What Novel Spectroscopic Techniques Can Tell us about the Physics of Strongly Correlated Materials

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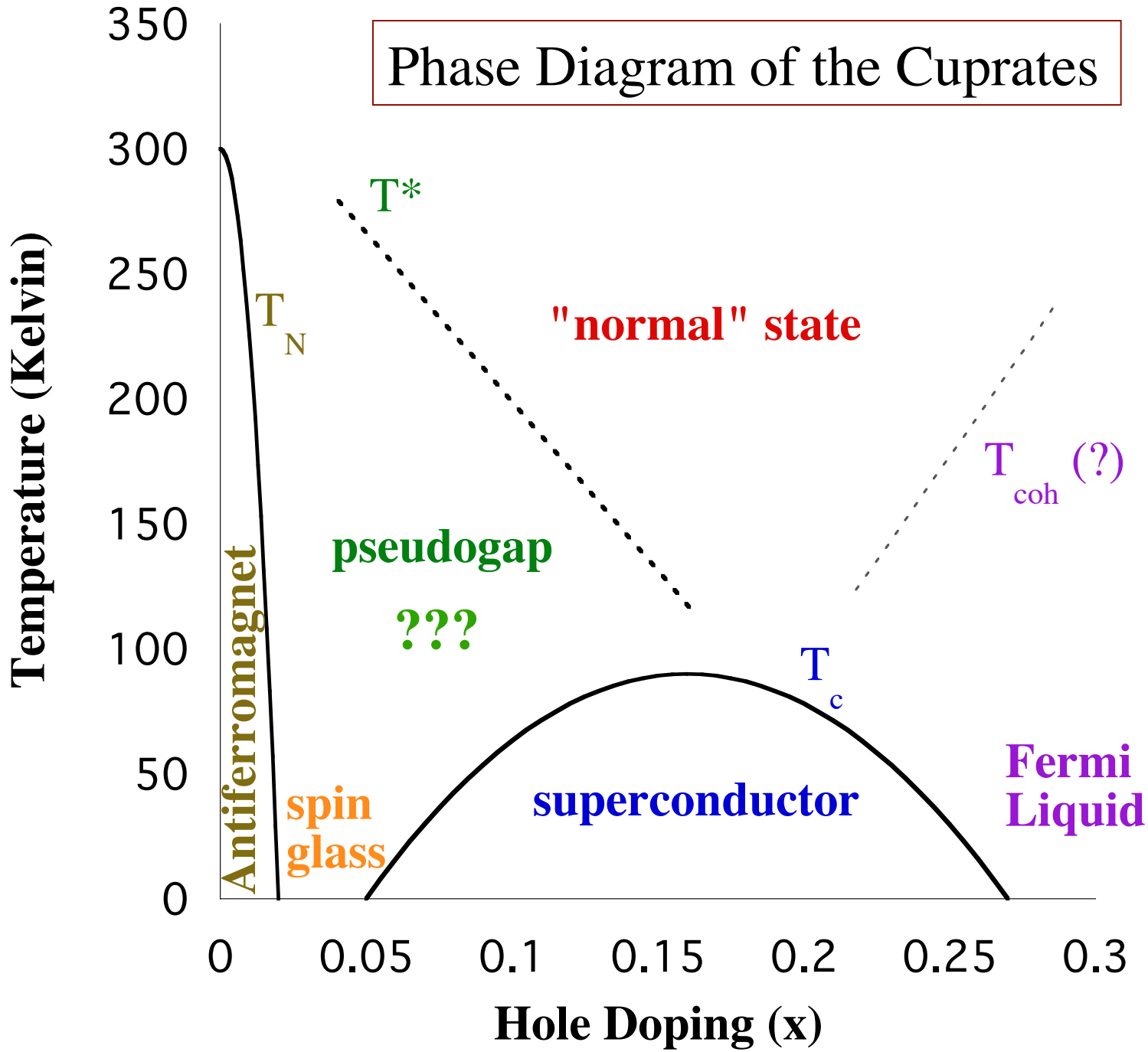
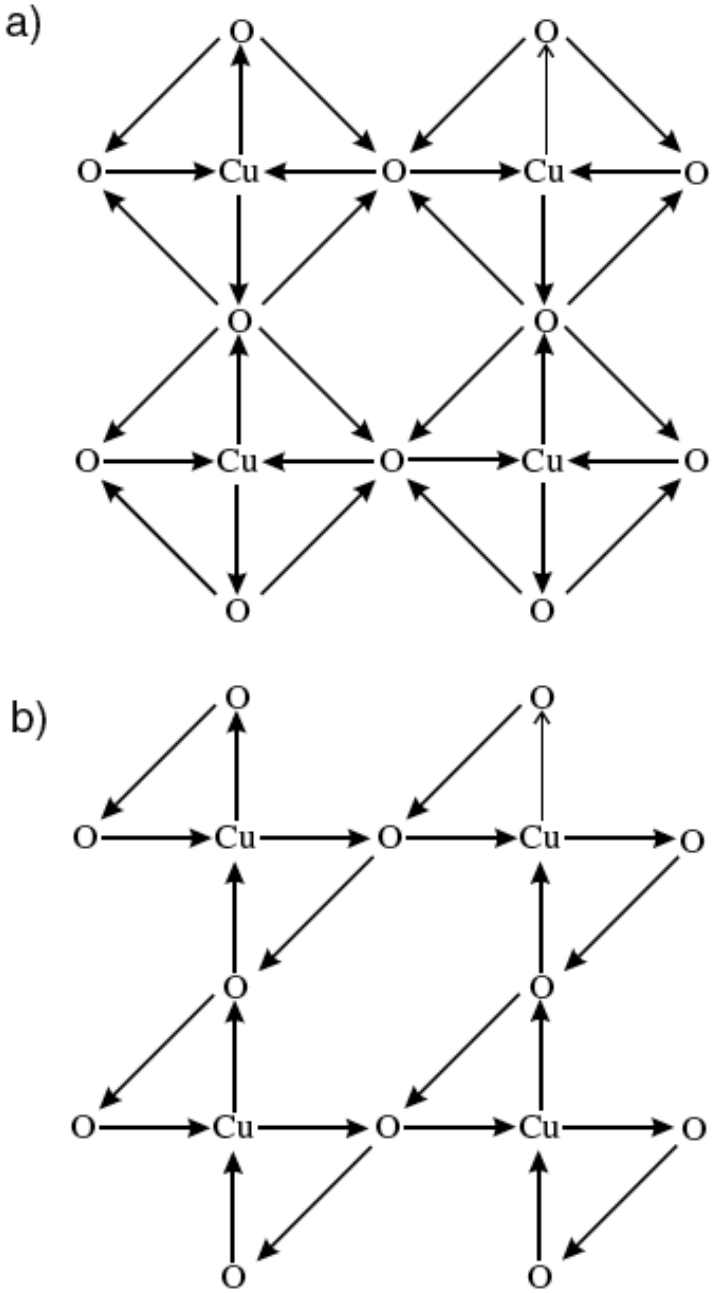
NSLS Talk, May 22, 2012

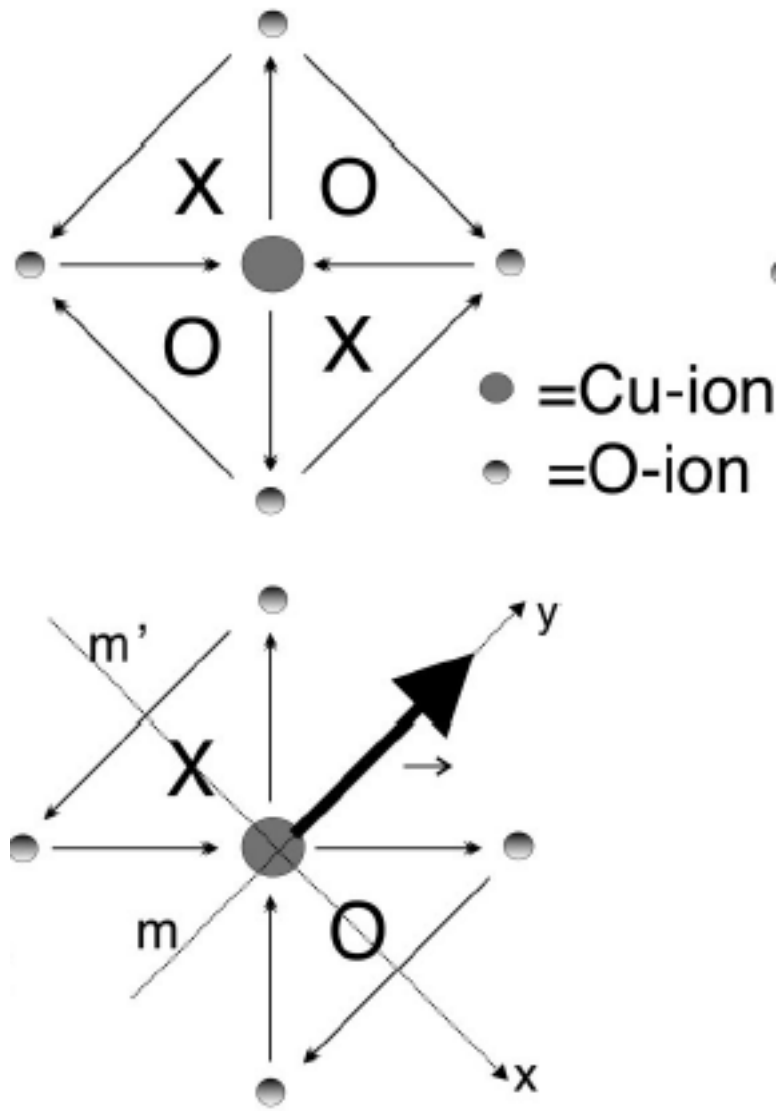

Phase Diagram of the Cuprates
Temperature (Kelvin)
350
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)
T*
"normal" state
T N
T coh (?)
pseudogap
???
T c
Antiferromagnet
spin glass
superconductor
Fermi Liquid

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?

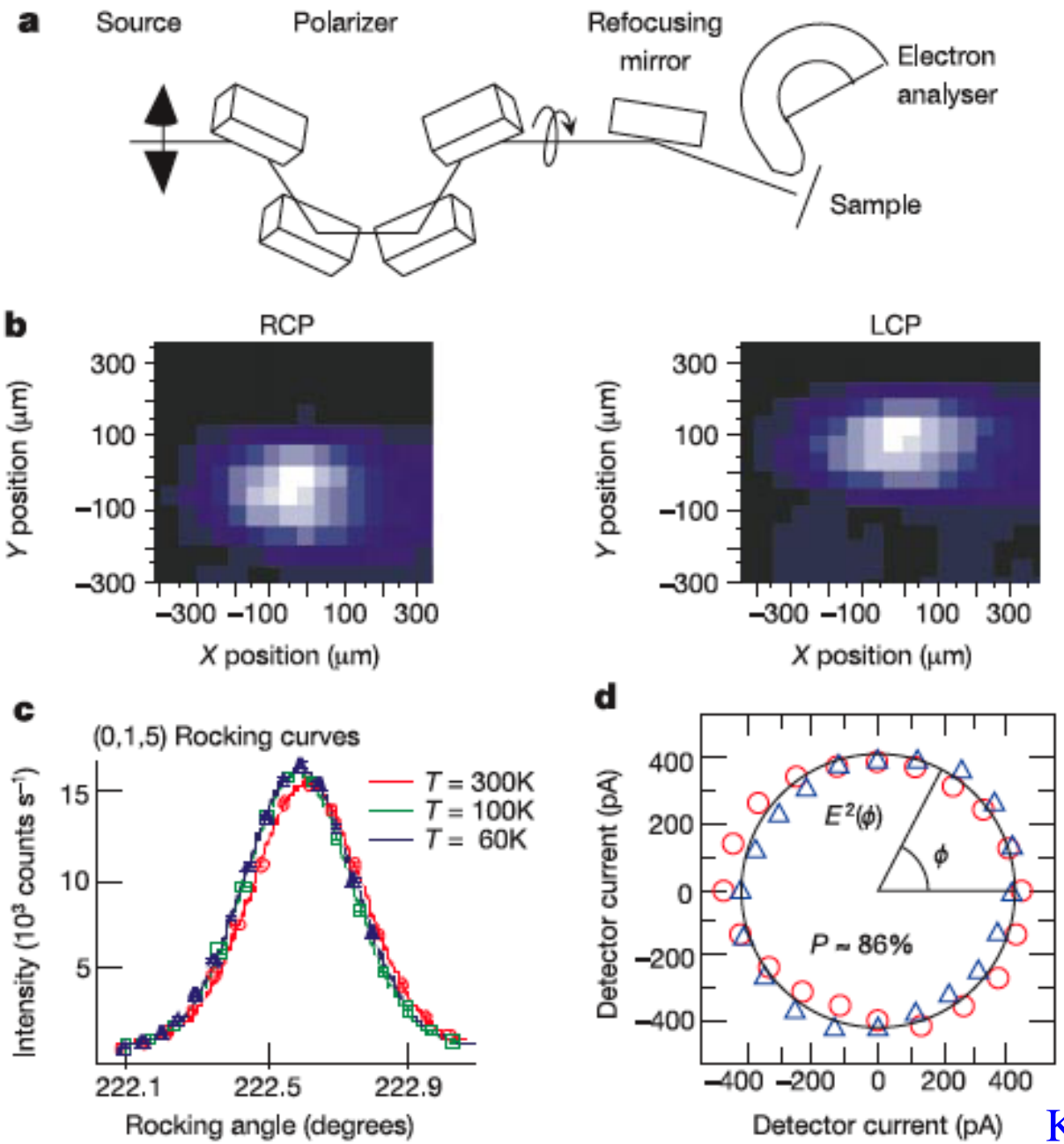
Orbital Currents





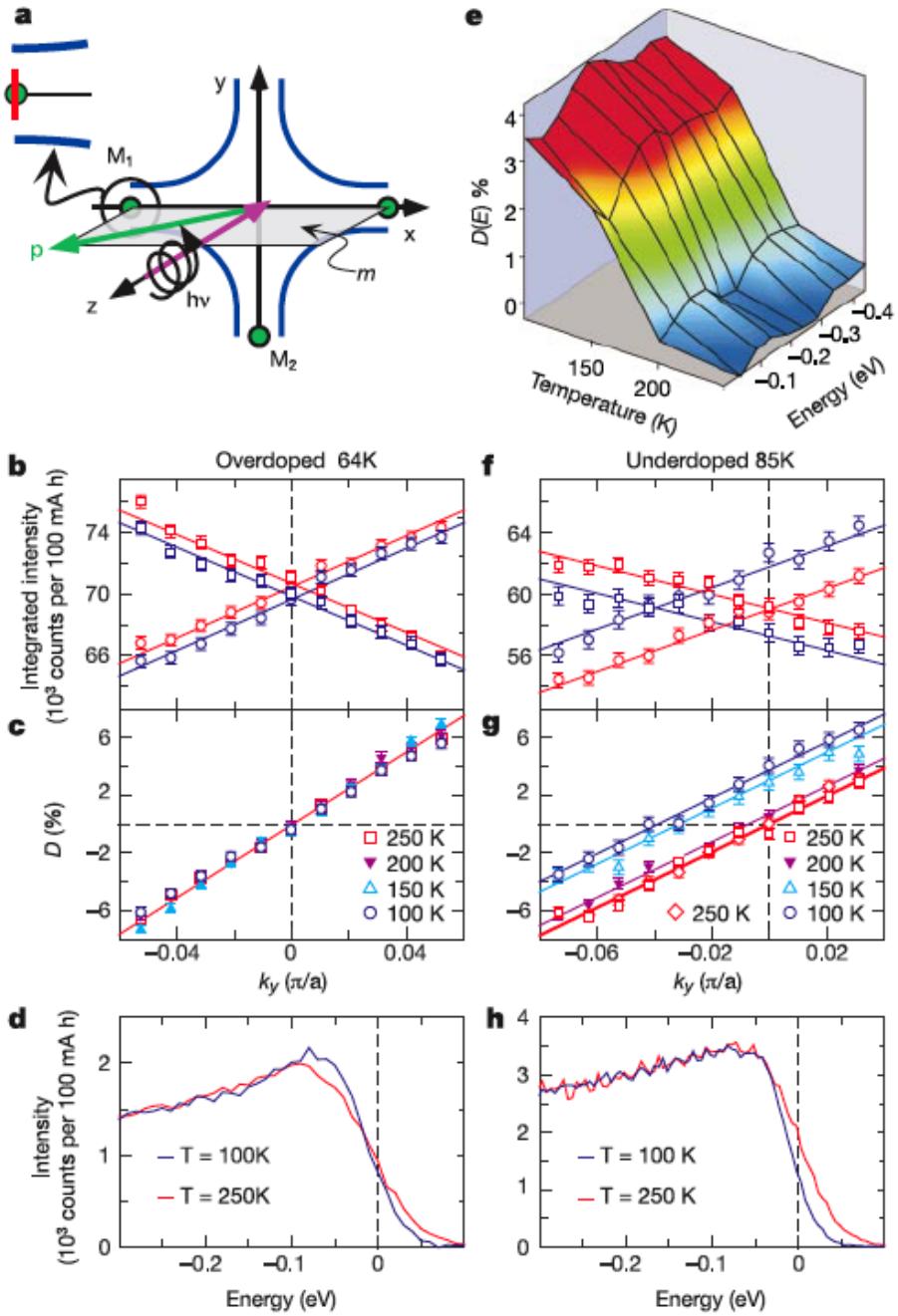
Simon & Varma, PRL 2002
Di Matteo & Varma, PRB 2003

