



Massachusetts
Institute of
Technology

Resonant X-ray Studies of Electronic Orders in Quantum Solids

Riccardo Comin

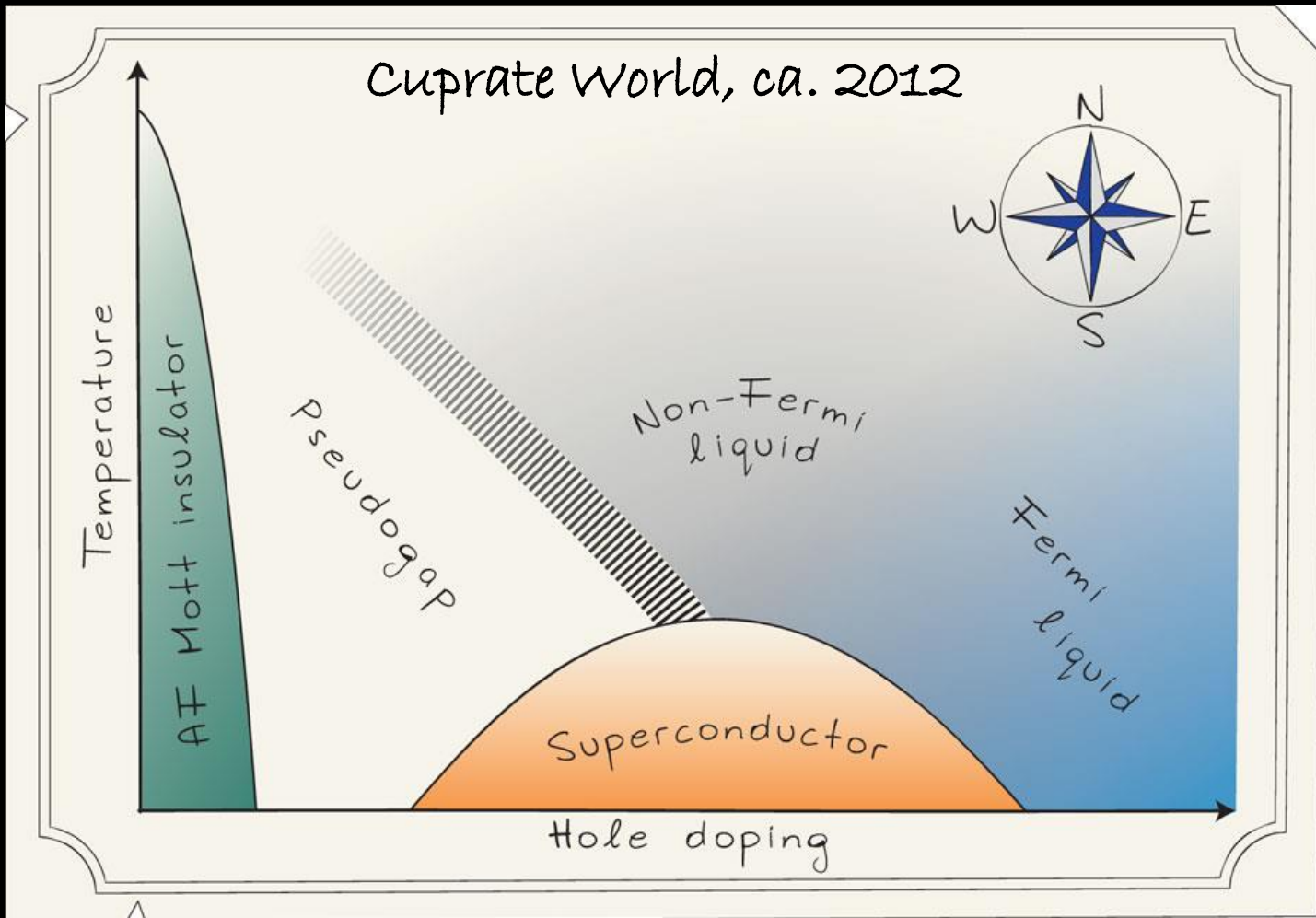
Massachusetts Institute of Technology

Correlated Electron Systems – Novel Developments
U. Minnesota, 18 May 2018

Outline

- Charge-density-waves in cuprates: where we at
- Resonant X-ray Scattering: a probe of charge/spin order
- Competing phases: from hole to electron doping
- A Wigner 'glass' across the AFM critical doping
- Scale-invariant spin textures in nickelates
(see also poster by Jiarui Li)

