Resonant Scattering of Coherent Soft X-Rays from Magnetic Domain Patterns

SSRL

Jan Lüning

Stanford Synchrotron Radiation Laboratory

- Motivation
- ‘Small’ Angle Scattering of Coherent X-rays
- Resonant Coherent X-ray Scattering
- What can we use the coherence for

Collaborators

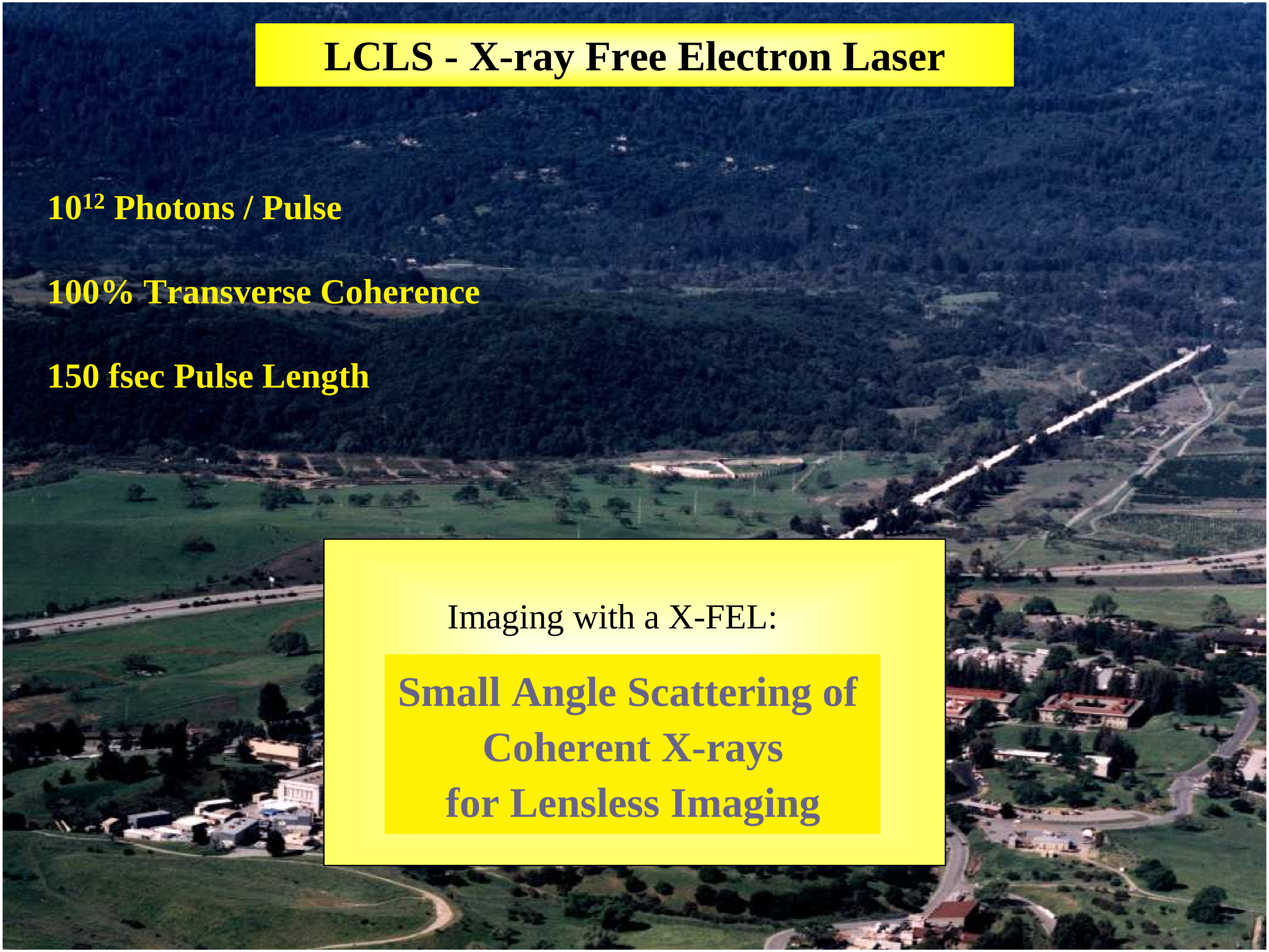
Stefan Eisebitt
Marcus Lörgen
Wolfgang Eberhardt

BESSY

Bill Schlotter
Scott Andrews
Jo Stöhr

SSRL

Pinholes	Charlie Rettner, IBM Almaden
Samples	Eric Fullerton, Olav Hellwig, Jan-Ulrich Thiele, IBM Almaden
X-ray microscopy	Greg Denbeaux, ALS

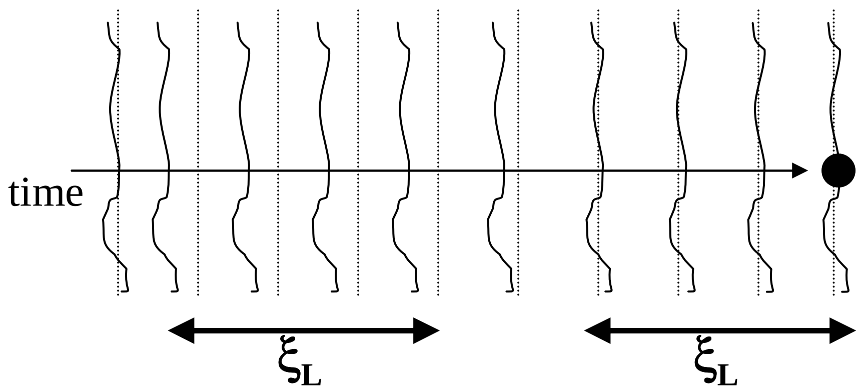

LCLS - X-ray Free Electron Laser
10^{12} Photons / Pulse
100% Transverse Coherence
150 fsec Pulse Length
Imaging with a X-FEL:
Small Angle Scattering of Coherent X-rays for Lensless Imaging

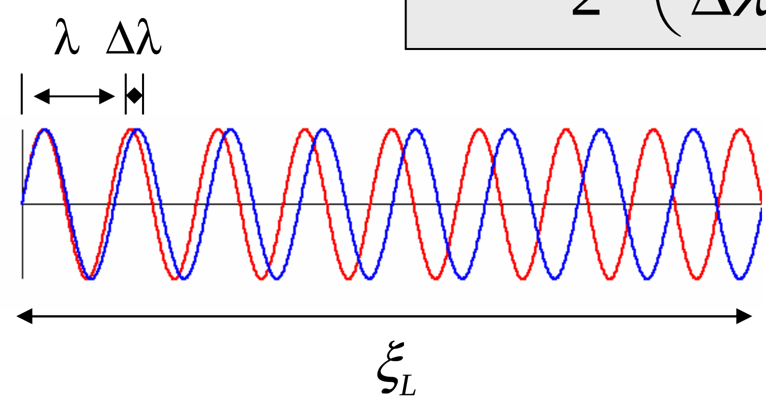
Coherence Lenghts

Temporal / Longitudinal coherence

$$\xi_L = \frac{\lambda}{2} \cdot \left(\frac{\lambda}{\Delta\lambda} \right)$$

Michelson Interferometer:
How long can path difference be?

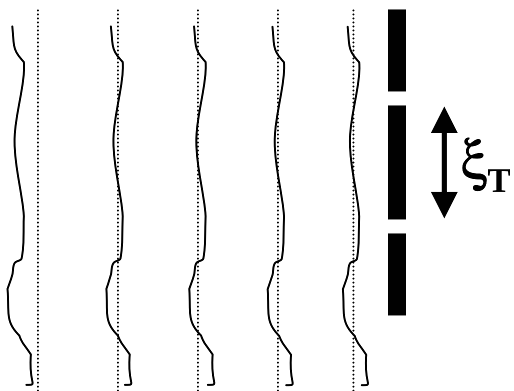


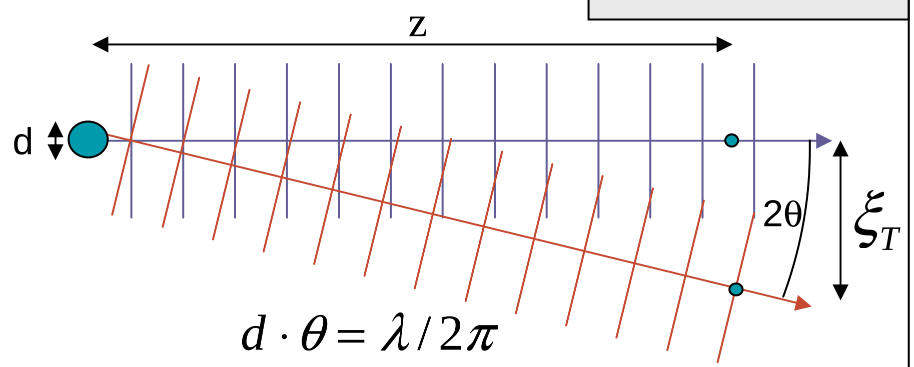


Transverse coherence

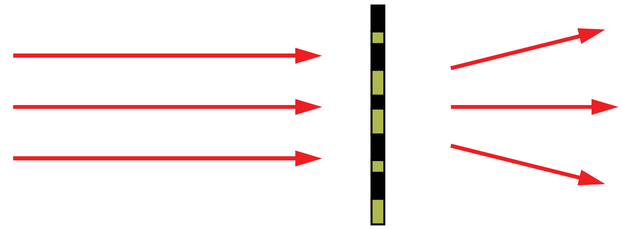
$$\xi_T = \frac{z\,\lambda}{2\,\pi\,d}$$

Young’s double slit:
How far apart can slits be?

