Il Linguaggio della Ricerca

Progetto di divulgazione scientifica dell'Area della Ricerca di Bologna

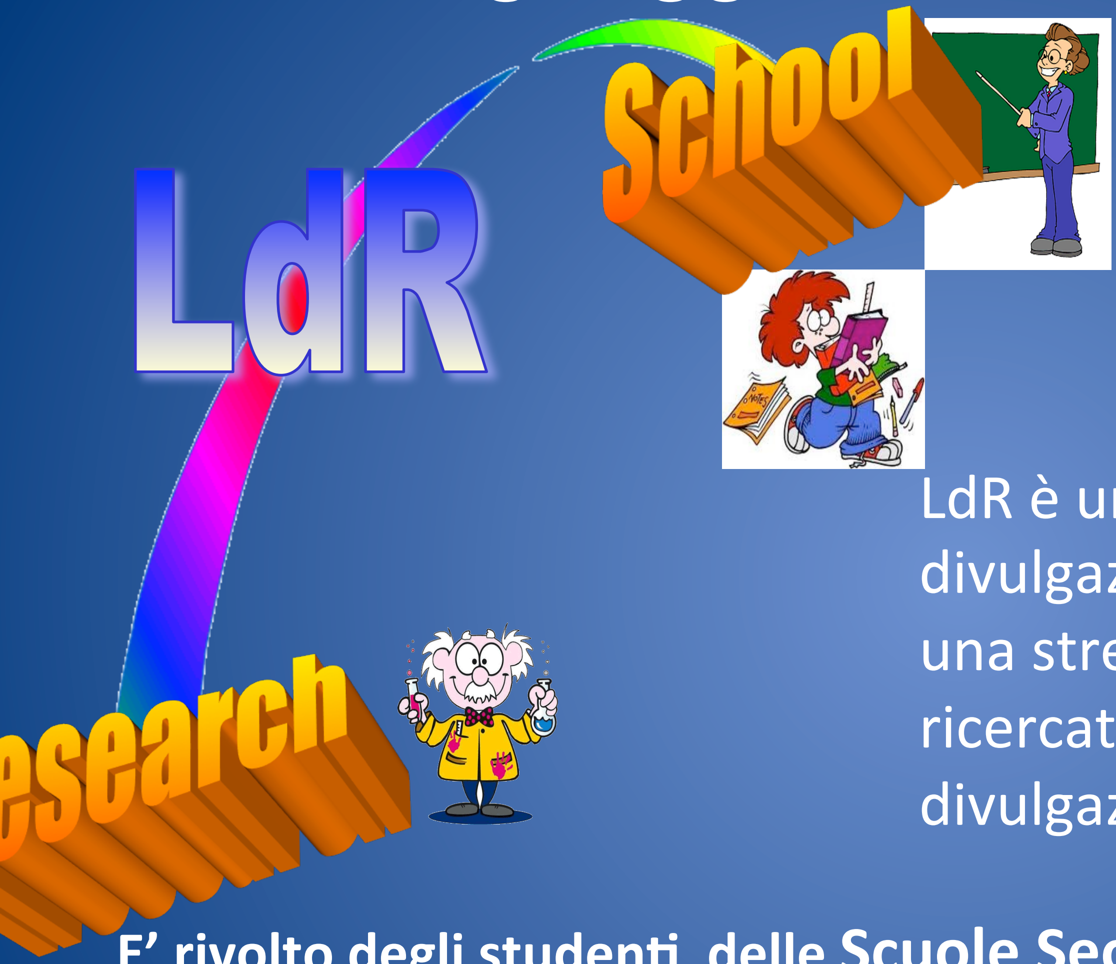
www.bo.cnr.it/linguaggiodellaricerca/

promosso dal **Consiglio Nazionale delle Ricerche** (CNR) e dall'**Istituto Nazionale di Astrofisica** (INAF), attivo dal 2003

National Research Council of Italy

INAF

Il Linguaggio della Ricerca (LdR)

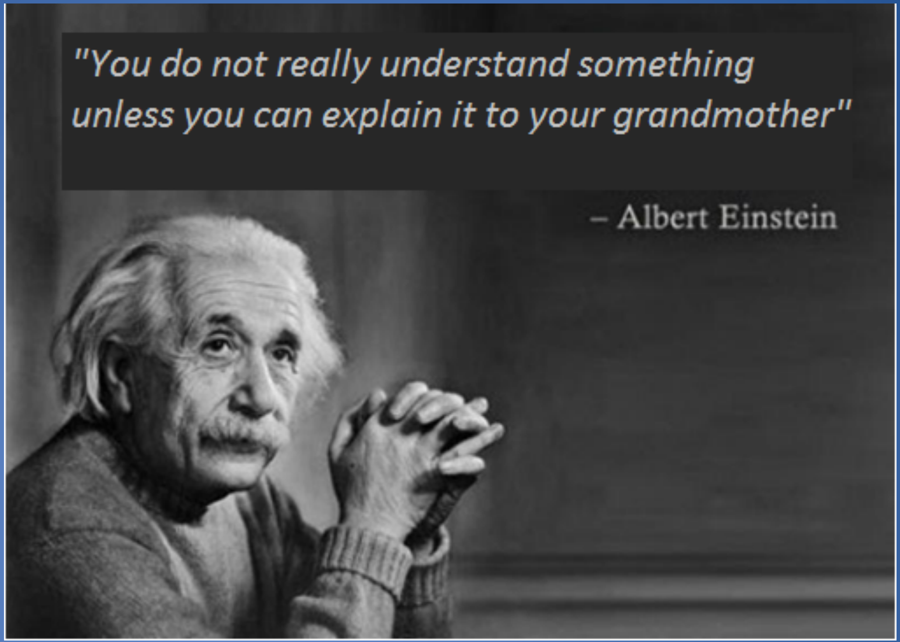


LdR è un progetto di divulgazione scientifica basato su una stretta collaborazione tra ricercatori, insegnanti e esperti di divulgazione.

E' rivolto degli studenti delle Scuole Secondarie di I° e II°grado allo scopo di suscitare l' interesse negli studenti verso il mondo della ricerca mediante il loro coinvolgimento nella divulgazione scientifica in italiano ed in inglese

Il Linguaggio della Ricerca (LdR)

Il nostro motto è :



Creare "mezzi" per raccontare in maniera creativa ed accattivante l'argomento scientifico porta ad sua una migliore comprensione

Una delle finalità di LdR è rendere gli studenti capaci di comunicare ad un pubblico non esperto l'esperienza vissuta entrando a contatto con i ricercatori del CNR, utilizzando in maniera corretta la terminologia scientifica nelle due lingue.

Le “fasi” del Progetto LdR

Siamo in questa fase!

1	2	3	4	5	6
Insegnante sceglie la lezione	*Definizione incontro con la classe*	*Ricercatore a...scuola*	*Creazione dei prod. divulgaztivi*	*Valutazione dei prodotti*	*Convegno Annuale*
Sett-Ott	Nov-Dic	Gen-Mar	Apr-Mag	Giu-Ago	Sett-Ott

… ma che cos'è un prodotto divulgativo?

Lavoro a gruppi e/o di classe

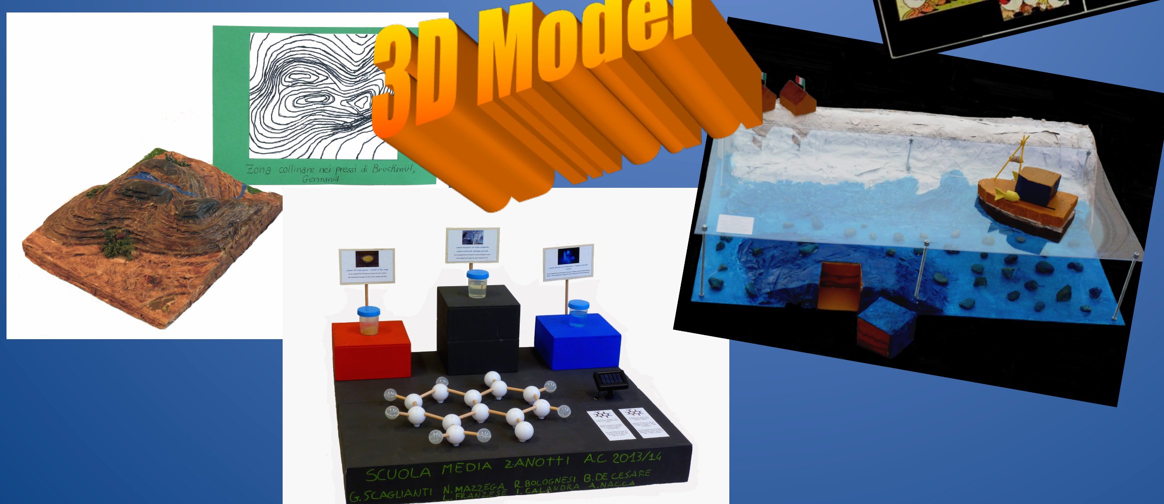
Journal

Poster

Web-site

Comic Strip

3D Model



Movie

XII Convegno Annuale: Sala Congressi - Area della Ricerca

Premiazioni

Sindaco di Bologna V. Merola

Mostra espositiva

La pagina Facebook

https://www.facebook.com/IlLinguaggioDellaRicerca

Realizzata dagli studenti

The most beautiful experiment

Giorgio Lulli
lulli@bo.imm.cnr.it

Consiglio Nazionale delle Ricerche
Istituto per la Microelettronica e i Microsistemi (CNR-IMM)
Bologna

ITIS Leonardo Da Vinci, Carpi, 10 novembre 2016

Summary

- **The most beautiful experiment: Why, Who, When, Where, What?**

- **The origins** (with a brief introduction on *waves*)

- **The *experimental* challenge: from the idea to the lab**

- **The *conceptual* challenge: from "classic thinking" to "quantum thinking"**

1) Why the "most beautiful"?

R. Crease

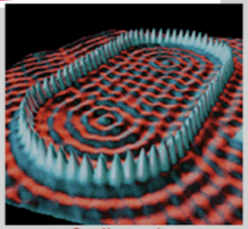
CRITICAL POINT **physicsworld**

May 2, 2002

The most beautiful experiment...

What is the most beautiful experiment in physics? Robert P Crease invites your suggestions.

In his new book *Meselson, Stahl, and the Replication of DNA*, science historian Frederic Holmes recounts the story of what one researcher called "the most beautiful experiment in biology". The so-called Meselson-Stahl experiment, which was carried out in 1957, confirmed that DNA replicates in the way predicted by the then recently discovered double-helix structure. When Holmes asked five researchers why this particular experiment was so beautiful, their answers included simplicity, precision, cleanness and strategic importance.



Small wonder

COMMENT: CRITICAL POINT

The most beautiful experiment

The most beautiful experiment in physics, according to a poll of *Physics World* readers, is the interference of single electrons in a Young's double slit. **Robert P Crease** reports

1 Young's double-slit experiment applied to the interference of single electrons
2 Galileo's experiment on falling bodies (1600s)
3 Millikan's oil-drop experiment (1910s)
4 Newton's decomposition of sunlight with a prism (1665–1666)
5 Young's light-interference experiment (1801)
6 Cavendish's torsion-bar experiment (1798)
7 Eratosthenes' measurement of the Earth's circumference (3rd century BC)
8 Galileo's experiments with rolling balls down inclined planes (1600s)
9 Rutherford's discovery of the nucleus (1911)
10 Foucault's pendulum (1851)

periment" of all time.

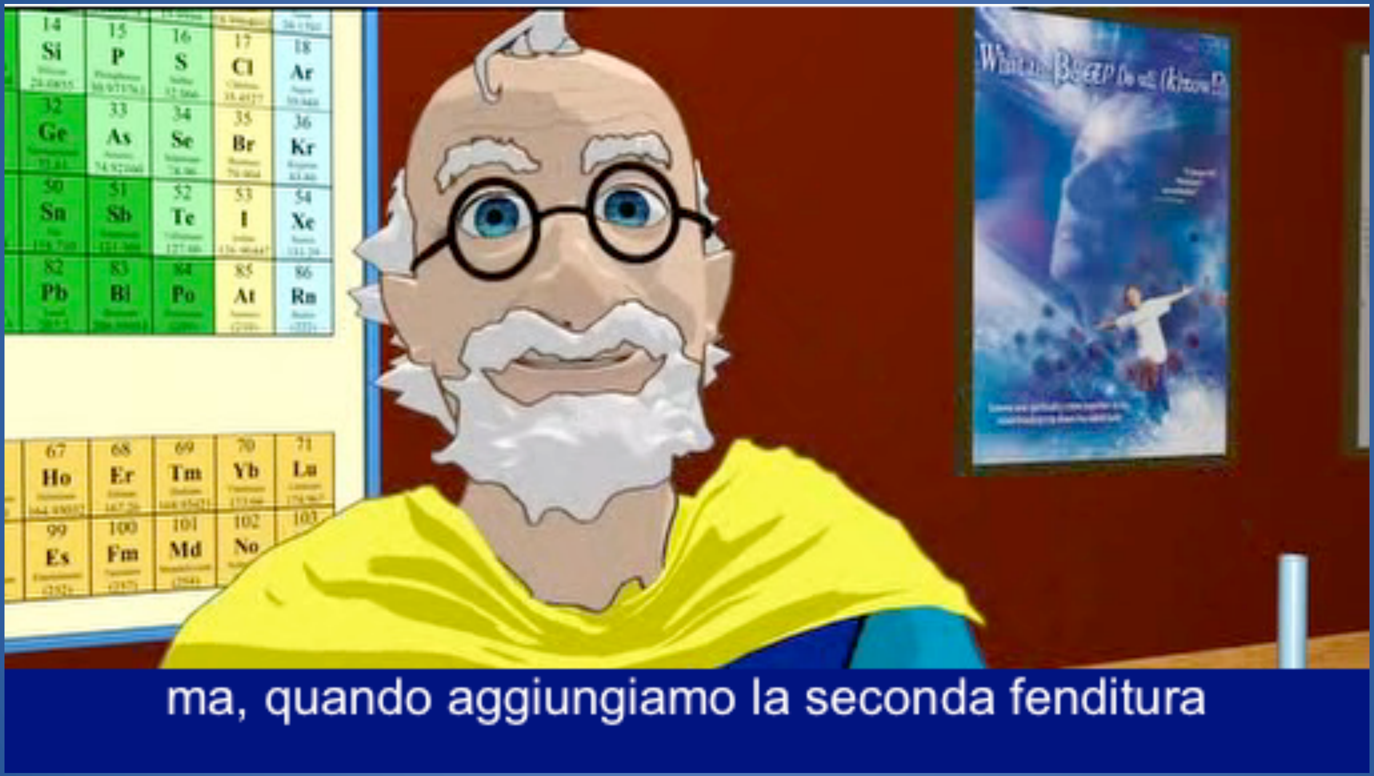
Readers also defined beautiful experiments in terms of "economy" – in other words how efficiently and dramatically the experiment made an important result stand

cited by readers might be called "deep play". This is the sense that we are actively engaged with something outside ourselves that is responding to us – rather than watching a game of our own construction or watching

marker and tape measure, claiming to have nearly cried the first time they saw it. Another described an impromptu game that he and classmates had invented at the end of a lab class, in which a liquid-nitro-

Physics World – May-September 2002

2) What is it?



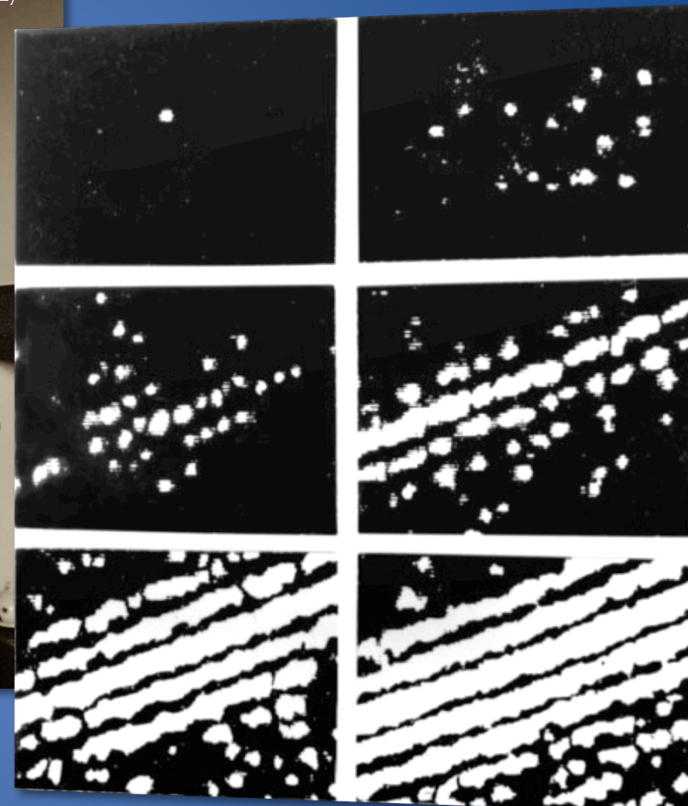
Dr. Quantum (*The infaumous double slit experiment* - YouTube)

3,4,5) Who dit it first? When? Where?

(1) Dipartimento di Fisica Università - Bologna
(2) CNR LAMEL (oggi IMM) - Bologna

1974: **Pier Giorgio Merli**, **Gian Franco Missiroli** e **Giulio Pozzi** observed for the first time single electron interference using in a creative way an *electron microscope* equipped with a *single electron detector*

1974-1976



P.G.Merli, G.F.Missiroli, G.Pozzi *On the statistical aspects of electron interference phenomena* Am. J. Phys. 44, 306 (1976)

2002 / 2003

impact on media

The origins

Waves

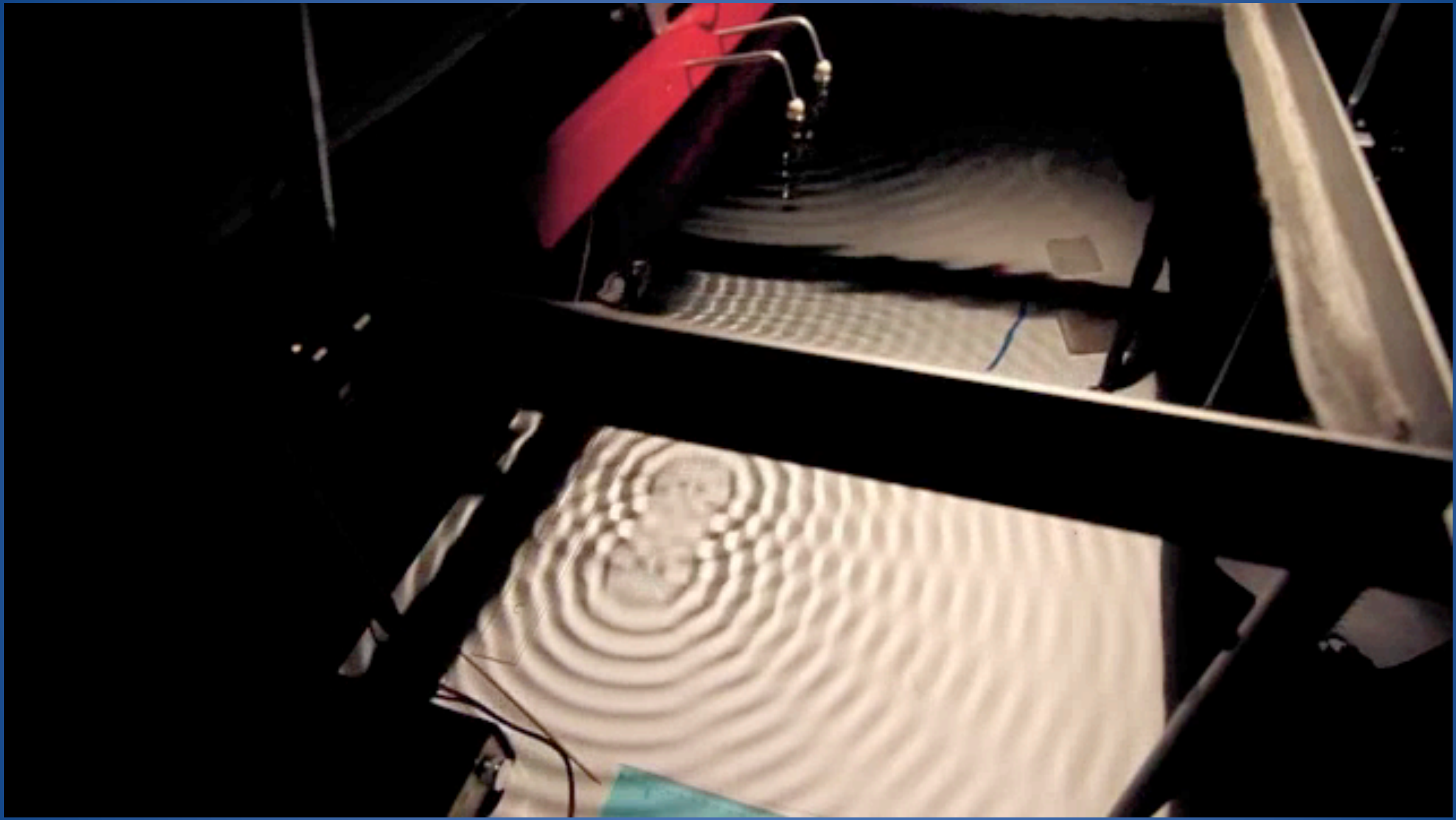
A **wave** is an oscillation accompanied by a transfer of energy that travel through a medium or in vacuum space

1) **MECHANICAL WAVES**: they require a material medium (water, air, metal, ...)

2) **ELECTROMAGNETIC (e-m) WAVES**: they don't require a medium, they consist of periodic oscillations of electrical and magnetic fields originally generated by charged particles, and can travel through *vacuum space*

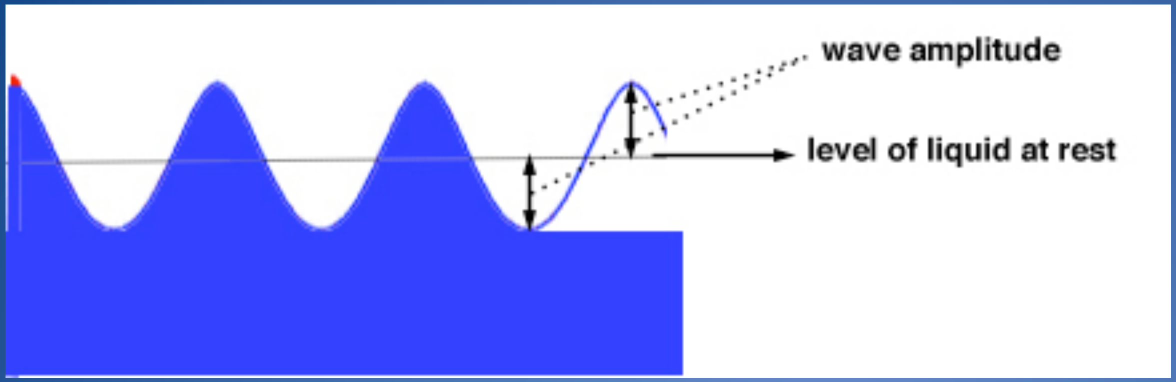
3) **GRAVITATIONAL WAVES**: analog to e-m waves, their existence has been demostrated earlier this year

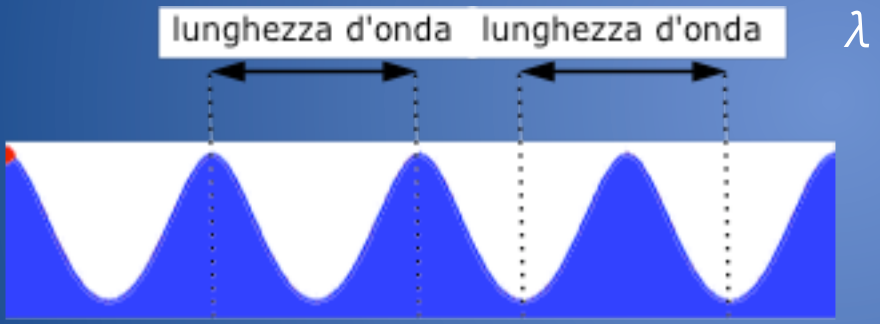
Material waves in water: the ripple tank



here we don't have slits, but point sources, the interference phenomenon is the same.

