

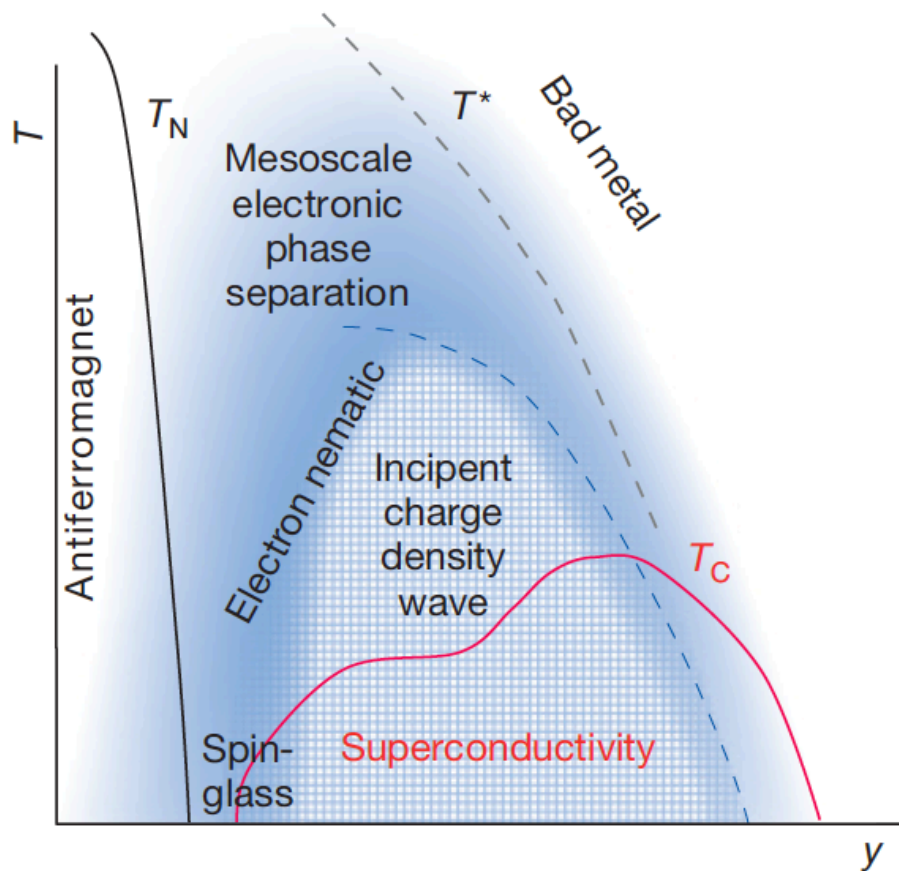
3D-COMPETITION:

SC versus CDW order in YBCO

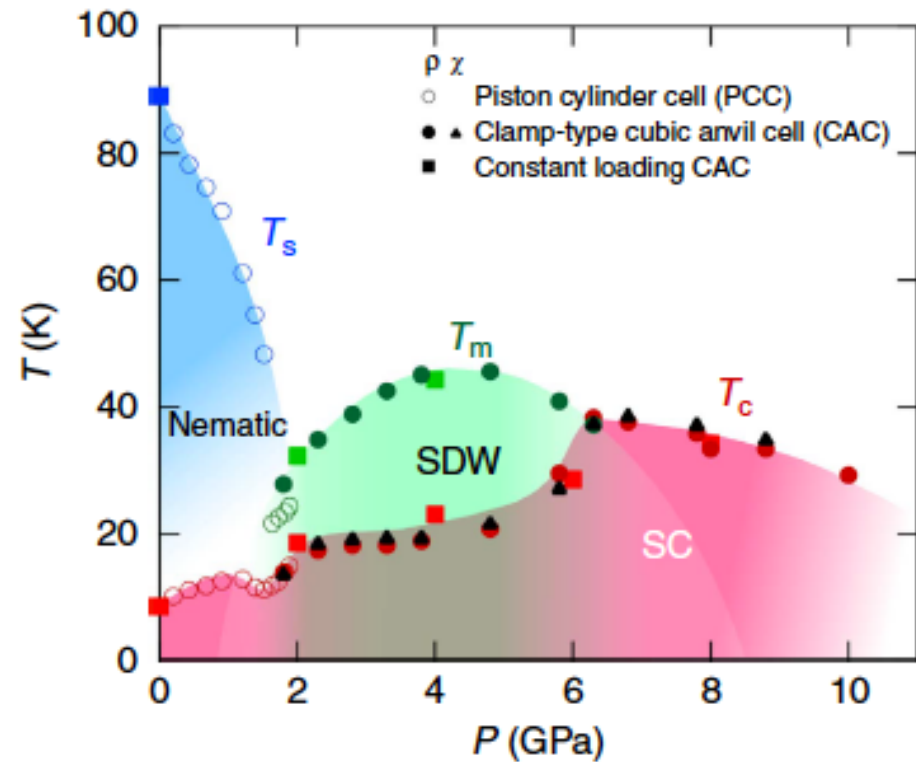
Johan Chang
University of Zurich



Complexity of competing phase

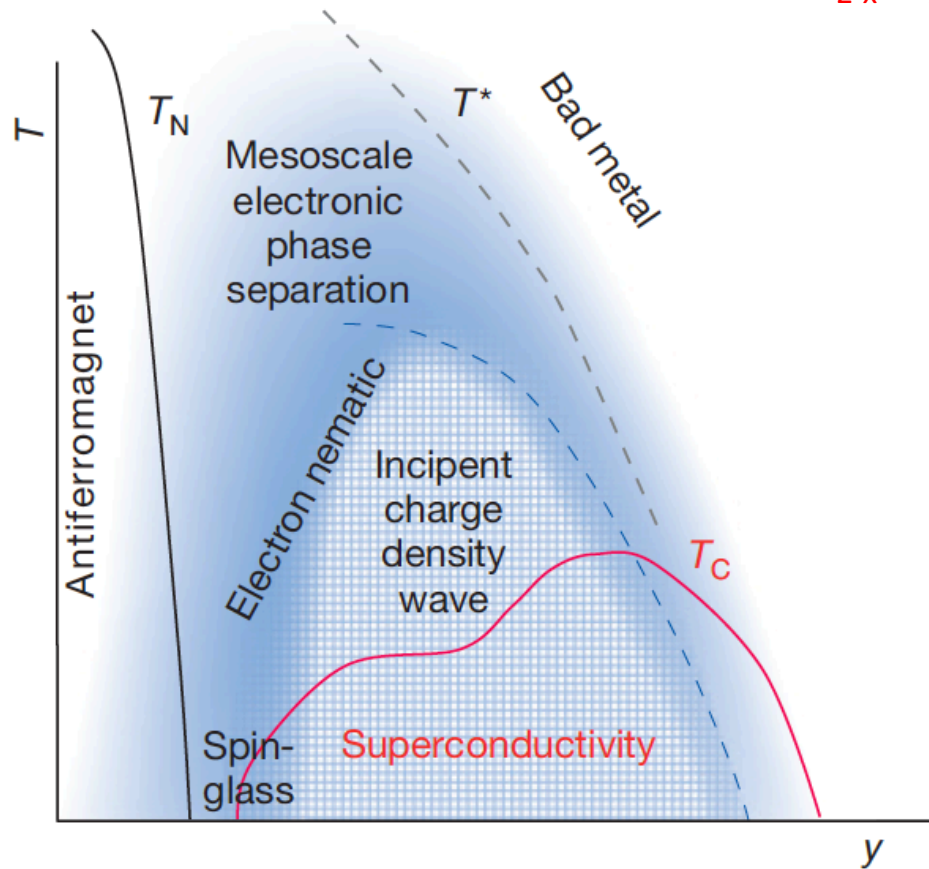


E. Fradkin & S. A. Kivelson
Nat. Phys. **8**, 864 (2012)

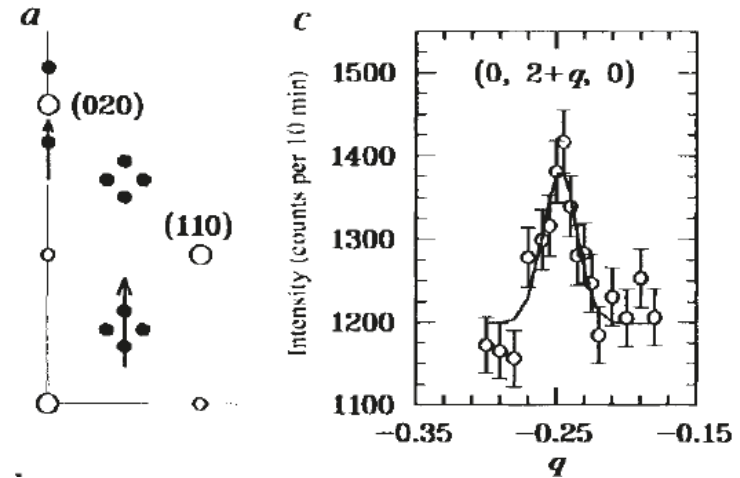


J.P. Sun *et al.*,
Nat. Comm. **7**, 12146 (2016)

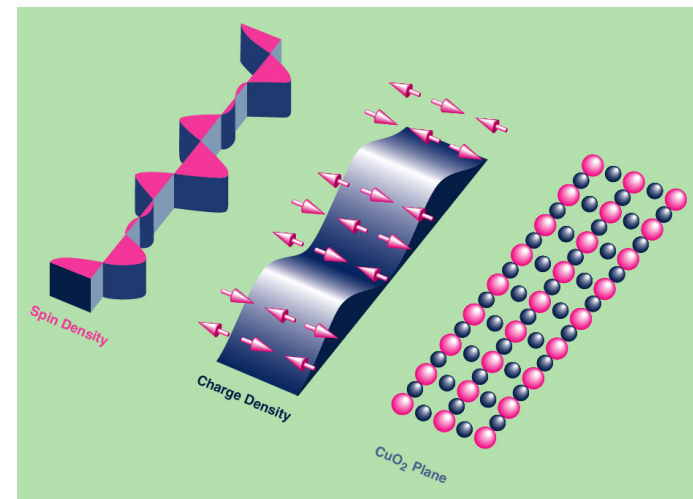
Stripe order: La-based cuprates



E. Fradkin & S. A. Kivelson
 Nat. Phys. **8**, 864 (2012)



John Tranquada et al., Nature **375**, 561 (1995)



<https://www.bnl.gov/newsroom/news.php?a=1865>

Outline

→ Field-induced charge order in $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$

S. Gerber *et al.*, *Science* **350**, 949 (2015)

H. Jang *et al.*, *PNAS* **113**, 14645 (2016)

J. Chang *et al.*, *Nat. Comm.* **7**, 11494 (2016) + new data

→ Electronic Structure of La-based cuprates

C. Matt *et al.*, arXiv:1707.08491v1

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O. Gutowski,
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S. M. Hayden



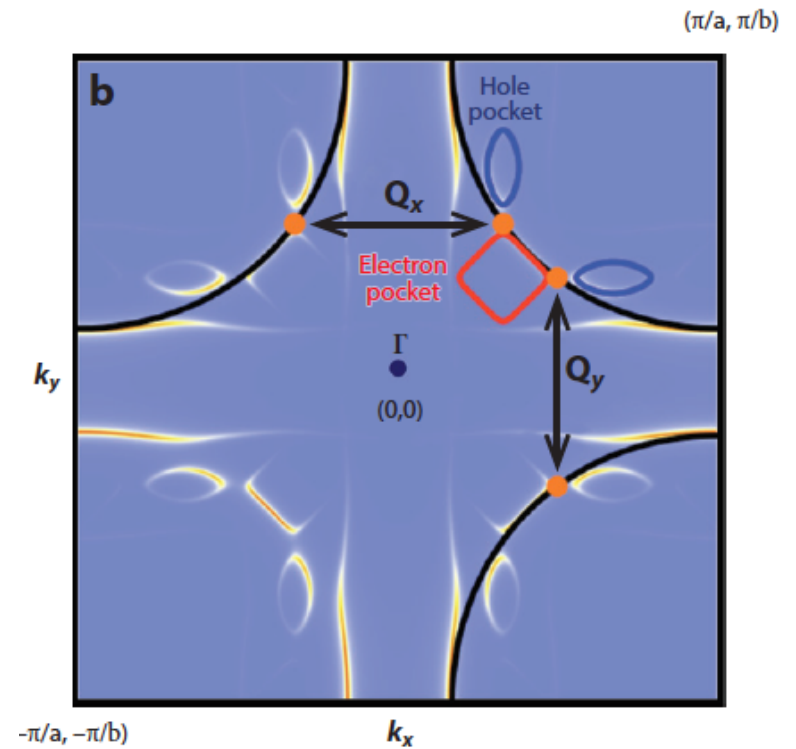
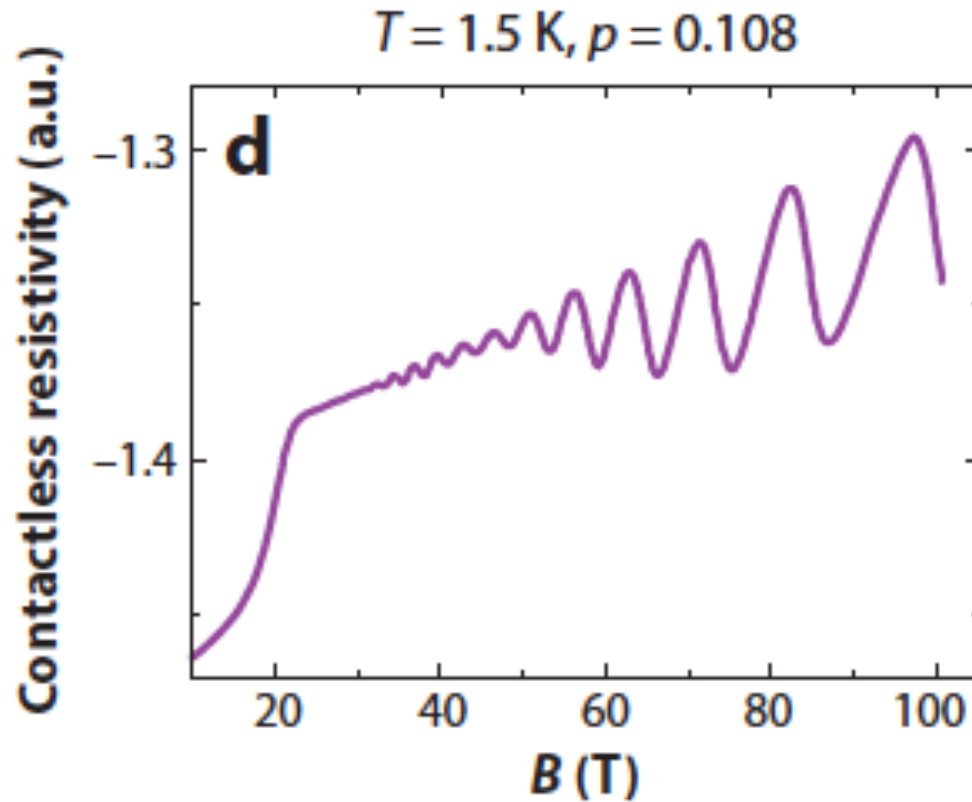
Markus Hücker



Oleh Ivashko



Quantum oscillations in $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$



N. Doiron-Leyraud et al.,
Nature **447**, 565 (2007)

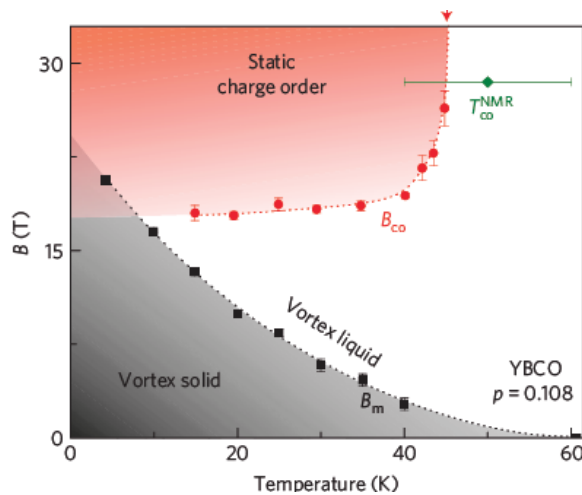
Suchitra E. Sebastian & Cyril Proust
Annu. Rev. Condens. Matter Phys. **6**:411–30 (2015)

Technique dependent Field-onset : YBCO

“Bi-axial”

