X-Ray Dichroism, Chirality, and Orbital Currents

Mike Norman

Materials Science Division
Argonne National Laboratory

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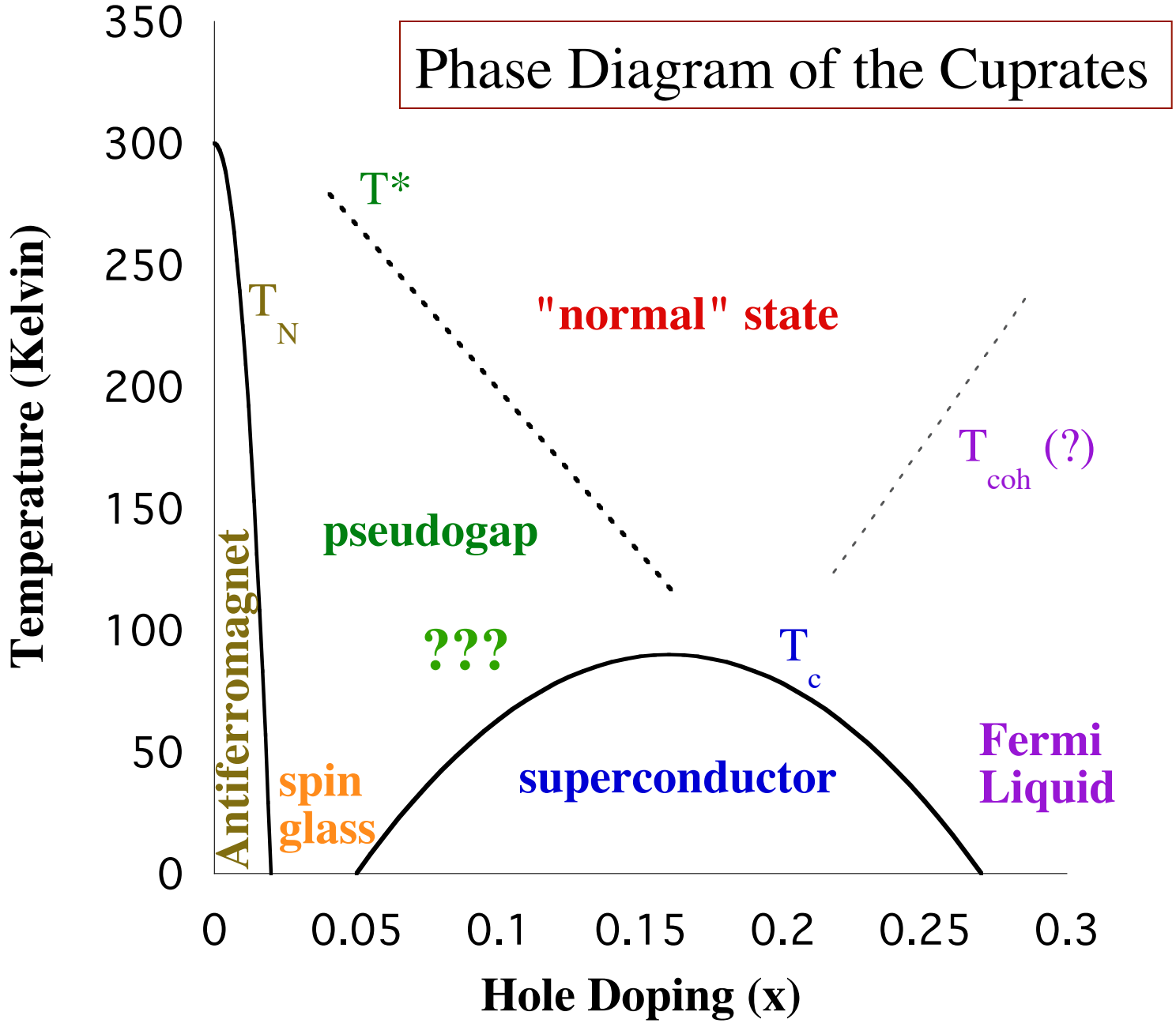
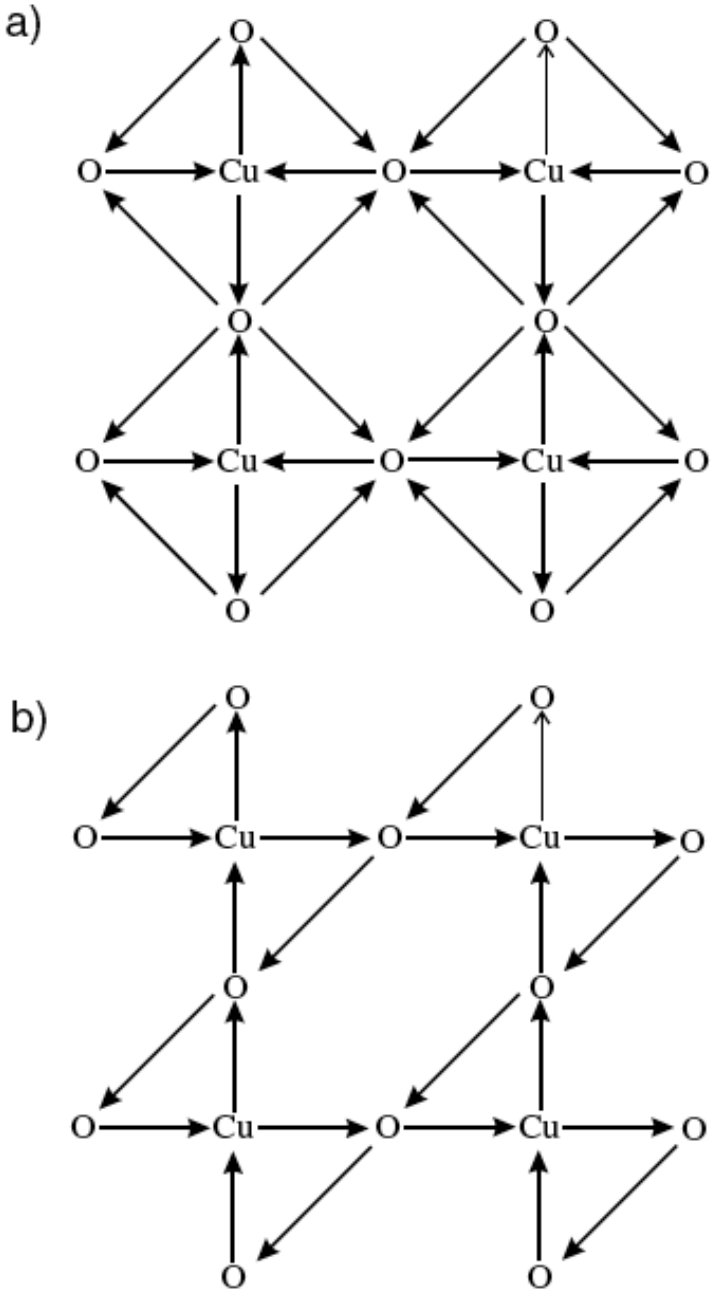


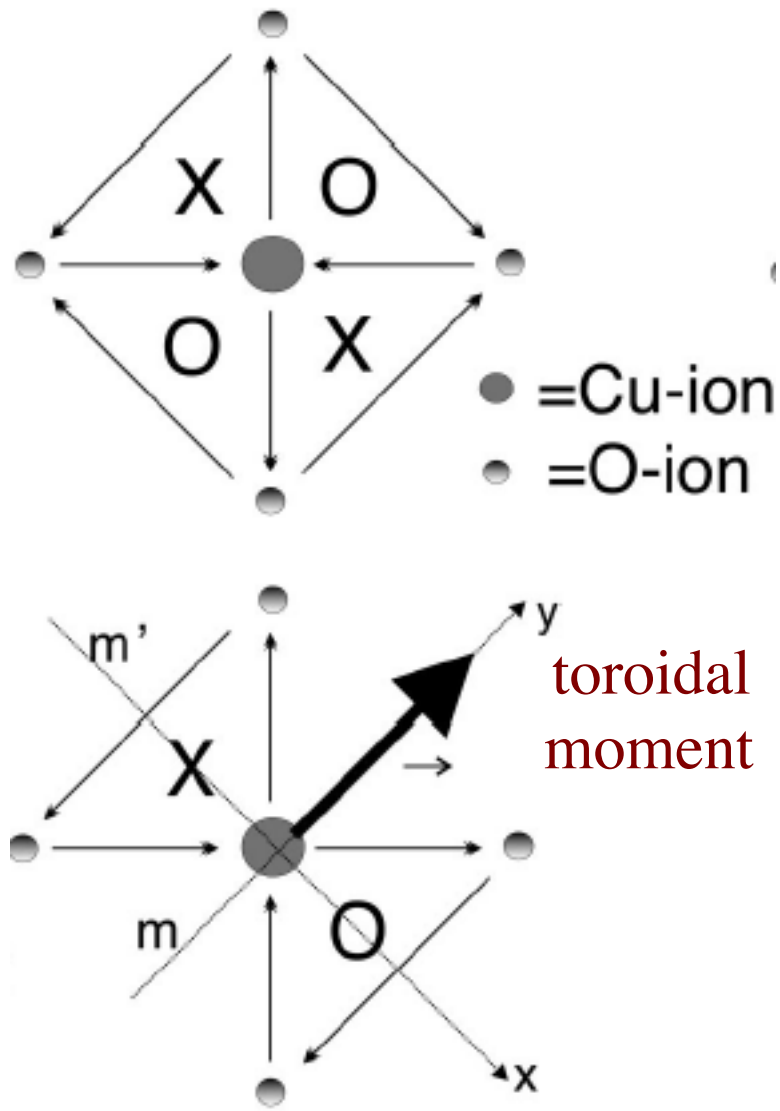
Norman *et al*, Adv Phys (2005)

What is the Pseudogap?

