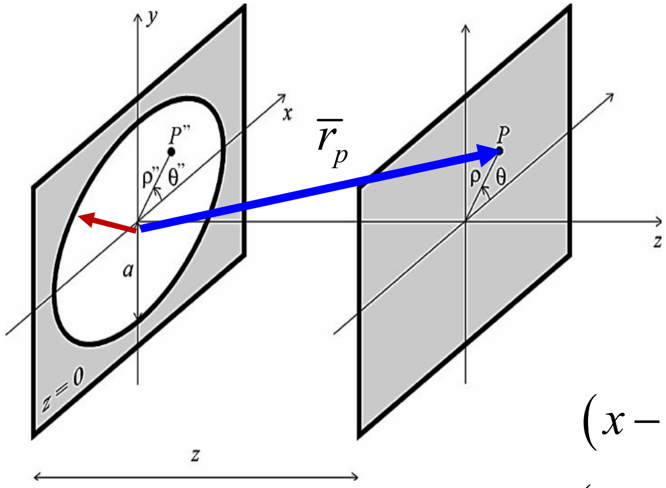
Integral Fresnel-Huygens com Simetria circular

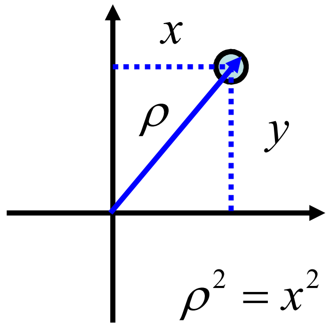
$$\mathcal{E}(x,y,z)=\frac{\mathcal{E}_0}{i\lambda z}\int_{-\infty}^{\infty}\int f(x',y')\,e^{ikz}\,\mathrm{e}^{ik\left[(x-x')^2+(y-y')^2\right]/2z}\,dx'dy'$$

Com simetria circular convêm usar coordenados polares



$$x'=\rho'\cos\theta' \qquad y'=\rho'\sin\theta'$$

$$x=\rho\cos\theta \qquad y=\rho\sin\theta$$



$$\rho^2=x^2+y^2$$

$$(x-x')^2=\rho^2\cos^2\theta-2\rho\rho'\cos\theta\cos\theta'+\rho'^2\cos^2\theta'$$

$$+(y-y')^2=\rho^2\sin^2\theta-2\rho\rho'\sin\theta\sin\theta'+\rho'^2\sin^2\theta'$$

$$\overline{r}_p=z+\rho^2/2z$$

$$(x-x')^2+(y-y')^2=\rho^2-2\rho\rho'\cos(\theta-\theta')+\rho'^2$$

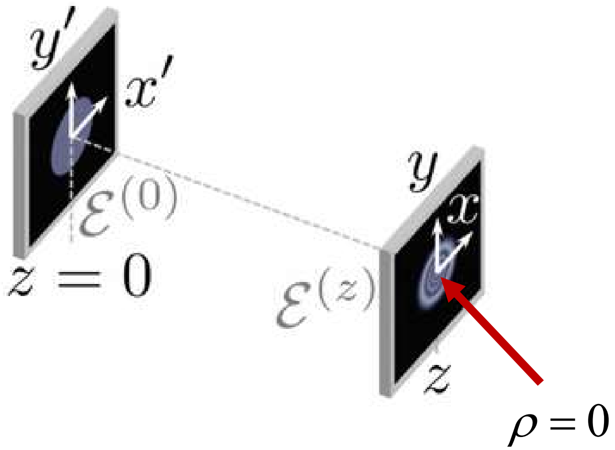
$$f(\rho')=\begin{cases}1 & \rho'<R_a\\ 0 & \rho'\geq R_a\end{cases}$$

$$\mathcal{E}(\rho,\theta,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ik\overline{r}_p}\int_0^{2\pi}d\theta'\int_0^{R_a}\rho'd\rho'\exp\left[-ik\frac{\rho\rho'}{z}\cos(\theta-\theta')+ik\frac{\rho'^2}{2z}\right]$$

Abertura circular irradiância no eixo ótico

$$\mathcal{E}(\rho,\theta,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ik\bar{r}_p}\int_0^{2\pi}d\theta'\int_0^{R_A}\rho' d\rho' \exp\left[-ik\frac{\rho\rho'}{z}\cos(\theta-\theta')+ik\frac{\rho'^2}{2z}\right]$$

Esta integral é difícil em geral e tem ser resolvida numericamente. No entanto no eixo ótico $\rho=0$



$$\mathcal{E}(\rho=0,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ikz}2\pi\int_0^{R_A}\rho' d\rho' \exp\left[ik\frac{\rho'^2}{2z}\right]$$

$$u'=\frac{ik\rho'^2}{2z}=\frac{i\pi\rho'^2}{\lambda z}\qquad \frac{\rho'^2}{2}=\frac{\lambda z}{i2\pi}u\qquad \rho' d\rho'=\frac{\lambda z}{i2\pi}du'$$

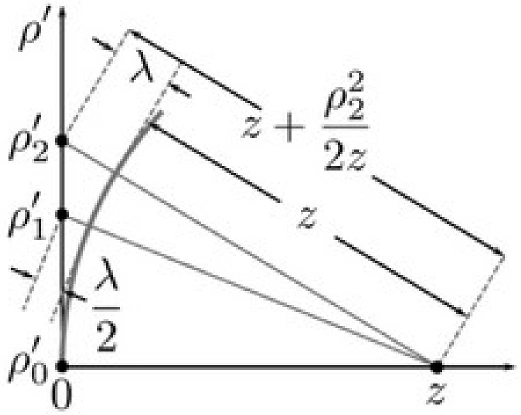
$$\mathcal{E}(\rho=0,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ikz}2\pi\frac{\lambda z}{i2\pi}\int_0^{i\pi R_A^2/\lambda z}\mathrm{e}^{u'}du'=-\mathcal{E}_0e^{ikz}\left[e^{i\pi R_A^2/\lambda z}-1\right]$$

$$=-2i\mathcal{E}_0e^{ikz}e^{i\pi R_A^2/2\lambda z}\left[\frac{e^{i\pi R_A^2/2\lambda z}-e^{-i\pi R_A^2/2\lambda z}}{2i}\right]$$

$$\mathcal{I}(\rho=0,z)=4\mathcal{I}_0\sin^2\left(\frac{\pi R_a^2}{2\lambda z}\right)$$

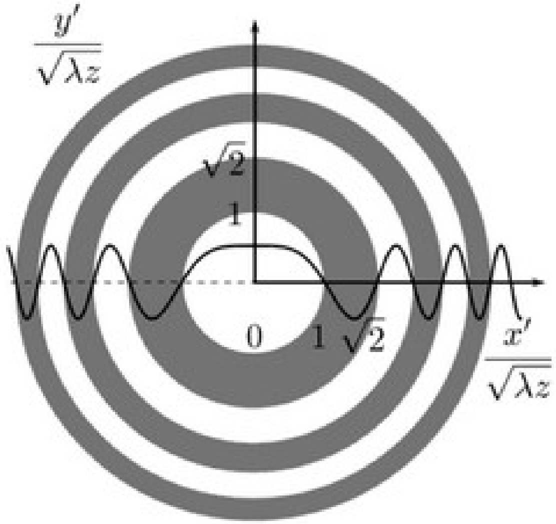
Intensidade no eixo ótico – as Zonas de Fresnel

No eixo ótico (r = 0) $\mathcal{E}(\rho=0,z)=\dfrac{\mathcal{E}_0}{i\lambda z}e^{ikz}2\pi\int_0^{R_a}\exp\left[i\dfrac{k\rho'^2}{2z}\right]\rho' d\rho'$



Considere um ponto fixo,z , no eixo ótica

A maneira que ρ´ aumenta a fase $e^{ik\rho'^2/2z}$ vai oscilar. Cada vez que a diferença em fase é igual meio ciclo, o sinal inverte.



Fresnel usou este efeito para definir zonas sobre qual o sinal da fase é positiva ou negativa

Zonas brancas (fase positiva)

Zonas cinzentas (fase negativa)

Raios limitadores $\dfrac{\rho_m'^2}{2z}=m\dfrac{\lambda}{2}$ $\qquad k\dfrac{\rho_m'^2}{2z}=m\pi$

$$\rho_m'=\sqrt{m\lambda z}$$

Abertura circular

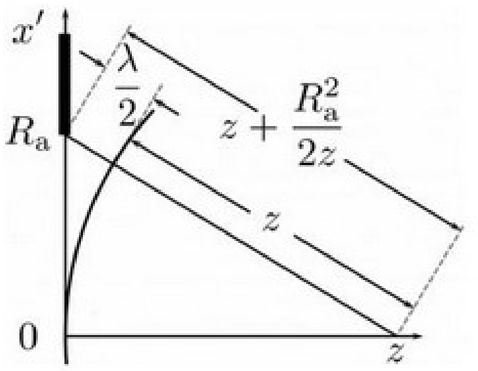
Imagine que temos uma abertura circular com um raio R_a que podemos variar.
Qual é a intensidade no eixo ótico (r =0) á uma distância z da abertura?

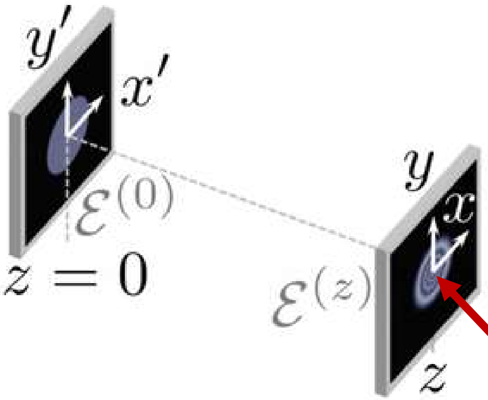
$$\mathcal{E}(\rho=0,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ikz}\int_0^{R_a}e^{ik\rho'^2/2z}\,2\pi\rho'\,d\rho' \qquad \rho'_m=\sqrt{m\lambda z}$$

$0\le R_a\le\rho'_1$ dentro a primeira zona Fresnel interferência é construtiva e a irradiância aumenta com Ra

