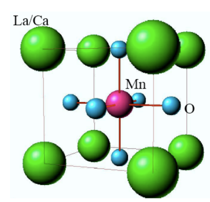
Resonant Coherent X-ray Imaging

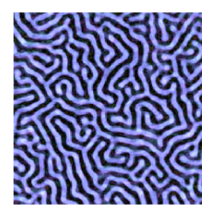
Ian McNulty

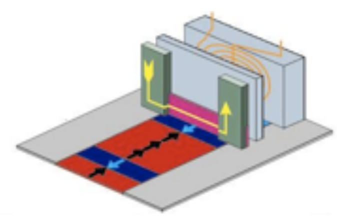
Advanced Photon Source

Workshop on Diffraction Microscopy, Holography and Ptychography using Coherent Beams

Cornell University, 7 June 2011



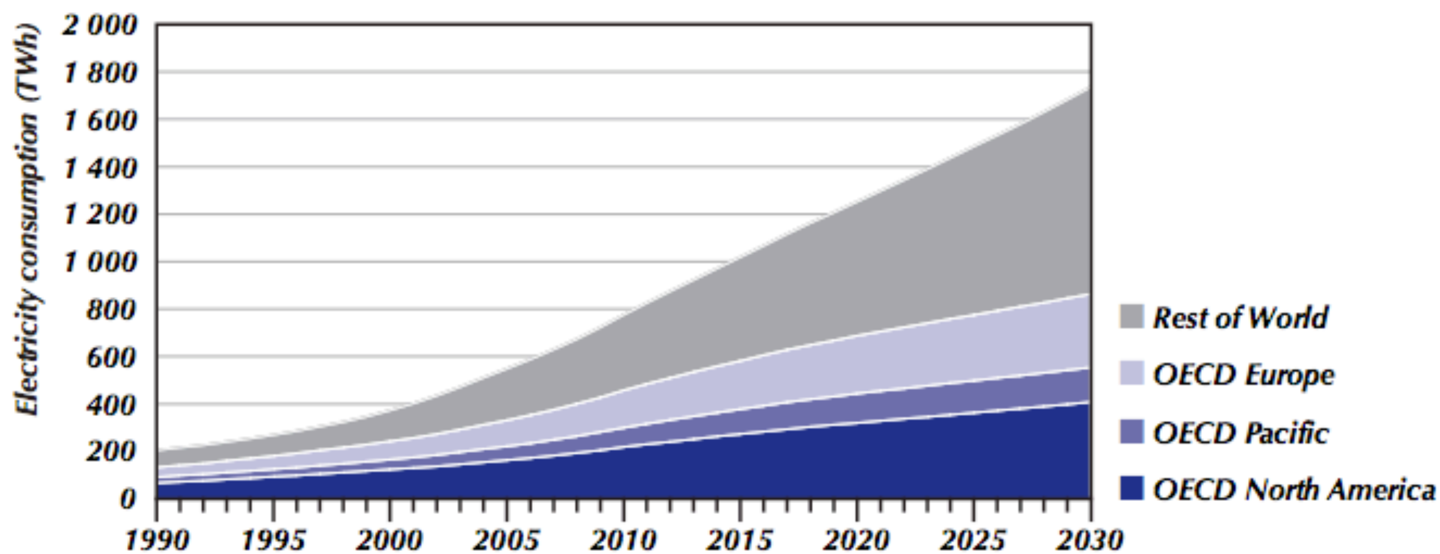




By 2010 there will be over 3.5 billion mobile phones subscribers, 2 billion TVs in use around the world and 1 billion personal computers. Electronic devices are a growing part of our lives and many of us can count between 20 and 30 separate items in our homes, from major items like televisions to a host of small gadgets. The communication and entertainment benefits these bring are not only going to people in wealthier nations – in Africa, for example, one in nine people now has a mobile phone. But as these electronic devices gain popularity, they account for a growing portion of household energy consumption.

Communication technologies (ICT) and consumer electronics (CE) now account for approximately 15% of global residential electricity consumption

Figure 3 • Estimated electricity consumption by ICT and CE equipment in the residential sector, by region, 1990-2030



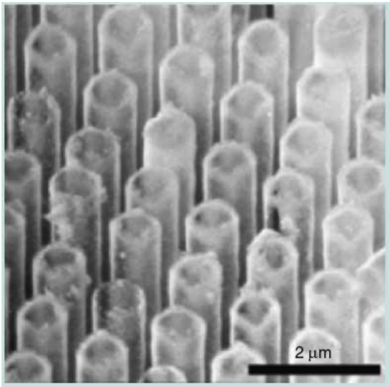
Source: IEA estimates.

Imagine …

- Spin-based non-volatile memory devices and transistors that take almost no power -> "Instant-on" computers

- Ultrafast devices in which a spin-polarized supercurrent propagates over long distances -> sat-phone-in-a-watch

- Room-temperature magnetic field sensors with the sensitivity of a SQUID; efficient, miniature cooling devices and high-power microwave, electron, and x-ray sources



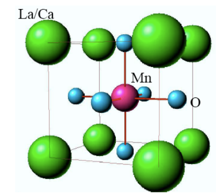
Ferroelectric $SrBi_2Ta_2O_9$ nanotubes

C.A.F. Vaz, Adv. Mater. 20, 1 (2010)

J.F. Scott, Science 315, 954 (2007)

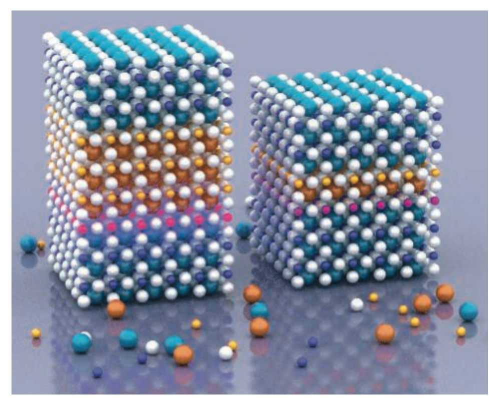
Challenging science in bulk condensed matter at the sub-10 nm scale

- Understand competing nanoscale phases and ordering with resultant strain in strongly correlated electron materials



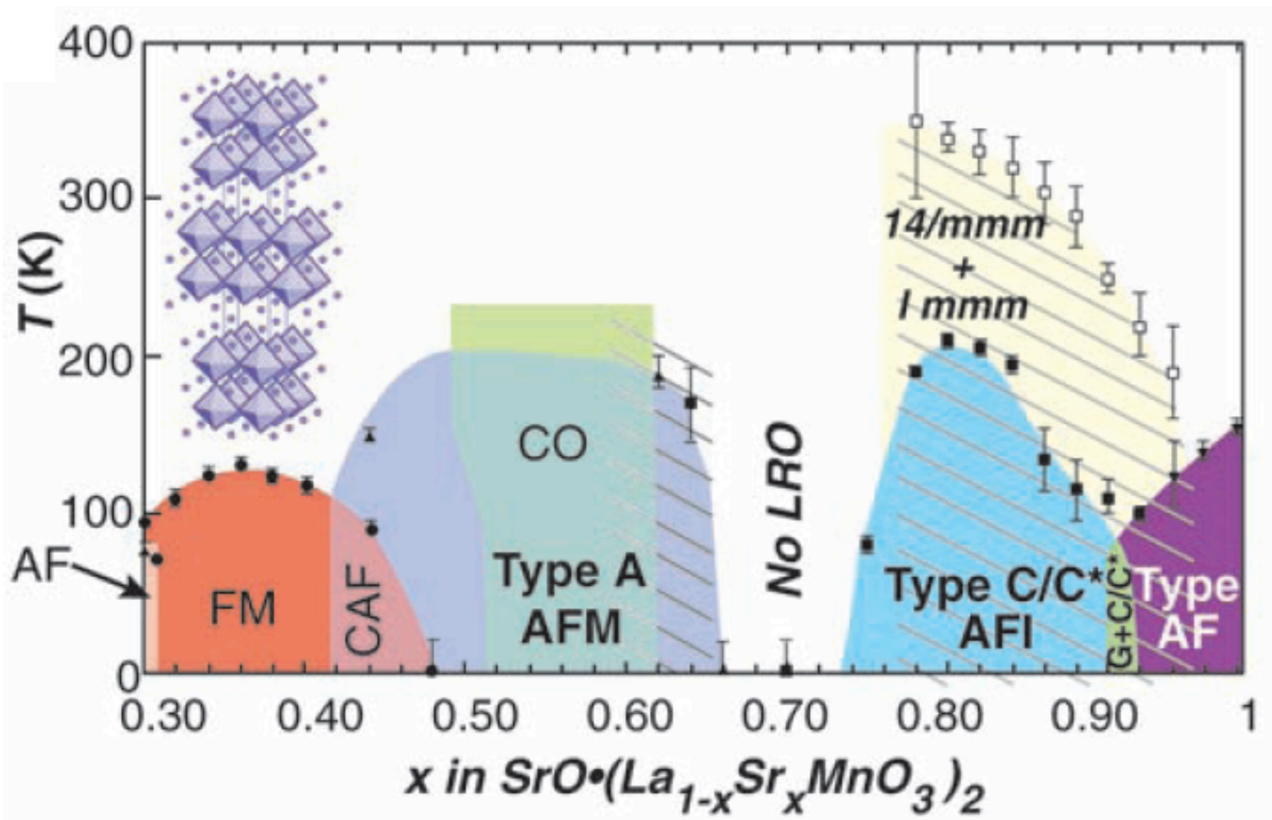
- Probe interfaces between different oxides with coupled order parameters, such as in bilayers and heterostructures of magnetoresistive and superconducting materials

- Map domain wall (magnetic, orbital, charge) structure, transport, and fluctuations in magnetic materials and devices with coupled order parameters



