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Progetto di divulgazione scientifica

"Il Linguaggio della Ricerca"

www.bo.cnr.it/linguaggiodellaricerca/

Promosso dal **Consiglio Nazionale delle Ricerche** (CNR) e dall'**Istituto Nazionale di Astrofisica** (INAF)

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Creazione di un PRODOTTO INFORMATIVO SULL'ARGOMENTO approfondito in questo incontro

in 2 lingue
Inglese-italiano

PRESENTAZIONE
del Ricercatore

Approccio pubblicitario

Come realizzarlo? Usare un linguaggio semplice, ma scientificamente corretto, immagini, colori, disegni, titoli simpatici, etc…

prodotto
di comunicazione
che illustra l'argomento
trattato

CONCORSO

Tipologie di prodotti

Fumetti

Articolo giornalistico divulgativo

DEPLIANT

Siti web

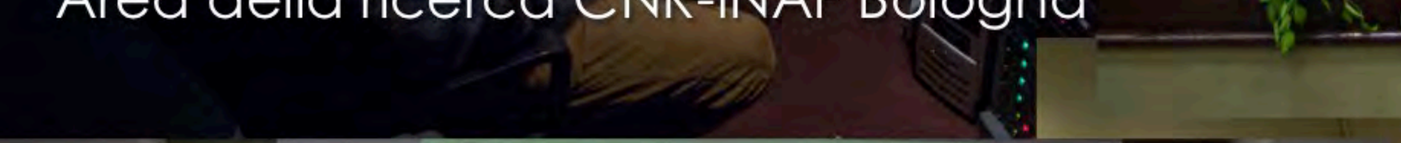
Filmati

Articolo giornalistico "specialistico"

Giornale

Poster

il linguaggio della ricerca
convegno 2013
Area della ricerca CNR-INAF Bologna



L'esperimento più bello

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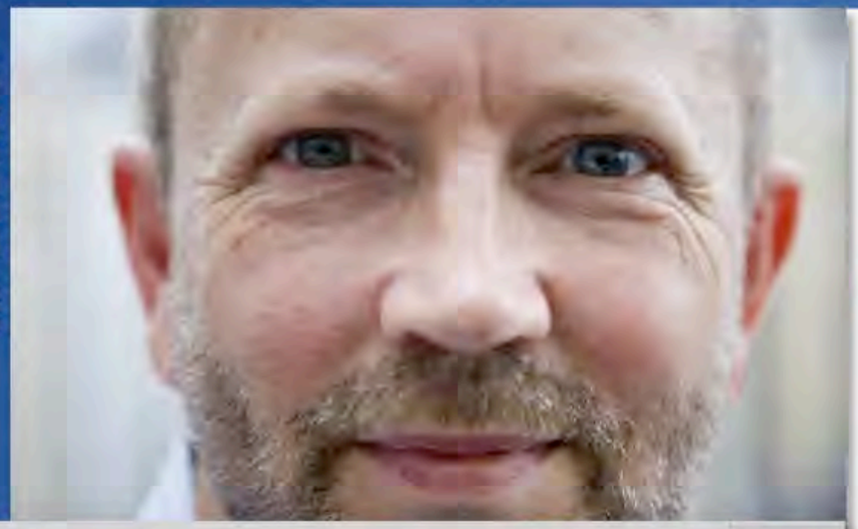
Consiglio Nazionale delle Ricerche
Istituto per la Microelettronica e i Microsistemi (CNR-IMM)
Bologna

Linguaggio della Ricerca - 2015

Perchè l'esperimento "più bello"?

R. Crease



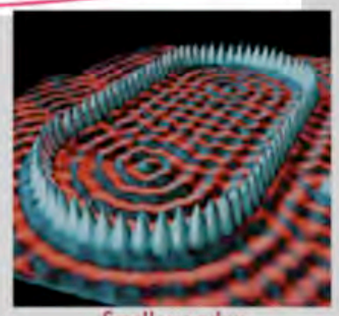
CRITICAL POINT **physicsworld**

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)

COMMENT: LETTERS

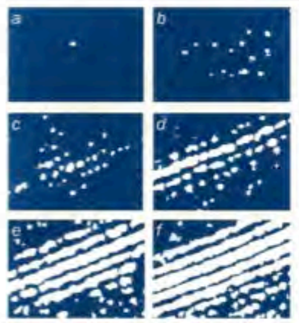
Letters to the editor can be sent by post to *Physics World*, Dirac House, Temple Back, Bristol BS1 6BE, UK, by e-mail to pwld@iop.org or by fax to +44 (0)117 925 1942. Please include your address and a daytime telephone number. We reserve the right to edit letters.

The double-slit experiment with single electrons

The article "A brief history of the double-slit experiment" (September 2002 p15; correction October p17) describes how Claus Jönsson of the University of Tübingen performed the first double-slit interference experiment with electrons in 1961. It then goes on to say: "The next milestone – an experiment in which there was just one electron in the apparatus at any one time – was reached by Akira Tonomura and co-workers at Hitachi in 1989 when they observed the build-up of the fringe pattern with a very weak electron source and an electron biprism (*Am. J. Phys.* **57** 117–120)."

In fact, I believe that the first double-slit experiment with single electrons was performed by Pier Giorgio Merli, GianFranco Missiroli and Giulio Pozzi in Bologna in 1974 – some 15 years before the Hitachi experiment. Moreover, the Bologna experiment was performed under very difficult experimental conditions: the intrinsic coherence of the thermionic electron source used by the Bologna group was much lower than that of the field-emission source in the Hitachi experiment.

The Bologna experiment is reported in a



A series of images filmed directly from a TV monitor as the electron current density is increased (a)–(f). The integration time remains constant at 0.04 s. As there is only one electron in the apparatus at a given time, the images show how an interference pattern can be built up from single-electron events. This can be seen more clearly in the film "Electron interference" (www.lamel.bo.cnr.it/educational/educational.html).

Siemens Elmiskop IA and then used for didactic (*Am. J. Phys.* **41** 639–644) and research experiments (*J. Microscopie* **18** 103–108). We used the Elmiskop 101 for many experiments, such as the observation of the electrostatic field associated with p–n junctions (*J. Microscopie* **21** 11–20).

During this period we learned that Professors Angelo and Aurelio Bairati at the

experiments have not been performed and perhaps cannot be performed to continue." (G Gilson 1989 *Am. J. Phys.* **57** 680). Three of the seven papers that Gilson refers to were from our group in Bologna.

The main subject of our 1976 paper and the 1989 paper from the Hitachi group are the same: the single-electron build-up of the interference pattern and the statistical aspect of the phenomena. Obviously the electron-detection system used by the Hitachi group in 1989 was more sophisticated than the one we used in 1974. However, the sentence on page 118 of the paper by Tonomura *et al.*, which states that in our film we "showed the electron arrival in each frame without recording the cumulative arrivals", is not correct. This can be seen by watching the film and looking at figure 1 of our 1976 paper (a version of which is shown here).

Finally, it is also worth noting that the first double-slit experiment with single electrons was actually a by-product of research into the practical applications of electron interferometry.

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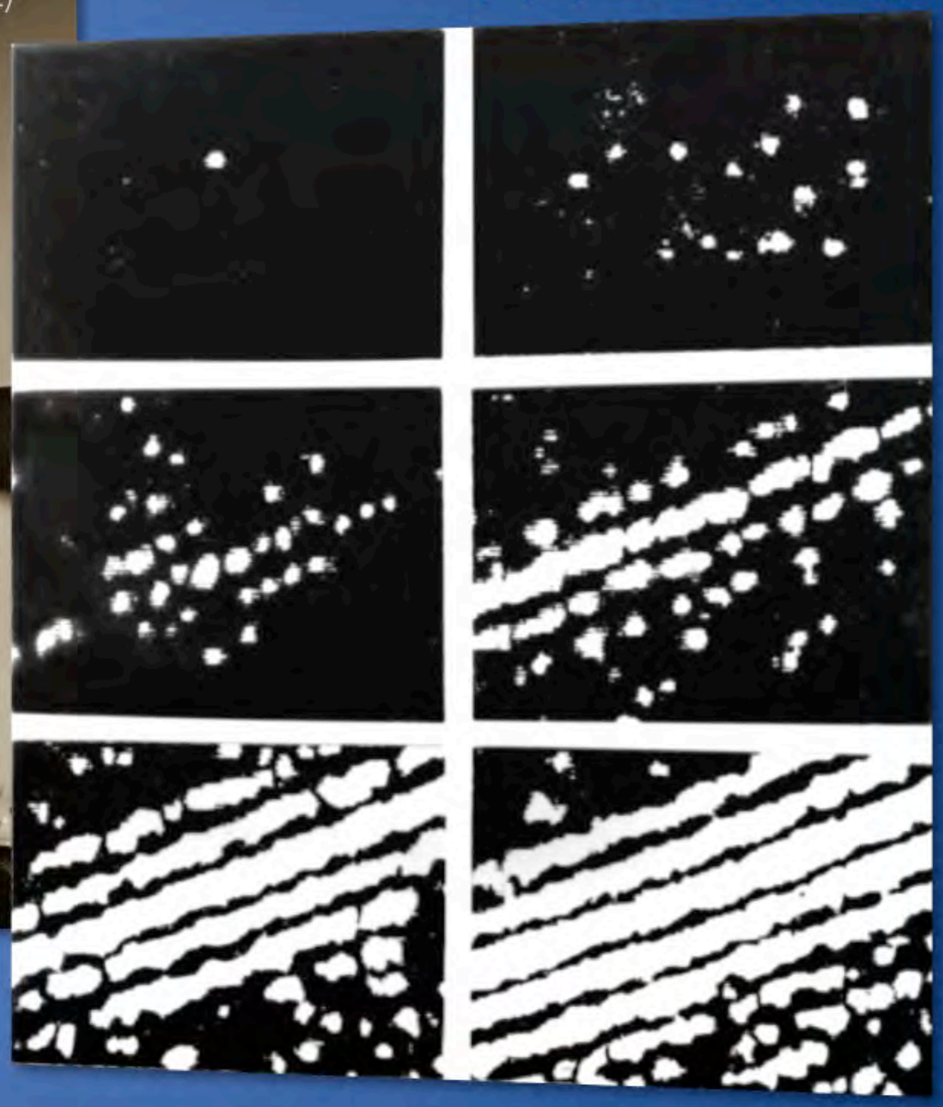
Physics World – Maggio-Settembre 2002

Chi lo ha fatto per primo?

2003 ©Pino Guidolotti

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

1974-1976



1974: **Pier Giorgio Merli**, **Gian Franco Missiroli** e **Giulio Pozzi** portano a termine per la prima volta l'interferenza di elettroni singoli, utilizzando in modo creativo un *microscopio elettronico* attrezzato con un *rivelatore di elettroni singoli*

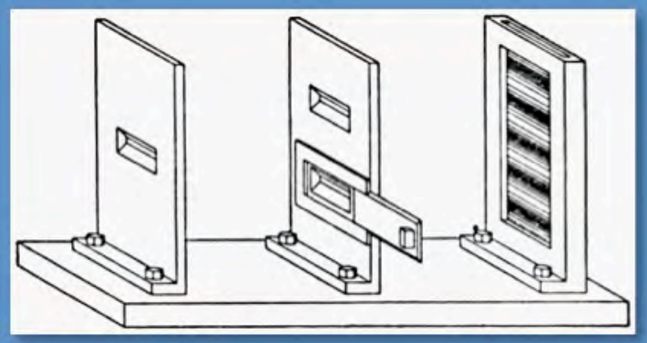
P.G.Merli, G.F.Missiroli, G.Pozzi *On the statistical aspects of electron interference phenomena* Am. J. Phys. 44, 306 (1976)

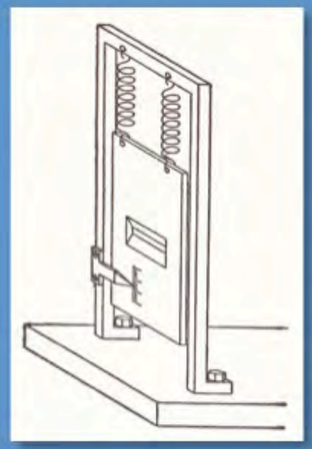
Come funziona?

Da "*The Fabric of Cosmos pt. 3: Quantum Leap*" (**Brian Greene**)

Nota storica

- **1927**: Einstein "inventa" l'esperimento più bello come esperimento *concettuale* (*gedankenexperiment*)





- nei quasi 50 anni successivi molti gruppi lavorano per realizzare questo esperimento, contribuendo a mettere a punto i necessari strumenti tecnici, fino alla prima realizzazione da parte di Merli, Missiroli e Pozzi

L'unico mistero...

"Decidemmo di esaminare un fenomeno [l'interferenza di elettroni singoli] che è impossibile, assolutamente impossibile spiegare in modo classico, e che sta al cuore della meccanica quantistica. In realtà contiene ***l'unico mistero****."*

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

"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

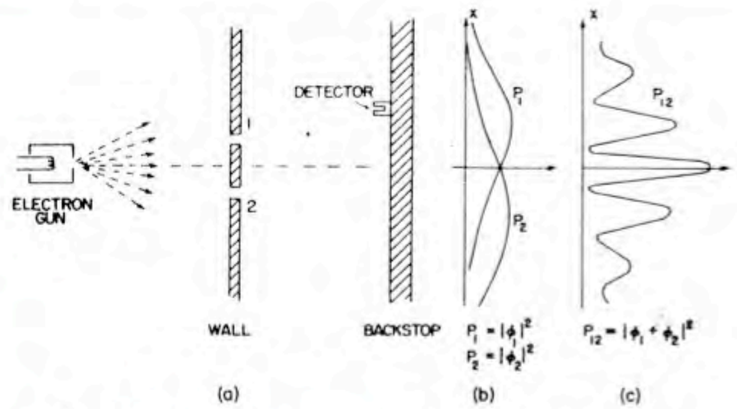


Fig. 1–3. Interference experiment with electrons.

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.

