Multiple component order parameter (and nodes) from ultrasound velocity (attenuation)

Experiments (Univ. of Toronto)

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Samples

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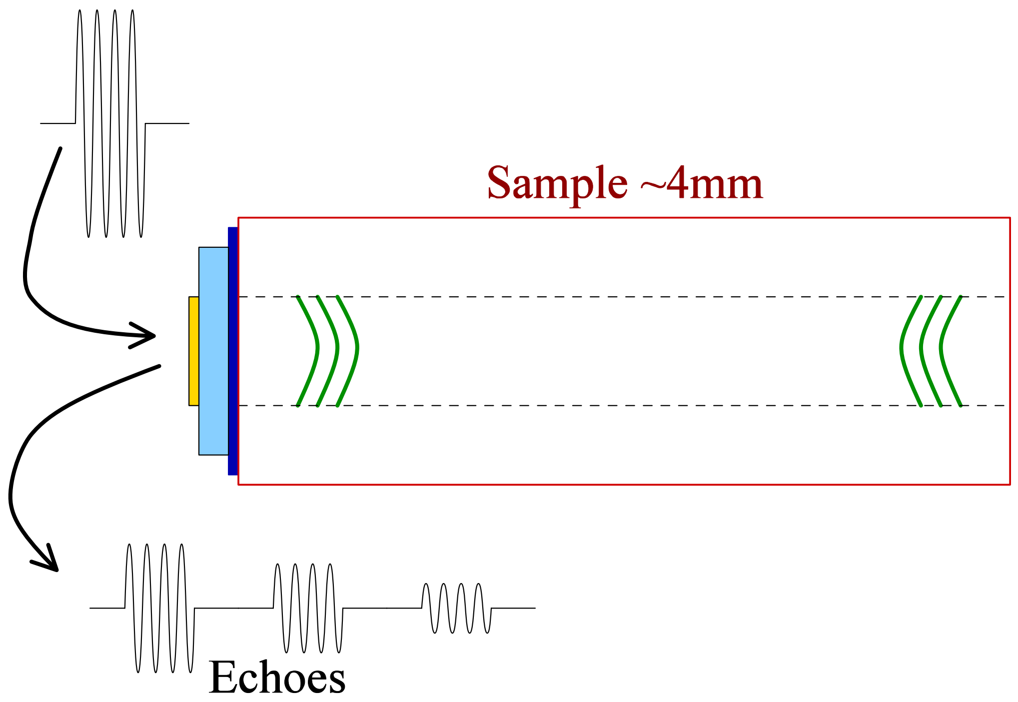
Plan

- Ultrasound Technique
- Sound velocity (multi-components)
- Ultrasound attenuation (nodes)