1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes/nematic
9. Valence bond solid/glass
10. Combination?

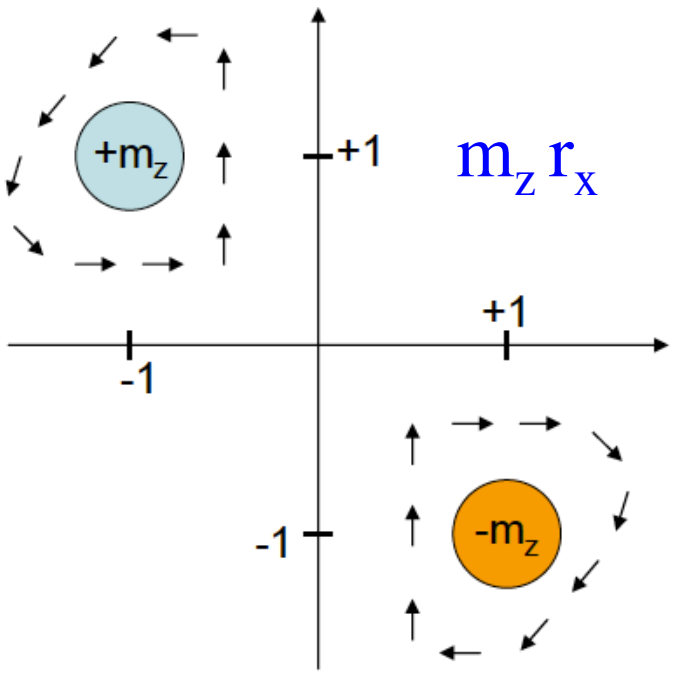
Orbital Currents

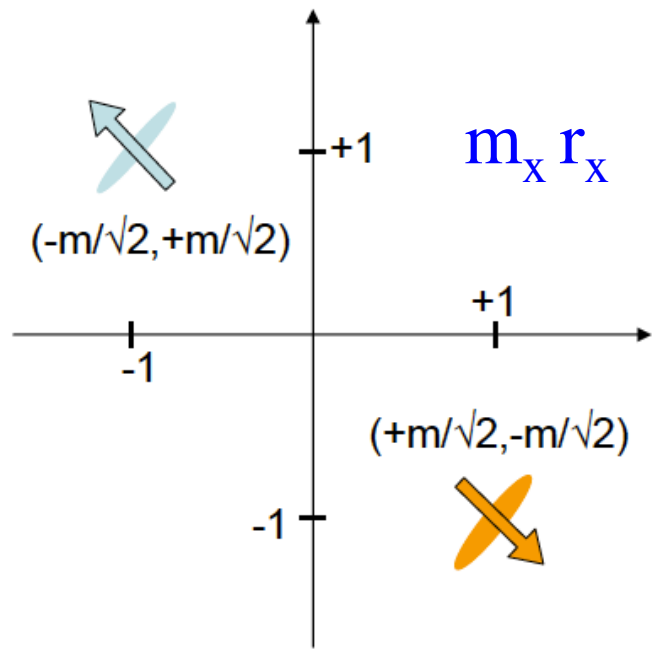




Simon & Varma, PRL (2002)
Di Matteo & Varma, PRB (2003)

Orbital Currents - Combinations of magnetic monopoles, toroidal dipoles & magnetic quadrupoles



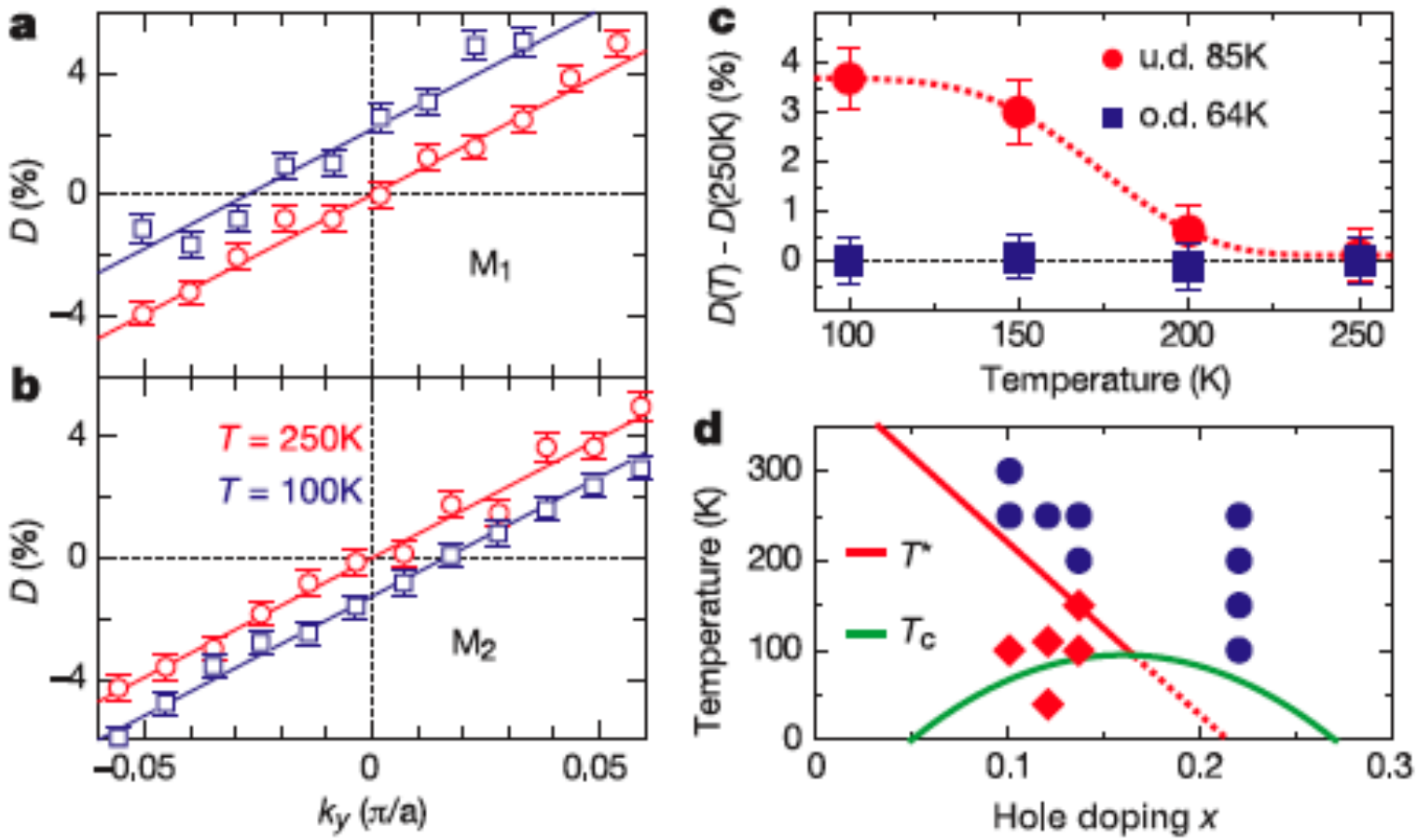


$$M_{ij} \equiv \sum_{\alpha=1,2} \left[m_i^\alpha r_j^\alpha + r_i^\alpha m_j^\alpha - \frac{2}{3}\delta_{ij} \sum_l m_l^\alpha r_l^\alpha \right]$$

$$T_{ij} \equiv \sum_{\alpha=1,2} [m_i^\alpha r_j^\alpha - r_i^\alpha m_j^\alpha]$$

Di Matteo & Norman, PRB (2012)

ARPES dichroism tracks the pseudogap
Question – chirality or time reversal breaking?

