Recent advances in ultrafast spectroscopies

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

People and Collaborations

•Ultrafast optics group (Università Cattolica, Brescia)
S. Dal Conte, ***S. Peli***, F. Banfi, G. Ferrini, C. Giannetti

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

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

•Equilibrium optical properties of HTSC
D. van der Marel (Université de Genève)

•Samples
A. Damascelli (University of British Columbia, Vancouver)

M. Greven (University of Minnesota & Stanford University)

H. Eisaki (NIST, Tsukuba, Japan)

Outline

•Time-resolved spectroscopies to disentangle the intertwined degrees of freedom (low-intensity regime)

•optical control of the electronic properties of correlated materials (high-intensity regime)

•broadband ultrafast optical spectroscopy on cuprates

Quasi-particle dynamics in HTSC (Bi2212)

equilibrium spectroscopy

optical properties

T_e | T_{bos} strongly-coupled | T_{bos} reservoir

occupation of el-states $f(E,T_e)$

Drude broadening $n(E,T_{bos})$

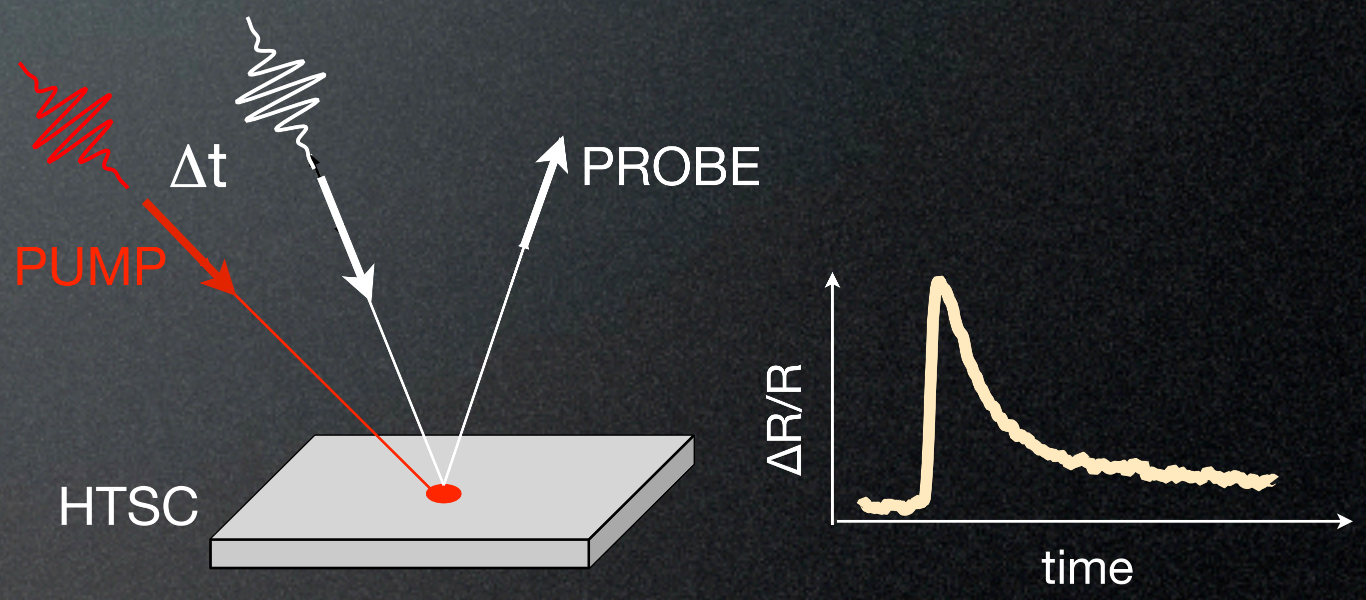
non-equilibrium spectroscopy

T_e → T_{bos} strongly-coupled → T_{bos} reservoir

occupation of el-states $f(E,T_e)$

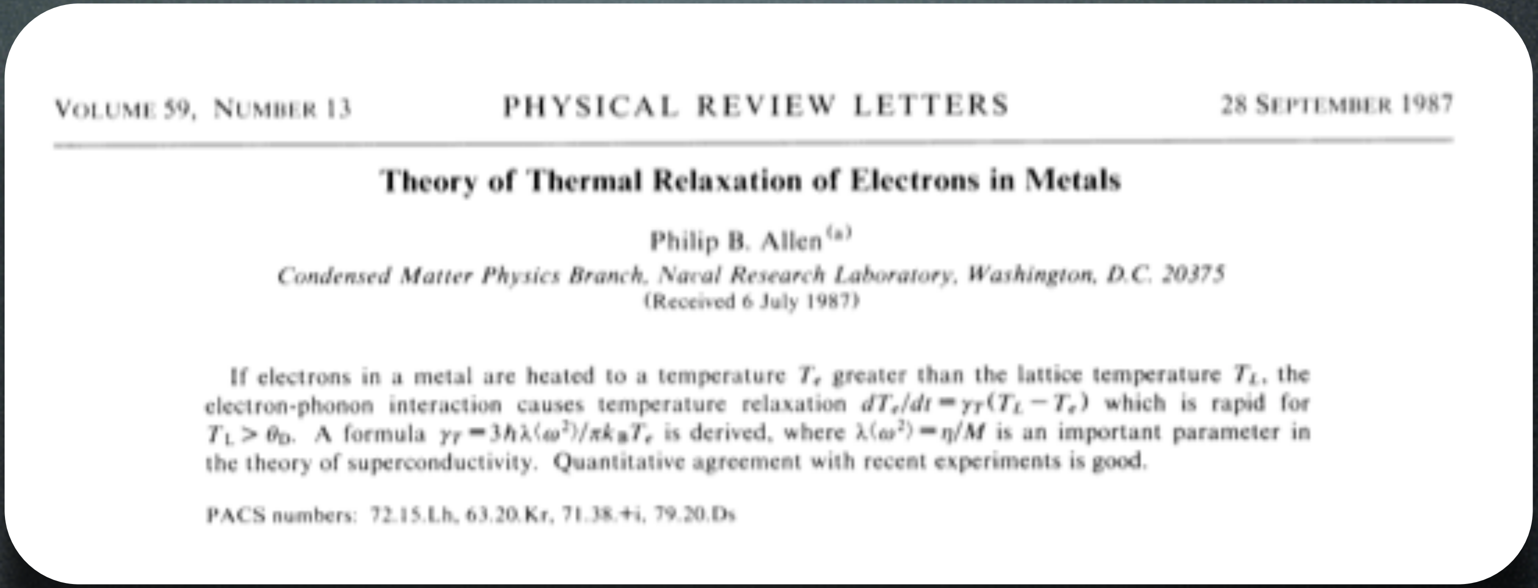
Drude broadening $n(E,T_e)$

different timescales



electron-phonon coupling and electron dynamics

METALS



VOLUME 59, NUMBER 13 PHYSICAL REVIEW LETTERS 28 SEPTEMBER 1987

Theory of Thermal Relaxation of Electrons in Metals

Philip B. Allen[a]
Condensed Matter Physics Branch, Naval Research Laboratory, Washington, D.C. 20375
(Received 6 July 1987)

If electrons in a metal are heated to a temperature T_e greater than the lattice temperature T_L, the electron-phonon interaction causes temperature relaxation $dT_e/dt = \gamma_T(T_L - T_e)$ which is rapid for $T_L > \Theta_D$. A formula $\gamma_T = 3\hbar\lambda\langle\omega^2\rangle/\pi k_B T_e$ is derived, where $\lambda\langle\omega^2\rangle = \eta/M$ is an important parameter in the theory of superconductivity. Quantitative agreement with recent experiments is good.

PACS numbers: 72.15.Lh, 63.20.Kr, 71.38.+i, 79.20.Ds

2-temperature model

$$\frac{\partial T_e}{\partial t} = \frac{G(\Pi_{lat}, T_{lat}, T_e)}{\gamma_e T_e} + \frac{p}{\gamma_e T_e}$$

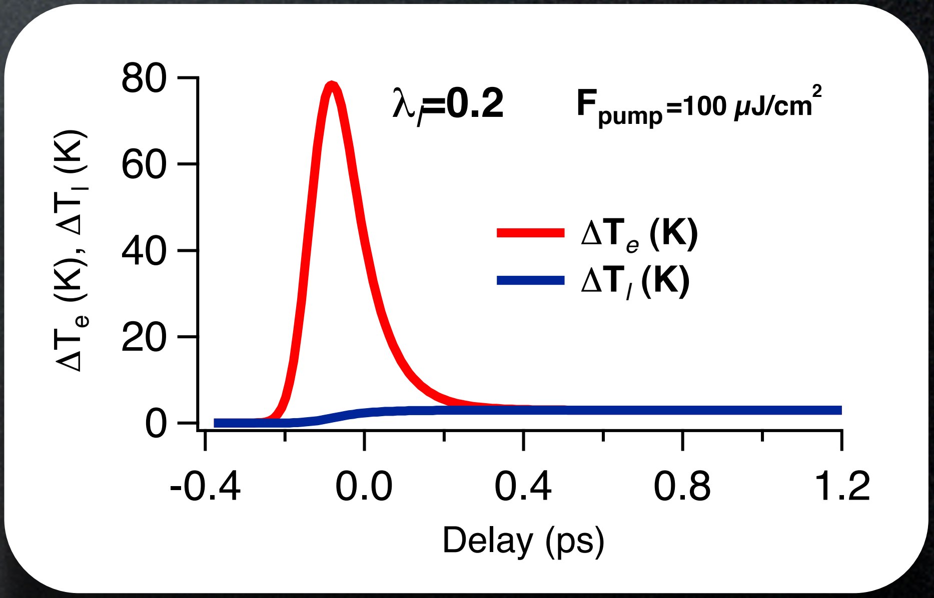
$$\frac{\partial T_{lat}}{\partial t} = -\frac{G(\Pi_{lat}, T_{lat}, T_e)}{C_{lat}}$$

