The room temperature precursor of the low-temperature ordered phases in copper oxides

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i-*Lamp*
(Interdisciplinary laboratories for advanced materials physics)

GO FAST
GOverning ultraFAST the conductivity of correlated material
SEVENTH FRAMEWORK PROGRAMME

Outline

- Spontaneous symmetry-breaking in copper oxides: charge order
- Ultrafast spectroscopies to investigate the role of the Mott-like excitations
- The room temperature precursor of charge-order in cuprates

S. Peli et al. *arXiv:1508.03075* (2015)

People and Collaborations

•Ultrafast optics group (Università Cattolica, Brescia)
S. Peli, N. Nembrini, F. Banfi, G. Ferrini, C. Giannetti

•Ultrafast optics group (Università degli Studi di Trieste)
F. Cilento, D. Fausti, F. Parmigiani

•Ultrafast optics group (Politecnico di Milano)
S. Dal Conte, D. Brida, G. Cerullo

•Equilibrium spectroscopies
R. Comin, B. Ludbrook, A. Damascelli (University of British Columbia, Vancouver)
M. Greven (University of Minnesota & Stanford University)
B. Keimer (MPG-UBC center for QM)

•Non-equilibrium models of correlated materials
L. Vidmar (LMU Munich), M. Mierzejewski (Katowice), J. Bonca (Ljubljana)
M. Capone, M. Fabrizio (SISSA, Trieste)

•Equilibrium optical properties of HTSC
D. Van der Marel (Université de Genève)
S. Lupi (La Sapienza, Roma)

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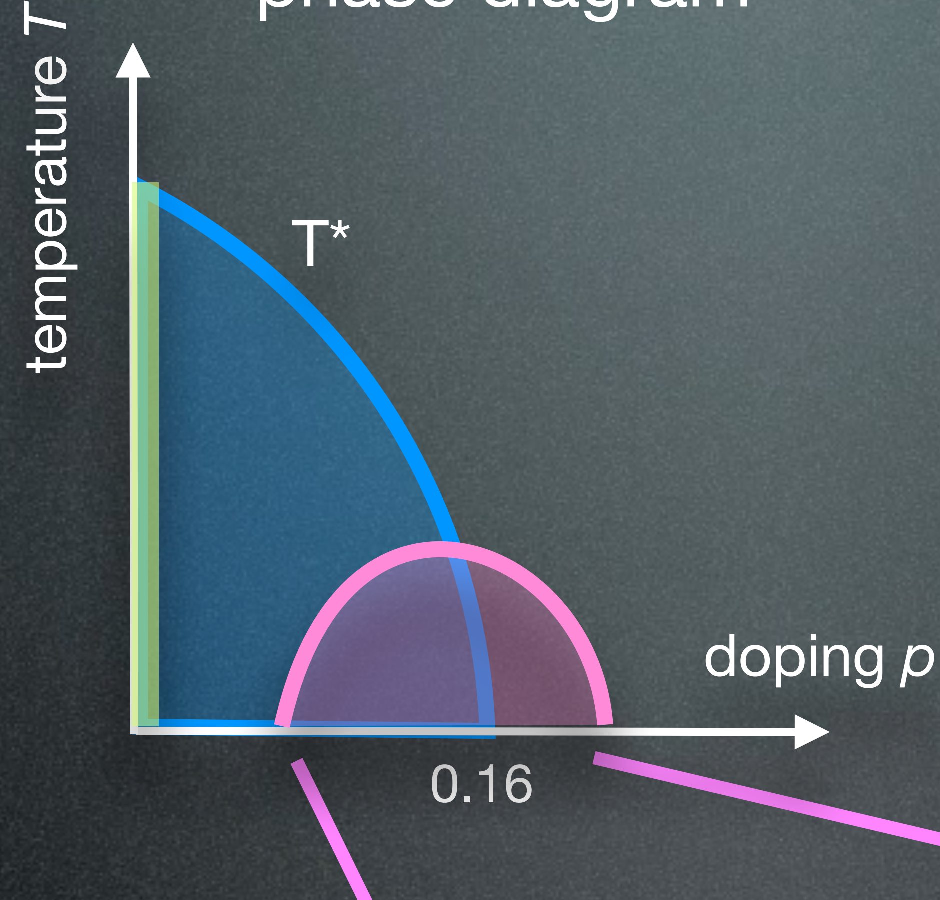
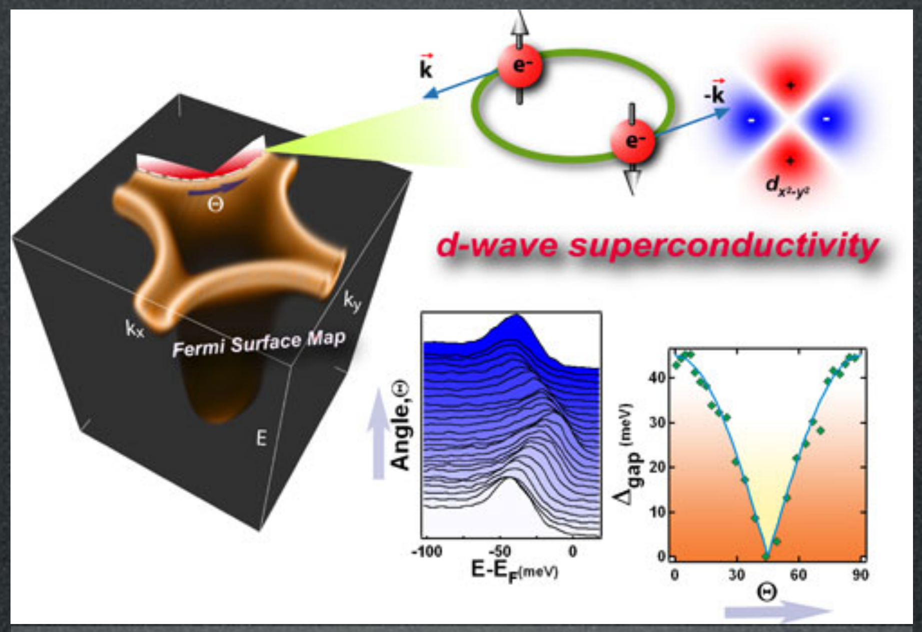
The phase diagram of copper oxides

phase diagram



d-wave superconducting gap

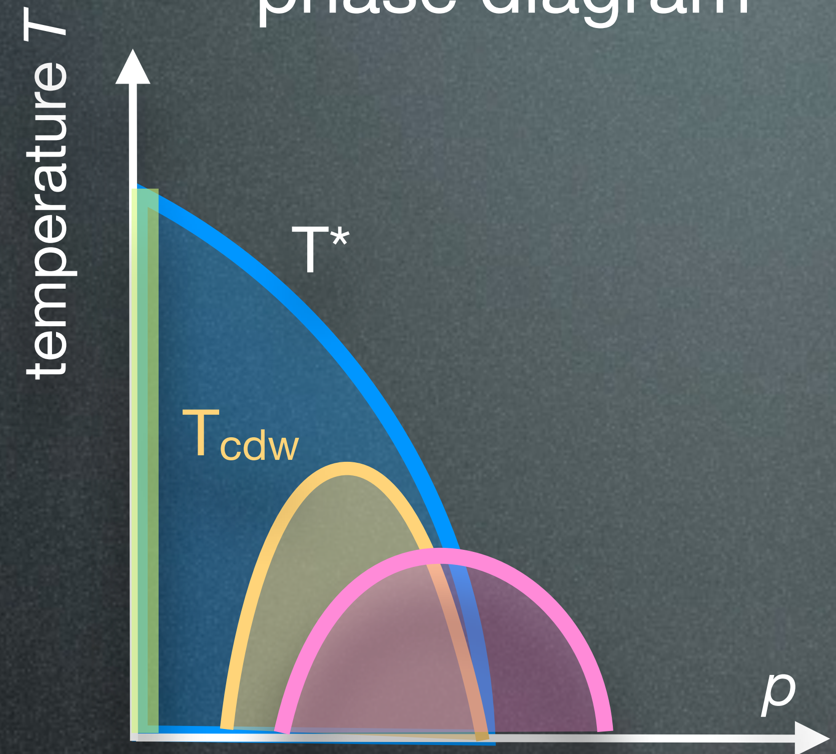


ZX Shen's group

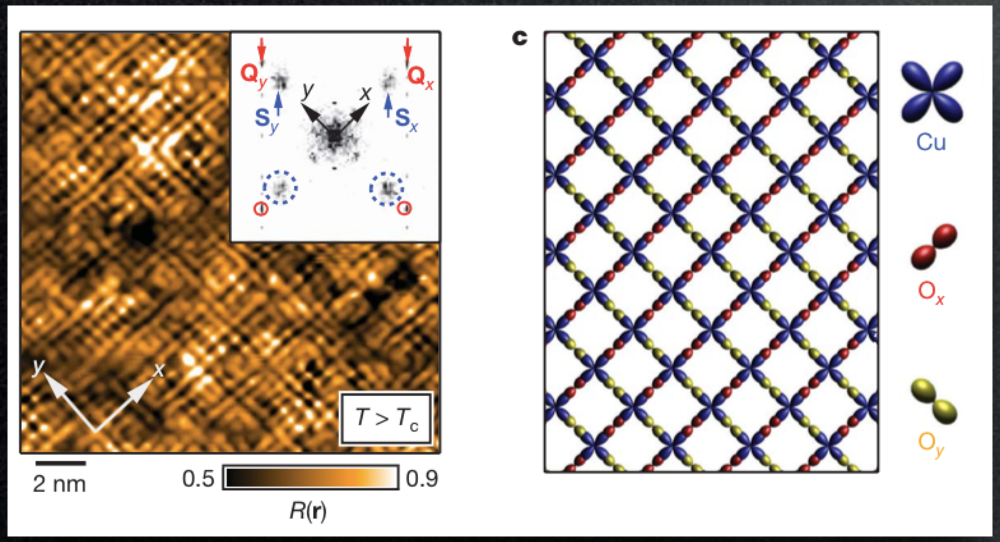
superconductivity on top of a very unconventional ground state!

charge-order

phase diagram



STM on Bi2212

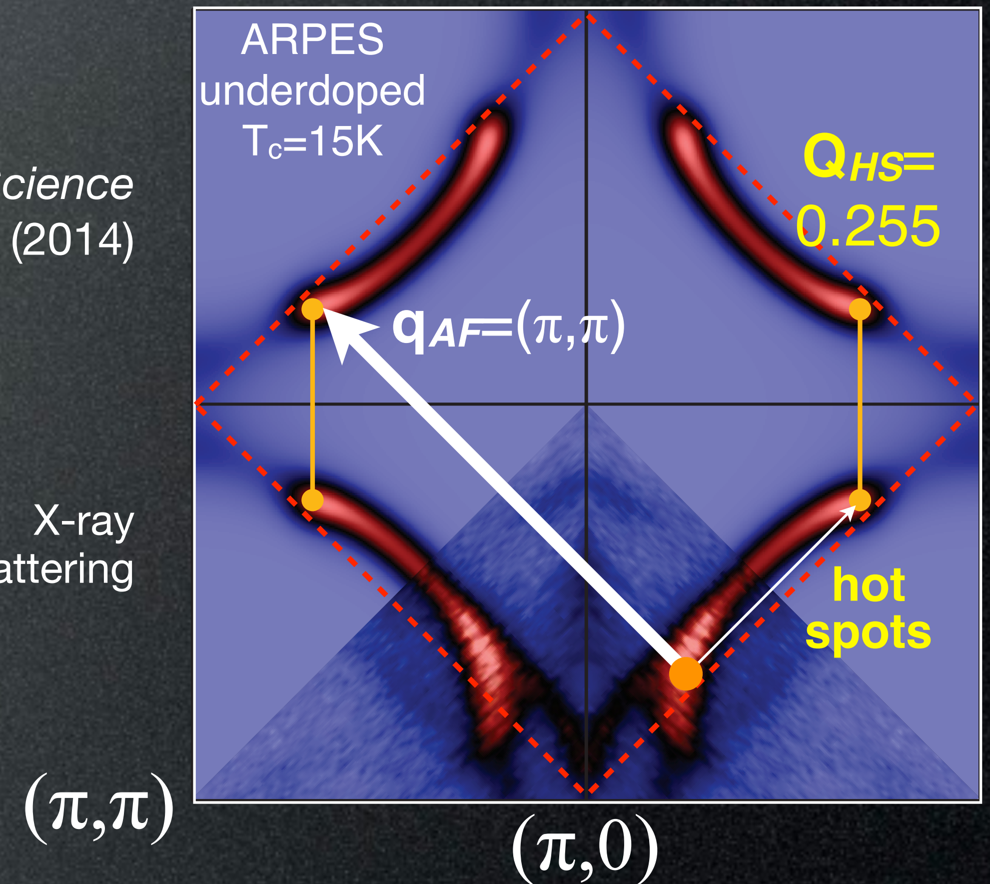


M.J. Lawler et al. *Nature* **466**, 347 (2010)

Bi2201

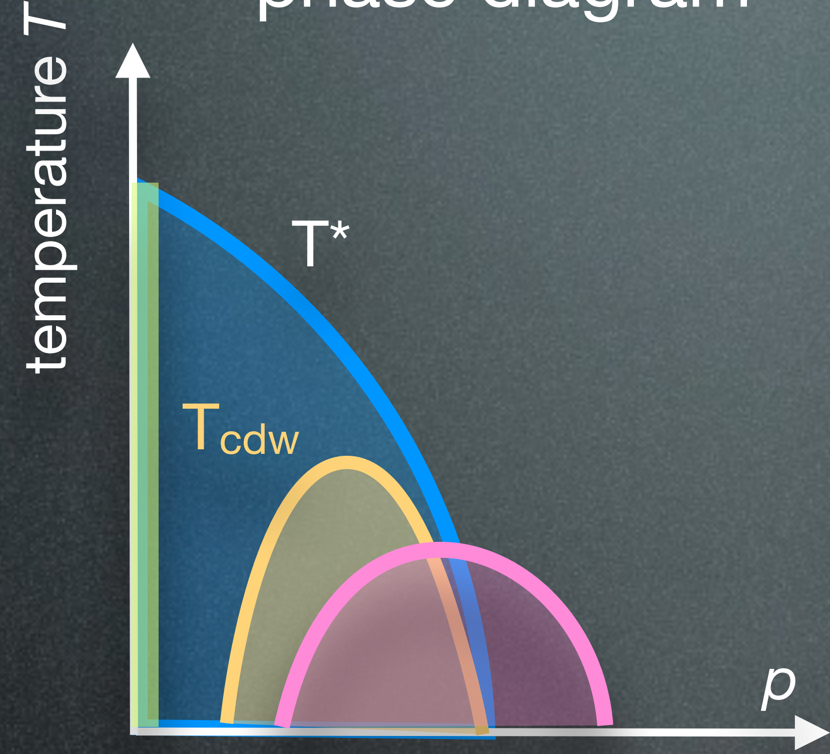
R. Comin et al. *Science* **343**, 390 (2014)

