# Lecture : Coherence

## *School of Crystallography 2024*


Vincent JACQUES
*Laboratoire de Physique des Solides, CNRS, Université Paris-Saclay, 91405 Orsay*
vincent.jacques@universite-paris-saclay.fr

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# Coherence
# *Outline of the Lecture*

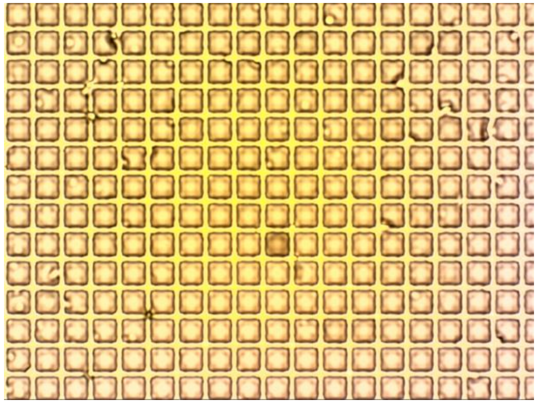
- Reflections on Coherence… From Visible to X-rays
- Generating and Using X-ray Coherence – From the Source Point to the Detector
  - Definition of Beam Coherence: Volume and Degree of Coherence
  - Natural Emergence of Coherence: Generating Coherent X-rays from Incoherent Sources
  - Measuring X-ray Coherence: Diffracting Object and Near/Far-field Detection
- Current Use of Coherent X-rays in Condensed Matter
  - What Can We Expect to See in X-ray Diffraction on Disordered Systems?
  - Structural Studies through Direct Analysis of Speckle Patterns
  - Coherent Diffraction Imaging:
    - Forward Techniques: CDI, Holography, Ptychography, Phase Contrast Tomography
    - In Bragg Condition: CDI, Holography, Ptychography
  - Slow Dynamics Experiments: XPCS (Forward or Bragg)
- New Opportunities Offered by Next-Generation Sources

# A Standard Coherent Source: The Visible Laser

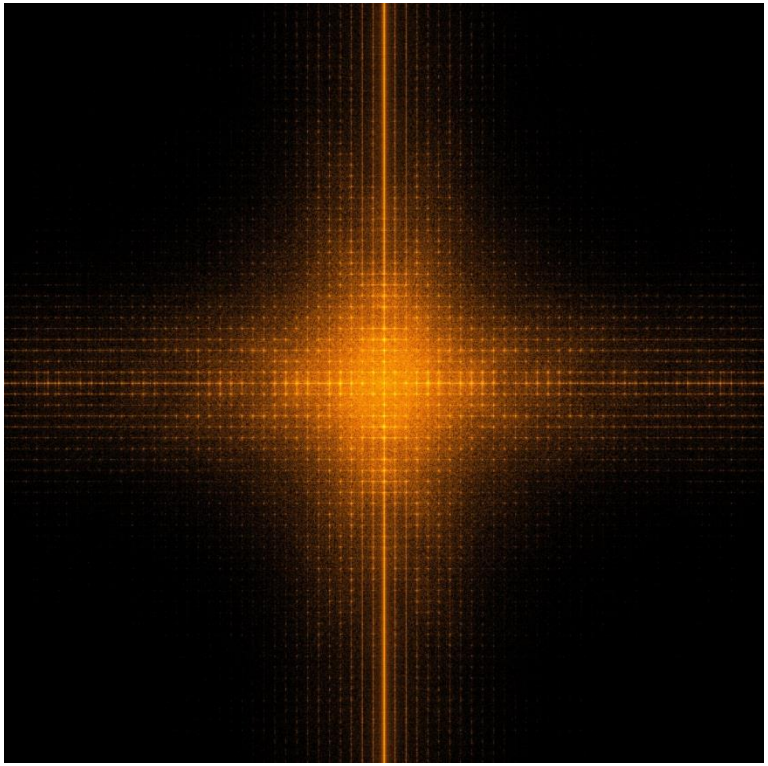
$\lambda$ = 530nm What is the typical object size that can diffract light?

Diffraction of a Grating by a Laser Beam?

Grating through binoculars

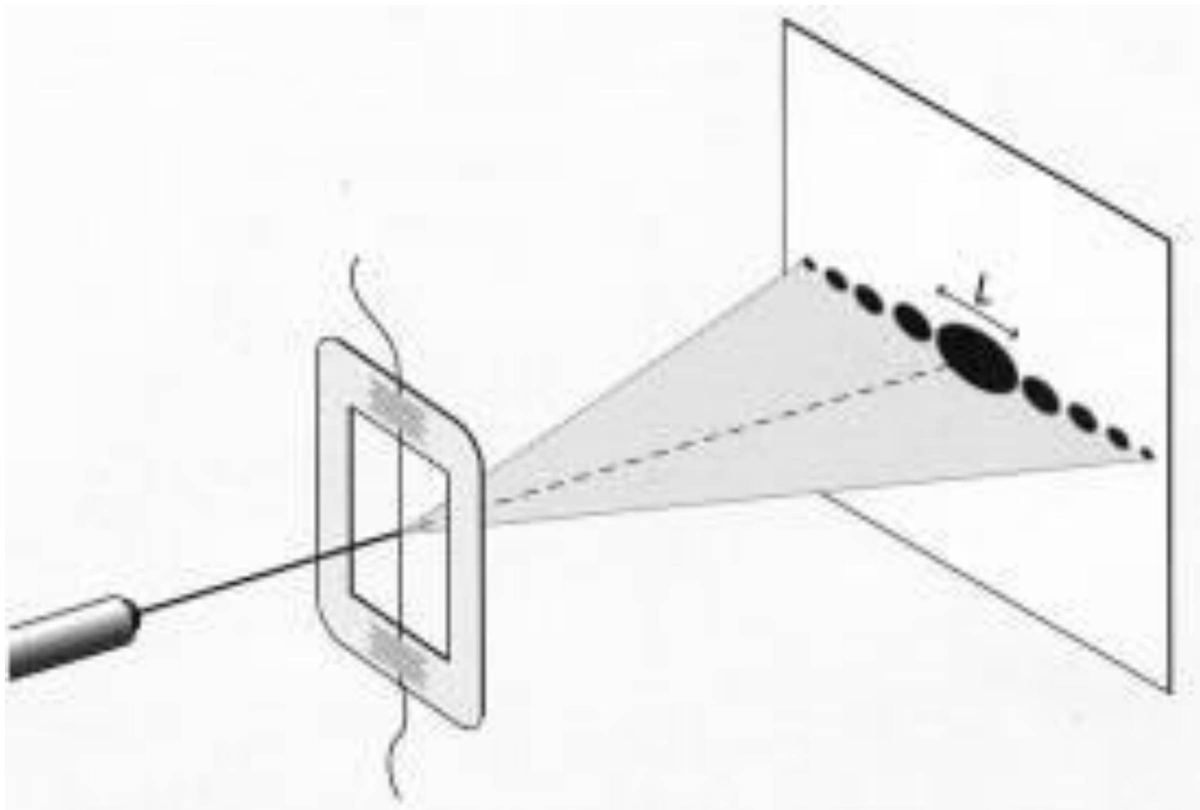


Fourier Transform



✓OK

# Diffraction of a hair by a laser beam?



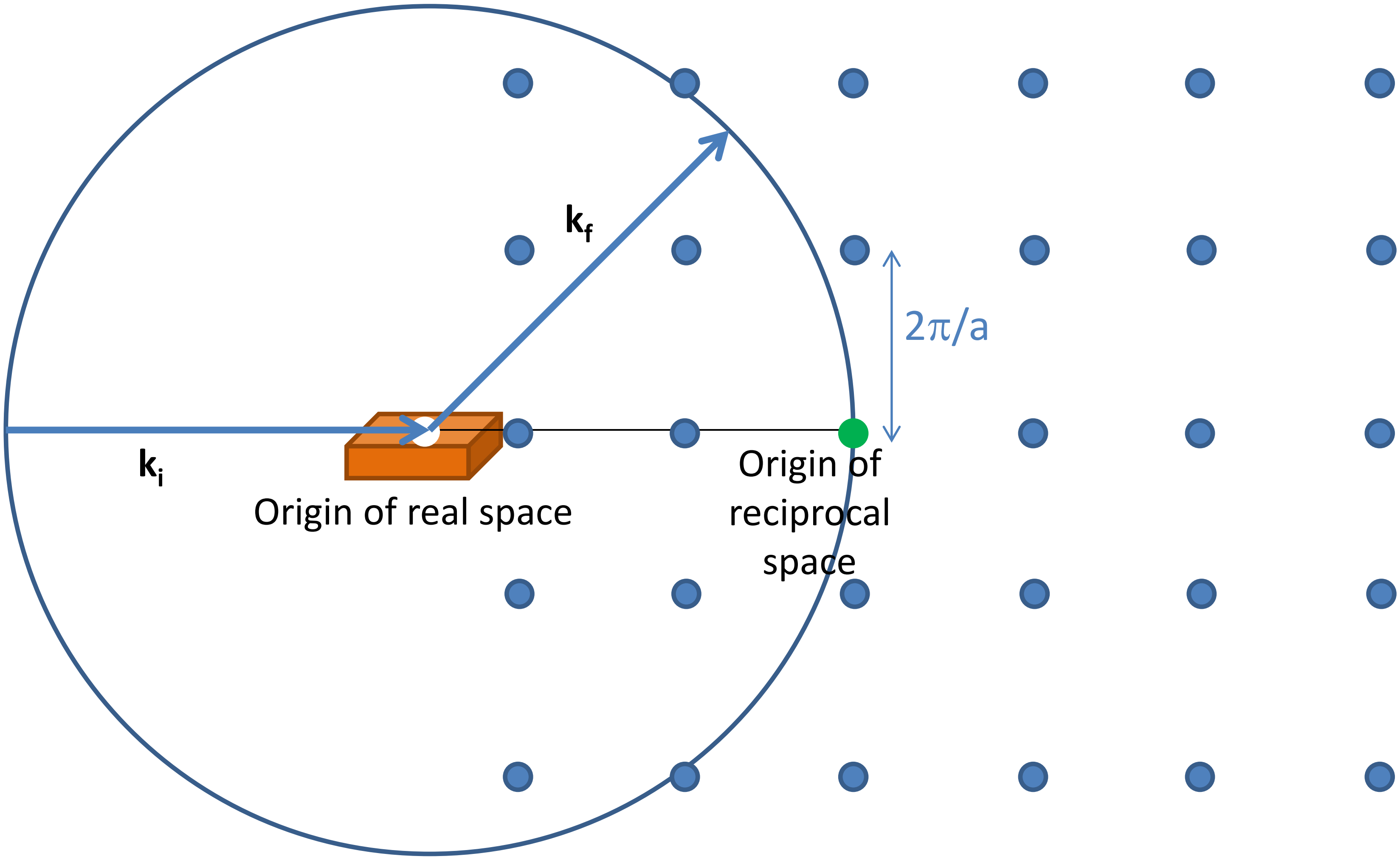
a~100µm…

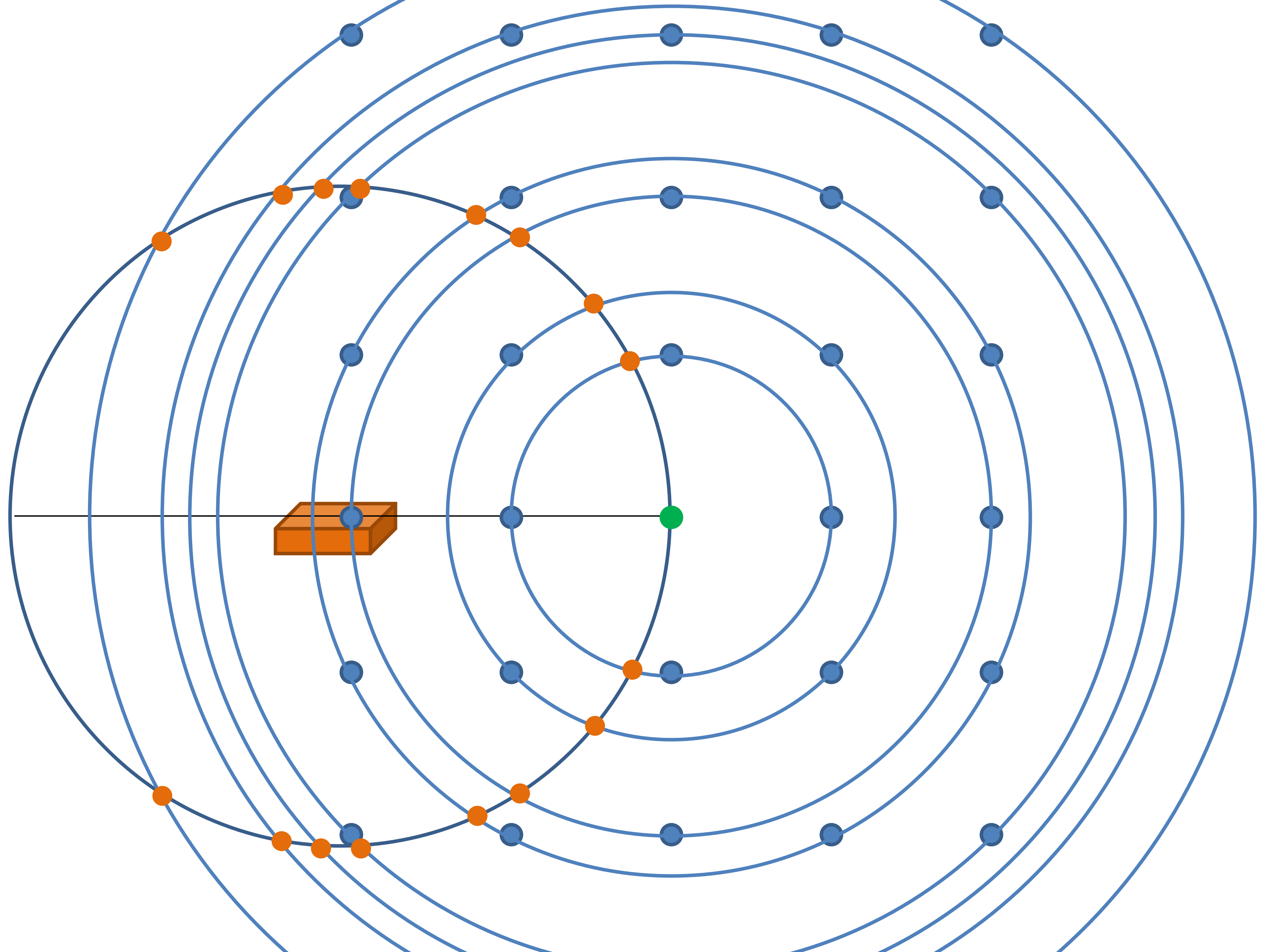
✓OK

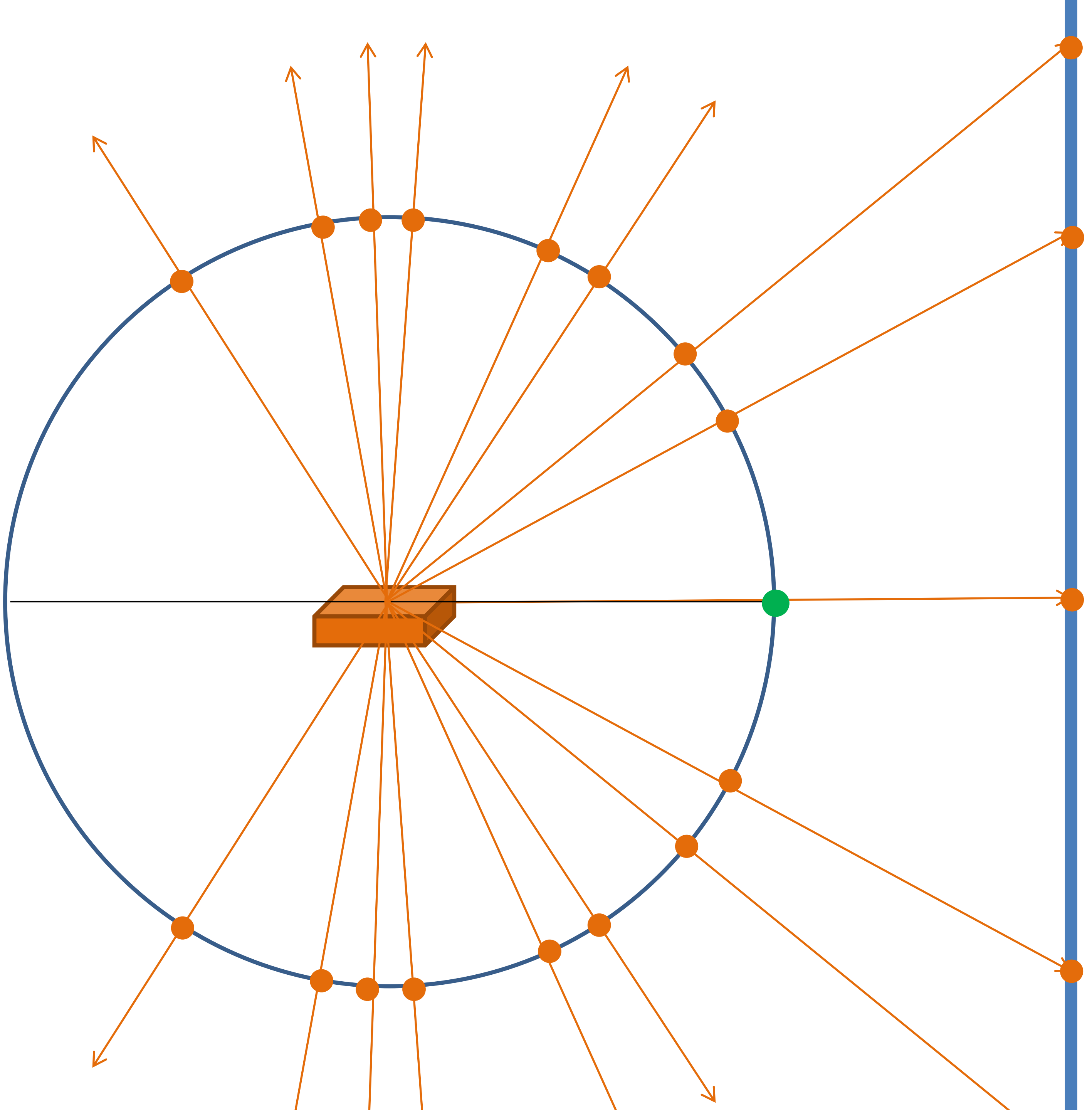
Following these observations, we can ask a few questions…

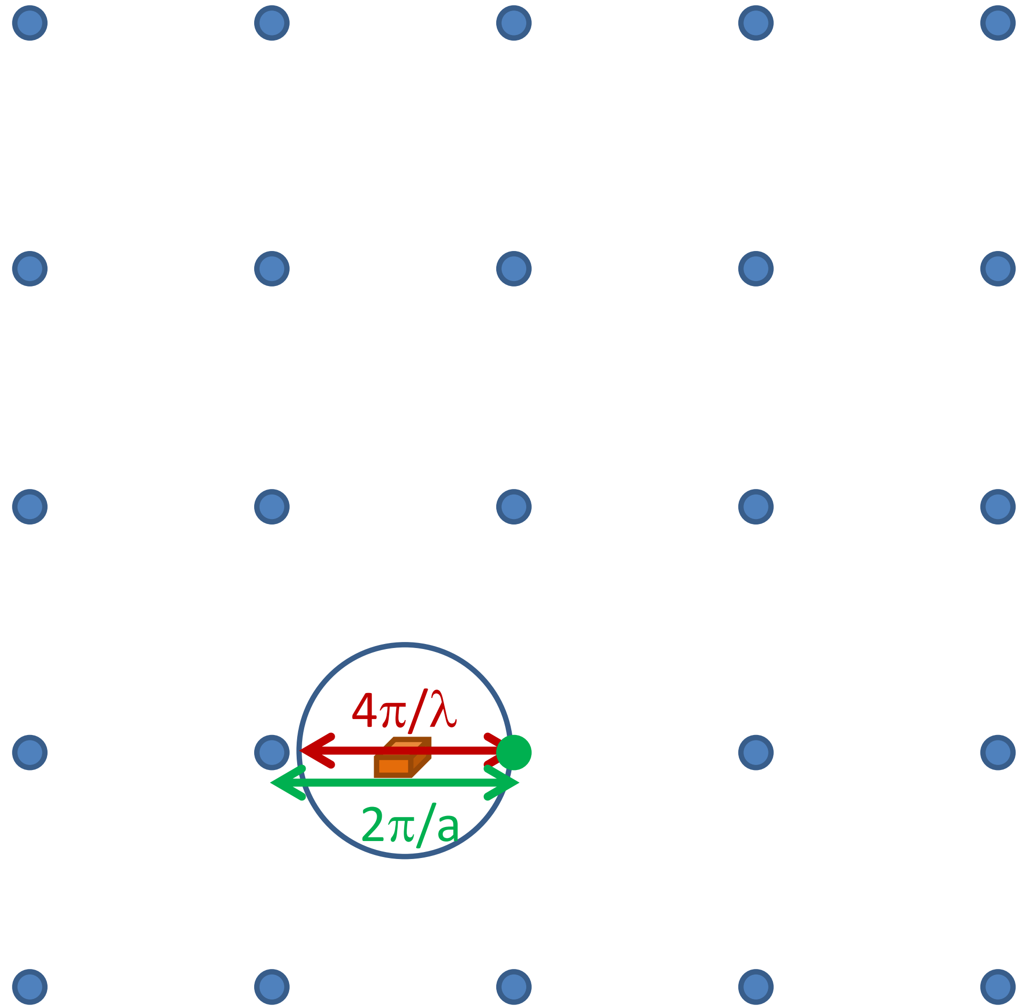
- What are the conditions on $\lambda$ and $a$ to observe a diffraction pattern?
- What are the properties of the laser necessary to get diffraction by these objects?
- Would the same experiments work with X-rays?
- What is coherence?
- How can coherent X-rays be generated in practice?
- How could a coherent X-ray beam be useful in condensed matter?

# What can be learned from Ewald's construction ?










To observe the diffraction of a beam having a wavelength λ by a crystal with lattice parameter $a$, it is necessary to have:

$$\frac{2\pi}{a} < \frac{4\pi}{\lambda}$$

**Diffraction condition :**

$$\boxed{\lambda < 2a}$$

$$\cancel{\lambda \sim a}$$

What length should be compared to $a$?

# Generating and Using X-ray Coherence – From the Source Point to the Detector

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  - Natural Emergence of Coherence: Generating Coherent X-rays from Incoherent Sources
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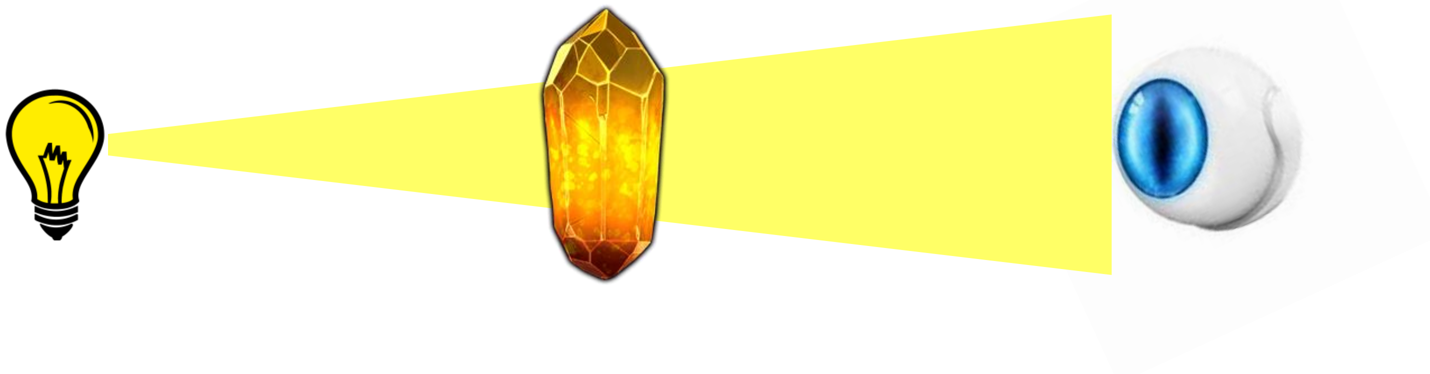
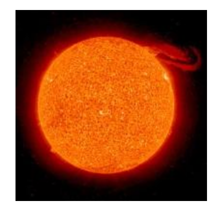
## Basic Experiment to Study an Object: Illuminate It

Necessary Equipment: A Source, an Object, a Detector

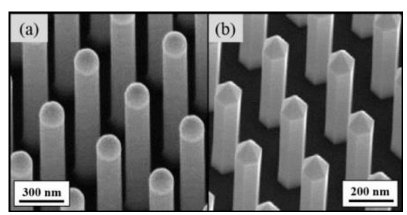


How to Introduce Coherence into This Experiment?