G/C_{lat} determines the dynamics in the time domain

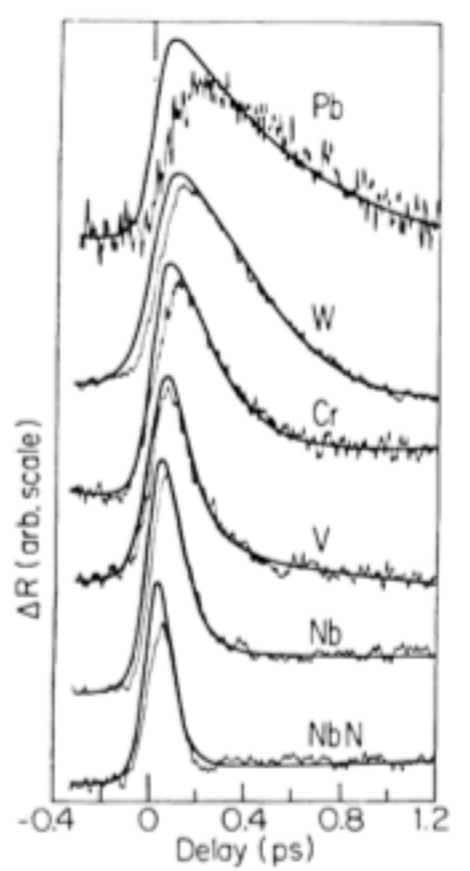
$$G(\Pi_b, T_b, T_e) = \frac{3\gamma_e}{\pi\hbar k_b^2}\int_0^\infty d\Omega \Pi_b(\Omega)\Omega^2[N(\Omega, T_b) - N(\Omega, T_e)]$$

e-ph coupling: bosonic function

temperature evolution



electron-phonon coupling in metals



	$T_c(0)$ (K)[a]	$\lambda_{exp}\langle\omega^2\rangle$ (meV^2)	$\langle\omega^2\rangle$ (meV^2)	λ_{exp}	λ_{th}
Cu	590	29 ± 4	377[b]	0.08 ± 0.01	0.10[b]
Au	650	23 ± 4	178[c]	0.13 ± 0.02	0.15[c]
Cr	716	128 ± 15	987[d]	0.13 ± 0.02	···
W	1200	112 ± 15	425[e]	0.26 ± 0.04	0.26[e]
V	700	280 ± 20	352[f]	0.80 ± 0.06	0.82[f]
Nb	790	320 ± 30	275[g]	1.16 ± 0.11	1.04[g]
Ti	820	350 ± 30	601[g]	0.58 ± 0.05	0.54[g]
Pb	570	45 ± 5	31[i]	1.45 ± 0.16	1.55[i]
NbN	1070	640 ± 40	673[j]	0.95 ± 0.06	1.46[j]
V_3Ga	1110	370 ± 60	448[k]	0.83 ± 0.13	1.12[k]

S.D. Brorson et al. *Phys. Rev. Lett.* **64,** 2172 (1990)

e-ph coupling

$$\lambda = 2\int \Pi(\Omega)/\Omega d\Omega$$

$\Pi(\Omega)=\alpha^2F(\Omega)$

Considering non-thermal distribution ($\tau_{e-e}>\tau_{e-ph}$):

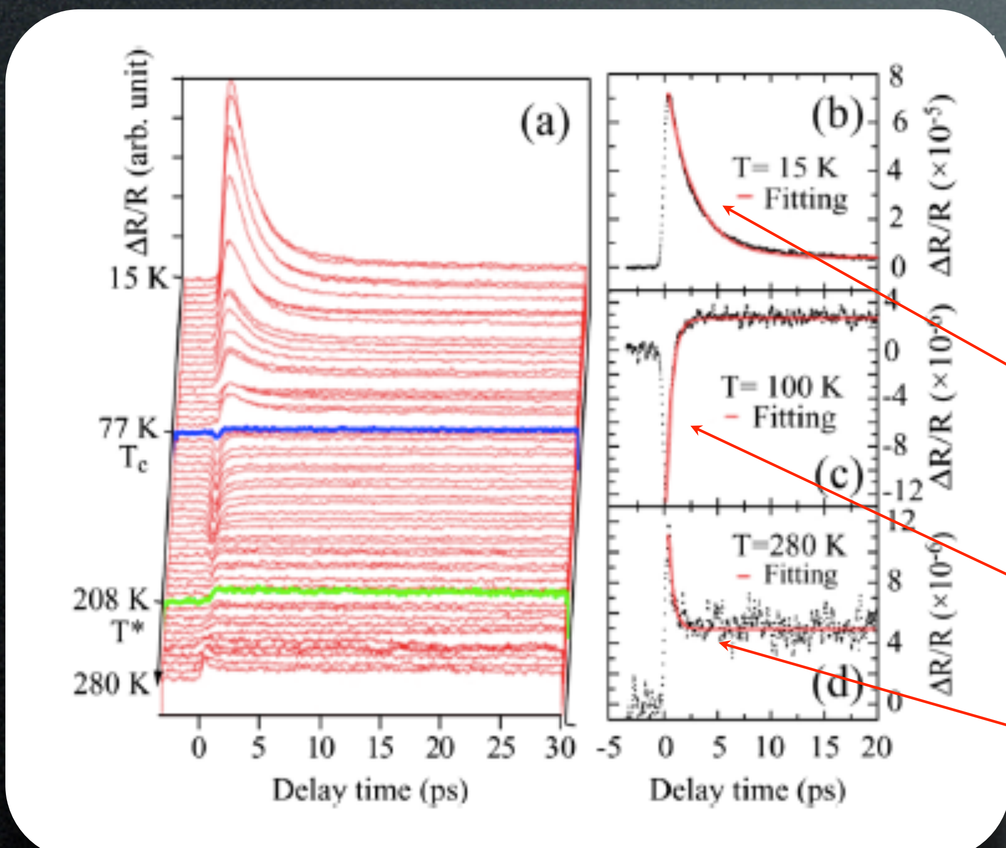
$$\lambda\langle\omega^2\rangle = \frac{2\pi}{3}\frac{k_B T_l}{\hbar\tau_{e-ph}}$$

V.V. Kabanov and A.S. Alexandrov, *Phys. Rev. B* **78**, 174514 (2008)
C. Gadermaier et al. *Phys. Rev. Lett.* **105**, 257001 (2010)

Quasi-particle dynamics in HTSC (Bi2212)

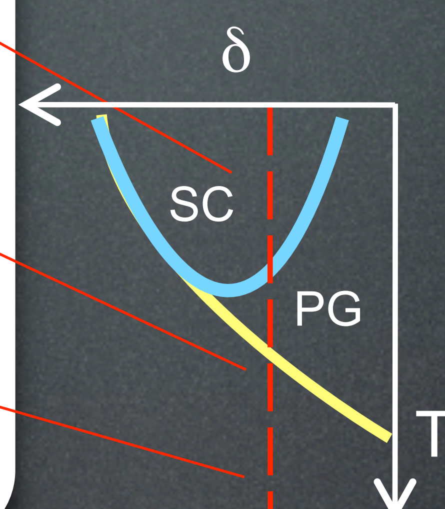
single-color experiments on superconducting cuprates at low temperature

a lot of works from the Ljubljana group...

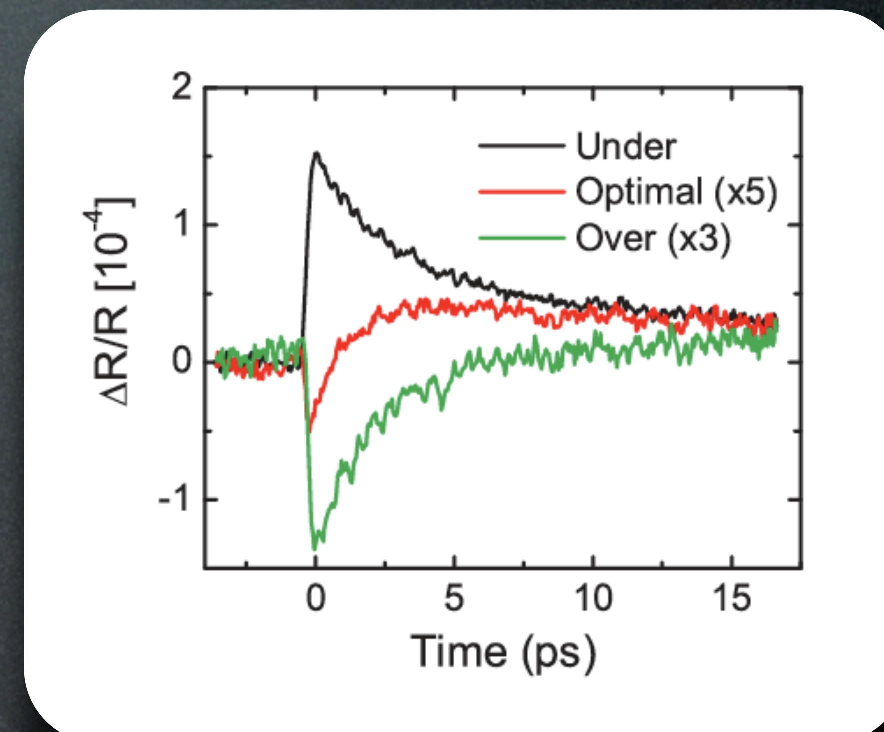


Y.H. Liu et al., *Phys. Rev. Lett.* **101**, 137003 (2008)

HTSC phase diagram



N. Gedik et al., *Phys. Rev. Lett.* **95**, 117005 (2005)

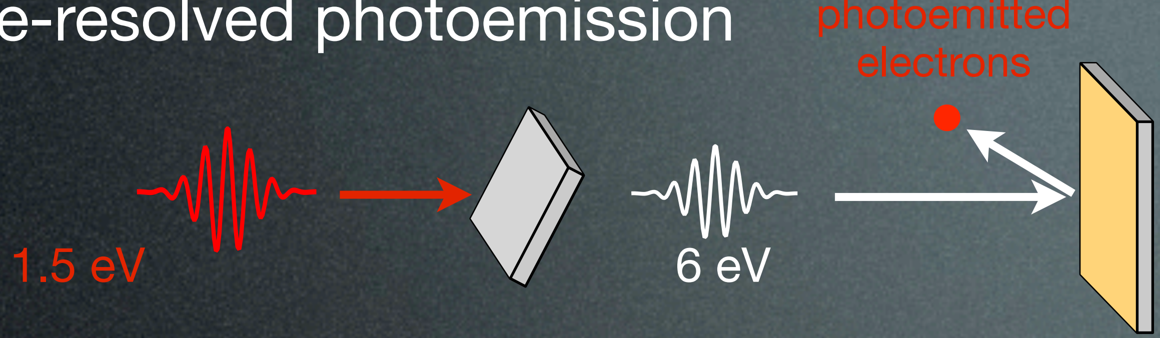


for $T<T_c$ slow dynamics described by Rothwarf-Taylor equations

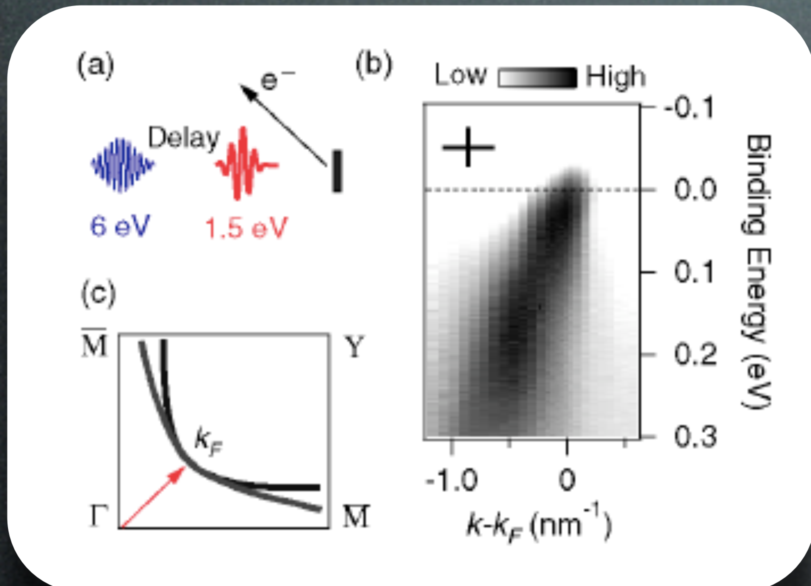
Which is the origin of the reflectivity variations at 1.55 eV?