X-ray scattering



charge-order

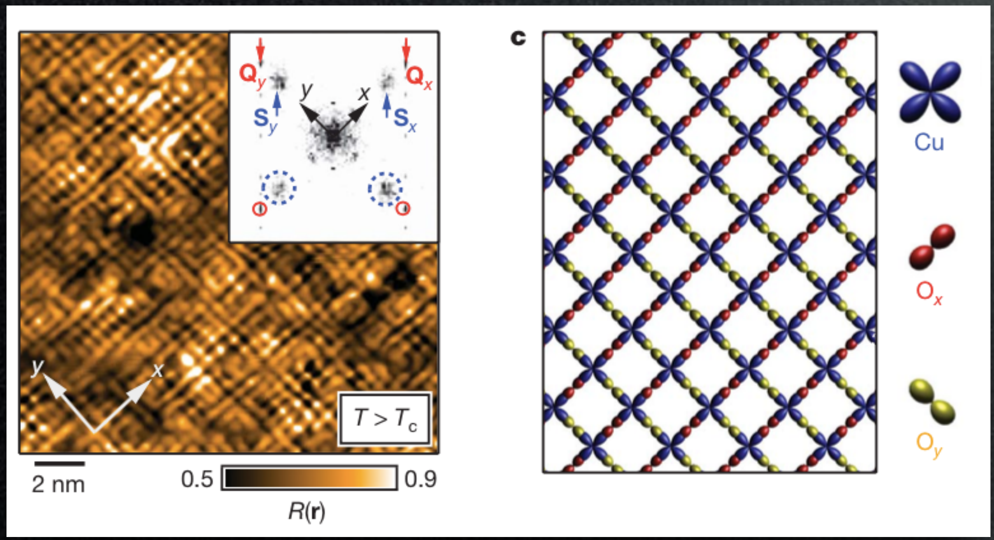
phase diagram



open problems:

- interplay with superconductivity
- origin of charge-order
- **relation with the "Mott" physics**

STM on Bi2212



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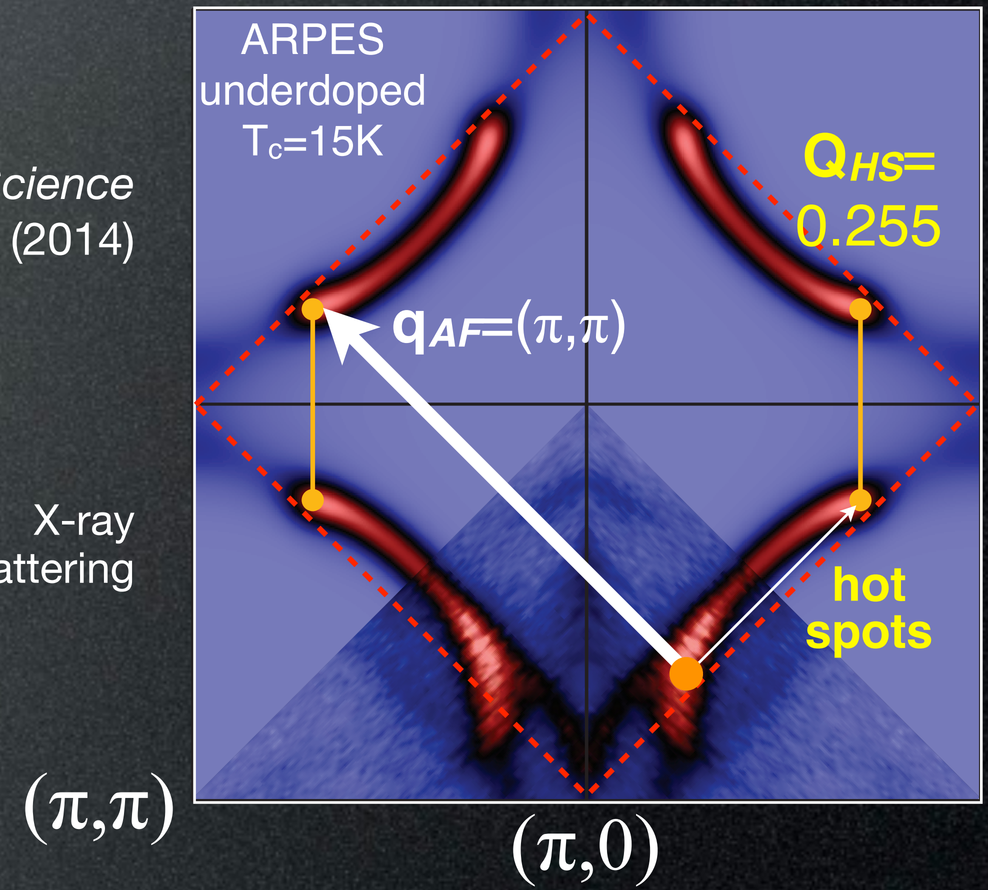


Relation between charge-order and the Mott physics

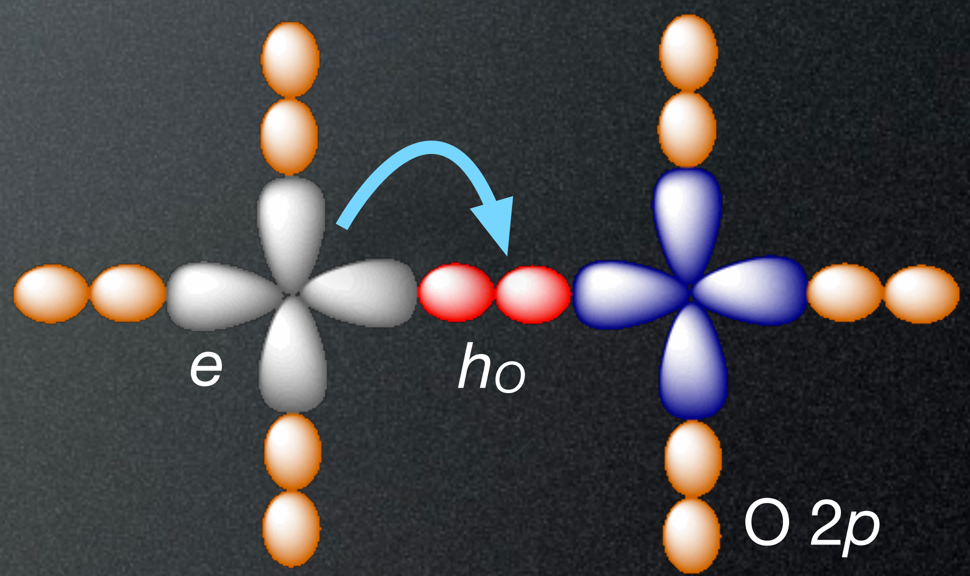
Is there any relation between the low-temperature charge-order and the Mott physics?

"Mott" physics in copper oxides

charge-transfer process at Δ_{CT}≃2 eV

➡ need for a high-energy probe >> $K_B T$

Cu $3d^9$ → Cu $3d^{10}$+h_O



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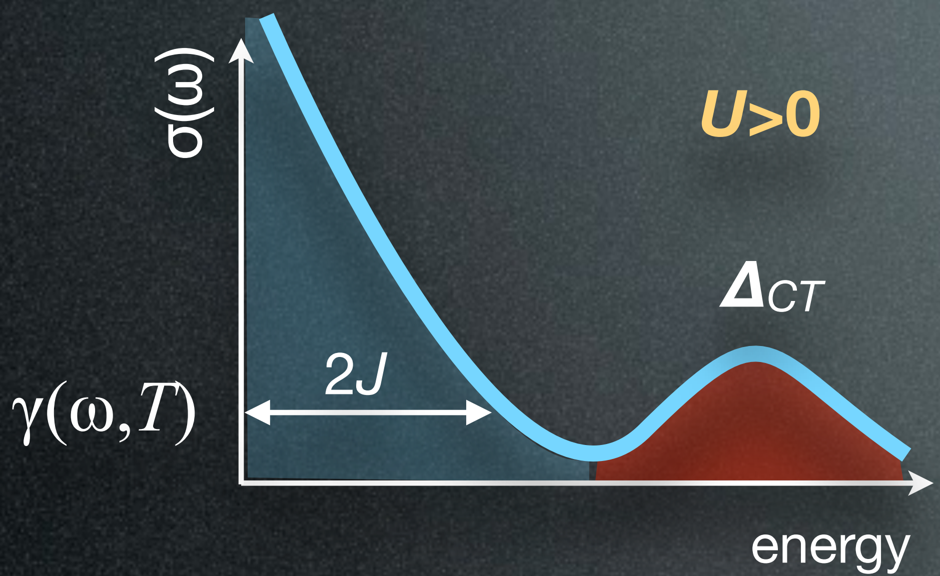
- Snapshots of the retarded-interaction with ultrafast fluctuations via 10 fs pulses

S. Dal Conte et al., *Science* **335**, 1600 (2012)
S. Dal Conte et al. *Nature Physics* **11**, 421 (2015)

the energy scales in optics (copper oxides)

equilibrium optical conductivity



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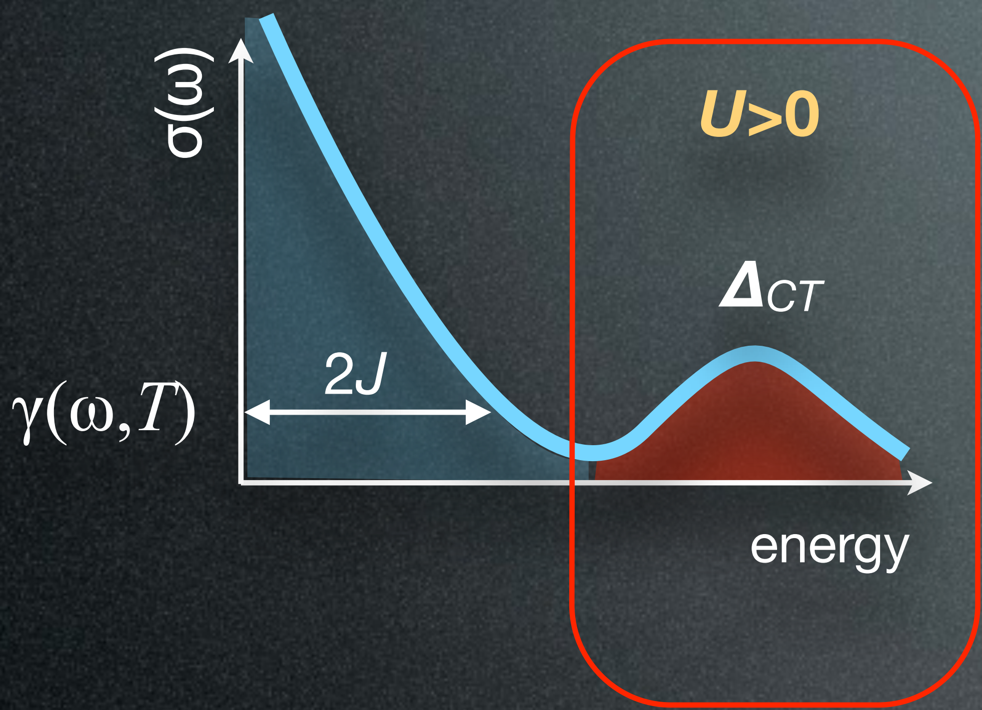

charge-transfer process
at $\Delta_{CT} \simeq 2$ eV

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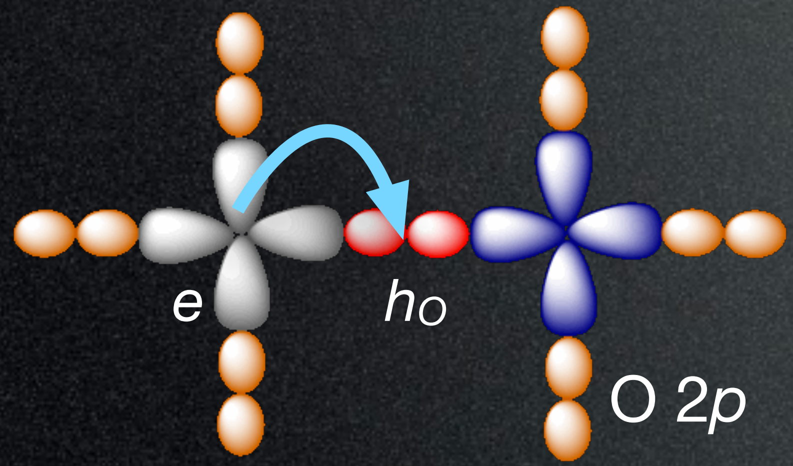

probe of the local correlations

the energy scales in optics (copper oxides)

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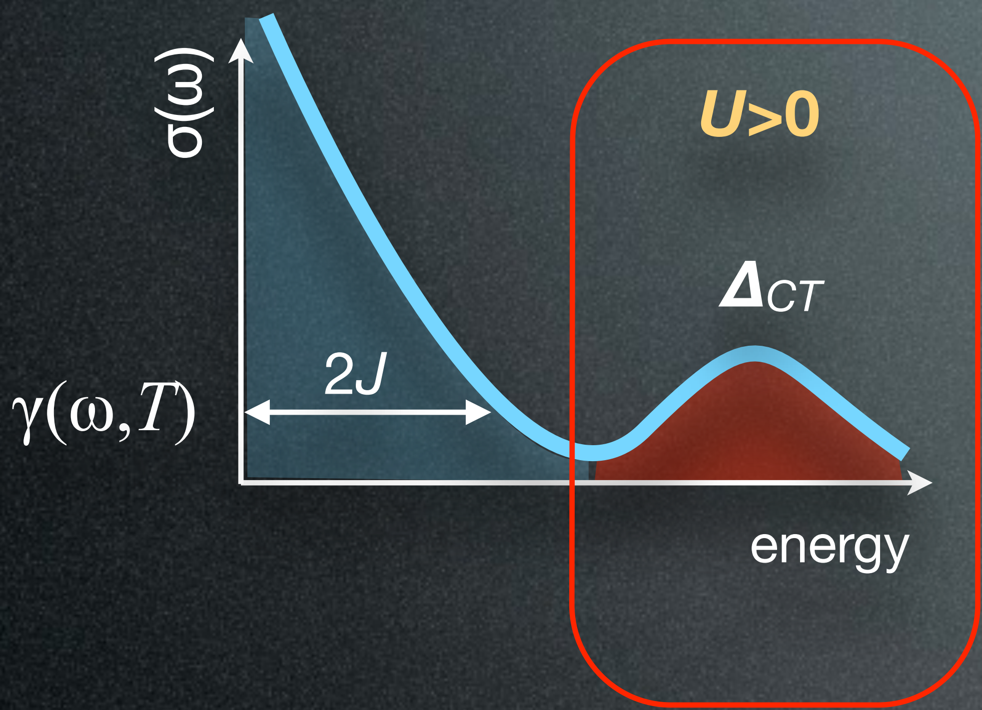

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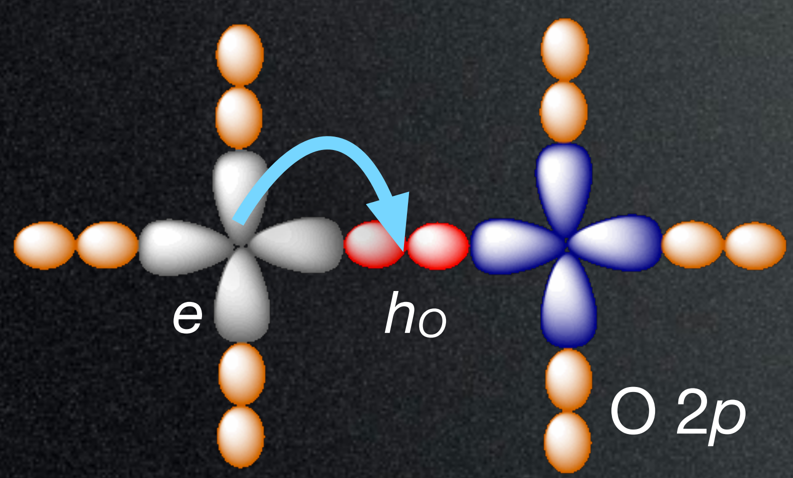

