Massachusetts Institute of Technology

Soft X-ray scattering and imaging of quantum electronic solids

Riccardo Comin

Massachusetts Institute of Technology

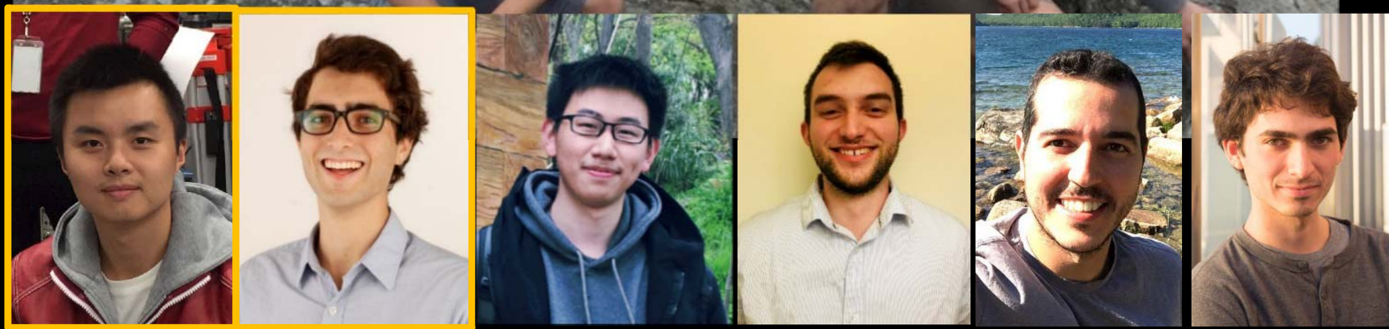
FUSEE workshop

Trieste, 11 Dec 2019

Outline

- Intro:
    - Density-wave phenomena
    - Resonant X-ray scattering
- Coherent soft X-ray imaging:
    - Resonant scanning nanodiffraction: scale-invariant nanoscale magnetic textures in rare earth nickelates
    - Coherent diffractive phase contrast imaging of antiferromagnetic domain textures

MIT Photon Scattering Lab



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scattering.mit.edu

Acknowledgments

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BROOKHAVEN NATIONAL LABORATORY

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Funding

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

CIQM CENTER for INTEGRATED QUANTUM MATERIALS

ALFRED P. SLOAN FOUNDATION 1934

NSF

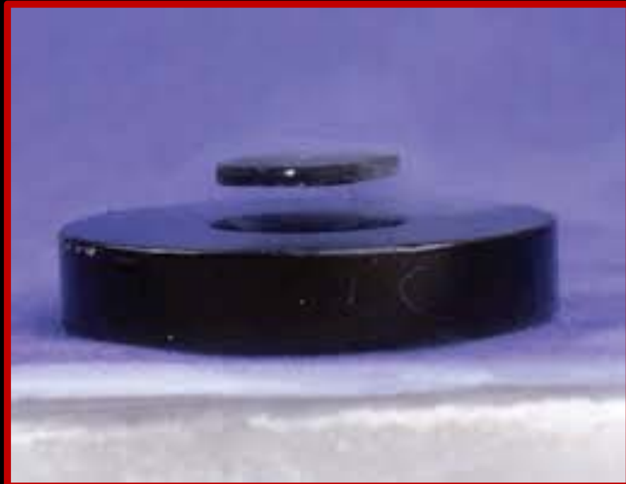
Density-wave phenomena in strongly-correlated matter

Strongly-interacting quantum matter

Fundamental building blocks

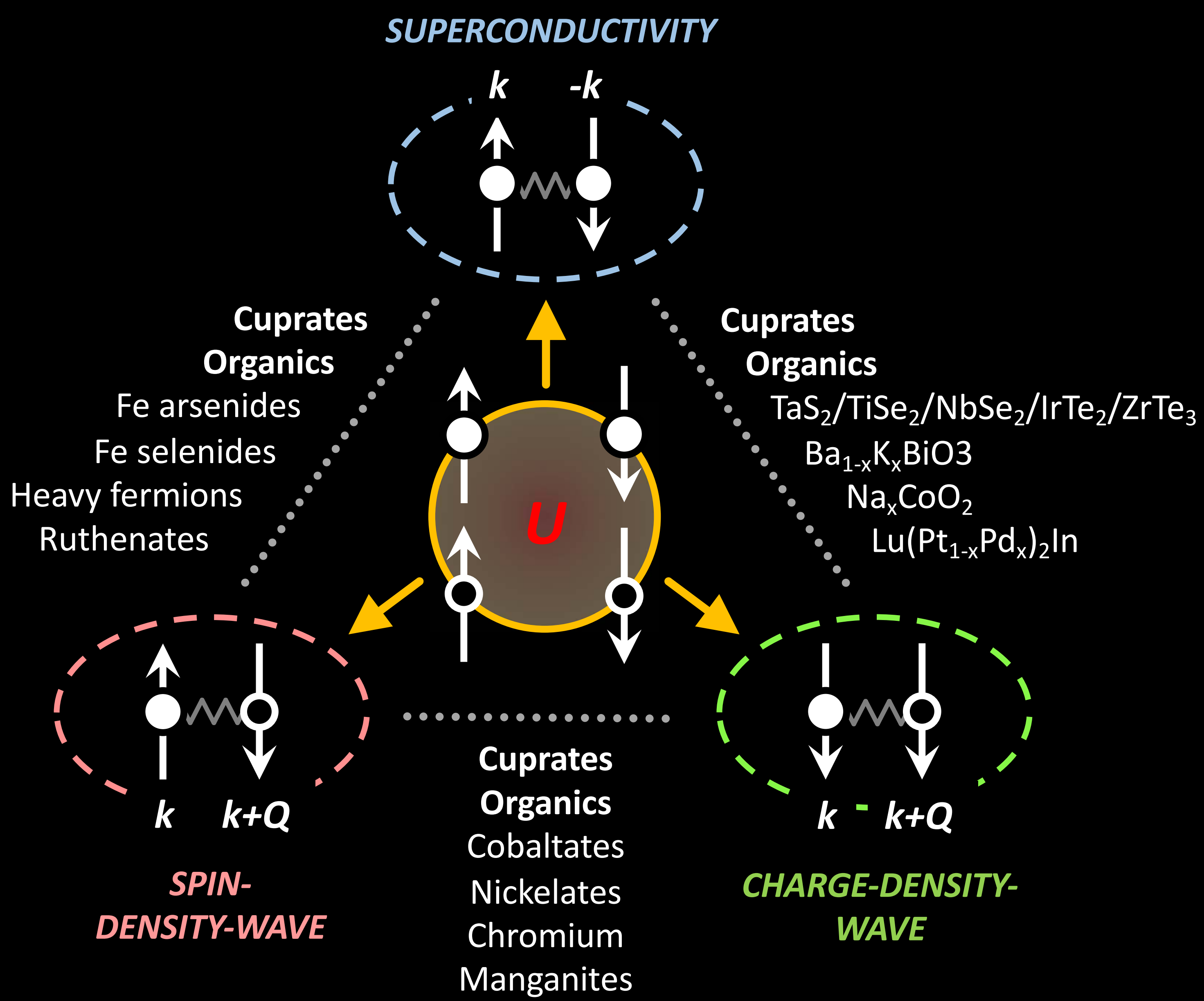
Interactions

Many-body phenomena

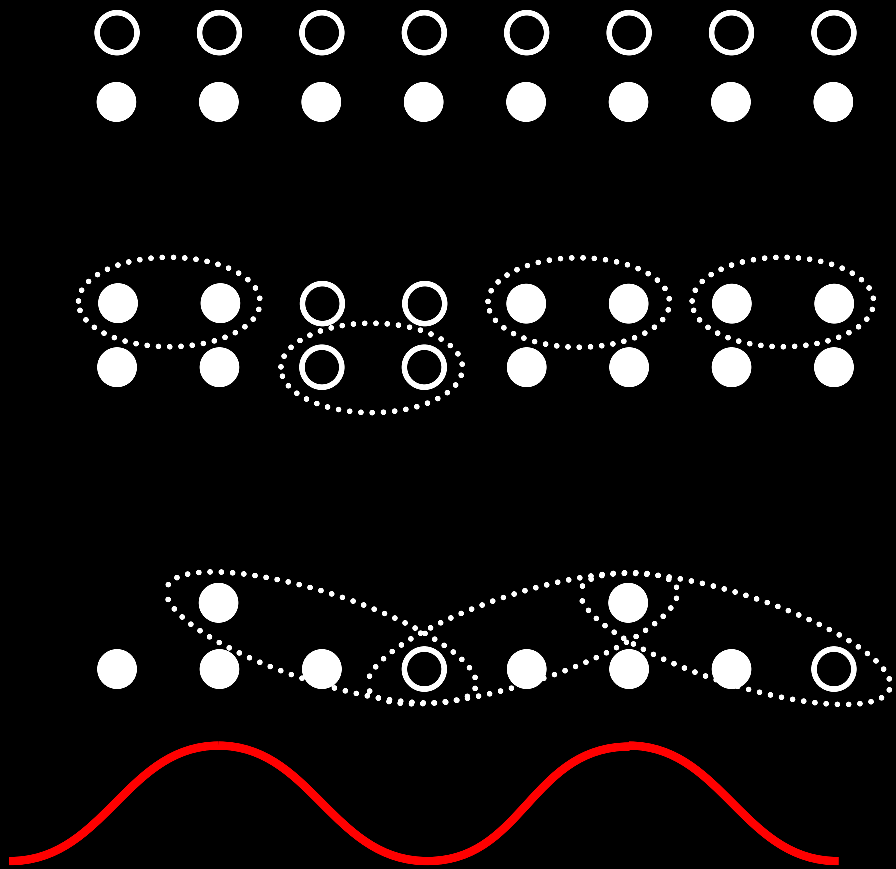


"More is different" (P.W. Anderson, 1972):
Interactions foster new organizing principles and collective behavior in many-body systems

Density-wave phases



Instabilities of a strongly-interacting electron system



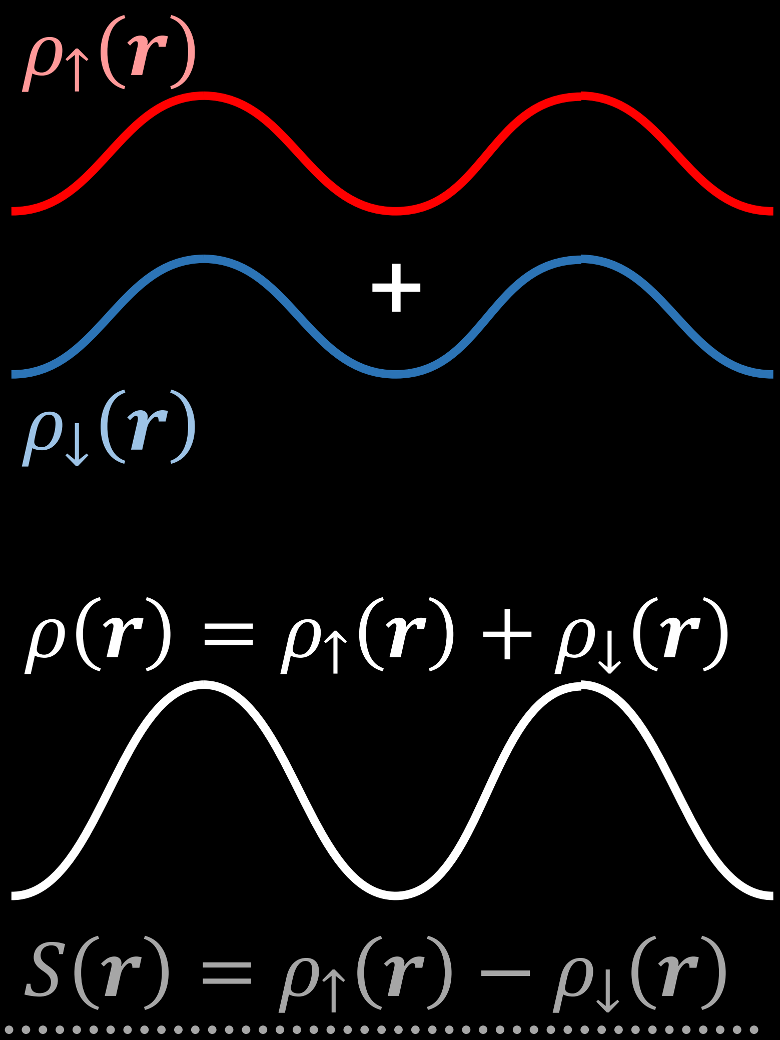
Mott-Hubbard ground state

Superconductivity (Cooper pairing)

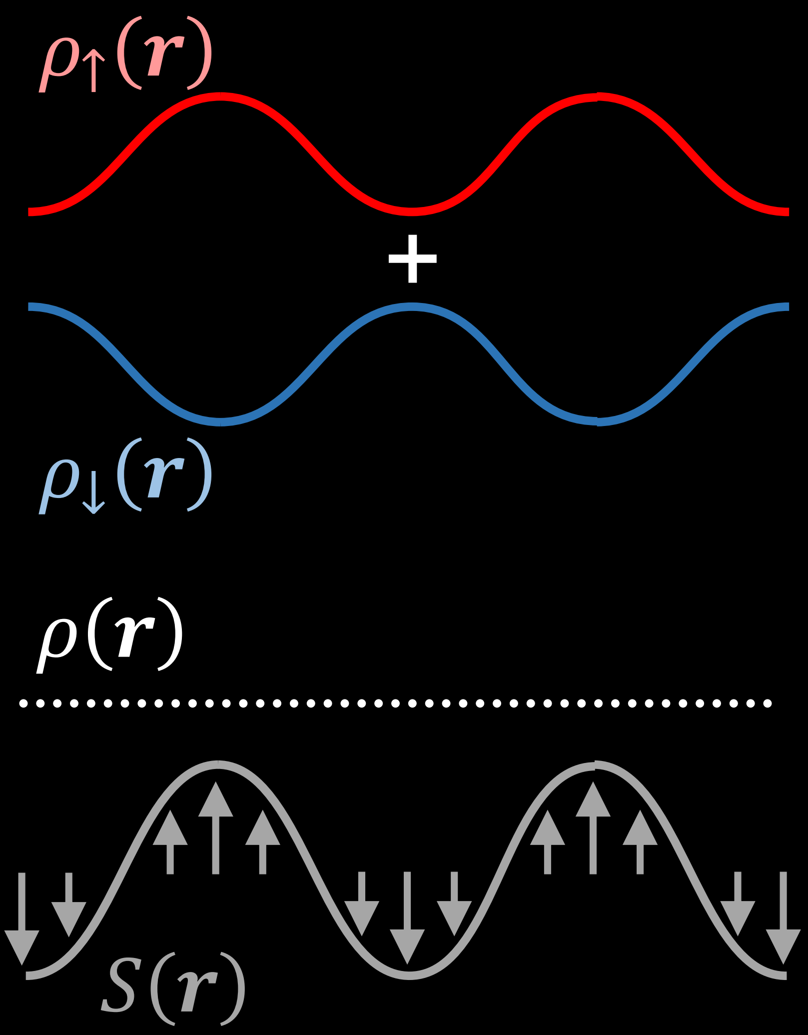
Density-wave (particle-hole pairing)