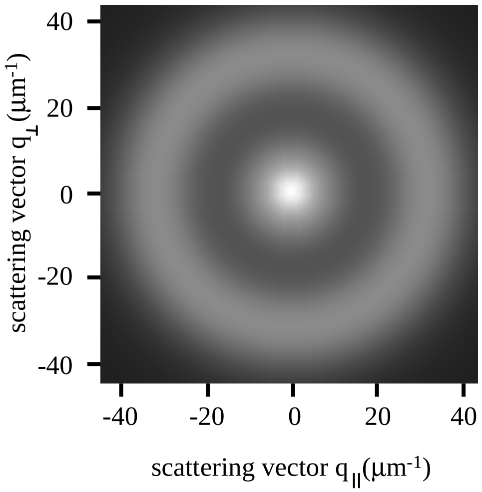




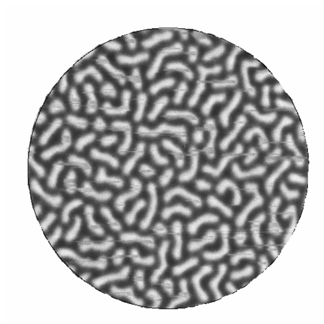
Incoherent vs. Coherent Small Angle X-ray Scattering



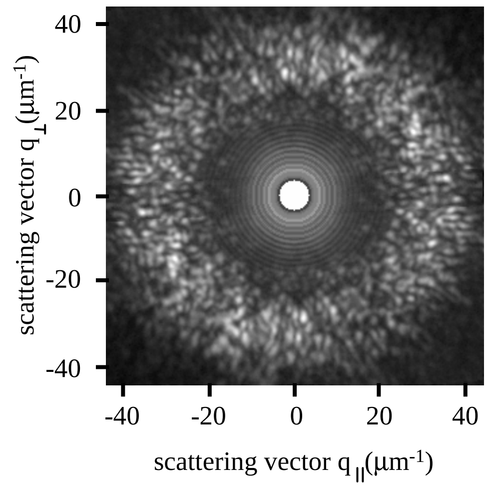
SAXS



Sample without long range order



Speckle



- Coherence length smaller than illuminated area.
- Incoherent superposition of 'local' speckle images.

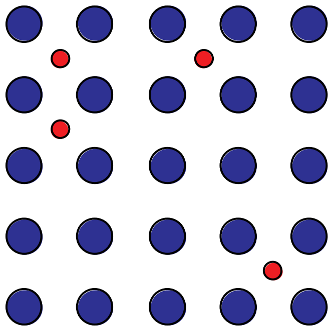
⇒ Information about sample statistics

- Coherence length larger than illuminated area.
- Scattering from all 'domains' adds up coherently.

⇒ Information about true sample structure

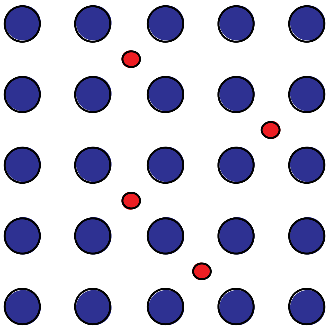
Coherence Benefits

Sensitivity to individual sample
beyond statistical information



Same average periodic lattice
Same average deviation from lattice
⇒ **same incoherent SAXS**

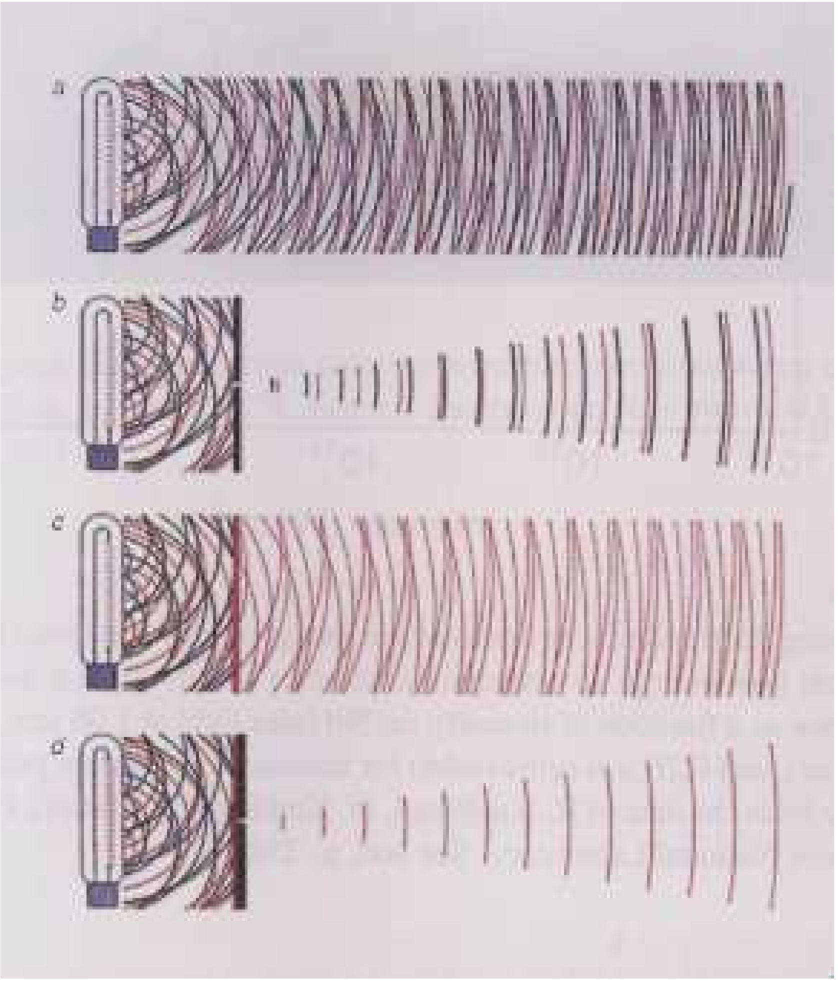
Different individual configurations
⇒ **distinct SPECKLE patterns**



Applications

- Sample fingerprint
- Dynamics
- Imaging

How to Make a Photon Beam Coherent



A. Schawlow, Sci. Am. **219**, 120 (Sept 1968)

Synchrotron sources are polychromatic and incoherent/chaotic

Pinhole:
spatial filtering $\rightarrow$ lateral coherence

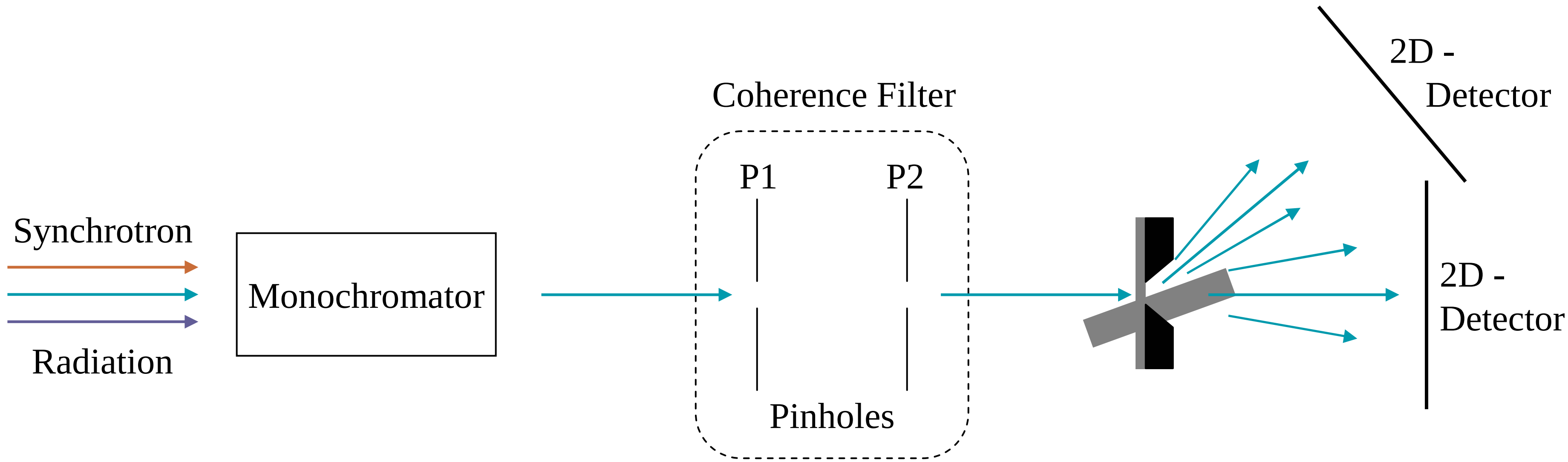
Monochromator:
spectral filtering $\rightarrow$ longitudinal coherence