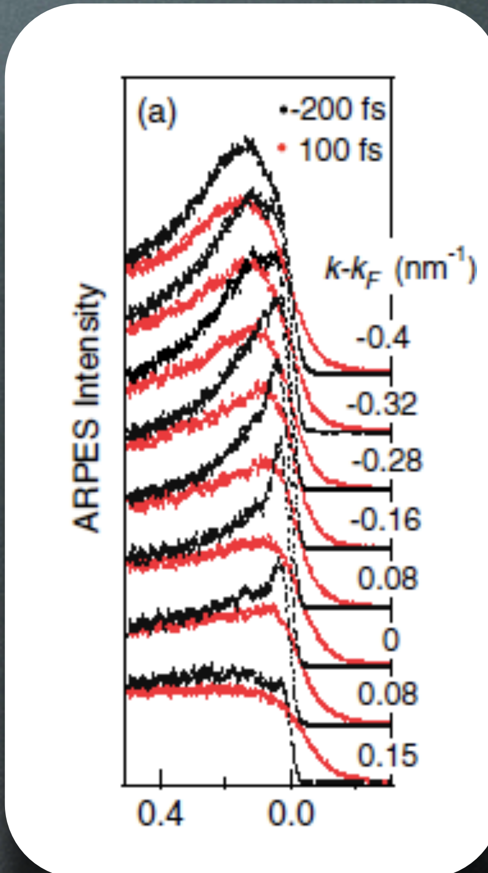
Other time-resolved techniques (Bi2212)

Time-resolved photoemission



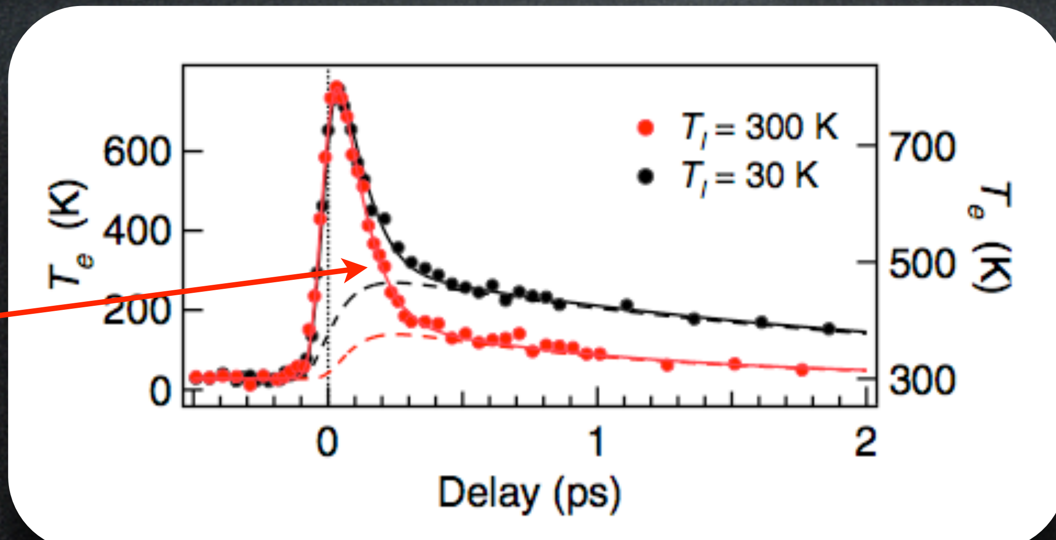
L. Perfetti et al.,
Phys. Rev. Lett. **99**,
197001 (2007)





- direct probe of the electron distribution
- probe limited to the gap-node region, due to the small photon energy

2 dynamics

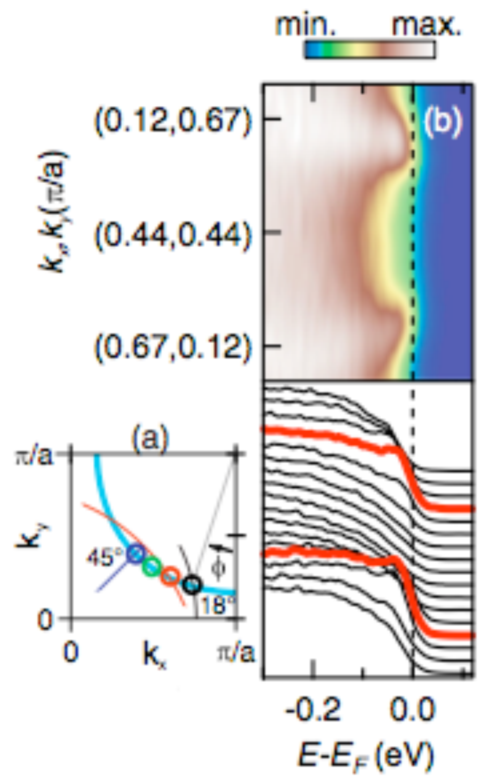


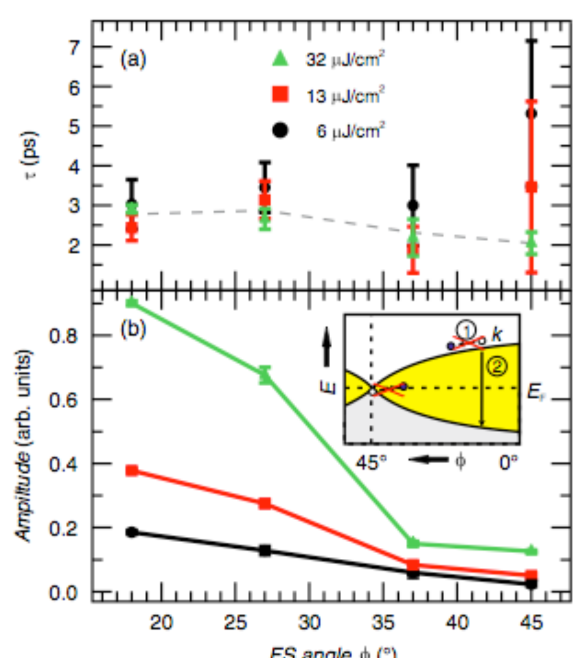
- beyond the 2-temp. model: strong coupling with a subset of phonons

Other time-resolved techniques (Bi2212)

Exploring the entire Brillouin zone

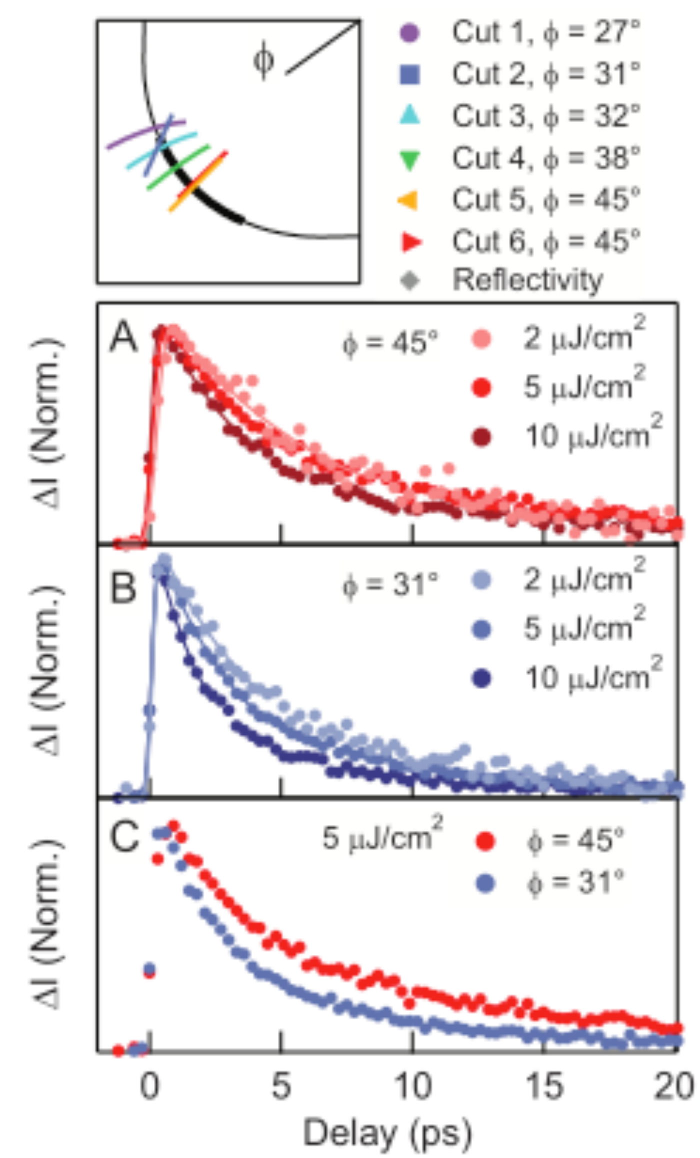
R. Cortés et al. *Phys. Rev. Lett.* **107**, 097002 (2011)





J. Graf et al. *Nature Physics* **7**, 805 (2011)

C.L. Smallwood et al. *Science* **336**, 1137 (2012)

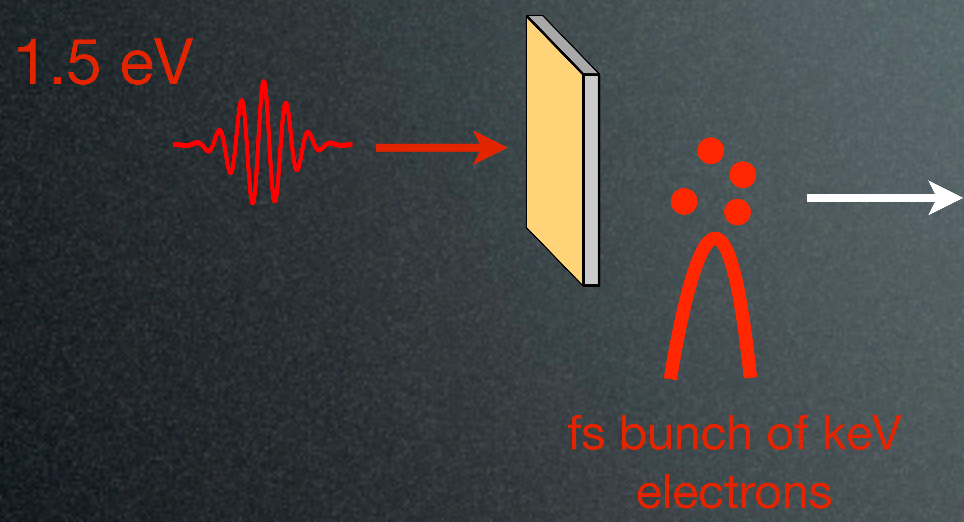


- relaxation INDEPENDENT of the k-space position
- non-thermal electron distribution