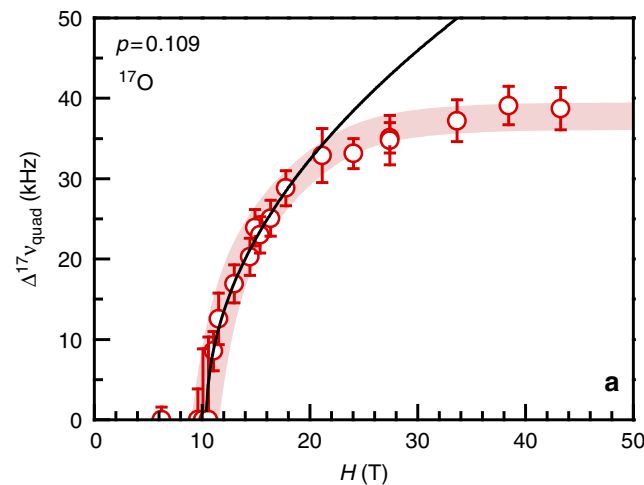
$Q=(\delta, 0, 0.5)$ and $(0, \delta, 0.5)$
 $\delta \sim 1/3$

Ultra-sound
 17 Tesla



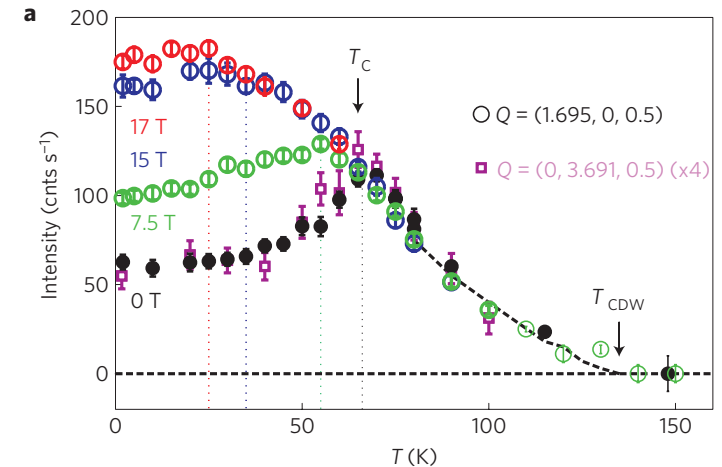
D. Leboeuf *et al.*,
 Nat. Phys. **9**, 79–83 (2013)

NMR
 10 Tesla



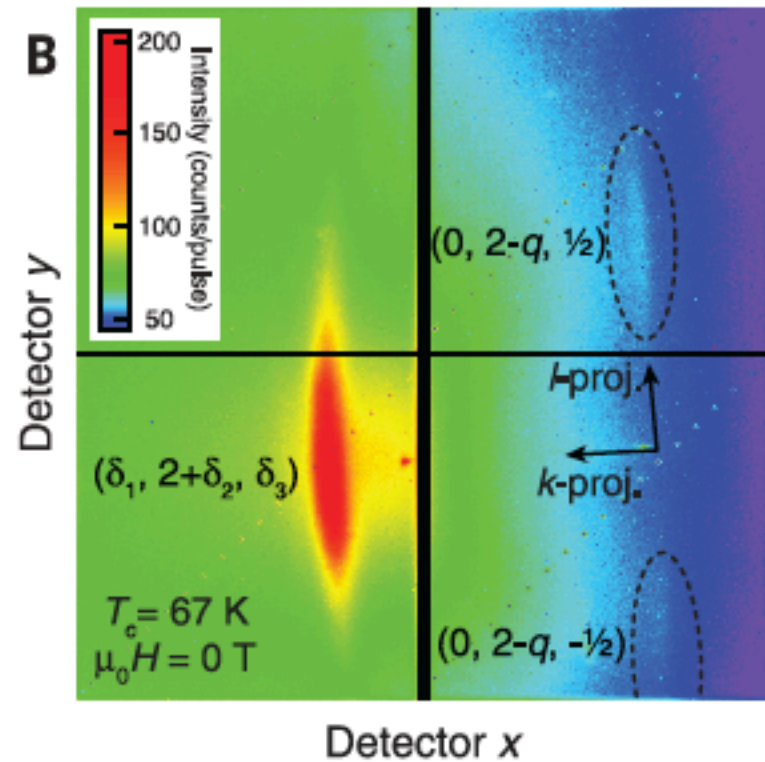
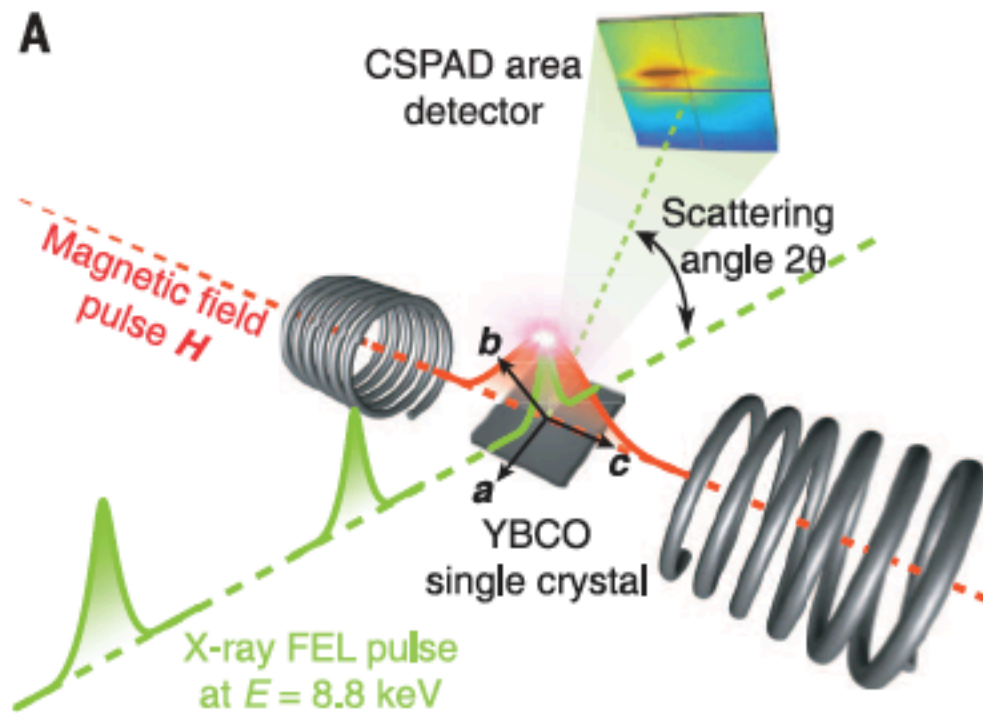
Wu *et al.*,
 Nature **477**, 191 (2011)

X-ray diffractions
 0 Tesla



J. Chang *et al.*,
 Nature Physics **8**, 871-876 (2012)
 Ghiringhelli *et al.*,
 Science **337**, 821-825 (2012)

XFEL and pulsed magnetic fields

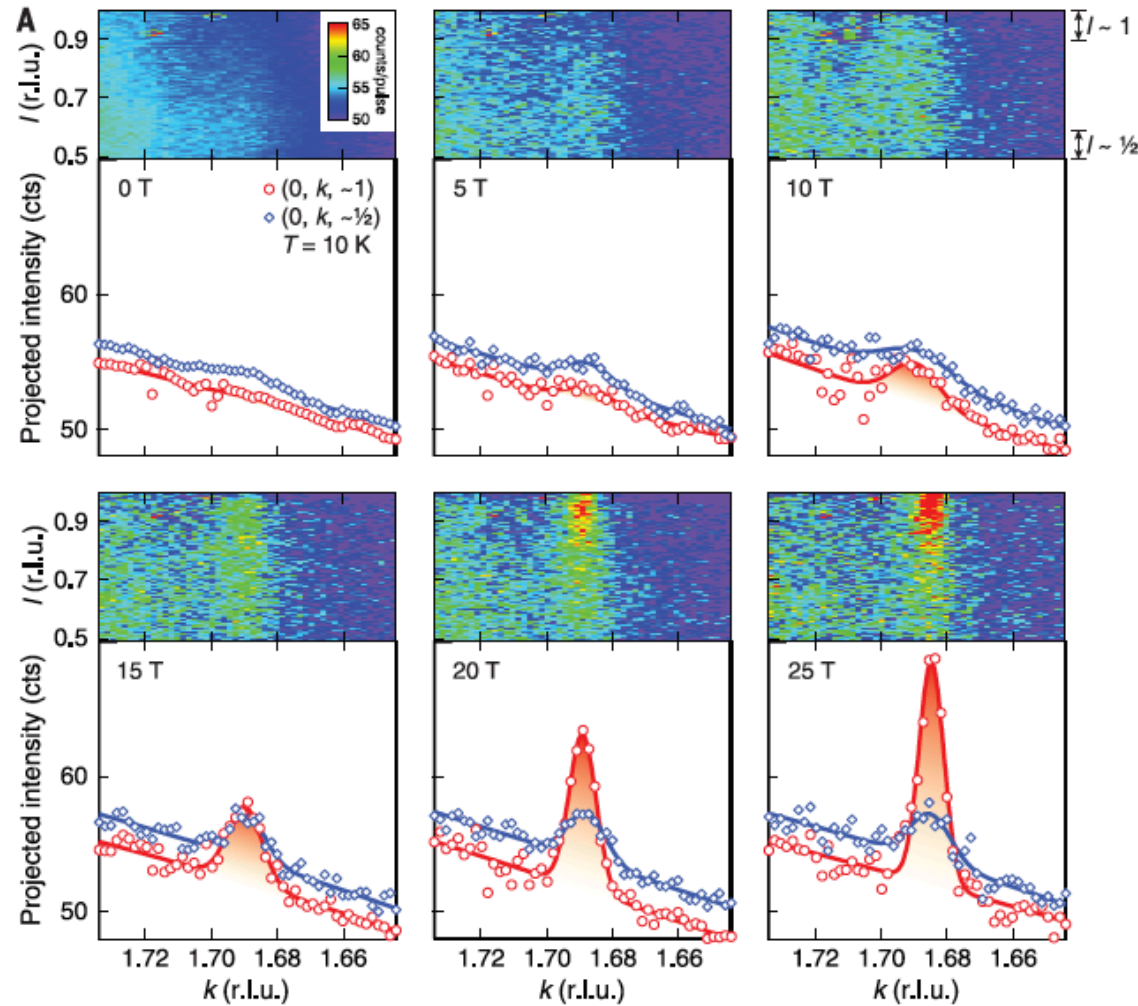


“Bi-axial”

$Q = (\delta, 0, 0.5)$ and $(0, \delta, 0.5)$

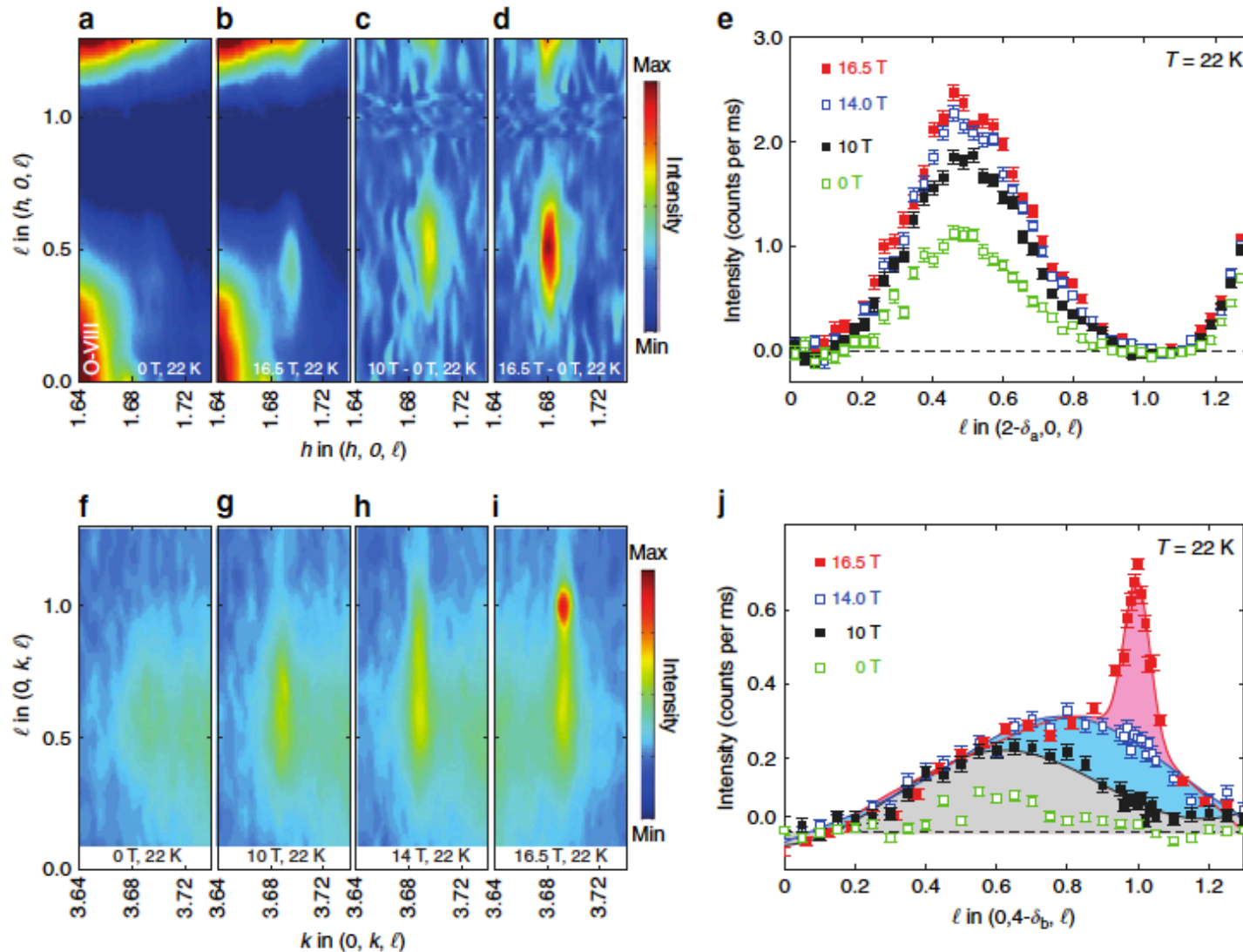
S. Gerber *et al.*, Science **350**, 949 (2015)

New charge-density-wave stacking



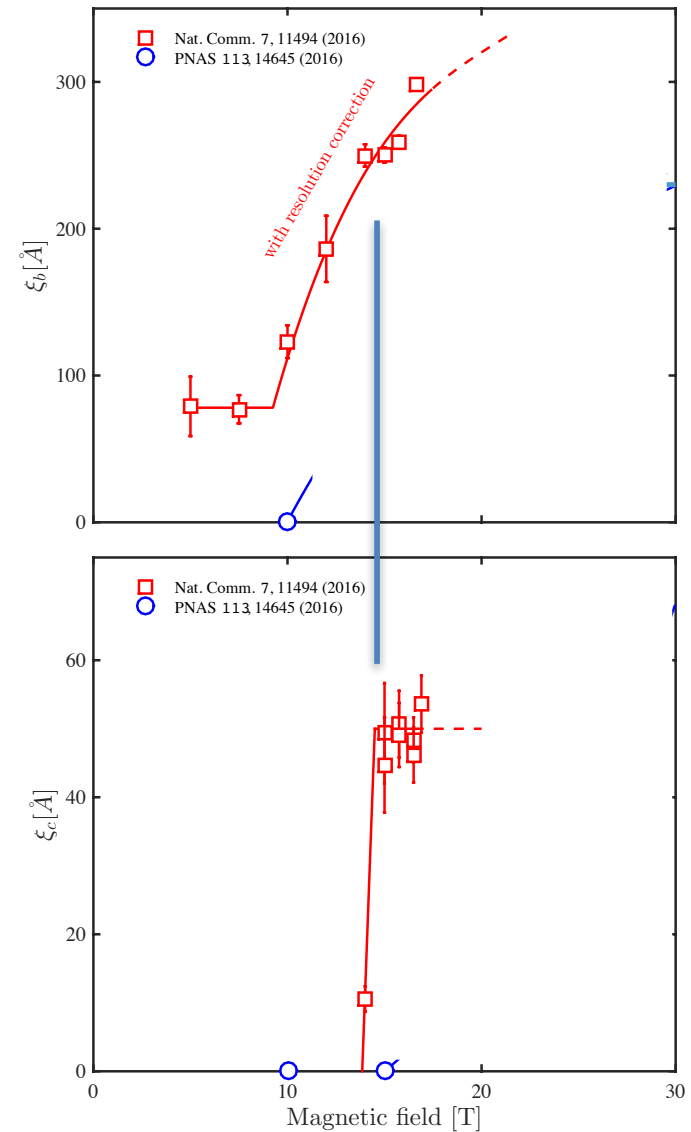
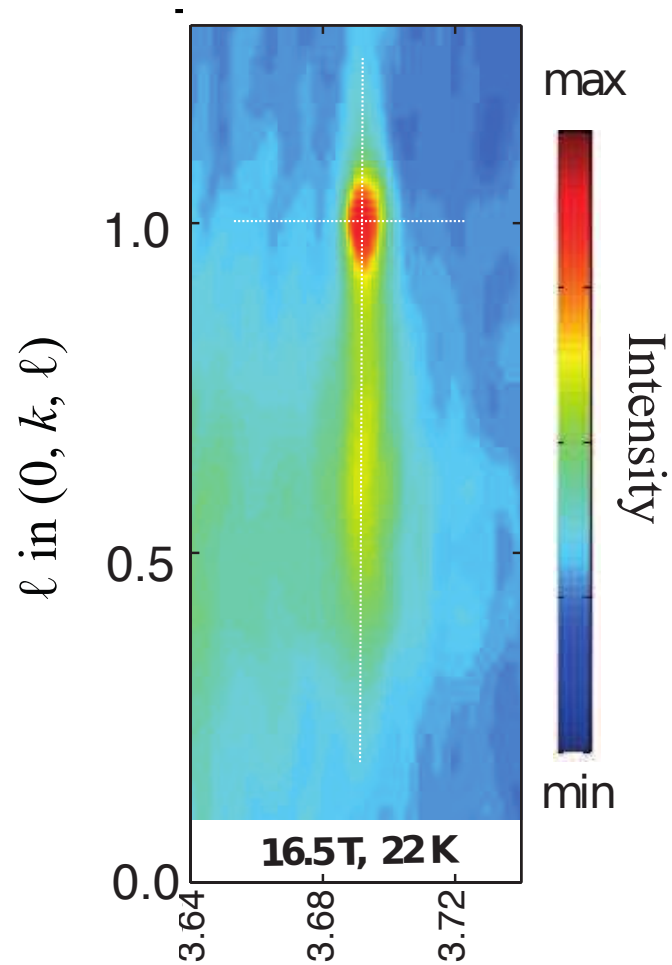
$$Q = (0, \delta, 1)$$