- On the source side ?



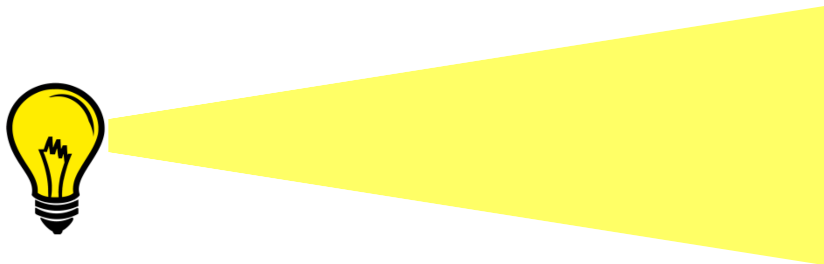
- On the object side ?




- Set Up Under Specific Observation Conditions / Use a Special Detector ?

# Where does the coherence of a beam come from?

What limits the validity of the summation of light amplitudes?

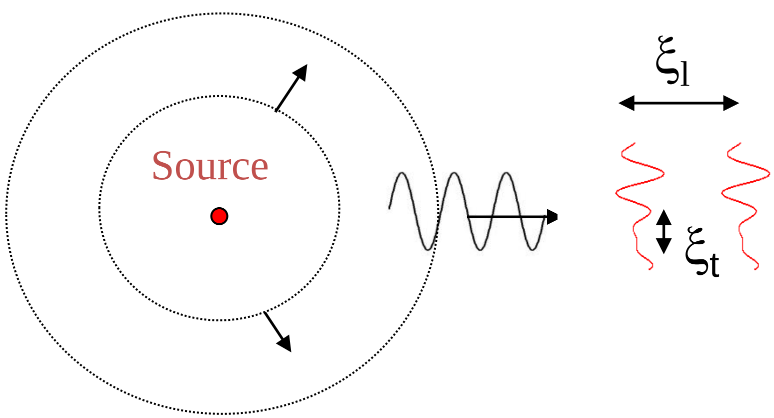


Beam monochromaticity

↓

*Longitudinal coherence length*

$\xi_l$

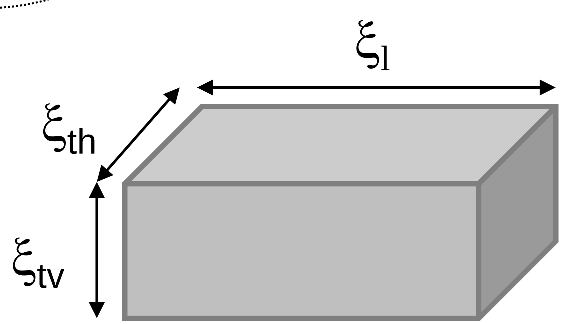



The source numerical aperture at a given point

↓

*Transverse coherence length*

$\xi_t$

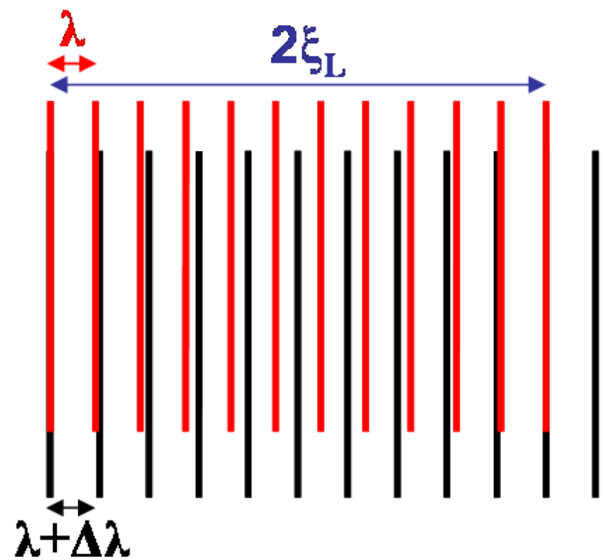



*Coherence volume*

# Longitudinal coherence length (temporal)

Plane wave with spectral bandwidth $\Delta\lambda$ around $\lambda$






$\xi_L$ : distance upon which two beams having a wavelength difference $\Delta\lambda$ will be out-of-phase

$$2\xi_L = (N+1)\lambda = N(\lambda + \Delta\lambda) \quad \rightarrow \quad N = \frac{\lambda}{\Delta\lambda}$$

$$\rightarrow \quad 2\xi_L = \frac{\lambda^2}{\Delta\lambda} + \lambda \sim \frac{\lambda^2}{\Delta\lambda} \qquad \text{if} \quad \Delta\lambda << \lambda$$

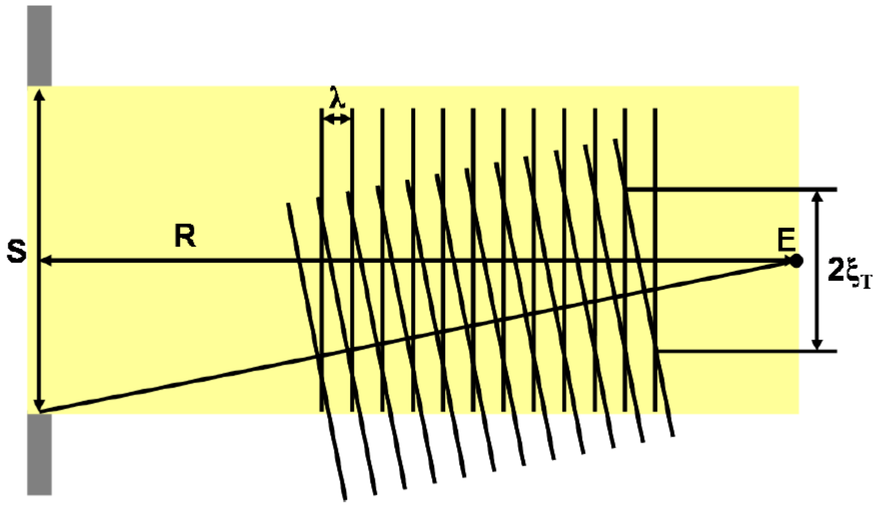
$$\boxed{2\xi_L = \frac{\lambda^2}{\Delta\lambda}}$$

Proportional to $\lambda$ , inversely proportional to $\Delta\lambda/\lambda$

→ The smaller $\lambda$ , the smaller $\xi_l$ …

# Transverse coherence length (spatial)

Extended monochromatic source




$\xi_T$ : length perpendicular to **k** for which two beams having an incidence difference $\alpha$ will be out-of-phase

$$tg(\alpha) = \frac{S}{R} = \frac{\lambda}{2\xi_T}$$

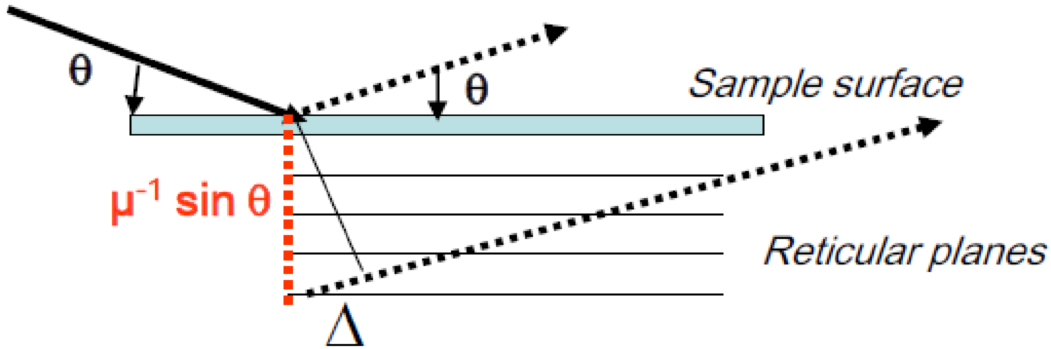
$$\boxed{2\xi_T = \frac{\lambda R}{S}}$$

$\frac{S}{R}$ Numerical aperture of the source

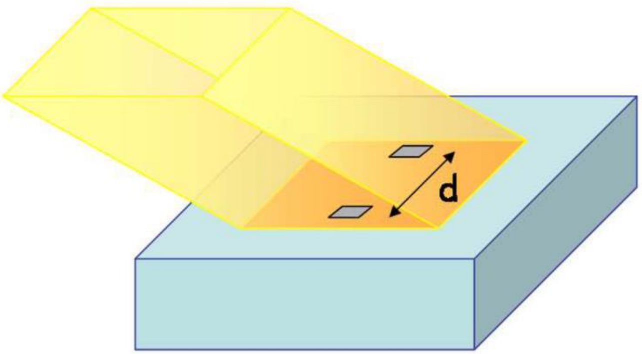
Proportional to $\lambda$
Proportional to the source-sample distance
Inversely proportional to the source size

# Link Between the Coherence Volume and the Sample Volumes

$$2\xi_L = \frac{\lambda^2}{\Delta\lambda}$$



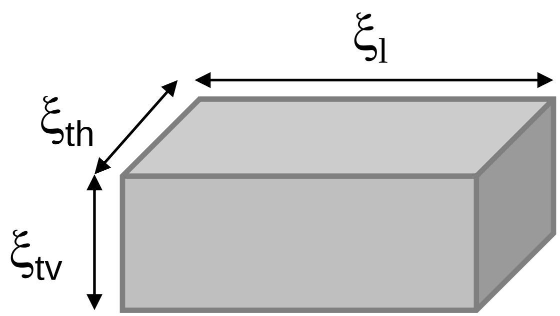

$$2\xi_T = \frac{\lambda R}{S}$$




Interferences are possible if:

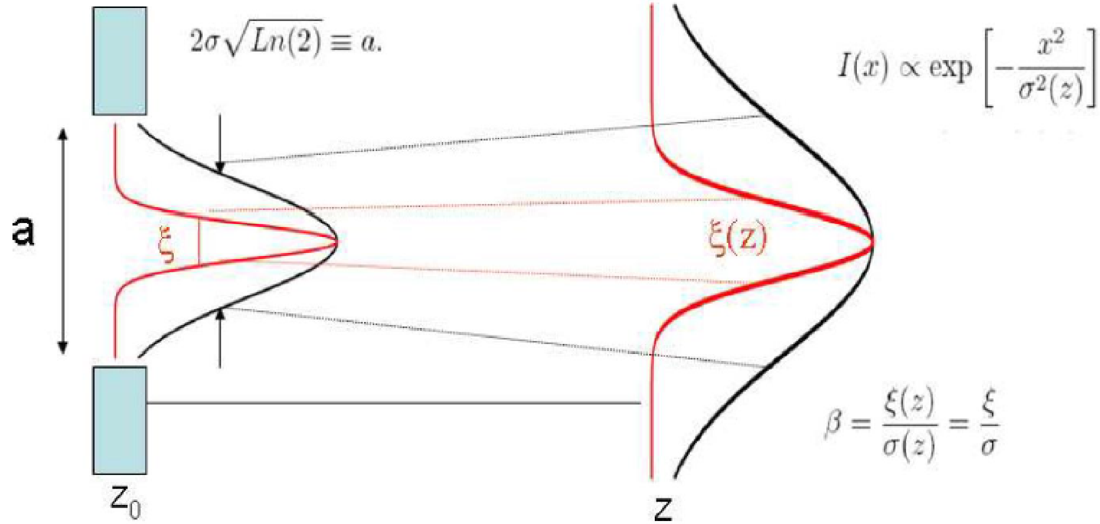
$$\Delta = 2\mu^{-1} sin^2\theta \quad < \xi_L$$

$$d < \lambda$$



# How to Gain Spatial Coherence (easily)?

***Propagation of a partially coherent beam***




*Beam size $\sigma(z)$ :*

$$\sigma^2(z) = \sigma^2 + \left(\frac{z\lambda}{2\pi}\right)^2 \left(\frac{\xi^2 + 2\sigma^2}{\sigma^2\xi^2}\right)$$

*Transverse coherence length $\xi(z)$:*

$$\xi^2(z) = \xi^2 + \left(\frac{z\lambda}{2\pi}\right)^2 \left(\frac{\xi^2 + 2\sigma^2}{\sigma^4}\right)$$

*1. If source is incoherent:* $\xi \longrightarrow 0$ $\quad \xi(z) = \left(\frac{z\lambda}{\pi}\right)\left(\frac{1}{\sigma}\right)$

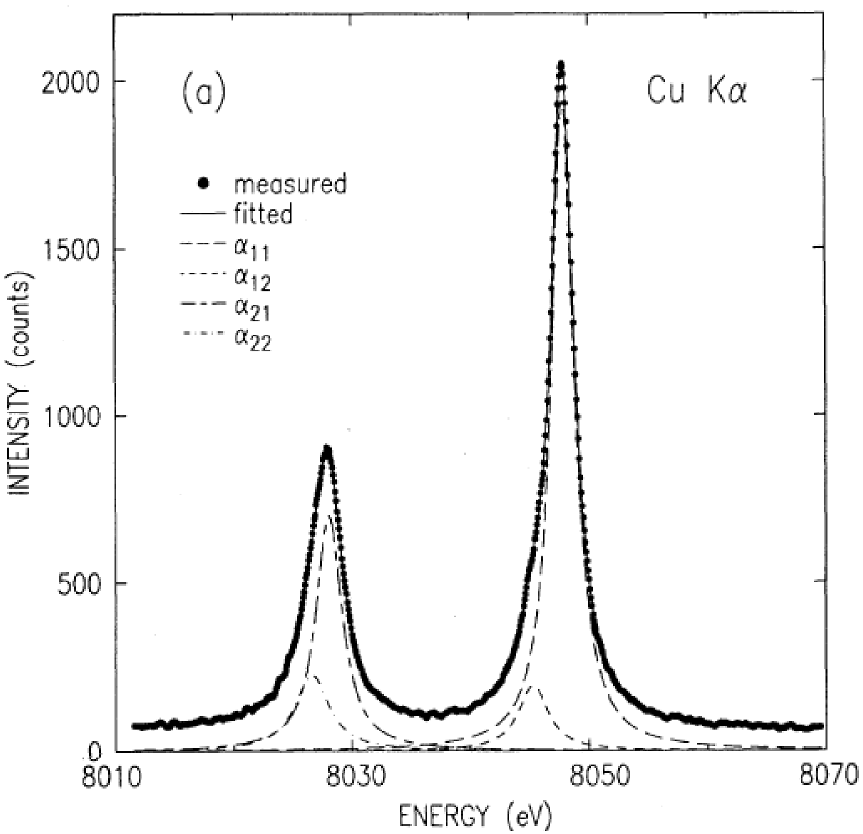
We can get a coherent beam from an intrinsically incoherent source (like the sun)

*2. Coherence Degree:* $\beta = \frac{\xi(z)}{\sigma(z)} = \frac{\xi}{\sigma}$

The coherence degree is constant through propagation

# A Bit of Pragmatism: Coherence in Numbers…

With wavelengths more than 1000 times smaller than visible wavelengths, what values do we obtain?

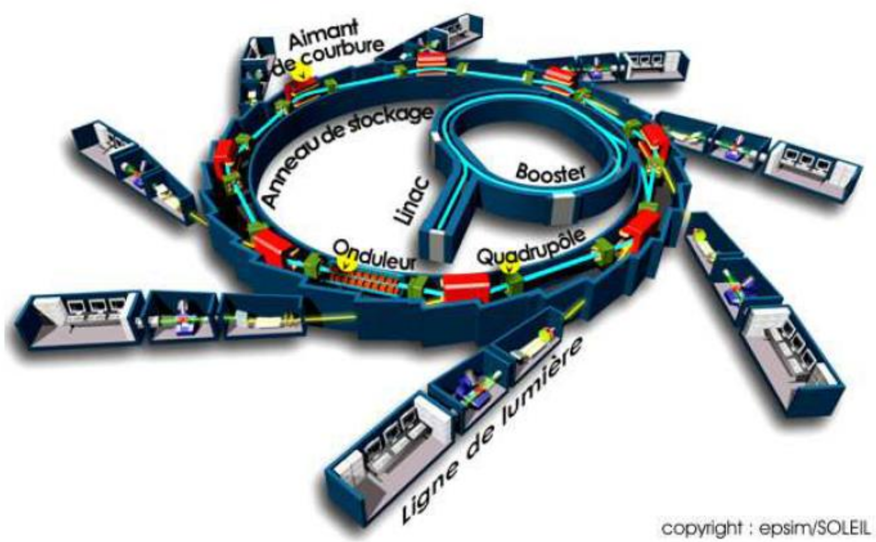


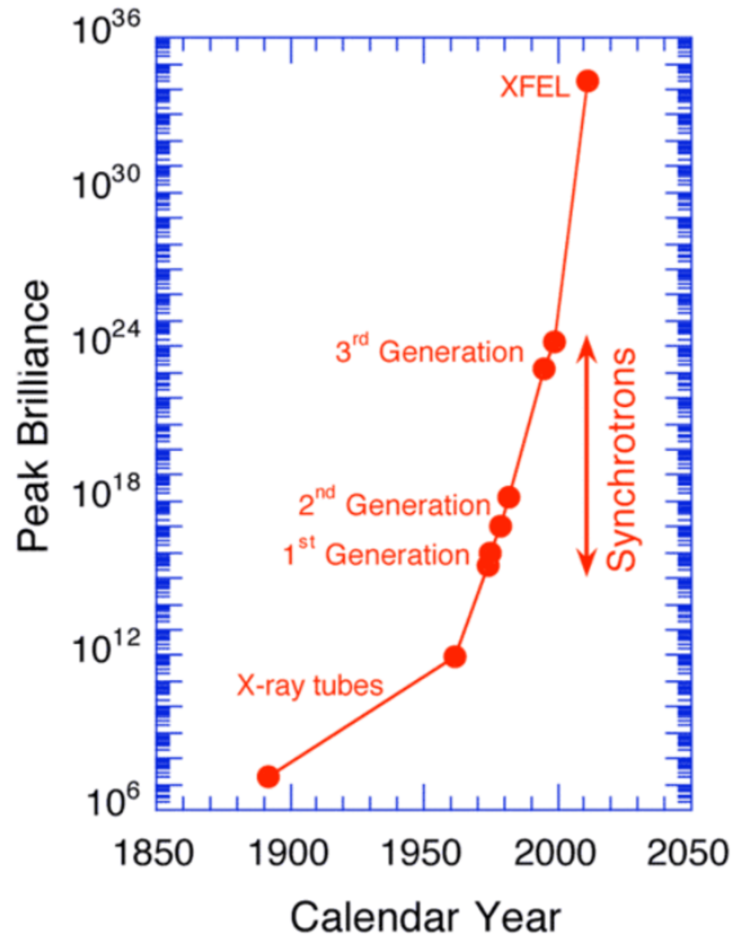

In the laboratory with a monochromatic source (copper anticathode):
$\Delta E/E = 3/8000 = 3.7.10^{-4}$ ➔ $\xi_L$ ~ 400 nm

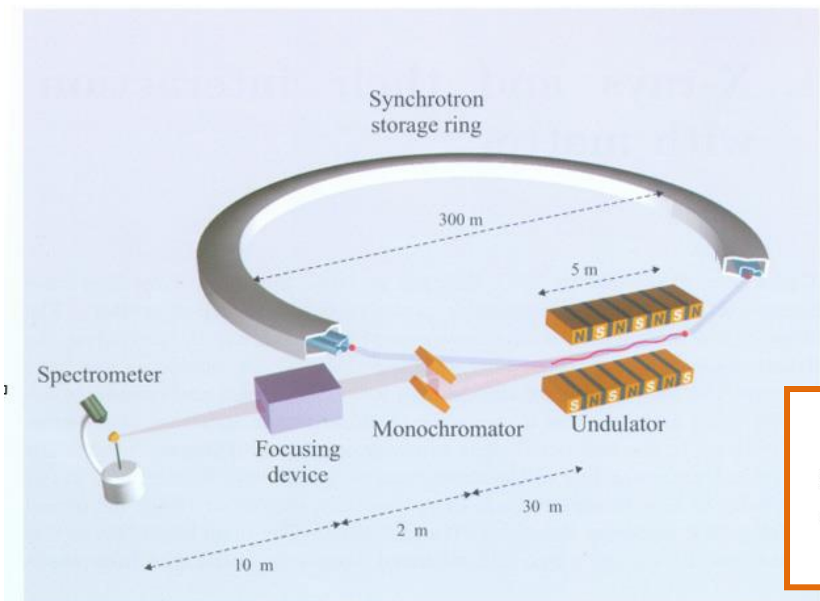
With a laboratory monochromatic microfocus source: S = 1mm; distance: 1m
$\xi_T = 1.5.10^{-10}/10^{-3}$ ➔ $\xi_T$ = 150 nm

Possible, but how many photons remain within an aperture of 150x400 nm?

# Increase Coherent Flux Using Large Scale Instruments




$$2\xi_T = \frac{\lambda R}{S}$$

We gain on:
S, R, and especially brightness (low emittance)

# With an undulator beamline at SOLEIL

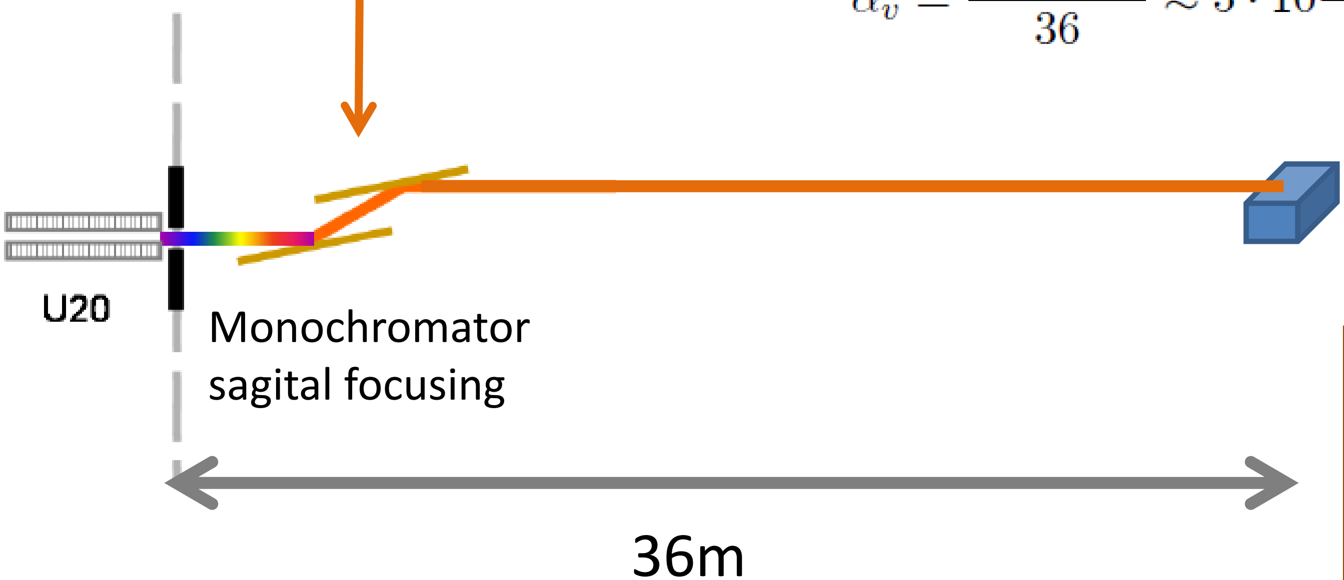
$$\boxed{2\xi_L = \frac{\lambda^2}{\Delta\lambda}}$$

Mono Si(111):
$\frac{\Delta\lambda}{\lambda} = 1{,}4.10^{-4}$

$$\boxed{2\xi_T = \frac{\lambda R}{S}}$$

$$\alpha_h = \frac{911 \cdot 10^{-6}}{36} \approx 2,53 \cdot 10{-}5\ rad \ = \ 25,3\ \mu rad$$

$$\alpha_v = \frac{19 \cdot 10^{-6}}{36} \approx 5 \cdot 10{-}7\ rad \ = \ 0,527\ \mu rad$$



