Dynamics of fluctuations in high temperature superconductors far from equilibrium

L. Perfetti, Laboratoire des Solides Irradiés, Ecole Polytechnique

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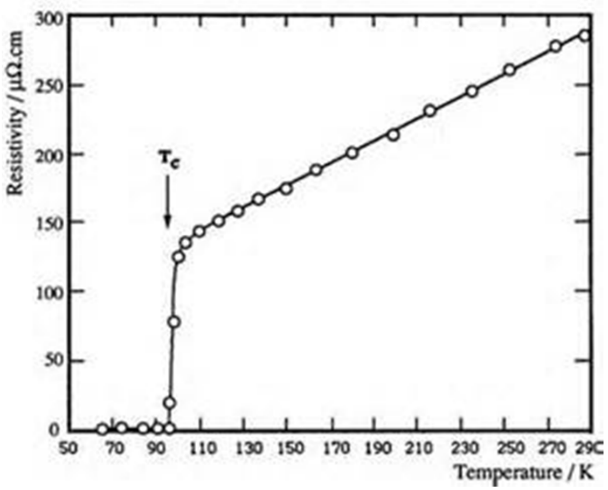
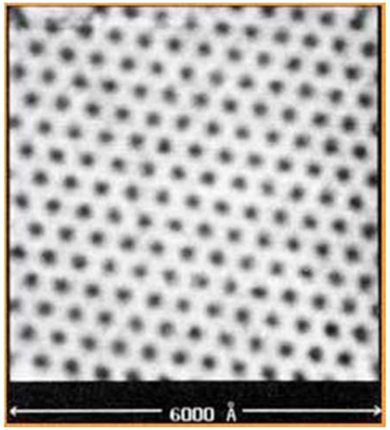


Superconductors display amazing properties:

- Dissipation-less conductivity
- Perfect diamagnetism
- Magnetic flux quantization



STM image of vortex lattice

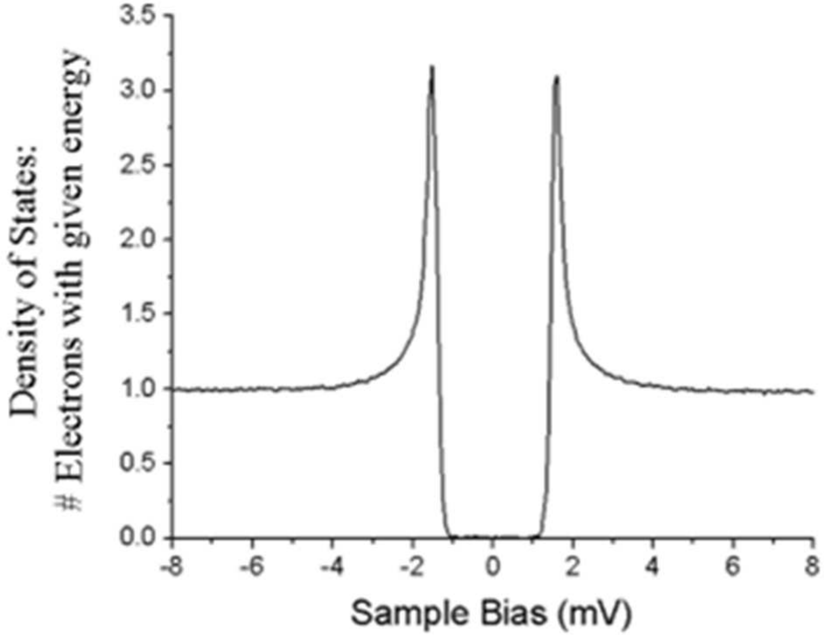
Superconductivity is described by a paring amplitude of time reversal symmetry states

$$\psi(x) = |\psi(x)|e^{i\phi(x)}$$

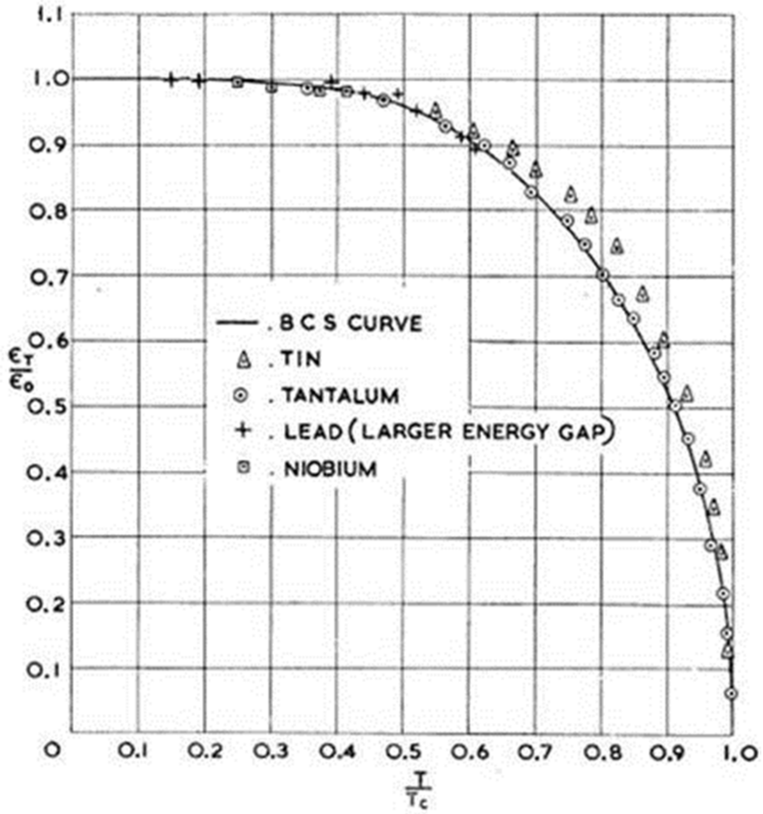
Average of the pairing amplitude becomes non-zero below the transition temperature

$$\Delta = \frac{1}{L^d}|\int \langle \psi(x) \rangle dx|$$

An energy gap Δ develops in the excitation spectrum



Tunneling experiments on Lead



Typical interaction time between electrons forming a Cooper pair $\hbar/\Delta$

In the ballistic regime electrons will be paired over a distance $\xi_0 \approx \frac{\hbar v_F}{\Delta}$

In conventional superconductors $\xi_0 \approx$ 1 μm

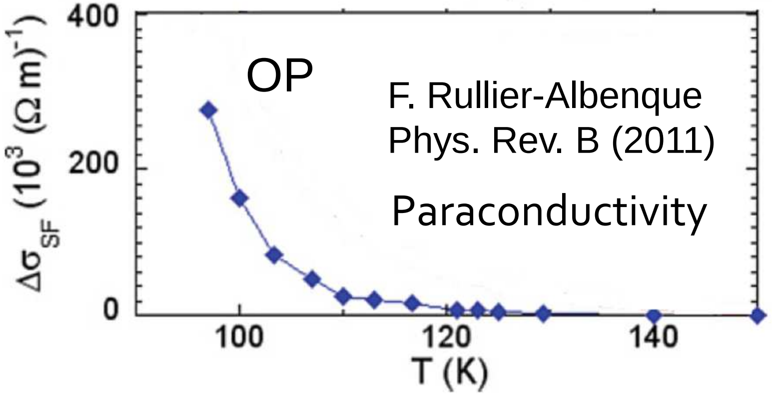
10^8 Cooper pairs occupy a volume ξ_0^3 and fluctuations of ψ take place on a negligible temperature window

In high temperature superconductors $\xi_0 \approx$ 2 nm

Fluctuations of $\psi(x) = |\psi(x)|e^{i\phi(x)}$ are measurable

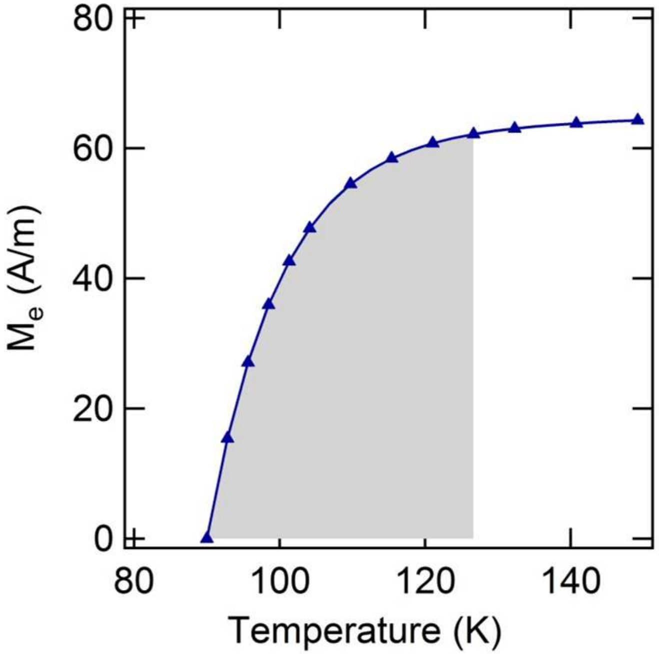
Copper-Oxigen compound $\mathbf{Bi_2Sr_2CaCu_2O_{8+\delta}}$

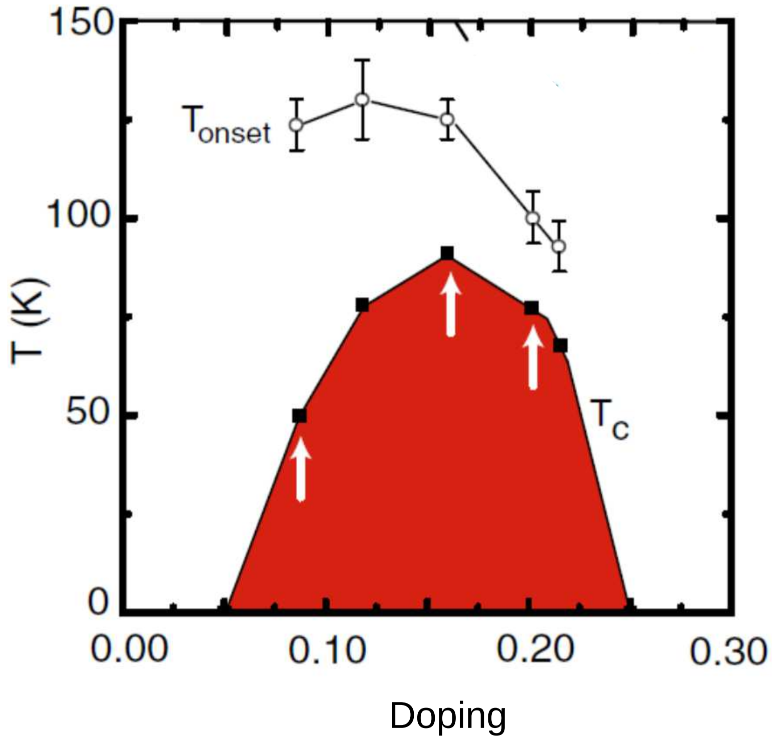
Fluctuations of superconductivity are observed in thermodynamic and transport properties



Y. Wang, Phys. Rev. Lett. (2005)

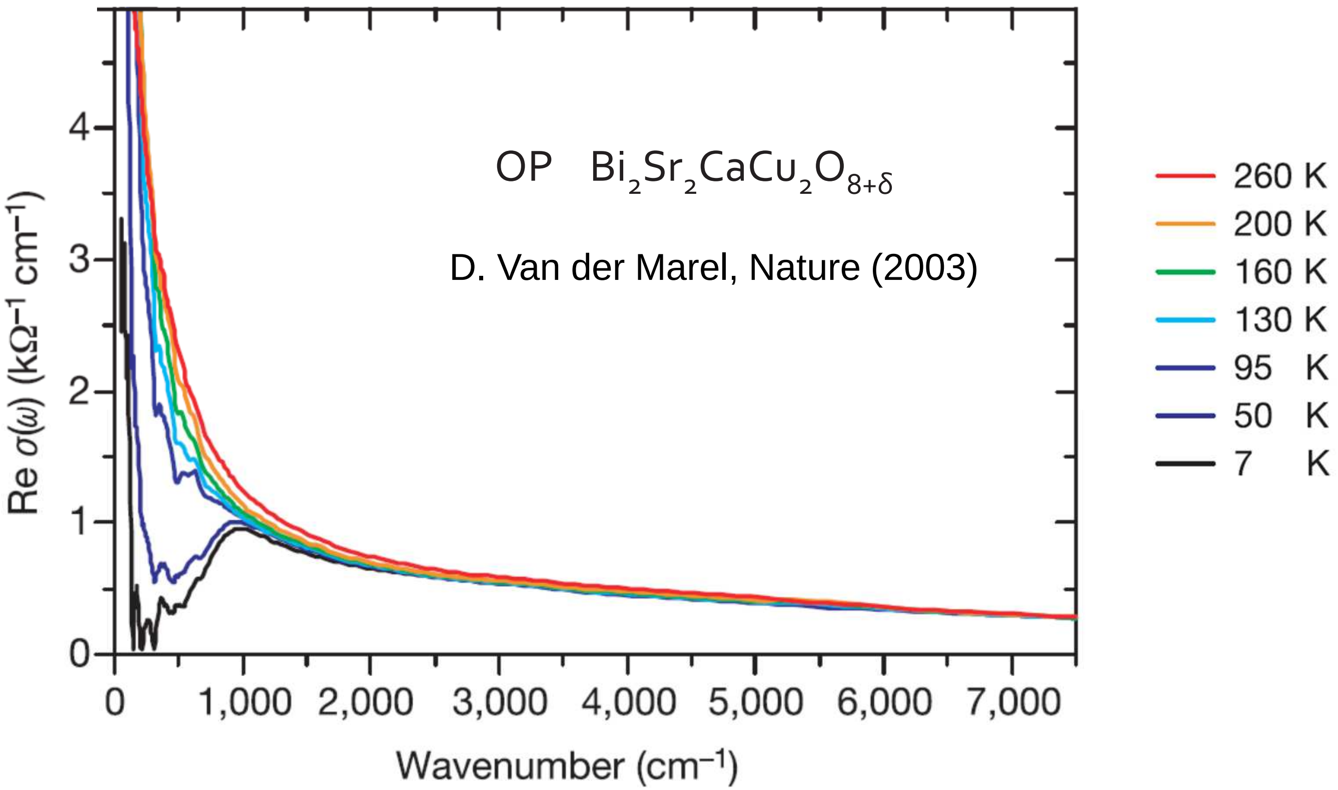
Diamagnetism





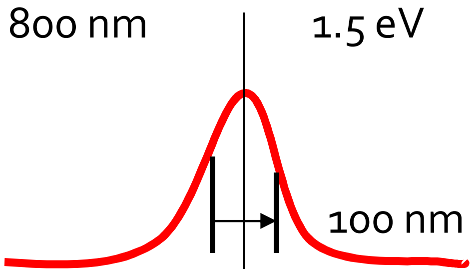
Can we be sensitive enough and fast enough to observe superconducting fluctuations in real time?

