Novel Trends in Photoemission, ALS user meeting, Berkeley, Oct 4, 2011

High-T_c superconductors investigated with time- and angle-resolved photoemission

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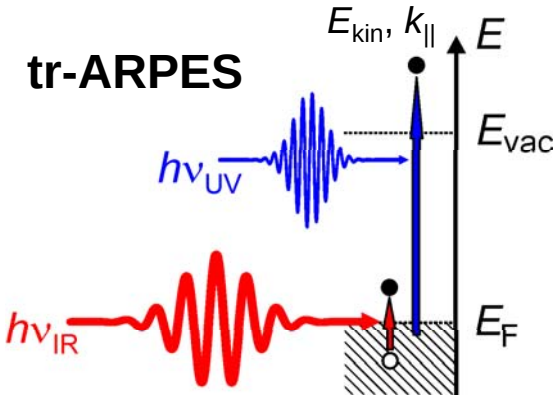
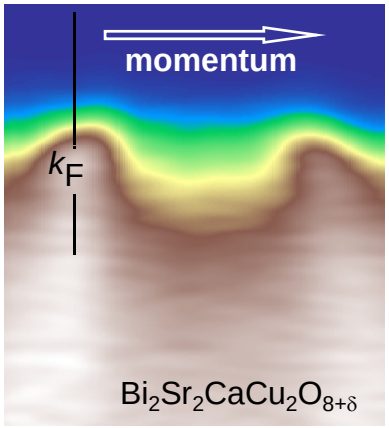
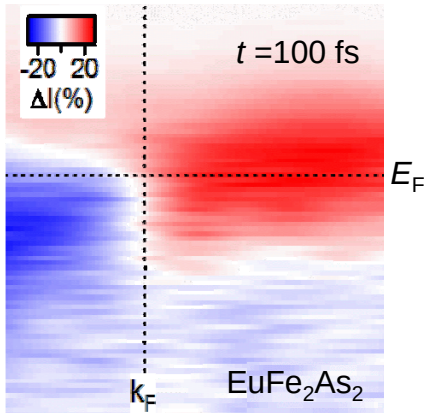
www.uni-due.de/agbovensiepen

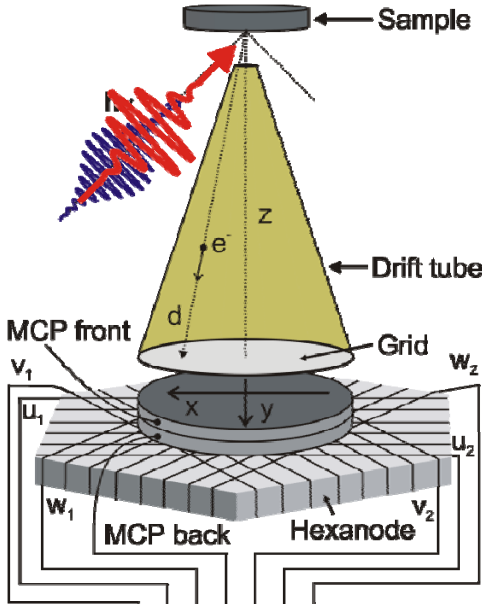
(1) Relaxation of hot quasiparticles through Cooper pair reformation in $Bi_2Sr_2CaCu_2O_{8-\delta}$

(2) Momentum-dependent quasiparticle dynamics in $EuFe_2As_2$



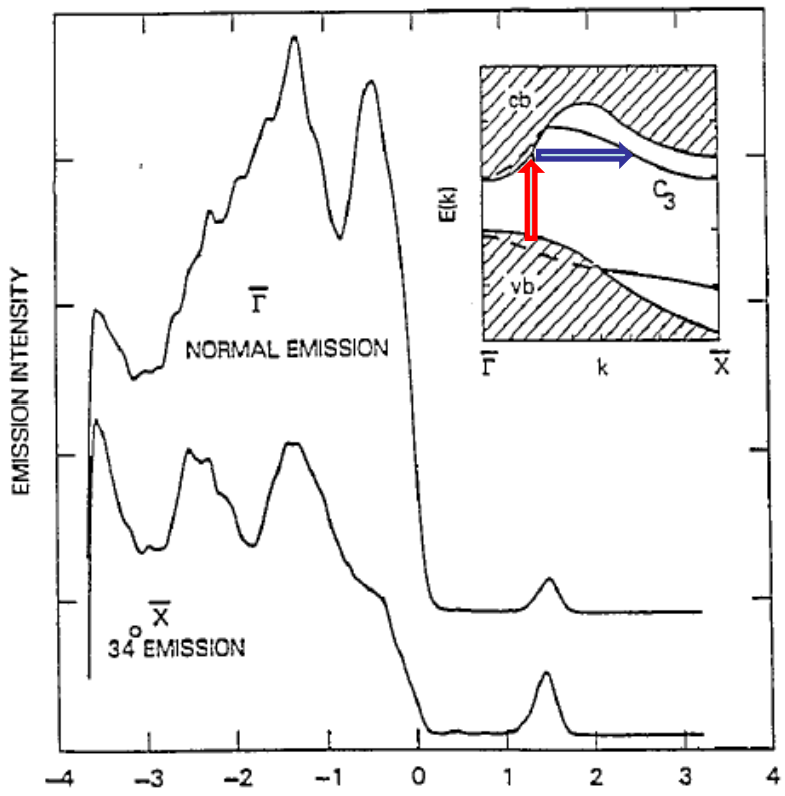




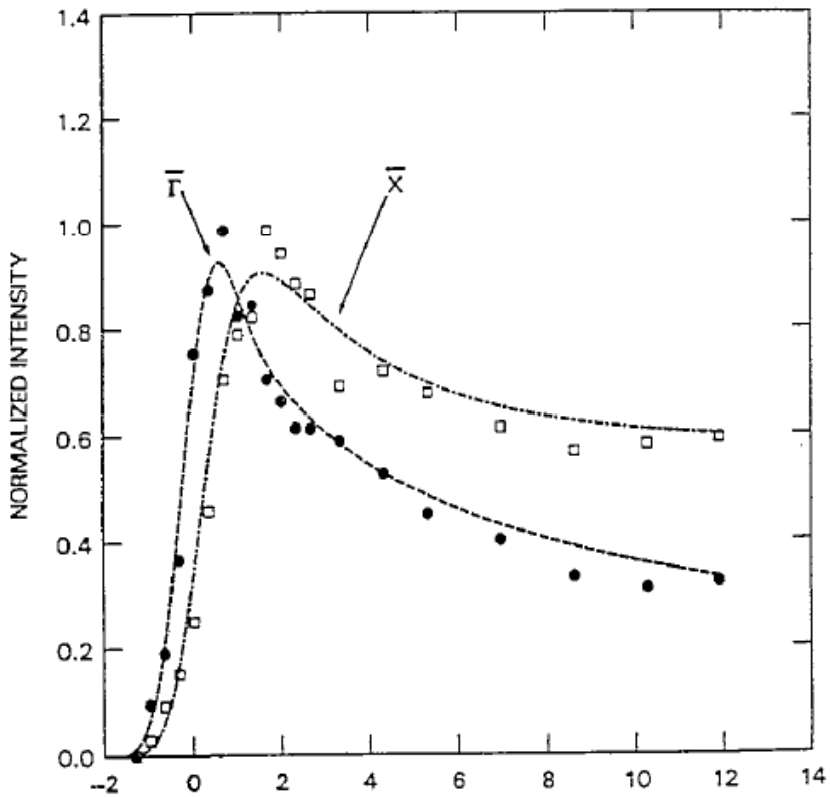


momentum-dependent hot electron relaxation

intervalley scattering at the GaAs(110) surface $h\nu$=10.7 eV, 100 Hz dye laser



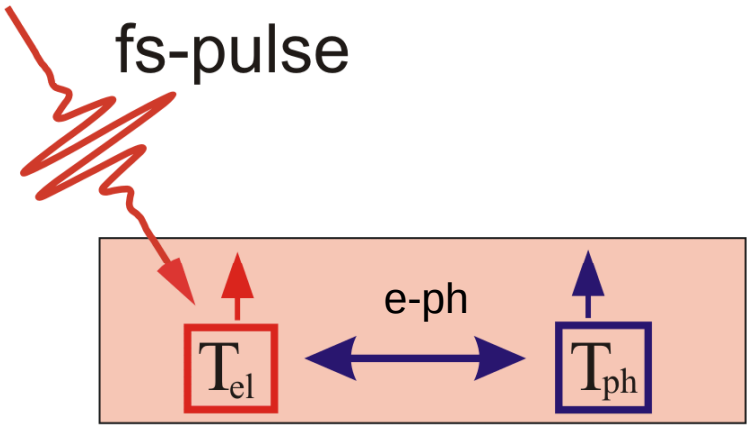
binding energy (eV)

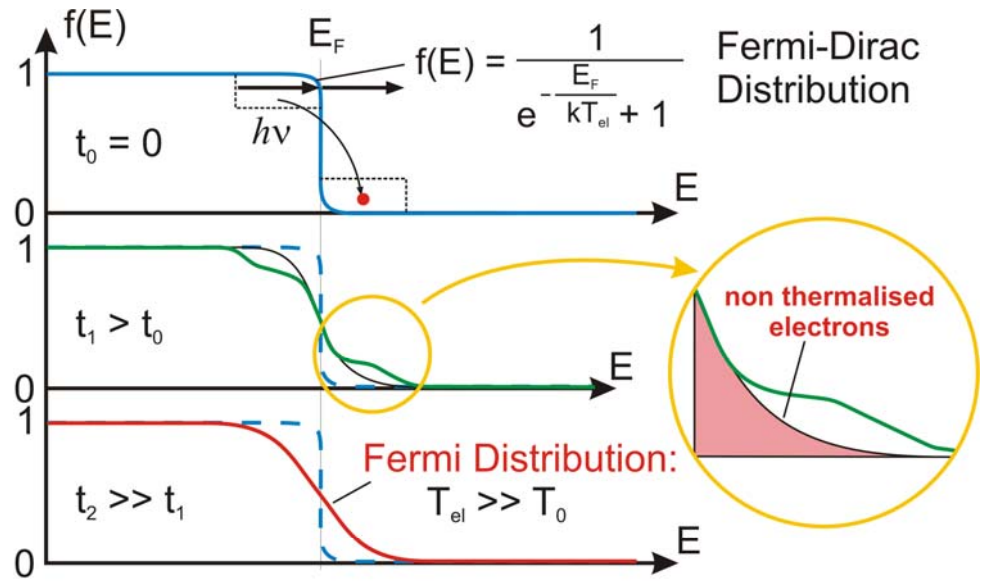


delay (picoseconds)

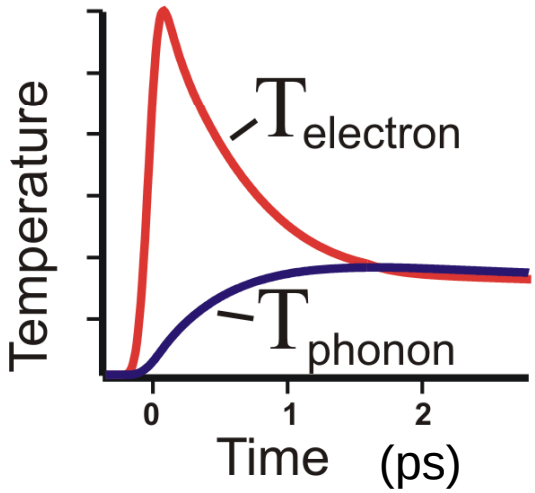
R. Haight, Surf. Sci. Rep. **21**, 275 (1995)

relaxation of hot electron distributions: 2TM





W.S. Fann, R. Storz, H.W. K. Tom, J.Bokor PRB **46** (1992), 13592



two temperature model

transport dissipation opt. exc.