Field-induced 3D charge density-wave ordering

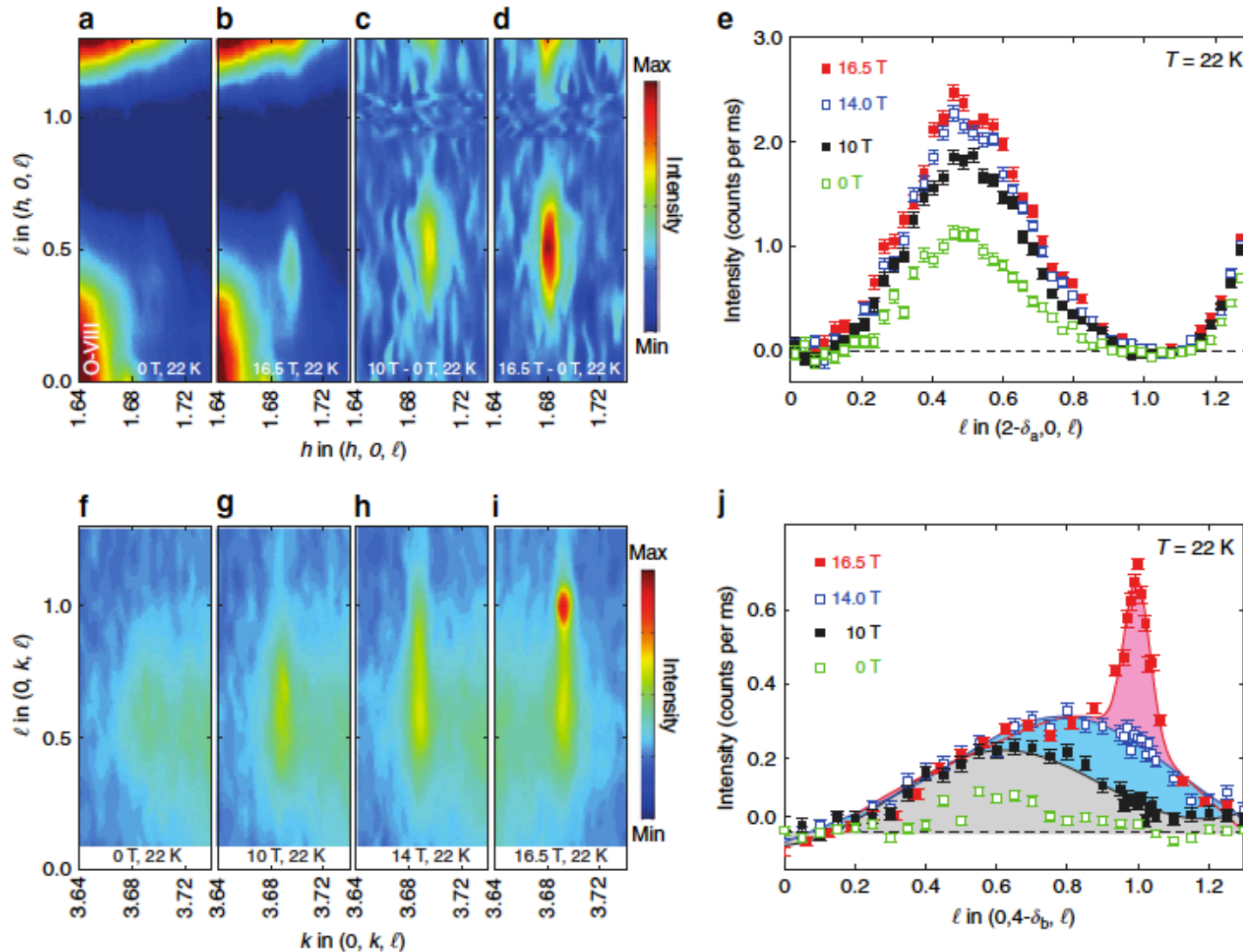


J. Chang et al., Nat. Comm. 7, 11494 (2016)

Two-stage transition

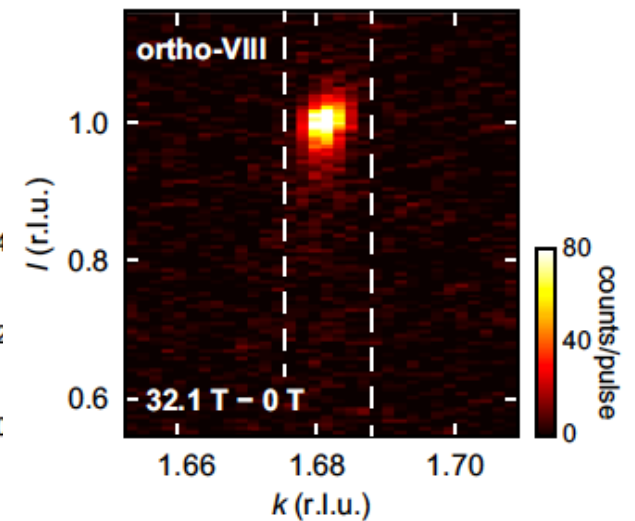
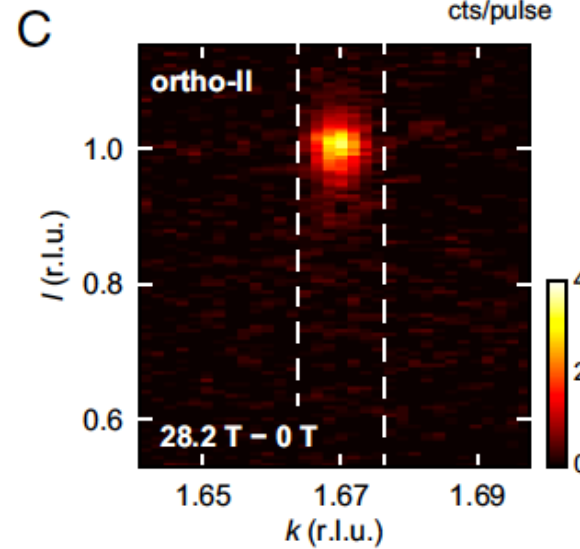
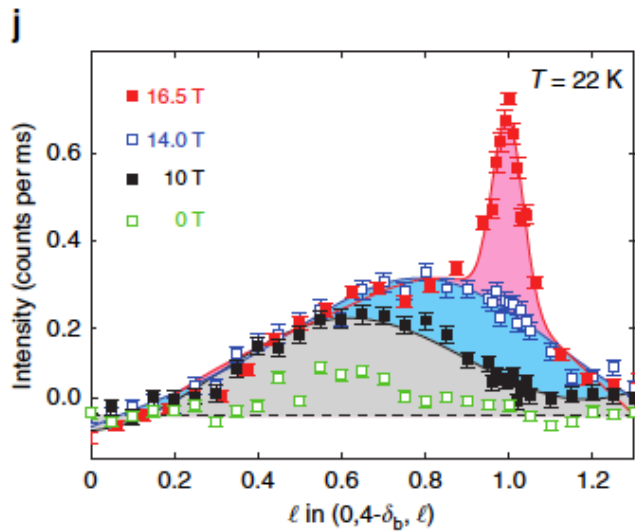
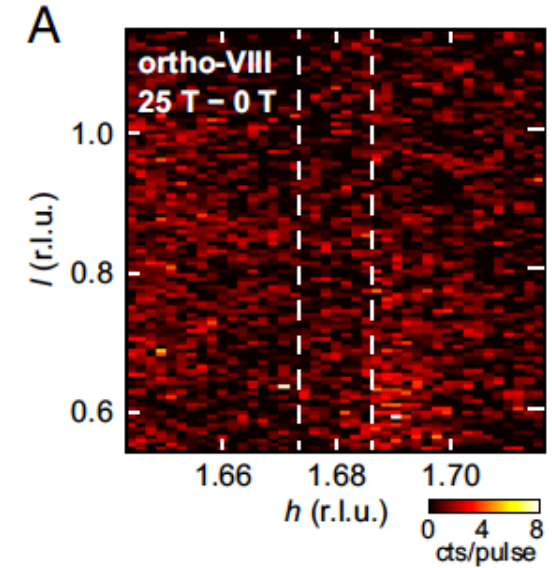
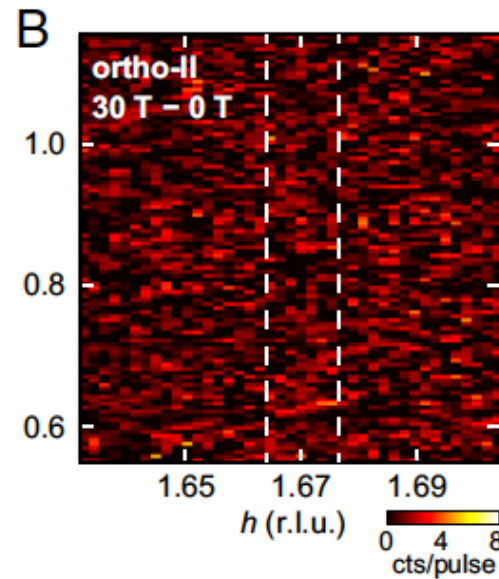
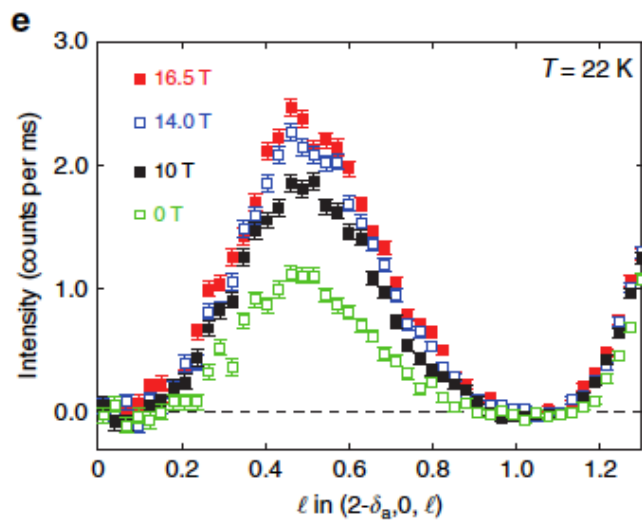


