Quantitative Electron Microscopy 2025

11th – 23th May 2025

6th Edition

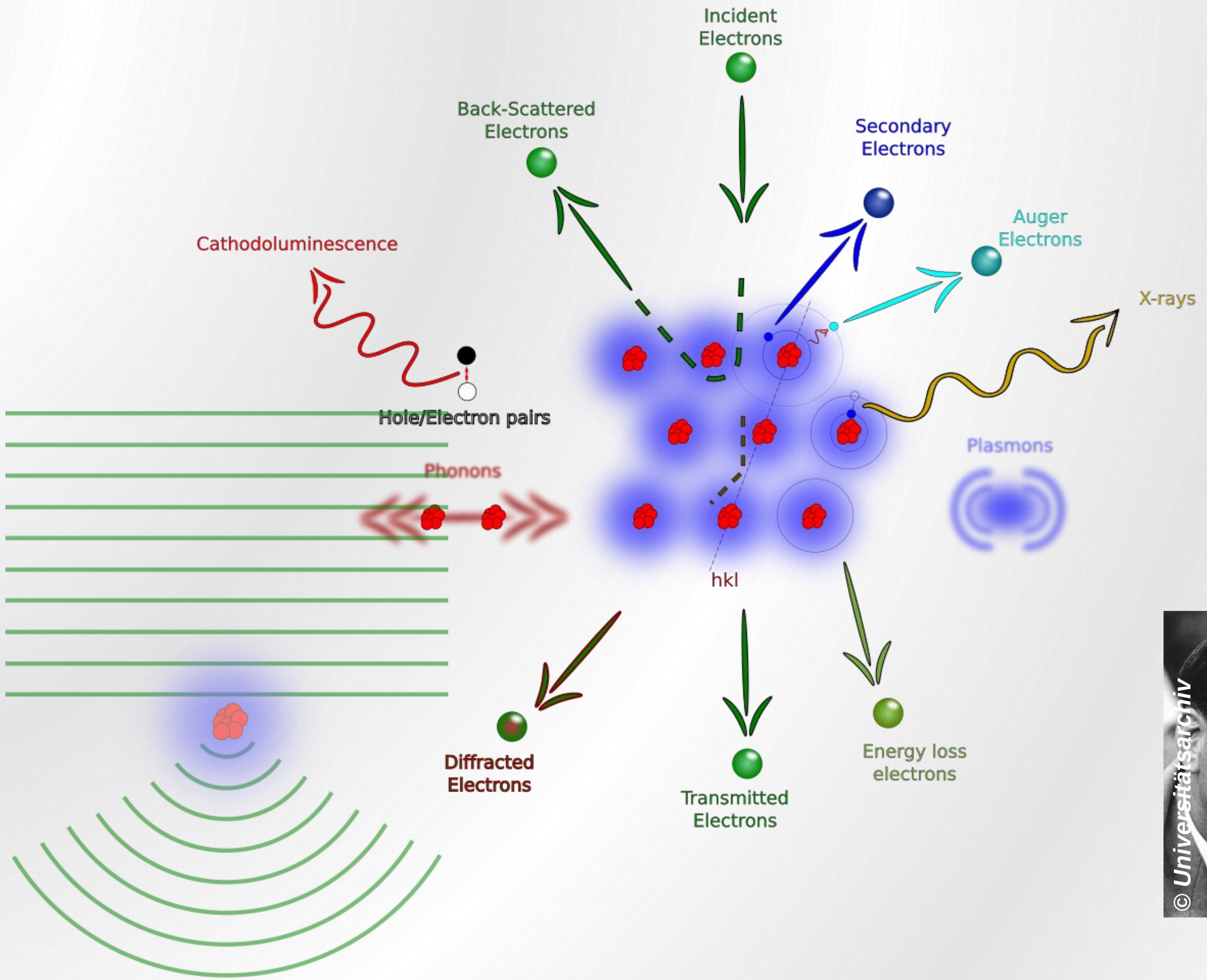
Port-Barcarès

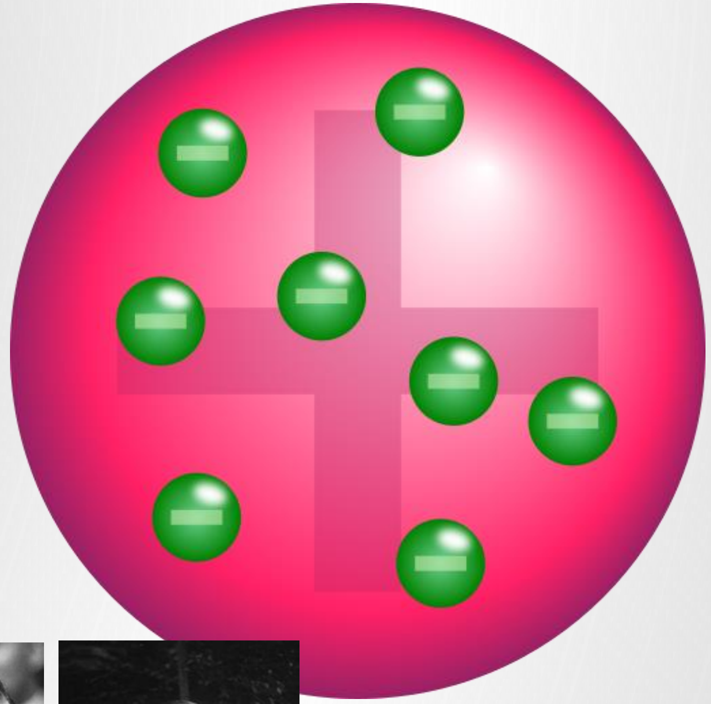
Review and News of Quantitative TEM technique

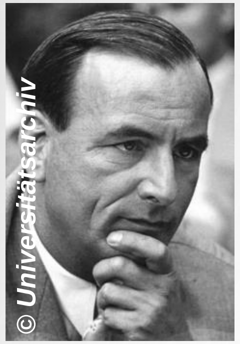
Aurélien Masseboeuf

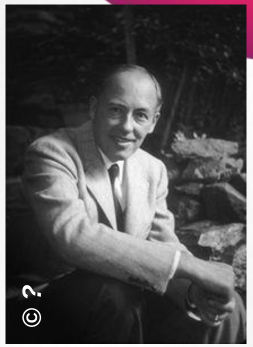
Introduction to Transmission, Electron & Microscopy

Introduction to Transmission, Electron & Microscopy









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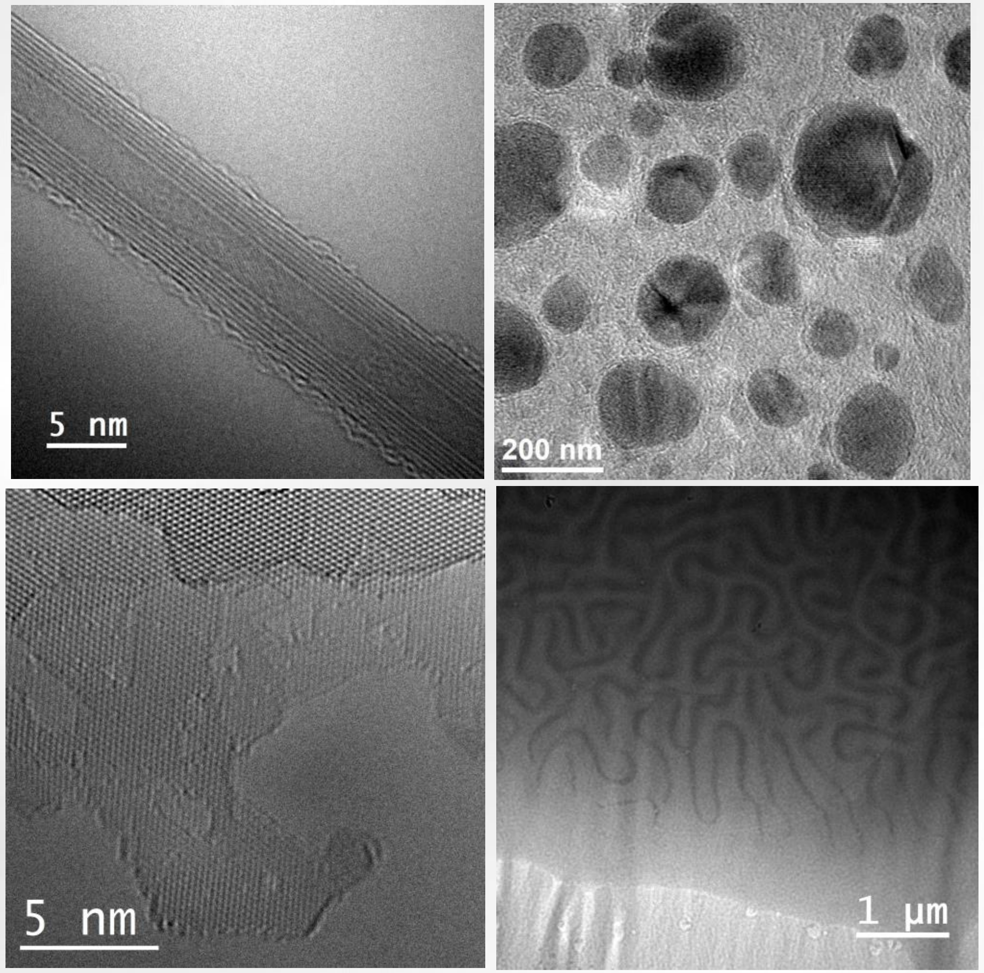
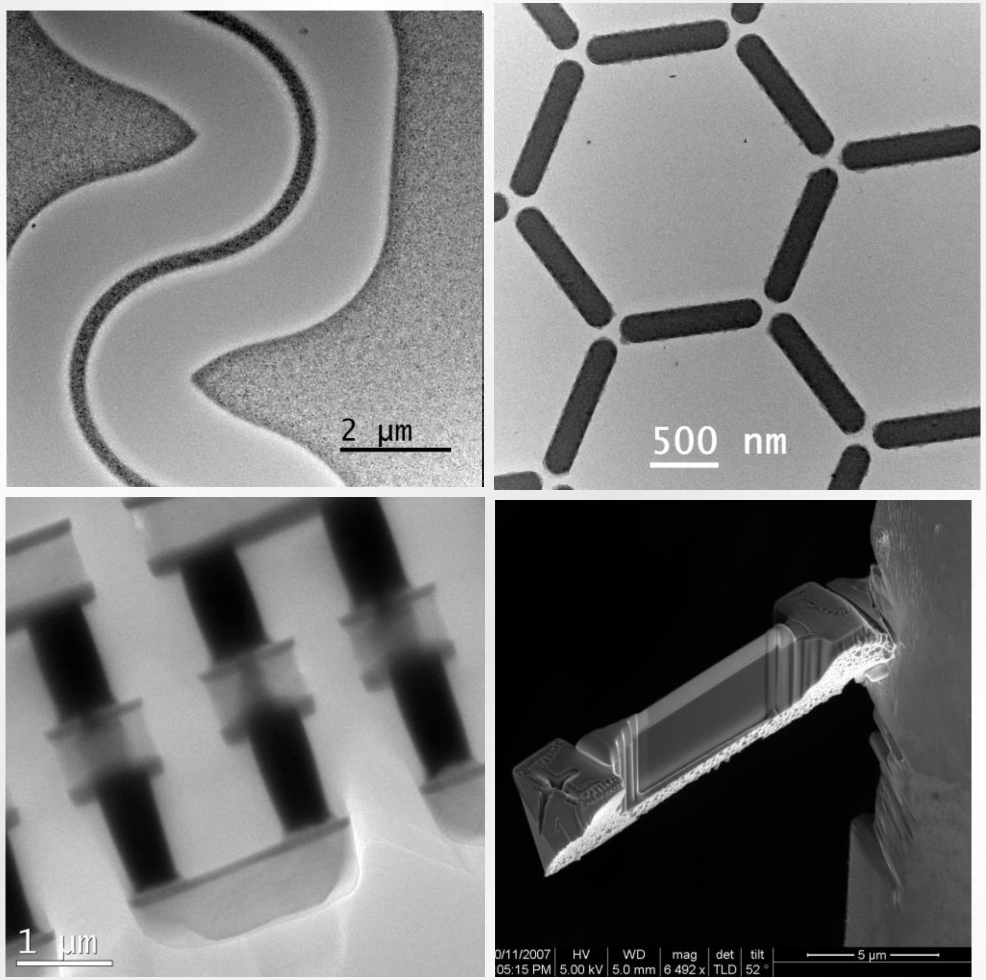


Samples have to be thin

< 100 nm

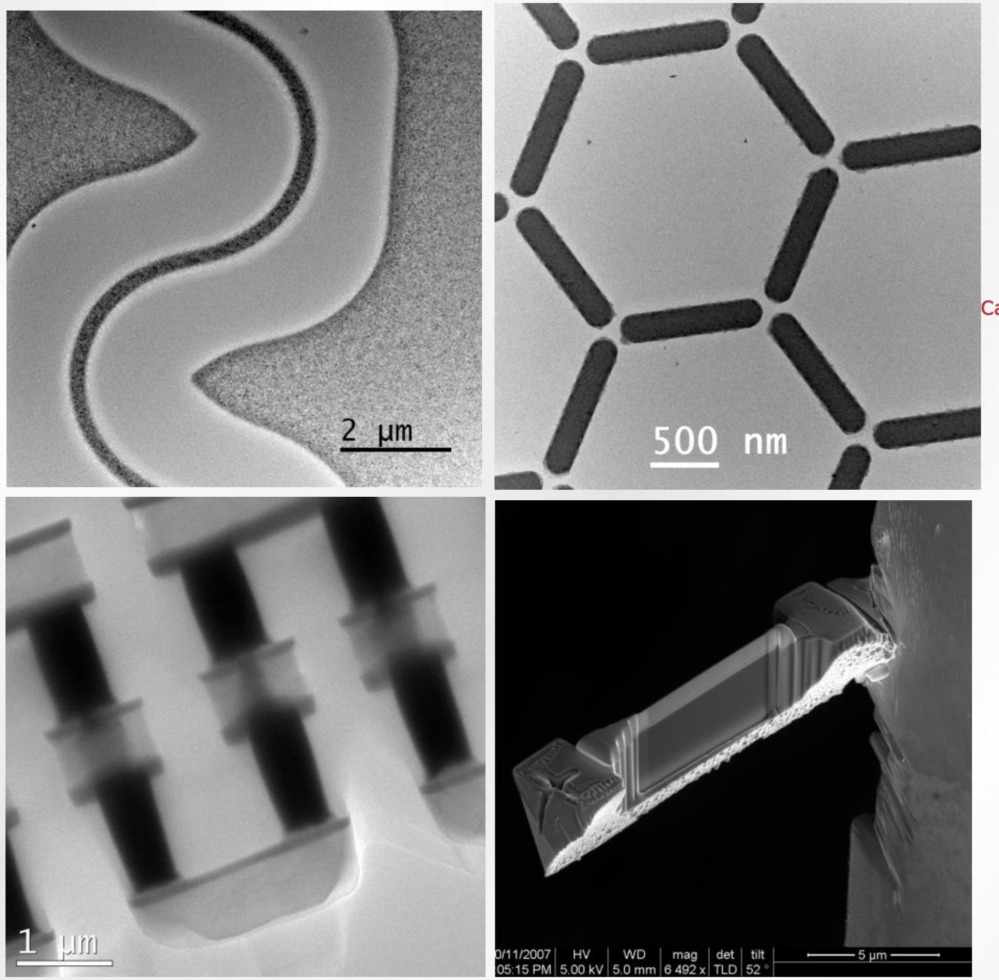
Introduction to Transmission, Electron & Microscopy



Samples have to be thin (or thinned)

< 100 nm

Introduction to Transmission, Electron & Microscopy



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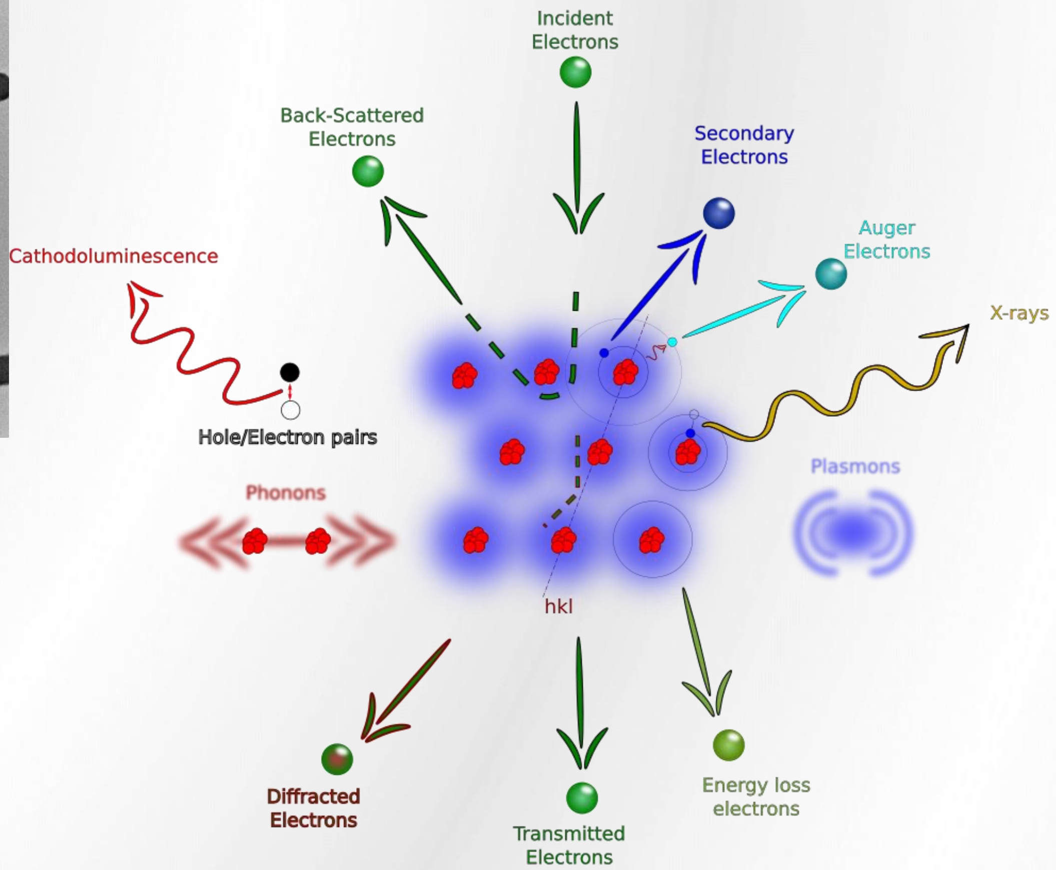
< 100 nm



Electron are not only transmitted !

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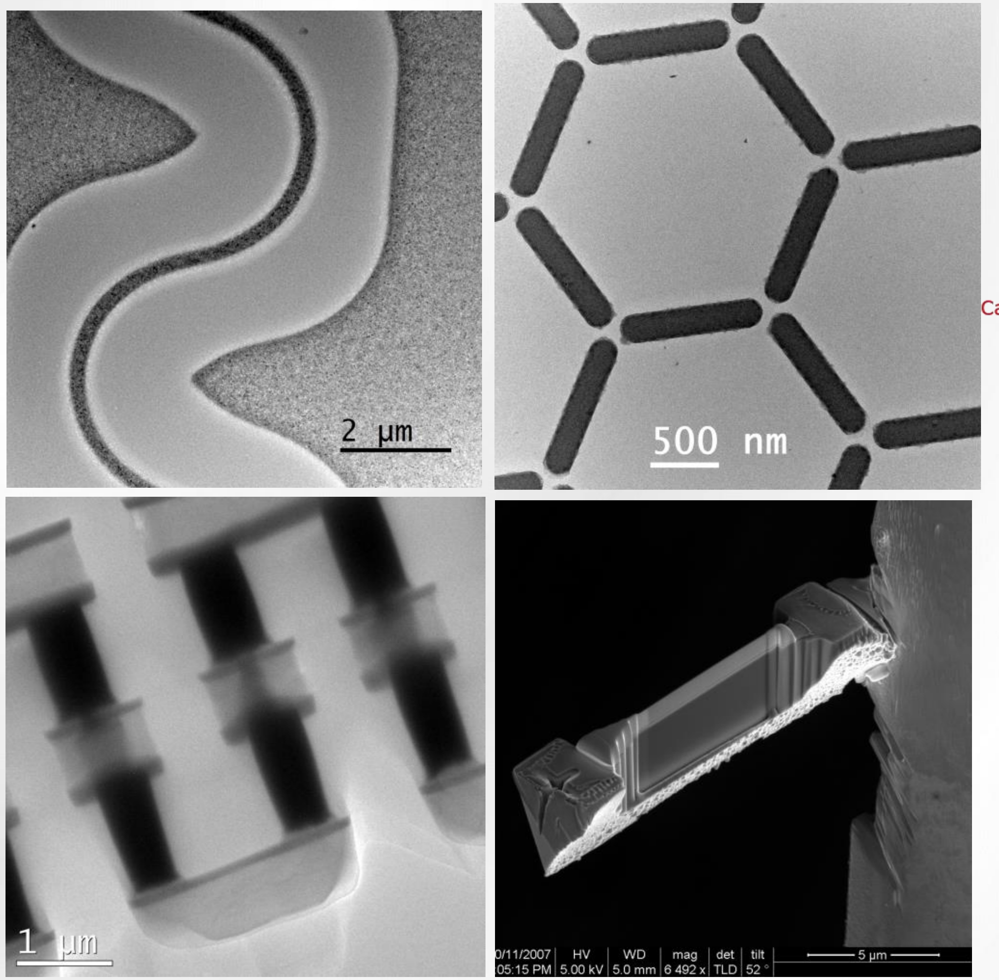

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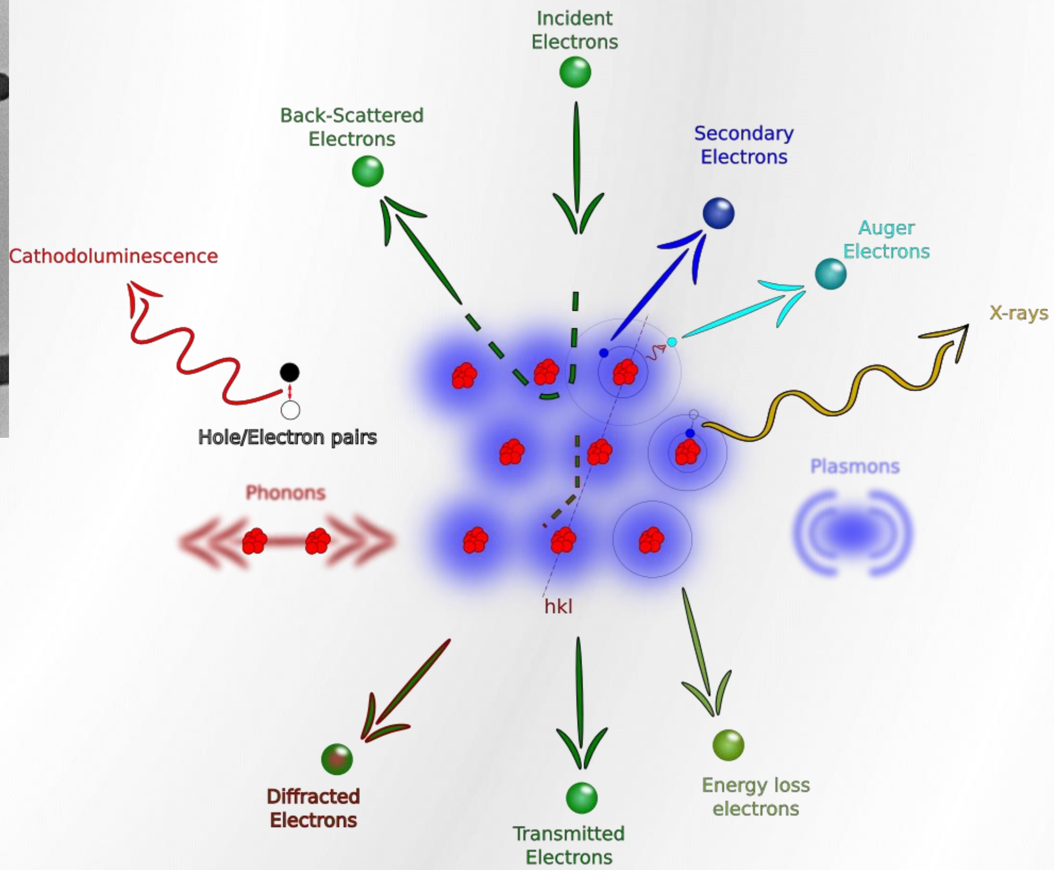

Electron are not only transmitted !

Kinematic Vs Dynamic

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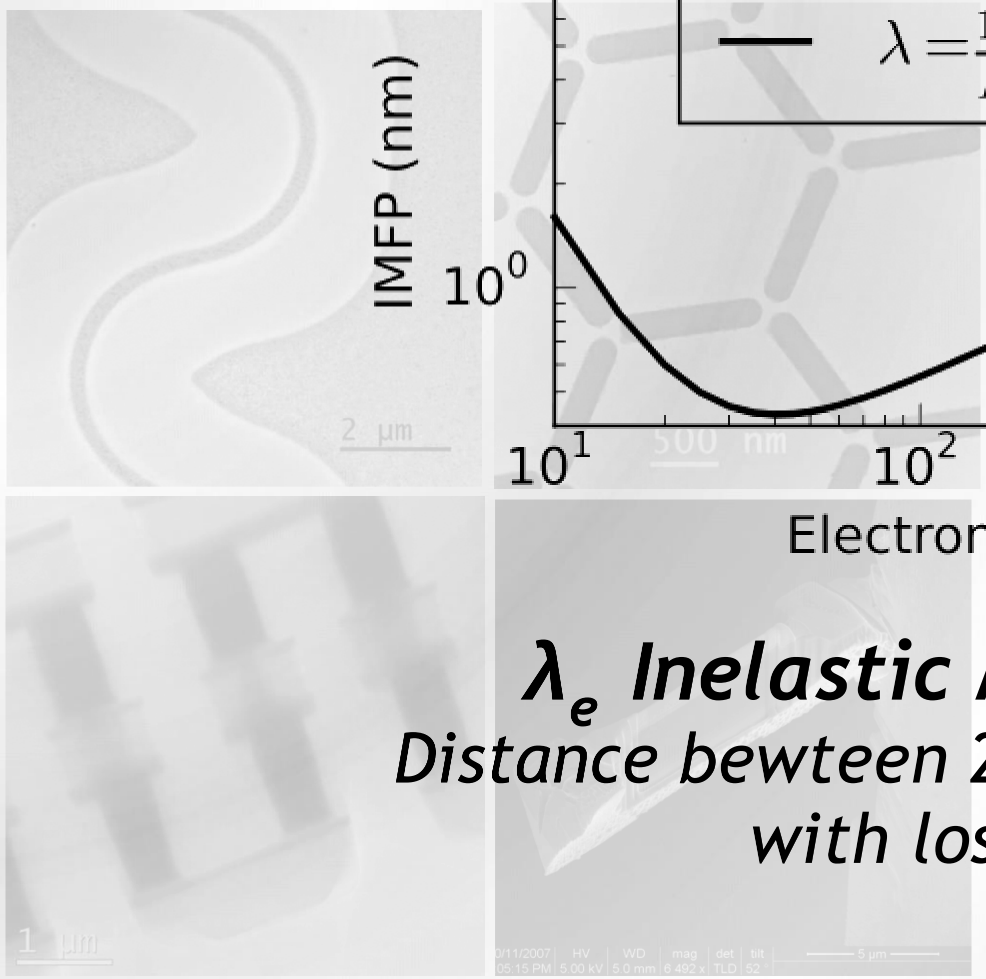

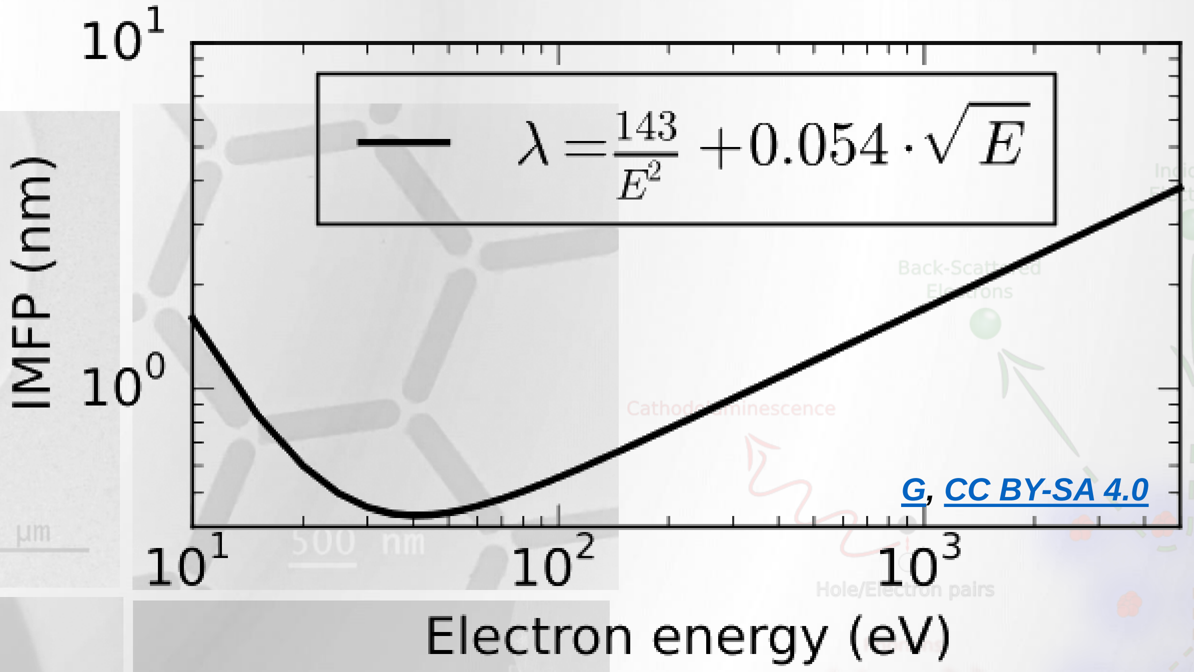

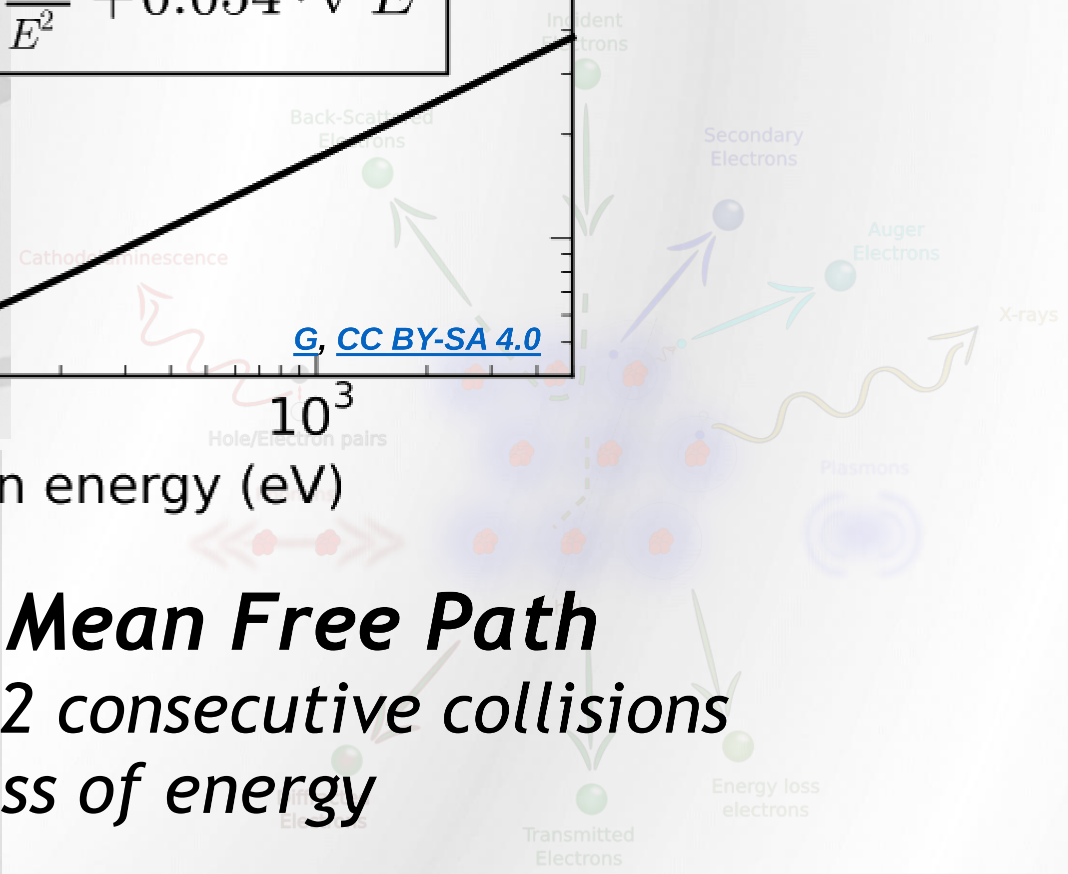

λ_e Inelastic Mean Free Path

Distance bewteen 2 consecutive collisions with loss of energy

Samples have to be thin (or thinned)

< 100 nm

Electron are not only transmitted !

Cinematic Vs Dynamic

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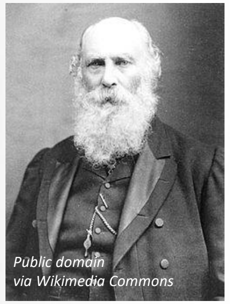
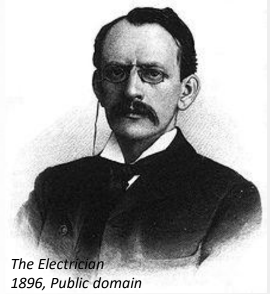
The Electrician
1896, Public domain

1897

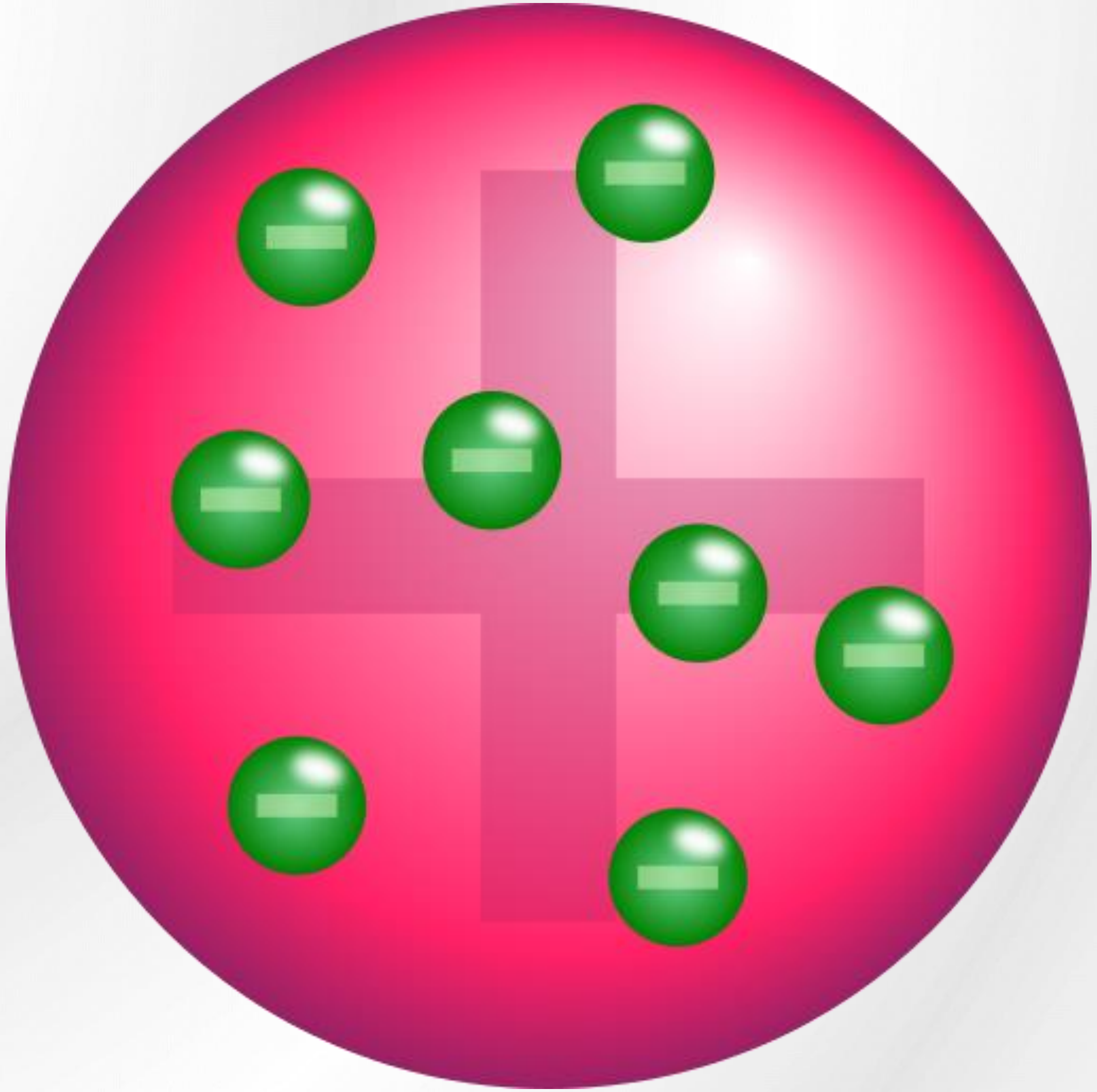
Introduction to Transmission, <u>Electron</u> & Microscopy



1891



1897



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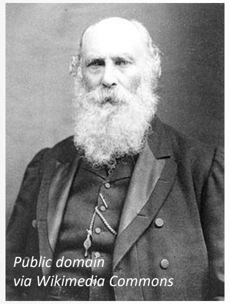

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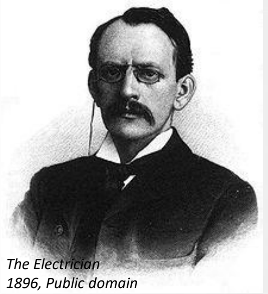
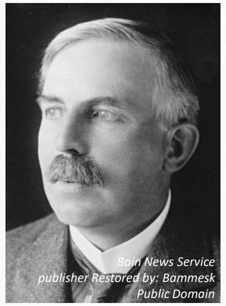
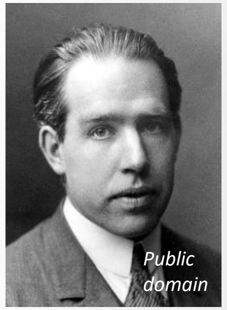


1897

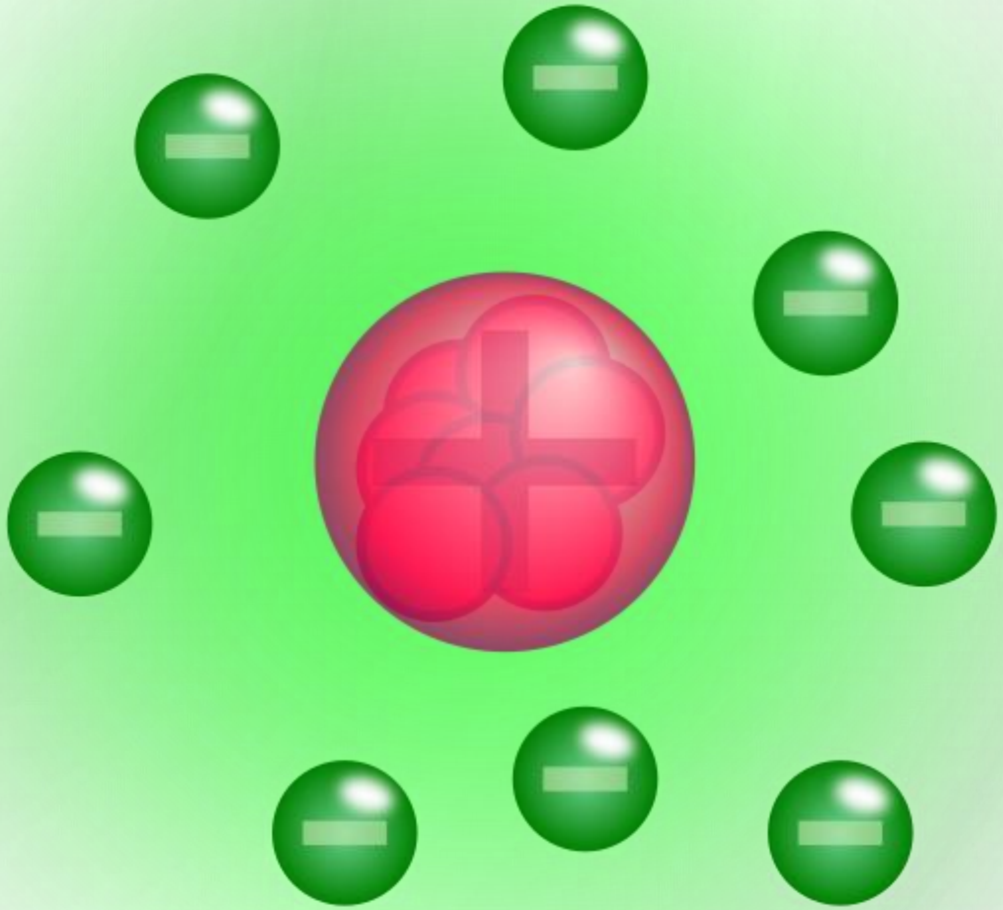
1904



1911



1913



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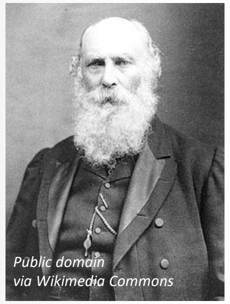

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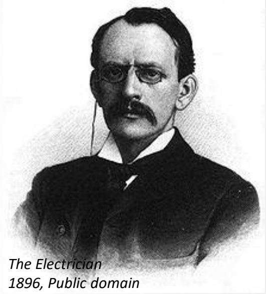


1897

$q \sim 10^{-19}$ C [A.s]

$m_0 \sim 10^{-30}$ kg

https://www.bipm.org/en/measurement-units/si-defining-constants

Table 1. The seven defining constants of the SI and the seven corresponding units they define

Defining constant	Symbol	Numerical value	Unit
hyperfine transition frequency of Cs	$\Delta\nu_{Cs}$	9 192 631 770	Hz
speed of light in vacuum	c	299 792 458	m s^{-1}
Planck constant	h	6.626 070 15 × 10^{-34}	J s
elementary charge	e	1.602 176 634 × 10^{-19}	C
Boltzmann constant	k	1.380 649 × 10^{-23}	J K^{-1}
Avogadro constant	N_A	6.022 140 76 × 10^{23}	mol^{-1}
luminous efficacy	K_{cd}	683	lm W^{-1}

https://physics.nist.gov/cgi-bin/cuu/Value?esme

The NIST Reference on
Constants, Units, and Uncertainty

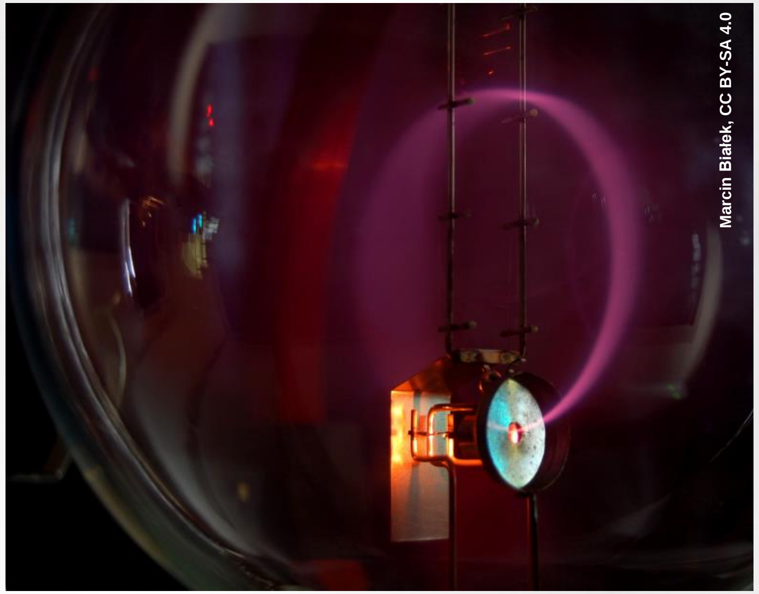
Constants Topics:
Values
Energy Equivalents
Searchable Bibliography
Background
Constants Bibliography

Fundamental Physical Constants

Correlation coefficient between two constants

electron charge to mass quotient
$-e/m_e$

Numerical value	-1.758 820 010 76 x 10^{11} C kg^{-1}
Standard uncertainty	0.000 000 000 53 x 10^{11} C kg^{-1}
Relative standard uncertainty	3.0 x 10^{-10}
Concise form	-1.758 820 010 76(53) x 10^{11} C kg^{-1}



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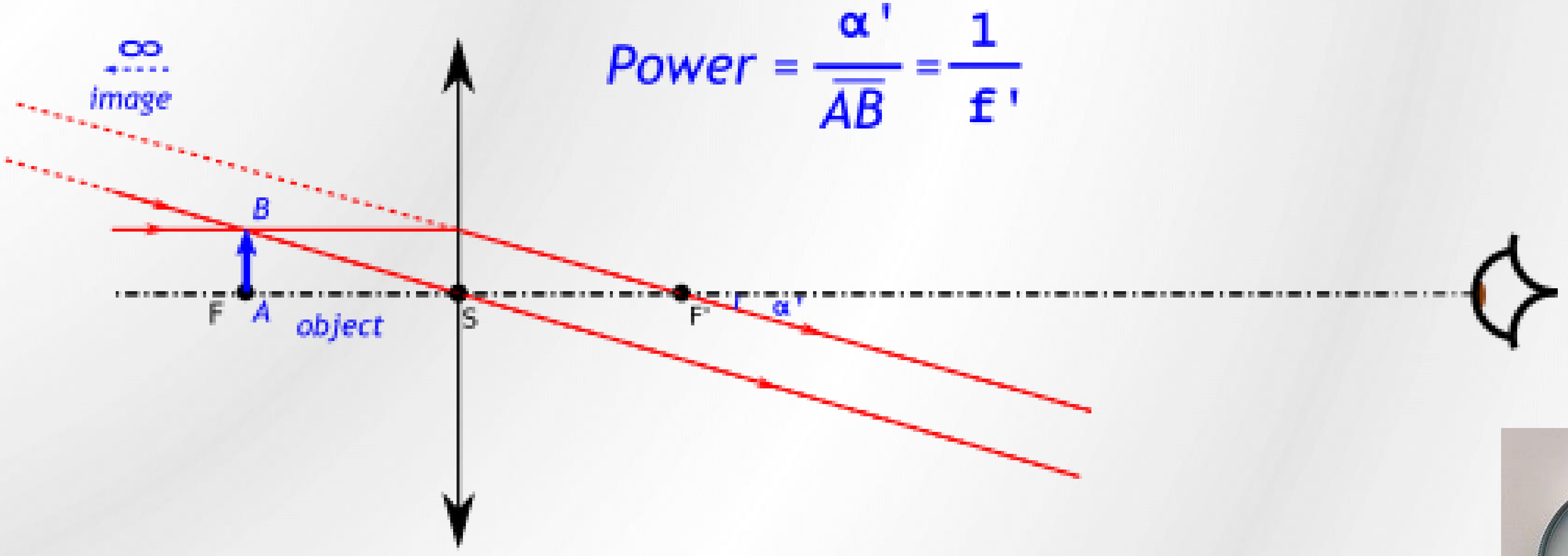
Introduction to Transmission, Electron & <u>Microscopy</u>

1590 ?



Magnifying glass

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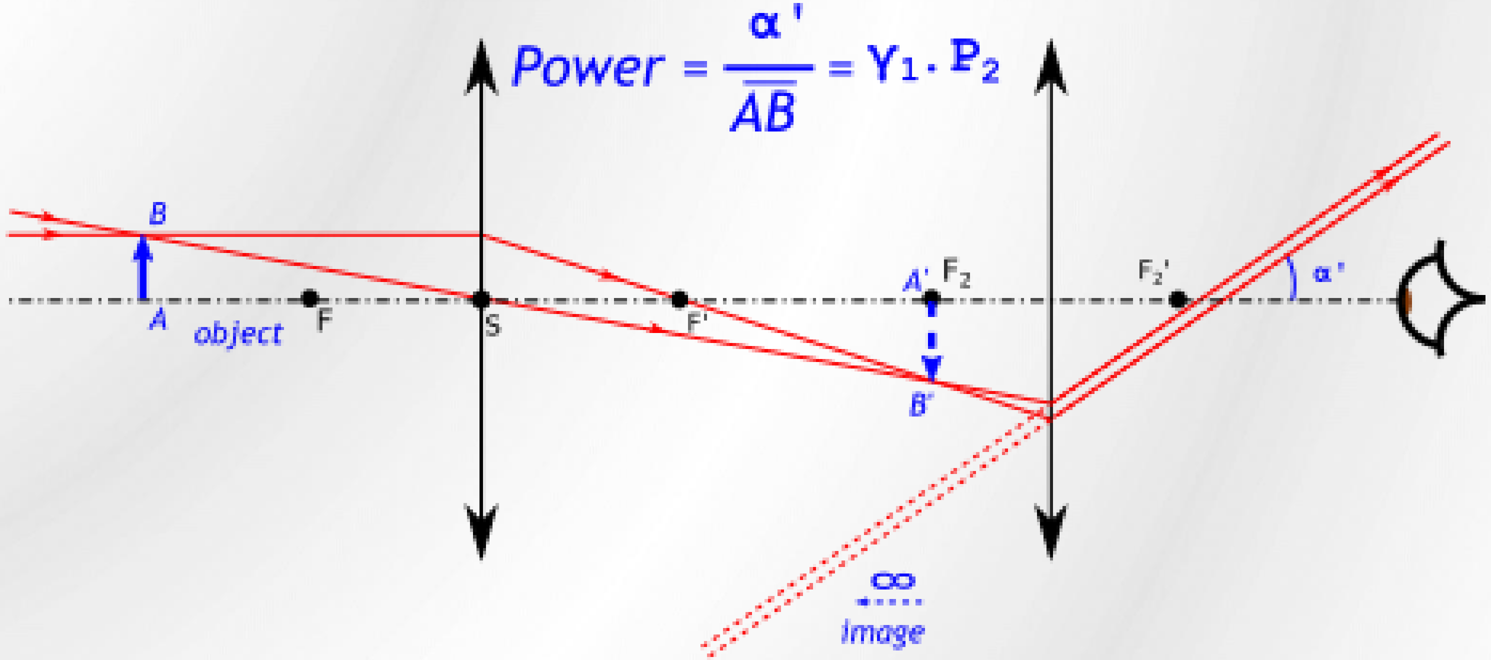
1590 ?