$\rho(\boldsymbol{r})$

Density-wave phases

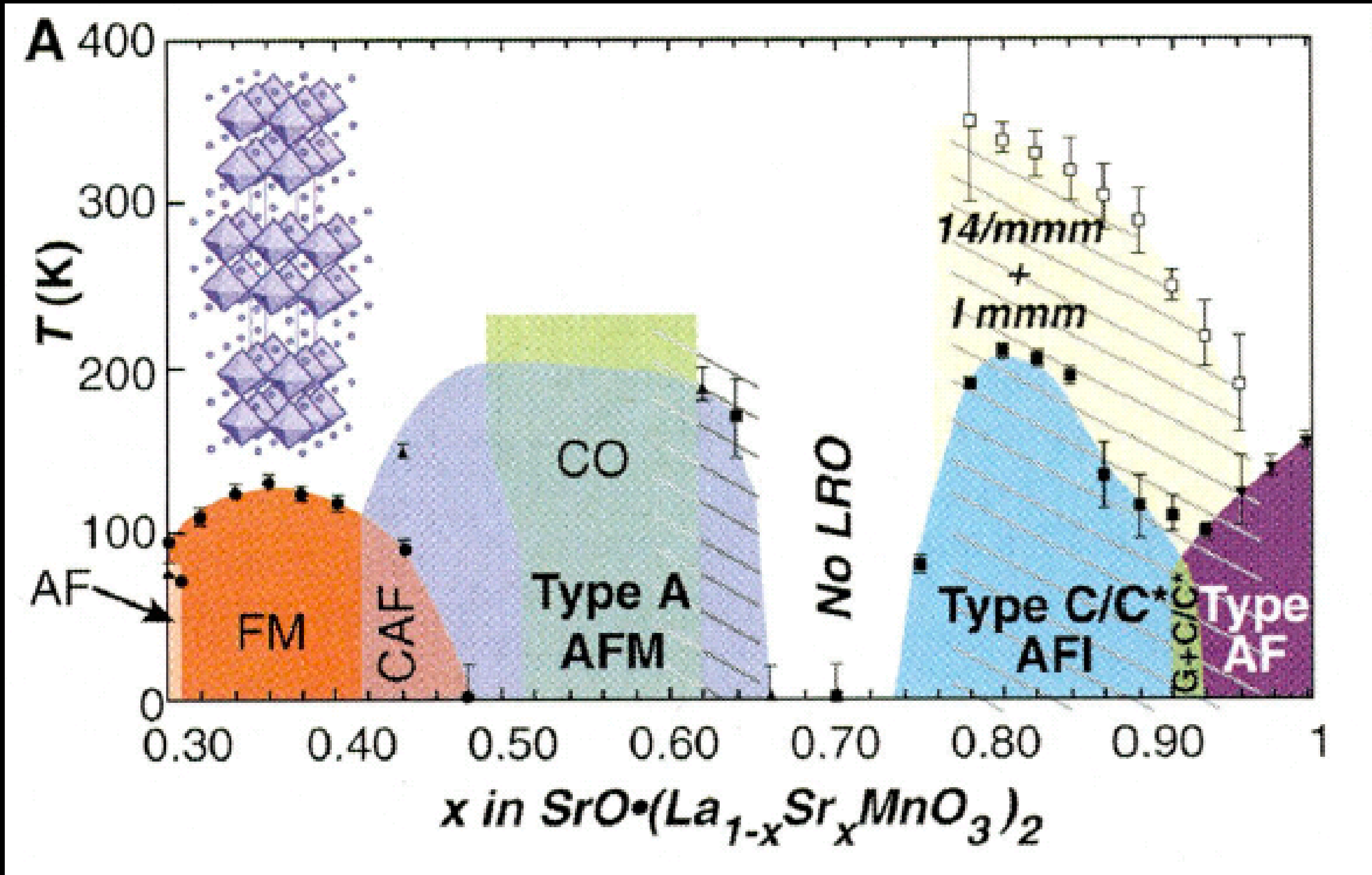


Charge-density-wave



Spin-density-wave

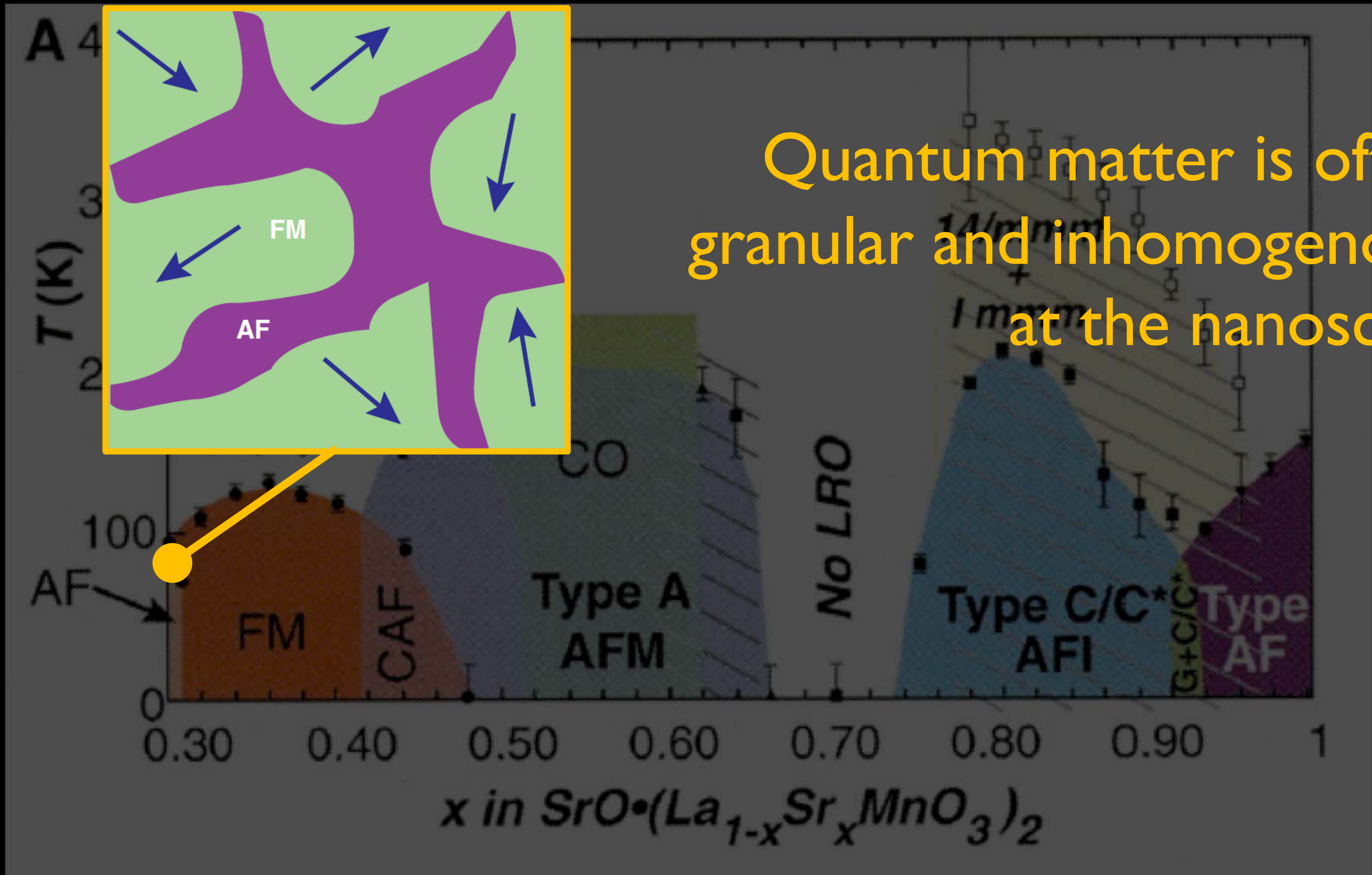
Strongly-interacting quantum matter



E. Dagotto, *Science* **309**, 257 (2005)

Strongly-interacting quantum matter

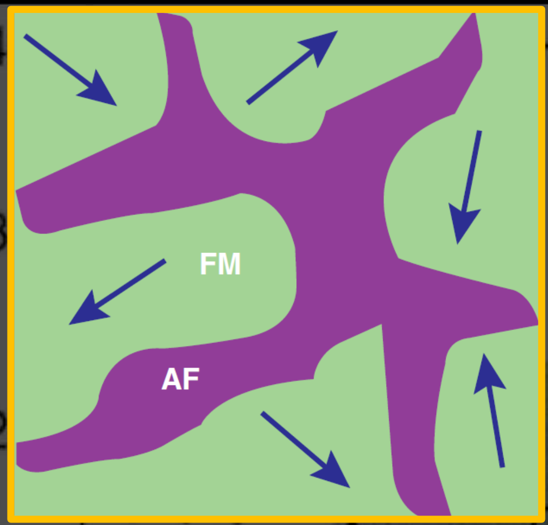
Phase segregation



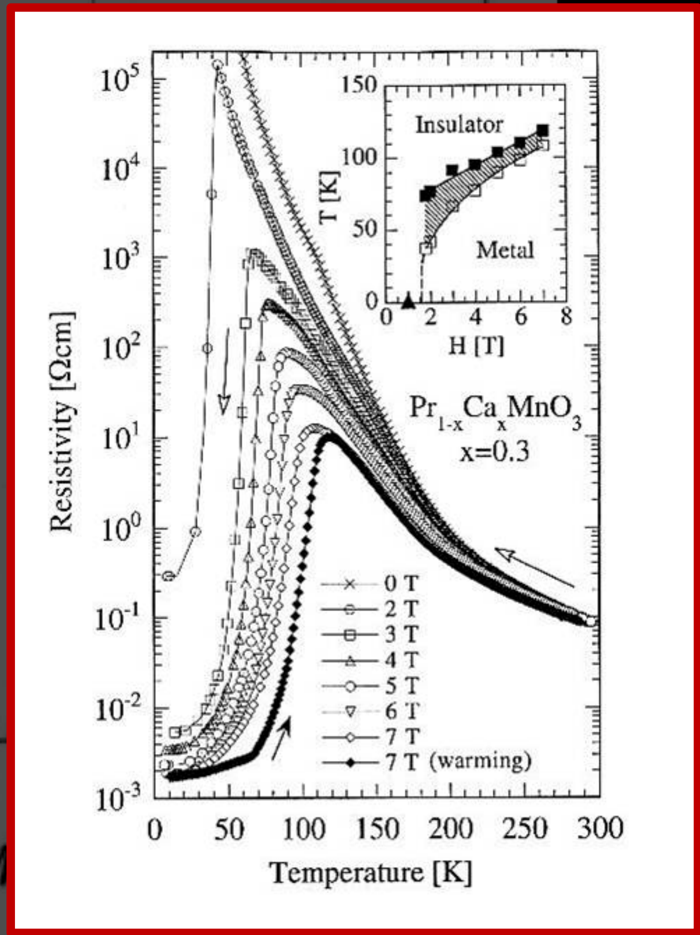
Quantum matter is often granular and inhomogenous at the nanoscale

Strongly-interacting quantum matter

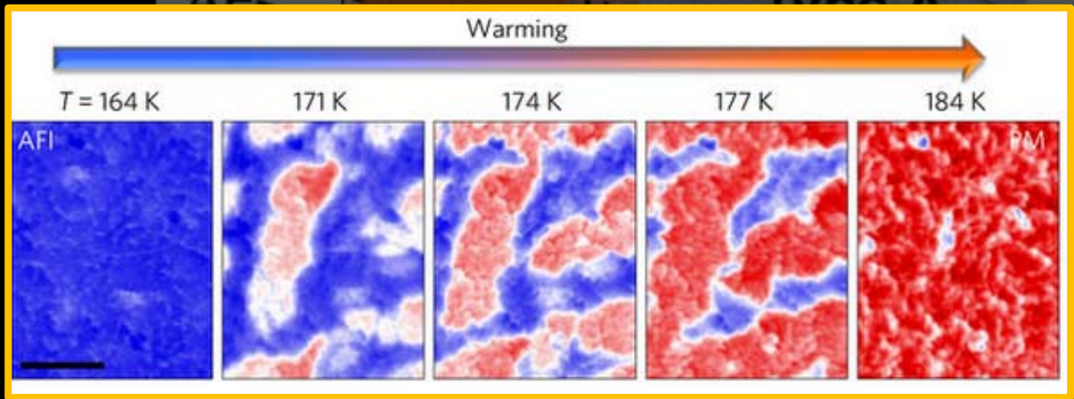
Phase segregation



Colossal resistive switching



Percolation phenomena

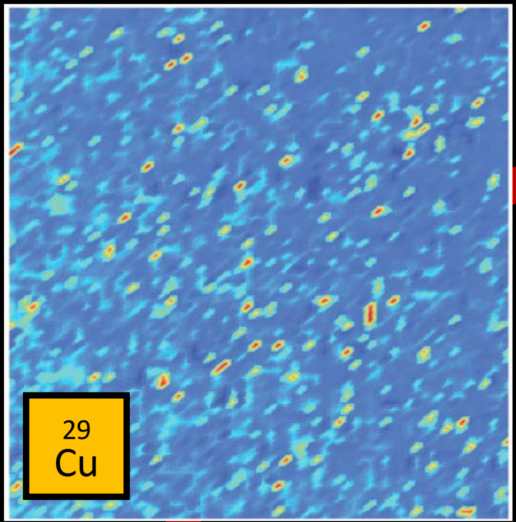


A. S. McLeod, *Nat. Physics* **13**, 80 (2017)

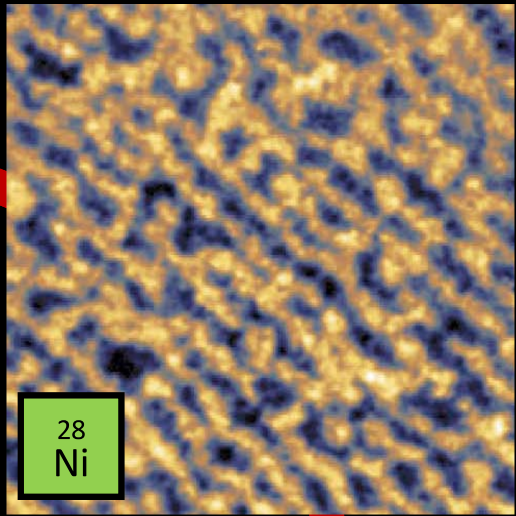
Y. Tomioka, *et al.*, *Physics of Manganites* (1999)

Strongly-interacting quantum matter

Charge order



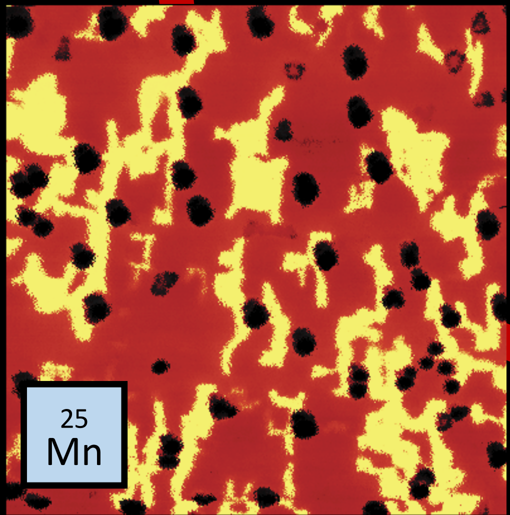
Metal-insulator transition



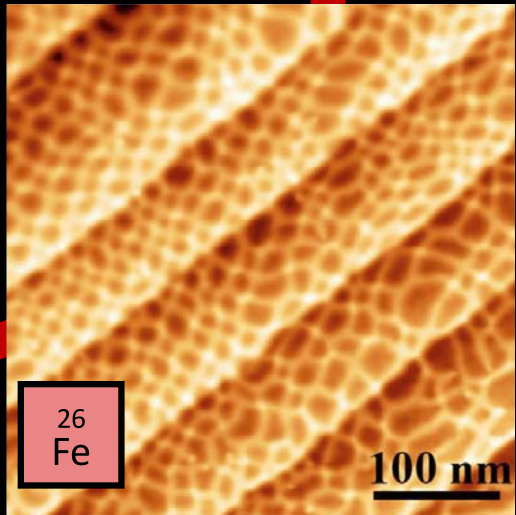
Emergent nanoscale textures

⇕

Macroscale quantum phenomena



Spin order



Superconductivity

Soft X-ray scattering probes of density waves

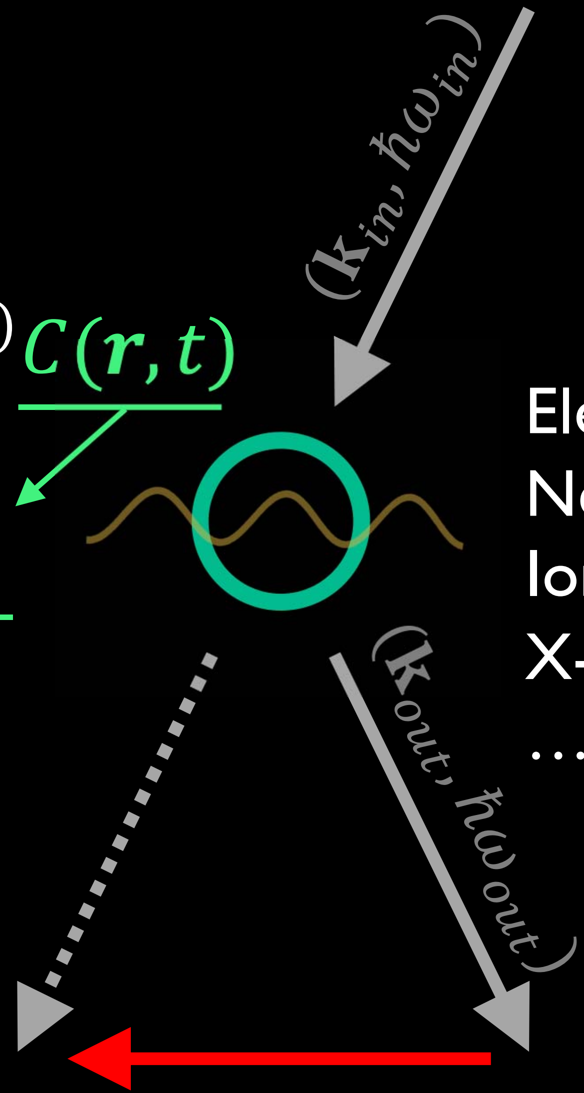
Scattering probes

Structure factor

$$S(\boldsymbol{Q}, \omega) =$$

$$= \int dt\, d\boldsymbol{r}\, e^{i(\boldsymbol{Q}\cdot\boldsymbol{r} - \omega t)} C(\boldsymbol{r}, t)$$

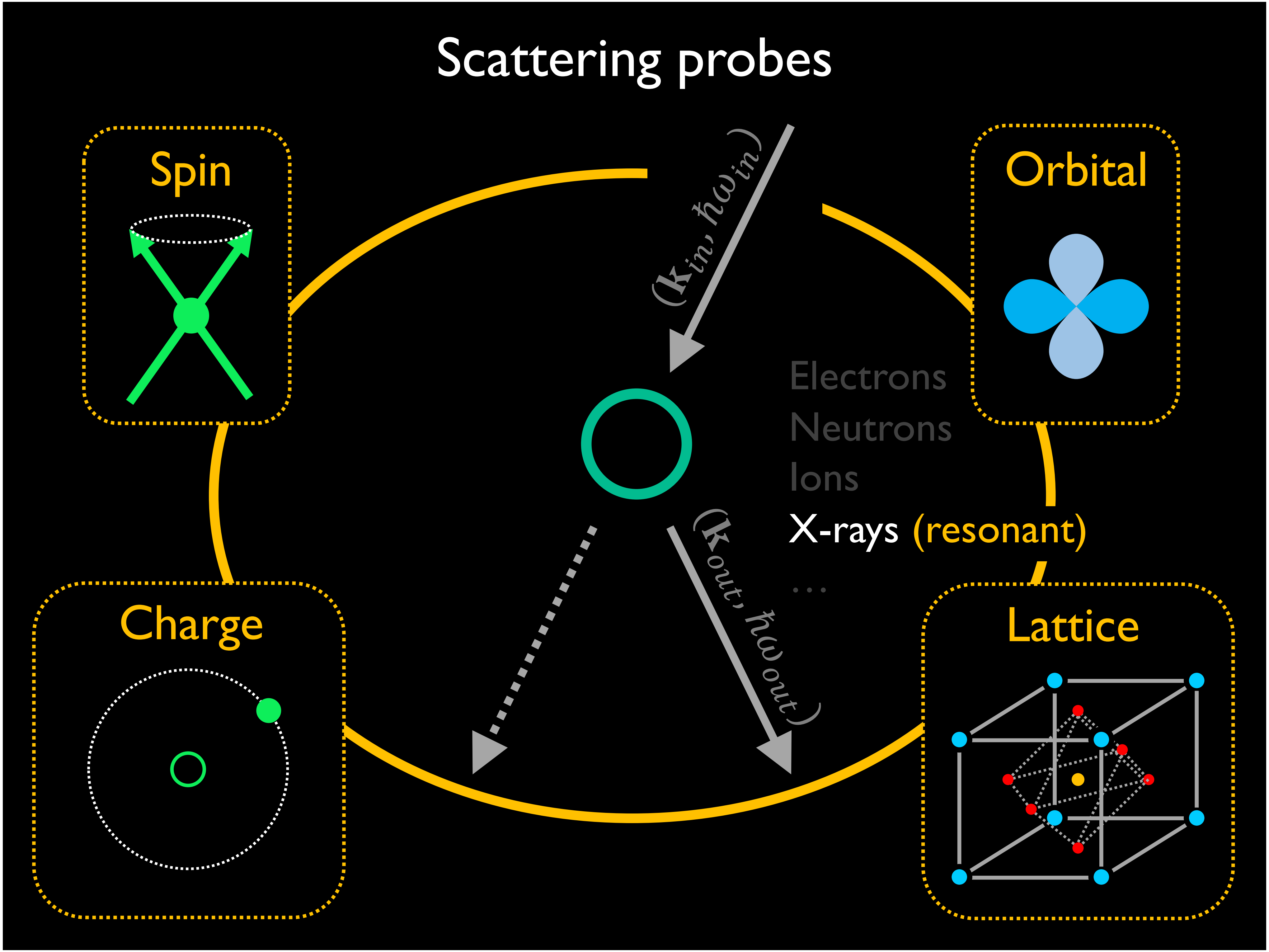
Correlation function (density-density, spin-spin, …)