Field-induced 3D charge density-wave ordering



J. Chang et al., Nat. Comm. 7, 11494 (2016)

3D charge density-wave ordering: b-axis only

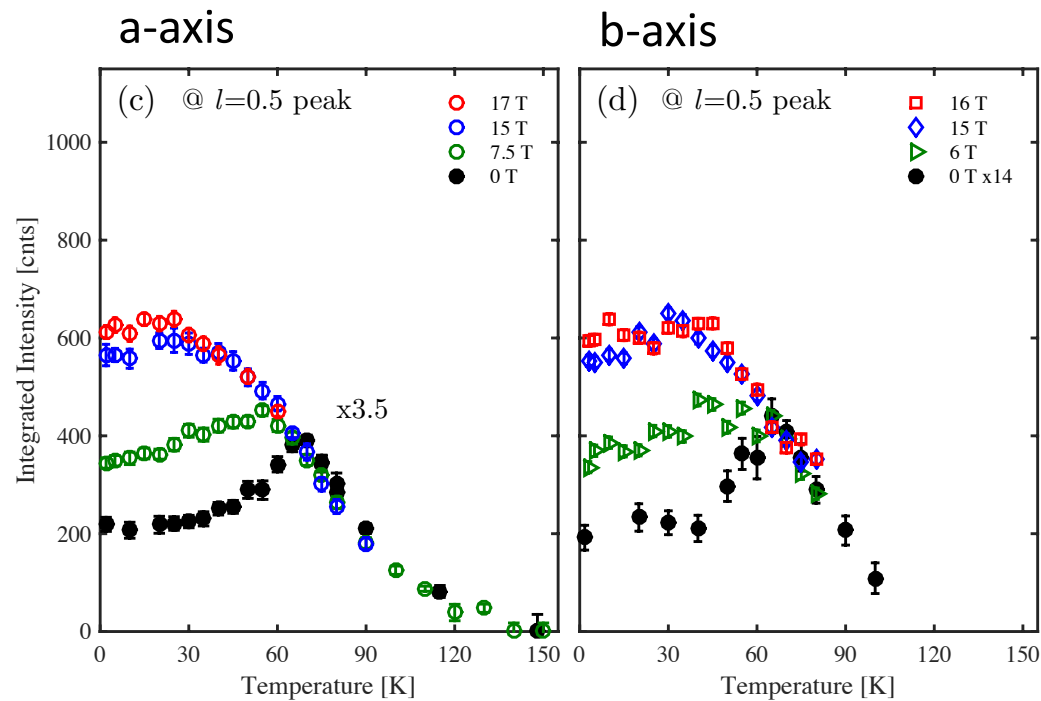


*J. Chang et al.,
Nat. Comm. 7, 11494 (2016)*

*H. Jang et al.,
PNAS 113, 14645 (2016)*

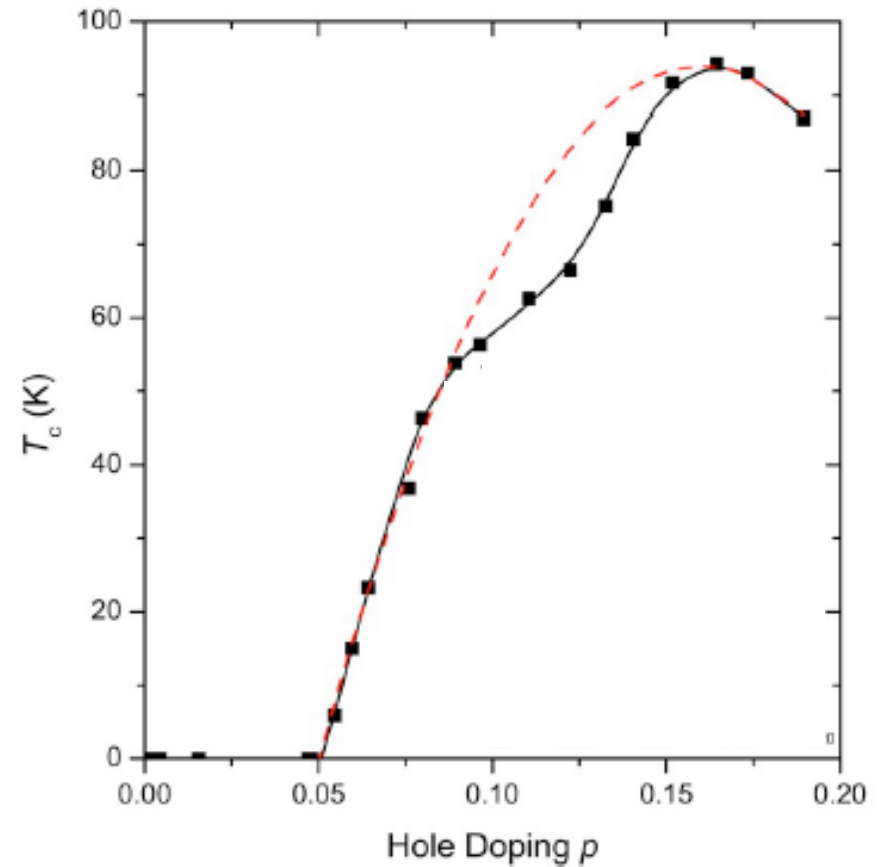
Phase competition: Low-field

CDW order



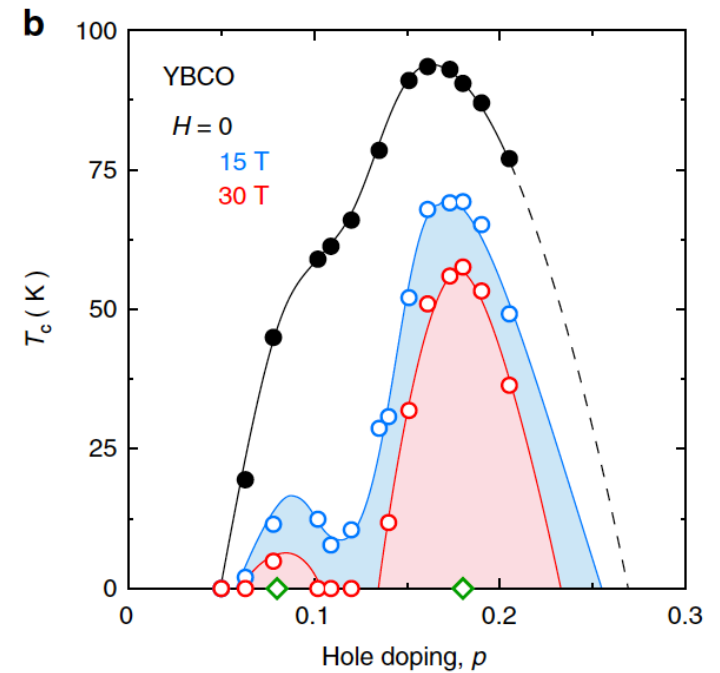
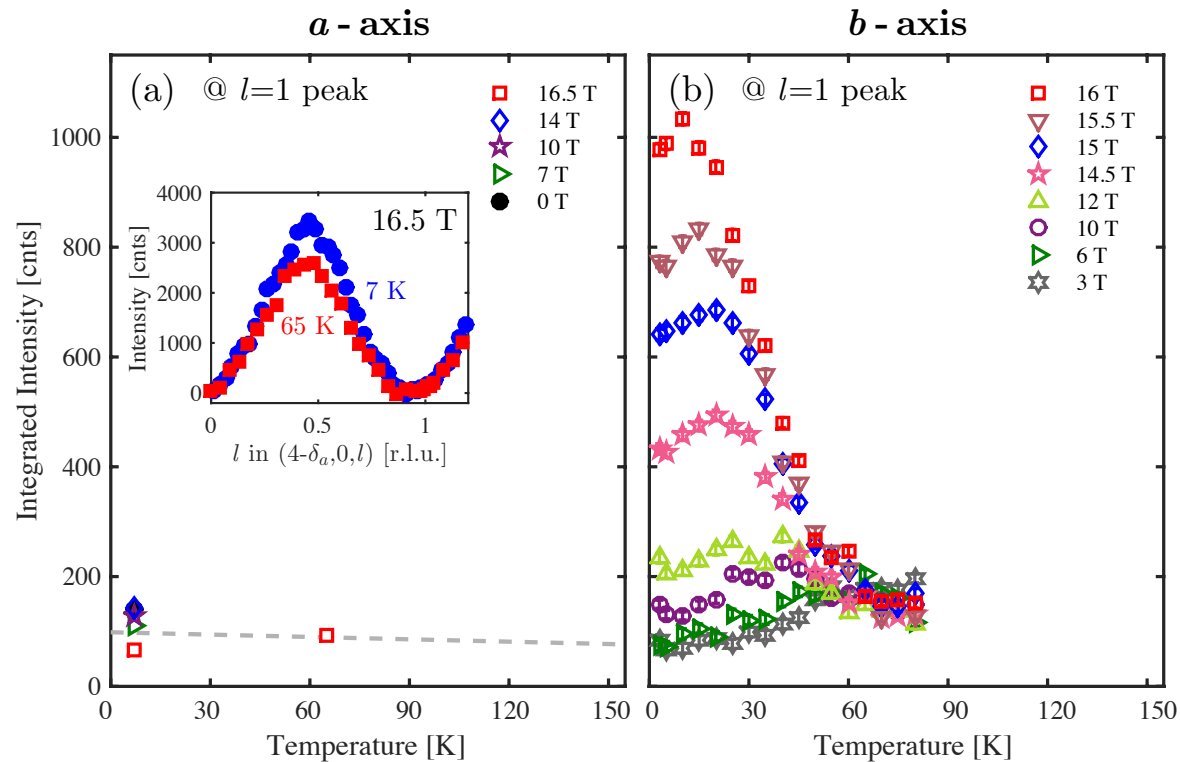
J. Chang *et al.*,
Nature Physics **8**, 871-876 (2012)

Superconductivity



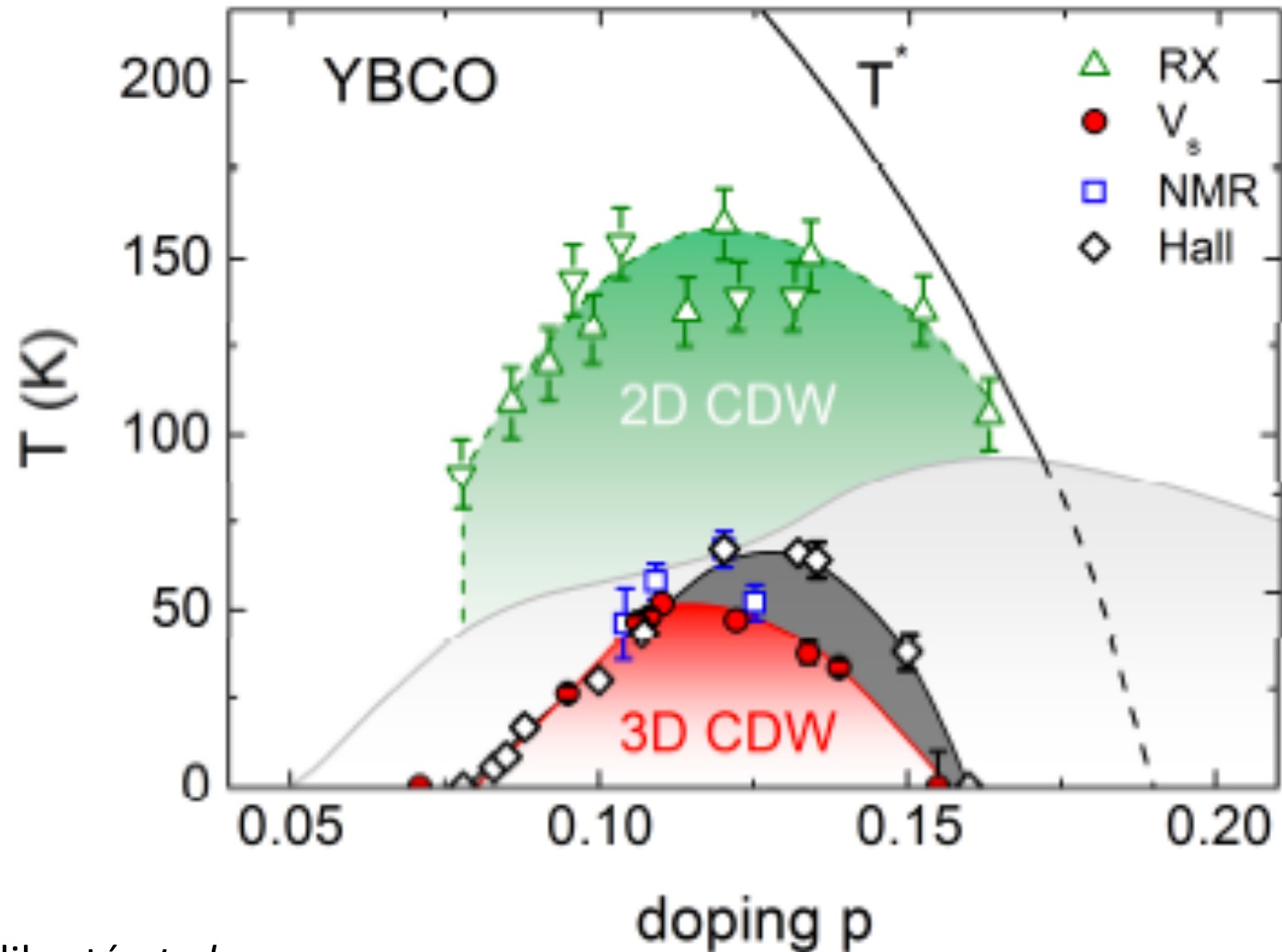
Liang *et al.*,
PRB **73**, 180505 (2006)

Phase competition: High-field



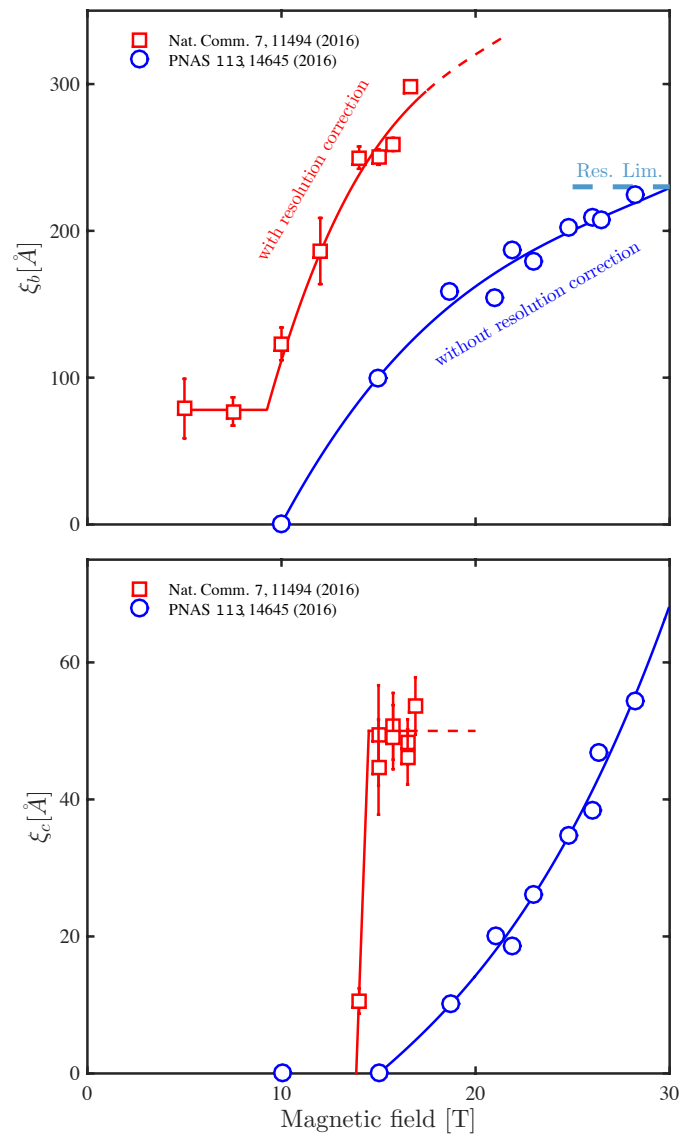
Grisonache et al.,
Nat. Comm. 5:3280 (2014)
Ramshaw et al.,
Science 348, 317 (2015)

High-field phase diagram

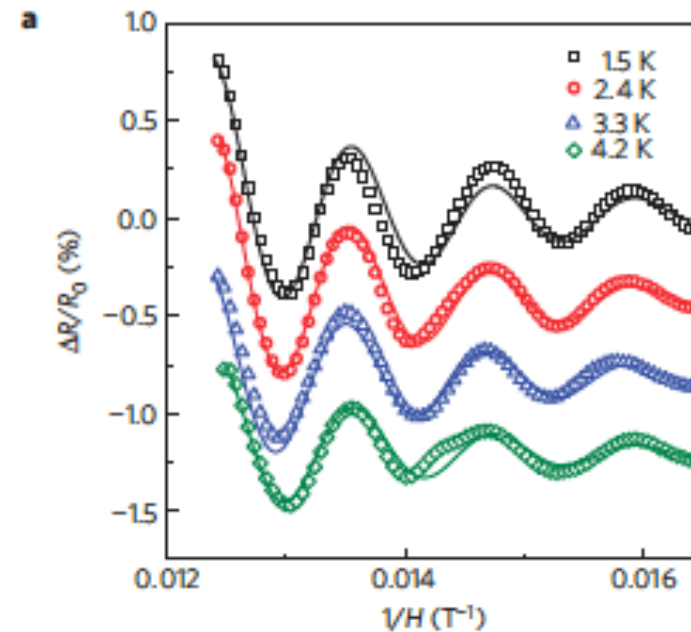


F. Laliberté *et al.*,
arxiv:1705.07763

Remaining Questions



Quantum Oscillations Hg1201 and YBCO



N. Barisic et al.,
Nat. Phys. 9, 761 (2013)

Outline

→ Field-induced charge order in $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$

S. Gerber *et al.*, *Science* **350**, 949 (2015)

H. Jang *et al.*, *PNAS* **113**, 14645 (2016)

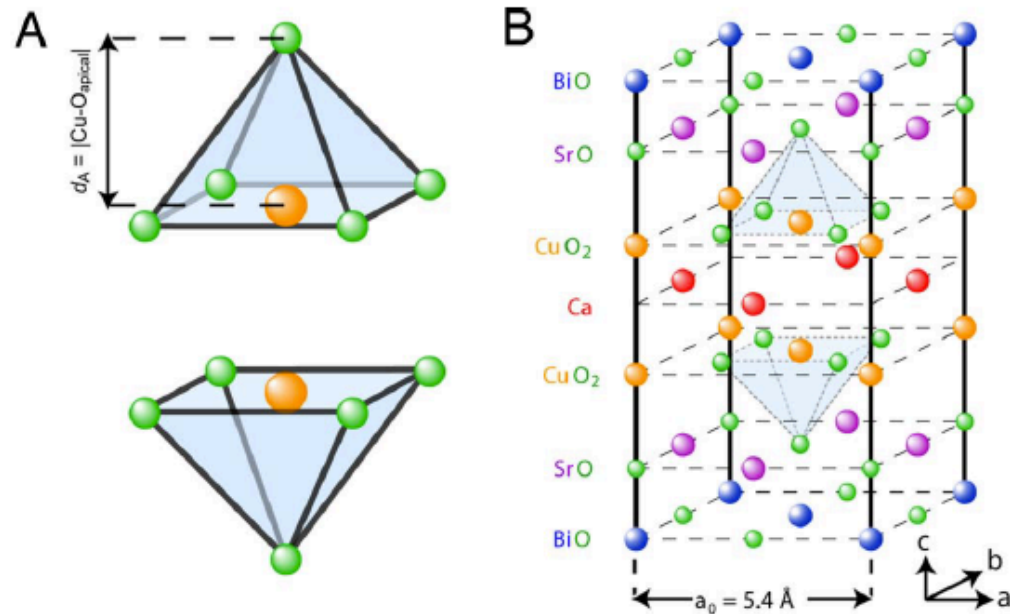
J. Chang *et al.*, *Nat. Comm.* **7**, 11494 (2016) + new data