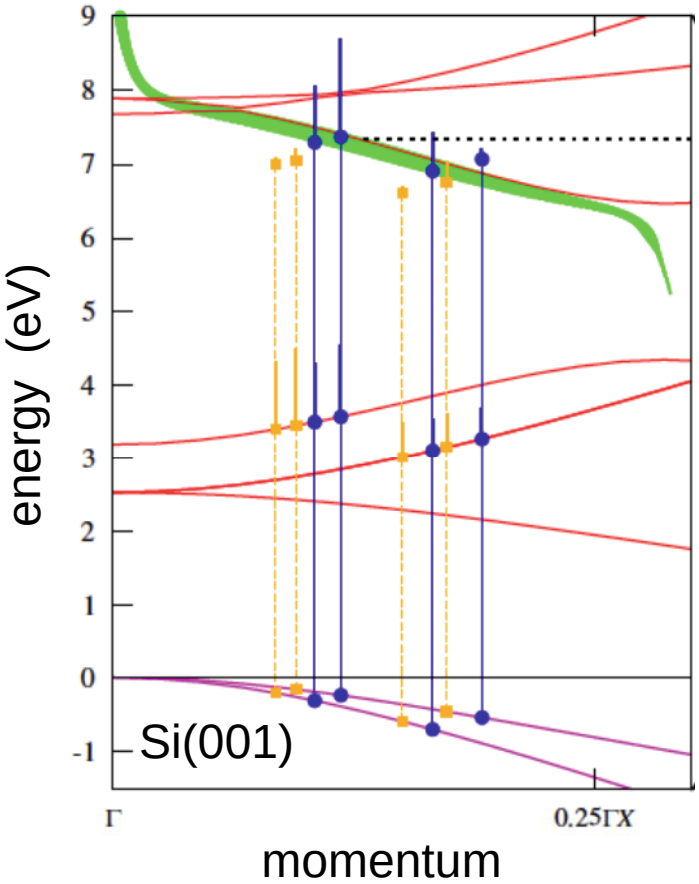
$$C_e(T_e)\frac{\partial T_e}{\partial t} = \nabla(\kappa \nabla T_e) - \boxed{H(T_e, T_l)} + S(z,t)$$

$$C_l(T_l)\frac{\partial T_l}{\partial t} = \boxed{H(T_e, T_l)}$$

Anisimov et al., Sov. Phys. JETP **39**, 375 (1974)

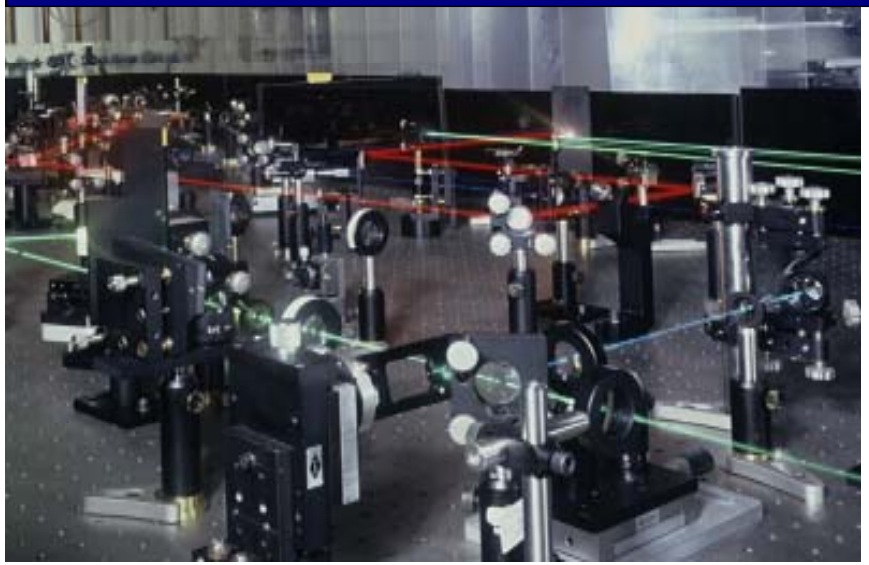
relaxation of hot electron distributions: 2TM

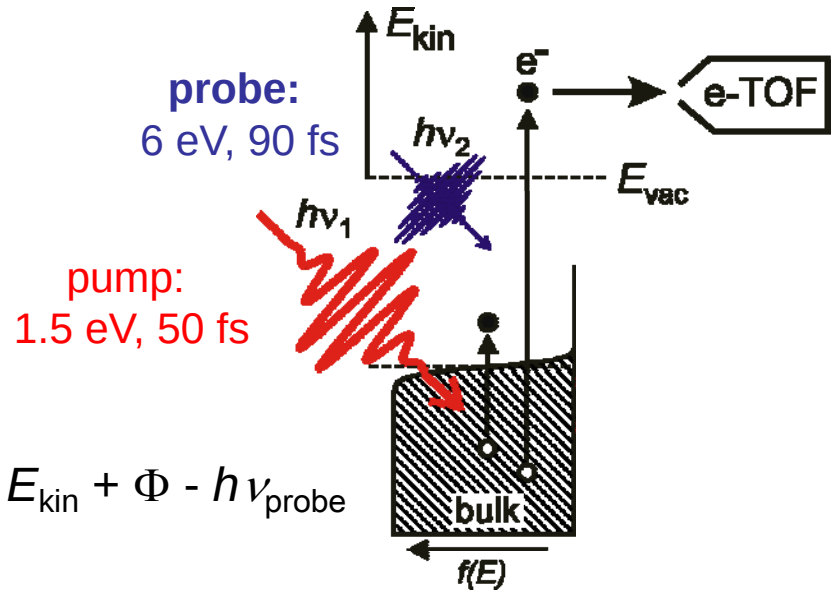
H. Petek et al.



- **resonant contributions**
  (pump and probe)
- **effects of pump fluence**

time-resolved photoelectron spectroscopy

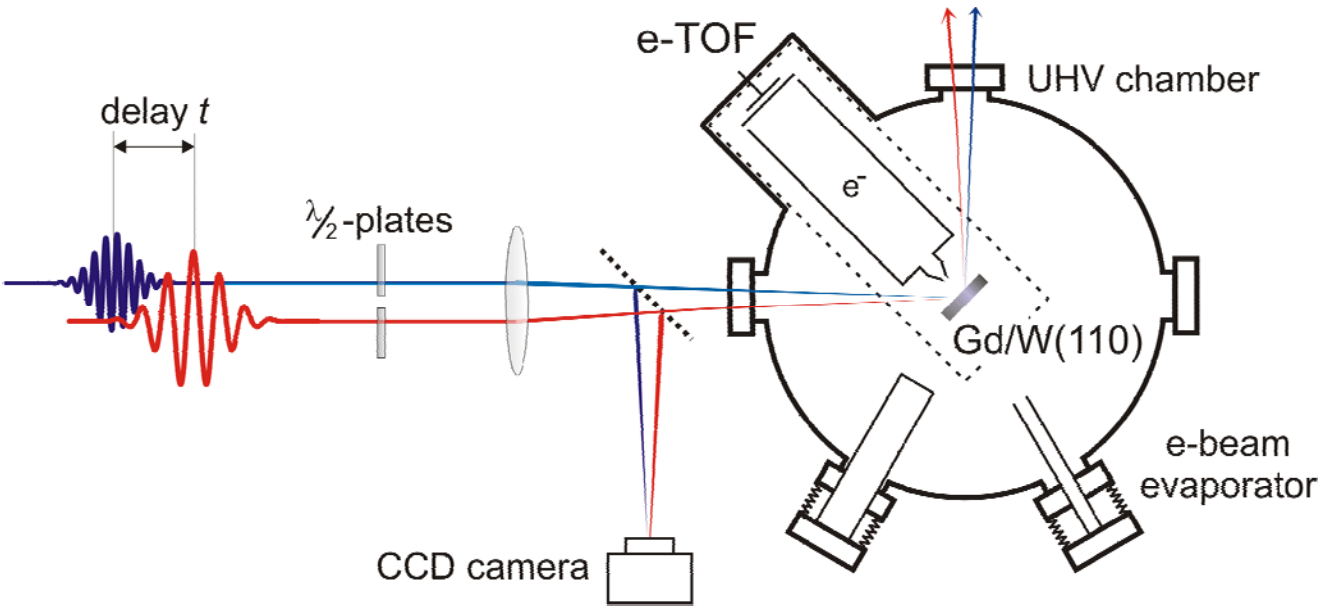




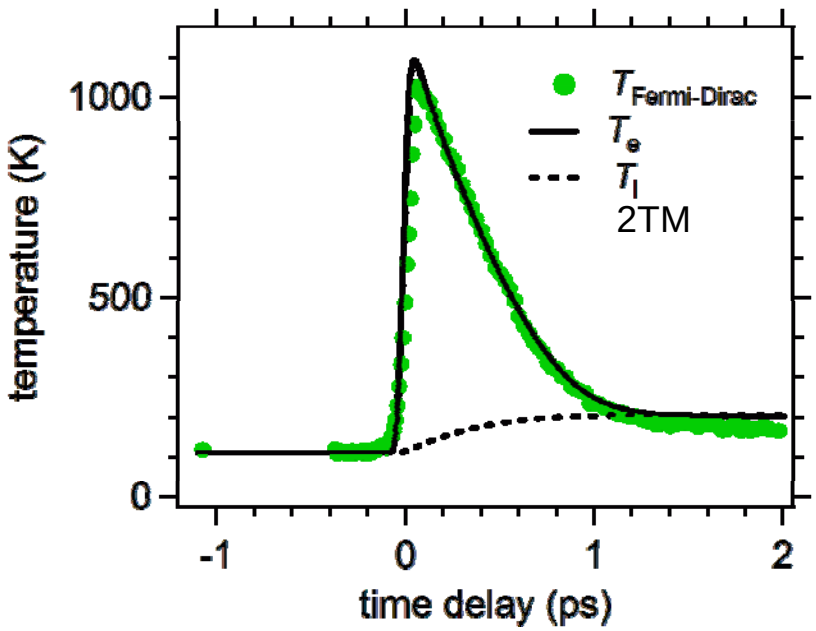
$$E\text{-}E_F = E_{kin} + \Phi - h\nu_{probe}$$

