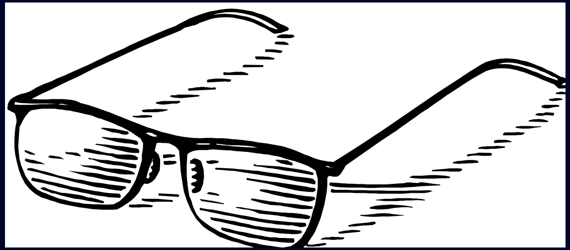
Elementos de Óptica

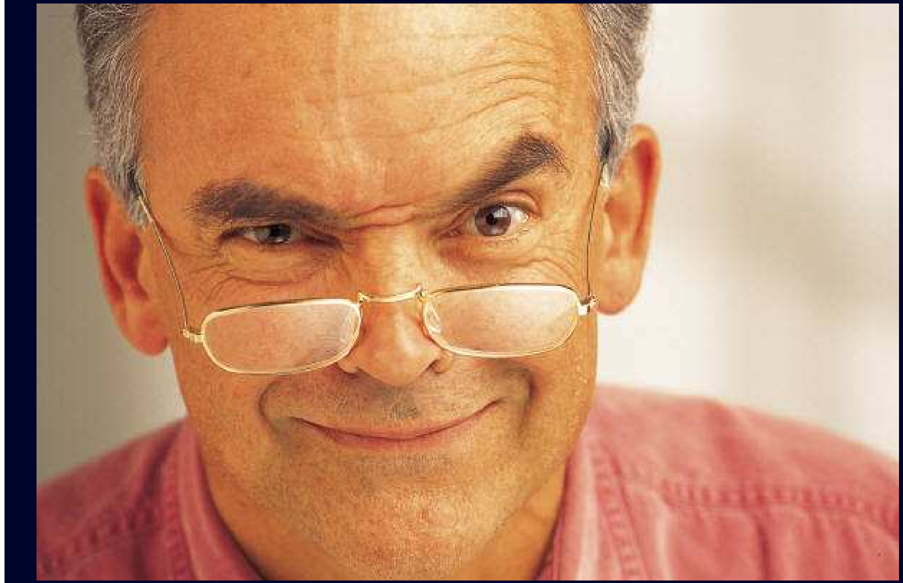
Carlos Lenz Cesar. Instituto de Física Gleb Wataghin

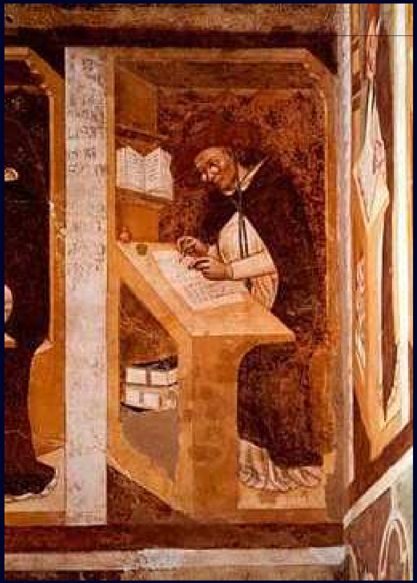
A revolução dos óculos – início: 1280-1300

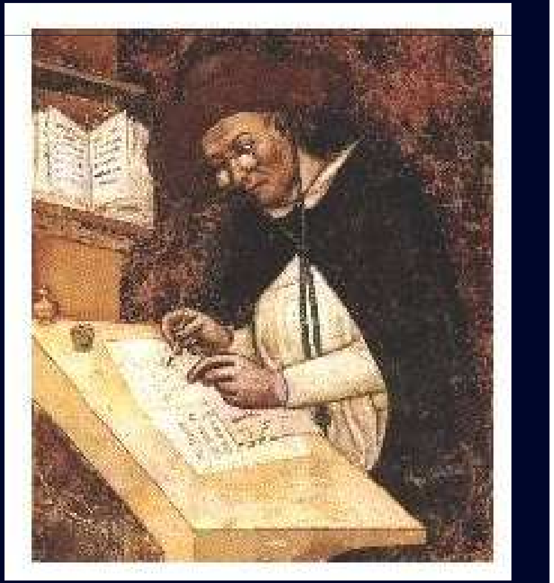
Uma das invenções mais importantes dos últimos 2000 anos [Newsweek 1999]



Artesãos, médicos … com mais de 40 anos continuaram trabalhando



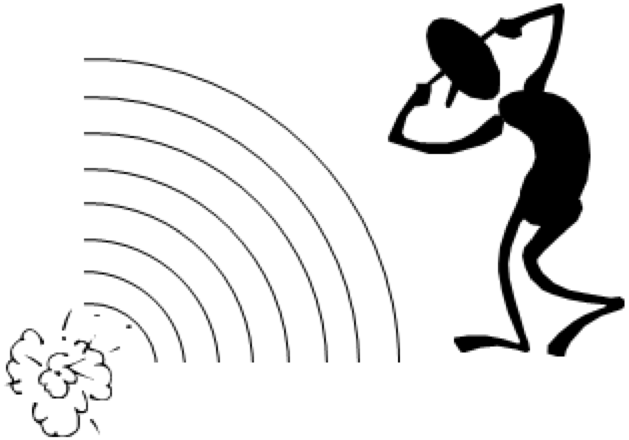




Primeira pintura de uma pessoa usando óculos:
Tommaso da Modena 1352

ONDAS

Através das ondas nos escutamos



Ondas acústicas

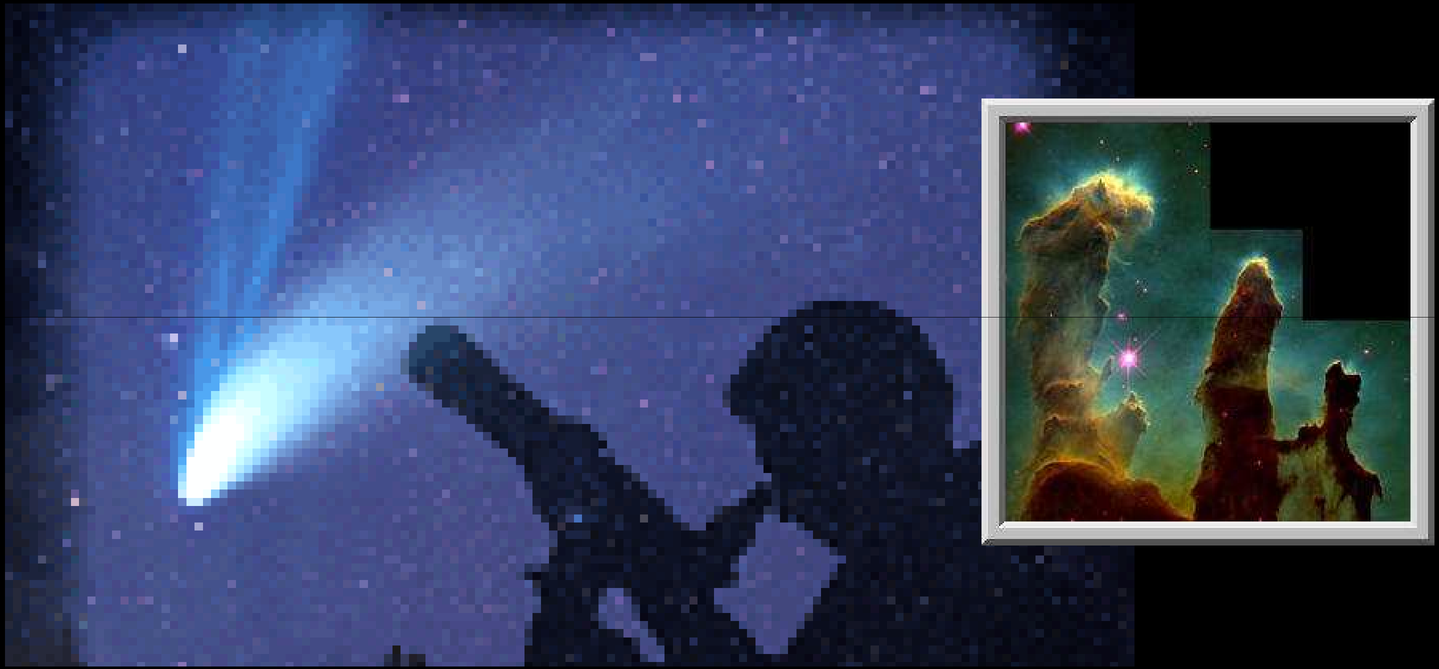
e enxergamos

Ondas eletromagnéticas

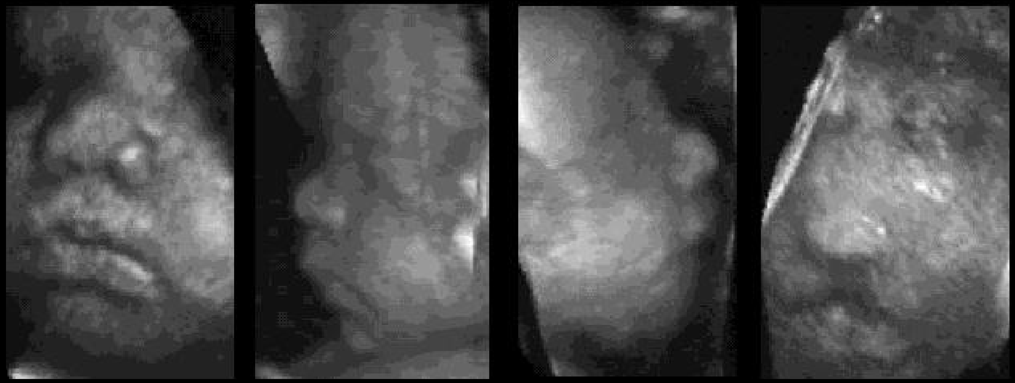
Sempre que a distância é grande utilizamos ondas.

TV - Rádio - Telefone

Observando o céu:
descobrindo o que existe nas estrelas



Usando o Ultrassom - bêbe ainda na barriga da mãe



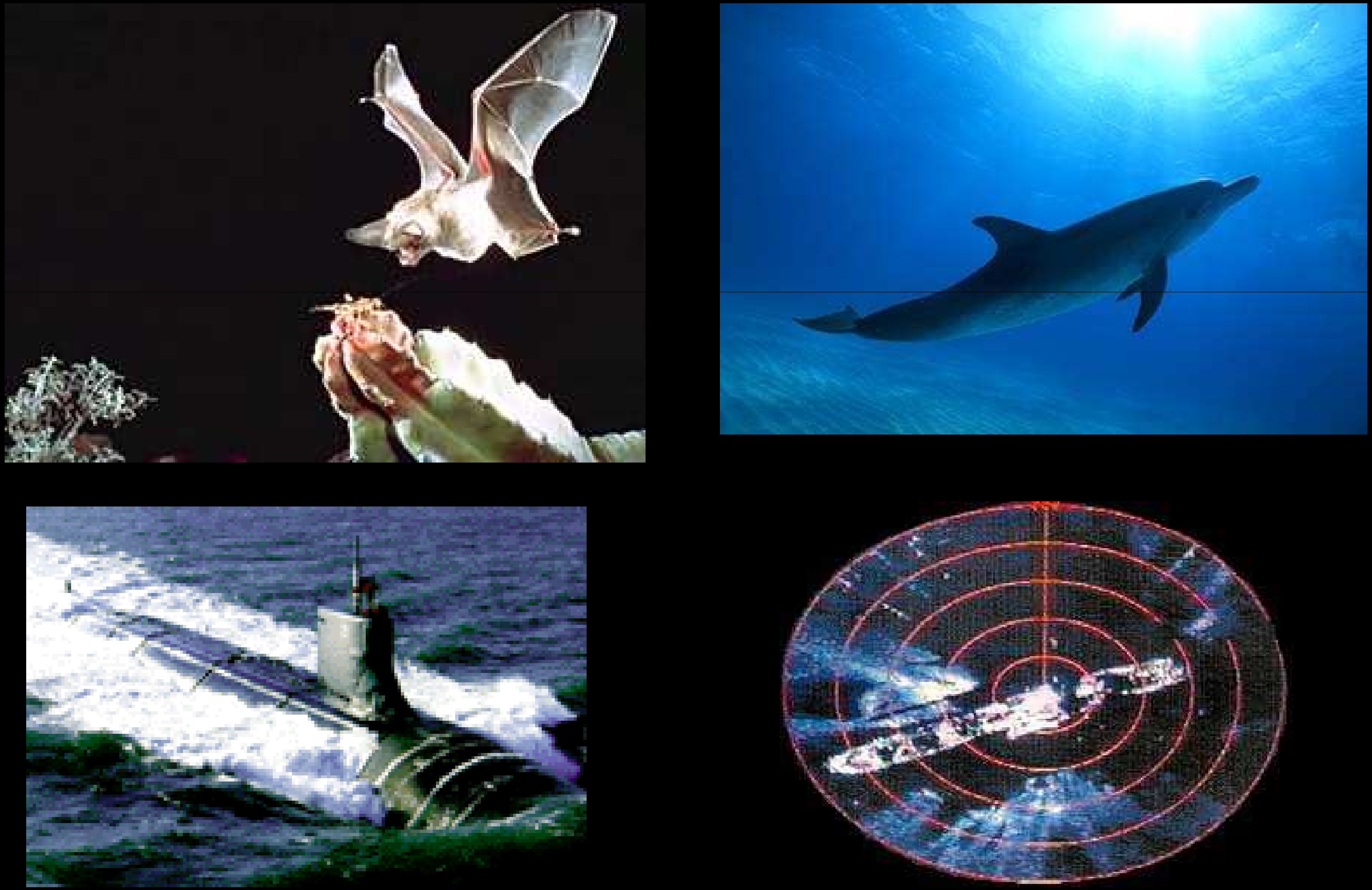
Advantages of Waves:

Can be detected very far away

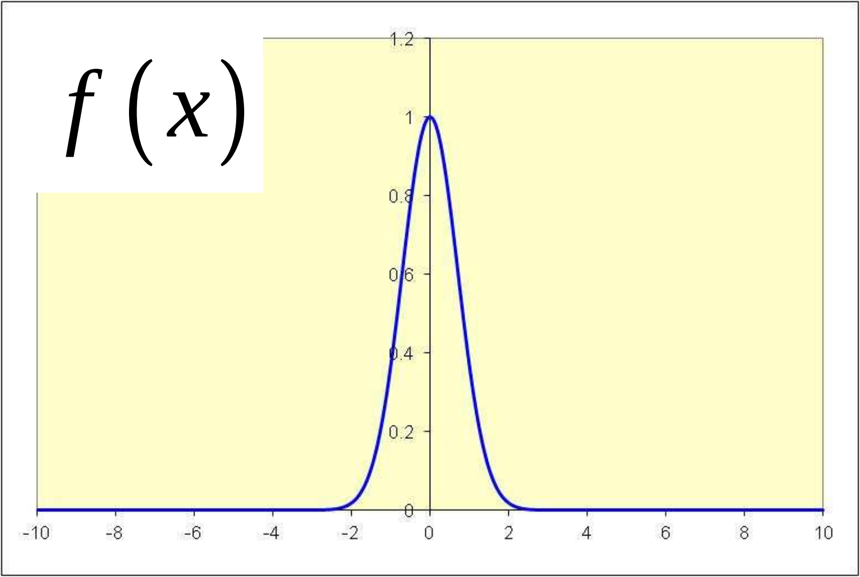
Capable to transpass materials

Non destructive observation

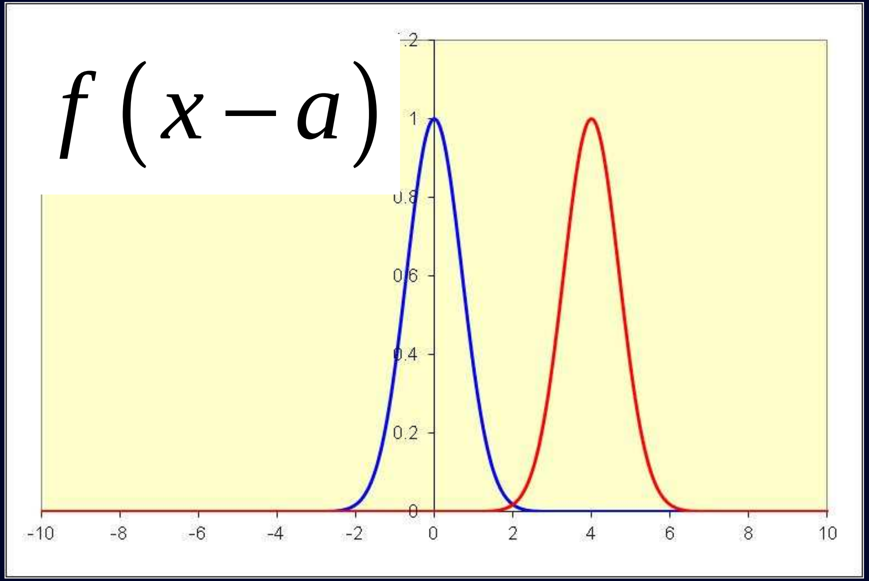
The sonar



ONDA



$f(x)$

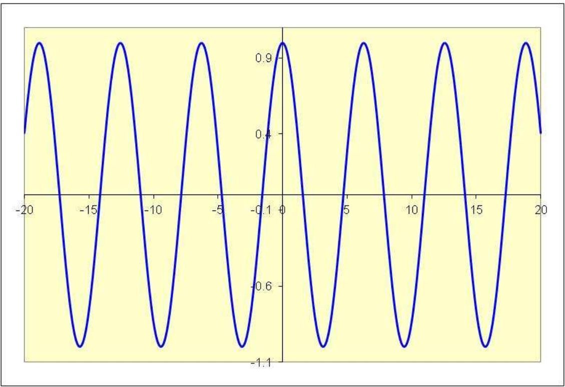


$f(x-a)$

$$f(x - \mathrm{v}t)$$

ONDA HARMÔNICA

$$f\left(x-\mathrm{v}\,t\right)=A\cos\left[k\,x-\omega t\right]$$



Velocidade da Onda:

$$f\left(x-\mathrm{v}\,t\right)=\cos\left[k\left(x-\frac{\omega}{k}t\right)\right]$$

$$\mathrm{v}=\frac{\omega}{k}$$

Onda se repete em λ [comprimento de onda]

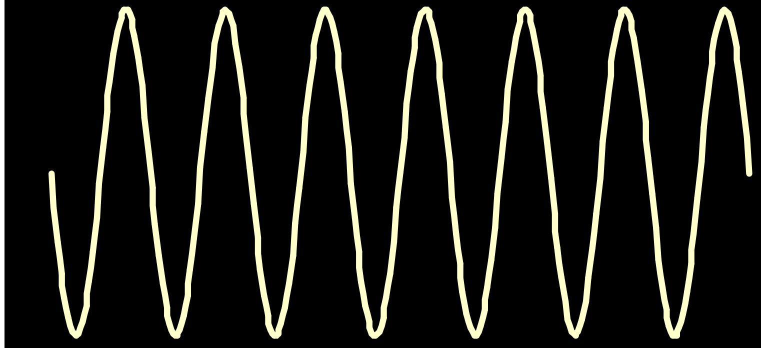
$$k\lambda=2\pi\ \rightarrow\ k=\frac{2\pi}{\lambda}$$

