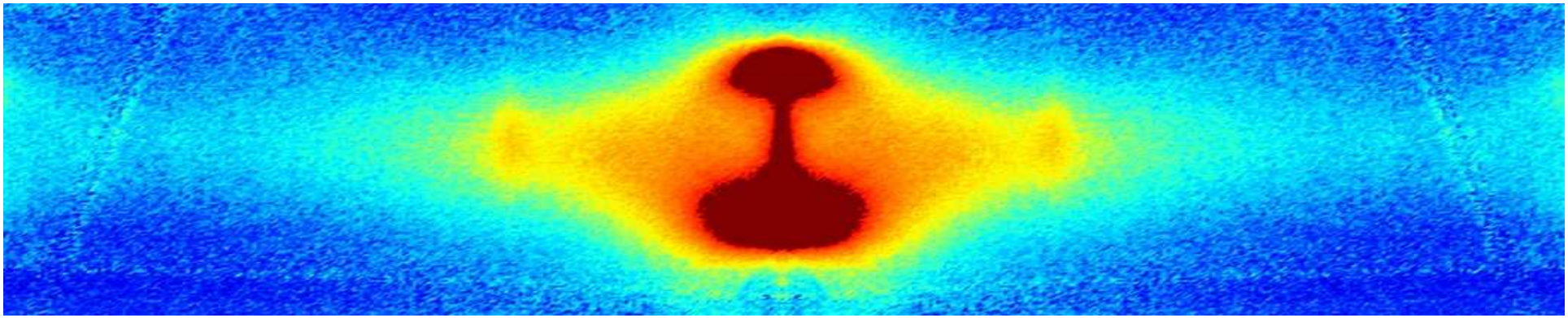
High Tc cuprates:

Recent insights from X-ray scattering



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Theory

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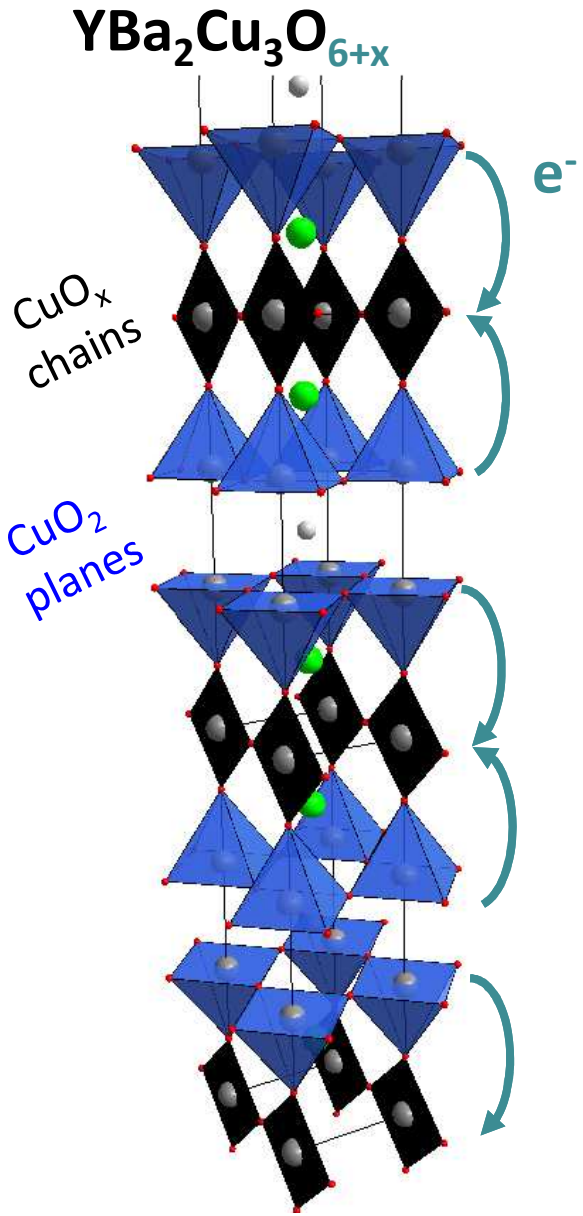
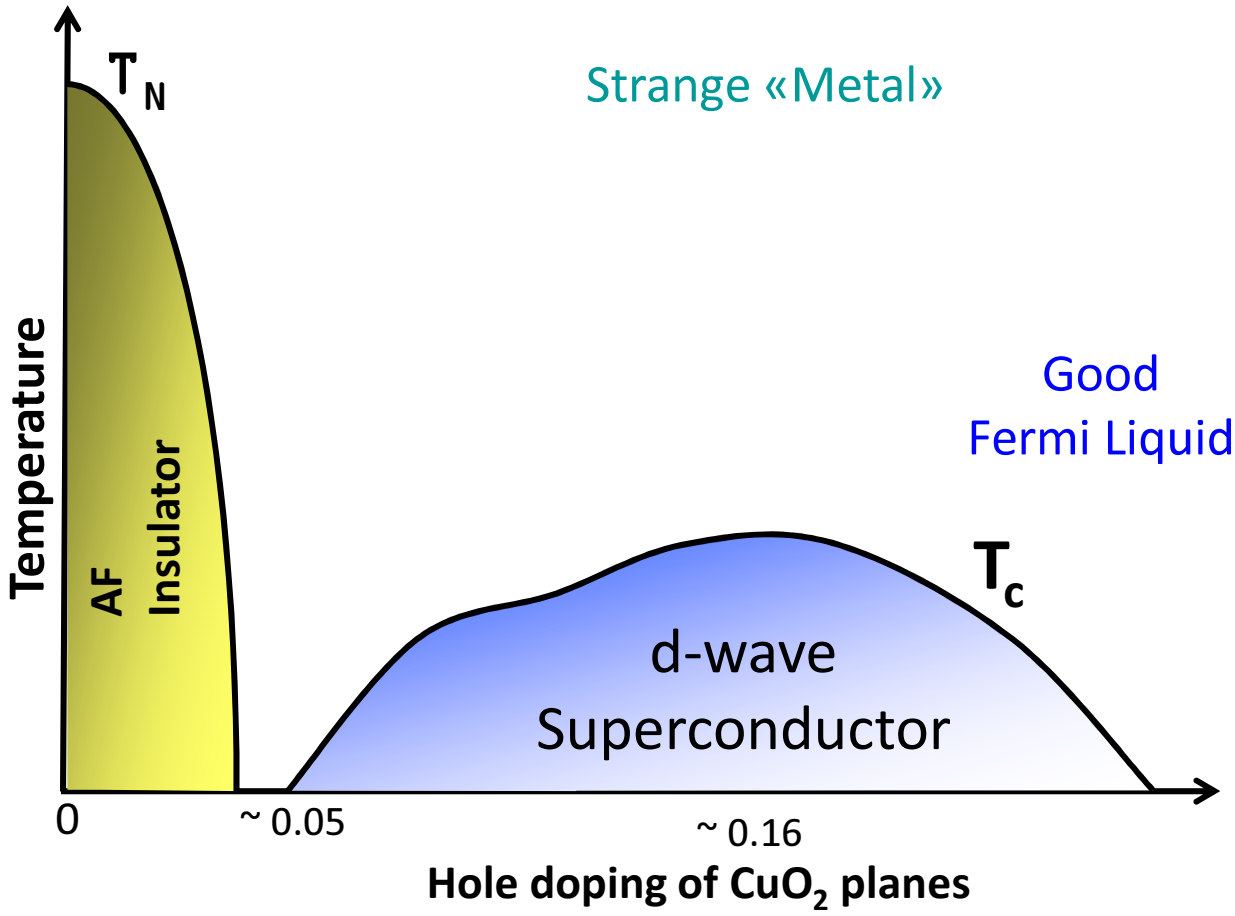
Cuprates Phase Diagram

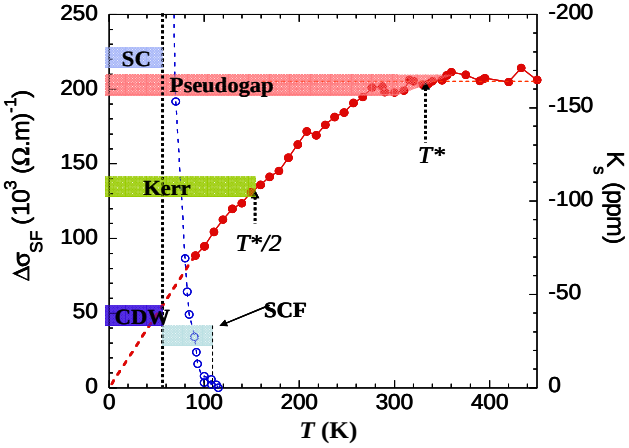




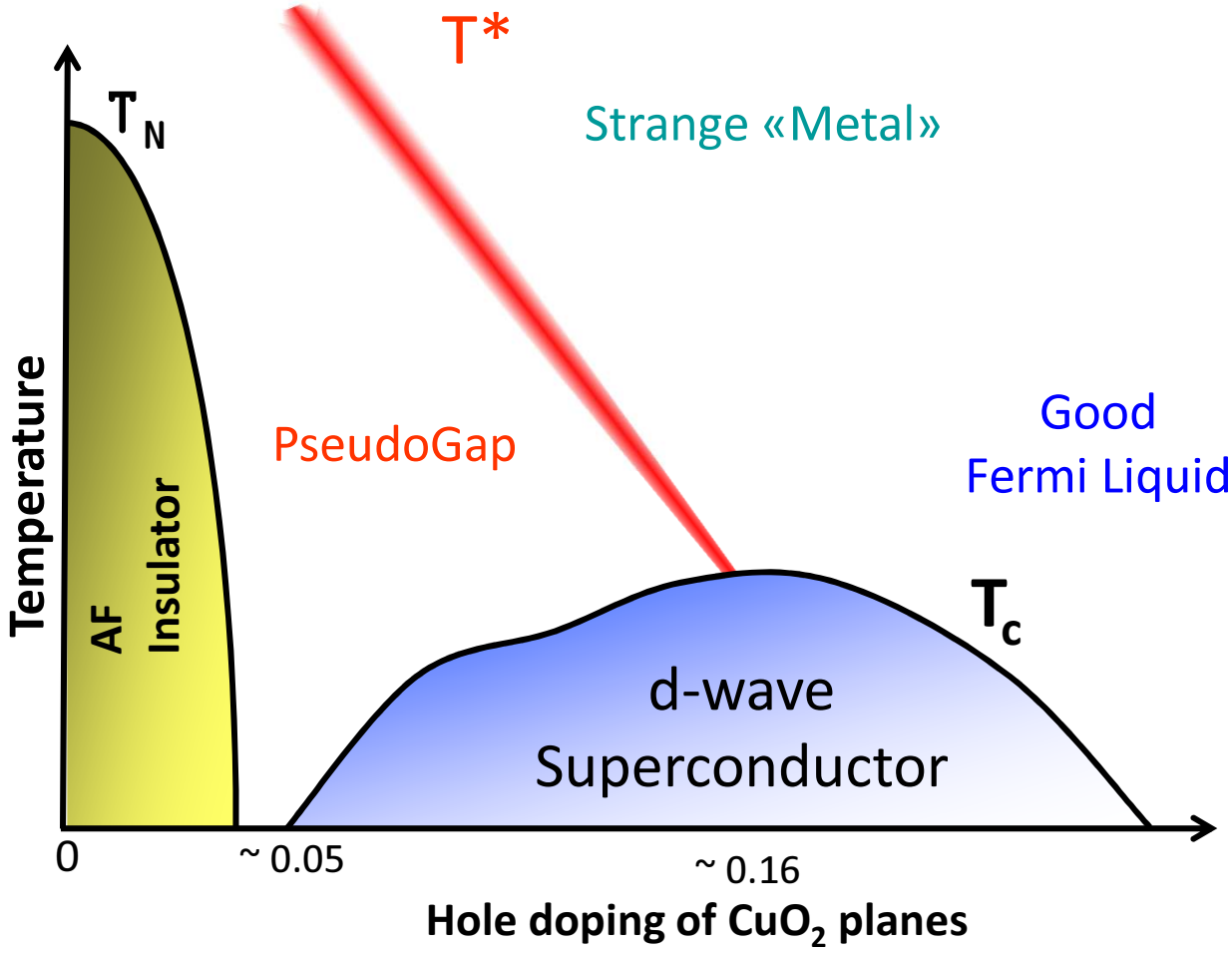
1) Origin of superconductivity ?

