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Superconductivity, Glue, and the Pseudogap

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- Superconductivity—its not just about zero resistance.
- Glue-gotta have it! What does it glue? Why is it needed?
- Pseudogap—I'm not going tell you what it is because I don't know. But I now do know some important properties. And by the end of the talk, you'll get the importance of the Nature paper title.

Bounding the pseudogap with a line of phase transitions in $YBa_2Cu_3O_{6+\delta}$, Arkady Shekhter, B. J. Ramshaw, Ruixing Liang, W. N. Hardy, D. A. Bonn, Fedor F. Balakirev, Ross D. McDonald, Jon B. Betts, Scott C. Riggs & Albert Migliori, Nature 498, 75–77 (06 June 2013)

Energy Security Council

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Superconductivity is a quantum superfluid of electrons

Electrons are fermions, with spin ½. No two can have the same quantum state of energy and spin. We know how to make a quantum theory of metals from this.

Understanding the quantum theory of metals is not enough to predict that superconductivity exists. Superconductivity is a poster child for “correlated electrons”.

New physics must be brought to bear to make a superfluid of electrons.

To get to a superfluid we need to glue electrons together in pairs.

The type of glue is *unimportant*. Its properties are.

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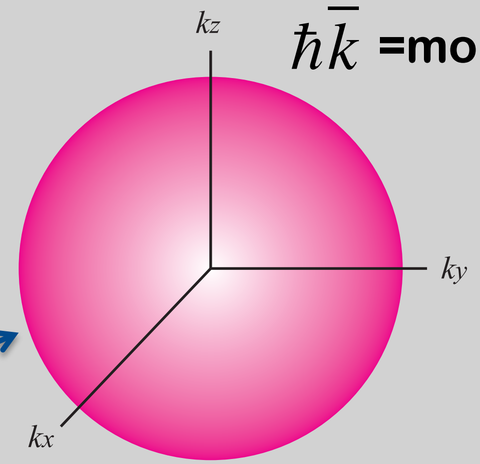
The quantum theory of metals sets an energy scale

Every electron has to have a different state in a metal.

This means that as we add electrons to a box full of nicely arranged nuclei, every two electrons (spin up, spin down) go in with higher and higher energy until the solid is electrically neutral.

The quantum theory of metals:

$\hbar\bar{k}$ =momentum.

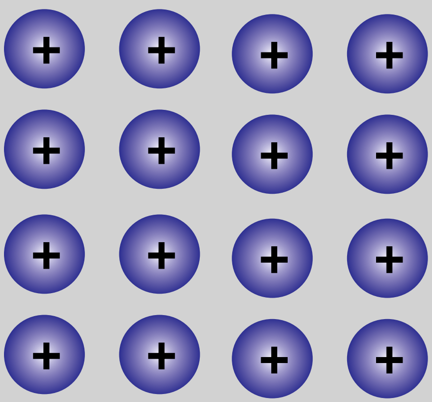


ε_{Fermi} is the energy of the surface in momentum space inside which all the electrons reside.

$\varepsilon = f\left(k_x, k_y, k_z\right)$ is the energy of an electron

We'll use temperature as the unit of energy.
The energy of electrons at the Fermi surface is ~30,000K
That's our first energy scale.

“Screening” is the collective response of ions and electrons



The positive ions in a solid combine with negative electrons to make an electrically neutral system.

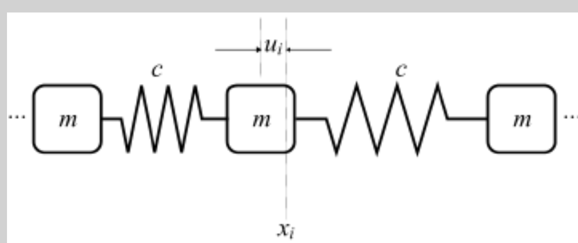
Ions can move a little bit to block the long range repulsion of electrons from each other.

The motion can be dynamic—this produces the dielectric response.

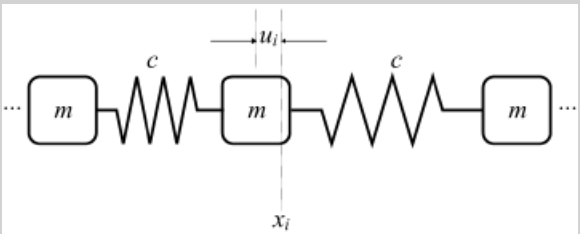
The dielectric response ensures that the “coulomb repulsion” acts only over *very very* short distances-less than a unit cell.

This response “screens” electrons and ions from each other at long range.

It also makes the ions look like masses and springs (short range forces).

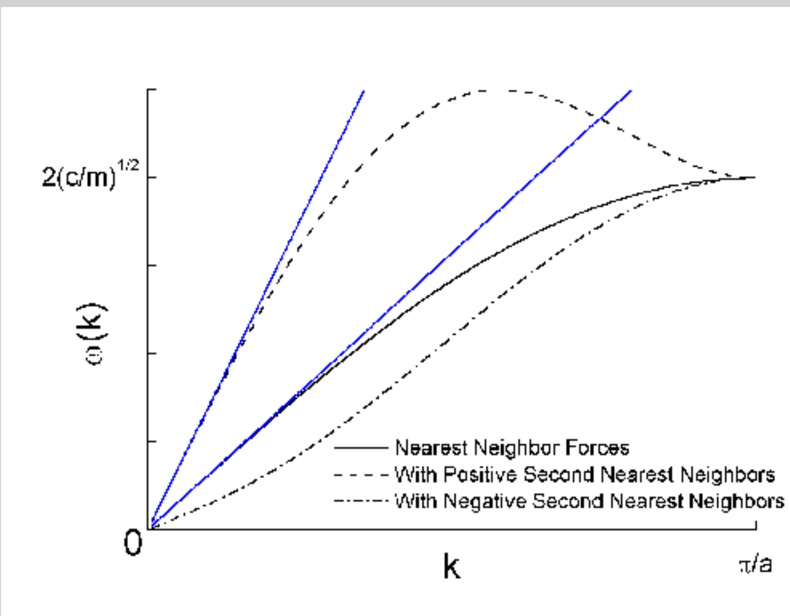


The quantum theory of vibrations analyzes masses and springs



Screening makes atoms and bonds look like masses and springs, a bunch of coupled quantum harmonic oscillators.

The quanta are phonons.



With 10^{23} atoms, the allowed phonon energies make a nice smooth curve, the dispersion curve. *The initial slopes are the sound speeds.*

The highest frequency vibrations are about 300K, the Debye energy.

That's our second energy scale.

Electrons couple to phonons—the form is almost obvious

Bardeen, Cooper, Schreiffer, Gorkov, Abrikosov, Dzyaloshinskii knew this:

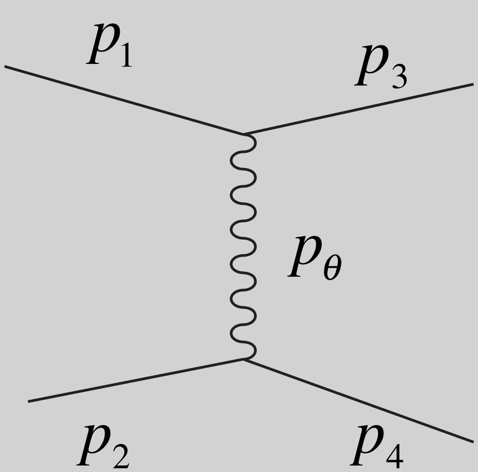
•Electrons move at 300 times the speed of sound(Quantum theory of metals).

•The electrons tweak the lattice for short times (a non-resonant drive) creating a brief distortion or virtual phonon (Quantum theory of phonons) that takes a long time to recover (300K) and so is “retarded”.

•The effect on an electron by another electron that disturbed the lattice briefly looks something like a harmonic oscillator driven off resonance:

$$\frac{\omega_0^2\left(\vec{k}\right)}{\omega^2\left(\vec{k}\right)-\omega_0^2\left(\vec{k}\right)}$$

Think of an electron whizzing by a mass and spring where the mass has charge.



$$\omega\left(\vec{k}\right)=\left(e_3-e_1\right)$$ is the energy shift of the electron

$$\omega_0\left(\vec{k}\right)=u\ \left(\vec{p}_3-\vec{p}_1\right)$$ is phonon energy determined by its momentum (dispersion curve).

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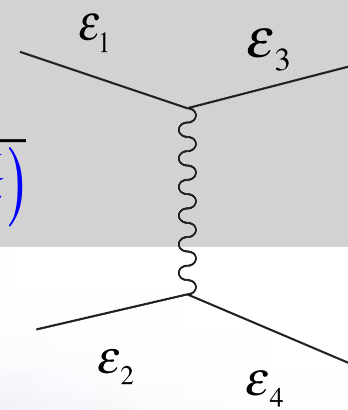
Everything happens well inside the Debye energy

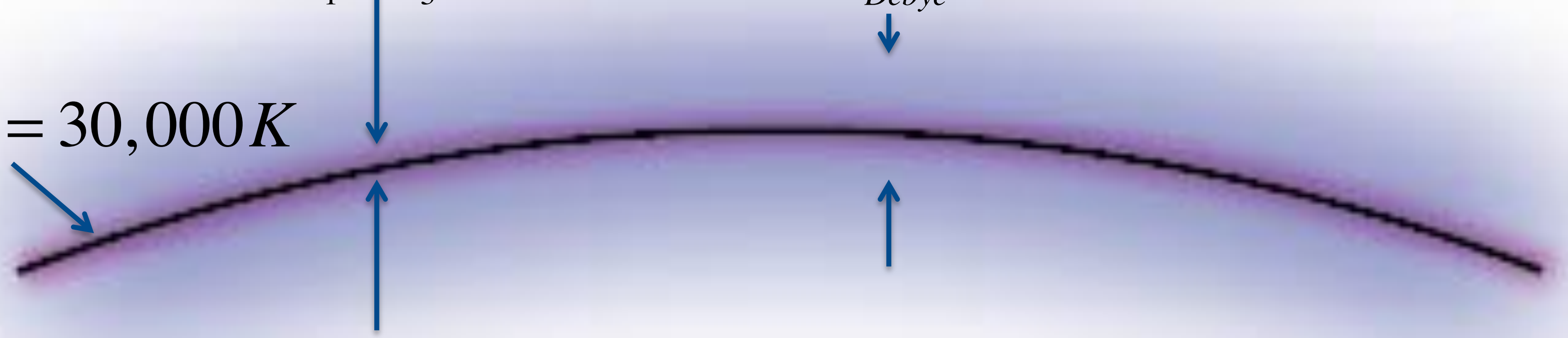
Harmonic oscillator and electron-phonon coupling = $\dfrac{\omega_0^2(\vec{k})}{\omega^2(\vec{k})-\omega_0^2(\vec{k})}$