Microscope

Introduction to Transmission, Electron & Microscopy

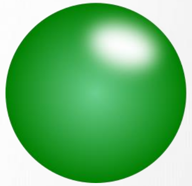
1590 ?

$$Power = \frac{\alpha'}{\overline{AB}} = \frac{1}{\overline{HF}} = \frac{\Delta}{f_1 f_2}$$

Microscope
(Centered system)

Just an « enhanced » magnifying glass

Introduction to Transmission, Electron & Microscopy



$m_0 \sim 10^{-30}$ kg

$q \sim 10^{-19}$ C

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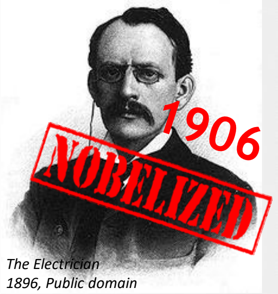
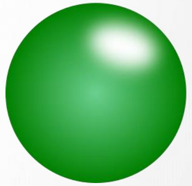


1906



m_0 ~ 10^{-30} kg

q ~ 10^{-19} C

Particle description :

- a mass and a charge
- elastic/inelastic collision
- accelerable (electric field)
- trajectory tunable (electro-magnetic field)

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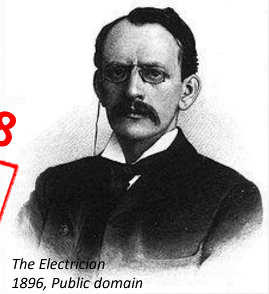
1928



1906

$m_0 \sim 10^{-30}$ kg

$q \sim 10^{-19}$ C

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

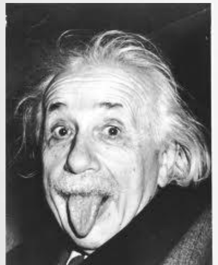
Particle description :

- a mass and a charge
- elastic/inelastic collision
- accelerable (electric field)
- trajectory tunable (electro-magnetic field)

Wave description :

- classical and wave optic description
- energy/wavelength relation
- Amplitude/Phase
- Interferometry capacity

Introduction to Transmission, Electron & Microscopy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1928


The Electrician 1896, Public domain

1906


Nobel Fundation Public domain


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1937

m_0 ~ 10^{-30} kg

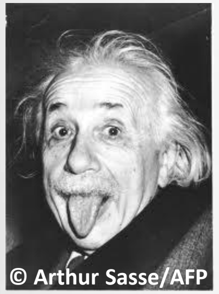
q ~ 10^{-19} C

E (V)		λ (10^{-12} m)
10 kV	→	**12,3**
100 kV	→	**3,7**
1 MV	→	**0,9**

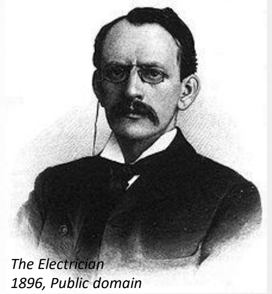
- accelerable (electric field)

- energy/wavelength relation

Introduction to Transmission, Electron & Microscopy



1928



1906

1937

$m_0 \sim 10^{-30}$ kg

$q \sim 10^{-19}$ C

$$\lambda = \frac{h}{mv}\sqrt{1-\frac{v^2}{c^2}}$$

E (V)		λ (10^{-12} m)	v (1/c)
10 kV	→	12,3	20%
100 kV	→	3,7	50%
1 MV	→	0,9	95%

- accelerable (electric field)

- energy/wavelength relation

$$\frac{v}{c} = \sqrt{1-\frac{1}{(1+eV/(m_0c^2))^2}}$$

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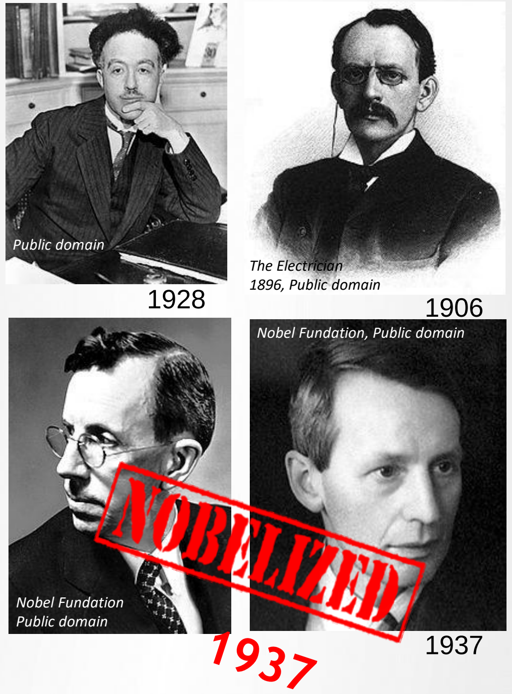
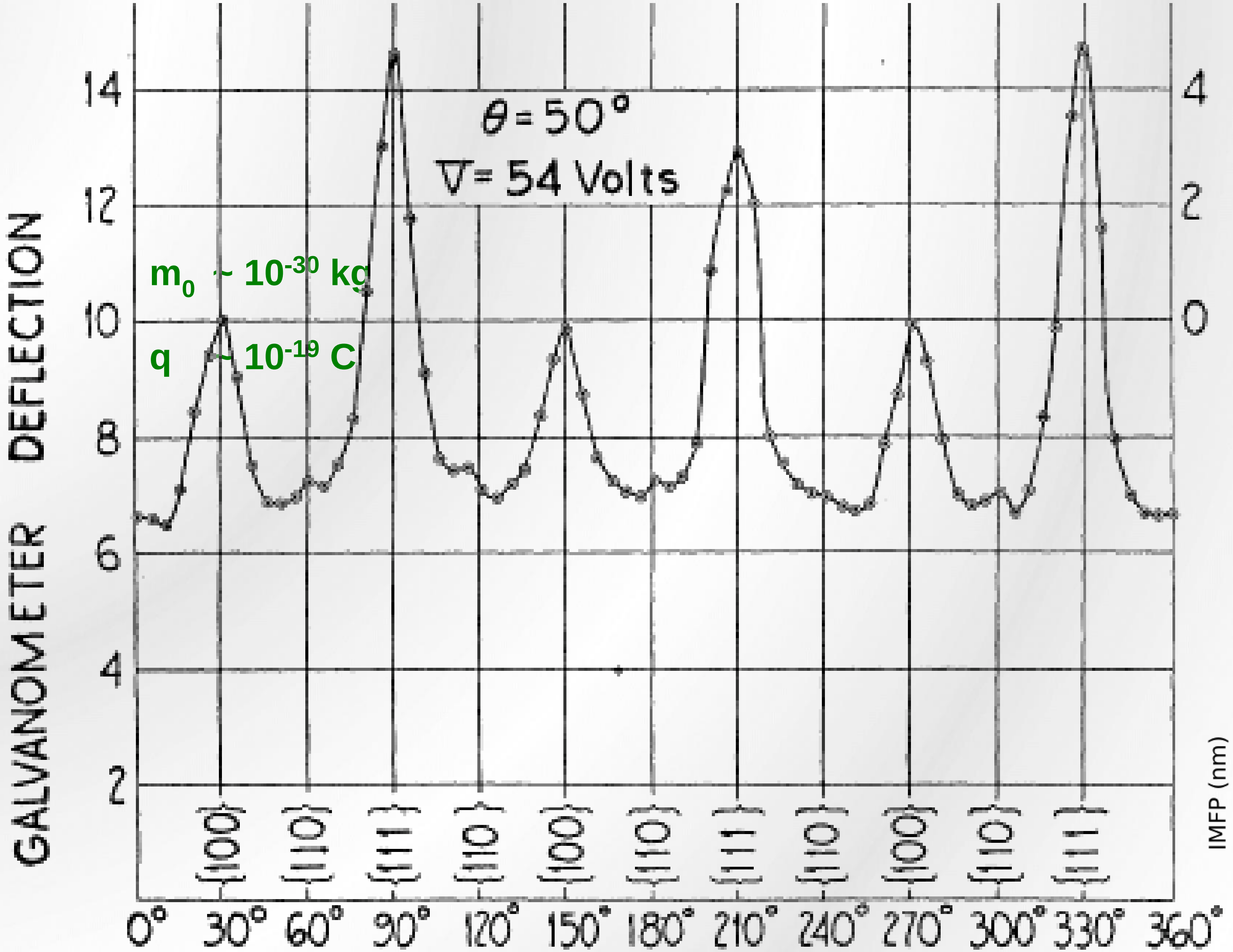
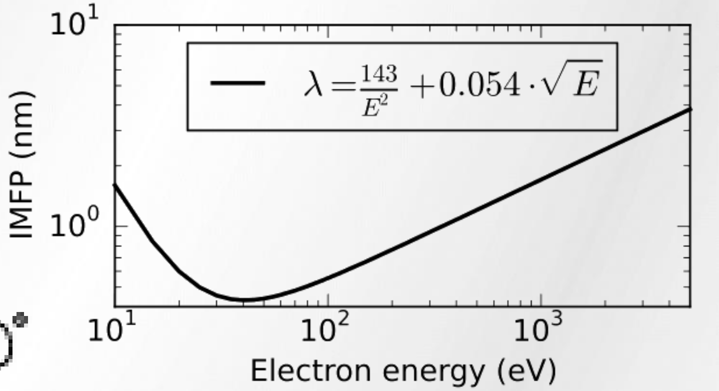




Davisson, C. & Germer, L. H.
Phys. Rev. **30**, 705–740 *(1927)*



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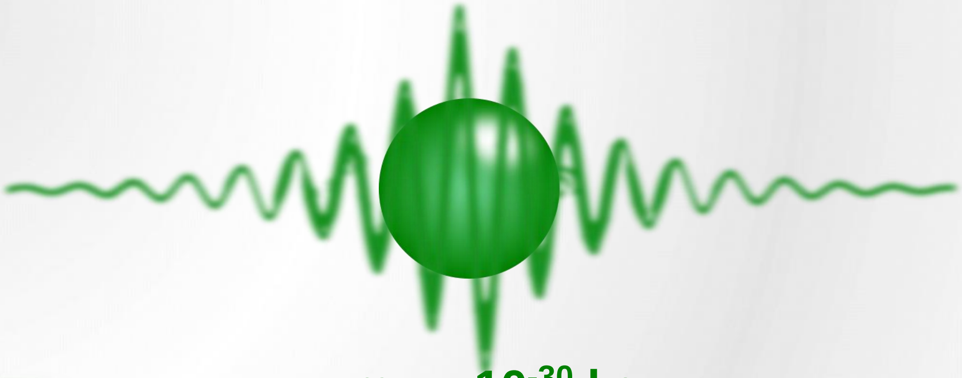
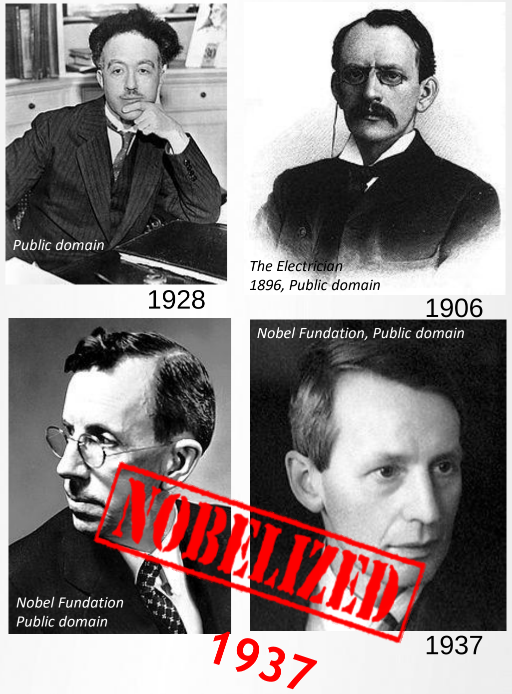


m_0 ~ 10^{-30} kg

q ~ 10^{-19} C

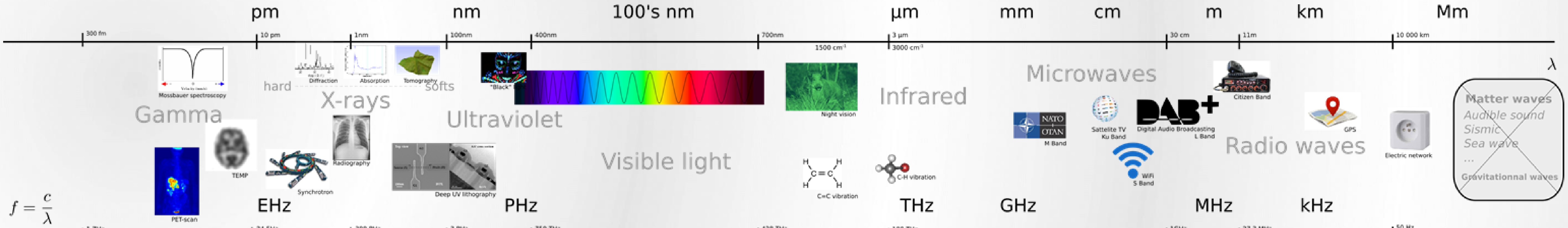
$$\lambda = \frac{h}{mv}$$



E (V)		λ (10^{-12} m)
10 kV	→	12,3
100 kV	→	3,7
1 MV	→	0,9

- accelerable (electric field)

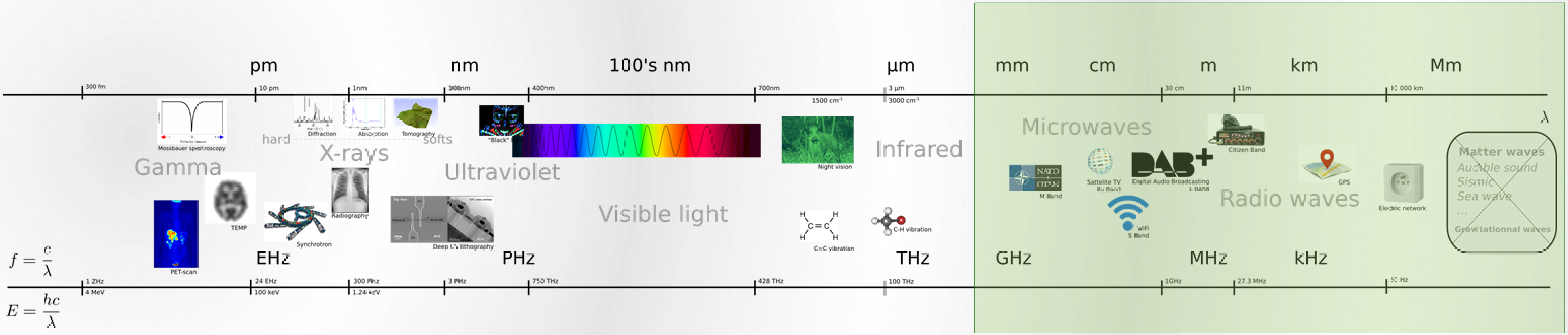
- energy/wavelength relation



$f = \frac{c}{\lambda}$

$E = \frac{hc}{\lambda}$

E (V)		λ (10^{-12} m)	v (1/c)
10 kV	→	12,3	20%
100 kV	→	3,7	50%
1 MV	→	0,9	95%



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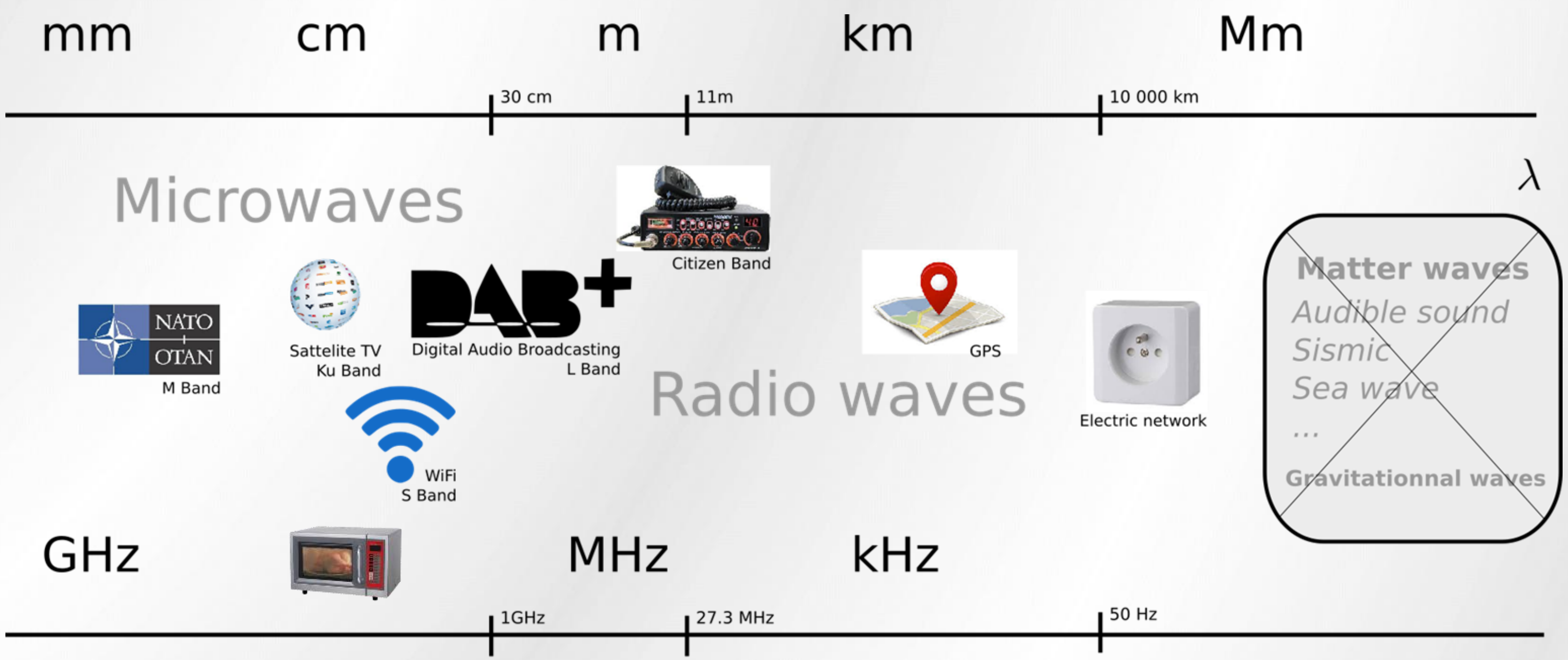

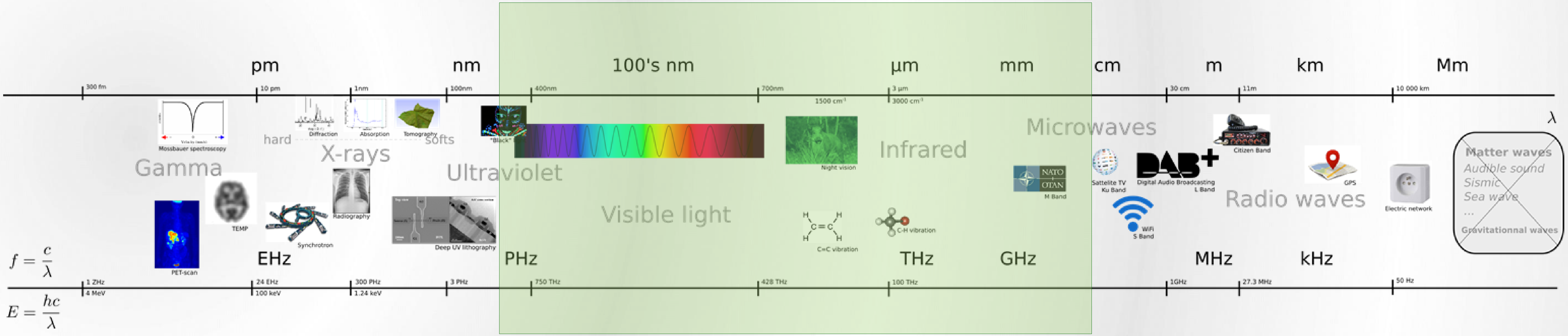

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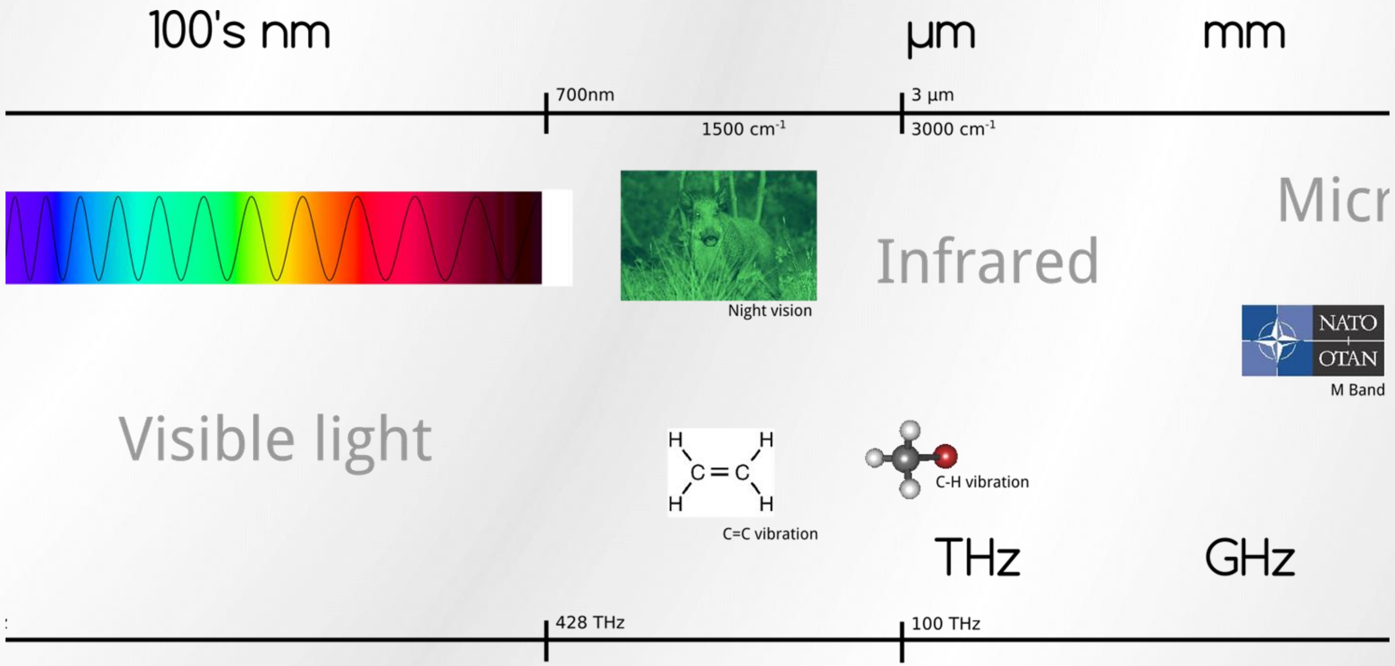
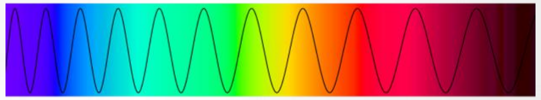


Interlude on wave diffusion

Incoming wavelength

100's nm



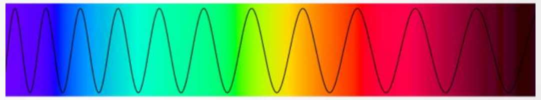
Visible light

Interlude on wave diffusion

Incoming wavelength

100's nm

Diffusing element



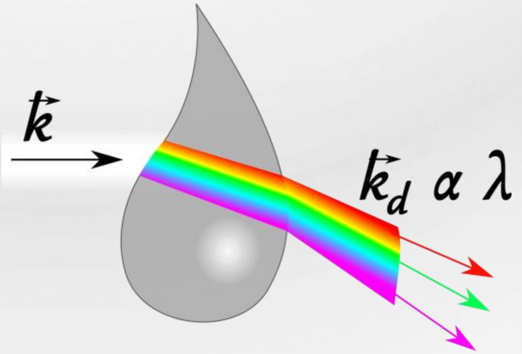
Visible light

Interlude on wave diffusion

Incoming wavelength

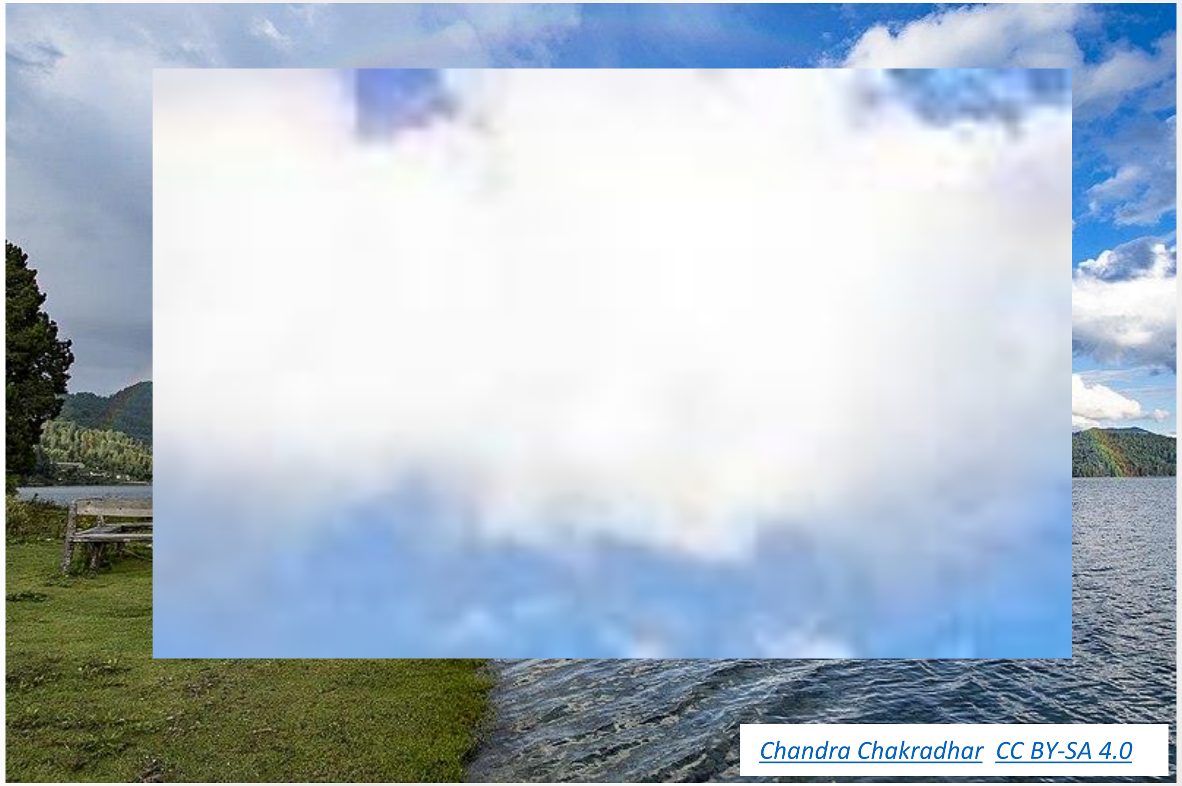
100's nm

Diffusing element ***~mm***



Optical refraction

Interlude on wave diffusion

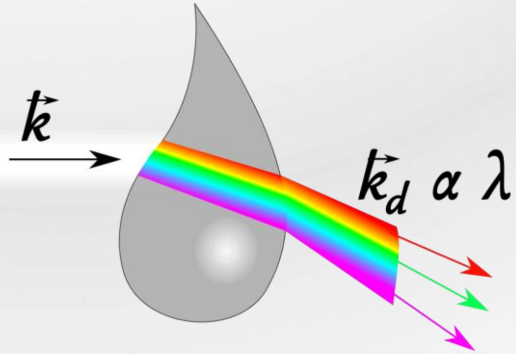


Incoming wavelength

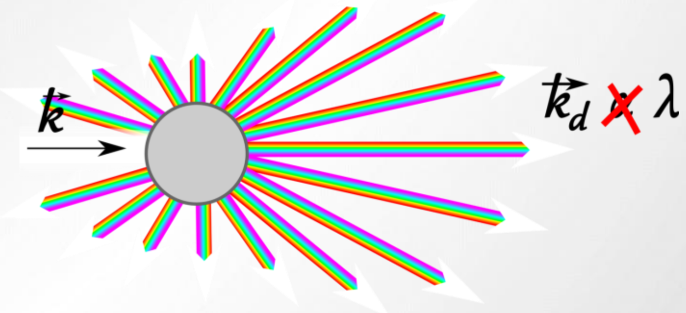
100's nm

Diffusing element **~*mm***

~*µm*



Optical refraction

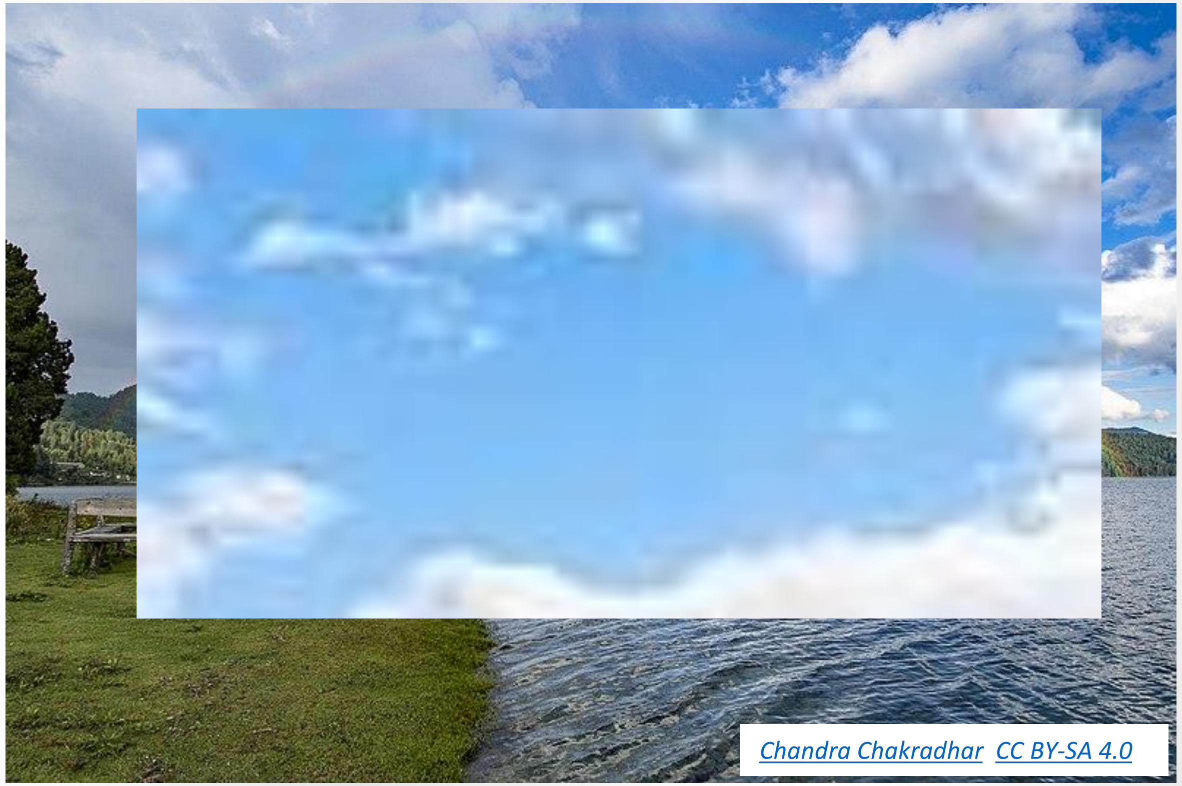


Mie Diffusion

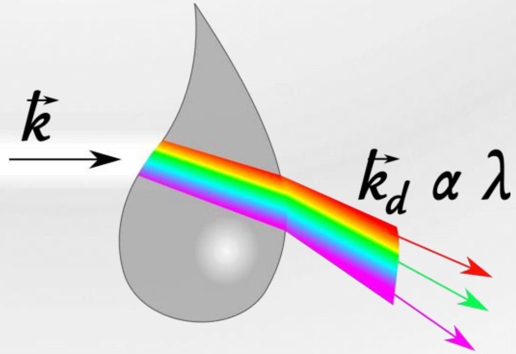
Interlude on wave diffusion

Incoming wavelength

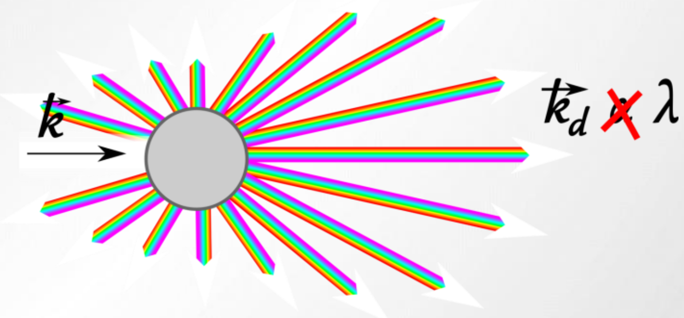
100's nm



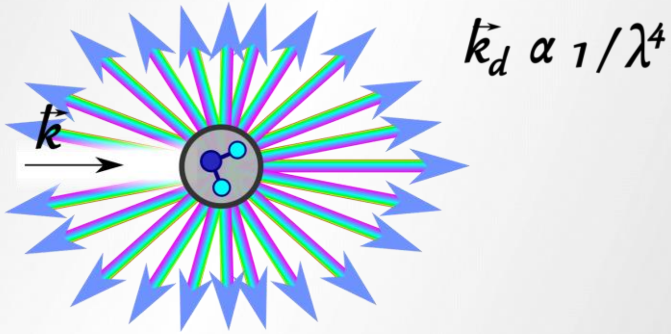
Diffusing element ***~mm*** ***~µm*** ***~nm***



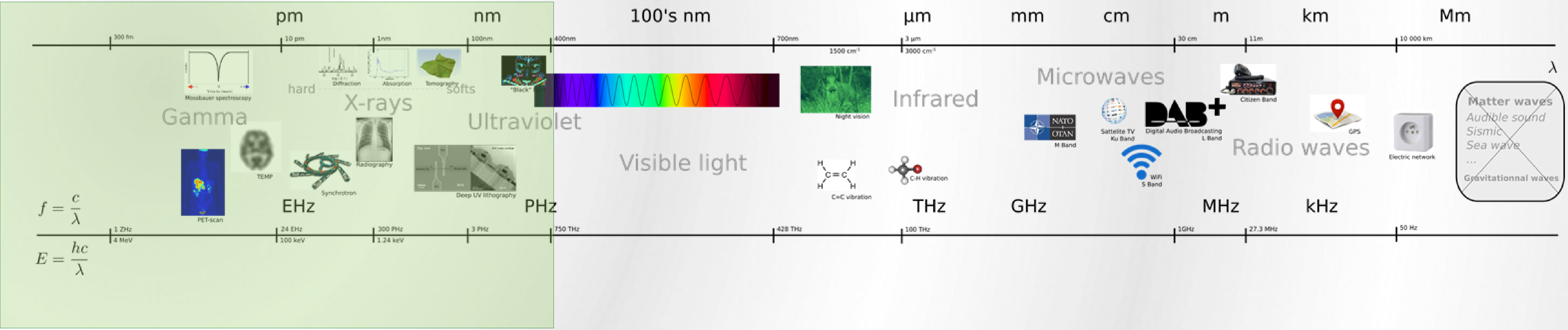
Optical refraction



Mie Diffusion



Rayleigh Diffusion



E (V)		λ (10^{-12} m)
10 kV	→	12,3
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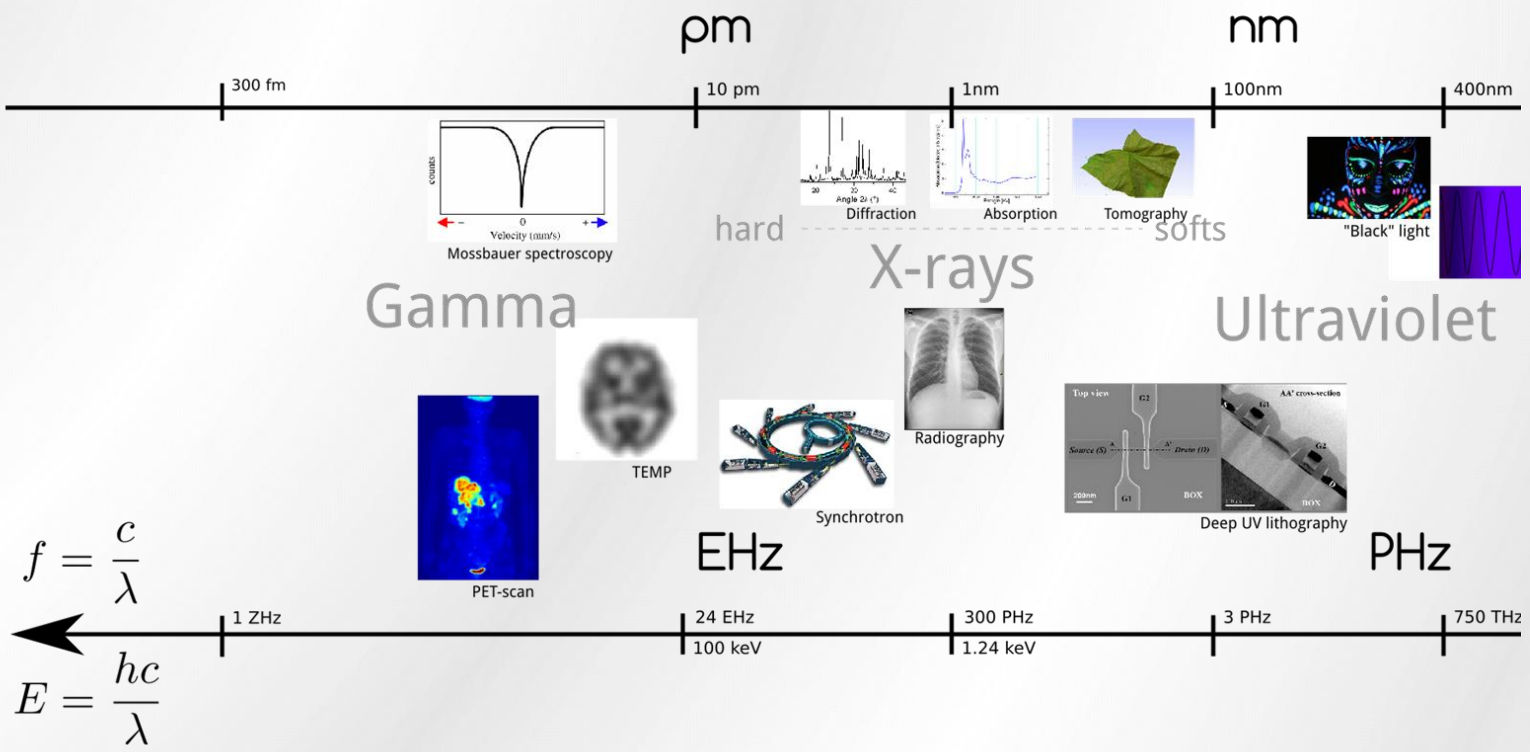
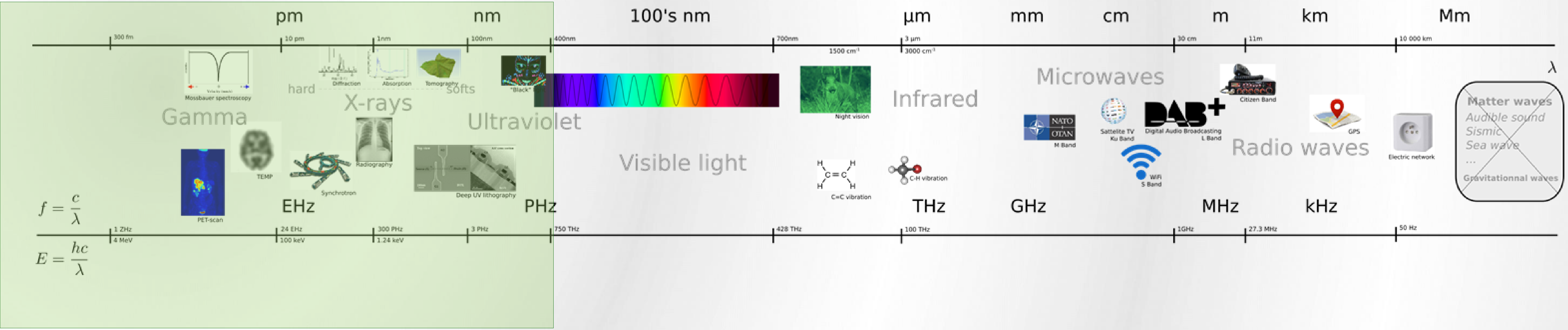
1 MV	→	0,9





E (V)		λ (10^{-12} m)
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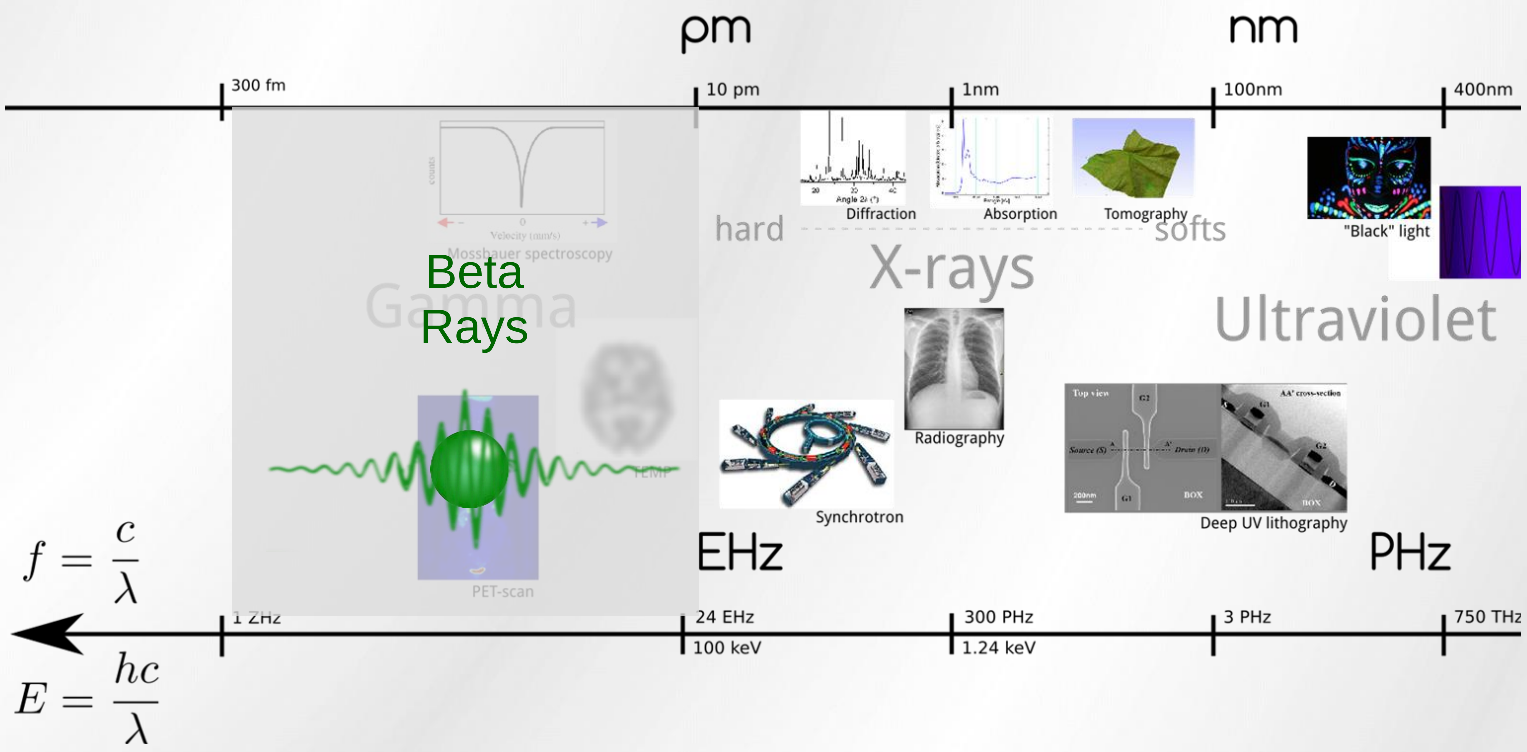
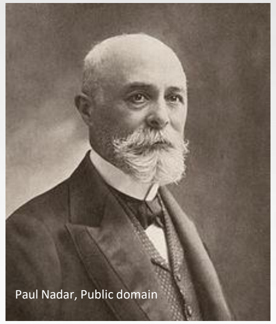




Wave description

$\lambda \sim$ pm

Incident Electrons

$m_0 \sim 10^{-30}$ kg
$q \sim 10^{-19}$ C

Particle description

Electron & Matter Interaction

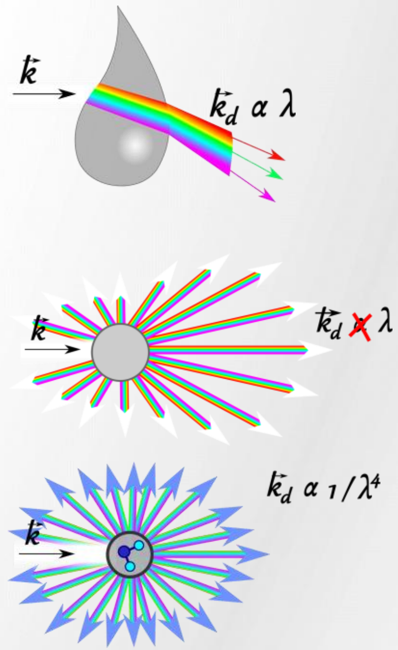
E (V)		λ (10^{-12} m)
10 kV	→	12,3
100 kV	→	3,7
1 MV	→	0,9

Wave description

λ ~ pm

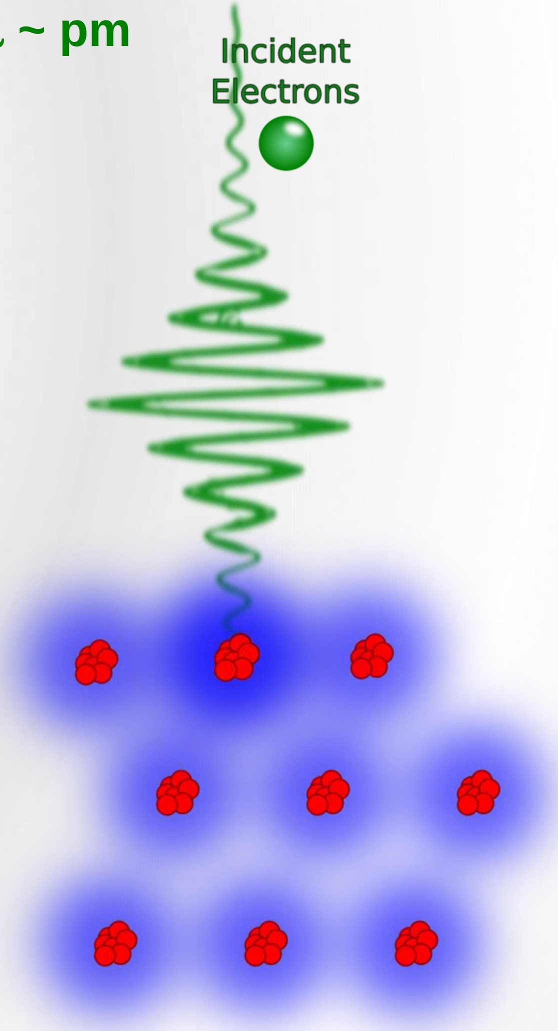
E (V)		λ (10^{-12} m)
10 kV	→	12,3
100 kV	→	3,7
1 MV	→	0,9

What kind of diffusion ?



Wave description

$\lambda \sim$ pm



E (V)		λ (10^{-12} m)
10 kV	→	**12,3**
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Particle description

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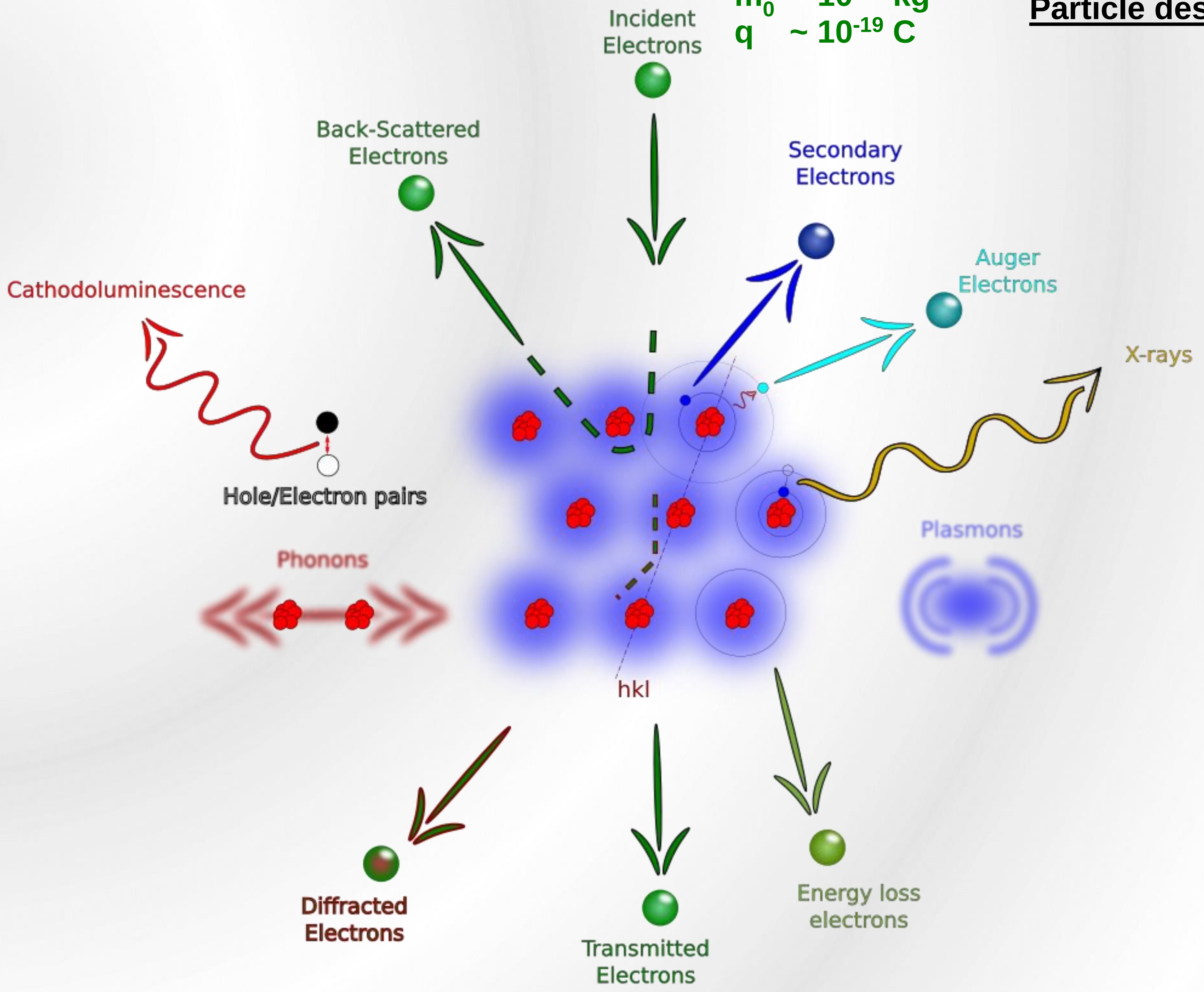

Interlude on electrons

From what you have already seen and/or easily find on the web, you should be able to calculate the **maximum number of electrons** (particles) we found **at the same single time** :

=> **in the TEM column**
=> in the TEM sample

$$\frac{v}{c} = \sqrt{1 - \frac{1}{(1 + eV/(m_0 c^2))^2}}$$

Given datas (useful or useless) :

Cold Field emission gun operated @ 3kV

Gun emission current : 100µA

Accelerating voltage : 200kV

Line tube diameter : 5 mm

Beam current : 500 pA

Number of lens in the projection system : 3

Objective lens focal length : 500 µm

Magnification used : 10^6 X

Electron rest mass : 9.1 10^{-31} kg

Elementary charge : 1.6 10^{-19} eV

Interlude on electrons

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electrons travelling @ 77 % of *c*

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1 electron « every » 0,32 ns

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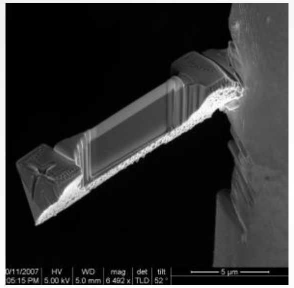
$$\frac{v}{c} = \sqrt{1 - \frac{1}{(1 + eV/(m_0c^2))^2}}$$

electrons travelling @ 77 % of *c*

1 electron « every » 0,32 ns

TEM column
~3 m height



TEM sample
~100nm thick

Interlude on electrons

From what you have already seen and/or easily find on the web, you should be able to calculate the **maximum number of electrons** (particles) we found **at the same single time** :

=> in the TEM column
=> in the TEM sample

Given datas (useful or useless) :

Cold Field emission gun operated @ 3kV

Gun emission current : 100µA

Accelerating voltage : 200kV

Line tube diameter : 5 mm

Beam current : 500 pA

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Objective lens focal length : 500 µm

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Elementary charge : $1.6\ 10^{-19}$ A.s

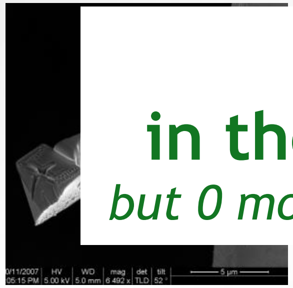
$$\frac{v}{c} = \sqrt{1 - \frac{1}{(1 + eV/(m_0c^2))^2}}$$

electrons travelling @ 77 % of *c*

1 electron « every » 0,32 ns

1 electron « every » 6.4 cm

~ 30 e^-
in the column

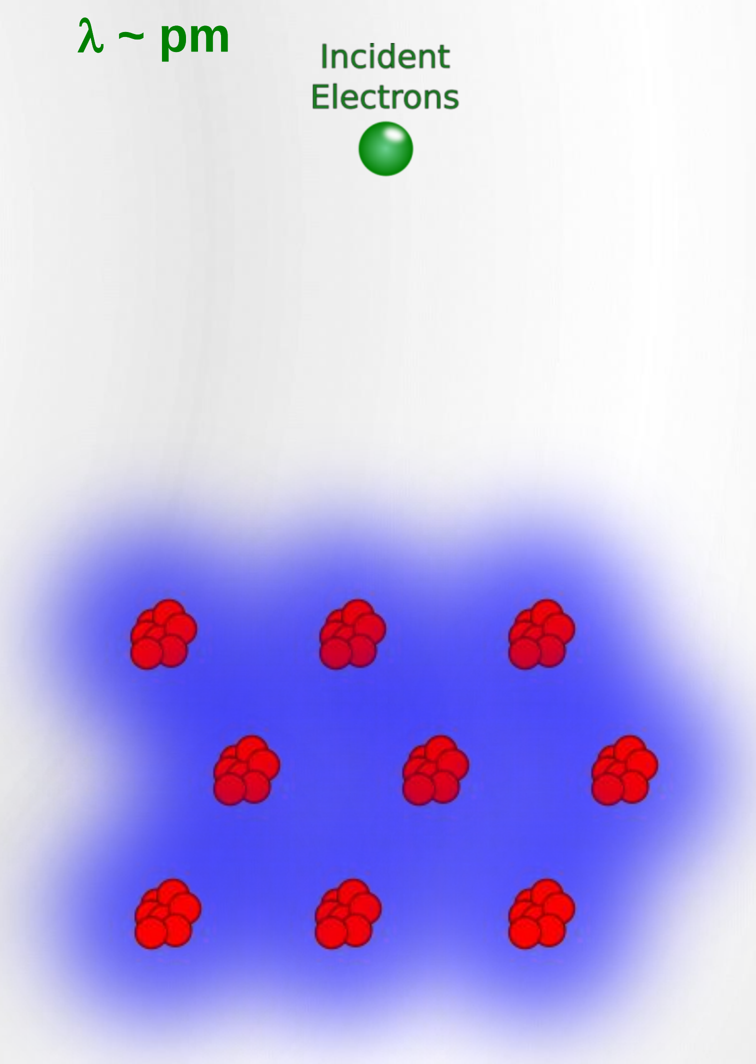


1 e^-
in the sample
but 0 most of the time

le
ick

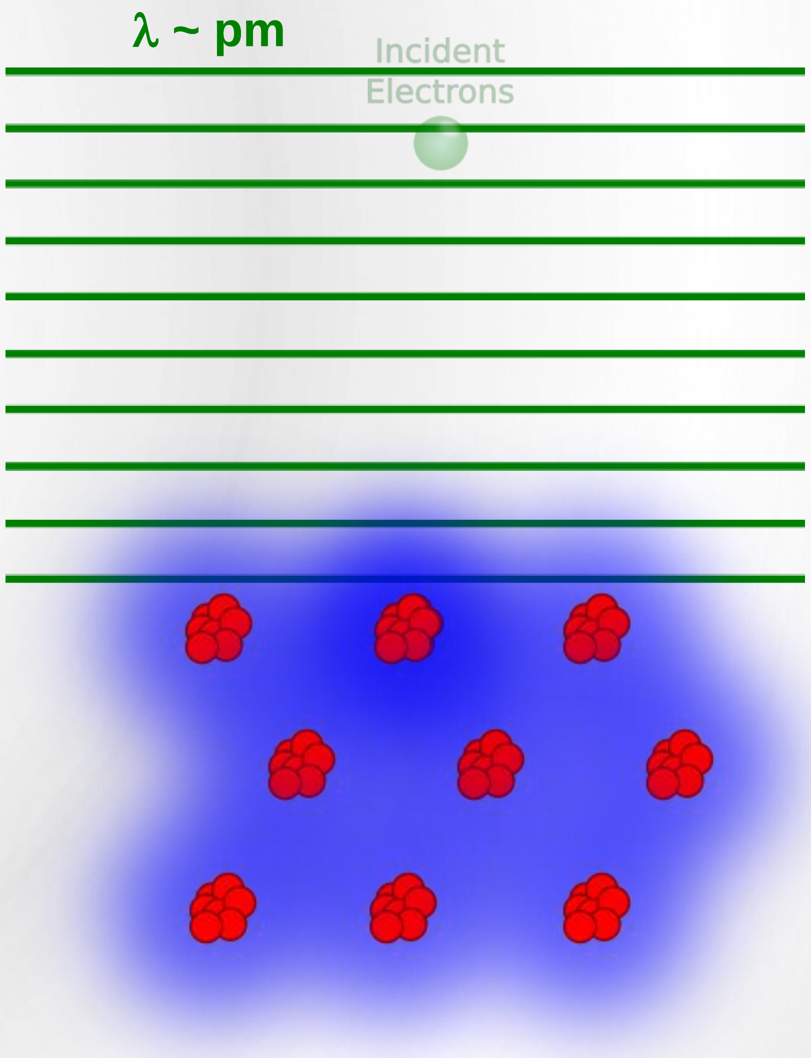
Wave description

$$\Psi = Ae^{i\Phi}$$



Wave description

$$\Psi = Ae^{i\Phi}$$



Wave description

λ ~ pm

$$\Psi = Ae^{i\Phi}$$

$$\Phi = \phi + \vec{k} \cdot \vec{r} - \omega t$$

Periodic along space

$$\|\vec{k}\| = \frac{2\pi}{\lambda}$$

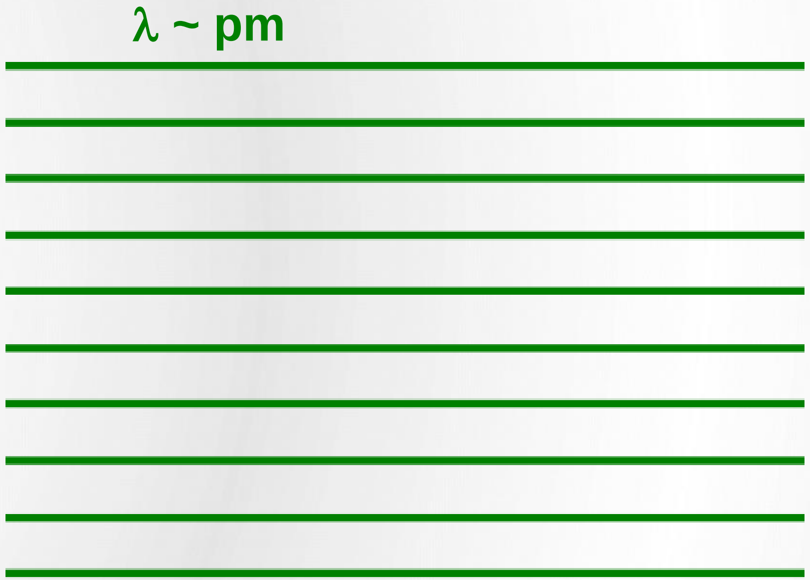
wavelength

Periodic along time

$$\omega = \|\vec{k}\| v_p$$

phase velocity

Wave description

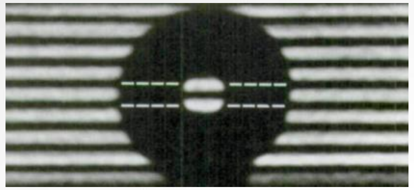


$$\Psi = Ae^{i\Phi}$$

$$\Phi = \phi + \vec{k} \cdot \vec{r} - \omega t$$

Physic at play

$$\phi$$



Tonomura, A. et al. Phys. Rev. Lett. 56, 792–795 (1986)

