Shining a light on synchrotron light

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OUTLINE

Brilliance, emittance… coherence

Synchrotron light: waves and photons

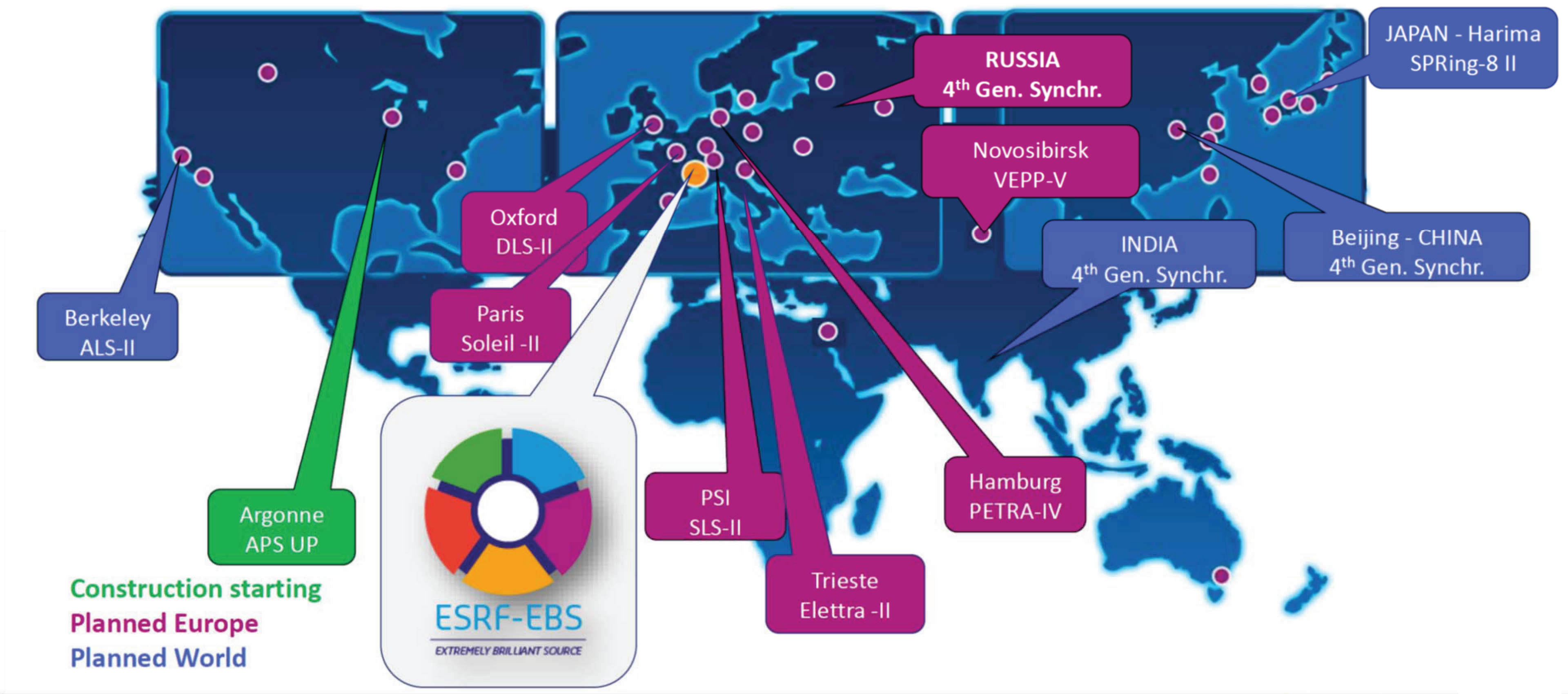
Scattering and absorption

Diffraction, Spectroscopy, Imaging beamlines

Conclusion


Why?
Because its light is brilliant
There are now
more than 50 synchrotron light sources
In the world.

At least 13 upgrade programs in the world…
…to increase brilliance



Credit: Francesco Sette ESRF

Brilliance

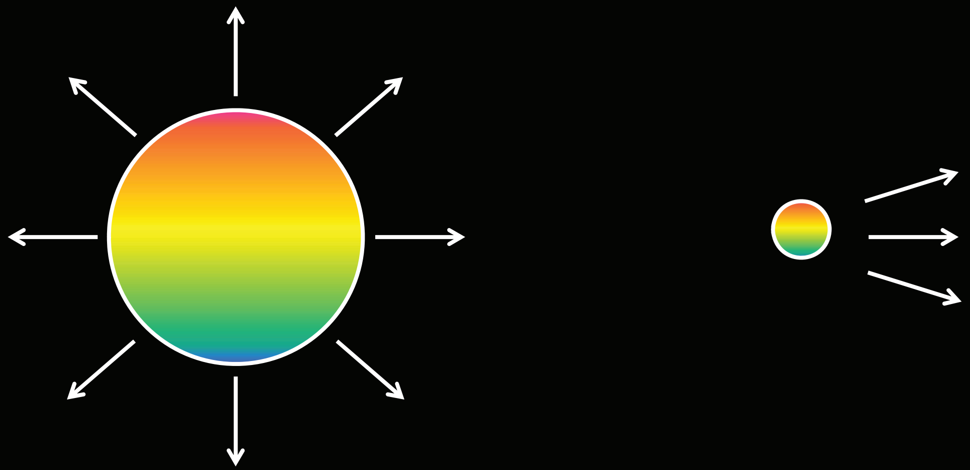
Emittance

Coherence

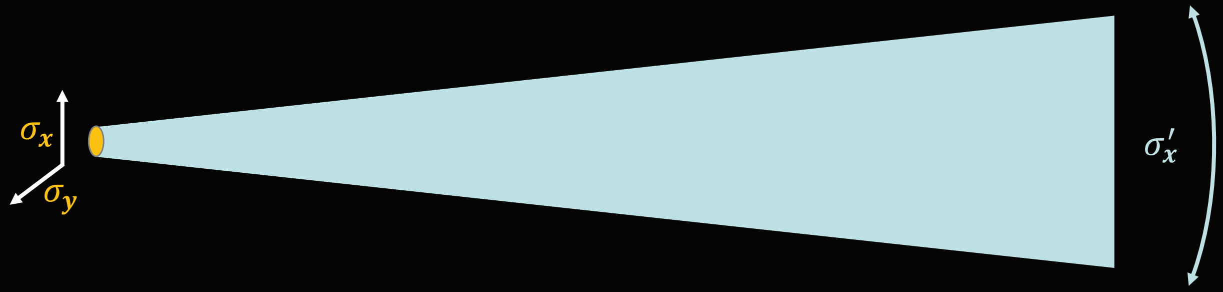
Brilliance (or brighness) of a light Source

The more a source is :
Intense
Small
Parrallel

The more it is brilliant



Light source
(and spectral brilliance)



Flux : in ph/s in $\frac{1}{1000}$ bandwidth

Source size σ_x, σ_y: in mm

Divergence σ'_x, σ'_y: in mrad

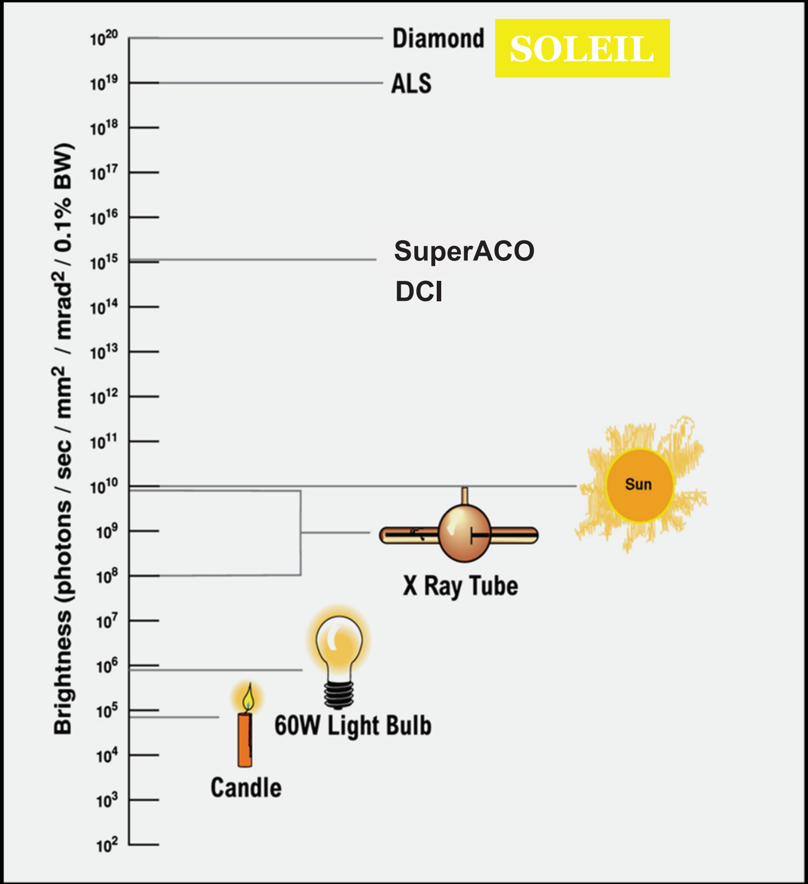
Spectral brilliance:

Flux divided by size and divergence of the source

$$B = \frac{F}{\sigma_x \sigma'_x \sigma_y \sigma'_y}$$

$$\frac{[\text{ph/s}]}{[\text{mm}]^2[\text{mrad}]^2[0{,}1\%\text{bandwidth}]} \text{ (= UB)}$$

Brilliance: a figure of merit



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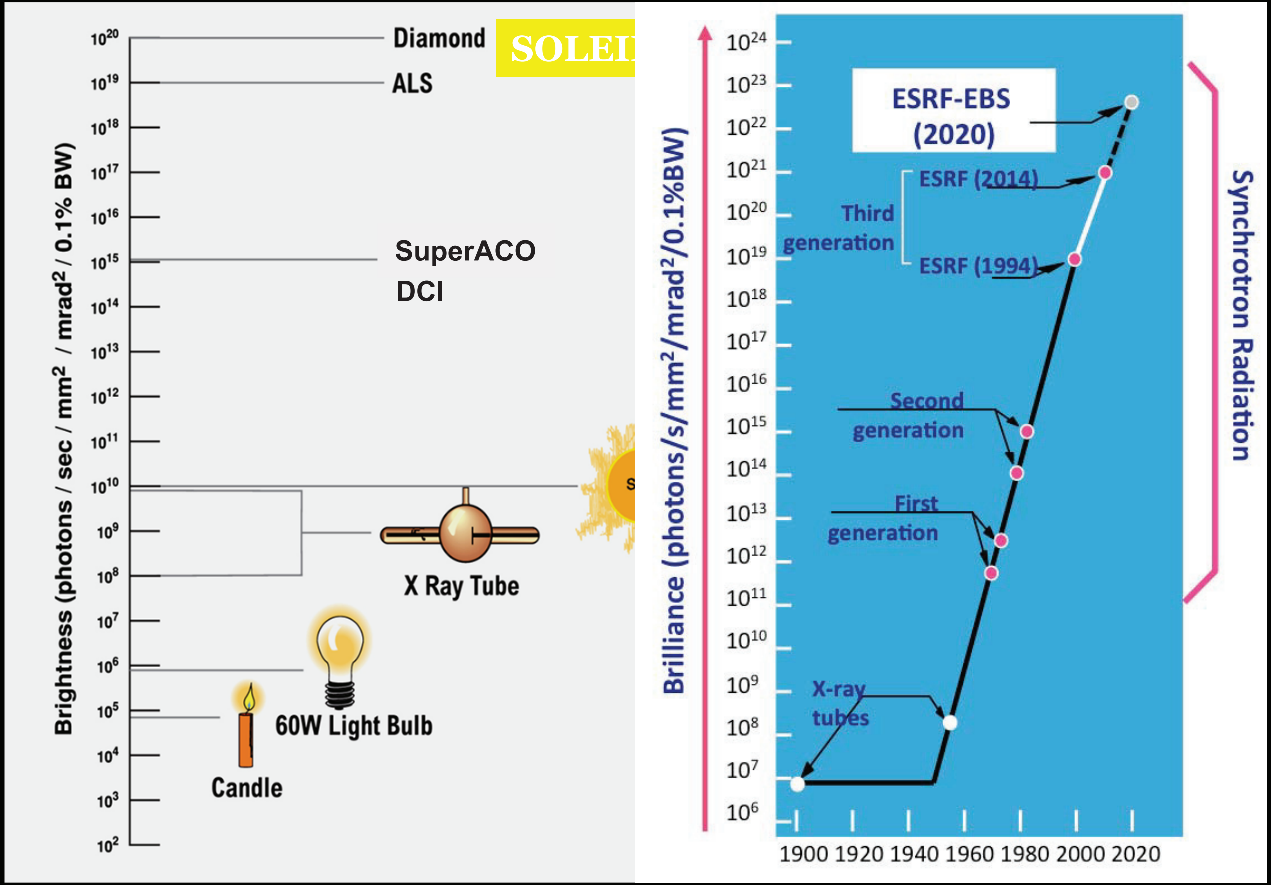

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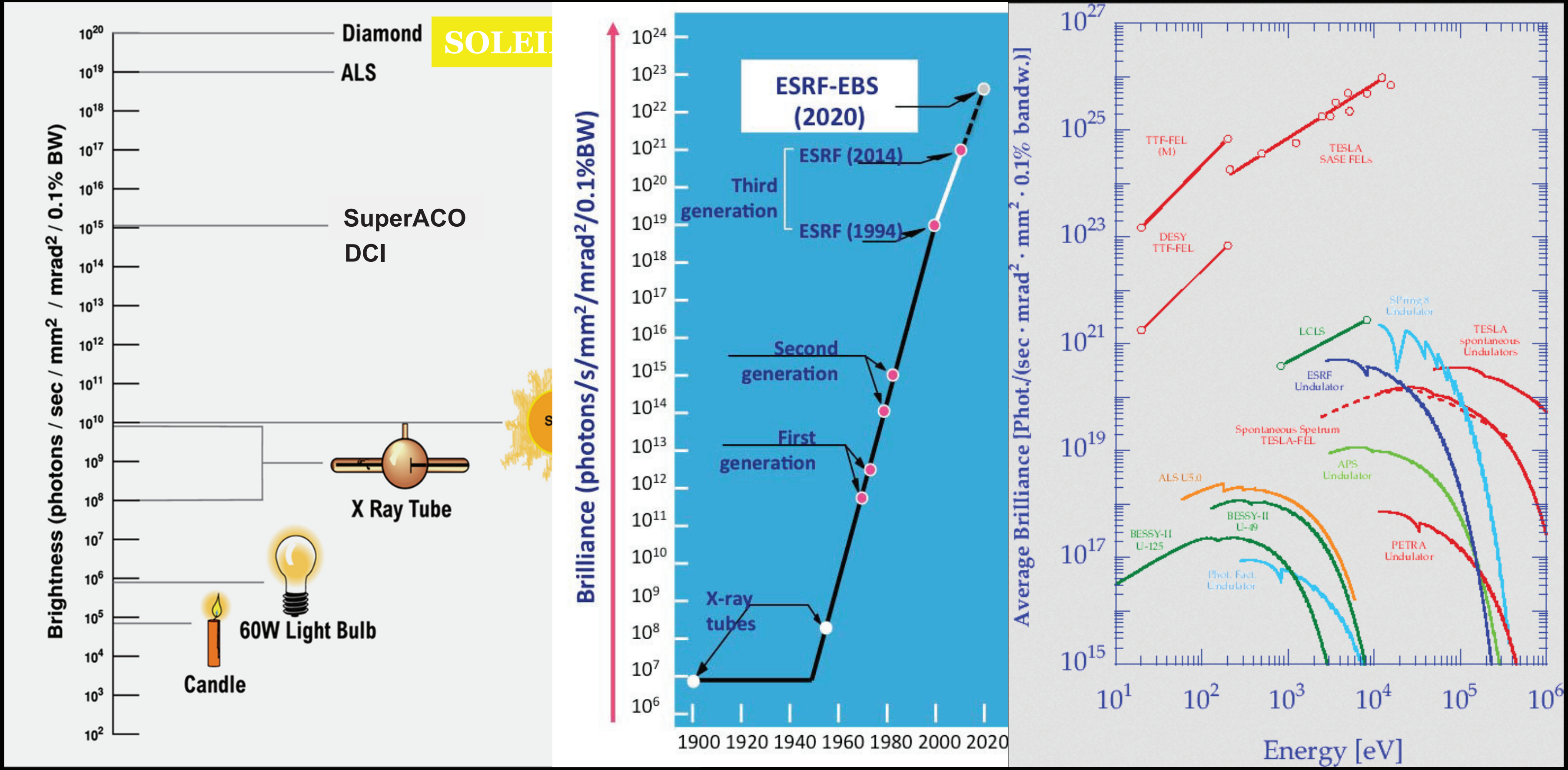
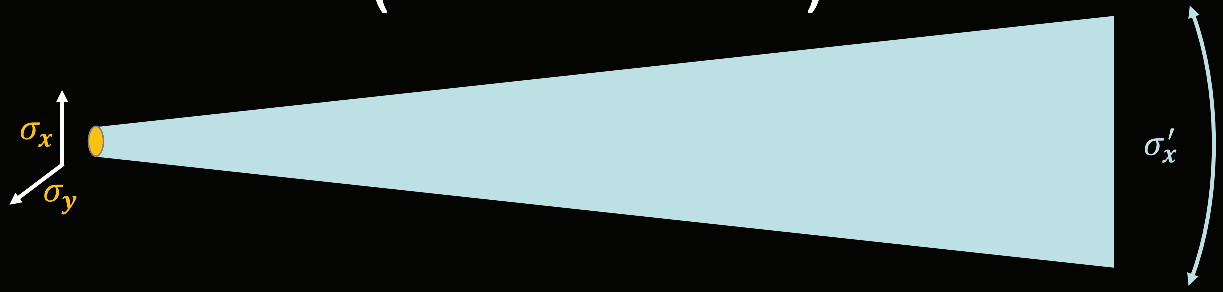


Light source
(and emittance)



$$B = \frac{F}{\sigma_x \sigma'_x \sigma_y \sigma'_y}$$

Emittance: $\varepsilon_x = \sigma_x \sigma'_x$
Vertical x and horizontal y

$$B = \frac{F}{\varepsilon_x \varepsilon_y}$$

The smaller the emittance
The higher the brilliance

Brilliance and emittance

$$B = \frac{F}{\varepsilon_x \varepsilon_y}$$

Increasing the brilliance consists in decreasing the emittance
Yes, but there is a lower limit for the emittance:

The limit of diffraction

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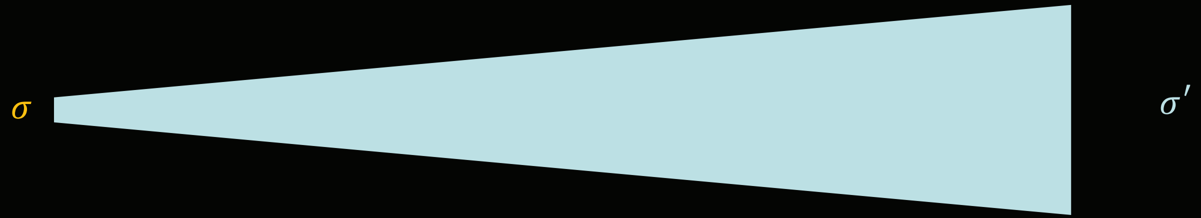

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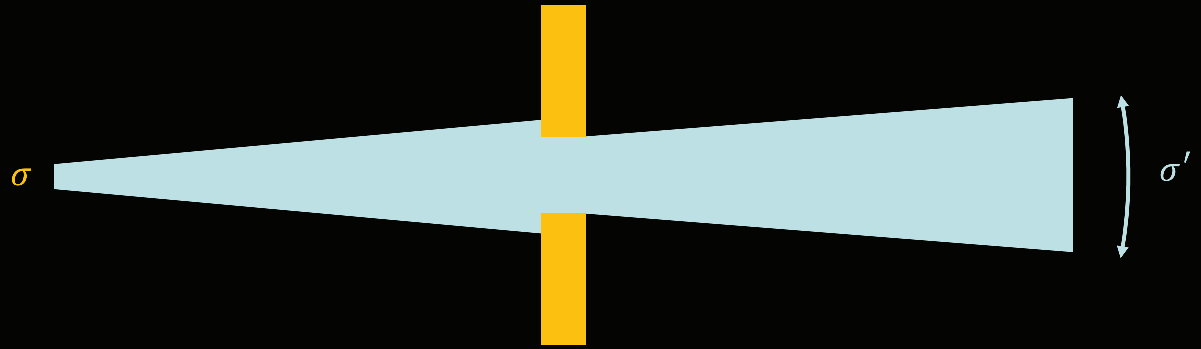

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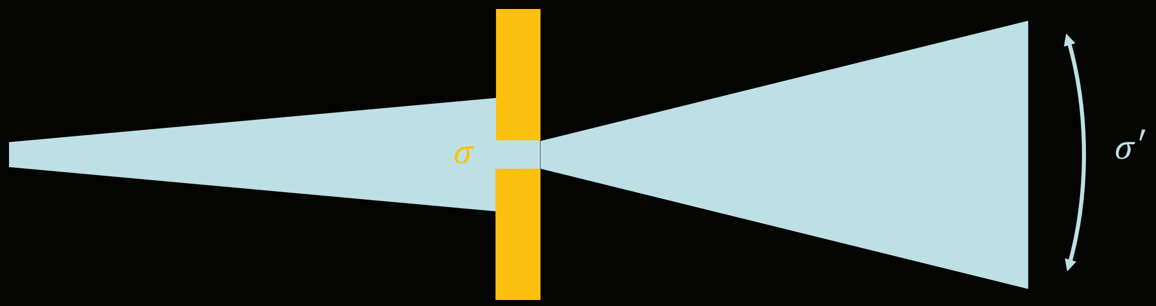

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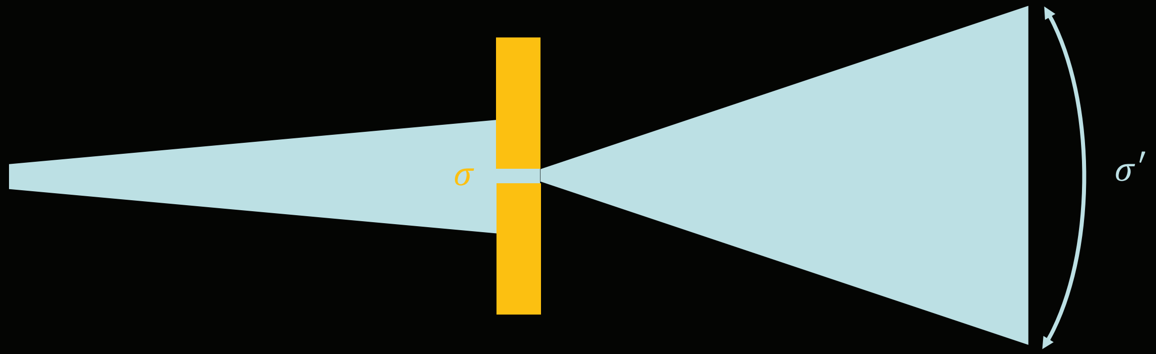

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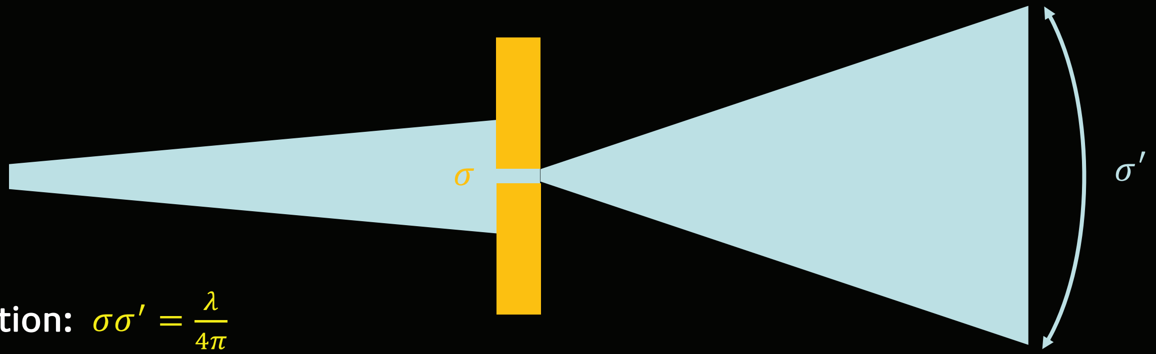