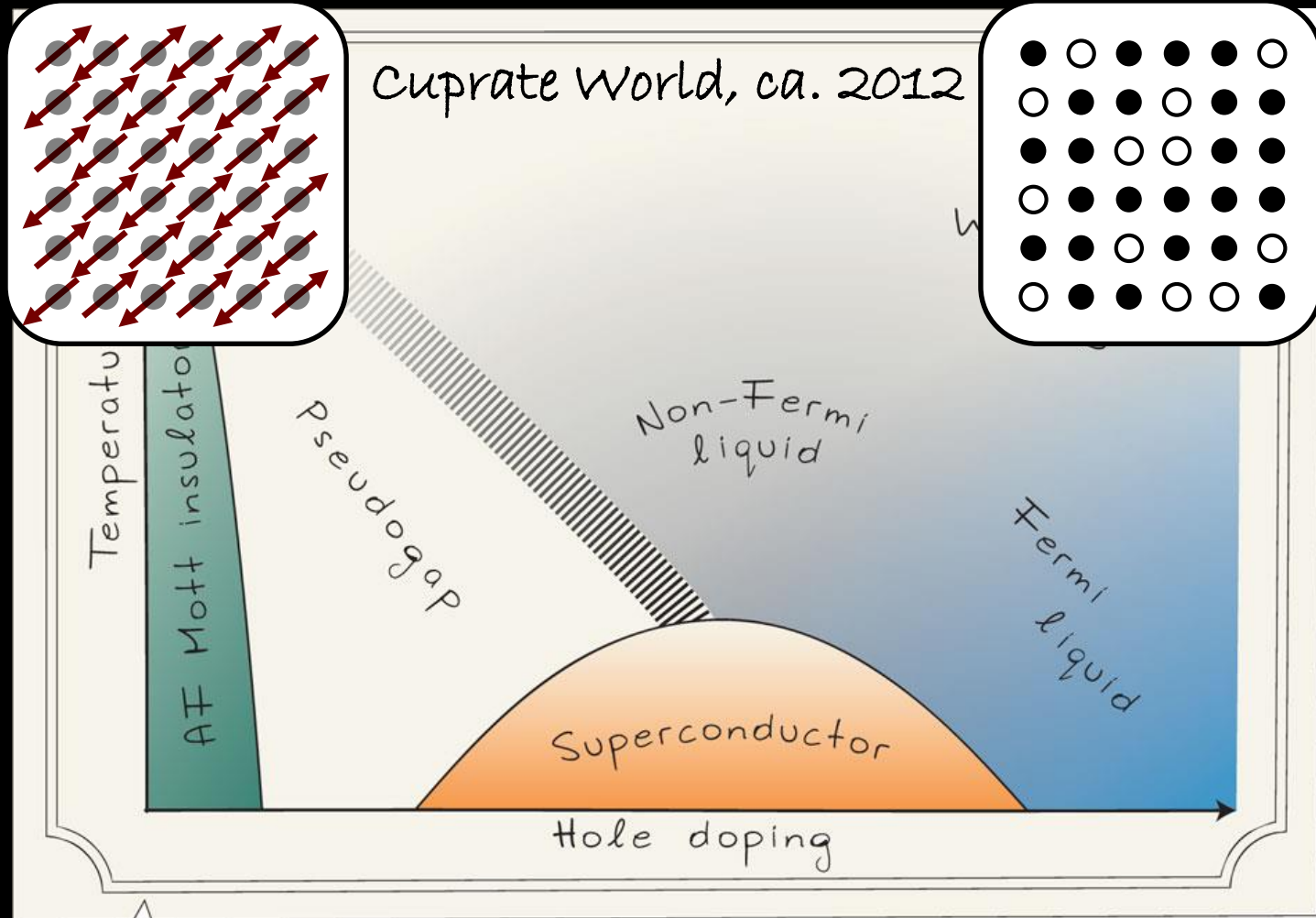
Cuprates



Cuprates

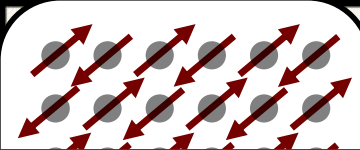
Mott insulator

Fermi liquid



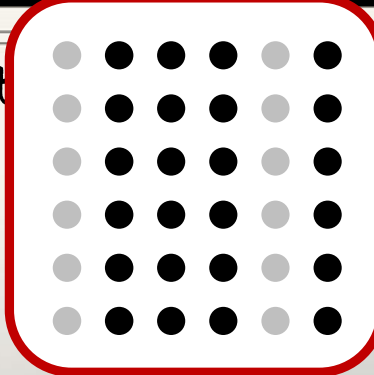
Cuprates

Mott insulator



Cuprat

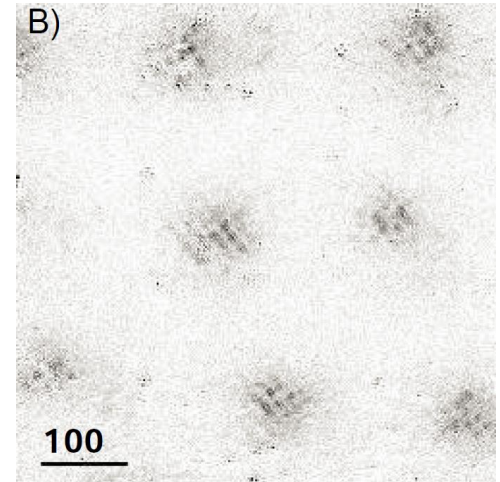
Charge order



Fermi liquid

STM

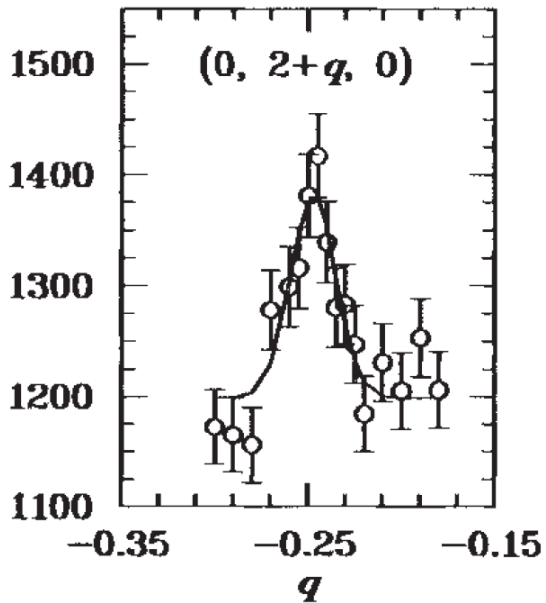
4-unit-cell DOS modulation



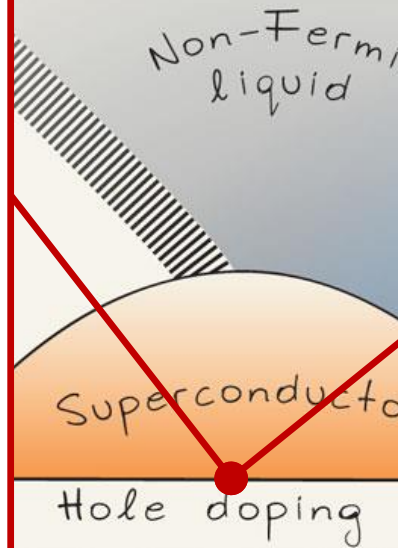
Hoffman et al., Science 2002

Scattering

1/4 wavevector charge diffraction

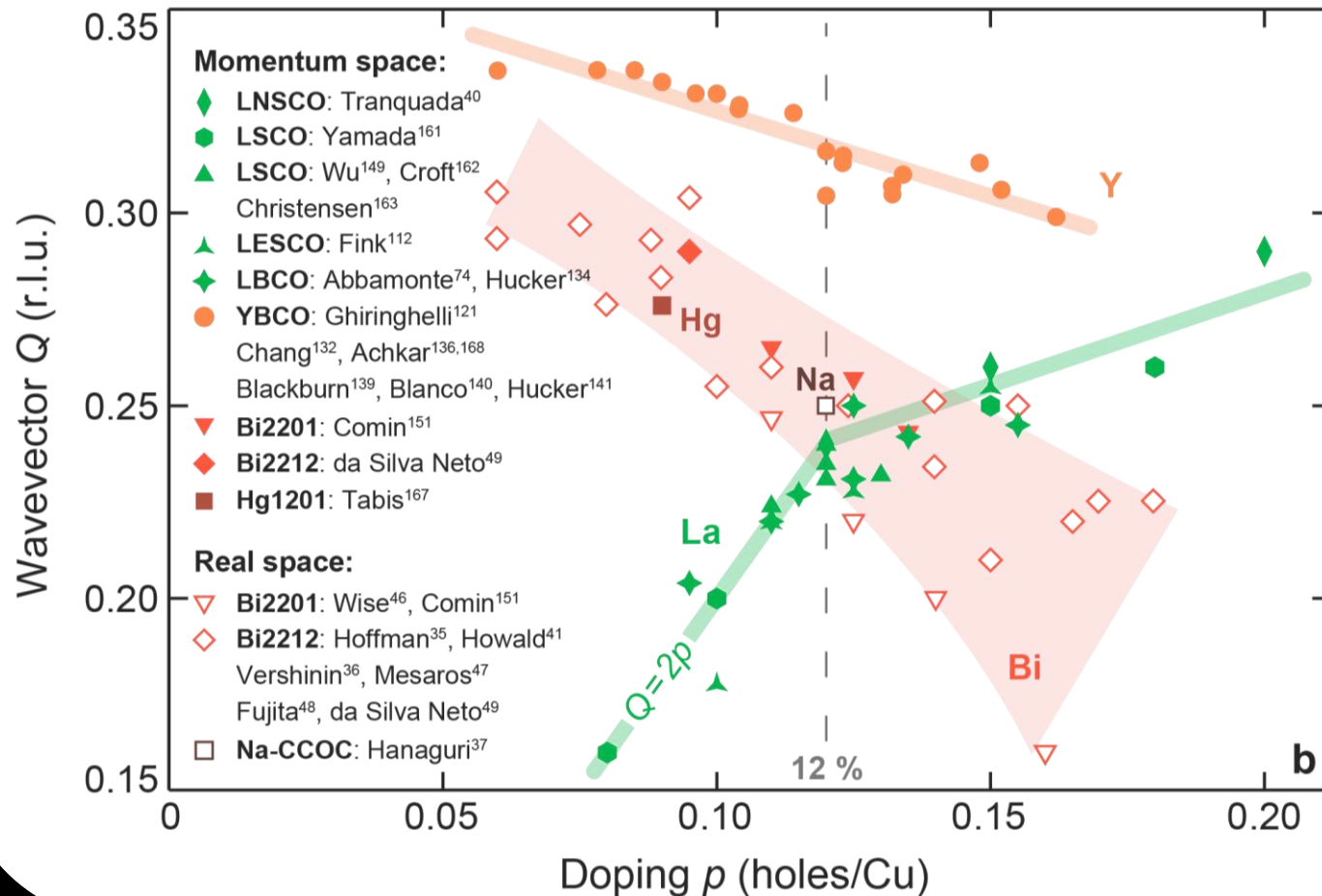


Tranquada et al., Nature 1995

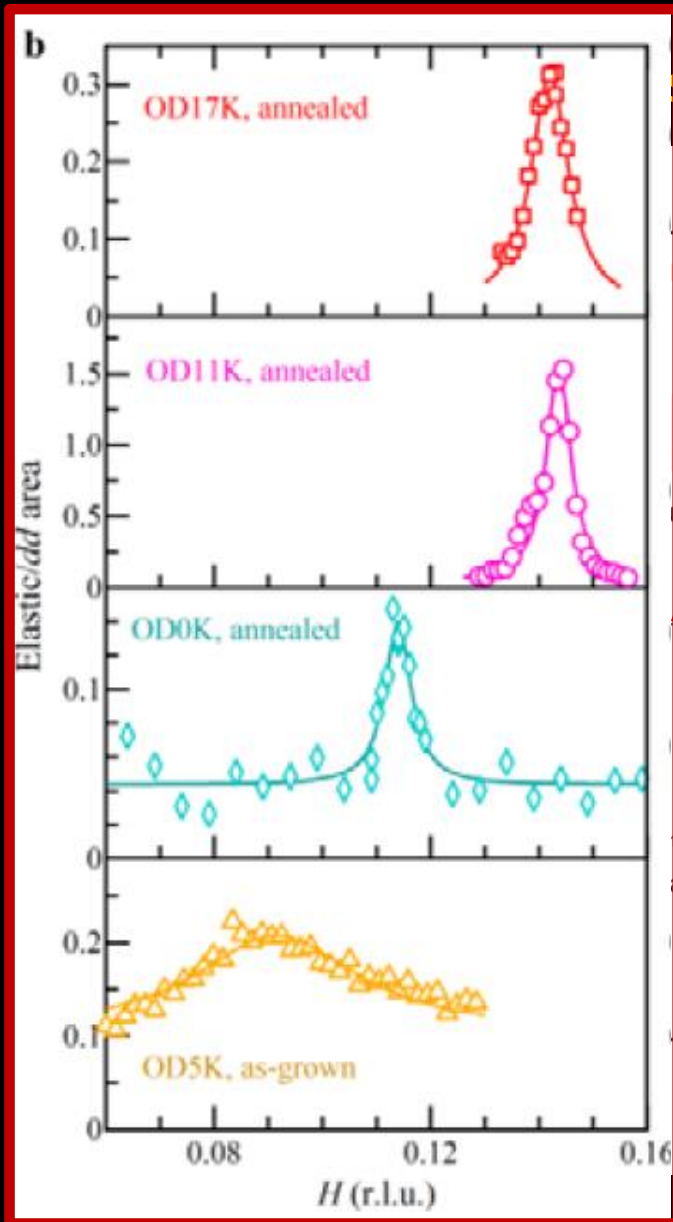


Charge order in cuprates

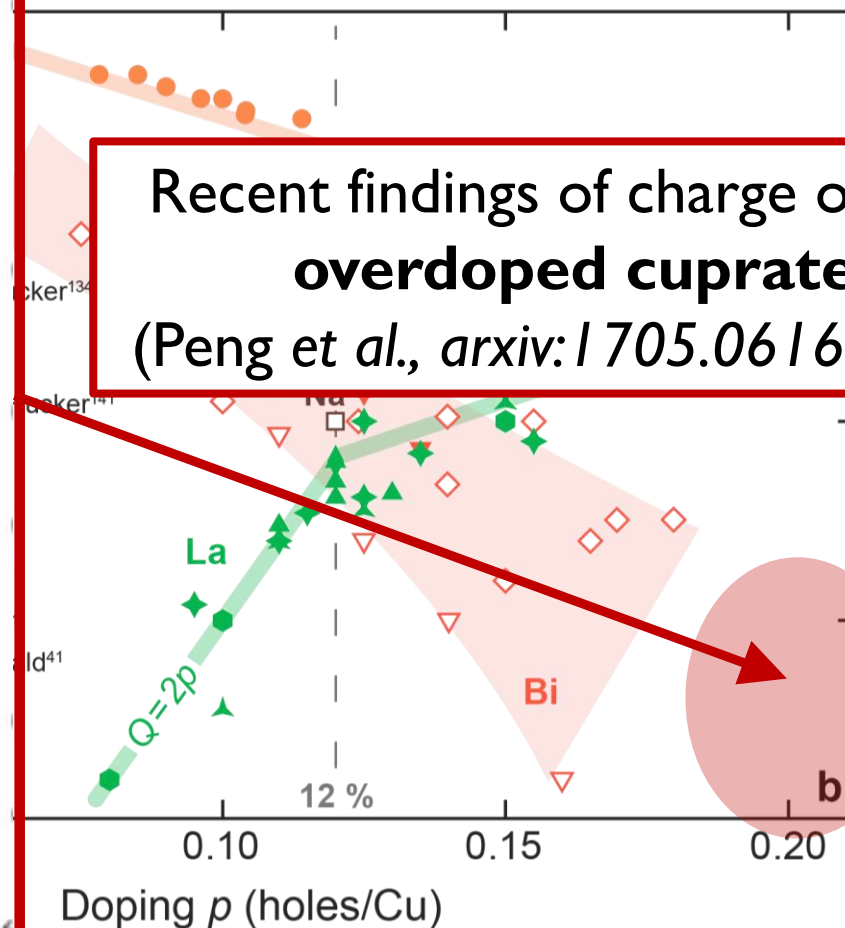
Flash-forward to 2018



Charge order in cuprates

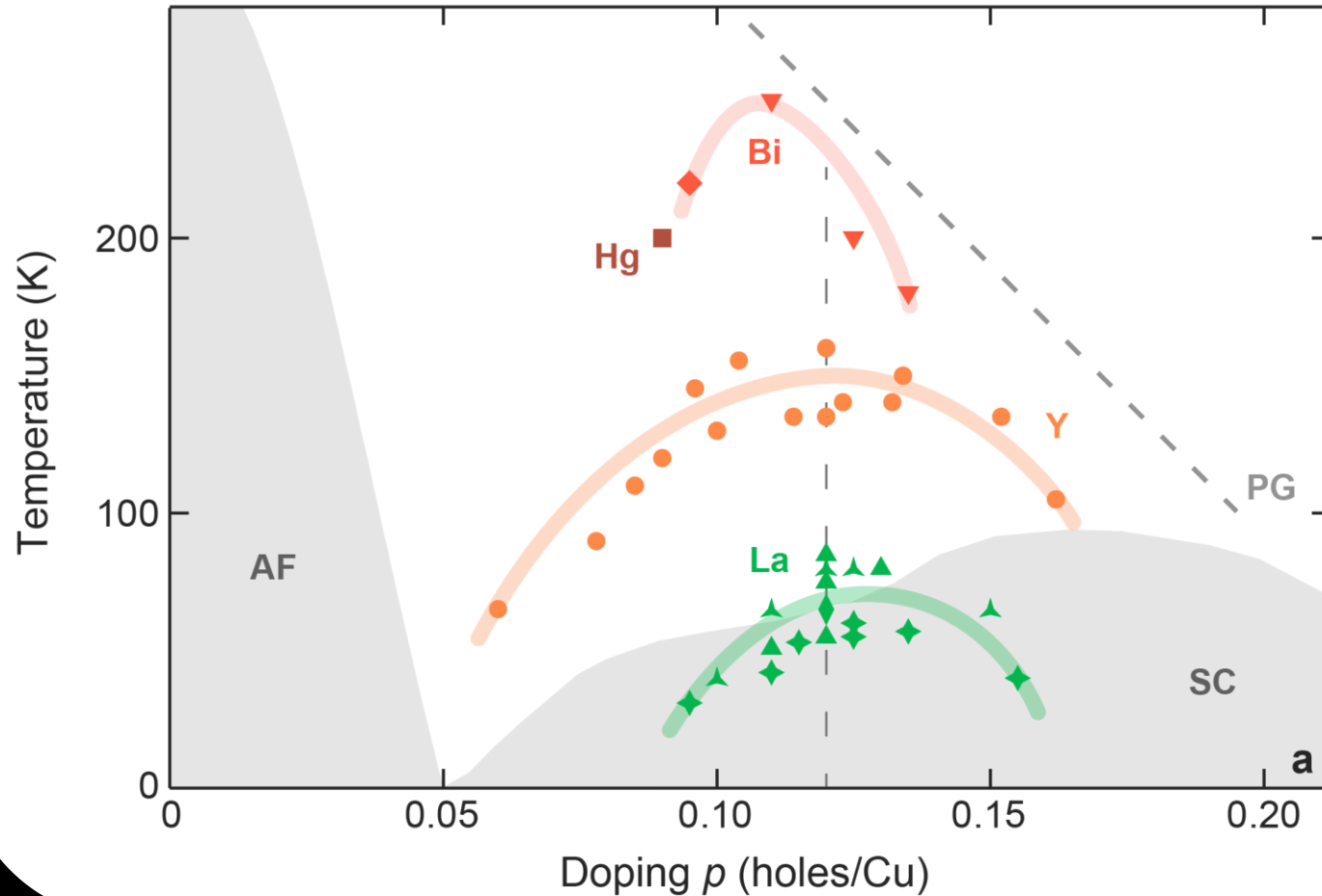


sh-forward to 2018



Charge order in cuprates

Flash-forward to 2018

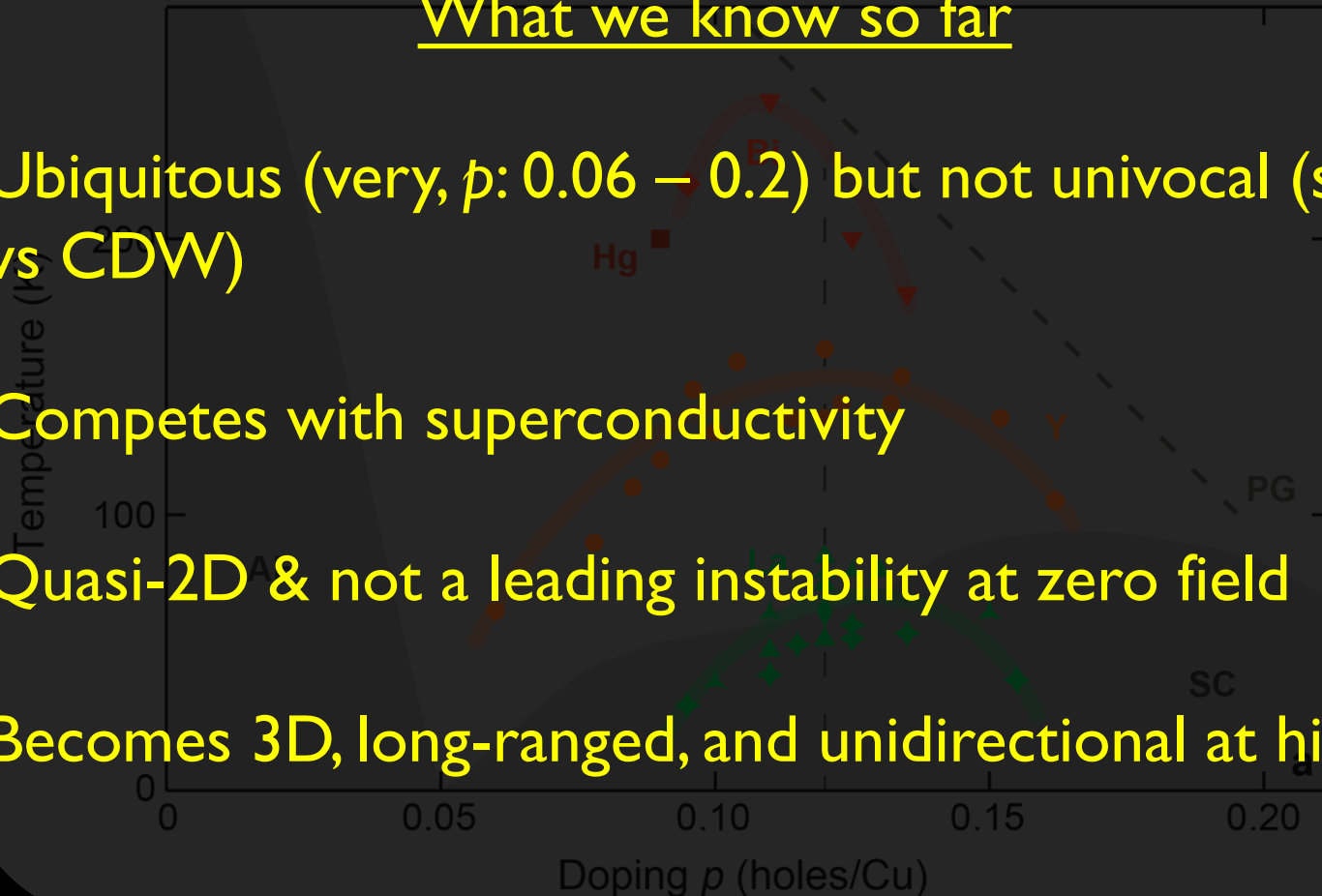


Charge order in cuprates

Flash-forward to 2018

What we know so far

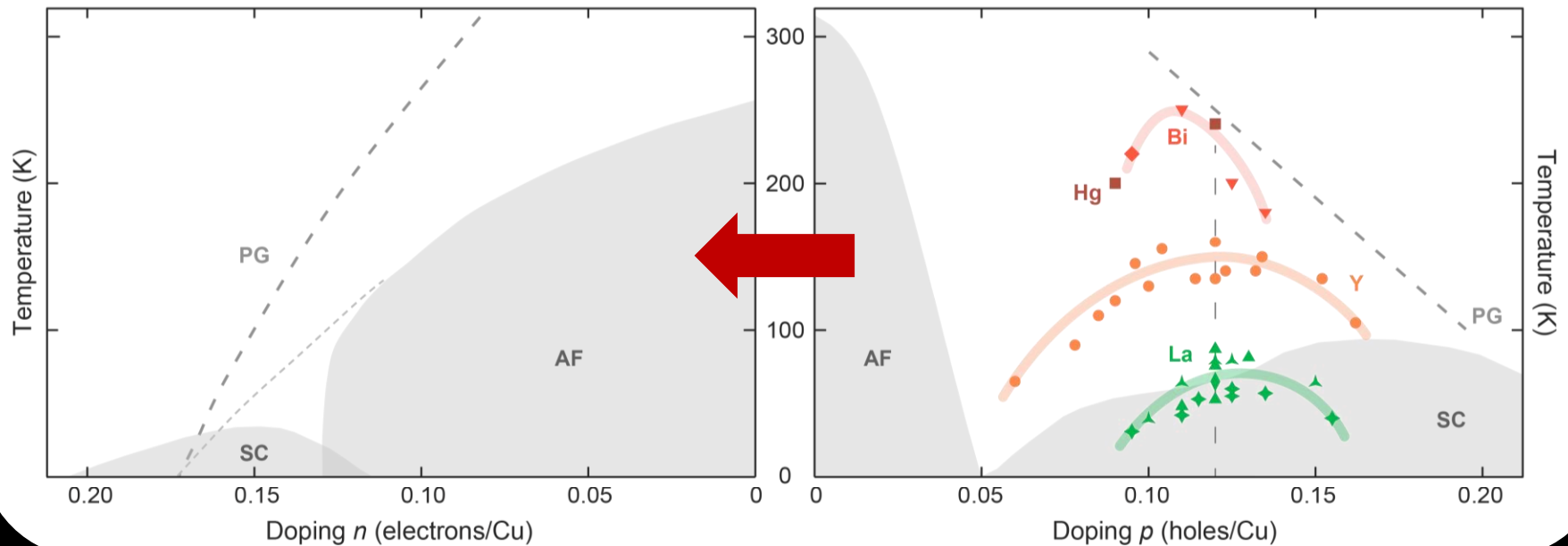
- Ubiquitous (very, $p: 0.06 - 0.2$) but not univocal (stripes vs CDW)
- Competes with superconductivity
- Quasi-2D & not a leading instability at zero field
- Becomes 3D, long-ranged, and unidirectional at high field



Charge order in cuprates

Electron doped cuprates

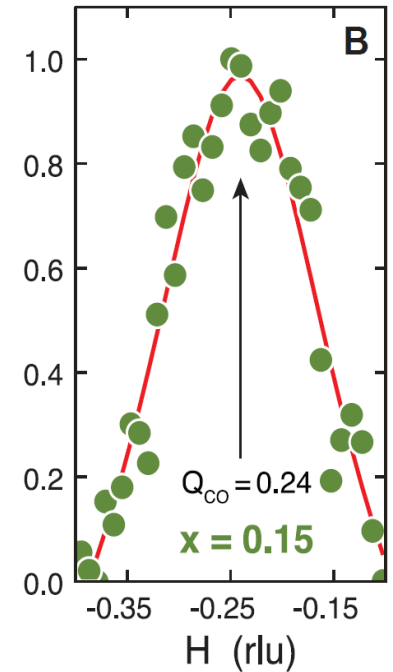
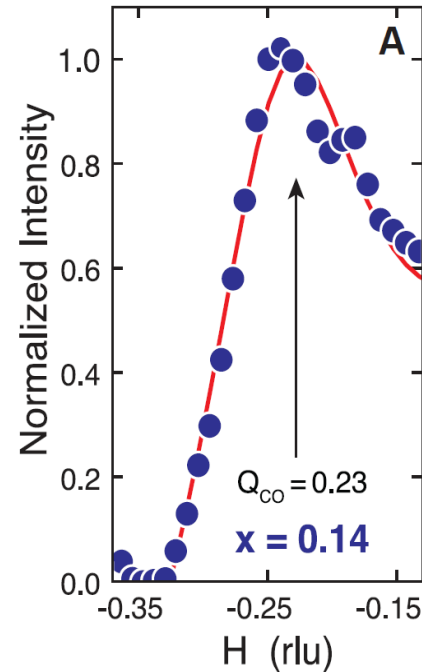
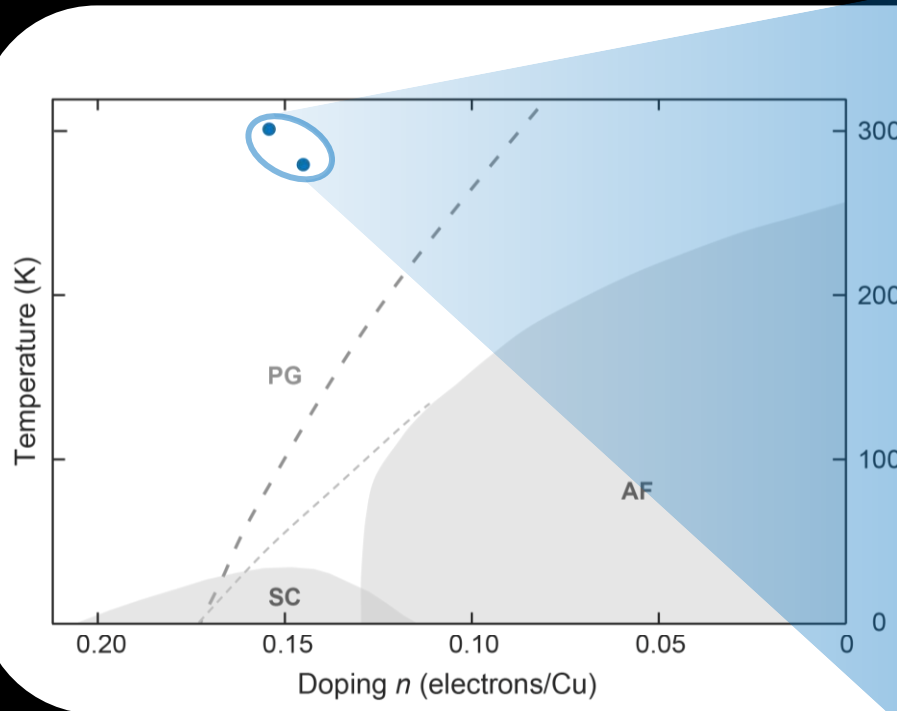
Hole doped cuprates