Cuprates Phase Diagram

PseudoGap Puzzle



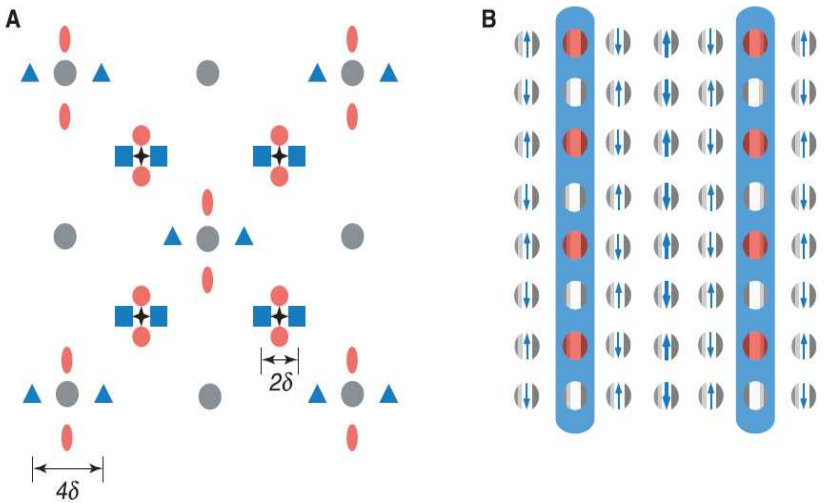
Alloul C.R.Phys. 15 519 (2014)



1) Origin of superconductivity ?

2) Interplay with other possible ground states ?

Stripe order in $La_{2-x-}Ba_xCuO_4$ & $La_{2-x-y}(Nd,Eu)_ySr_xCuO_4$



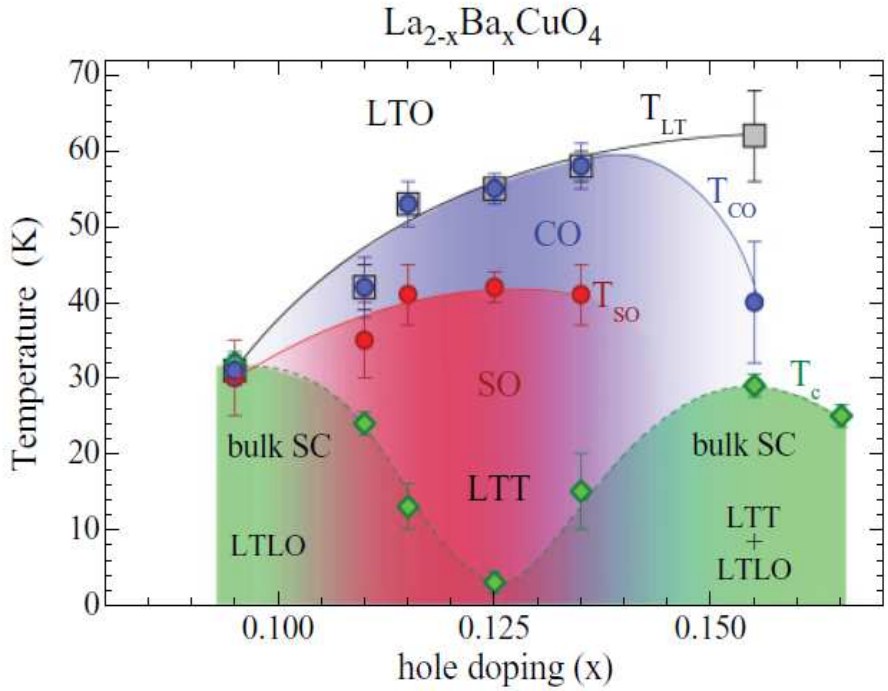
Orenstein & Millis, Science **88** 468 (2000)

- Static Spin Order @ δ

accompanied with

- Static Charge Order @ 2δ

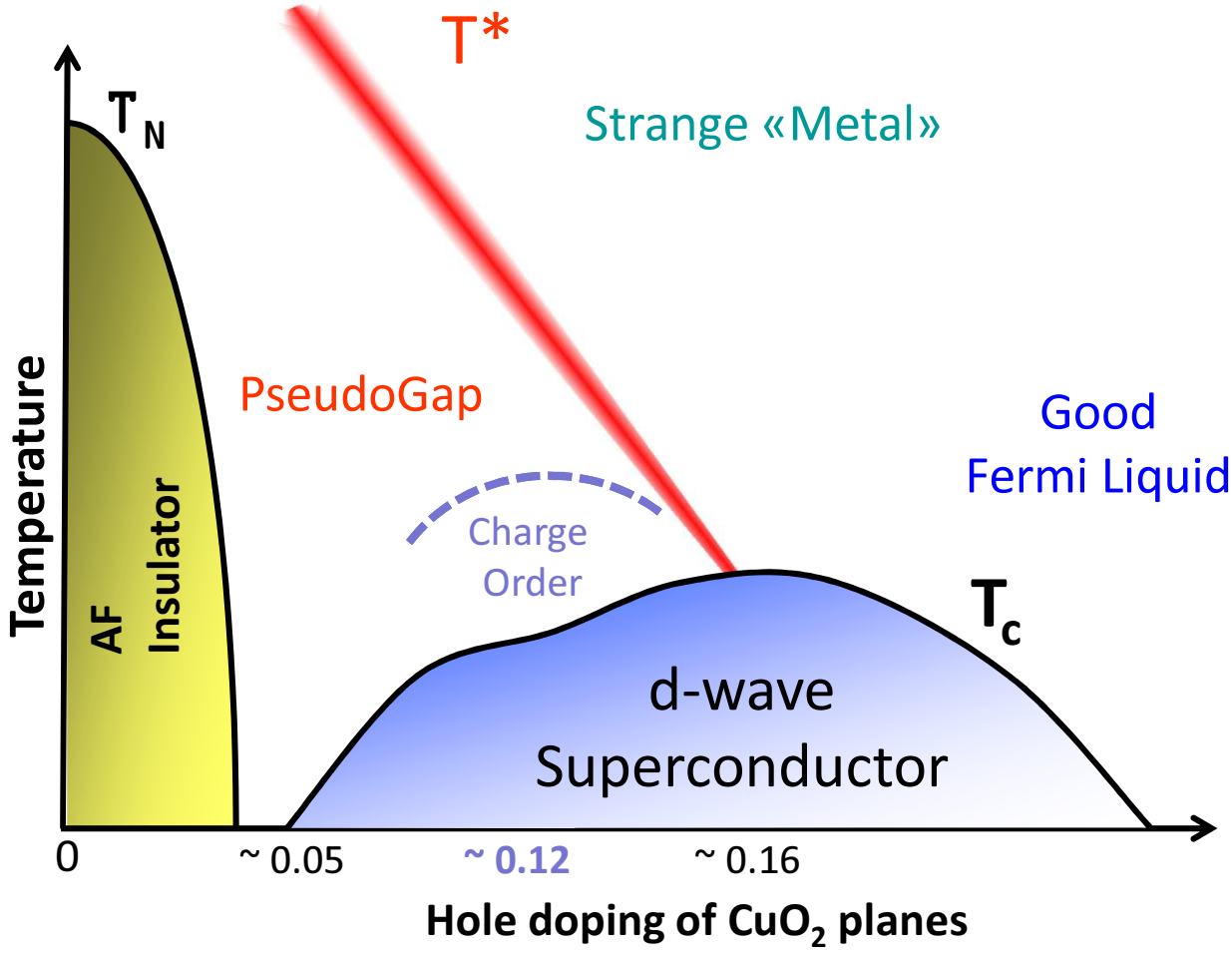
Zaanen & Gunnarsson, PRL 40 7391 (1989)



Hücker et al. PRB **83**, 104506 (2011)

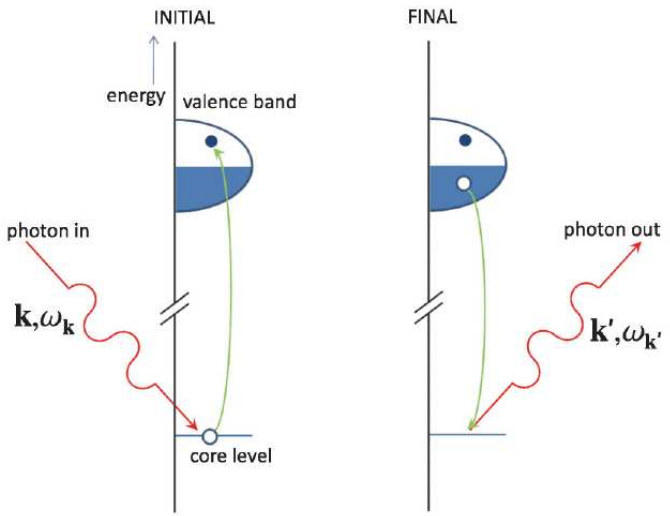
Is stripness universal in cuprates ?

Cuprates Phase Diagram



In a nutshell: Ubiquitous 'Charge Order' (YBCO/Bi2201/Bi2212/Hg1201/LSCO)
What is common to 214 stripes ?

Resonant x-ray Scattering (RIXS & REXS)

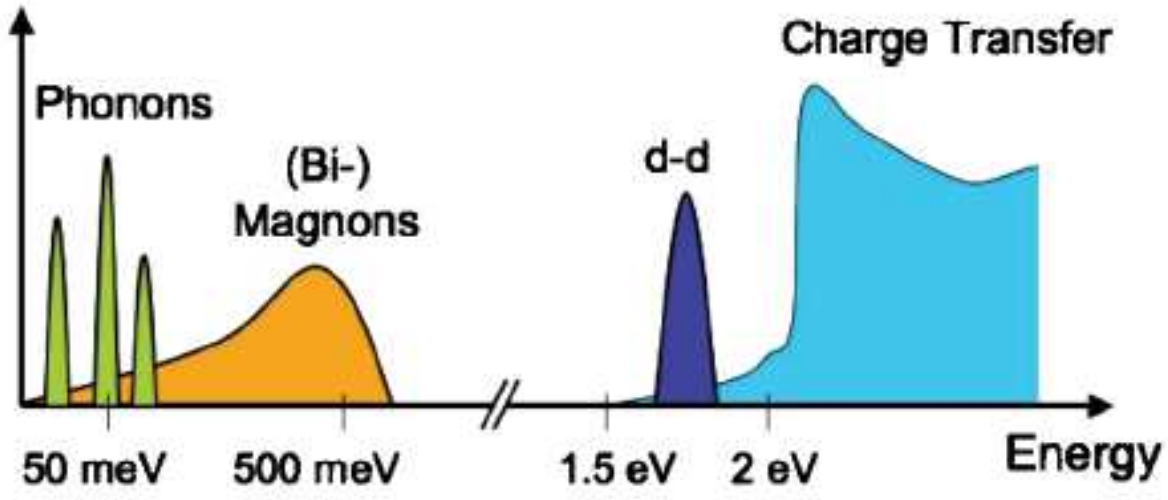


- ω_I tuned to some absorption edge
  (**Element & site specific**/Huge cross section)
- Inelastic (**RIXS**) or Energy Integrated (**REXS**)
- Momentum transfer
  (Dispersion)
- Polarization dependence
  (**Selection Rules**)

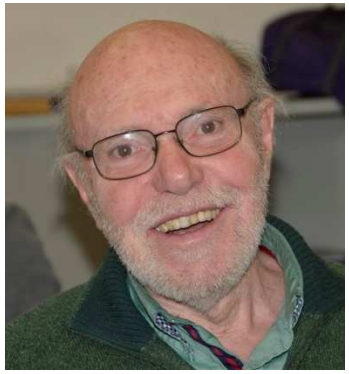
Recent Reviews

RIXS: Ament, et al.
RMP **83**, 705 (2011)

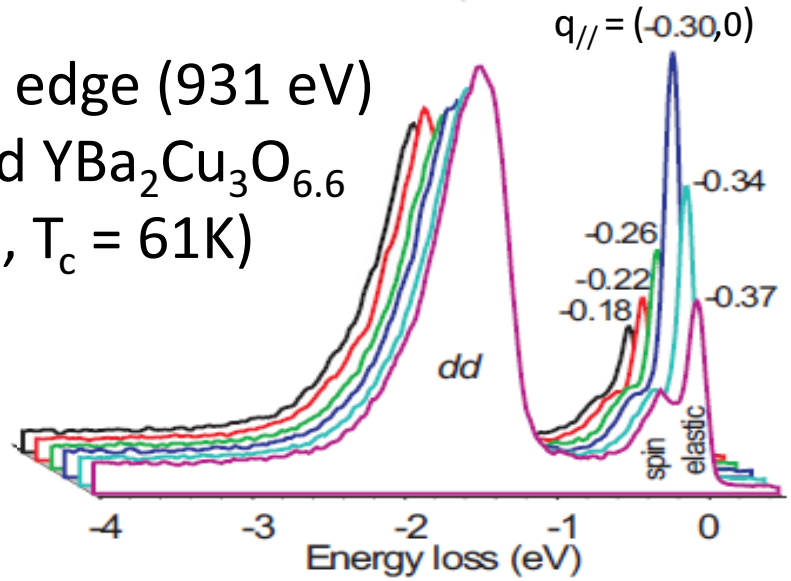
REXS: Fink et al.
RPP **76**, 056502 (2013)