The interaction is attractive if

$\varepsilon_1 - \varepsilon_3$ is much less than ε_{Debye}

$\varepsilon_{Fermi} = 30{,}000K$

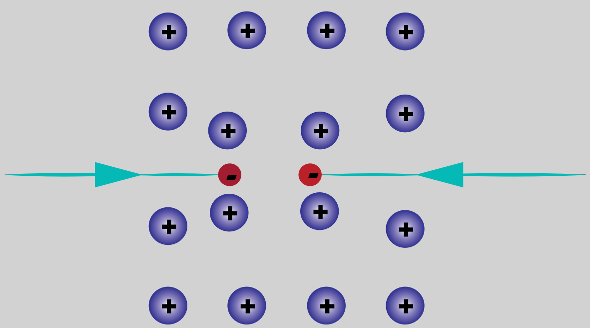


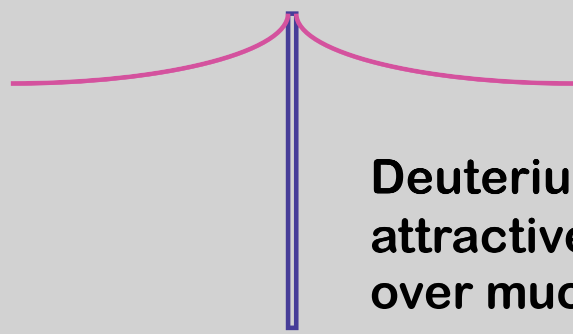
- **A 1D attractive potential, no matter how weak, produces bound state—** ***everybody knew this.***

- **If two electrons are constrained to sharp Fermi surface in momentum space, right where they cross, the electron-phonon interaction acts and is attractive, but longer range and delayed compared to unscreened super-short-range coulomb repulsion.**

Why they got the Nobel Prize

•Some electrons form a bound state no matter how weak the attraction (quasi 1D potential analogy *but in momentum space*). Key insight by Cooper.





Deuterium analogy: very short range attractive nuclear force stabilizes over much longer distance.

•The system energy is lowered because every electron close to Fermi surface can find a mate. All pairs have zero momentum, a good quantum number.

•Pairs form state that does not conserve charge—that is, the number of pairs in the ground state is not fixed by anything. Very controversial at the time—Key insight by Bardeen, Cooper, Schreiffer.

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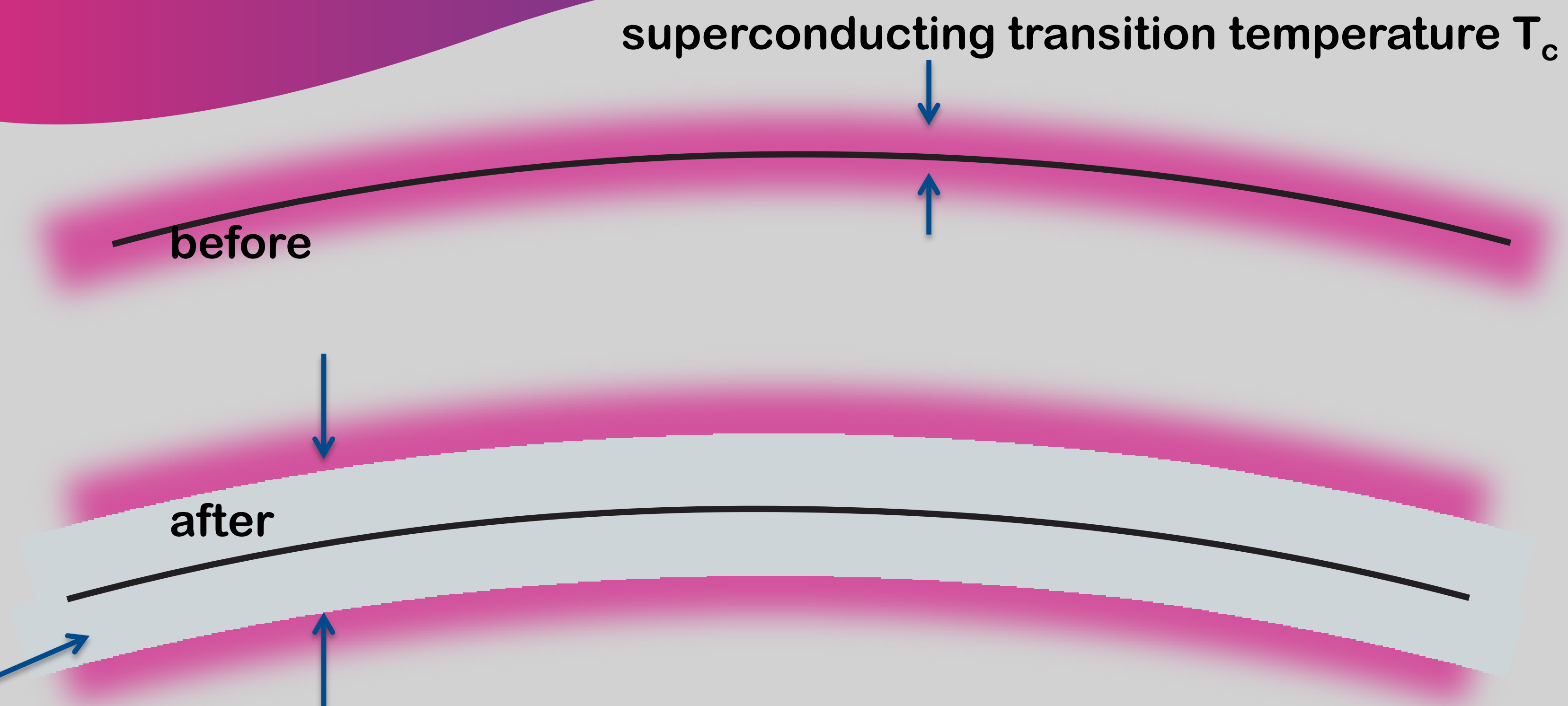
A cartoon here is useful



- Gap forms where states were removed by pairs.

- *The system does not make bosons*-that is, pairs do not form and then condense. Its really a single process-as soon as a pair with zero momentum forms, it superconducts.

- Its the size of the bound pair and the very low Debye frequency that leaves time for fast electrons to talk to each other via phonons: interaction time is determined roughly by the spatial extent of the pair (coherence length $\xi(T)$) , and the Fermi velocity.

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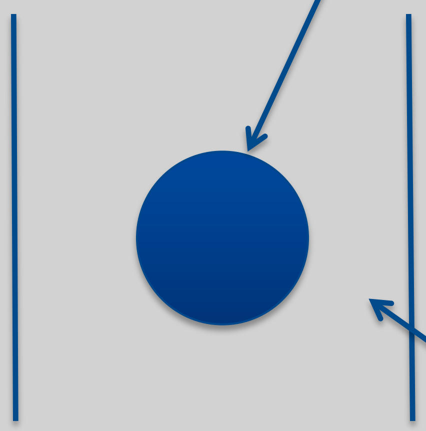
Just one more thing about the "field" of pairs

The superfluid has charge q, mass m of order Avogadro's number. Remember, charge is not a good quantum number.



$$F = ma = qE_0 e^{i\omega t} = m\frac{dv}{dt}$$

$$\sigma = \frac{I}{E} = \frac{q^2}{i\omega m}$$

The superfluid looks like an inductor (inertial)-easy to see why the current goes to infinity when a DC field is applied (Kramers Kroenig)-just like an inductor.

Electric field E(t)

The skin depth is $\lambda = \sqrt{\frac{2}{\omega\sigma\mu}}$ independent of frequency!

A frequency-independent skin depth means that any magnetic field, even a DC one, only penetrates a small distance-the Meissner effect.

This leads to a good *order parameter* for the phase, the thermodynamic critical field H_c .

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Continuous (second order) phase transitions have slow fluctuations

- The glue we're looking for in high T_c superconductors must force slow dynamics if the electrons (30,000K) are to interact on high T_c energy scales (100K).
- If by tuning some parameter, a line of second order phase transitions ends at zero temperature, then the end point is a quantum critical point.
- Second order phase transitions have dynamic fluctuations with time scales determined only by the phase transition temperature. Just right for glue.
- This glue can be present at temperatures far from the second order phase transition.

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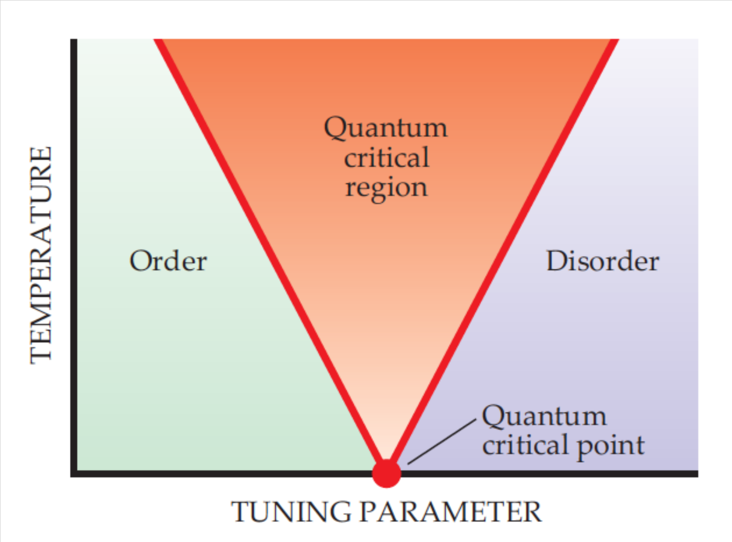
The glue for high T_c superconductors?



