Cuprate high-T_c superconductivity: Insights from a model system

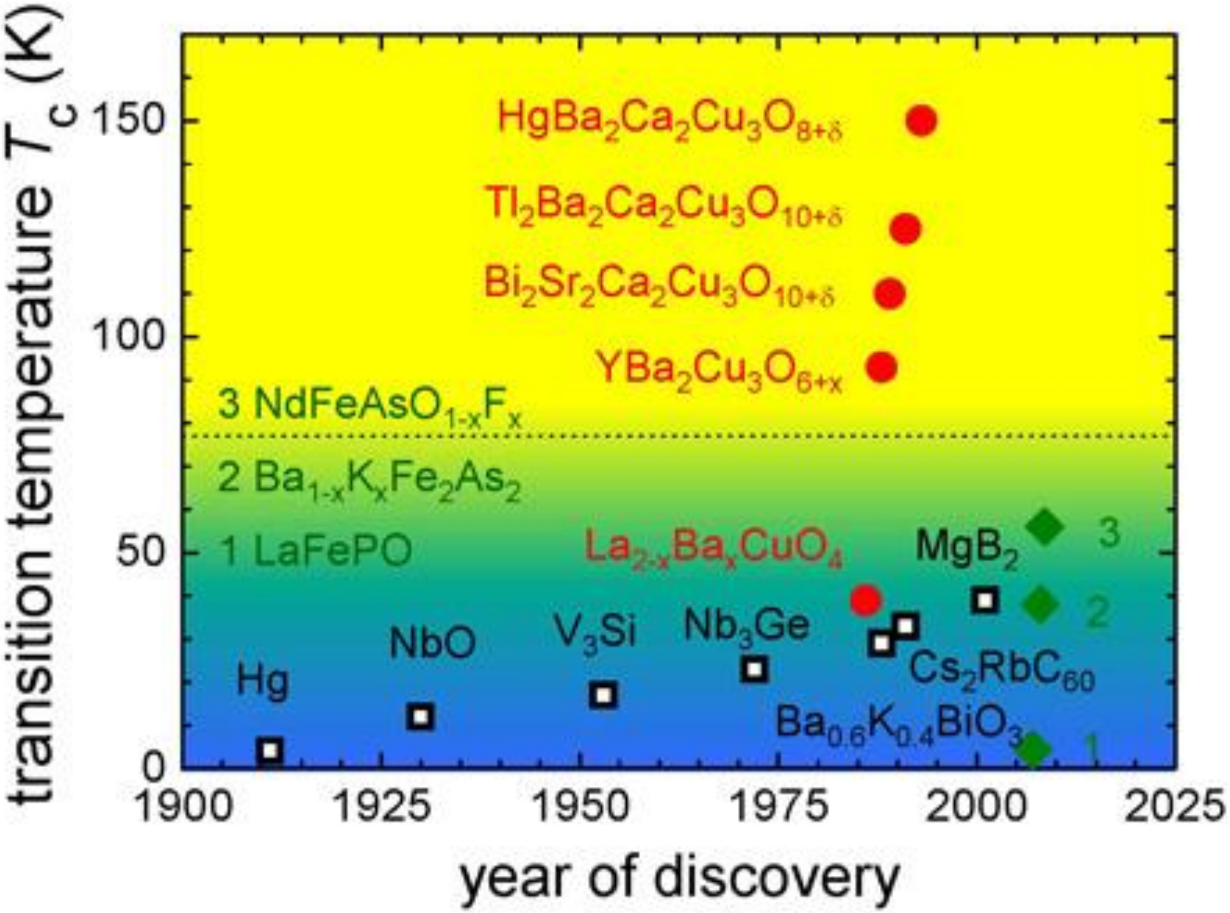
李源

北京大学量子材料科学中心

Outline

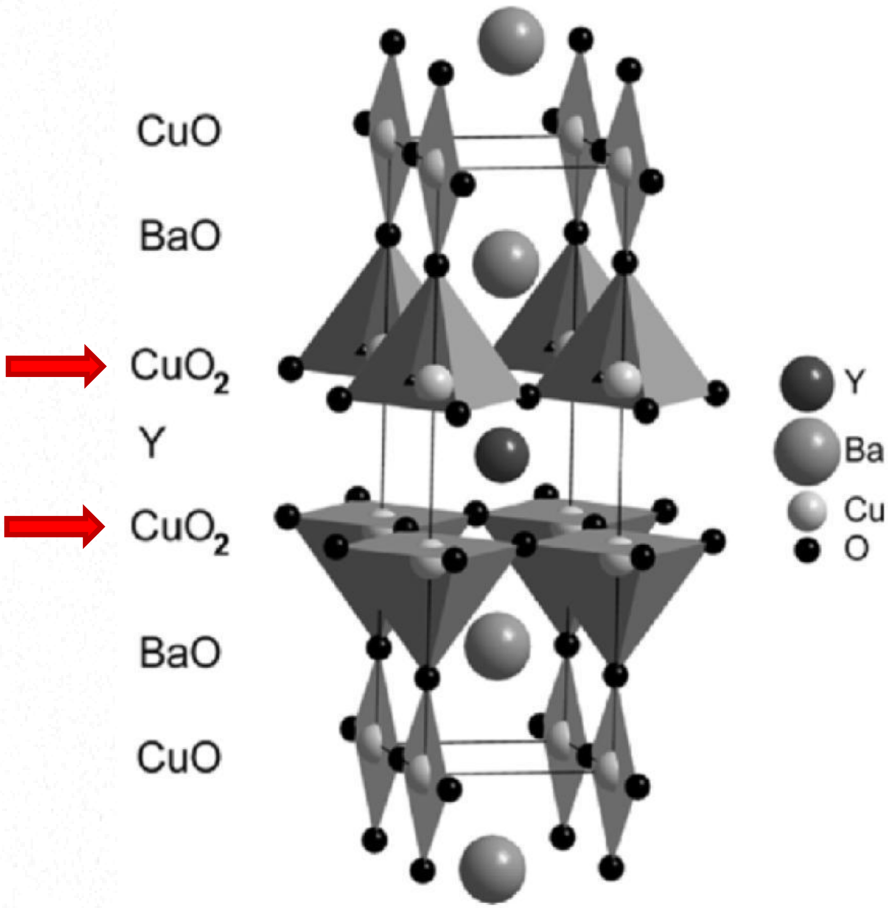
- Introduction
  - HTSC and the cuprates
  - Spectroscopic methods applied to the high-T_c problem
- Model system $HgBa_2CuO_{4+\delta}$
- Topics:
  1. The neutron resonant mode
  2. Pseudogap magnetism
  3. Energy $2\Delta_{sc}$ and above
- Summary

T_c over the years

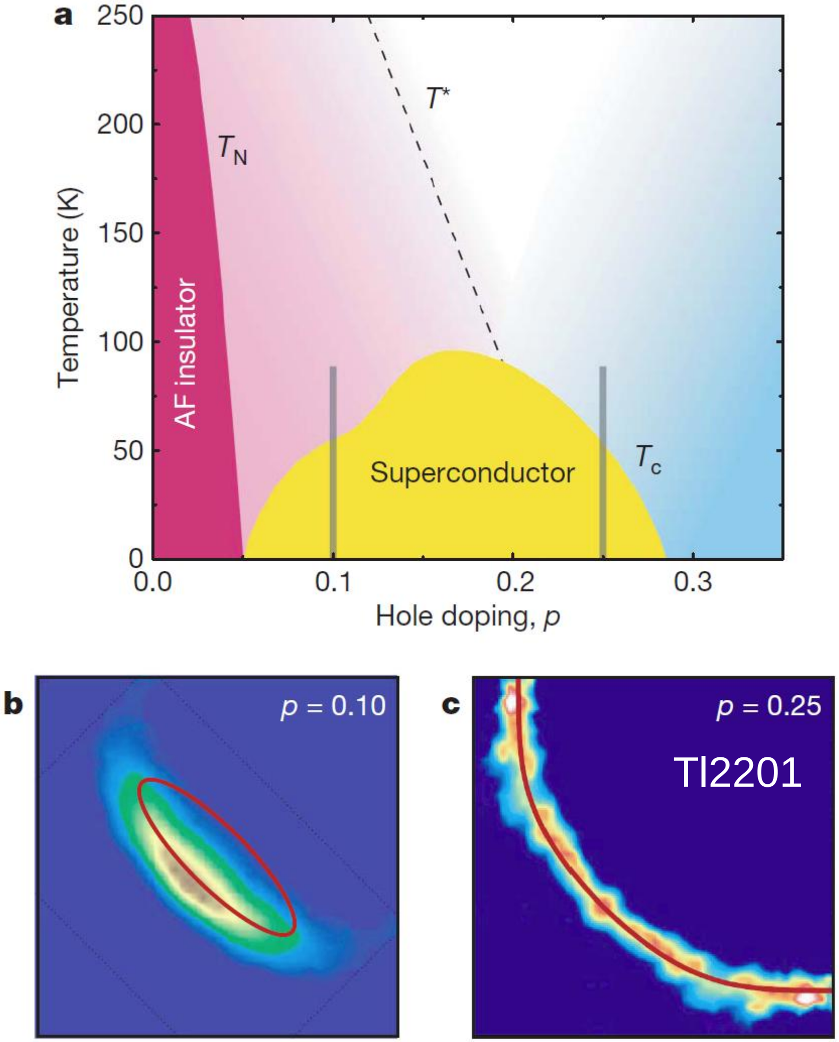


courtesy of Rudi Hackl

Cuprates: crystal and electronic structure

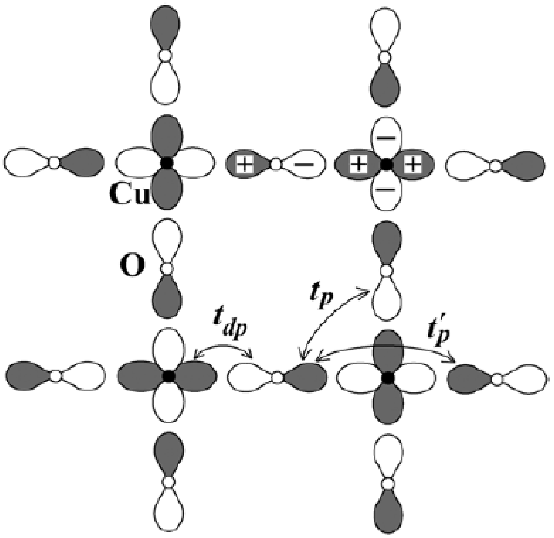


Fisher et al., in *Handbook of high-temperature superconductivity*, Springer (2007)



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

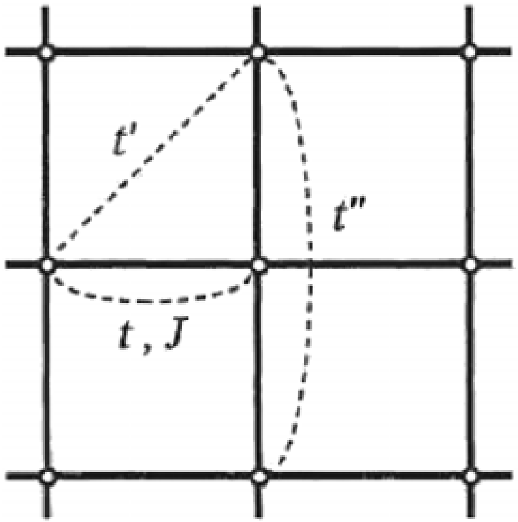
Cuprates: crystal and electronic structure



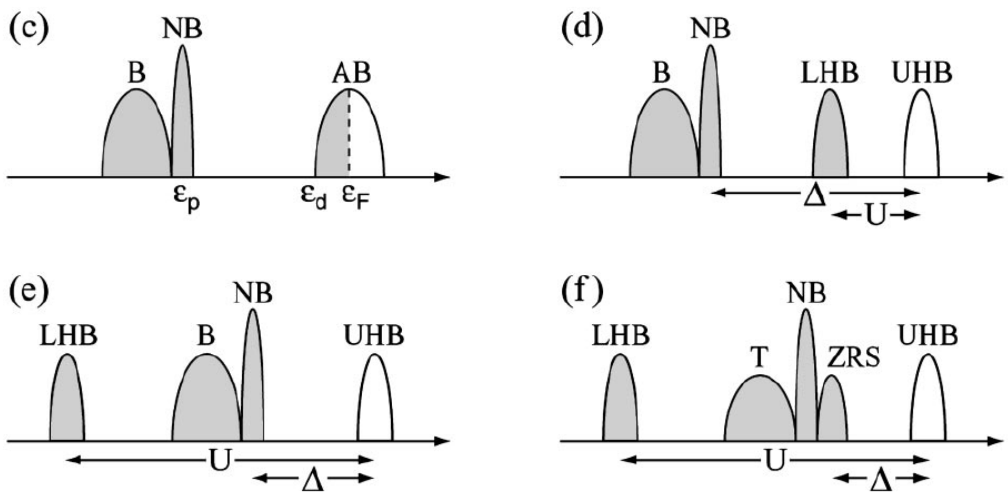
three-band model

$t_{dp} << U$, $t_{dp} << \Delta_{dp}$

t_p, t'_p negligible



t-J model



RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 34, NUMBER 11 1 DECEMBER 1986

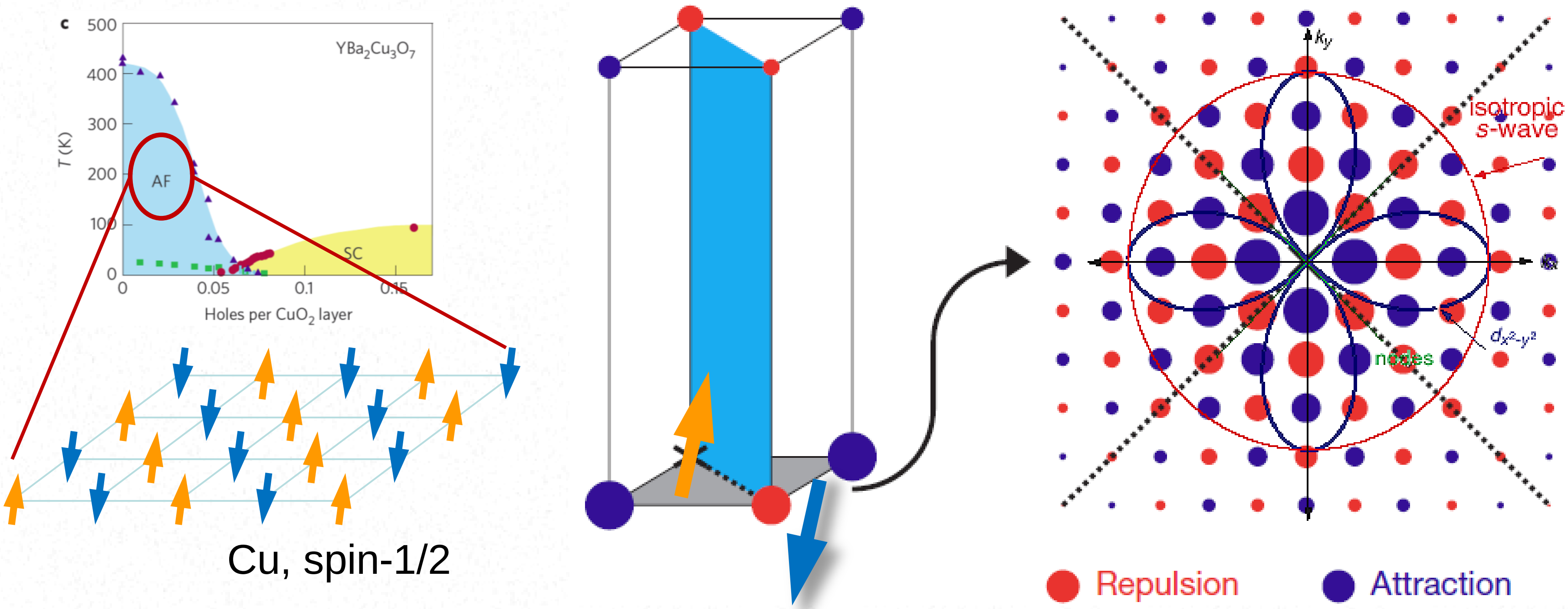
d-wave pairing near a spin-density-wave instability

D. J. Scalapino, E. Loh, Jr.,* and J. E. Hirsch†

Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

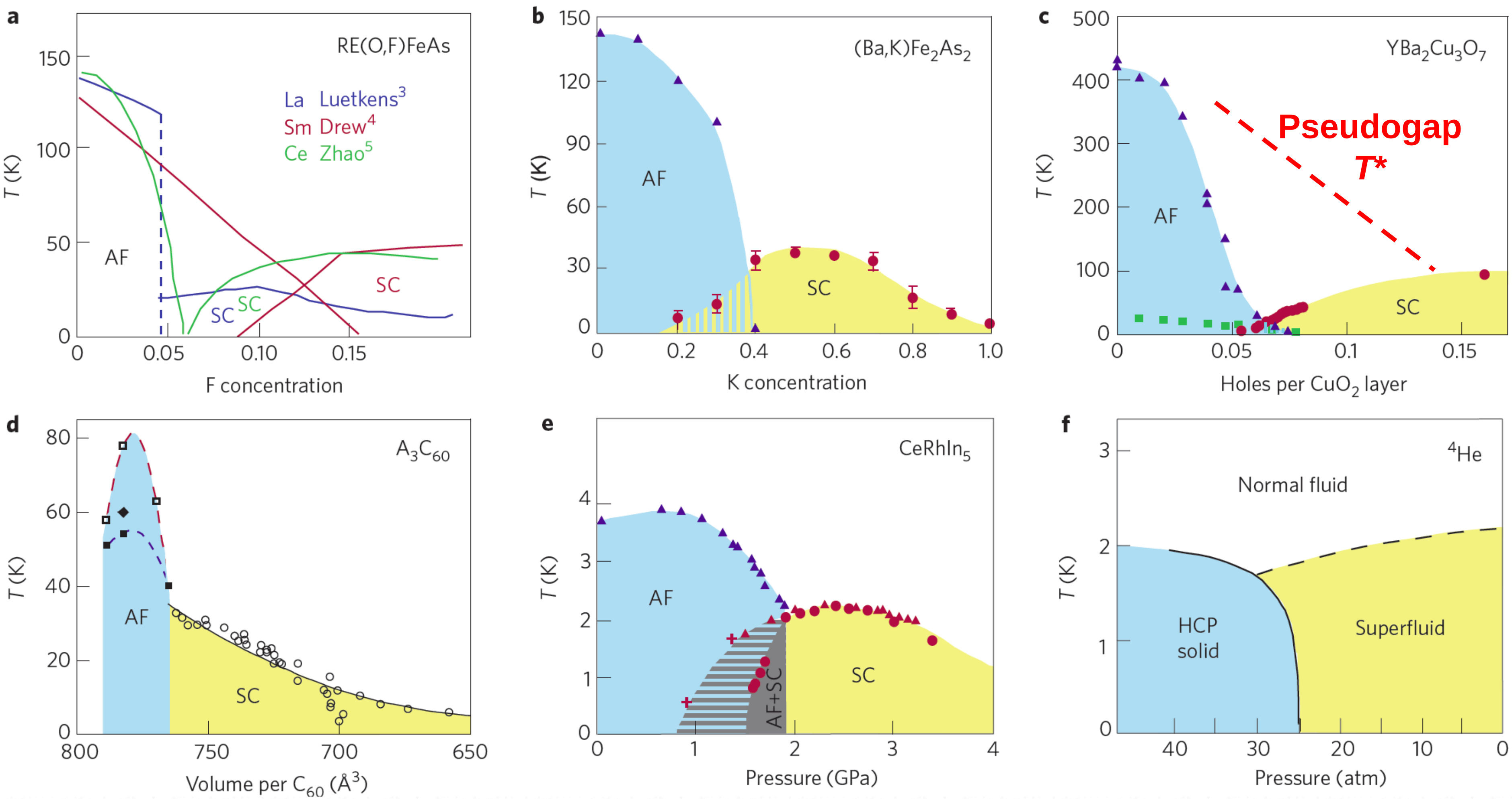
(Received 23 June 1986)

We investigate the three-dimensional Hubbard model and show that paramagnon exchange near a spin-density-wave instability gives rise to a strong singlet d-wave pairing interaction. For a cubic band the singlet $(d_{x^2-y^2}$ and $d_{3z^2-r^2})$ channels are enhanced while the singlet (d_{xy}, d_{xz}, d_{yz}) and triplet p-wave channels are suppressed. A unique feature of this pairing mechanism is its sensitivity to band structure and band filling.



Monthoux, Pines & Lonzarich, *Nature* **450**, 1177 (2006)

Unconventional SC near AF instability



Uemura, *Nature Materials* **8**, 253 (2009)

Some important questions

- Q: What's the pairing symmetry?
- Q: What causes the pseudogap above T_c?
- Q: Is there a competing order other than AFM?
- Q: Which bosonic modes are important?
- Q: What's the minimal microscopic model?

Outline

- Introduction

  - HTSC and the cuprates

  - Spectroscopic methods applied to the high-T_c problem

- Model system $HgBa_2CuO_{4+\delta}$

- Topics:

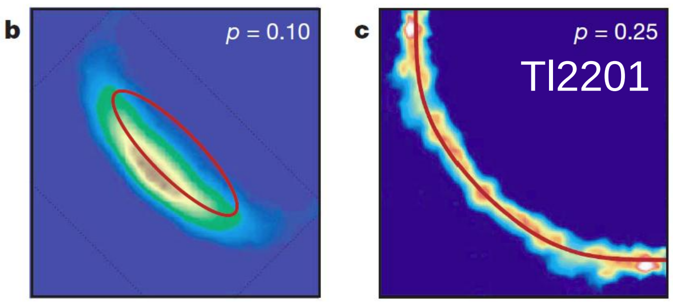
  1. The neutron resonant mode

  2. Pseudogap magnetism

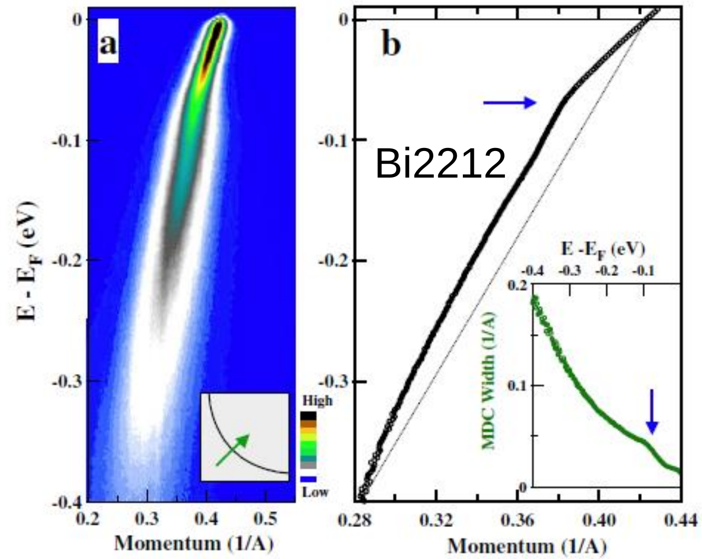
  3. Energy $2\Delta_{sc}$ and above

- Summary

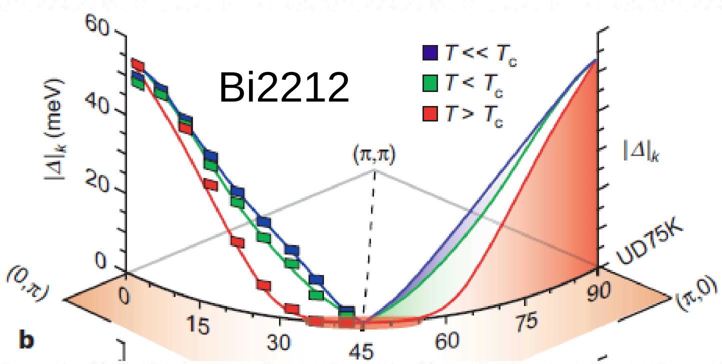
ARPES



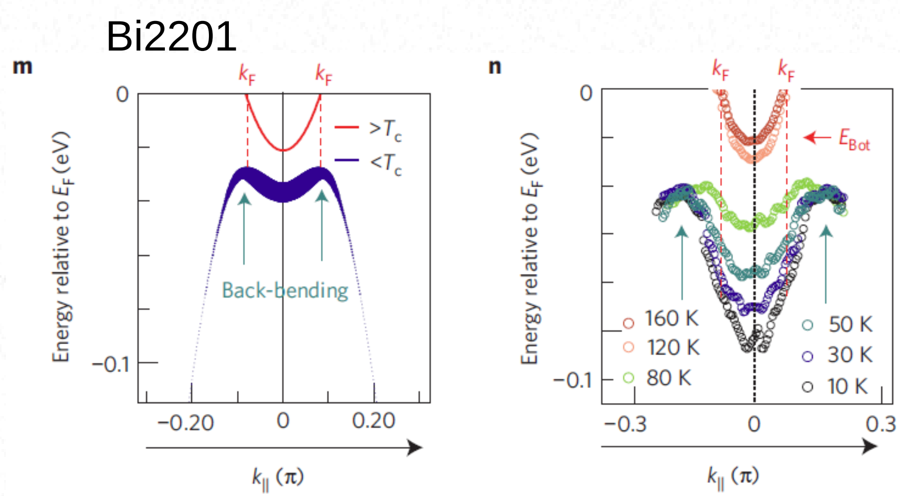
Doiron-Leyraud *et al.*, *Nature* **447**, 565 (2007)



Zhang *et al.*, *PRL* **100**, 107002 (2008)

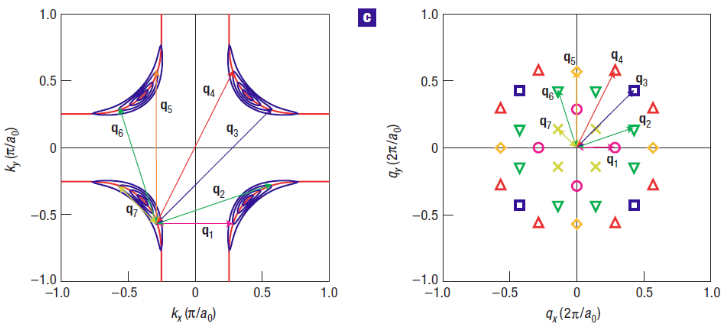


Lee *et al.*, *Nature* **450**, 81 (2007)



Hashimoto *et al.*, *Nat. Phys.* **6**, 414 (2010)

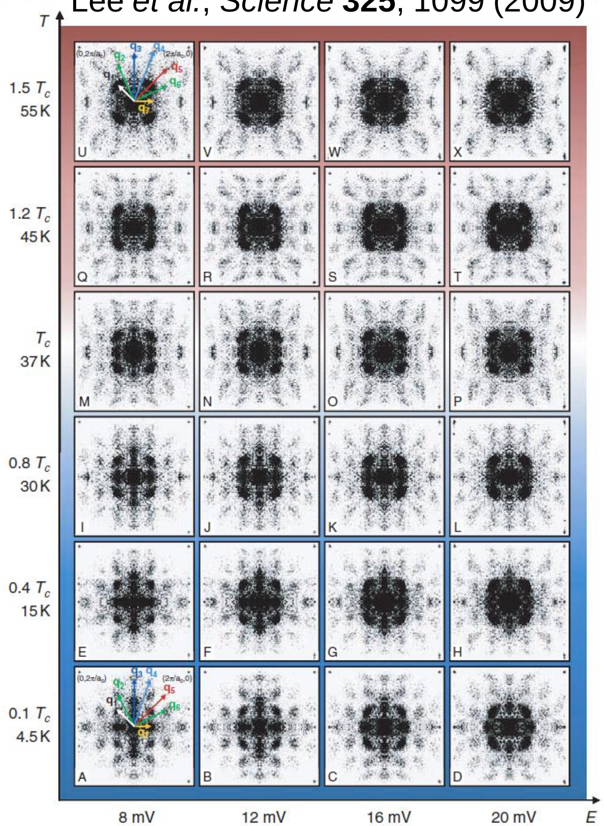
STM/STS

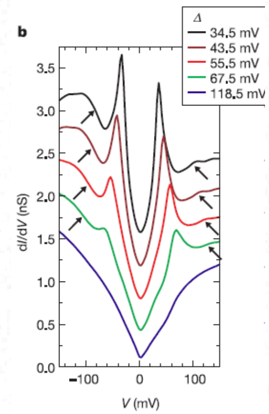


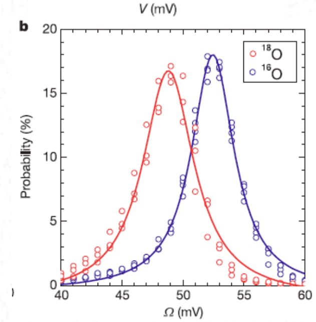
Doiron-Leyraud *et al.*, *Nature* **447**, 565 (2007)