- relaxation DEPENDENT on the k-space position

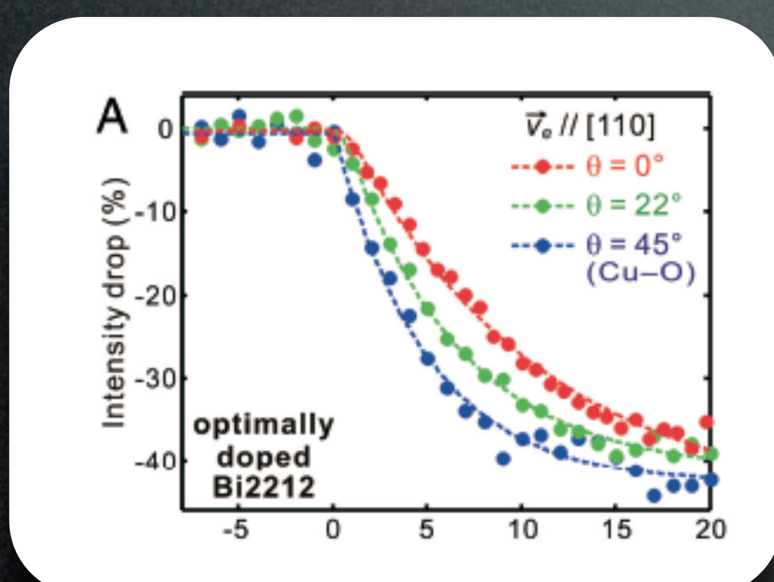
Other time-resolved techniques (Bi2212)

Time-resolved electron diffraction



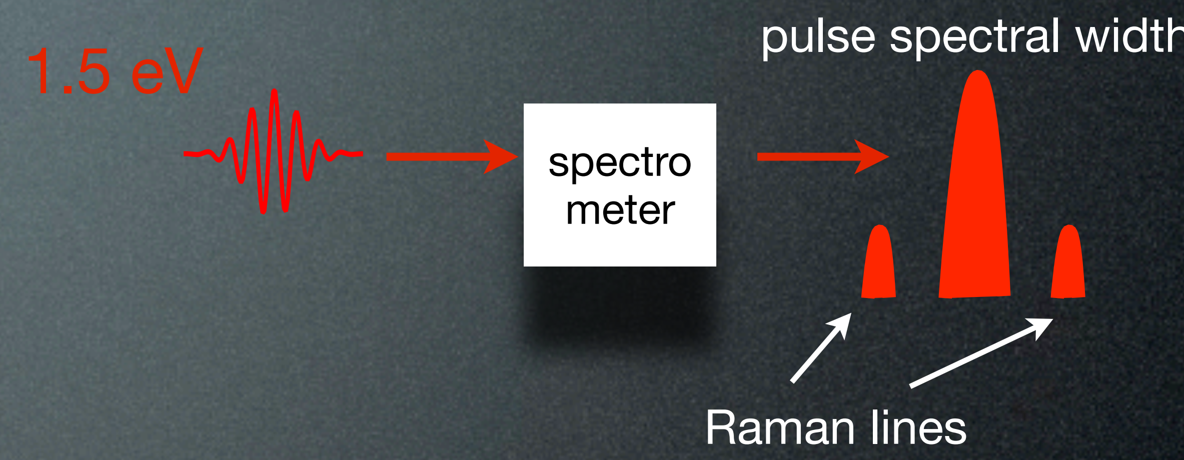
Anisotropic electron-phonon coupling

- $\lambda_{e\text{-}ph}$=0.08-0.55
- fluence > 1 mJ/cm^2

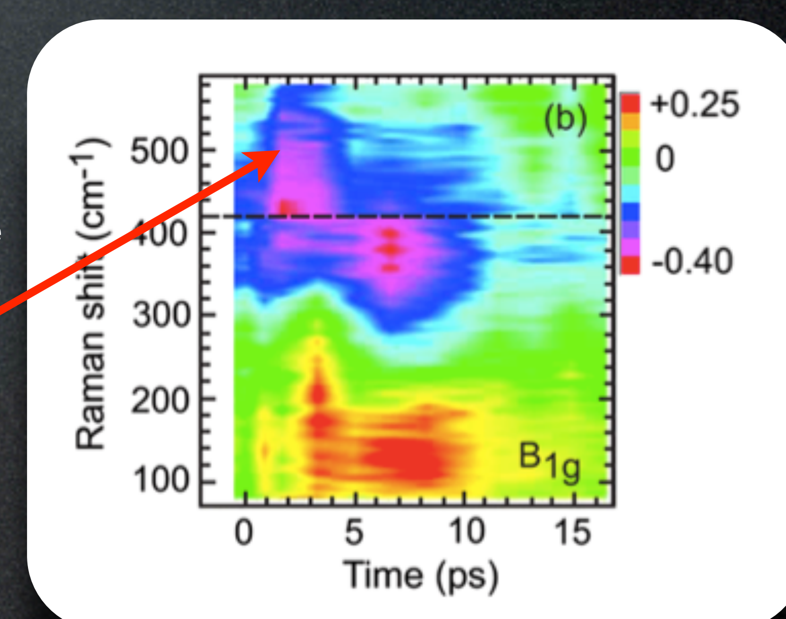


F. Carbone et al., *P.N.A.S.* **105**, 20161 (2008)

Time-resolved Raman scattering



emission of in-plane oxygen breathing modes on the ps timescale



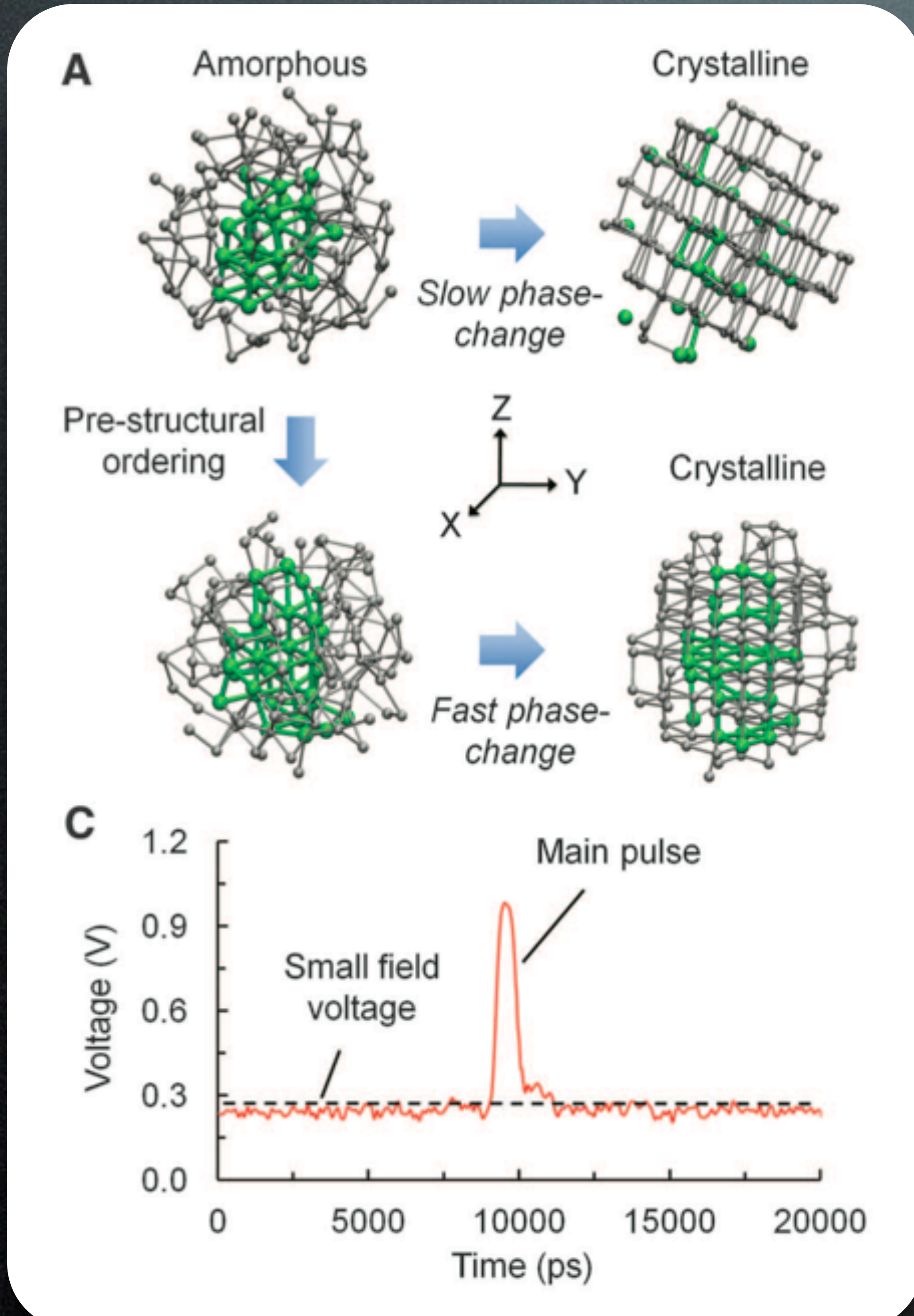
R.P. Saichu et al., *Phys. Rev. Lett.* **102**, 177004 (2009)

Outline

- Time-resolved spectroscopies to disentangle the intertwined degrees of freedom (low-intensity regime)
- optical control of the electronic properties of correlated materials (high-intensity regime)
- broadband ultrafast optical spectroscopy on cuprates