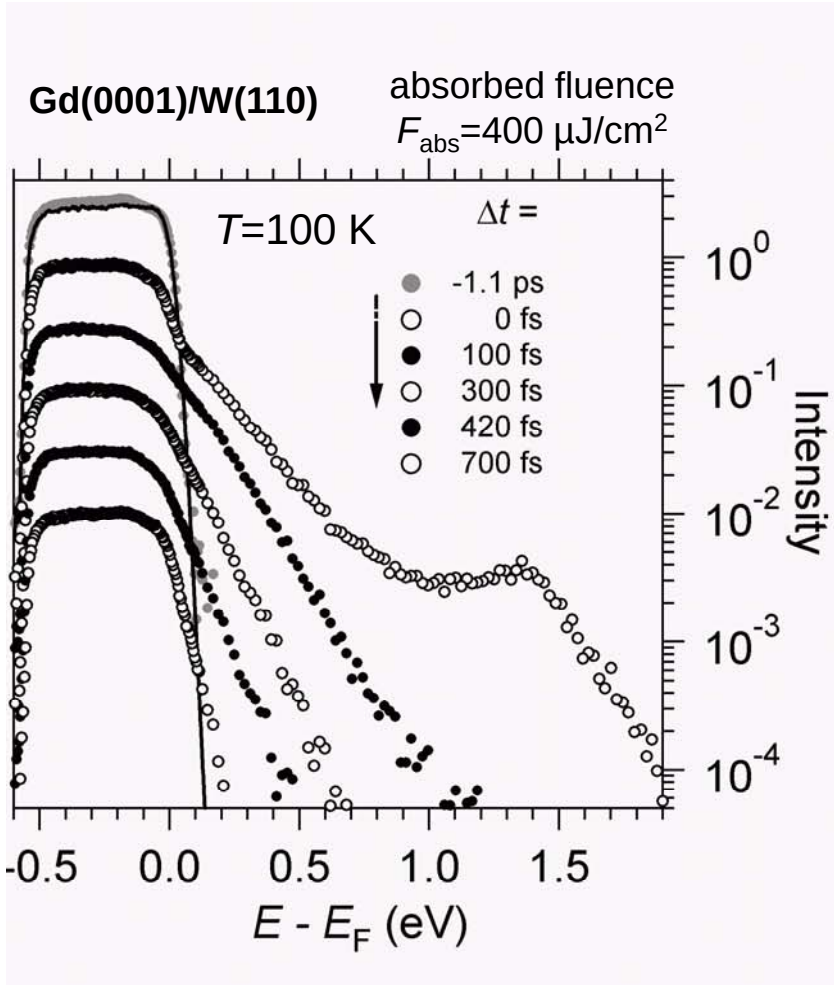
amplified
Ti:Sa laser

800 nm
300 kHz
6 µJ



transient temperature analysis

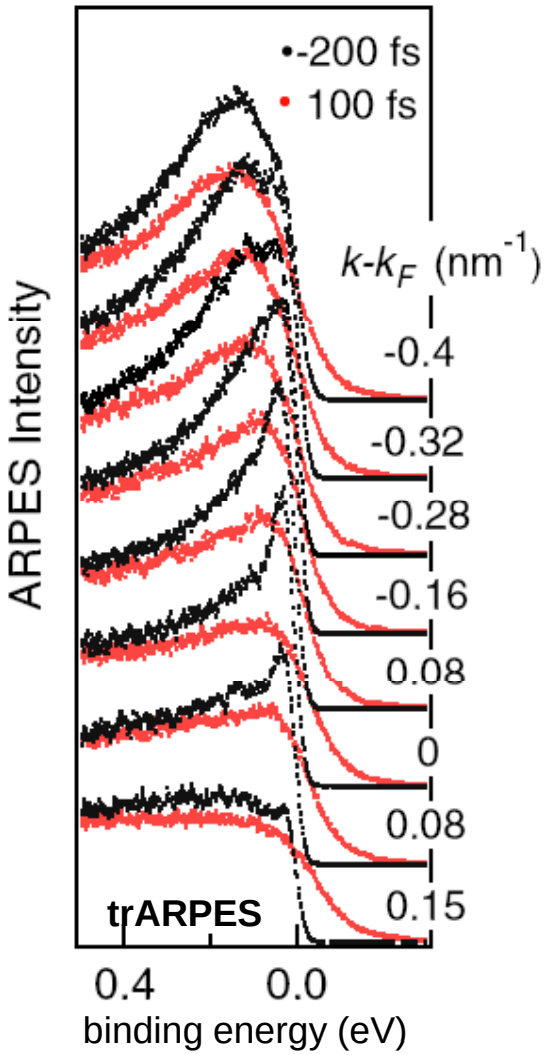


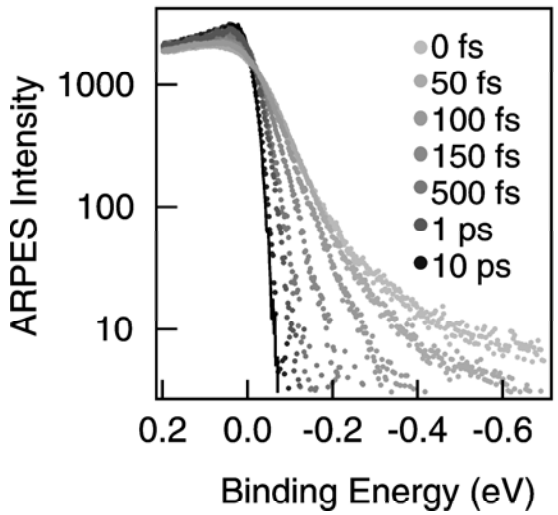


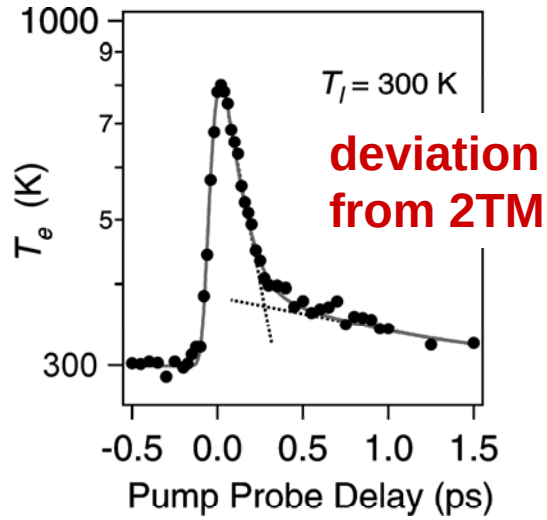
U. Bovensiepen, J. Phys.: Cond. Matter **19**, 083201 (2007)

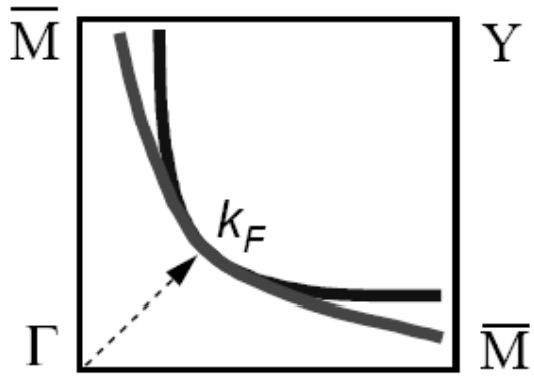
tr-ARPES on BSCCO: analysis of $T_e(t)$

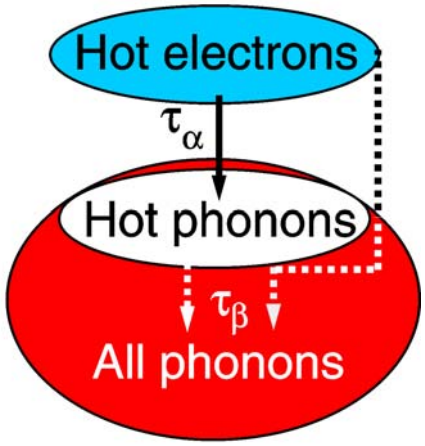
F = 500 μJ/cm^2









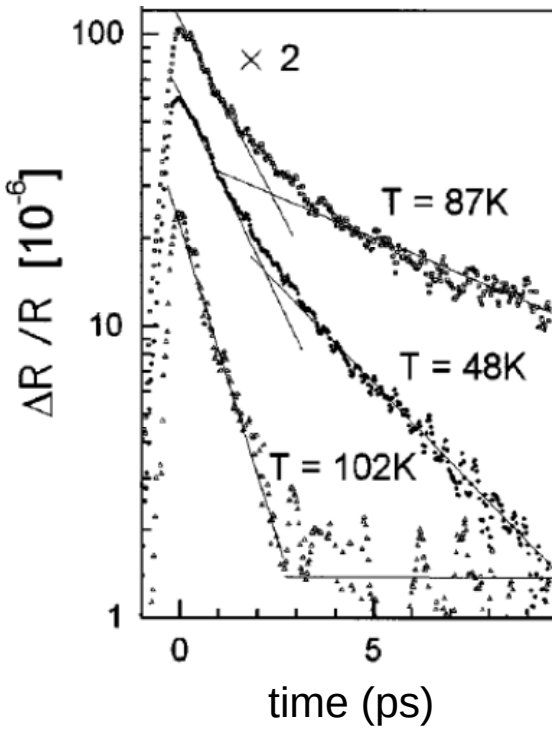


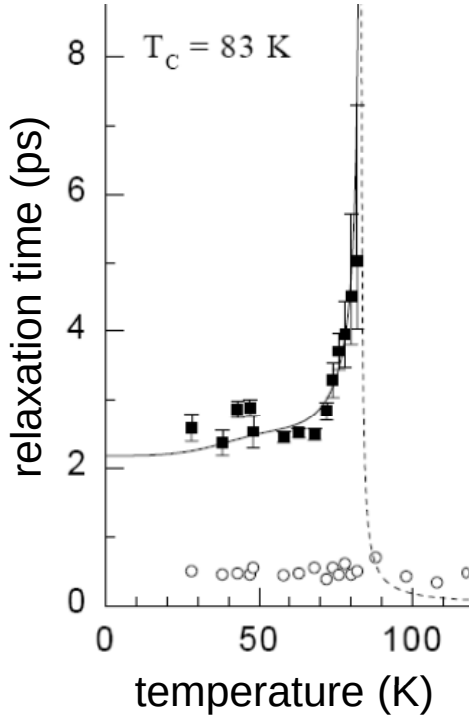
$\lambda\Omega^2$ = 360±30 meV
buckling / stretching CuO planes
Ω = 40 meV $\Rightarrow \lambda < 0.25$

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

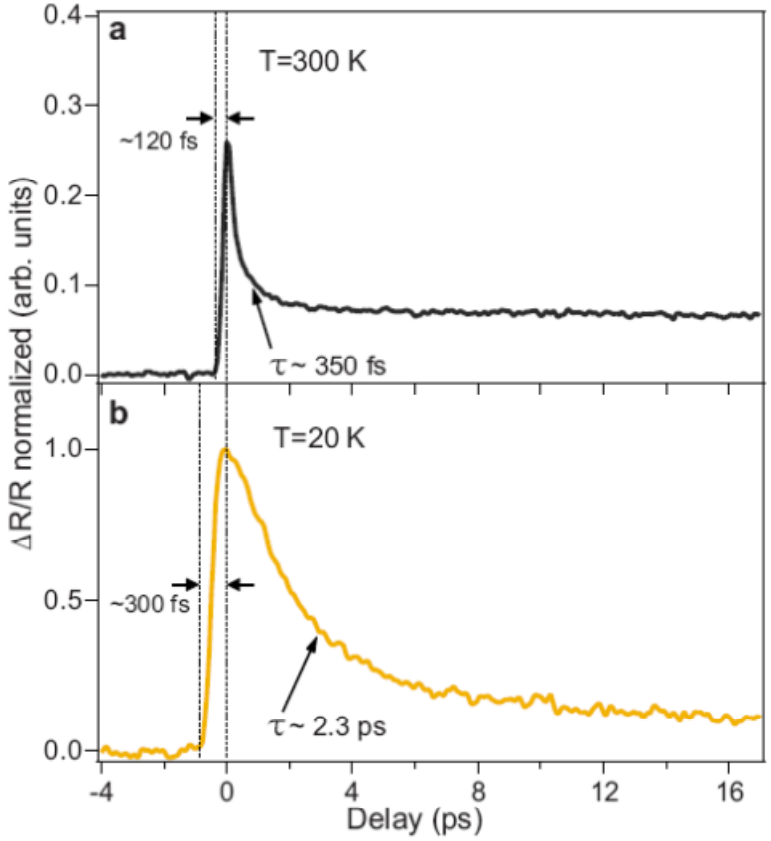
optical pump-probe experiments in HTSC

F = 40 μJ/cm^2





$Y_{1-x}Ca_xBa_2Cu_3O_{7-\delta}$
Demsar et al., Phys. Rev. Lett. **82**, 4918 (1999)



$Bi_2Sr_2CaCu_2O_{8+\delta}$
Gianetti et al., Phys. Rev. B **79**, 224502 (2009)