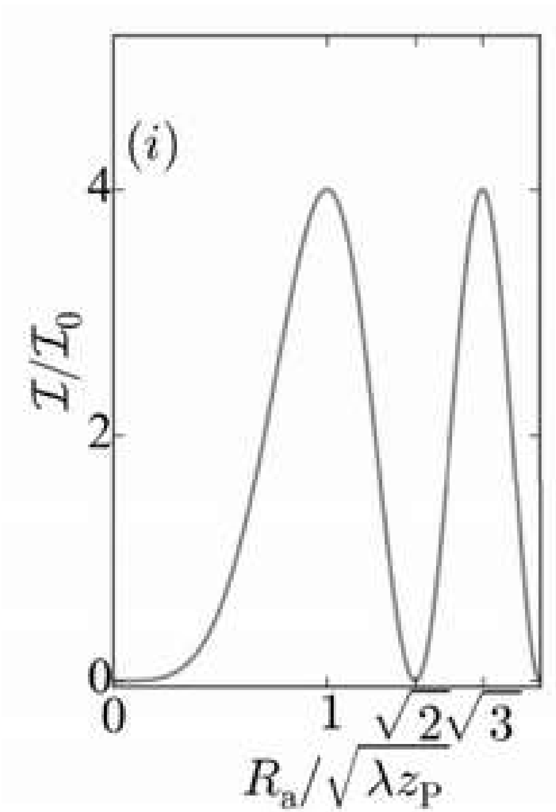
$\rho_1\le R_a\le\rho_2$ Começa haver interferência destrutiva e a irradiância no eixo vai diminuir até atingir 0 quando Ra = ρ_2

$\vdots$





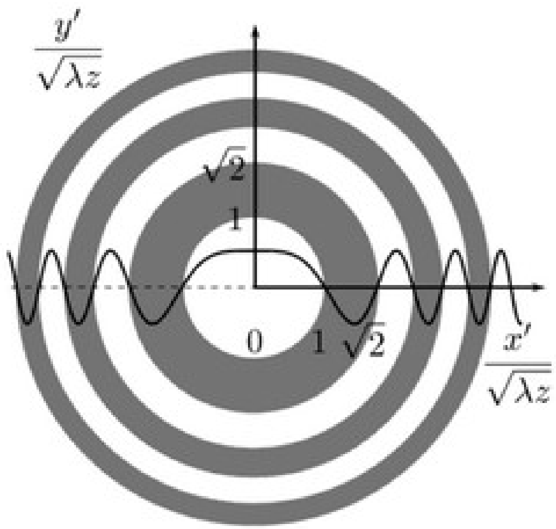
$\rho=0$



z = z_p fixo, variar R_a

$$\mathcal{I}(\rho=0,z)=4\mathcal{I}_0\sin^2\left(\frac{\pi R_a^2}{2\lambda z}\right)$$

Zonas de Fresnel



$$\rho'_m = \sqrt{m\lambda z}$$

Note que depende da distância entre a abertura e o plano de observação (z)

A área entre ρ'_{m-1} e ρ'_m

é a m^{issima} zona Fresnel

Todas as zonas têm a mesma área

$$\pi\left(\rho'^2_{m+1} - \rho'^2_m\right) = \pi\lambda z\left(m+1-m\right) = \pi\lambda z$$

Placa de Fresnel

Se eliminamos todas as zonas cinzentas (ou em alternativa todas as zona brancas) a luz que passa pelos os restantes zonas vai interfere construtivamente (no eixo).

É equivalente á uma lente

$$f = \frac{\rho'^2_1}{\lambda}$$

i.e. foca uma onda plana na posição z = f

Útil nas situações em que refração não é uma opção (Raios X, focagem dum feixe de átomos neutrais,…)

Uma placa Fresnel para átomos de He

Lentes Fresnel

Abertura circular irradiância no eixo ótico

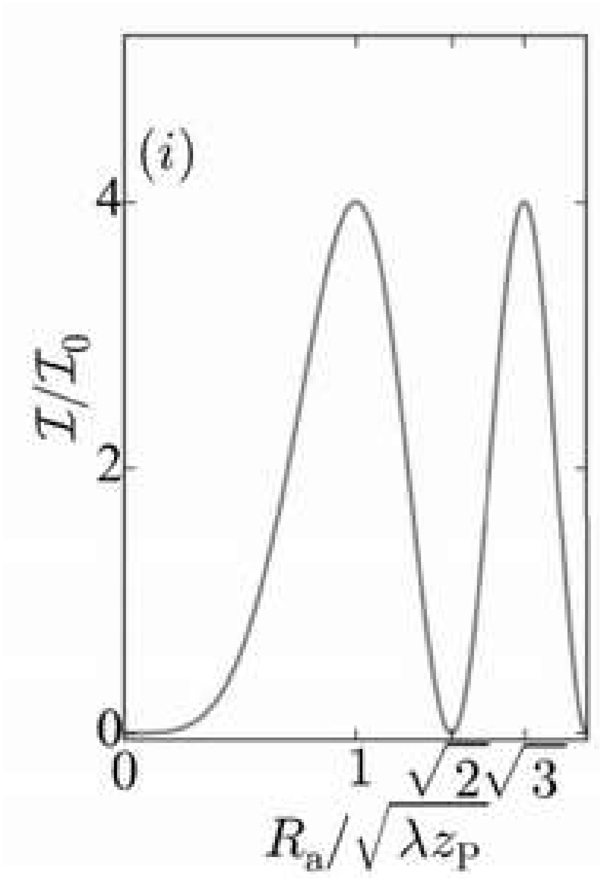
$$\mathcal{E}(\rho=0,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ikz}\int_0^{R_a}e^{ik\rho'^2/2z}2\pi\rho' d\rho'$$

$$=\frac{\mathcal{E}_0}{i\lambda z}e^{ikz}\frac{2\pi z}{ik}\left[e^{ikR_a^2/2z}-1\right]$$

$$=-2i\mathcal{E}_0 e^{ikz}e^{ikR_a^2/4z}\left[\frac{e^{ikR_a^2/4z}-e^{-ikR_a^2/4z}}{2i}\right]$$

$$=-2i\mathcal{E}_0 e^{ikz}e^{ikR_a^2/4z}\sin\left(\frac{kR_a^2}{4z}\right)$$

$$\mathcal{I}(\rho=0,z)=4\mathcal{I}_0\sin^2\left(\frac{\pi R_a^2}{2\lambda z}\right)$$



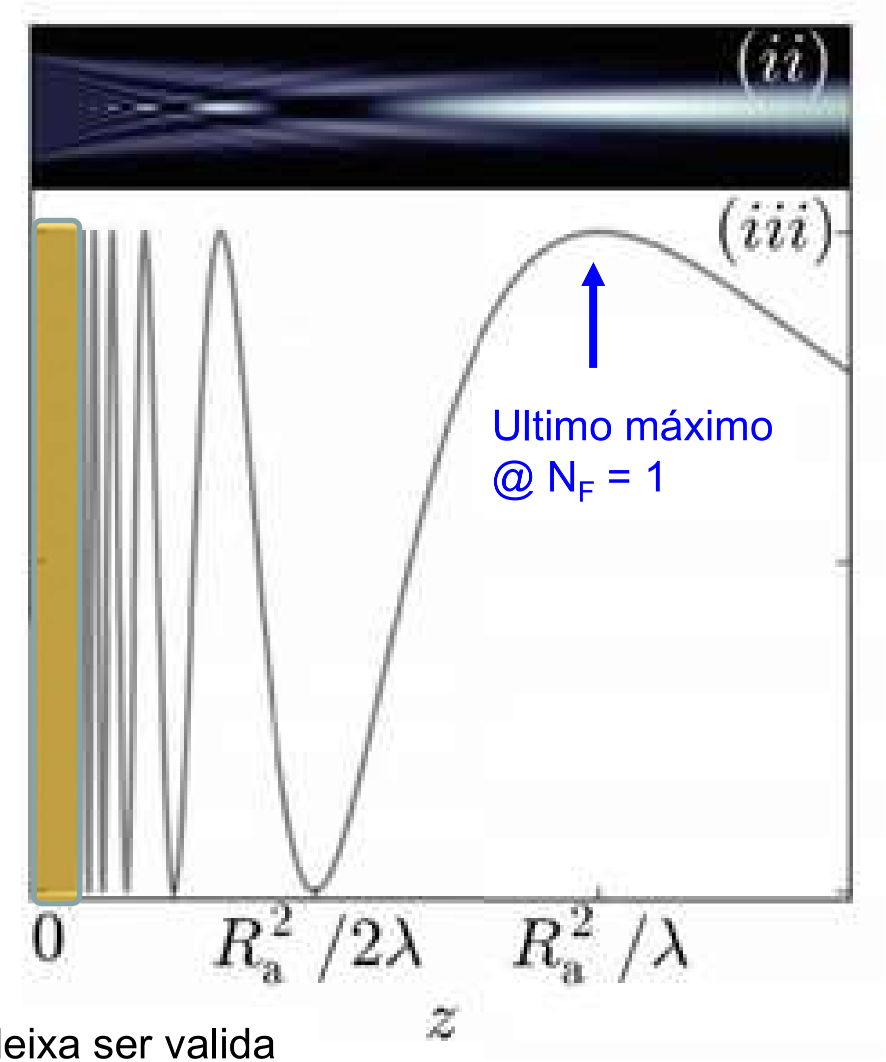
$z = z_p$ fixo, variar R_a

Variação da intensidade ao longo do eixo ótico

$$\mathcal{I}(\rho = 0, z) = 4\mathcal{I}_0 \sin^2\left(\frac{\pi R_a^2}{2\lambda z}\right)$$

$$N_F = \frac{R_a^2}{\lambda z}$$ Número Fresnel

Quando $N_F \ll 1$
no limite paraxial
a padrão de difração fica mais estável
e mais simples, tal como aconteceu
no caso duma fenda simples.



Quando $z < R_a$ a aproximação de Fresnel deixa ser valida

Variação da padrão de difração com z

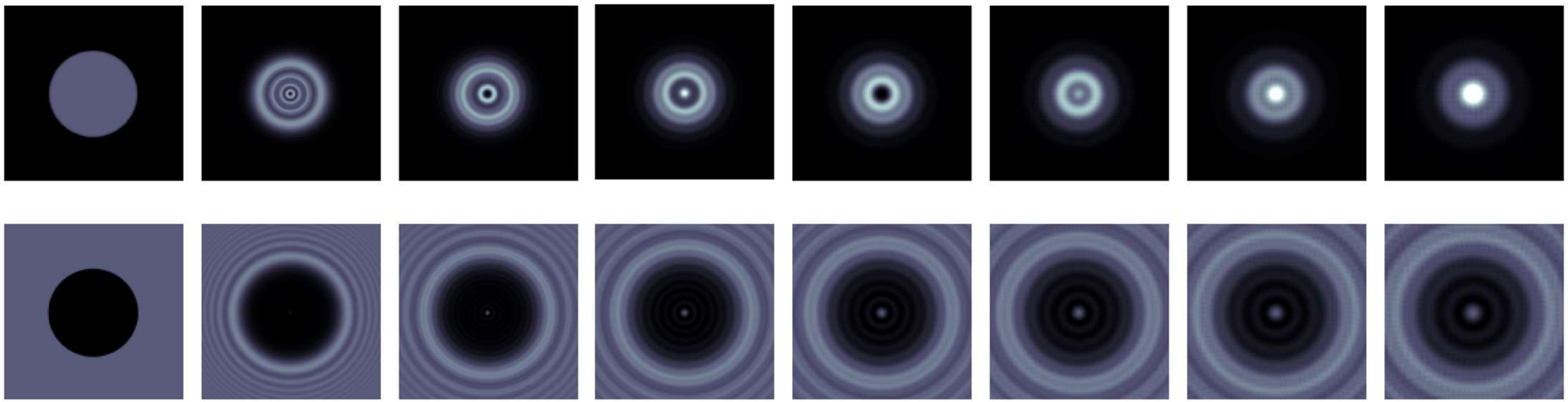
$$\mathcal{I}(\rho,\theta,z)=\mathcal{I}_0\left|\int_0^{2\pi}d\theta'\int_0^{R_A}\rho' d\rho' \exp\left[-ik\frac{\rho\rho'}{z}\cos(\theta-\theta')+ik\frac{\rho'^2}{2z}\right]\right|^2$$