Fast enough is possible with femtosecond lasers



Sensitive enough if we down-convert the optical pulses in the mid-infrared spectral region

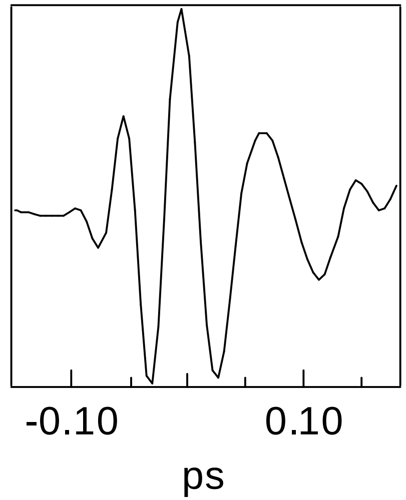
Time Resolved TeraHertz spectroscopy

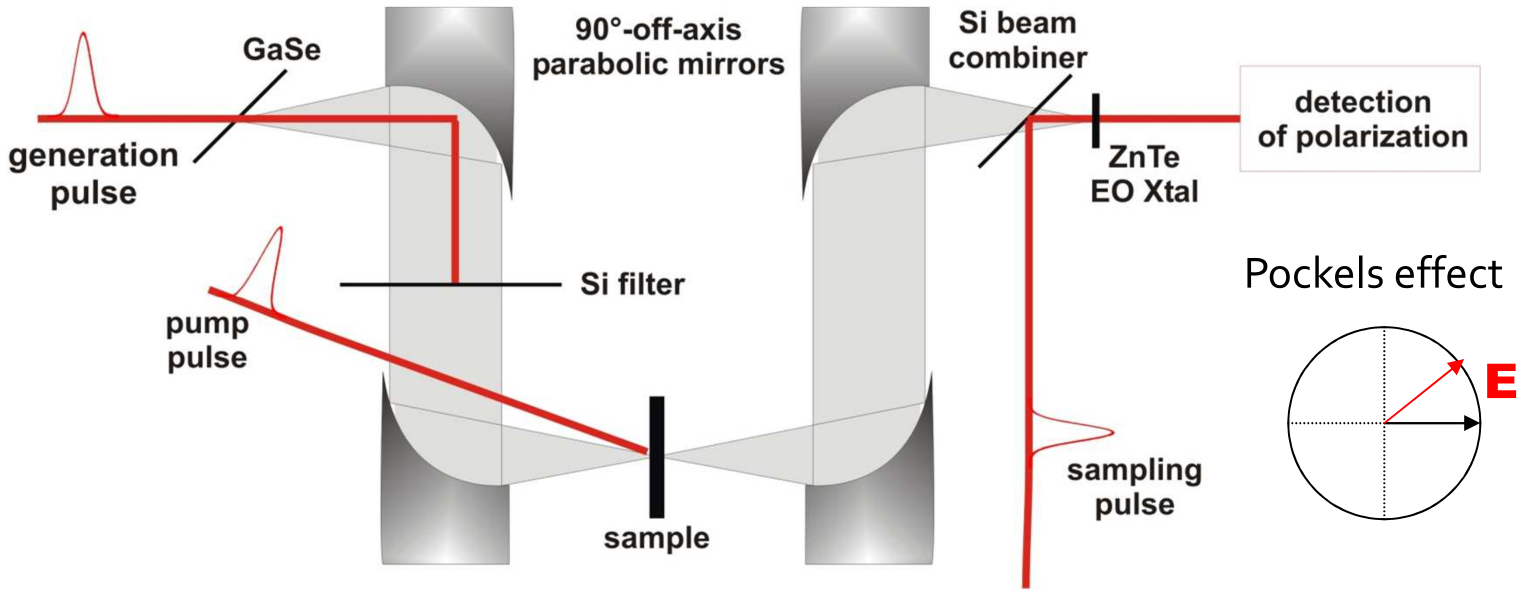


Frequency Mixing

Broad band
10 - 40 THz

Ultrafast 100 fs

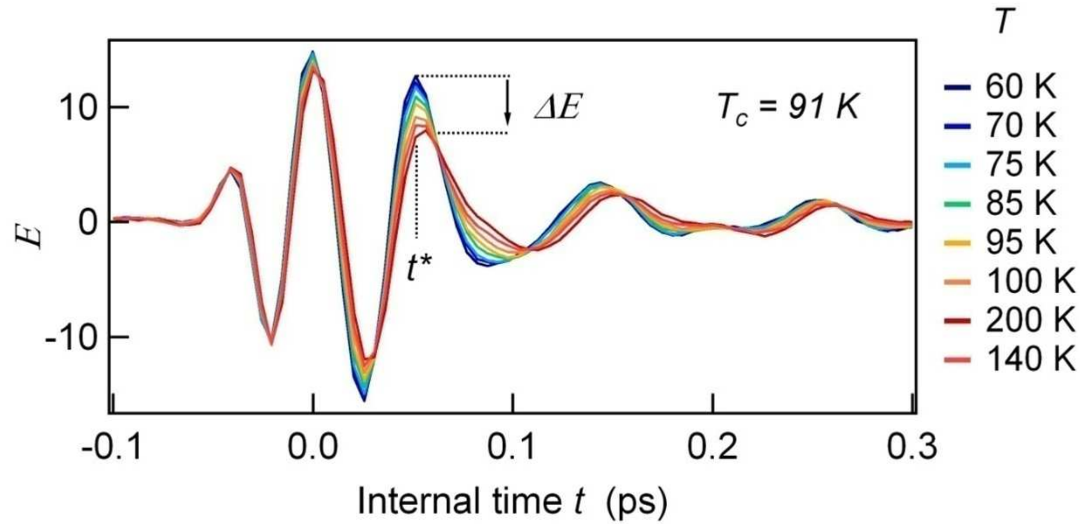


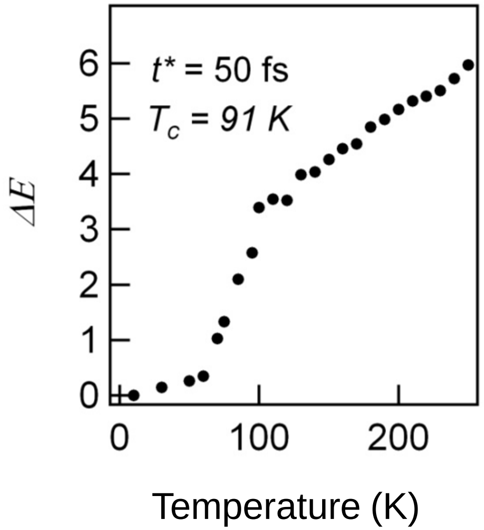


Pockels effect

Optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$

Transmitted Electric Field

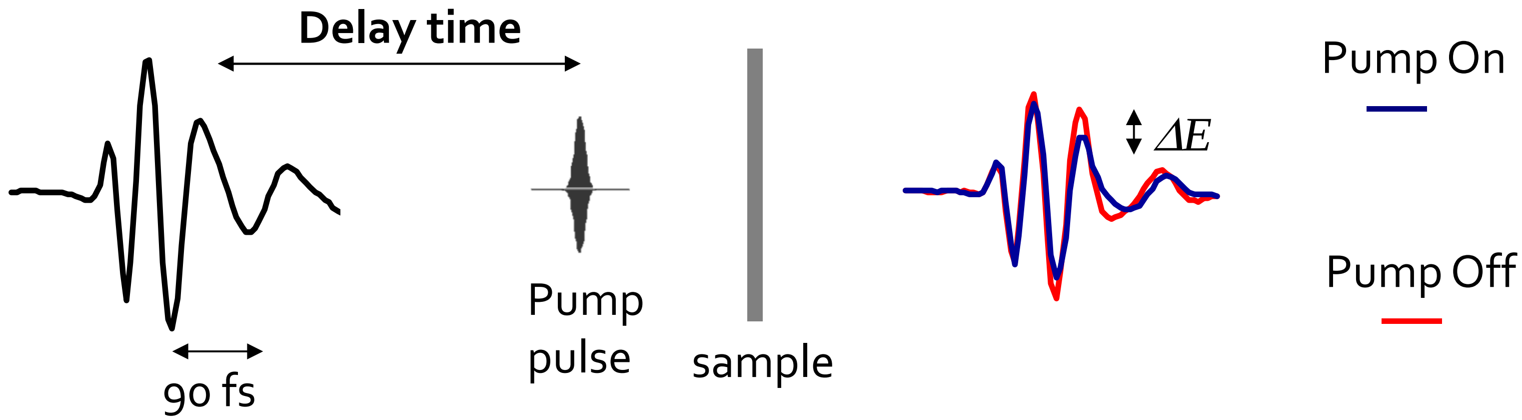


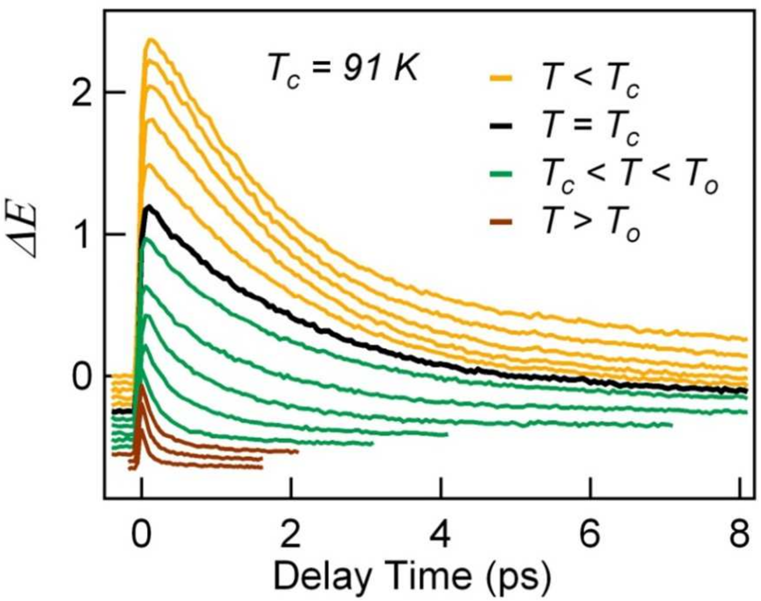


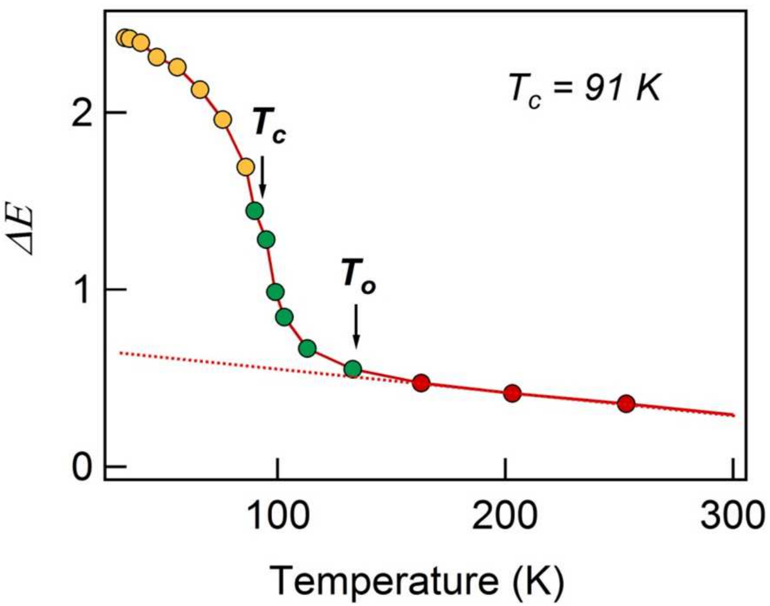
Drop of the scattering rate due to the DOS reduction near to the Fermi level

Conceptually similar to ultrasound absorption in conventional superconductors

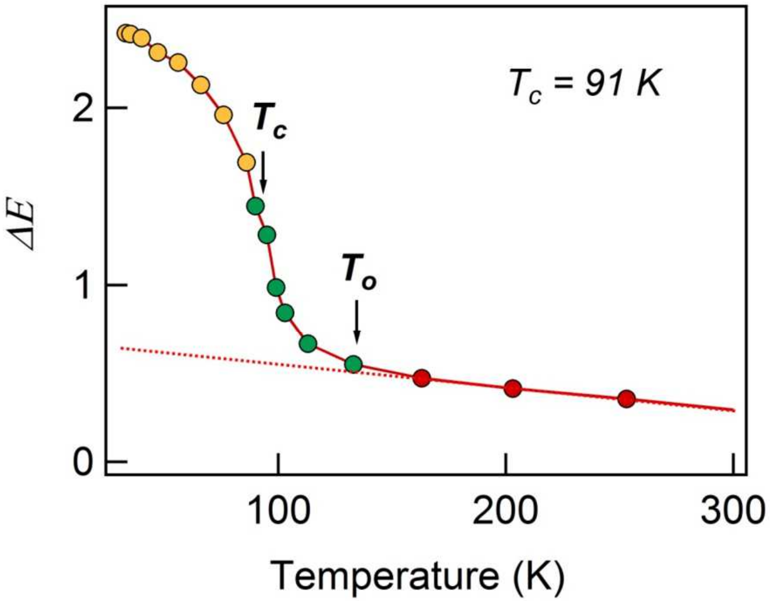
Detection of the dynamics



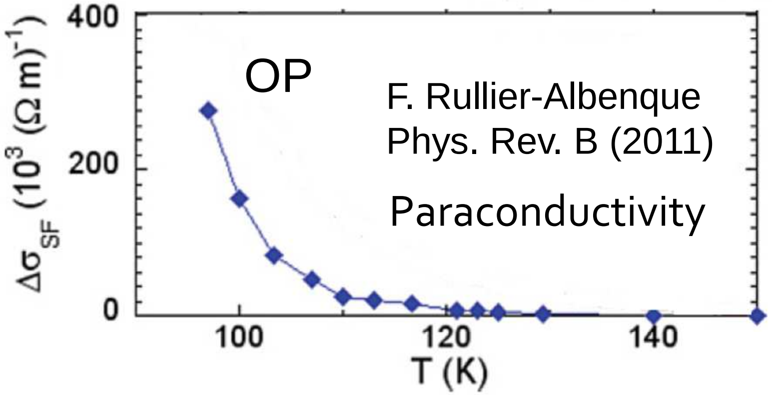




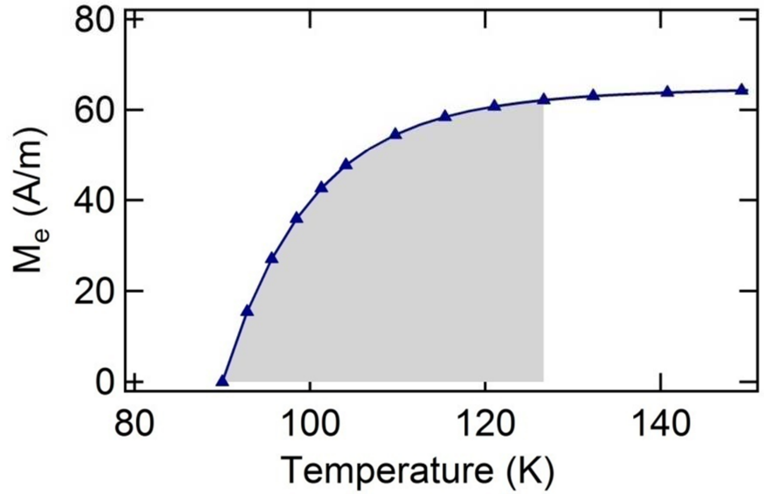
Size of the critical region



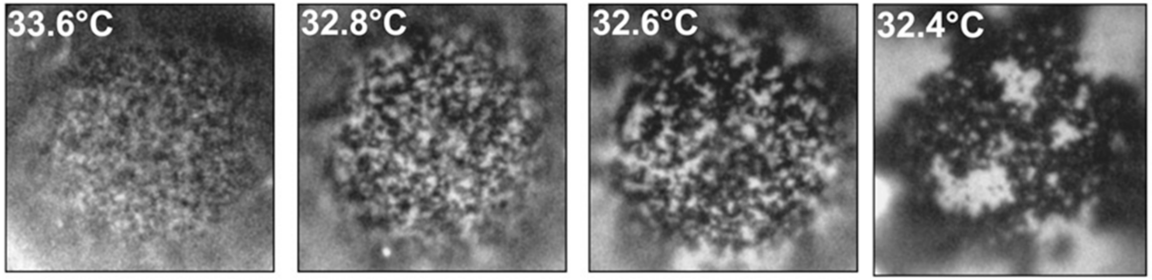
Same onset T_o observed in paraconductivity, Diamagnetism, Nernst effect