Richard Feynman: *La fisica di Feynman, vol. 3 Meccanica Quantistica*

1923: Louis De Broglie e l'elettrone-onda

Lunghezza d'onda elettroni

$$\lambda = \frac{h}{m_0 v}$$ *h*: costante di Planck

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

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

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

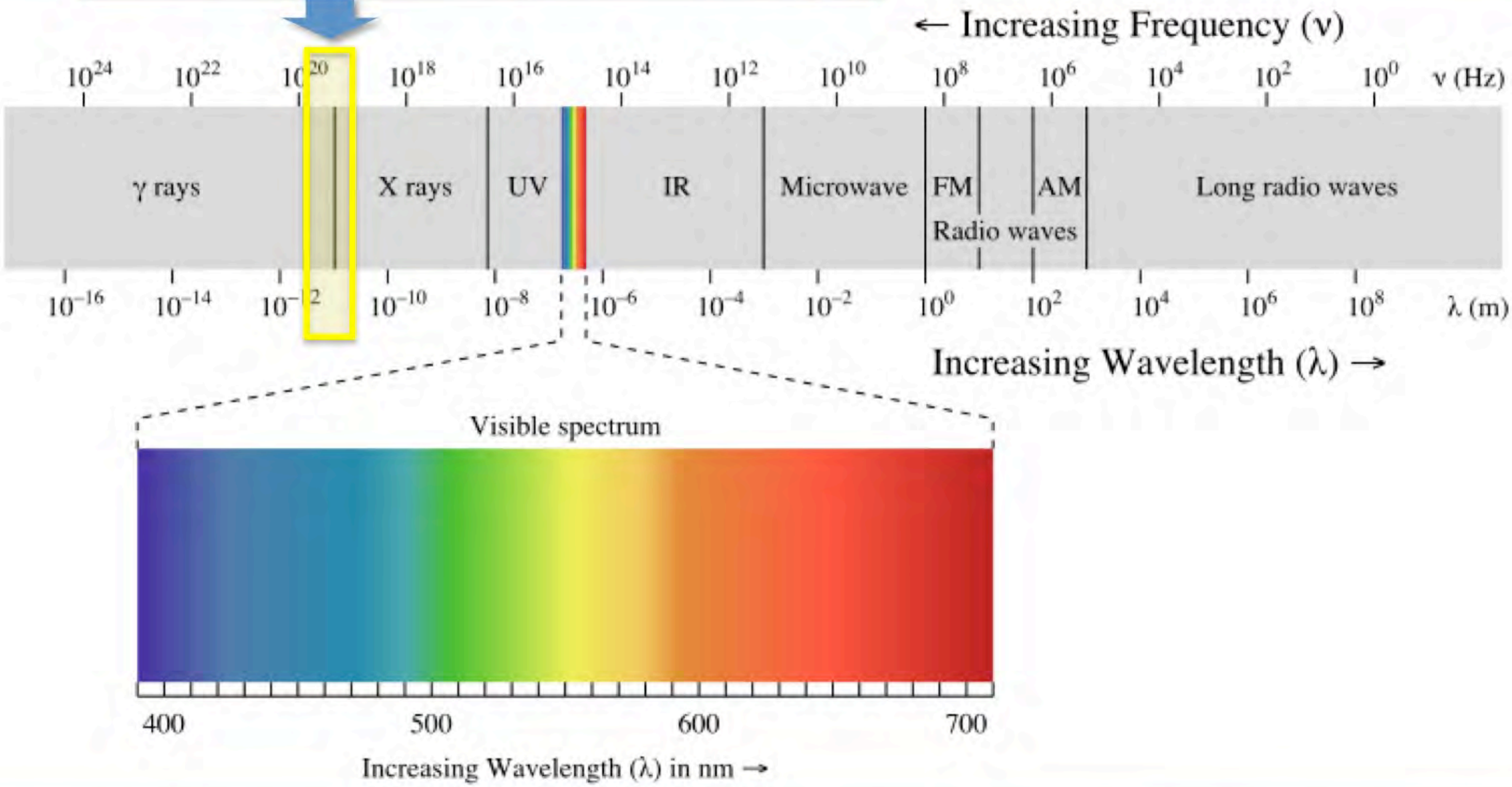
$$\lambda = \frac{h}{[2 m_0 eV (1 + \frac{eV}{2 m_0 c^2})]^{1/2}}$$ *(relativistica)*

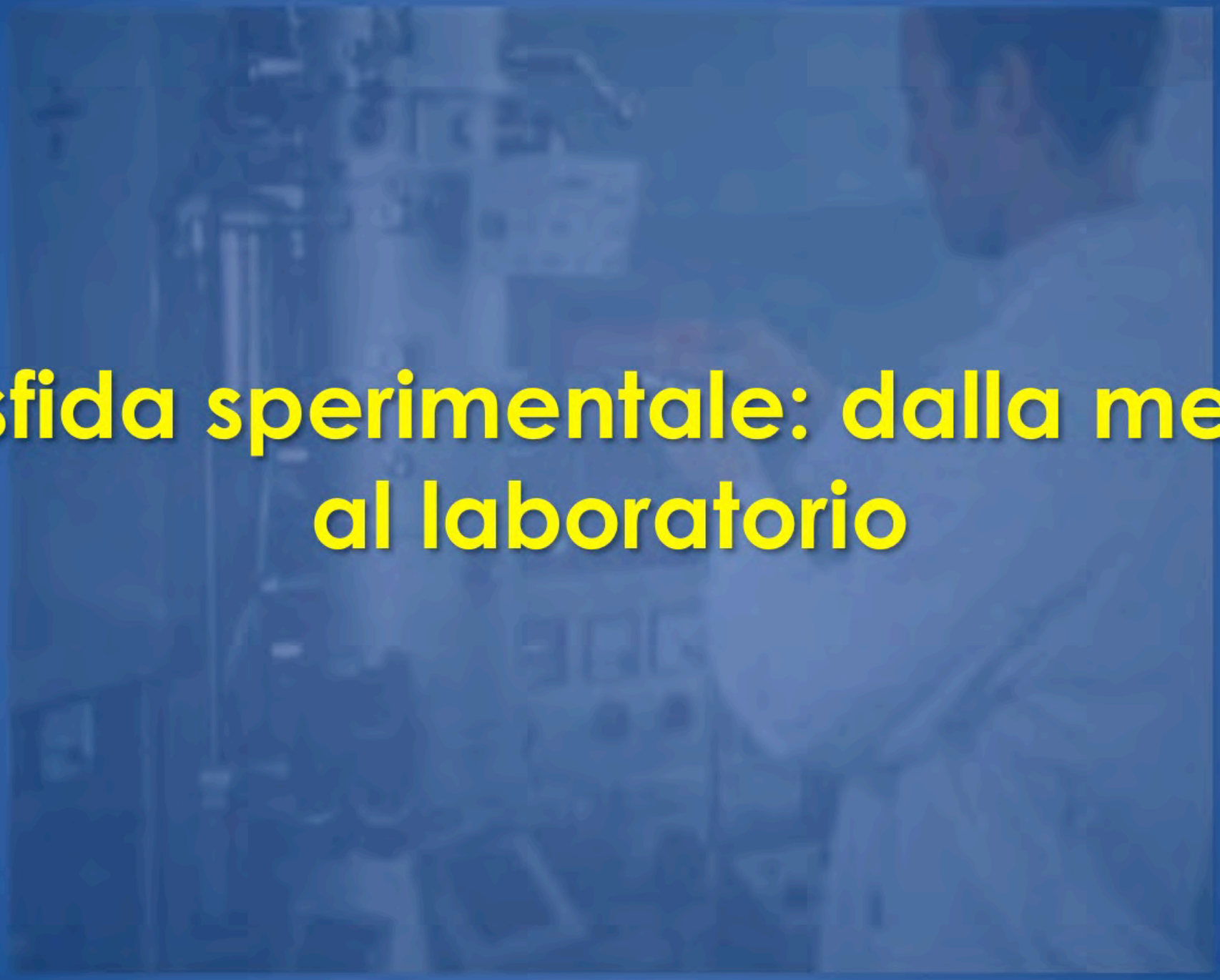
$$\lambda = \frac{1.266}{(1 + 0.9788 \times 10^{-6} V) V^{1/2}}$$ *V (volt) → λ (nm)*

tensione accelerazione (volt)	lunghezza d'onda	
1000	0.04 nm	4×10^{-11} m
100000	0.004 nm	4×10^{-12} m

Lunghezza d'onda elettroni

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

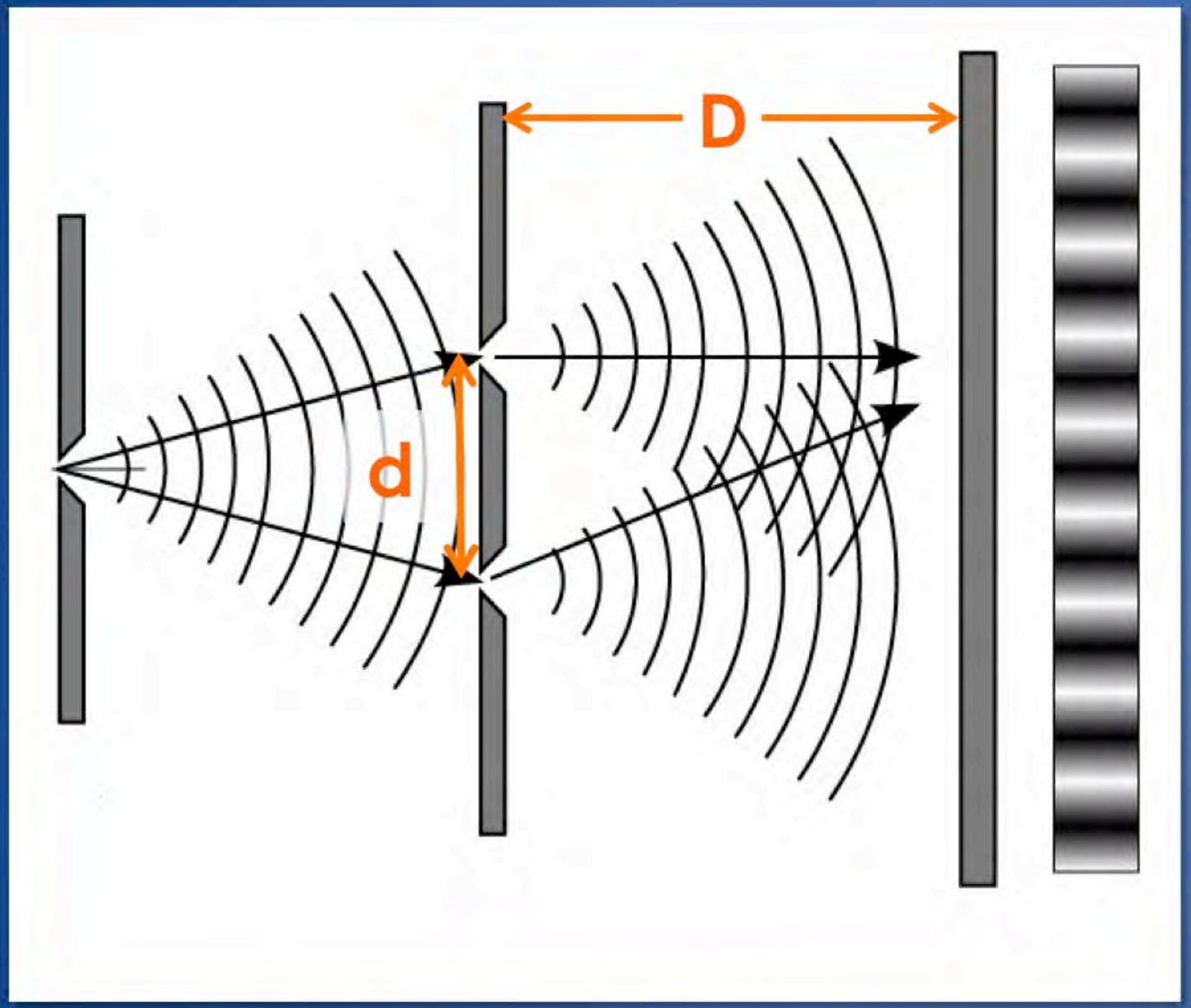




La sfida sperimentale: dalla mente al laboratorio

Giorgio Lulli – CNR-IMM

Interferenza e visibilità delle frange



spaziatura tra le frange

$x \approx \lambda D/d$ (d<<D)

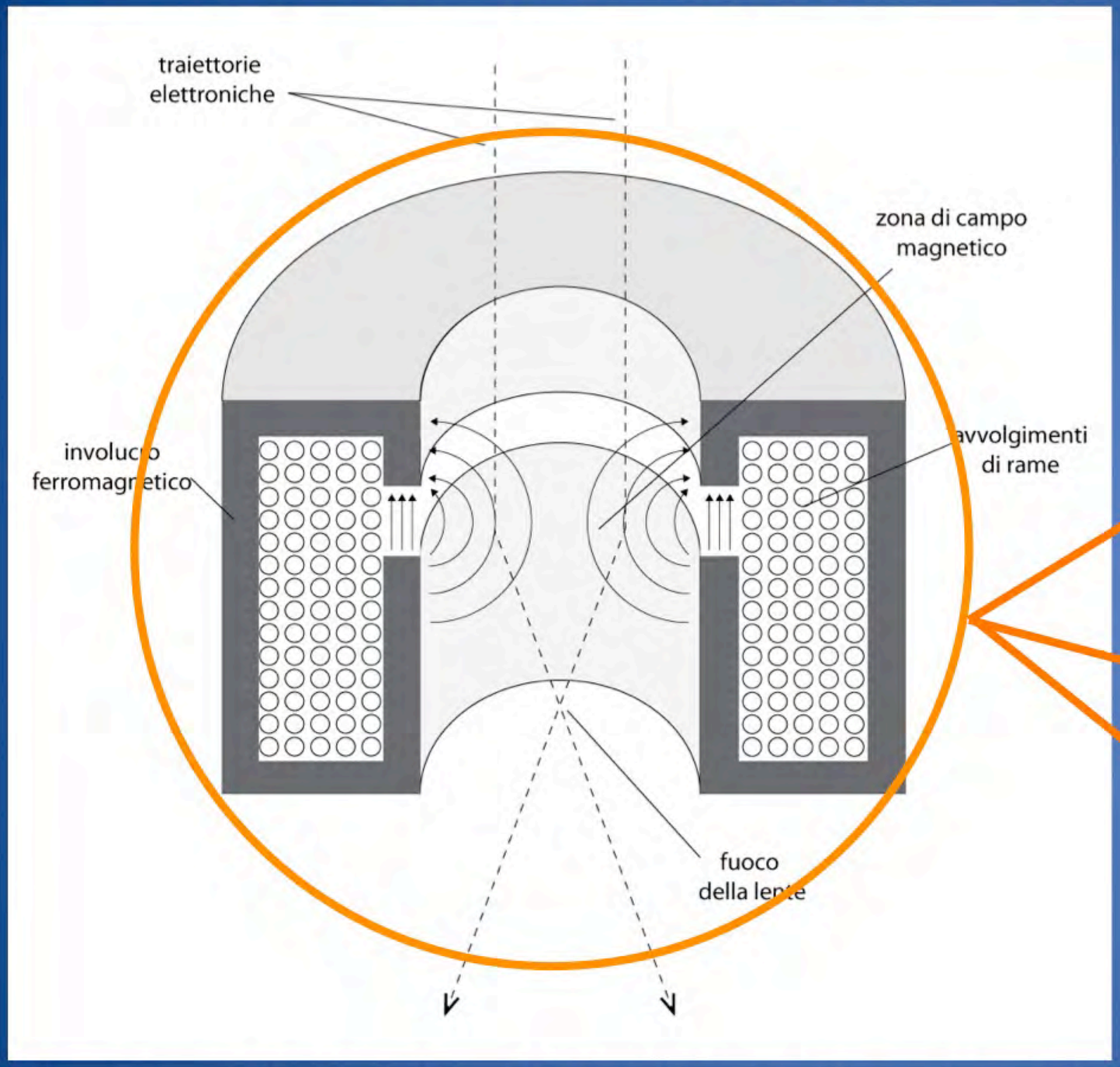
x (risoluz. occhio) ≈ **0.1 mm**
λ_{el} (100keV) = **0.004 nm**

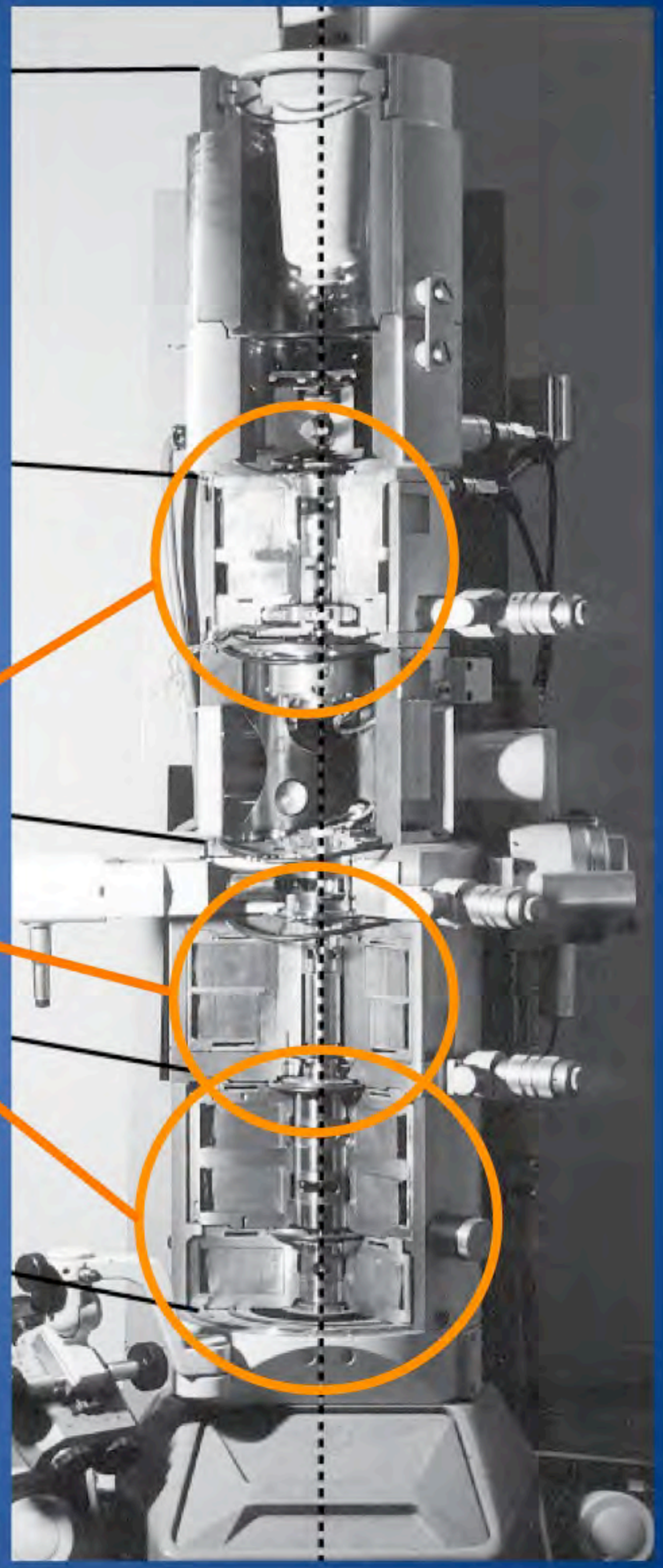
per vedere le frange a
D = 30 cm ⇒ d~1 nm