→ Electronic Structure of La-based cuprates

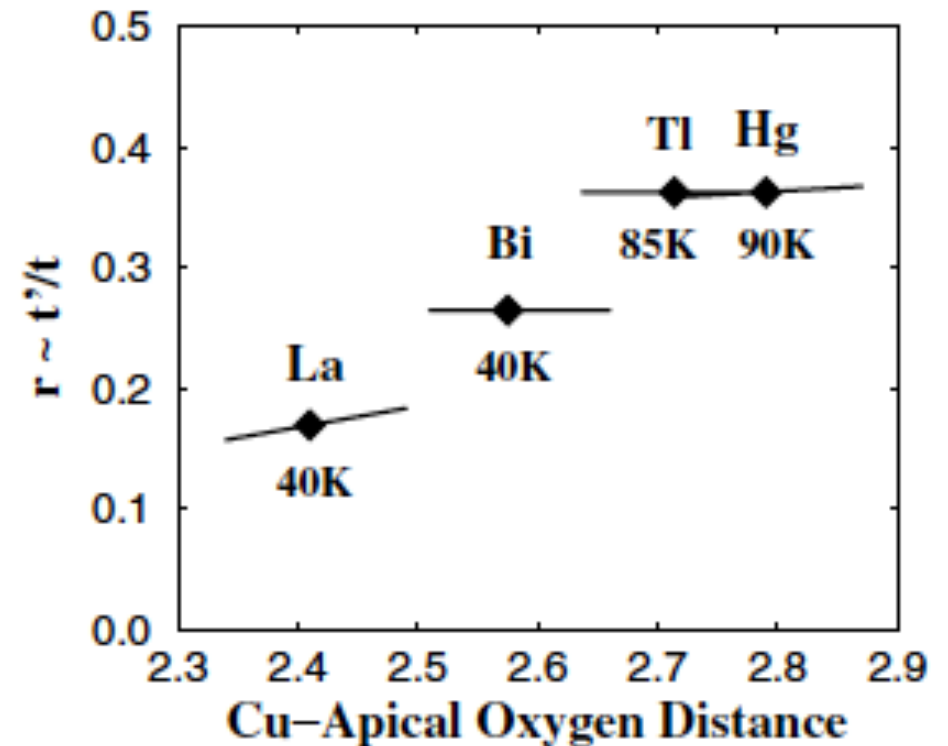
C. Matt *et al.*, arXiv:1707.08491v1

Experimental evidence:

Larger apical distance – higher T_c

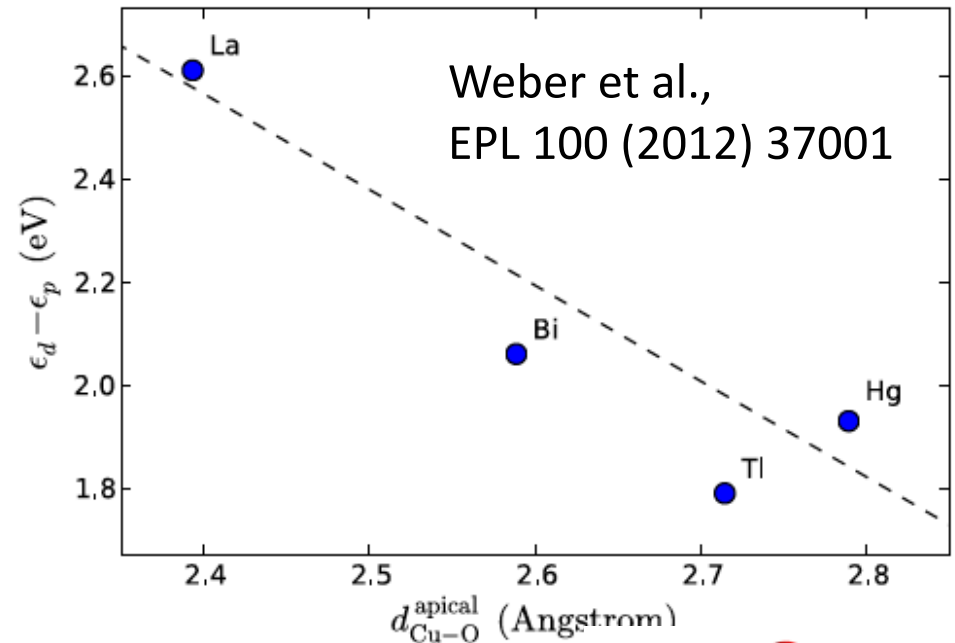
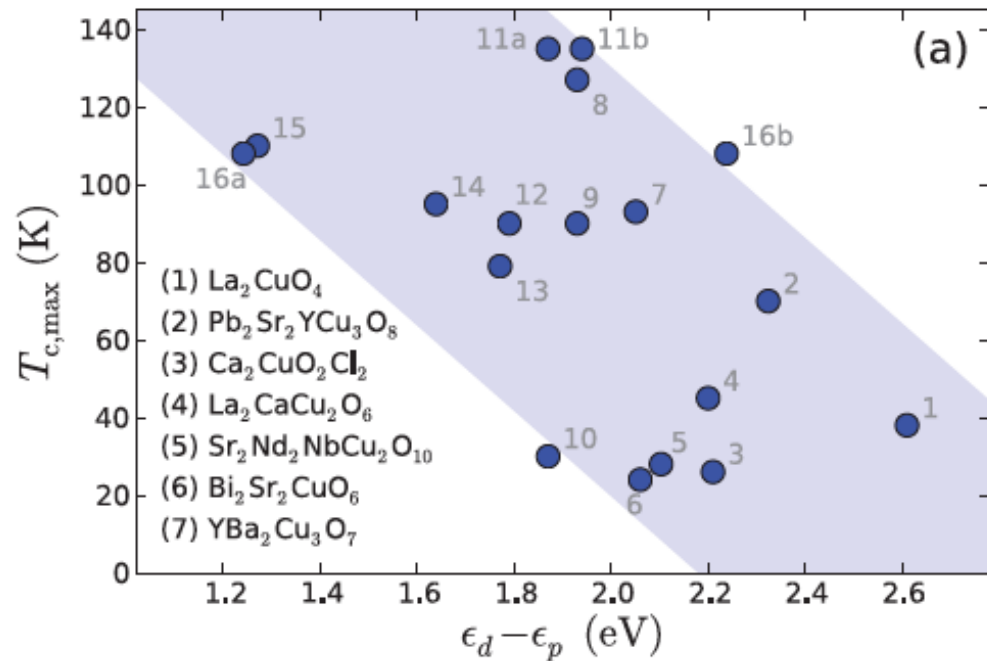


J. A. Slezak et al.,
PNAC 105, 3203 (2008)



Pavarini et al.,
PRL 87, 047003 (2001)

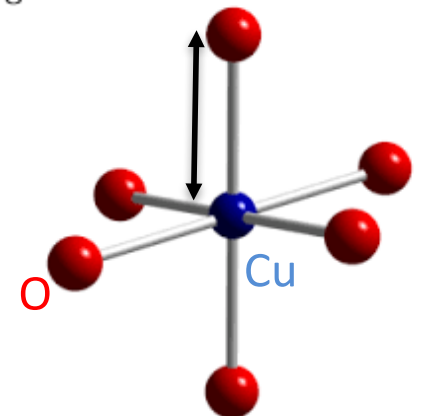
Magnetic Analog to Isotope effect: Reformulated



$\epsilon_d - \epsilon_p = \text{Charge Transfer gap} \sim U$

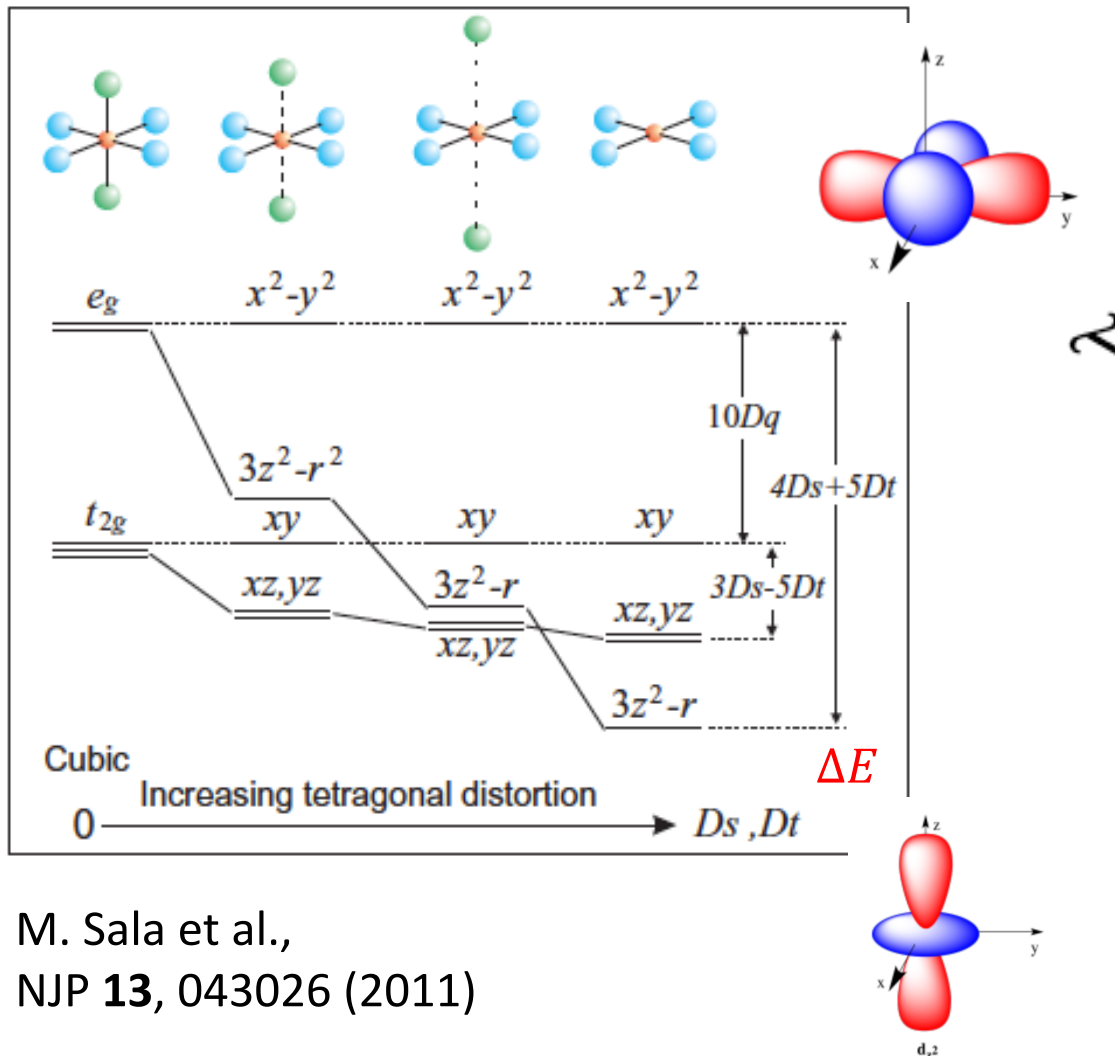
$U = \text{Coulomb interaction}$

$$J = t^2/U \sim T_c$$

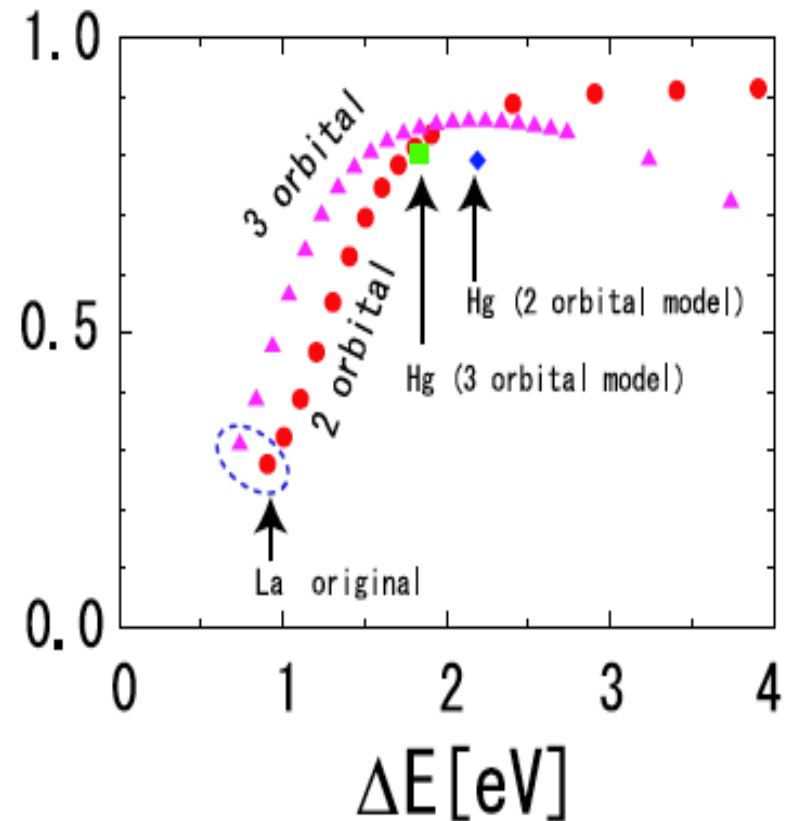


Orbital Physics:

Hybridization sabotages T_c

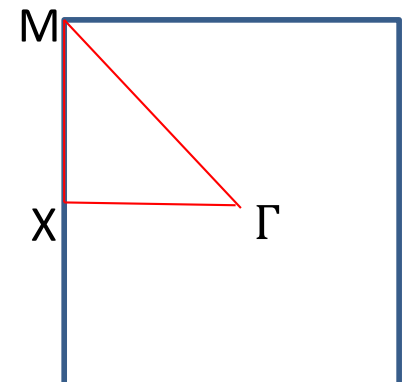
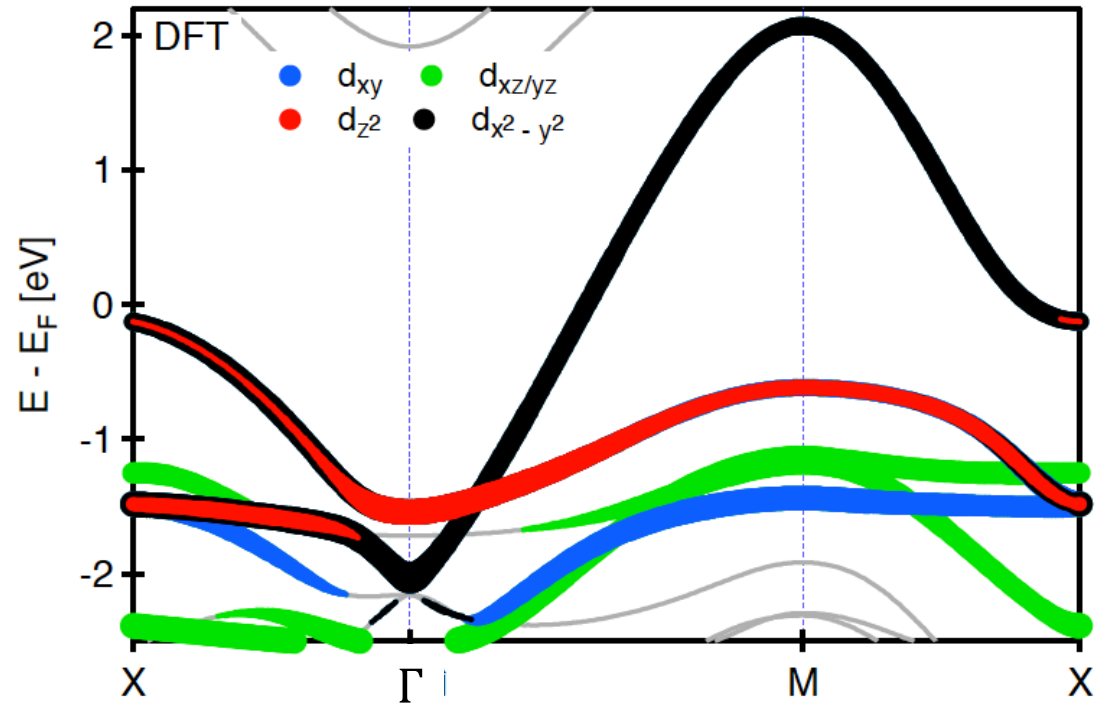
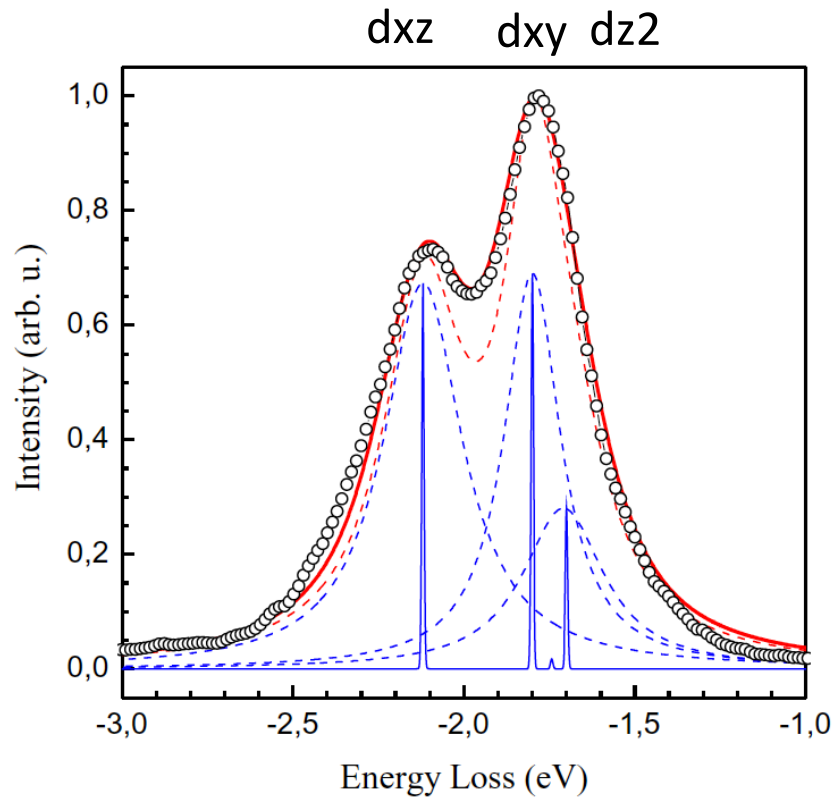


