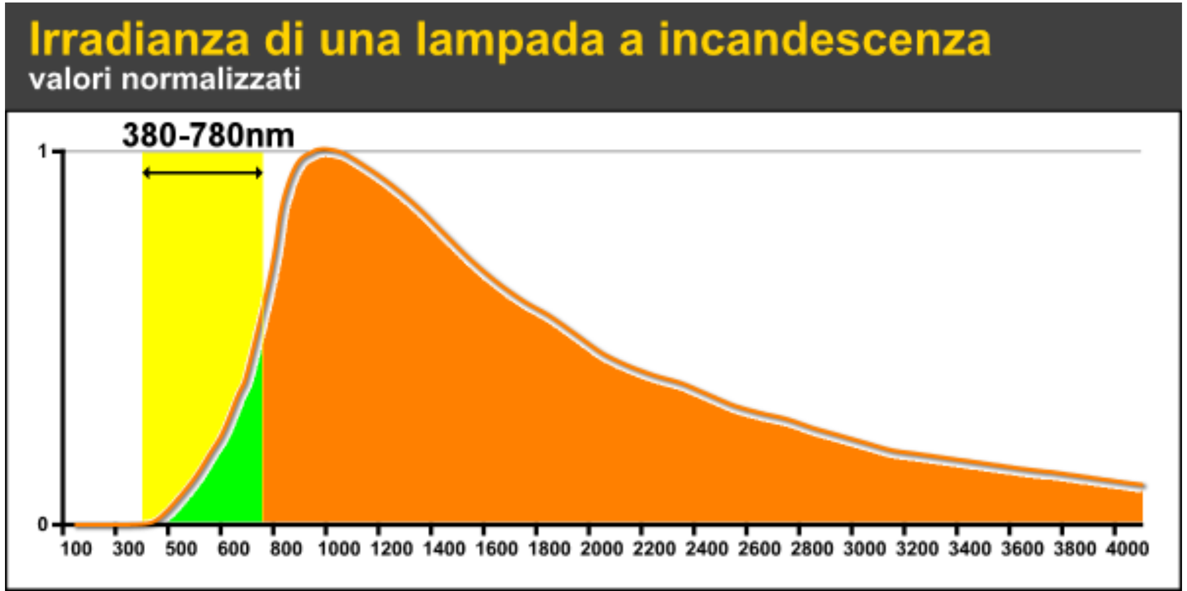
La velocità della luce nel vuoto ha lo stesso valore ***c*** in tutte le direzioni e in tutti i sistemi di riferimento inerziali.

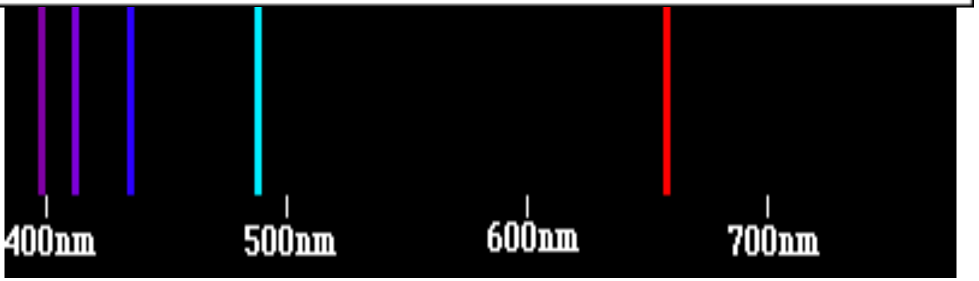
$$\boldsymbol{C} = 299\,792\,458 \text{ m / s}$$

Spettro delle sorgenti luminose

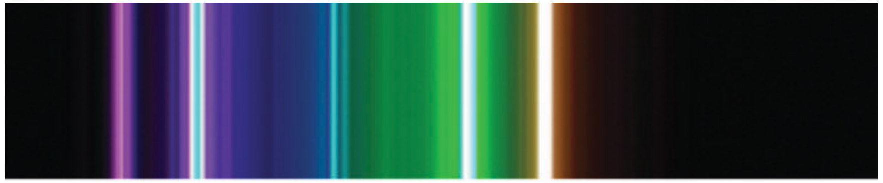

400nm
500nm
600nm
700nm

Solidi: Spettro continuo

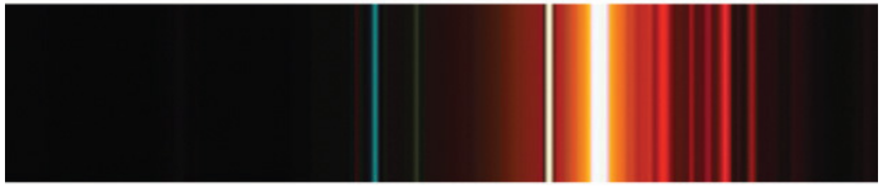



400nm
500nm
600nm
700nm

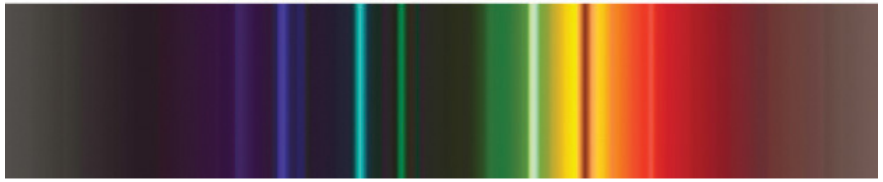
Spettro di H nel visibile



Hg vapor spectrum (350-700 nm)



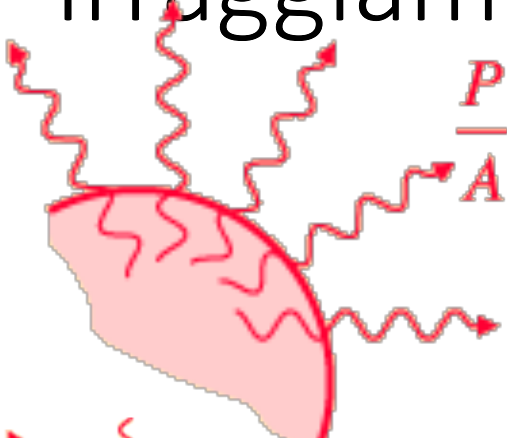
Low-pressure Na spectrum (350-700 nm)



High-pressure Na spectrum (350-700 nm)

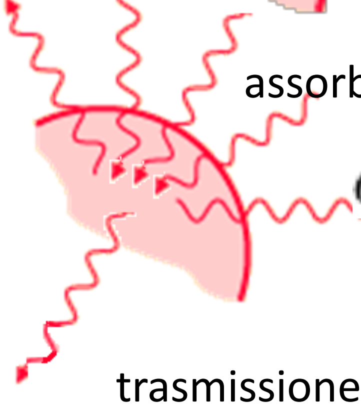
Gas: Spettro discreto

Irraggiamento



$$\frac{P}{A} = \sigma T^4 \; j/\,m^2 s$$ Stefan-Boltzmann Law

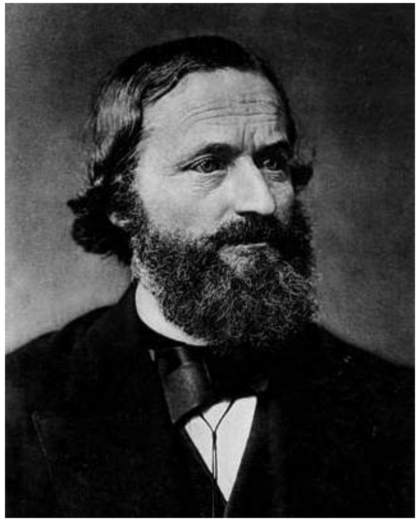
$$\sigma_e = 5.6703 \times 10^{-8}\, watt\,/\,m^2 K^4$$


assorbimento
riflessione
trasmissione

$$\frac{P}{A} = e\sigma T^4$$

$$\alpha + \rho + \tau = 1$$

$$P = e\sigma A(T^4 - T_C^4)$$



G. R. G. Kirchhoff

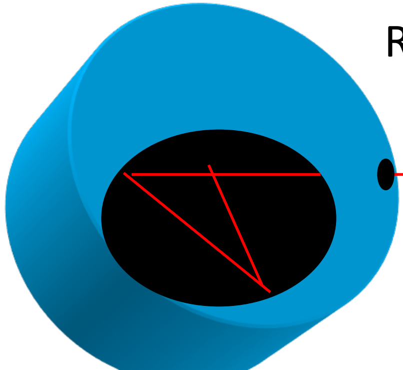
«per ogni sostanza il comportamento rispetto all'emissione e all'assorbimento, a parità di temperature, è il medesimo»