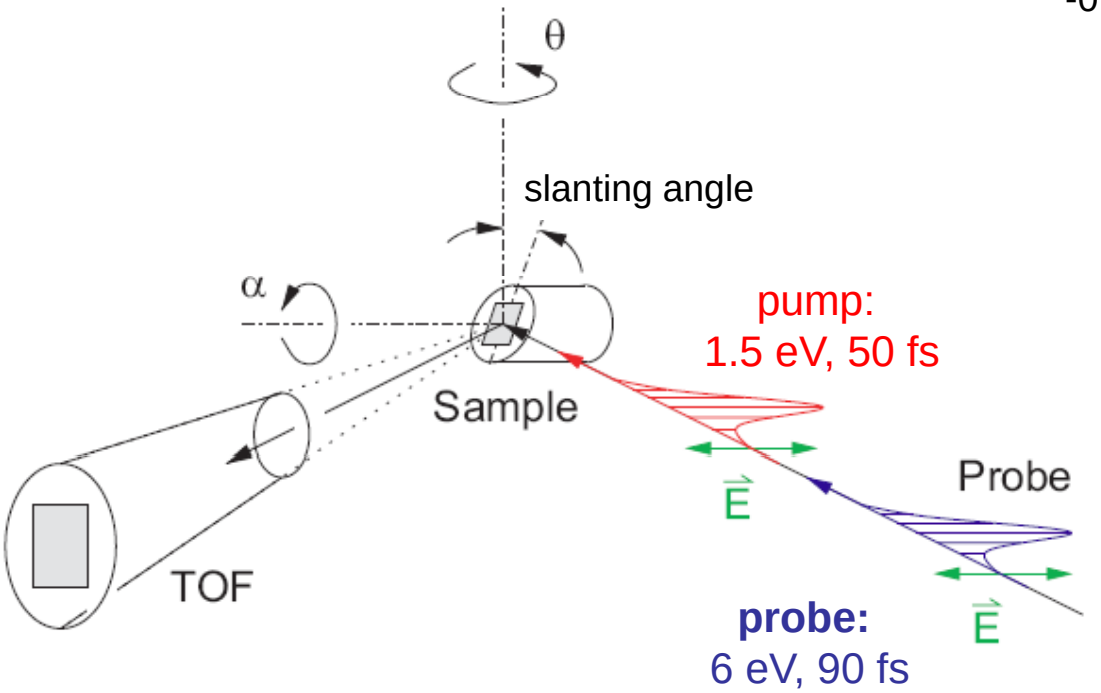
see also work by, e.g.,
Kaindl, Gedik, Orenstein

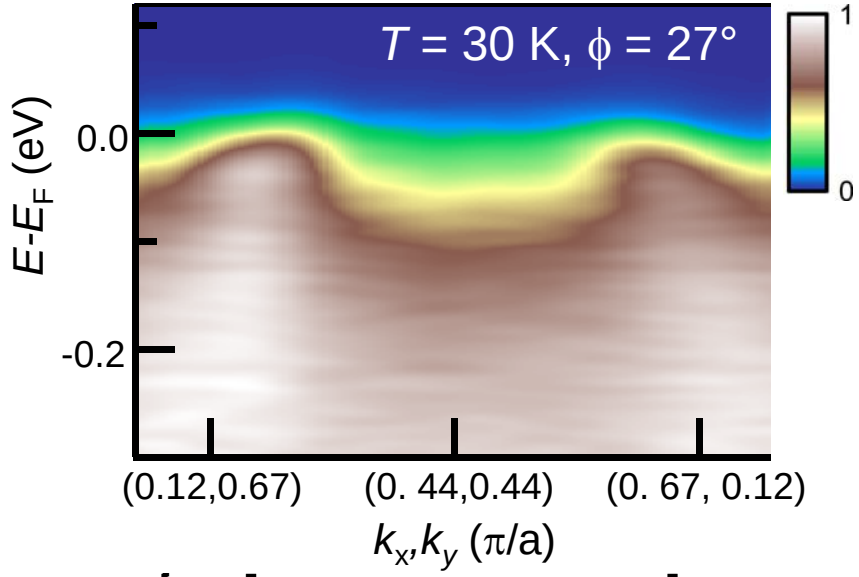
1) Cooper pair reformation in superconducting BSCCO

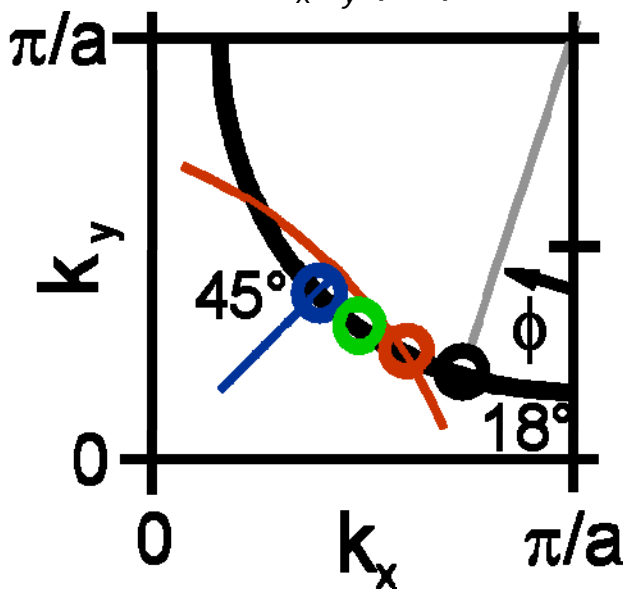
L. Rettig (U Duisburg-Essen)
R. Cortés, M. Wolf (FHI Berlin)
Y. Yoshida, H. Eisaki
(NIAIST Tsukuba)

time-resolved laser ARPES of $Bi_2Sr_2CaCu_2O_{8+\delta}$

$$k_{||} = \sqrt{2m_e E_{\text{kin}}}/\hbar \cdot \sin\theta$$

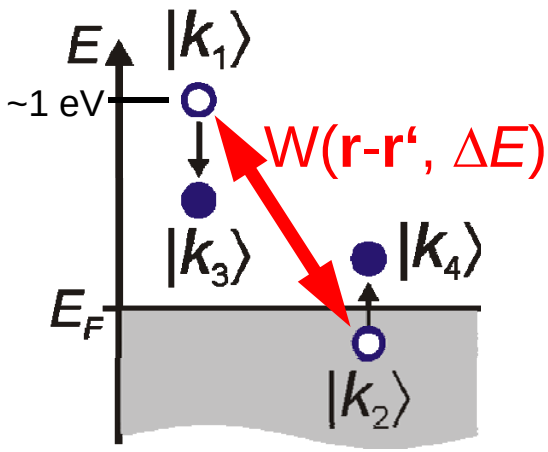




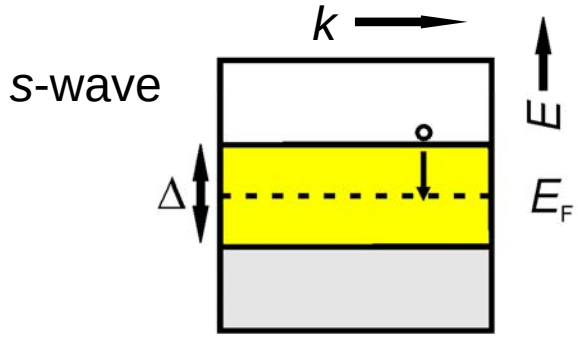


Schmitt et al., Science **321**, 1649 (2008)

quasiparticle decay in metals and superconductors

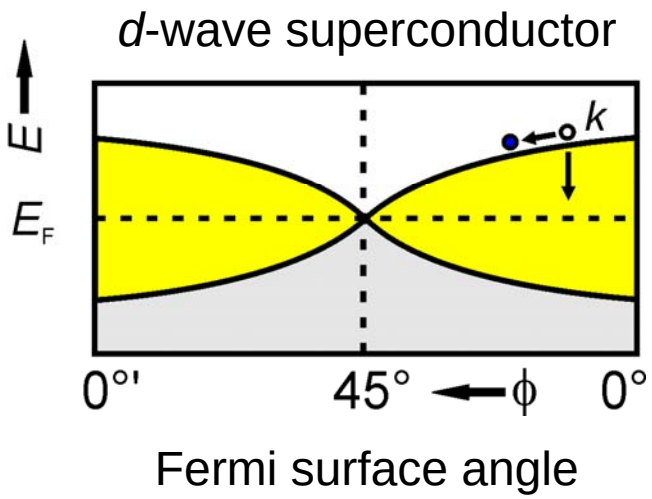


Kirchmann et al., Nature Physics **6**, 782 (2010)



competition of

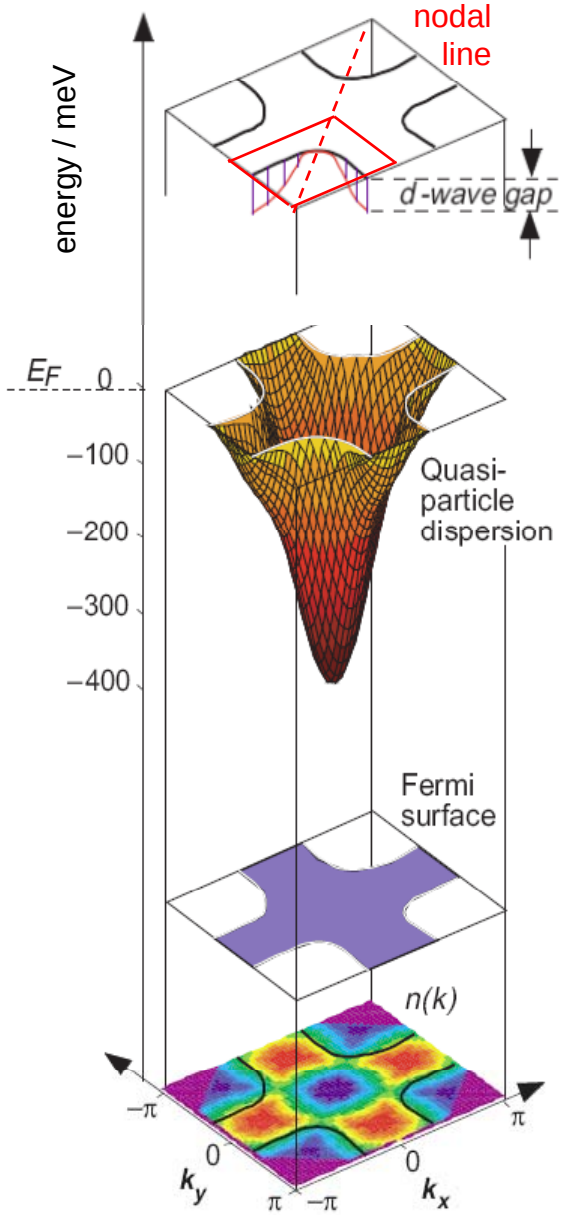
- thermalization of excited quasiparticles
- recombination into Cooper pairs

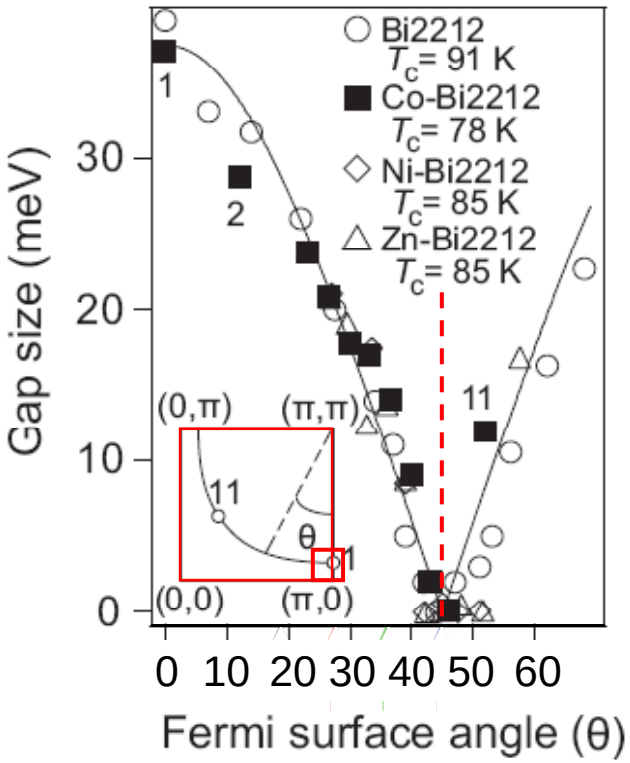


➡ analysis of elementary scattering processes in HTSC

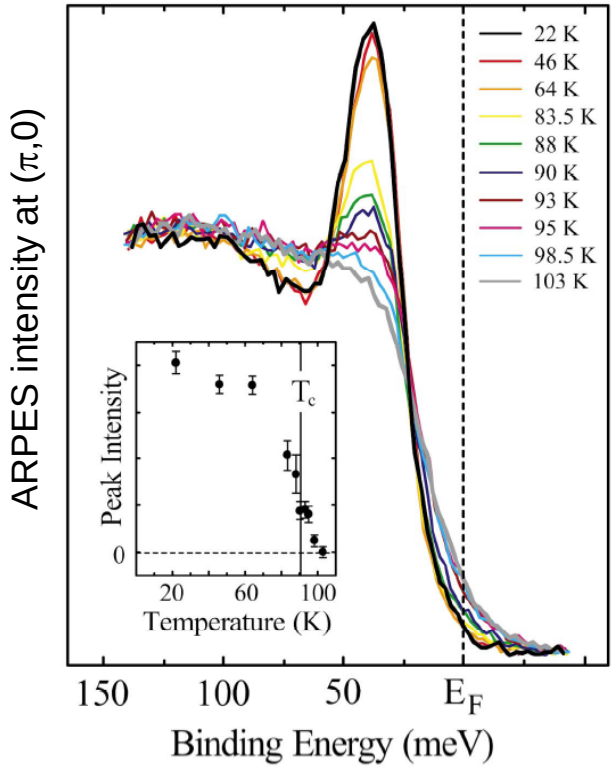
ARPES analysis of $Bi_2Sr_2CaCu_2O_{8+\delta}$

