Uniaxial Pressure on Strongly Correlated Materials

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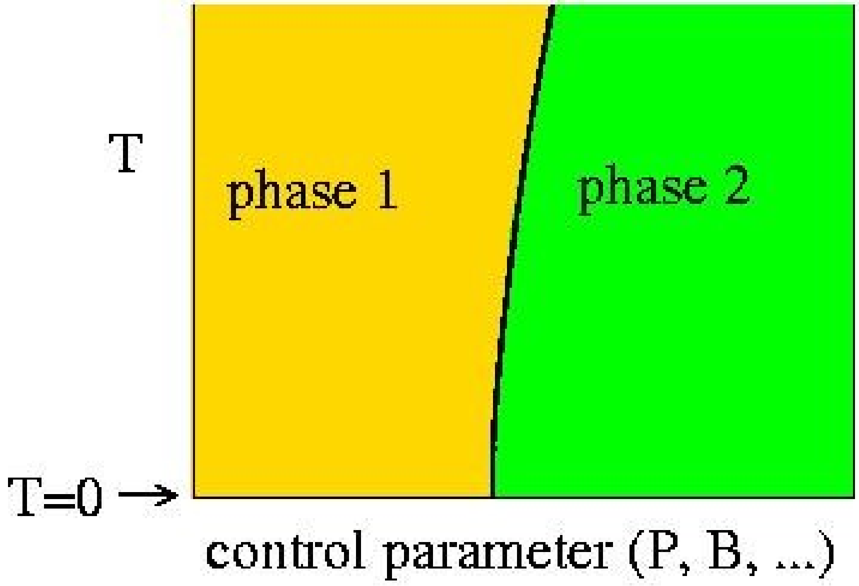
Quantum Critical Points