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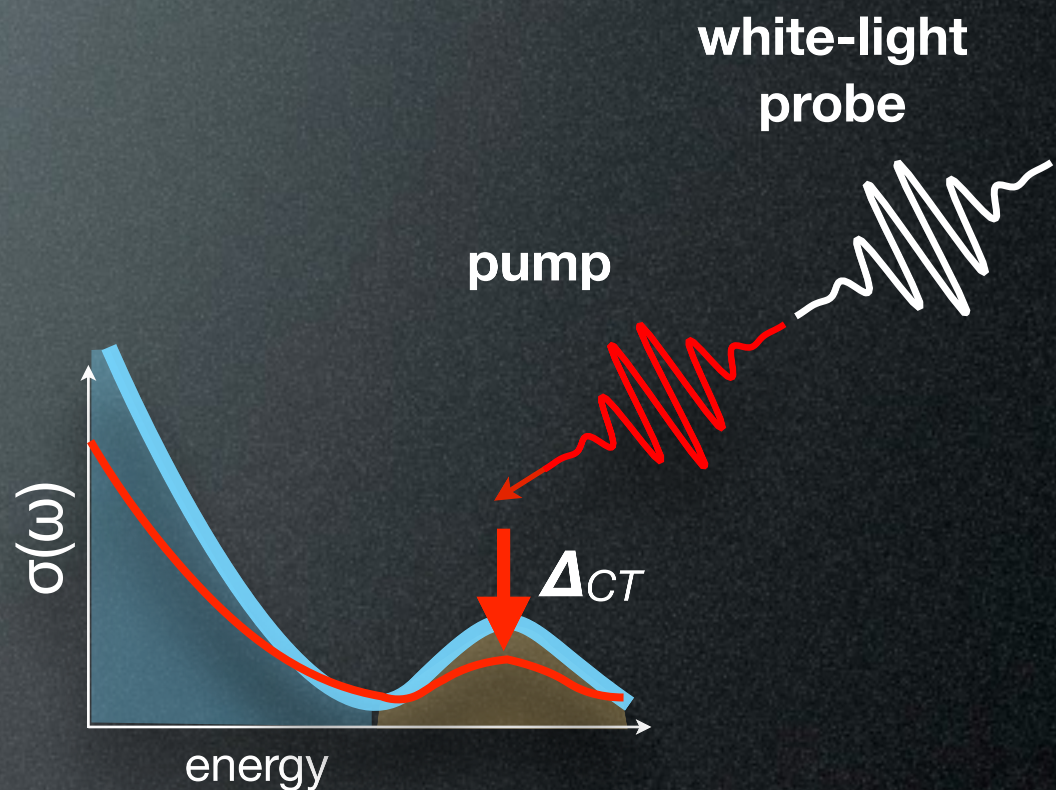

strongly-correlated scenario:
probe of local correlations through the
CT process

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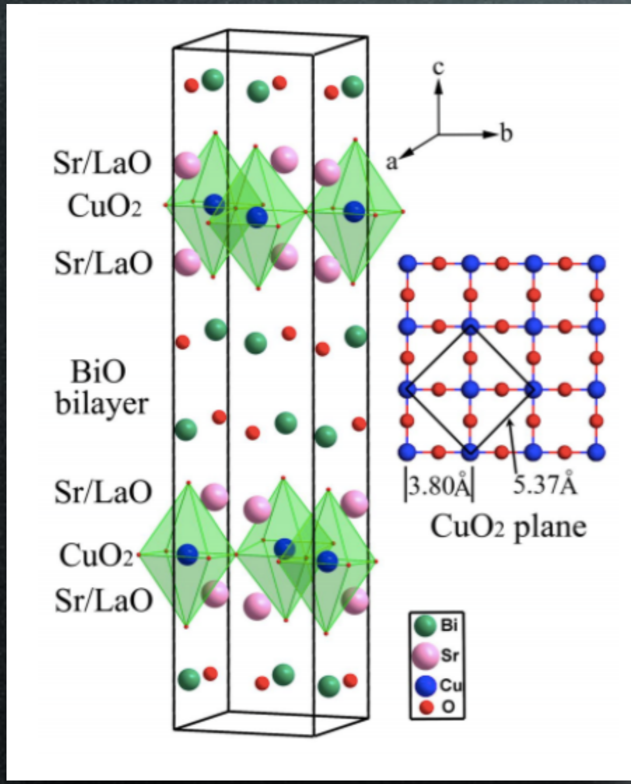
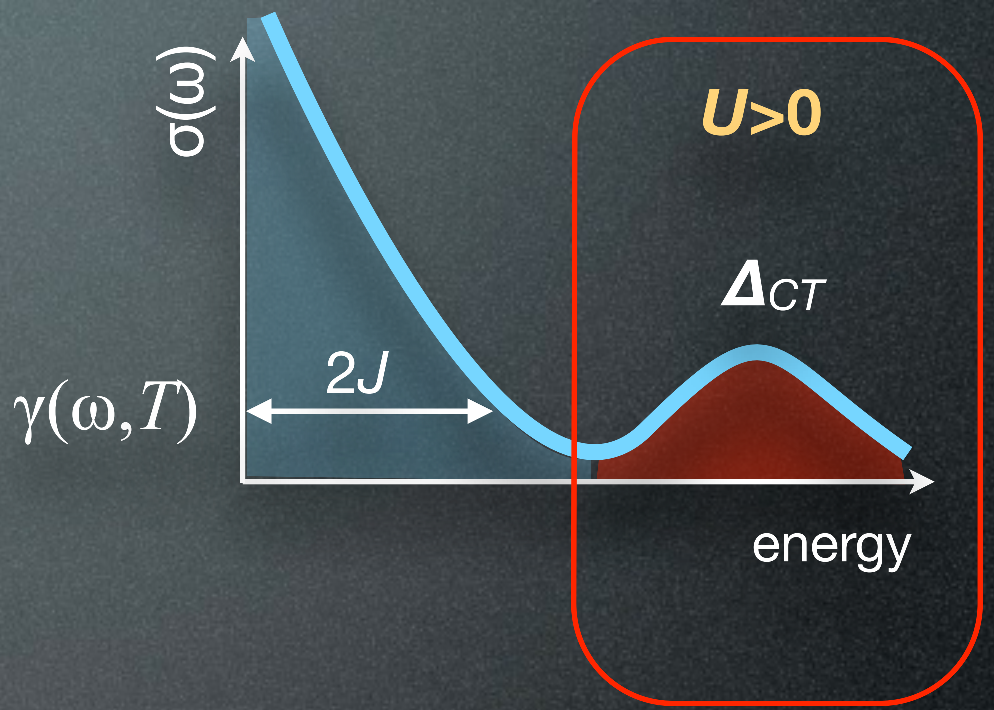
Equilibrium optical properties of Bi2201



$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$



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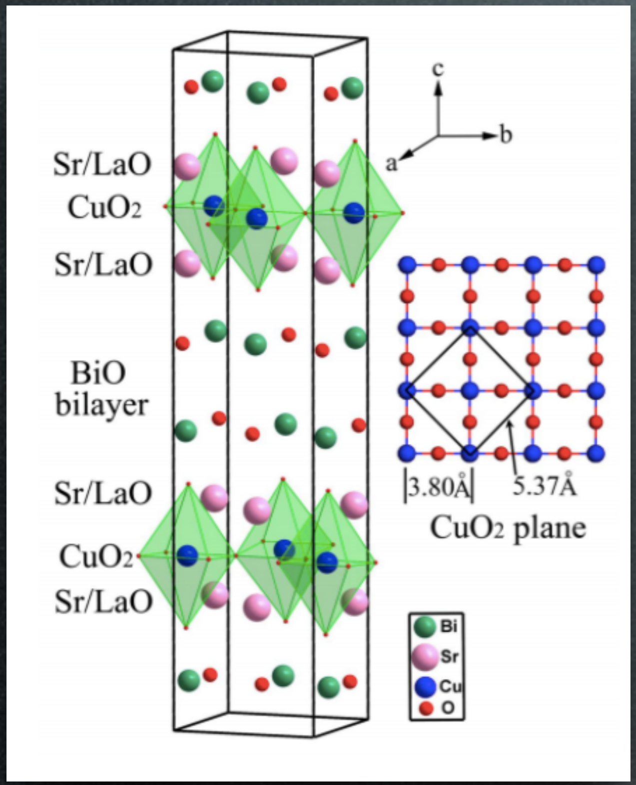

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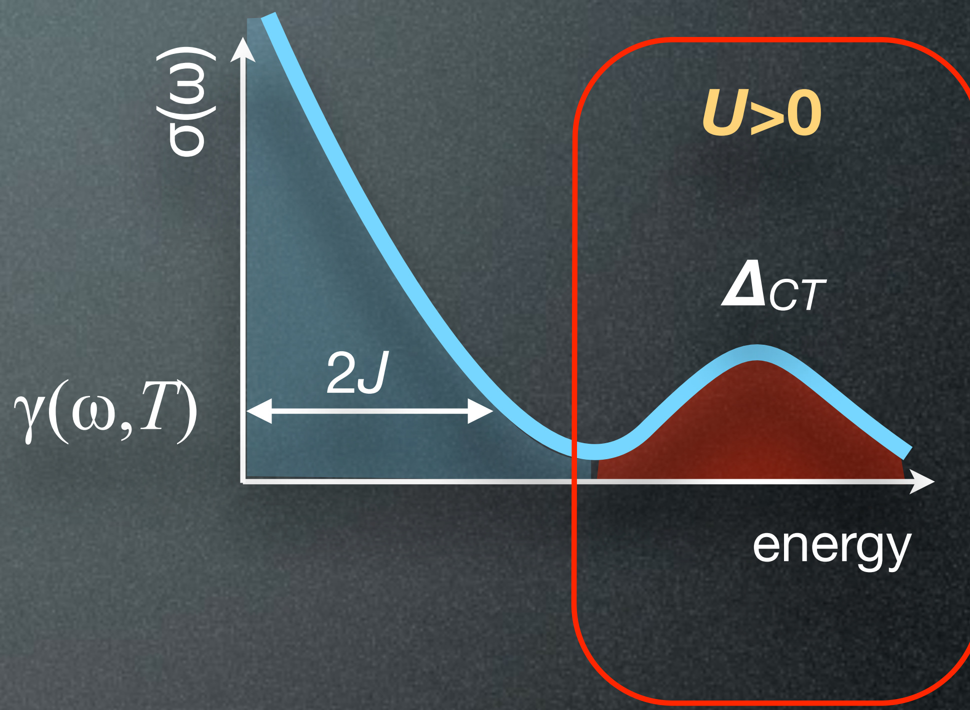
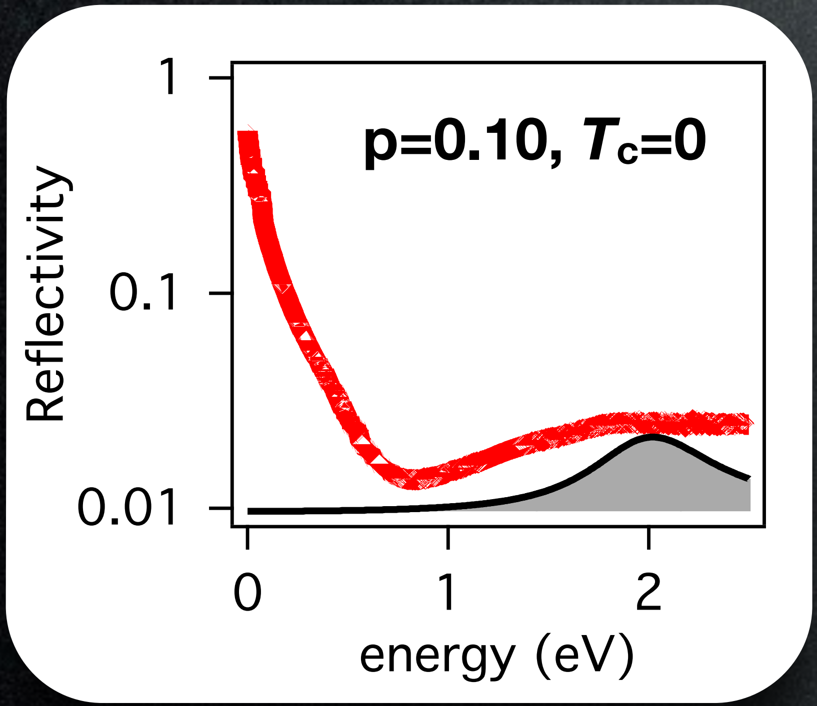
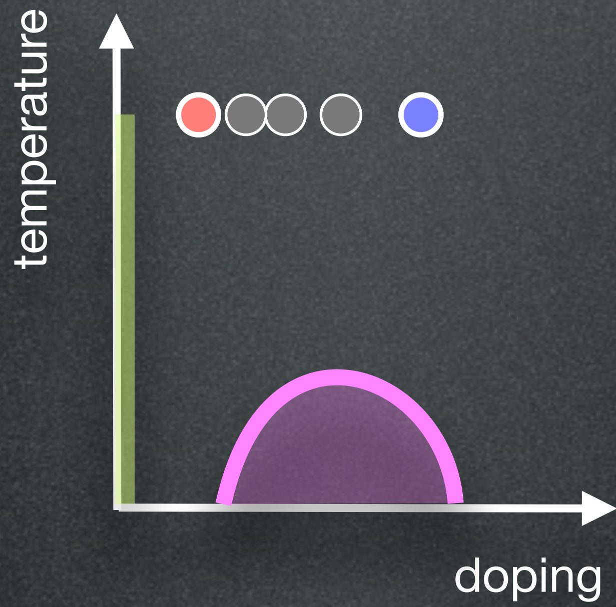
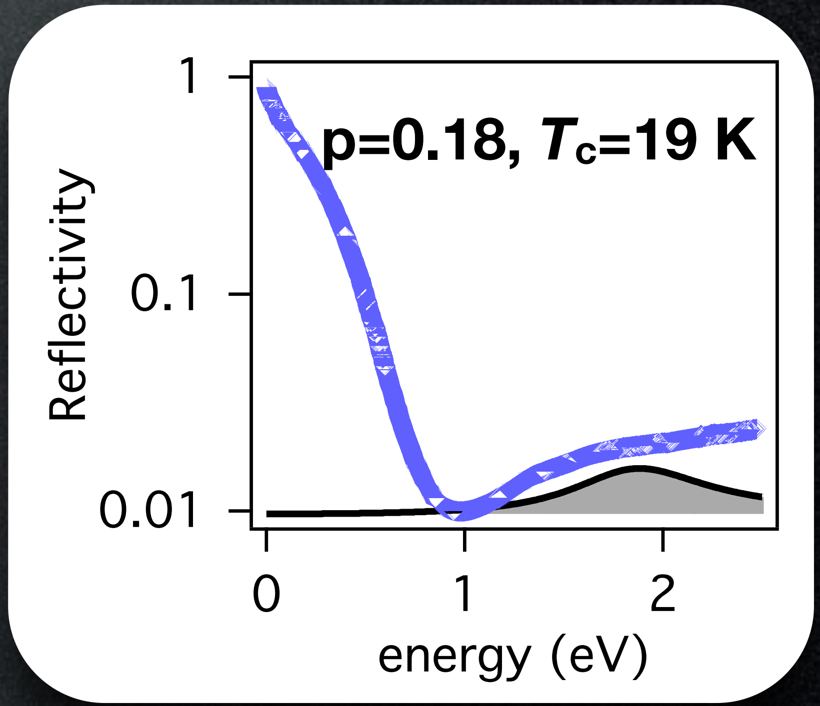