Theory of diffraction: $\sigma\sigma' = \frac{\lambda}{4\pi}$

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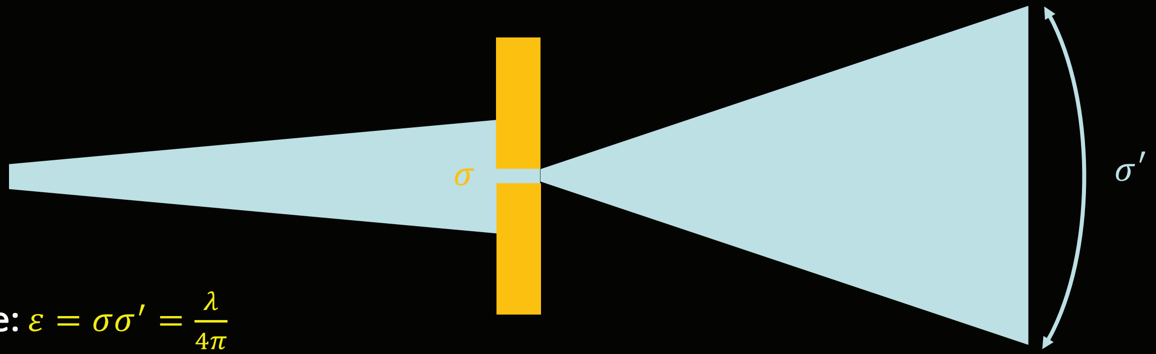


Mimimum emittance: $\varepsilon = \sigma\sigma' = \frac{\lambda}{4\pi}$

Rule of the thumb: 10 keV ⇔10 pm.rad

Diffraction limited or Extremely brilliant

Reaching this value would give fully coherent beam
And an extremely brilliant beam

Currently ESRF : 3800 pm.rad; APS 3000 pm.rad; SOLEIL 3700 pm.rad

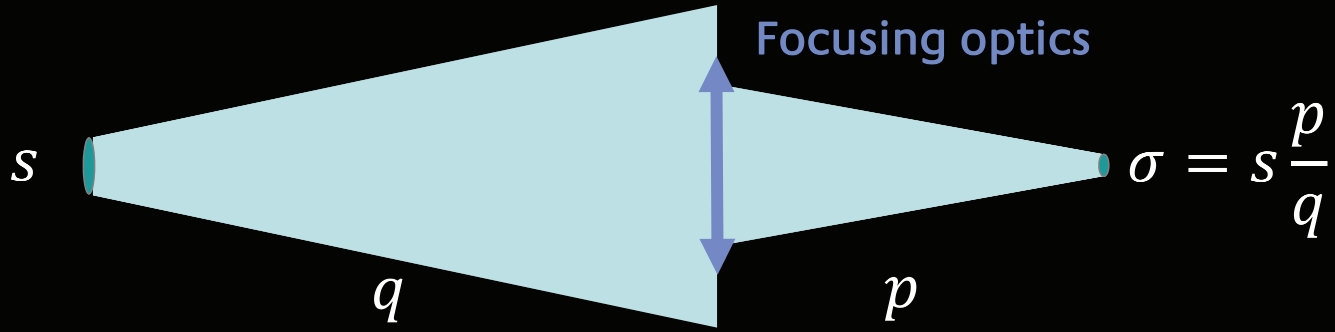
New possibilities using multi-bend achromat lattice
MAX IV 330 pm.rad; EBS-ESRF 134 pm.rad
Projects: SOLEIL 70 pm.rad; PETRA IV: 10 pm.rad

Increasing the brilliance: why?

Nanobeams

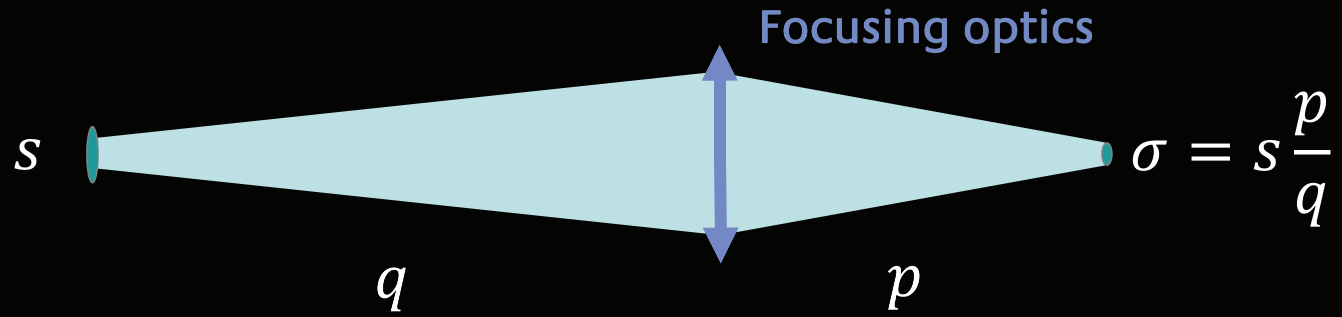
Coherence

Why increasing the brilliance?



Beam is easier to focus (few 10 nm)
S is small (brilliance)
Adapted to small numerical aperture of optics (brilliance)
p/q is small (long beamlines);

Why increasing the brilliance?



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Diffraction micro- and nano-crystals ; extreme conditions
Scanning imaging (sub-micron, STXM)
Parallel beam (powder diffraction, SAXS)
Coherence

Characteristics of synchrotron light

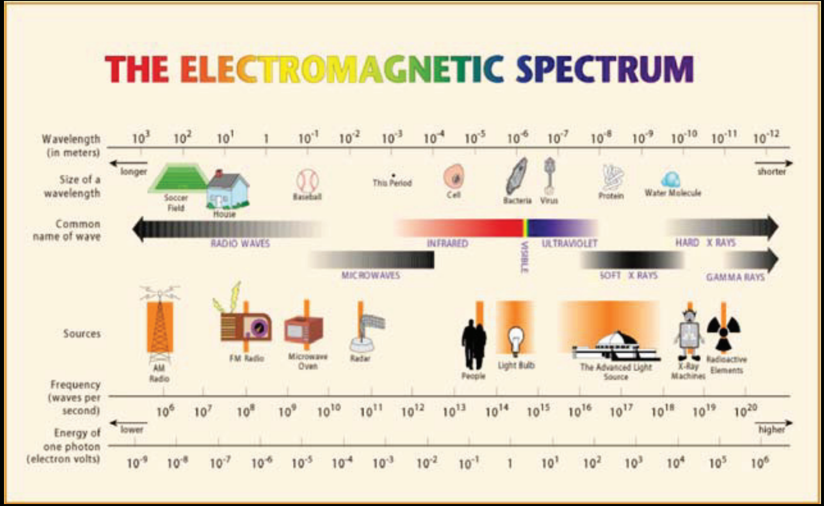
Thomas Young

1773-1829

Augustin Fresnel

1788-1827

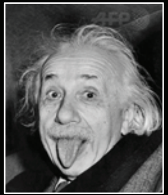
~ 1800



Max Plank

1858-1947

Albert Einstein



1879-1955

~ 1900

Waves are caracterized by their:

Wavelengths λ (Å, nm), frequencies ν (Hz)

Needed to interpret phenomena where scattering is involved

Photons are caracterized by their:

Energy $h\nu$ (eV)

Needed to interpret phenomena where absorption is involved

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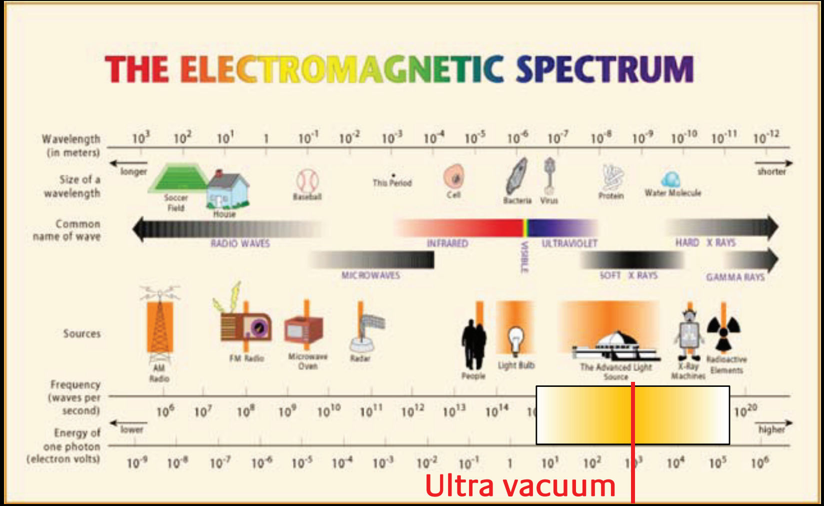

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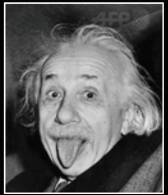

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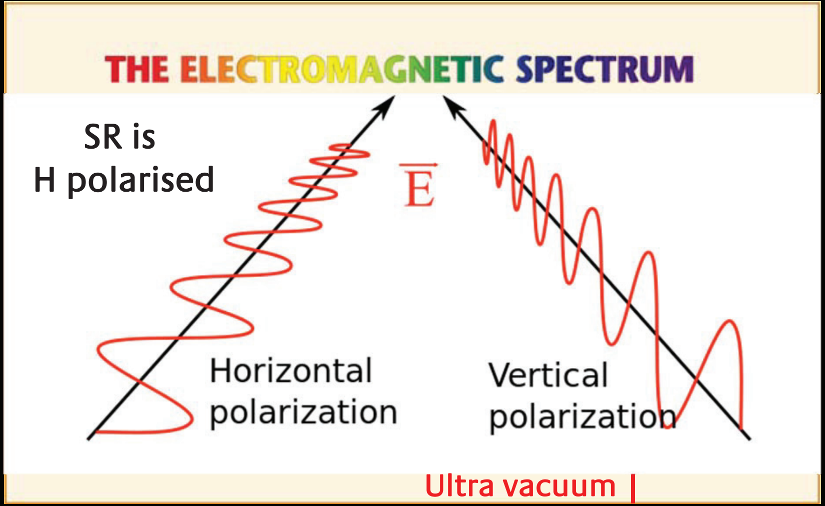

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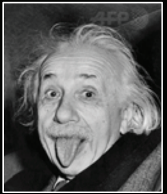

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Complementarity

Two families of beamlines

Beamlines using scattering
(and diffraction)

- Diffraction beamlines (MX)
- Small angle scattering (SAXS)
- Surface diffraction

Beamlines using absorption
(and associated phenomena)

- X-ray Absorption Spectroscopy (XAS-EXAFS-XANES)
- Photoelectron spectroscopy (PES-ARPES)

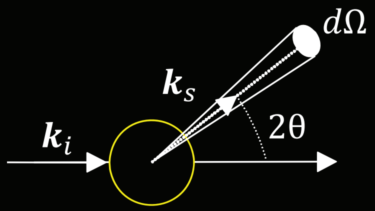
Imaging beamlines

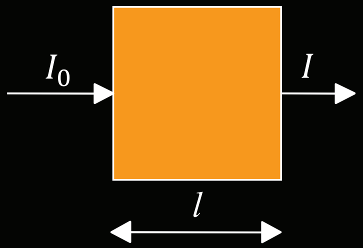
Can use both!
XPEEM, STXM, Tomography
Coherent diffraction imaging, Ptychography

Two processes of interaction between x-ray and matter

Scattering and Absorption

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

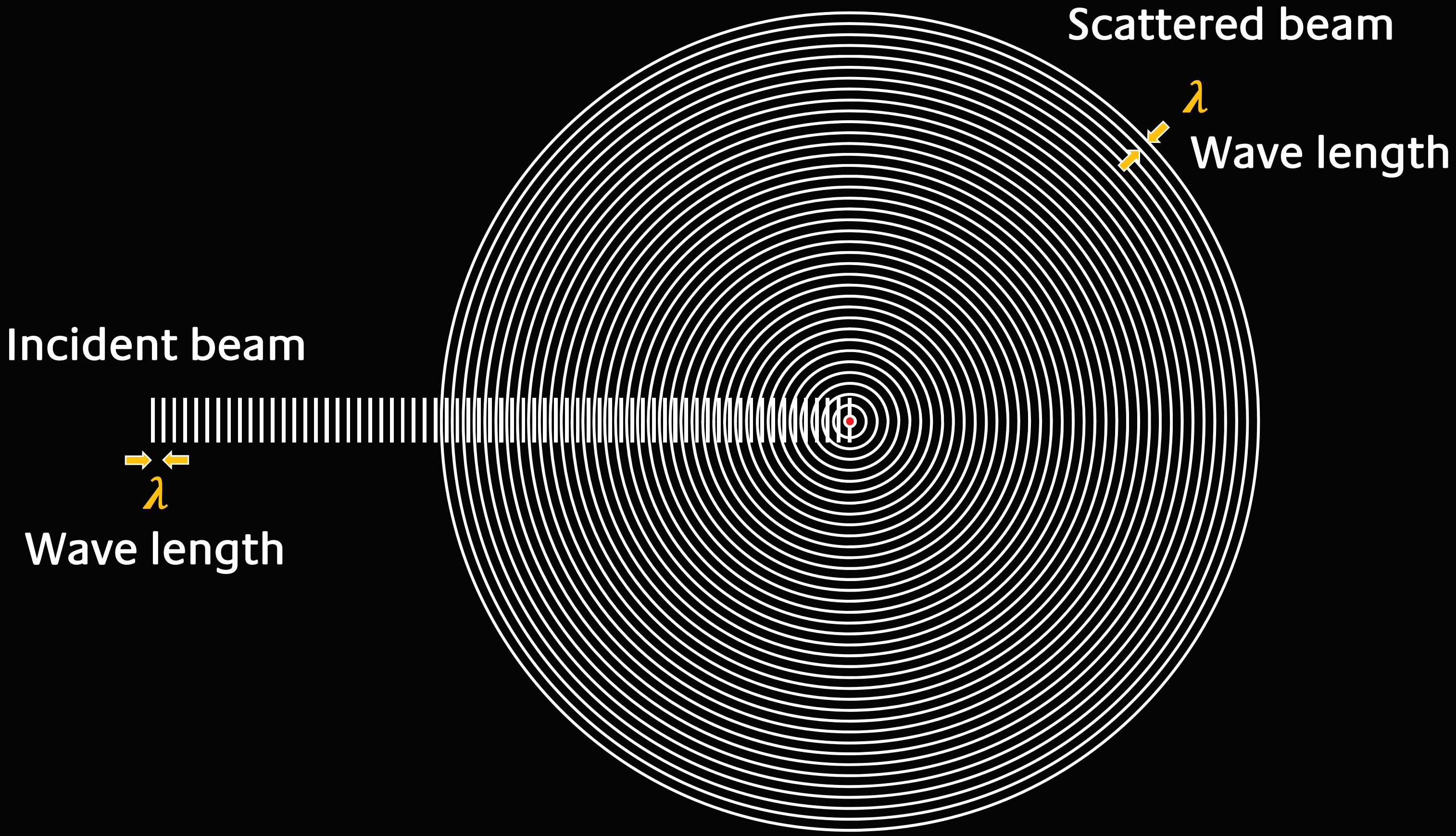




$$I = I_0 e^{-\mu l}$$

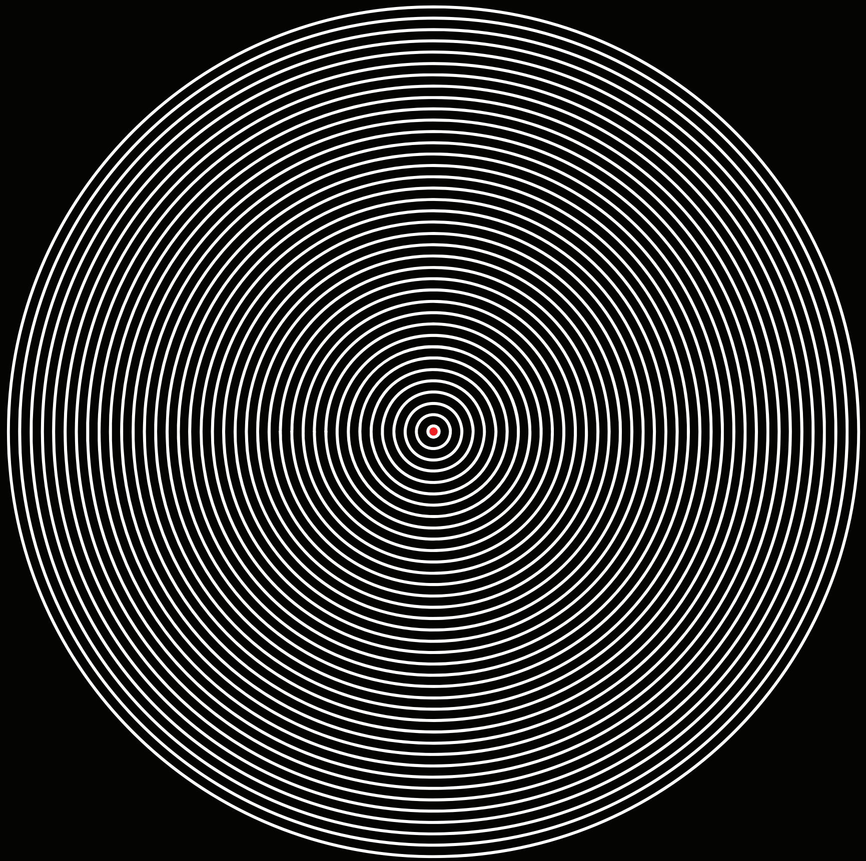
Scattering and diffraction

Scattering



Diffraction: principle

Interference



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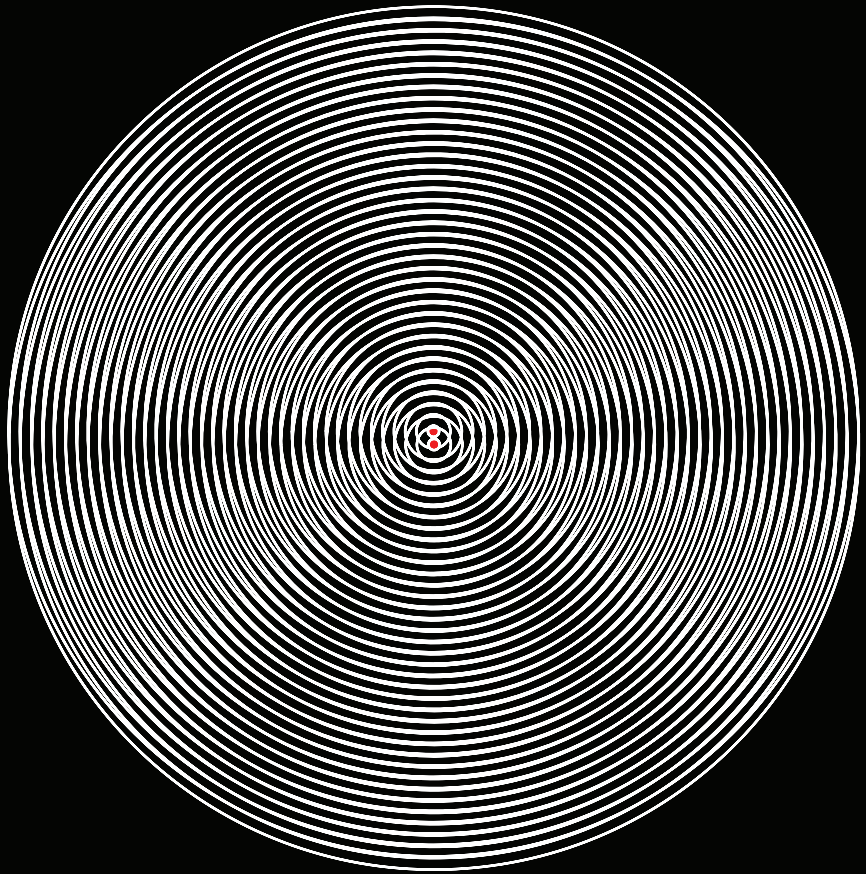

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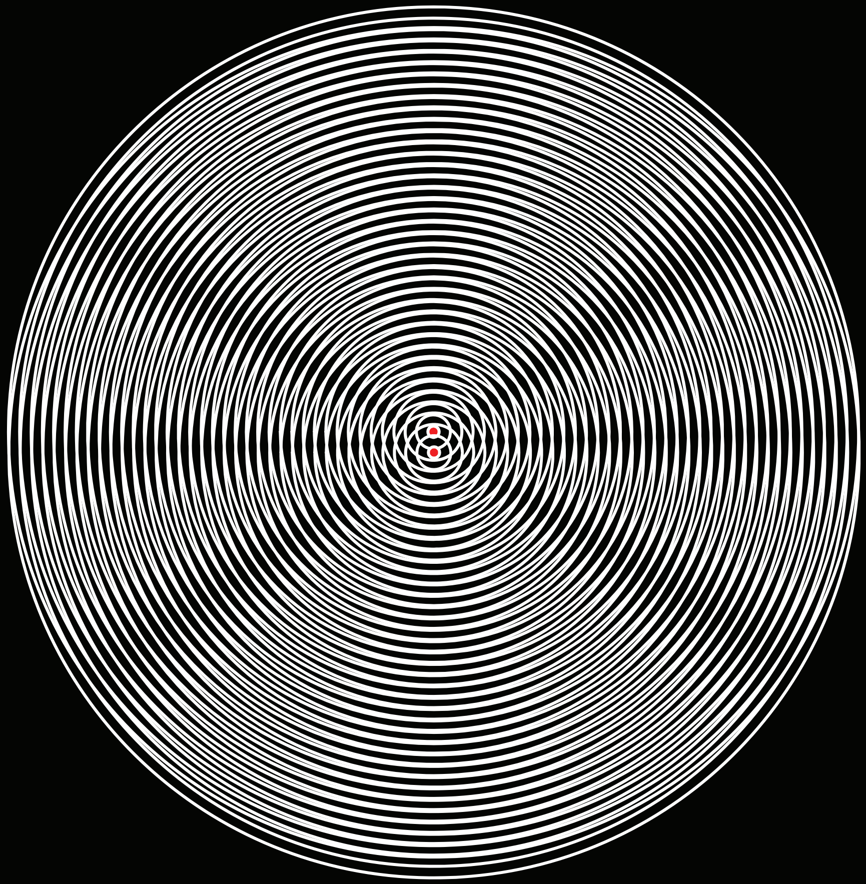

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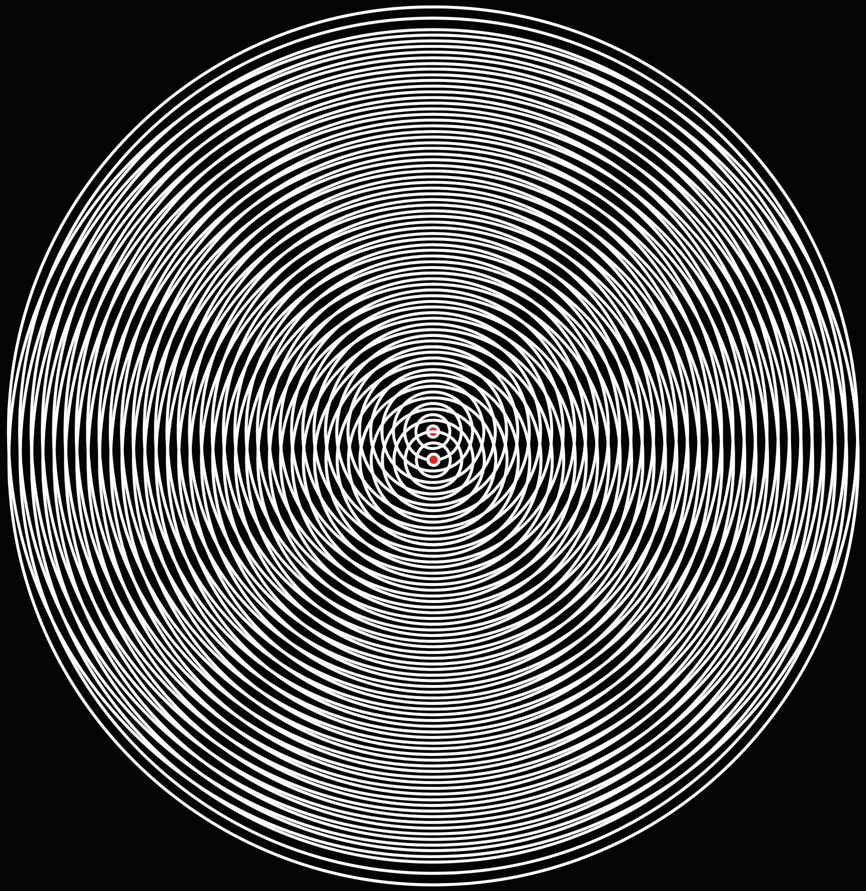