Waves in water: amplitude, wavelenght and frequency





frequency (ν) = number of oscillation/second

wave propagation velocity = $v = \lambda\,\nu \;\Rightarrow\; \lambda = v/\nu$

ν and λ are inversely proportional, higher frequencies correspond to smaller wavelengths

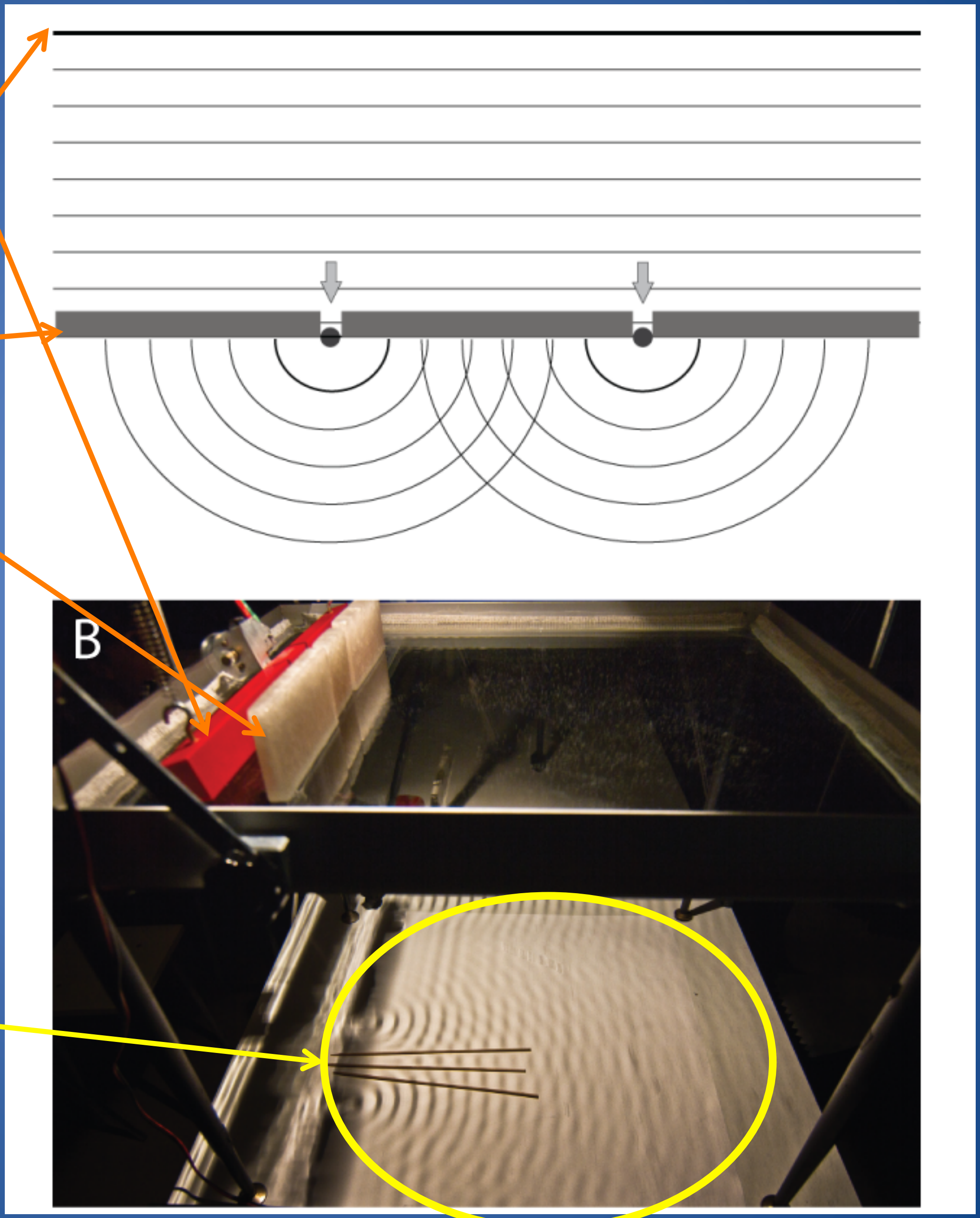
Material waves in water: the ripple tank

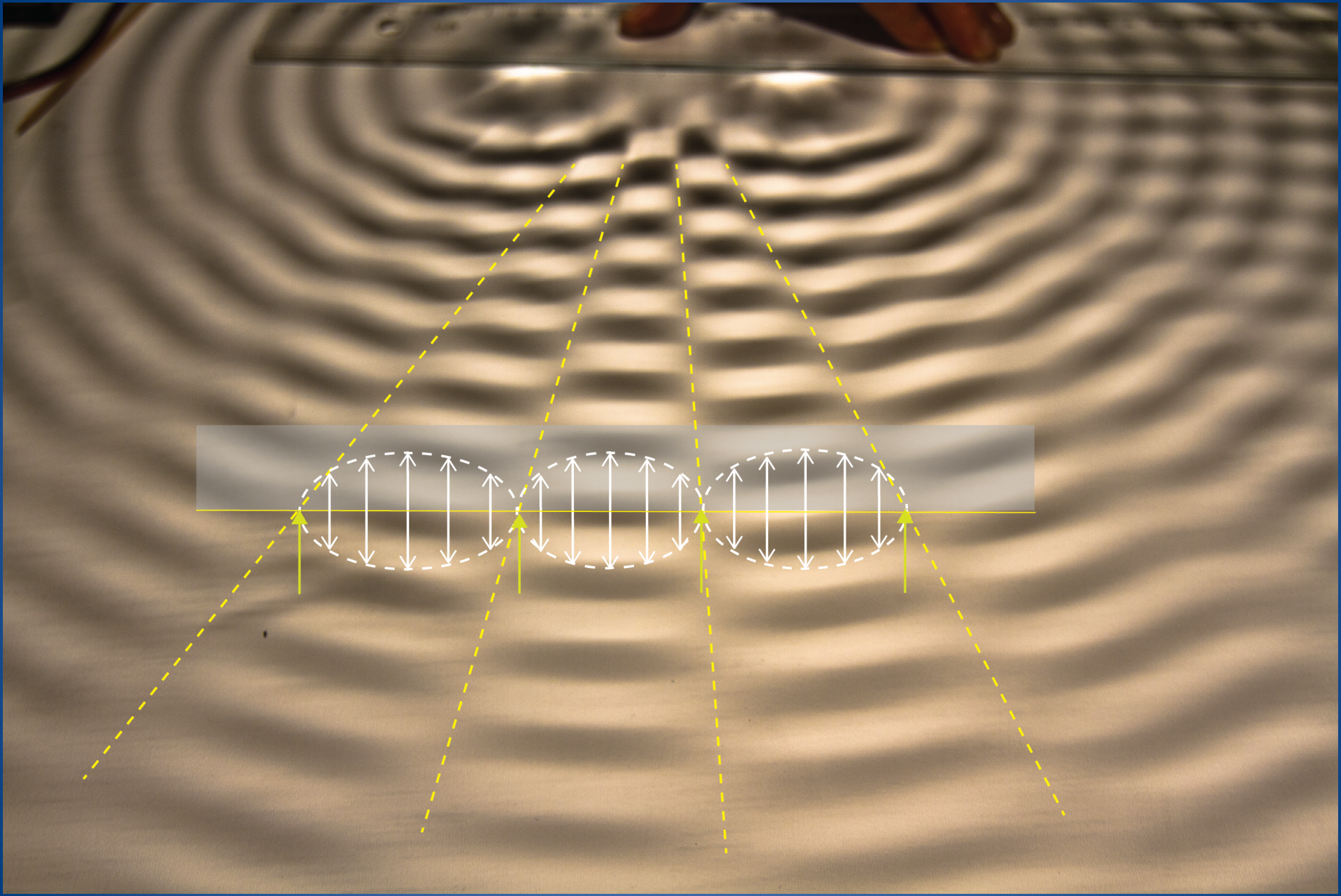
The double-slit experiment with the ripple tank

source of rectilinear waves

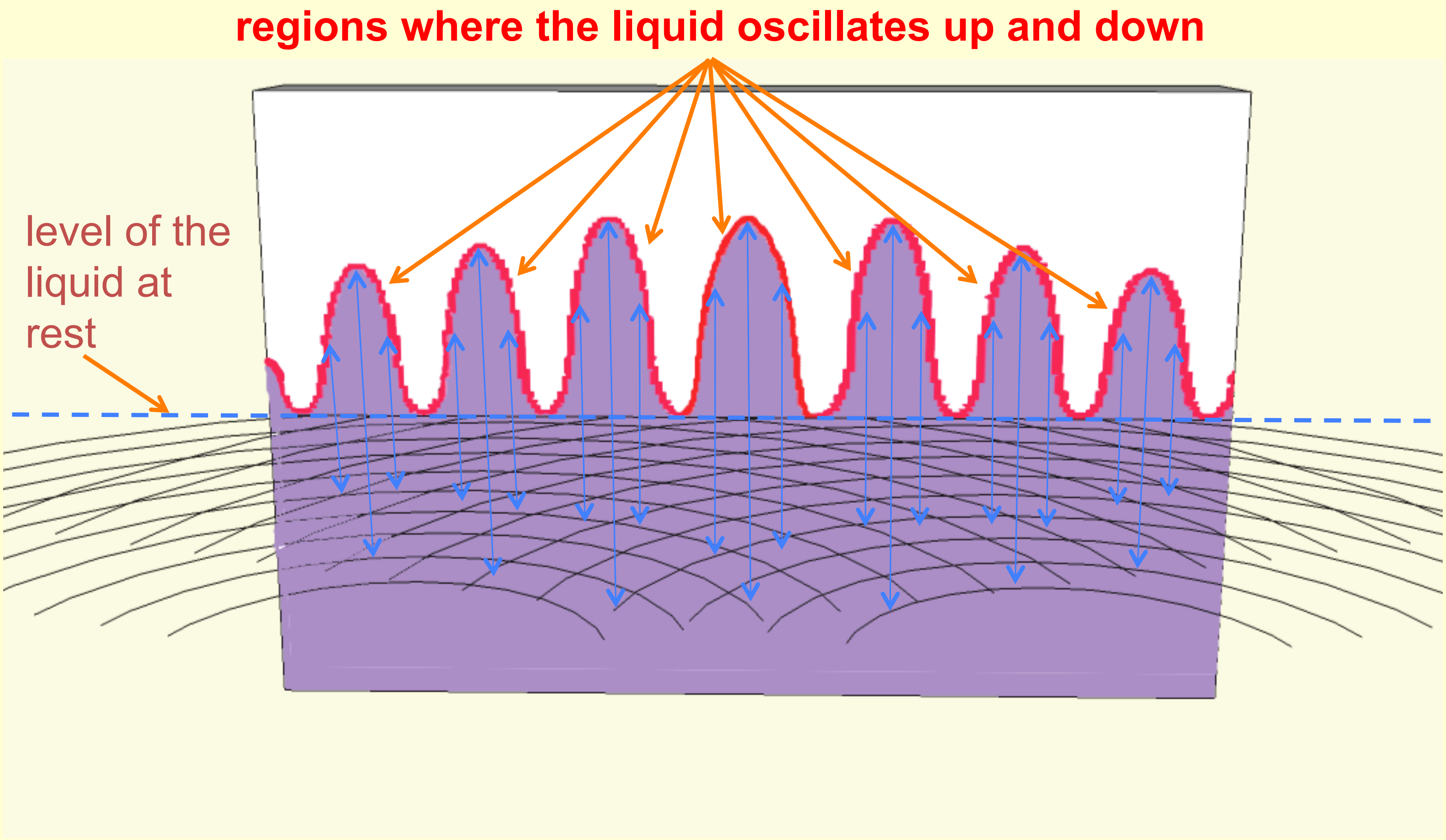
slits

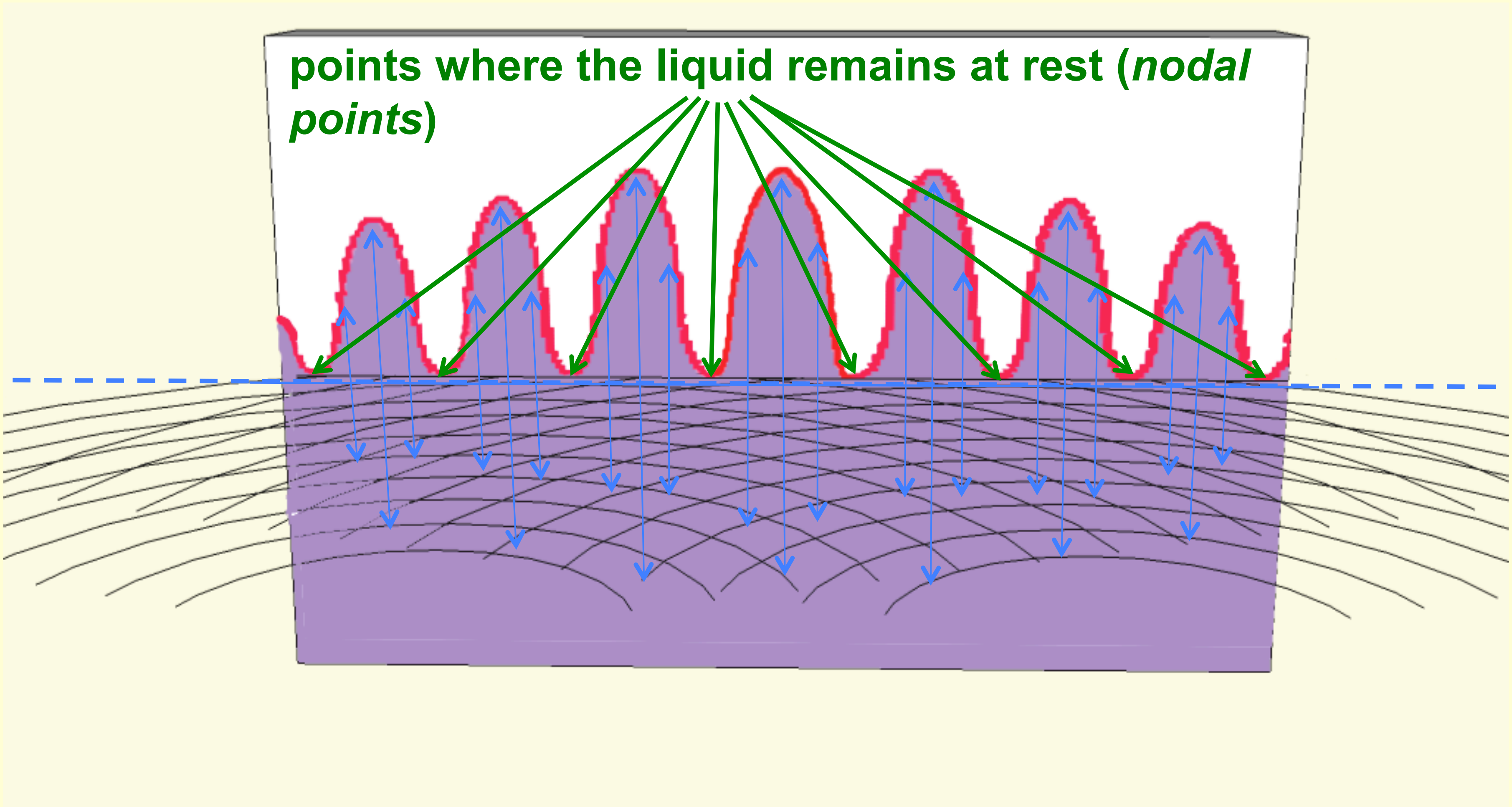
beyond the slits the interference pattern is the same observed with the two point sources





pattern observed in the ripple tank interference experiment


regions where the liquid oscillates up and down
level of the liquid at rest


points where the liquid remains at rest (*nodal points*)

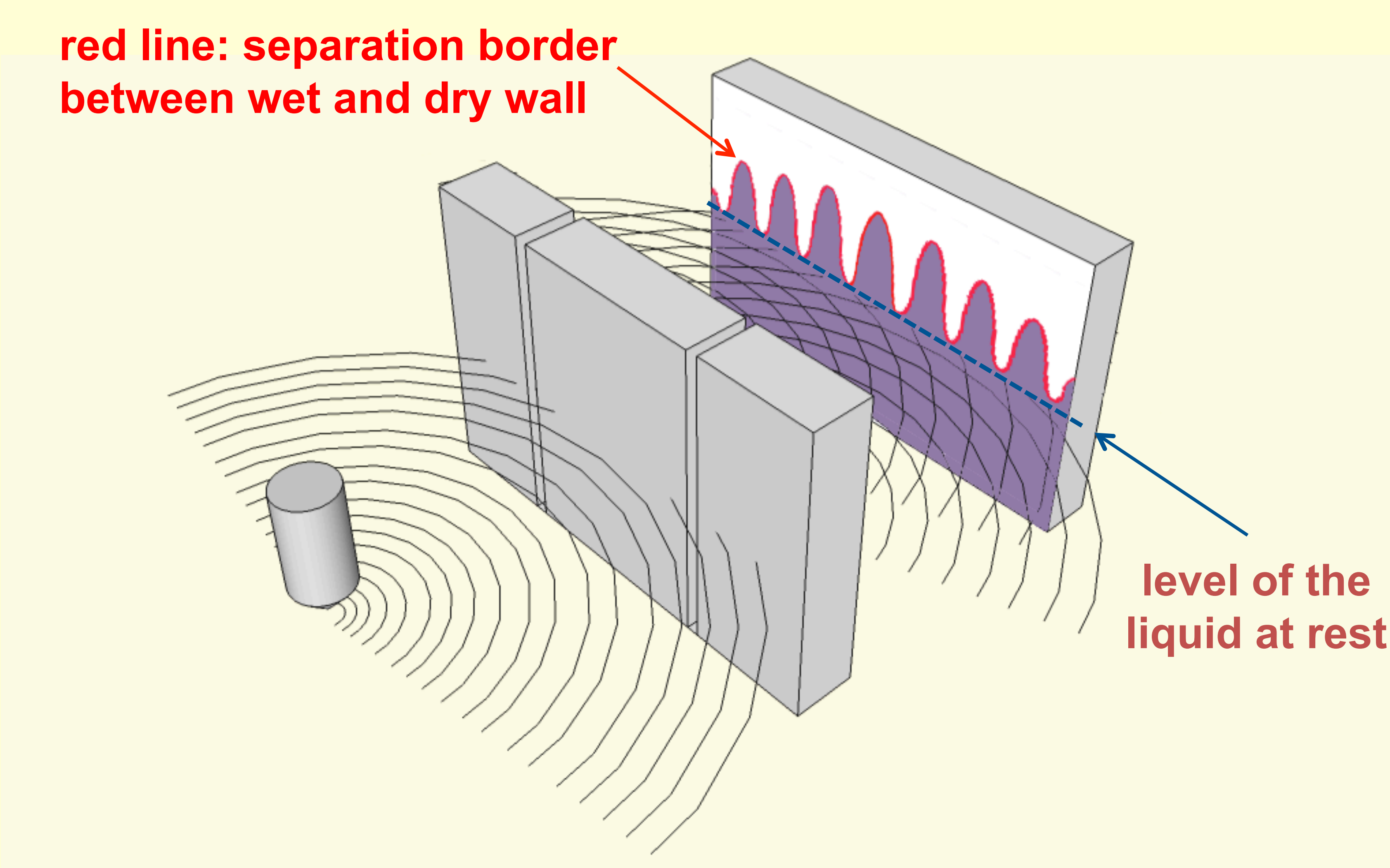


figure representative of the oscillation ***amplitude*** (A) of the liquid *frange di interferenza*

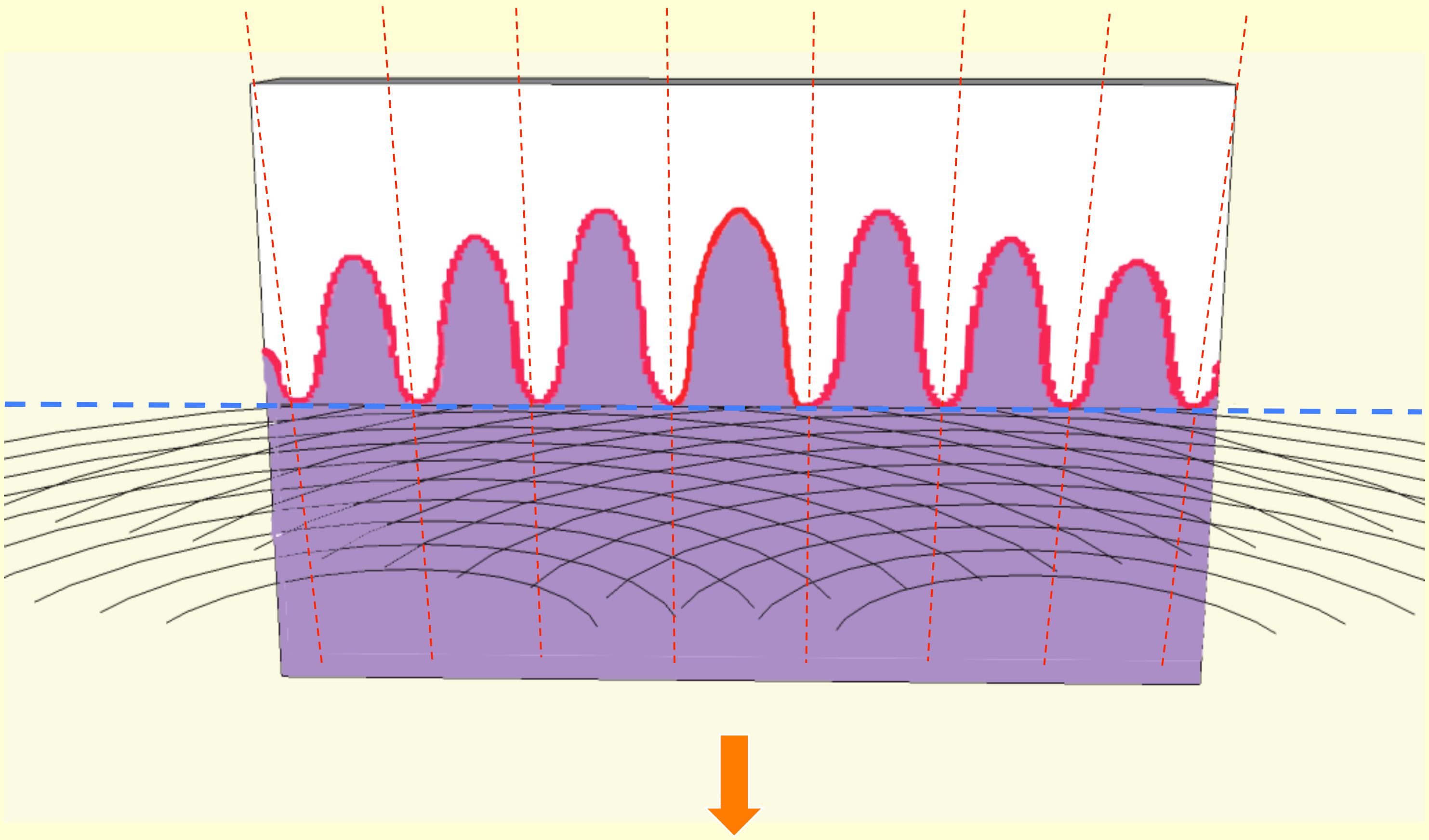


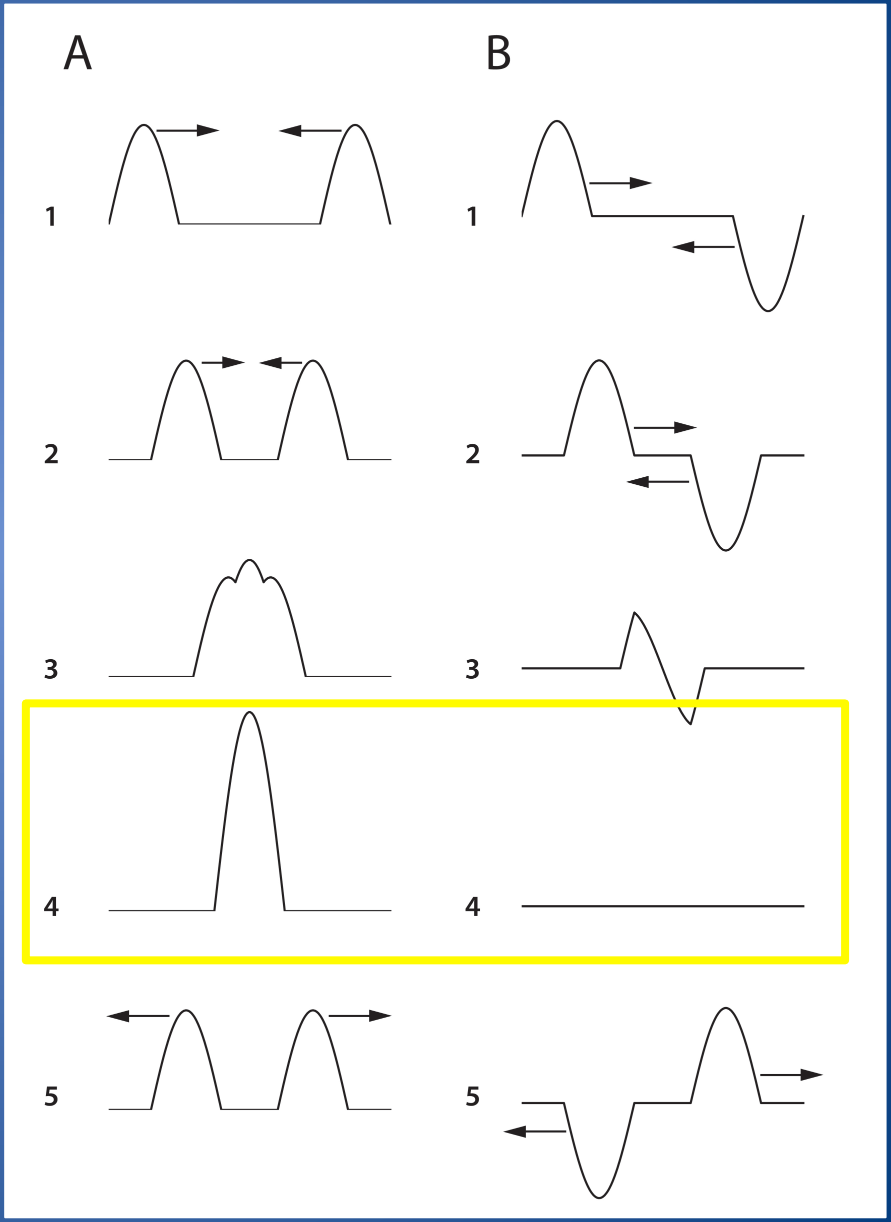
figure representative of the oscillation ***amplitude*** (A) of the liquid

The origin of interference: **the superposition principle**

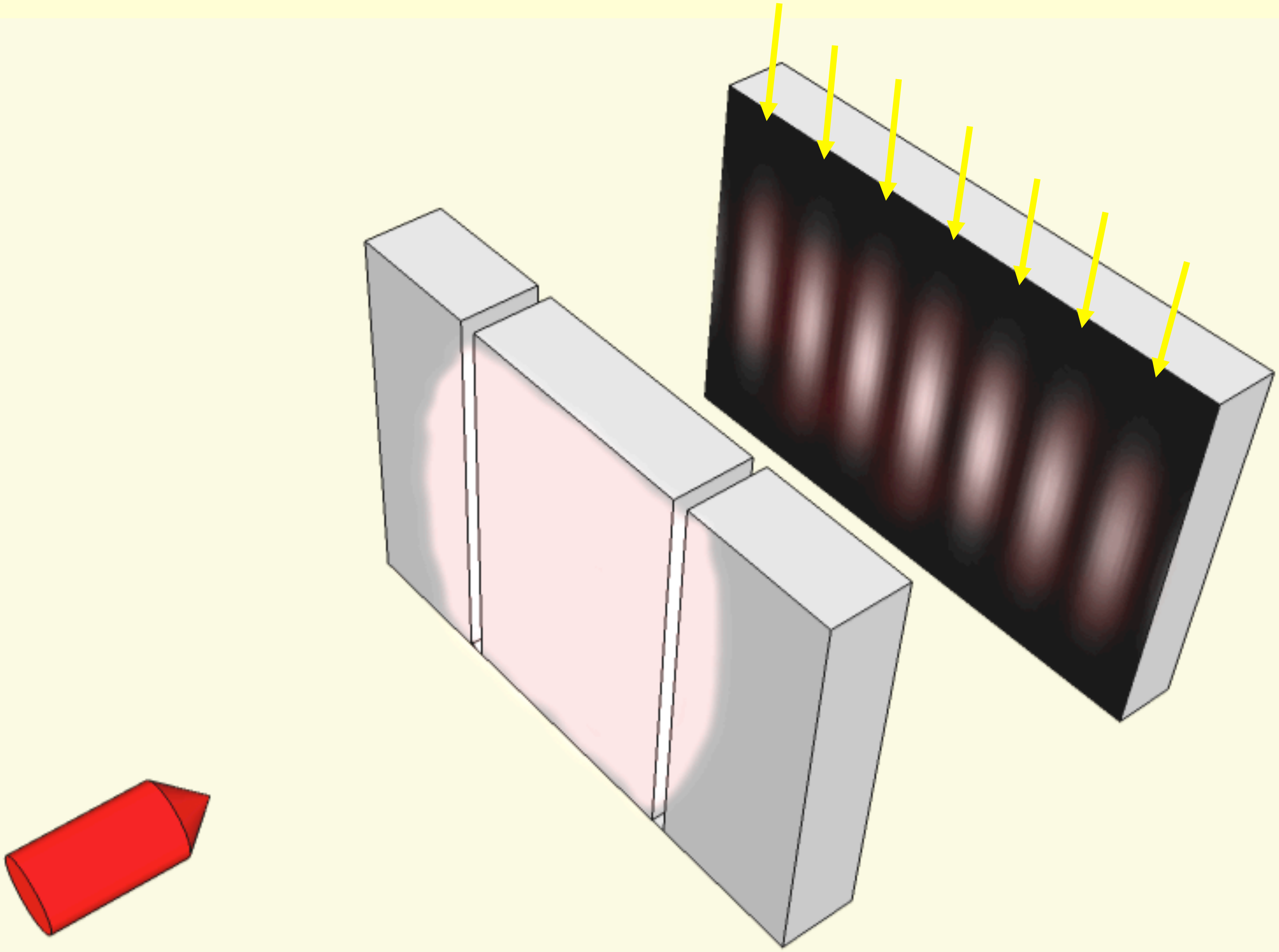
When waves meet in space they combine according to the **superposition principle**

The net amplitude caused by two or more waves traversing the same space is the (algebraic) sum of the amplitudes which would have been produced by the individual waves separately

