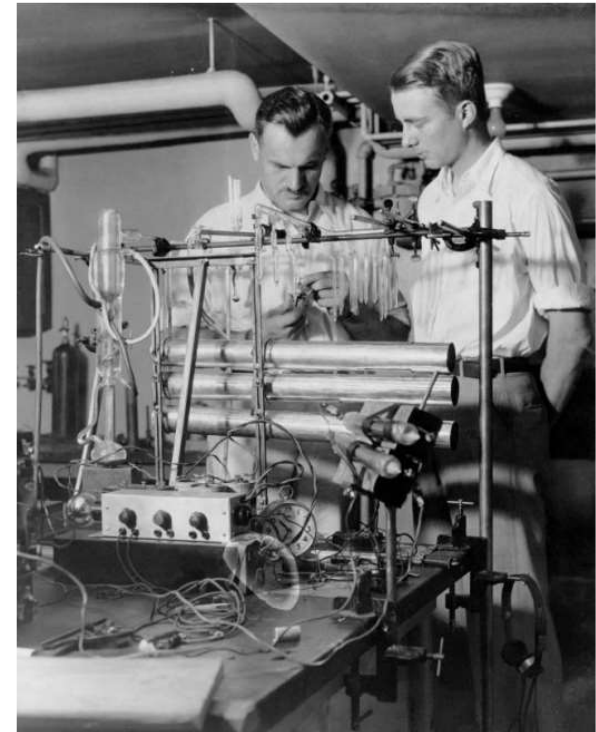


Evidência experimental para teoria quântica da luz

Radiação do corpo negro



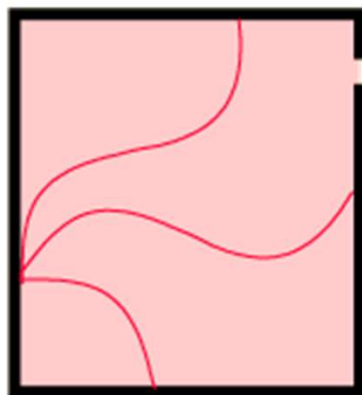
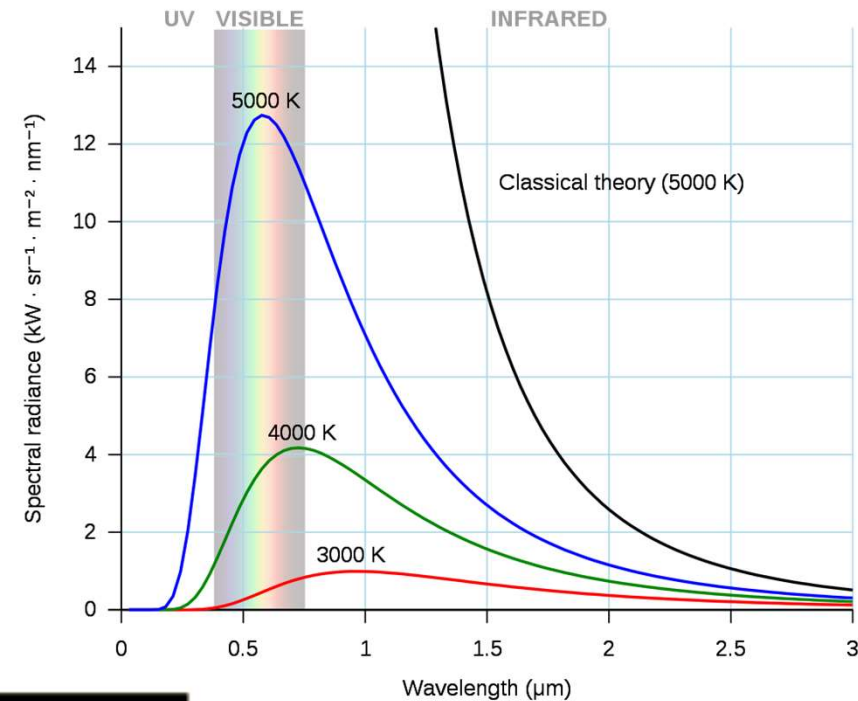
Dispersão de Compton



O efeito fotoelétrico



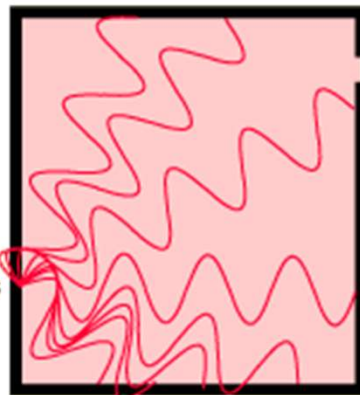
As primeiras fissuras na fundação clássica



Number of modes
per unit frequency
per unit volume

$$\frac{8\pi f^2}{c^3}$$

For higher frequencies
you can fit more modes
into the cavity. For
double the frequency,
four times as many
modes.

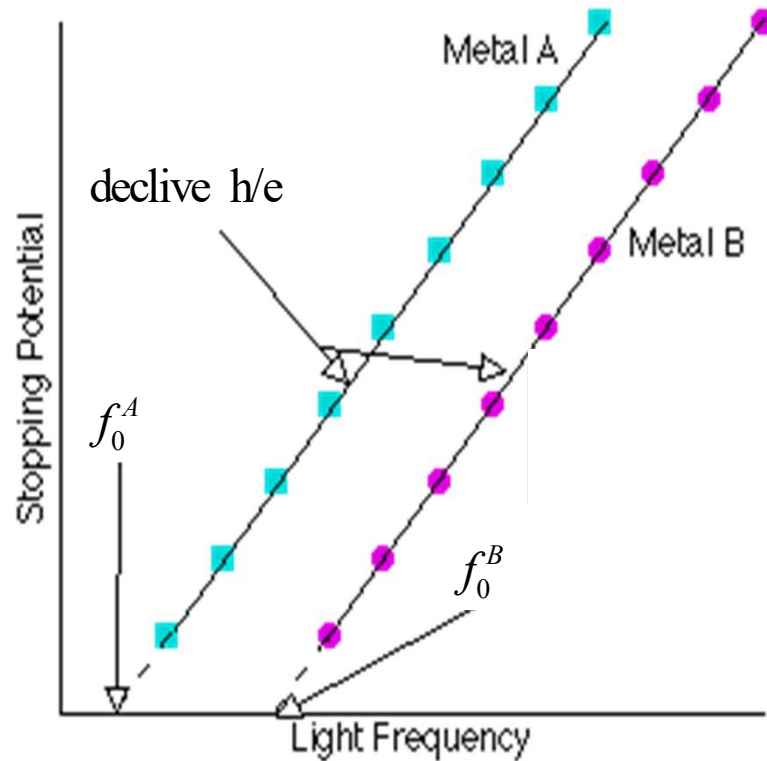


Cada modo ocupado
tem uma energia média $k_B T$



Corpo negro só
absorve (emite)
radiação em
pacotes de
energia $\Delta E = hf$

Efeito fotoelétrico



Energia dum fóton

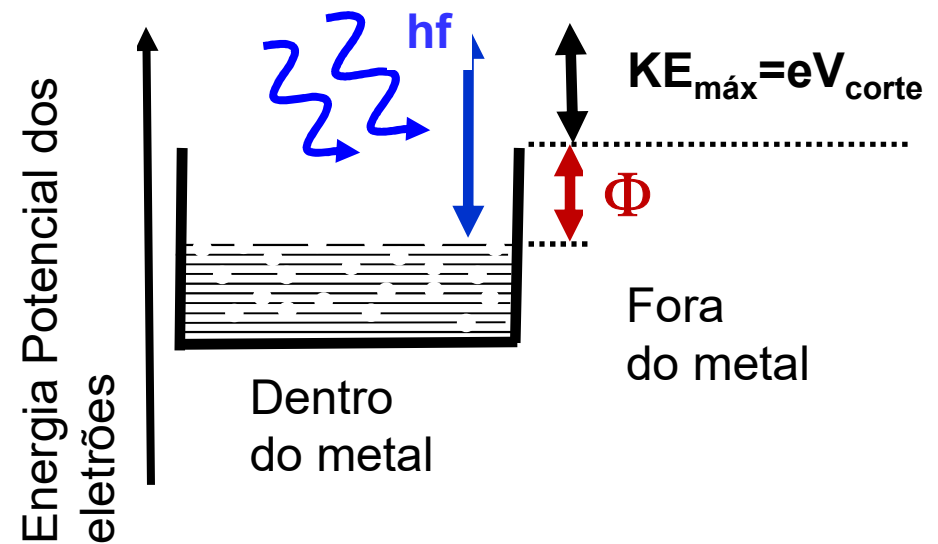
$$E_{\text{fóton}} = hf = \frac{hc}{\lambda} \approx \frac{1240 \text{ eV}(nm)}{\lambda}$$