Y. Wang, Phys. Rev. Lett. (2005)



Approaching the critical point $\longrightarrow$ T_c



fluctuating domains of the ordered phase

Size of fluctuations grows

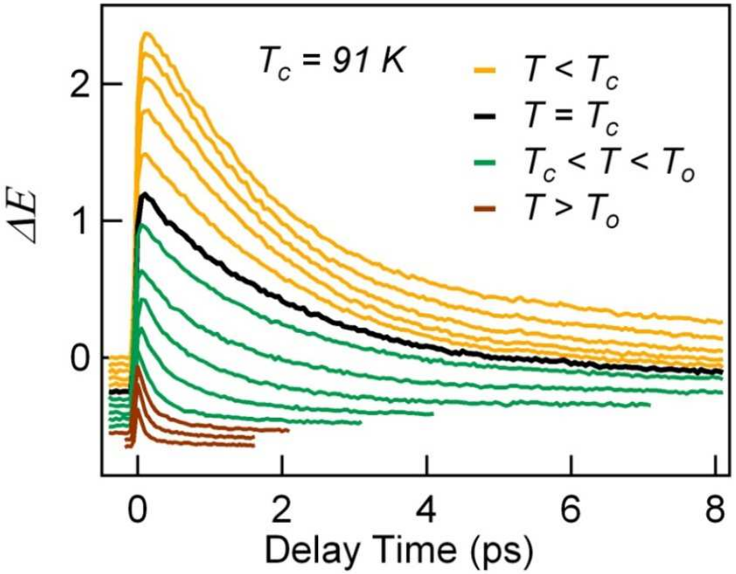
$$\xi \cong \frac{1}{(T - T_c)^{\nu}}$$

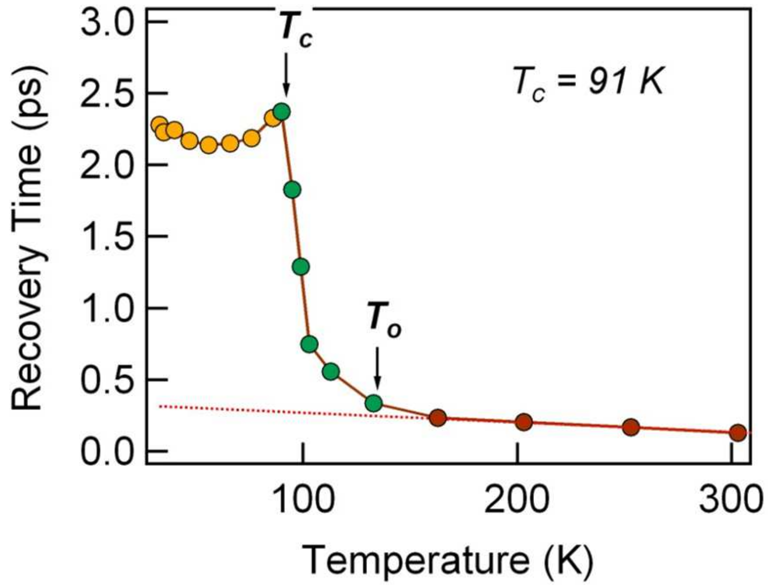
The dynamics becomes slower

$$\tau_c \cong \frac{1}{(T - T_c)^{\beta}}$$

Universality:

power laws depend only on **dimensionality, symmetry of the order parameter and interaction range**

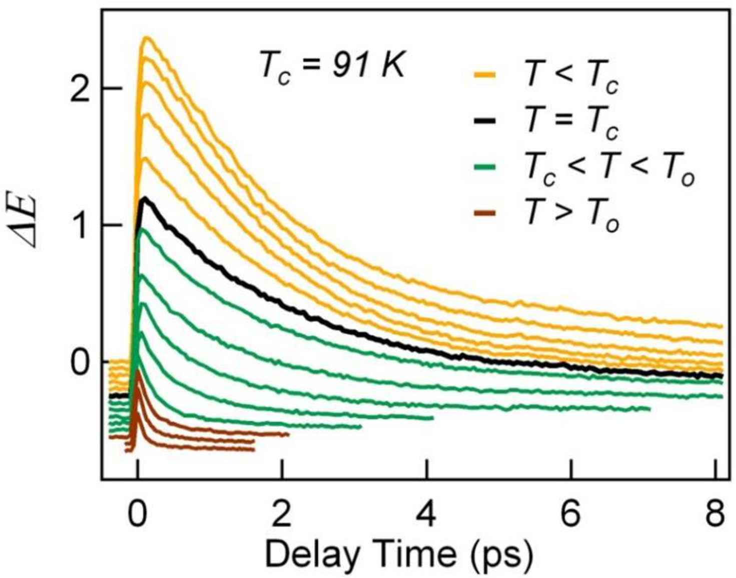


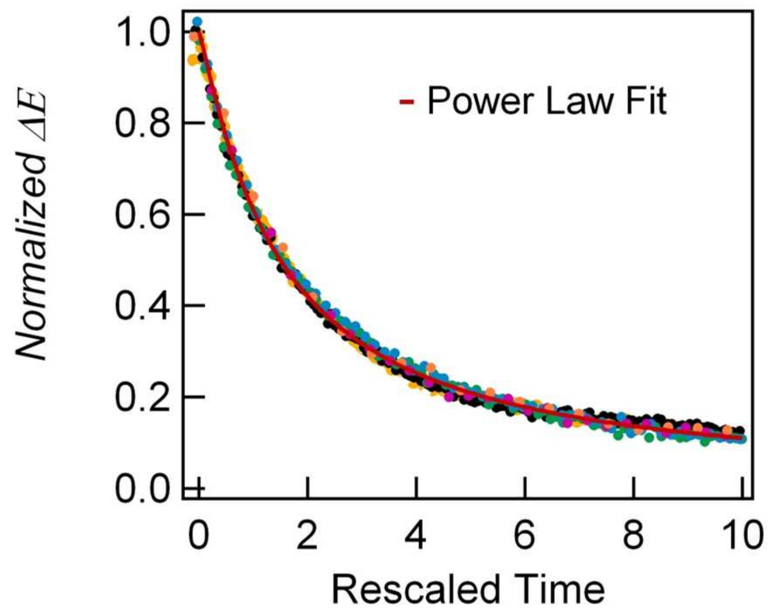


Slowing down of fluctuations in the critical region

Recovery time $$\tau_c \cong \frac{1}{(T - T_c)^{\beta}}$$

Scaling !!





In the critical region all curves follow an universal power law

Hint of universality

$$\frac{1}{1+(\tau/\tau_c)^{\alpha}}$$

In the gapless phase it is possible to derive he Time Dependent Ginzburg Landau (TDGL) equation

$$\frac{d\psi}{d\tau} + \frac{\psi}{\tau_{GL}}(1 + \frac{|\psi|^2}{\Delta^2}) - D\nabla^2\psi + \eta(x,\tau) = 0$$

M. Cyrot
Rep. Prog. Phys. (1973)

The system is described by a single diverging time scale

$$\tau_{GL} = \frac{\xi^2}{D} \propto \frac{1}{T - T_c}$$

Theory predicts

$$\tau_{GL}^{-1} = \frac{c^2}{48\pi\sigma_{dc}\lambda^2}$$

$$\tau_{GL}^{-1} = 4(T/T_c - 1)\ \mathrm{ps}^{-1}$$

We add white noise to account for the finite possibility of thermally excited configurations $\psi(x,\tau)$

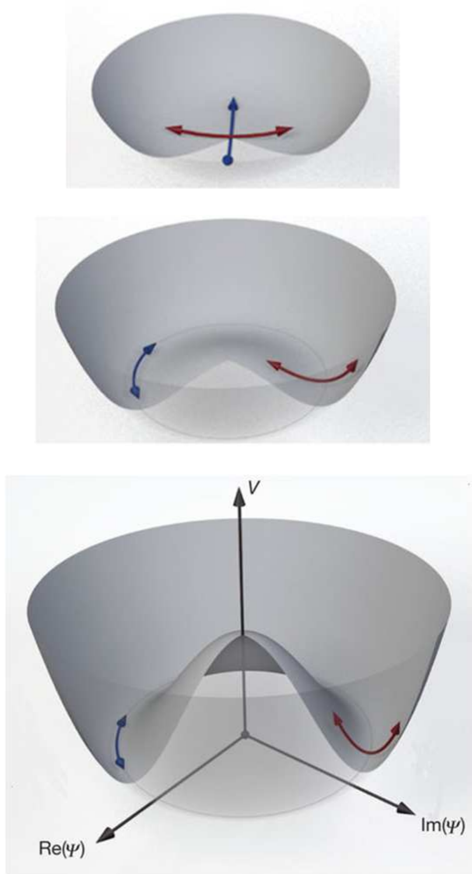
$$\langle\eta(x,\tau)\eta(x,\tau')\rangle = 2Sk_BT\delta(x - x')\delta(\tau - \tau')$$

Sudden quench hypothesis

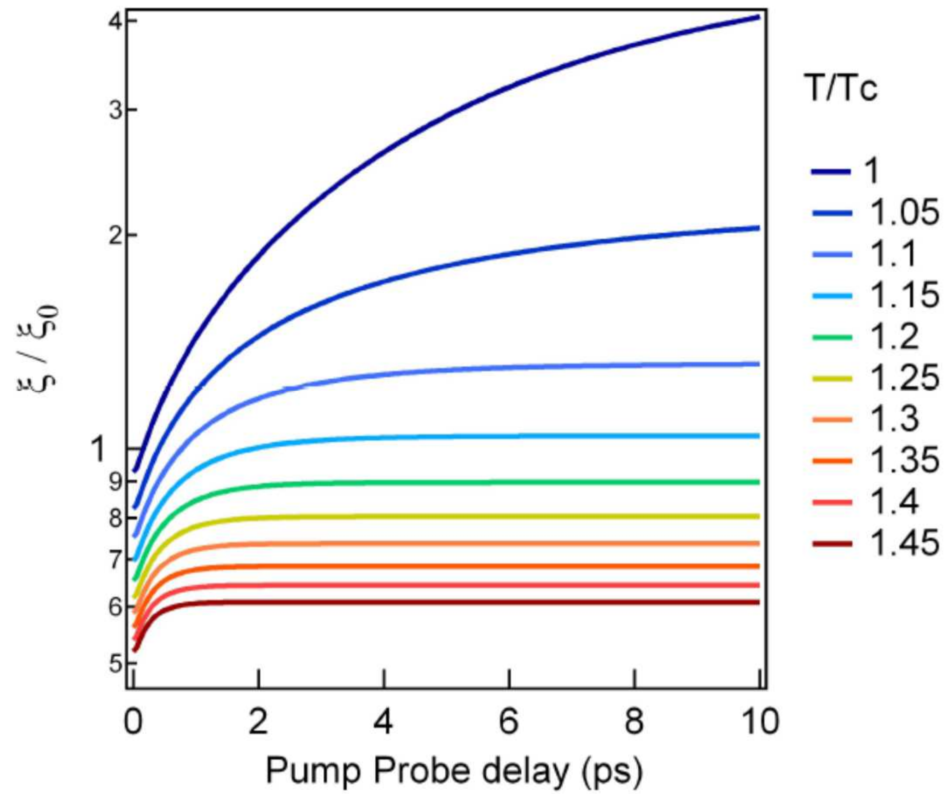
Fast degrees of freedoom reach equilibrium conditions Just after photoexcitation

Slow degrees of freedom follow the dynamics imposed by a coarse grained free energy

justified only in a gapless regime



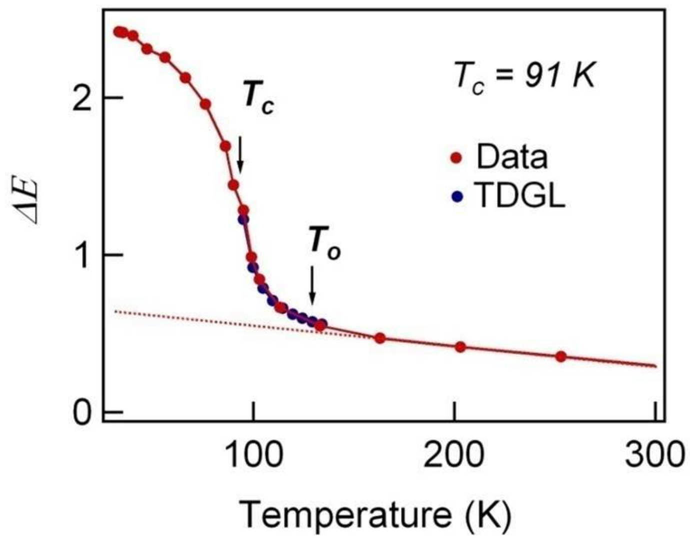
Temporal evolution of the coherence length

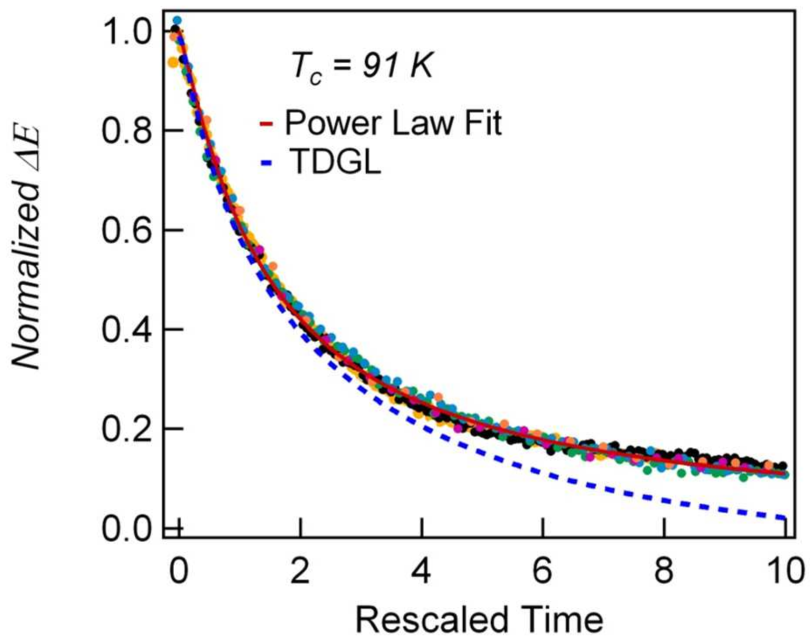


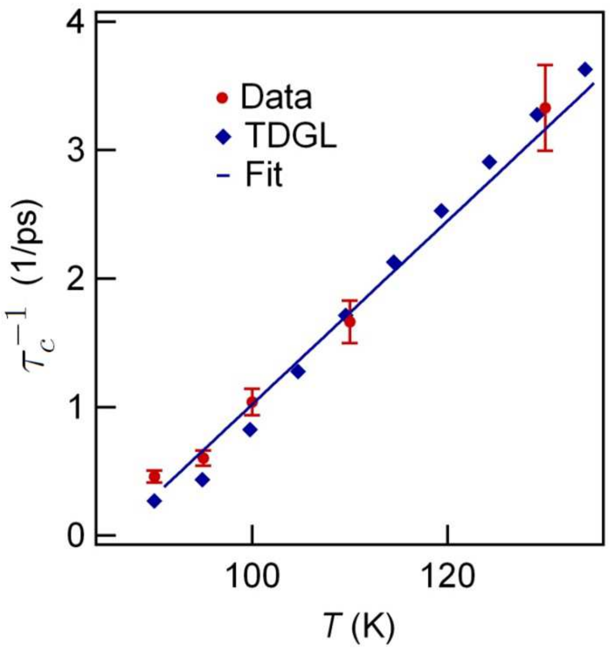
Far-infrared conductivity Aslamazov-Larkin, Maki-Thompson

