What's Up with the Cuprates?

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AJL@80 – March 30, 2018


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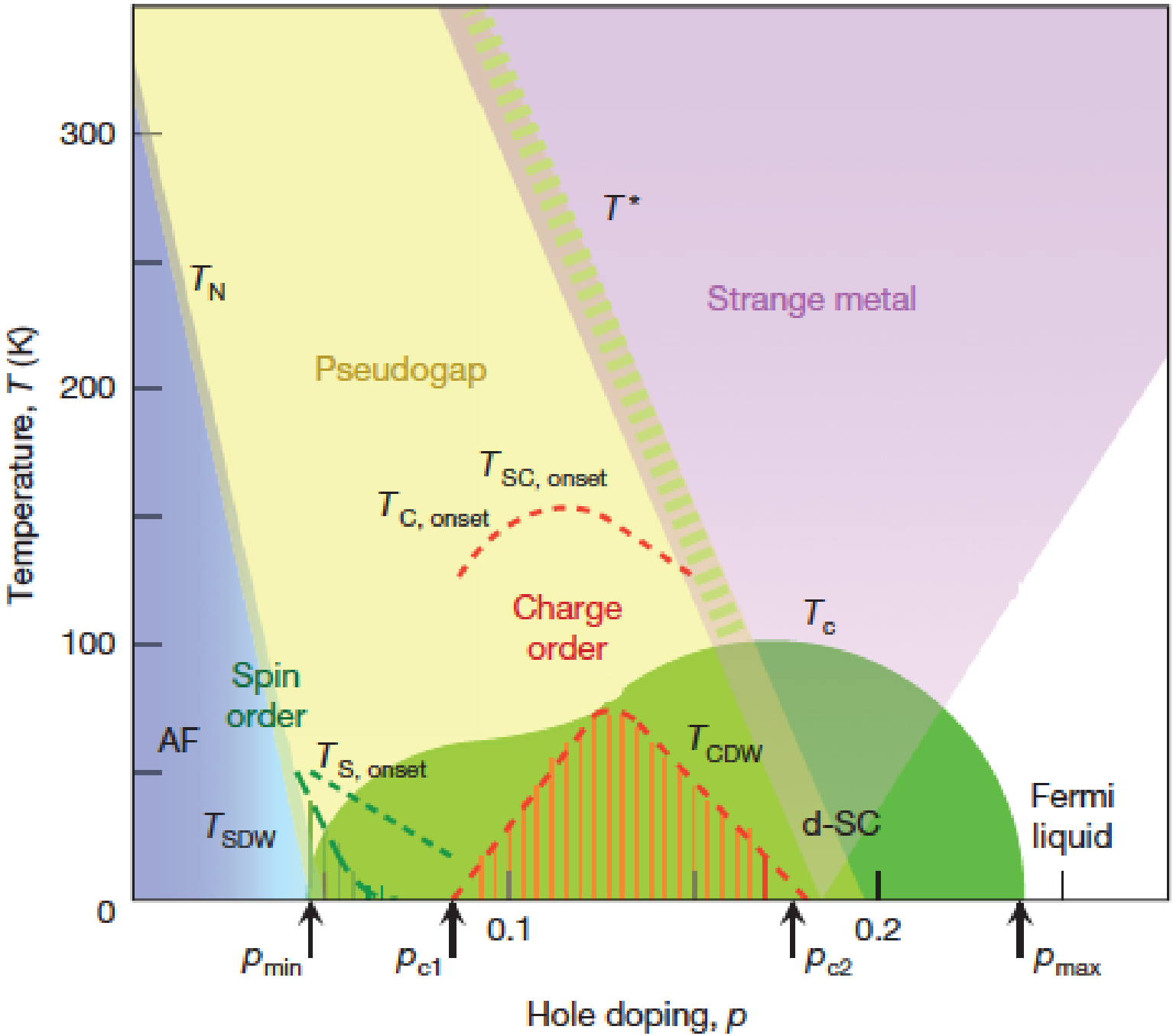
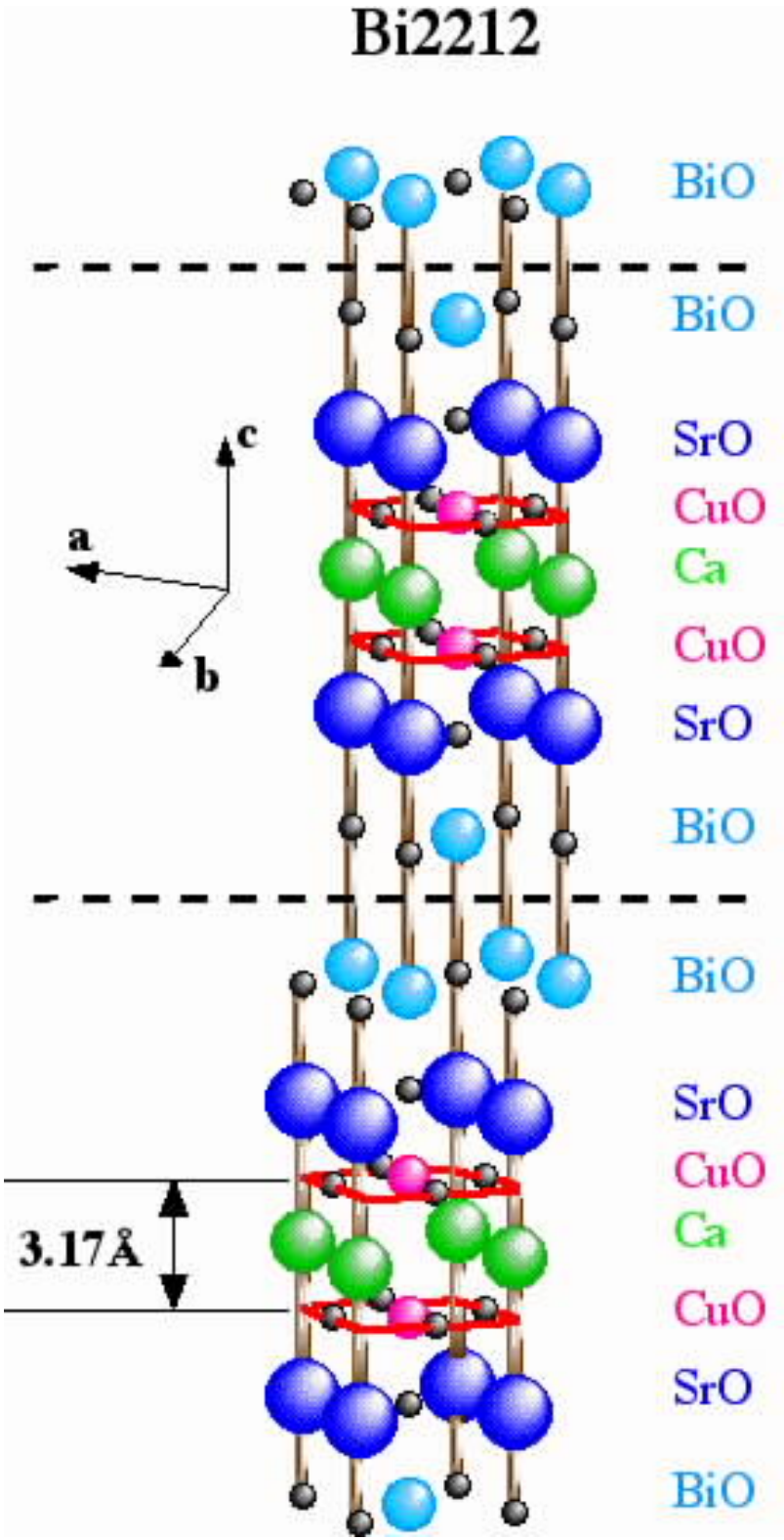
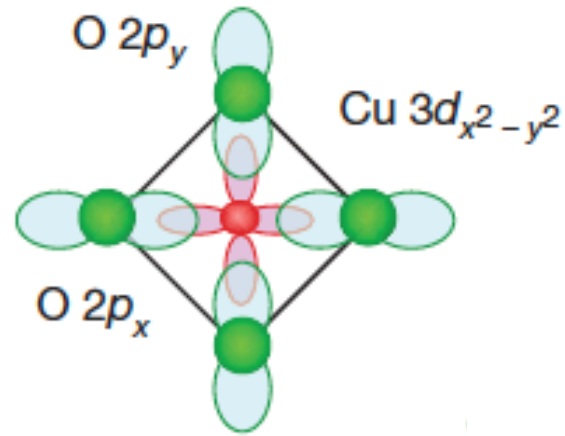
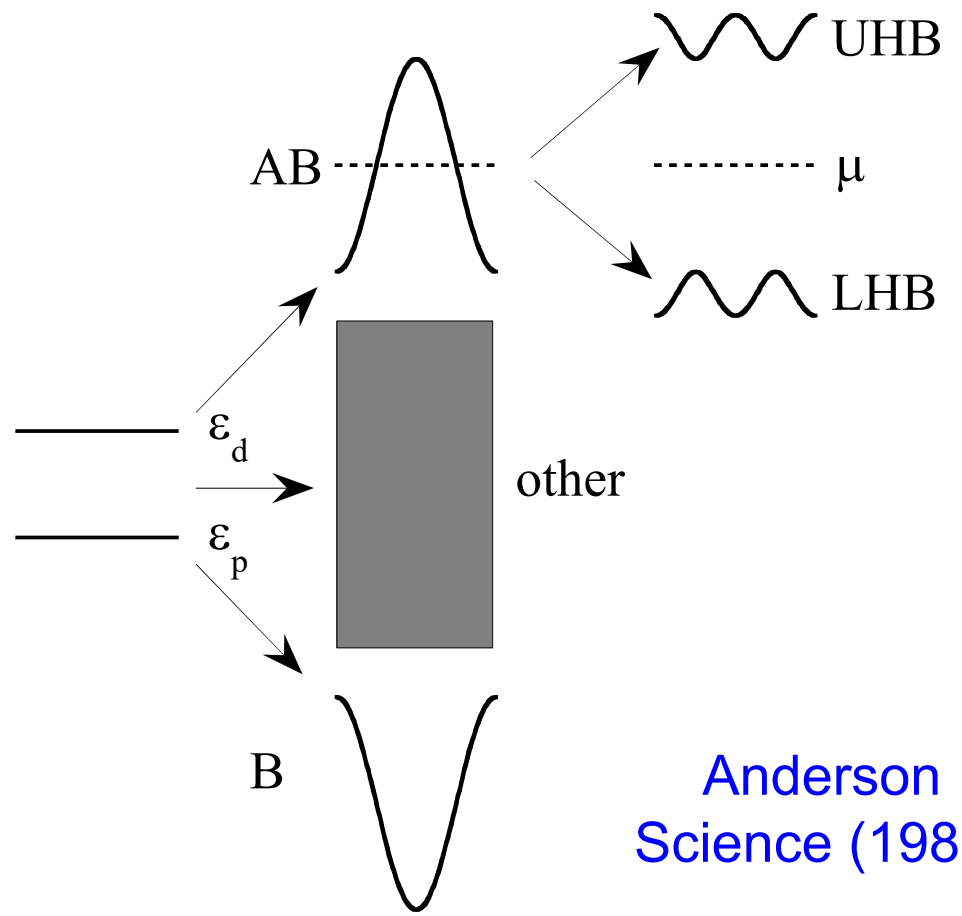


Keimer *et al.*, Nature (2015)

Electronic Structure of Cuprates

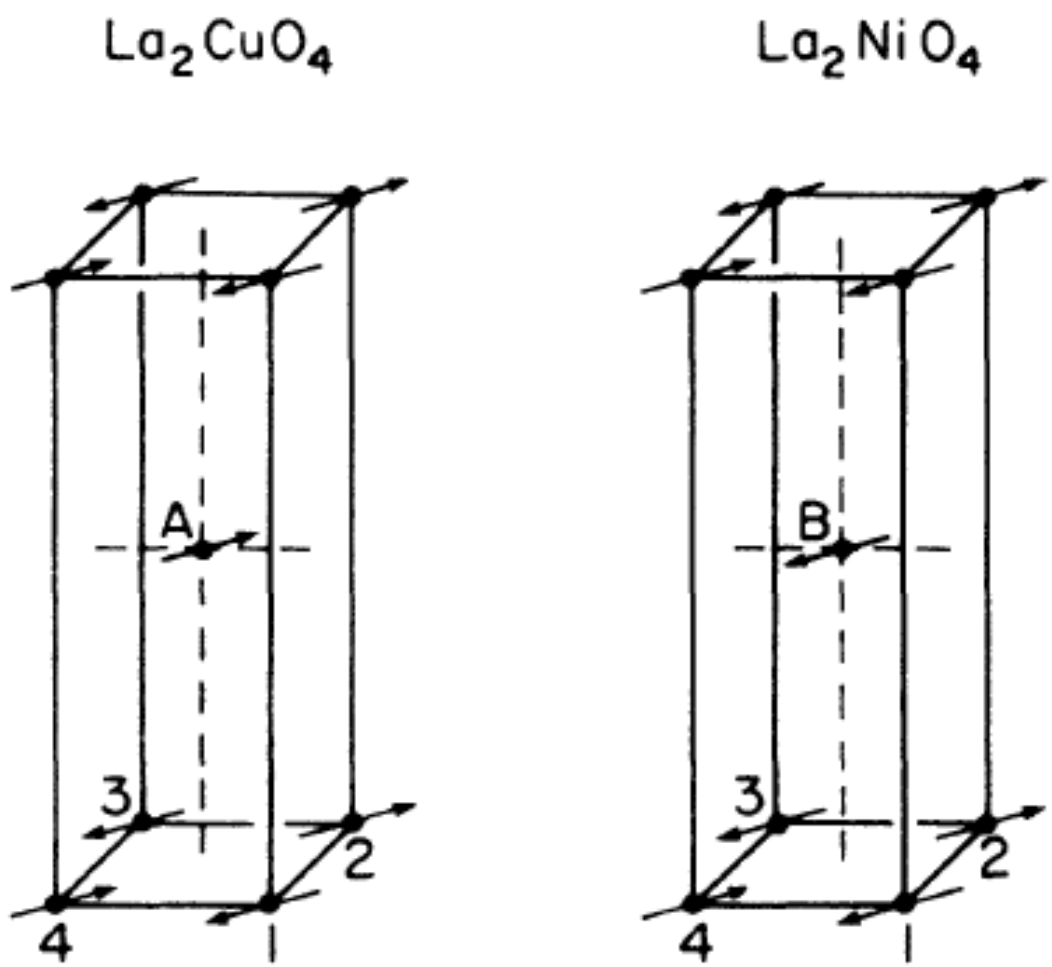






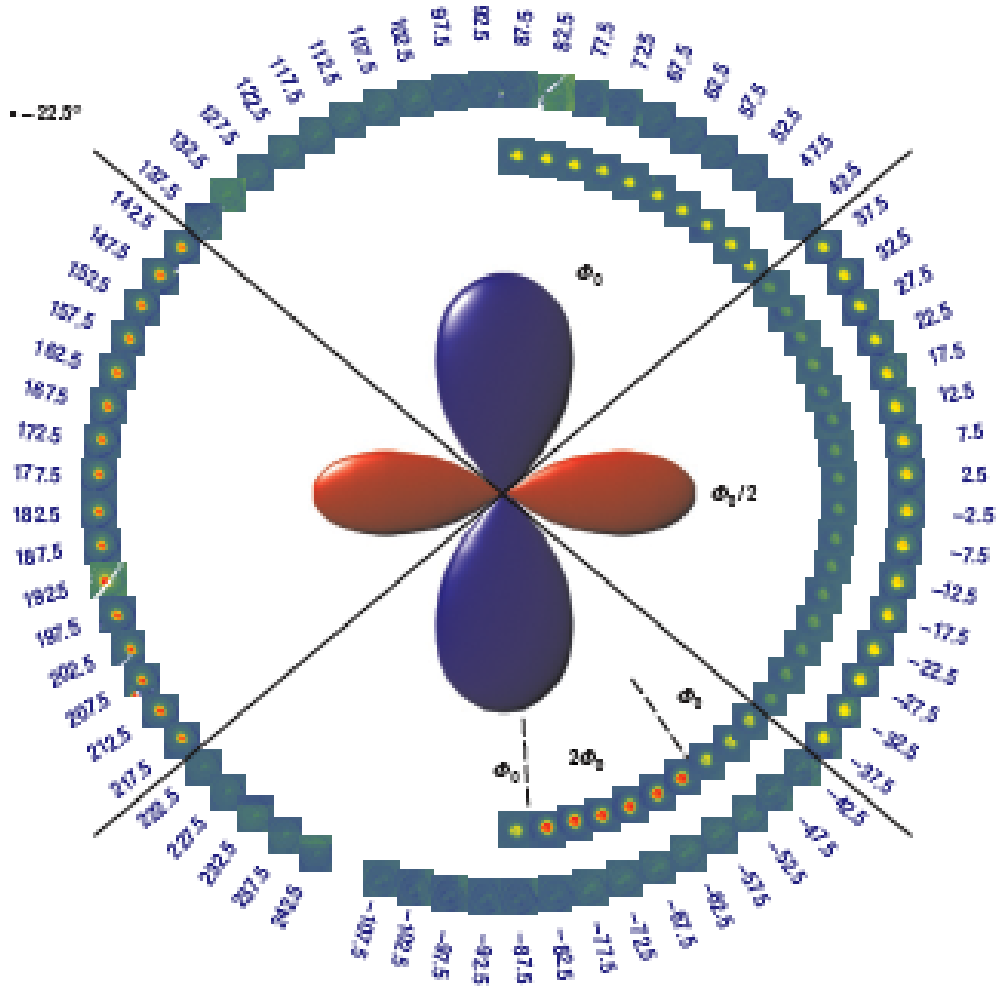
Anderson
Science (1987)

The Undoped Phase is a Neel antiferromagnet



Vaknin *et al.*, PRB (1990)