$$hf = eV_{\text{corte}} + \Phi$$

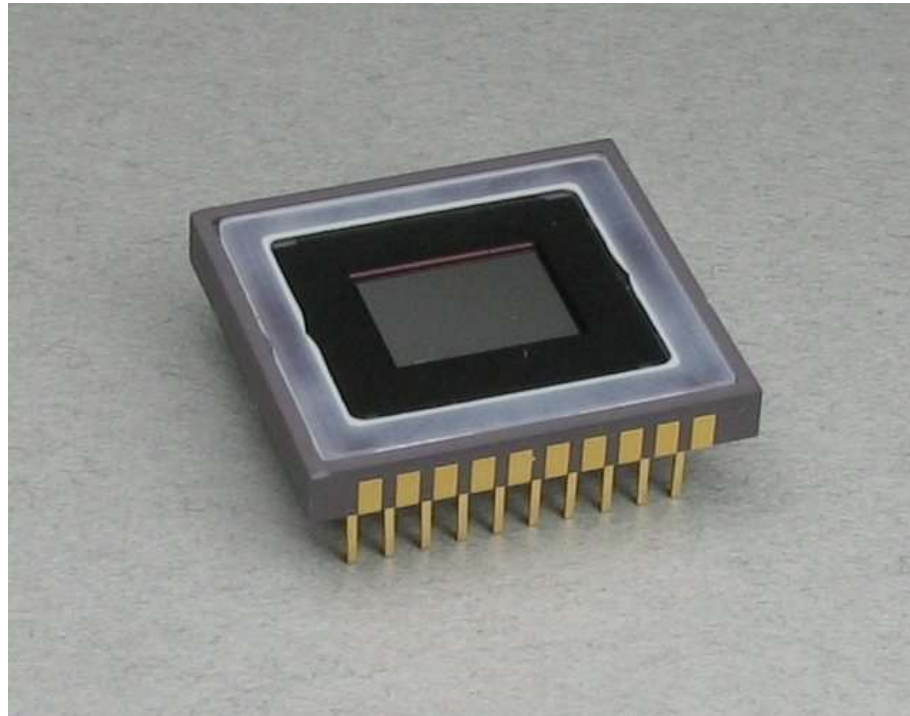
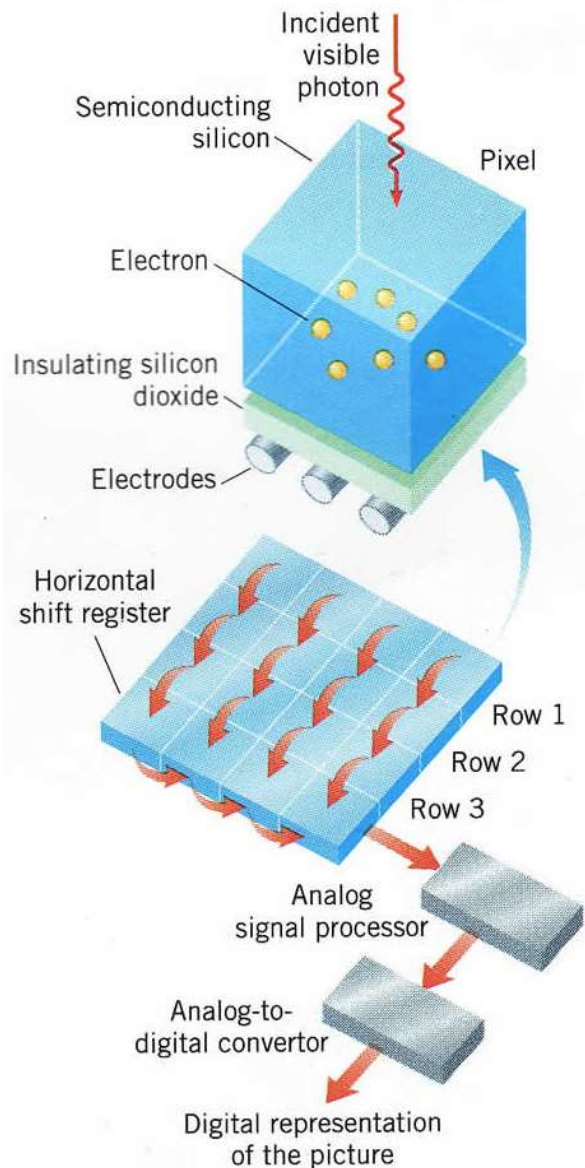
$$V_{\text{corte}} = \frac{h}{e} f - \frac{\Phi}{e}$$

Declive h/e

Função trabalho $\Phi = hf_0$



Câmaras CCD e CMOS



Cada “pichel” é uma experiência fotoelétrica isolada.

Elétrodos positivos atraem os foto eletrões onde são guardados até o ato de leitura.

Relutância de aceitar a quantização da radiação

A DIRECT PHOTOELECTRIC DETERMINATION OF PLANCK'S " h ."¹

BY R. A. MILLIKAN.

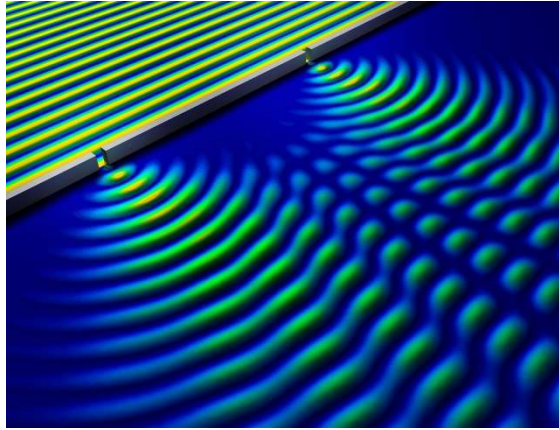
10. SUMMARY.

1. Einstein's photoelectric equation has been subjected to very searching tests and it appears in every case to predict exactly the observed results.

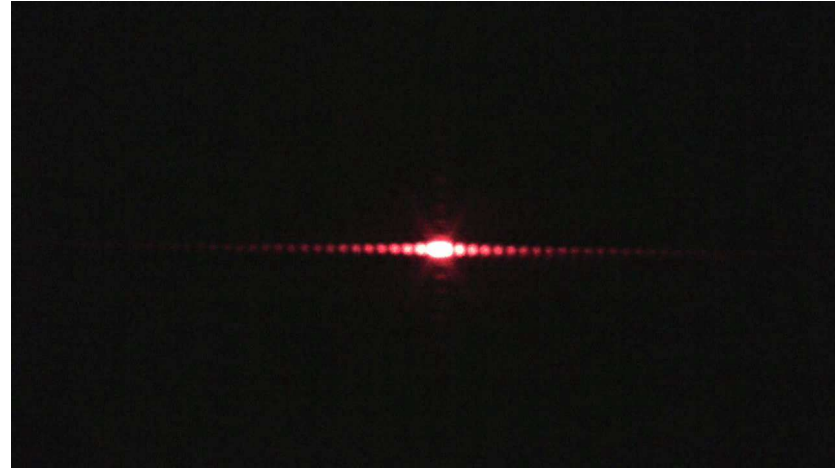
A ideia que a luz é um fenómeno ondulatório era muito enraizada.

Despite then the apparently complete success of the Einstein equation, the physical theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it.

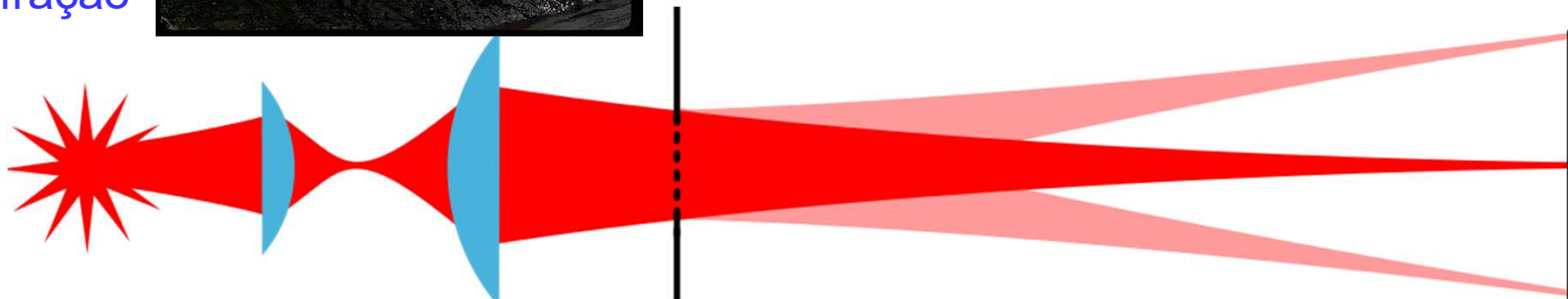
Efeitos ondulatórios com luz



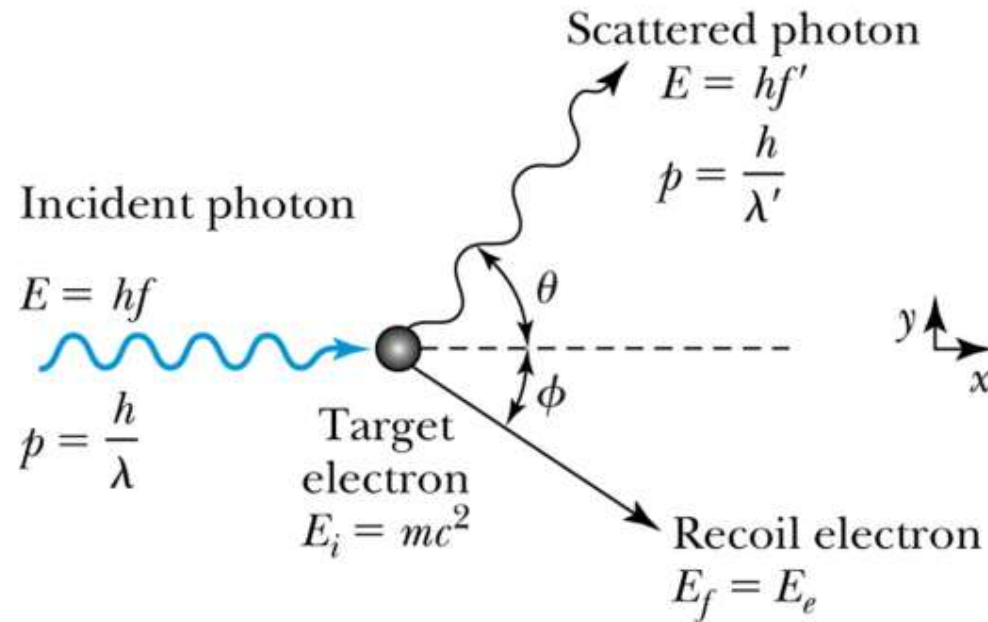
Dupla fenda interferência



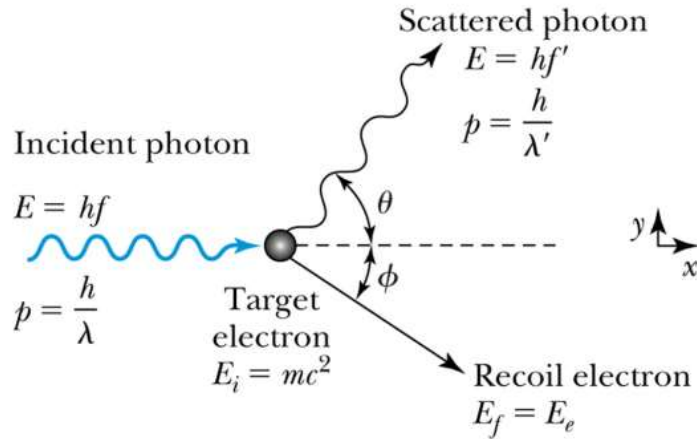
Difração



Efeito de Compton



Colisões entre fótons e elétrons.