ARPES Dichroism in Bi2212



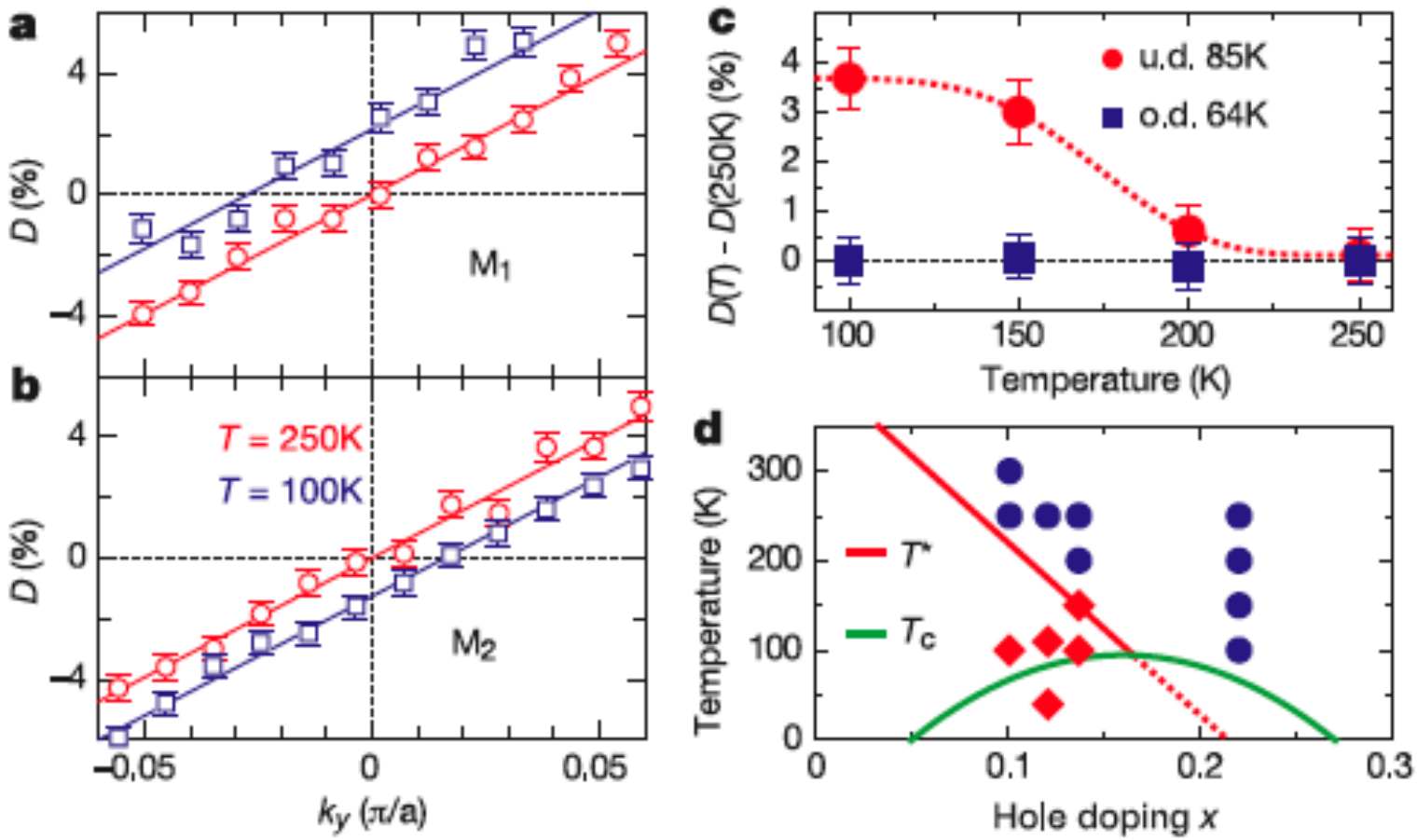
Kaminski *et al.*, Nature 2002

Shifting of the "mirror" plane with temperature



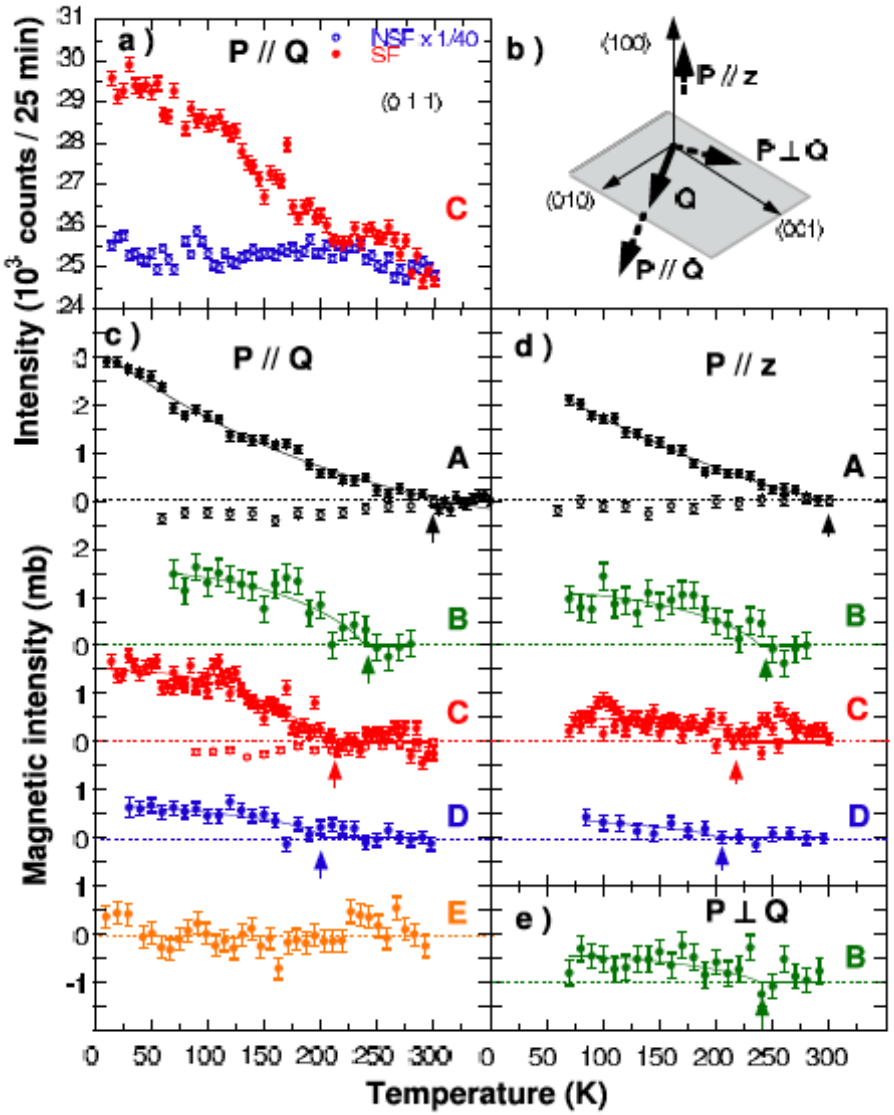
Kaminski *et al.*, Nature 2002

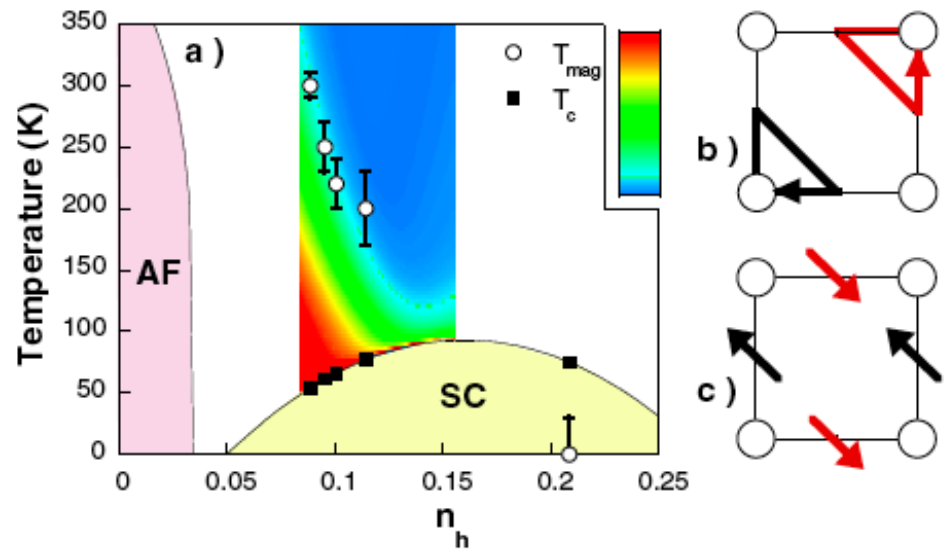
ARPES dichroism tracks the pseudogap



Kaminski *et al*., Nature 2002

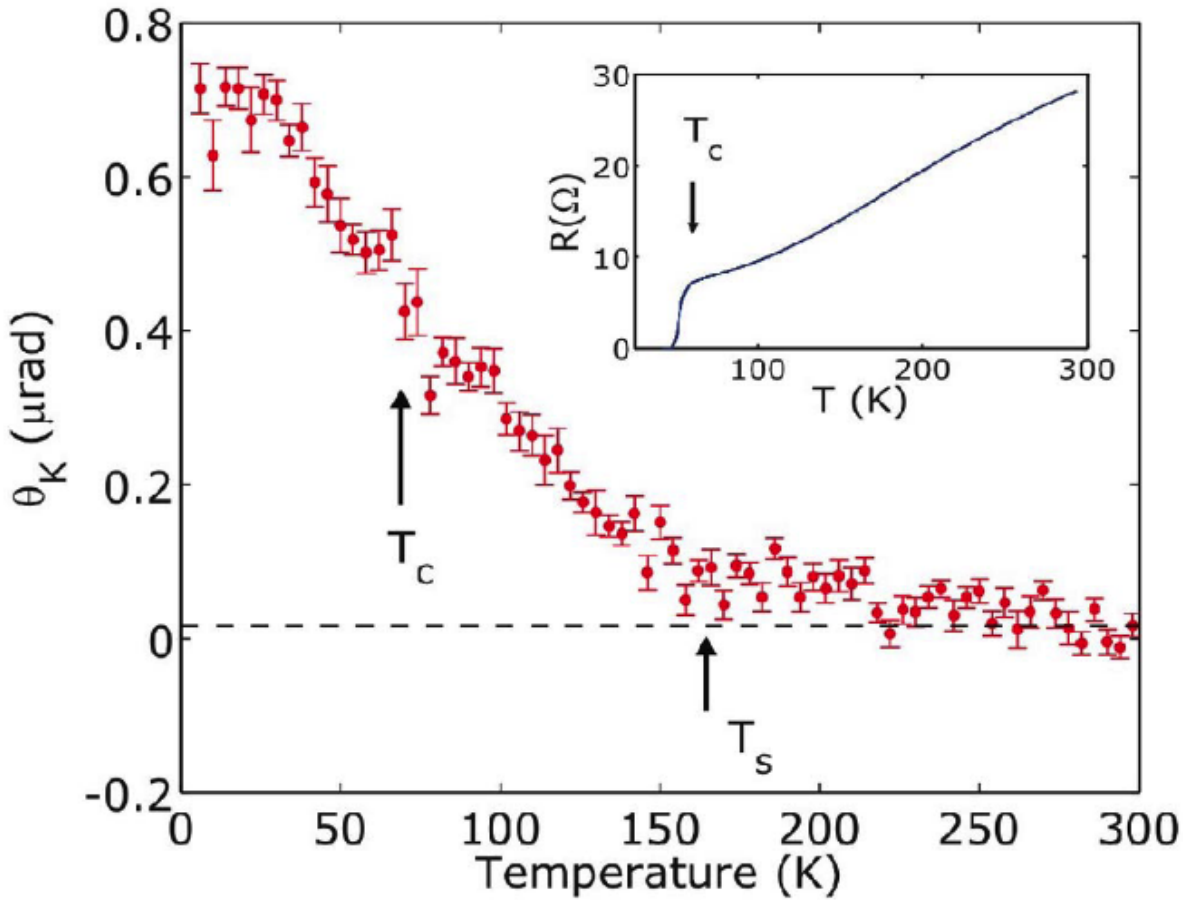
Polarized neutrons see it too





Fauque *et al*., PRL 2006

Polar Kerr Effect as well



Xia *et al*., PRL 2008

Optical Activity (E1-M1 or E1-E2)

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

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

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

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

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

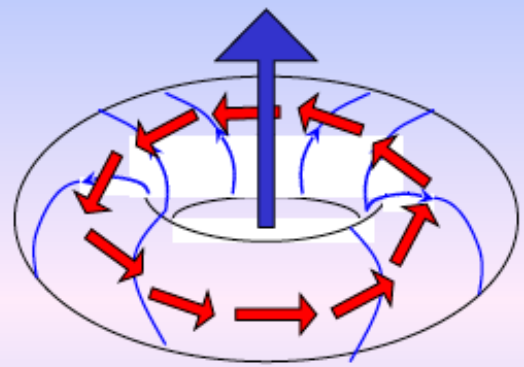
Dipole moments in matter

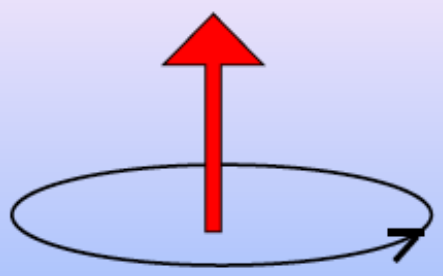
Electric dipole (d)

Polar Toroidal dipole (t)
or anapole

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

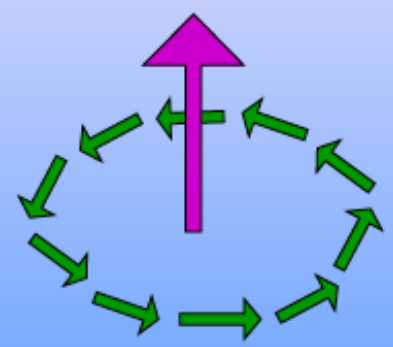
$$\mathbf{t} \equiv \frac{1}{2}\int \mathbf{r} \times \mathbf{m}\, dr$$





Magnetic dipole (m)

Axial Toroidal dipole (g)