Study interplay between CDW and other dominant instabilities in e-doped cuprates

Charge order in cuprates

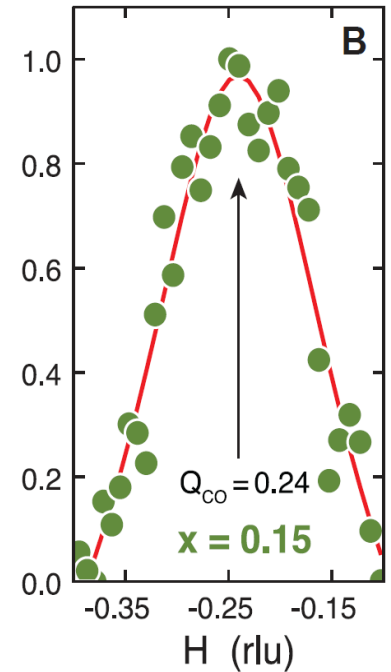
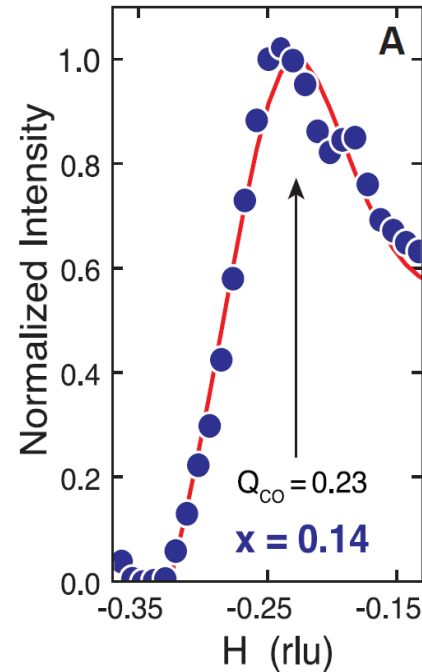
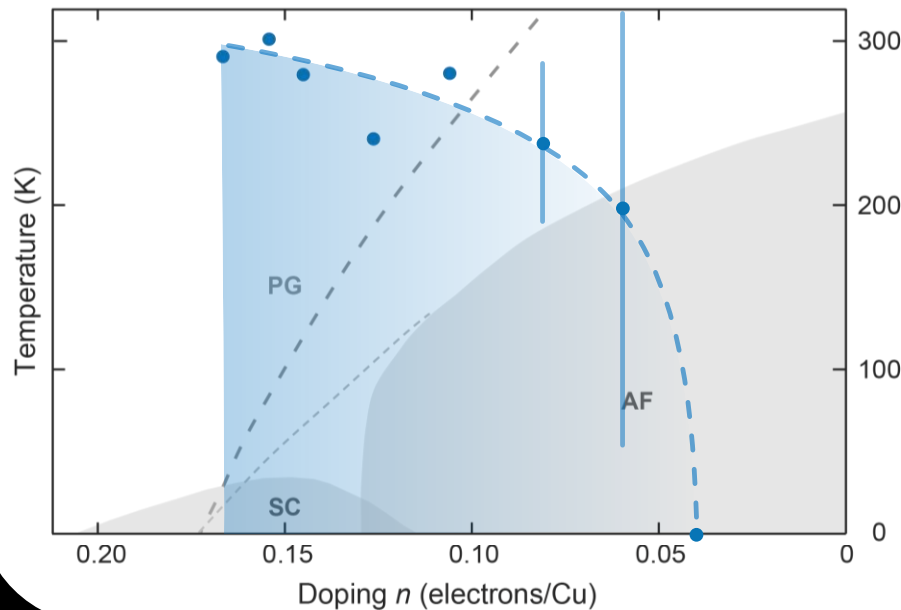
Electron doped cuprates



CDWs exist also in e-doped cuprates

Charge order in cuprates

Electron doped cuprates



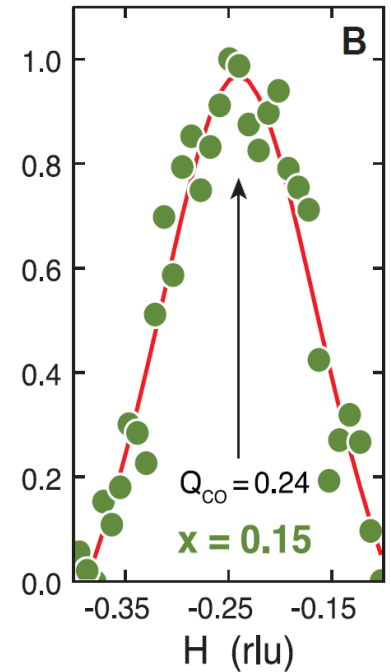
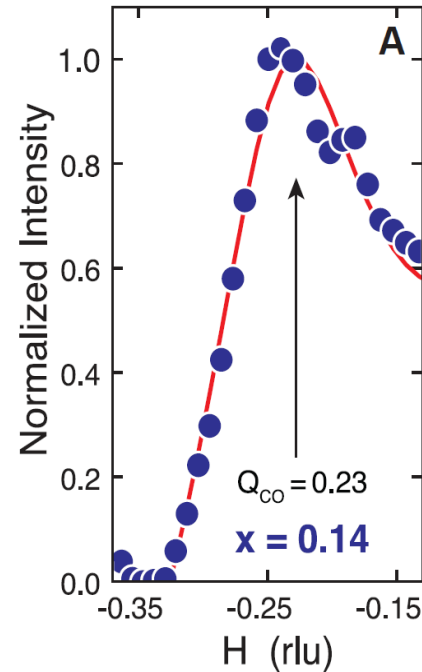
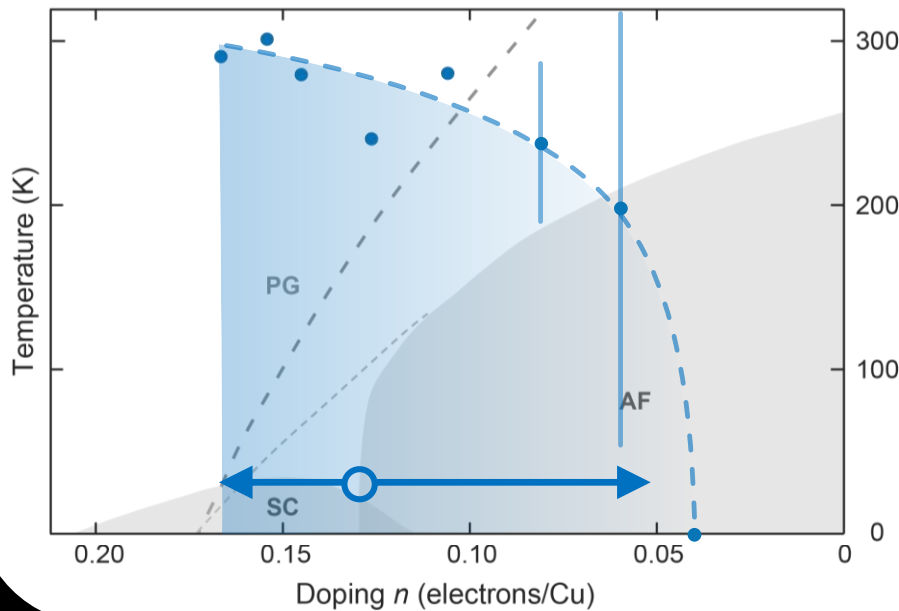
CDWs exist also in e-doped cuprates
(and span an extended doping range)

da Silva Neto, et al, *Science* 2015

da Silva Neto, et al, *Science Advances* 2016

Charge order in cuprates

Electron doped cuprates



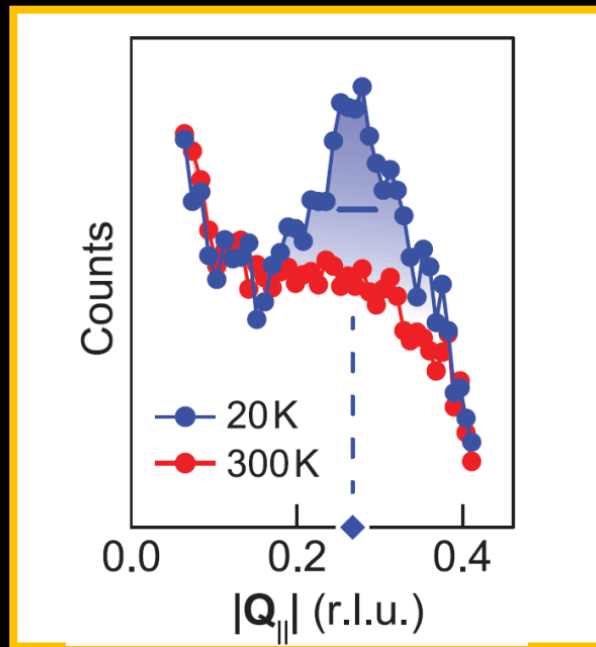
Coexistence between CDW and AFM

da Silva Neto, et al, *Science* 2015

da Silva Neto, et al, *Science Advances* 2016

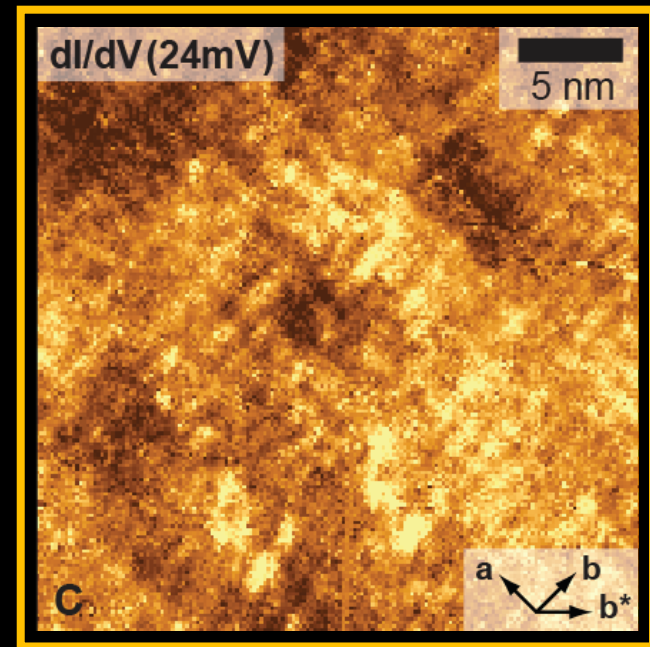
Probes of electronic orders

Reciprocal space
X-ray scattering



Diffraction peak at
 $Q=0.25$ r.l.u.