Onda se repete em τ [período da onda]

$$\omega\tau=2\pi\ \rightarrow\ \omega=\frac{2\pi}{\tau}$$

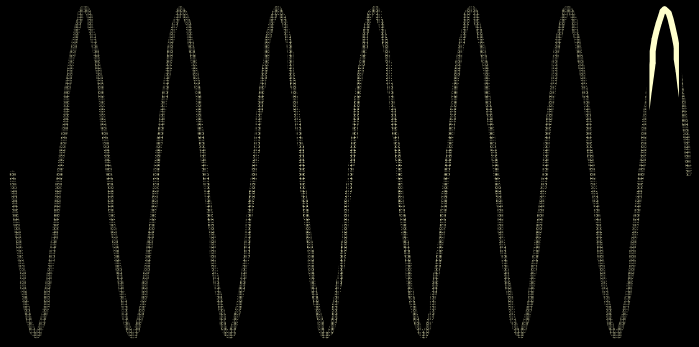
$$\lambda=\mathrm{v}\,\tau$$

Caracterizando uma Onda



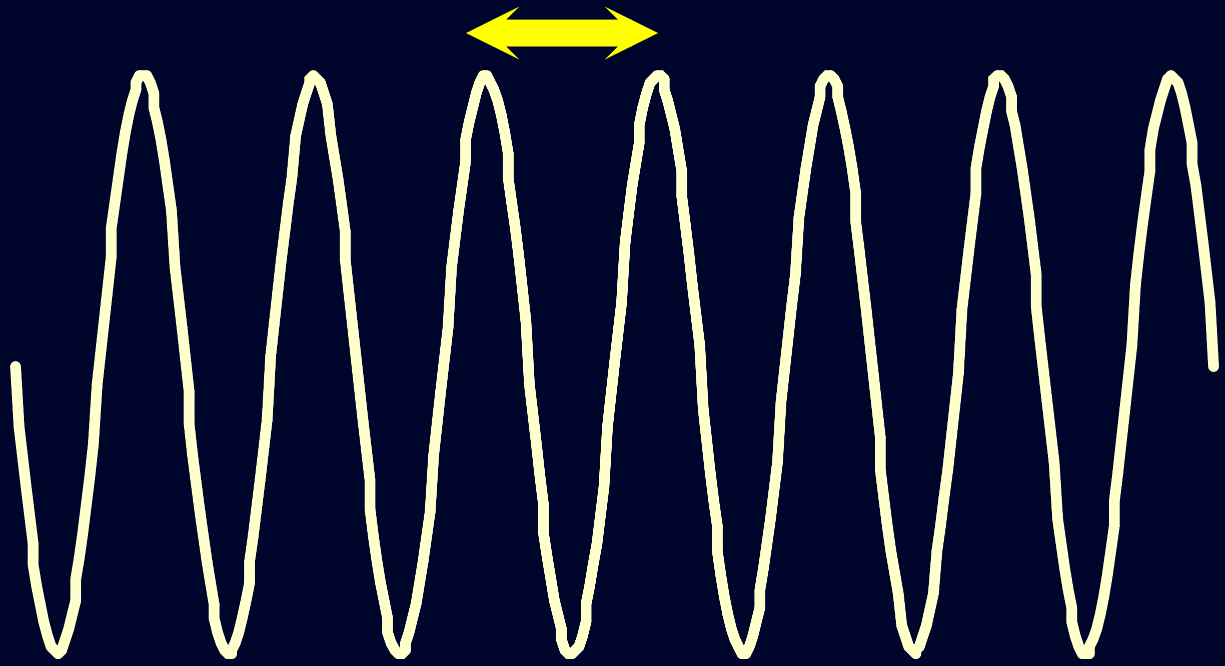
Velocidade: c

Freqüência: f   Período: $\tau = 1/f$



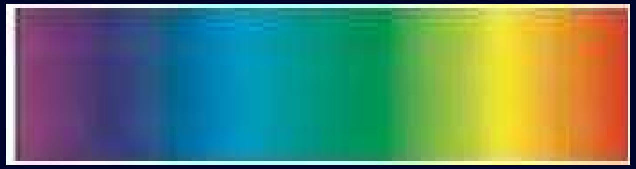
Comprimento de onda: λ

$$\lambda = c\,\tau$$



Espectro no dicionário: (do latim Spectrum)

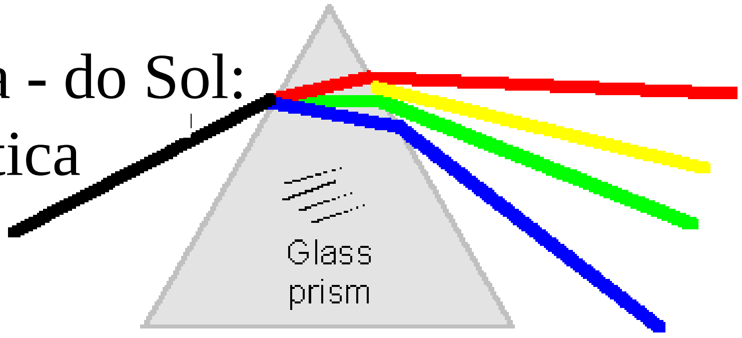
Fantasma, aparição ilusória
Presença ameaçadora - “espectro da fome”.

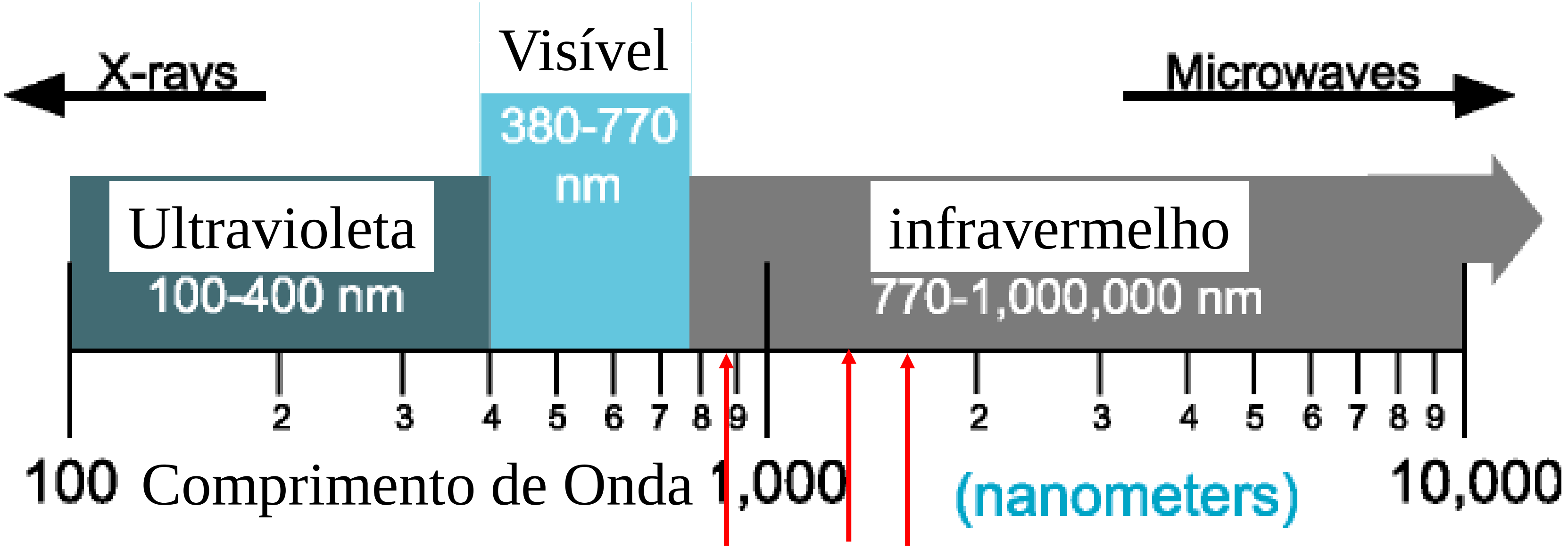


na física: decomposição da luz
na biologia: resposta de microorganismos à diferentes drogas
genericamente: decompor o todo em suas partes

Espectro Eletromagnético

Luz branca - do Sol:
Policromática


Glass
prism

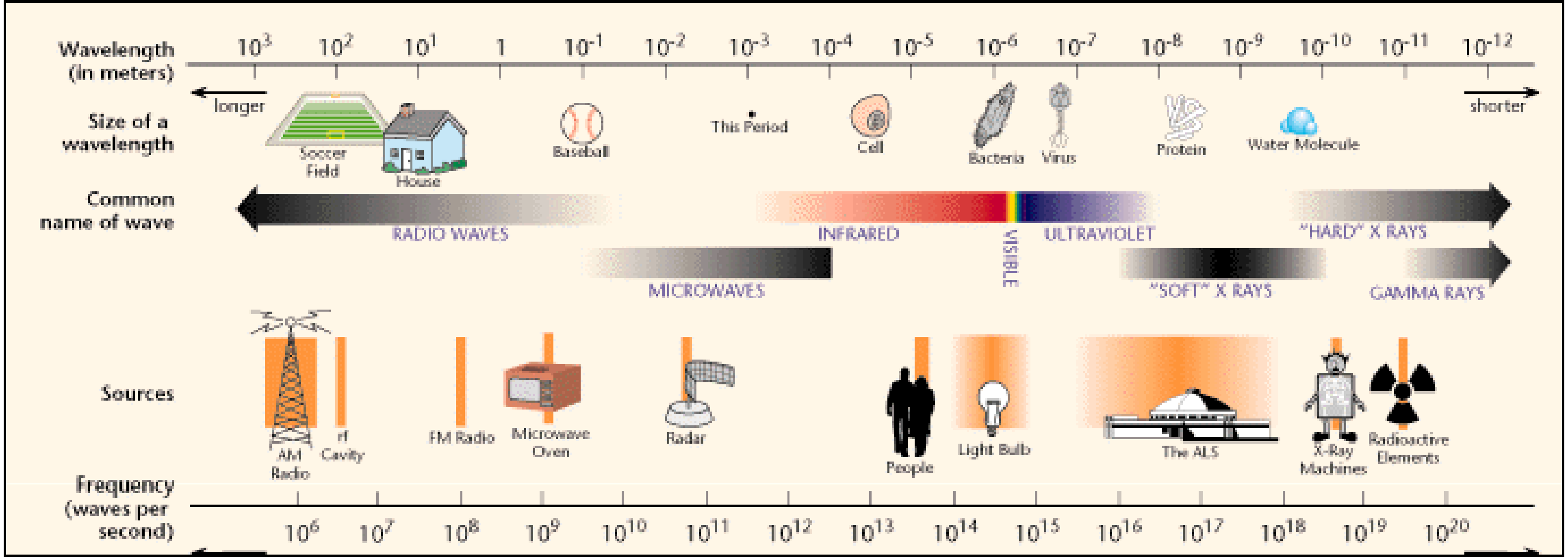

X-rays
Visível
380-770 nm
Microwaves
Ultravioleta
100-400 nm
infravermelho
770-1,000,000 nm
2
3
4
5
6
7
8
9
2
3
4
5
6
7
8
9
100
1,000
10,000
(nanometers)

Comprimento de Onda

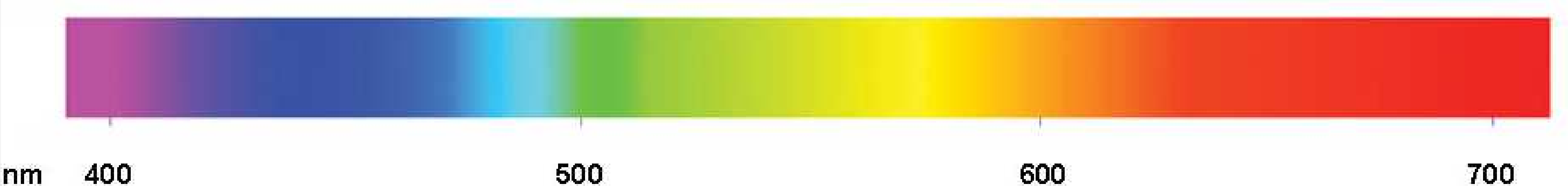
1 2 3

Comunicações Ópticas

Espectro Eletromagnético


Wavelength (in meters)
10³
10²
10¹
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10⁶
10⁷
10⁸
10⁹
10¹⁰
10¹¹
10¹²
10¹³
10¹⁴
10¹⁵
10¹⁶
10¹⁷
10¹⁸
10¹⁹
10²⁰

Vísivel


nm
400
500
600
700

Ultra violeta não atinge a retina – olhos menores vêm UV

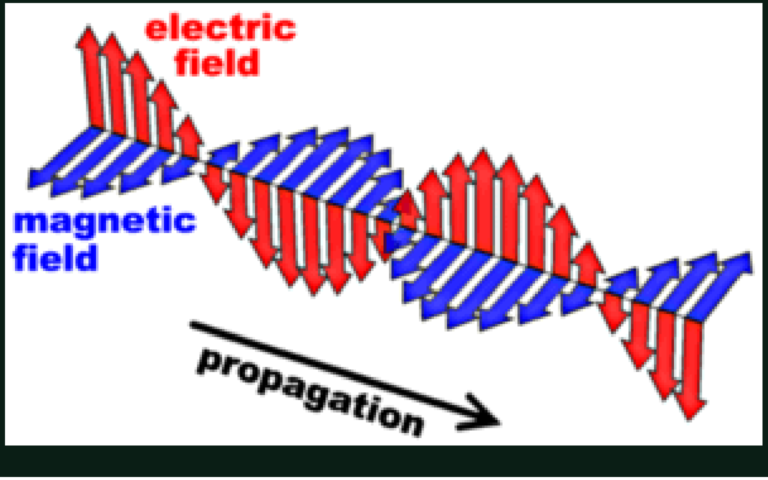
Infravermelho não é detectado

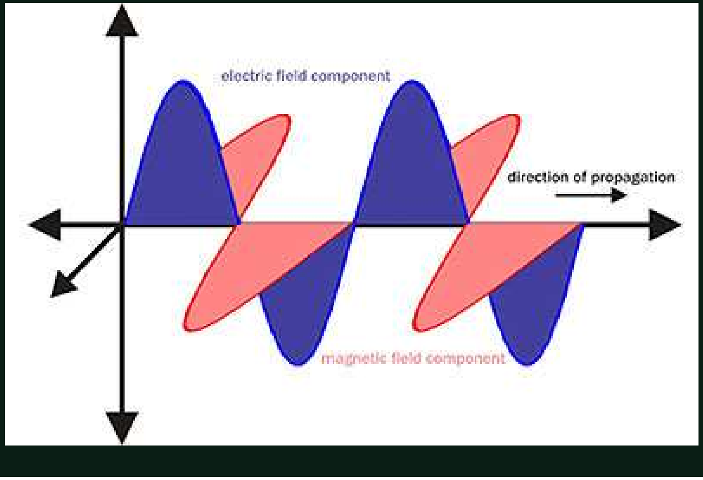
Ondas podem ser:

Transversais [POLARIZAÇÃO]

Longitudinais

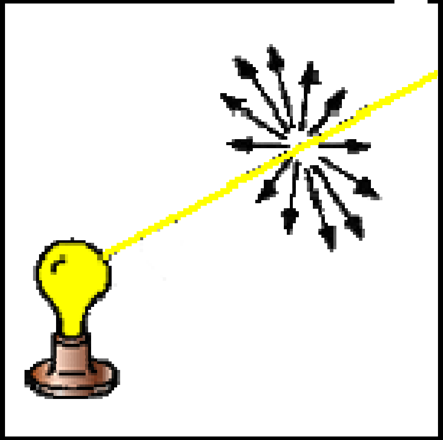
Ondas ópticas são TRANSVERSAIS: $\Psi = \vec{E}\cos[k\,x - \omega t]$


electric field
magnetic field
propagation

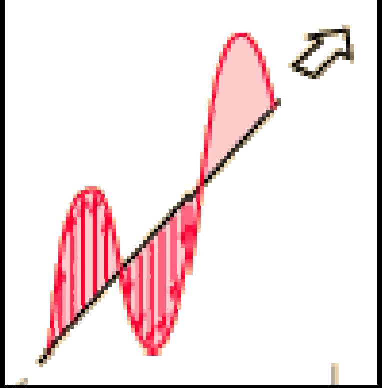

electric field component
direction of propagation
magnetic field component

Estados de polarização:

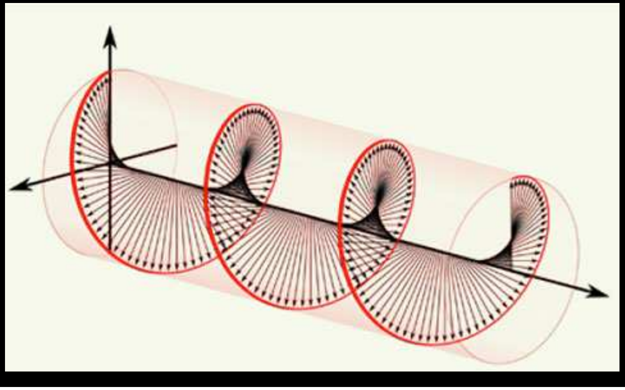
Despolarizado:



Linearmente polarizado:

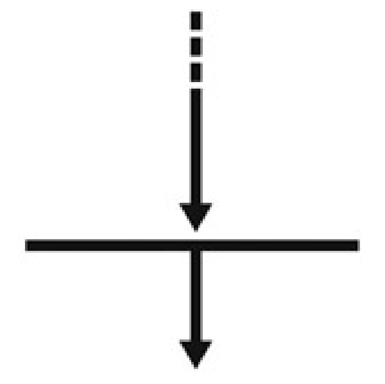


Circularmente polarizado:

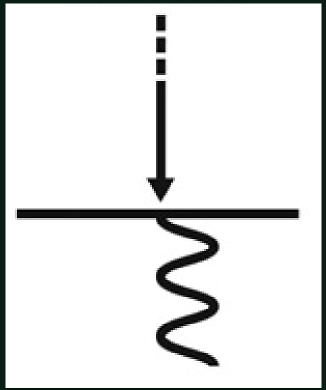


Ondas podem ser:

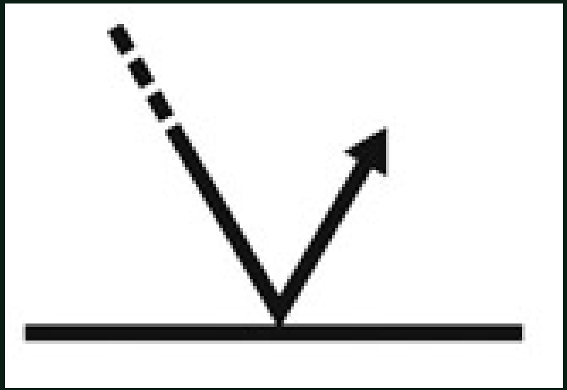
transmitidas



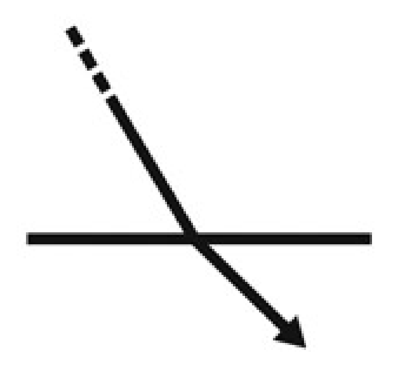
absorvidas



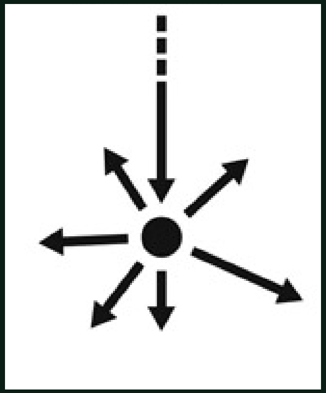
refletidas



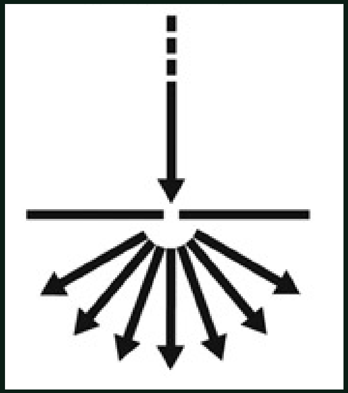
refratadas



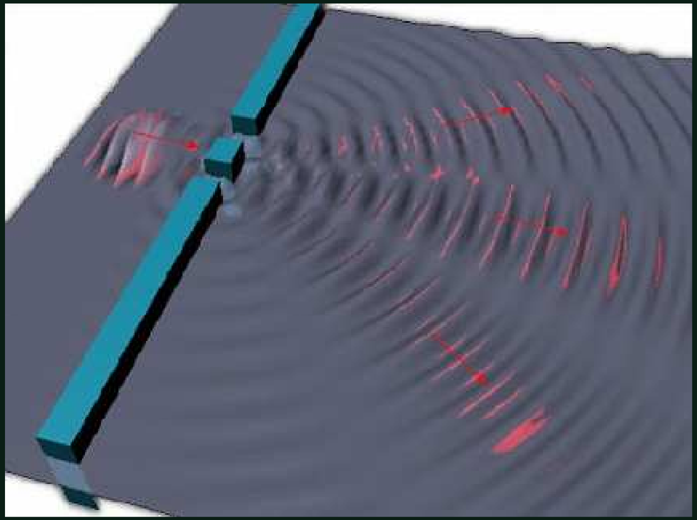
espalhadas



difratadas

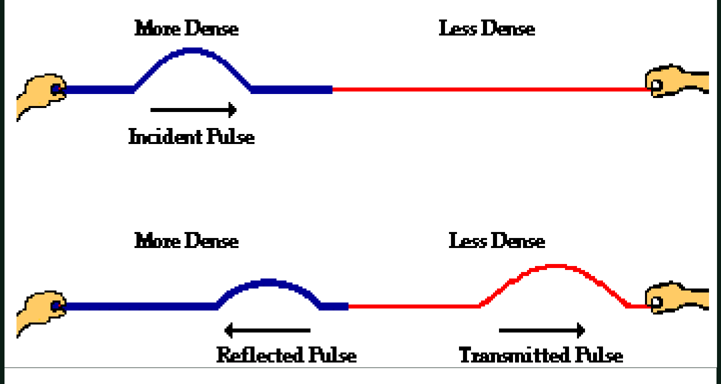


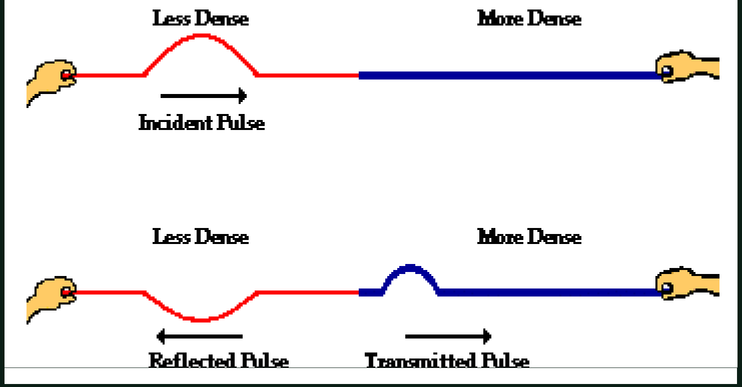
Duas ondas sofrem interferência



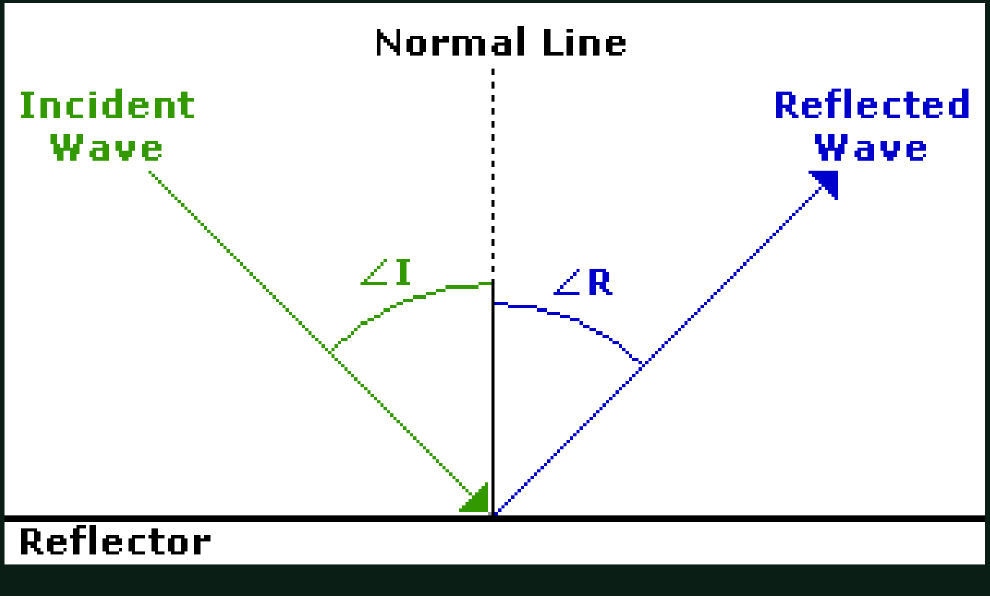
Reflexões

Reflexão ocorre sempre que dois meios são diferentes impedância – índice de refração


More Dense
Less Dense
Incident Pulse
More Dense
Less Dense
Reflected Pulse
Transmitted Pulse

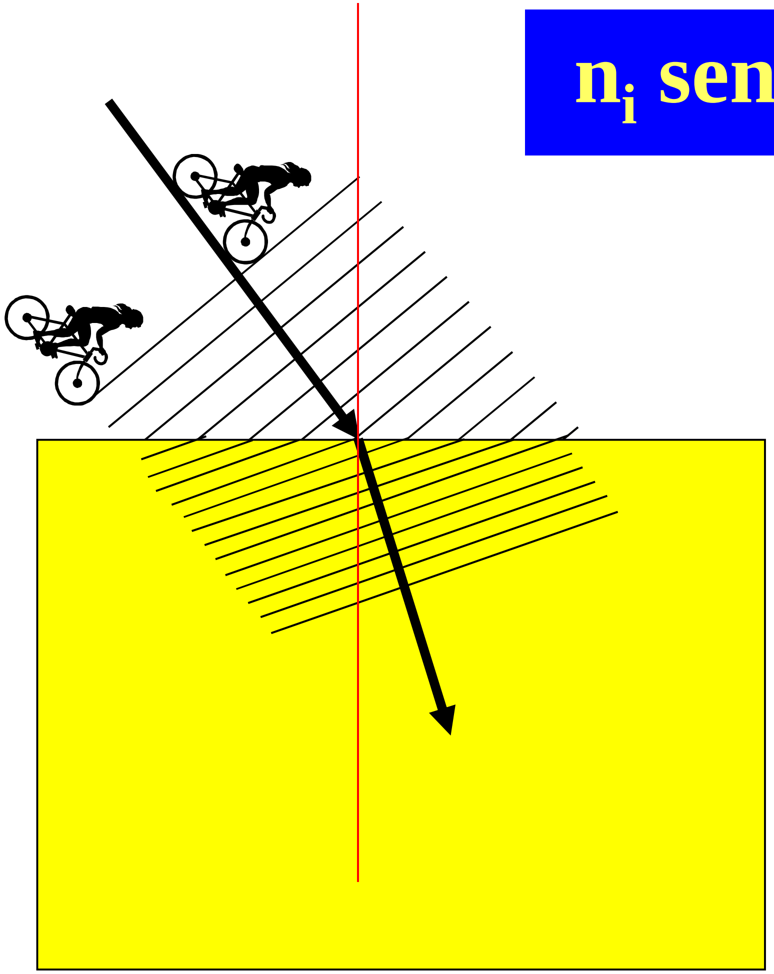

Less Dense
More Dense
Incident Pulse
Less Dense
More Dense
Reflected Pulse
Transmitted Pulse

Ângulo de incidência igual ao de reflexão

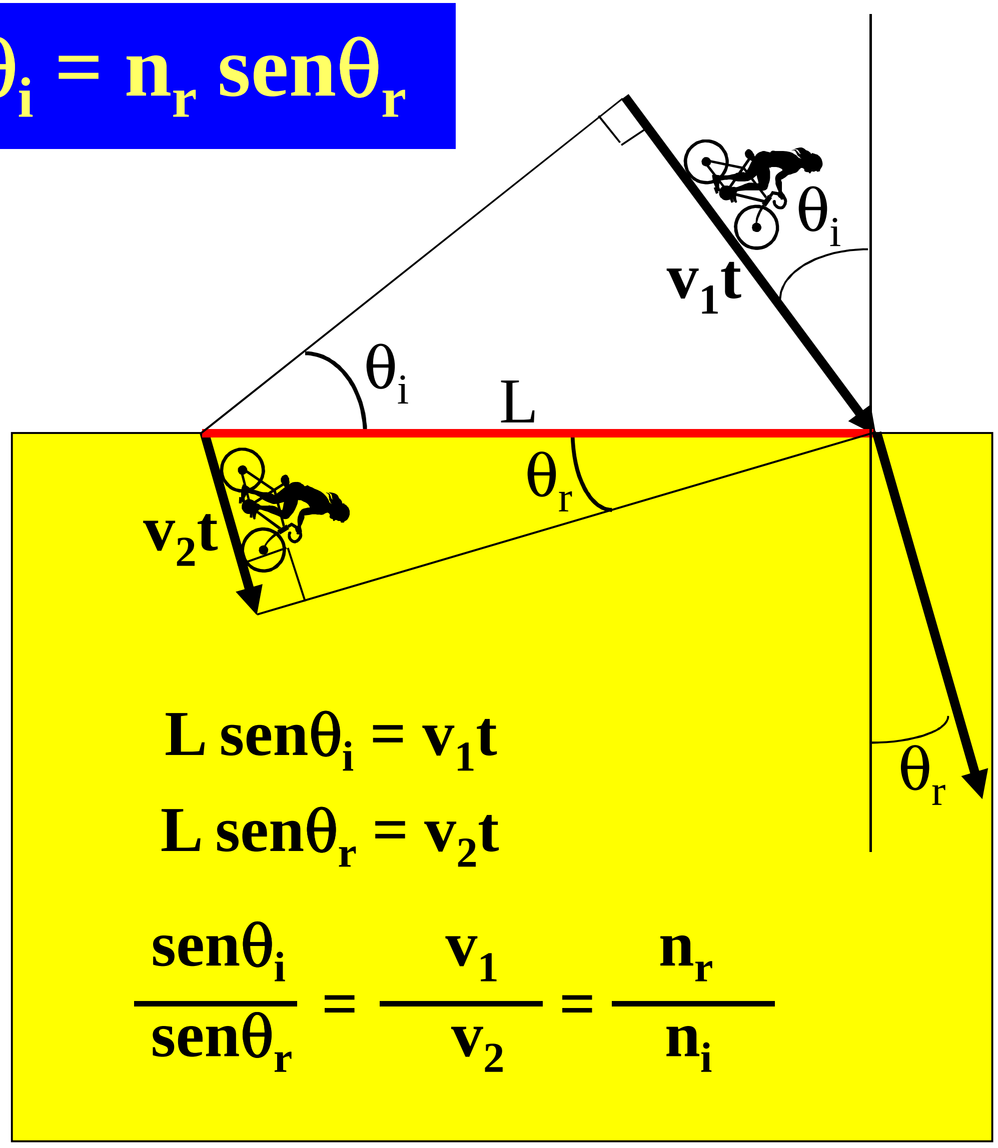

Normal Line
Incident Wave
Reflected Wave
∠I
∠R
Reflector

Refração: Snell (1580-1626) is still alive

$$n_i \,\mathrm{sen}\theta_i = n_r \,\mathrm{sen}\theta_r$$



$$k_{vac} = \frac{2\pi}{\lambda} \qquad k_{meio} = \frac{2\pi n}{\lambda}$$



$$L\,\mathrm{sen}\theta_i = v_1 t$$

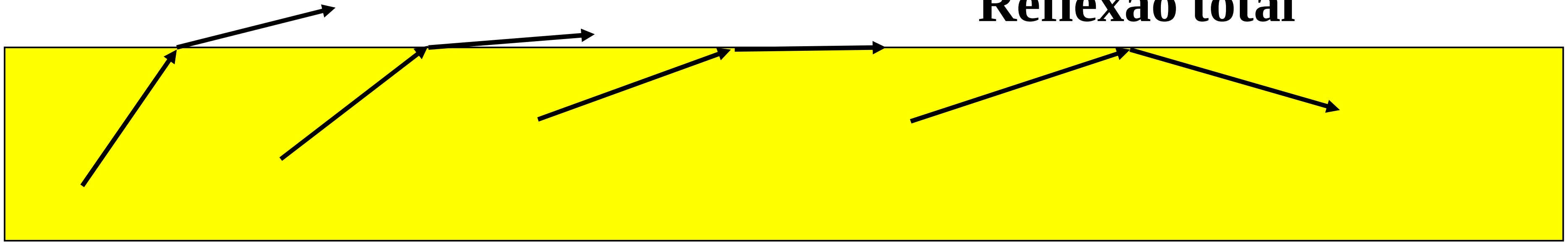
$$L\,\mathrm{sen}\theta_r = v_2 t$$

$$\frac{\mathrm{sen}\theta_i}{\mathrm{sen}\theta_r} = \frac{v_1}{v_2} = \frac{n_r}{n_i}$$