Simulação numérica da integral

$z=0$

Abertura circular

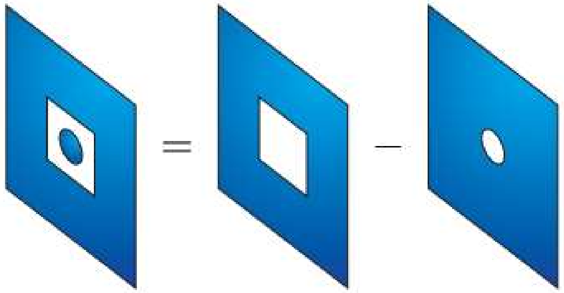
$z=\dfrac{R_a^2}{\lambda}$



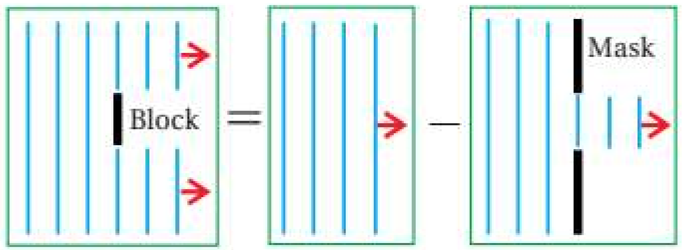
Disco circular

Principio de Babinet

O principio de Babinet é efetivamente o principio de sobreposição



Jaques Babinet
(1794-1872)



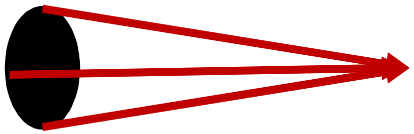
Em particular considere um disco circular
O campo no eixo ótico é

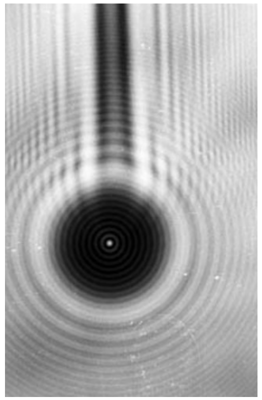
$$\mathcal{E}_{disco}\left(\rho=0,z\right)=\mathcal{E}_{plana}\left(0,z\right)-\mathcal{E}_{abertura}\left(0,z\right)$$

$$=\mathcal{E}_0 e^{ikz}+\mathcal{E}_0 e^{ikz}\left[e^{i\pi R_a^2/\lambda z}-1\right]$$

$$=\mathcal{E}_0 e^{ikz}e^{i\pi R_a^2/\lambda z}$$

$$\mathcal{I}_{disco}\left(\rho=0,z\right)=\mathcal{I}_0$$





Interferência construtiva no centro do disco

O spot de Poisson/Arago

Complementaridade

No limite Fraunhofer a integral Fresnel de difração é uma transformada Fourier

$N_F \ll 1$ Desprezar termos $\frac{x'^2}{z\lambda}, \frac{y'^2}{z\lambda}$ $N_F \sim \frac{(\text{tamnaho da abertura})^2}{\lambda z}$

$$\mathcal{E}(x,y,z) = \frac{\mathcal{E}_0}{i\lambda z} e^{ikz} \int_{-\infty}^{\infty}\int f(x',y') \mathrm{e}^{\left\{ik\left[(x-x')^2+(y-y')^2\right]/2z\right\}} dx'dy'$$

$$\Rightarrow \frac{\mathcal{E}_0}{i\lambda z} e^{ikz} e^{ik(x^2+y^2)/2z} \int_{-\infty}^{\infty}\int f(x',y') \mathrm{e}^{-ik[xx'+yy']/z} dx'dy'$$

Uma abertura complementaria (uma que é o inverso da abertura original) da a mesma padrão (exceto no eixo ótico)

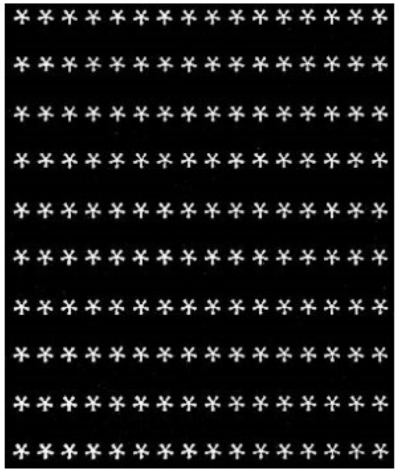
$$\mathcal{E}_{comp}(x,y,z) = \frac{\mathcal{E}_0}{i\lambda z} e^{ikz} e^{ik(x^2+y^2)/2z} \int_{-\infty}^{\infty}\int \left[1 - f(x',y')\right] \mathrm{e}^{-ik[xx'+yy']/z} dx'dy'$$

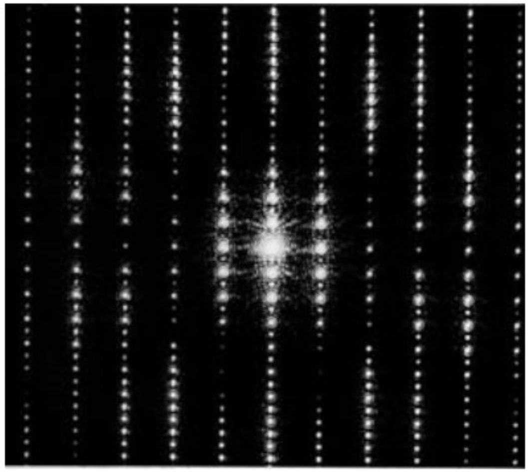
$$= -\mathcal{E}_{original}(x,y,z) + -i\mathcal{E}_0 \lambda z e^{ikz} 2\pi\delta(x)\delta(y)$$

Exceto na origem $\mathcal{E}_{comp}(x,y,z) = -\mathcal{E}_{original}(x,y,z)$ $\mathcal{I}_{comp}(x,y,z) = \mathcal{I}_{original}(x,y,z)$

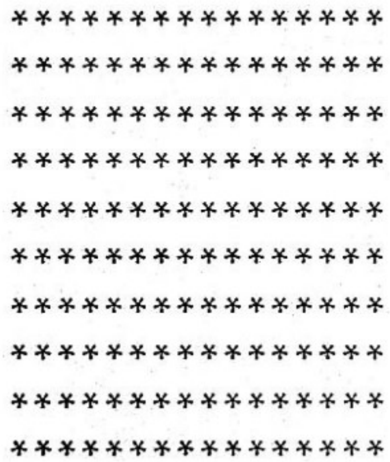
Exemplo do principio de Babinet

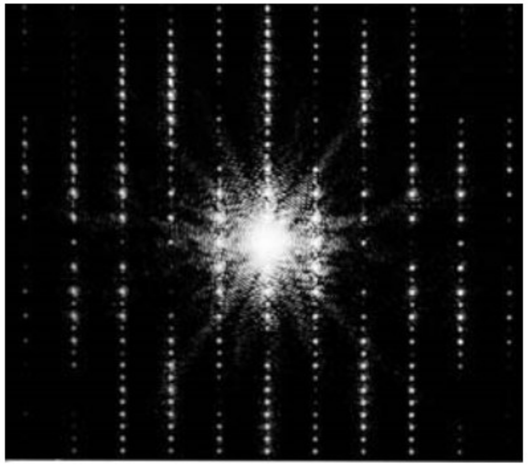
Uma rede
de buracos





Uma rede
de anti-buracos





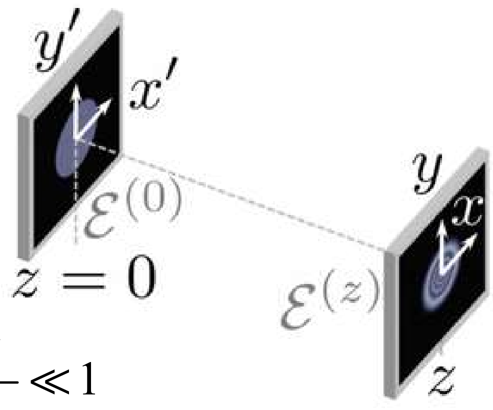
Difração de abertura circulares

Integral da difração de Fresnel

$$\mathcal{E}(\rho,\theta,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ik\bar{r}_p}\int_0^{2\pi}d\theta'\int_0^{R_A}\rho' d\rho' \exp\left[-ik\frac{\rho\rho'}{z}\cos(\theta-\theta')+ik\frac{\rho'^2}{2z}\right]$$

Para o caso de uma abertura circular com diâmetro D, existe 2 casos particulares onde a dependência nos termo $\rho'^2/2z$

é anulada / desprezável



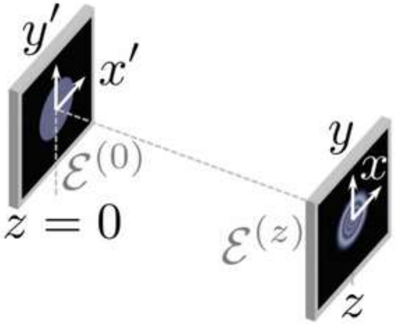
Caso I : Onda plana incidente, no limite Fraunhofer $N_F=\dfrac{D^2}{4\lambda z}\ll 1$

$$\frac{k\rho'^2}{2z}\le\pi\frac{D^2}{\lambda z}=4\pi N_F\ll 1$$

$$\mathcal{E}(\rho,\theta,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ik\bar{r}_p}\int_0^{2\pi}d\theta'\int_0^{R_A}\rho' d\rho' \exp\left[-ik\frac{\rho\rho'}{z}\cos(\theta-\theta')+ik\cancel{\frac{\rho'^2}{2z}}\right]$$

Difração de abertura circulares

Integral Fresnel de difração



$$\mathcal{E}(\rho,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ikz-ik\rho^2/2z}\underbrace{\int_0^{2\pi}d\phi'\int_0^{D/2}\rho' d\rho'\,\mathrm{e}^{\left[-ik\rho\rho'\cos(\phi-\phi')/z\right]}}$$