Mid-infared conductivity scales as: $\ln(\xi/\xi_0)$

F. Federici Phys. Rev. B (1997)
A. Petkovic Phys. Rev. B (2011)





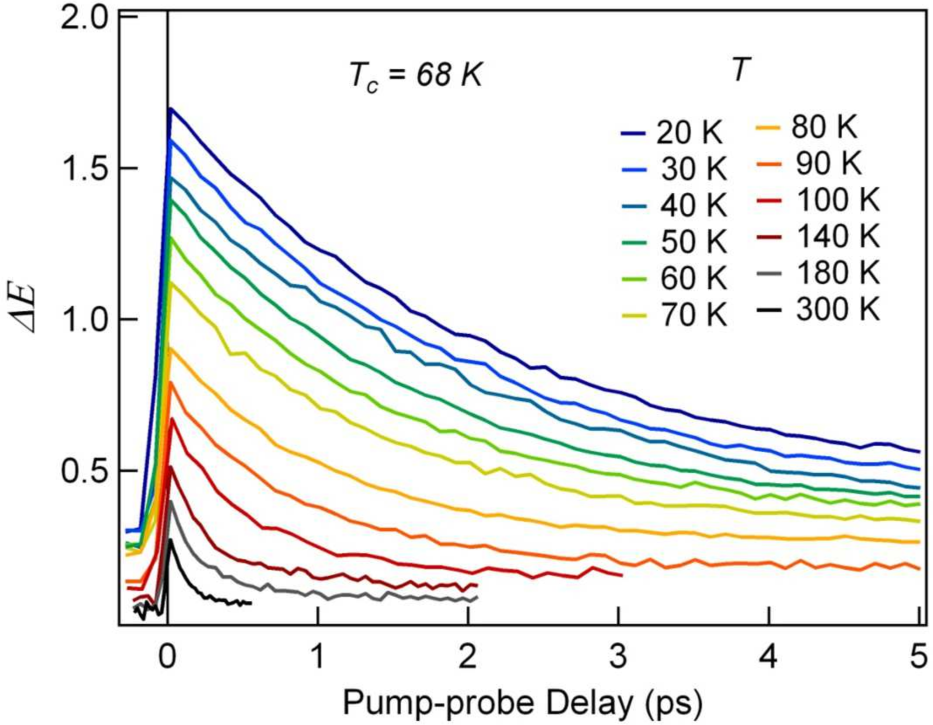


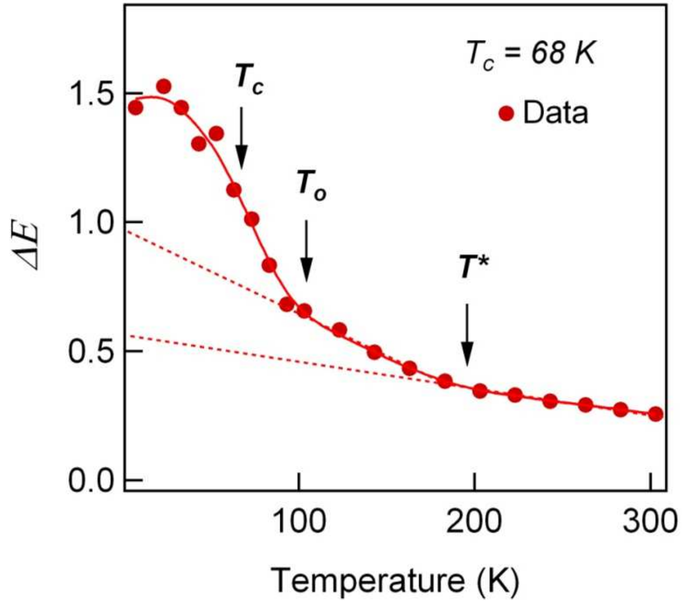
TDGL predicts an exponential decay and not power law!

TDGL accounts for the amplitude of the fluctuations and the scaling

$$\tau_c \cong \frac{1}{(T - T_c)}$$

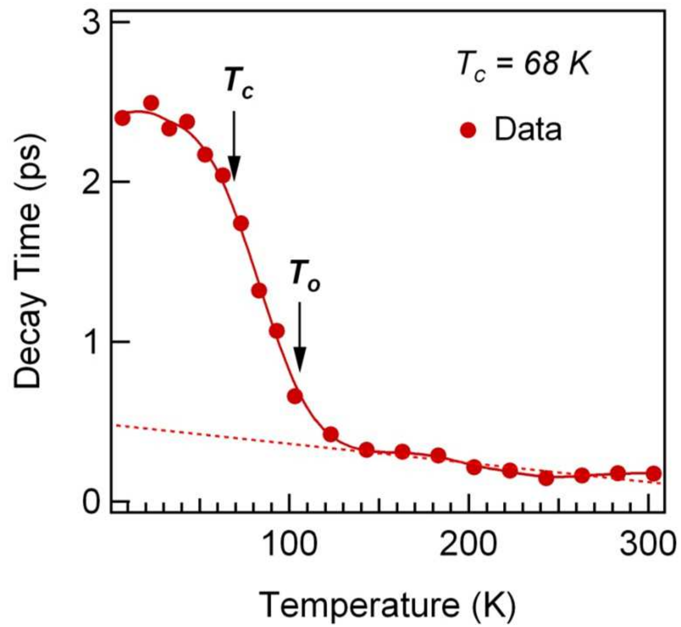
Underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$





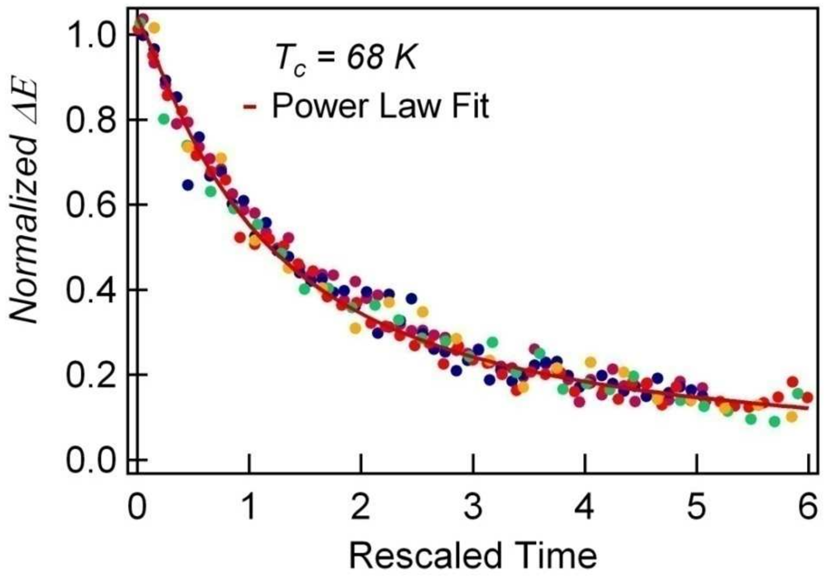
Onset occuring at $T_o = 1.4\ T_c$

Observation at T^* of a kink Pseudogap!?



Increase of decay time below T_o

No critical behaviour at T^* Crossover

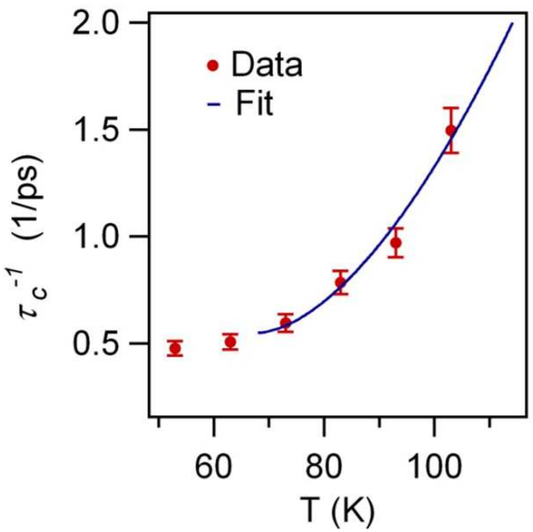


Scaling law respected also in underdoped sample

$$\frac{1}{1+(\tau/\tau_c)^\alpha}$$

$$\alpha = 1.2$$

The critical exponent α does not depend on doping



The slowing down of ψ matches the power law

$$\tau_c \cong \frac{1}{(T-T_c)^\beta} \quad \text{with} \quad \beta = 1.7$$

Different from TDGL!

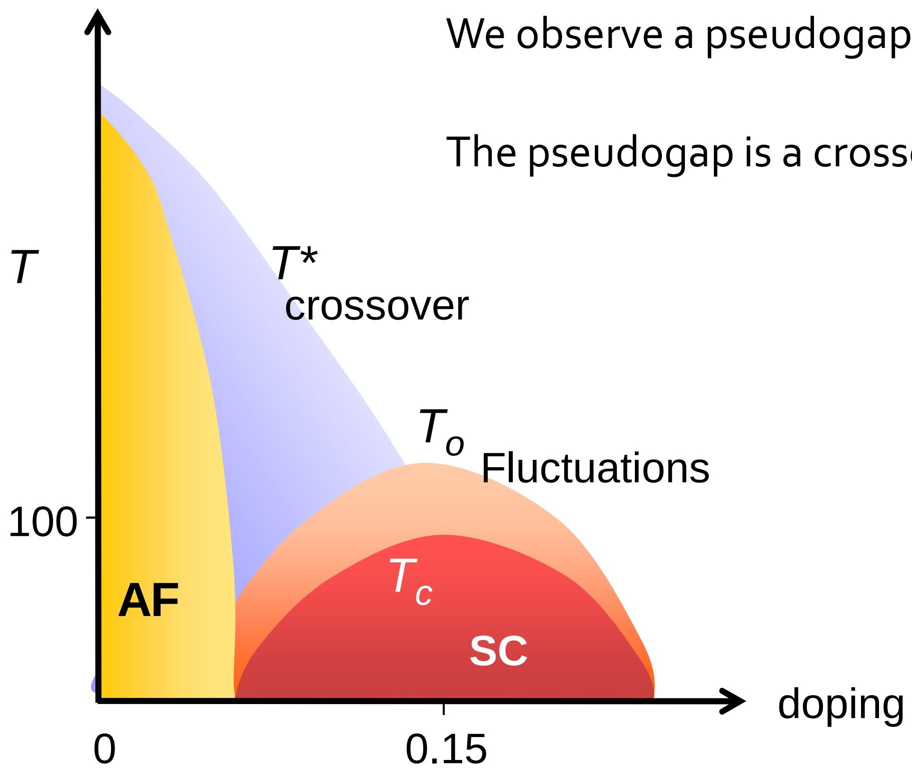
Which pictures emerge from our data?

Fluctuations extend up to 1.4 T_c both in underdoped and optimally doped cuprates

We do not observe a pseudogap at optimal doping

We observe a pseudogap in a strongly underdoped compound

The pseudogap is a crossover without any critical behaviour

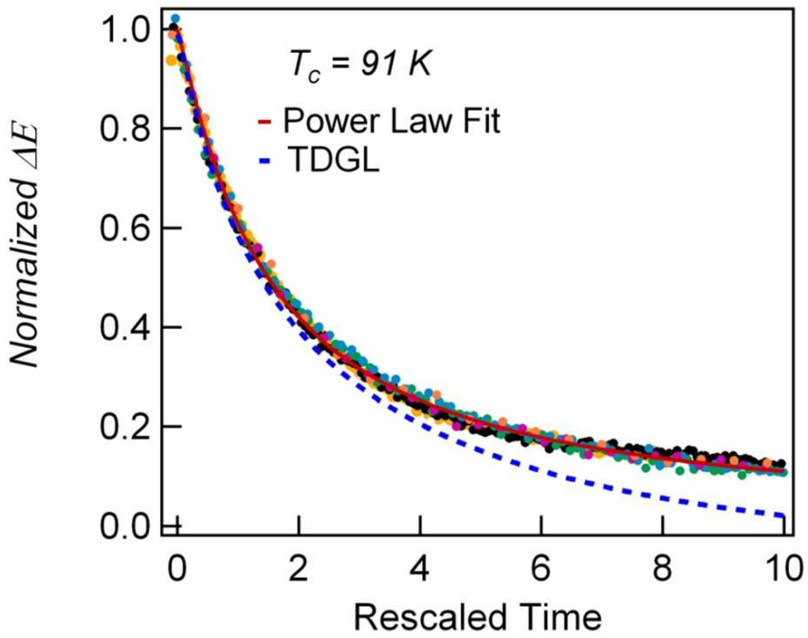


M. Norman Adv. Phys. (2005)

S. Hufner, Rep. Prog. Phys. (2008)

P. Wahl Nature physics (2012)

Origin of the powerlaw



Possible reasons

- ✓ Failure of the sudden quench hypothesis
- ✓ coarsening related to disorder
- ✓ presence of a conserved density

Scaling $$\frac{1}{1+(\tau/\tau_c)^{\alpha}}$$

Presence of a conserved field *m*

TABLE I. Some dynamical models treated by renormalization-group methods.