$$e = \alpha$$

II Principio della Termodinamica

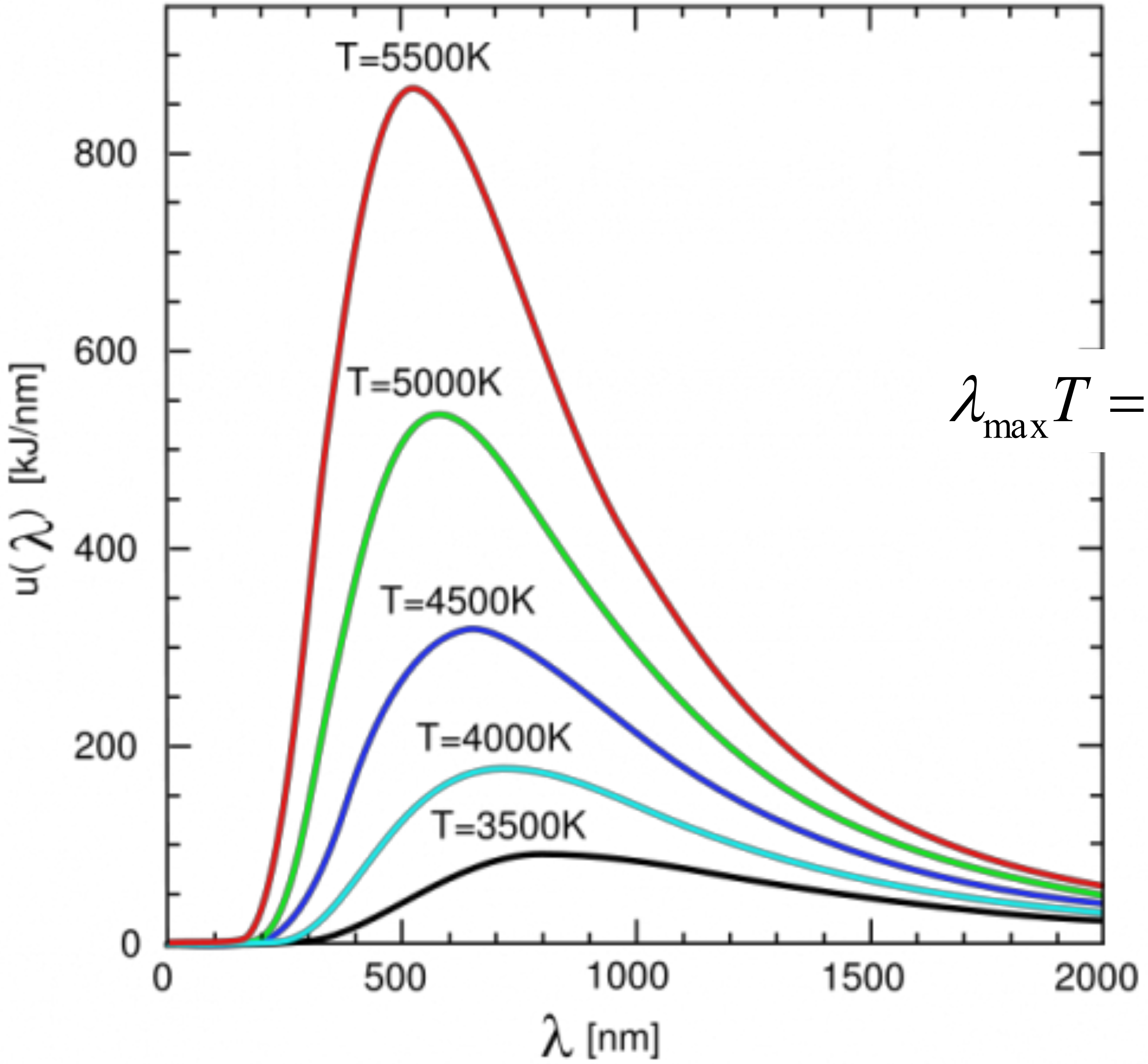
Radiatore Perfetto
CORPO NERO

Assorbitore Perfetto
CORPO NERO



$$P_{emiss} = f(T)$$

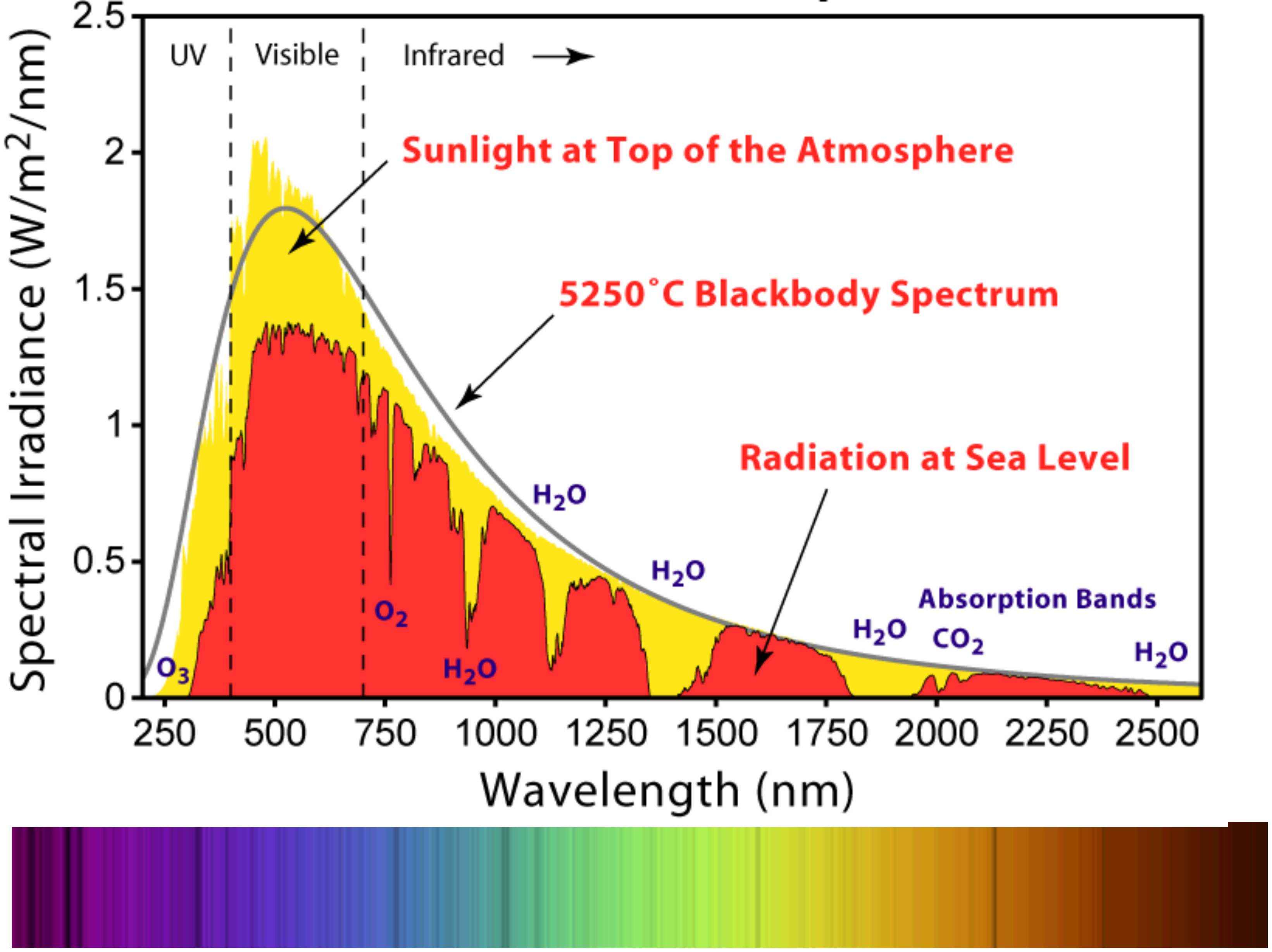
Spettro di corpo nero



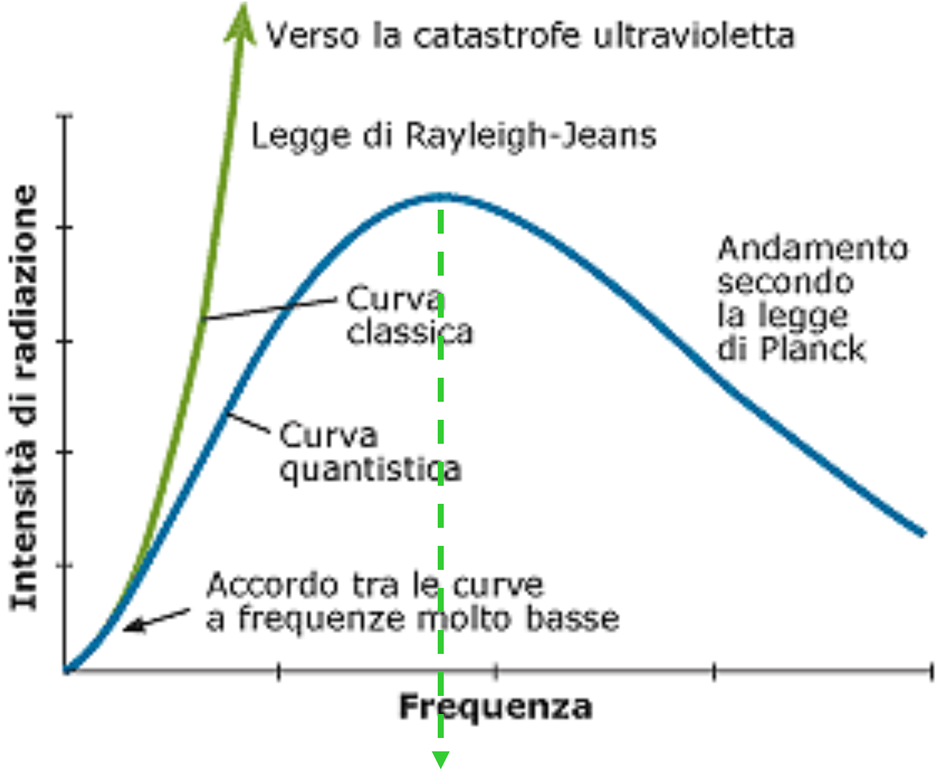
Legge di Wien

$$\lambda_{\max} T = 2.898 \times 10^{-3} m\ {}^{0}K$$

Solar Radiation Spectrum



La quantizzazione di Planck



M. Planck

Statistica Boltzmann

$$\langle \varepsilon \rangle (\nu) = \frac{\int_0^\infty E\, e^{-E/kT}}{\int_0^\infty e^{-E/kT}} \approx \nu^2 T$$

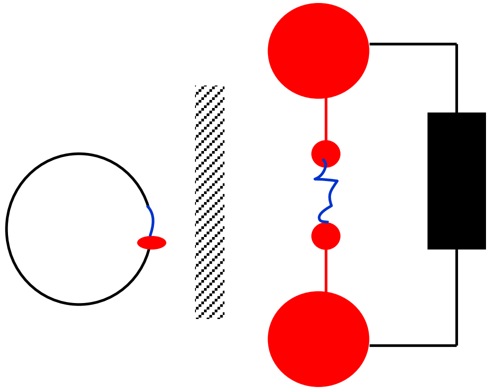
Ipotesi di Planck (1900): per ogni data frequenza, il sistema materiale può scambiare con la radiazione **multipli interi** di un quanto fondamentale.

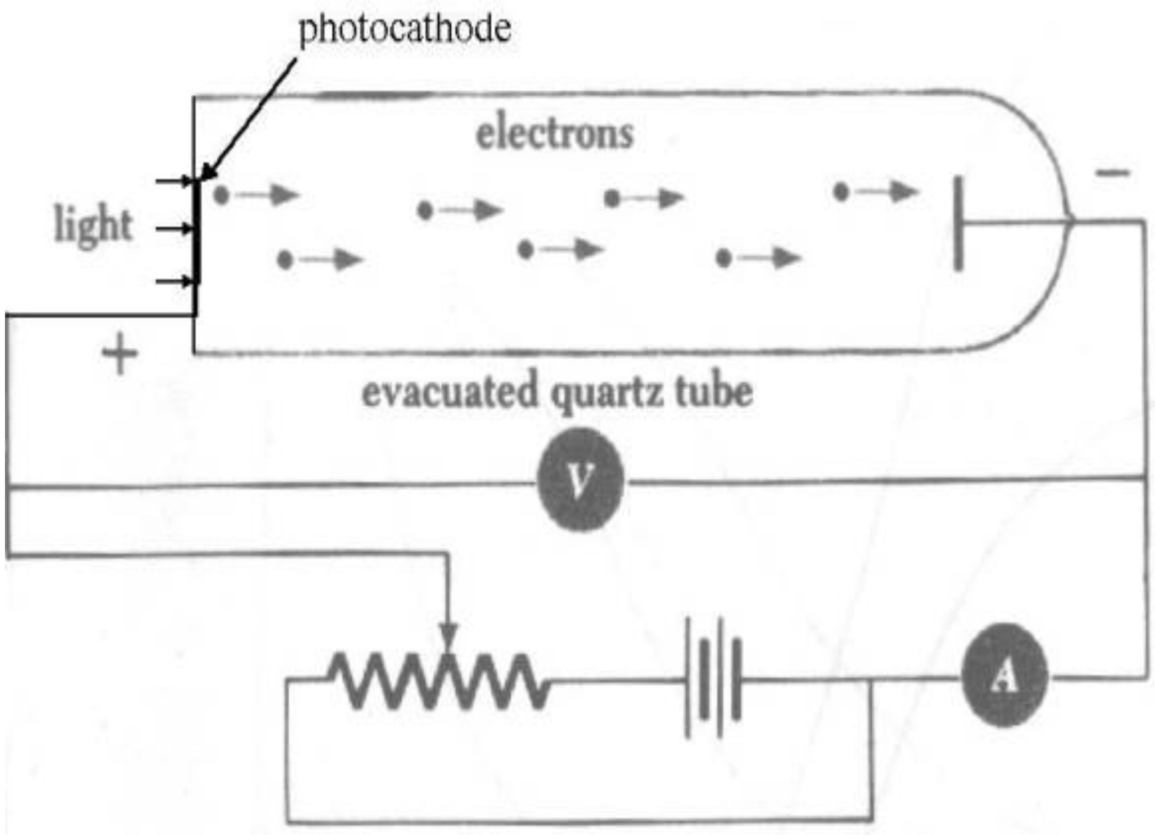
$$\boxed{\Delta E = h\nu} \Rightarrow \langle \varepsilon \rangle (\nu) \approx \frac{h\nu^3}{e^{\frac{h\nu}{k_B T}} - 1}$$

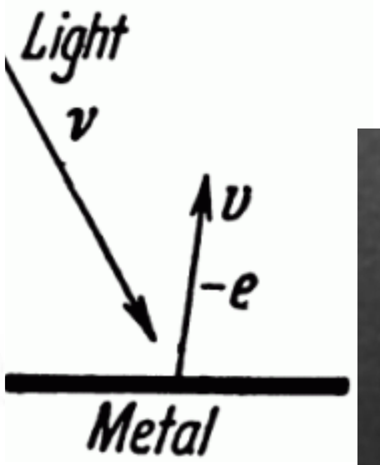
http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

L'effetto Fotoelettrico

Quarzo	SI
Gesso	SI
Vetro	Ridotta
Legno	Nulla



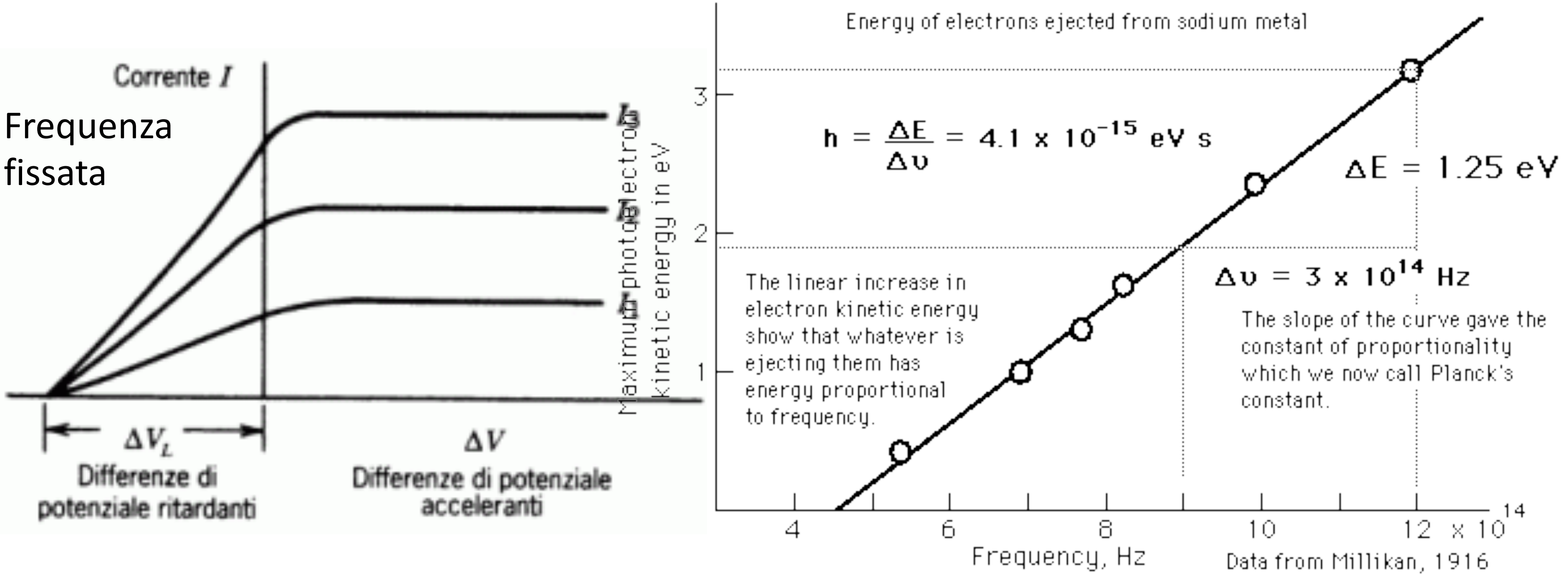

photocathode
electrons
light
−
+
evacuated quartz tube
V
A


Light
ν
v
−e
Metal

Hertz, 1887

Lenard
1899 - 1902

Relazioni caratteristiche dell'effetto fotoelettrico



Frequenza fissata

$$h = \frac{\Delta E}{\Delta \nu} = 4.1 \times 10^{-15} \text{ eV s}$$

The linear increase in electron kinetic energy show that whatever is ejecting them has energy proportional to frequency.

The slope of the curve gave the constant of proportionality which we now call Planck's constant.

- **Solo luce con frequenza > frequenza di soglia produce una corrente**
- **La corrente è attivata in tempi < 10^{-6} s**
- **L'azione "puntuale" della luce incidente**
- **Proporzionalita' tra corrente e intensità luminosa incidente**
- **Il potenziale di arresto è proporzionale alla frequenza della luce incidente**

Incoerente con la Fisica Classica !!!