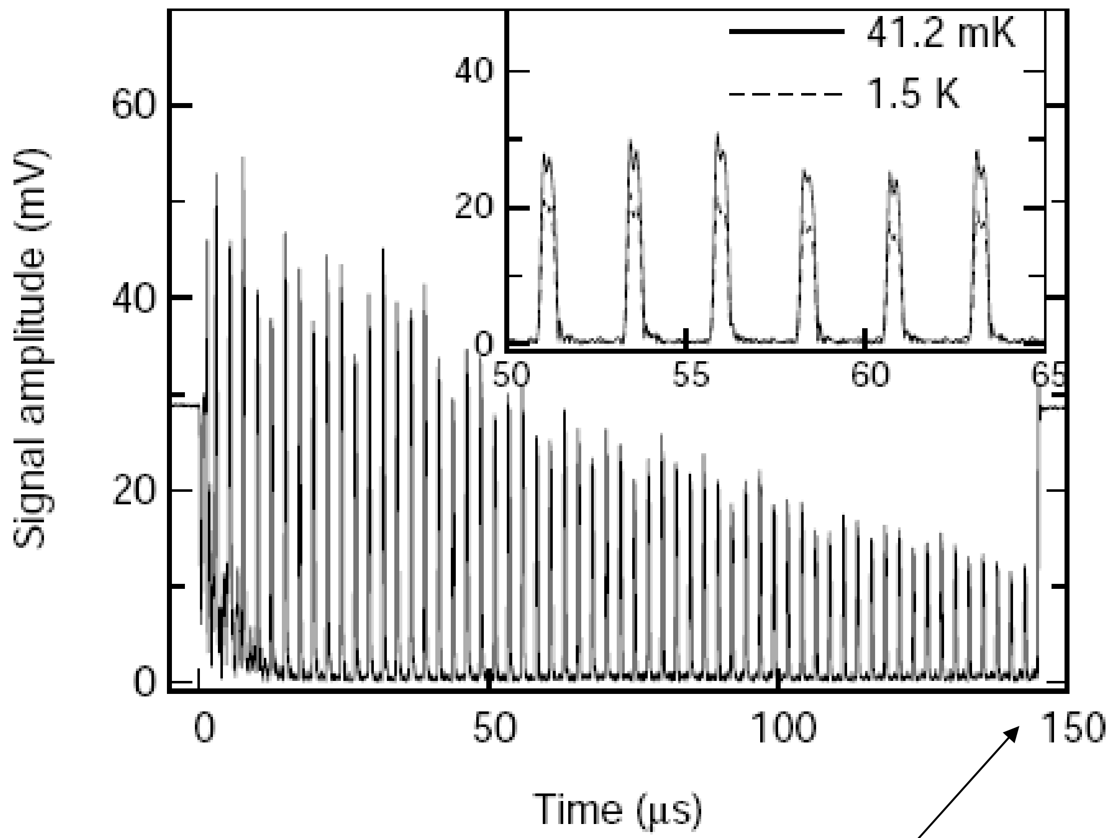
Ultrasound Technique



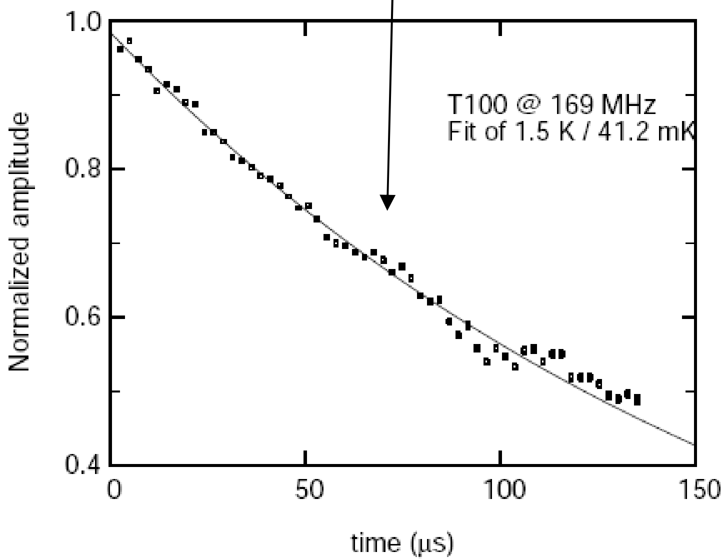
f = 20-500 Mhz
echo spacing 2L/v
~1-3 µs
λ = 5 – 300 µm

- Send pulses from one end
- Pulse propagates and echoes
- Detect the echoes at either ends
- Extract amplitude of echoes: Attenuation
- Extract time between echoes: Coarse sound velocity
- Extract phase of echoes vs original pulse: fine sound velocity
- Other techniques are available to extract just the sound velocity.

Signal



Attenuation



60+ echoes, 0.5+ m of travel

Samples

Grown by floating zone method (image furnace)

- Large crystals (diameter ~3mm)
- Very high quality
- Oriented, cut, polished to have crystals for sound propagation along 100, 110 and 001

Velocity Theory

- Sound velocity ↔ Elastic constants $v_s = \sqrt{\frac{C}{\rho}}$
- For Tetragonal symmetry there are 6 independent elastic tensor elements (C_{11}, C_{33}, C_{12}, C_{13}, C_{44} and C_{66})
- They combine differently for different measurement geometry: L100 = C_{11}, L110 = ½ (C_{11} + C_{12} +2C_{66}), T100 = C_{66}, T110 = ½ (C_{11} – C_{12}). For in-plane polarisation
- (1=xx, 2=yy, 3=zz, 4=xz, 6=xy)