$$P_{in}^{fot\tilde{a}o} = (hf / c, hf / c, 0, 0)$$

$$P_{in}^e = (mc, 0, 0, 0)$$

$$P_{final}^{fot\tilde{a}o} = (hf' / c, hf' \cos \theta / c, hf' \sin \theta / c, 0)$$

$$P_{final}^e = (\gamma mc, \gamma mv \cos \phi, -\gamma mv \sin \phi, 0)$$

$$P_{in}^{fot\tilde{a}o} + P_{in}^e = P_{final}^{fot\tilde{a}o} + P_{final}^e$$

$$(P_{in}^{fot\tilde{a}o} + P_{in}^e - P_{final}^{fot\tilde{a}o}) \bullet (P_{in}^{fot\tilde{a}o} + P_{in}^e - P_{final}^{fot\tilde{a}o}) = P_{final}^e \bullet P_{final}^e$$

$$P_{in}^{fot\tilde{a}o} + P_{in}^e - P_{final}^{fot\tilde{a}o} = P_{final}^e$$

$$\vdots$$

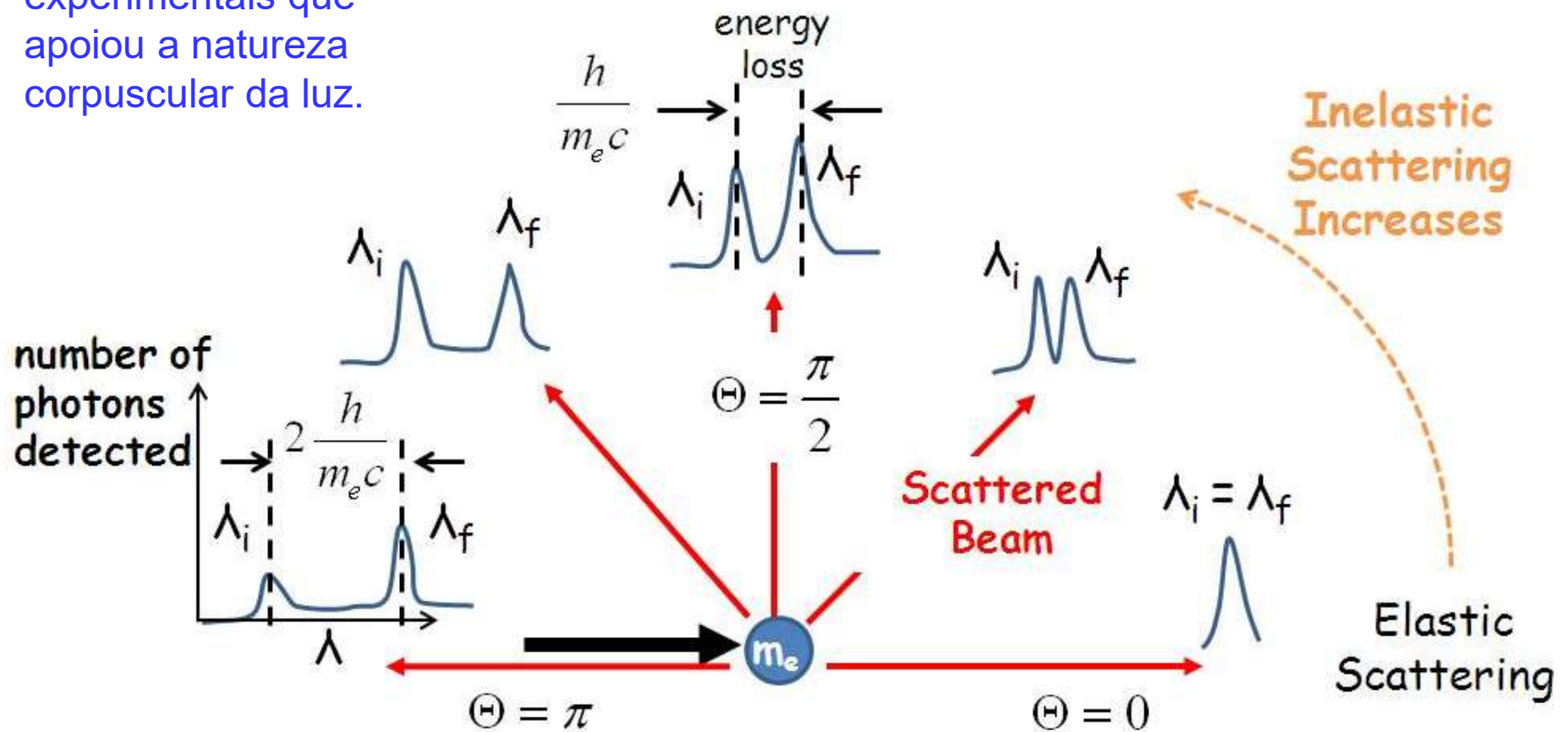
$$f \lambda = c$$

$$\lambda' - \lambda = \frac{h}{mc^2} [1 - \cos \theta]$$

Dispersão Compton

Um dos primeiros resultados experimentais que apoiou a natureza corpuscular da luz.

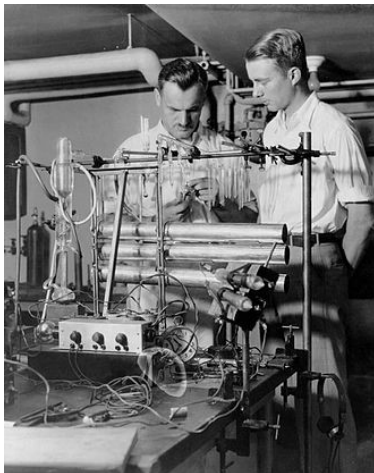
$$\lambda_f - \lambda_i = \frac{h}{mc}(1 - \cos \Theta)$$



Experiência de Arthur Compton



Artur Compton
1892-1962
Nobel 1927



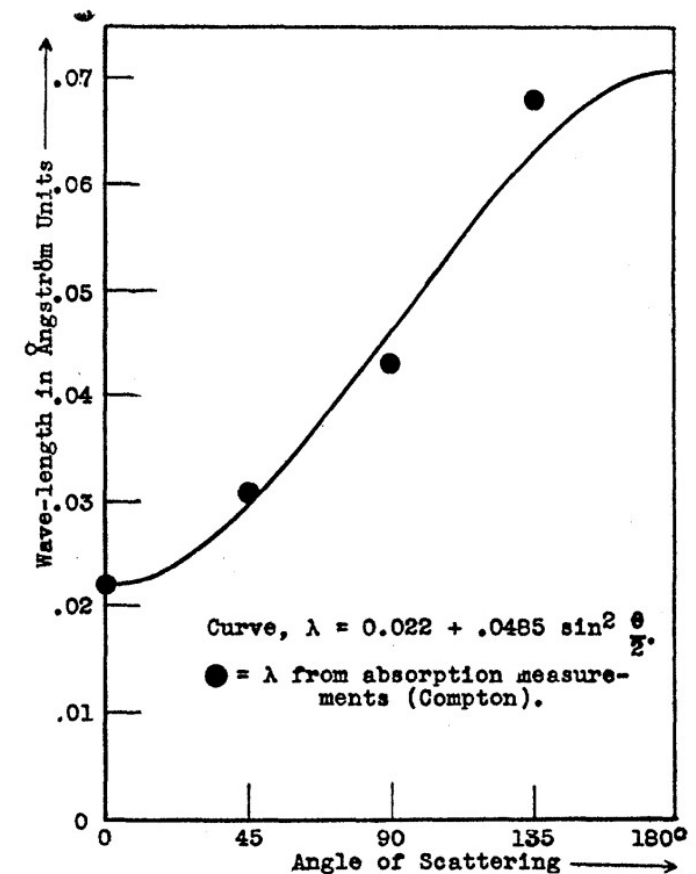
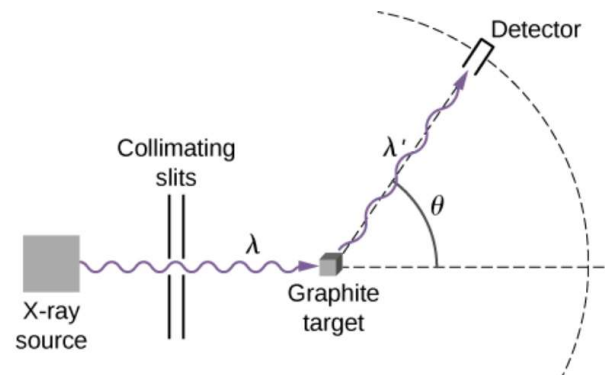
THE PHYSICAL REVIEW