L’idea di Einstein

Nel 1905 Albert Einstein assunse l’ipotesi di Planck che la radiazione incidente è costituita da pacchetti (“quanti”) di energia

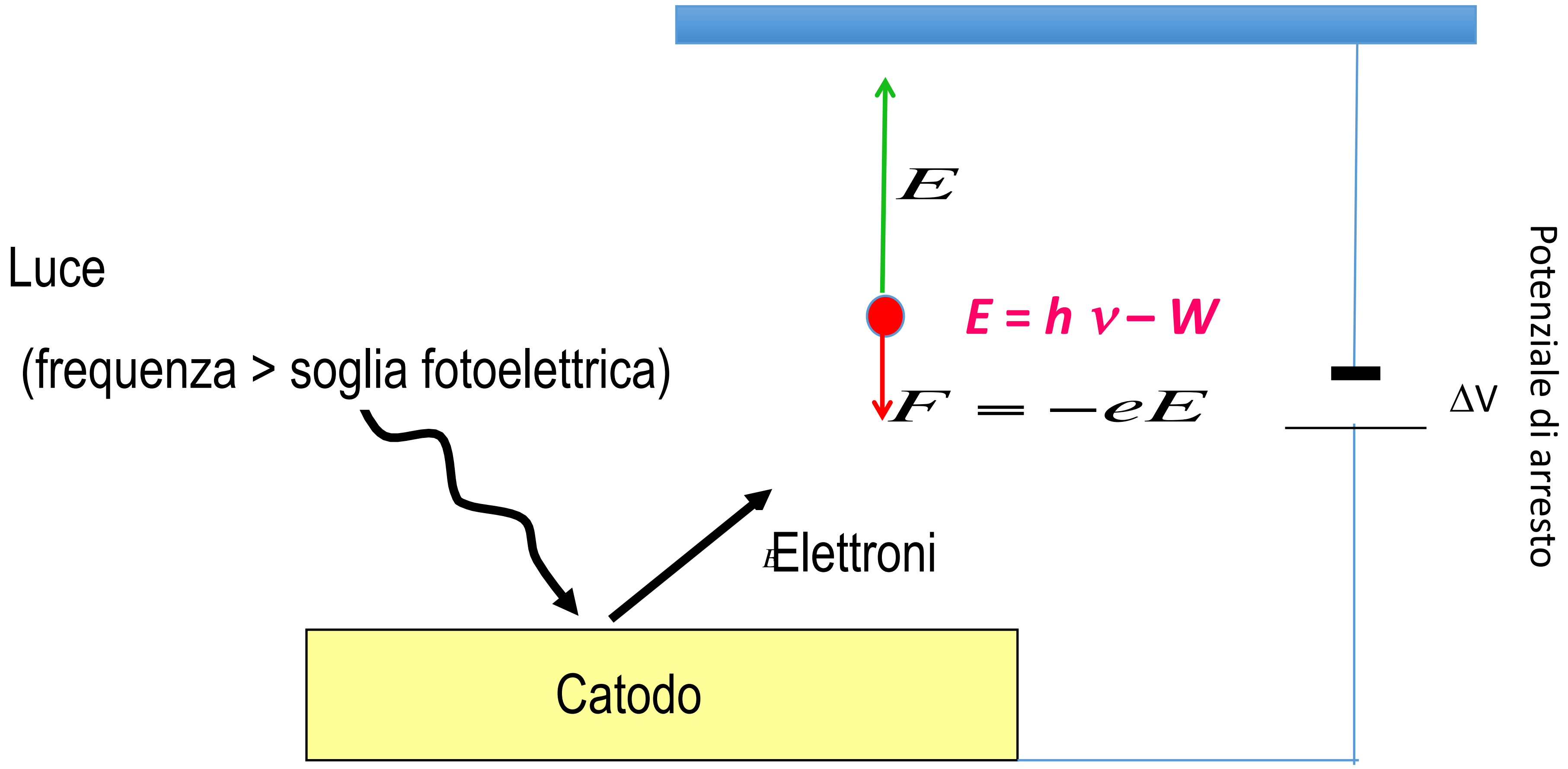
$$E = h\nu$$

dove ν e\` la frequenza e $h$ e\` una costante (costante di Planck).

Nella fotoemissione, uno di questi quanti di energia viene assorbito da un elettrone del fotocatodo, ed emesso con energia

$$E = h\nu - W$$

dove l’energia minima necessaria ad estrarre l’elettrone, chiamata “lavoro di estrazione “, si è indicata con W.



Luce

(frequenza > soglia fotoelettrica)

Elettroni

Catodo

E

$E = h\nu - W$

$F = -eE$

ΔV

Potenziale di arresto

Affinché l'elettrone emesso riesca a raggiungere l'anodo a potenziale di arrresto pari a – ΔV, rispetto al catodo emettitore, deve possedere una energia a E = e ΔV.

$$e\,\Delta V = E = h\,\nu - W \quad \Rightarrow \quad \Delta V = h/e\;\nu - W/e$$

¡ Fotoni !

Elettromagnetismo Classico:

legge di dispersione

$$\lambda \nu = c$$

impulso/energia

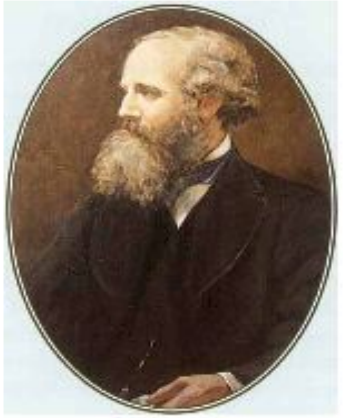
$$p = \frac{E}{c}$$

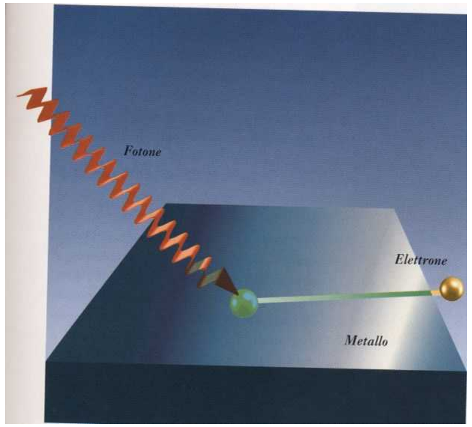
Planck

Einstein

$$\boxed{E = h\nu, \quad p = \frac{h}{\lambda}}$$

Relazioni di Planck - Einstein


James Clerk Maxwell
1831 - 1879



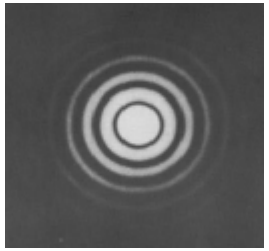
$$E^2 - p^2c^2 = m_0{}^2c^4$$

Invariante
Relativistico
Energia/impulso

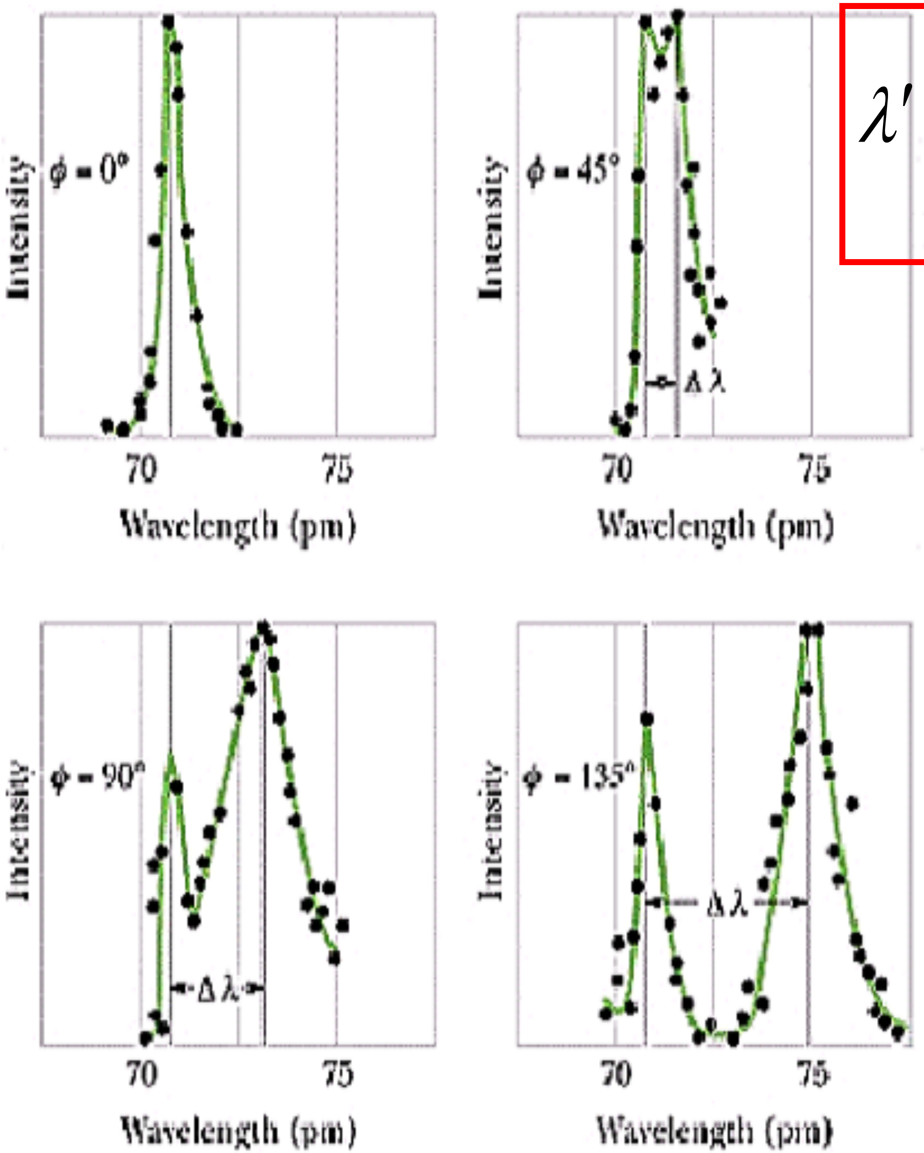
$$\boxed{m_{fotone} = 0}$$

Einstein interpreta I pacchetti di energia luminosa
come **particelle** di massa a riposo nulla,
che possono viaggiare solo alla velocità della luce.

... e la DIFFRAZIONE !?!



Effetto Compton

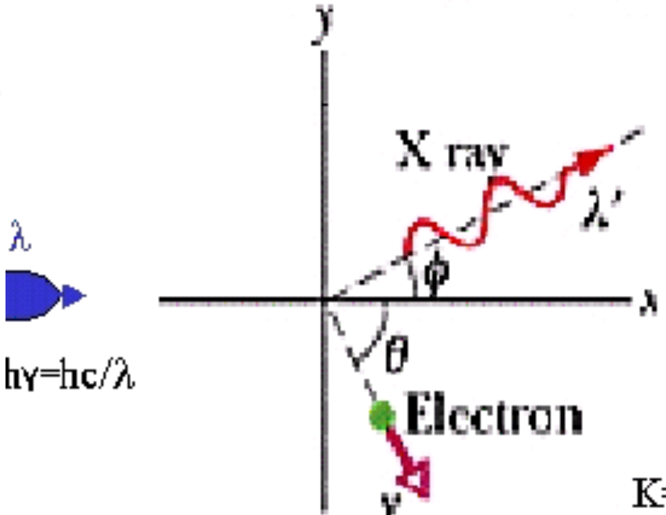


$$\boxed{\lambda' - \lambda = \frac{h}{m_{el}c}\left(1 - \cos\theta\right)}$$

$$\lambda\,\nu = c$$

A. Compton

$E' = h\gamma' = hc/\lambda'$



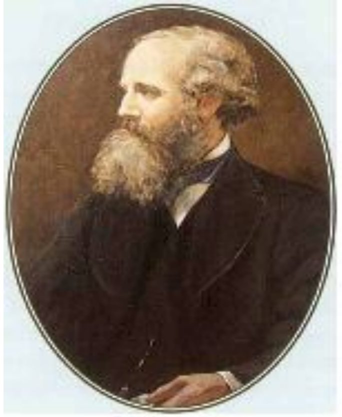
$h\gamma = hc/\lambda$

$K = m_e c^2(\gamma - 1)$

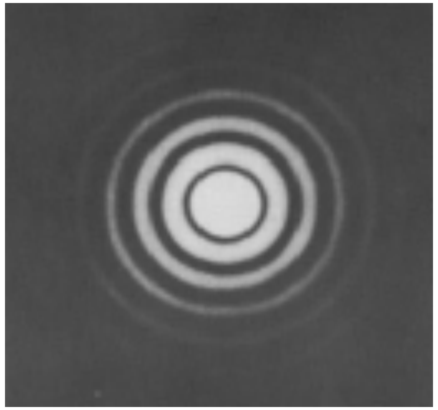
- Cons. dell'energia $$E = E' + K$$
- Cons. Quantità di moto $$\vec{p}_X = \vec{p}_X{}' + \vec{p}_{el}$$

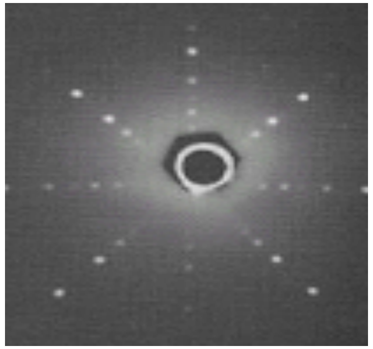
$$p_X = \frac{h}{\lambda},\ p'_X = \frac{h}{\lambda'},\ p_{el} = \gamma m_{el} v$$