Velocity theory

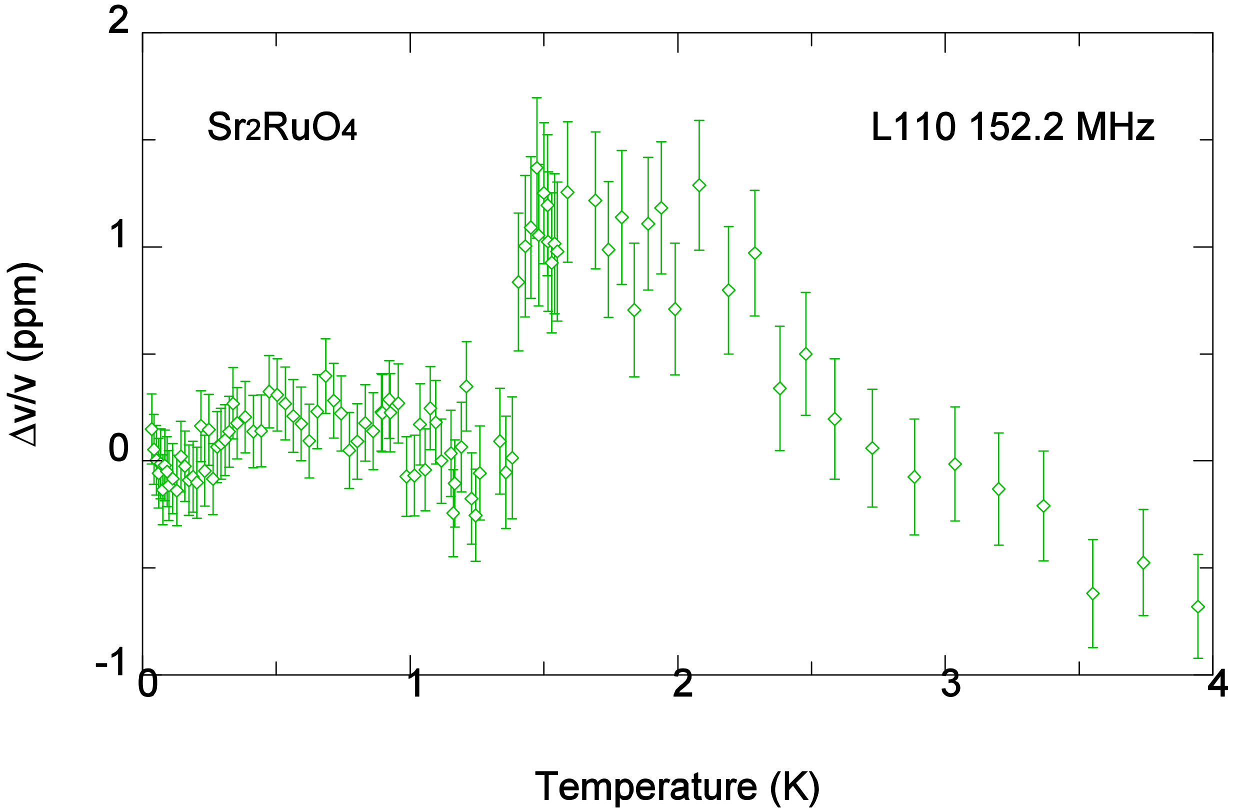
- Coupling with superconductivity near Tc (jump and change of slope

$$\Delta C_{ij} = C_{ij}^S - C_{ij}^N = -\frac{\Delta C_e}{T_c}\frac{\partial T_c}{\partial s_i}\frac{\partial T_c}{\partial s_j}$$