M. Sala et al.,
NJP **13**, 043026 (2011)



Sakakibara et al.,
PRL **105**, 057003 (2010)

RIXS vs DFT Structure



RIXS – La_2CuO_4
 M. Moretti Sala *et al.*,
 NJP 13, 043026 (2011)

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Zurich^{UZH}**

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UNIVERSITET

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札幌市立大学
SAPPORO CITY UNIVERSITY

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Migaku Oda

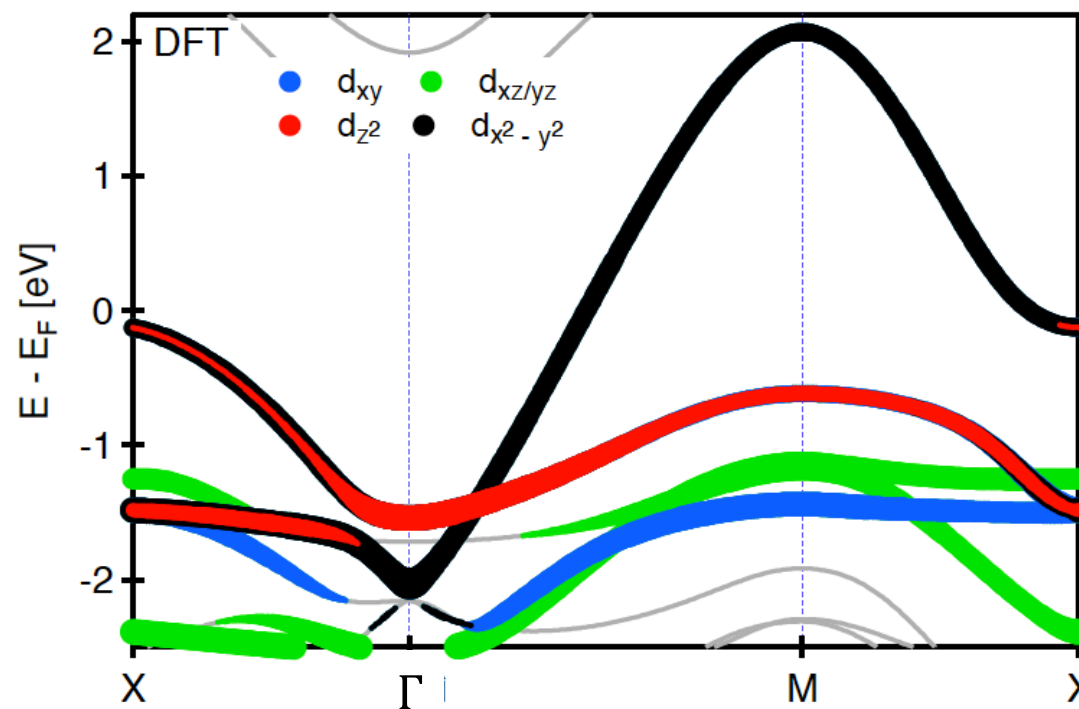
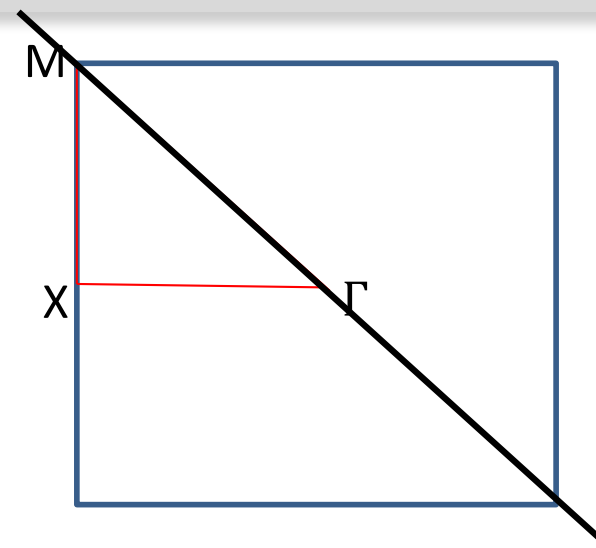
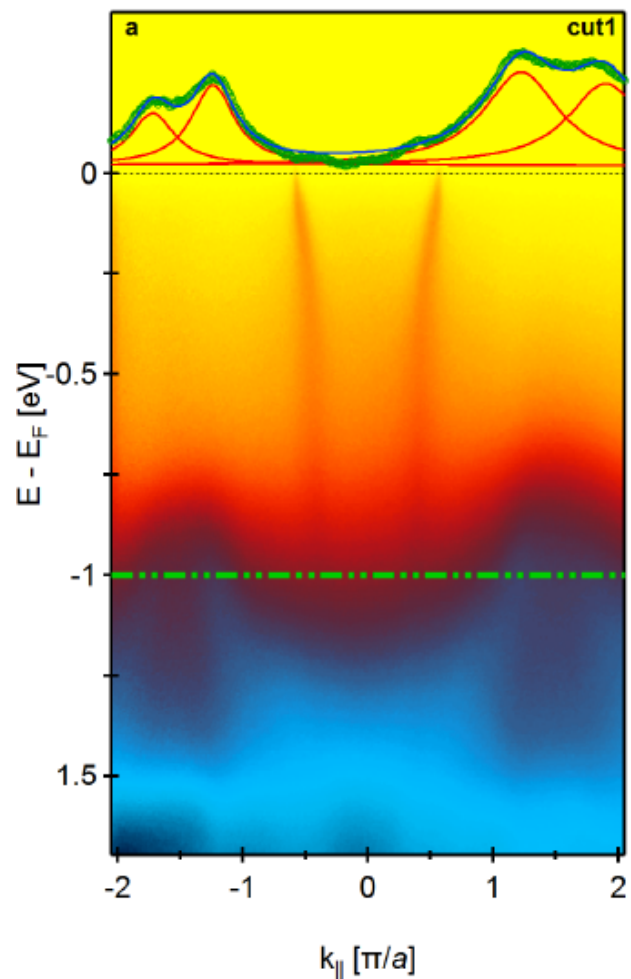


Olivier Lipscombe
Stephen Hayden

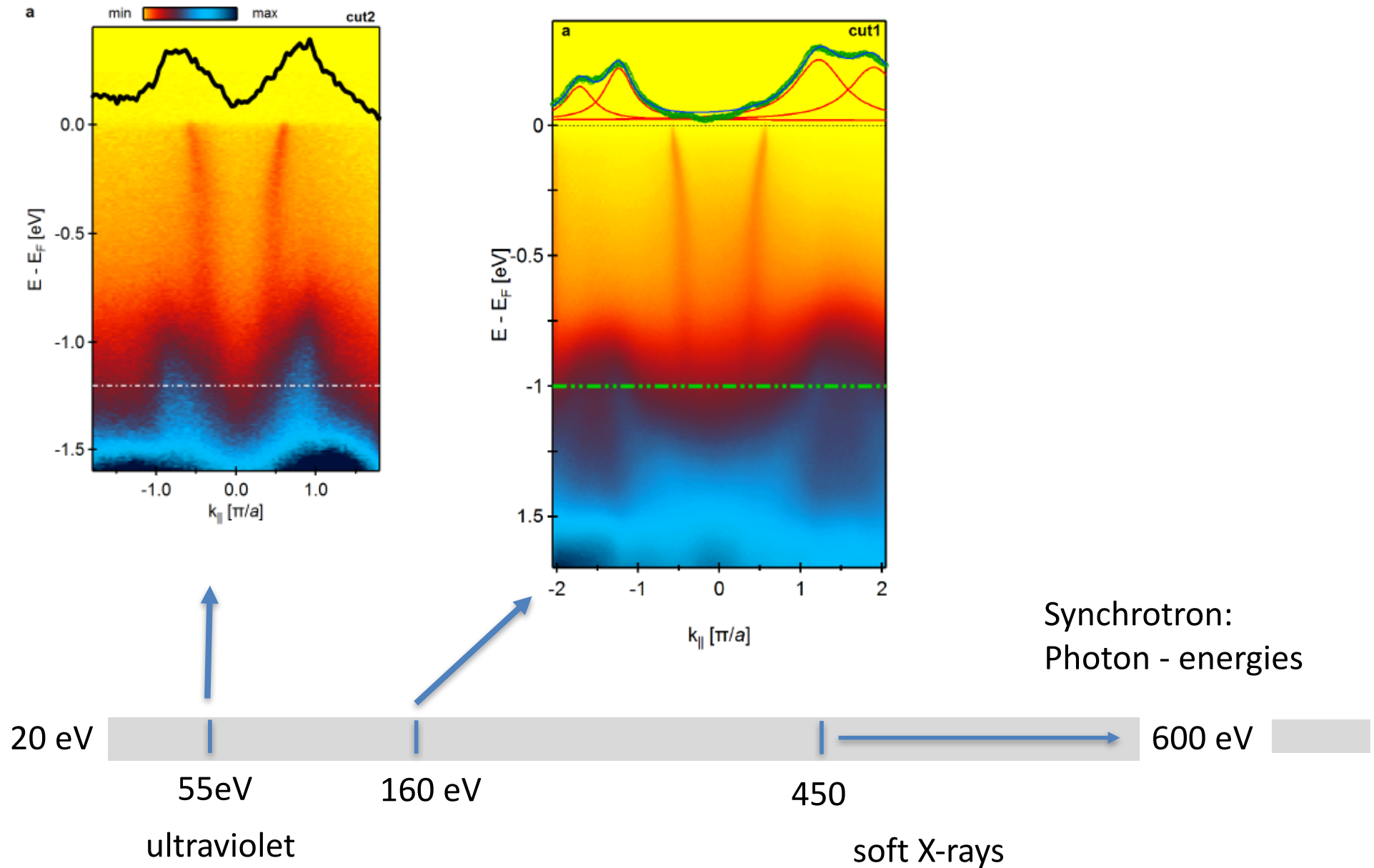
Ultraviolet ARPES (160 eV)

