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Magnetic Scattering and Spectroscopy at the APS

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X-ray Science Division
Advanced Photon Source

3-Way Meeting
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U.S. Department of Energy

UChicago Argonne LLC

Office of Science
U.S. DEPARTMENT OF ENERGY

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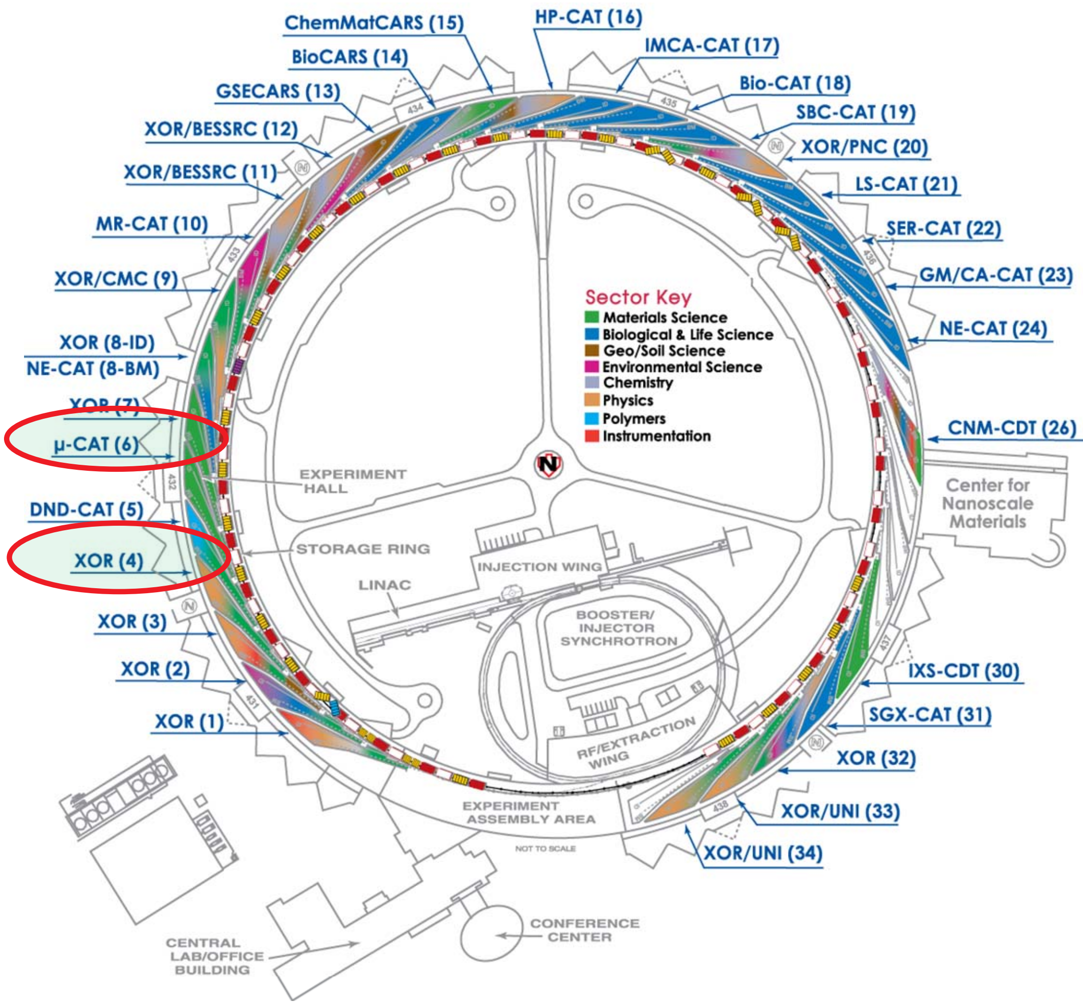
Beamlines for Magnetic Research at the APS

- **4-ID-C**
  - ***Soft x-ray Spectroscopy***
    - **XMCD, XMLD**
  - ***X-PEEM Imaging***

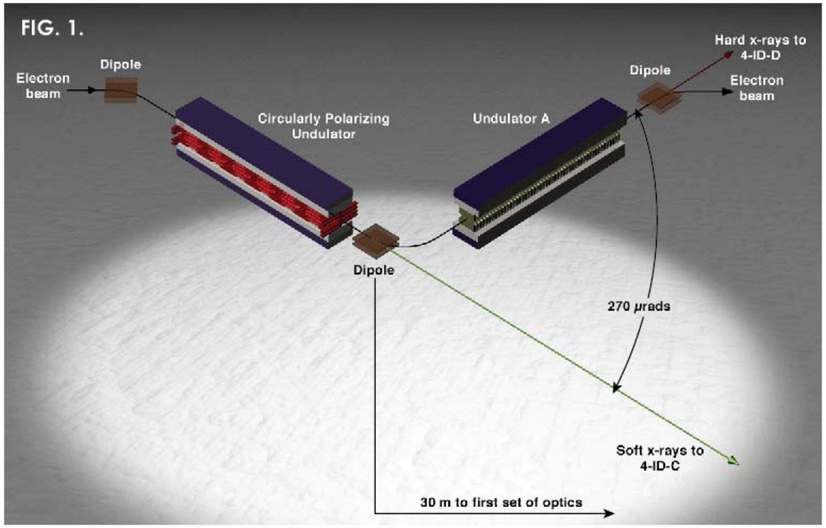
- **4-ID-D**
  - ***XMCD Spectroscopy***
  - ***Magnetic diffraction***
  - ***In-field diffraction***

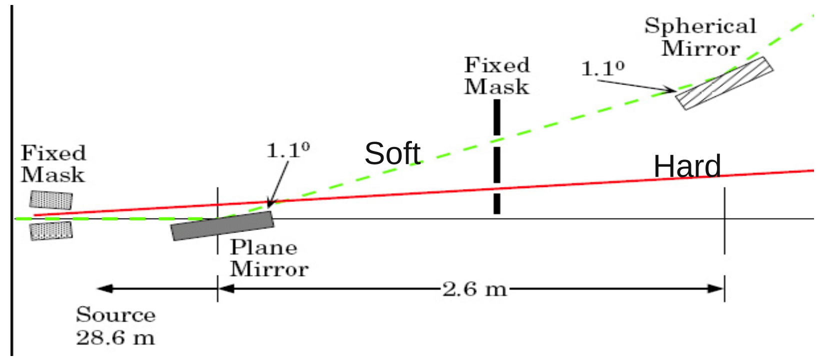
- **6-ID (XOR/μ-CAT)**
  - ***Magnetic diffraction 50%***



4-ID: Magnetic Scattering & Spectroscopy

First demonstration of canted undulators at APS.





Horizontal mirrors separate soft x-ray beam into downstream experimental stations.