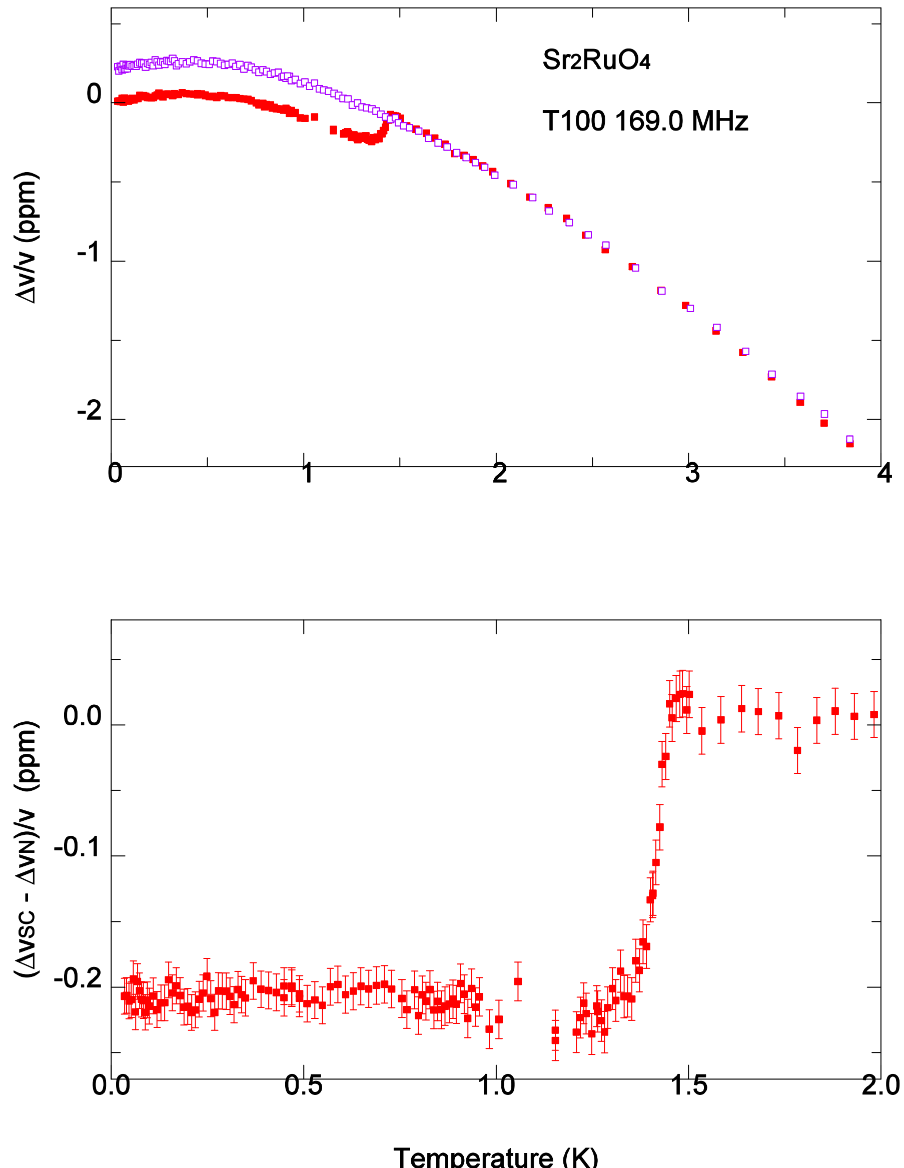
$$\left.\frac{\partial C_{ij}^S}{\partial T}\right|_{T_c} - \left.\frac{\partial C_{ij}^N}{\partial T}\right|_{T_c} \approx \frac{\Delta C_e}{T_c}\frac{\partial^2 T_c}{\partial s_i \partial s_j}$$