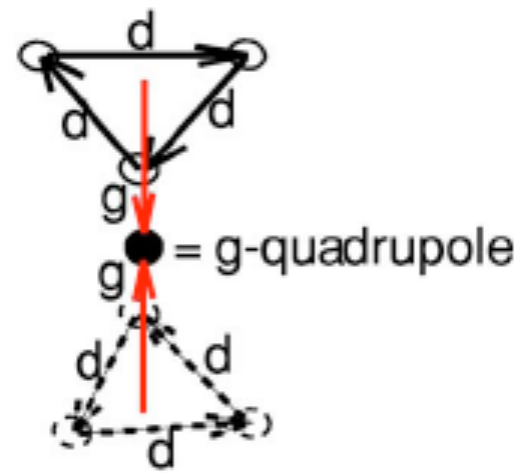


$$\mathbf{g} \equiv \frac{1}{2}\int \mathbf{r} \times \mathbf{d}\, dr$$

X-ray Natural Circular Dichroism (XNCD)

E1-E2 interference (broken inversion symmetry)

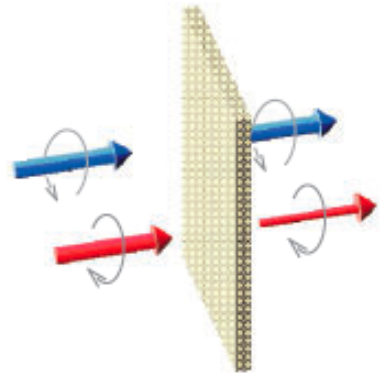
$$\vec{L} \cdot (\hat{\epsilon}^* \times \hat{\epsilon})(\vec{\Omega} \cdot \hat{k})$$



where

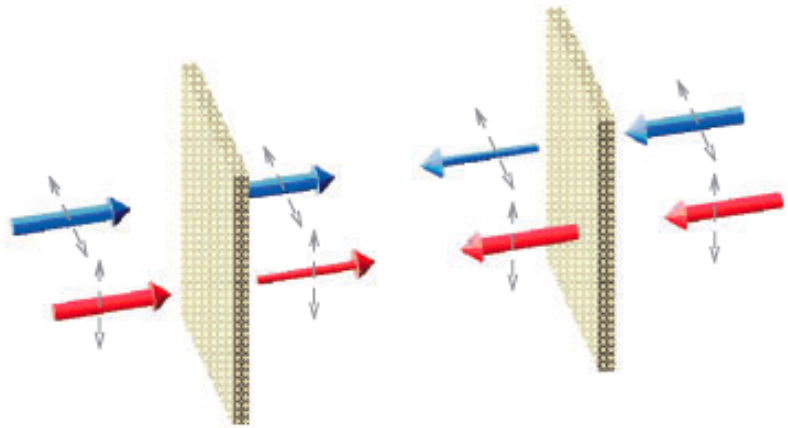
- **L** is the orbital angular momentum
- **k** is the wavevector of the x-ray
- **ε** is the polarization of the x-ray
- **Ω** is the toroidal momentum operator

(a) X-ray natural circular dichroism

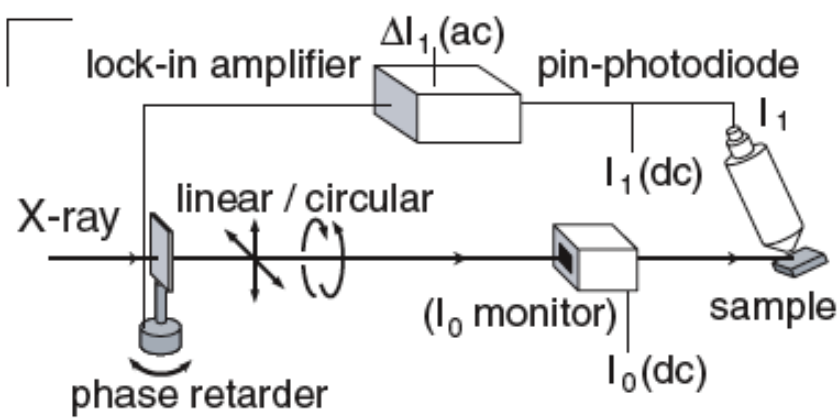


Tests inversion

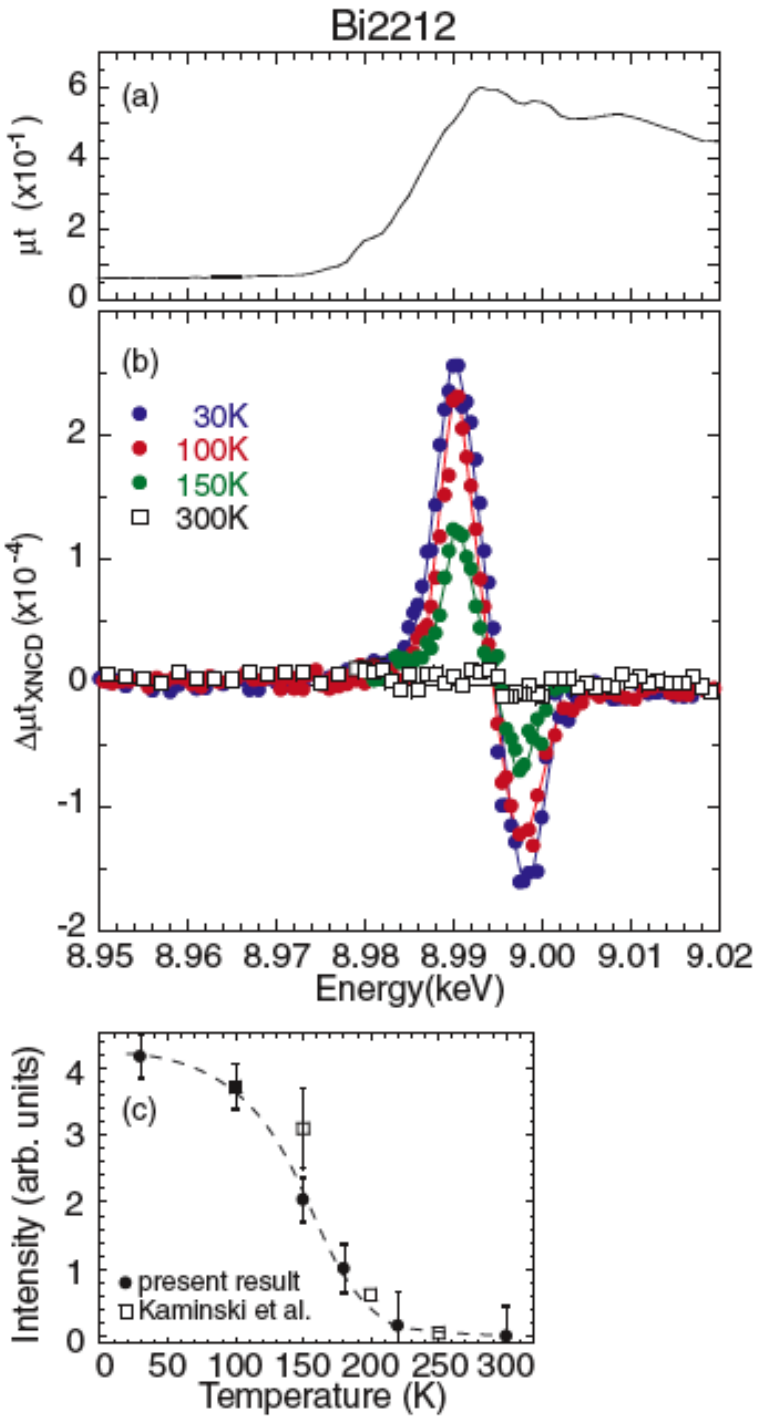
(b) nonreciprocal X-ray linear dichroism



Tests time reversal & inversion



Kubota *et al.*, JPSJ (2006)



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

Signal tracks ARPES dichroism

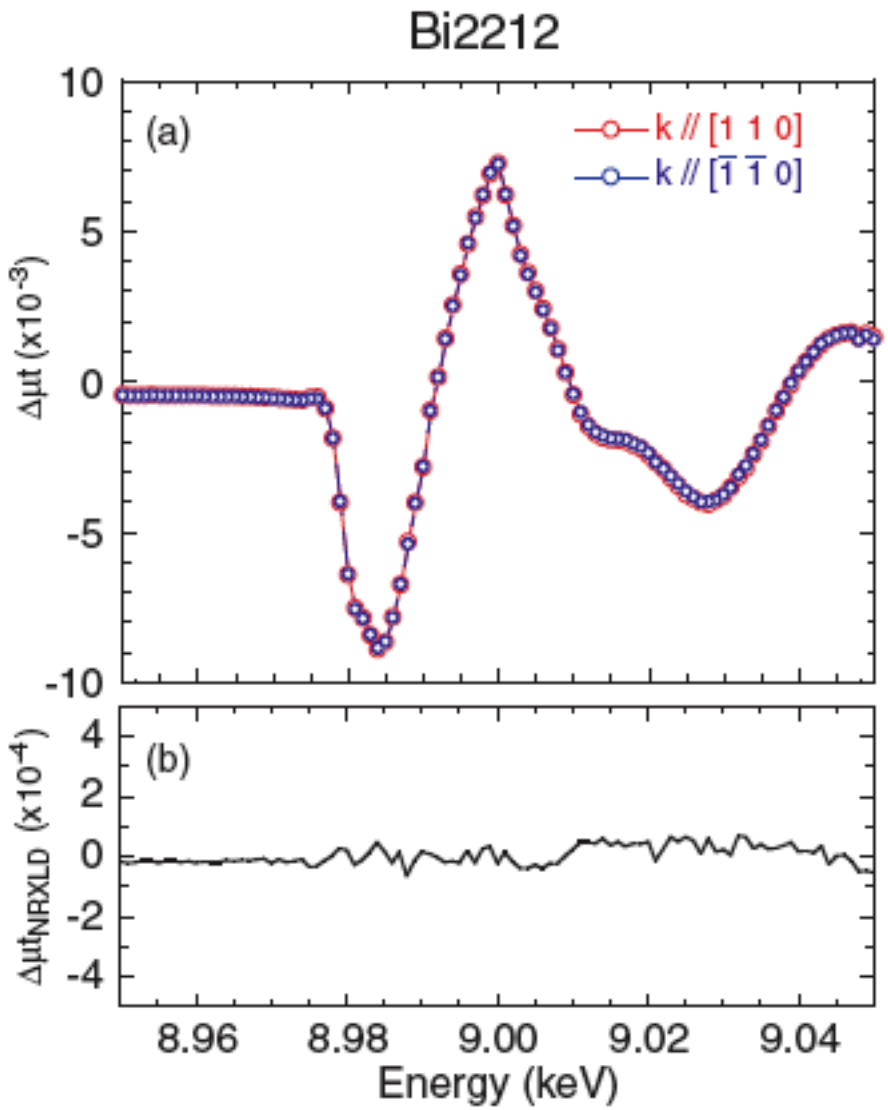
<u>Unusual aspects</u>

1. Simple +/- peak profile

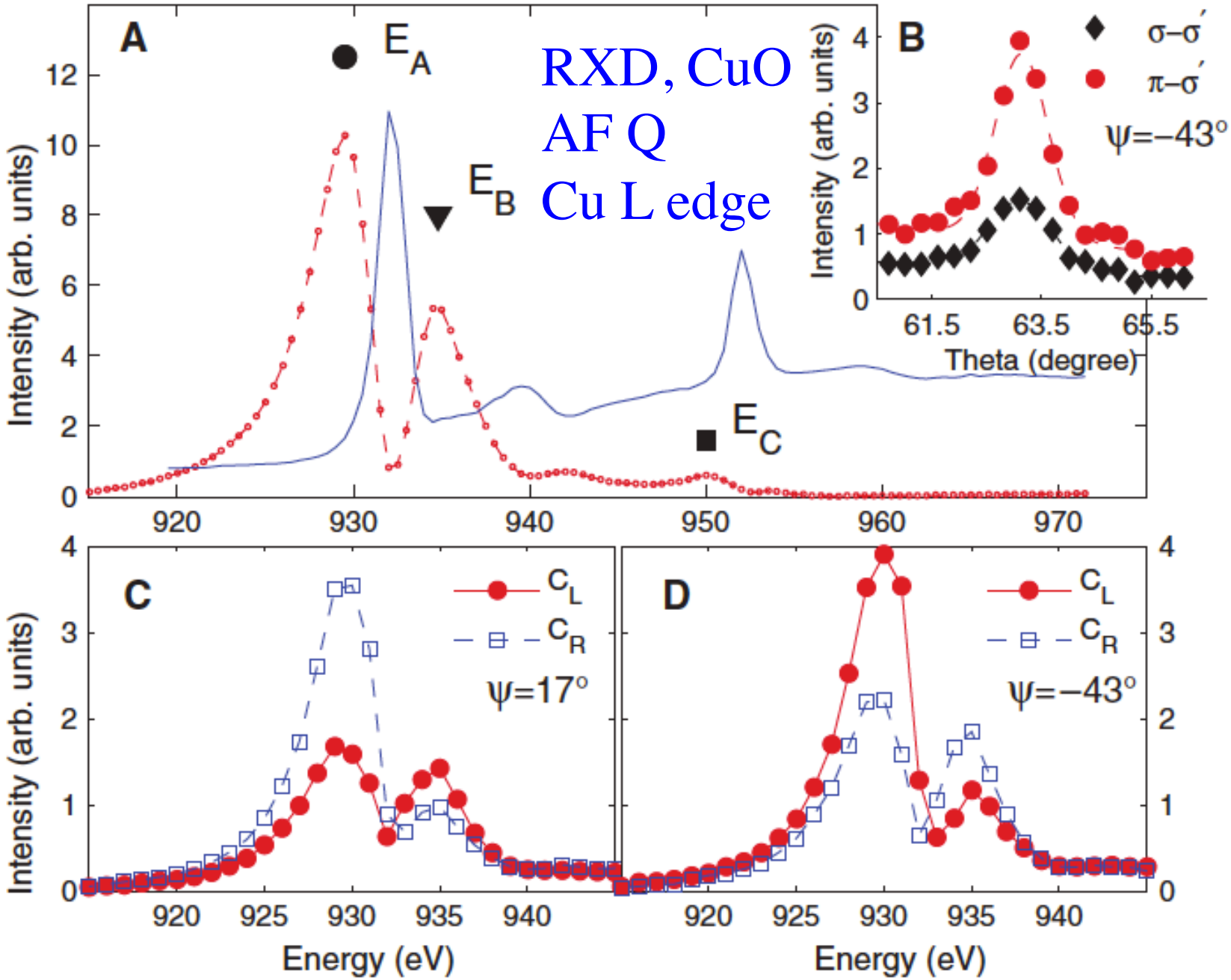
2. Peaks at edge, not pre-edge

Kubota *et al.*, JPSJ (2006)

Non reciprocal X ray linear dichroism (null result)