Breaking the Speed Limits of Phase-Change Memory

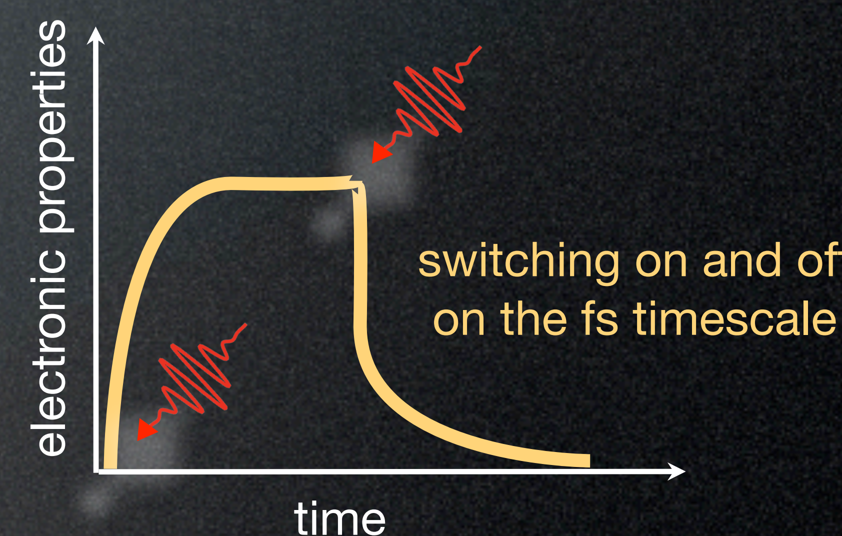
$Ge_2Sb_2Te_5$



D. Loke et al. *Science* **336,** 1566 (2012)

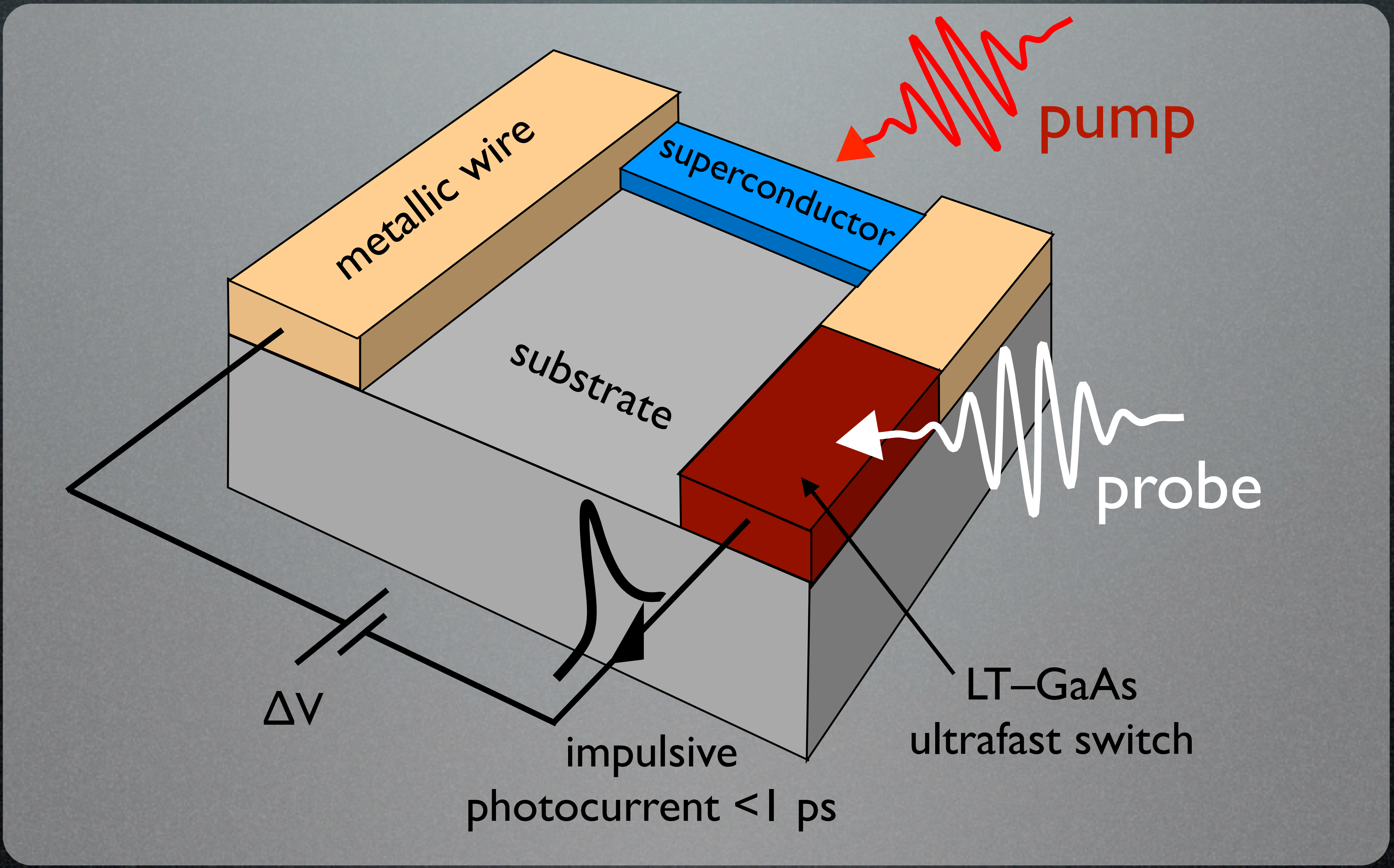
bottleneck for structural rearrangement in PCRAM:

500 ps



Breaking the Speed Limits of Phase-Change Memory

using optical pulses to control superconductivity in a realistic device



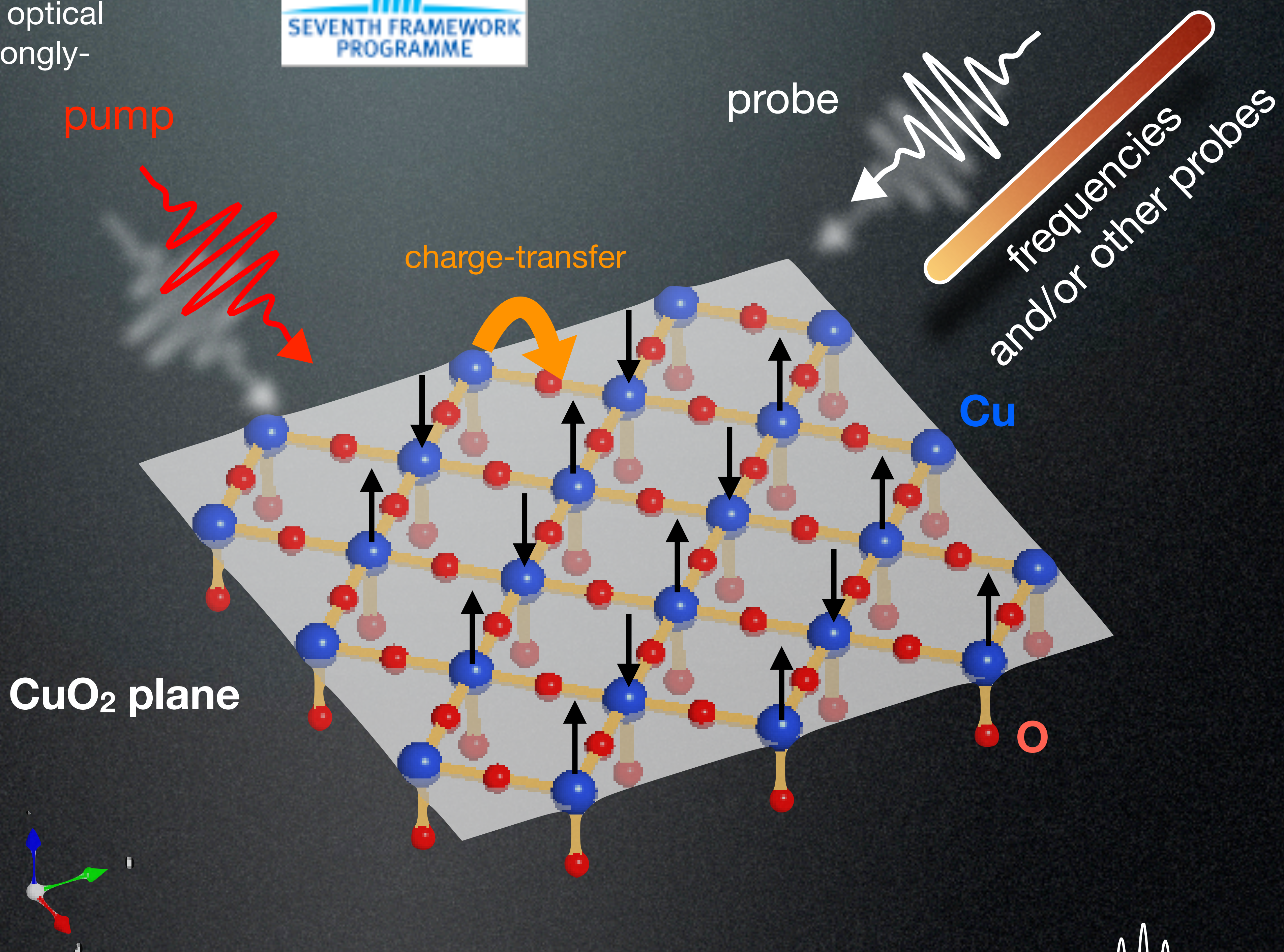
Governing ultrafast the conductivity of correlated materials

GO FAST

GOAL: Development of theoretical and experimental tools to achieve the optical control of electronic phases in strongly-correlated materials

- Time-dependent DMFT (SISSA)
- Time-resolved broadband spectroscopies (THz-visible) (Brescia, Trieste, Nijmegen)
- Time-resolved photoemission (Duisburg, Orsay)
- Time-resolved X-ray diffraction, electron diffraction (Duisburg)

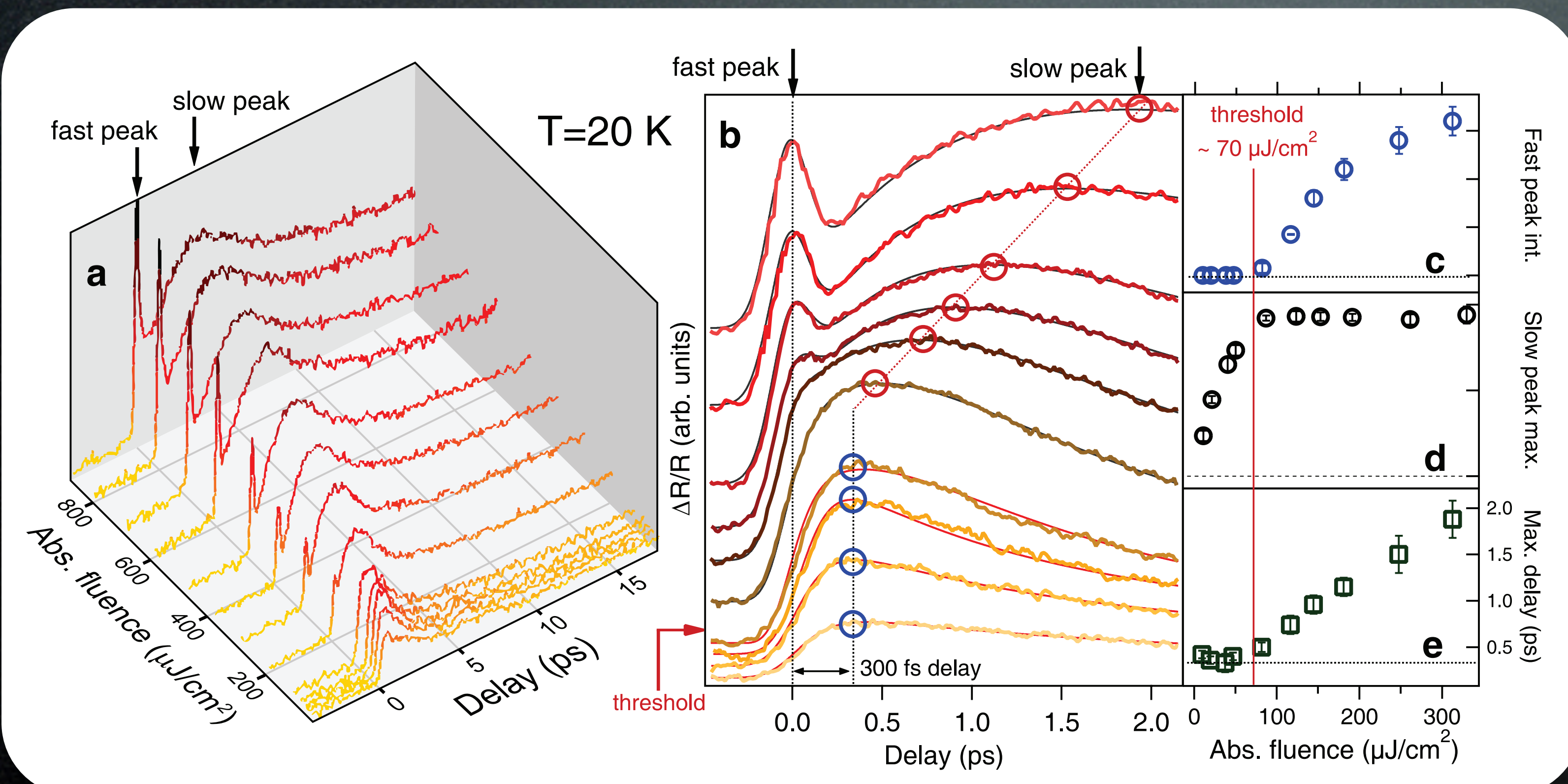
+
Micron Technology, Inc.
MenloSystems GmbH