... troppo piccolo!

ipotesi (oggi) tecnologicamente realistica:
d ~ 100 nm ⇒ D ~ 30 m

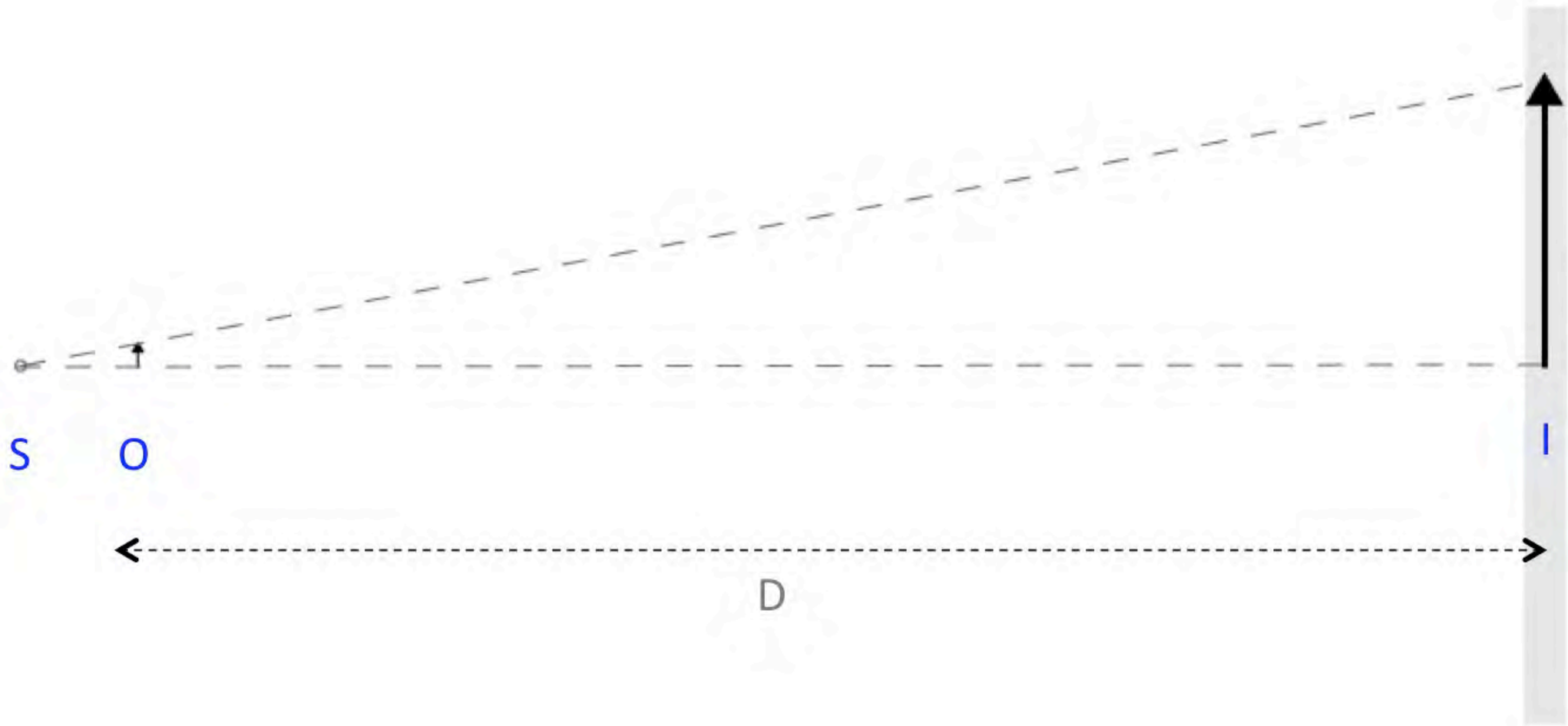
lente elettro-magnetica per elettroni





il costituente fondamentale del *microscopio elettronico (in trasmissione)*

Effetto di una lente



proiezione geometrica da sorgente puntiforme

Effetto di una lente

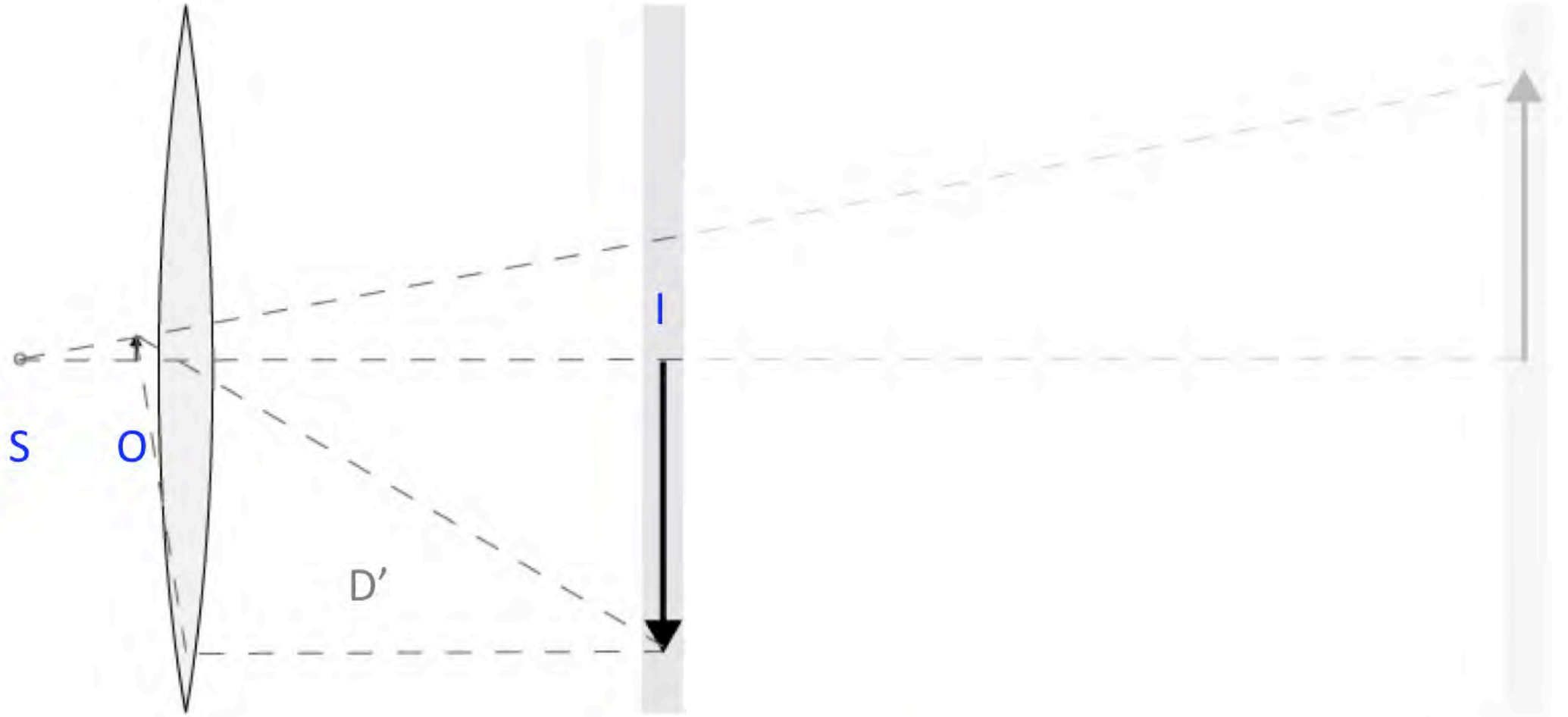
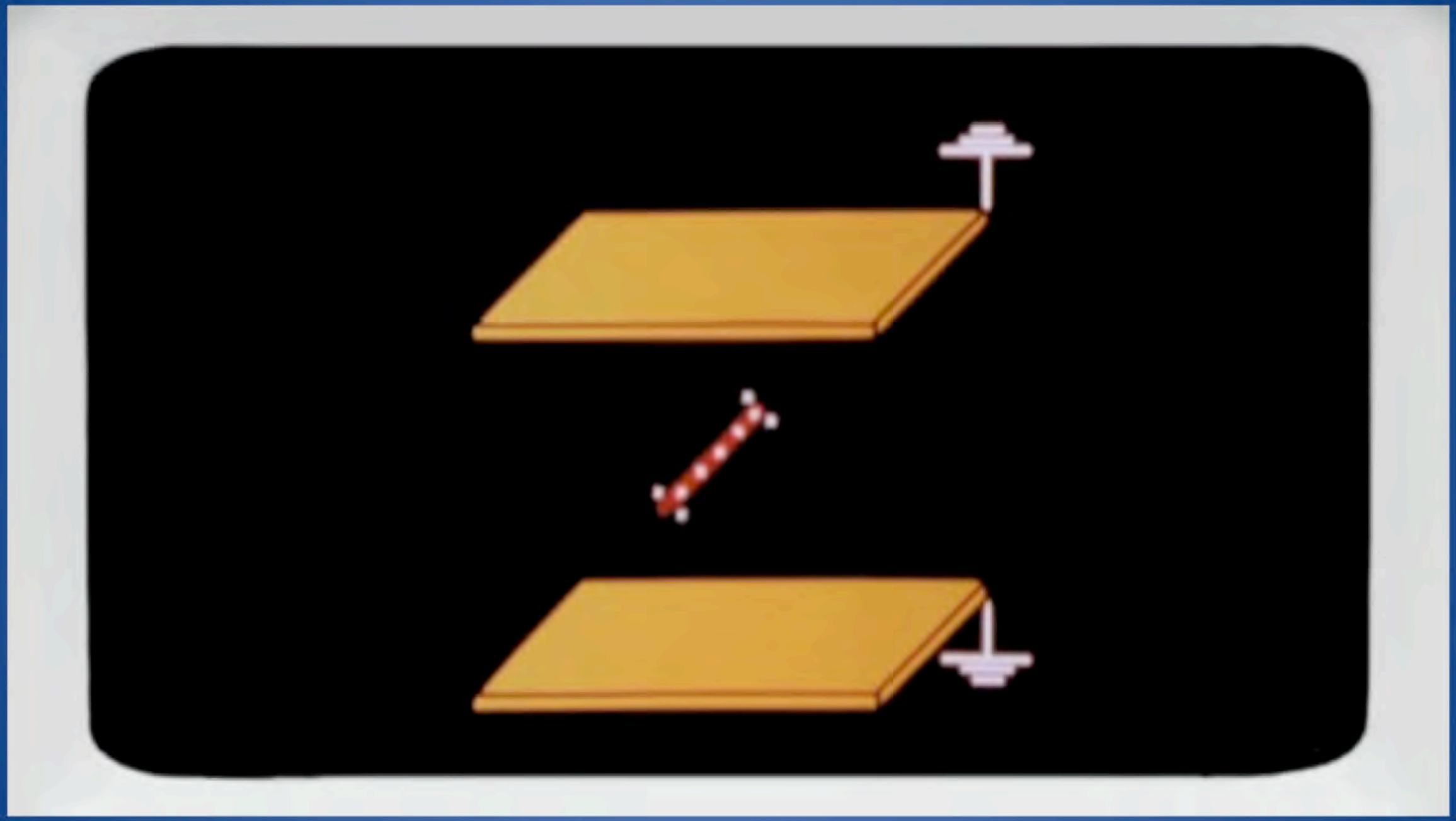


immagine delle stesse dimensioni del caso precedente, ma molto più vicina all’oggetto (e ribaltata ...)