Ronning et al., Science **282**, 2067 (1998)





Terashima et al.,
J. Phys. Chem. Solids **67**, 271 (2006)



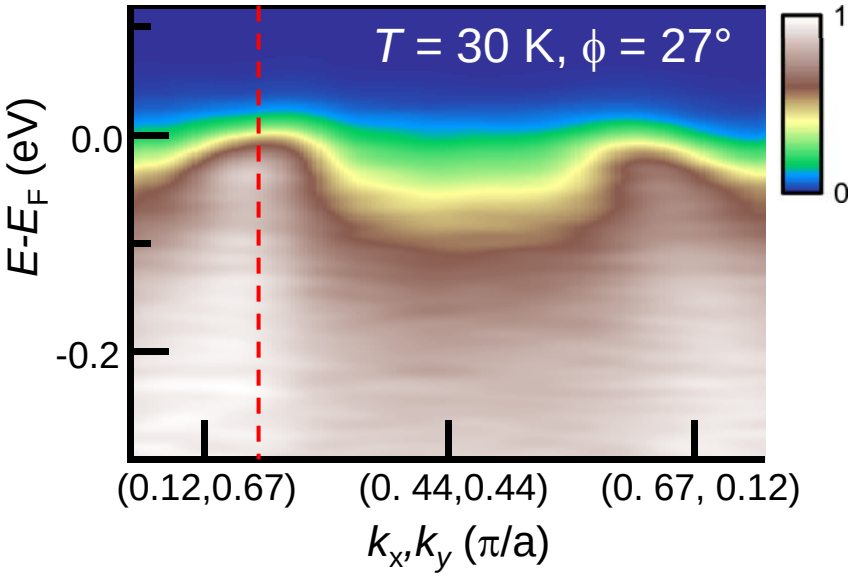
Fedorov et al.,
Phys. Rev. Lett. **82**, 2179 (1999)

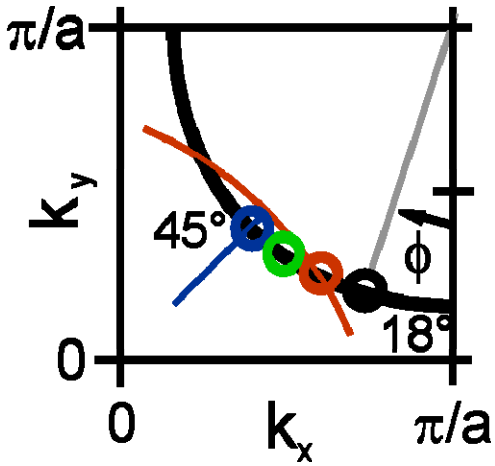
momentum-dependent gap size of a *d*-wave SC

SC quasiparticle peak in ARPES

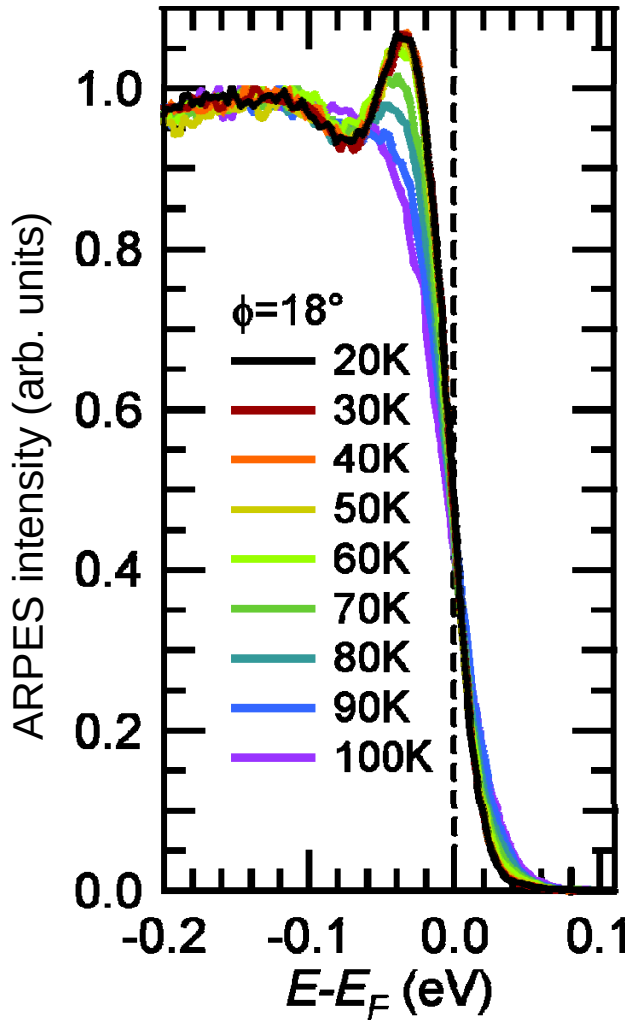
temperature-dependent spectra

optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$



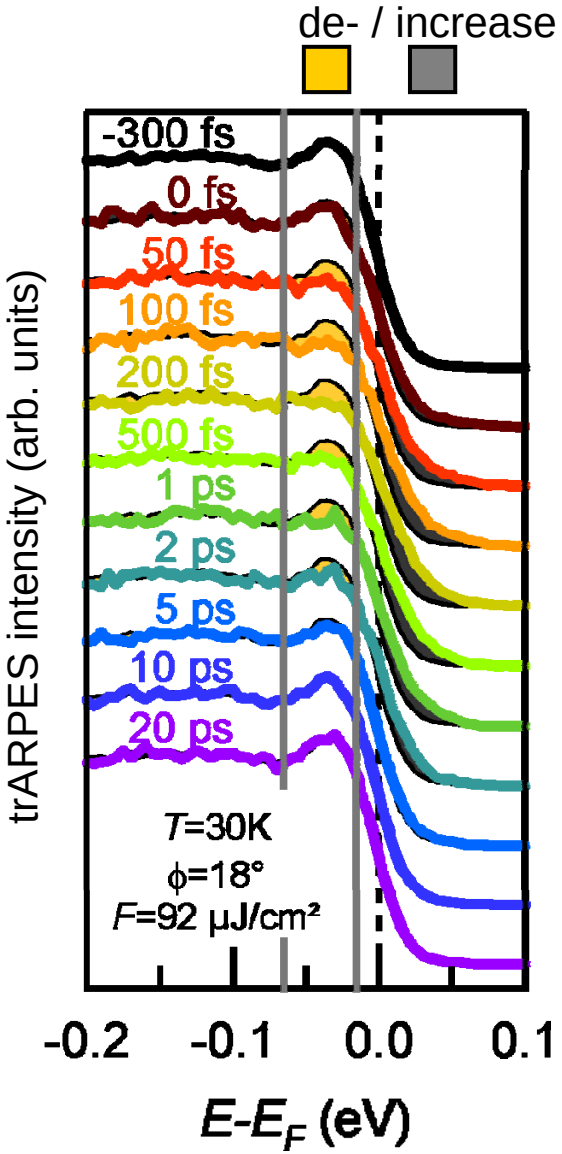


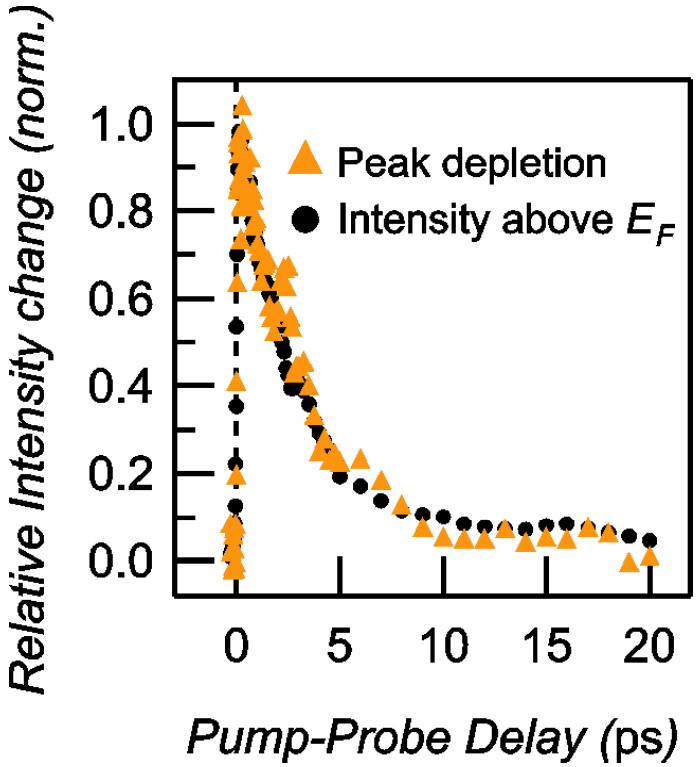
Quasi-particle peak as indication of the superconducting state



Its **depletion** measures the loss in the SC condensate density

coupled SC and QP density





Quasi-particle peak recovers during 5 ps

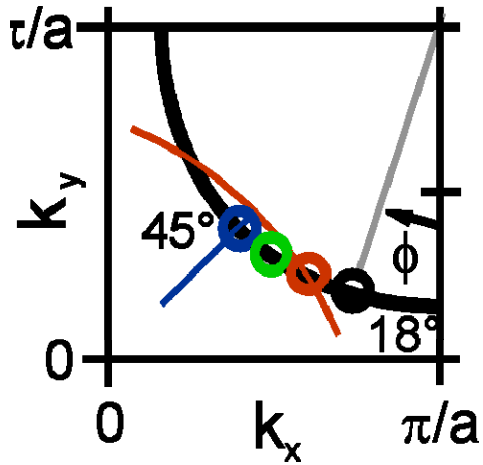
➡Cooper pair recombination

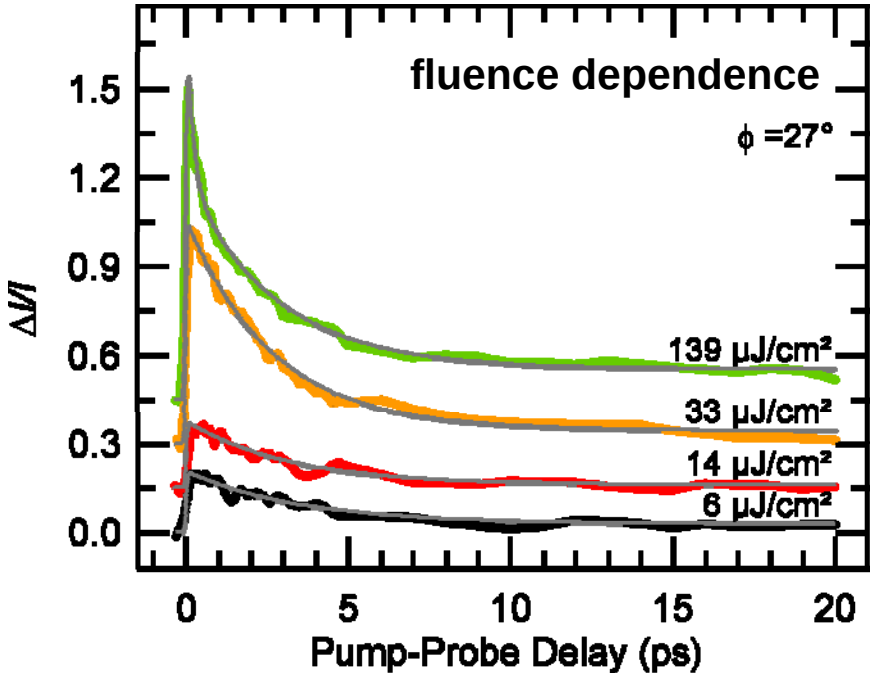
Peak depletion scales with the intensity above E_F.