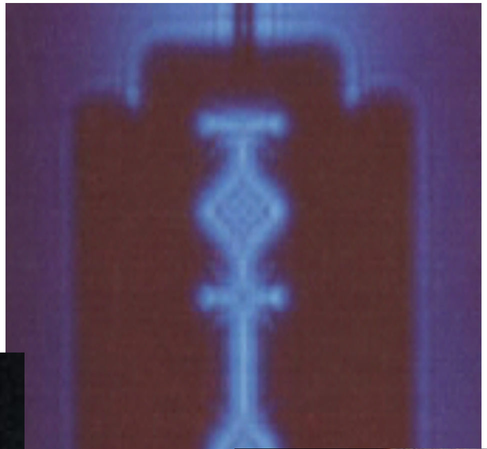
Diffrazione

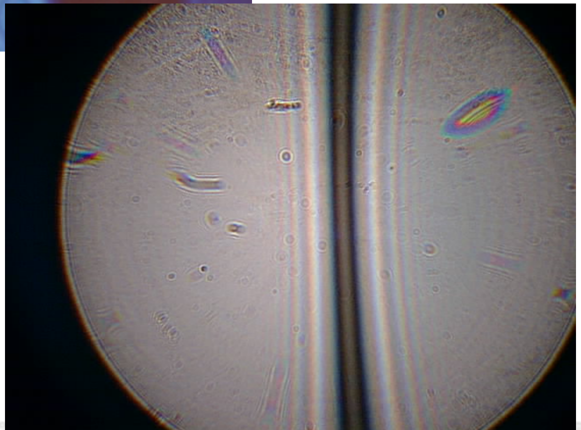

James Clerk Maxwell
1831 - 1879

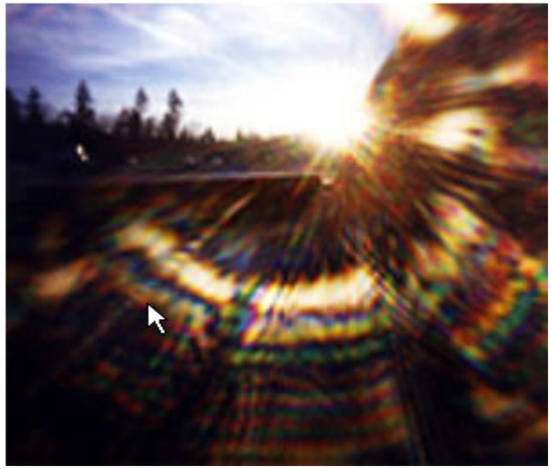
Elettromagnetismo
Classico

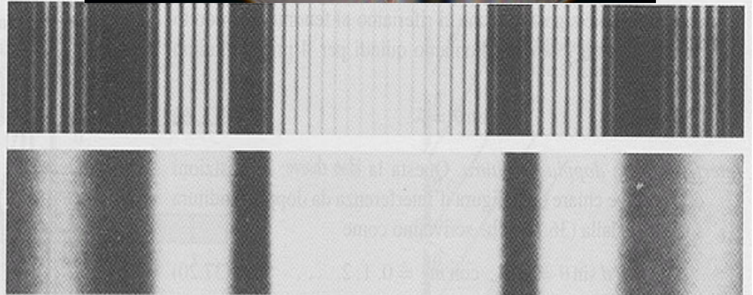






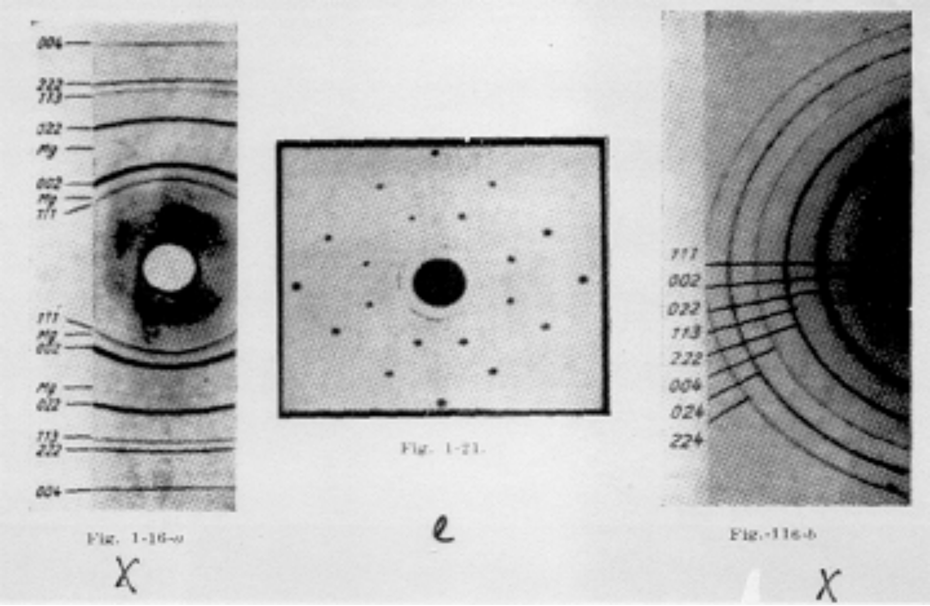


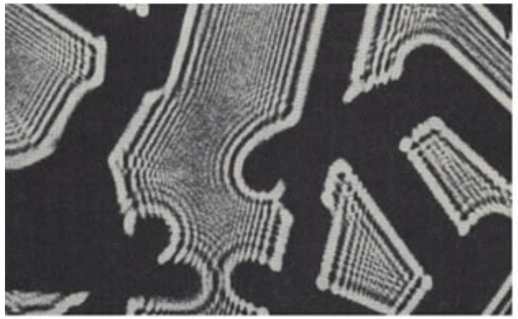




$$a \sin\theta = n\lambda$$

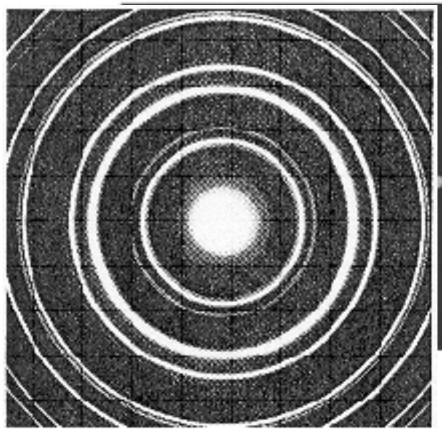
Diffrazione di luce e di particelle

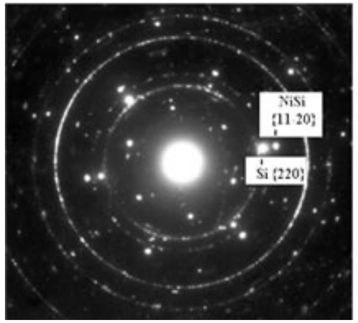

004
222
113
022
Mg
002
Mg
111
111
Mg
002
Mg
022
113
222
004
Fig. 1-16-a
X
Fig. 1-21
e
111
002
022
113
222
004
024
224
Fig. 1-16-b
X



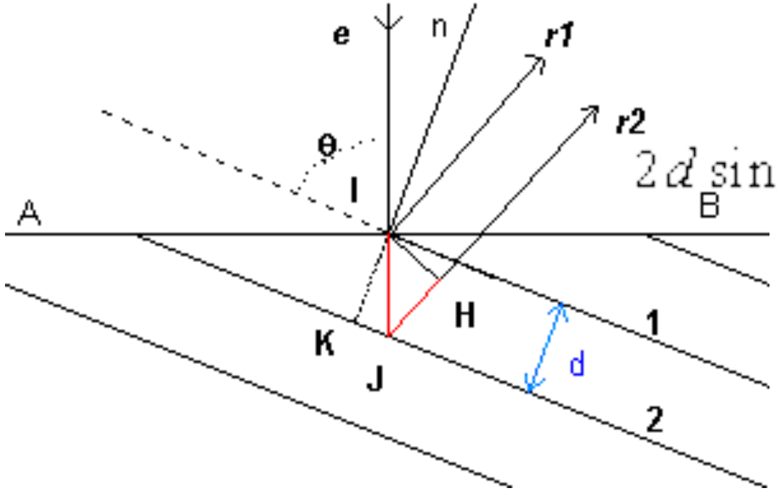
Diffrazione di elettroni su cristalli di ossido di Zn (Fresnel)

Elettroni su Au policristallino



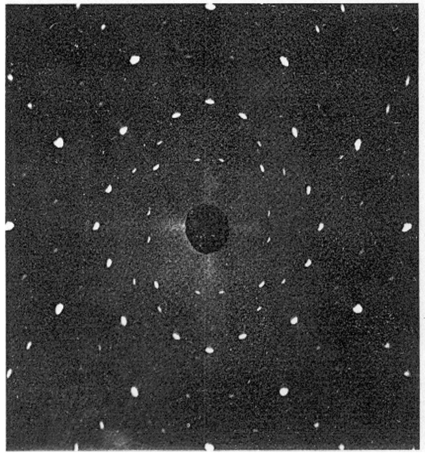

NiSi {11·20}
Si {220}

Diffrazione di elettroni su NiSi

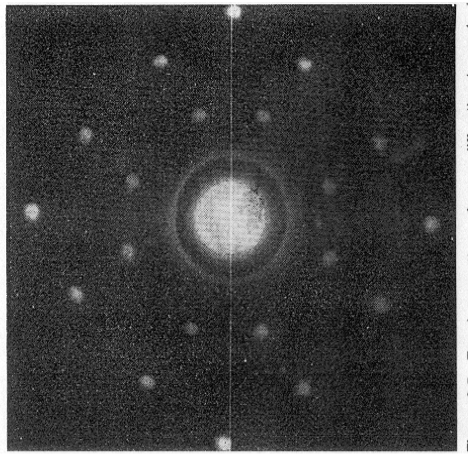

e
n
r1
r2
θ
I
A
B
H
K
J
d
1
2

$$2d\sin\theta = n\lambda$$

Diffrazione di Bragg

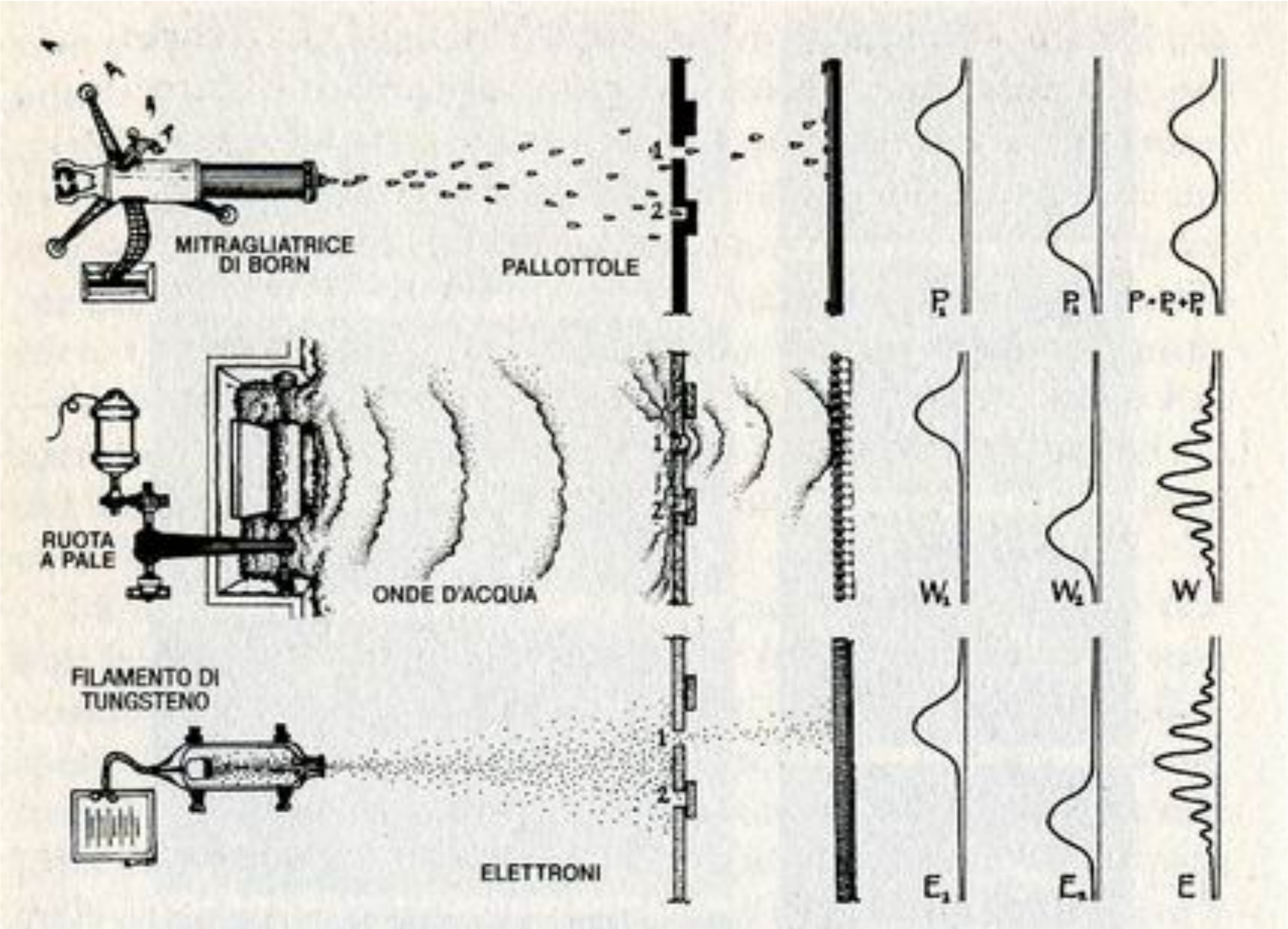


Raggi X su un monocristallo di NaCl

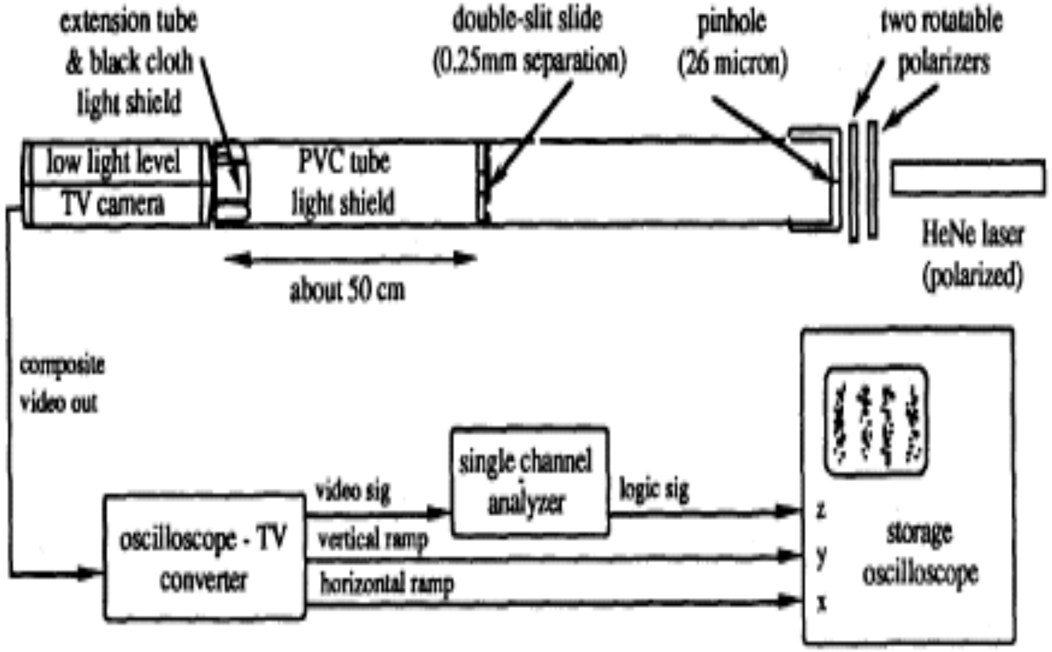


Neutroni termici su un monocristallo di NaCl

Particelle – onde su due fenditure


MITRAGLIATRICE DI BORN
PALLOTTOLE
1
2
P_1
P_2
$P = P_1 + P_2$
RUOTA A PALE
ONDE D'ACQUA
1
2
W_1
W_2
W
FILAMENTO DI TUNGSTENO
ELETTRONI
1
2
E_1
E_2
E