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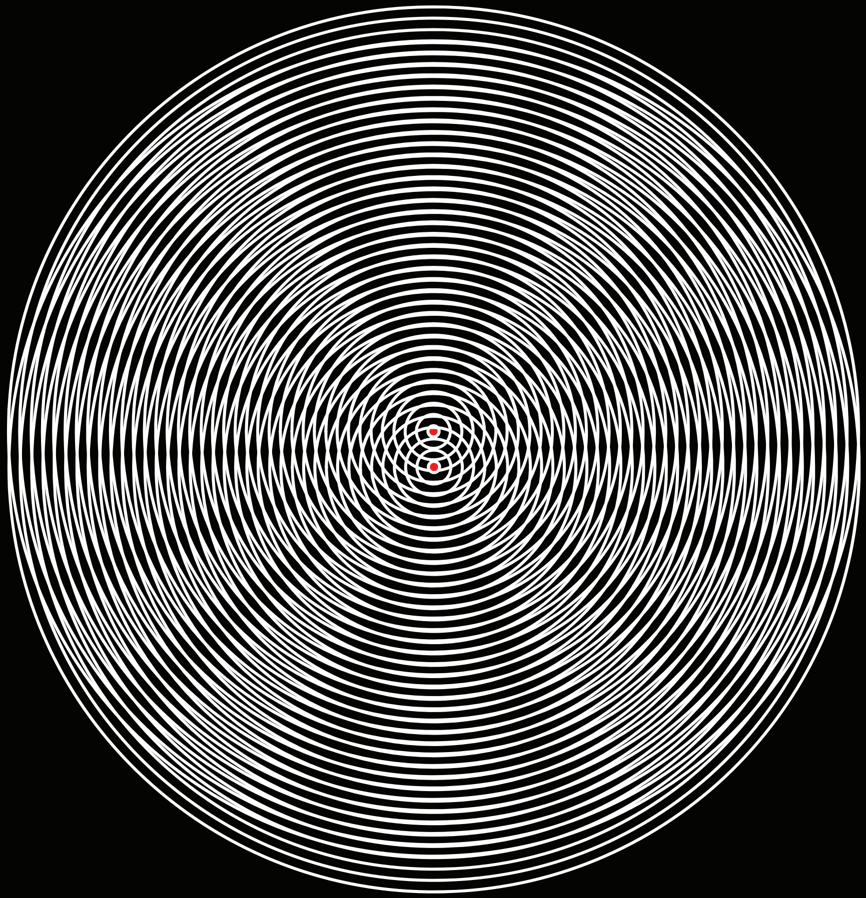

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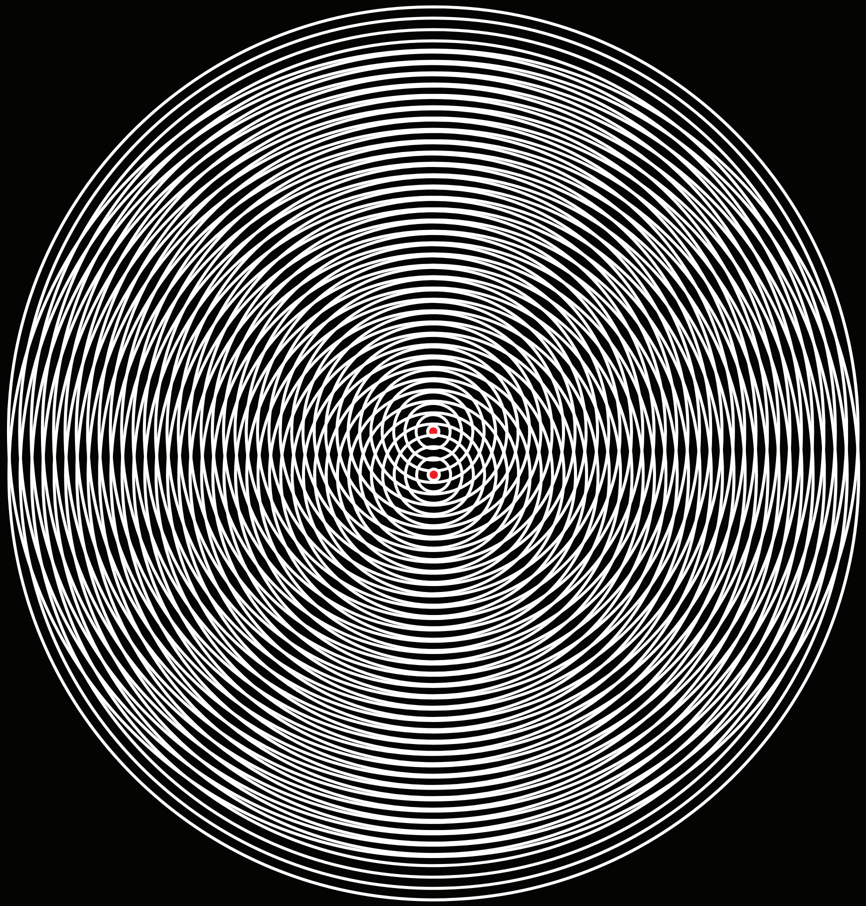

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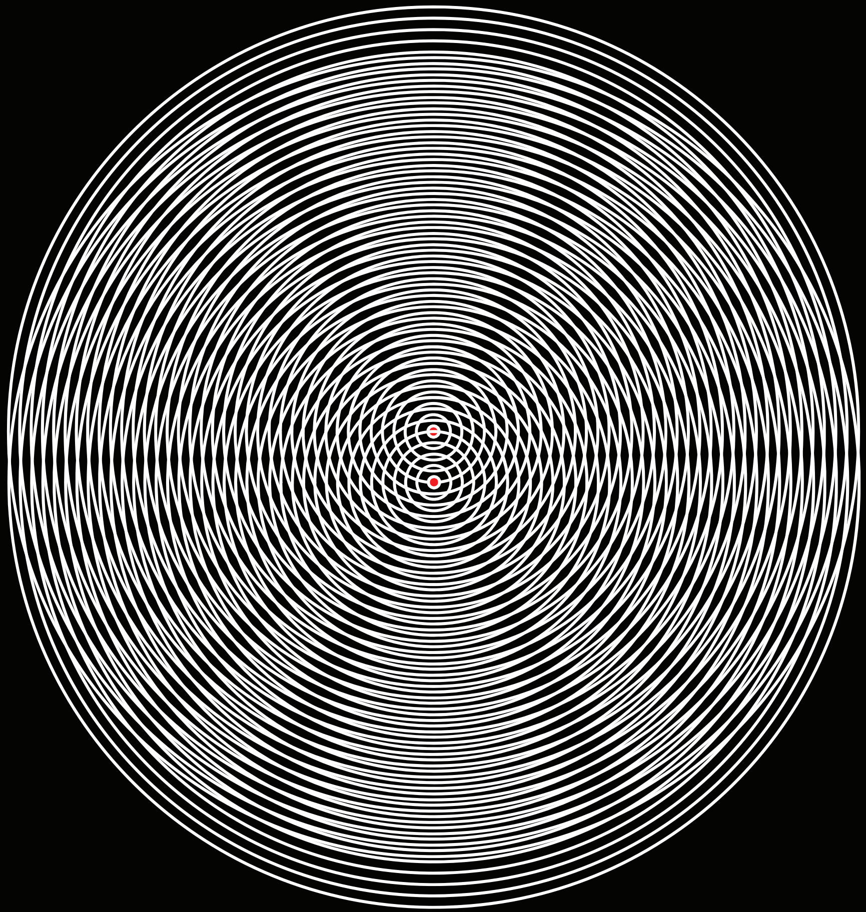

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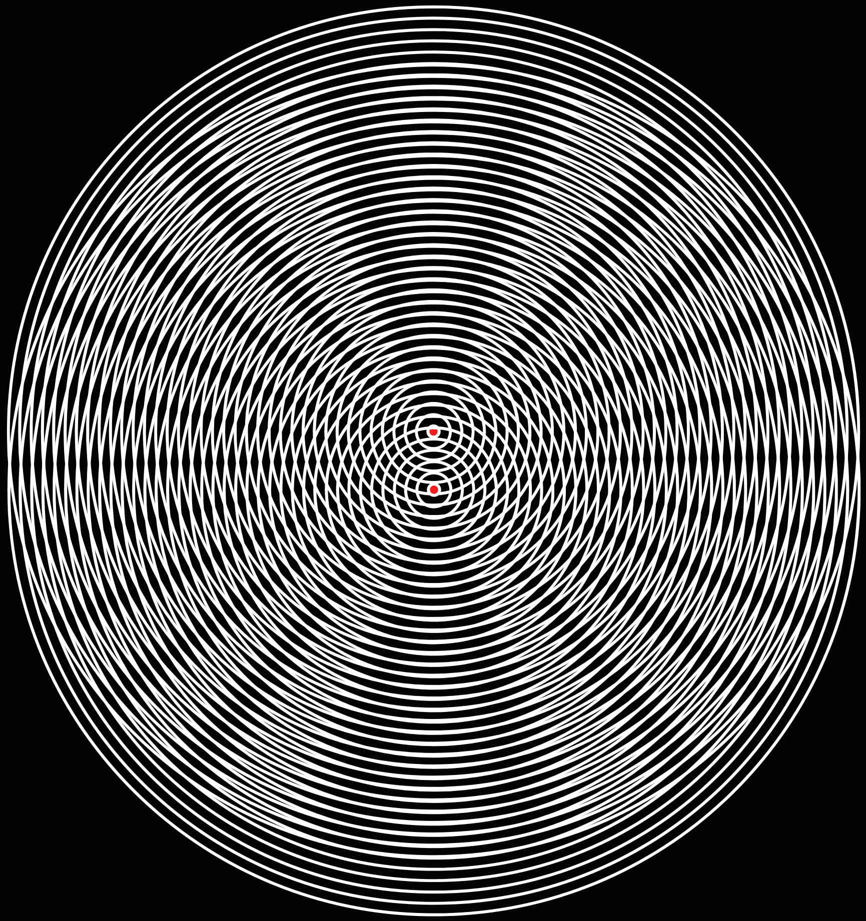

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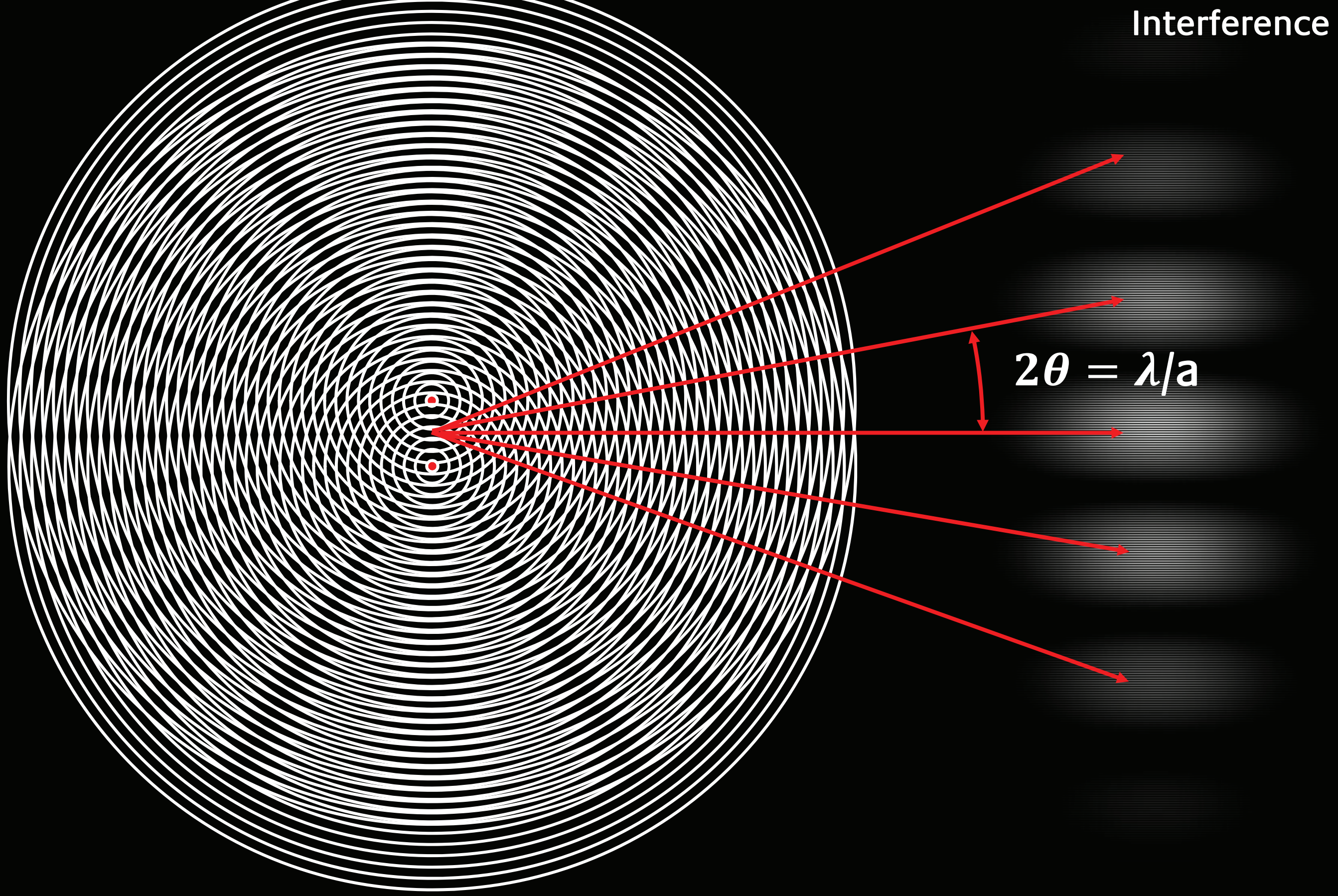
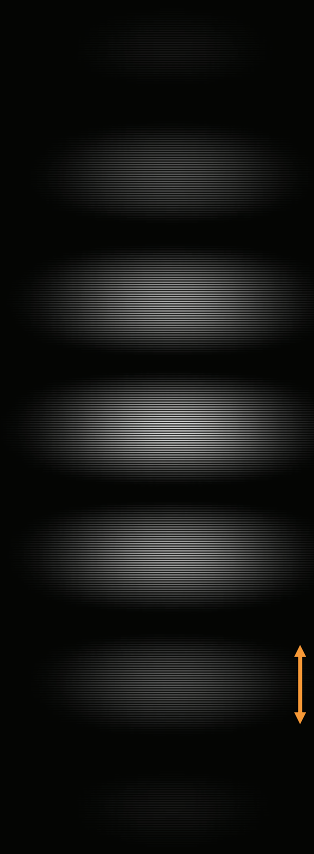


To measure distance: a measure angle: 2θ

Diffraction is essentially Goniometry (and detection)

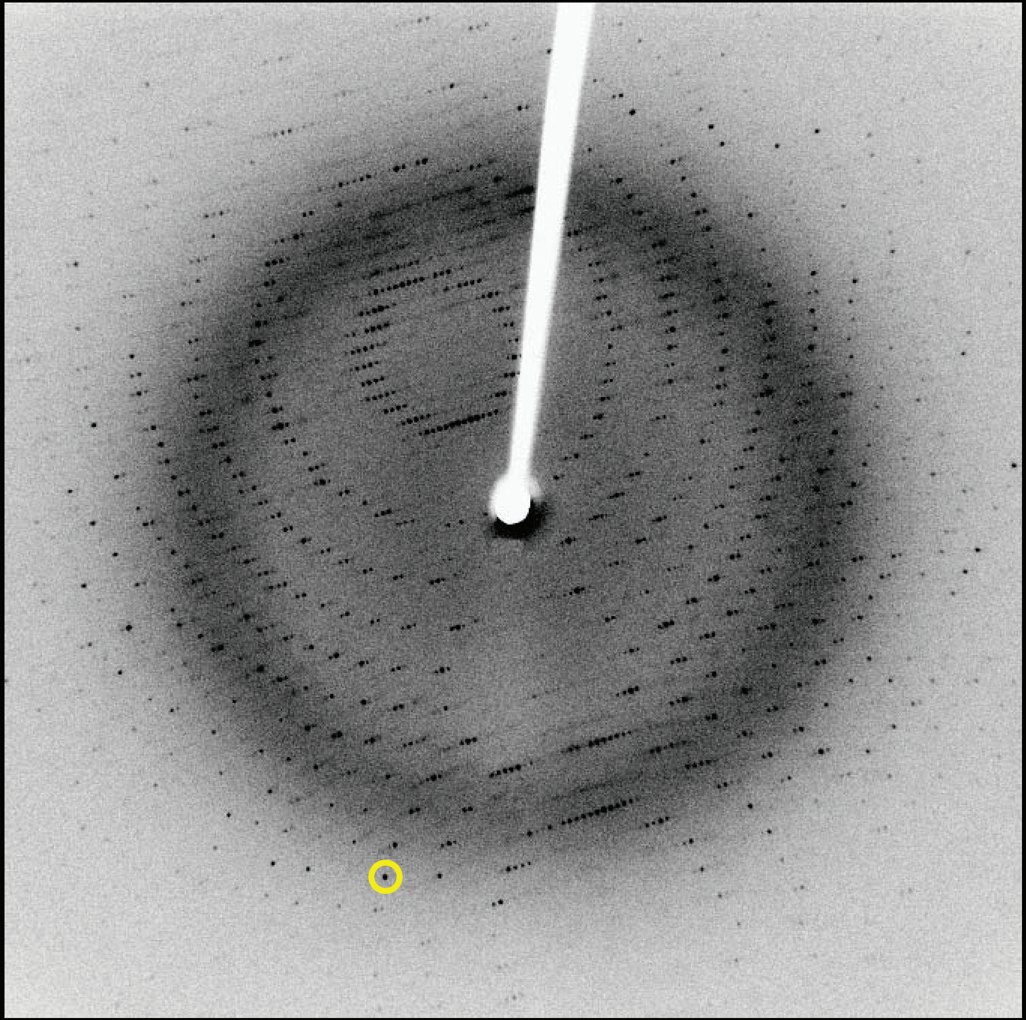
To measure angles as precisely as possible

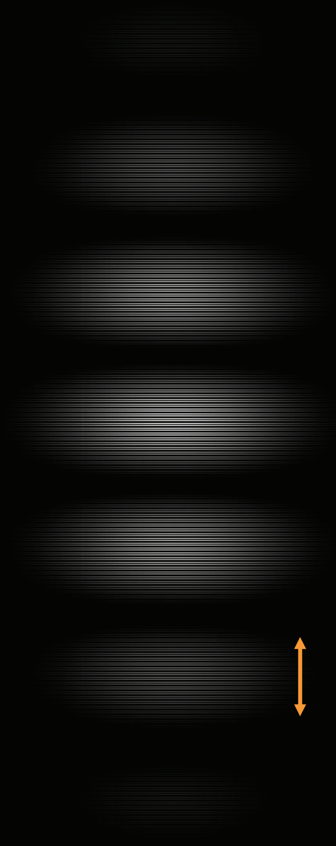
Diffraction: principle



With 2 atoms
spots are broad

Diffraction: principle



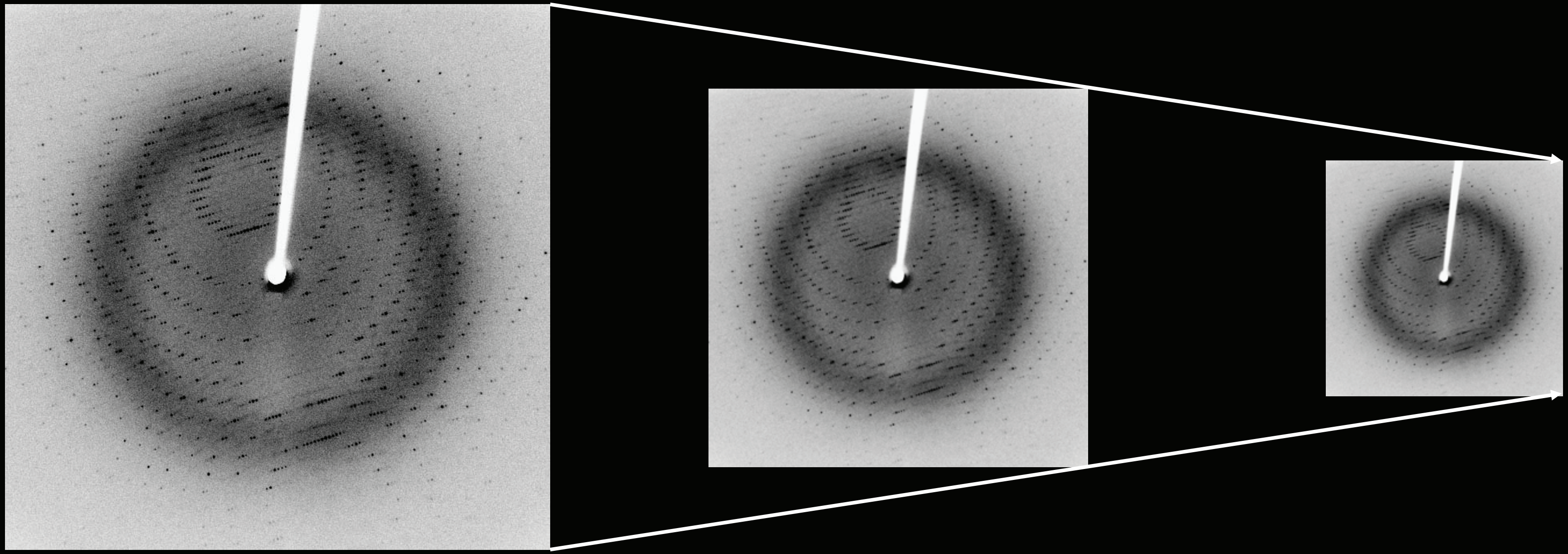


With 2 atoms
spots are broad
With many as in a crysta
very narrow (5 μrad = arc s

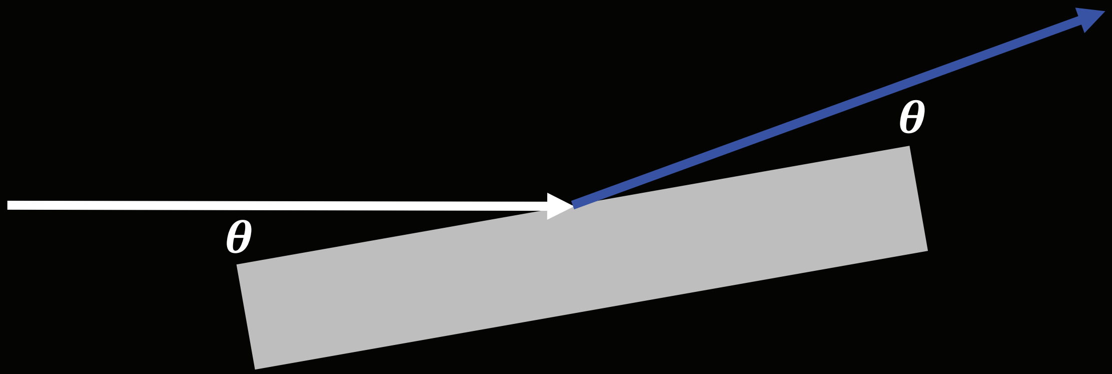
Diffraction: principle

Because $2\theta = \lambda/a$

Diffraction is **more difficult** at high energy (small λ)