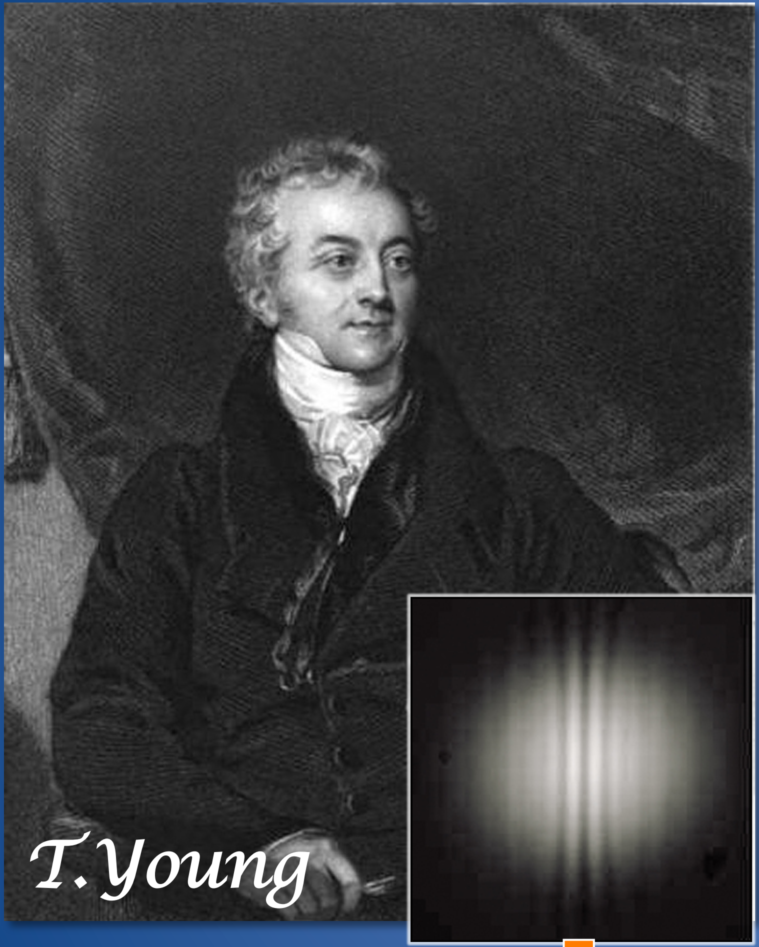
This effect may give origin to regions where the amplitude is enhanced (4A) and regions where it becomes zero (4B)

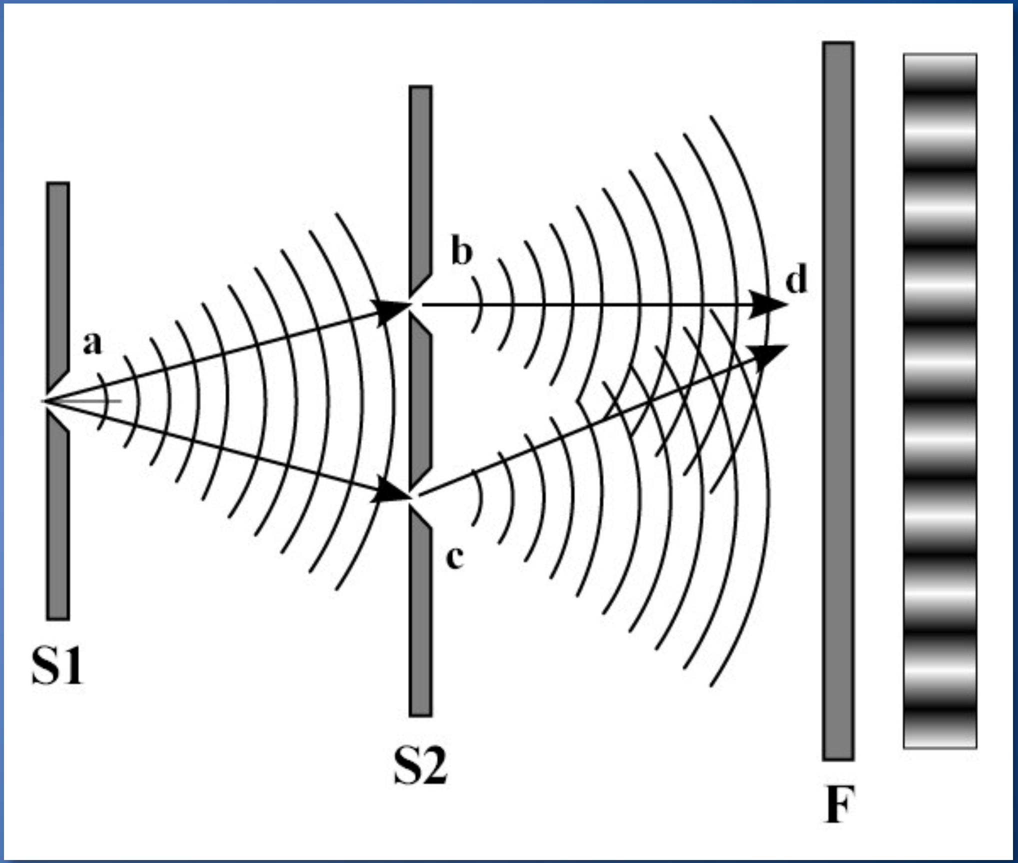


case 3: high intensity light beam (Young's experiment, 1801)



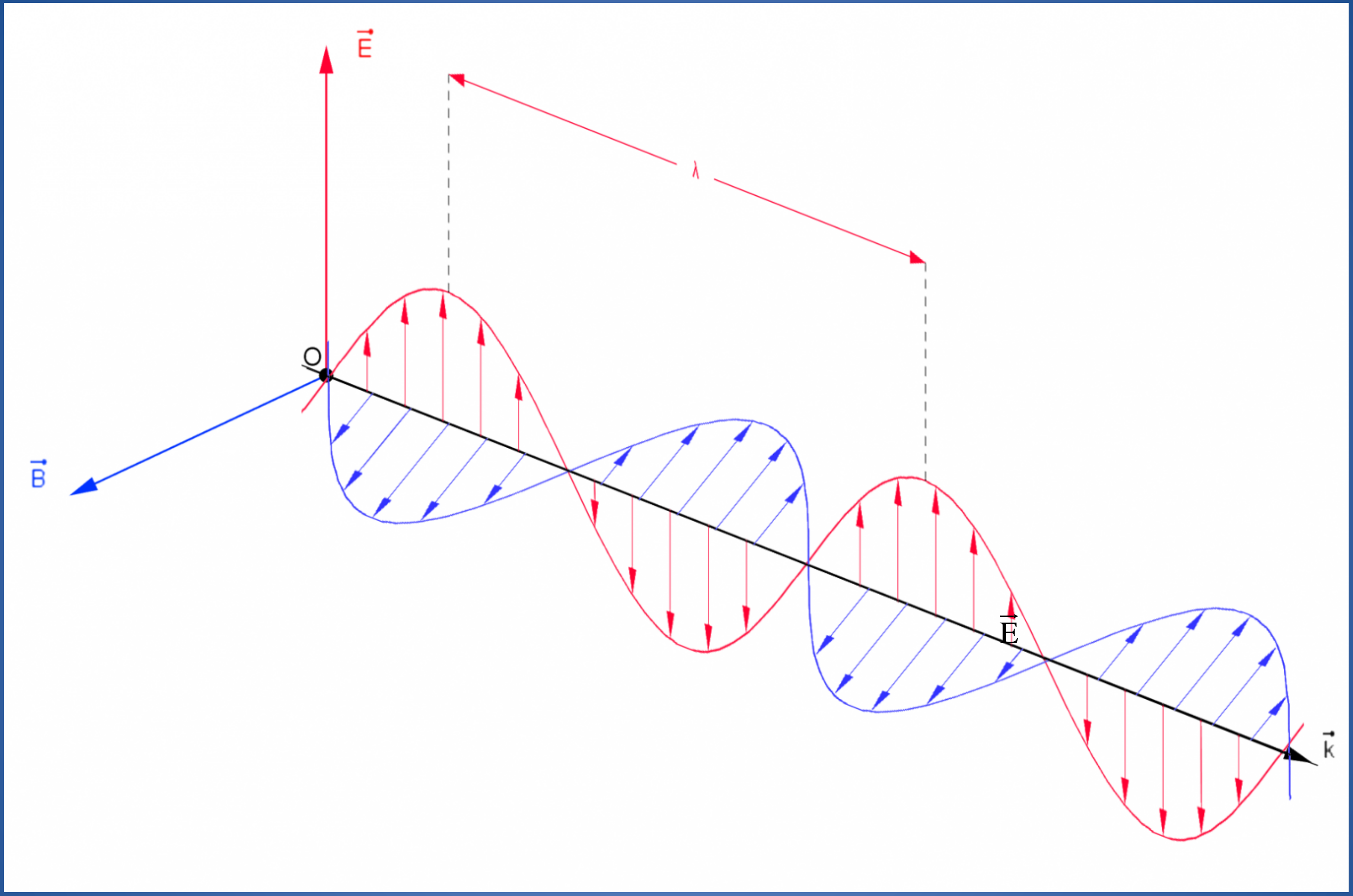
1801: Young's double slit experiment





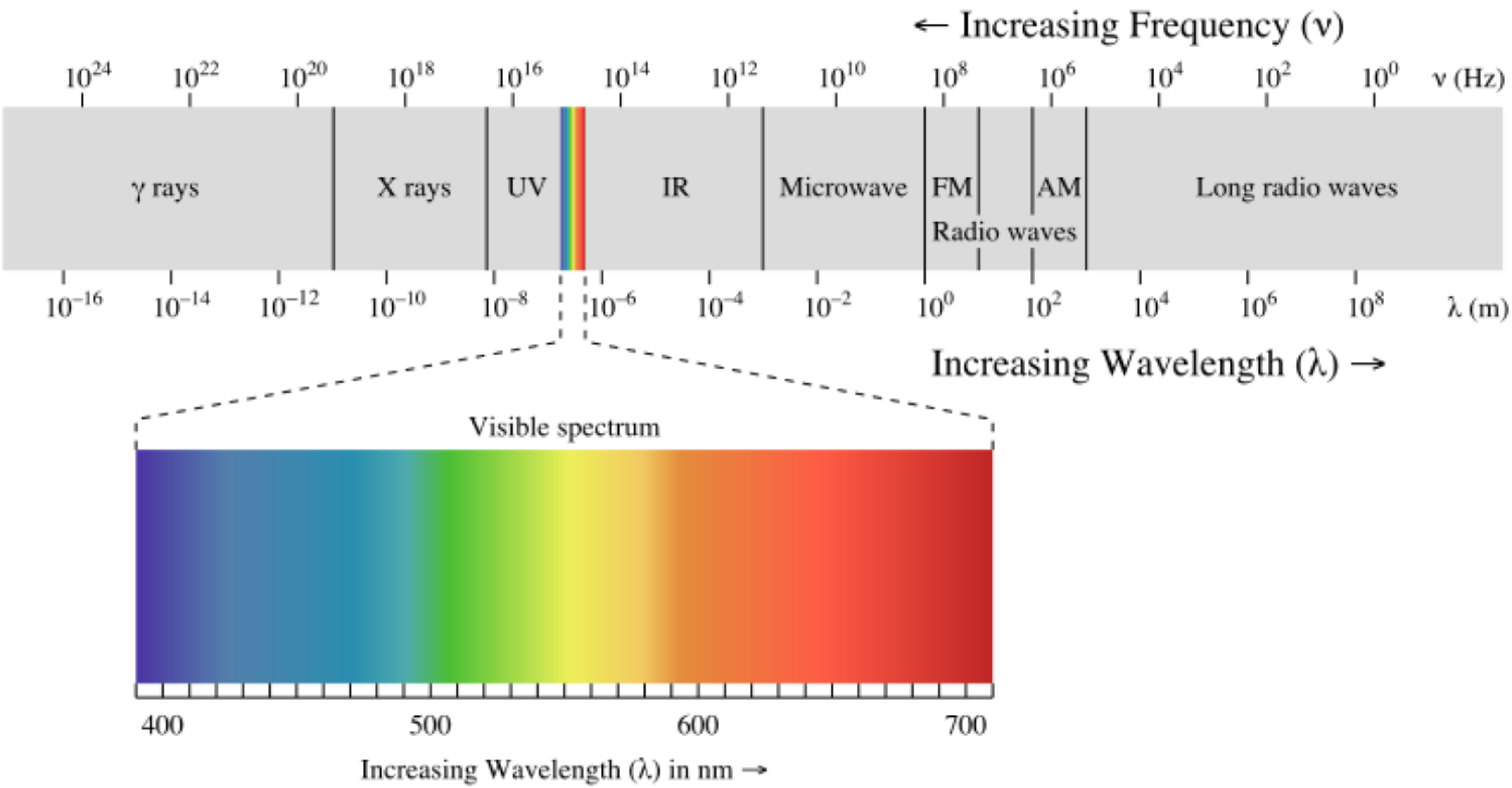
interference → light = wave

Electromagnetic (e-m) waves



Electric $\vec{E}$ and magnetic $\vec{B}$ fields which propagate in *vacuum* at the speed of light *c*

Spectrum of e-m waves



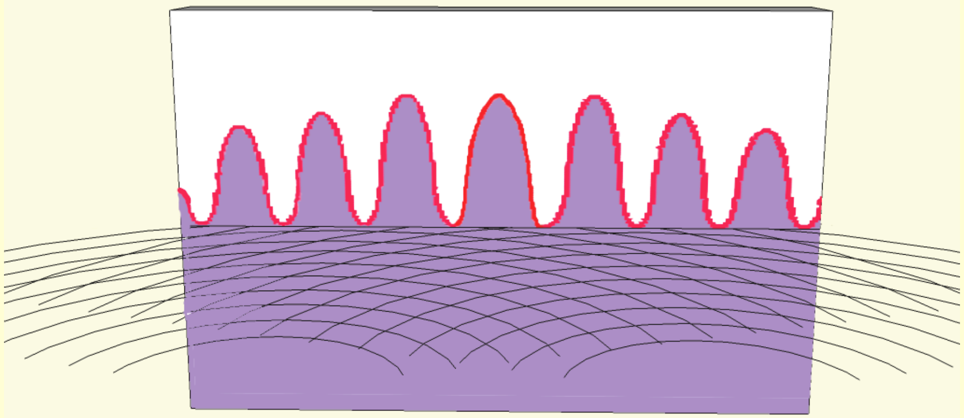


figure representative of the oscillation ***amplitude*** (A) of the liquid

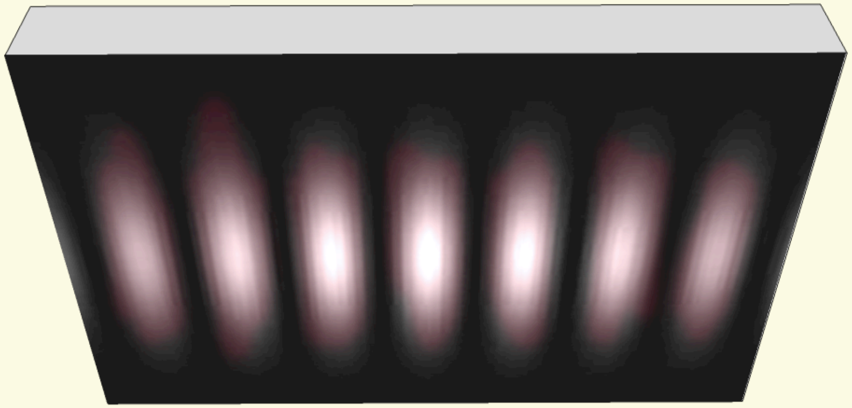
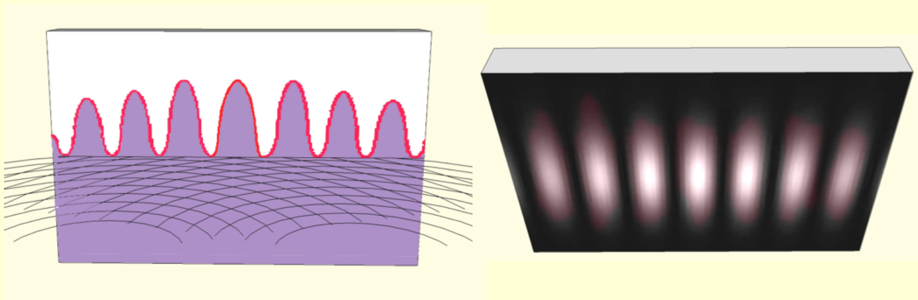
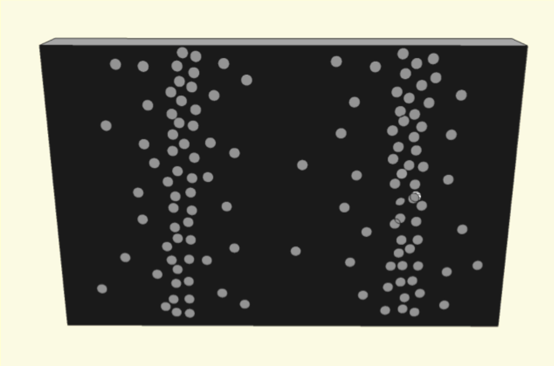


figure representative of the ***intensity*** of the light wave (related to the intensity of the e.m. field) $\mathbf{I \propto A^2}$

result of the classic two-slit experiment





waves: superposition principle → interference fringes

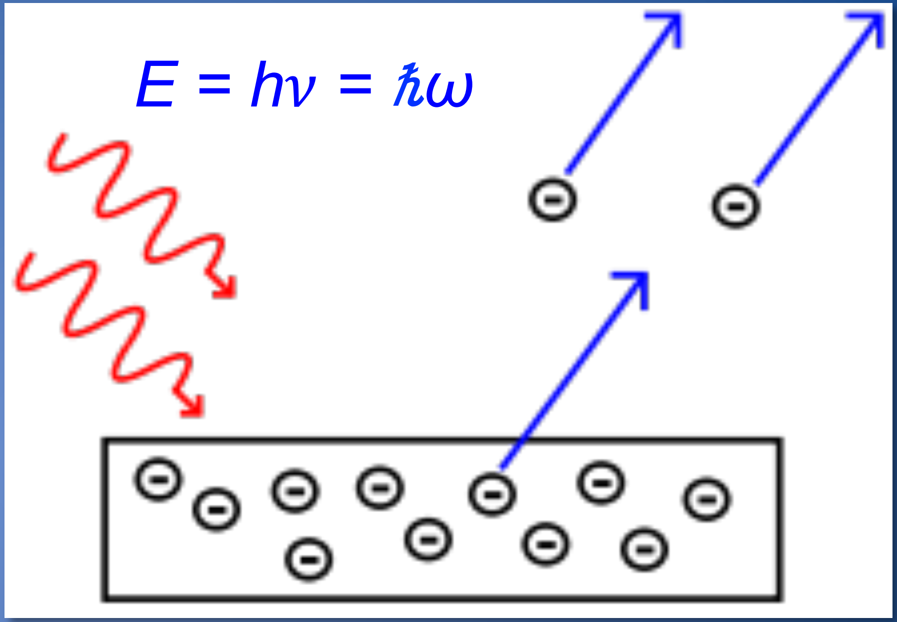
spatial extension, continuity, concept of *field*, ...

particles: newtonian mechanics (no superposition!)→two bands

spatial localization, discreteness, trajectories, ...

1905: Einstein, the photoelectric effect and light quanta

"On a Heuristic Viewpoint Concerning the Production and Transformation of Light"



h = **Planck's constant** = 6.63×10^{-27} cm^2gs^{-1}

$\hbar = h/2\pi$

photoelectric effect ➡ **light = particles**

(*light quanta or photons*)

1905: Einstein, the photoelectric effect and light quanta

"On a Heuristic Viewpoint Concerning the Production and Transformation of Light"

According to the classical electromagnetic theory, electron emission should increase with increasing the *intensity* ($\propto$*amplitude*^{2}) of the incident e-m wave.

Actually the features of electron emission depend mainly on the *frequency (= c/ λ)*:

- below some threshold value of frequency, which depends on the material, there is no emission, independently on the intensity of the e-m radiation
- above the threshold the kinetic *energy* of emitted electrons increases with increasing the *frequency* of e-m radiation (energy of light quanta), their *number* increasies with increasing the radiation *intensity* (number of light quanta)

1905: Einstein, the photoelectric effect and light quanta

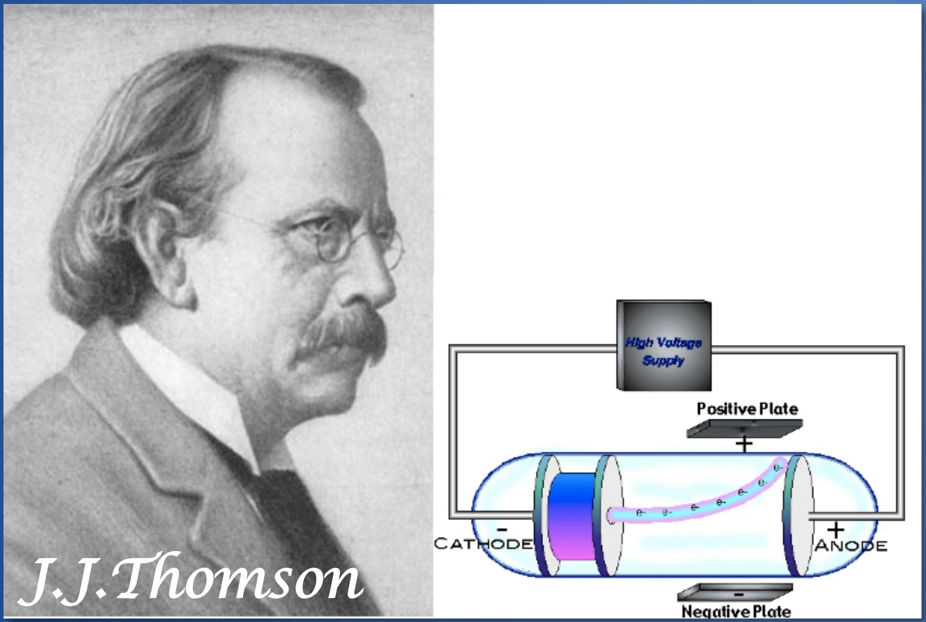
"On a Heuristic Viewpoint Concerning the Production and Transformation of Light"

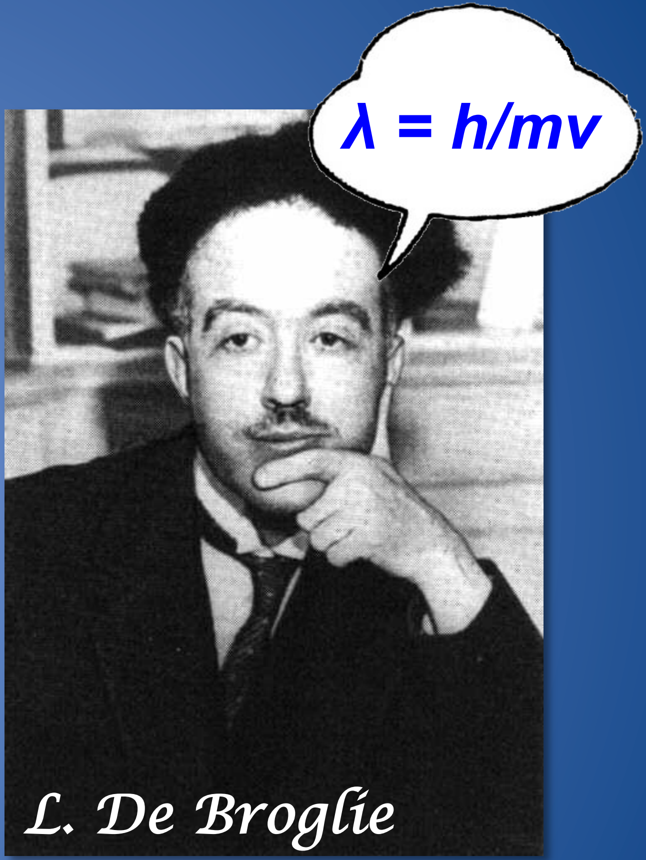
thresholds for photoelectric emission in various metals

VALORI DI SOGLIA PER L'EMISSIONE DI ELETTRONI DA UN METALLO

(1) Metallo	(2) E. fotoni (eV)	(3) E. fotoni (J)	(4) frequenza (f) = E(J)/h	(5) lungh. d'onda (λ) = c/f	(6) Rad. E.M.
Potassio (K)	2,25 eV	3,60 x 10^{-19}J	5,43 x 10^{14}Hz	552 x 10^{-9}m = 552 nm	luce verde
Sodio (Na)	2,28 eV	3,65 x 10^{-19}J	5,51 x 10^{14}Hz	544 x 10^{-9}m = 544 nm	luce verde
Calcio (Ca)	3,20 eV	5,13 x 10^{-19}J	7,74 x 10^{14}Hz	388 x 10^{-9}m = 388 nm	luce viola
Torio (Th)	3,47 eV	5,56 x 10^{-19}J	8,39 x 10^{14}Hz	357 x 10^{-9}m = 357 nm	raggi u.v.
Zinco (Zn)	4,27 eV	6,84 x 10^{-19}J	1,03 x 10^{15}Hz	291 x 10^{-9}m = 291 nm	raggi u.v.
Rame (Cu)	4,48 eV	7,18 x 10^{-19}J	1,08 x 10^{15}Hz	278 x 10^{-9}m = 278 nm	raggi u.v.
Ferro (Fe)	4,63 eV	7,42 x 10^{-19}J	1,12 x 10^{15}Hz	268 x 10^{-9}m = 268 nm	raggi u.v.
Argento (Ag)	4,70 eV	7,53 x 10^{-19}J	1,14 x 10^{15}Hz	263 x 10^{-9}m = 263 nm	raggi u.v.
Nichel (Ni)	4,91 eV	7,86 x 10^{-19}J	1,19 x 10^{15}Hz	252 x 10^{-9}m = 252 nm	raggi u.v.

Electrons?



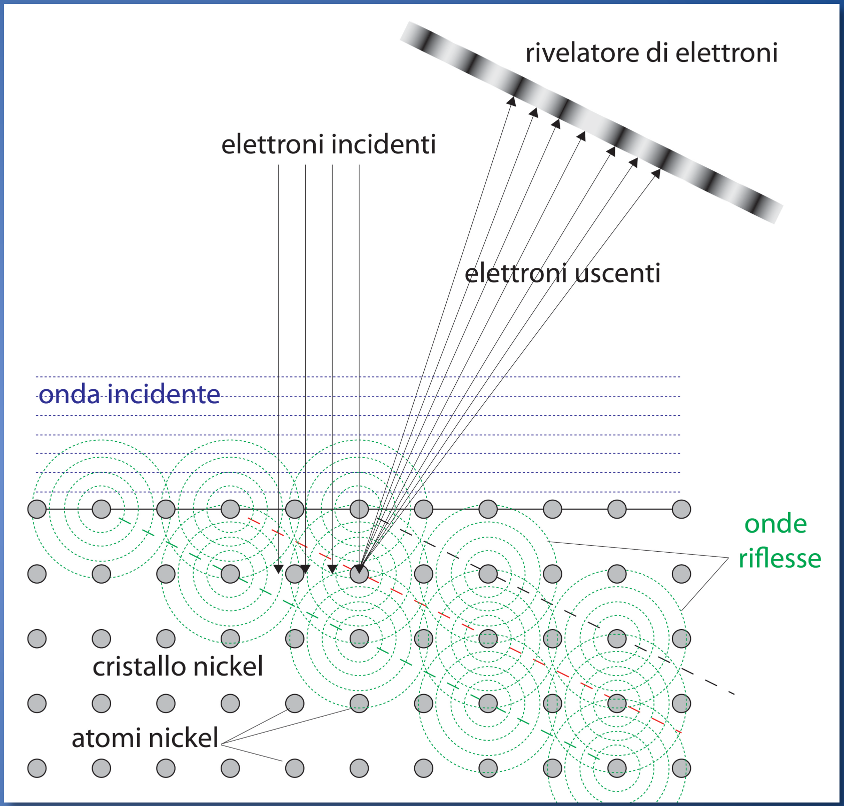


1897: corpuscles

1923: waves!