Complex disorder: nanoscale phase separation

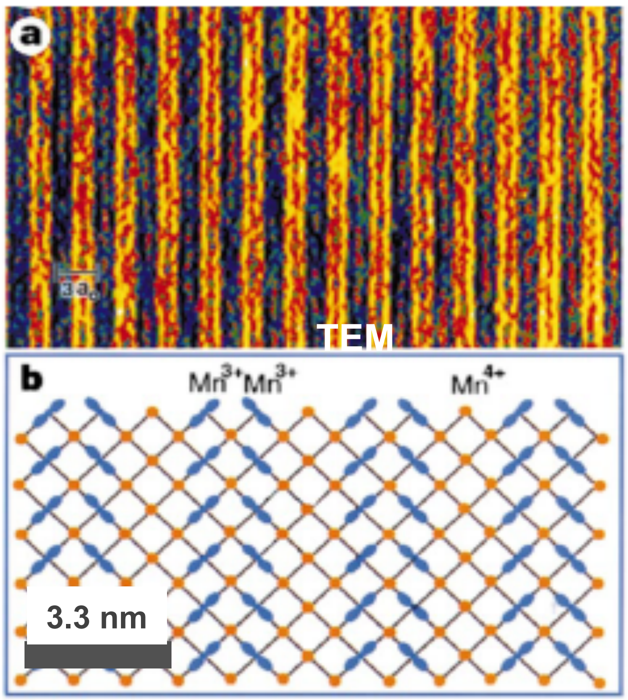
Strongly competing ground-state spin, charge, orbital, lattice degrees of freedom give rise to complex phase diagrams → phase separation



E. Dagotto, Science 309, 262 (2005)

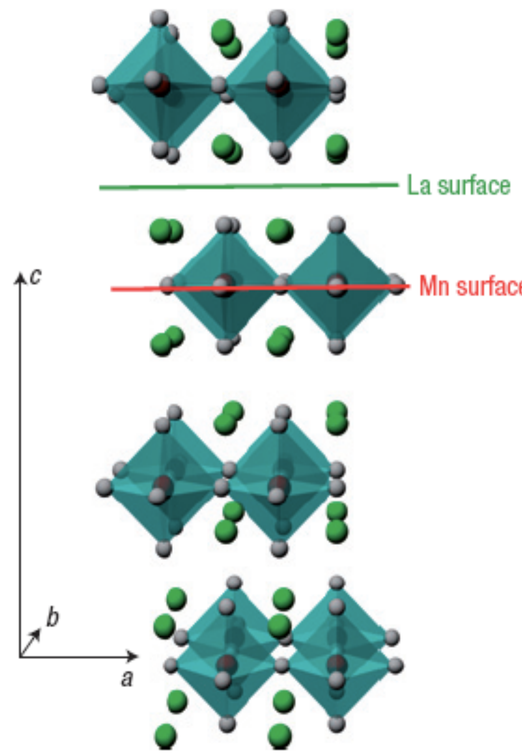
Charge and orbital ordering have been observed in thin samples and at surfaces

Charge-ordered stripes imaged by TEM. More the exception than the rule that such structures can be seen!



$La_{0.33}Ca_{0.67}MnO_3$

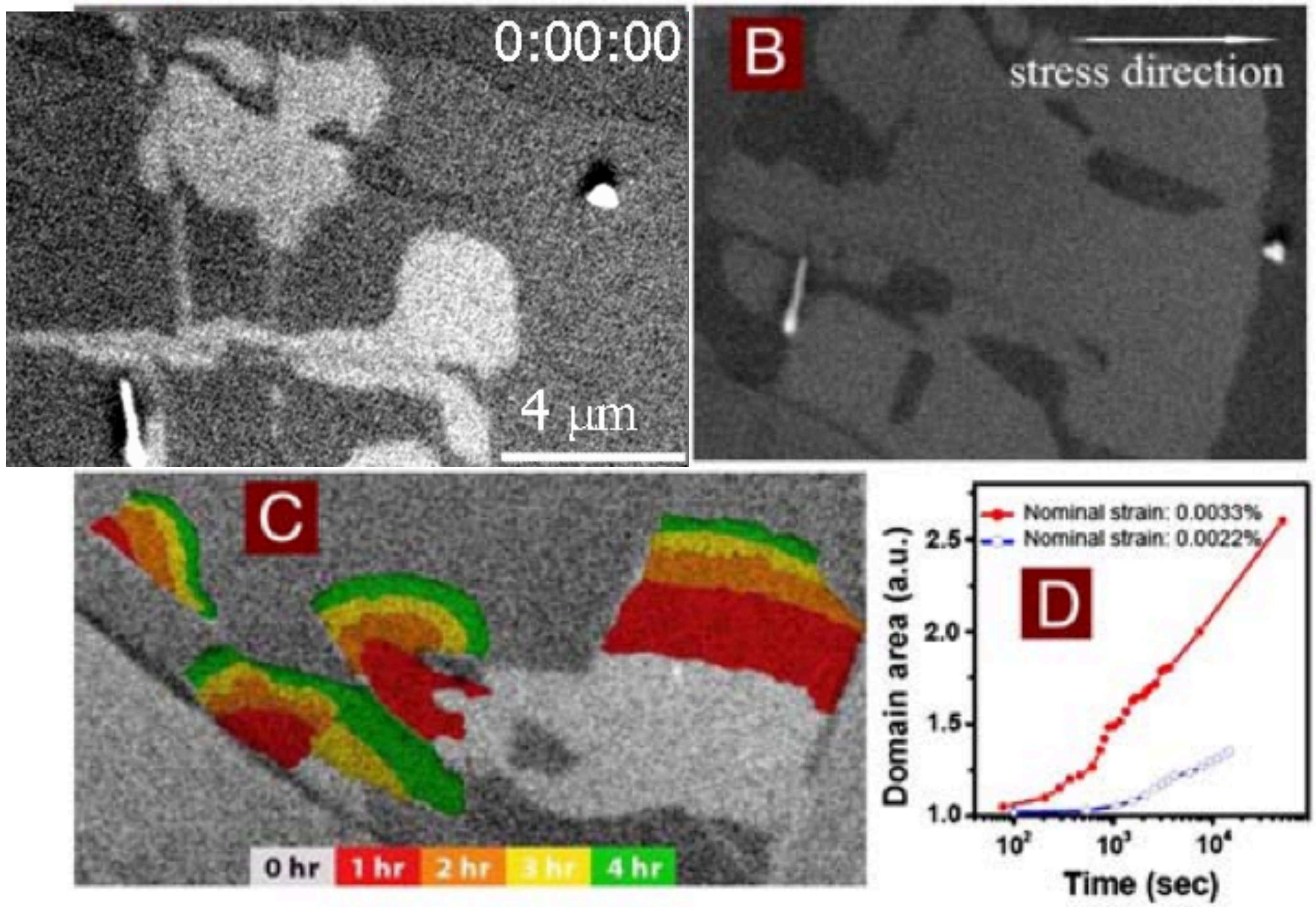
How do surfaces effect orbital ordering compared to the bulk?



S. Mori, Nature 392, 473 (1998)

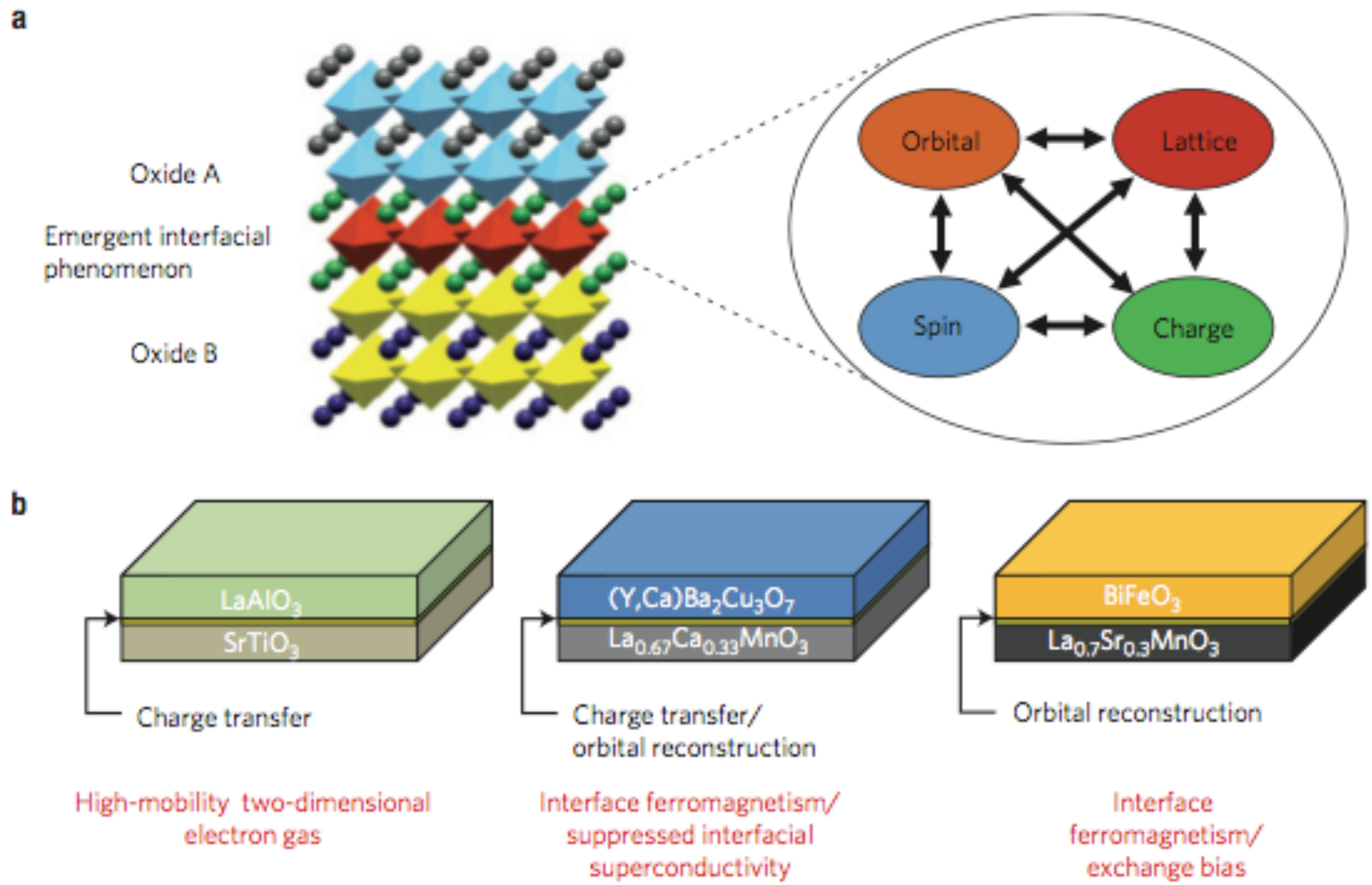
Y. Wakabayashi, Nature Materials 6, 972 (2007)

Surface probes are incredibly powerful ...
but many interesting problems are buried in bulk



T.-H. Kim, PNAS 107, 5272, (2010)

Combining multiferroics with correlated electron materials enables new, more sensitive devices



S.M. Wu, Nature Materials 9, 756 (2010)

How to study spin and strain at domain boundaries, under useful conditions, at the nanoscale?