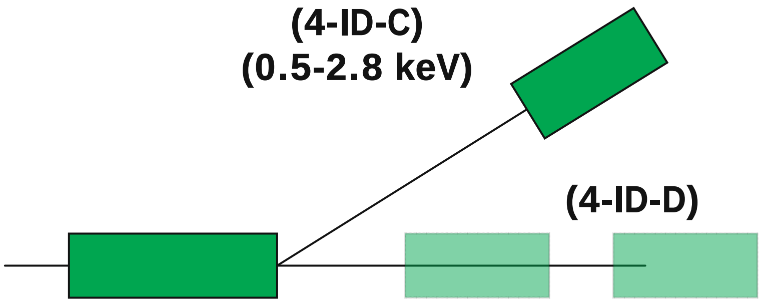
4-ID-C

- **Soft x-ray (UHV)**
- **0.5 → 2.8 keV**
- **CPU Source (CP,LP)**

4-ID-D

- **Hard x-ray**
- **2.5 → 40 keV**
- **3.3 cm Und. Source (LP)**

4-ID-C - Soft X-ray Magnetic Spect., Scat., & Imaging



Techniques:

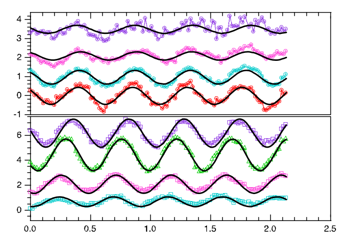
- XMCD, XRMS ~70%
- X-PEEM ~20%

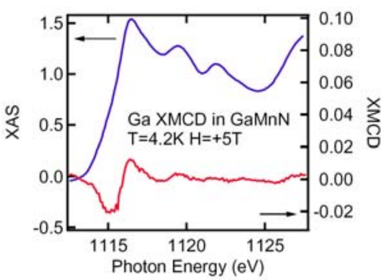
XMCD and XRMS
Beamline Staff
Photoemission Electron Microscopy

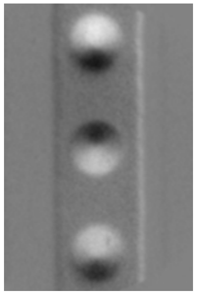
Low and High field magnets
John Freeland - XMCD, XRMS
Magnetic imaging ~100nm resolution, ~100 ps
- Magnetic Thin films

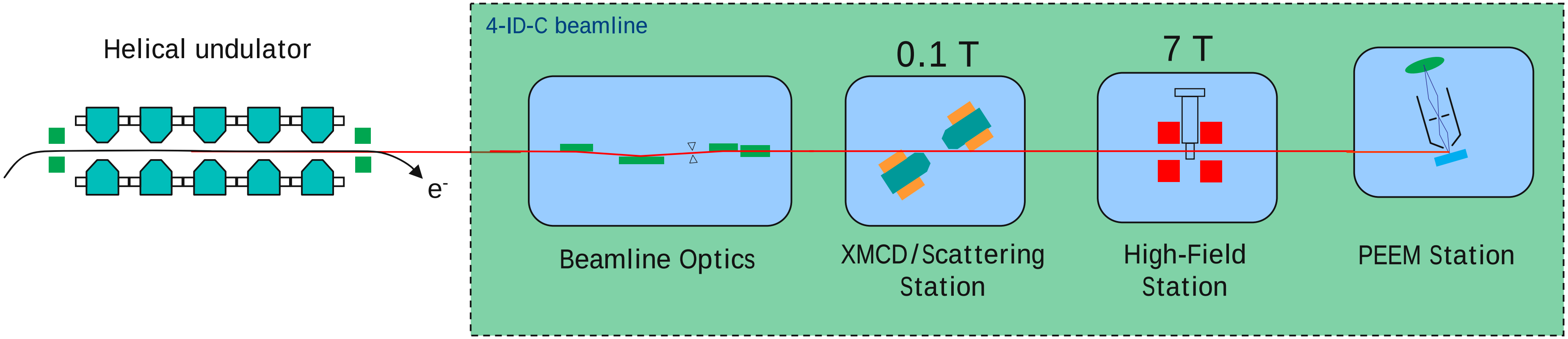
David Keavney - X-PEEM, XMCD
- Vortex dynamics
- Magnetic Semiconductors
- Shape effects
- Complex Oxides

Richard Rosenberg - XPS, XEOL
Upgrade to Low temperatures 2007 (~80K)
Upgrade to higher field octupole magnet 2008



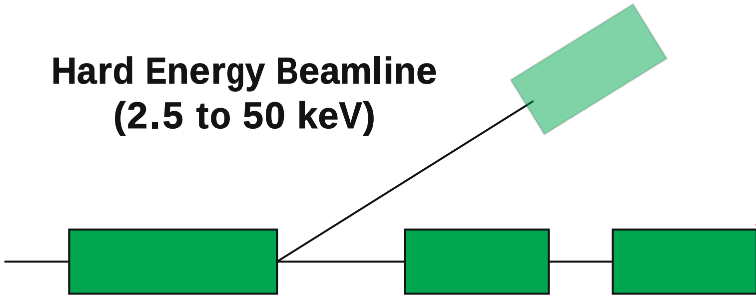






4-ID-D: Hard x-ray magnetic scattering & spectroscopy

Hard Energy Beamline
(2.5 to 50 keV)



Techniques:
- XMCD 50%
- Resonant Scattering 40%
- In-Field Scattering 10%

Beamline Staff

Daniel Haskel - XMCD

Zahir Islam - XMS, High Field

Yejun Feng - XMS, High Pressure

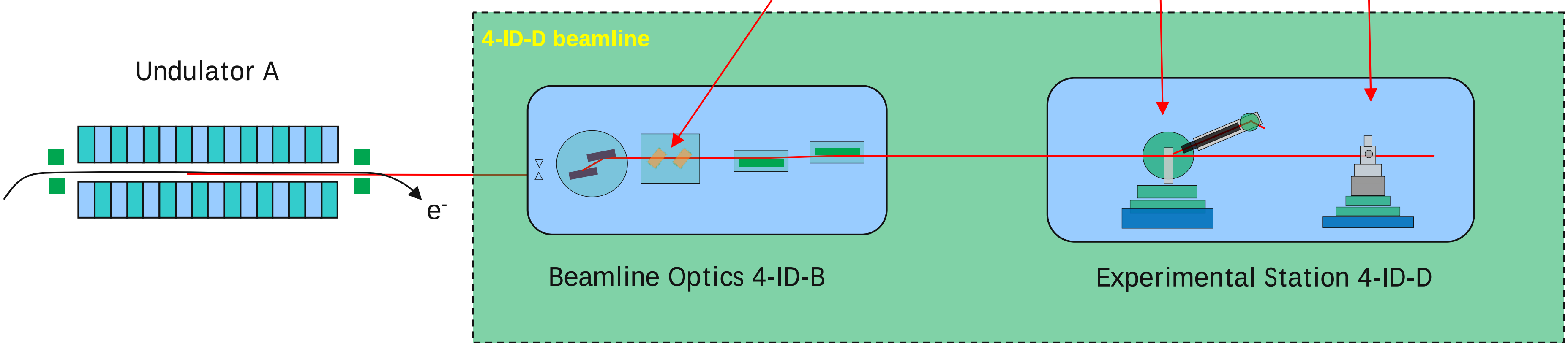
Psi diffractometer

Resonant diffraction & reflectivity
- Temperature range
- 1.4 to 800K
- Polarization analysis
- High pressure magnetic scattering

Cryogen Free magnets
- Horizontal field
  - XMCD
  - In-field diffraction
- Vertical field
  - In-field diffraction
- Temperature 4K to 325K