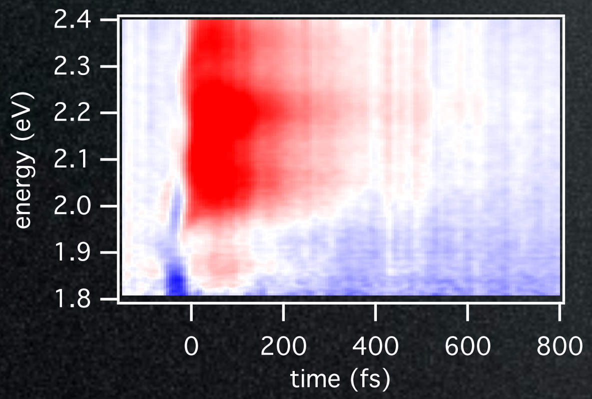


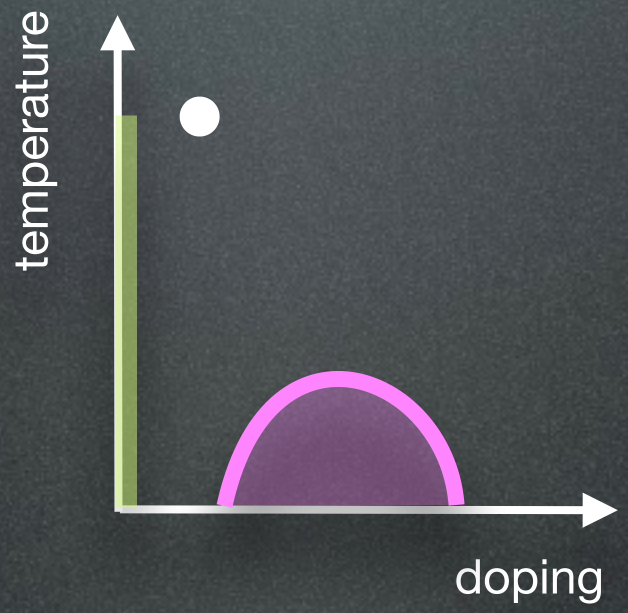
A non-equilibrium phase diagram for cuprates

UNDERDOPED SYSTEMS: $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

T=300 K

p=0.10, T_c=0





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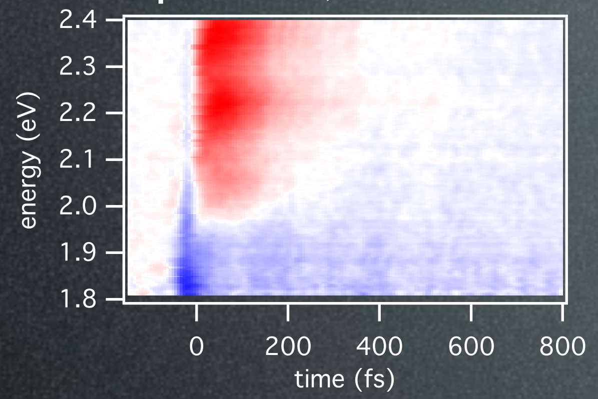
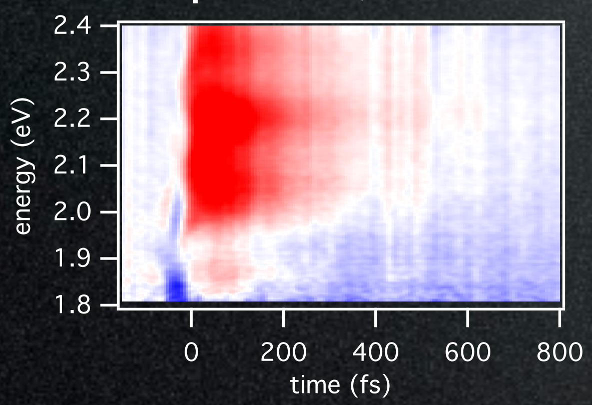
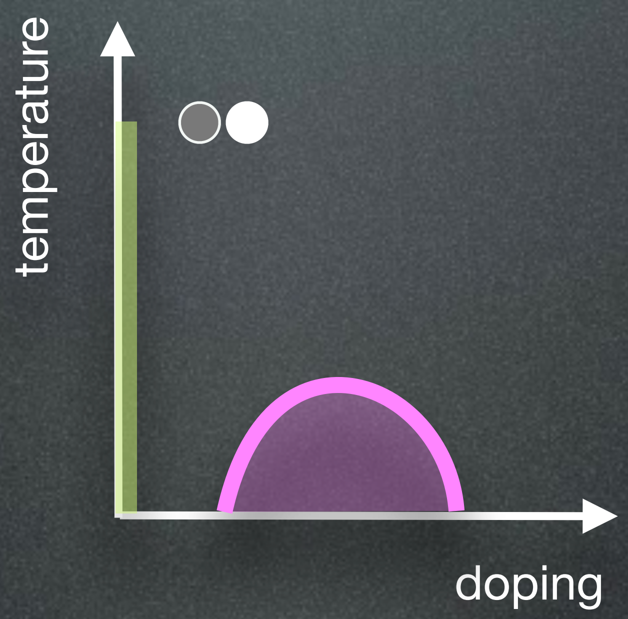
UNDERDOPED SYSTEMS: $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

p=0.12, T_c=13 K



p=0.10, T_c=0





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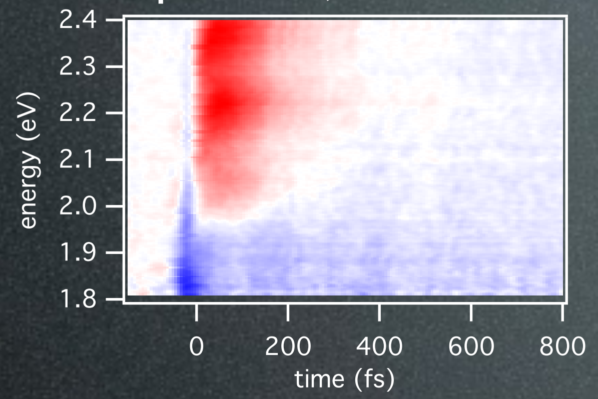
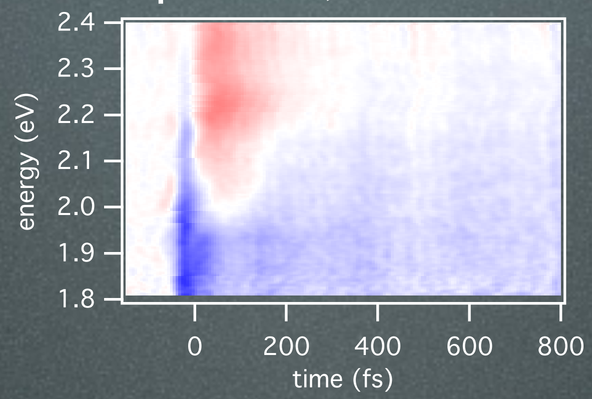
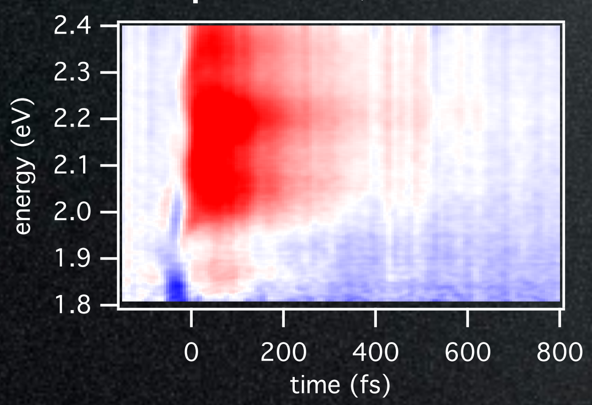
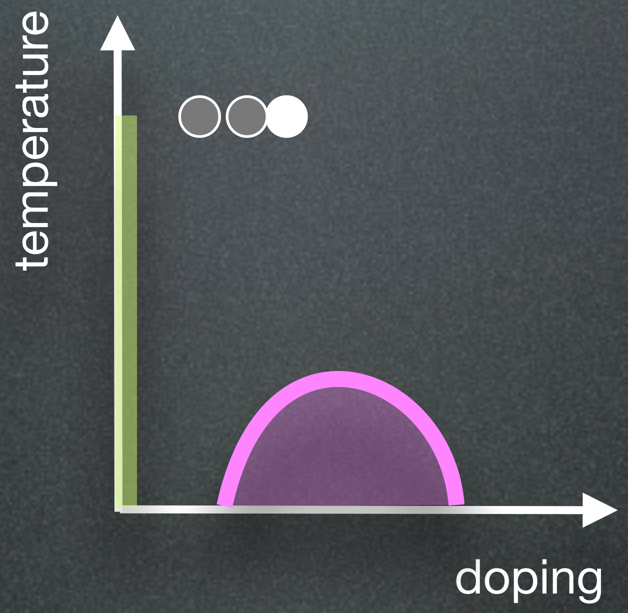


p=0.13, T_c=17 K



p=0.10, T_c=0





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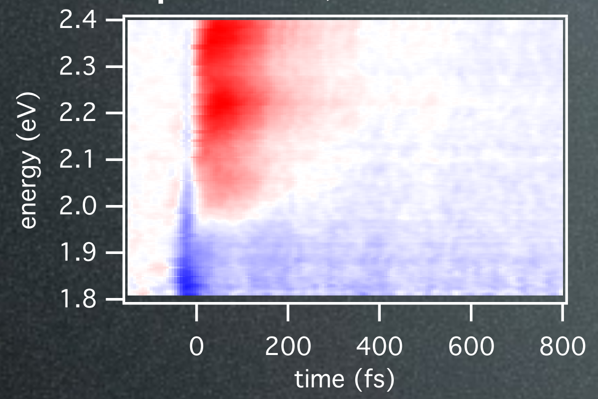

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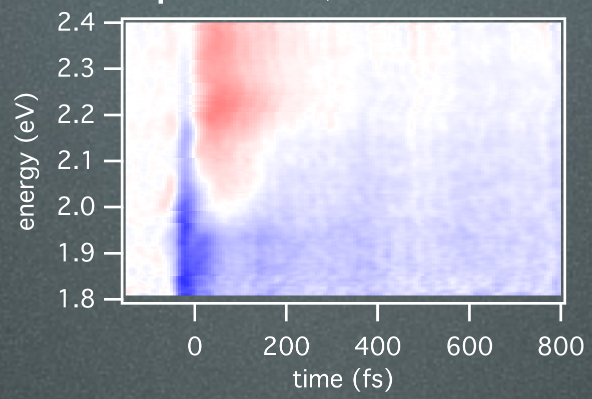
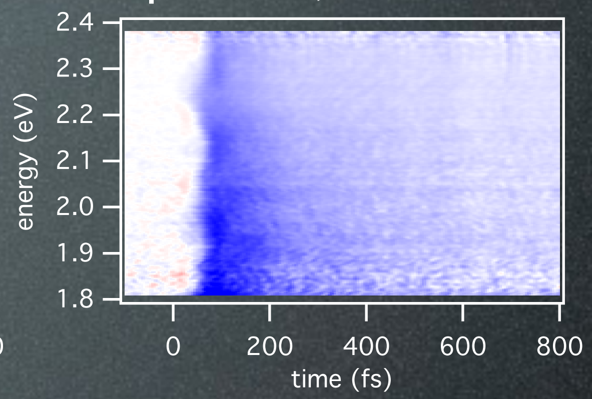
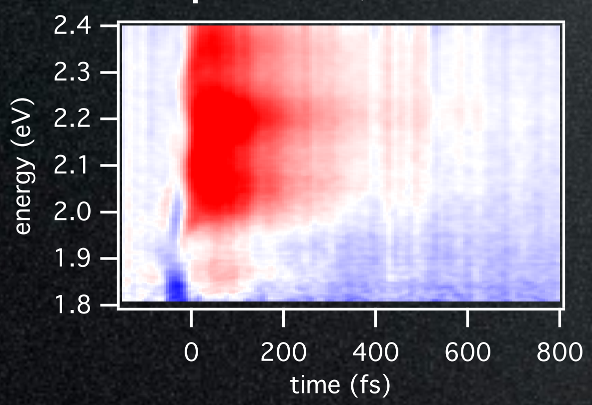
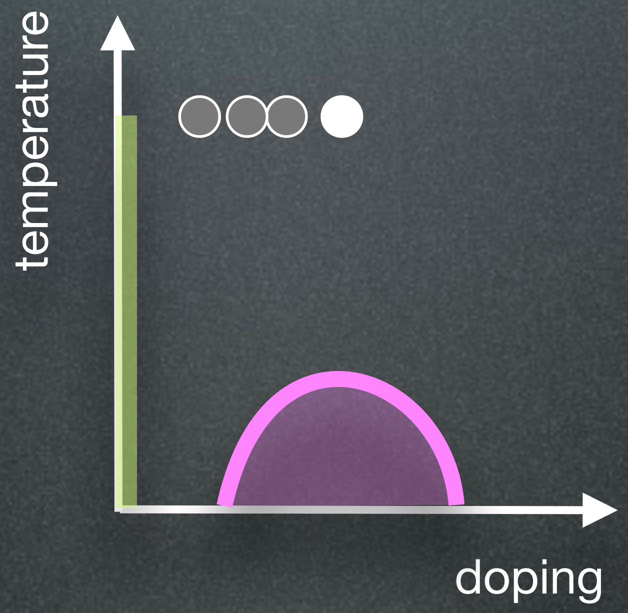


p=0.16, T_c=33 K



p=0.10, T_c=0





A non-equilibrium phase diagram for cuprates

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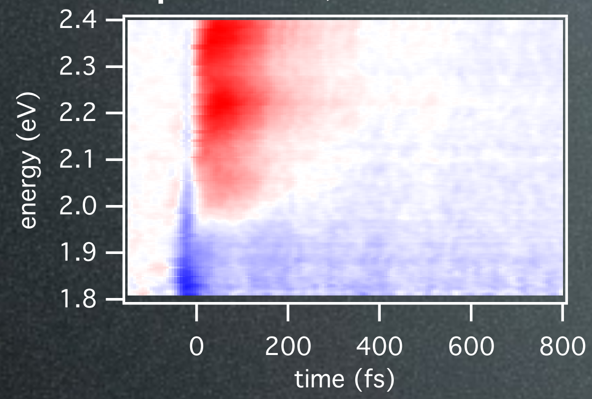

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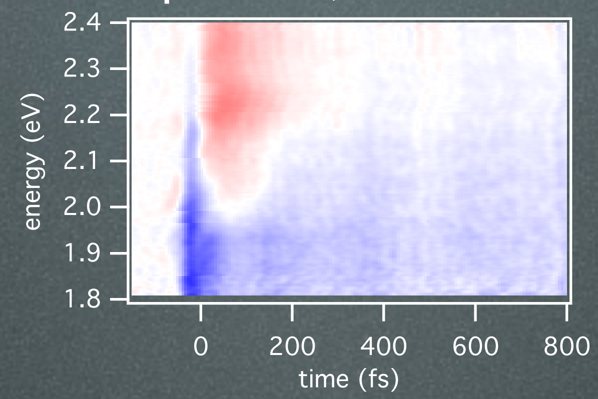

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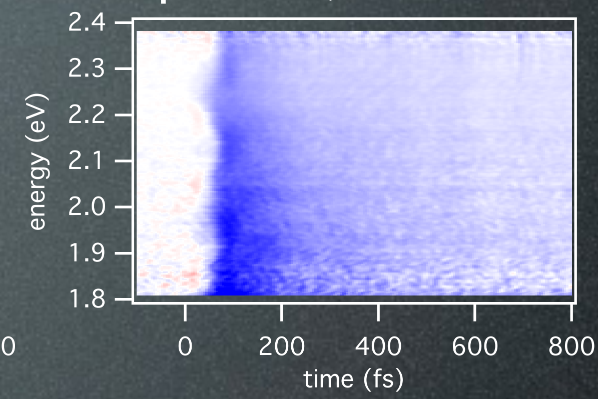