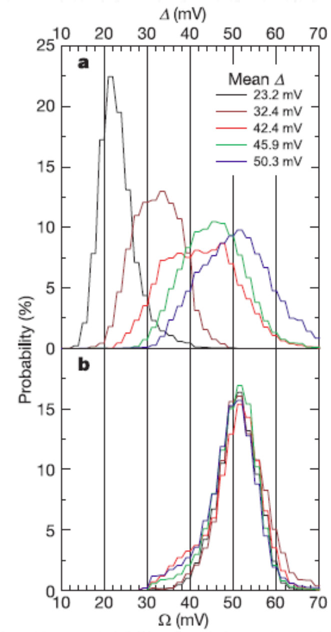
Lee *et al.*, *Science* **325**, 1099 (2009)

Bi2212





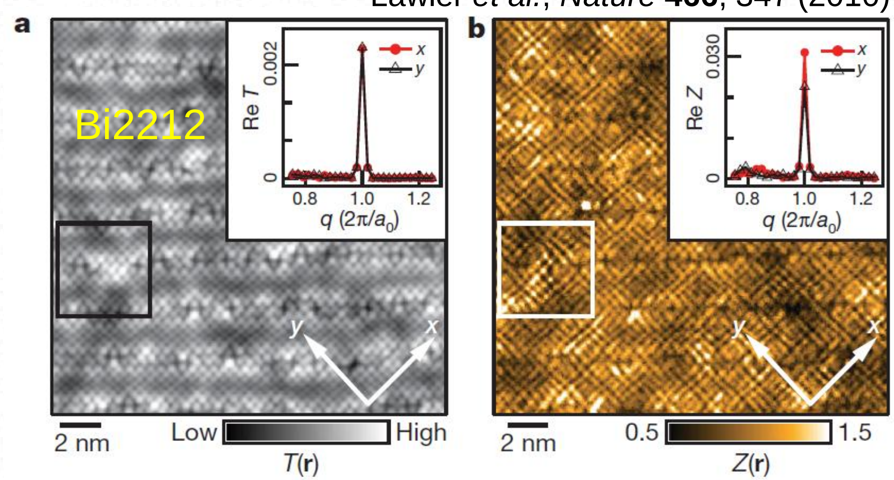




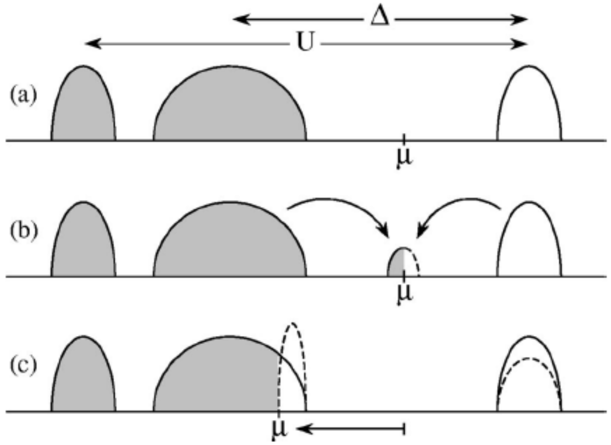
Bi2212

Lee *et al.*, *Nature* **442**, 546 (2006)

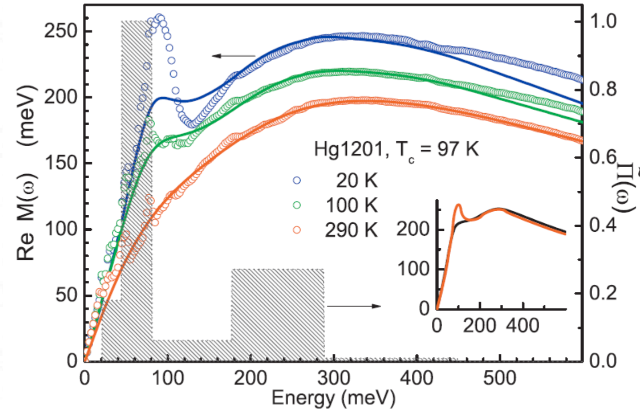
Lawler *et al.*, *Nature* **466**, 347 (2010)



Optical conductivity

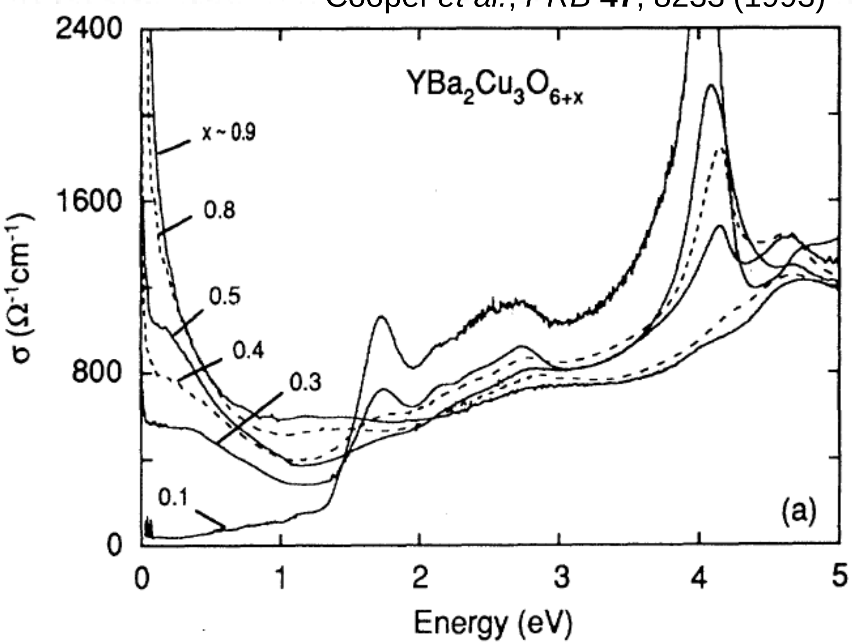


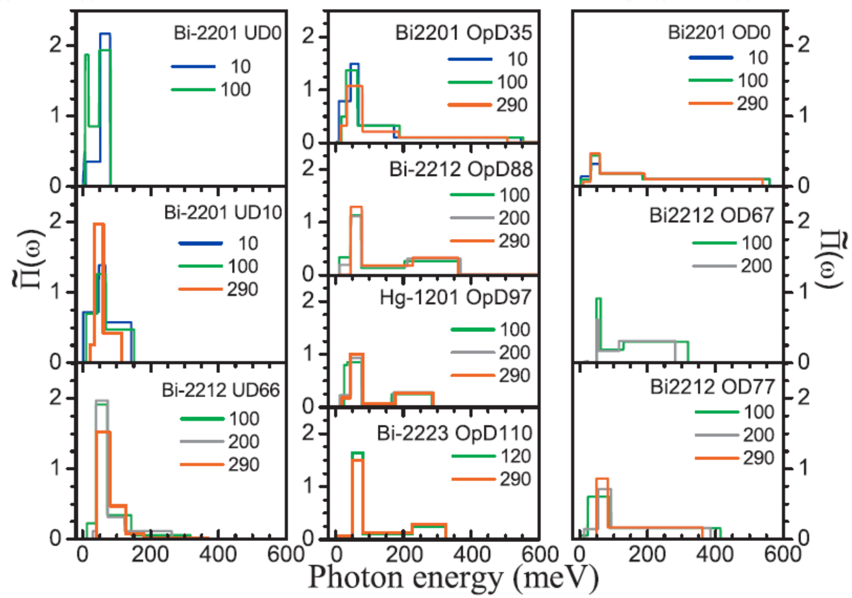
Damascelli, Hussain and Shen, *RMP* **75**, 473 (2003)



$$4\pi\sigma(\omega) = \frac{i\omega_p^2}{\omega + \hat{M}(\omega)}$$

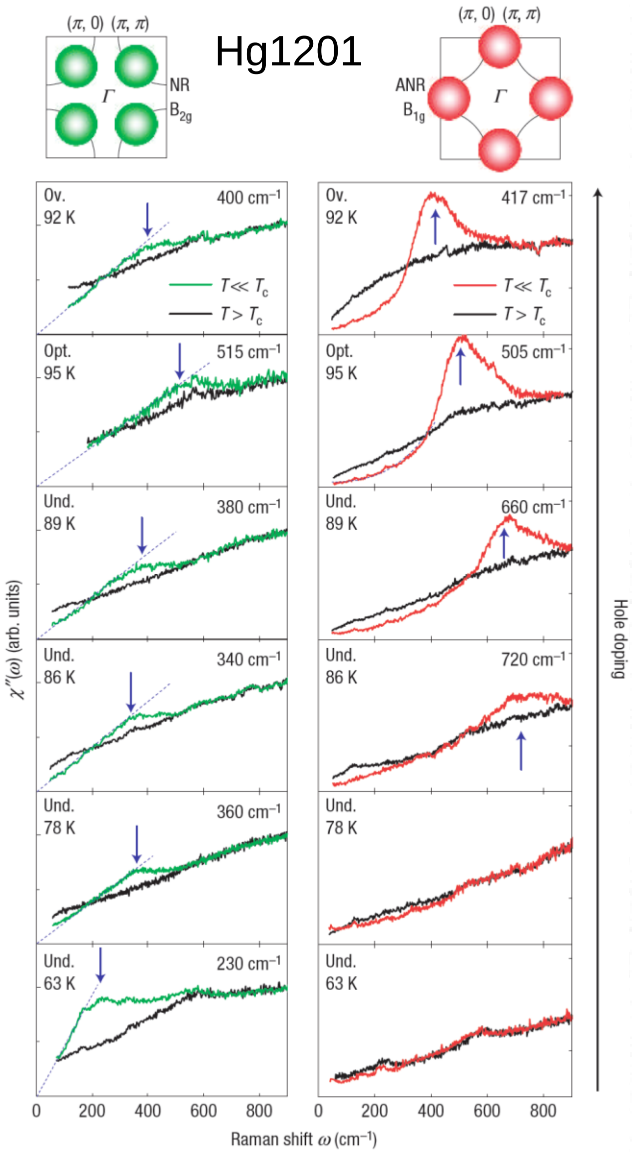
Cooper *et al.*, *PRB* **47**, 8233 (1993)



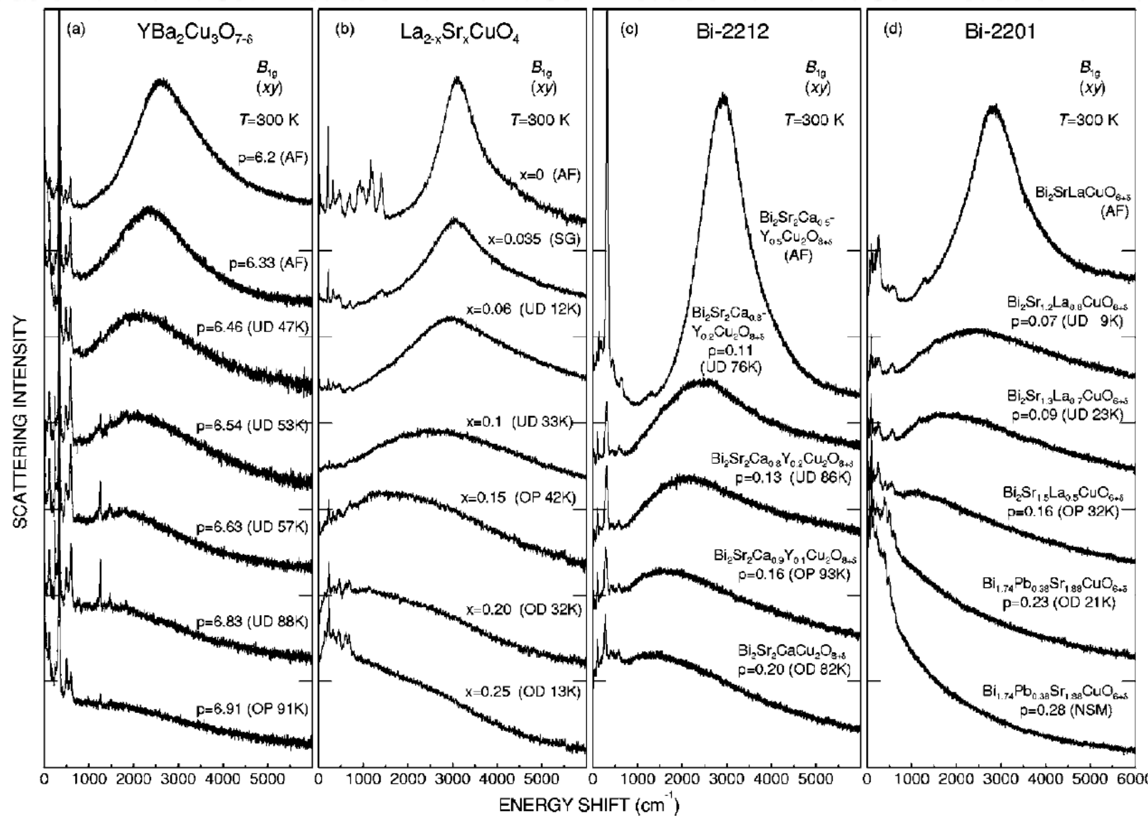


van Heumen *et al.*, *PRB* **79**, 184512 (2009)

Raman scattering

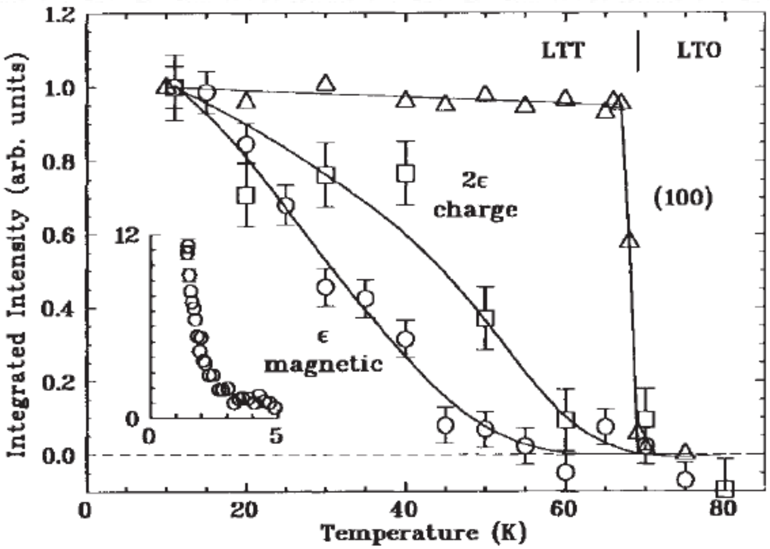


Le Tacon *et al.*, *Nat. Phys.* **2**, 537 (2006)



Sugai *et al.*, *PRB* **68**, 184504 (2003)

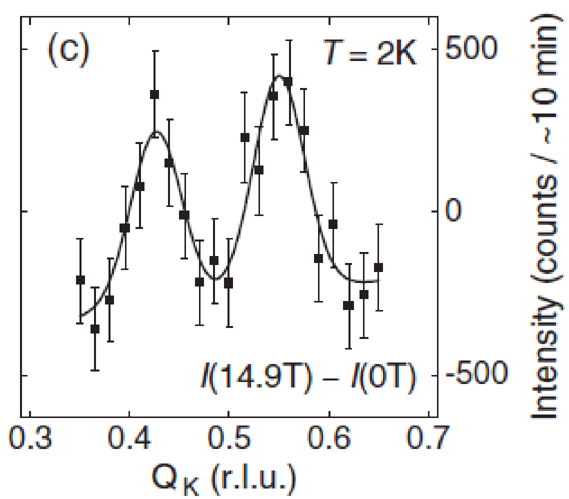
Neutron scattering

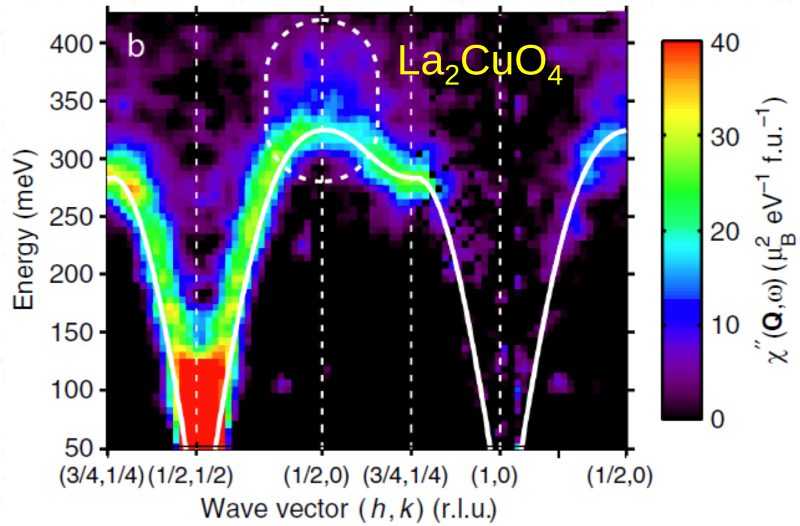


Nd-LSCO Tranquada *et al.*, *Nature* **375**, 561 (1995)

Haug *et al.*, *PRL* **103**, 017001 (2009)

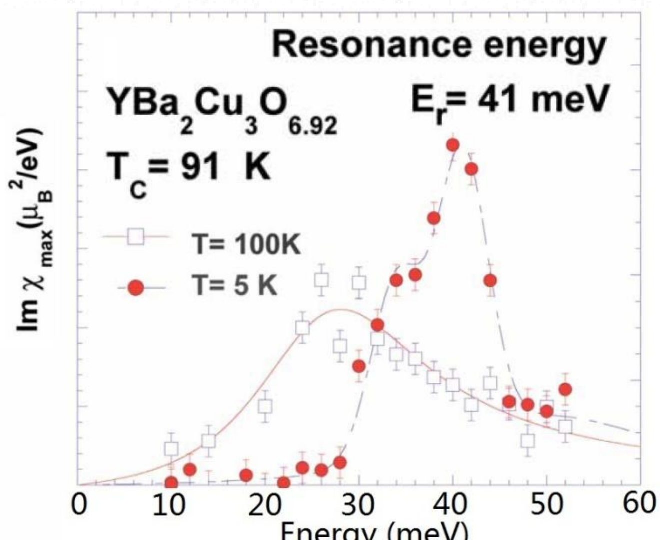
YBCO



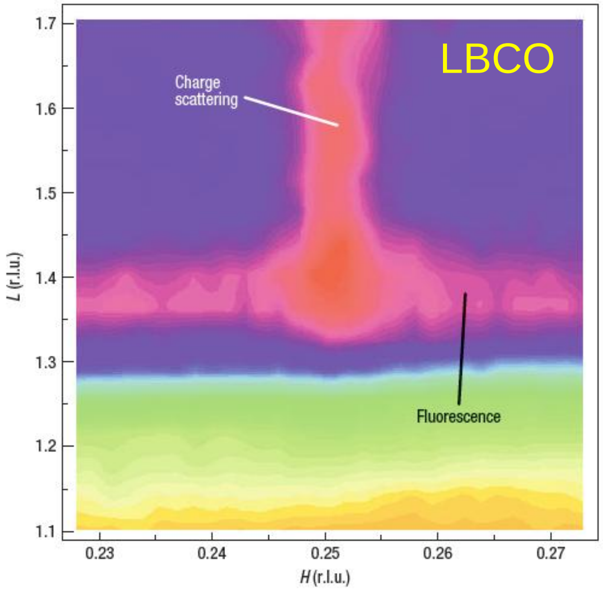


Headings *et al.*, *PRL* **105**, 247001 (2010)

Eschrig *et al.*, *Adv. Phys.* **55**, 47 (2006)

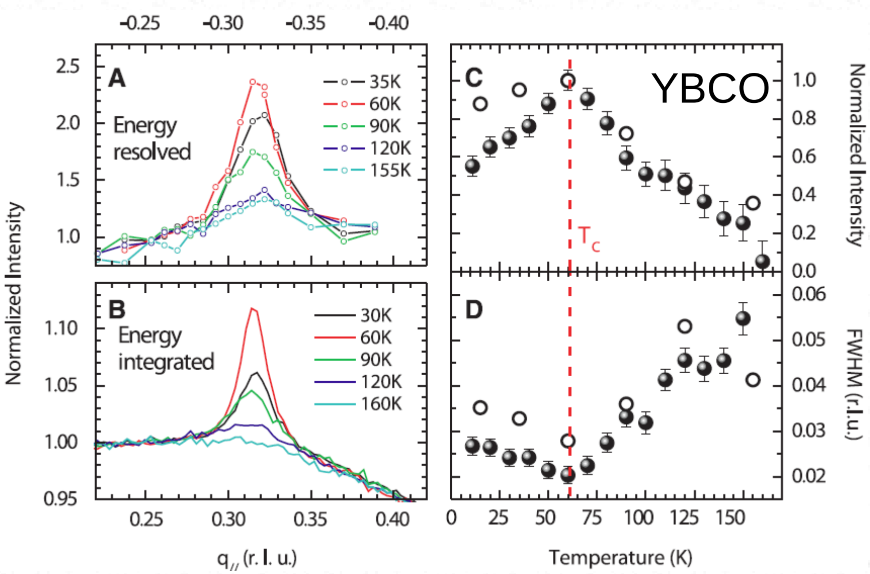


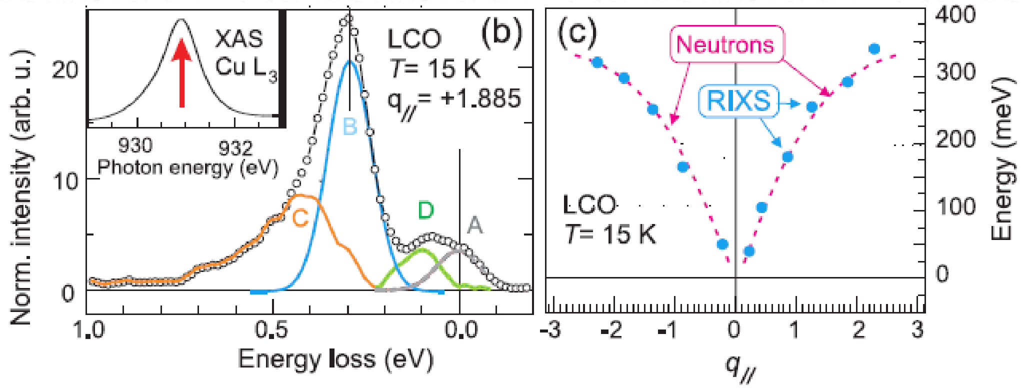
(Resonant) X-ray scattering



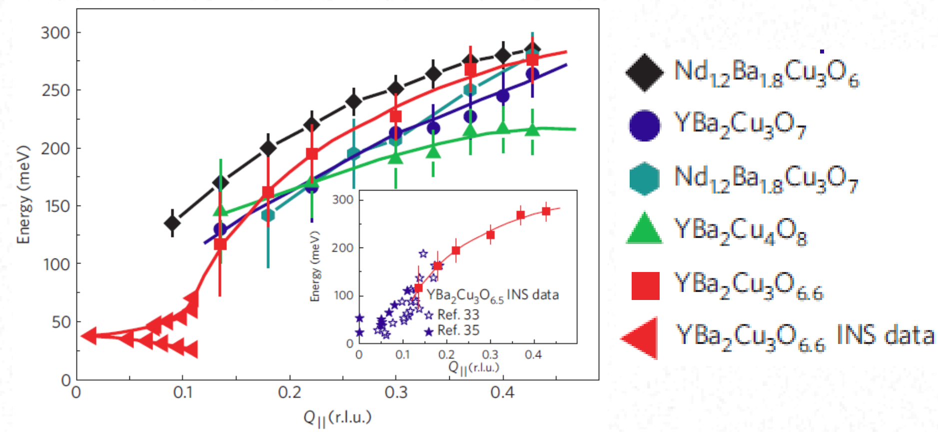
Abbamonte *et al.*, *Nat. Phys.* **1**, 155 (2005)

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





Braicovich *et al.*, *PRL* **104**, 077002 (2010)



Le Tacon *et al.*, *Nat. Phys.* **7**, 725 (2011)

Some important questions

- Q: What's the pairing symmetry?

  A: *d*-wave.

- Q: What causes the pseudogap above T_c?

  A: There is evidence for both pre-formed pairs and competing order.

- Q: Is there a competing order other than AFM?

  A: CDW, SDW, intra-unit-cell order are all possible.

- Q: Which bosonic modes are important?

  A: Both magnetic excitations and phonons are prominent.

  (Which one is the "pairing glue" is a separate question!)

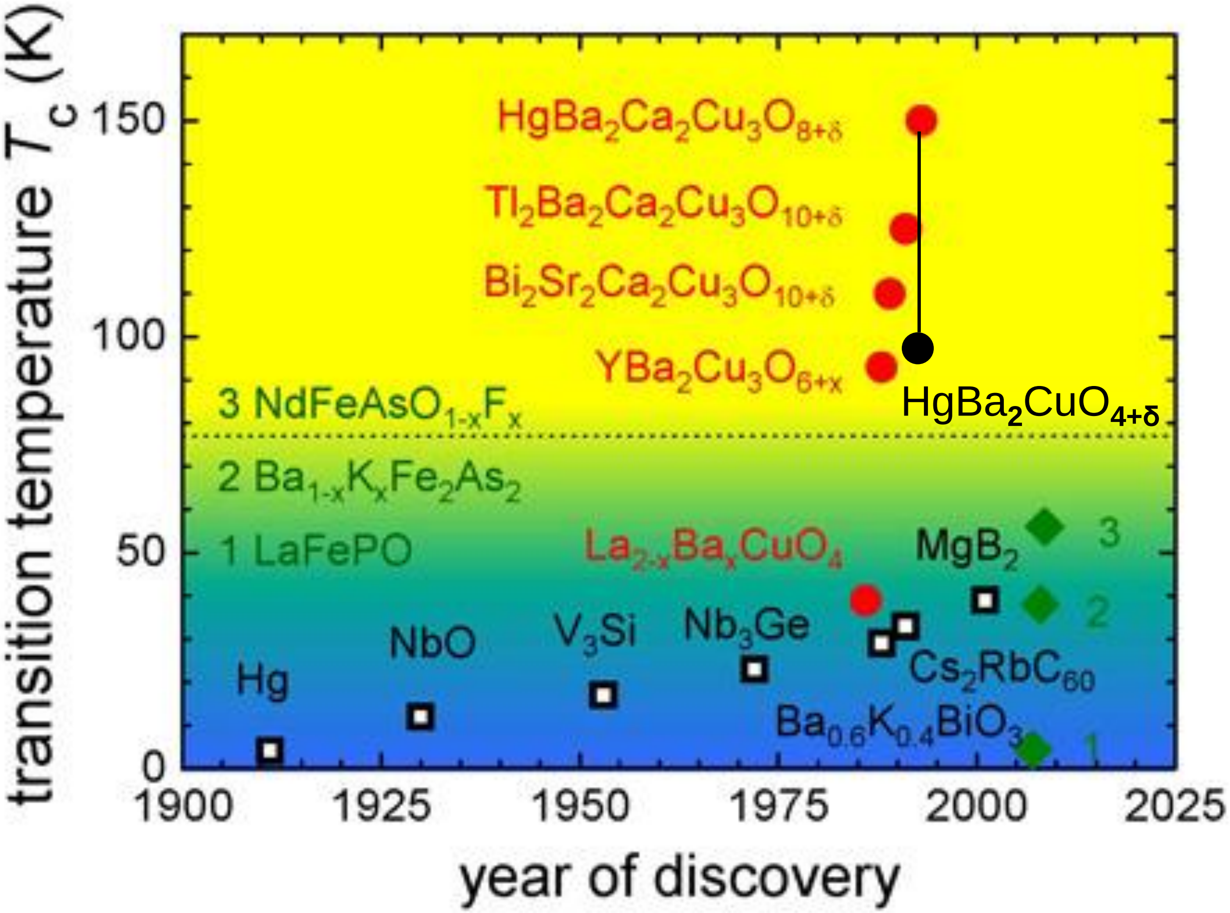
- Q: What's the minimal microscopic model?

  A: Single-band models are accepted as there is no strong violation.