Phase Retarding Optics

Manipulate beam polarization
- Thin diamond crystals
- Transmission (I~0.3I$_o$)
- P_c ~0.98, P_l ~ 0.85
- Rapid Helicity reversal (lock-in detection)
- Low Energy (<2.5 keV)



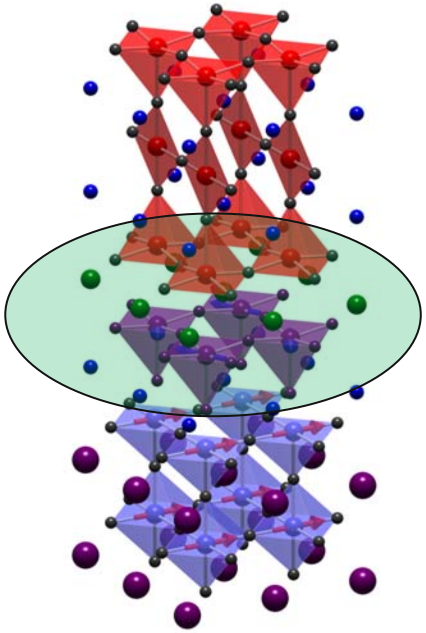
Complex oxide interface physics

Jak Chakhalian

John Freeland

Bernard Keimer

NIU **Michel van Veenendaal**

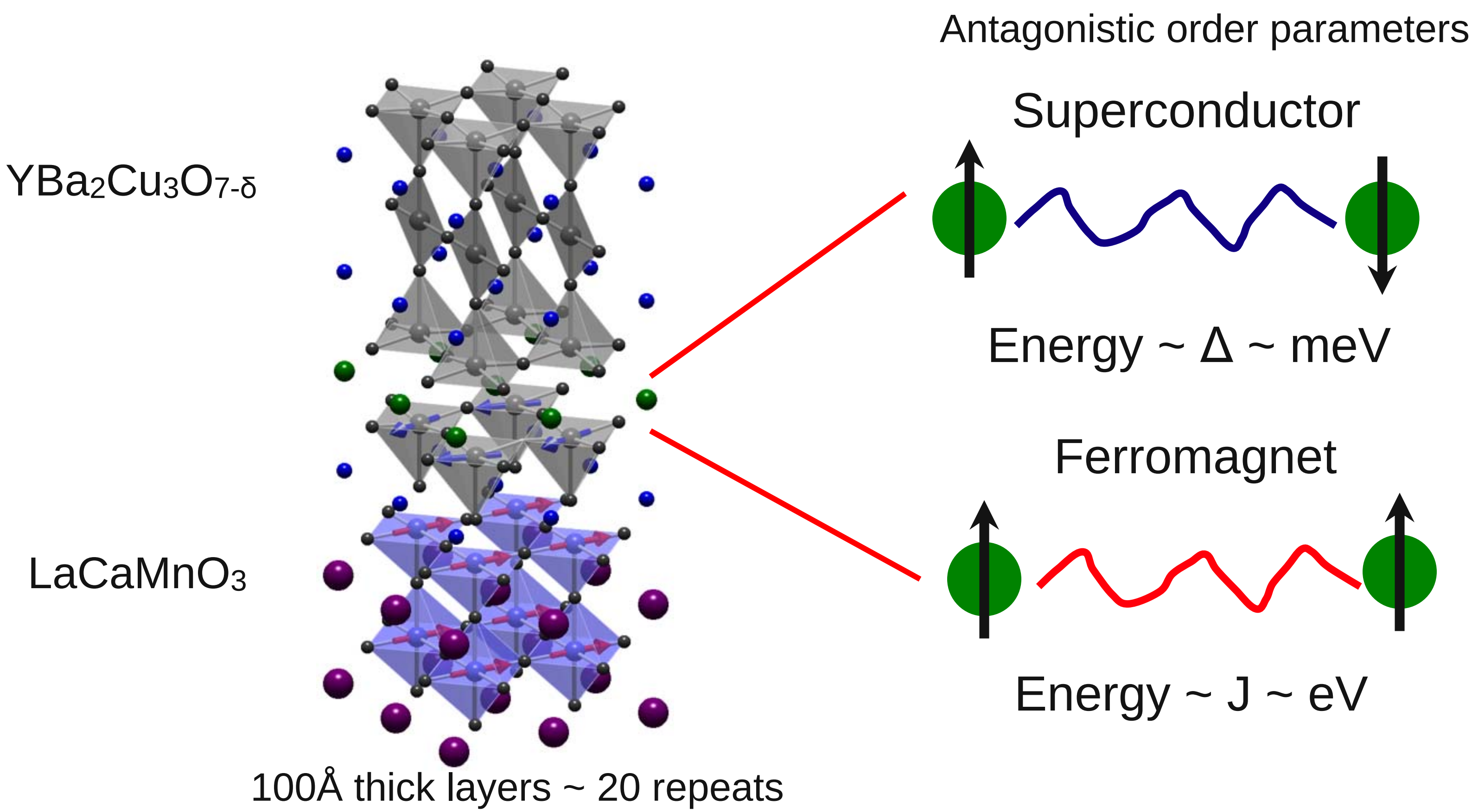


Pulsed laser deposition →create new types of layered oxide materials.

What happens near the interface?

- New properties that are not present in the bulk constituents
- Changes in local charge/valence
- Lattice reconstruction
- Magnetic and Orbital ordering

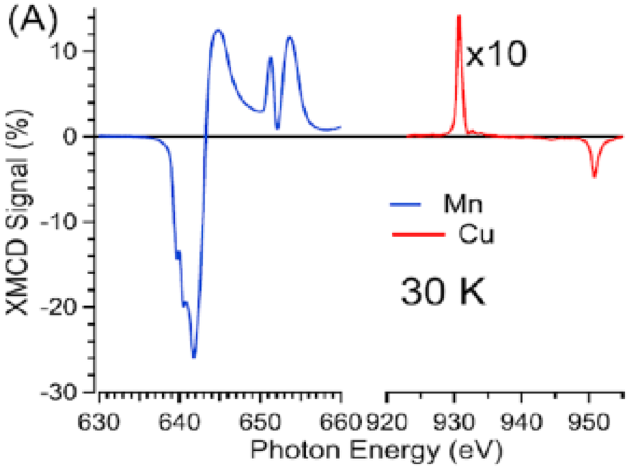
Superconducting-Ferromagnetic Interface



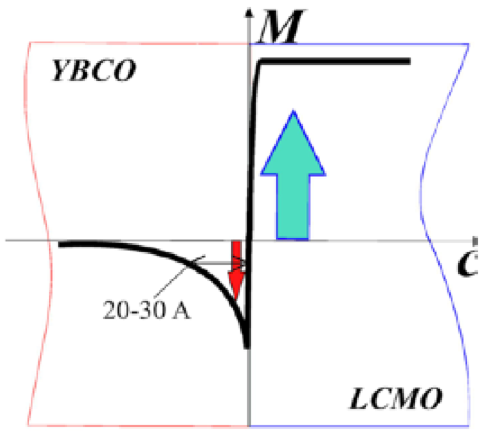
Expect singlet pairs to be broken by strong FM order

XMCD from YBCO/LCMO SuperLattice

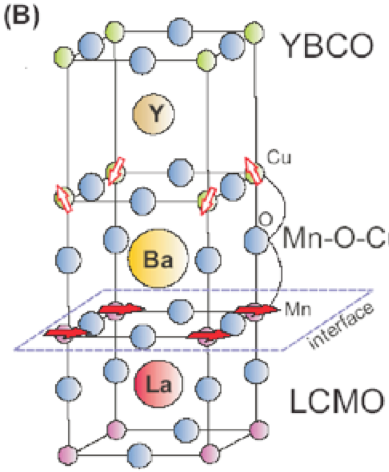
XMCD



Magnetization Profile



Antiferromagnetic Super-exchange



J_{AF}

•XMCD signal indicates that there is a magnetic moment on Cu. Cu moment is antiparallel to Mn.