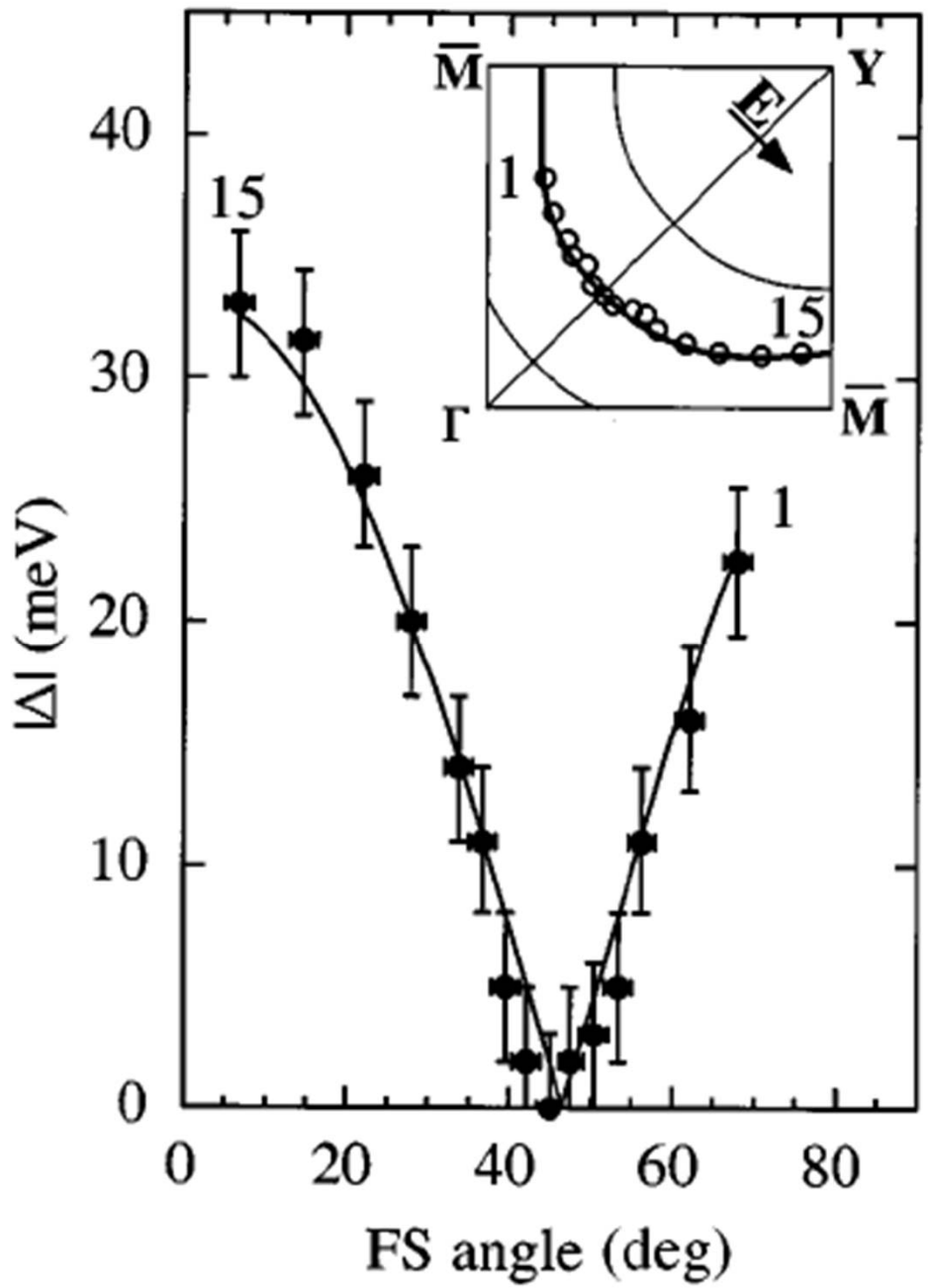
d-wave pairing revealed by phase sensitive tunneling
(Buckley Prize –van Harlingen, Ginsberg, Kirtley, Tsuei – 1998)
(with the experiment suggested by Tony)



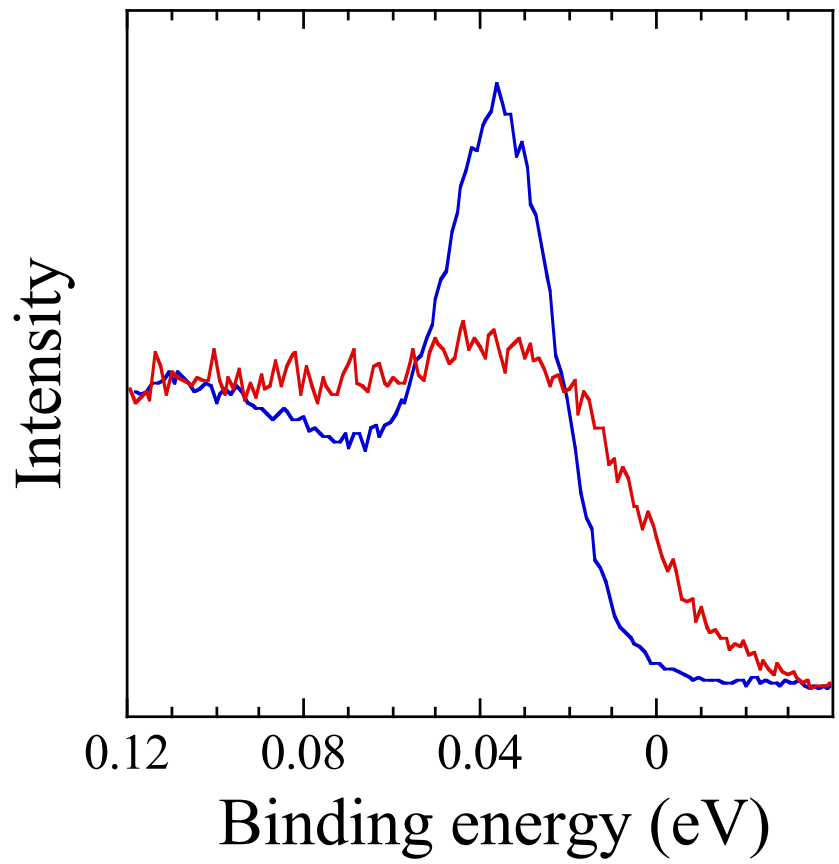
Kirtley *et al.*, Nature Physics (2006)

d-wave pairs involve electrons on near neighbor copper sites (Buckley Prize – Campuzano, Johnson, Shen – 2011)

$\Delta_k = \cos(k_x a) - \cos(k_y a)$

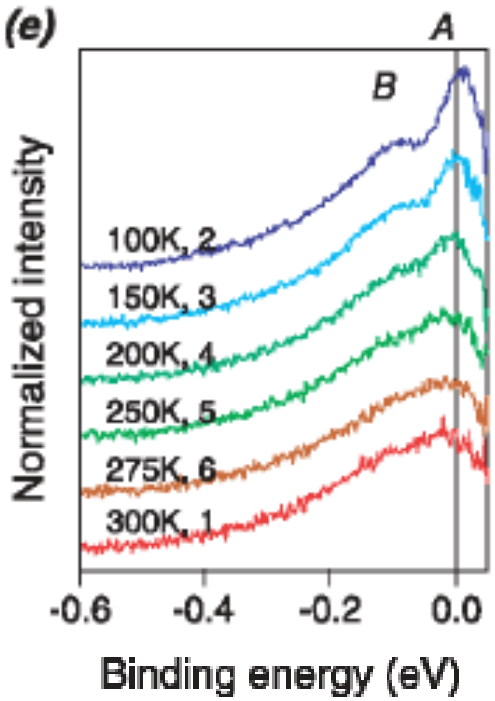


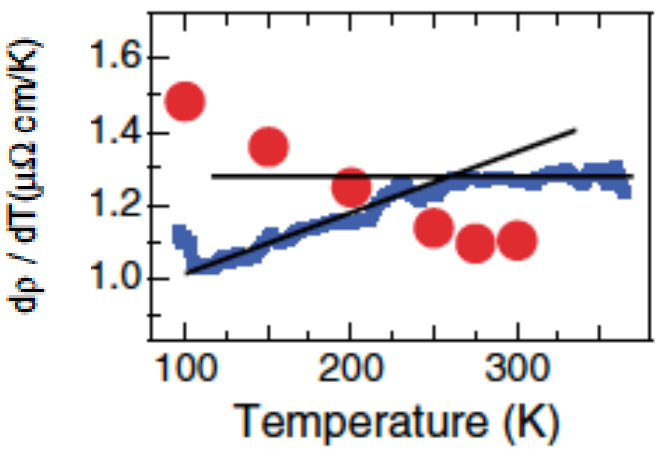
Incoherent normal state
Coherent superconductor

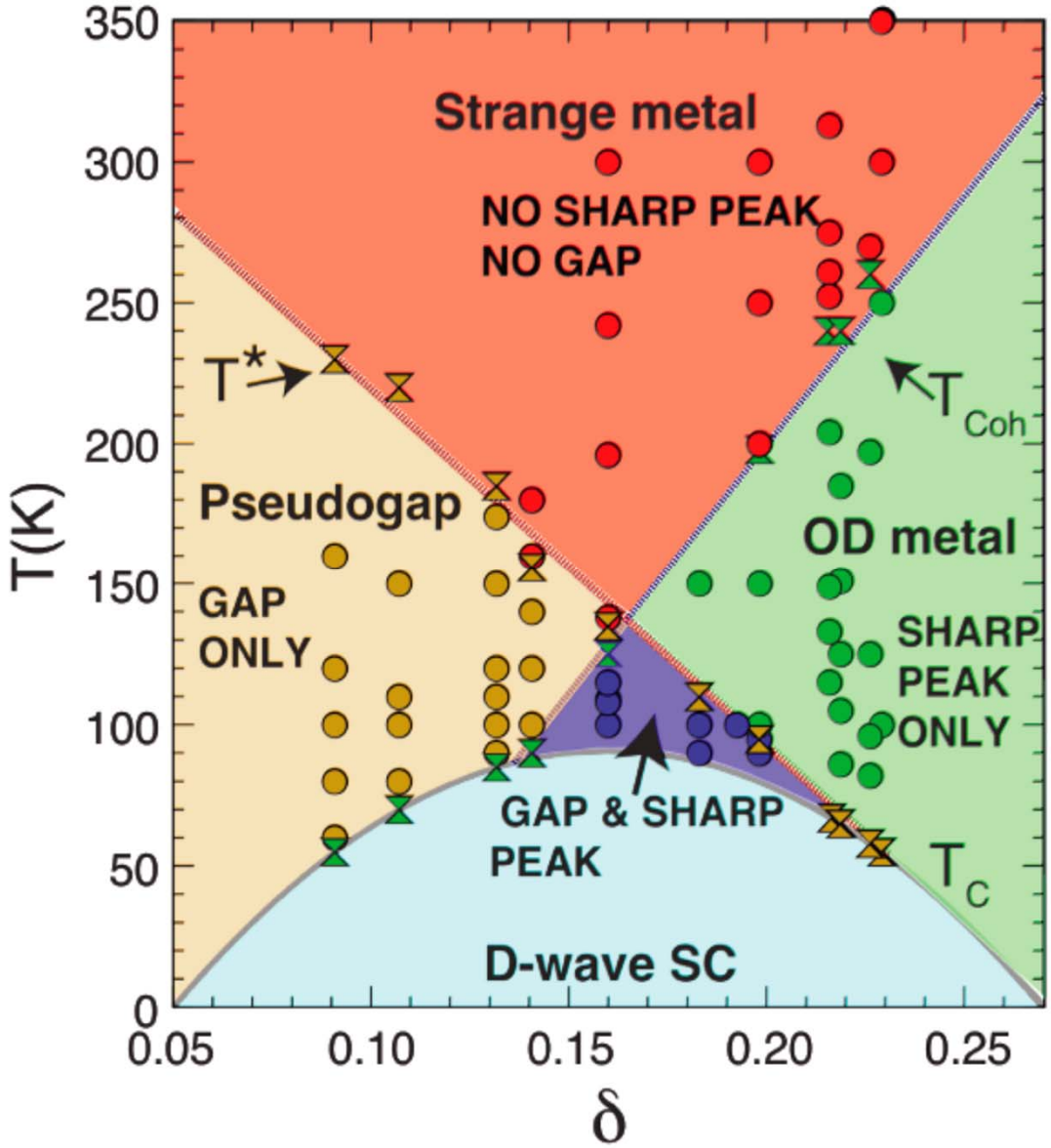


Ding *et al.*, PRB (1996)
Norman *et al.*, PRL (1997)

Coherent quasiparticles in superconducting and overdoped phases



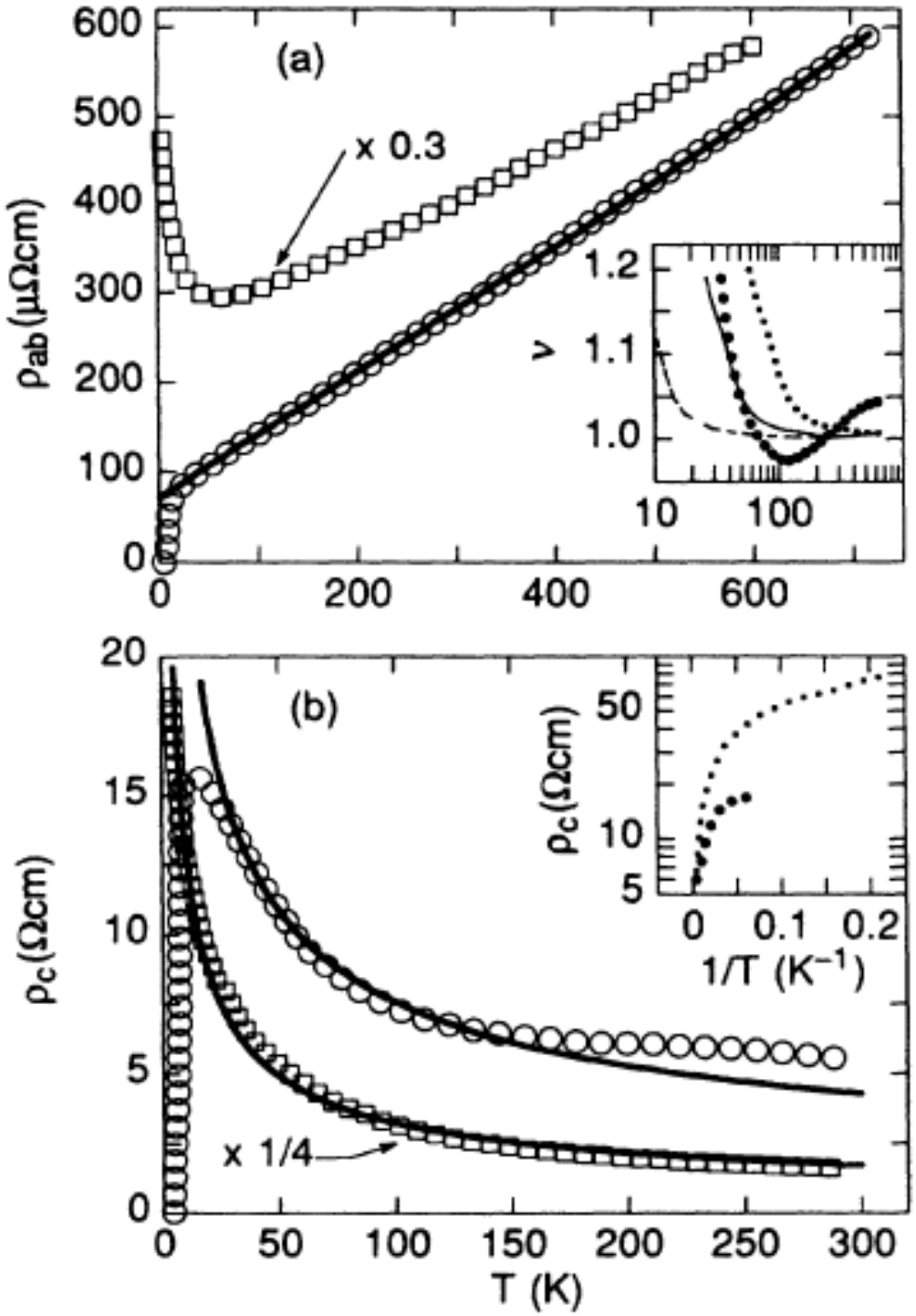




Kaminski *et al.*, PRL (2003)

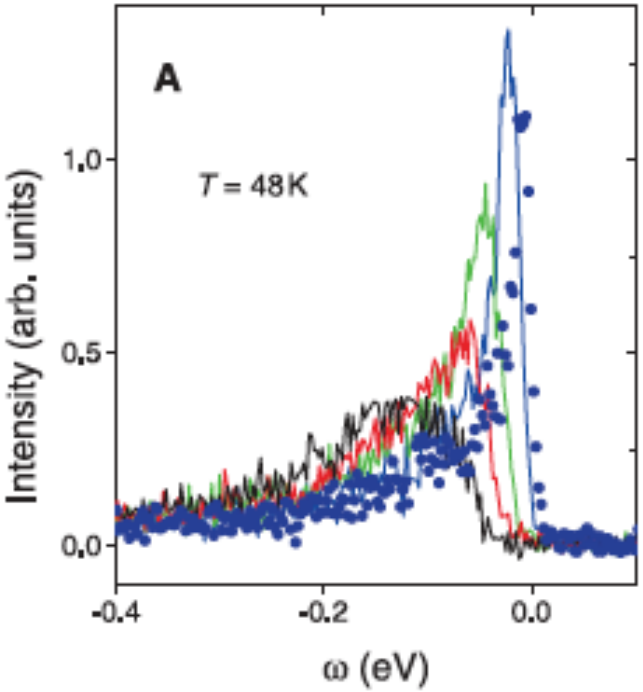
Chatterjee *et al.*, PNAS (2011)

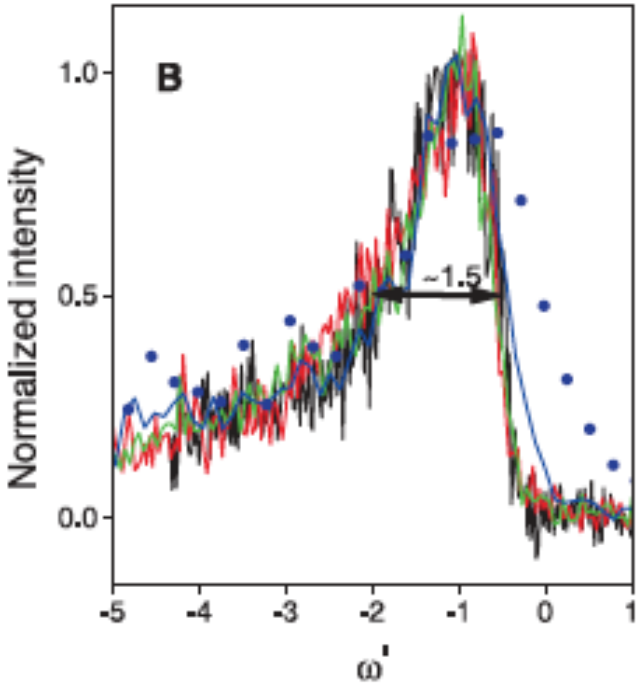
The Strange Metal Phase exhibits linear T resistivity

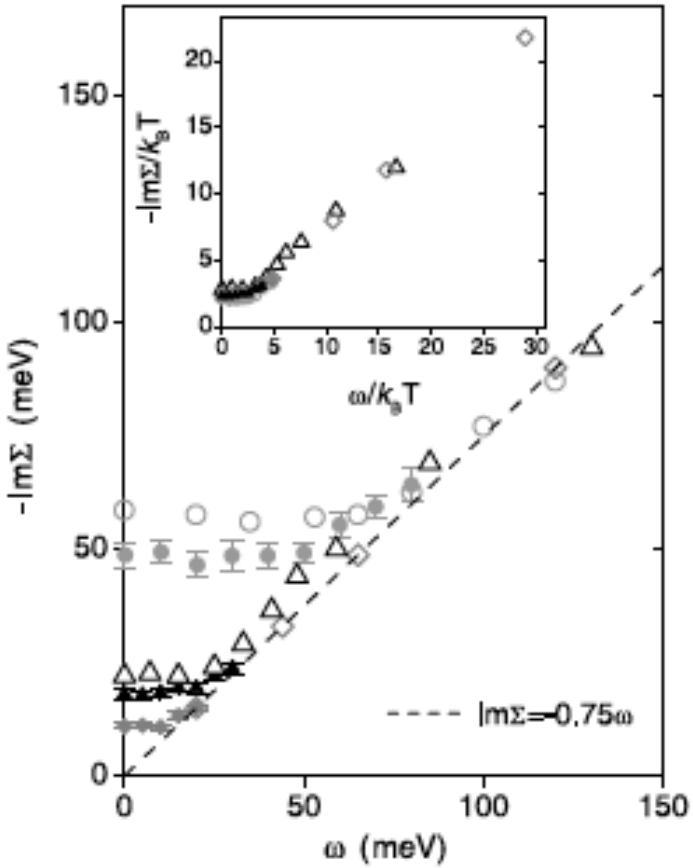


Martin *et al.*, PRB (1990)