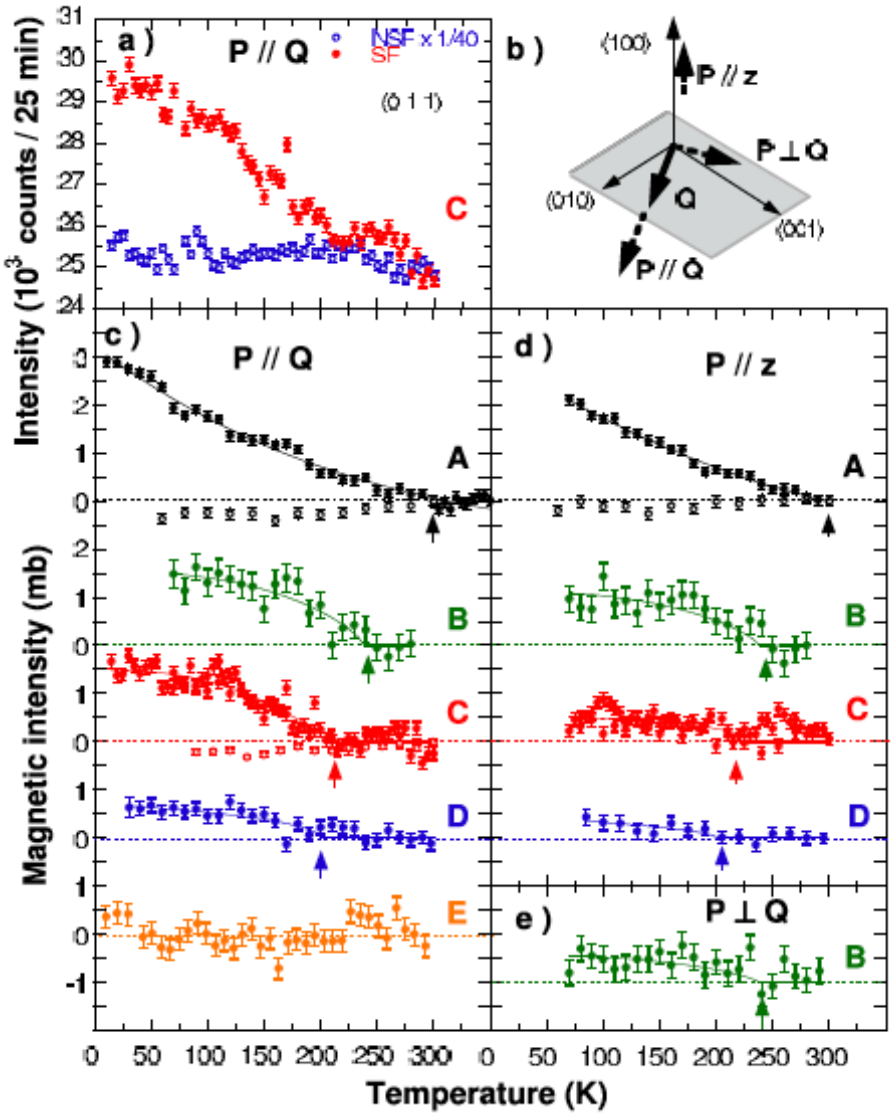


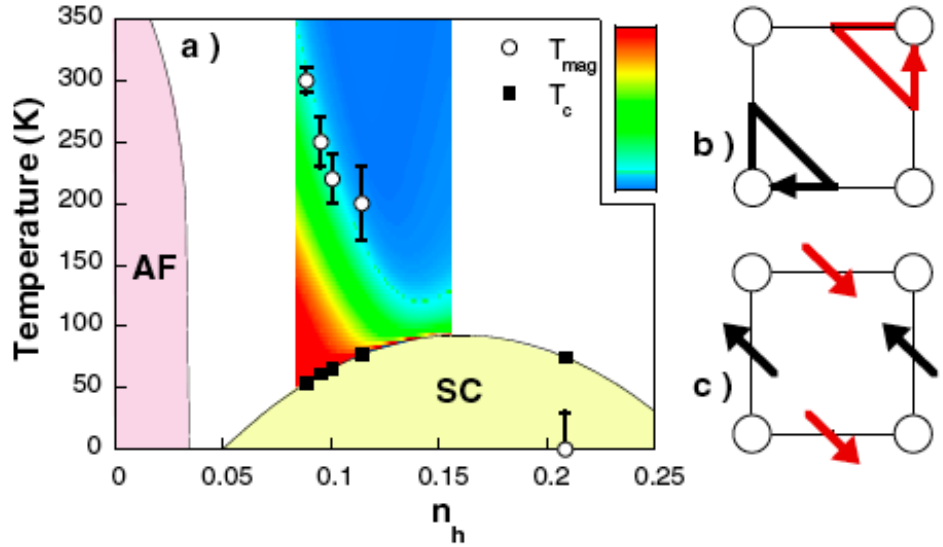
↑

mirror plane

Kaminski *et al*., Nature 2002

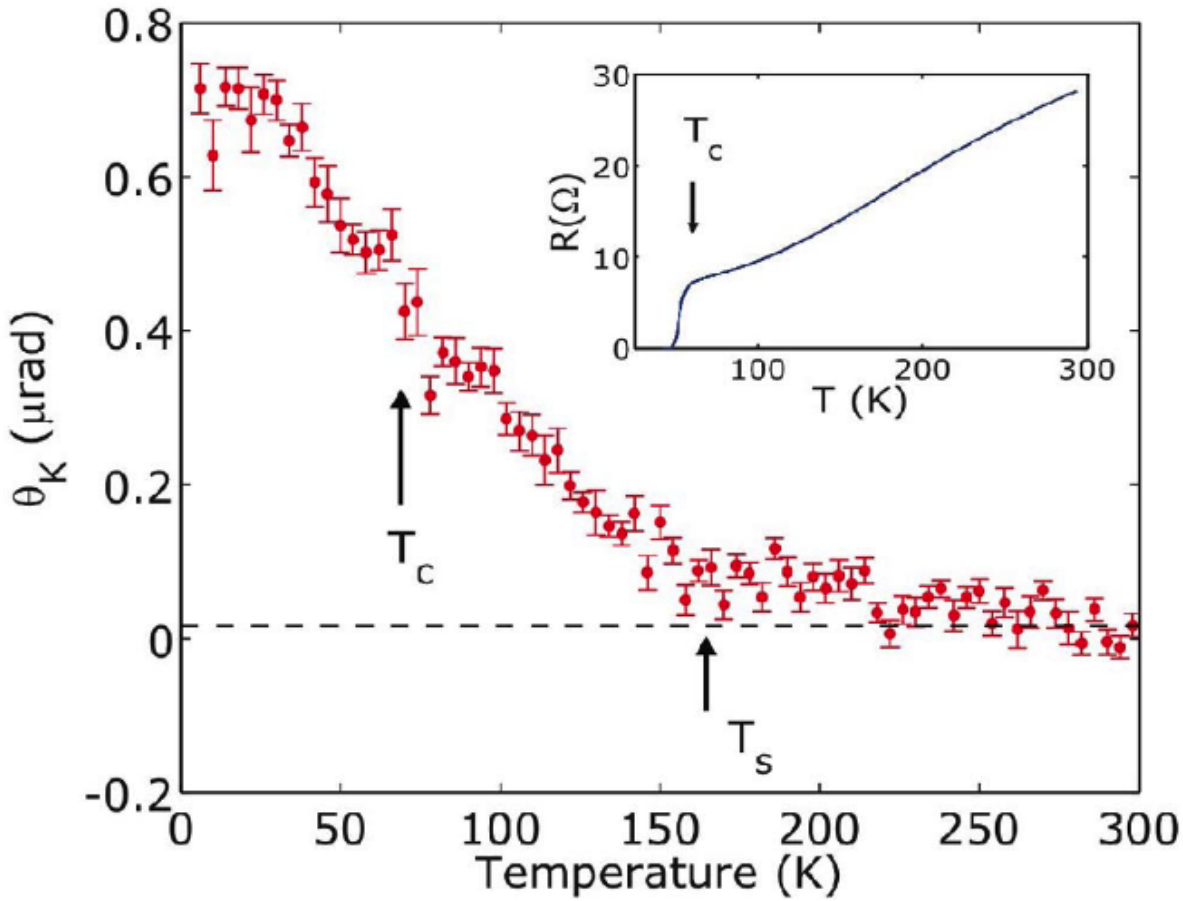
Polarized neutrons see intra-unit cell magnetism





Fauque *et al*., PRL 2006

Polar Kerr Effect seen as well (time reversal breaking?)



Chirality instead?