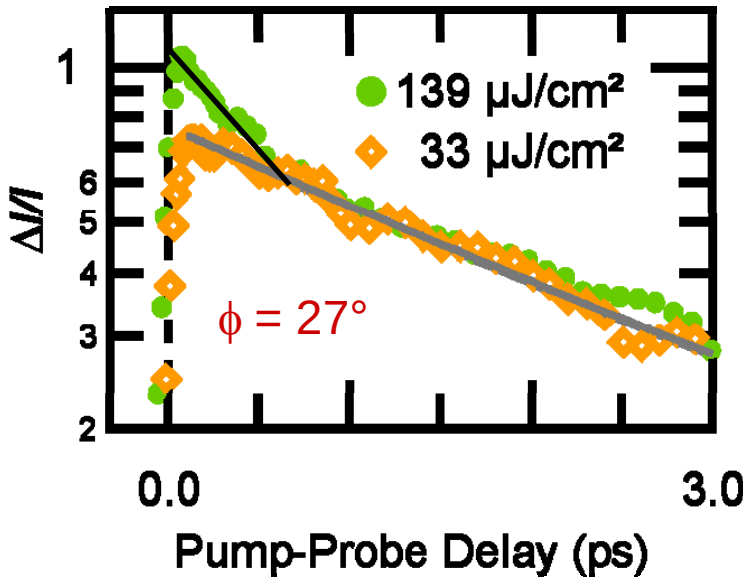
➡Analyse intensity above E_F for a systematic study.

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

relaxation dynamics

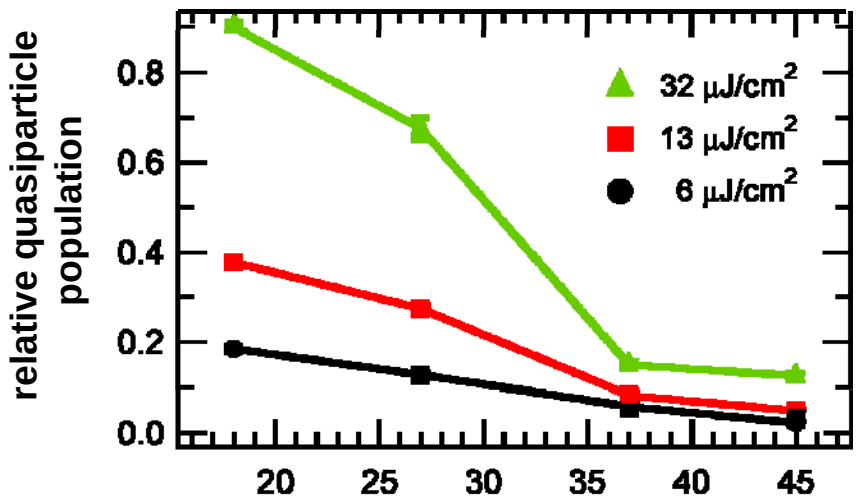


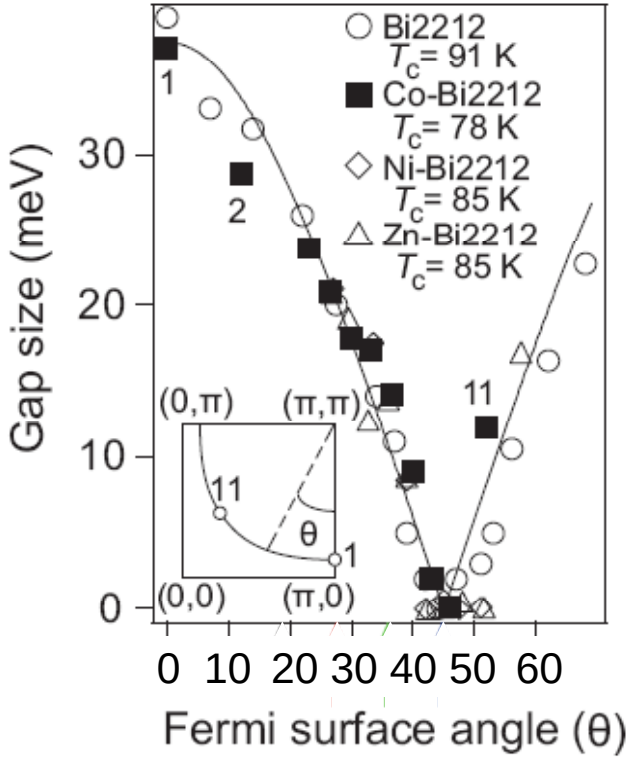




low fluence data ➡ single component decay
discussion of amplitude and decay time

momentum-dependent population

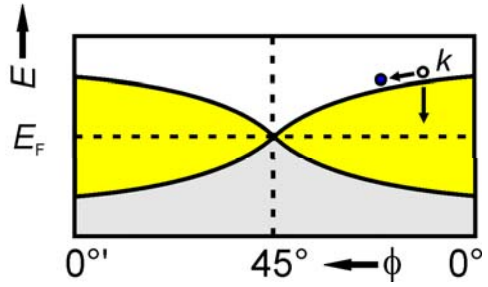




momentum-dependent population

➡ **meta-stable antinodal quasi-particles**

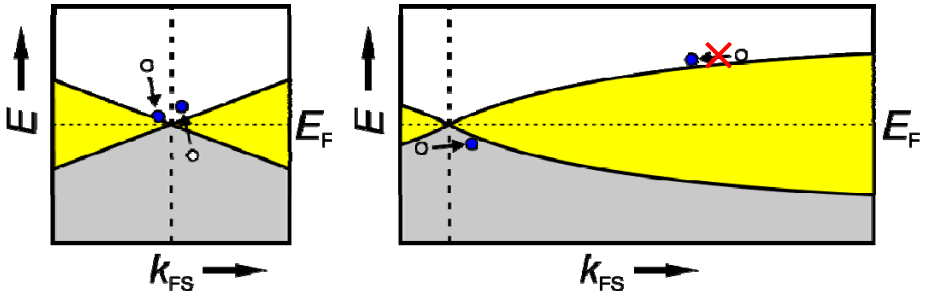
Howell et al., Phys. Rev. Lett. **92**, 037003 (2004)
Gedik et al., Phys. Rev. B **70**, 015405 (2004)



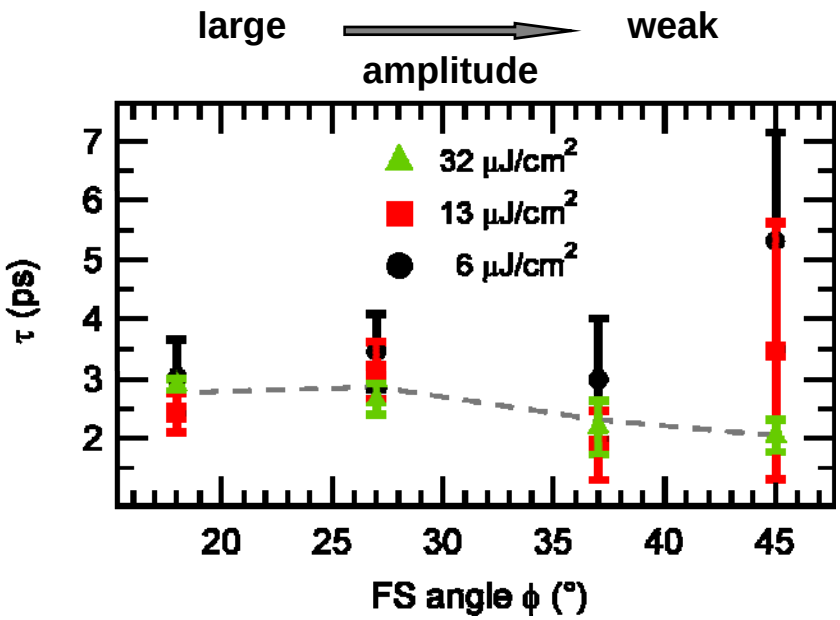
Fermi surface angle

nodal QP: decay by e-e scattering at the nodal point

antinodal QP: decay by e-e scattering essentially blocked

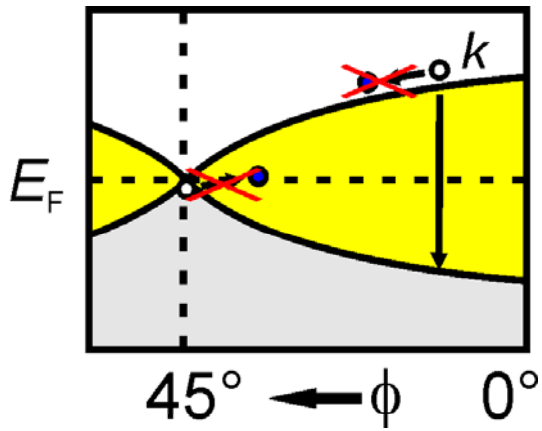


Cooper pair recombination decay times

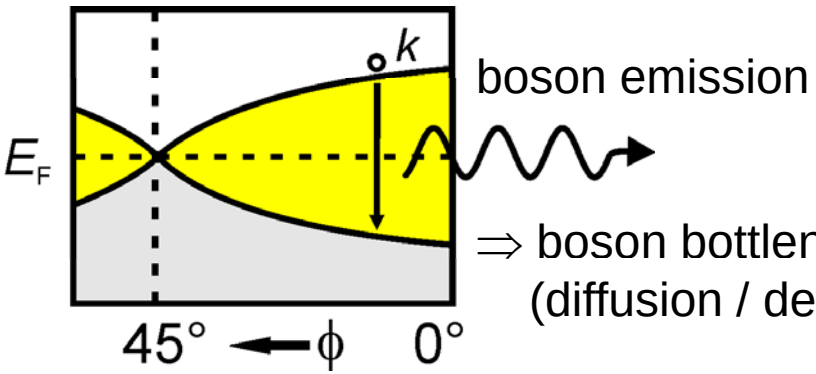


recombination rate is independent on momentum

momentum-independent relaxation rates



consistent with metastable antinodal quasi-particles



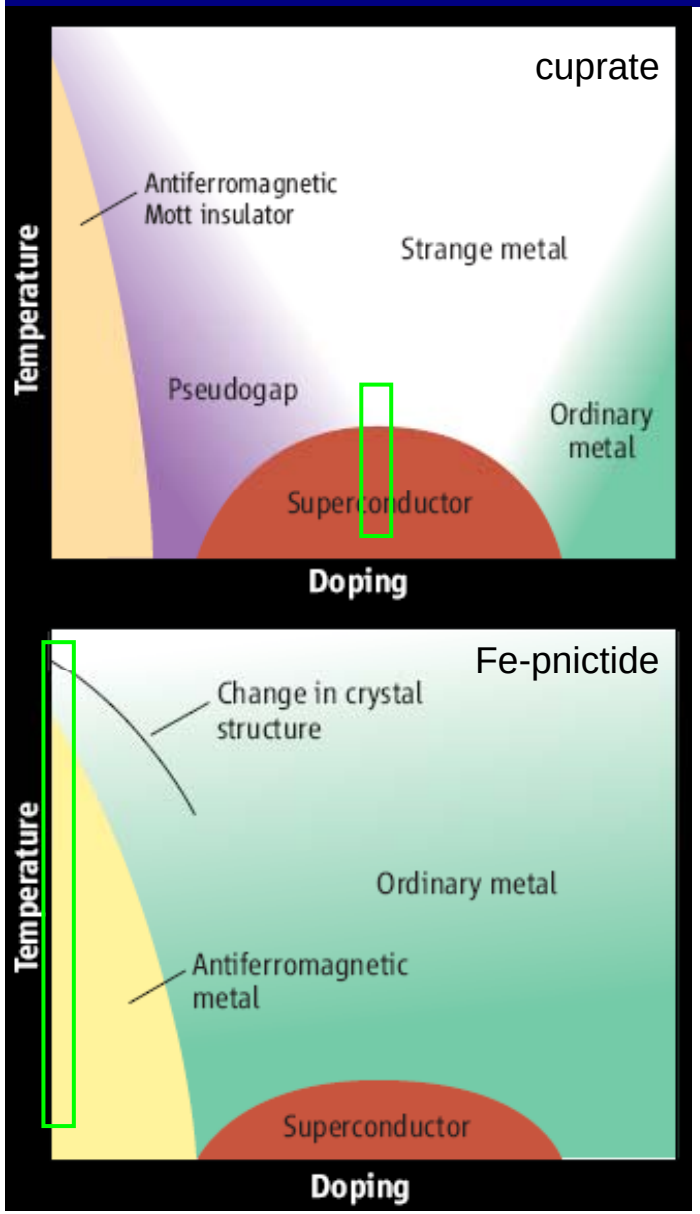
⇒ boson bottleneck (diffusion / decay limited)