- ΔC_e is specific heat jump, s_i is strain
- But + and – shear strain (s_6) have to give the same answer → Jump absent in linear order
- Unless we have multiple components

Longitudinal Velocity L110



Transverse velocity T100

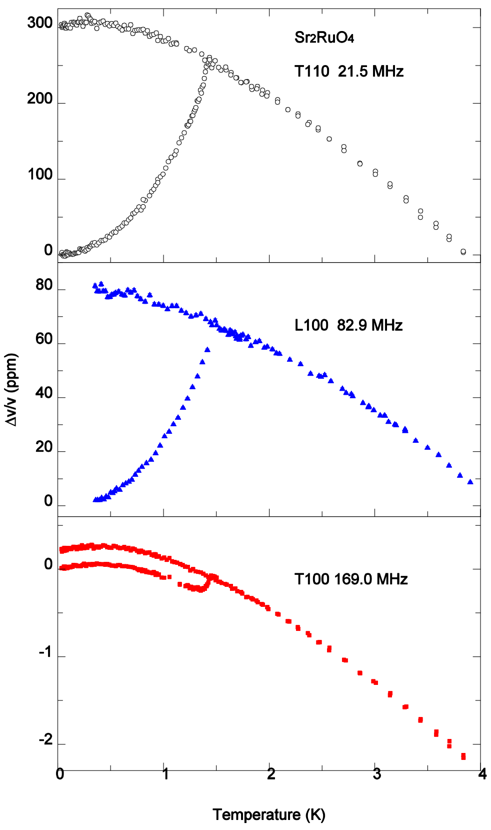


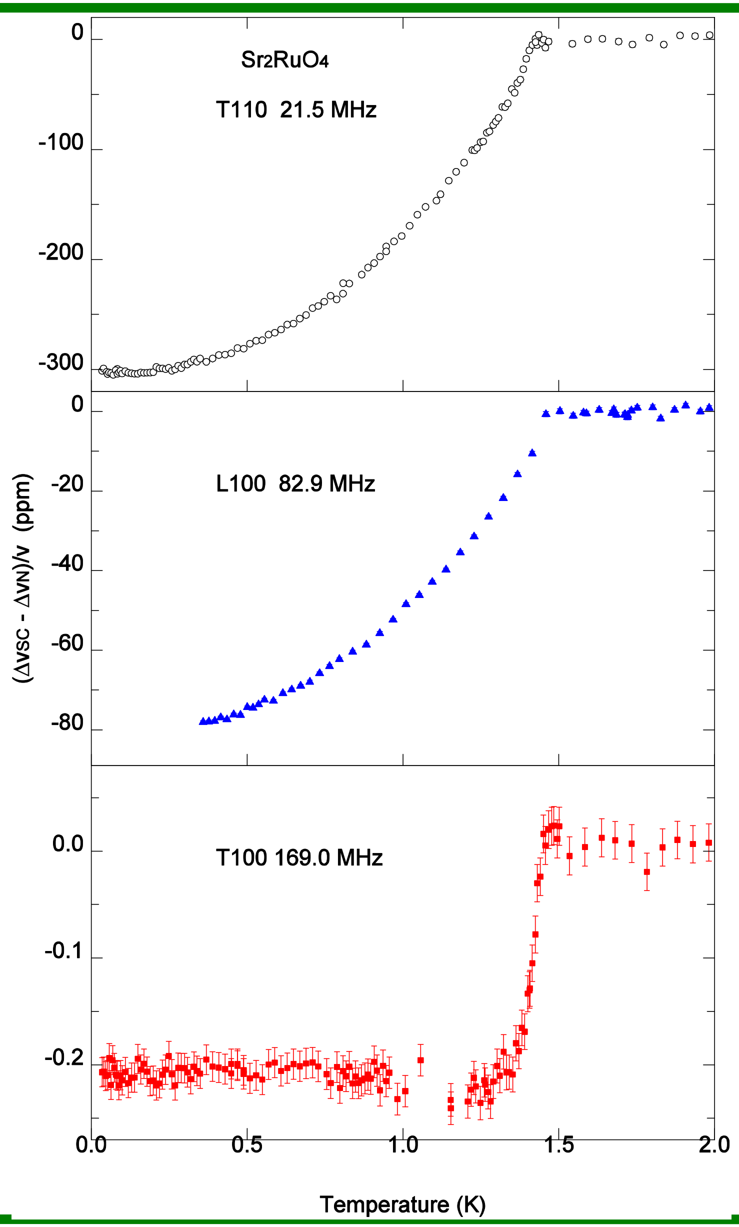
T100 transverse mode
Normal vs SC data

There is a 0.2 ppm jump

Predicted for Upt3 but not seen (not sensitive enough?: Bruls et al. PRL 65, 2294).