Monochromator: principle

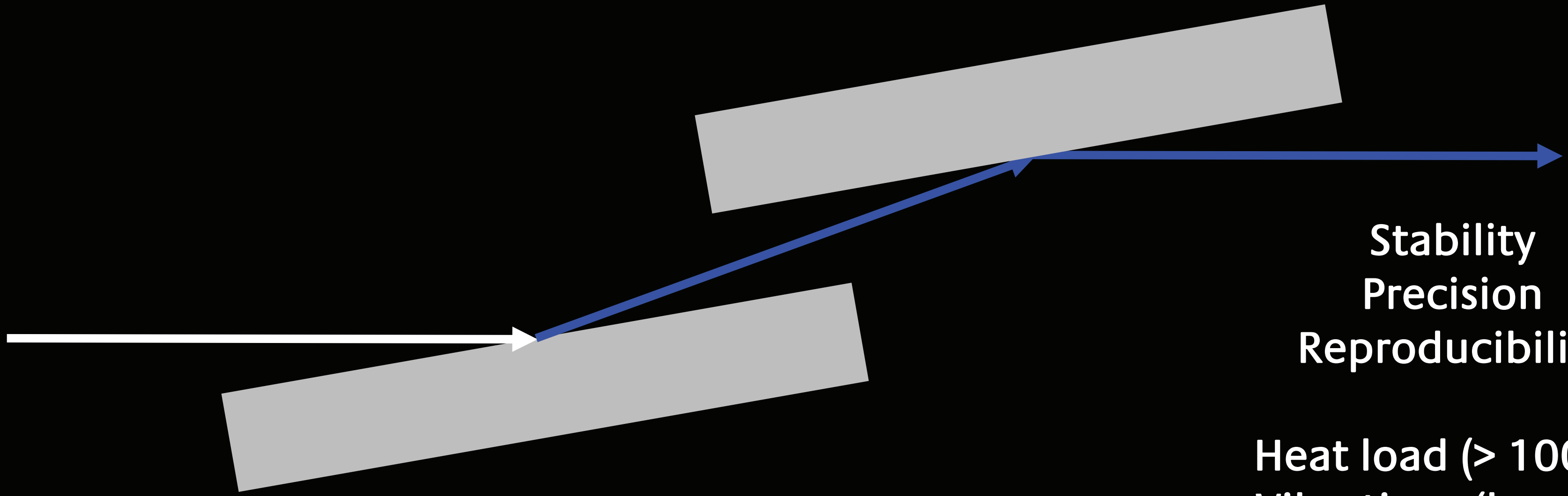


Bragg law

$$2d \sin\theta = \lambda$$

Monochromator: principle

Double Crystal Monochromator



Stability
Precision
Reproducibility

Heat load (> 100 W)
Vibrations (long BL)

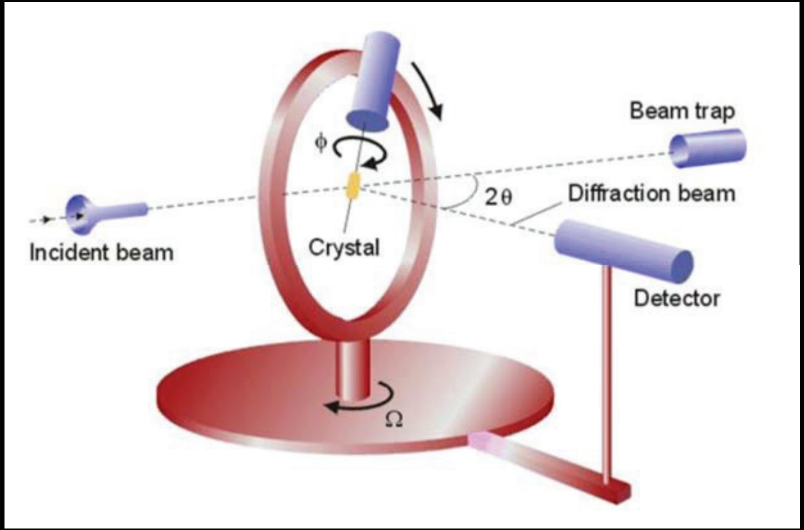
Brilliance: bump

Bragg law

$$2d \sin \theta = \lambda$$

Diffraction: the 4-circle diffractometer

An assembly of 4 goniometers to adjust crystal (3) and detector (1)



Euler
Vs
Kappa

High precision goniometers (1 arc sec)
Sphere of Confusion (5 µm or better)
or Cylinder of Confusion

More circles for complex sample environments
Nano beams, very small SOC
Detectors are more and more heavy (arms)
Because of H polarization, better to work in vertical plane

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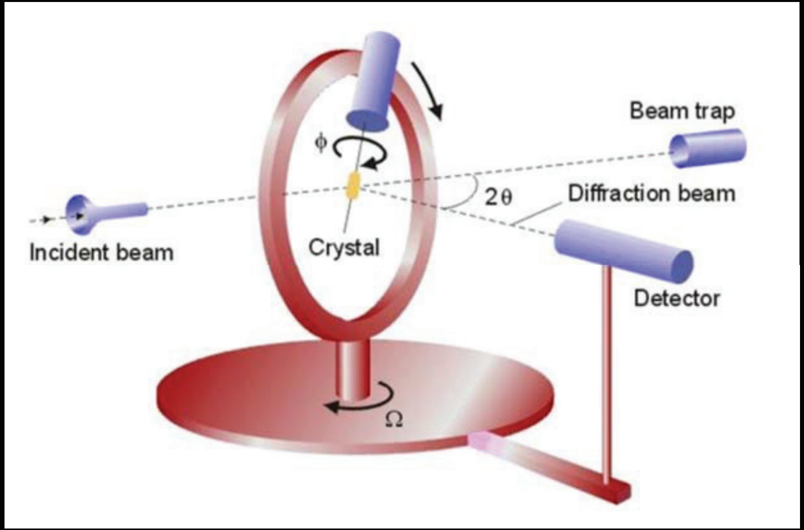

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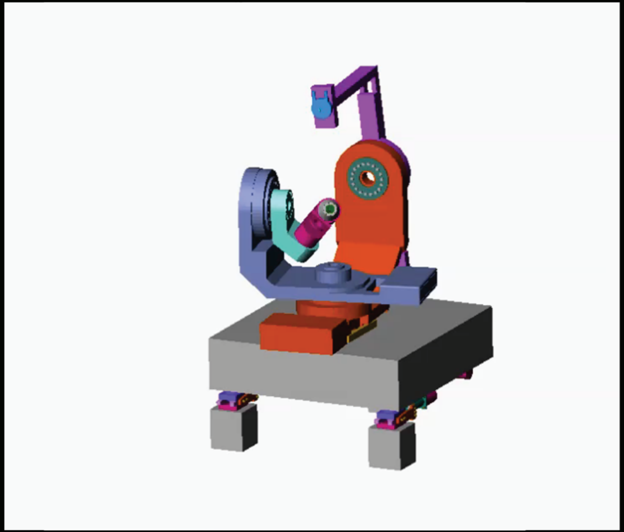

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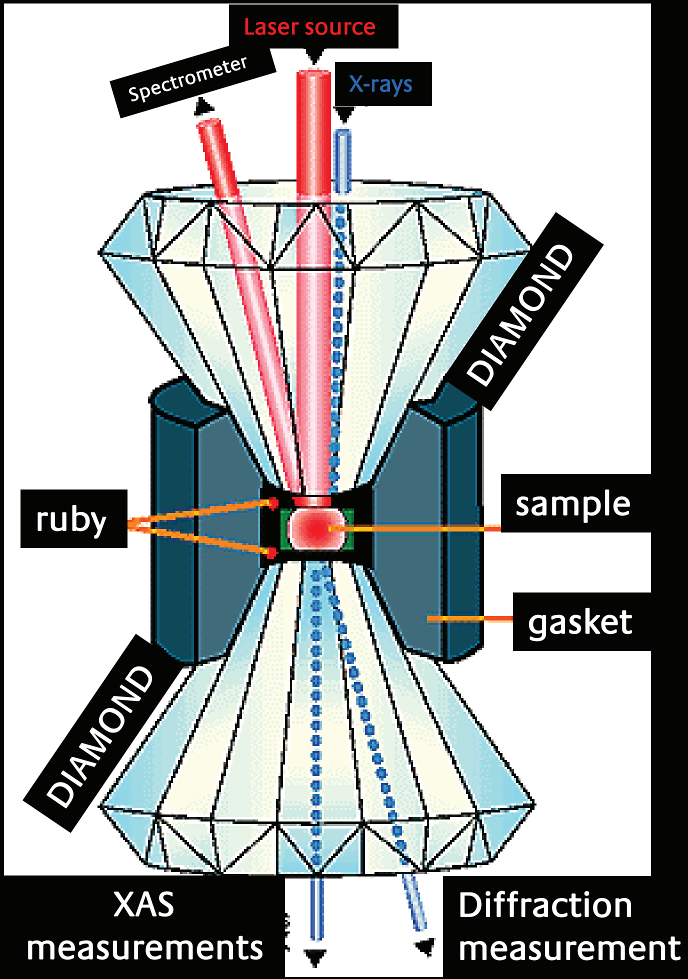
Nano-beams are necessary to reach
Ultra high pressure
In Diamond anvil cells

The higher the pressure
The smaller the aperture
The smaller the beam

Mechanical challenge:

Low (high) temperature
High pressure



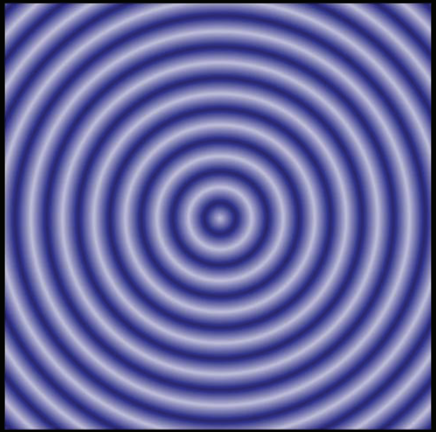
Brilliance

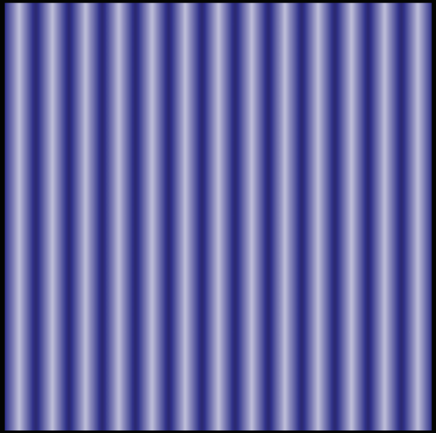
Emittance

Coherence

What is coherence?

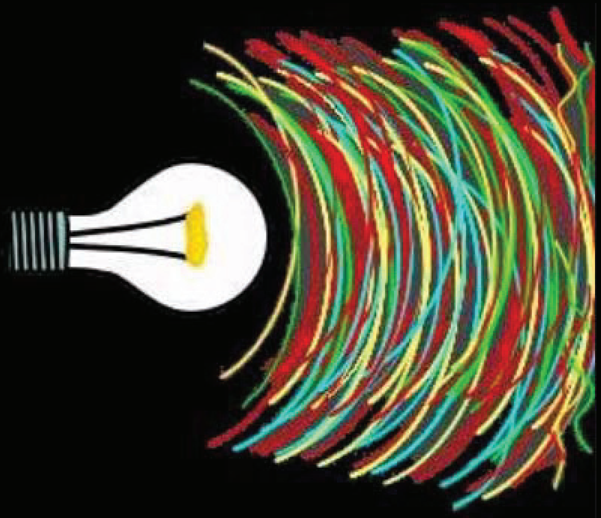
Light wave is coherent if it looks like a perfect spherical or plane wave





What is coherence?

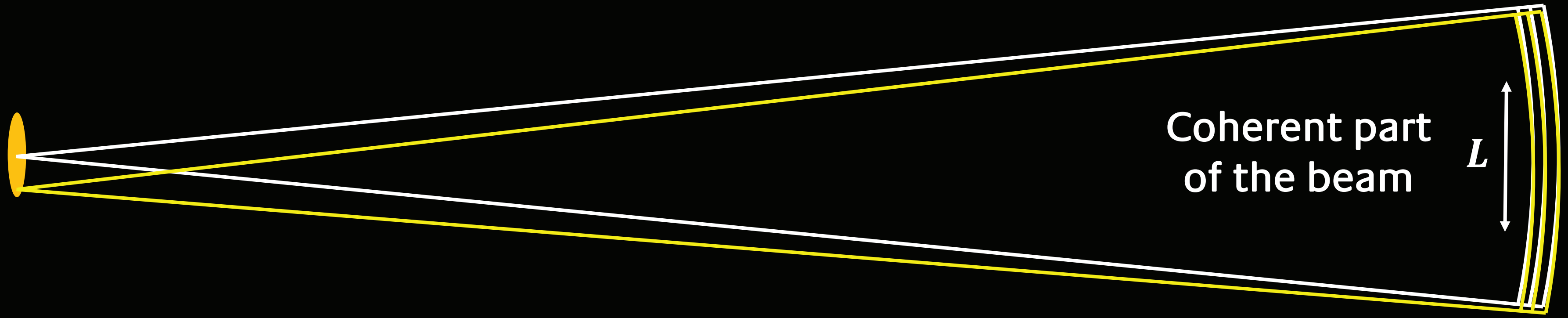
Unfortunately, light (even synchrotron light) looks like that:



The longitudinal coherence is given by the wave length purity (monochromator)

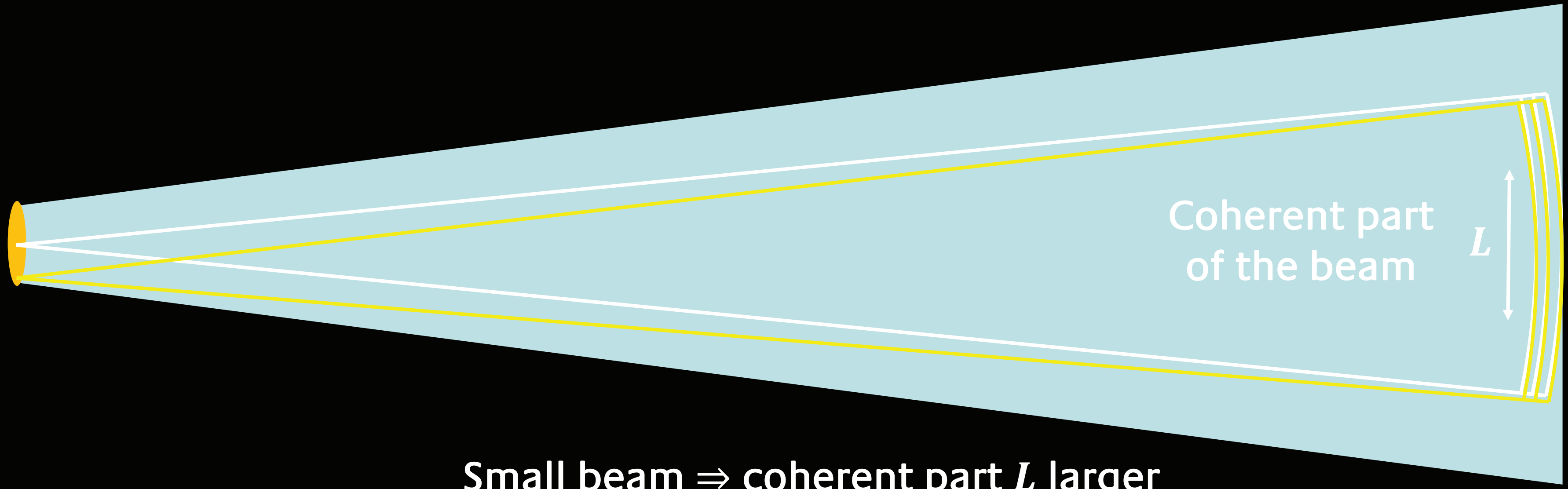
The transverse coherence depends on the size of the source

Brilliance vs Coherence



Small beam ⇒ coherent part L larger

Brilliance vs Coherence



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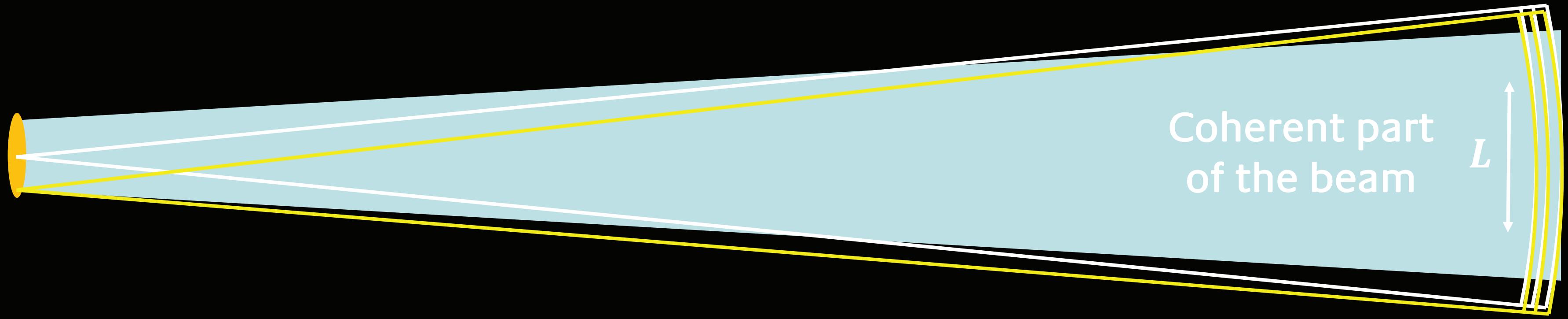

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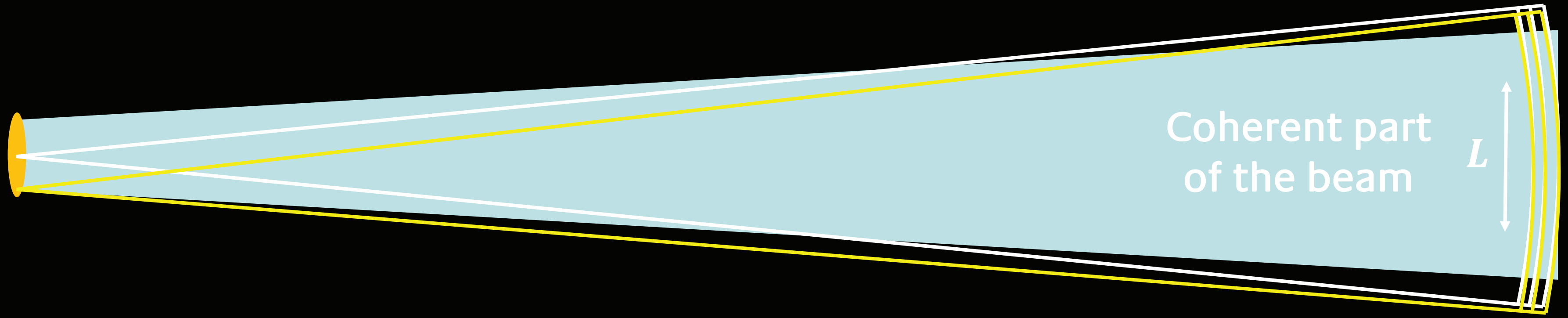
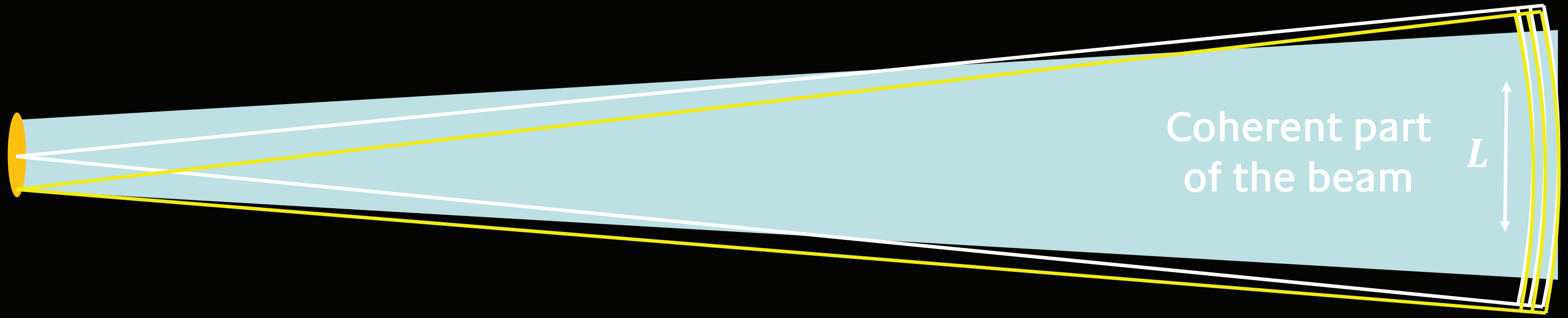


Small beam ⇒ coherent part L larger
Small divergence ⇒ more flux in the coherent part

Brilliance vs Coherence



Small beam ⇒ coherent part L larger

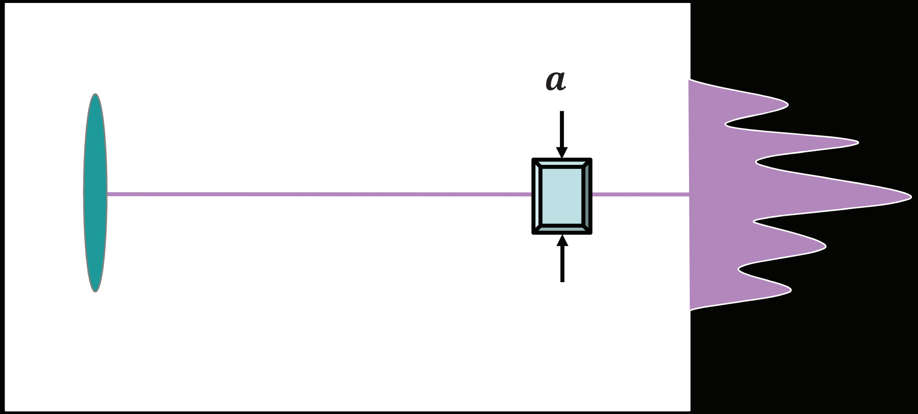
Small divergence ⇒ more flux in the coherent part

More brilliance ⇒ More coherence!

$$F_{coh} \square B\lambda^2$$

Why coherence?

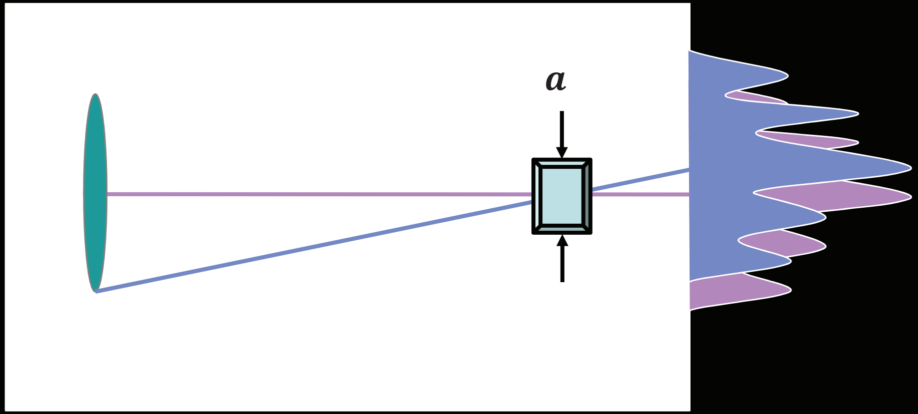
To measure the speckles



Fringes (or speckles) are visible iff $a < L$

Why coherence?