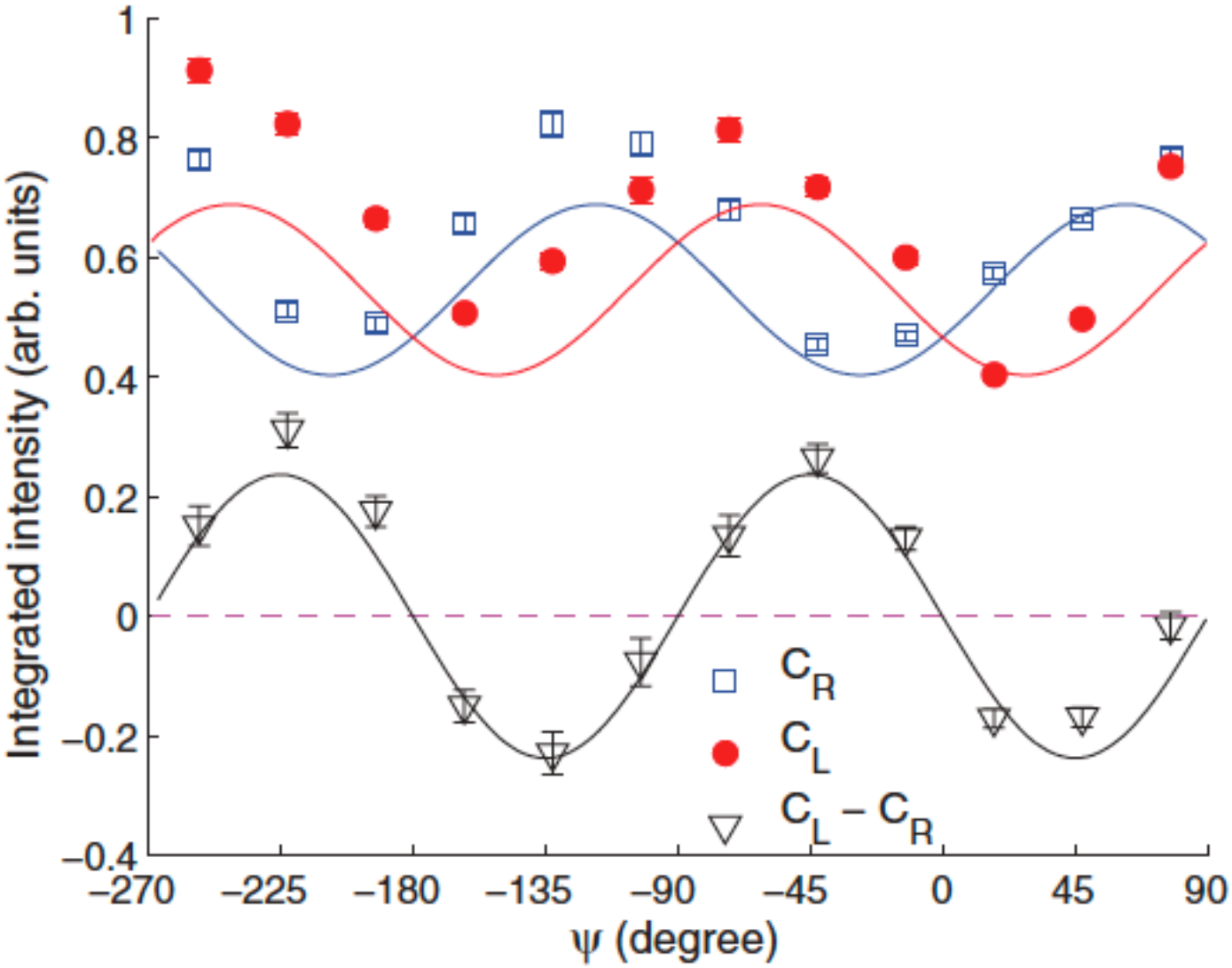


Kubota *et al.*, JPSJ (2006)



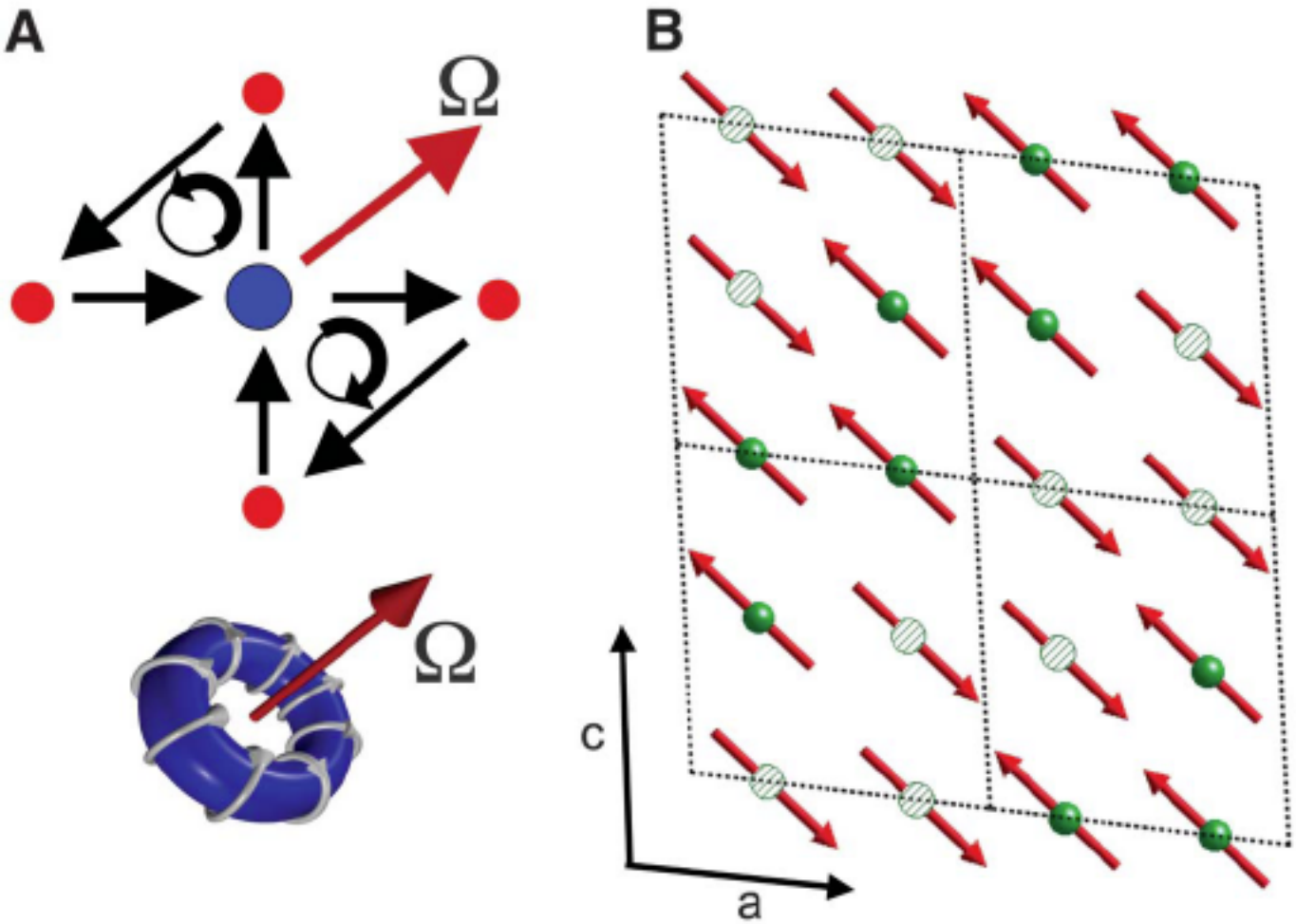
Scagnoli *et al*., Science (2011)

Dichroism in CuO (commensurate AF phase) – sin(2ψ)



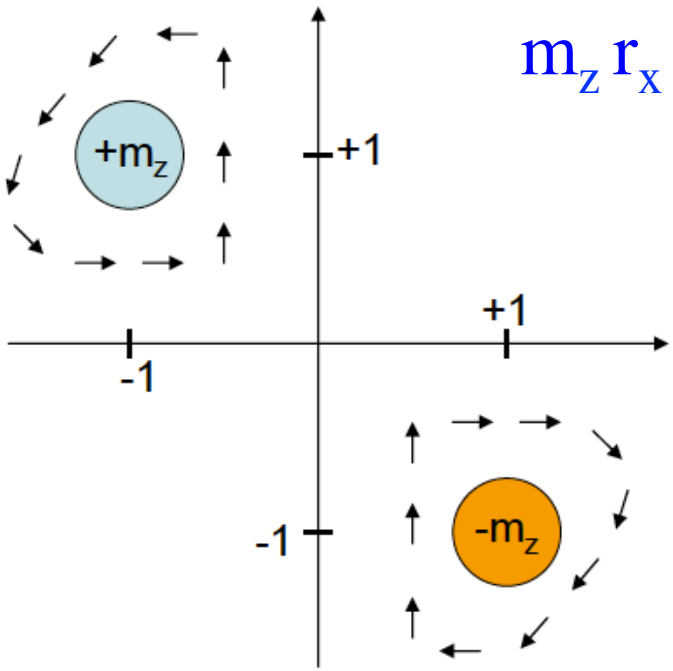
Scagnoli *et al*., Science (2011)

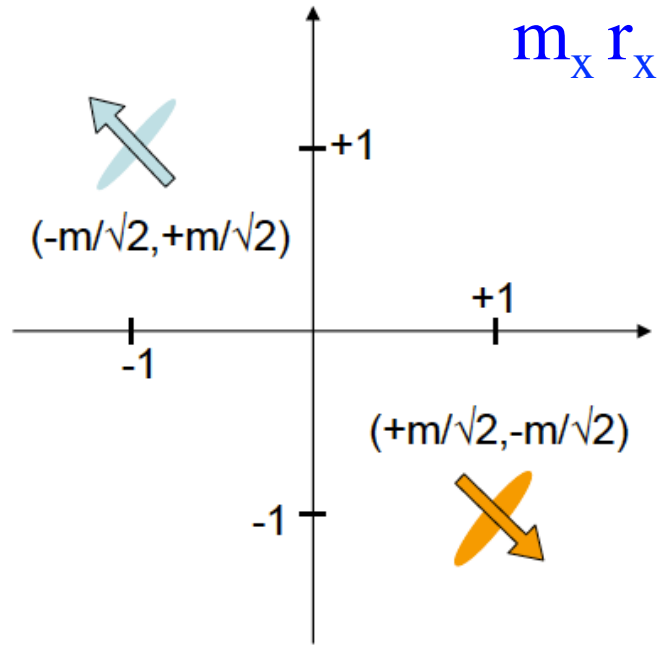
Anapole Moments in the Commensurate AF Phase of CuO?



Scagnoli *et al*., Science (2011)

Orbital Currents – Combination of anapole & magnetic quadrupole



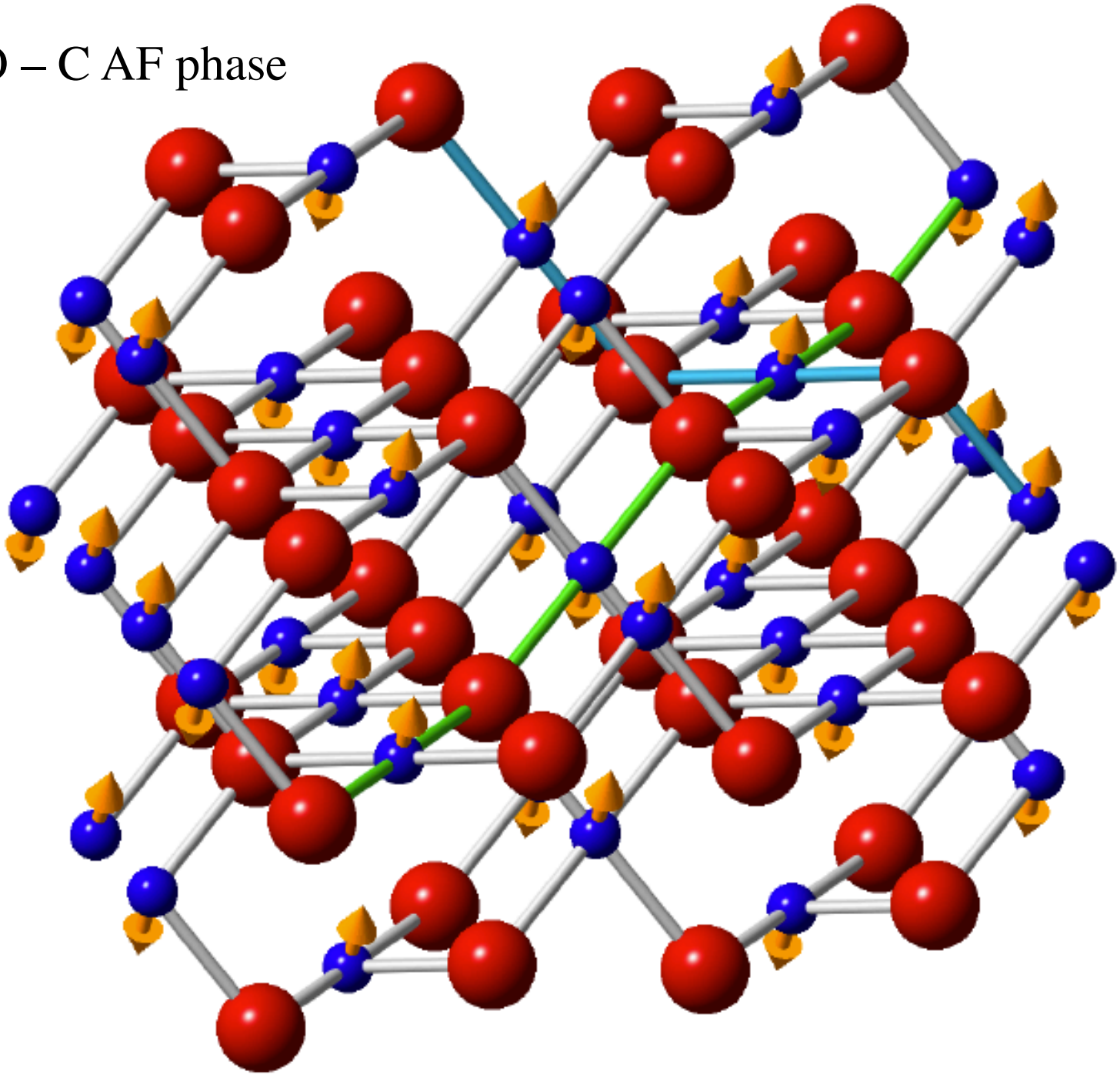


$$M_{ij} \equiv \sum_{\alpha=1,2} \left[m_i^\alpha r_j^\alpha + r_i^\alpha m_j^\alpha - \frac{2}{3}\delta_{ij} \sum_l m_l^\alpha r_l^\alpha \right]$$

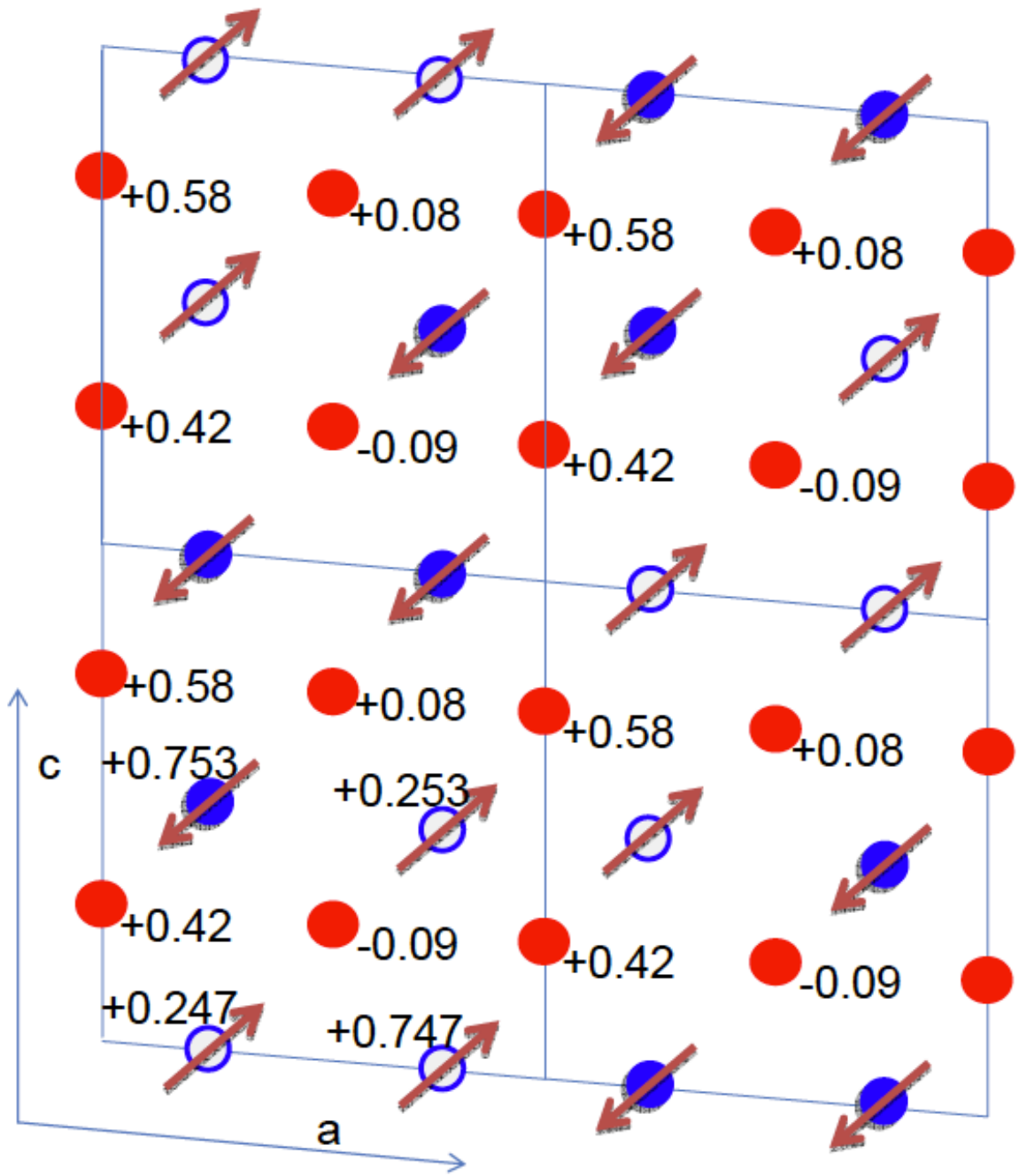
$$T_{ij} \equiv \sum_{\alpha=1,2} [m_i^\alpha r_j^\alpha - r_i^\alpha m_j^\alpha]$$