Il biprisma elettronico: un'alternativa alle fenditure



G.Lulli et al. documentario *"L'esperimento più bello"* 2011

spessore del filo ≈ 0.5 - 1 μ m

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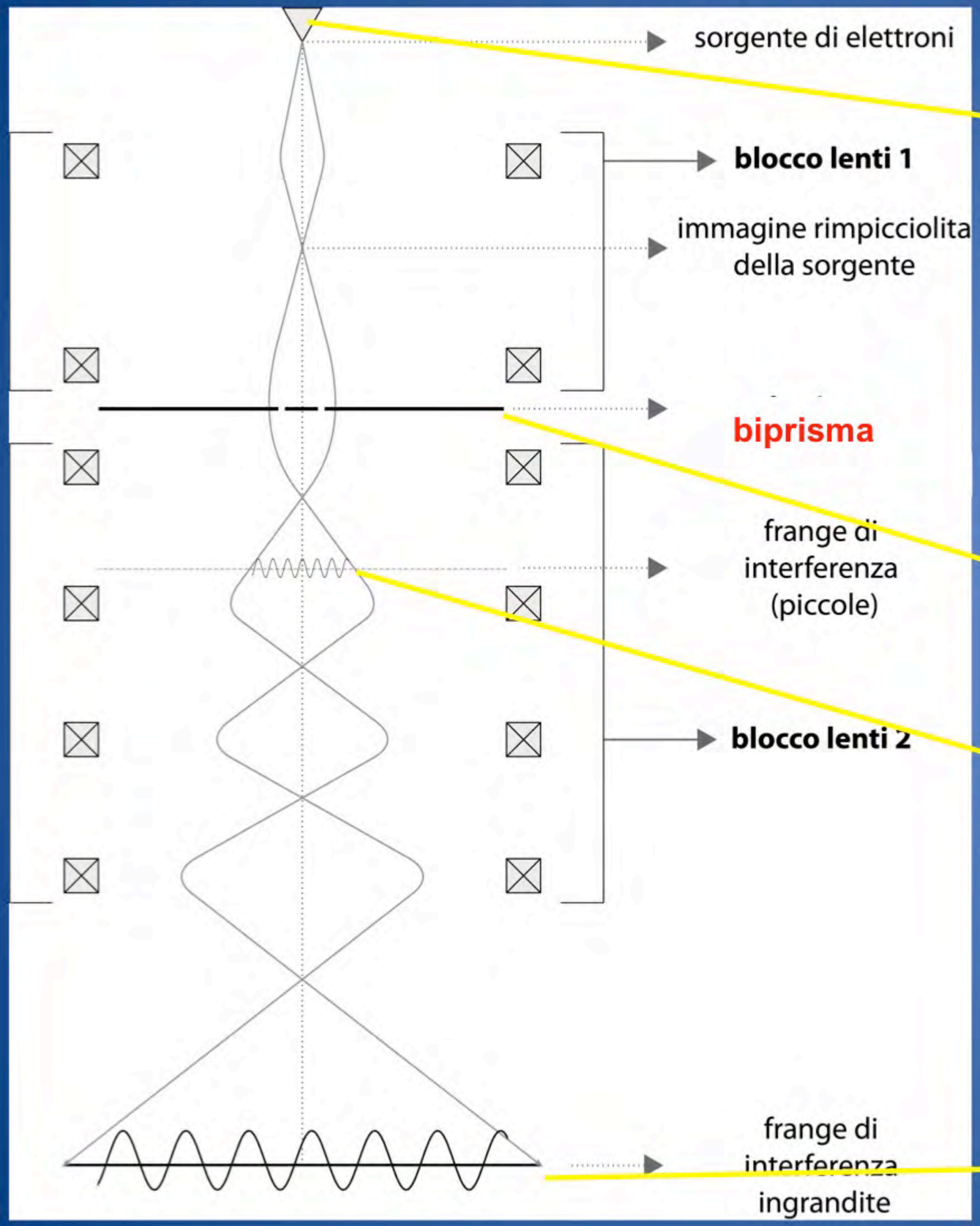
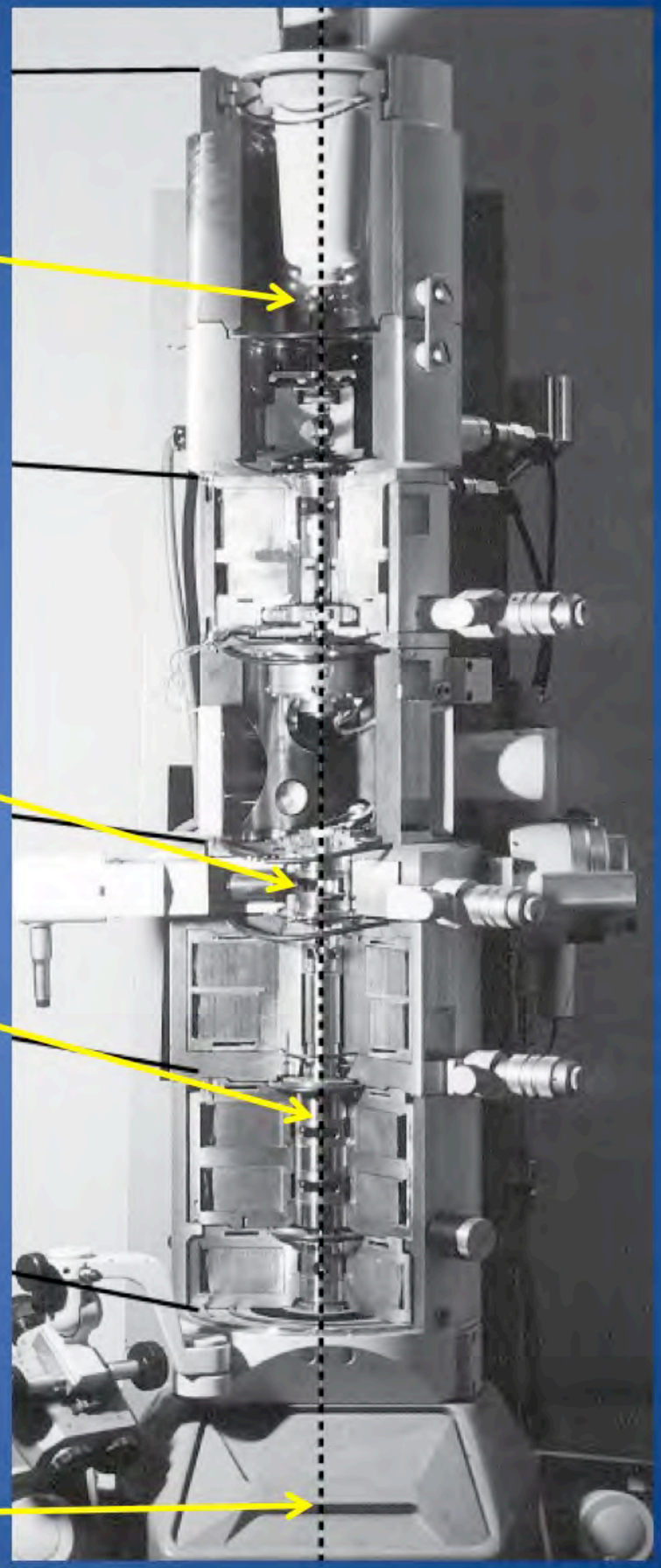
Giorgio Lulli – CNR-IMM

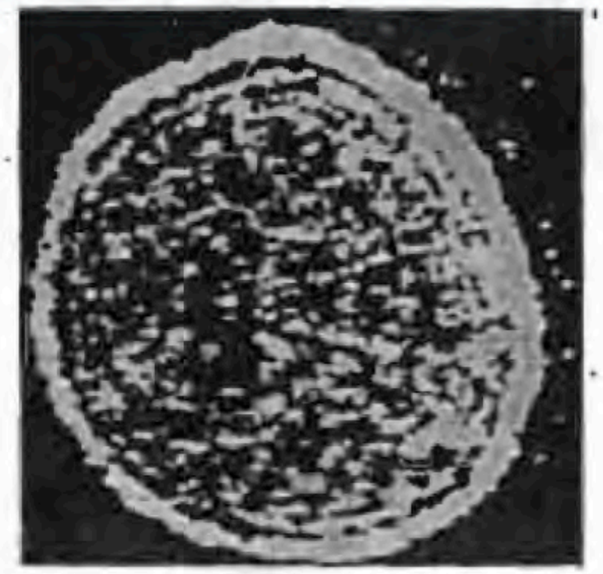
Interferenza di elettroni nel microscopio elettronico





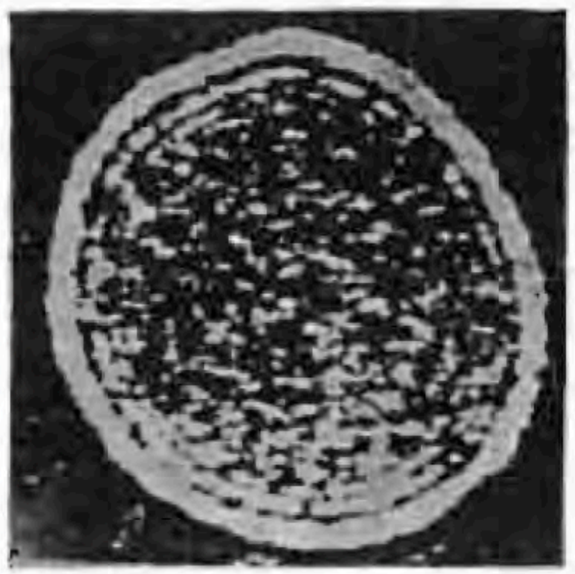
K.H. Hermann (Siemens) Intensificatore di immagine (1971)

τ = 1/25 s



τ = 10 s

τ = 20 s

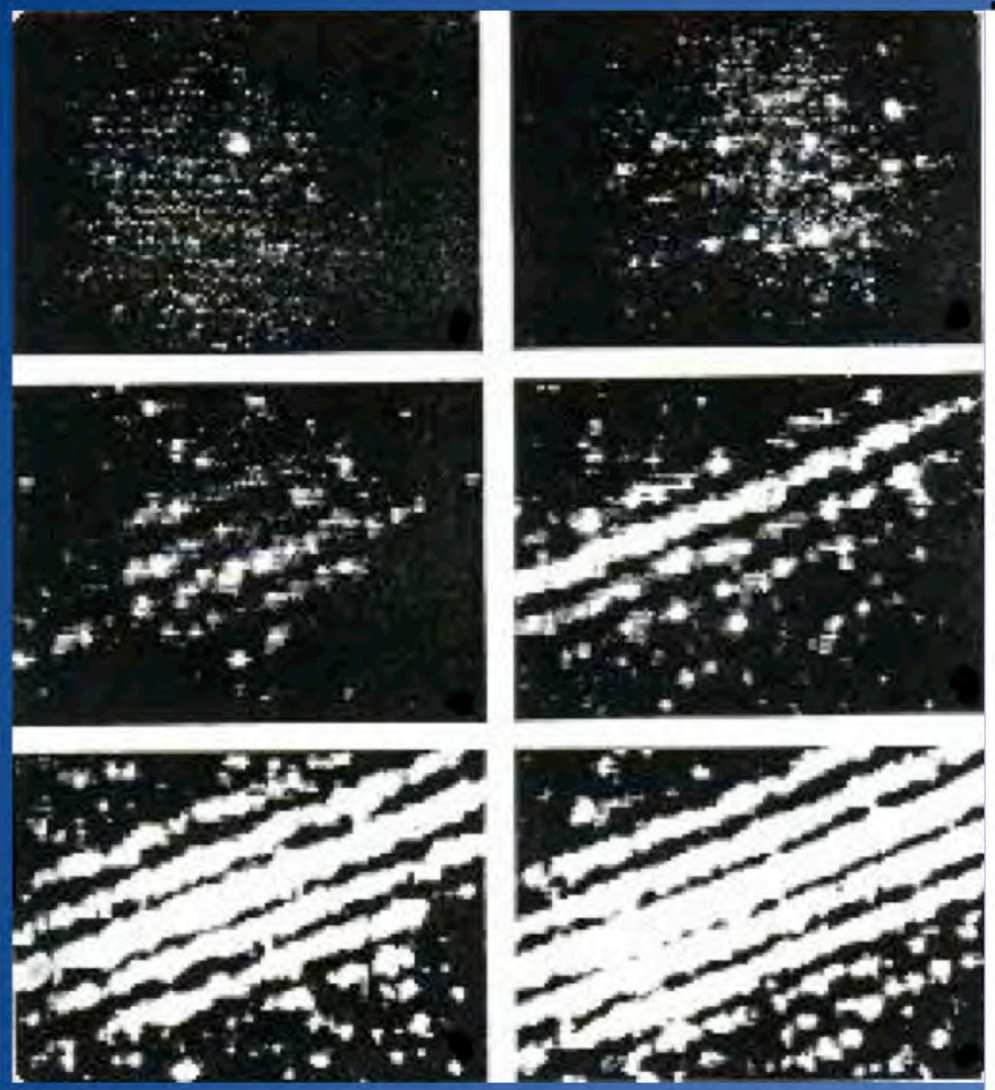


τ = 60 s

τ = 120 s

Il primo rivelatore di elettroni singoli

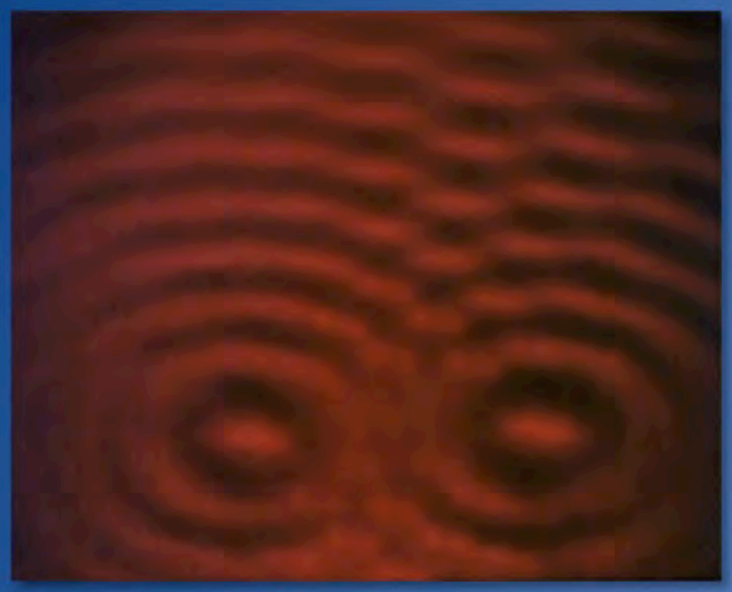
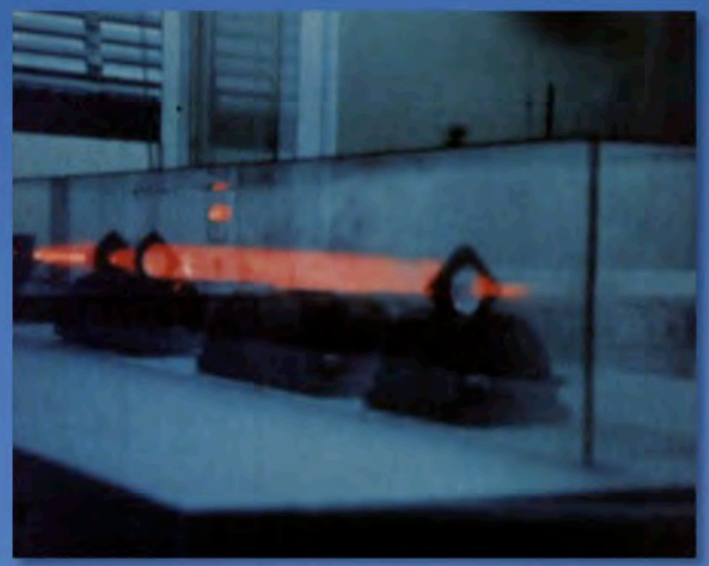
Esperimento Merli Missiroli Pozzi (1974-1976)



microscopio elettronico + biprisma + rivelatore elettroni singoli

Il primo esperimento di interferenza in cui si visualizzano i singoli elettroni: l'esperimento più bello! *(Physics World 2002)*

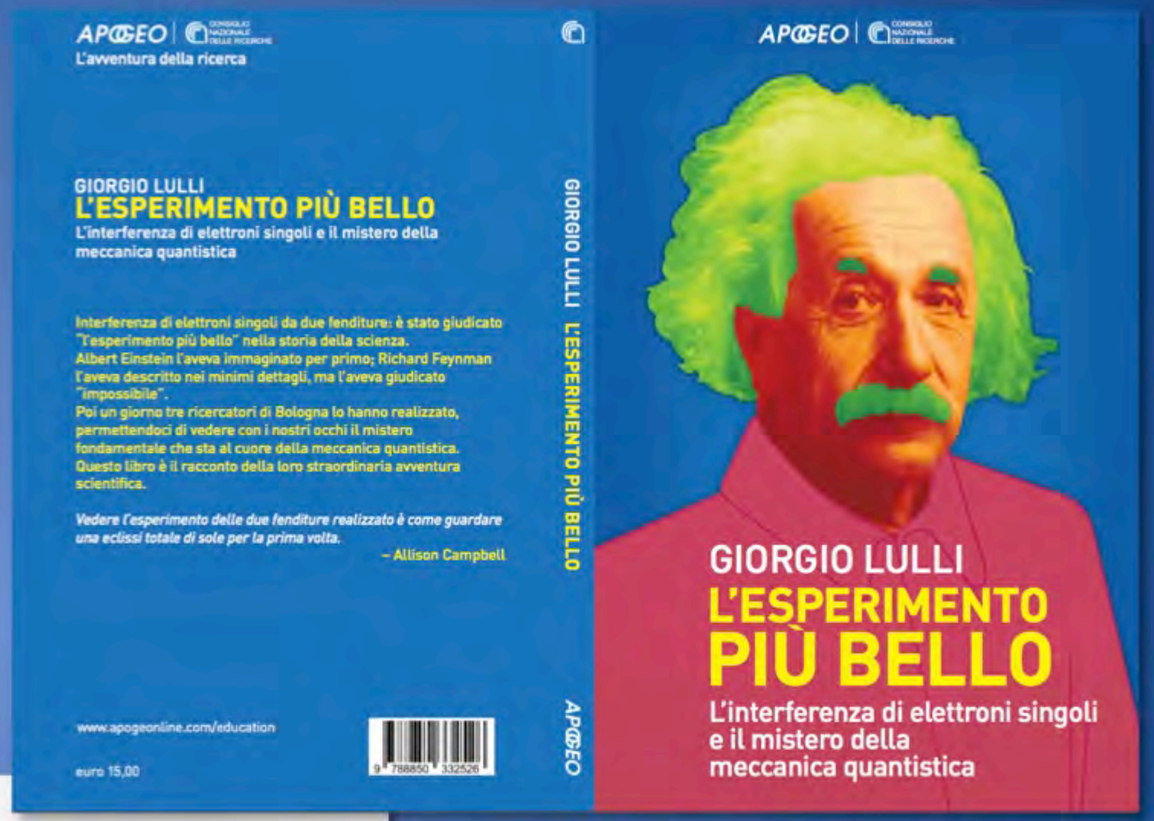
1976: il film “Interferenza di elettroni”