Outline

- Introduction
  - HTSC and the cuprates
  - Spectroscopic methods applied to the high-T_c problem
- Model system $HgBa_2CuO_{4+\delta}$
- Topics:
  1. The neutron resonant mode
  2. Pseudogap magnetism
  3. Energy $2\Delta_{sc}$ and above
- Summary

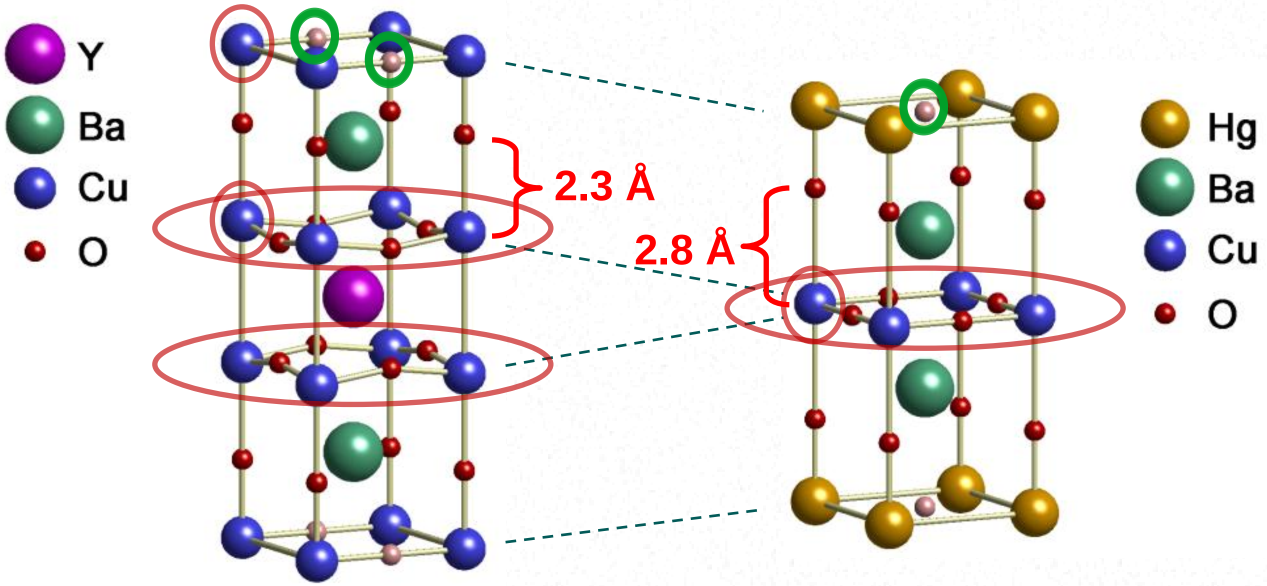
T_c over the years



Putilin *et al.*, *Nature* **362**, 226 (1993)

courtesy of Rudi Hackl

Model system $HgBa_2CuO_{4+\delta}$



$YBa_2Cu_3O_{6+\delta}$

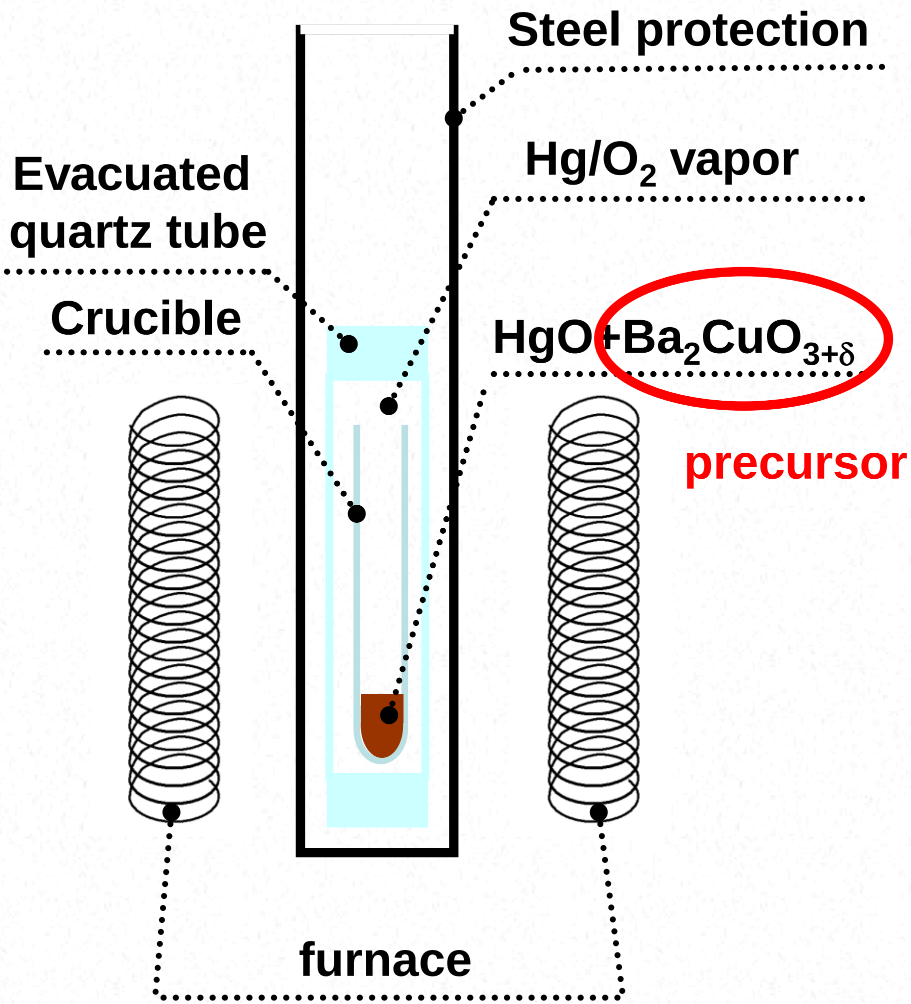
$T_{c,max}$ = 92 K

$HgBa_2CuO_{4+\delta}$
(Hg1201)

$T_{c,max}$ = 97 K

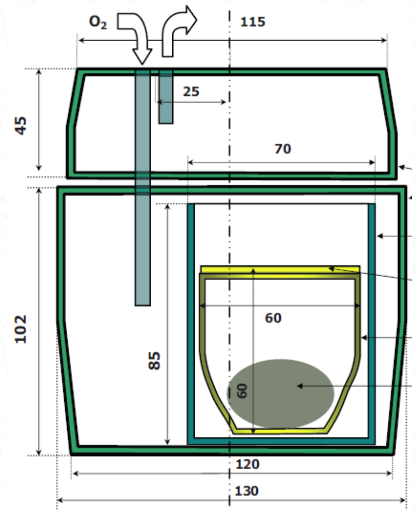
- Single layer, tetragonal
- Single Cu site, flat Cu-O sheet
- Doping disorder confined to far away from the Cu-O sheets
- Highest T_c (max. 97 K) among single-layer compounds

Challenges from the synthesis

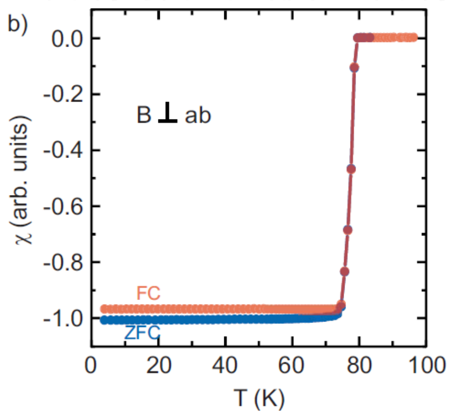


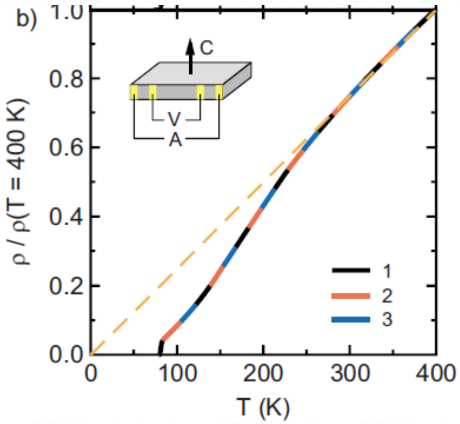
Principles of synthesis:
Zhao, *et al.*, *Adv. Mater.* **18**, 3243 (2006)

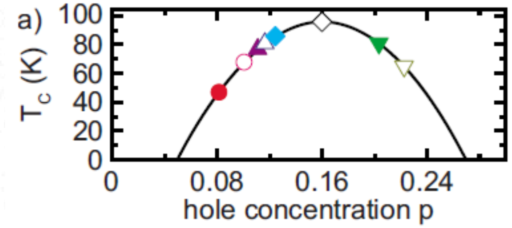
- Mercury is toxic ☹
- Synthesis requires high pressure
- Purity against crystal size

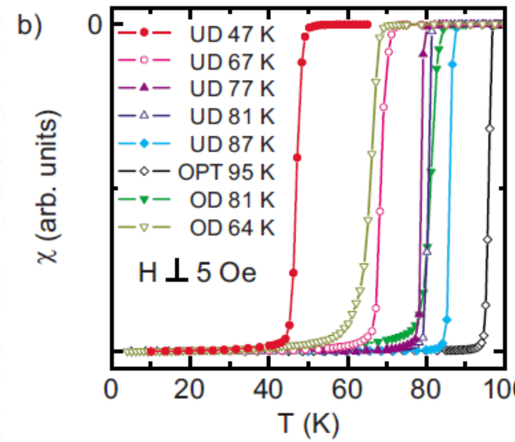


Pure and big single crystals



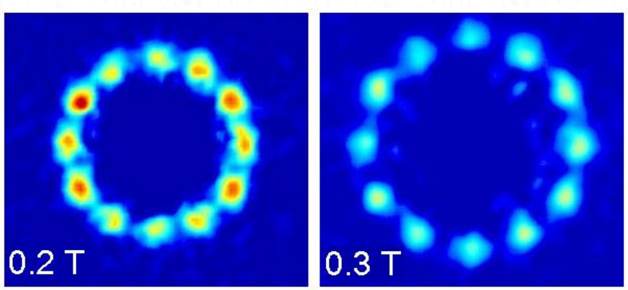


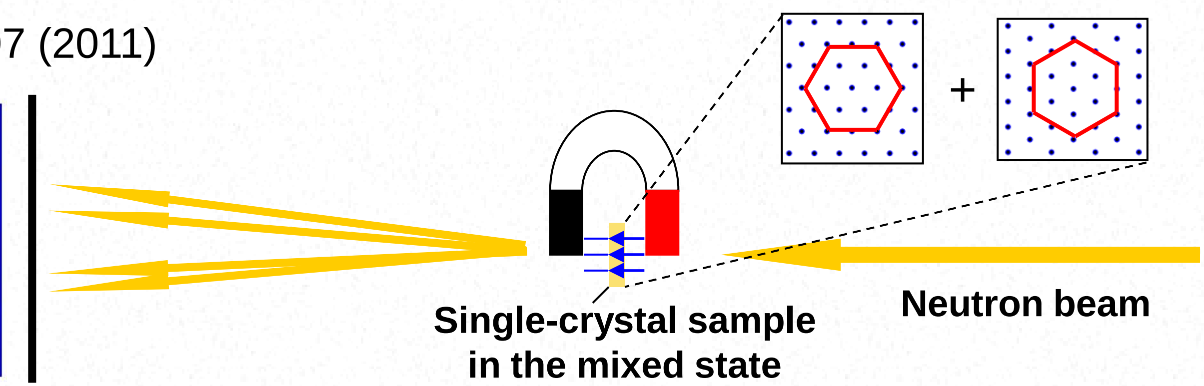




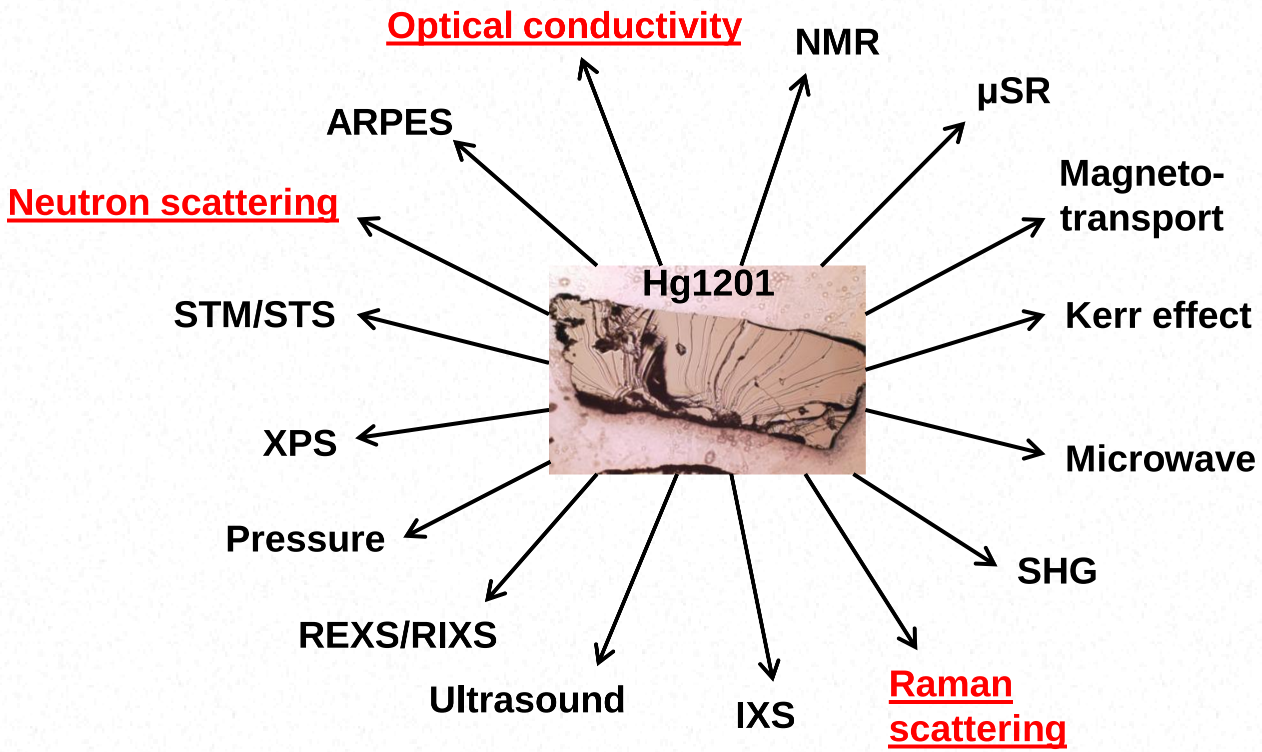
Barišić, YL, *et al.*, *PRB* **78**, 054518 (2008)

YL *et al.*, *Phys. Rev. B* **83**, 054507 (2011)





Work since 2008



Neutron scattering

Properties of neutron

charge 0， spin 1/2
magnetic moment (P), energy (E)
and momentum (k)

scattering due to nuclear and electromagnetic interaction

Thermal neutron

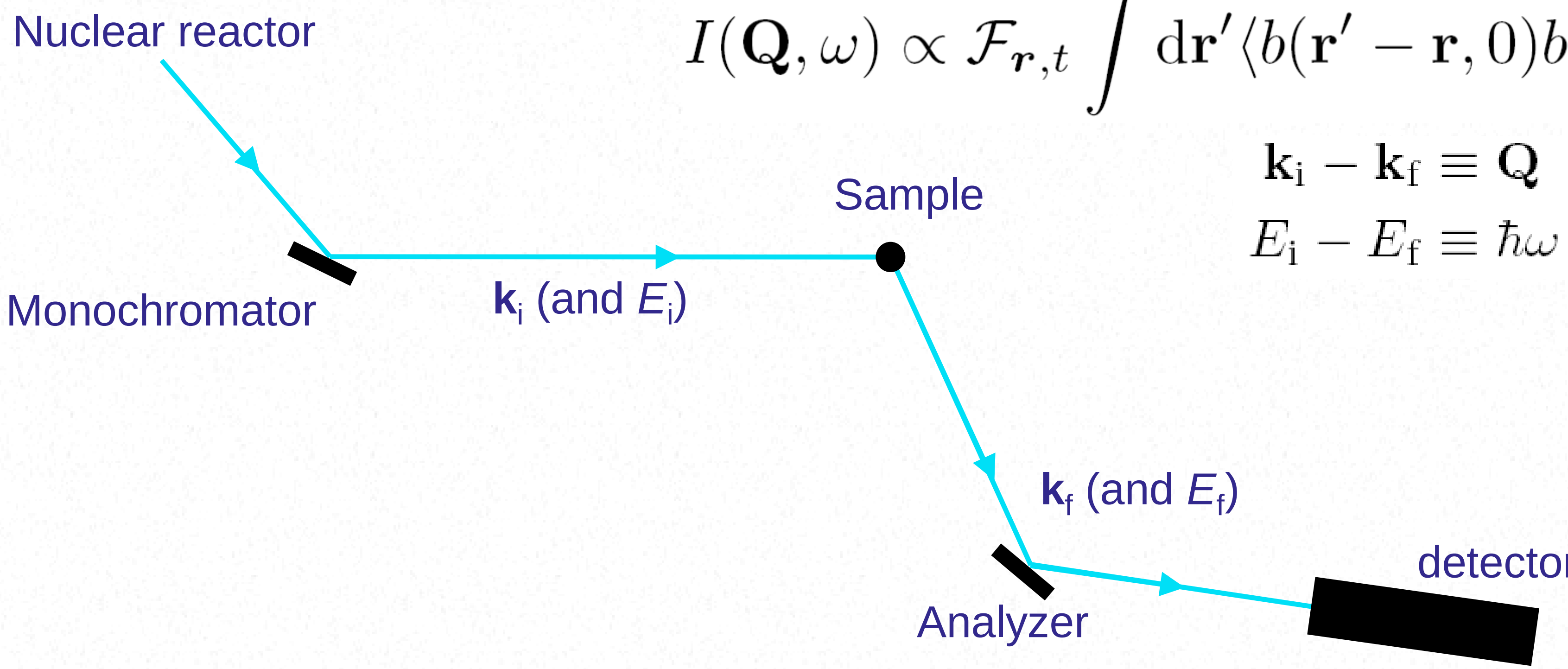
***E* = 10–100 meV, *k* = 2–7 Å^{-1}**

match typical energy and momentum in solid state physics

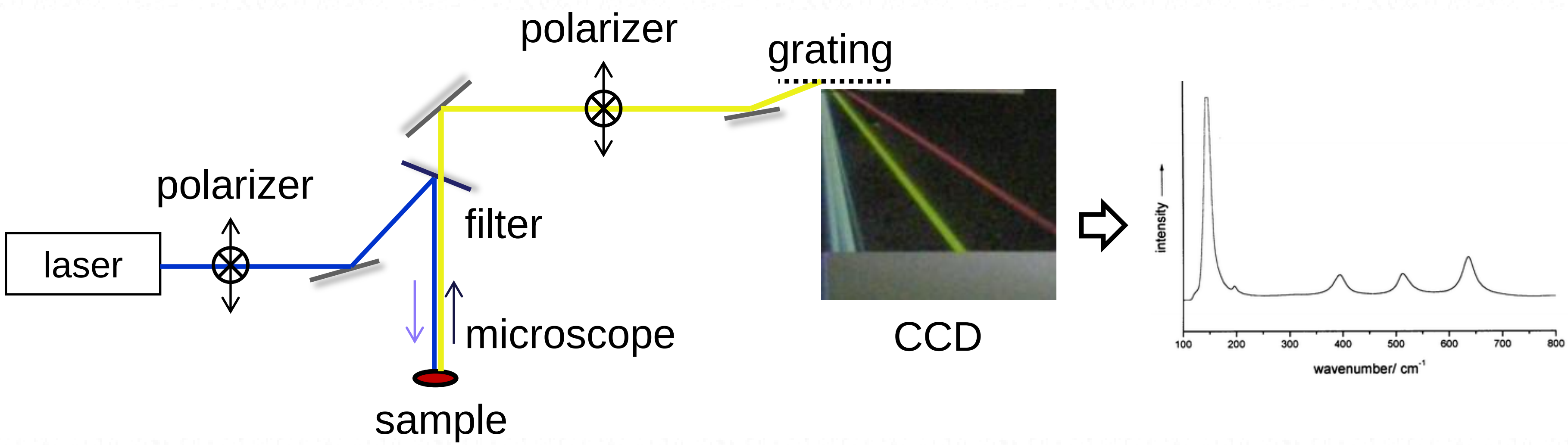
$$I(\mathbf{Q},\omega) \propto \mathcal{F}_{\boldsymbol{r},t} \int \mathrm{d}\mathbf{r}' \langle b(\mathbf{r}'-\mathbf{r},0)\, b(\mathbf{r}',t)\rangle$$

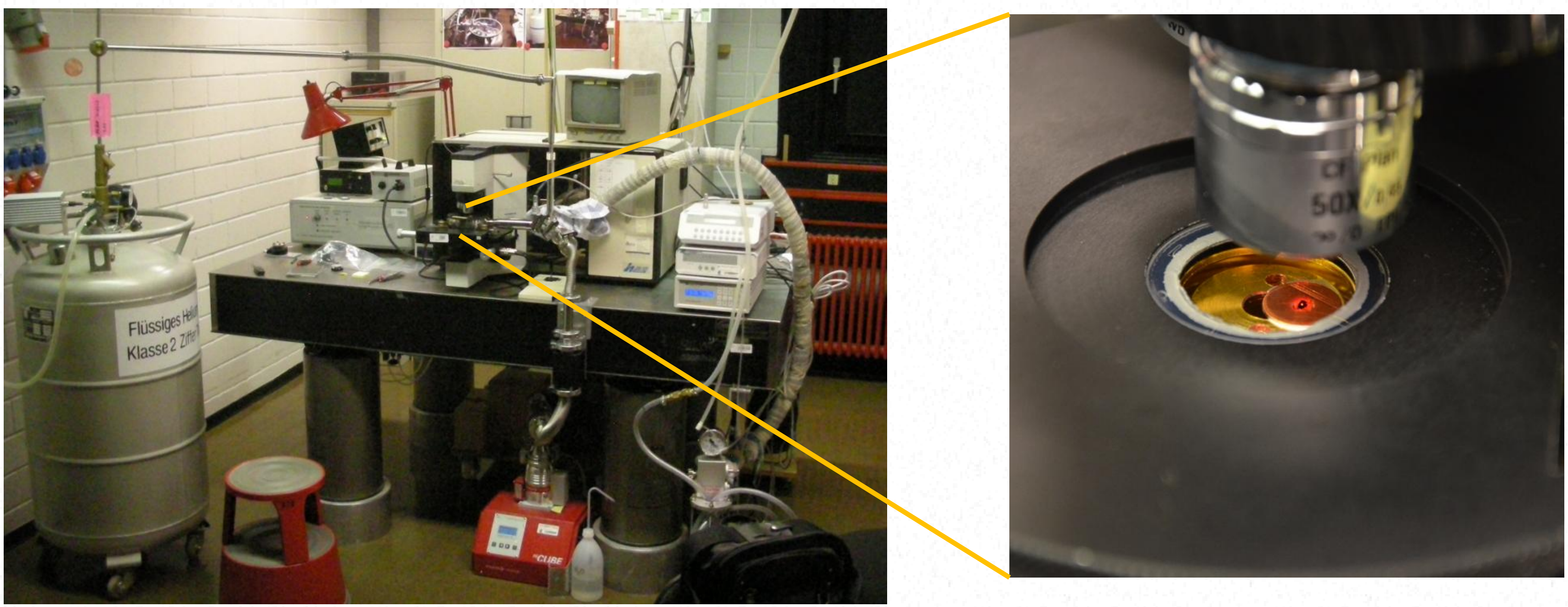
$$\mathbf{k}_\mathrm{i} - \mathbf{k}_\mathrm{f} \equiv \mathbf{Q}$$

$$E_\mathrm{i} - E_\mathrm{f} \equiv \hbar\omega \to \omega$$

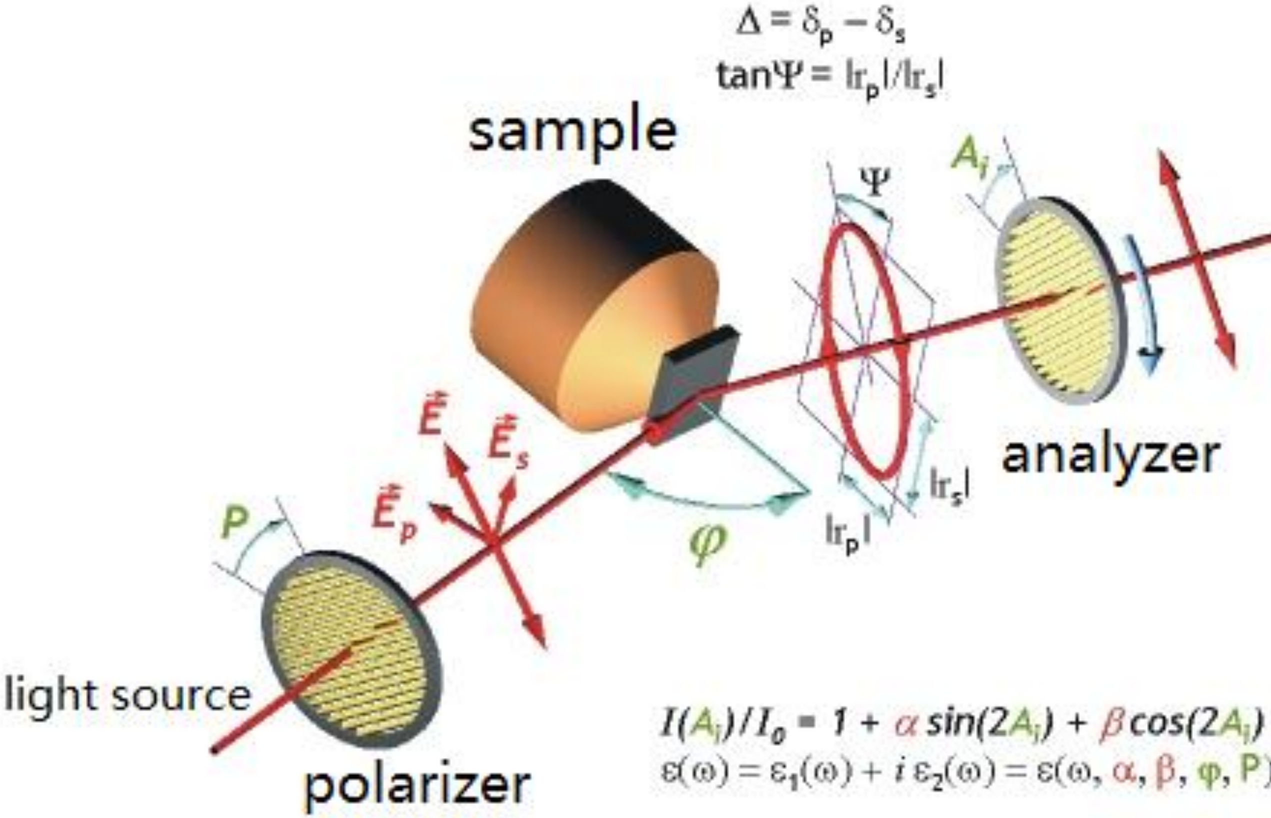


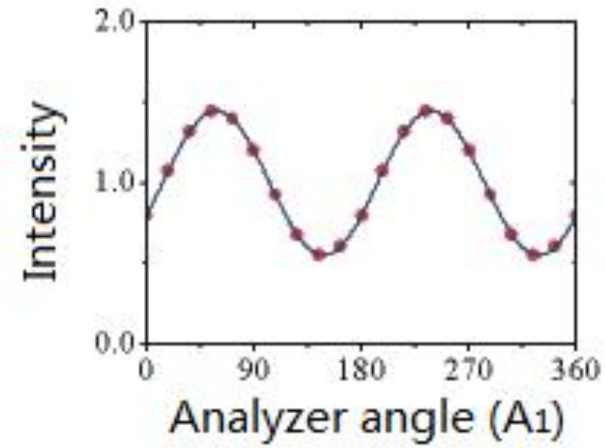
Raman scattering





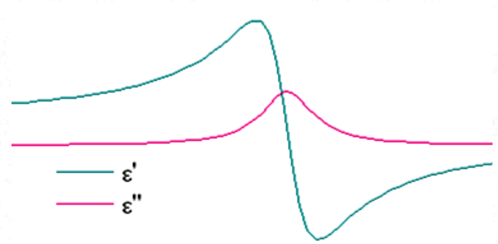
Optical ellipsometry





($\sigma_1 \sim \omega\, \varepsilon_2$)

$$\varepsilon(\omega) = (n + i\kappa)^2 = 1 + \frac{e^2 N}{\varepsilon_0 m V} \frac{1}{(\omega_0^2 - 2i\beta\omega - \omega^2)}$$



Outline

- Introduction

  - HTSC and the cuprates

  - Spectroscopic methods applied to the high-T_c problem

- Model system $HgBa_2CuO_{4+\delta}$

- Topics:

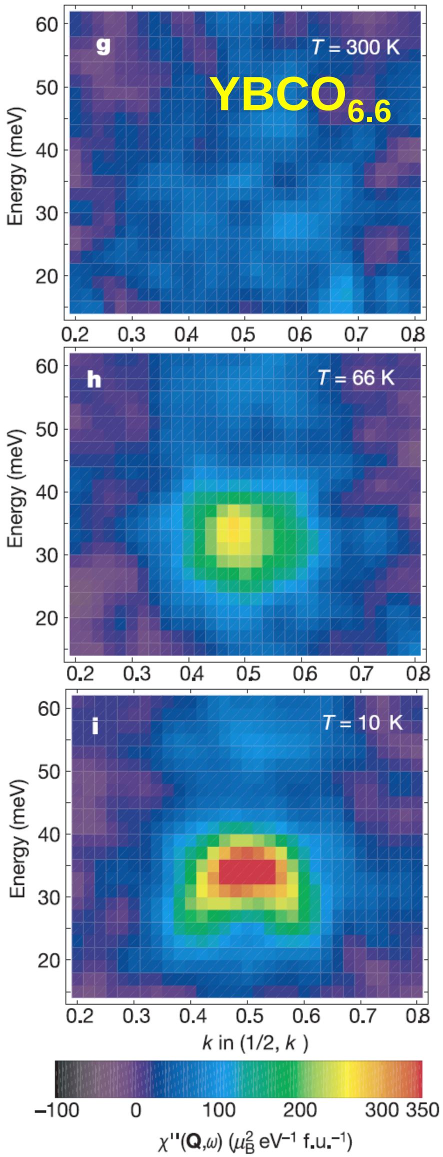
  1. The neutron resonant mode

  2. Pseudogap magnetism

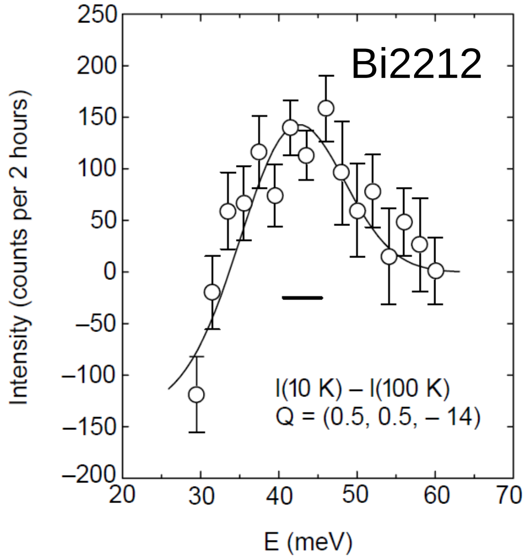
  3. Energy $2\Delta_{sc}$ and above

- Summary

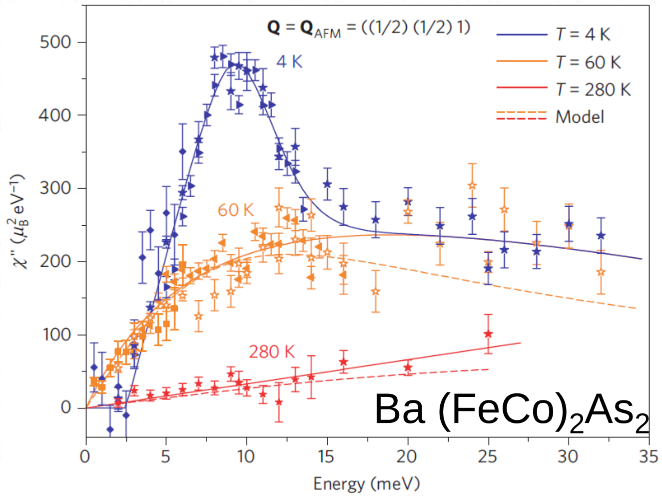
The neutron resonant mode



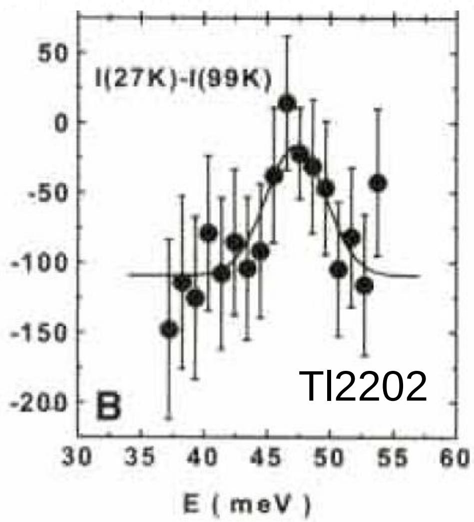
Hayden *et al.*, *Nature* **429**, 531 (2004)



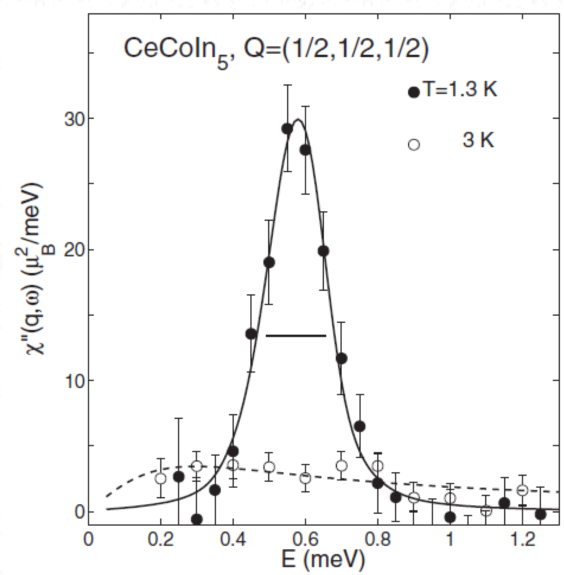
Fong *et al.*, *Nature* **398**, 588 (1999)



Inosov *et al.*, *Nat. Phys.* **6**, 178 (2010)

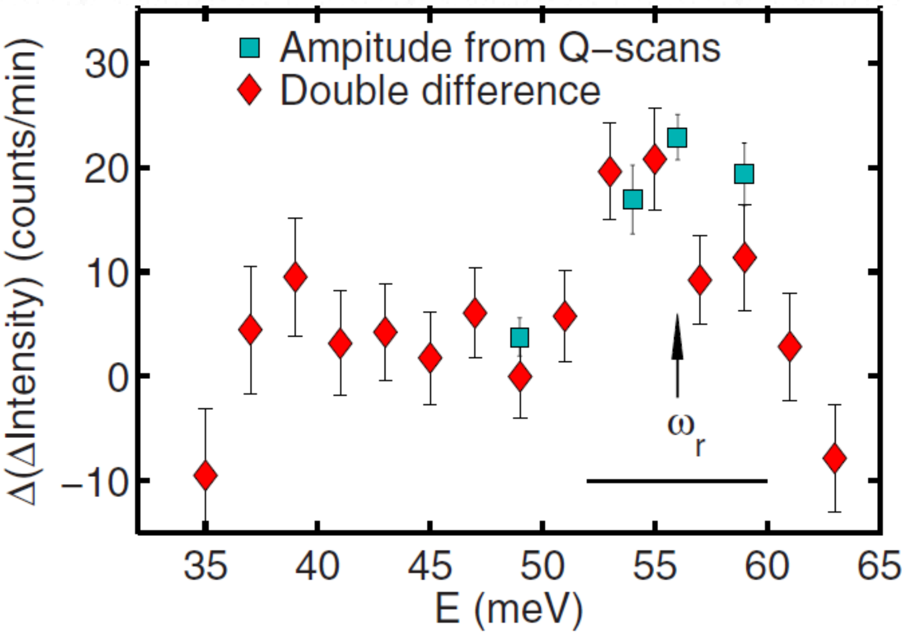


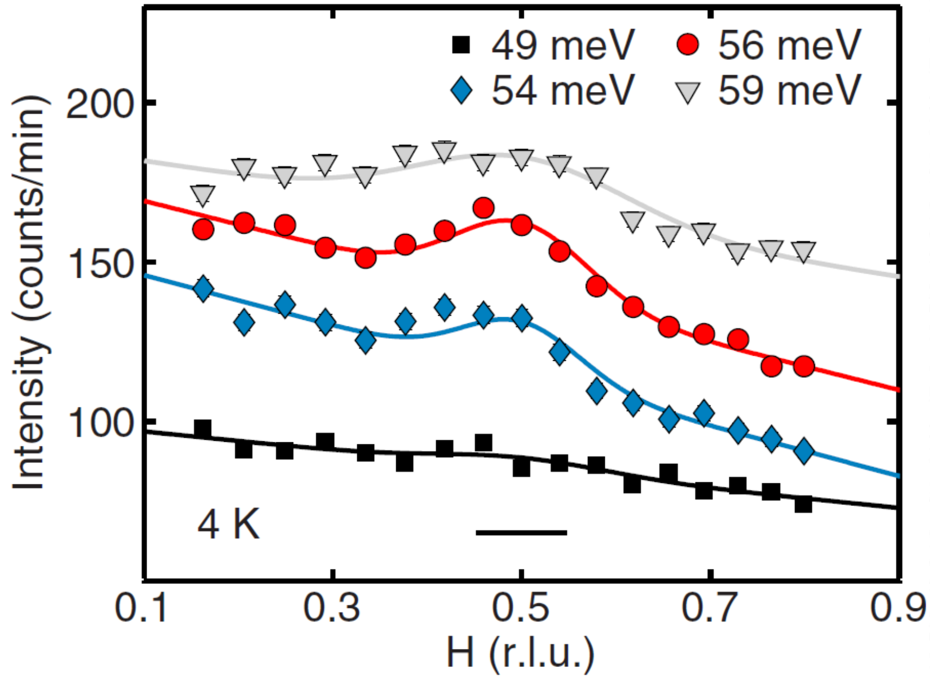
He *et al.*, *Science* **295**, 1045 (2002)



Stock *et al.*, *PRL* **100**, 087001 (2008)

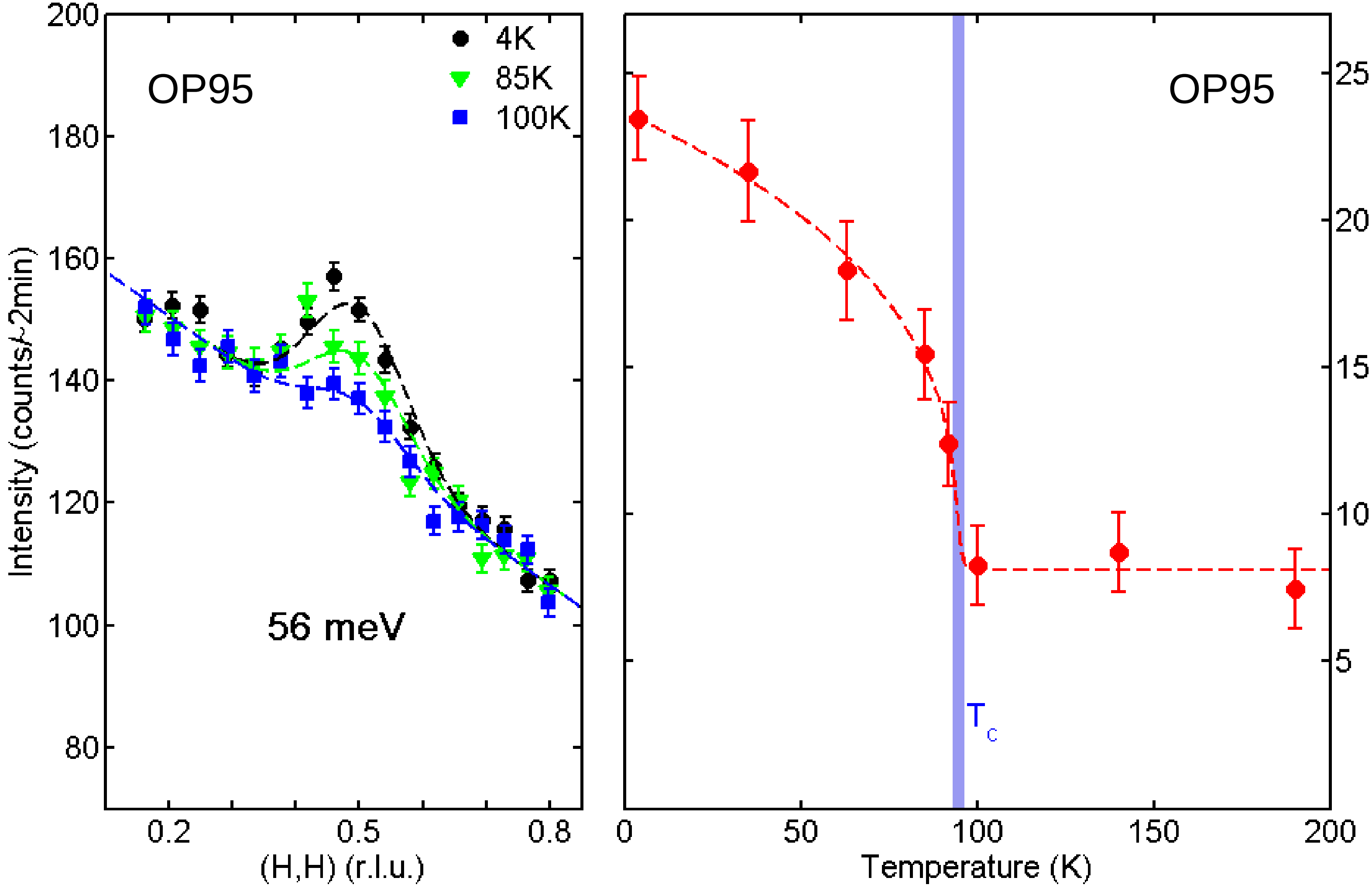
Resonant mode in Hg1201





Yu, YL *et al.*, *PRB* **81**, 064518 (2010)

Resonant mode in Hg1201

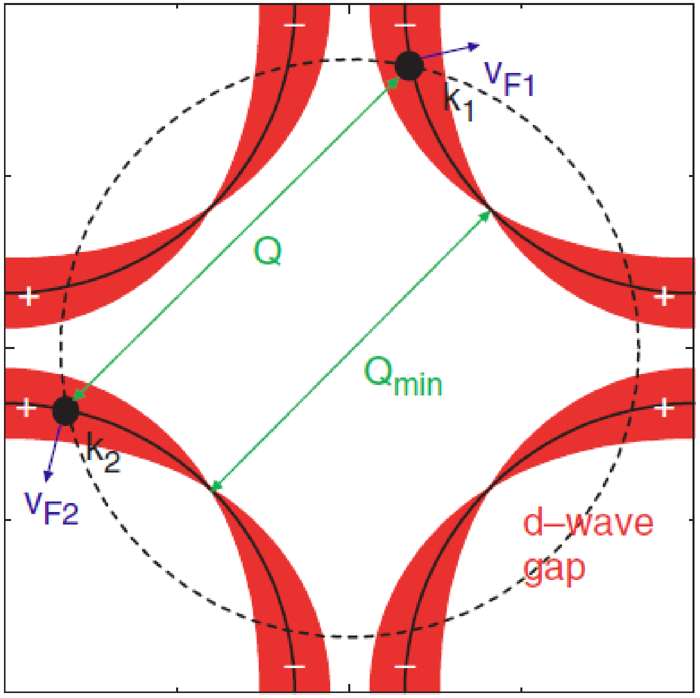


Yu, YL *et al.*, *PRB* **81**, 064518 (2010)

Resonant mode in Hg1201

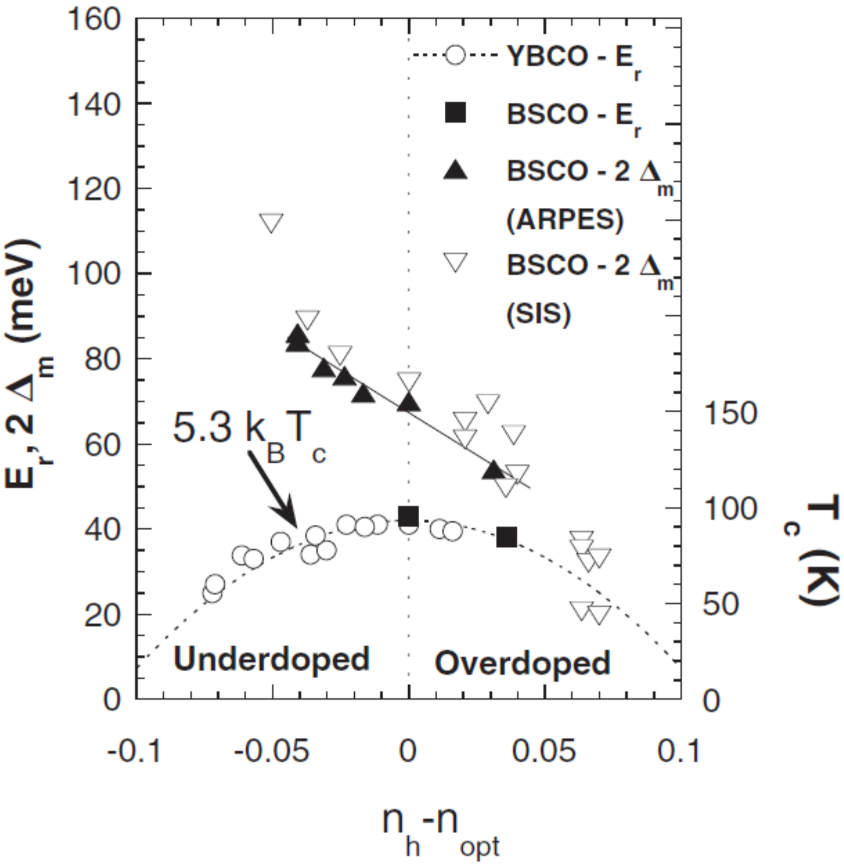
- We confirmed the universal presence of the resonant mode
- Sign-changing Δ_{sc} connected by $\mathbf{q}_{res}$: as expected from *d*-wave

Coherence factor: $$\frac{1}{2}\left(1-\frac{\Delta(k)\Delta(k+q^*)}{\mathcal{E}(k)\mathcal{E}(k+q^*)}\right)$$

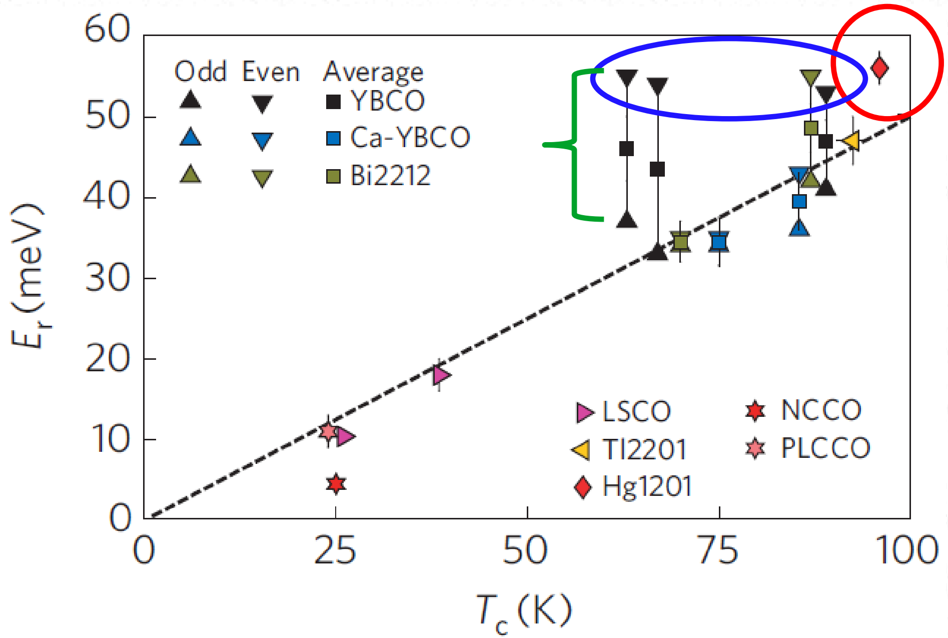


Eschrig *et al.*, *Adv. Phys.* **55**, 47 (2006)

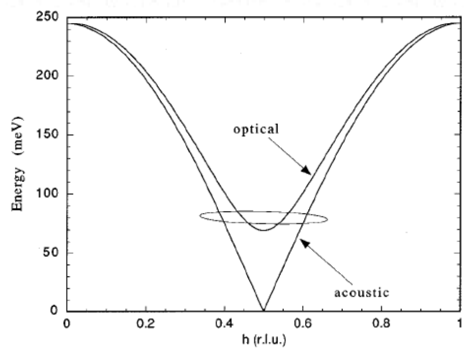
Conventional wisdom: $E_r \propto T_c$



Sidis *et al.*, *Phys. Stat. Sol.* **241**, 1204 (2004)



Yu, YL *et al.*, *Nature Physics* **5**, 873 (2009)

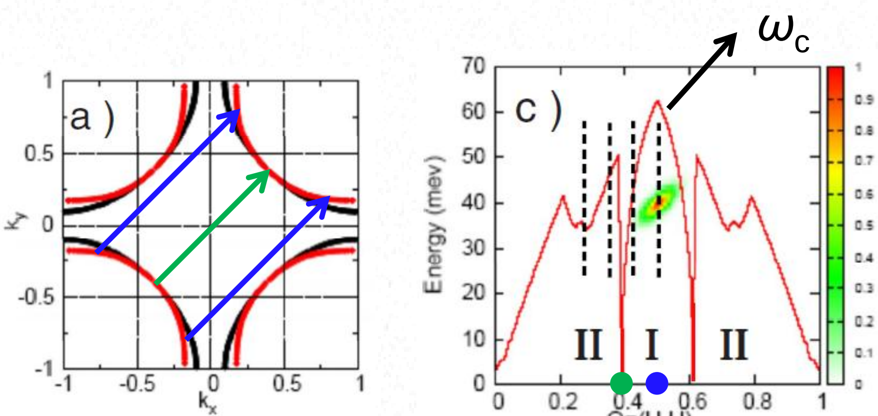


Consistent with

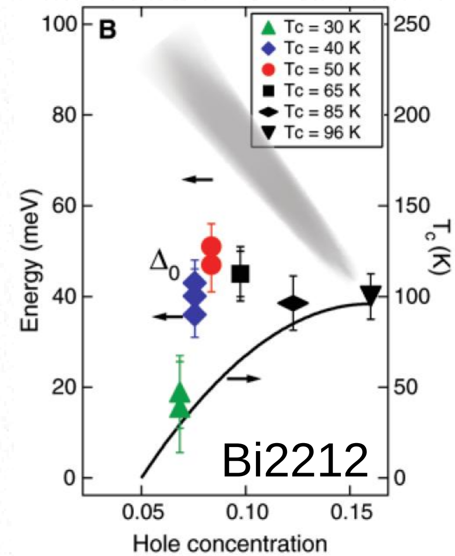
$$J_\perp \sim 10\ \mathrm{meV}$$

Reznik *et al.*, *PRB* **53**, R14741 (1996)

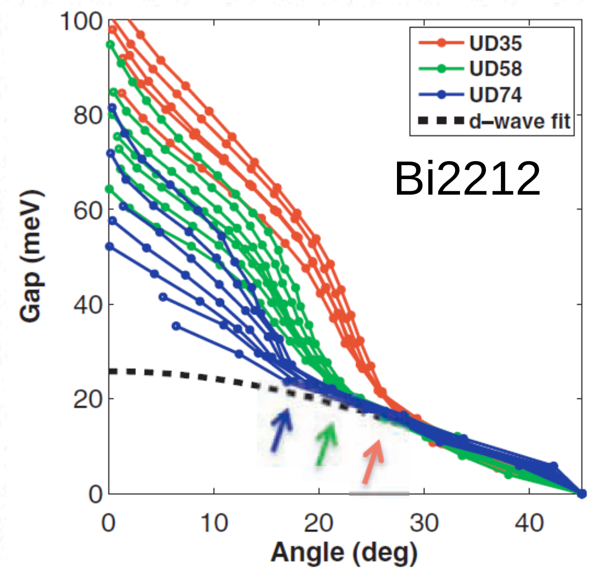
Superconducting gap: Δ_{sc}



Fauque *et al.*, *PRB* **76**, 214512 (2007)



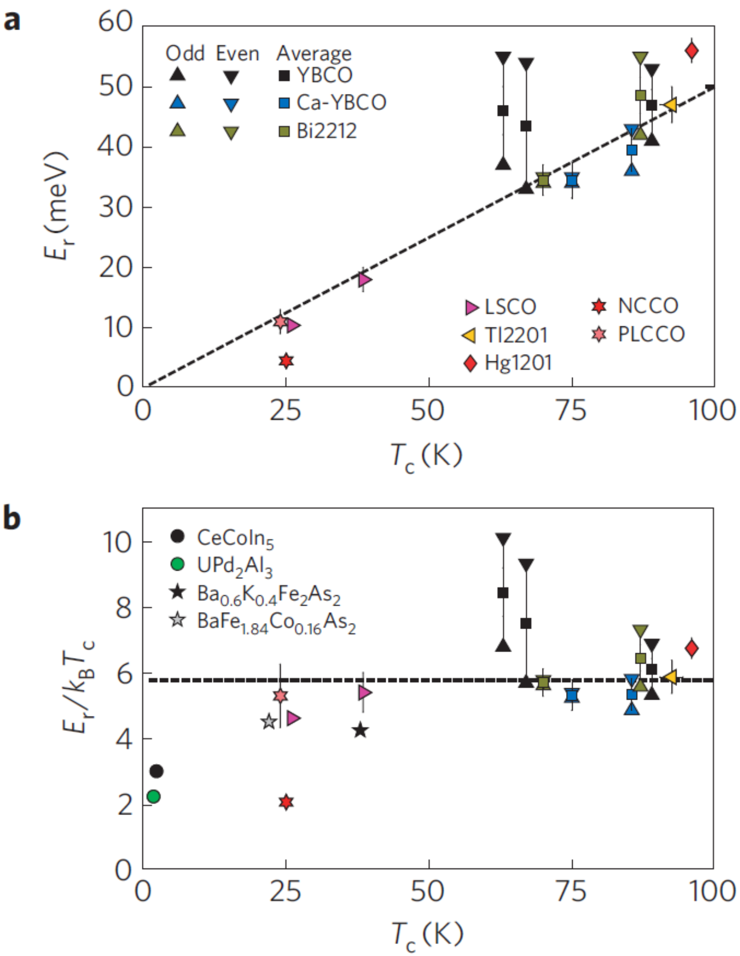
Tanaka *et al.*, *Science* **314**, 1910 (2006)

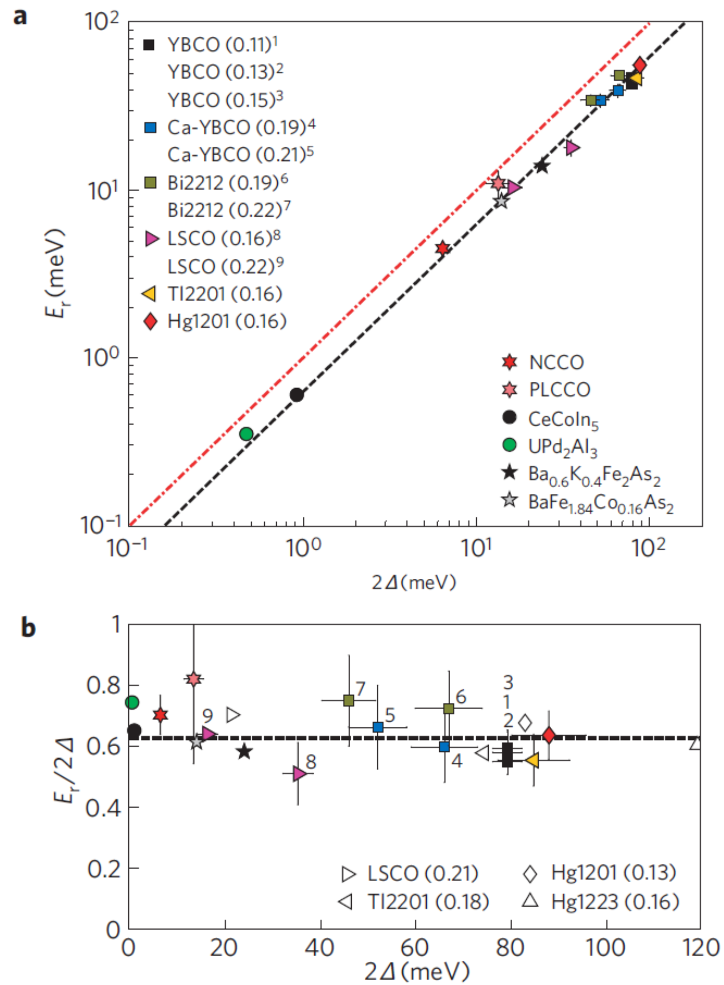


Pushp *et al.*, *Science* **324**, 1689 (2009)

Universal E_r-Δ_{sc} scaling

- Δ is not proportional to T_c in underdoped systems
- One should consider both resonant modes in bilayer systems





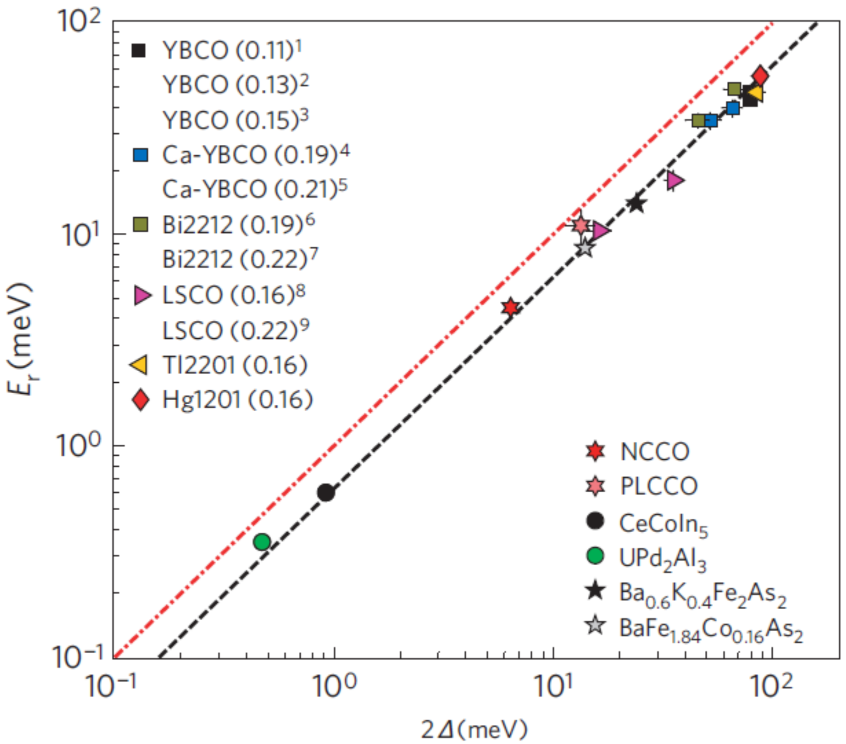
Yu, YL *et al.*, *Nature Physics* **5**, 873 (2009)