- Copper oxide superconductors show ‘strange metal’ behavior suggestive of strong fluctuations associated with a quantum critical point.
- Our work reveals a line of classical phase transitions terminating at zero temperature near optimal doping inside the superconducting ‘dome’--I’ll explain this later.
- This is referred to as the ‘pseudogap’ because evidence exists for partial gapping of the conduction electrons.
- Until now there was no compelling thermodynamic evidence as to whether the pseudogap is a distinct phase or a continuous evolution of physical properties on cooling.

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Ultrasound sees all

- Sound speeds depend on compressibility, a thermodynamic susceptibility.
- Any phase transition has a signature in the compressibility.
- Let's see what a superconductor does (more theory by an experimentalist).

energy $$\Delta F\big|_{Tc} = H_c^2\left(T_c, B, P\right) = 0$$

volume $$\left.\frac{\partial \Delta F}{\partial P}\right|_{Tc} = \Delta V\big|_{Tc} = H_c \left.\frac{\partial H_c}{\partial P}\right|_{Tc} = 0$$

never zero

stiffness $$\left.\frac{\partial^2 \Delta F}{\partial P^2}\right|_{Tc} = \left.\frac{\partial \Delta V}{\partial P}\right|_{Tc} = \frac{1}{c_{ij}} = H_c \left.\frac{\partial^2 H_c}{\partial P^2}\right|_{Tc} + \left.\left(\frac{\partial H_c}{\partial P}\right)^2\right|_{Tc}$$

$$H_c(T_c) = 0$$

There is *always* a step discontinuity at the superconducting transition in elastic stiffness.

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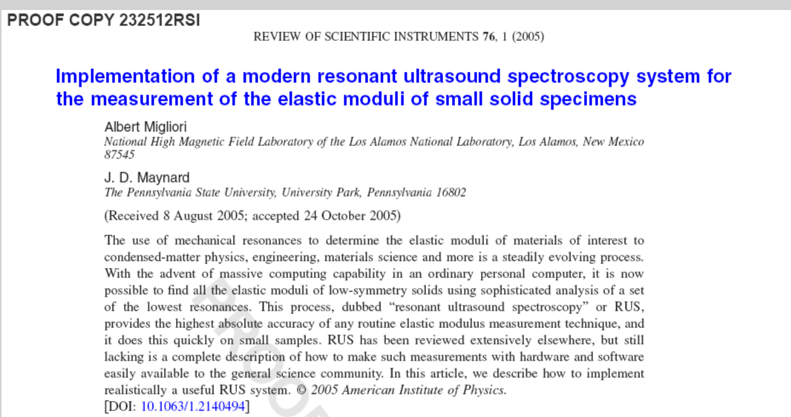
Resonant Ultrasound Spectroscopy is simple

Resonant ultrasound spectroscopy (RUS) uses the mechanical resonances of small samples to extract all the components of the elastic tensor at the same time.

RUS and other ultrasound techniques measure the *adiabatic* moduli-typically within 1% of isothermal moduli in solids.

Only RUS measures the true thermodynamic attenuation, independent of defects and scattering, transducer misalignment.



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REVIEW OF SCIENTIFIC INSTRUMENTS 76, 1 (2005)

Implementation of a modern resonant ultrasound spectroscopy system for the measurement of the elastic moduli of small solid specimens

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The use of mechanical resonances to determine the elastic moduli of materials of interest to condensed-matter physics, engineering, materials science and more is a steadily evolving process. With the advent of massive computing capability in an ordinary personal computer, it is now possible to find all the elastic moduli of low-symmetry solids using sophisticated analysis of a set of the lowest resonances. This process, dubbed "resonant ultrasound spectroscopy" or RUS, provides the highest absolute accuracy of any routine elastic modulus measurement technique, and it does this quickly on small samples. RUS has been reviewed extensively elsewhere, but still lacking is a complete description of how to make such measurements with hardware and software easily available to the general science community. In this article, we describe how to implement realistically a useful RUS system. © *2005 American Institute of Physics.*

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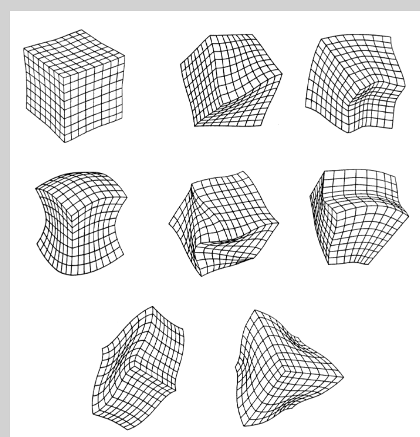
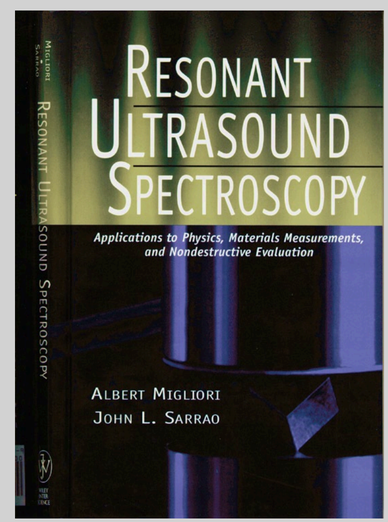
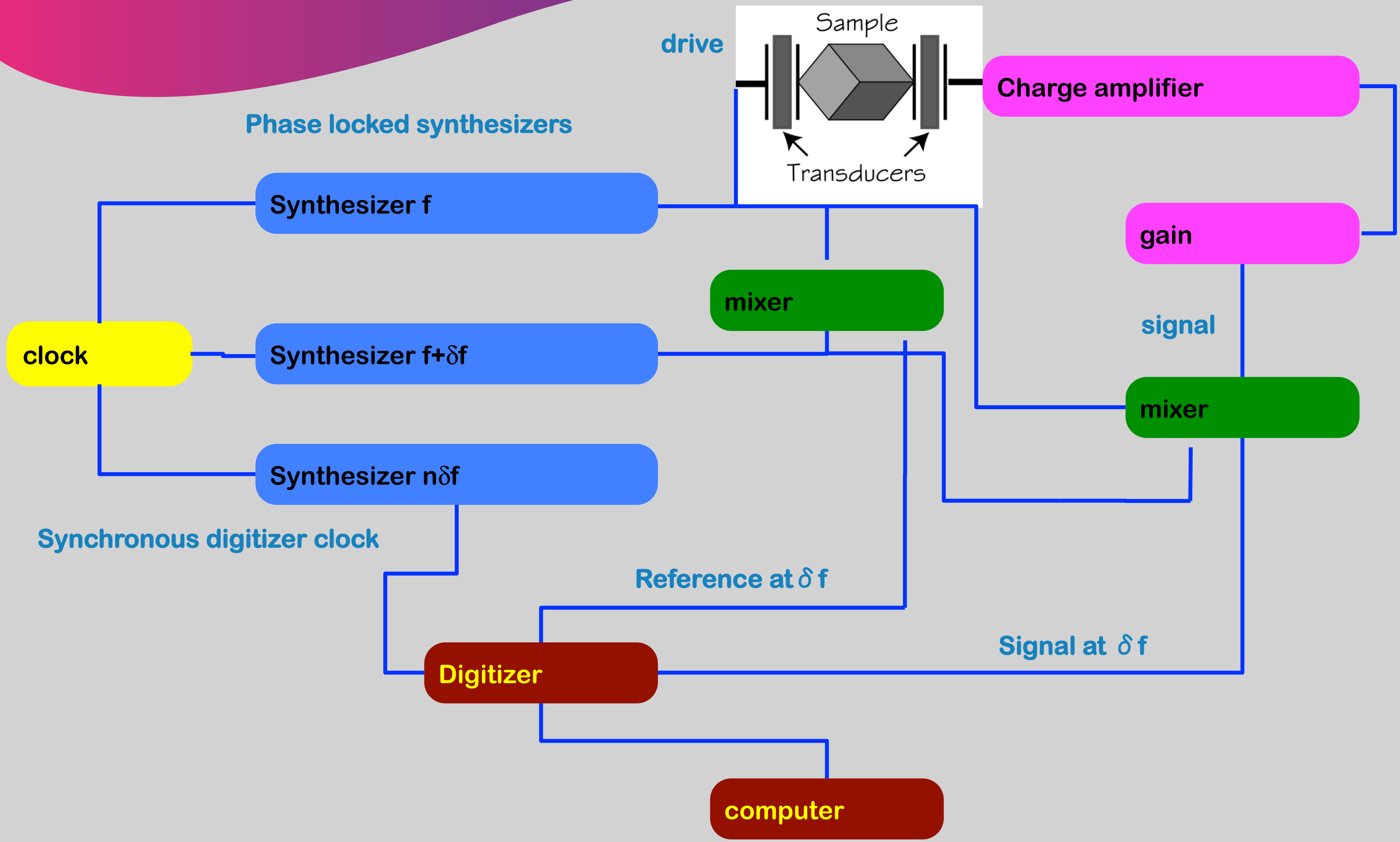