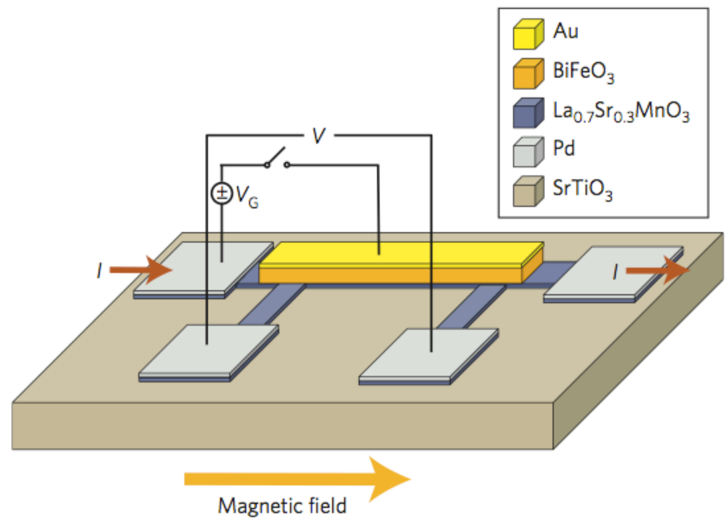
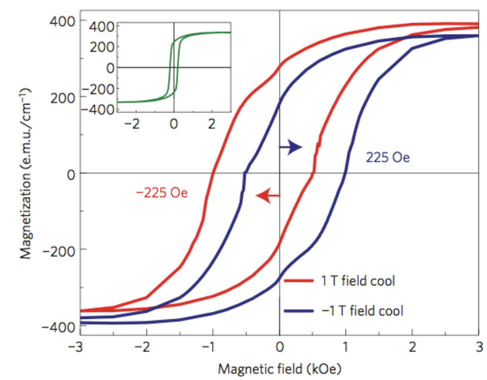
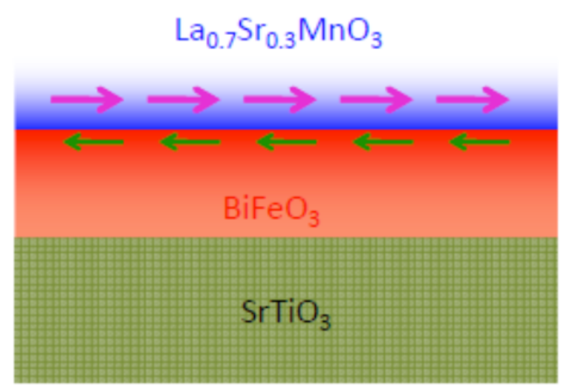


Figure 3 | A schematic of the BFO/LSMO field-effect device. To change the BFO polarization, a voltage pulse V_G is applied between the gate and the LSMO channel. The magnetic field for MR measurements is applied parallel to the direction of the current.





XMCD spectra at Mn and Fe L-edges strongly suggests that in the first few nm of the BFO film, a new spin structure is present with antiparallel coupling between bulk Mn and interfacial Fe spins. This enhanced magnetism is markedly different from that in the remainder of the BFO film.

S.M. Wu, Nature Materials 9, 756 (2010)

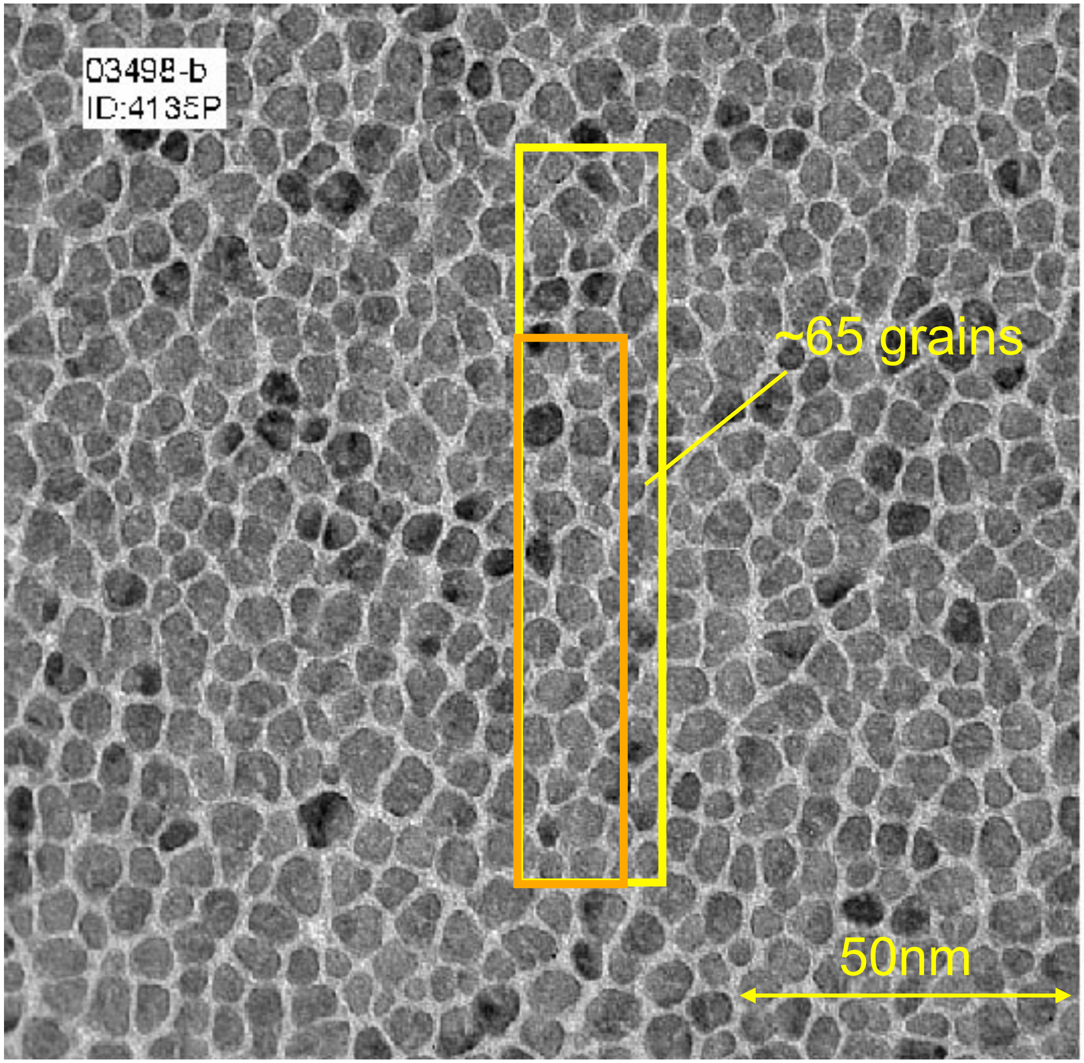
X-rays offer:

- Short wavelengths, high spatial resolution
- Weakly interacting, high penetration
- Coupling to core-level electrons: "clean" measurement of electronic and chemical states
- Coupling to electronic spin via polarization: probe magnetic and orbital states

CDI offers:

- Amplitude and phase imaging with strain sensitivity and spatial resolution beyond the limits of x-ray lenses
- Working distance for high and low temperature, pressure, fields

Beyond today's magnetic storage media



current demonstrations approach 400 Gb/in^2 ➔ 40 grains/bit

Problem

Why not make one grain per bit (domain limited)?