Implication

- Unexpected from a simple RPA excitonic picture

$$\chi(q,\omega) = \frac{\chi_0(q,\omega)}{1 + J(q)\,\chi_0(q,\omega)}$$

- Implies a much deeper connection between magnetic fluctuations (entire spectrum) and superconductivity



Yu, YL *et al.*, *Nature Physics* **5**, 873 (2009)

VOLUME 88, NUMBER 25 PHYSICAL REVIEW LETTERS 24 JUNE 2002

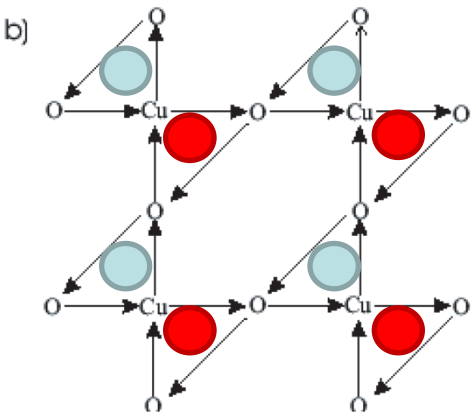
Spin-1 Neutron Resonance Peak Cannot Account for Electronic Anomalies in the Cuprate Superconductors

Hae-Young Kee,[1,2] Steven A. Kivelson,[1] and G. Aeppli[3]

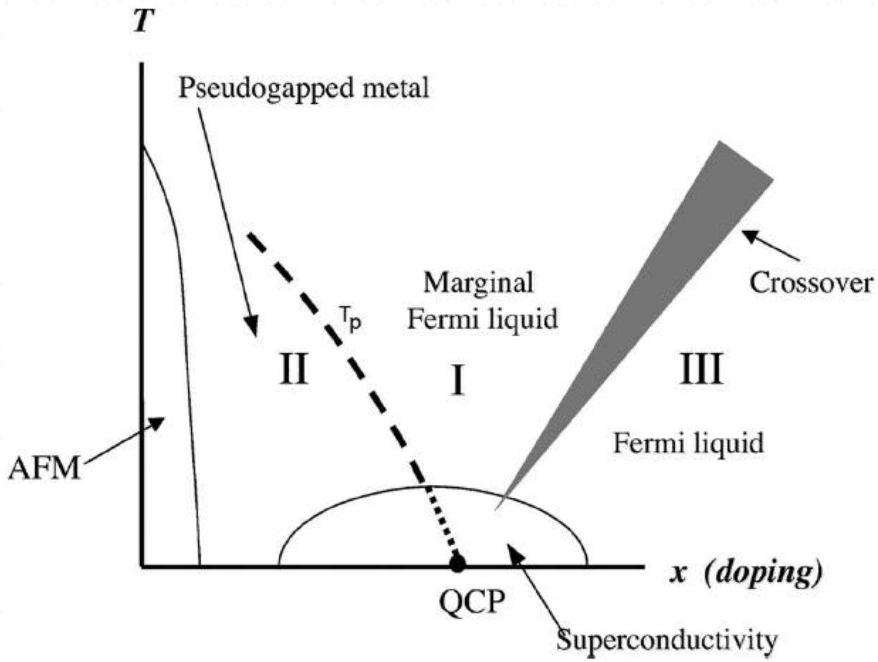
Outline

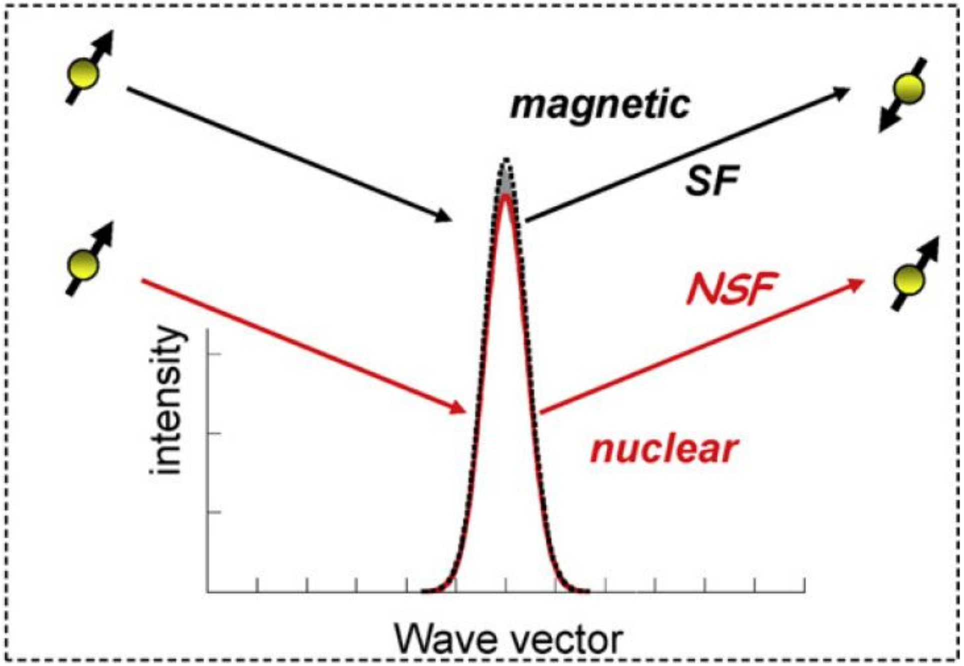
- Introduction
  - \- HTSC and the cuprates
  - \- Spectroscopic methods applied to the high-T_c problem
- Model system $HgBa_2CuO_{4+\delta}$
- Topics:
  1. The neutron resonant mode
  2. Pseudogap magnetism
  3. Energy $2\Delta_{sc}$ and above
- Summary

“Orbital current” order



Varma, *PRB* **73**, 155113 (2006)





Bourges & Sidis, *C.R. Physique* **12**, 461 (2011)

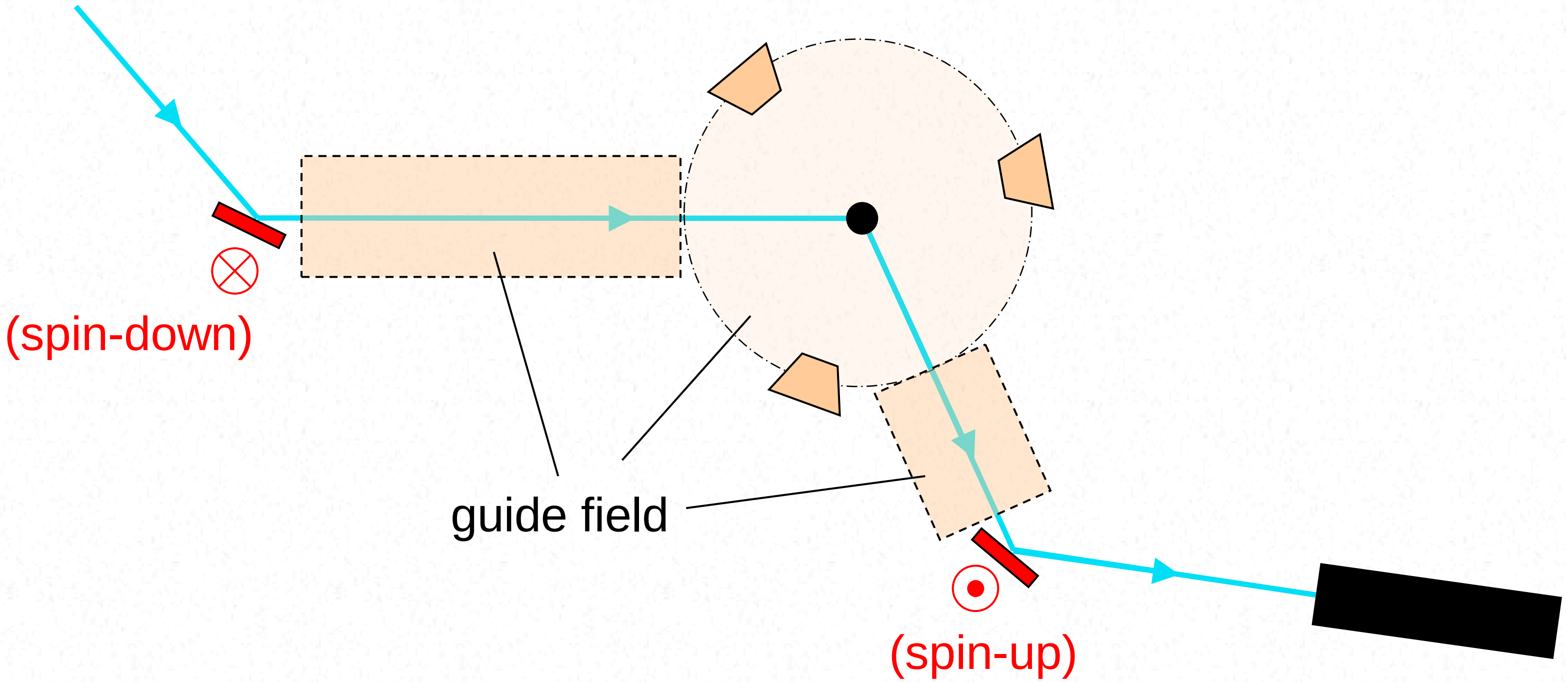
Spin-polarized neutron scattering

Properties of neutron

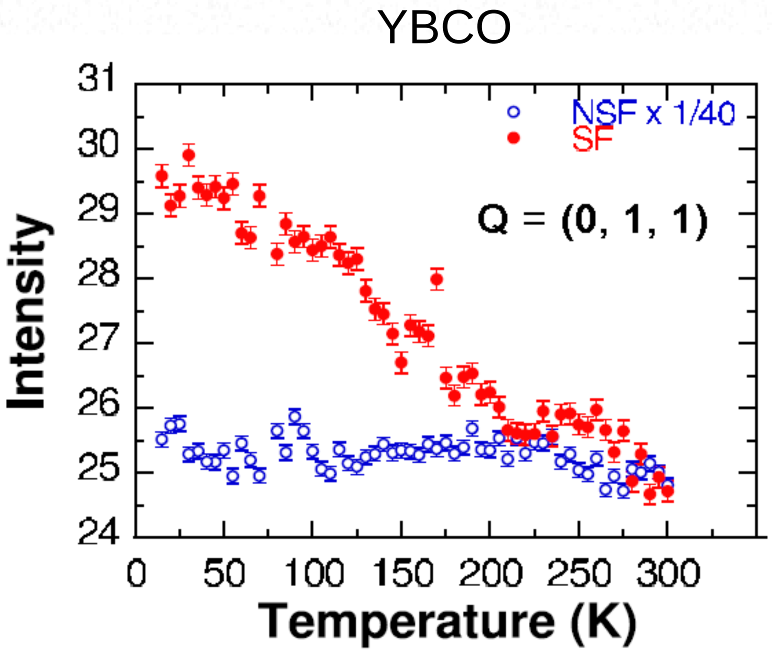
charge 0， spin 1/2
magnetic moment (P), energy (E)
and momentum (k)

scattering due to nuclear and electromagnetic interaction

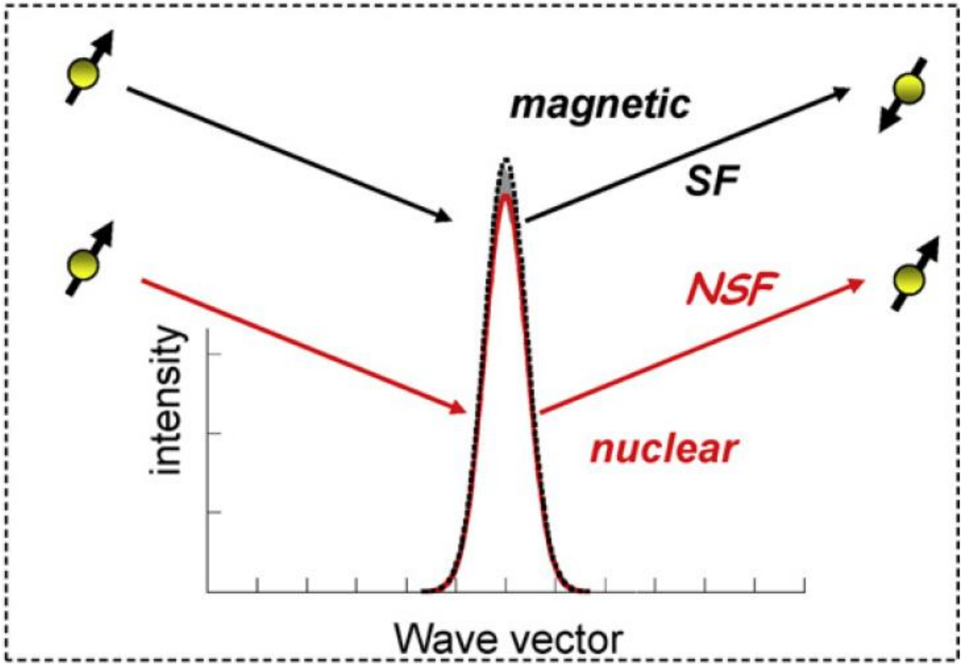
Spin-flip scattering all comes from electromagnetic interaction



Intra-unit-cell order: initial evidence



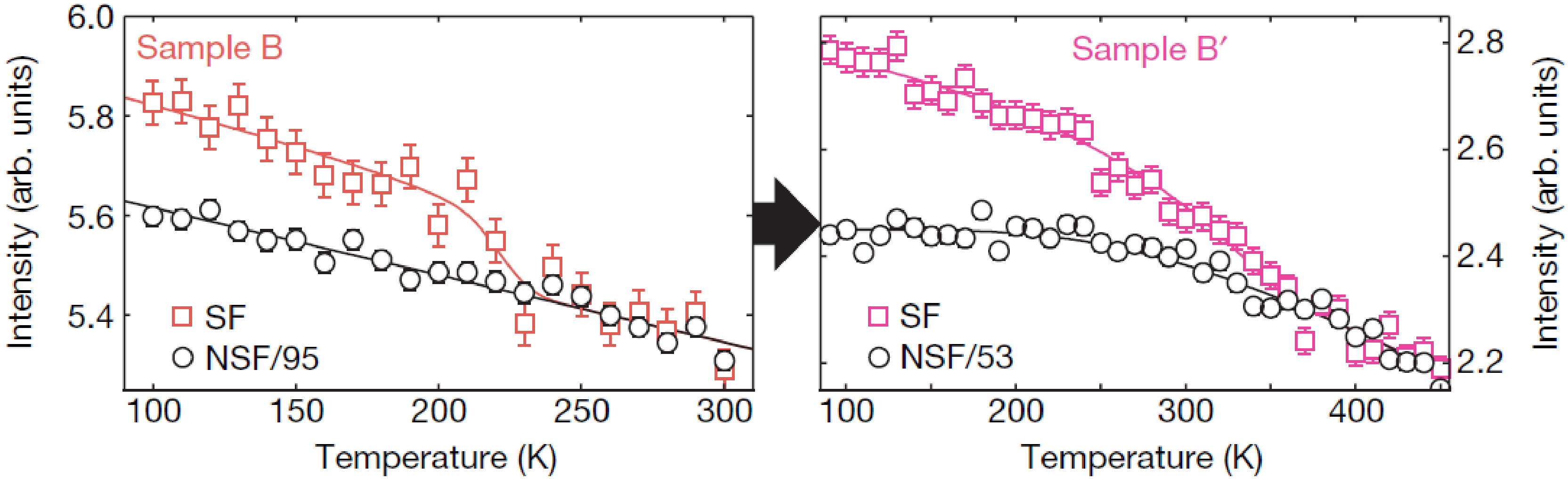
Fauqué *et al.*, *PRL* **96**, 197001 (2006)

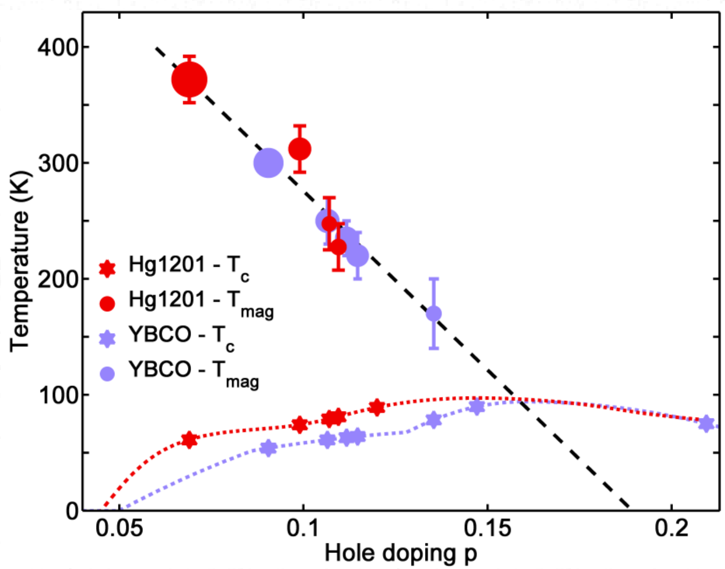


Bourges & Sidis, *C.R. Physique* **12**, 461 (2011)

Intra-unit-cell order: confirmed in Hg1201

(1 0 1) Bragg peak



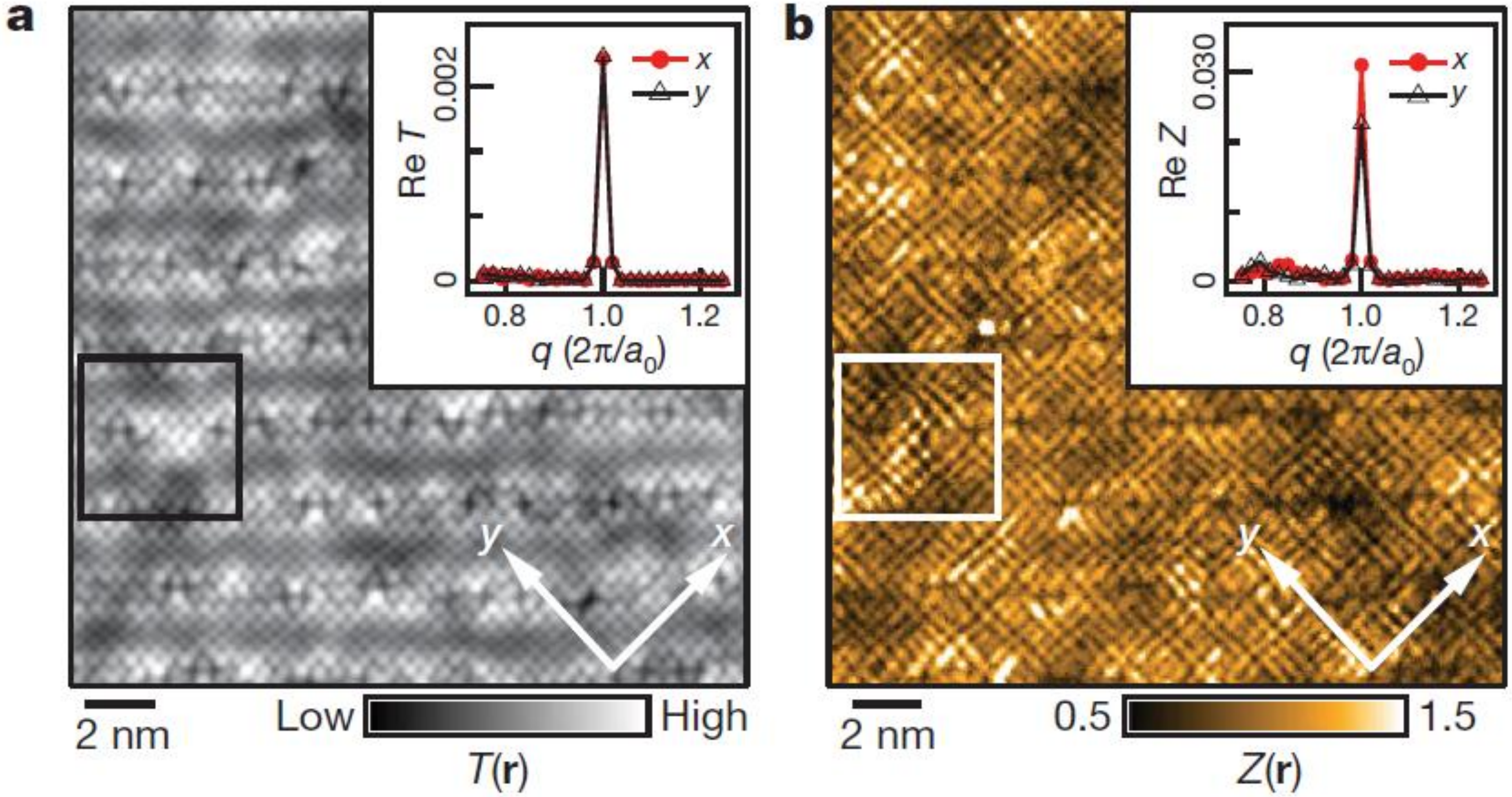


YL *et al.*, *Nature* **455**, 372 (2008)

YL *et al.*, *PRB* **84**, 224508 (2012)

Intra-unit-cell order: evidence from STM/STS

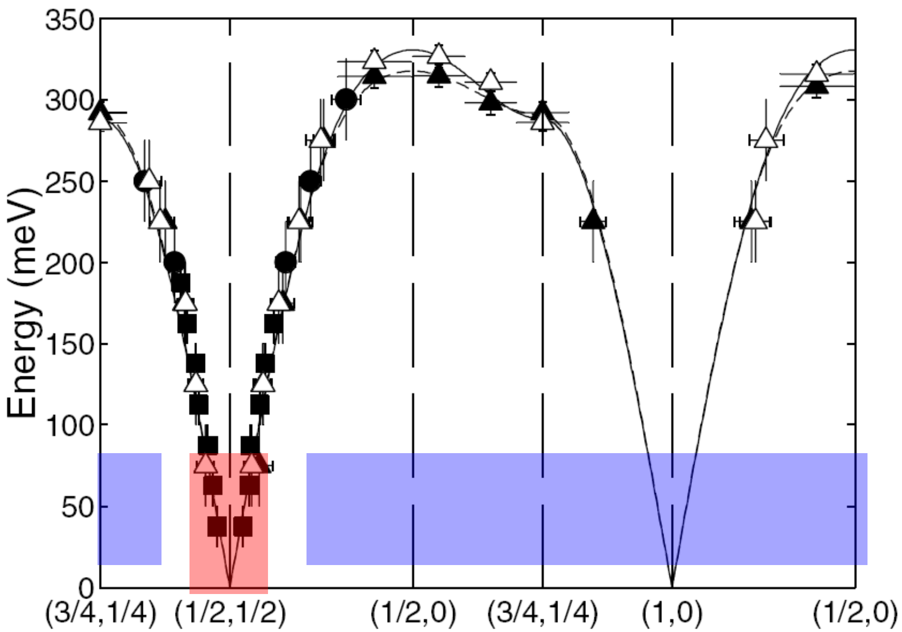
Lawler *et al.*, *Nature* **466**, 347 (2010)



New excitations in the pseudogap state

AF-type fluctuations near (1/2,1/2), including the resonance

New excitations



Spin waves in La_2CuO_4

Coldea *et al.*, *PRL* **86**, 5377 (2001)

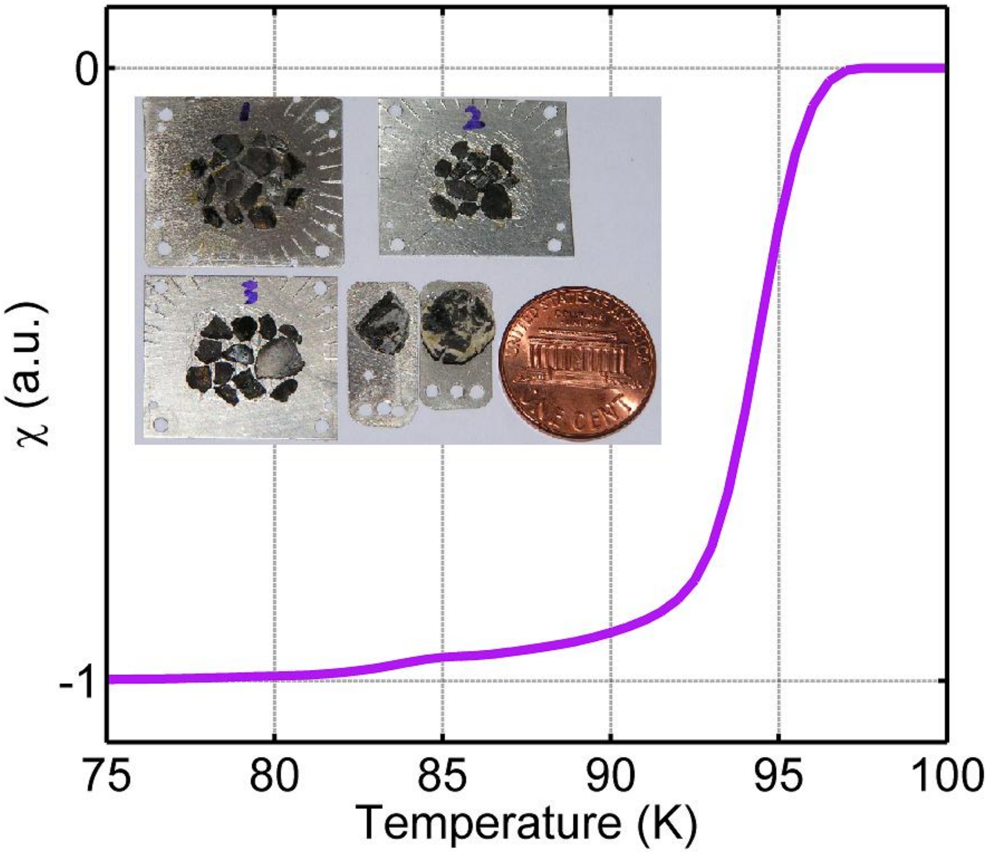
Related publications:

YL *et al.*, *Nature* **468**, 283 (2010)

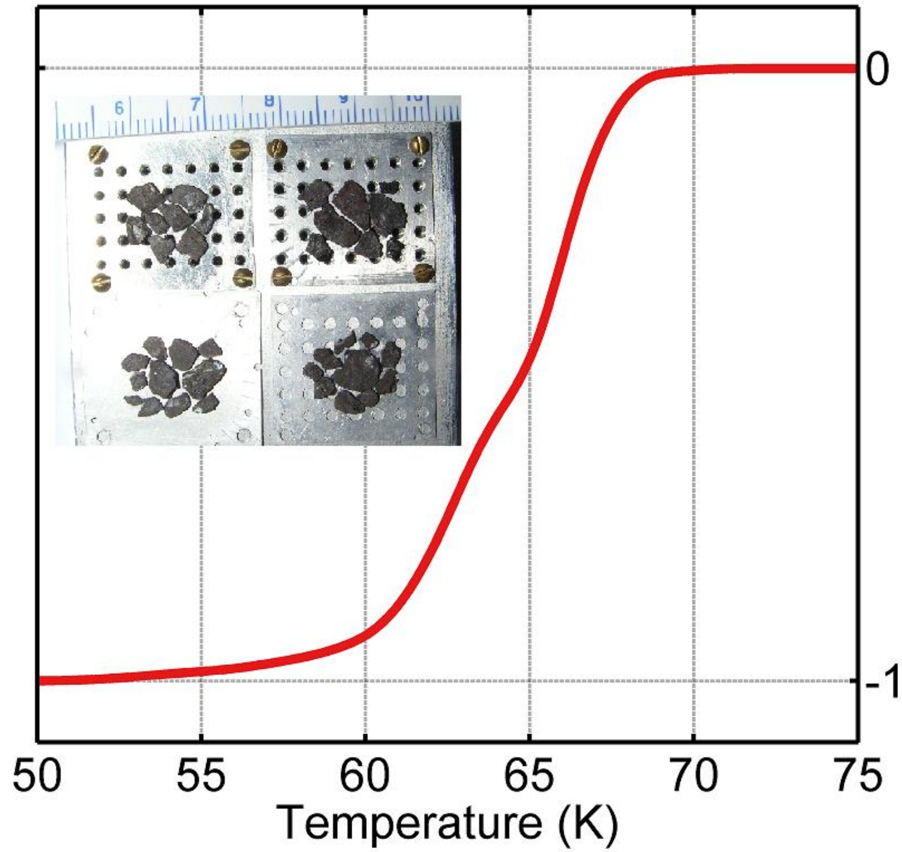
YL *et al.*, *Nat. Phys.* **8**, 404 (2012)