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phase velocity

Wave description

λ ~ pm

$$\Psi = Ae^{i\Phi}$$

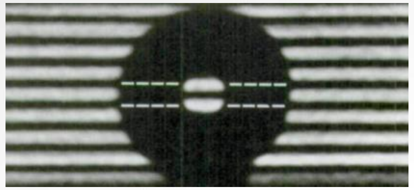
$$\Phi = \phi + \vec{k} \cdot \vec{r} - \omega t$$

Wave propagator
(d'Alembert operator)

$$\nabla^2 \Psi = \frac{1}{c^2} \frac{\partial \Psi}{\partial t}$$

Physic at play

$$\phi$$



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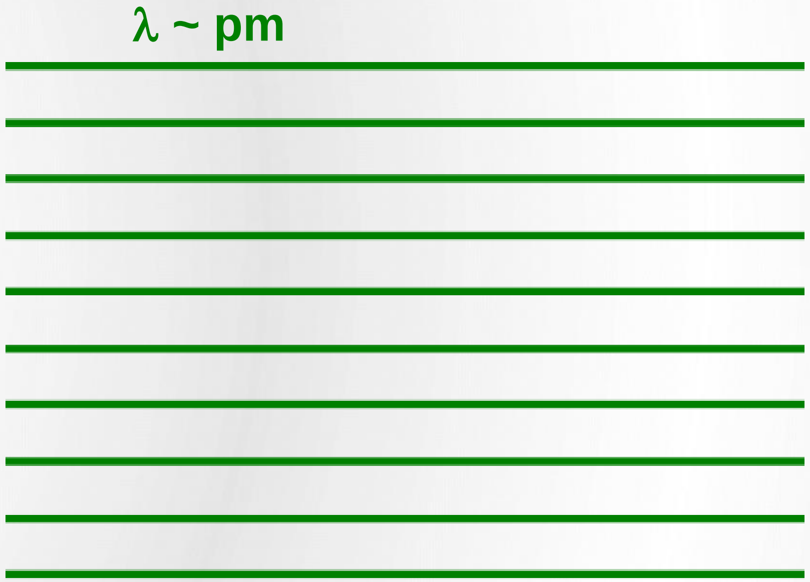
Wave description



$$\Psi = Ae^{i\Phi}$$

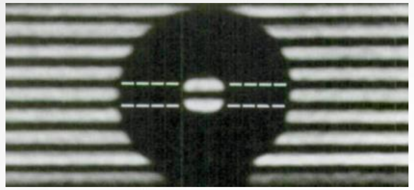
$$\Phi = \phi + \vec{k} \cdot \vec{r} - \omega t$$

Helmolz equation
(time-independant wave eq.)

$$\nabla^2\Psi = -k^2\Psi$$

Physic at play

$$\phi$$



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Periodic along space

$$||\vec{k}|| = \frac{2\pi}{\lambda}$$

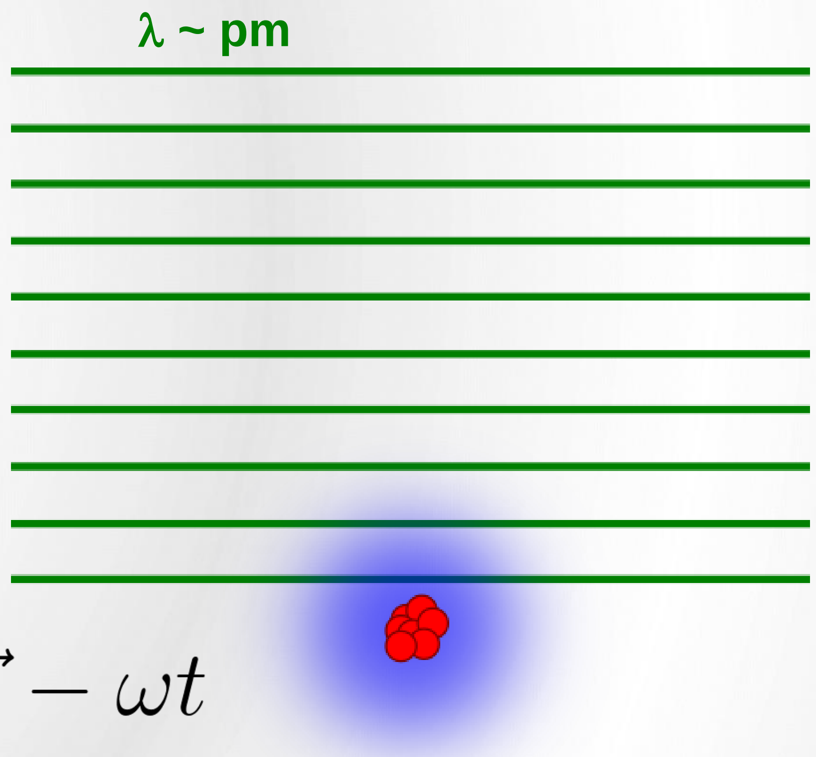
wavelength

Periodic along time

$$\omega = ||\vec{k}||v_p$$

phase velocity

Wave description




US Public domain


After Maurice Quentin de La Tour, Public domain

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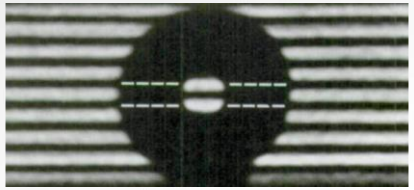
$$\Phi = \phi + \vec{k}\cdot\vec{r} - \omega t$$

Helmolz equation
(time-independant wave eq.)

$$\nabla^2\Psi = -k^2\Psi$$

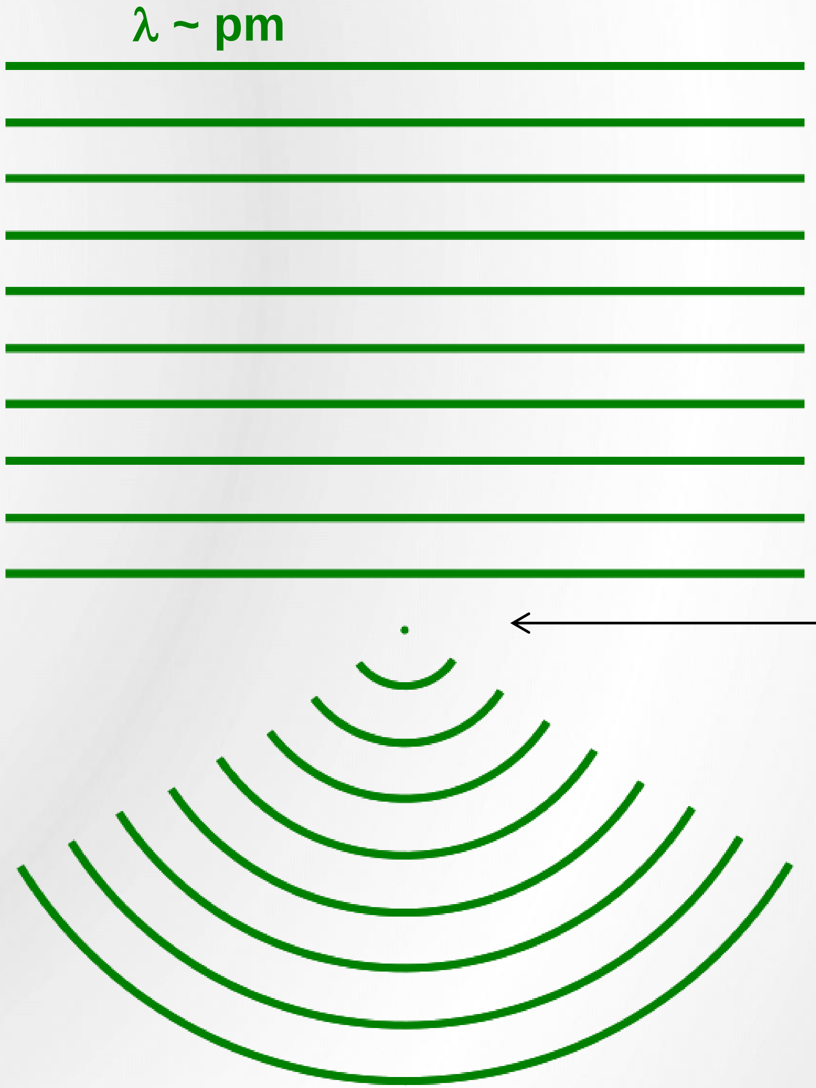
Physic at play	Periodic along space	Periodic along time
ϕ	$\lVert\vec{k}\rVert = \frac{2\pi}{\lambda}$	$\omega = \lVert\vec{k}\rVert v_p$
	wavelength	*phase velocity*



Tonomura, A. et al. Phys. Rev. Lett. 56, 792–795 (1986)

Wave description

$$\Psi = Ae^{i\Phi}$$



Huygens – Fresnel principle

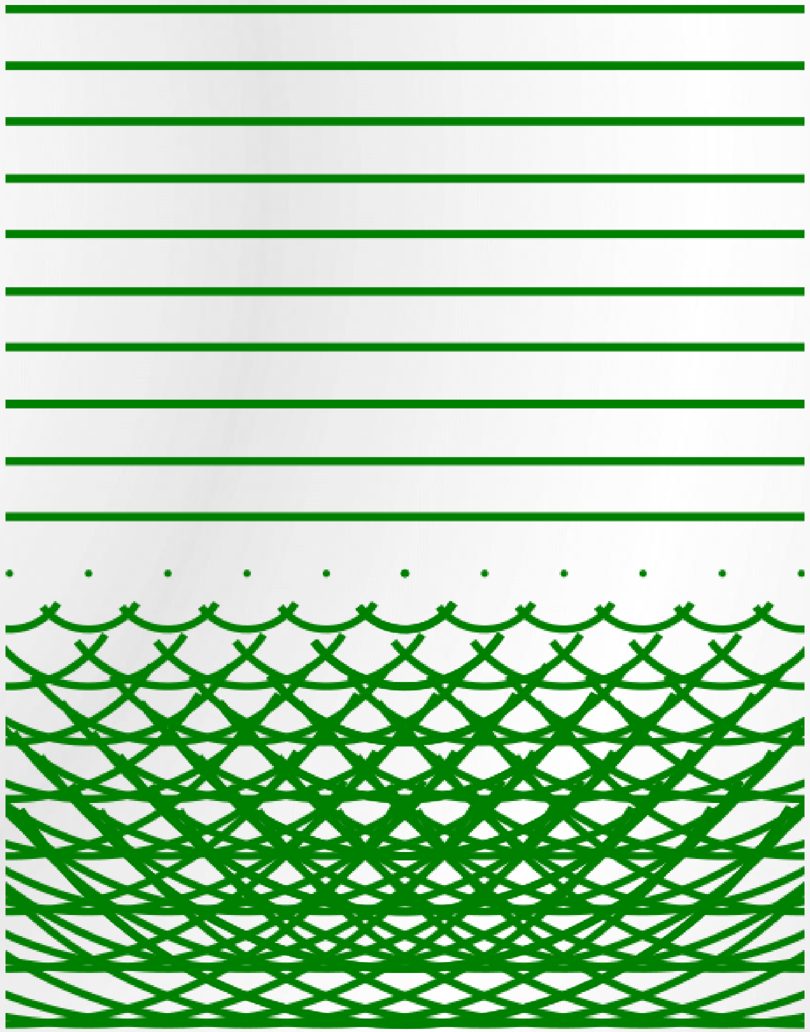
$$\|\vec{k}\| = \frac{2\pi}{\lambda}$$

*Each point of space
receiving a wave
is emitting a spherical wave
of same frequency*

Wave description

$$\Psi = Ae^{i\Phi}$$

$\lambda \sim$ pm



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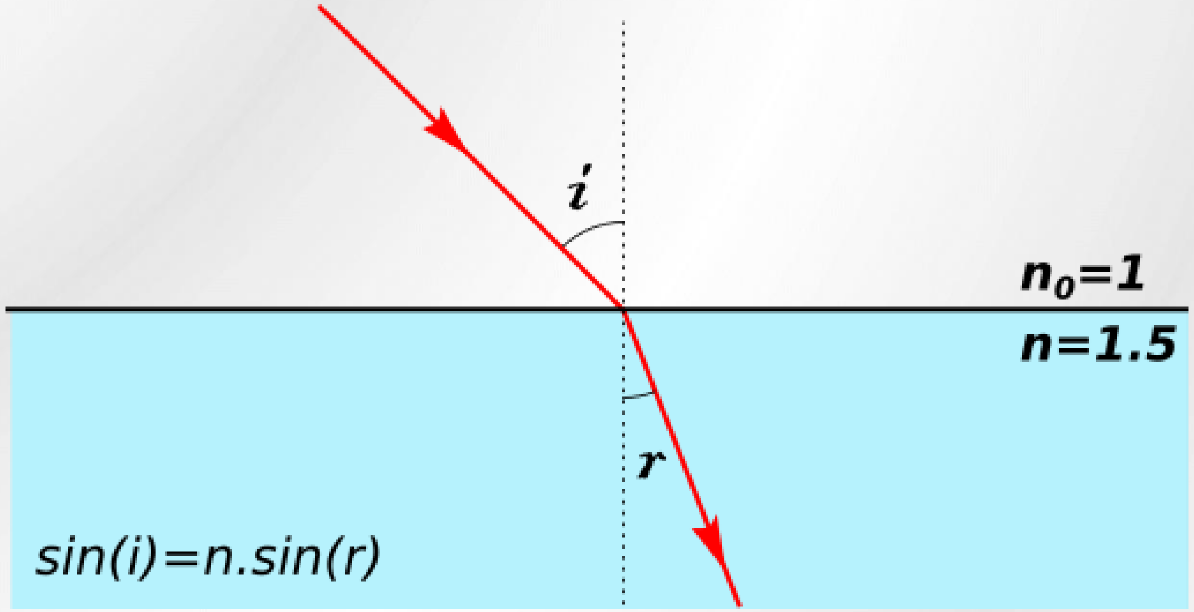
Wave description

$\lambda \sim$ pm

$$\Psi = Ae^{i\Phi}$$

Huygens – Fresnel principle

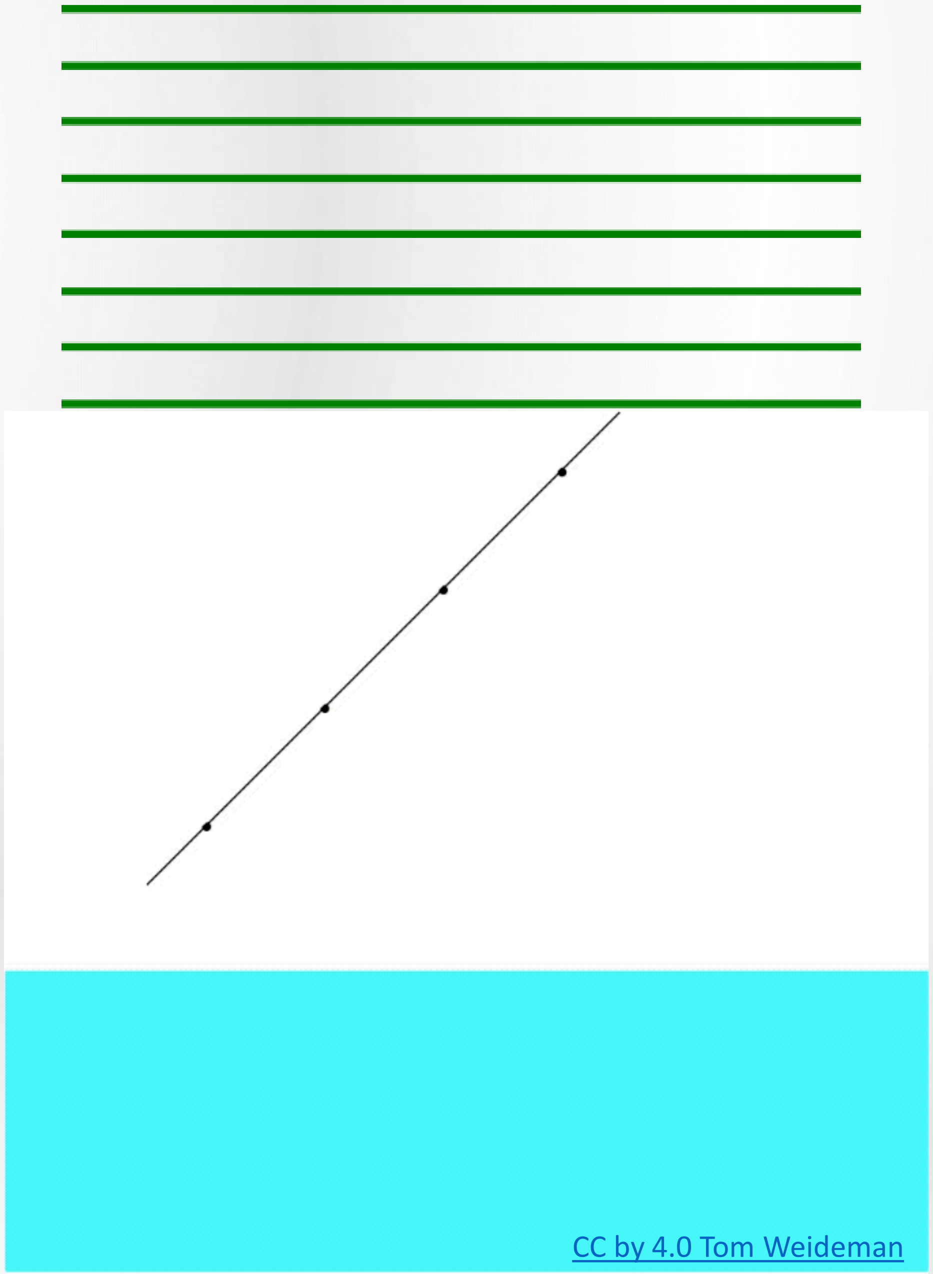


Each point of space
receiving a wave
is emitting a spherical wave
of same frequency

Wave description

$$\Psi = Ae^{i\Phi}$$

λ ~ pm

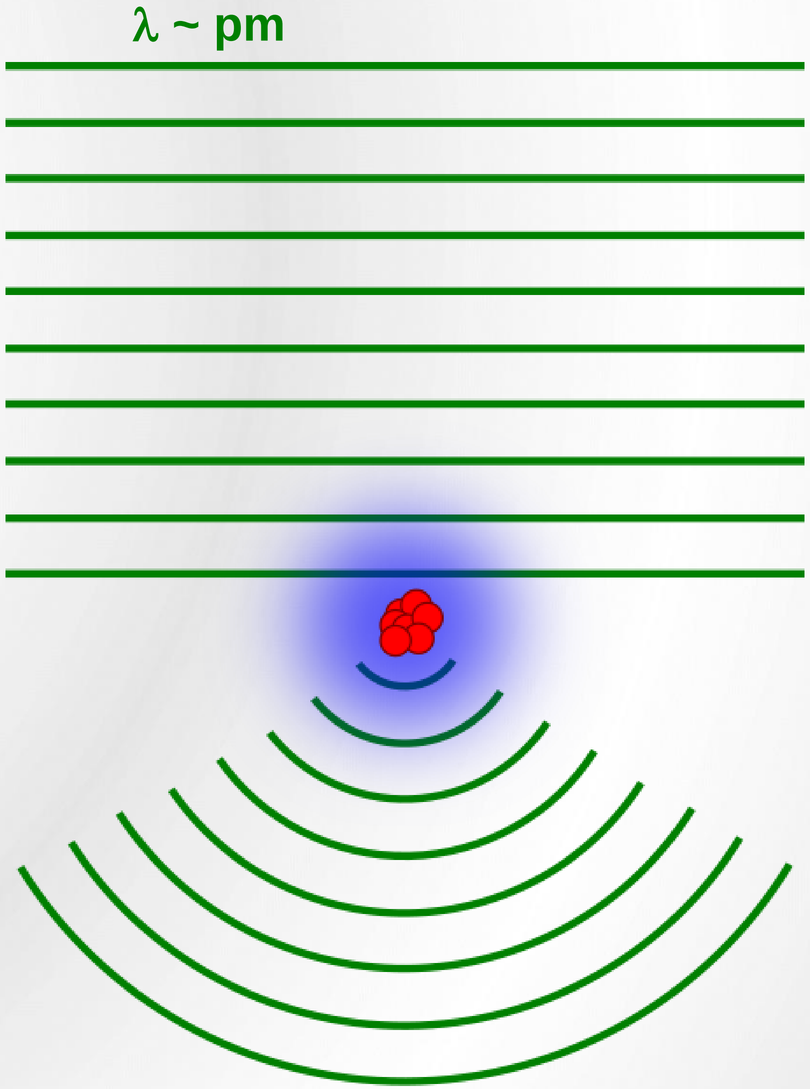


Huygens – Fresnel principle

Each point of space receiving a wave is emitting a spherical wave of same frequency

Wave description

$$\Psi = Ae^{i\Phi}$$



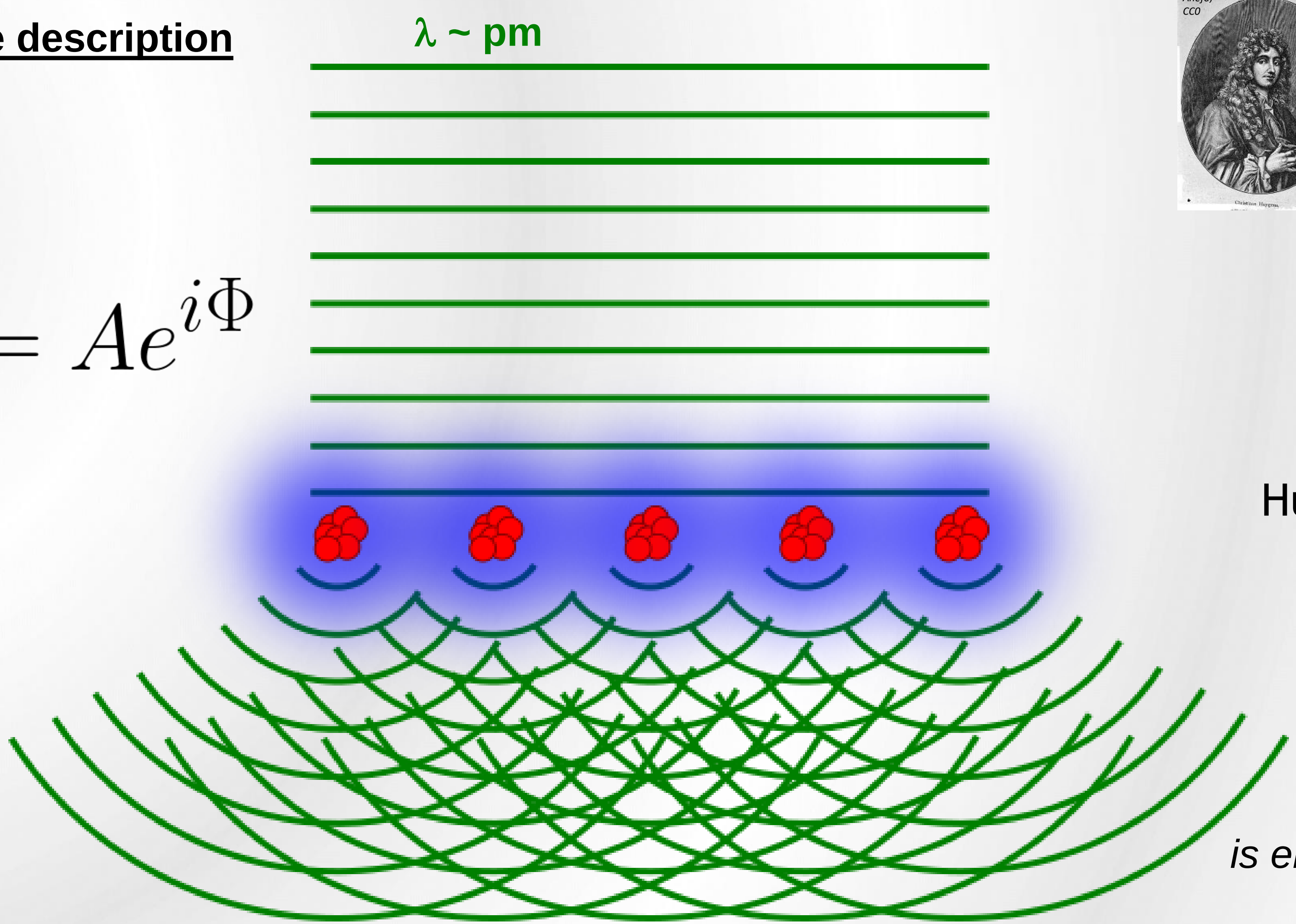
$$||\vec{k}|| = \frac{2\pi}{\lambda}$$

Huygens – Fresnel principle

Each point of space receiving a wave is emitting a spherical wave of same frequency

Wave description

$$\Psi = A e^{i\Phi}$$



Huygens – Fresnel principle

Each point of space receiving a wave is emitting a spherical wave of same frequency

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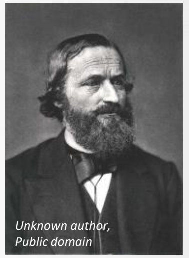
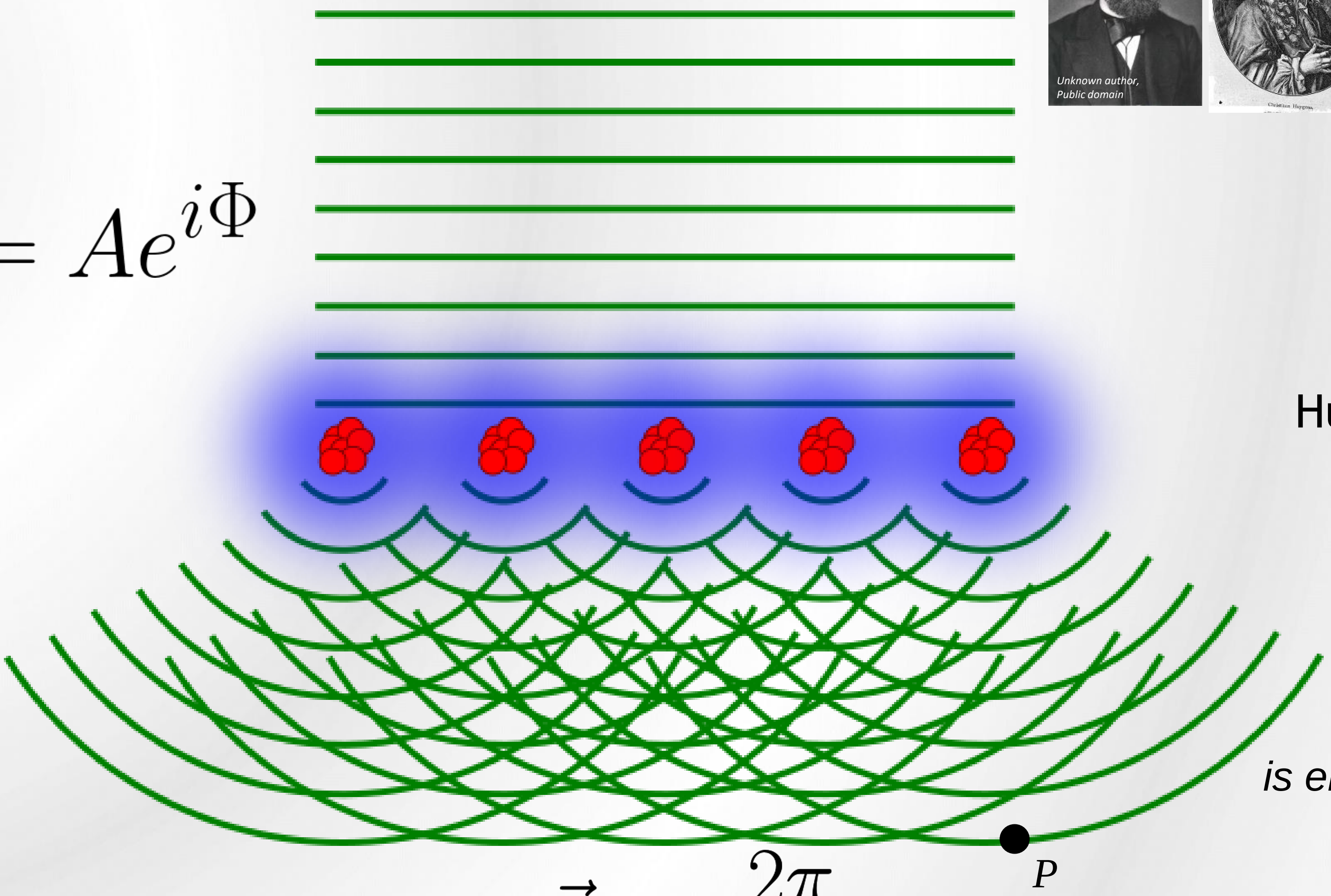
Wave description



$$\Psi = Ae^{i\Phi}$$



Huygens – Fresnel principle

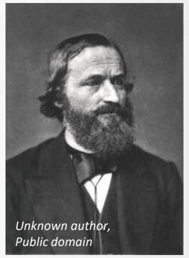
Each point of space receiving a wave is emitting a spherical wave of same frequency

$$\|\vec{k}\| = \frac{2\pi}{\lambda}$$

Kirchhoff integral

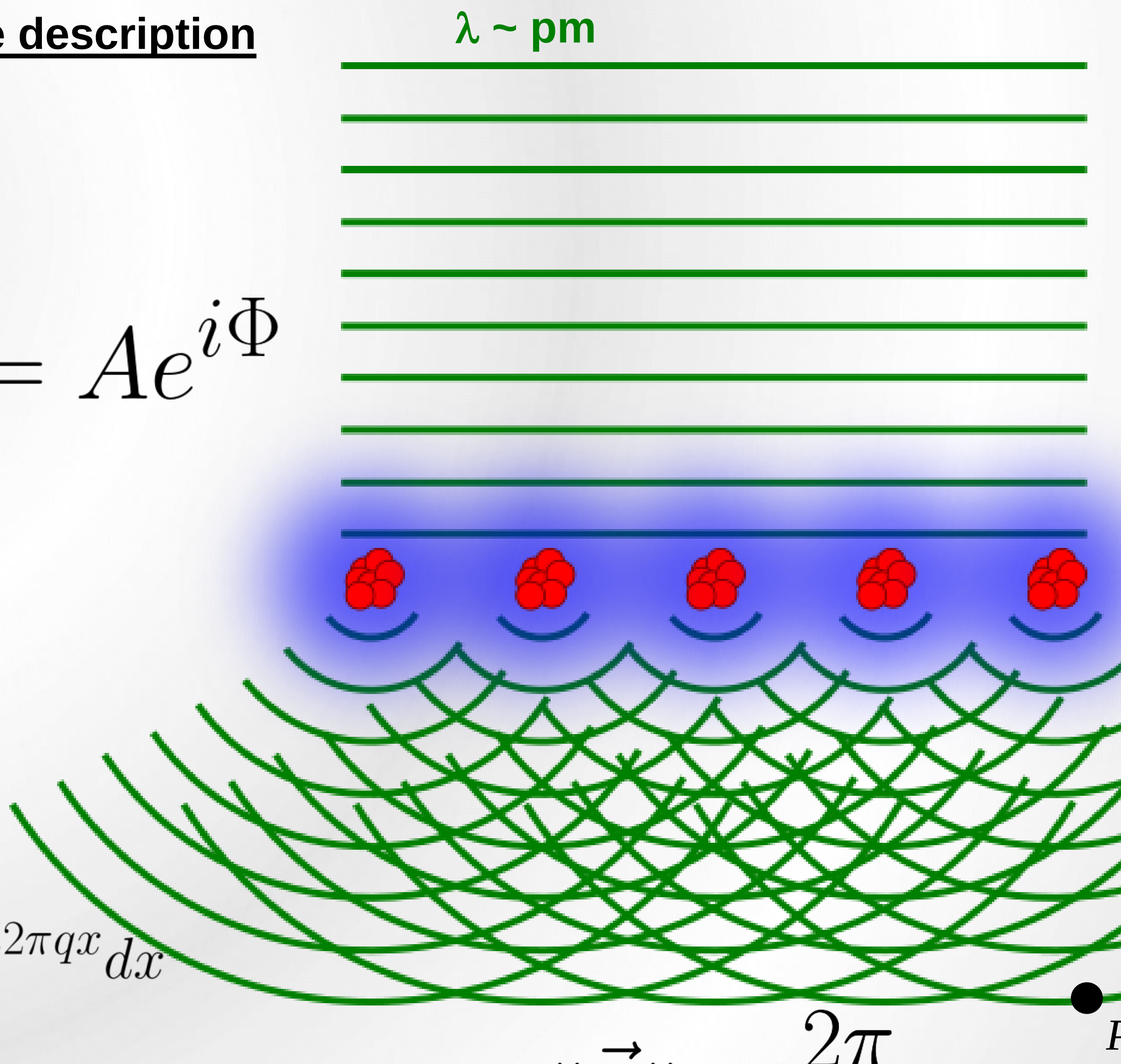
mathematical model of the H-F principle

$$\Psi_P = C \int \Psi(\vec{r}) \frac{e^{i2\pi\vec{k}\cdot(\vec{r}_P - \vec{r})}}{\vec{r}_P - \vec{r}} d\vec{r}$$



Wave description

$$\Psi = Ae^{i\Phi}$$



Huygens – Fresnel principle

Each point of space receiving a wave is emitting a spherical wave of same frequency

$$f(q) = \int_{\infty} f(x)e^{-i2\pi qx}dx$$

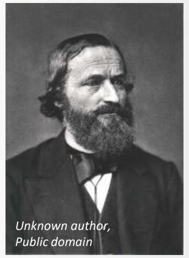
$$\|\vec{k}\| = \frac{2\pi}{\lambda}$$

Kirchhoff integral

mathematical model of the H-F principle

$$\Psi_P = C\int \Psi(\vec{r})\frac{e^{i2\pi\vec{k}\cdot(\vec{r}_P-\vec{r})}}{\vec{r}_P-\vec{r}}d\vec{r}$$

Wave description



$$\Psi = Ae^{i\Phi}$$

$$\boldsymbol{FT}\left[\Psi\right]$$

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Kirchhoff integral

mathematical model of the H-F principle

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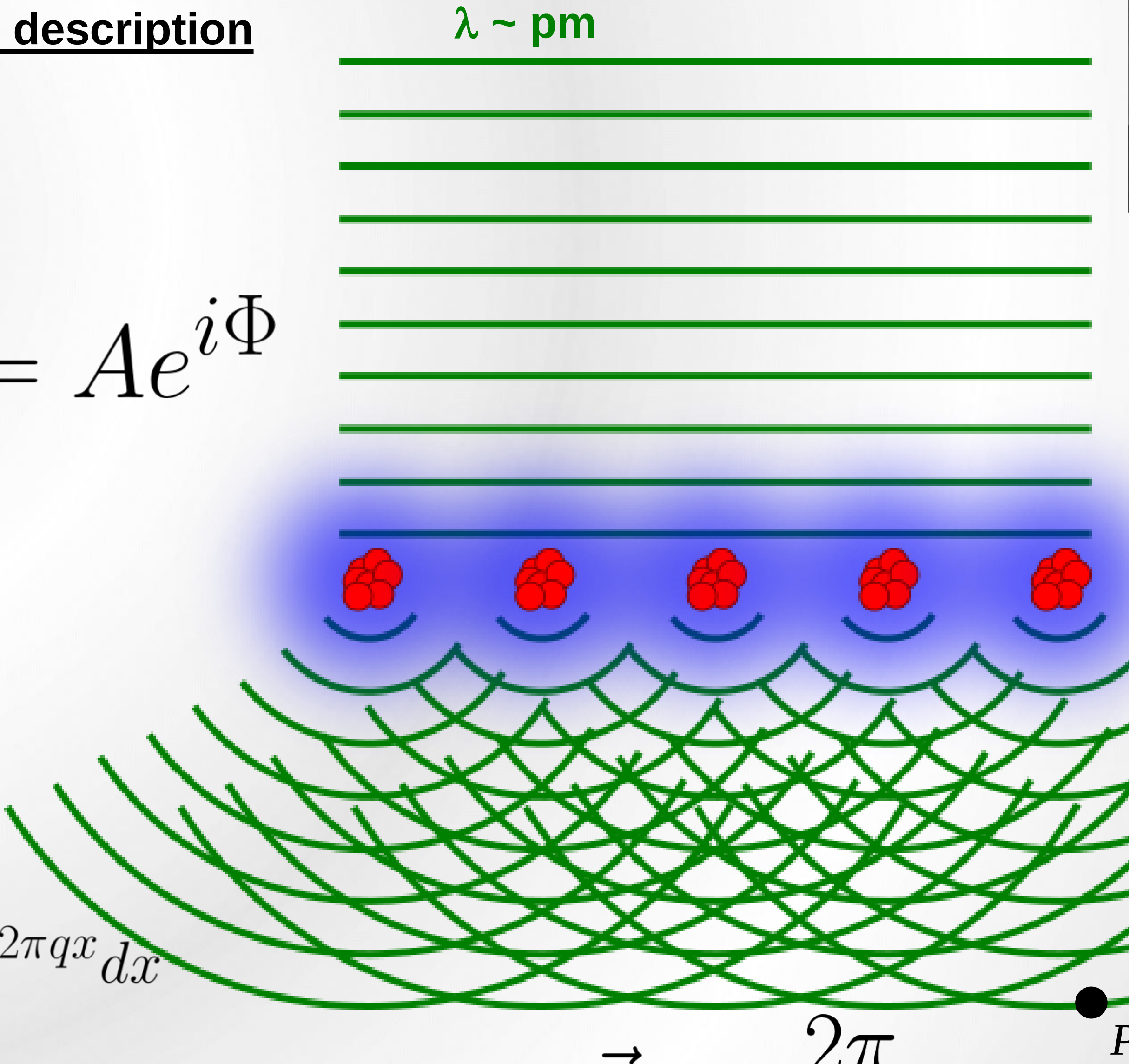

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Huygens – Fresnel principle

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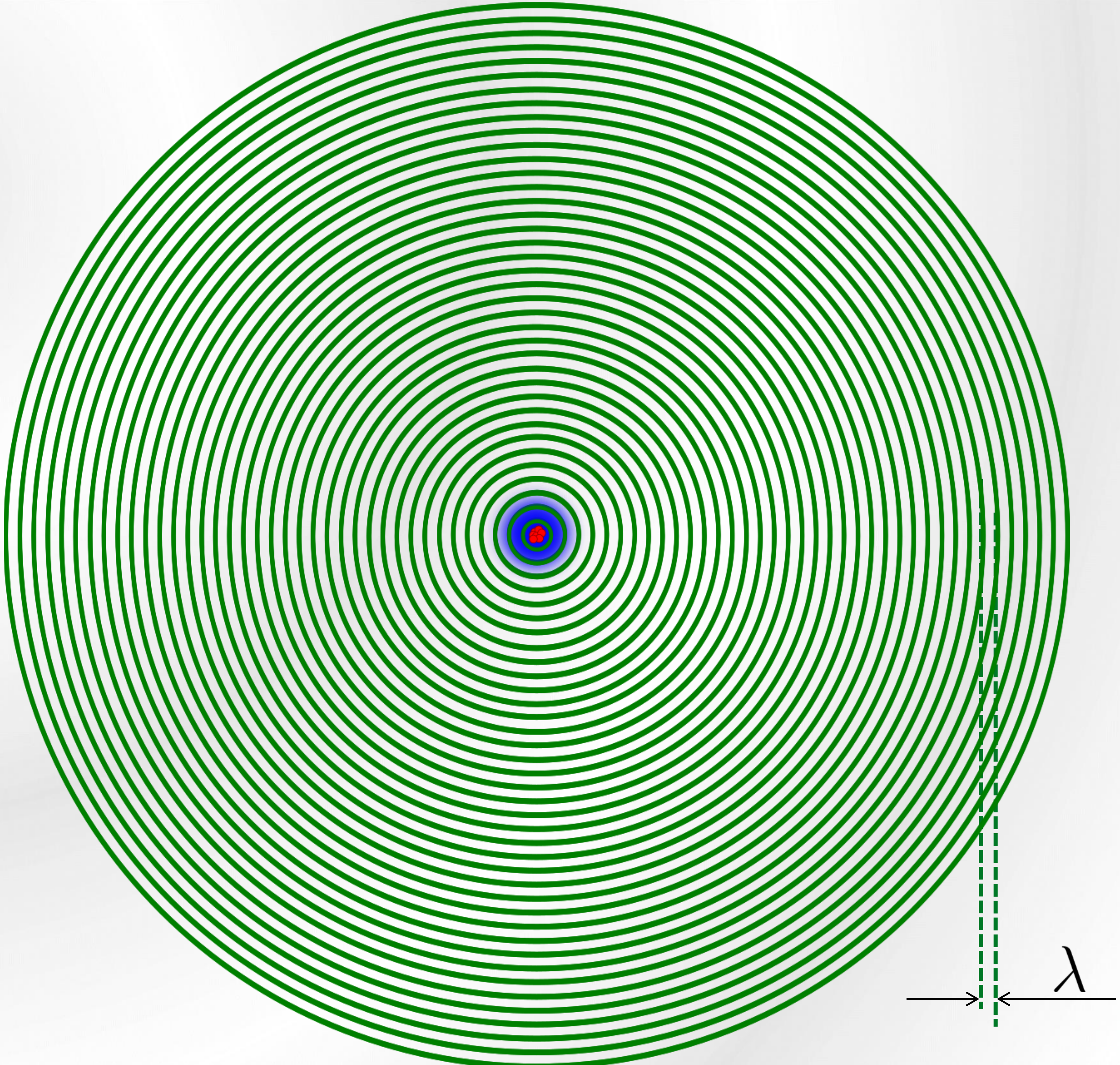
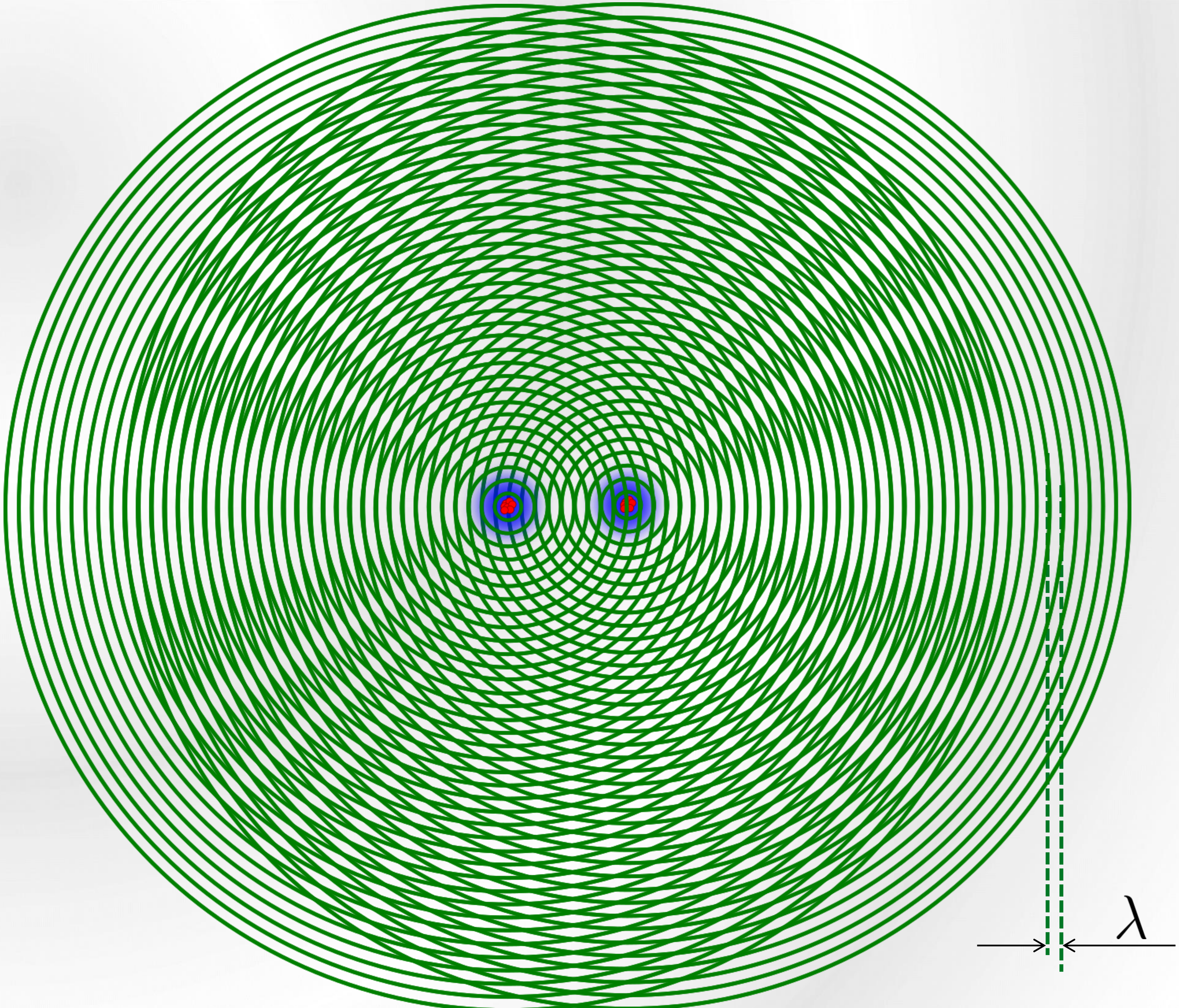
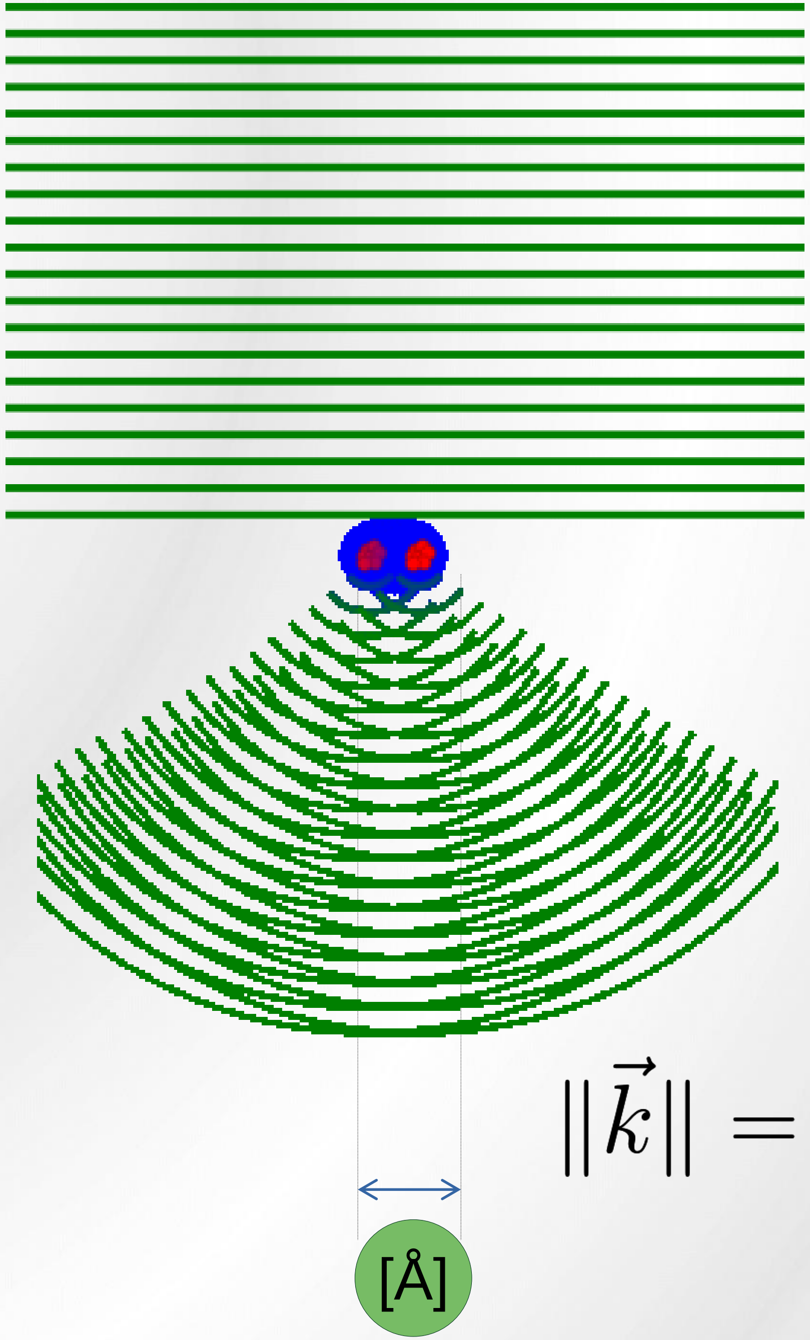

λ


λ

Wave description

λ ~ pm

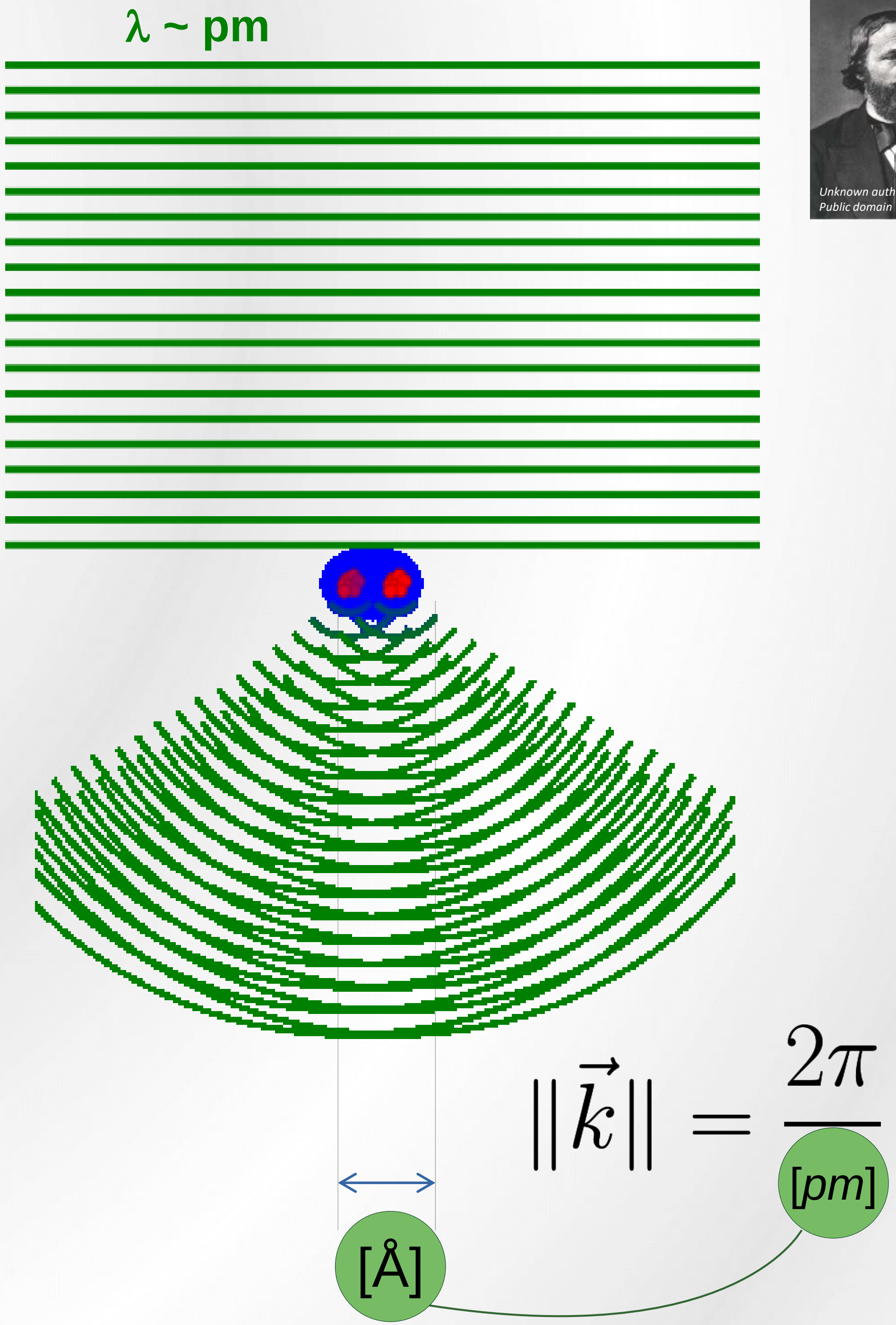
$$\Psi = Ae^{i\Phi}$$



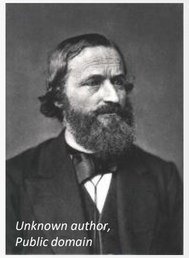
$$\|\vec{k}\| = \frac{2\pi}{\lambda}$$

Wave description

$$\Psi = Ae^{i\Phi}$$



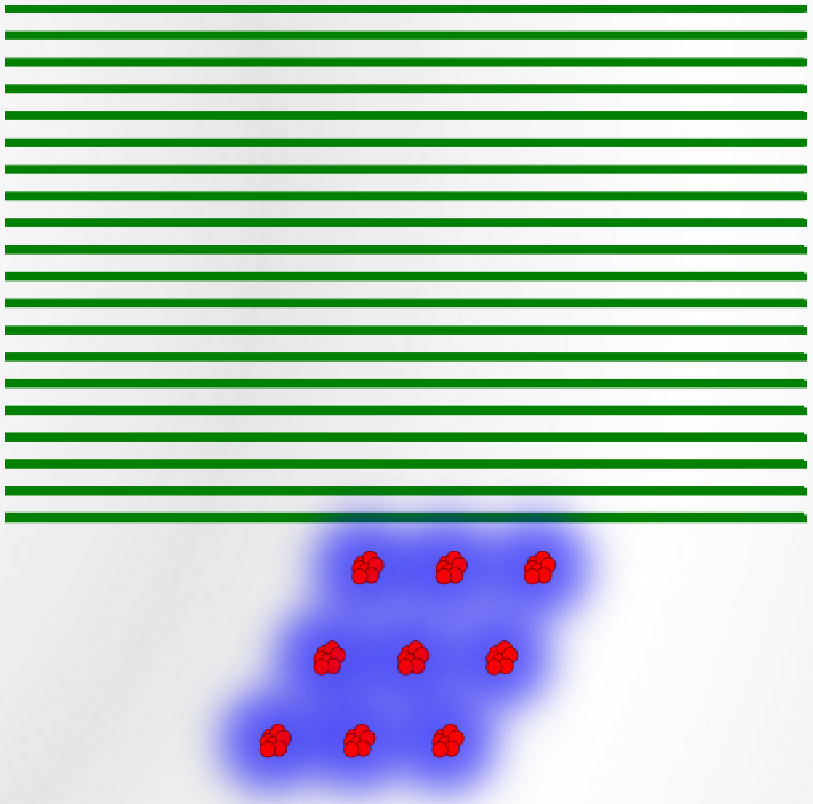
$$\|\vec{k}\| = \frac{2\pi}{[pm]}$$

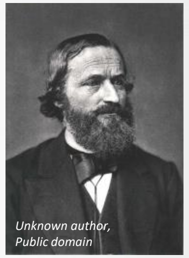


Wave description

$$\Psi = Ae^{i\Phi}$$

λ ~ pm

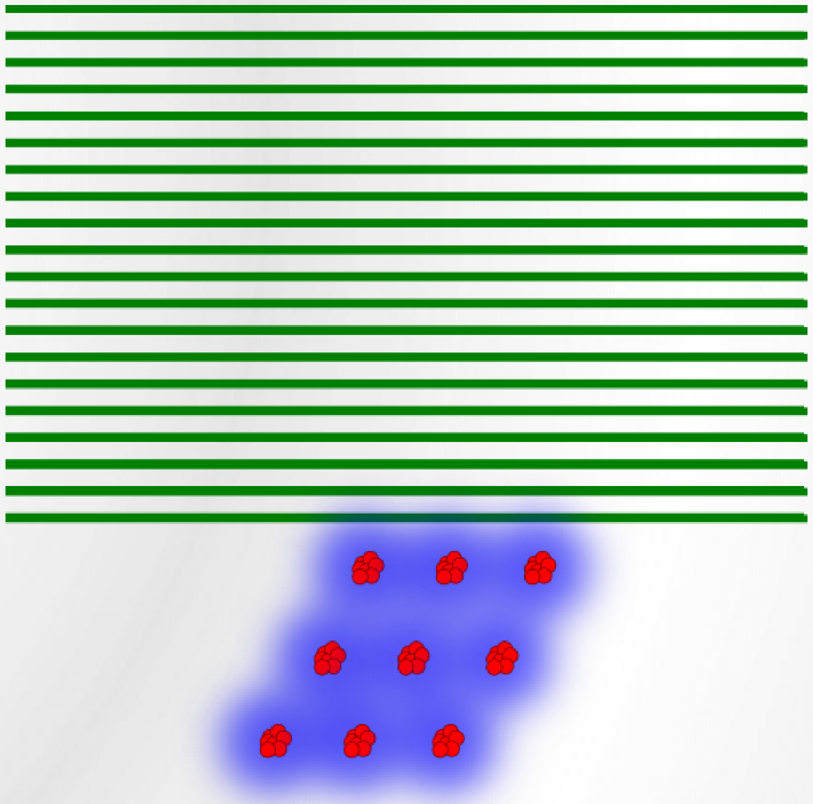




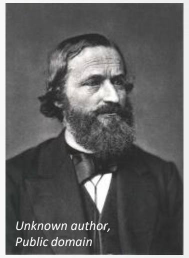
1912

Wave description

λ ~ pm



$$\Psi = A e^{i\Phi}$$



1912

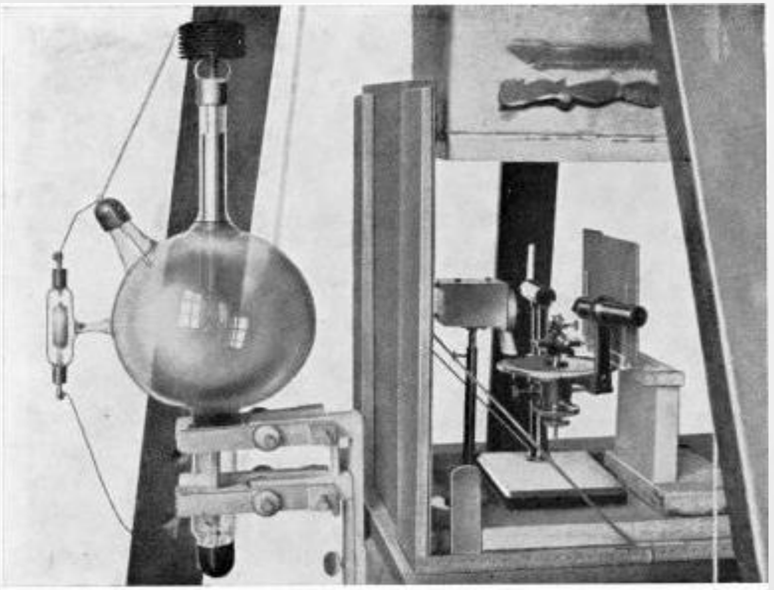


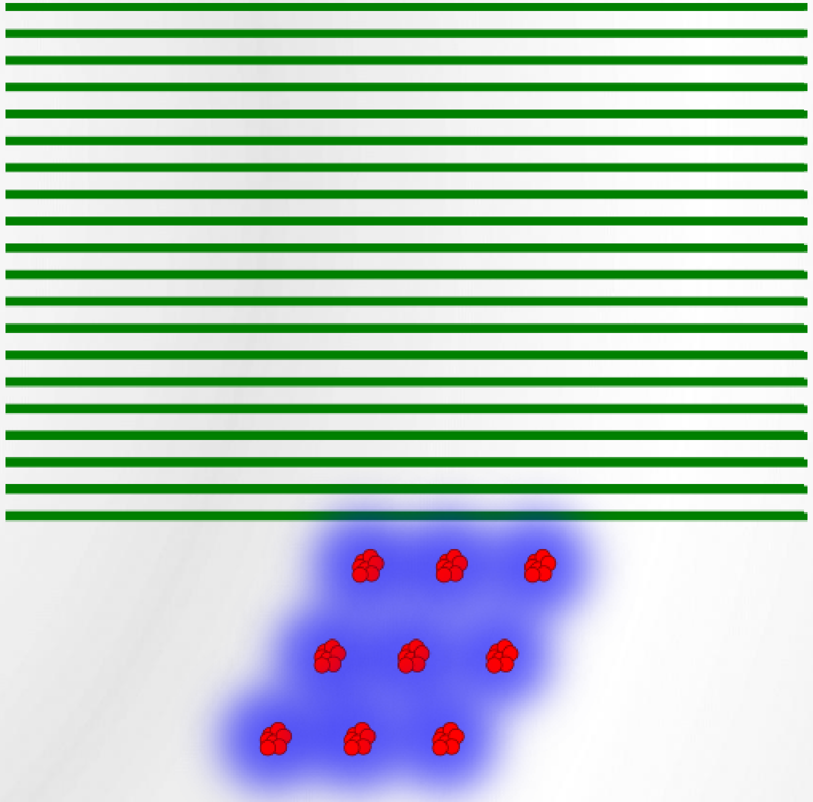
Fig. 4-4(2). Friedrich & Knipping's improved set-up.