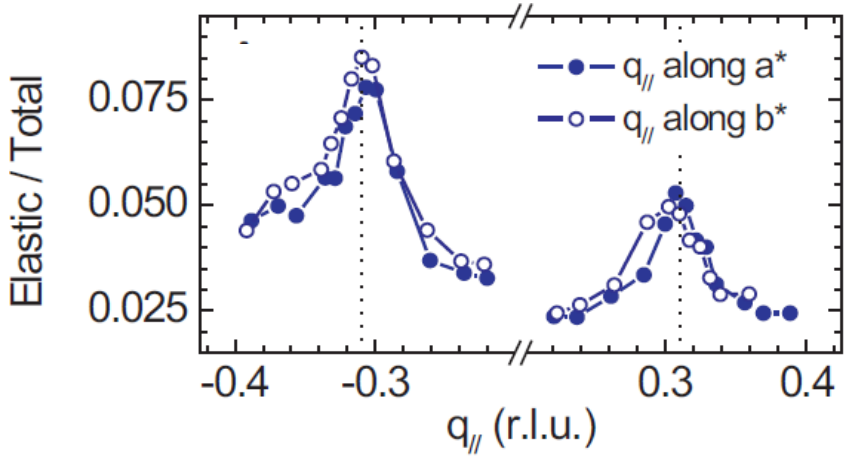
Anomalous momentum dependence of the elastic line

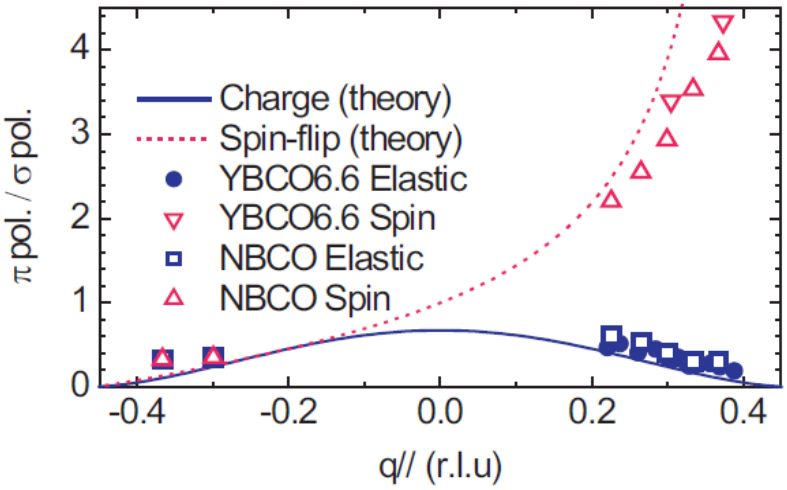


RIXS @ Cu L_3 edge (931 eV)
Underdoped $YBa_2Cu_3O_{6.6}$
(p ~0.12, T_c = 61K)



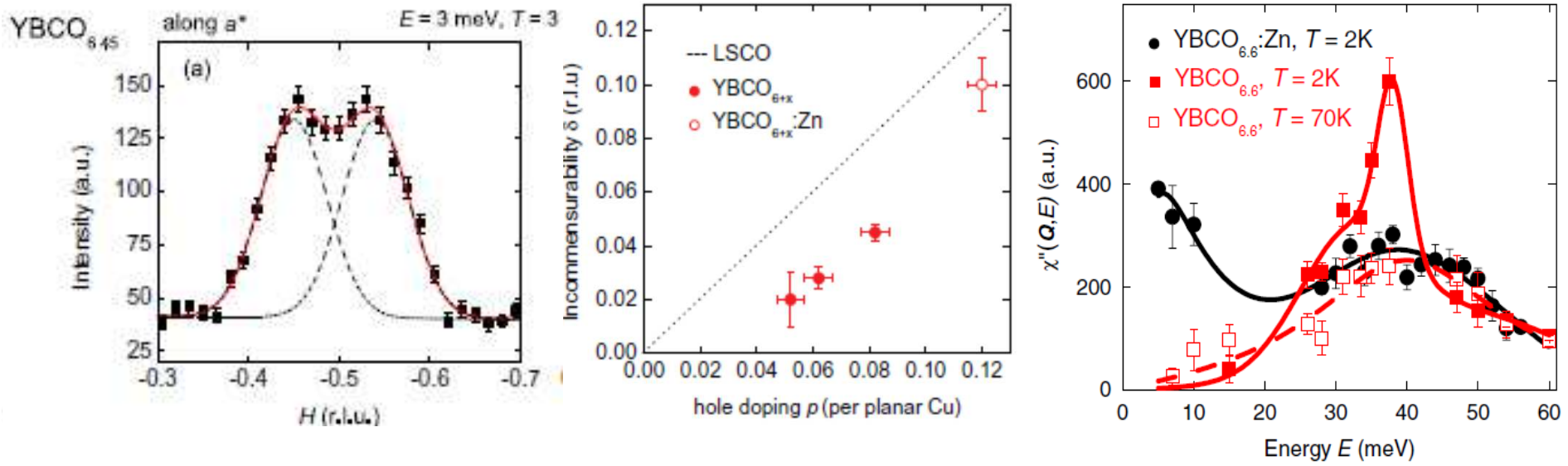
Ghiringhelli, MLT et al. Science **337**, 821(2012)





Bi-axial Spatial Modulation of **Charge in CuO_2 planes** 'CDW'

Magnetic Structure of YBCO w/Doping from INS



Haug et al. NJP **12**, 105006 (2010)

Suchaneck et al.
PRL **105**, 037207 (2010)

- Lightly doped YBCO: Incommensurate, quasi-static, short-range magnetism
- The incommensurability increases with the hole doping
- No more static magnetism above p~0.1: only fluctuations

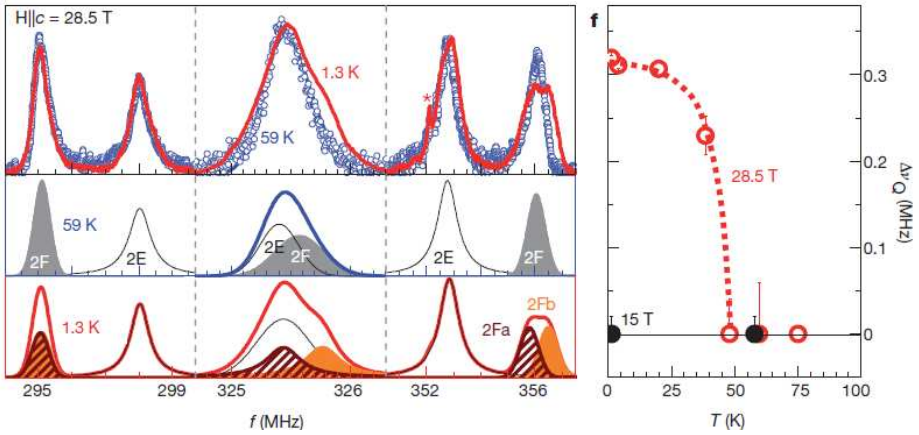
No relation btw charge and spin incommensurabilities

No 'stripes' in YBCO

Other evidences for CDW in YBCO

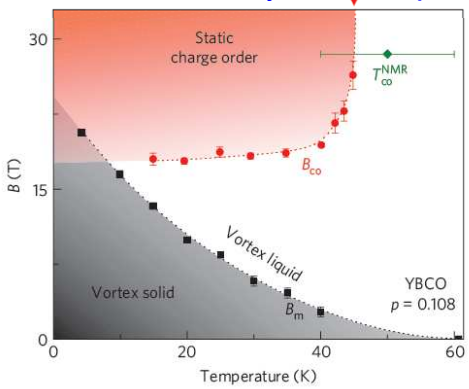
Charge modulation at low T, high field

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



Bi-axial, Static order (=Thermodynamic transition) under high field.

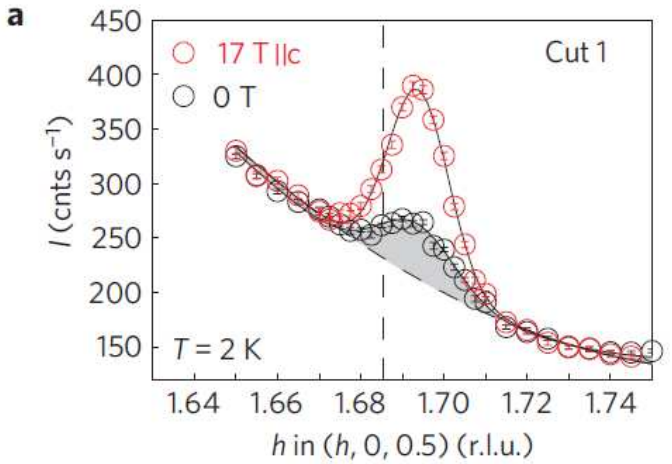
Leboeuf et al. Nat.Phys. **9** 79 (2013)

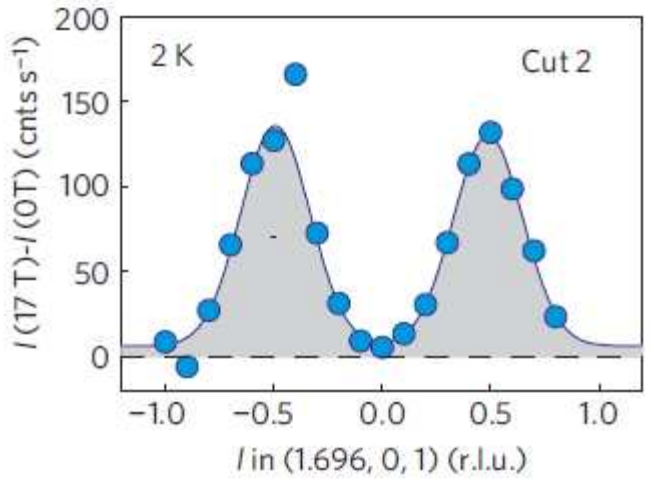


L = 0.5: Doubling of unit cell along c-axis

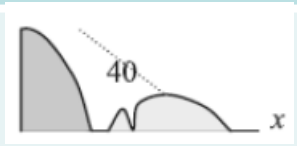
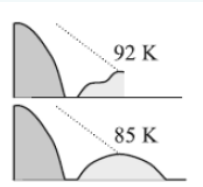
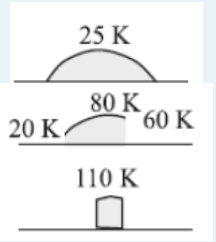
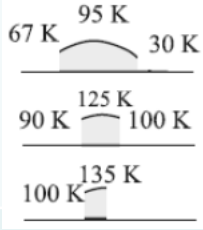
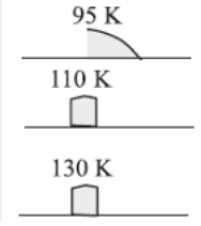
Field enhancement of the CDW (HXRD)

Chang et al. Nat.Phys. **8** 871 (2012)





Diversity vs Universality

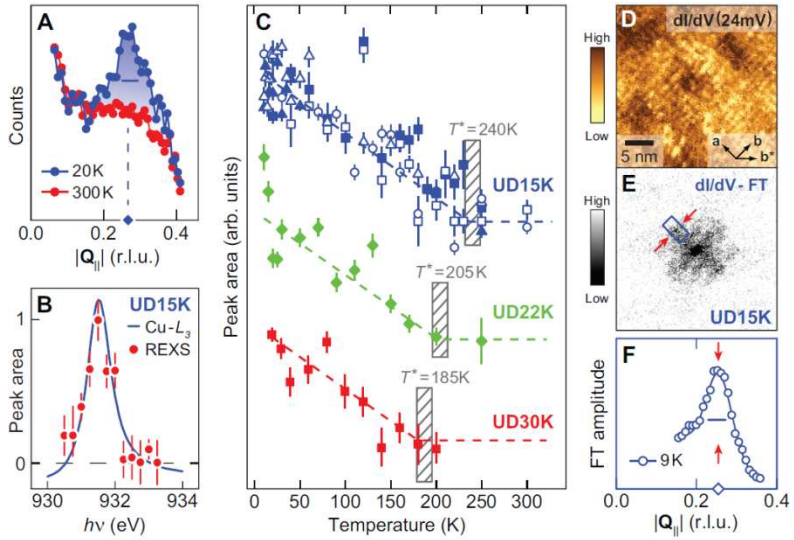
Family		Phase Diagram	Homogeneous	Large Crystals	Cleavable Surfaces
La-based	$La_{2-x}Ba_xCuO_4$ $La_{2-x-y}(Nd,Eu)_ySr_xCuO_4$		NO	YES	So so
Y-based	$YBa_2Cu_3O_{6+x}$ $Y_{1-y}Ca_yBa_2Cu_3O_{6+x}$		YES	YES YES	NO NO
Bi-based	$Bi_2Sr_{1+y}La_{1-y}CuO_{6+x}$ $Bi_2Sr_2Ca_{1-y}Y_yCu_2O_{8+x}$ $Bi_2Sr_2Ca_2Cu_3O_{10+x}$		NO NO NO	NO NO NO	YES
Hg-based	$HgBa_2CuO_{4+x}$ $HgBa_2CaCu_2O_{6+x}$ $HgBa_2Ca_2Cu_3O_{8+x}$		YES ? ?	YES NO NO	NO
Tl-based	$Tl_2Ba_2CuO_{6+x}$ $Tl_2Ba_2CaCu_2O_{8+x}$ $Tl_2Ba_2Ca_2Cu_3O_{10+x}$		YES ? ?	NO NO NO	So so