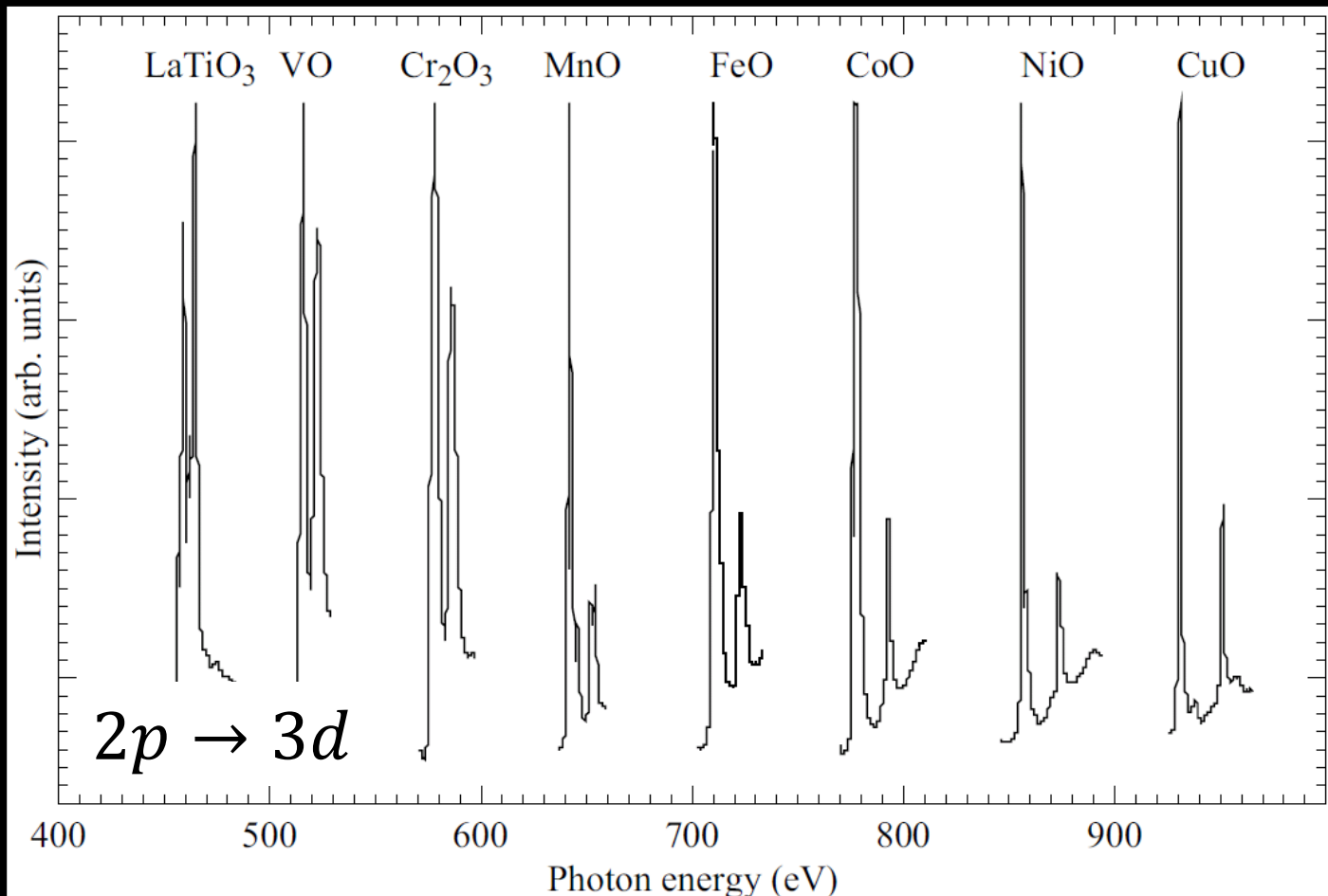
Real space
Scanning microscopy



4-unit-cell density of
states modulation

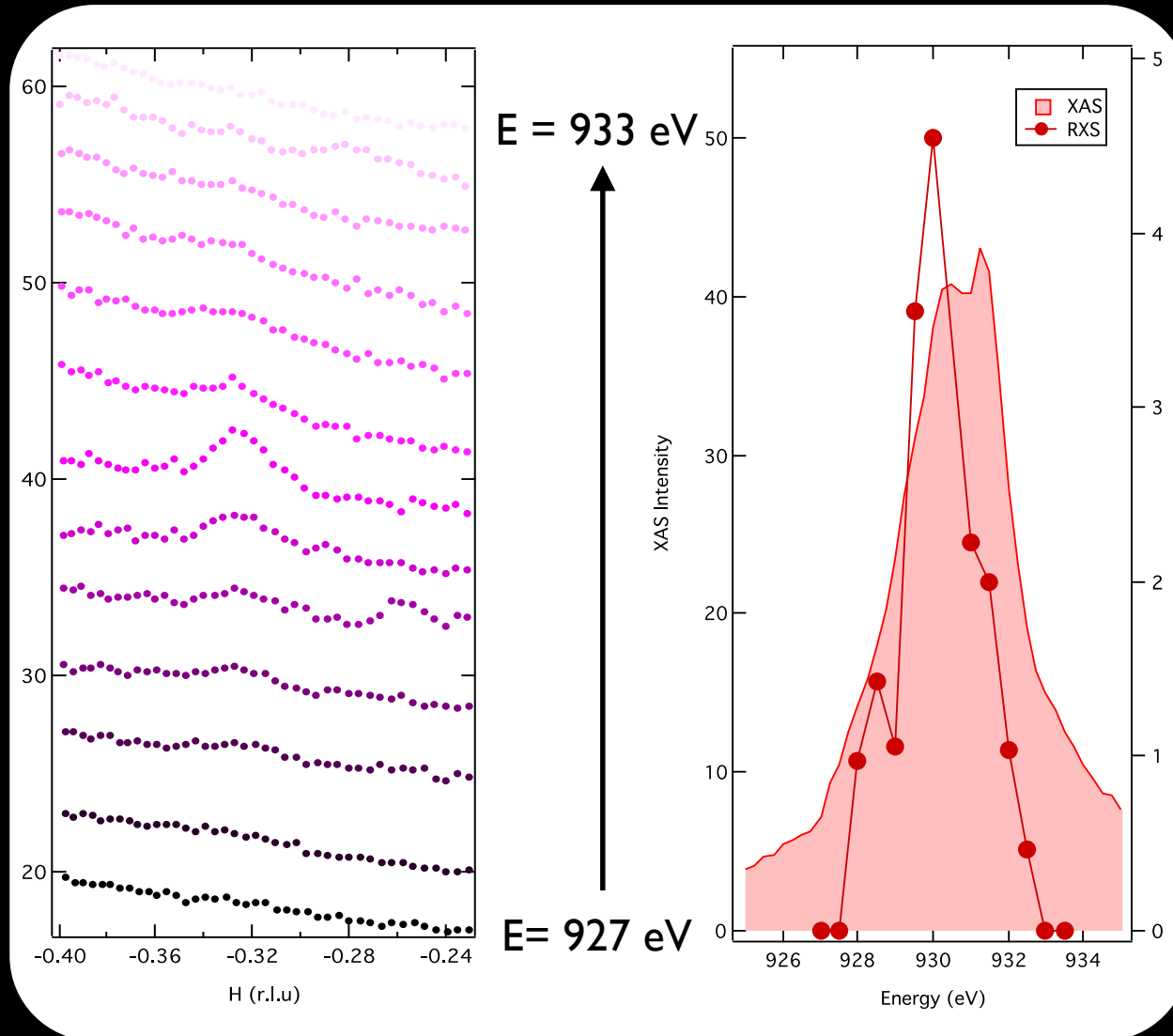
Resonant scattering

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



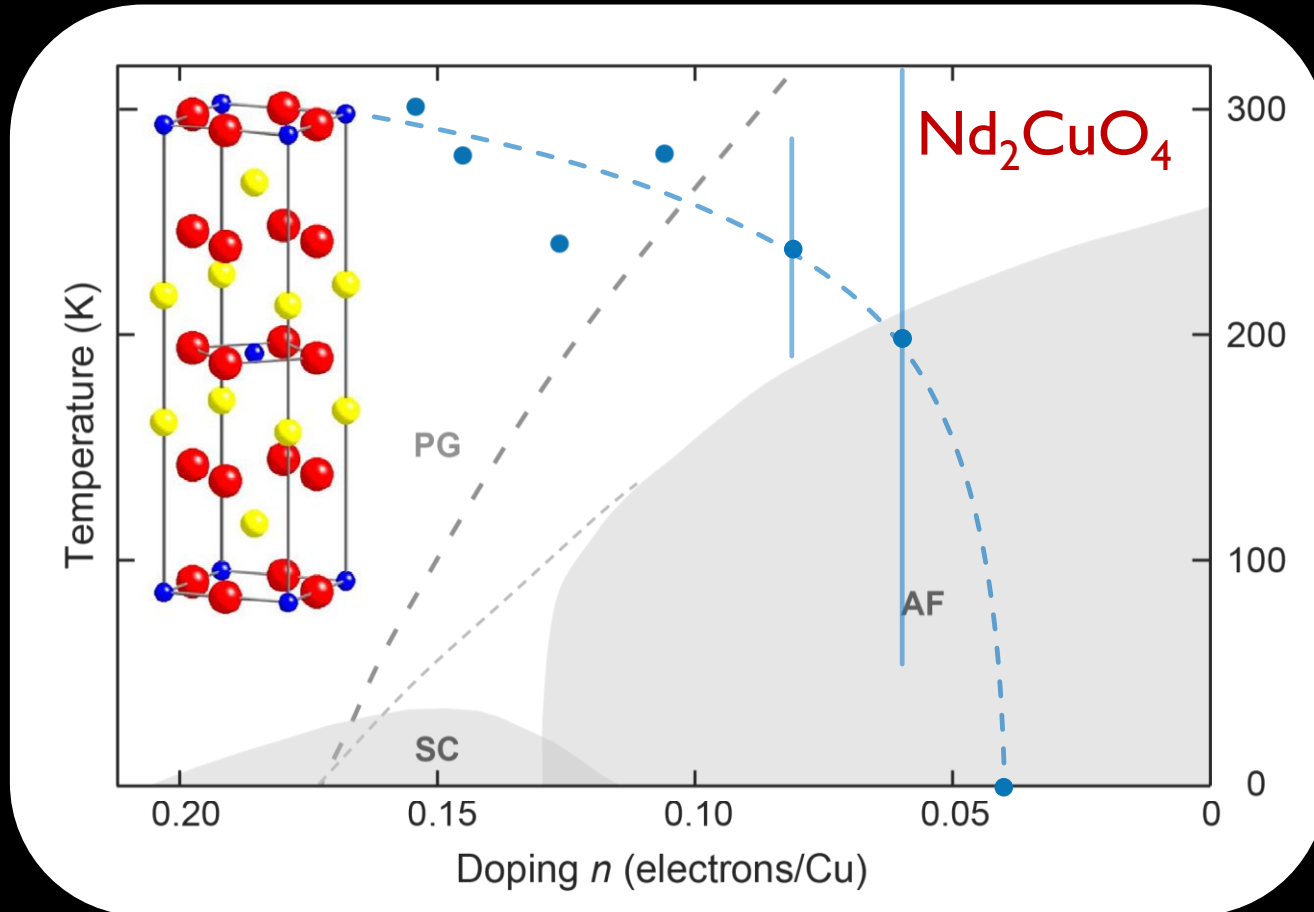
Resonant scattering

Charge
order in
 Nd_2CuO_4



Electron-doped cuprates

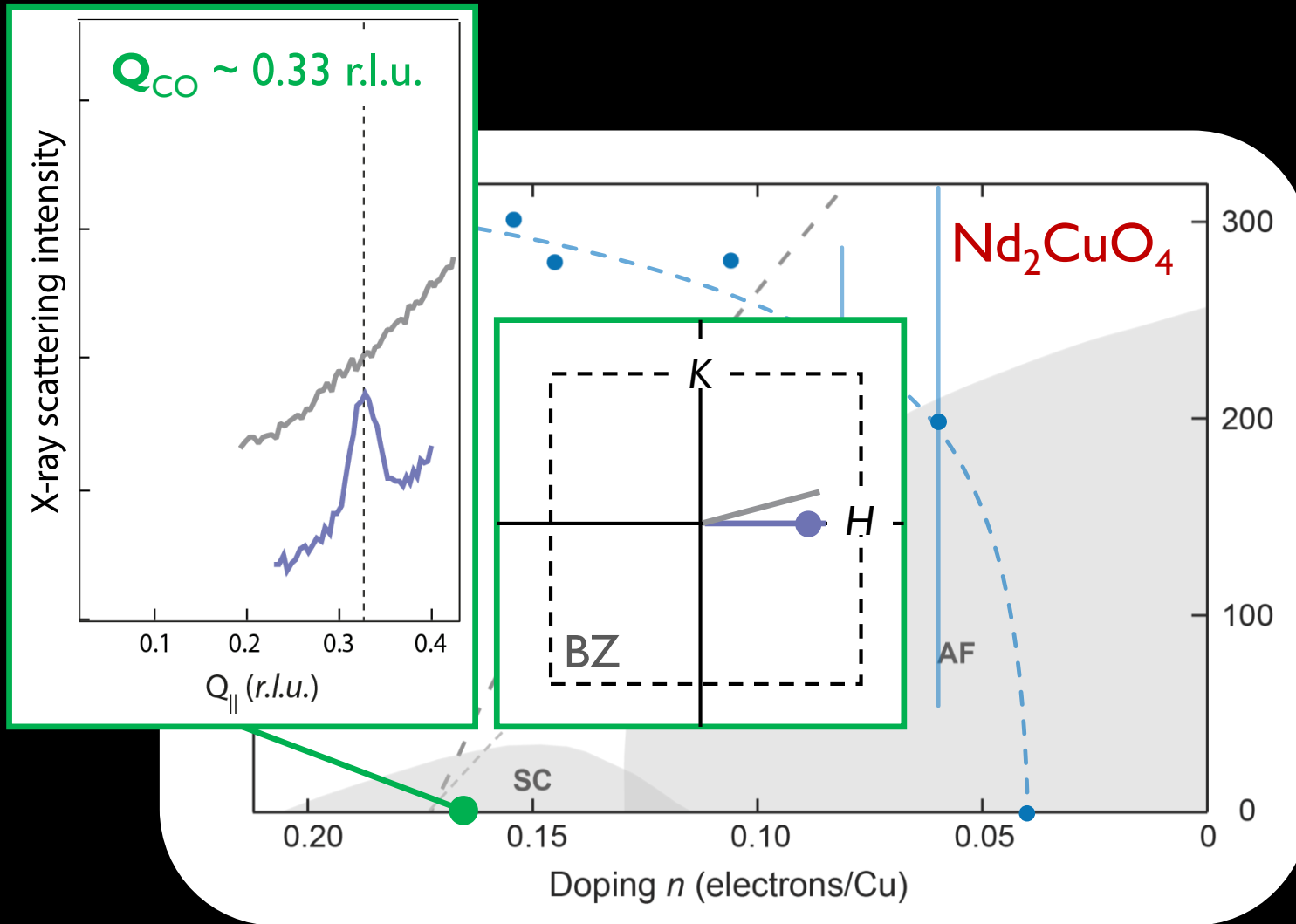
How does charge order evolve vs electron doping?



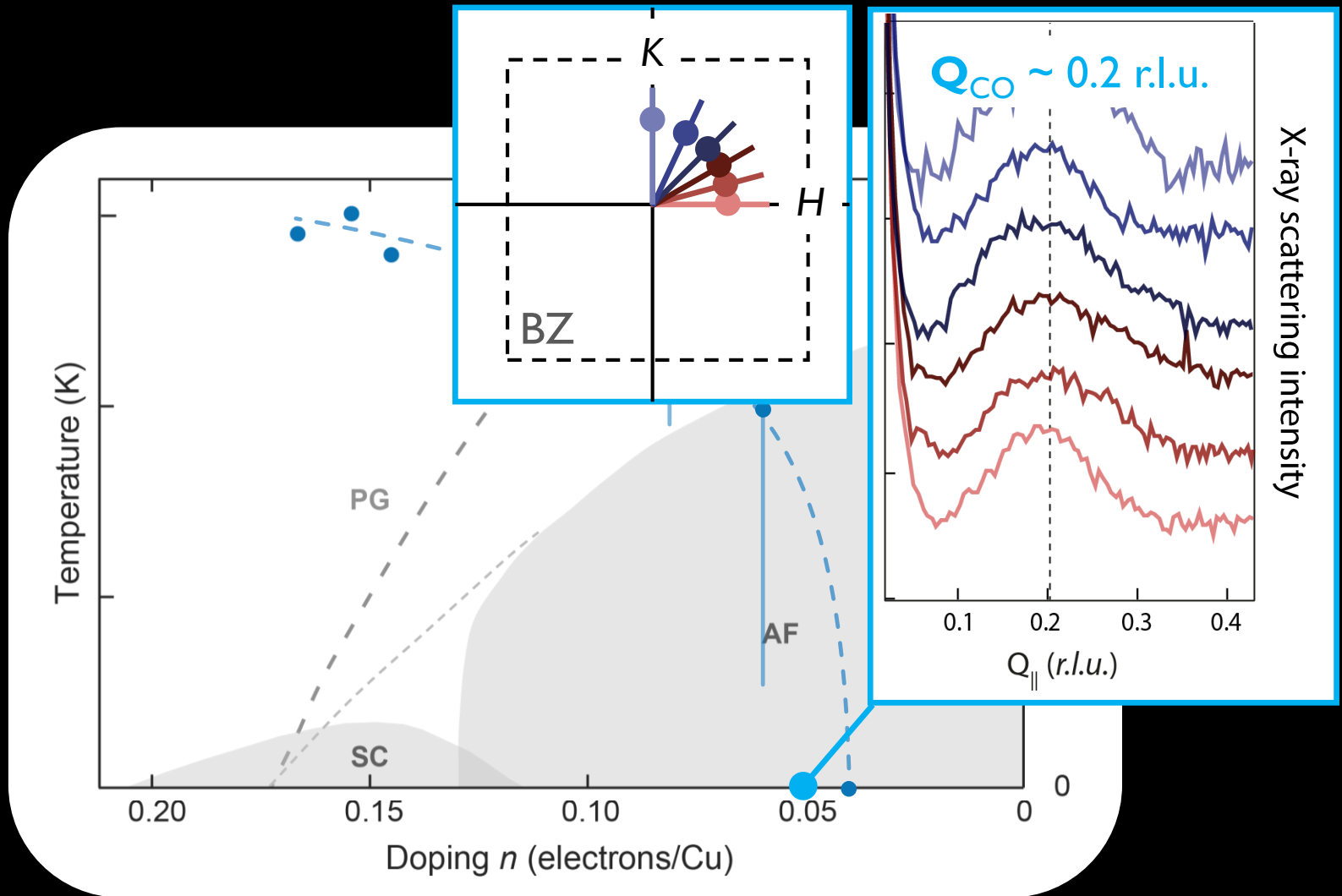
Min Gu
Kang



Electron-doped cuprates

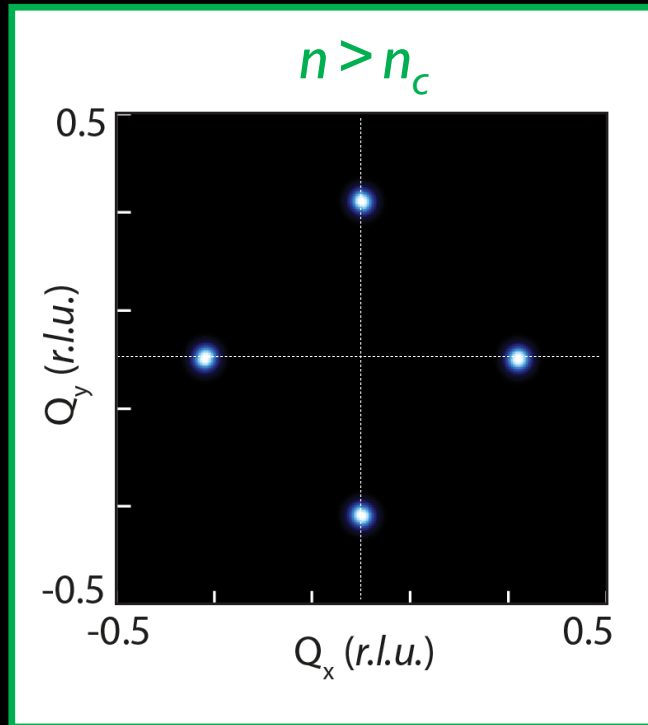


Electron-doped cuprates

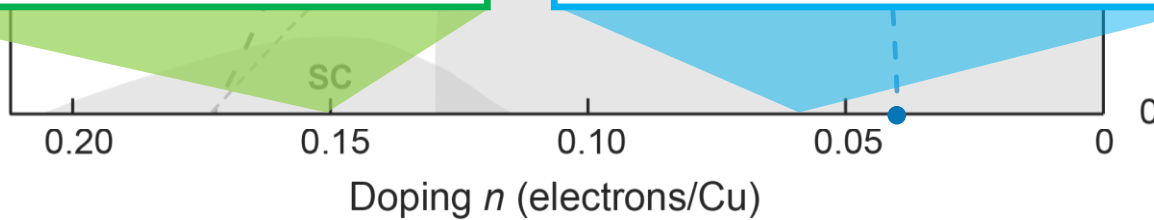
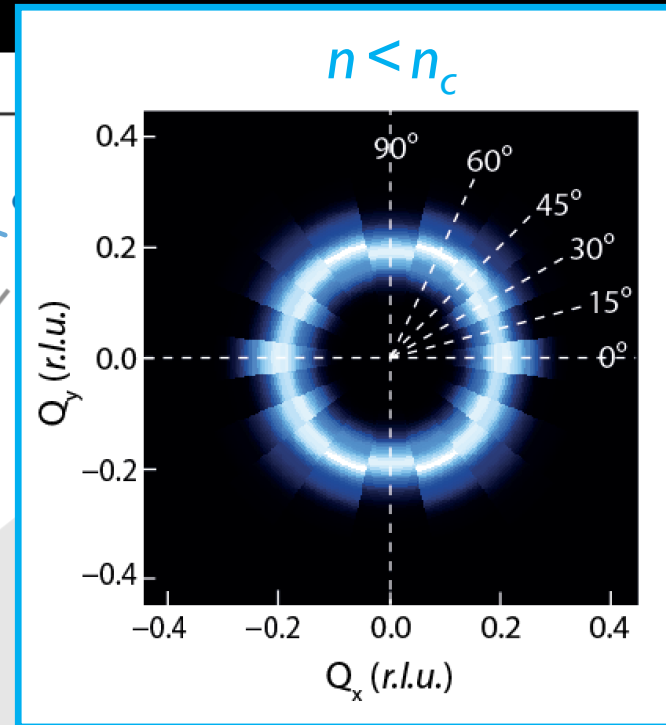


Electron-doped cuprates

Wigner crystal

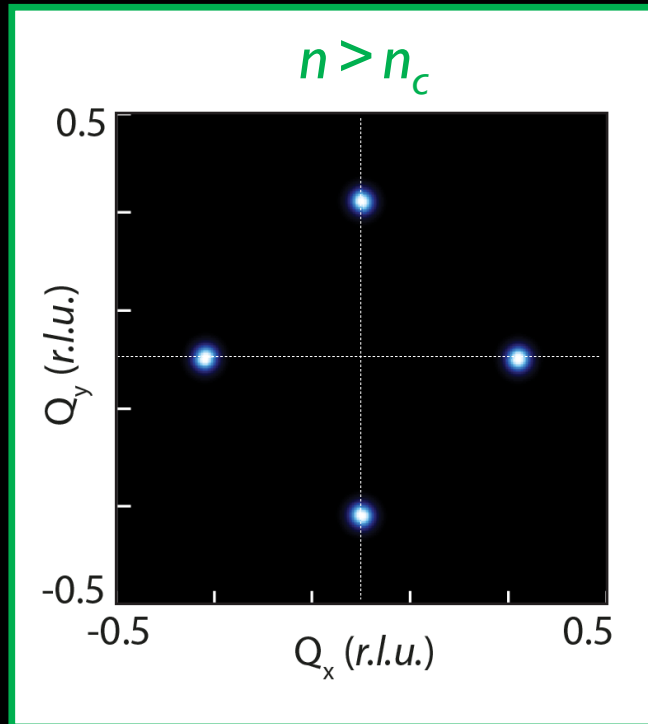


Wigner 'glass'



Electron-doped cuprates

Wigner crystal

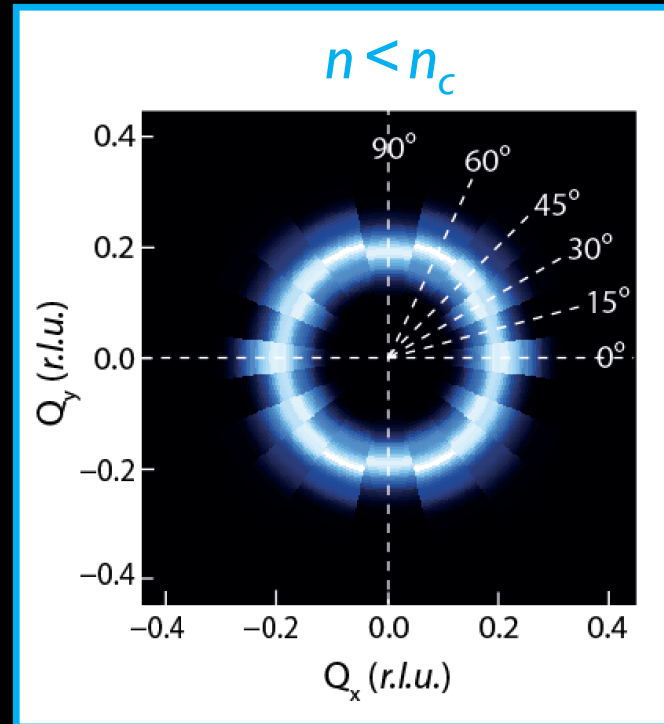


$Q \sim 0.33$ r.l.u.