Ewald, P. P. Fifty Years of X-Ray Diffraction
Doi:10.1007/978-1-4615-9961-6.
https://www.iucr.org/publications/iucr/50yearsx

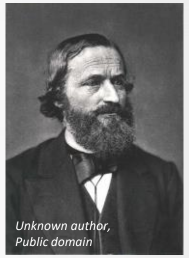
Wave description

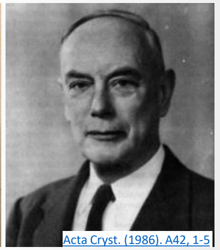
$$\Psi = Ae^{i\Phi}$$

λ ~ pm

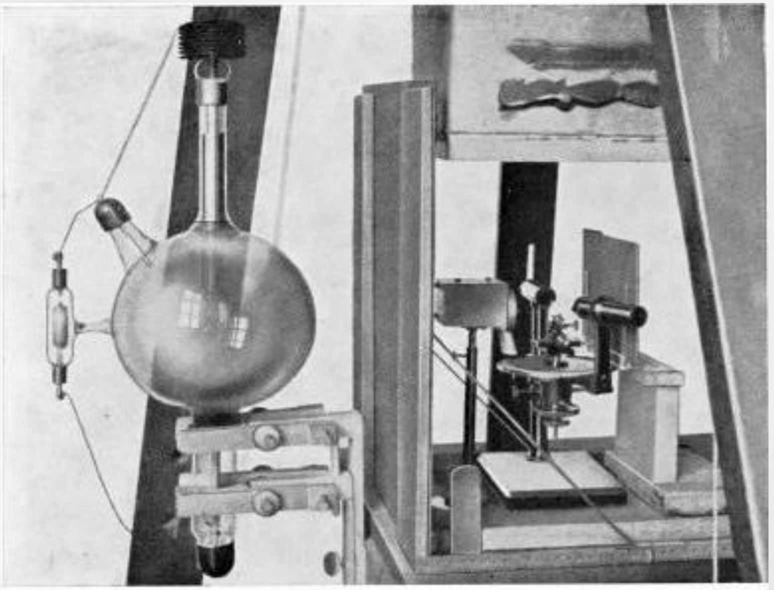


Blende Zns





1912



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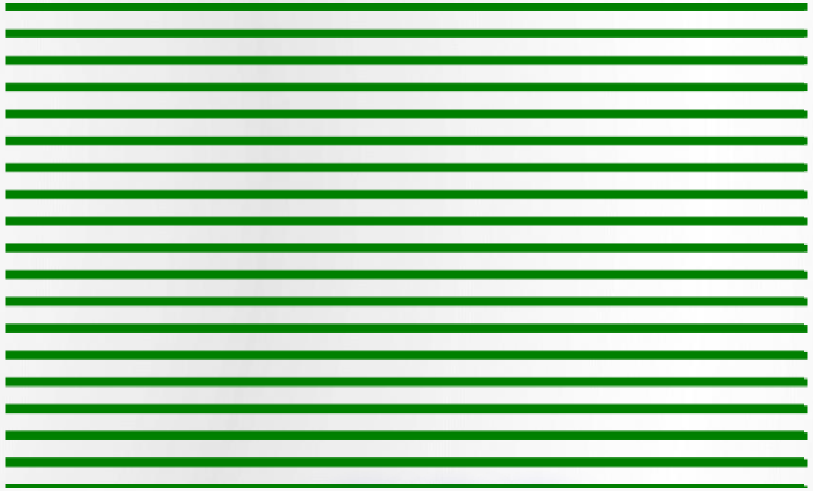
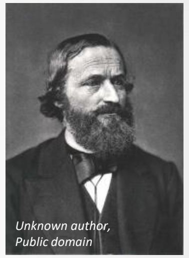
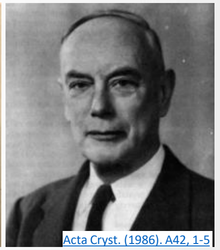
Wave description

λ ~ pm



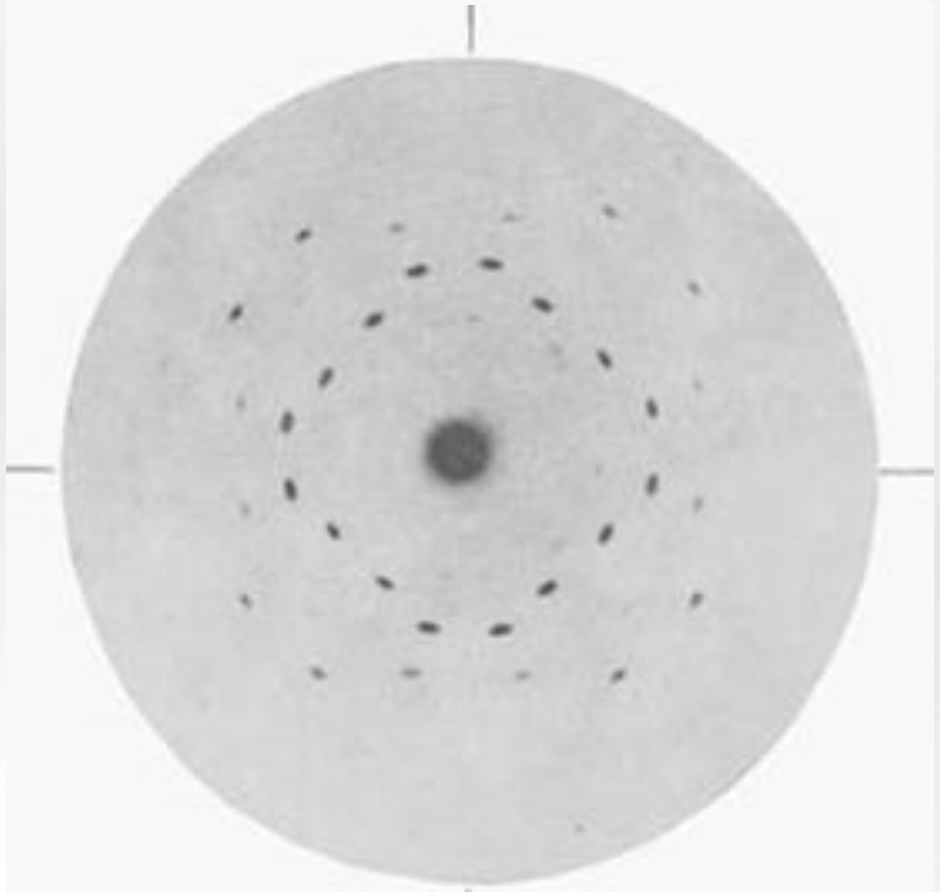
$$\Psi = Ae^{i\Phi}$$





1912

Fig. 4–4(3) and (4). Zincblende Laue photographs along four-fold and three-fold axes. (Laue, Friedrich & Knipping, *Sitz.ber. Bayer. Akademie d. Wiss.* 8. Juni 1912).



Blende Zns

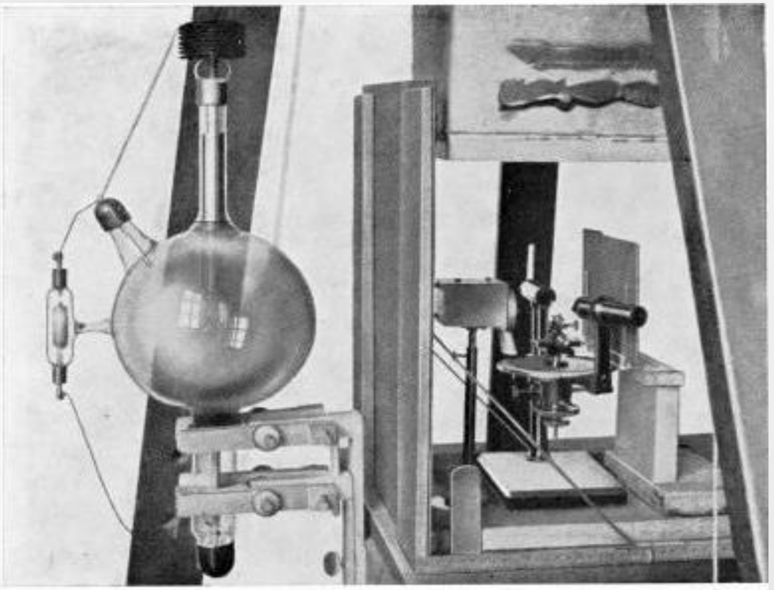
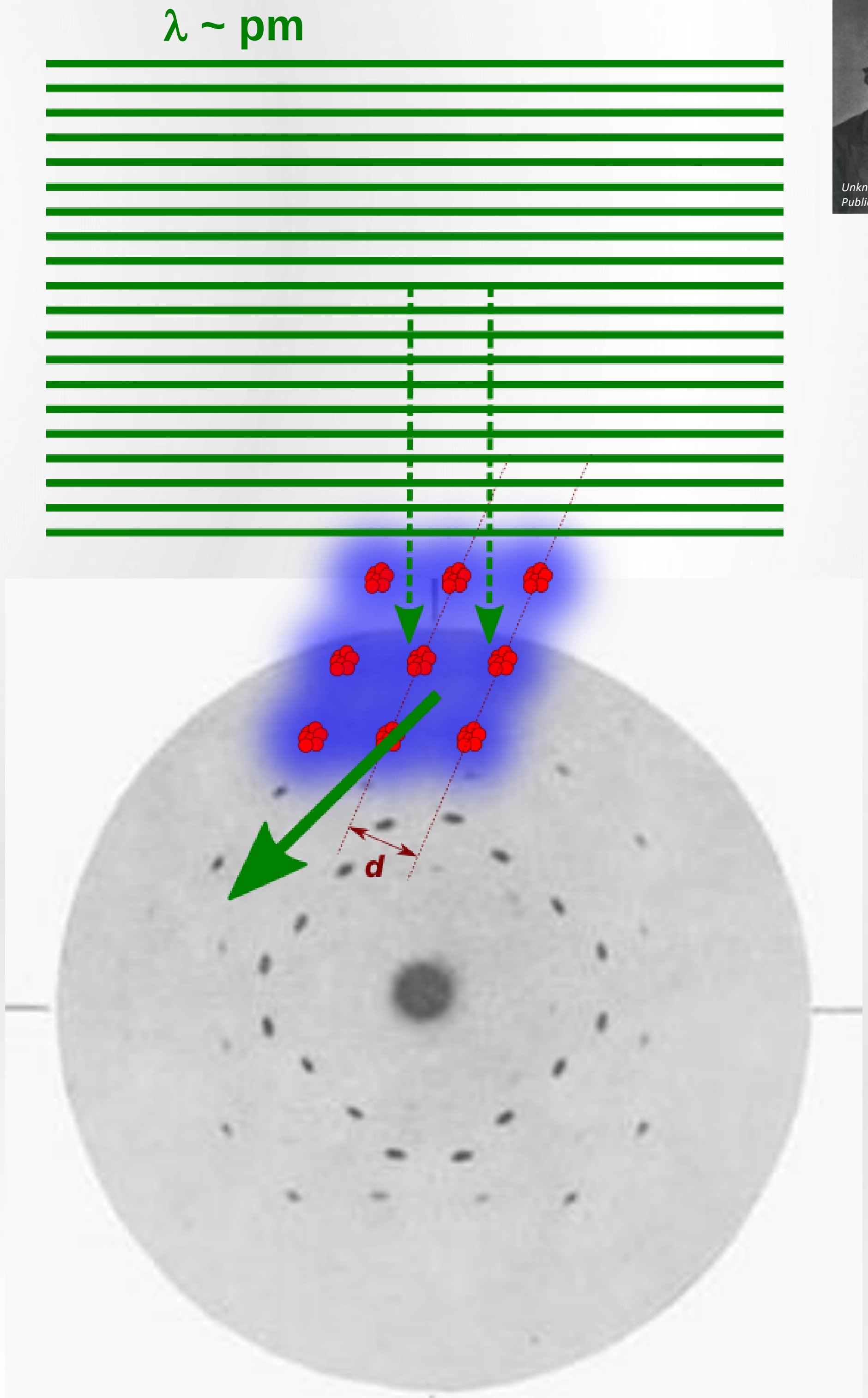


Fig. 4–4(2). Friedrich & Knipping's improved set-up.

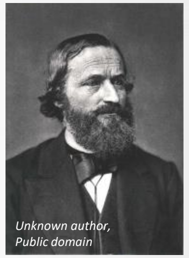
Ewald, P. P. Fifty Years of X-Ray Diffraction
Doi:10.1007/978-1-4615-9961-6.
https://www.iucr.org/publications/iucr/50yearsx

Wave description

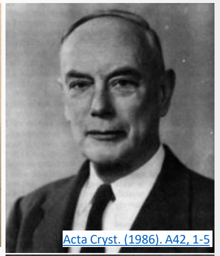
$$\Psi = Ae^{i\Phi}$$

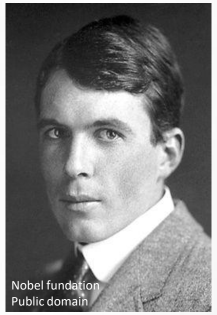


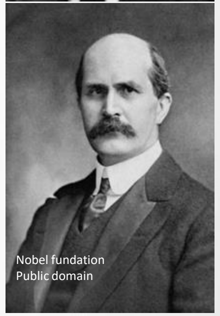
Blende Zns



1912



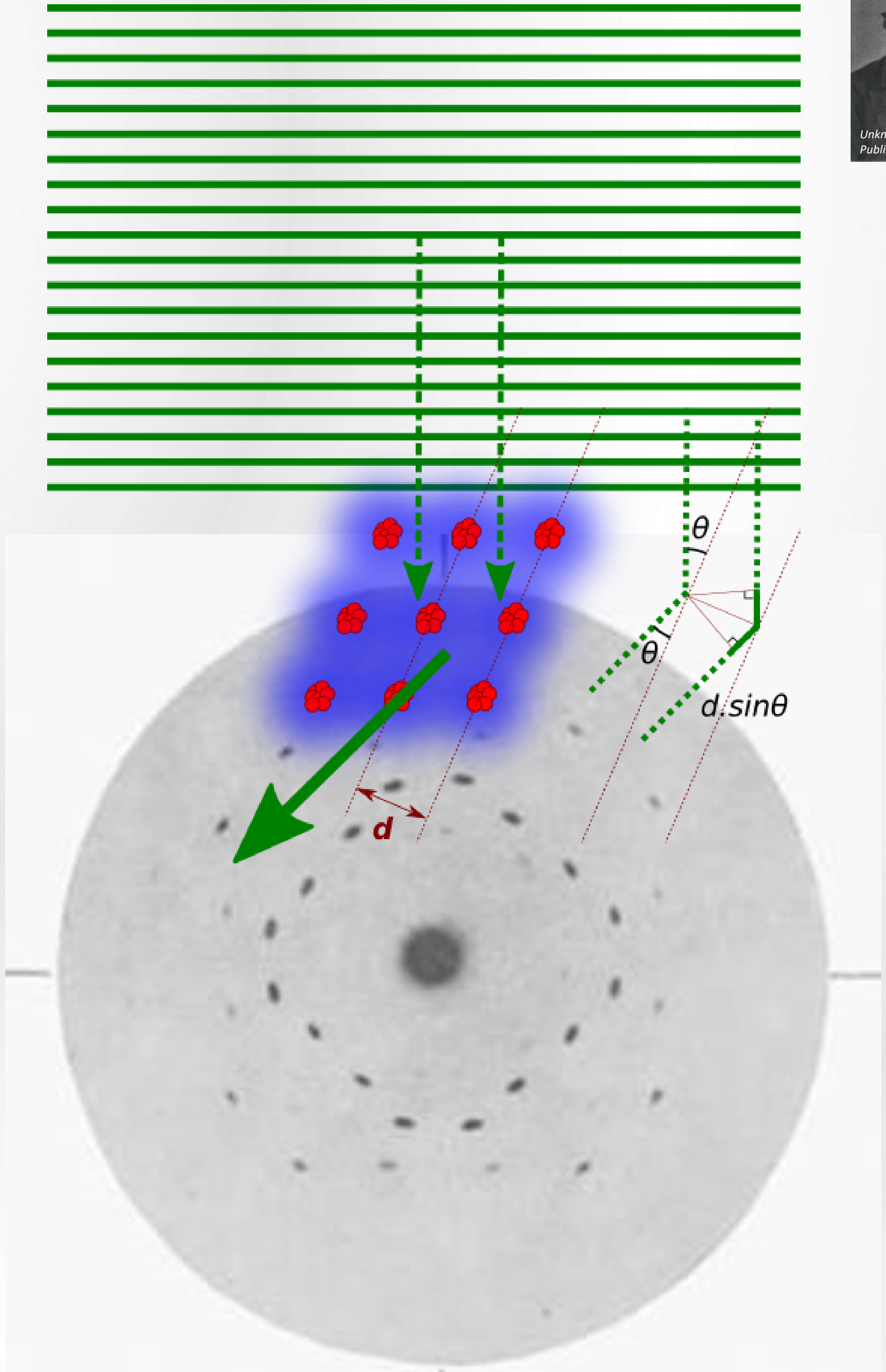




Wave description

$$\Psi = Ae^{i\Phi}$$

λ ~ pm



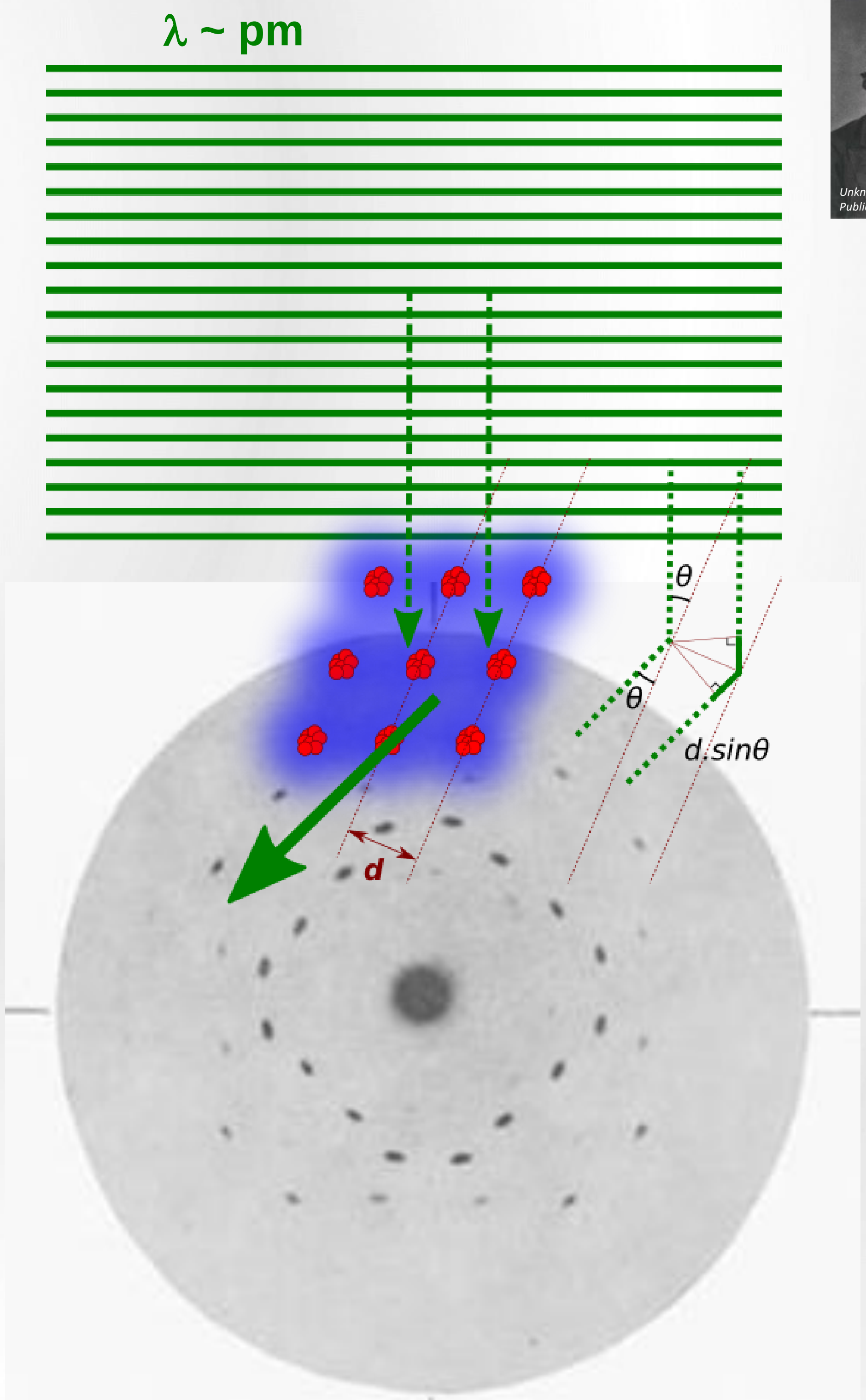
Blende Zns

1912

$$2d_{hkl} \cdot sin\theta = n \cdot \lambda$$

Wave description

$$\Psi = Ae^{i\Phi}$$



Blende Zns

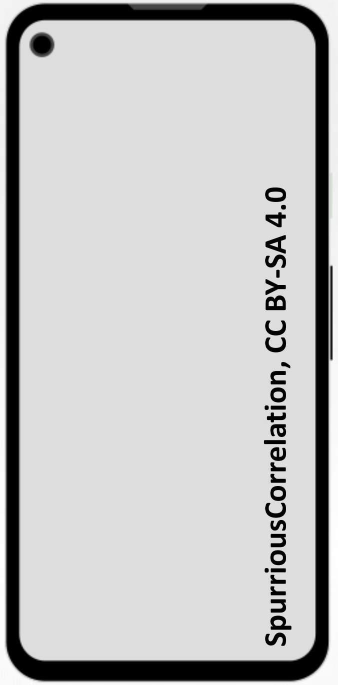
1912

Bragg's Law

$$2d_{hkl} \cdot sin\theta = n \cdot \lambda$$

Laue Conditions

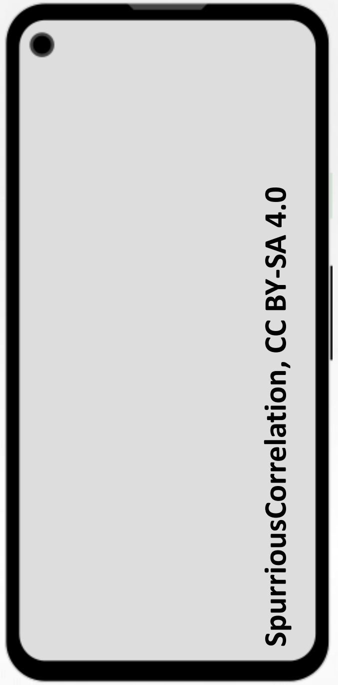
Interlude on diffraction



Google Pixel 4a

pixels per inch ?

Interlude on diffraction



Google Pixel 4a

pixels per inch ?

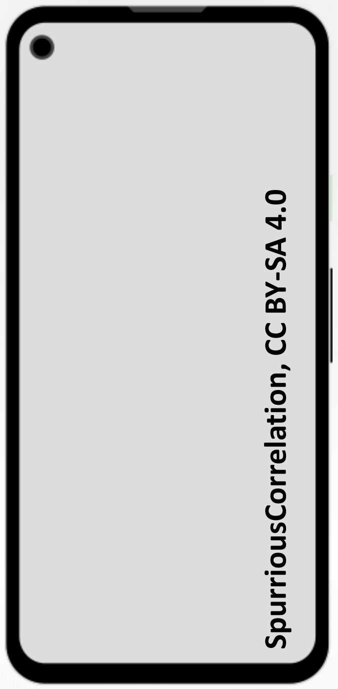
Caractéristiques :

Classe de laser :	3R (IIIa)
Puissance :	<5mW
Longueur d'onde :	532nm
Piles :	2 x AAA, (2 x 1.5V)
Boitier :	métallique
Portée :	plus de 2000 mètres

https://www.apinex.com/det/JLPS-20B.html

λ = 532 nm

Interlude on diffraction

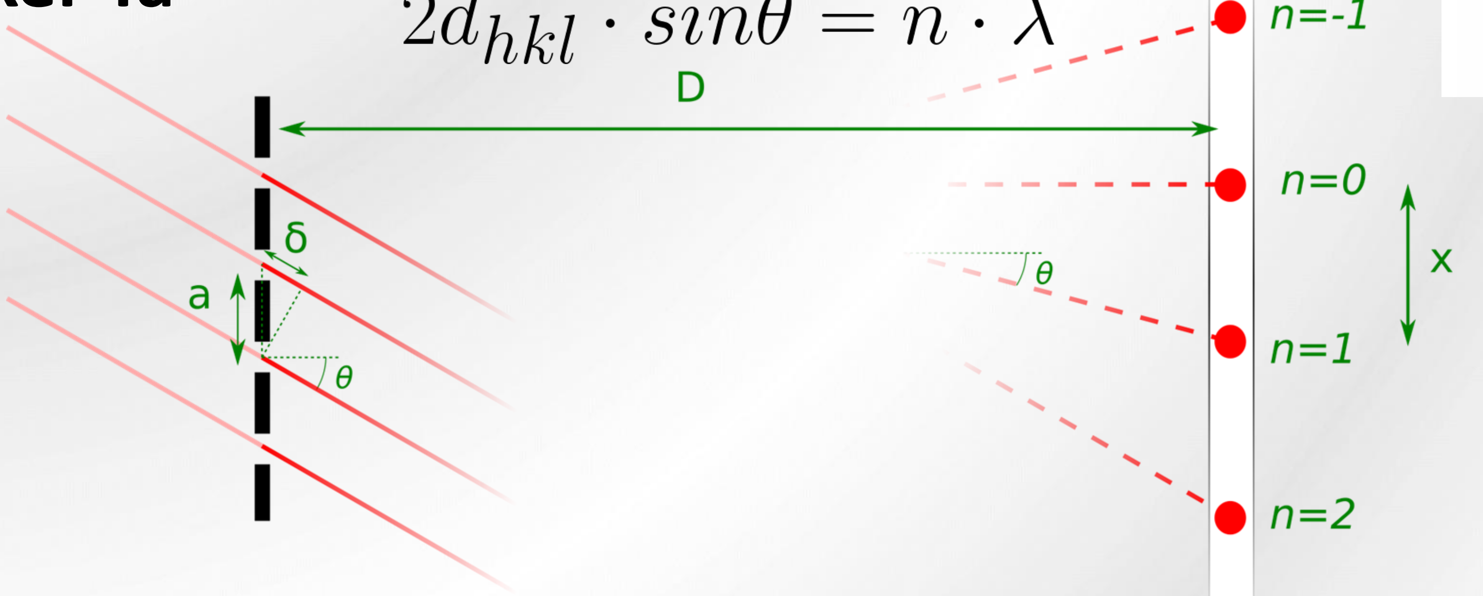


Google Pixel 4a

pixels per inch ?

Bragg's Law

$$2d_{hkl} \cdot sin\theta = n \cdot \lambda$$



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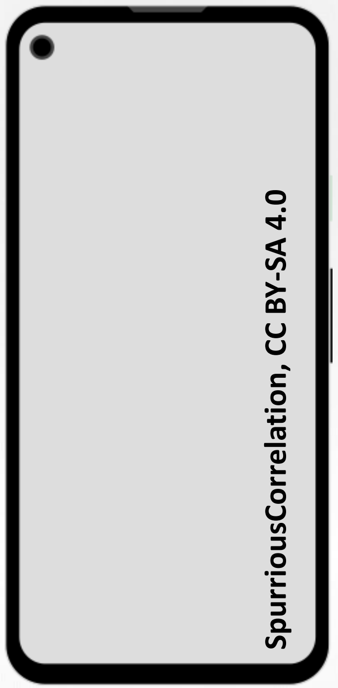
Interlude on diffraction



Google Pixel 4a

$$\delta = a \cdot sin\theta$$

$$\delta = \frac{a \cdot x}{D} = n \cdot \lambda$$

pixels per inch ?

Caractéristiques :

Classe de laser :	3R (IIIa)
Puissance :	<5mW
Longueur d'onde :	532nm
Piles :	2 x AAA, (2 x 1.5V)
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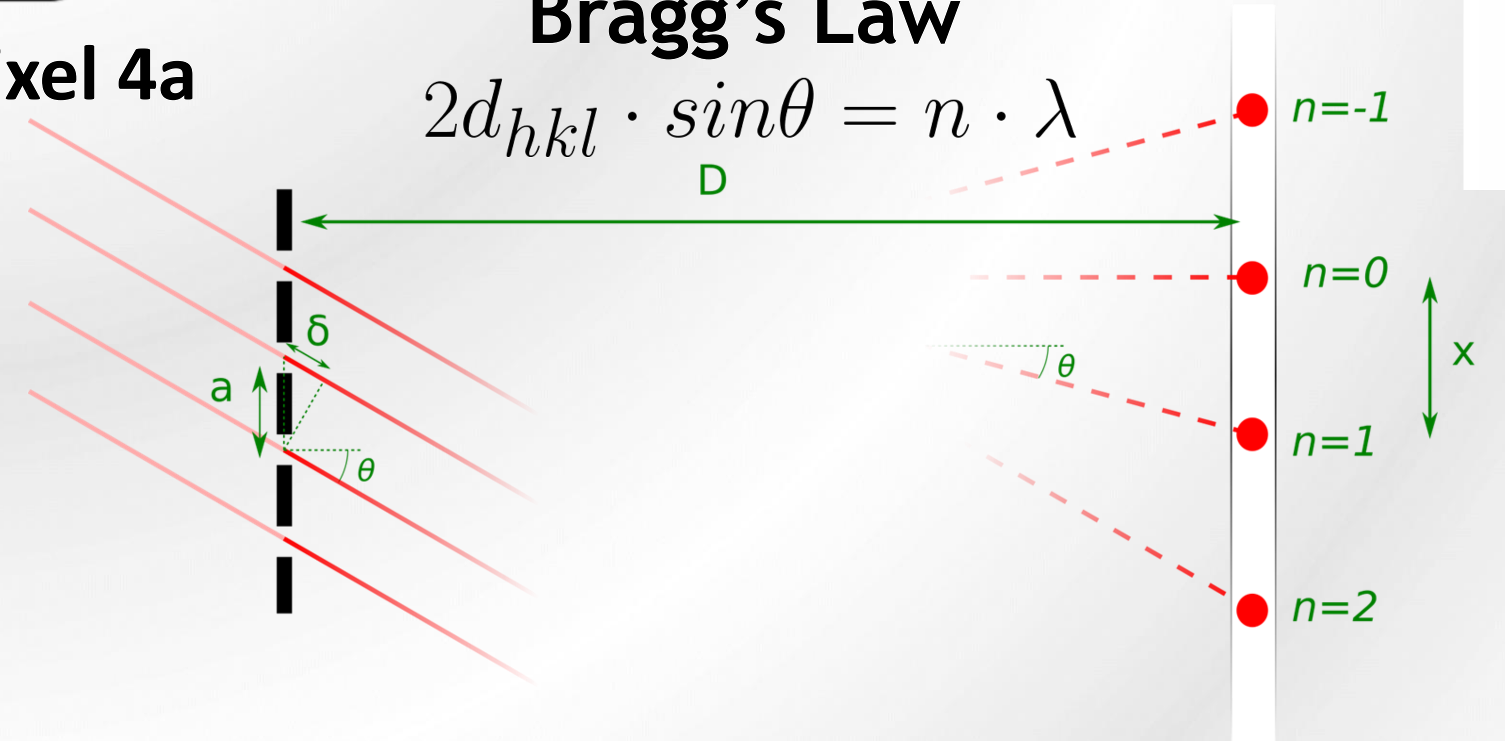
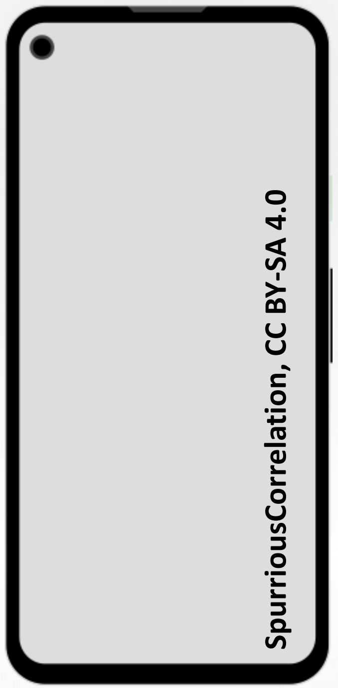
Bragg's Law

$$2d_{hkl} \cdot sin\theta = n \cdot \lambda$$



Interlude on diffraction



Google Pixel 4a

Display	FHD+ OLED, 2340 × 1080 resolution (19.5:9 aspect ratio) Gorilla Glass 3 **Pixel 4a**: 5.8 in (147.3 mm), 443 ppi

443 pixels per inch

Caractéristiques :

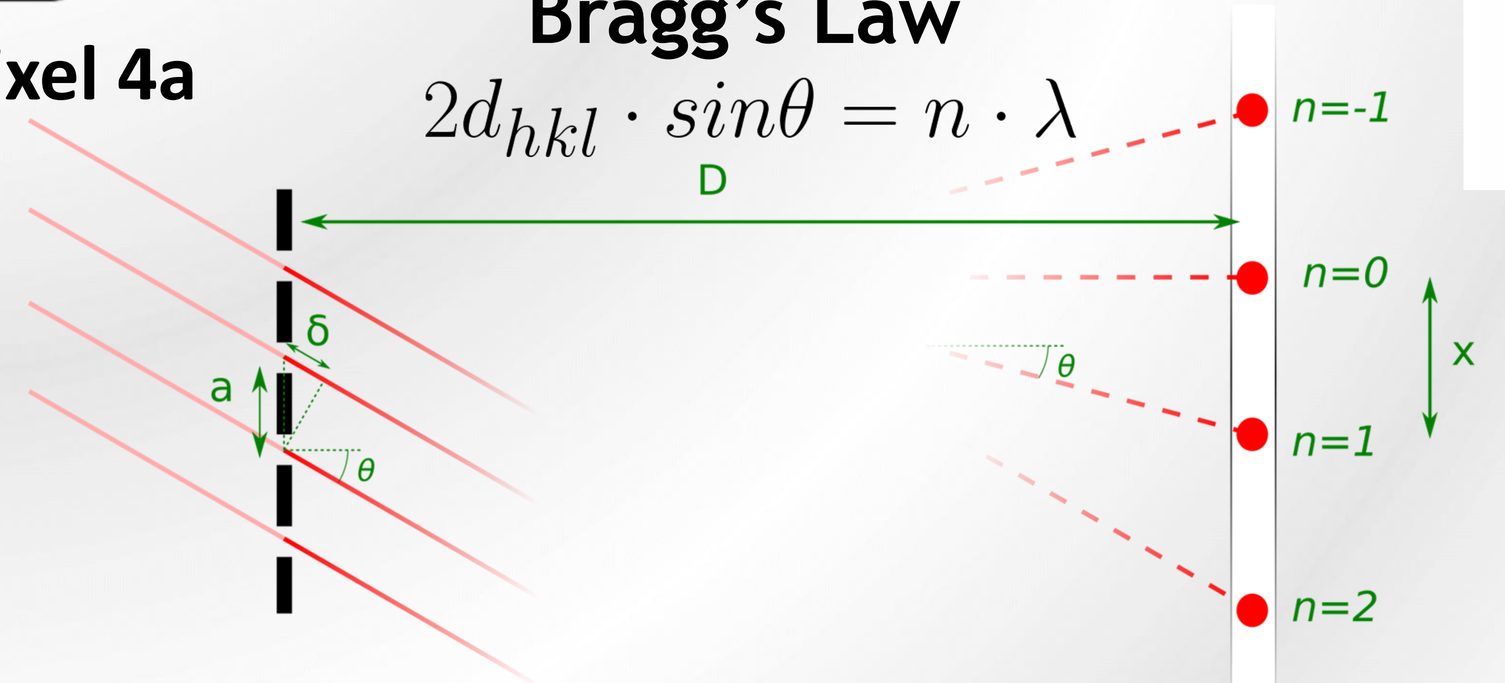
Classe de laser :	3R (IIIa)
Puissance :	<5mW
Longueur d'onde :	532nm
Piles :	2 x AAA, (2 x 1.5V)
Boitier :	métallique
Portée :	plus de 2000 mètres

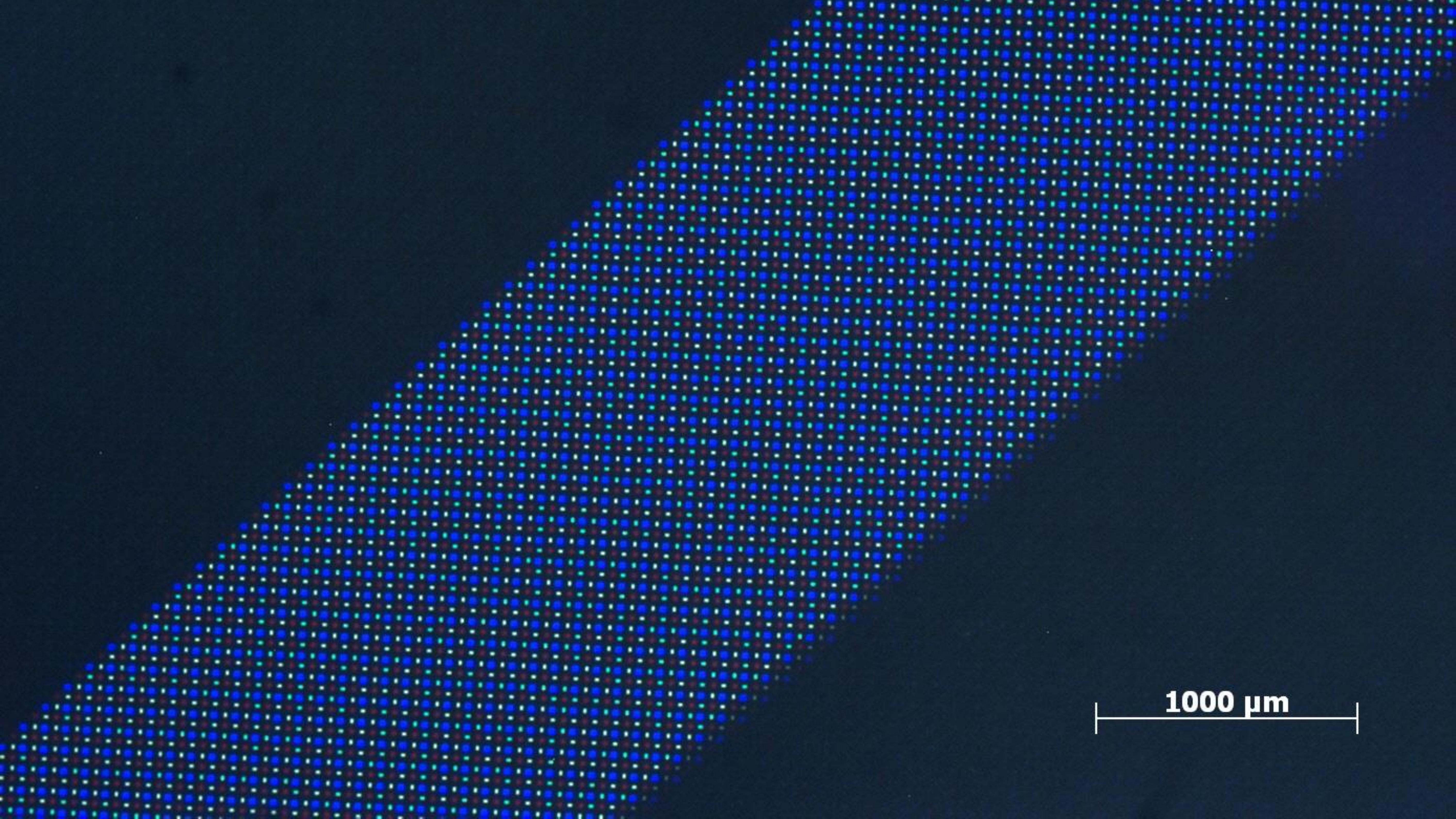
https://www.apinex.com/det/JLPS-20B.html