Too-small grains become thermally unstable

Opportunity

Denser storage: smaller domains, repeatable switching

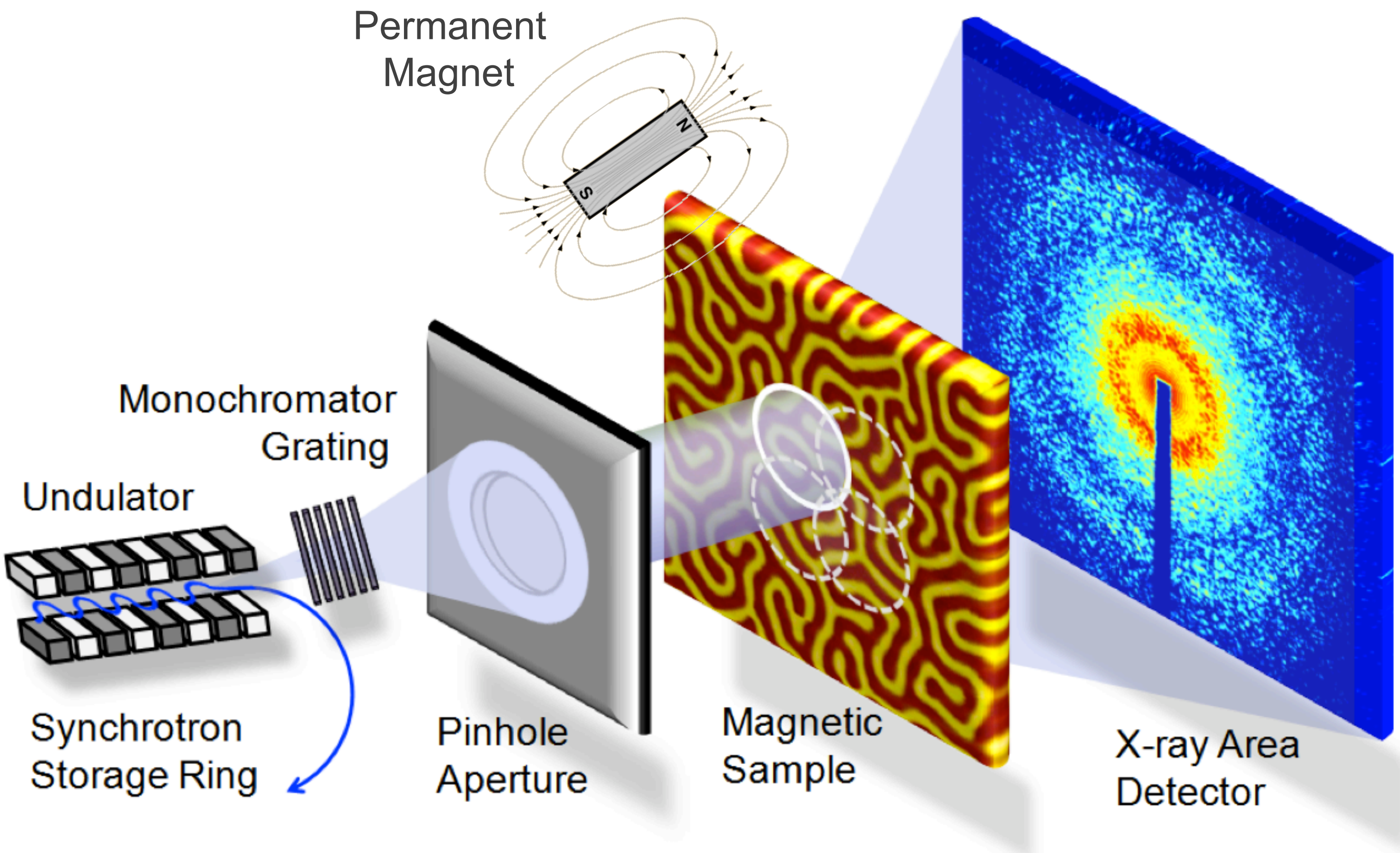
- Resolve internal structure during bit reversal, correlate with magnetic behavior

- Reveal functionality of buried layers in complex devices

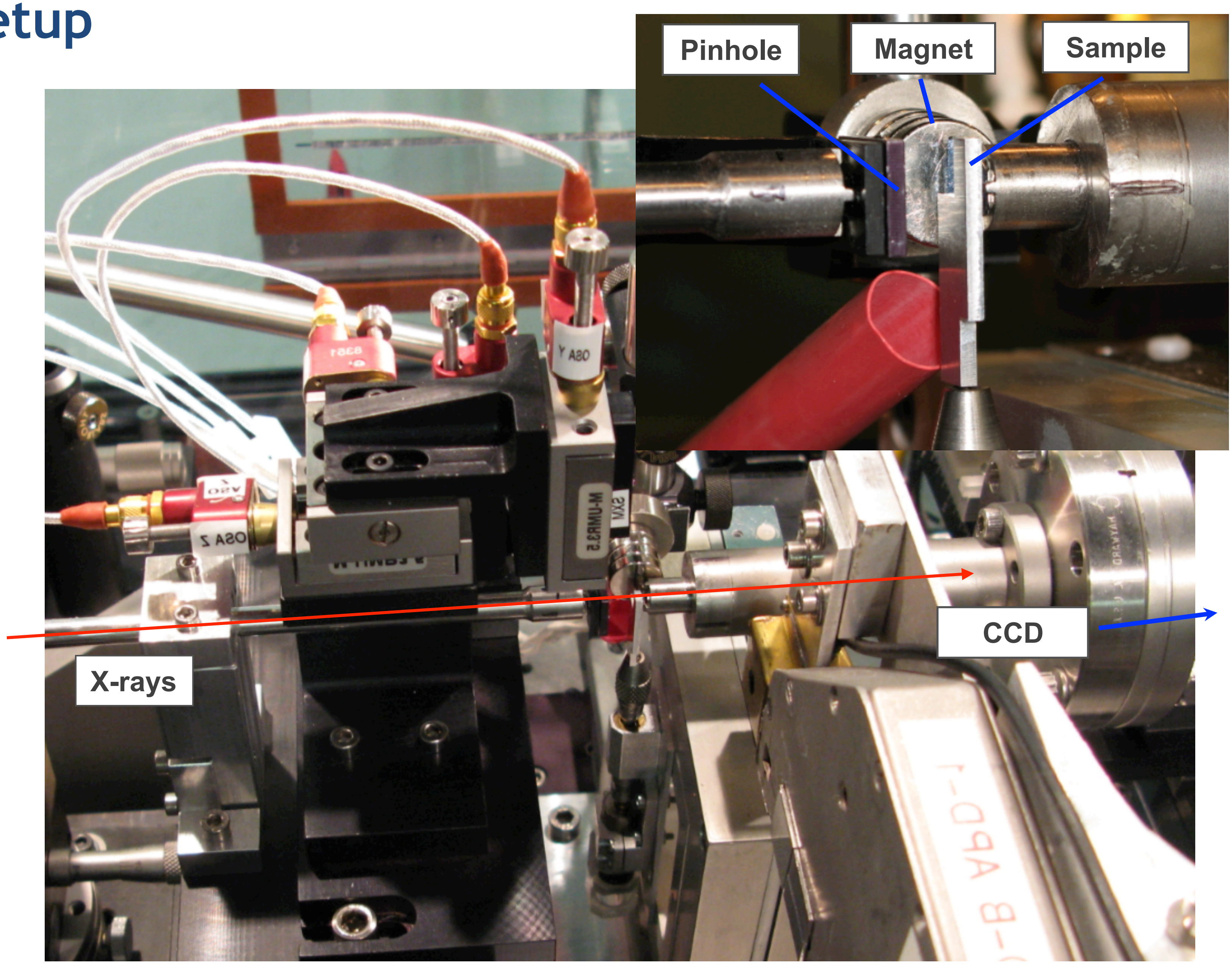
- What is happening on the bit side-walls and edges?

H.J. Richter, MMM (Nov. 2005)

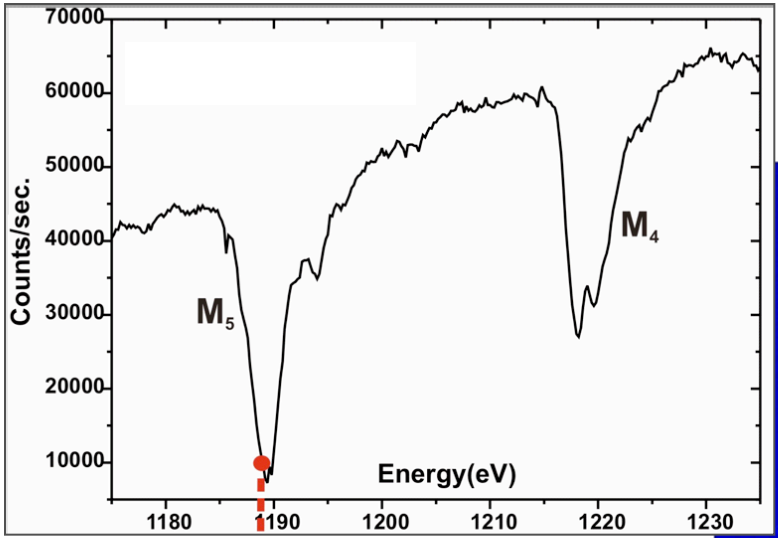
Lensless approach

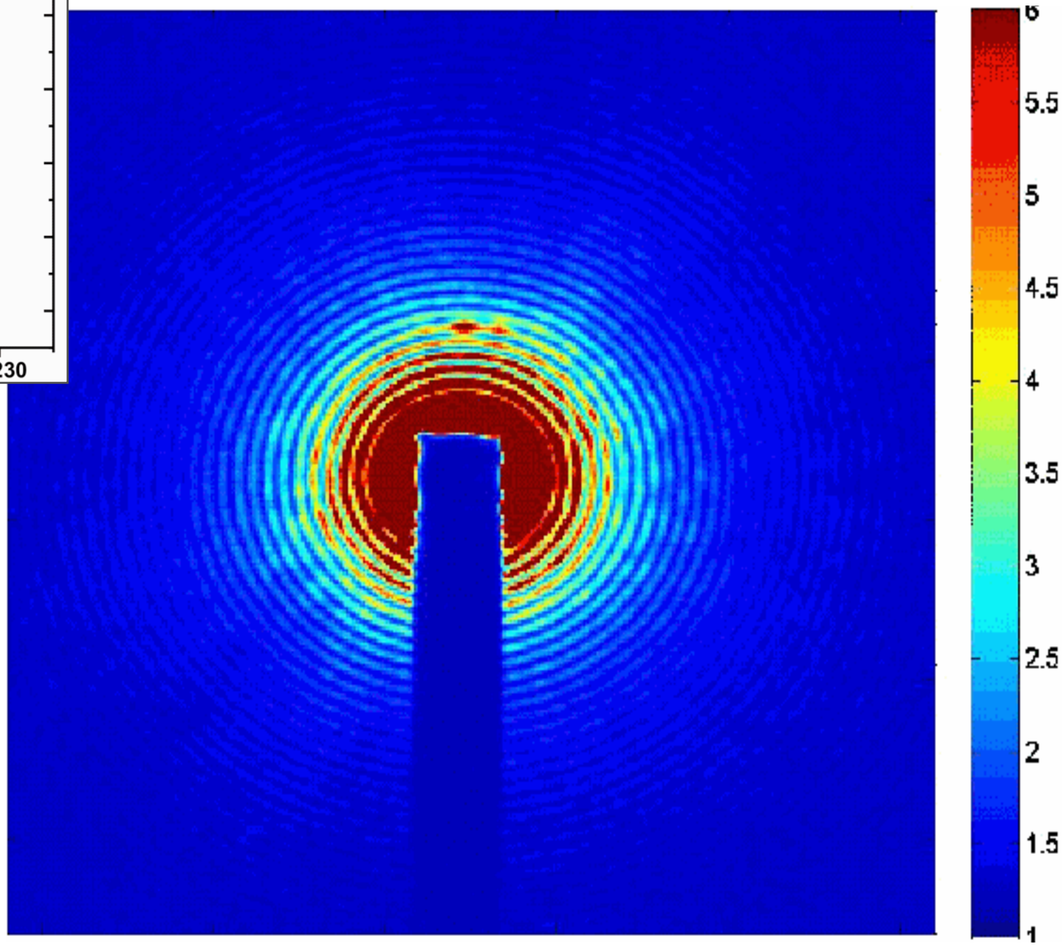


Setup



Resonant scattering vs. photon energy





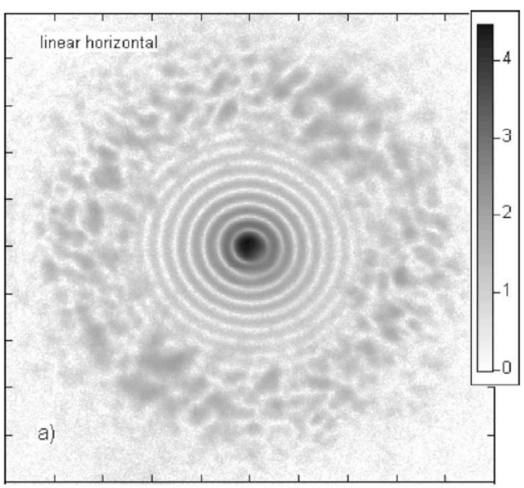
Coherent diffraction with linearly polarized light