Transformada Fourier duma abertura circular do diâmetro D

ajuda dum amigo matemático

$$\int_0^{2\pi}d\phi'\,\mathrm{e}^{\left[-ik\rho\rho'\cos(\phi-\phi')/z\right]}=2\pi J_0\left(\frac{k\rho\rho'}{z}\right)$$

$$\int_0^{D/2}\rho' d\rho' J_0\left(\frac{k\rho\rho'}{z}\right)=\frac{Dz}{2k\rho}J_1\left(\frac{kD\rho}{2z}\right)$$

Friedrich Bessel
(1784-1846)

$$\mathcal{E}(\rho,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ikz-ik\rho^2/2z}\frac{\pi Dz}{k\rho}J_1\left(\frac{kD\rho}{2z}\right)$$

Difração de abertura circulares

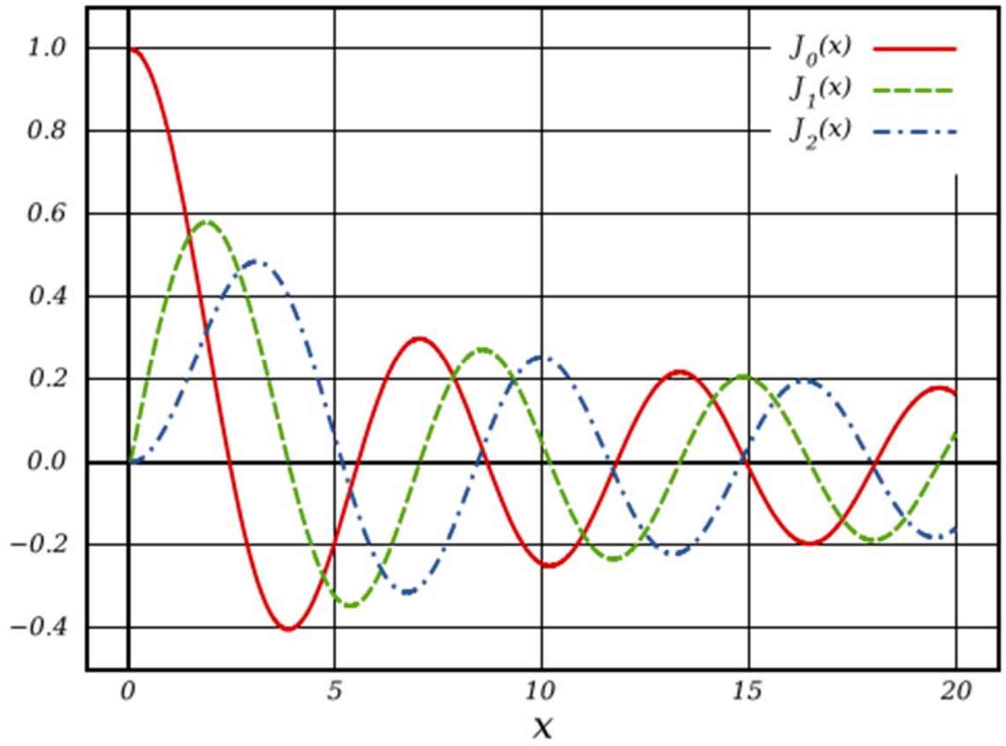
Integral Fresnel de difração limite Fraunhofer

$$\mathcal{E}(\rho,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ikz-ik\rho^2/2z}\frac{\pi Dz}{k\rho}J_1\left(\frac{kD\rho}{2z}\right)$$

$$=-i\mathcal{E}_0 e^{ikz-ik\rho^2/2z}\frac{D}{2\rho}J_1(kD\rho/2z)$$

$$\mathcal{I}(\rho,z)=\mathcal{I}_0\left(\frac{\pi D^2}{4\lambda z}\right)^2\underbrace{\left[2\frac{J_1(kD\rho/2z)}{(kD\rho/2z)}\right]^2}_{\mathrm{jinc}^2(kD\rho/2z)}$$

$$\lim_{\xi\to 0}\underbrace{\left[2\frac{J_1(\xi)}{\xi}\right]^2}_{\mathrm{jinc}^2(\xi)}=1$$

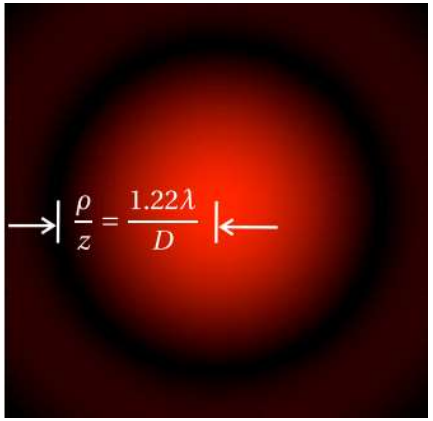


Zeros de J_1 @ 3.8317, 7.0156, 10.1735,…

O padrão de Airy

$$\mathcal{I}(\rho,z)=\mathcal{I}_0\left(\frac{\pi D^2}{4\lambda z}\right)^2\underbrace{\left[2\frac{J_1(kD\rho/2z)}{(kD\rho/2z)}\right]^2}_{\mathrm{jinc}^2(kD\rho/2z)}$$

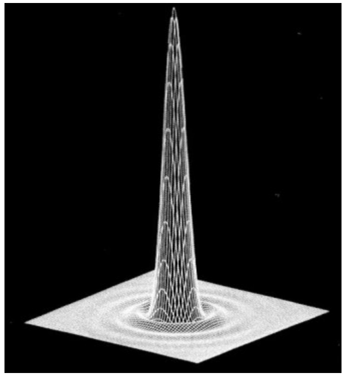
$$=\mathcal{I}_0(\pi N_F)^2\,\mathrm{jinc}^2(4\pi N_F\rho/D)$$

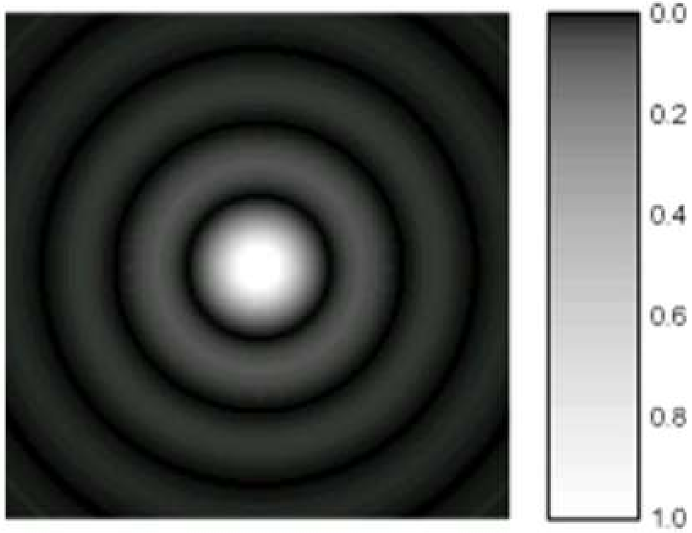


Sir George Biddell Airy
1801-1892

Esta padrão é conhecida como o "padrão de Airy"