Model	Designation	System	Dimension order of parameter	Non-conserved fields	Conserved fields	Non-vanishing Poisson bracket
Relaxational	A	Kinetic Ising anisotropic magnets	n	ψ	None	None
	B	Kinetic Ising uniaxial ferromagnet	n	None	ψ	None
	C	Anisotropic magnets structural transition	n	ψ	m	None
Fluid	H	Gas–liquid binary fluid	1	None	ψ $\mathbf{j}$	$\{\psi, \mathbf{j}\}$
Symmetric planar magnet	E	Easy-plane magnet, $h_z = 0$	2	ψ	m	$\{\psi, m\}$
Asymmetric planar magnet	F	Easy-plane magnet, $h_z \neq 0$ superfluid helium	2	ψ	m	$\{\psi, m\}$
Isotropic antiferromagnet	G	Heisenberg antiferromagnet	3	ψ	$\mathbf{m}$	$\{\psi, \mathbf{m}\}$
Isotropic ferromagnet	J	Heisenberg ferromagnet	3	None	ψ	$\{\psi, \psi\}$

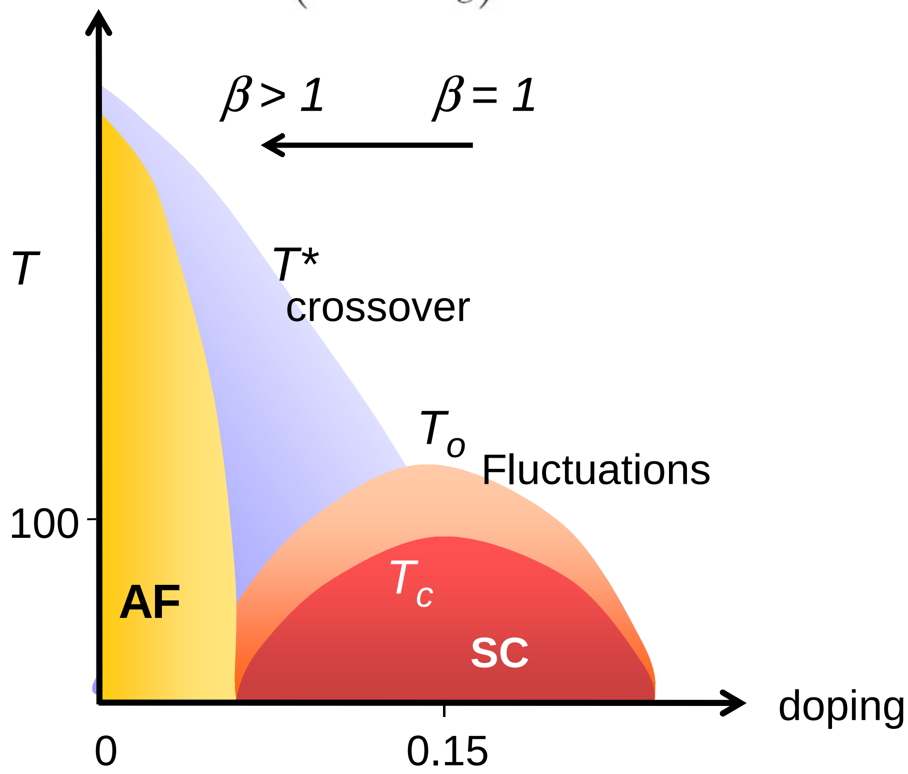
Halperin classification scheme

P. C. Hohenberg, B. I. Halperin, Rev. Mod. Phys. 1977

Doping indepent scaling law

$$\frac{1}{1+(\tau/\tau_c)^\alpha}$$

$$\tau_c \cong \frac{1}{(T-T_c)^\beta}$$



U(1) does not describe high temperature superconductivity

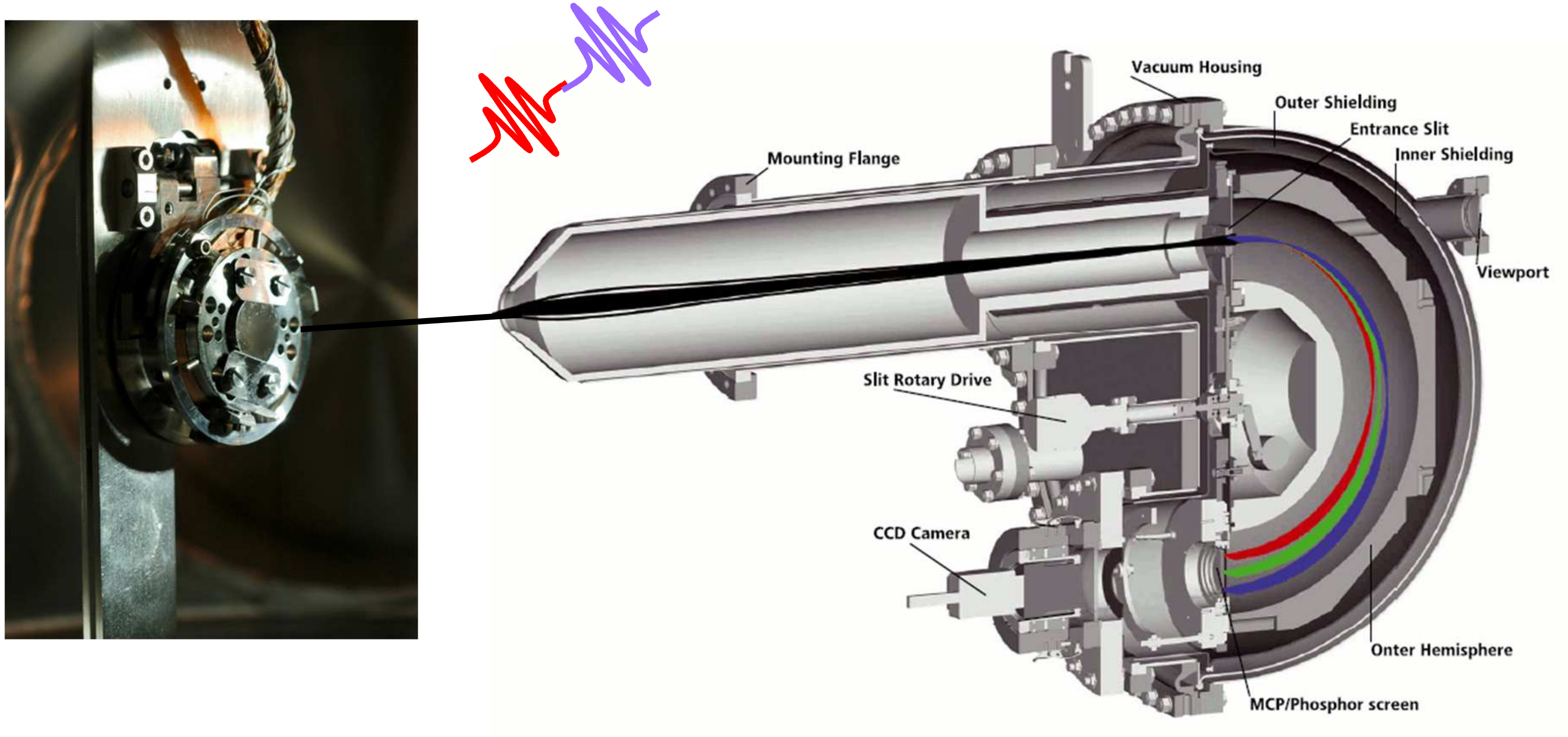
Which model predicts the correct behaviour?

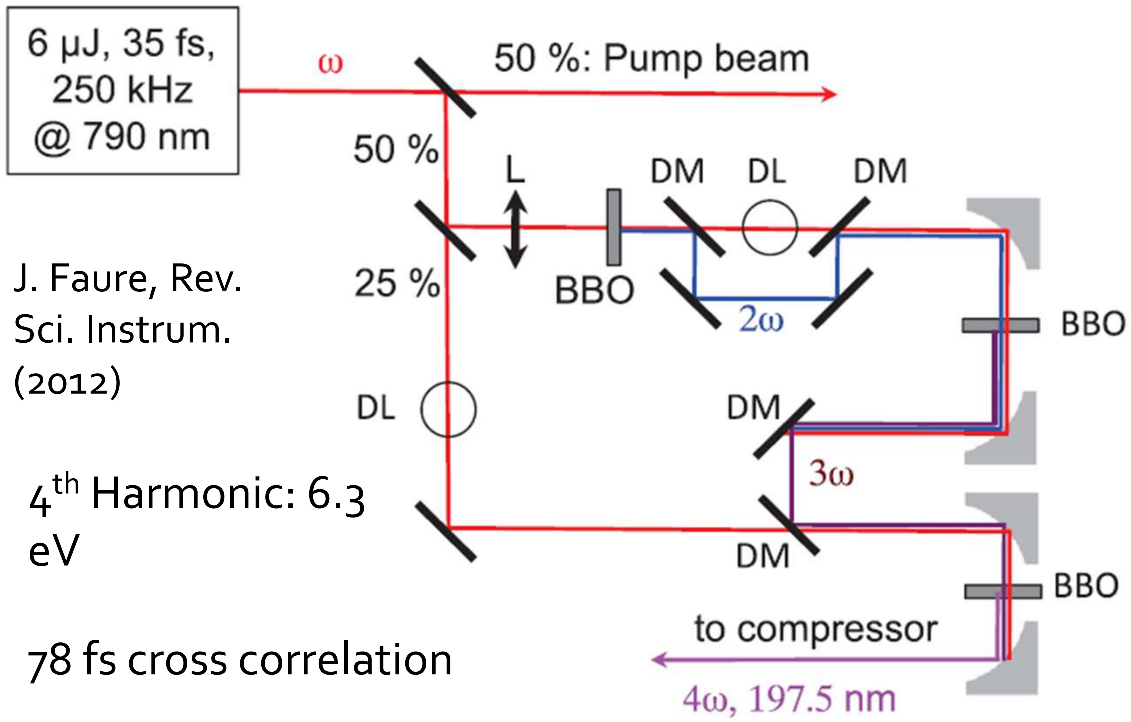
SO(4) competition with charge density wave

SO(5) competition with staggered antiferromagnetism

....

Angle Resolved Photoelectron Spectroscopy

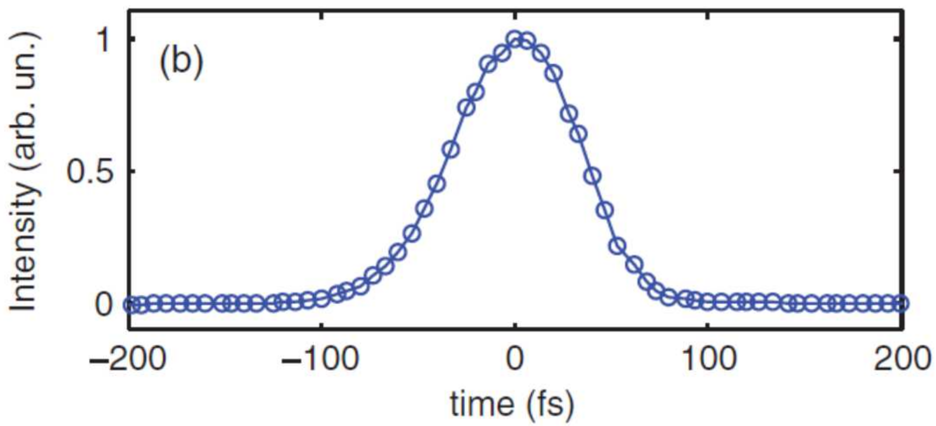




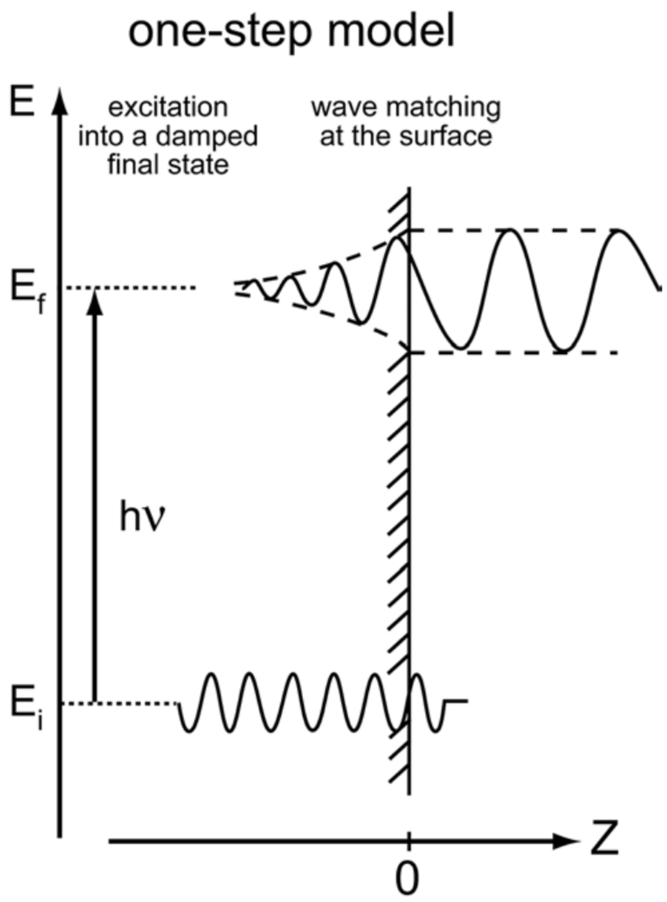
J. Faure, Rev. Sci. Instrum. (2012)