1927: an experiment on electron diffraction

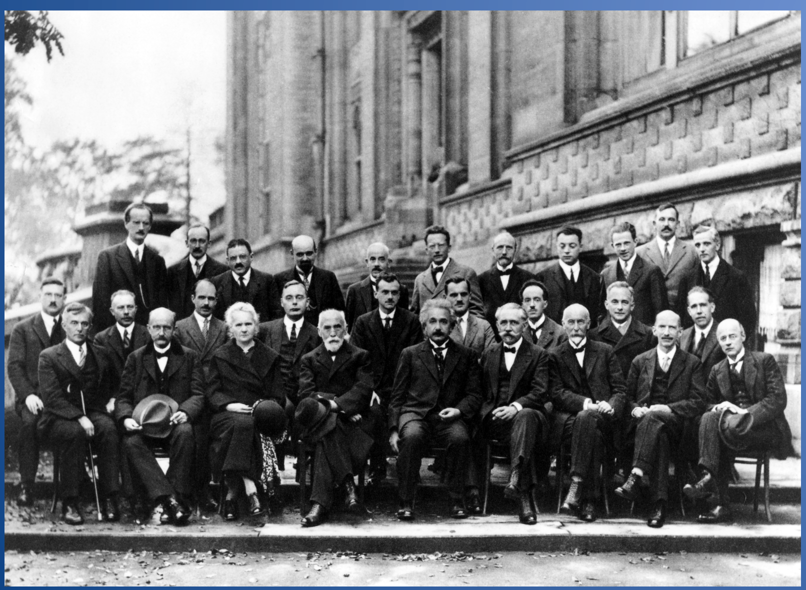
C. Davisson, D. Germer

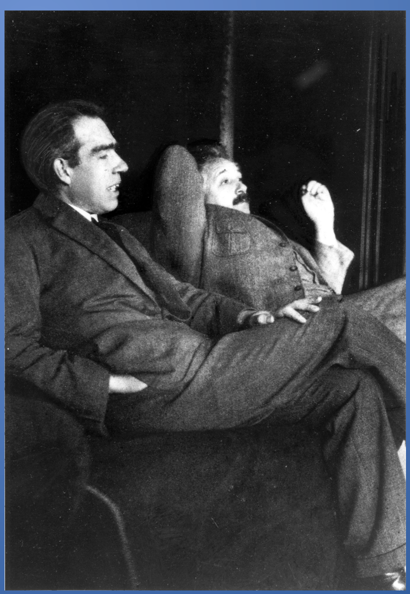


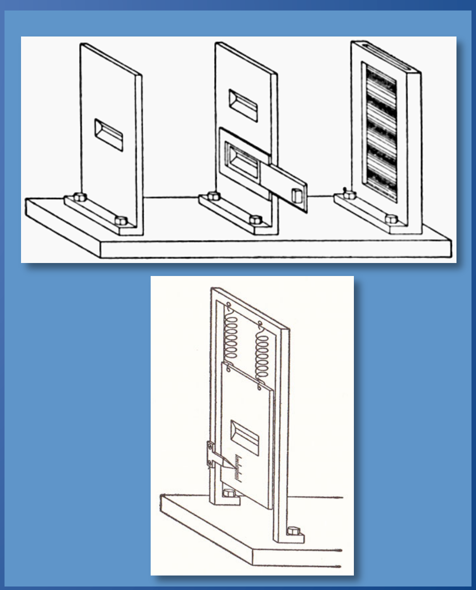
4 years later: experimental demonstration of the wave behavior of electrons ⇒ ***diffraction*** from a crystal (Ni): **results confirm the De Broglie hypothesis.**

1927: a conceptual experiment

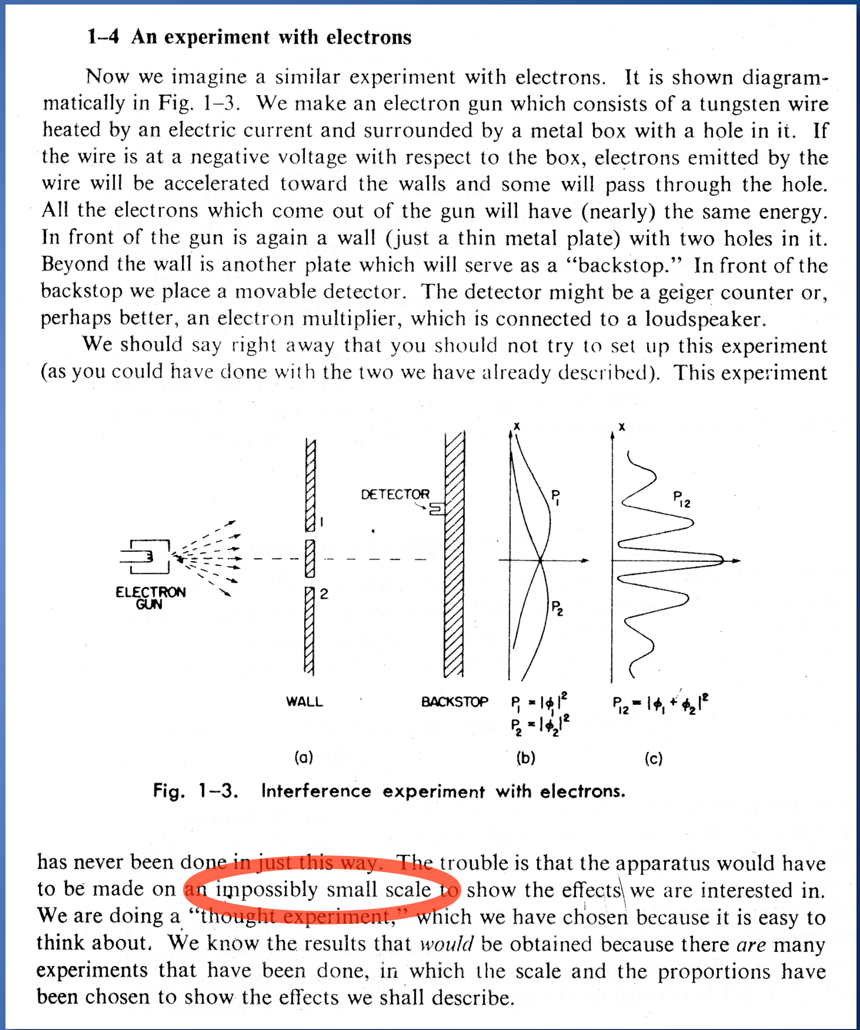
- 5th Solvay Conference "Electrons and Photons": Einstein invents the most beautiful experiment as a conceptual (*gedanken*) *experiment* in an attempt (failed) to find a violation of the Bohr's complementarity principle.







1963: the only mistery… "impossibly small scale.."



1–4 An experiment with electrons

Now we imagine a similar experiment with electrons. It is shown diagrammatically in Fig. 1–3. We make an electron gun which consists of a tungsten wire heated by an electric current and surrounded by a metal box with a hole in it. If the wire is at a negative voltage with respect to the box, electrons emitted by the wire will be accelerated toward the walls and some will pass through the hole. All the electrons which come out of the gun will have (nearly) the same energy. In front of the gun is again a wall (just a thin metal plate) with two holes in it. Beyond the wall is another plate which will serve as a "backstop." In front of the backstop we place a movable detector. The detector might be a geiger counter or, perhaps better, an electron multiplier, which is connected to a loudspeaker.

We should say right away that you should not try to set up this experiment (as you could have done with the two we have already described). This experiment

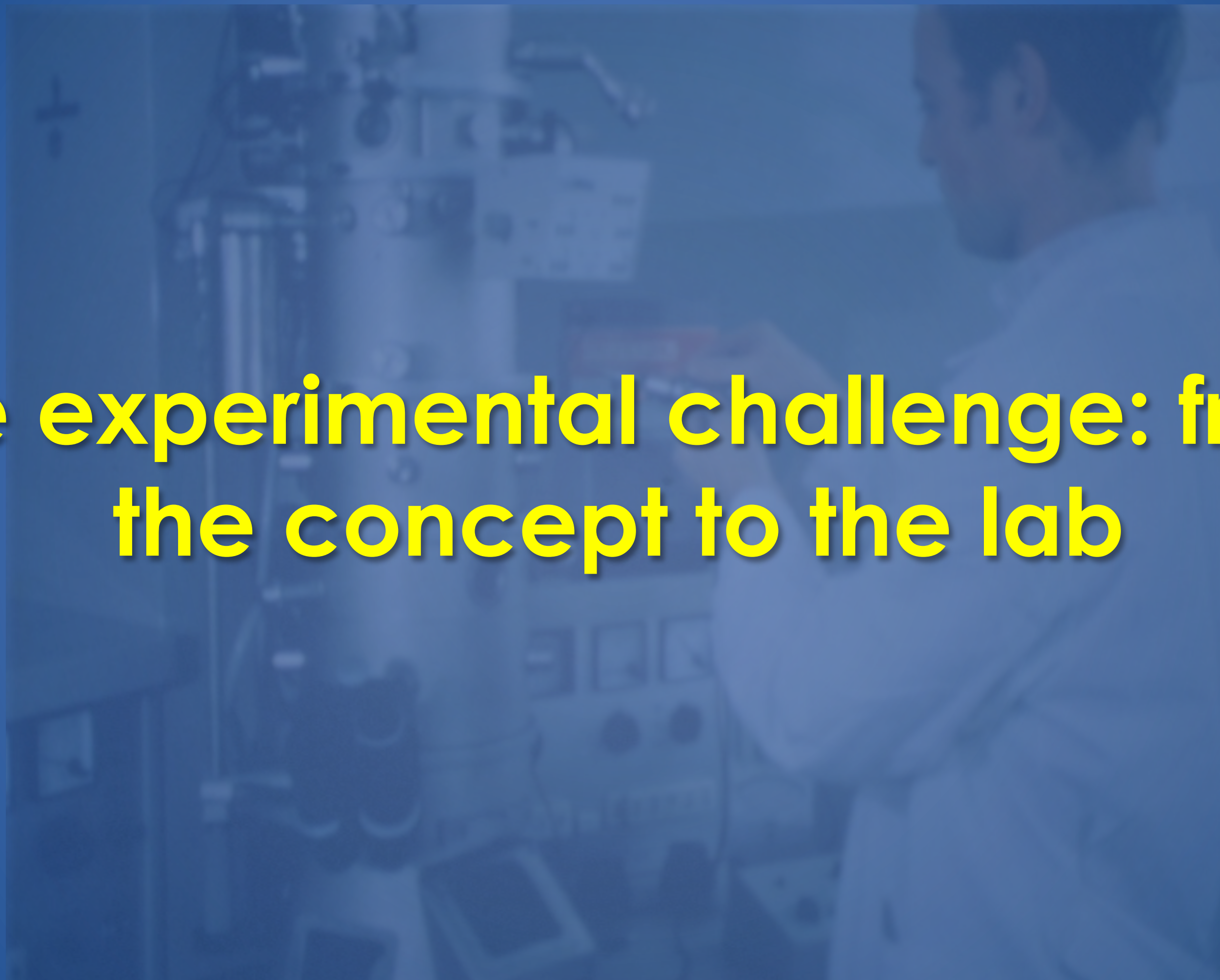
Fig. 1–3. Interference experiment with electrons.

has never been done in just this way. The trouble is that the apparatus would have to be made on an impossibly small scale to show the effects we are interested in. We are doing a "thought experiment," which we have chosen because it is easy to think about. We know the results that *would* be obtained because there *are* many experiments that have been done, in which the scale and the proportions have been chosen to show the effects we shall describe.

"We choose to examine a phenomenon [n.d.r. the single electron interference] which is impossible, absolutely impossible to explain in any classical way, e which has in it ***the heart of quantum mechanics****. In reality, it contains* ***the only mistery.****"*

Richard Feynman – *La fisica di Feynman, vol. 3 Meccanica Quantistica (1963)*

The experimental challenge: from the concept to the lab



Electron wavelength

$$\lambda = \frac{h}{m_0 v}$$

h: Planck's constant

$$eV = \frac{m_0 v^2}{2}$$

$$m_0 v = (2m_0 eV)^{1/2}$$

$$\lambda = \frac{h}{(2m_0 eV)^{1/2}}$$

$$\lambda = \frac{h}{[2m_0 eV(1 + \frac{eV}{2m_0 c^2})]^{1/2}}$$

(relativistic correction)

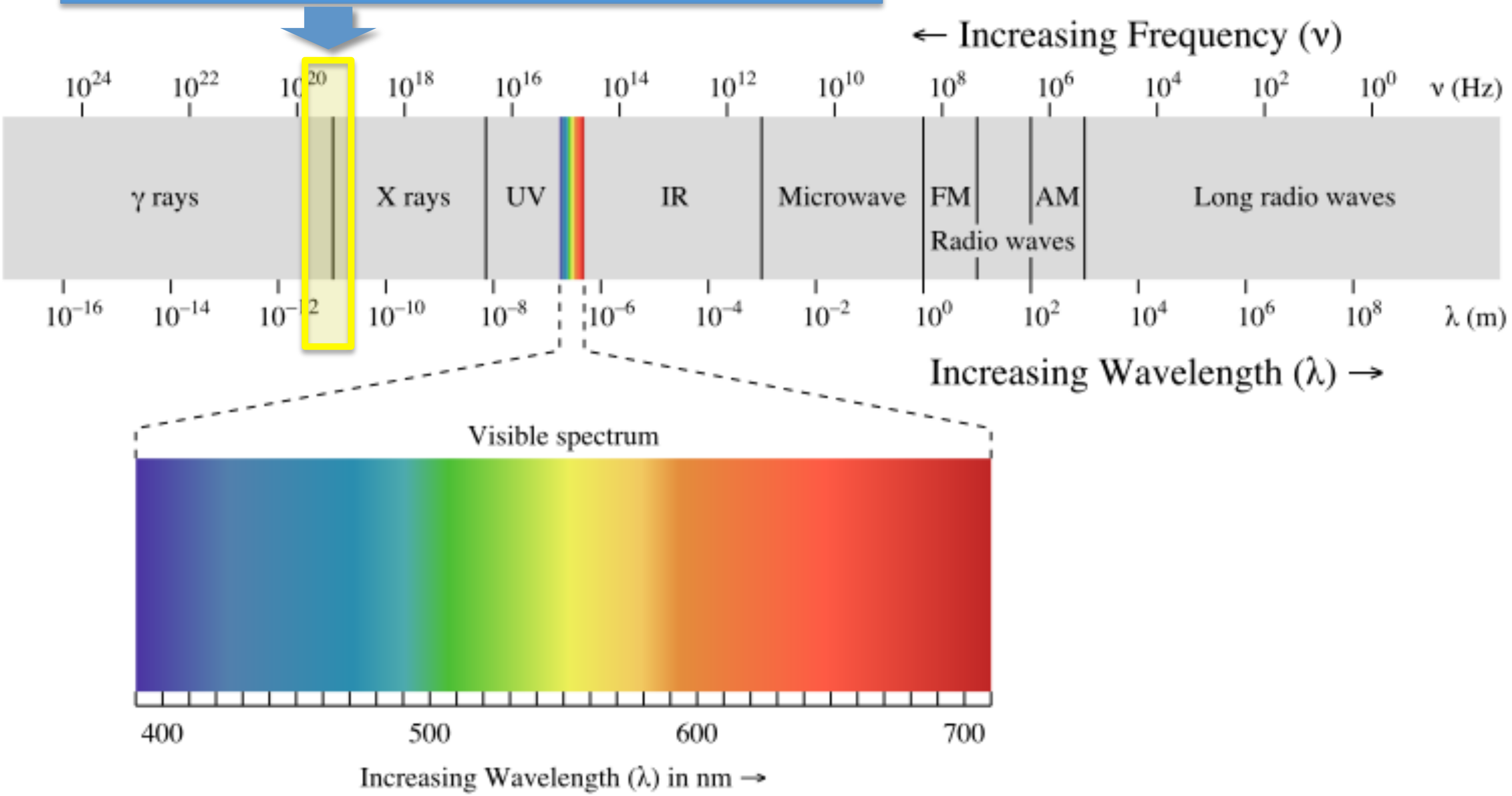
$$\lambda = \frac{1.266}{(1 + 0.9788 \times 10^{-6} V)V^{1/2}}$$

V (volt) → λ (nm)

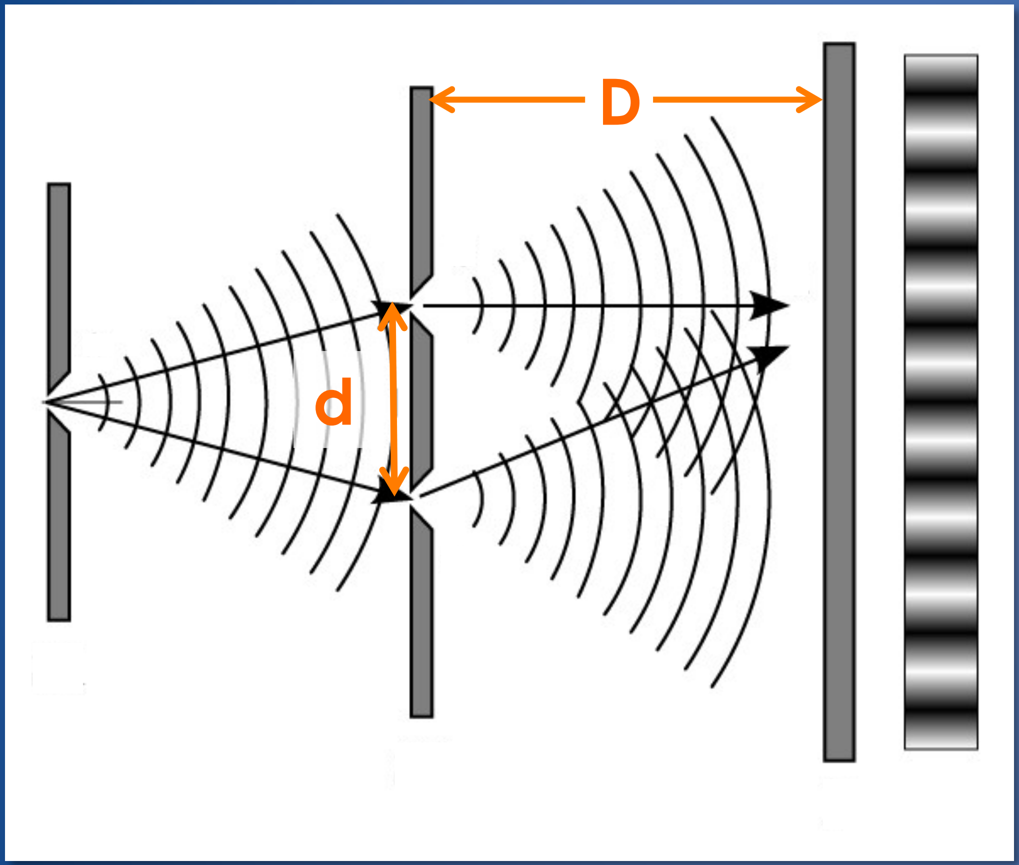
acceleration potential (volt)	**wavelength**	
1000	0.04 nm	4×10^{-11} m
100000	0.004 nm	4×10^{-12} m

Electron wavelength

electrons 100-1 keV $\lambda_{el} \sim 10^{-4} - 10^{-5}\ \lambda_{light}$



Fringes visibility



Fringe's spacing

$\updownarrow$ **$x \simeq \lambda D/d$** (d<<D)

x (eye's resol.) ≈ **0.1 mm**
λ_{el} (100keV) = **0.004 nm**

to see fringes at a distance
of **D** = **30 cm**
must be **d~1 nm**

... actually too small!

a more realistic possibility allowed by today's technology:
d ~ 100 nm ⇒ D ~ 30 m (much longer than an electron microscope...)

To summarize

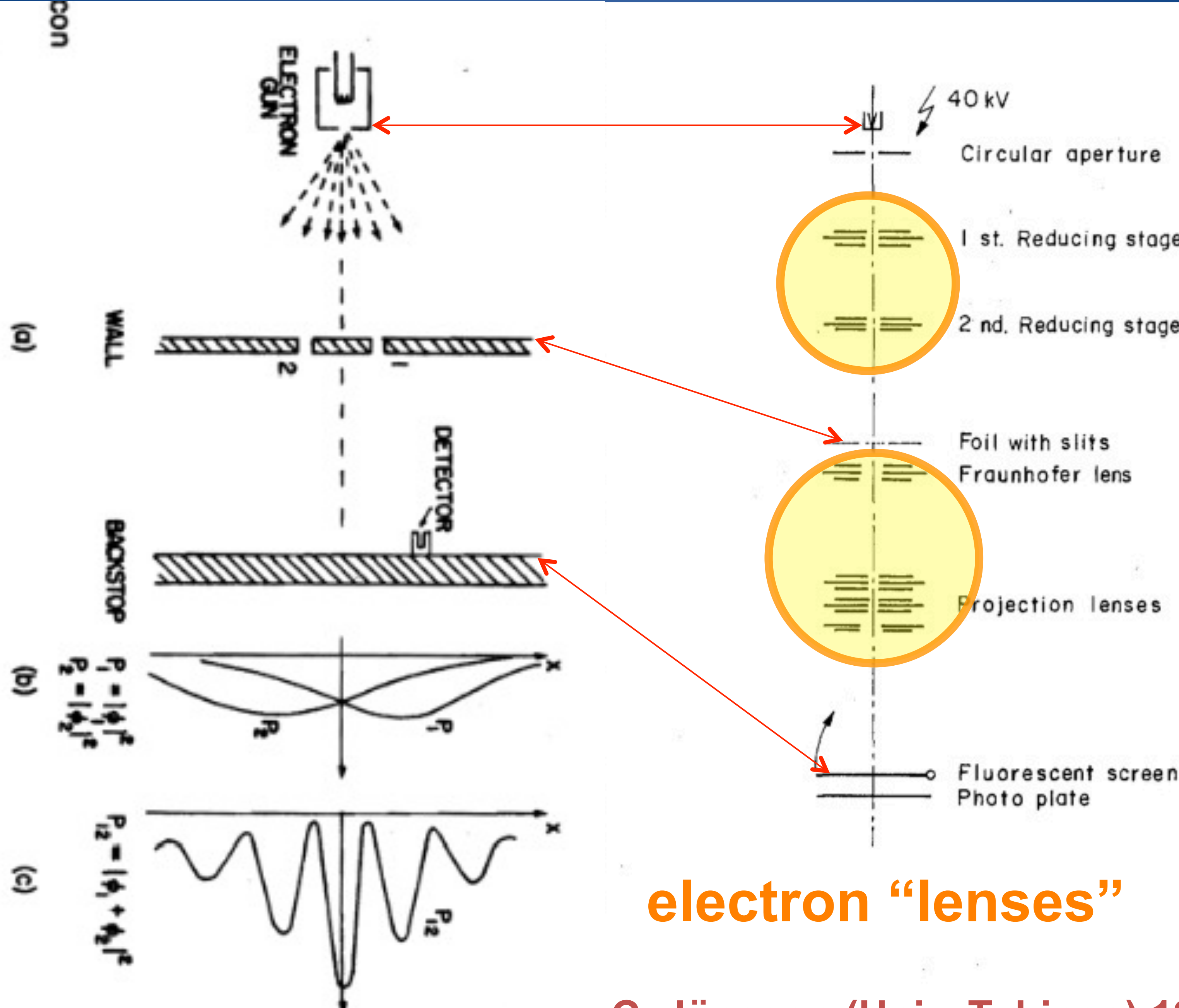
Fringe's visibility criterion (and *coherence limits*) call for a geometry where:

- size of the primary source, slits apertures and distances between slits are similar to the wavelength;

(very difficult to obtain, especially for electrons, due to their small wavelength) or, in alternative,

- slits-source and slits-detector distances are sufficiently large (a few tens of meters).

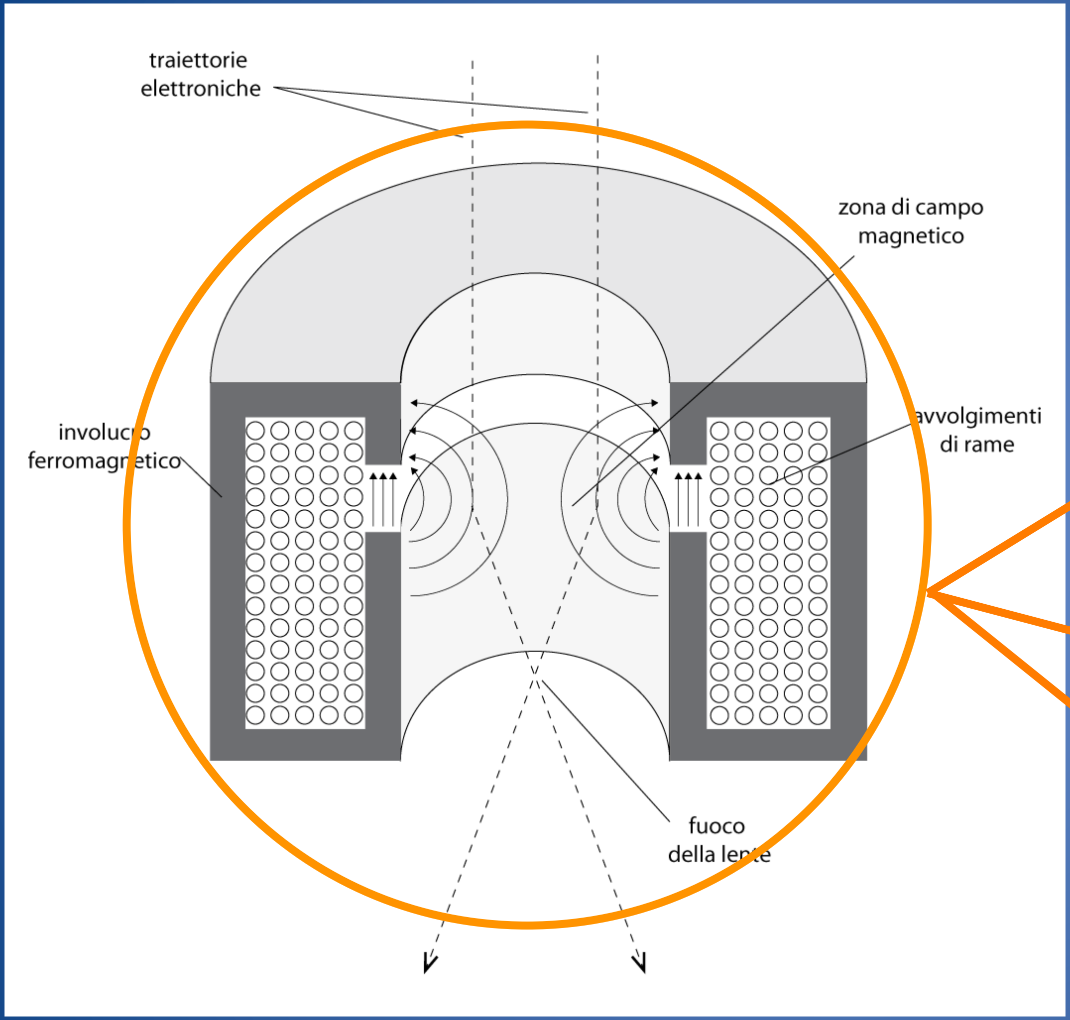
Also this alternative is not easy to be implemented in a lab, however there is a "trick" which allows to fullfill these conditions within the length (1-1.5 mt) of an electron microscope ...