A maior parte da intensidade está no pico central

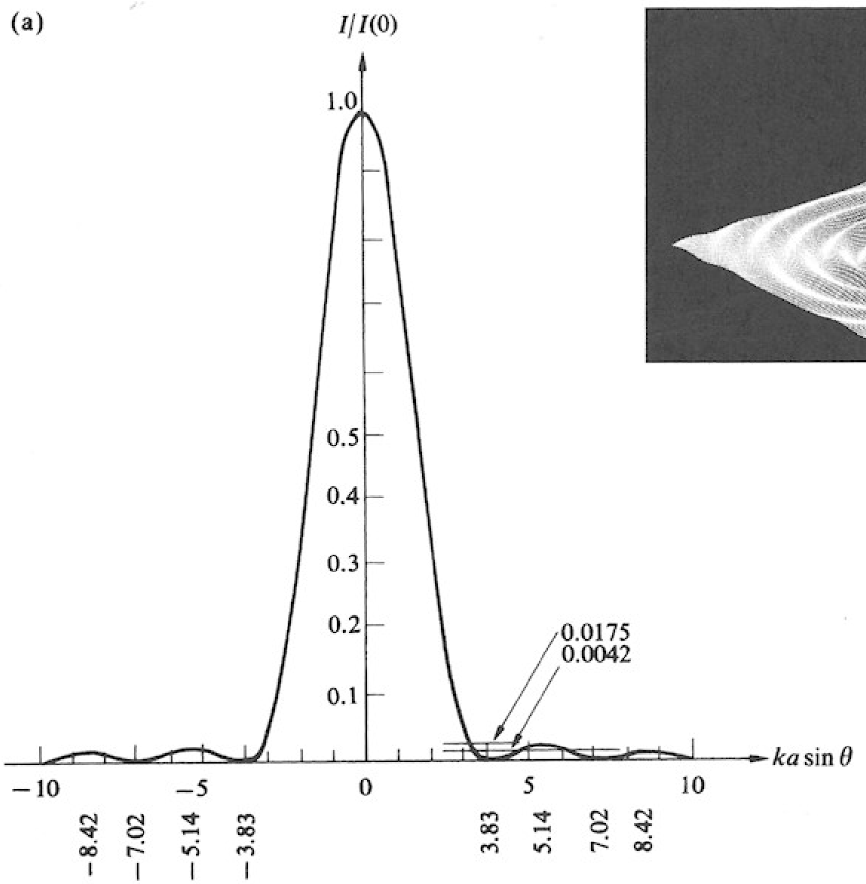




Padrão de Airy

campo

irradiância



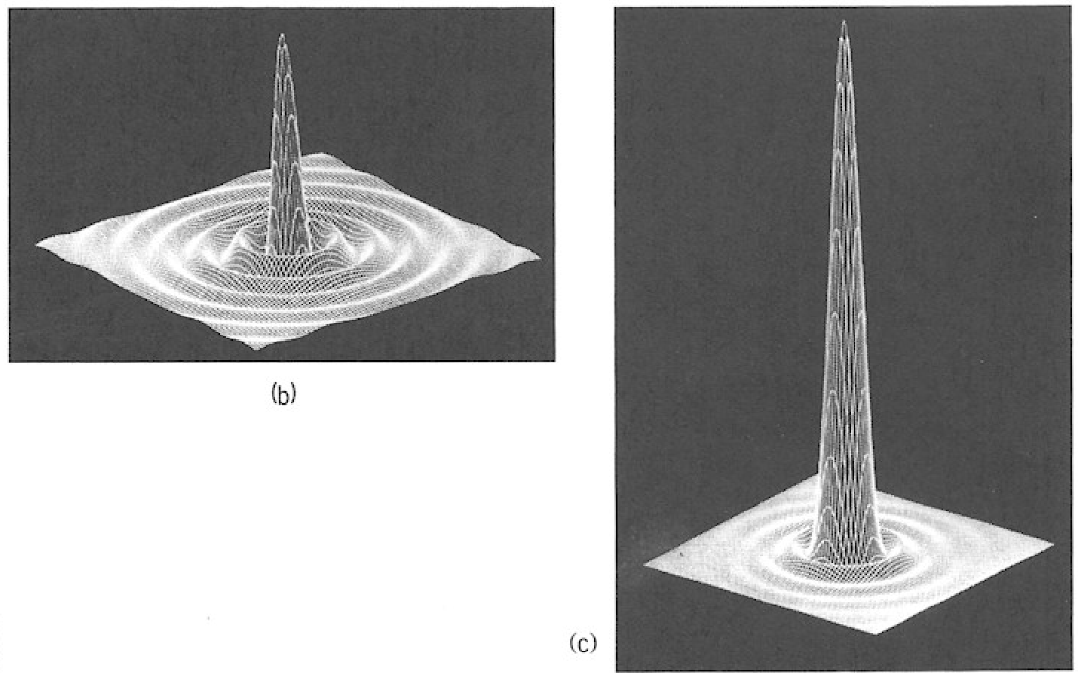
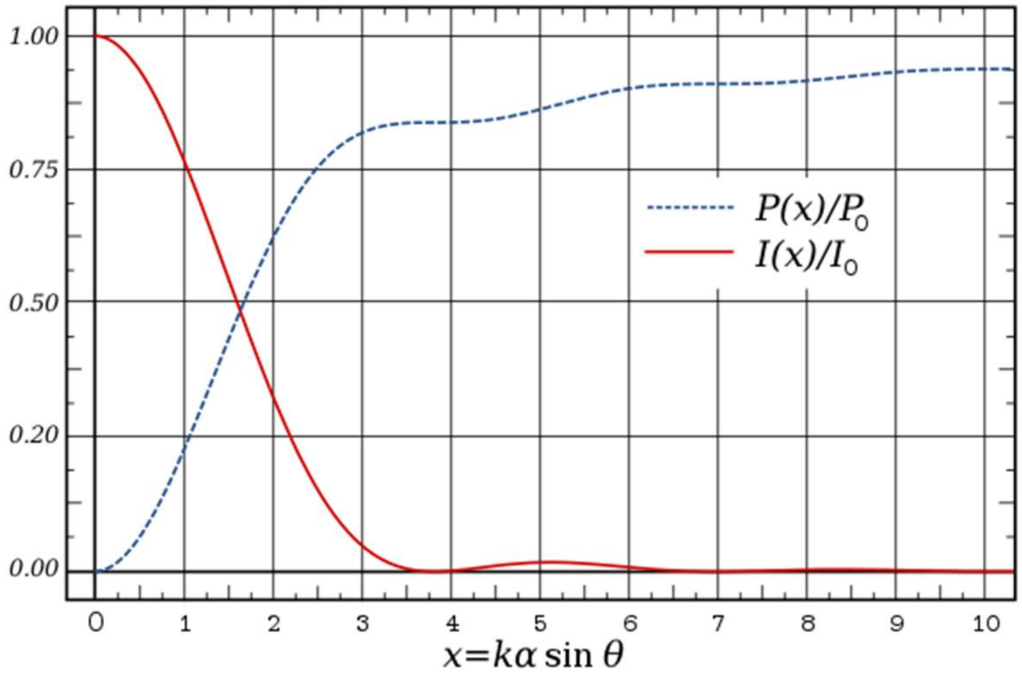


Figure 10.23 (*a*) The Airy pattern. (*b*) Electric field created by Fraunhofer diffraction at a circular aperture. (*c*) Irradiance resulting from Fraunhofer diffraction at a circular aperture. (Photos courtesy R. G. Wilson, Illinois Wesleyan University.)

$$\mathcal{I}(\rho, z) = \mathcal{I}_0 \left(\frac{\pi D^2}{4\lambda z}\right)^2 \left[2\frac{J_1(kD\rho/2z)}{(kD\rho/2z)}\right]^2$$

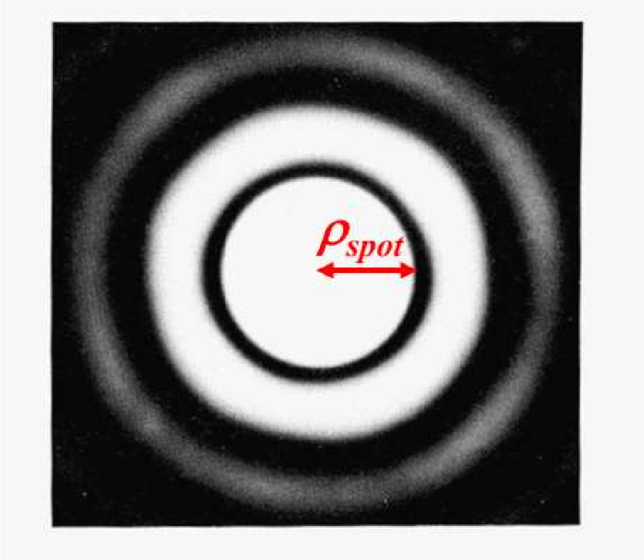
A maior parte da potencia está no pico central



$$\frac{\int_0^{3.8317} \rho \, d\rho \left[\frac{J_1(\rho)}{(p)} \right]^2}{\int_0^{\infty} \rho \, d\rho \left[\frac{J_1(\rho)}{(p)} \right]^2} \approx 0,838$$

Cerca de 83,8% da potência total está dentro no pico central

Tamanho do spot central



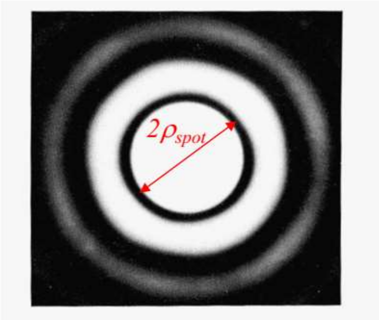
Definir o tamanho do spot centro como a distância radial do centro até o primeiro mínimo

$$\mathcal{I}(\rho,z)=\mathcal{I}_0\left(\frac{\pi D^2}{4\lambda z}\right)^2\left[2\frac{J_1(kD\rho/2z)}{(kD\rho/2z)}\right]^2$$

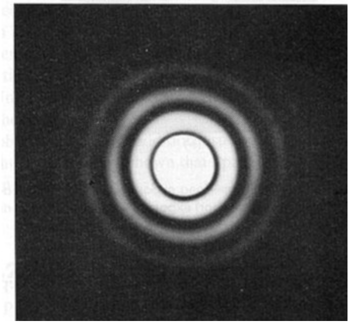
$$J_1(\xi)=0 \quad \xi\approx 3.83$$

$$\frac{kD\rho_{spot}}{2z}=\frac{\pi D\rho_{spot}}{\lambda z}\approx 3.83$$

$$\rho_{spot}\approx\frac{3.83}{\pi}\frac{\lambda z}{D}=\boxed{1.22\frac{\lambda z}{D}}$$



Abertura menor



Abertura maior

$$\rho_{spot}\sim\frac{\lambda z}{D}$$

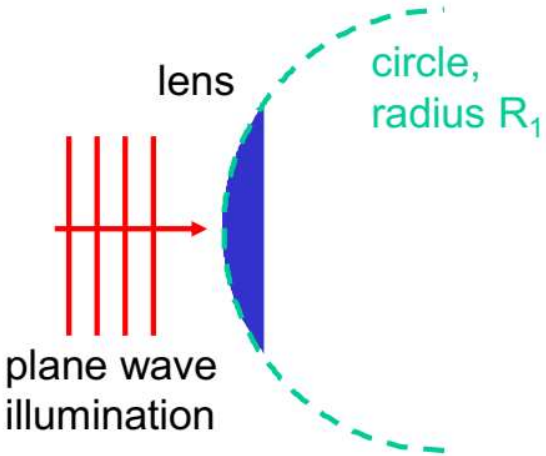
Característica de difração

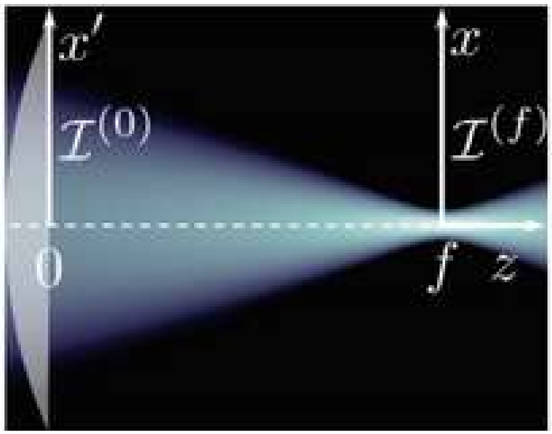
Simetria circular - Difração Fraunhofer

Integral da difração de Fresnel em coordenados polares

$$\mathcal{E}(\rho,\theta,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ik\bar{r}_p}\int_0^{2\pi}d\theta'\int_0^{R_A}\rho' d\rho' \exp\left[-ik\frac{\rho\rho'}{z}\cos(\theta-\theta')+ik\frac{\rho'^2}{2z}\right]$$

Caso II : Onda plana incidente numa lente fina, observação no plano focal duma lente

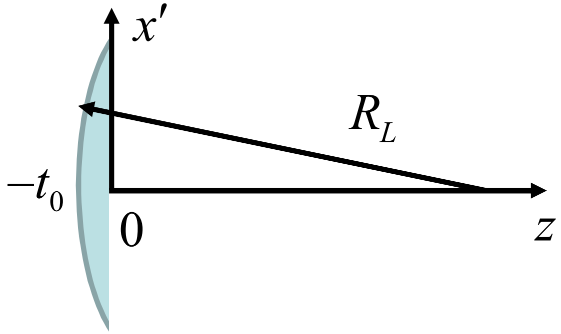




Qual a função da abertura duma lente?

$$f_{lente}(\rho')=?$$

Função da abertura duma lenta plana-convexa



A espessura da lenta
nos coordenados (x´, y´)

$$t(x', y') = \sqrt{R_L^2 - (x'^2 + y'^2)} - R_L + t_0$$
$$\approx R_L - \rho'^2 / 2R_L - R_L + t_0 = t_0 - \rho'^2 / 2R_L$$

Ao atravessar da lente a fase que uma onda plana adquira é

$$\mathcal{E}(x', y') = \mathcal{E}_0 e^{ik(t_0 - t)} e^{ikn_l t} = \mathcal{E}_0 e^{ikt_0} e^{ik(n_l - 1)t}$$
$$\approx \mathcal{E}_0 e^{inkt_0} \exp\left[-ik(n_l - 1)\rho'^2 / 2R_L\right]$$
$$= \mathcal{E}_0 e^{inkt_0} \exp\left[-ik\rho'^2 / 2f\right]$$

Lente delgada plano-convexa

$$\frac{1}{f} = \frac{(n_l - 1)}{R_L}$$

Desprezando a fase global

$$f(\rho') = \begin{cases} \exp\left[-ik\rho'^2 / 2f\right] & \rho' < D_L / 2 \\ 0 & \rho' > D_L / 2 \end{cases}$$