To measure the speckles



Fringes (or speckles) are visible iff $a < L$

Why coherence?

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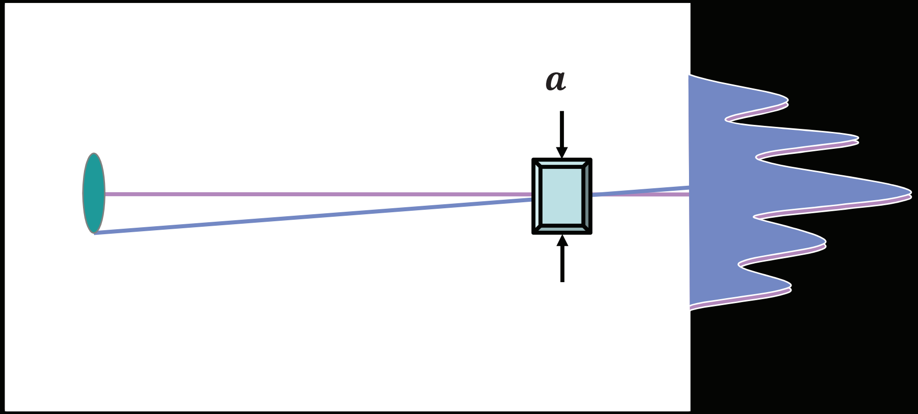

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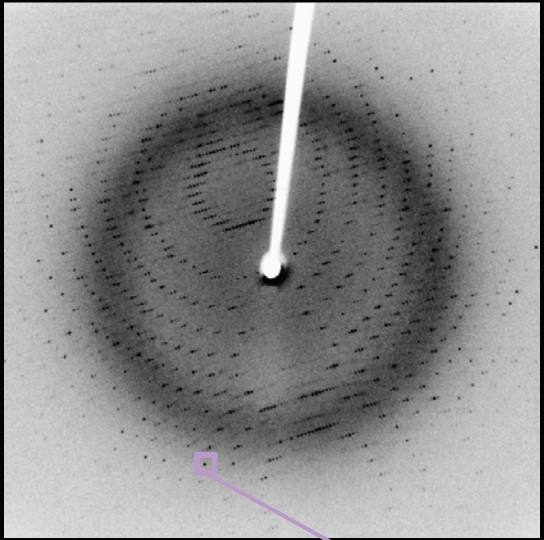

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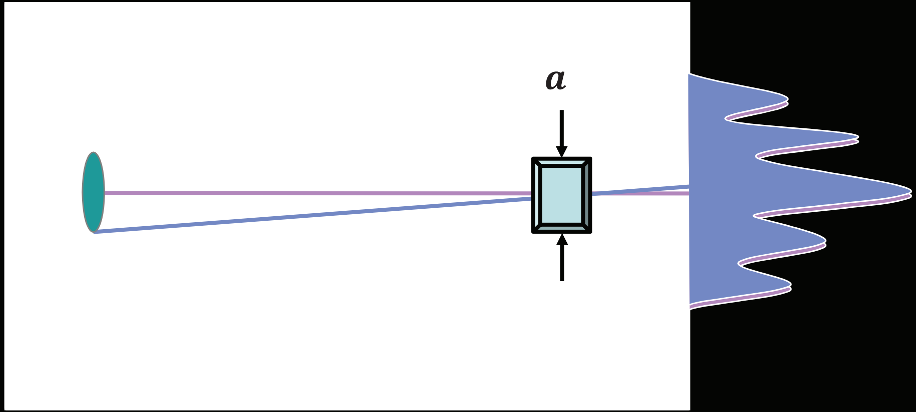
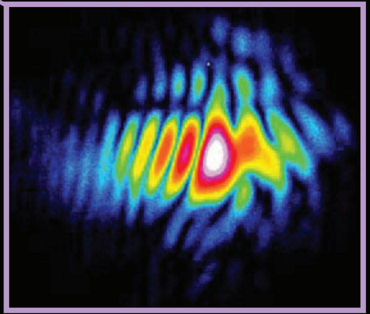
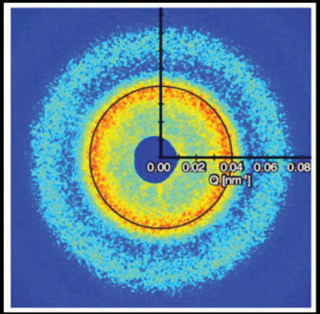


Fringes (or speckles) are visible iff $a < L$

New imaging Techniques: CDI, Ptycho.

(Much) more demanding of stability (10 µrad)





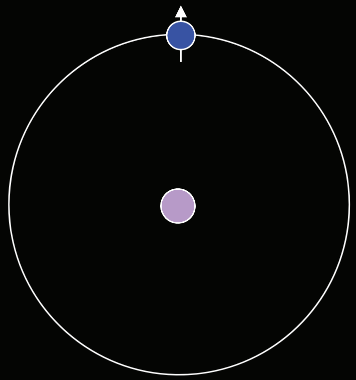
P. Wochner et al., *PNAS* **106**, **11511** **(2009)**.

T. Head-Gordon et al., *Chem. Rev.* **102**, **2651** **(2002)**.

Absorption
(and related techniques)

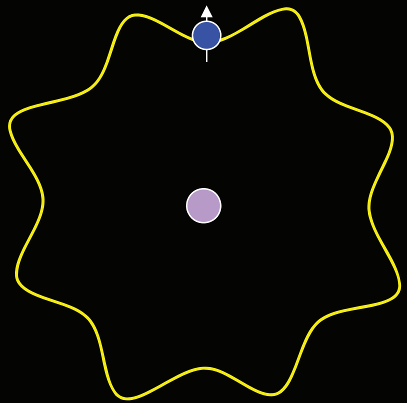
Absorption: energy levels in atoms

Where are the orbits of electron?



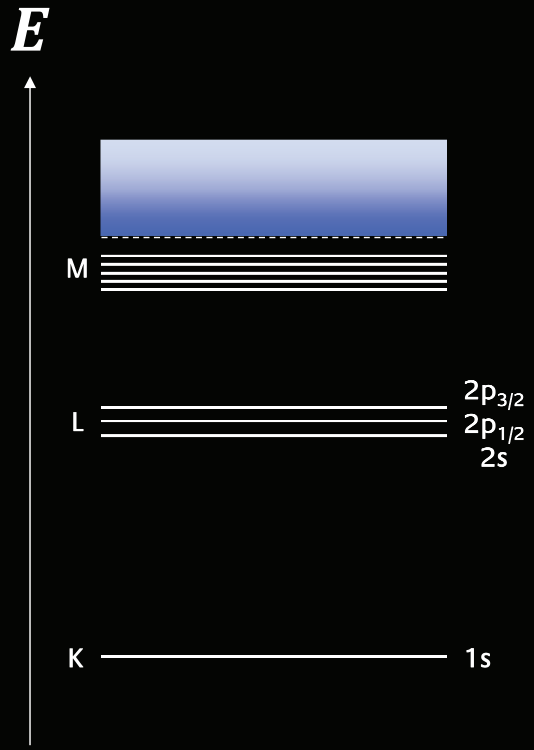
Absorption: energy levels in atoms

Where are the orbits of electron?
Because they are also waves...



A few possibilities
called
Atomic orbital

Absorption: energy levels in atoms



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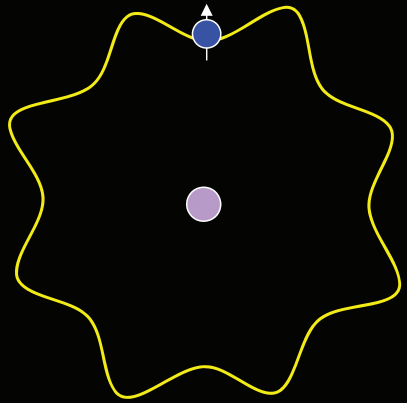

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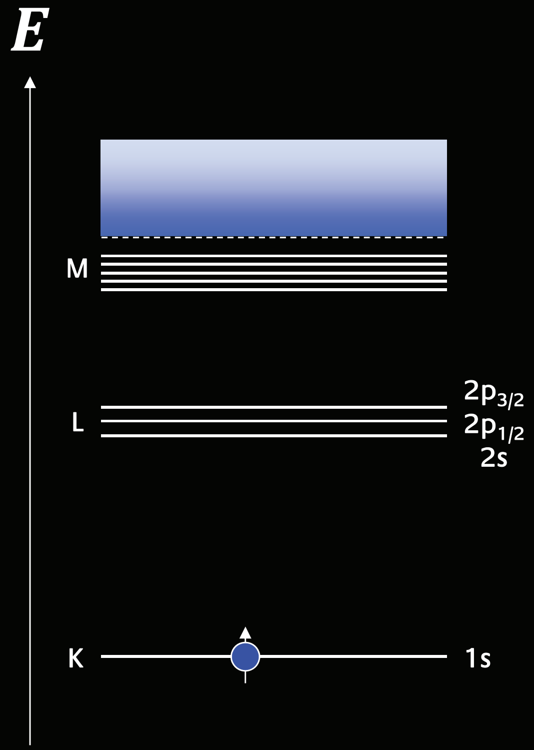

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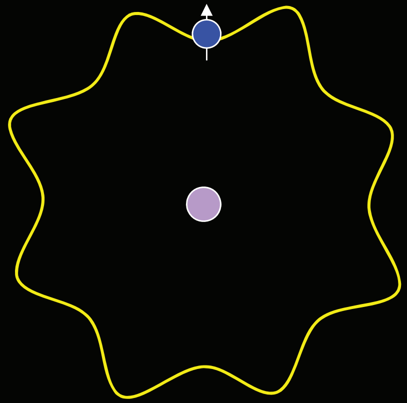

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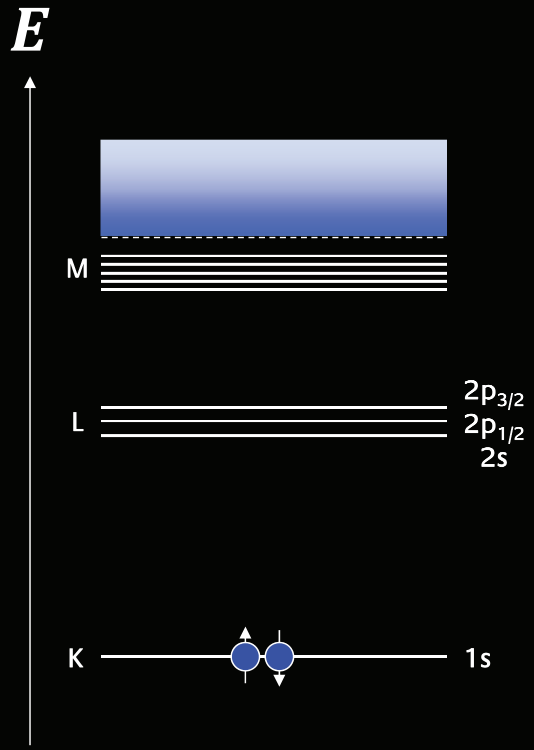

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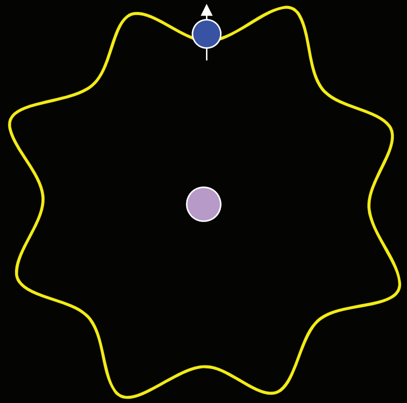

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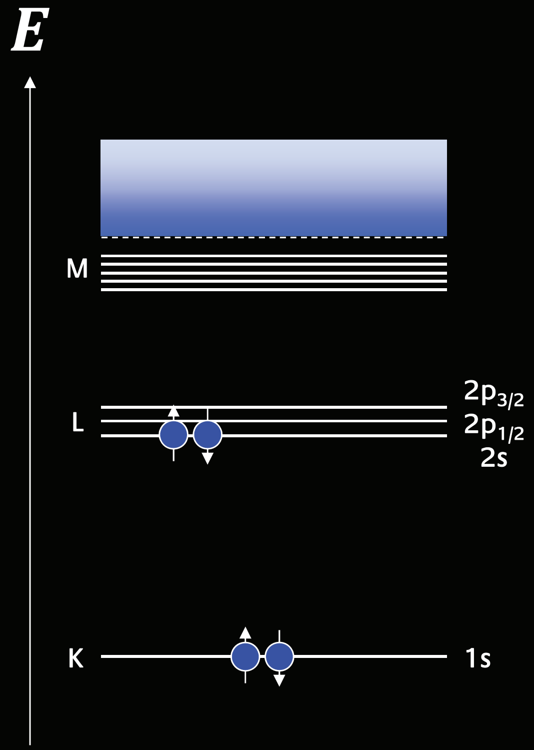

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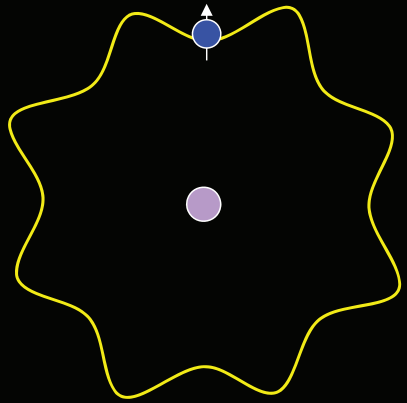

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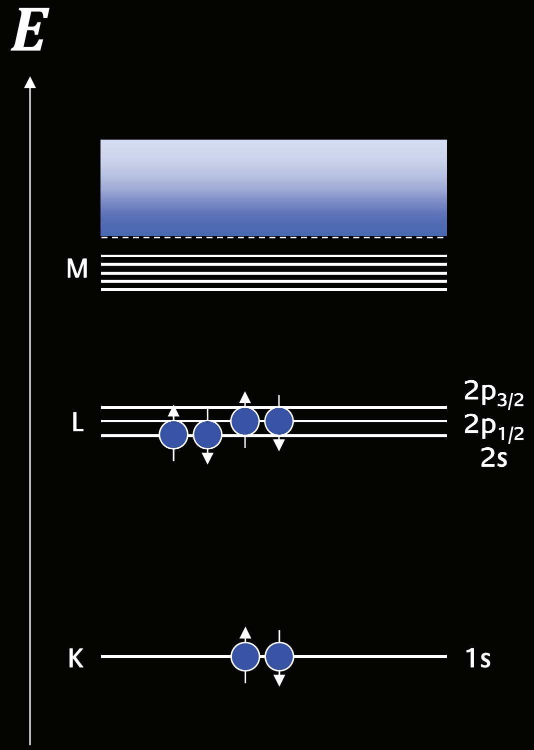

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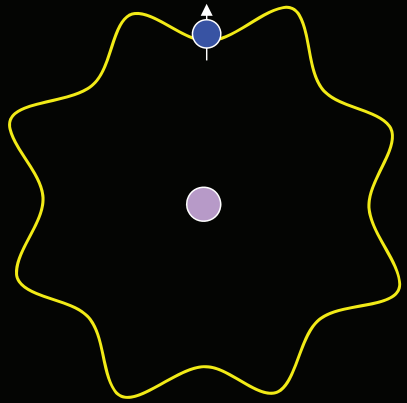

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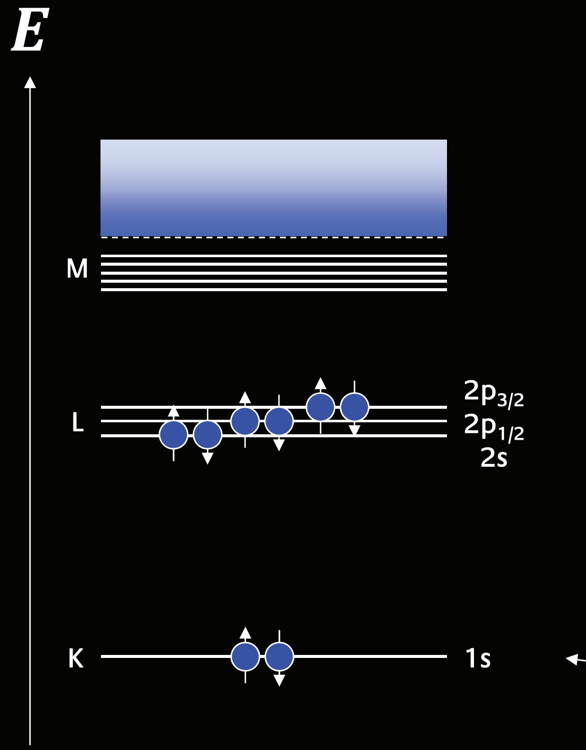

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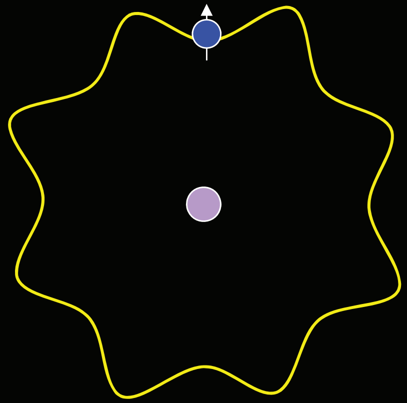

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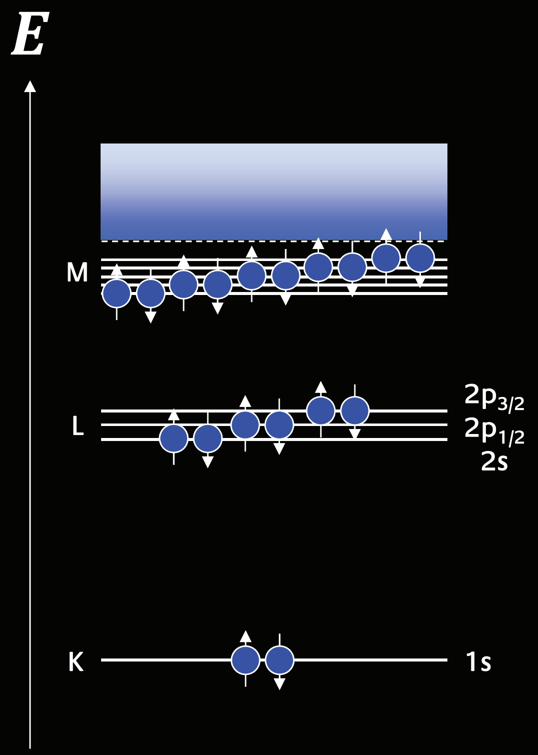

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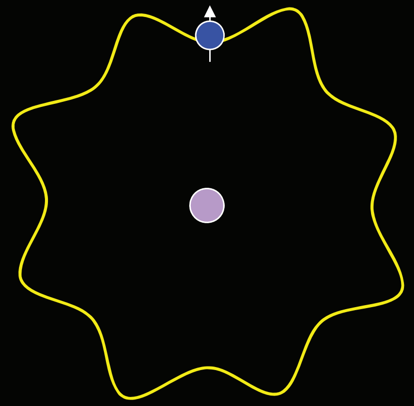

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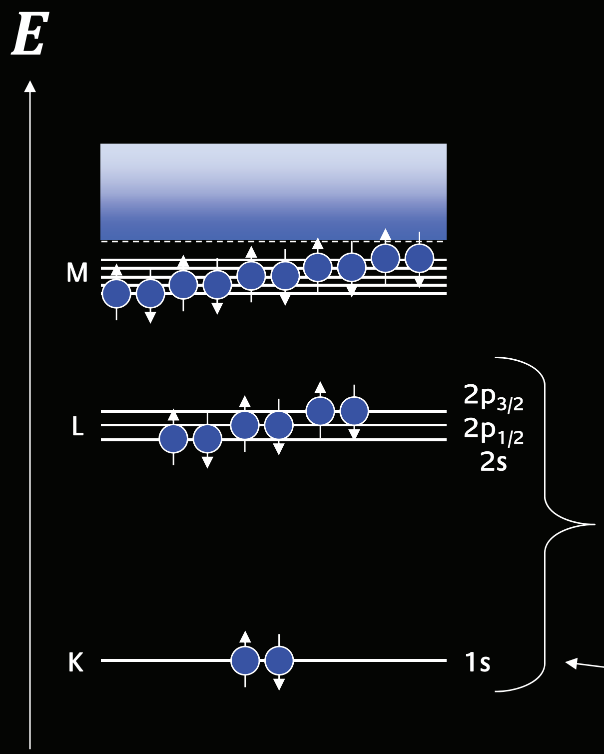
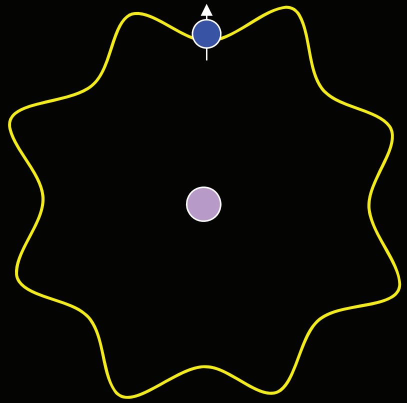
Absorption: energy levels in atoms



Core level
(discrete)
Bound electrons

Where are the orbits of electron?
Because they are also waves...

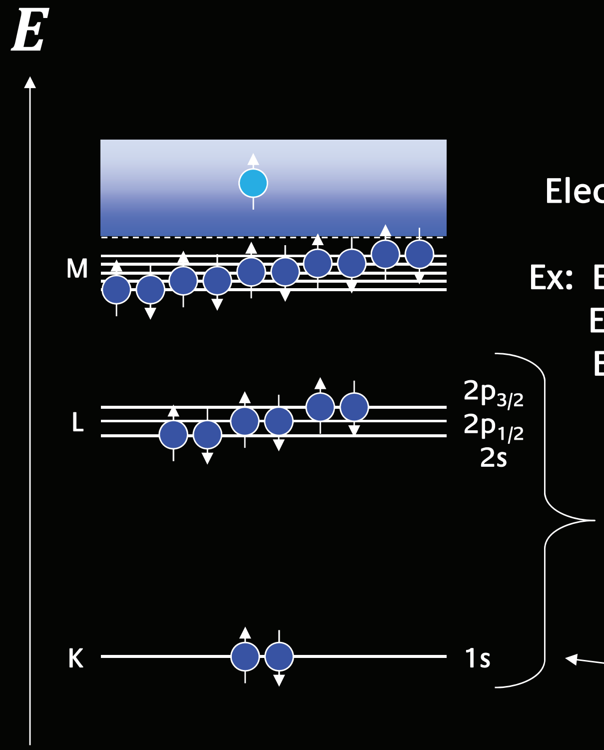


A few possibilities
called
Atomic orbital

Absorption: energy levels in atoms

Vacuum
(continuum)
Free electrons

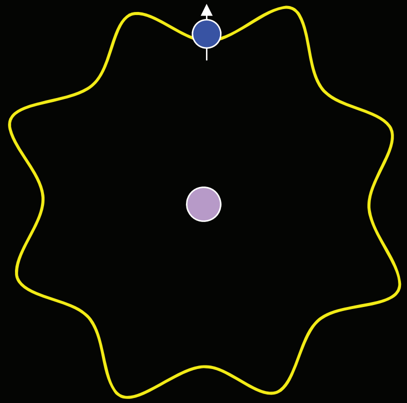
Core level
(discrete)
Bound electrons



Electron energy

Ex: E_K(Ag)=25 keV
E_K(Kr)=14 keV
E_K(Fe)=7 keV

Where are the orbits of electron?
Because they are also waves...