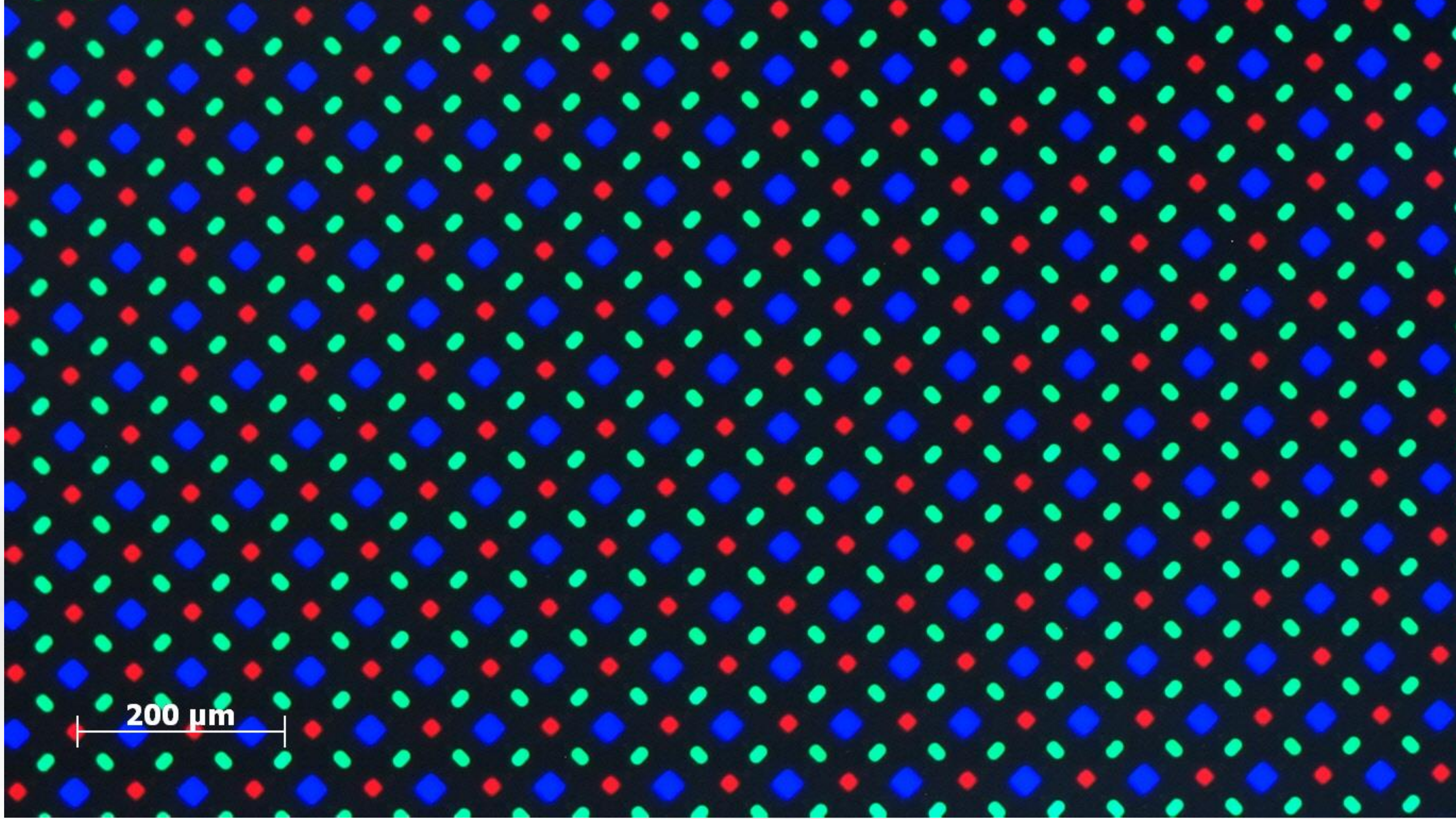
λ = 532 nm

Bragg's Law

$$2d_{hkl} \cdot sin\theta = n \cdot \lambda$$

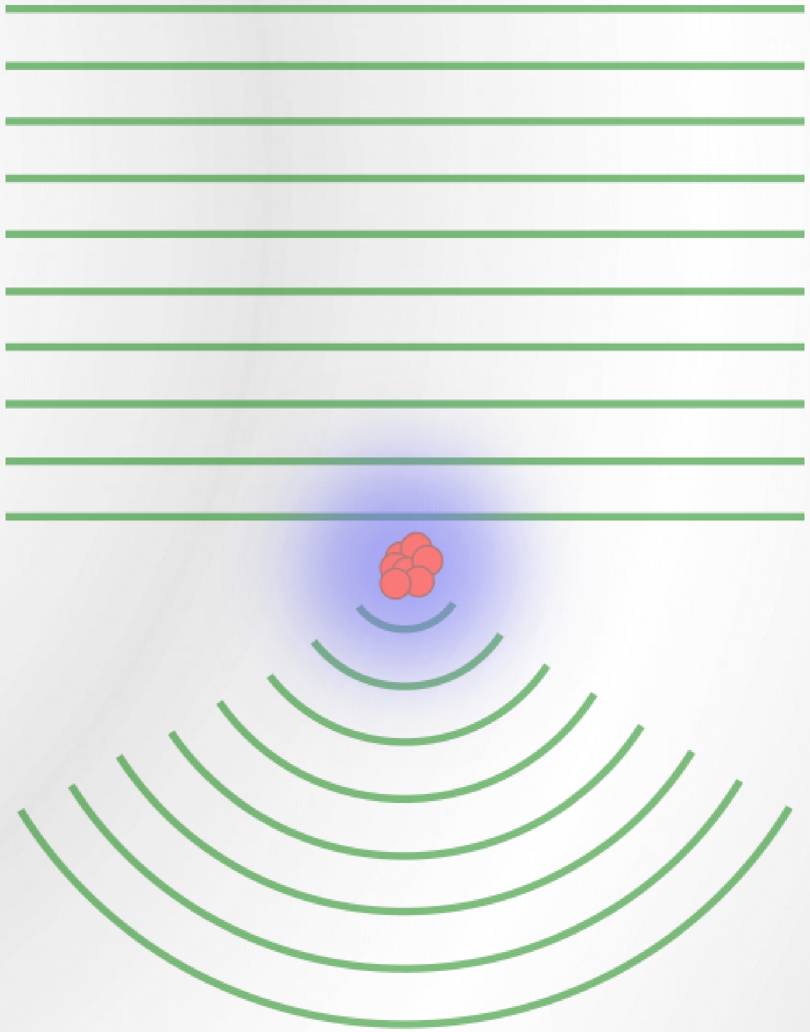



1000 µm


200 µm

Wave description

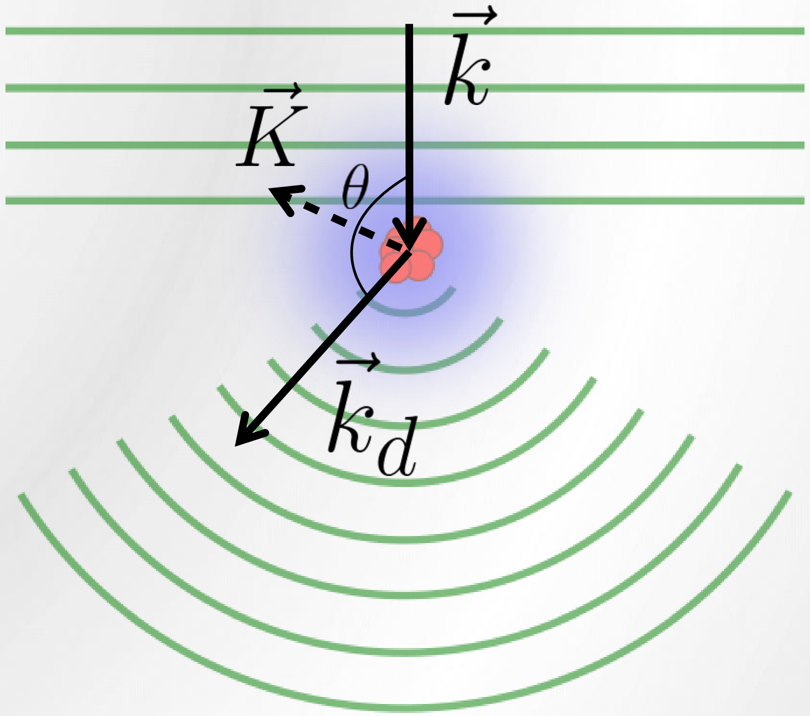
λ ~ pm



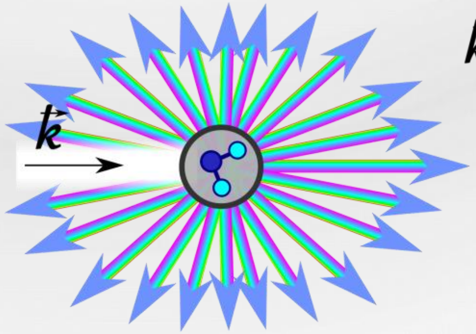
$$\|\vec{k}\| = \frac{2\pi}{\lambda}$$

Wave description

λ ~ pm



$$\|\vec{k}\| = \frac{2\pi}{\lambda}$$

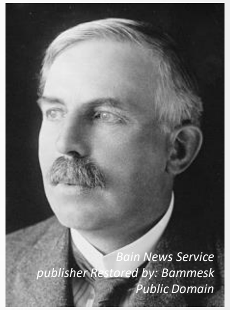


$\vec{k}_d \propto 1/\lambda^4$

Rayleigh Diffusion

Wave description

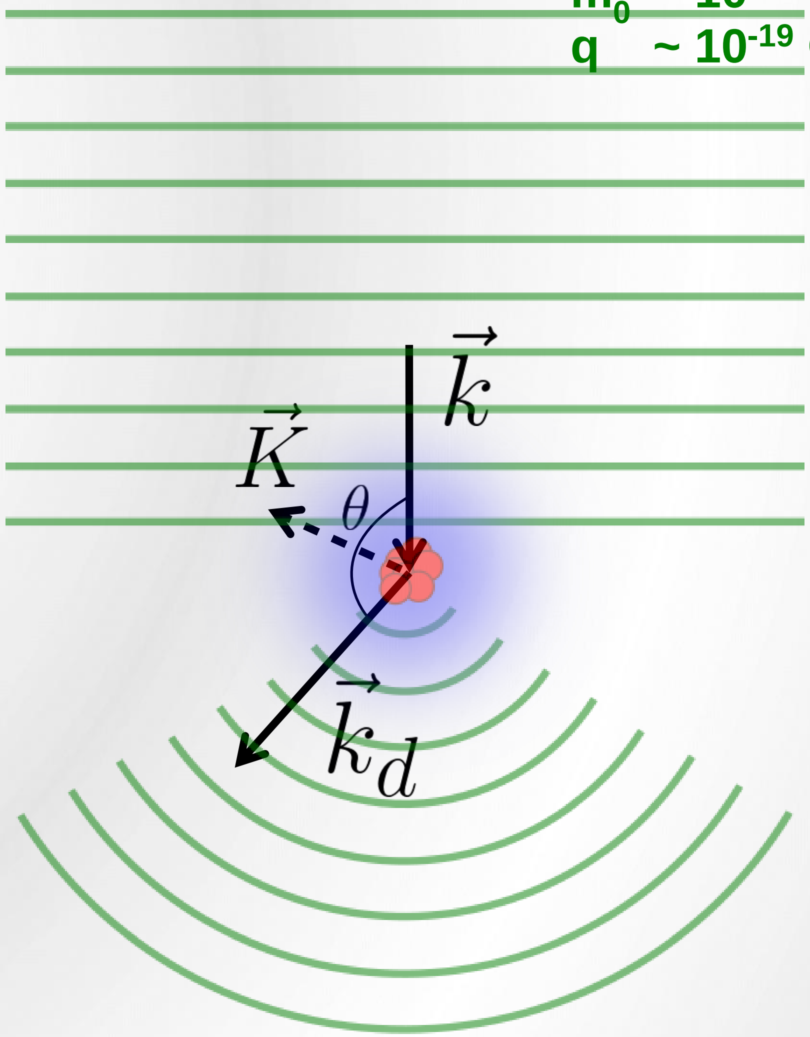
Particle description

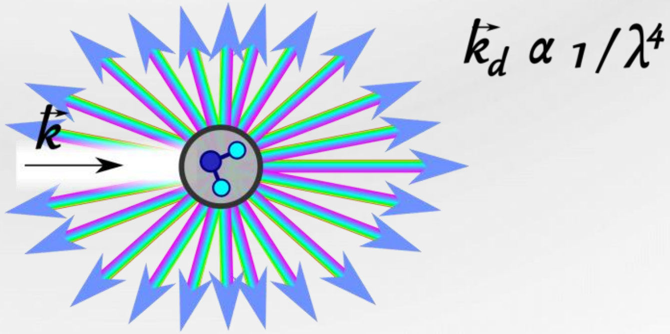


$\lambda \sim$ pm

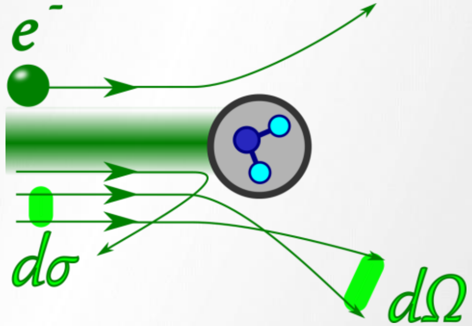
$m_0 \sim 10^{-30}$ kg

$q \sim 10^{-19}$ C





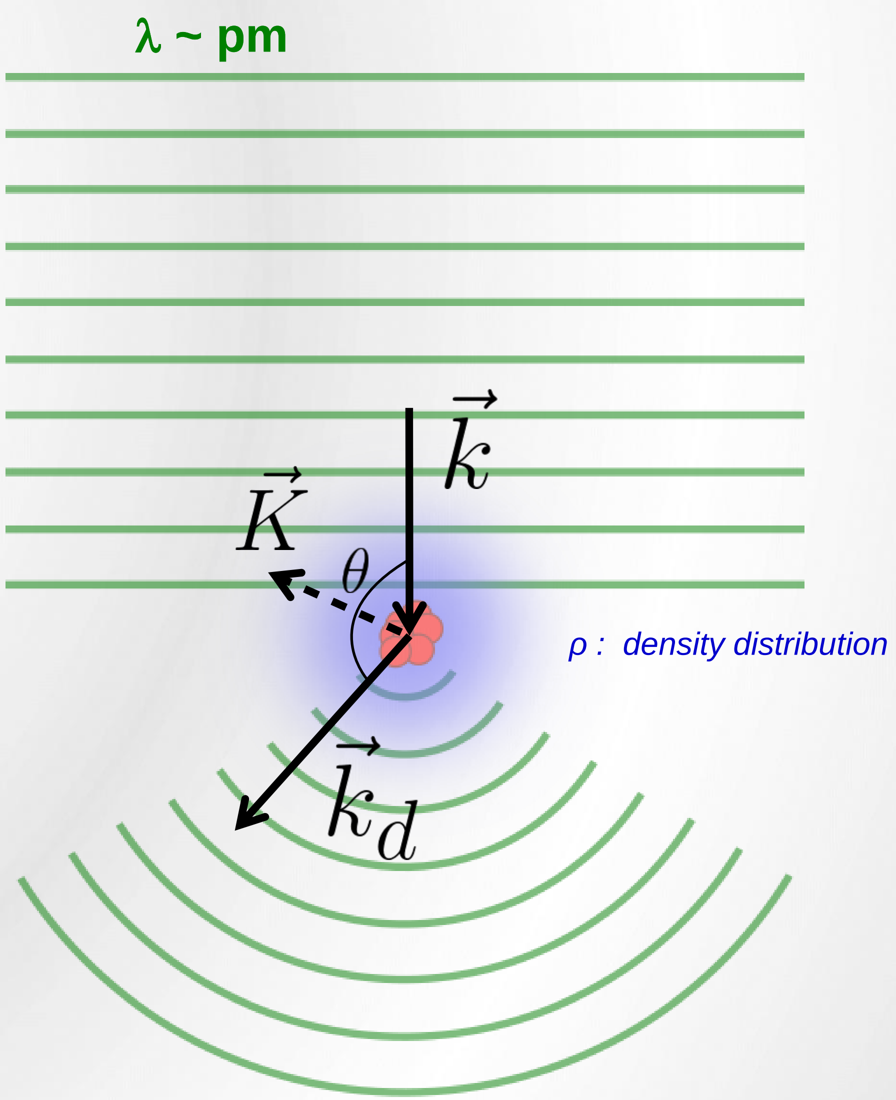
$$\|\vec{k}\| = \frac{2\pi}{\lambda}$$



Rayleigh Diffusion

Rutherford Diffusion

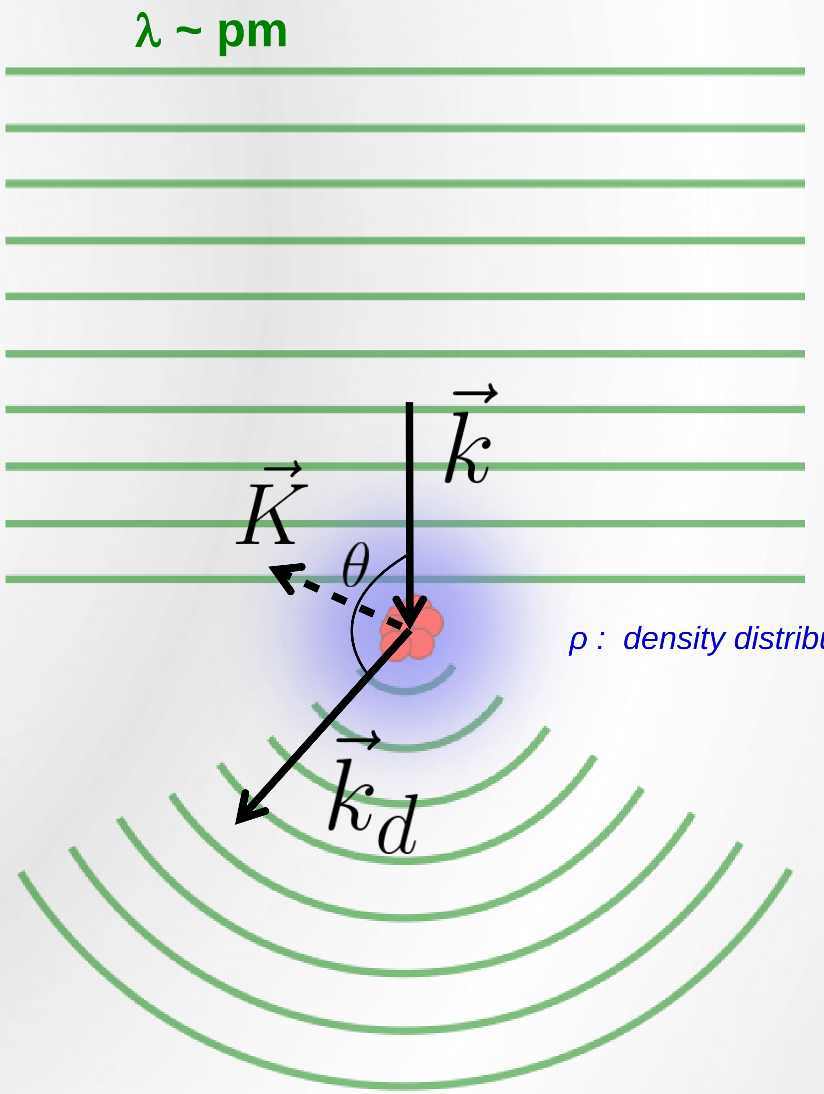
Wave description



$$f(\vec{K}) = \int_\infty \rho(\vec{r}) e^{i\vec{K}\cdot\vec{r}} d\vec{r}$$

Wave description

$$f(\vec{K}) = \int_{\infty} \rho(\vec{r}) e^{i\vec{K}\cdot\vec{r}} d\vec{r}$$

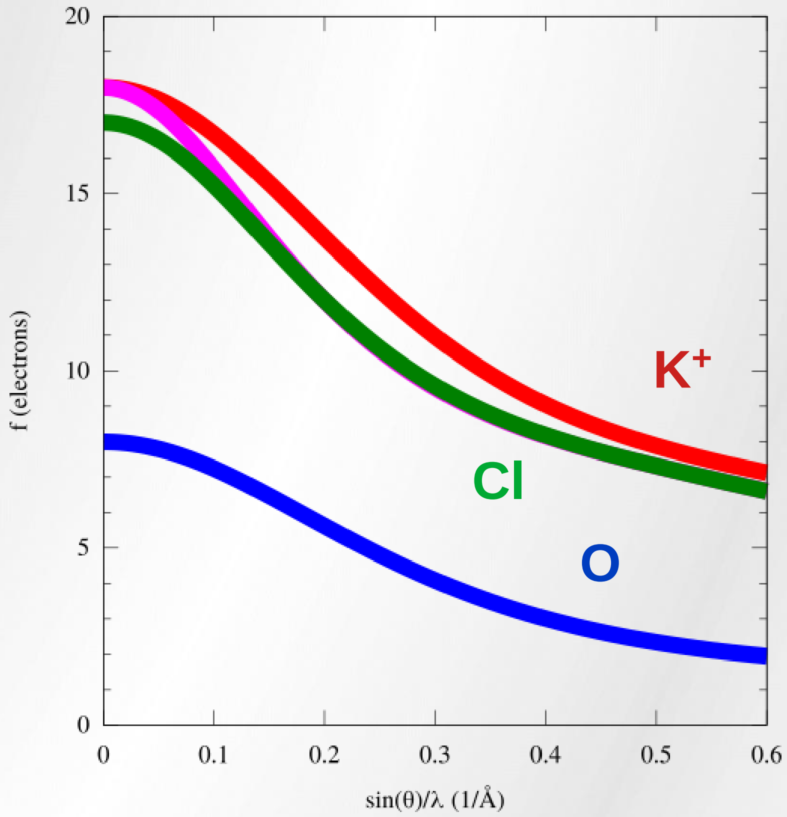


ρ : density distribution

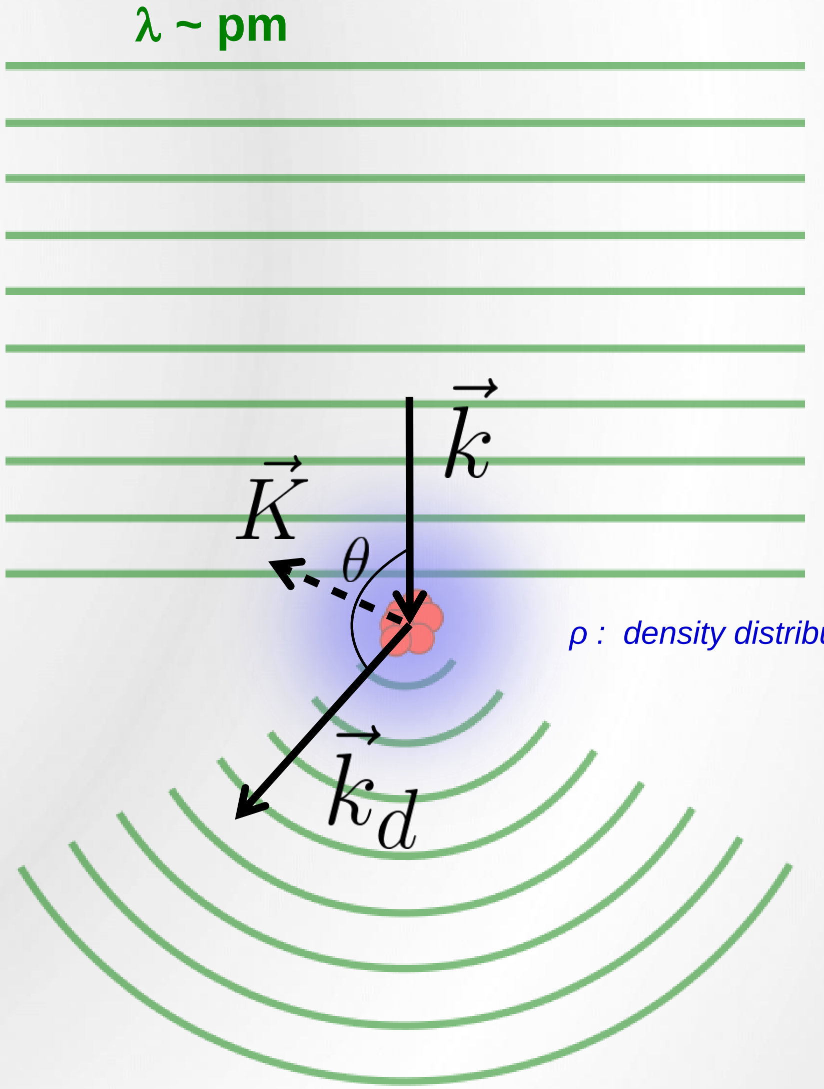
$$\boldsymbol{FT}\,[\rho]$$

$$f(q) = \int_{\infty} f(x) e^{-i2\pi qx} dx$$

Atomic Form Factor



<u>**Wave description**</u>



ρ : *density distribution*

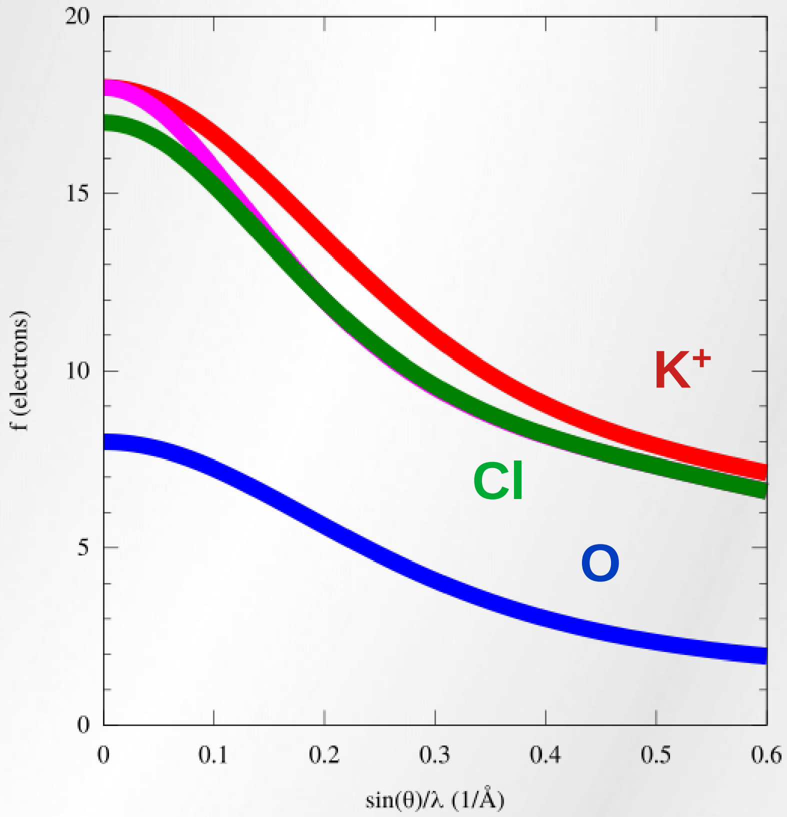
$$f(\vec{K}) = \int_{\infty} \rho(\vec{r}) e^{i\vec{K}\cdot\vec{r}} d\vec{r}$$

$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

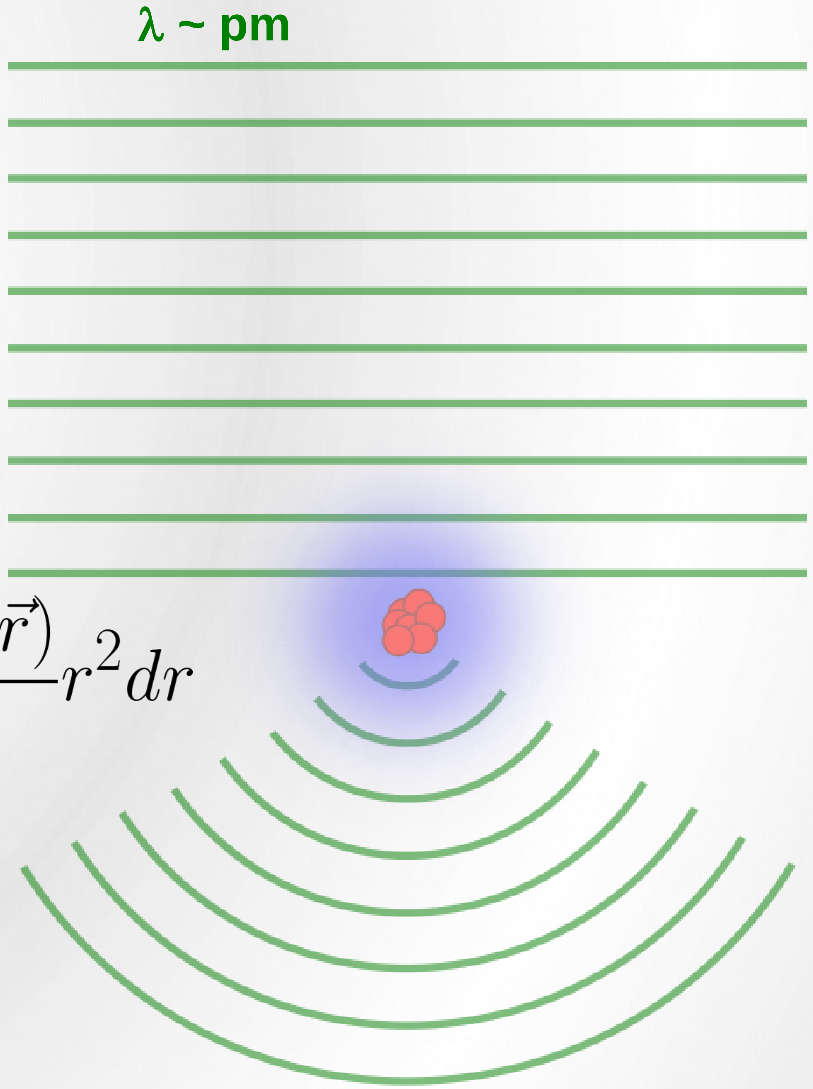
$$\boldsymbol{FT}\,[\rho]$$

$$f(q) = \int_{\infty} f(x) e^{-i2\pi qx} dx$$

Atomic Form Factor



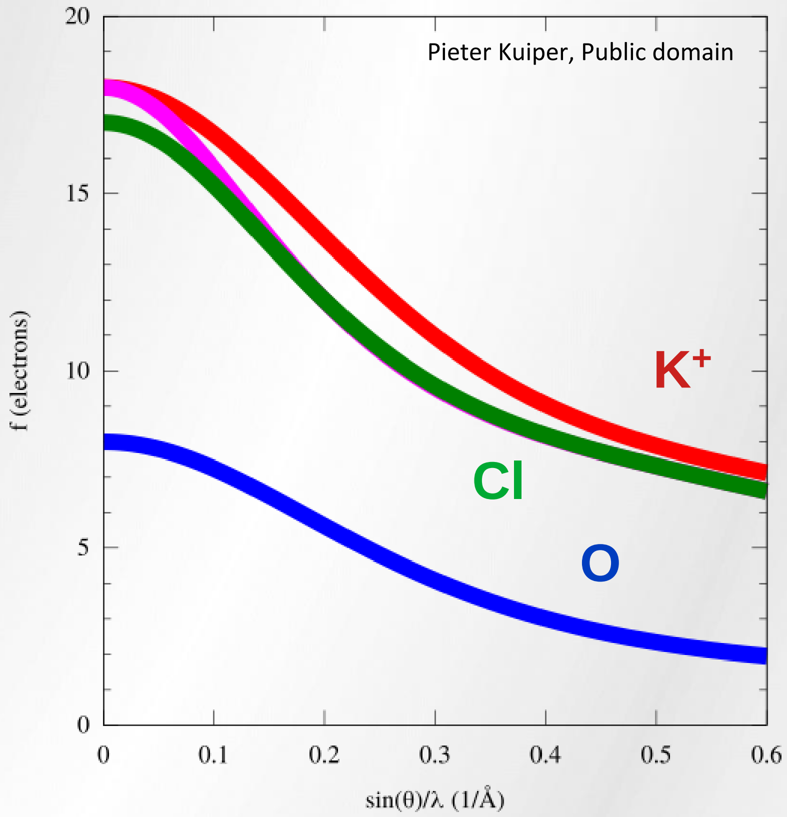
Wave description



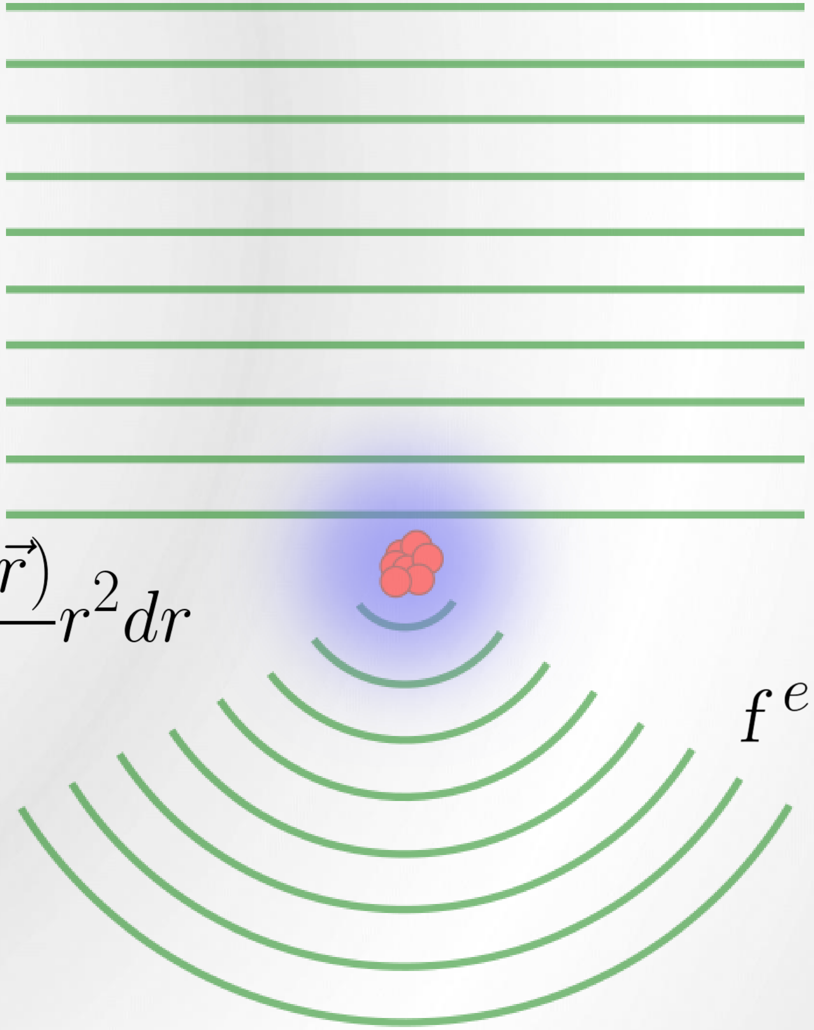
$$f^X(\vec{K}) = 4\pi \int_0^\infty \rho(\vec{r}) \frac{sin(\vec{K}\cdot\vec{r})}{\vec{K}\cdot\vec{r}} r^2 dr$$

$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d \cdot \vec{r}}$$

Atomic Form Factor



Wave description $\lambda \sim$ pm $q \sim 10^{-19}$ C **Particle description**



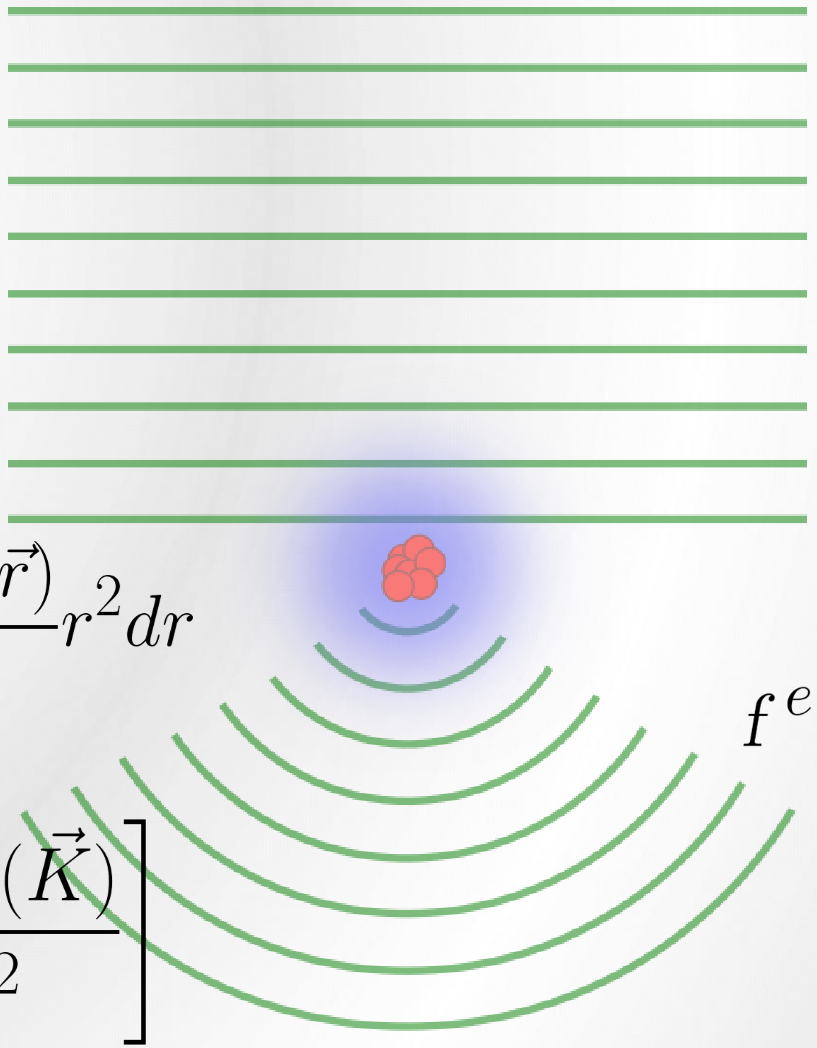
$$f^{X}(\vec{K}) = 4\pi \int_{0}^{\infty} \rho(\vec{r}) \frac{sin(\vec{K}\cdot\vec{r})}{\vec{K}\cdot\vec{r}} r^2 dr$$

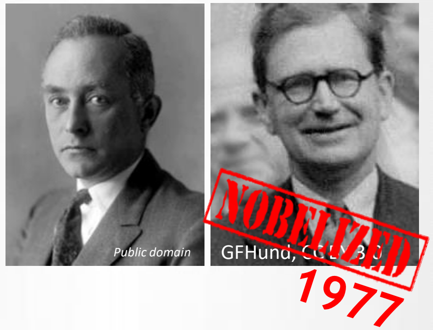
Atomic Form Factor

$$f^{e}(\vec{K}) = \frac{2me}{\hbar^2} \int_{0}^{\infty} V(\vec{r}) \frac{sin(\vec{K}\cdot\vec{r})}{\vec{K}\cdot\vec{r}} r^2 dr$$

$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

Wave description $\lambda \sim$ pm q $\sim 10^{-19}$ C **Particle description**





$$f^{X}(\vec{K}) = 4\pi \int_{0}^{\infty} \rho(\vec{r}) \frac{sin(\vec{K}\cdot\vec{r})}{\vec{K}\cdot\vec{r}} r^2 dr$$

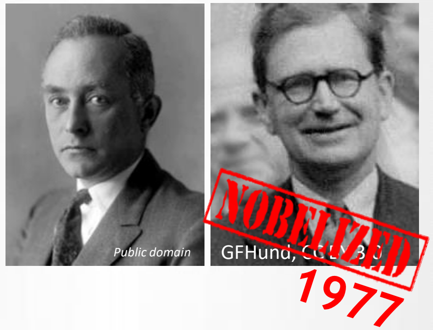
Atomic Form Factor

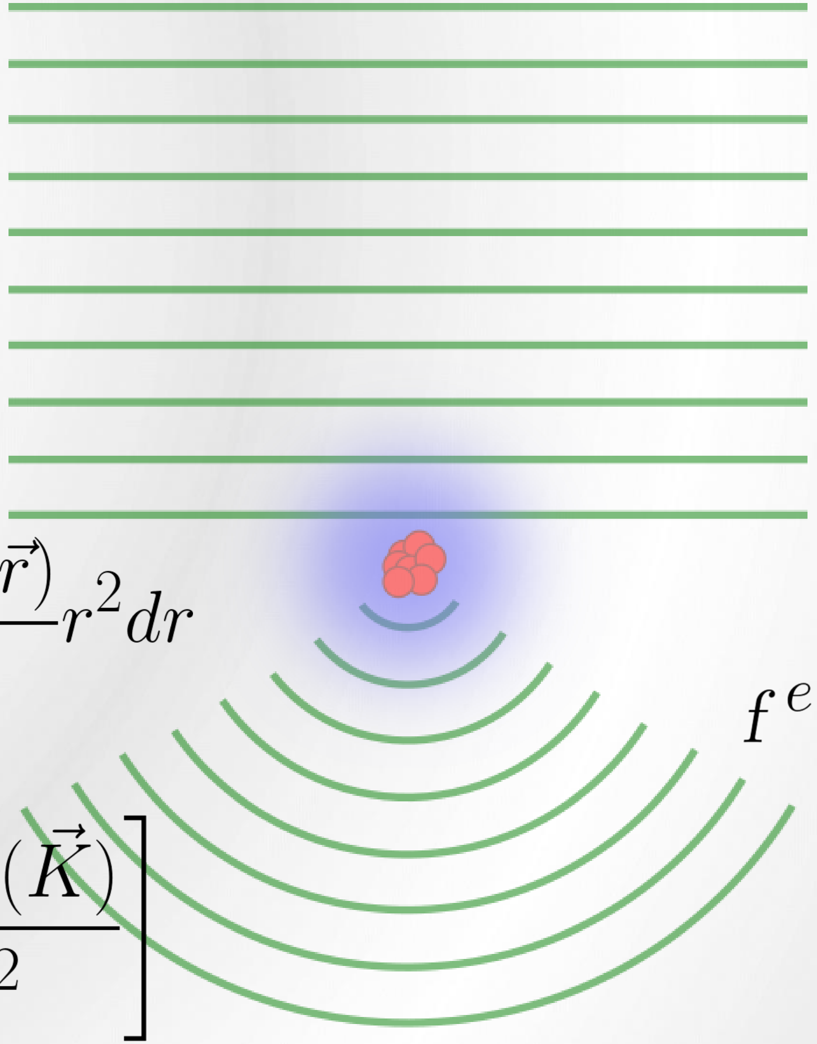
$$f^{e}(\vec{K}) = \frac{2me}{\hbar^2} \int_{0}^{\infty} V(\vec{r}) \frac{sin(\vec{K}\cdot\vec{r})}{\vec{K}\cdot\vec{r}} r^2 dr$$

$$f^{e}(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^{X}(\vec{K})}{\|\vec{K}\|^2}\right]$$

$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

Wave description $\lambda \sim$ pm   q $\sim 10^{-19}$ C **Particle description**





$$f^{X}(\vec{K}) = 4\pi \int_{0}^{\infty} \rho(\vec{r}) \frac{sin(\vec{K}\cdot\vec{r})}{\vec{K}\cdot\vec{r}} r^2 dr$$

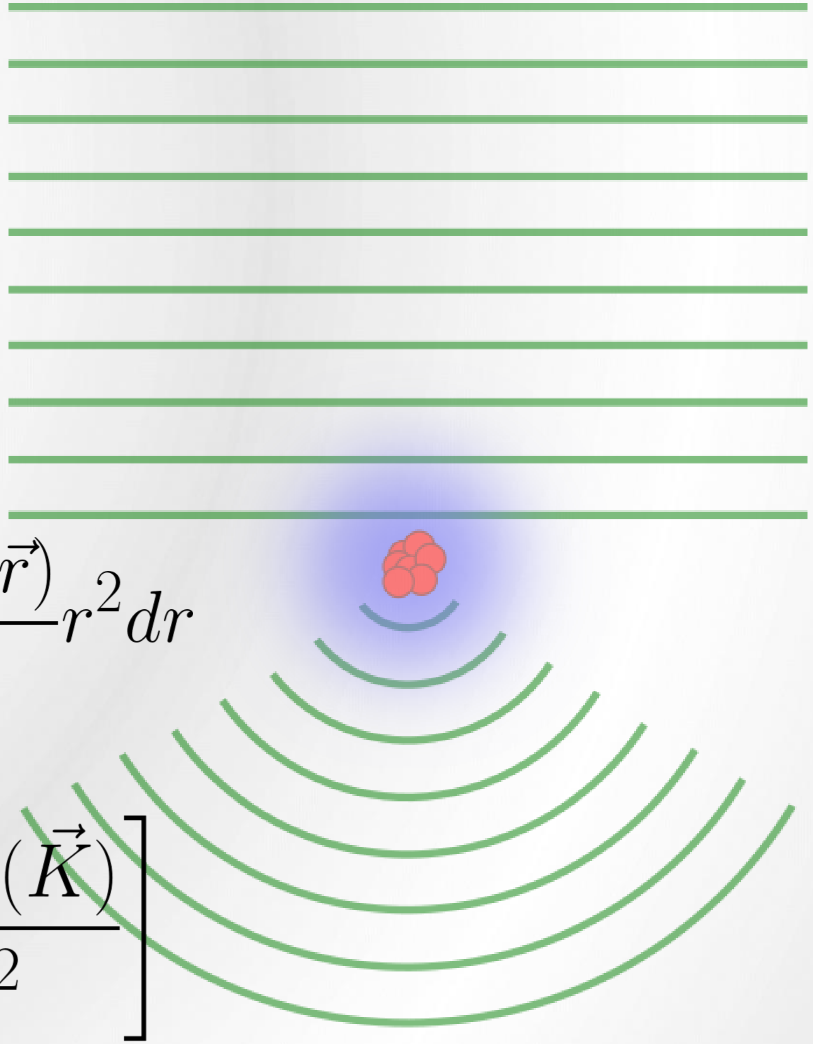
Atomic Form Factor

$$f^{e}(\vec{K}) = \frac{2me}{\hbar^2} \int_{0}^{\infty} V(\vec{r}) \frac{sin(\vec{K}\cdot\vec{r})}{\vec{K}\cdot\vec{r}} r^2 dr$$

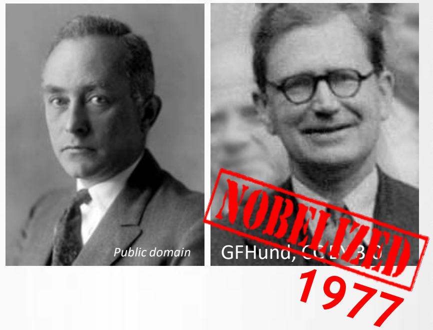
$$f^{e}(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^{X}(\vec{K})}{\|\vec{K}\|^2}\right]$$

$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

Wave description



Particle description



Atomic Form Factor

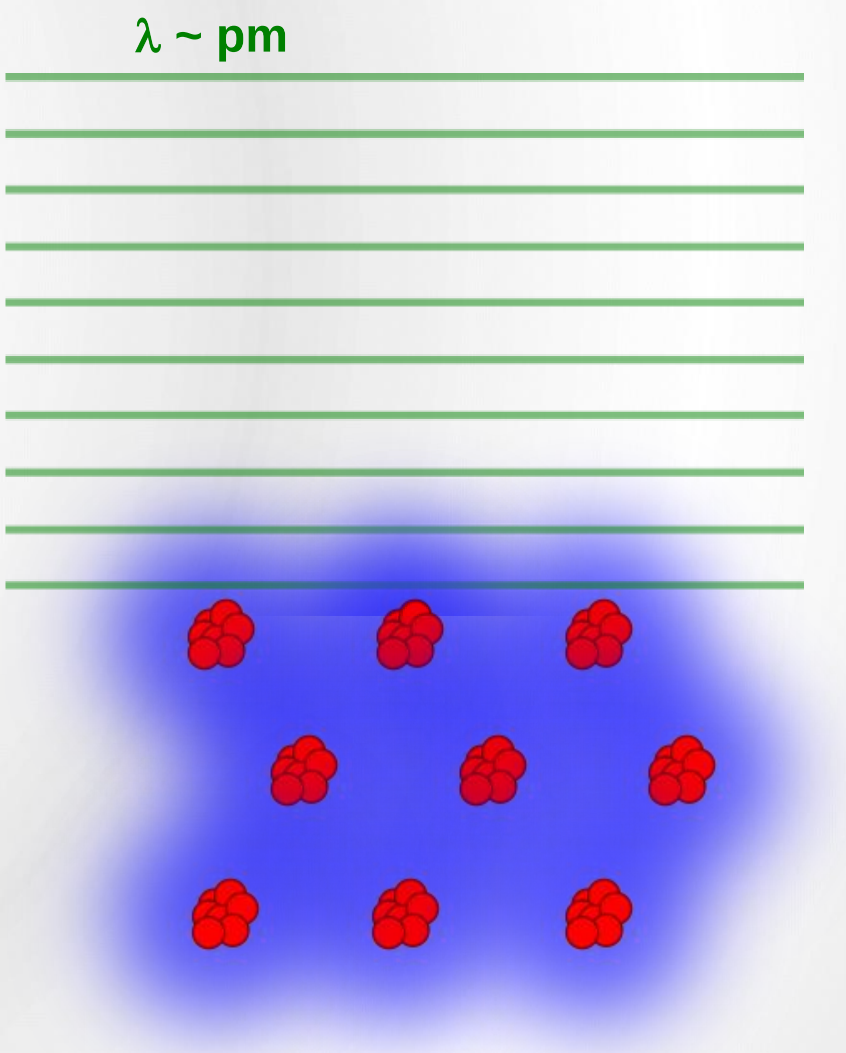
$$f^X(\vec{K}) = 4\pi \int_0^\infty \rho(\vec{r}) \frac{sin(\vec{K}\cdot\vec{r})}{\vec{K}\cdot\vec{r}} r^2 dr$$

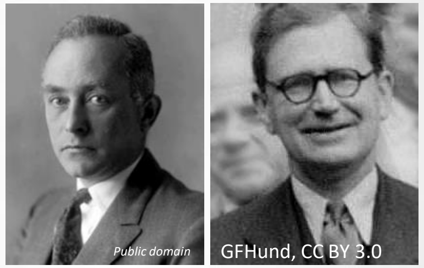
$$f^e(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^X(\vec{K})}{\|\vec{K}\|^2}\right]$$

$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

Wave description



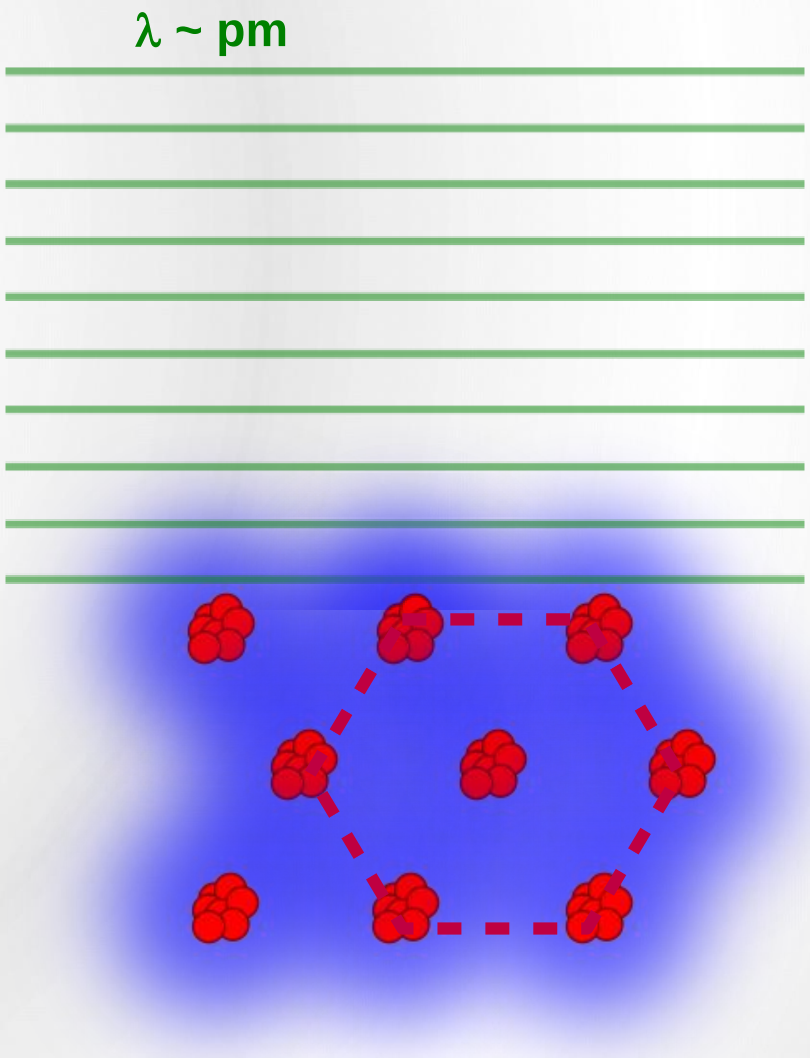


Atomic Form Factor

$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d \cdot \vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

Wave description



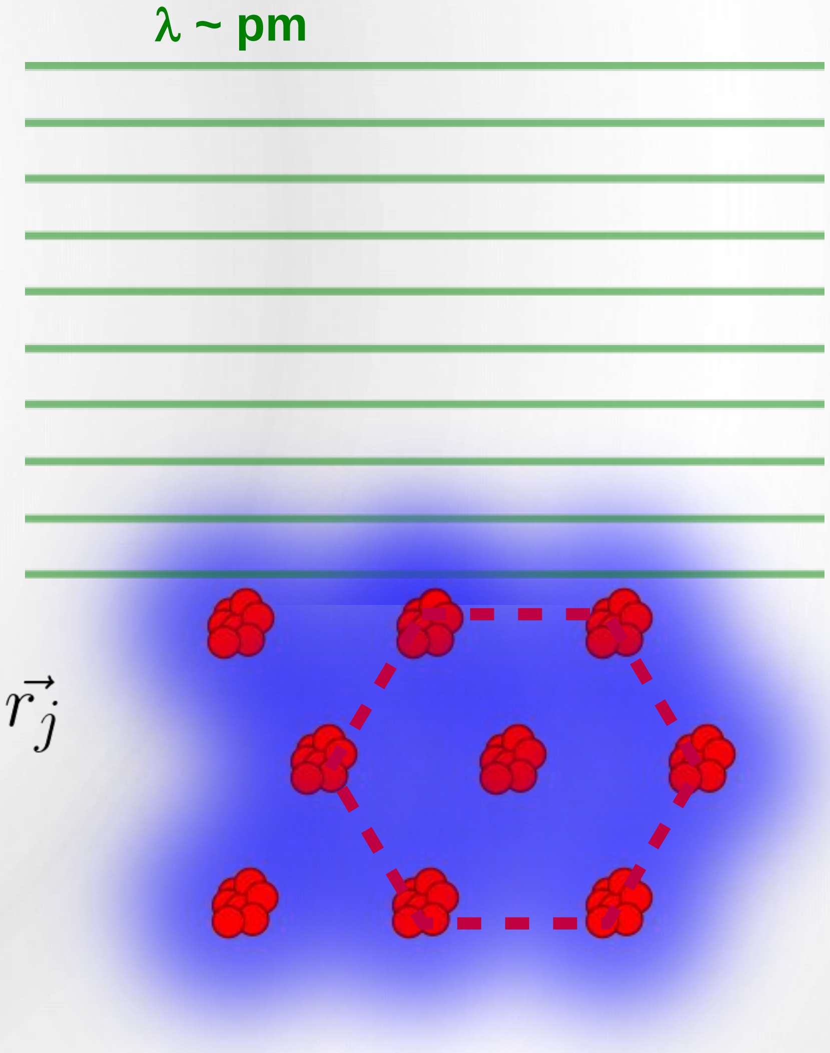
Atomic Form Factor

$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d \cdot \vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

$$\Psi = \sum_{mesh} \sum \Psi_d$$

Wave description



$$f(\vec{K}) = \int_{\infty} \rho(\vec{r}) e^{i\vec{K}\cdot\vec{r}} d\vec{r}$$

$$F(\vec{K}) = \sum_{j=1}^{n} f_j e^{i2\pi\vec{K}\cdot\vec{r_j}}$$

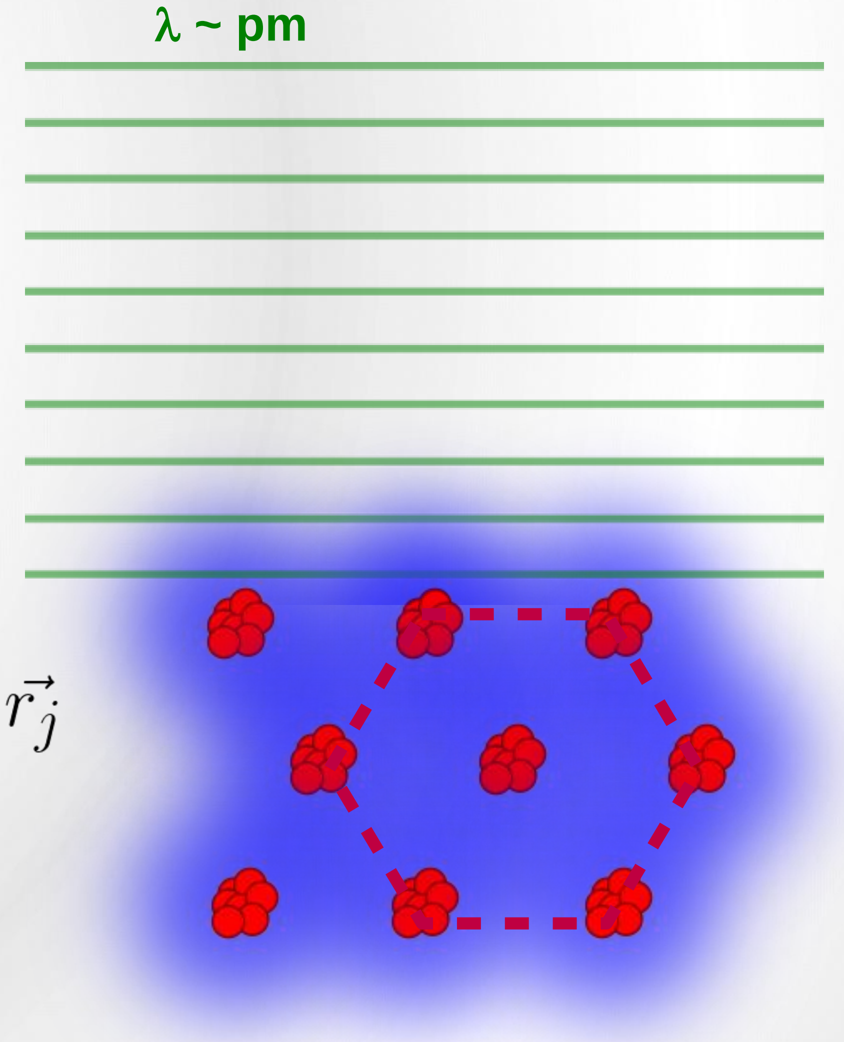
Structure Factor

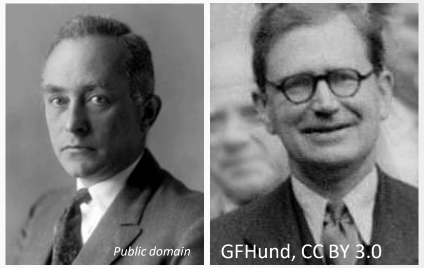
$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

$$\Psi = \sum_{mesh} \sum \Psi_d$$

Wave description





$$f(\vec{K}) = \int_{\infty} \rho(\vec{r}) e^{i\vec{K}\cdot\vec{r}} d\vec{r}$$

$$F(\vec{K}) = \sum_{j=1}^{n} f_j e^{i2\pi\vec{K}\cdot\vec{r}_j}$$

Structure Factor

$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

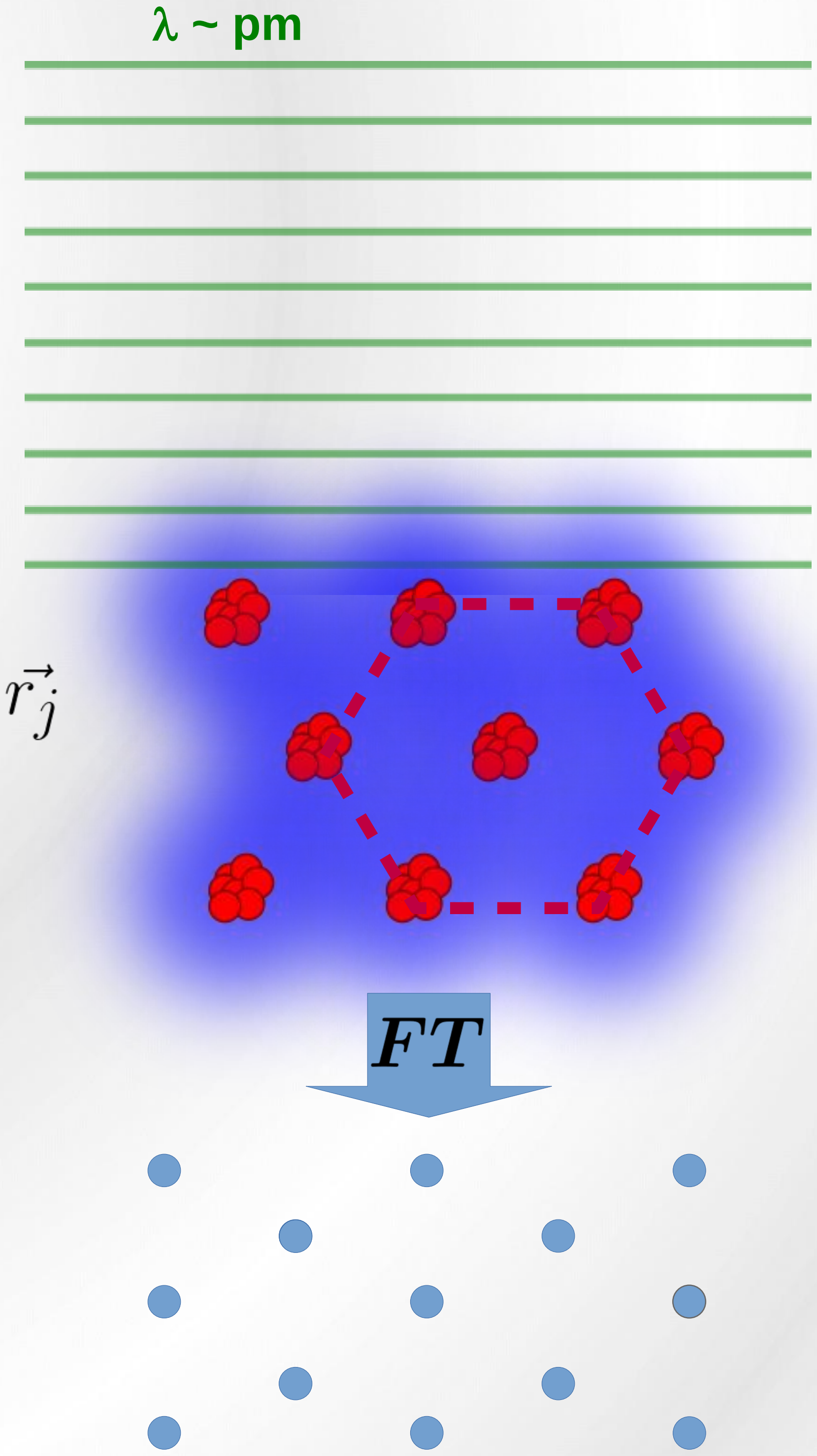
$$\Psi_{atom} = \sum \Psi_d$$

$$\Psi = \sum_{mesh} \sum \Psi_d$$

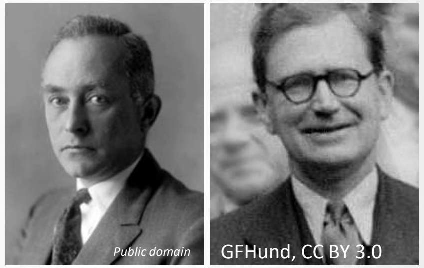
Wave description

$$f(\vec{K}) = \int_{\infty} \rho(\vec{r}) e^{i\vec{K}\cdot\vec{r}} d\vec{r}$$

$$F(\vec{K}) = \sum_{j=1}^{n} f_j e^{i2\pi\vec{K}\cdot\vec{r}_j}$$

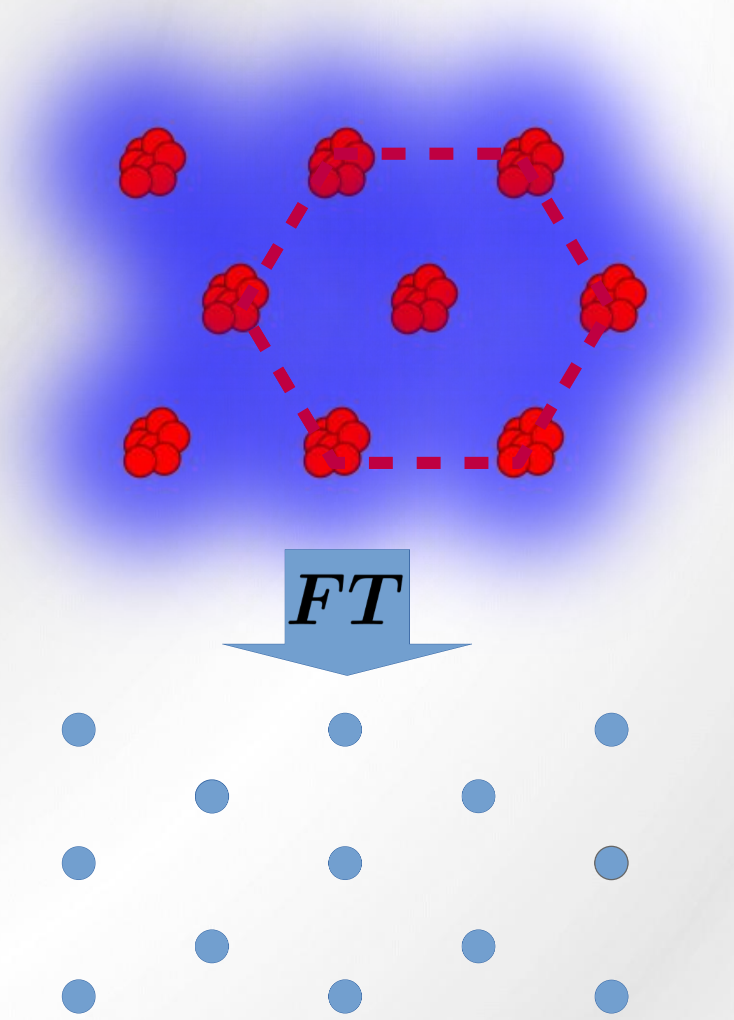



Julien-Léopold Boilly, Public domain



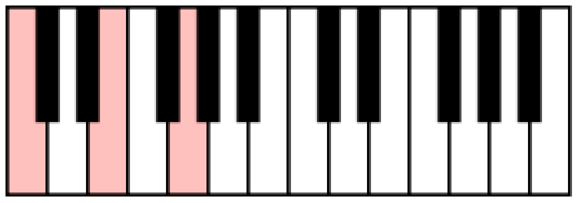
Reciprocal Lattice

Interlude on Reciprocal Space (k- or q- space)