Corr. length ~ 20 UC (long-ranged)

C_4 rotational symmetry

Wigner 'glass'



$Q \sim 0.2$ r.l.u.

Corr. length ~ 5 UC (short ranged)

C_∞ rotational symmetry

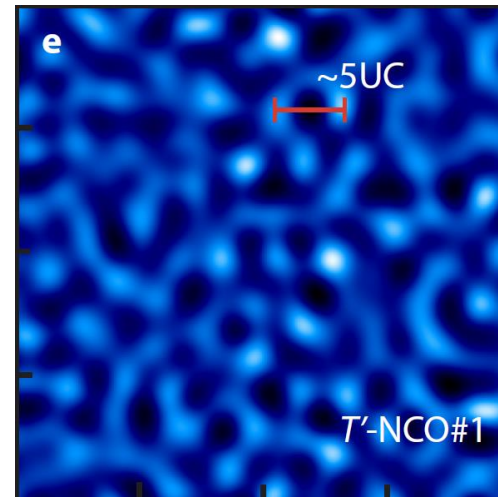
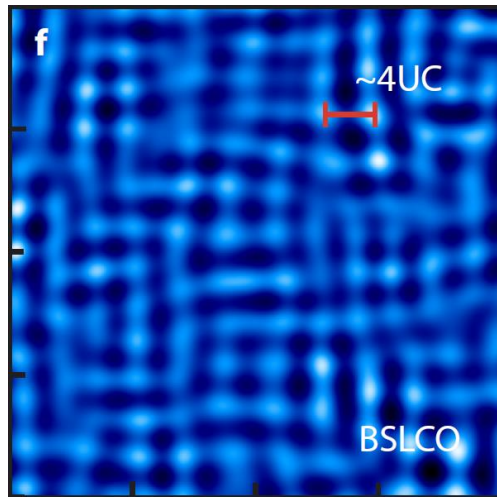
Electron-doped cuprates

Wigner crystal

Wigner 'glass'

$$n > n_c$$

$$n < n_c$$




NOT A
REAL STM

Charge order topology changes
across AFM critical doping

$Q \sim 0.33$ r.l.u.

$Q \sim 0.2$ r.l.u.

Corr. length ~ 20 UC (long-ranged)

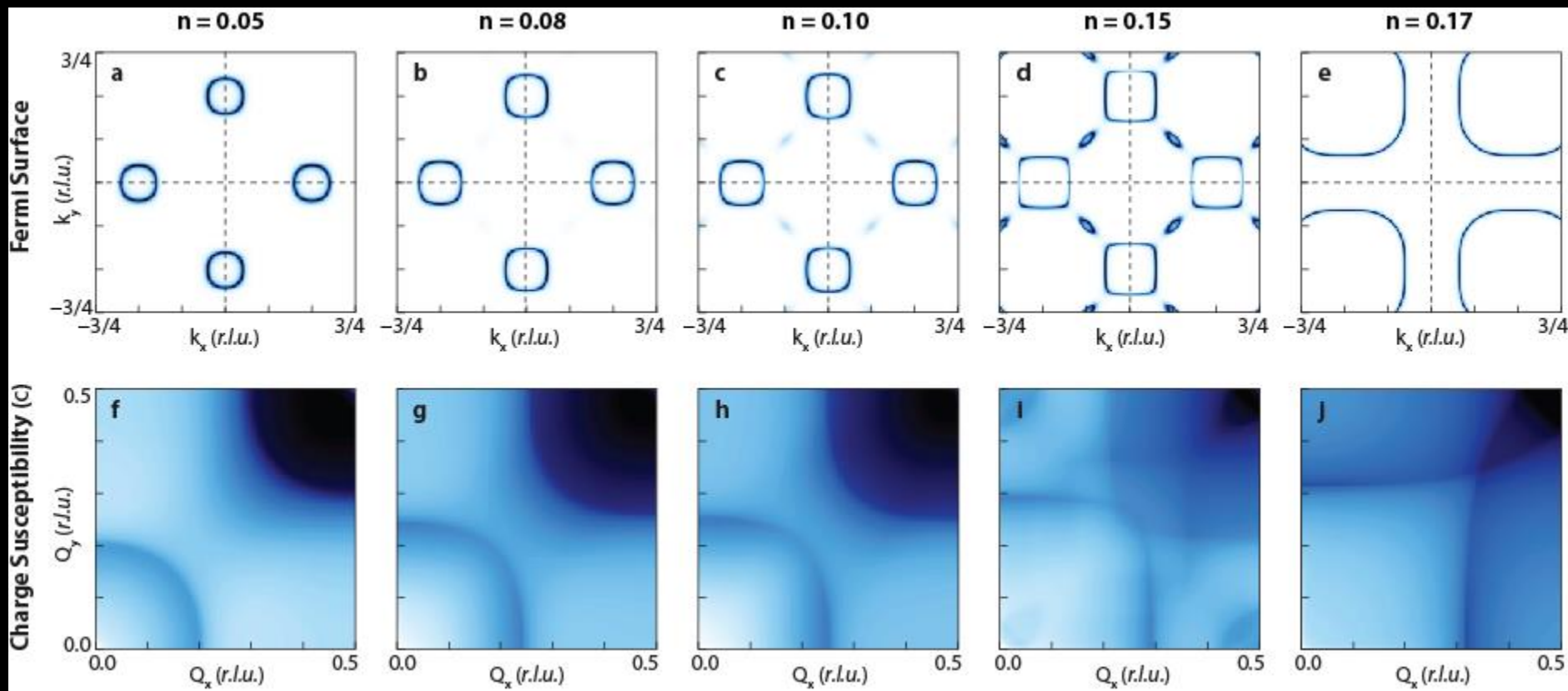
Corr. length ~ 5 UC (short ranged)

C_4 rotational symmetry

C_∞ rotational symmetry

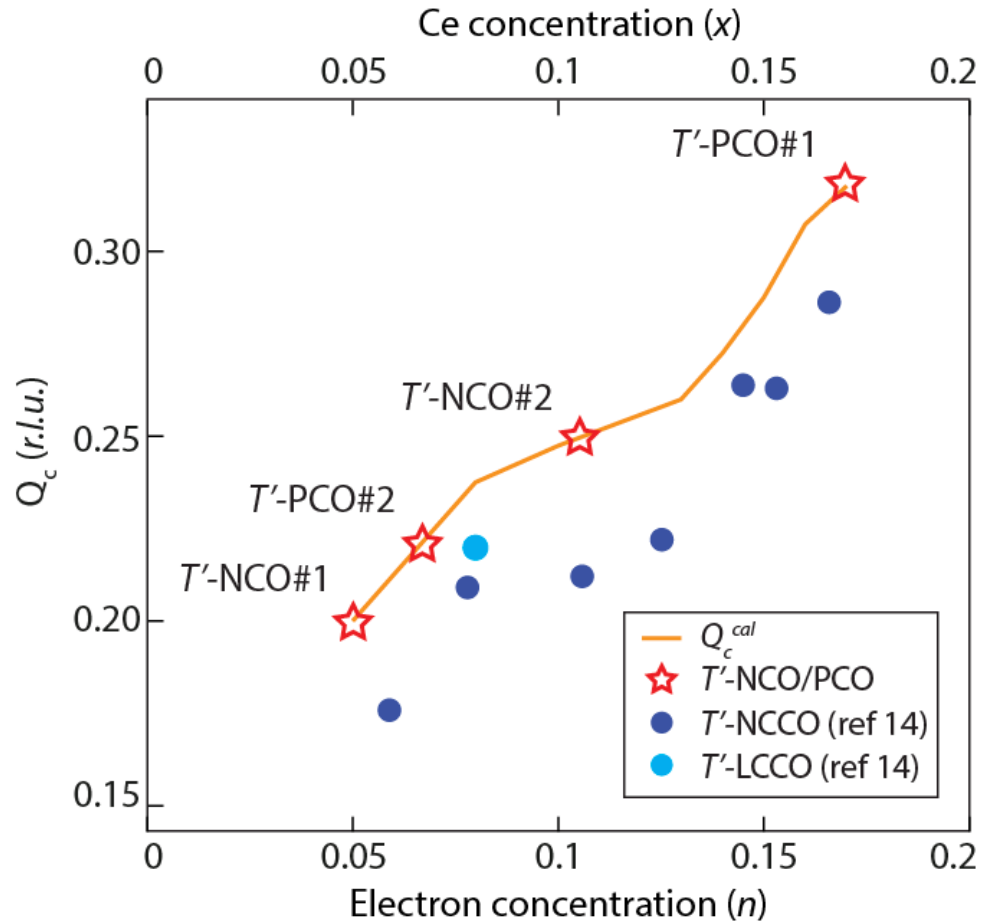
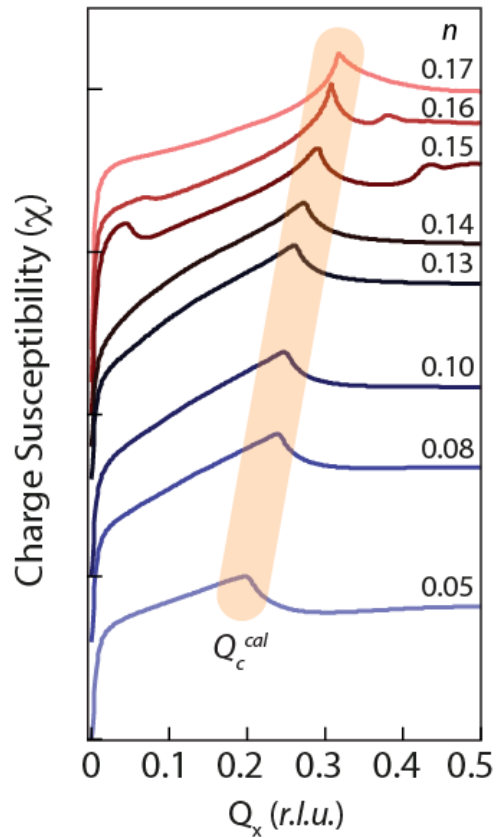
Electron-doped cuprates

Insights from the particle hole response...?



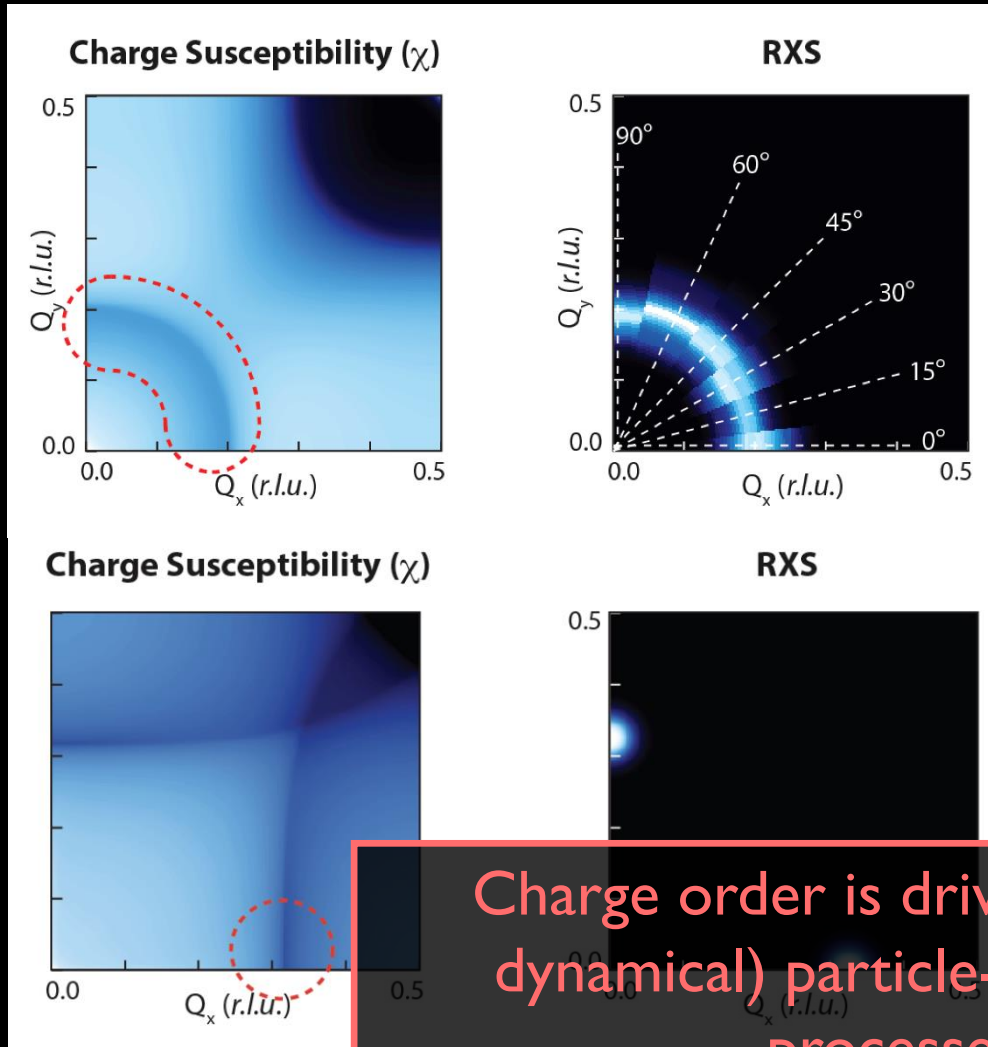
Courtesy of Tanmoy Das

Electron-doped cuprates



Electron-doped cuprates

Low doping limit
($n=0.05\sim 0.07$)

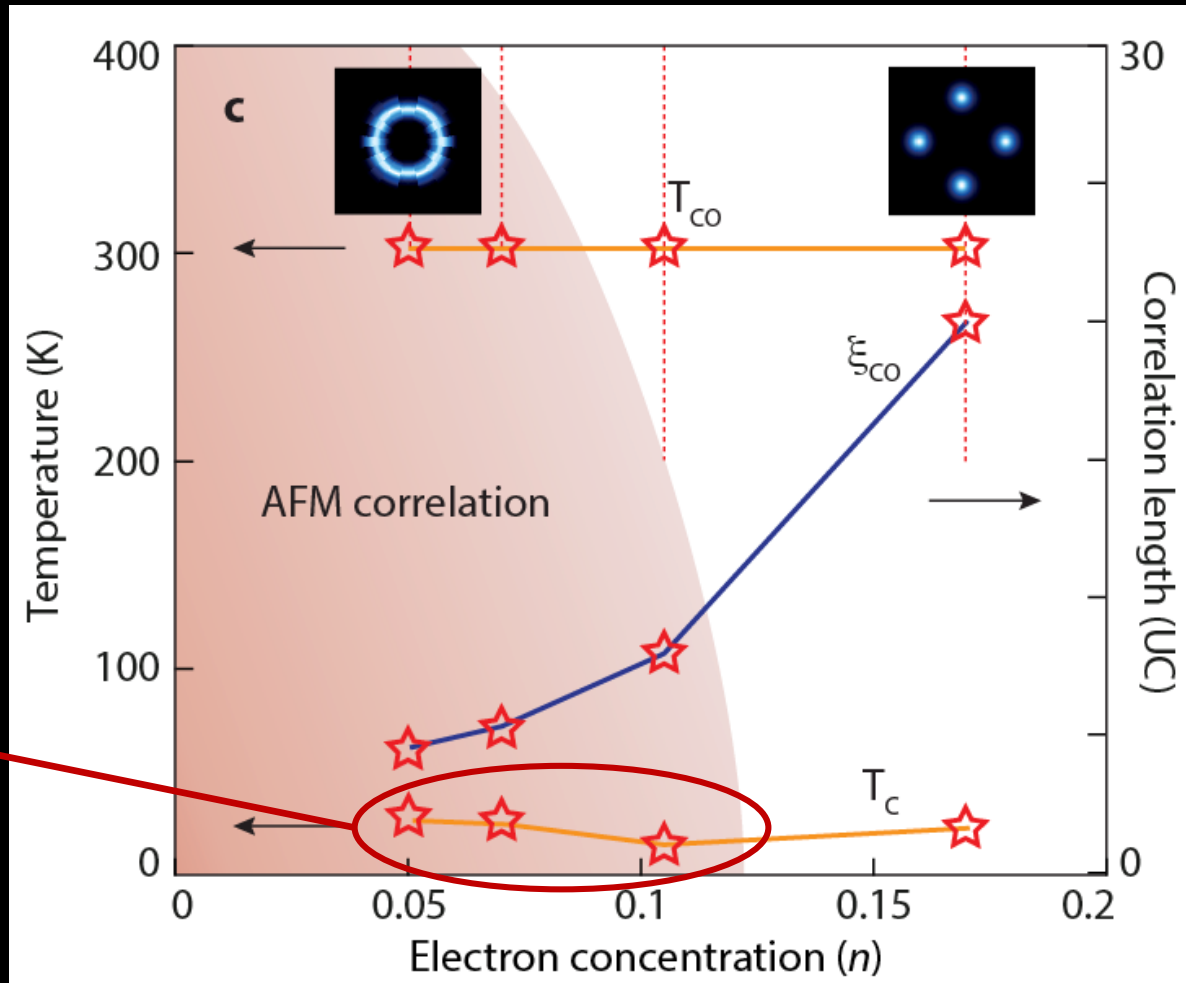


Red dotted regions highlight the local maxima of the charge susceptibility.