Adapted from J. Bobroff, Ann. Phys-Paris **30**, 1 (2005)

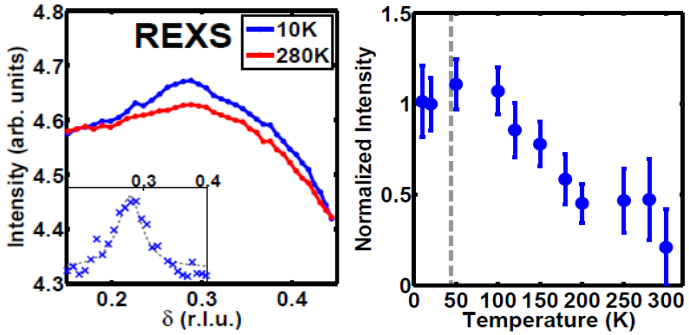
‘Universality’ of the CDW ?

$Bi_2Sr_{1+y}La_{1-y}CuO_{6+x}$ Comin et al. Science **343** 390 (2014)

REXS peak coincides with STM checkerboard

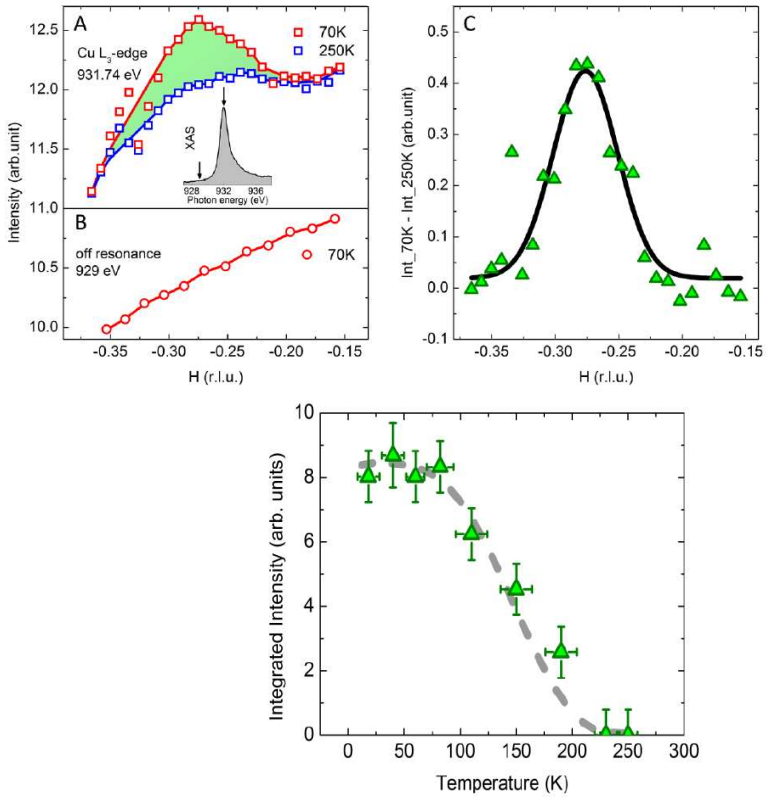


Bi2212 Da Silva Neto et al. Science **343** 393 (2014)



$HgBa_2CuO_{4+x}$ (p =0.09, T_c = 72 K)

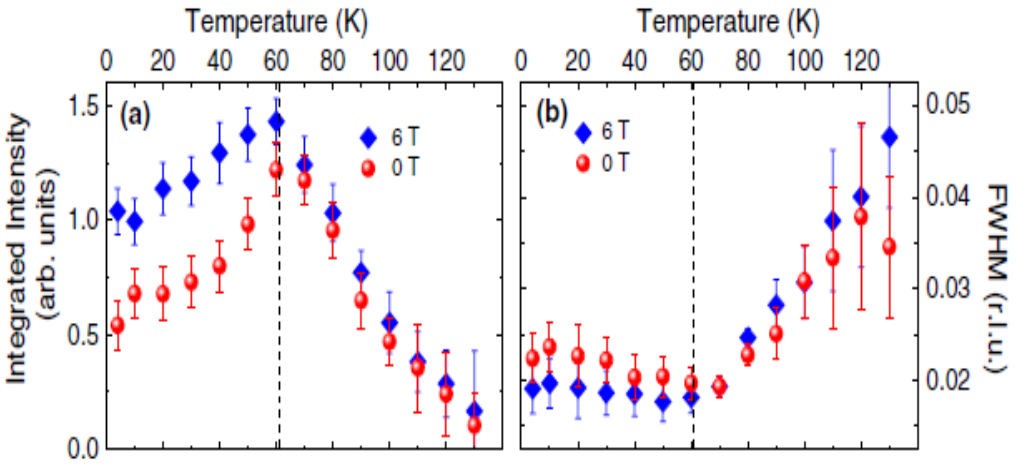
Tabis et al. (Nat. Com. 5 5875 (2014))



Charge peaks in underdoped YBCO, Bi2201, Bi2212, Hg1201 with comparable δ_{CDW}

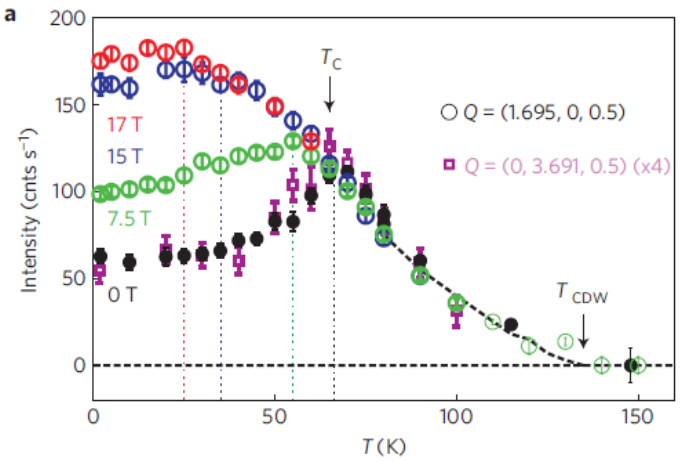
T- & H-dependence in $YBa_2Cu_3O_{6+x}$

REXS @ BESSY



Blanco-Canosa et al. PRL **110** 187001 (2013)

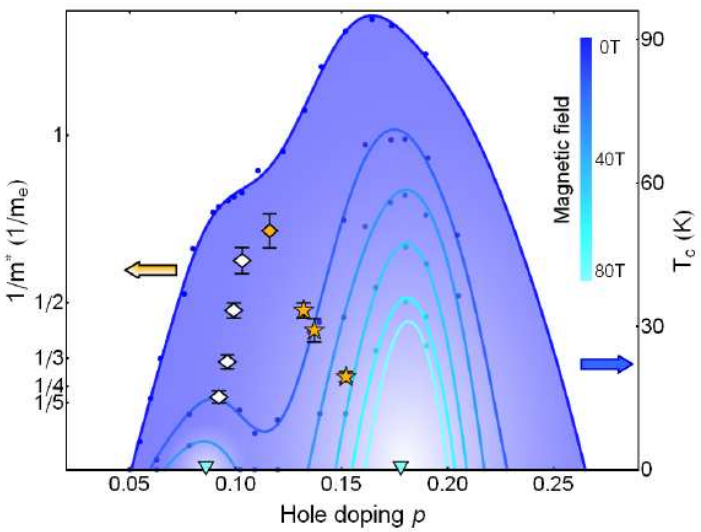
XRD @ DESY



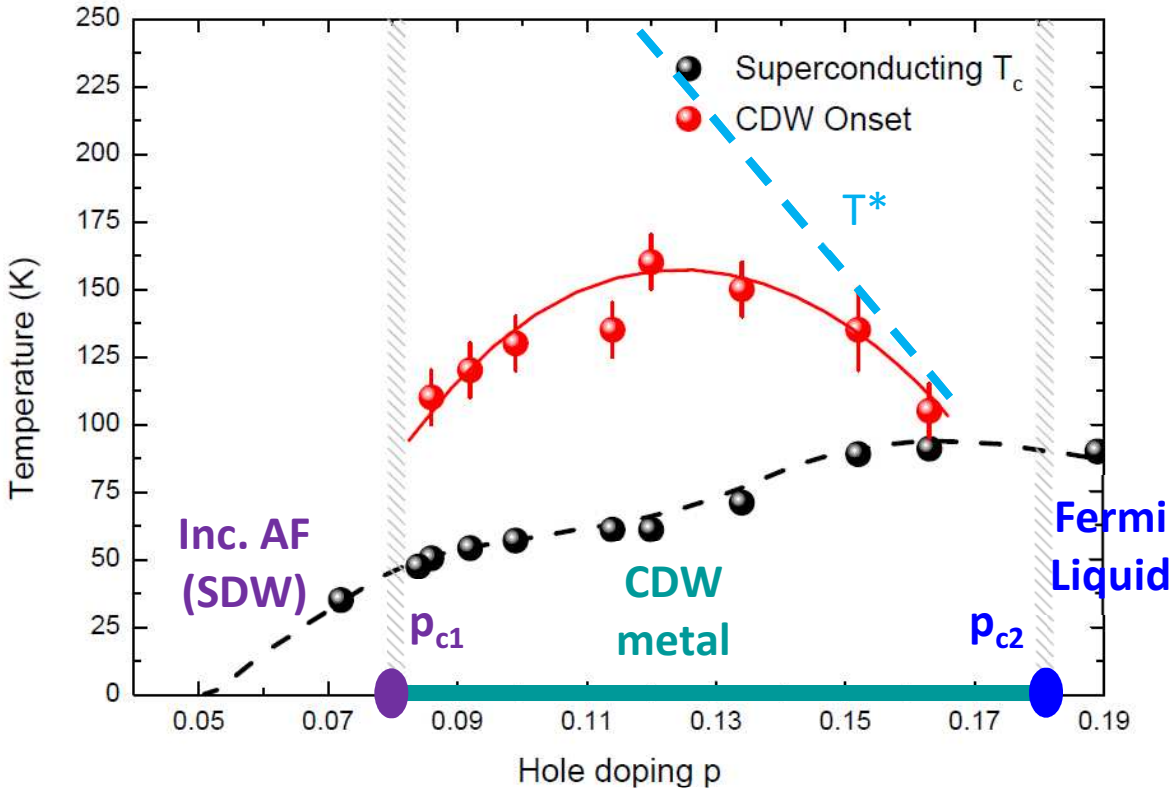
Chang et al. Nat.Phys. **8** 871 (2012)

- Clear evidence for a **competition with superconductivity**
- Absence of thermodynamic phase transition + ξ(T):
  Fluctuations of an incipient order?
- T_{CDW} **< T***