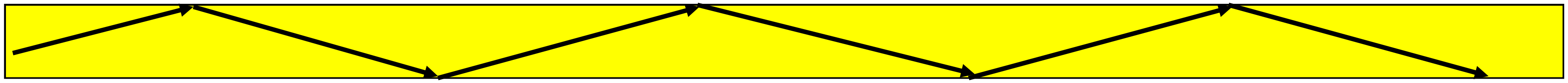
Reflexão interna total e a fibra óptica

$$\text{sen}\theta_{rit} = n_r / n_i$$

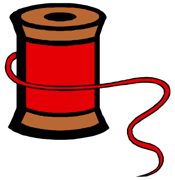
Reflexão total

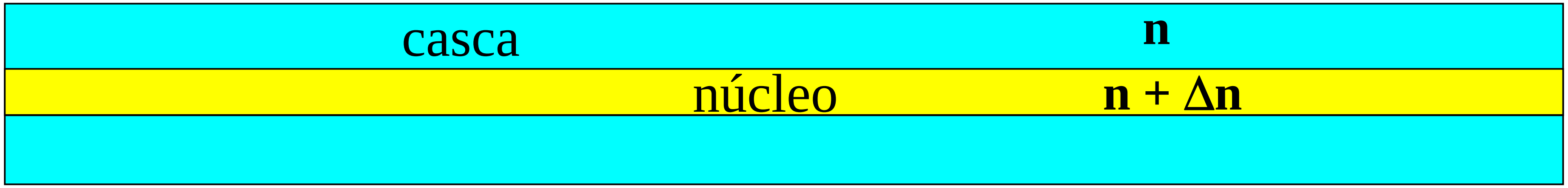


Fibra óptica



$$\text{sen}\theta = n / (n + \Delta n)$$

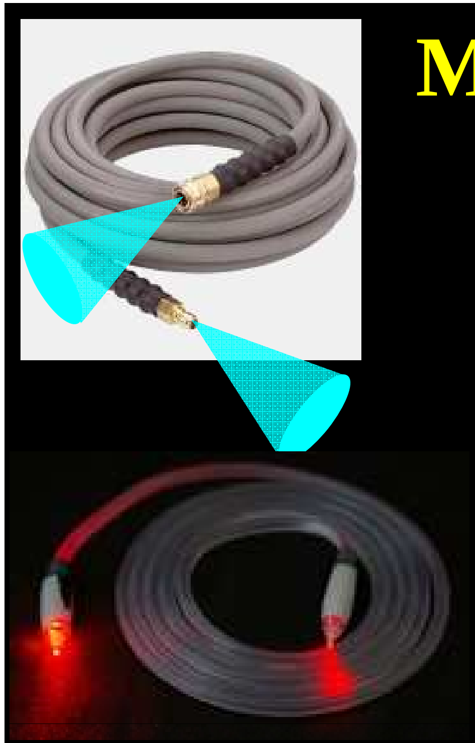


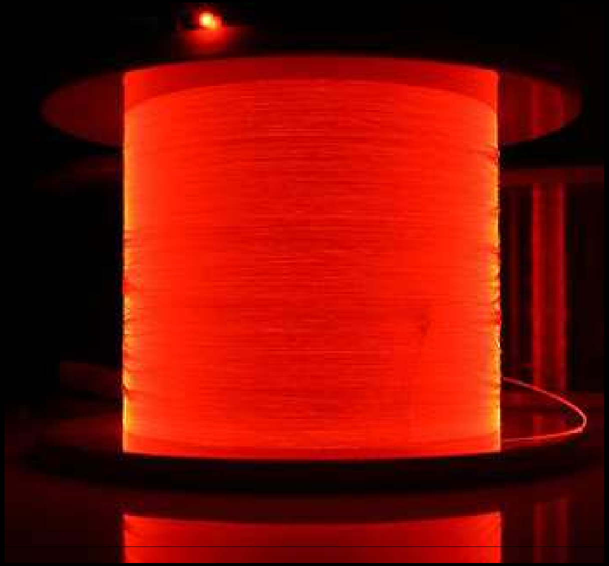


casca **n**

núcleo **n + Δn**

Mangueira de luz: fibras ópticas

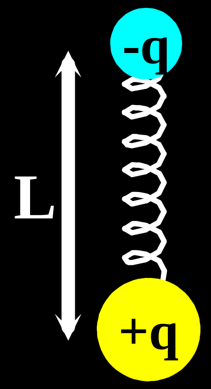




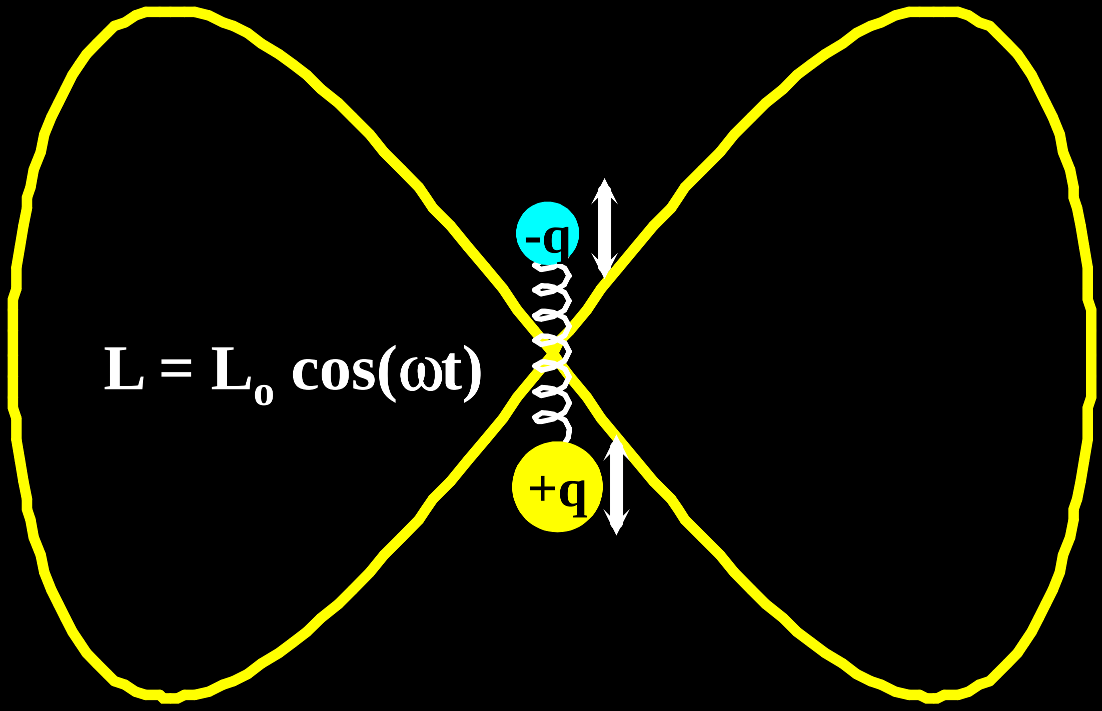
Moda FIBRA - LASER

Geração de radiação: Dipolo oscilante

momento de dipolo: $p = q\,L$

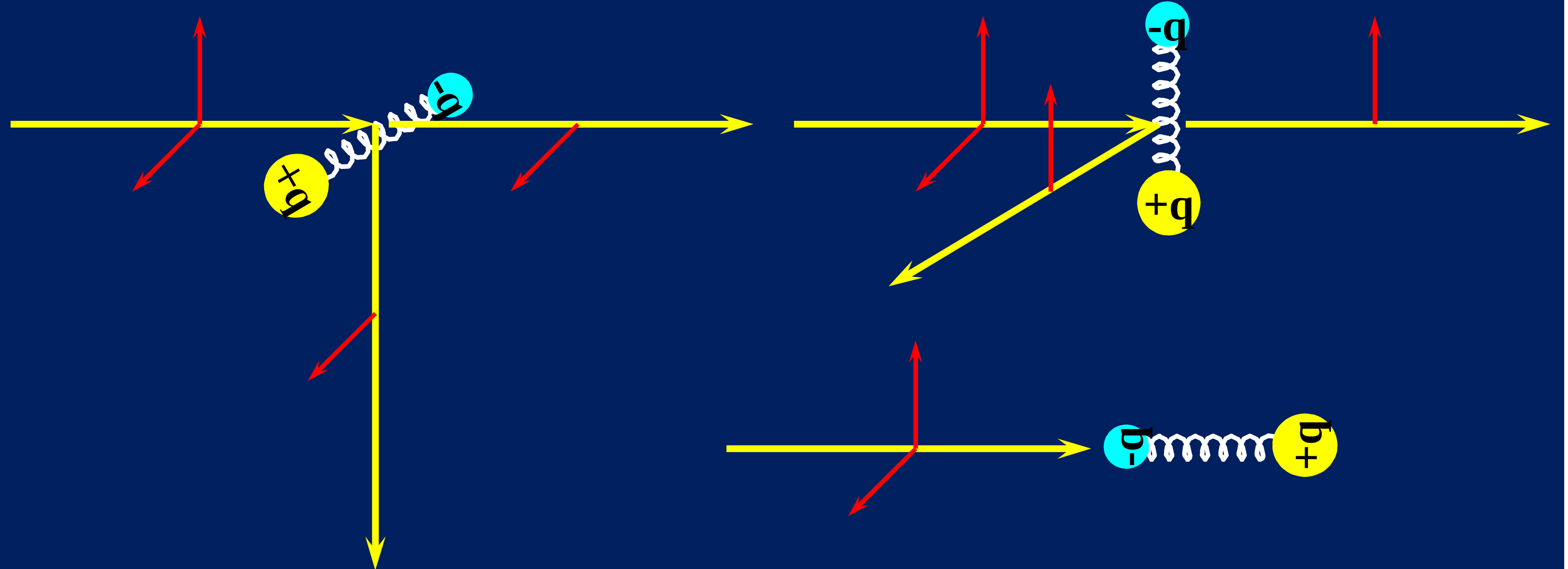


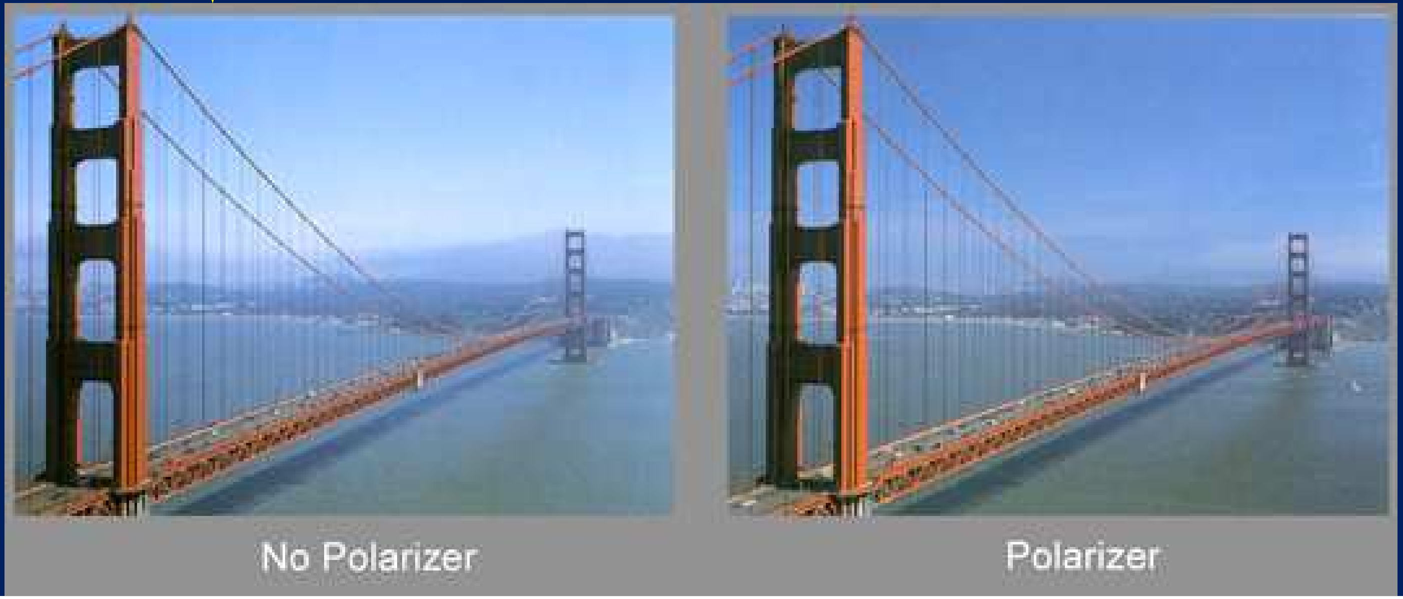
$L = L_o \cos(\omega t)$



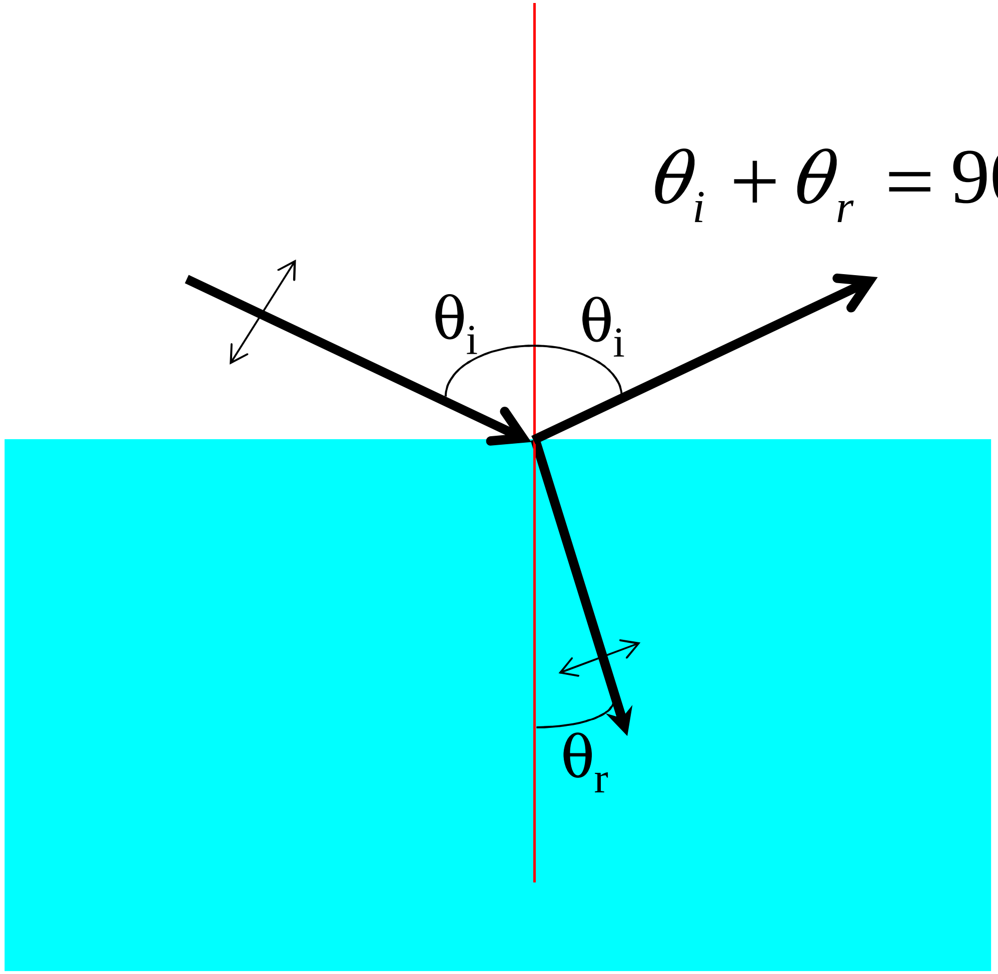
Padrão de Radiação

Polarização do céu

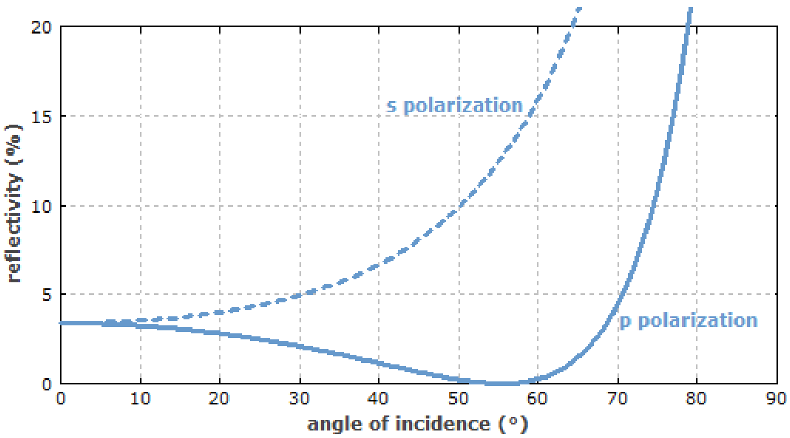



No Polarizer
Polarizer

Ângulo de Brewster



$$\theta_i + \theta_r = 90^o$$

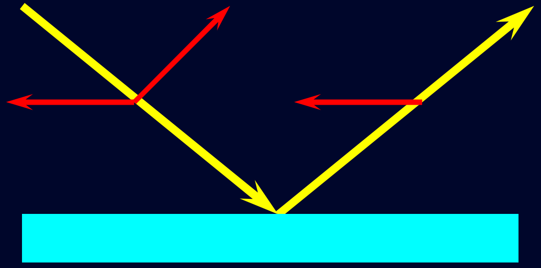


$$n_i \sin\theta_i = n_r \sin\theta_r = n_r \sin[90-\theta_i]$$

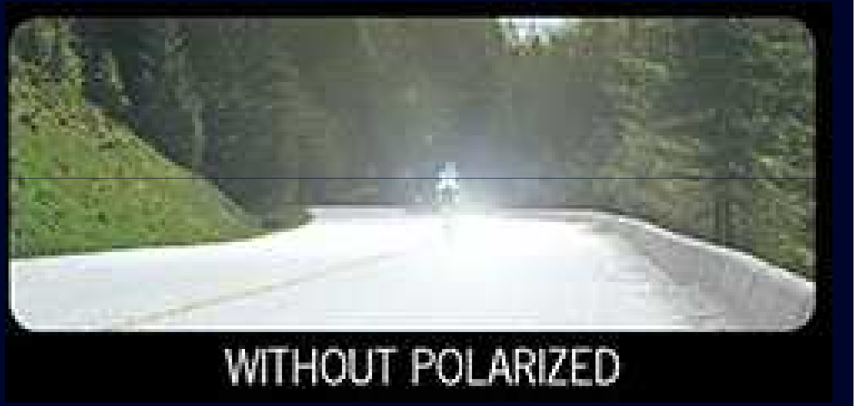
$$n_i \sin\theta_i = n_r \cos\theta_i$$

$$\tan\theta_{Brewster} = \frac{n_r}{n_i}$$

Óculos polarizado: evita reflexão direta

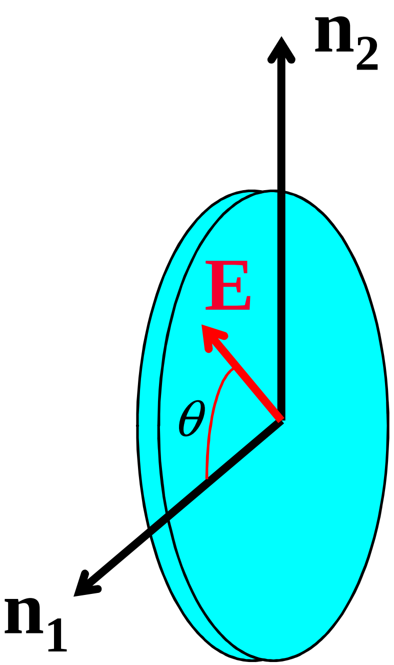


Without polarized lenses
With polarized lenses


WITHOUT POLARIZED

WITH POLARIZED

Estados de Polarização em placas birefringentes



$$E_x = E_o \cos[\frac{2\pi n_1 \ell}{\lambda} - \omega t] \cos\theta$$

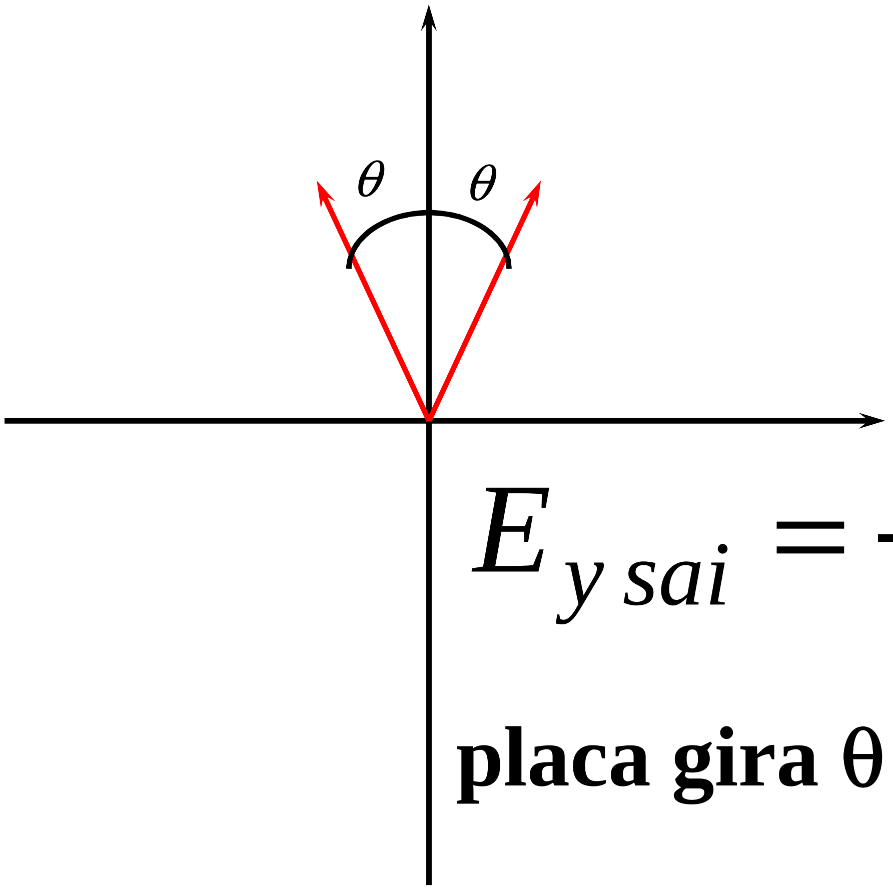
$$E_y = E_o \cos[\frac{2\pi n_2 \ell}{\lambda} - \omega t] \sin\theta$$

$$E_y = E_o \cos[\frac{2\pi n_1 \ell}{\lambda} - \omega t - \frac{2\pi \, \Delta n \, \ell}{\lambda}] \sin\theta$$

Placa de meia onda

$$E_y = E_o \cos[\frac{2\pi n_1 \ell}{\lambda} - \omega t - \frac{2\pi\, \Delta n\, \ell}{\lambda}] \sin\theta \qquad \frac{2\pi\, \Delta n\, \ell}{\lambda} = \pi$$

$$\Delta n\, \ell = \frac{\lambda}{2}$$



$$E_{y\, sai} = -E_{y\, entra}$$

placa gira θ e polarização gira 2θ

Placa de um quarto de onda

$$E_y = E_o \cos[\frac{2\pi n_1 \ell}{\lambda} - \omega t - \frac{2\pi \,\Delta n \,\ell}{\lambda}] \sin\theta \qquad \frac{2\pi \,\Delta n \,\ell}{\lambda} = \frac{\pi}{2}$$

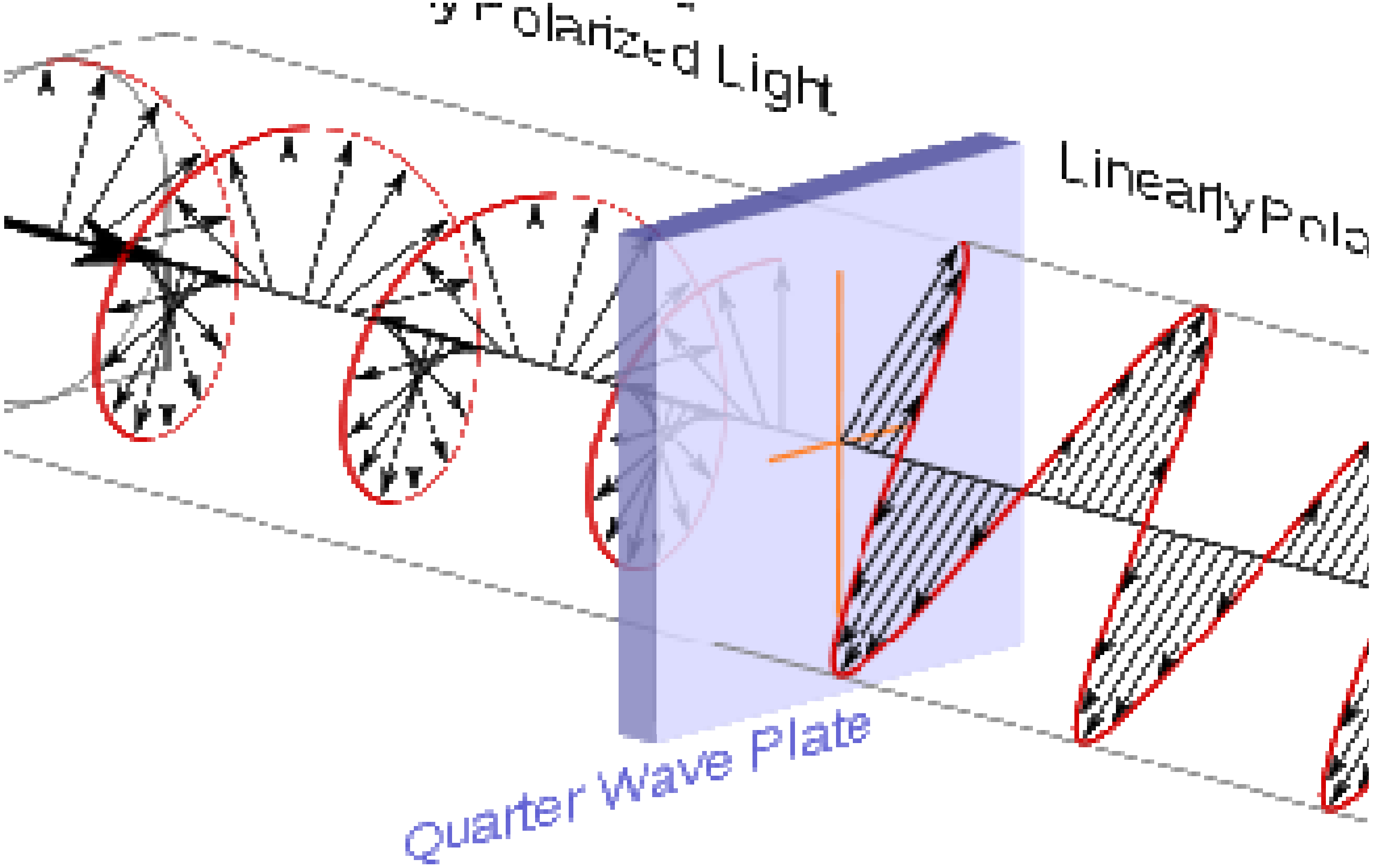
$$E_x = E_o \cos[\frac{2\pi n_1 \ell}{\lambda} - \omega t] \cos\theta$$

$$\Delta n \,\ell = \frac{\lambda}{4}$$

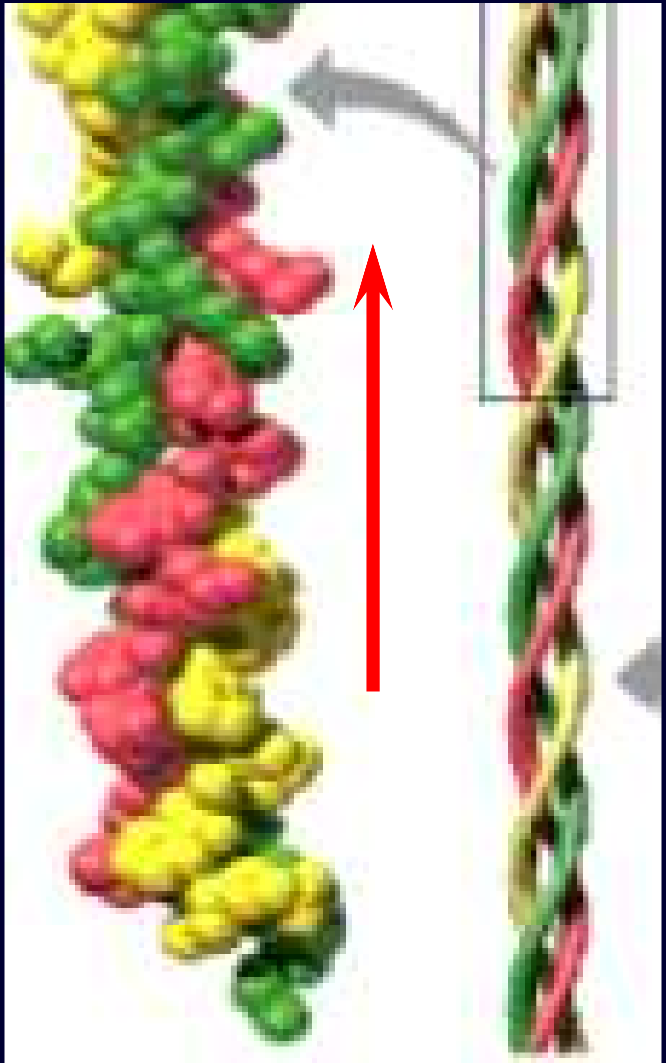
$$E_y = E_o \sin[\frac{2\pi n_1 \ell}{\lambda} - \omega t] \sin\theta$$

Feixe sai circularmente/elipticamente polarizado

Filme 3D usando placas de ¼ de onda


Polarized Light
Linearly Pola
Quarter Wave Plate

Polarização faz diferença: SHG
Fibrilas de colágeno



Porque ondas interferem?