High doping limit
($n=0.15\sim 0.17$)

Charge order is driven by (possibly dynamical) particle-hole scattering processes across the FS

Electron-doped cuprates



Are these samples AFM?

CDWs in electron-doped cuprates: summary

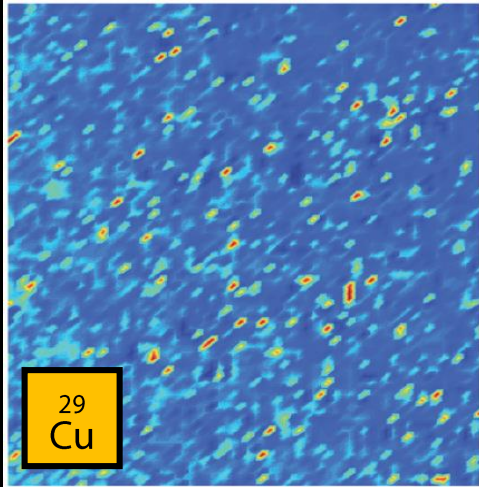
Open questions

- Is there a direct correlation between AFM order and the structure of density correlations?
- Does the topology of the structure factor change abruptly across the AFM p_c ?
- Phase separation of coexisting orders? (AFM, SC, CDW)
- How does the electronic structure reconcile a strongly-varying CDW wavevector and a nearly doping-independent superconducting transition?

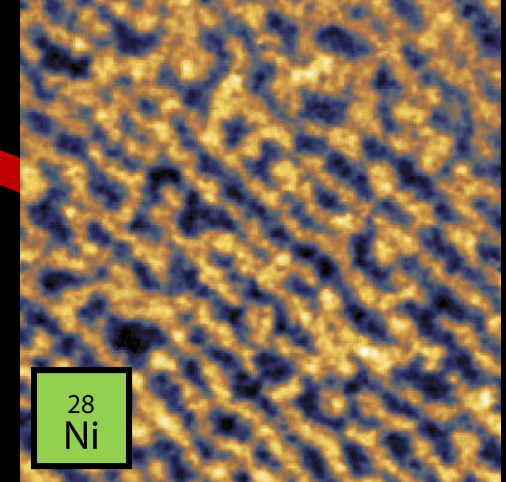
Charge/spin orders at the nanoscale

Strongly-interacting quantum matter

Charge order



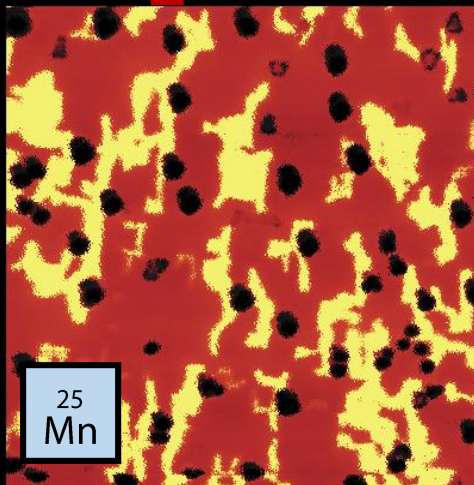
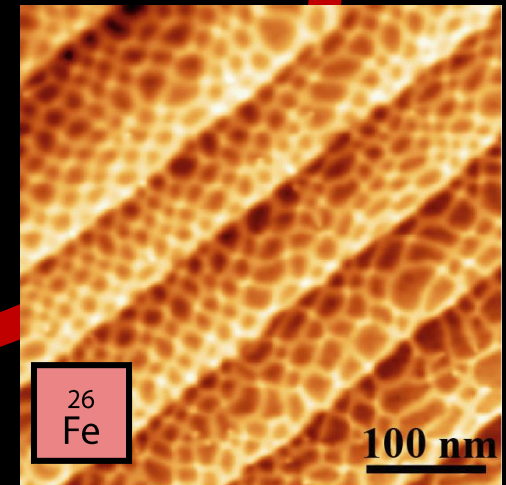
Metal-insulator transition



Emergent
spatial
textures



Nanoscale
phase
competition

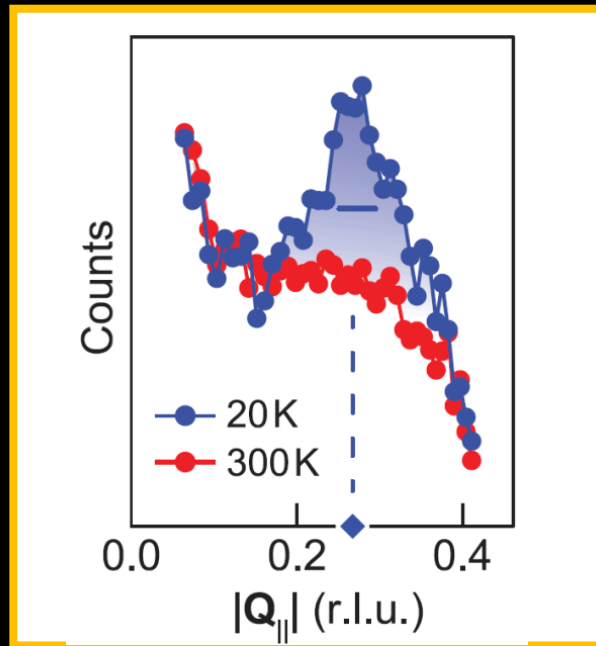


Spin order

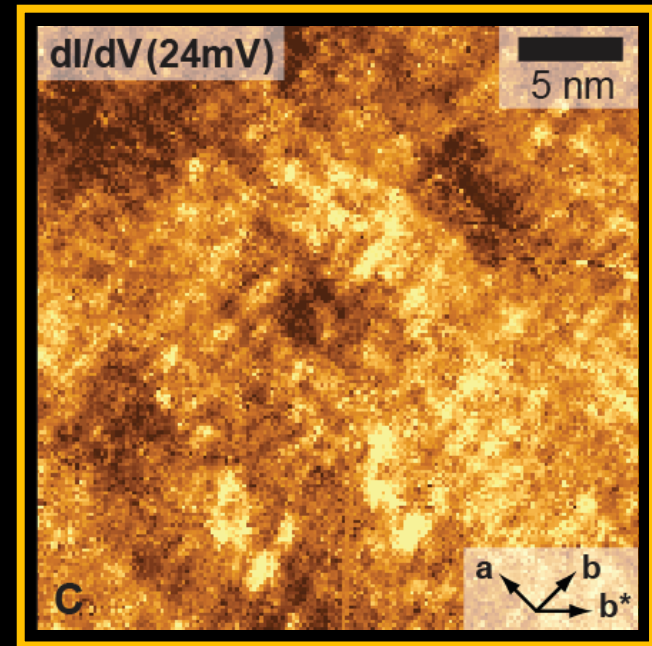
Superconductivity

Electronic orders at the nanoscale

Reciprocal space (scattering)



Real space (microscopy)



Information is **AVERAGED**
(density-density correlations)

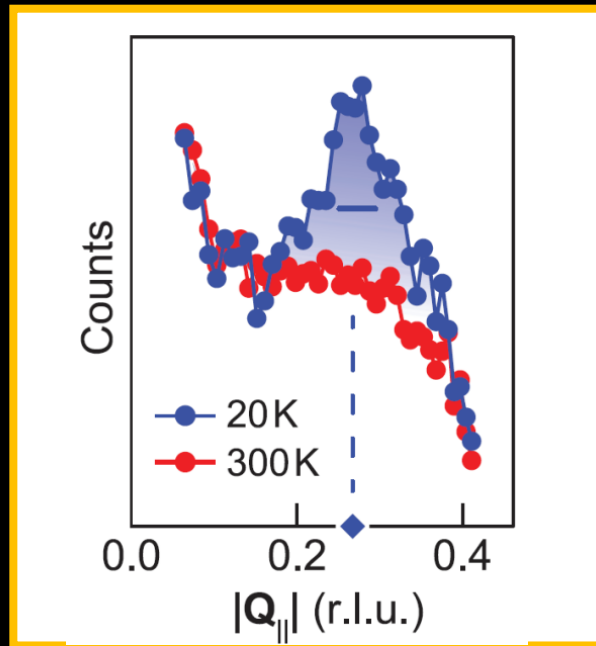
Amplitude of complex field: $|\rho(\vec{Q})|$

Information is **LOCAL**
(density of states)

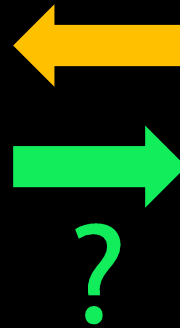
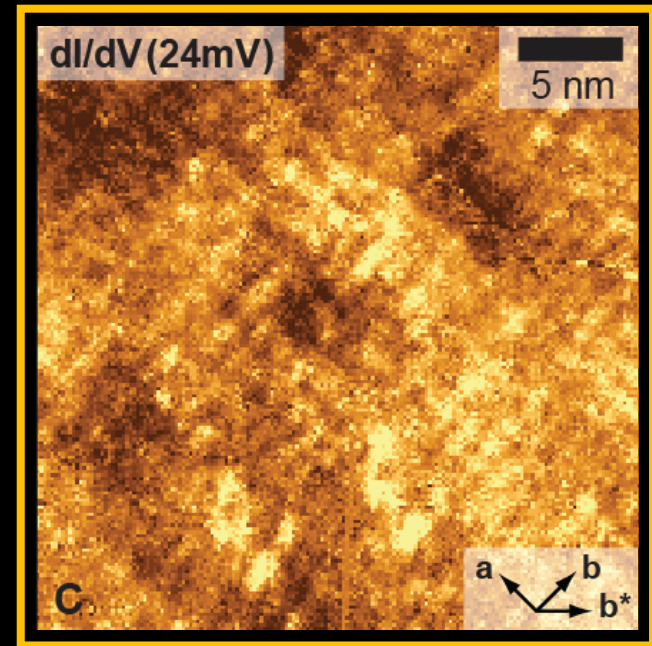
Real field: $\rho(\vec{r})$

Electronic orders at the nanoscale

Reciprocal space
(scattering)



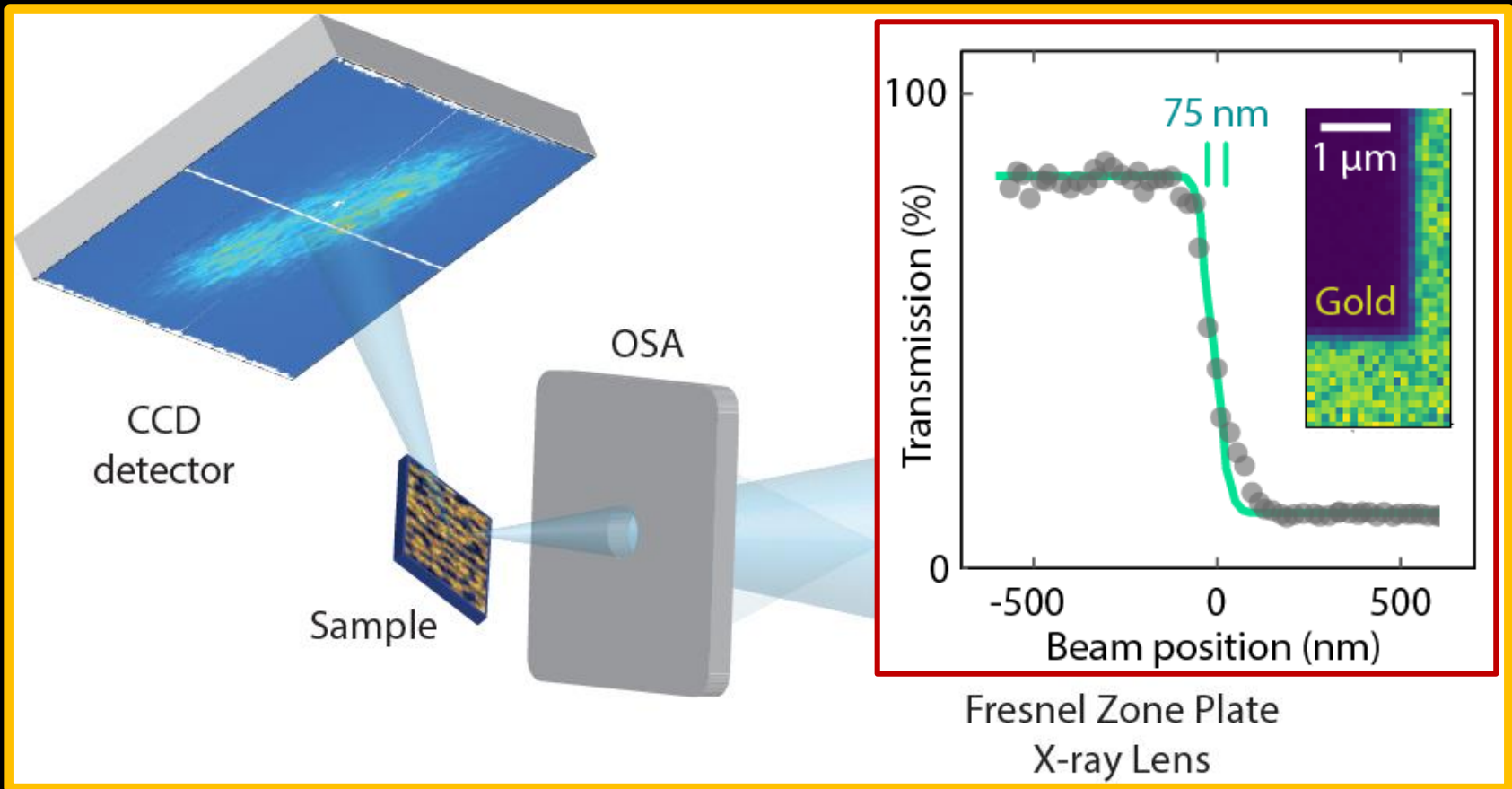
Real space
(microscopy)



Can we recover complementary real-space info?