No plano focal duma lenta

$$\mathcal{E}(\rho,\theta,z)=\frac{\mathcal{E}_0}{i\lambda z}e^{ik\bar{r}_p}\int_0^{2\pi}d\theta'\int_0^{D_L/2}f(\rho')\rho' d\rho' \exp\left[-ik\frac{\rho\rho'}{z}\cos(\theta-\theta')+ik\frac{\rho'^2}{2z}\right]$$

$$f(\rho')=\exp\left[-ik\rho'^2/2f\right]$$

No plano z = f as fases proporcionais $k\rho'^2/2f$ cortam

Efetivamente a lente transporta o limite z→∞ ao plano focal

$$\mathcal{E}_{lente}(\rho,\theta,z=f)=\frac{\mathcal{E}_0}{i\lambda f}e^{ikz-ik\rho^2/2f}\int_0^{2\pi}d\theta'\int_0^{D_L/2}\rho' d\rho'\, \mathrm{e}^{\left[-ik\rho\rho'\cos(\theta-\theta')/f\right]}$$

Igual ao caso I: Limite Fraunhofer $\quad N_F=\dfrac{D^2}{4z\lambda}\ll 1$

$$\mathcal{I}_{lente}(\rho,z=f)=\mathcal{I}_0\left(\frac{\pi D^2}{4\lambda f}\right)^2\left[2\frac{J_1(kD\rho/2f)}{(kD\rho/2f)}\right]^2$$

Ótica Fourier

Logo o plano focal duma lente é o plano Fourier (Limite Fraunhofer)

$$\mathcal{E}_{lente}\left(\rho,\theta,z=f\right)=\frac{\mathcal{E}_0}{i\lambda f}e^{ikz-ik\rho^2/2f}\int_0^{2\pi}d\theta'\int_0^{D_L/2}\rho' d\rho'\, \mathrm{e}^{\left[-ik\rho\rho'\cos(\theta-\theta')/f\right]}$$

$$x=\rho\cos\theta$$

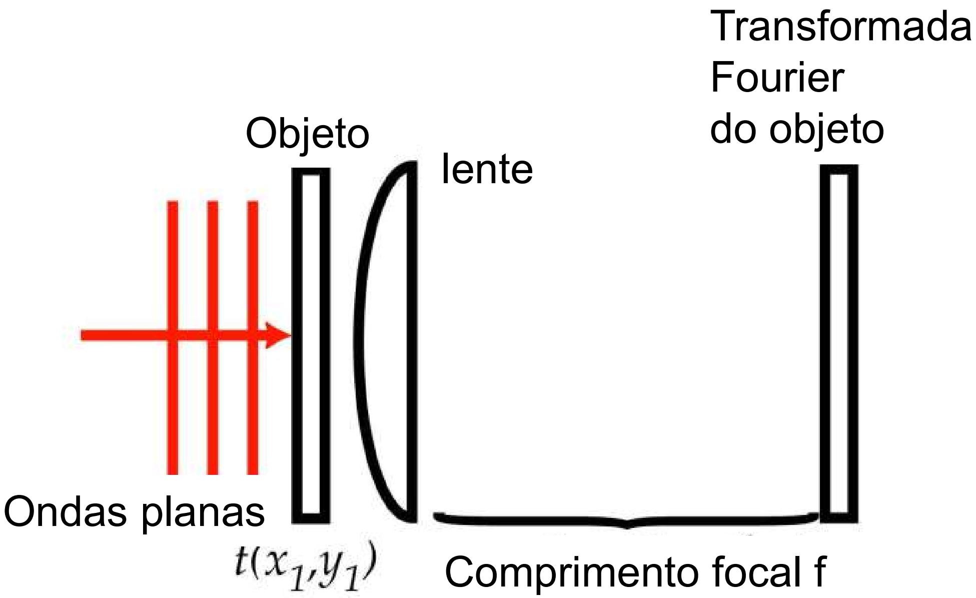
$$y=\rho\sin\theta$$

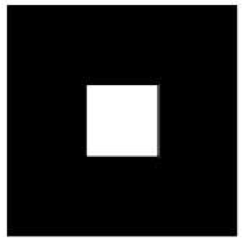
$$\mathcal{E}_{lente}\left(x,y,z=f\right)=\frac{\mathcal{E}_0}{i\lambda f}e^{ikz-ik(x^2+y^2)/2f}\iint_{lente}dx'dy'\,\mathrm{e}^{-i2\pi(xx'+yy')/\lambda f}$$