Samples

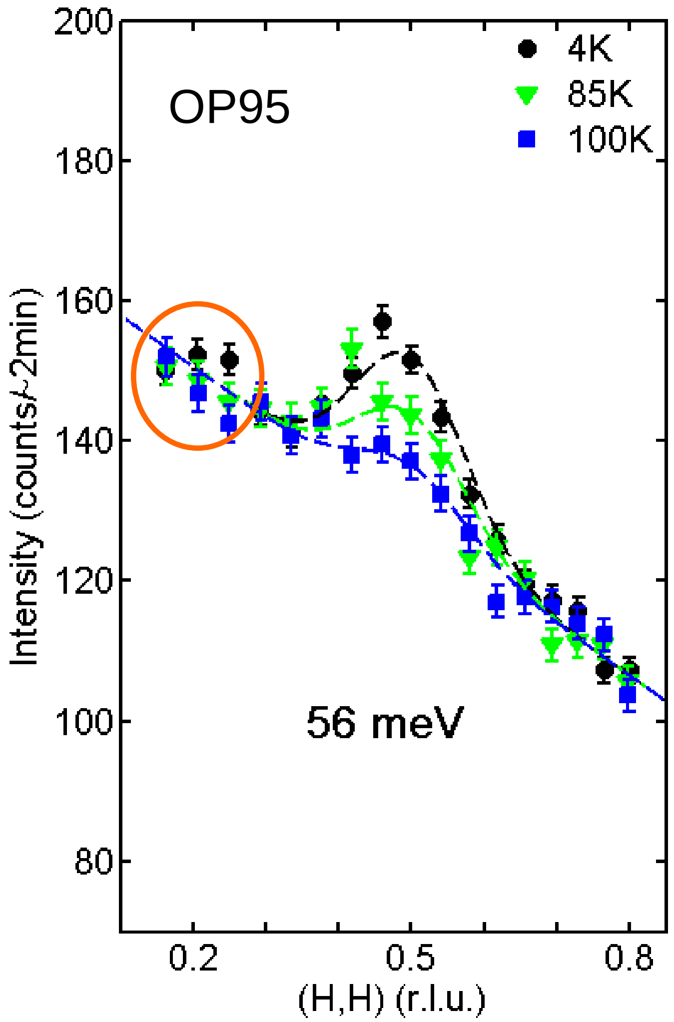
"OP95"

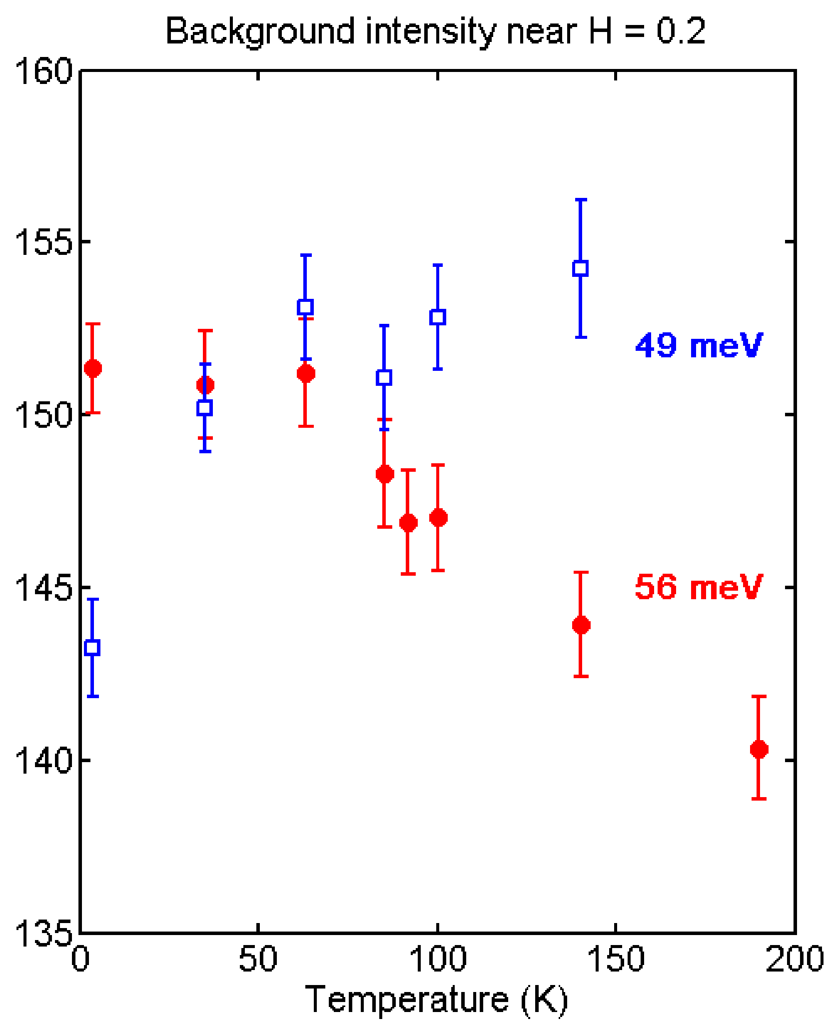


"UD65"



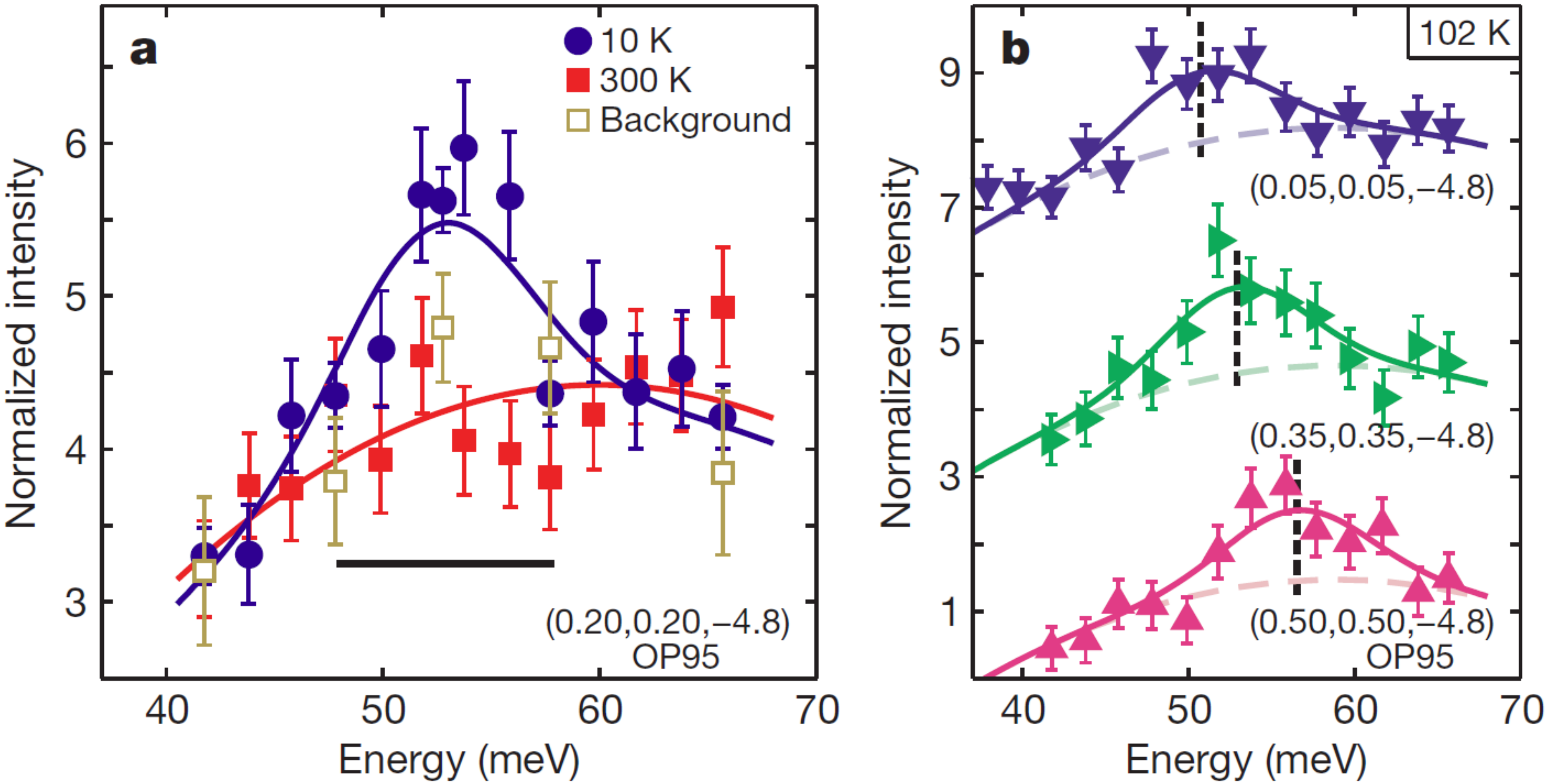
Unusual aspect of the resonance data





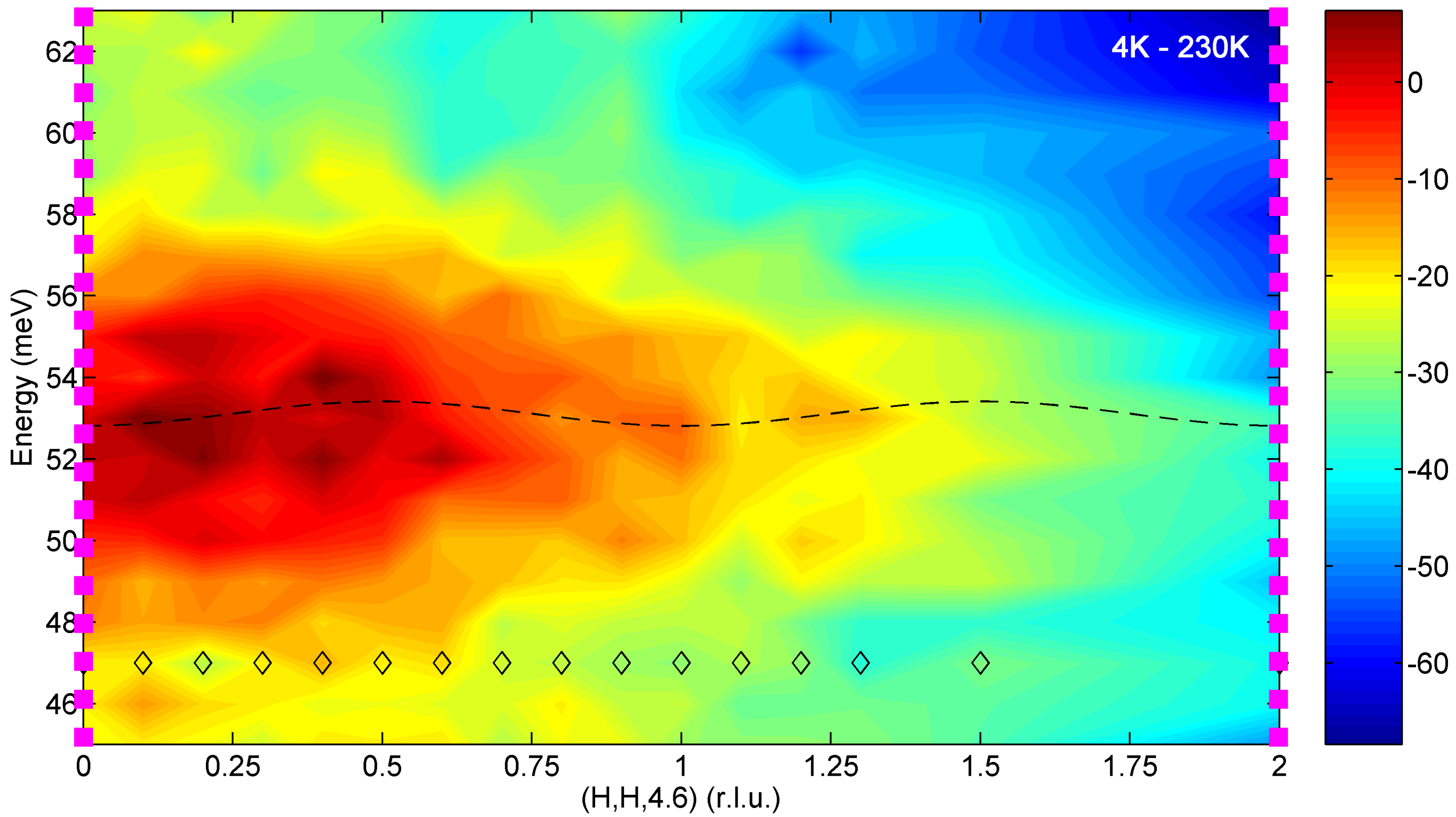
Verification of magnetic origin

Measured in spin-flip geometry

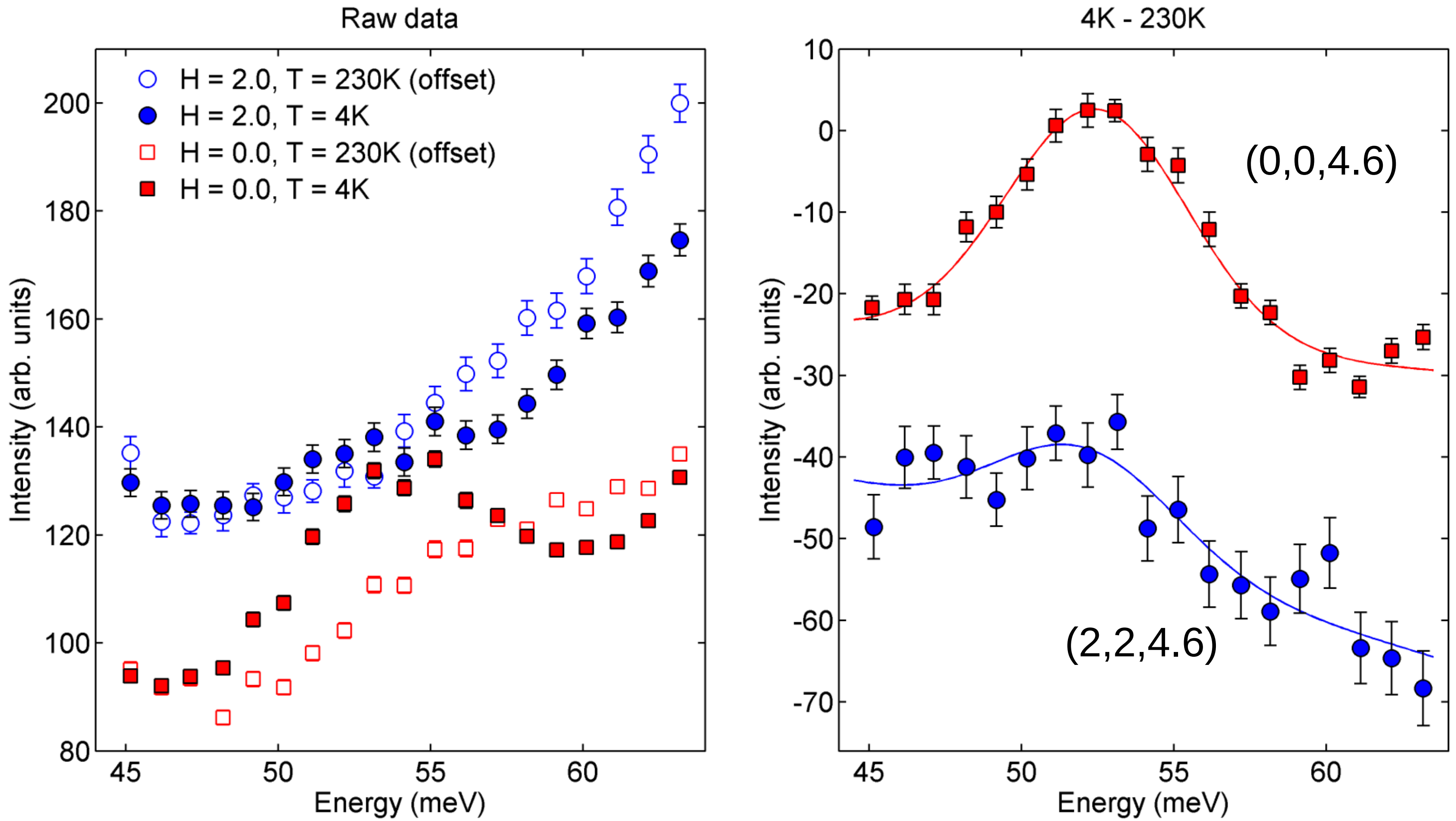


Almost disperseless excitation

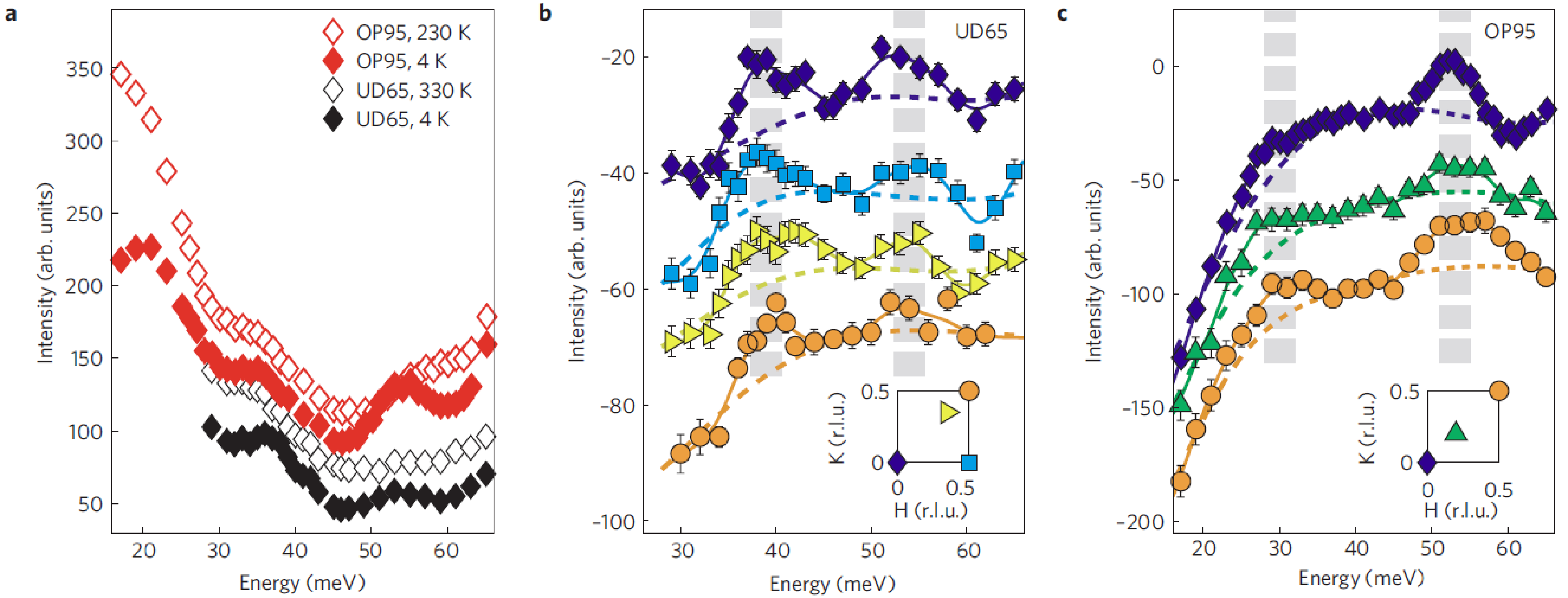
Sample: OP95



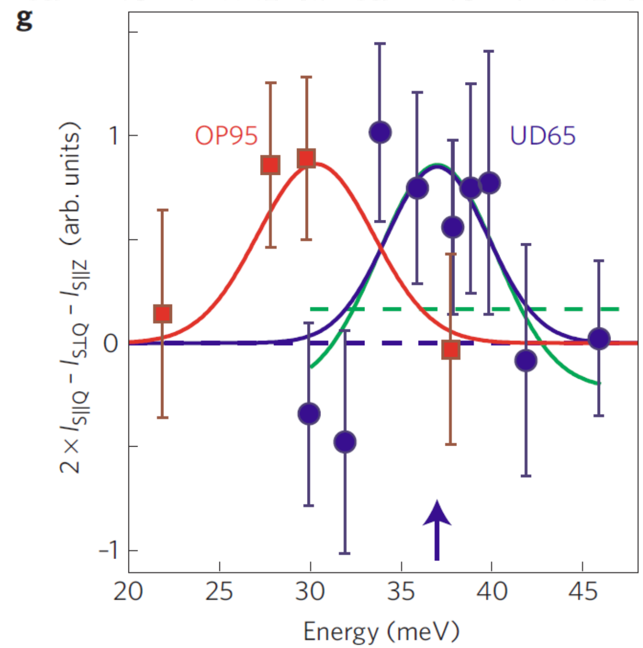
Sample: OP95


Raw data
H = 2.0, T = 230K (offset)
H = 2.0, T = 4K
H = 0.0, T = 230K (offset)
H = 0.0, T = 4K
Intensity (arb. units)
Energy (meV)
80
100
120
140
160
180
200
45
50
55
60
4K - 230K
(0,0,4.6)
(2,2,4.6)
Intensity (arb. units)
Energy (meV)
10
0
-10
-20
-30
-40
-50
-60
-70
45
50
55
60

A second excitation branch

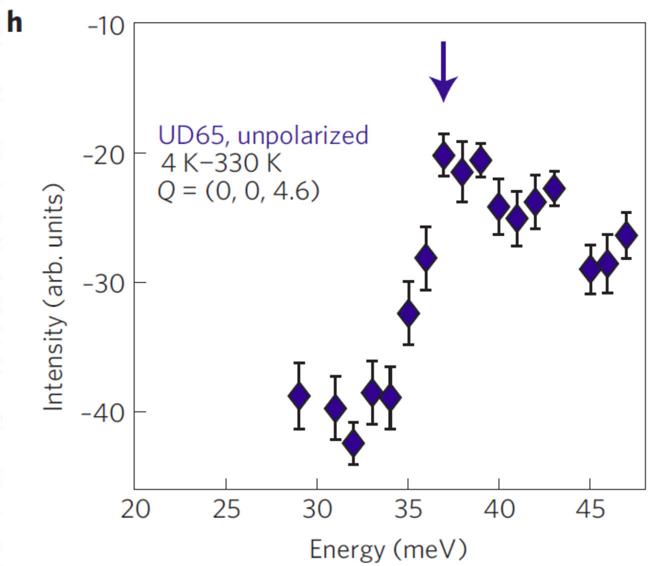


Verification of magnetic origin



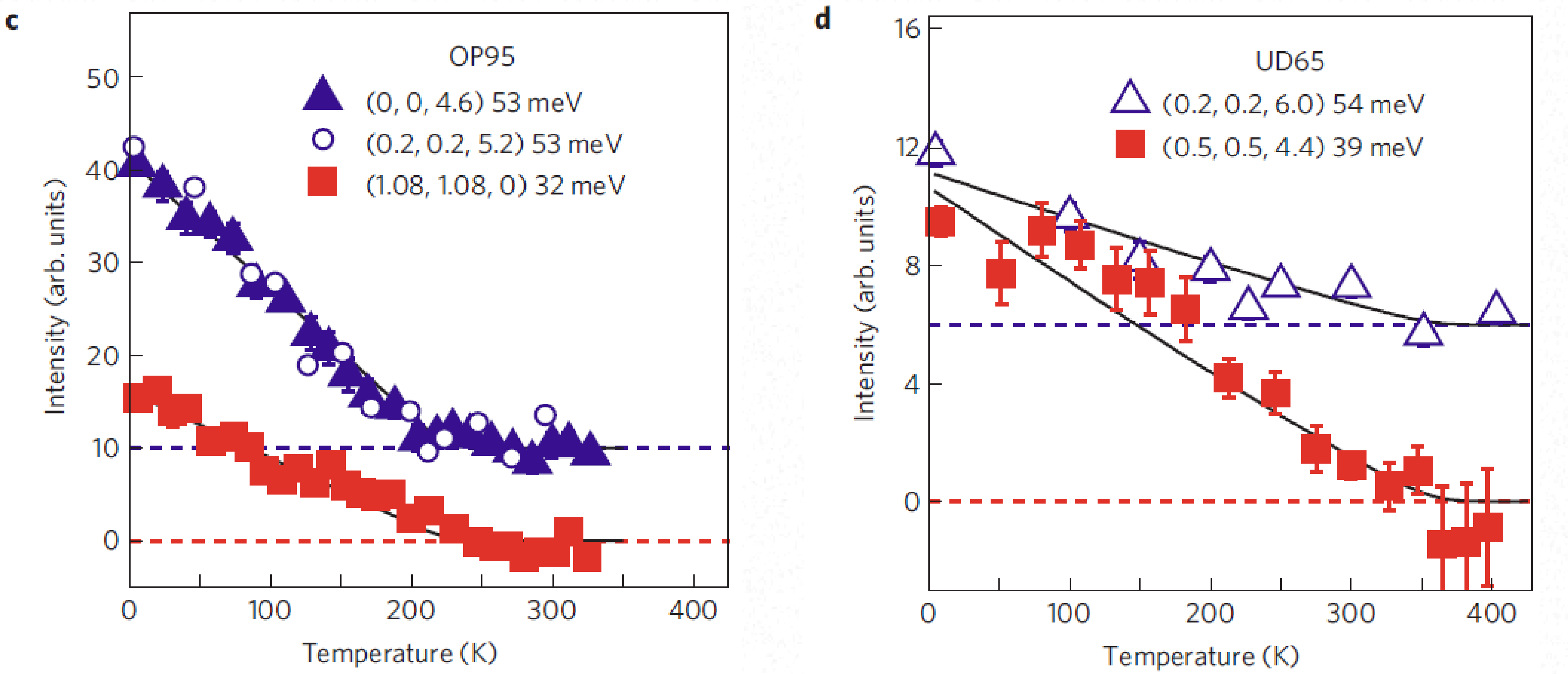
~ 125 hours

(entire beam time)