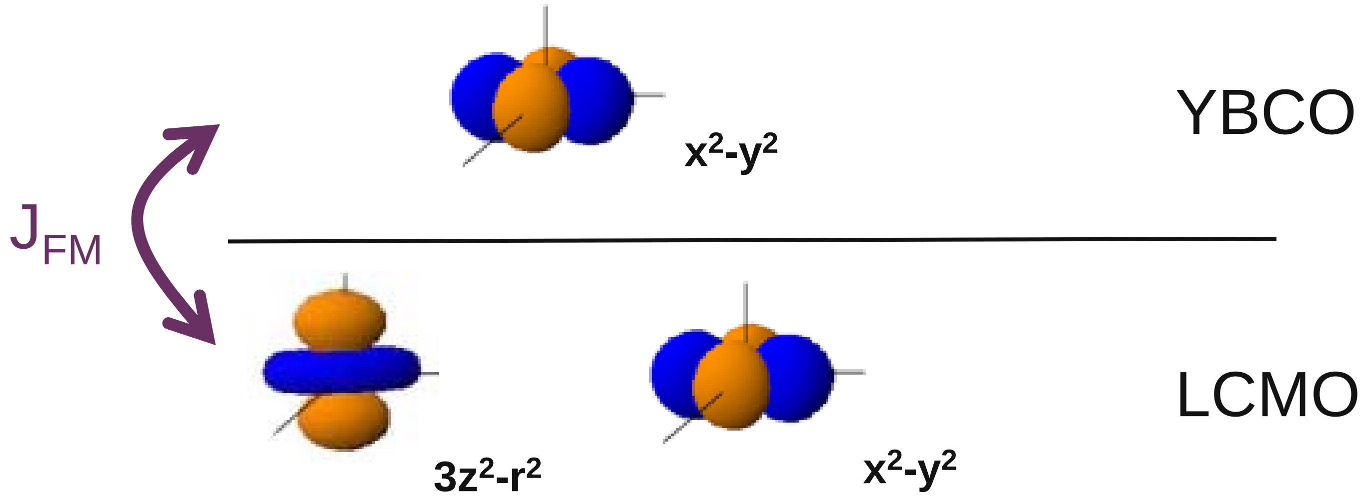
•Combined with neutron reflectivity to obtain depth profile

•Canted state forms in CuO_2 plane, Cu moment ~0.2 μ_B/Cu atom

J. Stahn, J. Chakhalian et al. Phys. Rev. B **71**, R140509 (2005)
J. Chakhalian, J. Freeland et al. Nature Physics **2**, 244(2006)

Exchange coupling across interface

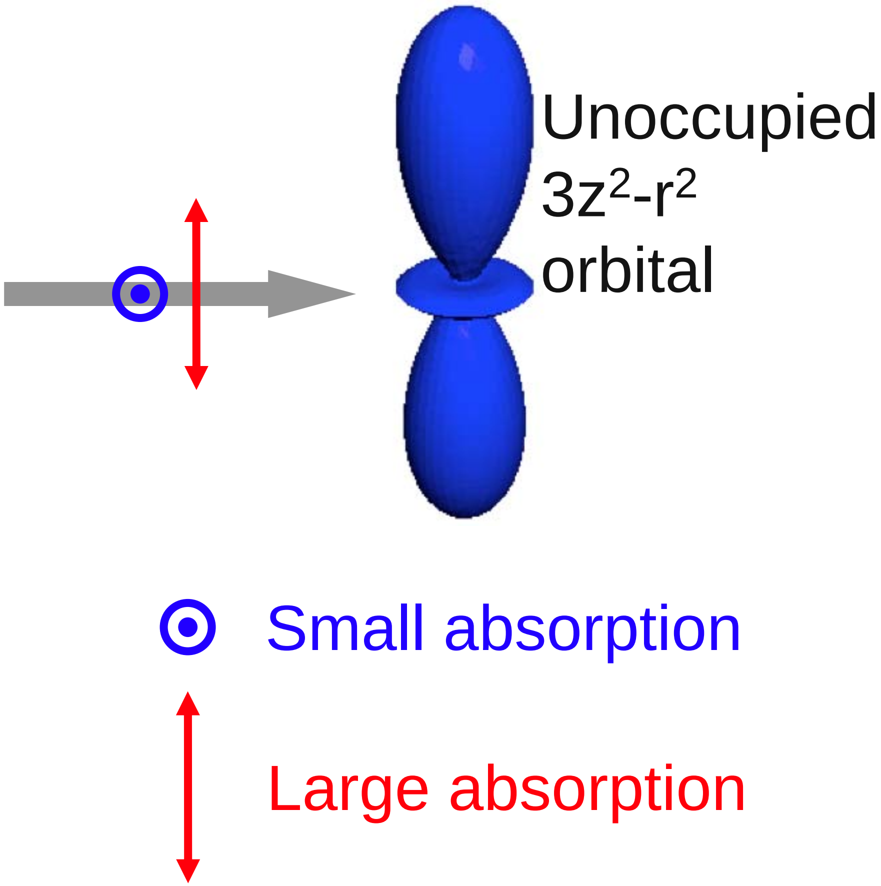
If unoccupied orbitals maintain bulk arrangement near interface



Expect weak ferromagnetic exchange at the the interface

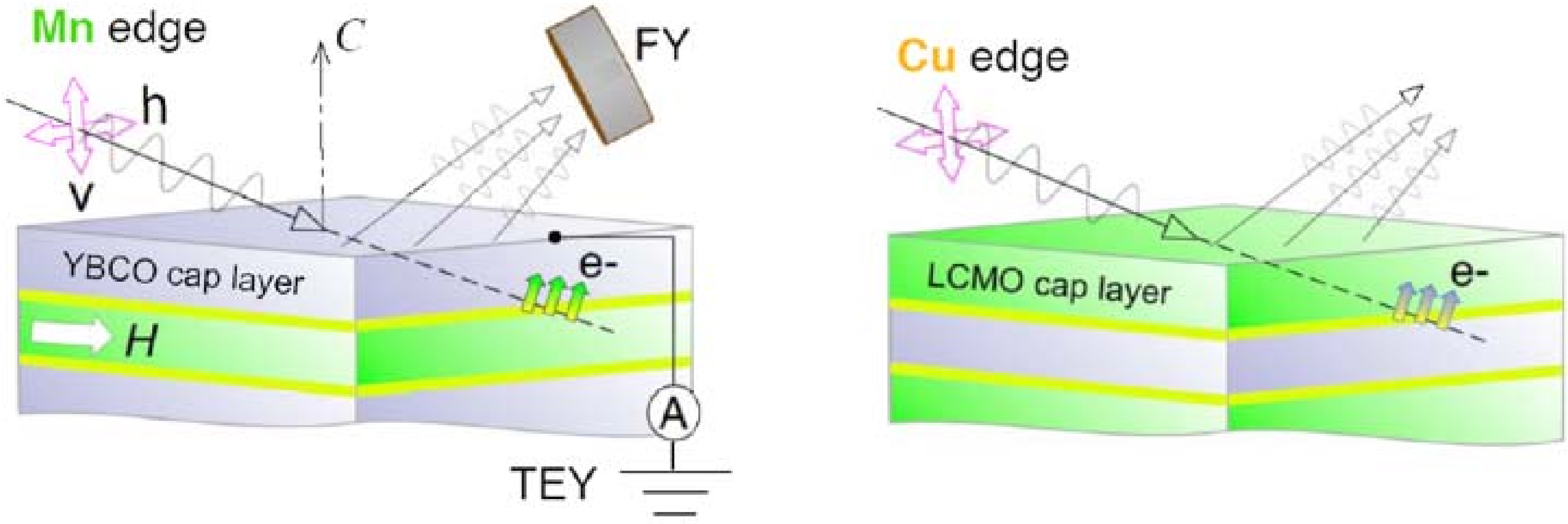
Experiments shows the opposite → orbitals reorder?