Electrons
Neutrons
Ions
X-rays
…

Momentum $\mathbf{Q} = \mathbf{k}_{in} - \mathbf{k}_{out}$

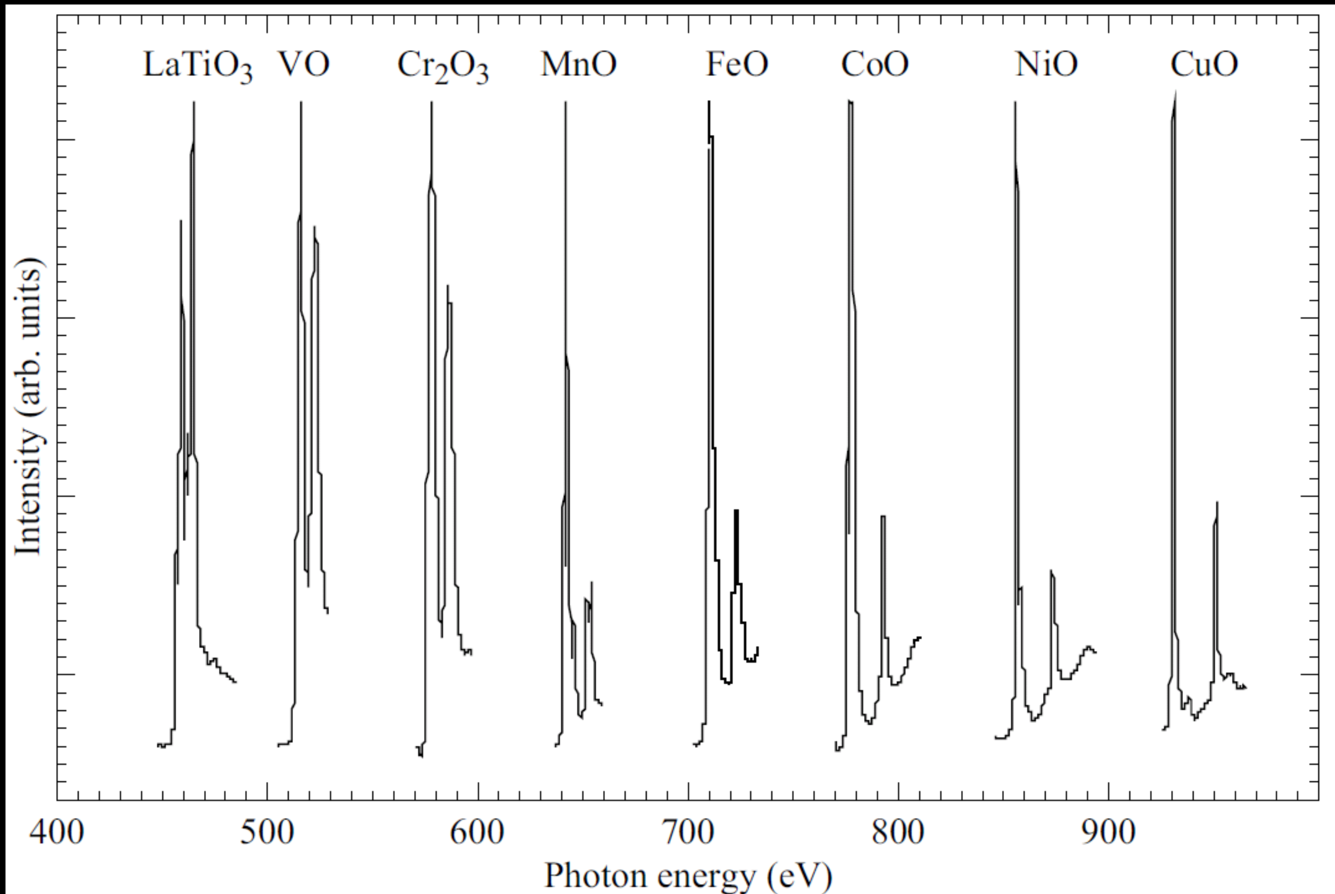
Energy $\omega = \omega_{in} - \omega_{out}$



Scattering probes
Spin
Orbital
Charge
Lattice
$(\mathbf{k}_{in}, \hbar\omega_{in})$
$(\mathbf{k}_{out}, \hbar\omega_{out})$
Electrons
Neutrons
Ions
X-rays (resonant)
...

Resonant scattering

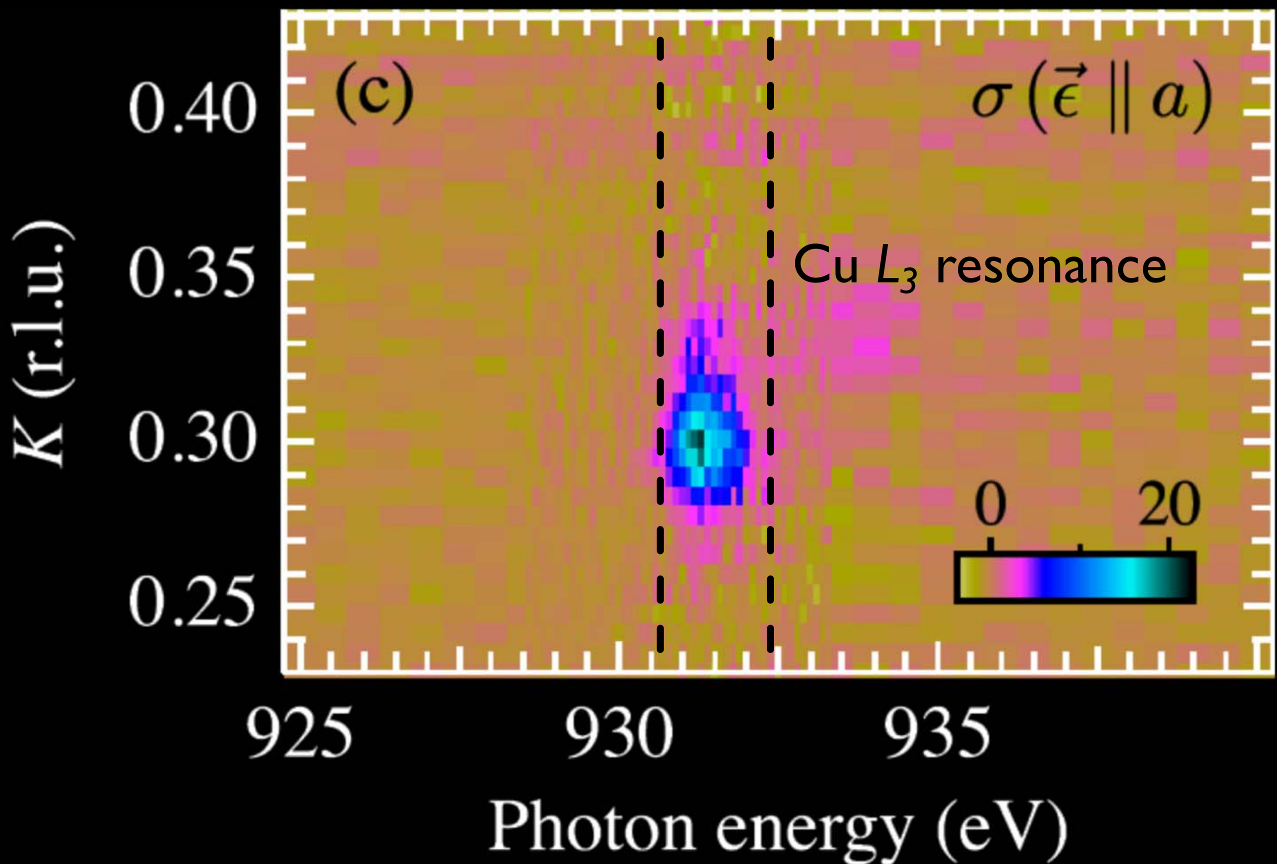
22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu

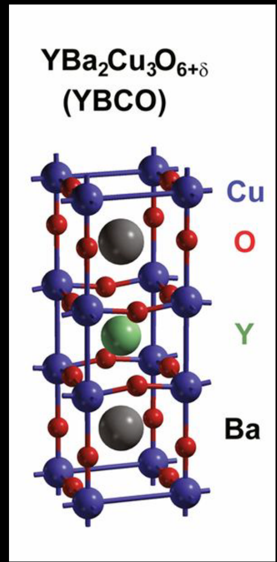


Strongly energy-dependent X-ray scattering amplitude

Resonant scattering

Charge order in copper oxide high-temperature superconductors

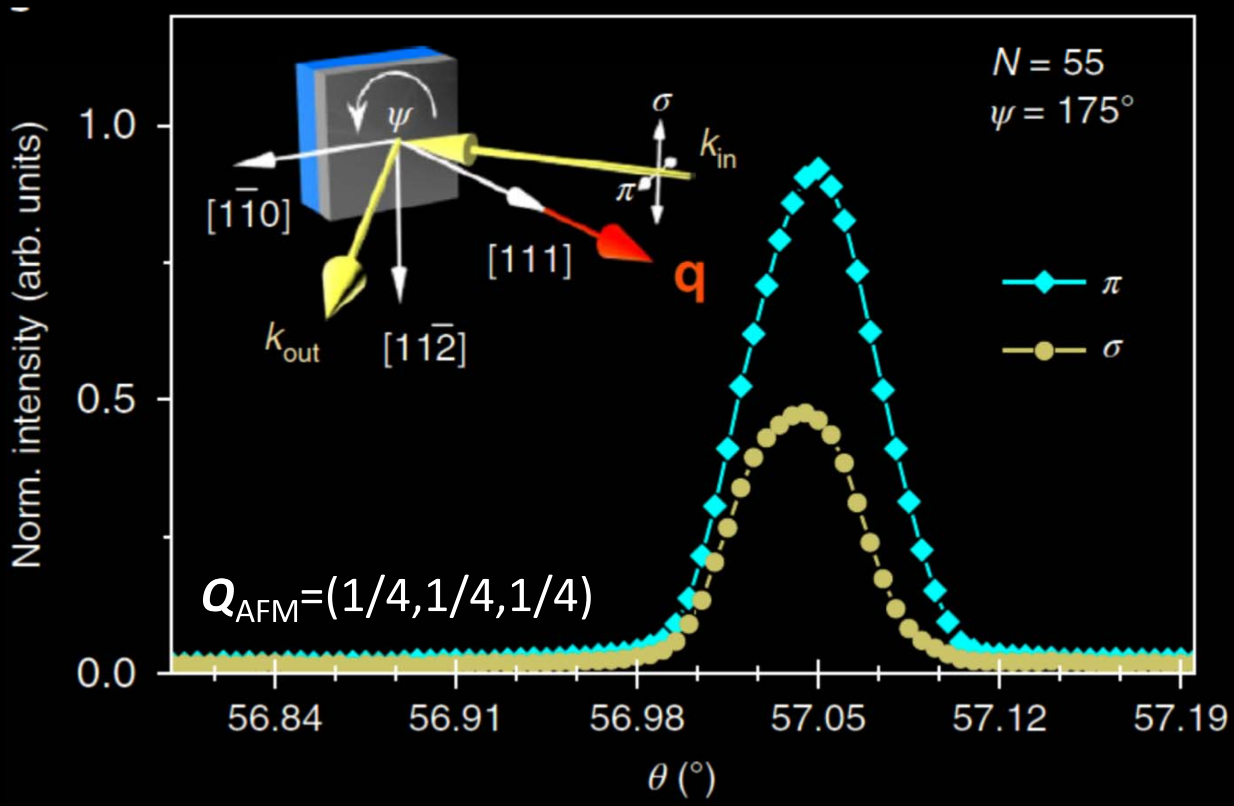


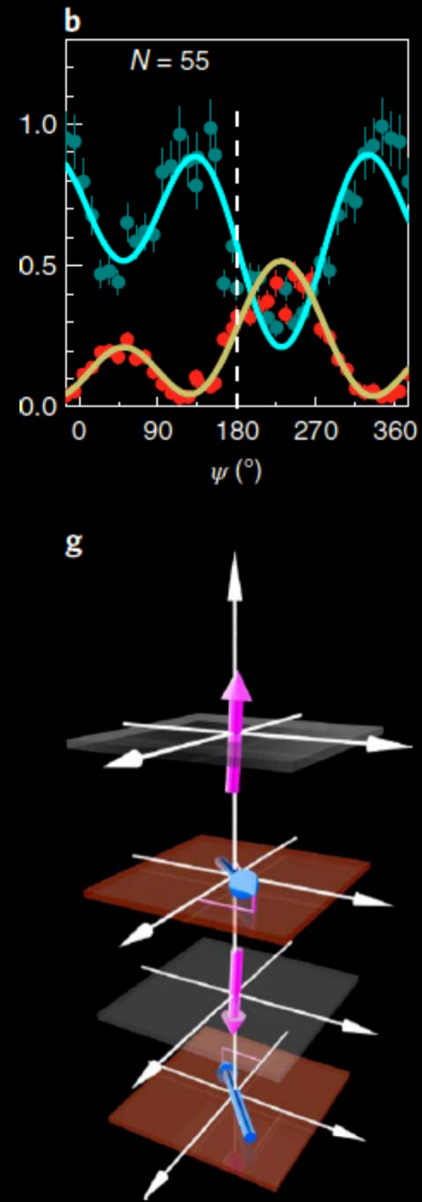


A. Achkar *et al.*, *Phys. Rev. Lett.* **109**, 167001 (2012)

Resonant scattering

Antiferromagnetic order in rare earth nickelates

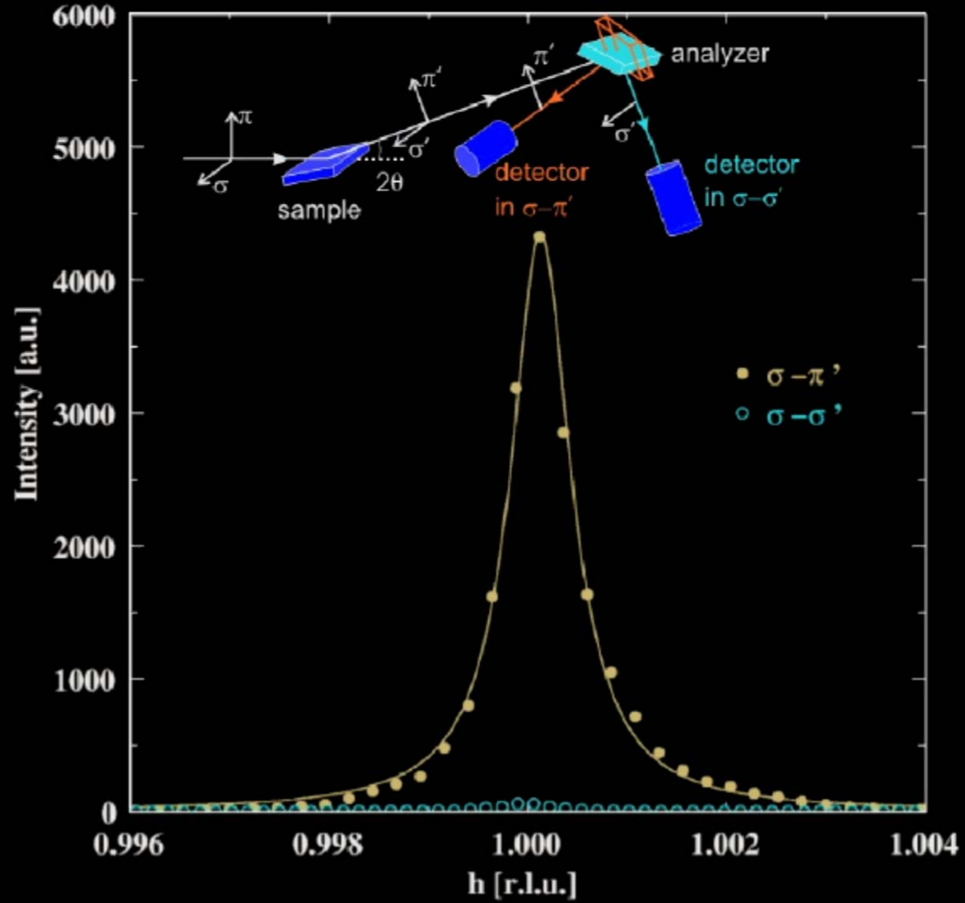


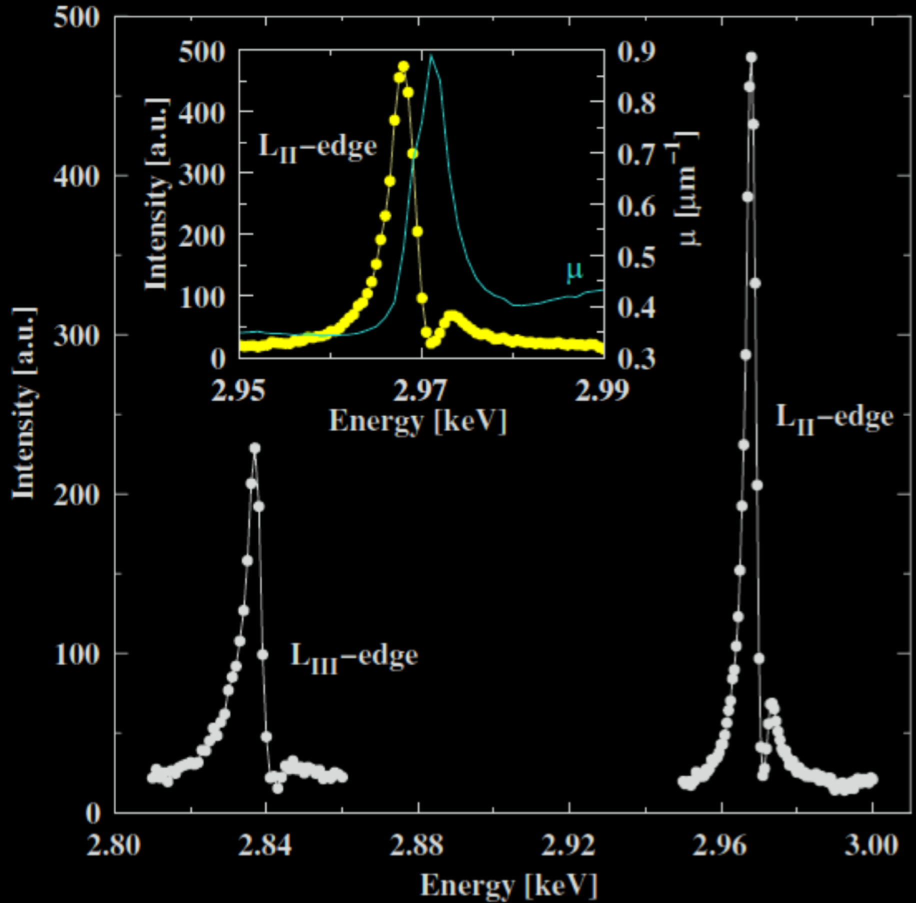


M. Hepting *et al.*, *Nature Physics* **14**, 1097 (2018)

Resonant scattering

Orbital (+ magnetic) ordering in layered ruthenate Ca_2RuO_4



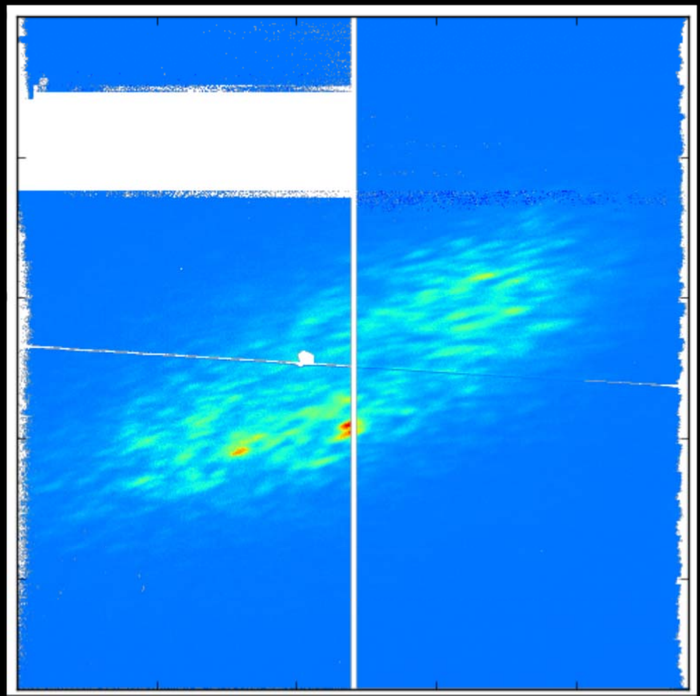


I. Zegkinoglou *et al.*, *Phys. Rev. Lett.* **95**, 136401 (2005)

Nanoscale electronic textures and coherent X-ray imaging

Electronic orders at the nanoscale

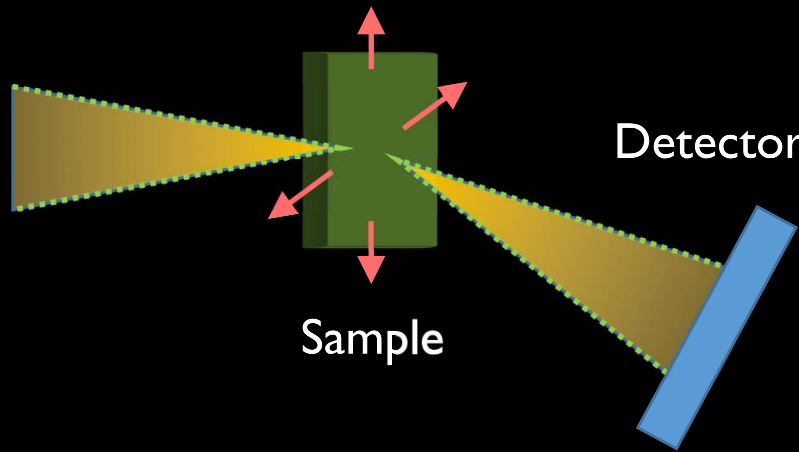
Reciprocal space
(scattering)



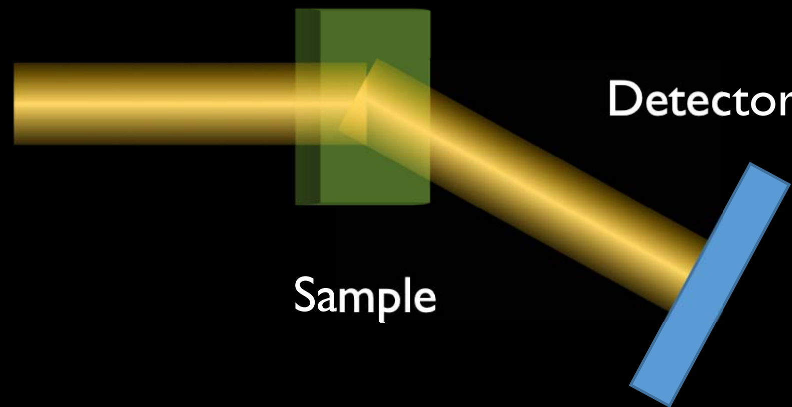
Recover real-space information

HOW

Scanning nanodiffraction (50 nm)



Full-field lensless imaging (10 nm)



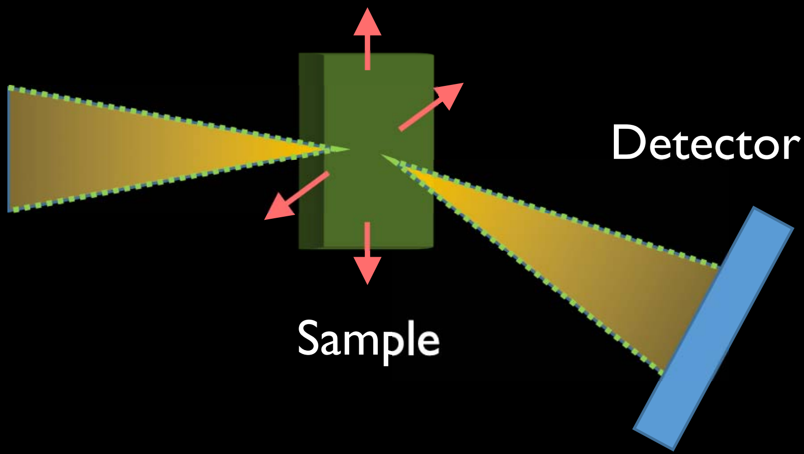
Electronic orders at the nanoscale

WHY

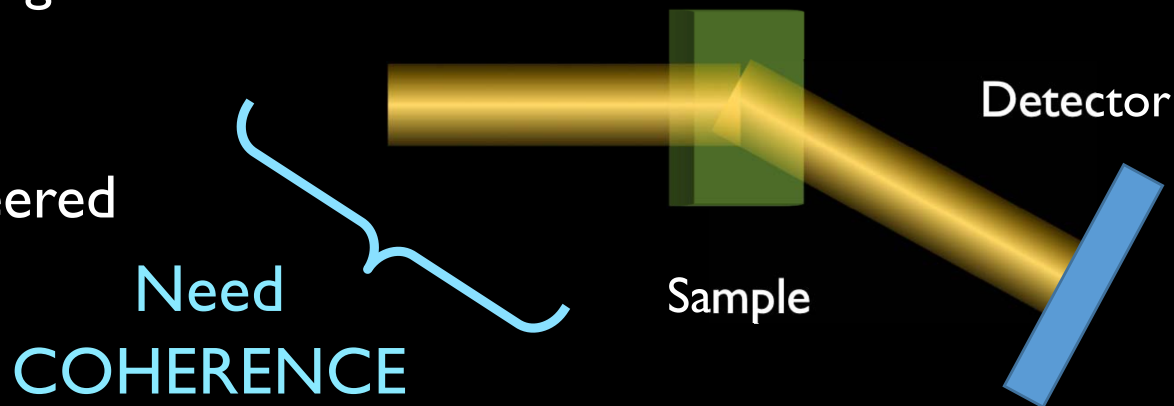
- Nanoscale granularity:
  - Intrinsic (phase competition & segregation)
  - Extrinsic (disorder, defects, doping, …)
- Scale-invariant phenomena:
  - Extended range of length scales (10 nm to 10 μm)
- Emergent physics at the edge or boundary:
  - Domain walls; lateral interfaces; nanoengineered structures

HOW

Scanning nanodiffraction (50 nm)



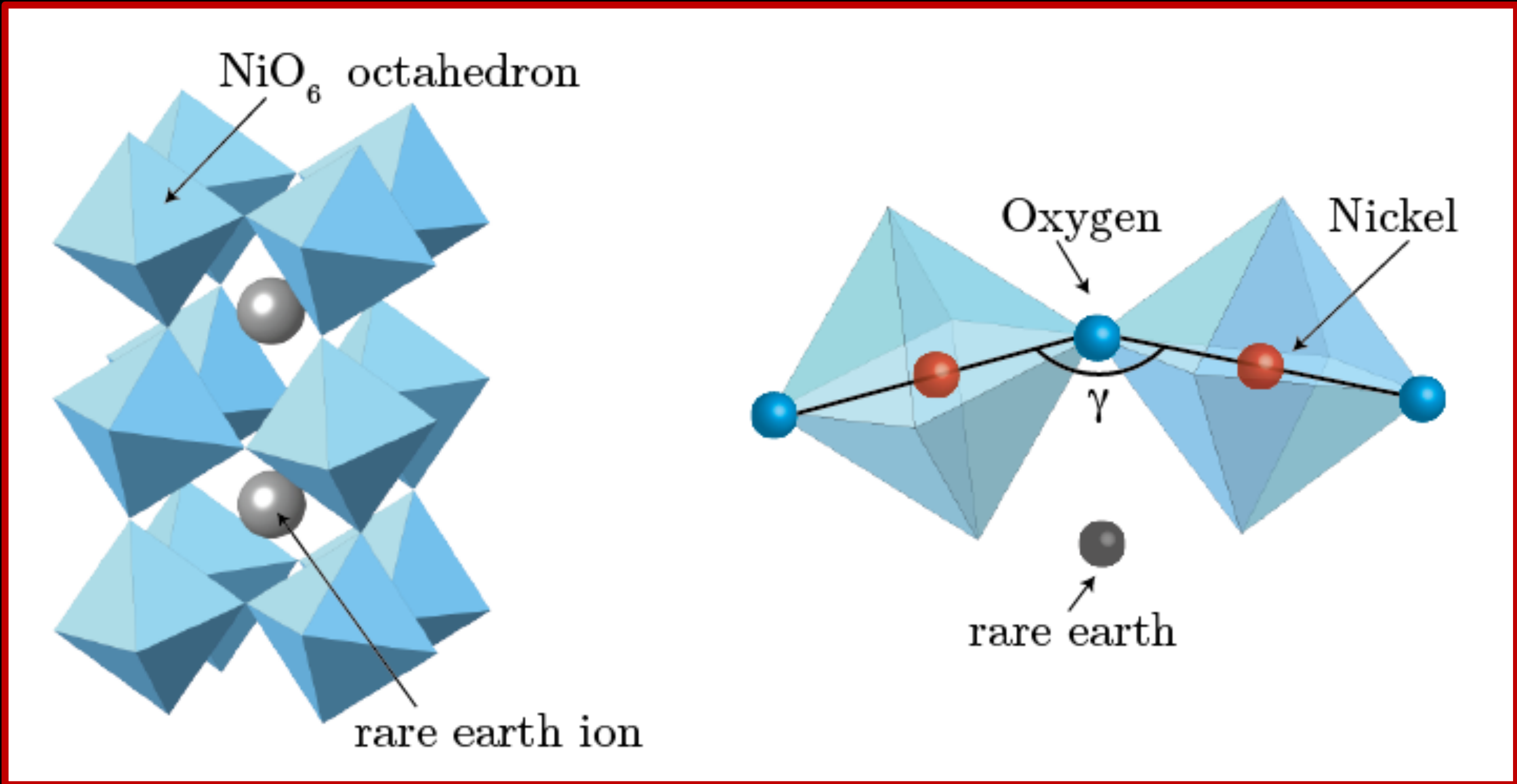
Full-field lensless imaging (10 nm)



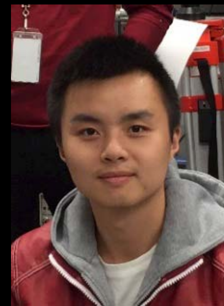
Spin-density-waves and scale-invariant spin textures in nickel oxides

Rare earth nickelates

$RNiO_3$



Jiarui Li

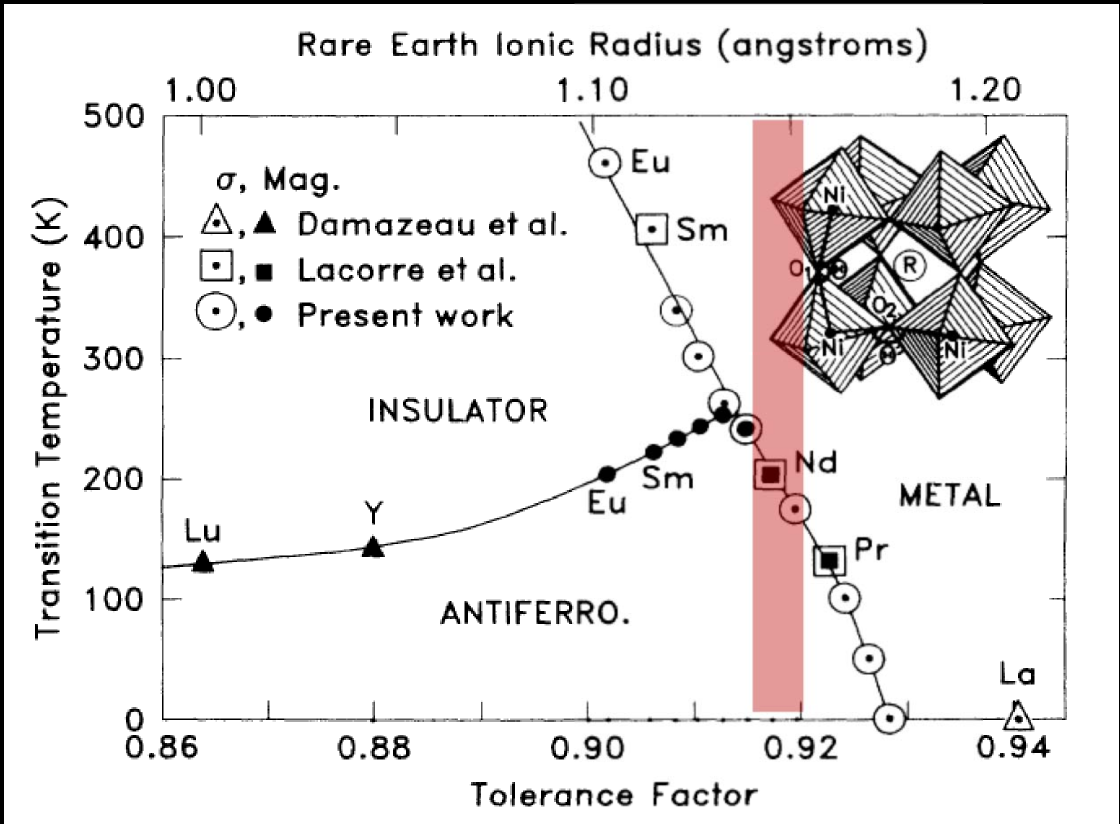


Johnny Pelliciari

J. Li, …, RC, *Nature Comm.* **10**, 4568 (2019)

Rare earth nickelates

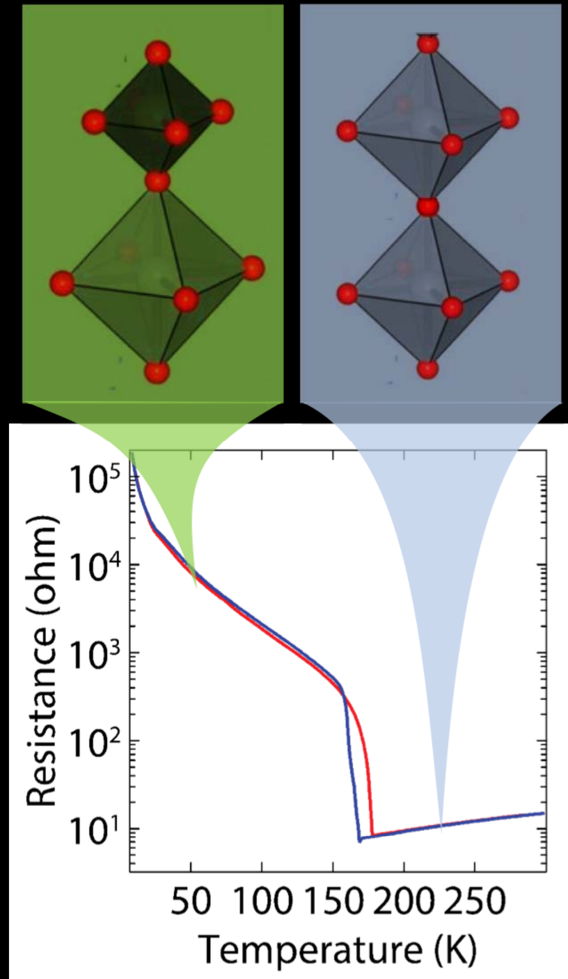
Torrance *et al.* PRB 1992



← Quantum tuning parameter →

*P*2$_1$/*n* (insulator)