This is reflected in the T and ω dependences of ARPES linewidths

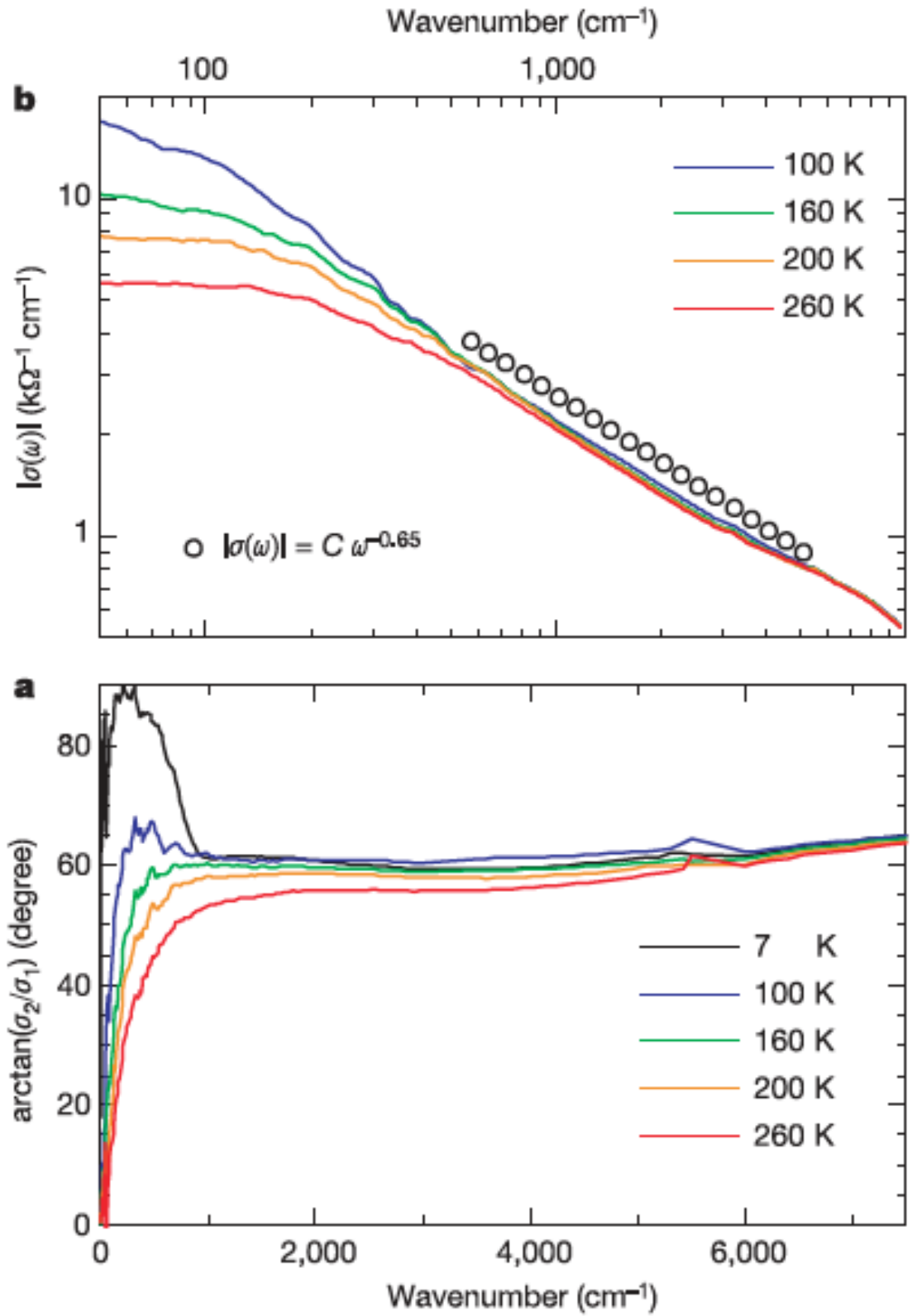




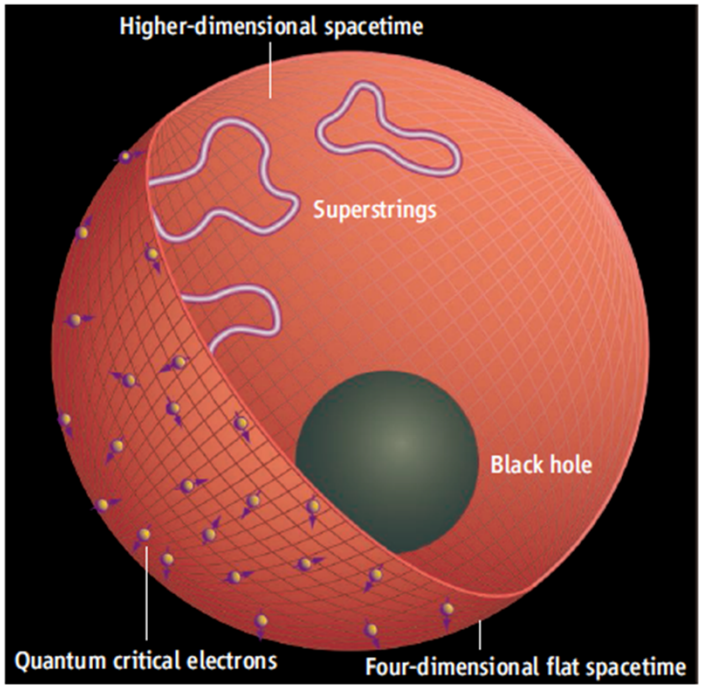


Valla *et al.*, Science (1999)

As well as that of optics data



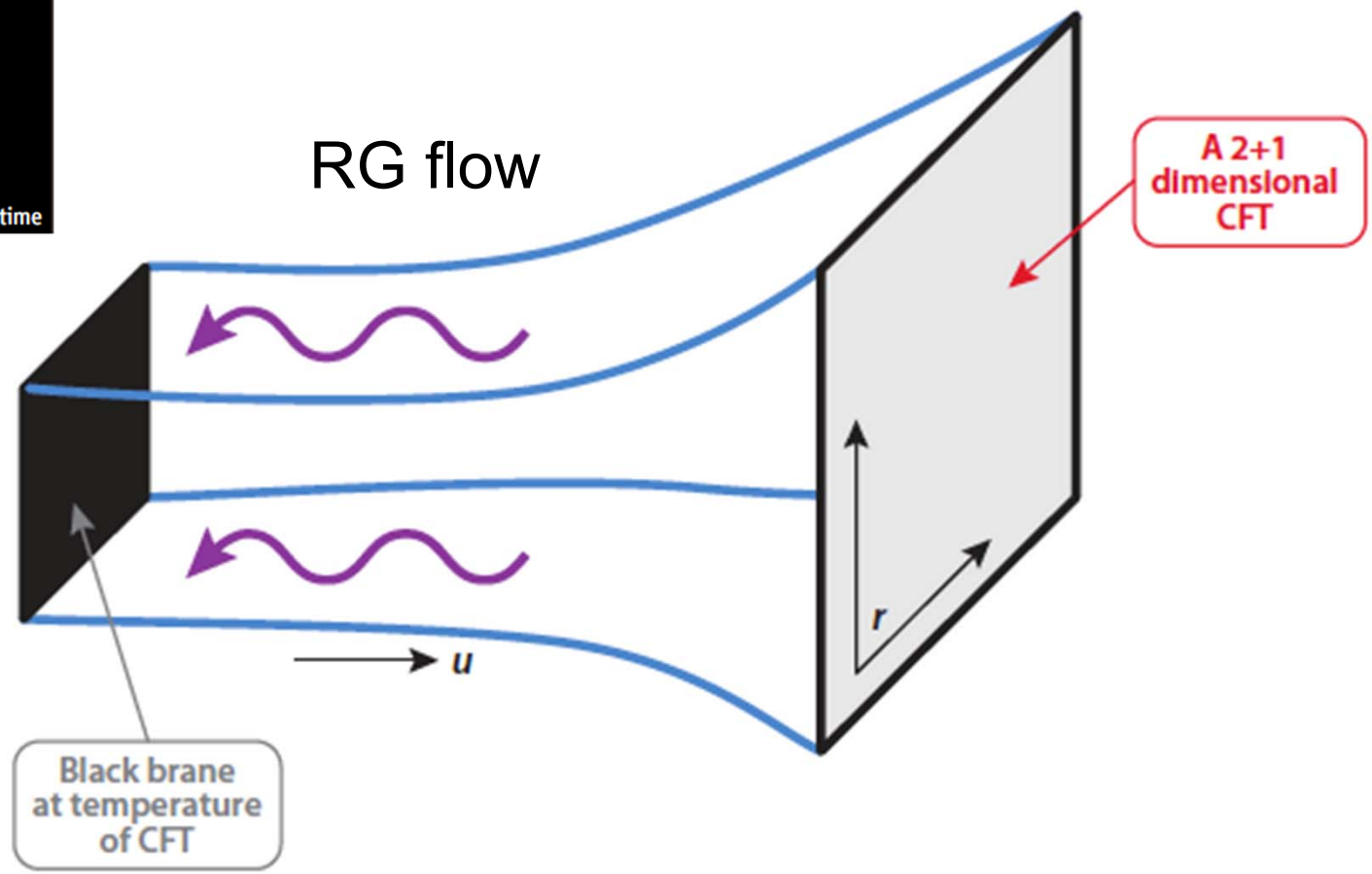
van der Marel *et al.*, Nature (2003)



Holographic Approach – AdS/CFT

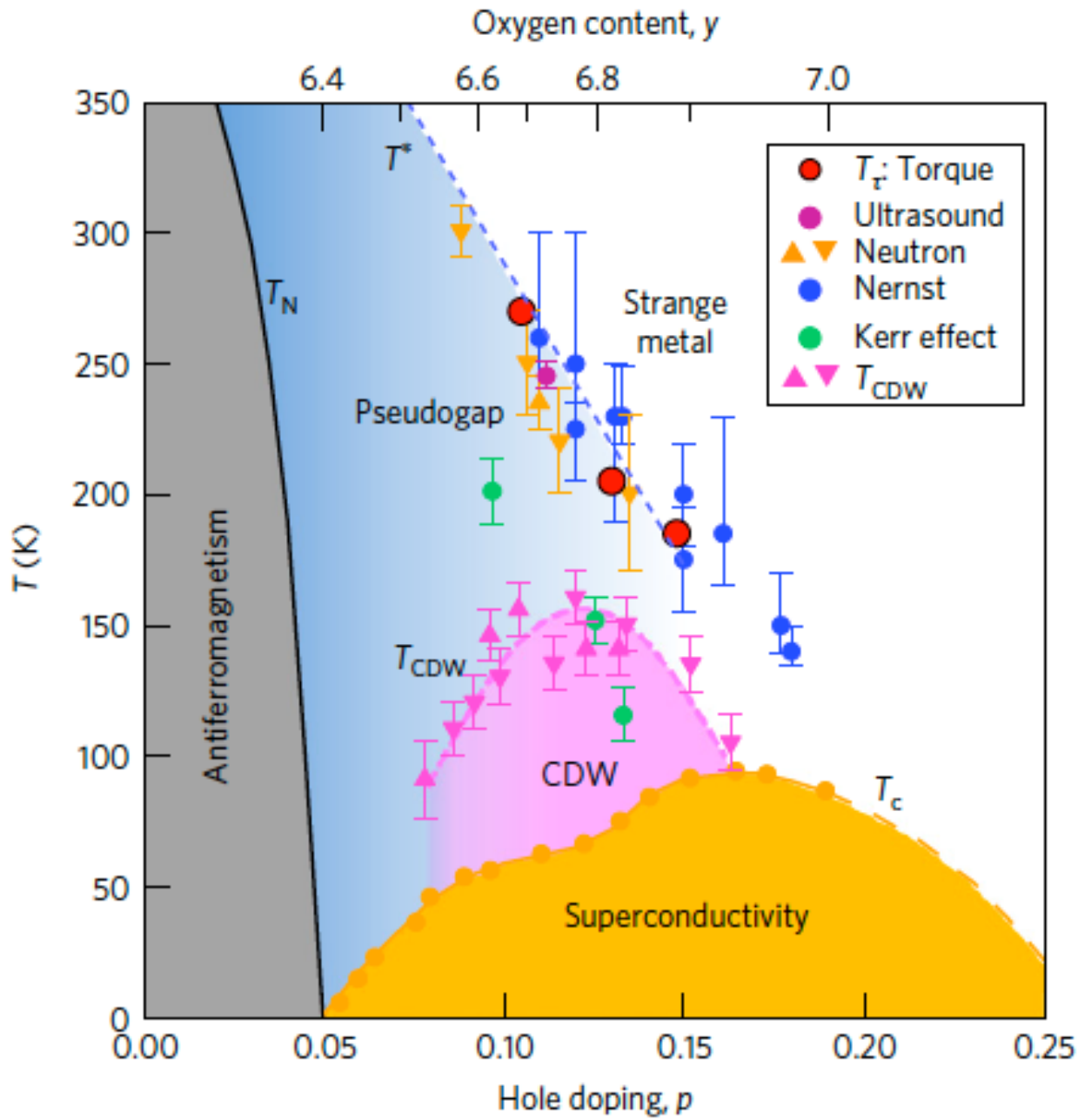
"Planckian" dynamics, $\tau \sim h/2\pi k_B T$

$AdS_2 \rightarrow CFT_1$



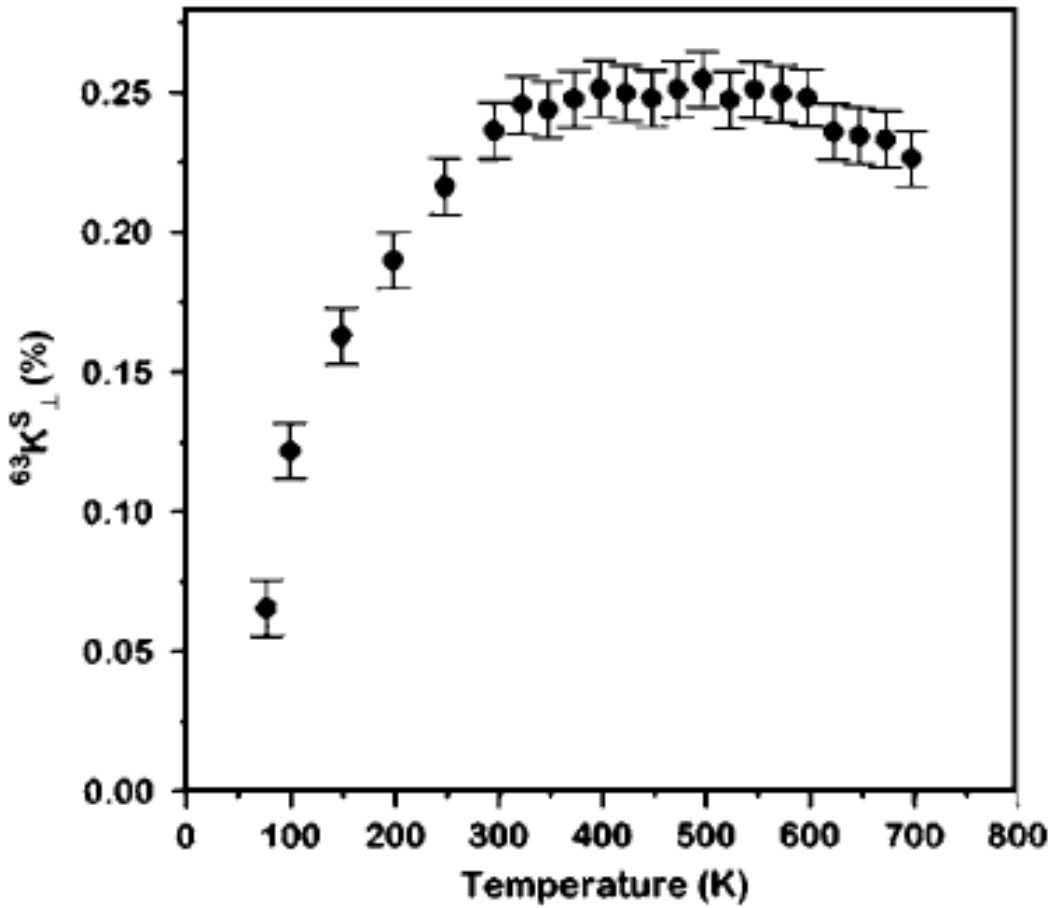
Hartnoll, Science (2008)
Sachdev, Ann. Rev. CMP (2012)
Zaanen *et al.*, Cambridge (2016)

Near T* (pseudogap line), anomalies are seen in various properties



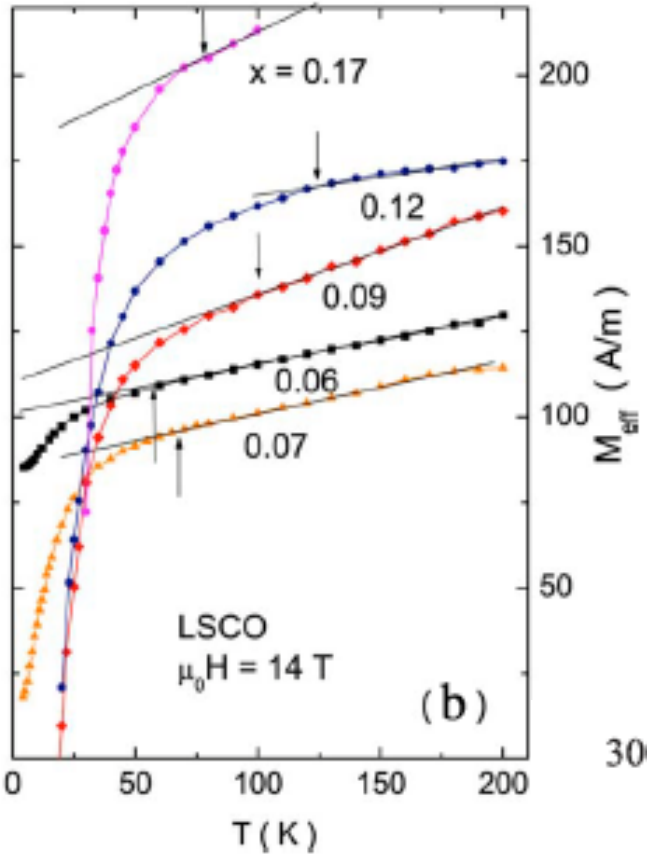
Sato *et al.*, Nature Physics (2017)

Singlet Formation (NMR, bulk susceptibility)

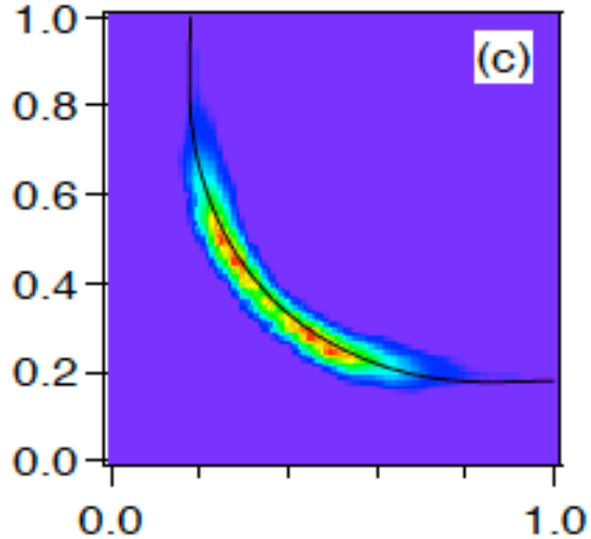


Curro *et al.*, PRB (1997)
Lee *et al.*, RMP (2006)

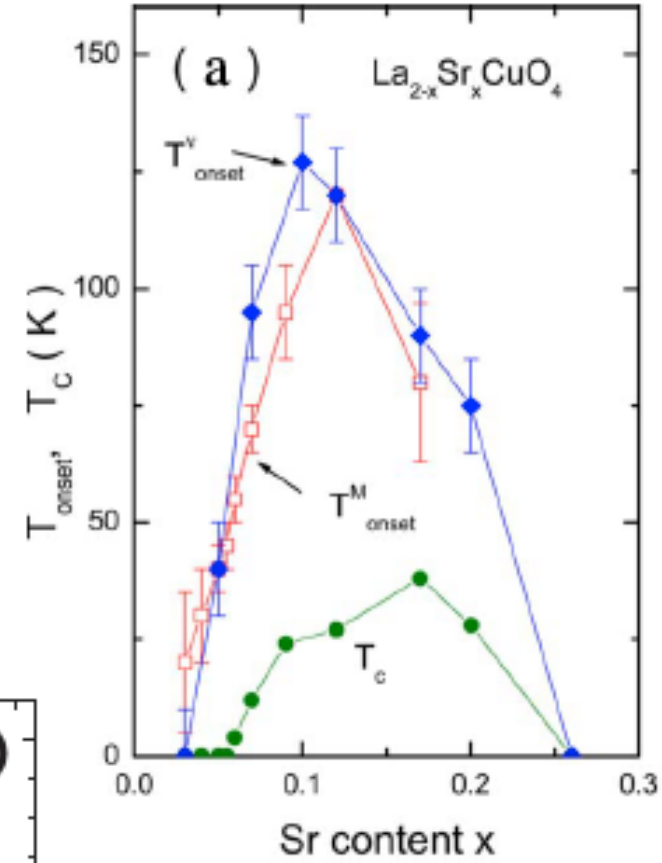
“Pre-formed” Pairs (ARPES, Nernst, diamagnetism, optics, etc.)