Frequências espaciais

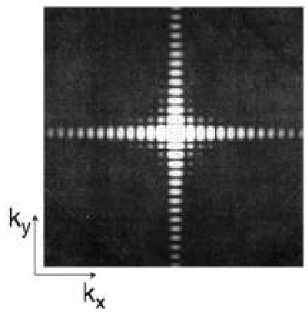
$$k_x=2\pi x/\lambda f$$

$$k_y=2\pi y/\lambda f$$



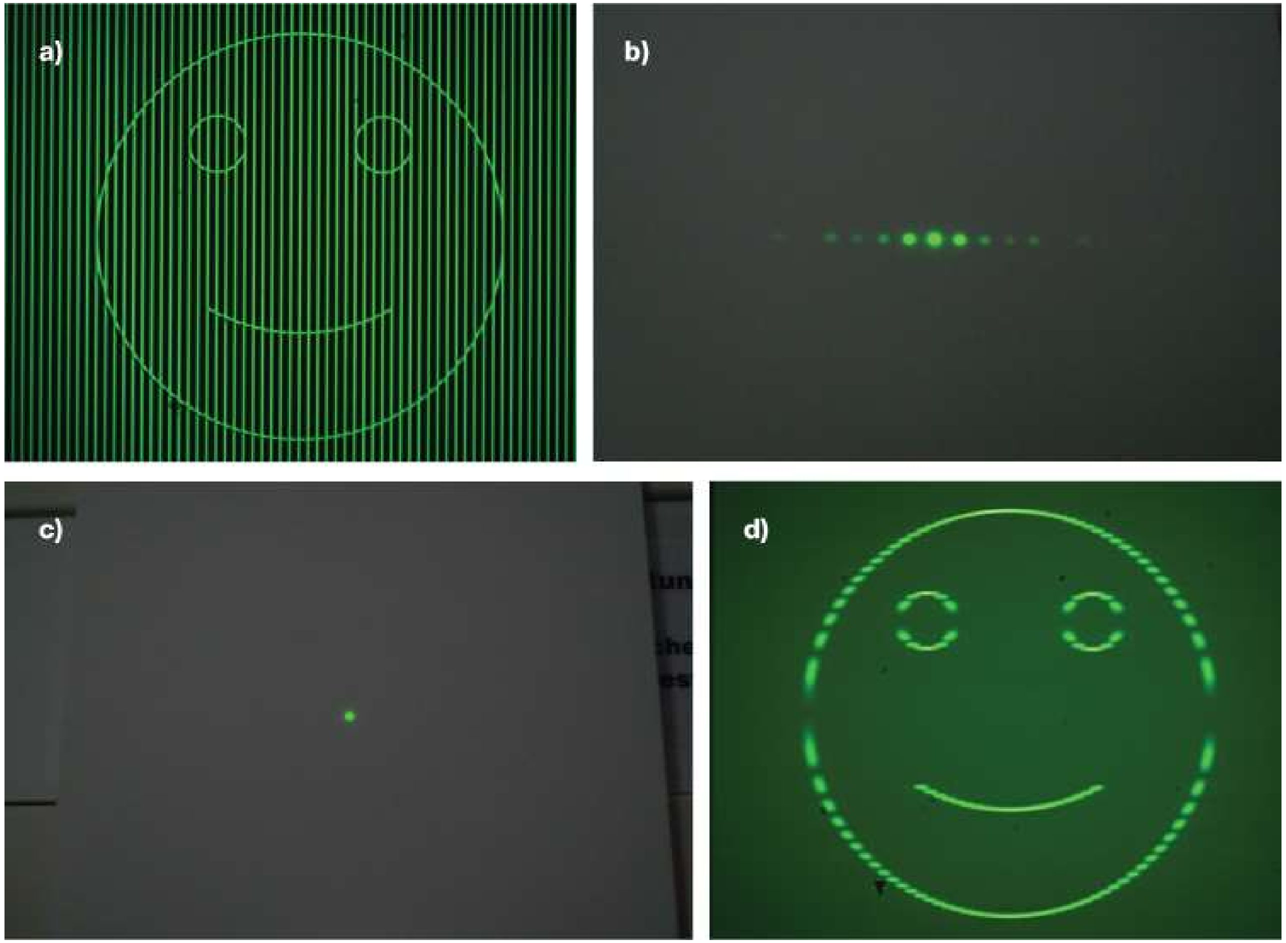


Objeto um ecrã opaco com uma abertura retangular



A transformada Fourier do rectangulo

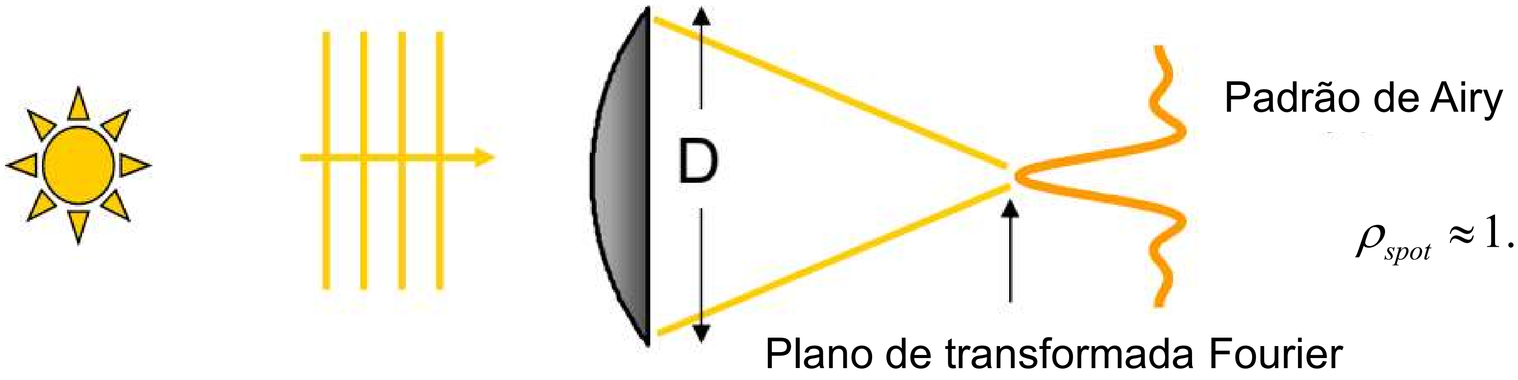
Exemplo de Processamento Ótico



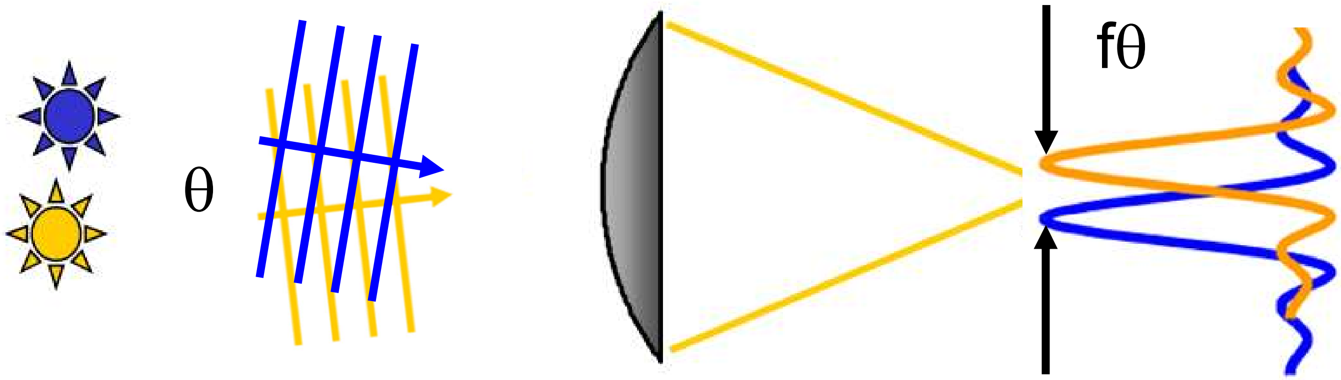
A smiley face behind bars (a) generates a Fourier pattern of dots (b). When a slit is used to block all but the zeroth order of the pattern (c), the bars disappear and the smiley is free (d).

Limite da difração

Imagine que utilize um telescópio para observar uma estrela distante

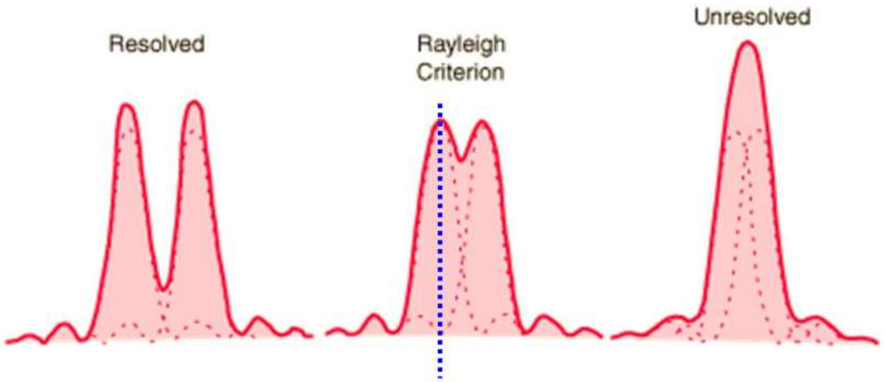


$$\rho_{spot} \approx 1.22 \frac{\lambda f}{D}$$



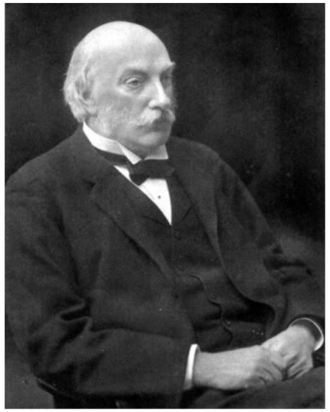
Será possível distinguir as duas estrelas?

Critério de Rayleigh



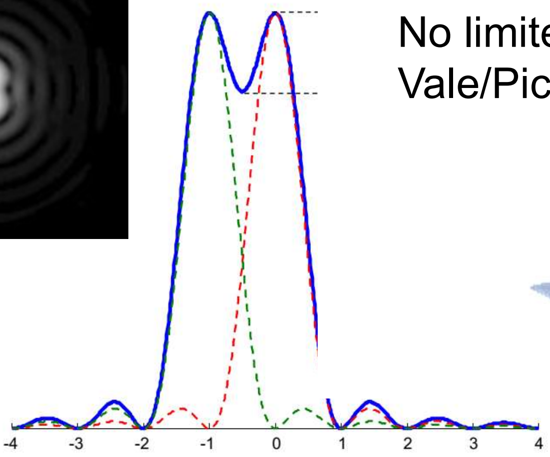
$$f\theta_{\min} = \rho_{spot} \approx 1.22\frac{\lambda f}{D}$$

$$\theta_{\min} \approx 1.22\frac{\lambda}{D}$$

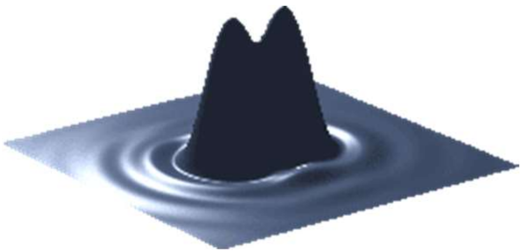


John William Strutt,
3rd Baron Rayleigh
1842 - 1919

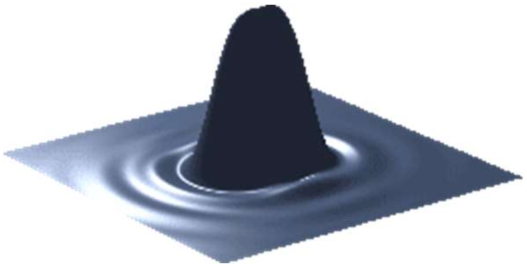
Limite de resolução: quando o máximo de uma padrão é sobreposto no primeiro mínimo da outra padrão. (É algo arbitrário)



No limite de Rayleigh a razão Vale/Pico é ~ 73%

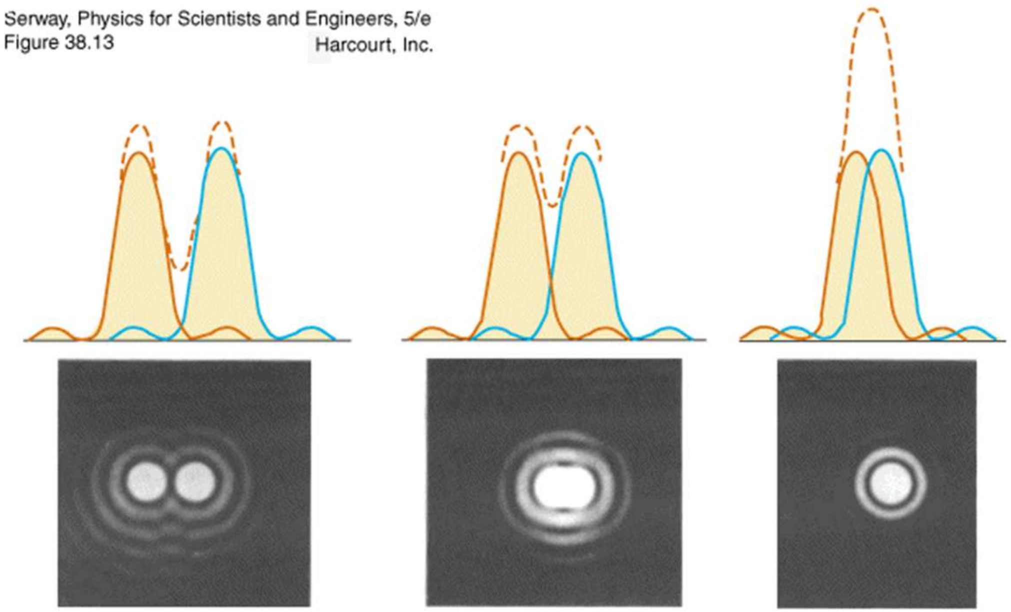


No limite



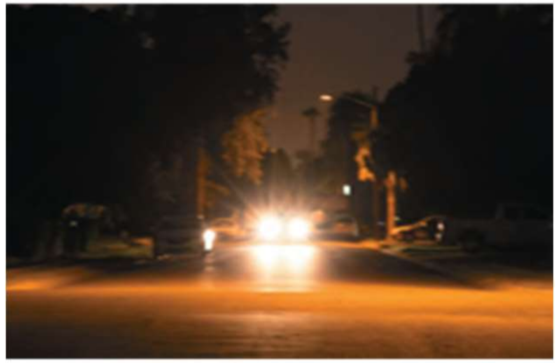
Não resolvidos

Serway, Physics for Scientists and Engineers, 5/e
Figure 38.13 Harcourt, Inc.



(a) (b) (c)