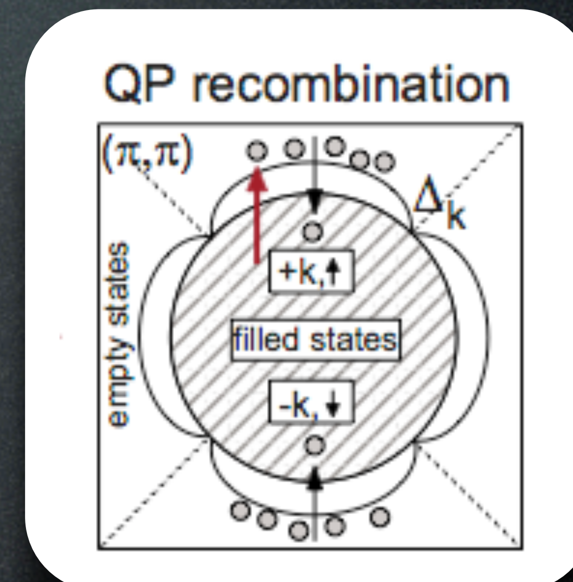


Non-thermal quenching of superconductivity

Non-thermal photo-induced phase transition
(Bi2212)

- fluence constraint for experiments < 70 μJ/cm^2 (underdoped, T=20K)





first or second order?

in non-equilibrium conditions

$F_{SC}(P,T,n) = F_N(P,T,n)$

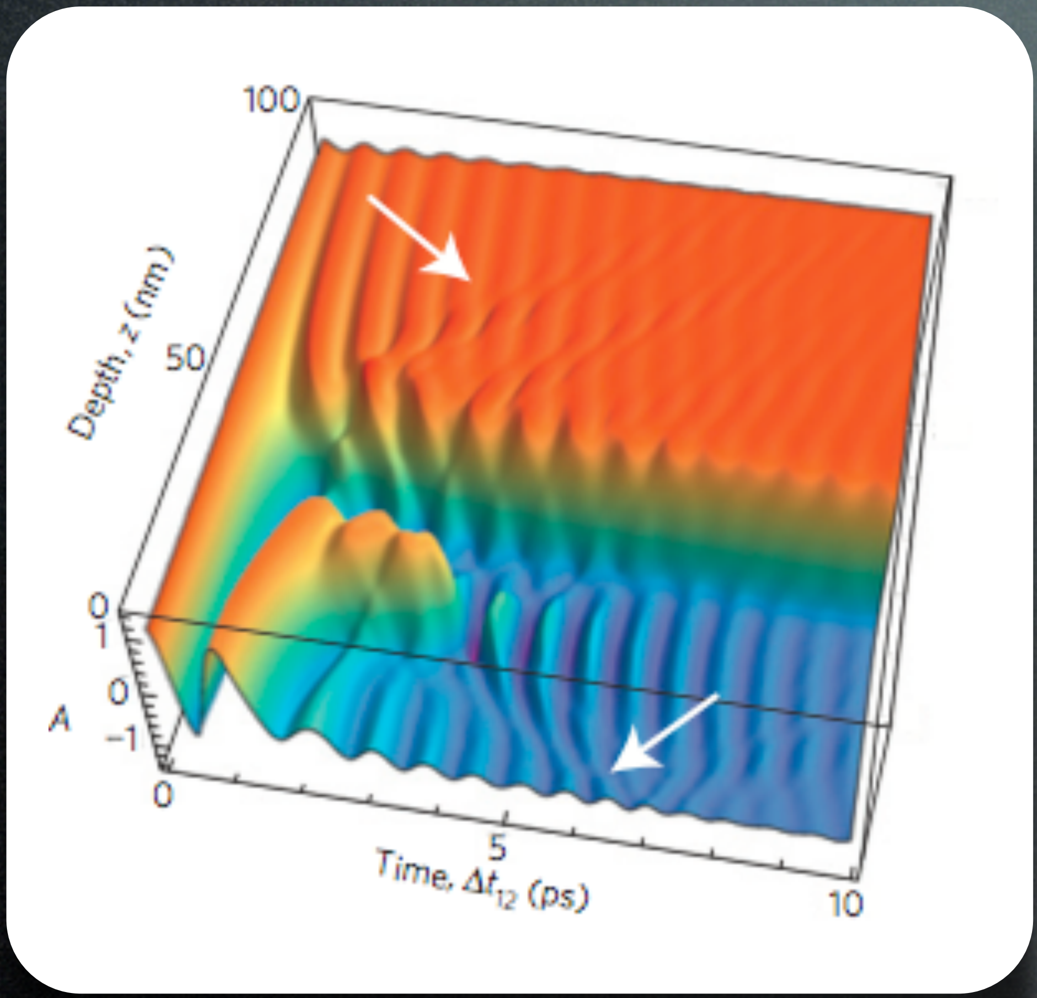
before complete closing of $\Delta_{SC}(T)$

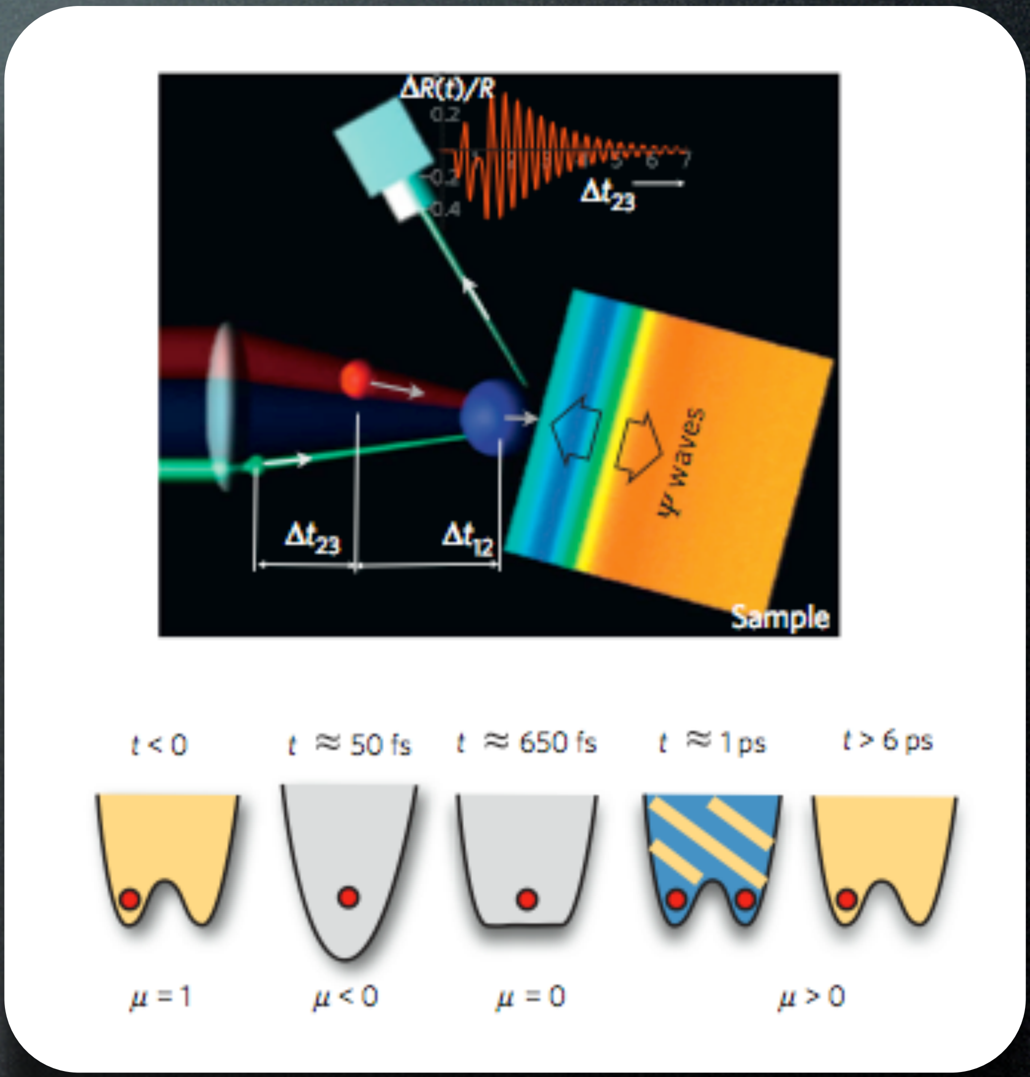
E.J Nicol and J.P. Carbotte
Phys. Rev. B **67**, 214506 (2003)

R.A. Kaindl et al. *Phys. Rev. B* **72,** 060510R (2005)
P. Kusar et al. *Phys. Rev. Lett.* **101**, 227001 (2008)
C. Giannetti et al., *Phys. Rev. B* **79**, 224502 (2009)
G. Coslovich et al., *Phys. Rev. B* **83**, 064519 (2011)
L. Stojchevska et al. *Phys. Rev. B* **84**, 180507 (2011)

Role of the inhomogeneities in the excitation process

Time-evolution of the order parameter within Ginzburg-Landau model in CDW materials





$$U = \int dz \left(-\frac{1}{2}(1-\eta)\frac{\Delta(t,z)^2}{\Delta_0^2} + \frac{1}{4}\frac{\Delta(t,z)^4}{\Delta_0^4} + \frac{1}{2}\frac{\xi^2}{\Delta_0^2}\left(\frac{\partial \Delta(t,z)}{\partial z}\right)^2 \right)$$