Full phase sensitive acoustic detection employed



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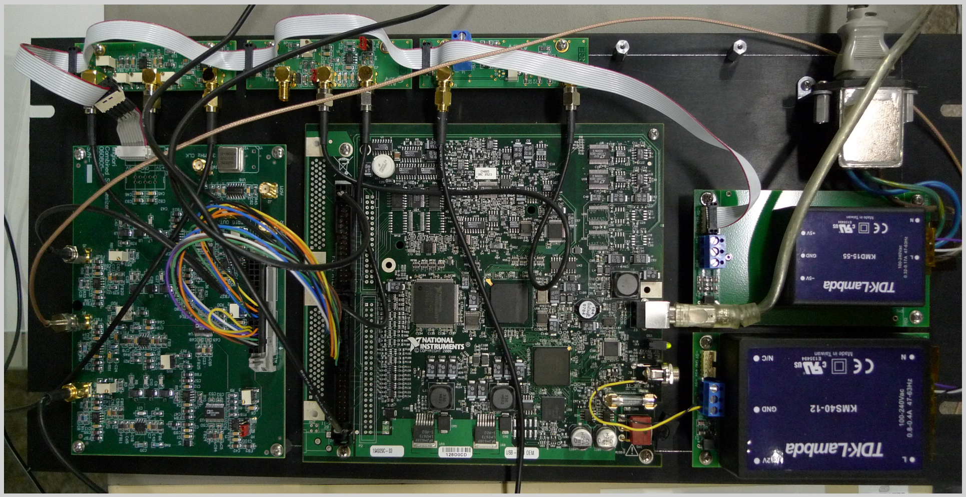
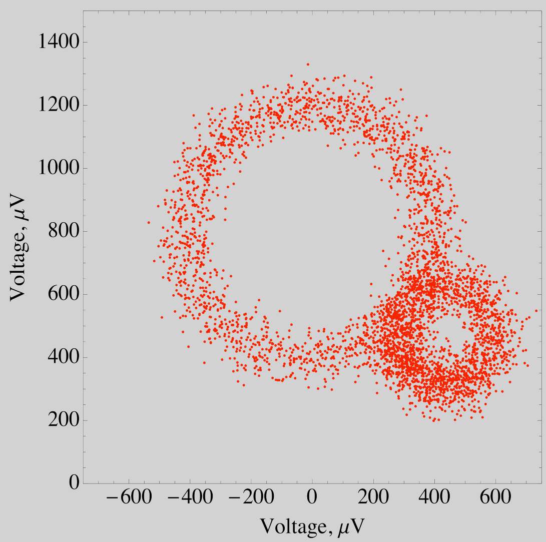
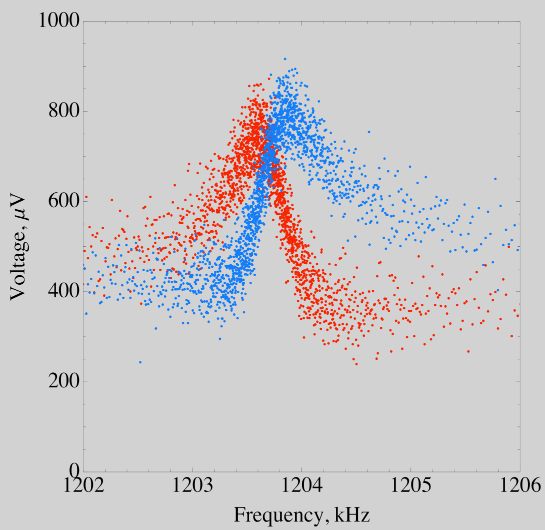
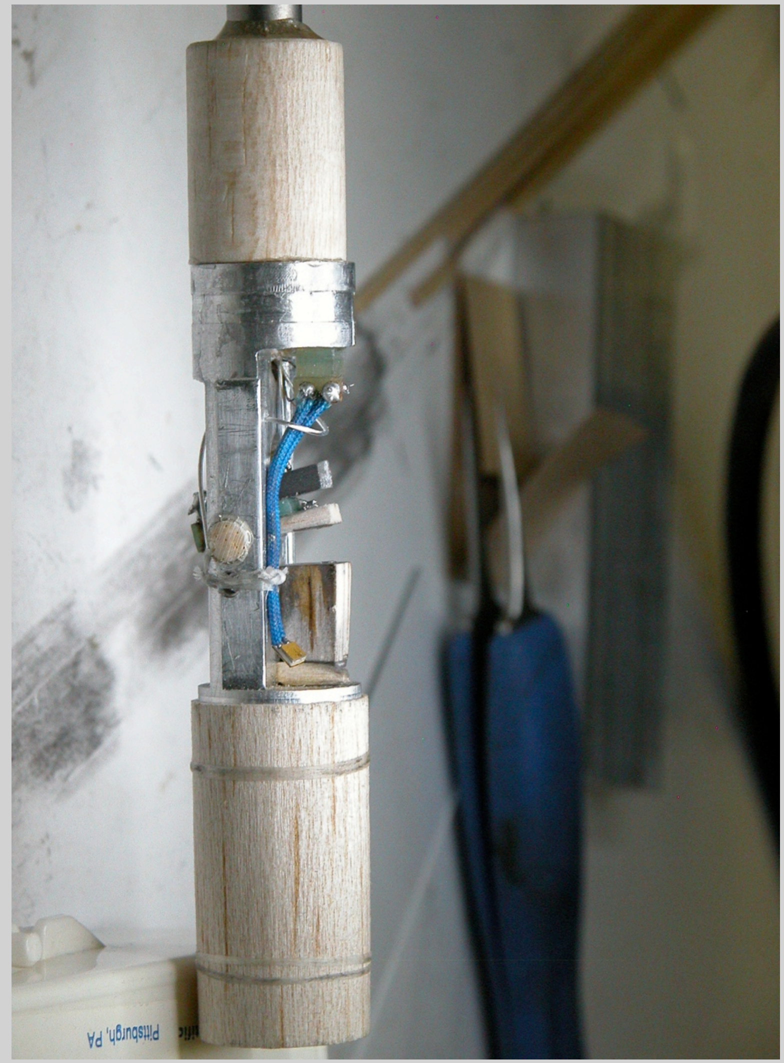
Amazing signal/noise/extraction methods

we roll our own









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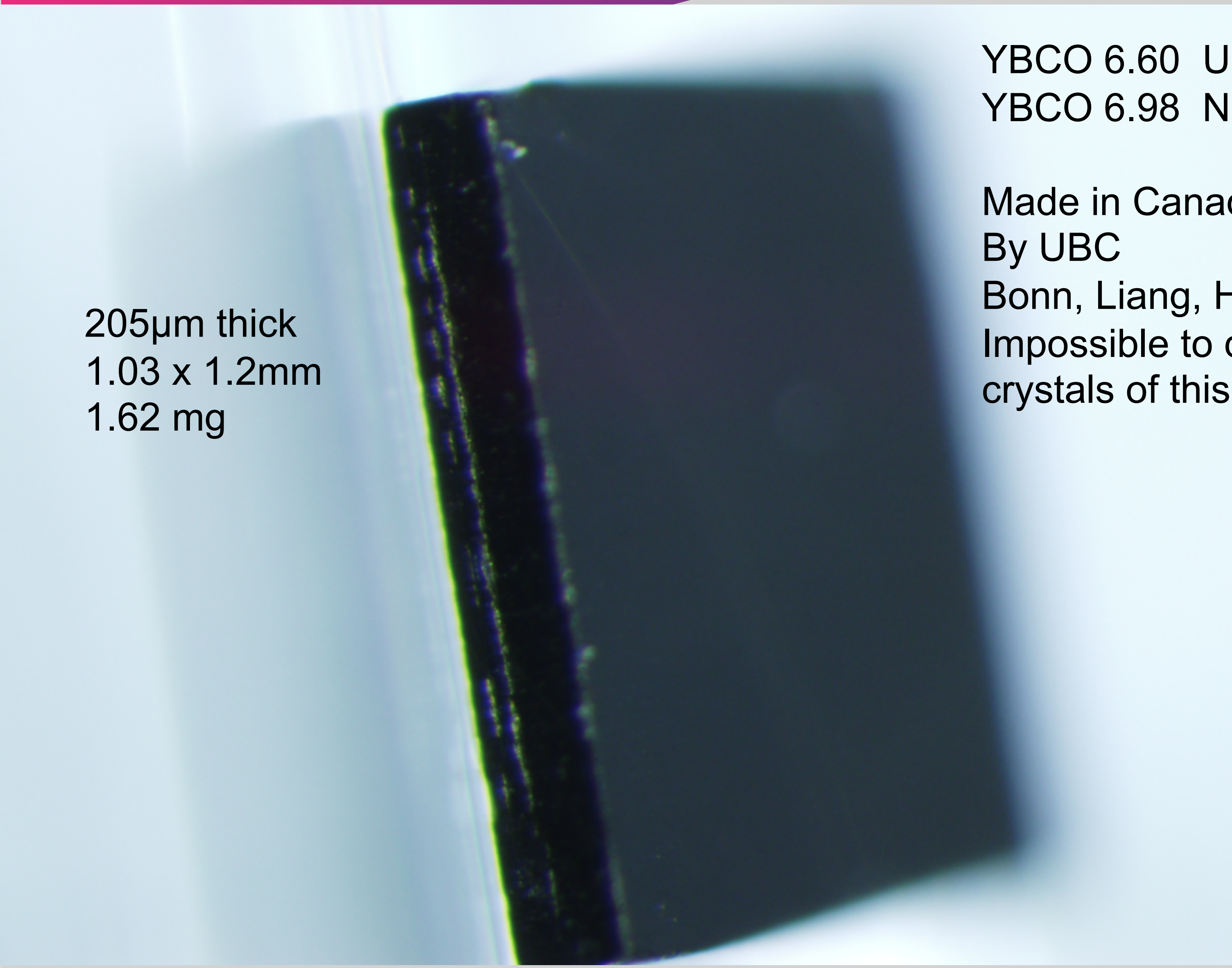
Tiny single detwinned crystals are *required*