Linearly polarized x-rays probe orbital occupation



Interface sensitivity

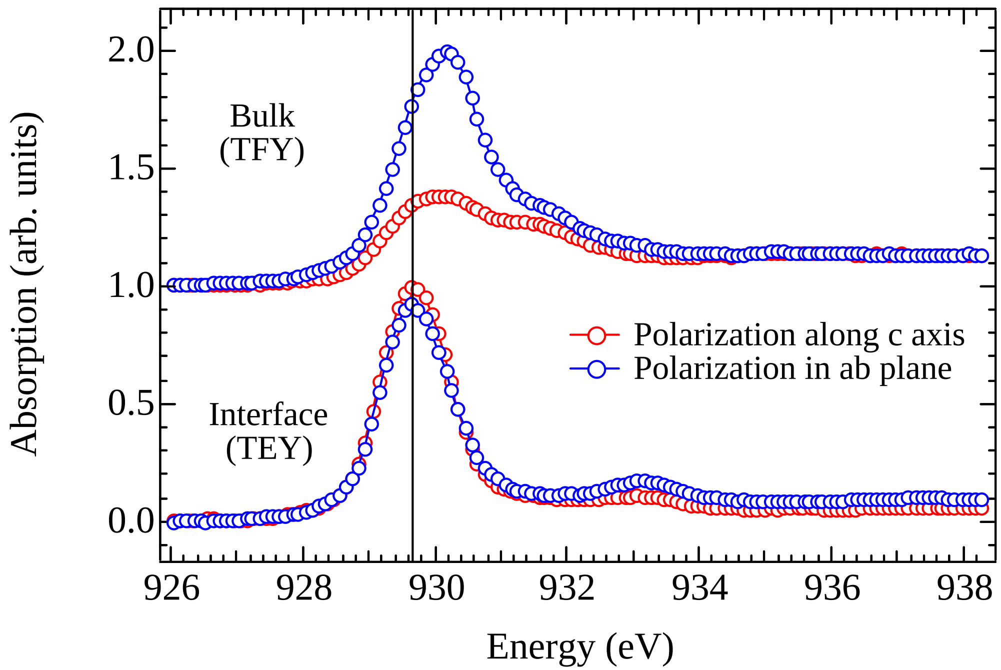
Sensitivity to interface using different capping layers

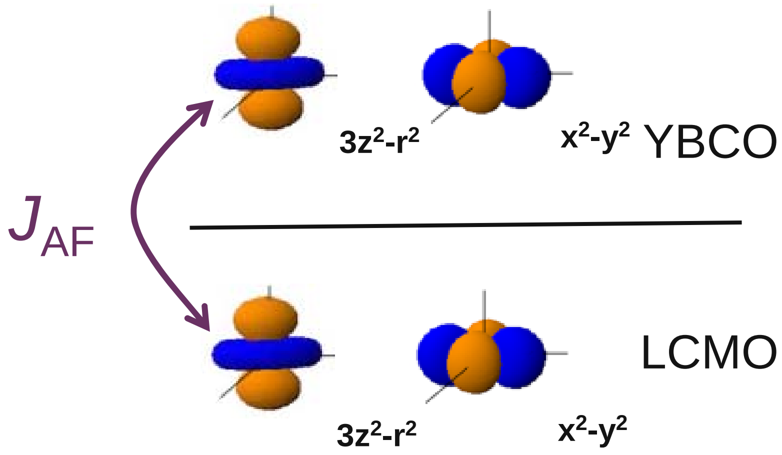


FY Bulk sensitive

TEY Low electron escape depth → probes first interface only

Linear dichroism at Cu L edge





FY matches data on bulk YBCO

TEY Energy shift in absorption → Charge transfer ($0.2e^-$)
Isotropic absorption → reconstruction at interface

J. Chakhalian, J. Freeland, *et al.* Science **318**, 1114 (2007)

Magnetic scattering at high pressure

Developing high pressure instrumentation for both XMCD and magnetic scattering.
Application of pressure compresses the lattice resulting in band broadening thereby affecting magnetic exchange.