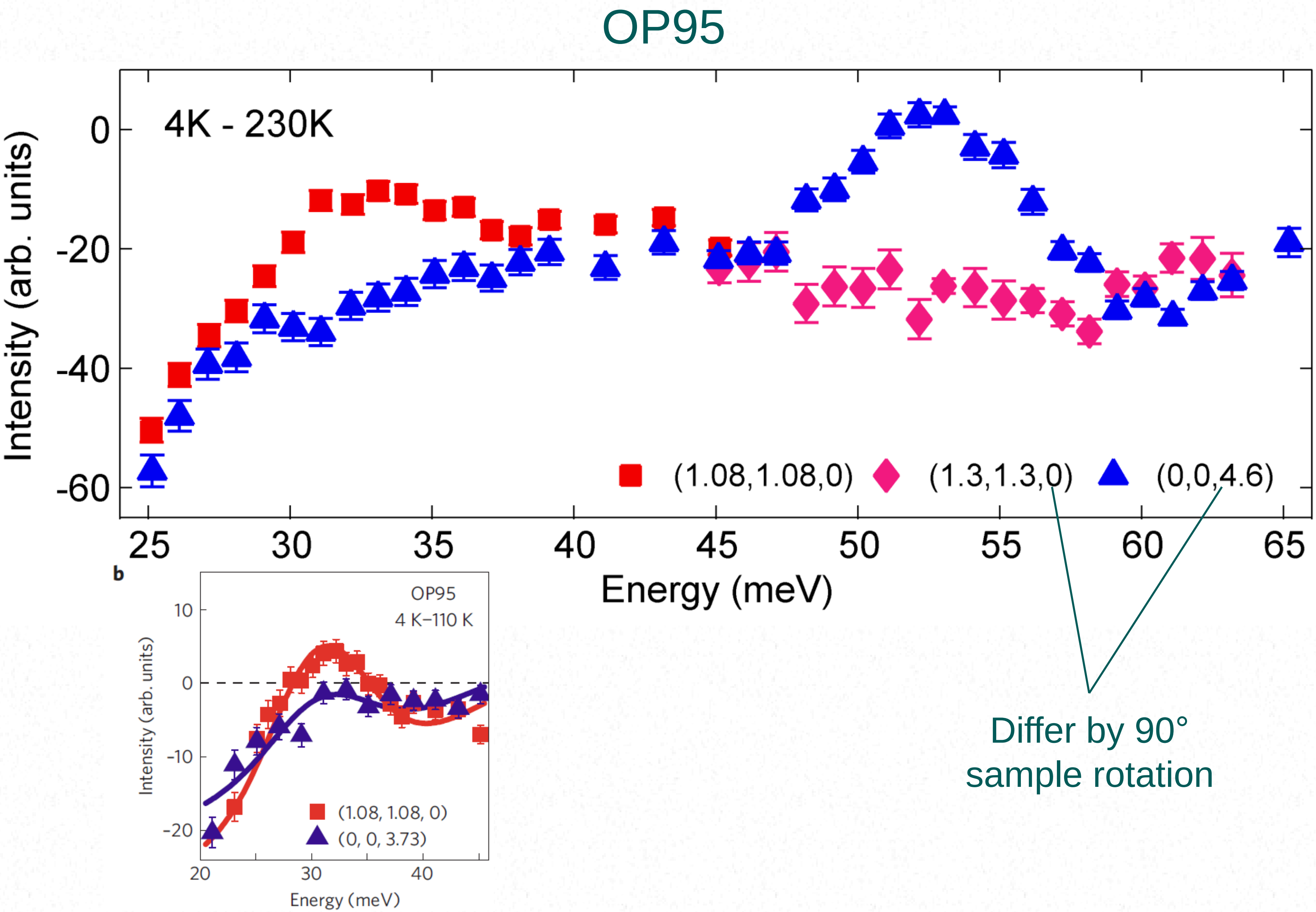


~ 6 hours

T dependence

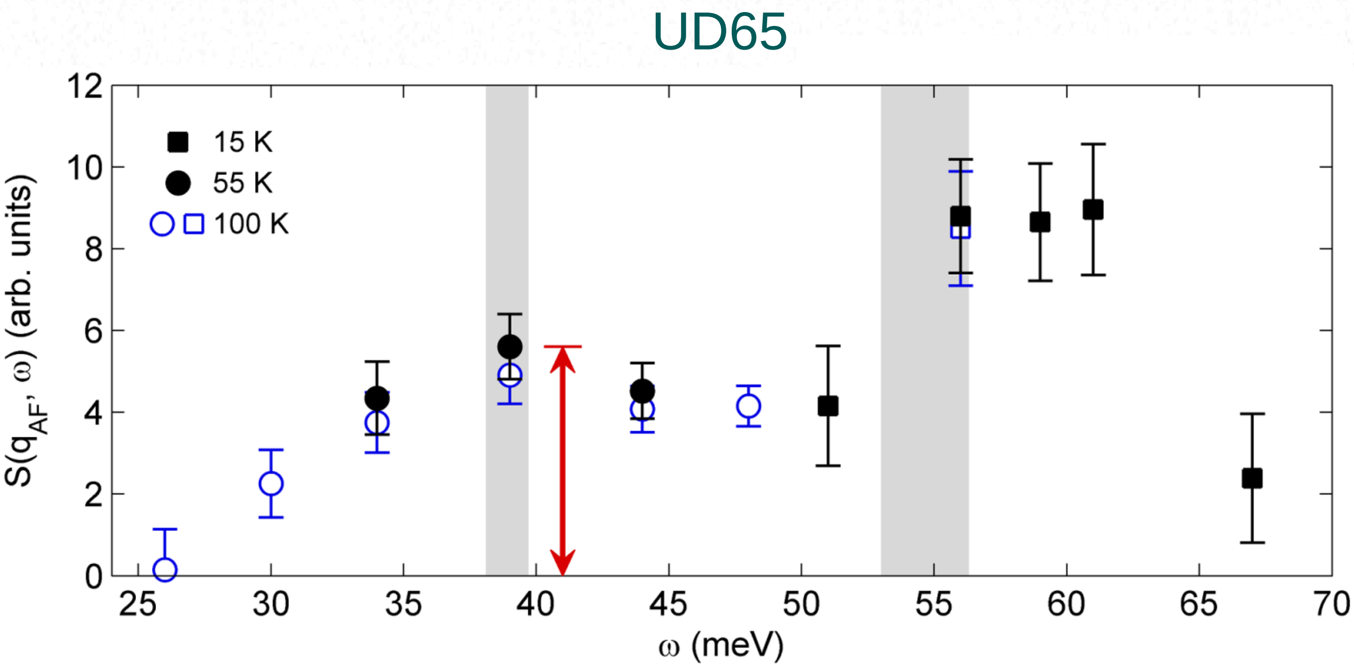


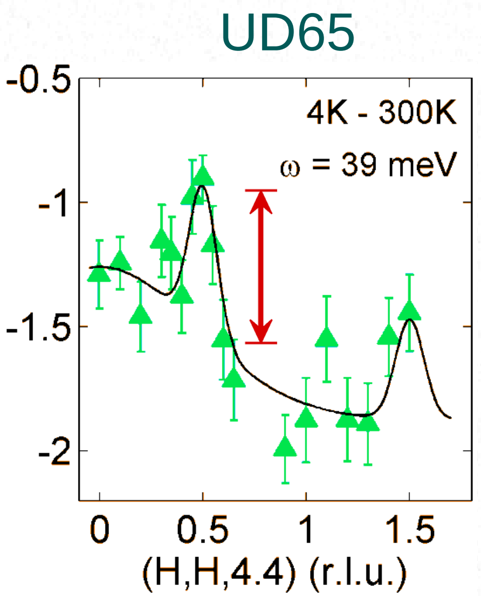
Q dependence



Differ by 90° sample rotation

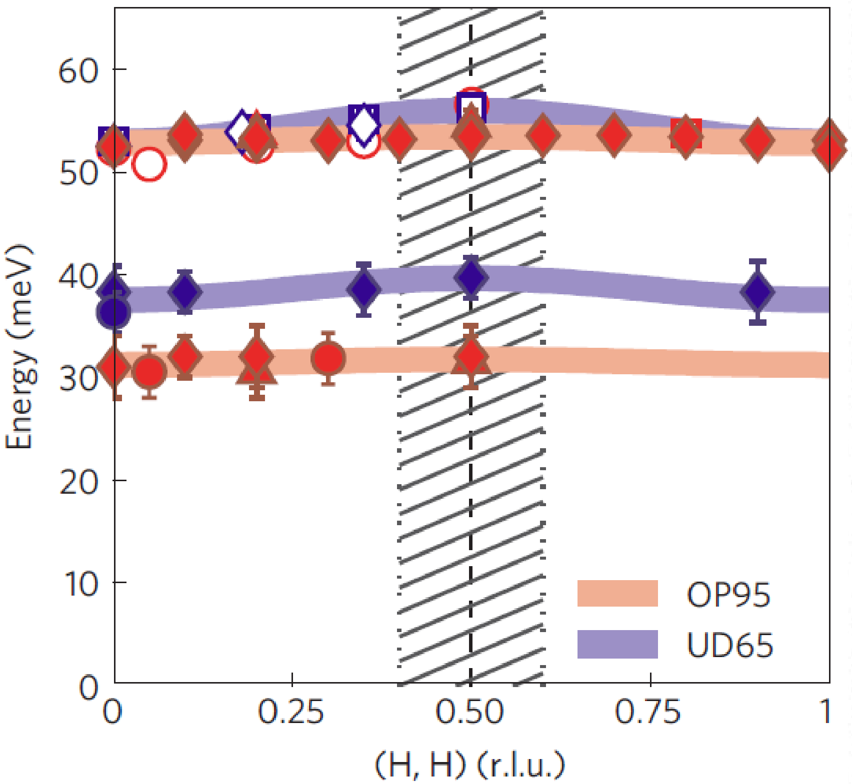
Connection to signal maxima at (1/2,1/2)





New excitation summary

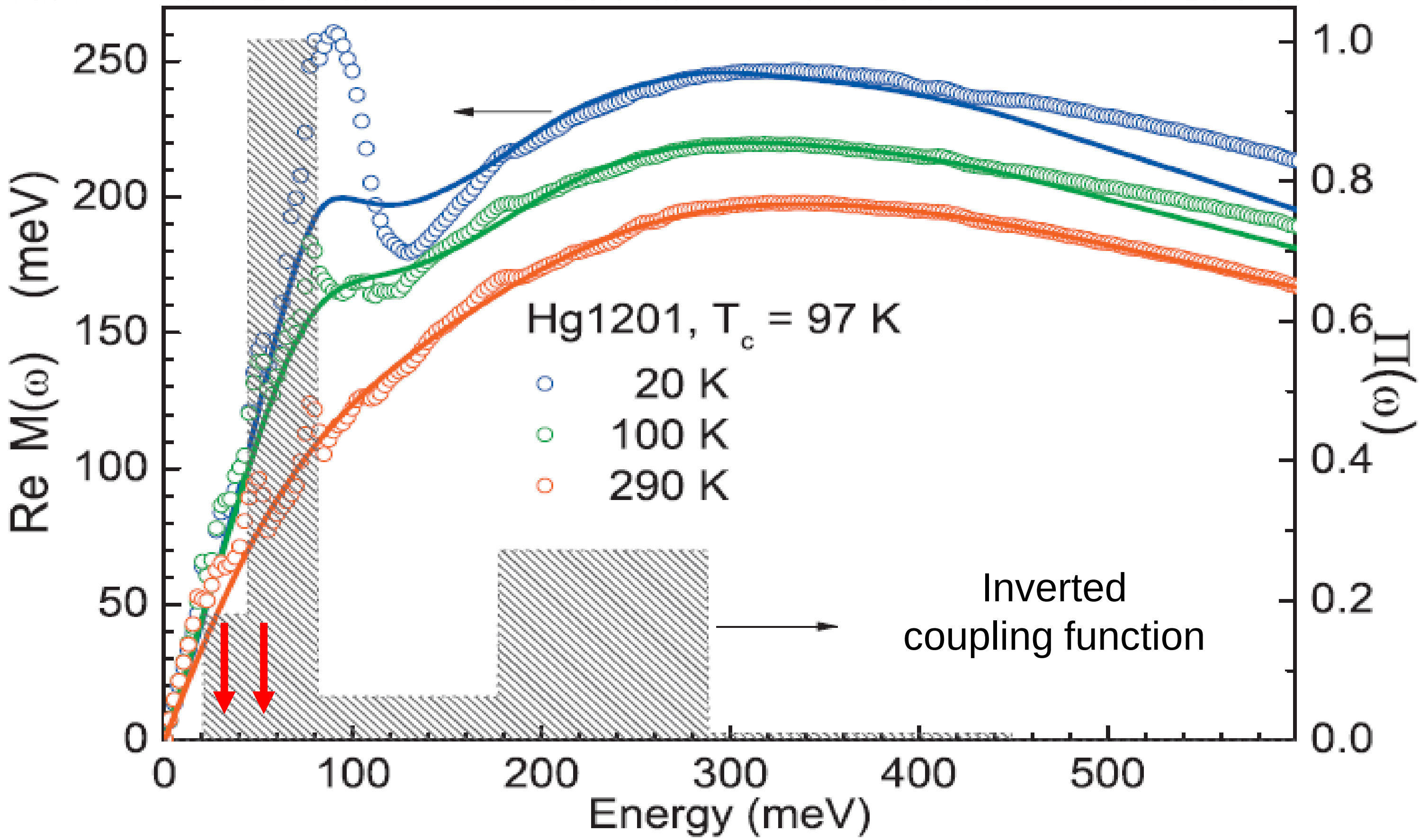
- Two almost disperseless modes
- Verified to be magnetic
- Set in below ~ *T**
- One energy decreases with doping
- Mysterious Q dependence of intensity
- Connection to AF fluctuations



YL *et al.*, *Nature* **468**, 283 (2010)

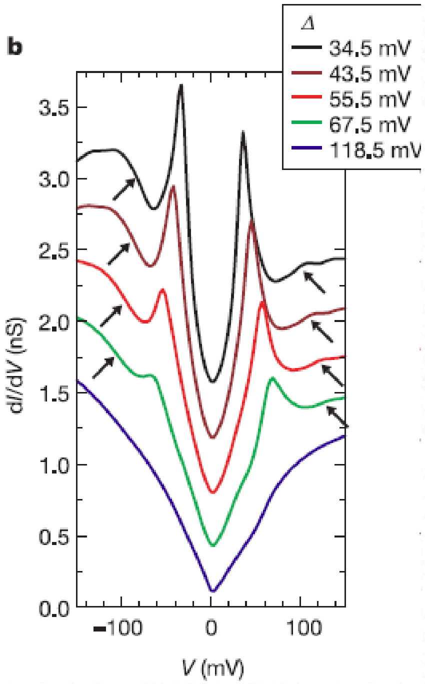
YL *et al.*, *Nat. Phys.* **8**, 404 (2012)

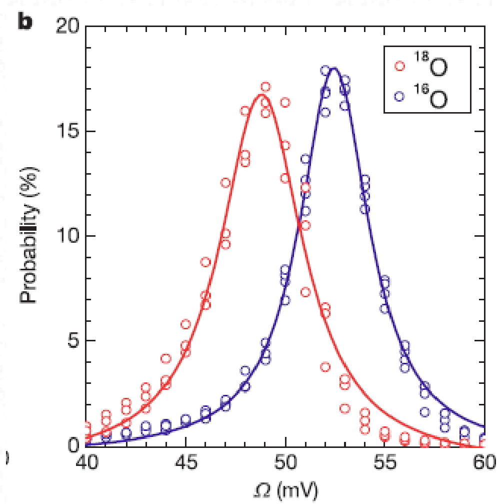
Electron-boson coupling

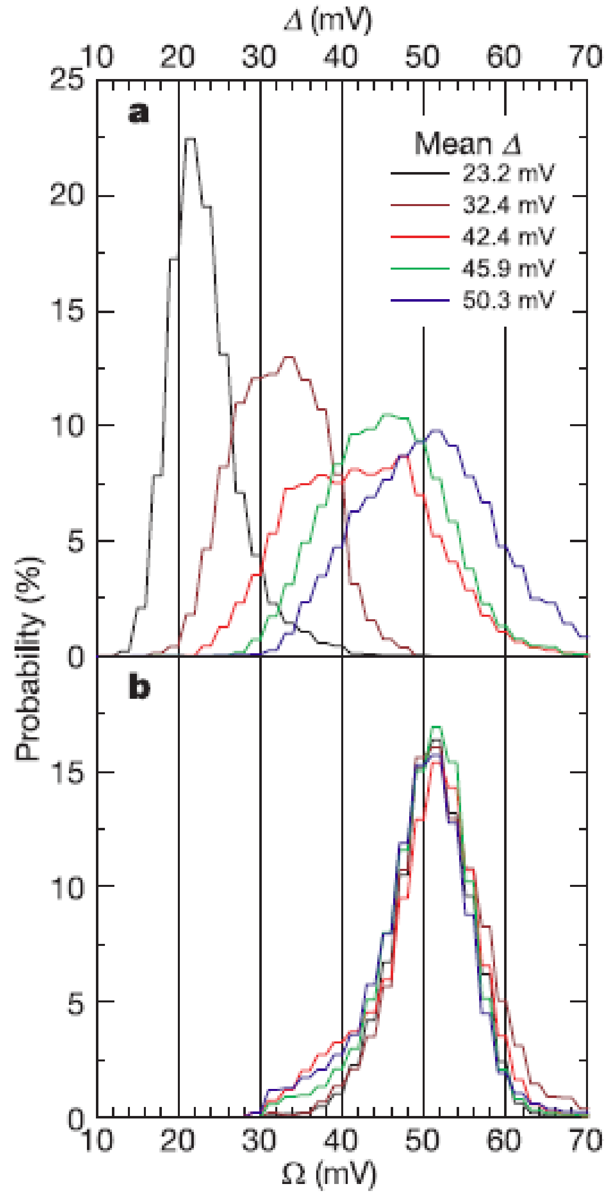


van Heumen *et al.*, *PRB* **79**, 184512 (2009)

Electron-boson coupling



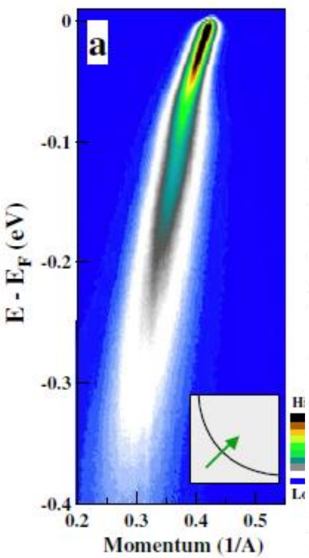


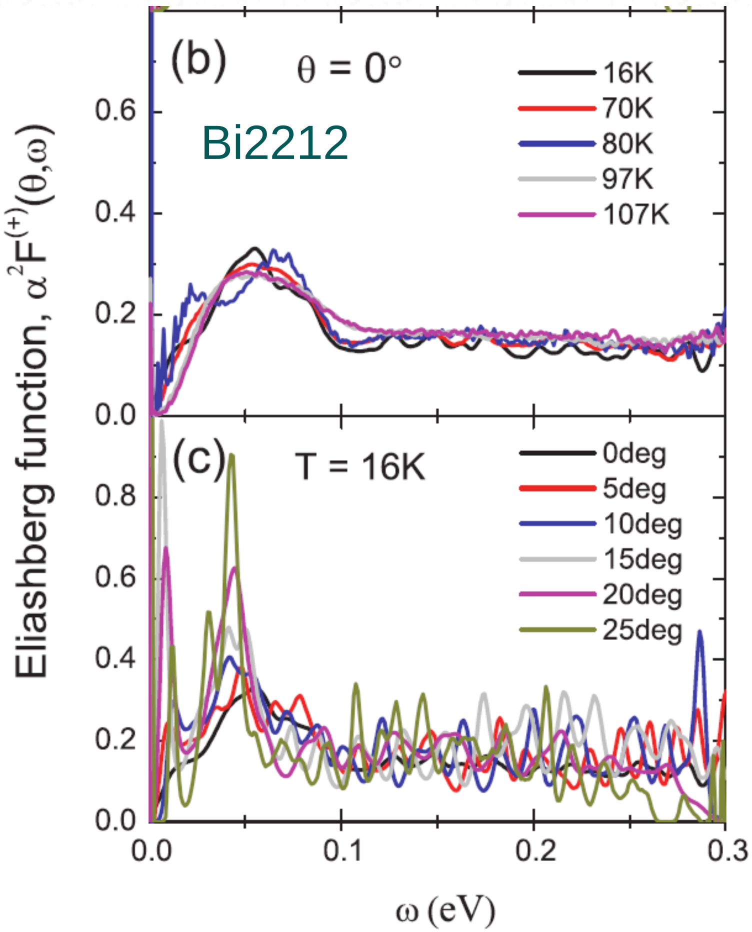


Bi2212

Lee *et al.*, *Nature* **442**, 546 (2006)

Electron-boson coupling



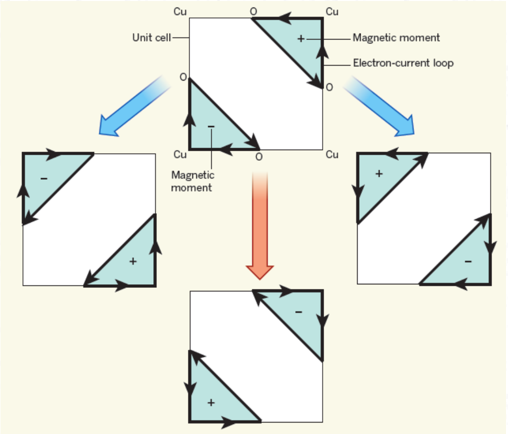


Inverted from high-resolution ARPES data taken by Xingjiang Zhou's group

Yun *et al.*, *PRB* **84**, 104521 (2011)

What are these excitations?

1. Excitations from “orbital currents”?



- Two modes, same *T** as seen by neutron diffraction
- Q-dependence, relation to AF fluctuations

See Varma, *Nature* **468**, 184 (2012)

2. Admixture between AF fluctuations and phonons?

- Multiple modes, Q-dependence, coincidence with AF fluctuation maxima
- Lack of systematic theory

3. Local modes?

- Weak dispersion, Q-dependence
- Coincidence with AF fluctuation maxima, large spectral weight

See, *e.g.*, Martin *et al.*, *PRB* **70**, 224514 (2004)

Outline

- Introduction
  - HTSC and the cuprates
  - Spectroscopic methods applied to the high-T_c problem
- Model system $HgBa_2CuO_{4+\delta}$
- Topics:
  1. The neutron resonant mode
  2. Pseudogap magnetism
  3. Energy $2\Delta_{sc}$ and above
- Summary

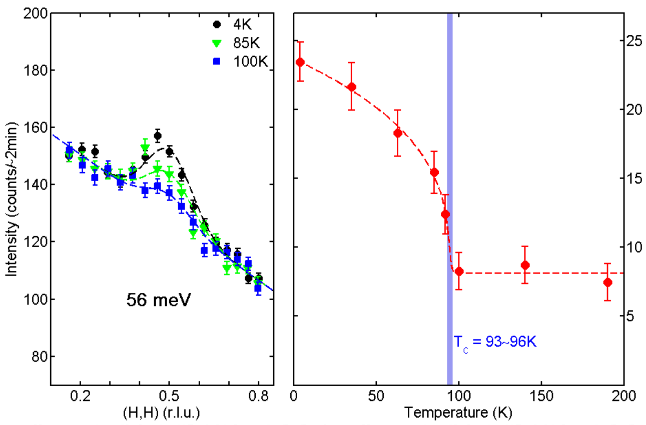
Phonon-mediated superconductivity

Lattice vibration

Magnetic fluctuation mediated superconductivity

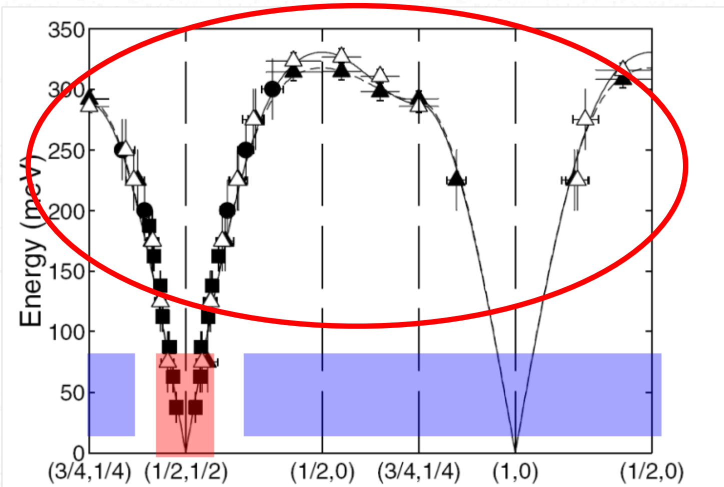
Desire to form pairs

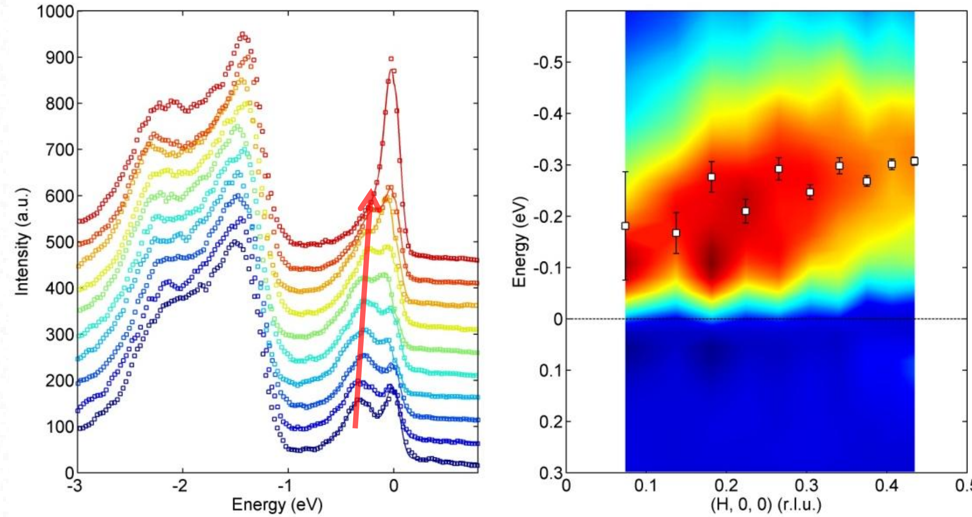
Magnetism



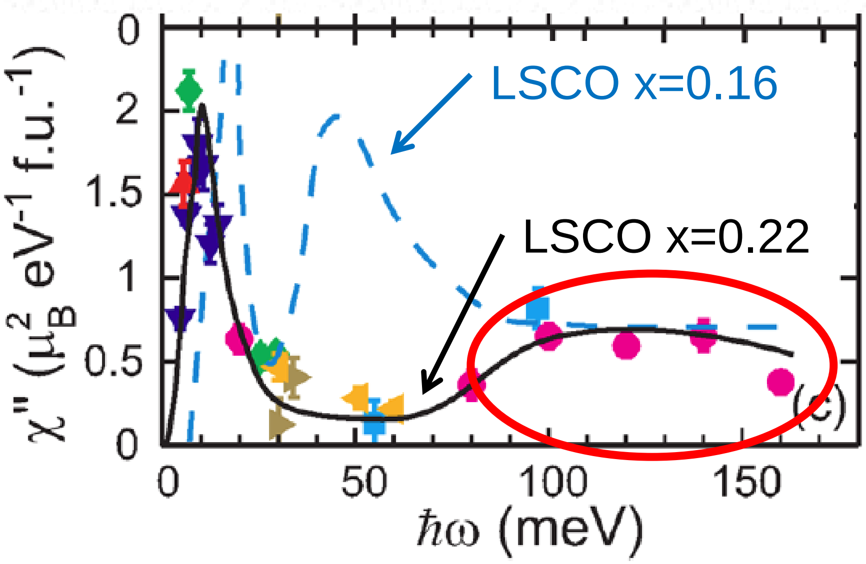
A feedback effect due to pairing can be expected on the magnetic fluctuations

More “juice” at higher energy

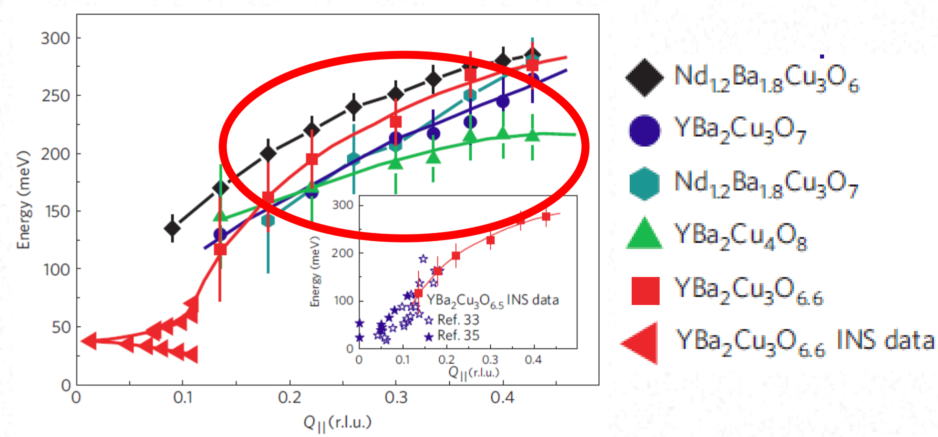




Hg1201, data taken last week at SLS
with Le Tacon, Tabis, Braicovich



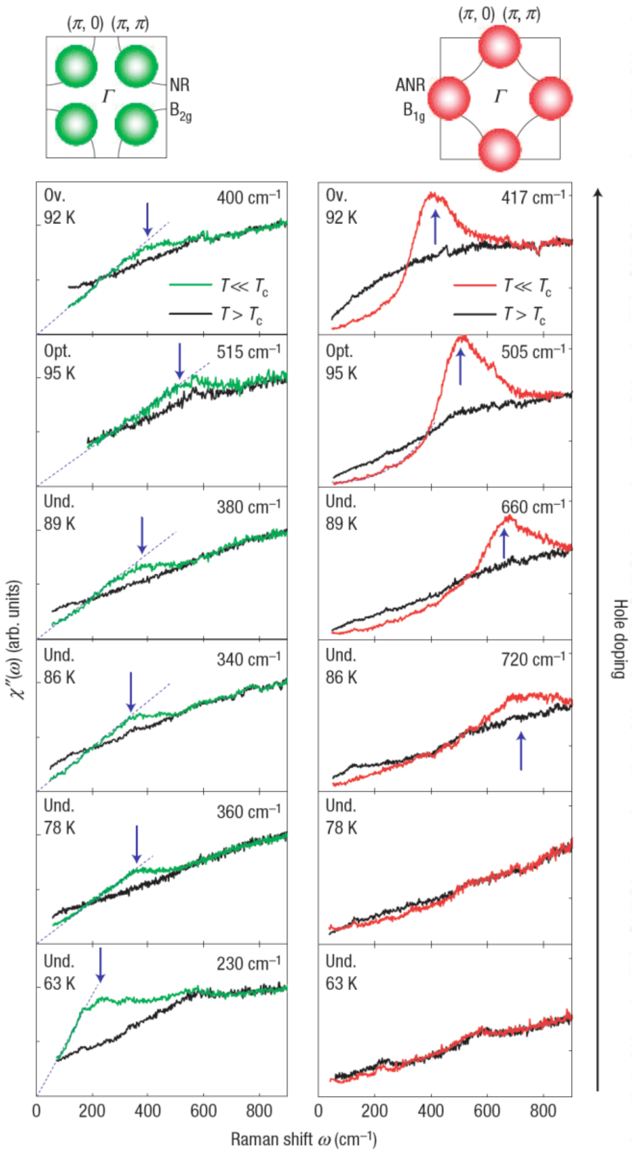
Lipscombe *et al.*, *PRL* **99**, 067002 (2004)

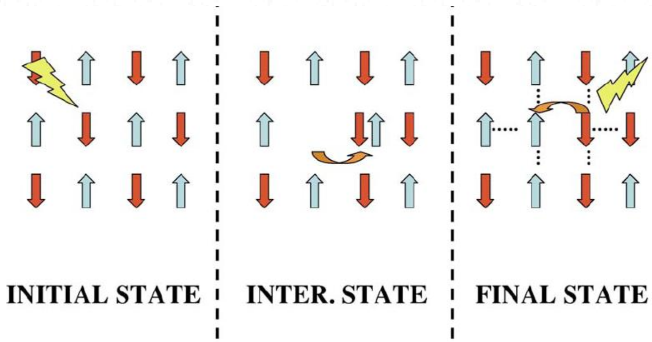


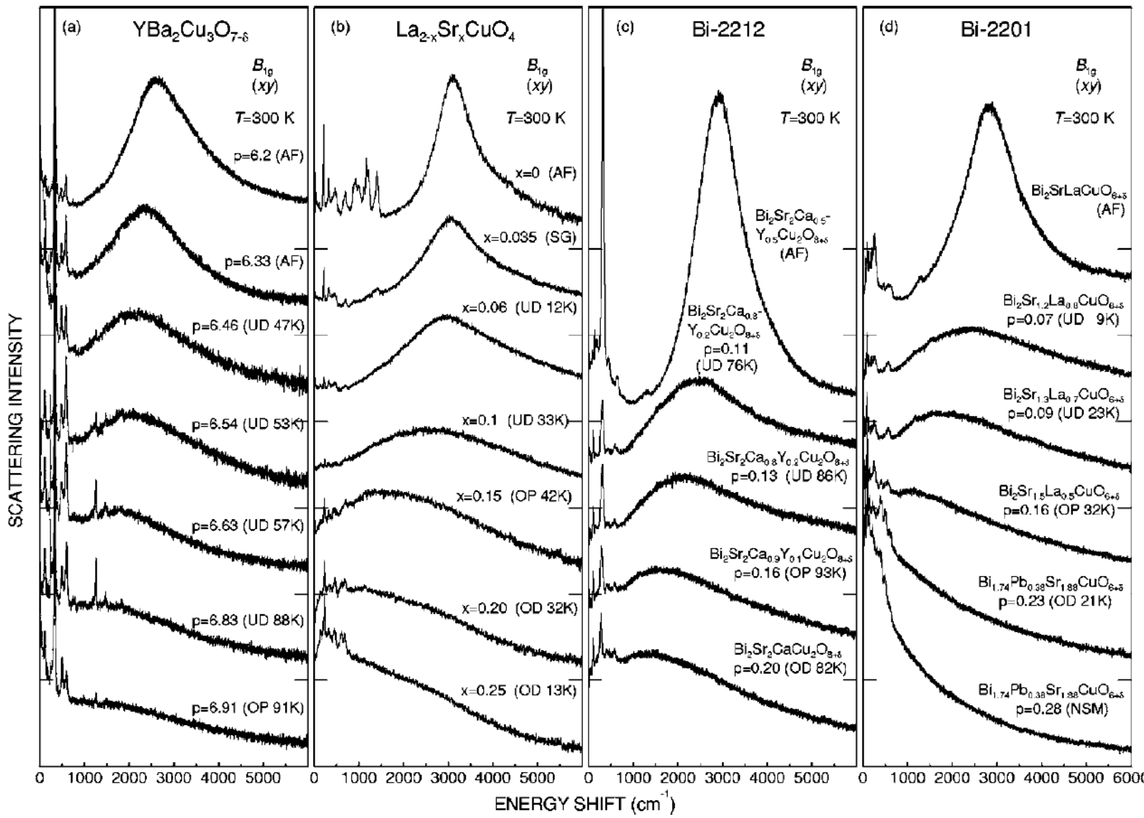
Le Tacon *et al.*, *Nat. Phys.* **7**, 725 (2011)

How about correlation between high-energy magnetic excitations and SC as we change temperature and doping?