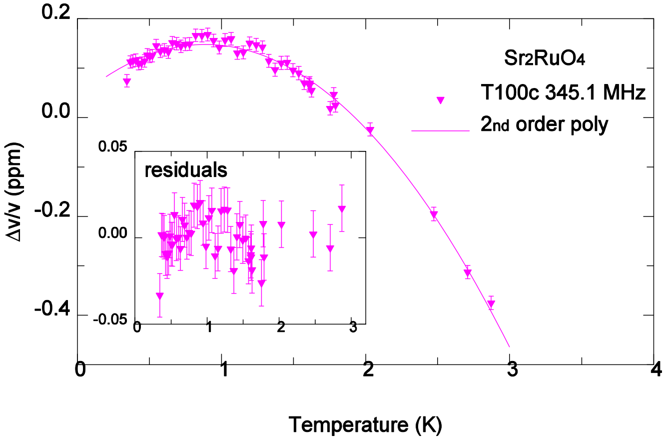
Other velocities



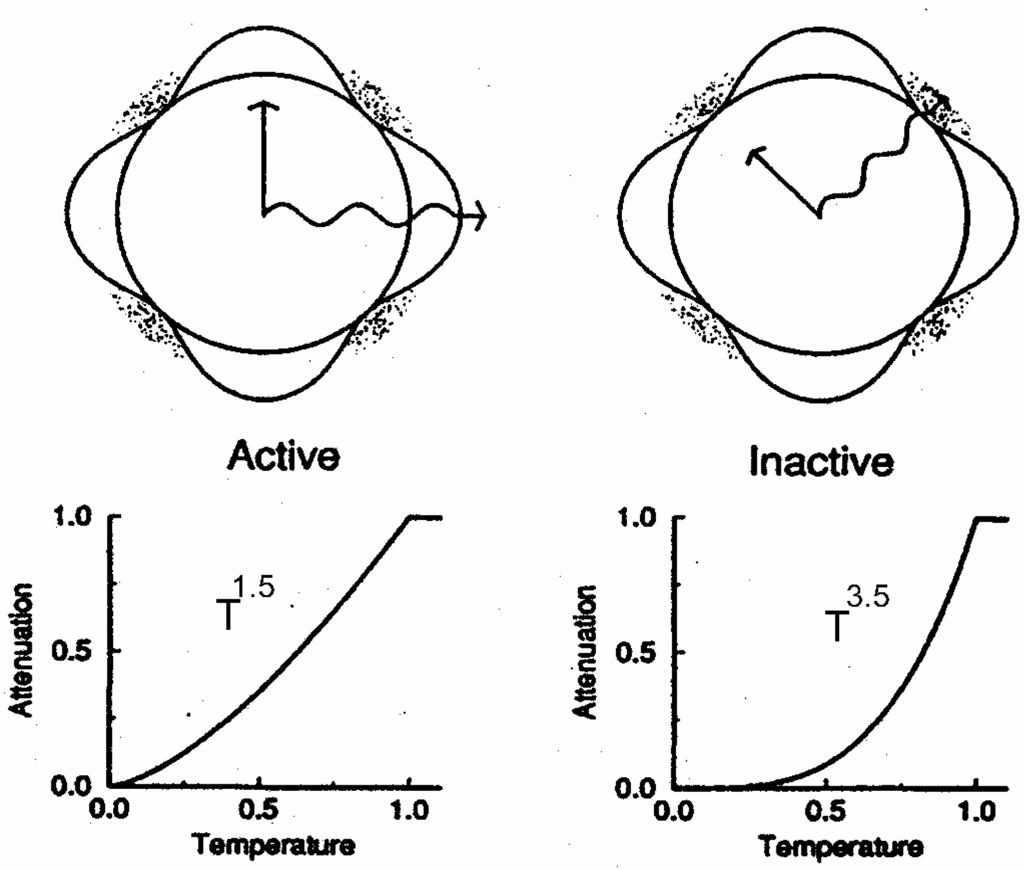


Estimated jump is 3 ppm for L100

Some of the change can come from coupling to attenuation in measurement



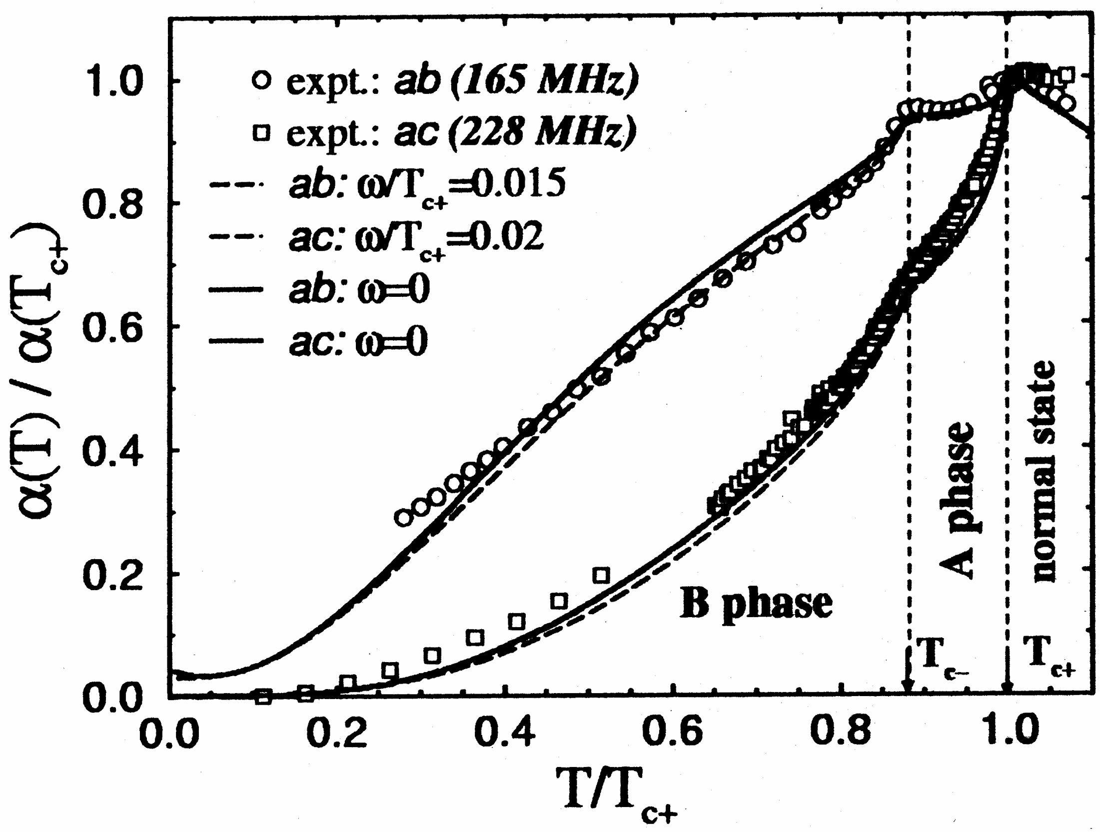
Attenuation theory



Need to be in low frequency (the hydrodynamic limit, $\alpha \sim \omega^2$, $q\ell << 1$) where electronic attenuation is related to electronic viscosity tensor. Other is quantum limit and $\alpha \sim \omega$