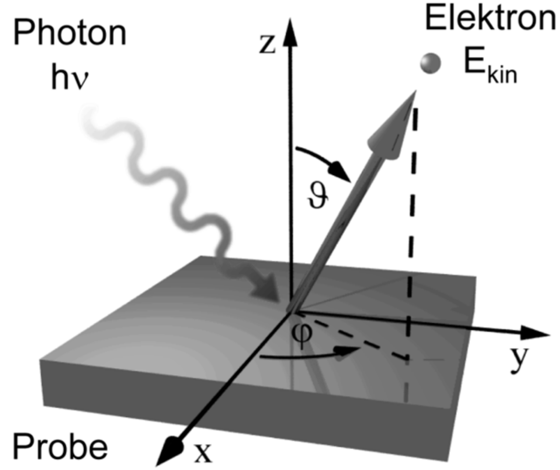
4th Harmonic: 6.3 eV

78 fs cross correlation



ARPES principles



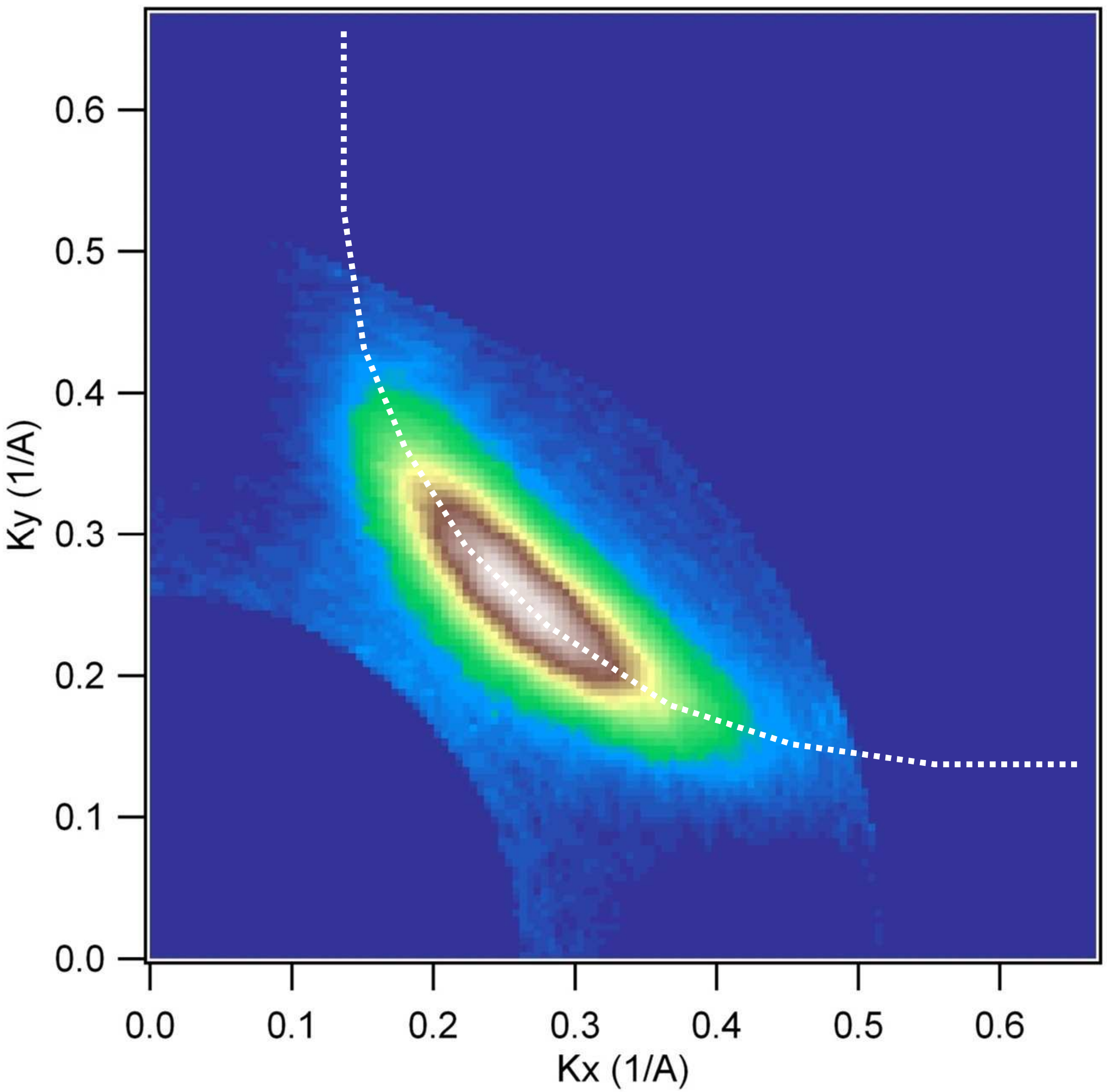


$$E = h\nu - \phi - E_{kin}$$

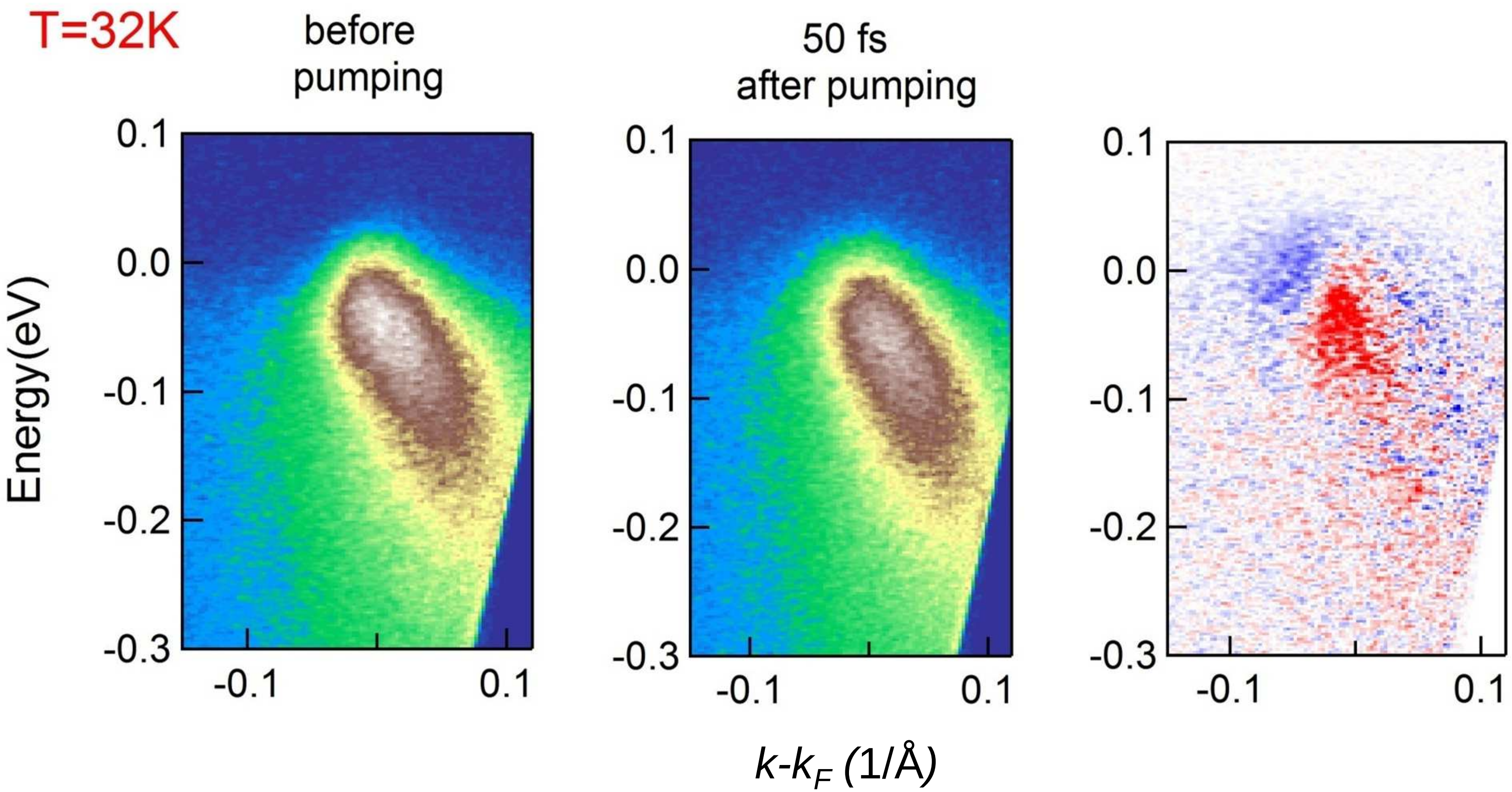
$$\boldsymbol{k}_{\parallel} = \frac{1}{\hbar}\sqrt{2mE_{kin}} \cdot \sin\vartheta$$

φ Direction

Fermi surface with 6.3 eV photons

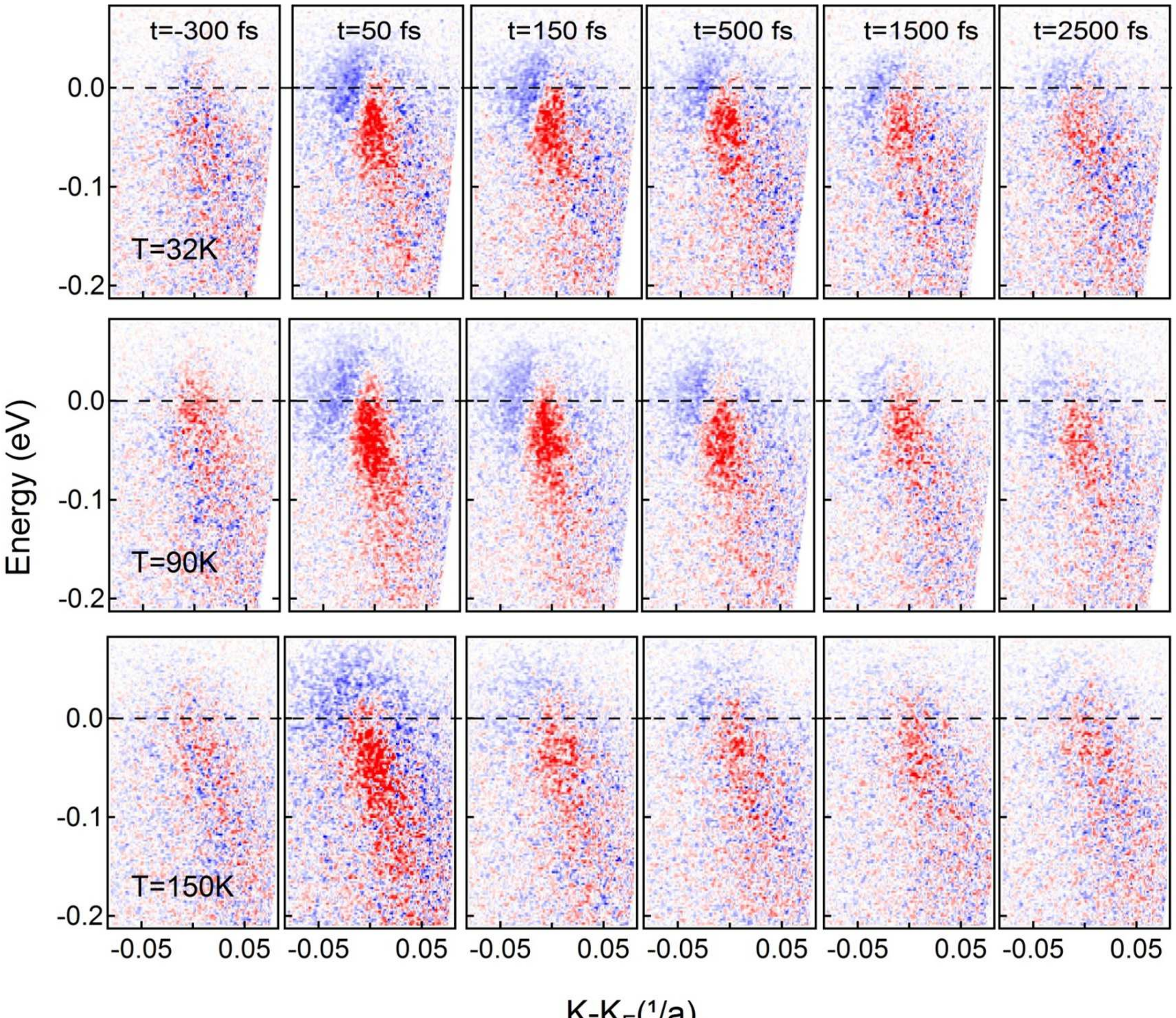


Photoexcitation of nodal quasiparticle

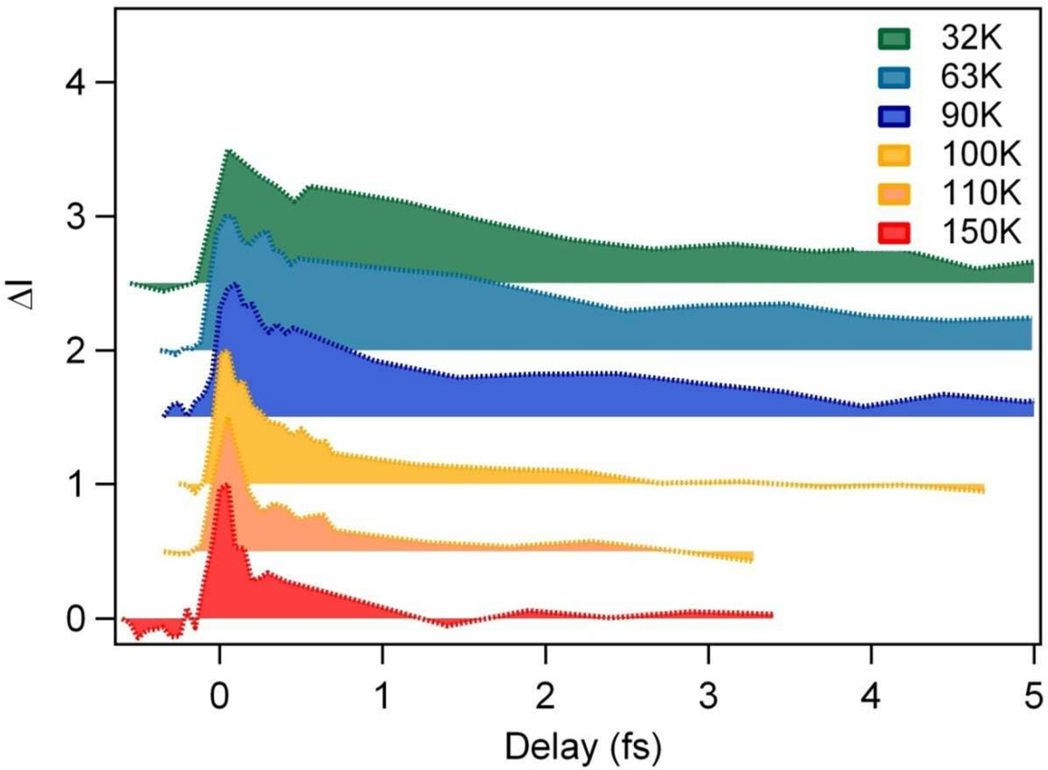


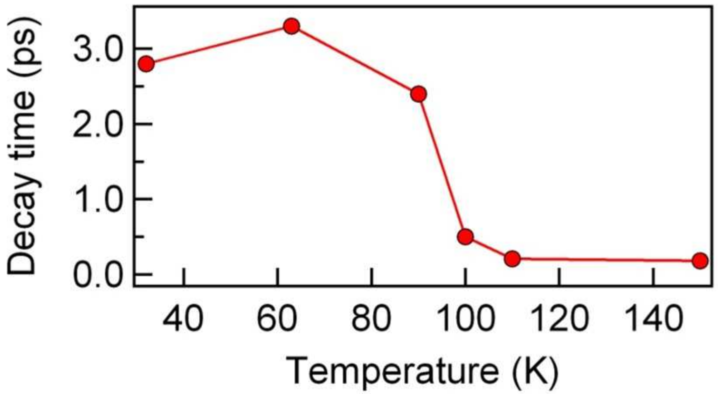
Signal dominated by the non-equilibrium distribution $f(\omega,\tau)$

Relaxation ruled by the energy dissipation in the lattice modes



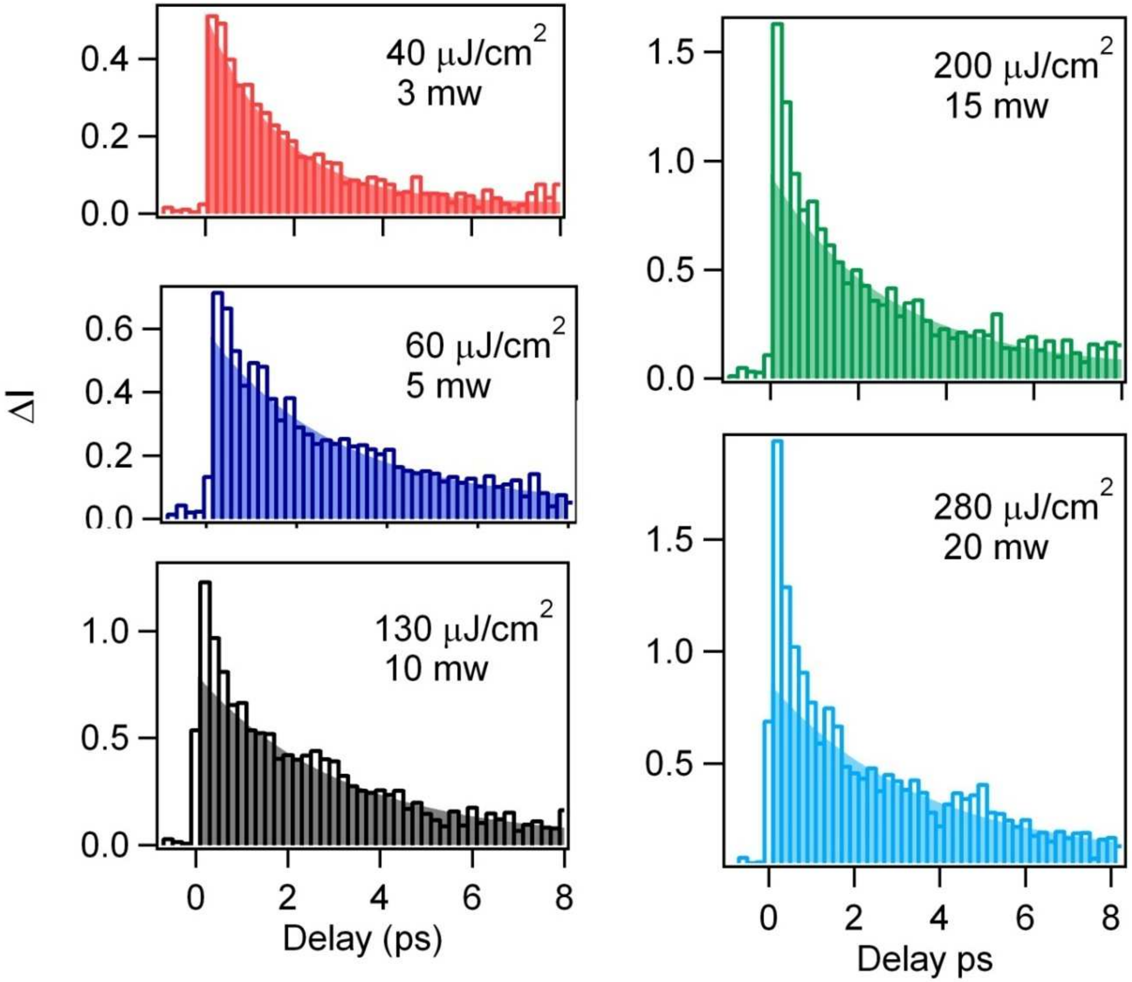
t=-300 fs
t=50 fs
t=150 fs
t=500 fs
t=1500 fs
t=2500 fs
T=32K
T=90K
T=150K
Energy (eV)
0.0
-0.1
-0.2
-0.05
0.05
K-K$_F$(¹/a)