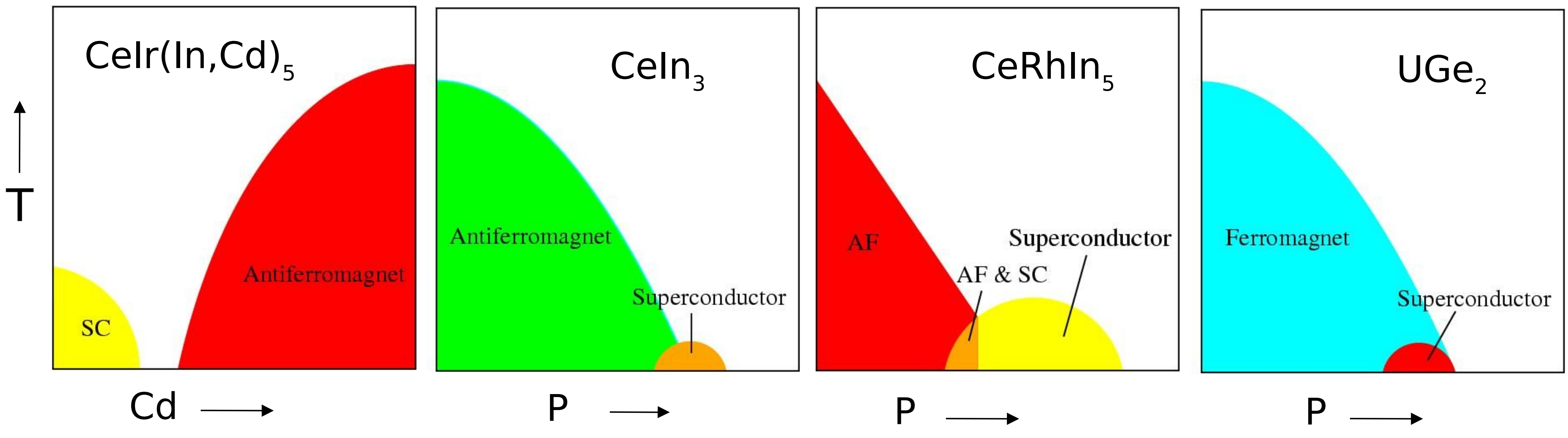
Phase Transitions at T=0

driven by control parameter: alloying, pressure, or magnetic field



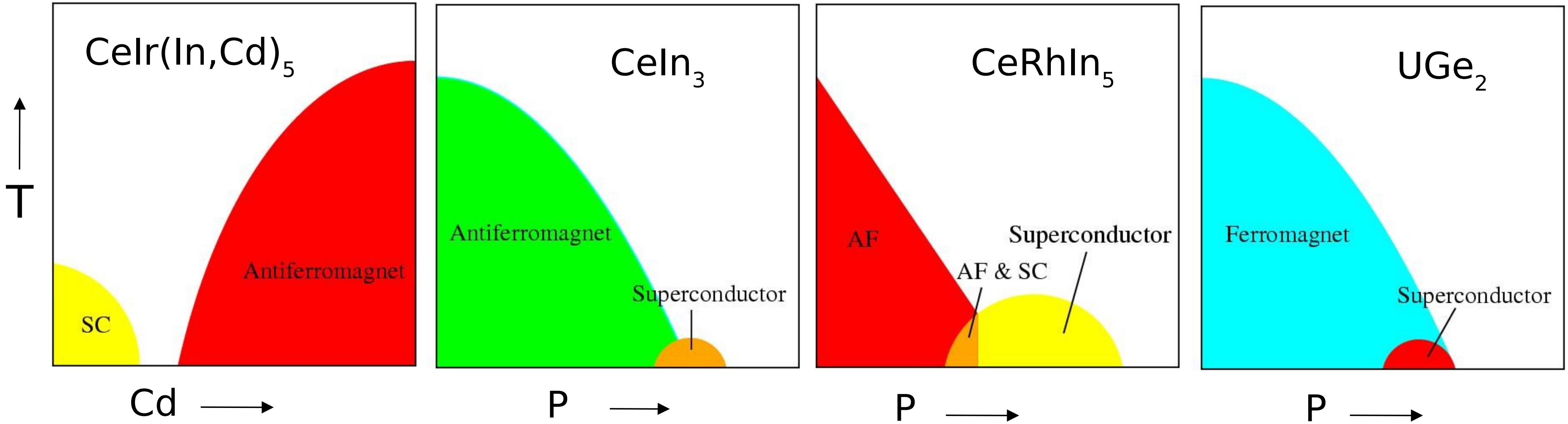
Can lead to a variety of unusual correlated behaviors

Phase diagrams follow certain trends...



- superconducting dome near disappearance of magnetism
- non-Fermi liquid regime in “normal metal”: unusual temperature dependence of resistivity, susceptibility, heat capacity, etc.
- unconventional superconductivity (nodes in energy gap, and resulting power-law temperature dependences)
- low dimensionality favors superconductivity

...but also have key differences



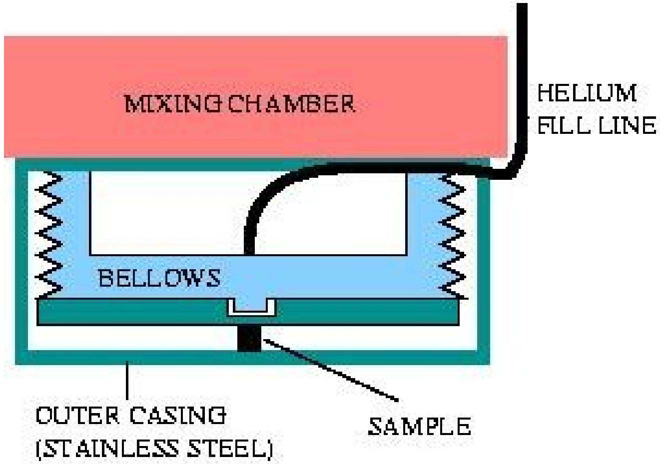
- different flavors of magnetism
- exact superconducting dome location varies; superconductivity may or may not coexist with magnetism
- widely different transition temperatures: <1K to >100K
- node structures differ among materials
- extra phases transitions in some compounds (structural; multiple magnetic or superconducting phases; or unknown phases)

Controlled studies needed!