A QUANTUM THEORY OF THE SCATTERING OF X-RAYS
BY LIGHT ELEMENTS

BY ARTHUR H. COMPTON

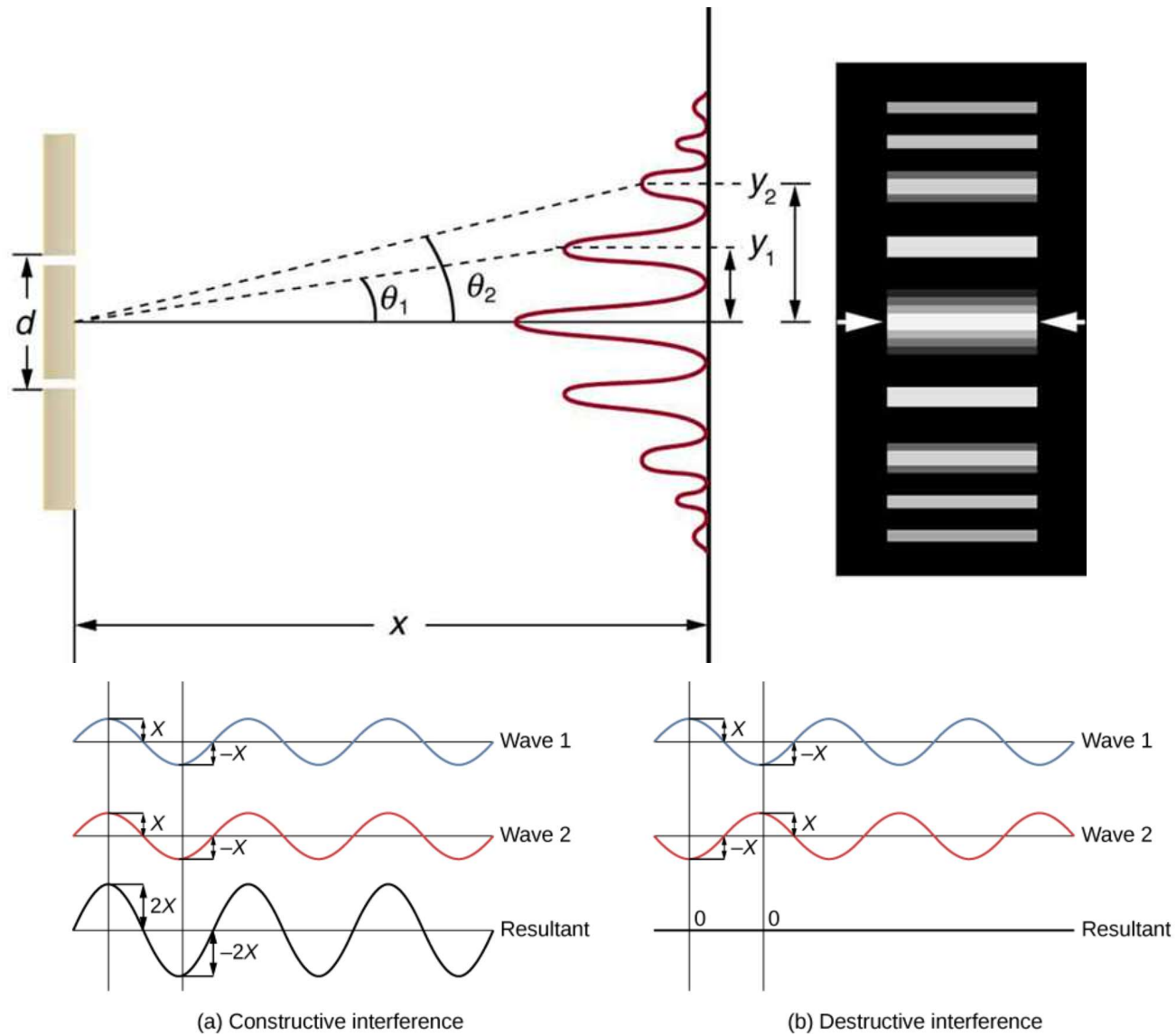
$$\lambda_f - \lambda_i = \frac{h}{mc}(1 - \cos \Theta)$$
$$= 2 \frac{h}{mc} \sin^2 \left(\frac{\Theta}{2} \right)$$

$$2 \frac{h}{mc} \approx 4.853 \text{ pm} = 0.0485 \text{ Angstrom}$$

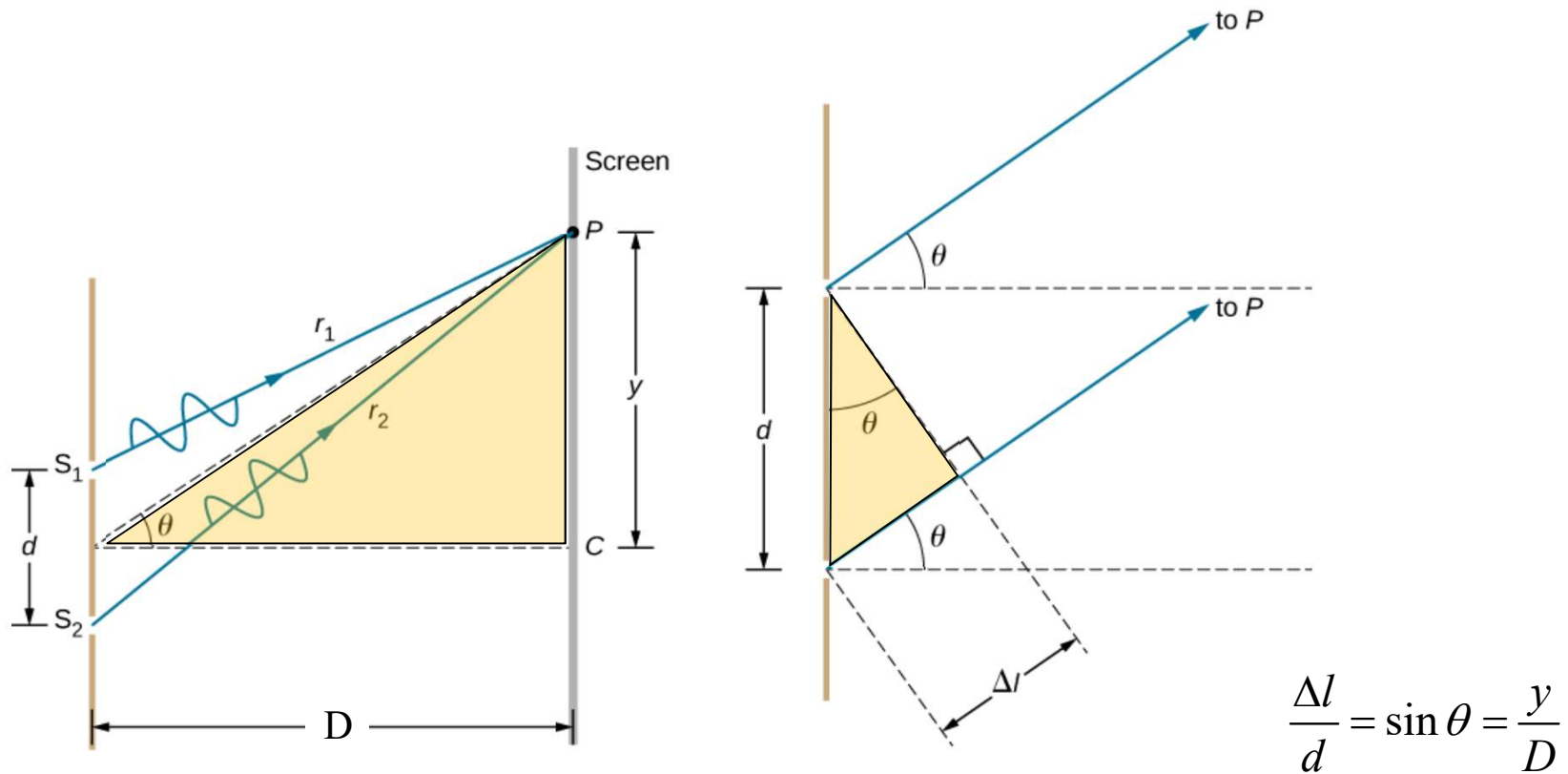


A.H. Compton, *Phys. Rev.* **22** 409 (1923)

Experiência da Dupla fenda de Young (1805)



Contas



É assumido que $d \ll D$ (distância entre fendas e écran)
Neste caso os raios r_1 e r_2 são quase paralelos

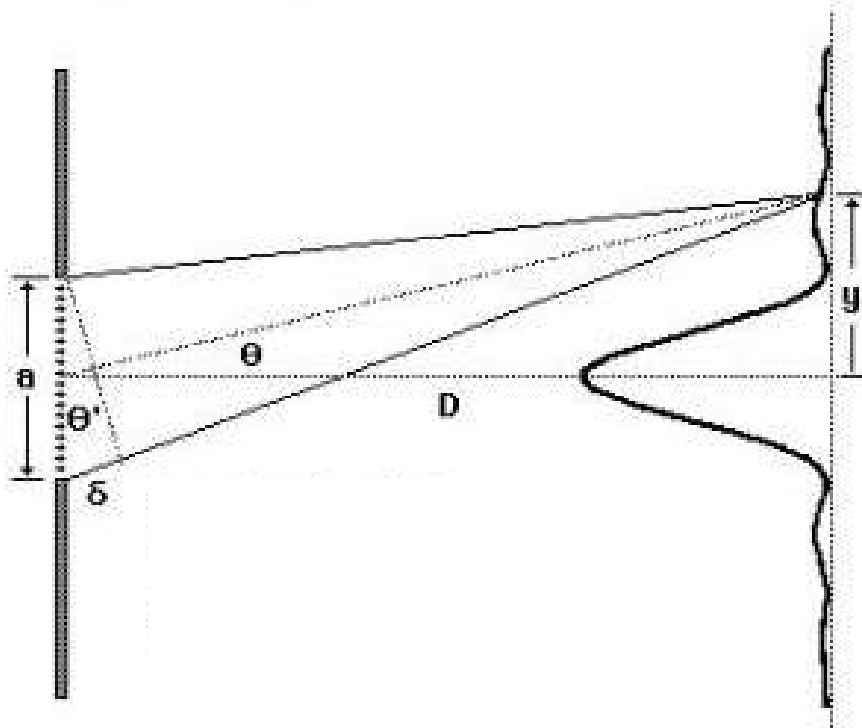
Interferência construtiva quando

$$\Delta l = m\lambda \Rightarrow y_{\text{brilhante}} = m\lambda(D/d)$$

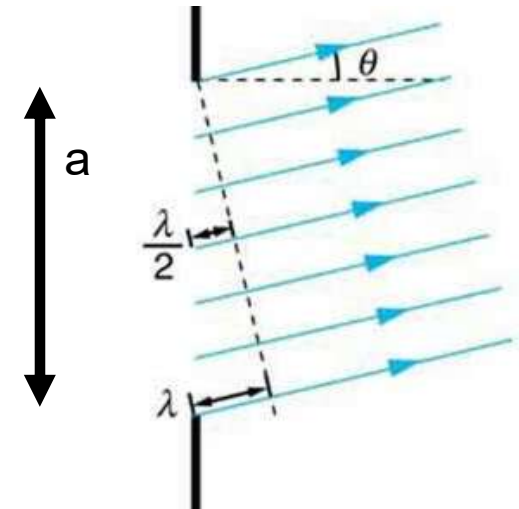
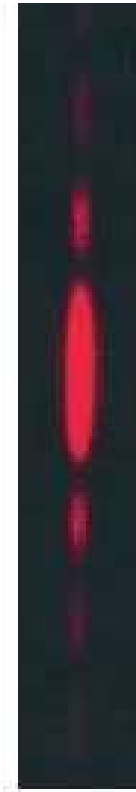
Interferência destrutiva quando

$$\Delta l = \left(m + \frac{1}{2}\right)\lambda \Rightarrow y_{\text{escuro}} = \left(m + \frac{1}{2}\right)\lambda(D/d)$$

Uma Fenda só: Difração



Dividir as ondas em pares lançados com uma distância $a/2$ na fenda.