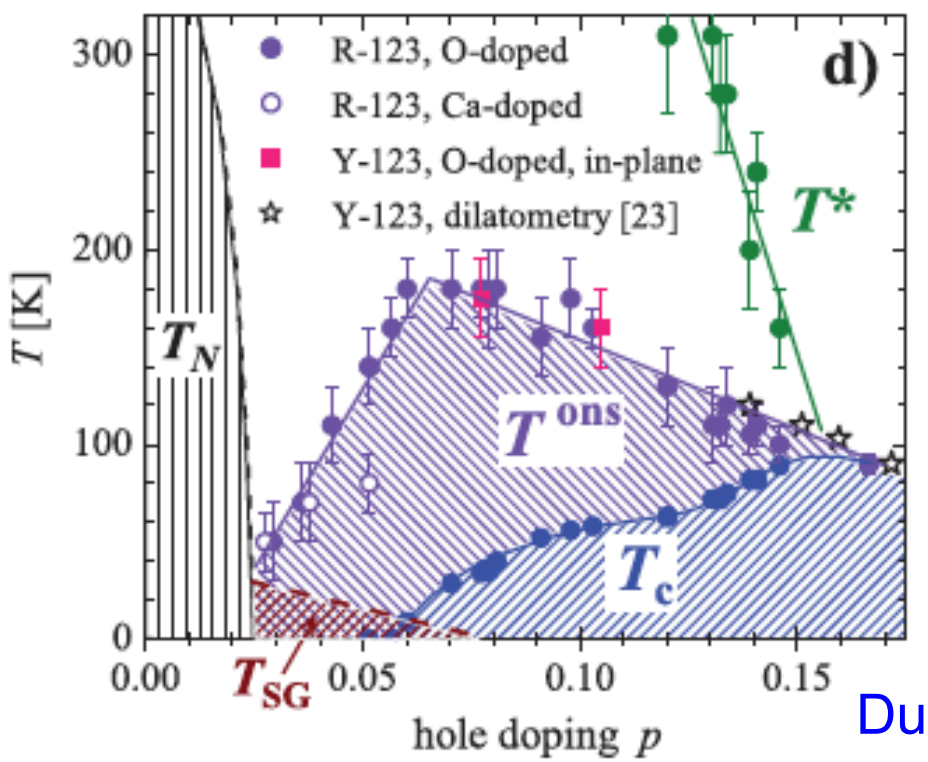
Li *et al*., PRB (2010)



Norman *et al*., PRB (2007)

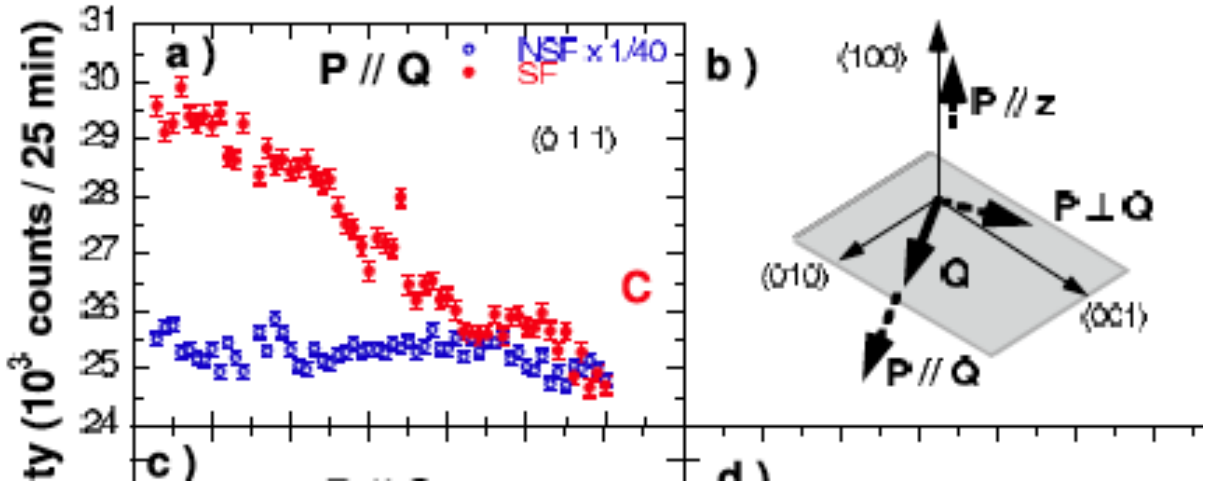


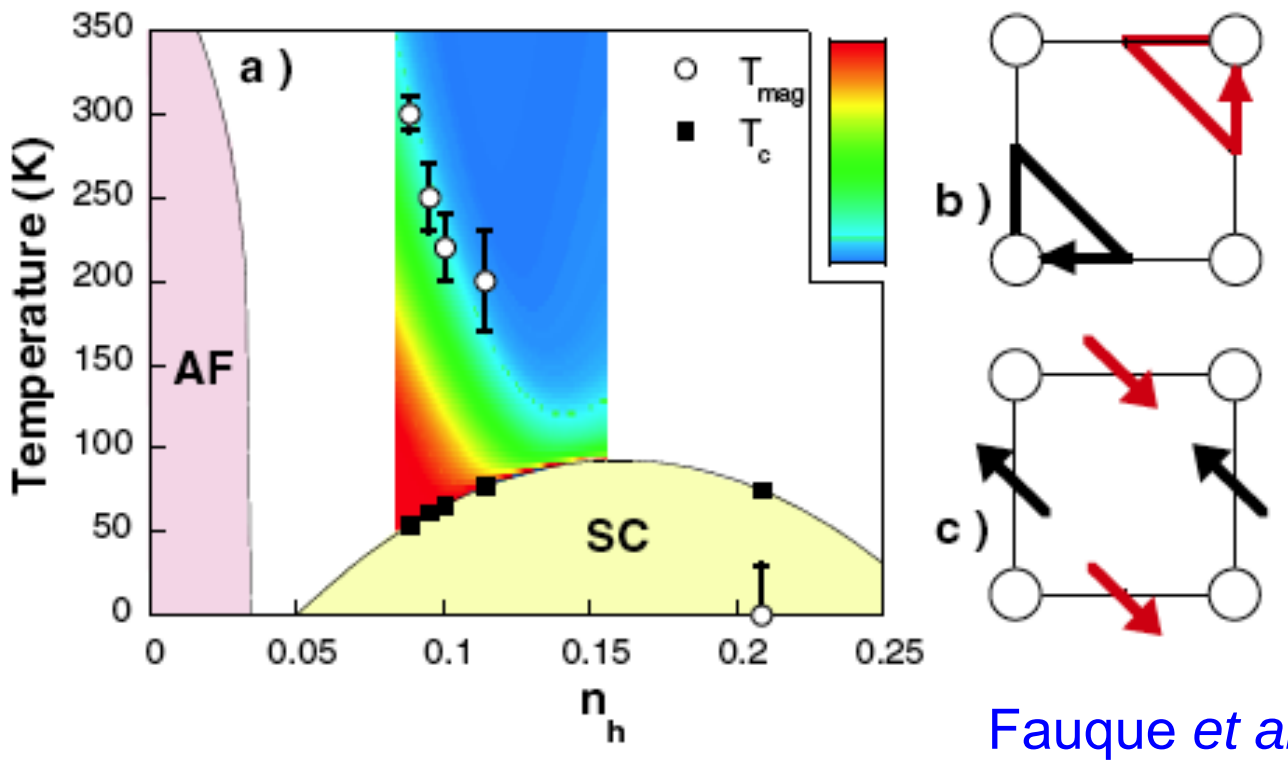
Li *et al*., PRB (2010)



Dubroka *et al*., PRL (2011)

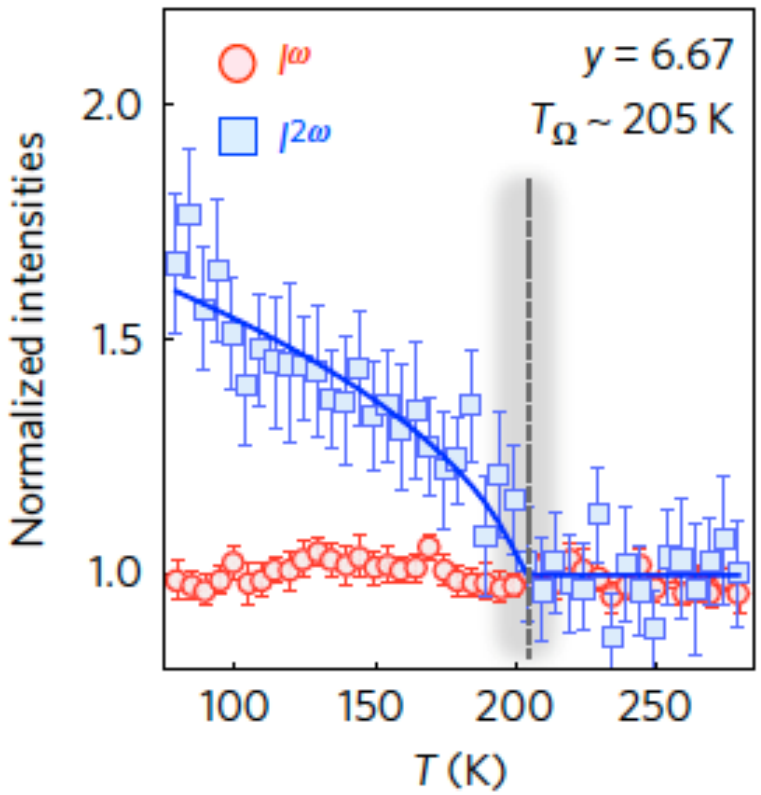
Loop Current Order (Varma)

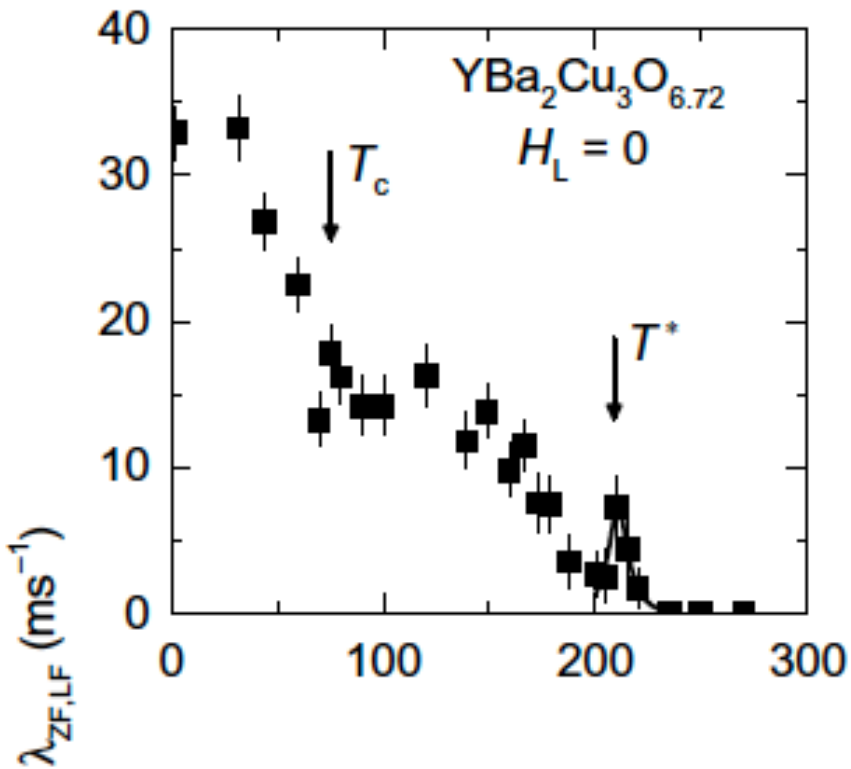




Fauque *et al*., PRL (2006)

Recent corroborating evidence (SHG, μSR)

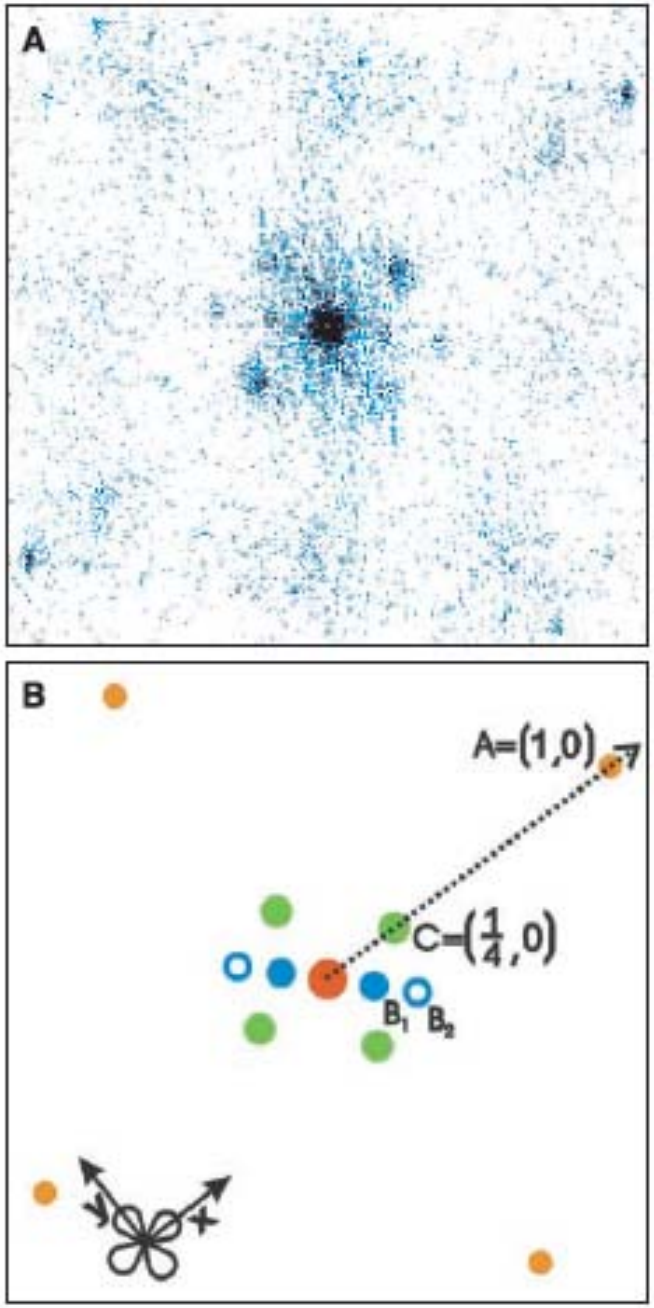


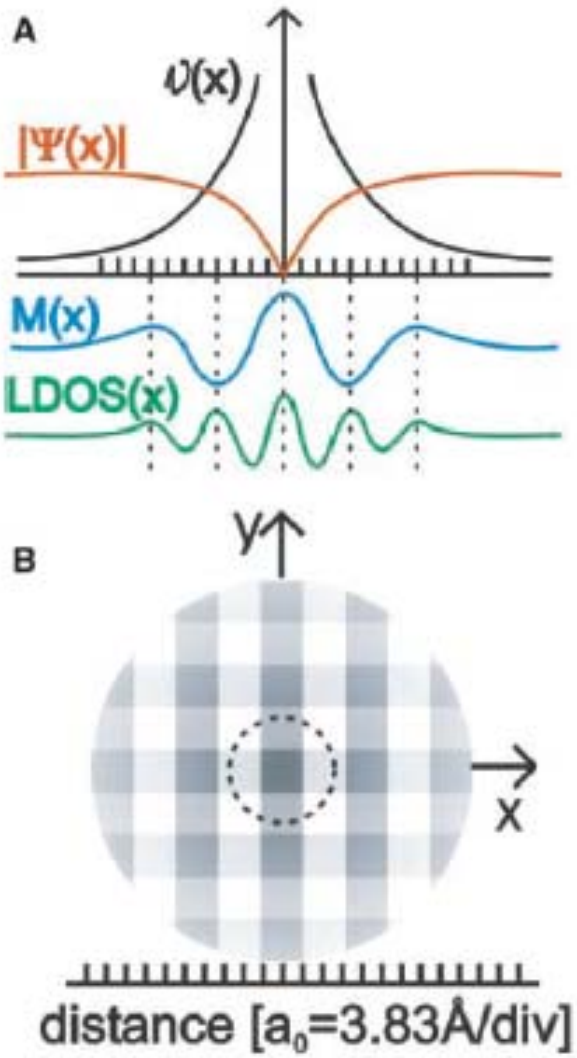


Zhao *et al*., Nature Physics (2016)

Zhang *et al*., Sci. Adv. (2018)