Each helicity: $\left|FT\{\text{probe}+\text{object}\}\right|^2 = |\hat{P}|^2 + |\hat{O}|^2 + (\text{cross-terms})$ → 0

RCP: $I_R = \left[\hat{P} + \hat{O}_R\right]^2$

LCP: $I_L = \left[\hat{P} + \hat{O}_L\right]^2$

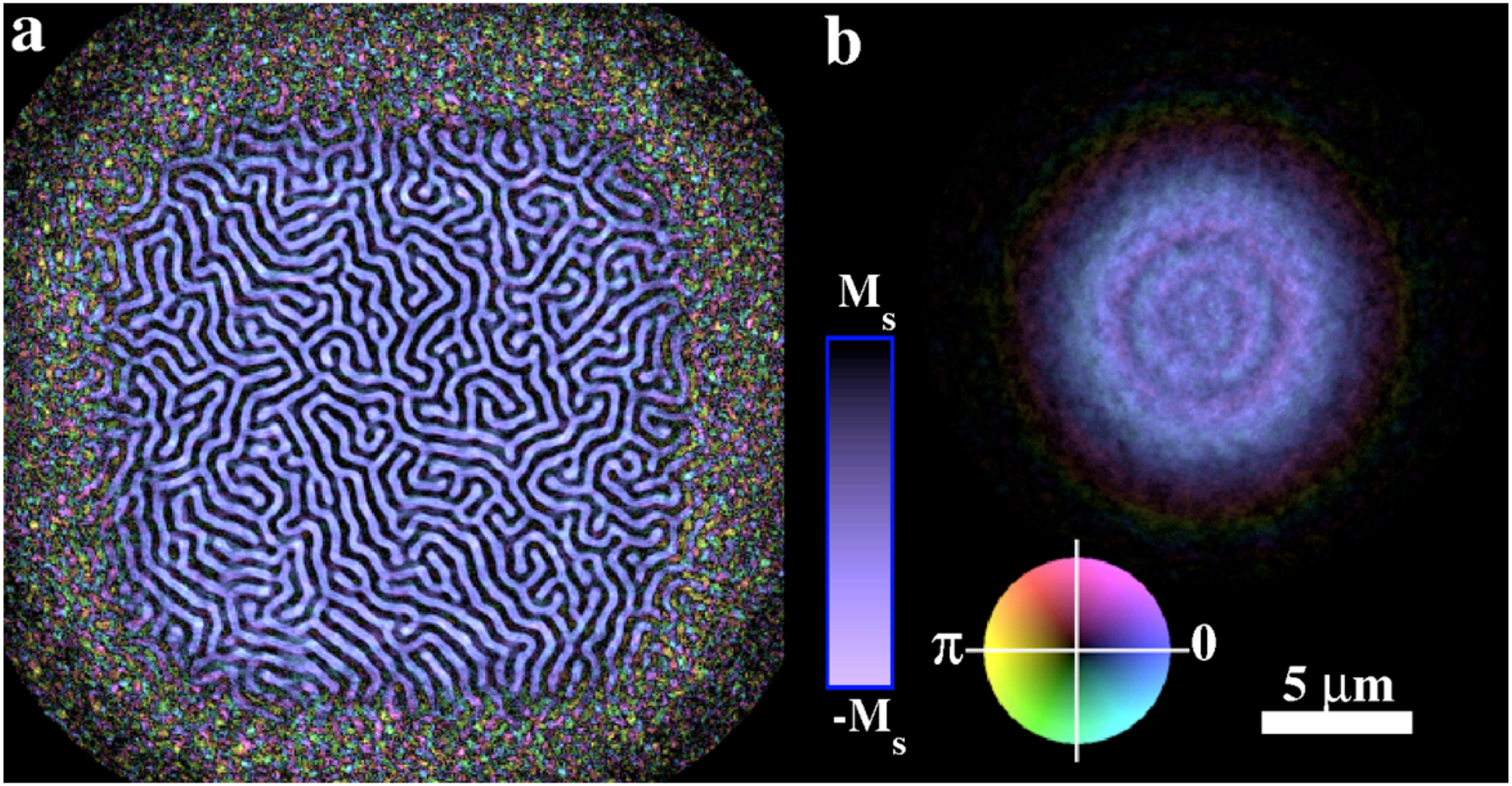
For LP = RCP + LCP, we measure: $I_R + I_L = 2\left(\hat{P}^2 + \hat{O}^2\right)$



- Resonant scattering does not interfere with probe function
- Can just subtract probe (sample-out measurement) !

S. Eisebitt, PRB 68, 104419 (2003)

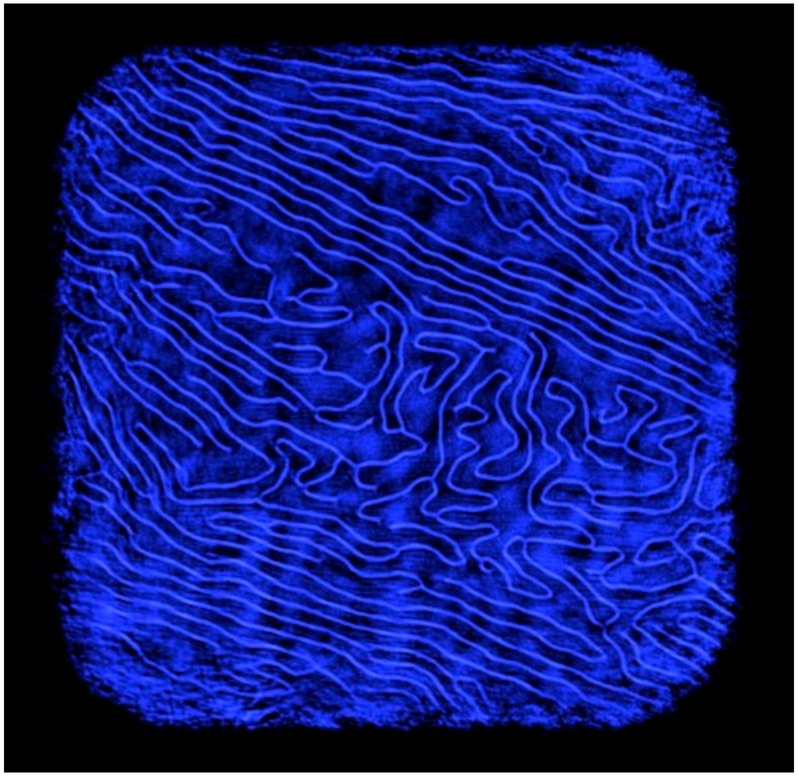
Reconstructed domain structure and probe function

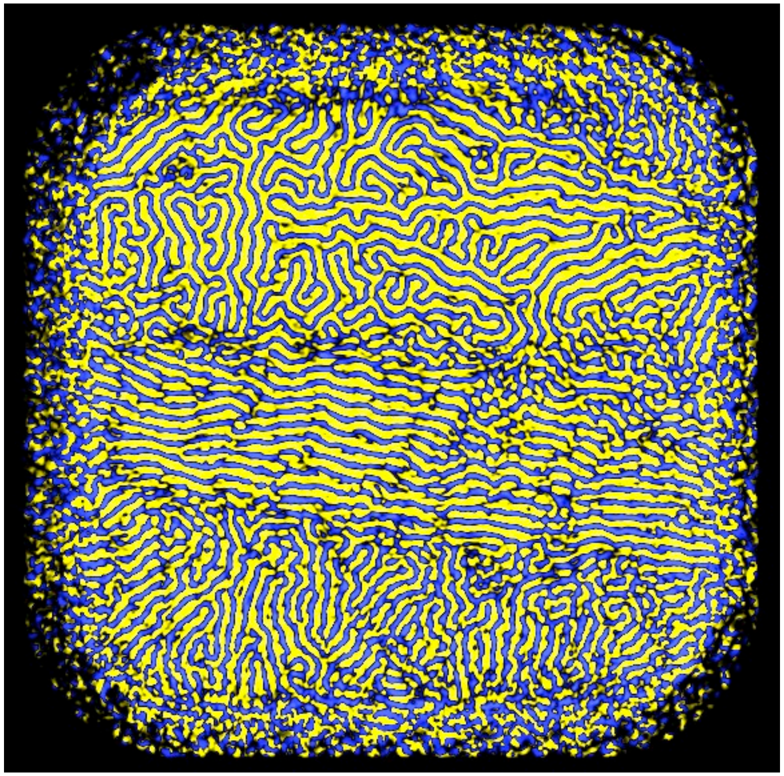


Sample scan: $(14 \times 2\ \mu m)^2 \times (40 \times 1\ s)$ exposures

A. Tripathi et al., PNAS (2011)

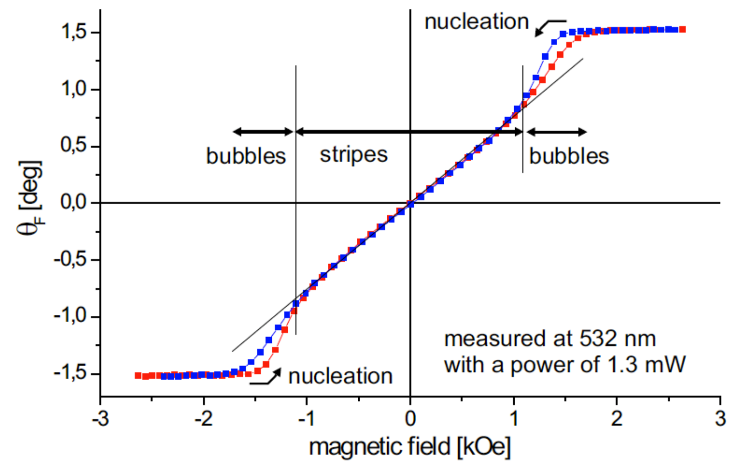
Many domain configurations are possible, depending on the magnetic history of the system