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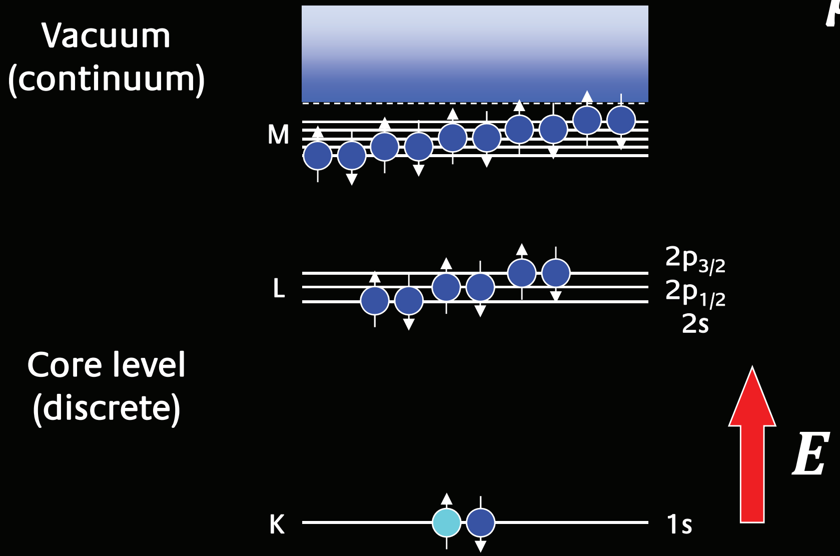
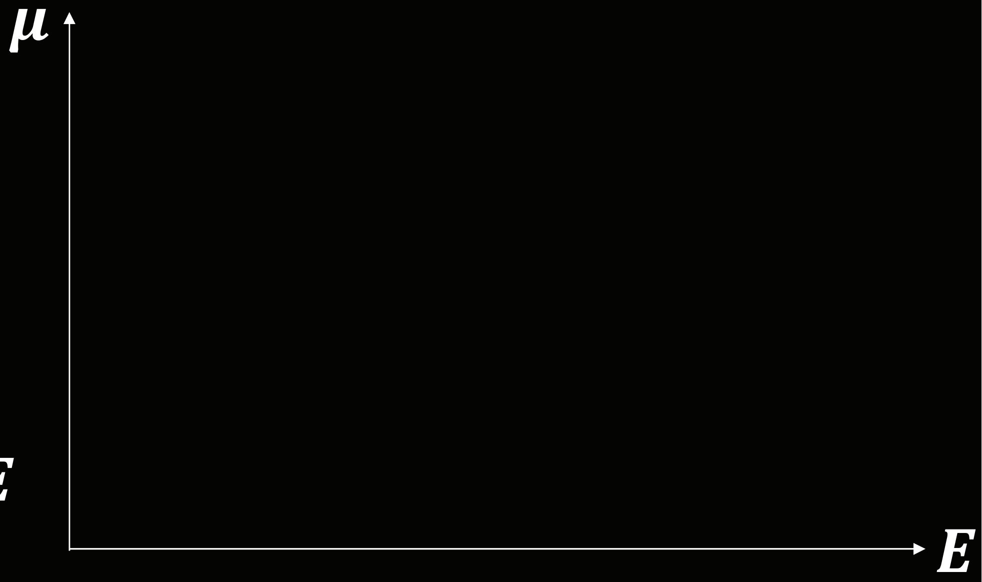
called
Atomic orbital

Absorption: increase of coefficient μ





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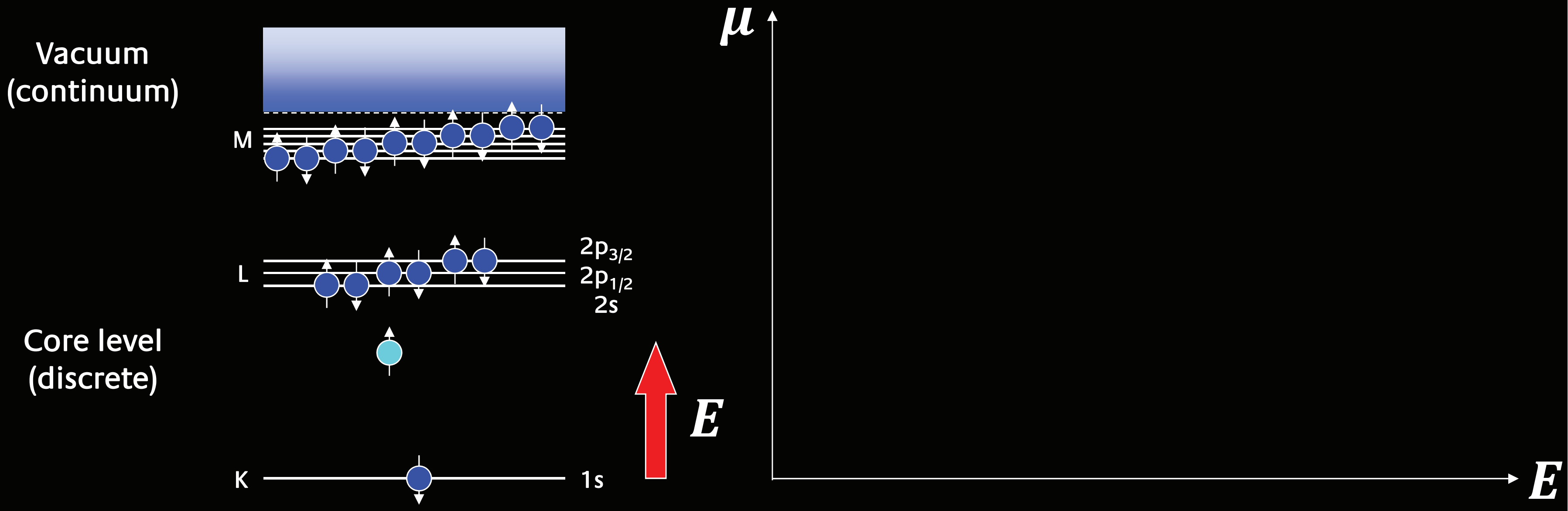

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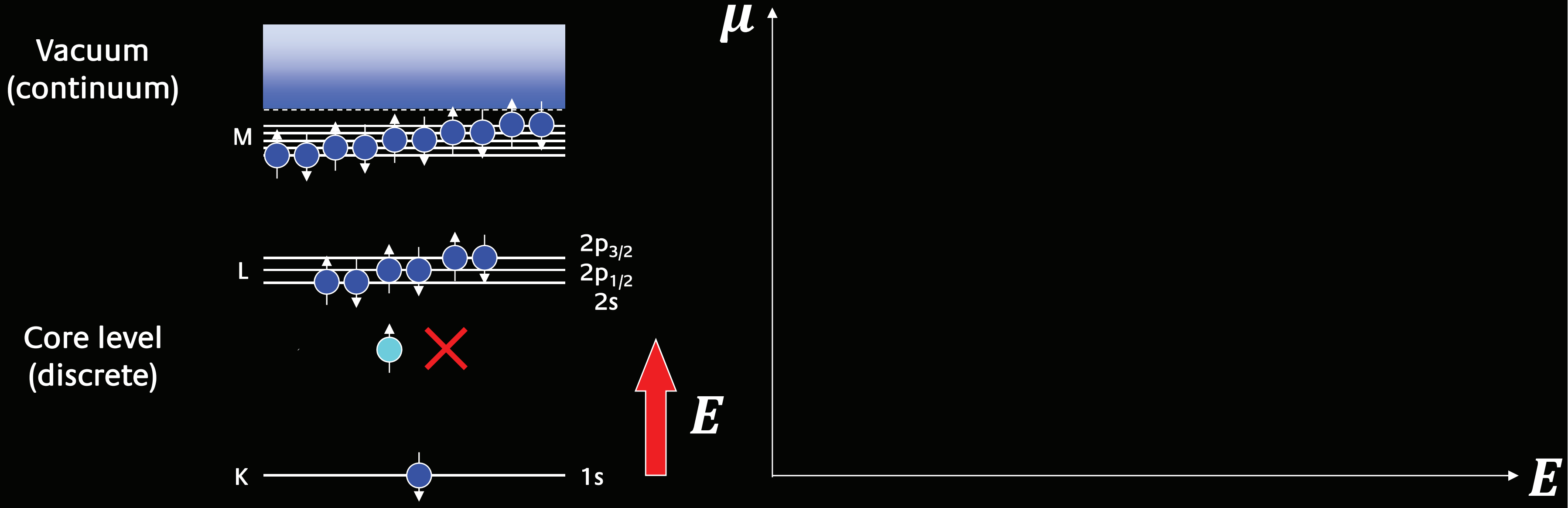

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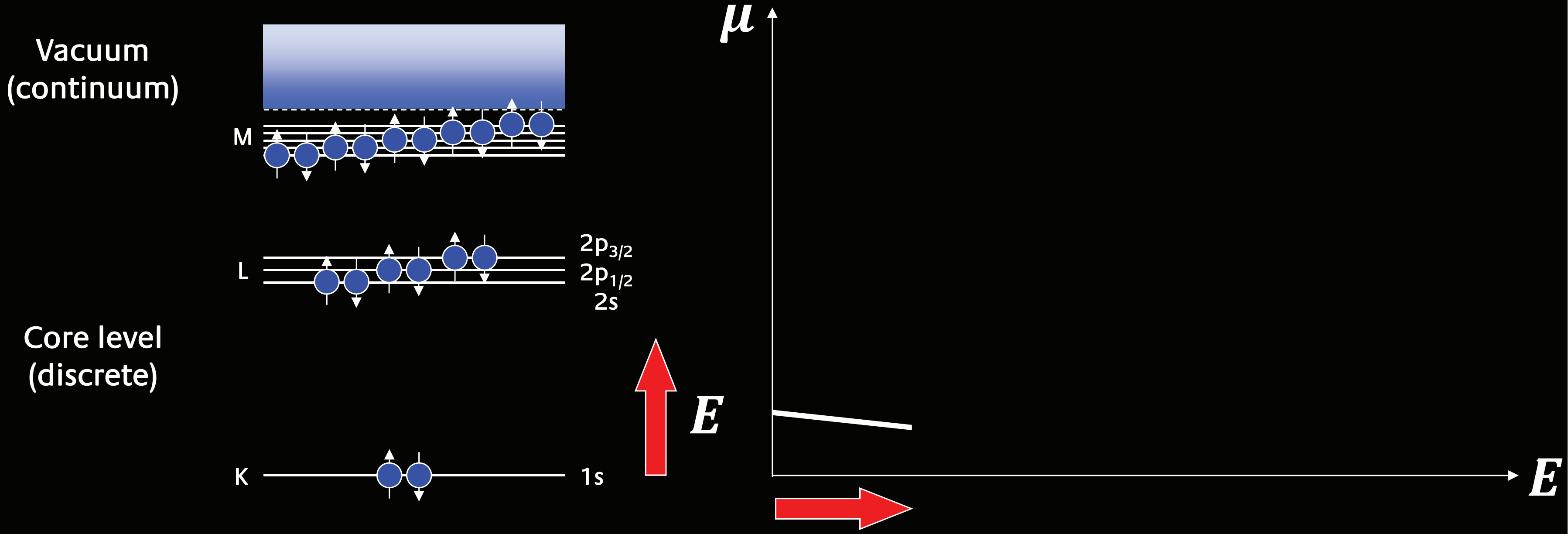

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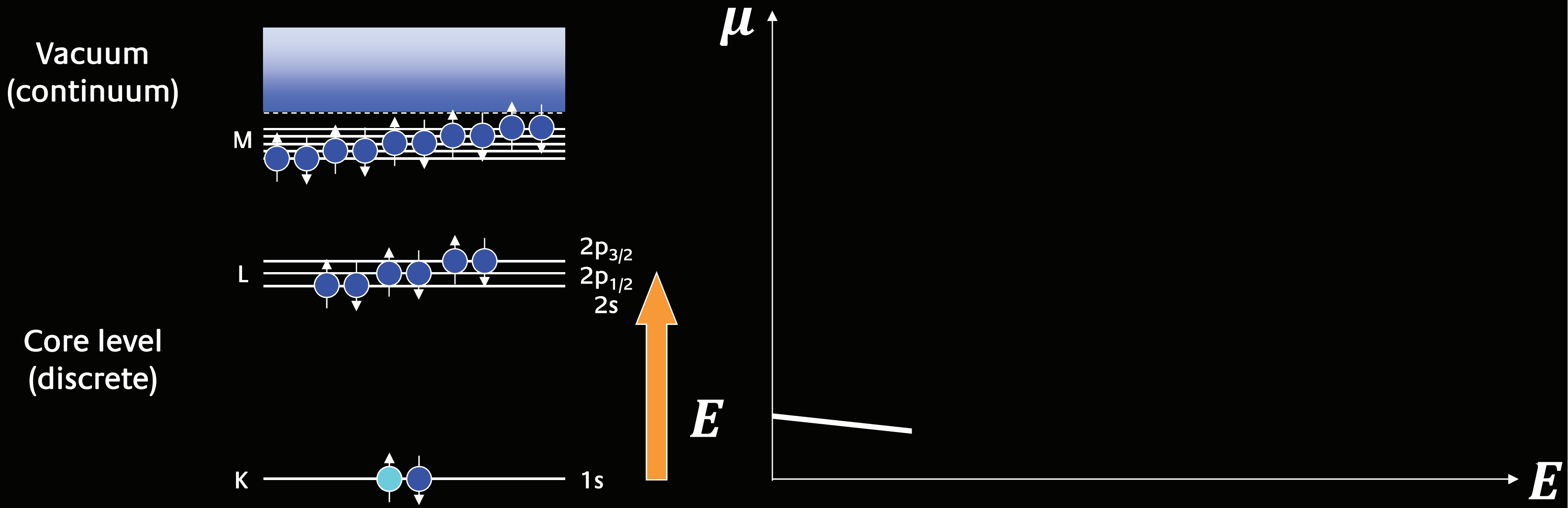

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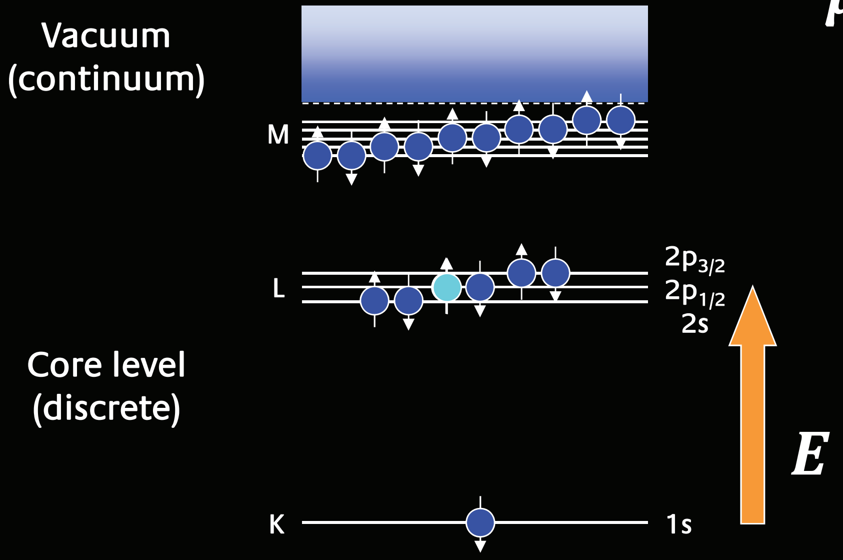

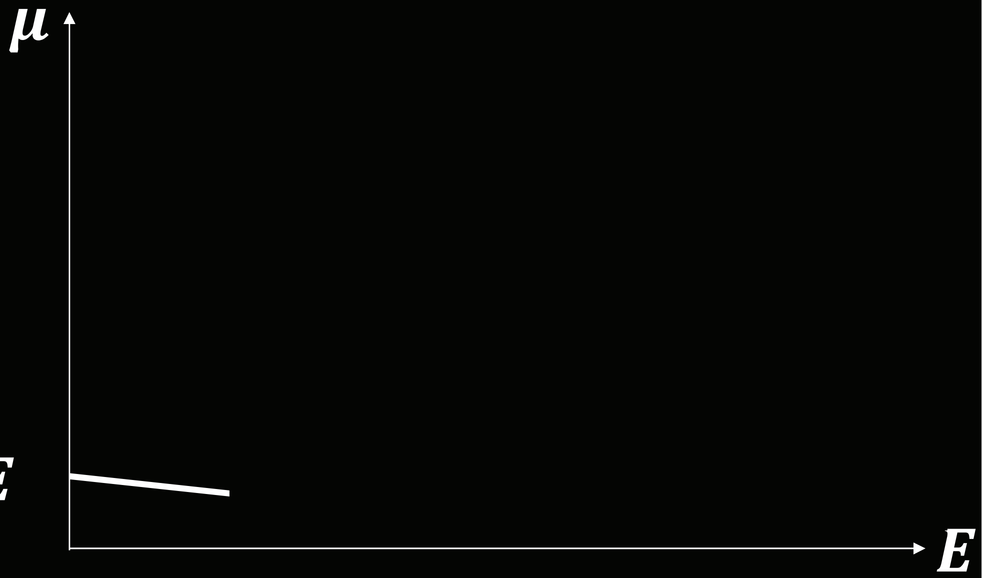

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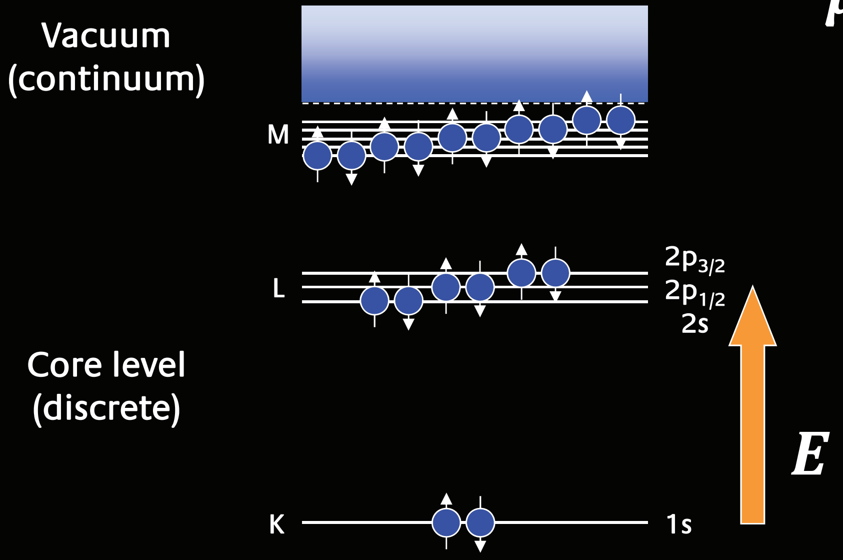

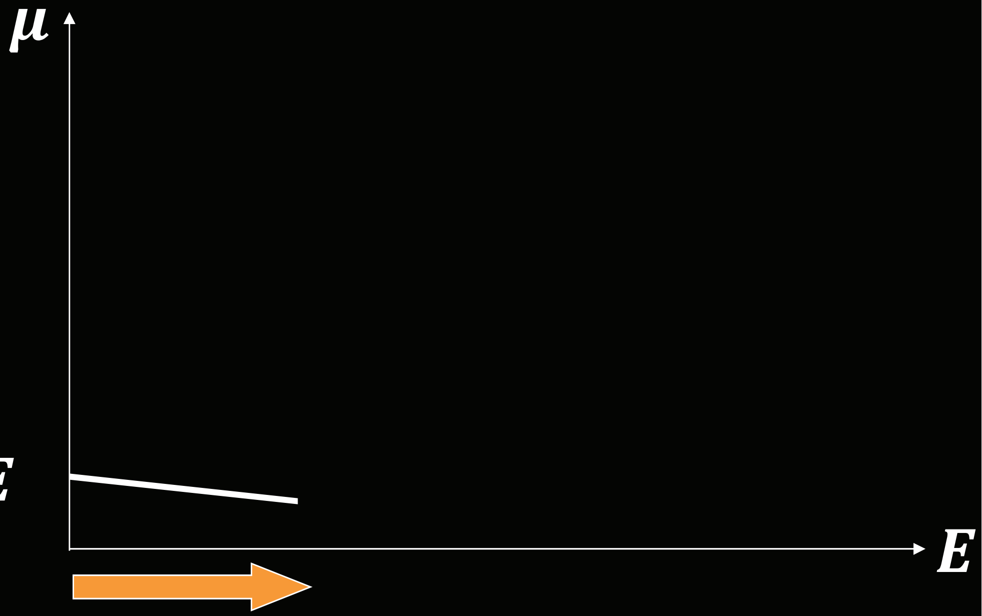

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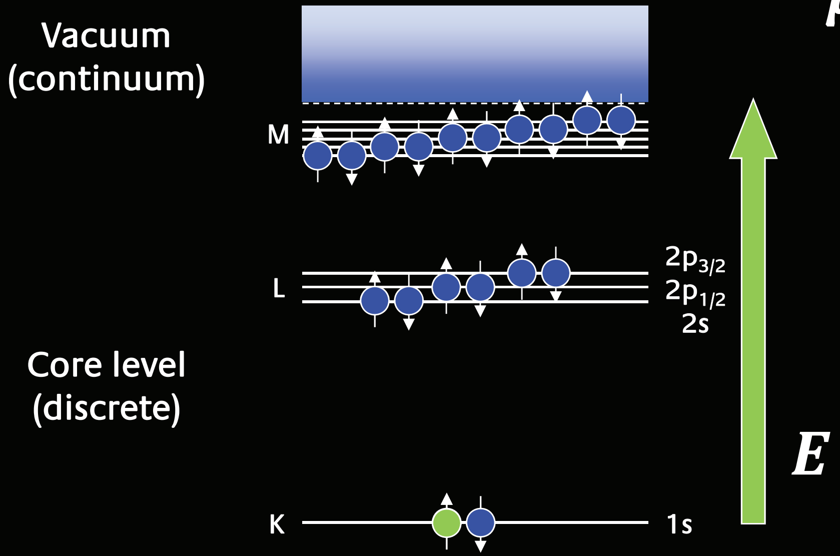

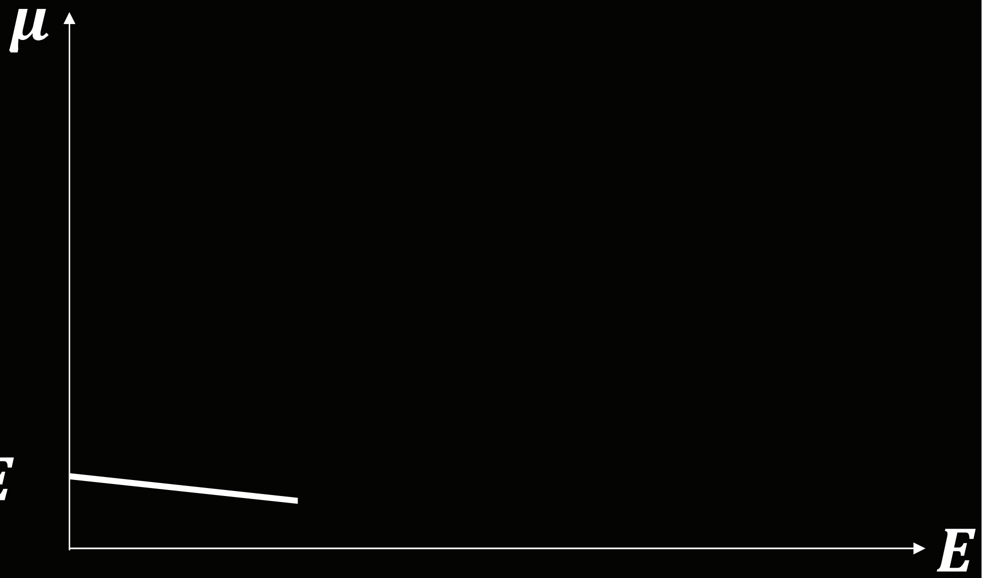

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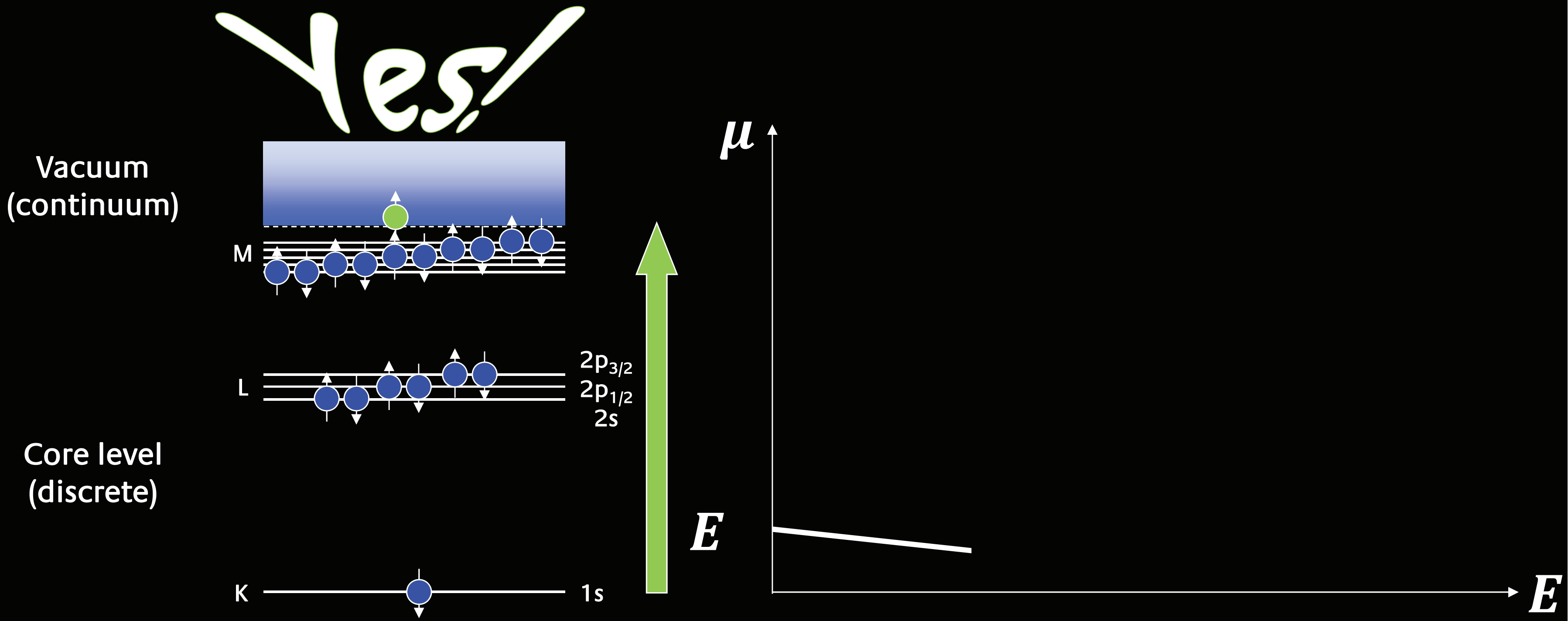