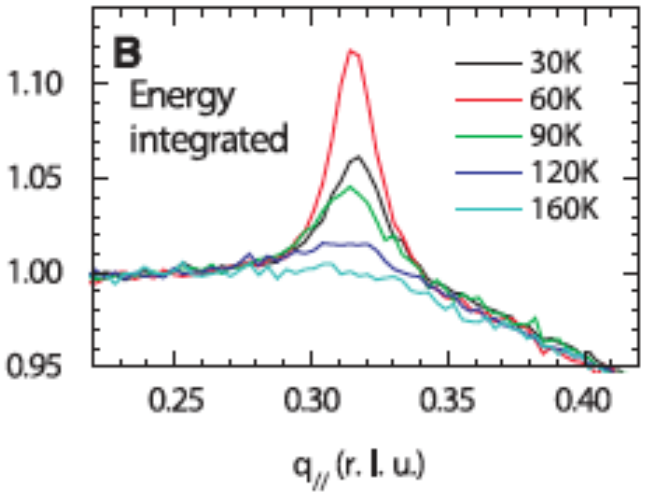
Charge order in vortex “halos” of Bi2212 (STM)

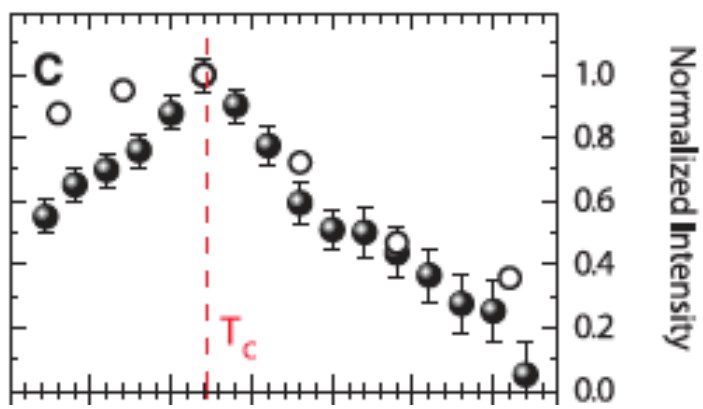


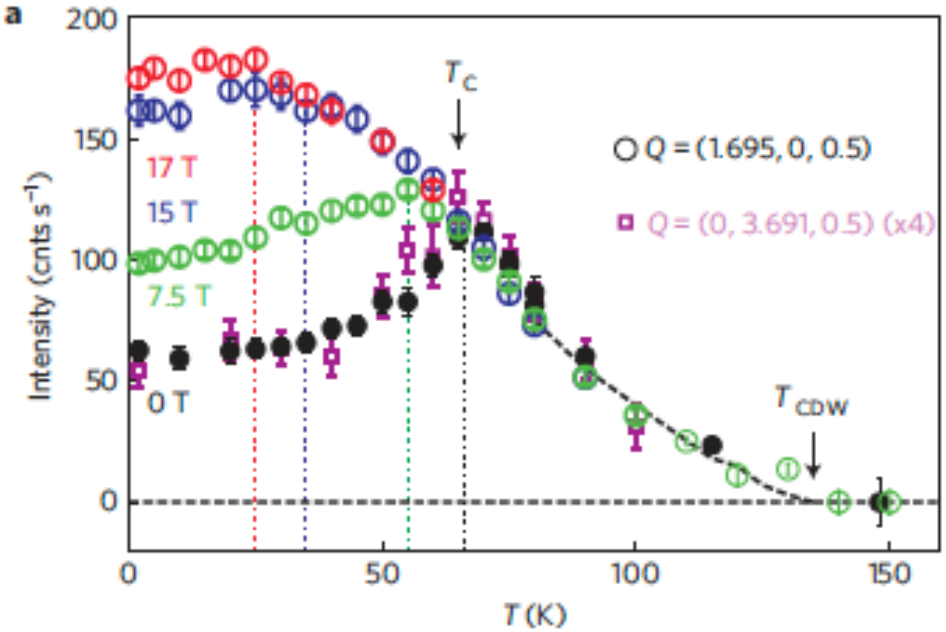


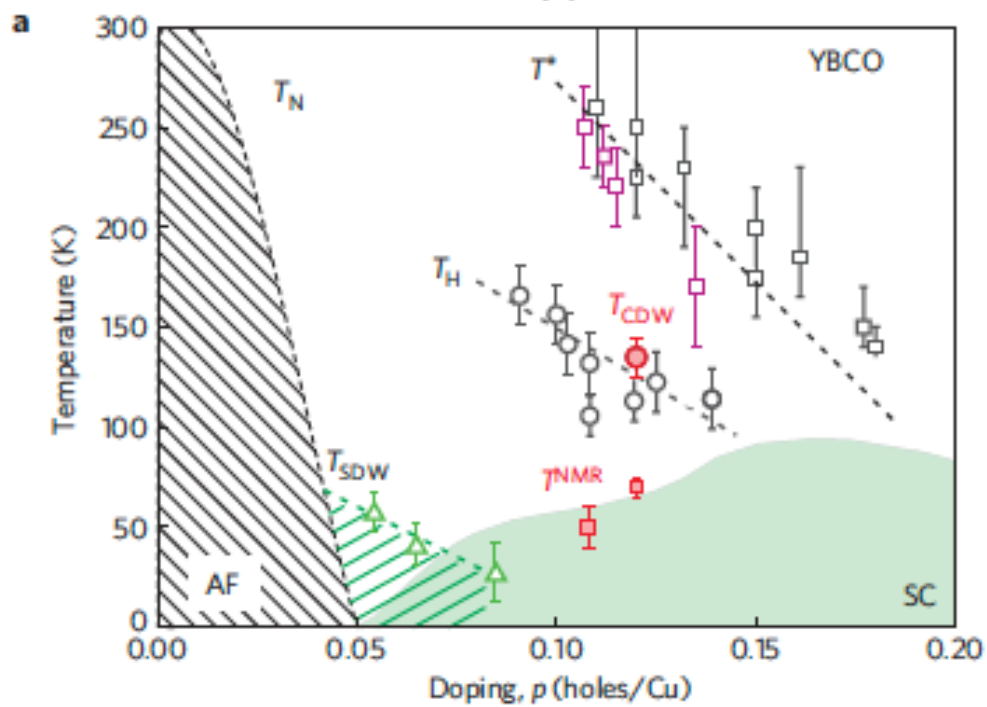
Hoffman *et al.*, Science (2002)

Short range charge order in YBCO (resonant & hard x-rays)





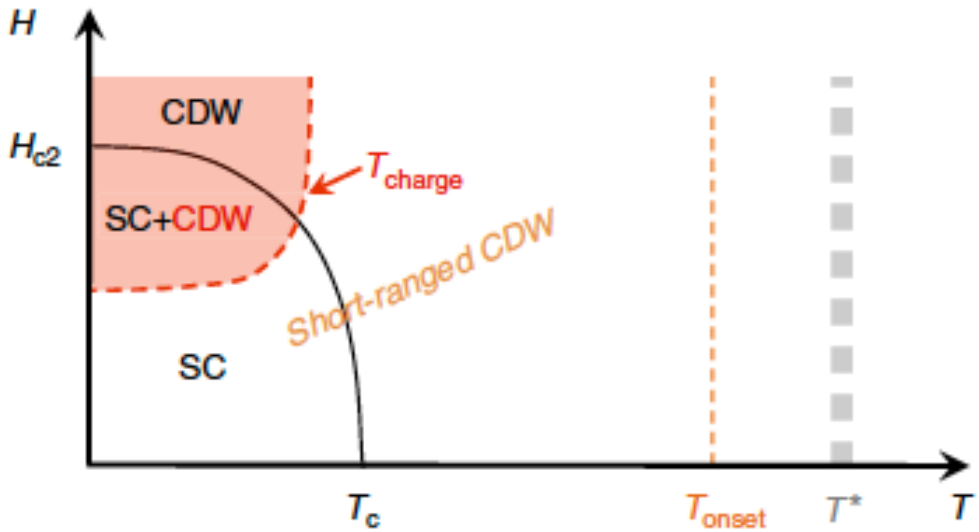


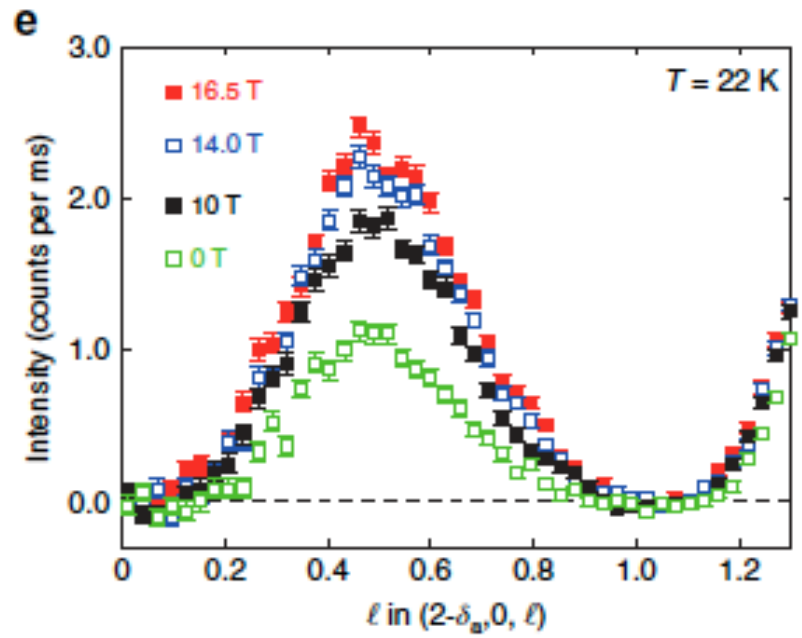


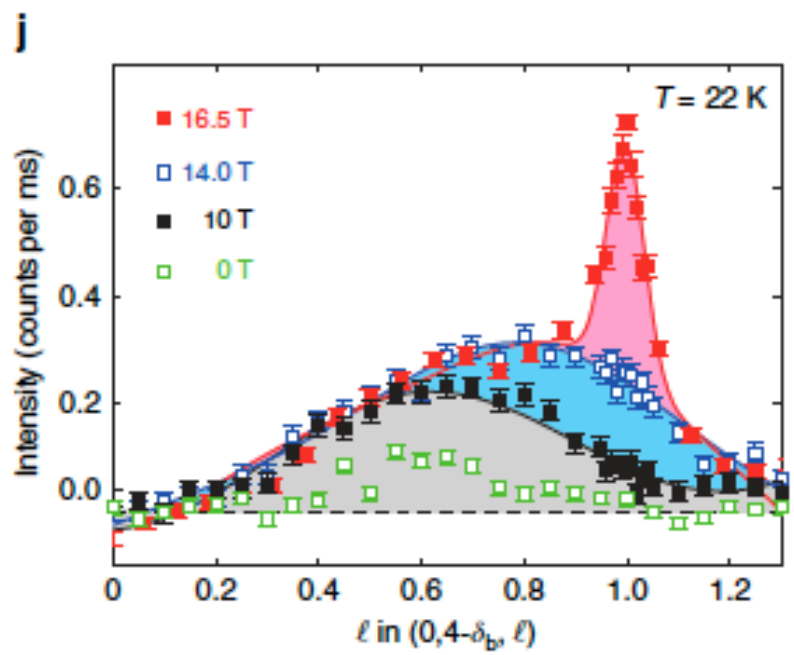
Ghiringhelli *et al.*, Science (2012)

Chang *et al.*, Nature Physics (2012)

Charge order becomes long ranged in a field (NMR, x-rays)

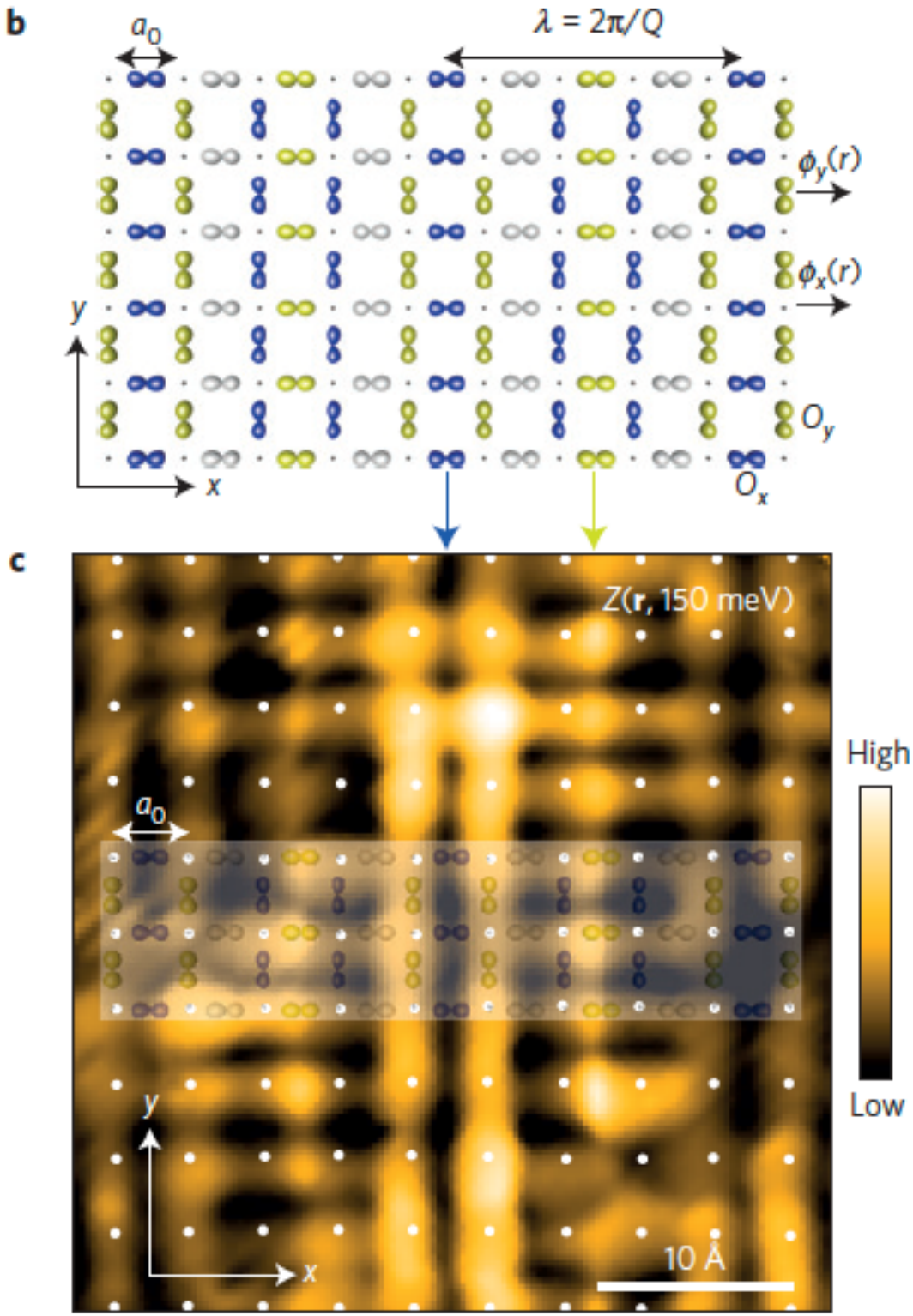






Wu *et al.*, Nature Comm. (2015)

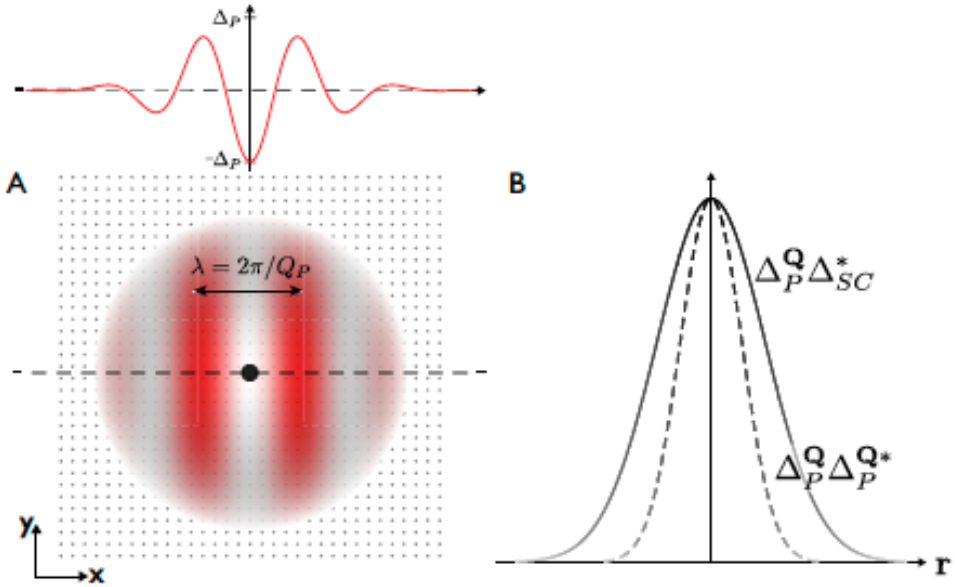
Chang *et al.*, Nature Comm. (2016)

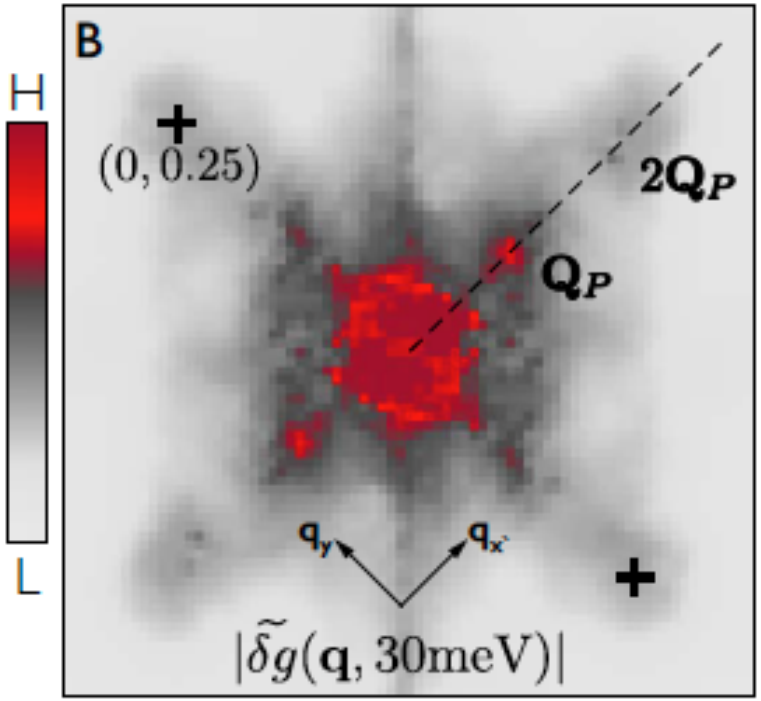


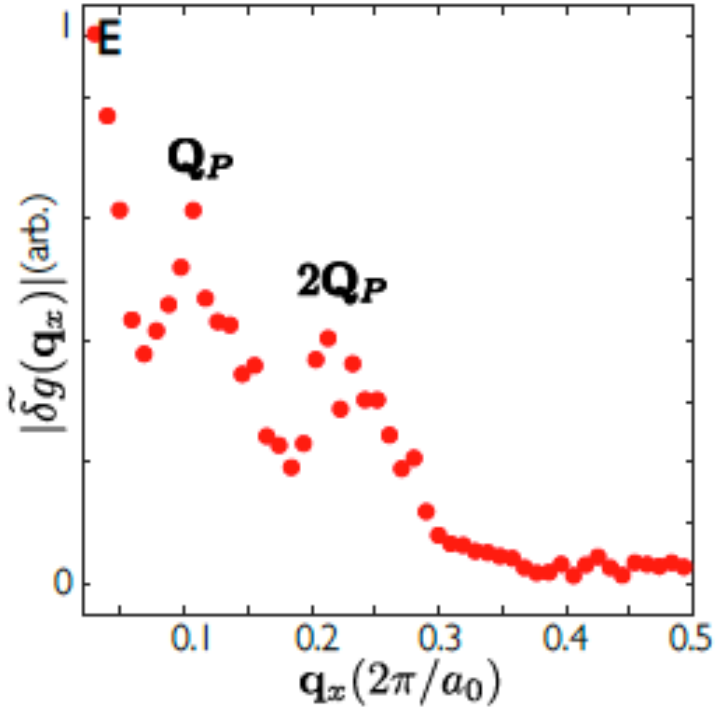
STM reveals a d-wave form factor for the CDW