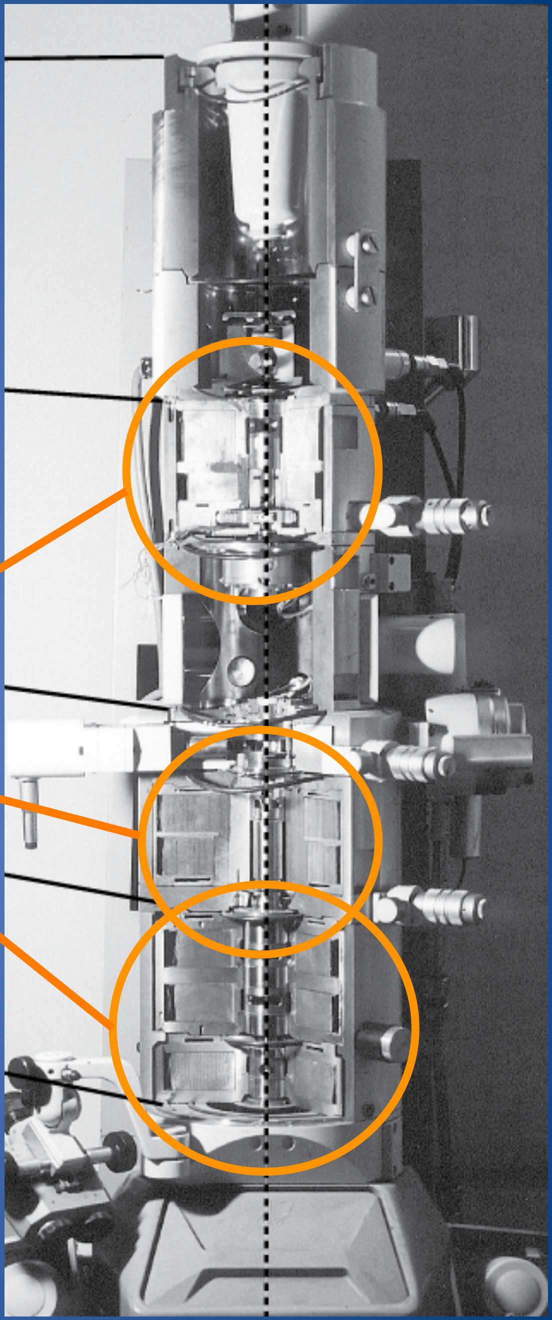


electron “lenses”

C. Jönsson (Univ. Tubinga) 1961

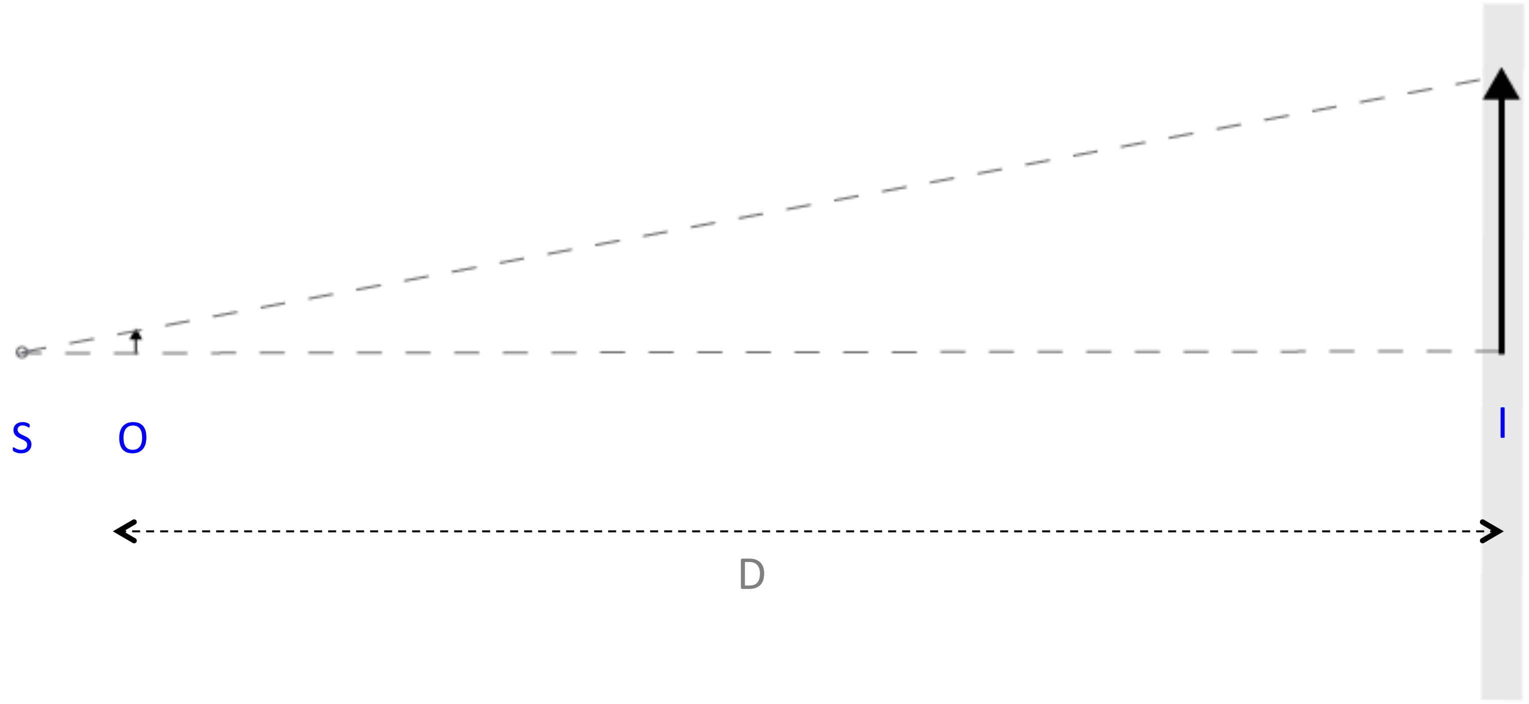
electromagnetic lens for electrons





the device in the heart of the *electron microscope* (here we speak of the *Transmission Electron Microscope - TEM*)

The magnifying effect of a lens



geometrical projection from a point source

The magnifying effect of a lens

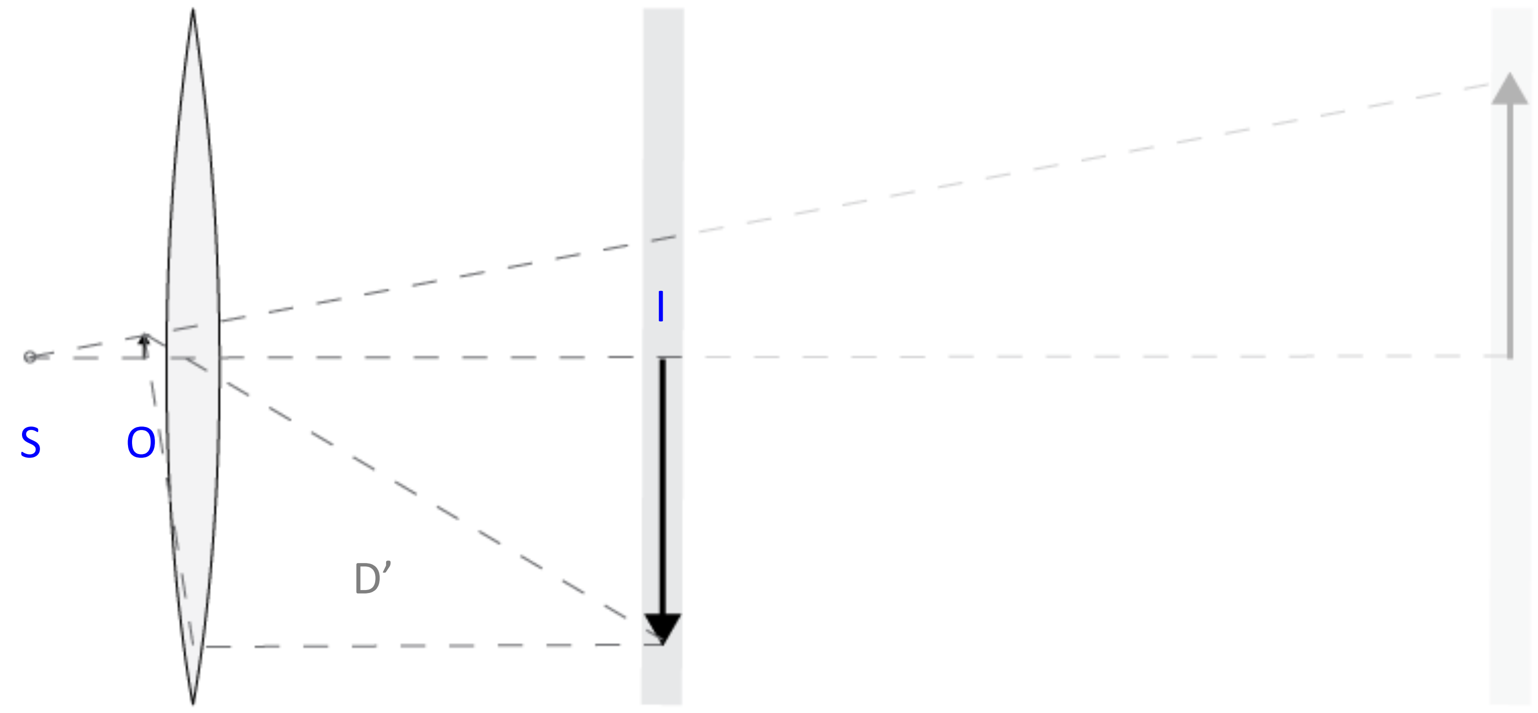
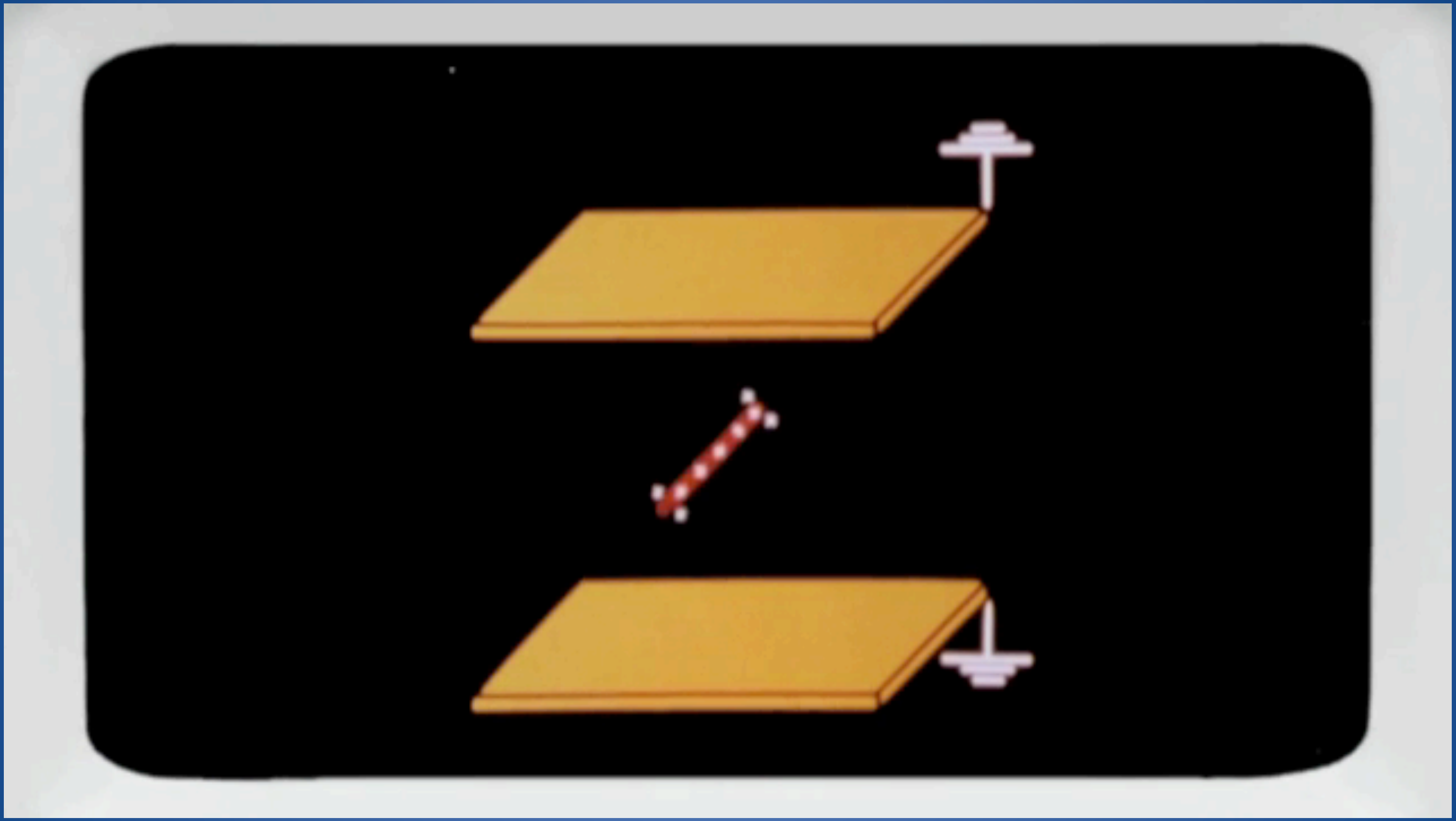
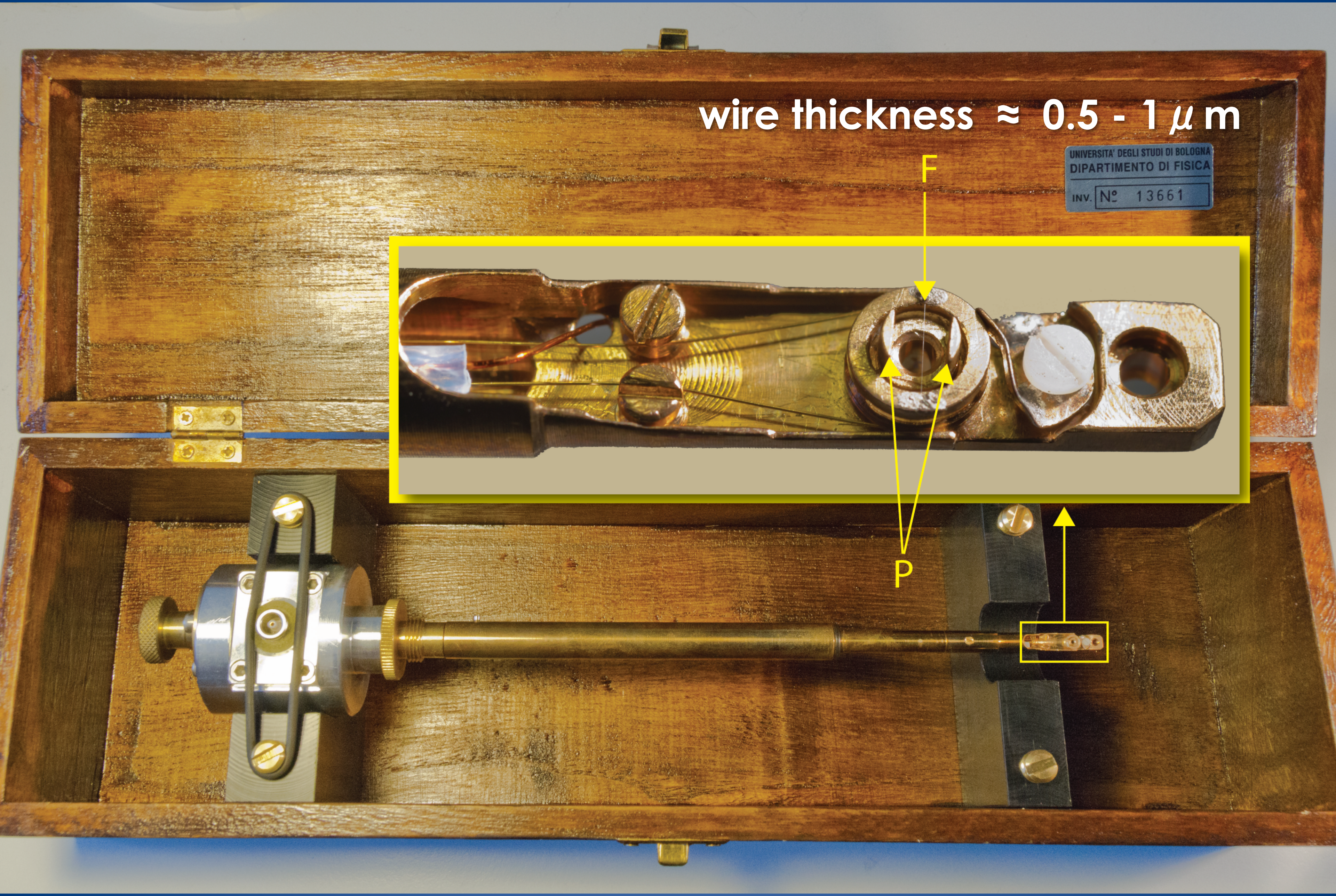


image of the same size than the previous one, but much closer to the object (and reversed)

Electron biprism: an alternative to the double slit



G.Lulli et al. from the documentary *"L'esperimento più bello"* 2011


wire thickness ≈ 0.5 - 1 μm
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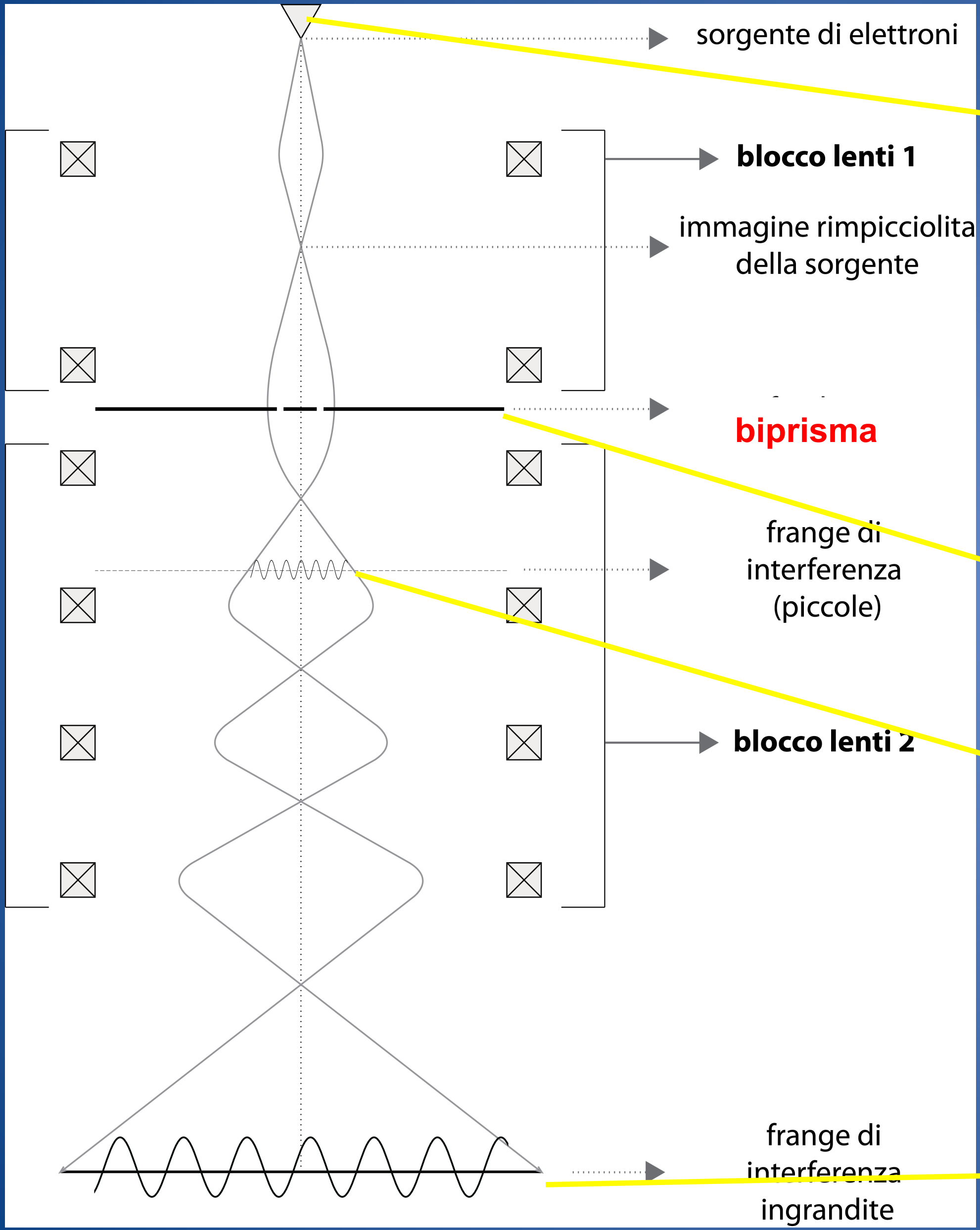
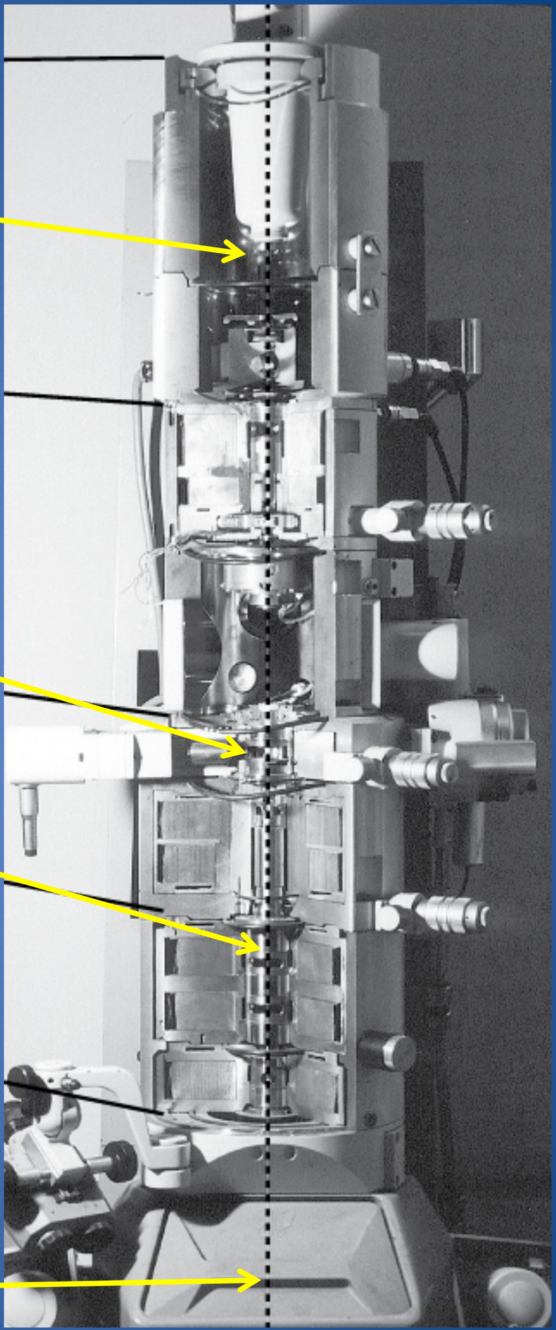
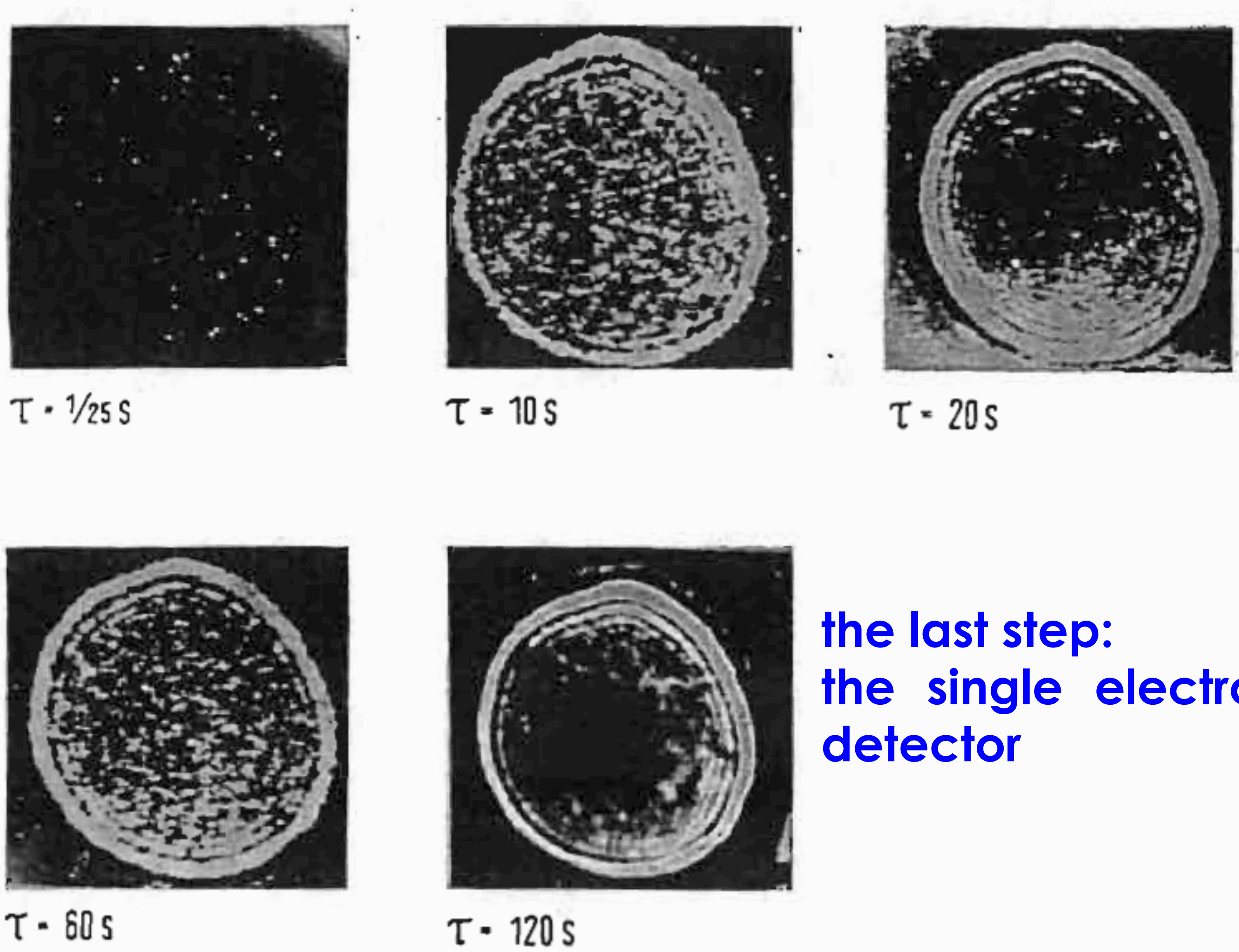
electron interference inside a TEM