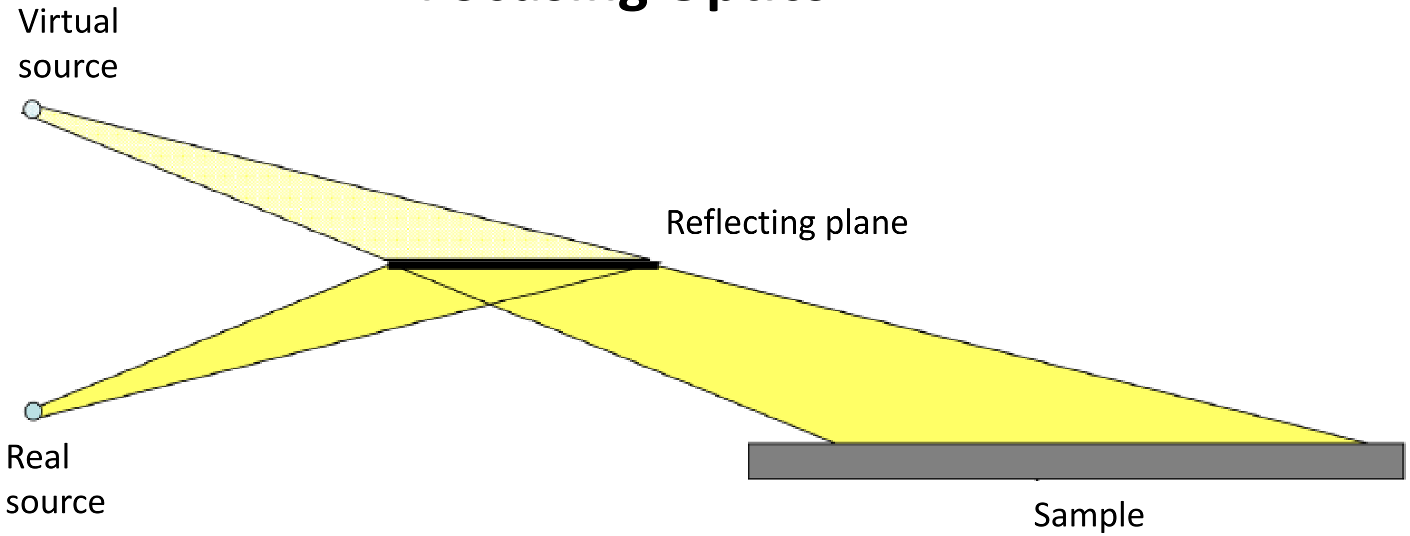

At 8keV:

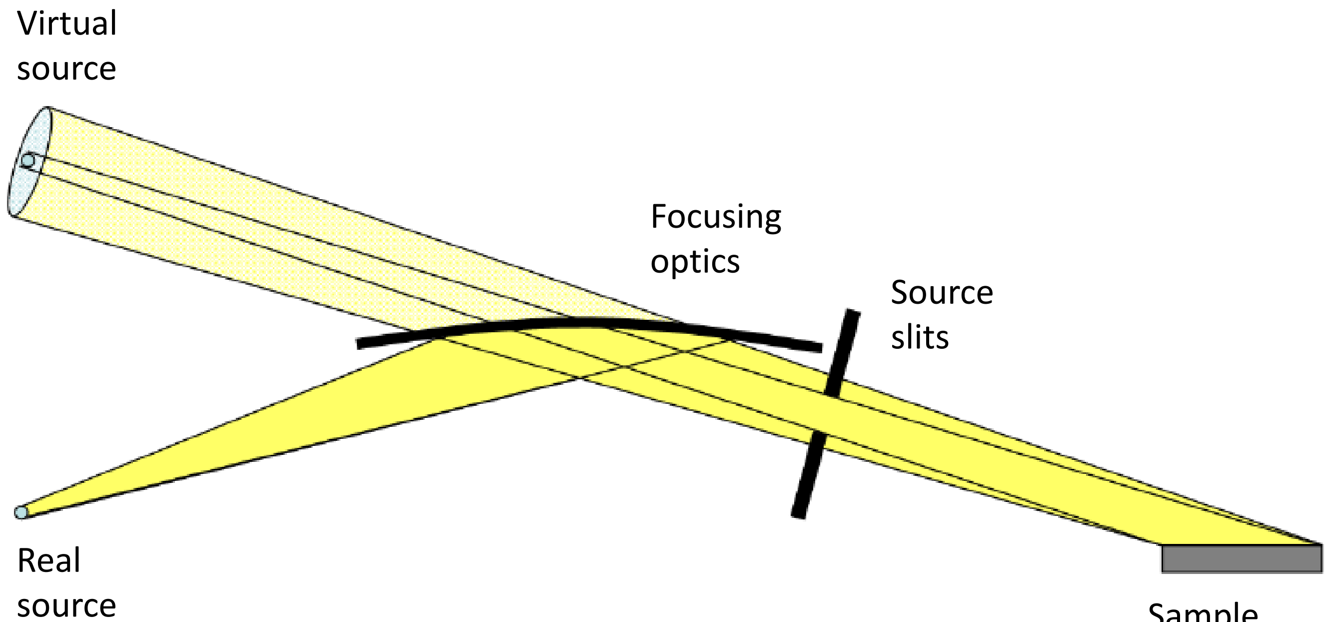
$\xi_L = 0{,}5\ \mu m$

$\xi_{Th} = 6\ \mu m$

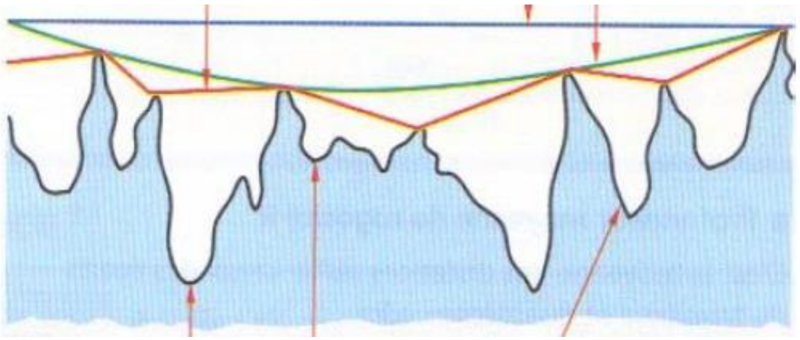
$\xi_{Tv} = 280\ \mu m$

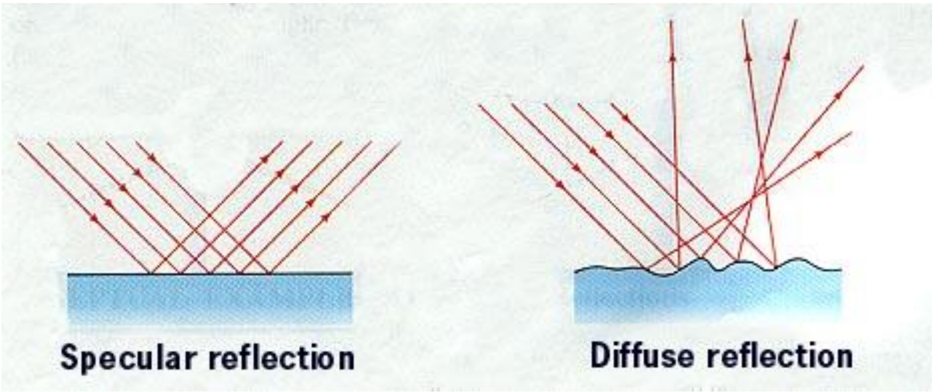
# Influence of Optical Elements on Coherence
# Focusing Optics



# Influence of Optical Elements on Coherence
# Surface rugosity






With X-rays, the surface roughness must be compared to $\lambda$...

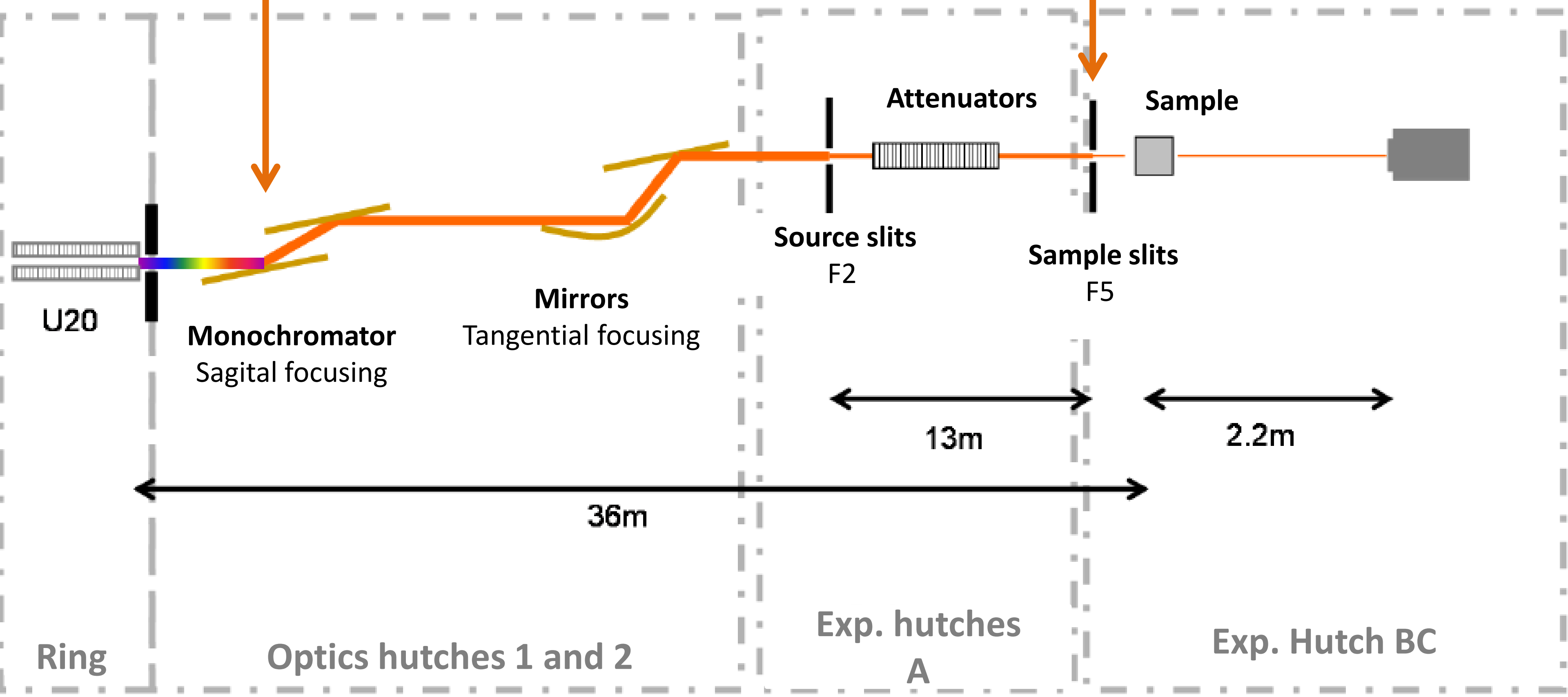
Optical elements quickly degrade the coherence of an X-ray beam...It is necessary to use secondary sources after the optics and let the beam propagate freely as much as possible.

# Coherence setup of the CRISTAL beamline at SOLEIL

$$2\xi_L = \frac{\lambda^2}{\Delta\lambda}$$

$$2\xi_T = \frac{\lambda R}{S}$$

With a secondary source:
$\xi_{Th} = \xi_{Tv} \sim 20\ \mu m$
$\beta$ near 100%

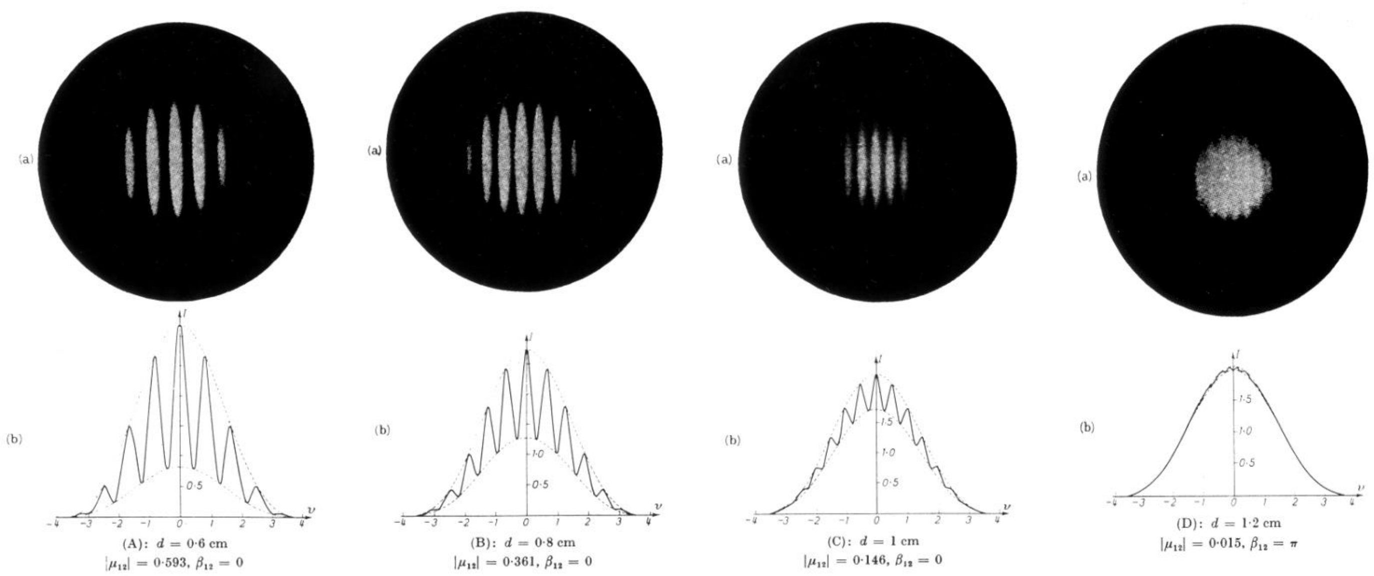


# Measuring the Coherence Degree of an X-ray Beam

*Young's double slit experiment*

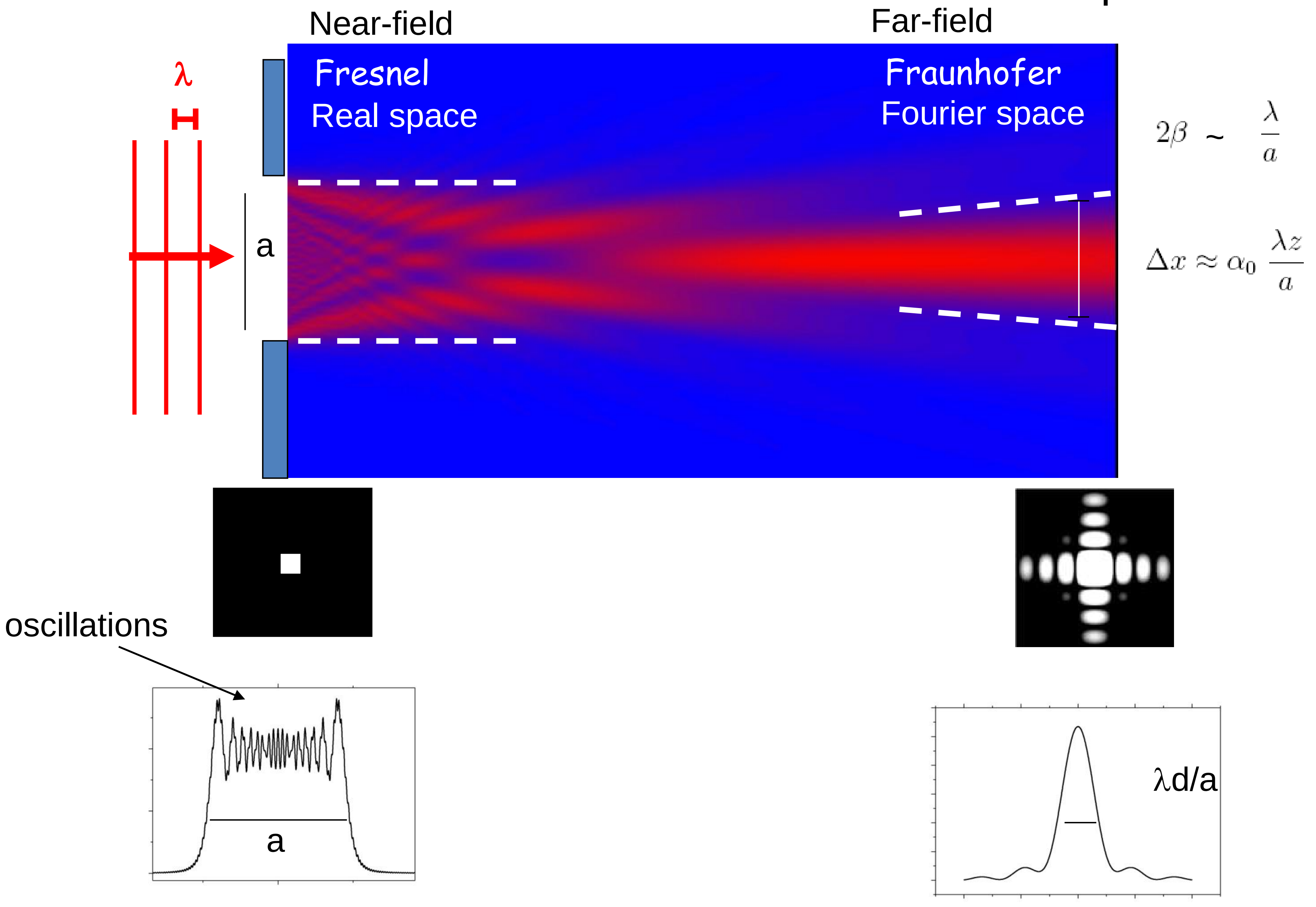

**Conditions of coherence: $\xi_t > a$:**

$d<\xi_t$ $d>\xi_t$




The visibility of the fringes is related to the degree of coherence.
At synchrotron facilities → measure the degree of coherence with slits?

# How to switch from far-field to near-field? Not so simple !



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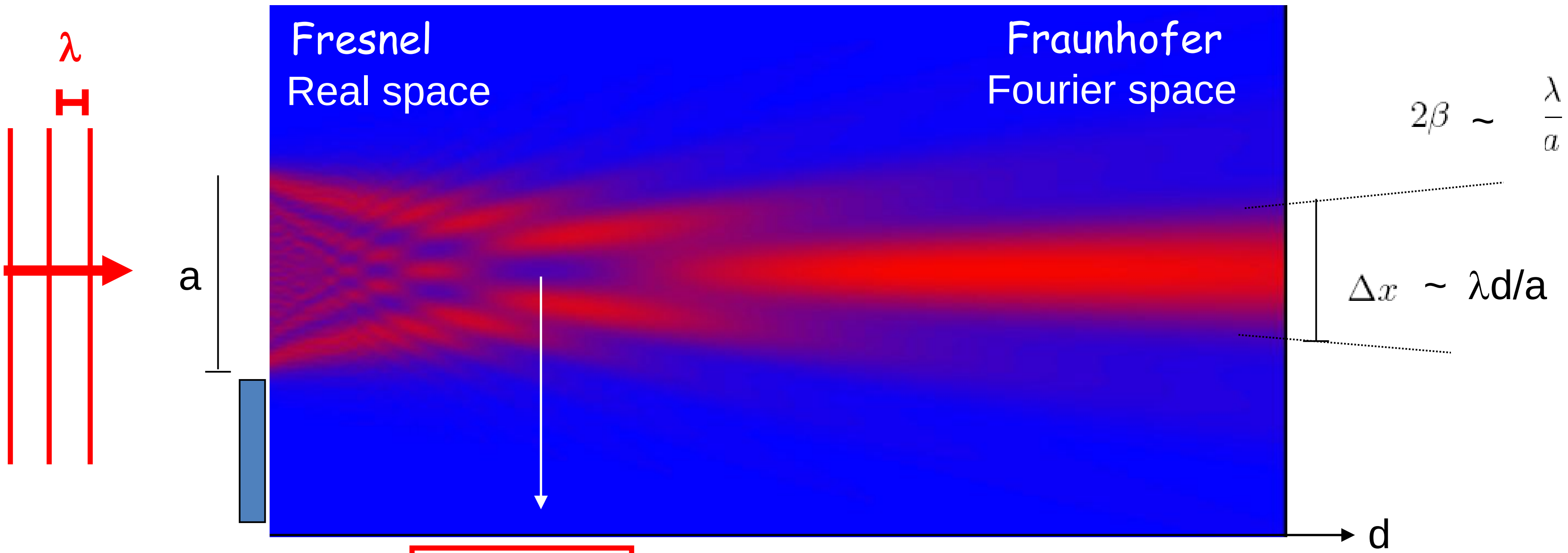
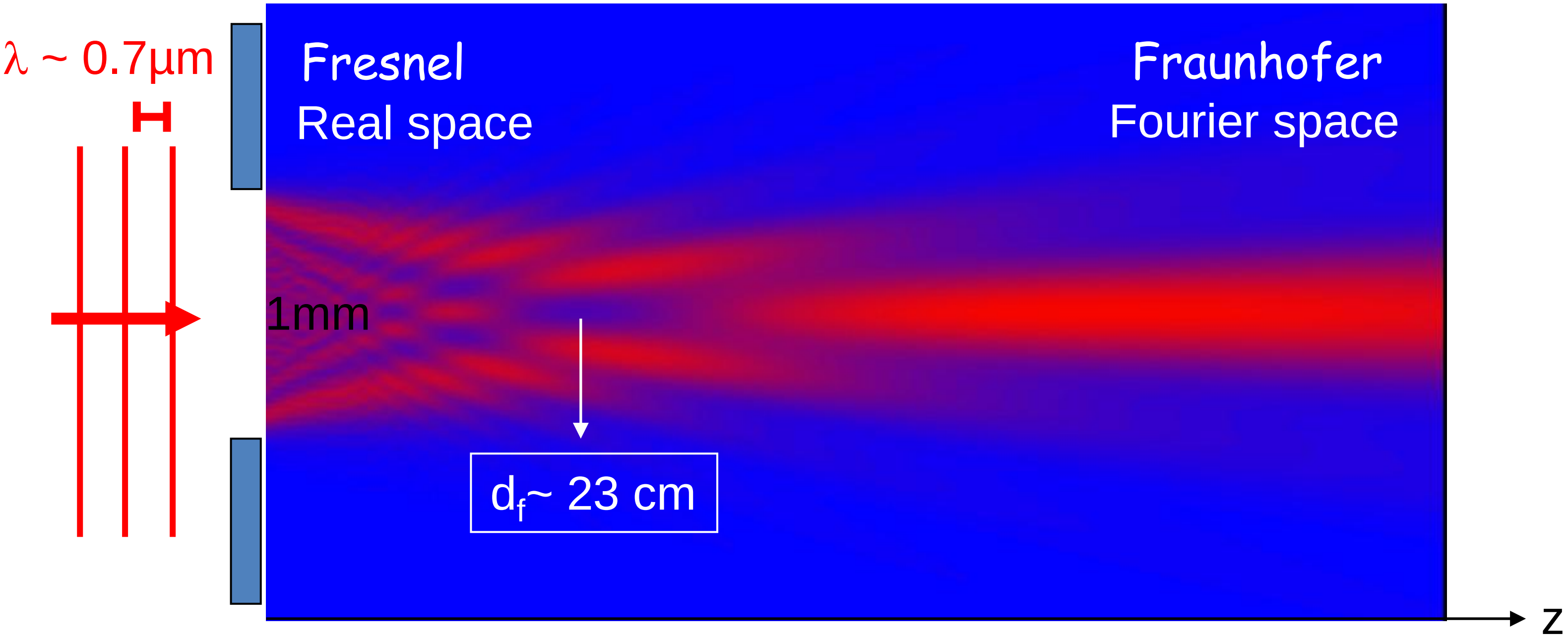



Separation distance: $\boxed{d_f \sim \frac{a^2}{\lambda}}$

1. $\Delta x = a$
   $\lambda d/a = a \Rightarrow d = a^2/\lambda$

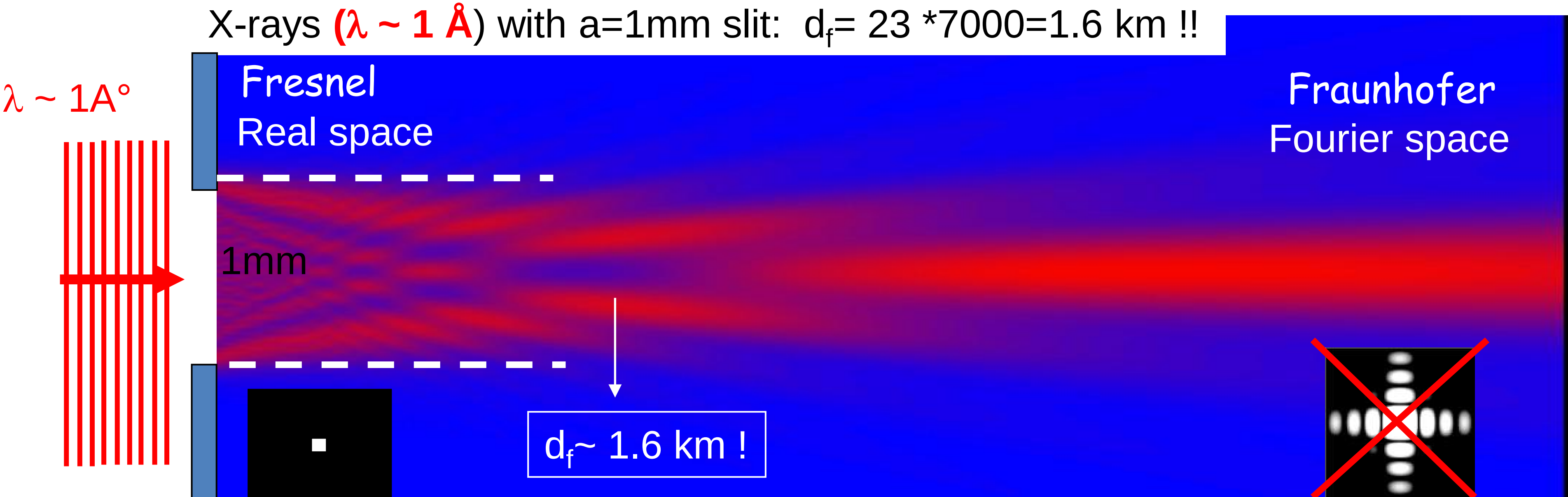
2. simulations: $d_f \approx \frac{a^2}{6.6\ \lambda}$