Di Matteo & Norman, arXiv (2012)

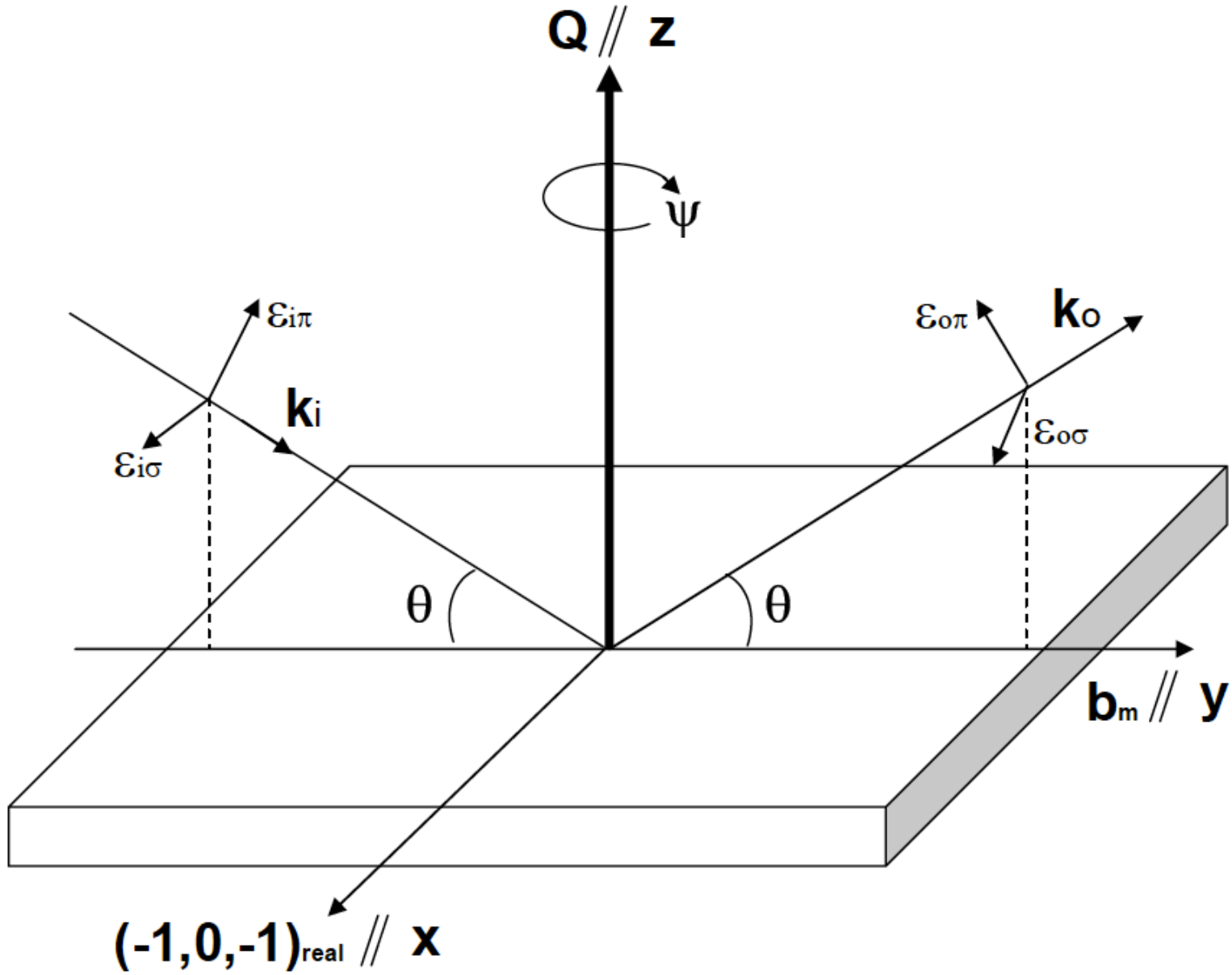
CuO – C AF phase



Spin and “anapole” orientation



RXD Scattering Geometry (b is along moment direction, z along Q)



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

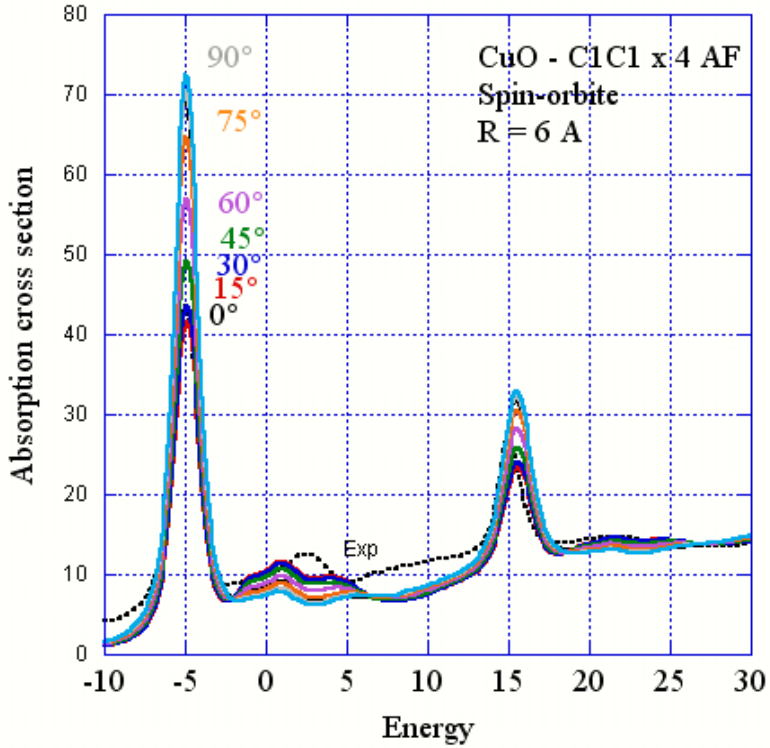
$$
\begin{aligned}
f_1^{\mathrm{E1-E1}}(\sigma\sigma) &= 0 \\
f_1^{\mathrm{E1-E1}}(\sigma\pi) &= -im_y \cos\theta \cos\psi \\
f_1^{\mathrm{E1-E1}}(\pi\sigma) &= im_y \cos\theta \cos\psi \\
f_1^{\mathrm{E1-E1}}(\pi\pi) &= im_y \sin(2\theta) \sin\psi
\end{aligned}
$$

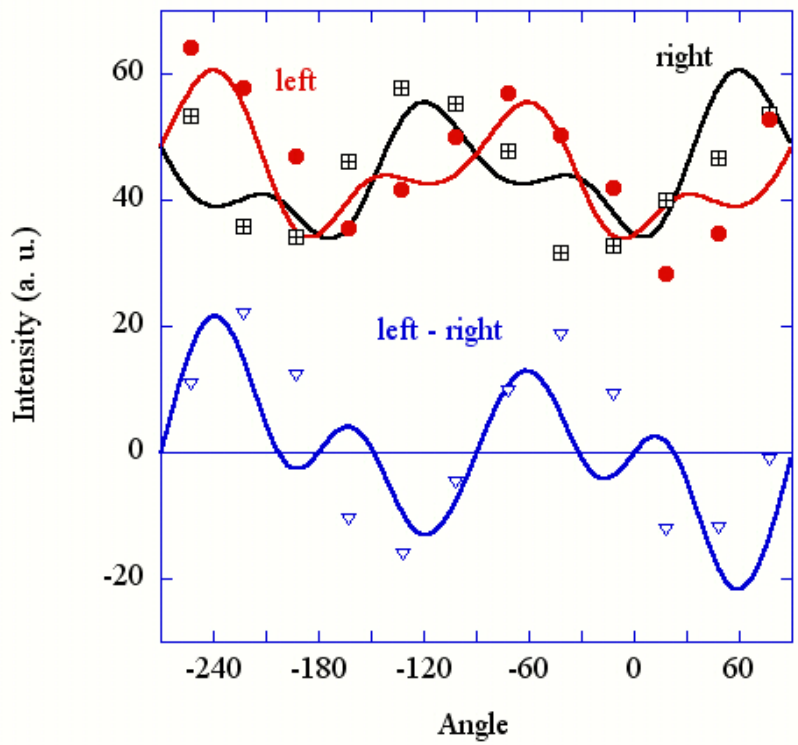
$$
\begin{aligned}
f_{1a}(\sigma\sigma) &= 2T_x \cos\theta \sin\psi \\
f_{1a}(\sigma\pi) &= -T_x \sin(2\theta) \cos\psi \\
f_{1a}(\pi\sigma) &= T_x \sin(2\theta) \cos\psi \\
f_{1a}(\pi\pi) &= 2T_x \cos\theta \sin\psi
\end{aligned}
$$

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

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

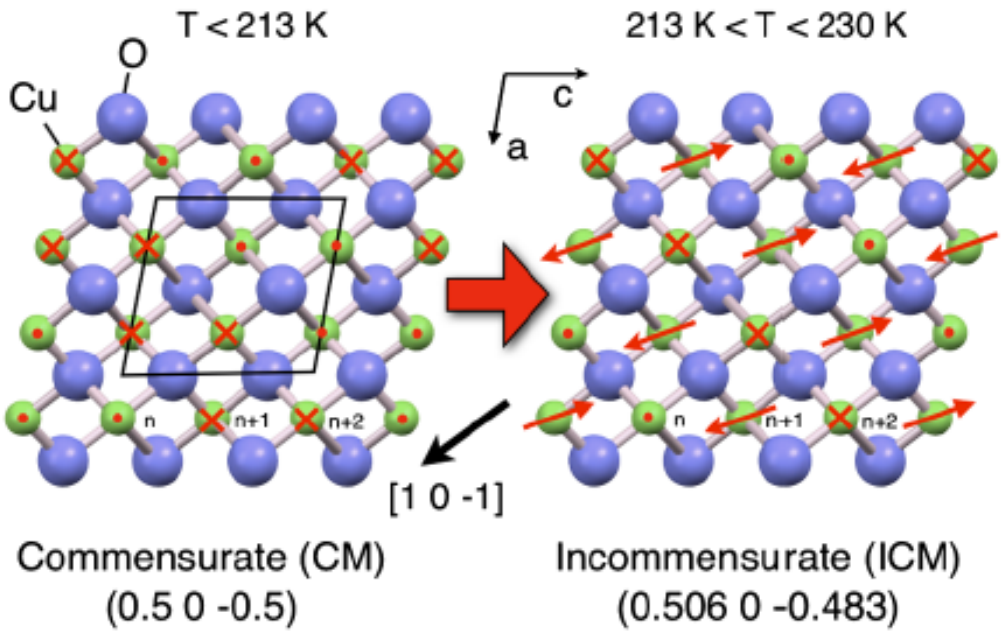
Monoclinic structure leads to a rotation of the light (linear dichroism)