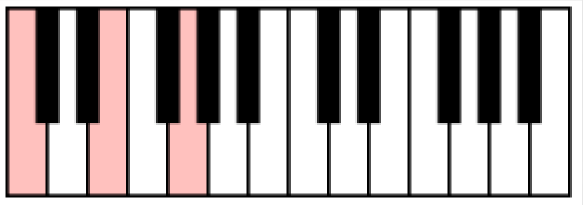
Interlude on Reciprocal Space (k- or q- space)

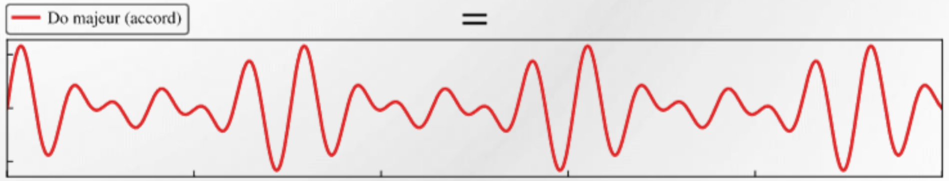
C major



Interlude on Reciprocal Space (k- or q- space)

C major

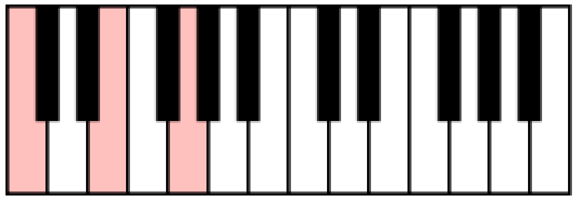


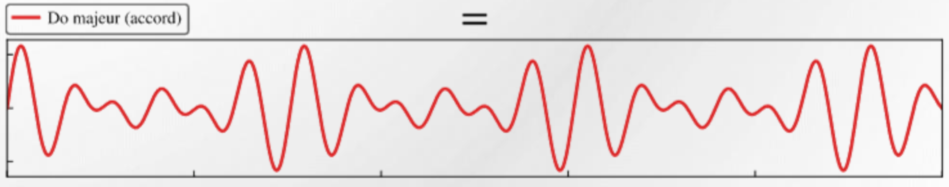


Time scale

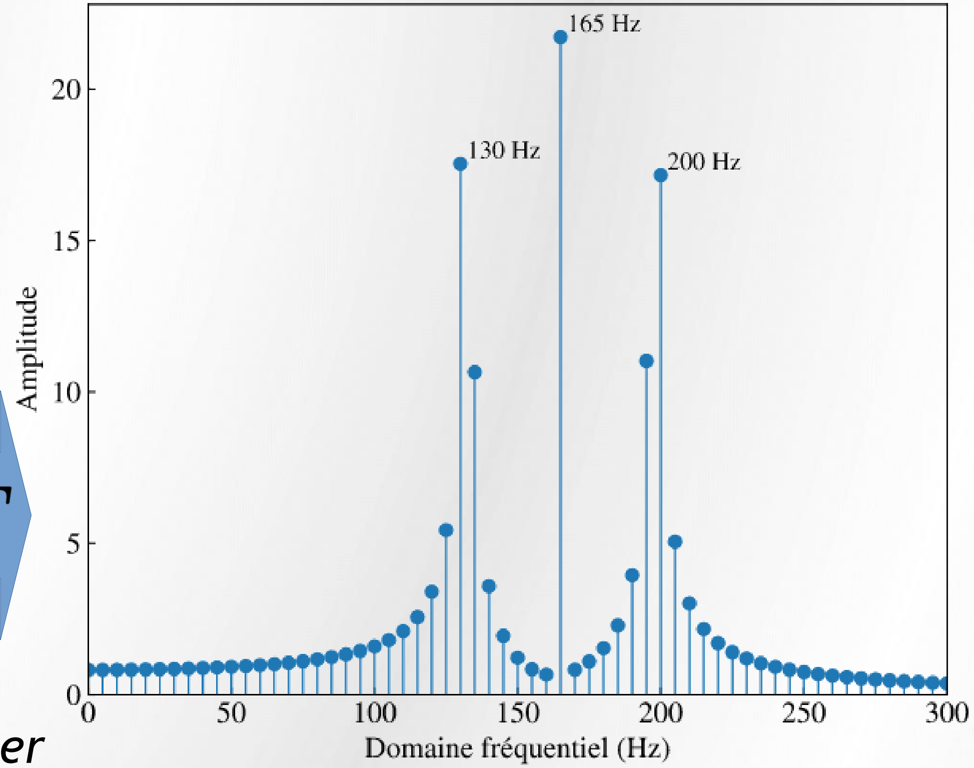
Interlude on Reciprocal Space (k- or q- space)

C major





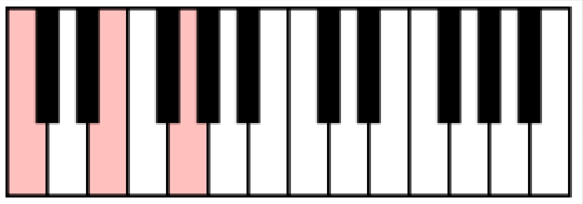
Fourier Transform

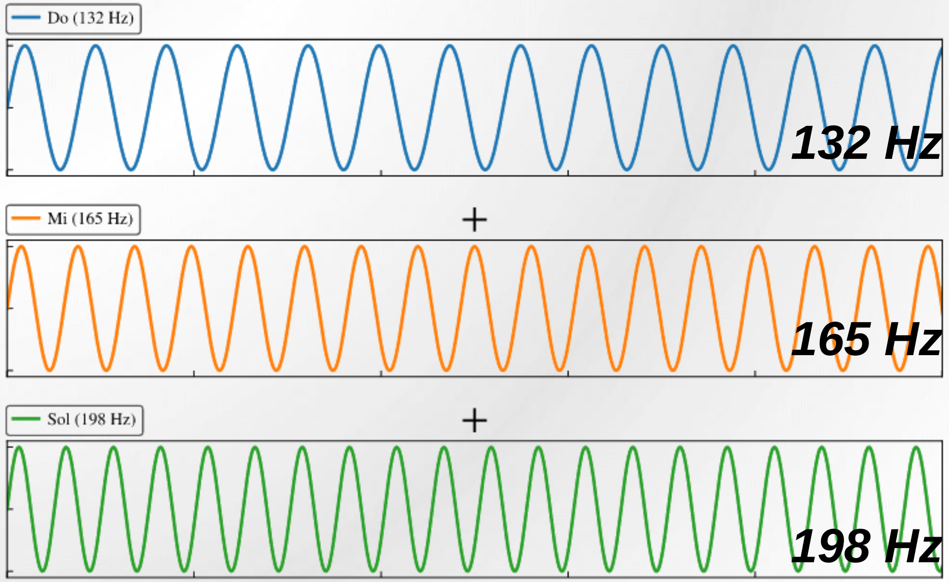


Time scale ⬬ ⬬ *Frequential scale*

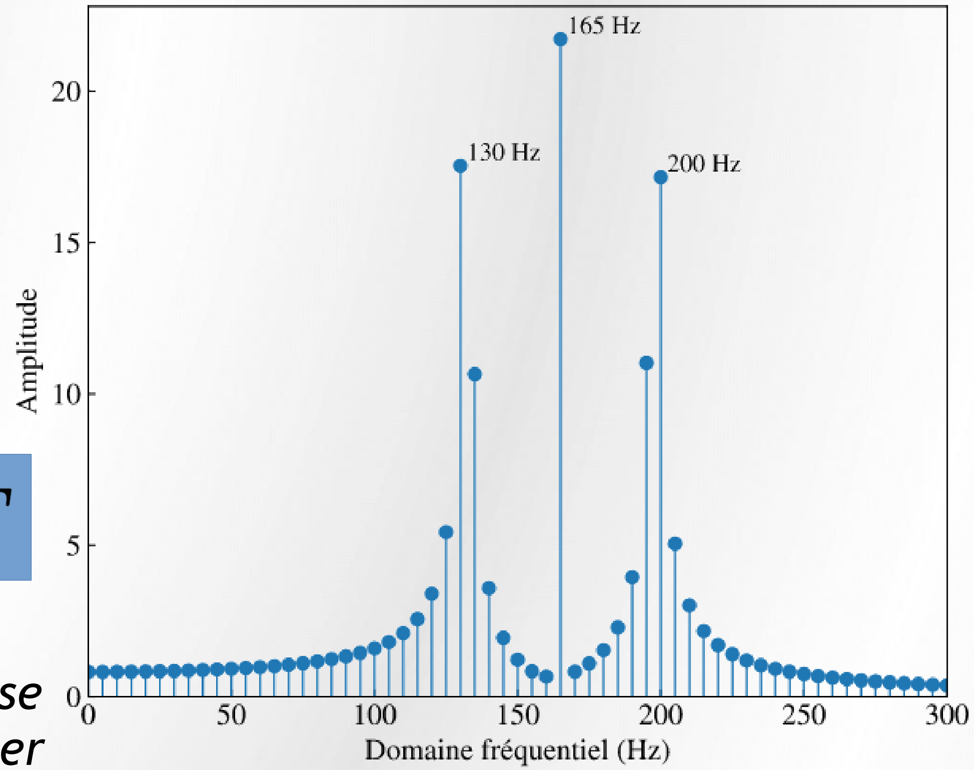
Interlude on Reciprocal Space (k- or q- space)

C major





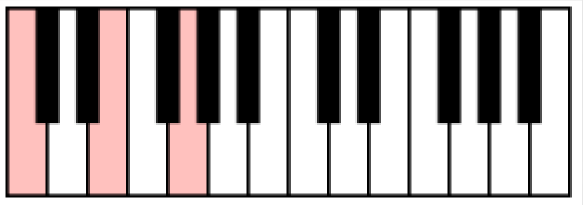
Inverse Fourier Transform

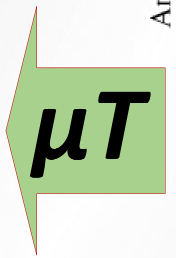


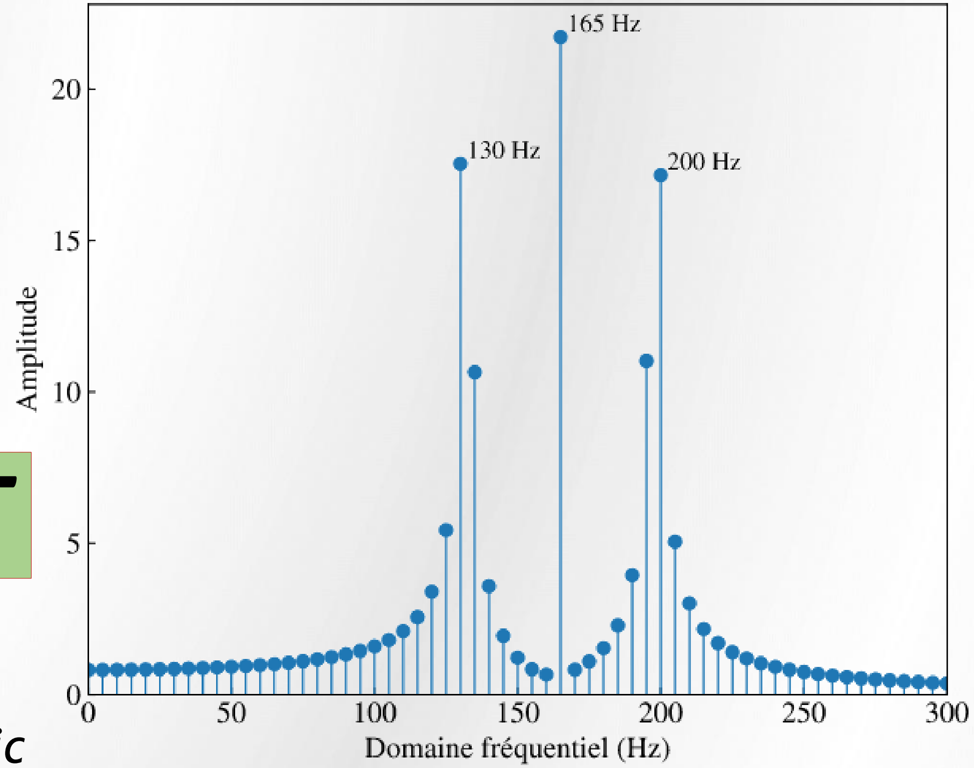
Time scale ⬤ ⬤ *Frequential scale*

Interlude on Reciprocal Space (k- or q- space)

C major







Music Transform

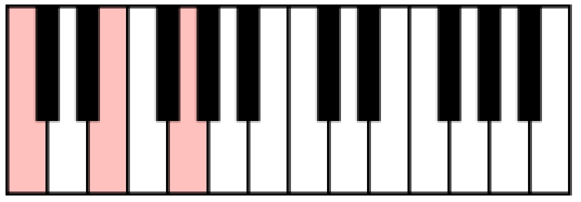
C

Song space
Time scale

Chord space
Frequential scale

Interlude on Reciprocal Space (k- or q- space)

C major

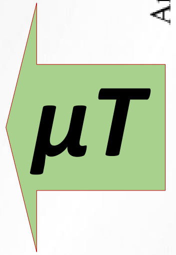


Tomorrow Never Knows (1966)

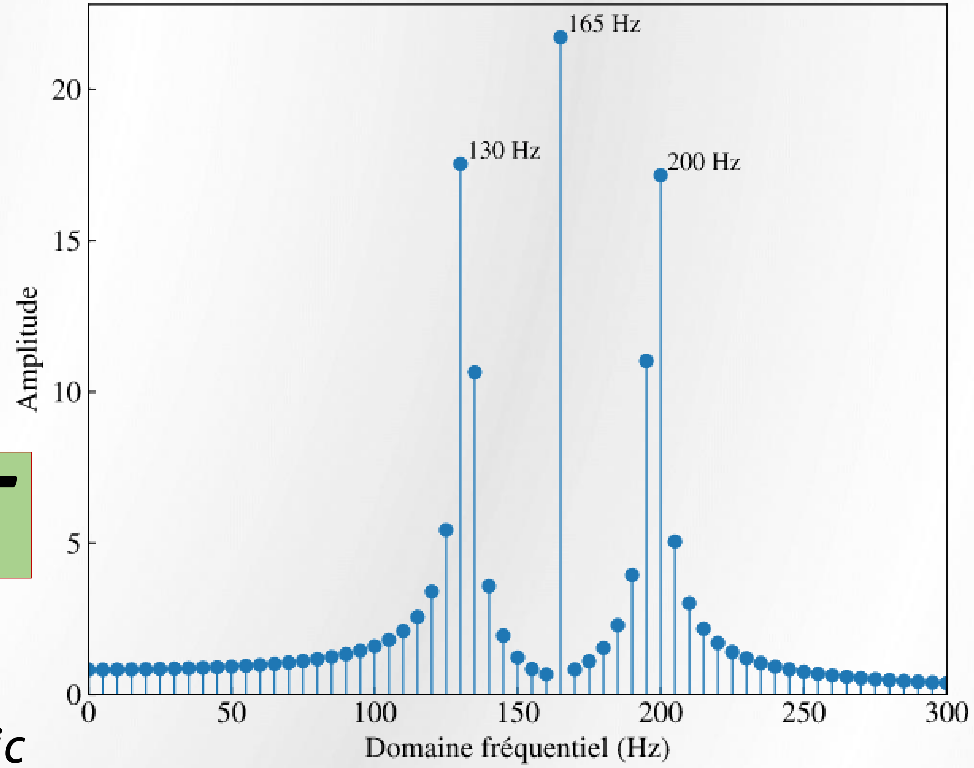
https://www.youtube.com/watch?v=pHNbHn3i9S4

Song space

Time scale



Music Transform



C

Chord space

Frequential scale

Interlude on Reciprocal Space (k- or q- space)

μT

Music Transform

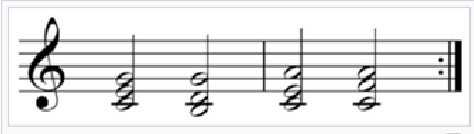
Song space

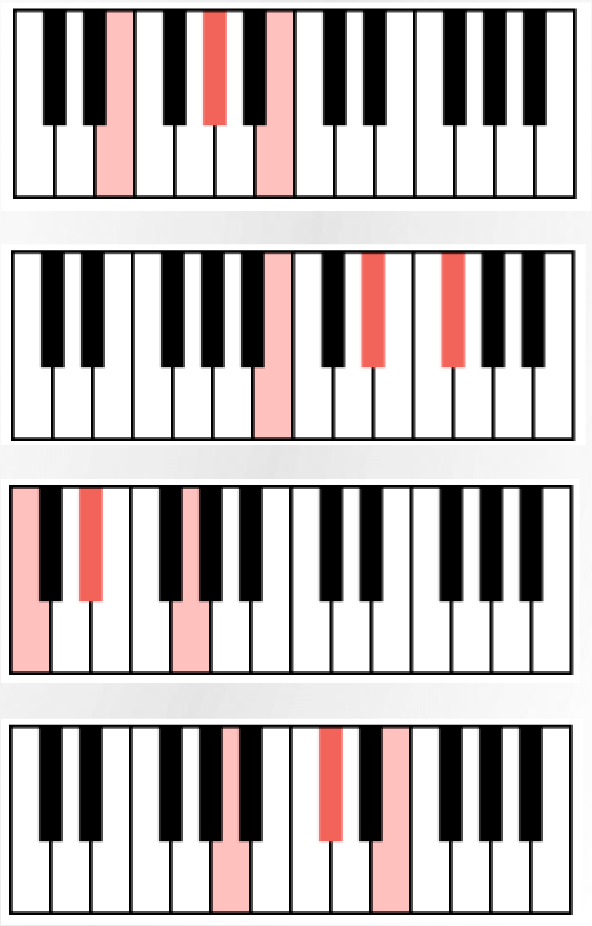
Time scale

Chord space

Frequential scale

Interlude on Reciprocal Space (k- or q- space)





μT

Music Transform

E	B	Cs m	A

Song space
Time scale

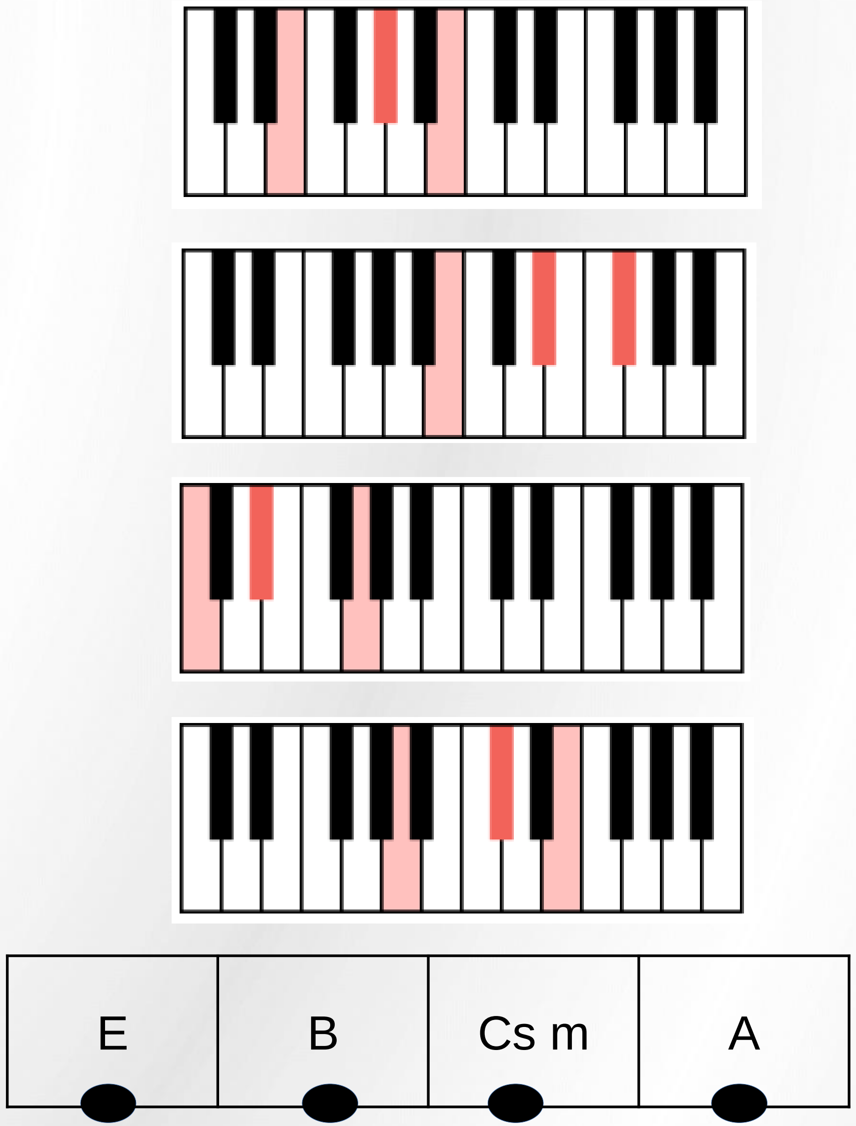
Chord space
Frequential scale

Interlude on Reciprocal Space (k- or q- space)

https://www.youtube.com/watch?v=oOlDewpCfZQ

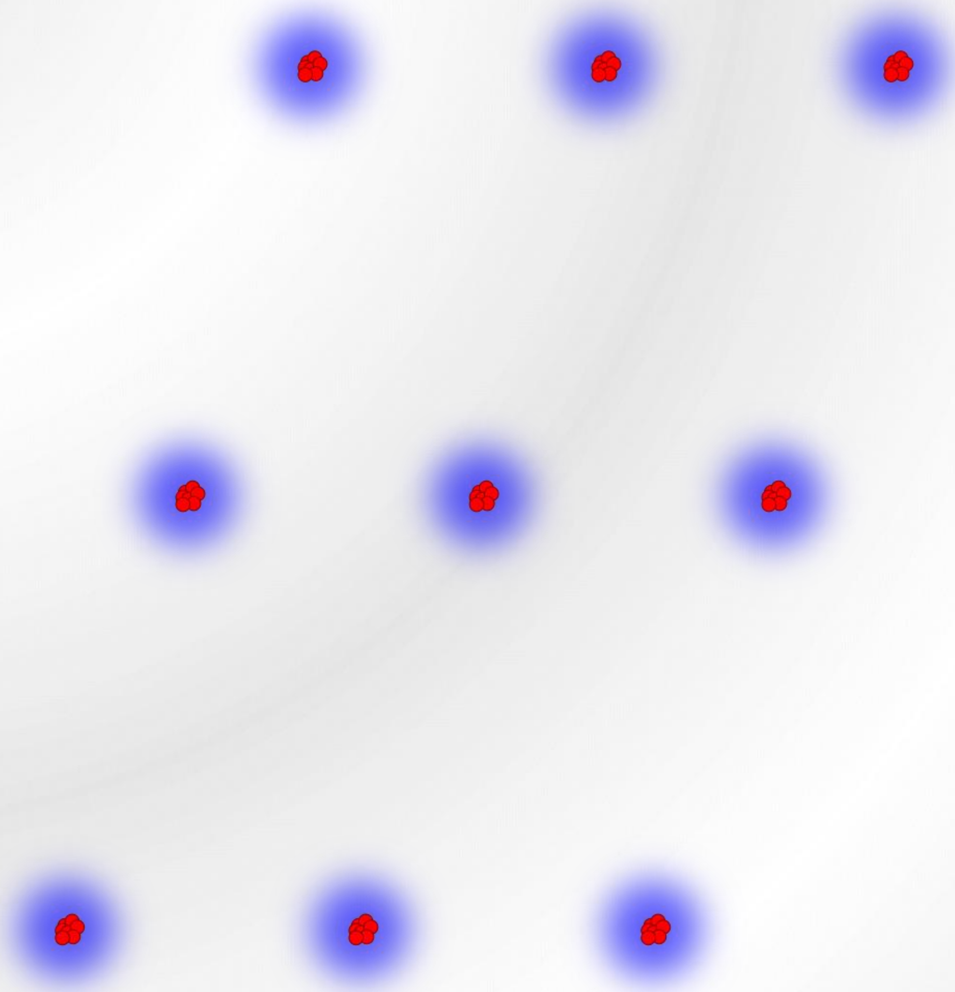
Song space
Time scale

Inverse Musical Transform



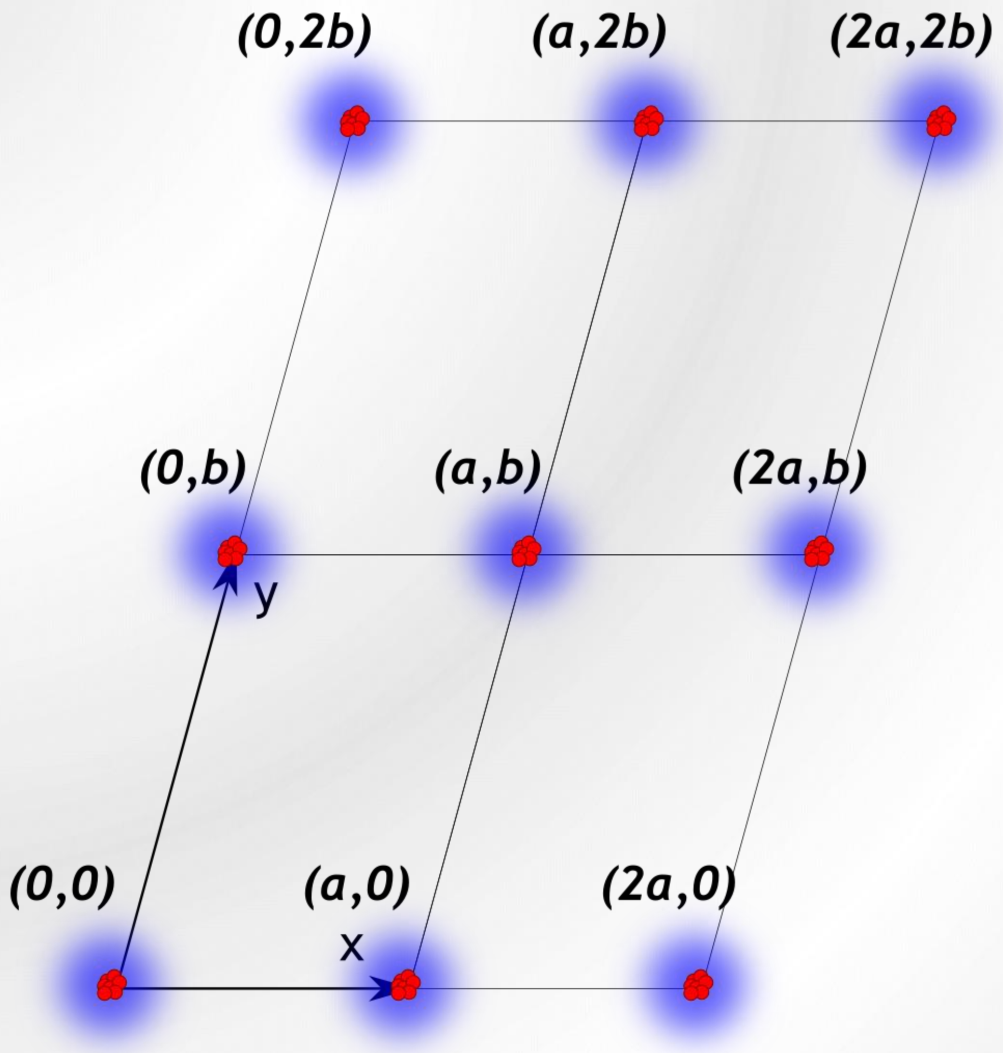
Chord space
Frequential scale

Interlude on Reciprocal Space (k- or q- space)



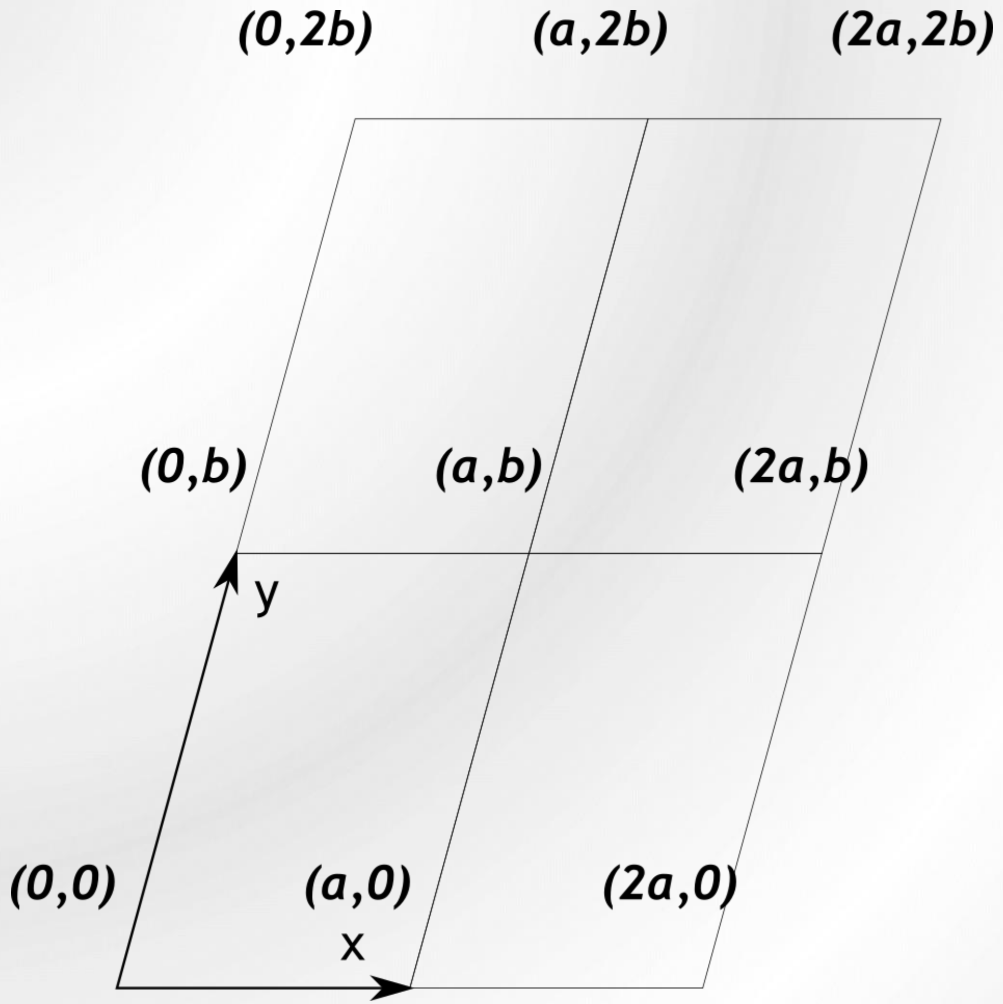
Length space

Interlude on Reciprocal Space (k- or q- space)



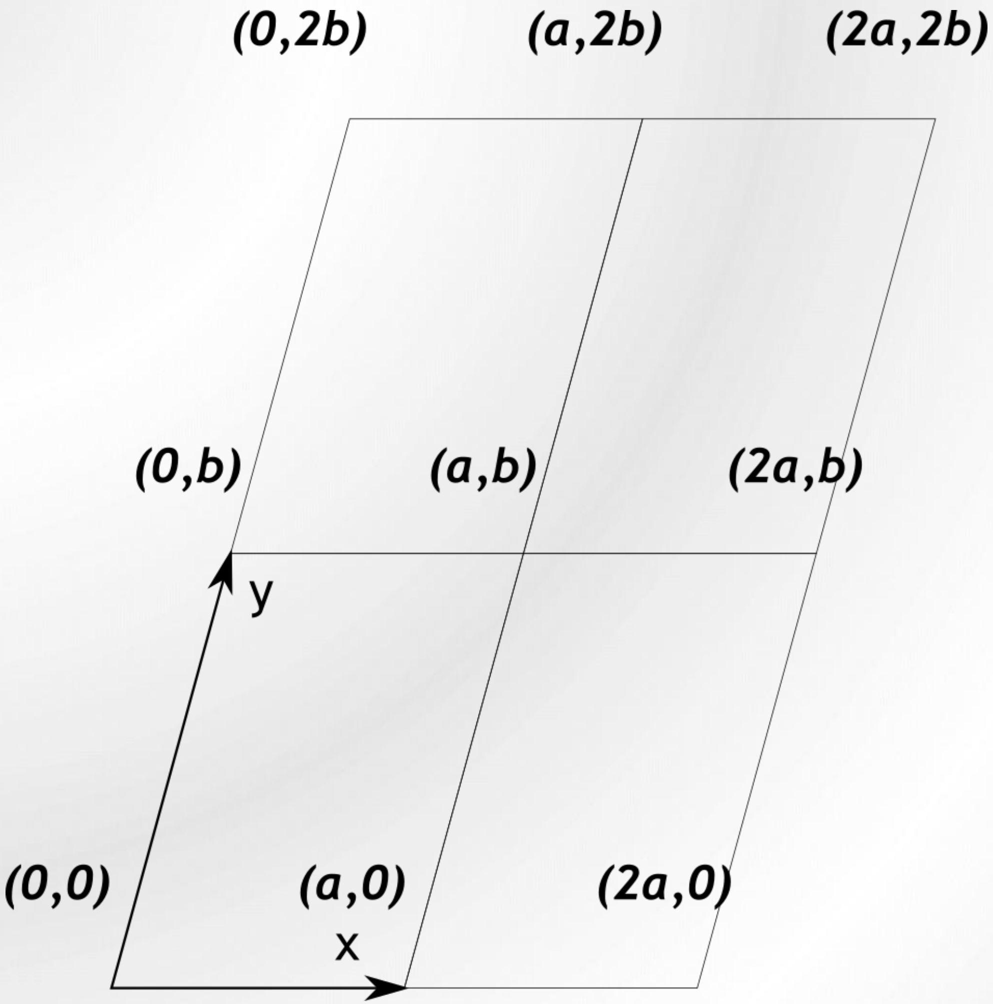
Length space

Interlude on Reciprocal Space (k- or q- space)

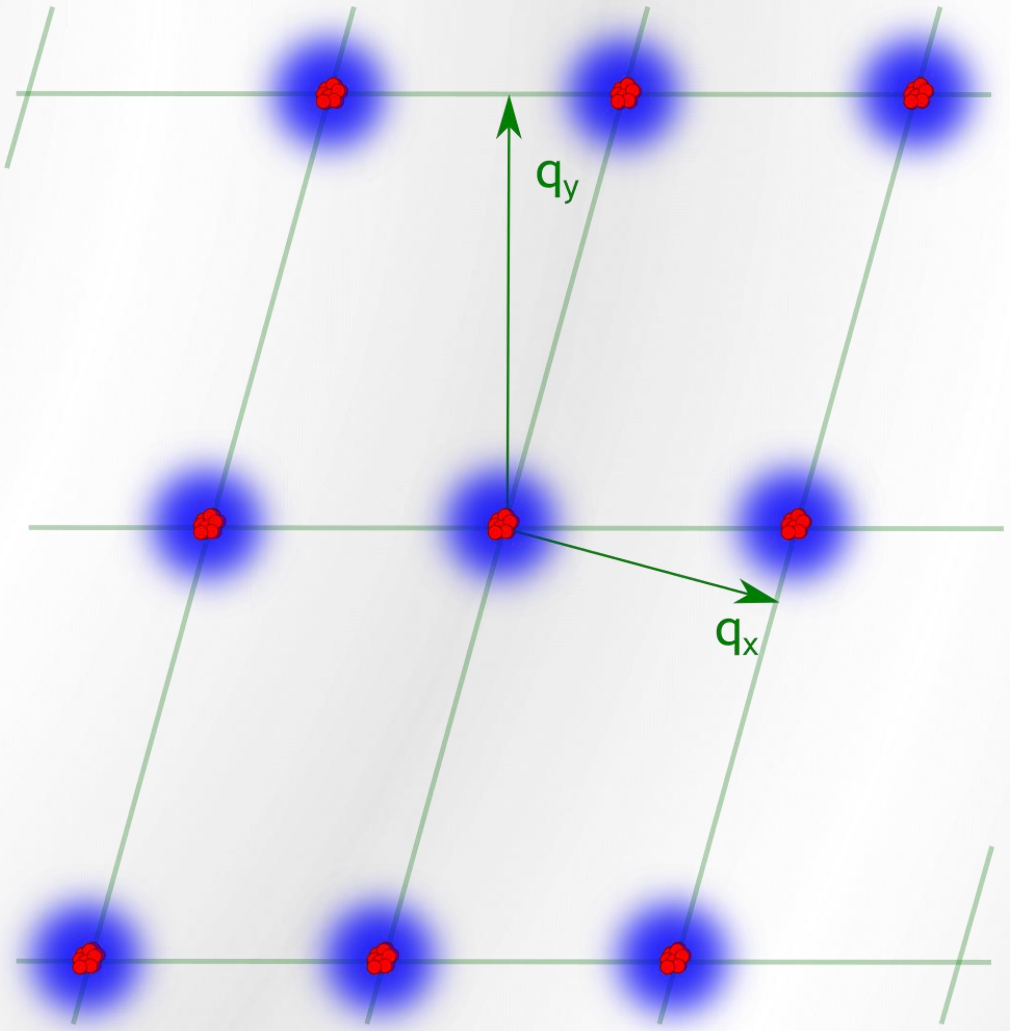


Length space

Interlude on Reciprocal Space (k- or q- space)

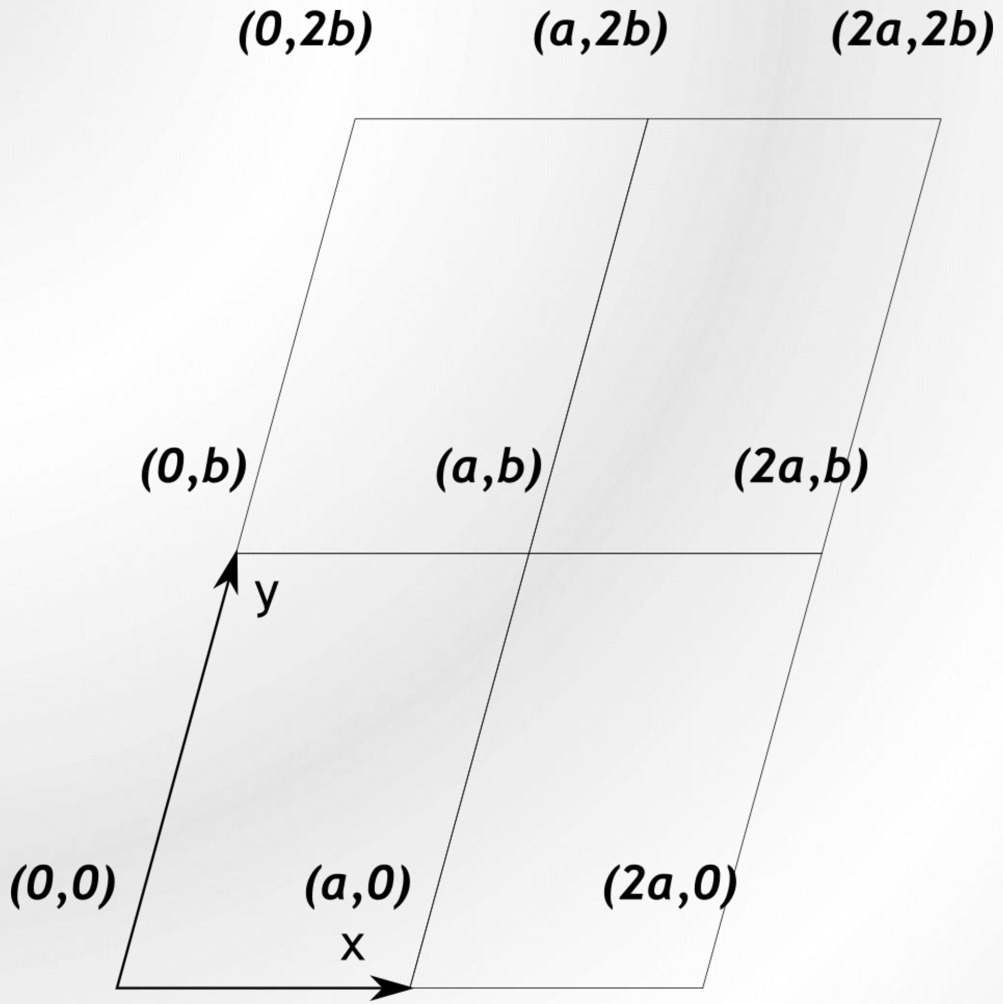


Length space

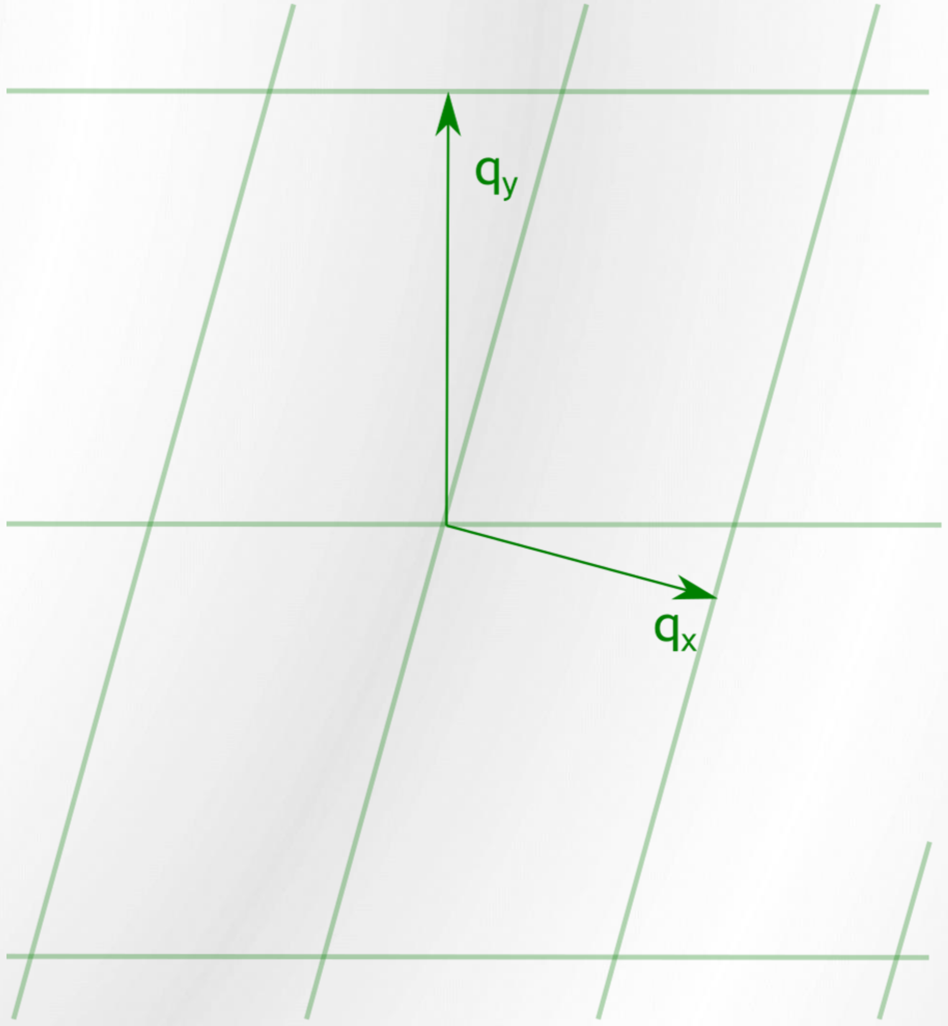


Frequential space

Interlude on Reciprocal Space (k- or q- space)

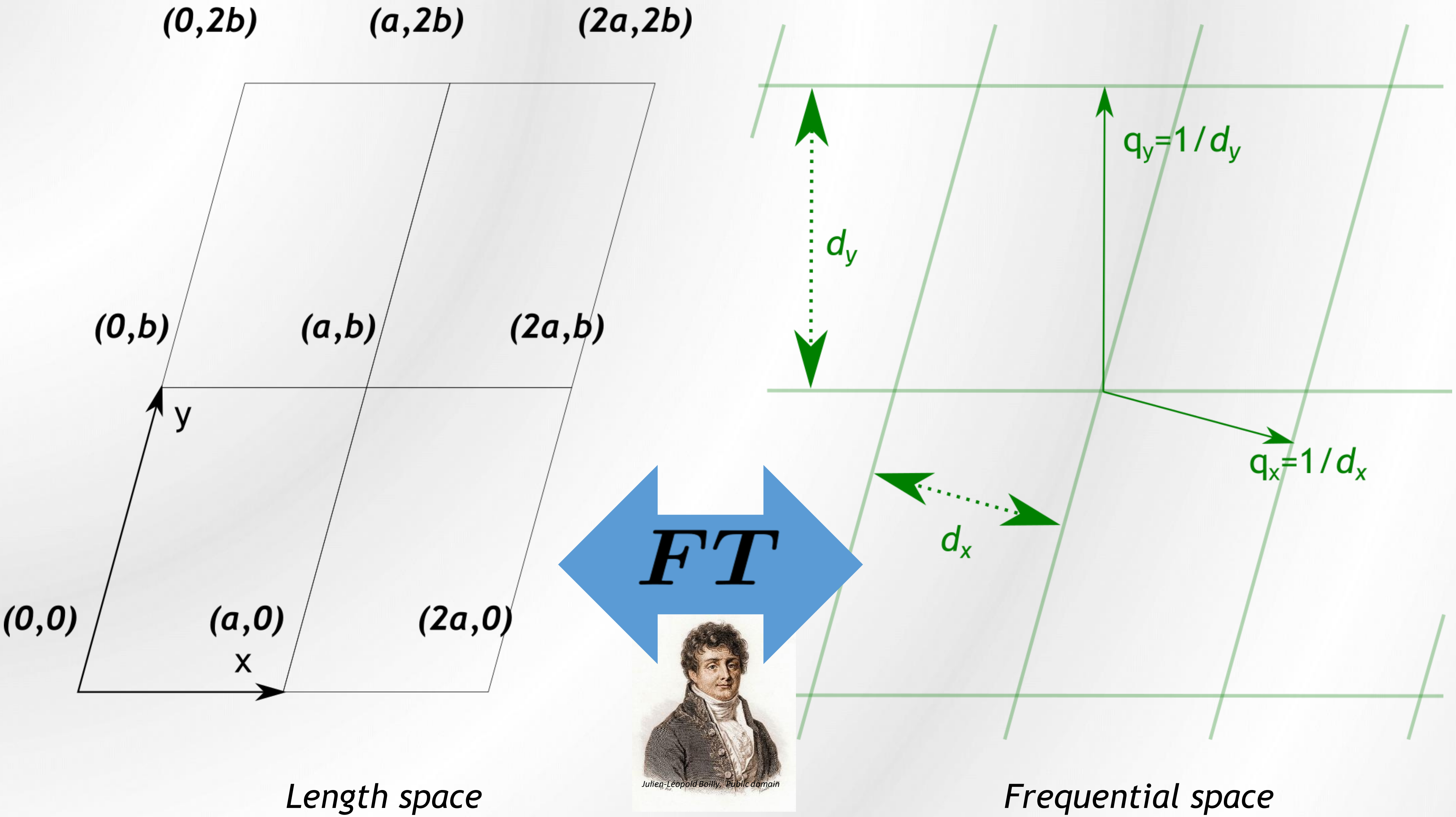


Length space



Frequential space

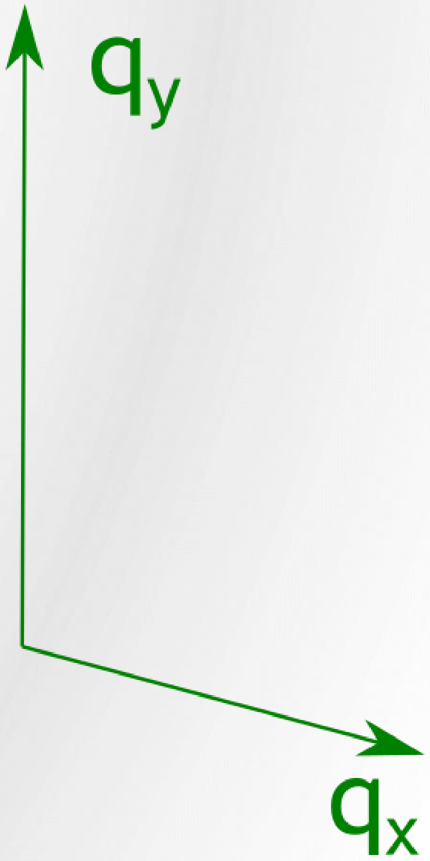
Interlude on Reciprocal Space (k- or q- space)



Length space

Frequential space

Interlude on Reciprocal Space (k- or q- space)