Intensidade proporcional a E^2

$$\Psi = \vec{E}\cos\left[k\,x - \omega t\right] \qquad I \propto \left|\vec{E}\right|^2$$

Duas ondas – qual operação vem primeiro?

Soma e eleva ao quadrado $I_{total} \propto \left|\vec{E}_1 + \vec{E}_2\right|^2$

Eleva ao quadrado e soma $I_{total} \propto \left|\vec{E}_1\right|^2 + \left|\vec{E}_2\right|^2$

$$\left|E_1\cos(\theta_1) + E_2\cos(\theta_2)\right|^2 = E_1^2\cos^2(\theta_1) + 2E_1E_2\cos(\theta_1)\cos(\theta_2) + E_2^2\cos^2(\theta_2)$$

O termo $2E_1E_2\cos(\theta_1)\cos(\theta_2)$ gera a interferência!

A trigonometria e a interferência

$$\cos(a+b) = \cos a \cos b - \sin a \sin b$$

$$\underline{\cos(a-b) = \cos a \cos b + \sin a \sin b}$$

$$\cos a \cos b = \frac{1}{2}\cos(a+b) + \frac{1}{2}\cos(a-b)$$

Invertendo

$$a+b = \theta_2$$

$$a-b = \theta_1$$

$$a = \left(\frac{\theta_2+\theta_1}{2}\right) \qquad b = \left(\frac{\theta_2-\theta_1}{2}\right)$$

$$\cos(\theta_2) + \cos(\theta_1) = 2\cos\left(\frac{\theta_2+\theta_1}{2}\right)\cos\left(\frac{\theta_2-\theta_1}{2}\right)$$

Interferência

$$\cos(\theta_2)+\cos(\theta_1)=2\cos\left(\frac{\theta_2+\theta_1}{2}\right)\cos\left(\frac{\theta_2-\theta_1}{2}\right)$$

$$y_1 = y_o\cos(kx_1-\omega t)$$

$$y_2 = y_o\cos(kx_2-\omega t)$$

$$y_1+y_2=2\cos\left[\frac{k}{2}(x_2+x_1)-\omega t\right]\cos\left[\frac{k}{2}(x_2-x_1)\right]$$

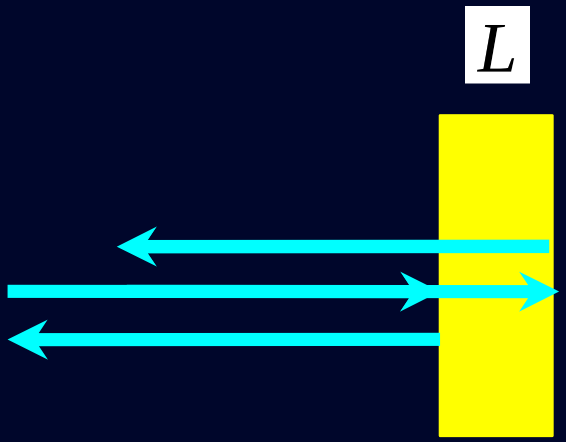
Máximo se: $\cos\left[\frac{k}{2}(x_2-x_1)\right]=\pm 1\rightarrow\frac{\pi}{\lambda}\delta x=m\pi$ $\quad \delta x = m\lambda$

Mínimo se: $\cos\left[\frac{k}{2}(x_2-x_1)\right]=0$ $\quad \delta x=\left(m+\frac{1}{2}\right)\lambda$

Espelhos dielétricos: Filtros dicróicos

Máximo se: $\delta x = m\lambda$

Mínimo se: $\delta x = \left(m + \frac{1}{2} \right) \lambda$

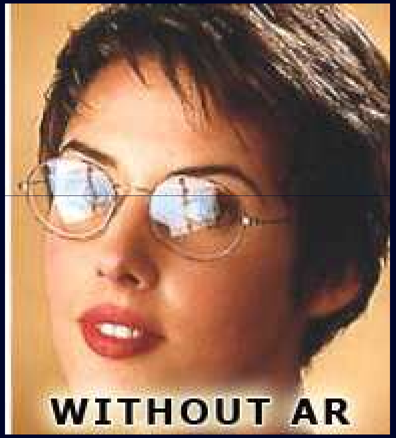


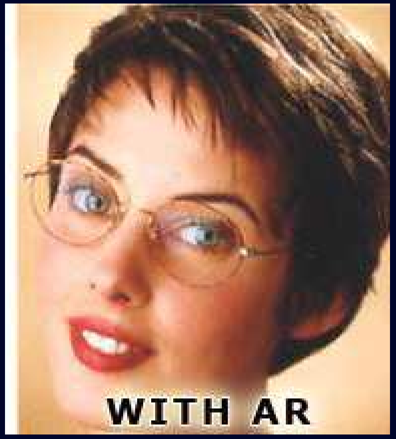
Anti-reflection

$\lambda = 4L$

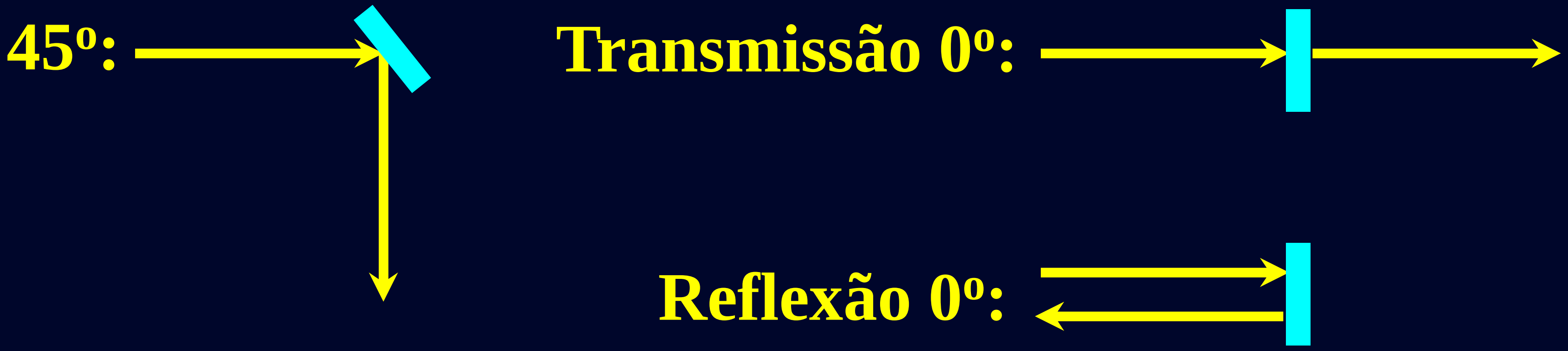
Espelho perfeito

$\lambda = 2L$





Geometria dos filtros dicróicos:

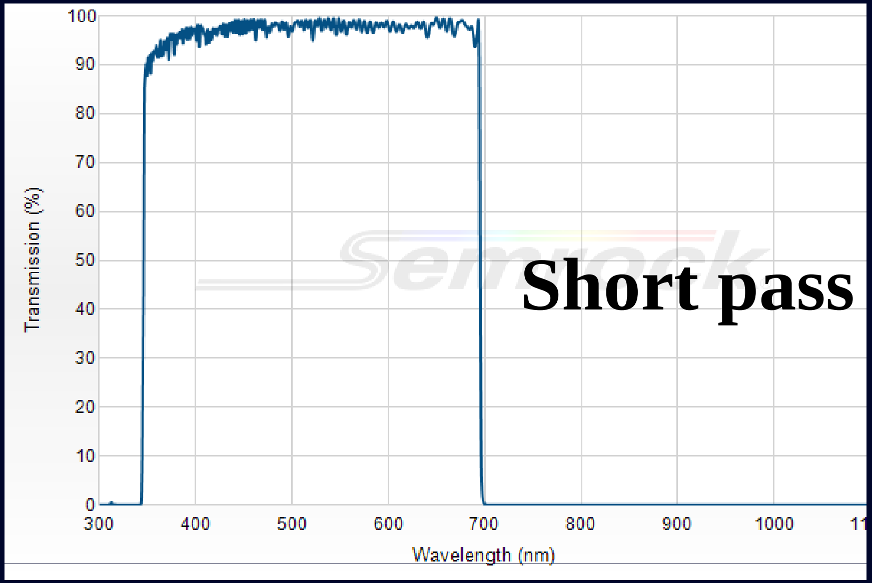


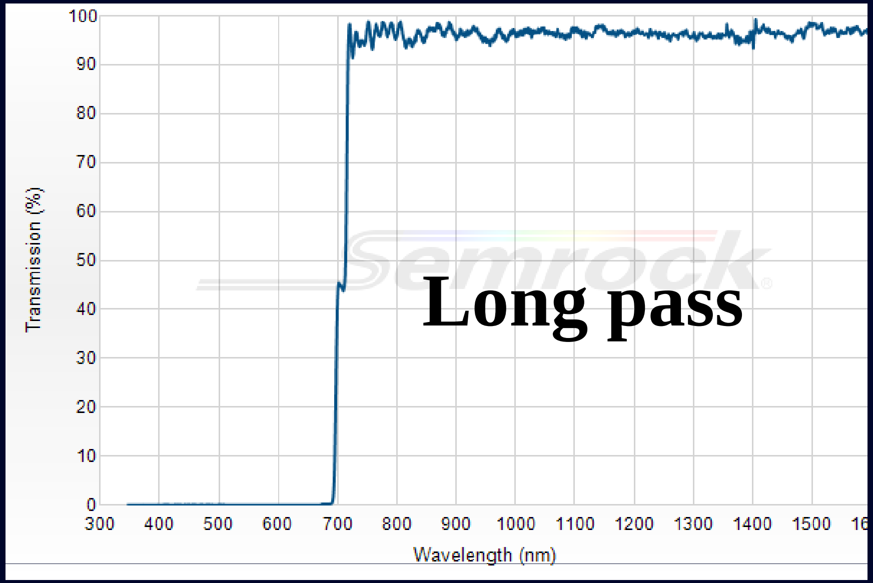
45º:

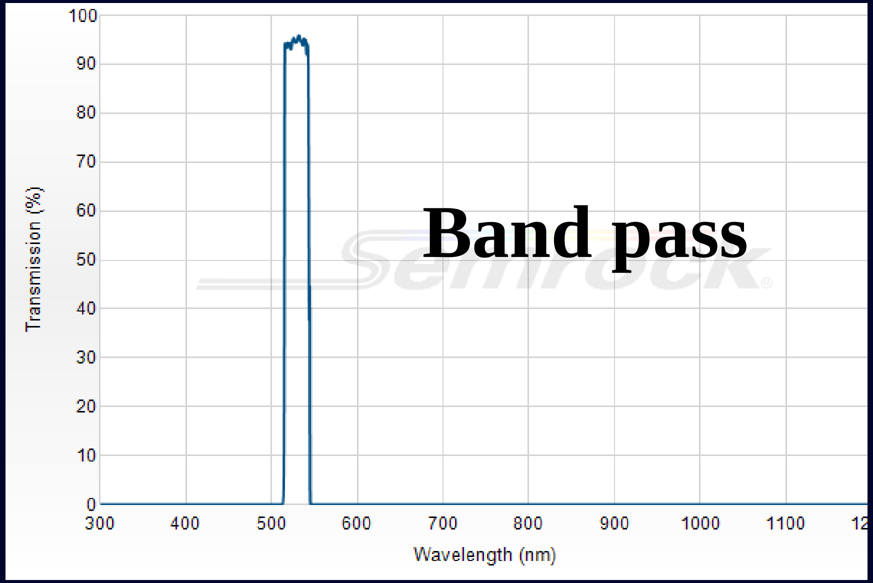
Transmissão 0º:

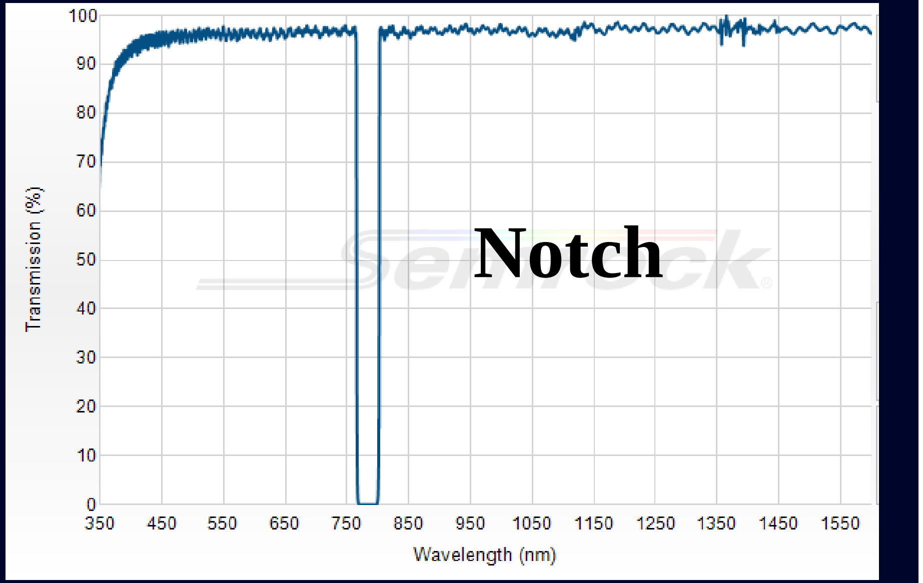
Reflexão 0º:

Tipos de filtros dicróicos:

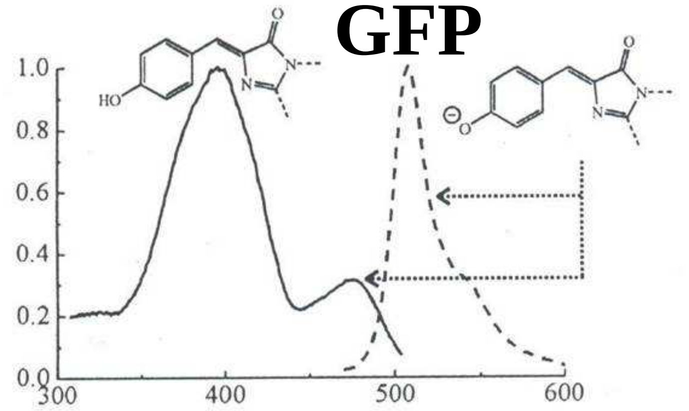

Short pass


Long pass

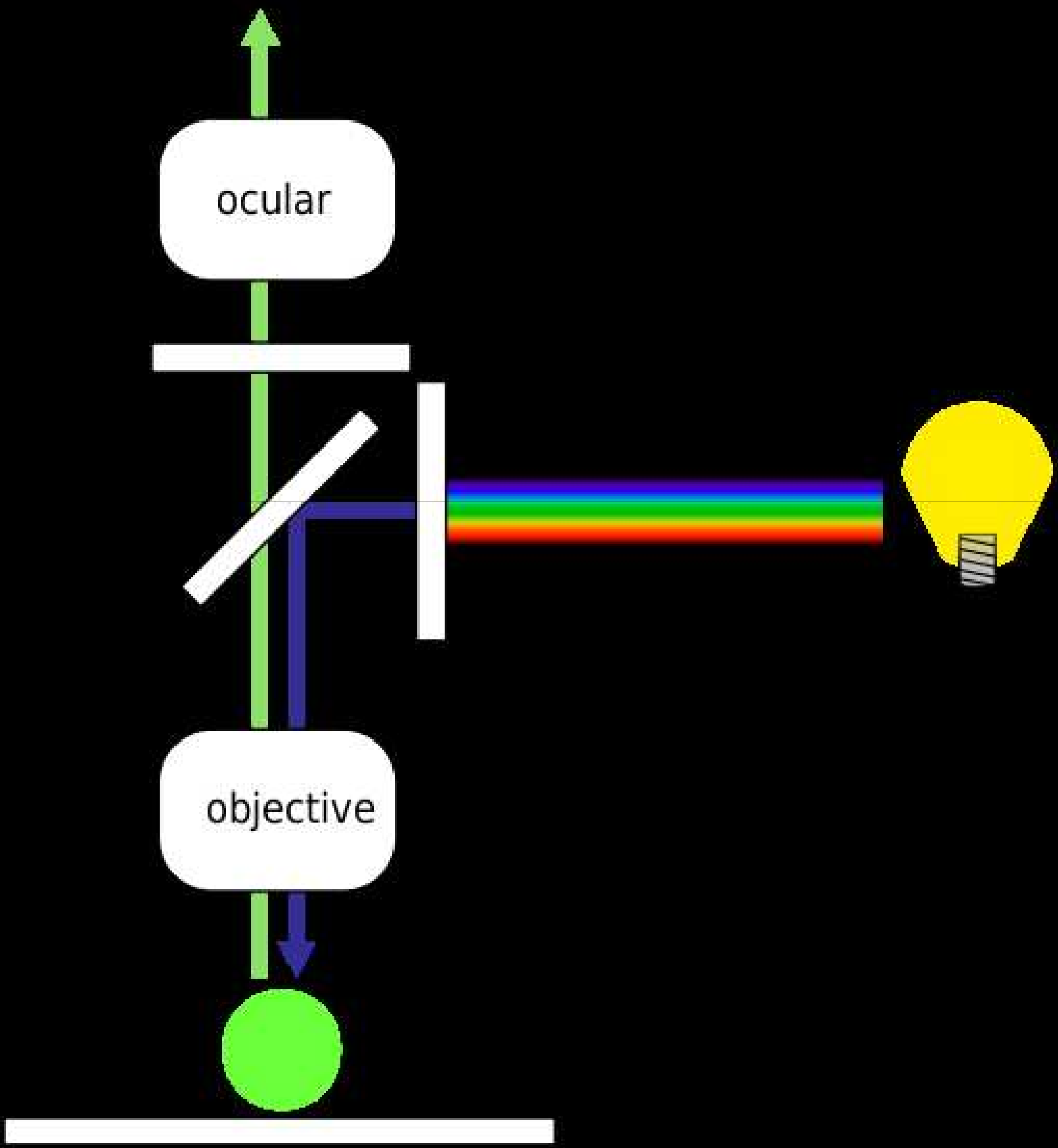

Band pass


Notch

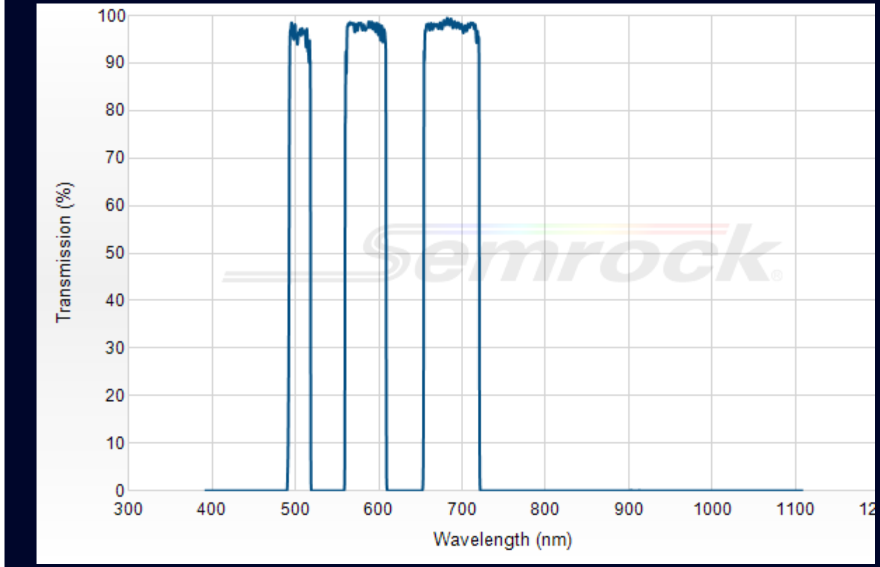
Cubos de filtros para fluorescência



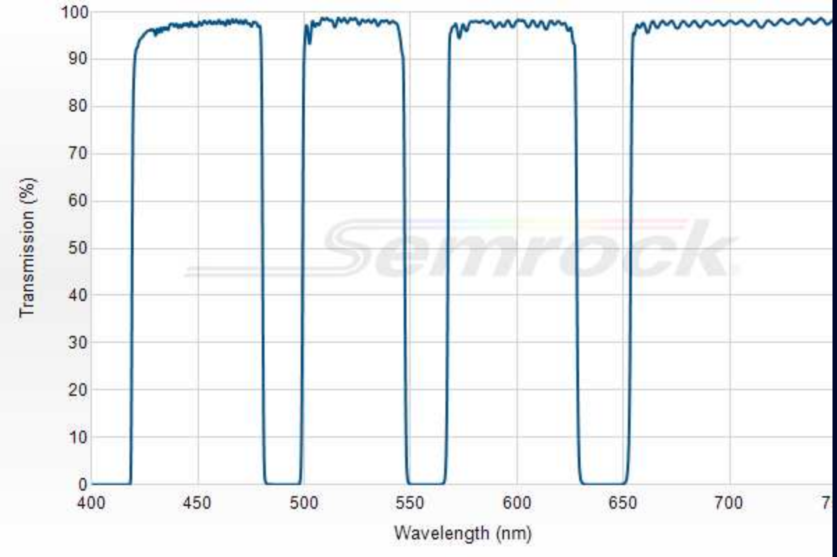
Banda de excitação **Banda de emissão**


ocular
objective

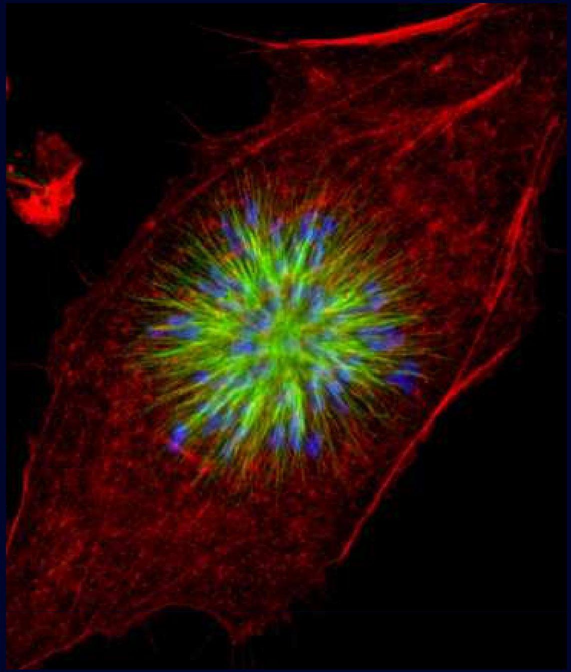
Filtros para marcação multicores

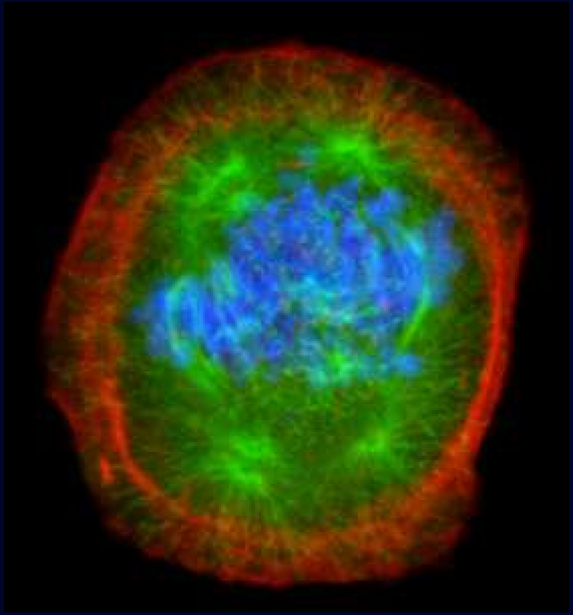


MultiBand



MultiNotch

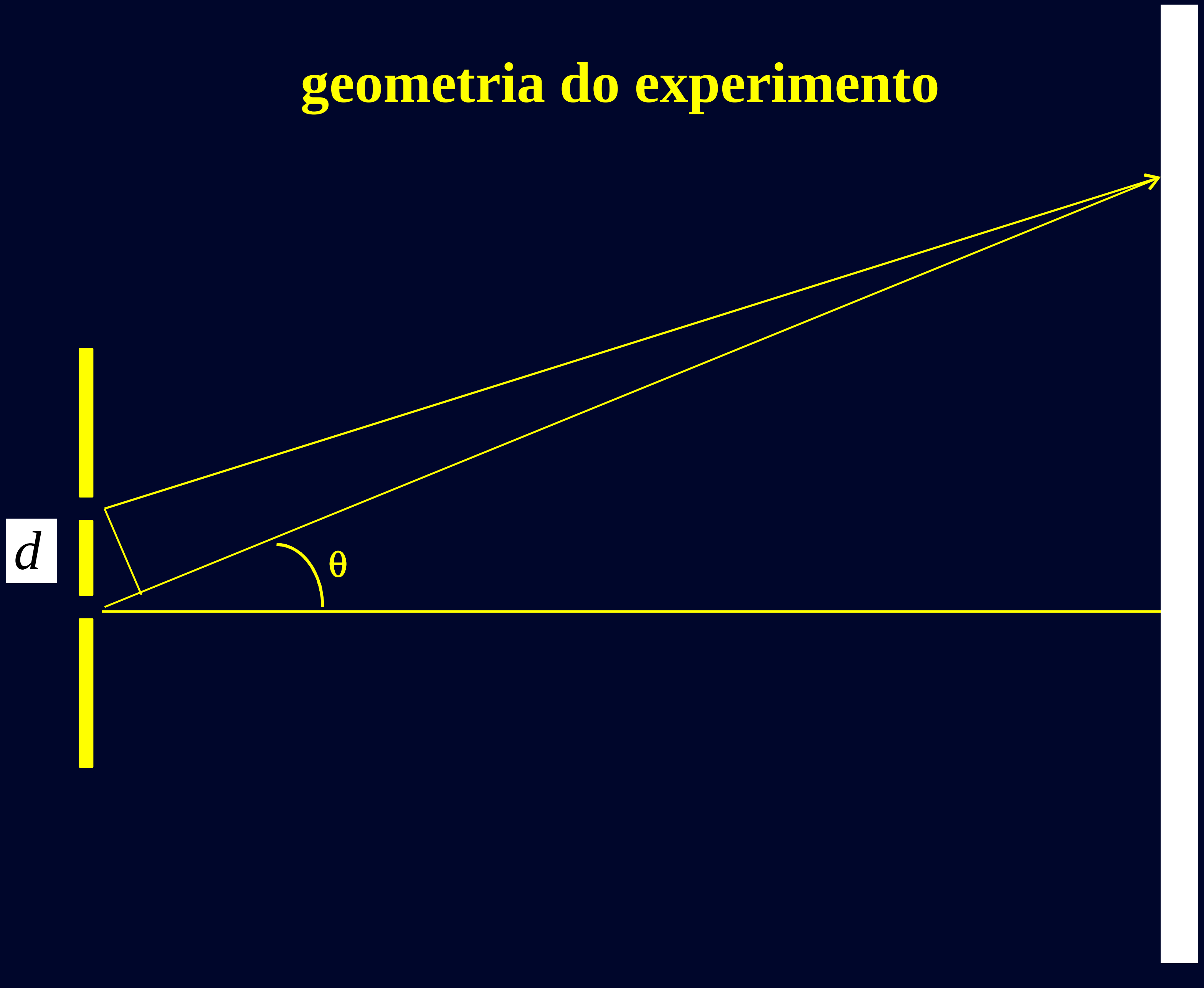




Bovine endothelial

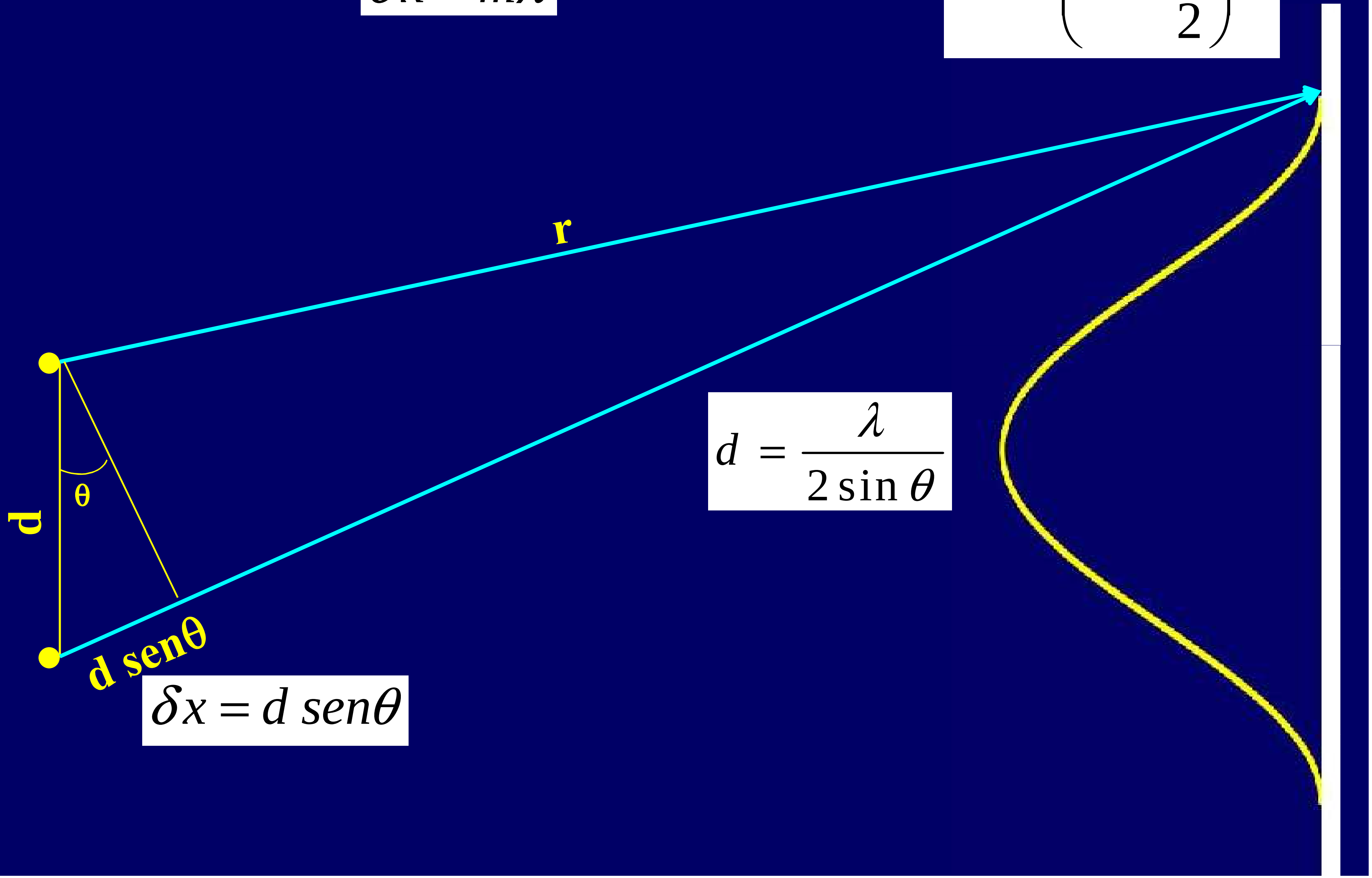
Interferência fenda dupla

geometria do experimento



Interferência fenda dupla

Máximo se: $\delta x = m\lambda$ **Mínimo se:** $\delta x = \left(m + \frac{1}{2} \right) \lambda$

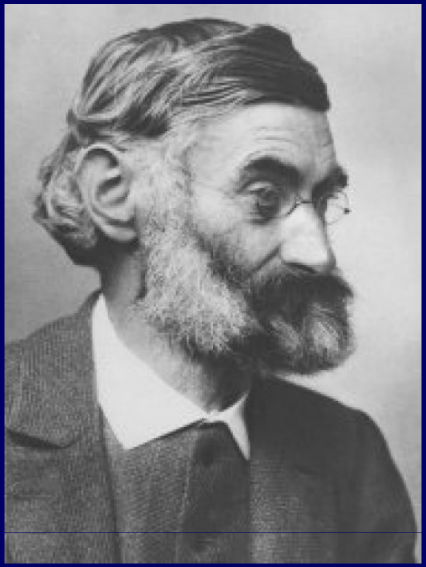


$$d = \frac{\lambda}{2 \sin \theta}$$

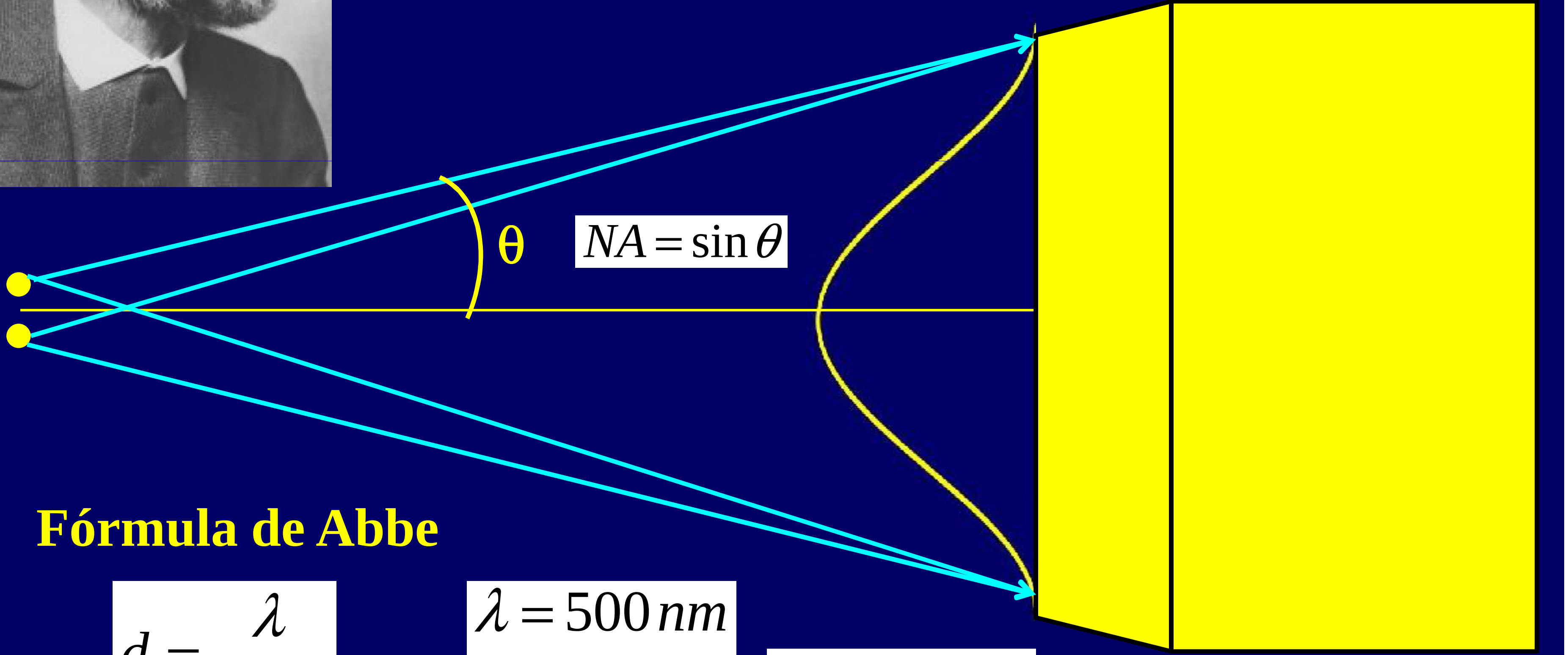
$$\delta x = d\ sen\theta$$

Qual o limite de RESOLUÇÃO? DIFRAÇÃO

1878 – Ernest Abbe 1840-15 e a fórmula da resolução espacial



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



$$NA = \sin\theta$$

Fórmula de Abbe

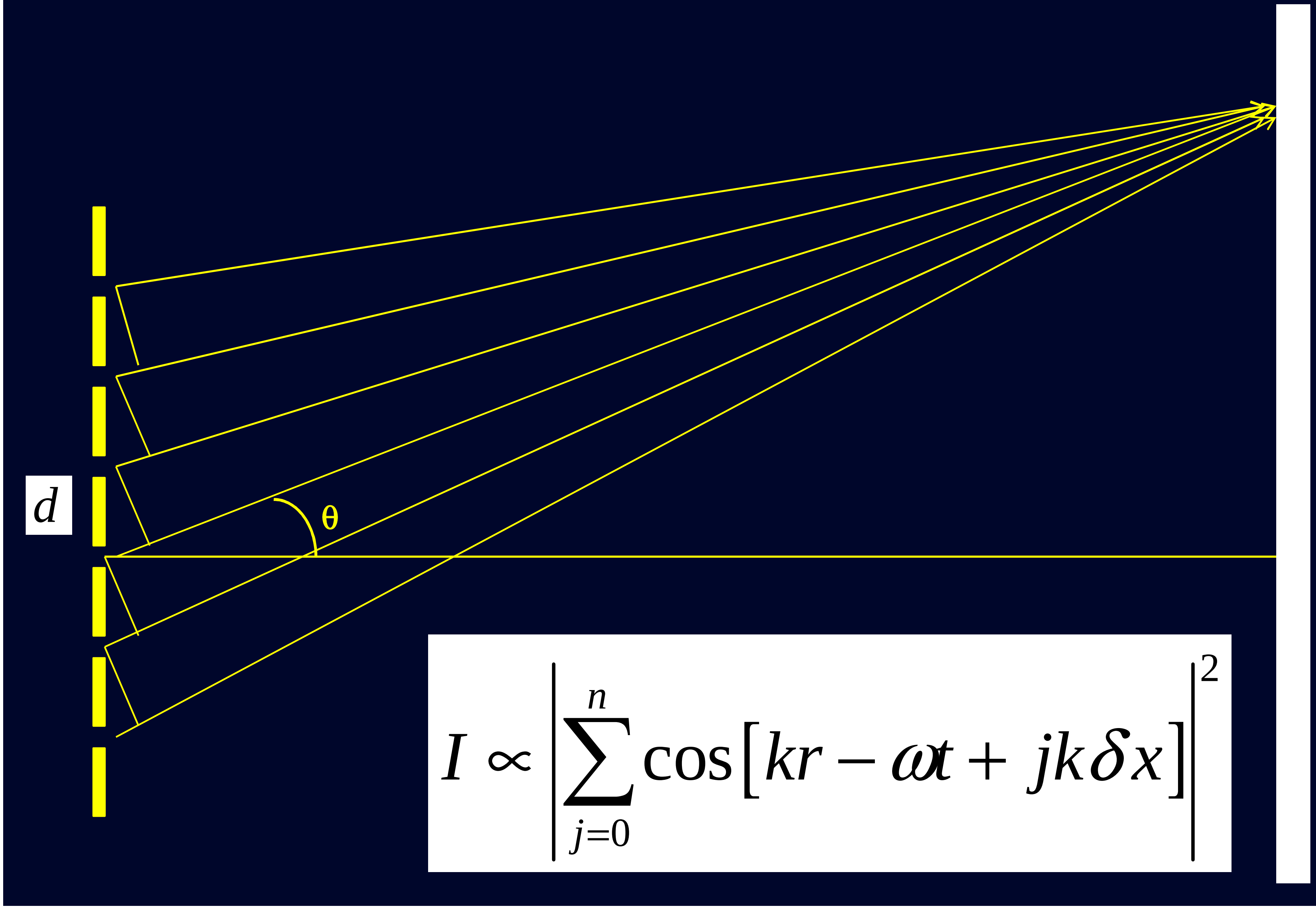
$$d = \frac{\lambda}{2NA}$$

$$\lambda = 500\,nm$$

$$NA = 1$$

$$d = 250\,nm$$

Multiplas fendas



$$I \propto \left| \sum_{j=0}^{n} \cos\left[kr - \omega t + jk\delta x \right] \right|^2$$