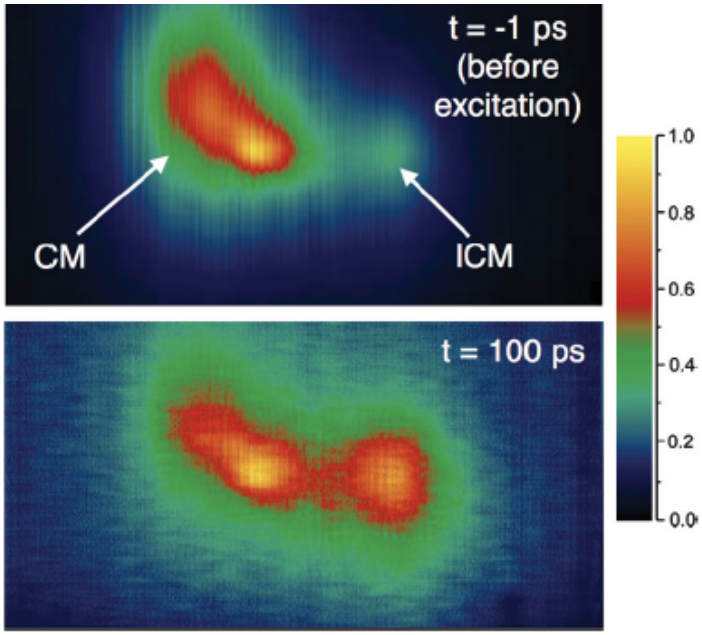


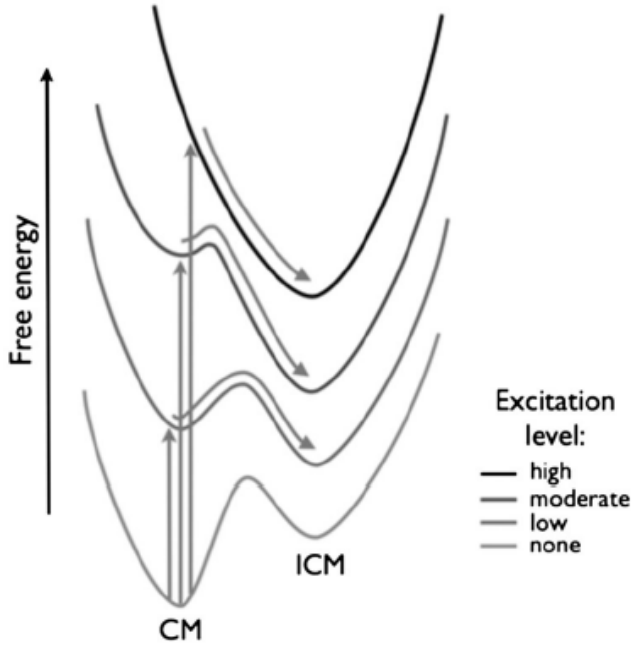


Yves Joly, private communication

C AF converted to IC AF in CuO by pumping

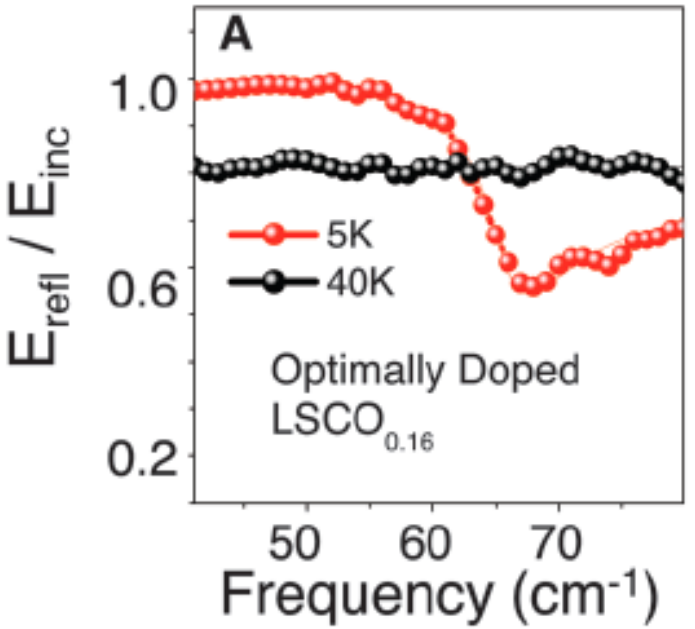


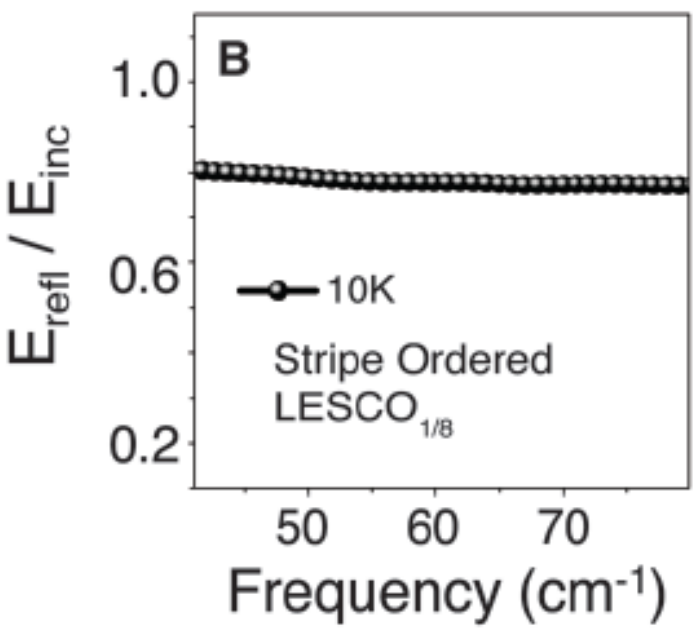


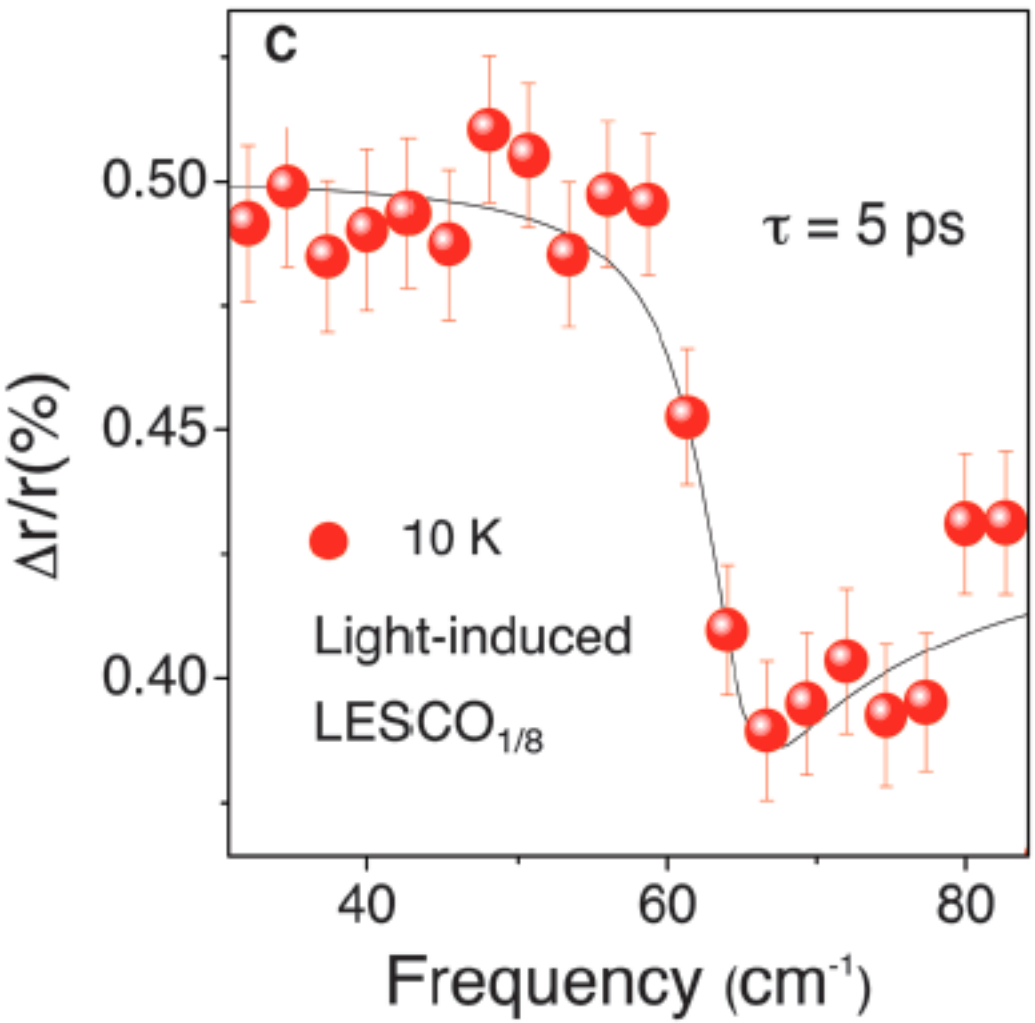


Johnson *et al*., PRL (2012)

Converting a Striped Ordered Cuprate into a Superconductor

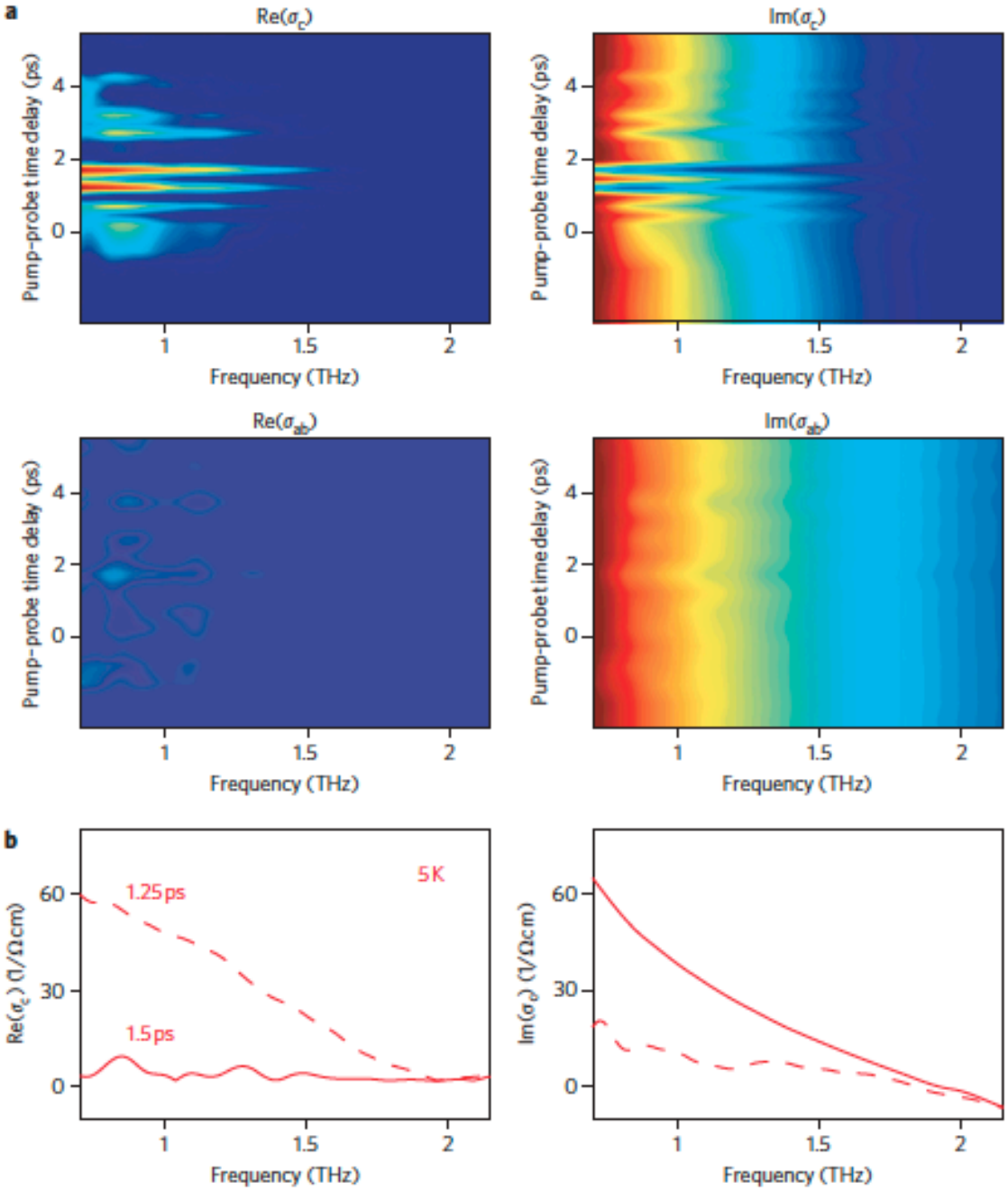


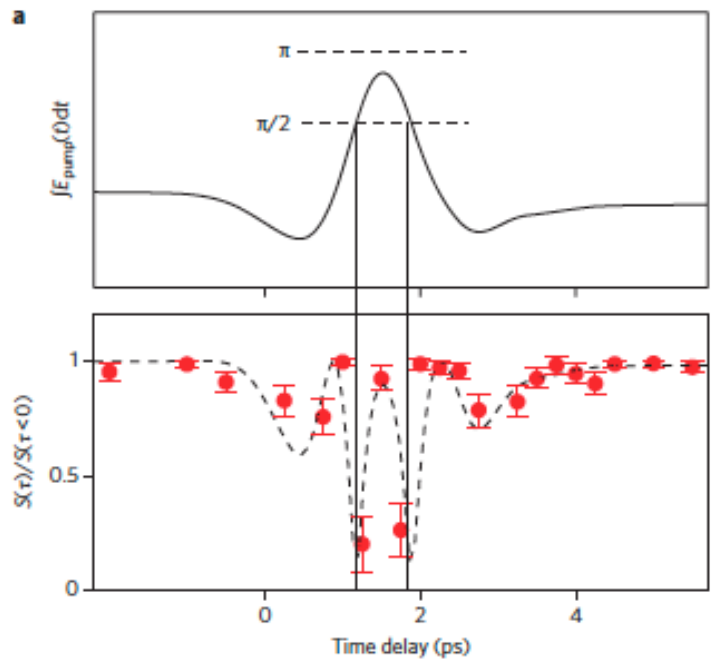




Fausti *et al.*, Science (2011)

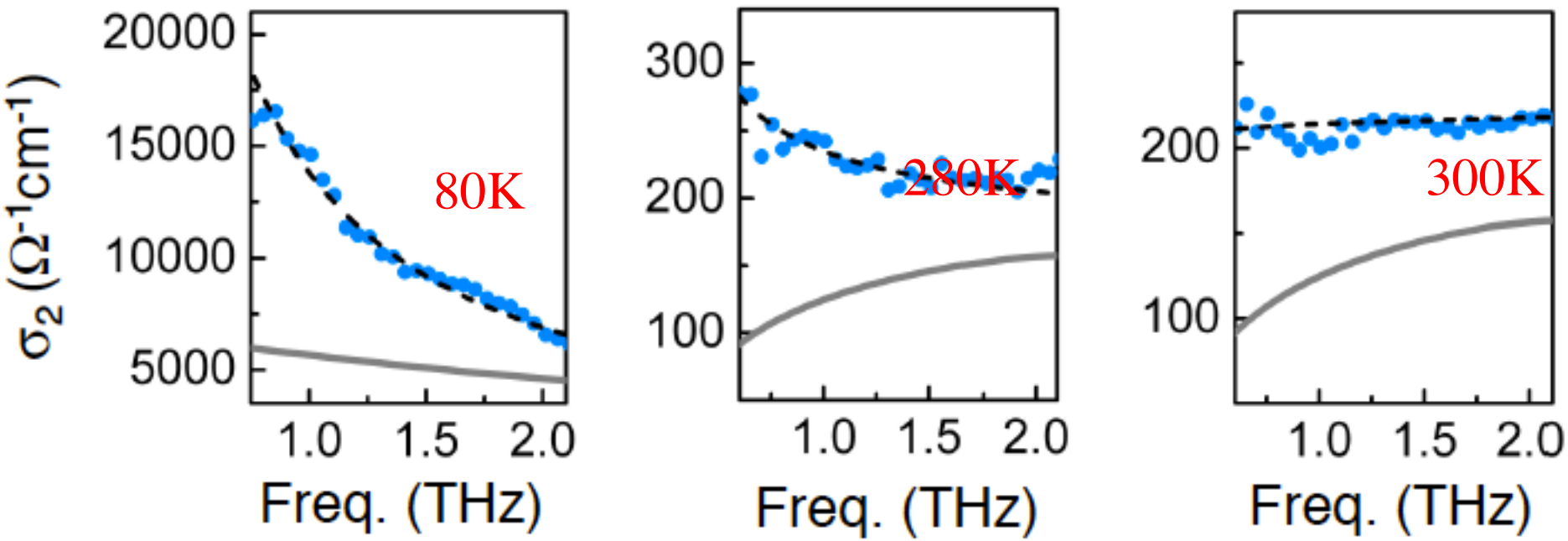
Time Dependent Superconductivity from Time Dependent Josephson Phase

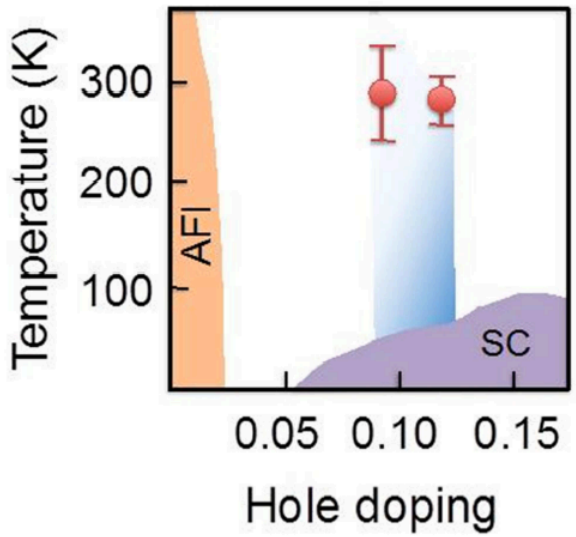




Dienst *et al.*, Nature Phot. (2011)