Temperature and doping dependence



Ramshaw et al. arxiv:1409.3990



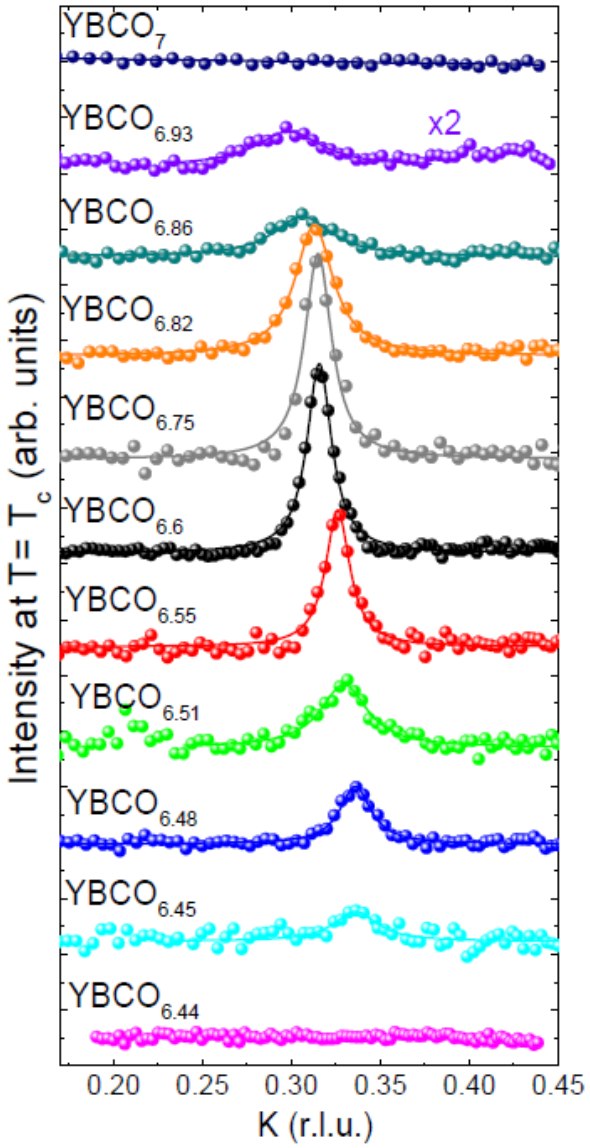
$T_{CDW}(p)$ is dome like ≠ T*: **CDW is not the Pseudogap**

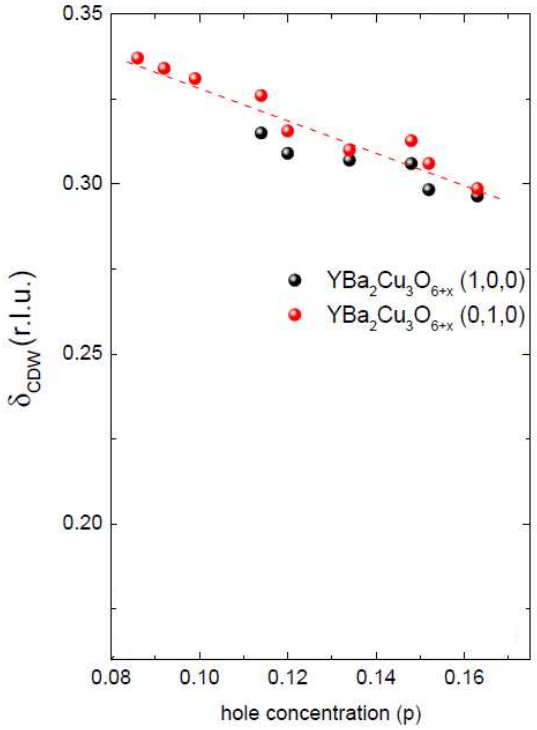
CDW exists in the region where
QOs are seen and transport indicates a **FS reconstruction**

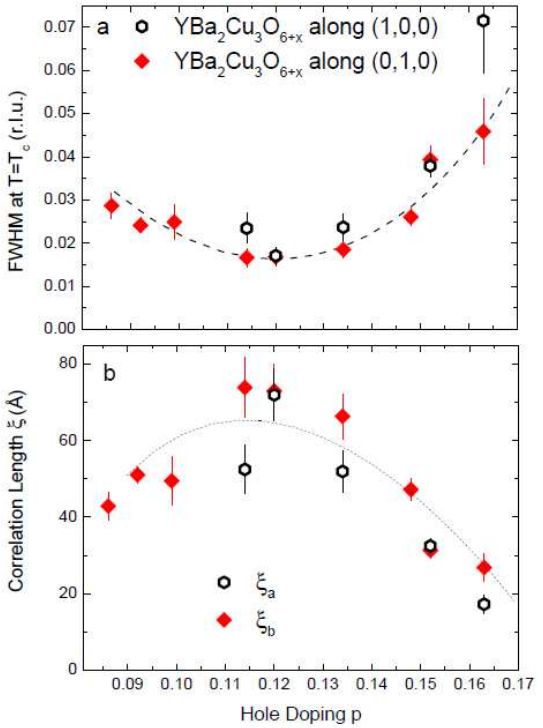
2 quantum critical points under the dome ?

cf. Hc_2 (Grissonnanche et al. Nat. Comm. **5** 3280 (2014)),
QOs (Ramshaw et al. arxiv:1409.3990) & STM (Fujita et al. Science **344** 612 (2014))

Doping dependence in $YBa_2Cu_3O_{6+x}$



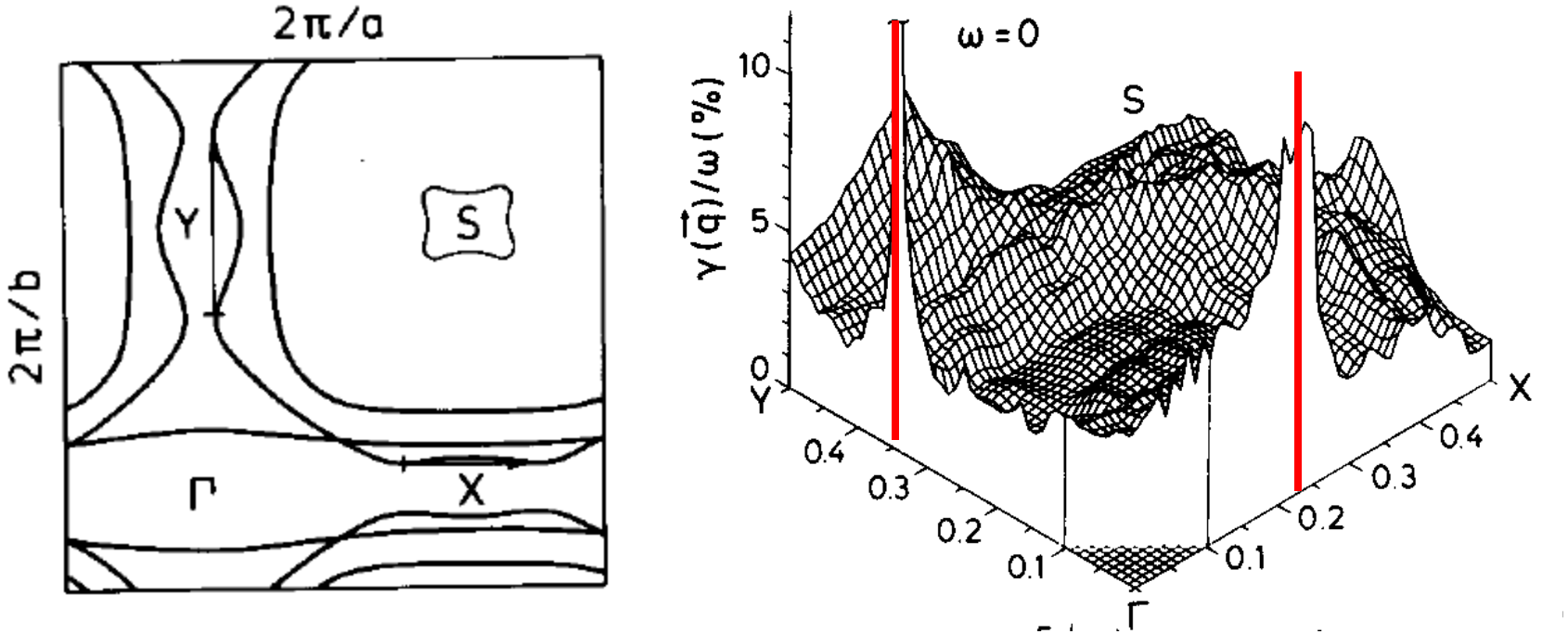




- CDW for doping levels $0.08 < p < 0.16$
- ξ, intensity, T_{CDW} max around p ~0.12
- δ_{CDW} **decreases** with increasing doping (*link with the Fermi Surface ?*)

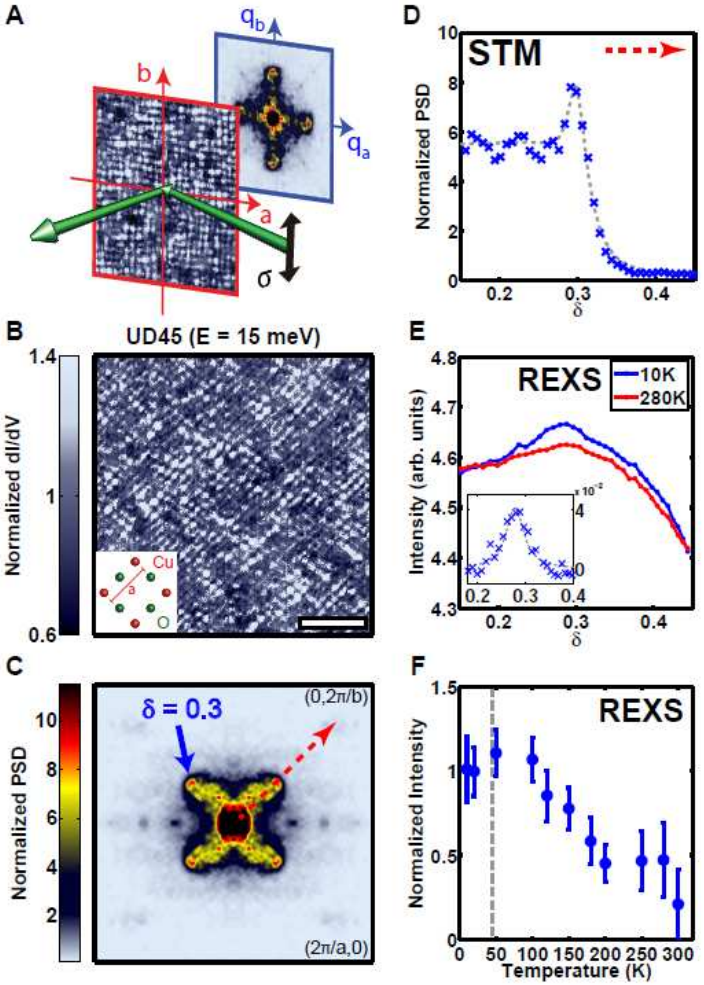
Blanco-Canosa et al. PRB **90**, 054513 (2014)
Huecker et al. PRB **90**, 054514 (2014)

Case of YBCO: Fermi Surface Nesting ?

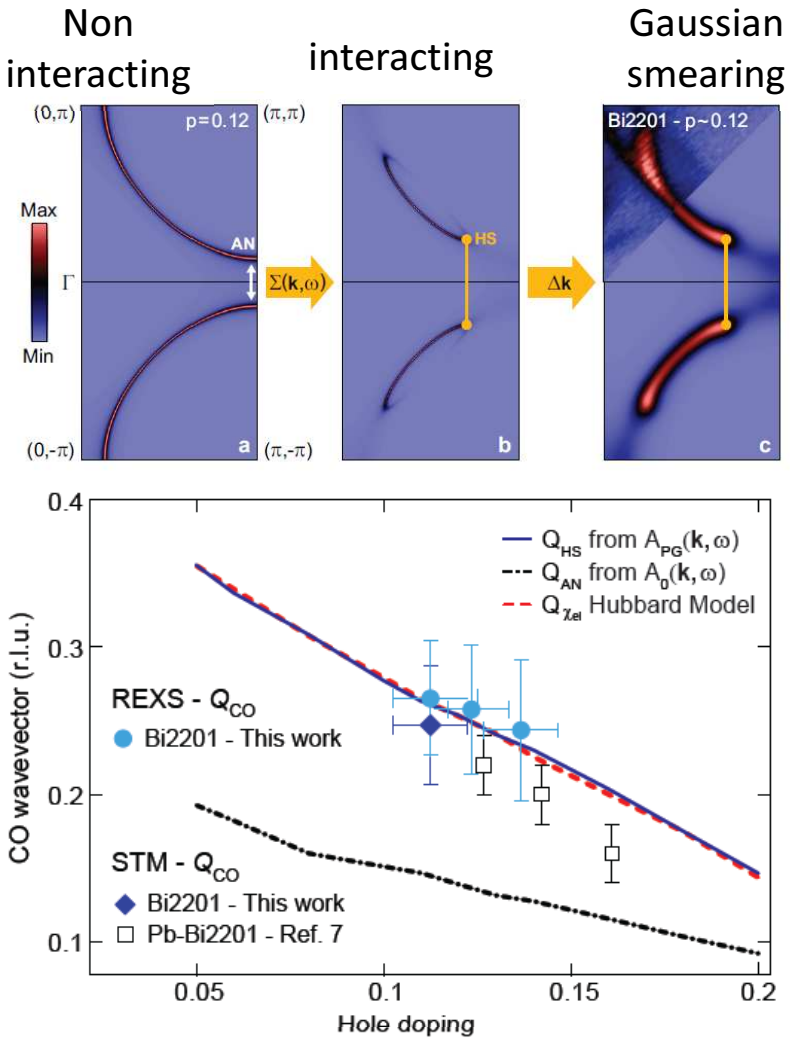


O.K. Andersen et al. Physica C 1991

Any nesting in underdoped cuprates (Bi-based)?