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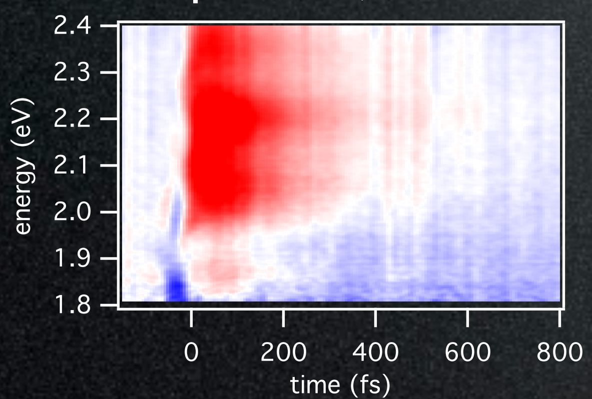
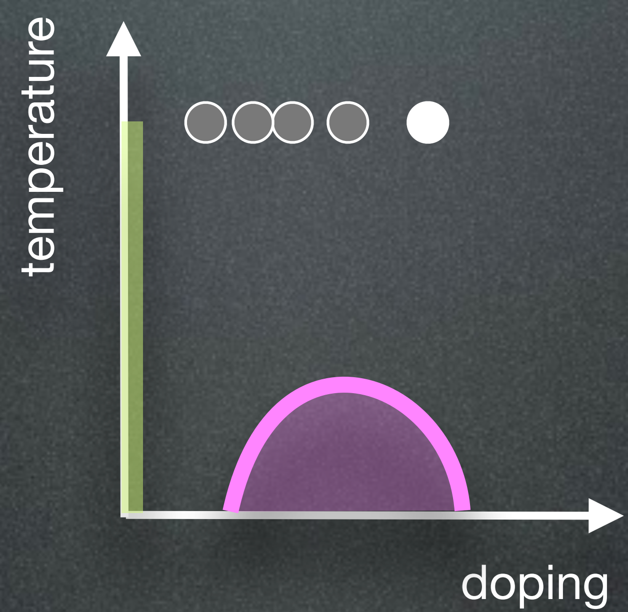
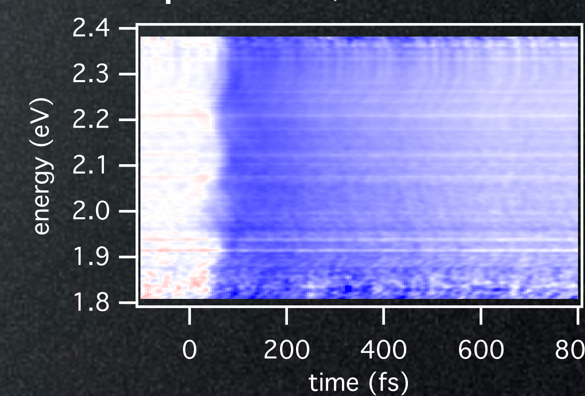


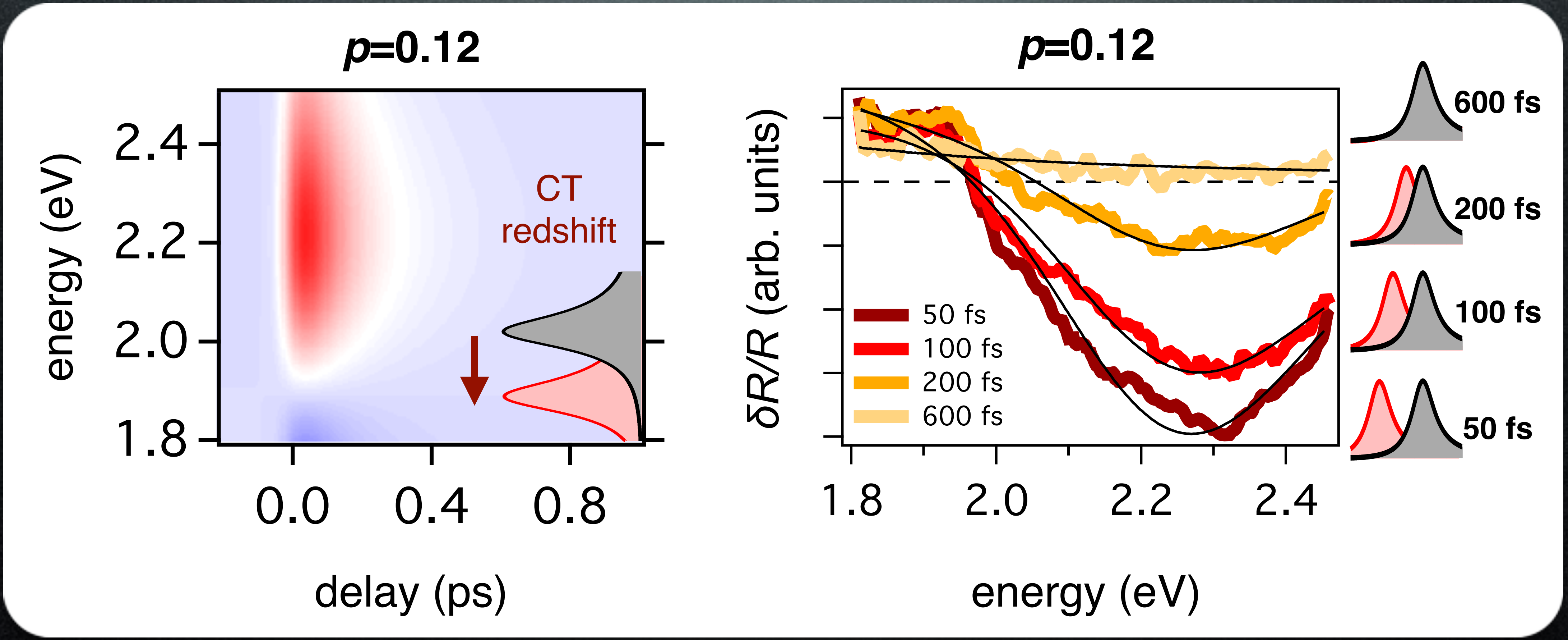


p=0.18, T_c=19 K



Main facts

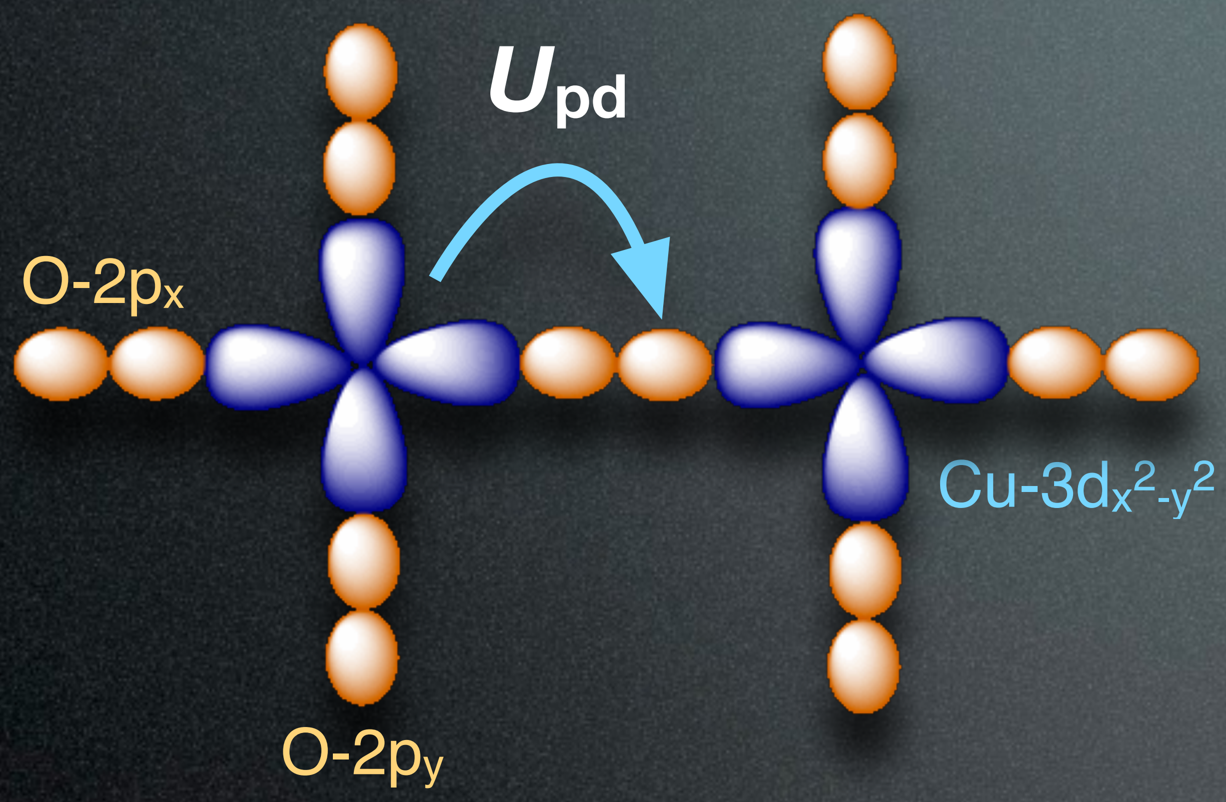
$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$
p=0.12, T_c=13 K



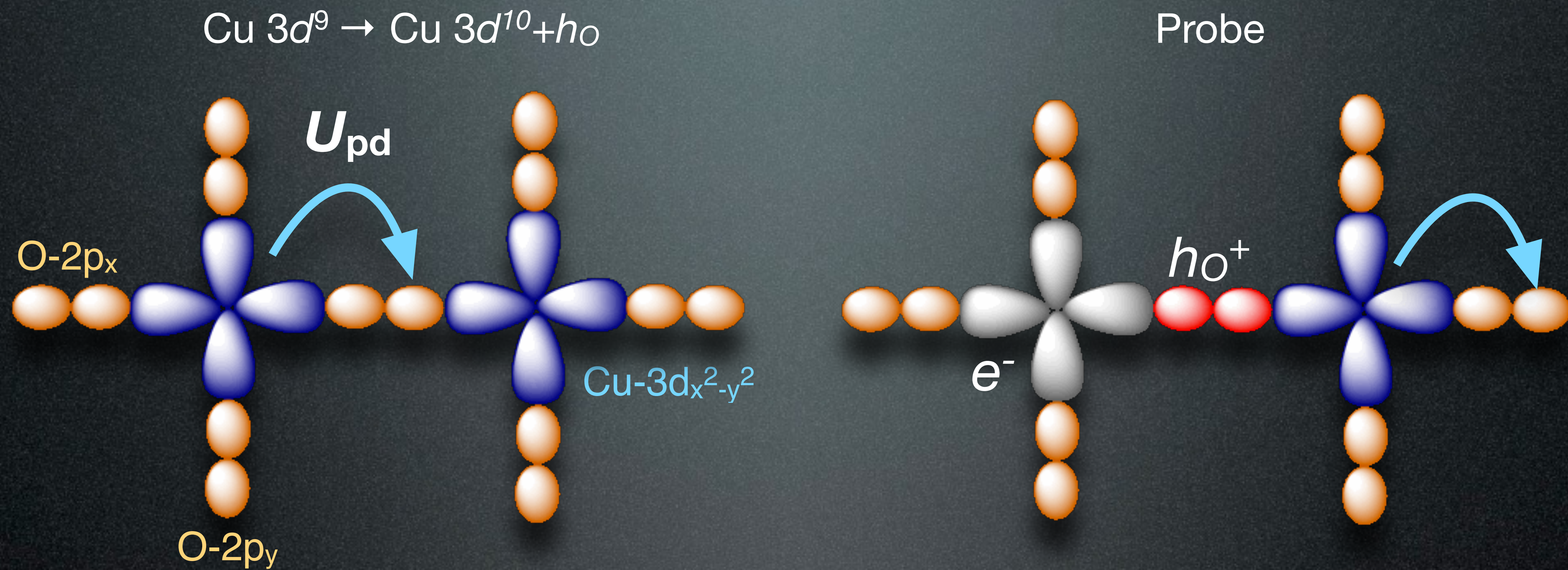
- transient redshift of the CT peak
- independent of the pump energy (1.5, 1.9, 3 eV)

CT redshift

Cu $3d^9 \rightarrow$ Cu $3d^{10}+h_O$



CT redshift



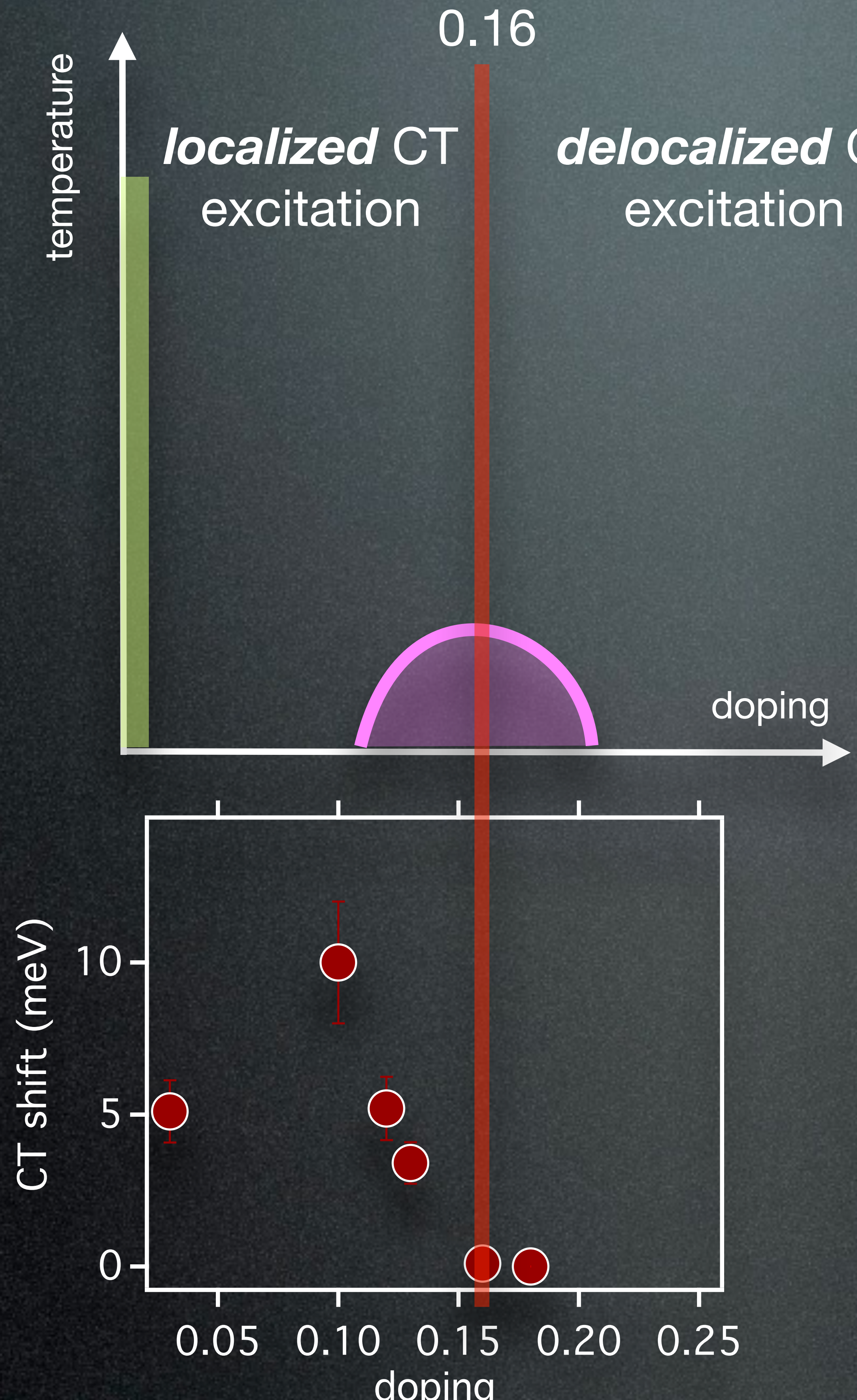
Local picture: localized excitons with binding energy ∝ U_{pd}

$$\delta\Delta_{CT} = -\left(2U_{pd} - \frac{5}{24}U_{pp}\right)\,|\delta\epsilon_{\downarrow}|$$

mean-field calculation by M. Fabrizio

see also B. Mansart et al. *PNAS* **110**, 4539 (2013)