# How to switch from far-field to near-field? Not so simple !



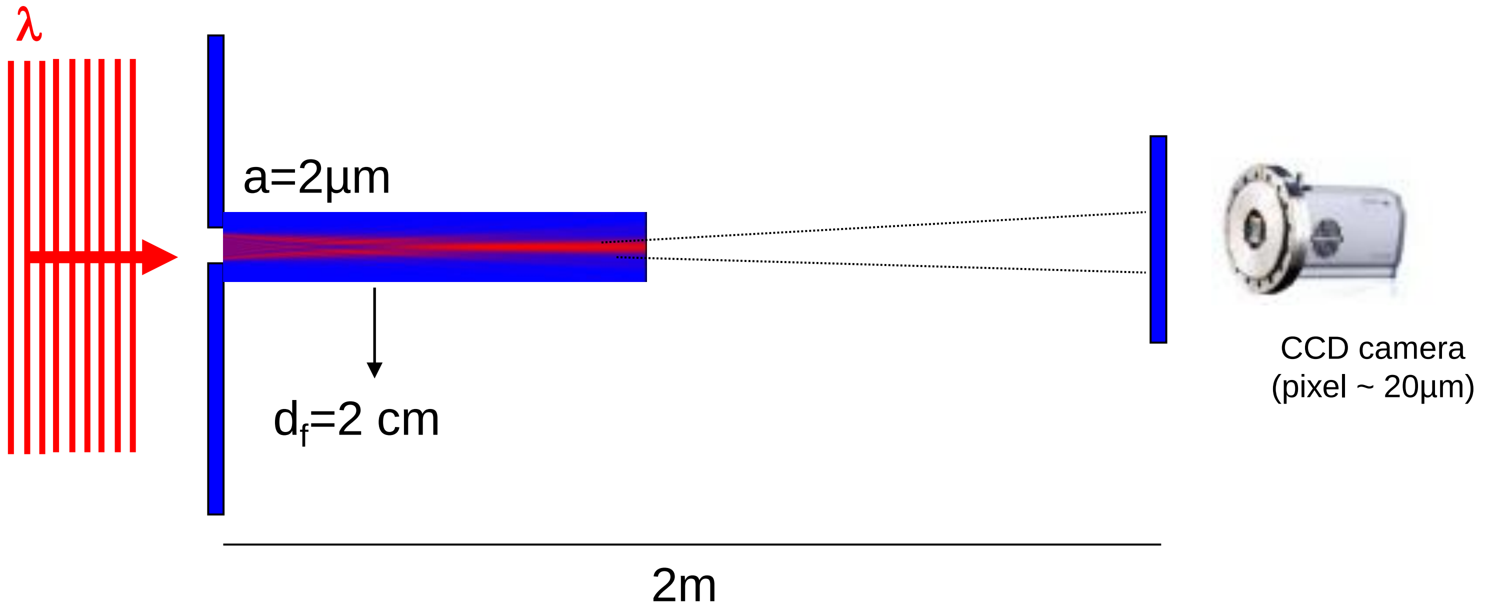

Red light ($\lambda \sim 0.7\mu m$) with a=1mm slit:  $d_f$= 23 cm

X-rays (**$\lambda \sim 1$ Å**) with a=1mm slit:  $d_f$= 23 *7000=1.6 km !!



# How to switch from far-field to near-field? Not so simple !

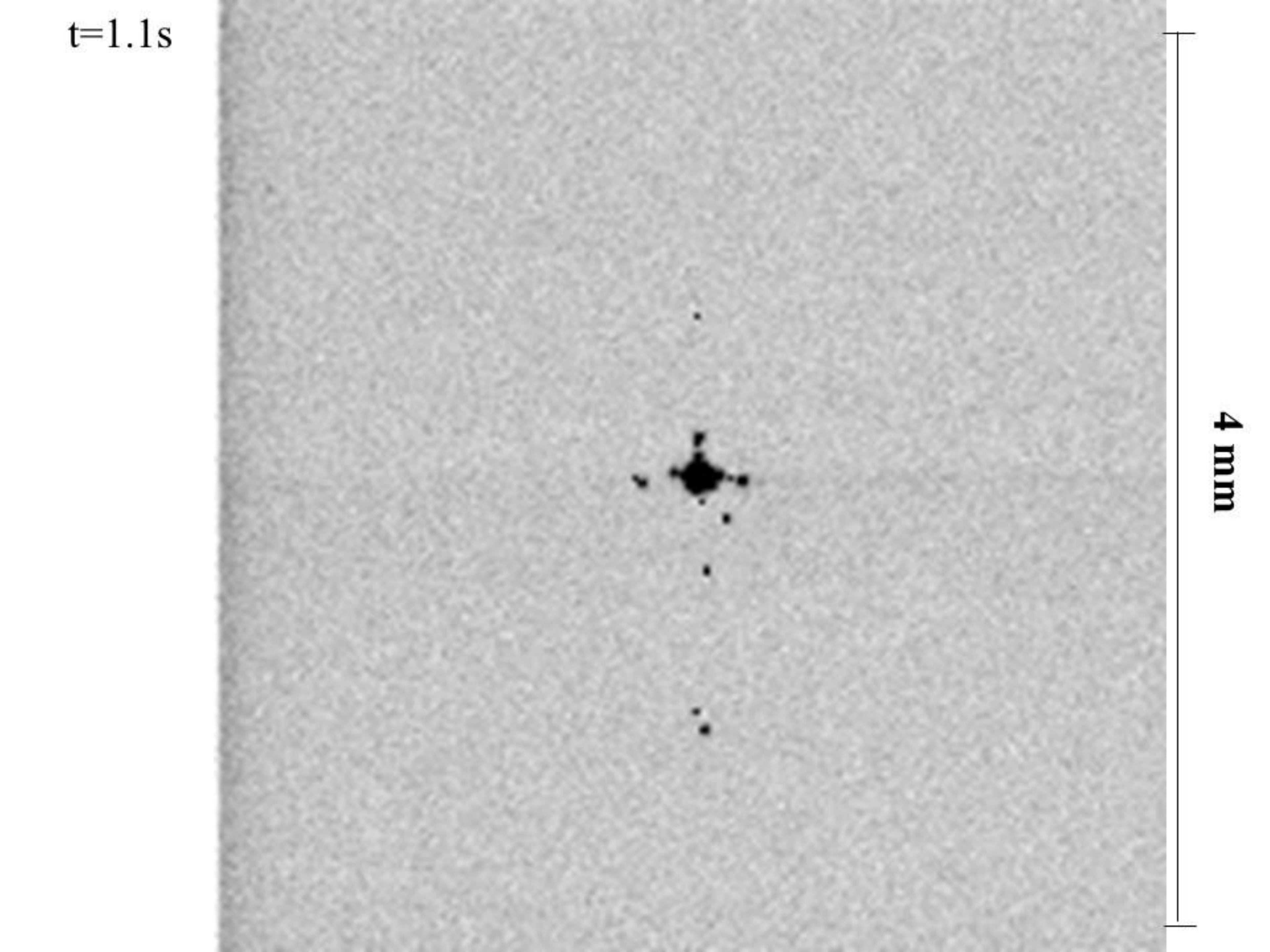
X-rays **(λ ~ 1 Å)** with a=2µm slit: $d_f$= 2 cm



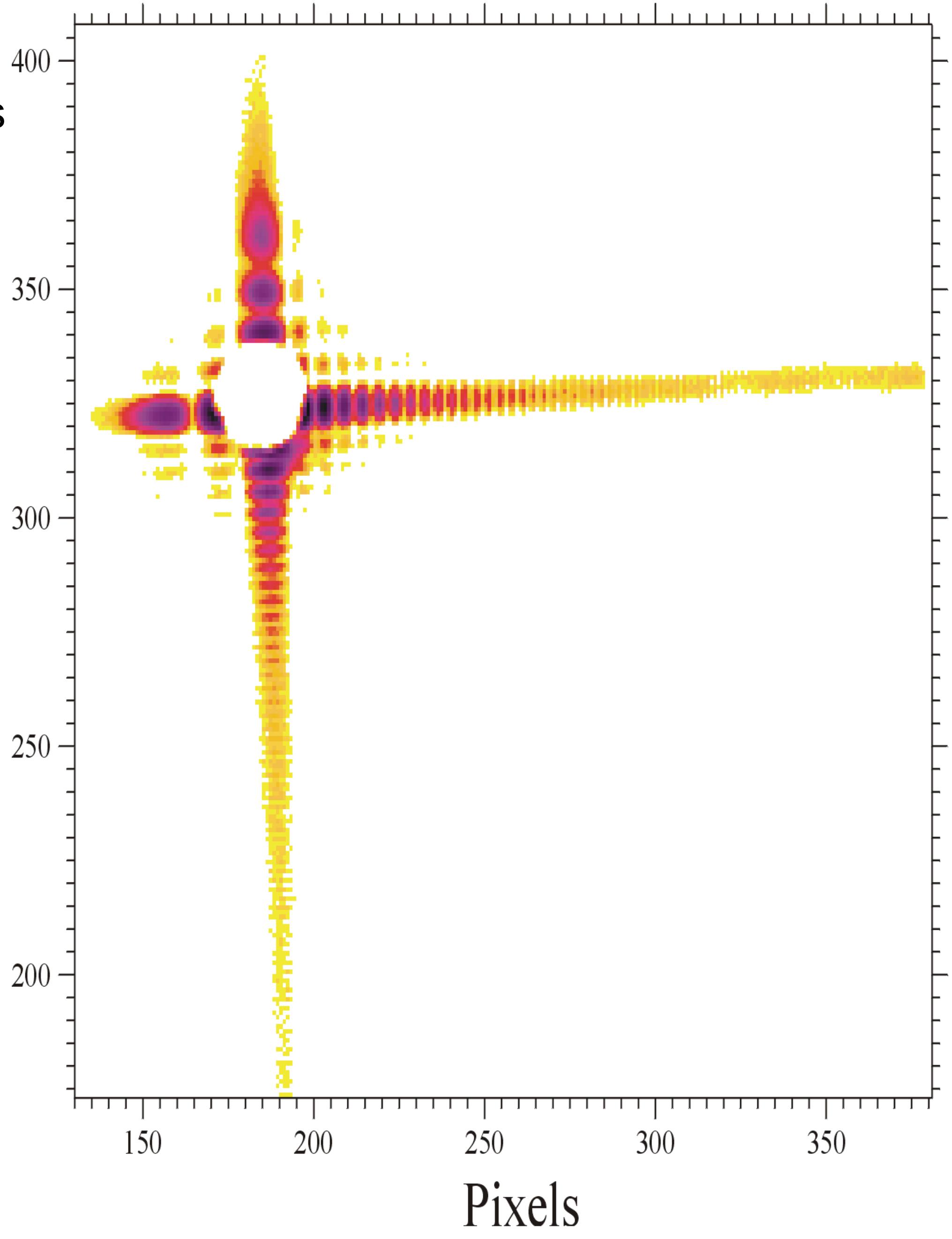

A 2µm hole : very small !… need bright x-ray sources

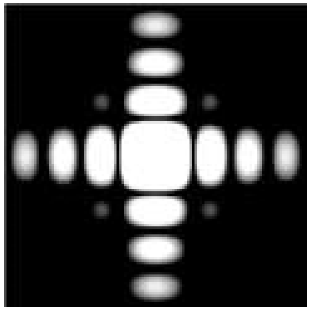
↓

synchrotrons

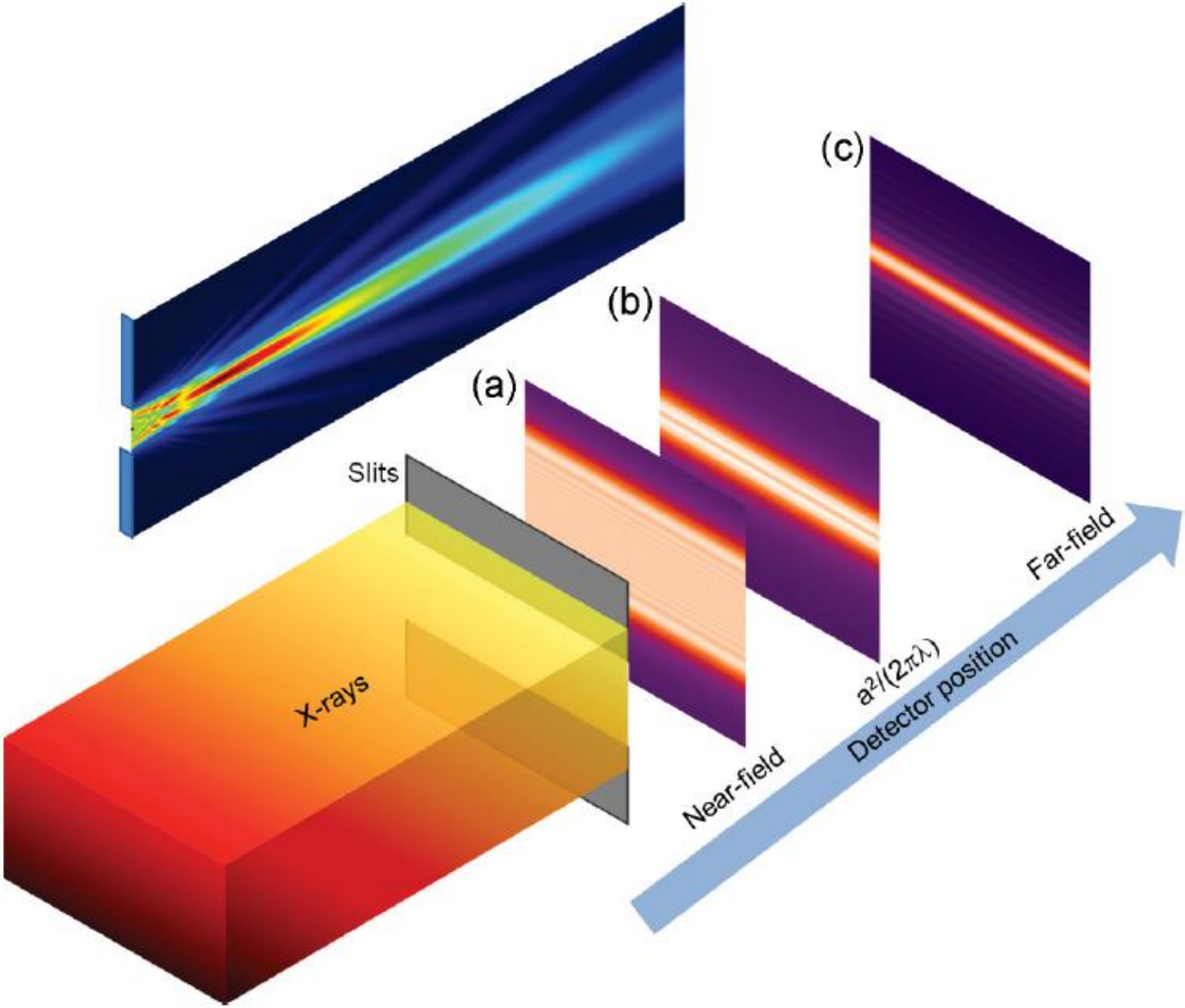

t=1.1s
4 mm

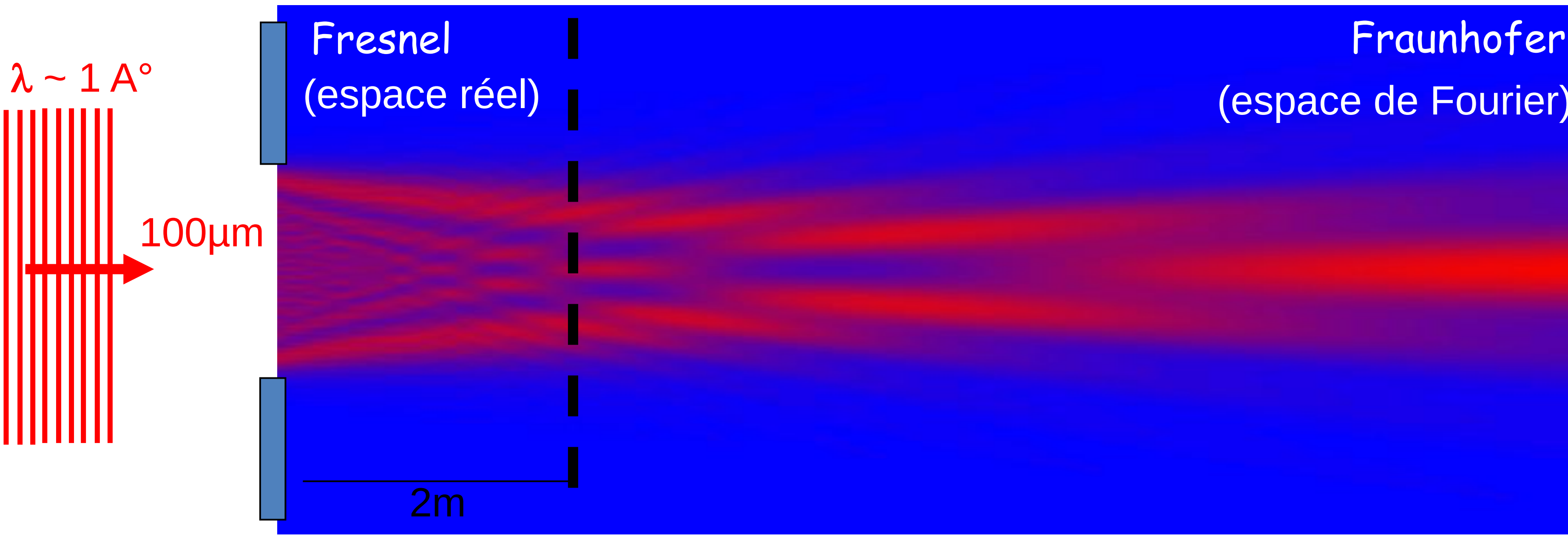
Sum over
1000 images of 0.1s



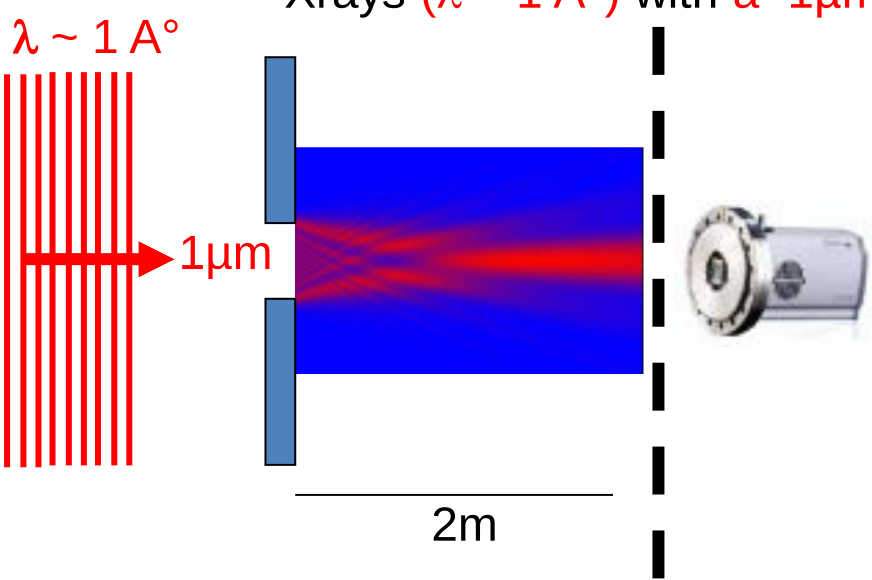
# Measurement at the CRISTAL beamline of SOLEIL





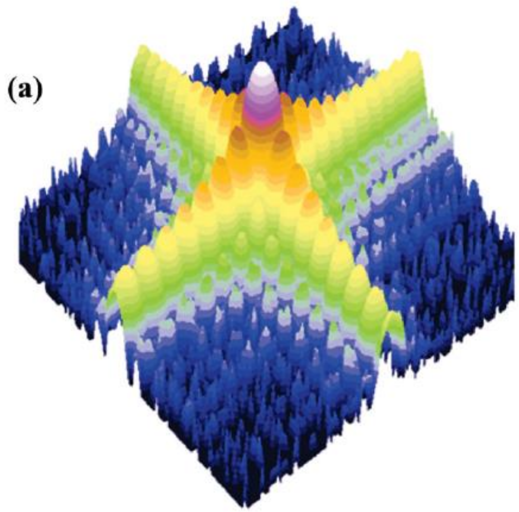

Xrays (λ ~ 1 A°) with a=100µm: $d_f$= 100m

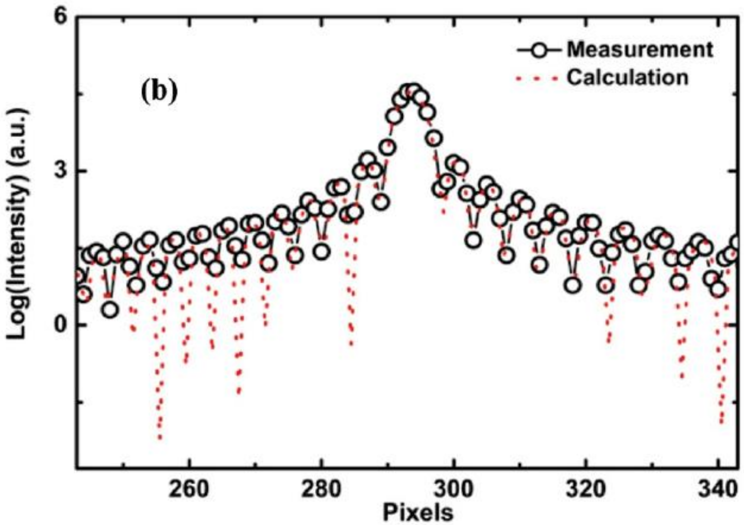
Xrays (λ ~ 1 A°) with a=1µm: $d_f$= 2 mm