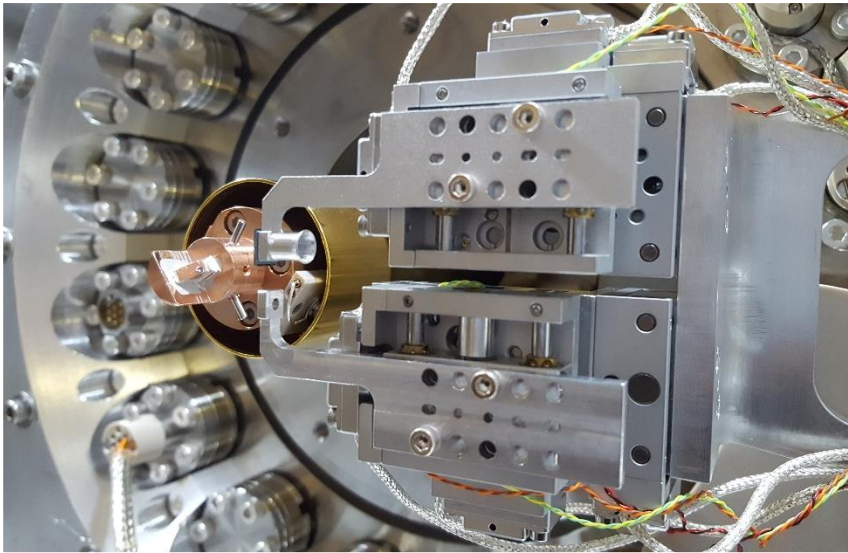
Soft X-ray nanodiffraction

Scanning resonant nanodiffraction

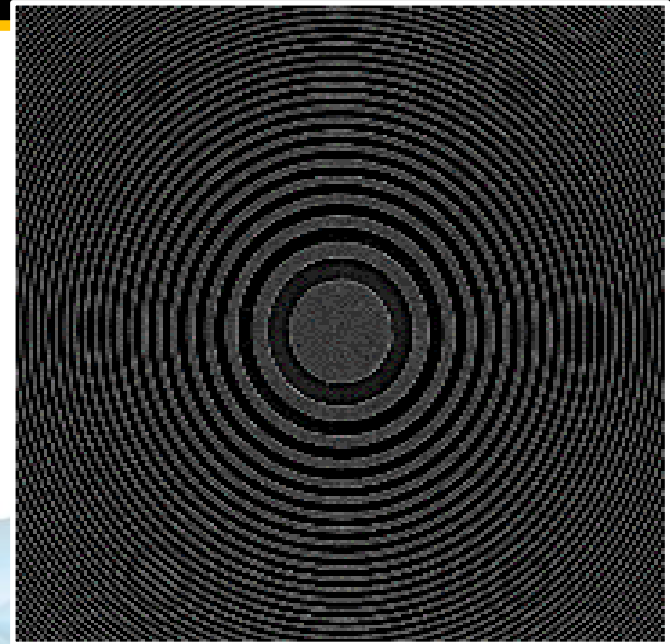


Soft X-ray nanodiffraction

Scanning resonant nanodiffraction



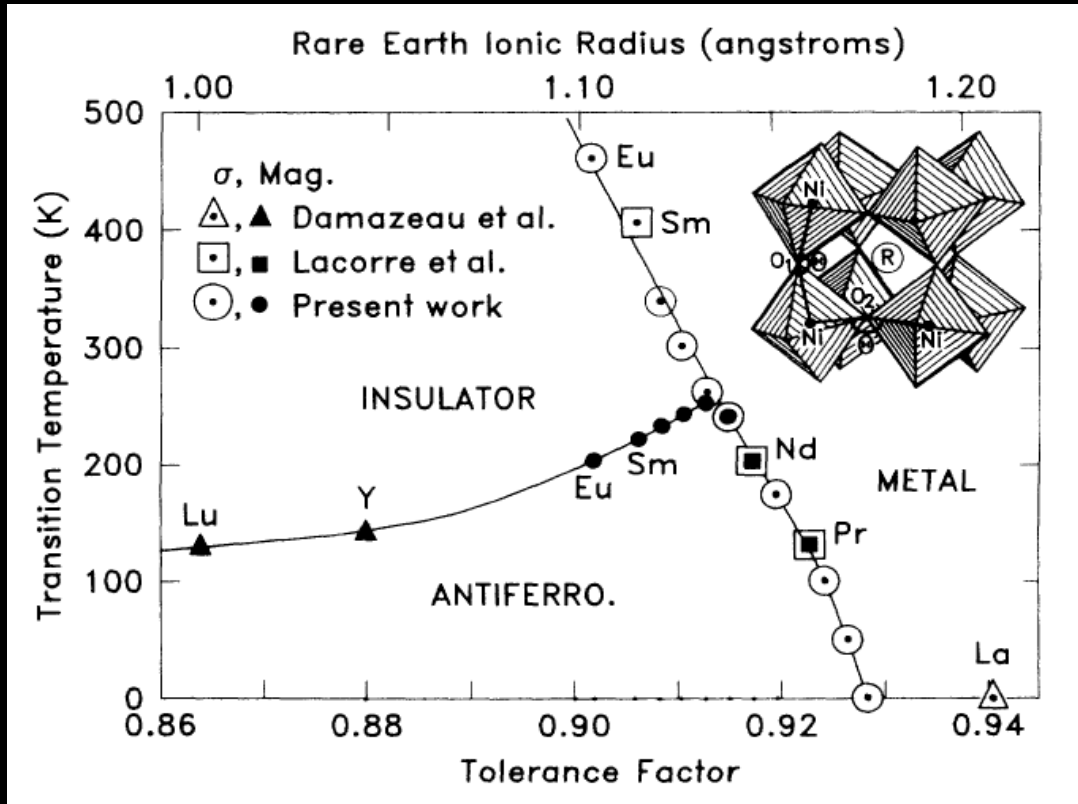
sample



Fresnel Zone Plate
X-ray Lens

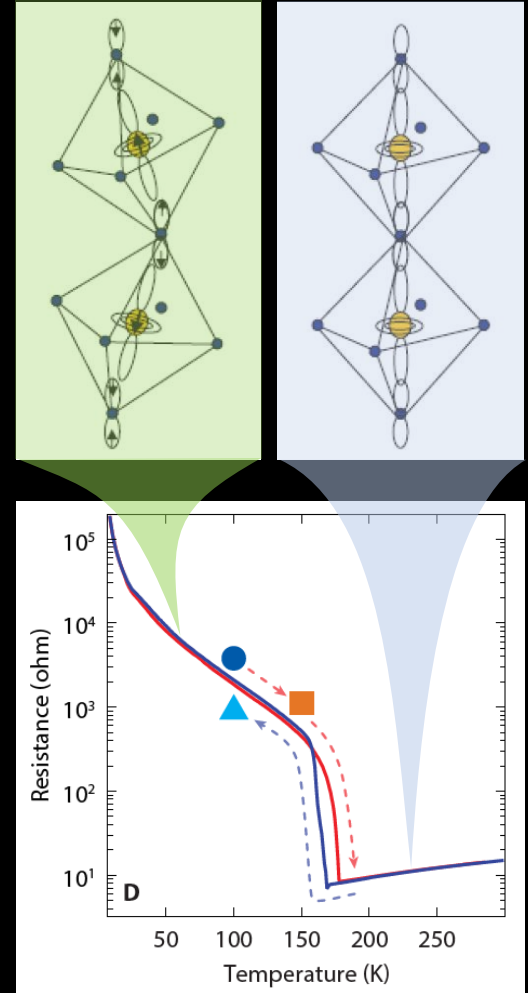
Rare earth nickelates

Cubic nickelate perovskites



Torrance et al. PRB 1992

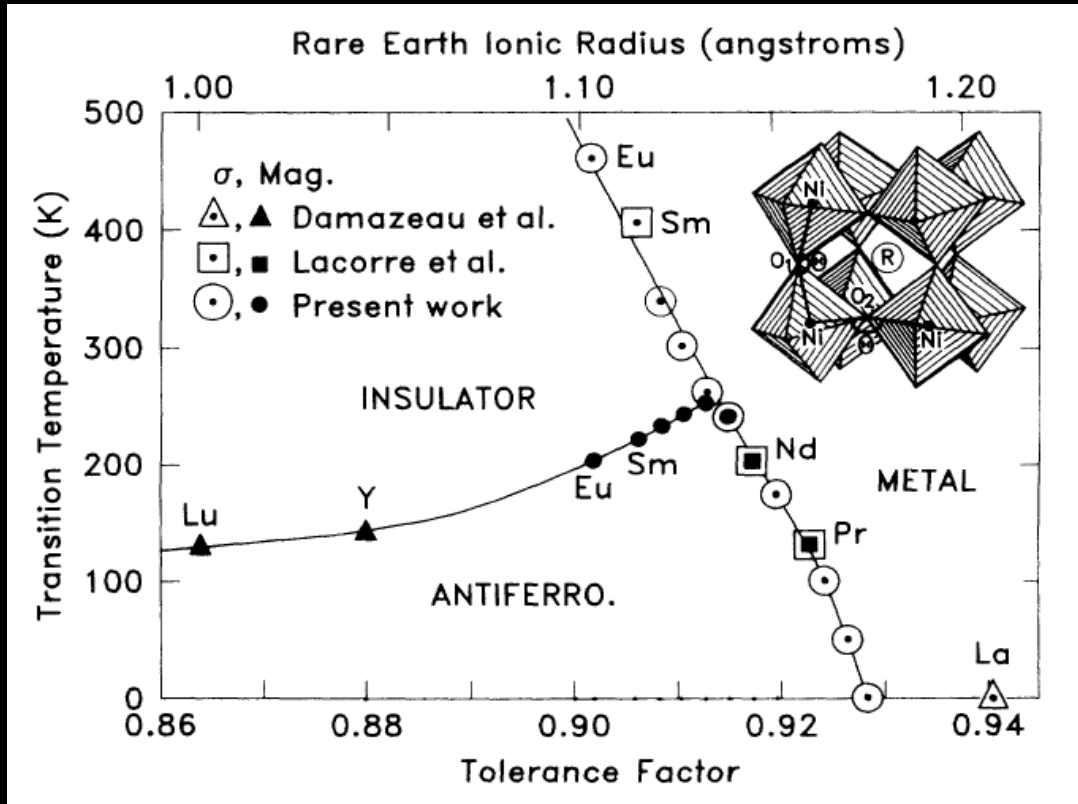
Low-T (insulator) High-T (metal)



Metal insulator transition

Rare earth nickelates

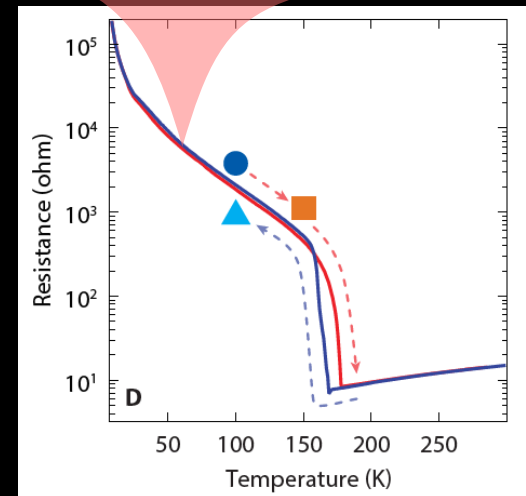
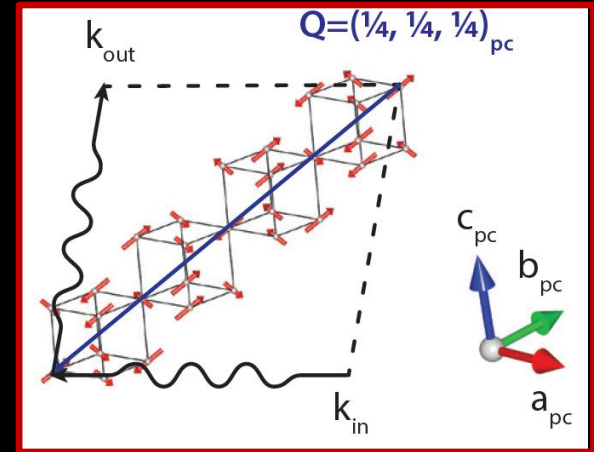
Cubic nickelate perovskites



Torrance *et al.* PRB 1992

Goal: map antiferromagnetic order across metal-insulator transition

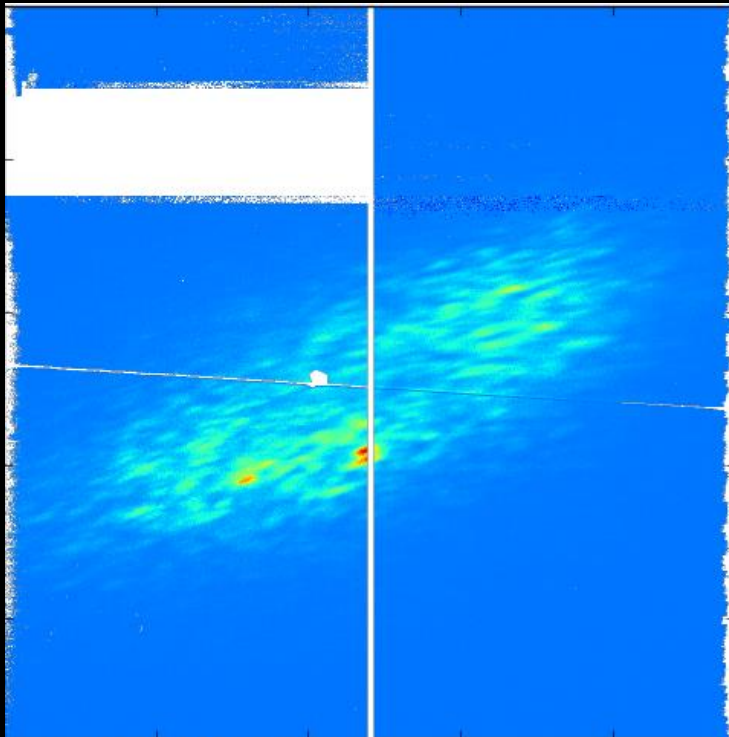
Magnetic order



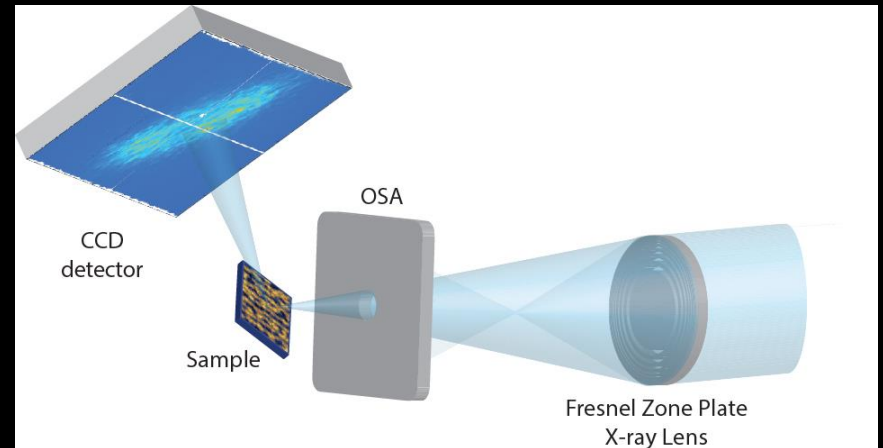
Metal insulator transition

Rare earth nickelates

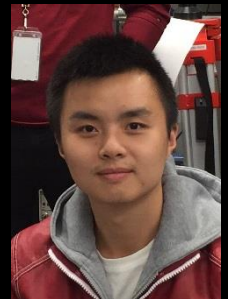
RECIPROCAL SPACE



Coherent magnetic scattering from
spin-density wave in NdNiO_3



Jiarui Li

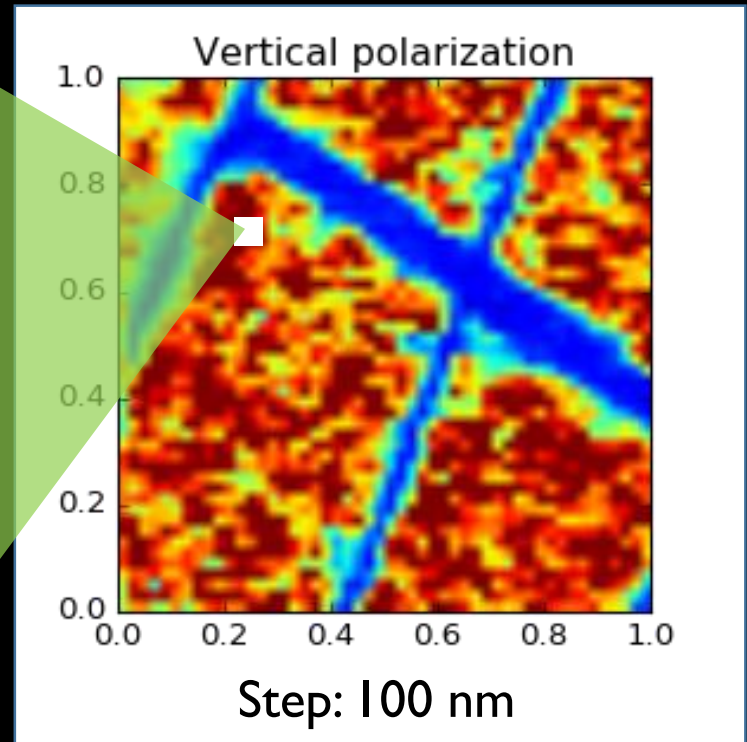
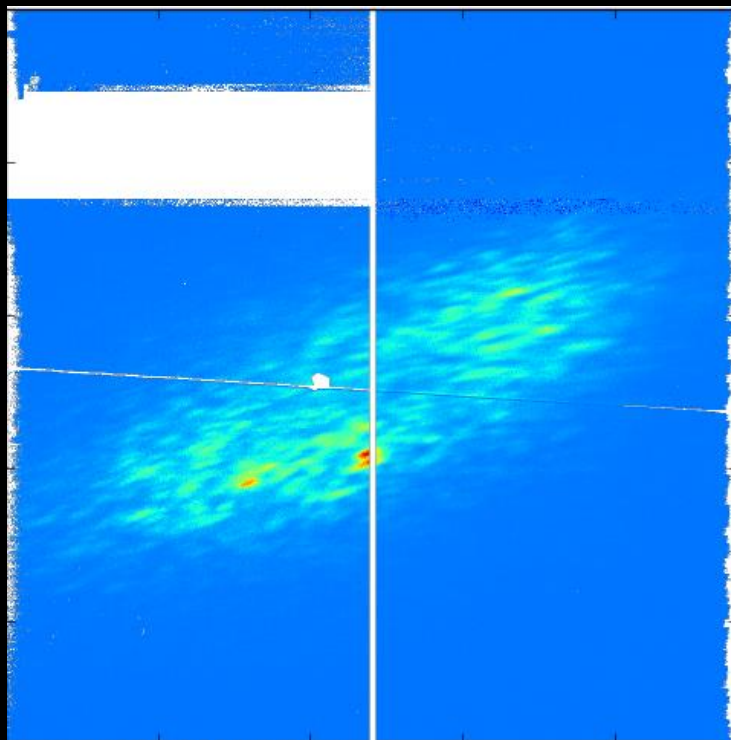


Rare earth nickelates

RECIPROCAL SPACE



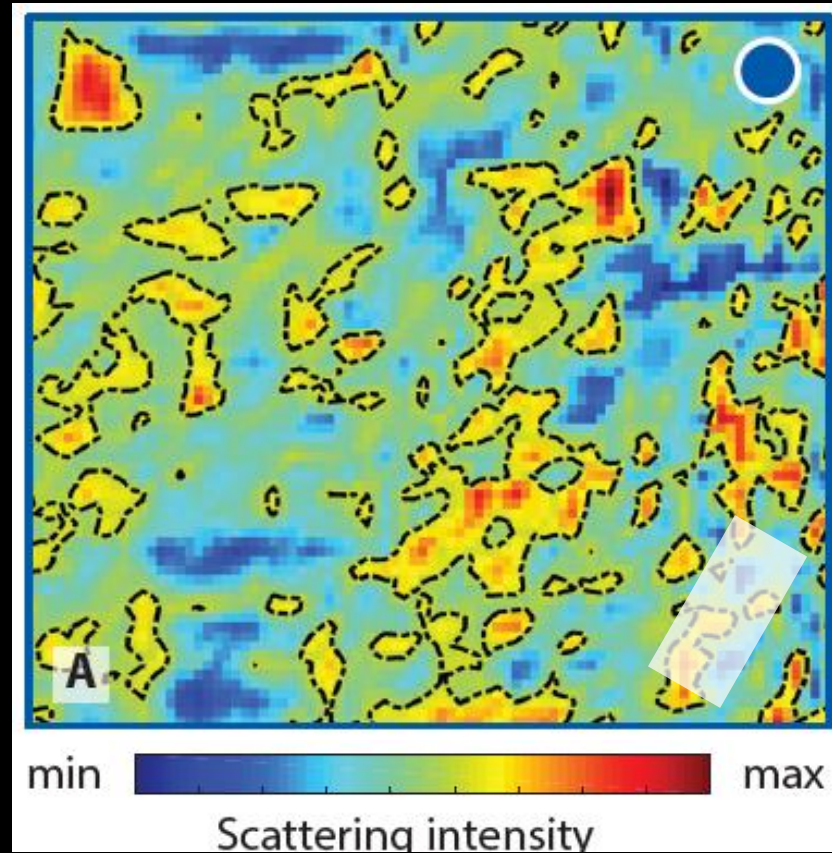
REAL SPACE (mapping)