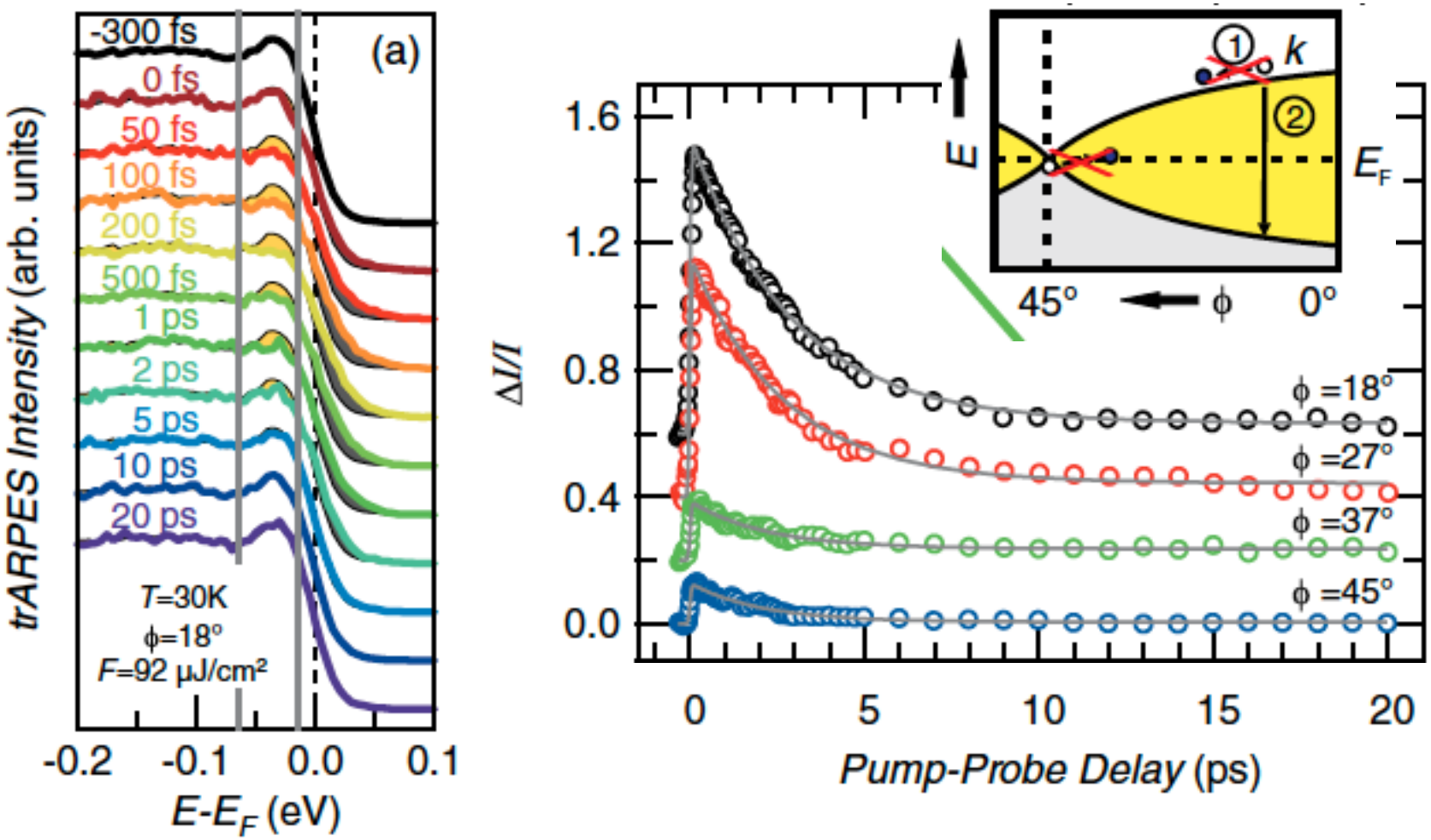
Transient Superconductivity from Pumping the Apical Oxygen - YBCO





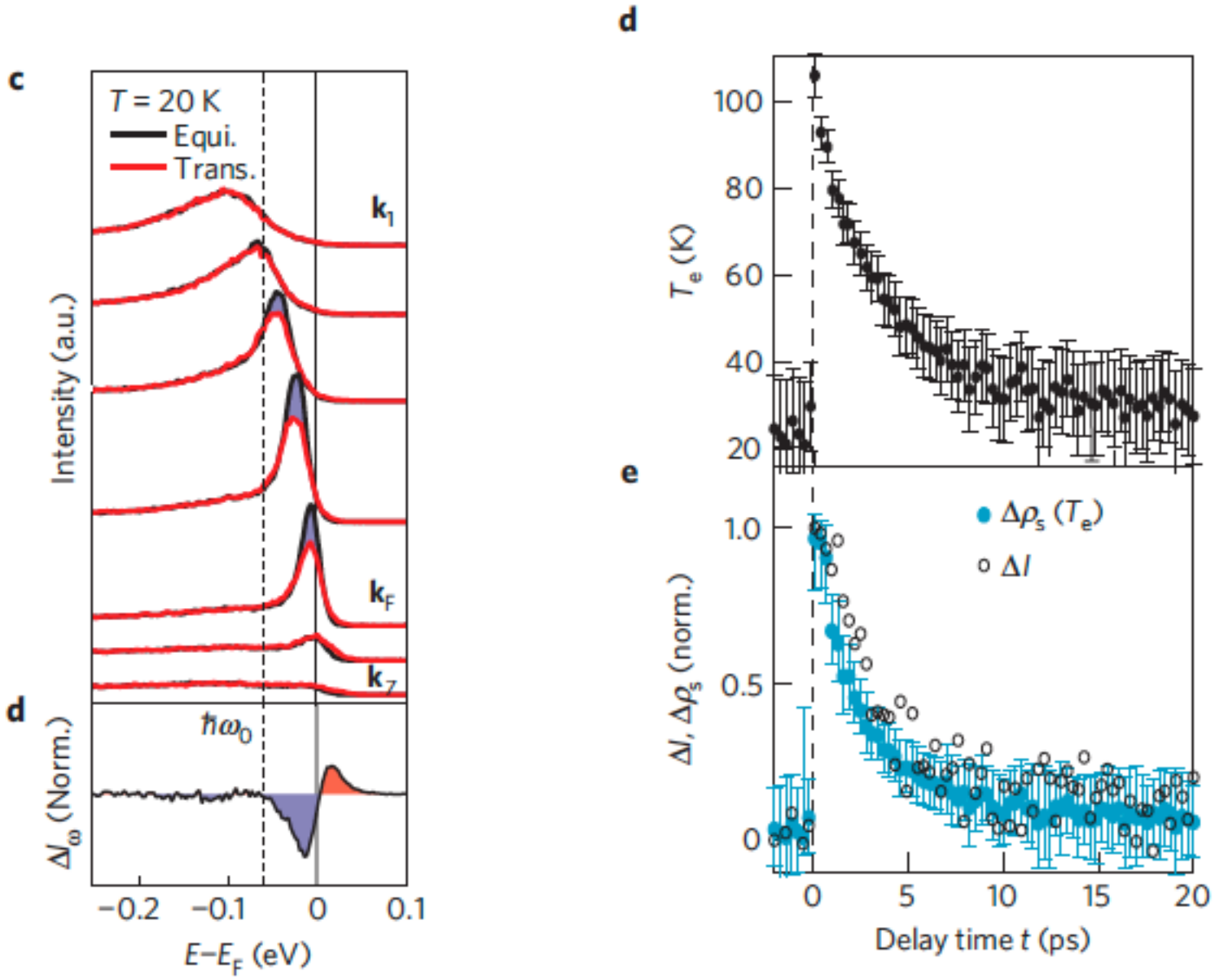
Kaiser *et al.*, arXiv (2012)

Suppression of Antinodal Qusiparticles in Bi2212



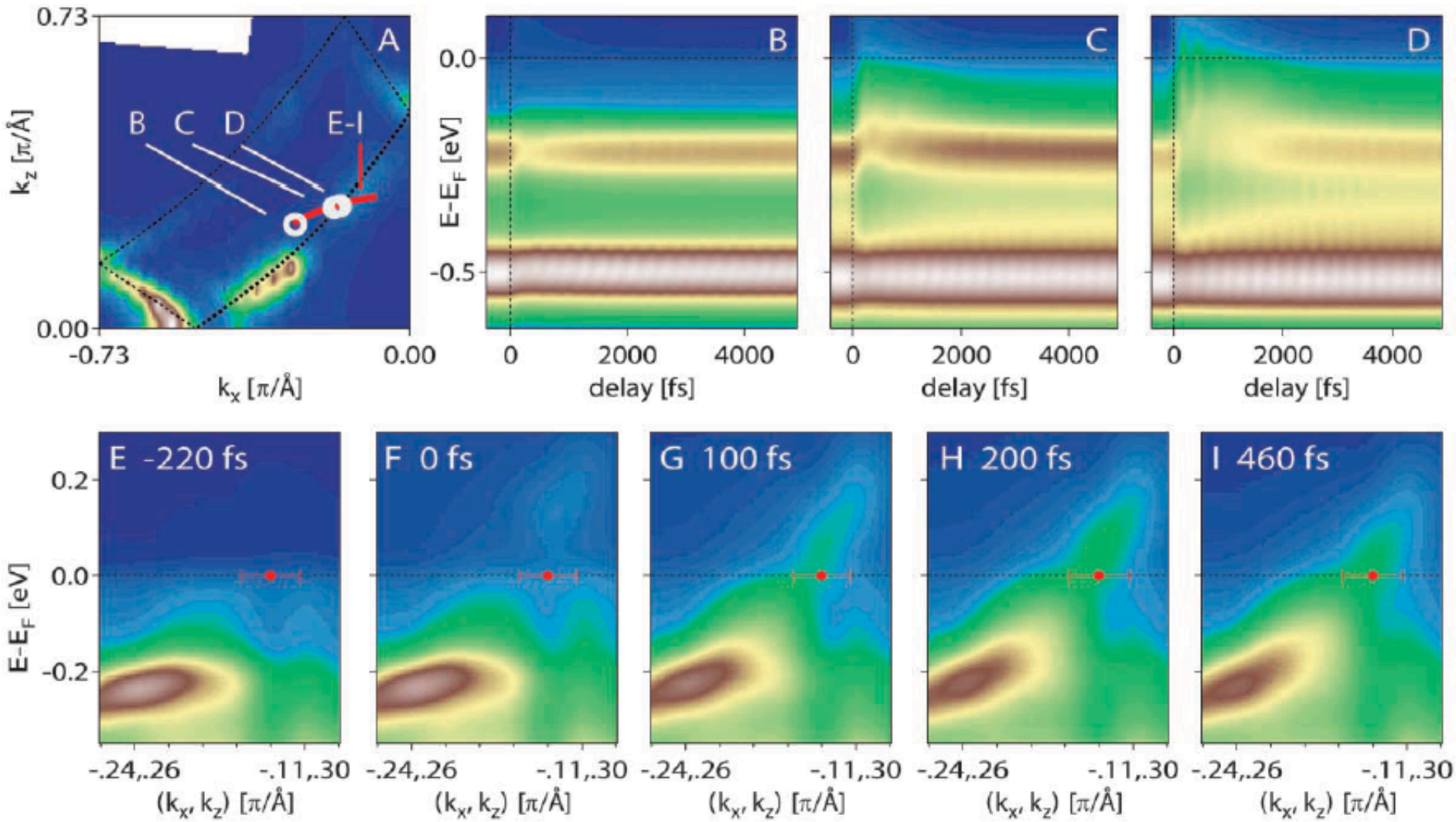
Cortes *et al*., PRL (2011)

Suppression of Nodal Qusiparticles in Bi2212



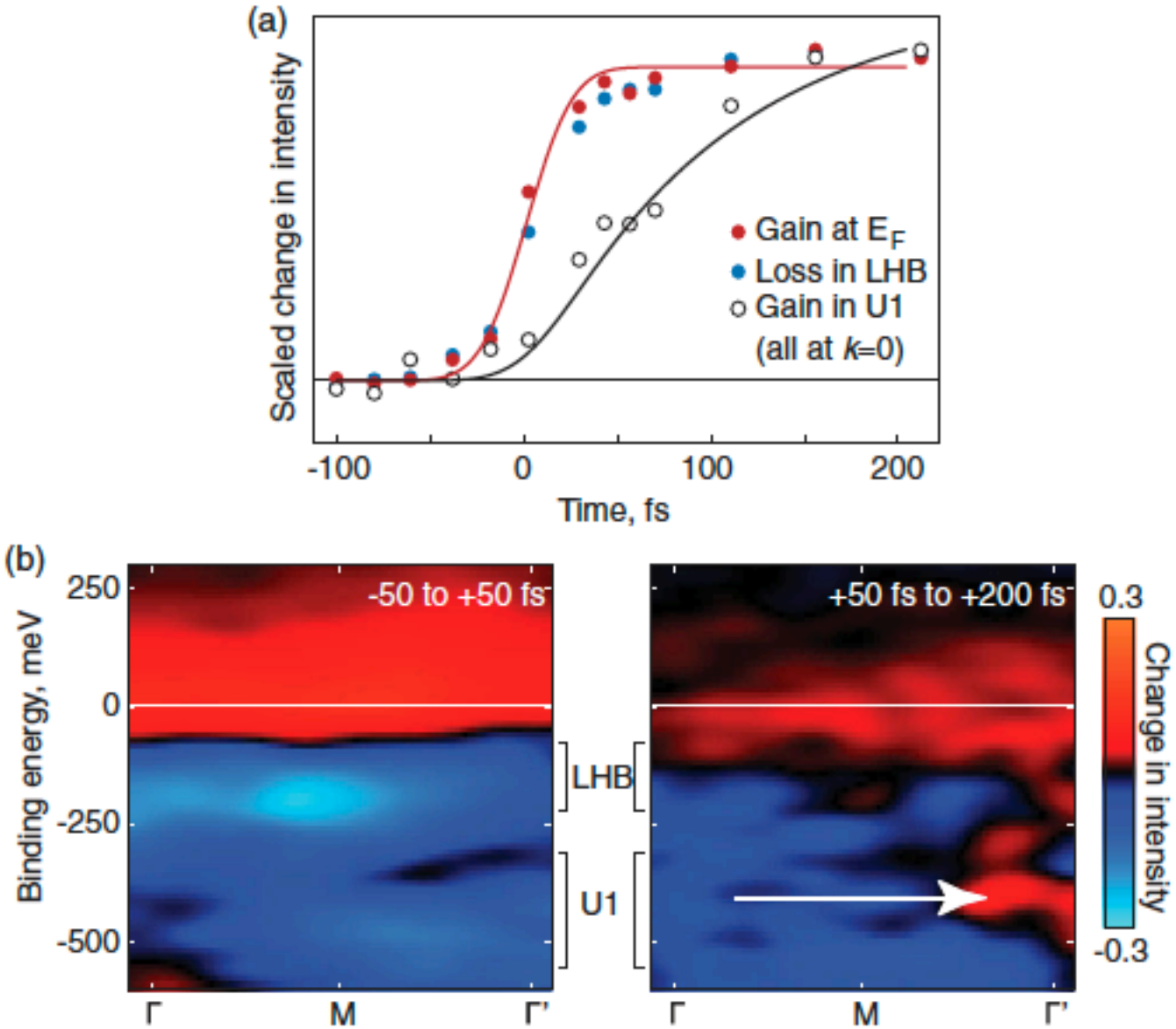
Graf *et al*., Nature Phys. (2011)

ARPES Pump Probe studies of CDW phase in $TbTe_3$



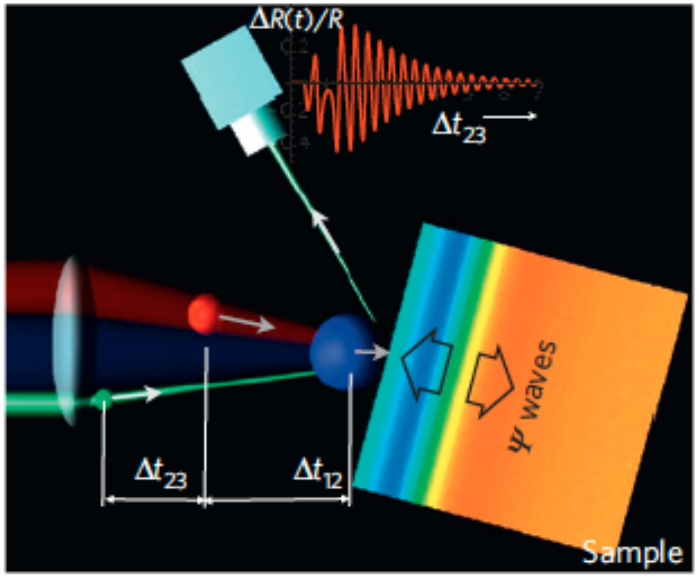
Schmitt *et al*., Science (2008)

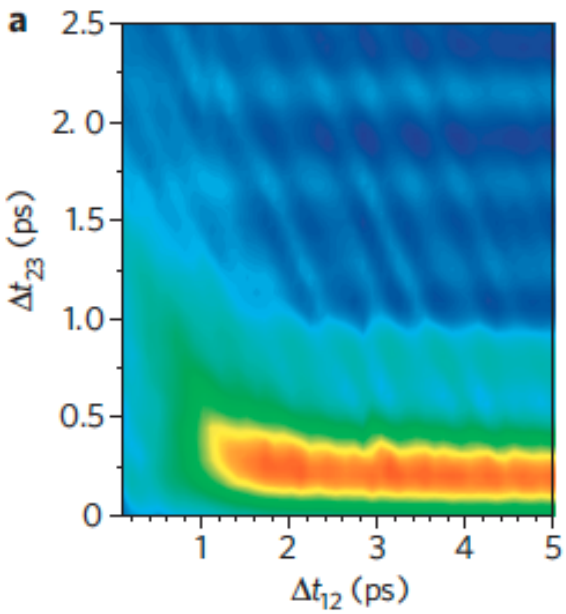
Decoupling of CDW and shadow bands in TaS_2