J. Moreno and P. Coleman, PRB 53 (1996) R2995

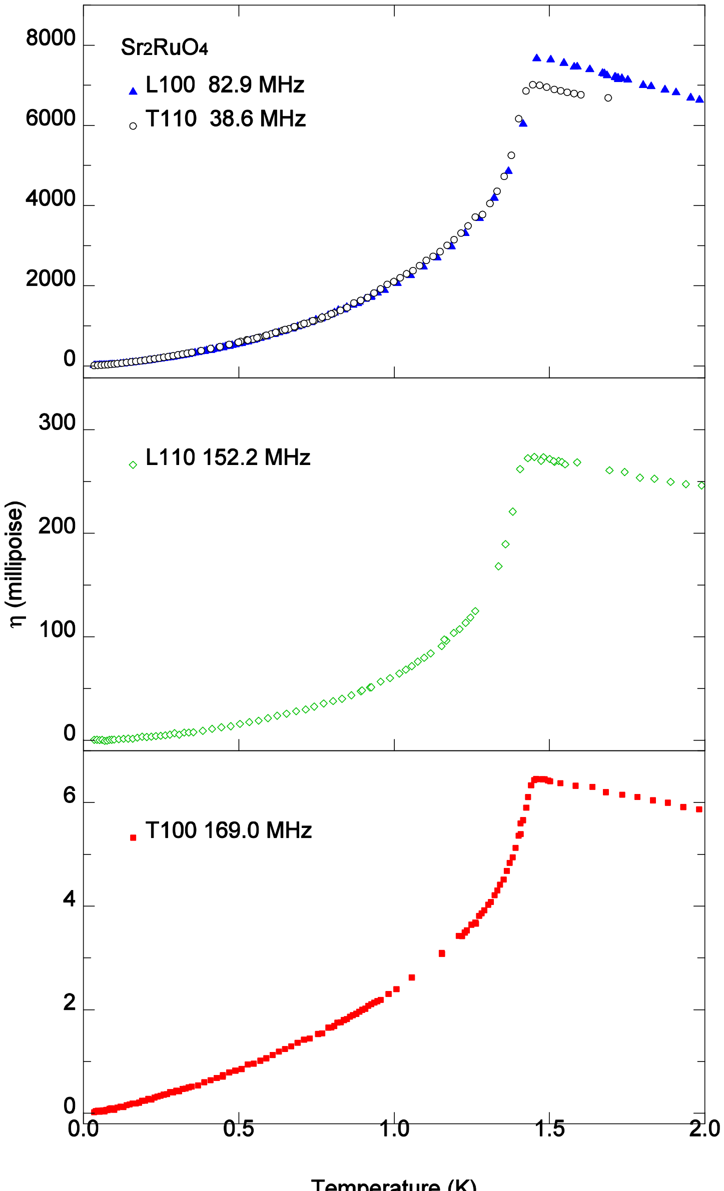
UPt_3 example



Ellman, Taillefer and Poirier PRB (96)

Line of nodes in basal plane of UPt_3

Ultrasound attenuation



Large normal state anisotropy

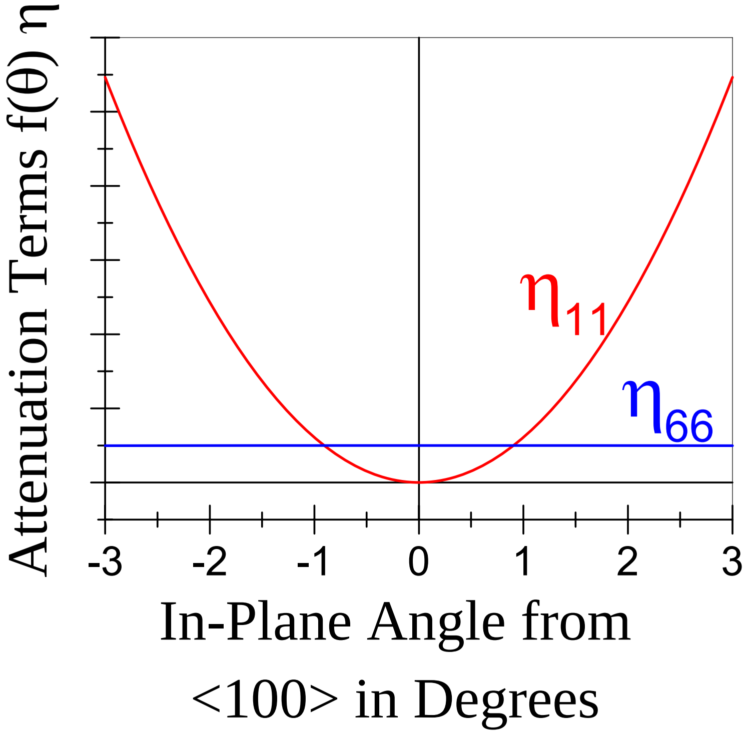
Power laws down to 40 mK
→ Nodes

Weak power law anisotropy
→ gap structure?

Note that zero of attenuation is set by extrapolation and not measured

Lupien *et al*. PRL 86 (2001) 5986.