Spatially and spectrally filtered beam is coherent

Coherence ~ Brilliance $\cdot \lambda^3$

$\Rightarrow$ Undulator source allows to extract a 'sufficient' coherent flux

Coherent Illumination Realization



Monochromator defines

longitudinal coherence length

$$\xi_L = \frac{\lambda^2}{2\Delta\lambda} = \frac{\lambda}{2} \cdot \left(\frac{\lambda}{\Delta\lambda} \right)$$

Pinhole Size and Distance defines

transverse coherence length

$$\xi_T = \frac{z\lambda}{2\pi d}$$

Coherent Flux
~ Brilliance · λ^3

$E = 775$ eV $\quad \frac{E}{\Delta E} = 5000$

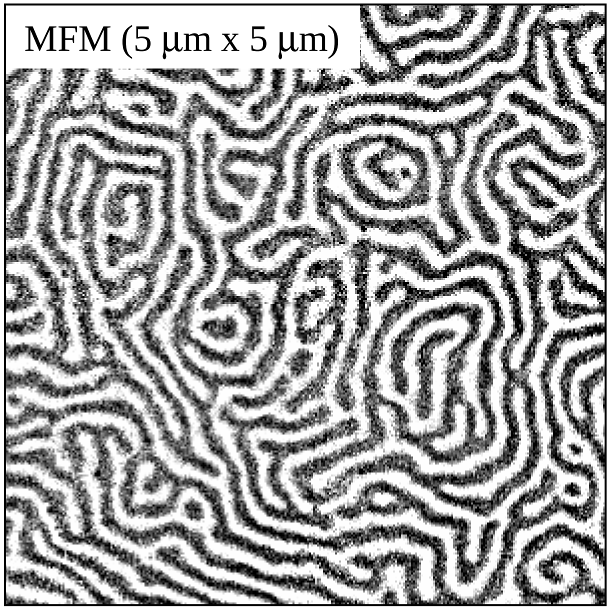
$\Rightarrow \xi_L = 4\ \mu m$

For 50 - 5 µm apertures:

$\Rightarrow \xi_T = 10 - 100\ \mu m$

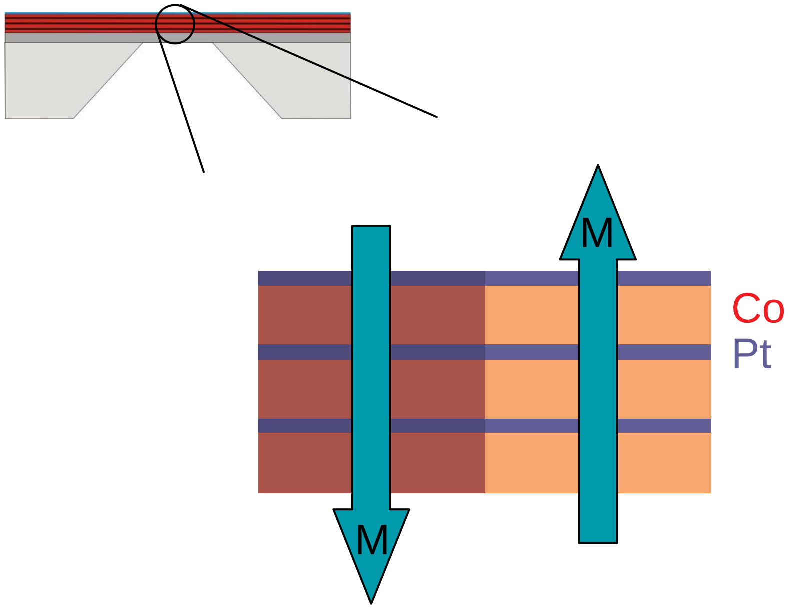
Magnetic Worm Domain Sample

Top view



Magnetic test medium for
resonant coherent
x-ray scattering

Side view



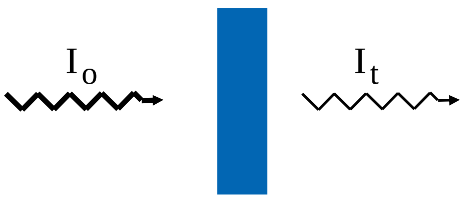
Sample: E. Fullerton, O. Hellwig
J.-U. Thiele, IBM Almaden

SiN_x(160 nm) / Pt (20 nm) /
[Co (3 nm) / Pt (0.7 nm)]$_{50}$ /
Pt (2 nm)

perpendicular magnetization

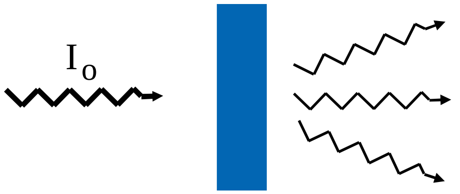
X-Ray Magnetic Circular Dichroism in Absorption and Scattering

Absorption



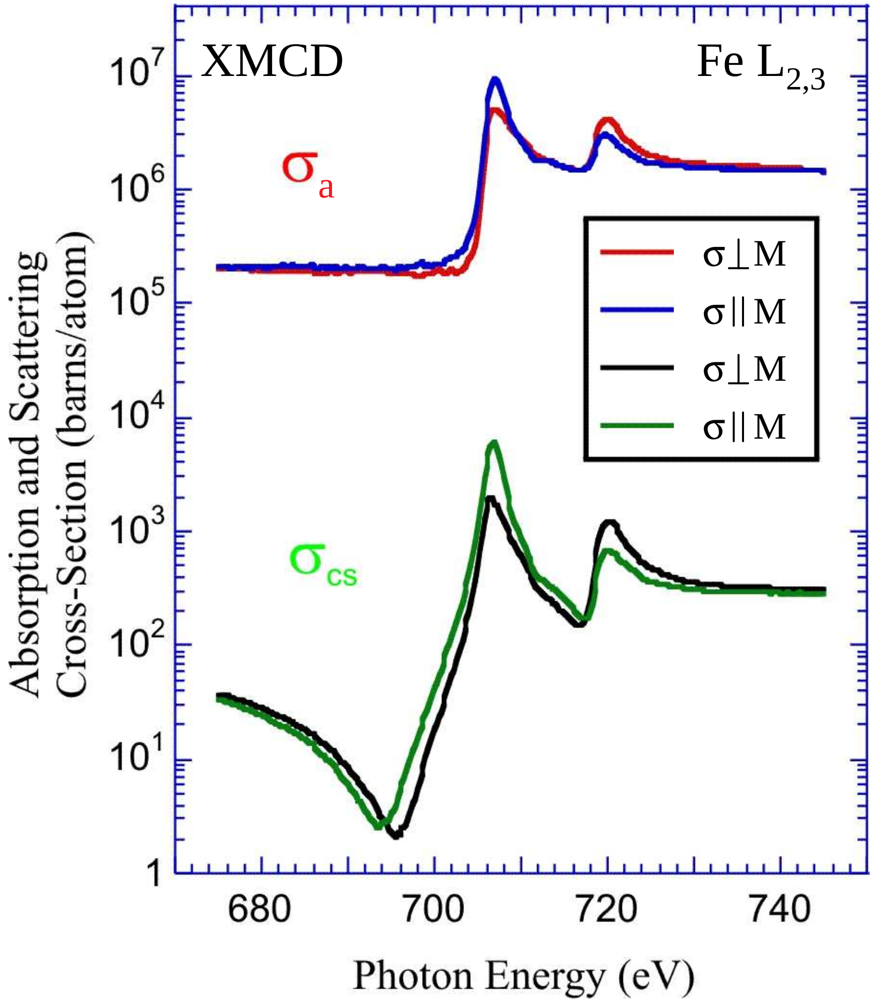
$$I_t = I_o \, e^{-\sigma_a \rho t}$$

Small Angle Scattering



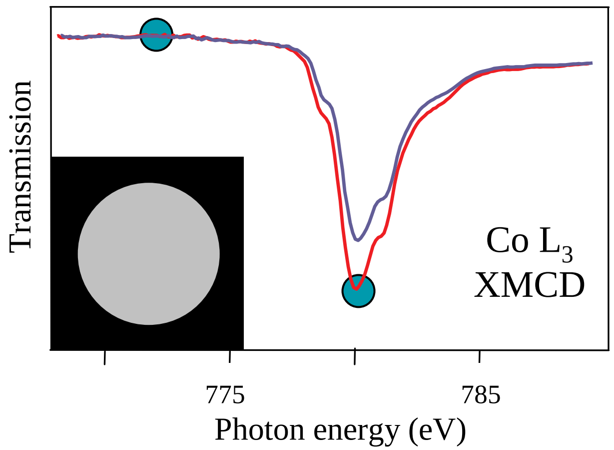
$$I_{cs} = I_o \; \sigma_{cs} / \sigma_a$$