E. H. Da Silva Neto et al. Science **343** 393 (2014)

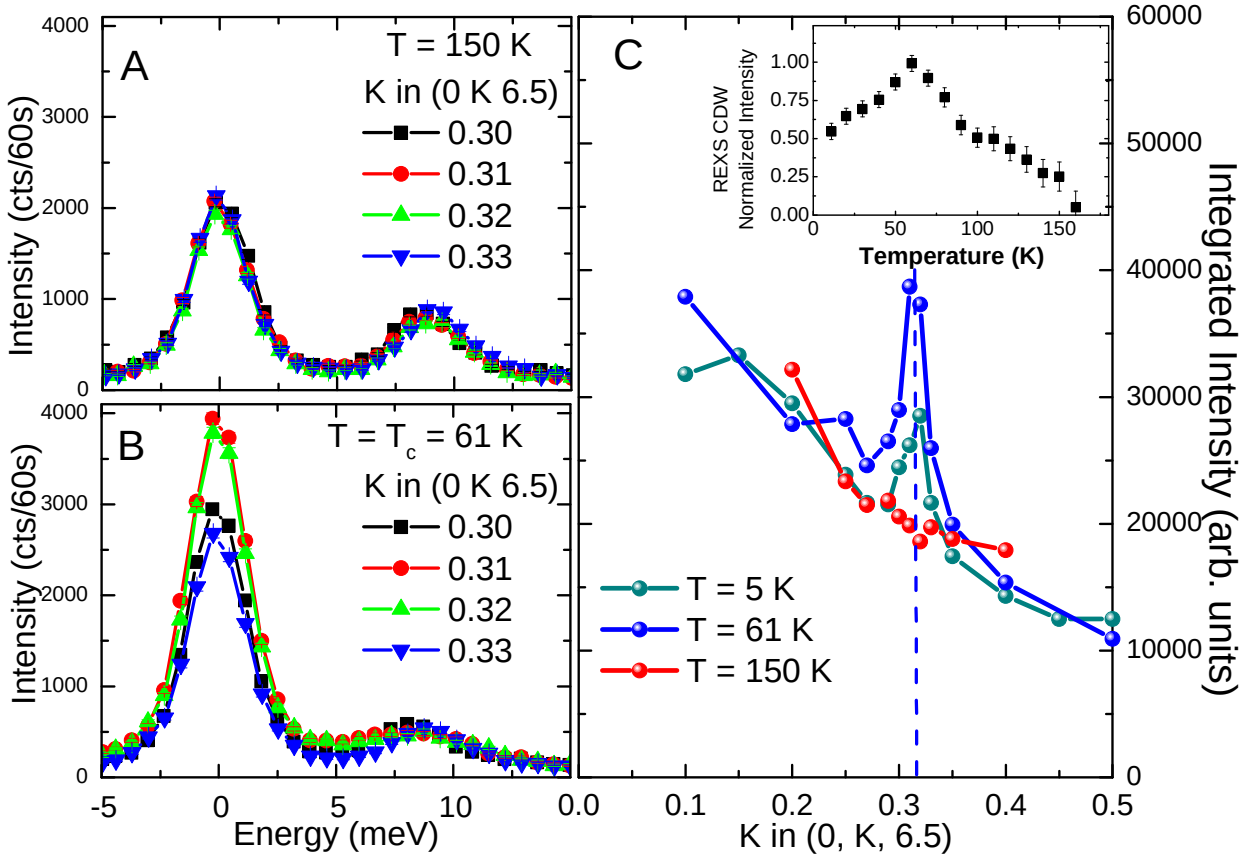


R. Comin et al. Science **343** 390 (2014)

Incipient Instability of the Pseudogap Fermi Surface ?

Static order vs fluctuations?

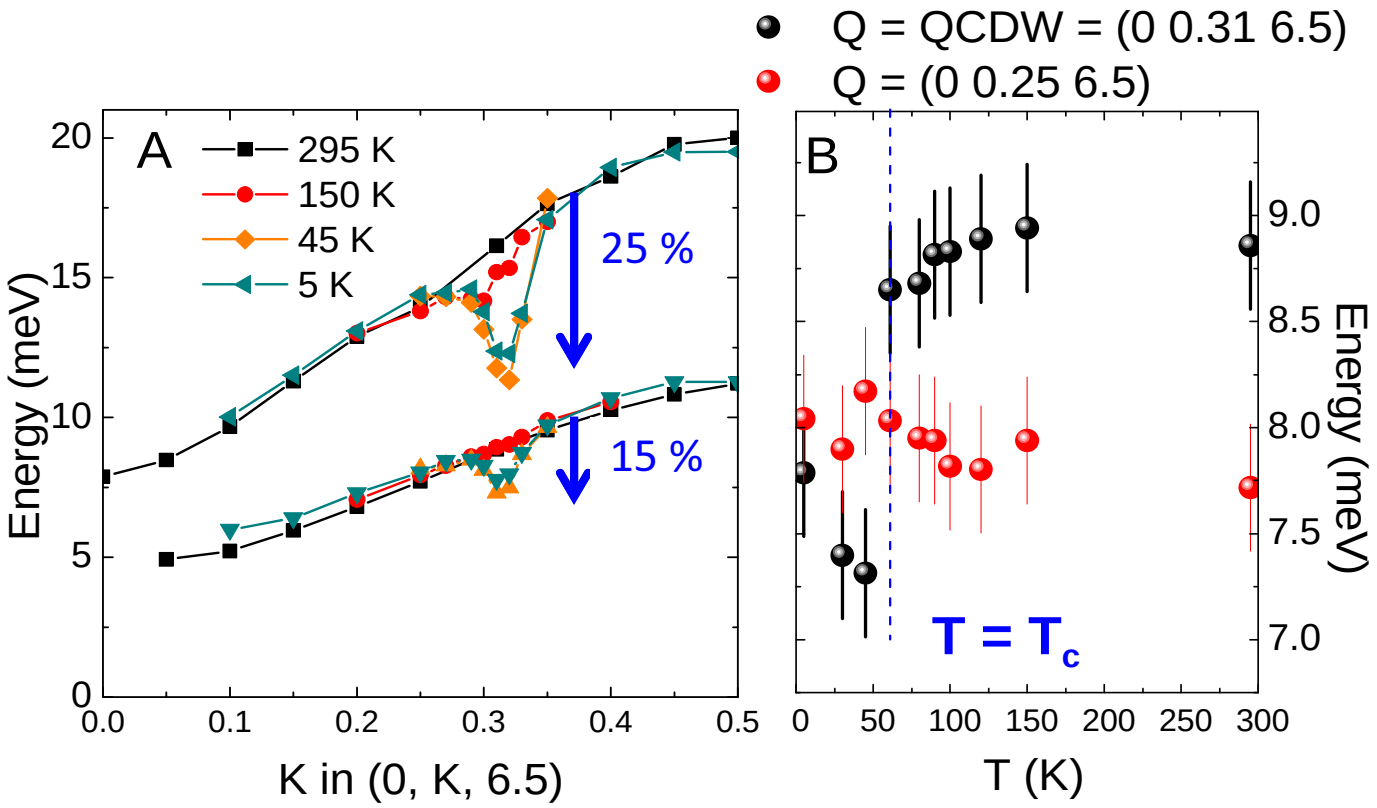
High resolution inelastic x-ray scattering



MLT et al. Nature Physics 10, 52 (2014)

- 'central peak' analogous to that seen in 'classical' phase transitions
- "Slow" fluctuations: pinning of CDW nanodomains (ξ~5-6nm) on defects
  (cf. NMR T. Wu et al. Nat. Com. **6** 6438 (2015))

Superconductivity induced phonon-renormalization (YBCO)



GIANT superconductivity induced phonon renormalization at Q_{CDW}

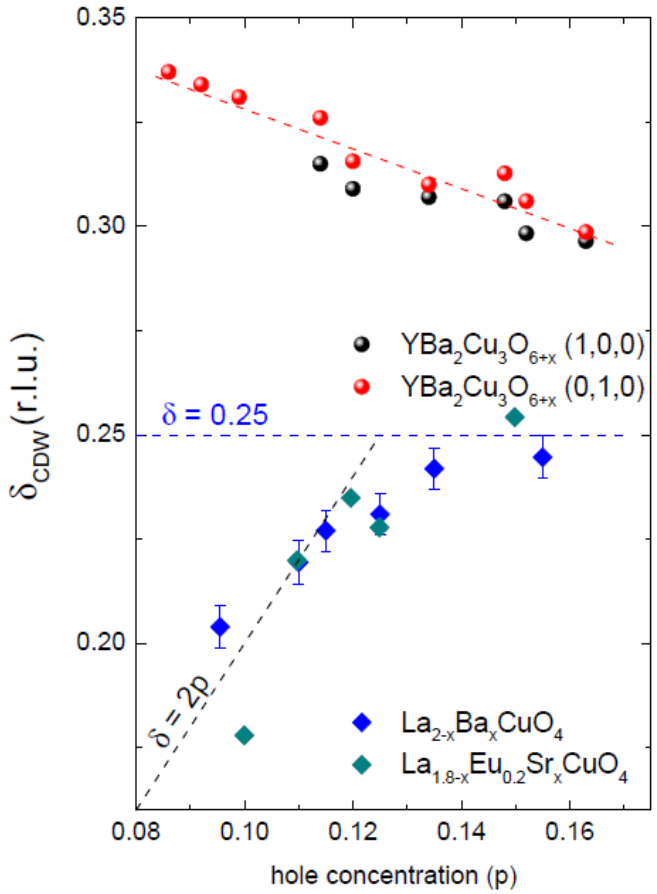
Kohn anomaly feature in the SC state: Fermi Surface effect

Soft phonon but no soft-mode driven CDW

Are 214 stripes & 123 CDW two sides of the same coin ?

A disturbing difference… opposite doping dependence of δ_{CDW}

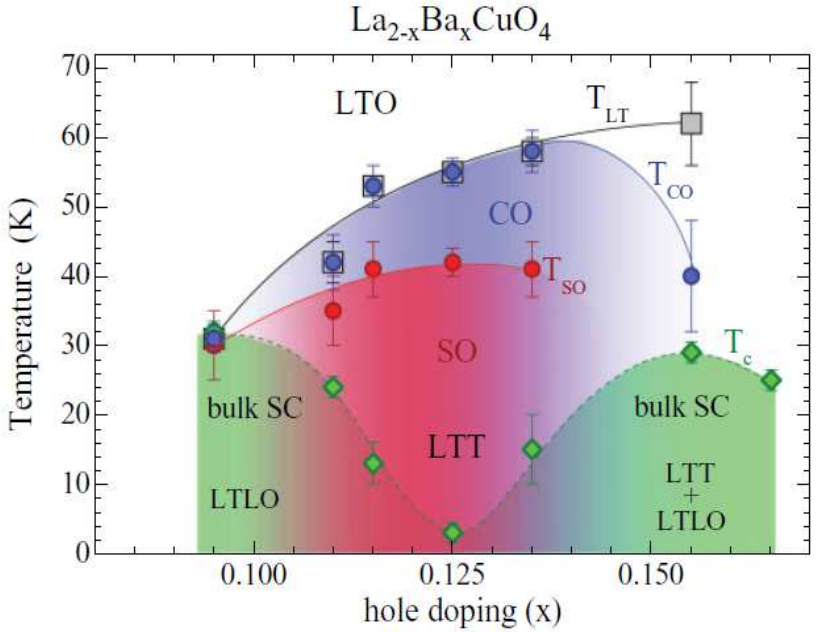
- In 214 charge and spin are locked-in ('stripes')
- in 123 charge and spin appear independent from each other



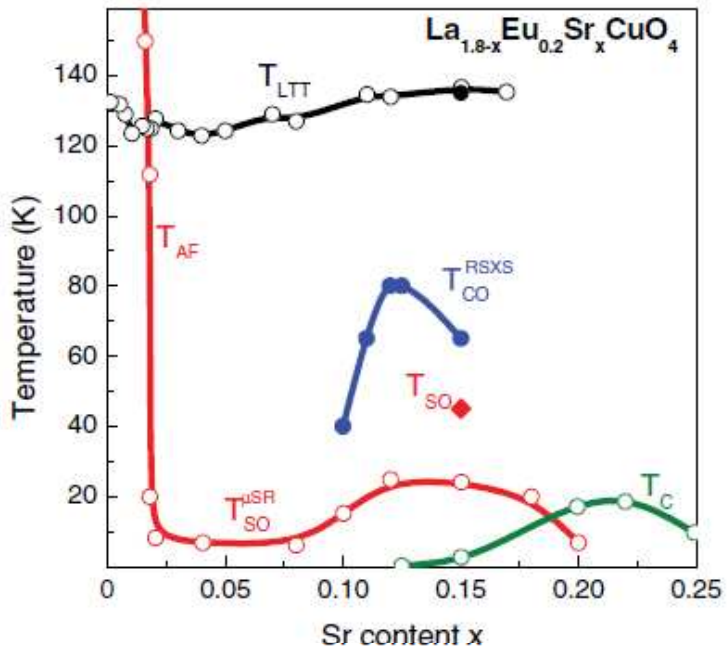
Blanco-Canosa et al. PRB **90**, 054513 (2014)

Are 214 stripes & 123 CDW to sides of the same coin ?