Hamidian *et al*., Nature Phys. (2015)

Pair Density Wave State in the vortex “halo” (STM)



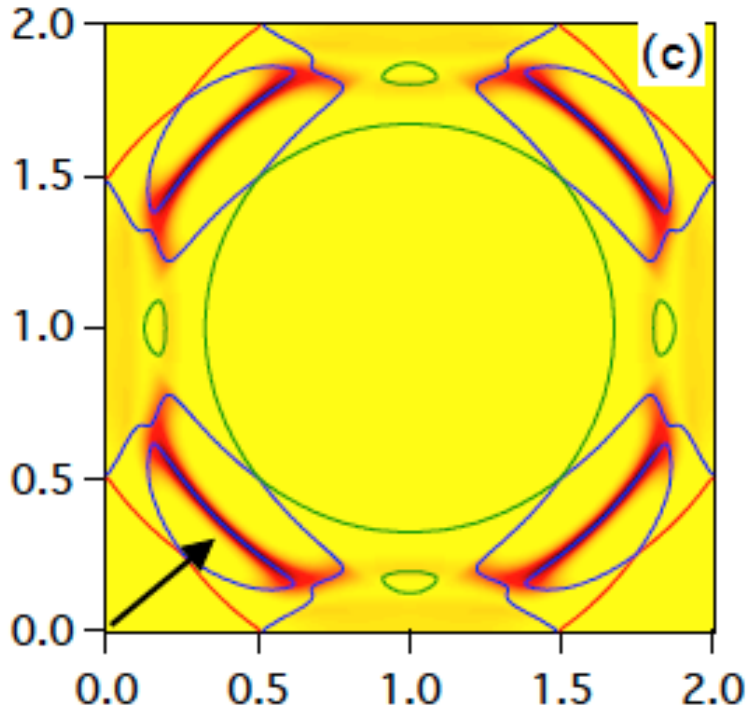


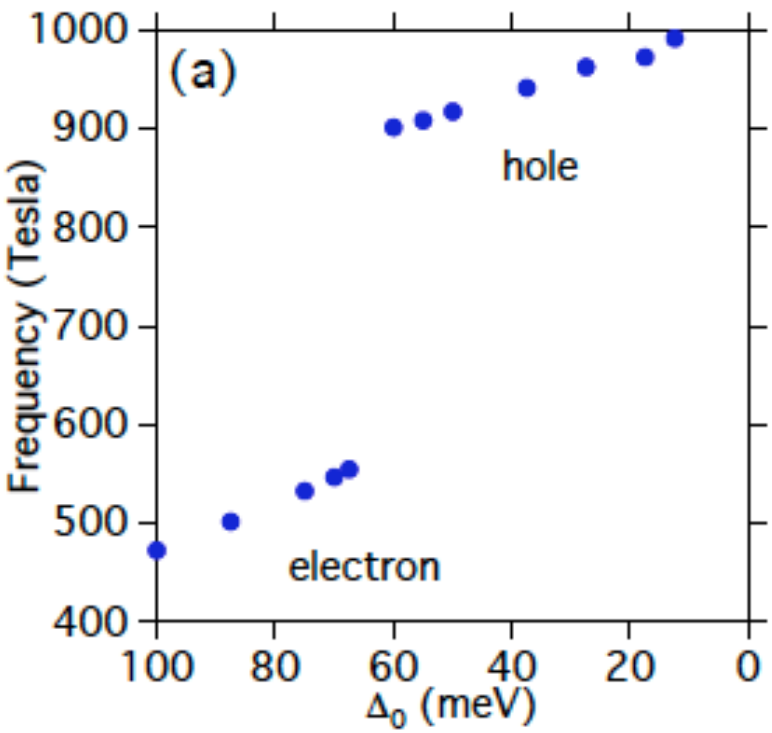


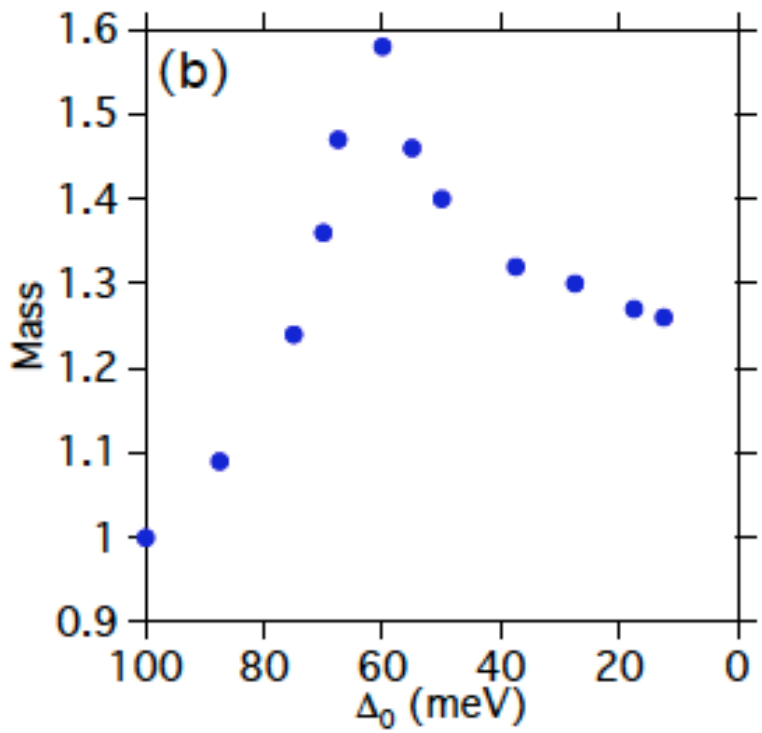
(see also Wang *et al* & Dai *et al*, arXiv)

Edkins *et al*., arXiv (2018)

Is a biaxial PDW the origin of the small electron pocket seen by dHvA?





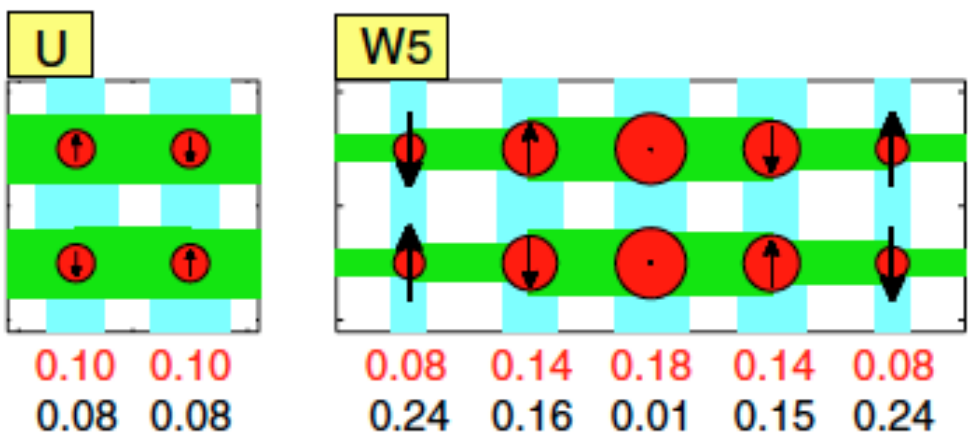


Norman & Davis
arXiv (2018)

Origin of Superconductivity

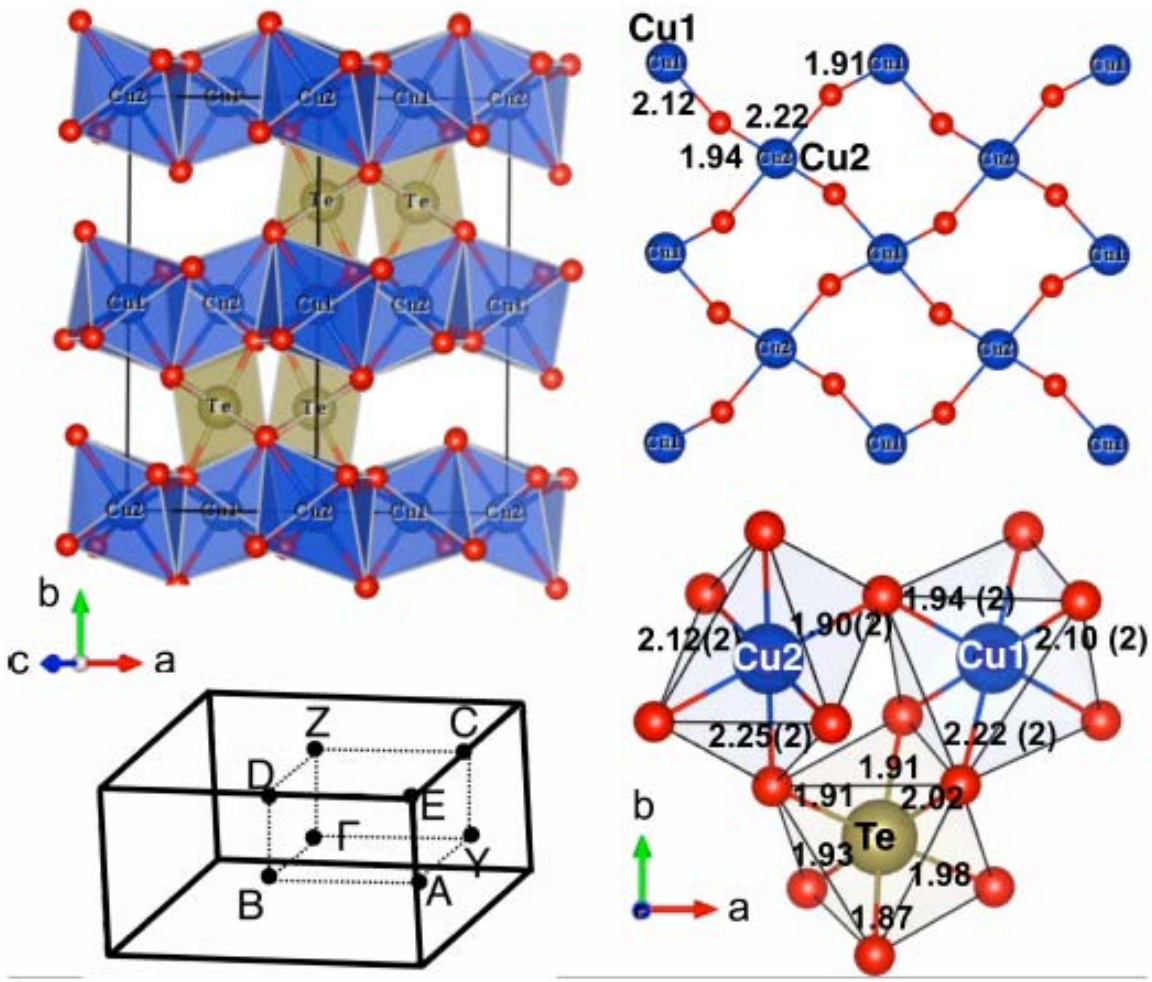
- Doped Mott Insulator
- Doped Spin Liquid
- Spin fluctuations
- Coulomb correlations (Leggett, see talk by van der Marel)
- Role of charge fluctuations and the lattice

Numerical Studies (DMFT, FRG, QMC, DMRG, PEPS, DMET)



Corboz, Rice, Troyer, PRL (2014)
Zheng *et al*., Science (2017)
Huang *et al*., Science (2017)

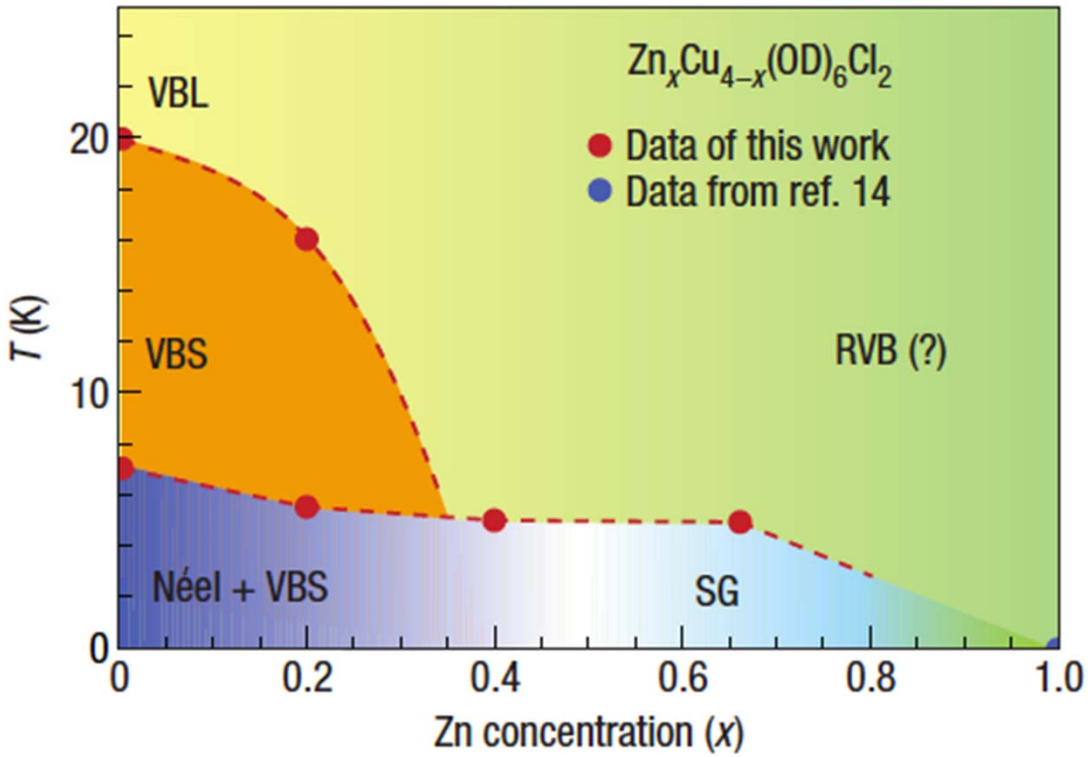
$CuTeO_4$ - Monoclinic distorted CuO_2 square net
CuO_6 quasi-octahedral, Cu-O-Cu bond angles 122.5° & 126.1°

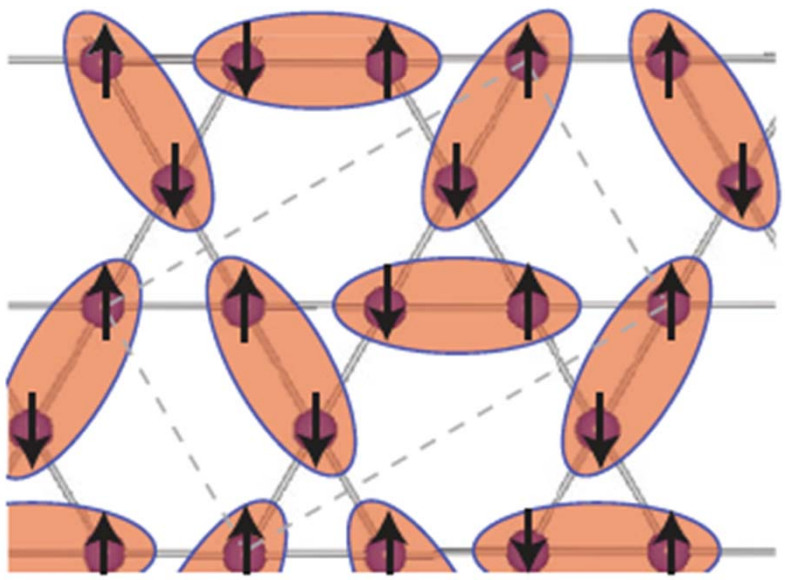


$CuTeO_4$ - Falck *et al.*, Acta Cryst. B (1978)
grown hydrothermally at 650 C
but Cu_3TeO_6 more thermodynamically stable

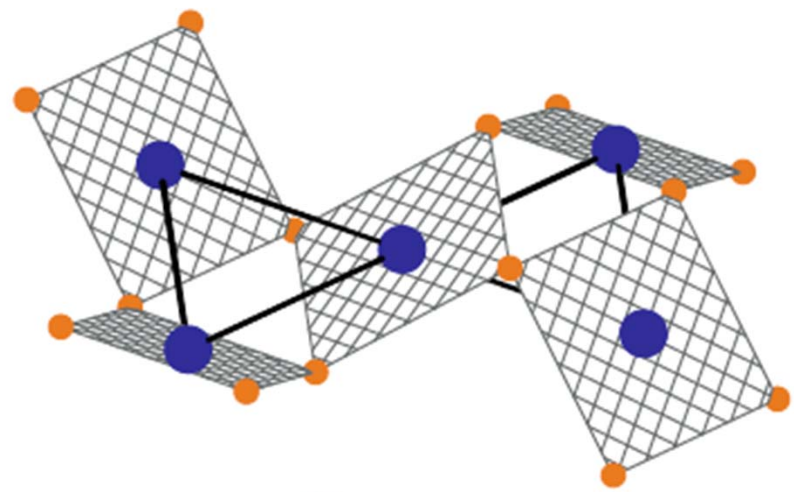
Botana & Norman, PRB (2017)

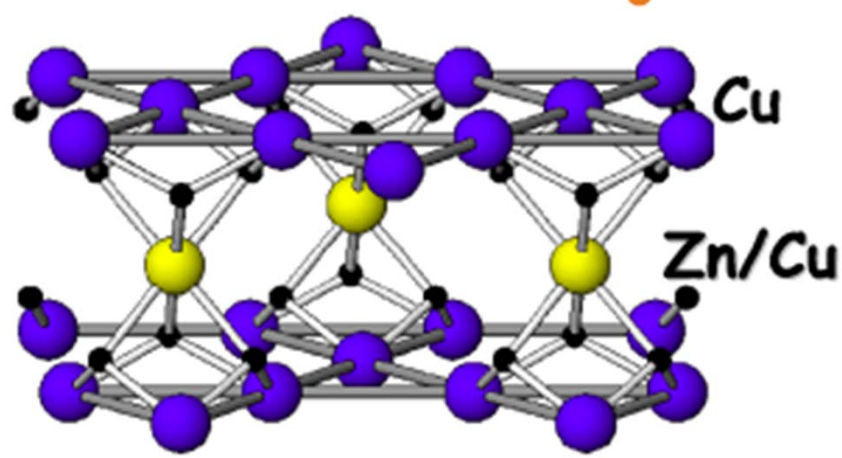
Herbertsmithite - $ZnCu_3(OH)_6Cl_2$ – a Kagome quantum spin liquid