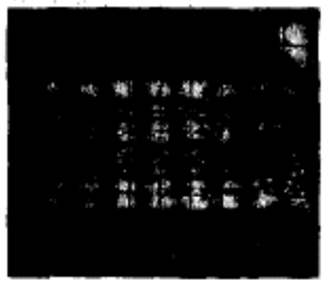
Diffrazione di singolo fotone


extension tube
& black cloth
light shield
double-slit slide
(0.25mm separation)
pinhole
(26 micron)
two rotatable
polarizers
low light level
TV camera
PVC tube
light shield
HeNe laser
(polarized)
about 50 cm
composite
video out
single channel
analyzer
video sig
logic sig
oscilloscope - TV
converter
vertical ramp
horizontal ramp
z
y
x
storage
oscilloscope

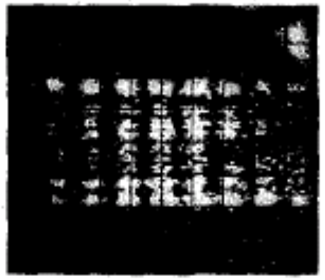
Wolfgang Rueckner and Paul Titcomb Am. J. Phys. **64** (2), February 1996 184

(a) 5 seconds

(b) 30 seconds



(c) 1 minute



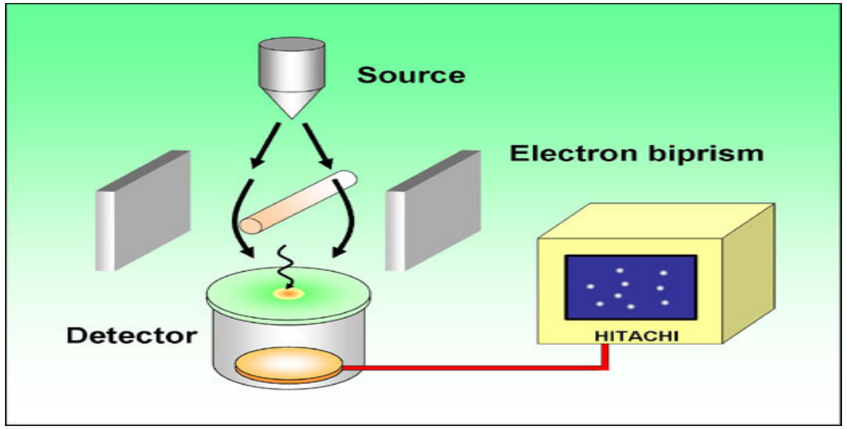
(d) 2 minutes

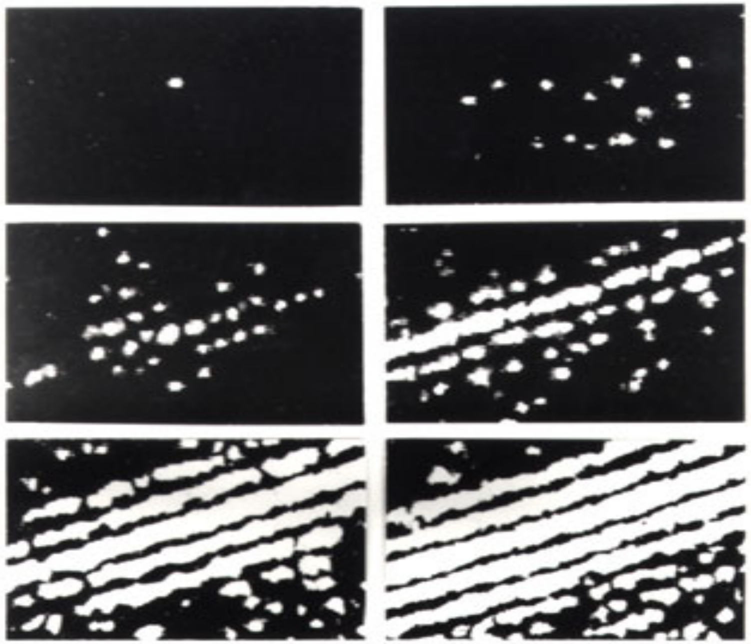
(e) 1 minute

(f) 2 minutes

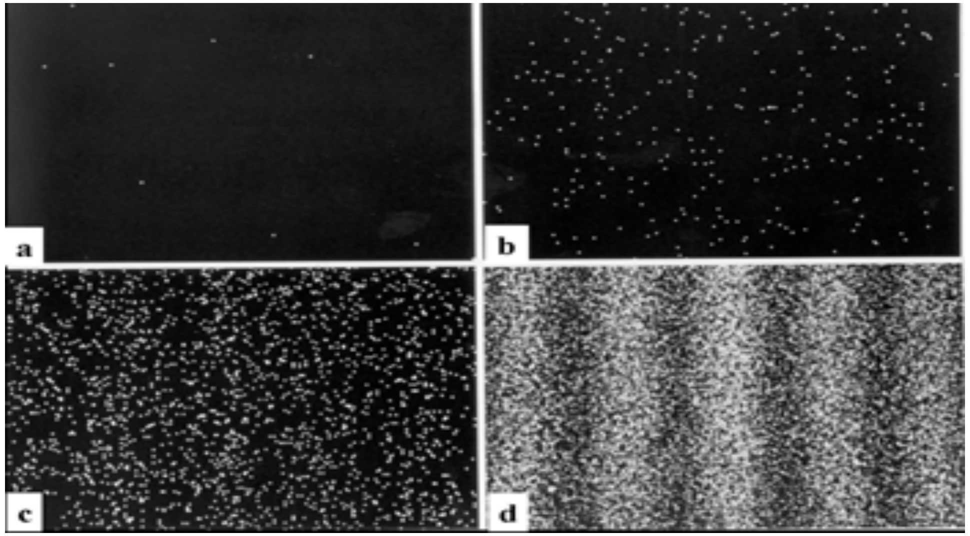
Fig. 2. Photographs of the storage oscilloscope display. (a)–(d) The accumulation of the double slit events; (e) one slit open followed by (f) the other slit open.

Elettrone su doppia fenditura


Source
Electron biprism
Detector
HITACHI



P.G. Merli, G.F. Missiroli, G. Pozzi,
***Am. J. Phys.* 44 (1976) 306-7.**



https://www.youtube.com/watch?v=jvO0P5-SMxk

http://physicsweb.org/articles/world/15/9/1/1

Ipotesi di de Broglie (1924)

Simmetria in Natura

Onde → Particelle . Particelle → Onde ?

Rel. Planck-Einstein

de Broglie postula
$$\begin{cases} \lambda = \dfrac{h}{p} \\ \nu = \dfrac{h}{E} \end{cases}$$

quantità osservate per una particella

1) Qual è il significato fisico di tali onde ?

2) A quale equazione soddisfano ?

E. Schrödinger (1926)

Fissato $\bar{p}$ (per es. $\bar{p} = p\hat{x}$) $\longrightarrow \lambda = \frac{h}{p} \rightarrow k = \frac{2\pi}{\lambda} \rightarrow \underline{\underline{e^{i(kx-\omega(k)t)}}}$

onda

Quanto vale $\omega(k)$?

Complementarietà onda-corpuscolo

- La Fisica possiede una* “costante di scala” universale:

il quanto d’azione

$$h = 6.626068 \times 10^{-34}\ \mathrm{m^2\ kg / s} \qquad \hbar = h/2\pi$$

determina la *granularità intrinseca* della natura,

- Complementarietà e Relazioni di Planck – Einstein – de Broglie:

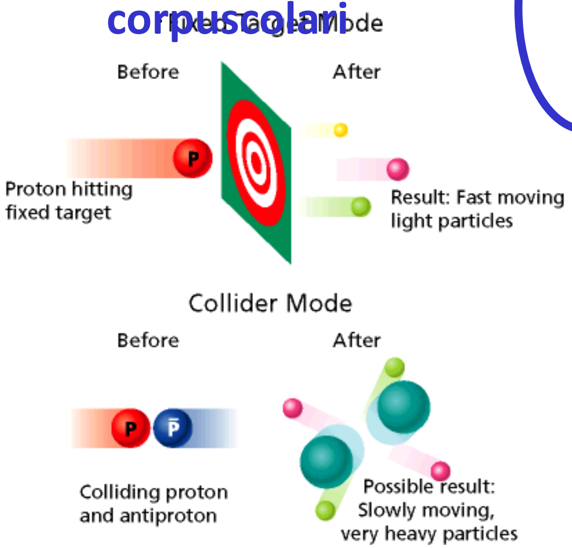
proporzionalità fra grandezze complementari di un **oggetto quantistico**

Grandezze corpuscolari

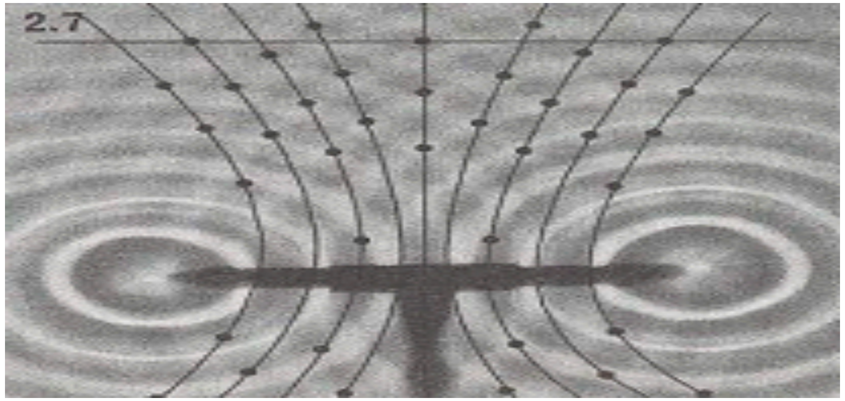
$$E = h\omega / 2\pi = \hbar\omega$$

$$p = h / \lambda = 2\pi\hbar / \lambda = \hbar k$$

Grandezze “ondulatorie”



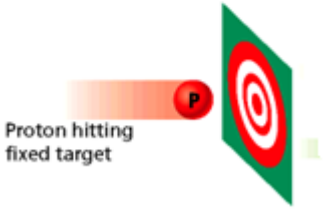
Fixed Target Mode
Before
After
P
Proton hitting
fixed target
Result: Fast moving
light particles
Collider Mode
Before
After
P
P̄
Colliding proton
and antiproton
Possible result:
Slowly moving,
very heavy particles



- Altre scale universali:

$c = 299\,792\,458\ \mathrm{m\ s^{-1}}$	Velocità della luce
$\alpha = 0.00729735$	Cost. Struttura Fine
$M_{\mathrm{Planck}} = 1.3 \times 10^{19}\ \mathrm{GeV}$	Massa di Planck

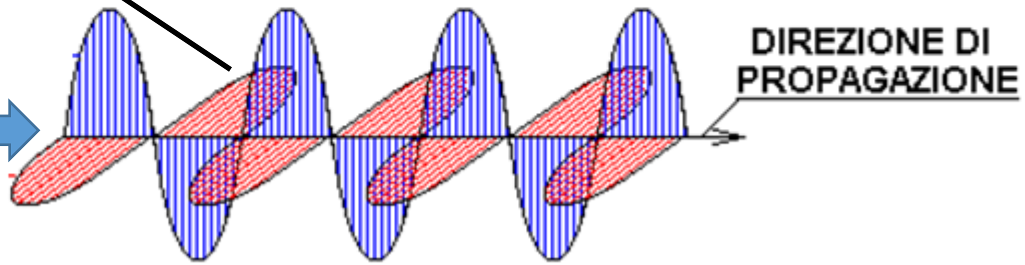
Onde e Probabilita’