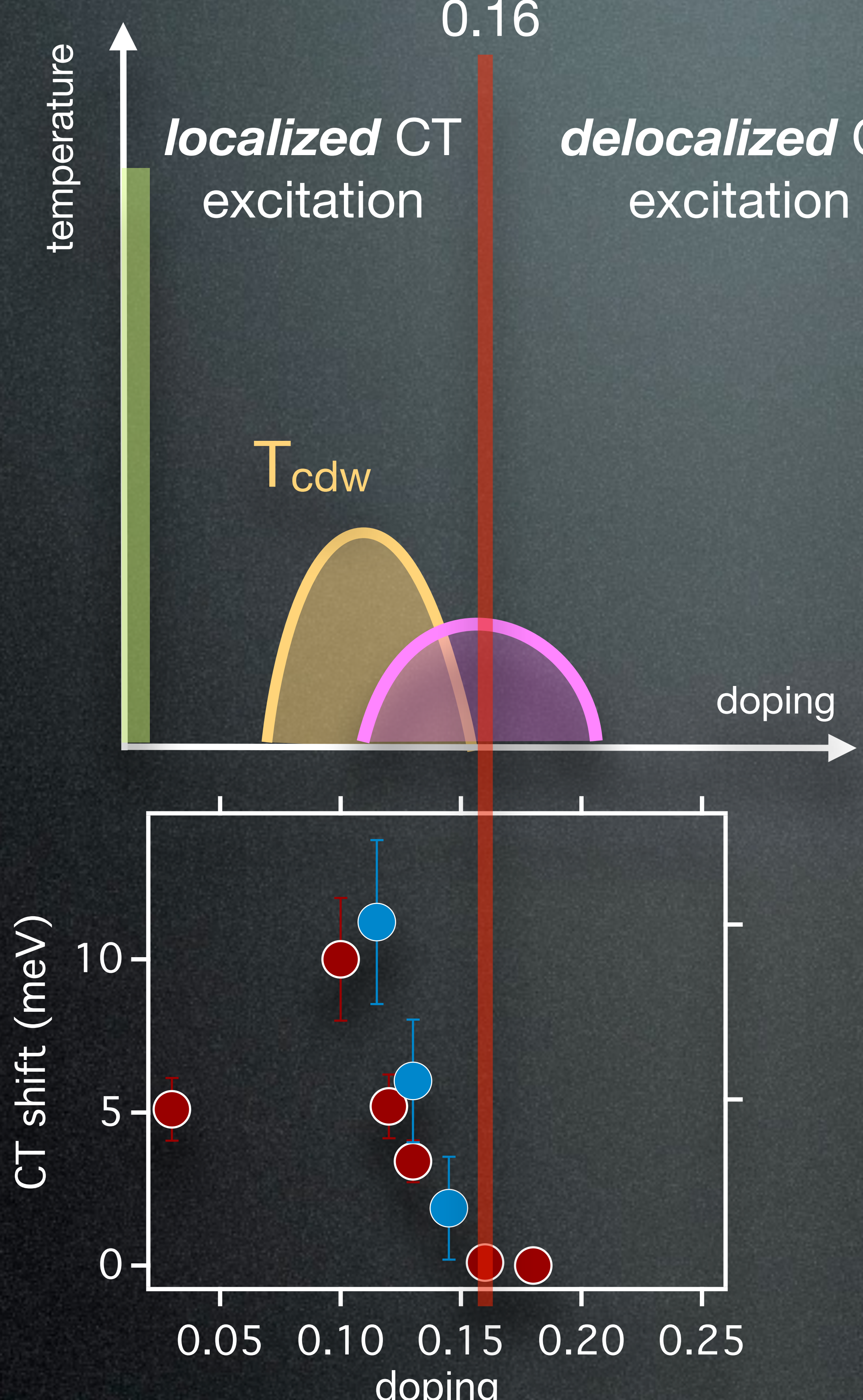
A non-equilibrium phase diagram for cuprates



p_{cr}=0.16±0.01

- transition in the high-energy physics (CT redshift) at T=300K

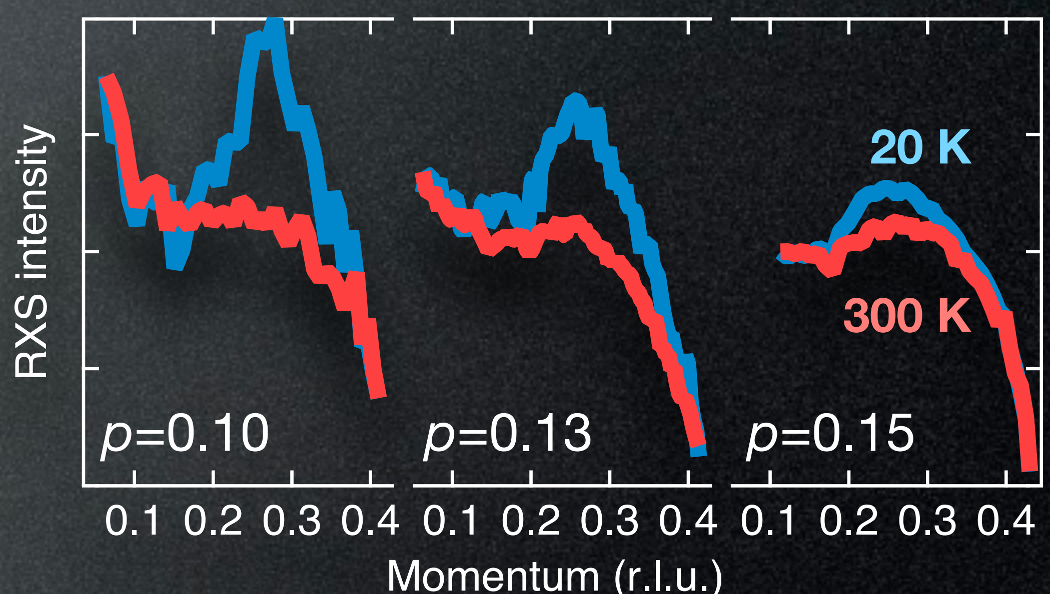
A non-equilibrium phase diagram for cuprates



p_{cr}=0.16±0.01

- transition in the high-energy physics (CT redshift) at T=300K
- disappearance of the charge-order

CDW measured by RXS

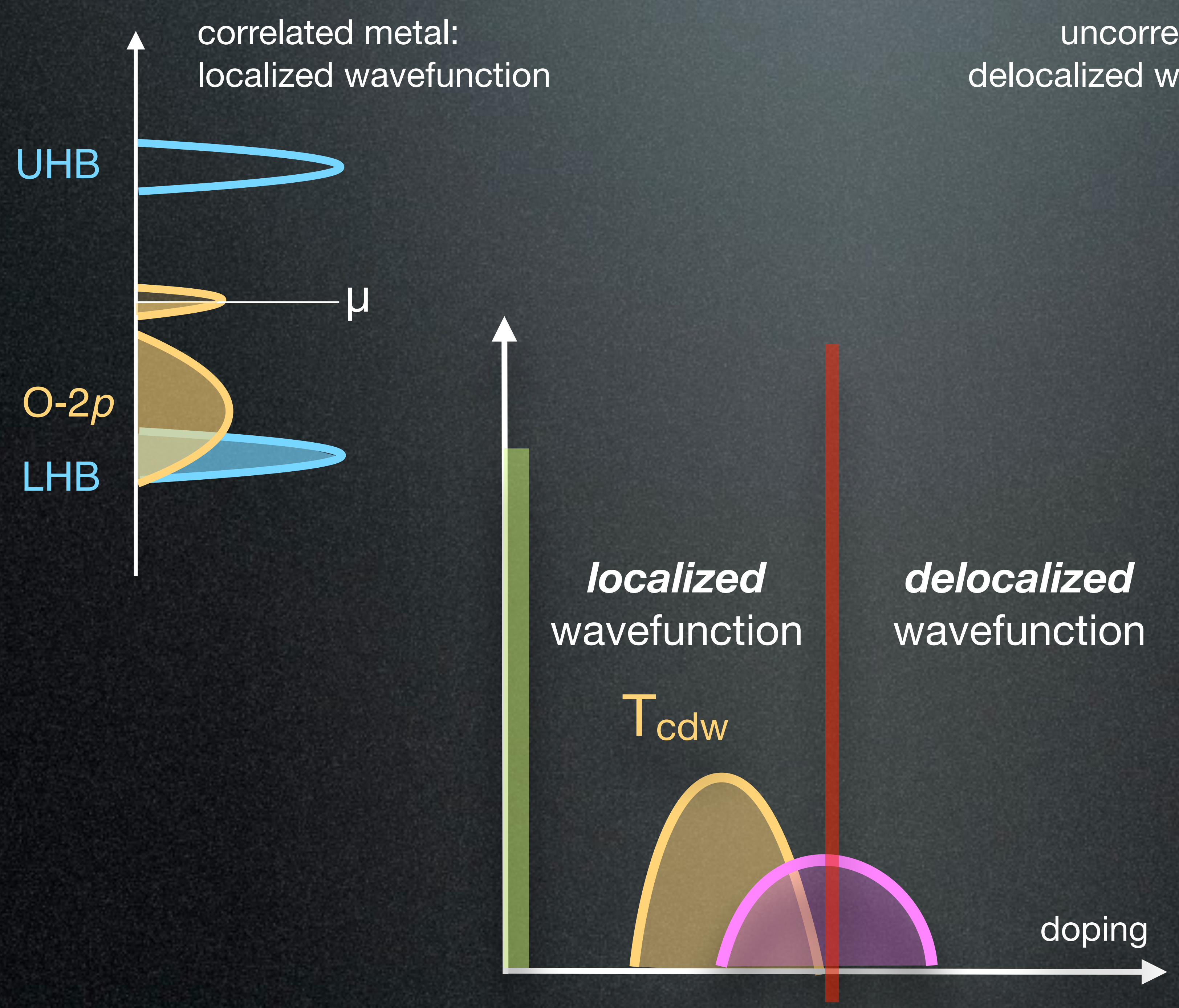


R. Comin, Science 343, 390 (2014)

Conclusions

low-temperature CDW emerges only for $p<p_{cr}$

→ consequence of a precursive correlated state



Conclusions

- charge-order is the low-energy manifestation of a correlated state dominated by the local Cu-3*d*–O-2*p* interactions

- the quenching of the O-2*p*→Cu-3*d* charge fluctuations at the energy scale Δ_{CT} plays a relevant role

- the oxygen orbitals are strongly involved→beyond single-band Hubbard model

- Does the high-energy transition at p≈0.16 have more general consequences?

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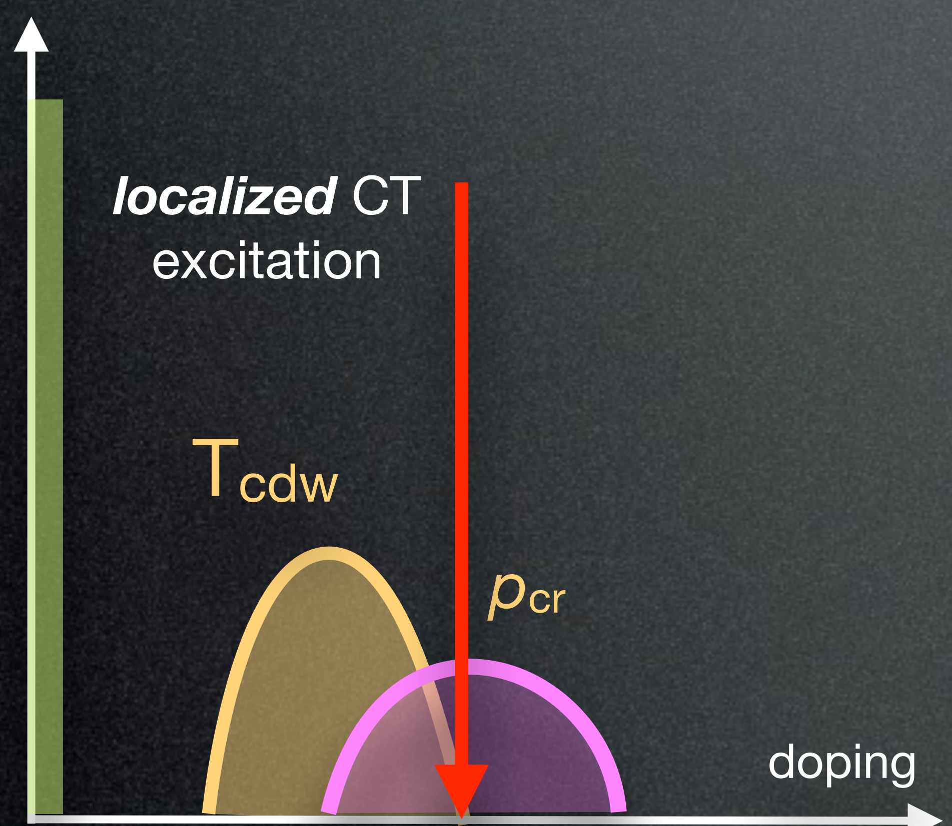
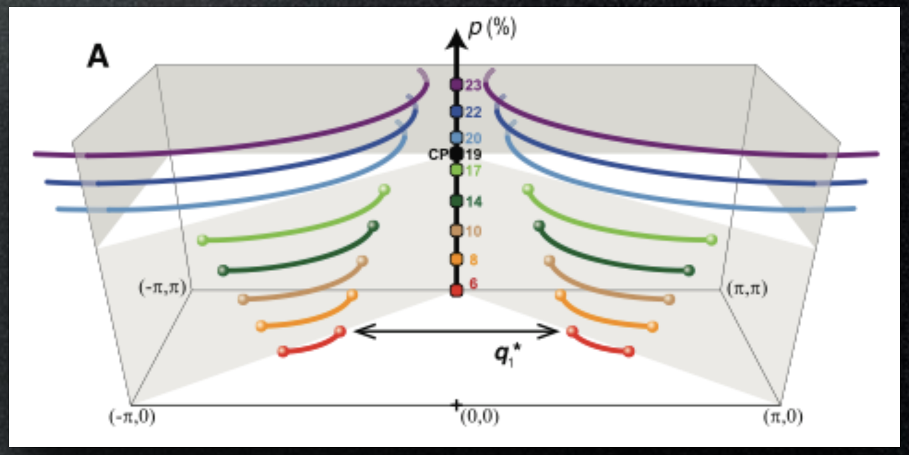