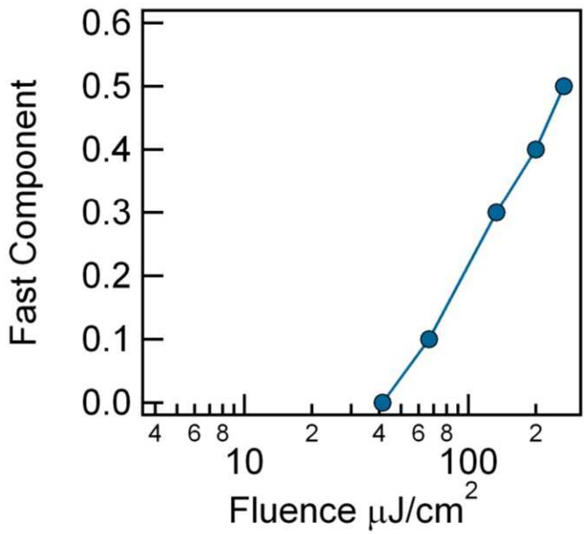
In the superconducting phase the Cooper pairs prevent the fast energy relaxation of the electrons

Similar to THz transmission



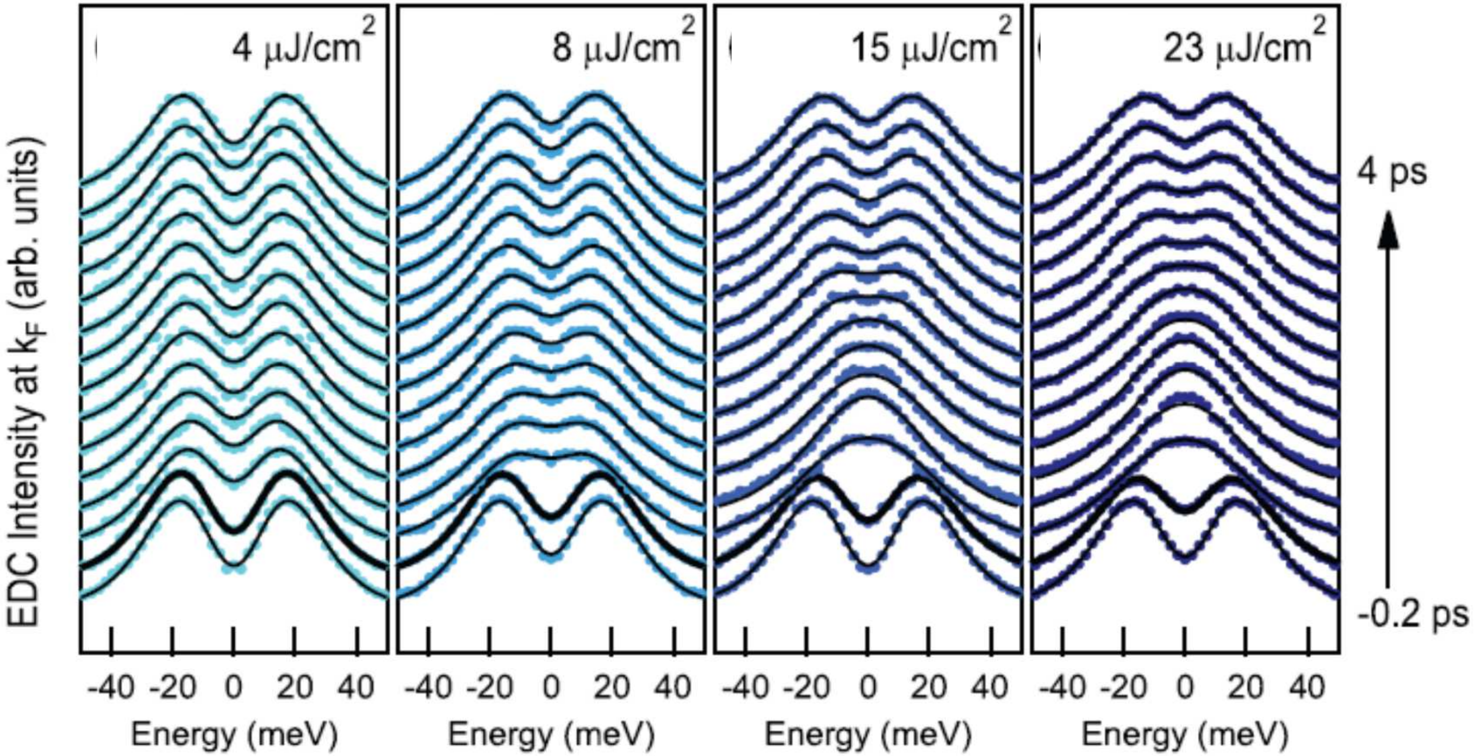
Fast component becomes visible for fluences higher than 60 microJ/cm²

Closing of superconducting gap?



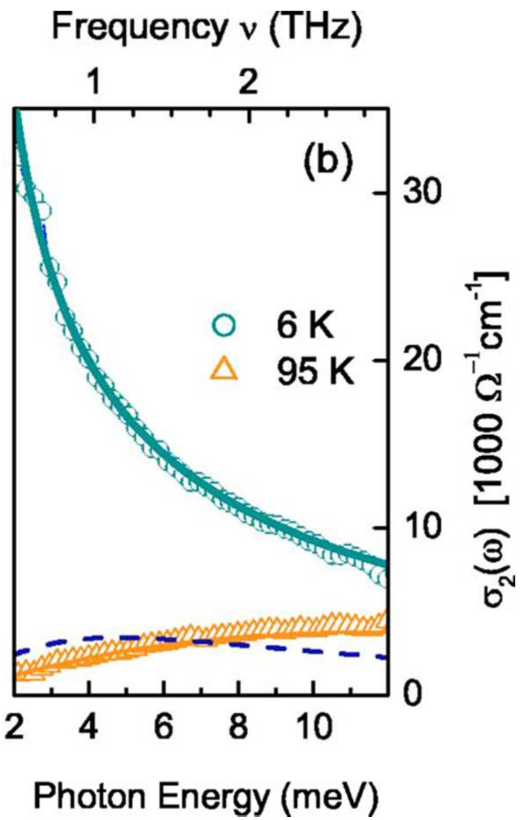
Single Particle gap filled at 15 microJoule/cm²

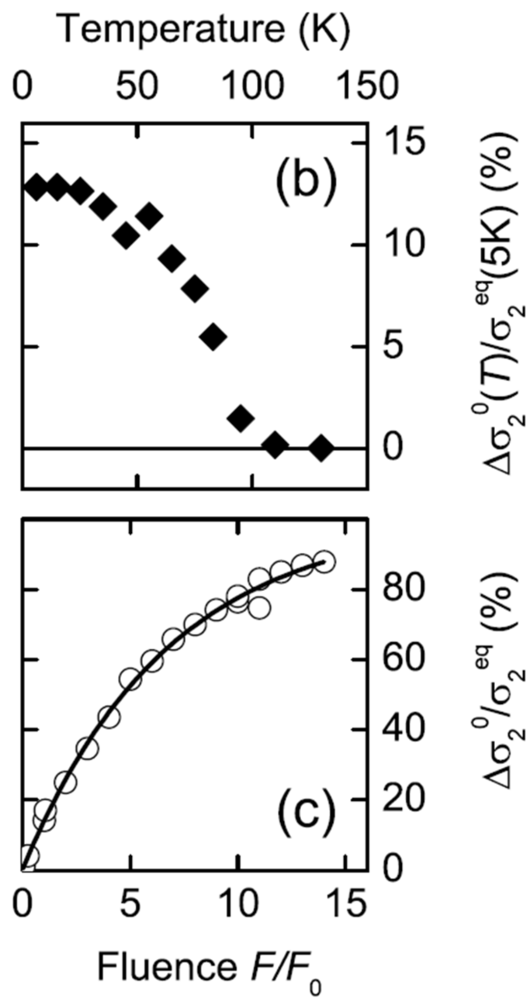
C. L. Smallwood PRB 2014



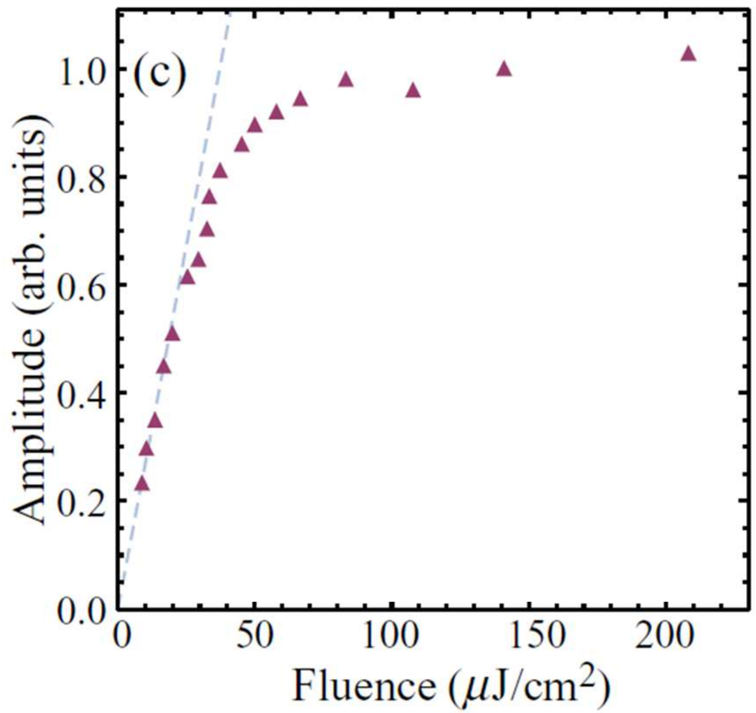
Superfluid density vanishes with 12 microJoule/cm²

M. A. Carnahan Physica C (2004)





Near infrared optics on bulk samples



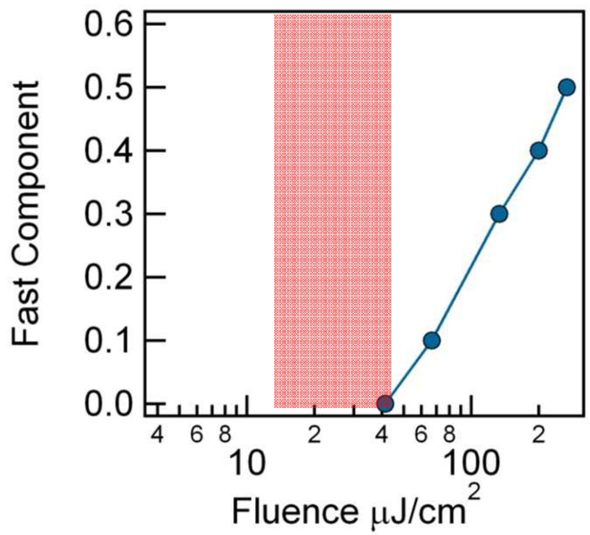
Presence of competing signal

Probe of a region that is not uniformly excited

Y. Toda, Phys. Rev. B (2011)

Superconductivity in optimally doped BSCCO is destroied at 16 microJoule/cm²

Existence of photoexictation densities with no order parameter and weak dissipation



Presence of a regime with no phase coherence

$$\Delta = \frac{1}{L^d} \left| \int \langle \psi(x) \rangle dx \right| = 0$$

but with finite stiffness

Conclusions

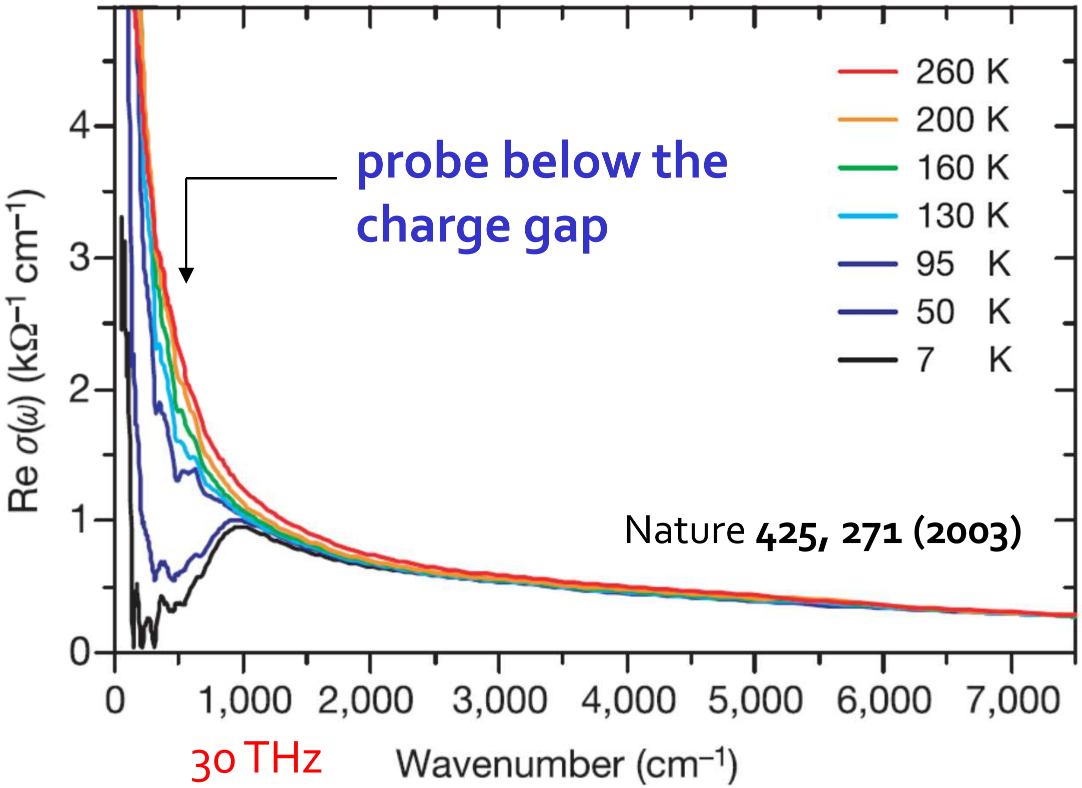
The dynamics of critical fluctuations in high temperature superconductors suggest the coupling to a conserved field