Hosur et al, PRB (2013)

Orenstein & Moore, PRB (2013)

Xia *et al*., PRL 2008

X-ray Optical Activity (E1-E2)

1. X-ray natural circular dichroism (XNCD)
Alagna *et al*., PRL 1998; Goulon *et al*., JCP 1998 ($LiIO_3$)
(time reversal even part of $\sigma^L - \sigma^R$)

2. Non-reciprocal x-ray linear dichroism (NRXLD)
Goulon *et al*., PRL 2000 (V_2O_3)
(time reversal odd part of $\sigma^{90} - \sigma^0$)

3. X-ray magneto-chiral dichroism (XMχD)
Goulon *et al*., PRL 2002 (Cr_2O_3)
($\sigma(\mathbf{H}) - \sigma(\mathbf{-H})$)

4. X-ray non-reciprocal directional dichroism (XNDD)
Kubota *et al*., PRL 2004 ($GaFeO_3$)
($\sigma^{90}(\mathbf{H}) - \sigma^{90}(\mathbf{-H})$)

5. X-ray circular intensity differential (XCID)
Goulon *et al*., JPCM 2007 (ZnO)
(polar vector part of $\sigma^L - \sigma^R$)

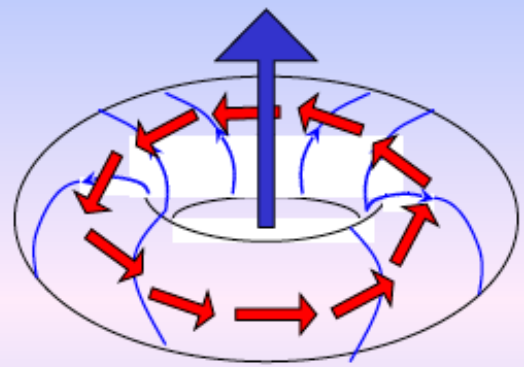
Dipole moments in matter

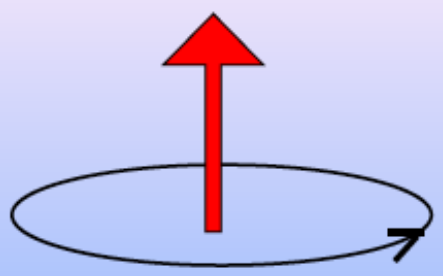
Electric dipole (d)

Polar Toroidal dipole (t)
or anapole

as $\mathbf{j} = \mathbf{curl}\,\mathbf{m}$

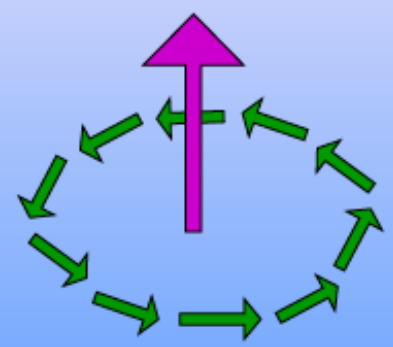
$$\mathbf{t} \equiv \frac{1}{2}\int \mathbf{r} \times \mathbf{m}\, dr$$





Magnetic dipole (m)

Axial Toroidal dipole (g)

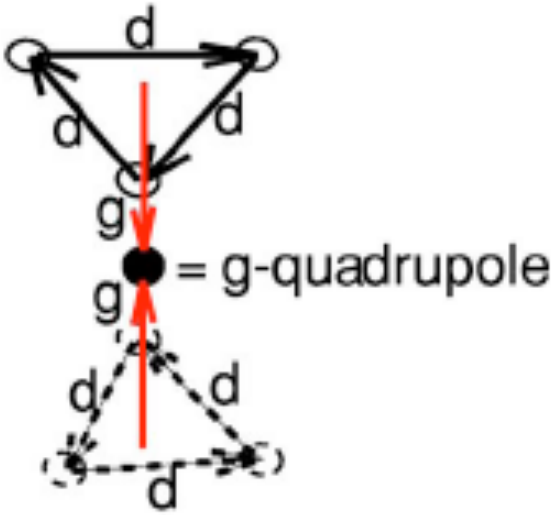


$$\mathbf{g} \equiv \frac{1}{2}\int \mathbf{r} \times \mathbf{d}\, dr$$

X-ray Natural Circular Dichroism (XNCD)

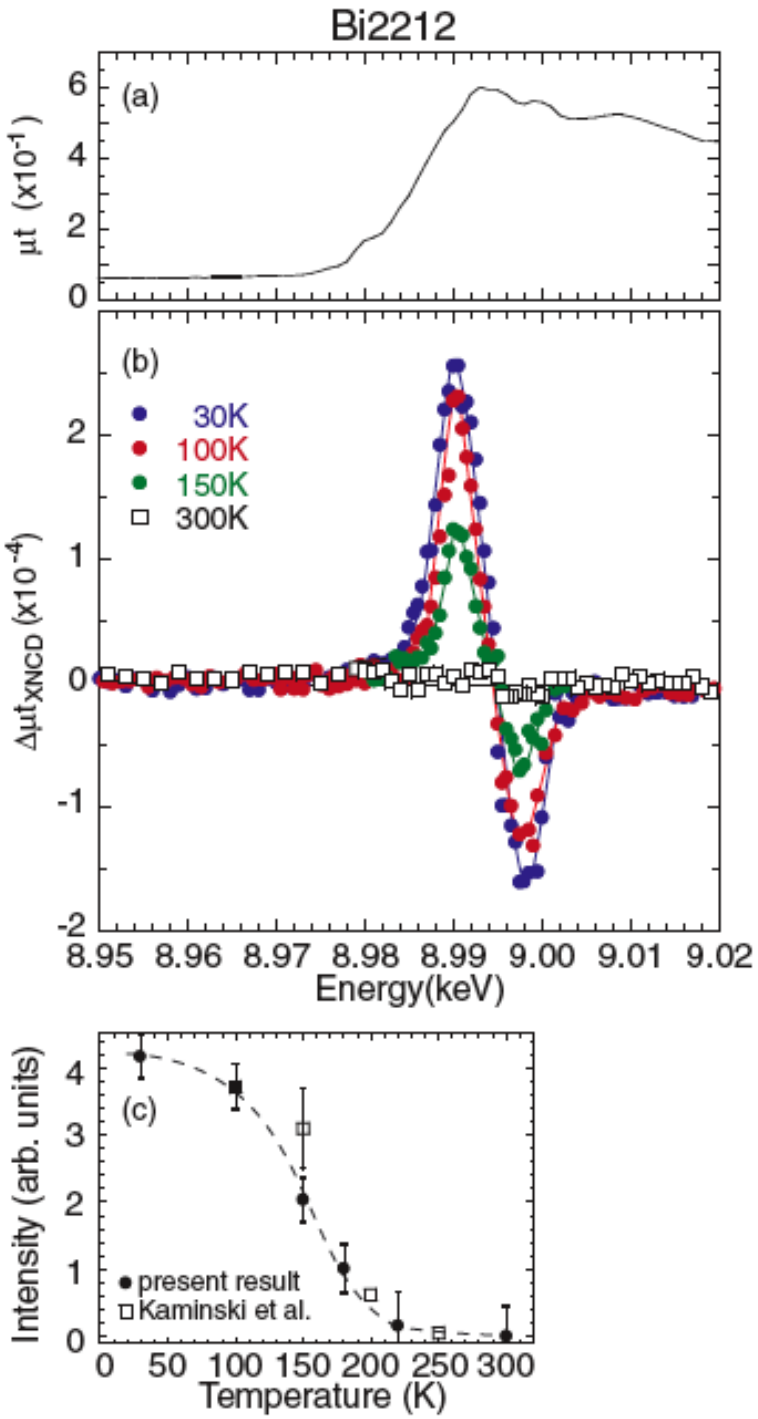
E1-E2 interference (broken inversion symmetry)

$$\vec{L} \cdot (\hat{\epsilon}^* \times \hat{\epsilon})(\vec{\Omega} \cdot \hat{k})$$



where

- **L** is the orbital angular momentum
- **k** is the wavevector of the x-ray
- **ε** is the polarization of the x-ray
- **Ω** is the toroidal moment operator