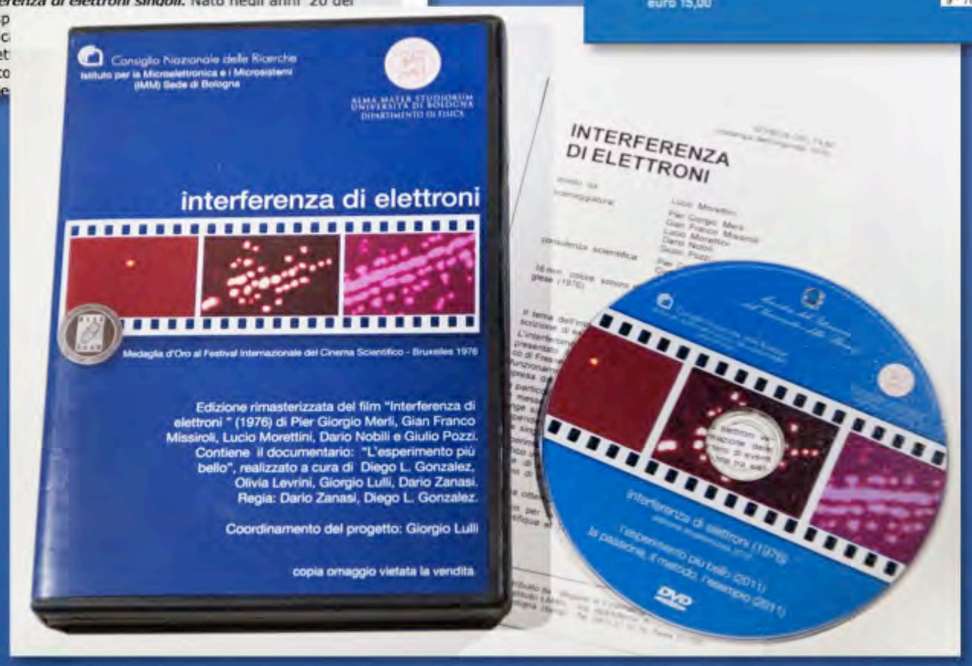
Medaglia d’Oro al Festival Internazionale del Cinema Scientifico - Bruxelles 1976

Per saperne di più

dal 2009



2013

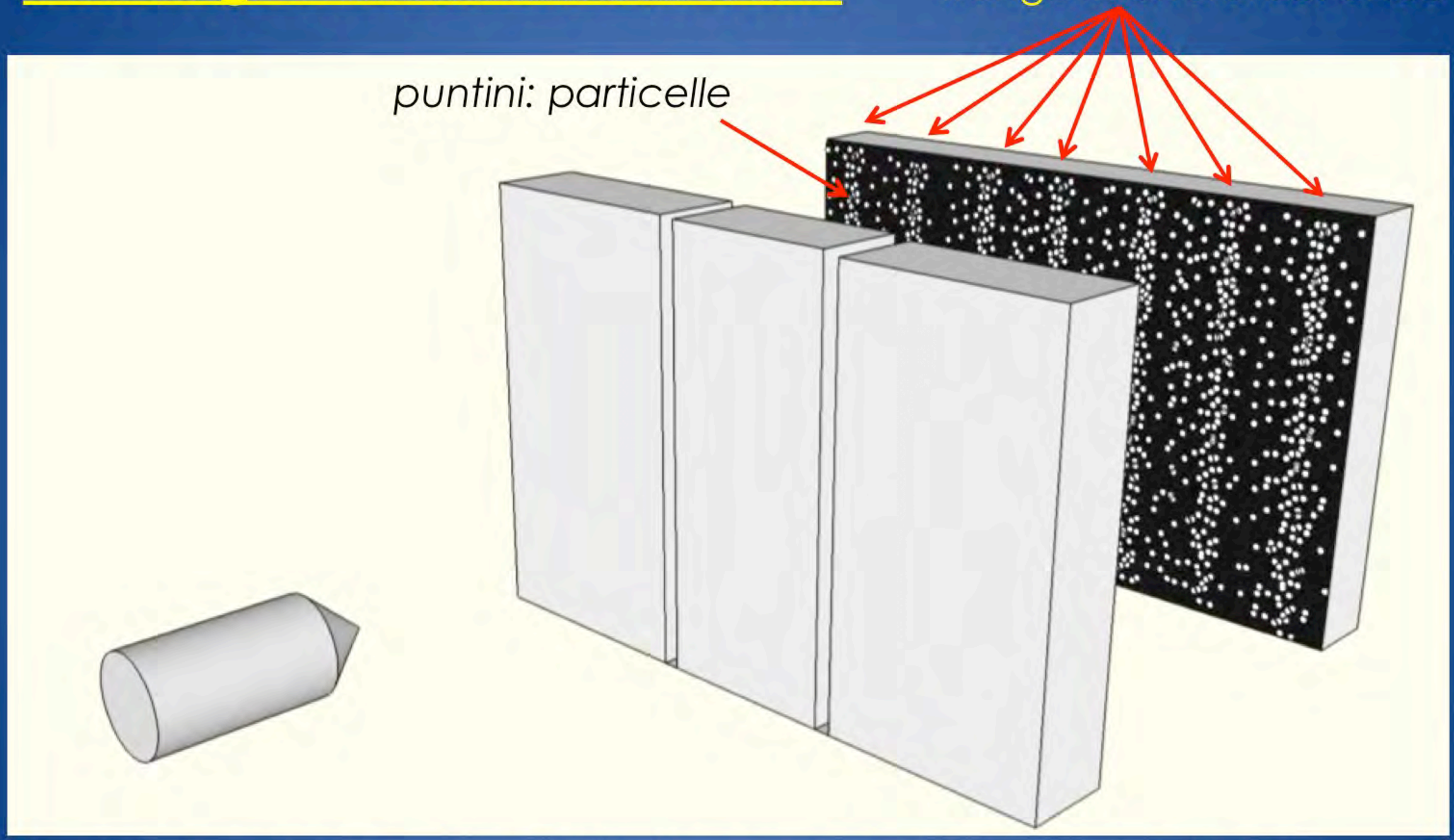


2010

La sfida concettuale: dal “pensare classico” al “pensare quantistico”

Giorgio Lulli – CNR-IMM

.. un singolo elettrone alla volta



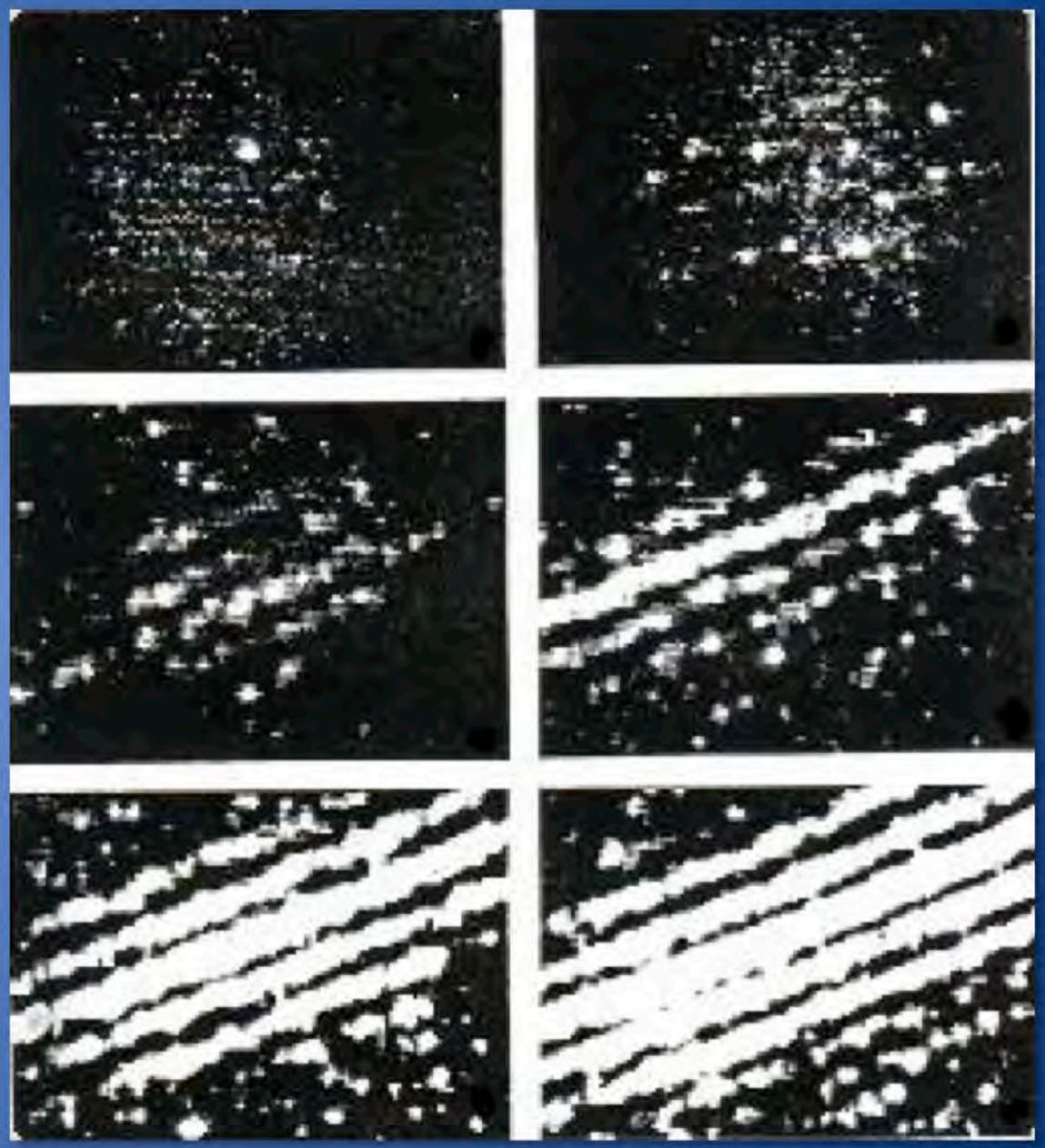
segnali di *particelle* .. ma distribuite come nell'interferenza di *onde*
effetto che non può essere dovuto a una *interazione* tra elettroni

La lettura dell'esperimento secondo Merli, Missiroli, Pozzi

1. ogni singolo elettrone/fotone/ ecc. viene rivelato come ***particella***

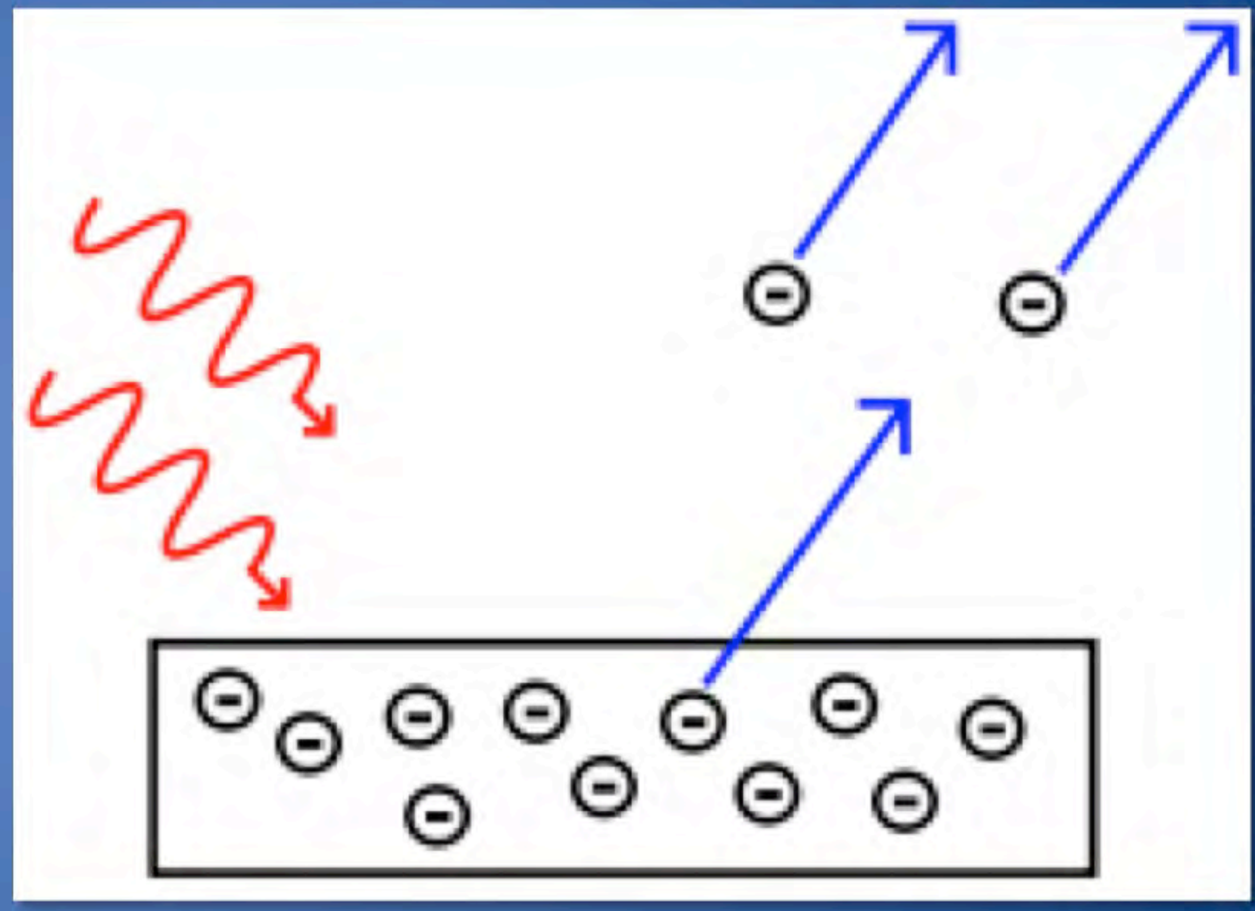
2. il ***comportamento ondulatorio*** (***frange***) risulta evidente solo dopo aver osservato molti (>1000) eventi ⇒ effetto ***statistico***

3. la ***distribuzione della probabilità*** di arrivo degli elettroni sullo schermo, ha la ***forma matematica*** della distribuzione di intensità delle frange in un esperimento di interferenza di onde classiche. Non onda reale quindi, ma ***"onda di probabilità"***



... ma cosa spinge ciascun *singolo* elettrone a seguire questa distribuzione?

Einstein, l'effetto fotoelettrico e i quanti di luce



effetto fotoelettrico → **luce = particelle**
(*quanti* di luce o *fotoni*)

Interferenza di fotoni singoli (Jacques *et al.* 2005)

mailto:roch@physique.ens-cachan.fr

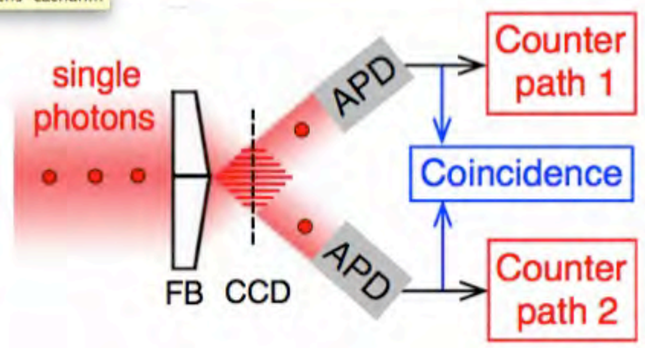


Fig. 1. Wavefront-splitting set-up based on a Fresnel's biprism (FB). APDs are avalanche silicon photodiodes operating in photon counting regime. An intensified CCD camera (dash line) records interference fringes in the overlapping region of the two deviated wavefronts. When the CCD is removed, it is 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)

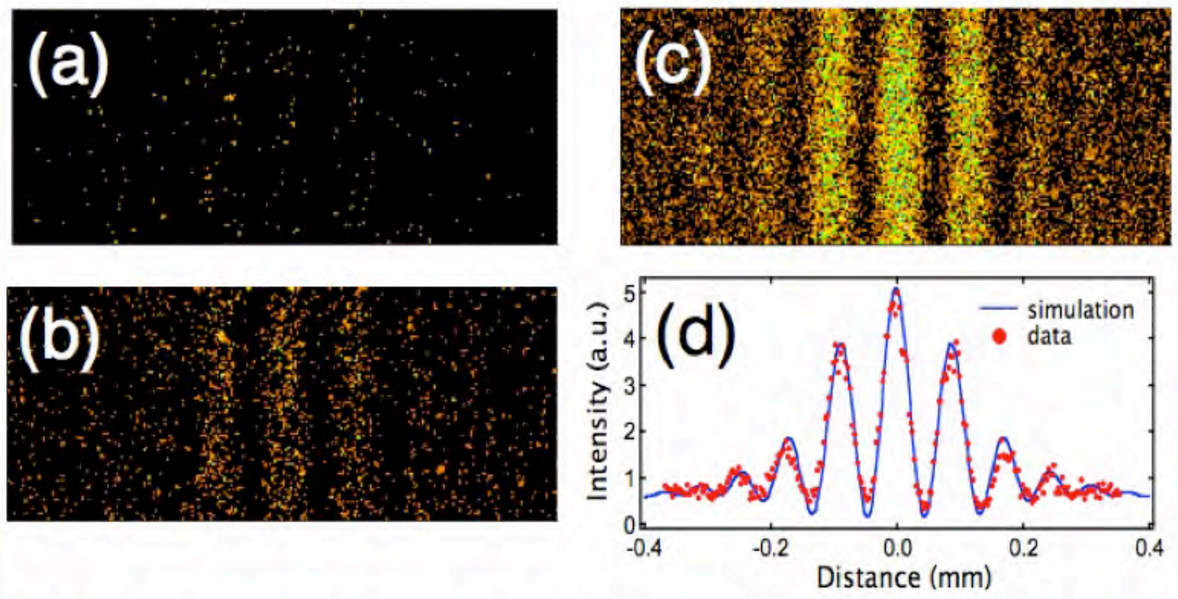


Fig. 4. Observation of the interference pattern expanded by the eyepiece and recorded by the intensified CCD camera. Image (a) (resp. (b) and (c)) is made of 272 photocounts (resp. 2240 and 19773) corresponding to an exposure duration of 20 s (resp. 200 s and 2000 s). Graph (d) displays the resulting 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.

si ottiene esattamente lo stesso risultato usando un fascio debolissimo di luce..
ma anche un fascio di *neutroni*, di *atomi*, persino di *molecole* ..