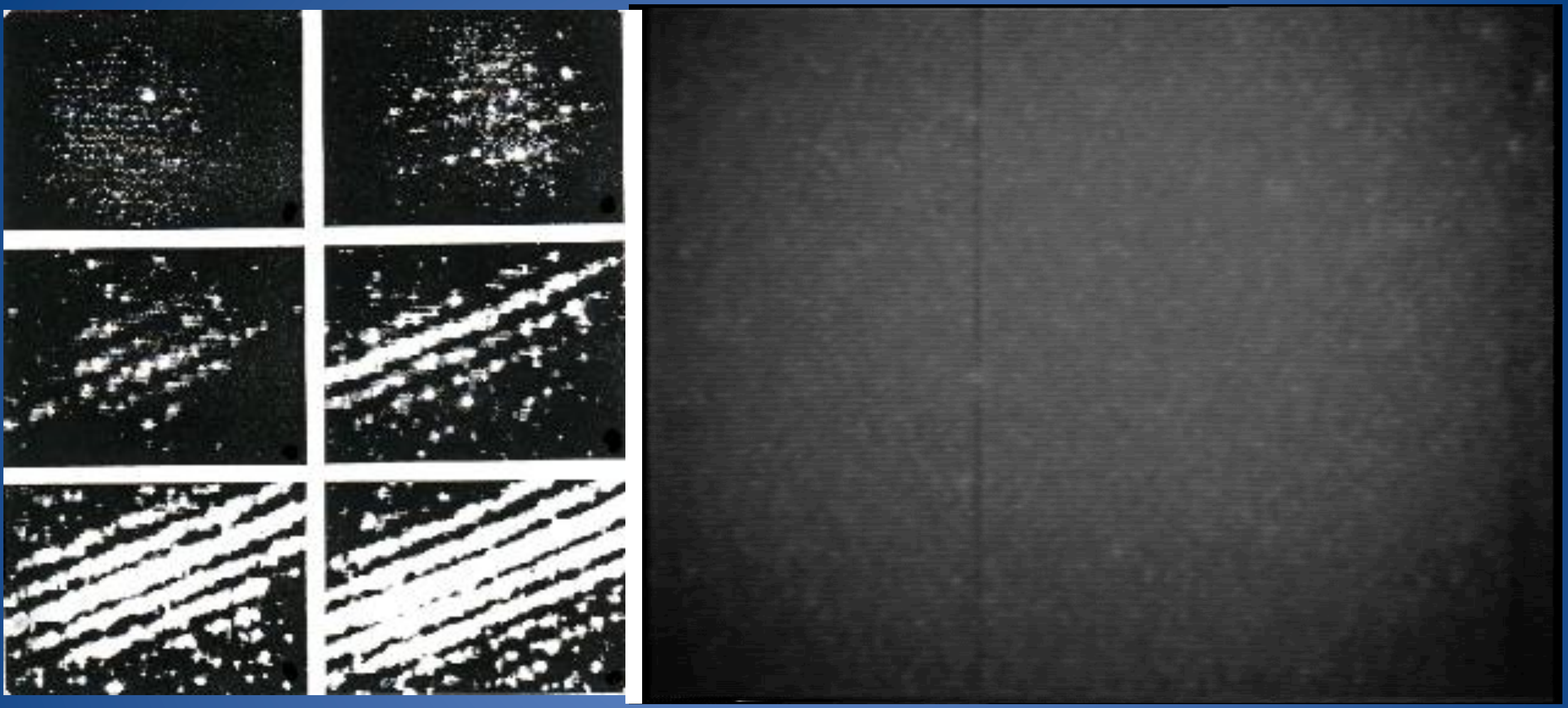


K.H. Hermann (Siemens) image intensifier (1971)



the last step: the single electron detector

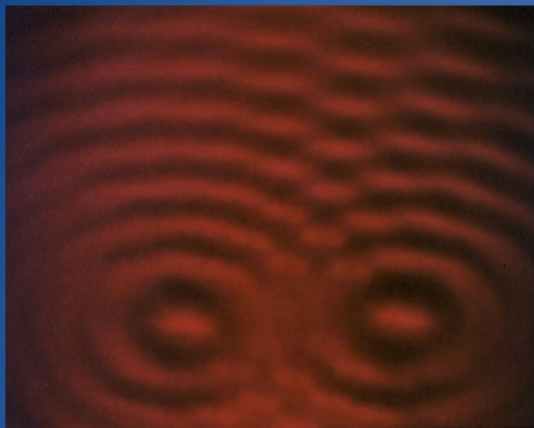
Merli Missiroli Pozzi experiment (1974-1976)

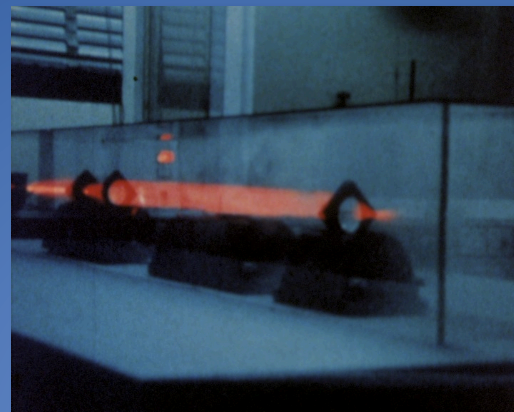


TEM + biprism + single electron detector

the first interference experiment where single electrons are visualized : the most beautiful experiment! *(Physics World 2002)*

1976: The movie "Electron Interference"



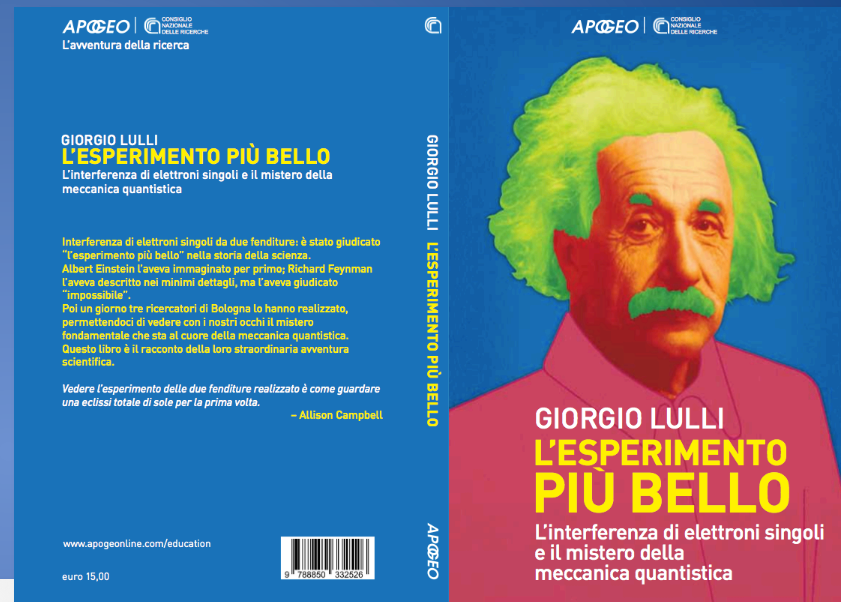


Gold medal for physics at the International Scientific Film Festival - Brussels 1976

more info on the most beautiful experiment and its story

dal 2009

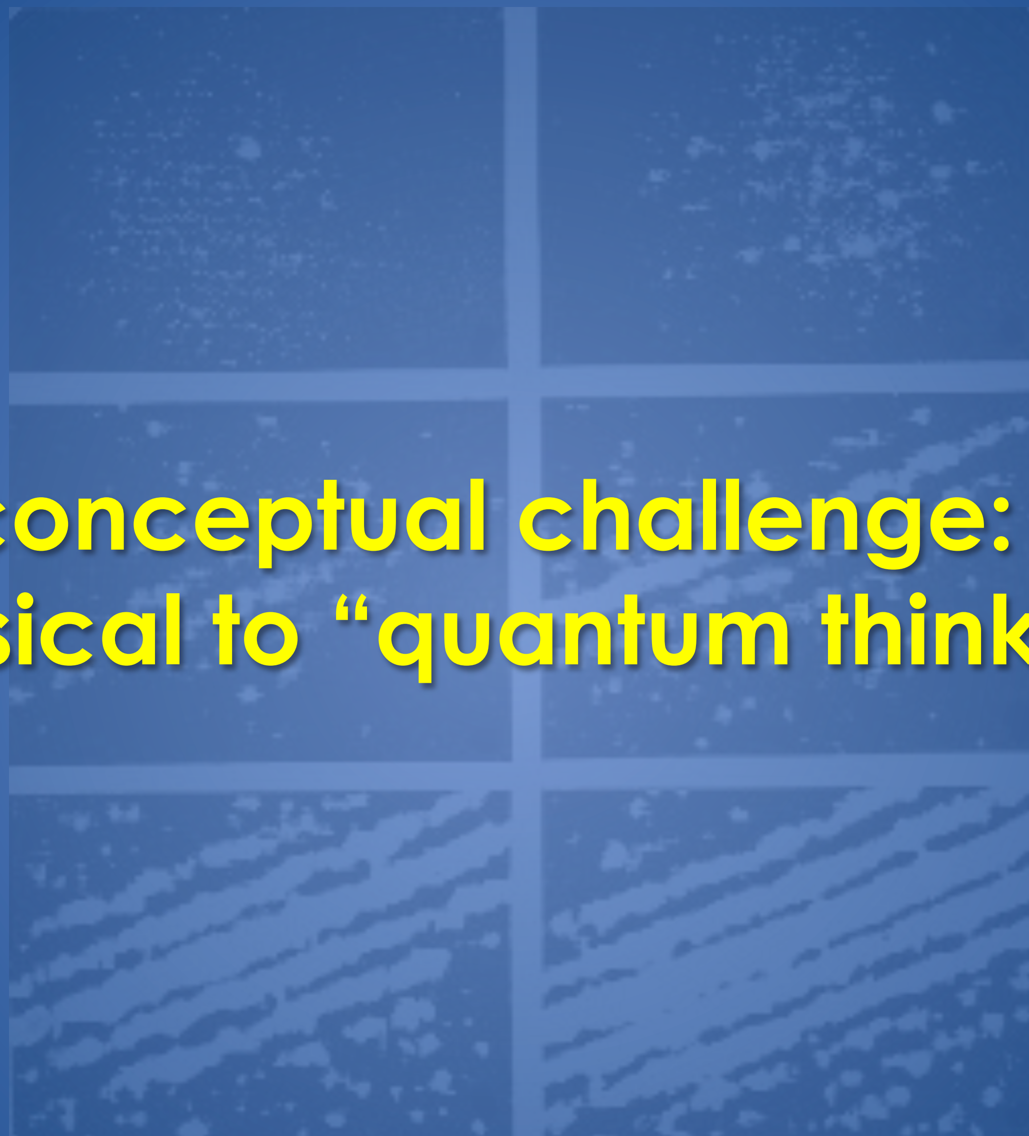
2010



2013

Materials related to this presentation (pdf slides and embedded movies):

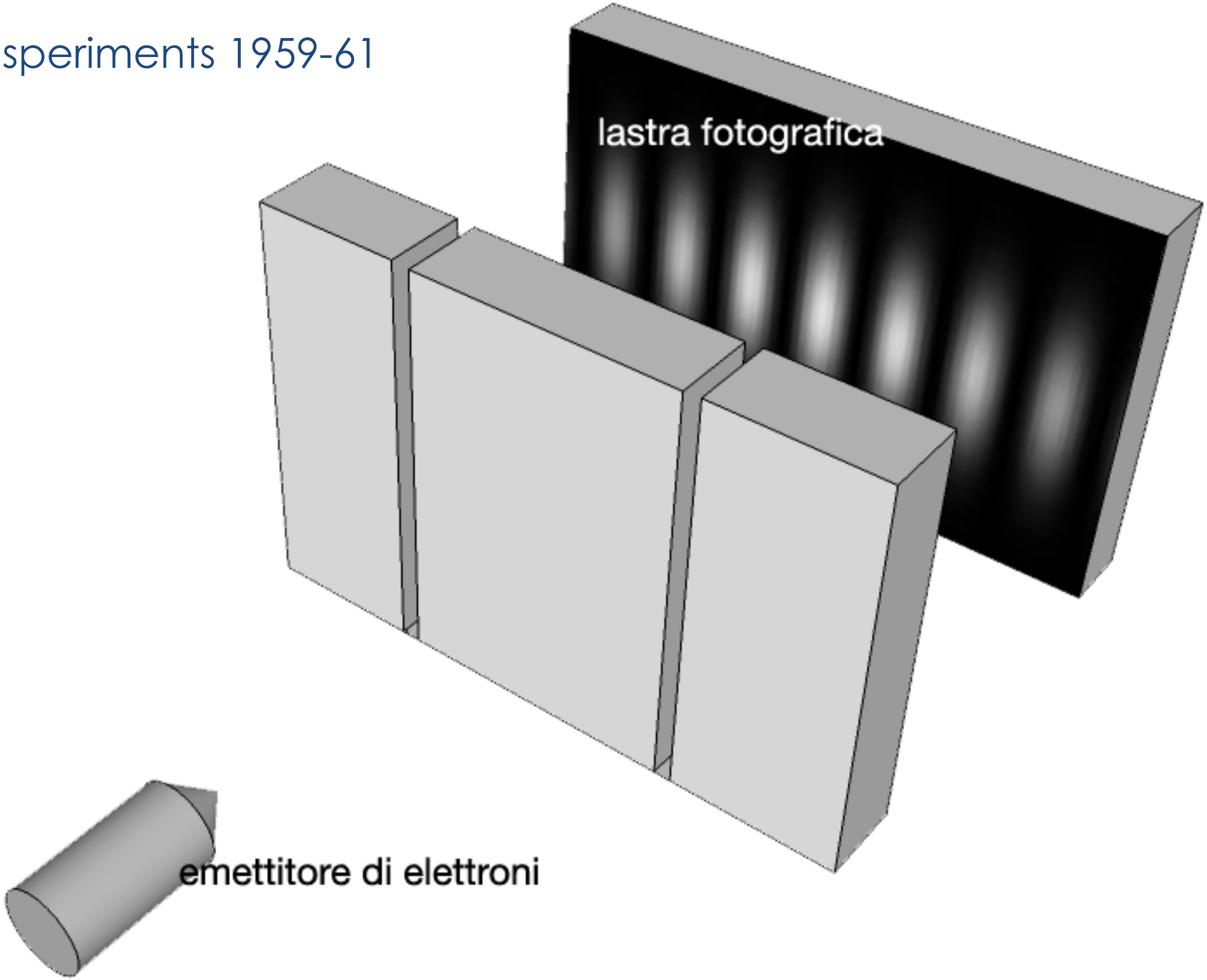
http://l-esperimento-piu-bello-della-fisica.bo.imm.cnr.it/didattica/materialeldr.html



The conceptual challenge: from classical to “quantum thinking”

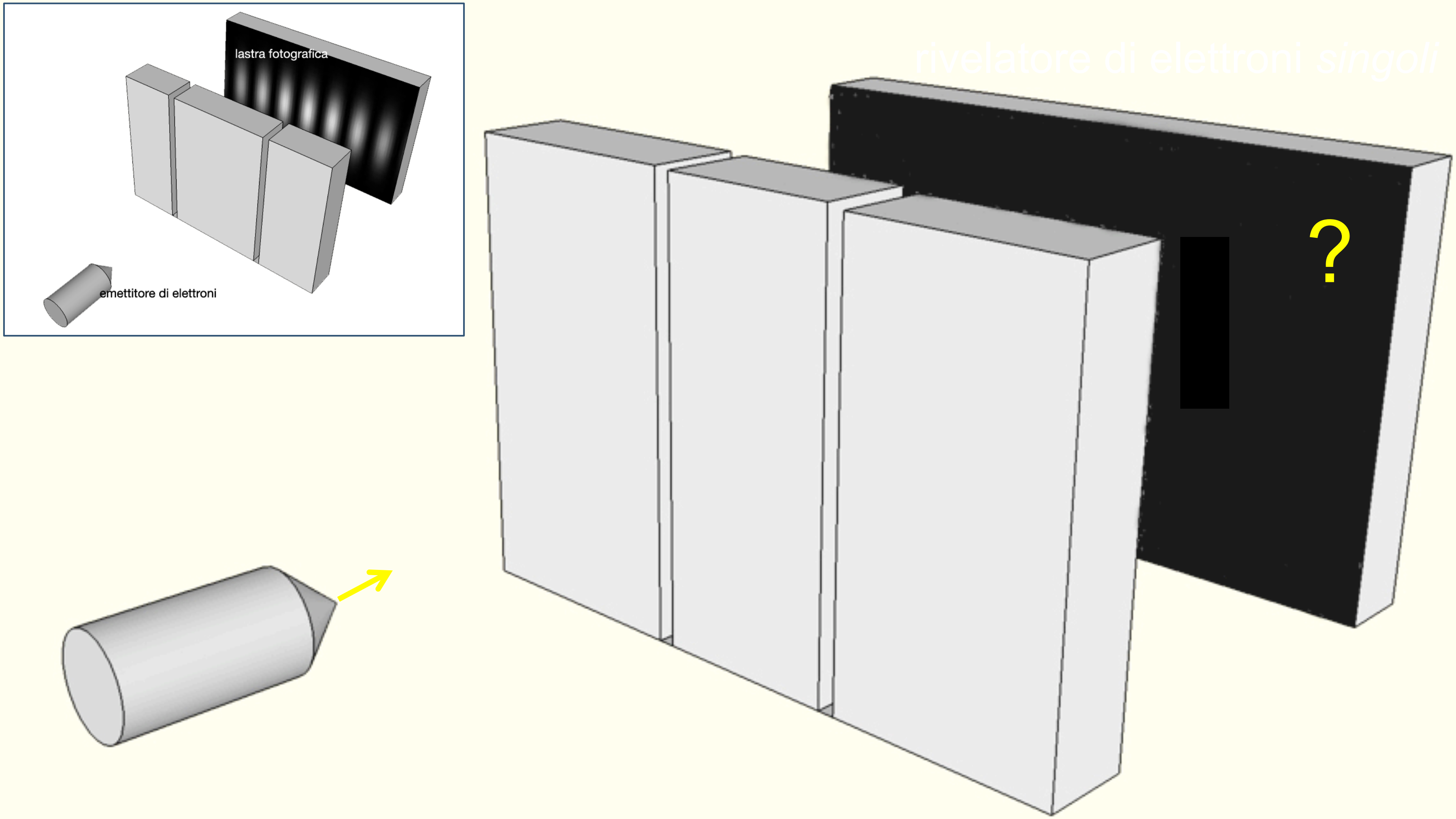
case 4: high *intensity* electron beam on a photographic plate

(*) esperiments 1959-61



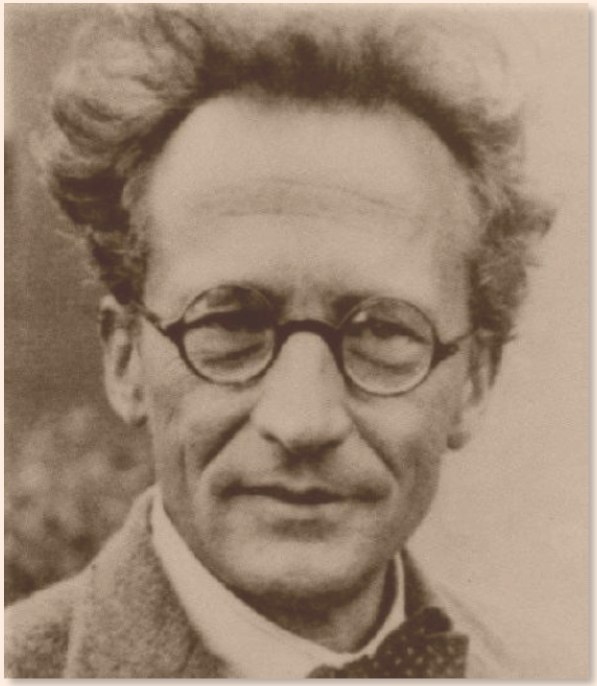
apparently ***wave*** behavior ... **are electrons waves**?

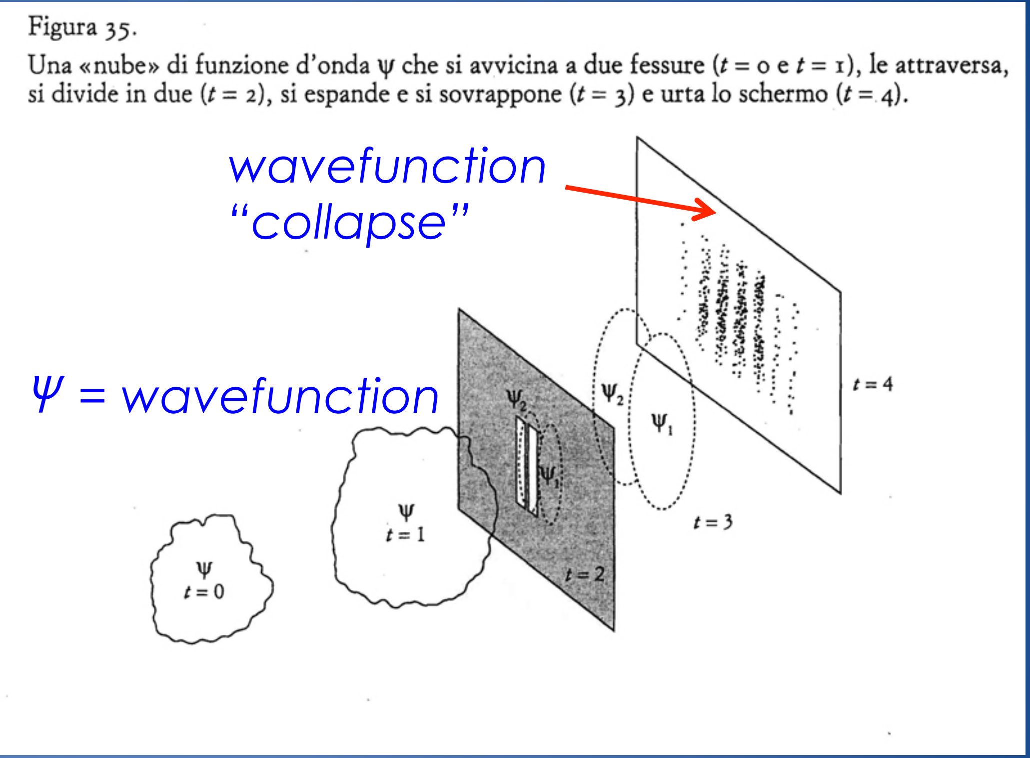
case 5: very weak electron beam (*one electron at a time*)



we observe a single point impact, *not* a weak interference pattern

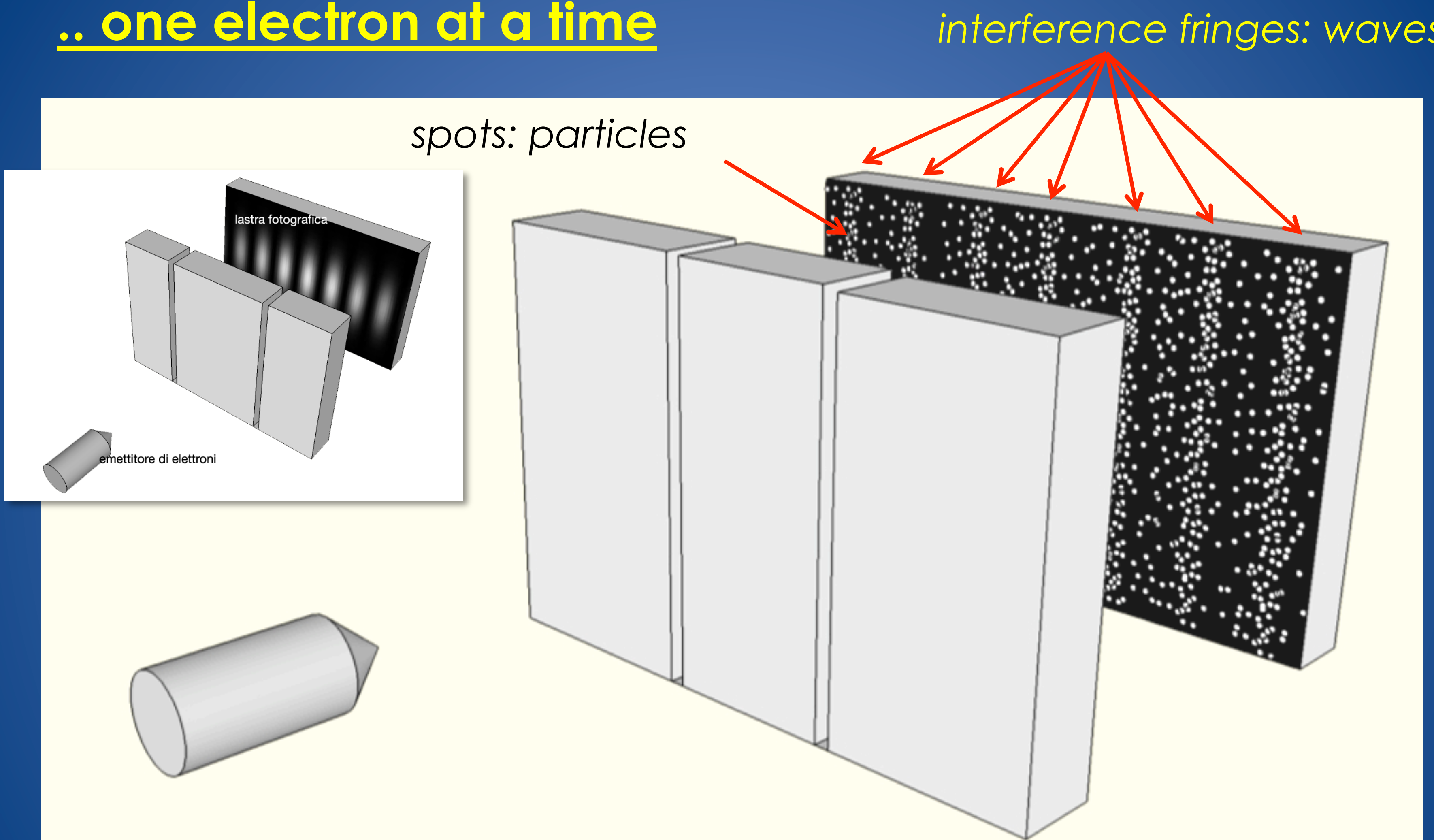
E. Schrödinger: electron = wave





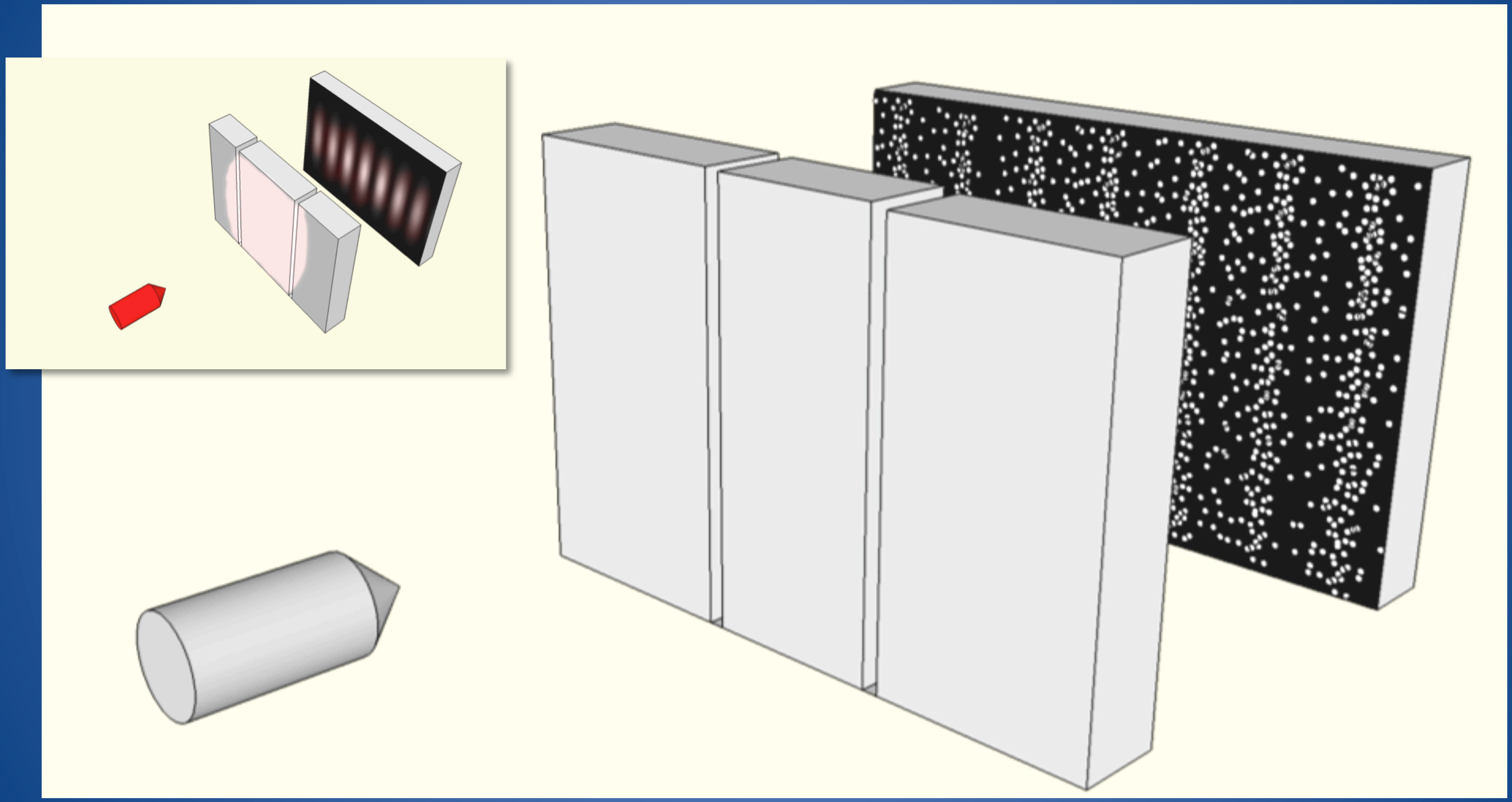
The hypothesis of an extended electron-wave spanning both slits, requires that such a wave collapses ***instantaneously*** into a single point when reaching the detector ...