$$\theta_{\min} \approx 1.22\frac{\lambda}{D}$$



Telescópio de Hubble

Espelho principal tem um diâmeter D = 2,4m

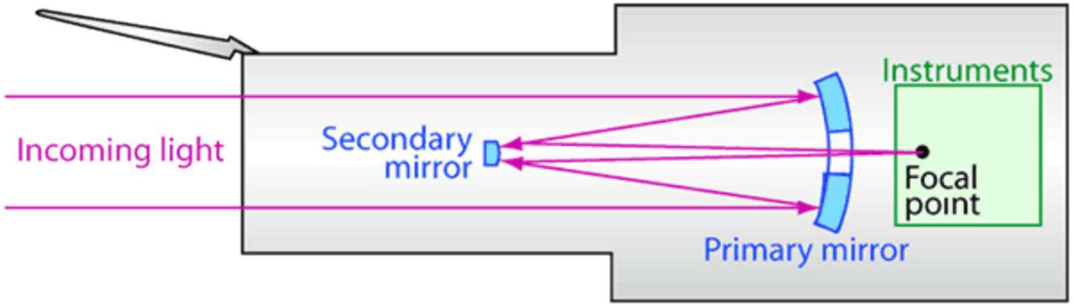
Luz @ $\lambda = 500\ nm$ luz verde

$$\theta_{\min} \approx 1.22\frac{\lambda}{D}$$

$$\approx 1.22\frac{5x10^{-7}\,m}{2.4m}$$

$$\approx 2.5x10^{-7}\,radianos$$

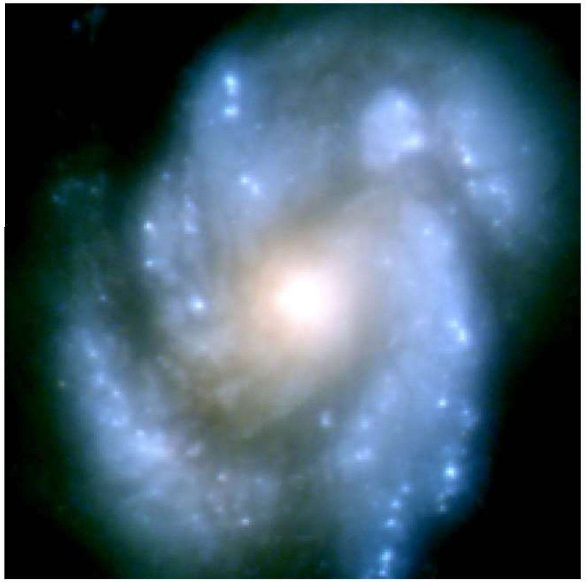
0.05 arco segundos



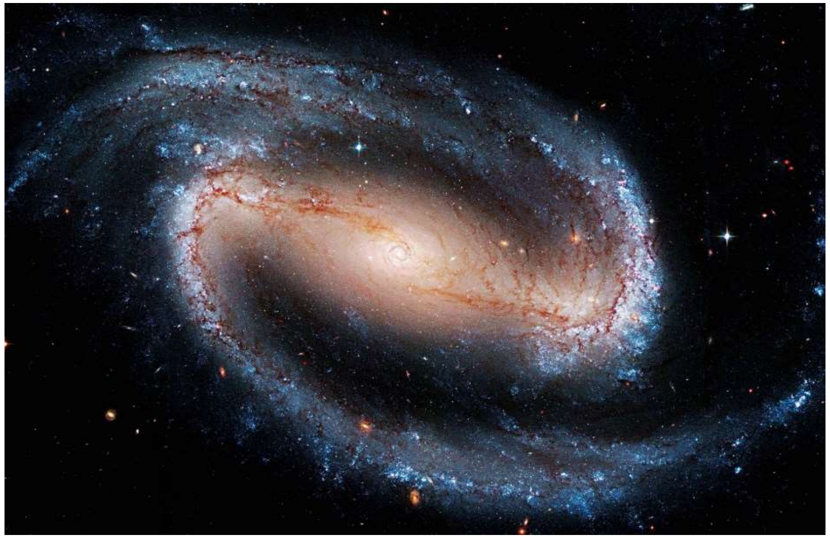
Na prática o limite da resolução é cerca de 0.1 arco segundos devida aberração esférica ~2x o limite de difração

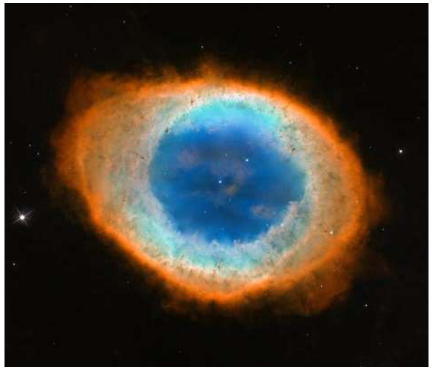
This photograph shows the Hubble Space Telescope's primary mirror being ground at the *Perkin-Elmer Corporation's* large optics fabrication facility in 1979, more than a decade before its very small but very significant flaw was discovered.

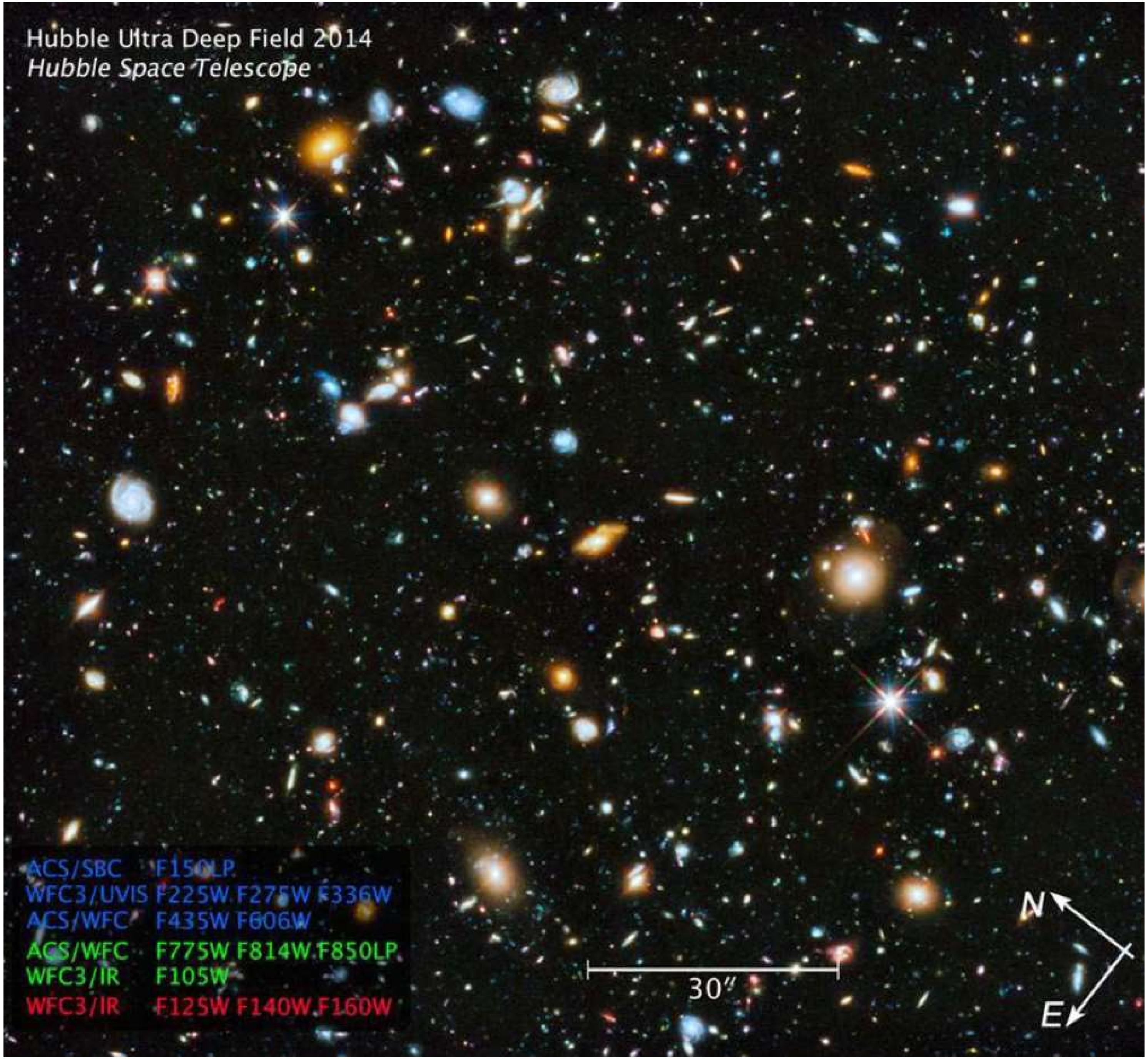
Antes



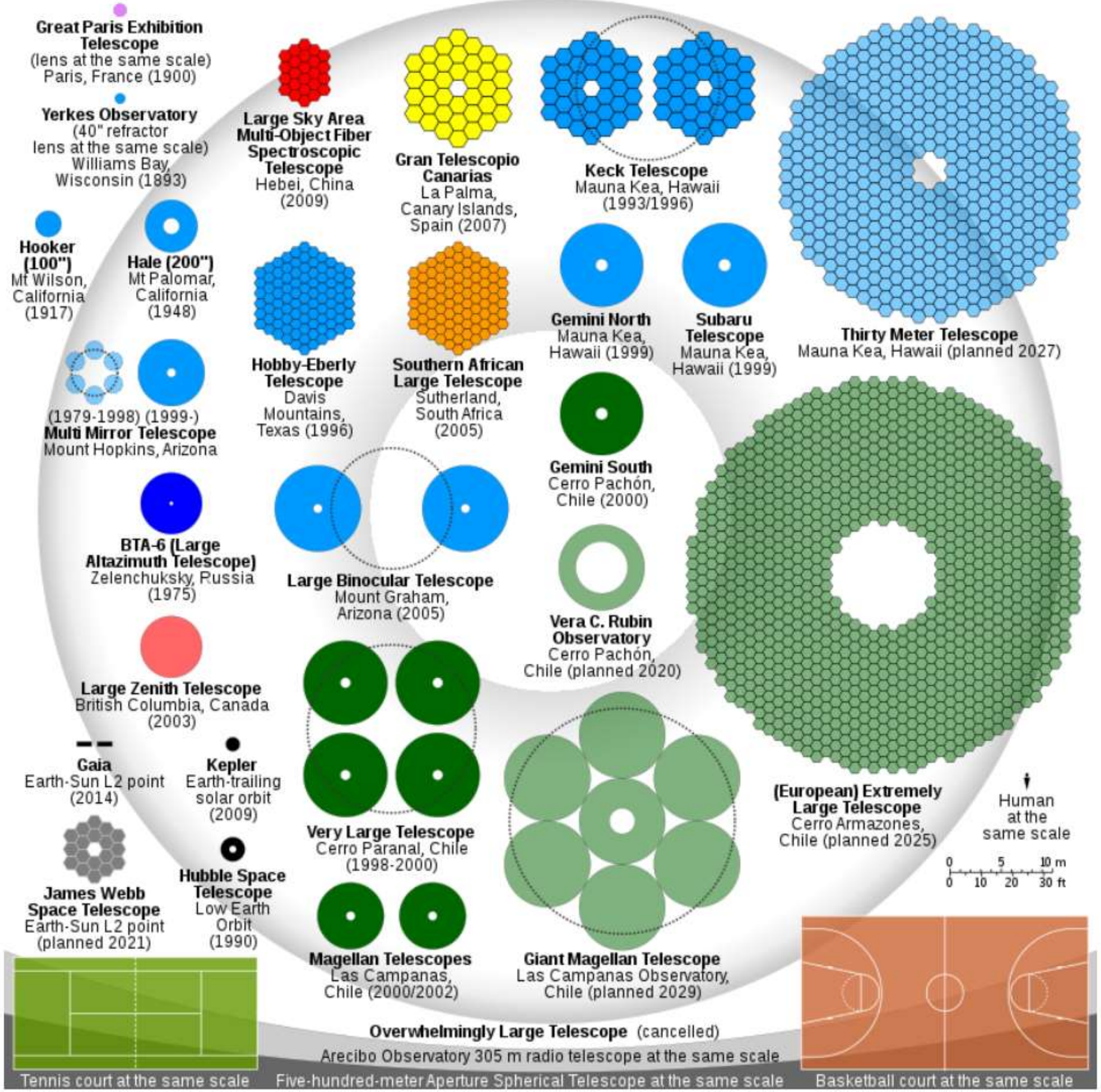
Depois a correção


WFPC2
1995
ACS/WFCx2
2004
Photo Credit: T. Rector (University of Alaska Anchorage)






Hubble Ultra Deep Field 2014
Hubble Space Telescope
ACS/SBC F150LP
WFC3/UVIS F225W F275W F336W
ACS/WFC F435W F606W
ACS/WFC F775W F814W F850LP
WFC3/IR F105W
WFC3/IR F125W F140W F160W
30″
N
E



https://en.wikipedia.org/wiki/List_of_largest_optical_reflecting_telescopes