XNCD
Underdoped Bi2212
(T_c = 80K)
Cu K edge

Signal tracks ARPES dichroism

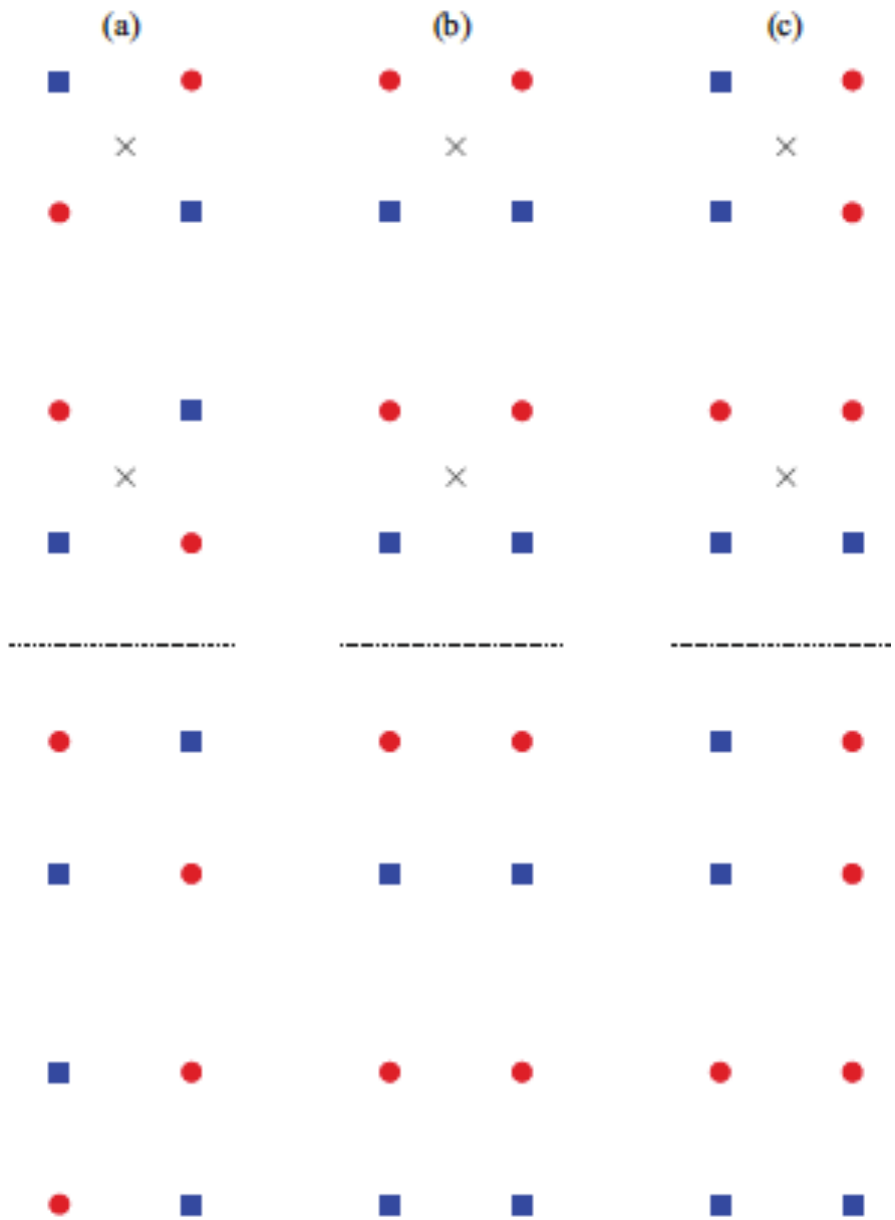
<u>Unusual aspects</u>

1. Simple +/- peak profile

2. Peaks at edge, not pre-edge

Kubota *et al.*, JPSJ (2006)

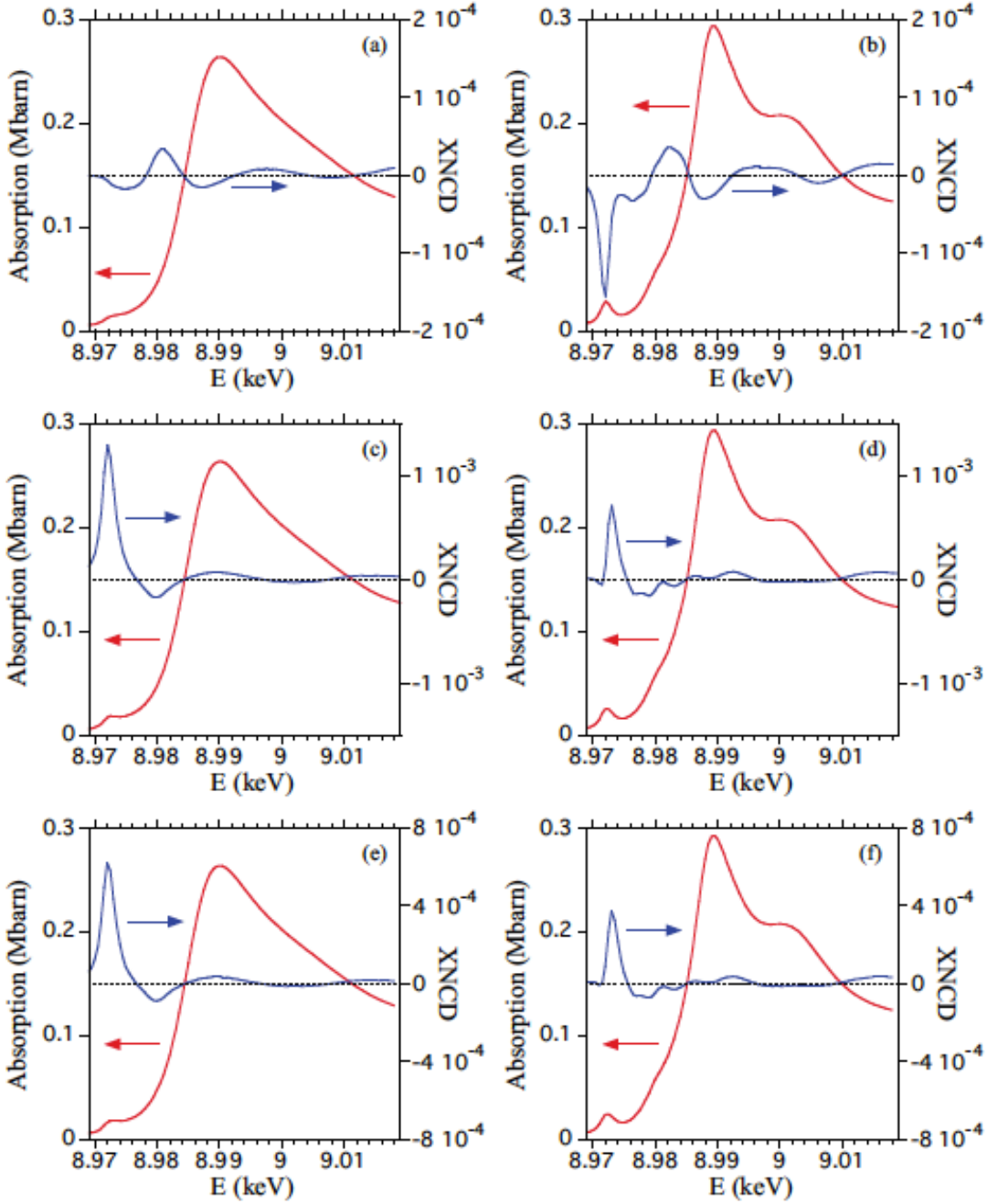
Charge Ordering on oxygen sites (blue + vs red -)?



← glide plane between Bi2212 CuO_2 bilayers

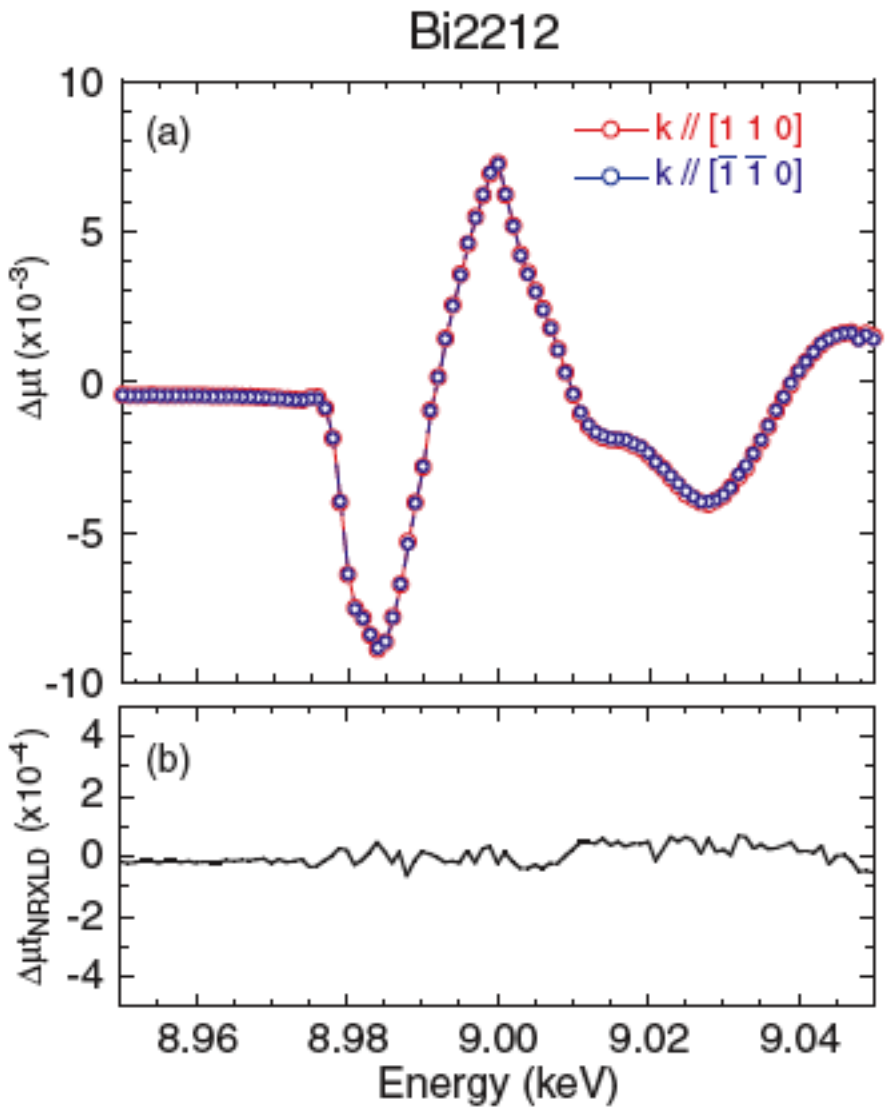
Norman, PRB (2013)

Resulting XNCD signature (Bi2212)