Raman scattering



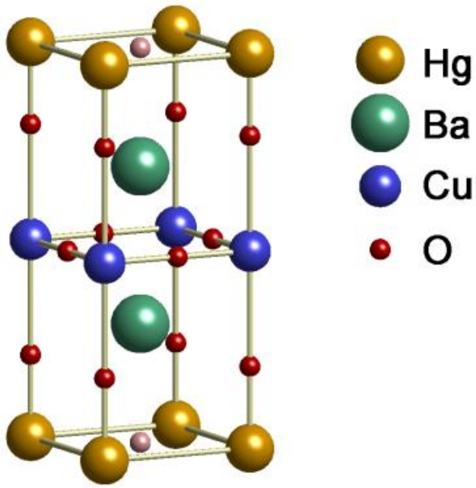


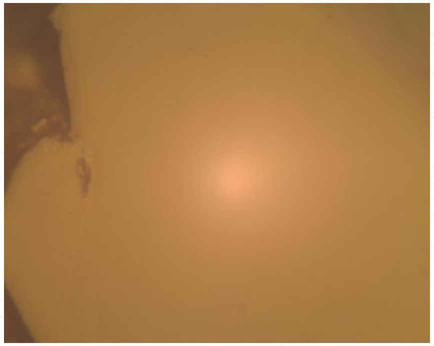


Le Tacon *et al.*, *Nat. Phys.* **2**, 537 (2006)

Sugai *et al.*, *PRB* **68**, 184504 (2003)

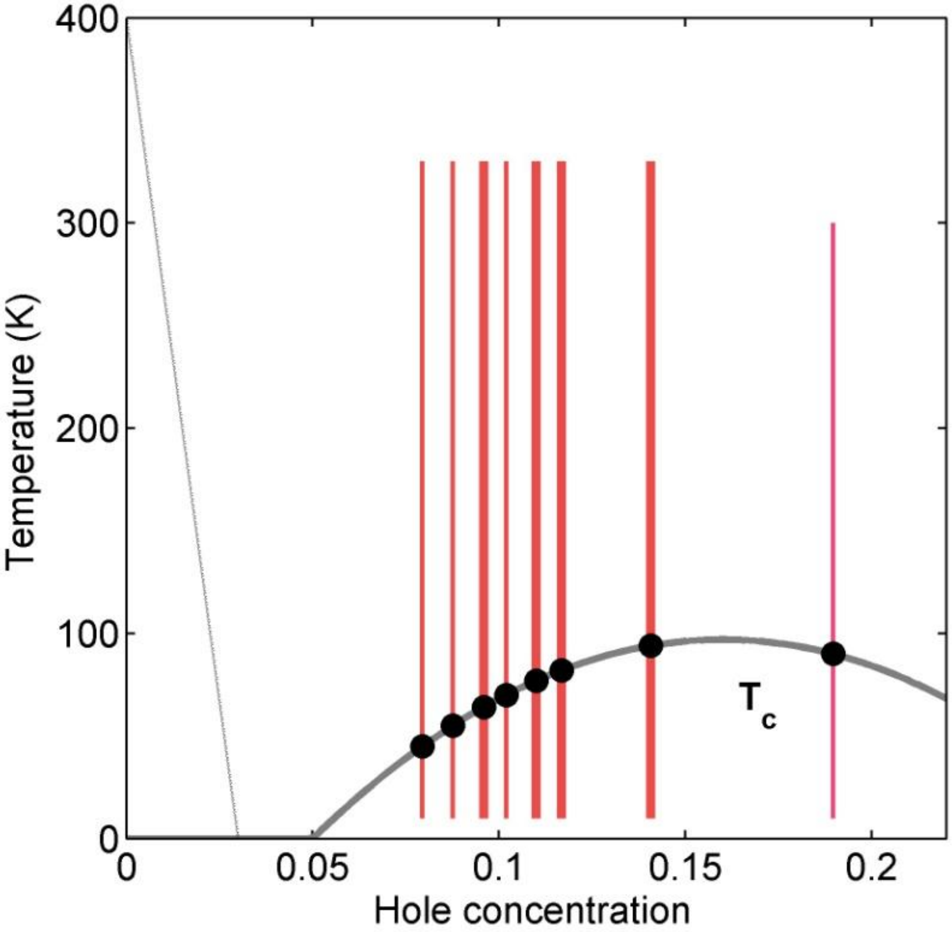
Samples

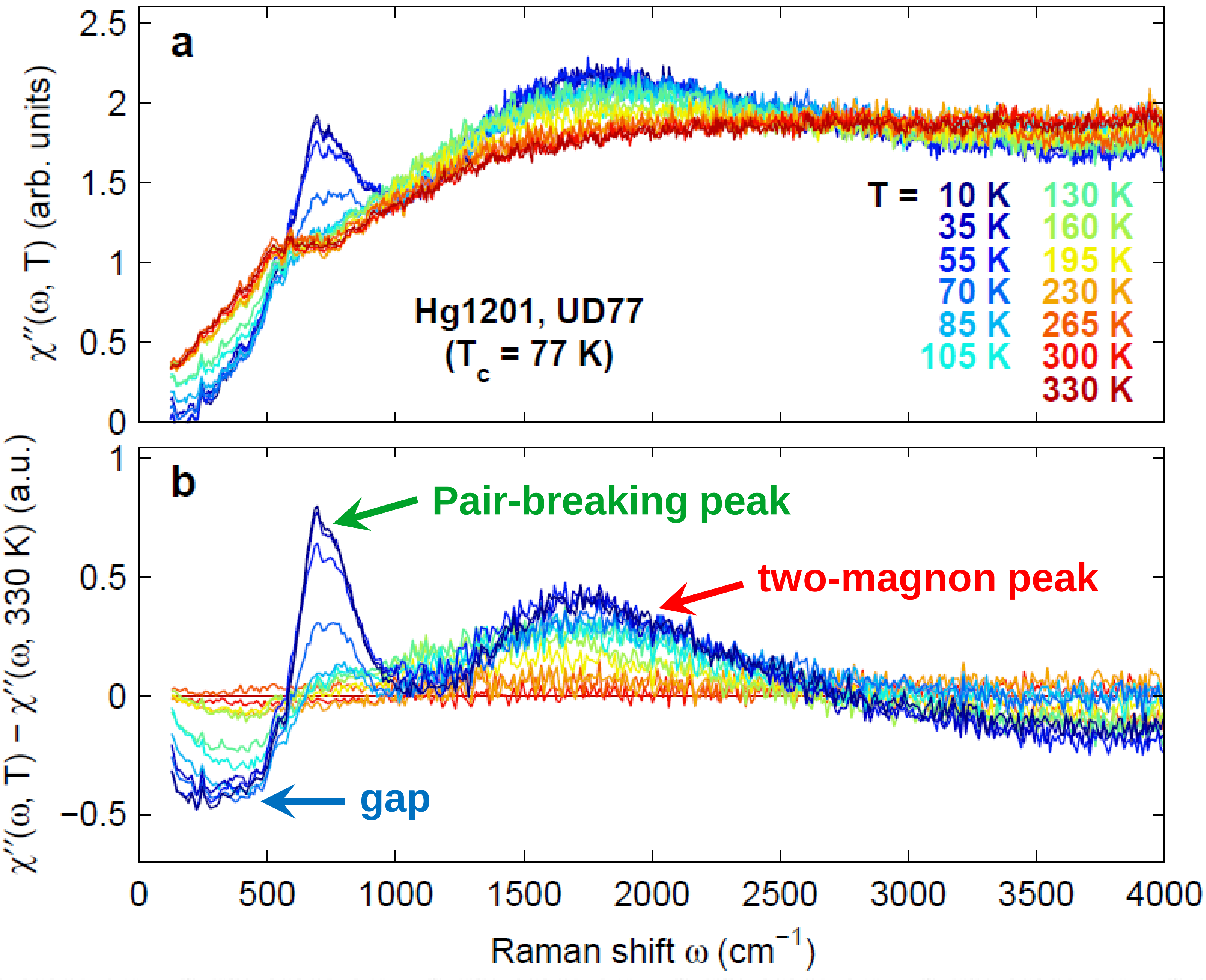


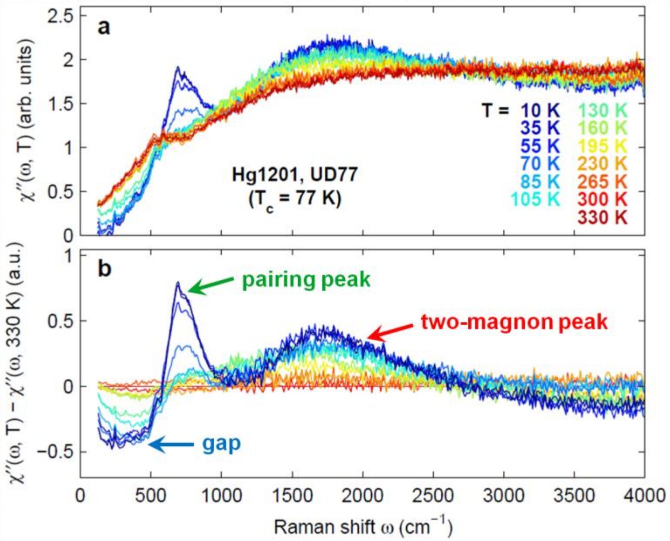


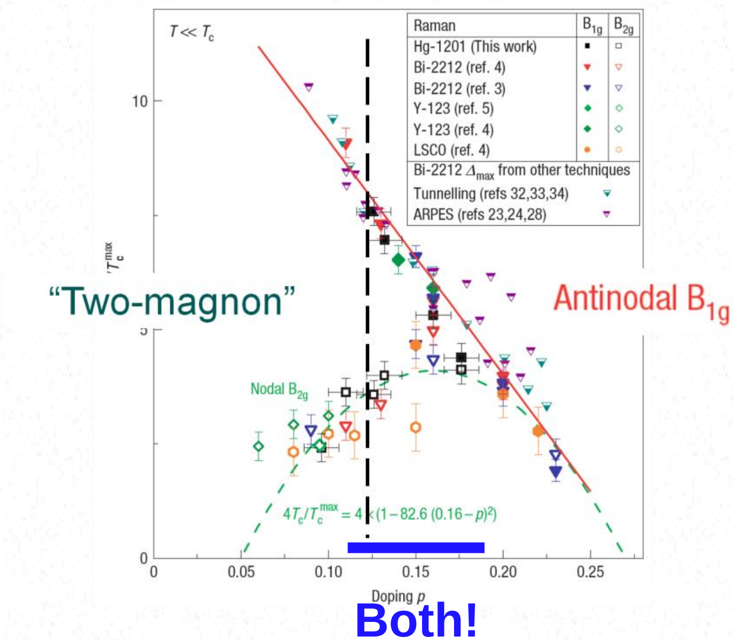
Freshly prepared sample surface (50x)

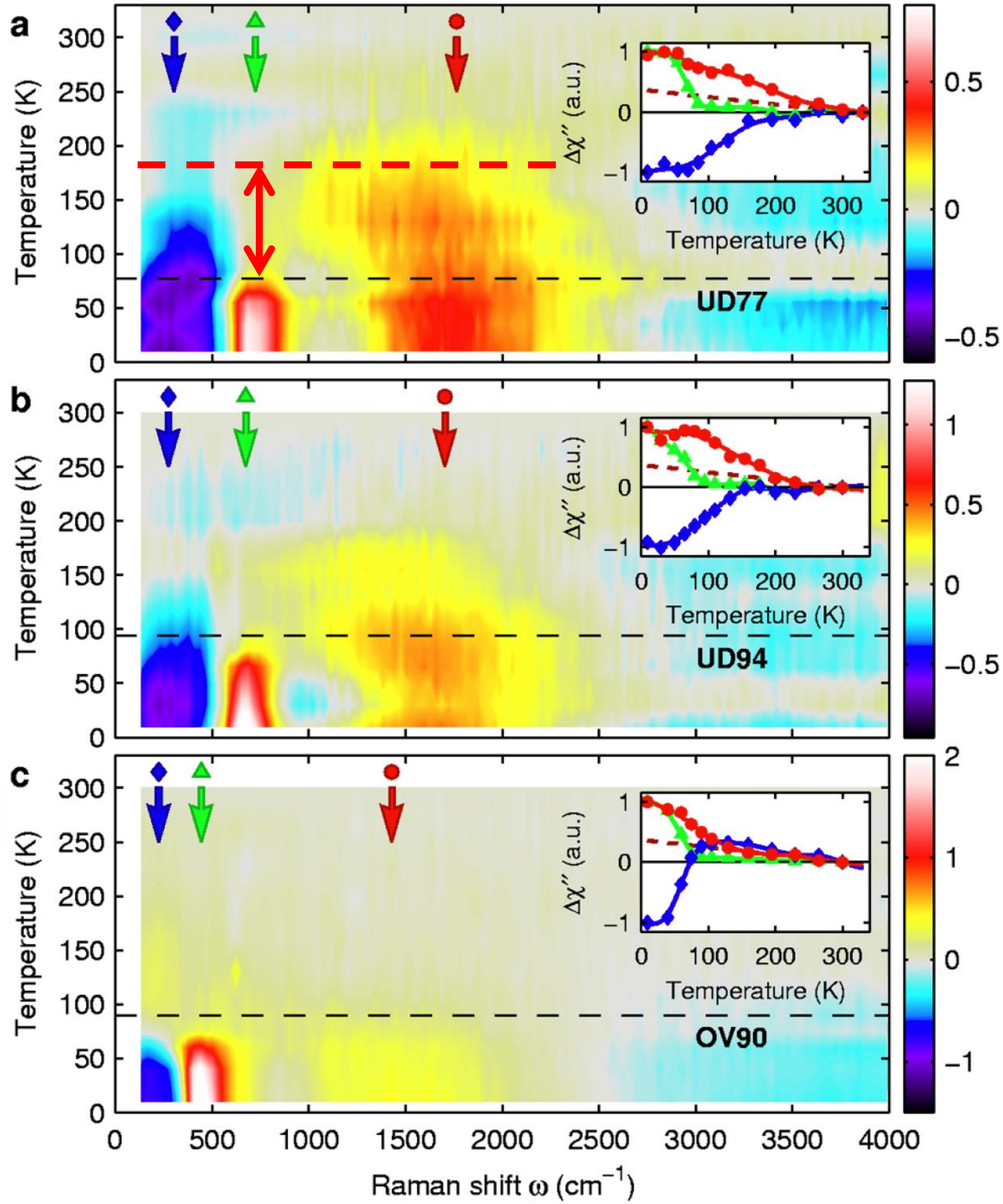
Our p- and T-range



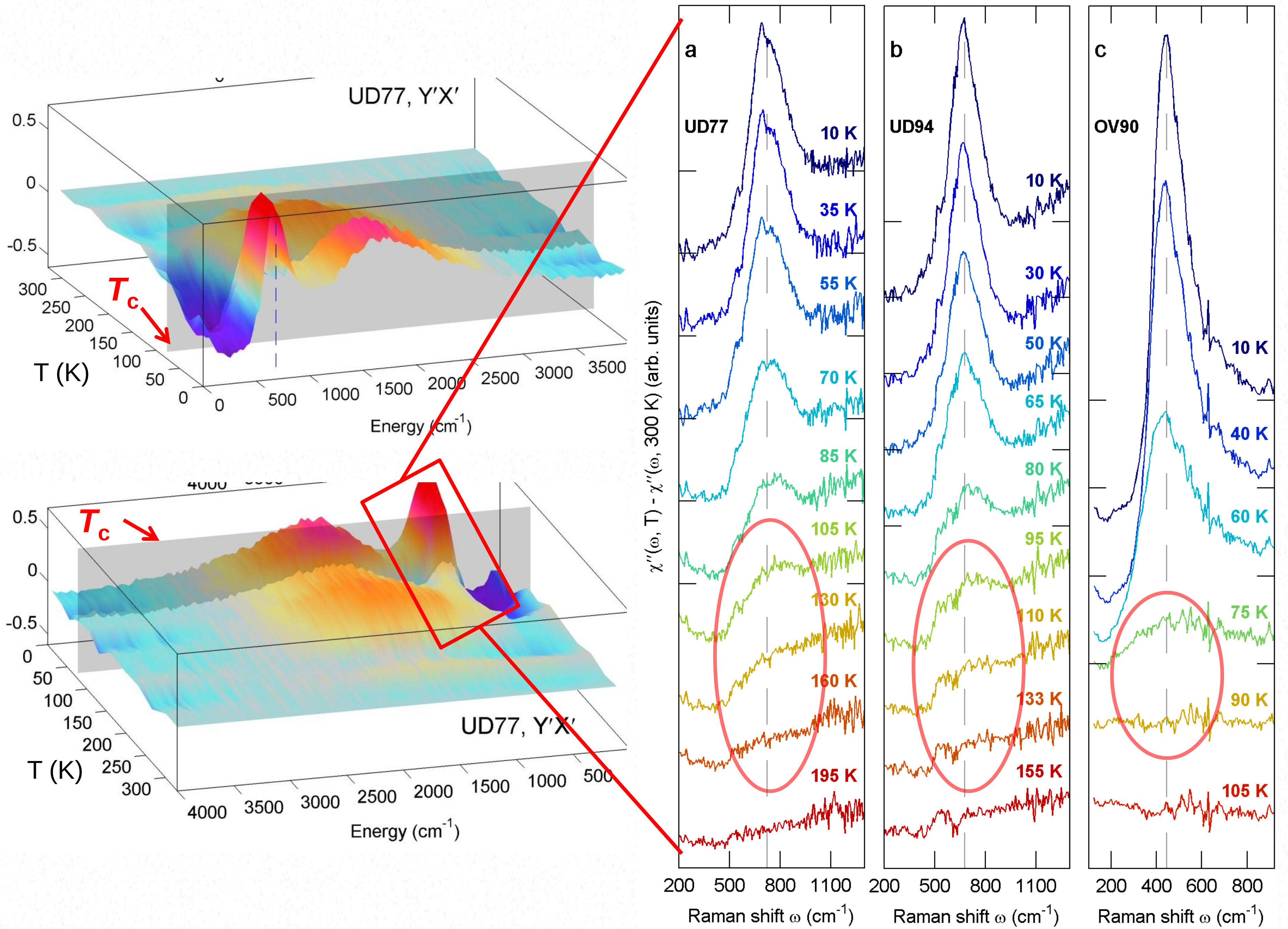

a
b
2.5
2
1.5
1
0.5
0
−0.5
χ''(ω, T) (arb. units)
χ''(ω, T) − χ''(ω, 330 K) (a.u.)
Hg1201, UD77
(T_c = 77 K)
T = 10 K
35 K
55 K
70 K
85 K
105 K
130 K
160 K
195 K
230 K
265 K
300 K
330 K
Pair-breaking peak
two-magnon peak
gap
0
500
1000
1500
2000
2500
3000
3500
4000
Raman shift ω (cm^−1)







Le Tacon *et al.*, *Nat. Phys.* **2**, 537 (2006)



UD77, Y′X′
T (K)
Energy (cm^{-1})
T_c
a
b
c
UD77
UD94
OV90
10 K
35 K
55 K
70 K
85 K
105 K
130 K
160 K
195 K
30 K
50 K
65 K
80 K
95 K
110 K
133 K
155 K
40 K
60 K
75 K
90 K
105 K
χ″(ω, T) - χ″(ω, 300 K) (arb. units)
Raman shift ω (cm^{-1})

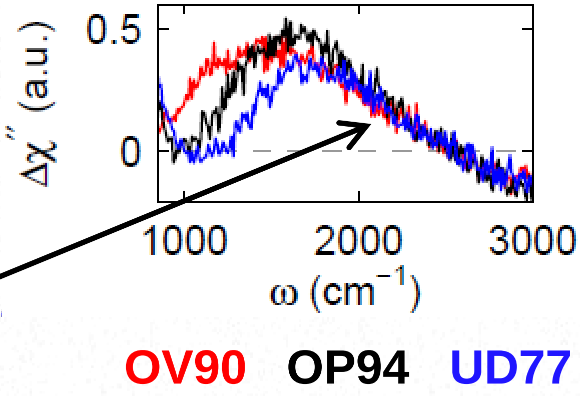
High-energy feedback effect

- ❑ Enhancement of two-magnon peak when the gap opens
- ❑ Pre-formed pairs observed around the same temperature

High-energy feedback effect similar to the resonant mode!

Reasons for the “two-magnon” name:

- ❑ Selection rule is correct (B_{1g})
- ❑ Energy agrees with reported values
- ❑ “Leading edge” insensitive to doping



YL *et al.*, *Phys. Rev. Lett.* **108**, 227003 (2012)

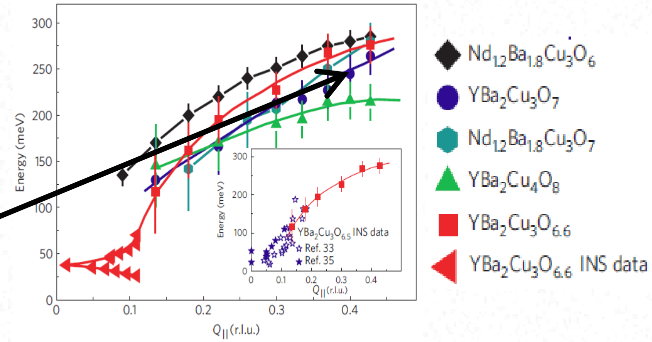
High-energy feedback effect

- ❑ Enhancement of two-magnon peak when the gap opens
- ❑ Pre-formed pairs observed around the same temperature

High-energy feedback effect similar to the resonant mode!

Reasons for the “two-magnon” name:

- ❑ Selection rule is correct (B_{1g})
- ❑ Energy agrees with reported values
- ❑ “Leading edge” insensitive to doping



YL *et al.*, *Phys. Rev. Lett.* **108**, 227003 (2012)

Outline

- Introduction

  - HTSC and the cuprates

  - Spectroscopic methods applied to the high-T_c problem

- Model system $HgBa_2CuO_{4+\delta}$

- Topics:

  1. The neutron resonant mode

  2. Pseudogap magnetism

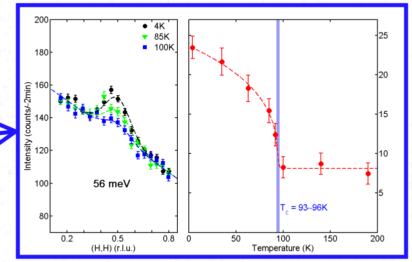
  3. Energy $2\Delta_{sc}$ and above

- Summary

Some important questions

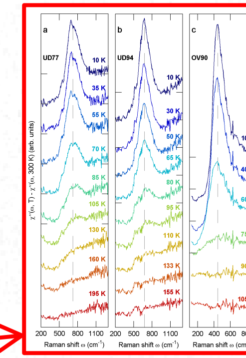
- Q: What's the pairing symmetry?

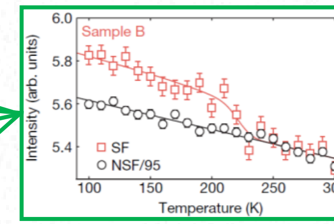
  A: *d*-wave.



- Q: What causes the pseudogap above T_c?

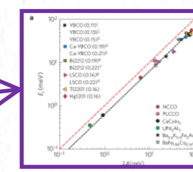
  A: Evidence for pre-formed pairs and competing order.

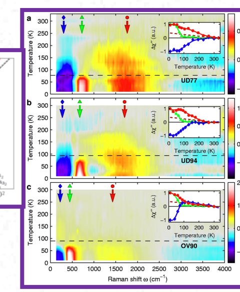




- Q: Is there a competing order other than AFM?

  A: CDW, SDW, intra-unit-cell order are all possible.

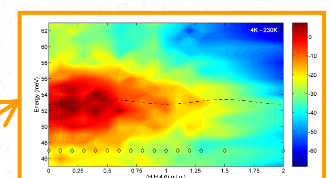




- Q: Which bosonic modes are important?

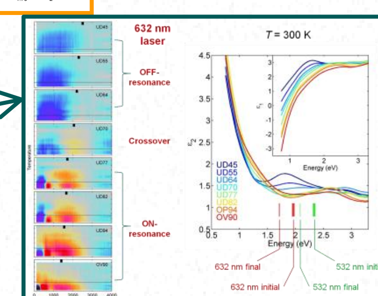
  A: Magnetic excitations, phonons, AND

  perhaps modes with *mixed degrees of freedom.*



- Q: What's the minimal microscopic model?

  A: Single-band models may be insufficient.



Collaborators

Neutron Scattering

Guichuan Yu (U. Minnesota)

Martin Greven (U. Minnesota)

Paul Steffens (ILL, Grenoble)

Richard A. Mole (FRM-II, Garching)

Klaudia Hradil (FRM-II, Garching)

Nikola Egentenmeyer (PSI, Villigen)

Jorge Gavilano (PSI, Villigen)

Victor Balédent (LLB, Saclay)

Yvan Sidis (LLB, Saclay)

Philippe Bourges (LLB, Saclay)

Raman Scattering

Mathieu Le Tacon (MPI, Stuttgart)

Mohammad Bakr (MPI, Stuttgart)

Bernhard Keimer (MPI, Stuttgart)

Rudi Hackl (WMI, Garching)

Optical Ellipsometry

Yulia Matiks (MPI, Stuttgart)

Alexander V. Boris (MPI, Stuttgart)

Theory

Damien Terrade (MPI, Stuttgart)

Dirk Manske (MPI, Stuttgart)

Alexander Yaresko (MPI, Stuttgart)

Samples and Characterization

Mun K. Chan (U. Minnesota)

Lina Ji (U. Minnesota)

Neven Barišić (U. Minnesota)

Xudong Zhao (U. Minnesota, Jilin Univ.)

Toshinao Loew (MPI, Stuttgart)

Chengtian Lin (MPI, Stuttgart)

Thank you!