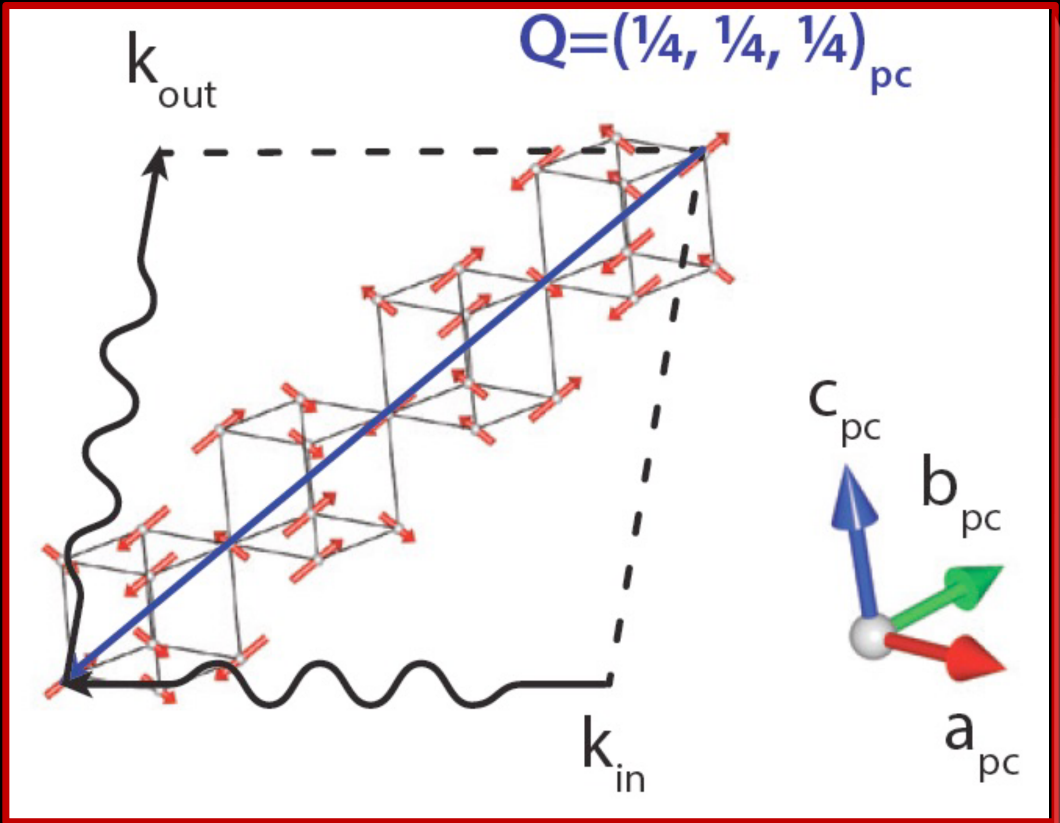
Pbnm (metal)



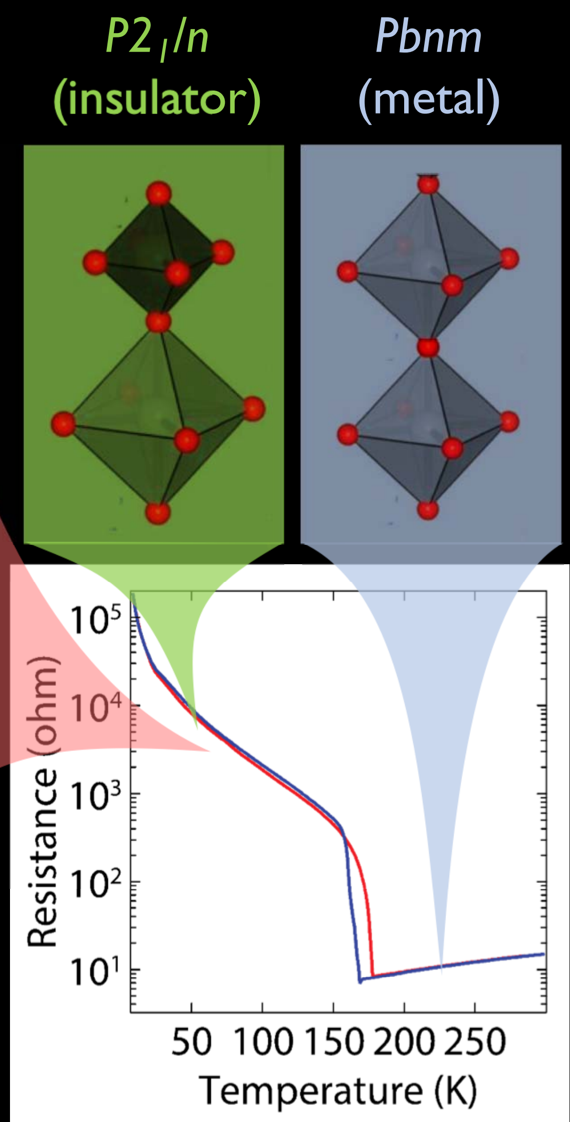
Metal insulator transition

J. Li, …, RC, *Nature Comm.* **10**, 4568 (2019)

Rare earth nickelates



Magnetic order



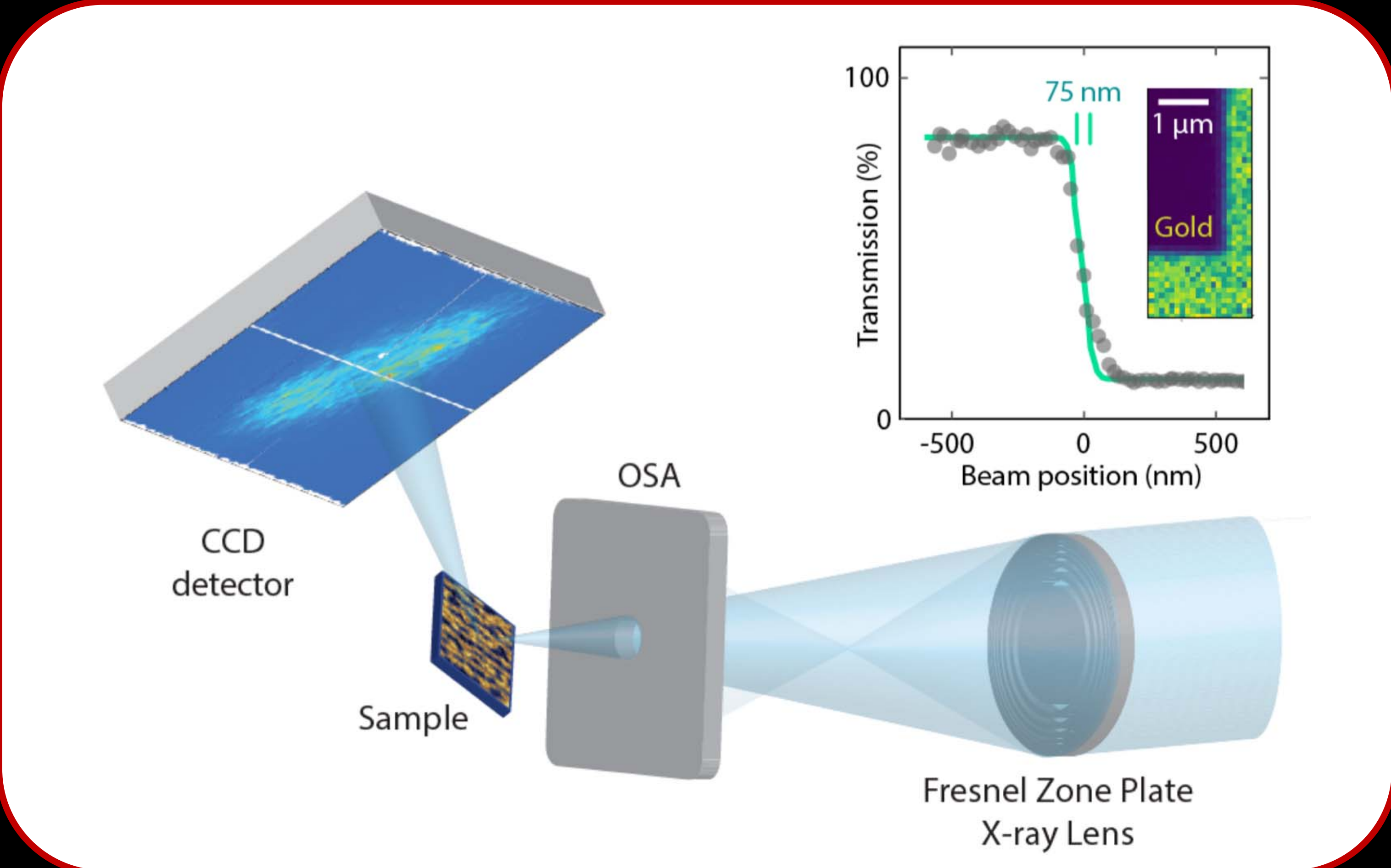
Metal insulator transition

Goal: map the charge and spin textures across the metal-insulator/Neel transition

J. Li, …, RC, *Nature Comm.* **10**, 4568 (2019)

Spin textures in nickelates

Resonant scattering at the nanoscale

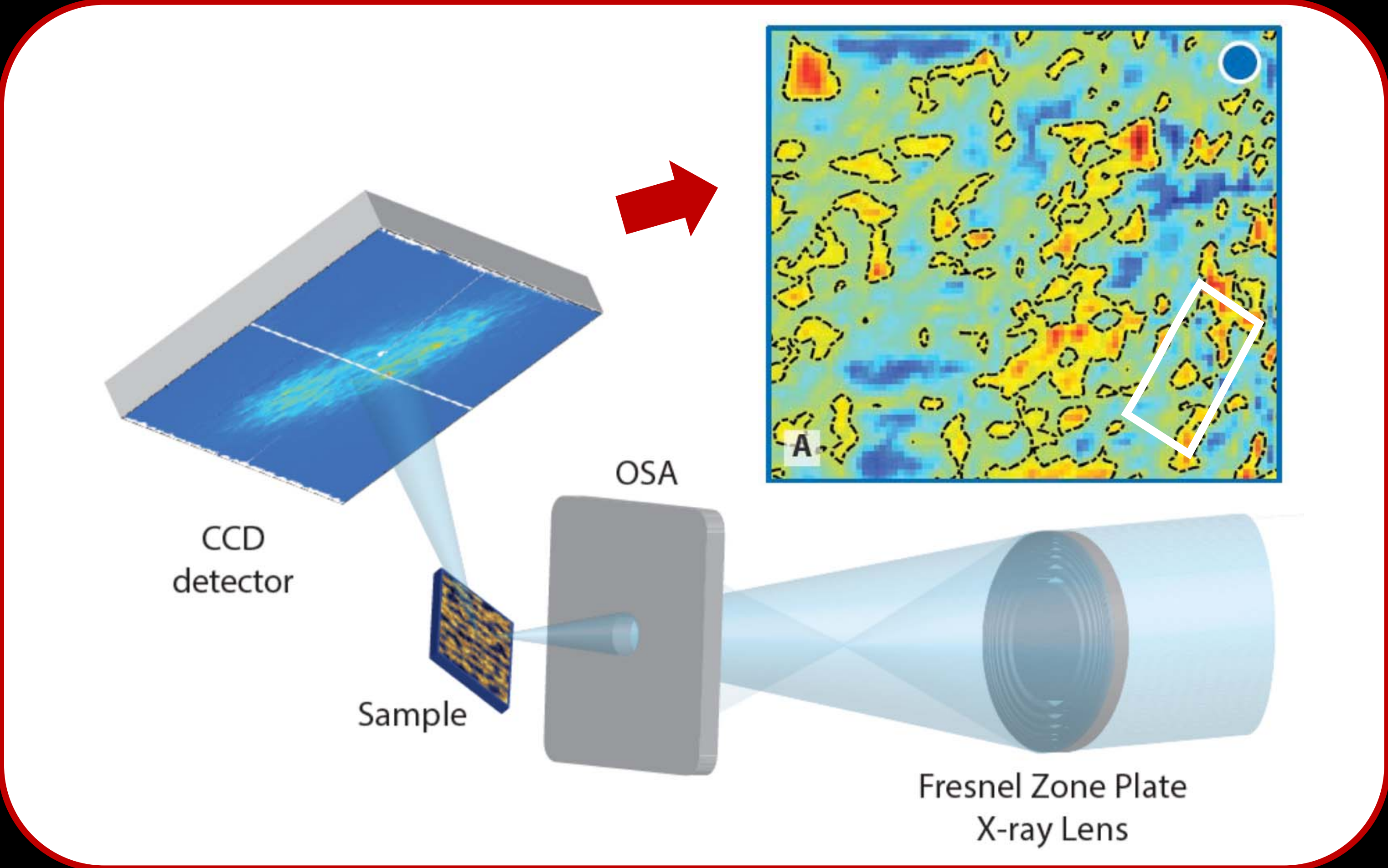


BROOKHAVEN NATIONAL LABORATORY National Synchrotron Light Source II

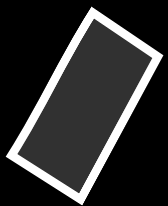
CSX-1 (23-ID-1)
Coherent Soft X-ray Scattering