p_{cr}→transition from closed Fermi surface to disconnected arcs

K. Fujita et al. *Science* **344**, 612 (2014)
Y. He et al. *Science* **344**, 608 (2014)



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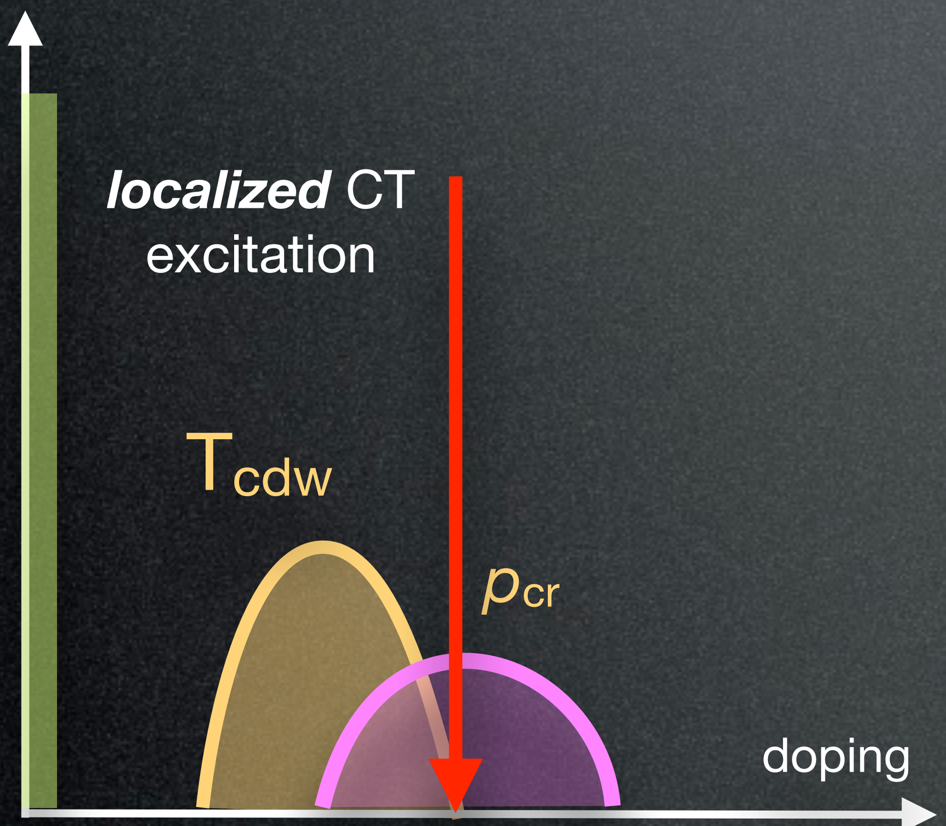
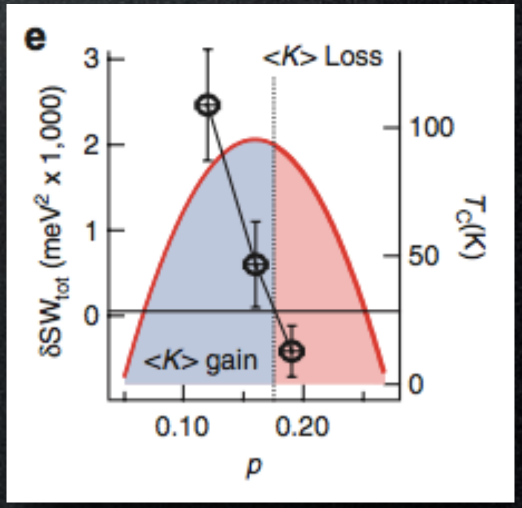


p_{cr}→transition from kinetic energy gain to k.e. loss

C. Giannetti et al., *Nature Commun.* 2:353 (2011)



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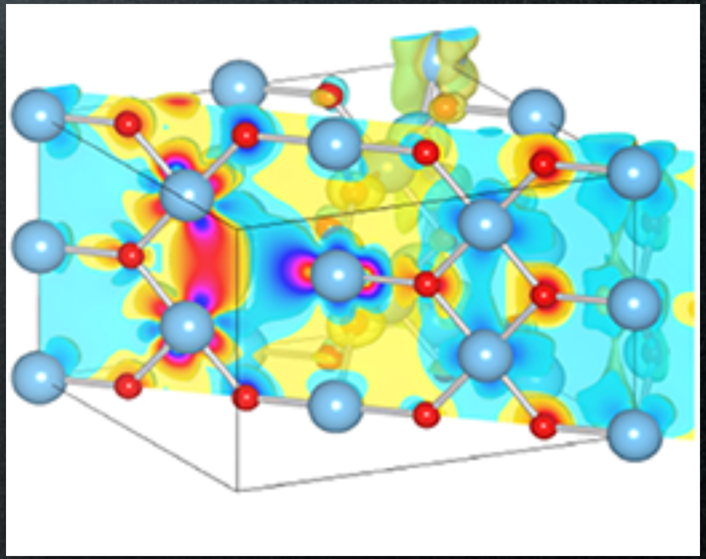
12-18 November, Brescia



- Oxides: cuprates, vanadates, manganites and other
  3*d*/4*d* compounds
- Oxide interfaces and superlattices
- Correlated-oxide based devices
- Non-equilibrium phenomena in oxides
- Models and theory for materials and spectroscopies

we are waiting for you in Brescia!!!

Thank you!

Outline

- Spontaneous symmetry-breaking in copper oxides: charge order

- Ultrafast spectroscopies to investigate the role of the Mott-like excitations

- The room temperature precursor of charge-order in cuprates

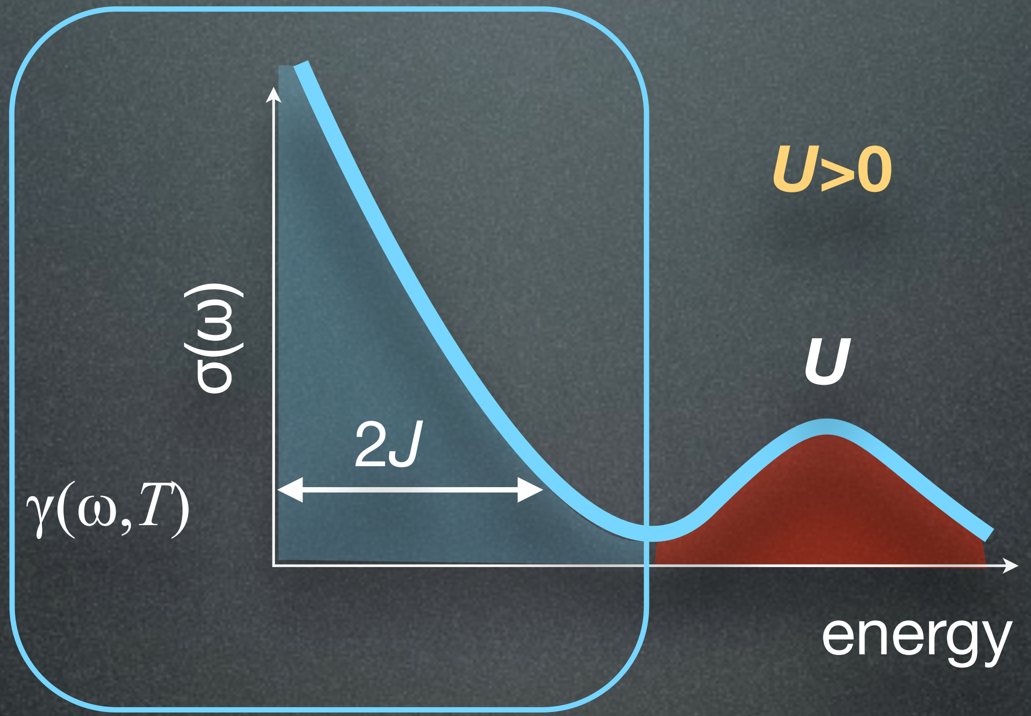
S. Peli et al. *arXiv:1508.03075* (2015)

- Snapshots of the retarded-interaction with ultrafast fluctuations via 10 fs pulses

S. Dal Conte et al., *Science* **335**, 1600 (2012)
S. Dal Conte et al. *Nature Physics* **11**, 421 (2015)

Extended Drude Model

equilibrium optical conductivity

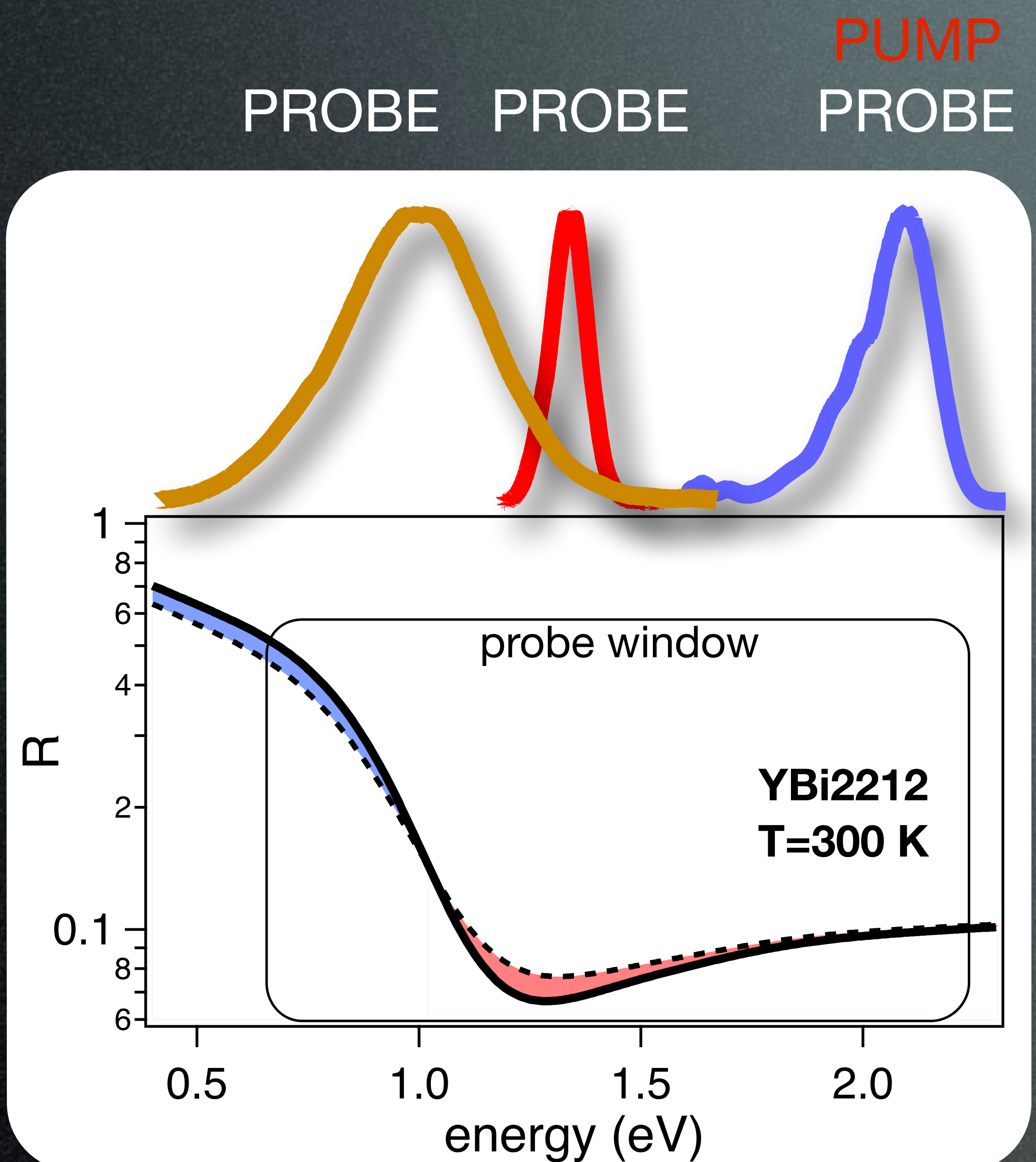


Extended Drude dielectric function

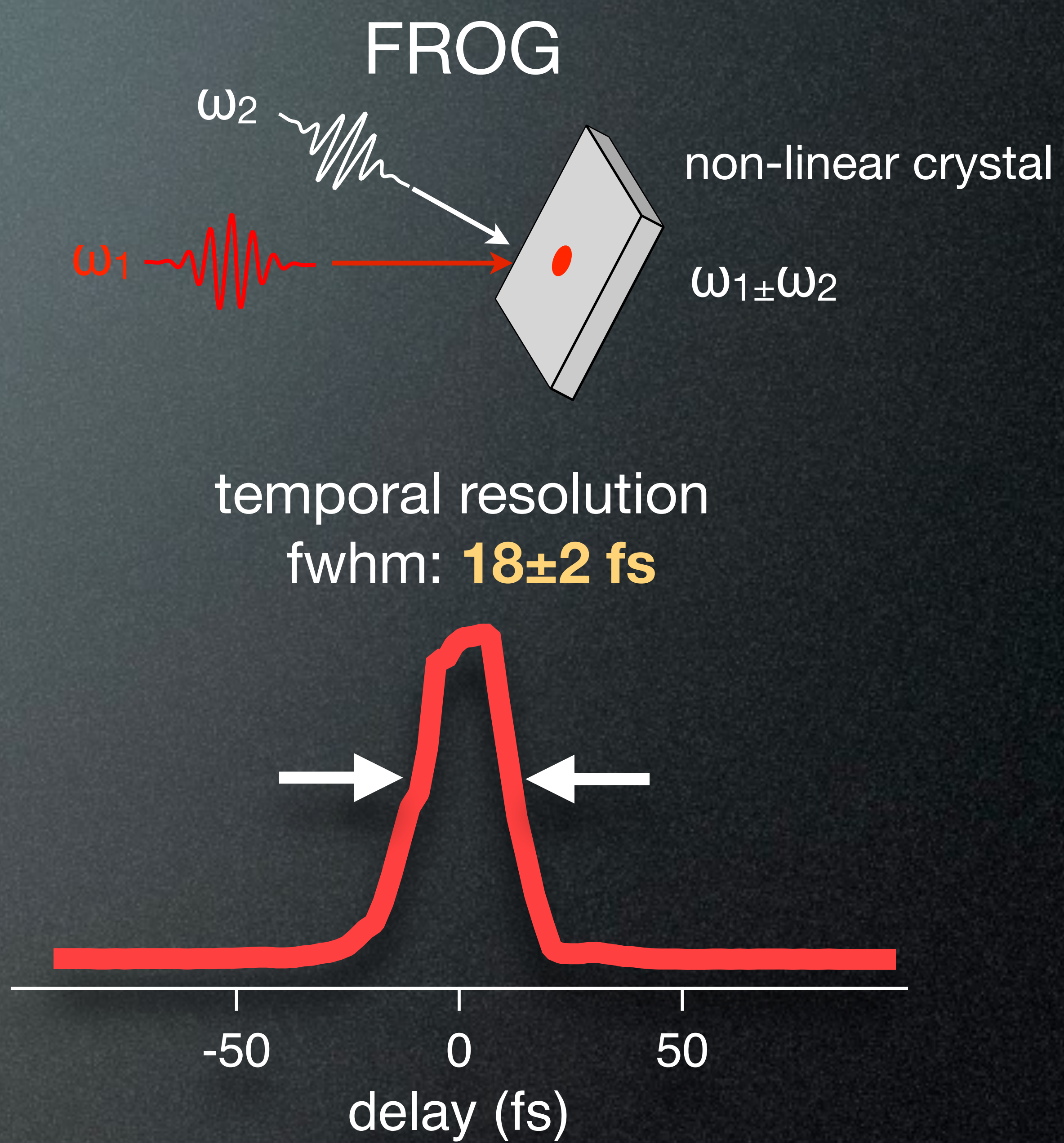
$$\epsilon_D(\omega, T) = 1 - \frac{{\omega_p}^2}{\omega(\omega + M(\omega, T))}$$