Interferenza di neutroni termici (Zeilinger *et al.* 1988)

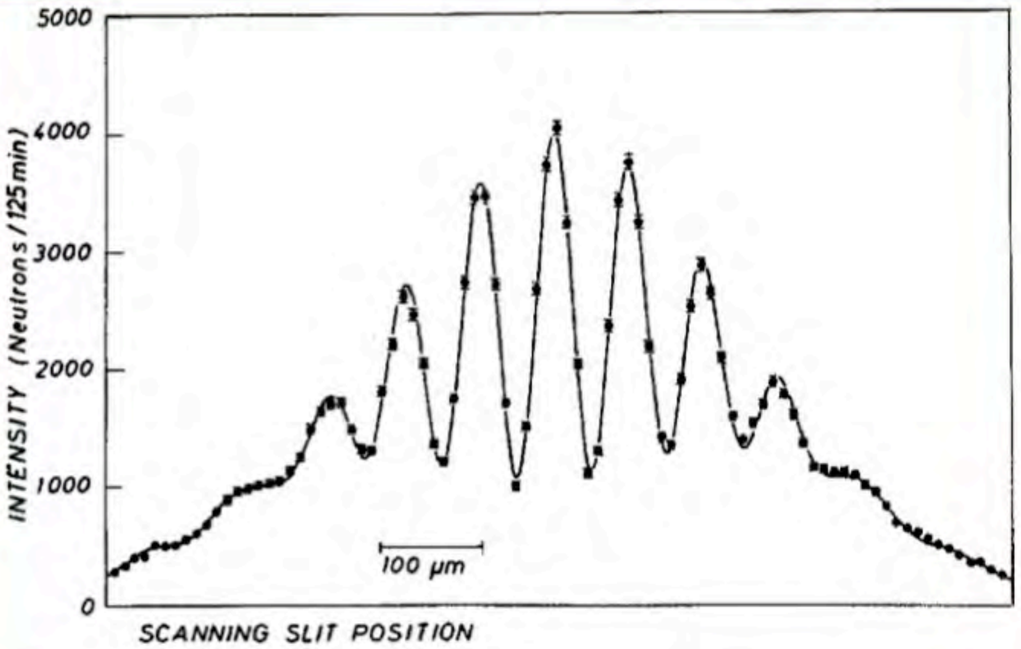


FIG. 1. A double-slit diffraction pattern measured with very cold neutrons with a wavelength of 2 nm corresponding to a velocity of 200 ms^{-1}. The two slits were 22 μm and 23 μm wide, respectively, separated by a distance of 104 μm. The resulting diffraction angles were only of the order of 10 μrad, 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

distanza tra fenditure d = 104 μm

(larghezza fenditure 22 μm)

criterio visibilità frange λ D/d = 0.1 mm

distanza fenditure rivelatore D = **5 m**

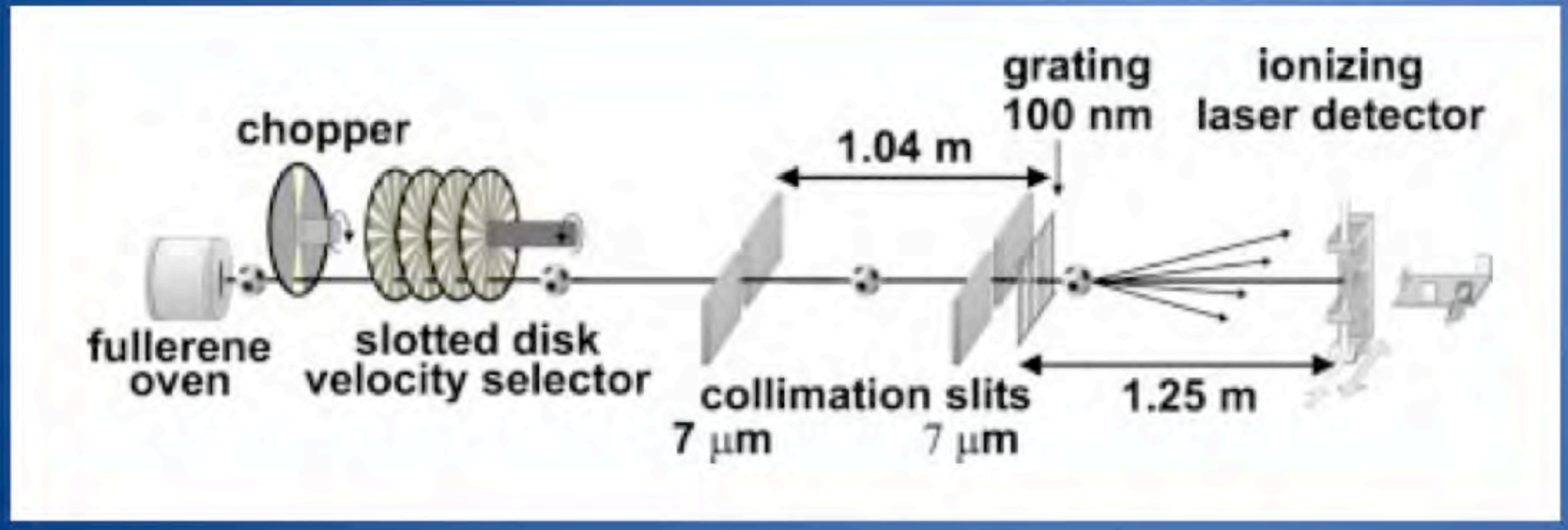
Interferenza di molecole C_{60} (Arntd *et al.* 1999)

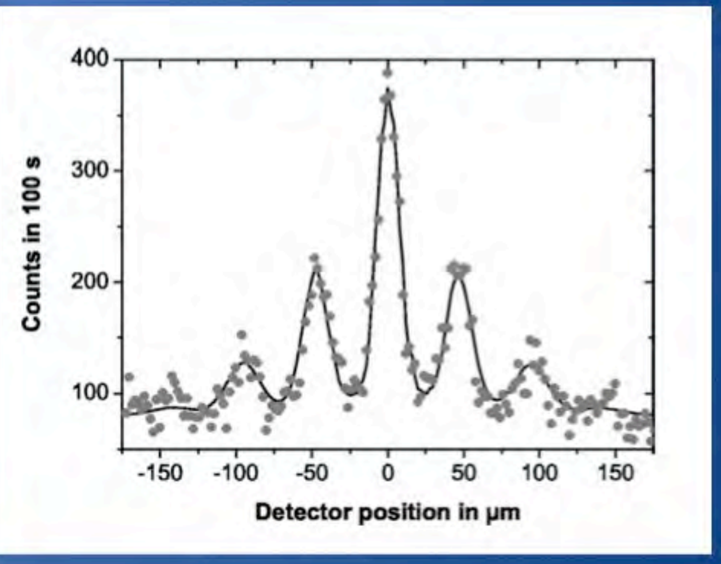
Fig. 2. The fullerene molecule C_{60}, consisting of 60 carbon atoms arranged in a truncated icosahedral shape, is the smallest known natural soccer ball.

mass = **720** AMU

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

$\lambda =$ 0.0028 nm





d = 100 nm (larghezza fenditure 50nm)

distanza fenditure-rivelatore = 1.25 m

Interferenza di molecole $C_{32}H_{18}N_8$ e $C_{48}H_{26}F_{24}N_8O_8$ (Juffmann et al. 2012)

LETTERS NATURE NANOTECHNOLOGY DOI: 10.1038/NNANO.2012.34

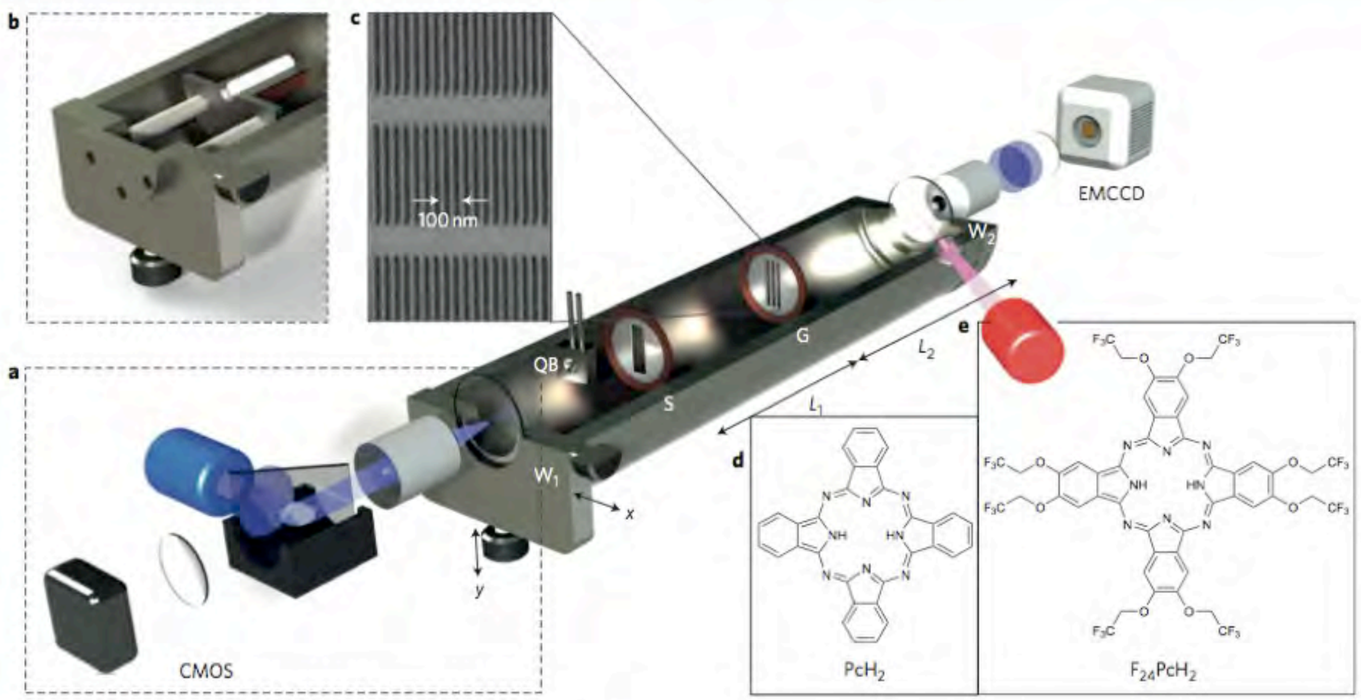
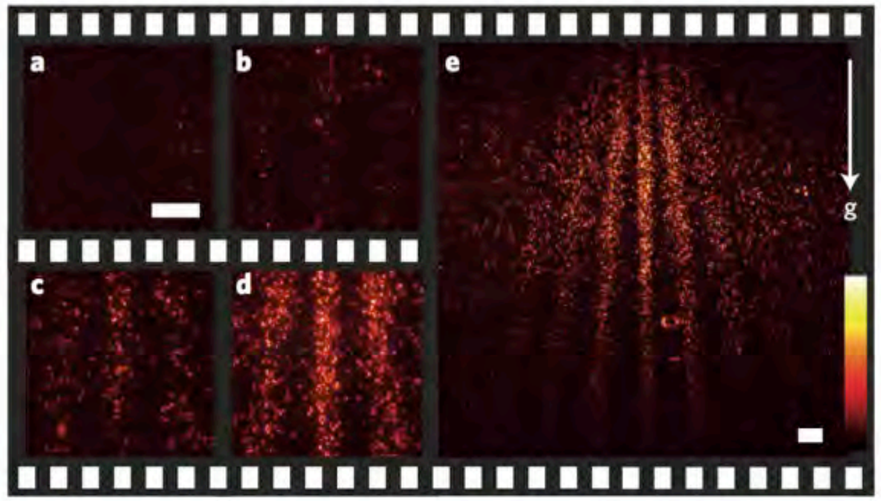


Figure 1 | Set-up for laser-evaporation, diffraction and nano-imaging of complex molecules. a, Thermolabile molecules are ejected by laser micro-evaporation. A blue diode laser (445 nm, 50 mW) is focused onto window W_1 to evaporate the molecules coated on its inner surface. A CMOS camera and a quartz 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

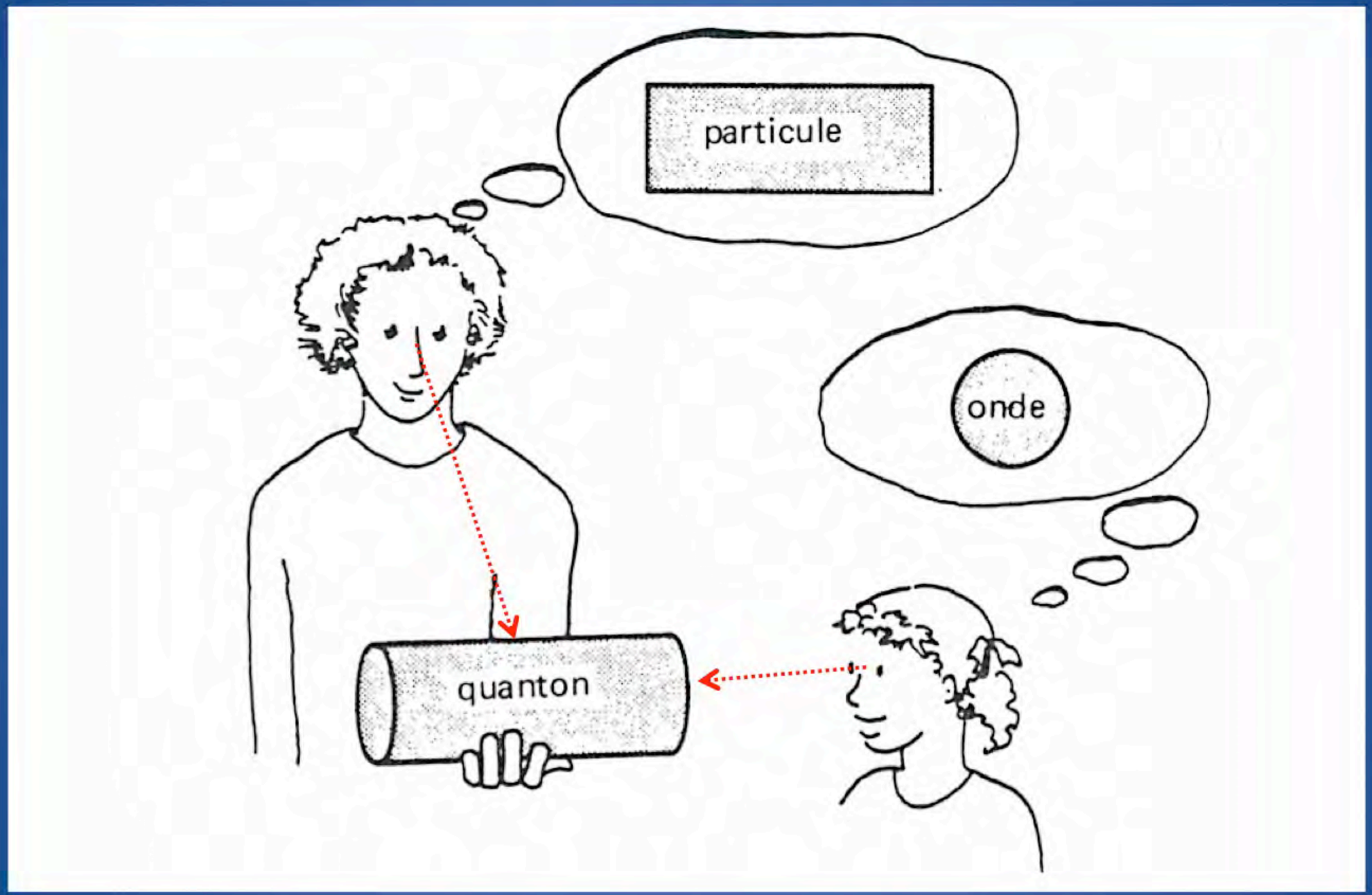
$v \simeq$ 150 ms^{-1}
$\lambda =$ 0.0052 nm
d = 100 nm (larghezza fenditure 50nm)

distanza fenditure-rivelatore ~ 0.5 m

Elettroni, fotoni, neutroni, atomi, molecole...