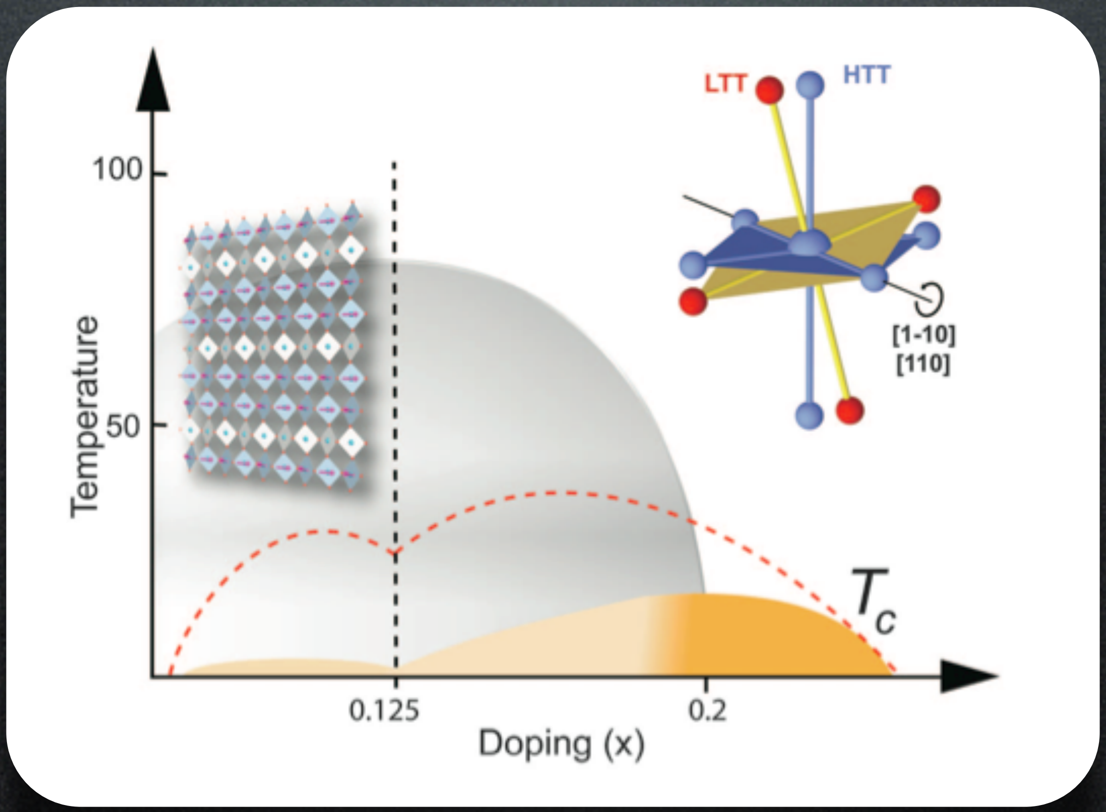
R. Yusupov et al., *Nature Physics* **6,** 681 (2010)

Photoinducing transient superconductivity

possible routes to control superconductivity

- Optically removing competing orders
- Effective cooling of low-energy excitations through THz pumping (Tinkham)
- Photoinducing changes in the electronic structure of correlated materials

THz PUMP



D. Fausti et al., *Science* **331**, 189 (2011)

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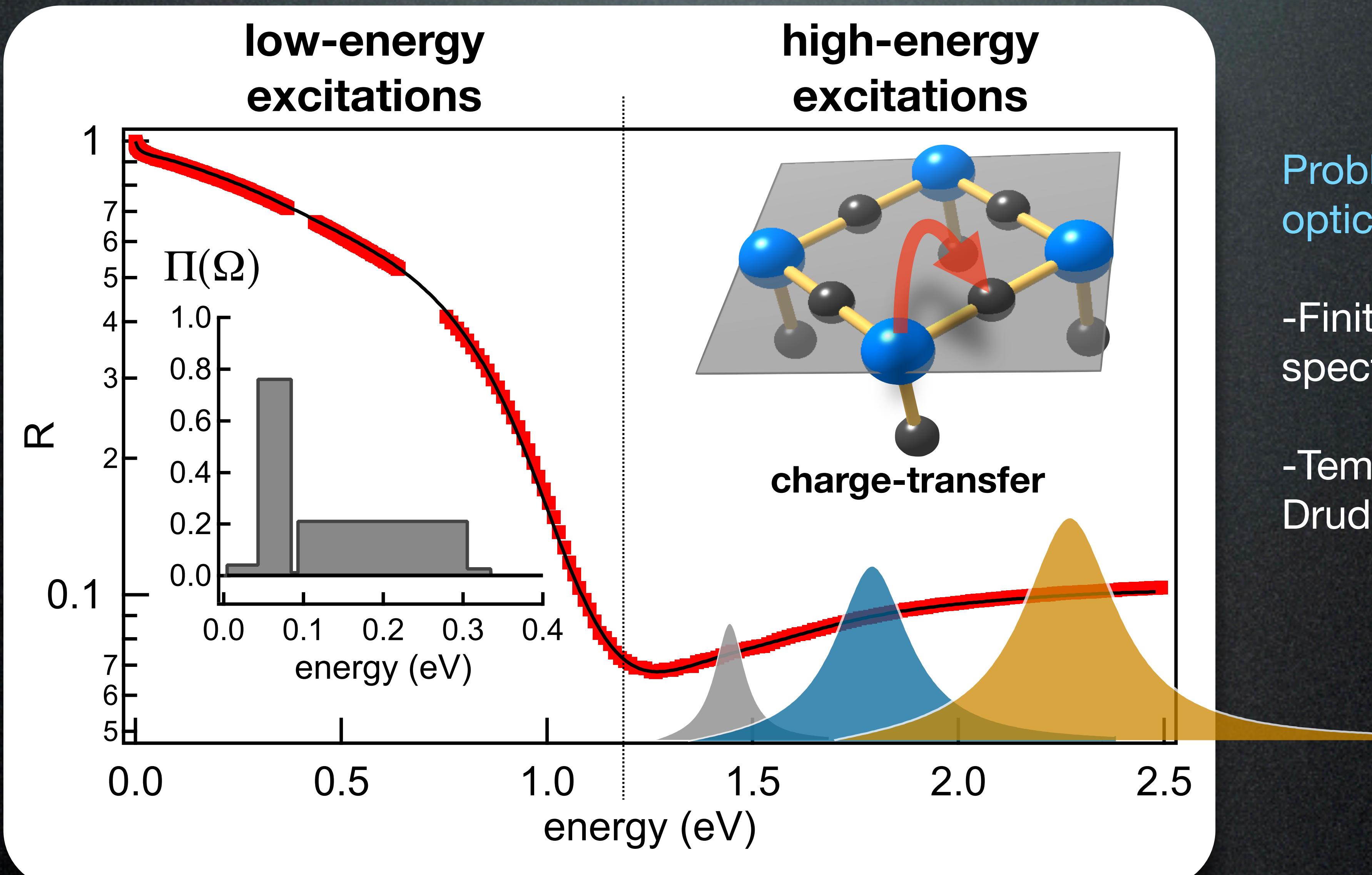
Optical properties of a cuprate superconductor

extended Drude

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

Lorentz oscillators



Problems of equilibrium optical spectroscopy:

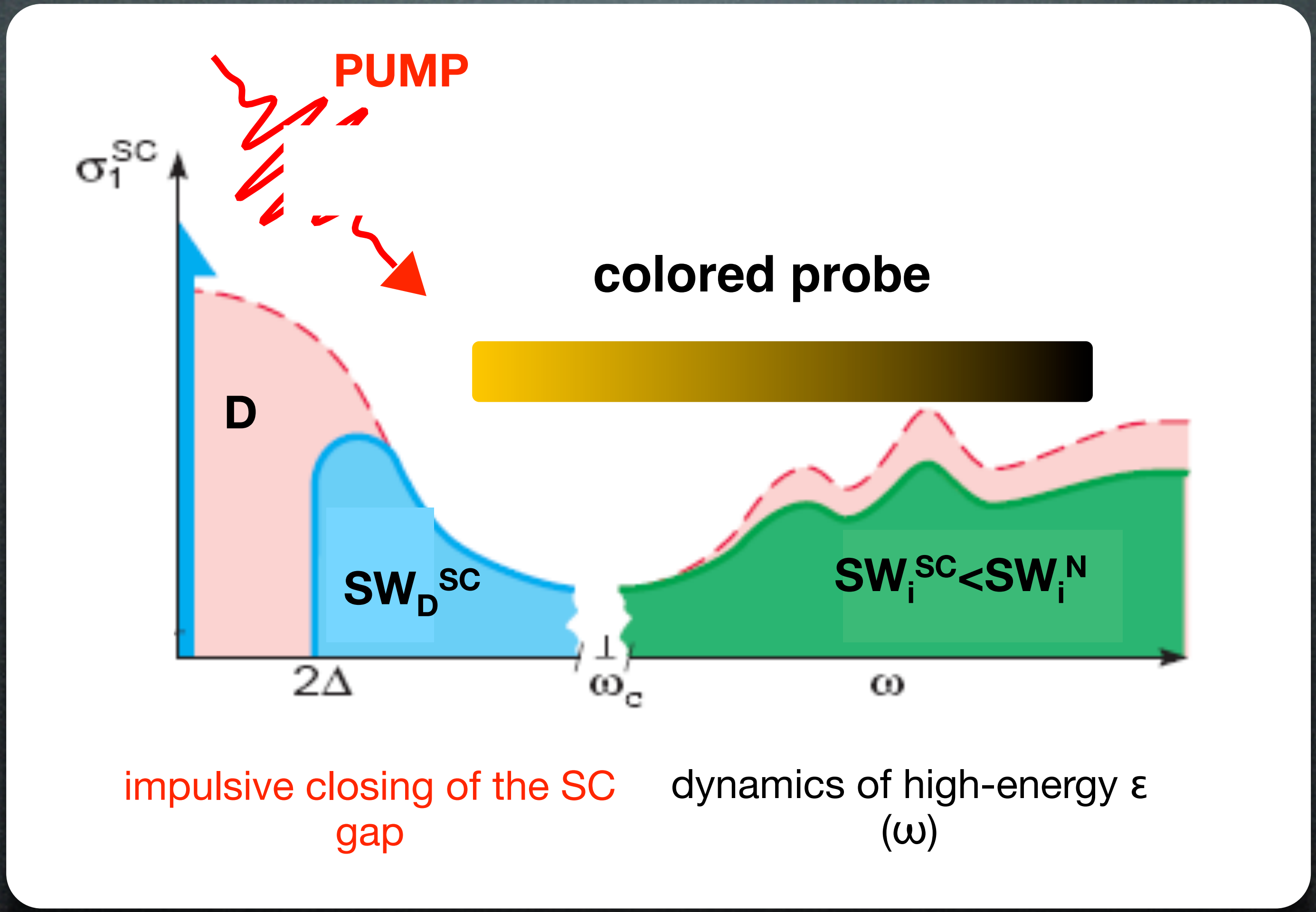
-Finite cut-off for calculating spectral weight shifts