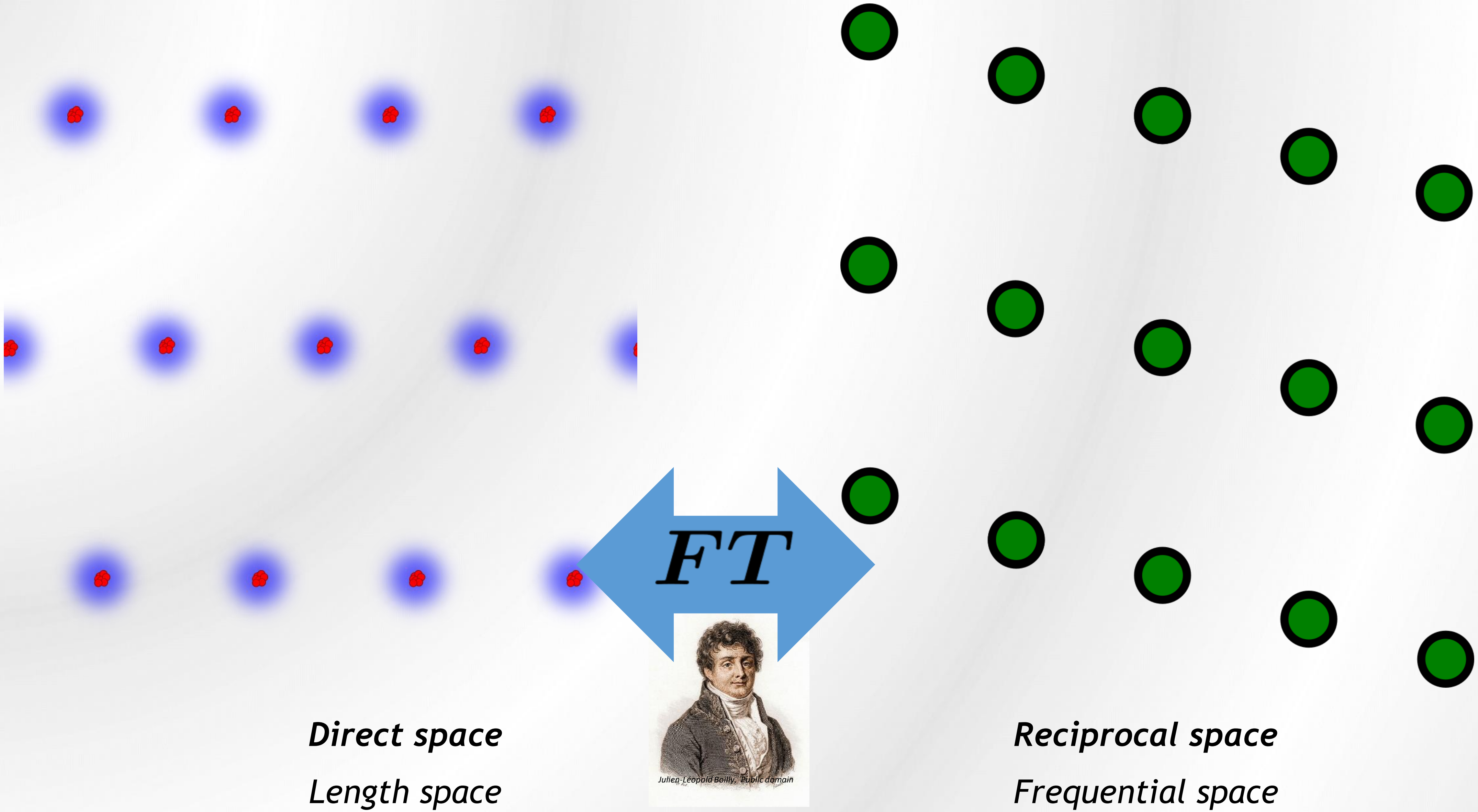
Direct space

Length space

Reciprocal space

Frequential space

Interlude on Reciprocal Space (k- or q- space)



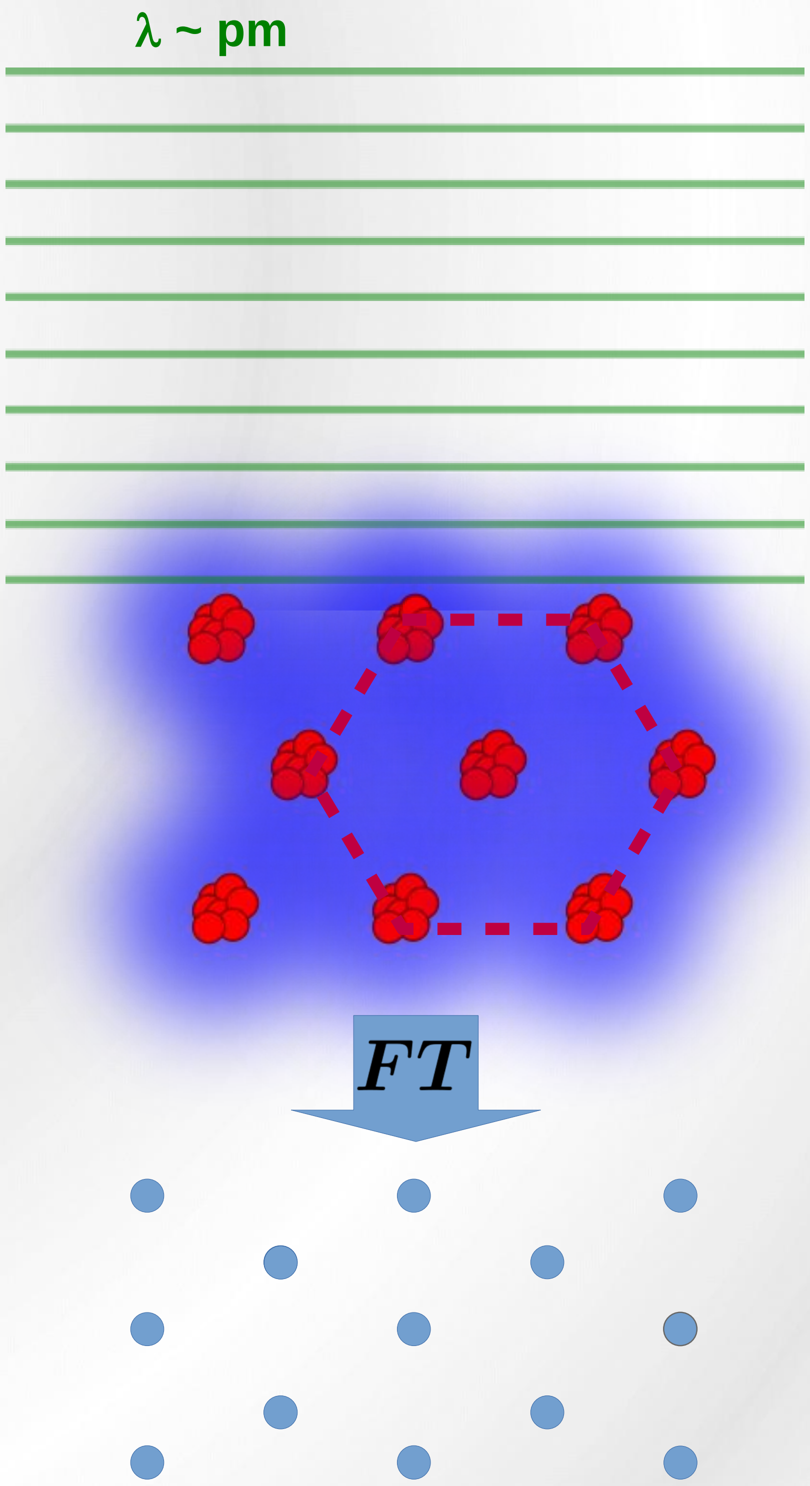
Wave description

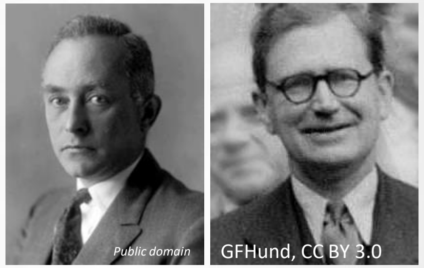
$$f^{e}(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^{X}(\vec{K})}{\|\vec{K}\|^2}\right]$$

$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d \cdot \vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

$$\Psi = \sum_{mesh} \sum \Psi_d$$





Reciprocal Lattice

Wave description

$$f^{e}(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^{X}(\vec{K})}{\|\vec{K}\|^2}\right]$$

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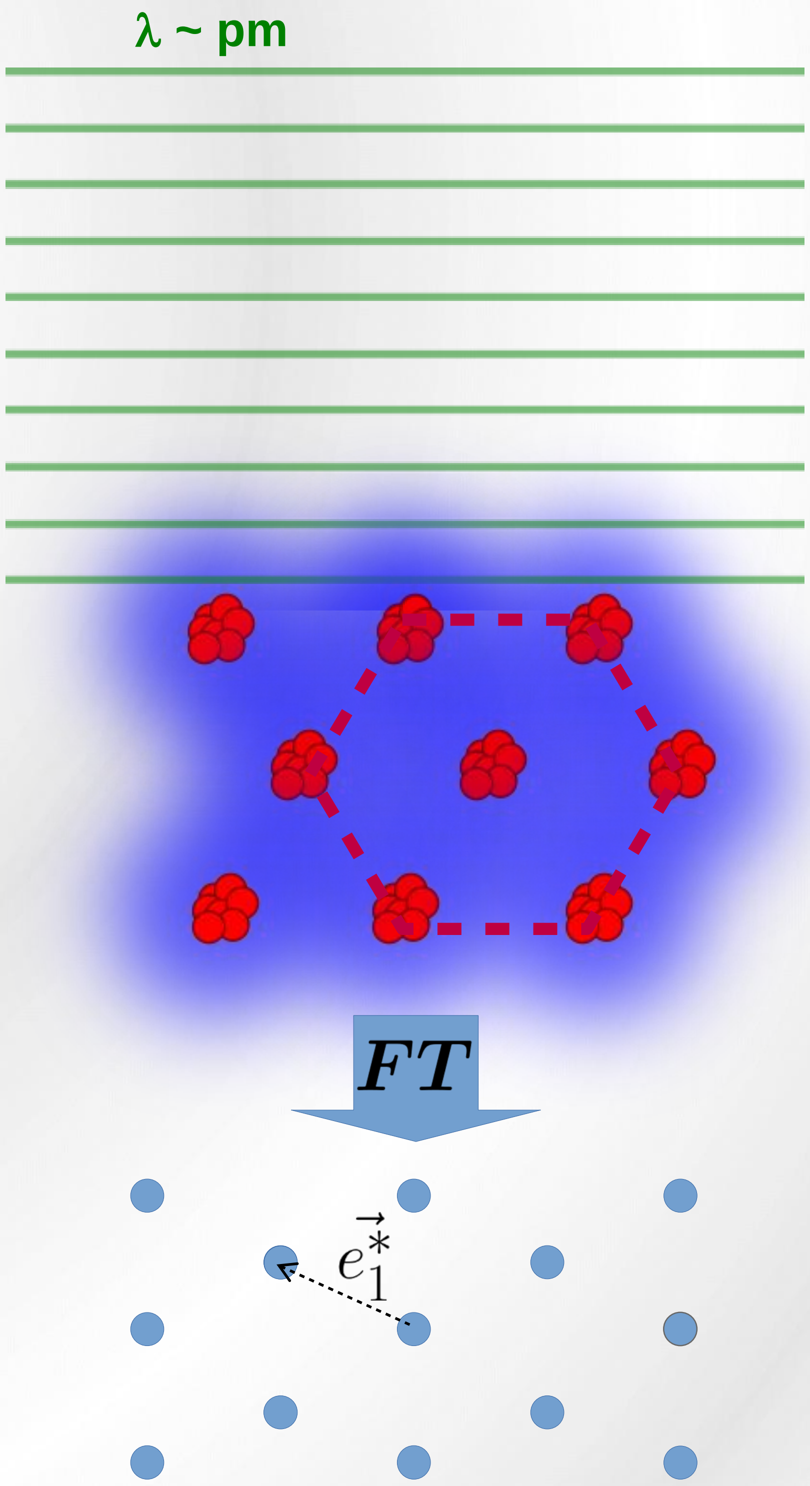

Reciprocal Lattice

Wave description

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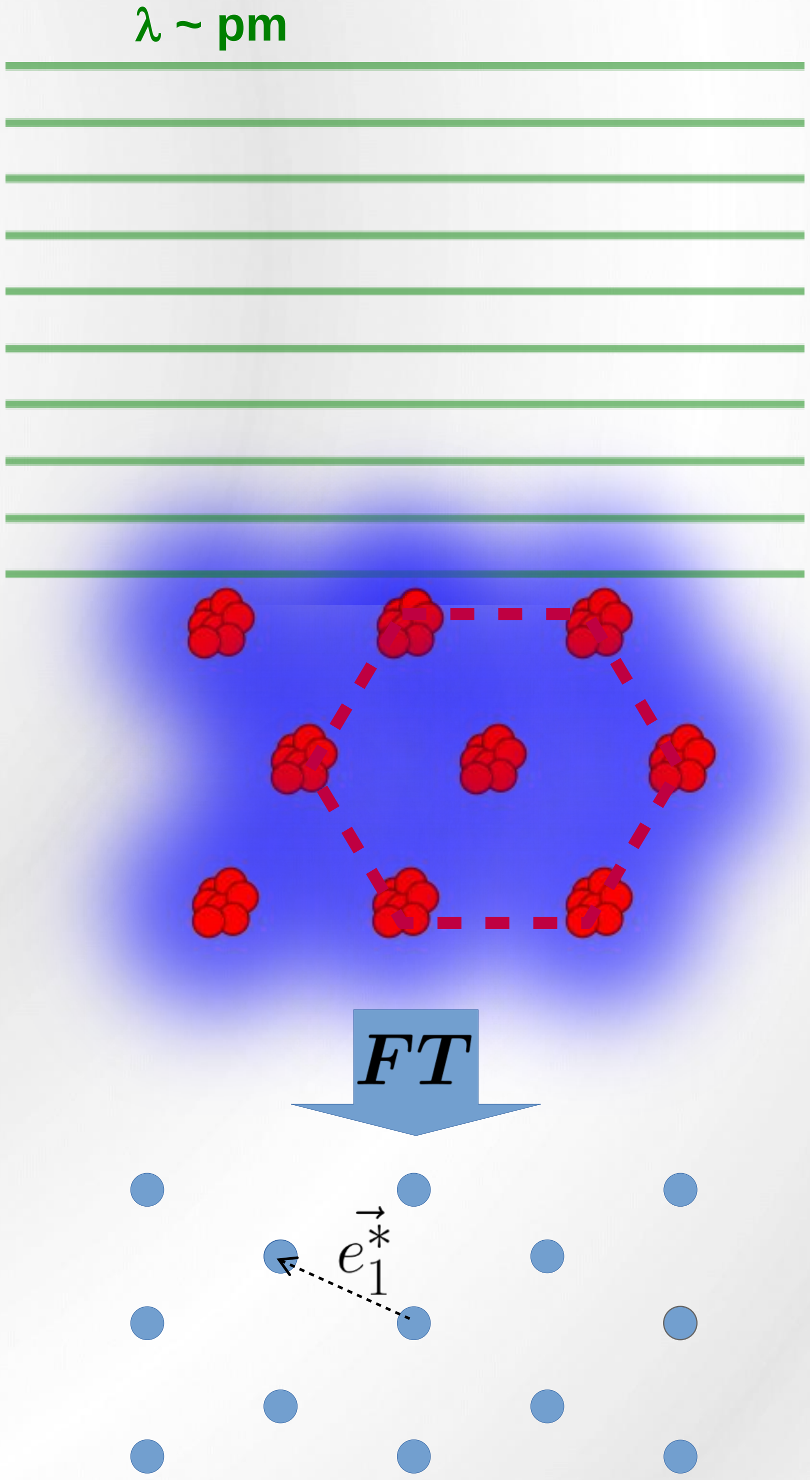
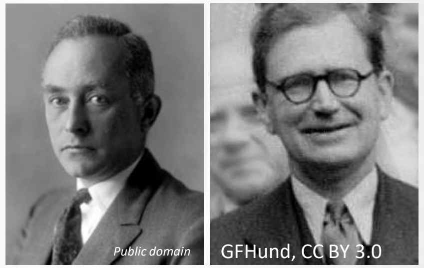
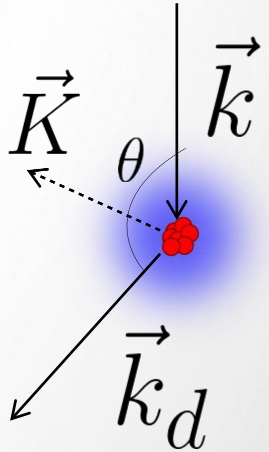




Reciprocal Lattice



Wave description

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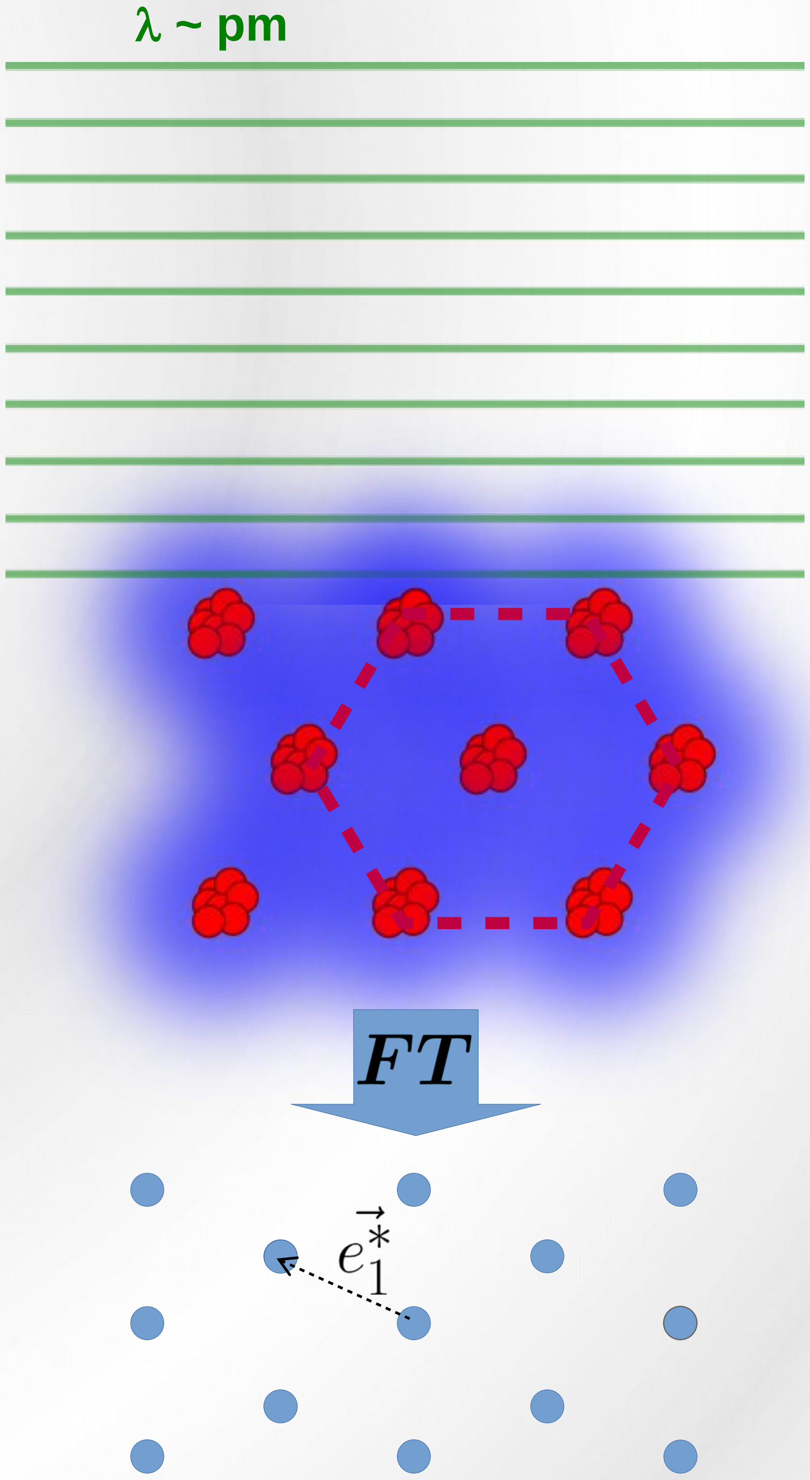
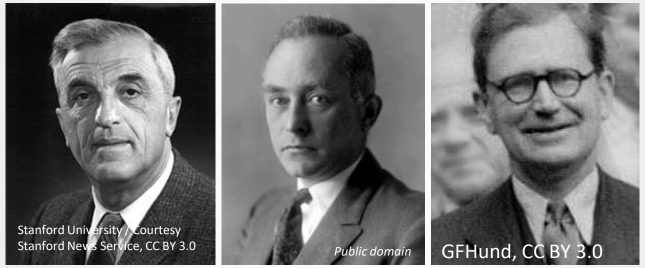
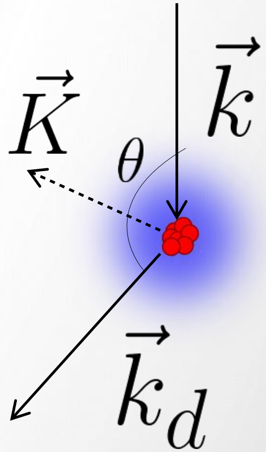




Reciprocal Lattice

$$\vec{e}_1^{\,*} = \vec{K}$$



Wave description

$$f^{e}(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^{X}(\vec{K})}{\|\vec{K}\|^2}\right]$$

$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d \cdot \vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

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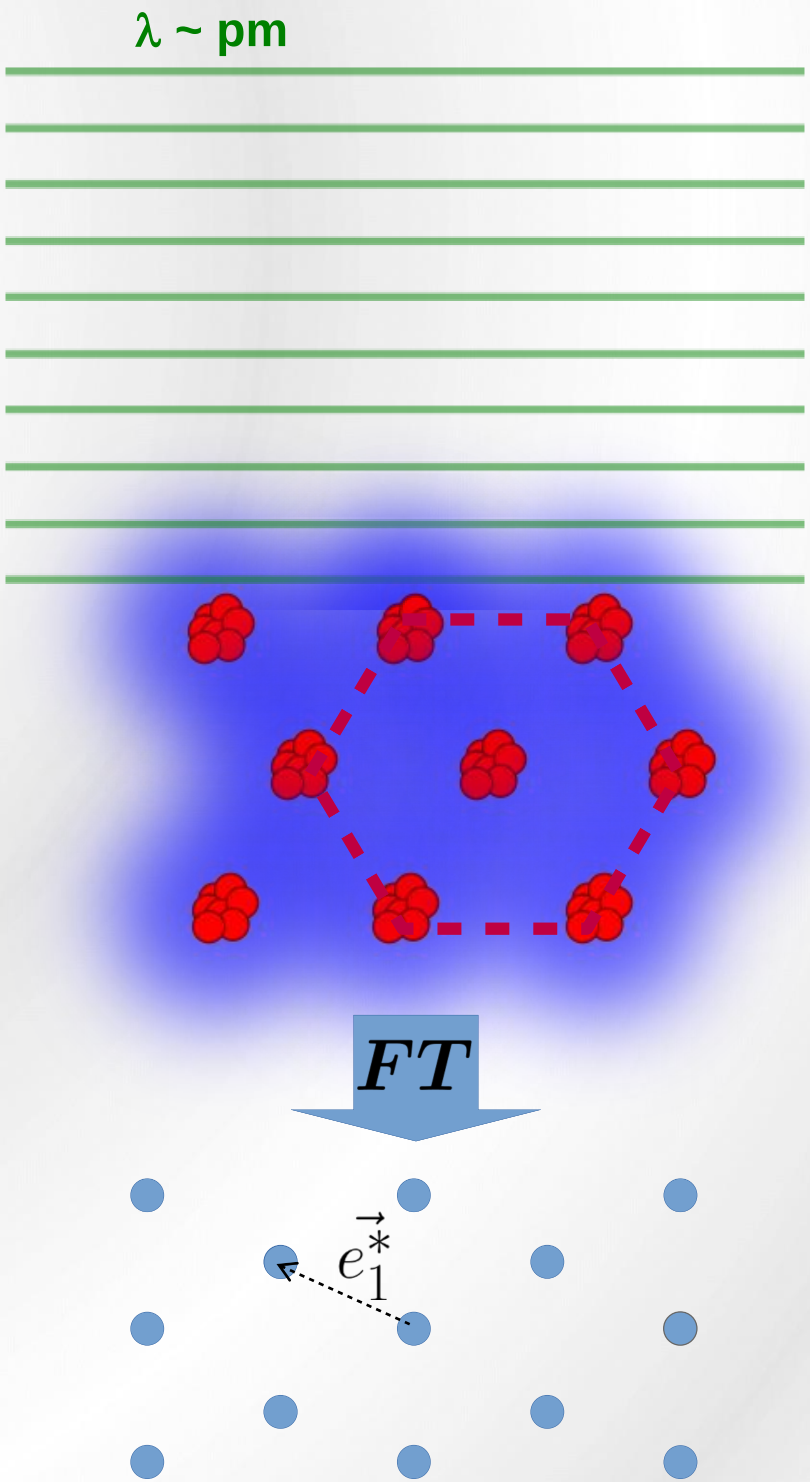
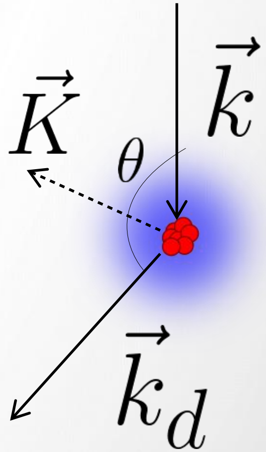


Reciprocal Lattice

Laue Conditions

$$\vec{e}_1^{\,*} = \vec{K}$$



Wave description

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$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

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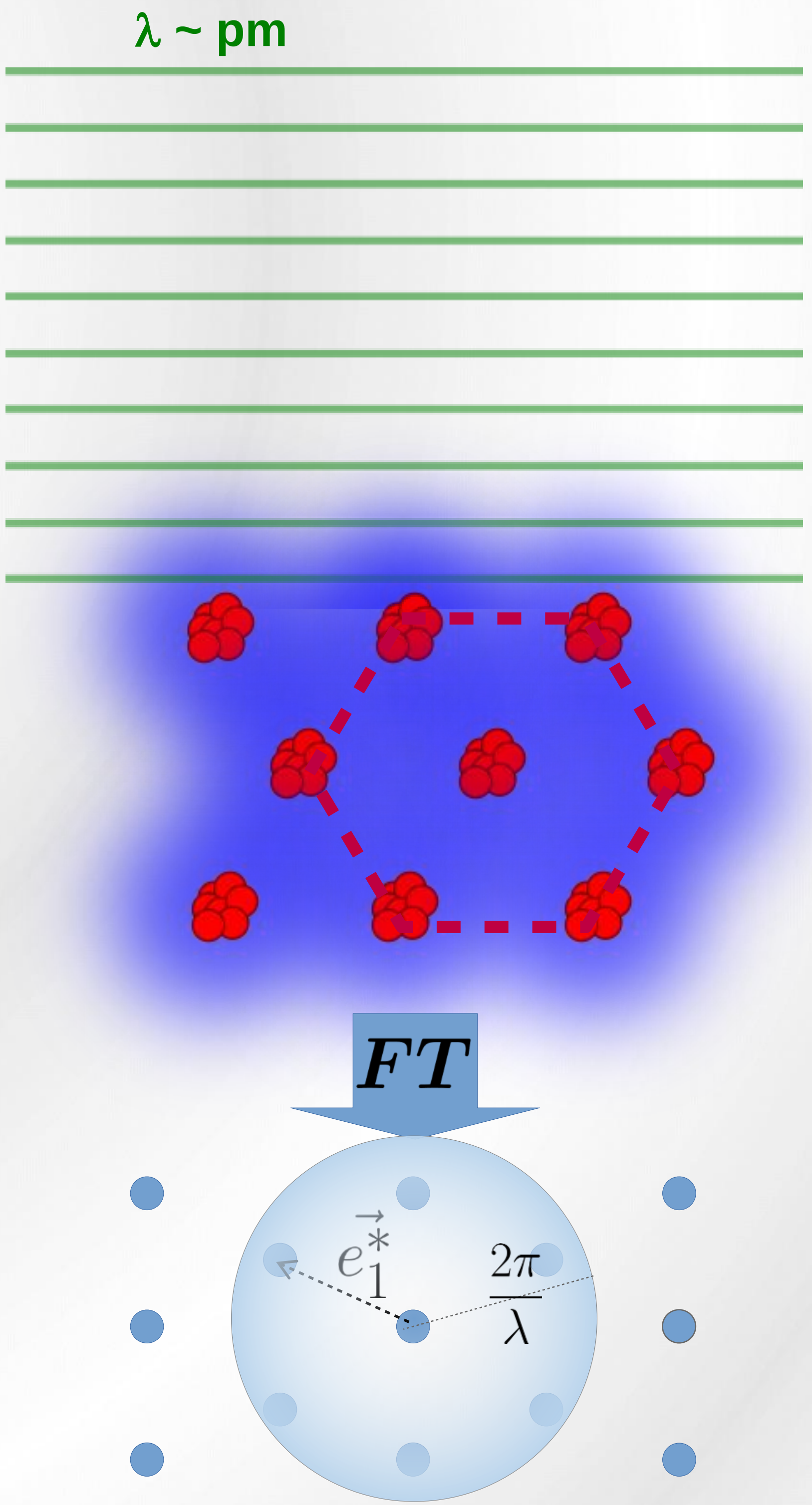
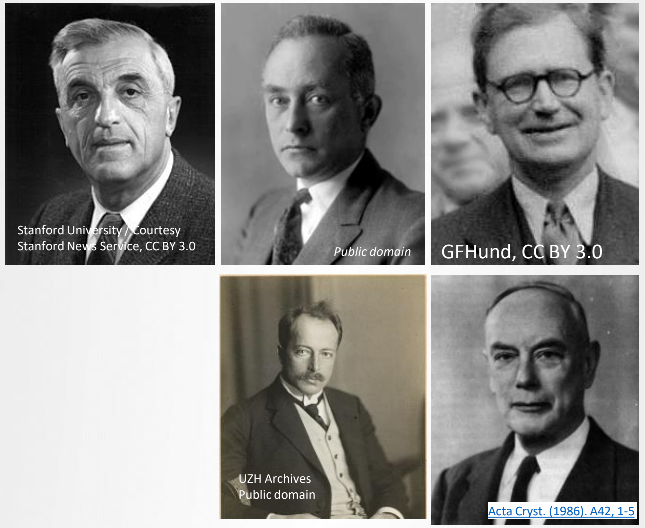
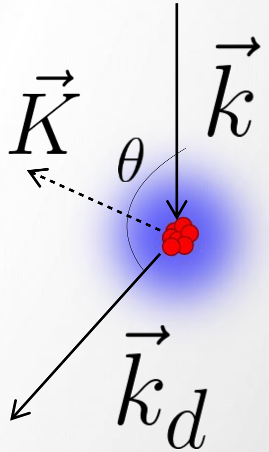




Reciprocal Lattice

Laue Conditions
Ewald Sphere

$$\vec{e}_1^{\,*} = \vec{K}$$



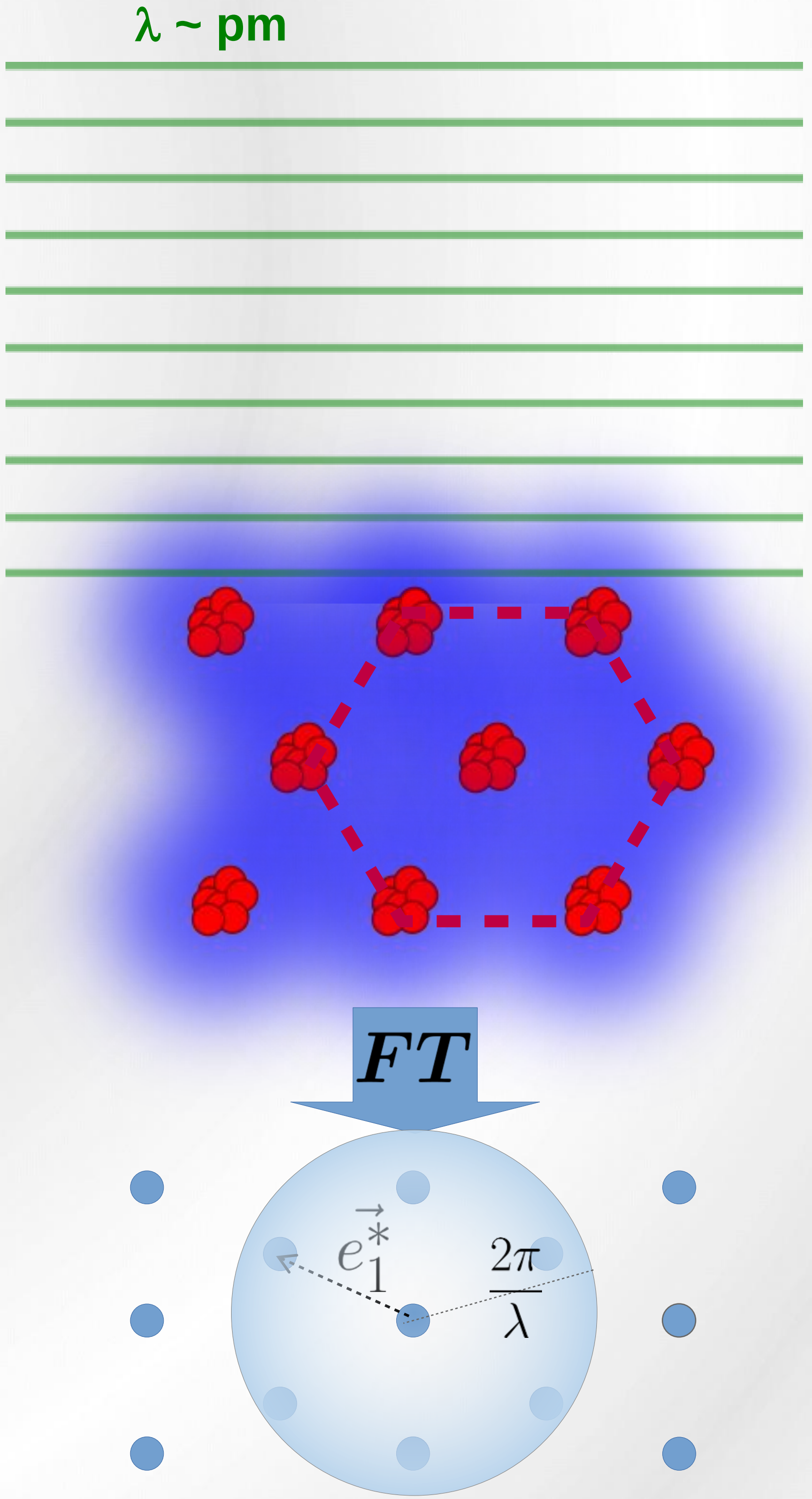
Wave description

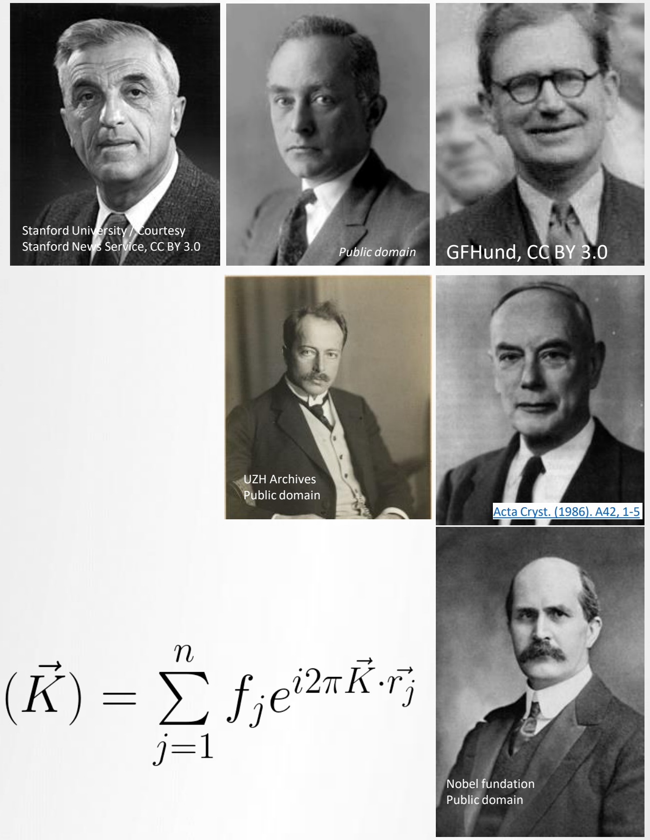
$$f^{e}(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^{X}(\vec{K})}{\|\vec{K}\|^2}\right]$$

$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d \cdot \vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

$$\Psi = \sum_{mesh} \sum \Psi_d$$

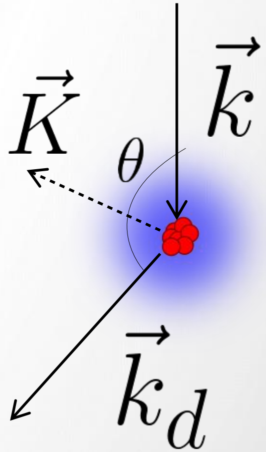




$$F(\vec{K}) = \sum_{j=1}^{n} f_j e^{i2\pi\vec{K}\cdot\vec{r}_j}$$

Bragg law
Laue Conditions
Ewald Sphere

$$\vec{e}_1^{\,*} = \vec{K}$$



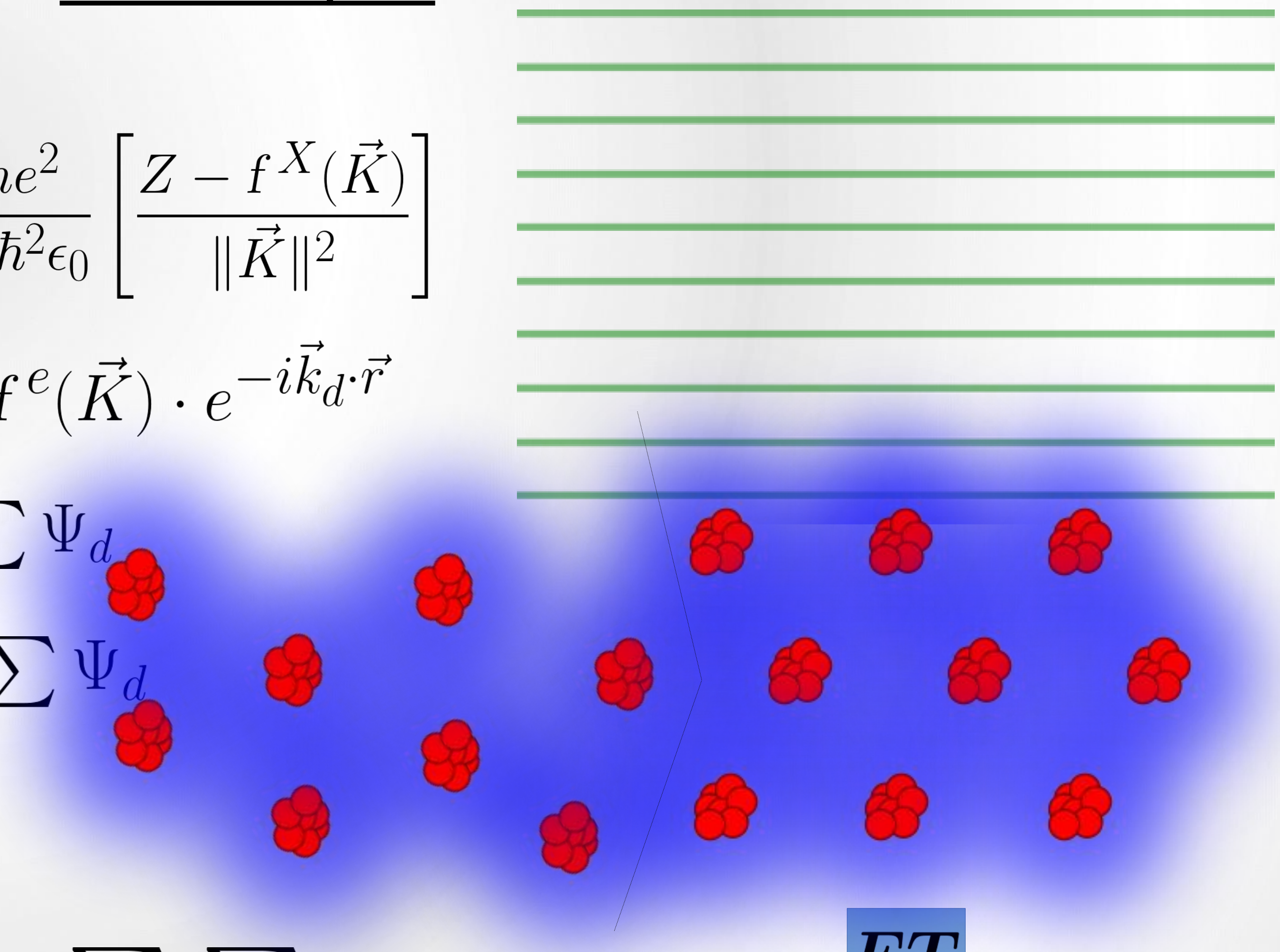
Wave description

$$f^e(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^X(\vec{K})}{\|\vec{K}\|^2}\right]$$

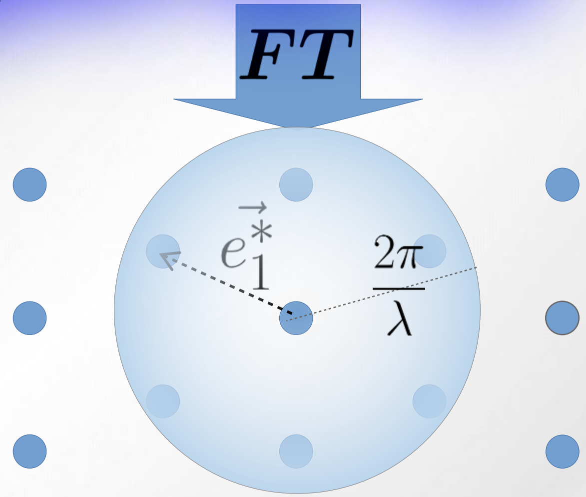
$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

$$\Psi_{atom} = \sum \Psi_d$$

$$\Psi = \sum_{mesh} \sum \Psi_d$$



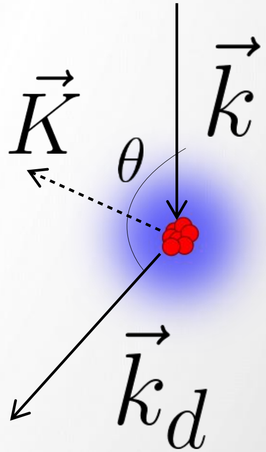
$$\Psi = \sum_{crystal} \sum_{mesh} \sum \Psi_d$$



$$S(\vec{K}) = \sum_{crystal} e^{i2\pi\vec{K}\cdot\vec{u}_{mesh}}$$

Form Factor

$$\vec{e}_1^* = \vec{K}$$



Wave description

$$f^{e}(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^{X}(\vec{K})}{\|\vec{K}\|^2}\right]$$

$$\Psi_d = \Psi_i \cdot f^{e}(\vec{K}) \cdot e^{-i\vec{k}_d \cdot \vec{r}}$$

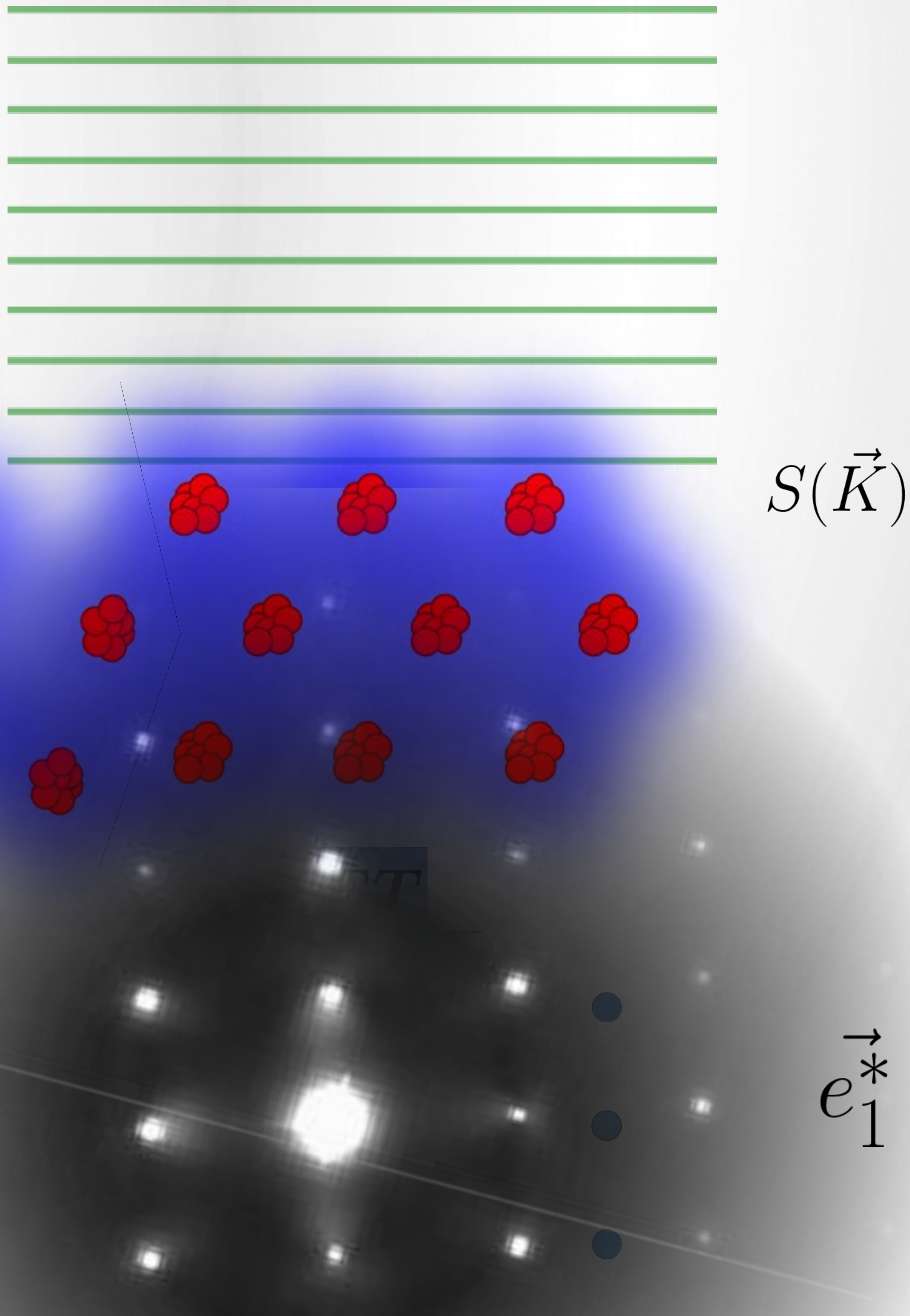
$$\Psi_{atom} = \sum \Psi_d$$

$$\Psi = \sum_{mesh} \sum \Psi_d$$

$$\Psi = \sum_{crystal} \sum_{mesh} \sum \Psi_d$$

$$I = \|\Psi\Psi^*\|^2$$

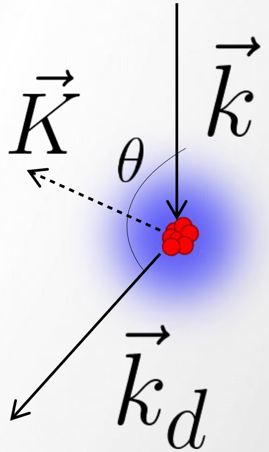
λ ~ pm



$$S(\vec{K}) = \sum_{crystal} e^{i2\pi\vec{K}\cdot\vec{u}_{mesh}}$$

Form Factor

$$\vec{e}_1^{\,*} = \vec{K}$$



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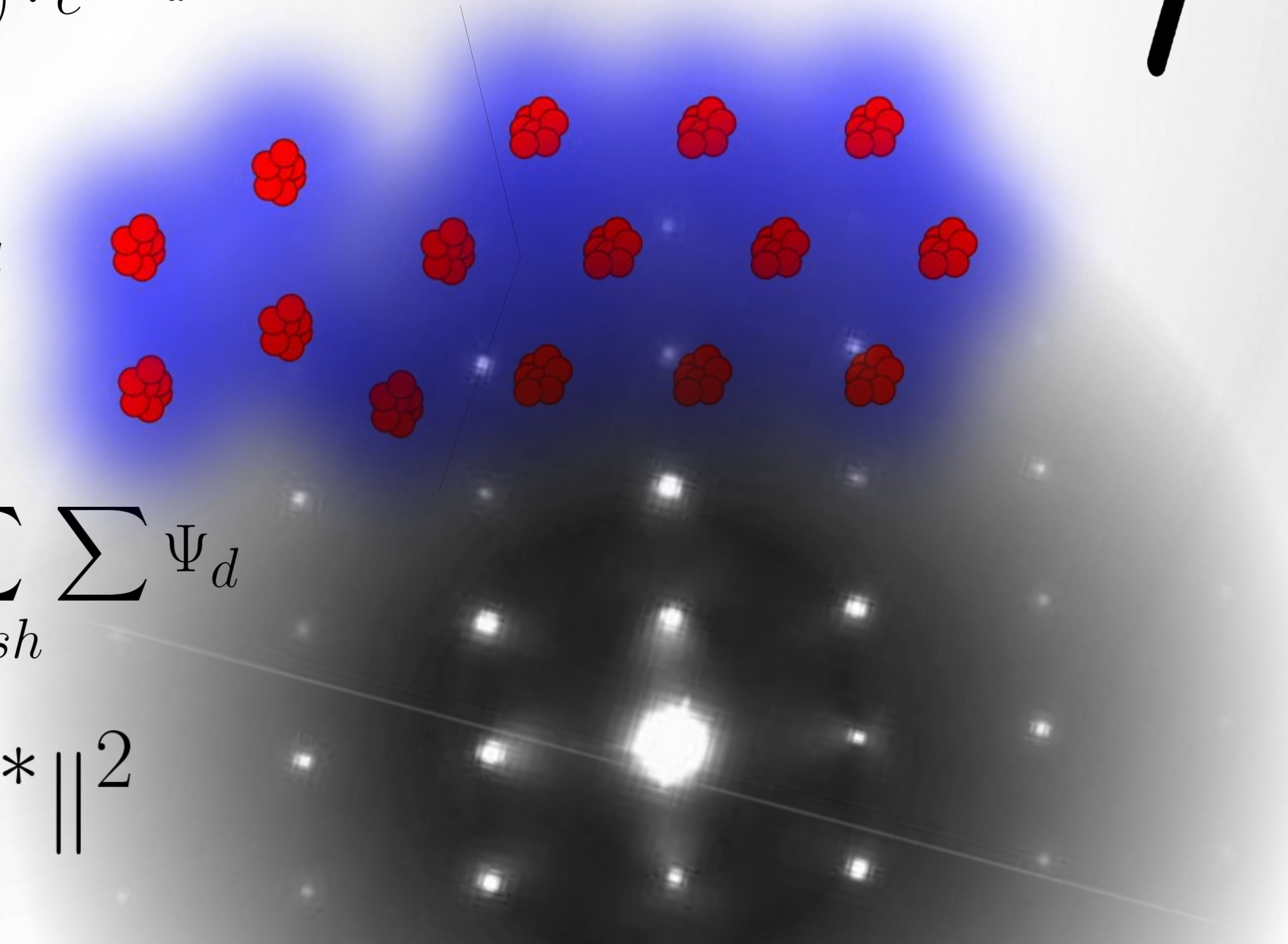
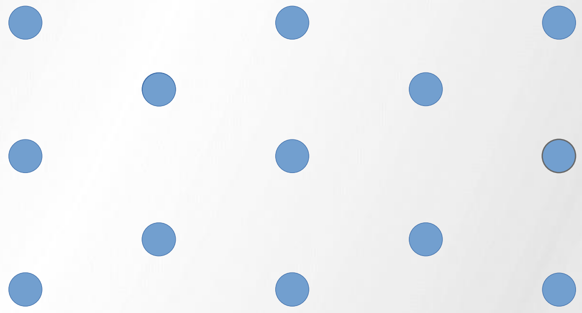
Diffraction ≠ Fourier Transform





Wave description

$$f^e(\vec{K}) = \frac{me^2}{2\pi\hbar^2\epsilon_0}\left[\frac{Z - f^X(\vec{K})}{\|\vec{K}\|^2}\right]$$

$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d\cdot\vec{r}}$$

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$$\Psi = \sum_{mesh} \sum \Psi_d$$

$$\Psi = \sum_{crystal} \sum_{mesh} \sum \Psi_d$$

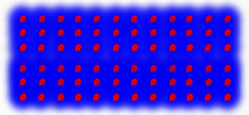
$$I = \|\Psi\Psi^*\|^2$$

Diffraction ≠ Fourier Transform

Here is the theory….

… how it works in practice ?

Introduction to Transmission, Electron & Microscopy

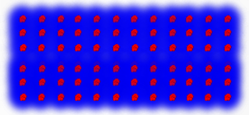


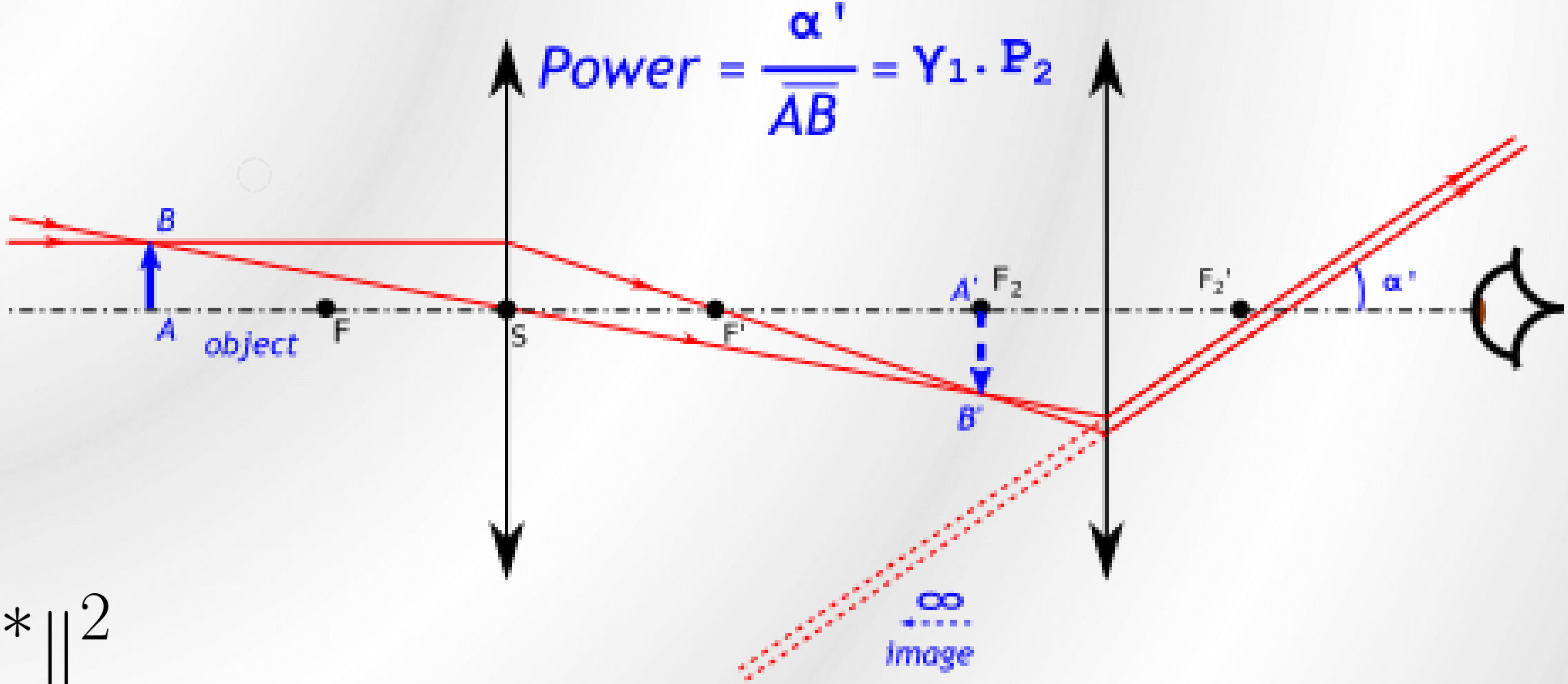
Here is the theory….