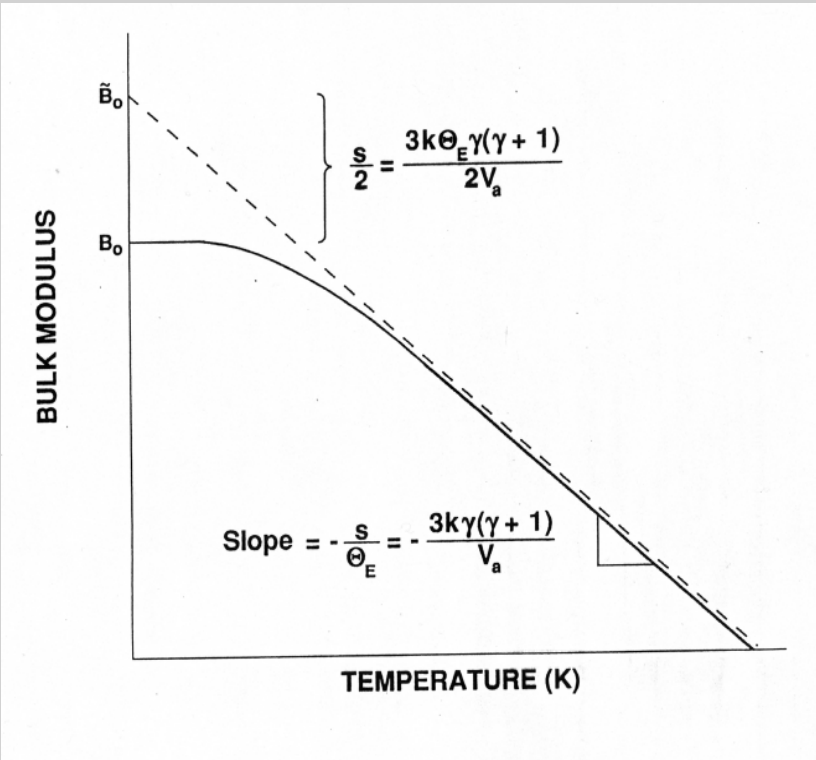


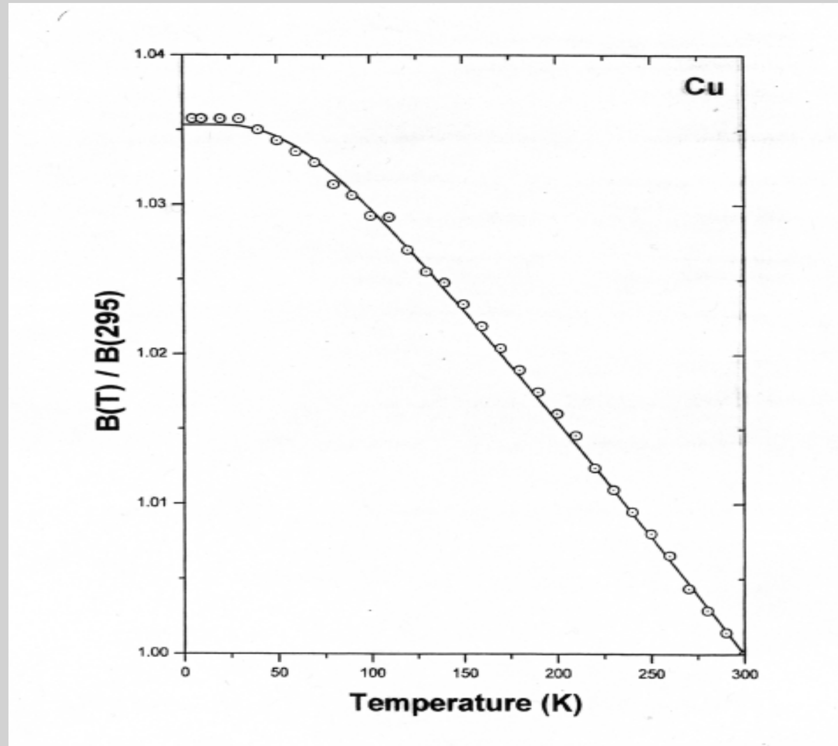
205µm thick
1.03 x 1.2mm
1.62 mg

YBCO 6.60 Underdoped T_c=61.6K
YBCO 6.98 Near optimal T_c=88.0K

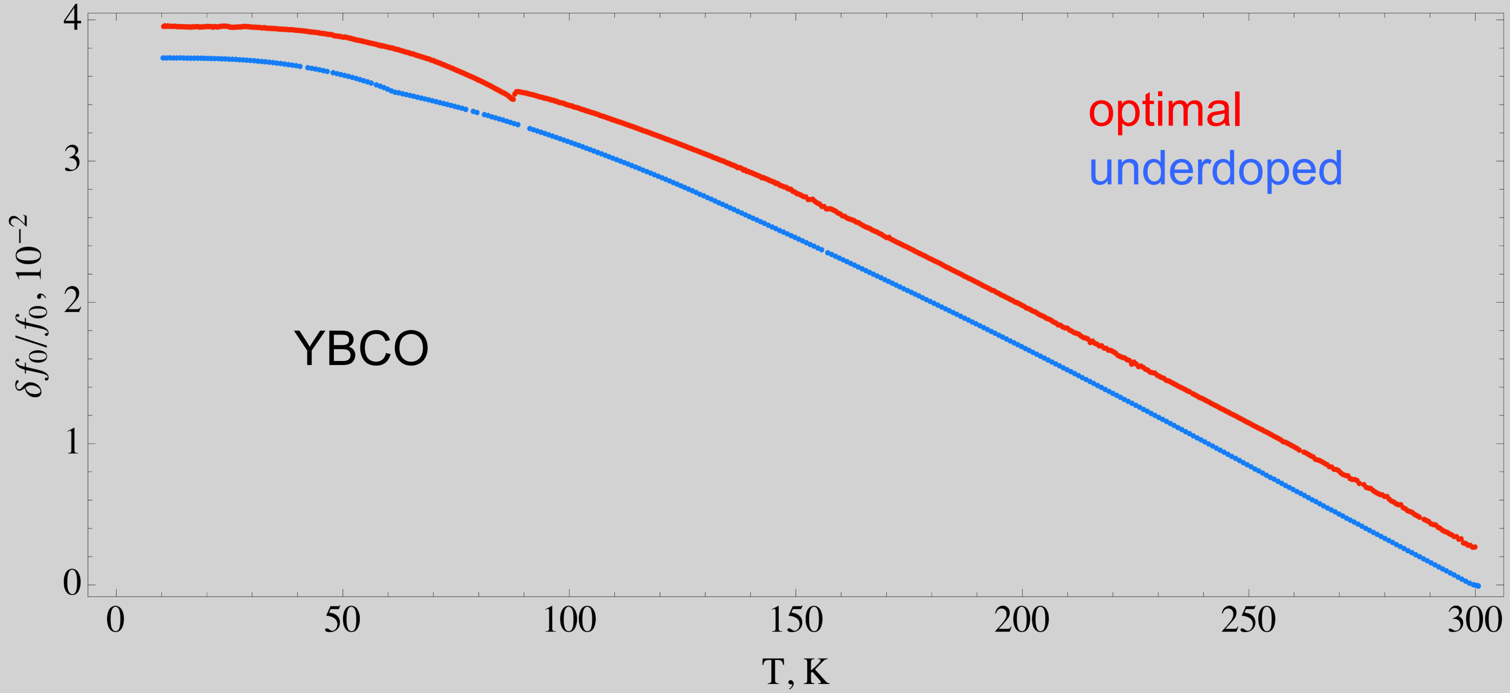
Made in Canada
By UBC
Bonn, Liang, Hardy
Impossible to do what we did without crystals of this quality

What is normal?





Overall smoothness and normal behavior



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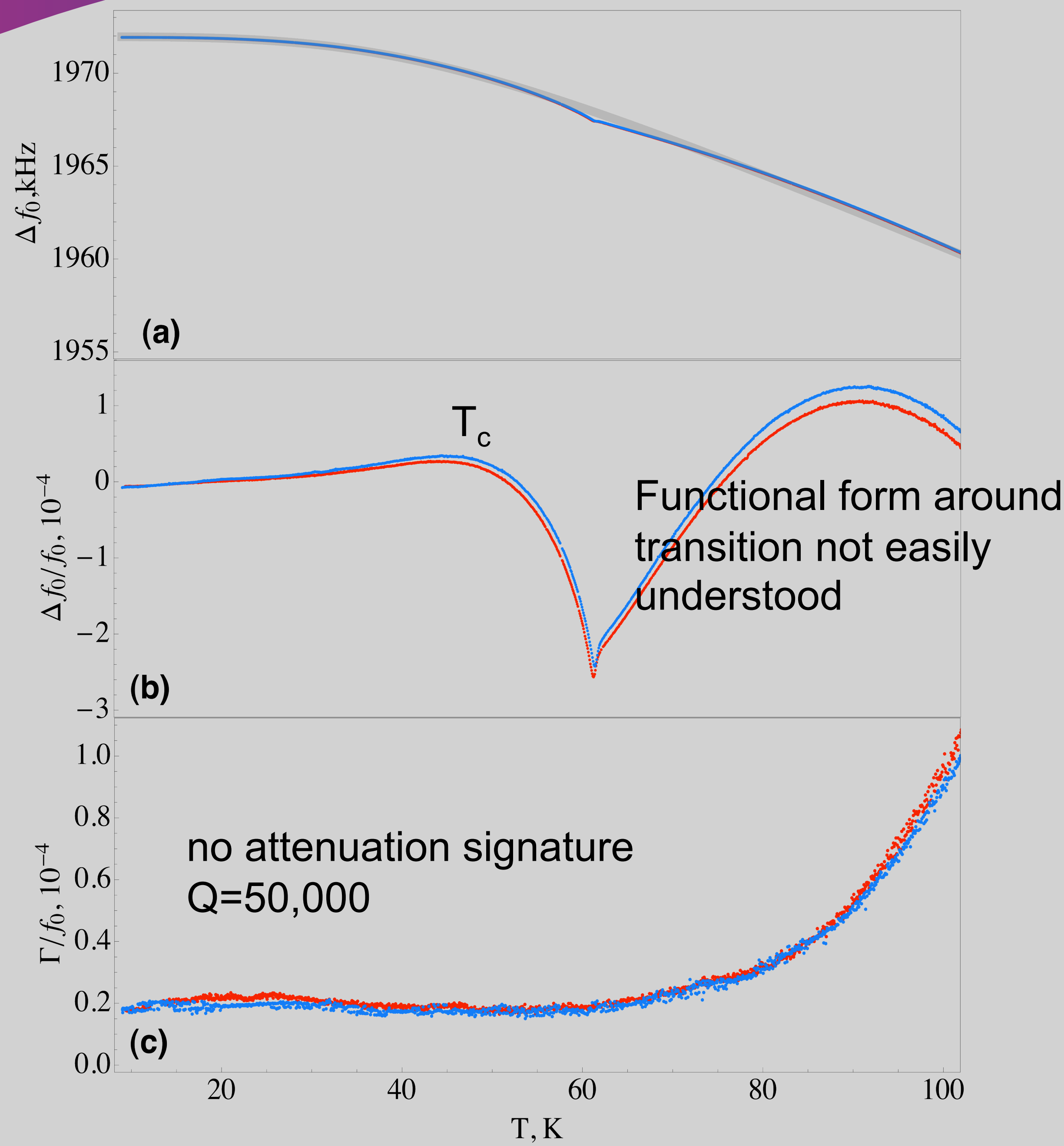
Elastic moduli and attenuation in underdoped YBCO at superconducting transition through the looking glass