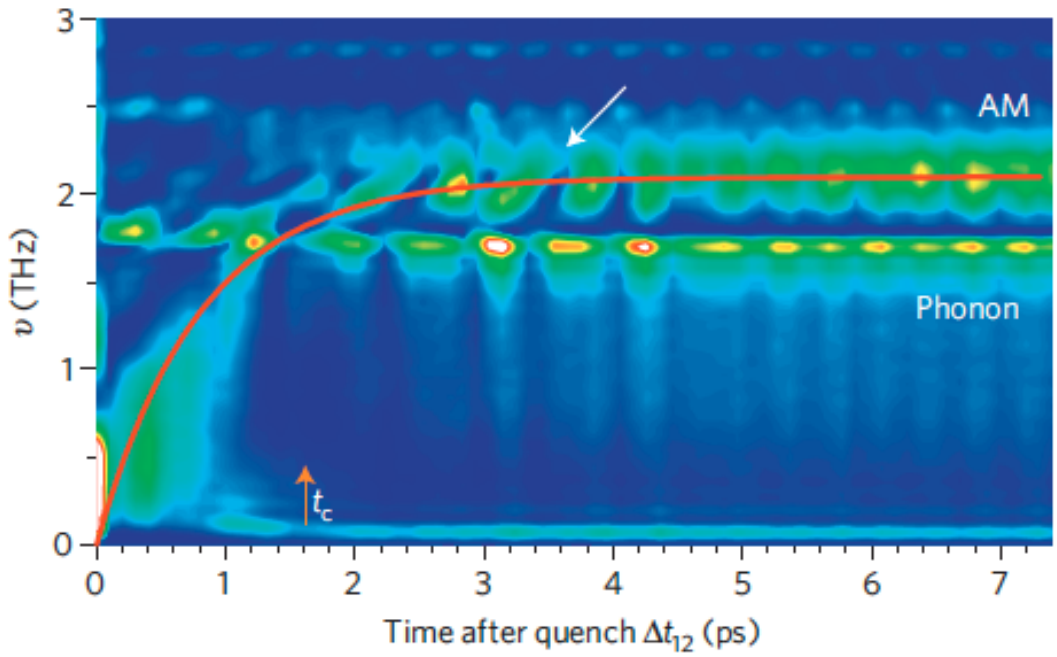


Petersen *et al.*, PRL (2011)

Order Parameter Dynamics in $TbTe_3$

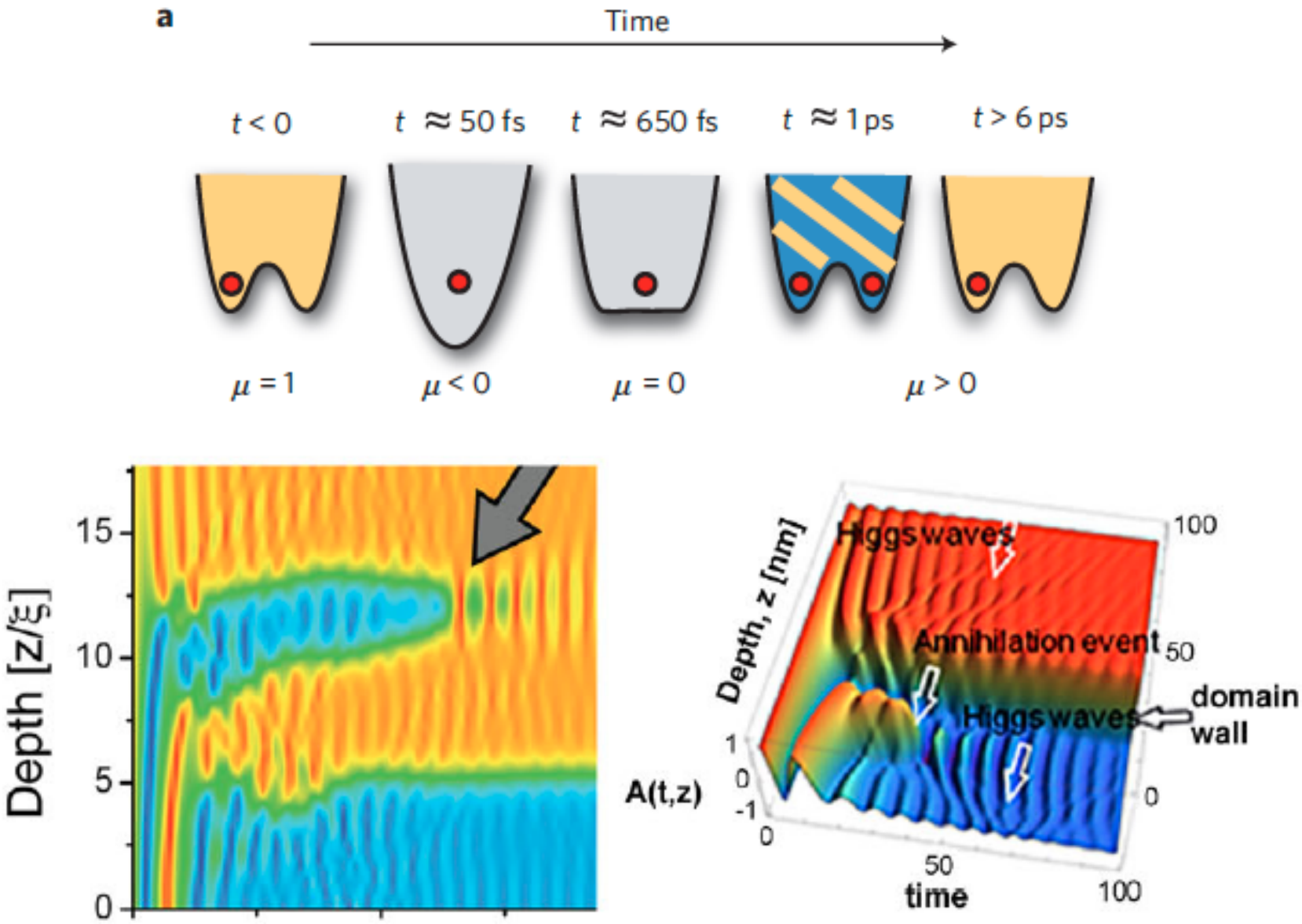






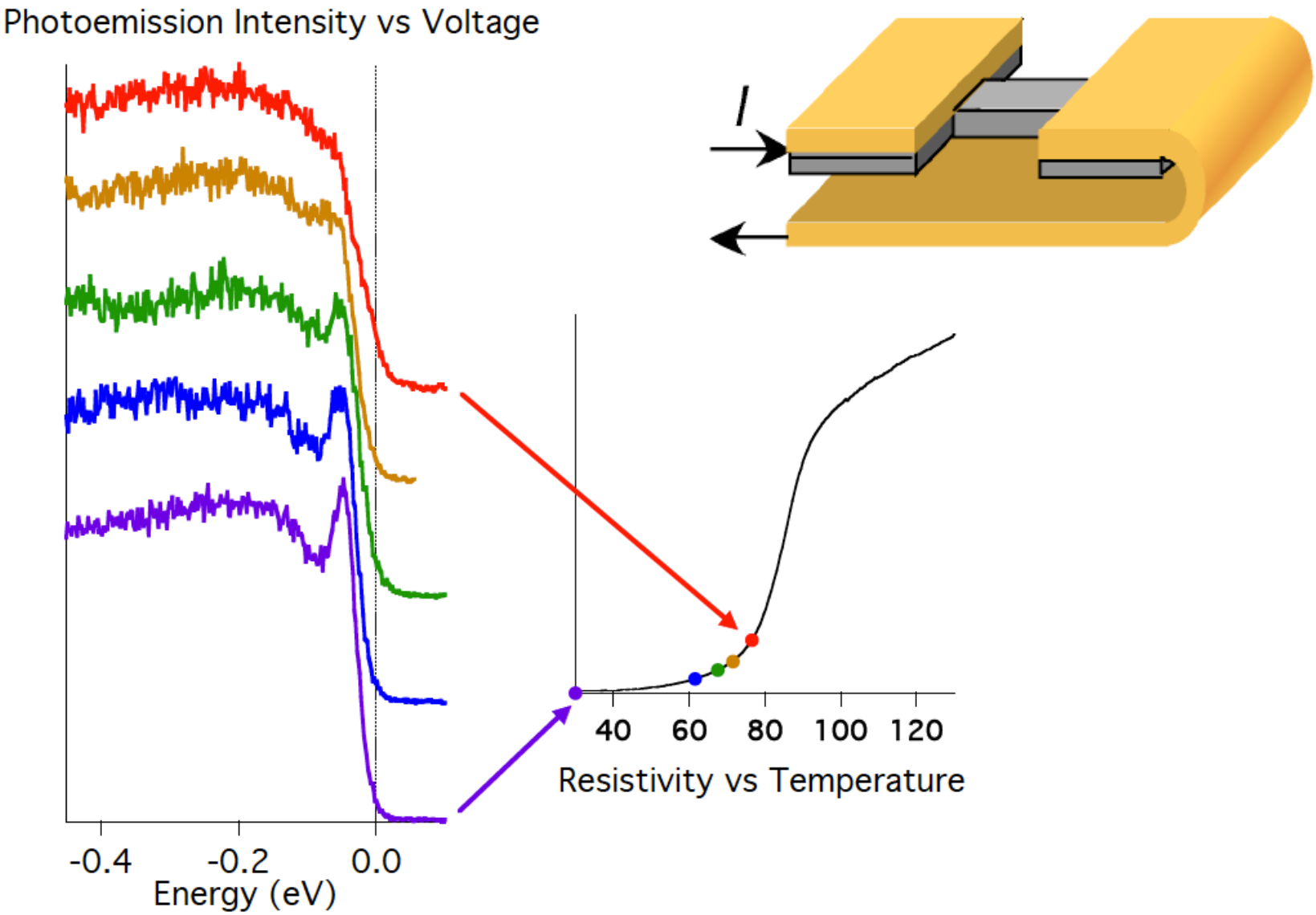
Yusupov *et al.*, Nat. Phys. (2010)

Order parameter domain creation and annihilation in $TbTe_3$



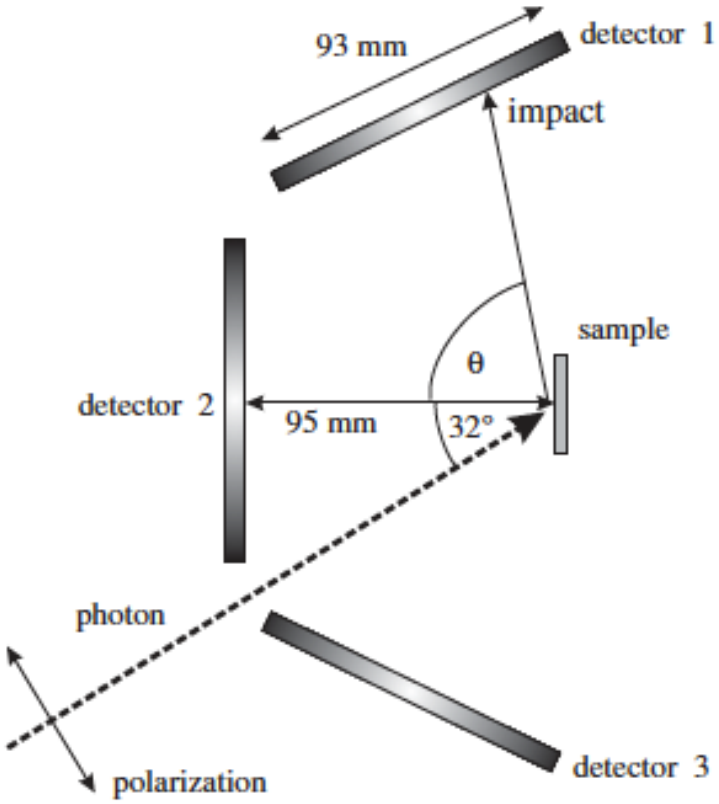
Yusupov *et al*., Nat. Phys. (2010)

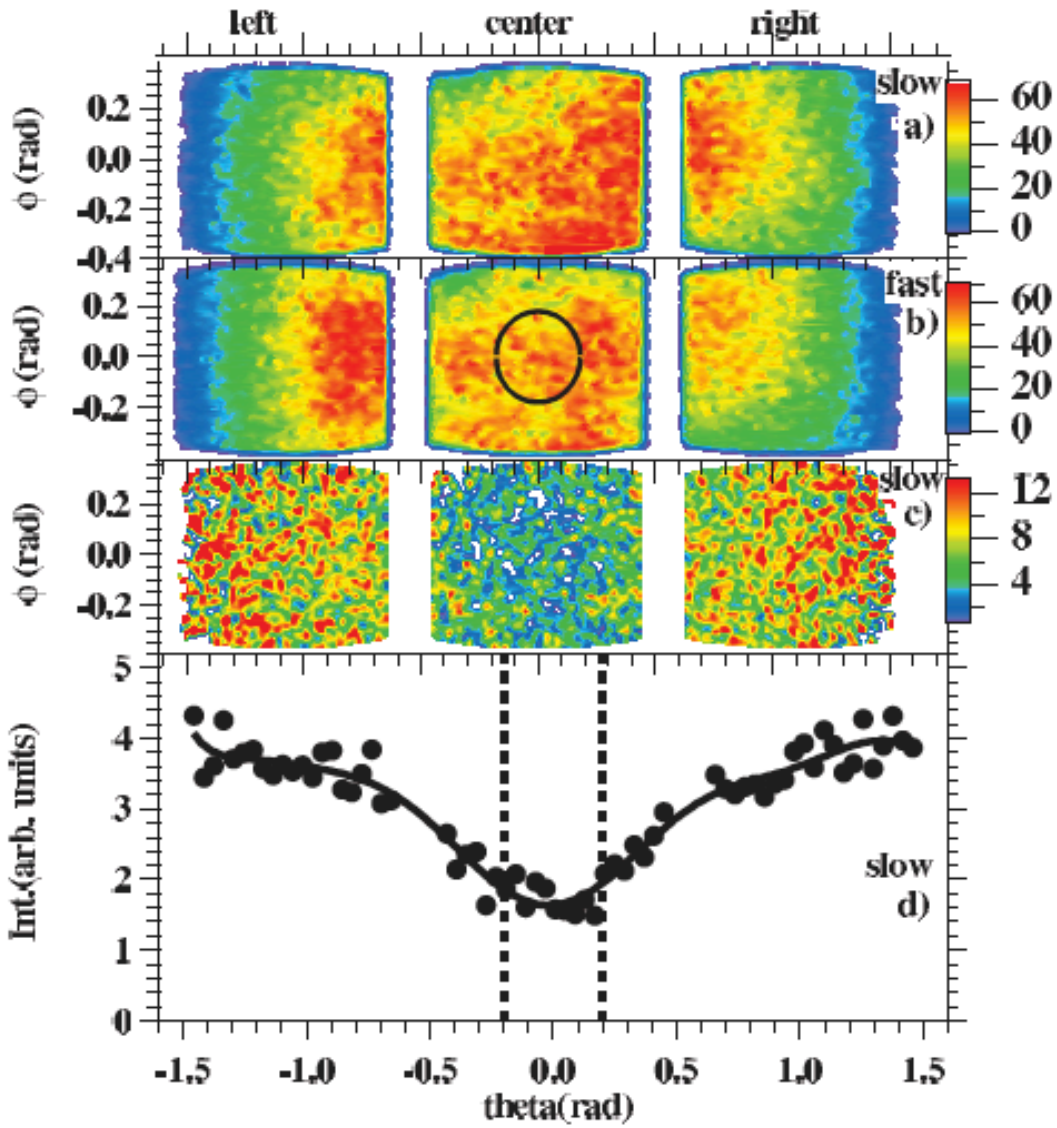
ARPES in Constant Voltage Mode (Bi2212)



Kaminski *et al*., unpublished

Exchange-Correlation Hole via Two Electron Photoemission (Cu)





Schumann *et al*., PRL (2007)