1. **particelle?** (non spiega le frange)
2. **onde?** (non spiega i puntini)
3. **particelle e onde?** (***"dualismo"***) (sono concetti in contraddizione)
4. **altro? ...**

Il “quantone” !



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

- classicamente, per interferire ci vogliono almeno ***due*** sorgenti di perturbazioni ondulatorie

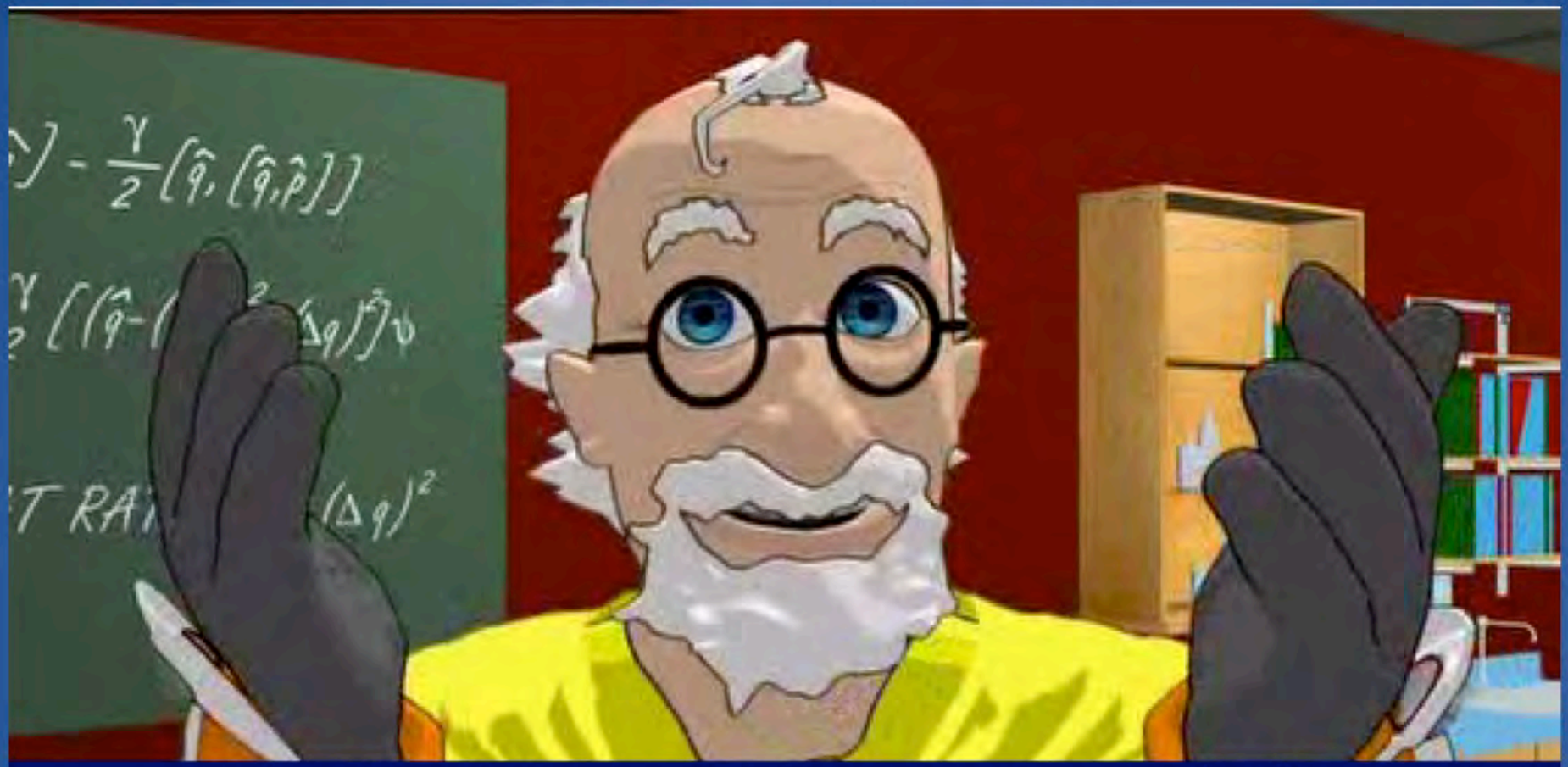
- qui mandiamo ***un solo*** elettrone/fotone per volta

- cosa interferisce con cosa?

"*ogni fotone [o elettrone] interferisce con sè stesso*"

Paul A. M. Dirac *I principi della meccanica quantistica* (Boringhieri, 1959) p.13

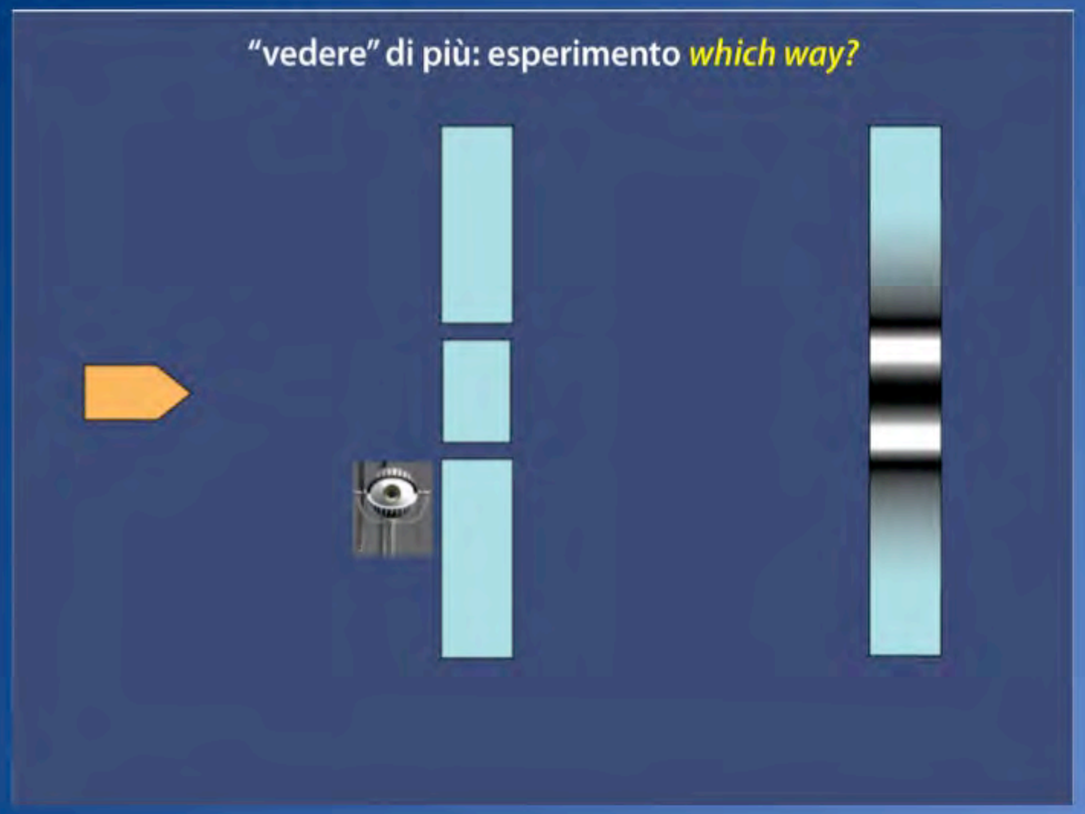
Un modo “naif” di visualizzare il fenomeno ..



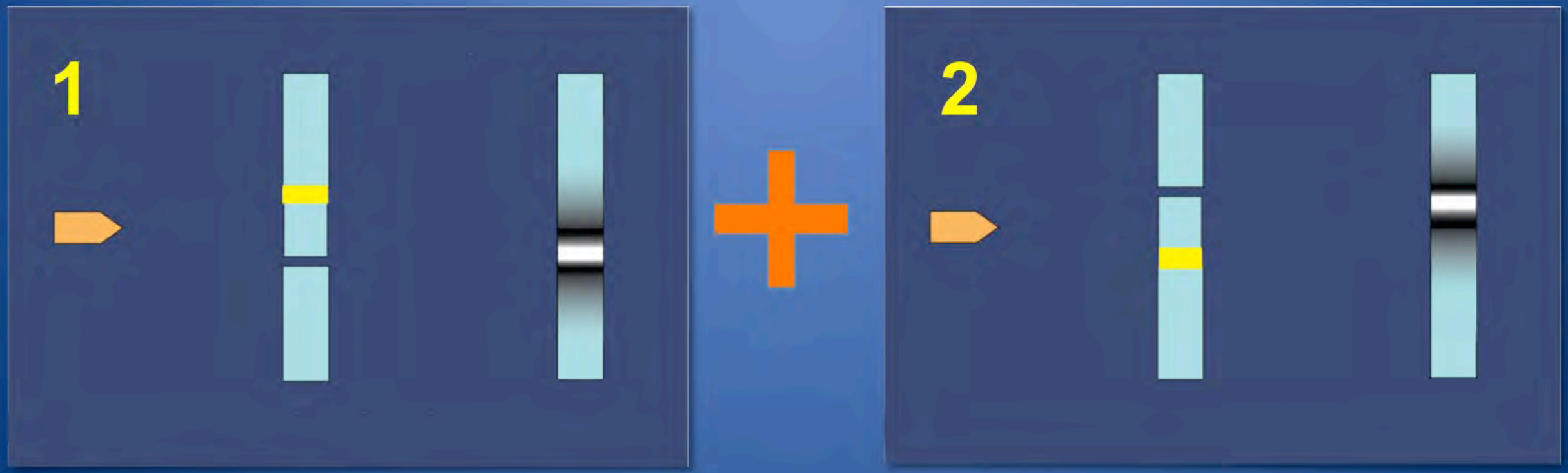
Dr. Quantum (*The infaumous double slit experiment* - YouTube)

Quale percorso? (*which path?* o *which way?*)

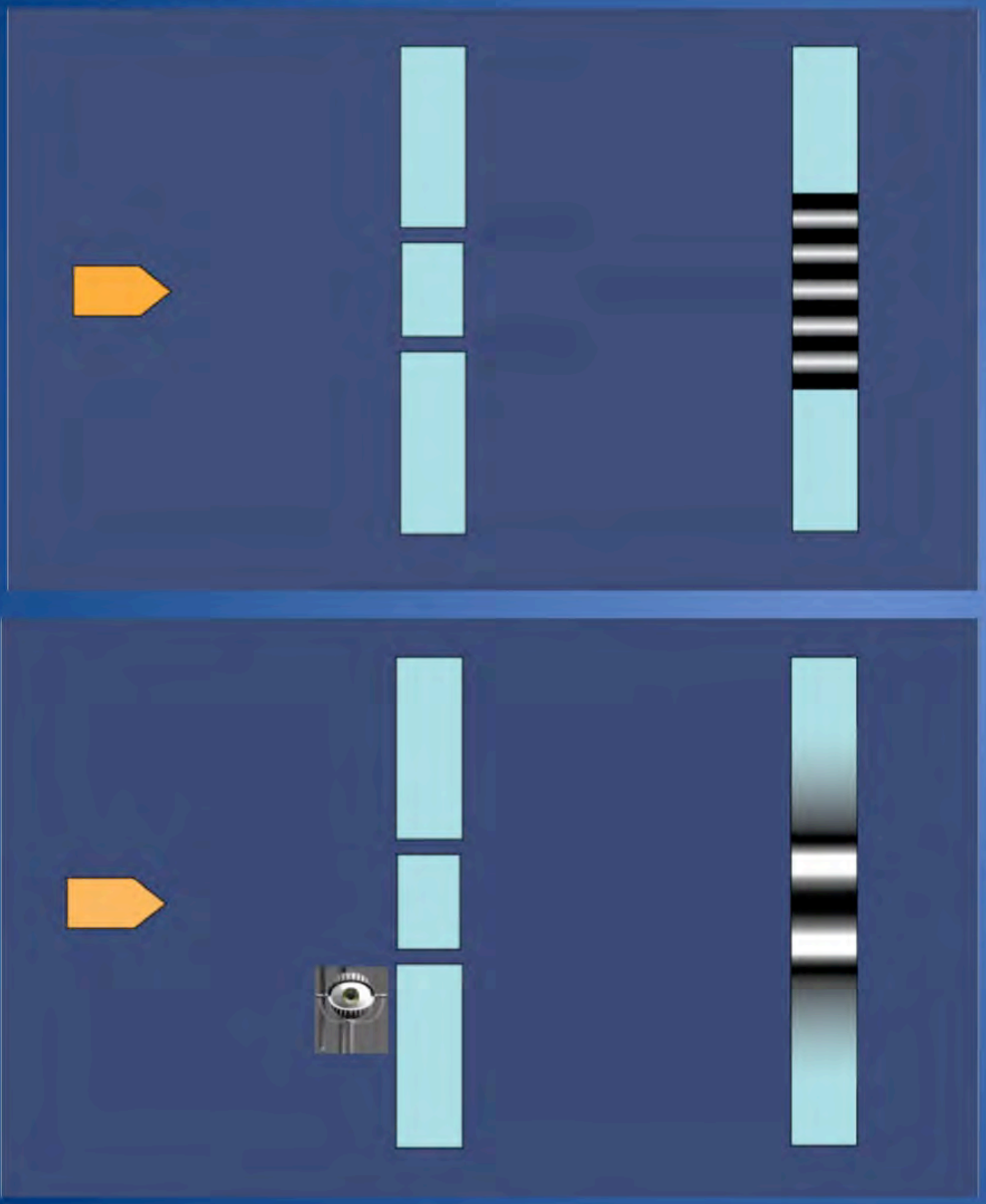
Dr. Quantum (*The infaumous double slit experiment* - YouTube)



si sommano le *intensità* delle figure prodotte da ciascuna fenditura, considerata ***separatamente*** ...



Riassumendo:



no informazione sul percorso
⇒ interferenza

informazione sul percorso
⇒ no interferenza

Cosa interferisce con cosa?

Qui non si tratta di oggetti fisici tradizionali, ma di entità ***astratte***, ovvero due ***percorsi "potenziali"***, che sovrapponendosi danno origine a interferenza (*ecco il senso che si può dare alla frase di Dirac*). In altri termini si può dire che a interferire sono "***onde di probabilità***"

Usando un apparato che può dirci quale delle due possibilità si verifica l'interferenza non si osserva più.

La scomparsa dell'interferenza ***non è*** dovuta al "disturbo" prodotto dalla misura.