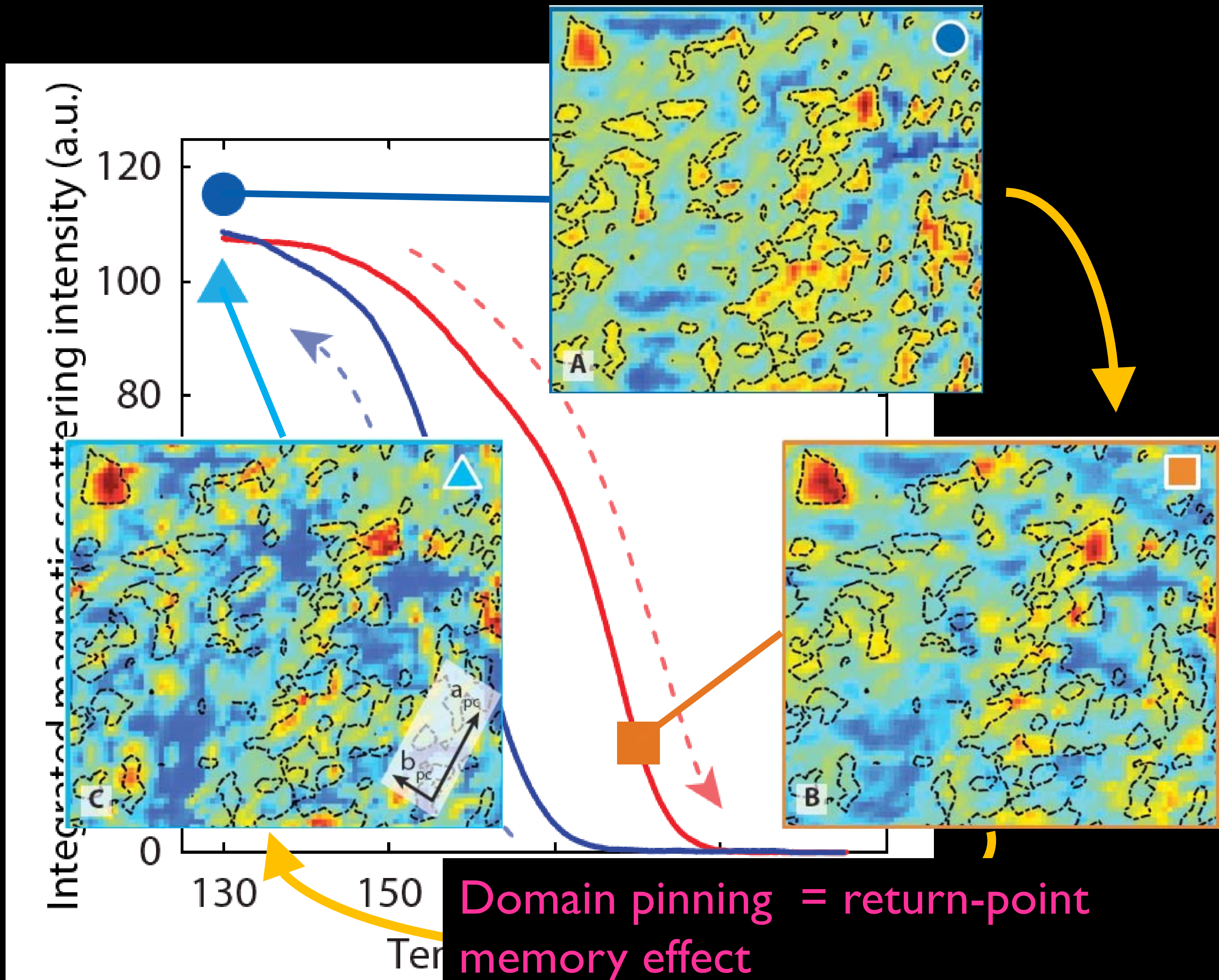
Spin textures in nickelates

Resonant scattering at the nanoscale



Spin textures in nickelates



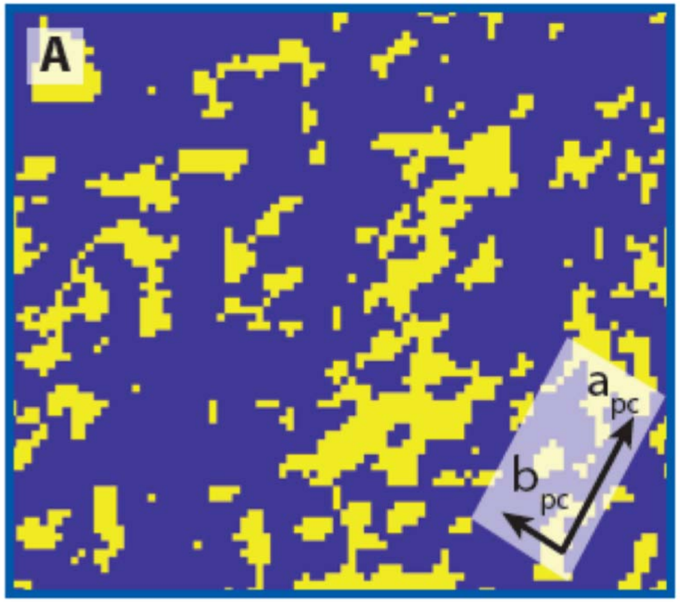


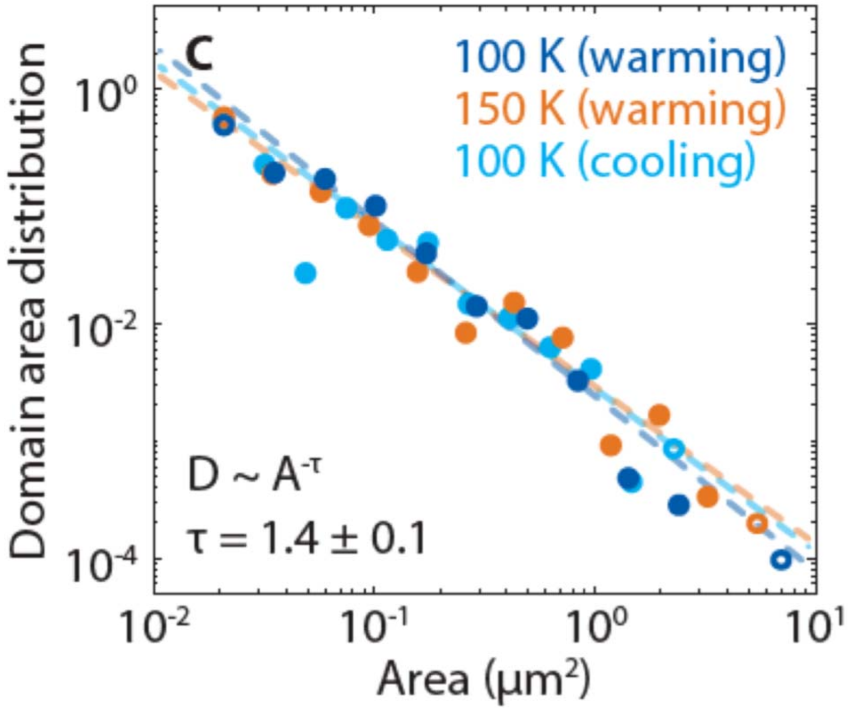
Domain pinning = return-point memory effect

J. Li, …, RC, *Nature Comm.* **10**, 4568 (2019)

Spin textures in nickelates

Domain map

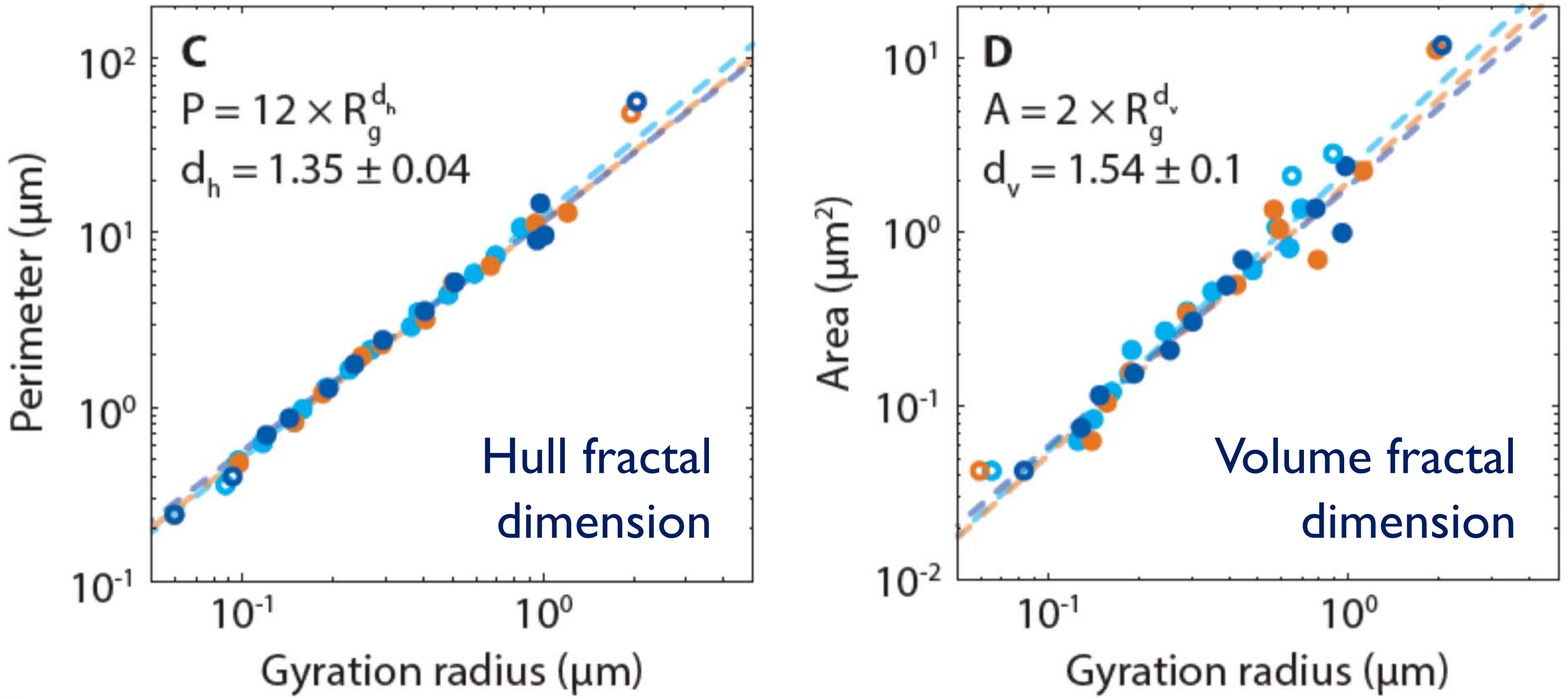




Scale-invariant (power-law) domain distributions

J. Li, …, RC, *Nature Comm.* **10**, 4568 (2019)

Spin textures in nickelates

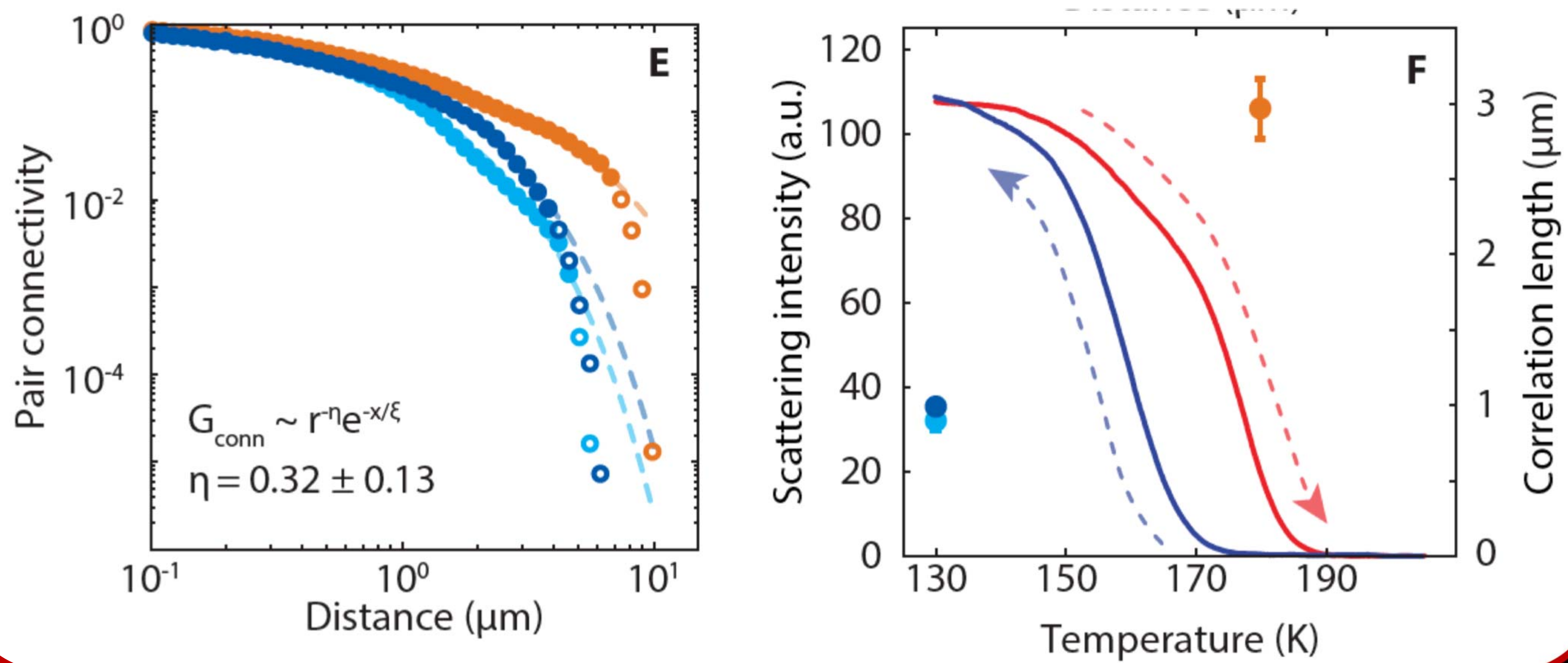


Non-Euclidean scaling between geometrical descriptors

Fractal magnetic texture

J. Li, …, RC, *Nature Comm.* **10**, 4568 (2019)

Spin textures in nickelates



Increasing pair connectivity correlation length
near the Neel transition

J. Li, …, RC, *Nature Comm.* **10**, 4568 (2019)

Resonant coherent diffractive imaging at 4th generation X-ray facilities

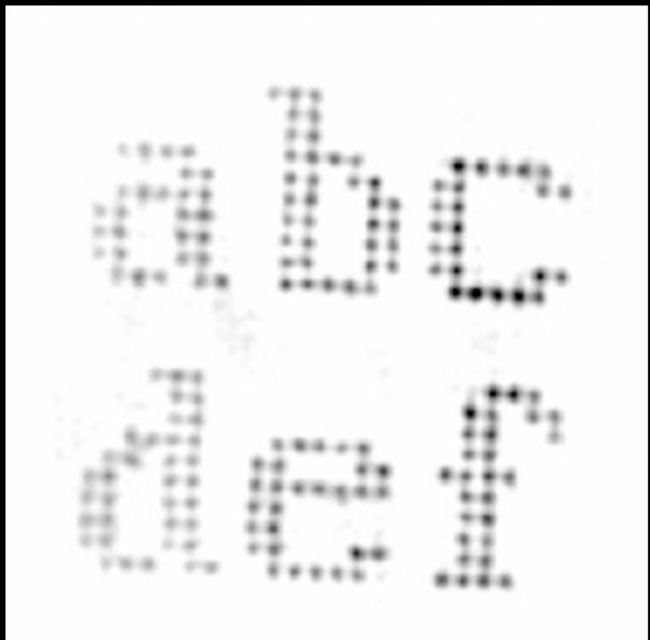
Coherent Lensless Imaging

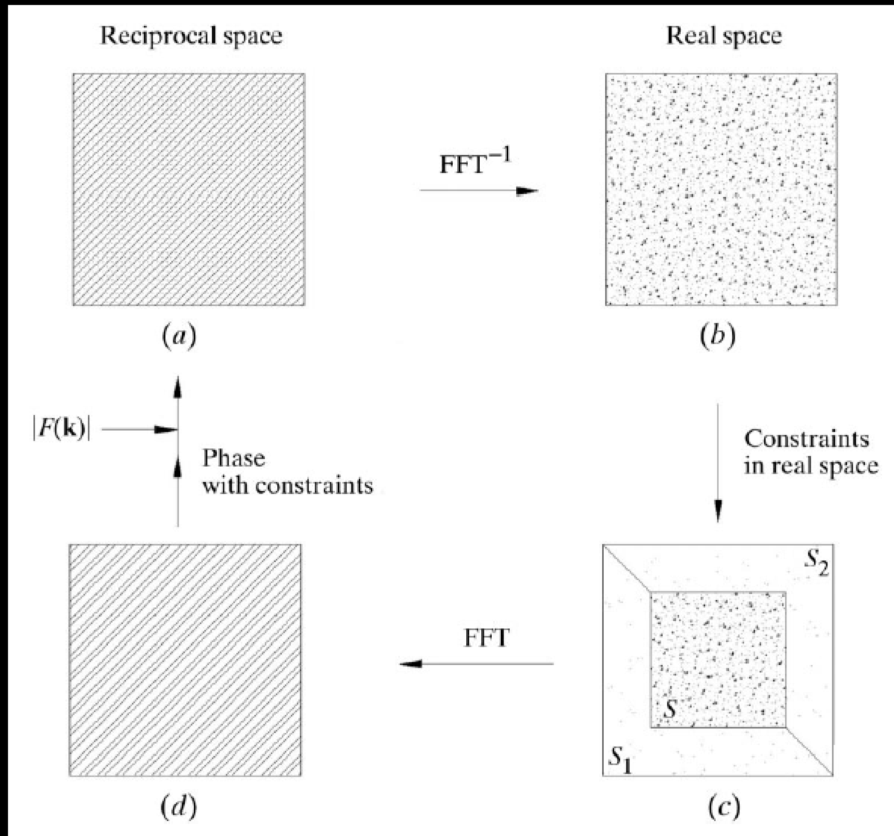
Extending the methodology of X-ray crystallography to allow imaging of micrometre-sized non-crystalline specimens

Jianwei Miao*, Pambos Charalambous†, Janos Kirz* & David Sayre*‡

On possible extensions of X-ray crystallography through diffraction-pattern oversampling

J. Miao*† and D. Sayre‡





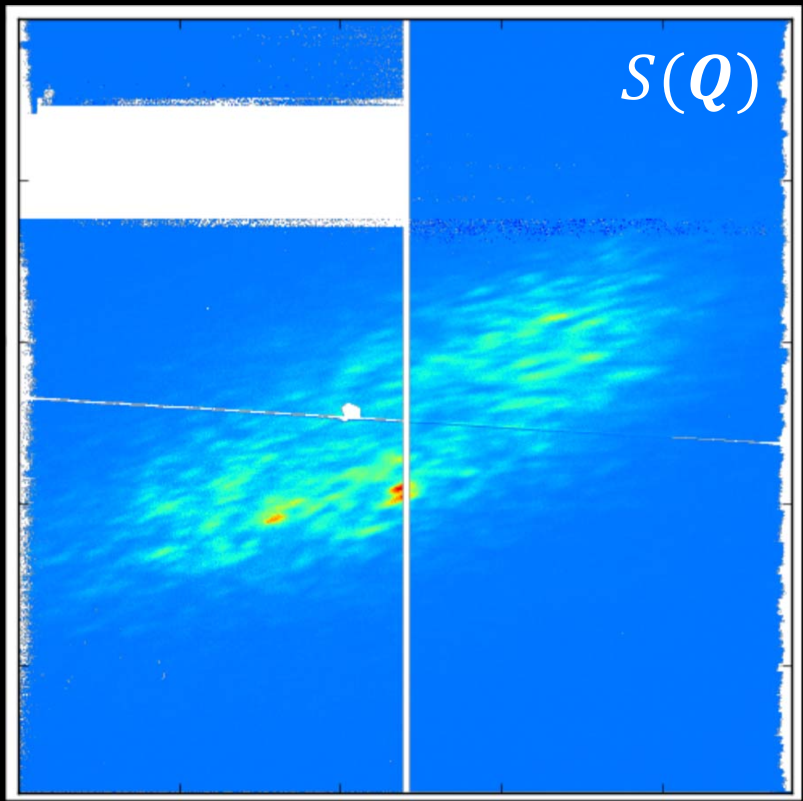
J. Miao, *et al.*, *Nature* **400**, 342 (1999)

J. Miao & D. Sayre, *Acta Cryst.* **A56**, 596 (2000)

D. Sayre, *Acta Cryst.* **5**, 843 (1952)

Coherent Lensless Imaging

RECIPROCAL SPACE



Coherent magnetic Bragg diffraction

$$S(\boldsymbol{Q}) = \left|\tilde{f}(\boldsymbol{Q})\right|^2$$

$$\tilde{f}(\boldsymbol{Q}) = \sqrt{S(\boldsymbol{Q})} \cdot \exp[i\phi(\boldsymbol{Q})]$$