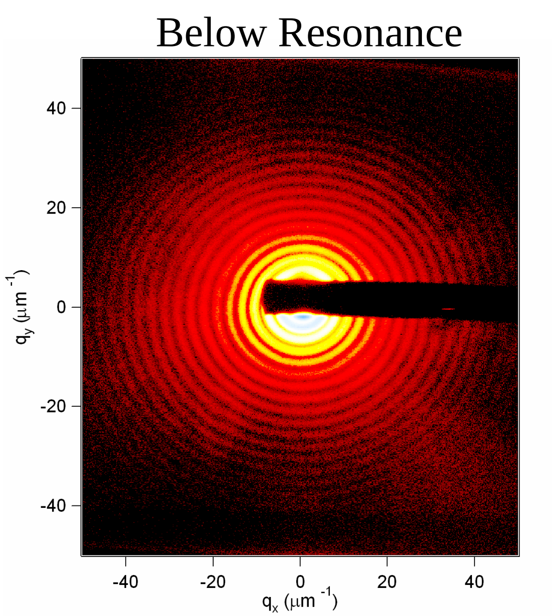
$$\sigma_{cs} = c \, | f_1 + i f_2 |$$

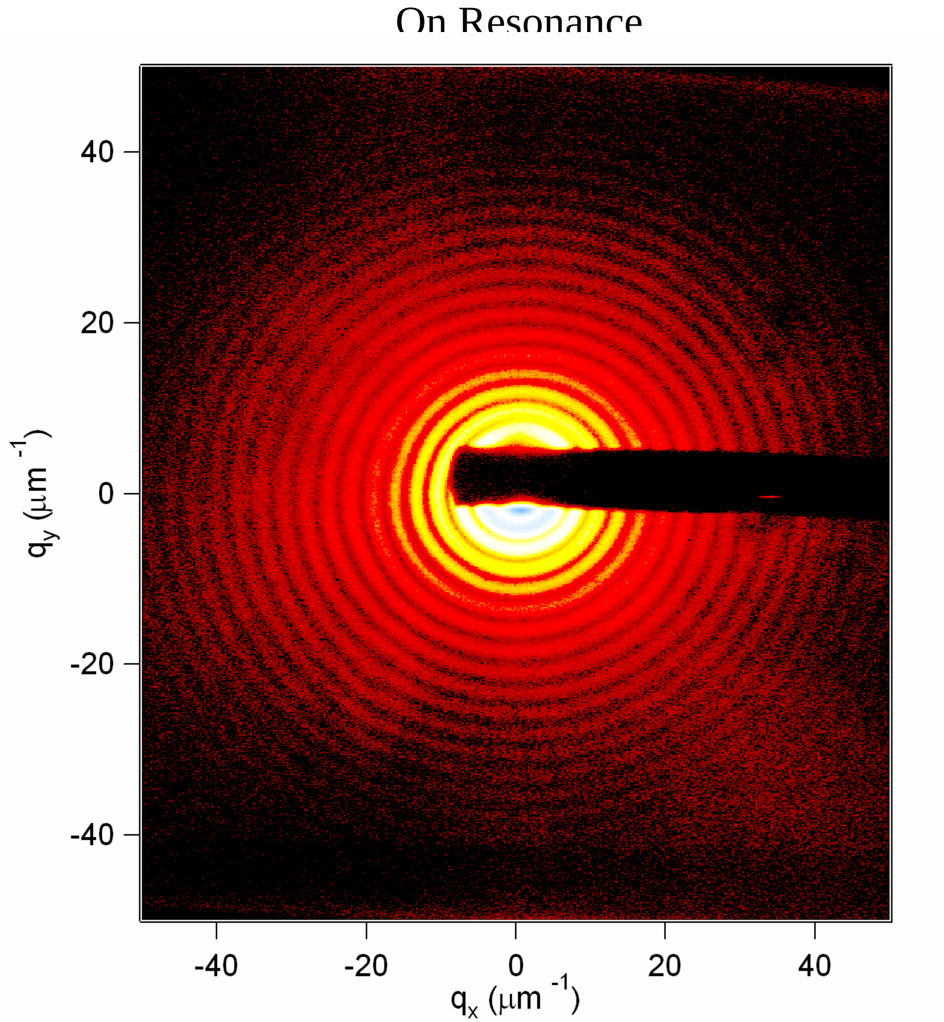


Data from Jeff Kortright (LBNL)

Magnetic Scattering Contrast



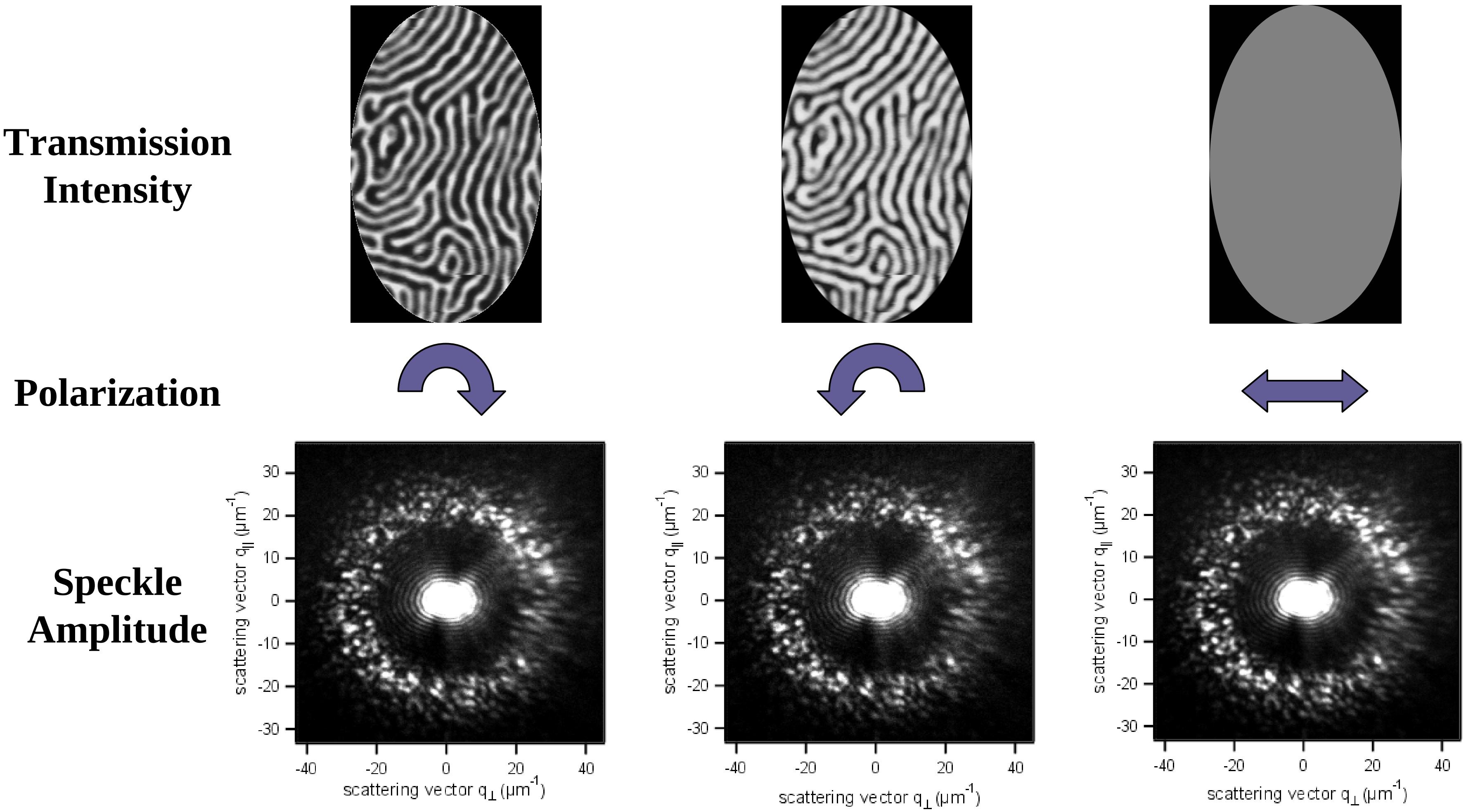




λ = 1.59 nm, 2.5 mm ∅ Pinhole
fully coherent illumination: visibility = 1, M = 1

Polarization Dependence

Thick Sample (10 penetration lengths)
∅ Pinhole >> ς (mag. domains)



1) Only same polarization channels can interfere

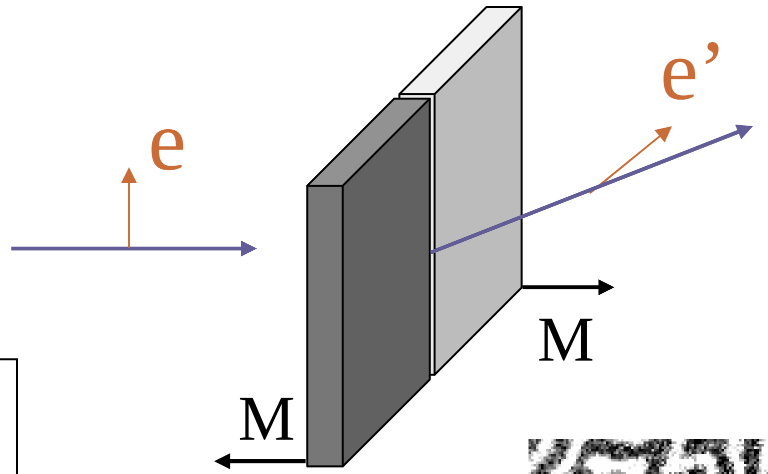
2) ∅ >> ς: • No interference between charge and magnetic scattering