Coherent magnetic scattering from spin-density wave in NdNiO_3

Nano-mapping of order parameter

Rare earth nickelates



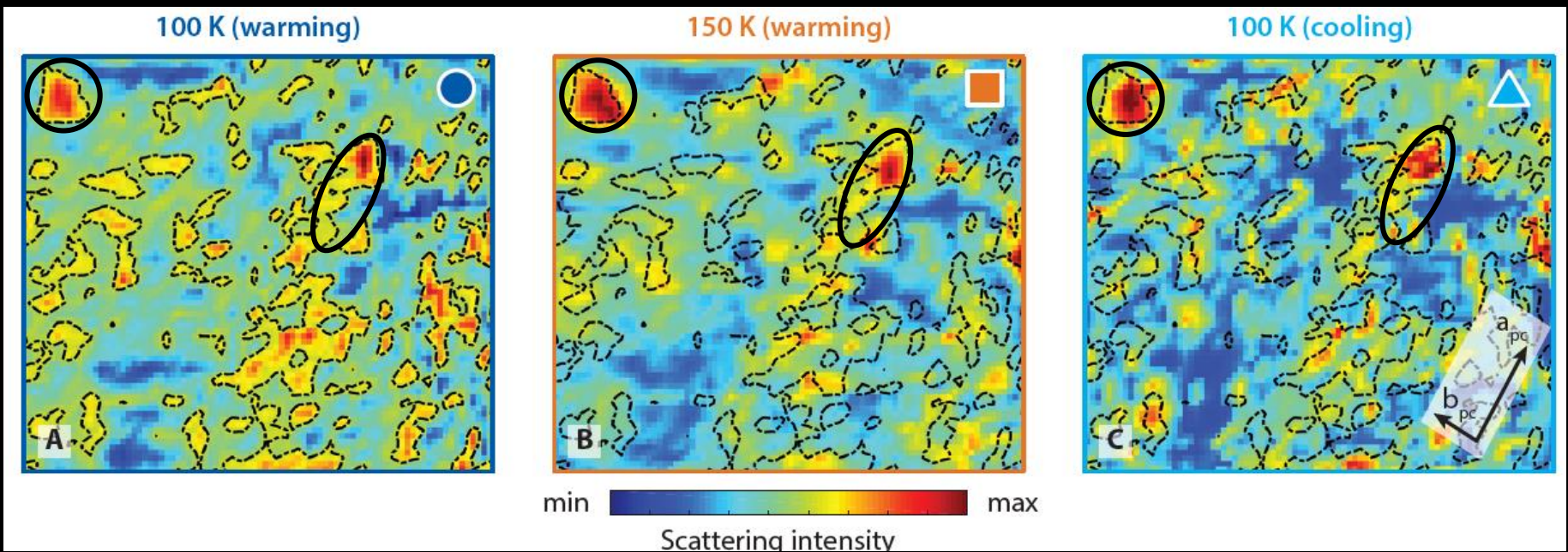
SDW order parameter

$1 \times 1 \mu\text{m}^2$
square

Nanoscale inhomogeneity on length scales $0.1 - 10 \mu\text{m}$

Rare earth nickelates

Mapping AFM domains across the magnetic and metal-insulator transition



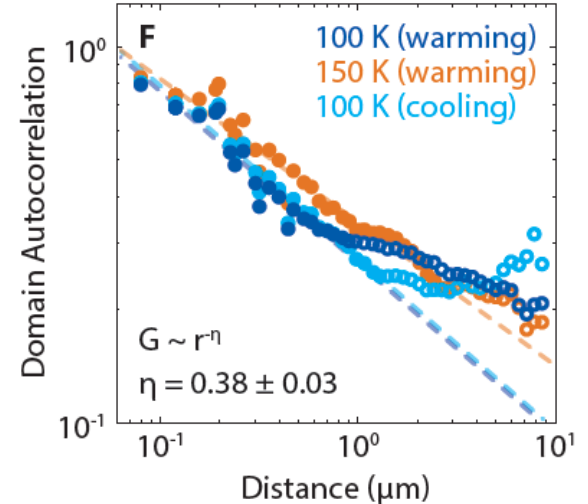
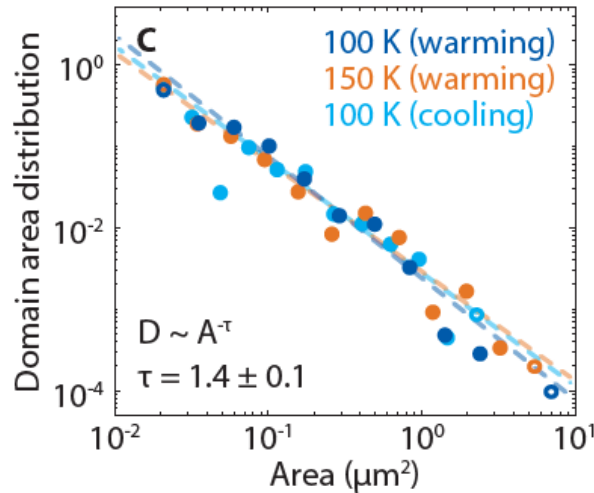
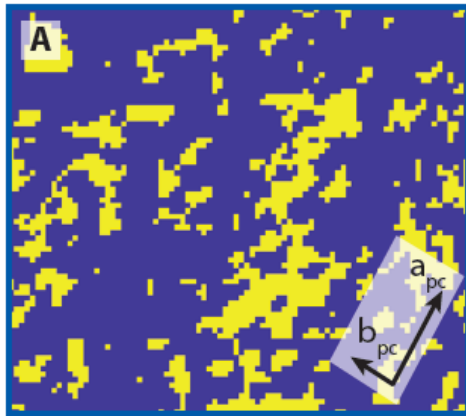
Domain pinning = memory effect

Possibly a hidden local parameter controlling domain nucleation

Rare earth nickelates

Scale-invariant textures – a **fractal** magnetic landscape

100 K (warming)



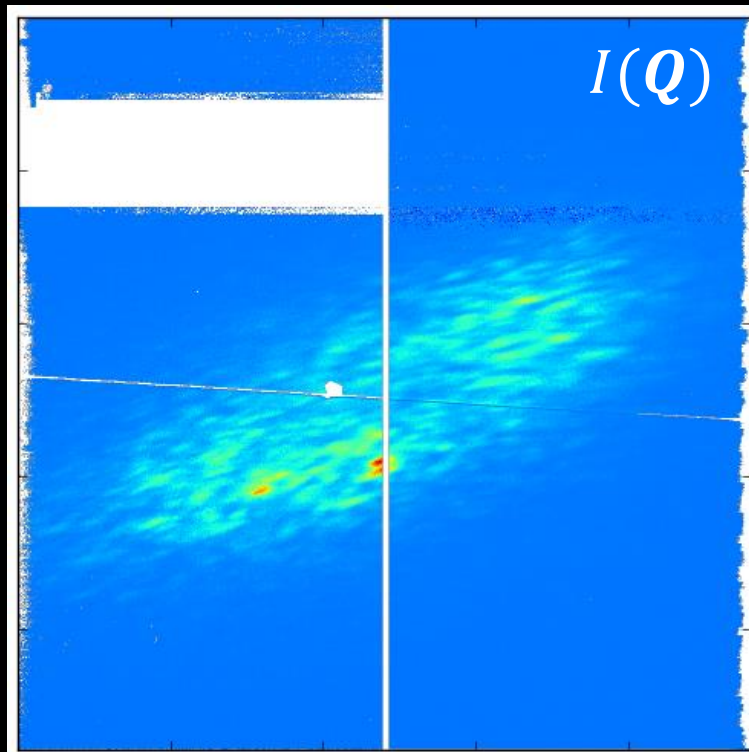
NdNiO₃ manifests near-critical behavior – static (quenched) spatial fluctuations appear at all length scales

Coherent Imaging

RECIPROCAL SPACE



REAL SPACE



Coherent magnetic scattering from
spin-density wave in NdNiO_3

Phase retrieval problem
(recover a complex Fourier
transform)

$$F(\mathbf{Q}) = \sqrt{I(\mathbf{Q})} \cdot \exp[i\phi(\mathbf{Q})]$$

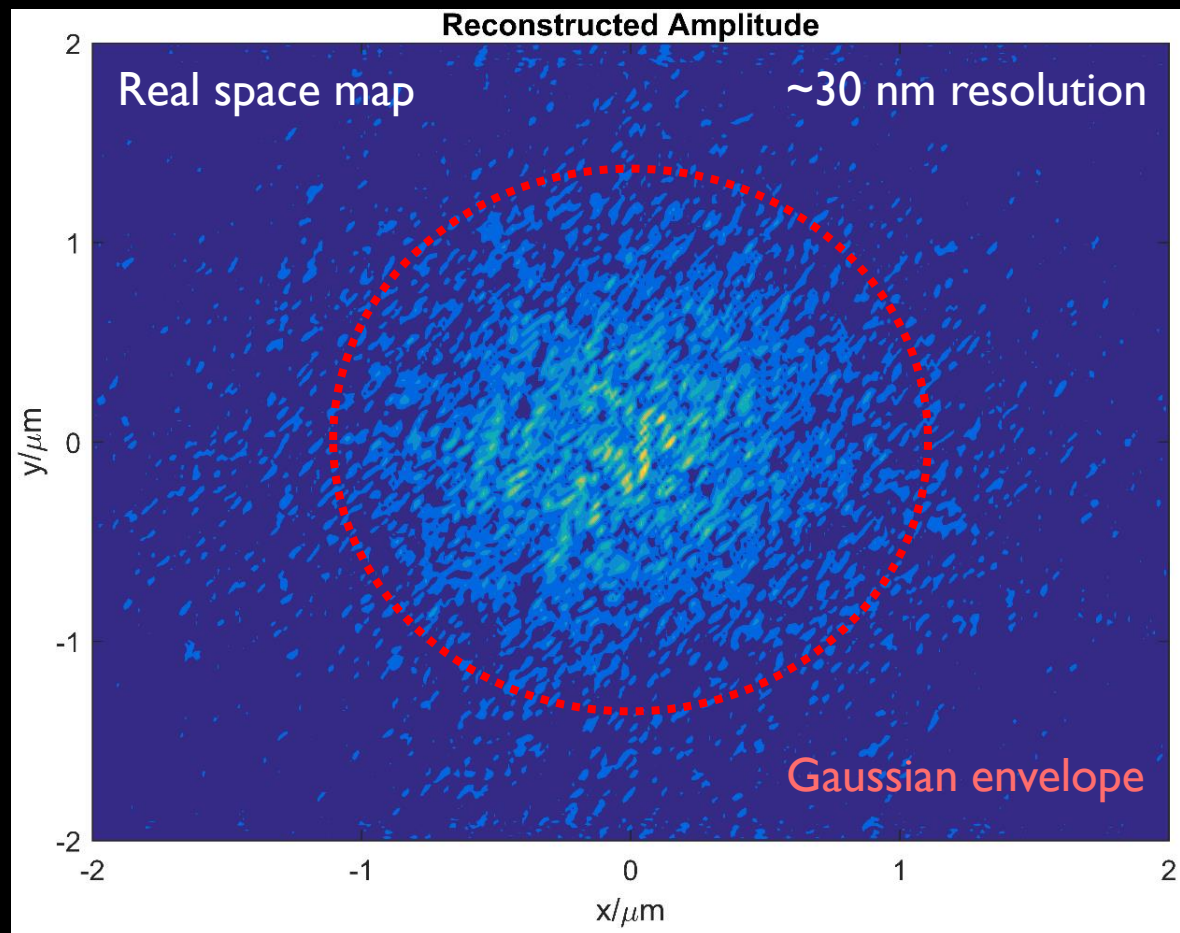


We need to recover the
phases of the exit waves

Coherent Imaging

COHERENT DIFFRACTIVE IMAGING

Some preliminary attempts in NdNiO_3 (*shrinkwrap*)

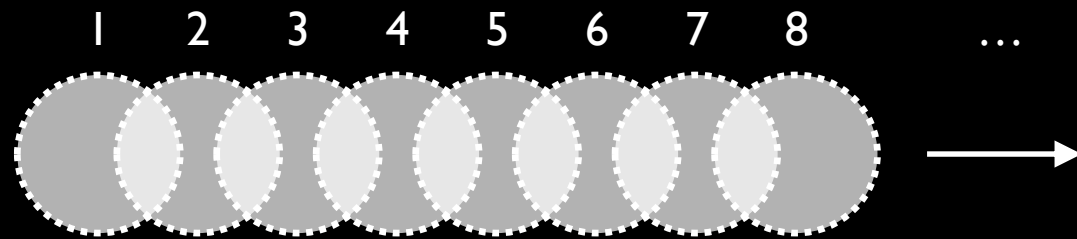


1 sec
acquisition
time!!

Coherent Imaging

PTYCHOGRAPHY

Measure overlapping regions and enforce a single-valued real field

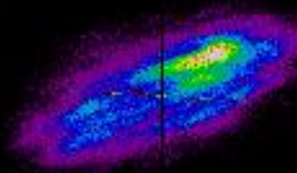
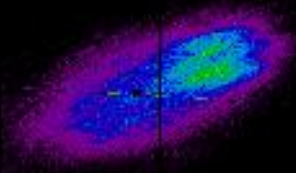
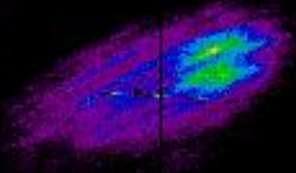
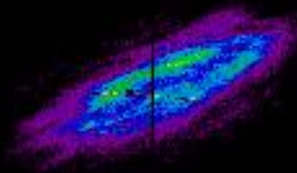


SPOT 1

SPOT 2

SPOT 3

SPOT 4

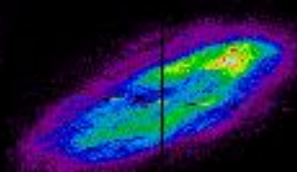
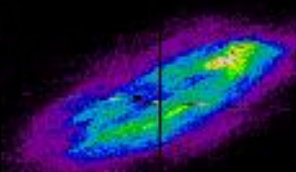
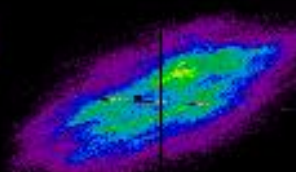
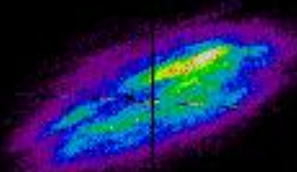


SPOT 5

SPOT 6

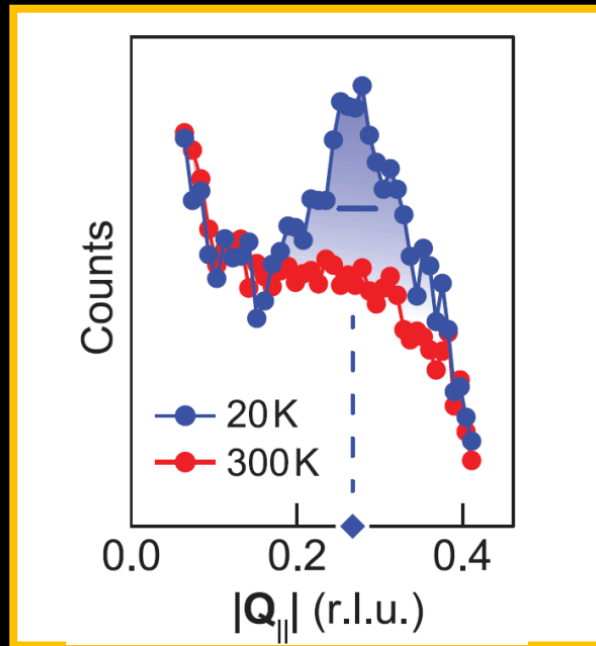
SPOT 7

SPOT 8

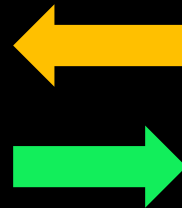
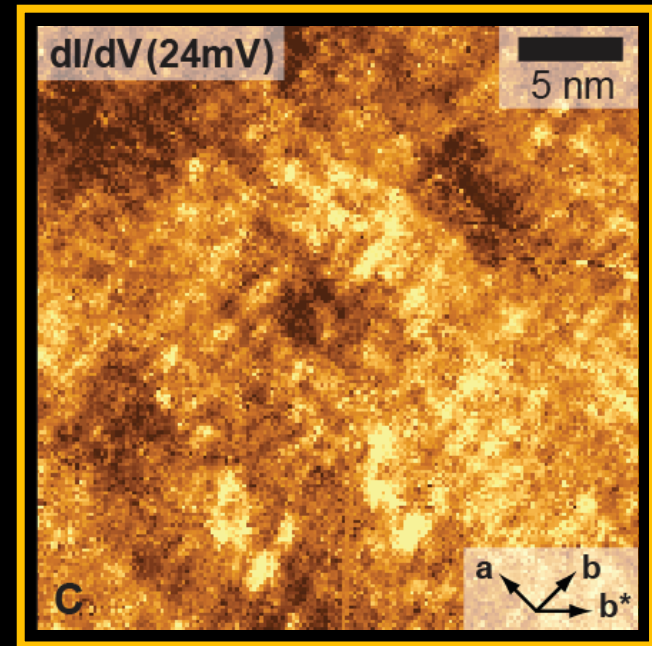


New opportunities at the horizon

Reciprocal space
(scattering)



Real space
(microscopy)



Can we recover complementary real-space info?

Yes, we can

Acknowledgments (cuprates)



MIT Photon Scattering Lab

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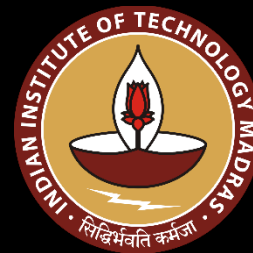
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