P
Proton hitting
fixed target

$$\longrightarrow \quad \Psi$$

Stato del sistema

(E, p) → (ω, λ) →


DIREZIONE DI
PROPAGAZIONE

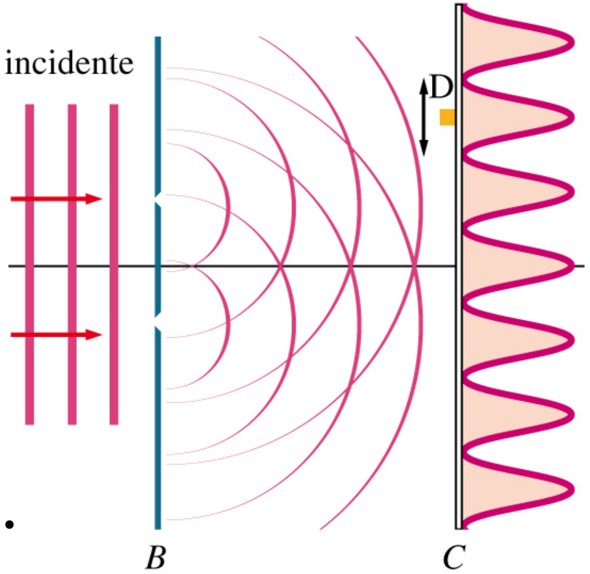
$$a\Psi_1 + b\Psi_2 = \Psi$$

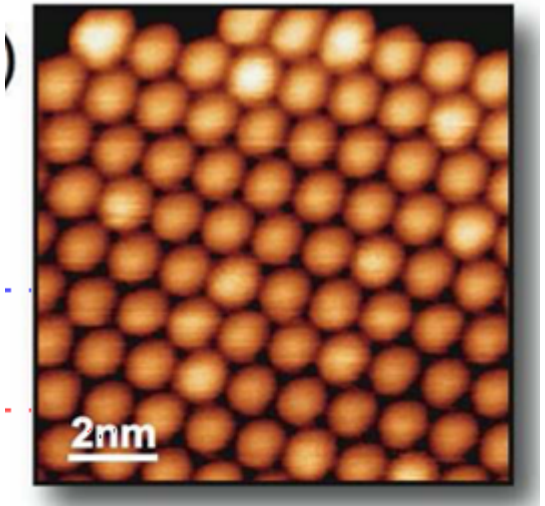
Gli Stati si sommano

$$\left|\Psi\left(\vec{x},t\right)\right|^2$$

Densita’ di **Probabilita’**
di presenza in $\vec{x}$

osservabile !!!


incidente
D
B
C



In generale:
lo stato di un sistema e’
l’insieme di delle distribuzioni
di probabilita’ dei possibili
OSSERVABILI

$$\hat{\vec{x}} \quad \hat{\vec{p}} \quad \hat{E}, \quad \hat{\vec{L}}, \quad \hat{\vec{S}},\ldots$$

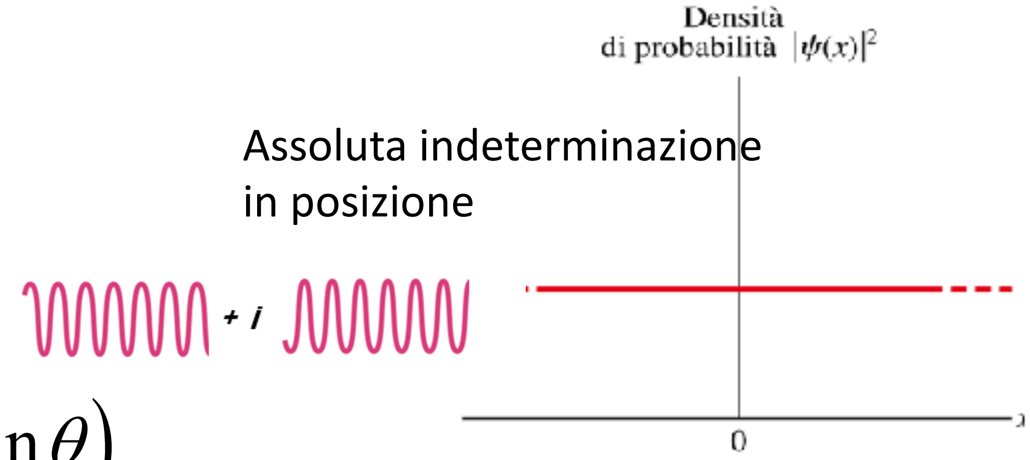
Osservabili incompatibili

Le distribuzioni di probabilita’ di differenti osservabili dinamiche possono essere correlate e in generale **non** possono essere scelte indipendentemente le une dalle altre

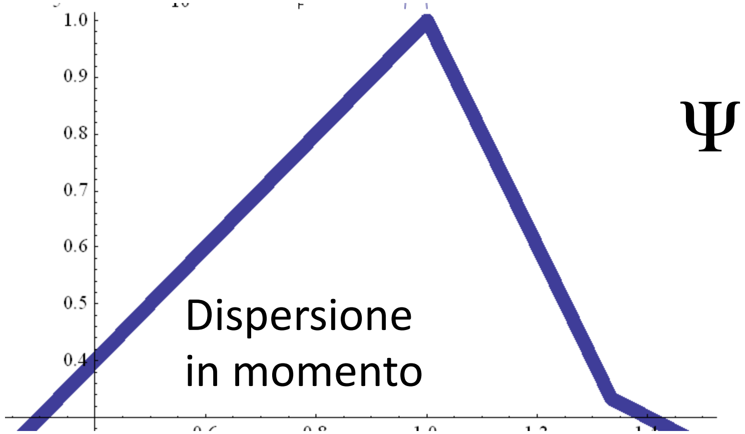
Assoluta precisione
in momento

$$\hat{\vec{p}} \rightarrow \vec{p} \quad \Rightarrow \quad \Psi \sim e^{-i/\hbar\ \vec{p}\cdot\vec{x}}$$

$$\left(e^{i\theta} = \cos\theta + i\sin\theta\right)$$

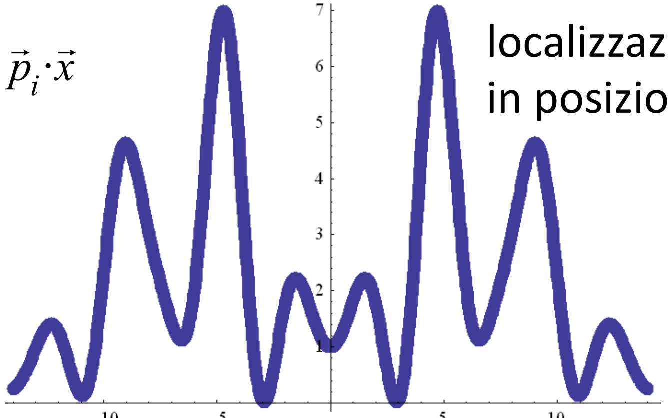


Assoluta indeterminazione
in posizione



Dispersione
in momento

$$\Psi \sim \sum \psi_i\ e^{-i/\hbar\ \vec{p}_i\cdot\vec{x}}$$



localizzazione
in posizione

Principio di indeterminazione di Heisenberg

$$\Delta x \cdot \Delta p_x \geq \hbar/2 \qquad \text{dove} \quad \hbar = h/2\pi$$

$$\Delta y \cdot \Delta p_y \geq \hbar/2 \qquad \text{(principio di indeterminazione di Heisenberg)}$$

$$\Delta z \cdot \Delta p_z \geq \hbar/2$$

Come esempio, Δx e Δp_x rappresentano le incertezze **intrinseche** nelle misure delle componenti di ***r*** e di ***p*** lungo *x*.

Equazione di Schroedinger

Una particella in moto lungo l’asse *x* attraverso una regione in cui le forze agenti sulla particella le conferiscono un’energia potenziale *V*(*x*) si ha:

$$\boxed{\frac{\hbar^2}{2m}\frac{d^2\Psi}{dx^2}+\left[E-V\left(x\right)\right]\Psi=0}$$

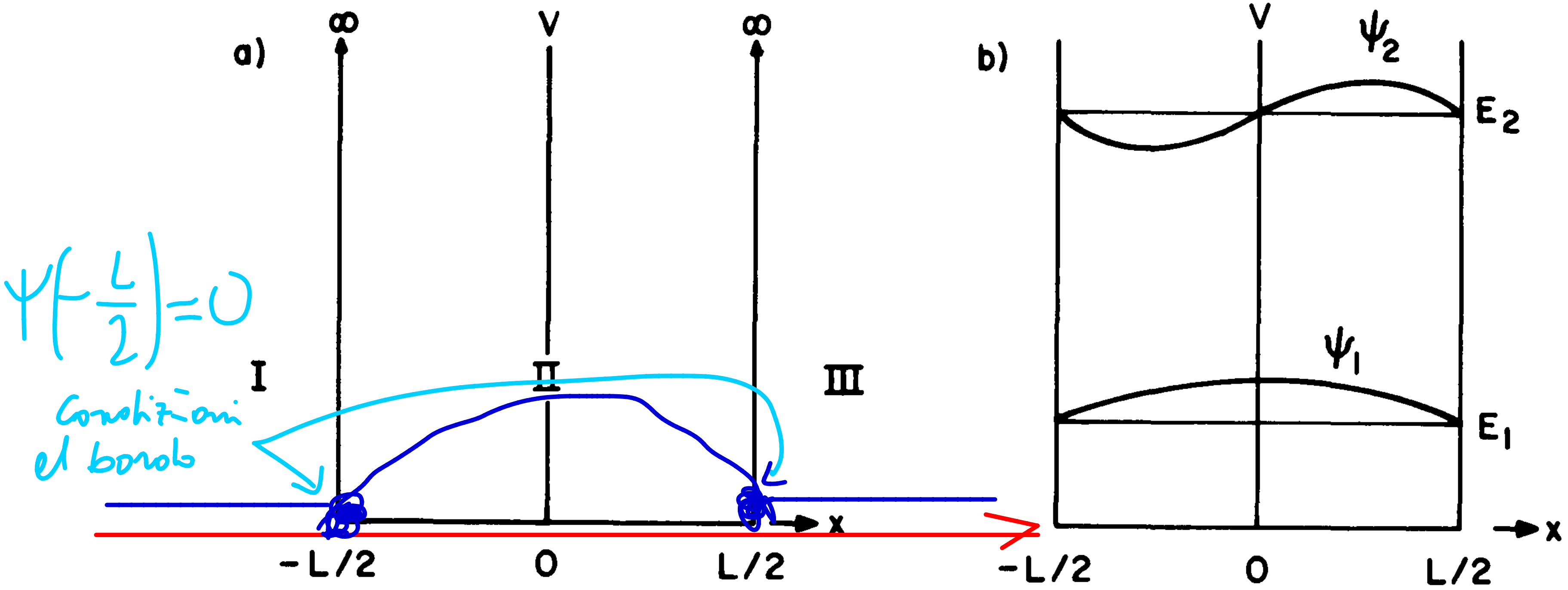
in cui *E* è l’energia meccanica totale della particella in moto.

Se *V*(*x*) è nullo, l’equazione descrive una **particella libera**,

$$\frac{d^2\psi}{dx^2}+\frac{2m}{\hbar^2}\left(\frac{mv^2}{2}\right)\psi=0\rightarrow\frac{d^2\psi}{dx^2}+\left(\frac{p}{\hbar}\right)^2\psi=0 \quad\longrightarrow\quad \psi\sim e^{\pm i/\hbar\,\vec{p}\cdot\vec{x}}$$

Potenziali a Pozzo Infinito

$\psi\left(\frac{L}{2}\right)=\psi\left(-\frac{L}{2}\right)=0$



a)
∞
V
∞
I
II
III
Condizioni al bordo
-L/2
0
L/2
x
b)
V
ψ_2
E_2
ψ_1
E_1
-L/2
0
L/2
x

The first two levels and wave functions in the box.

$$\psi_n(x)=\left(\frac{2}{L}\right)^{1/2}\sin\left(\frac{n\pi x}{L}\right),\qquad n \text{ even}$$

$$=\left(\frac{2}{L}\right)^{1/2}\cos\left(\frac{n\pi x}{L}\right),\qquad n \text{ odd}$$