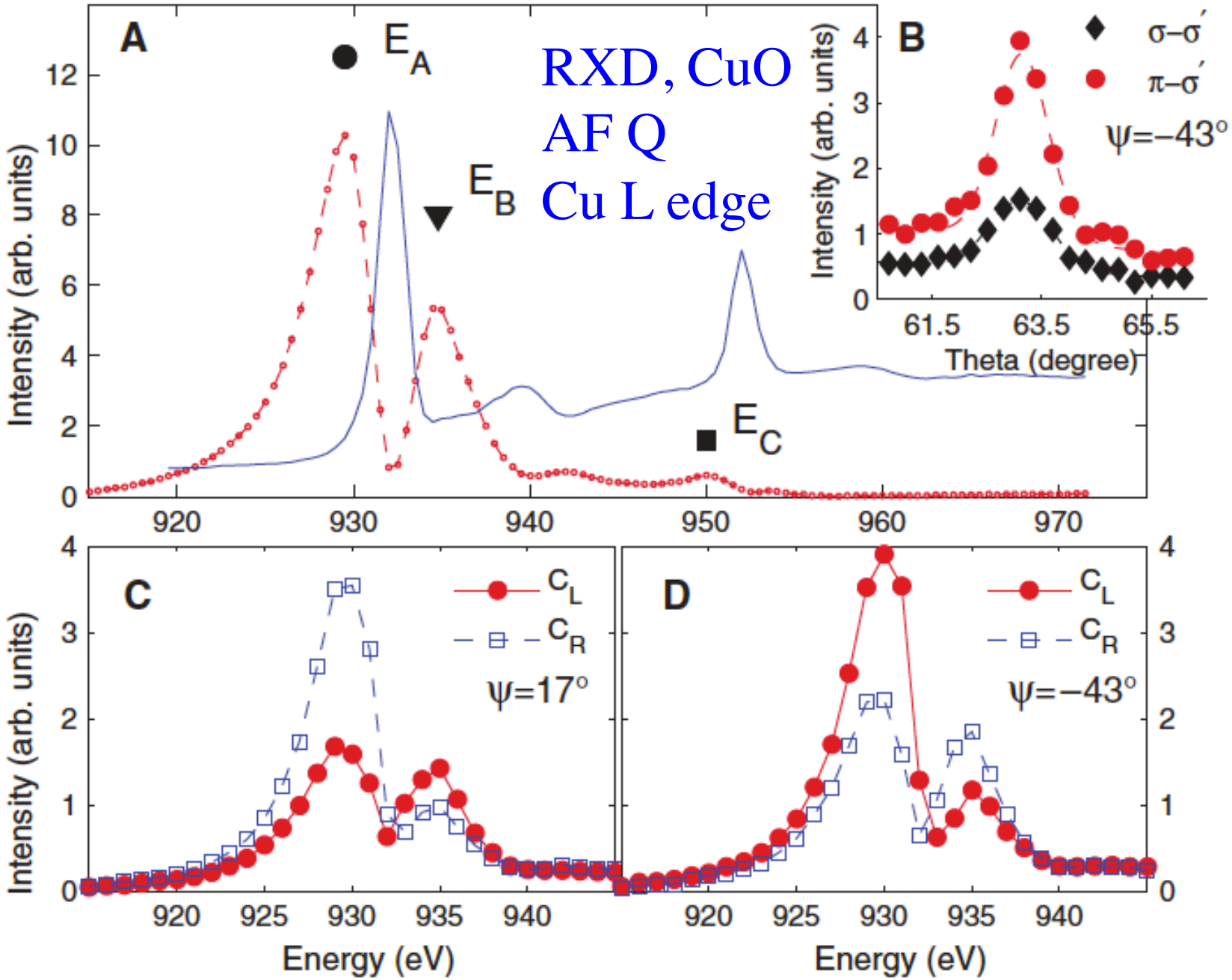


Norman, PRB (2013)

Non reciprocal X ray linear dichroism (null result)

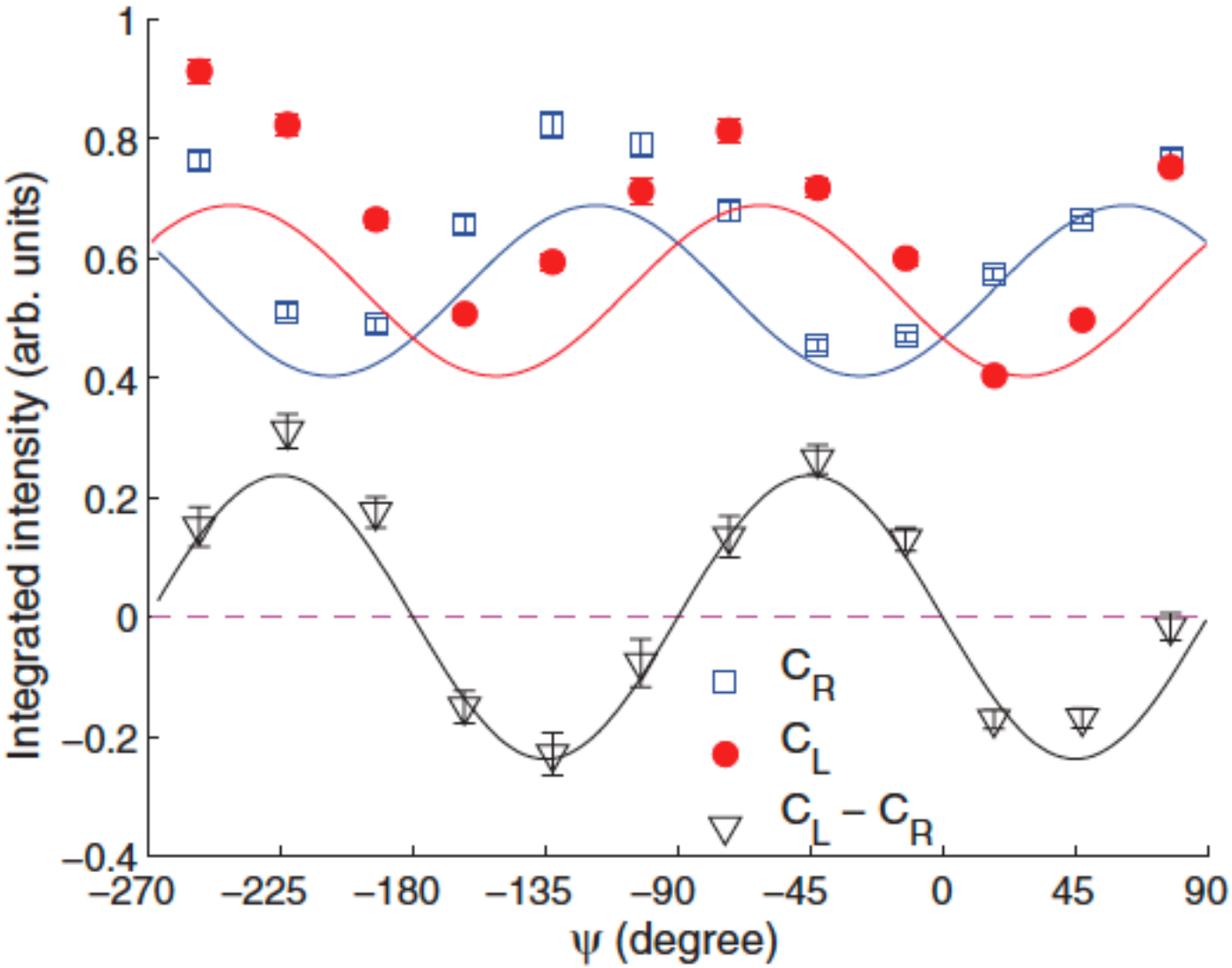


Kubota *et al*., JPSJ (2006)