Overdoped LSCO $x = 0.23$

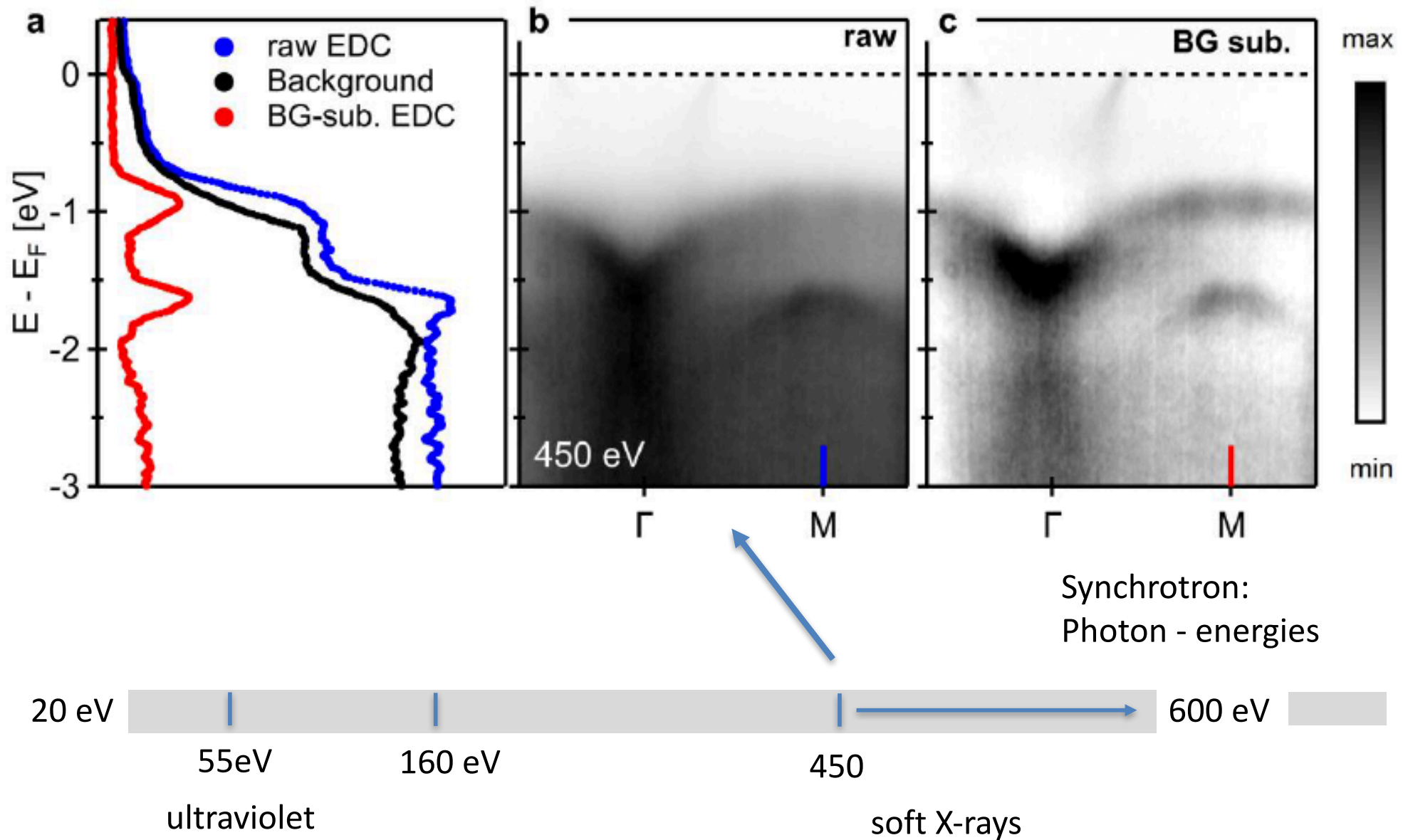
RAW SPECTRA



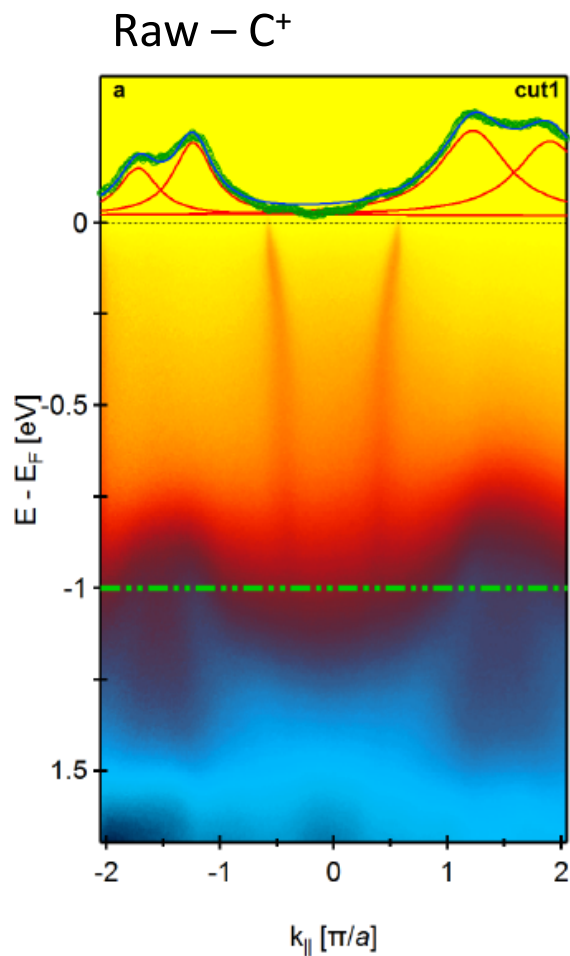
Tuning of Photon Energy



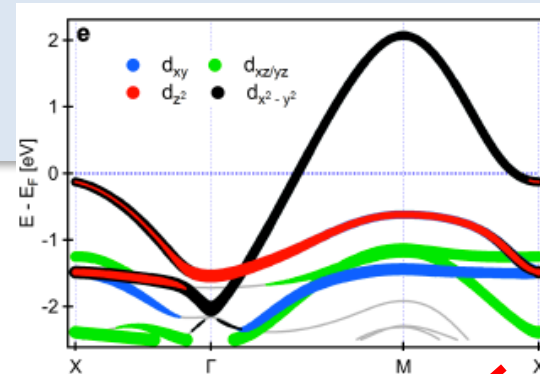
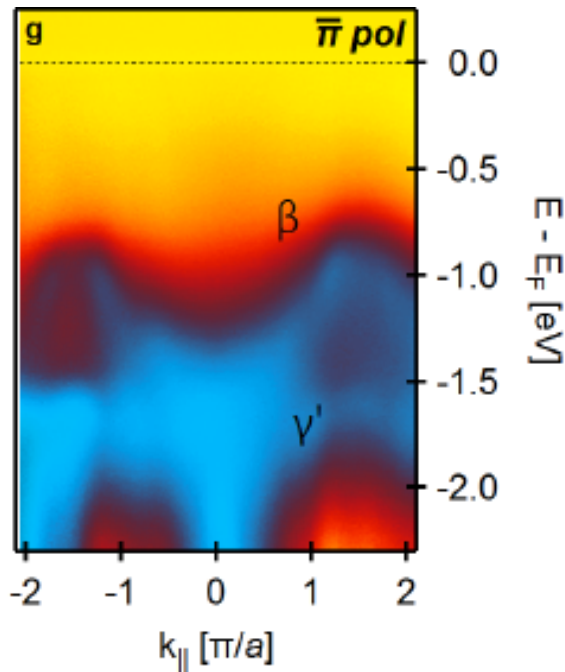
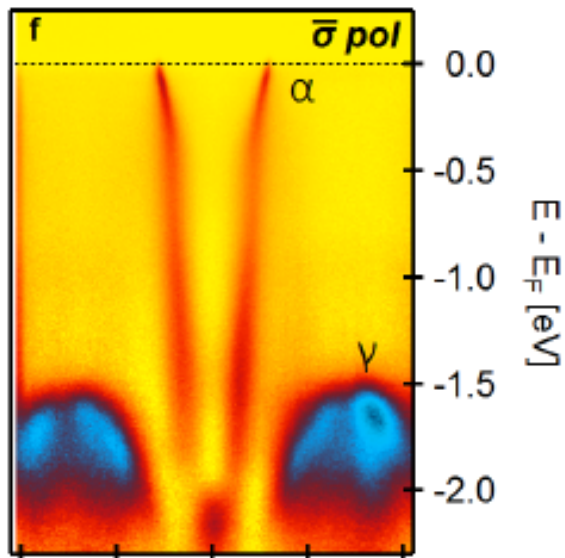
Background subtraction



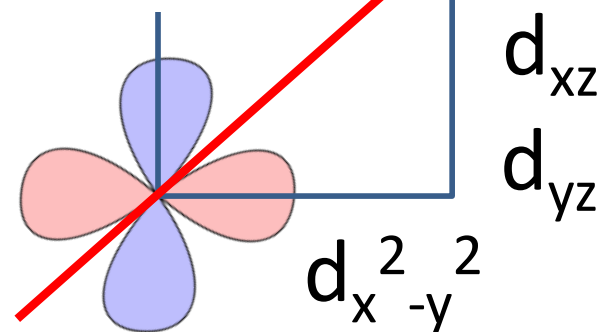
Photon polarization



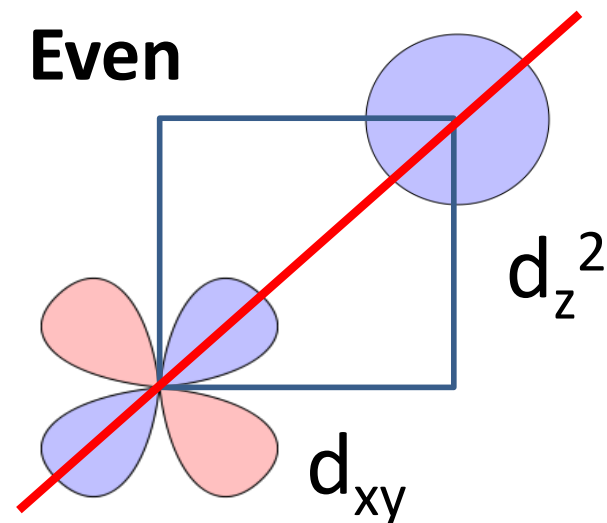
BG-subtracted



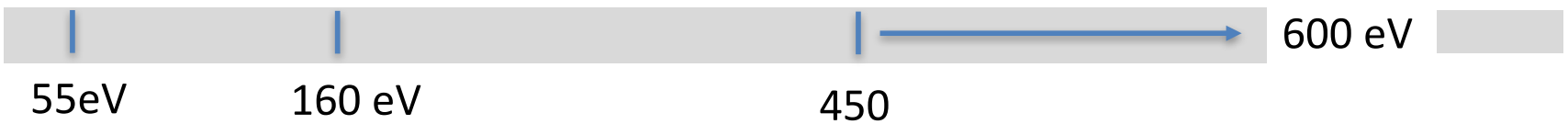
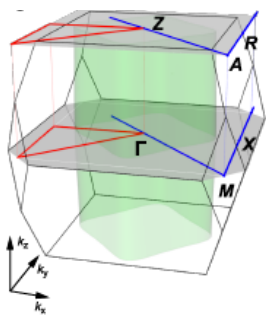
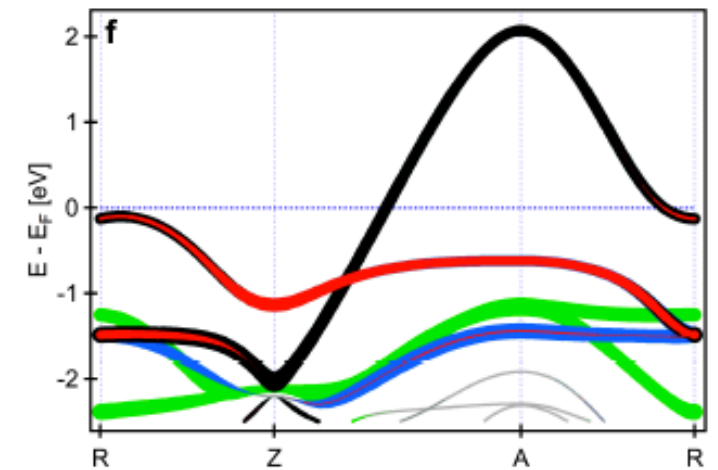
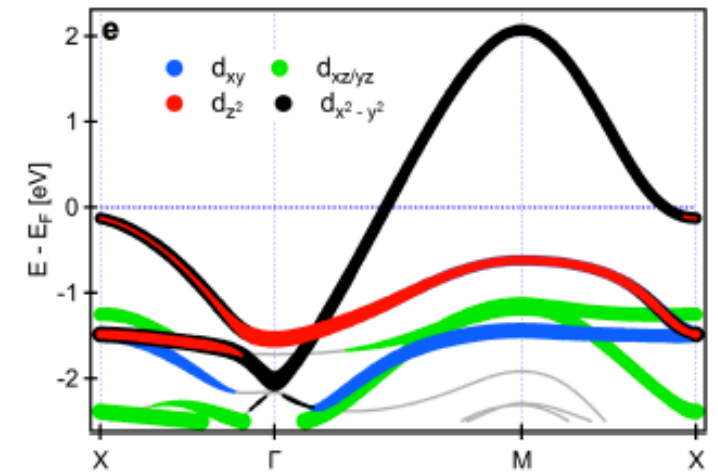
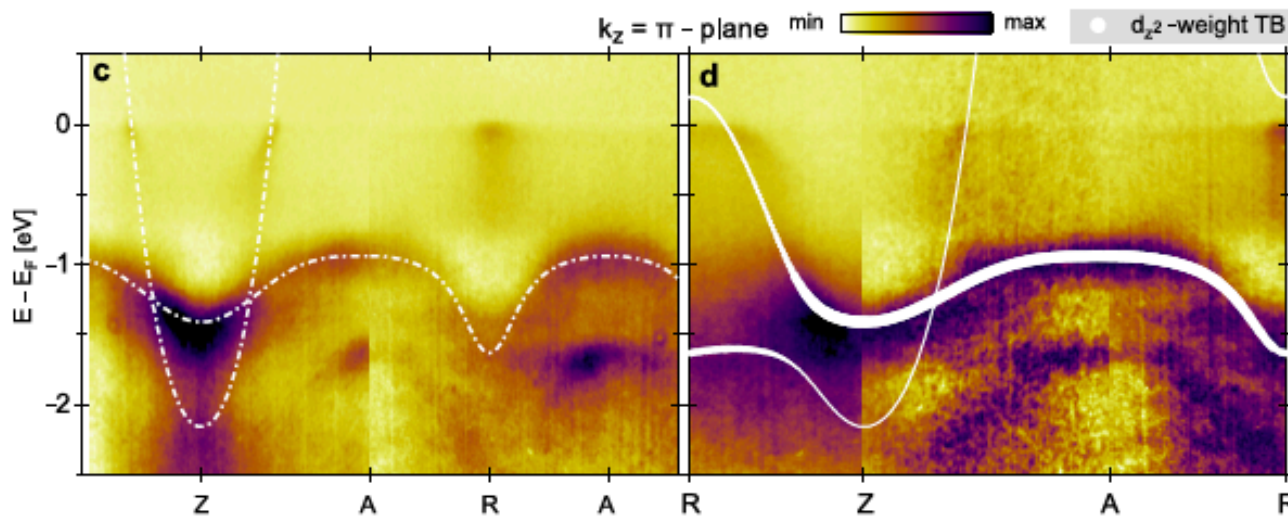
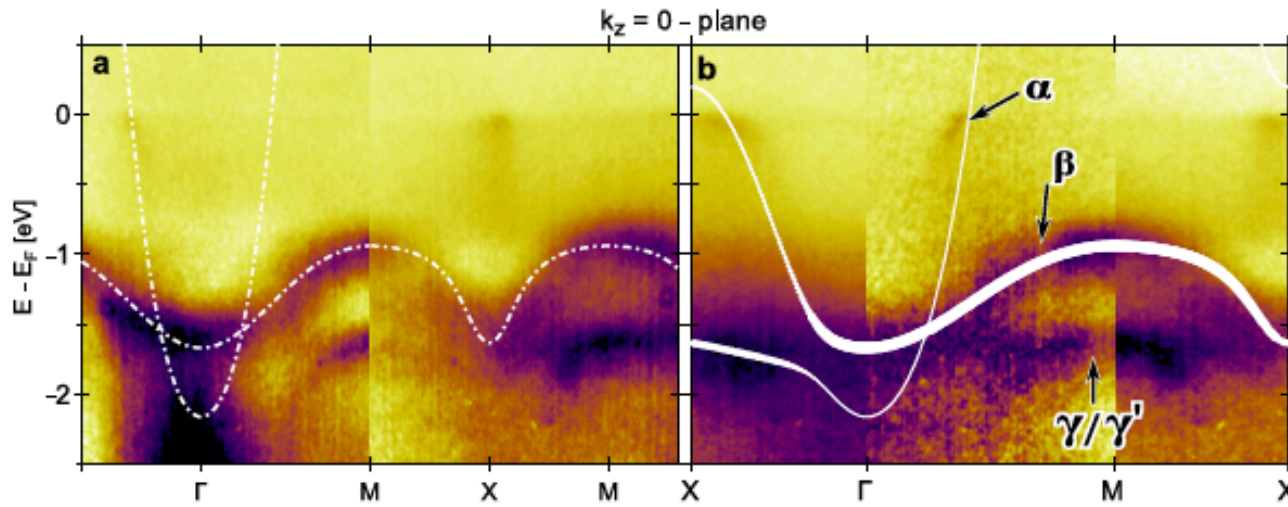
Not-Even