Quantizzazione dell'energia

$p_n = \hbar k_n$

$$E_n=\frac{\hbar^2k_n^2}{2m}=\frac{\hbar^2\pi^2n^2}{2mL^2}$$

Quantizzazione delle quantità di moto

$$\boxed{p_n = \frac{2n\hbar\pi}{L} \qquad n \in \mathbb{N}\setminus\{0\}}$$

$\sin\alpha = \frac{e^{i\alpha}-e^{-i\alpha}}{2}$

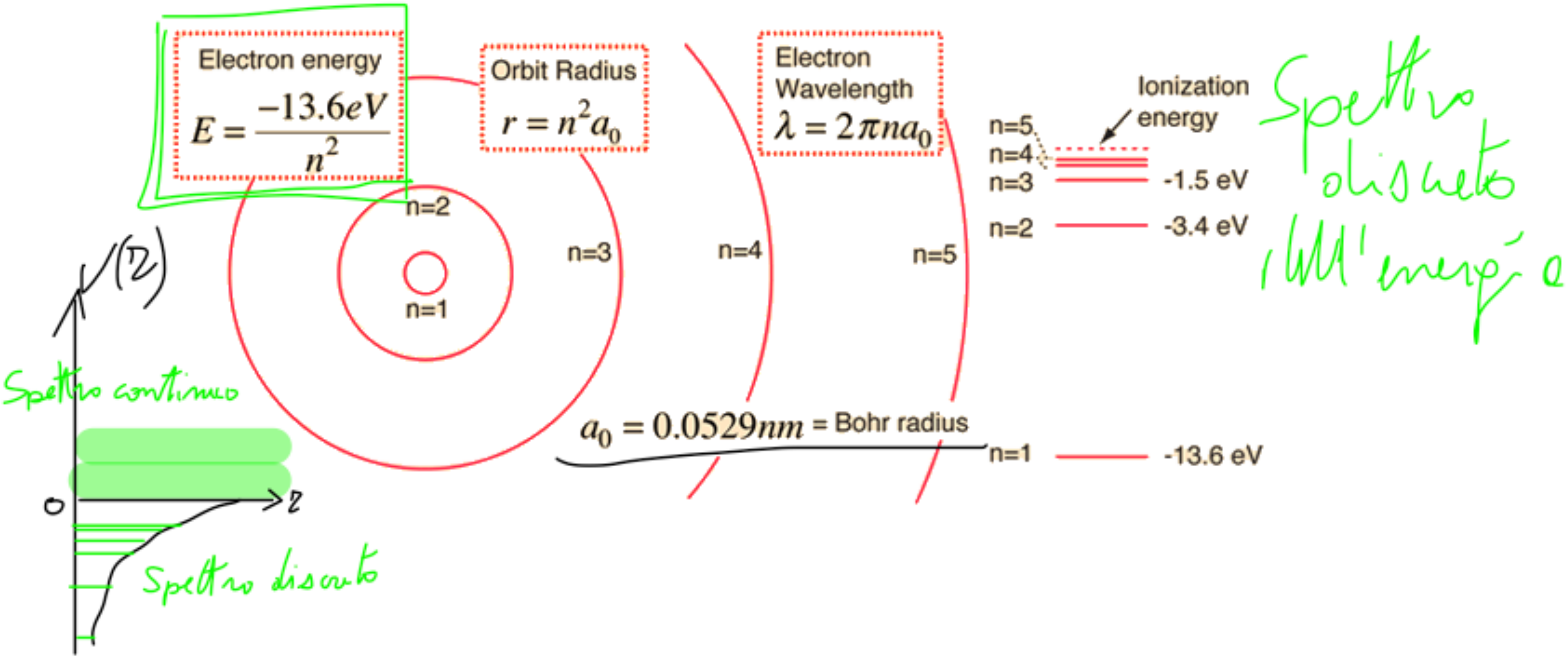
$\alpha = \frac{p}{\hbar}x$

$\sin\bar{\alpha} = 0 \quad \bar{\alpha} = n\pi$

$\bar{\alpha} = \frac{p}{\hbar}\frac{L}{2} = n\pi$

Spettro dell'energia per l'atomo di Idrogeno

$$V(r) = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r}$$



Electron energy

$$E = \frac{-13.6eV}{n^2}$$

Orbit Radius

$$r = n^2 a_0$$

Electron Wavelength

$$\lambda = 2\pi n a_0$$

$a_0 = 0.0529nm$ = Bohr radius

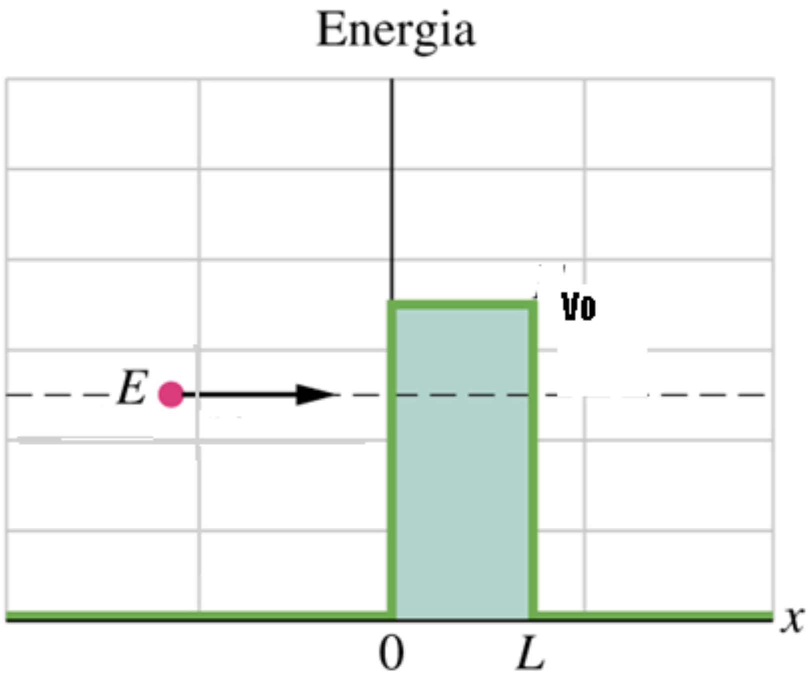
Spettro discreto dell'energia

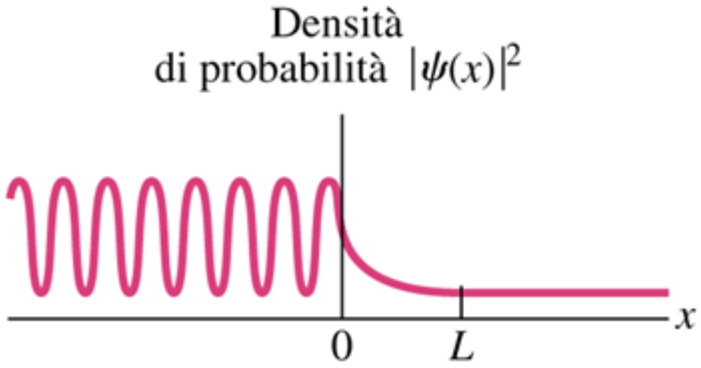
n=1
n=2
n=3
n=4
n=5
Ionization energy
n=5
n=4
n=3
-1.5 eV
n=2
-3.4 eV
n=1
-13.6 eV
V(r)
Spettro continuo
0
r
Spettro discreto

Effetto tunnel

Nella Meccanica Quantistica per una particella in moto con energia totale $E< V_0$ esiste una probabilità finita che l'onda di probabilita' *penetri* attraverso la barriera e giunga dall'altra parte.

Questo fenomeno prende il nome di **effetto tunnel**.


Energia
Vo
E
x
0
L

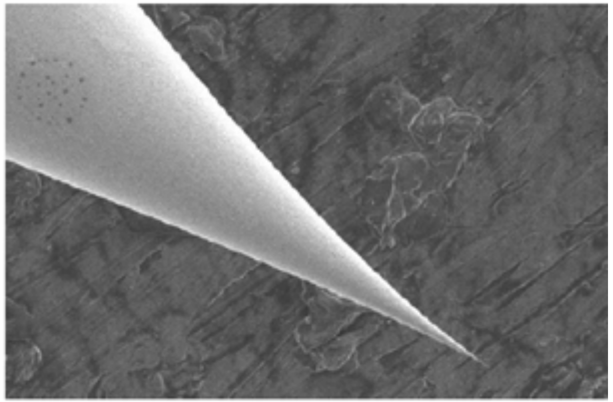

Densità
di probabilità $|\psi(x)|^2$
x
0
L

Coefficiente di trasmissione

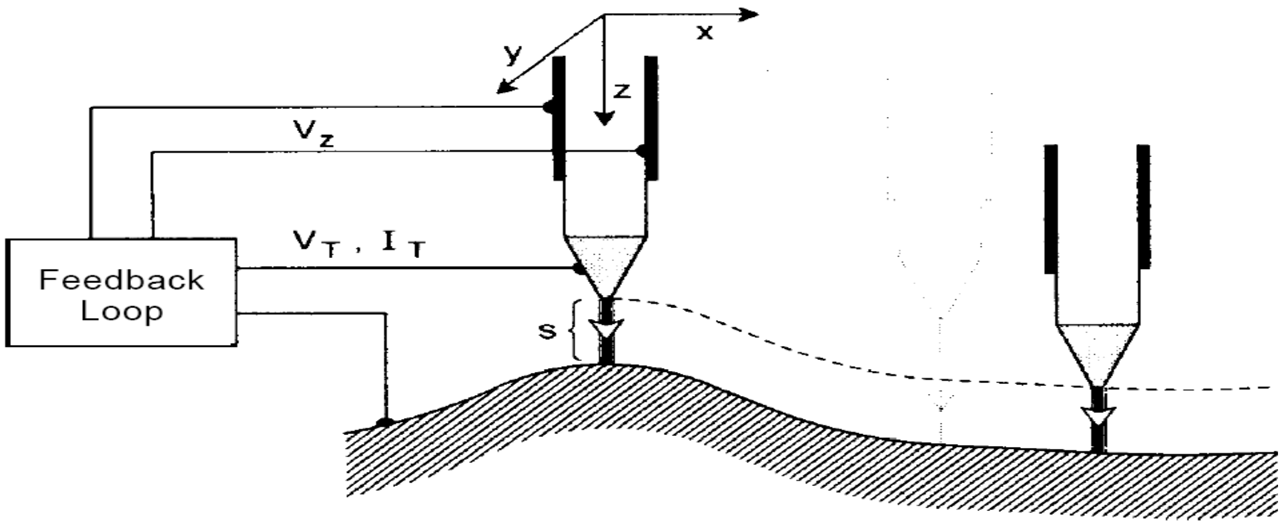
$$T \approx e^{-2bL} \qquad b = \sqrt{\frac{8\pi^2 m\left(U_b - E\right)}{h^2}}$$

G. Binnig, H. Rorher
Nobel 1986

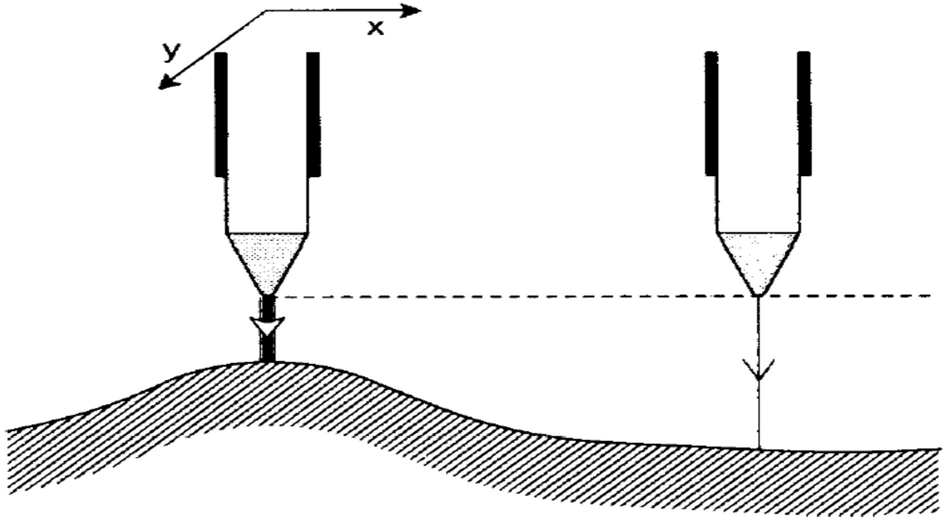
Microscopio ad Effetto Tunnel



Constant Current Mode

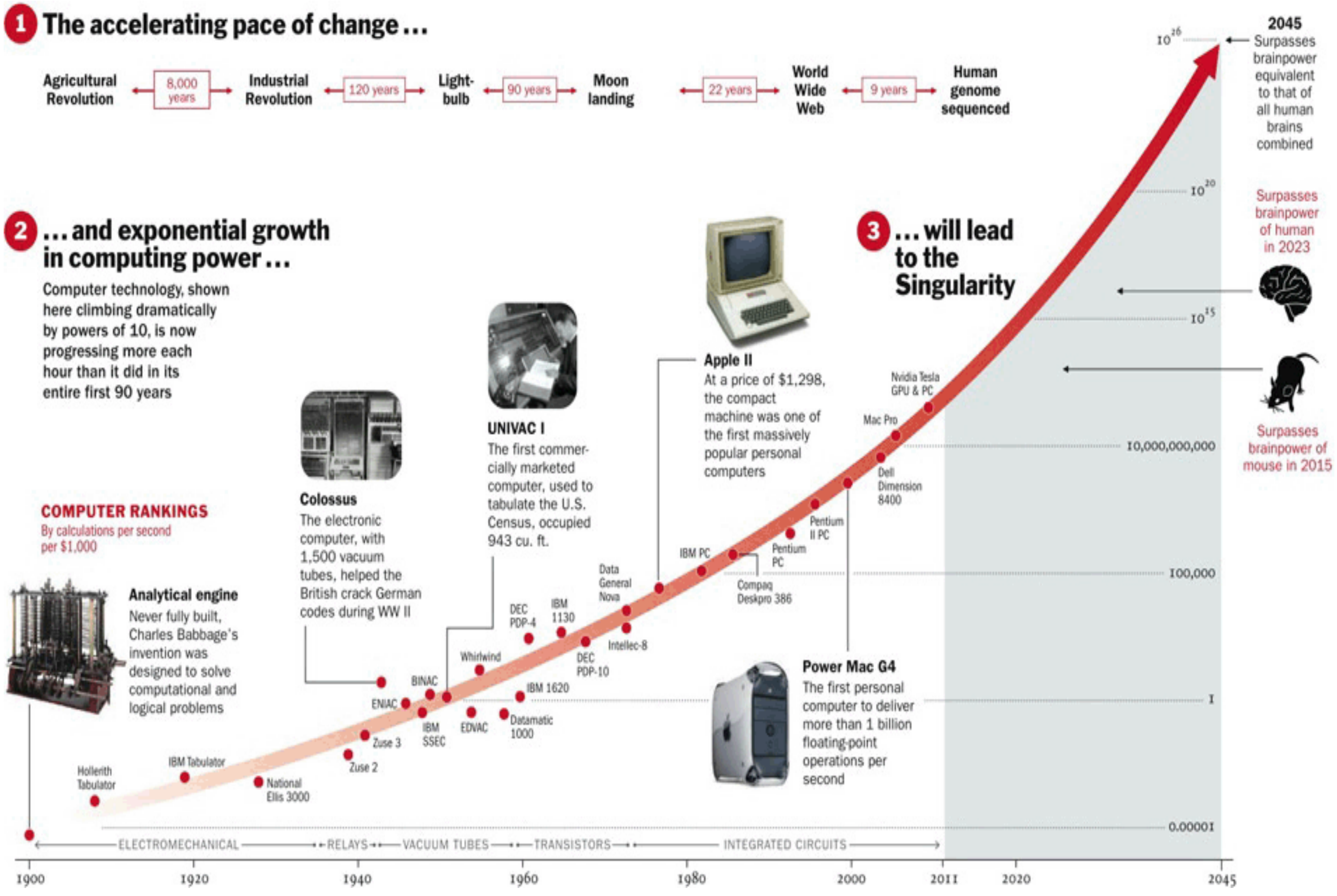

x
y
z
V_z
V_T, I_T
Feedback Loop
s

$V_z(V_x, V_y) \longrightarrow z(x, y)$



$\ln I(V_x, V_y) \longrightarrow \sqrt{\Phi} \cdot z(x, y)$

Potenza del transistor



1 **The accelerating pace of change …**

2 **… and exponential growth in computing power …**

Computer technology, shown here climbing dramatically by powers of 10, is now progressing more each hour than it did in its entire first 90 years

3 **… will lead to the Singularity**

COMPUTER RANKINGS
By calculations per second per $1,000

Analytical engine
Never fully built, Charles Babbage's invention was designed to solve computational and logical problems

Colossus
The electronic computer, with 1,500 vacuum tubes, helped the British crack German codes during WW II

UNIVAC I
The first commercially marketed computer, used to tabulate the U.S. Census, occupied 943 cu. ft.