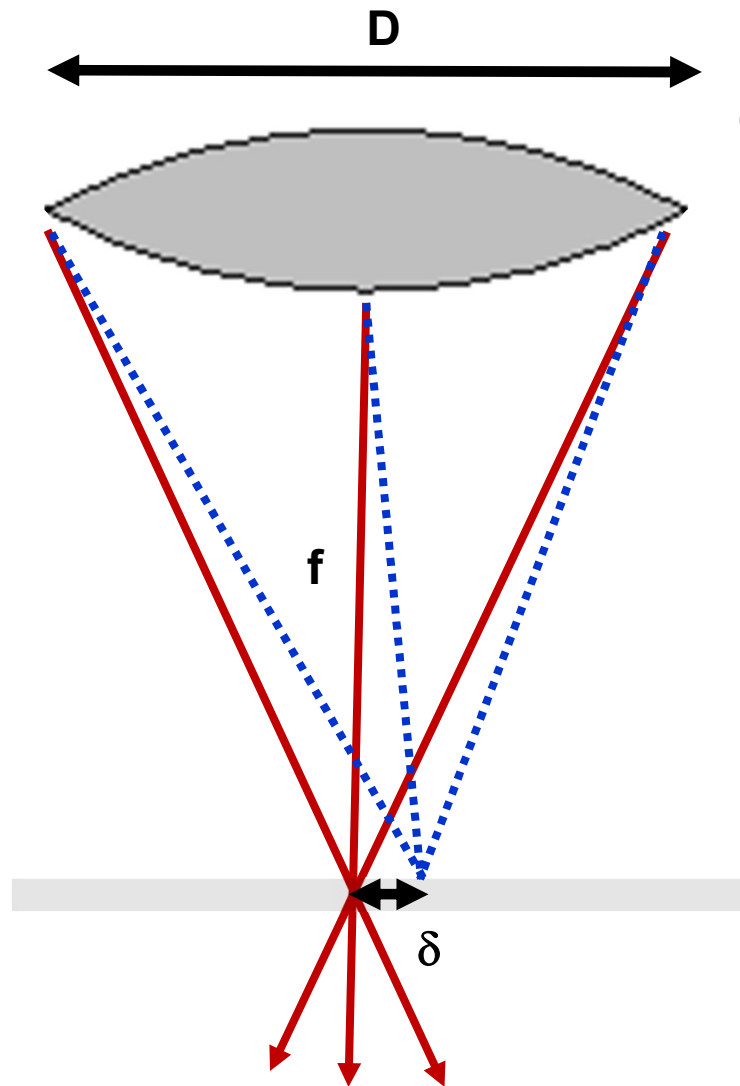


Primeiro mínimo

$$\frac{\lambda}{2} \sin \theta = \frac{a}{2}$$

$$y_{\text{escuro}} = D \sin \theta = \frac{m \lambda D}{a}$$

Aplicação: limite de resolução



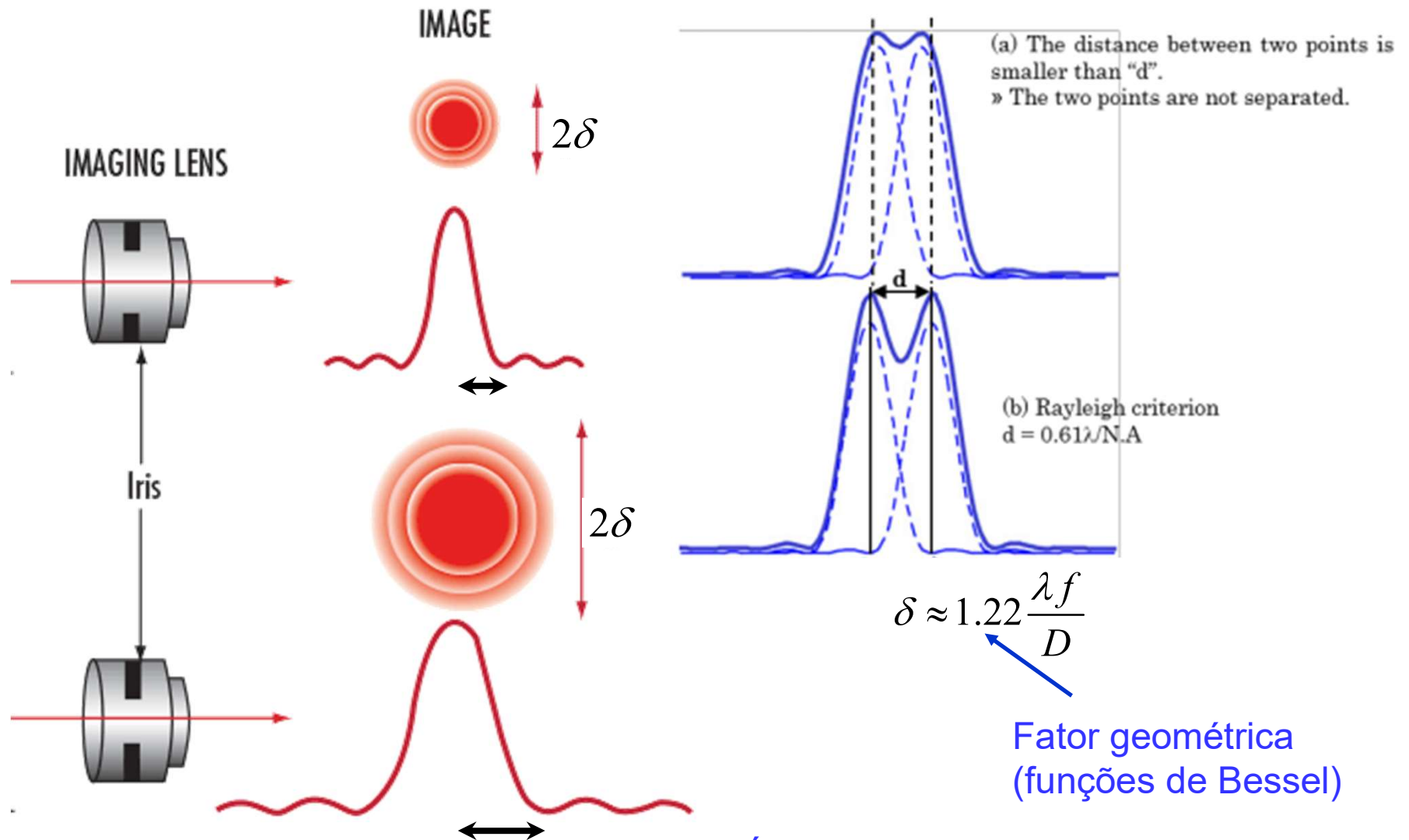
Lente fabricada a maneira que o percurso ótico até o foco é igual para todos os raios

Interferência destrutiva quando

$$y_{\text{escuro}} = D \sin \theta = \frac{m\lambda D}{a} \quad a \rightarrow D; D \rightarrow f$$

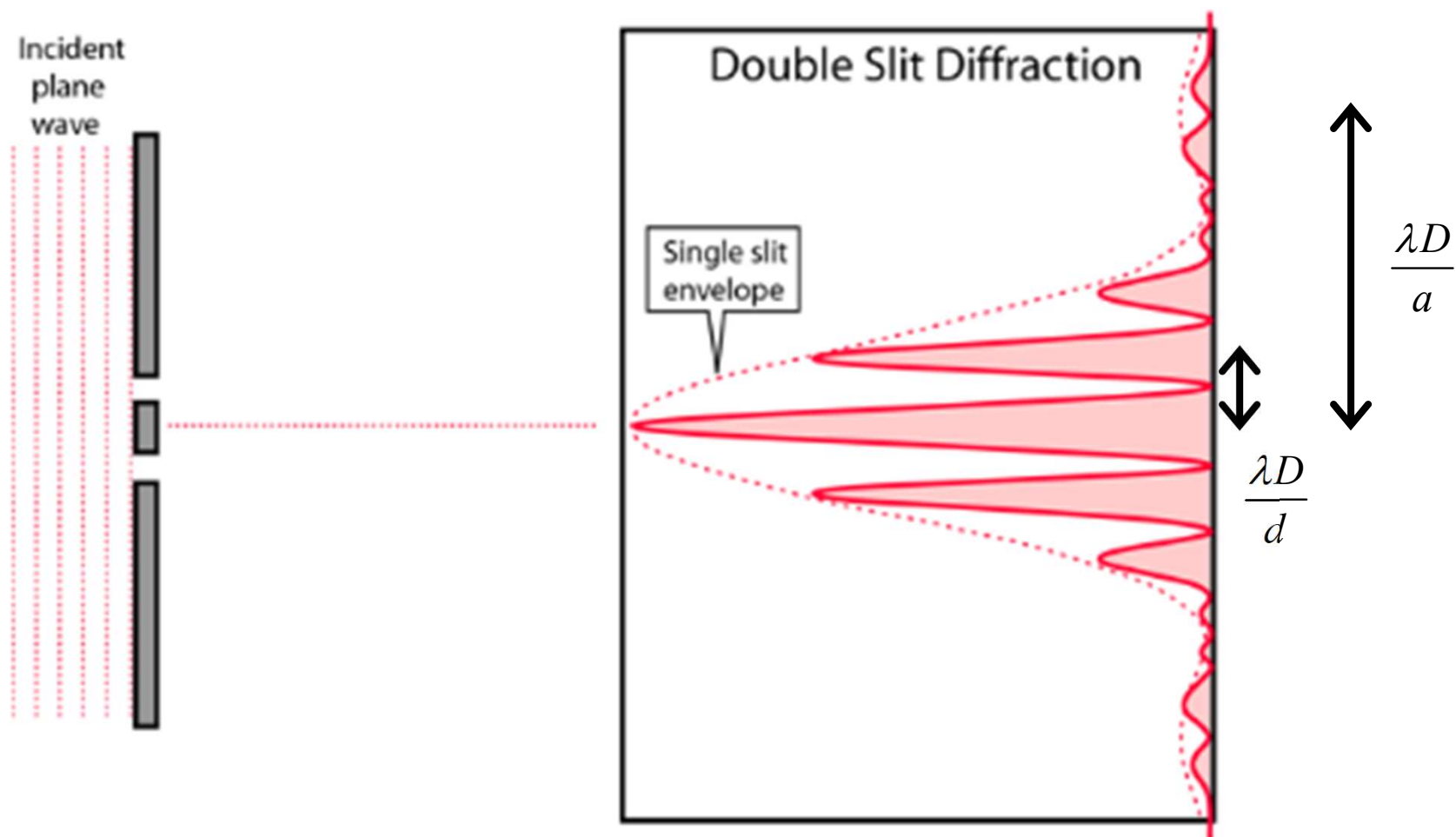
$$\delta \approx \lambda \frac{f}{D}$$

Resolução



É difícil fabricar uma lente para qual $f < D$
melhor resolução $\sim \lambda$.