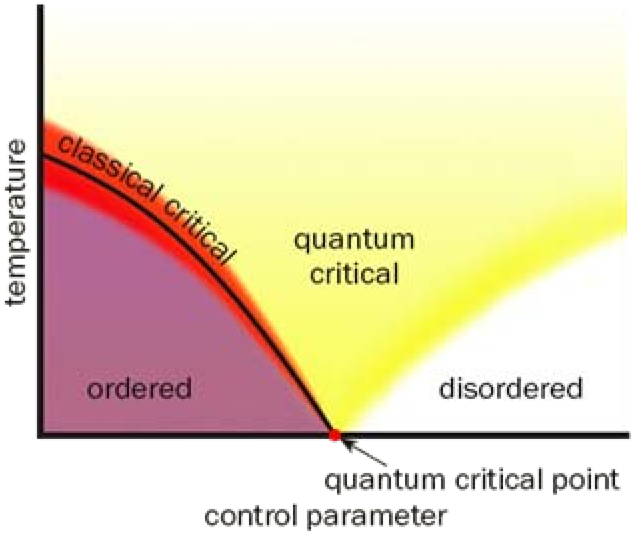
Magnetic Quantum Phase Transitions

Yejun Feng
Rafael Jaramillo
Thomas Rosenbaum

Zahir Islam
George Srajer

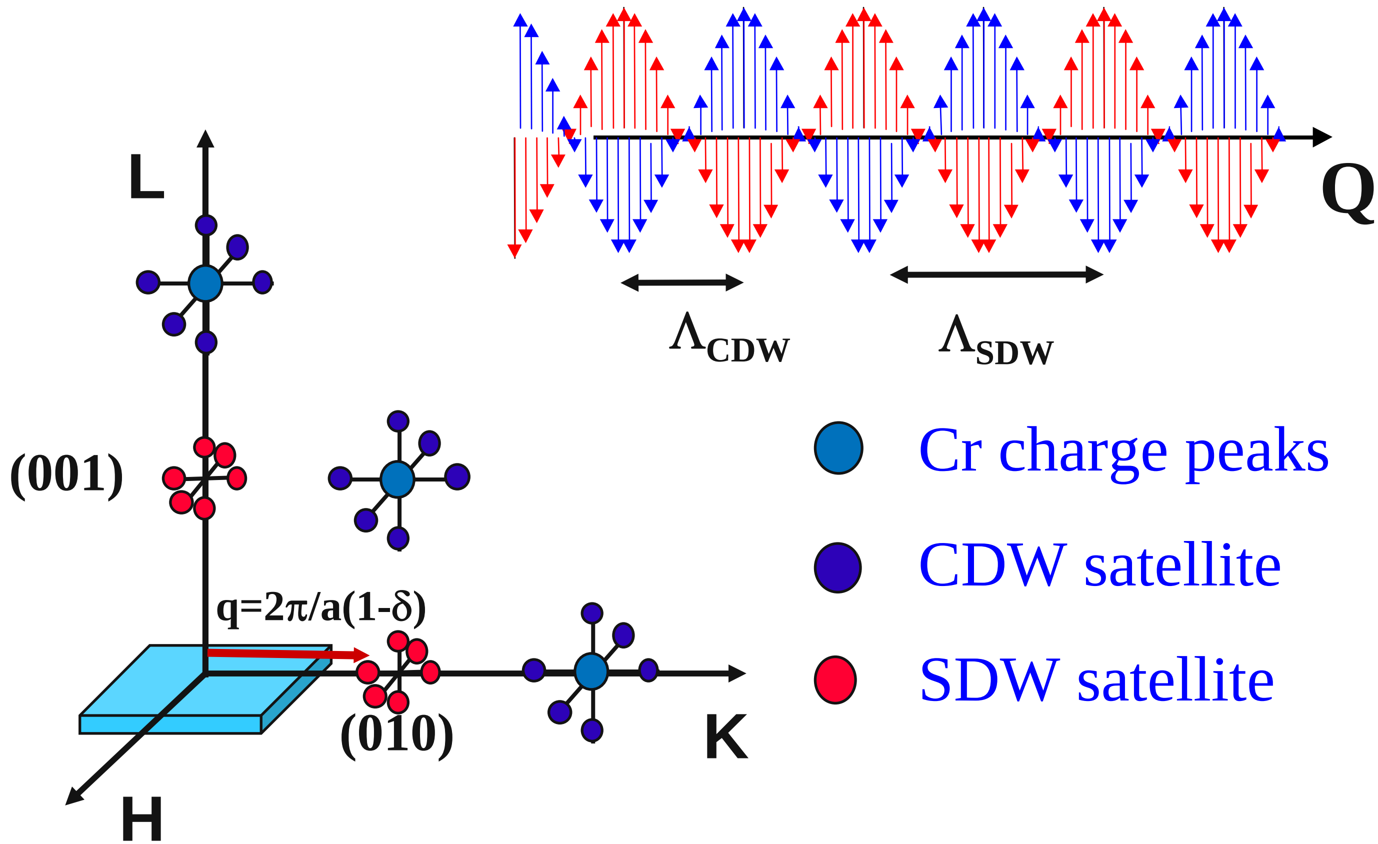
Maddury Somayazulu
Ho-kwang Mao

Gabriel Aeppli



•Fluctuations are quantum in nature rather than thermal $\Delta E \Delta t \approx \hbar$

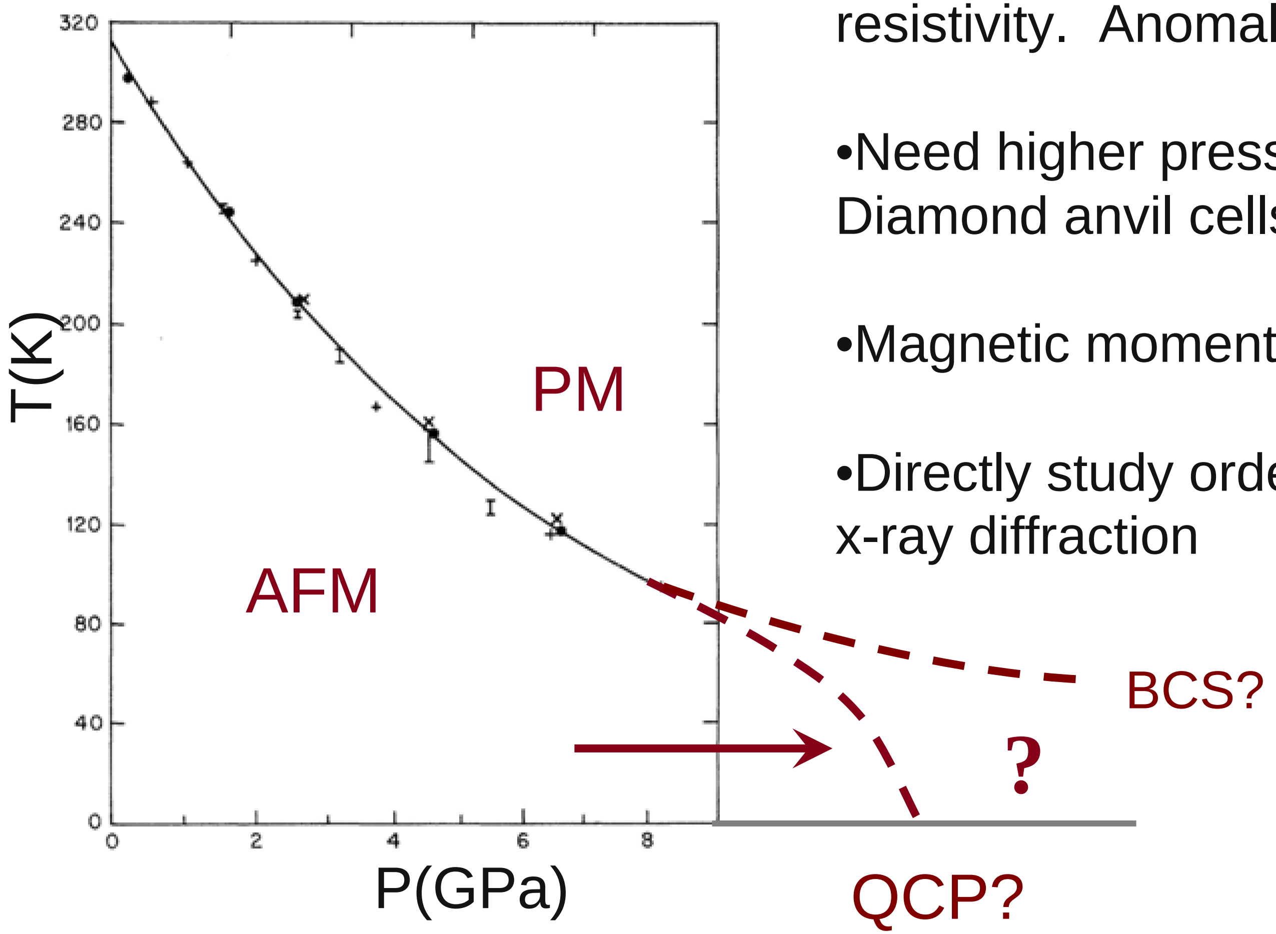
Cr Spin-Density/Charge Density Wave



Can use x-rays to measure order parameter to see how they scale.
Look for quantum critical behavior as pressure is increased.