Angular variation of viscosity

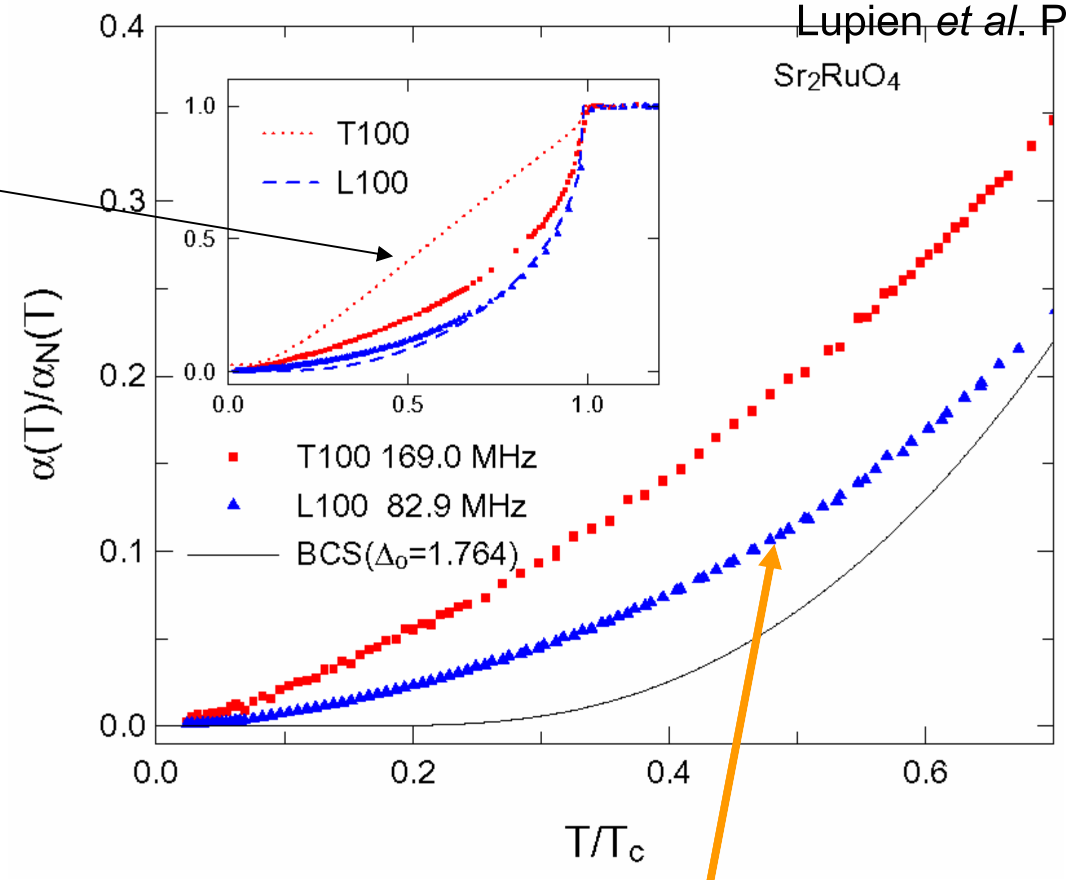


For η_{66} Require better than 1° alignment

Power law anisotropy

Lupien *et al*. PRL 86 (2001) 5986.

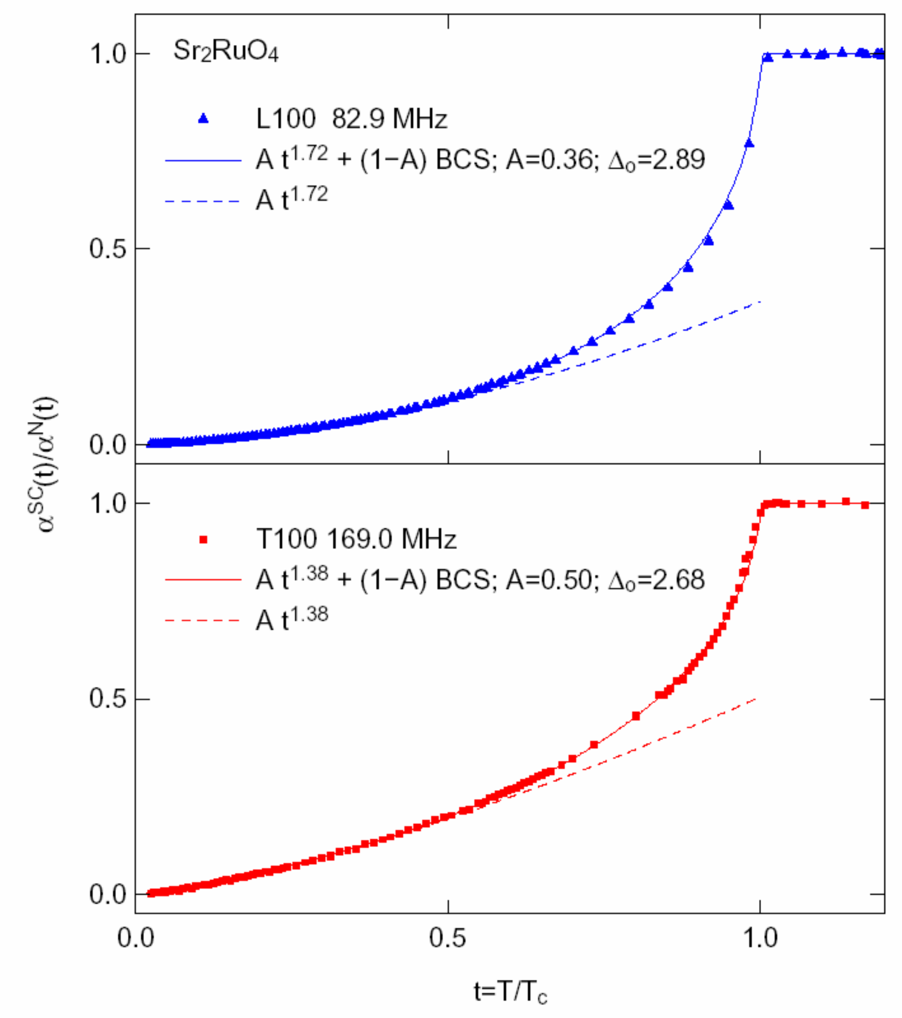
Lines are model from MJ Graf & AV Balatsky PRB 62, 9697 (2000).



• Power laws (not isotropic gap)

• Weak anisotropy

Power law fits



Zhitomirsky and Rice model, PRL **87** 057001 (2001):

p-wave on γ band and line nodes on α, β bands

Conclusions

- There is a jump in transverse sound velocity
  - Requires Multi-components order parameter
- Attenuation shows power laws and anisotropy
  - Power laws can mean nodes, small power law anisotropy is related to gap structure (horizontal?, ...)