-Temperature dependent Drude broadening

optimally-doped Bi2212. Data from van der Marel's group

time-resolved broadband spectroscopy

time+spectral resolution



differential model

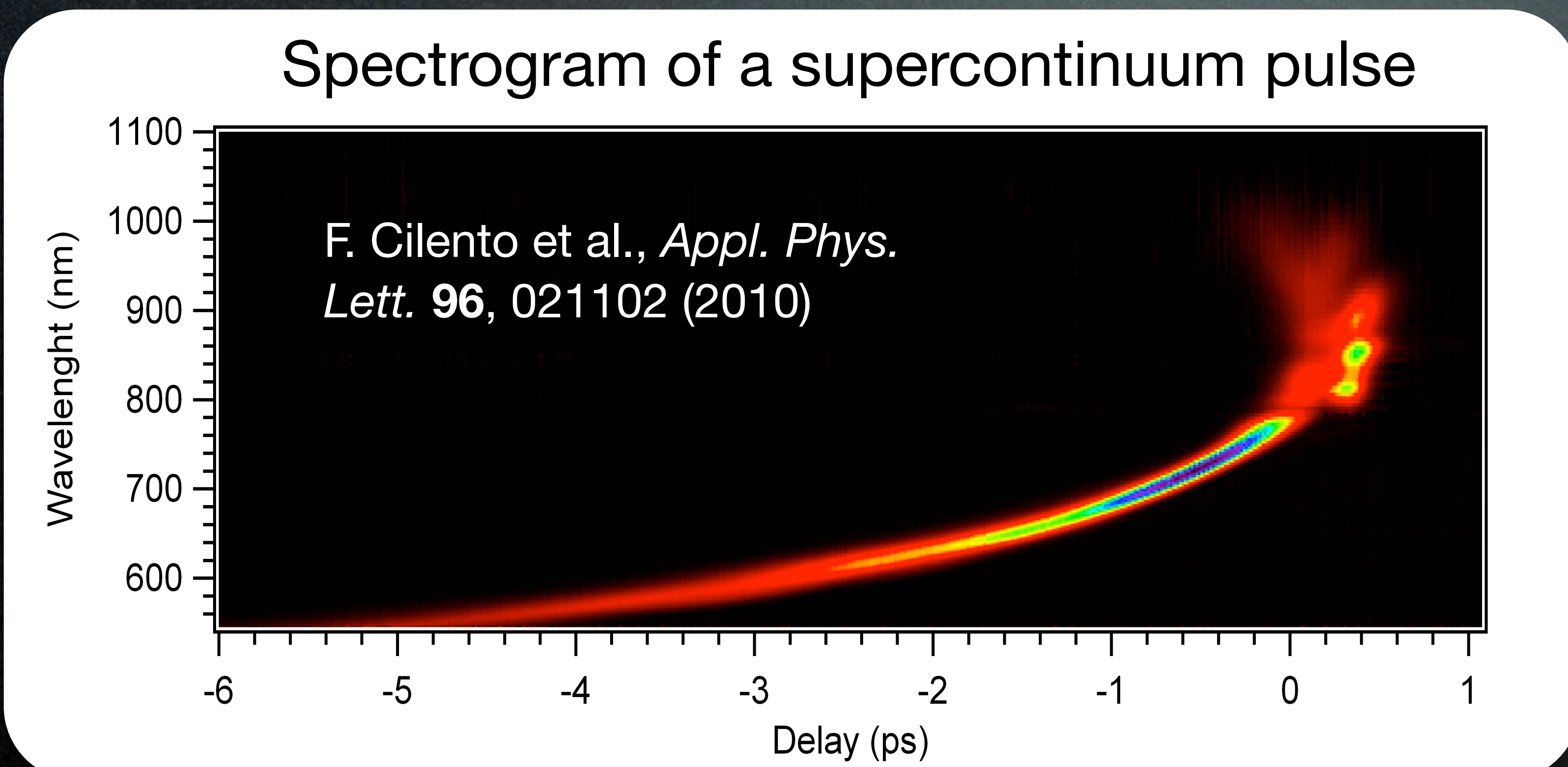
Fit function: $\delta\epsilon = \epsilon_{exc} - \epsilon_{eq}$ ➡ $$\frac{\delta R}{R}(\omega,t) = \frac{R_{exc}(\omega,t) - R_{eq}(\omega)}{R_{eq}(\omega)}$$

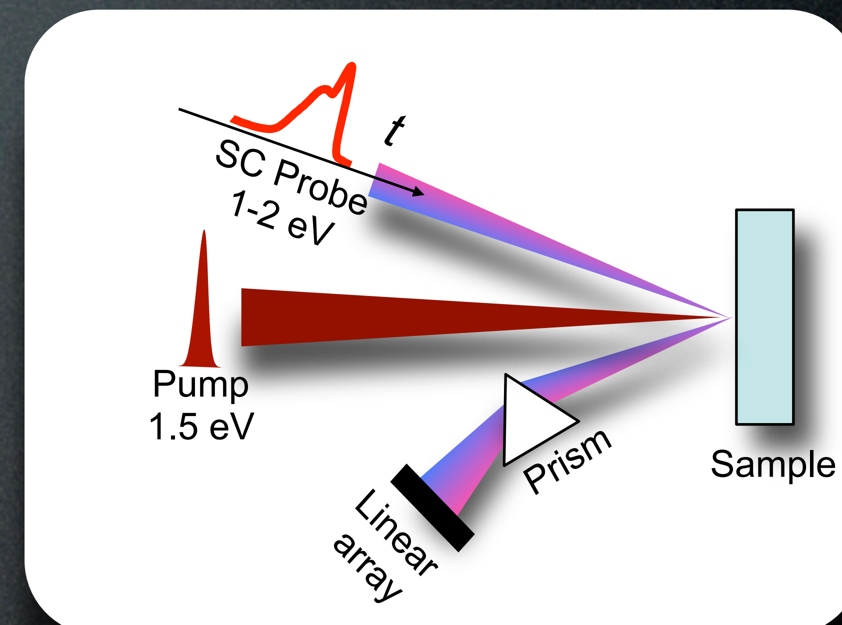
Time-resolved optical spectroscopy

problem:

avoid non-thermal destruction of the superconducting phase transition

Low-fluence (<20 μJ/cm^2) and high rep.rate ➡ supercontinuum by a photonic fiber





$$\frac{\delta R}{R}(\omega,t)=\frac{R_{exc}(\omega,t)-R_{eq}(\omega)}{R_{eq}(\omega)}$$

R.A. Kaindl et al. *Phys. Rev. B* **72,** 060510R (2005)
P. Kusar et al. *Phys. Rev. Lett.* **101**, 227001 (2008)
C. Giannetti et al., *Phys. Rev. B* **79**, 224502 (2009)
G. Coslovich et al., *Phys. Rev. B* **83**, 064519 (2011)
M. Beyer et al., *Phys. Rev. B* **83**, 214515 (2011)
L. Stojchevska et al. *Phys. Rev. B* **84**, 180507 (2011)

Time-resolved optical spectroscopy on Y-Bi2212

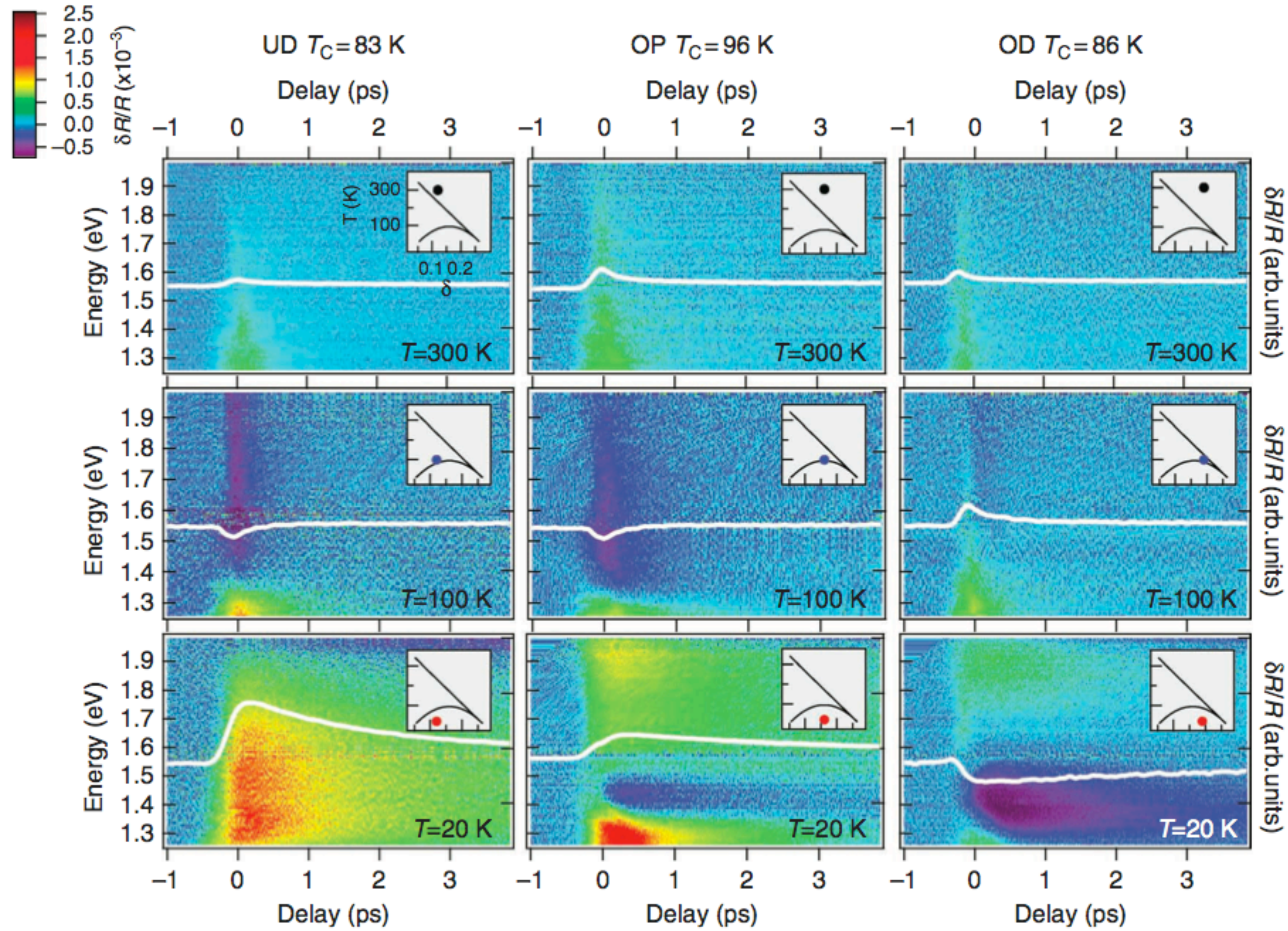
$$\frac{\delta R}{R}(\omega, t)$$

< 10 μJ/cm²

Normal state

Pseudogap state

Superconductive state



$Bi_2Sr_2Ca_{0.92}Y_{0.08}Cu_2O_{8+\delta}$

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

Conclusions

•Broadband optical spectroscopy is a novel tool to investigate the ultrafast dynamics in correlated materials and high-temperature superconductors

•Ultrashort light pulses can be used to optically control the electronic properties of correlated superconductors on the fs timescale