Transport measurements of T_N in Cr

D. McWhan, T. Rice
Phys. Rev. Lett. 19, 846 (1967)



•Measured T_N up to 6 GPa using resistivity. Anomaly @ T_N

•Need higher pressures:
Diamond anvil cells

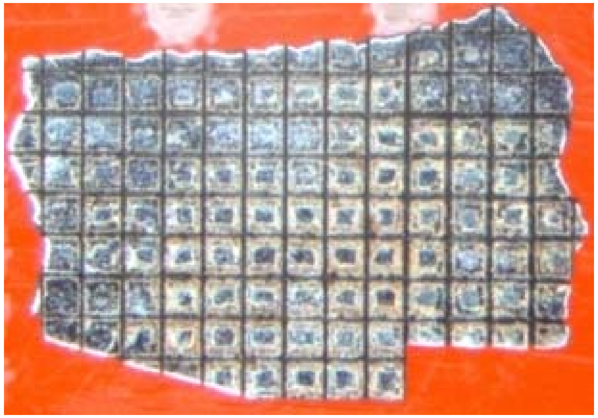
•Magnetic moment & wave vector?

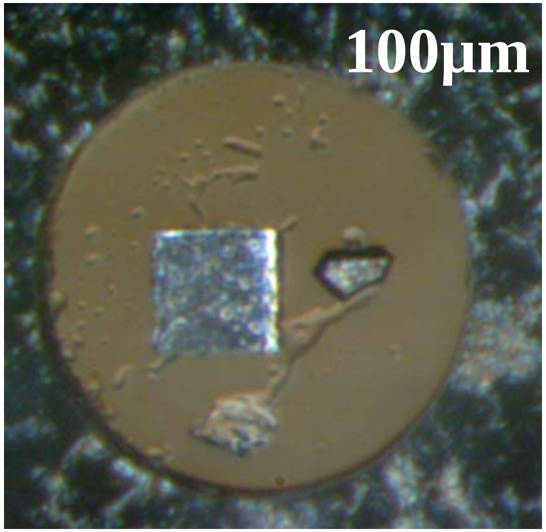
•Directly study order parameters with x-ray diffraction

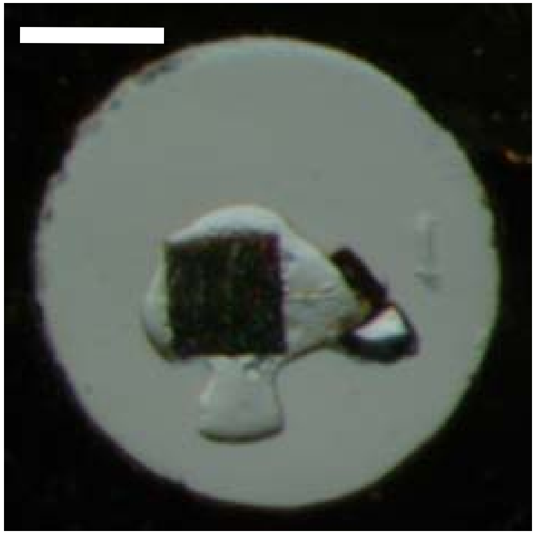
Sample Preparation/ Experimental Setup

Diamond Anvil Cell ∴ Need very small (oriented) crystals

Single crystal, ~ 100x100x40 μm^3, mosaic ~ 0.05^o



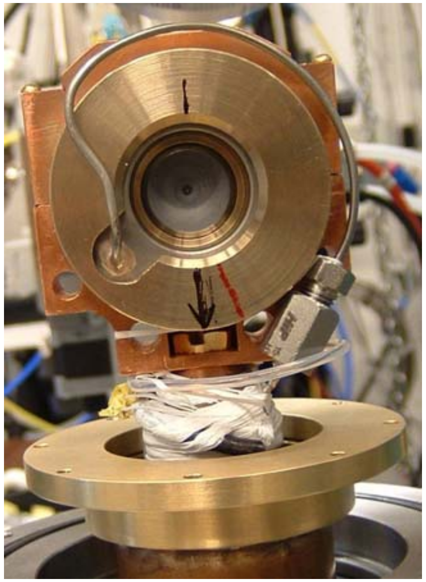


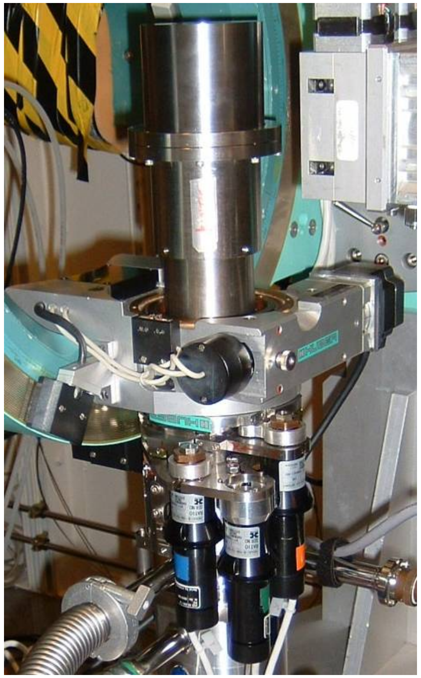


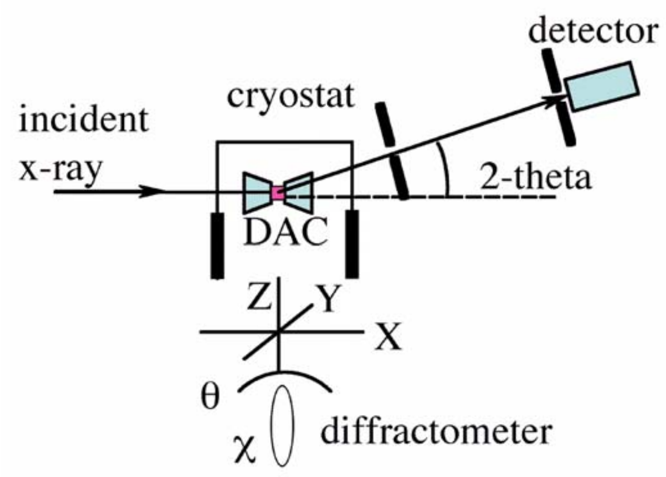
- Mechanically polish to 40μm
- Pulse laser dicing
- 5μm beam

- Etched to remove surface stress
- Sealed samples inside DAC
- Ruby (initial), silver (*in-situ*) manometers