… how it works in practice ?

$$I = ||\Psi\Psi^*||^2$$

Introduction to Transmission, Electron & Microscopy





$$I = \|\Psi\Psi^*\|^2$$

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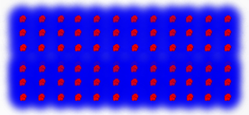

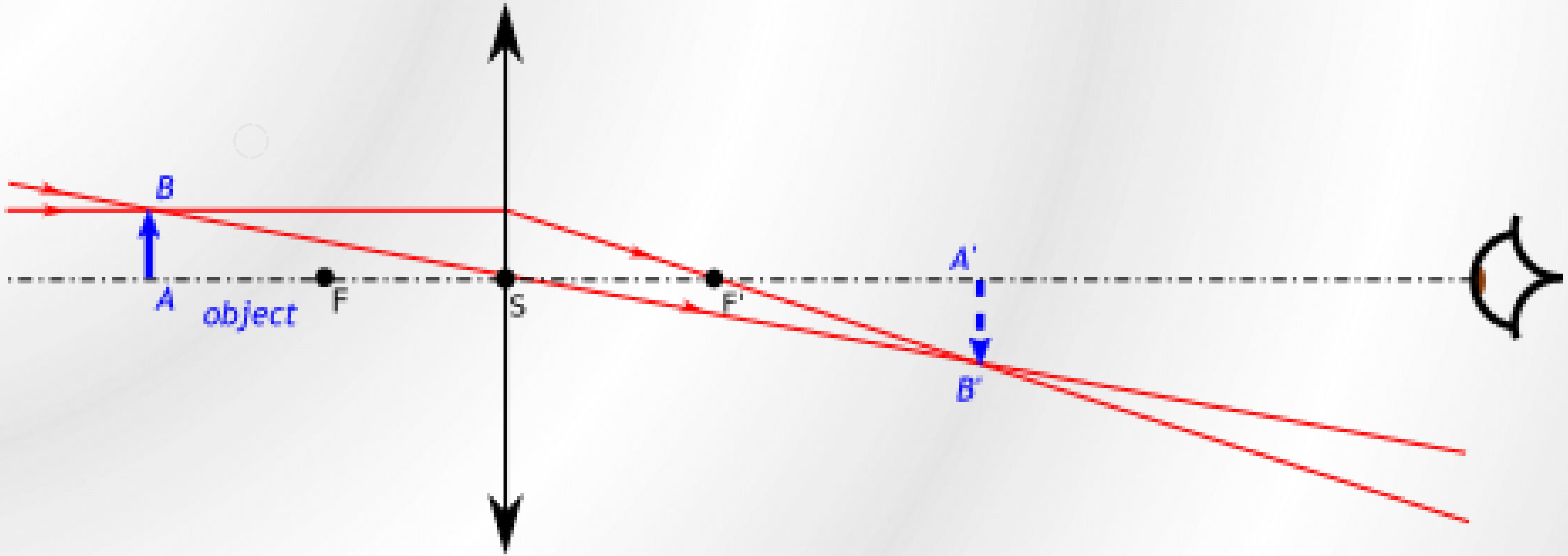

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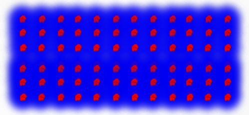

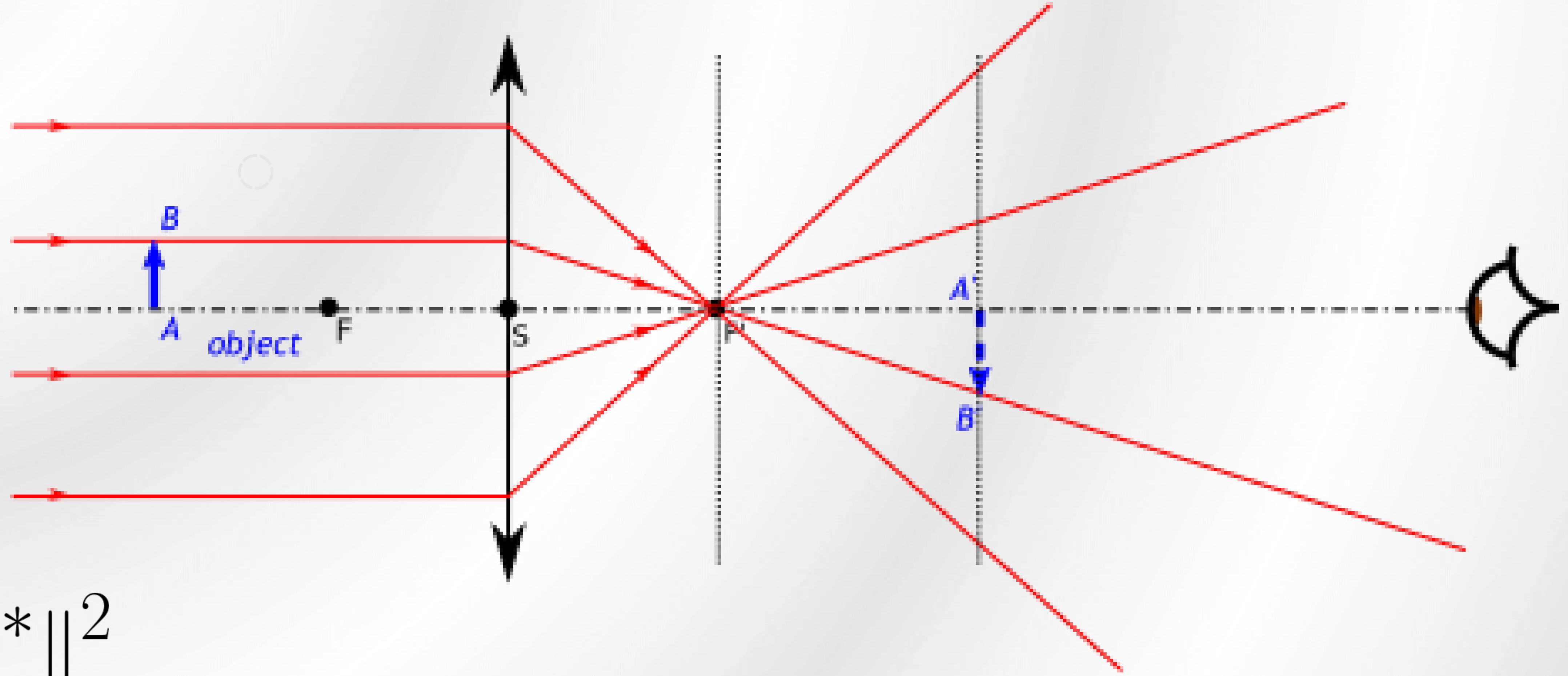

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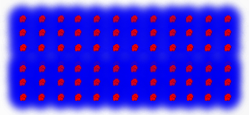

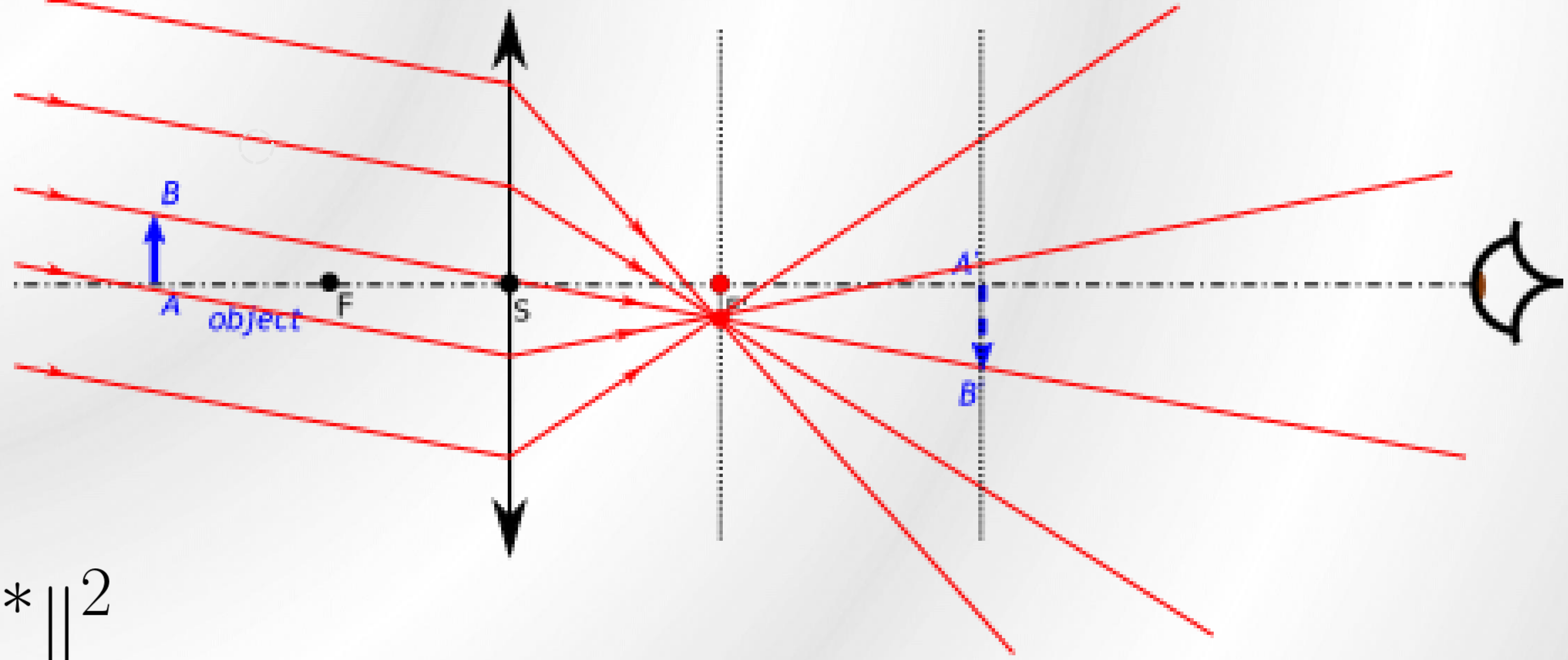

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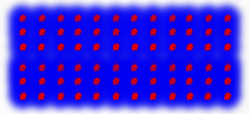

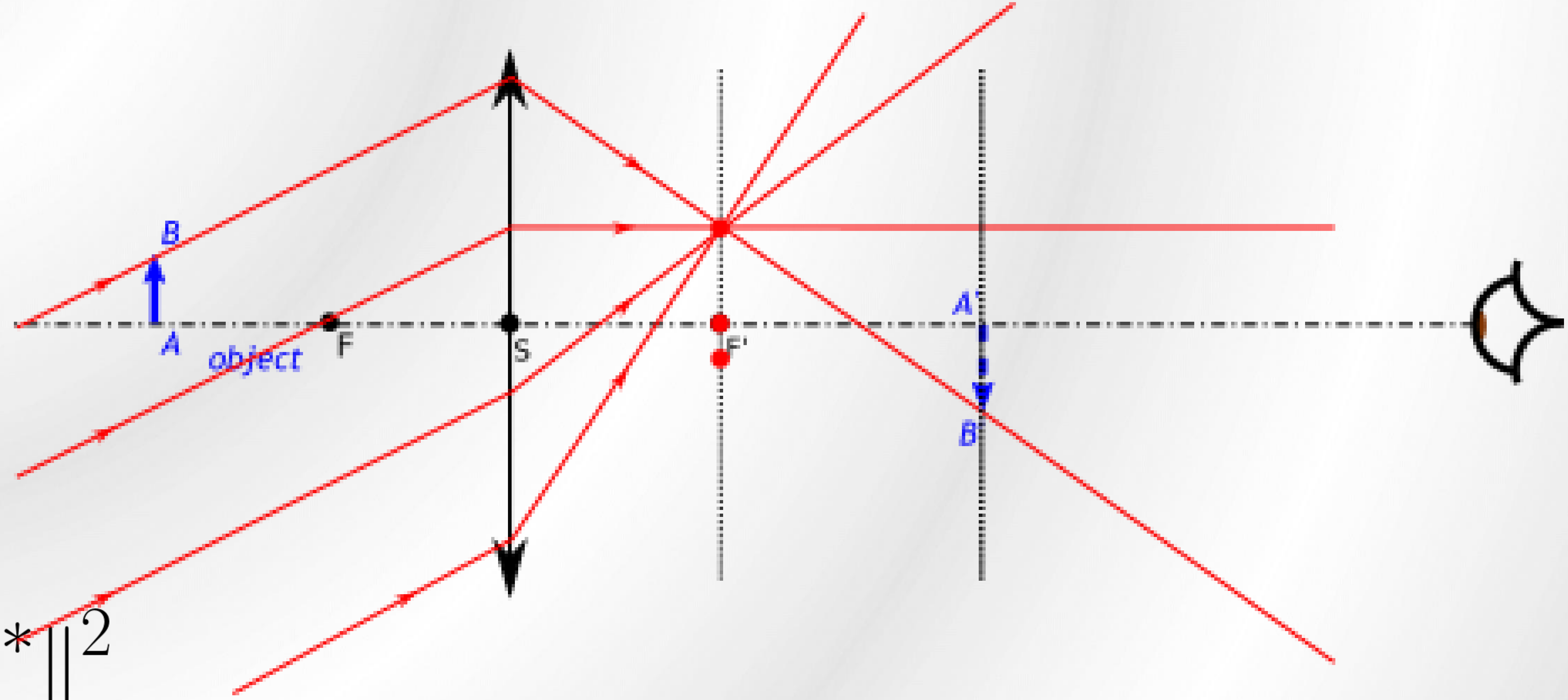

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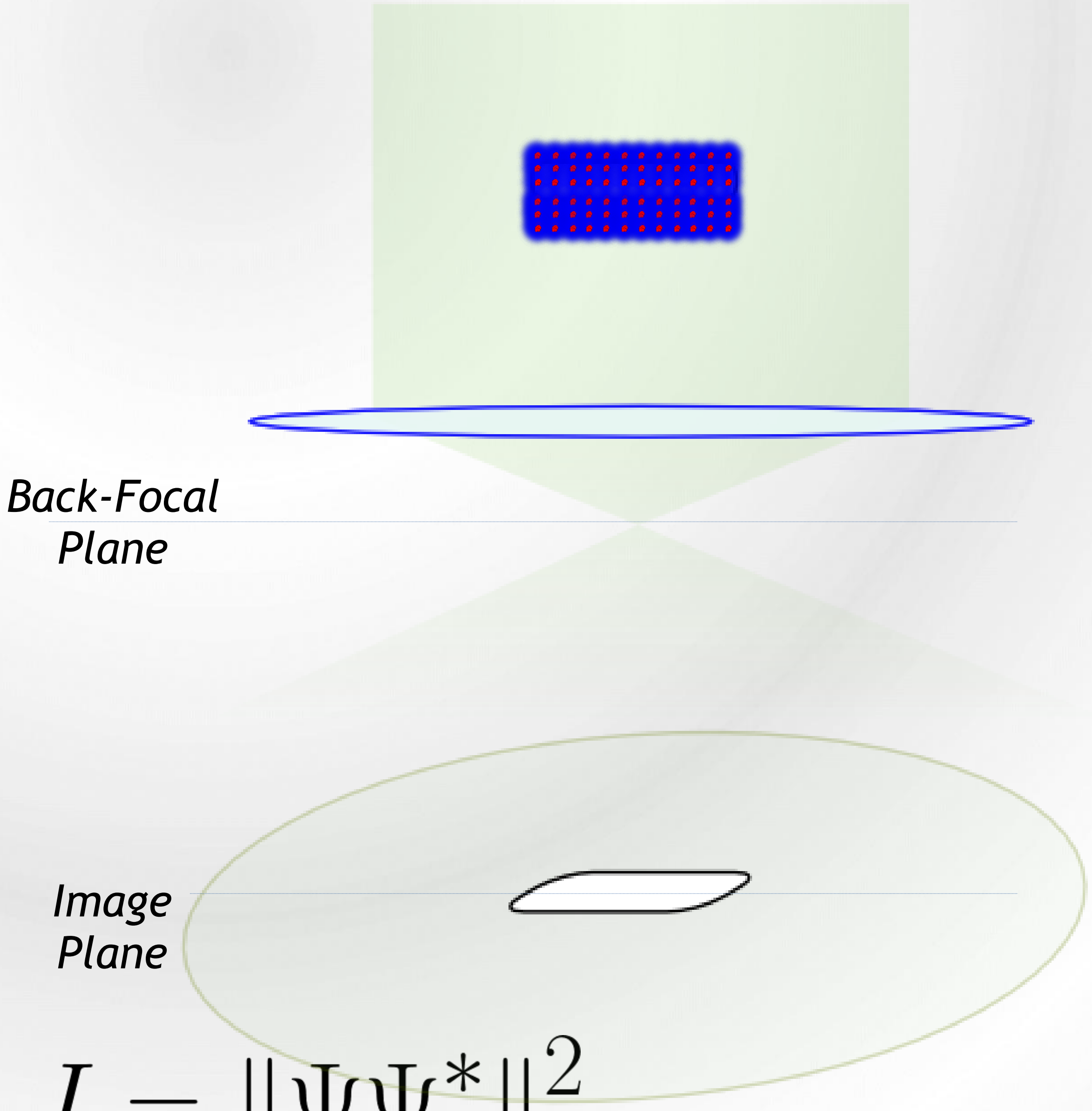

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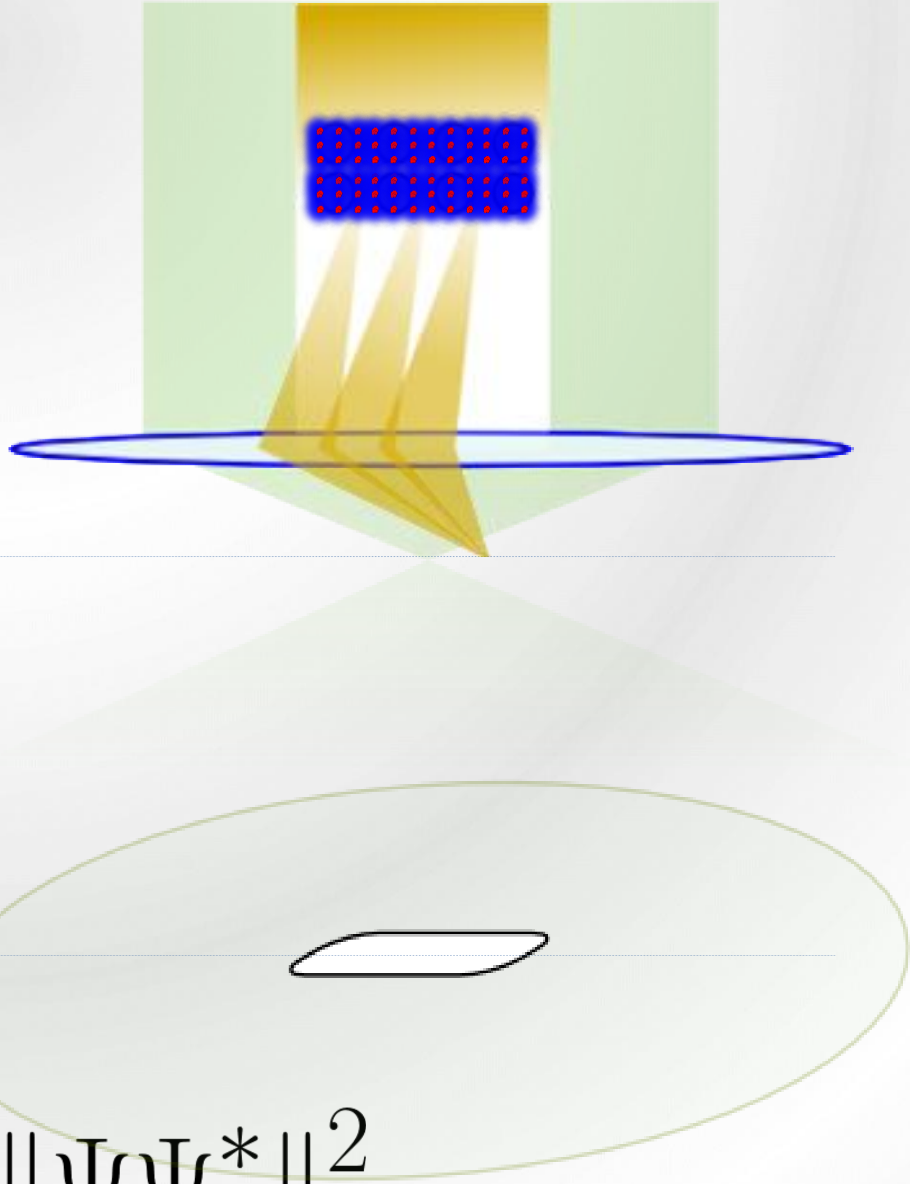
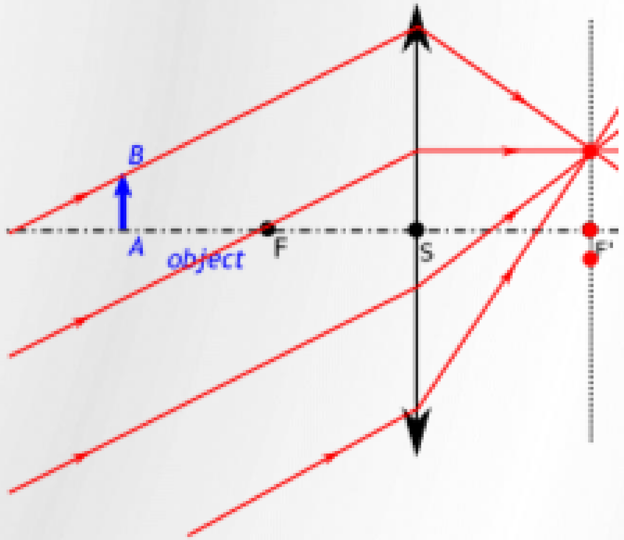


Back-Focal Plane

Image Plane

Electron diffraction



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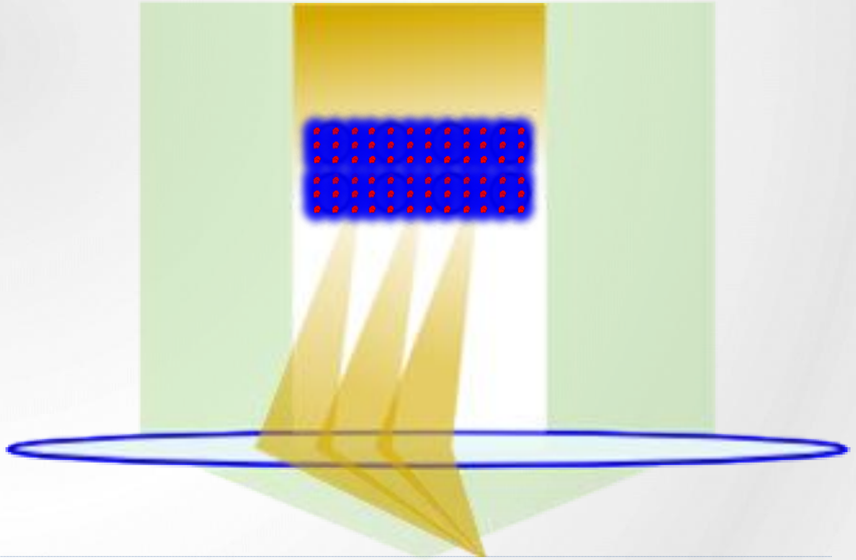
Introduction to Transmission, Electron & Microscopy



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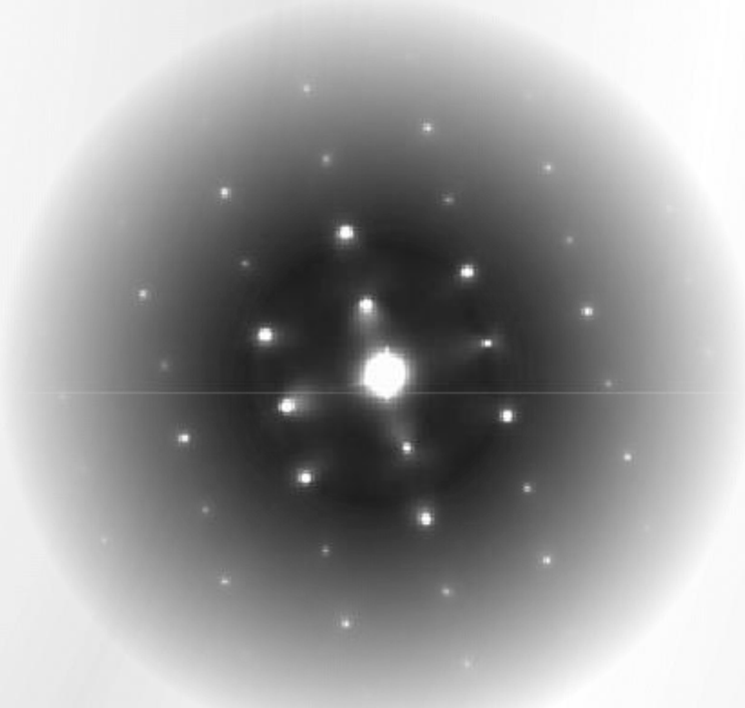
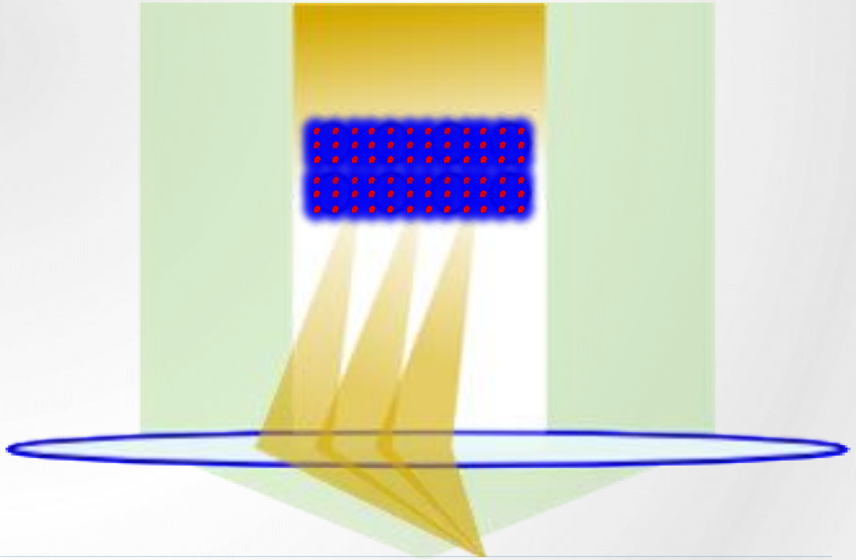


« Image » of Reciprocal Lattice

Image Plane

$$I = \|\Psi\Psi^*\|^2$$

Introduction to Transmission, Electron & Microscopy



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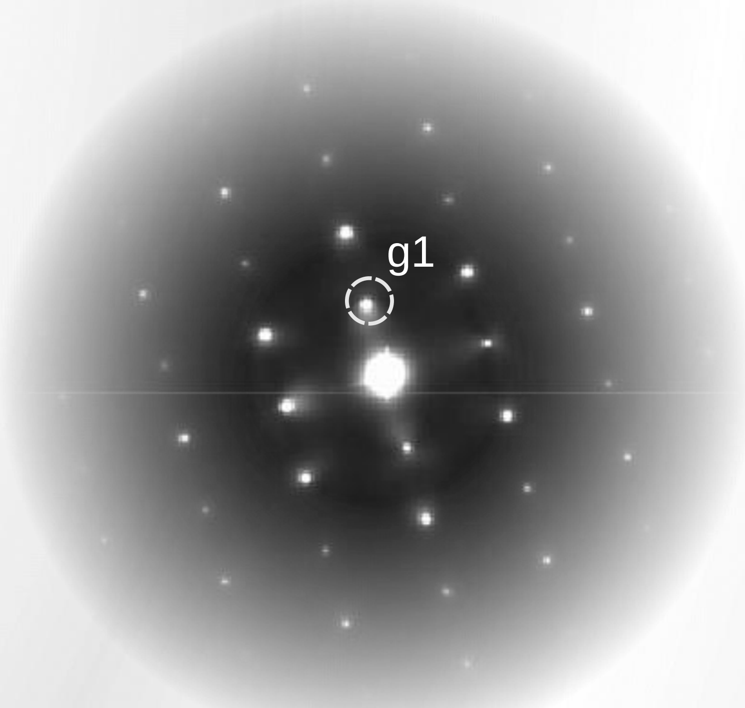

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Image Plane

$$I = \|\Psi\Psi^*\|^2$$

$$\Psi_d = \Psi_i \cdot f^e(\vec{K}) \cdot e^{-i\vec{k}_d \cdot \vec{r}}$$

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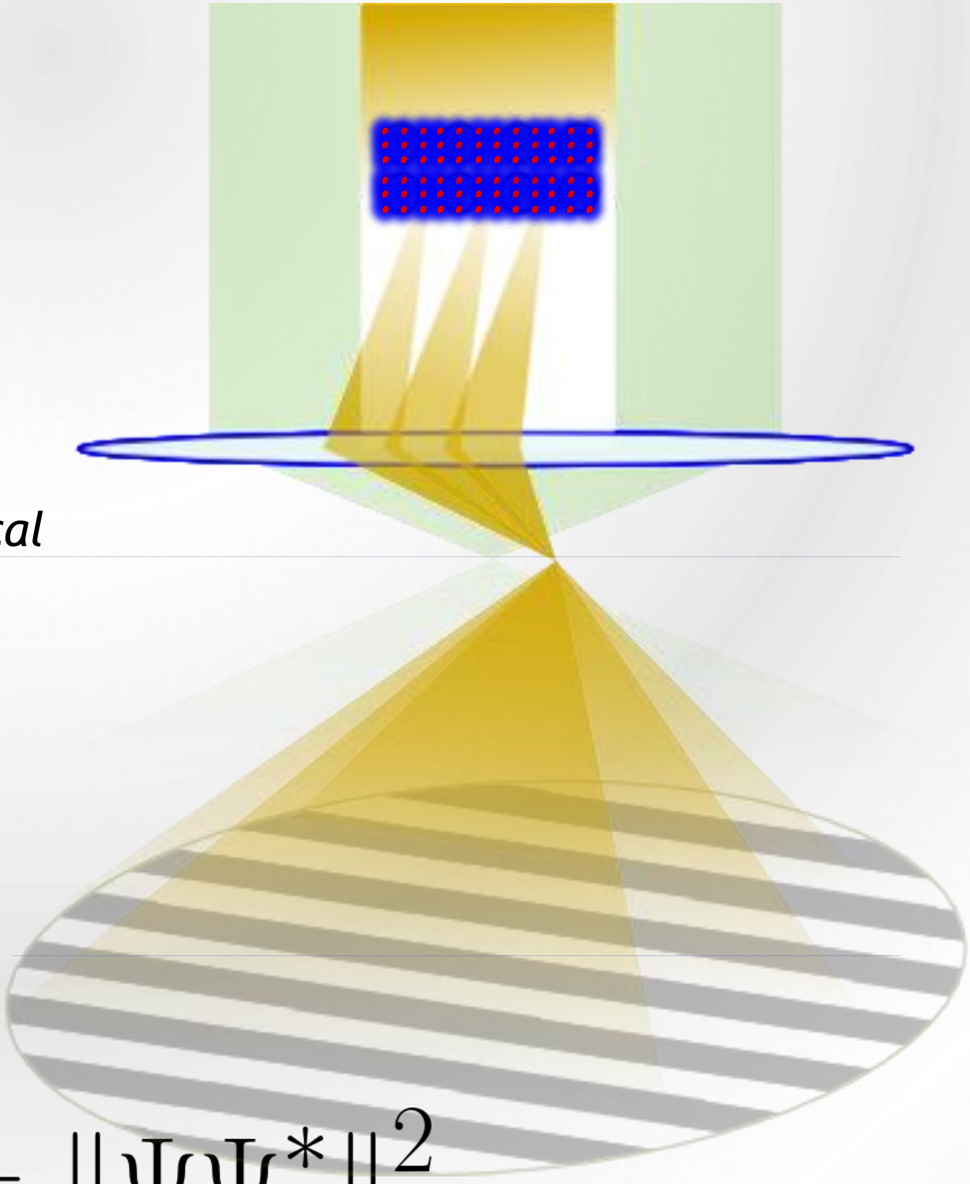

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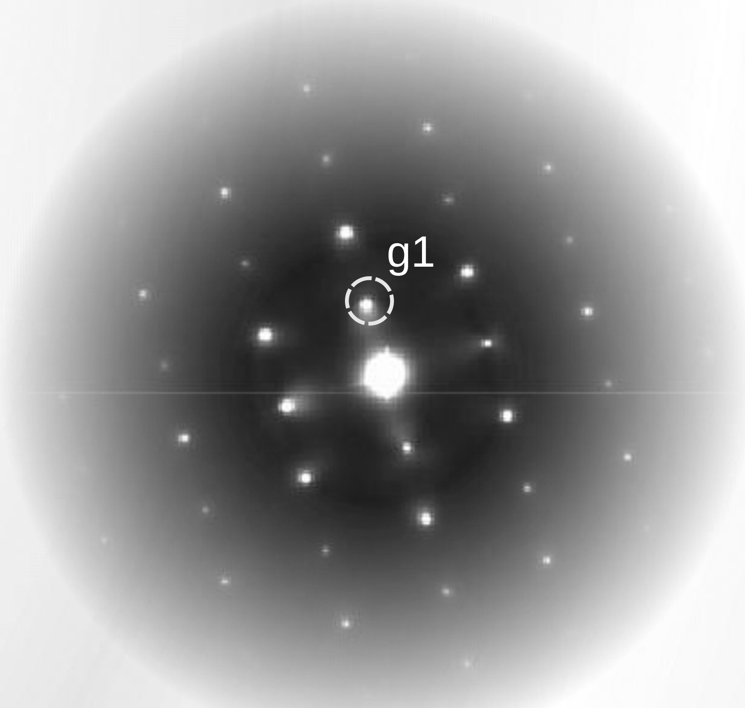
Electron diffraction



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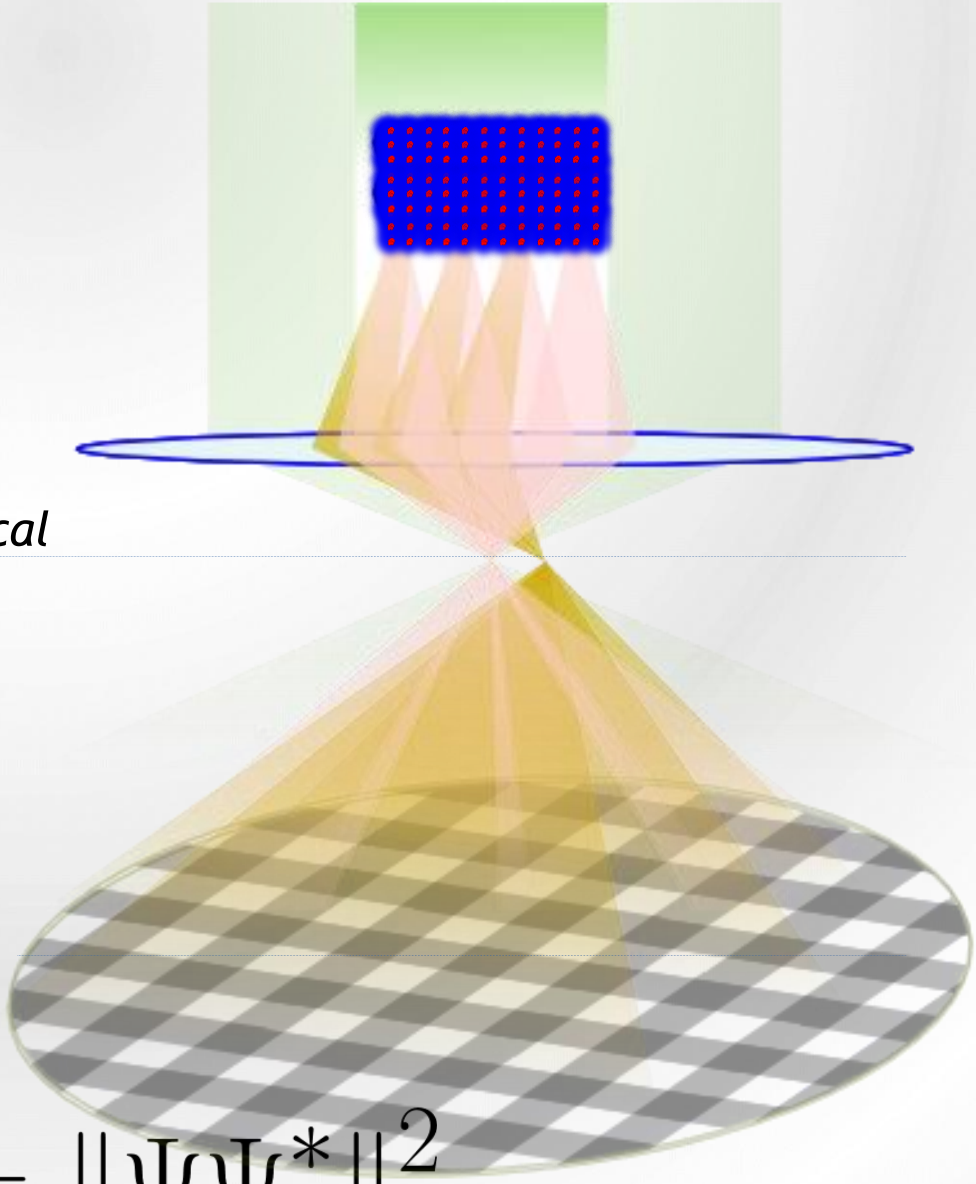

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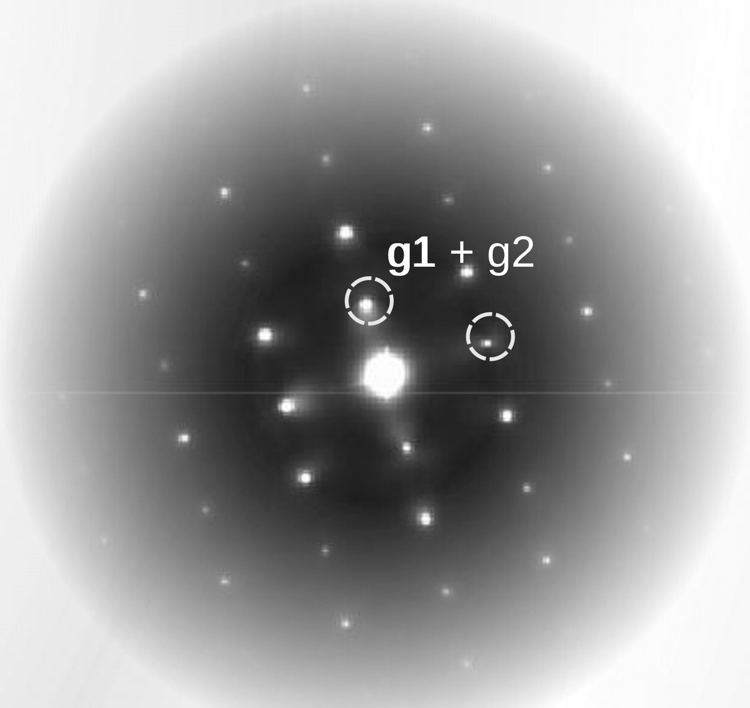
Electron diffraction



« Image » of Reciprocal Lattice

$$\Psi = \sum_g \tilde{\Psi}_g \cdot e^{2i\pi\vec{g}.\vec{r}}$$

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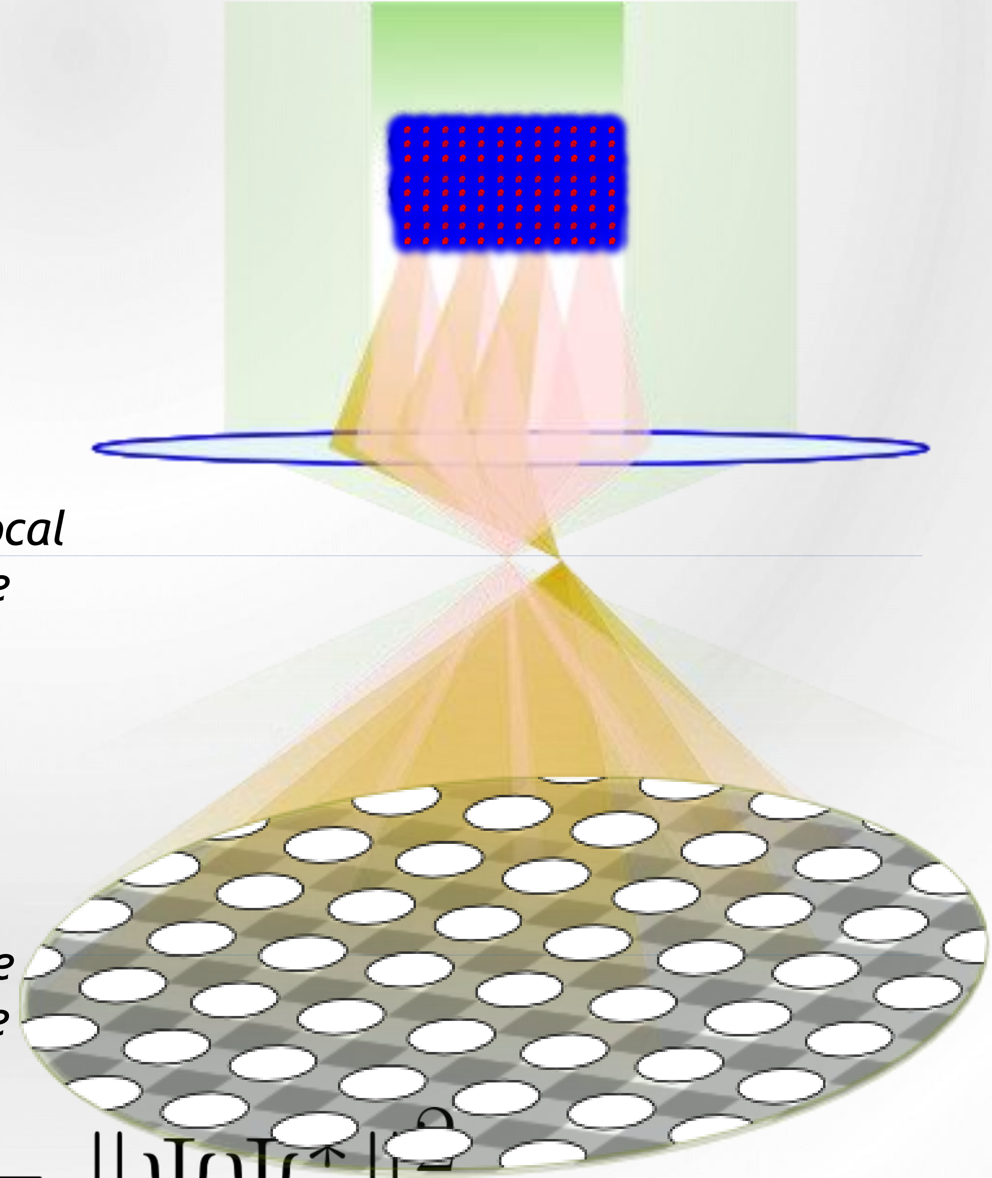

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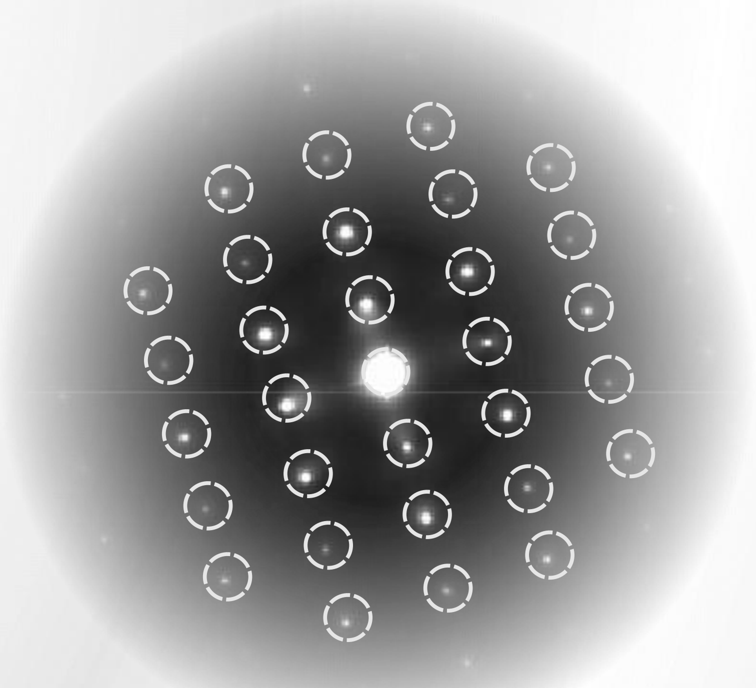
Electron diffraction



« Image » of Reciprocal Lattice

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Julien-Léopold Boilly, Public domain

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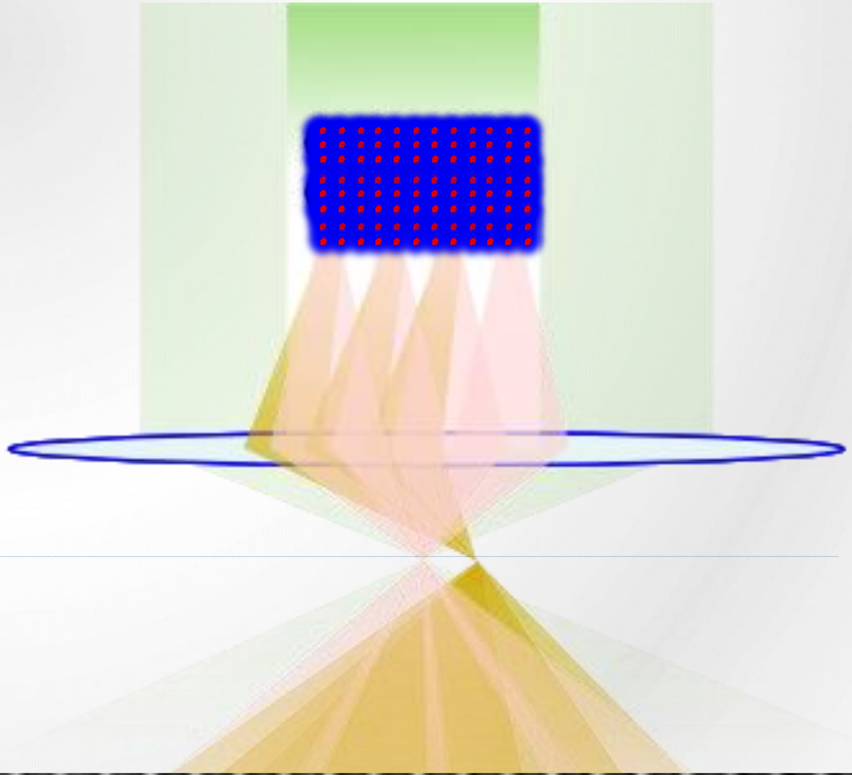
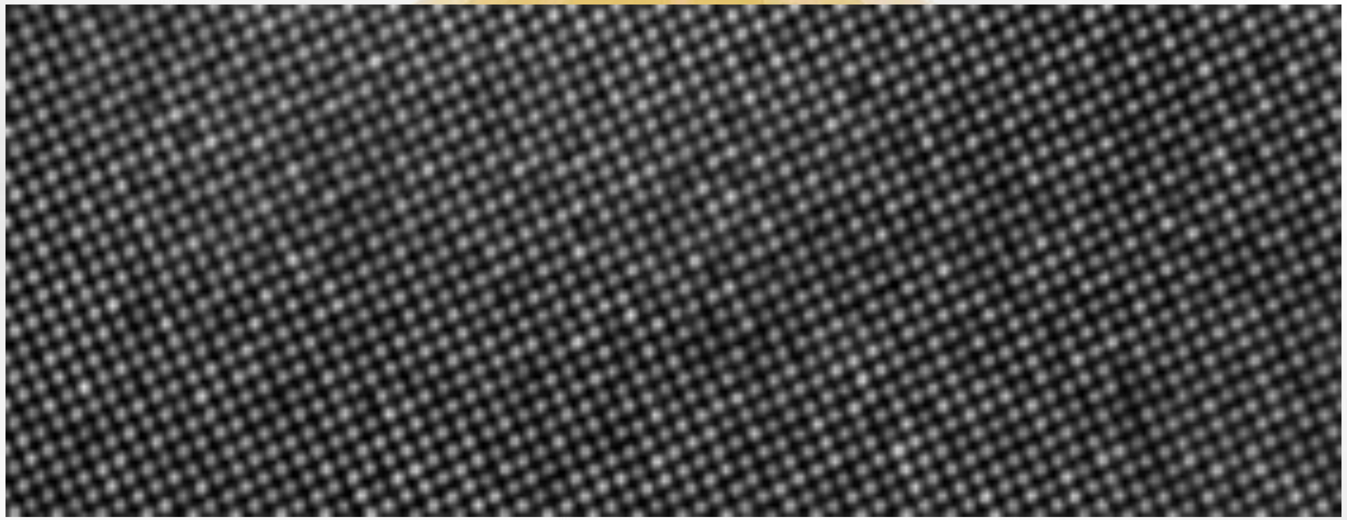
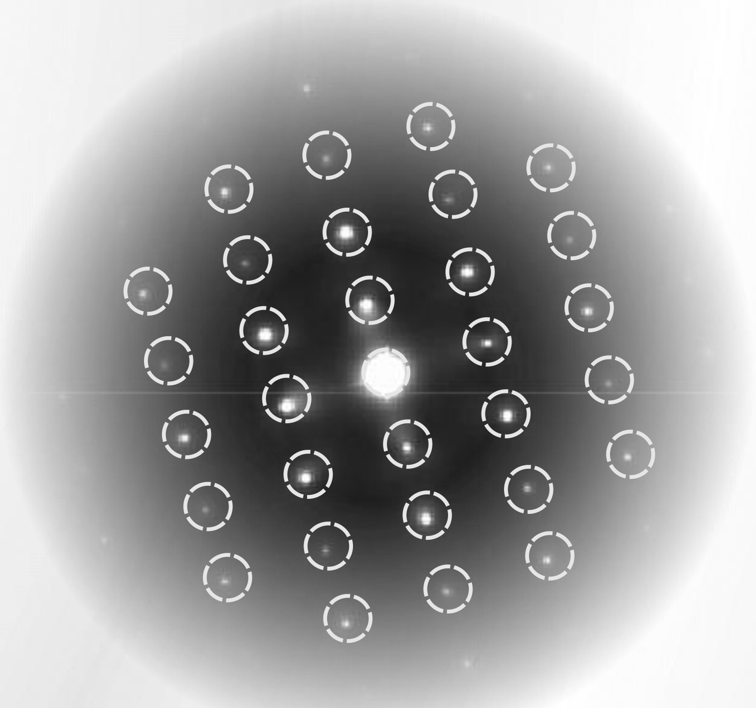


Back-Focal Plane



Electron diffraction



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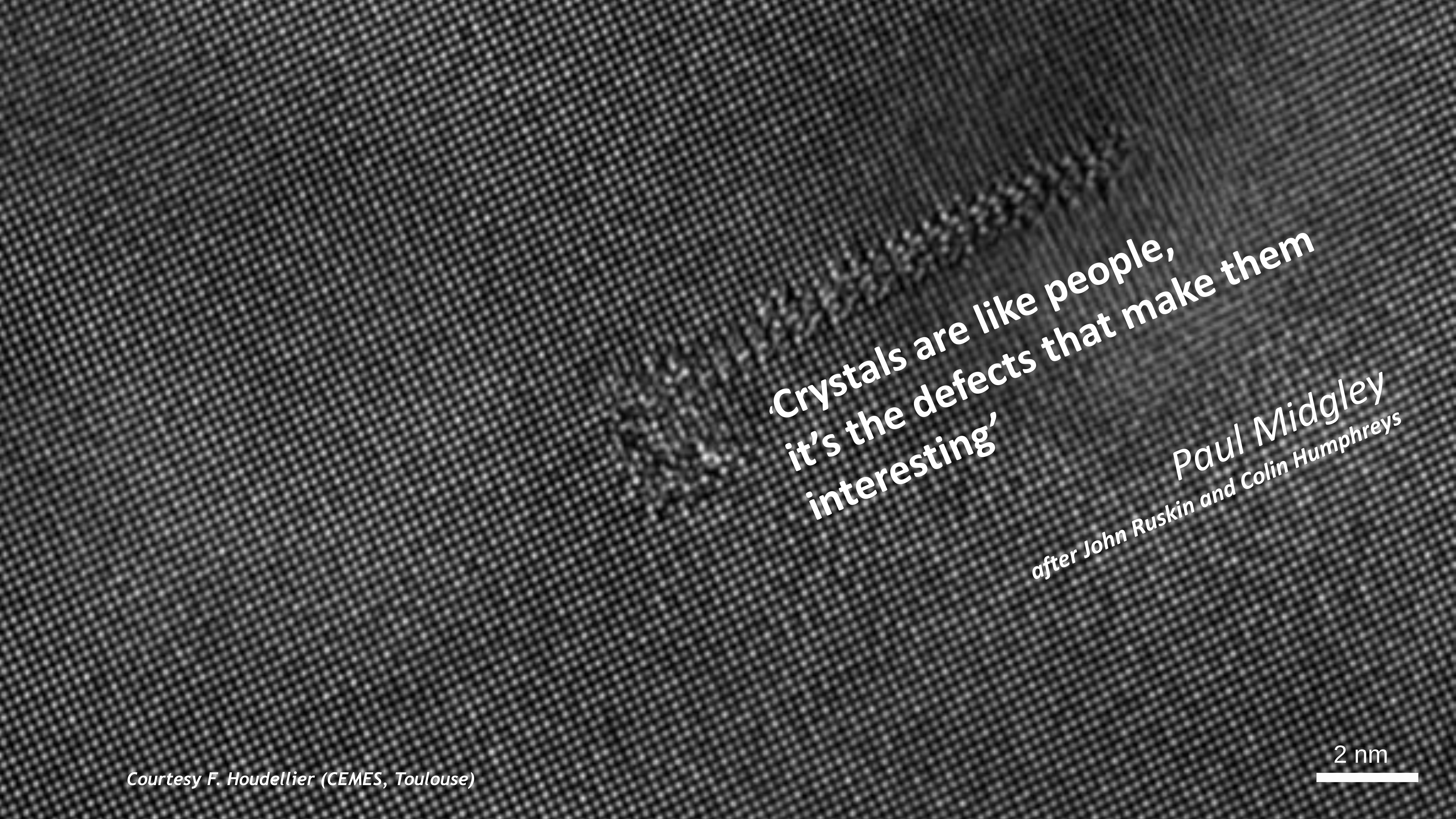
‘Crystals are like people,
it’s the defects that make them
interesting’
Paul Midgley
after John Ruskin and Colin Humphreys
2 nm
Courtesy F. Houdellier (CEMES, Toulouse)

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2 nm