Critical slowing down deviates from Gaussian fluctuations in the underdoped region of the phase diagram

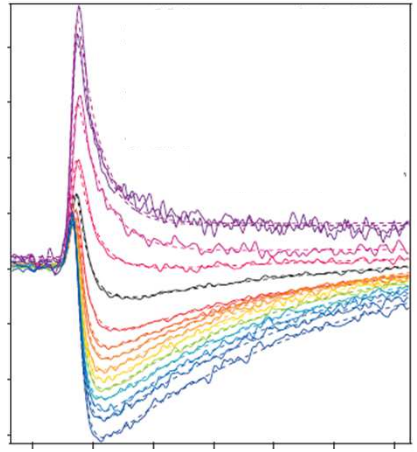
At low temperatures, a regime of excitation densities exist with no long range order but weak energy dissipation

Collaborators

T. Kampfrath and M. Wolf	TR-THz measurements
B. Sciolla and G. Biroli	Theory of critical phenomena
K. Van Der Beek and C. Piovera	K. Van Der Beek and C. Piovera

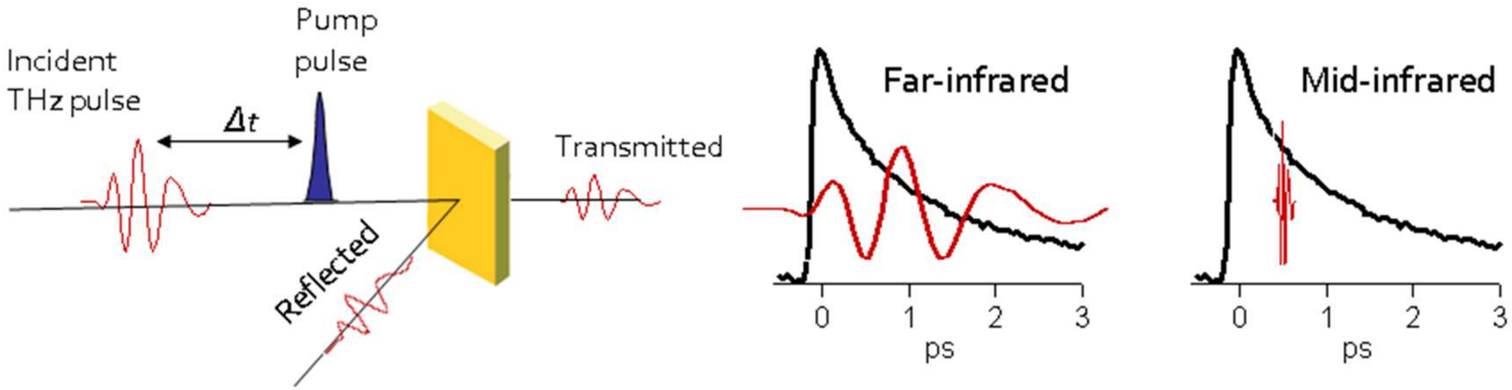


PRB **83, 064519 (2011)**



Competing signal in the visible spectral range

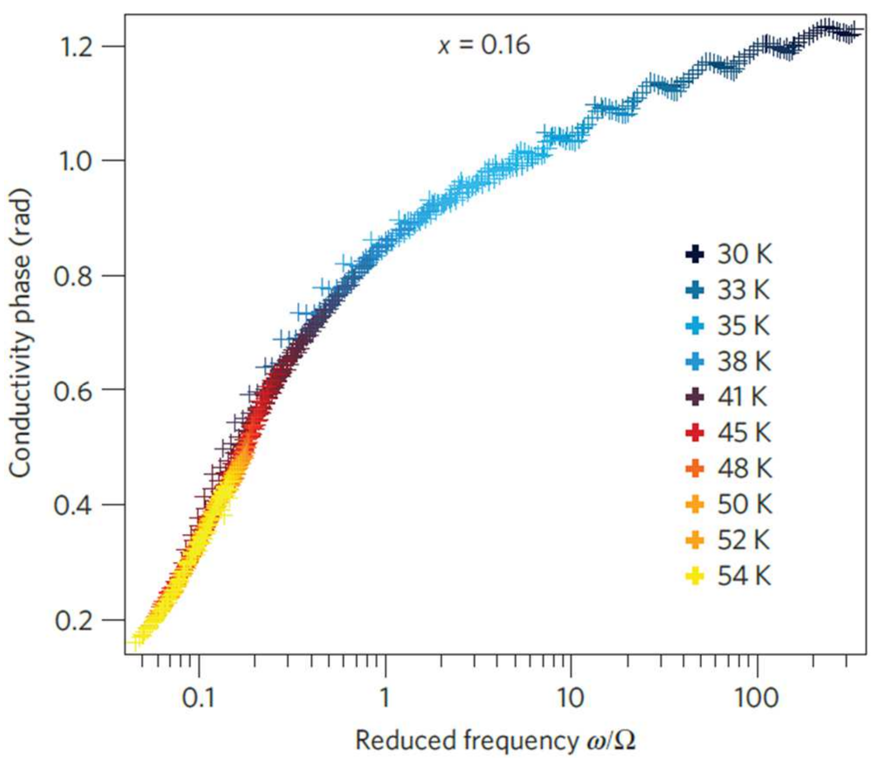
Far infrared pulses too long to resolve dynamics of fluctuations

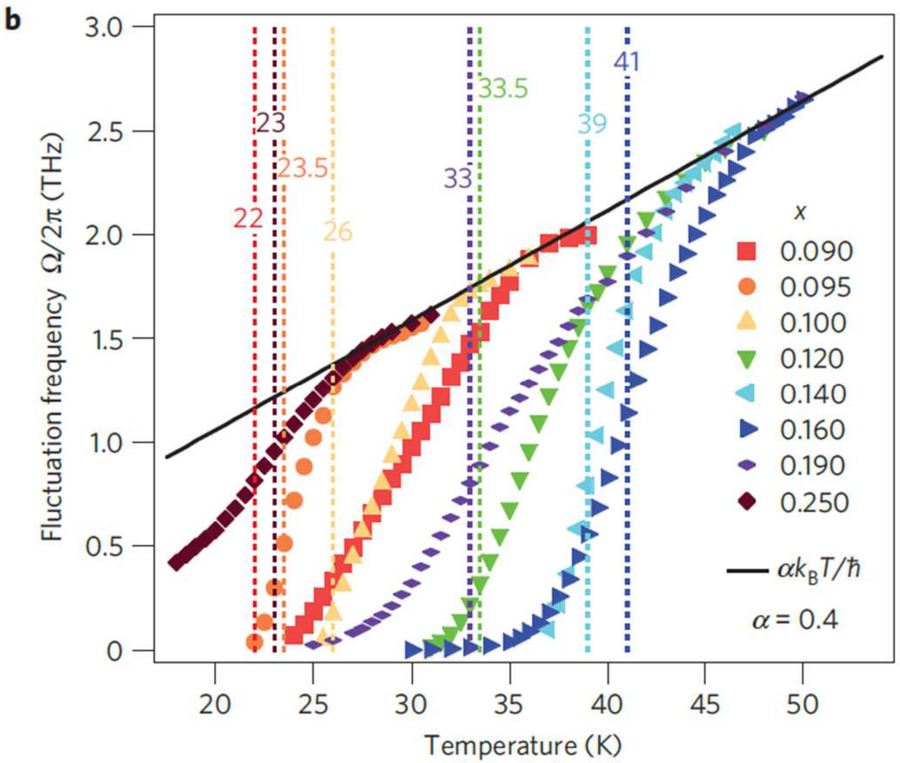


Paraconductivity measurements with low THz probes

Armitage

Nature Physics **7, 298 (2011)**



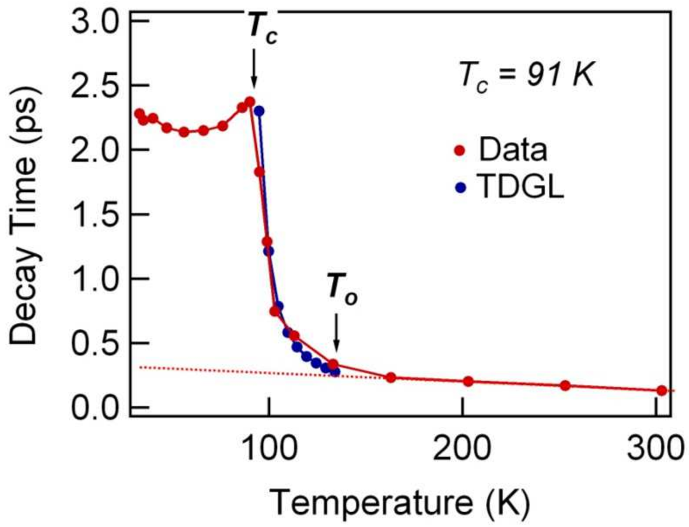


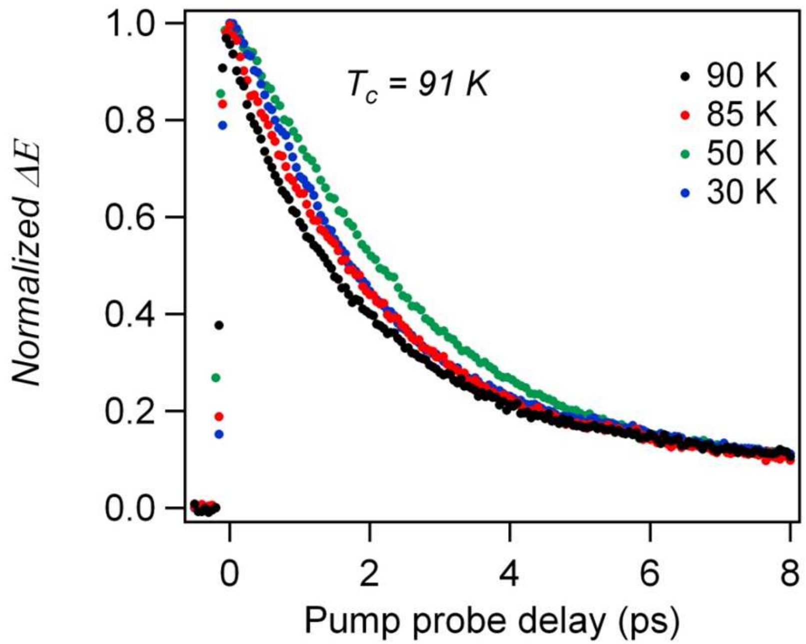
$$\sigma_{\mathrm{f}}(\omega) = \frac{G_{\mathrm{Q}}}{t} \frac{k_{\mathrm{B}} T_{\phi}{}^{0}}{\hbar\Omega} \mathcal{S}\left(\frac{\omega}{\Omega}\right)$$

Presence of inhomogeneous broadening

Superconducting phase: $\boldsymbol{T < T_c}$

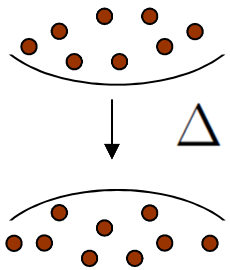
The relaxation takes place in ~ 2 ps





Slow motion regime

$$\hbar \frac{d}{d\tau}\Delta < \Delta^2$$

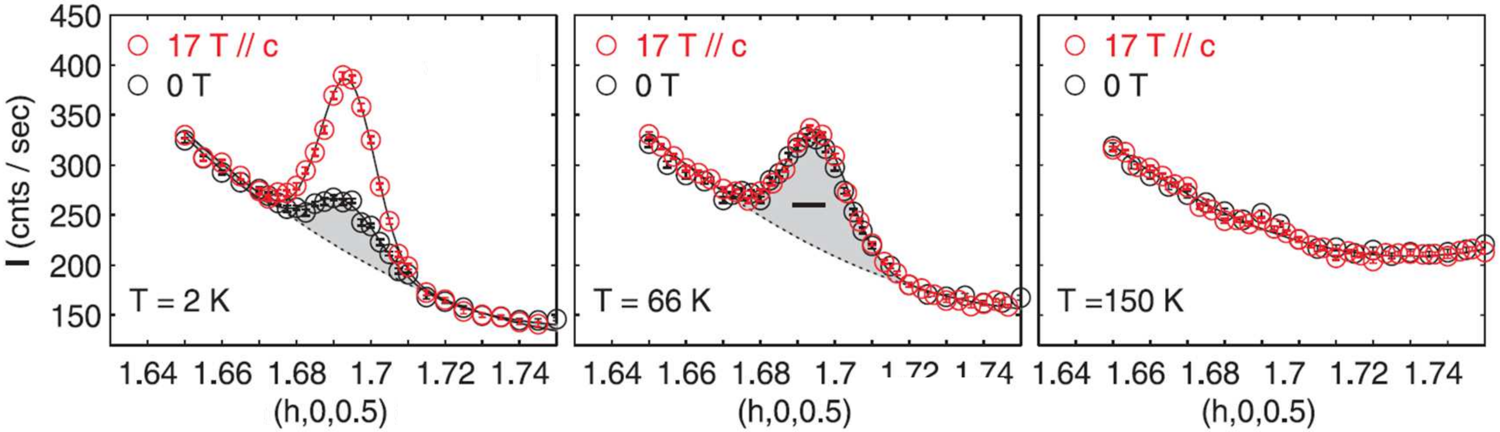


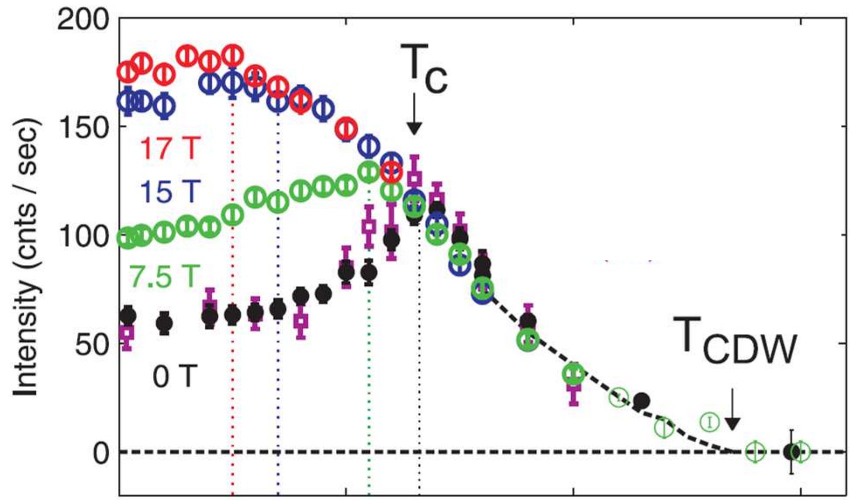
Phonon-bottleneck

V. V. Kabanov, Phys. Rev. Lett. (2005)

The temporal evolution of the order parameter is ruled by the dissipation of non-equilibrium quasiparticles via phonon emission

Contribution of XFELs





Observation of
competing order

Dynamics of charge
or spin fluctuations

J. Chang, Nature Phys. 2011