- Changing samples alters
  - lattice constants or even crystal structure
  - electron concentration within sample
  - magnetic properties
  - sample purity considerations
- Methods for tuning an individual sample:
  - magnetic field
  - pressure (hydrostatic)
  - pressure (uniaxial)

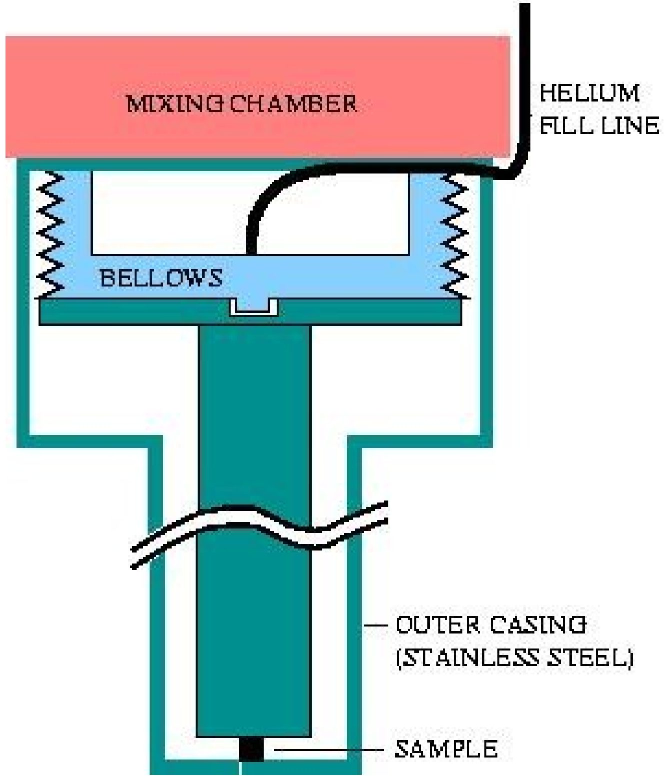
Pressure Cell Setup

- helium-activated bellows
- sample free to expand laterally



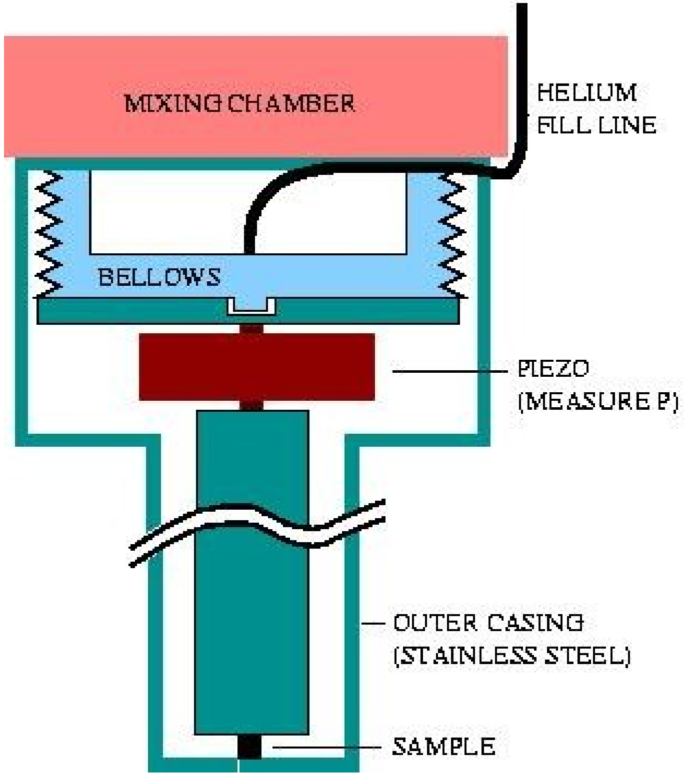
Pressure Cell Setup

- helium-activated bellows
- sample free to expand laterally
- centered in 8/10 Tesla magnet



