SCSR 2014 – Trieste, Italy – 11 December 2014

Photo-enhanced antinodal conductivity in the pseudogap state of high T_c cuprates

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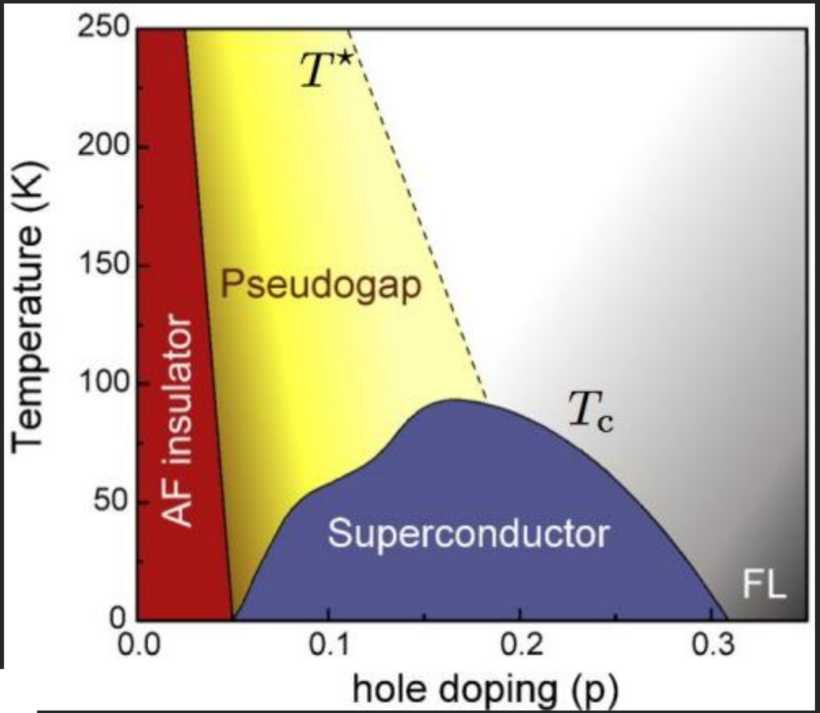
The Pseudogap and the Phase Diagram

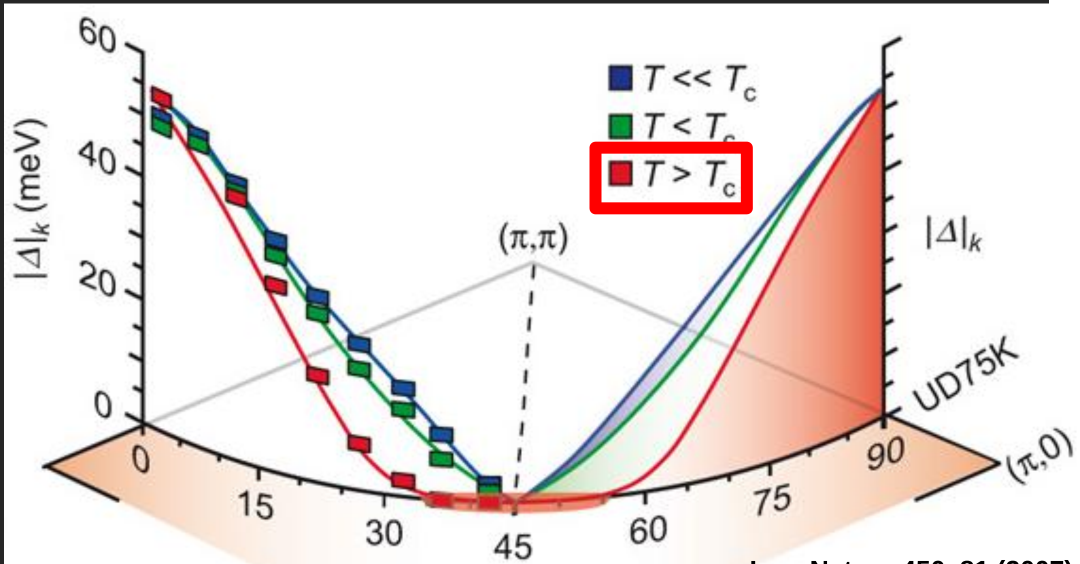
Motivations:

- Determine the phase diagram
- Understanding PG formation

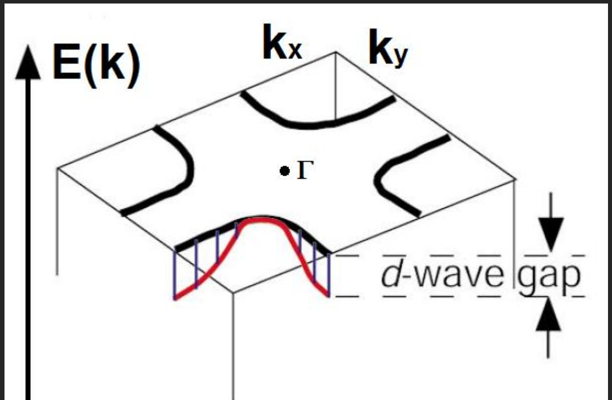
  Mottness?? Long range orders??

➔ Key role of Non-Equilibrium Approach





Lee, Nature 450, 81 (2007)

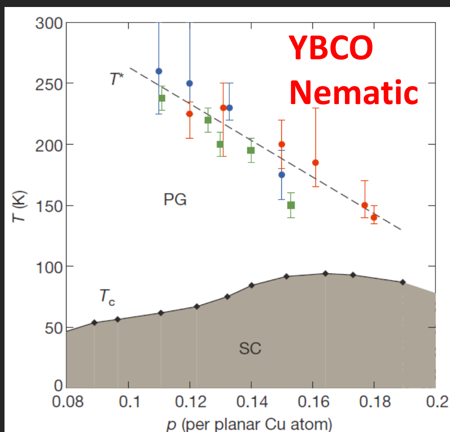


Damascelli, RMP 75, 473 (2003)

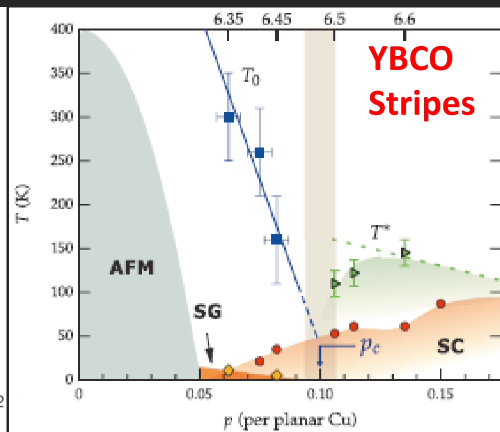
The Pseudogap

Is the Pseudogap related to the onset of long-range-orders?

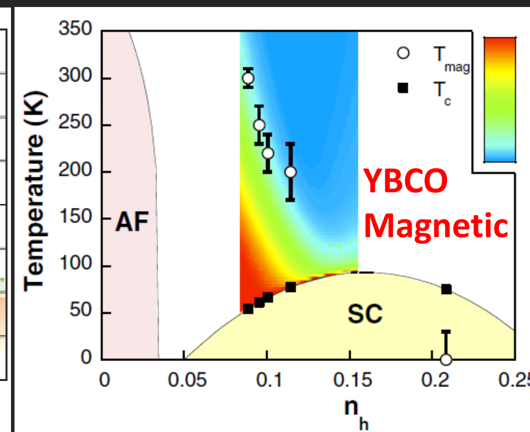
CDW, SDW, NEMATIC, STRIPES, MAGNETIC



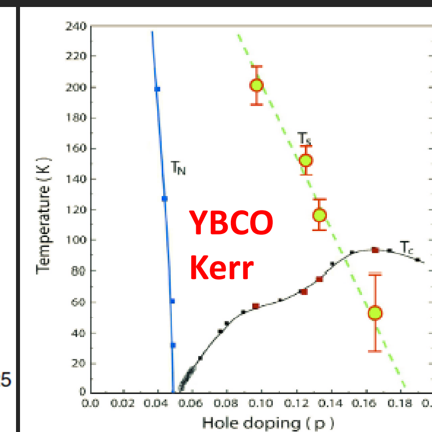
Daou, Nature (2010)