A disturbing difference… but…



Hücker et al. PRB **83**, 104506 (2011)

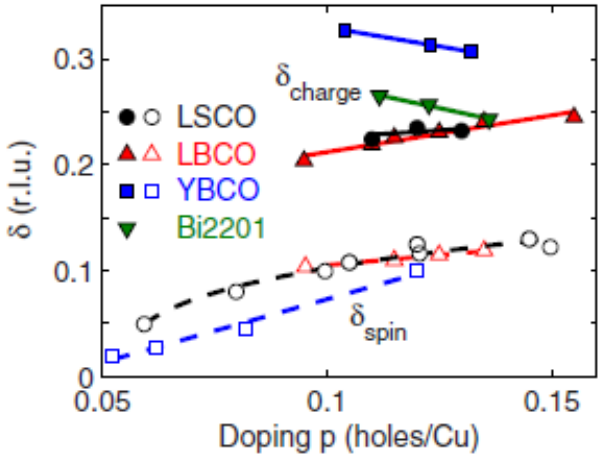


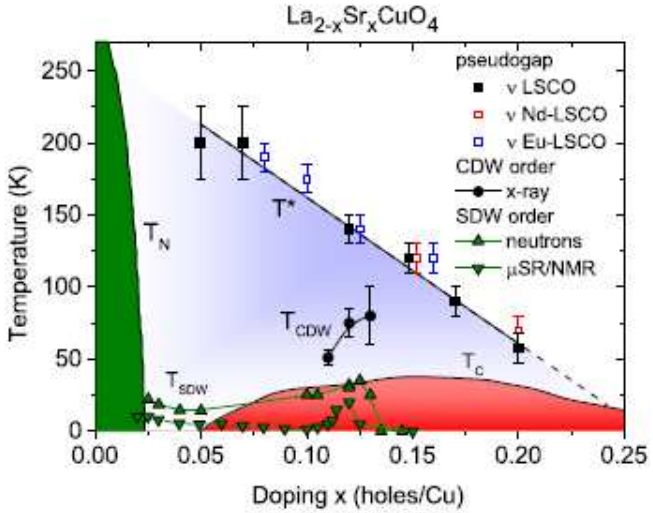
Fink et al. PRB **83**, 092503 (2011)

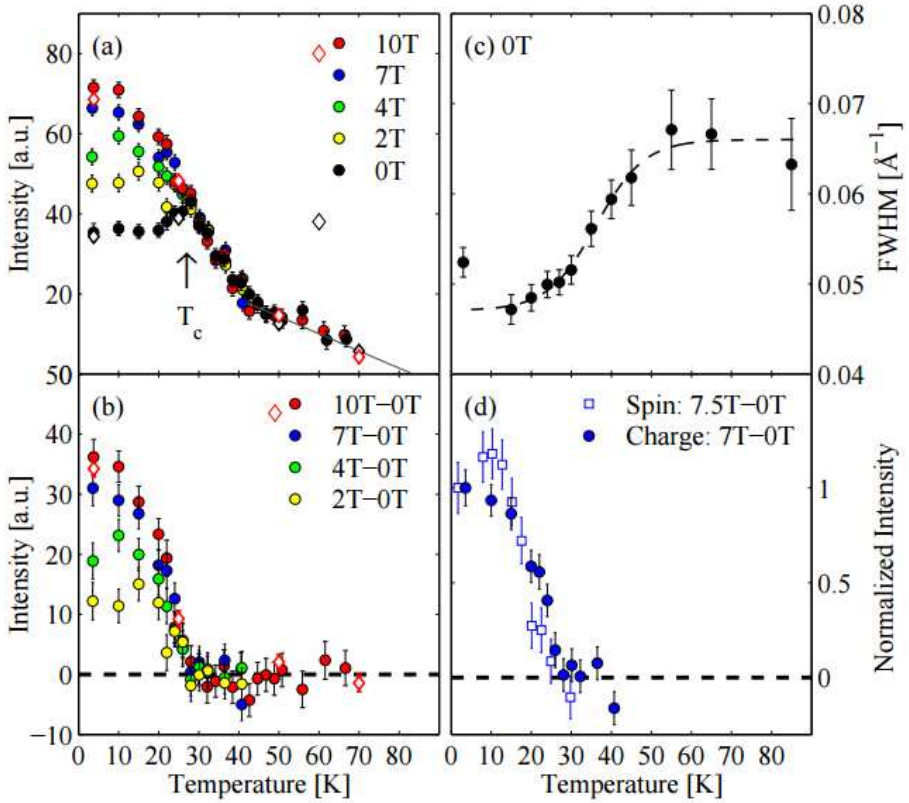
Charge order always appear before spin order in stripes

Does the LTT transition play any role ?

The missing link ?



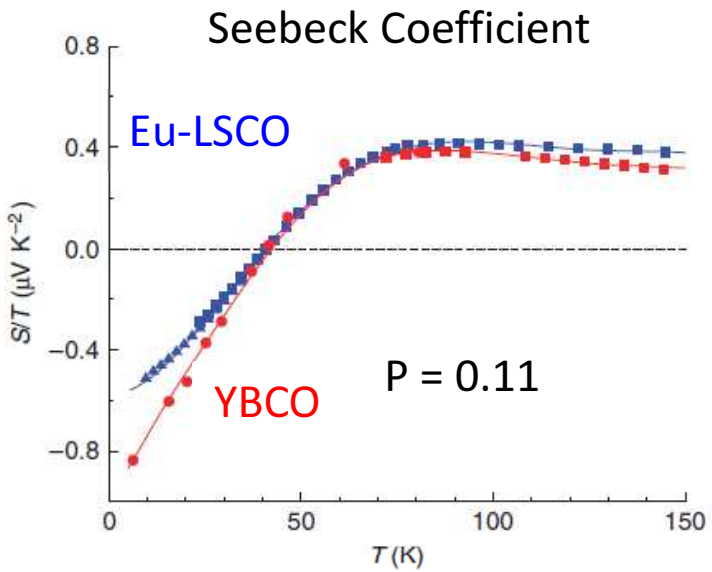




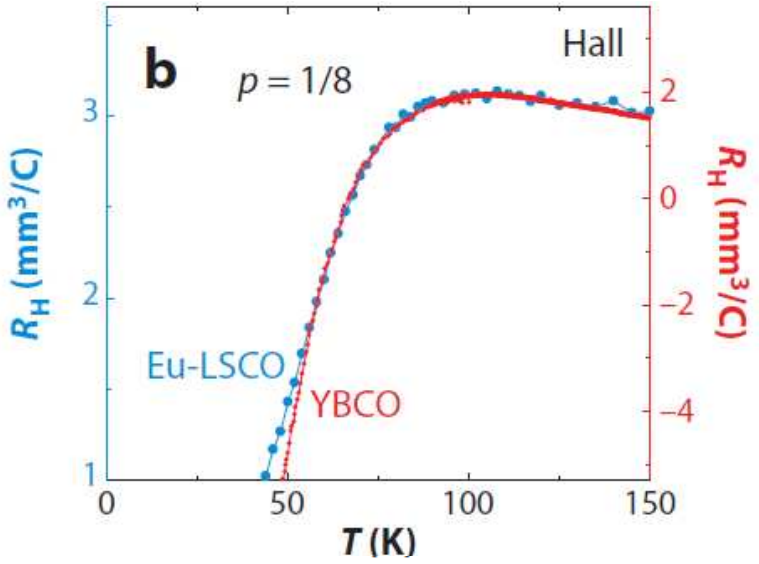
Croft et al. PRB 89 224513 (2014)
Thampy et al. PRB 90 100510 (2014)
N. B. Christensen et al. arxiv:1404.3192

- Similar phenomenology without LTT, but with smaller correlation lengths (~2-3)
- Enhancement of stripes (spin + charge) with Field below Tc only (as for CDW in YBCO)

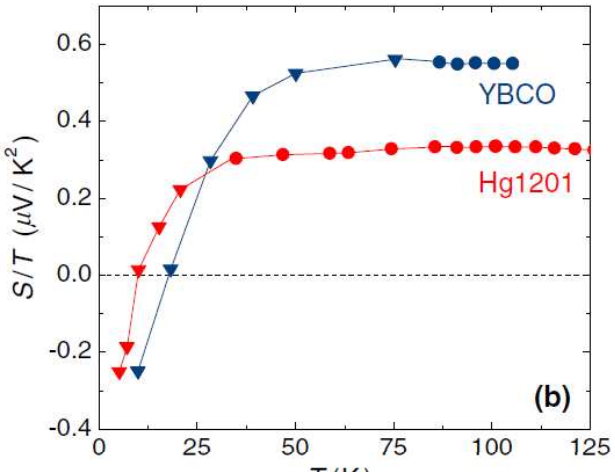
Striking similarities in the transport properties



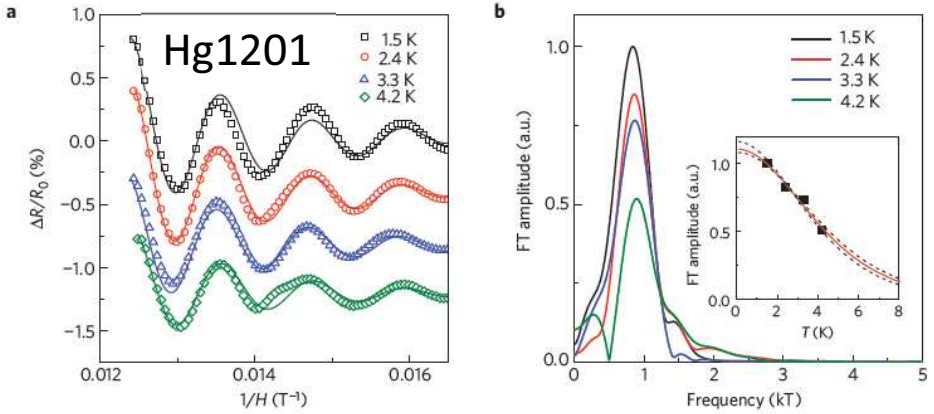
Laliberté et al. Nat. Com. 2, 432 (2011)



Taillefer, L. Annu. Rev. Cond. Matt. Phys. **1** 51 (2010)

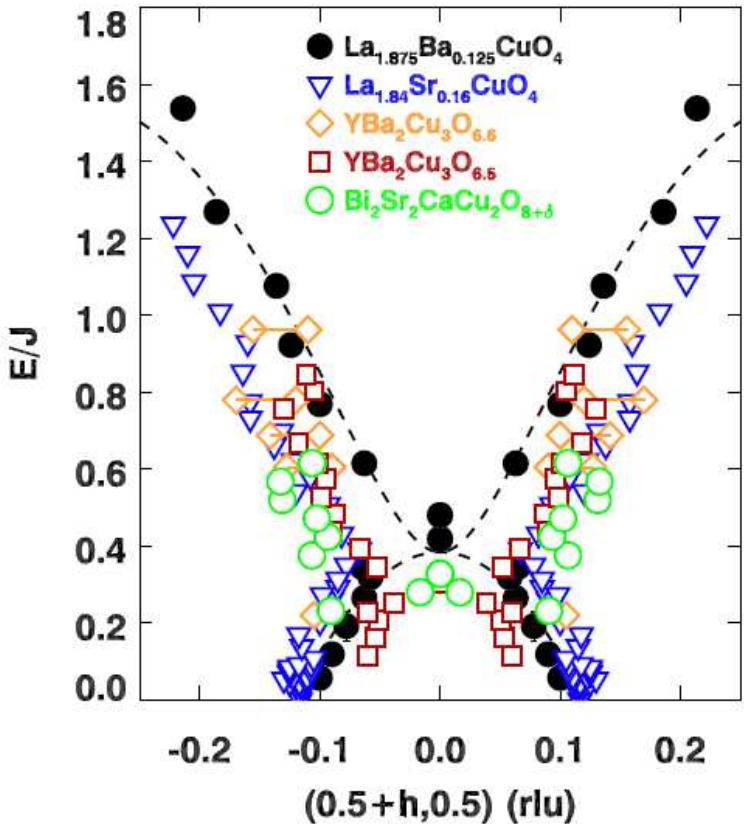


Doiron-Leyraud et al. PRX 3 0210119 (2013)



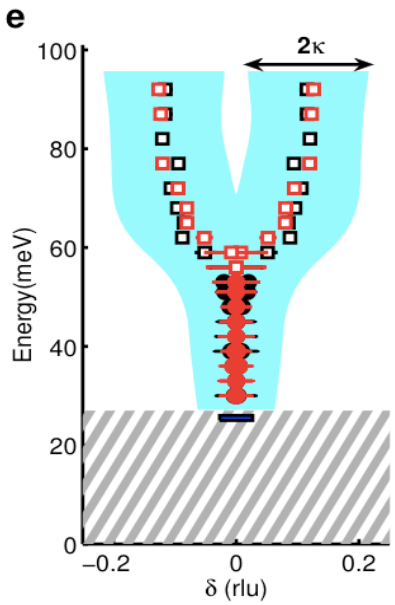
Barisic et al. Nat. Phys. 9 761 (2013)

What about magnetic structure & excitation spectra?