• Babinet's theorem for contrast inversion ⇒ same Speckle pattern

Polarization Dependent Resonant Magnetic Scattering

J. P. Hannon, G. T. Trammell, M. Blume, D. Gibbs, Phys. Rev. Lett 61, 1245 (1988)

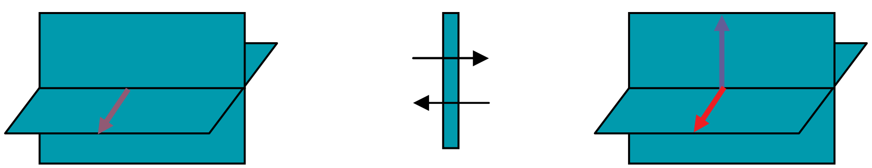
$$I \propto \left| \sum_n \exp(i\mathbf{q}\cdot\mathbf{r}_n) f_n \right|$$



Resonant scattering amplitude (in this geometry):

charge — magnetic (XMCD)

$$f_n = (\boldsymbol{e}'\cdot\boldsymbol{e})F_n^c - i(\boldsymbol{e}' \times \boldsymbol{e})\boldsymbol{M}_n\cdot F_n^{m_1}$$

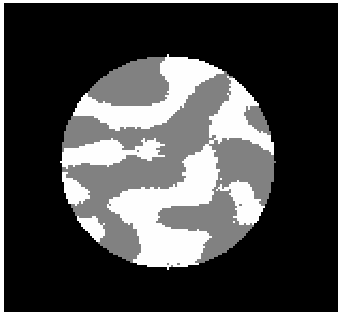


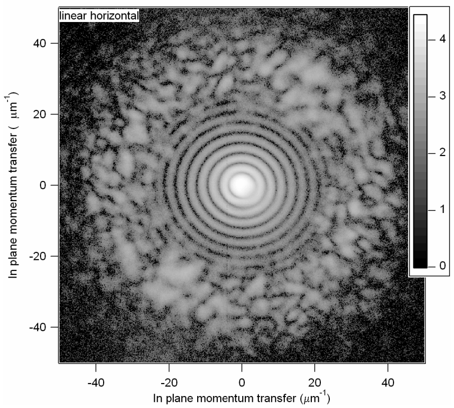
Circular polarization: Eigenstate

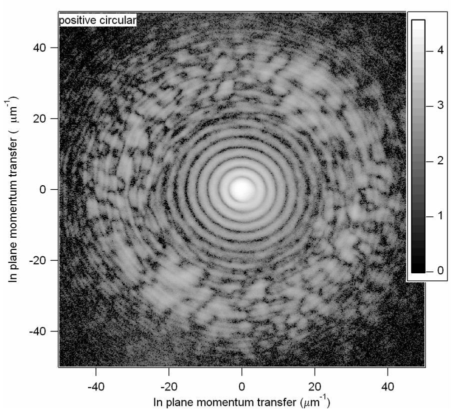
Linear Polarization: $\pi \rightarrow \sigma$, $\sigma \rightarrow \pi$

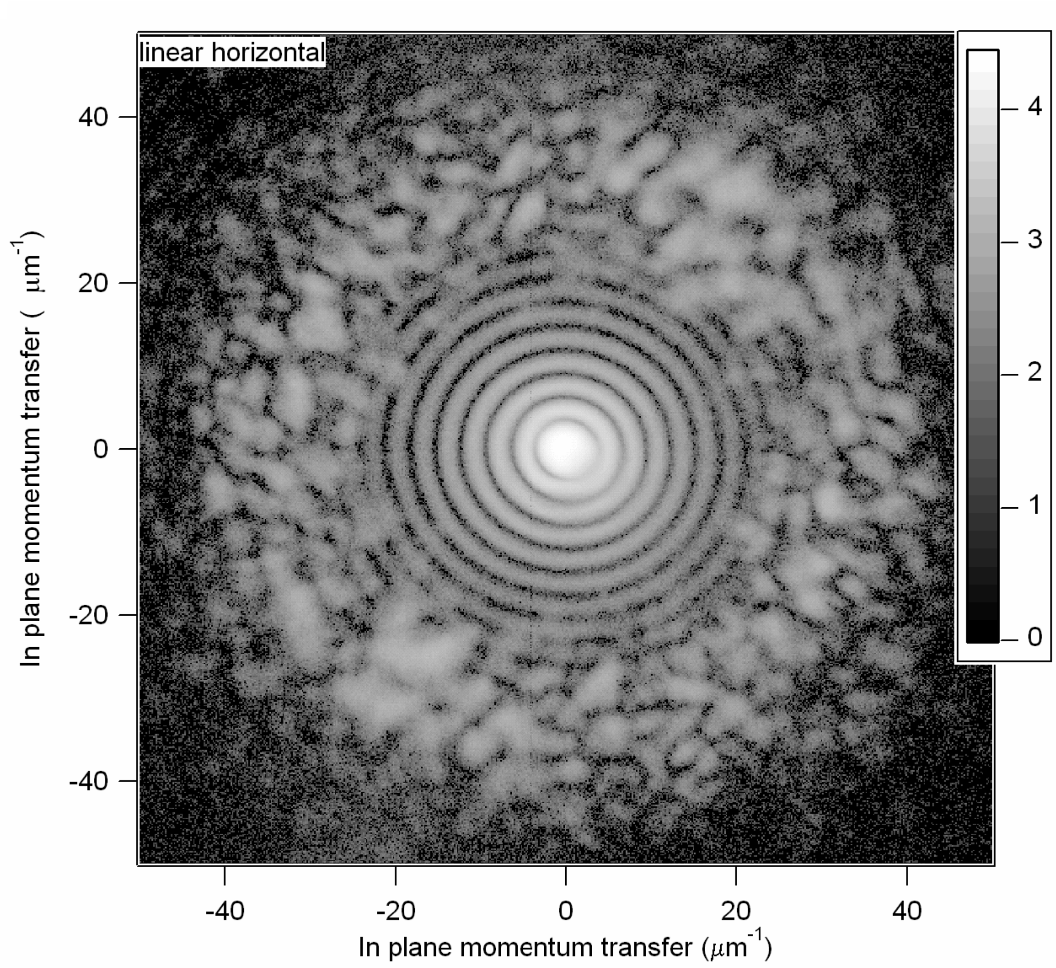
Interference of Charge and Magnetic Scattering