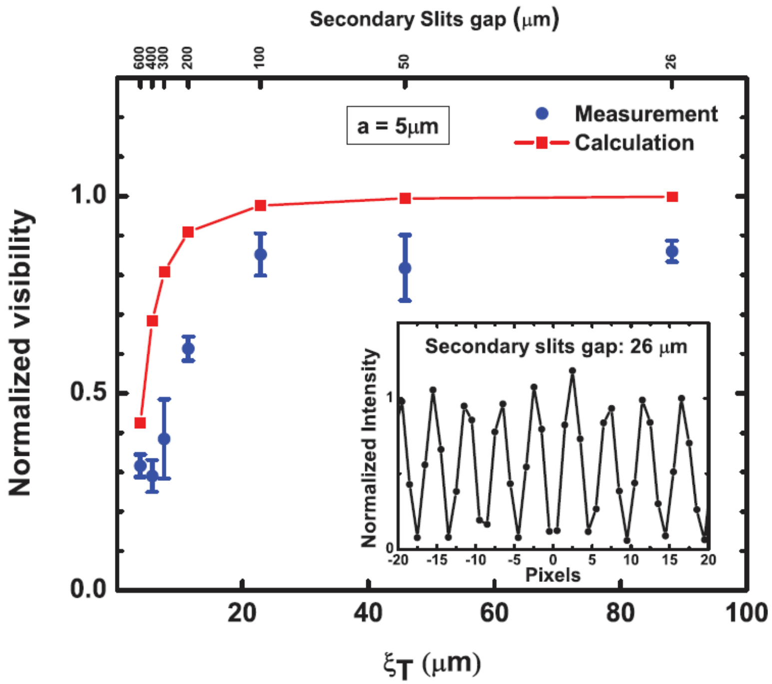



Ligne Cristal Soleil

# Visibility measurement in the far-field at CRISTAL



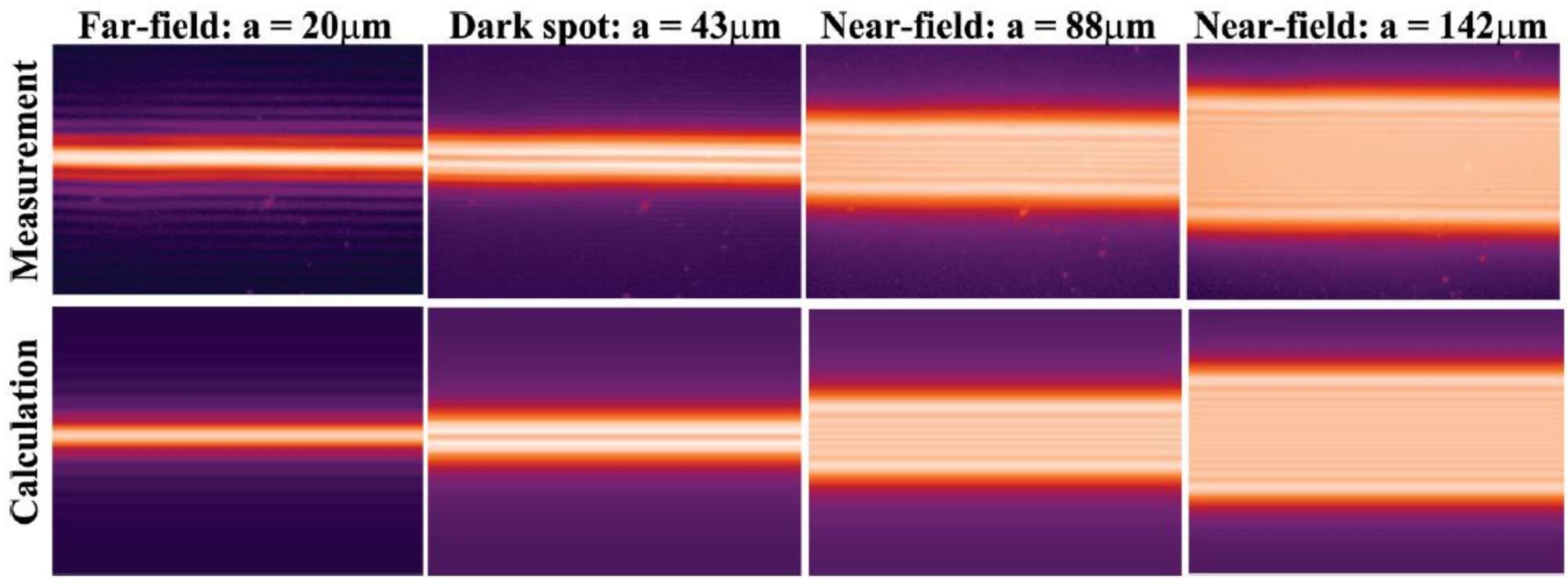



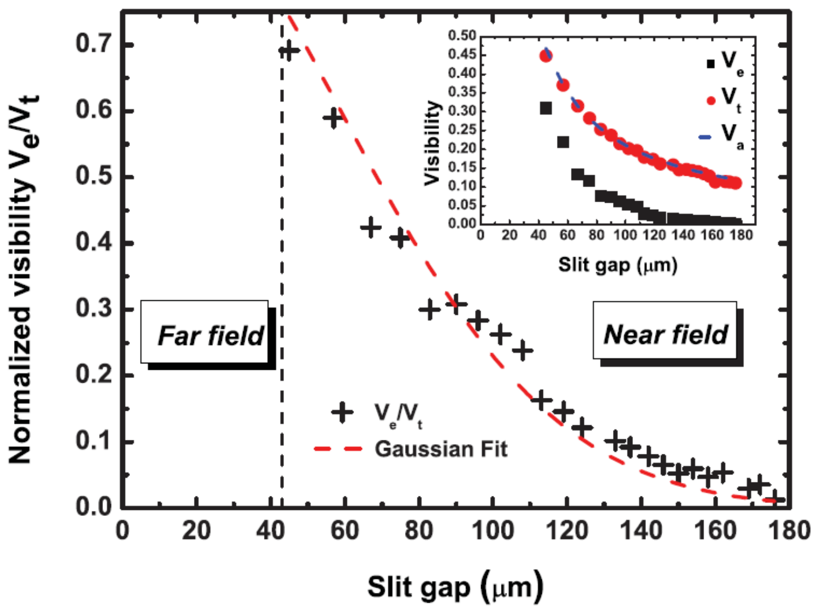




Measured visibility: $$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Calculated visibility (gaussian model): $$V(\xi_T) = e^{-\frac{a^2}{2\xi_T^2}}$$

# Measuring visibility in the near-field at CRISTAL




$$\frac{V_e}{V_t}(a) = e^{-\frac{a^2}{2\xi_{T_F}^2}}$$

$$\xi_{T_F} = 58 \pm 2\ \mu m$$

# Current Use of Coherent X-rays in Condensed Matter

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- Generating and Using X-ray Coherence – From the Source Point to the Detector
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  - What Can We Expect to See in X-ray Diffraction on Disordered Systems?
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# What does coherence bring in diffraction ?

Classical diffraction allows for a perfect determination of the **average structure** of crystals! This is done by measuring *a portion of reciprocal space*, applying *symmetry constraints*, and carefully analyzing the *intensities of the Bragg peaks*.

Coherent diffraction provides information about **deviations from the perfect arrangement**.

For a crystal with disorder: $A(\mathbf{q}) = \sum_{uvw} F_{uvw}(\mathbf{q}) e^{-i\mathbf{q}\cdot\mathbf{R}_{uvw}} = \sum_n F_n(\mathbf{q}) e^{-i\mathbf{q}\cdot\mathbf{r}_n}$

$$A^*(\mathbf{q})A(\mathbf{q}) = \sum_m \left( \sum_n F_n^* F_{n+m} \right) e^{-i\mathbf{q}\cdot\mathbf{r}_m}$$

$$\sum_n F_n^* F_{n+m} = N(m)\left(\langle F_0^* F_m\rangle + \Delta_m\right)$$

Fluctuation around average position

$$= |\langle F \rangle|^2 + \langle \phi_0^* \phi_m \rangle$$

with

$\phi_n = F_n - \langle F_n \rangle$ Deviation from the Average Structure Factors

# Intensity obtained in the case of a disordered crystal

$$I_{tot}(q) = I_B(q) + I_{DD}(q) + I_S(q)$$

$$I_B(\mathbf{q}) = |\langle F\rangle|^2 \sum_{hkl} \frac{|\Sigma(\mathbf{q}-\mathbf{Q}_{hkl})|^2}{v^2} \longrightarrow \text{Diffraction term}$$

$$I_{DD}(\mathbf{q}) = \sum_m N(m)\langle\phi_0^*\phi_m\rangle e^{-i\mathbf{q}\cdot\mathbf{r}_m} \longrightarrow \text{Diffuse scattering term}$$

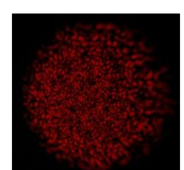
$$I_S(\mathbf{q}) = \sum_m N(m)\Delta_m e^{-i\mathbf{q}\cdot\mathbf{r}_m} \longrightarrow \text{Speckle term}$$

Fourier transform of fluctuations

Produces interference on the diffracted signal, called speckles.

Visible with a coherent beam, if the temporal fluctuations are slow compared to the acquisition time.

$I(\mathbf{q}) = |\langle A(\mathbf{q})\rangle|^2$

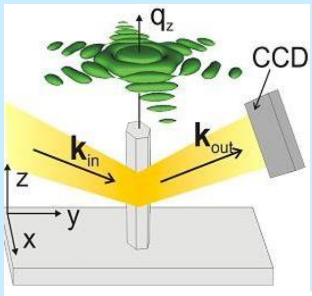


$I(\mathbf{q}) = |A(\mathbf{q})|^2$

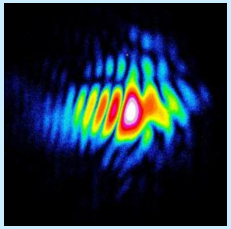
# Several Ways to Exploit X-ray Coherence

**Coherent X-rays**

## Imaging:
## Phase retrieval
(CDI, Ptychography Holography)

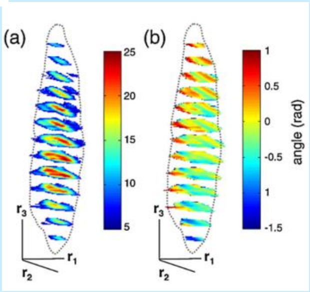



*A. Diaz et al., Phys. Rev. B 79, 125324 (2009)*



Bragg reflexion from a Au grain of 500nm

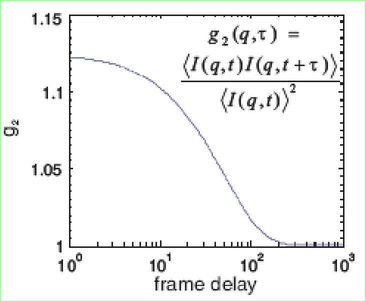
*N. Vaxelaire et al., Nucl. Inst. Meth. Phys. Res.* ***268****, 388 (2010)*

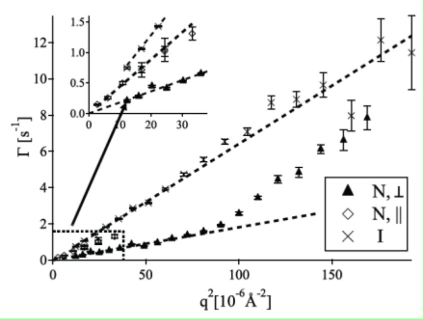



*V. Chamard et al., Phys. Rev. Lett. 104, 165501 (2010)*

➔ Displacement field

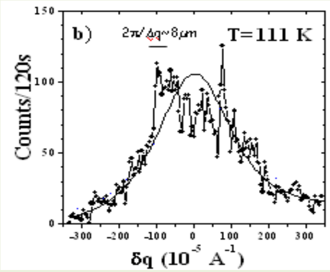
## XPCS: dynamics

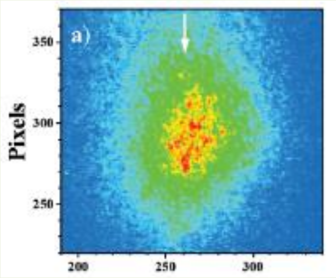



*A.S. Poulos, J. Chem. Phys.* ***132****, 091101 (2010)*

## Direct study of interferences




$SrTiO_3$

*S. Ravy et al., Phys. Rev. Lett.* ***98****, 105501*

➔ Phase transitions
➔ Phase defects

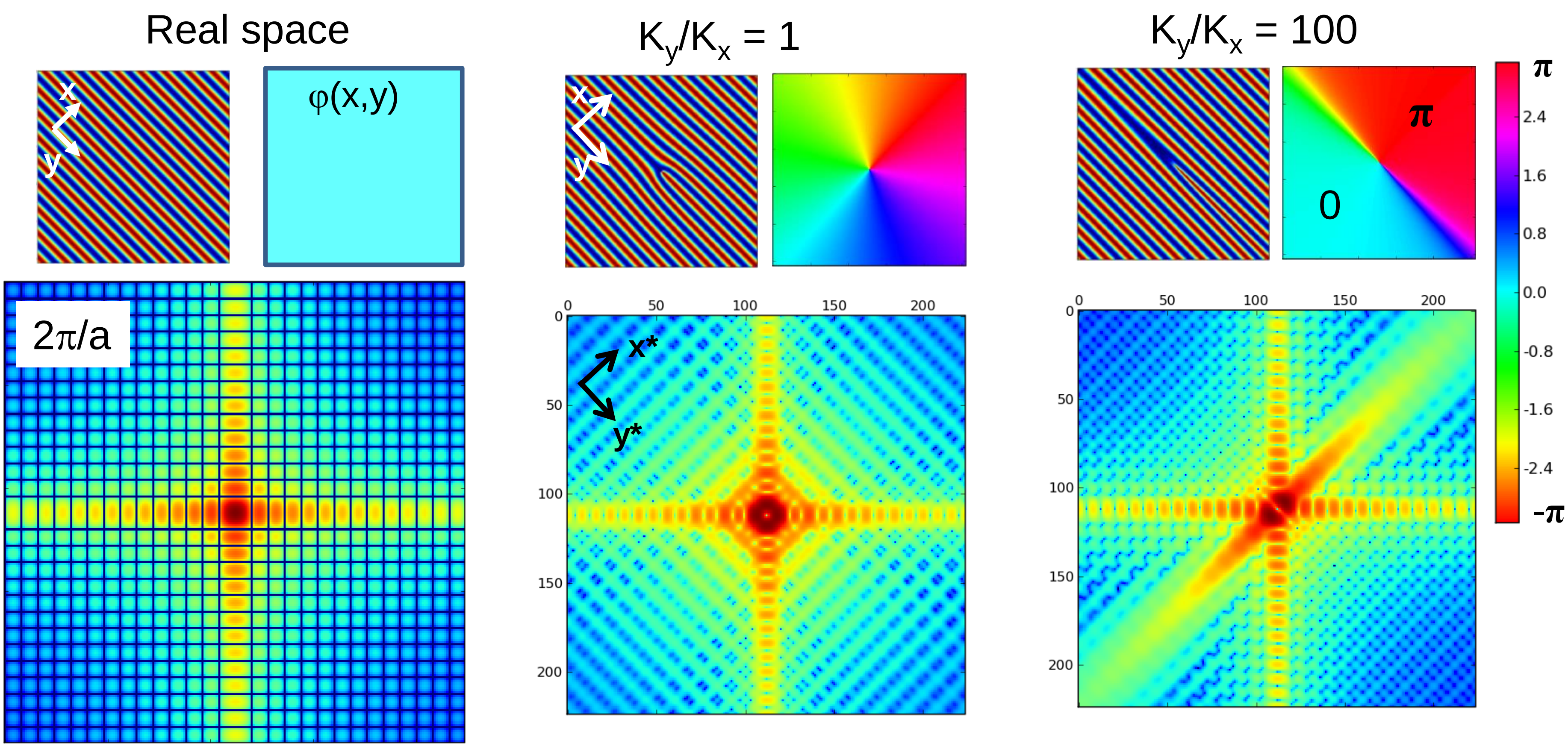
# Effect of a Single Dislocation on Coherent Bragg Diffraction

$$R(x,y,z) = \cos\left(\frac{2\pi x}{a} + \varphi(x,y)\right)$$

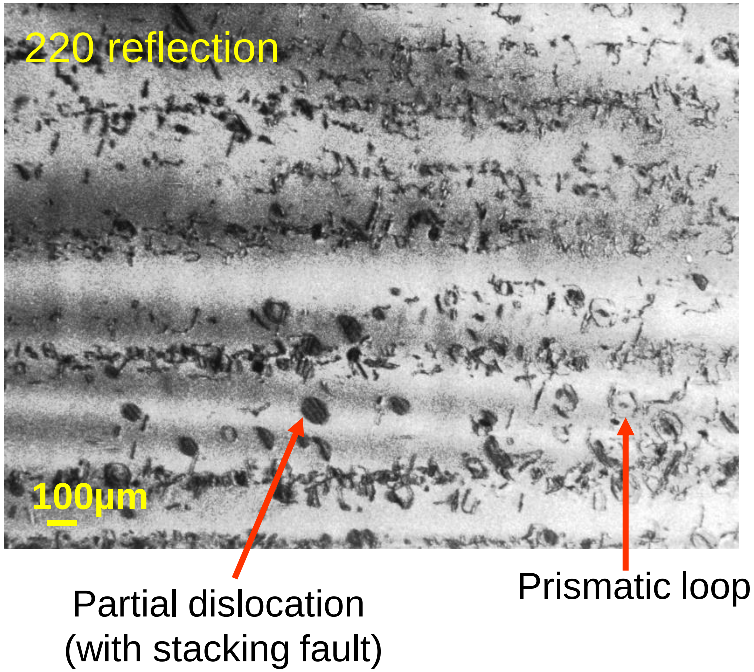
Elastic constants

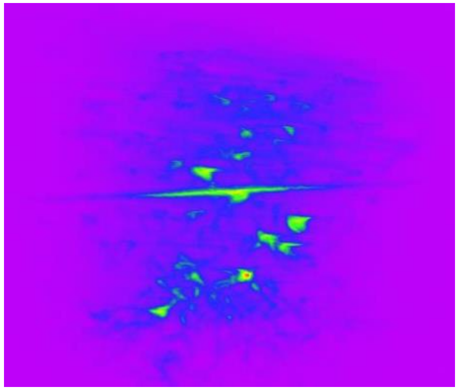
Position of the line

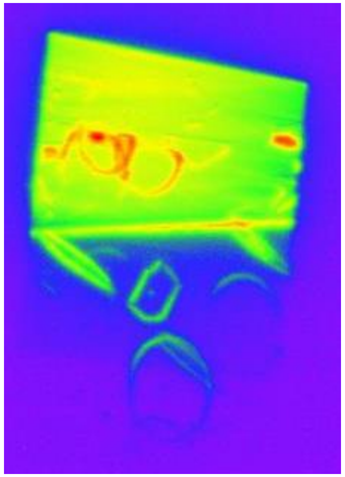
$$\varphi(x,y) = -\frac{\pi}{2} * sgn(y - y_0) + tan^{-1}\left(\sqrt{\frac{K_y}{K_x}}\,\frac{x - x_0}{y - y_0}\right)$$



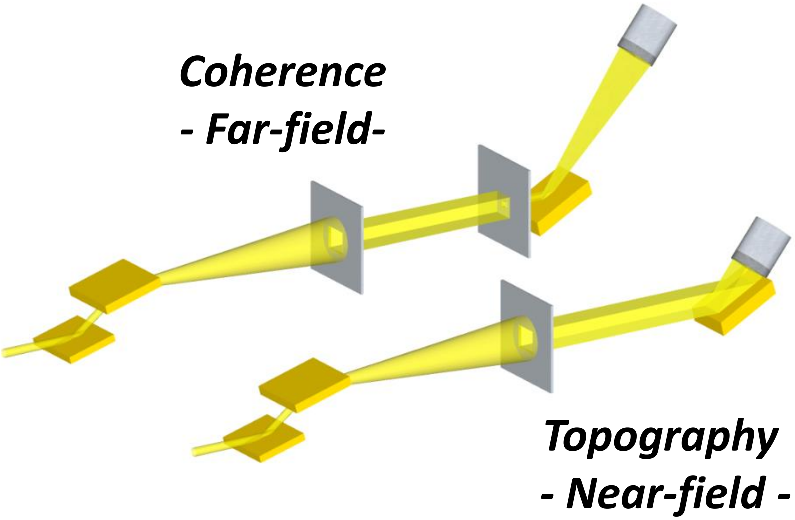
# Dislocation Loops in a Specific Si Sample



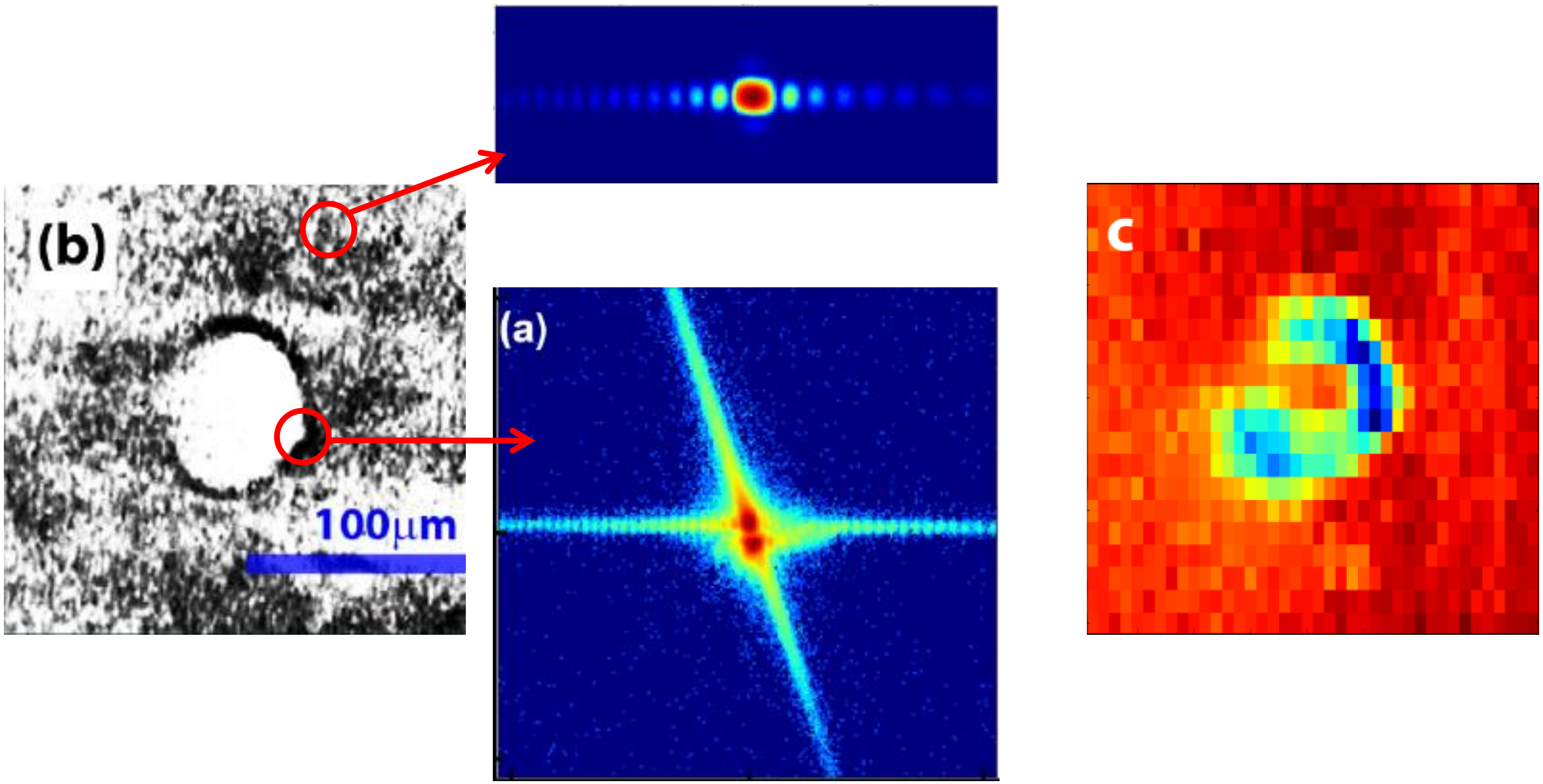





**Sample preparation:**
Growth under $O_2$
Annealing 35h under $O_2$
Defect Concentration : $10^{18}$ $cm^{-3}$

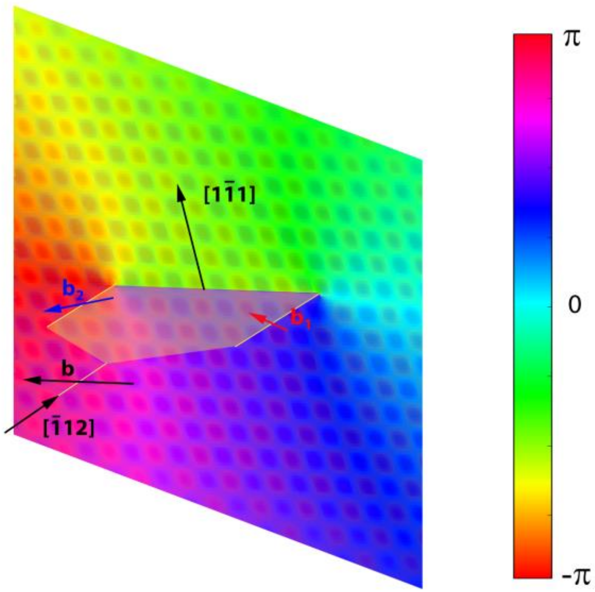


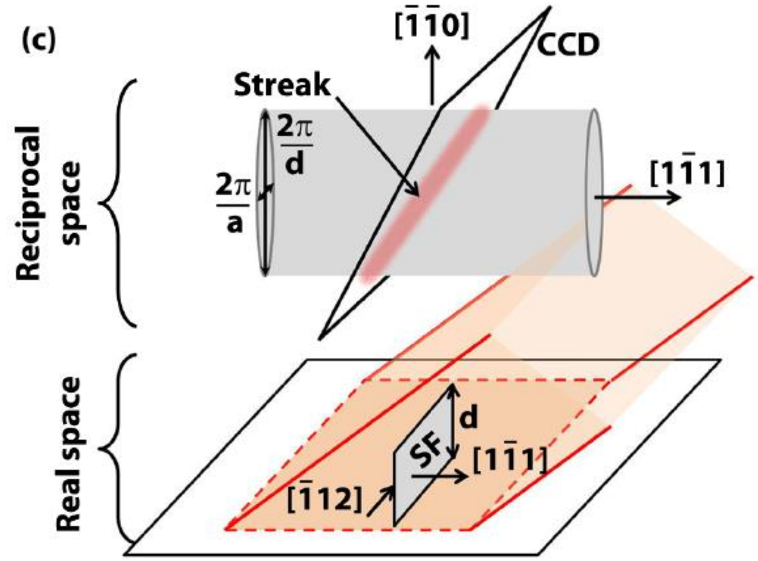
# Direct Imaging of the Dislocation Line Using a Coherent Beam