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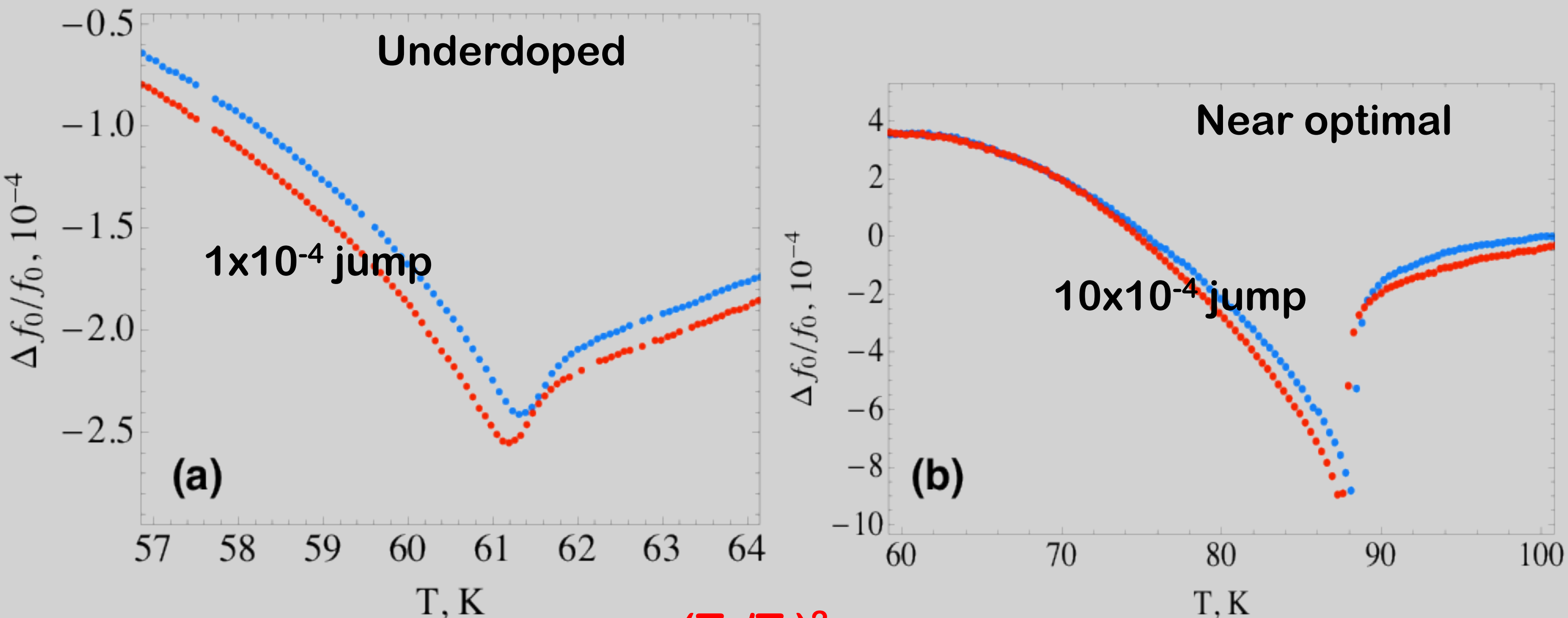
Detail of the superconducting transition seen through even stronger looking glass

- Step size depends on superconducting fraction.
- Transition width is sharper than most observations of YBCO.
- Size of jump makes sense if we observed full thermodynamic signature (no preformed pairs).



$(T_c/T_f)^2$

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Superconducting effects validate pseudogap observations

- Quantitative bounds on the discontinuity in the elastic moduli across the superconducting transition in two detwinned superconducting single crystals of YBCO, T_c = 61.6K and slightly overdoped, T_c = 88K.
- Full thermodynamic signature, ~ $(T_c/T_F)^2$, is observed within a fraction of a Kelvin of T_c.
- Strong attenuation increases and signatures in elastic moduli (an order of magnitude larger than at T_c) are observed at the pseudogap phase transition.
- Width of the ultrasonically-observed superconducting transitions provides a correct prediction of width of the pseudogap transition.

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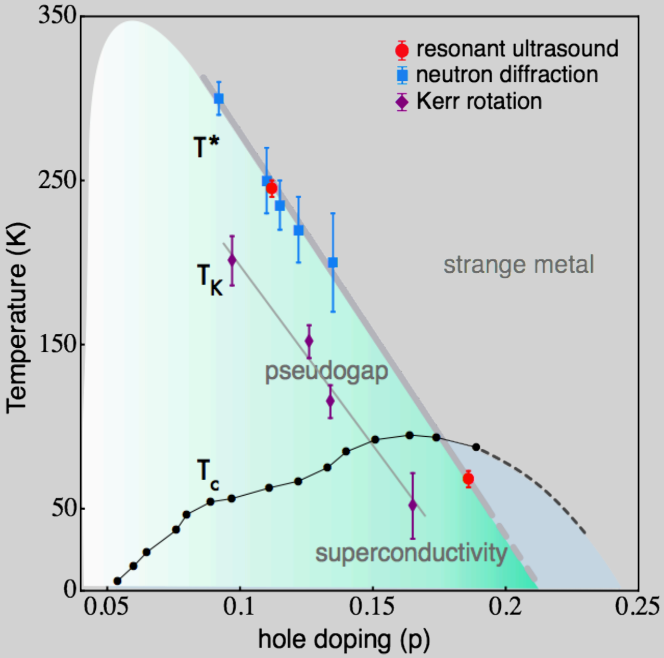
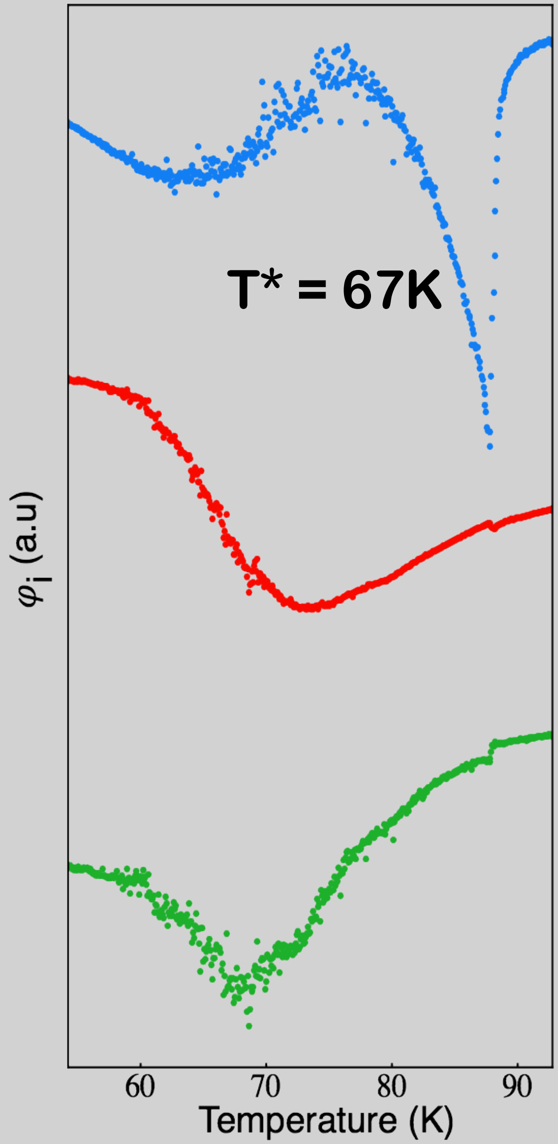
Pseudogap boundary in YBCO 6.98 (overdoped) Tc=88.0K



linear component analysis
of the temperature
dependence
of multiple resonances



- We can deconvolve resonances into types of temperature dependences.
- The point is that each resonance is a combination of the thermal response of several elastic moduli.
- Deconvolution produces the three types of thermal response.

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Consequences

•Unknown type of phase transition, conjectured to be second order with a magnetic order parameter.

•Our observed evolution of the pseudogap phase boundary from underdoped to overdoped establishes the presence of a quantum critical point inside the superconducting dome.

•This suggests a quantum-critical origin for both the strange metallic behavior and the glue mechanism of superconducting pairing.