∅ Pinhole > ς mag. domains









Interference = Positive-Circular — Linear

$$I_R - I_L = (Pin + Mag)^2 - (Pin^2 + Mag^2) = 2\,(Pin \cdot Mag)$$

WHAT CAN WE LEARN FROM SPECKLES

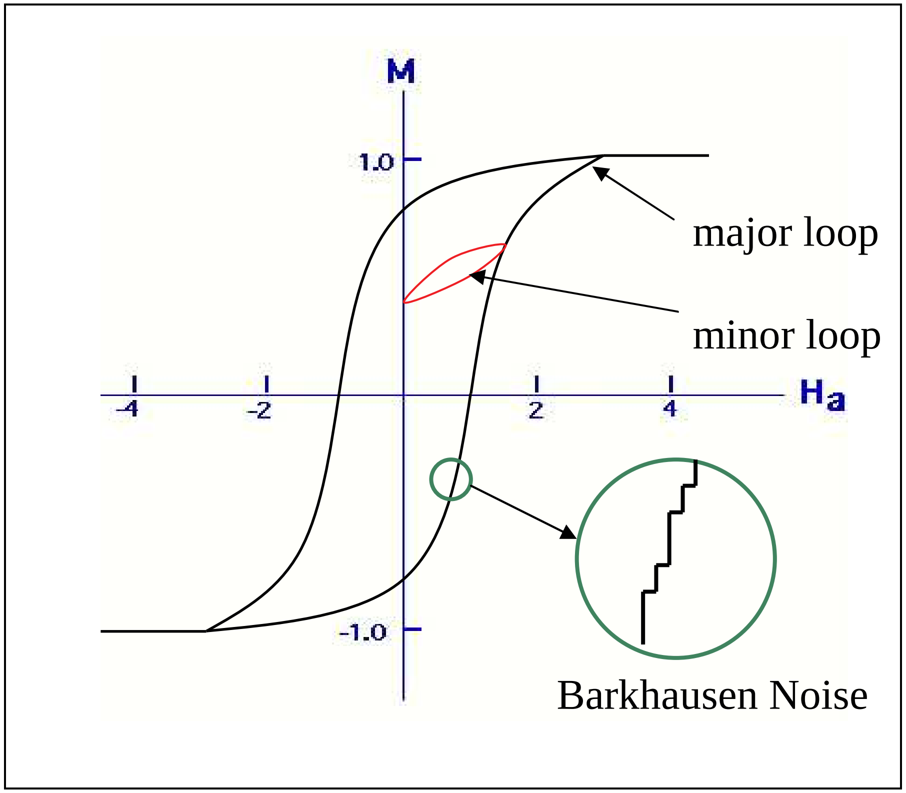
1. Fingerprint

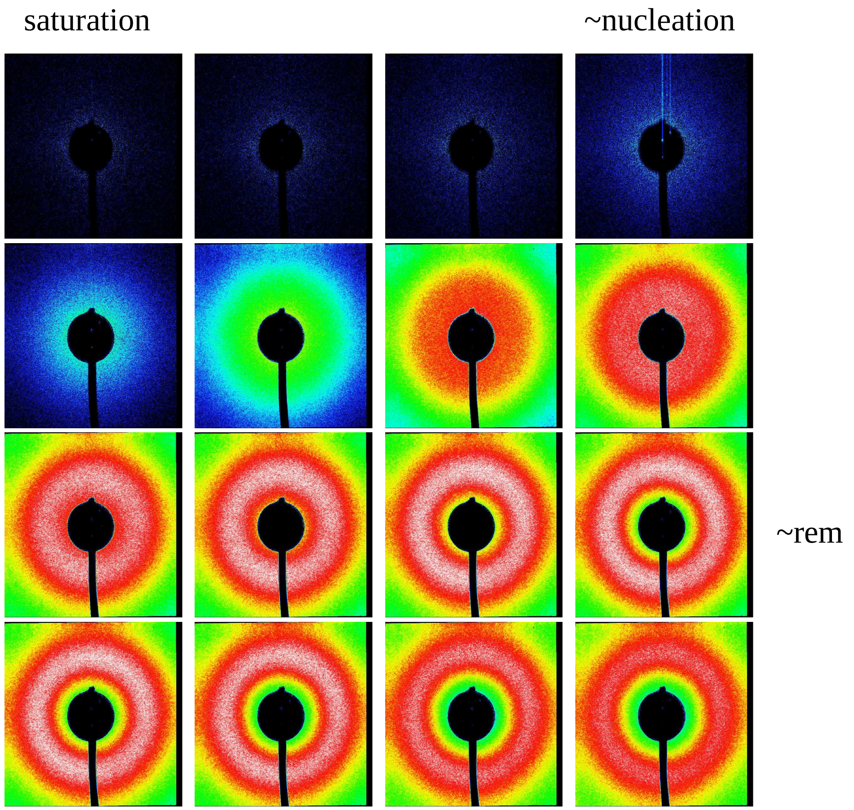
2. Imaging

3. Dynamics

Magnetic Return Point Memory

L. Sorensen, Univ. of Washington
S. Kevan, Univ. of Oregon





Use speckle pattern as a fingerprint for microscopic domain structure

The Phase Problem in X-ray Scattering

$A = M \cdot e^{i\Phi}$ Experiments are intensity measurements, phase information is lost

Fourier Space

Magn

Phase

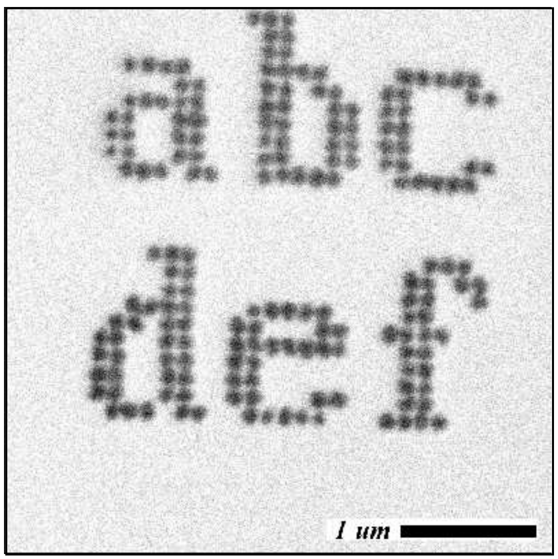
Real Space

Object Reconstruction from X-ray Speckle Pattern

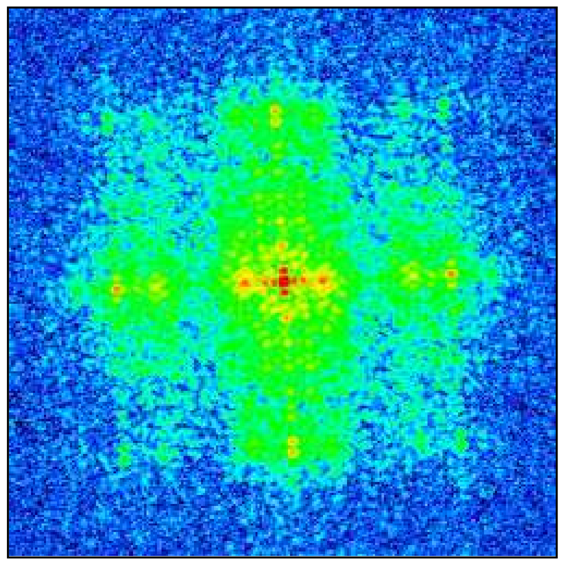
Sayre ('52), Gerchberg & Saxton ('72), Bates ('82), Fienup ('80's), Miao ('99)

Idea: Compensate for the missing phases with extra, non-redundant intensity measurements

SEM picture



Speckle

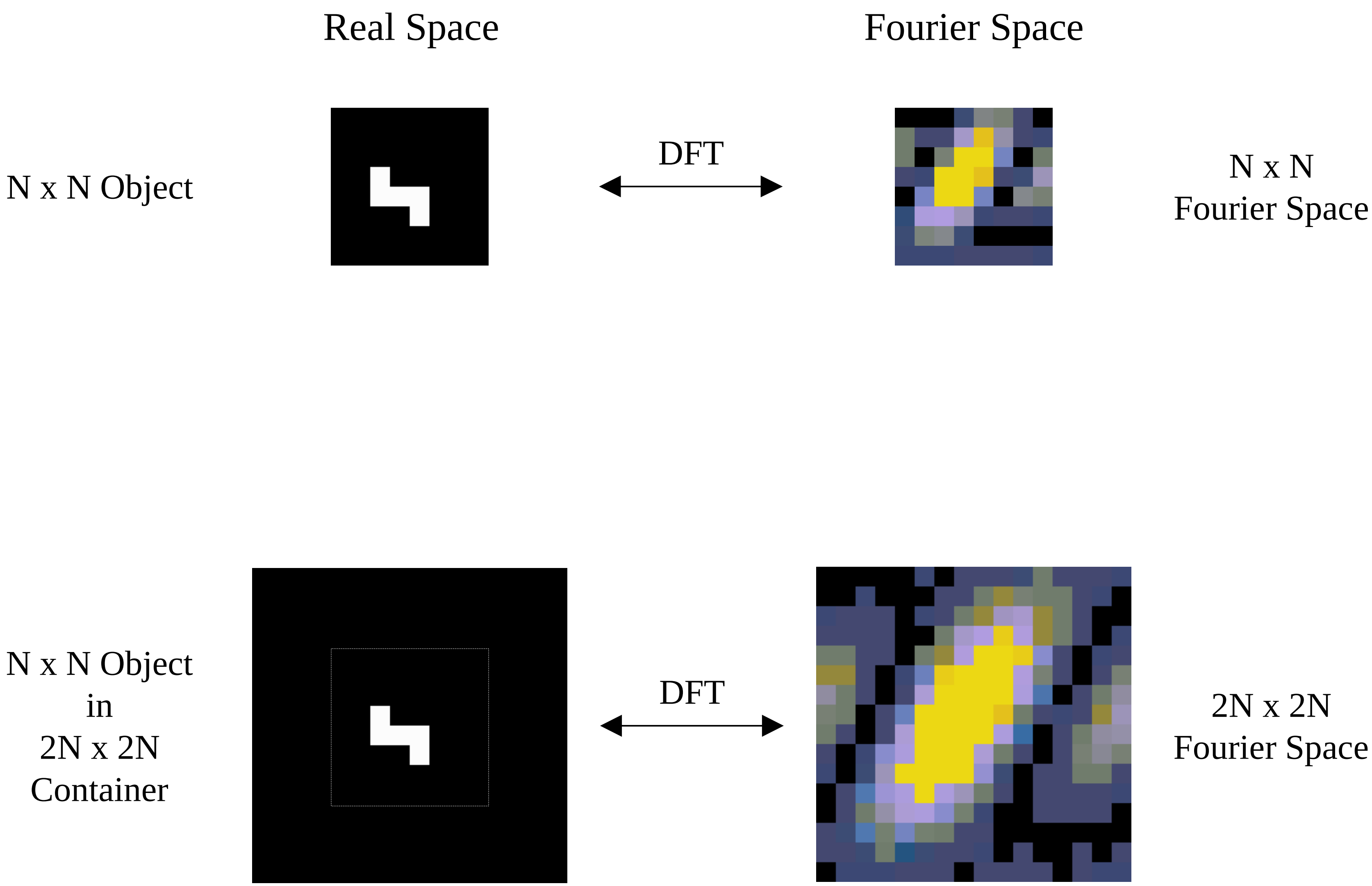


Reconstructed object

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

- Works for *non-periodic* samples
- Tomography
- 7 nm spatial resolution demonstrated

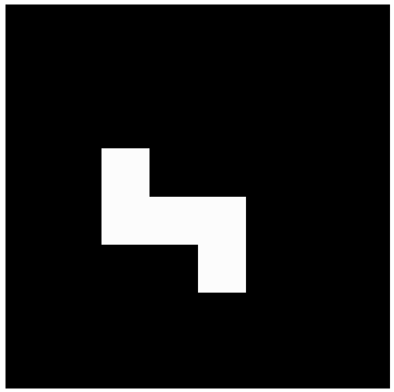
Object Frame Size and Fourier Transformation