Fujita. et al. JPSJ 81, 011007 (2012)

Hg1201



Chan et al. arxiv:1402.4517

- Universality of the incommensurate magnetic structure challenged

Some thoughts….

1) From Transport: Stripes and CDW at high field yield very similar FSR irrespective of the doping dependence of the incommensurabilities

2) From NMR and sound velocity measurement, a thermodynamic phase transition occurs in YBCO around 15 T below $T \sim T_c(H=0)$
without the slightest hint for spin order

NB: High field Charge Order might be different from the H=0 one

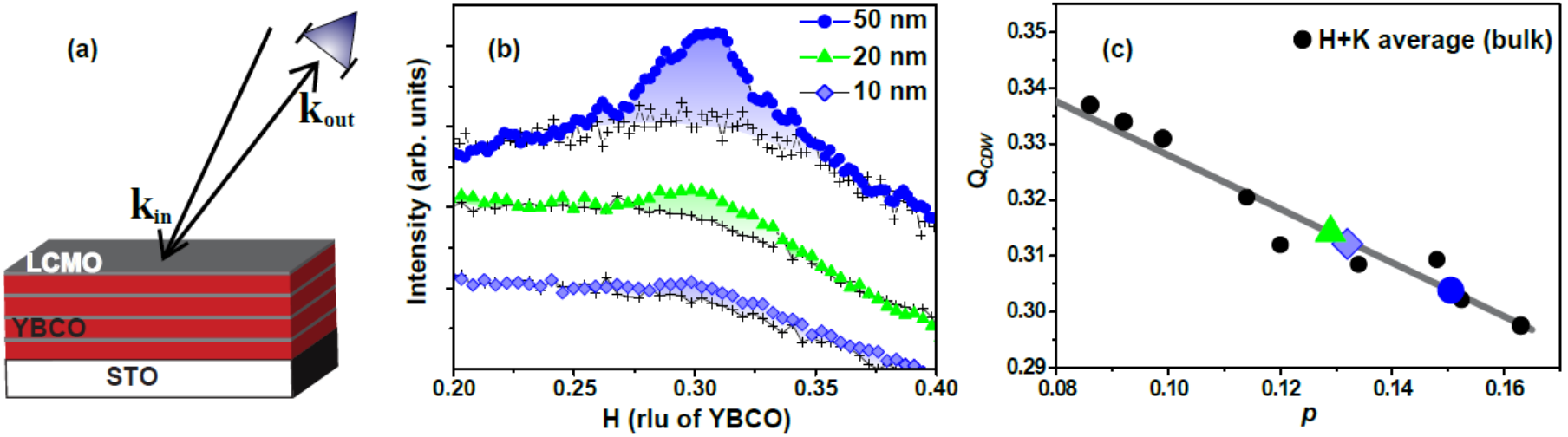
3) details about the spin excitations spectrum (spin gap, incommensurabilities) doesn't seem to matter at all as far as FSR is concerned

The charge is in charge

Bonus: Superlattices of $YBCO_7$/LCMO

Reduced T_c from charge transfer with LCMO

Sample	YBCO Thickness	LCMO Thickness	T_c	T_{Curie}
$(Y\text{-}10\ nm/L\text{-}10\ nm)_{15}$	10 nm	10 nm	45 K	230 K
$(Y\text{-}20\ nm/L\text{-}10\ nm)_{10}$	20 nm	10 nm	60 K	220 K
$(Y\text{-}50\ nm/L\text{-}10\ nm)_5$	50 nm	10 nm	82 K	230 K

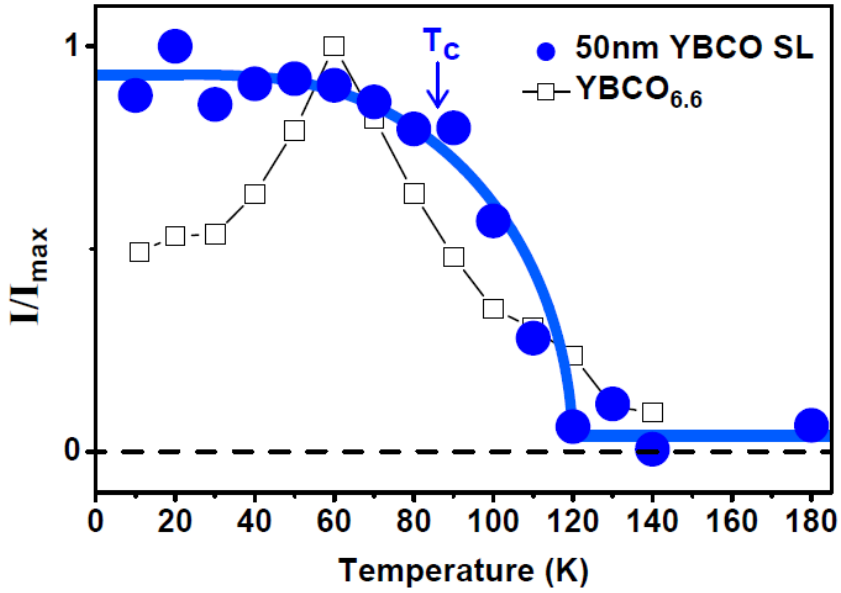


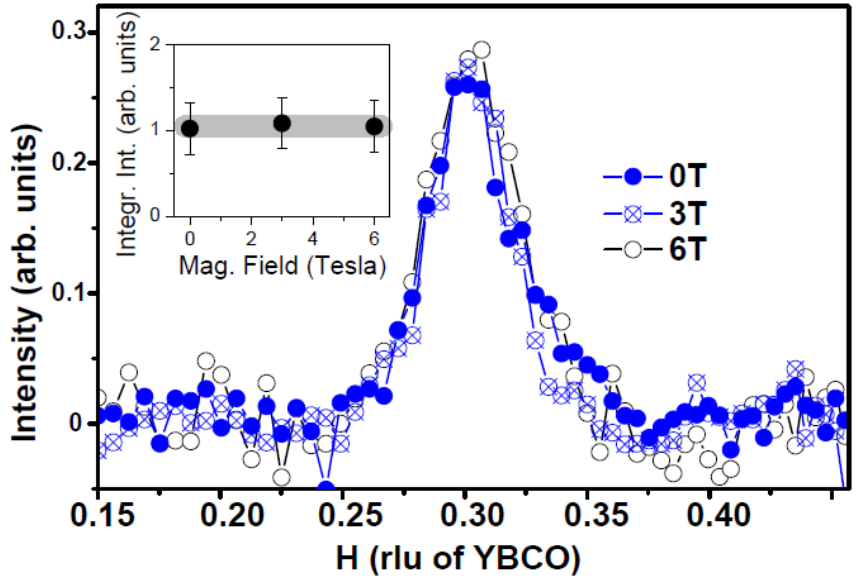
Unlike in the bulk, CDW from YBCO7

'Effective' doping in the YBCO layer from CDW peak position

Temperature and Field dependence in the SLs

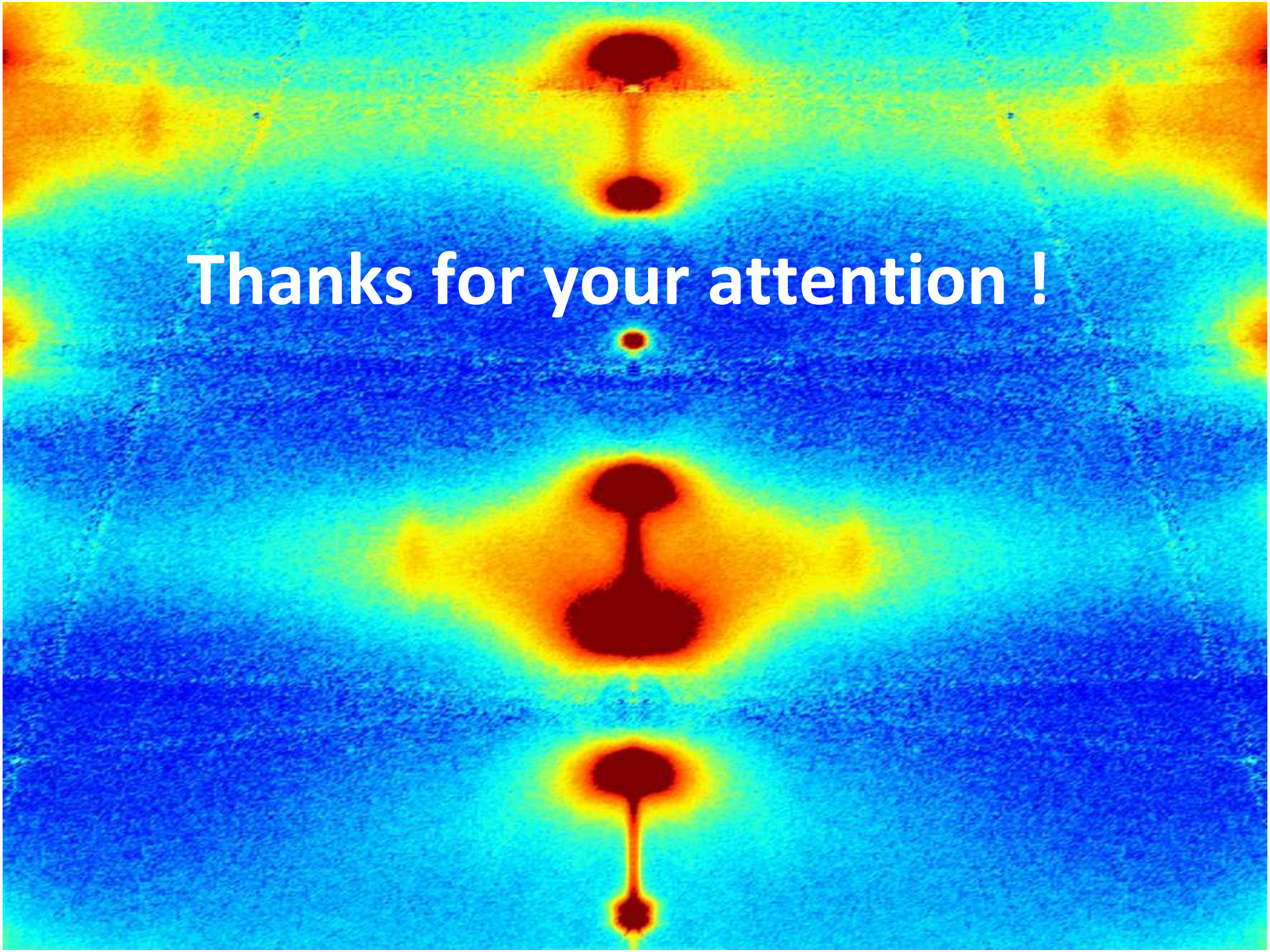
Frano et al. Submitted (2015)





- Order parameter like temperature depedence
- No effect of the magnetic field

Nucleation & Stabilization of the CDW by the hetero-interface


Thanks for your attention !