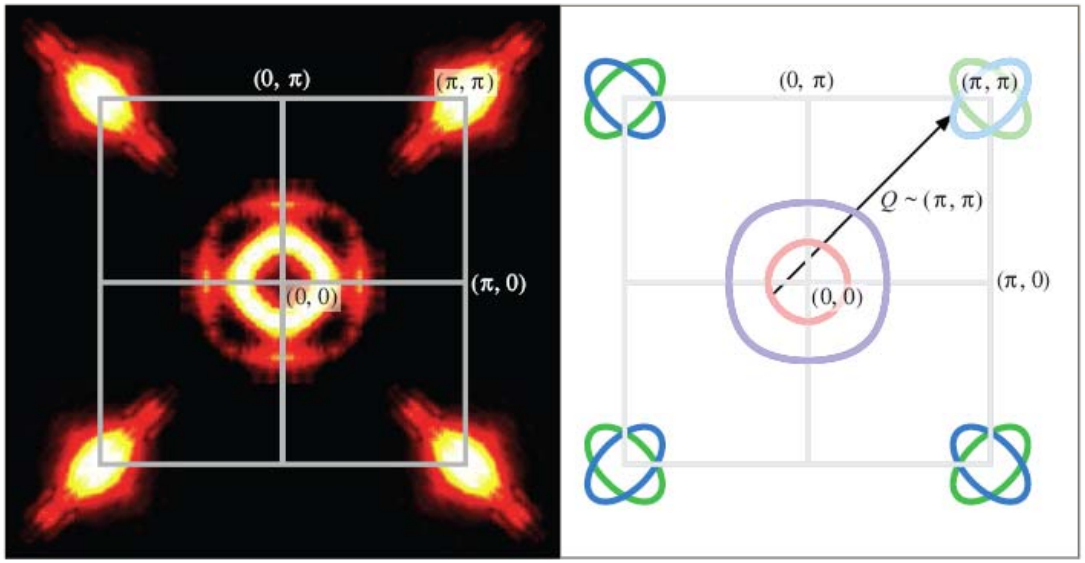
Cooper pair recombination as considered in time-resolved optical studies

Demsar et al., Phys. Rev. Lett. **82**, 4918 (1999)
Gedik et al., Phys. Rev. B **70**, 015405 (2004)
Kaindl et al., Phys. Rev. B **72**, 060510 R (2005)
Gianetti et al., Phys. Rev. B **79**, 224502 (2009)

2) Momentum-dependent quasi-particle dynamics in $EuFe_2As_2$

L. Rettig (U Duisburg-Essen)
R. Cortés, M. Wolf (FHI Berlin)
J. Fink (IFW Dresden),
P. Gegenwart, H.S. Jeevan (U Göttingen)



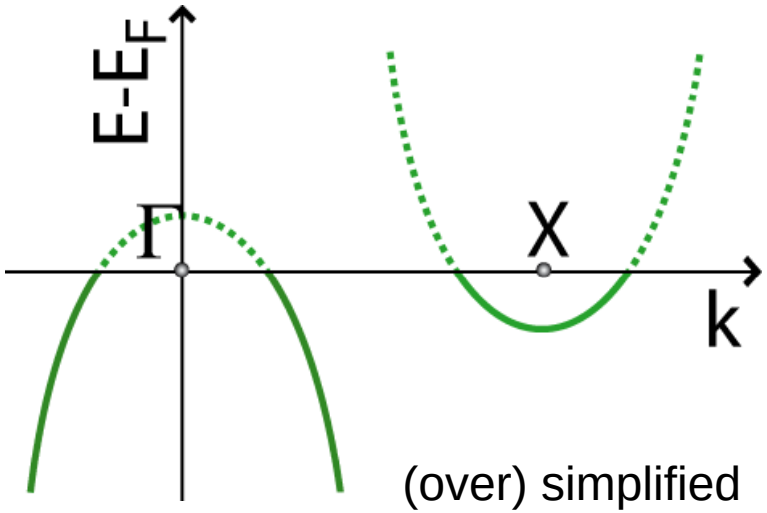


hole pockets at Γ, electron pockets at X

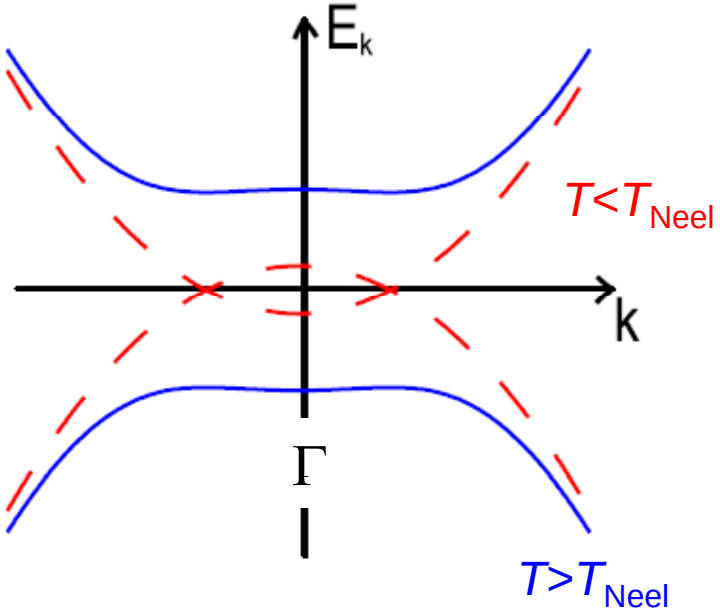
A. Cho, Science **327**, 1321 (2010)

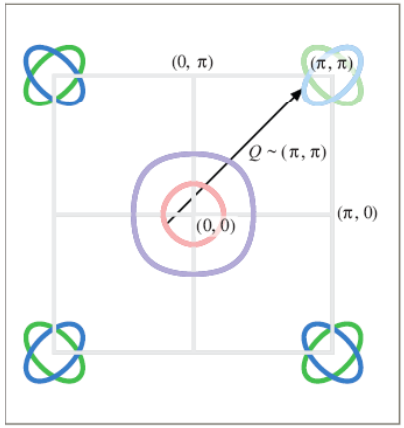
electronic structure of the parent compound

nesting ⇨ antiferromagnetic order



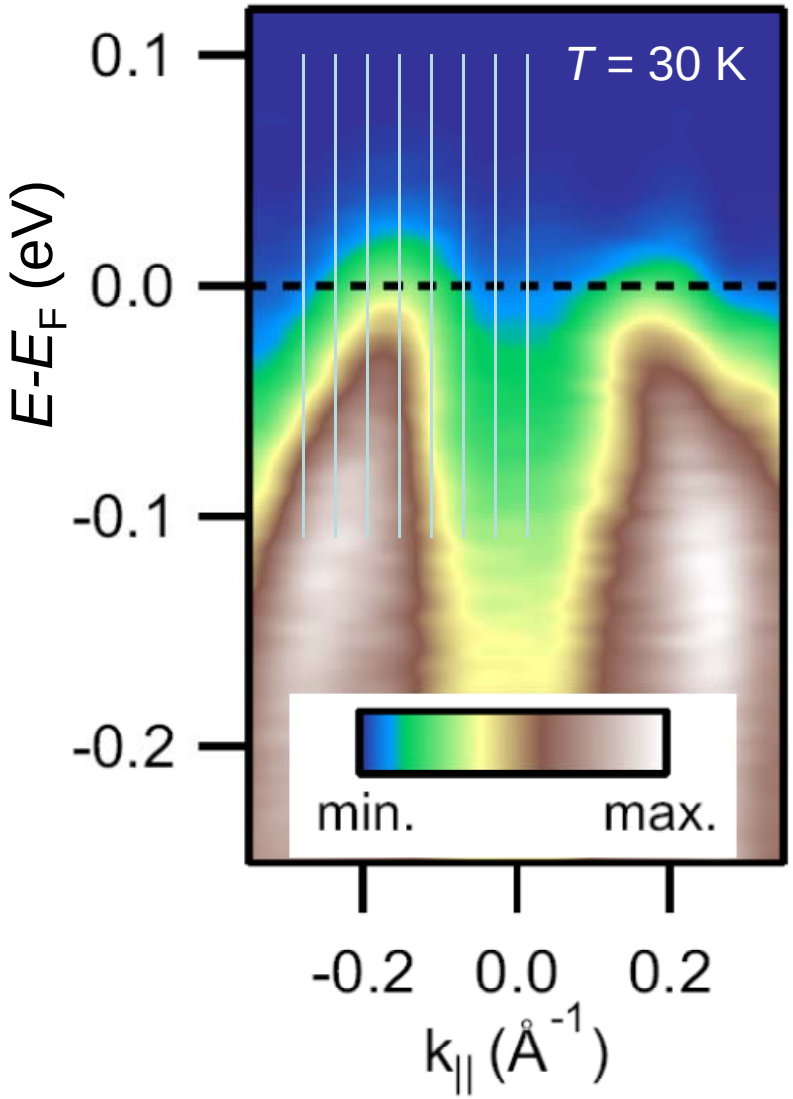
(over) simplified





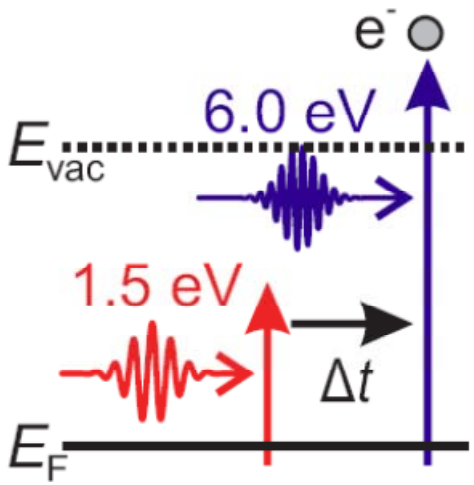
Eremin and Chubukov, Phys. Rev. B **81**, 024511 (2010)