Apple II
At a price of $1,298, the compact machine was one of the first massively popular personal computers

Power Mac G4
The first personal computer to deliver more than 1 billion floating-point operations per second

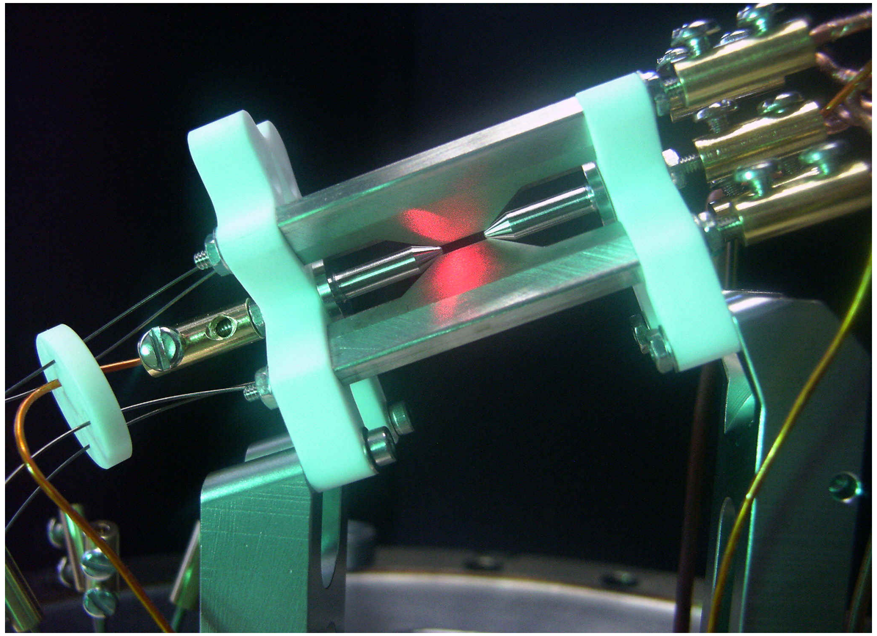
2045
Surpasses brainpower equivalent to that of all human brains combined

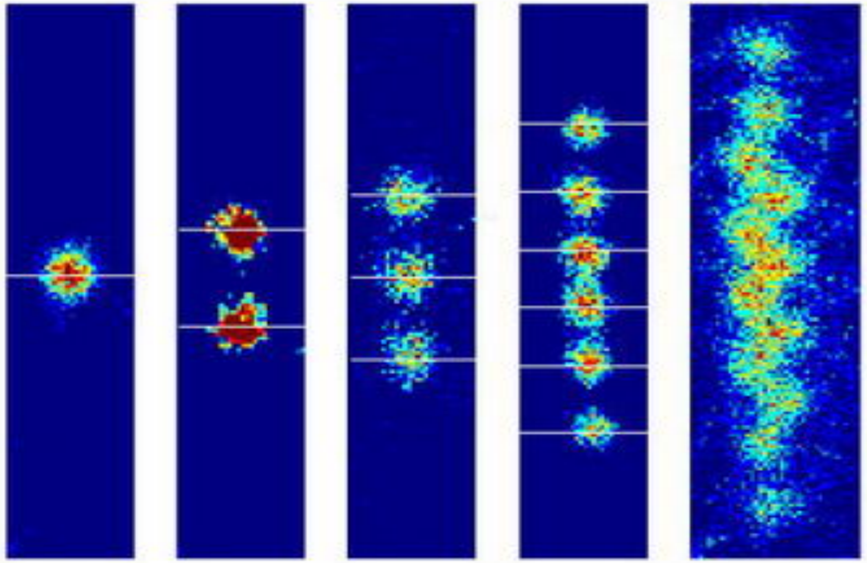
Surpasses brainpower of human in 2023

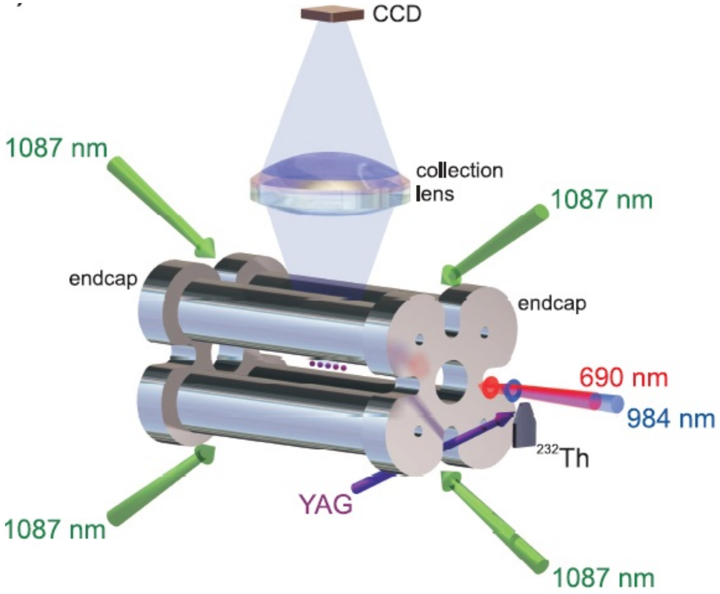
Surpasses brainpower of mouse in 2015

Agricultural Revolution
8,000 years
Industrial Revolution
120 years
Light-bulb
90 years
Moon landing
22 years
World Wide Web
9 years
Human genome sequenced
Hollerith Tabulator
IBM Tabulator
National Ellis 3000
Zuse 2
Zuse 3
ENIAC
BINAC
IBM SSEC
EDVAC
Whirlwind
Datamatic 1000
IBM 1620
DEC PDP-4
IBM 1130
DEC PDP-10
Data General Nova
Intellec-8
IBM PC
Compaq Deskpro 386
Pentium PC
Pentium II PC
Dell Dimension 8400
Mac Pro
Nvidia Tesla GPU & PC
10^{26}
10^{20}
10^{15}
10,000,000,000
100,000
1
0.00001
ELECTROMECHANICAL
RELAYS
VACUUM TUBES
TRANSISTORS
INTEGRATED CIRCUITS
1900
1920
1940
1960
1980
2000
2011
2020
2045

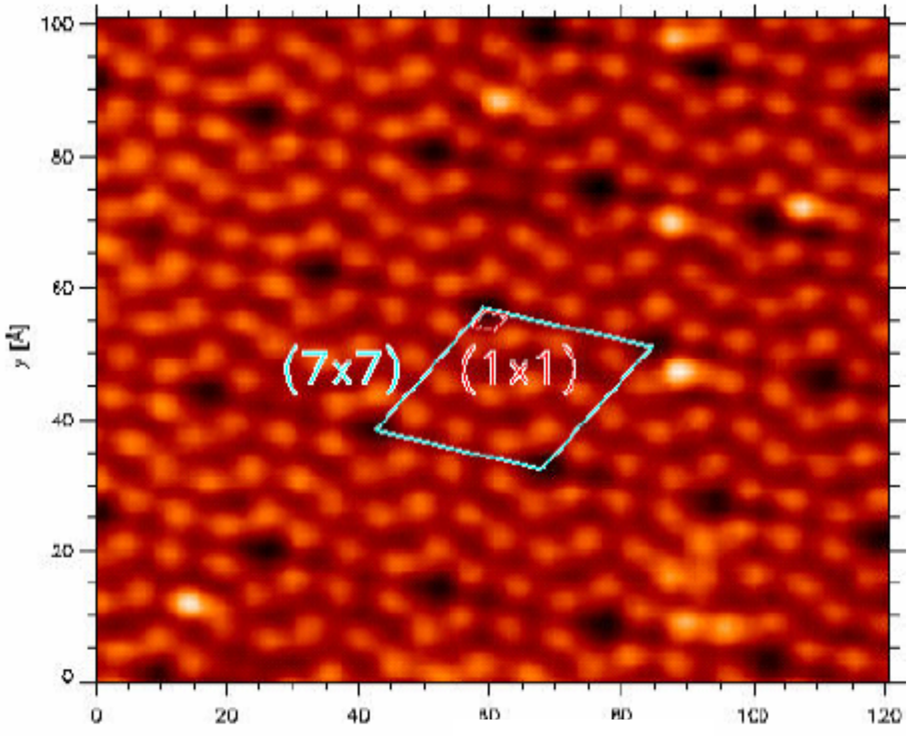
Atomi freddi e computer quantistici





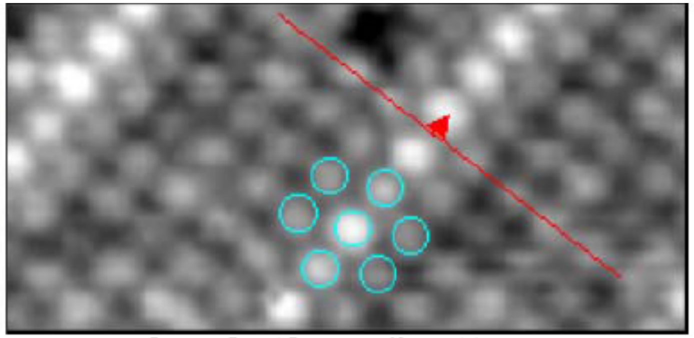

CCD
1087 nm
collection lens
1087 nm
endcap
endcap
690 nm
984 nm
232Th
YAG
1087 nm
1087 nm

Microscopio a Forza Atomica

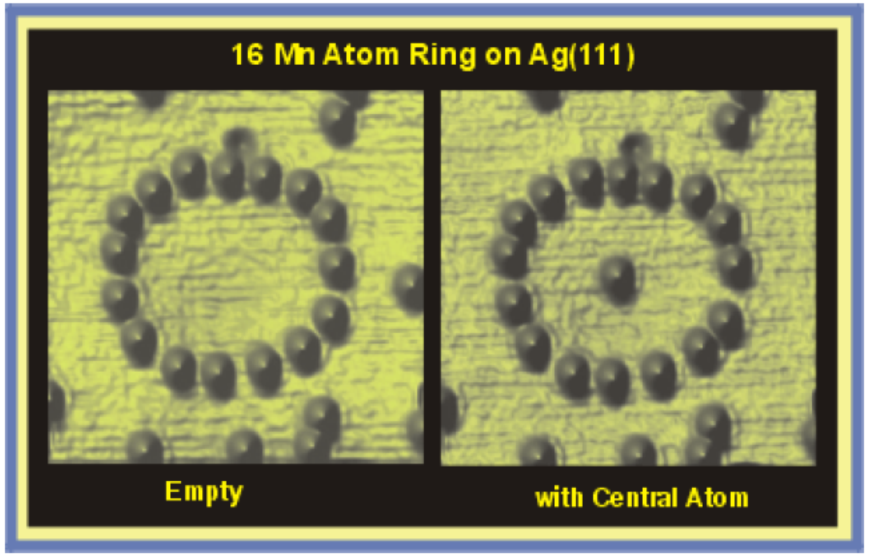

100
80
60
40
20
0
y [Å]
(7x7)
(1x1)
0
20
40
60
80
100
120

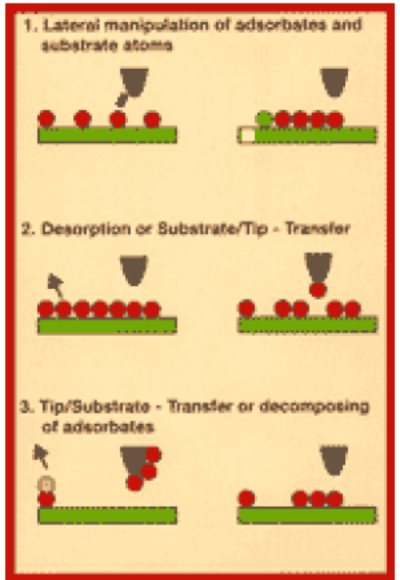
STM image
Si(111)-7x7

D.M. Eigler, E.K. Schweizer. **Positioning single atoms with a STM.** *Nature 344, 524-526 (1990)*



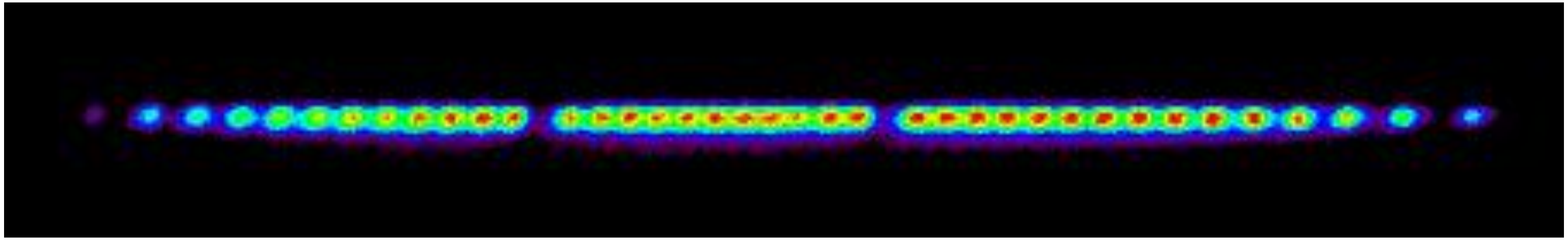
Further: **atom manipulation** (bottom-up approach to nanostructur


16 Mn Atom Ring on Ag(111)
Empty
with Central Atom


1. Lateral manipulation of adsorbates and substrate atoms
2. Desorption or Substrate/Tip - Transfer
3. Tip/Substrate - Transfer or decomposing of adsorbates

Tassonomia del Quantum Computer

- Ottici: Cavità QED, Ottica Lineare;
- Atomici: Trappole ioniche, Reticoli ottici;
- Stato Solido: Spin Nucleari,Spin Elettronici, Quantum Dots;
- Superconduttori: Coppie di Cooper, quanti di flusso magnetico,Squid



D. Wineland, NIST

Grazie