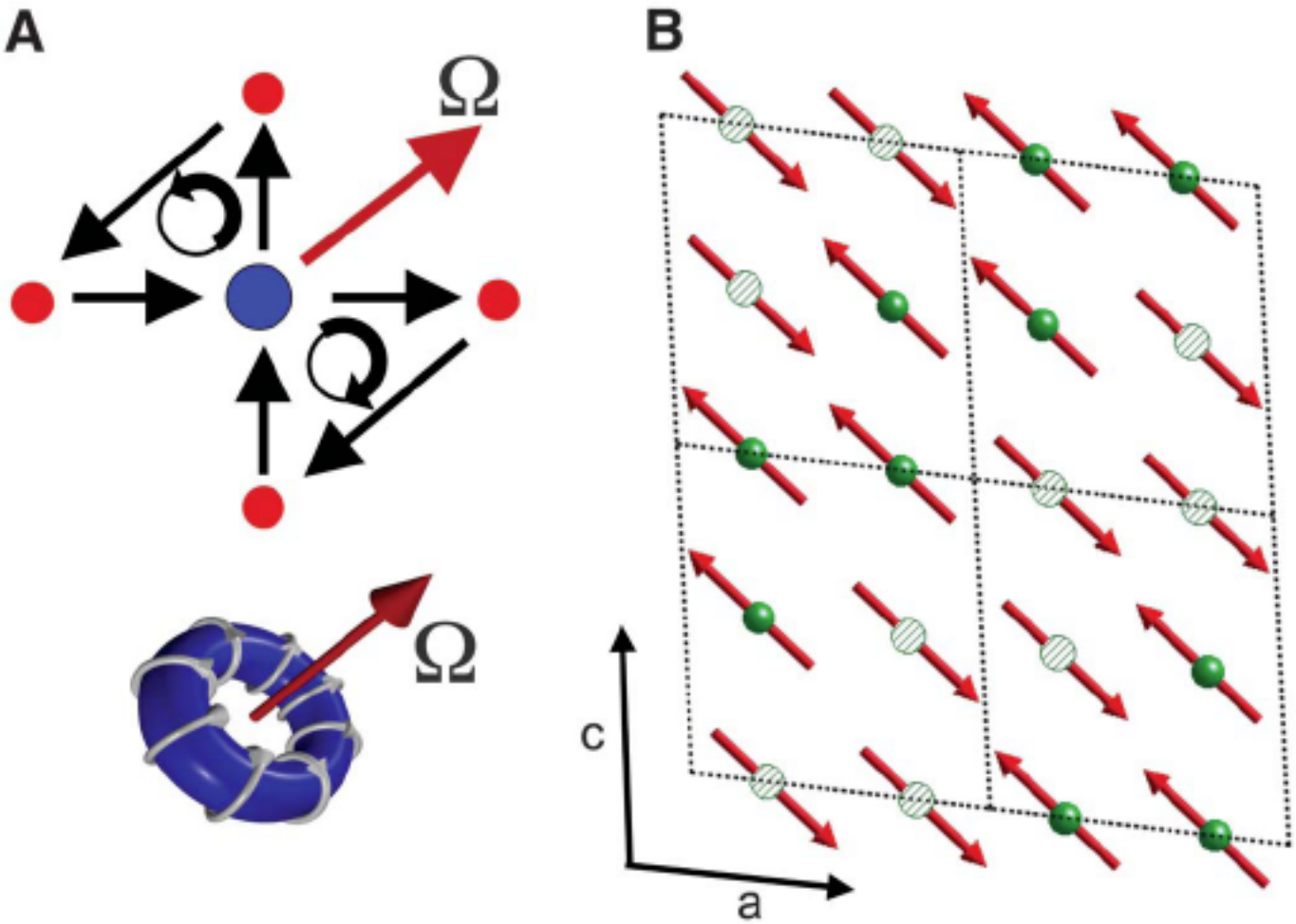
Scagnoli *et al*., Science (2011)

Dichroism in CuO (commensurate AF phase)
sin(2ψ) azimuthal dependence



Scagnoli *et al*., Science (2011)

Toroidal Moments in the Commensurate AF Phase of CuO?



Scagnoli *et al*., Science (2011)

Dichroism due to E1-E1, E1-M1 interference?

$$
\begin{aligned}
f_1^{\mathrm{E1-E1}}(\sigma\sigma) &= 0 \\
f_1^{\mathrm{E1-E1}}(\sigma\pi) &= -im_y \cos\theta \cos\psi \\
f_1^{\mathrm{E1-E1}}(\pi\sigma) &= im_y \cos\theta \cos\psi \\
f_1^{\mathrm{E1-E1}}(\pi\pi) &= im_y \sin(2\theta) \sin\psi
\end{aligned}
$$

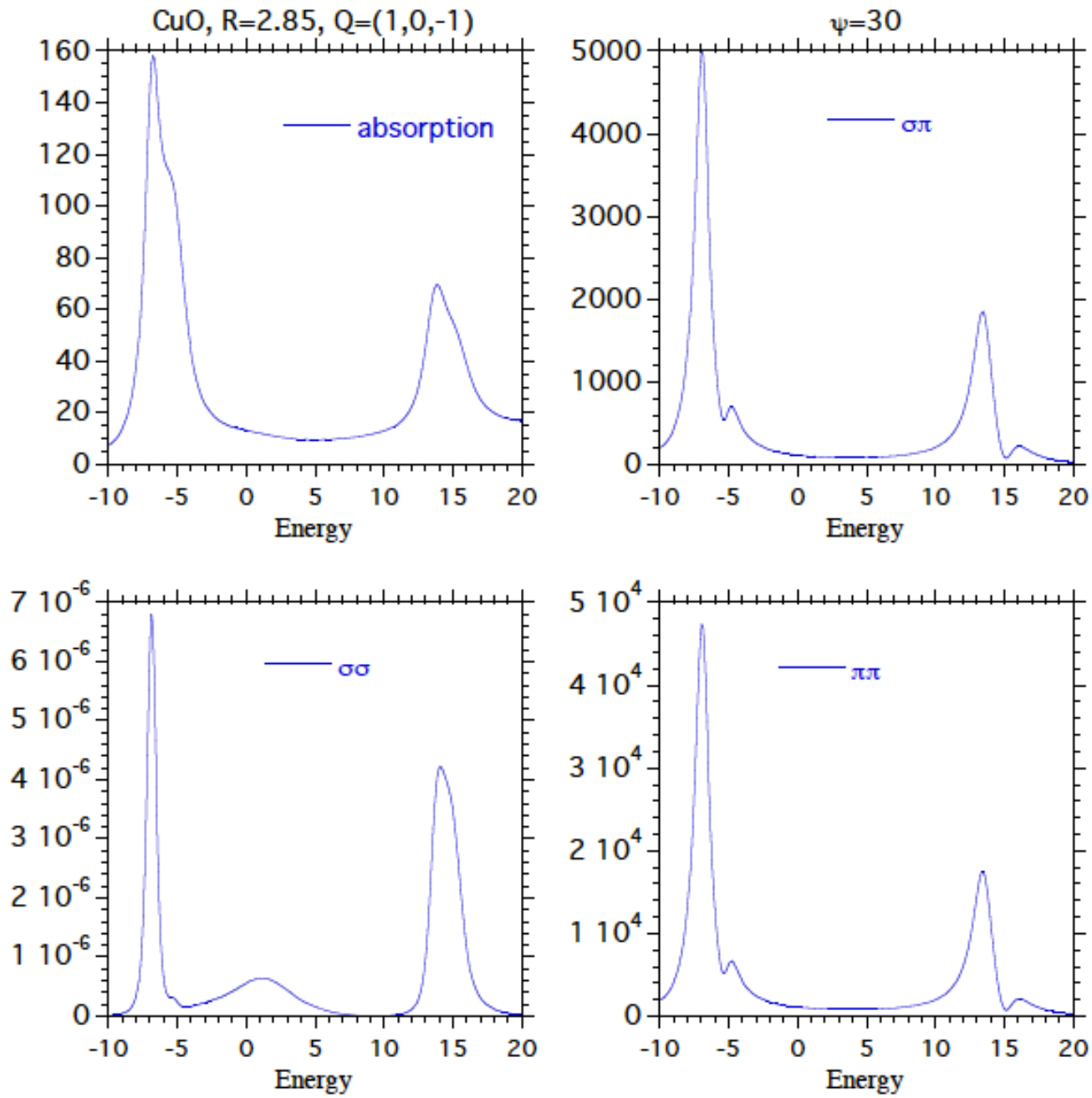
$$
\begin{aligned}
f_{1a}(\sigma\sigma) &= 2T_x \cos\theta \sin\psi \\
f_{1a}(\sigma\pi) &= -T_x \sin(2\theta) \cos\psi \\
f_{1a}(\pi\sigma) &= T_x \sin(2\theta) \cos\psi \\
f_{1a}(\pi\pi) &= 2T_x \cos\theta \sin\psi
\end{aligned}
$$

$$
\begin{aligned}
f_{1b}(\sigma\sigma) &= 2M_{yz} \cos\theta \sin\psi \\
f_{1b}(\sigma\pi) &= M_{xy} \cos^2\theta \sin(2\psi) \\
f_{1b}(\pi\sigma) &= M_{xy} \cos^2\theta \sin(2\psi) \\
f_{1b}(\pi\pi) &= -2M_{yz} \cos\theta \sin\psi
\end{aligned}
$$