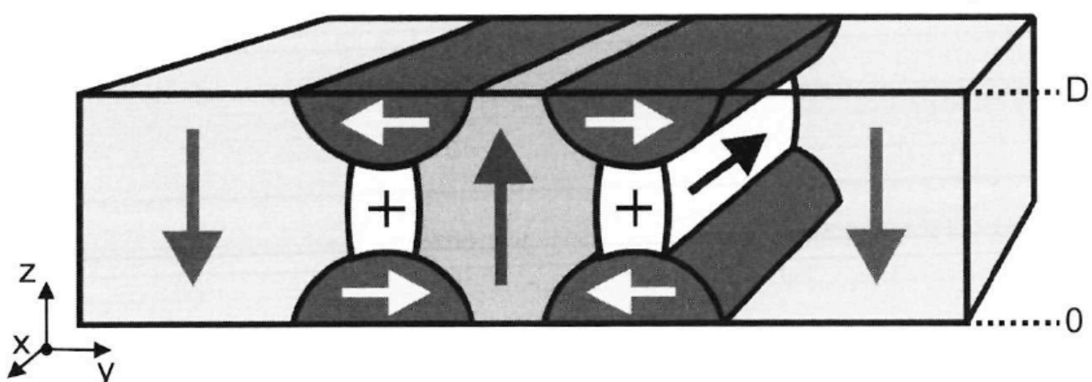
Open questions

- Take GdFe system through entire hysteresis curve.
  - Does structure reproduce?



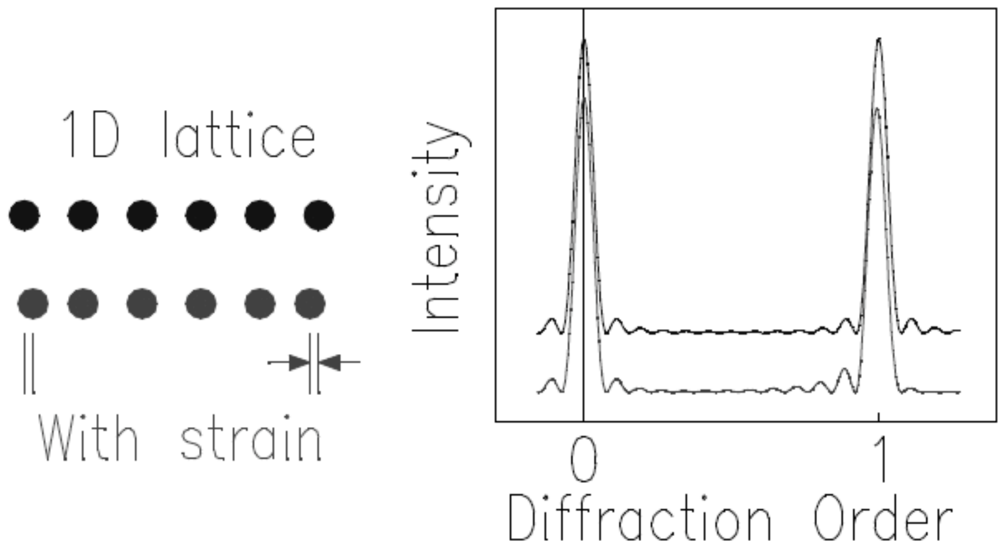
2)

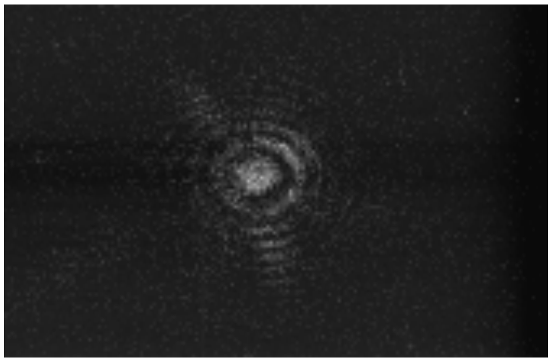
- With enough flux, can we resolve the domain walls themselves?

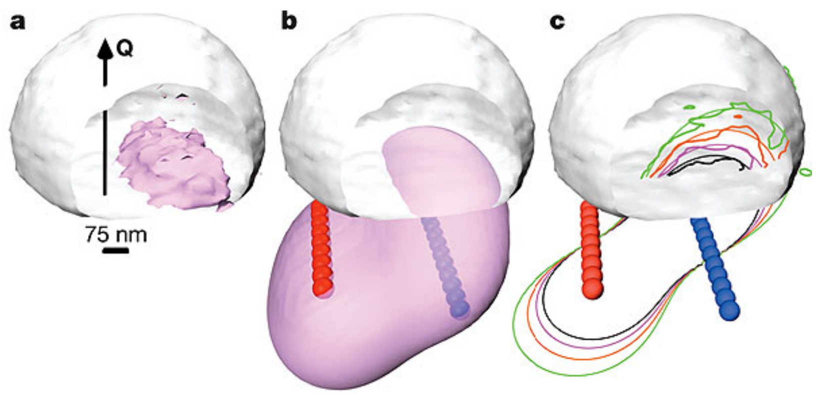


J.F. Peters, PhD Thesis (2003)

Asymmetries in the diffraction yield lattice strain



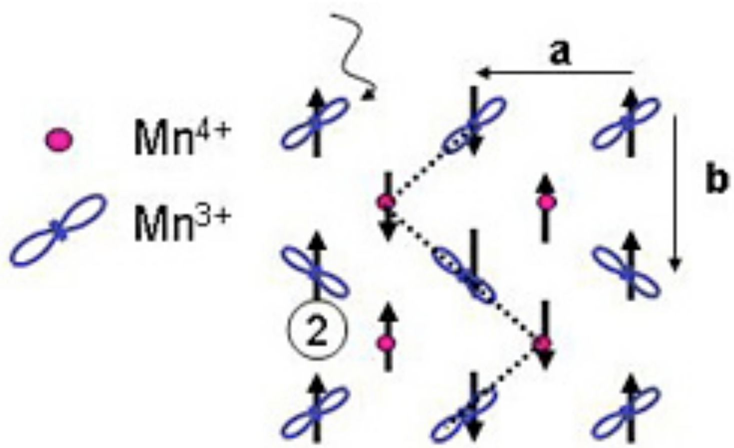




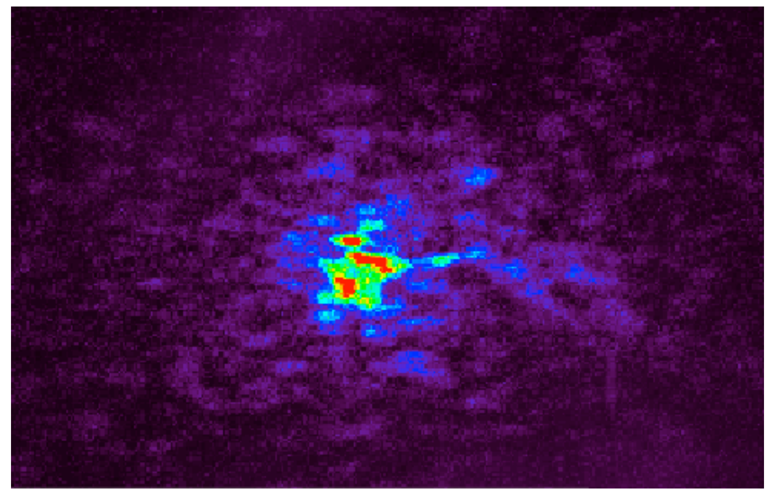
M. Pfeifer, *Nature* 442, 63 (2006)

Probing order parameters in the manganites

- Colossal magnetoresistance is exquisitely sensitive to competing orbital, charge, spin, and lattice degrees of freedom. Harnessing it may lead to denser magnetic storage and new spintronic and multiferroic devices.
- What are the order parameters and dynamics in doped manganites (e.g. in $Pr_{1-x}Ca_xMnO_3$)? What do they tell us about nanoscale phase separation and CMR?