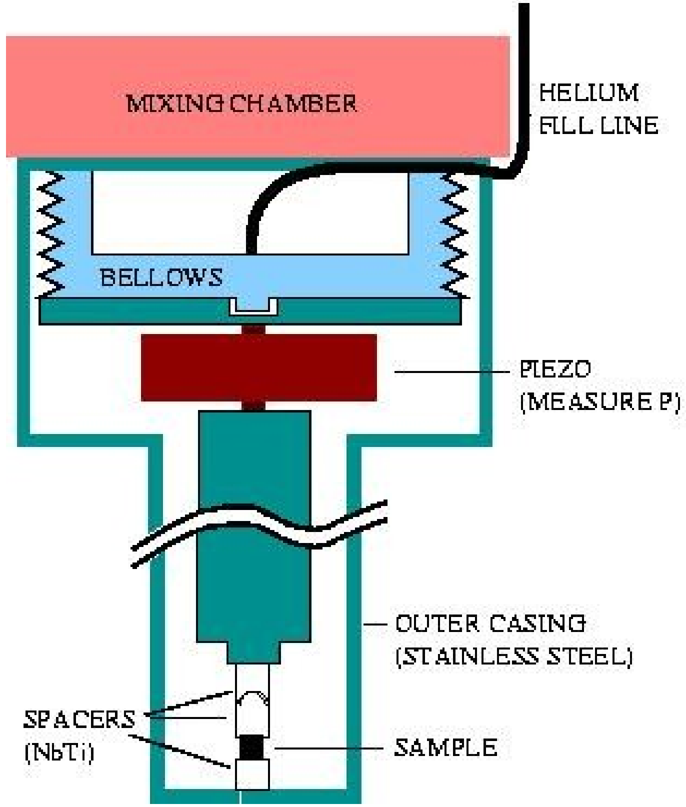
Pressure Cell Setup

- helium-activated bellows
- sample free to expand laterally
- centered in 8/10 Tesla magnet
- measure pressure with piezo



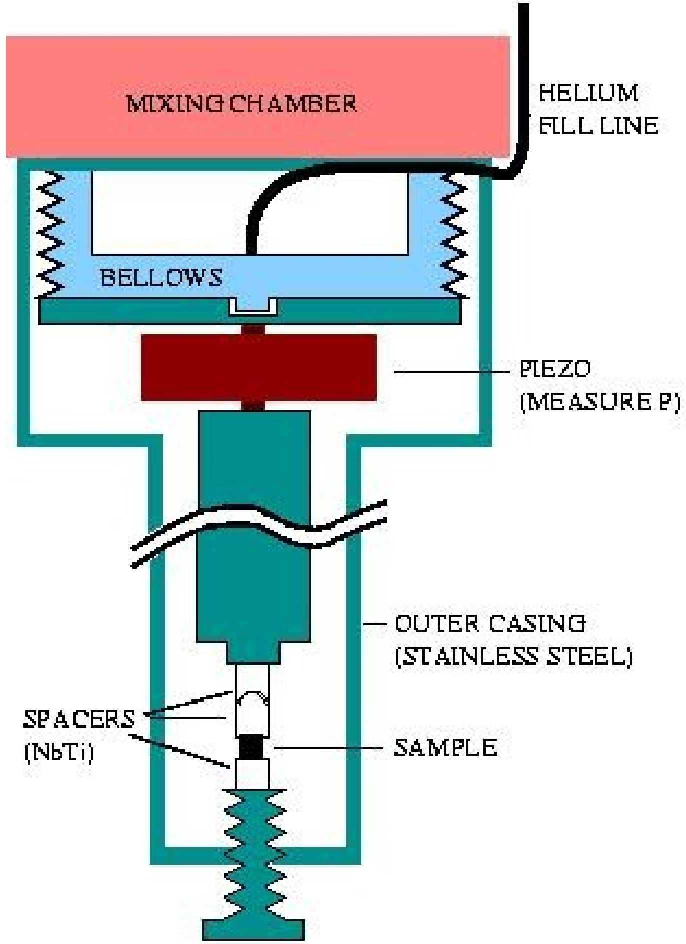
Pressure Cell Setup

- helium-activated bellows
- sample free to expand laterally
- centered in 8/10 Tesla magnet
- measure pressure with piezo
- spacers to adjust alignment



Pressure Cell Setup

- helium-activated bellows
- sample free to expand laterally
- centered in 8/10 Tesla magnet
- measure pressure with piezo
- spacers to adjust alignment
- adjust column length to cool under slight pressure
- cover *everything* with copper foil



Measurement Parameters

Sample size: at least 10 mg, after polishing, for heat capacity. Smaller samples can be used for χ measurements.

P_{max}: about 10 kbar, depending on sample size. Helium solidifies at 25 bar, but area ratio between bellows and sample is several hundred. (Hydrostatic P goes much higher.)

ΔP: better than 0.1 kbar. (Much smaller than hydrostatic P.) We are limited by measurement sensitivity, not pressure step sizes.