Multiplas fendas

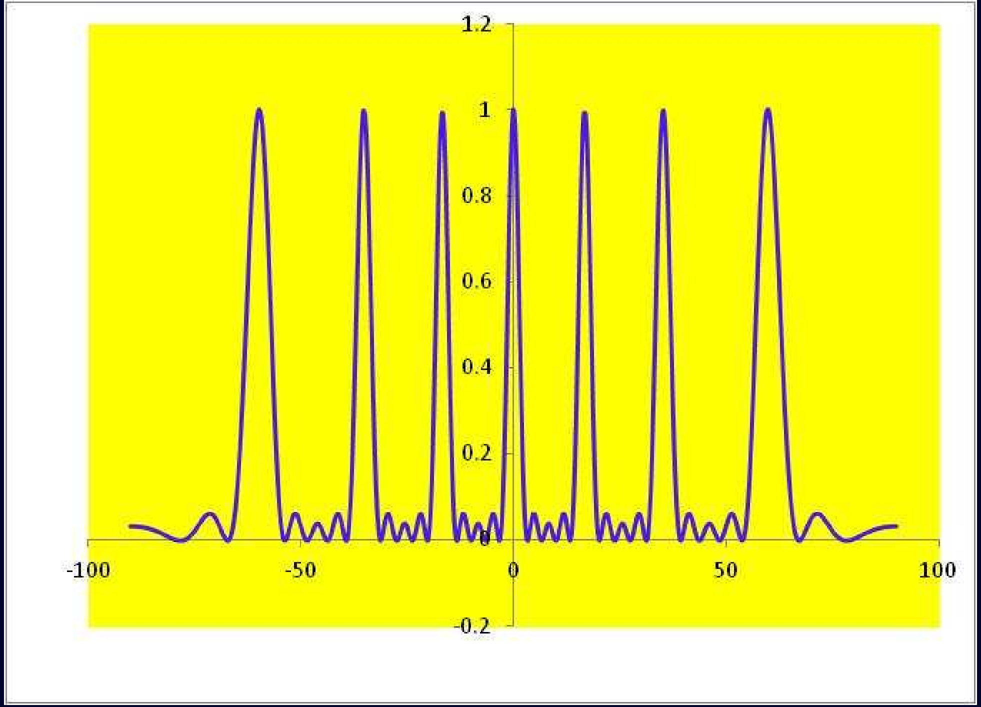
$$\sin\theta = \frac{\lambda}{Nd}$$

$$= 0$$

$$I \propto \frac{\sin^2\left(N\dfrac{\pi d\sin\theta}{\lambda}\right)}{\sin^2\left(\dfrac{\pi d\sin\theta}{\lambda}\right)}$$

$$= 0$$

$$\sin\theta = m\frac{\lambda}{d}$$



$$m = 0 \rightarrow ordem\,0$$

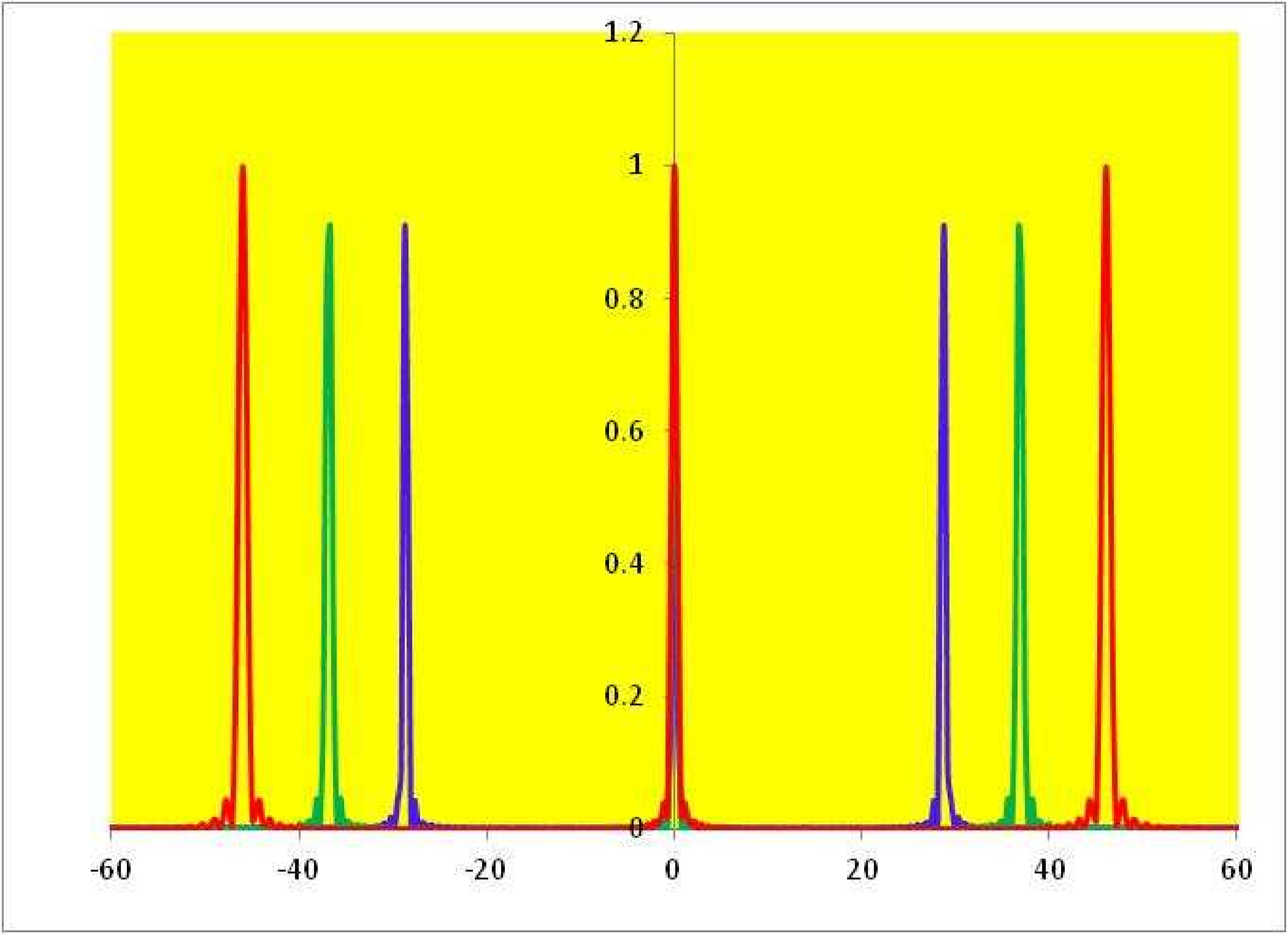
$$m = \pm 1 \rightarrow ordem\,1$$

$$m = \pm 2 \rightarrow ordem\,2$$

Grade de difração:

separando comprimentos de ondas

$$M = n^o \frac{\text{riscos}}{\text{mm}} \rightarrow d = \frac{1}{M}$$



Valores típicos

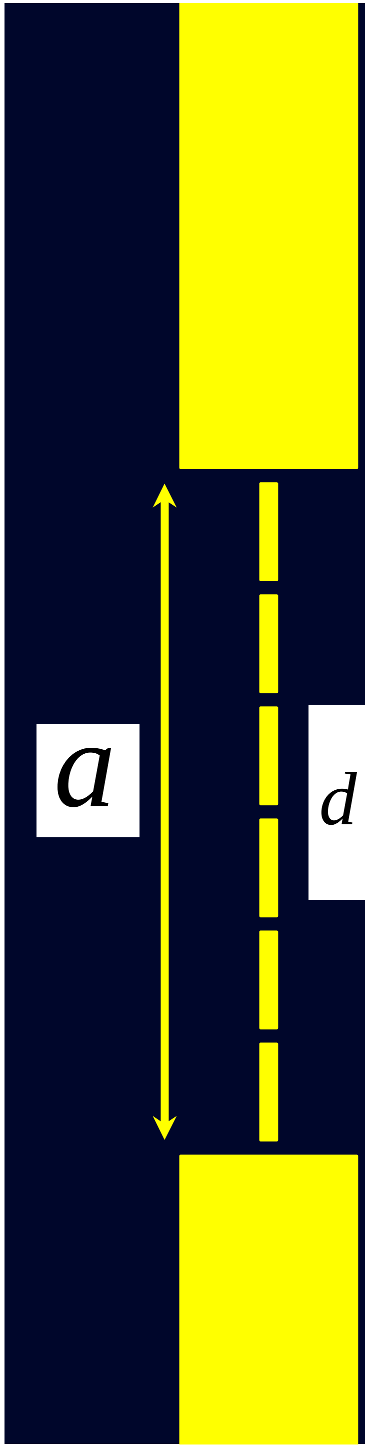
$$M = 300 \; {}^{g}\!/_{mm}$$

$$M = 600 \; {}^{g}\!/_{mm}$$

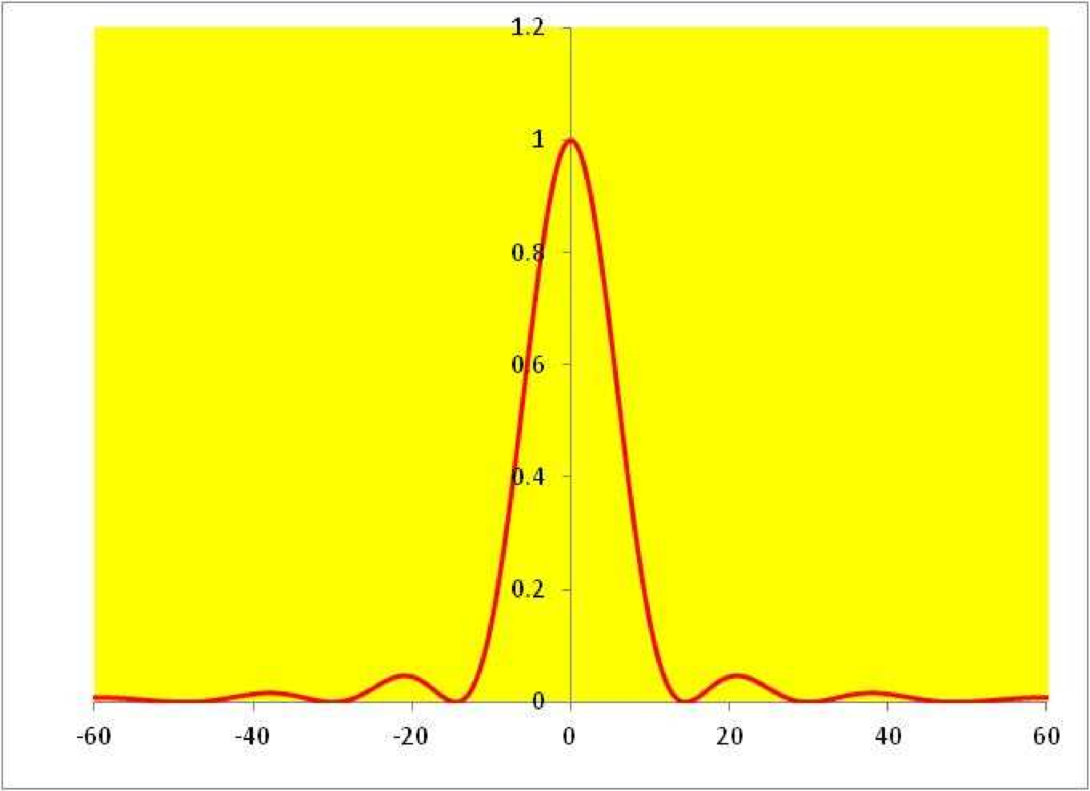
$$M = 1200 \; {}^{g}\!/_{mm}$$

DIFRAÇÃO

$$I \propto \frac{\sin^2\left(\frac{\pi a \sin\theta}{\lambda}\right)}{\sin^2\left(\frac{\pi a \sin\theta}{N\lambda}\right)} \equiv N^2 \frac{\sin^2\left(\frac{\pi a \sin\theta}{\lambda}\right)}{\left(\frac{\pi a \sin\theta}{\lambda}\right)^2}$$

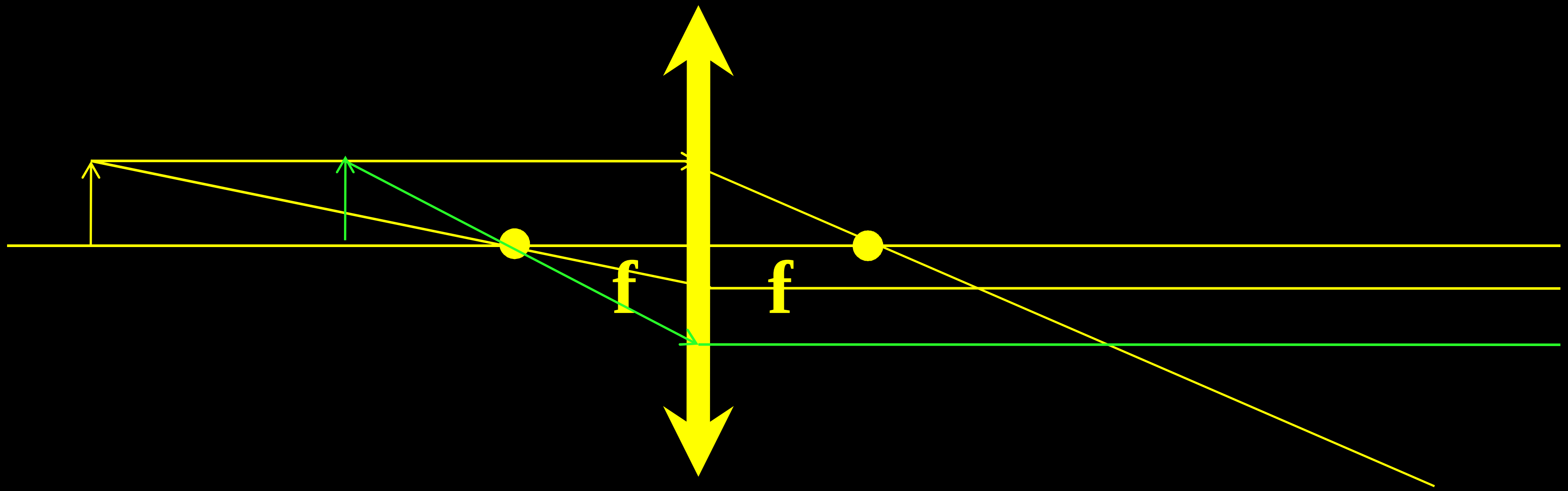


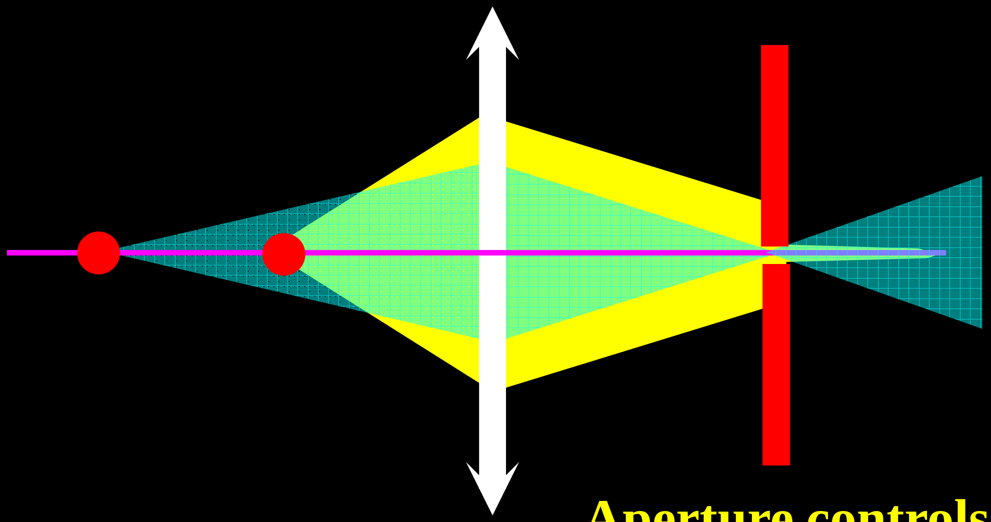
$$d = \frac{a}{n}\,[n \to \infty]$$



Entendendo o equipamento

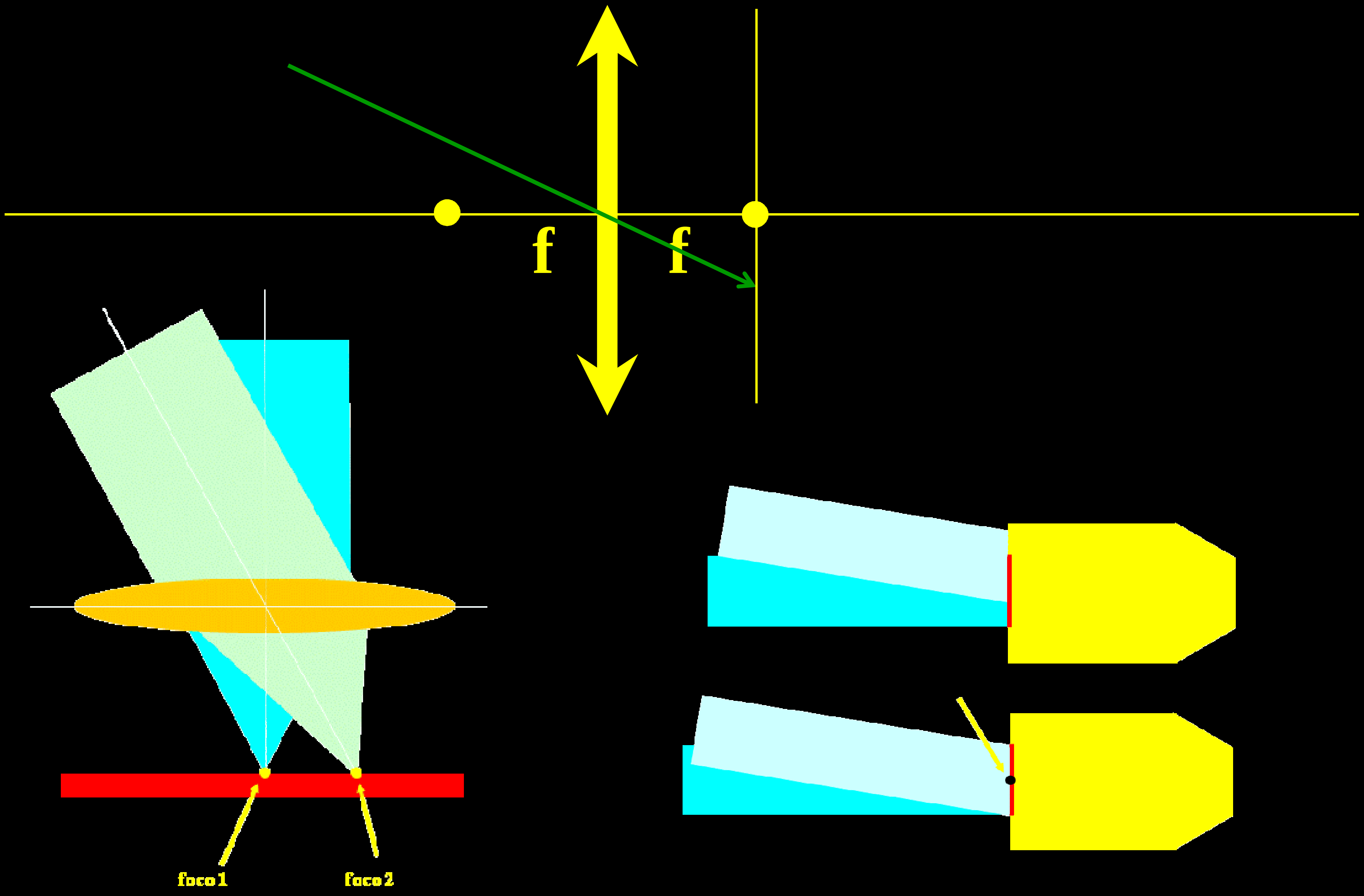
Lentes: raio paralelo passa no foco; passa no foco sai paralelo