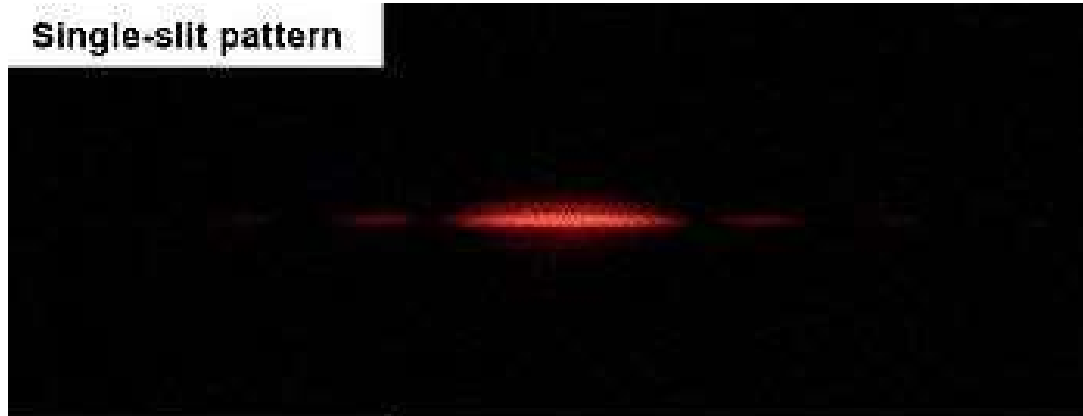
Em geral existe os dois efeitos



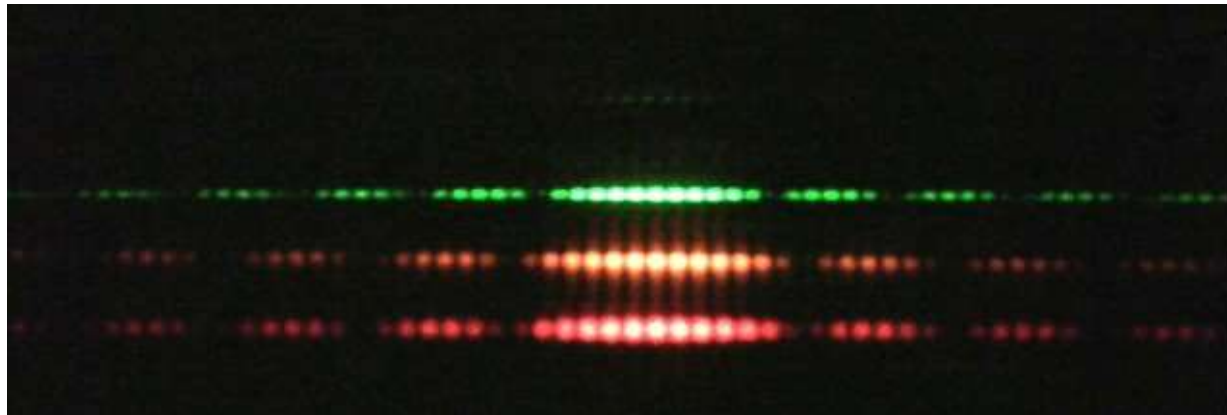
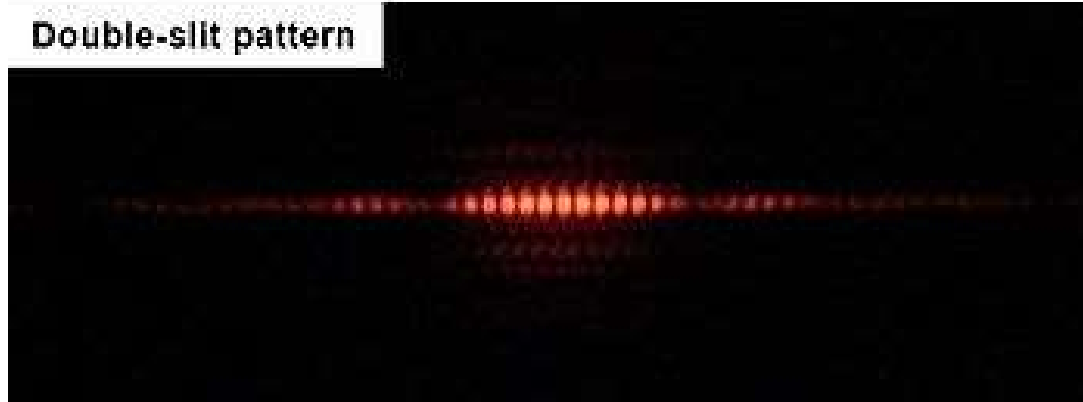
Distância entre as fendas = d
Largura duma fenda = a

Em geral existe os dois efeitos

Single-slit pattern

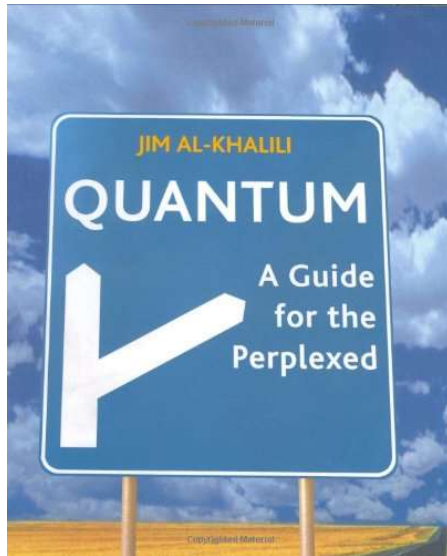


Double-slit pattern



Luz uma onda ou um fotão?

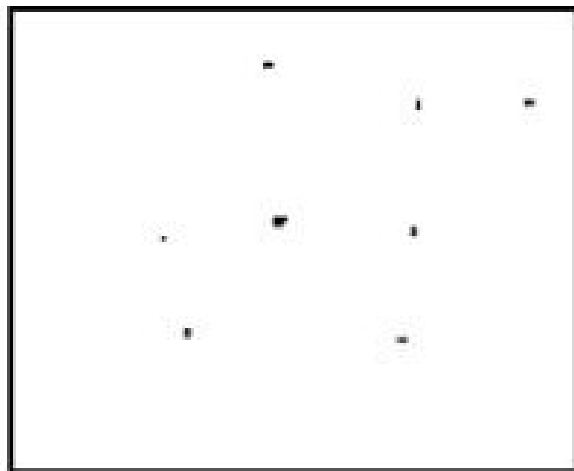
" I think I can safely say that nobody understands quantum mechanics." (R. Feynman)



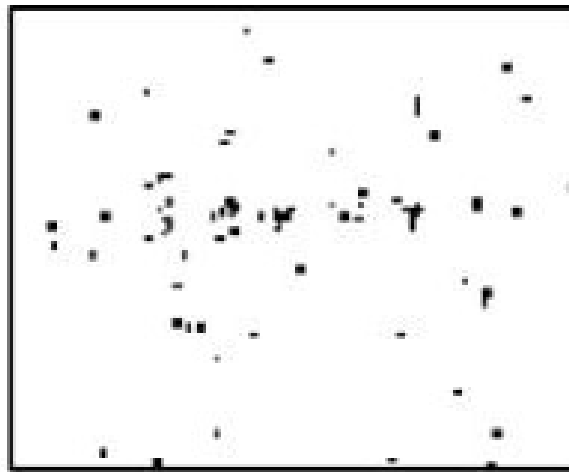
Richard Feynman (1918-1988)
Prémio Nobel 1965

Experiência de Young com reduzida intensidade

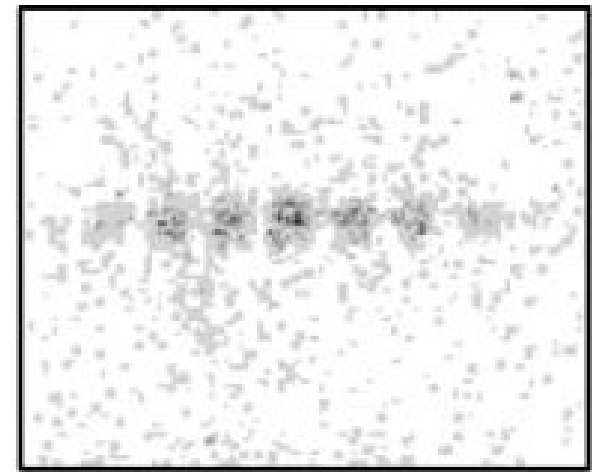
Detetor: câmara CCD detete fotões através o efeito fotoelétrico
píxeis – resolução espacial