‘Oversampling’ Solves Phase Problem

Sampling finer than the Bragg frequency (Shannon sampling)

N x N
Object



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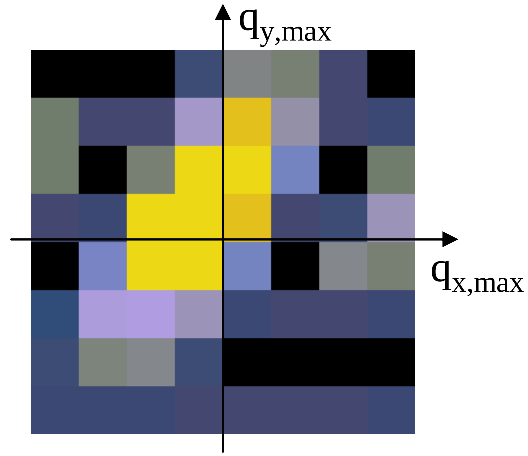
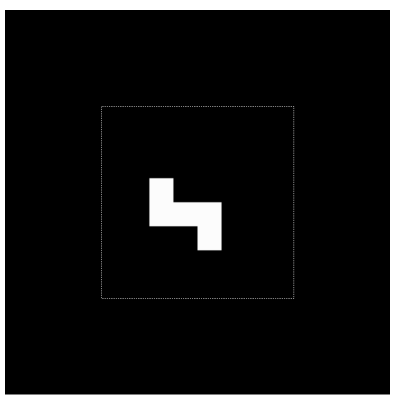


N x N
‘Detector’

N x N Object
in
2N x 2N
Container



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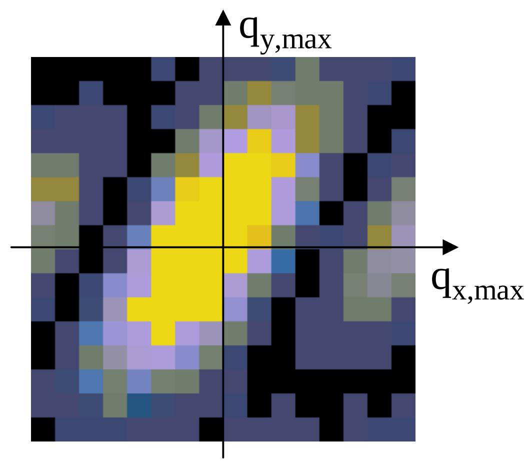


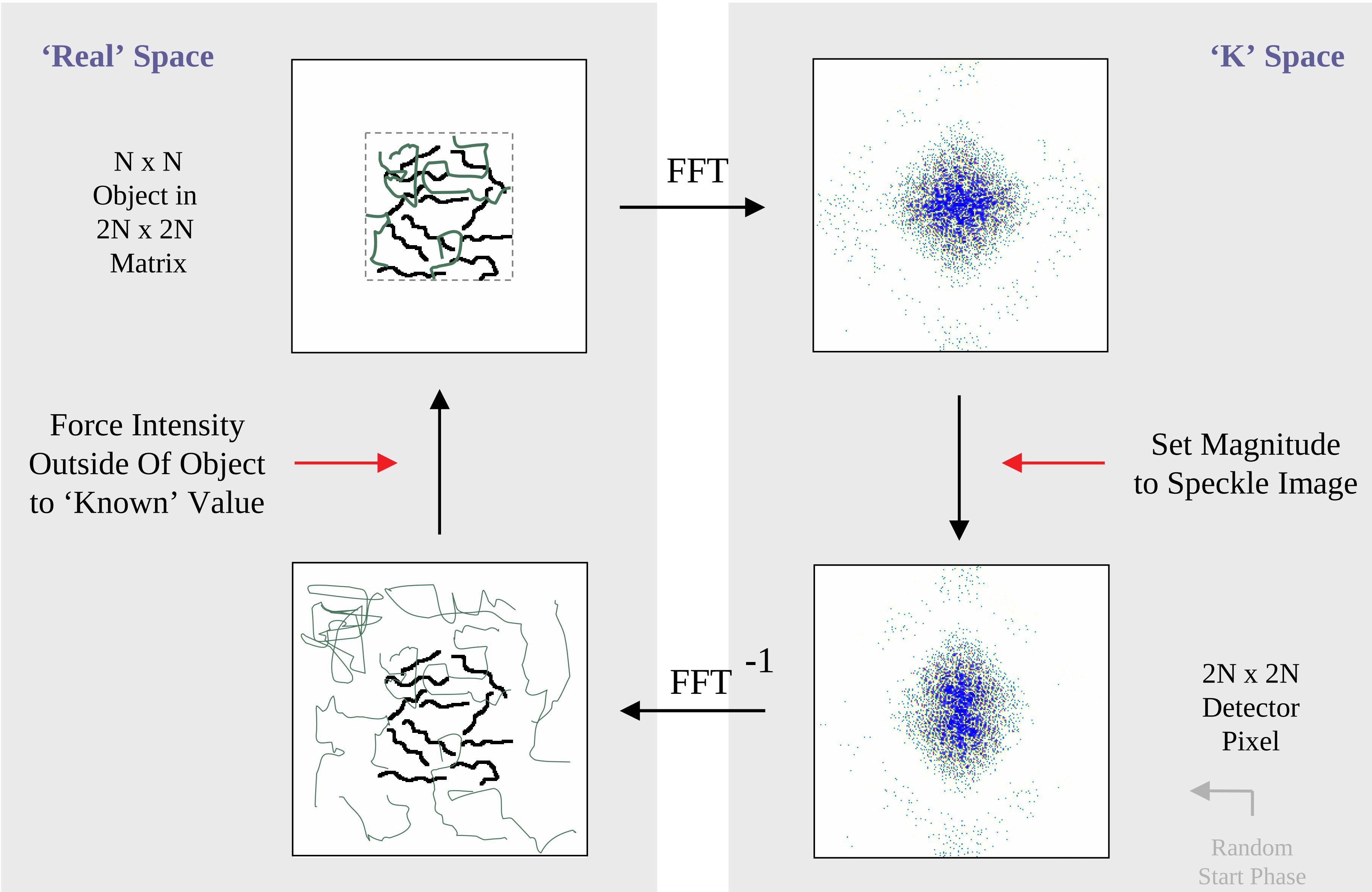
2N x 2N
‘Detector’

Real Space

‘K’ Space

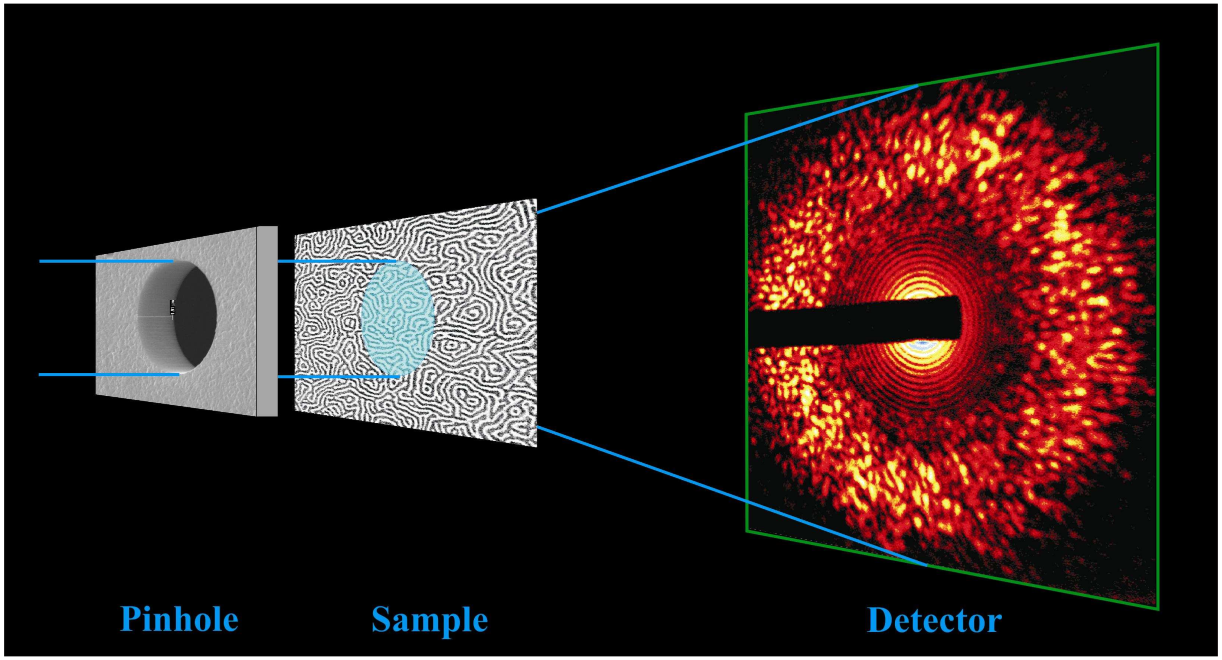
Iterative Algorithm for Phase Reconstruction