Resolution: 5µm

# Revealing a Large-Scale Dissociation



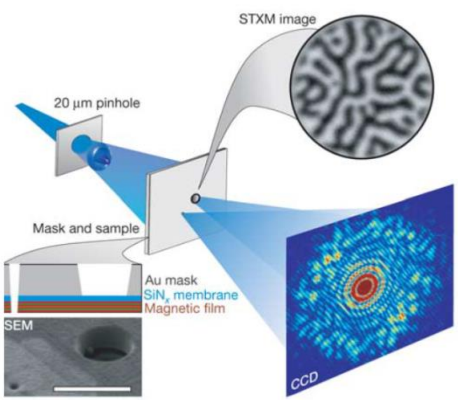

d ~ 500 nm

*V. Jacques et al., PRL **107**, 199602 (2011)*

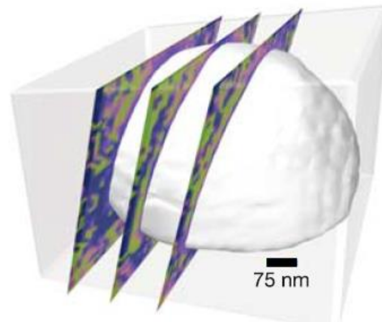
# Lensless Imaging using coherent x-rays

Principle: retrieve the phase lost during the measurement …
Several techniques…

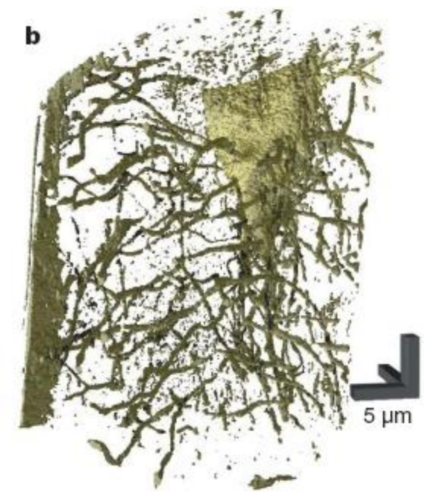
Holography




Coherent Diffraction Imaging (CDI)




Ptychography




These techniques can be used:

- in transmission near the reciprocal space origin : imaging local density
- In diffraction at wide angles: probing local displacement field

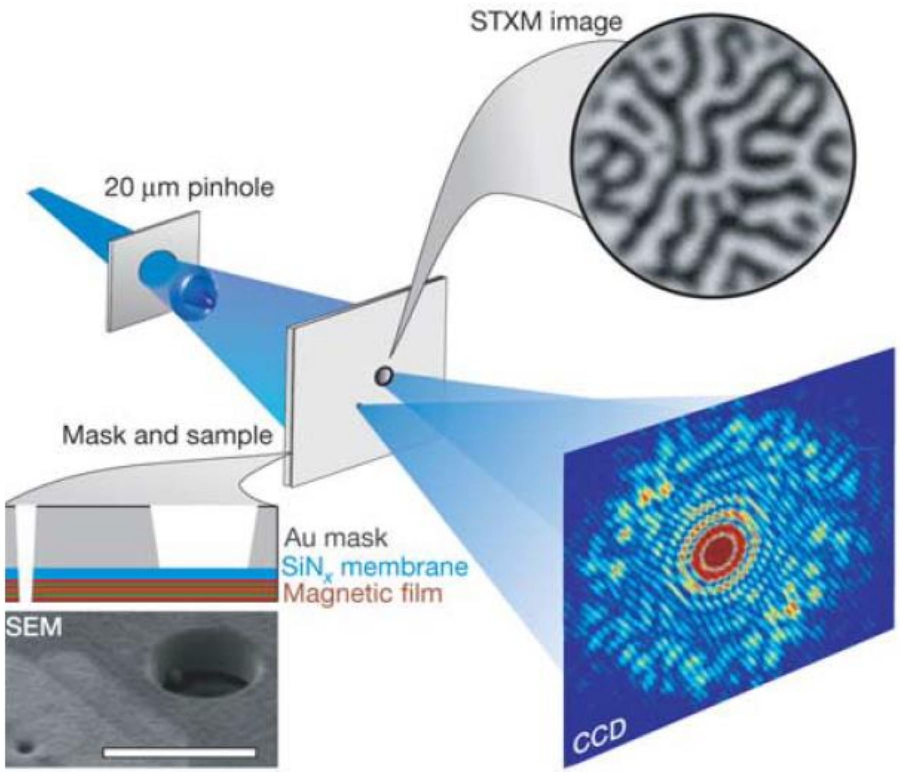
$$A(\mathbf{q}) = \sum_n F_n(\mathbf{q}) e^{-i\mathbf{q}\cdot\mathbf{r}_n}$$

$$r_n = r_0 + u_n$$

$$A(q) = \sum_n F_n(q) e^{-iq.r_0} e^{-iq.u_n}$$

Phase !

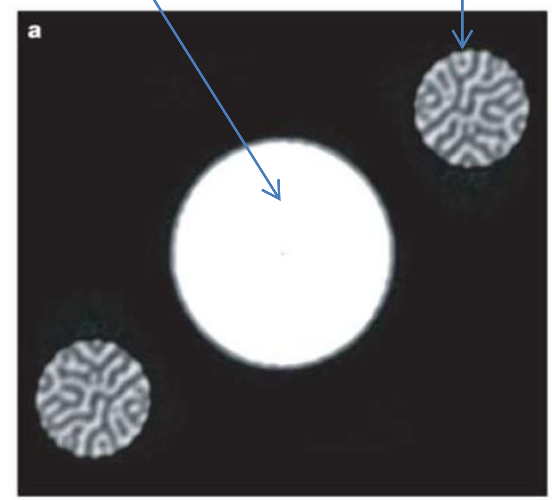
# X-ray Holography on a system having magnetic domains (CoPt)




TF$^{-1}$

Autocorrelation
object-object
+ hole-hole

Convolution
object-hole




**Lensless imaging of magnetic nanostructures by X-ray spectro-holography**

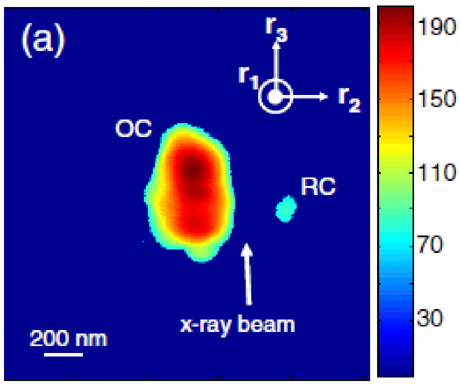

**S. Eisebitt[1], J. Lüning[2], W. F. Schlotter[2,3], M. Lörgen[1], O. Hellwig[1,4], W. Eberhardt[1] & J. Stöhr[2]**

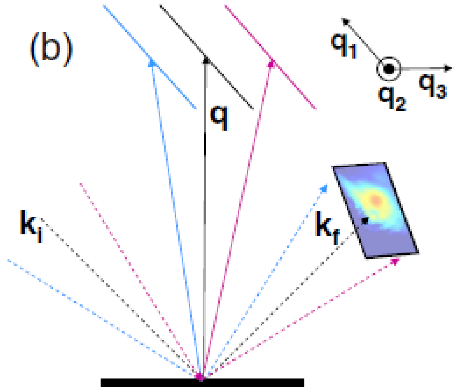


Resolution : 50nm

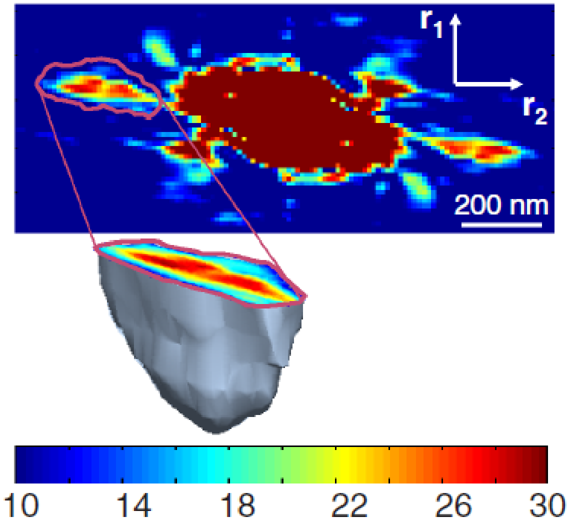
Eisebitt *et al.*, Nature432, 885 (2004)

# X-ray Holography in Bragg condition

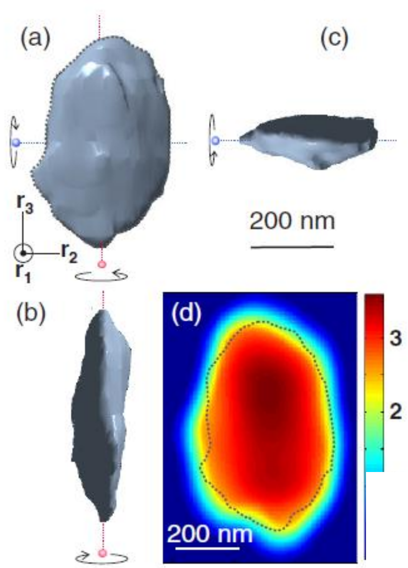


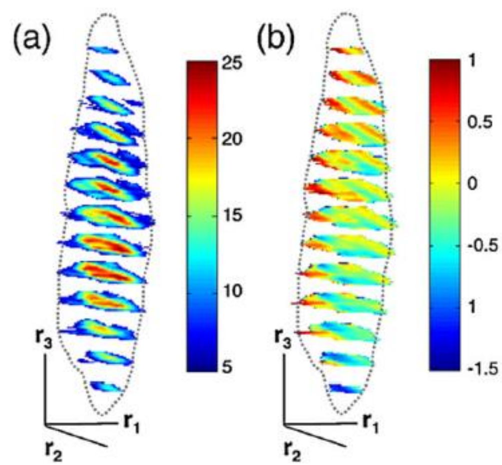

$TF^{-1}$

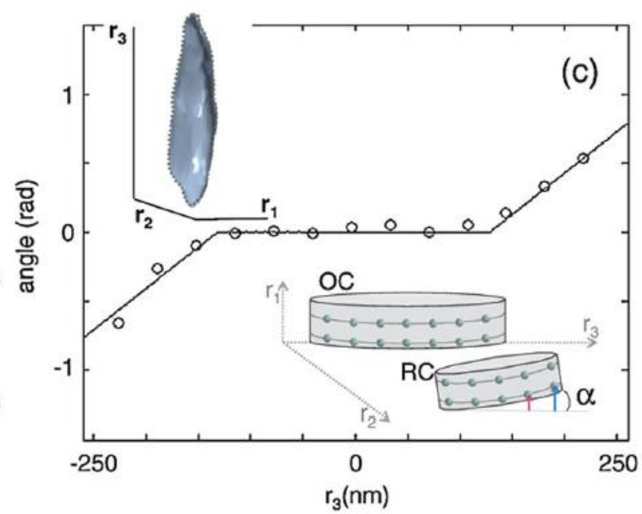



Density




Density Phase




Sensitivity to strain

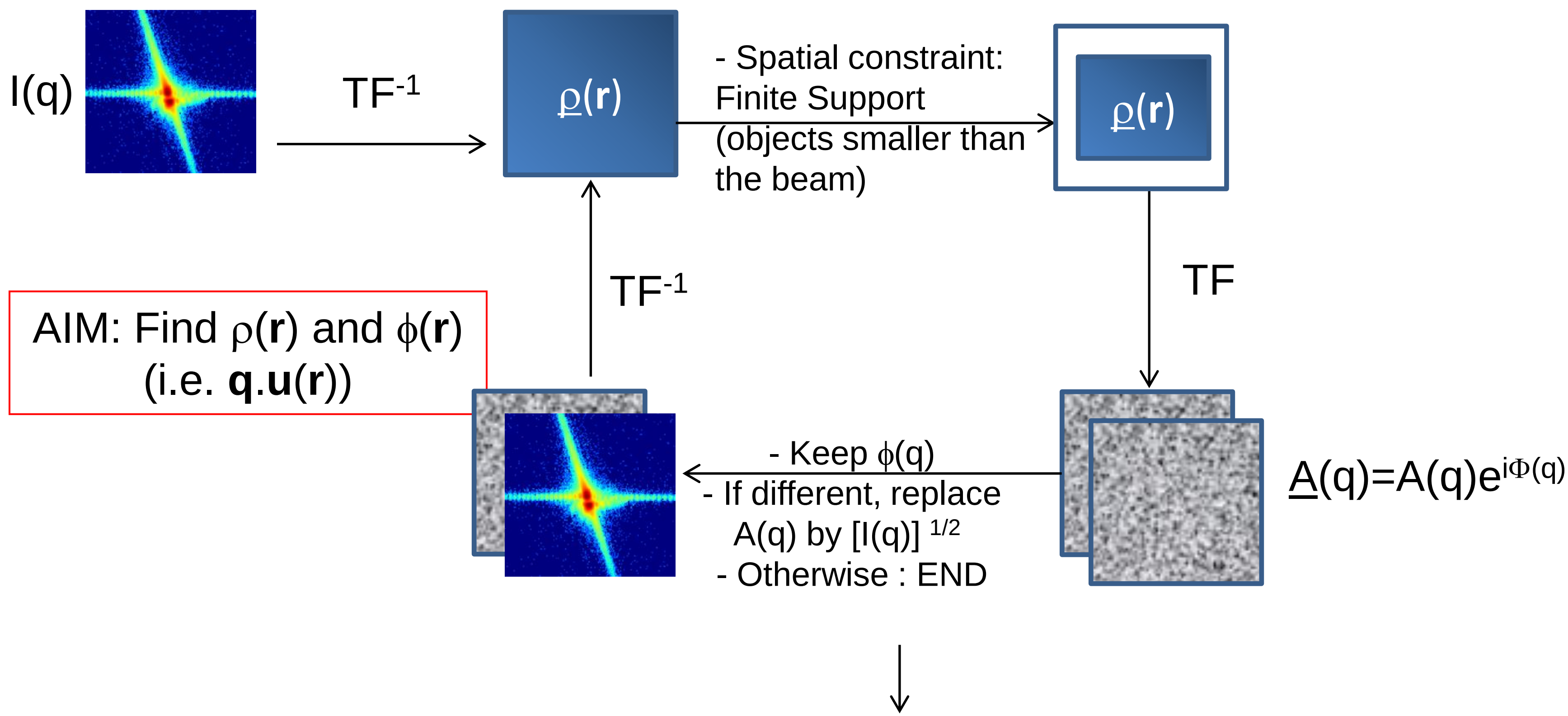
$$\Delta\varphi = \mathbf{k_f \cdot u - k_i \cdot u = Q \cdot u}$$

Chamard *et al.*, PRL 104, 165501 (2010)

# Phase Retrieval Algorithms for CDI

Recover the phase lost during the measurement using an algorithm that performs Fourier Transforms (FT) and Inverse Fourier Transforms ($FT^{-1}$) in a loop, until it converges to a solution, applying constraints in both real space and Fourier space.

## Coherent Diffraction Imaging (CDI): phase retrieval algorithm



# First Implementation of Forward CDI

Fourier space constraints real space constraints

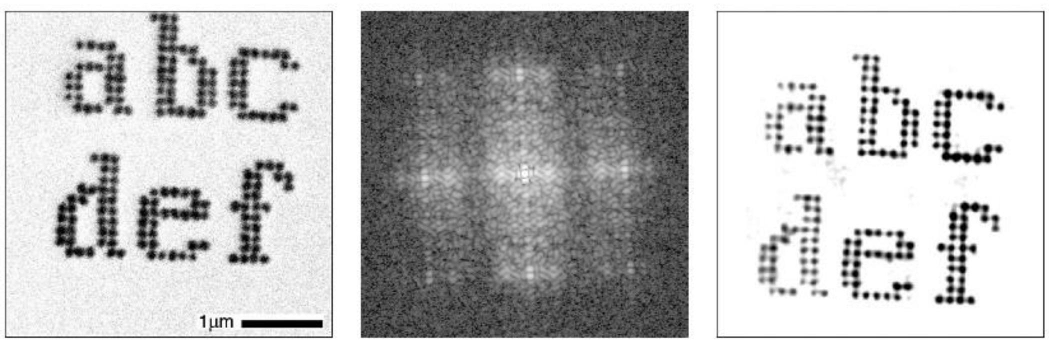
$$g_i(\mathbf{x}) \xrightarrow{\mathcal{F}} G_i(\mathbf{k}) = |G|\,\mathrm{e}^{i\phi} \longrightarrow G_i'(\mathbf{k}) = |F(\mathbf{k})|\,\mathrm{e}^{i\phi} \xrightarrow{\mathcal{F}^{-1}} g_i'(\mathbf{x}) \longrightarrow g_{i+1}(\mathbf{x})$$

- The error can only decrease... or stay the same.

J. R. Fienup *Optics Letters* **3** 27-29 (1978)

J. Miao, D. Sayre and H. N. Chapman *JOSA A* **15** 1662-1669 (1988)

## Experimental realization – 2D




**Original image** **Diffraction pattern** **Reconstructed image**

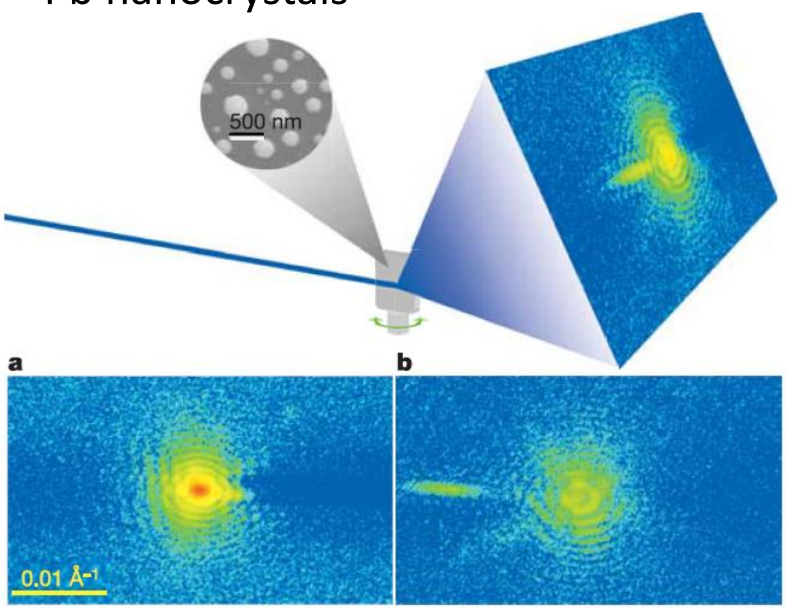
J. Miao *et al.* *Nature* **400** 342-344 (1999)

# CDI in Bragg Condition: Access to the Strain Field

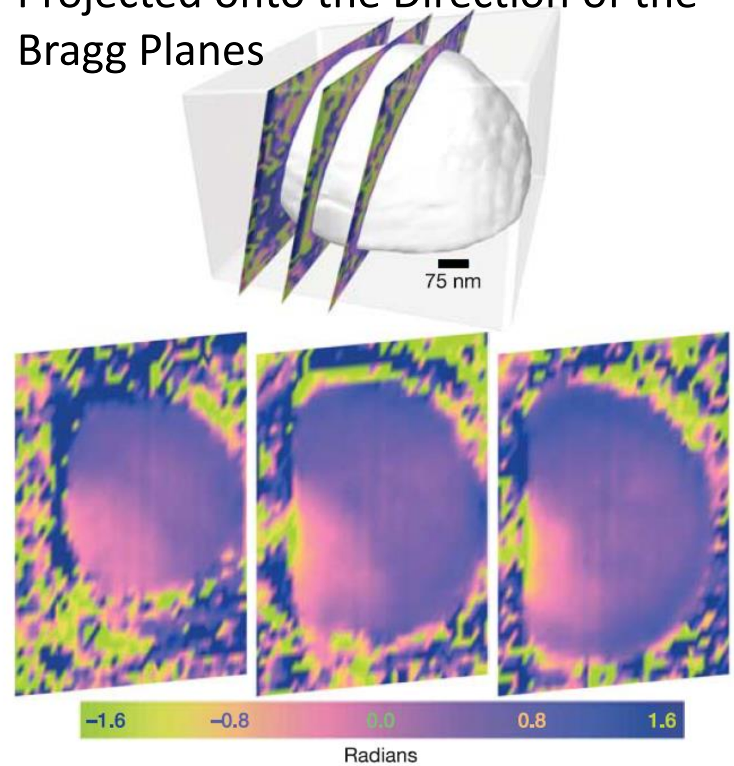
## Three-dimensional mapping of a deformation field inside a nanocrystal

Mark A. Pfeifer[1]†, Garth J. Williams[1]†, Ivan A. Vartanyants[1]†, Ross Harder[1] & Ian K. Robinson[1]†

Pb nanocrystals




Reconstruction of the Phase Projected onto the Direction of the Bragg Planes

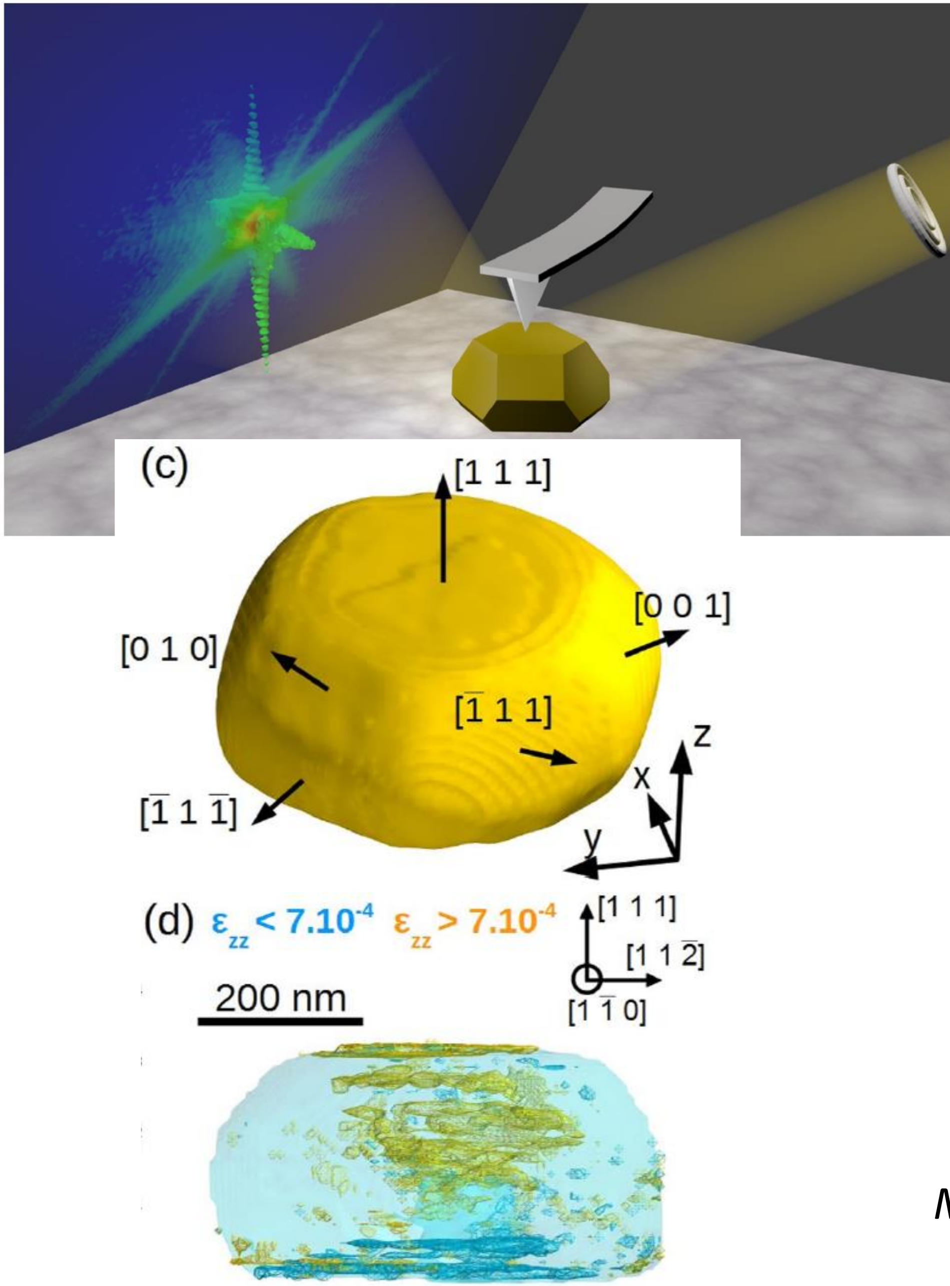



Sensitivity to strain

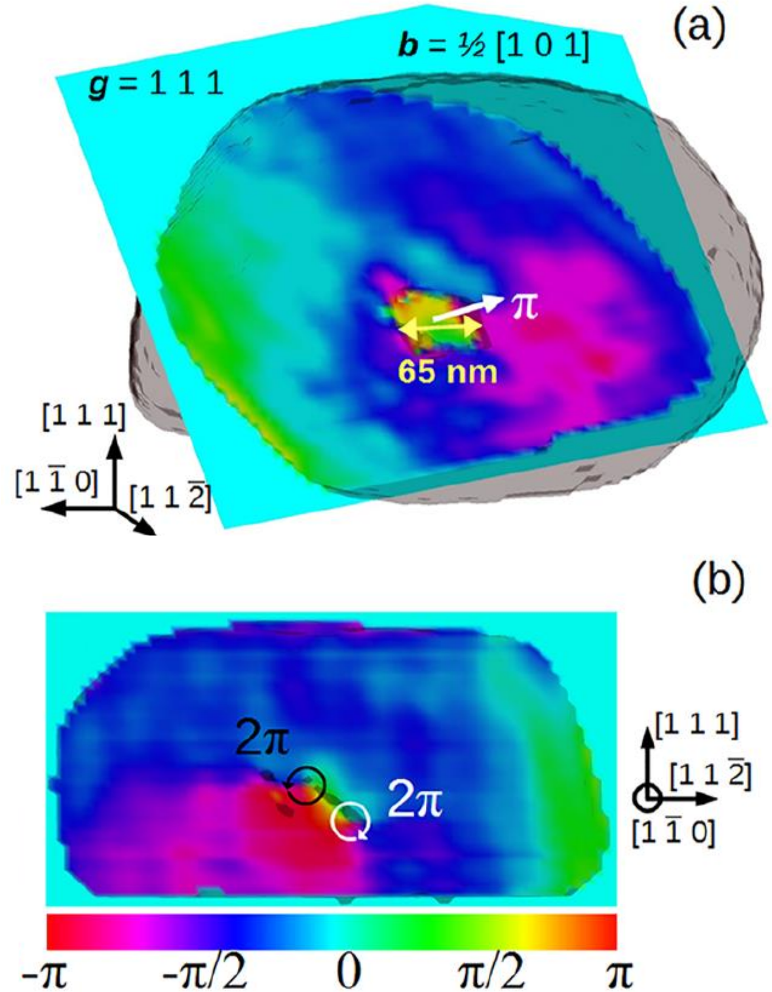
$$\Delta\varphi = \mathbf{k}_f\cdot\mathbf{u} - \mathbf{k}_i\cdot\mathbf{u} = \mathbf{Q}\cdot\mathbf{u}$$