Memory function

ultra high temporal resolution



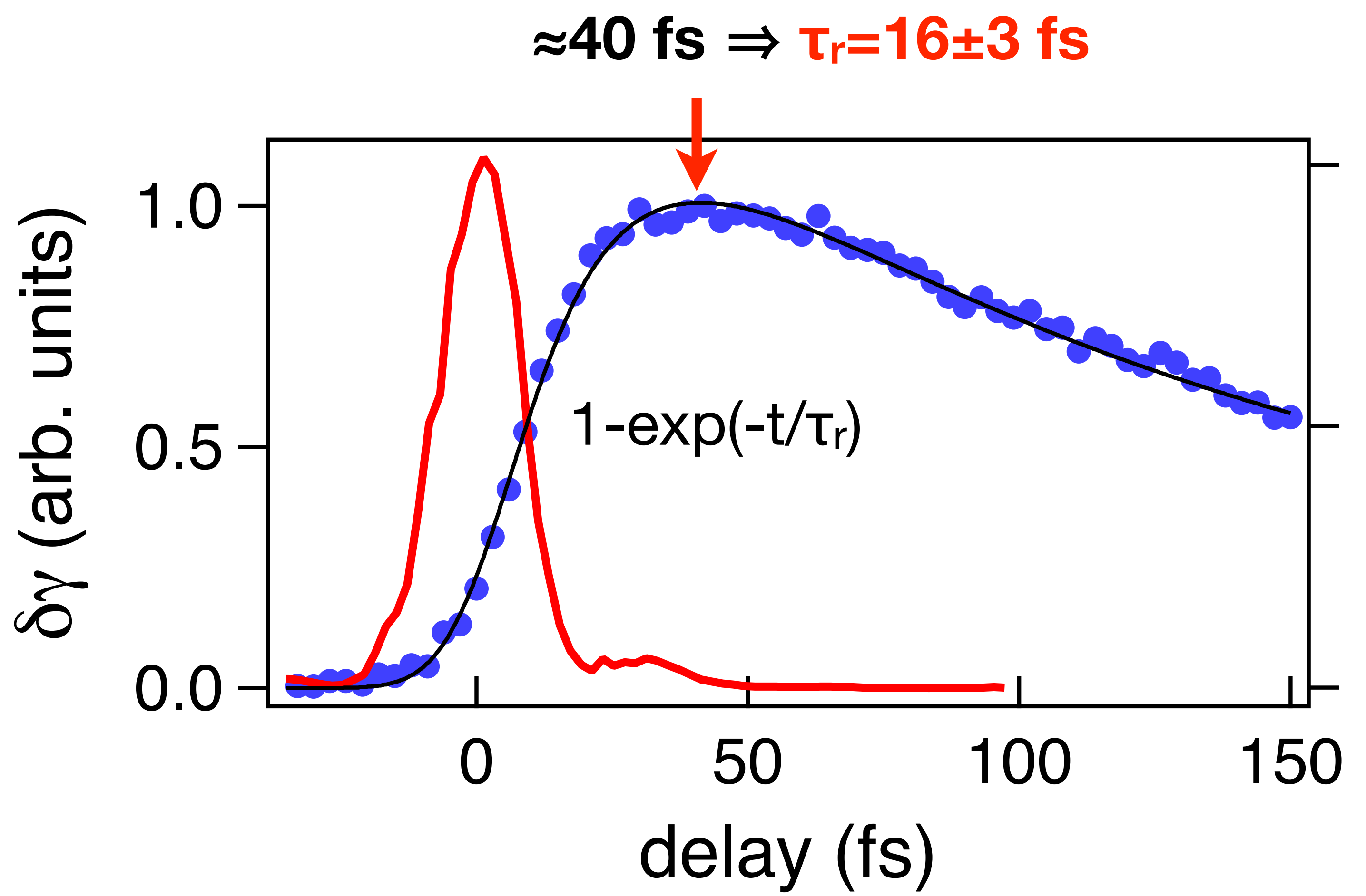
G. Cerullo's group (Politecnico of Milan)

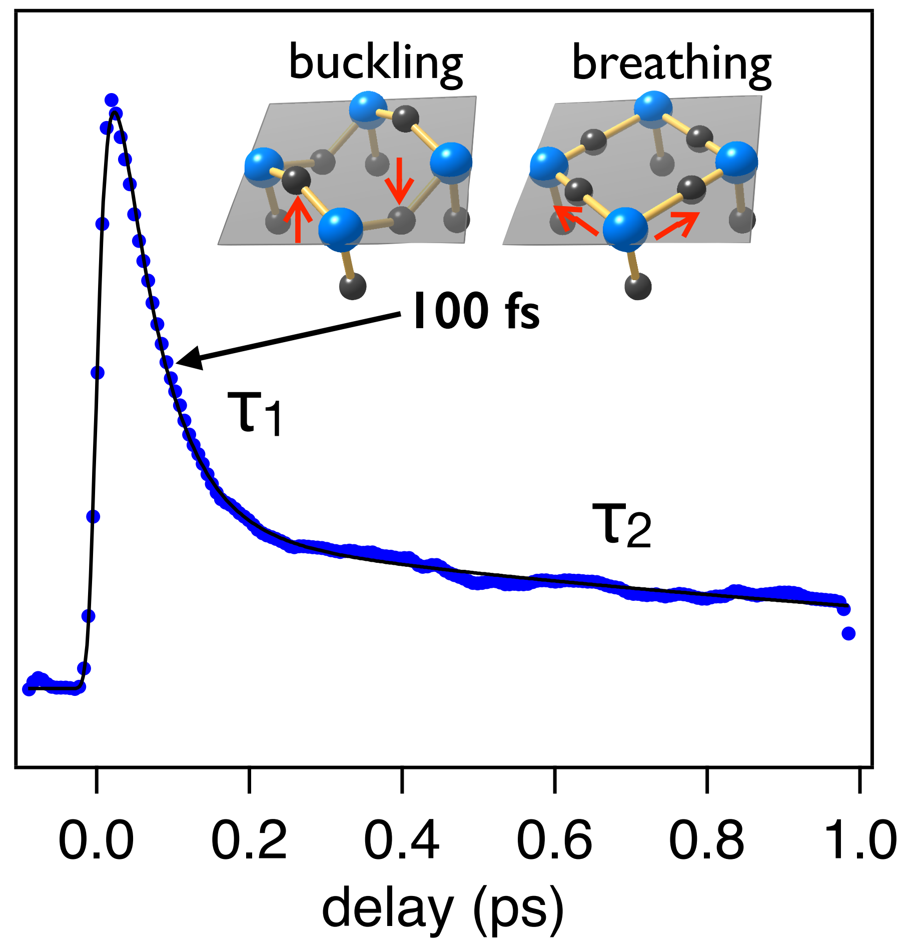


optimally doped $Bi_2Sr_2Y_{0.08}Ca_{0.92}Cu_2O_{8+\delta}$ (YBi2212)

T_c=96 K

retarded e-boson interaction



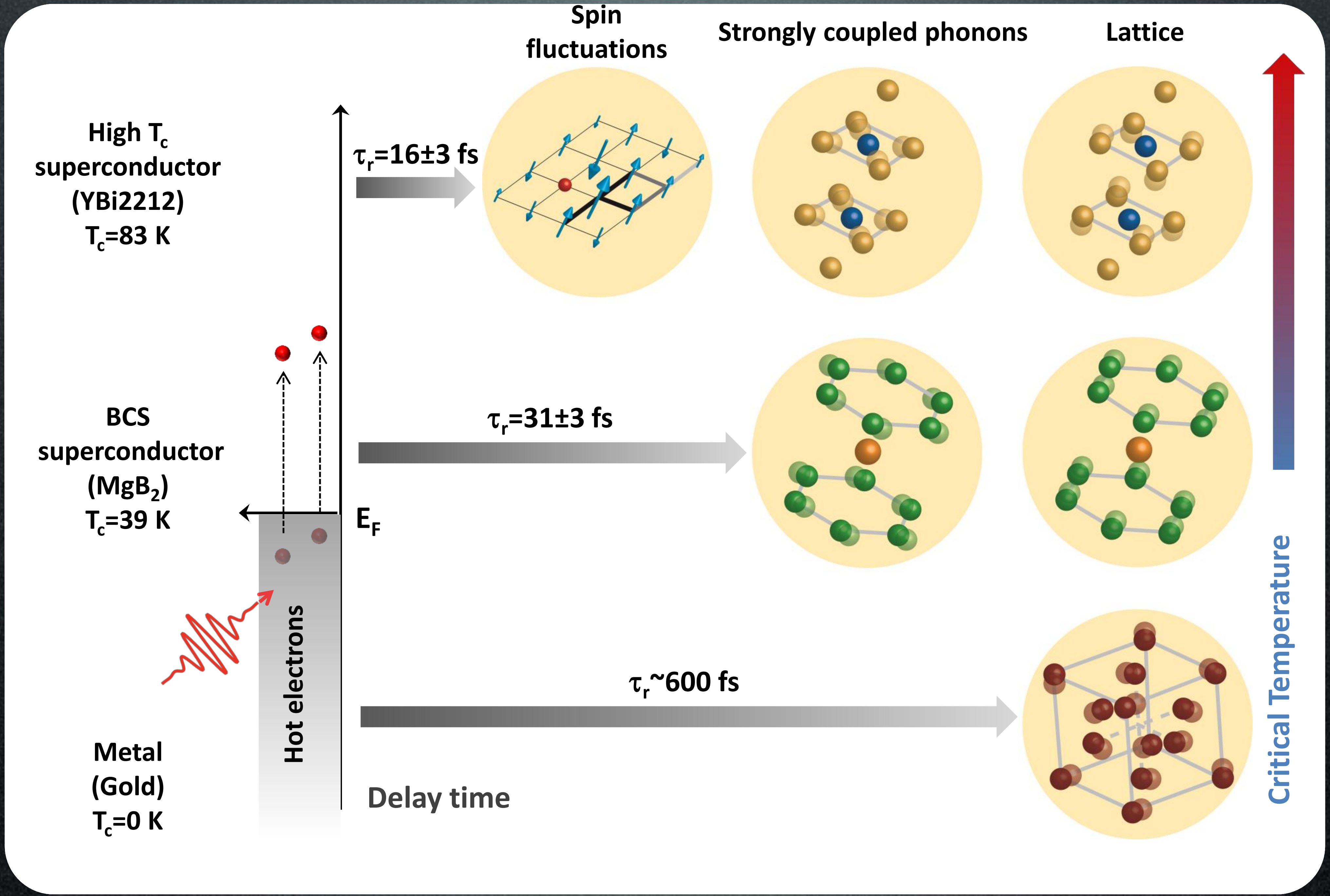


$\delta R(\omega) \propto \delta T_b$

e.g. L. Perfetti et al., *Phys. Rev. Lett.* **99**, 197001 (2007)

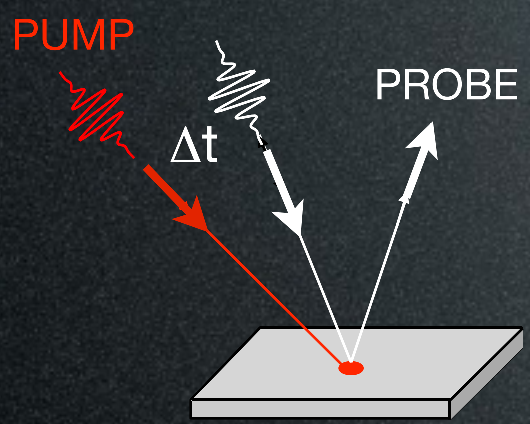
In 16 fs photoexcited carriers can exchange energy with bosons ✔

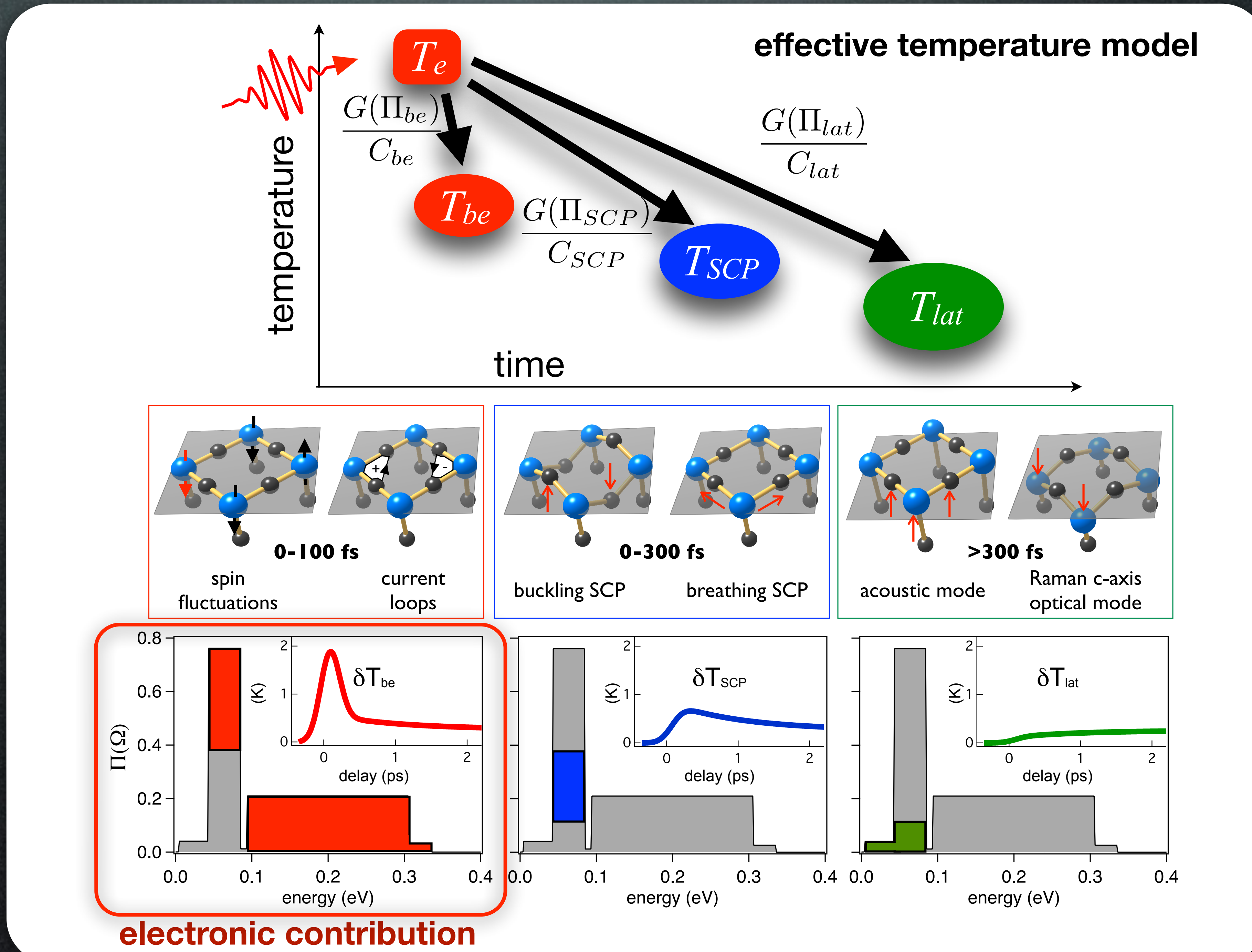
Summary



Spin fluctuations
Strongly coupled phonons
Lattice
High T_c superconductor (YBi2212) T_c=83 K
τ_r=16±3 fs
BCS superconductor (MgB_2) T_c=39 K
τ_r=31±3 fs
Metal (Gold) T_c=0 K
τ_r~600 fs
E_F
Hot electrons
Delay time
Critical Temperature

electron-boson coupling in CUPRATES





$$\Pi(\Omega) = \alpha^2 F(\Omega) + I^2\chi(\Omega)$$

E. van Heumen et al., *Phys. Rev. B* **79**, 184512 (2009)

J. Carbotte et al. *Rep. Prog. Phys.* **74**, 066501 (2011)

S. Dal Conte et al., *Science* **335**, 1600 (2012)

no time-resolution to directly disentangle di build-up of ***e-boson*** interactions

in agreement with the glue extracted from the Hubbard model

E. Gull & A.J. Millis *Phys. Rev. B* **90**, 041110 (2014)

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