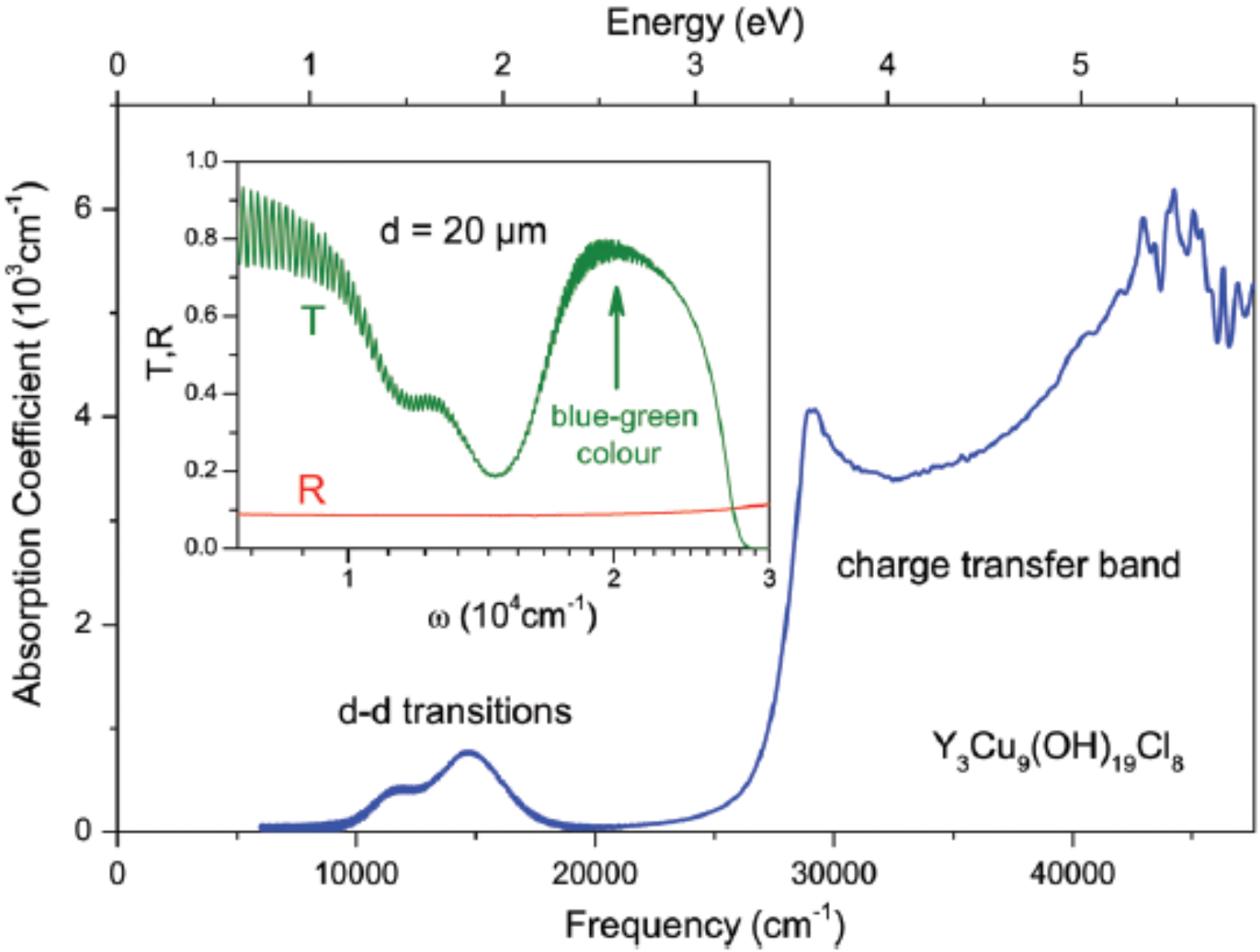
120 degree CuO bonds





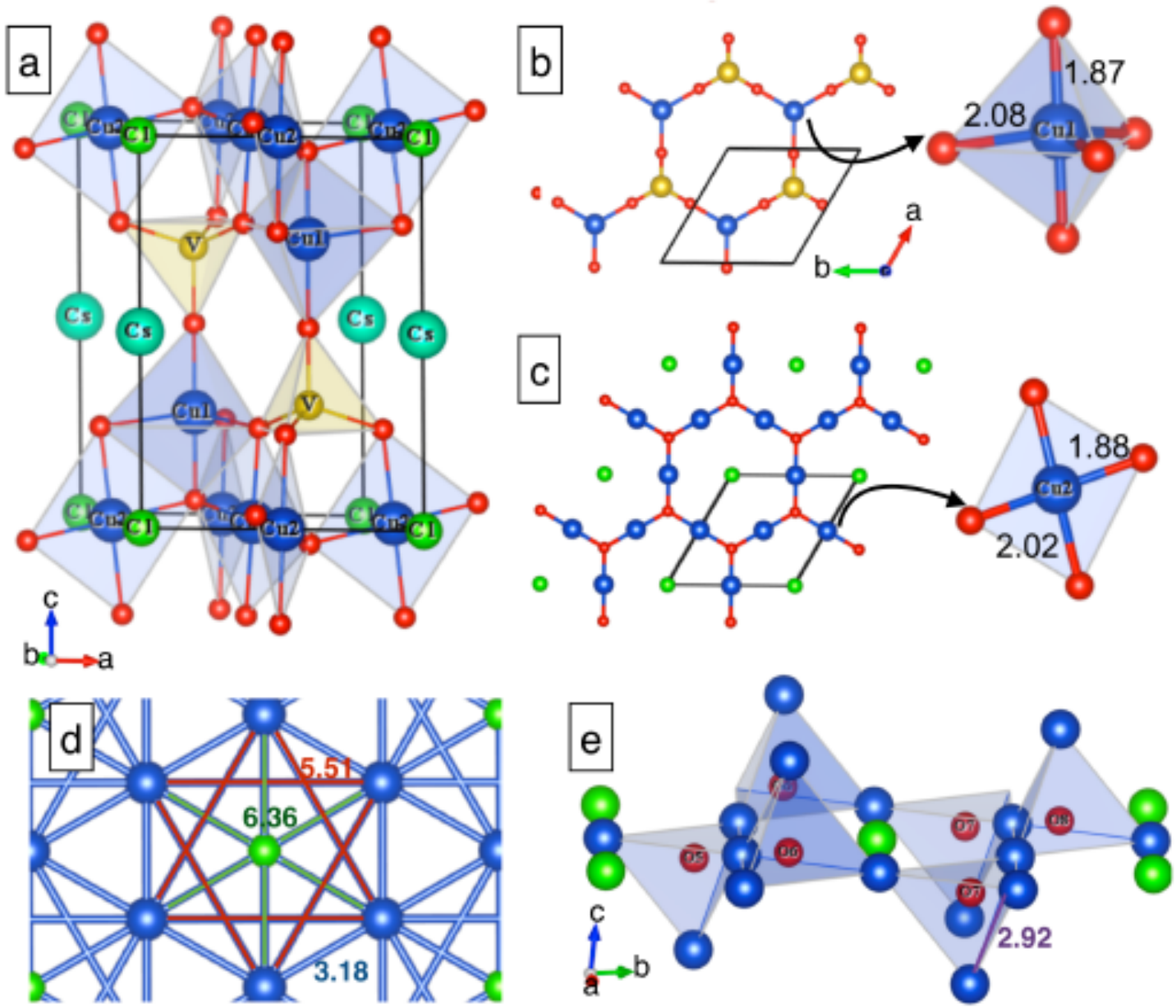
Shores *et al.*, JACS (2005)
Lee *et al.*, Nature Materials (2007)
Norman, RMP (2016)

Doping with Li leads to localized carriers – Kelly *et al*., PRX (2016)
Herbertsmithite has a much larger gap (~3.5 eV) than a cuprate



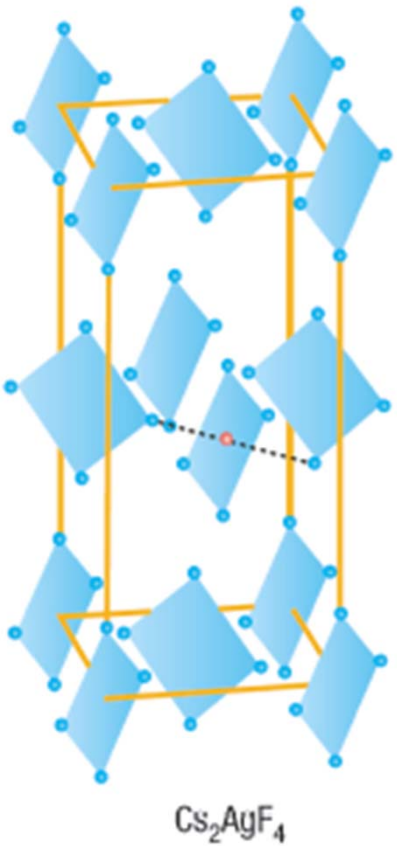
Puphal *et al.*, J Mater Chem C (2017)
Pustogow *et al*., Phys Rev B (2017)

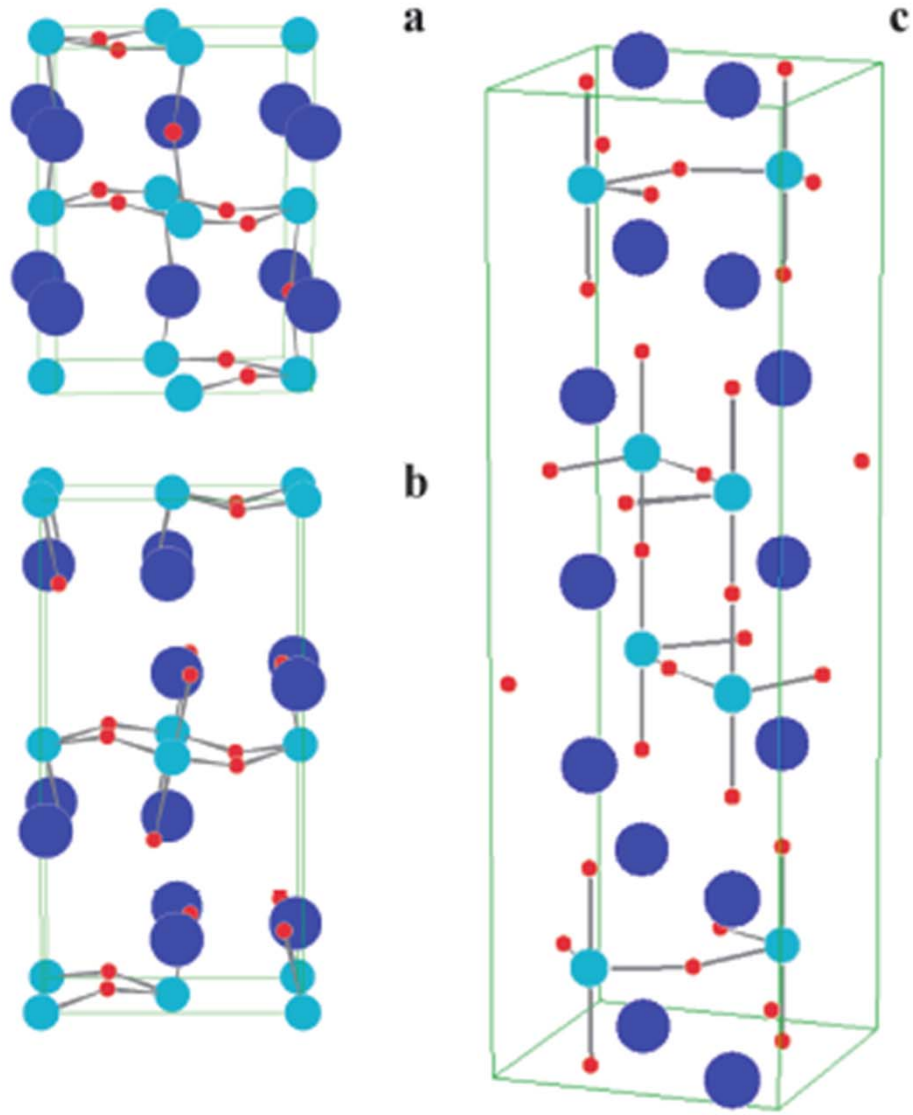
$Cu_5V_2O_{10}(CsCl)$, averievite, has a Cu kagome layer and Cu-V honeycomb layers separated by CsO_2 layers (a pyrochlore slab)



Botana, Zheng, Mitchell, Norman, unpublished

Fluoroargentates (analogues of cuprates?)



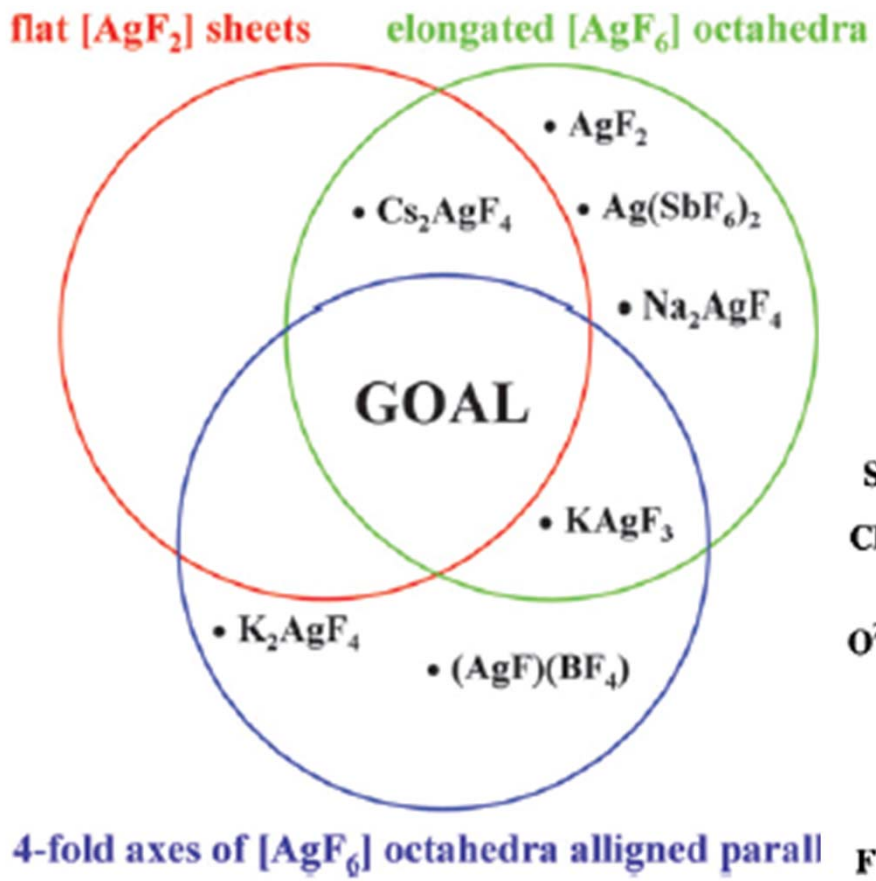


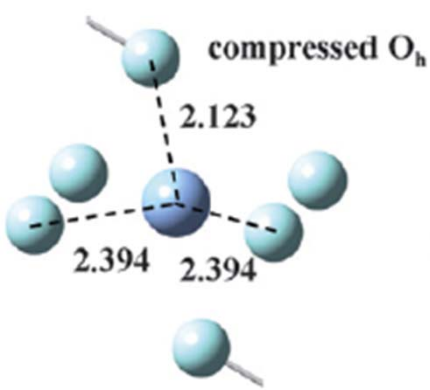
Cs_2AgF_4

$KAgF_3$, K_2AgF_4, $K_3Ag_2F_7$

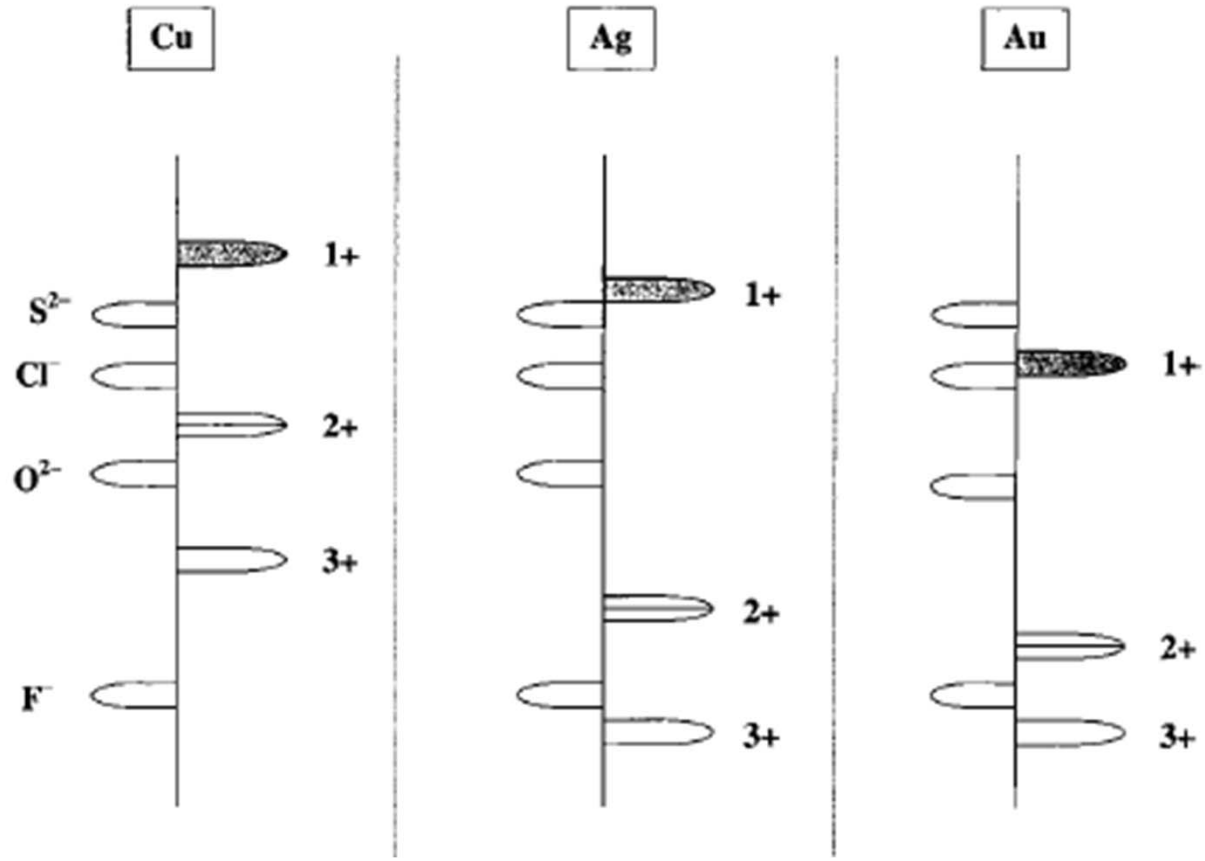
Mazej *et al.*, CrystEngComm (2009)