Nature 442, 63 (2006)

# A Dislocation Loop Appearing Under Strain




Applied Force : 560 nN

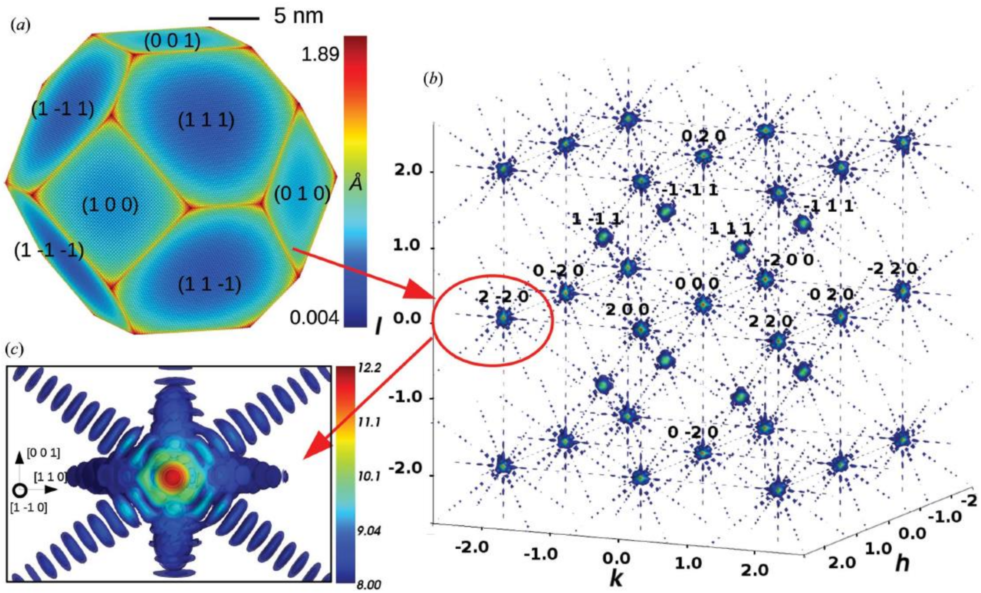


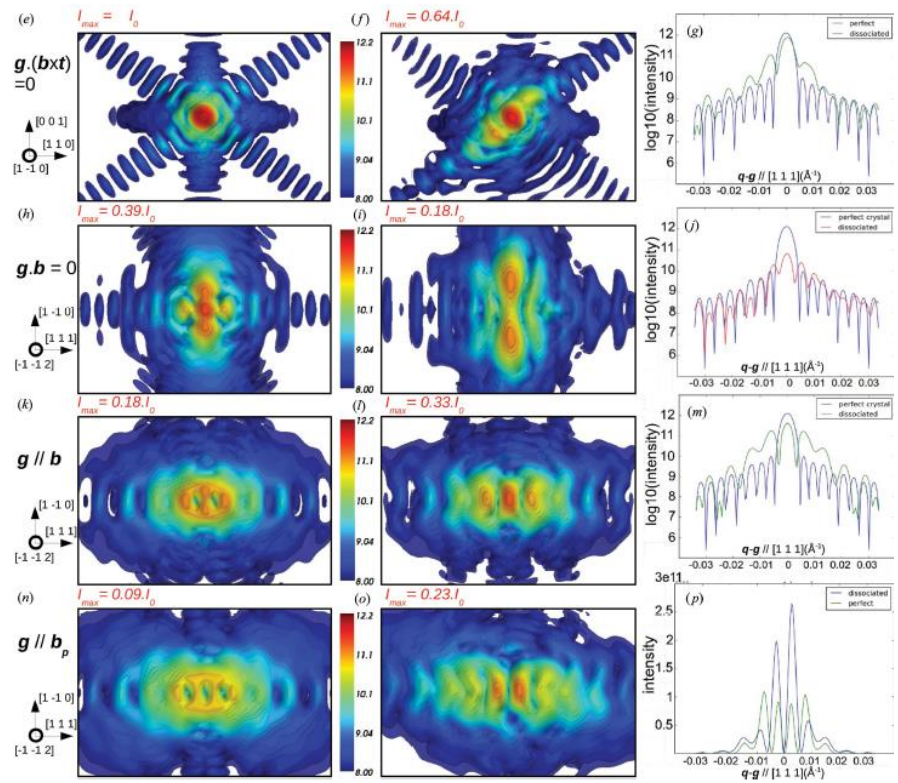

*M. Dupraz et al., Nano Letters **17**, 6696 (2017)*

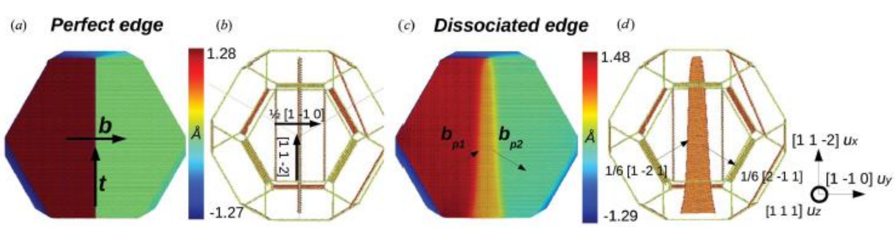
JOURNAL OF APPLIED CRYSTALLOGRAPHY
ISSN 1600-5767

# Signature of dislocations and stacking faults of face-centred cubic nanocrystals in coherent X-ray diffraction patterns: a numerical study

Maxime Dupraz,[a,b]* Guillaume Beutier,[a,b] David Rodney,[a,b,c] Dan Mordehai[d] and Marc Verdier[a,b]



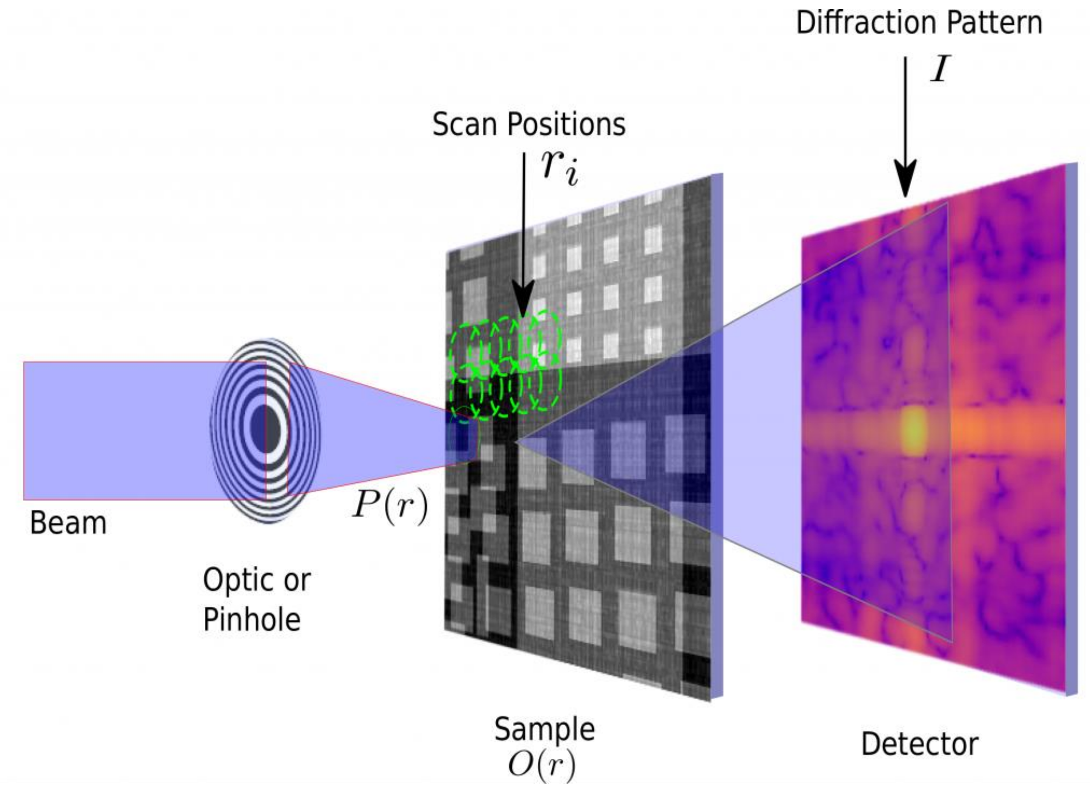




*M. Dupraz et al., J. Appl. Cryst.* ***48****, 621 (2015)*

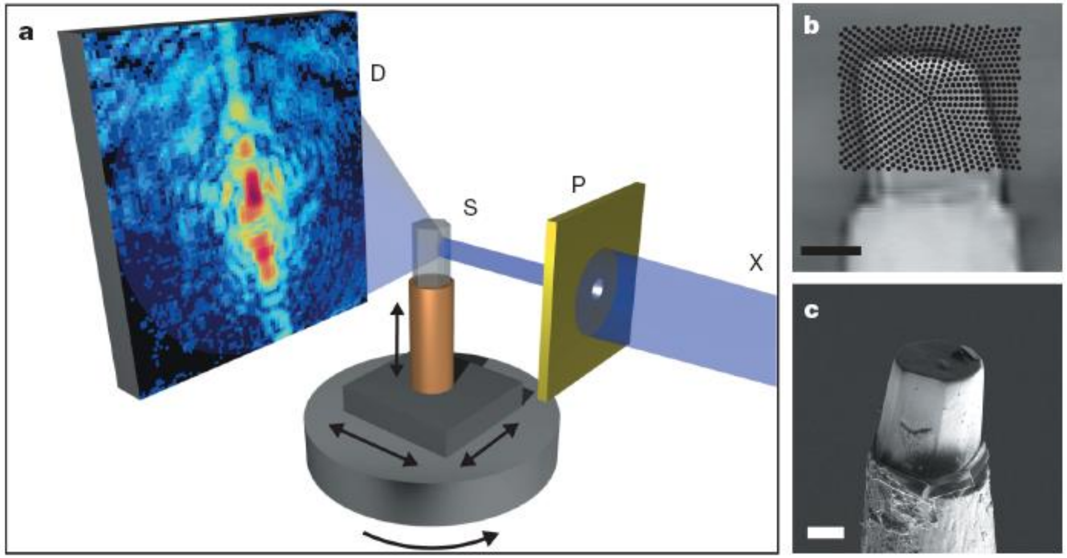
# Ptychography: lensless imaging on ‘big’ samples

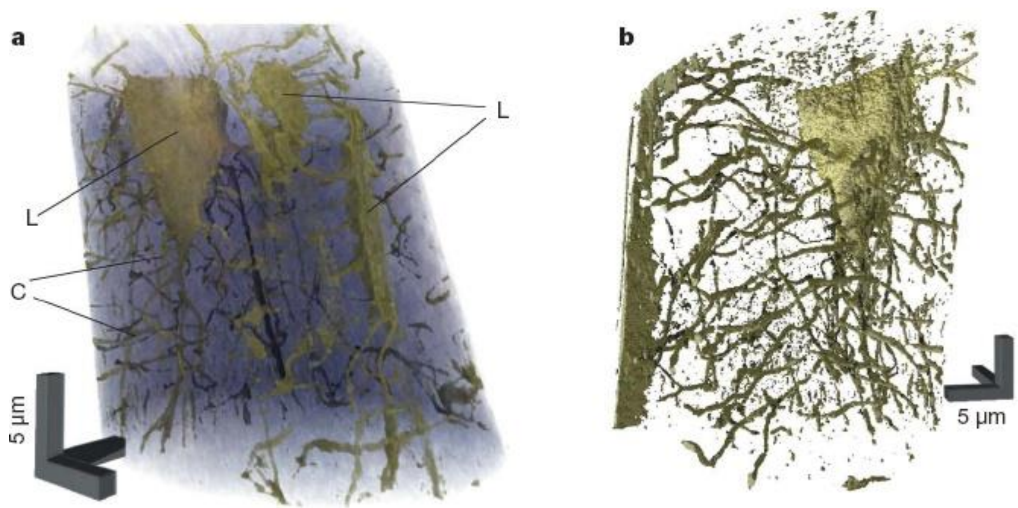
‘big’ = larger than the coherent beam used…




The CDI algorithm is applied to each image taken at each position.
Real space constraint: overlap between positions.

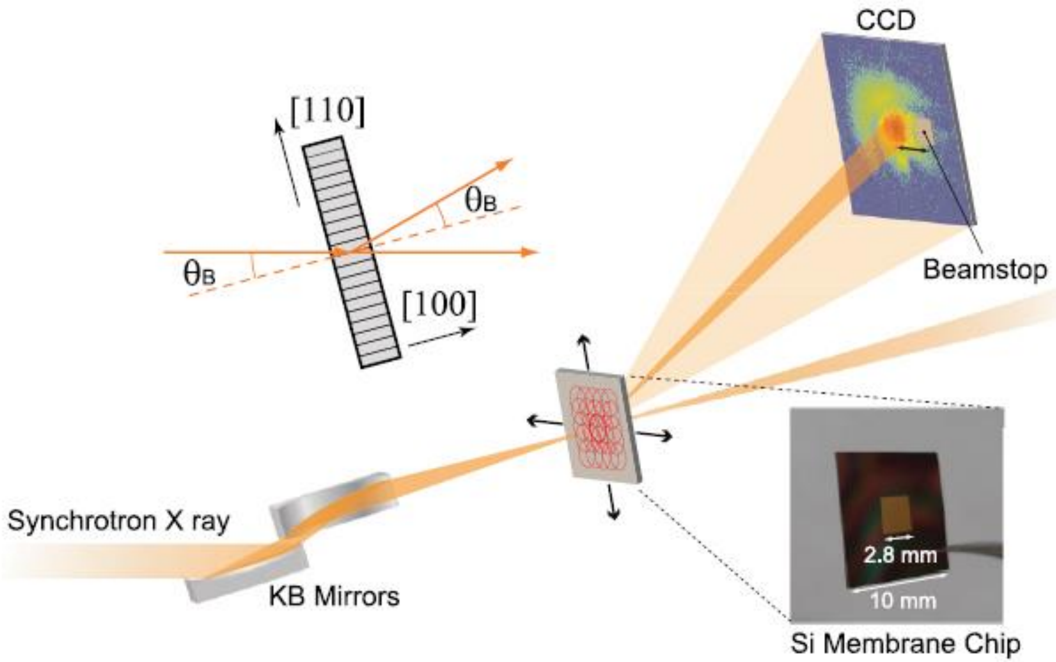
# Tomographic Ptychography on a Mouse Bone

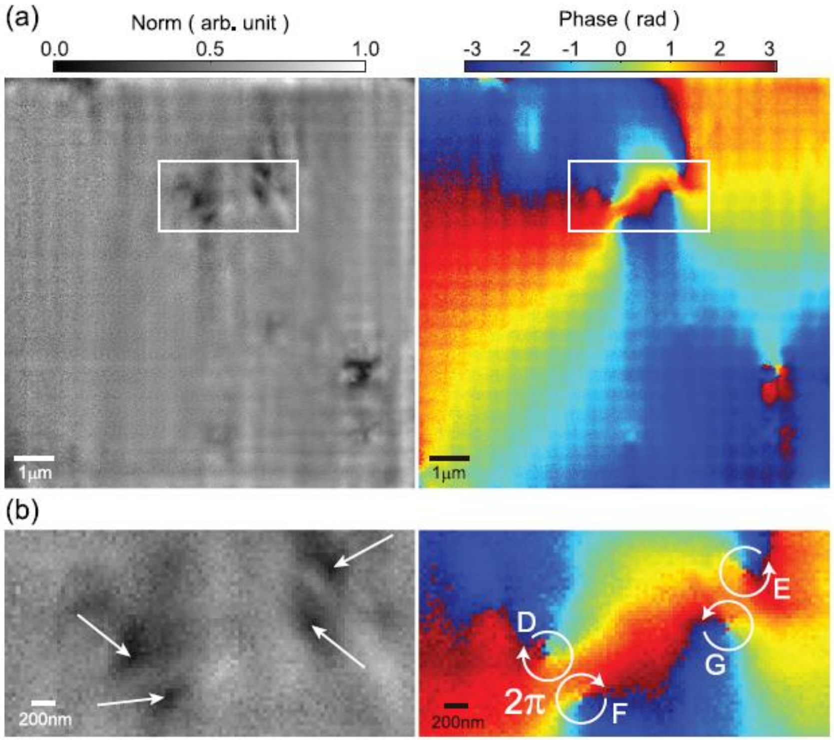



Dierolf et al., Nature 436, 467 (2010)

# Bragg Ptychography and Strain Field

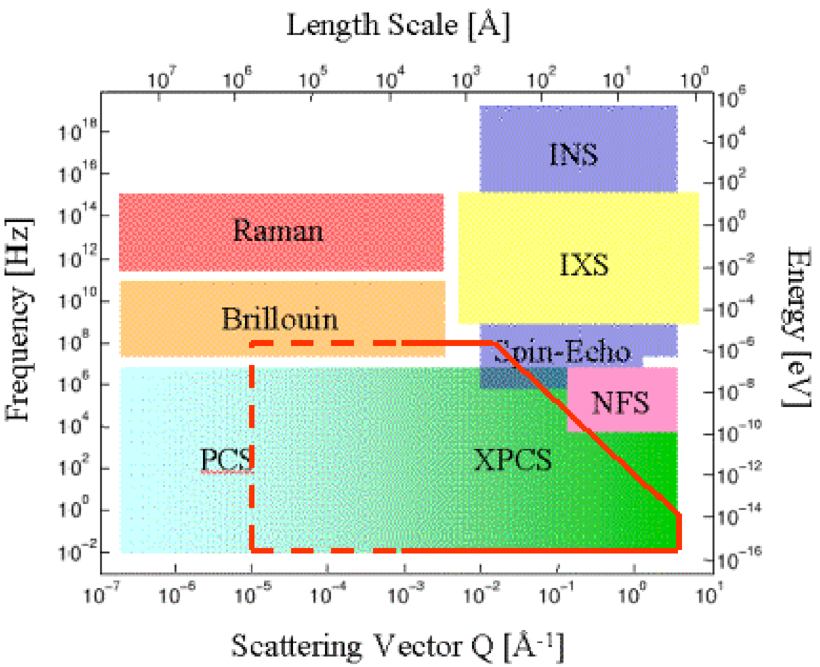


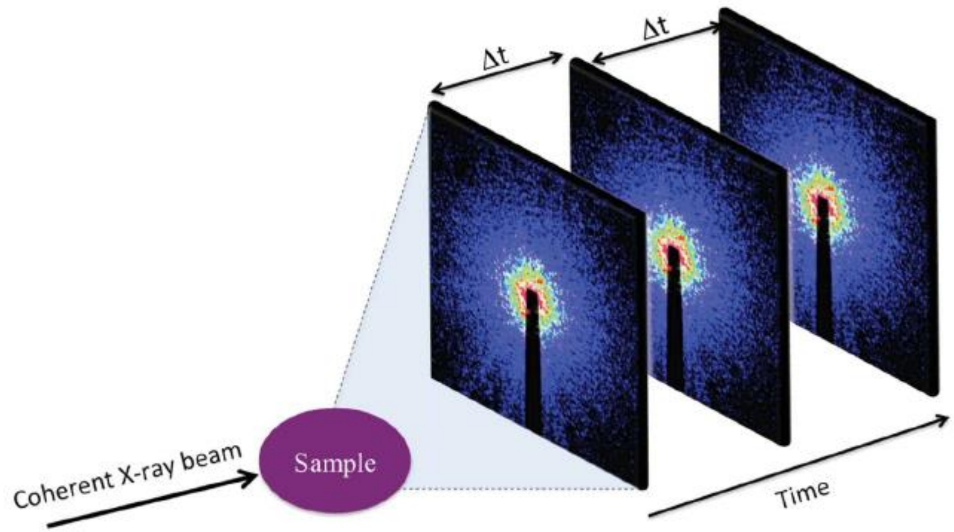




Strain field around dislocations !