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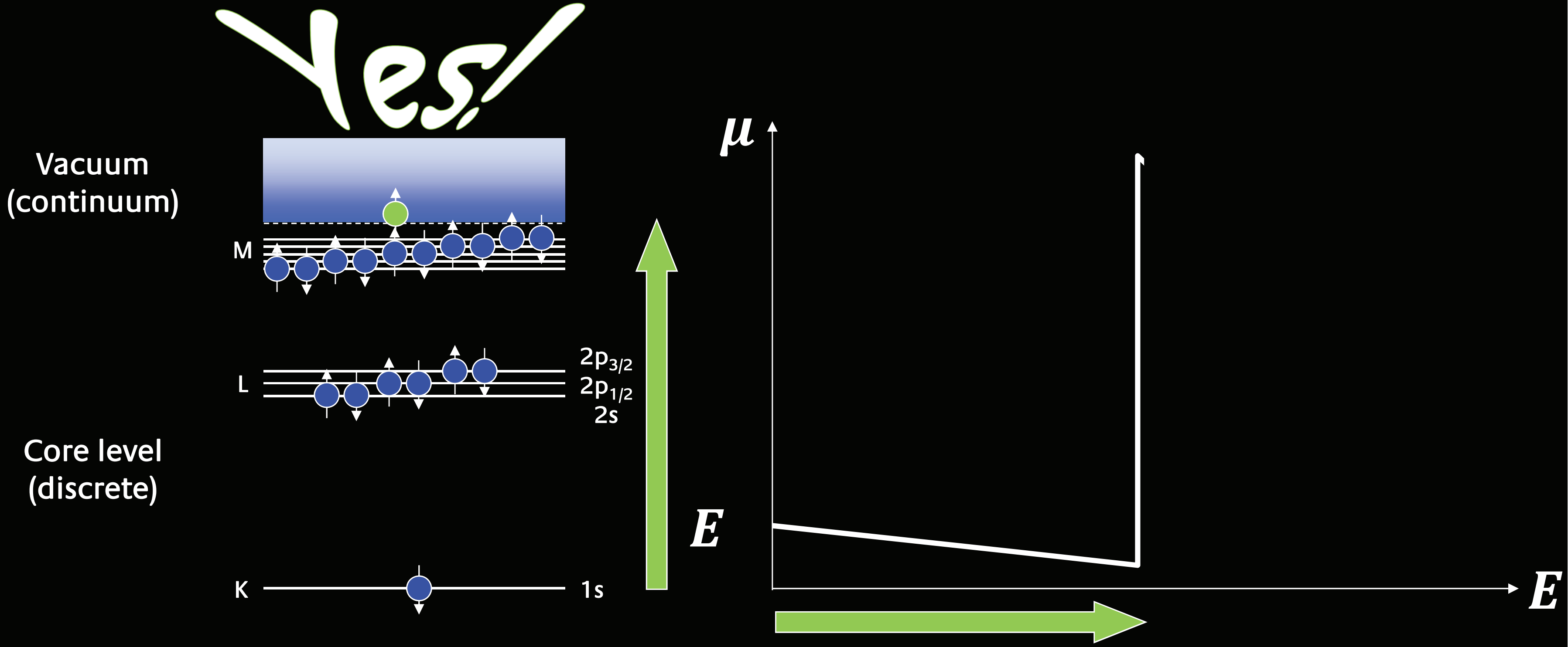

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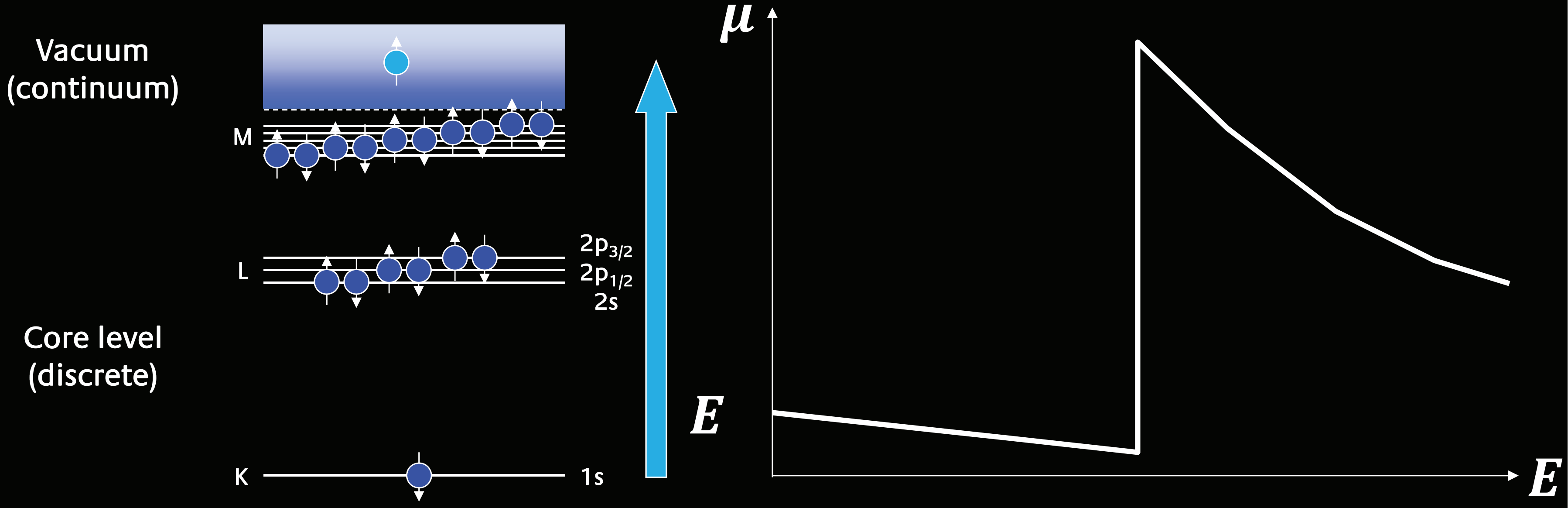

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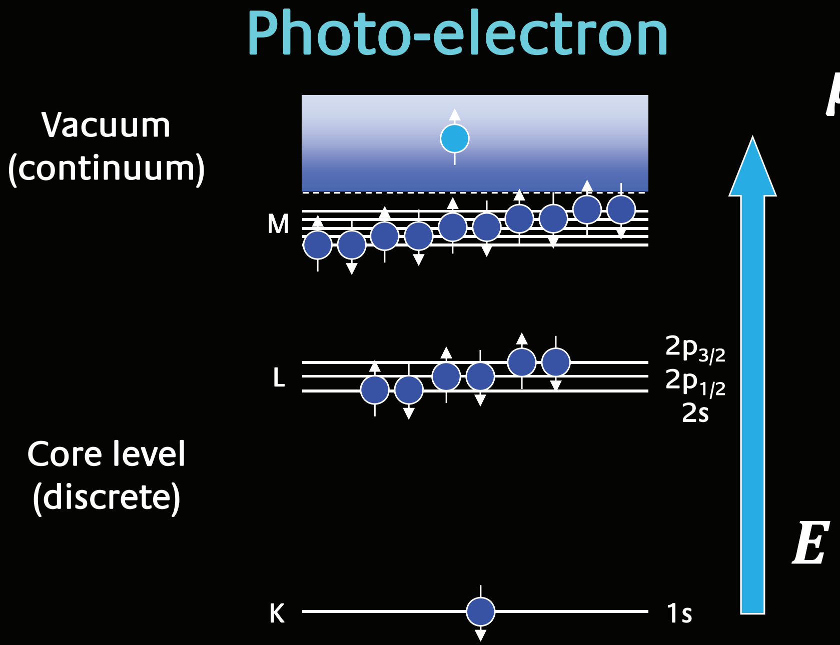
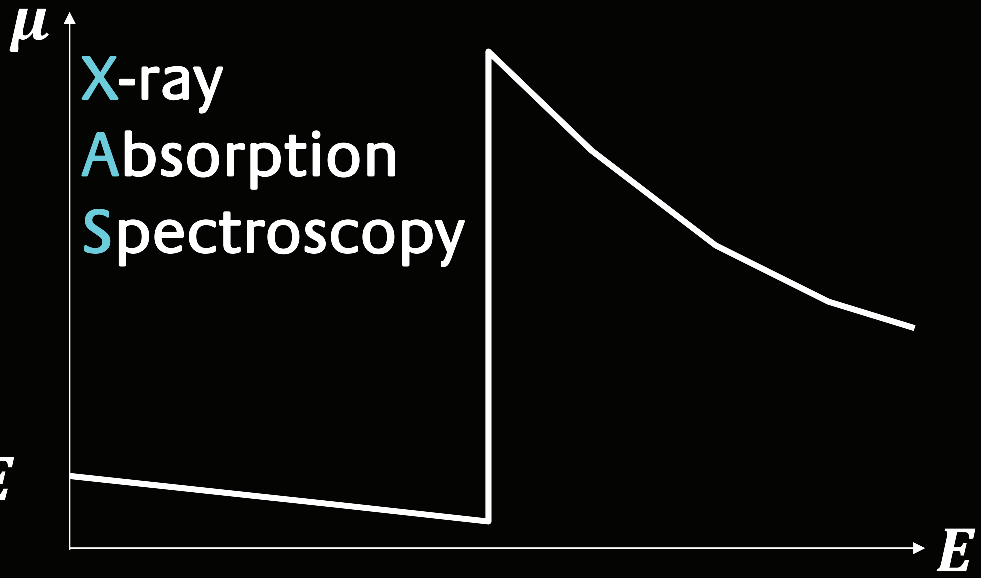
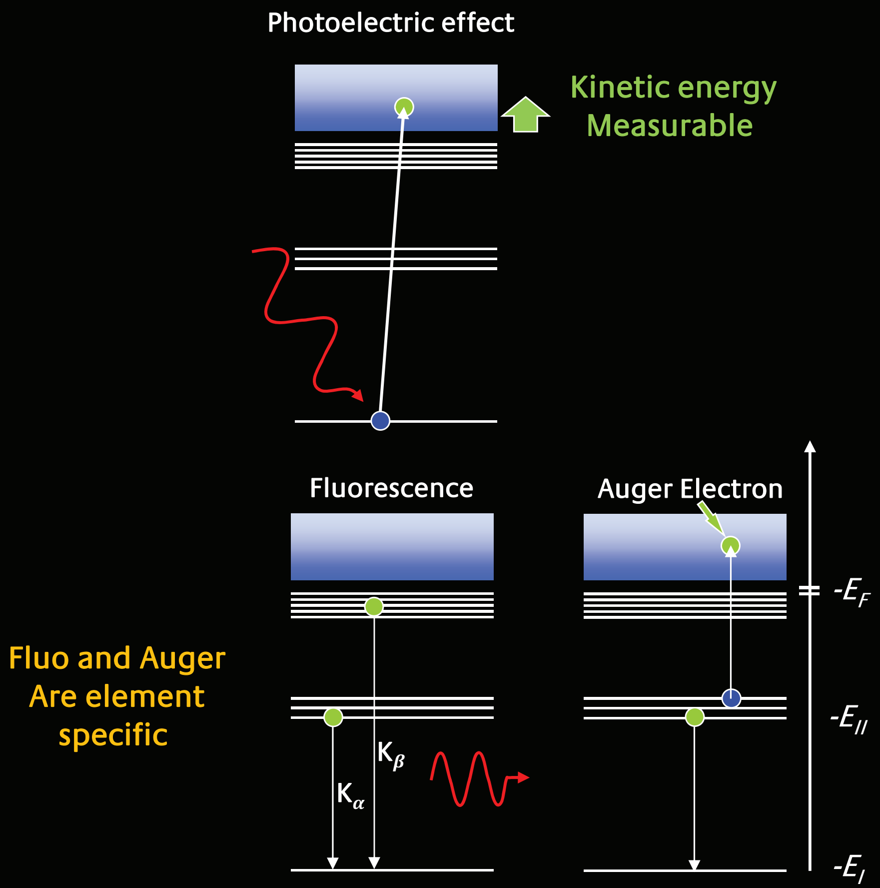




Element specific
K-edge, L-edge, etc.

Absorption: processes of relaxation



Atomic excitation:

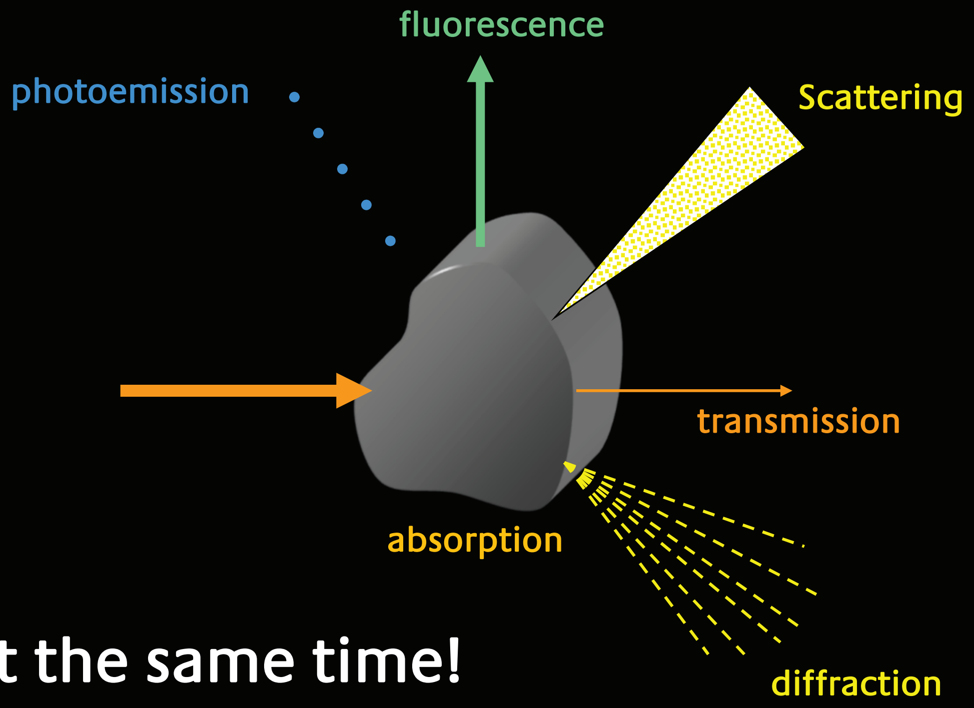
Absorption of photon (bulk)
Emission of Photo-electron
(surface ~10 nm, UHV)

Atomic relaxation:

Release of the excess of energy

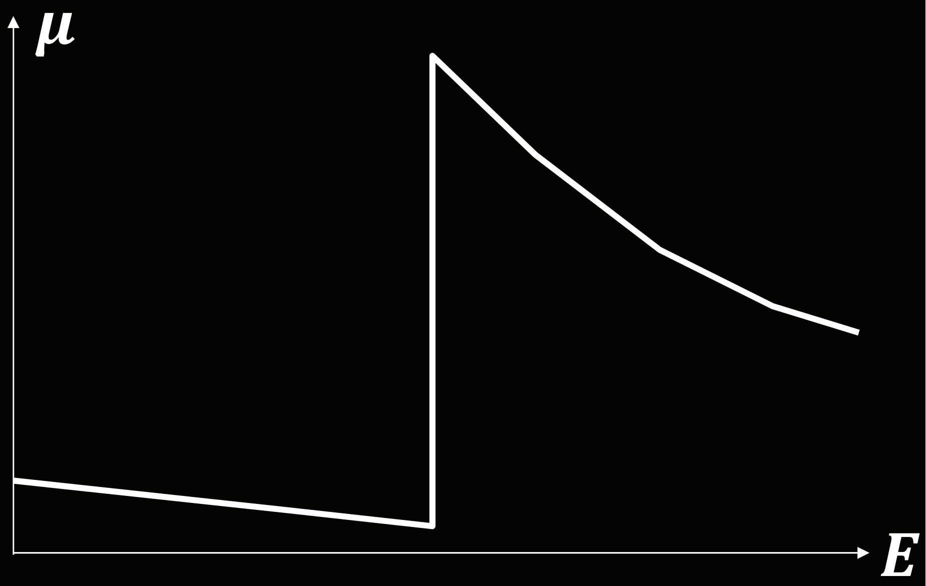
Emission of fluorescence photon
Emission of Auger electron

Interactions light/matter



All (almost) at the same time!

Absorption: XAS, EXAFS, XANES



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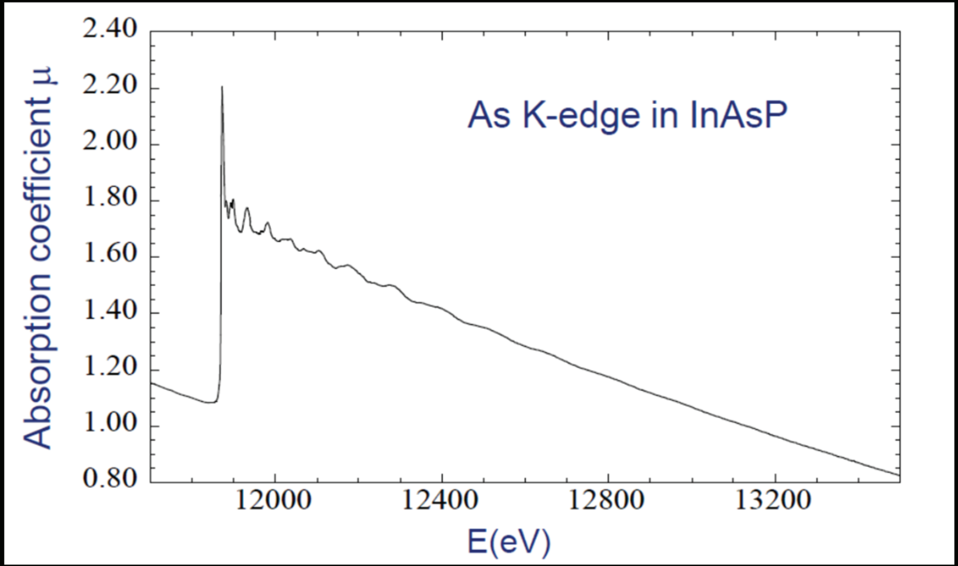

Credit Sakura Pascarelli @ ESRF

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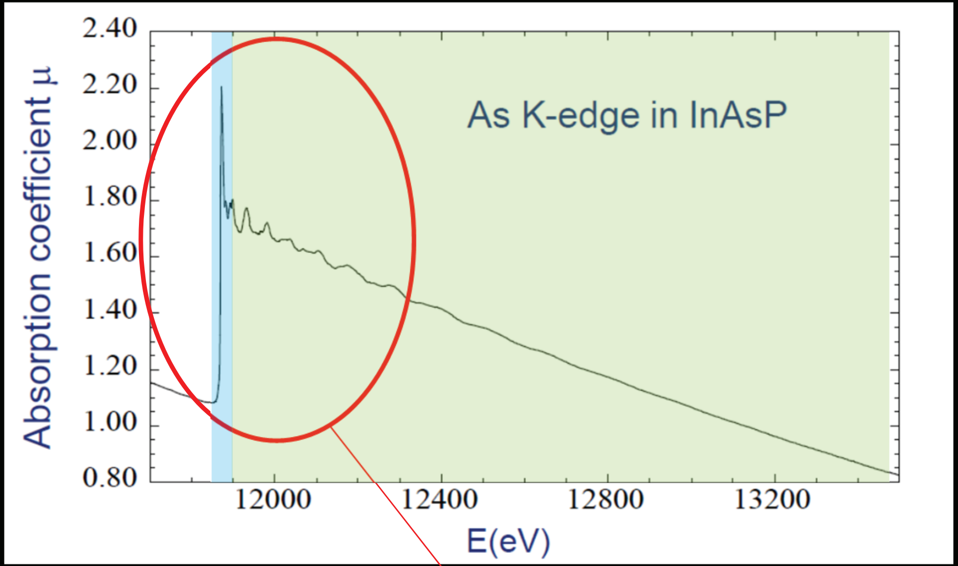


Credit Sakura Pascarelli @ ESRF

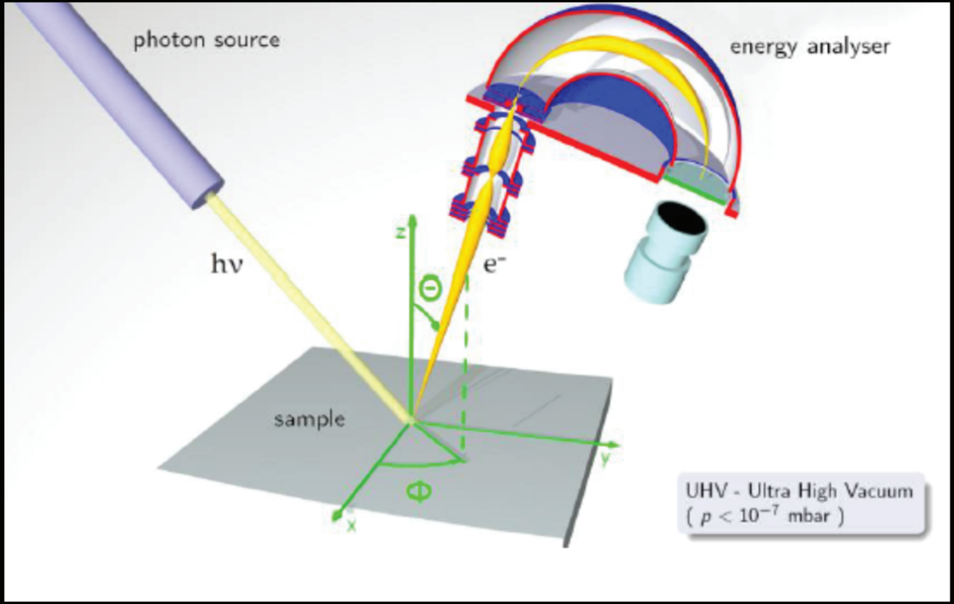
XAS measurements:

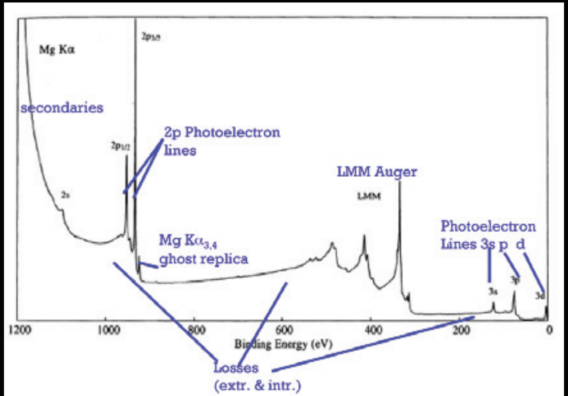
Absorption directly measured
Measurements of fluorescence
as a function of energy!