.. one electron at a time



particle like impacts.. but distributed as in wave interference

<u>an effect which can't be due to the *interaction* among different electrons</u>



a very weak light beam (one photon at a time):
same result!

Single photon intererence (Jacques *et al.* 2005)

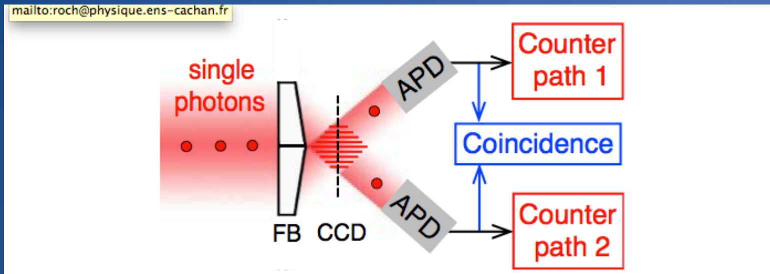


Fig. 1. Wavefront-splitting set-up based on a Fresnel's biprism (FB). APDs are avalanche silicon photodiodes operating in photon counting regime. An intensified CCD camera (dash line) records interference fringes in the overlapping region of the two deviated wavefronts. When the CCD is removed, it is then possible to demonstrate the single photon behaviour by recording the time coincidences events between the two output channels of the interferometer.

V. Jacques et al. *Single photon wavefront splitting interference* Eur. Phys. J. D 35, 561–565 (2005)

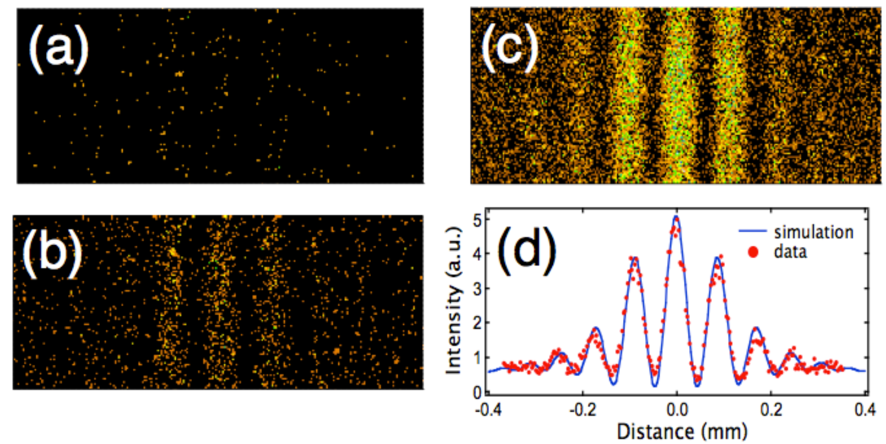


Fig. 4. Observation of the interference pattern expanded by the eyepiece and recorded by the intensified CCD camera. Image (a) (resp. (b) and (c)) is made of 272 photocounts (resp. 2240 and 19773) corresponding to an exposure duration of 20 s (resp. 200 s and 2000 s). Graph (d) displays the resulting interference fringes obtained by binning columns of CCD image (c) and fit of this interference pattern using coherent beam propagation in the Fresnel diffraction regime, and taking into account the finite temporal coherence due to the broad spectral emission of the NV colour centre. A visibility of 94% can be associated to the central fringe.

Thermal neutron interference (Zeilinger *et al.* 1988)

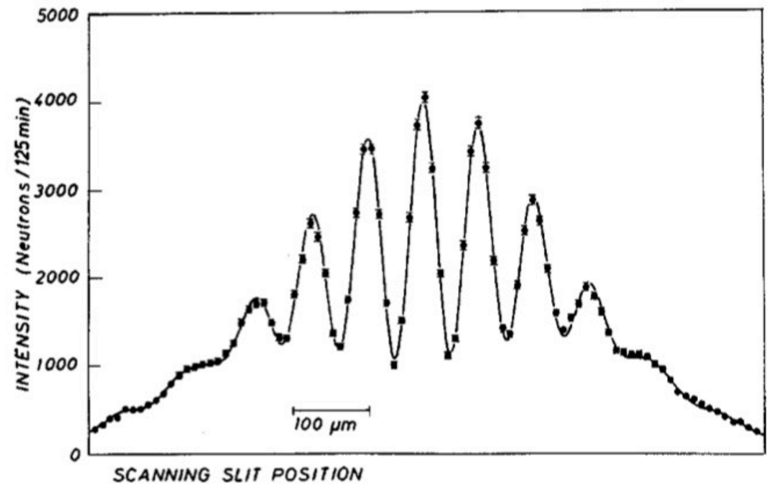


FIG. 1. A double-slit diffraction pattern measured with very cold neutrons with a wavelength of 2 nm corresponding to a velocity of 200 ms^{-1}. The two slits were 22 μm and 23 μm wide, respectively, separated by a distance of 104 μm. The resulting diffraction angles were only of the order of 10 μrad, hence the observation plane was located 5 m downstream from the double slit in order to resolve the interference pattern. (For experimental details see Zeilinger *et al.*, 1988.) The solid line represents first-principles prediction from quantum mechanics, including all features of the experimental apparatus. For example, the fact that the modulation of the interference pattern was not perfect can fully be understood on the basis that a broad wavelength band had to be used for intensity reasons and the experiment was not operated in the Fraunhofer regime.

mass = **1** AMU
v = 200 ms^{-1}
$\lambda_{neutroni}$ = 2 nm

λ = h/mv

slit spacing d = 104 μm
(slit aperture 22 μm)

fringe's visibility criterion:
$\lambda D/d$ = 0.1 mm

↓

slits-detector distance D = **5 m**

C_{60} single molecule interference (Arntd *et al.* 1999)

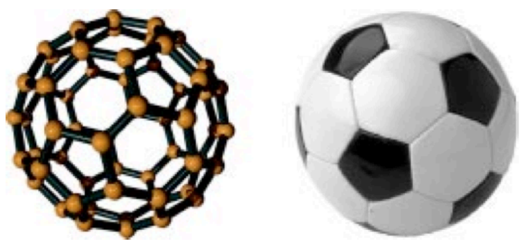
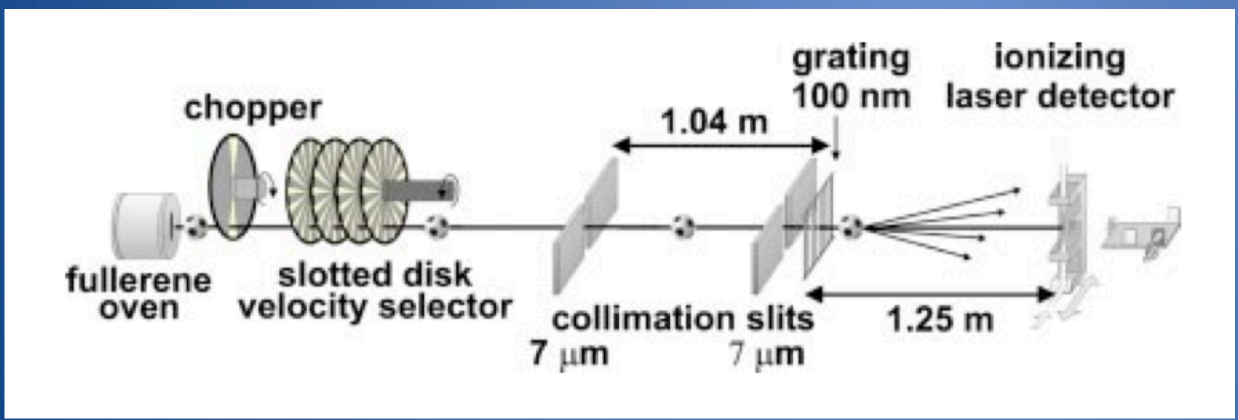


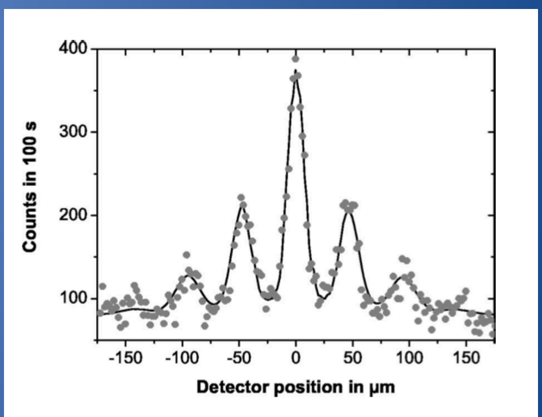
Fig. 2. The fullerene molecule C_{60}, consisting of 60 carbon atoms arranged in a truncated icosahedral shape, is the smallest known natural soccer ball.

mass = **720** AMU

v $\simeq$ 200 ms^{-1}

λ = 0.0028 nm





d = 100 nm (slit aperture 50nm)

slits-detector distance = 1.25 m

Single ($C_{32}H_{18}N_8$ and $C_{48}H_{26}F_{24}N_8O_8$) molecule interference (Juffmann et al. 2012)

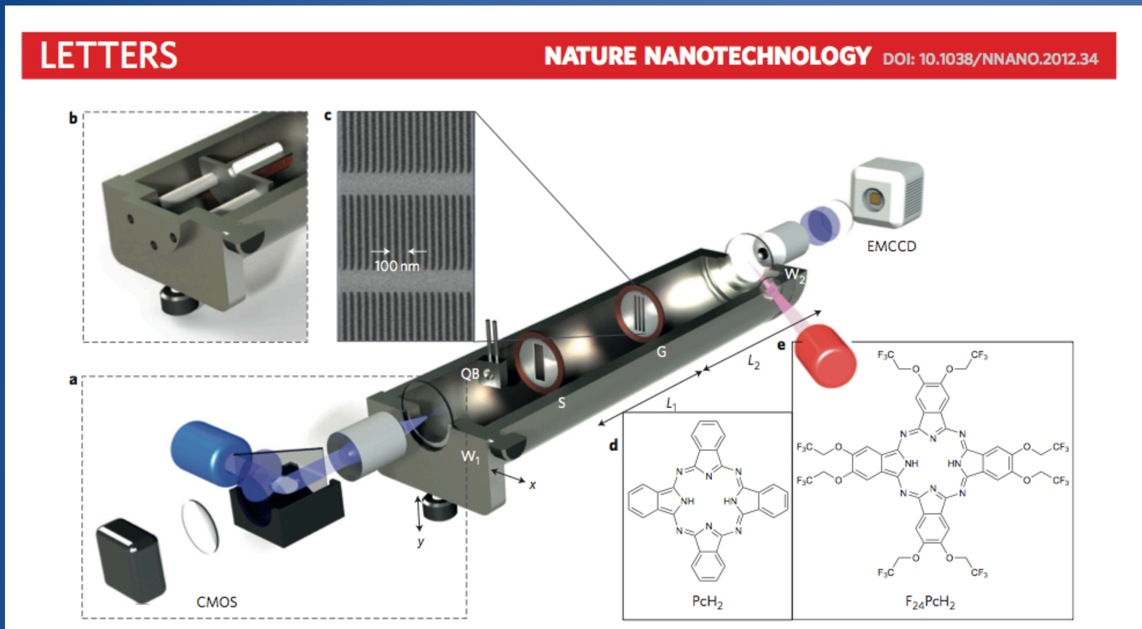
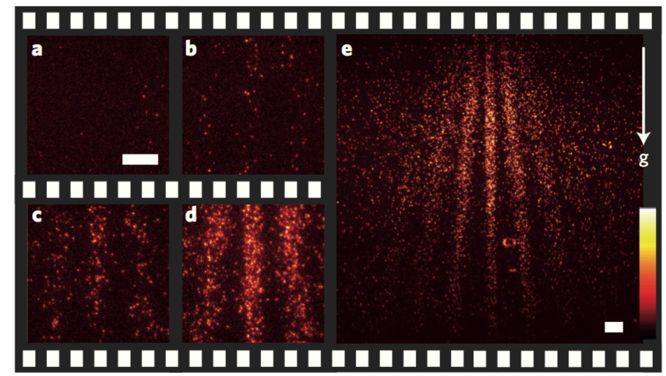


Figure 1 | Set-up for laser-evaporation, diffraction and nano-imaging of complex molecules. a, Thermolabile molecules are ejected by laser micro-evaporation. A blue diode laser (445 nm, 50 mW) is focused onto window W_1 to evaporate the molecules coated on its inner surface. A CMOS camera and a quartz balance (QB) monitor the evaporation area and the molecular flux. **b,** Stable molecules can be evaporated in a Knudsen cell. The collimation slit S defines the beam coherence. The molecular beam divergence is further narrowed by the width of the diffraction grating G. **c,** Electron micrograph showing that the grating is nanomachined into a 10-nm-thin SiN_x membrane with a period of $d = 100$ nm. The vacuum system is evacuated to 1×10^{-8} mbar. Molecules on quartz window W_2 are excited by a red diode laser (661 nm). High-resolution optics collects, filters and images the light onto an EMCCD camera. **d,e,** The molecules for this study: phthalocyanine PcH_2 ($C_{32}H_{18}N_8$, mass $m = 514$ AMU, number of atoms $N = 58$, **d**) and its derivative $F_{24}PcH_2$ ($C_{48}H_{26}F_{24}N_8O_8$, $m = 1{,}298$ AMU, $N = 114$, **e**). The mass, atomic number and internal complexity of $F_{24}PcH_2$ are approximately twice those of PcH_2.



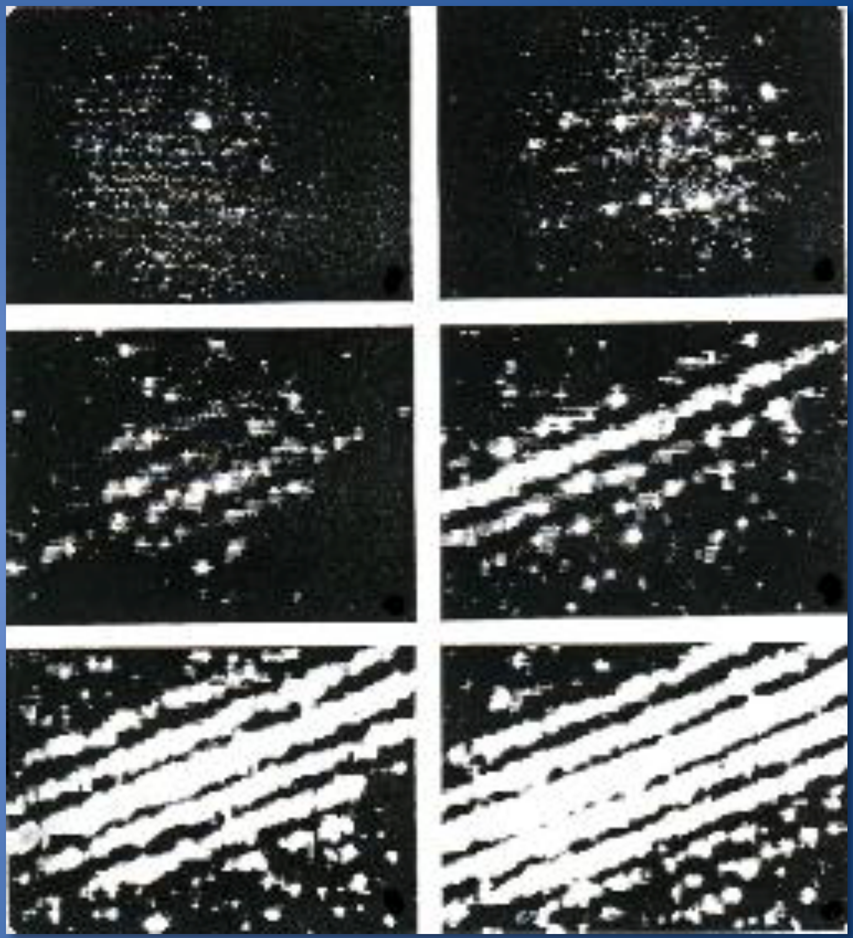
masses
514 AMU, **1298** AMU

v $\simeq$ 150 ms^{-1}
λ = 0.0052 nm
d = 100 nm (slit aperture 50nm)

slits-detector distance ~ 0.5 m

Some remarks on the MMP experiment

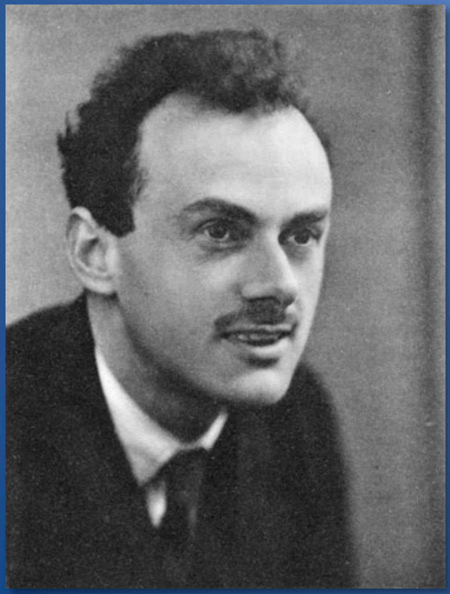
1. every single electron/ phonon ... is always detected as a ***particle***
2. its arrival point at the screen is unpredictable – i.e. the single electron behavior is not deterministic
3. ***fringes*** are clearly recognizable only after many (>1000) single impact events: they appear to be a ***statistical*** effect of the behavior of many electrons
4. the ***probability*** of an electron to hit a particular point of the screen is predictable and has the mathematical form of the fringe's intensity observed in a classical wave interference



Here we don't have a classical wave (material or electromagnetic) but a *"probability wave"*

Single electron: *what* interferes with *what*?

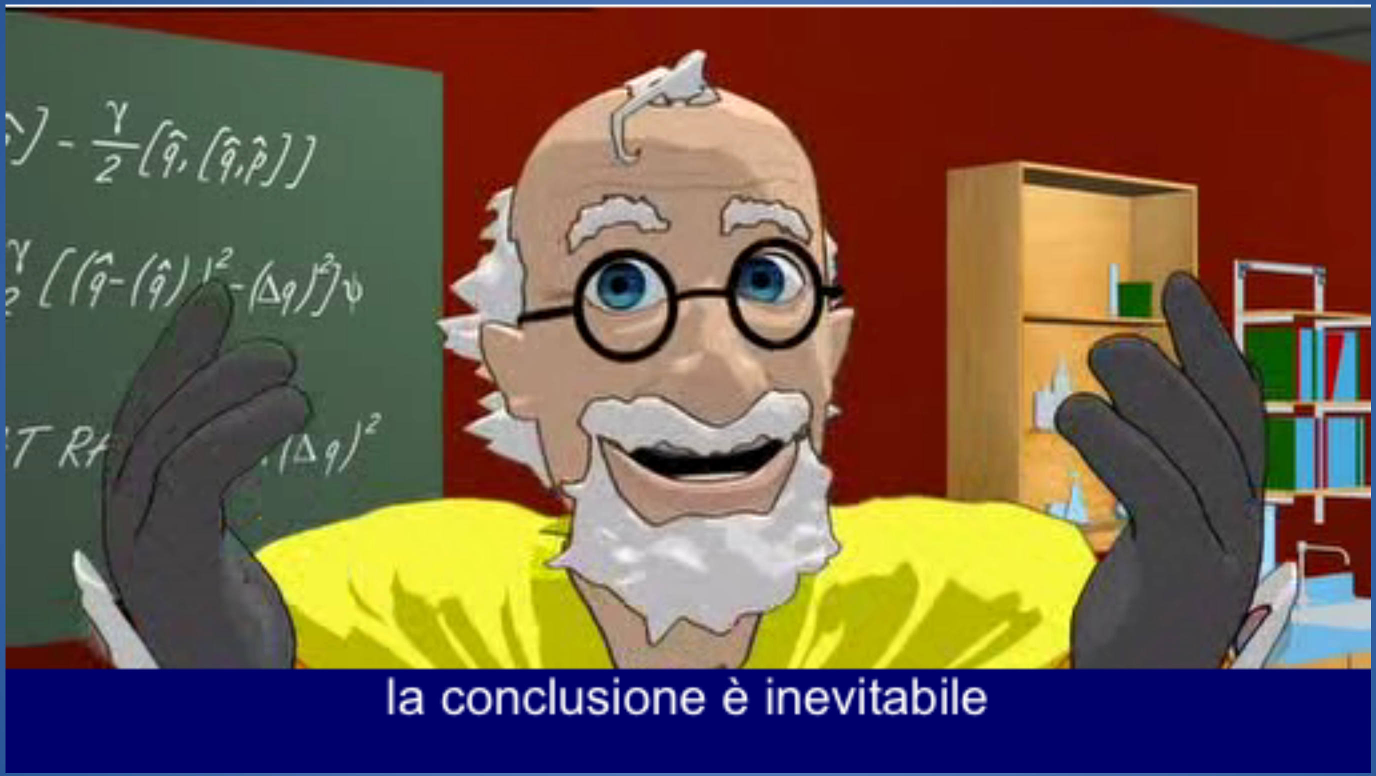
- classically, to interfere we need at least ***two*** wave sources/wavefronts
- here we shoot ***a single*** electron/photon at a time



"every photon [or electron] interferes with itself"

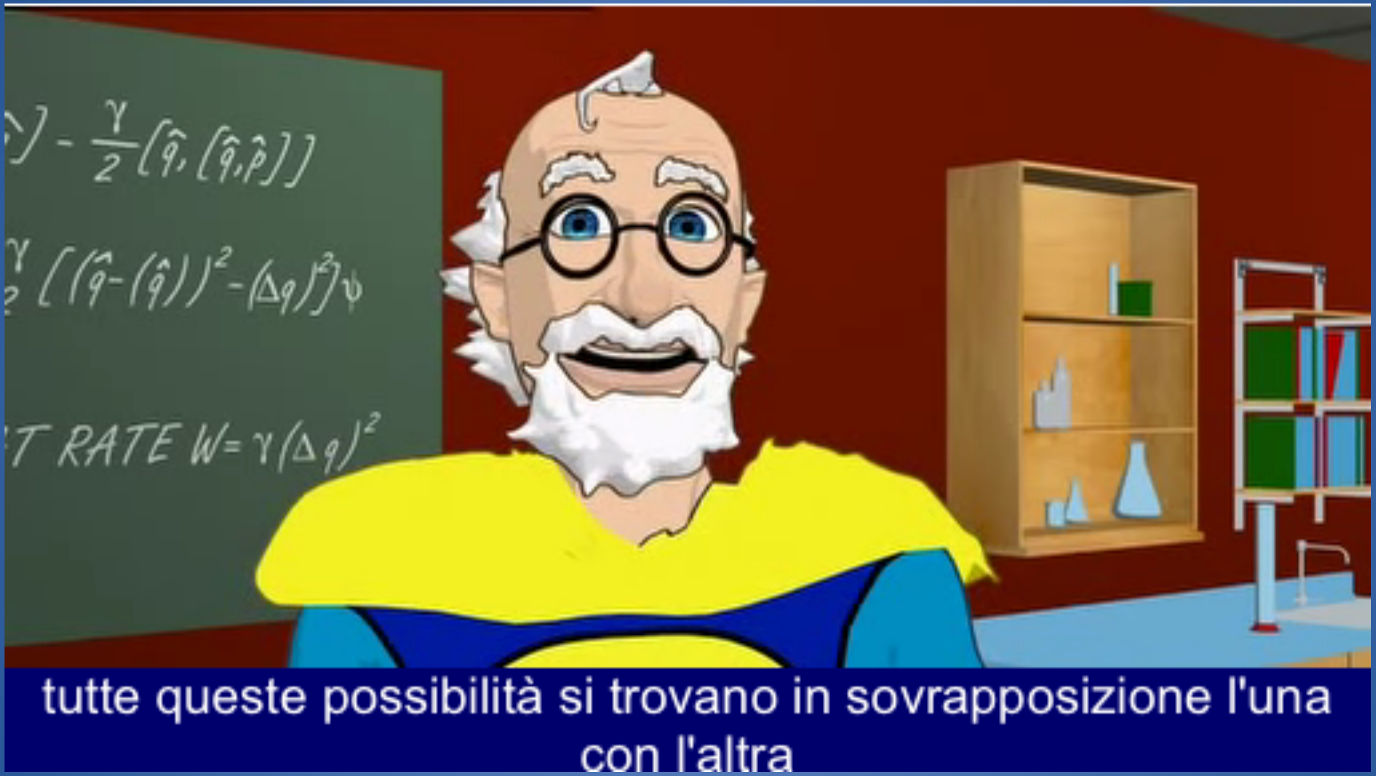
Paul A. M. Dirac *The principles of Quantum Mechanics* (Boringhieri, 1959) p.13

A“naive” way to visualize this effect...