Takahashi et al., PRB 87, 121201 (2013)

# Study of the Temporal Dynamics of Speckles: XPCS (X-ray Photon Correlation Spectroscopy)

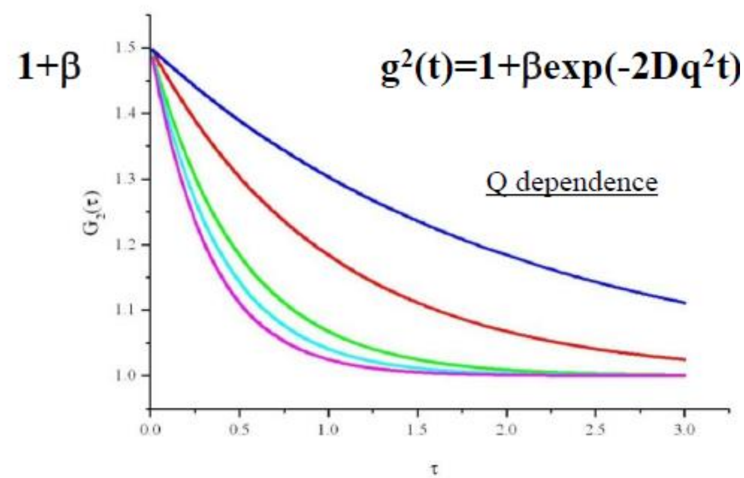



For a diffusive process :

$$g^2(t)=\langle I(q,t)I(q,t+\tau)\rangle/\langle I(q)\rangle^2=1+\beta\exp(-2Dq^2t)$$

β: degree of coherence



# New opportunities offered by next-generation sources

- Introduction: What are the key quantities to consider for coherence?
- Coherence: From the source point to the detector
- Current use of coherent X-rays
- New opportunities offered by next-generation sources
  - Coherence and nanofocusing
  - Next-generation synchrotron sources: ultimate storage rings
  - Coherence and time-resolved measurements at XFELs


SOLEIL
ESRF
DESY
ANKA
HZB
MAX IV
diamond
Argonne
NATIONAL LABORATORY
ALS
RHIC
nsls
LNLS
SESAME
INDUS i &
INDUS ii
SLRI
NUS
Australian
Synchrotron
SINAP
PAL
SPring-8
HiSOR

| | |
|---|---|
| Circumference | 528 m |
| No. of long straight sections / no. of available ID straights | 20 / 19 |
| Injection | Full-energy top-up from MAX IV Linac |
| Stored current | 500 mA |
| Horizontal emittance | ~200 - 330 pm rad (depending on ID gap settings) |
| Vertical emittance | 2 - 8 pm rad (depending on user demand) |
| Typical horizontal beam size at ID center | 42 - 54 micron (depending on horizontal emittance) |
| Typical horizontal beam divergence at ID center | 4.7 - 6.1 urad (depending on ID gap settings) |
| Typical vertical beam size at ID center | 2 - 4 micron (depending on choice of vertical emittance) |
| Typical vertical beam divergence at ID center | 1 - 2 urad (depending on choice of vertical emittance) |

## Machine characteristics

- **Very low emittance** (divided by ~10)
- **Very small source sizes** (divided by 10)
- **Brighter sources**

## Techniques

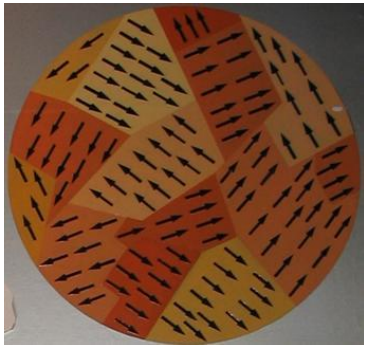
**COHERENCE**

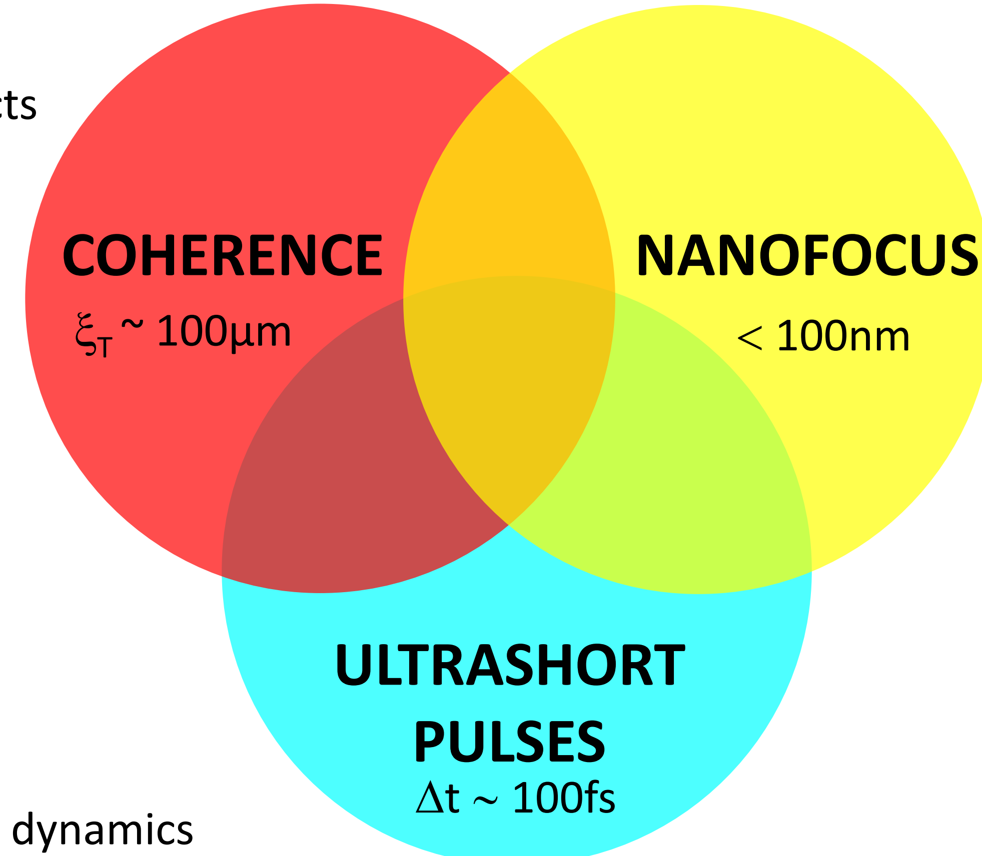
**NANOFOCUSING**

**TIME-RESOLVED**

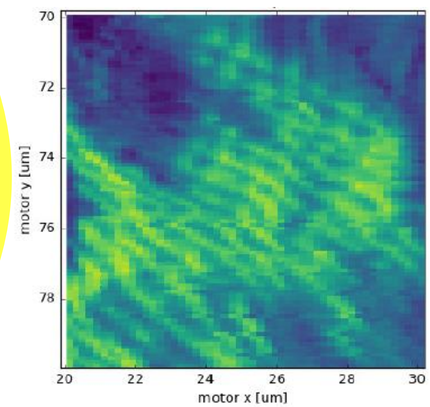
# Propriétés combinables pour explorer la matière de manière inédite!

Imaging
Phase objects/Defects

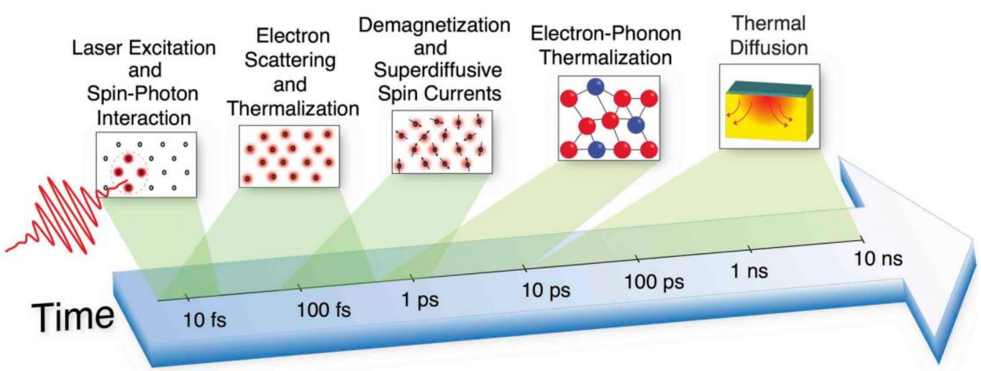




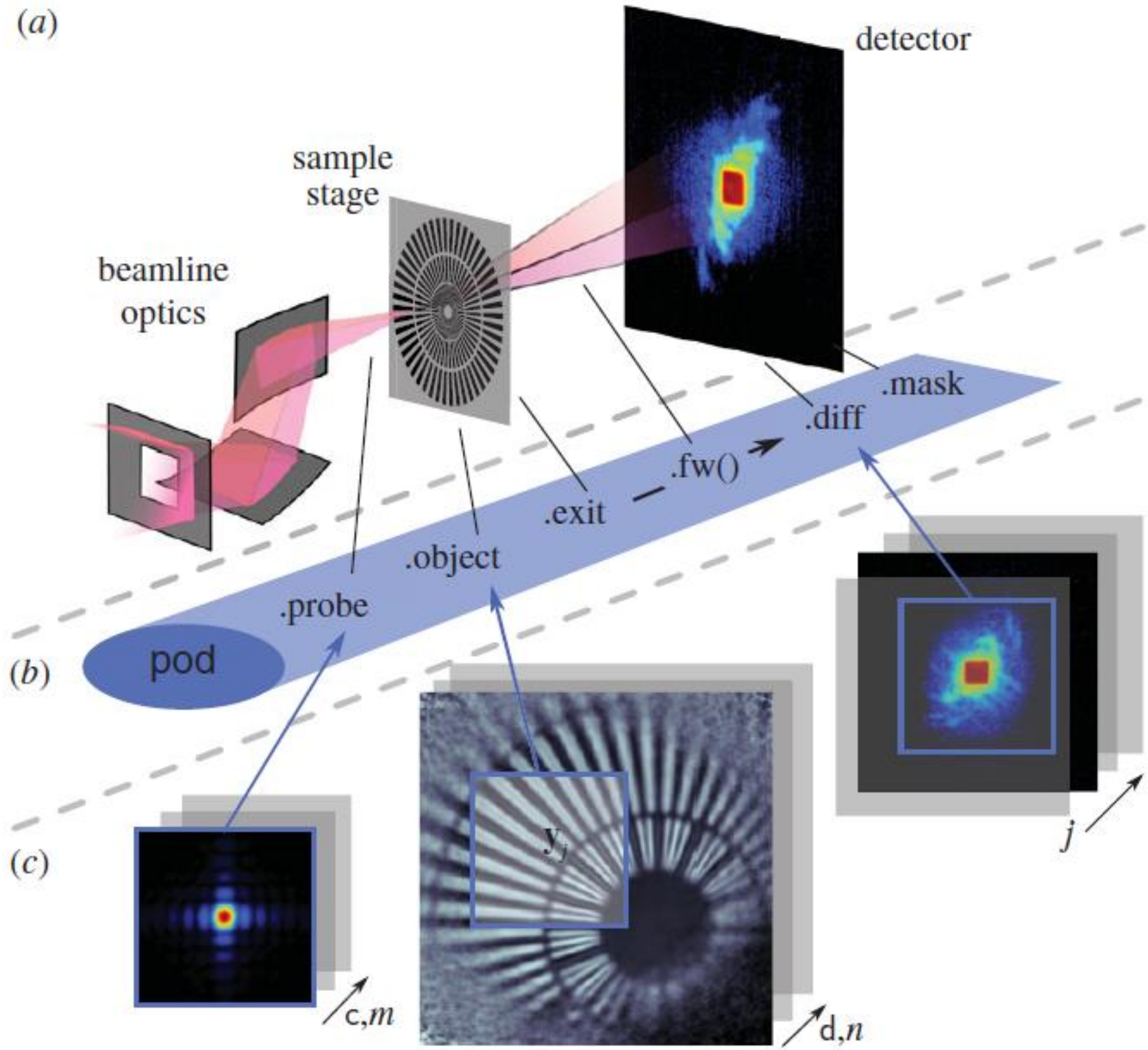

Micro/Nano Structure




Ultrafast dynamics



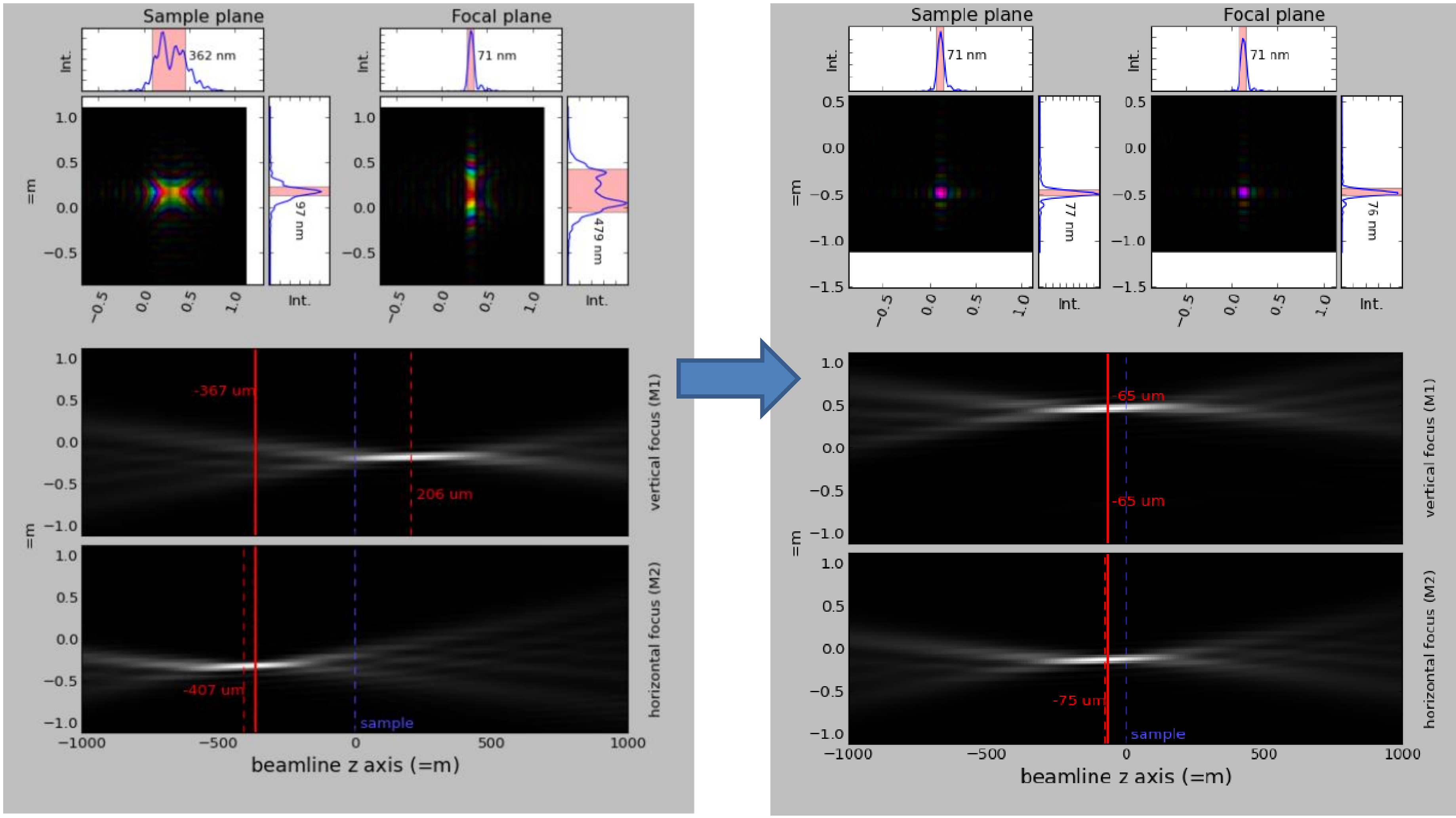
# Coherent X-ray Nanodiffraction Setup



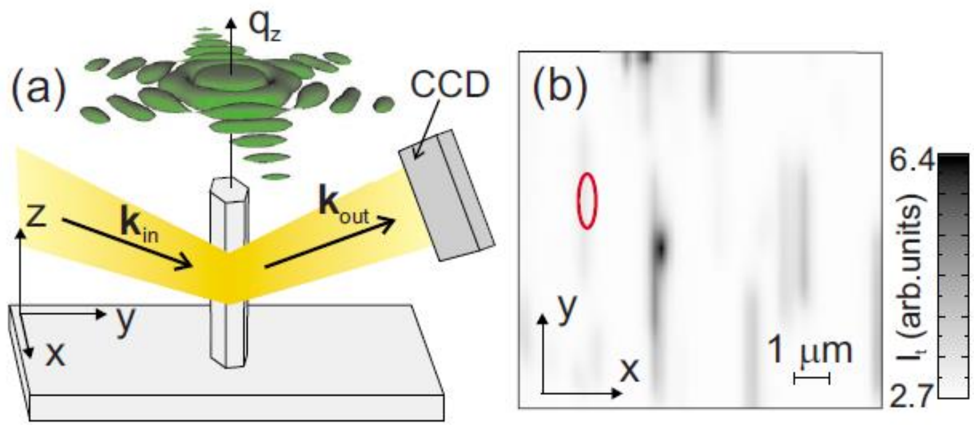

Enders, Thibault, Proc. R. Soc. A 472: 20160640 (2016)

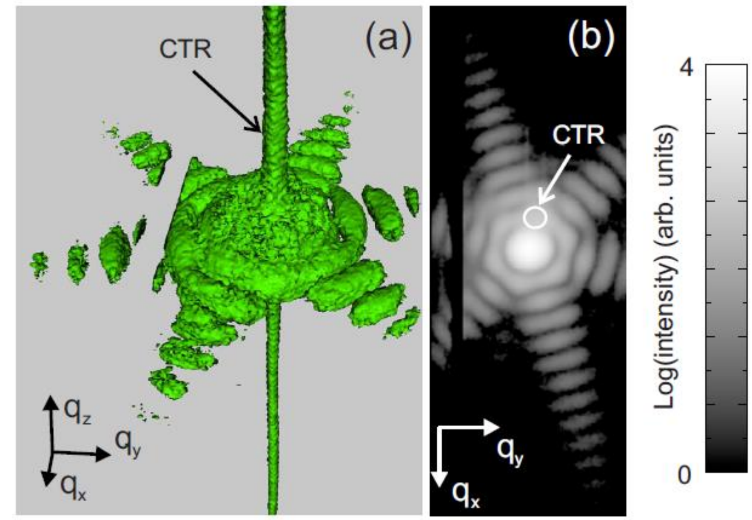
# Reconstruction of the Phase and Amplitude Profile of a Focused Beam by Ptychography

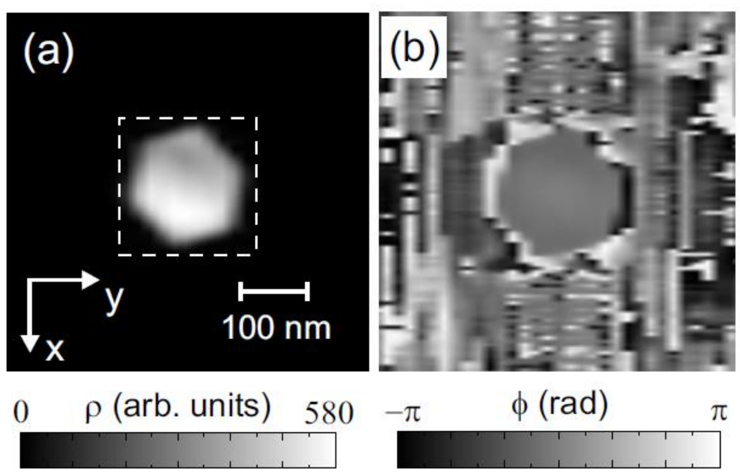
## Astigmatism Correction, Measurement of the Size, and Phase Profile of the Focused Beam



# Single InAs Nanowires Probed by Coherent Nanodiffraction

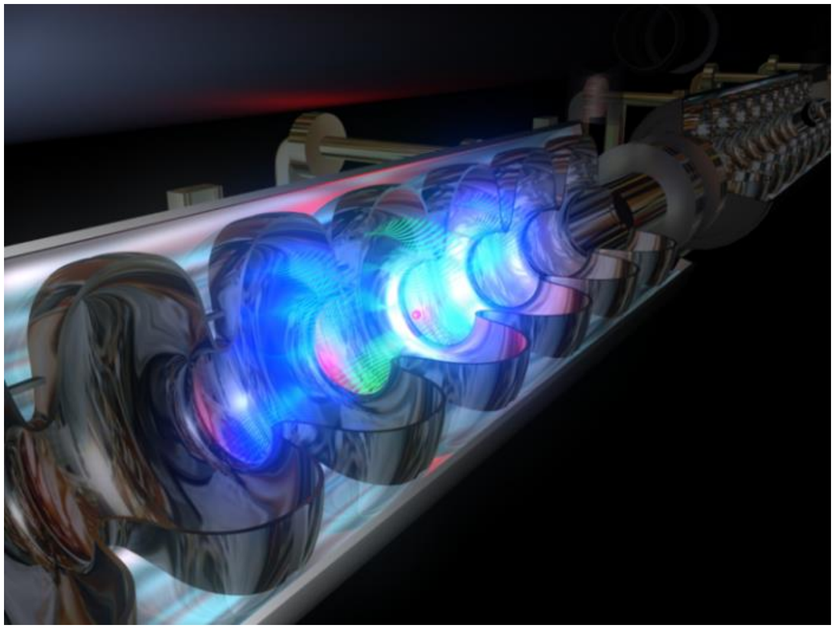


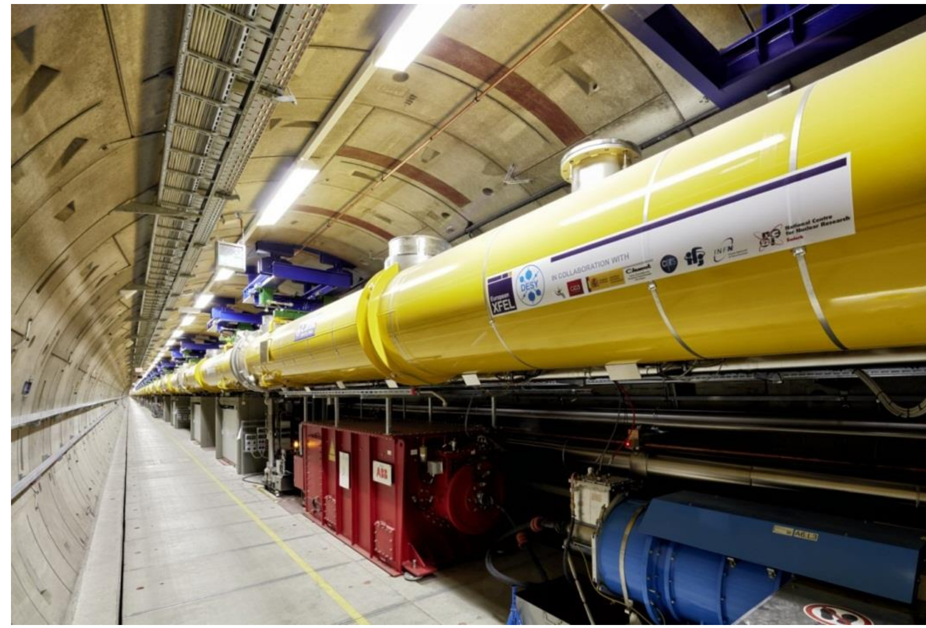




Diaz A. et al., PRB 79, 125324 (2009)

# Free-Electron X-ray Lasers:
# Naturally Coherent Sources with Ultrafast Pulses



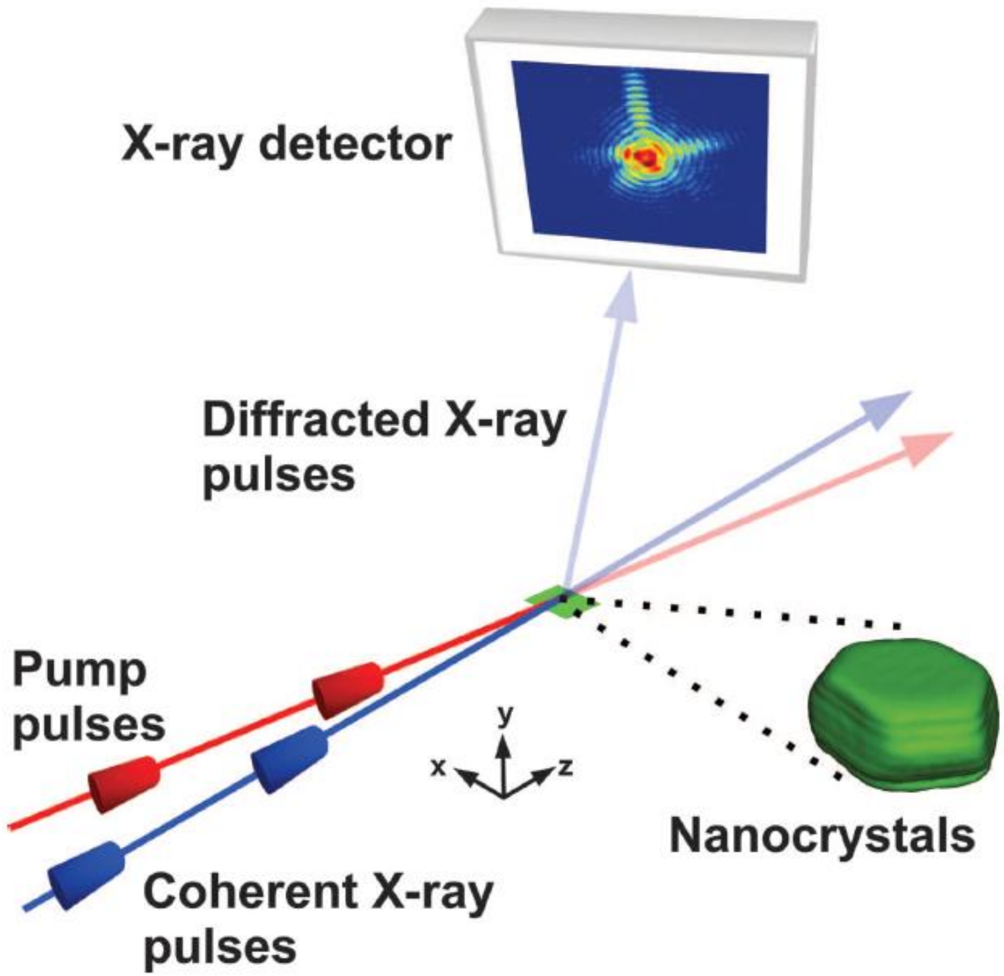


**Complementary** to Synchrotrons for Specific Studies

Advantages: Brightness, fs Temporal StructureDisadvantages: Stability, Sample Damage, Limited Access

# Combining coherence, nanodiffraction, and time-resolution at XFELs…

**Ultrafast Three-Dimensional Imaging of Lattice Dynamics in Individual Gold Nanocrystals**
J. N. Clark *et al.*
*Science* **341**, 56 (2013);
DOI: 10.1126/science.1236034



# … Imaging an acoustic phonon in a gold nanocrystal