No. of photons=19



No. of photons=203



No. of photons=5067

Increasing no. of photons



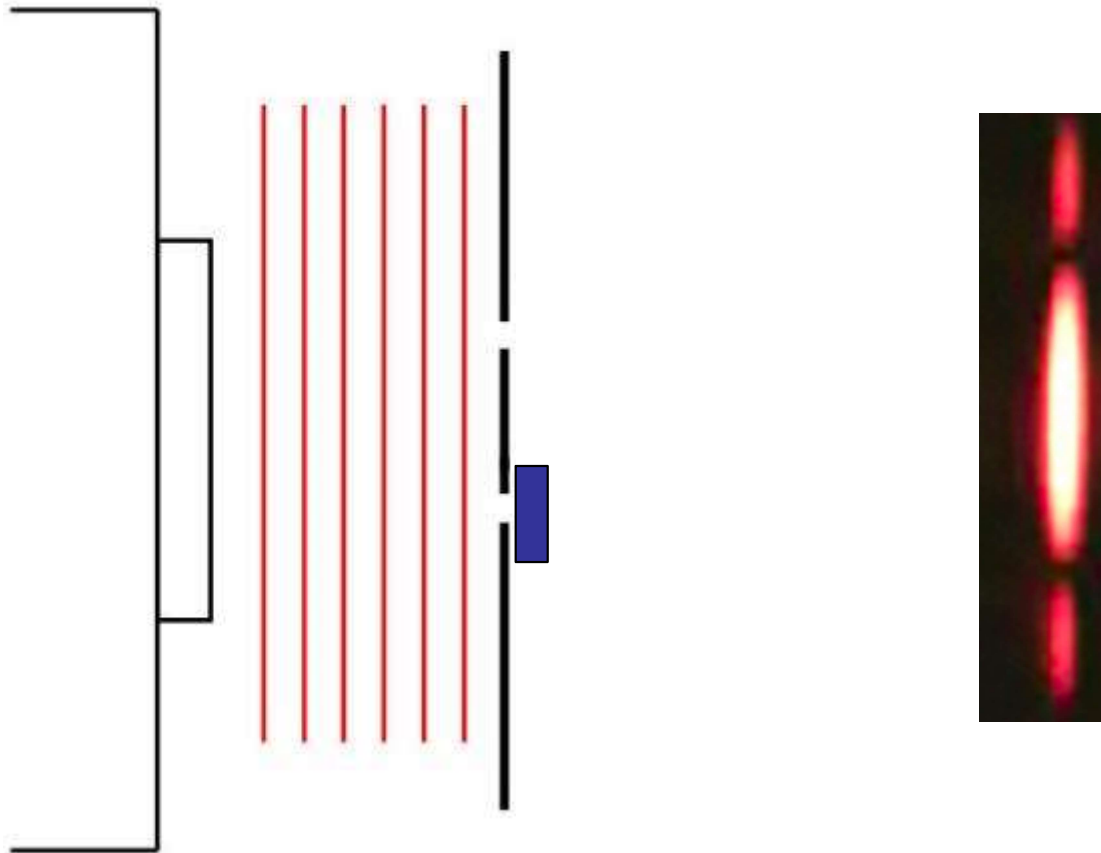
Fotão a fotão, a padrão de interferência aparece!

Luz manifesta características ondulatórios e corpusculares

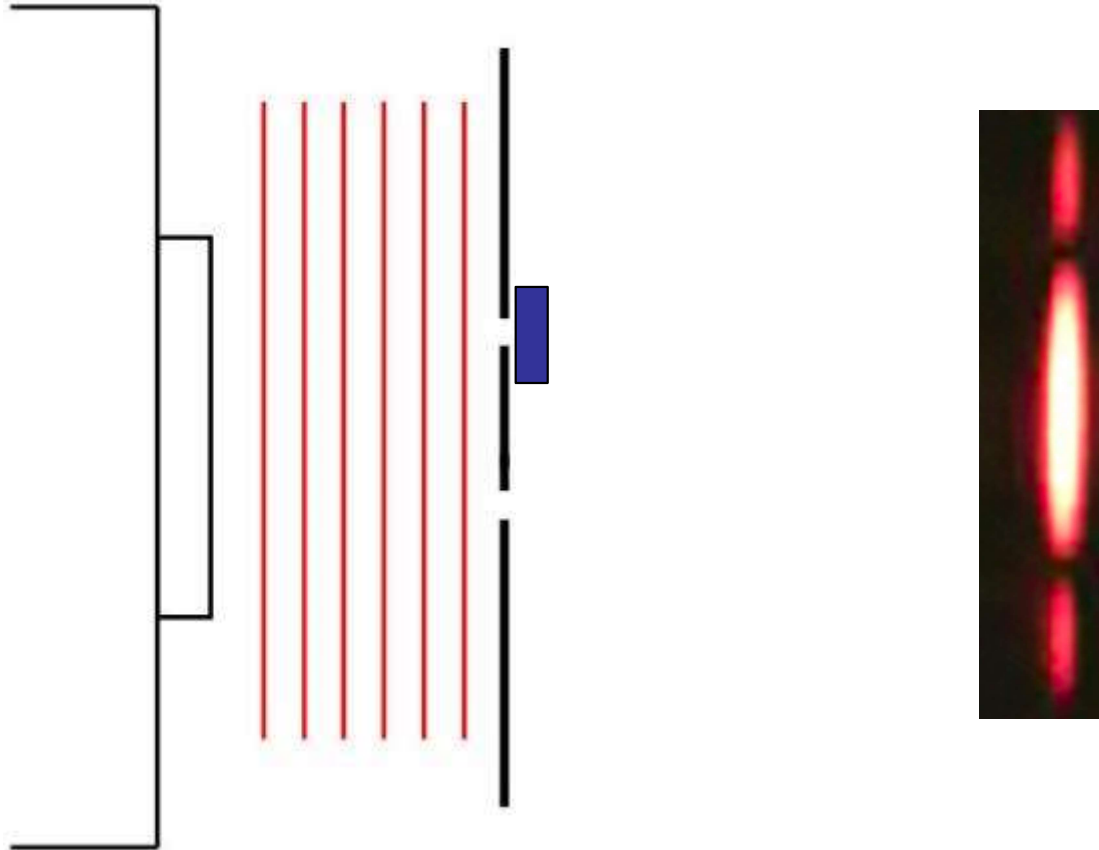
LIGHT IS A

WAVE!

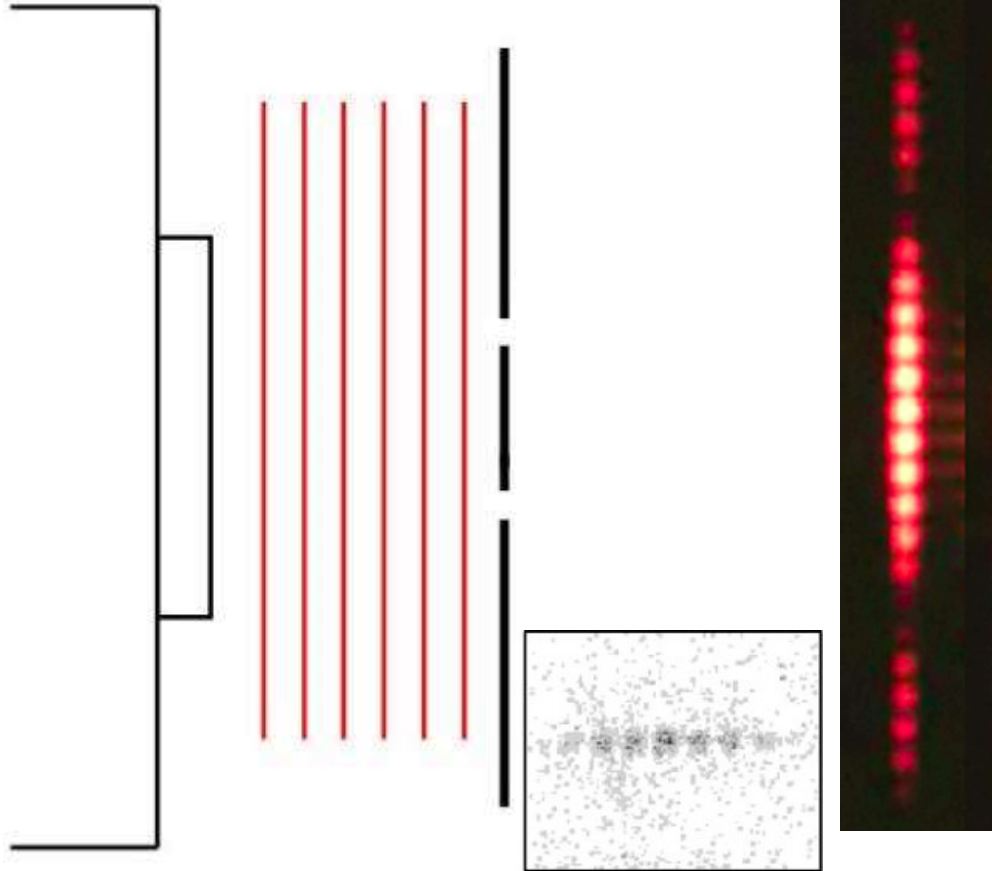
Uma fenda



Outra fenda



As duas Fendas



Feynman:
Cada trajetória possível é
caracterizada por uma
função ondulatória

$$\psi_1, \psi_2, \dots, \psi_n$$

- A probabilidade de detetar um fóton é dado pela valor absoluto quadrado da soma dos amplitudes

$$P(y) = \left| \sum_i \psi_i(y) \right|^2$$



Max Born

- Mais o fóton só pode ser detetado uma vez

Existe pontos que são iluminados quando uma ou outra fenda é destapada
mas ficam escuros quando ambas as fendas são destapadas

No entanto a padrão é construída fóton á fóton....

Cada fóton individual infere consigo próprio!



Louis de Broglie
1892-1987
Nobel 1929

Se a luz comporta como partículas com

uma energia $E = hf$

$$E^2 = p^2 c^2 + m^2 c^4$$

e um momento $p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$

Então talvez partículas com um momento p ,
podem se comportar como ondas com um
comprimento de onda

$$\lambda = \frac{h}{p}$$

Dupla fenda com elétrons



A probabilidade de detetar um elétron é dado pelo padrão de interferência.
Existe uma “onda” associada com a trajetória do elétron $\psi(\vec{r})$