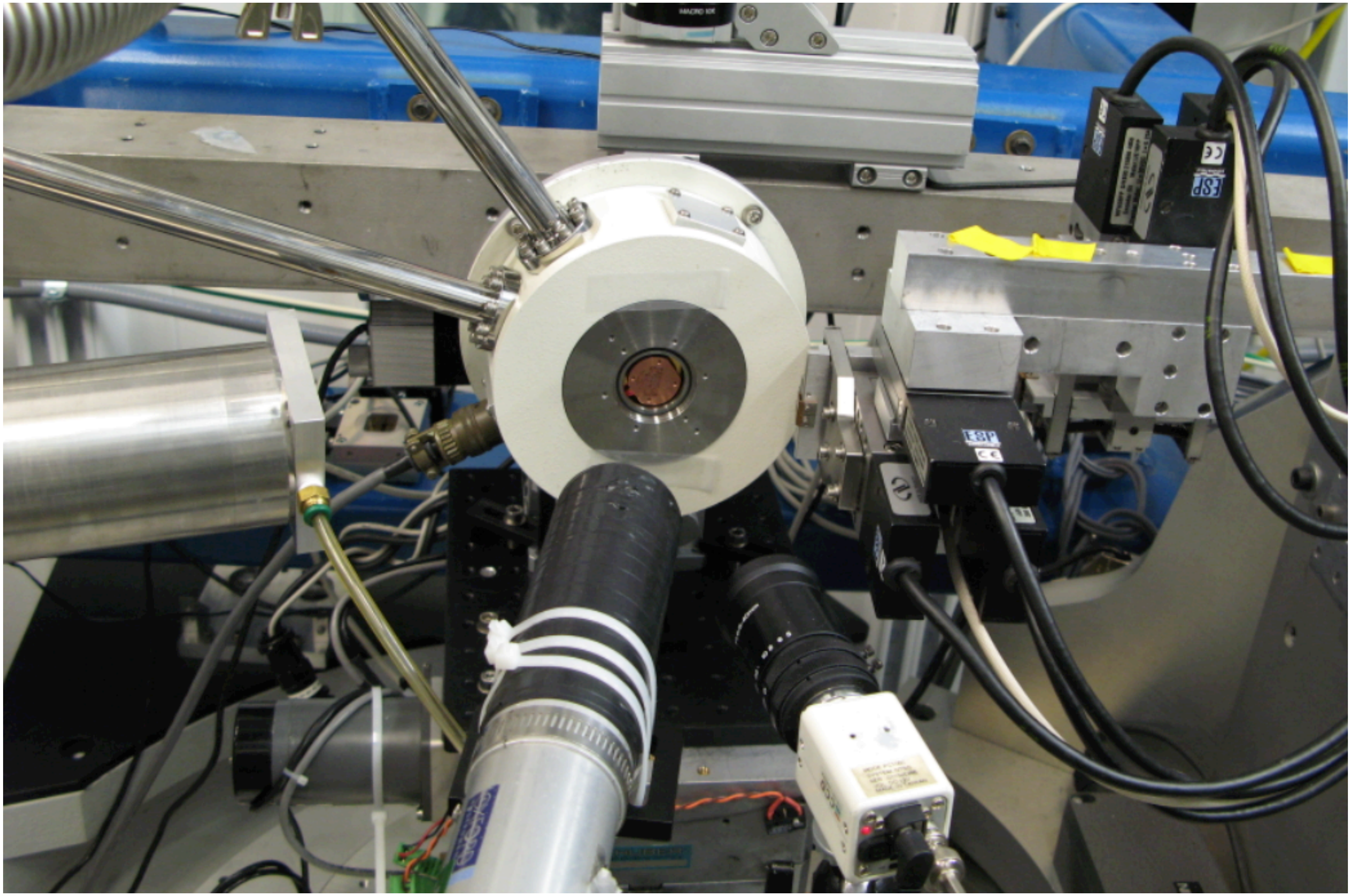
Some Mn atoms have an extra valence electron, causing orbitals to have a site-specific orientation, forming superlattice.



Resonant (010) "orbital speckle" from $LaMnO_3$ at 6.555 keV and 130 K (below $T_{Néel}$) using a 1 µm beam. 300-800 nm domains consistent with Nelson (2002).

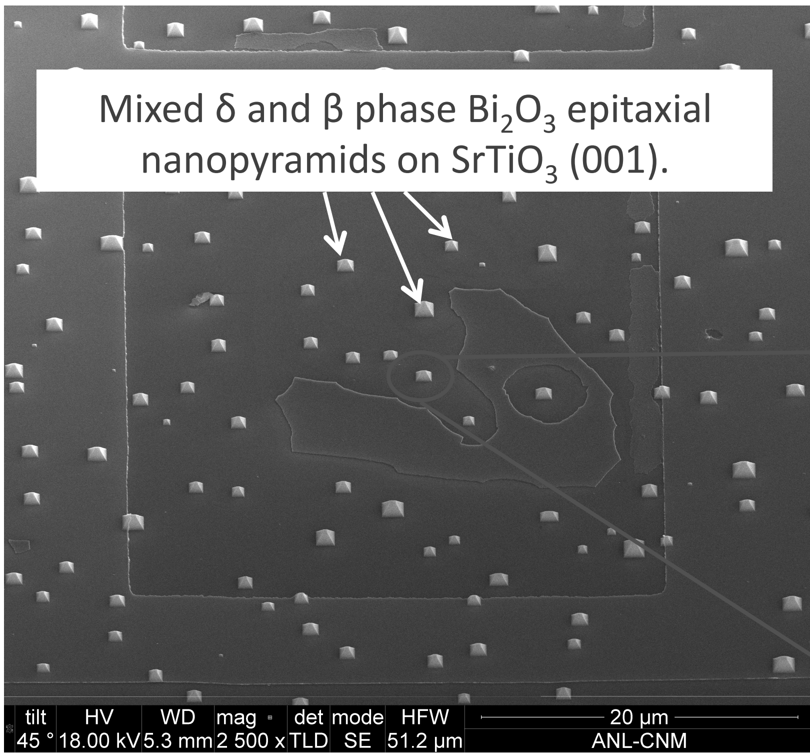
Specke contrast is good, but signal is weak: Exposures took ~100 s at APS. 3D and fast dynamics are inaccessible!

Bragg coherent diffraction at cryo temperatures

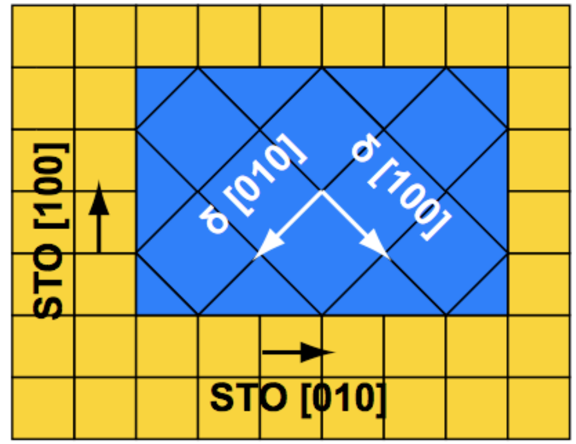


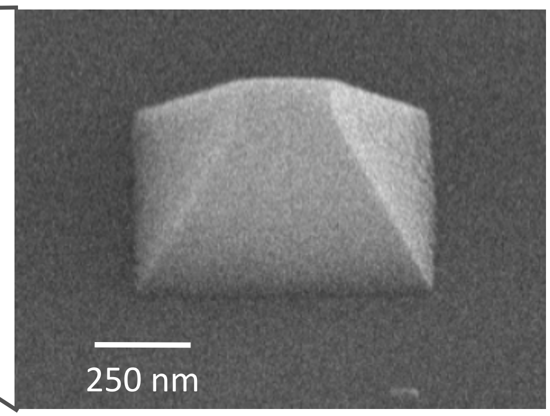
Strain in Bi_2O_3 nanocrystals

- The high temperature δ-phase Bi_2O_3 is an exceptional oxygen conductor.
  - Epitaxially stabilized at room temp.