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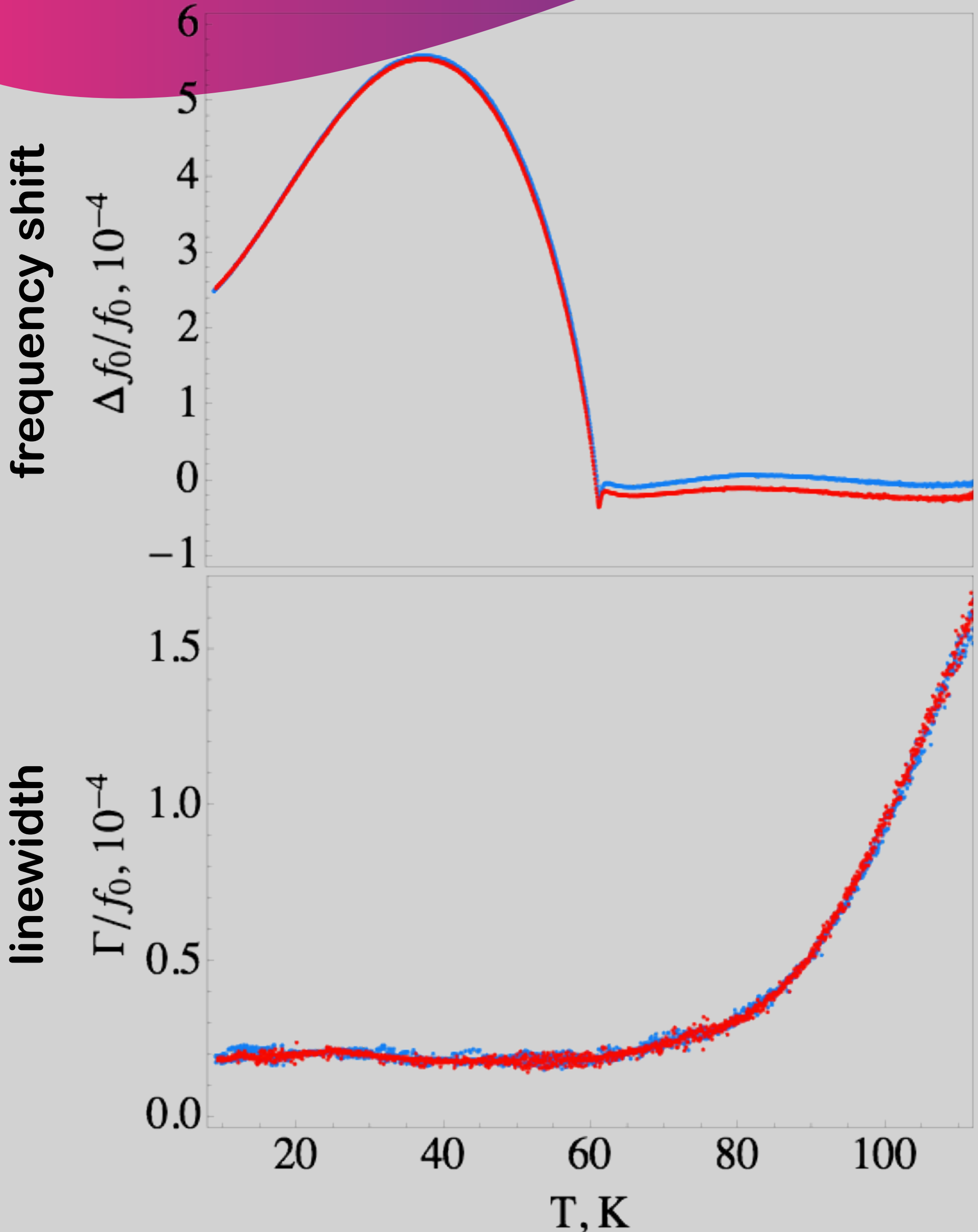
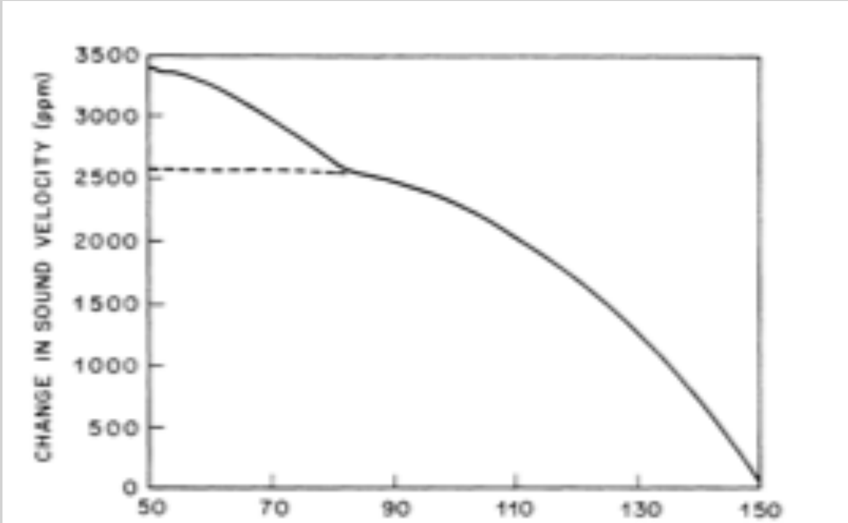
Detail of YBCO with normal background subtracted and comparisons