Temperature range: have used setup from 100 mK to 200 K.

Temperature for pressure changes: as low as 200 mK.

Magnetic field: up to 10 T, for measurements below 4 K only.

Measure: resistivity, susceptibility, heat capacity

Sample Considerations

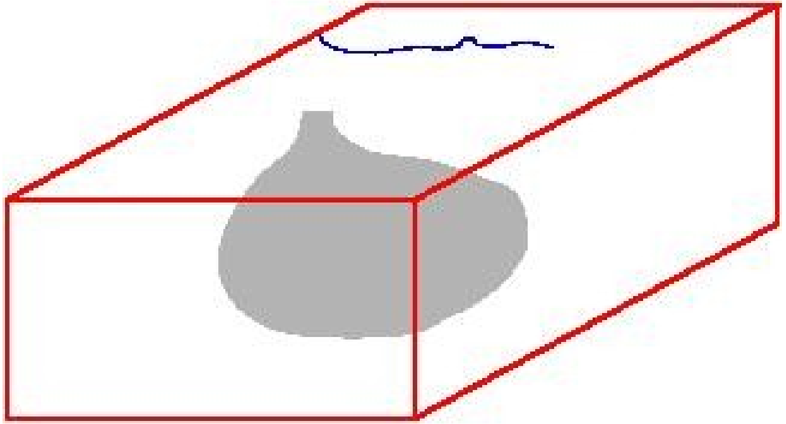
Polishing

two flat, parallel surfaces, for pressure application

all other surfaces perpendicular to these, for constant cross-section

No cracks

No occlusions

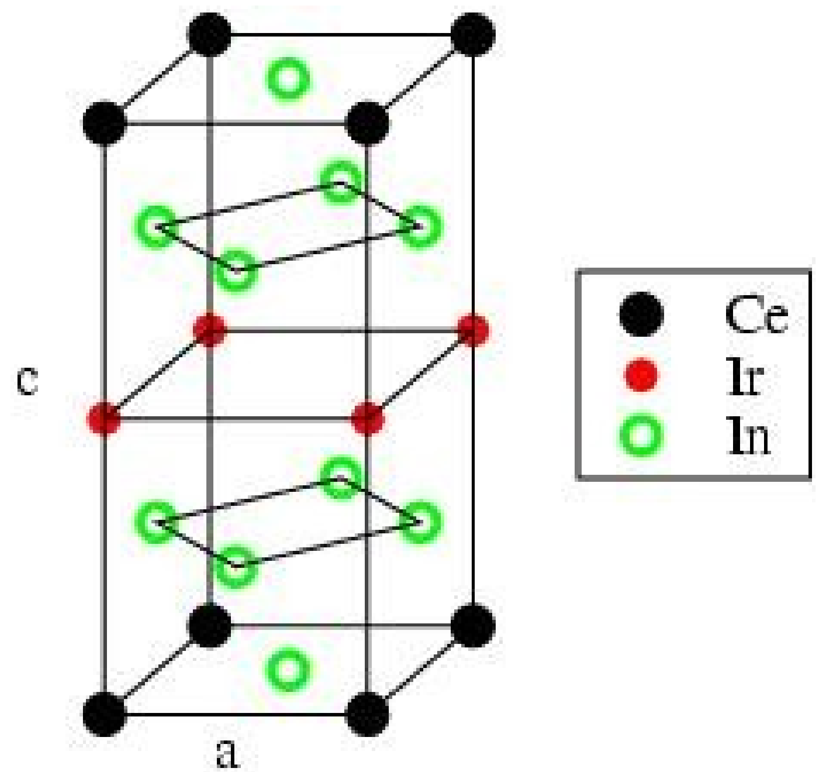


Need significant final size, for decent signal-to-noise

Often want single crystal samples

Ce(Ir,Rh,Co)In_5

- several types of behavior in a single crystal structure
- relatively easy to make; clean
- layered structure, similar to high-T_c superconductors
- special behavior:
  - disagreement in T_c from ρ, C
  - exotic vortex phase in $CeCoIn_5$ at high fields



Lattice Constants and Superconductivity

Trends in Tc:

$CeCoIn_5$	2.3 K
$CeIrIn_5$	0.4 K
$CeRhIn_5$	low mK or with P

Doesn't match ion size, or individual lattice parameters.