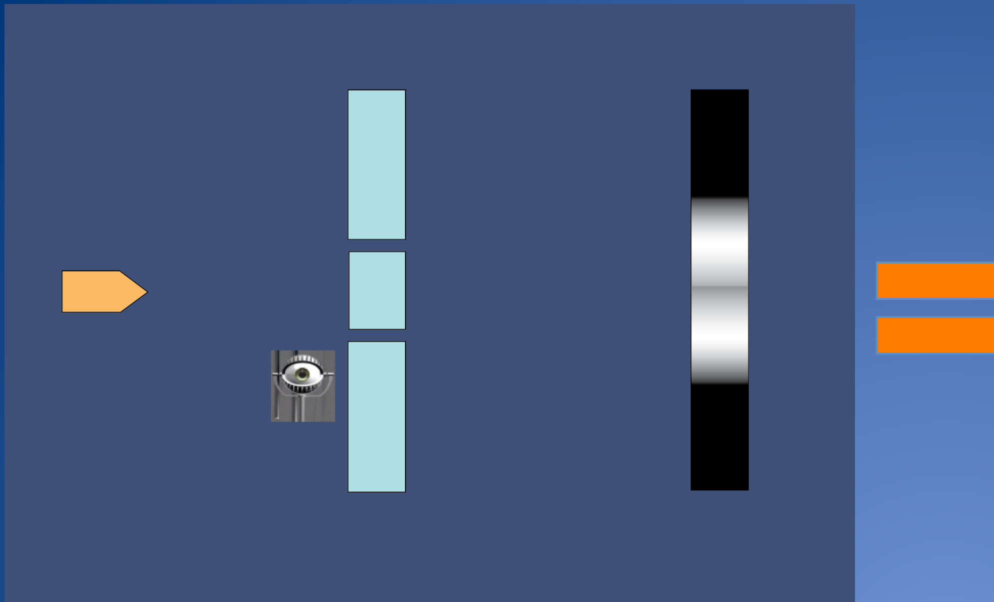


Dr. Quantum (*The infaumous double slit experiment* - YouTube)

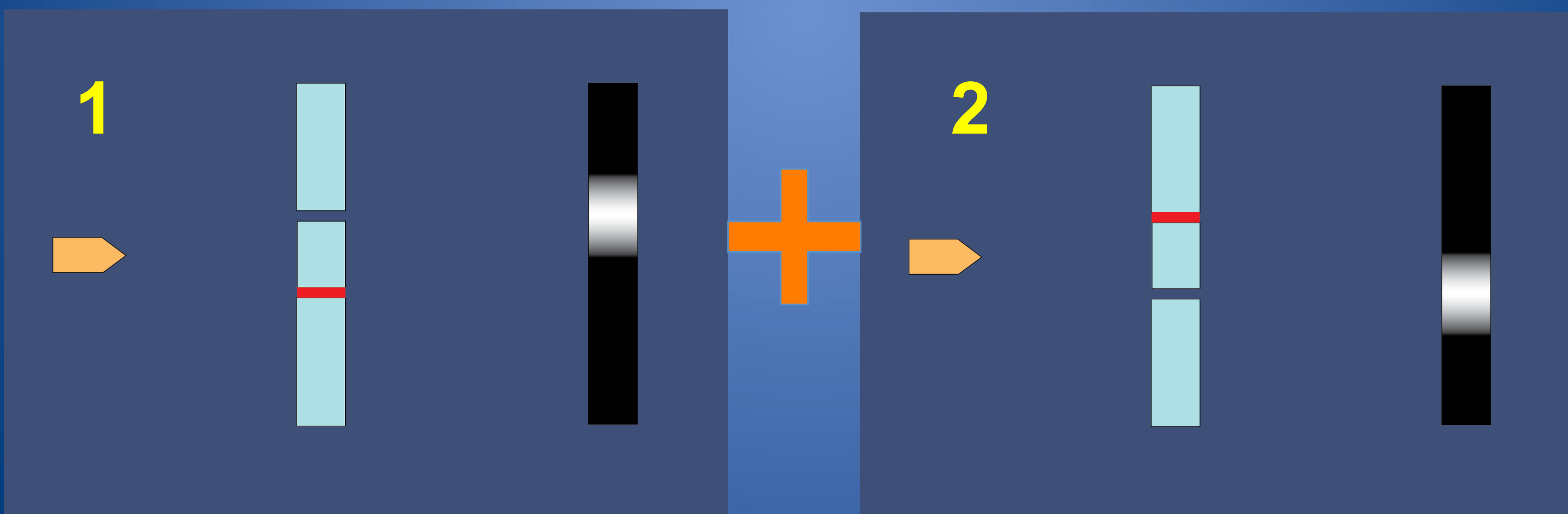
Which path? (or ***which way?*****)**



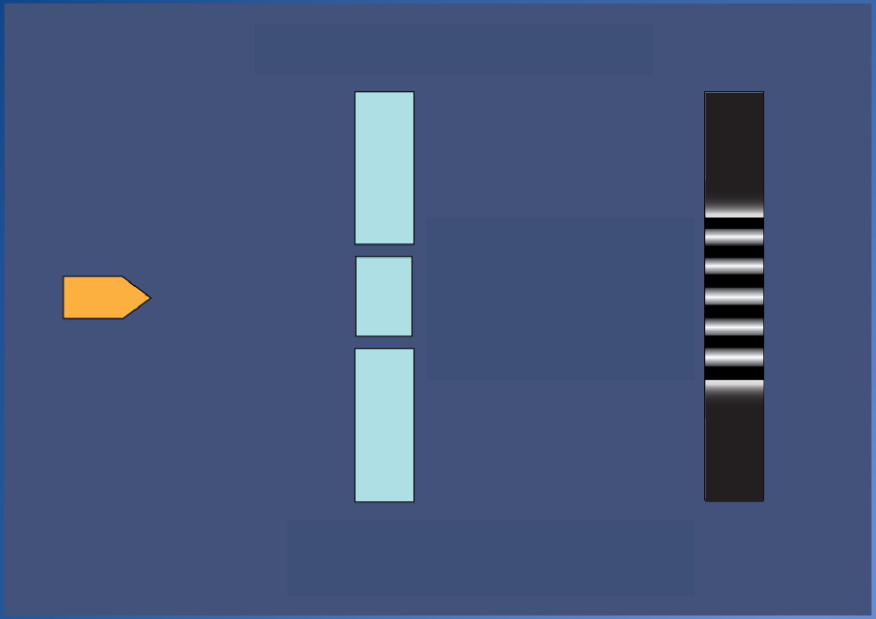
Dr. Quantum (*The infaumous double slit experiment* - YouTube)



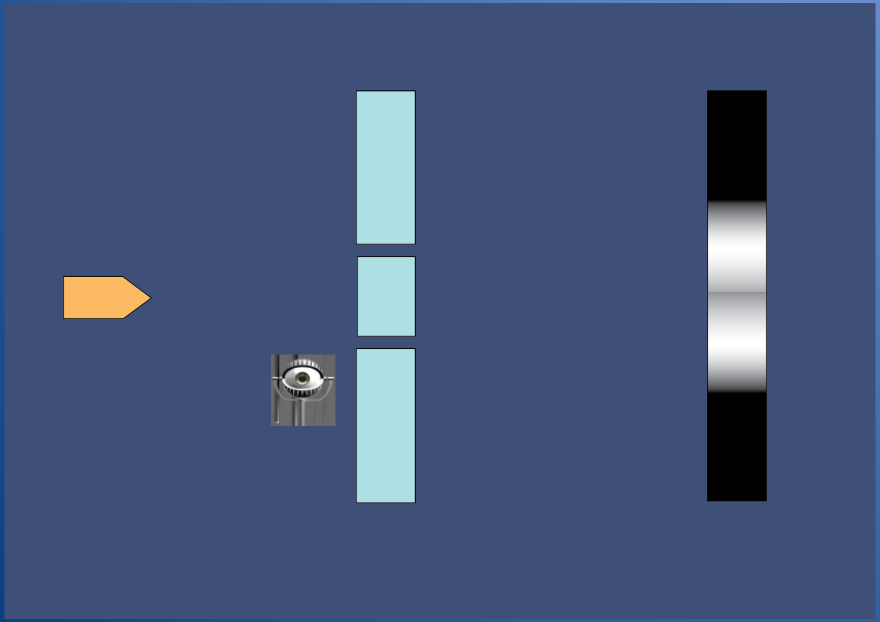
the figure is the sum of the intensity patterns of the two slits, treated ***<u>individually</u>*** ...



Summarizing:



no which path information
⇒ interference



which path information
⇒ no interference

Important!

if we use an apparatus which measures the passage through both slits we always observe the electron going through *one slit* *<u>or</u>* *the other*:

we never observe something like an electron which splits to go through both slits!

the effect is NOT DUE to the experimental “disturbance”

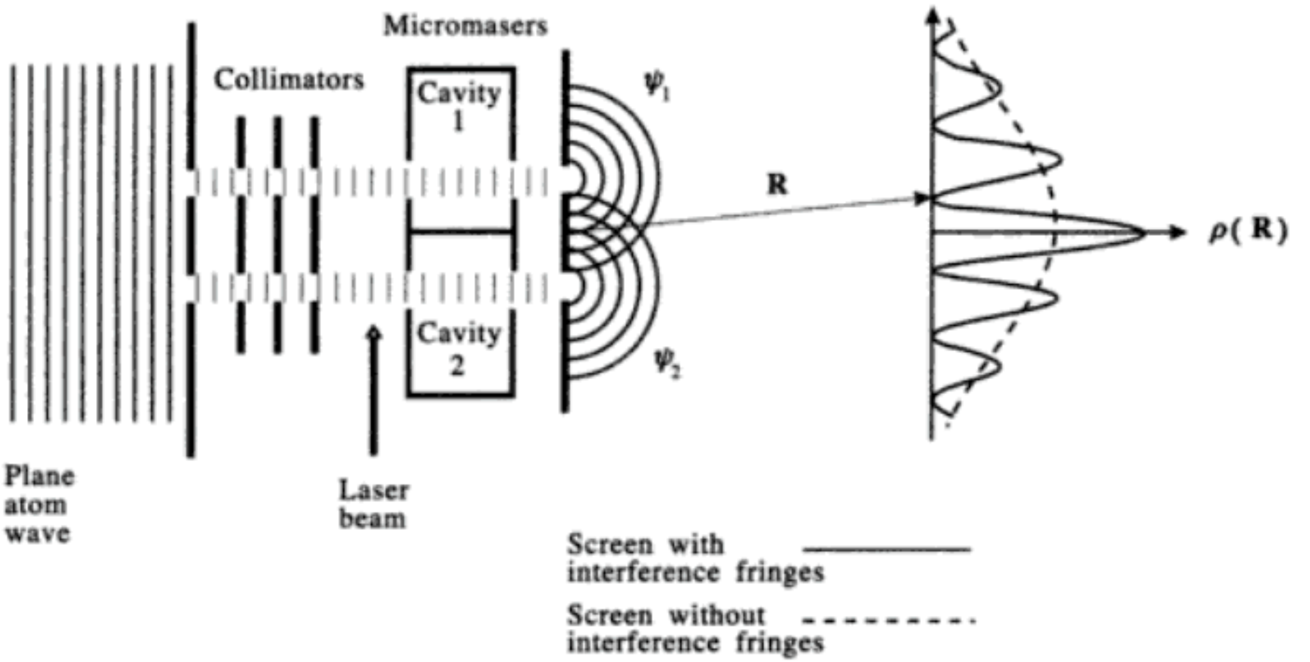
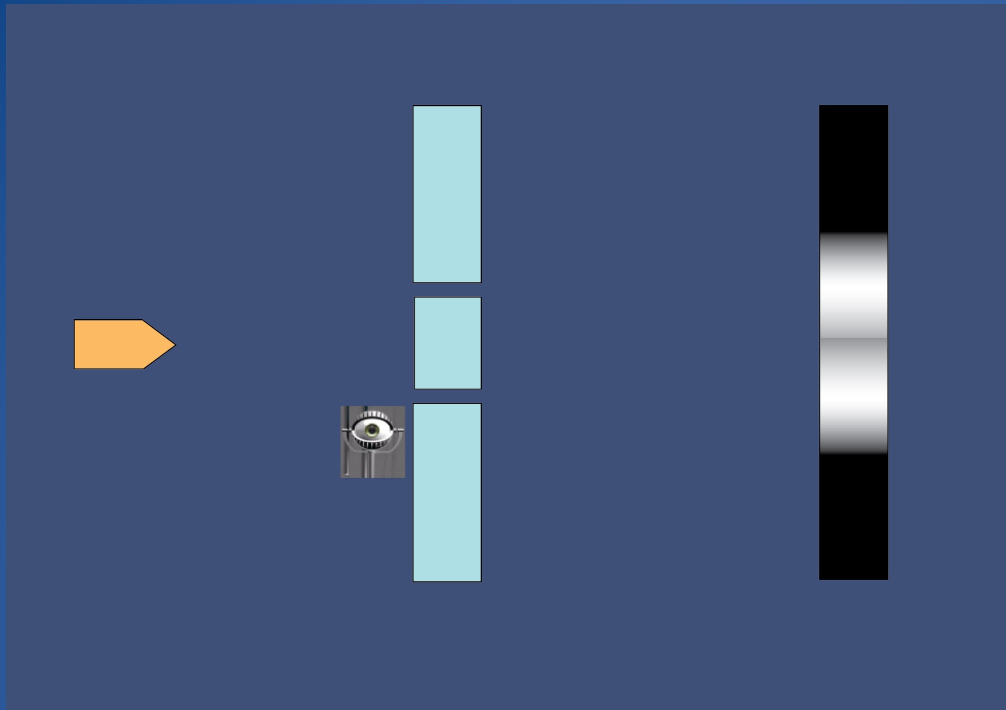
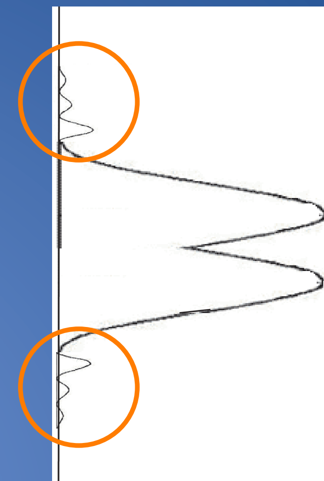
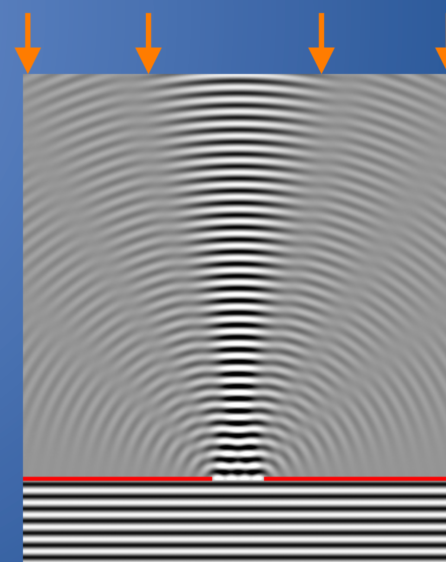


Fig. 20.3
Schematic diagram of the double-slit experiment with atoms. (From M. O. Scully, B.-G. Englert, and H. Walther, *Nature* **351**, 111 (1991).)

Schematic of a conceptual atom interference experiment of *Scully et al*. (1991) in which the determination of which way information induces a negligible momentum variation of the measured atom.
A real experiment inspired to this one was made in 1998 (*Durr et al. Nature, 395, 33, 1998*)







Important: it is wrong to say that in this case electrons behave as classical particles. We still observe intensity oscillations due to the *diffraction* of electrons from each single slit.

NO dualism classical-particle/quantum-wave

What interferes with what?

Not classical objects – such as matter or e.m. waves - but rather abstract entities, such as "***potential" paths (or alternatives)***. Are these entities which superimpose, giving origin to quantum interference (*the meaning we can attribute to the Dirac statement*).

An apparatus capable of measuring which-way information prevents interference, because now, for each electron, only one possible path is *actually* observed, only one alternative occurs.

The disappearance of interference is *not* due to the disturbance induced by the measuring apparatus!!

Interference of “alternatives”

The ***interference of alternatives*** is characteristic of quantum systems; classical alternatives do not interfere. (**B-G. Englert** *“Remarks of some basic issues in quantum mechanics”*)

[...] regardeless of the quantum system, any information – recorded or not – about the alternative taken by a quantum process capable of following more than one alternative, destroys the ***interference between alternatives***. (**R. Feynman, A. R. Hibbs** *“Quantum mechanics and path integrals”*)

Single electron interference may be considered as a prototype of a *two-state quantum system*

state 1 : electon going through slit 1
state 2 : electon going through slit 2

the state of the (*unobserved*) electron is the ***superposition*** of **state 1** and **state 2,** i.e. 1 <u>and</u> 2

if the electron is *observed,* the superposition ***collapses*** into one of the two states, i.e.1 <u>or</u> 2

The validity of the superposition principle in quantum physics is due to the linearity of quantum physics equation (*Schrödinger eqn.*).

Summarizing

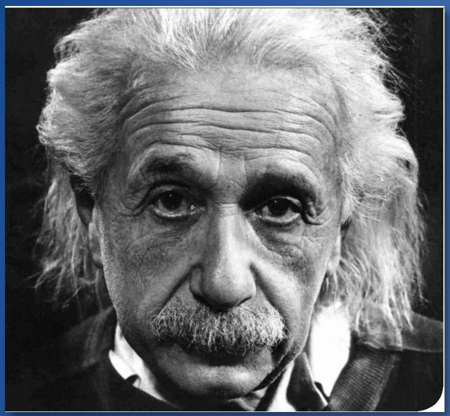
- In a system offering more than one alternatives, the state of the single electron/photon is ***undefined***, and described by the ***superposition*** of all possible alternatives (***states***). Quantum interference is the consequence of ***superposition of alternatives*** (***states***).

- What is defined is the ***probability*** of each alternative (state). This can be calculated exactly with quantum equations.

- The ***measurement*** "chooses" – in an *undeterministic* way! – one among the possible states, preventing superposition and, as a consequence, interference (***collapse***).

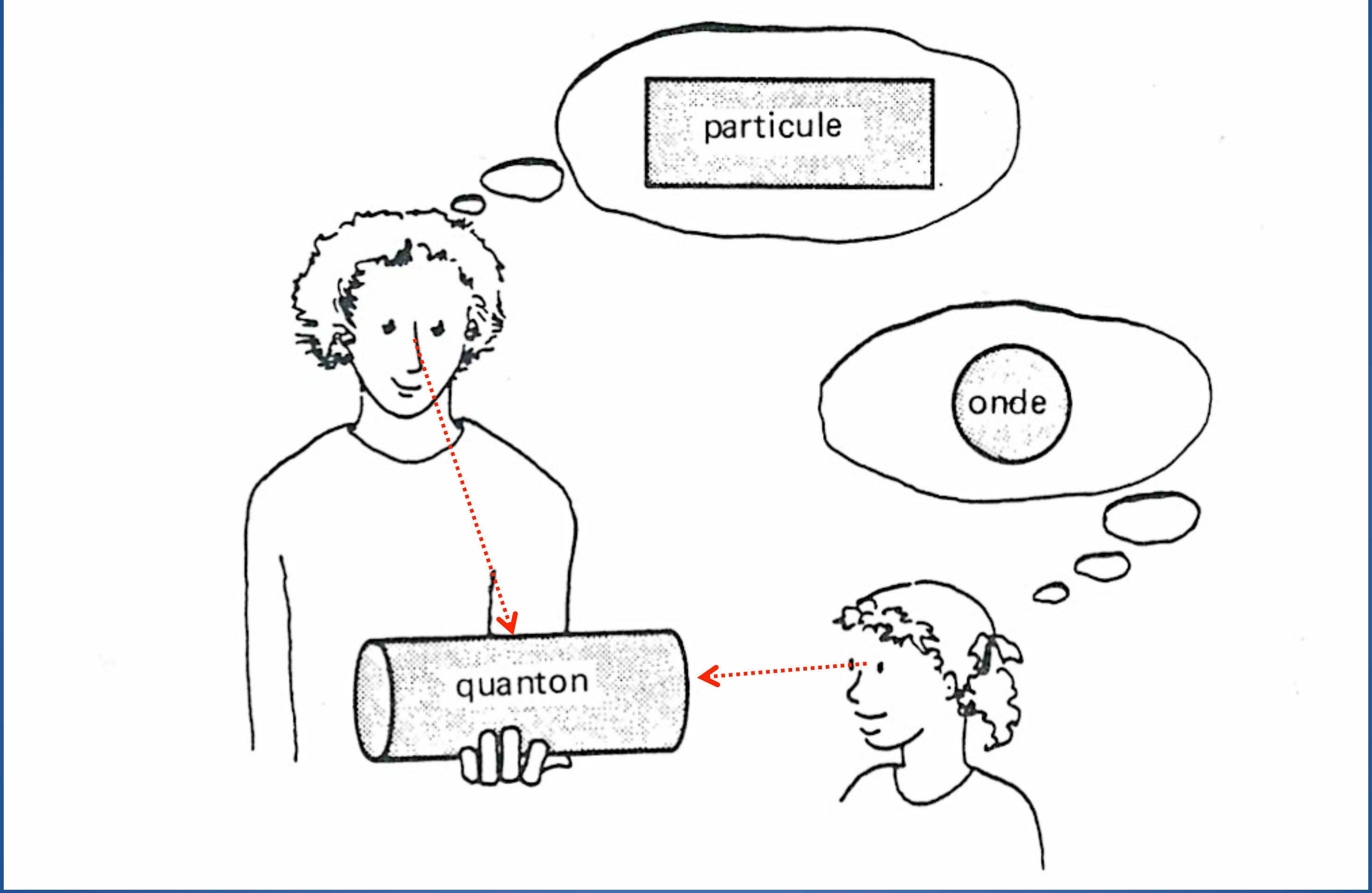
- The *measurement process*, even when not disturbing in appreciable way the quantum object, has a key role in collapsing all the possibilities into the one which is actually observed.

If all these quantum "oddities" puzzle you, you are in good good company ...



Some physicists, among them myself, cannot believe that we must abandon, actually and forever, the idea of *direct representation of physical reality in space and time*; or that we must accept the view that events in nature are analogous to a *game of chance*. Probably never before has a theory been evolved which has given a key to the interpretation and calculation of such a heterogeneous group of phenomena of experience as has quantum theory. In spite of this, however, I believe that the theory is apt to beguile us into error in our search for a uniform basis for physics, because, in my belief, ***it is an incomplete representation of real things***, although it is the only one which can be built out of the fundamental concepts of force and material points (quantum corrections to classical mechanics). *The incompleteness of the representation leads necessarily to the statistical nature (incompleteness) of the laws*. (***Albert Einstein***, *on Quantum Physics, 1954*)

Onda? Particella? ... No: “quantone” !



Jean-Marc Lévy Leblond, Francoise Balibar: *Quantique : Rudiments*

To be quantum-like....

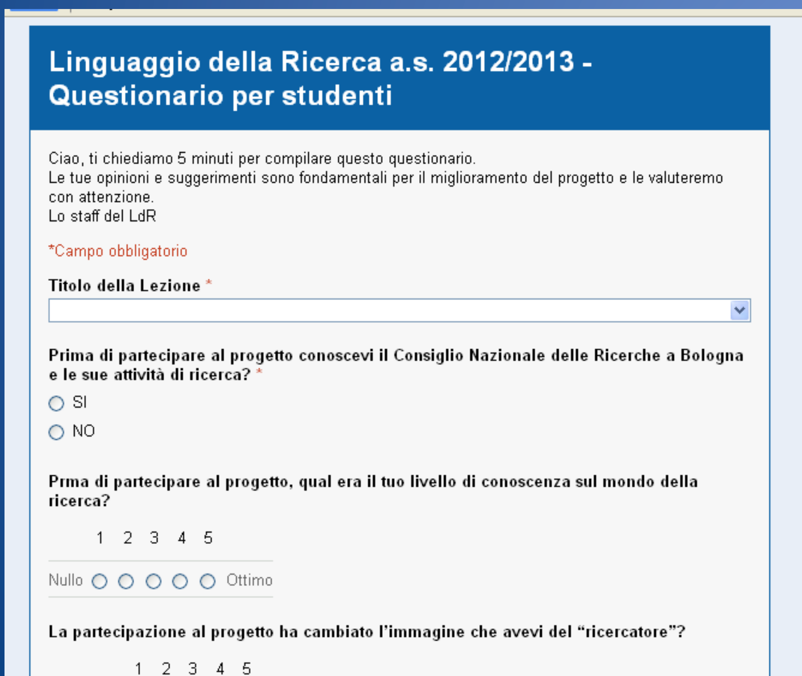
Y. Aharonov e D. Rohrlich "Quantum Paradoxes" (2005)

thanks for your attention!

Dopo la lezione: Feed-back On line

www.bo.cnr.it/linguaggiodellaricerca/

Per gli studenti



Linguaggio della Ricerca a.s. 2012/2013 - Questionario per studenti

Ciao, ti chiediamo 5 minuti per compilare questo questionario.
Le tue opinioni e suggerimenti sono fondamentali per il miglioramento del progetto e le valuteremo con attenzione.
Lo staff del LdR

*Campo obbligatorio

Titolo della Lezione *

Prima di partecipare al progetto conoscevi il Consiglio Nazionale delle Ricerche a Bologna e le sue attività di ricerca? *

SI

NO

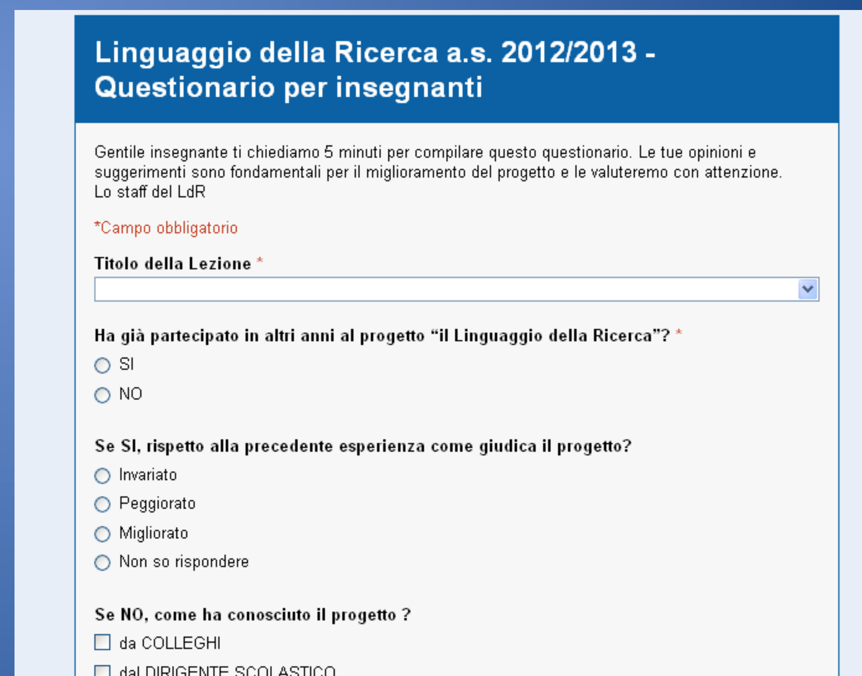
Prma di partecipare al progetto, qual era il tuo livello di conoscenza sul mondo della ricerca?

	1	2	3	4	5	
Nullo						Ottimo

La partecipazione al progetto ha cambiato l'immagine che avevi del "ricercatore"?

1 2 3 4 5

Per gli insegnanti



Linguaggio della Ricerca a.s. 2012/2013 - Questionario per insegnanti

Gentile insegnante ti chiediamo 5 minuti per compilare questo questionario. Le tue opinioni e suggerimenti sono fondamentali per il miglioramento del progetto e le valuteremo con attenzione.
Lo staff del LdR

*Campo obbligatorio

Titolo della Lezione *

Ha già partecipato in altri anni al progetto "il Linguaggio della Ricerca"? *

SI

NO

Se SI, rispetto alla precedente esperienza come giudica il progetto?

Invariato

Peggiorato

Migliorato

Non so rispondere

Se NO, come ha conosciuto il progetto ?

da COLLEGHI

dal DIRIGENTE SCOLASTICO

classe 4a Liceo Oriani – Ravenna (2013)

a nice example of creative elaboration of the subject