From measurement

We need to recover the phases of the exit waves

$$\tilde{f}(\boldsymbol{r})$$

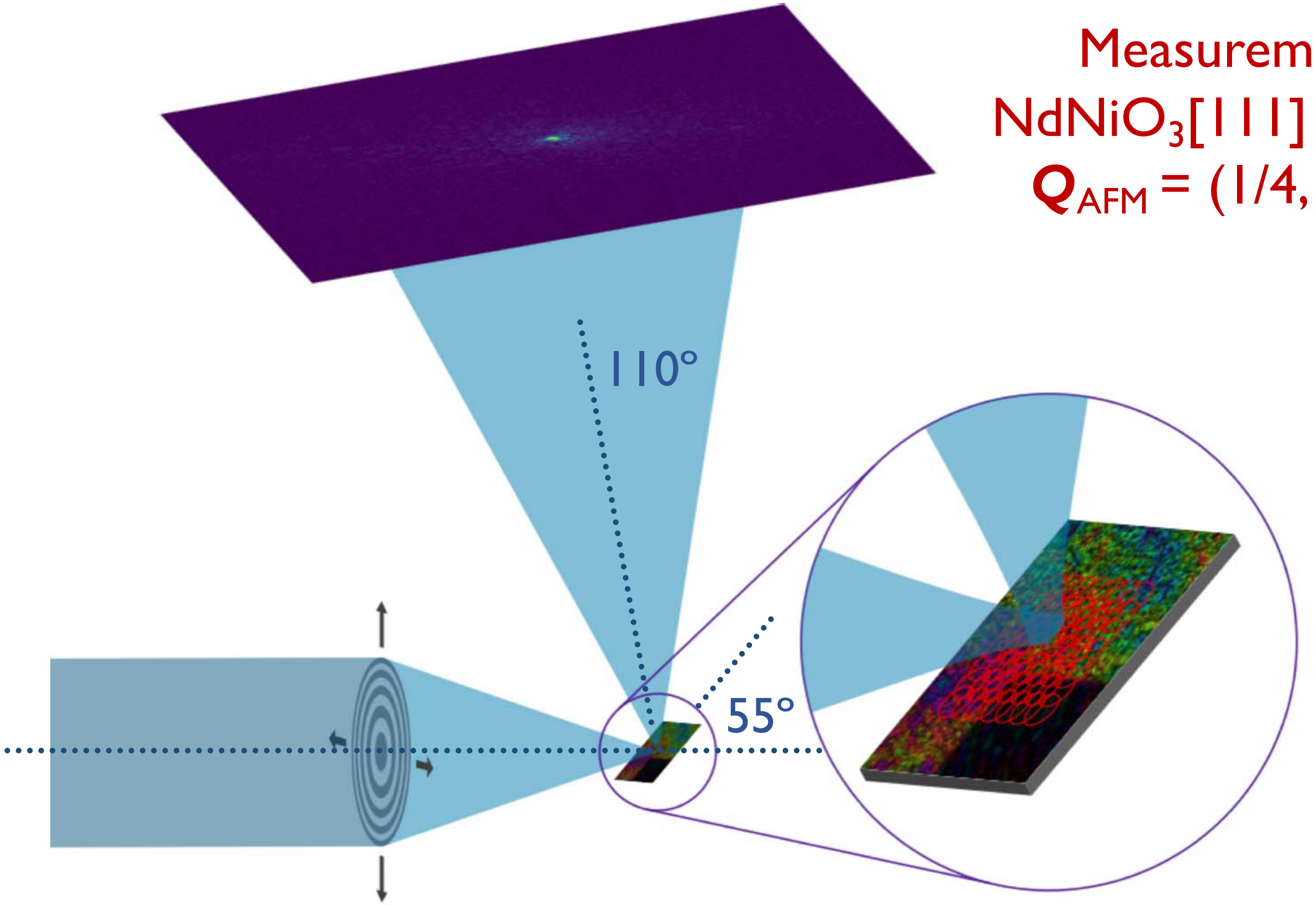
REAL SPACE

COMPUTATIONAL IMAGING

Coherent Lensless Imaging

Bragg ptychography

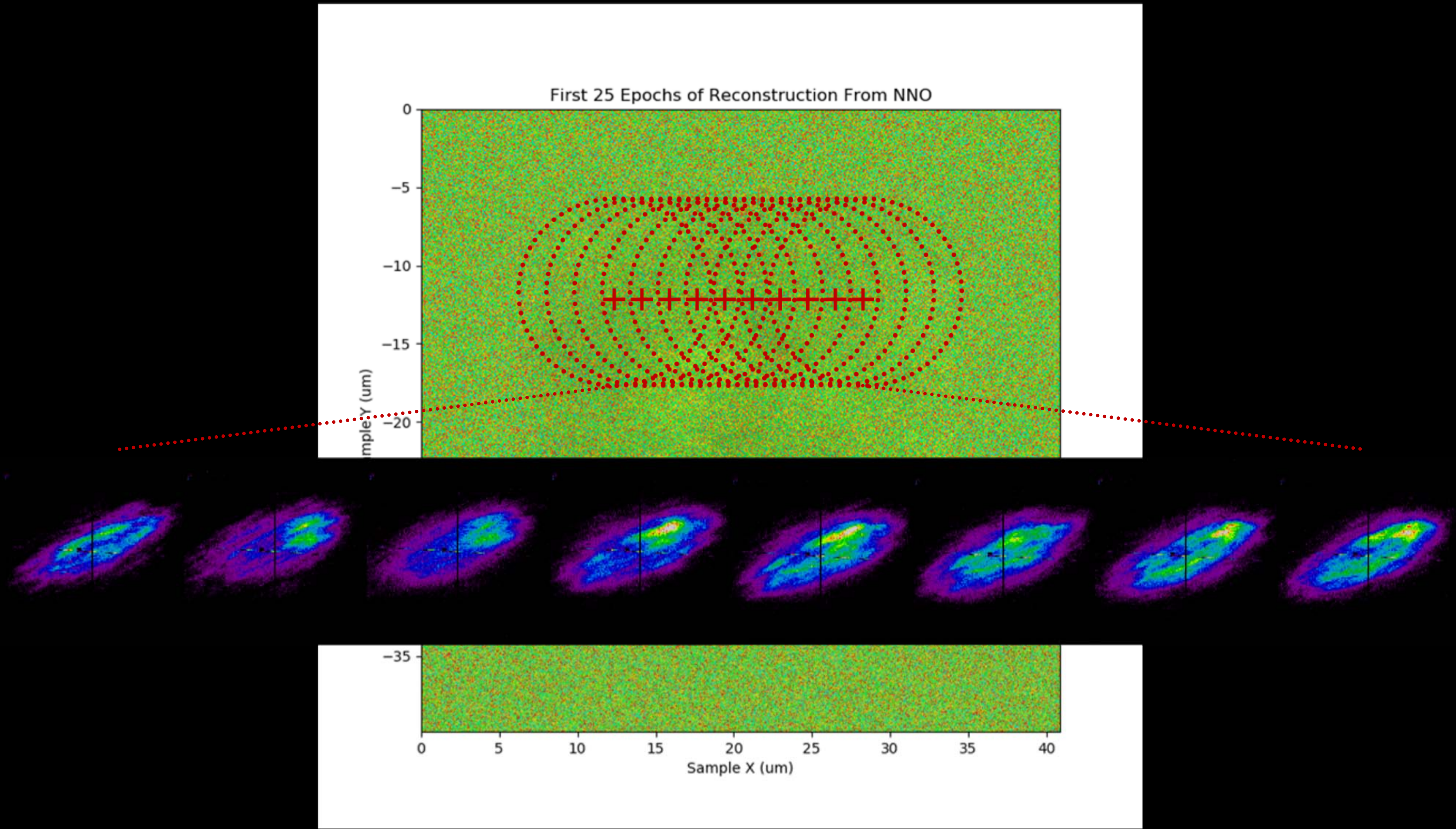
Measurements on $NdNiO_3[111]$ films at $\mathbf{Q}_{AFM}$ = (1/4,1/4,1/4)



Coherent Lensless Imaging

Bragg ptychography

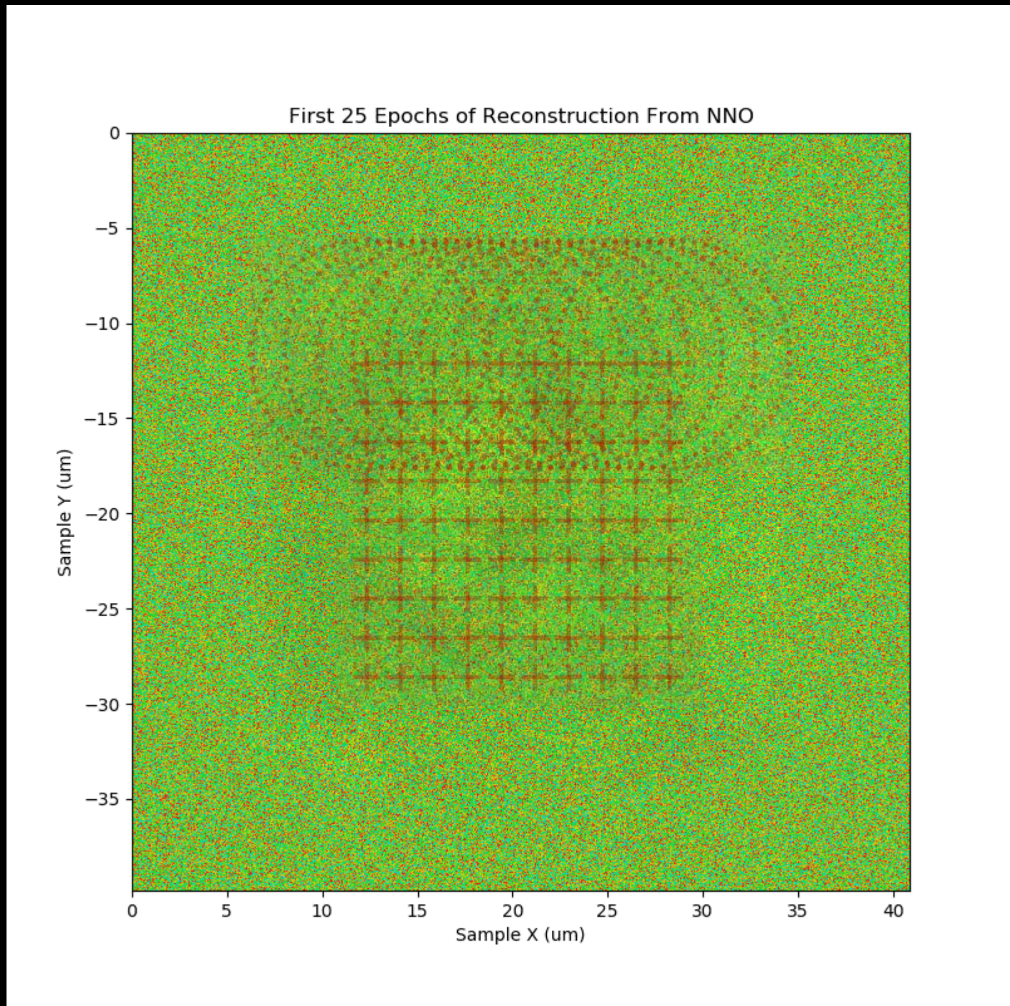
Measure overlapping regions and enforce a single-valued real field



Coherent Lensless Imaging

Bragg ptychography

Magnetic domain structure and nanoscale strain in rare earth nickelates

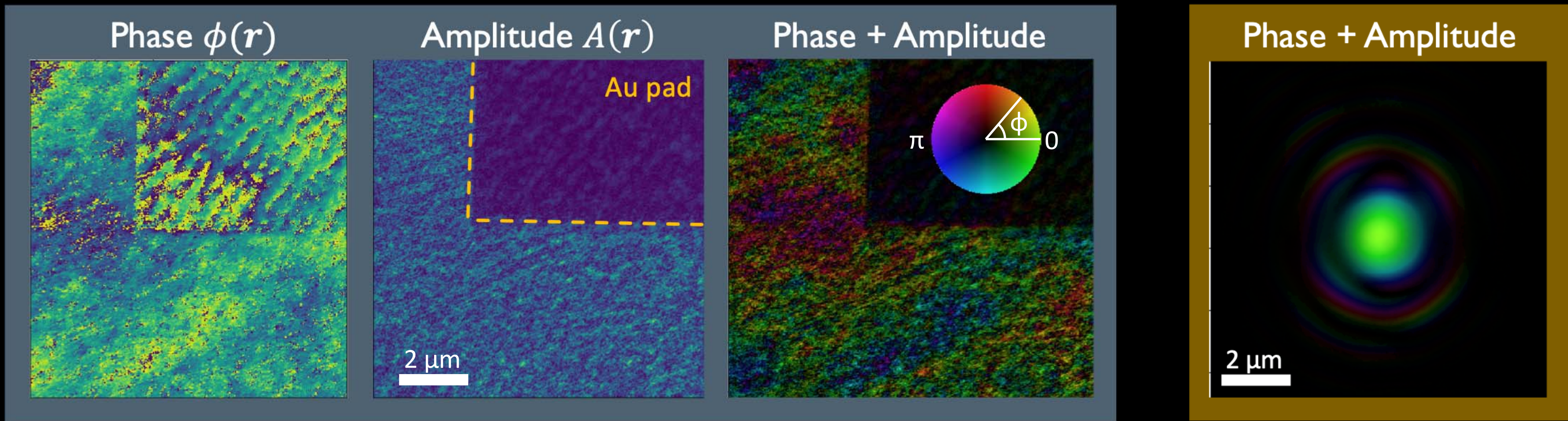


Coherent Diffractive Imaging

$$S(\boldsymbol{r}) = A(\boldsymbol{r}) \cos(\boldsymbol{Q}_{AFM} \cdot \boldsymbol{r} + \phi(\boldsymbol{r}))$$

Measurements on $NdNiO_3$[111] thin films at $\mathbf{Q}_{AFM}$ = (1/4,1/4,1/4)

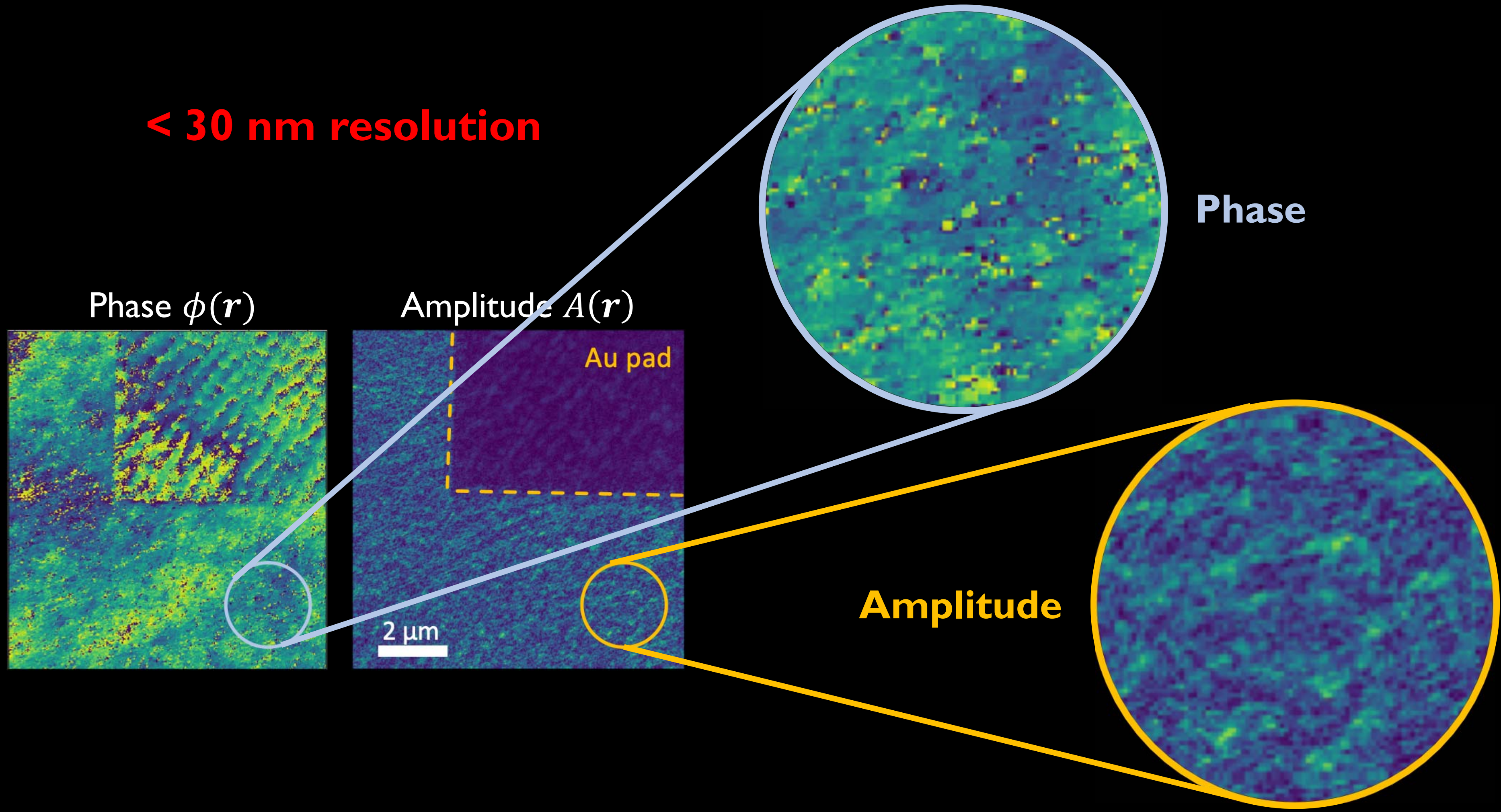
Object reconstruction *Probe reconstruction*



Coherent Diffractive Imaging

$$S(\boldsymbol{r}) = A(\boldsymbol{r}) \cos(\boldsymbol{Q}_{AFM} \cdot \boldsymbol{r} + \phi(\boldsymbol{r}))$$