Even

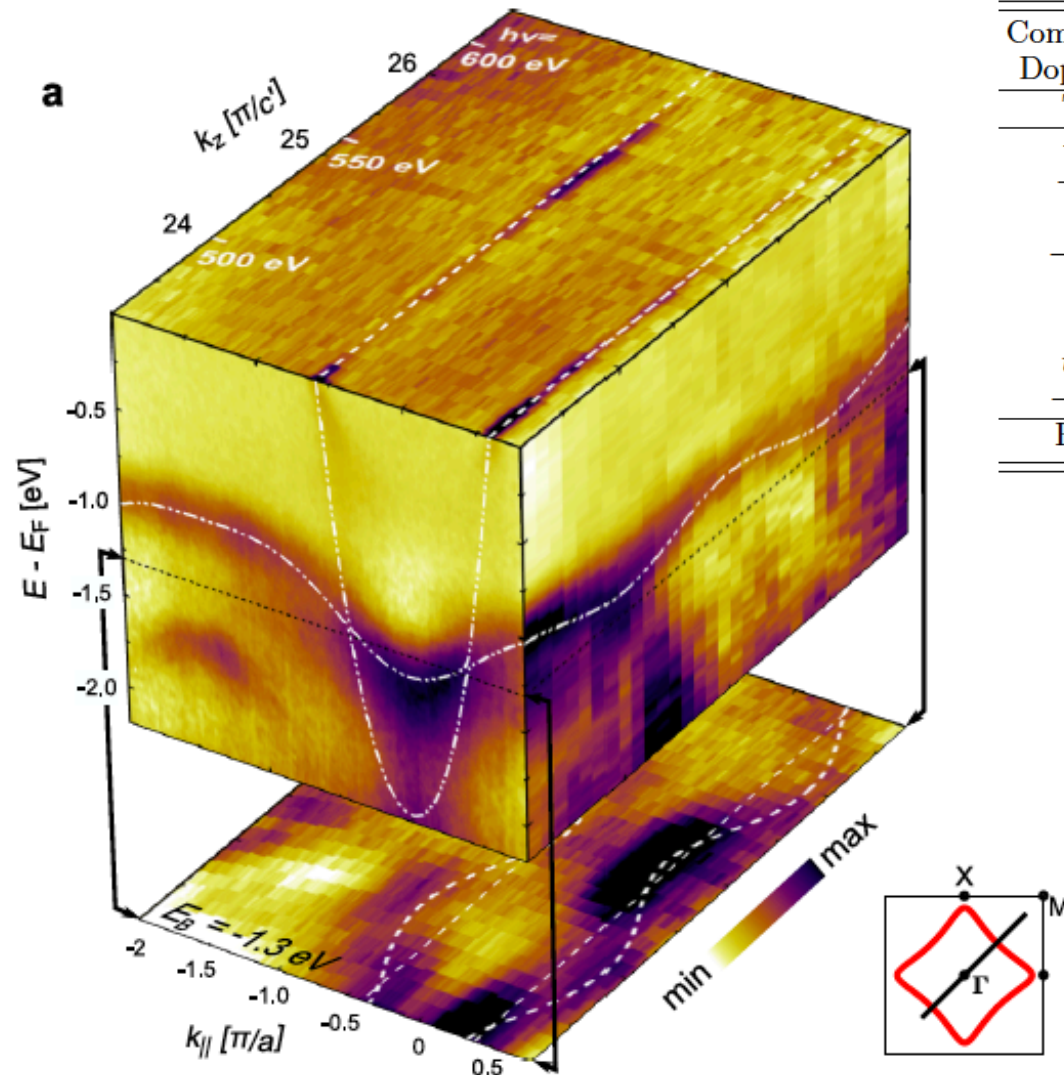


k_z -dependence



Synchrotron:
Photon - energies

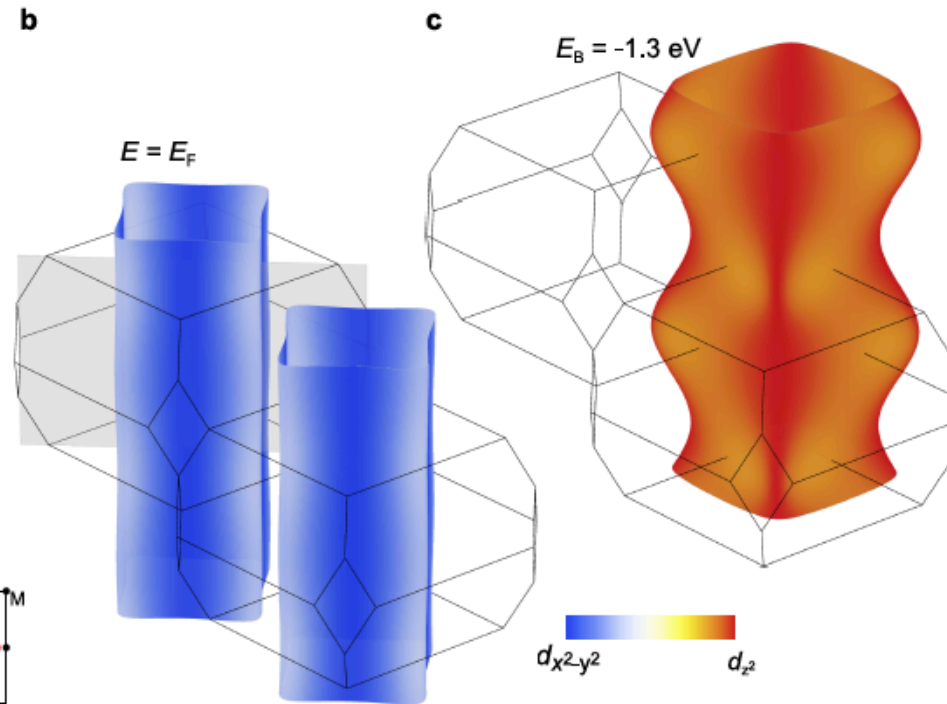
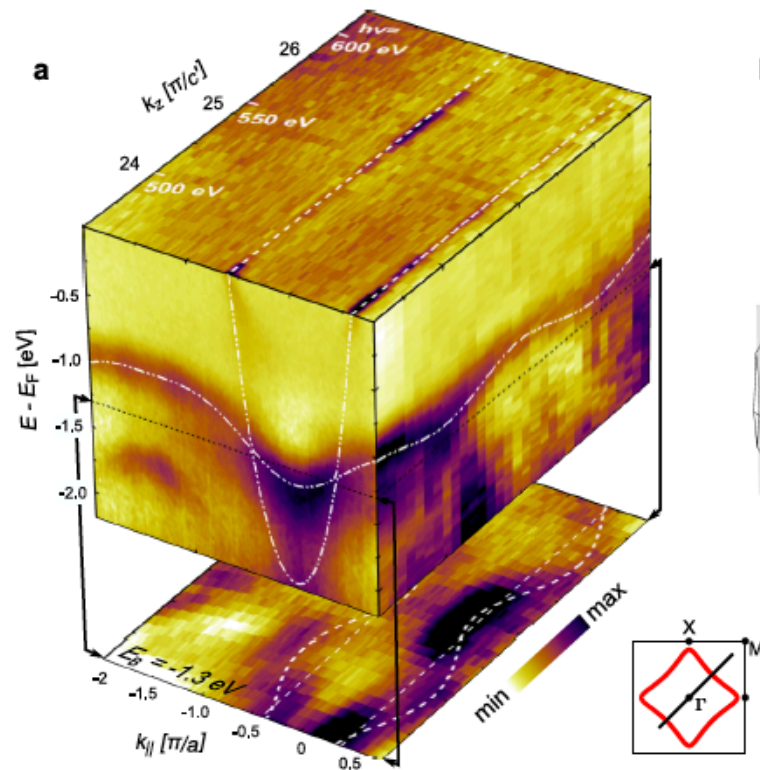
Tight – binding model



Compound	LSCO	Hg1201	Tl2201	LSCO
Doping p	0.22	0.16	0.26	0.23
Tight Binding Parameters in units of $t_{\alpha} = -1.21$ eV				
$-\mu$	0.88	1.27	1.35	0.96
$-t'_{\alpha}$	0.13	0.47	0.42	0.32
t''_{α}	0.065	0.02	0.02	0.0
$-t_{\alpha\beta}$	0	0	0	0.175
t_{β}	-	-	-	0.062
t'_{β}	-	-	-	0.017
$t_{\beta z}$	-	-	-	0.017
$-t'_{\beta z}$	-	-	-	0.0017
Ref.	15	29,30	31,32	This work

Out – of –plane hopping

$t_z \sim 20$ meV (from d_{z^2})



3D Band Structure

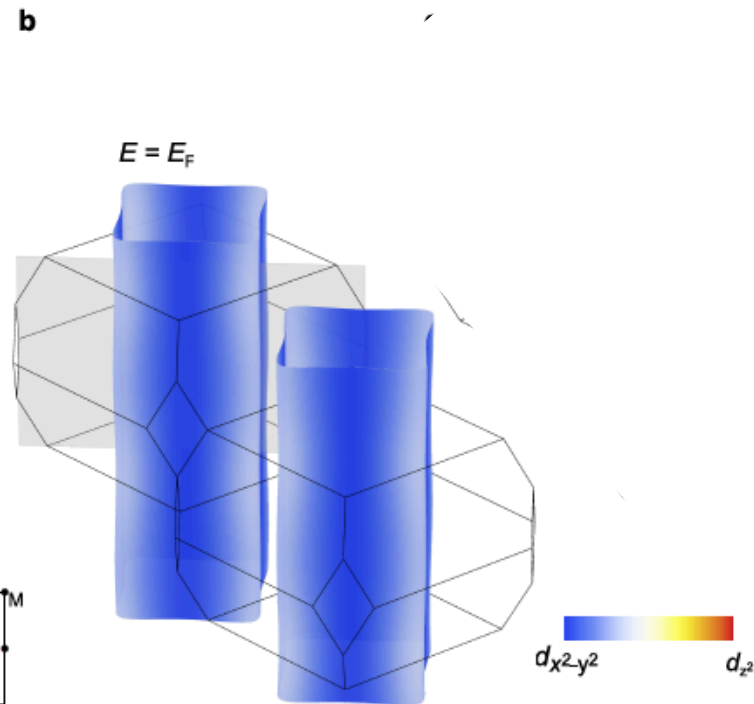
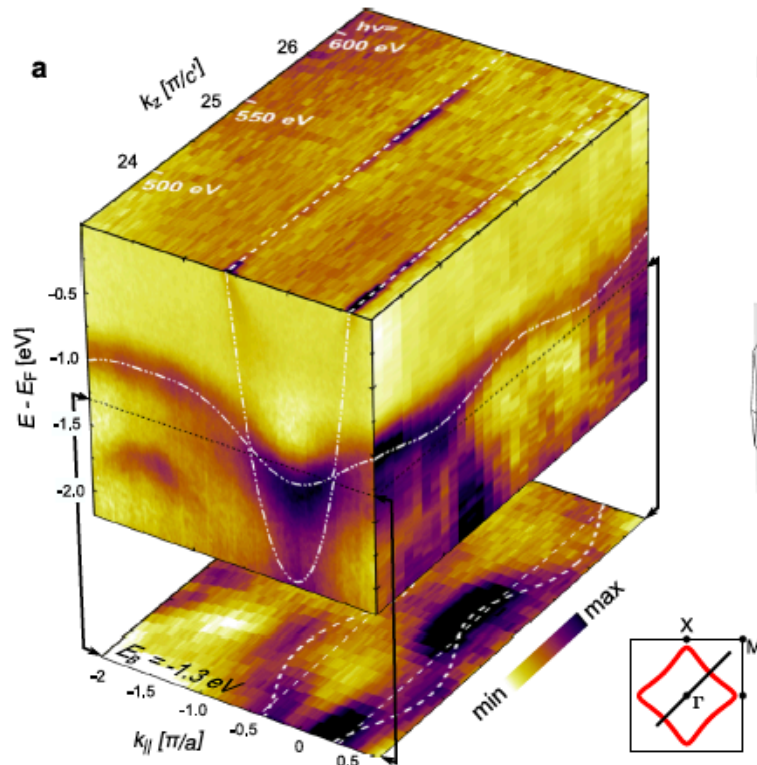
Tight-Binding model

Implications for superconductivity

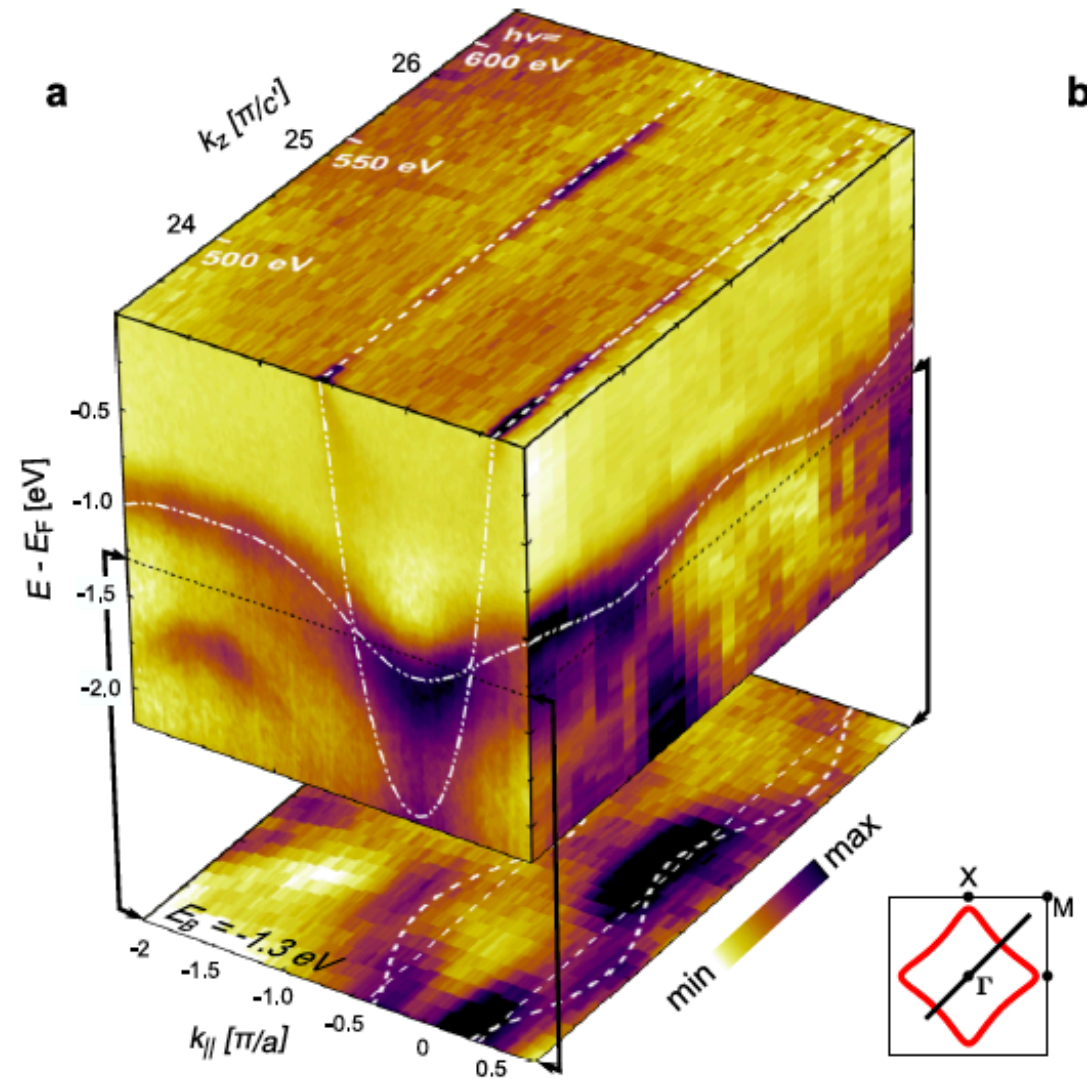
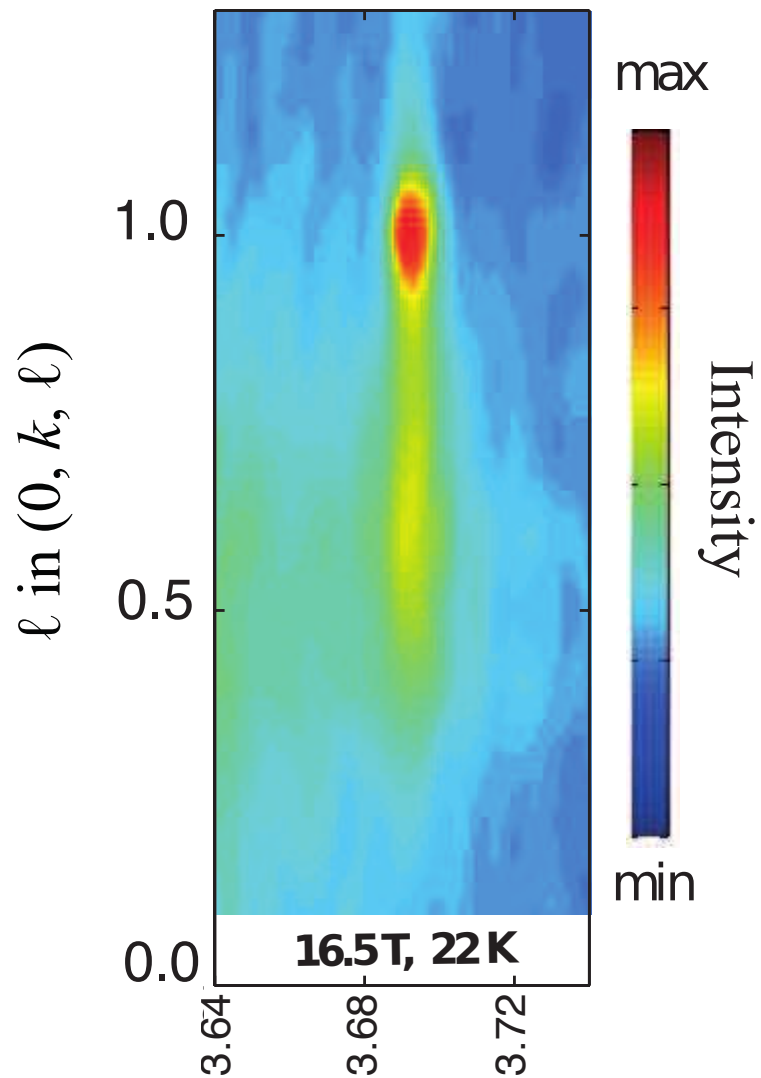
Restraining
Superconductivity



Fermi surface
Hybridization



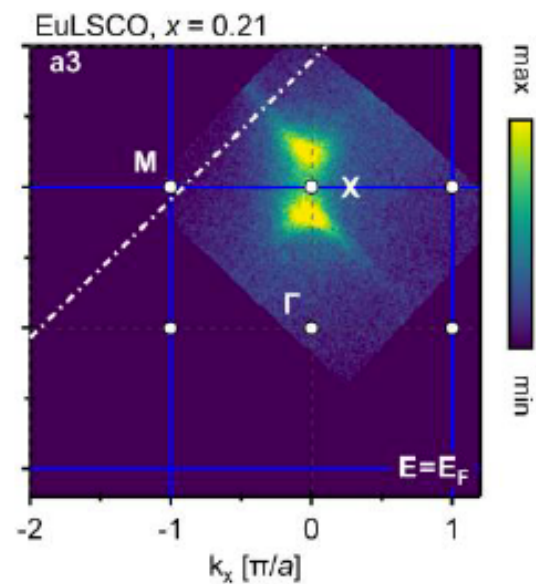
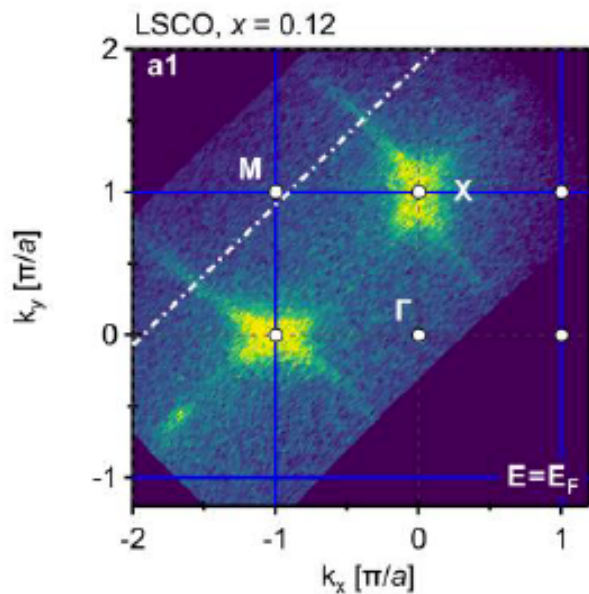
Summary



C. Matt *et al.*,
arXiv:1707.08491v1

Doping and crystal structure variation

LTO



LTT