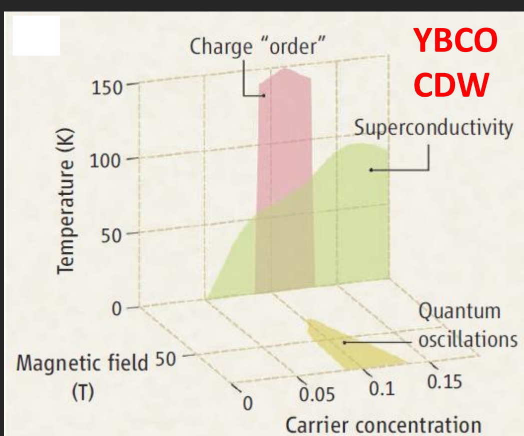
Baek, PRB (2012)



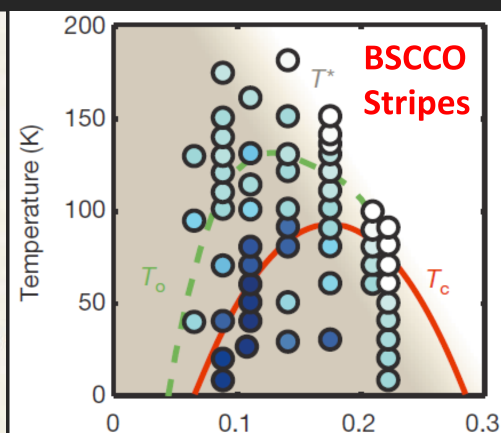
Fauque, PRL (2006)



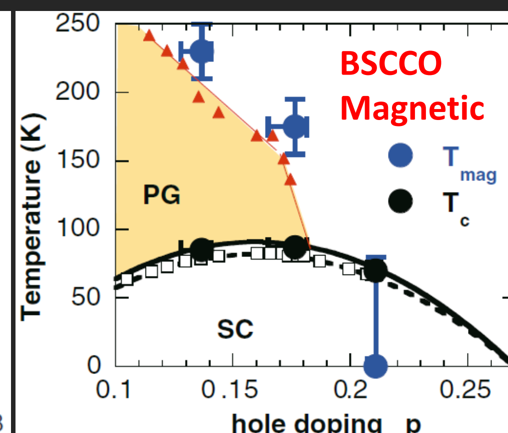
Xia, PRL (2008)



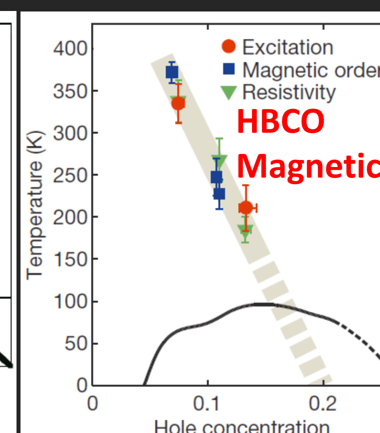
Ghiringhelli, Science (2012)



Parker, Nature (2010)



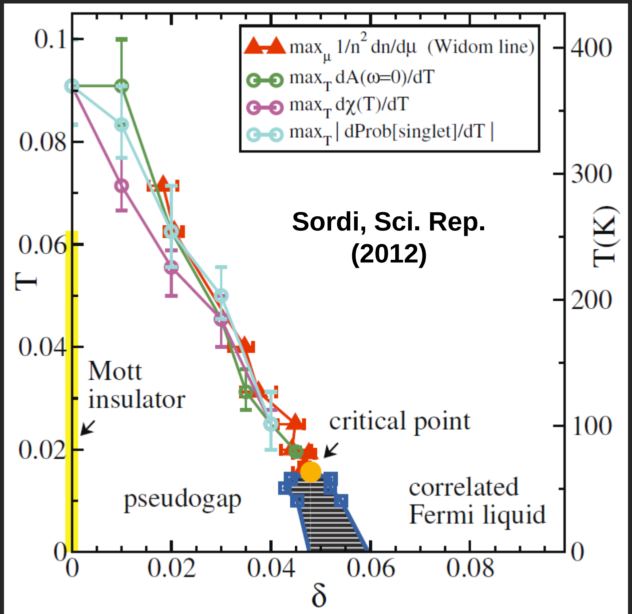
De Almeida, PRB (2012)



Li, Nature (2010)

➔ *Dependence on the details of structure*

Is it a phenomenon due to the short-range-correlations (Mottness)?



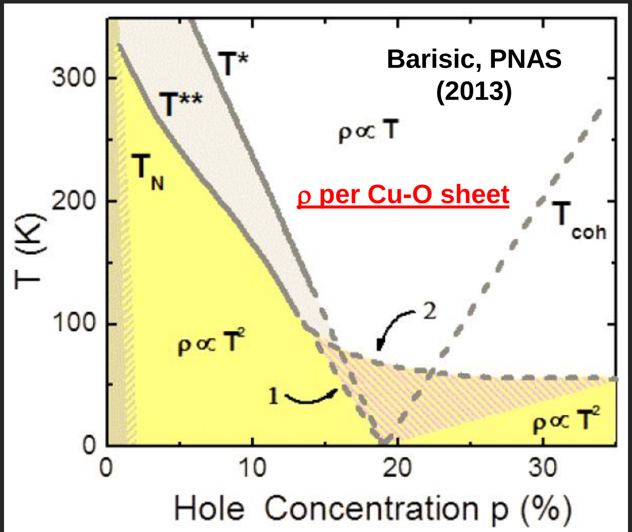
- Outcome from Hubbard Model solved by CDMFT

  (Columbia, Rutgers, Ecole Polytechnique, Sissa)

- T* delimits different dynamical regimes, indicating thermodynamic anomalies – Widom line
- No broken symmetries are invoked
- Indication for Mottness in the PG