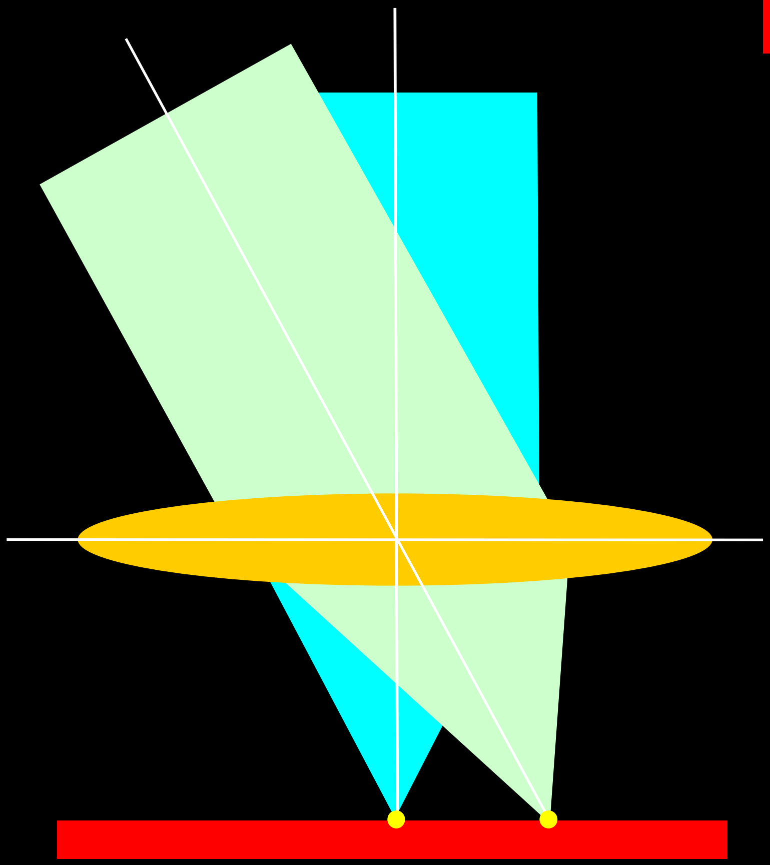


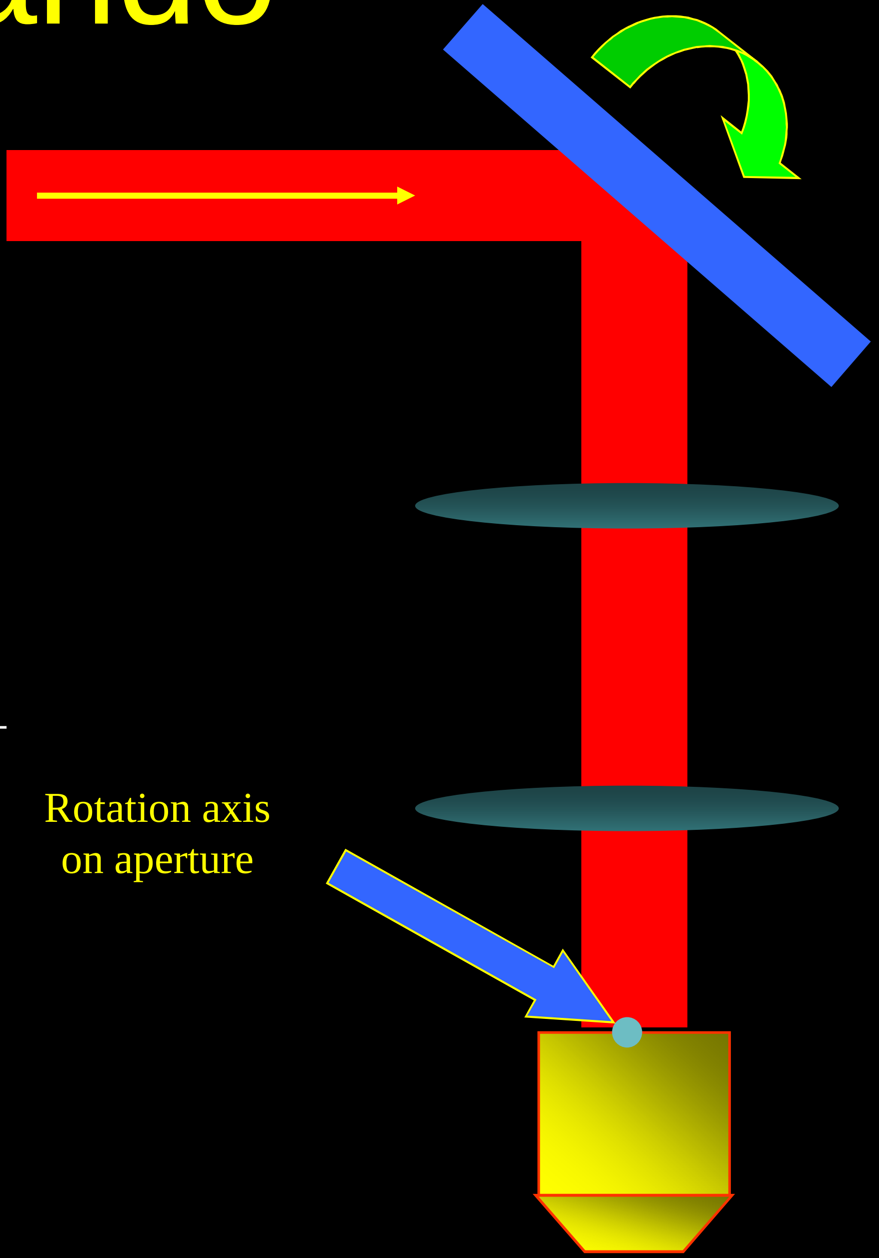
Aperture controls
Vertical resolution

Varredura - raio que passa no centro da lente não é desviado

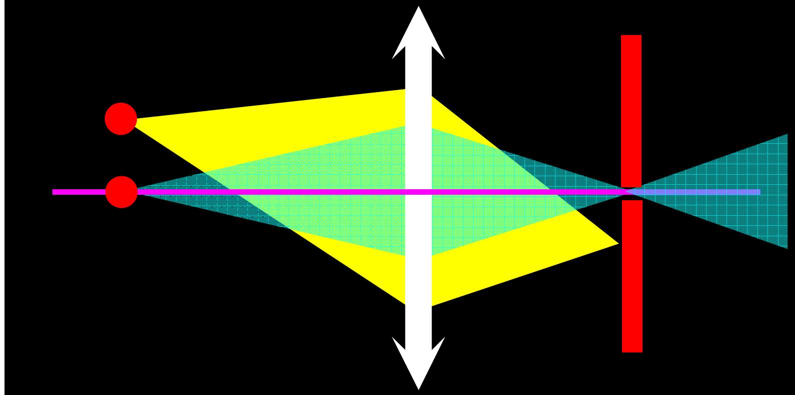

f
f
foco1
foco2

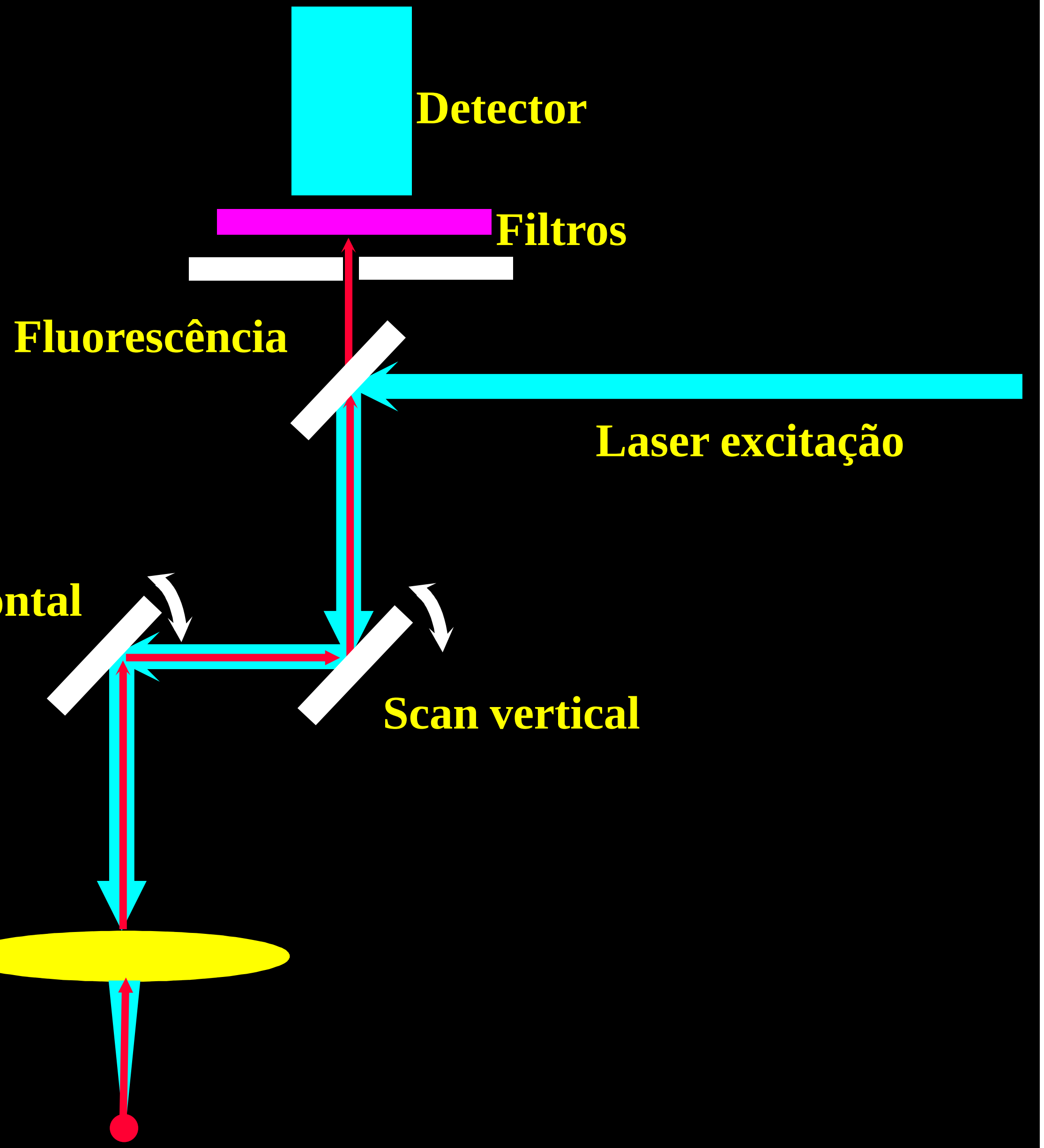
Pivotando




Rotation axis
on aperture

Microscopia confocal: descanning

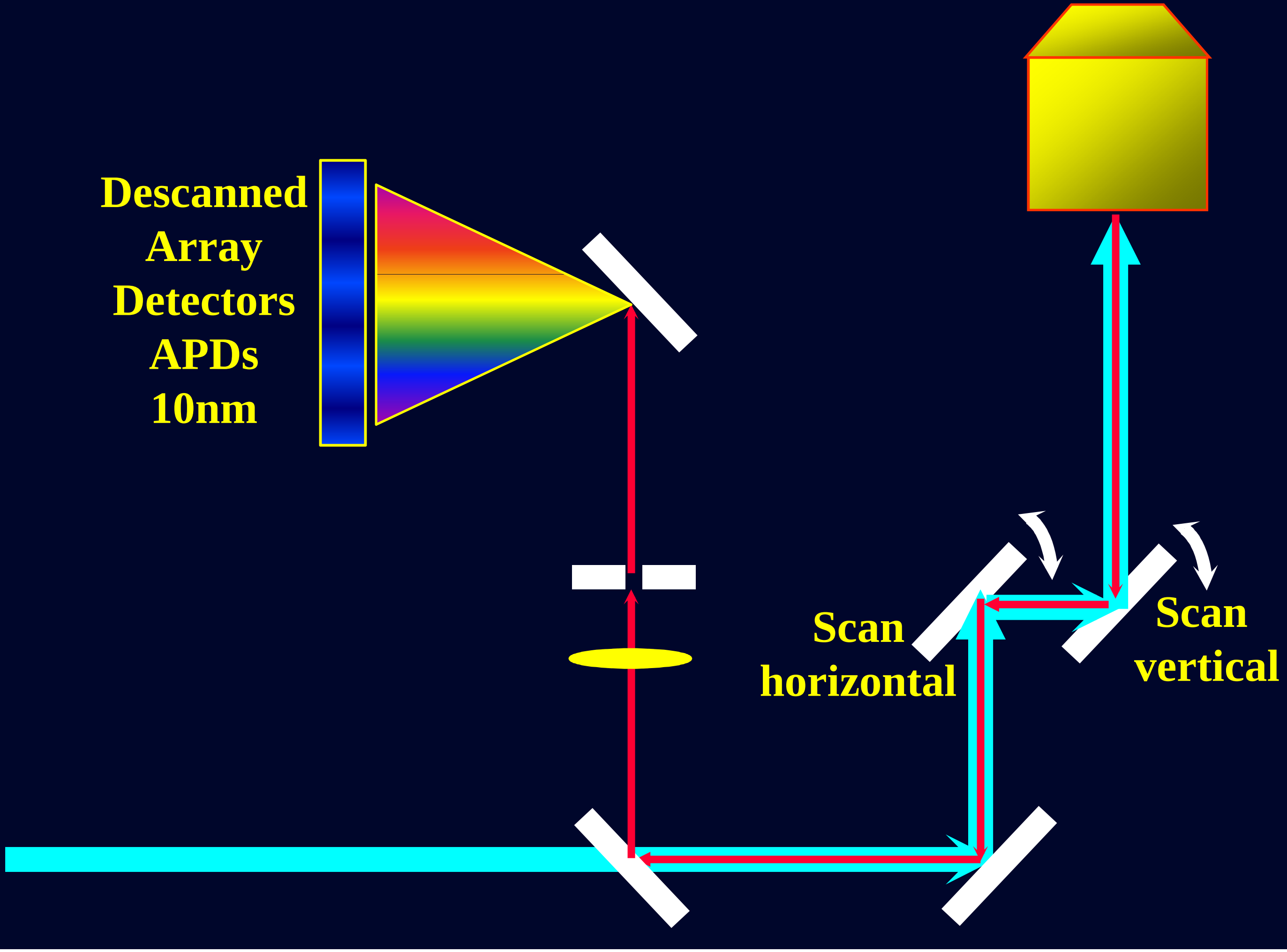



Detector
Filtros
Fluorescência
Laser excitação
Scan horizontal
Scan vertical

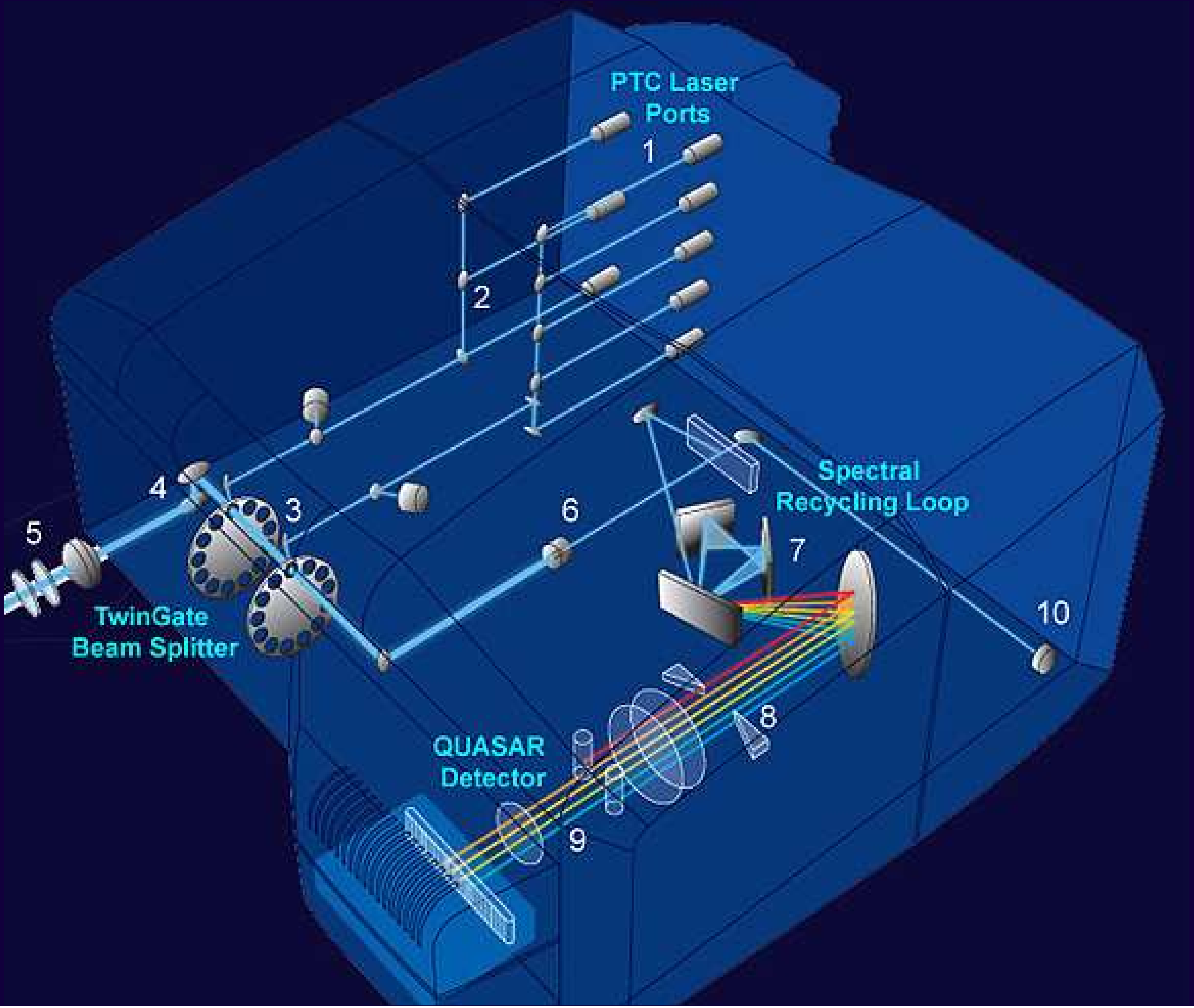
1 µs por pixel

1 s 1000 x 1000

Spectral Confocal microscope


Descanned
Array
Detectors
APDs
10nm
Scan
horizontal
Scan
vertical

Zeiss LSM 780 Scan Head


PTC Laser Ports
1
2
4
3
5
6
Spectral Recycling Loop
7
TwinGate Beam Splitter
10
8
QUASAR Detector
9

Obrigado pela atenção!

Thanks for the attention