laser-ARPES



$h\nu$= 6.0 eV

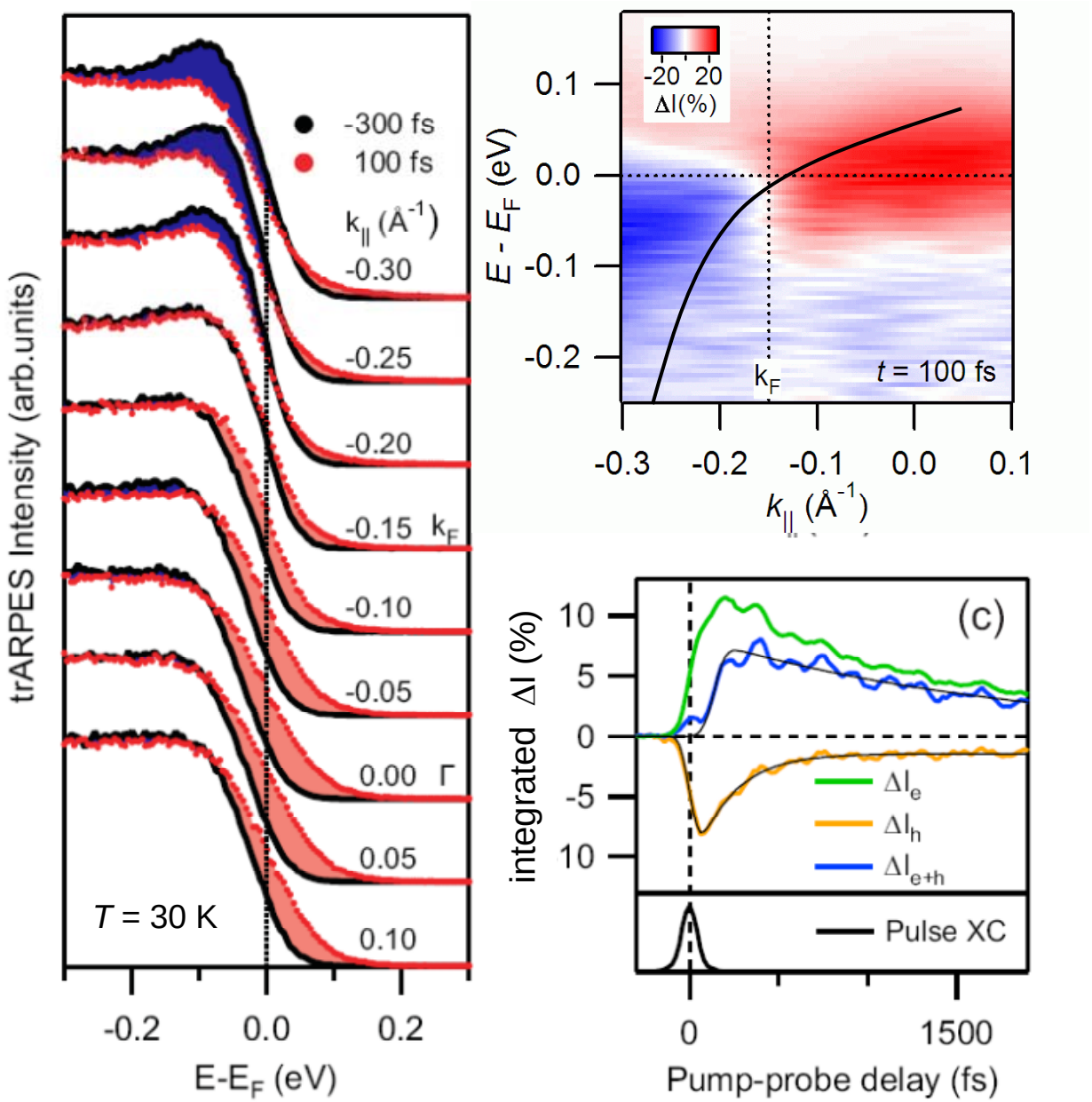
Measurements near Γ point



hole pocket is observed,

good agreement to synchrotron data

femtosecond time-resolved ARPES

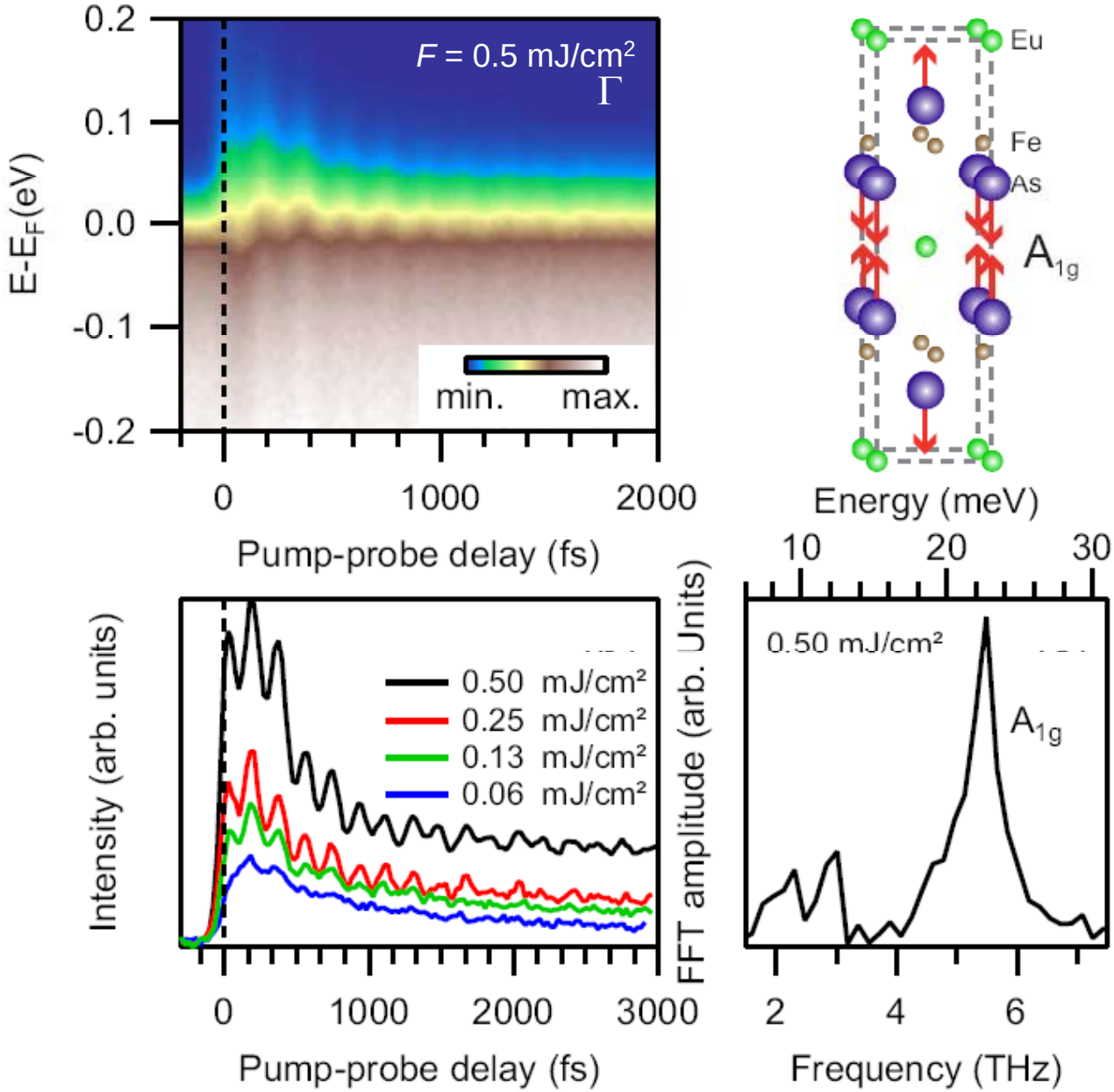


F = 280 μJ/cm^2

hot electron decay
τ_e= 800 fs

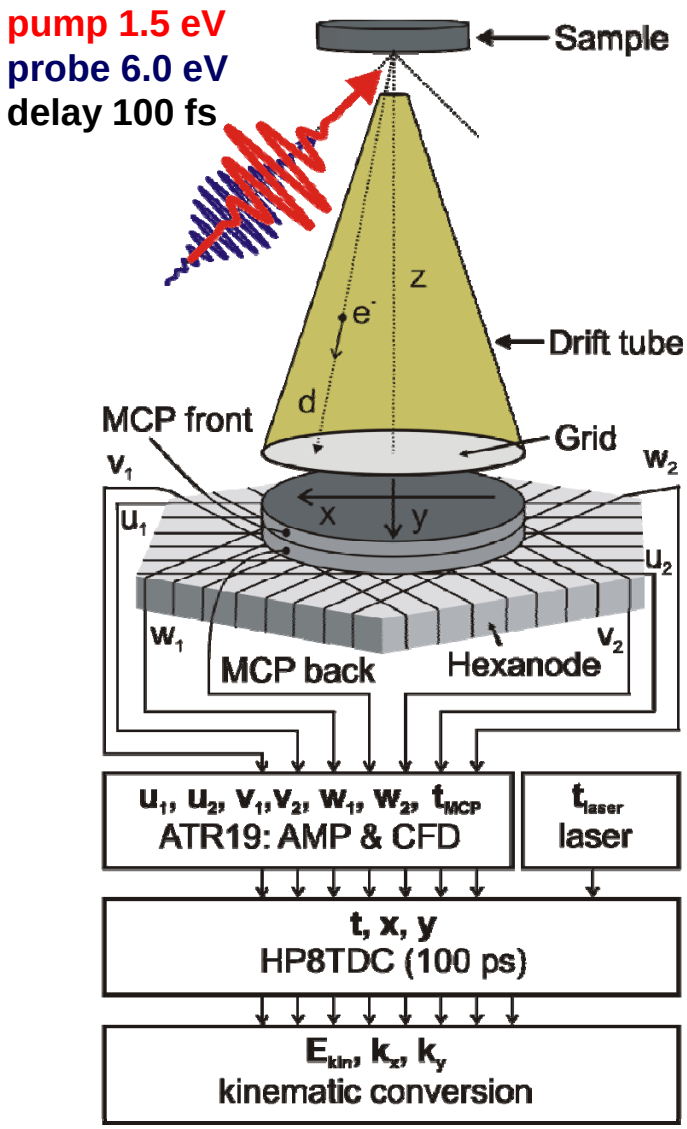
hot hole decay
τ_h= 150 fs

outlook: phonon excitation



Rettig et al.
arxiv.org/abs/1008.1561

Recent development: position sensitive eTOF



Kirchmann et al.,
Appl. Phys. A **91**, 211 (2008)

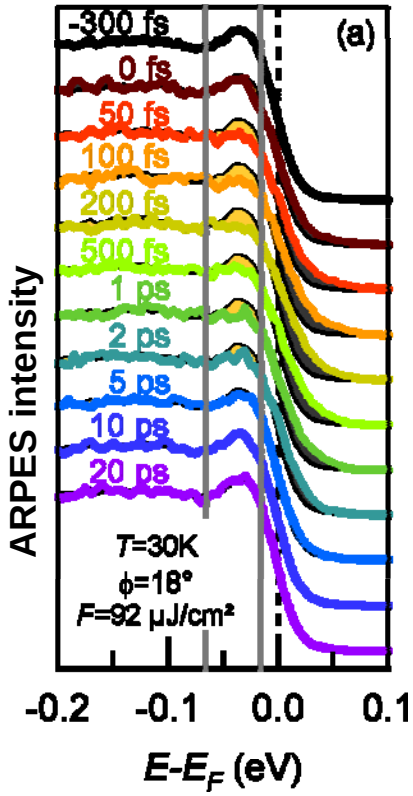
summary

femtosecond tr-ARPES

- tool to analyse momentum-dependent quasiparticle relaxation in the time domain

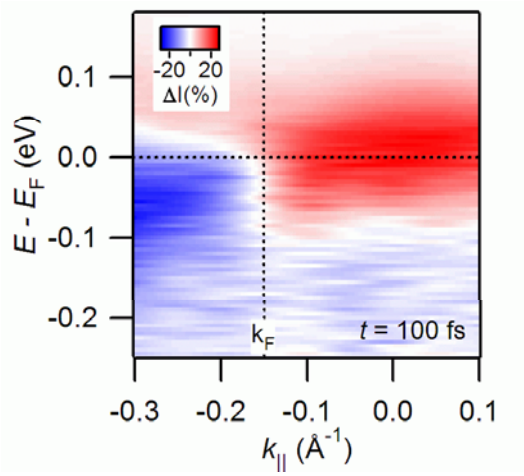
superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$

- pump-induced changes specific to superconductivity
- metastable antinodal quasiparticles
- diffusion / decay limited Cooper pair reformation



antiferromagnetic $EuFe_2As_2$

- anisotropic relaxation of electrons and holes ($T<T_{Neel}$)
- pronounced temperature dependence
- separation if photo-induced melting of antiferro-magnetic order vs. single quasiparticle relaxation



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