➔ *No experimental evidences exists that confirm this indication*

There are general and common trends

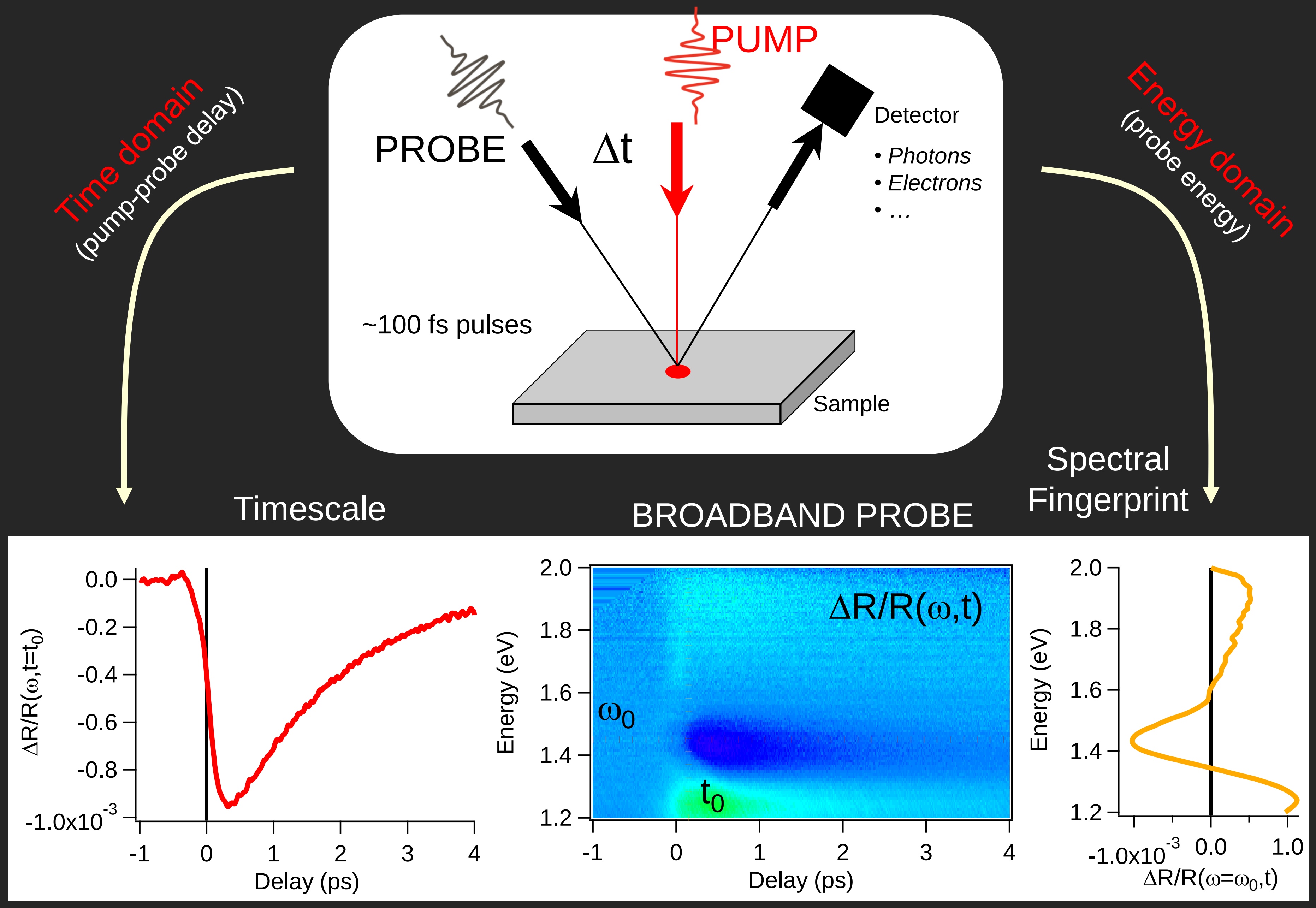


Resistivity

HBCO
YBCO
LSCO
TBCO

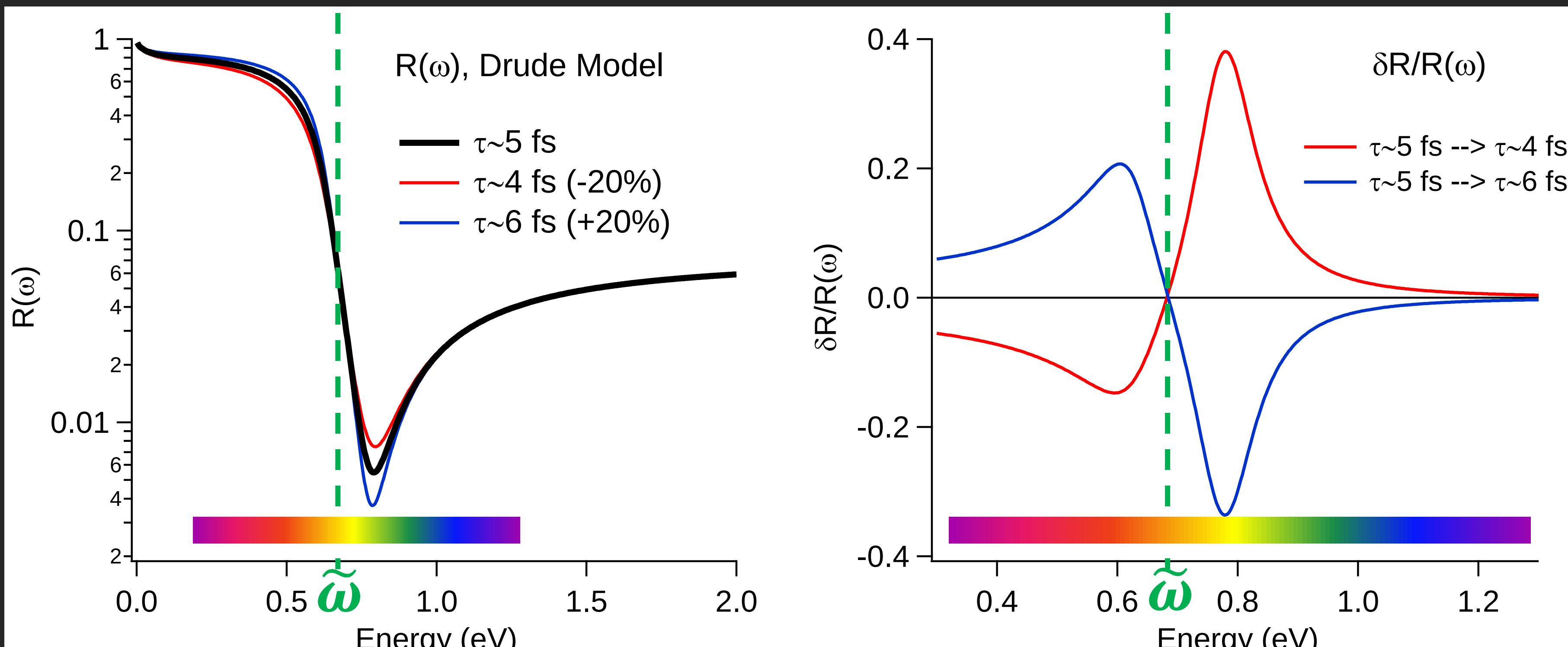
The departure from the T-linear behavior occurs at the same temperature, T, for 4 different compounds.*

Non-Equilibrium Approach & Time-Resolved Optical Spectroscopy



Isosbestic points and Reflectivity:

How to measure the electronic scattering rate at high photon energies



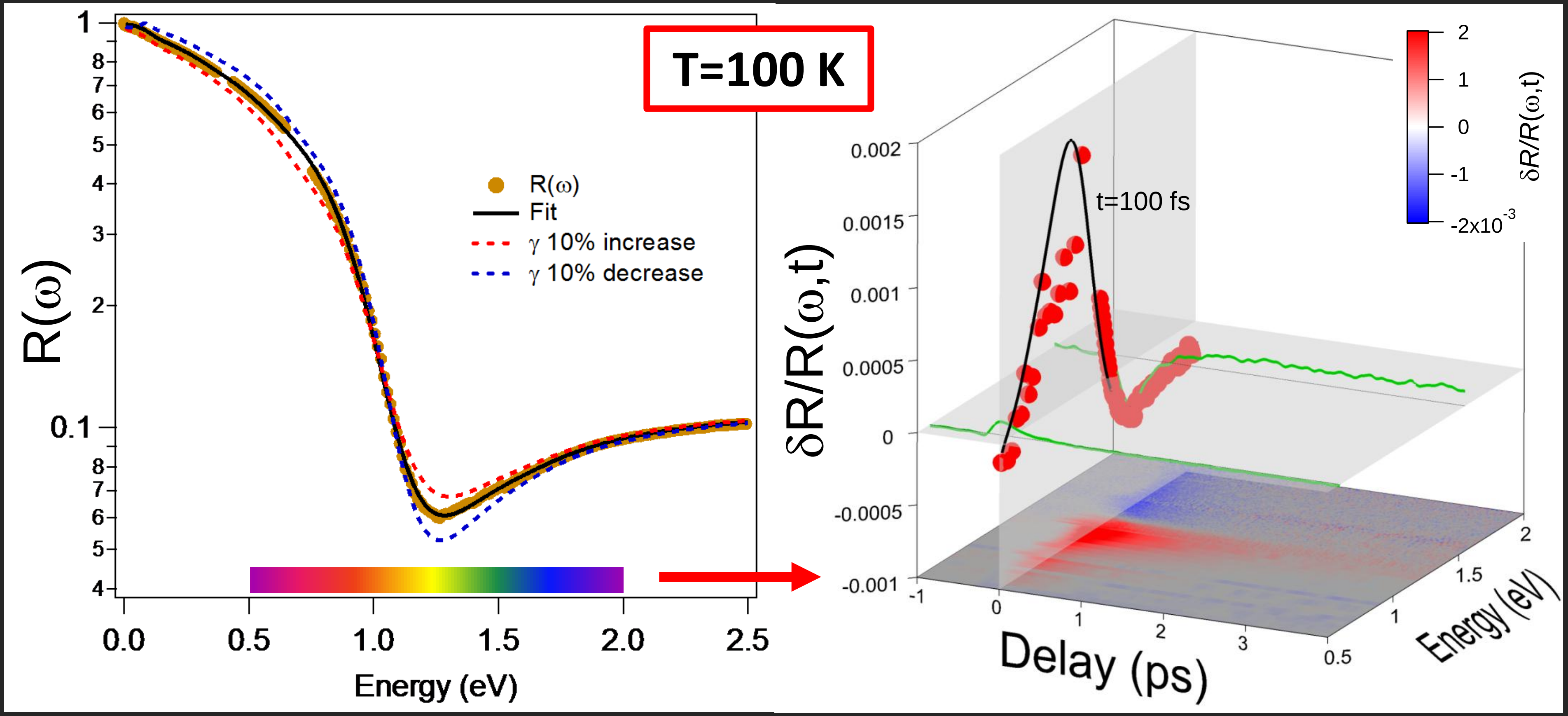
Non-equilibrium optics with spectral resolution can provide access to both energy&momentum conserving scattering processes and electronic scattering rate.