Constraints on monochromator
Reproducibility, precision, fixed exit
Dispersive XAS, quick EXAFS

Oscillations give information on atomic (EXAFS) and electronic (XANES) structure
Measurement of oscillations as precisely as possible

Photoemission spectroscopies



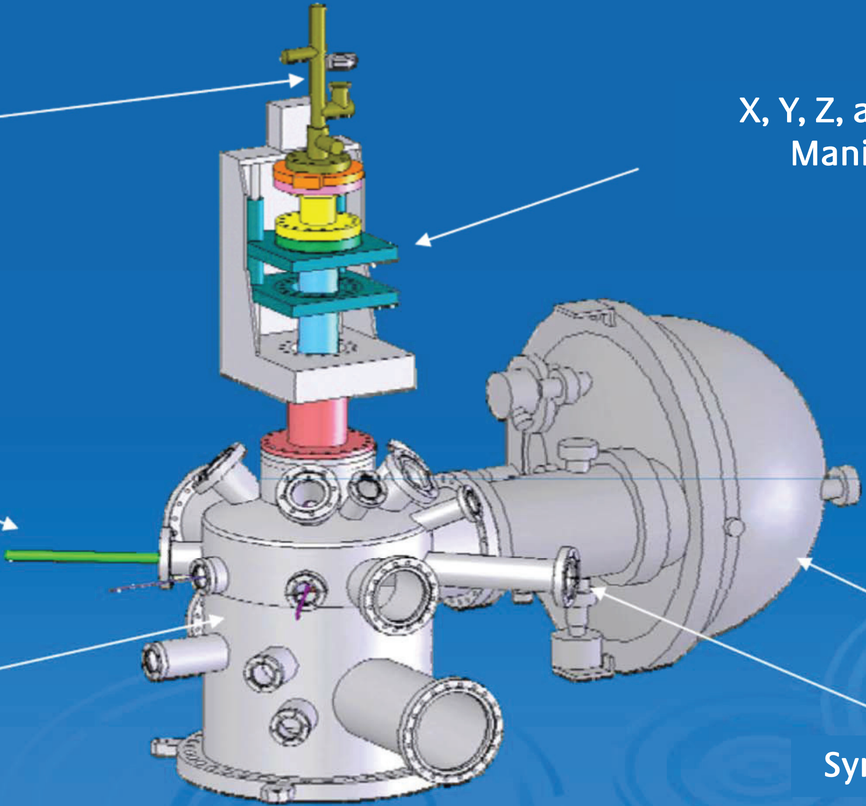


XPS: Measuring the photoemitted electrons as a function of electron energy

Angle Resolved Photo-Electron Spectroscopy (ARPES) as a function of angles (θ)
Temperature broadens the lines: low T

ARPES manipulators

Rotating the sample at very low T



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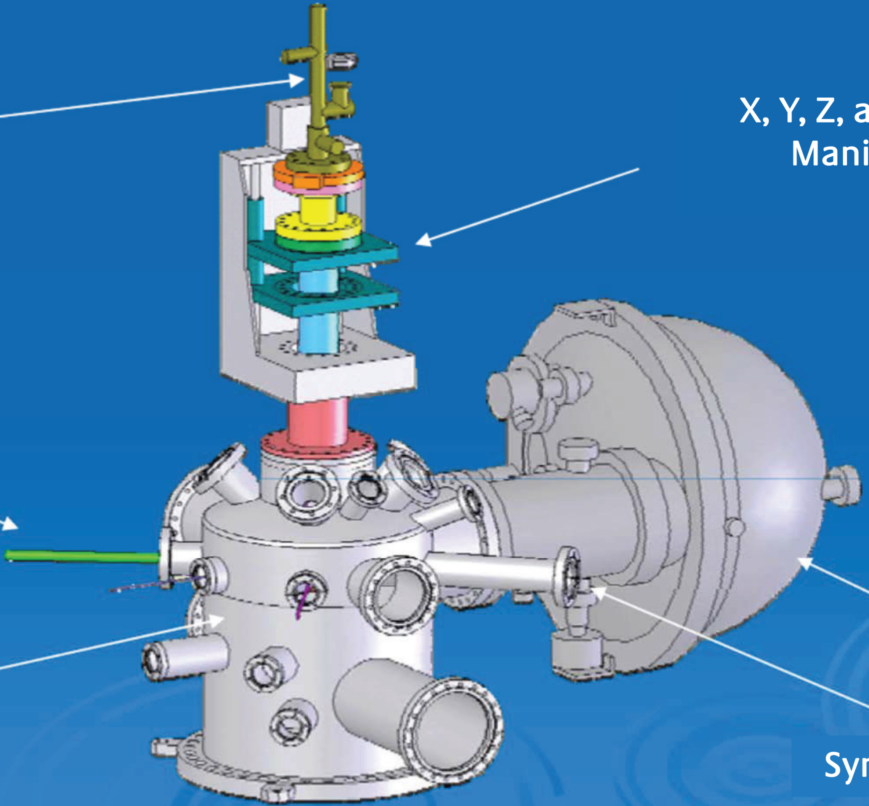
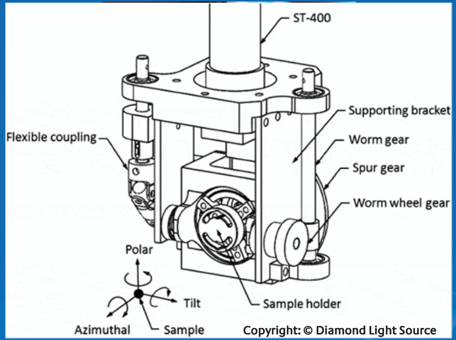


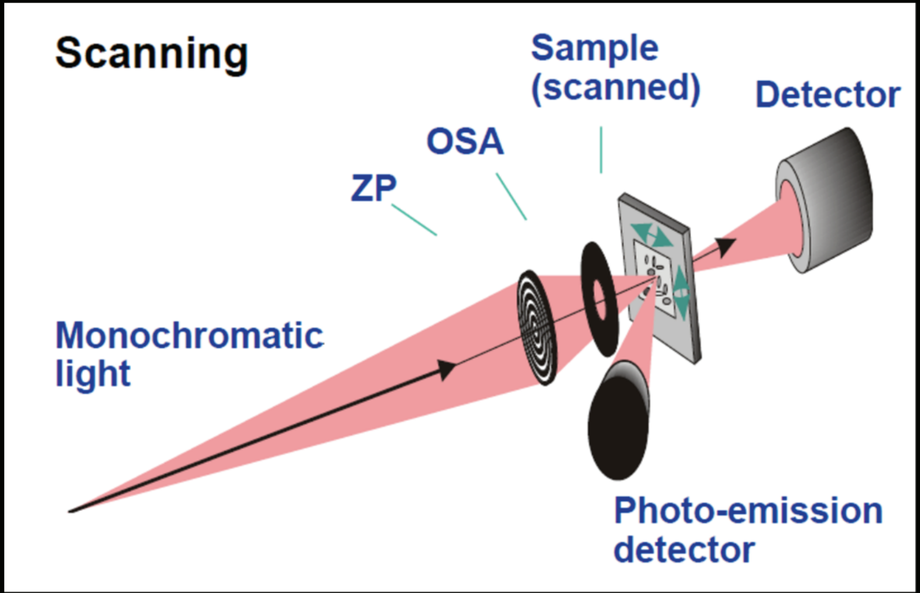


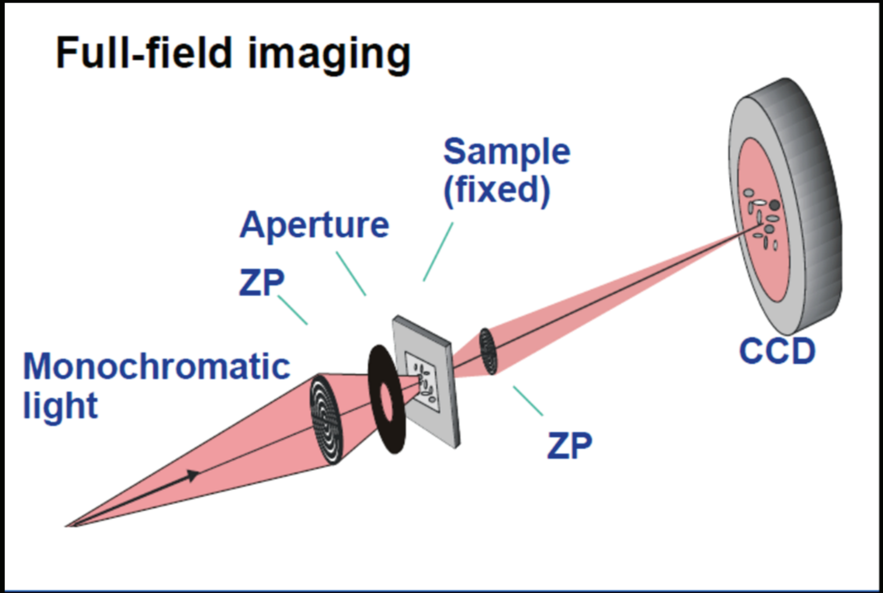
Towards 6-axis Low-T manipulator

Imaging

Two main classes of 2D imaging techniques

Contrast and resolution





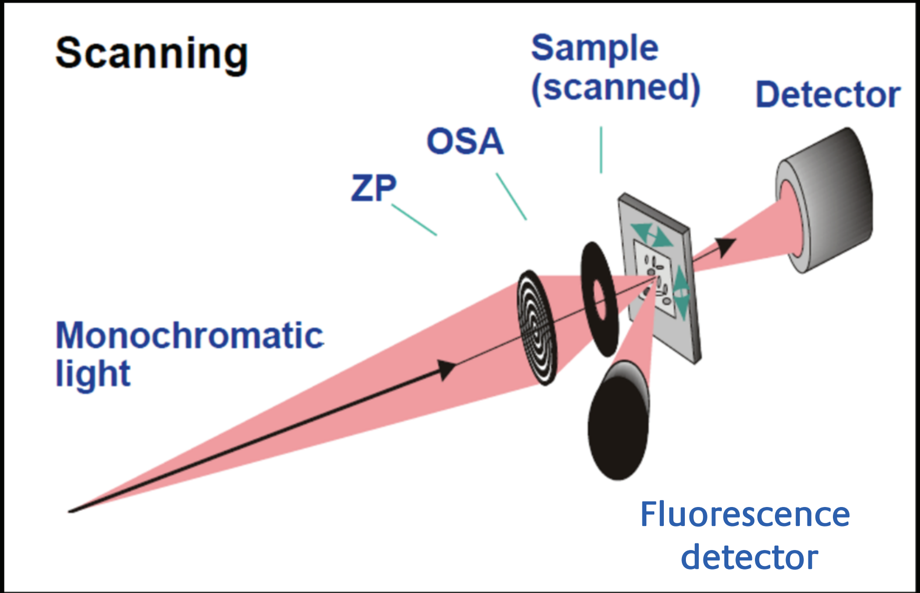
Photon efficiency
Different channels of measurements (XRD, XRF...)
Low speed; sensitive to drift

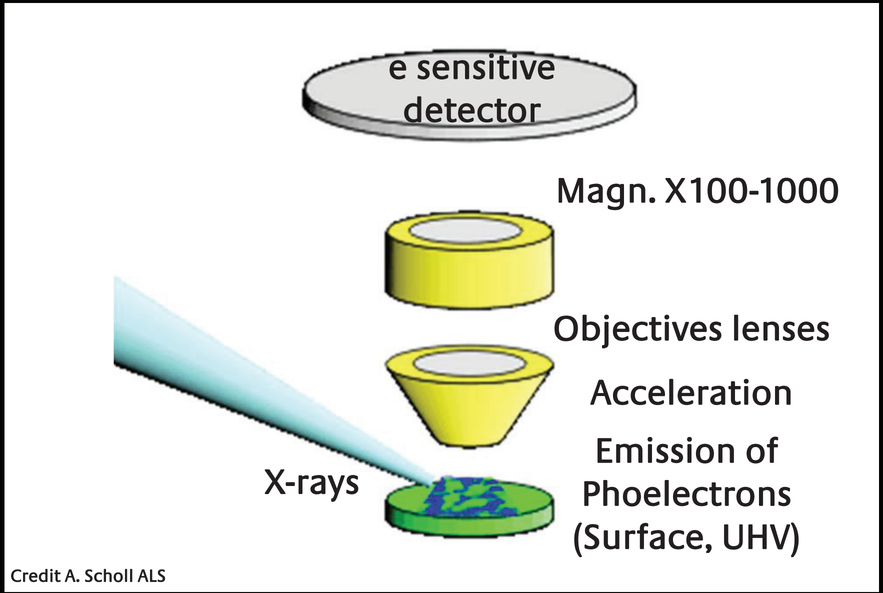
High speed: whole image at once
(Time-resolved expts)
Low photon efficiency
Background from other channels

Credit Alessandra Gianoncelli @ ELETTRA

Two main classes of imaging techniques

Examples using energy absorption to contrast





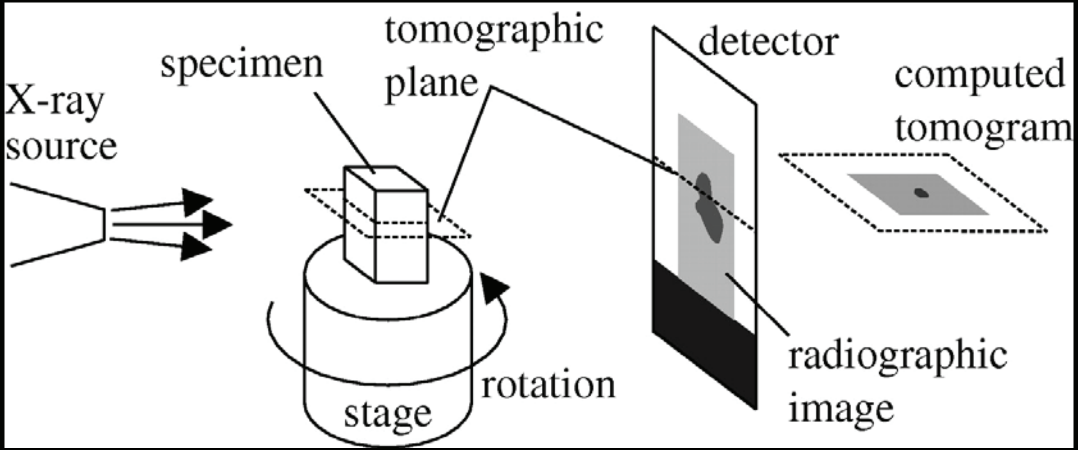
Scanning transmission X-ray spectroscopy (STXM)

Resolution a few tens of nm.
All scanning techniques need
very precise, fast and reproducible actuators

X-ray Photoemission Electron Microscopy (XPEEM)
Same principle as electron microscope.

3D imaging: tomography

Based on absorption



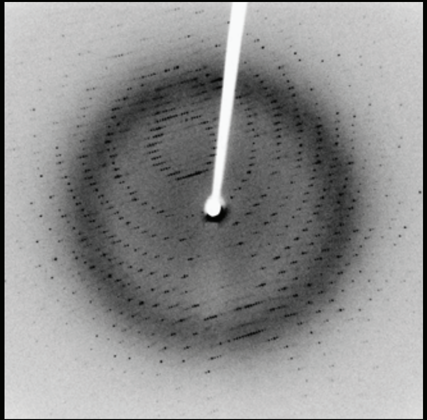
CREDIT P. Tafforeau ESRF

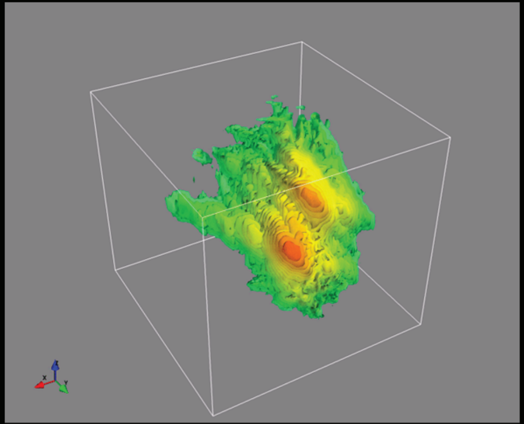
Measurement of absorption image, as a function of angle
Computation of the 3D object

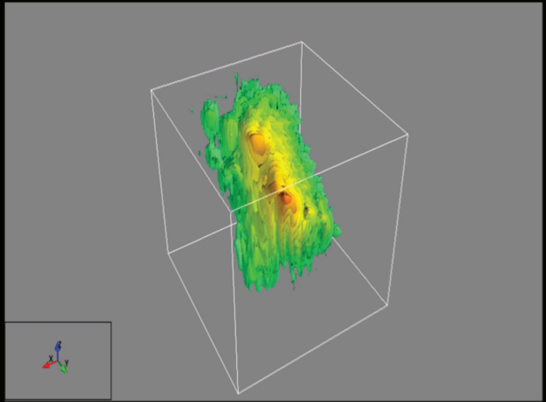
Need of high precision,
heavy load rotation stage (>50 kg, 100 nm, 60 rpm)

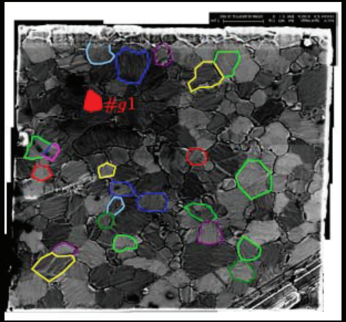
New 3D technique using coherence

Coherent Diffraction Imaging CDI



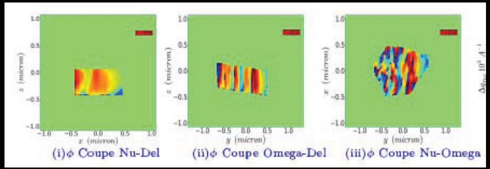






CREDIT: N. Vaxelaire, S. Labat IM2NP

Reconstruction of strain
In a sub-µ gold grain



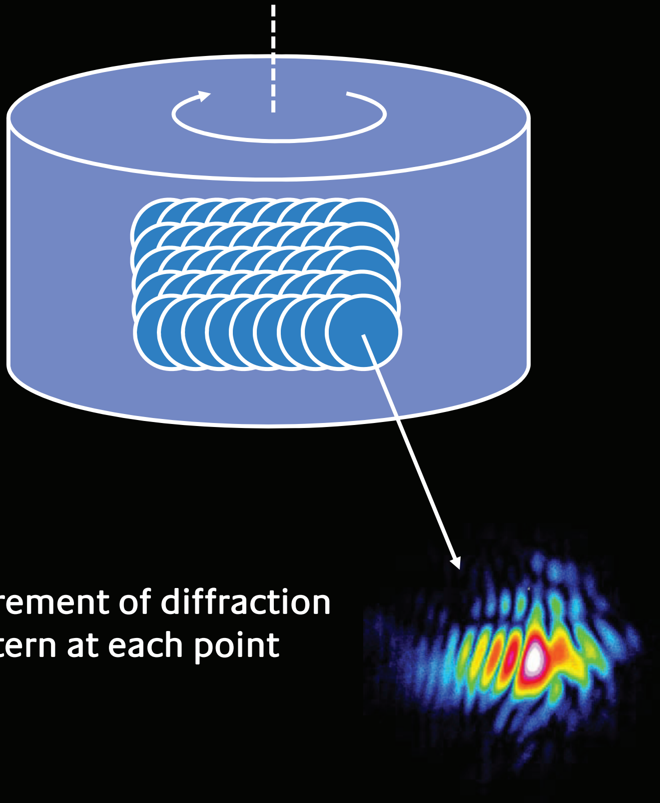
Principle:

Measurement of a Bragg spot
of a micrometric crystal
as a function of Bragg angle
In coherent conditions

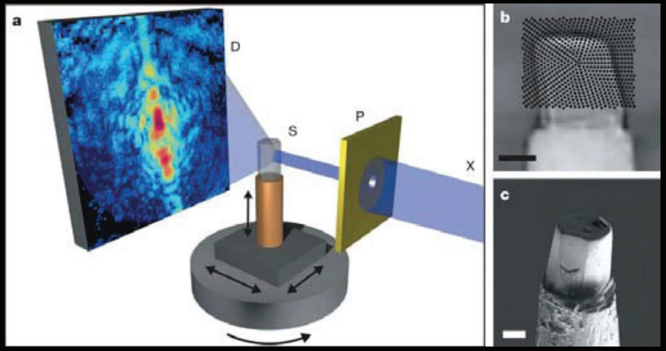
Very demanding expts:
Stability (coherence)
Precision of rotation stages
Sample environment (low T)

New 3D technique using coherence

Ptychography: raster scan with overlap, and rotation



Measurement of diffraction
Pattern at each point



First demonstrated at SLS (40h)
Dierolf et al. *Nature* 467 (2010)

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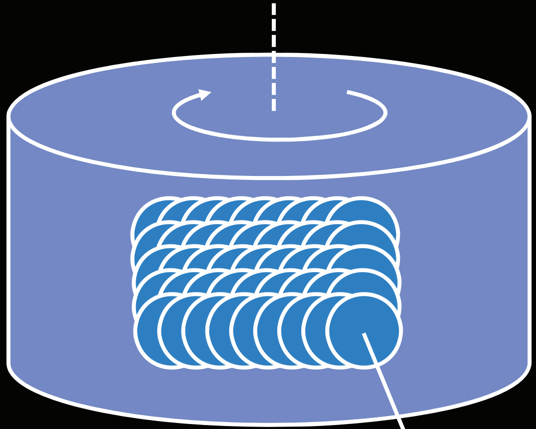

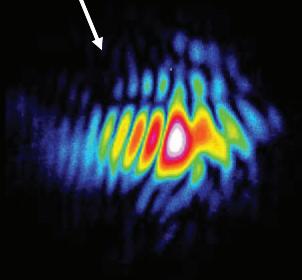

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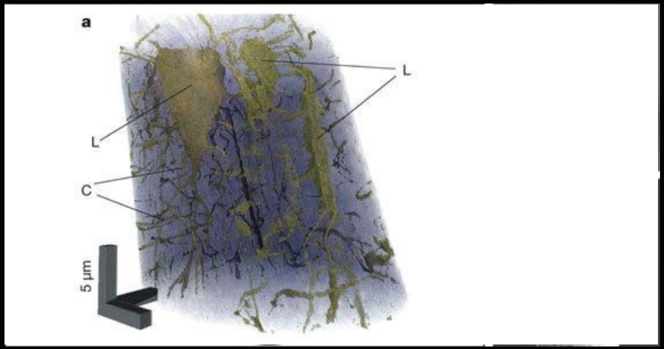

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Imaging techniques are called « lensless »

Long term stability (few hours)
Small intensity
Angular precision (coherence)

Conclusions

Increase of brilliance raises important stability issues:

Stability of monochromators (cooling systems)
To be scaled to the source size
Reproducibility (energy scans)

Temperature stability (thermal drifts)

Precision of angles (diffraction)
Precisions of all actuators for scanning (in the nm range)

Constraints on sample environments (low T, high P)

Thank you!