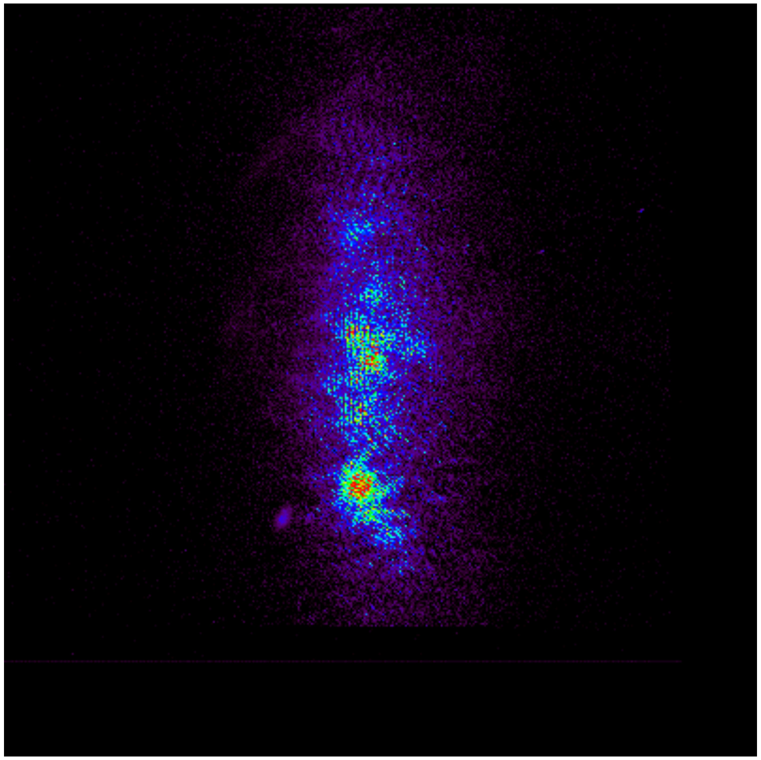
In-plane lattice orientations



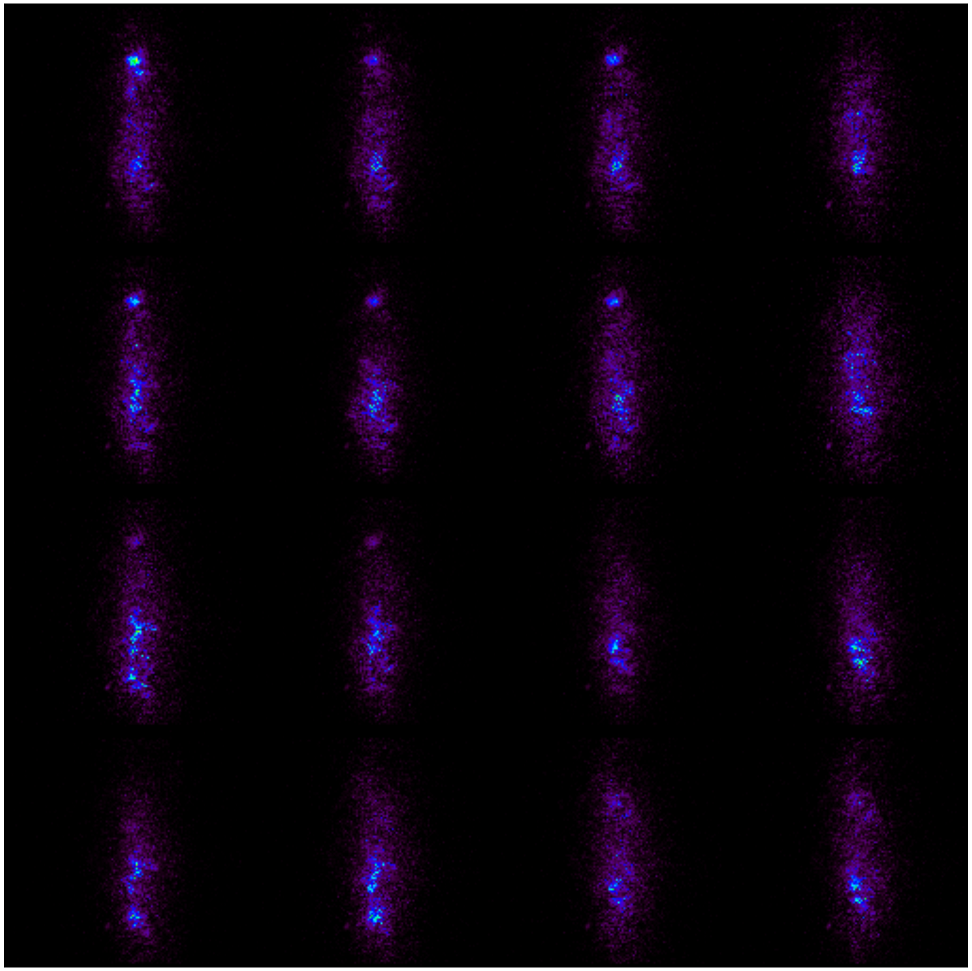


What is the role of elastic interfacial strain is phase stabilization and differentiation in δ and β Bi_2O_3 nanostructures?

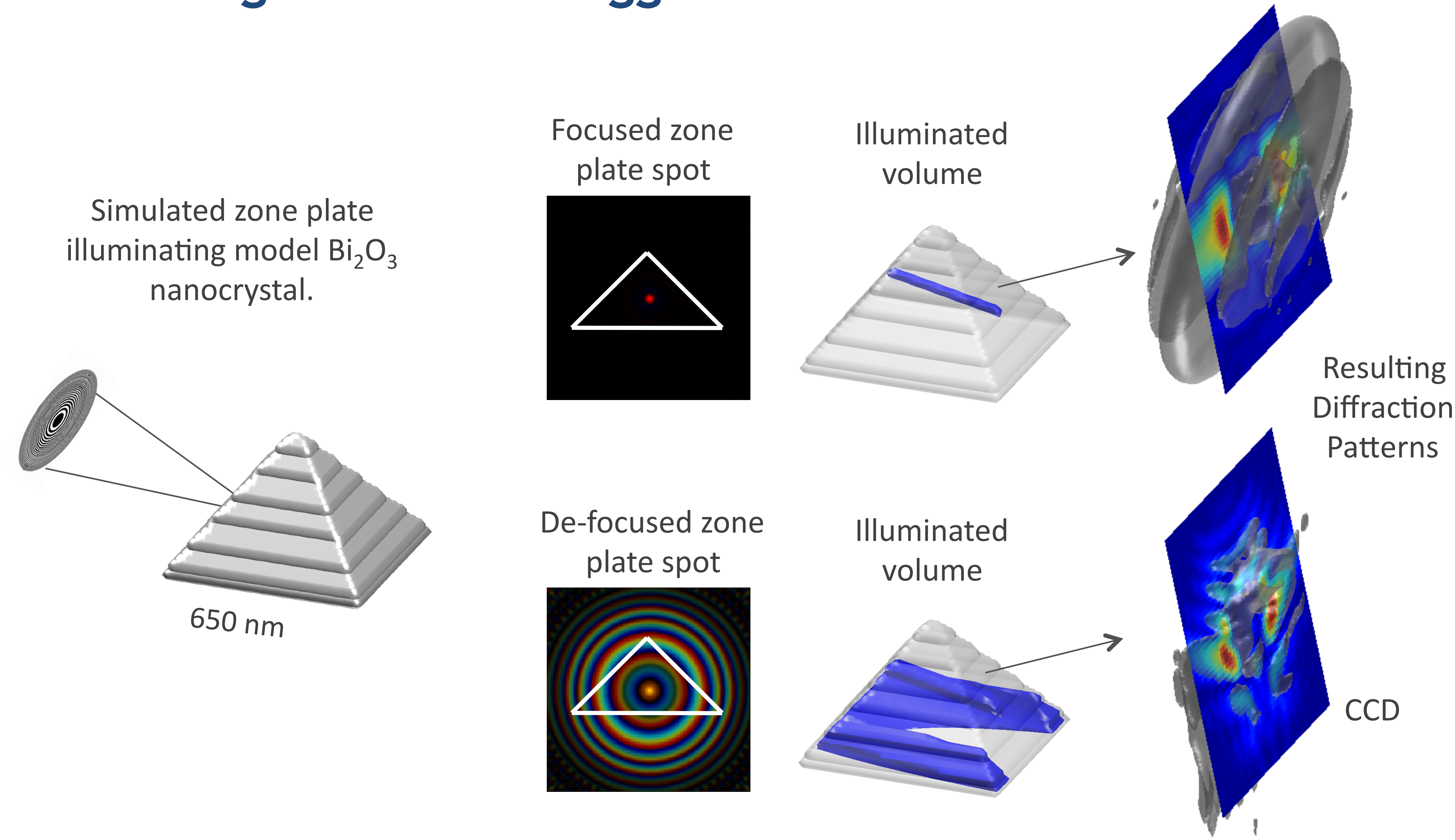
Scanning Bragg data: Bi_2O_3 nanocrystals



9 keV, ~ 1.5 µm beam, 0.5 x 3 µm steps



Convergent beam Bragg diffraction



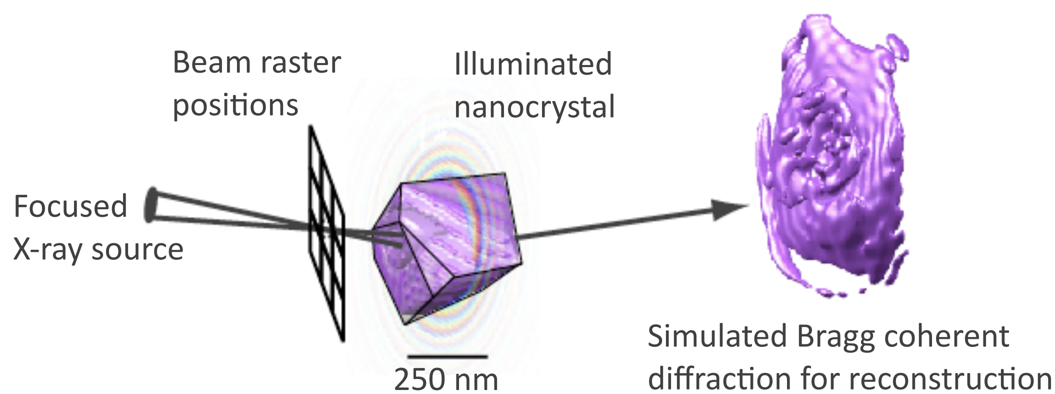
Diffraction complexity changes with focus

Simulations are working!

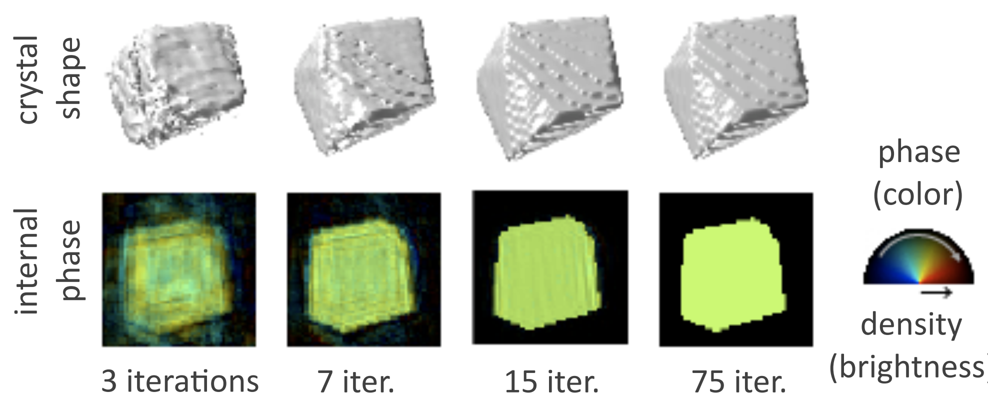
- **Achievement**
  - Successful simulation of 3D Bragg ptychography with focused beam
  - Relaxes the sample constraints of plane wave Bragg coherent imaging
- **Significance**
  - Enables the study of densely arranged, self-similar nanocrystals with focused coherent beams
  - Provides a roadmap to internal lattice strain imaging in extended crystal systems

S. O. Hruszkewycz,
Opt. Lett. 36, 2227 (2011)

Simulated nanocrystal diffraction



Ptychographic reconstruction



What do we need?

- Controllable polarization
- Stable beam, instrumentation
- Cryo to ~10 K, magnetic field to ~2 T
- Faster area detectors!

What are the challenges?

- Getting to 3D: how to both scan and rock while studying same volume in sample (sphere of confusion problem)
- Maintaining stability across wide temperature range -> *more flux helps!*

Conclusions

- We can probe magnetic ordering by resonant coherent diffractive imaging.

- We are making progress on scanning Bragg CDI, with both plane and convergent beams. However, significant challenges remain to handle sphere of confusion.

- We are currently at the ~20 nm scale on a 3rd generation SR with high contrast samples. Given 3rd-4th power scaling, can expect few-nm resolution with the ERL (worse for weakly scattering systems). Combined with resonant methods This opens up new territory, e.g. to study buried domain walls, that *cannot be addressed by other methods.*

- **The ERL offers unique truly unique opportunities for coherent x-ray imaging of both order and disorder in condensed matter exhibiting emergent properties.**

Acknowledgments

Ash Tripathi	UCSD/Argonne
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and Thank you !