$$\epsilon_D(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega^2 + i\gamma\omega} \qquad R(\omega) = \left|\frac{1-\sqrt{\varepsilon(\omega)}}{1+\sqrt{\varepsilon(\omega)}}\right|^2 \qquad \omega \sim \tilde{\omega}: \quad \delta R(\omega,\gamma) = \frac{\partial R}{\partial \gamma}(\omega)\,\delta\gamma$$

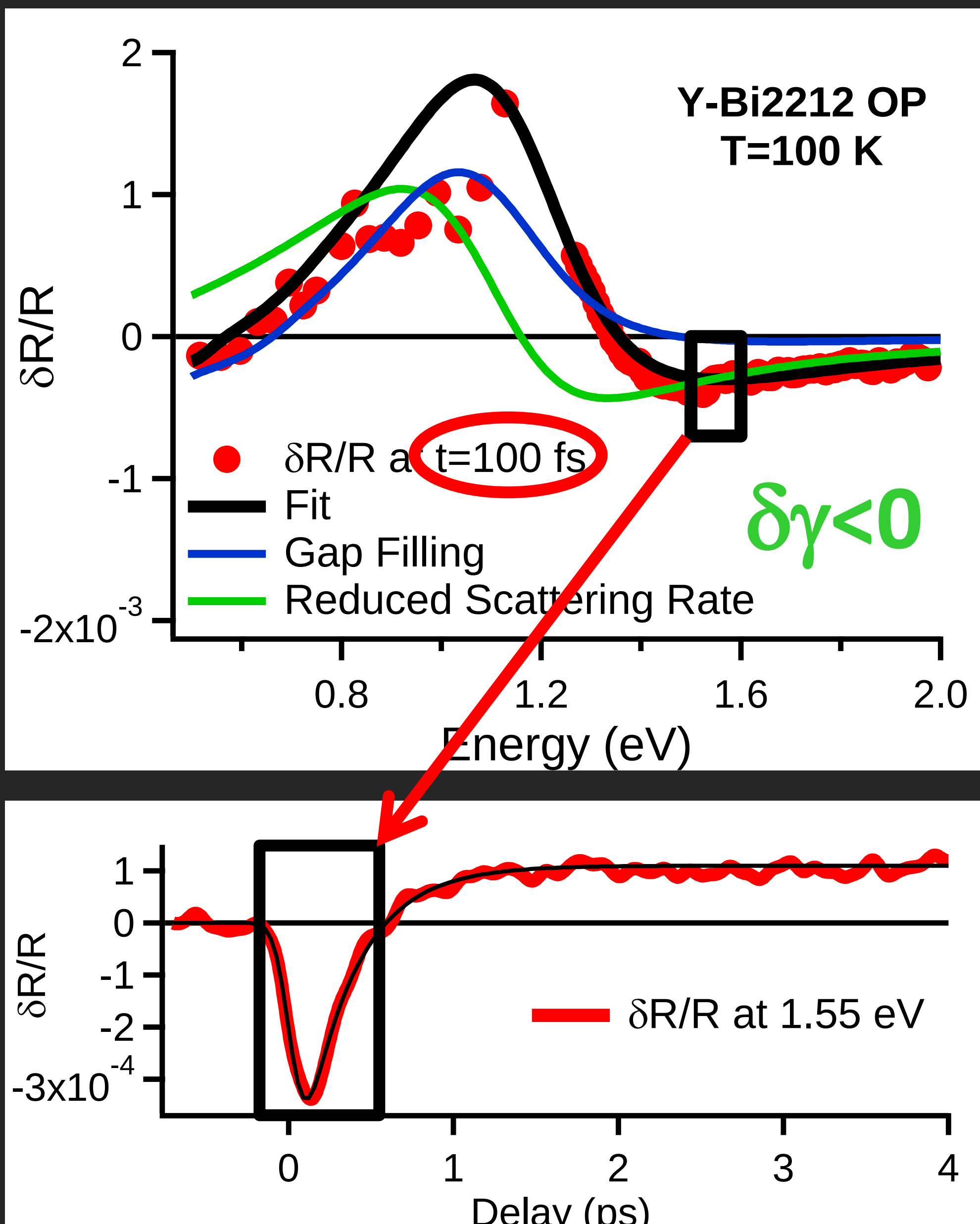
Equilibrium and Non-Equilibrium optical spectroscopic data

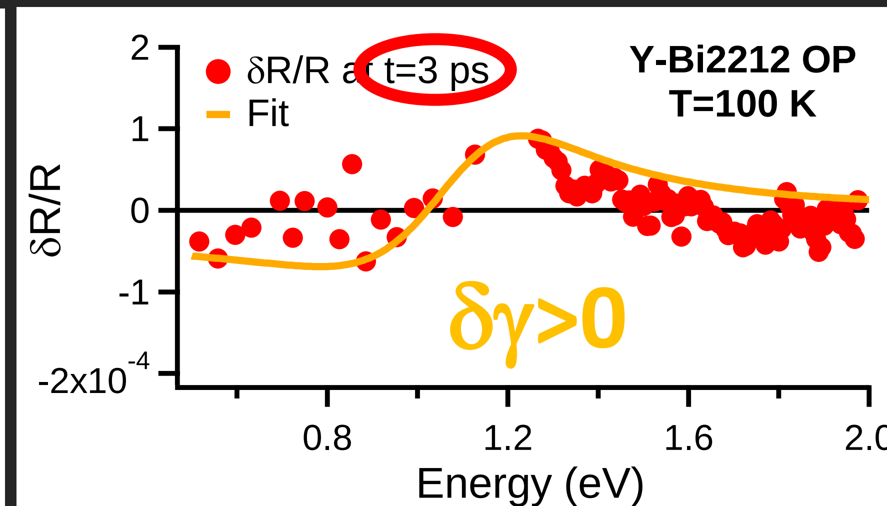
Optimally Doped $Bi_2Sr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$ (T_c=96 K)