Algorithm idea and method developed by Sayre, Gerchberg & Saxton, Bates, Fienup, Miao



J. Miao et al, Phys. Rev. B 67, 174104 (2003)

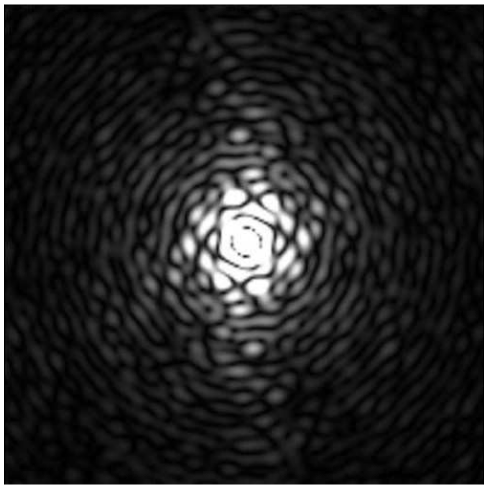
Resonant Magnetic Coherent X-ray Scattering



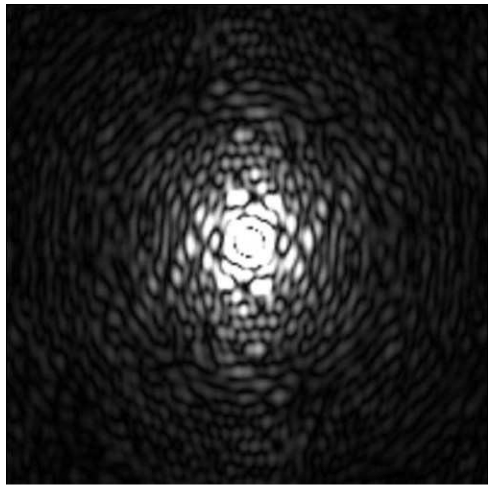
- Domain Structure is ‘complicated’
- ‘Required’ reference hole too small
- Sample has complex scattering amplitude
- Interference between charge and magnetic scattering
- Speckle pattern is not centro-symmetric (interference)

How to Obtain More Information?

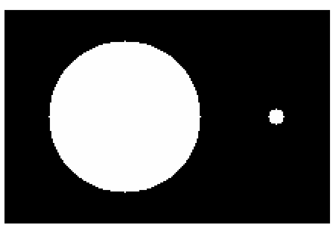
Reference Beam Holography



No reference hole

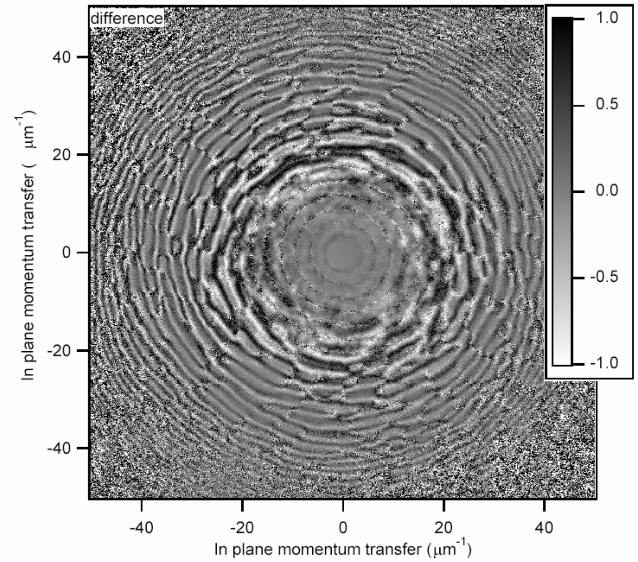


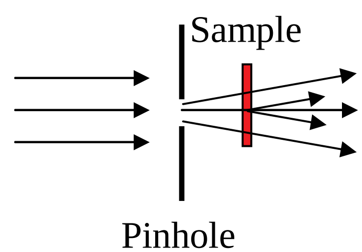
With reference hole



H. He et al., PRB **67**, 174114 (2003)

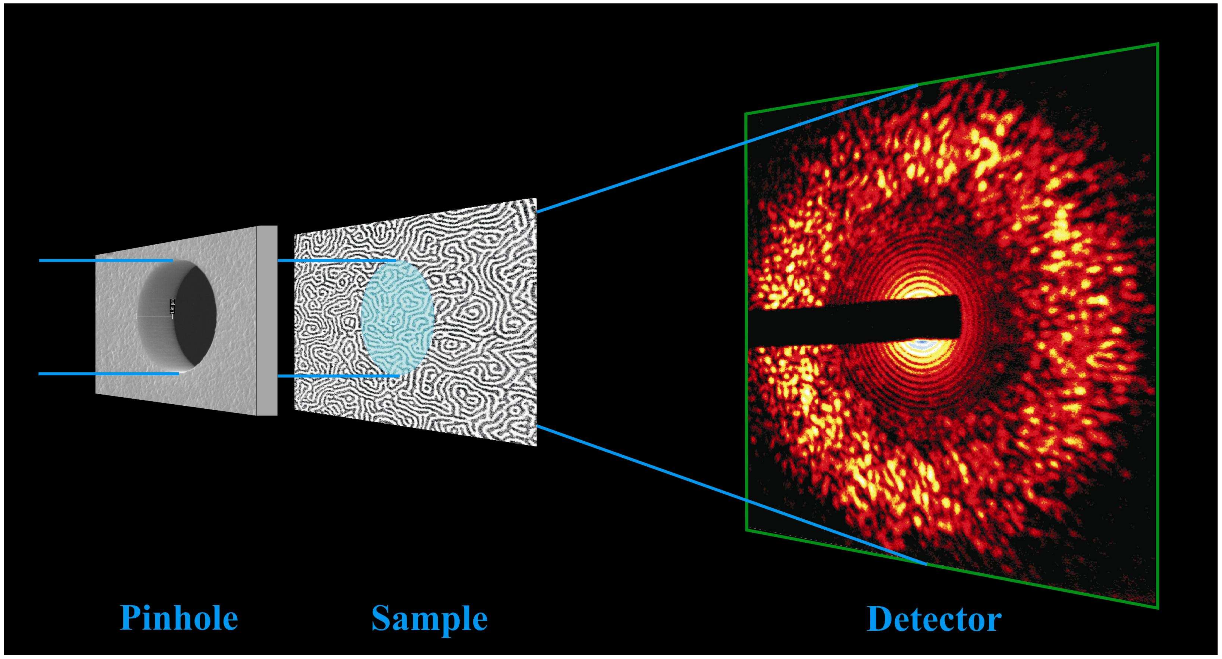
In-line Holography





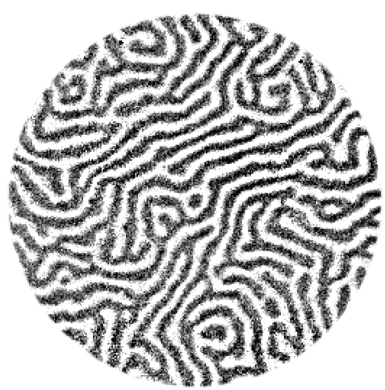
S. Eisebitt et al., PRB 2003

‘Reconstruction’ of a Magnetic Domain Structure



Phase problem can be solved by “oversampling” speckle image

Transmission
X-ray
Microscope



Reconstruction
from
Speckle Intensities

∅ 5 μm
(different areas)

Dynamics and Fluctuations of Phase Transitions

Incoherent SAXS
⇒ Domain Size (T)

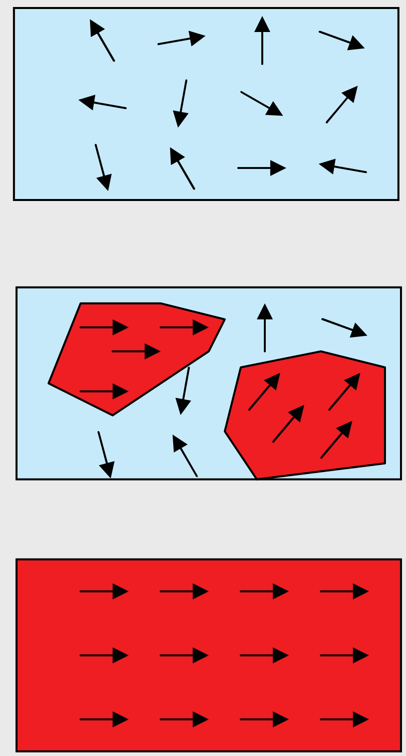
X-ray Photon Correlation Spectr.
⇒ Fluctuation Dynamics (T, t)

Snapshot Imaging
⇒ Correlations

$T > T_c$

$T \approx T_c$

$T < T_c$



Theory Predicts Divergence of Spin Block Size at Phase Transition

Coherence enables Investigation of Fluctuations beyond ‘Statistical Properties’

Summary

• Uniqueness of sample is preserved in coherent x-ray scattering

  • Speckle pattern is fingerprint of scattering object

  • Lensless imaging

  • X-ray correlation spectroscopy

•.LCLS has enough coherent photons per pulse for single shot imaging of magnetic domain structures

• Branchline dedicated to scattering of coherent soft x-rays at ALS (undulator) and SSRL (EPU)