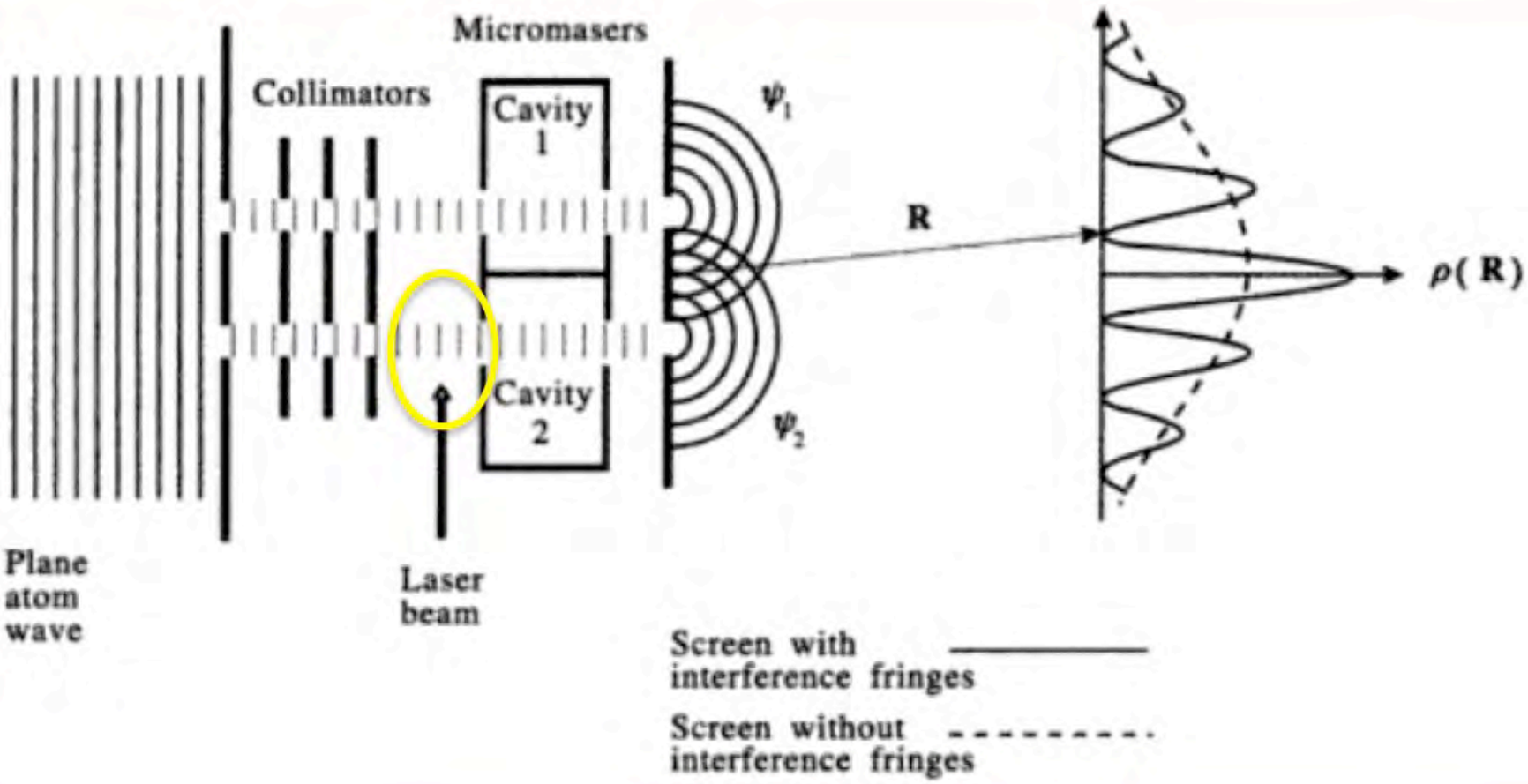


Fig. 20.3 Schematic diagram of the double-slit experiment with atoms. (From M. O. Scully, B.-G. Englert, and H. Walther, *Nature* **351**, 111 (1991).)

Schema dell'esperimento concettuale di *Scully et al.* (1991) in cui la determinazione del percorso produce una variazione di momento trascurabile sull'atomo

Un esperimento reale che si ispira a questo è stato fatto per la prima volta nel 1998 (*Durr et al. Nature, 395, 33, 1998*)

Una semplice regola per l'interferenza quantistica

L'interferenza di singoli oggetti quantistici si osserva quando questi hanno a disposizione più cammini per arrivare allo stesso rivelatore e nello stesso tempo la configurazione sperimentale non permette di distinguere tra questi cammini.

Interferenza di "alternative"

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"*)

Realtà *versus* possibilità

''But the atoms or the elementary particles are ***not real;*** they form a world of ***potentialities*** or ***possibilities*** rather than one of things and facts.'' (**W. Heisenberg**)

Riassumendo

- In un sistema a più cammini, il percorso di un elettrone/ fotone singolo ***è indefinito***, ed è descrivibile come ***sovrapposizione*** di tutti i cammini possibili. La ***sovrapposizione di alternative*** genera l'interferenza quantistica.

- Ciò che è definito è la ***probabilità*** di ciascuna alternativa. Questa si può calcolare con le equazioni della MQ.

- La ***misura*** annulla la sovrapposizione di possibilità, scegliendone una sola e cancellando così l'interferenza (***collasso***).

- Il processo di misura, anche se non perturba l'oggetto quantistico in modo apprezzabile, ha un ruolo attivo nel determinare lo stato che viene effettivamente osservato.

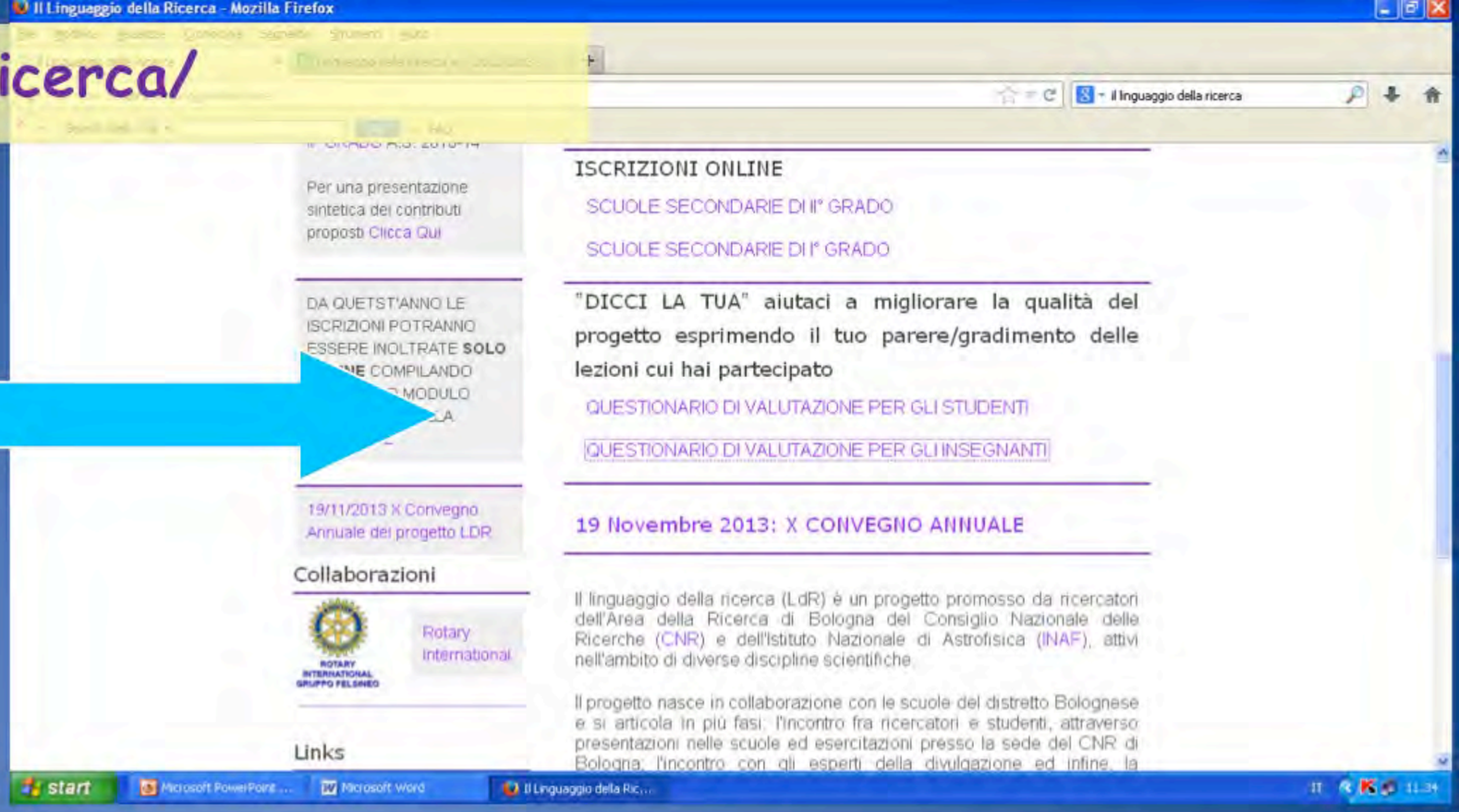
Essere quantistici ....

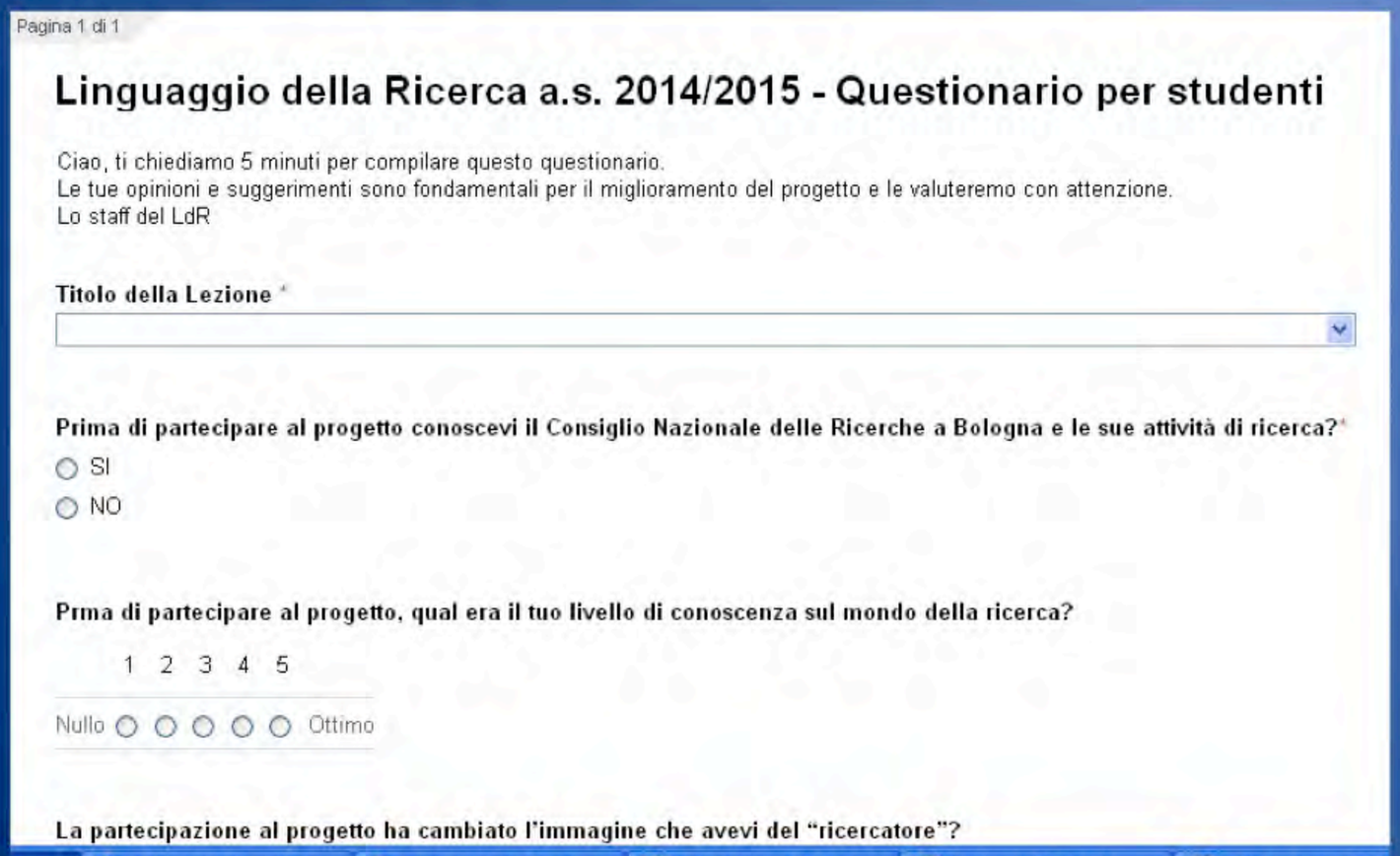
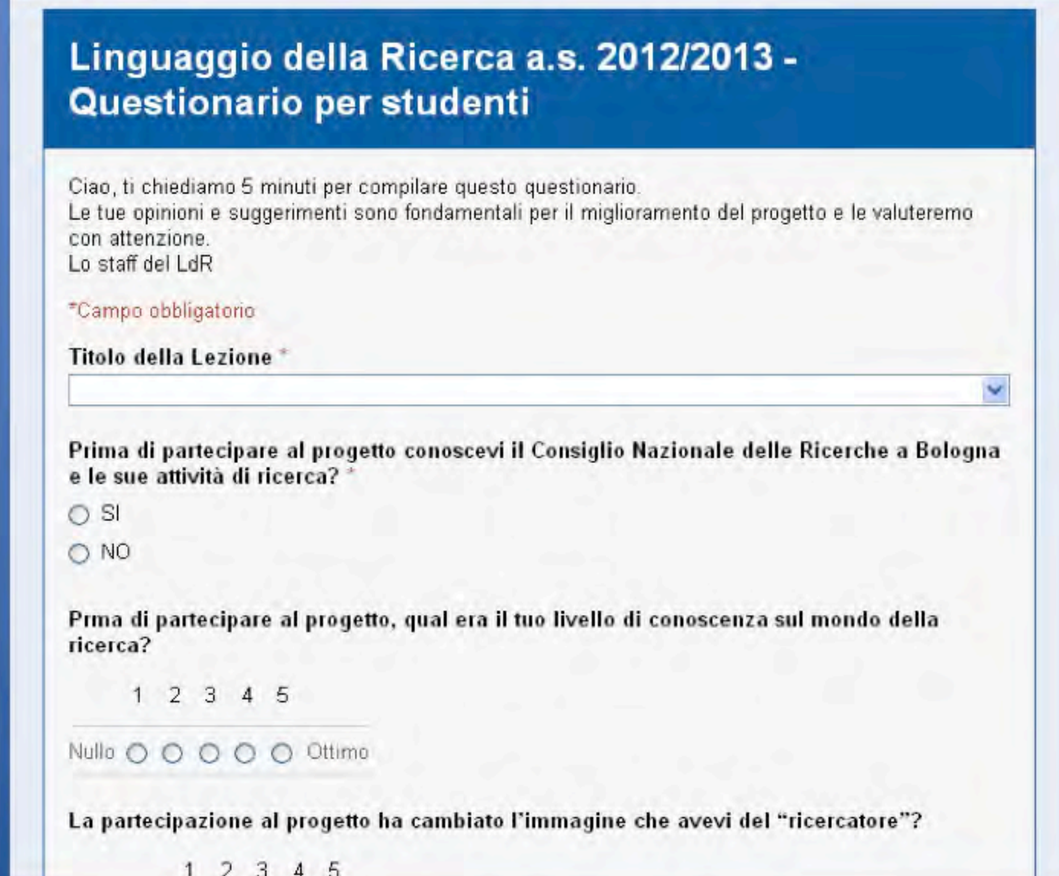
grazie per l'attenzione!

www.bo.cnr.it/linguaggiodella ricerca/

Ora tocca a voi….

“DICCI La TUA” dopo la lezione



Per gli Studenti

Per gli Insegnanti