Quantum Chemical Considerations – Silver Flourides





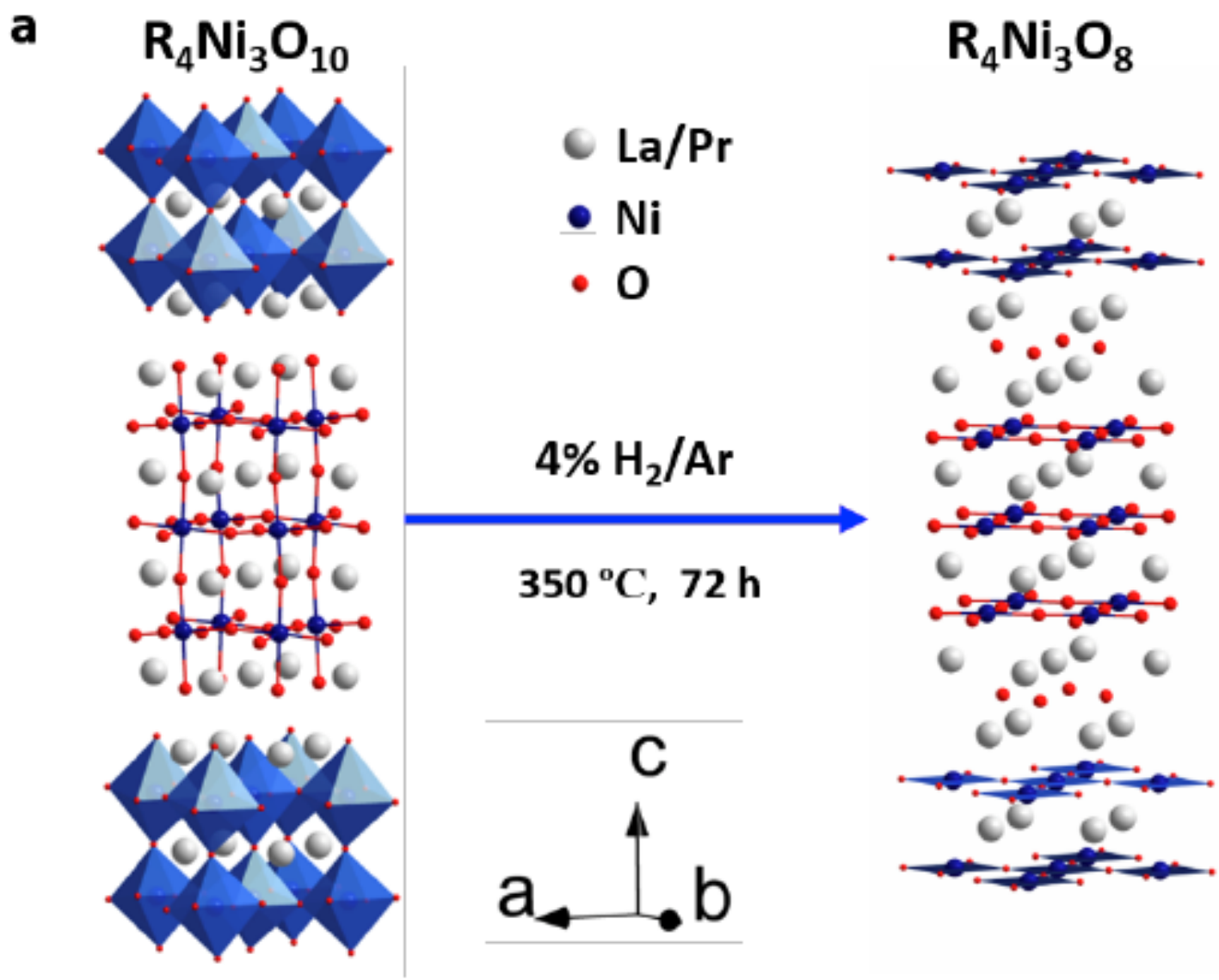
$Ag(BF_4)_2(FH)_4$



charge transfer gap

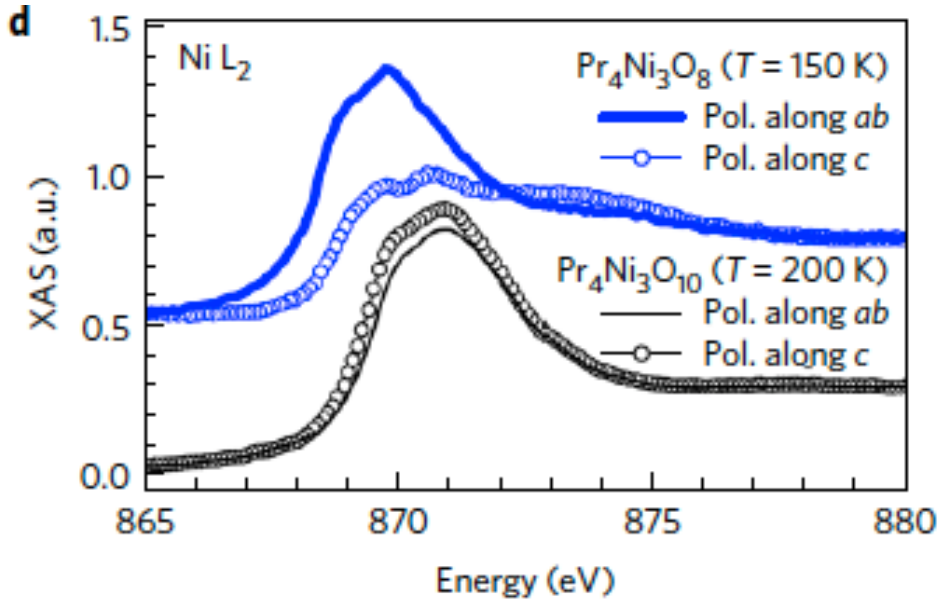
Grochala & Hoffmann, Angew Chem (2001)
Grochala, J. Mater. Chem. (2009)

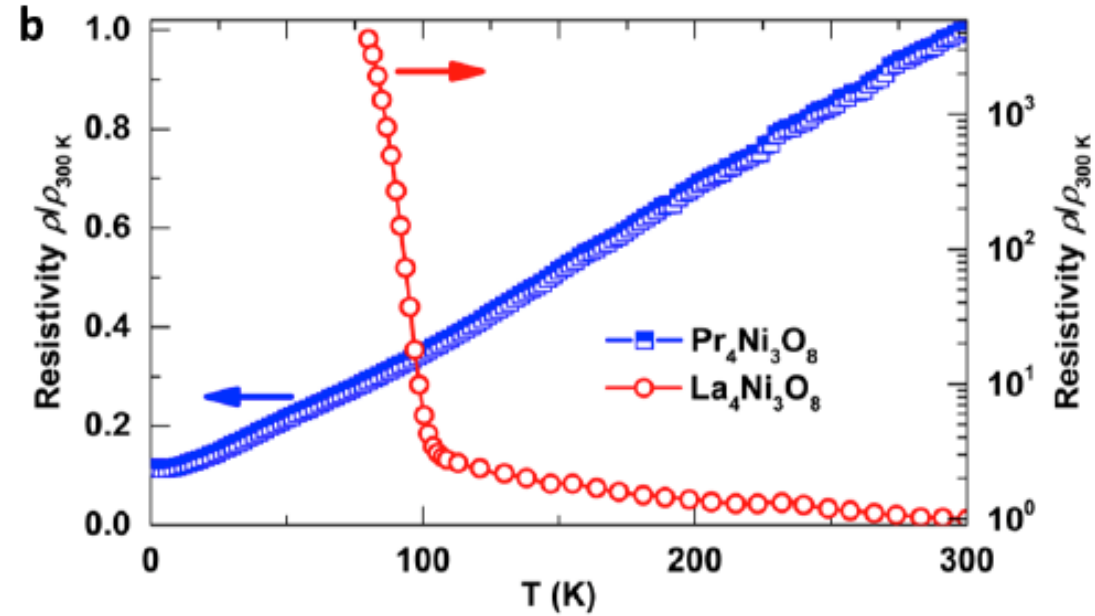
$R_4Ni_3O_8$ obtained from $R_4Ni_3O_{10}$ by hydrogen (topotactic) reduction resulting in the loss of apical oxygens

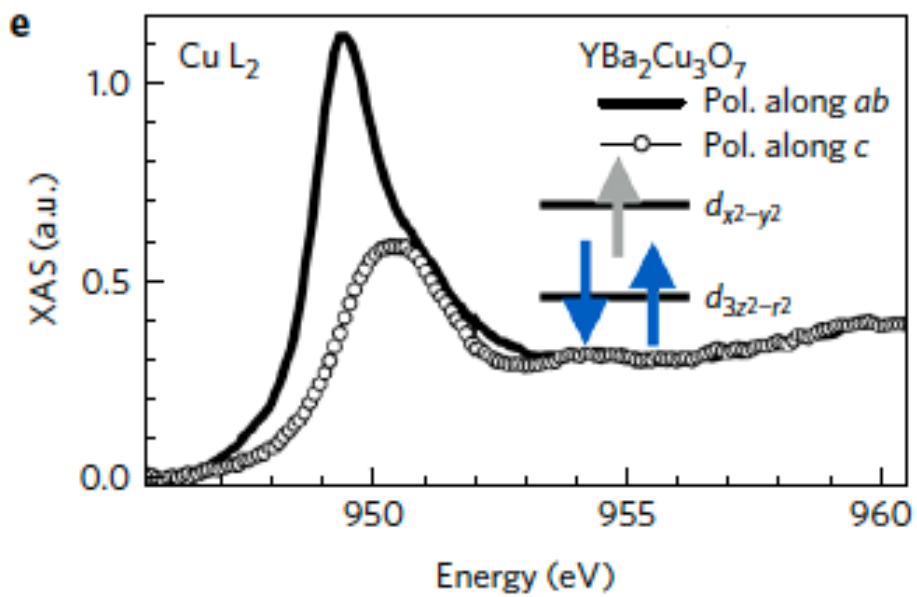


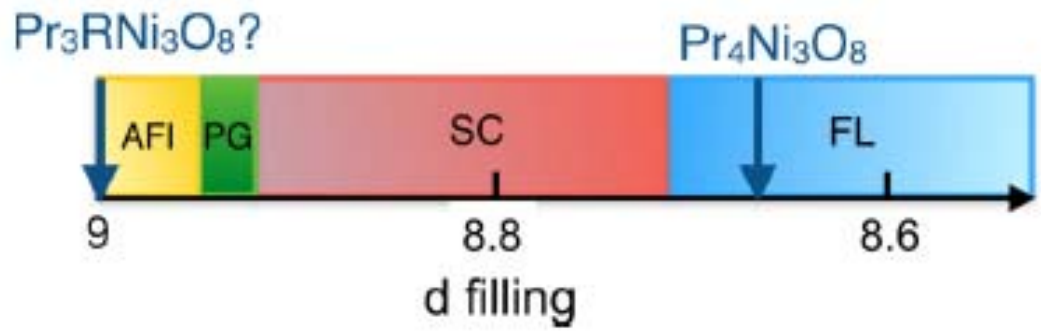
Zhang *et al.*, PNAS (2016)

Unlike La438, which is a charge stripe insulator, Pr438 is a metal with Ni dx^2-y^2 orbitals near E_F



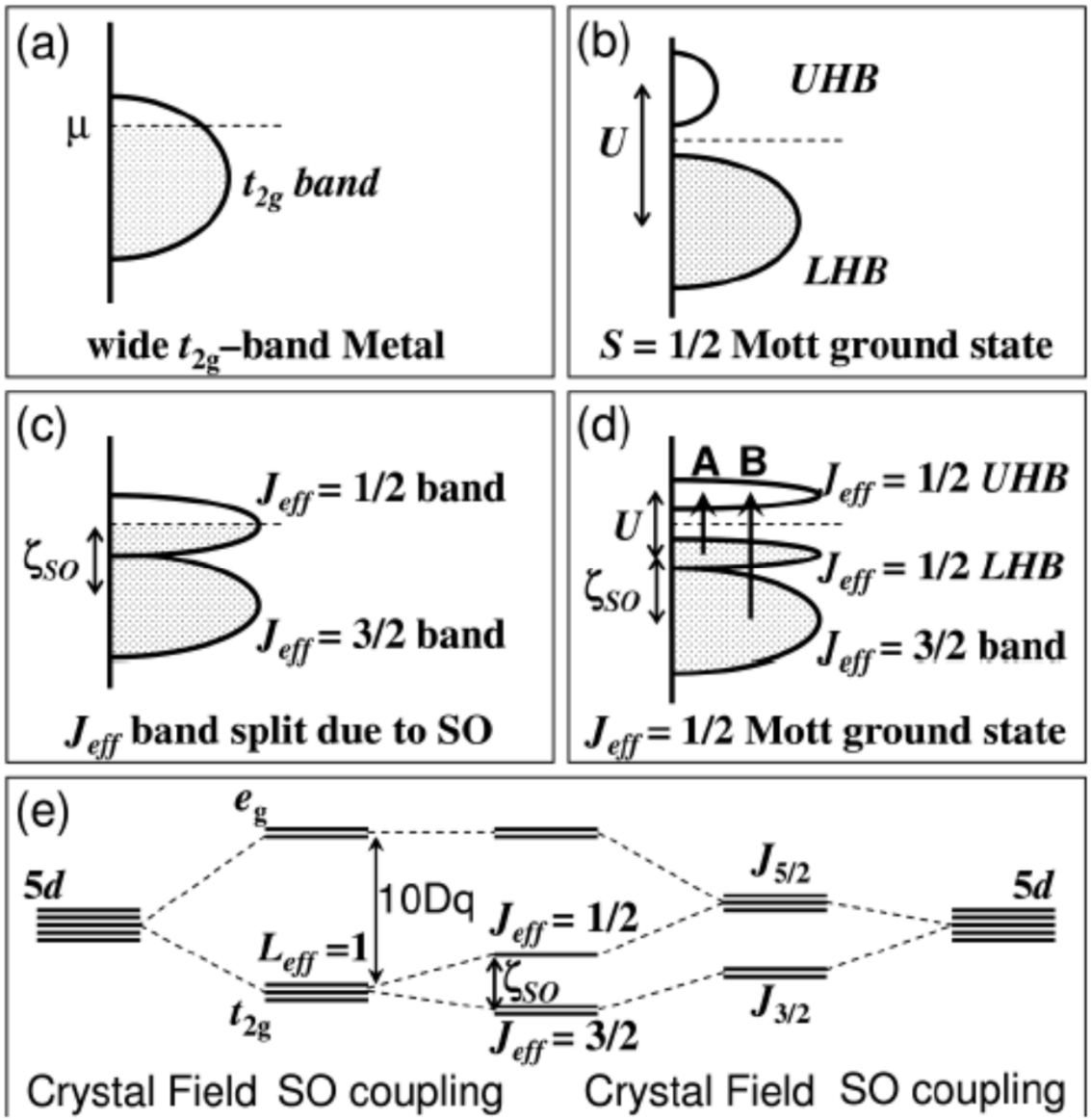






Zhang *et al.*, Nature Physics (2017)
Botana, Pardo, Norman, PRM (2017)

Iridates - spin-orbit plus d^5 configuration leads to a half filled band



Kim *et al.*, PRL (2009)

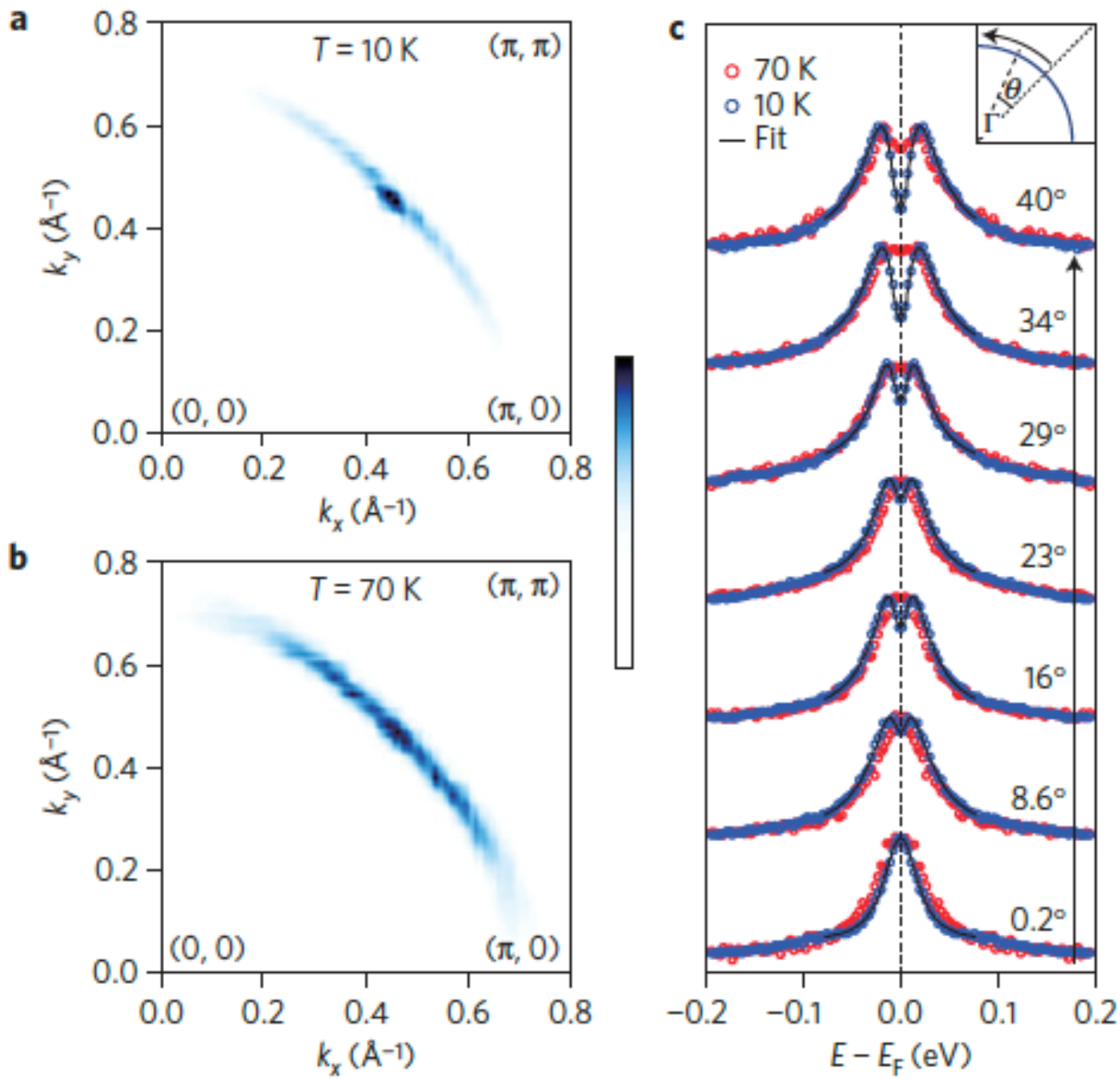
Cuprates are Mott insulators, have a half filled band, and a large superexchange J

So are iridates!

If doped, will they be high T_c superconductors?

Wang & Senthil, PRL (2011)

Fermi arcs and d-wave gaps in Sr_2IrO_4 via K-surface doping



Kim *et al.*, Nature Physics (2016)