Equilibrium | Out-of-Equilibrium



Modeling non-equilibrium optical properties



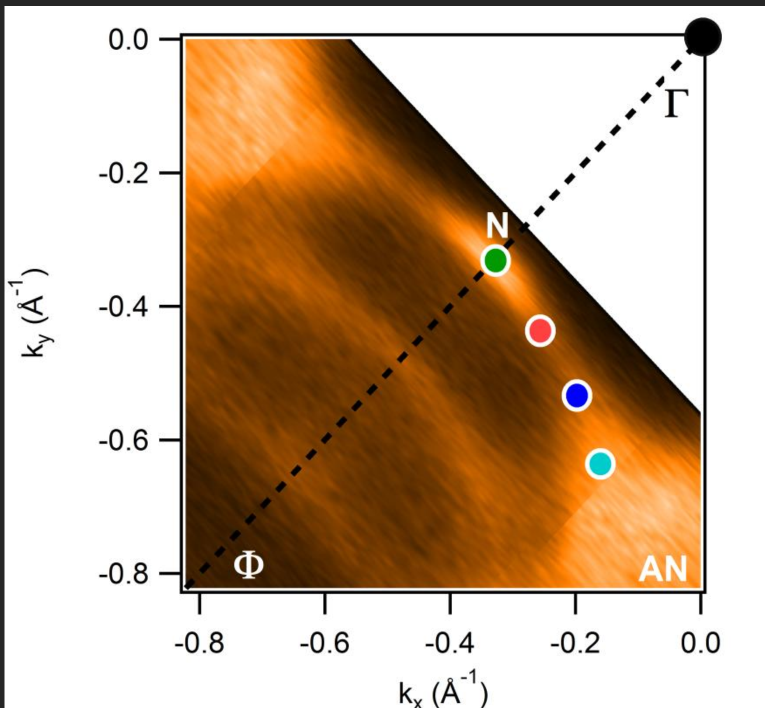


- **t < 1 ps:** **$\delta\gamma < 0$**
  transient *decrease* of scattering rate (impulsive effect)

- **t > 3 ps:** **$\delta\gamma > 0$**
  transient *increase* of scattering rate (thermal effect)

ARPES at Equilibrium and Out-of-Equilibrium

ARPES at Equilibrium



hν=21.2 eV T=100 K

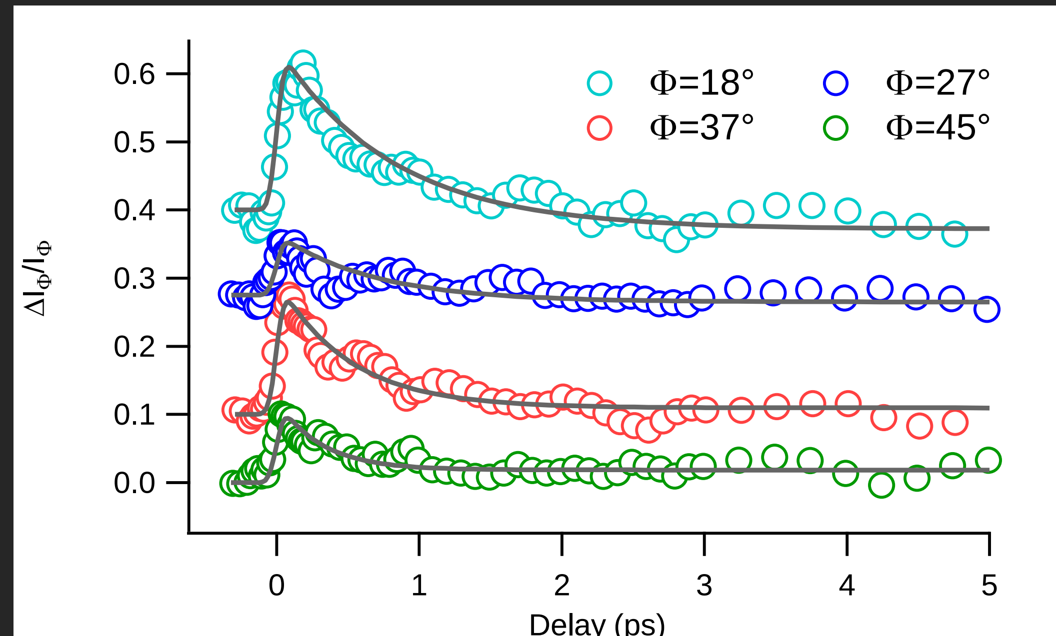
Equilibrium:

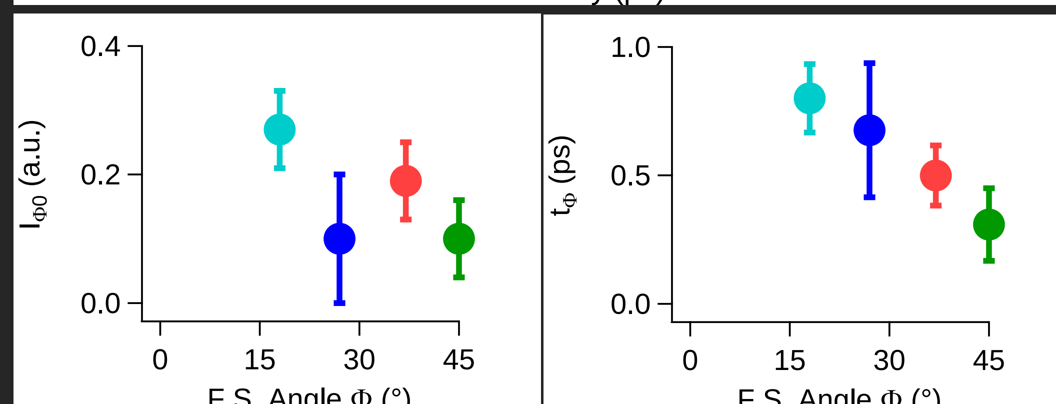
A. Damascelli, UBC, Vancouver

Non-Equilibrium:

U. Bovensiepen, Duisburg

ARPES Out-of-Equilibrium

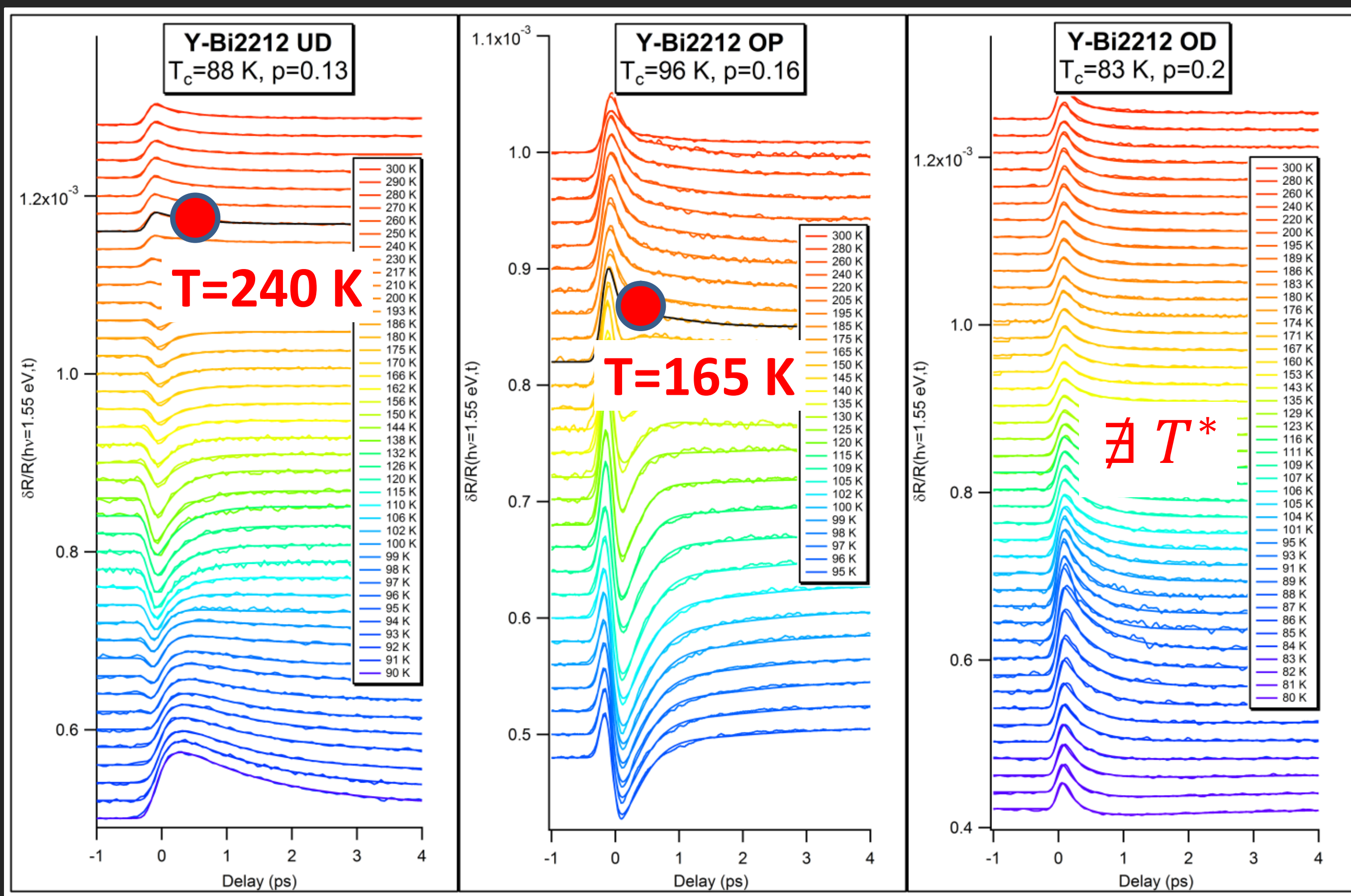


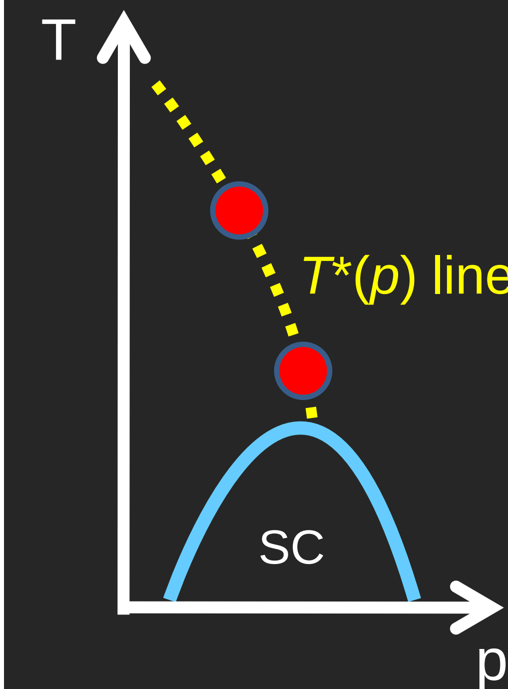


hν=6 eV T=100 K Pump=1.5 eV, 30 μJ/cm^2

Onset of the Pseudogap: T*=T*(p) from T-Scan

Y-Bi2212 Crystals with different doping level

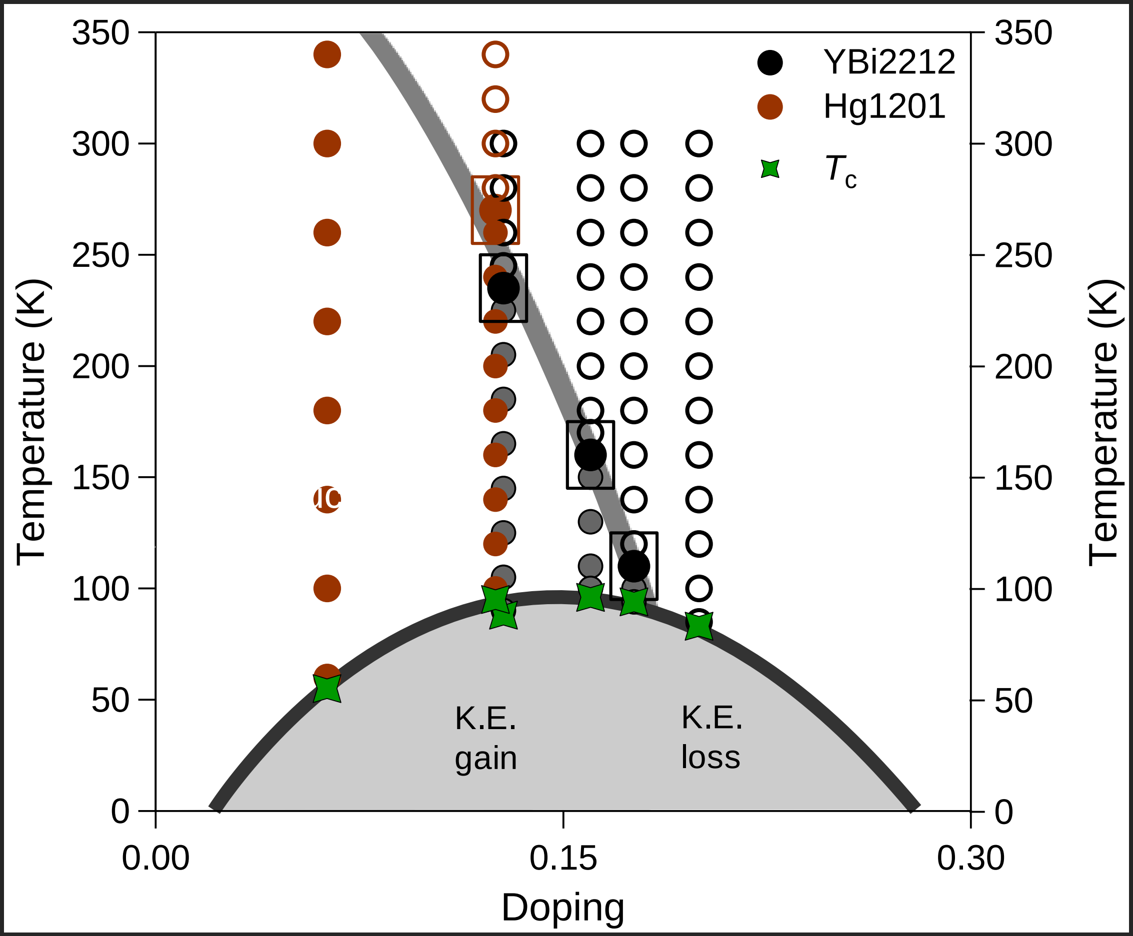




Temperature scan at 1.55 eV probe photon energy

Universal Phase Diagram

- Y-Bi2212: $T_{c,max}$=**96 K**, 2 CuO planes per U.C.
- Hg1201: $T_{c,max}$=**96 K**, 1 CuO plane per U.C.



T*(p) Line

Hg1201:

T*(p=0.125)=270 K
T_c=96 K

Y-Bi2212:

T*(p=0.13)=240 K
T_c=88 K

T*(p=0.16)=165 K
T_c=96 K

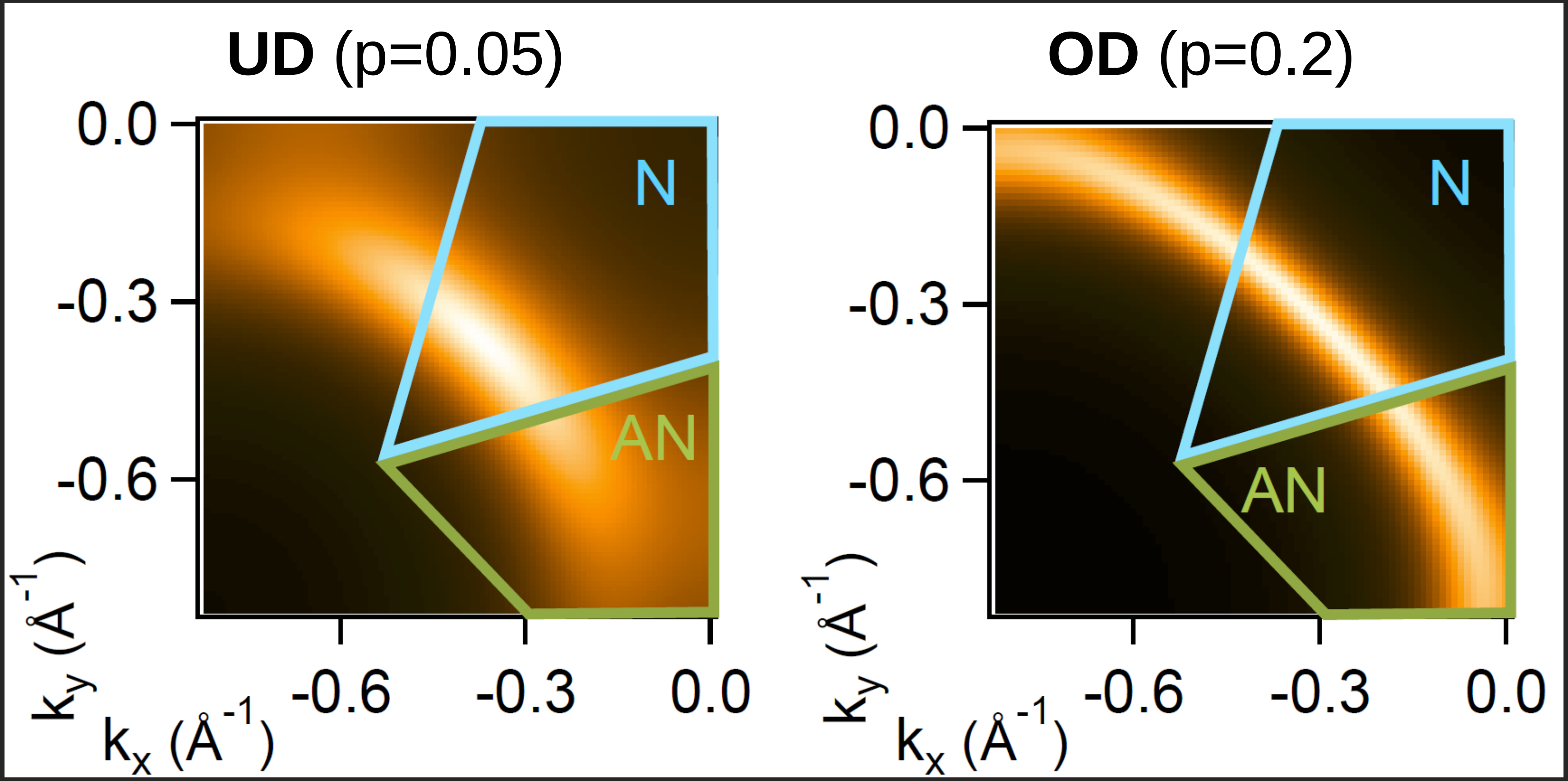
T*(p=0.18)=110 K
T_c=94 K

F. Cilento et al., Nat. Comm. 5, 4353 (2014) and arXiv 1405.5462

Hubbard Hamiltonian and CDMFT

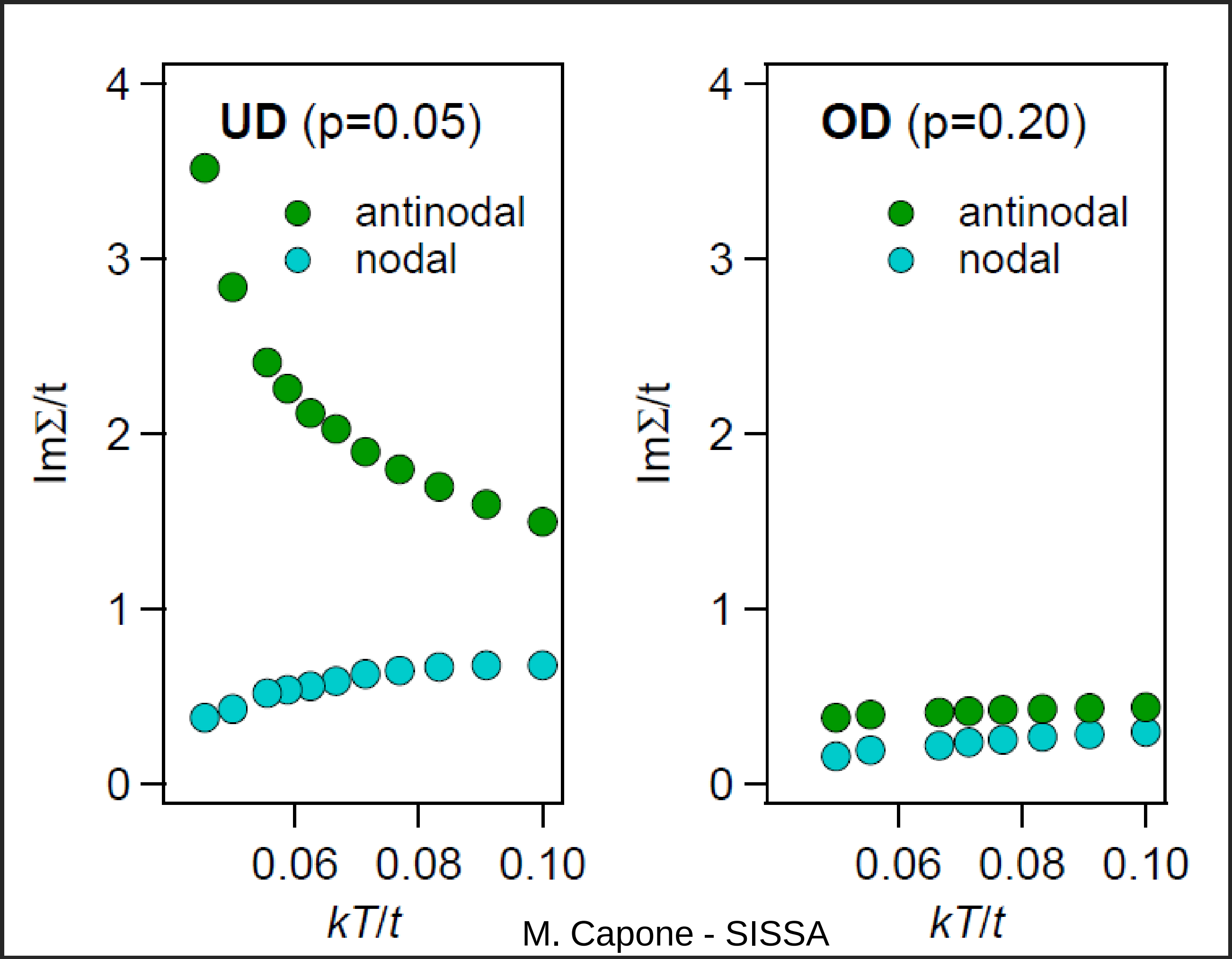
$$\hat{H} = -\sum_{i,j,\sigma}\left(t_{ij}\,\hat{c}^{\dagger}_{i\sigma}\hat{c}^{\dagger}_{j\sigma} + c.c.\right) + U\sum_{i}\hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow} - \mu\sum_{i}\hat{n}_{i}$$