Diamond anvil cells - Experimental Setup



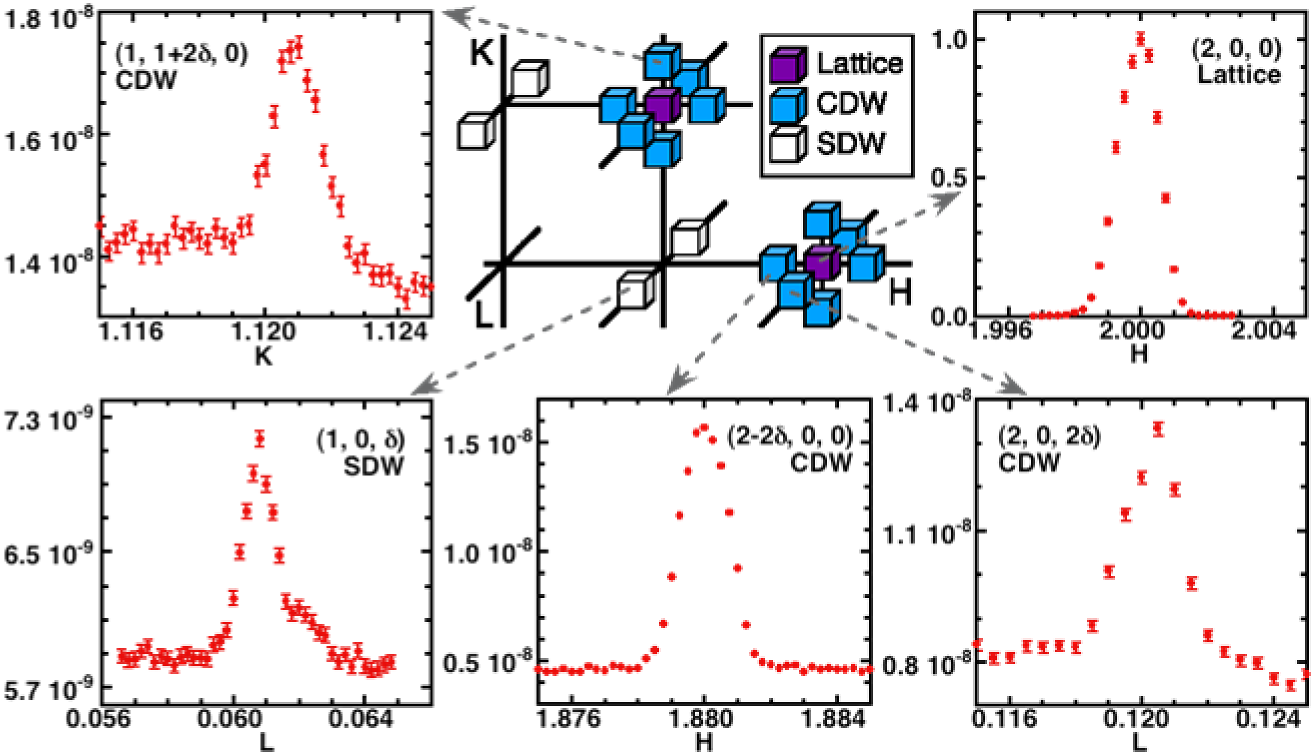




- **Diamonds**
  - culet: 800 μm
  - thickness: 2 mm
- **Helium-membrane DAC**
  - *in situ* ΔP at low *T*

- Helium refridgerator (~8K)
- X-Y-Z sample stage.
- Focused 20 keV x-rays ($100 \times 100 \mu m^2$).
- 2θ up to ~25˚ (40˚→70˚ under dev.)

Lattice, SDW, CDW @ 4GPa, 8.5K



Y. Feng *et al.*, *Phys. Rev. Lett.* **99**, 137201 (2007)

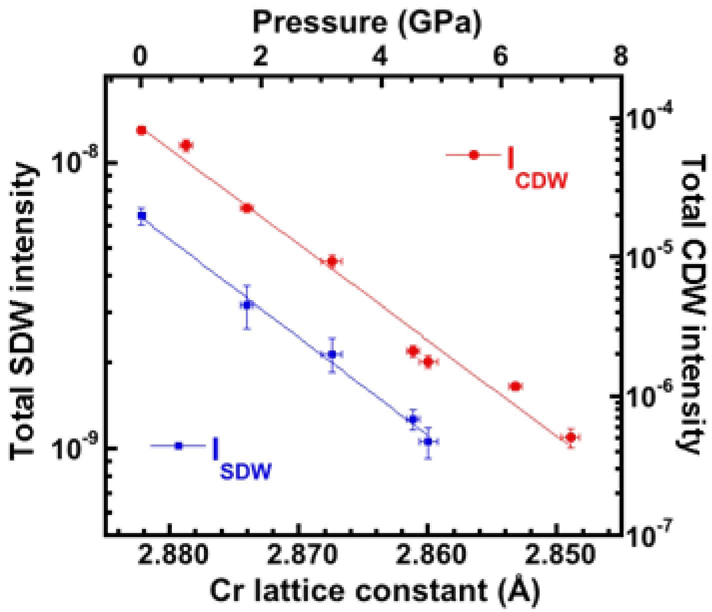
Peaks are 10^{-7} to 10^{-9} smaller than charge peak.

20 keV to penetrate DAC, ∴ not at a resonance.

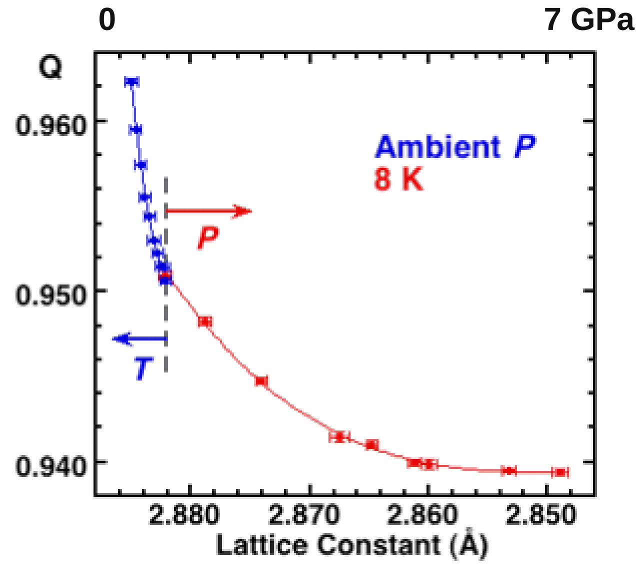
Need to measure all peaks to get domain distribution.

Pressure-dependence of CDW and SDW

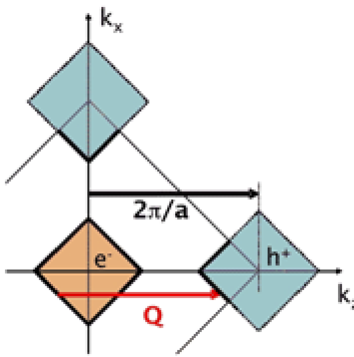
Intensity



Wave Vector



- Scaling law under pressure $I_{CDW}^{1/2} \sim I_{SDW} \sim \mu^2$ (BCS form)
- SDW/CDW scale exponentially with pressure (μ ~10% @ 8 GPa).
- Approaching rigid band model above 4 GPa.
- Order parameter evolution uncorrelated to band structure



Y.Feng, R. Jamarillo, *et al. Phys. Rev. Lett*. **99**, 137201 (2007)

Future directions in magnetic measurements

Future scientific opportunities lie at the extremes

Sensitivity, Time, Field, Pressure

- **Upgrading the optics on 4-ID-C**
  - **~2 order of magnitude gain in flux (greater sensitivity).**
- **Instruments for:**
  - **High-pressure (>100 GPa)**
  - **Low-temperatures (<1K)**
  - **High-field (Pulsed ~1ms, >60T & 13 Tesla-DC)**
- **High magnetic field scattering beamline (DC-Fields >30T)**