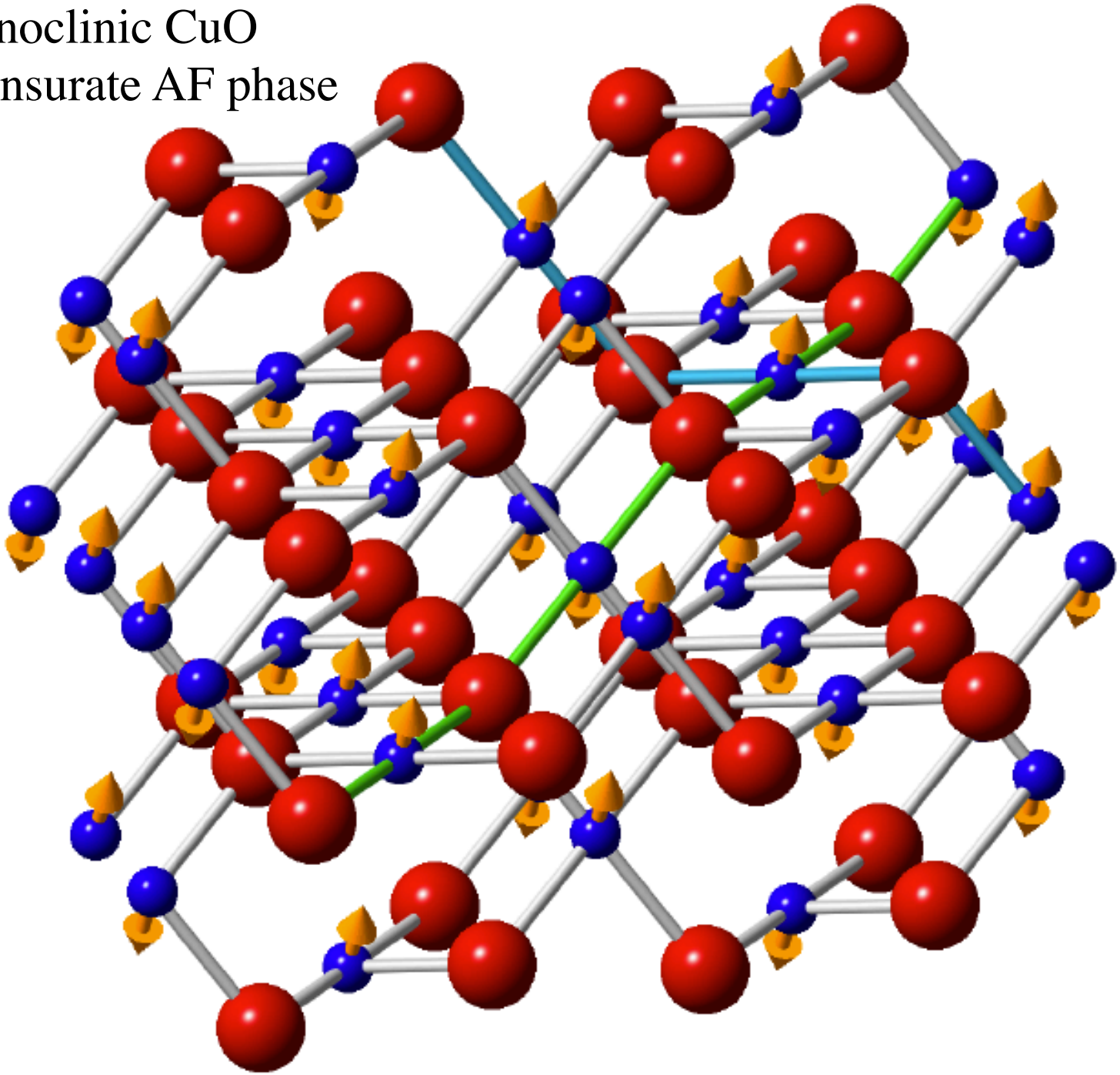
$$
\begin{aligned}
\Delta I &\propto m_y T_x \cos^4\theta \sin(2\psi) \\
&+ m_y M_{xy} \cos^3\theta \sin\theta \sin(2\psi) \sin\psi
\end{aligned}
$$

Di Matteo & Norman, PRB (2012)

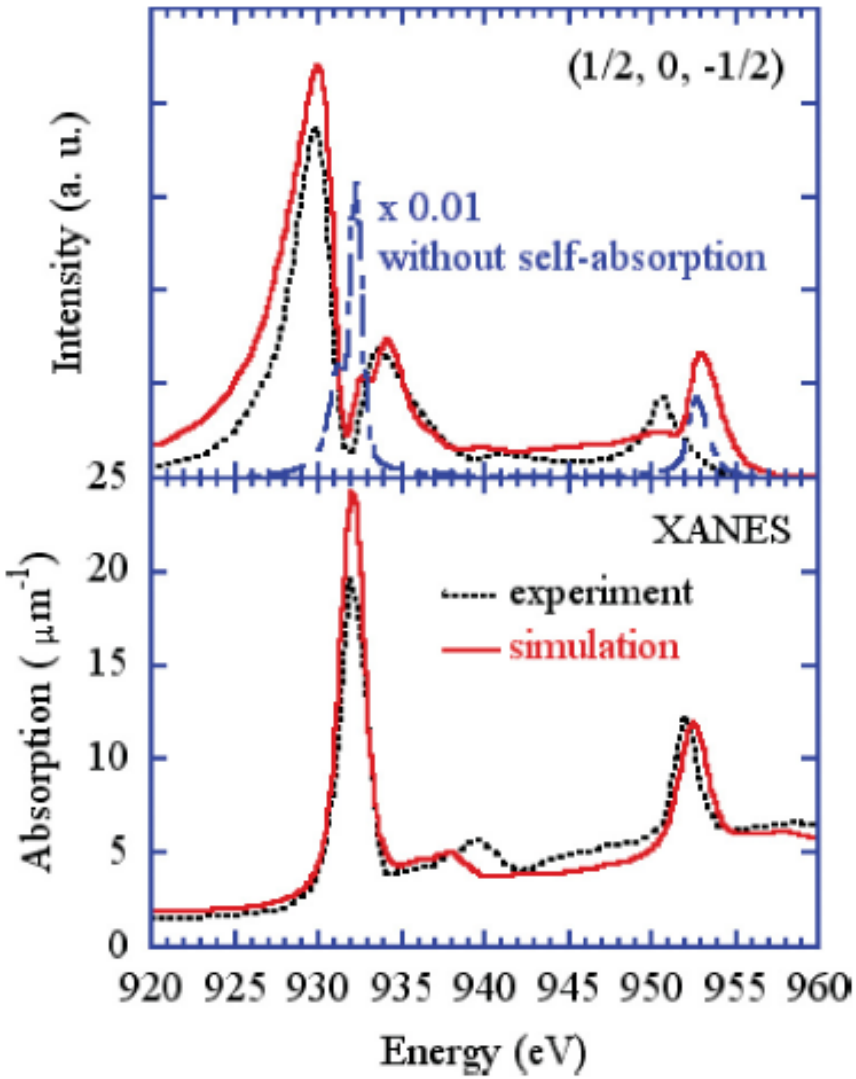
σσ scattering in RXD (due to E1-E2 terms) is << σπ and ππ terms

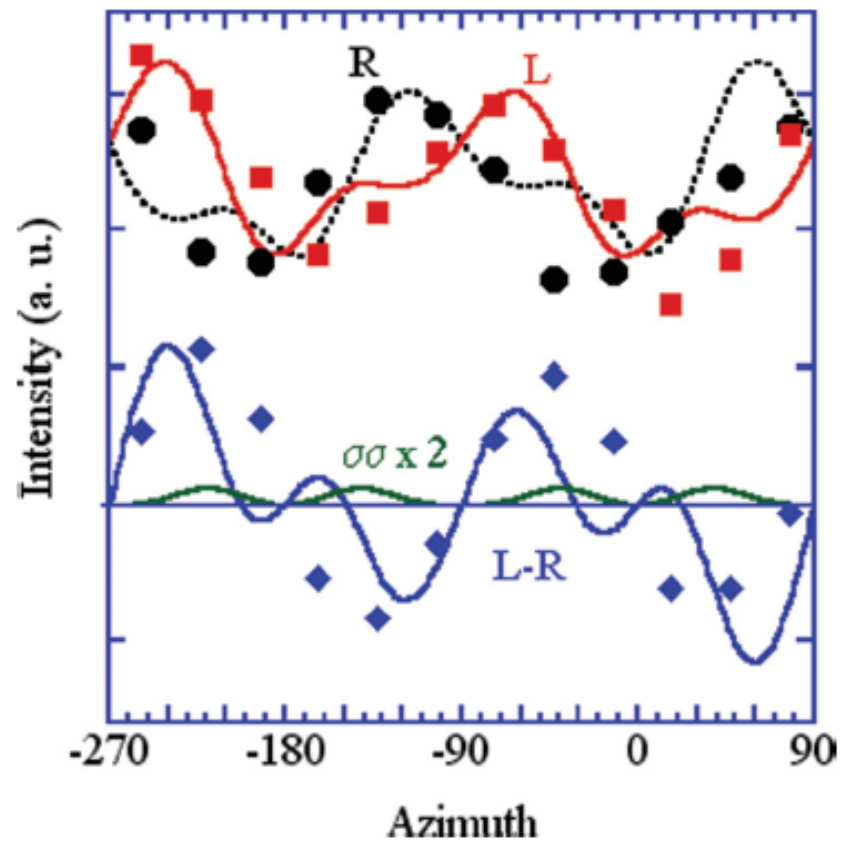


Monoclinic CuO
Commensurate AF phase



Monoclinic structure leads to a rotation of the light (linear dichroism)
So σσ signal due to contamination from σπ magnetic dipole contribution





Joly *et al*, PRB (2012)

σπ scattering in RXD dominated by anisotropic charge scattering

Hg1201
Q=(100)
Cu K edge
AF oxygens
S along c axis