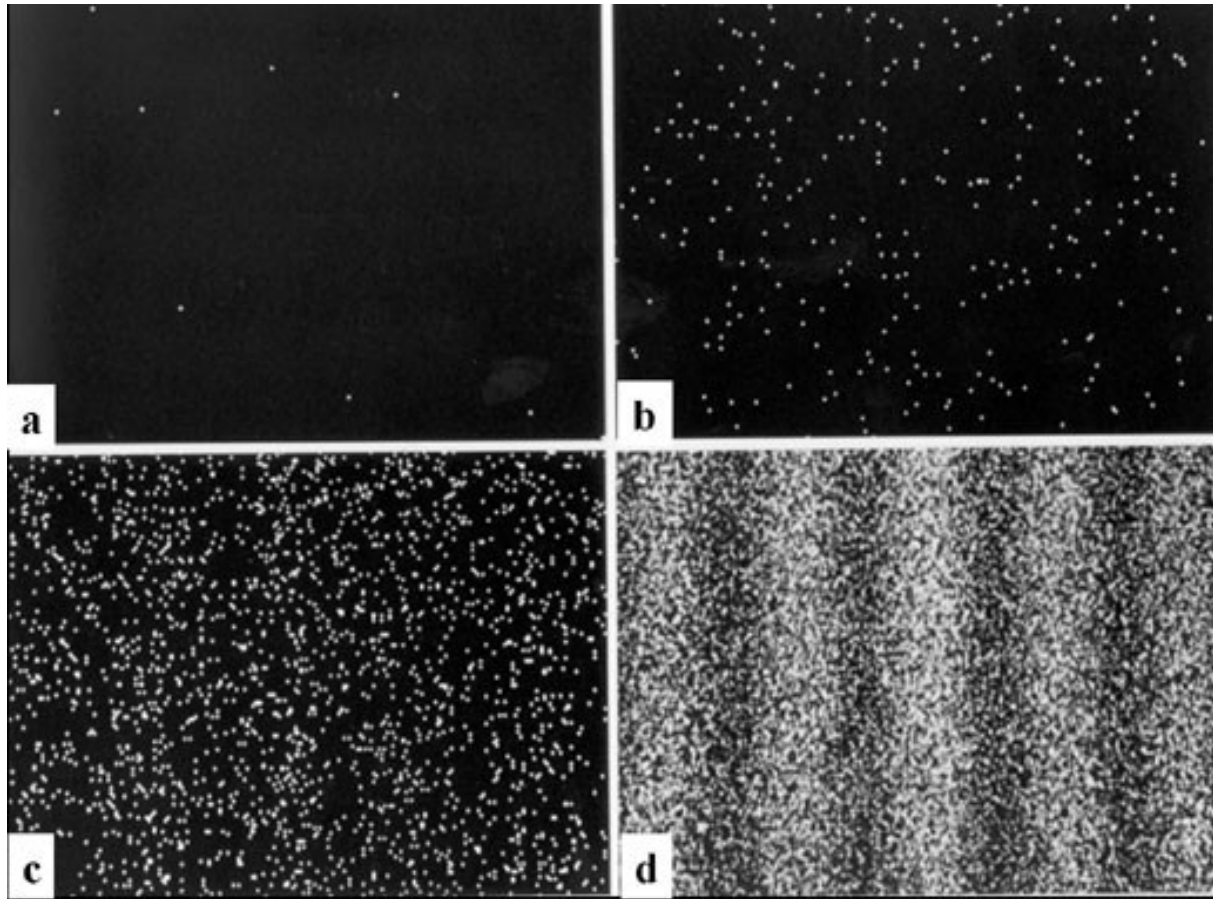
$$P(\vec{r}) = \left| \psi_1(\vec{r}) + \psi_2(\vec{r}) \right|^2$$

Princípio de Born



Max Born
Nobel 1954

Dupla Fenda com Eletrões



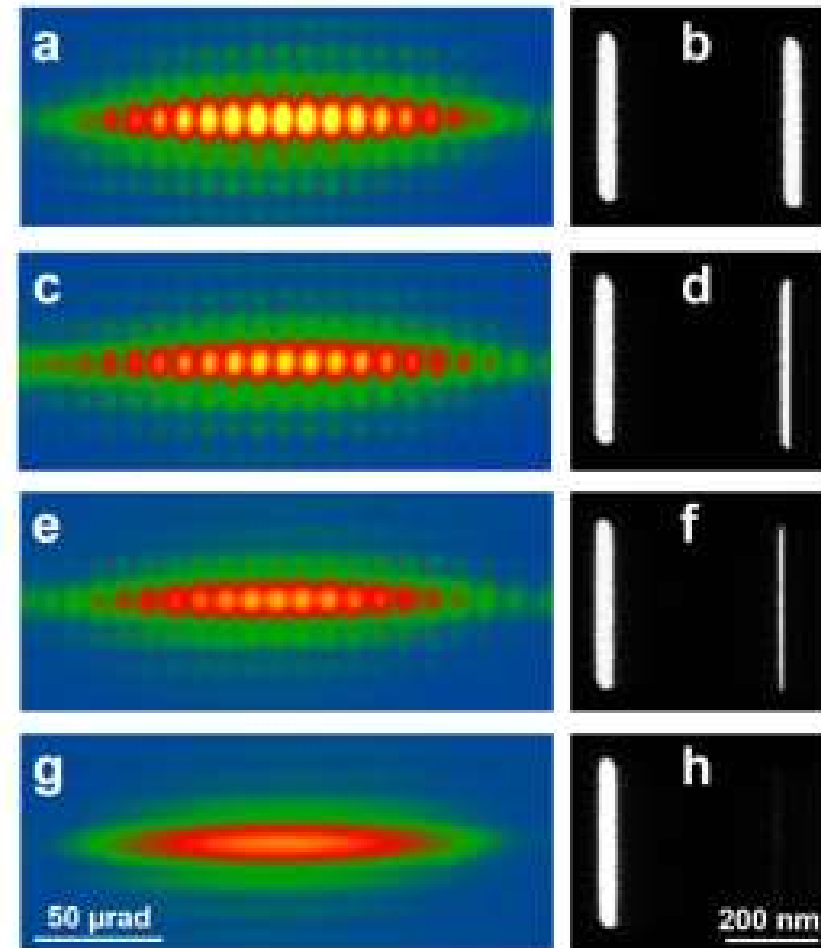
Akira Tonomura et al Hitachi (1989)

Dulpa Fenda de Young com elétrons

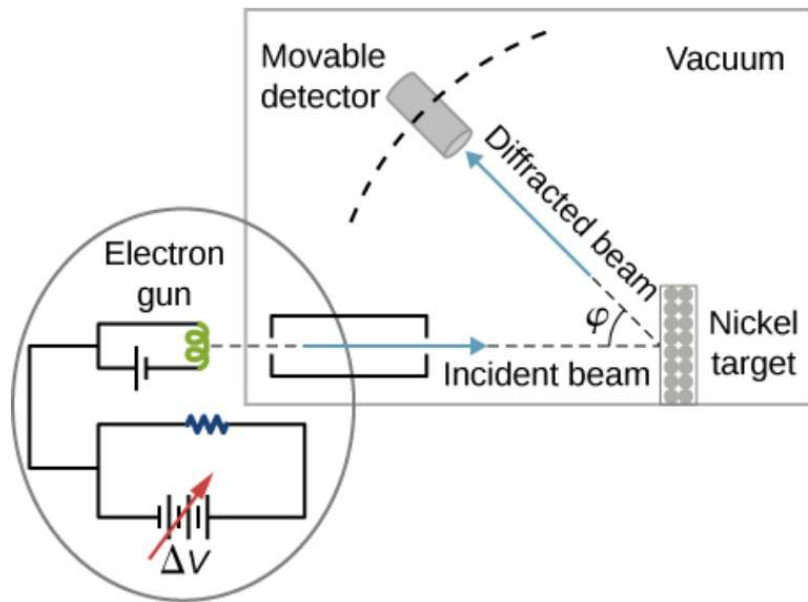
SCIENTIFIC REPORTS

The Young-Feynman controlled double-slit electron interference experiment

Amir H. Tavabi¹, Chris B. Boothroyd^{1,2}, Emrah Yücelen³, Stefano Frabboni^{4,5},
Gian Carlo Gazzadi⁵, Rafal E. Dunin-Borkowski¹ & Giulio Pozzi^{1,6}

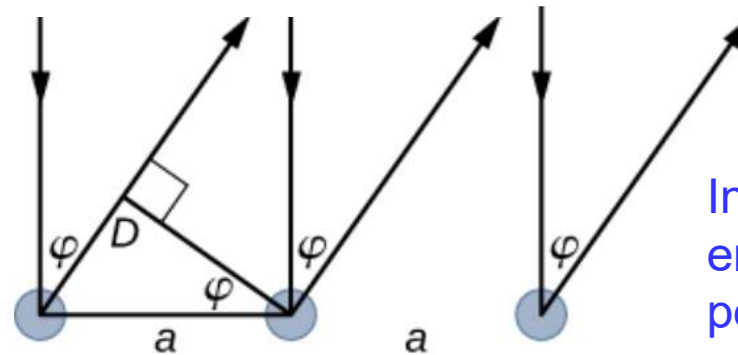


A Experiência de Davisson Germer



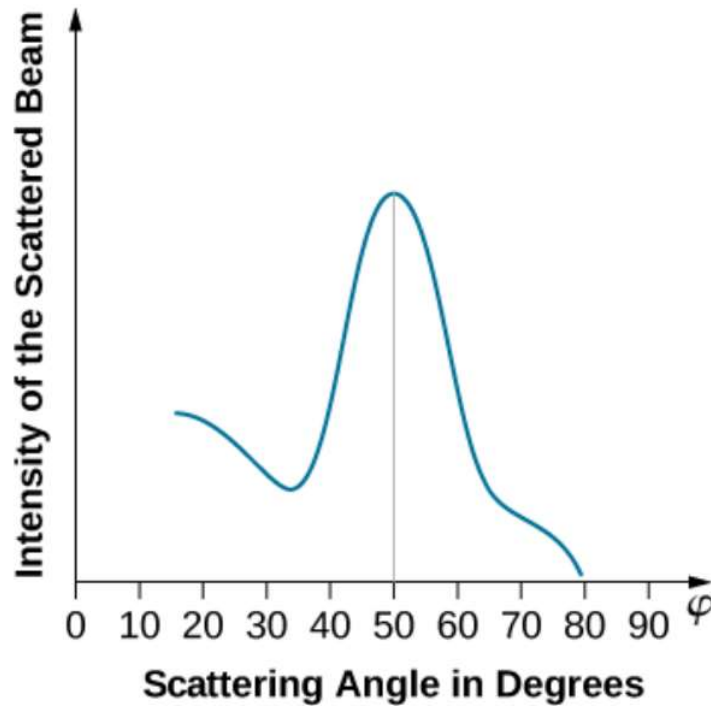
Lester Germer

Clinton Davisson



Interferência construtiva
entre os elétrons dispersas
pelos átomos de Ni

$$\begin{aligned} D &= a \sin \varphi \\ D &= n \lambda \quad n = 1, 2, 3, \dots \\ n\lambda &= a \sin \varphi \end{aligned}$$



$$\Delta V = 54 \text{ V}$$

$$\text{pico } \phi \approx 50^\circ$$

Interferência construtiva

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

$$= 0.165 \text{ nm}$$

$$\text{Ni } a = 0.215 \text{ nm}$$

Relação de Broglie

$$\lambda = \frac{h}{p}$$

$$\frac{p^2}{2m} = E = e\Delta V$$

$$p = \sqrt{2me\Delta V} \approx 3.97 \times 10^{-24} \frac{\text{kgm}}{\text{s}}$$

$$\lambda = 0.167 \text{ nm}$$