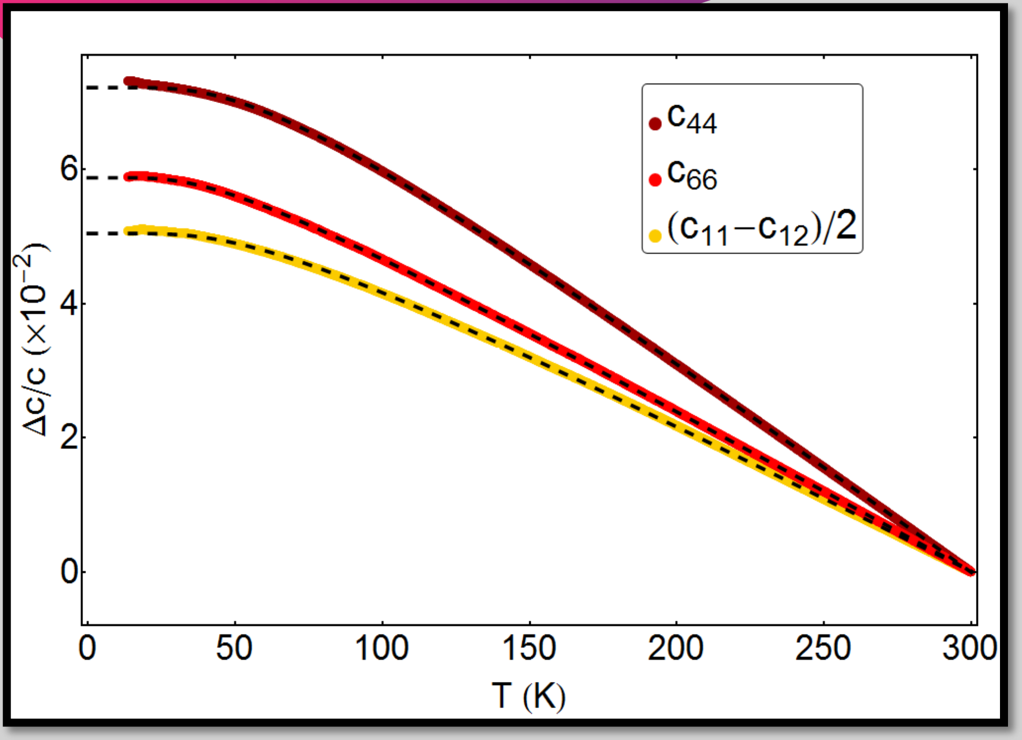


Sound velocity
Bishop et.al. (1987) YBCO-237

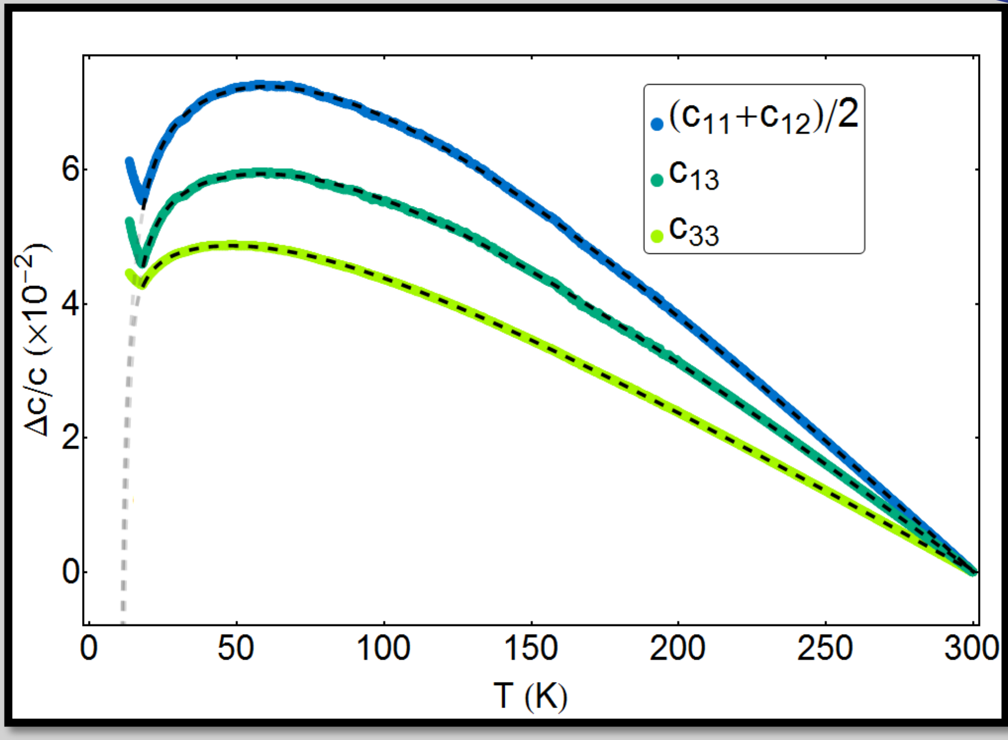


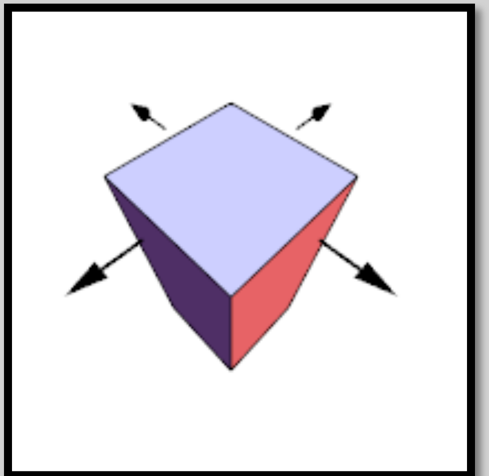
Valence Fluctuations in $PuCoGa_5$

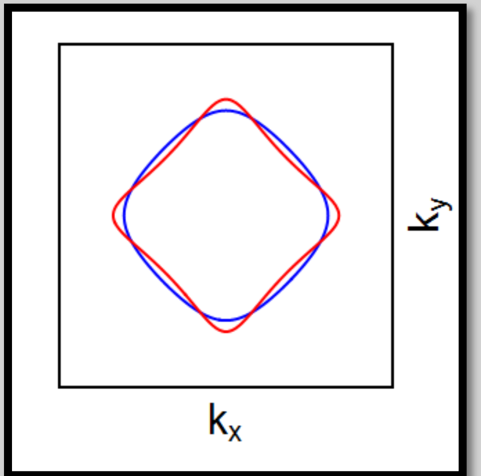
Shear

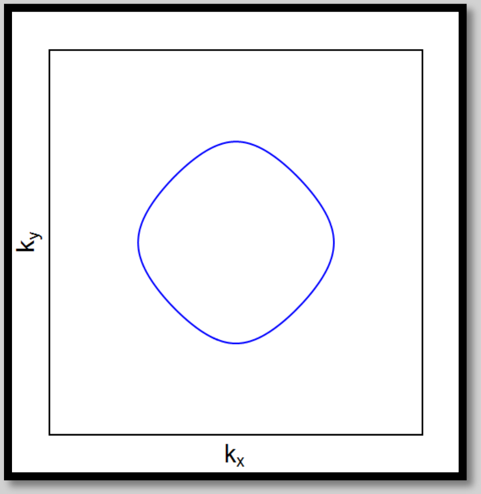


Compression









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Ultrasound provides important information

- Metallic plutonium compound, $PuCoGa_5$ has the highest superconducting transition temperature among the 115 family.
- The temperature dependence of the compressional moduli exhibits anomalous softening upon cooling over a broad temperature range which is truncated by superconductivity.
- The symmetry and temperature dependence of the softening implies the existence of a dynamic non-magnetic scalar order parameter.
- Because these fluctuations are suppressed with the opening of the superconducting gap at T_c, they are electronic in origin and reside at the Fermi surface.
- This lays the groundwork for connecting valence fluctuations to itinerant electronic behavior in a wide range of correlated electric systems.

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Symmetry of the order parameter is an important constraint

The expected behavior of the elastic moduli across the phase transition depends on the symmetry of the order parameter.

The order parameter in pseudogap phase in YBCO is magnetic and has E_u symmetry, a polar vector parallel to copper-oxide plane (based on neutron diffraction) =toroidal moment.

$$\eta = (\eta_x, \eta_y)$$

$$A_{1g} = \eta_x^2 + \eta_y^2$$
$$B_{1g} = \eta_x^2 - \eta_y^2$$
$$B_{2g} = \eta_x \eta_y$$

Linear coupling of strain to order parameter is generated from

$$F_2 = (\eta_x^2 + \eta_y^2)\underbrace{[\zeta_1(\epsilon_{xx} + \epsilon_{yy}) + \zeta_2\epsilon_{zz}]}_{\text{compressional}} + \zeta_3(\eta_x^2 - \eta_y^2)\underbrace{[\epsilon_{xx} - \epsilon_{yy}]}_{\text{shear}} + \zeta_4(\eta_x\eta_y)\underbrace{\epsilon_{xy}}_{\text{shear}}$$

In the symmetry-broken phase (cold) the order parameter bilinears which couple to shear strain average to zero (but may have an effect on ultrasound attenuation.)

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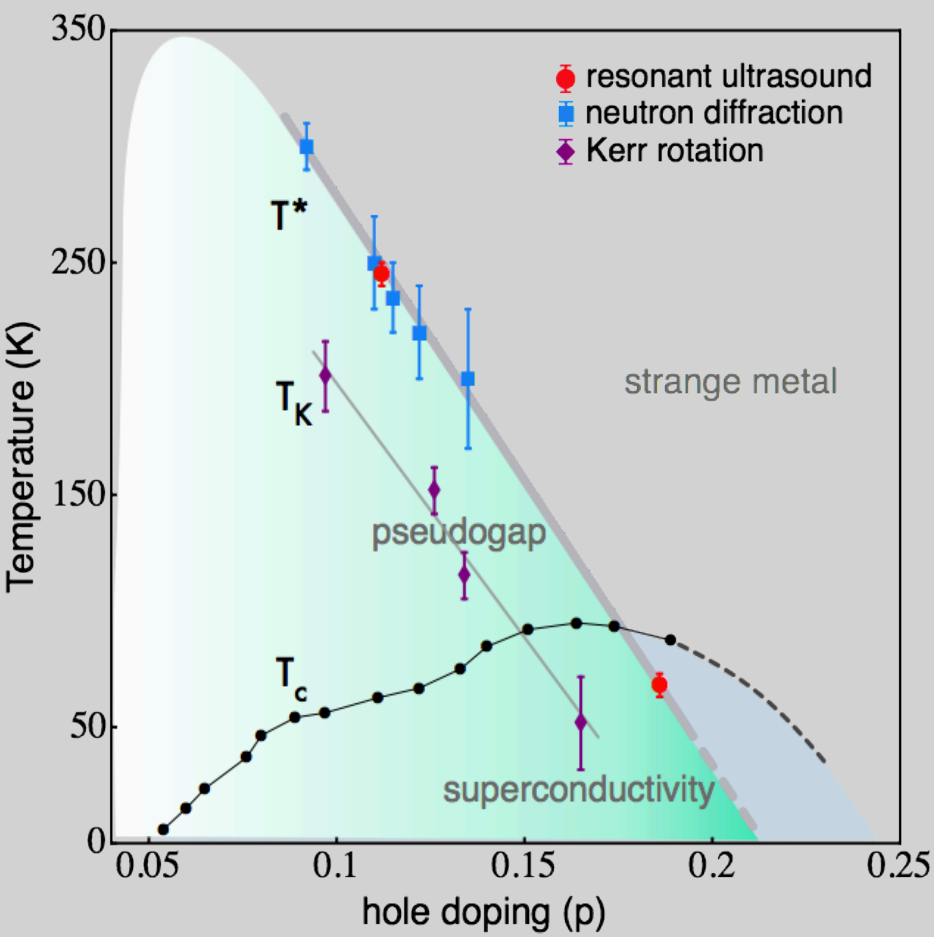
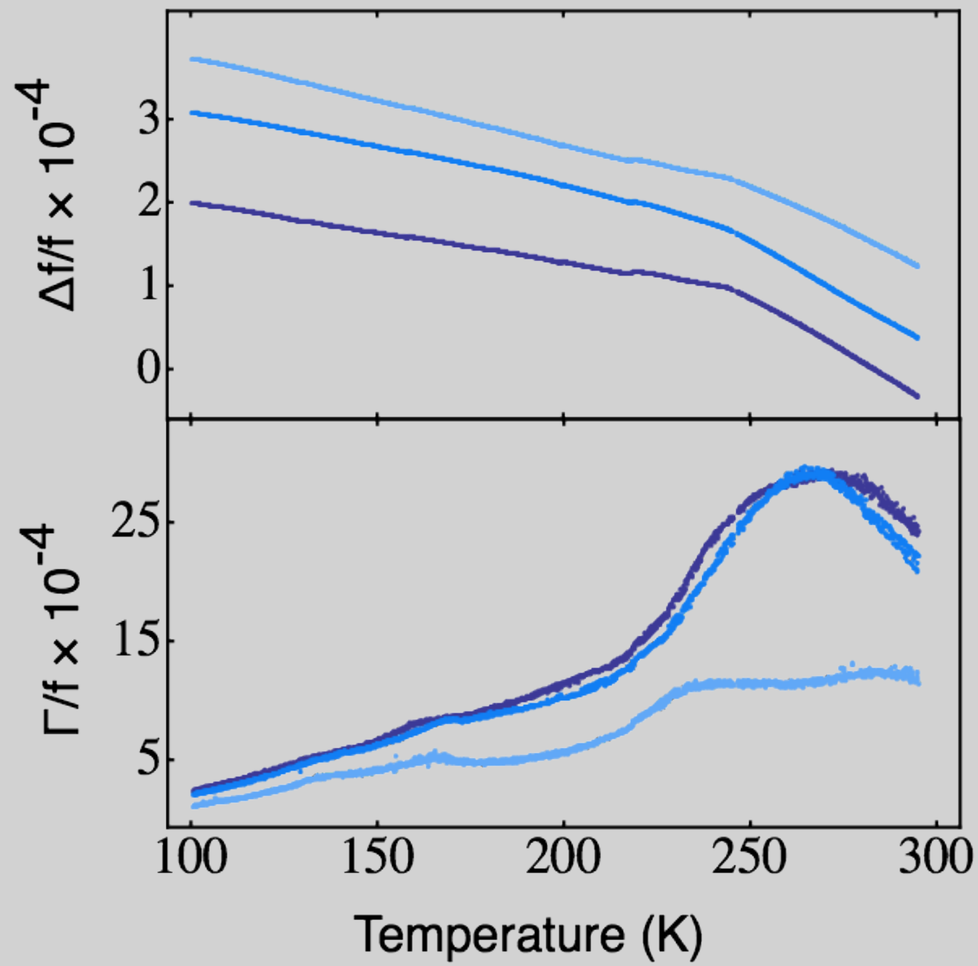
Pseudogap boundary in YBCO 6.60 (underdoped) T_c=61.6K



T* = 245K



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Pseudogap reveals itself

Unknown type of phase transition, conjectured to be second order with a magnetic order parameter.