M. Capone - SISSA



The N-AN Dichotomy in the Pseudogap

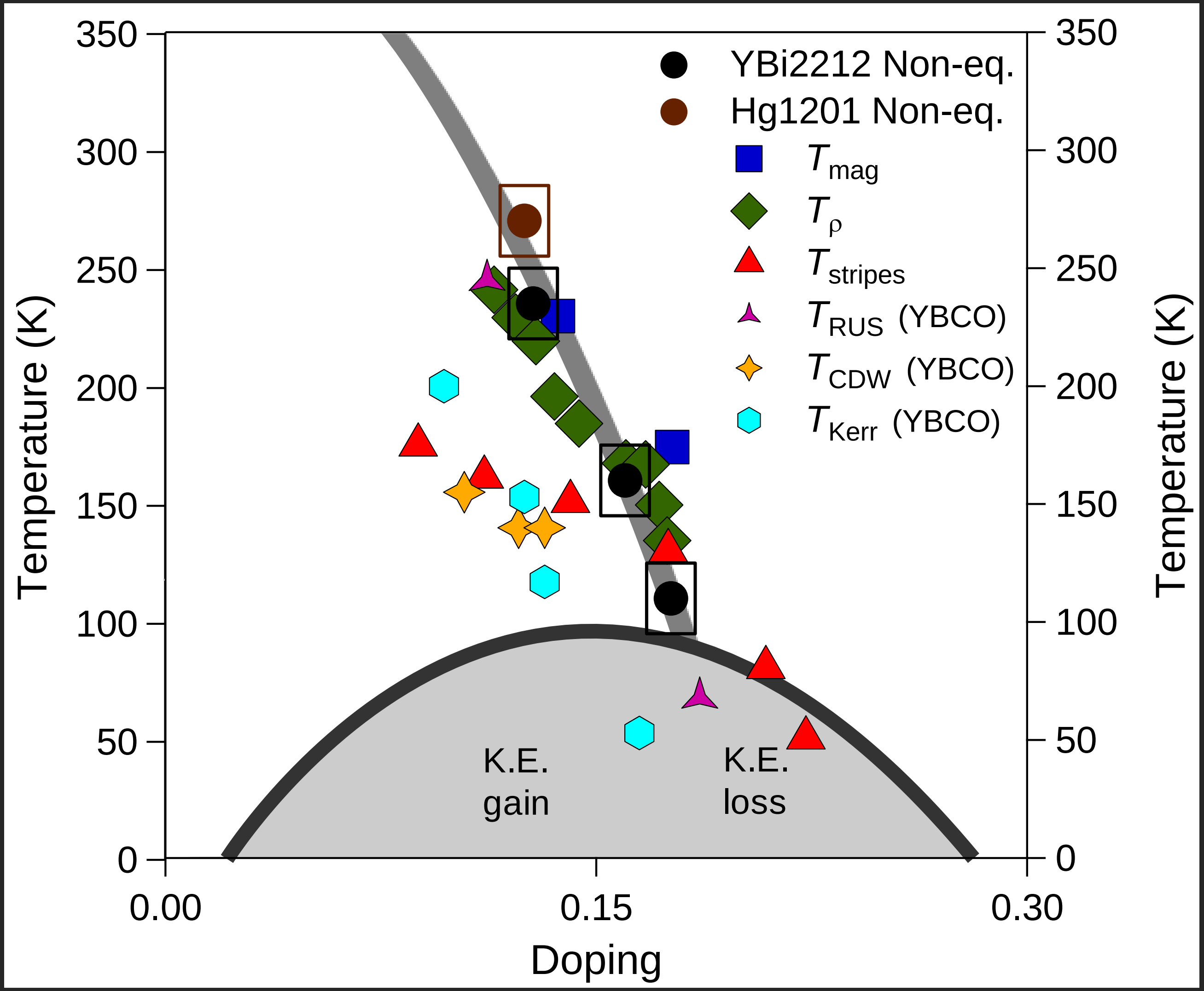
Nodal (N) and Antinodal (AN) scatering rate for UD and OD compounds



The electronic scattering rate as a measure of the degree of electronic correlations

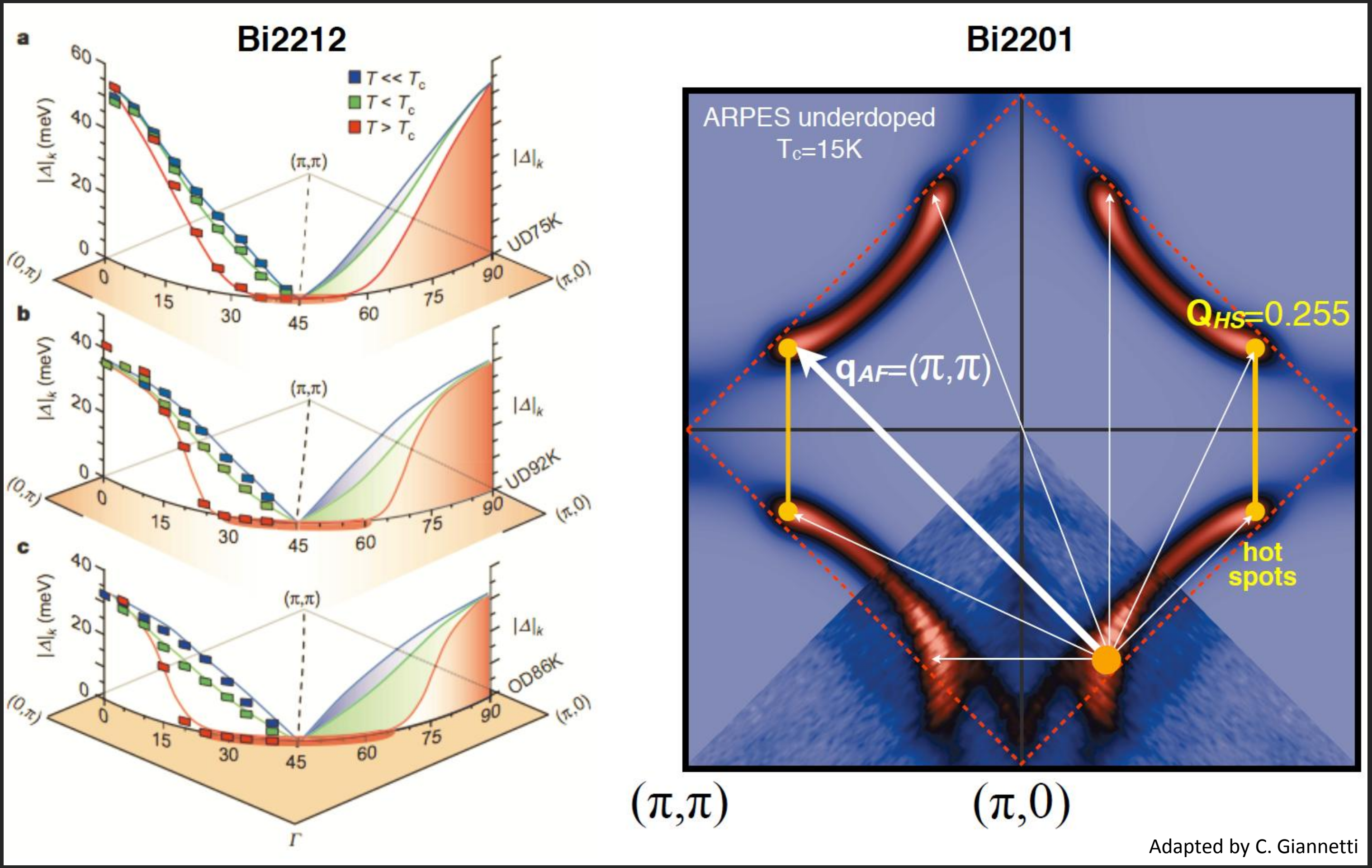
→ The absorption of the pump pulse renders the AN quasiparticles more metallic, less localized

The Phase Diagram



- Non equilibrium measurements reveal the Mottness associated to AN quasiparticles.
- Broken symmetries seem not to be related to the PG: are a consequence and not its cause.

Pseudogap and Ordering Tendencies



W. S. Lee et al., Nature 450, 81 (2007)

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

Q_{CO}~0.256 r.l.u. (REXS/STM) ←→ Q_{HS}~0.255 r.l.u. (ARPES)

Conclusions

- We revealed the fingerprint of Mottness for AN quasiparticles.
- The onset of the Mottness follows the T*(p) line.
- CDMFT simulations account for experimental results.
- The pseudogap phase is due to strong and short-ranged electronic correlations.
- Long-range orders are an effect of the Pseudogap, not its cause.

People, Collaborations, Acknowledgements

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  S. Dal Conte, D. Bossini, S. Peli, N. Nembrini, S. Mor, F. Banfi, G. Ferrini, C. Giannetti

- Equilibrium optical properties of HTSC

  D. van der Marel (Université de Genève)

- Equilibrium ARPES of HTSC

  R. Comin, A. Damascelli (University of British Columbia, Vancouver)

- Non-Equilibrium ARPES of HTSC

  L. Rettig, U. Bovensiepen (University of Duisburg)

- Non-equilibrium models of correlated materials

  M. Capone, M. Fabrizio (SISSA, Trieste)

- Samples

  A. Damascelli (University of British Columbia, Vancouver)

  M. Greven (University of Minnesota & Stanford University)

  H. Eisaki (NIST, Tsukuba, Japan)