< 30 nm resolution



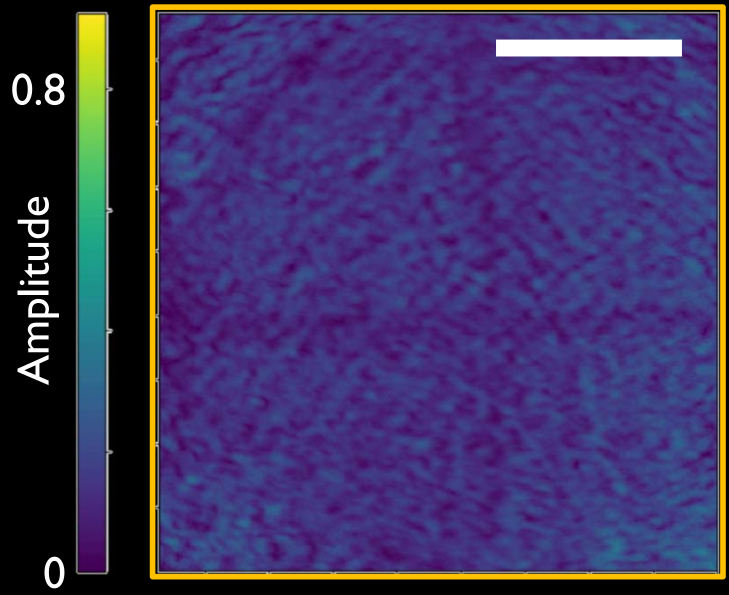
Coherent Lensless Imaging

Bragg ptychography

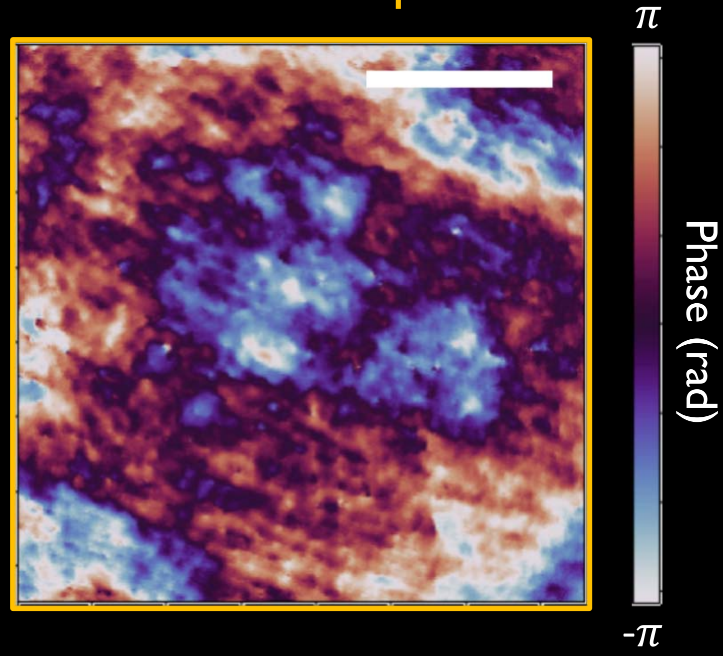
$$S(\boldsymbol{r}) = A(\boldsymbol{r})\cos(\boldsymbol{Q}_{AFM}\cdot\boldsymbol{r} + \phi(\boldsymbol{r}))$$

ORDER PARAMETER

Amplitude map



Phase map

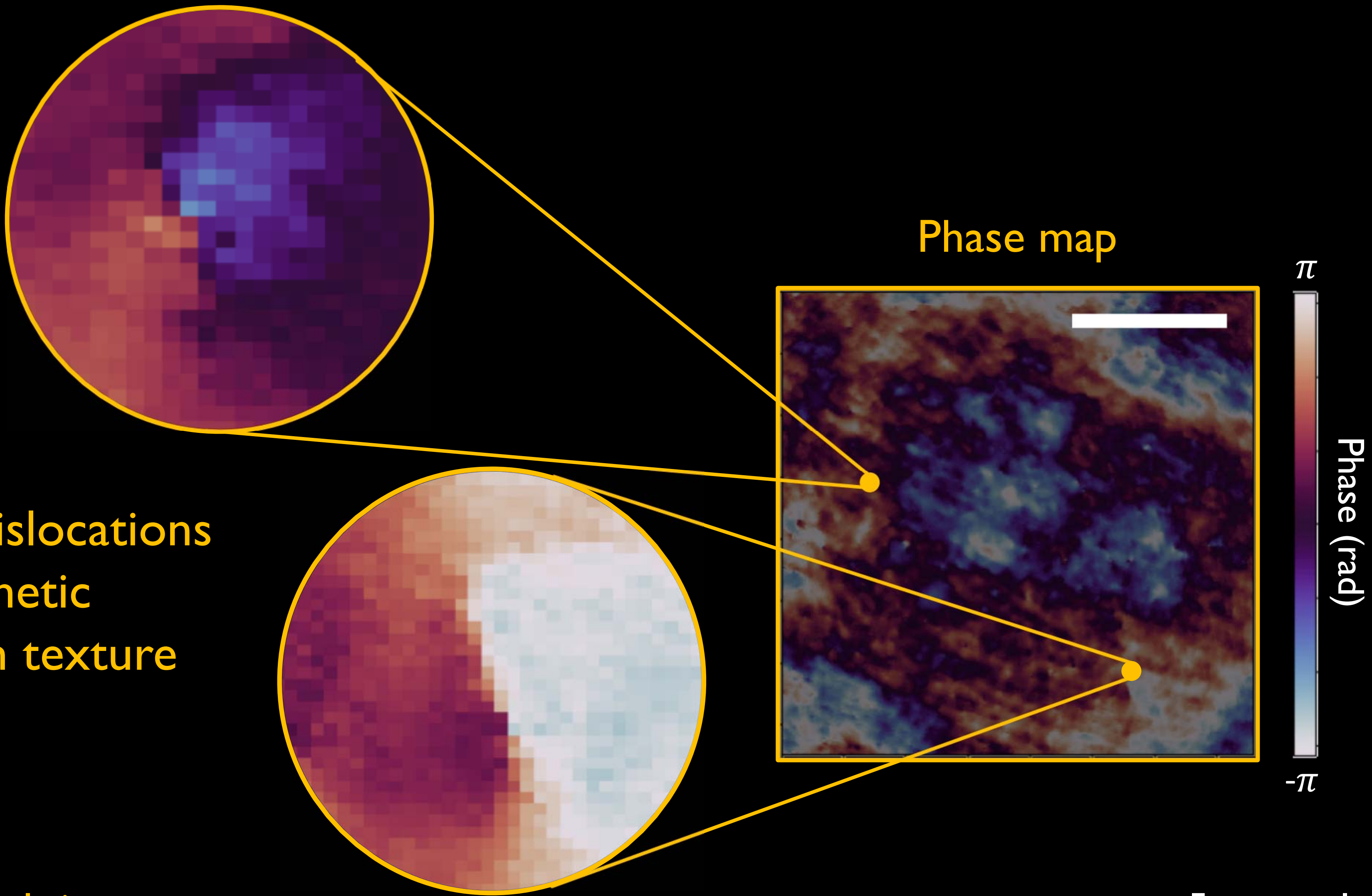


30 nm pixel size

5 μm scale bar

Coherent Lensless Imaging

Bragg ptychography



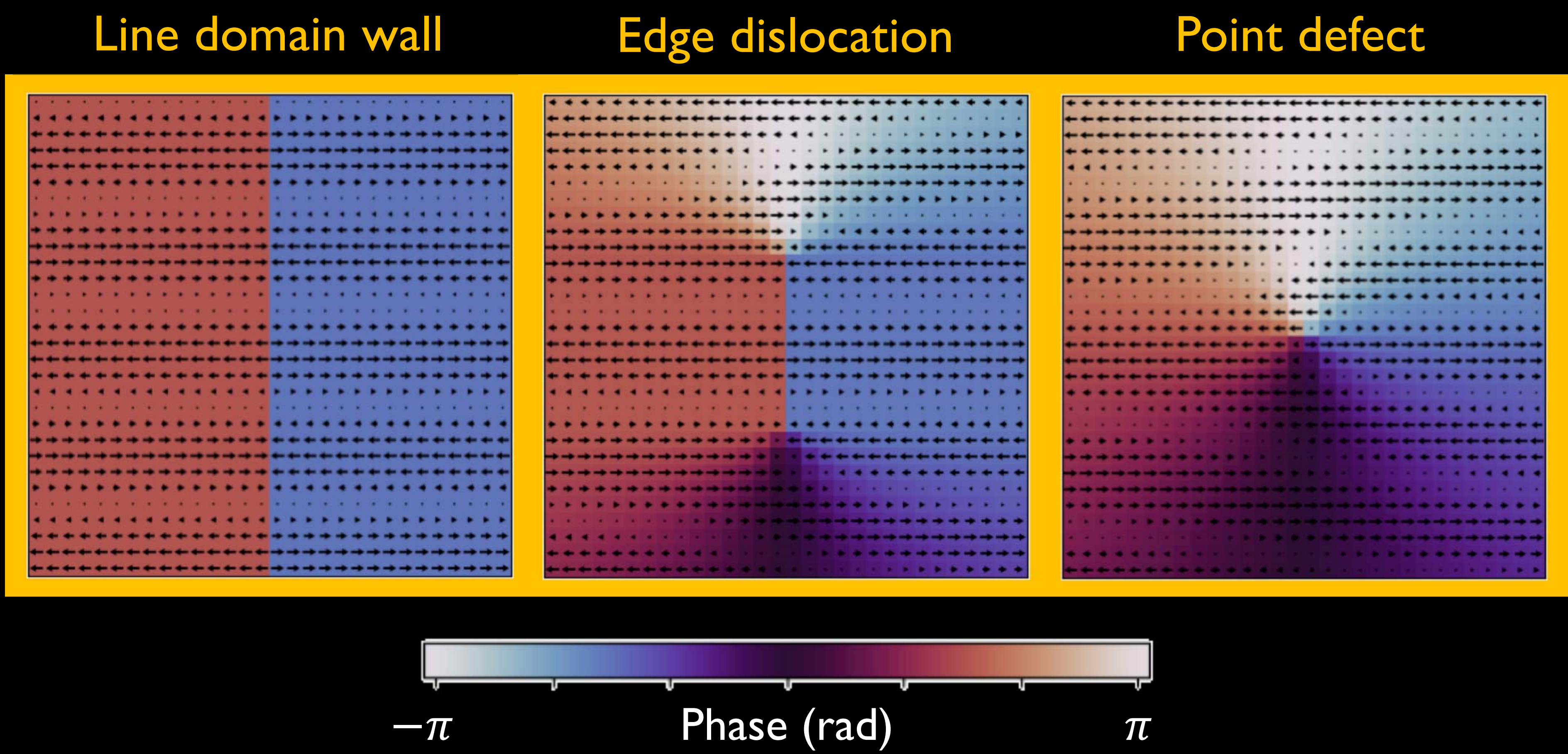
Edge dislocations in magnetic domain texture

30 nm pixel size

5 μm scale bar

Coherent Lensless Imaging

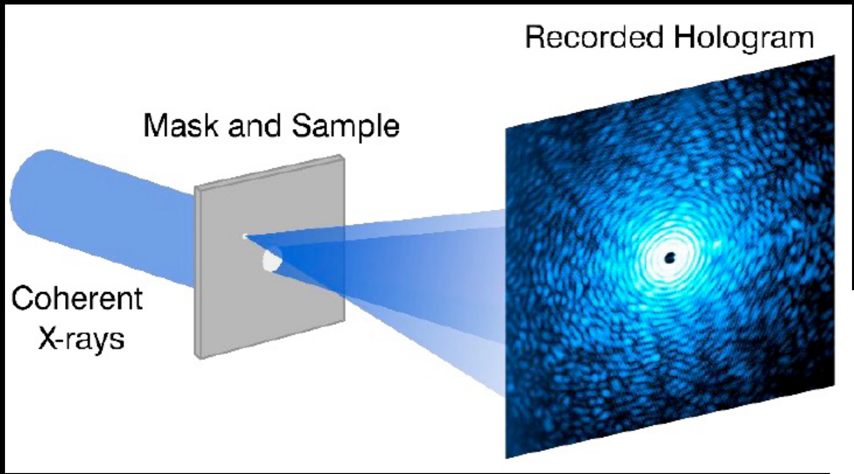
Defects in magnetic order parameter



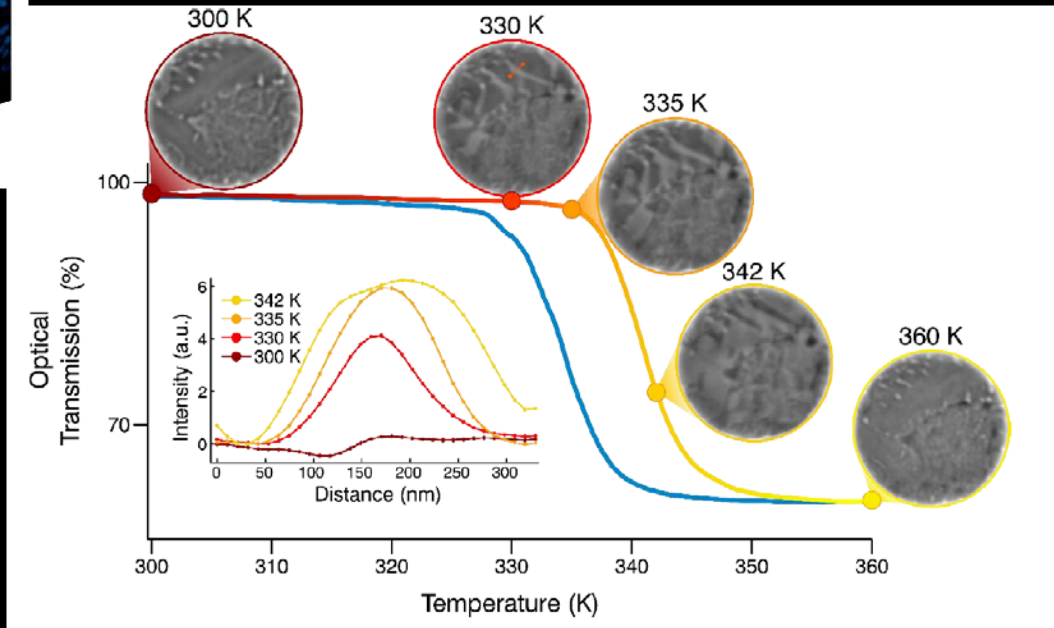
Coherent Diffractive Imaging

Moving forward to single-shot imaging

Resonant holography



Metal-insulator transition in VO_2
(~40 nm resolution)



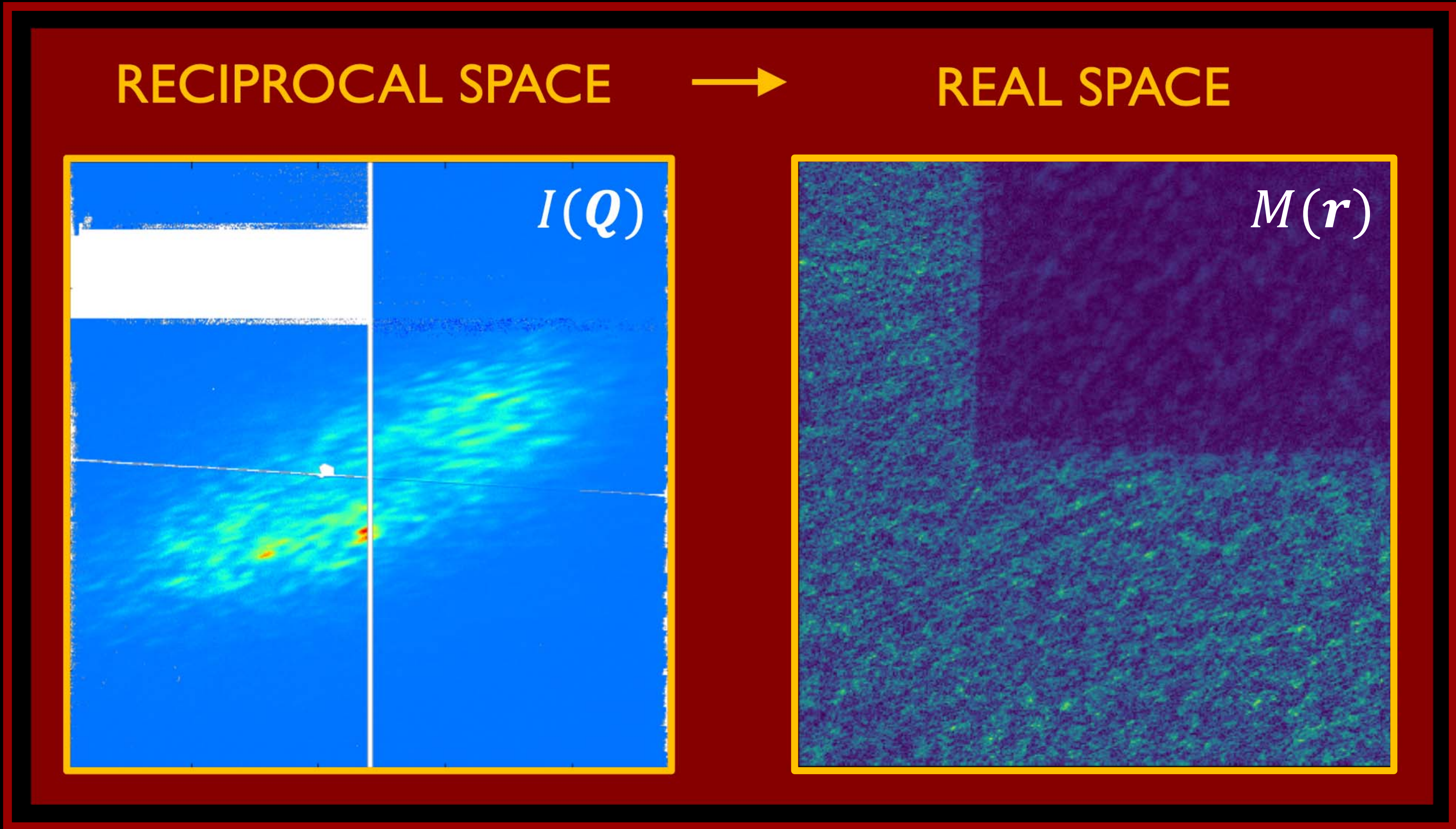
Imaging charge/spin textures around Q~0 (forward scattering)

Vidas *et al.*, Nano Letters **18**, 3449 (2018)

Coherent Diffractive Imaging @ CXFEL

Typical probing conditions for resonant soft X-ray CDI:	*vs.*	SX seeded FEL @ FERMI possible targets?:
• 500-1000 eV range, tunable		Hopefully!
• Polarization control		YES
• Single mode probe improves quality and robustness of reconstruction		Seeded beam is more ideal than SASE
• 10^{12} ph/s flux yields peak count rate: ~10-100 kHz/pix		$10^{11\text{-}12}$ ph/pulse for single shot experiments
• Transverse (longitud.) coherence length > 10 μm (500 nm)		Long. OK – $\lambda/\Delta\lambda > 1000$ Transv. presumably also OK
• Need focusing down to ~1-5 μm		sub-μm with appropriate optics

Summary



Spatiotemporal imaging requires a full-field, single-shot probe of real-space textures with stable wavelength. New opportunities for soft X-ray diffractive imaging to reveal the nanoscale dynamics of collective states of matter

Thank you for your attention!