- **T_c linear in *c/a* for pure compounds and alloys**
- uniaxial P: vary *c/a* without sample-to-sample variations
- predictions from thermal expansion:

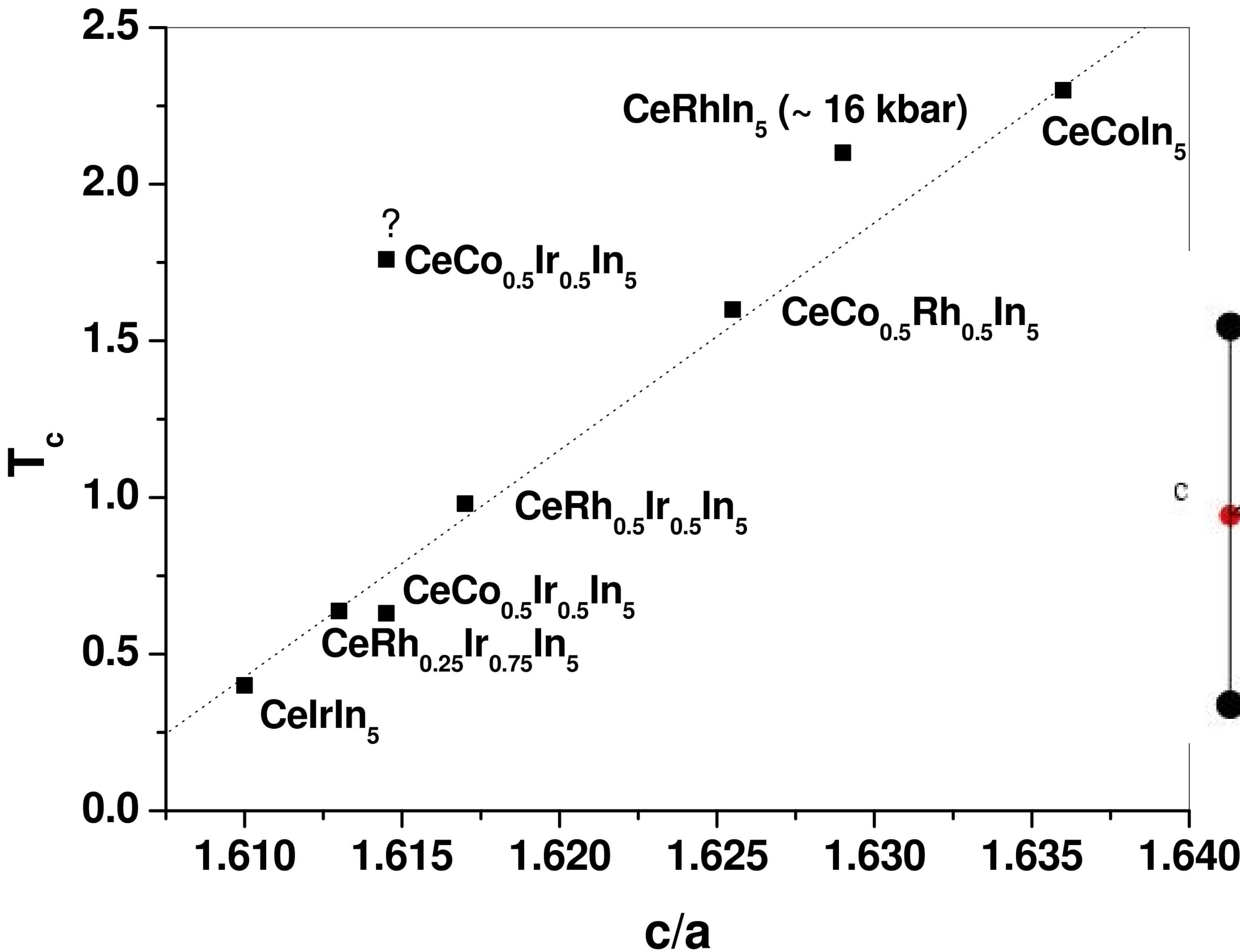
$$\frac{\partial T_c}{\partial P_a} = 54 \text{ mK/kbar}$$

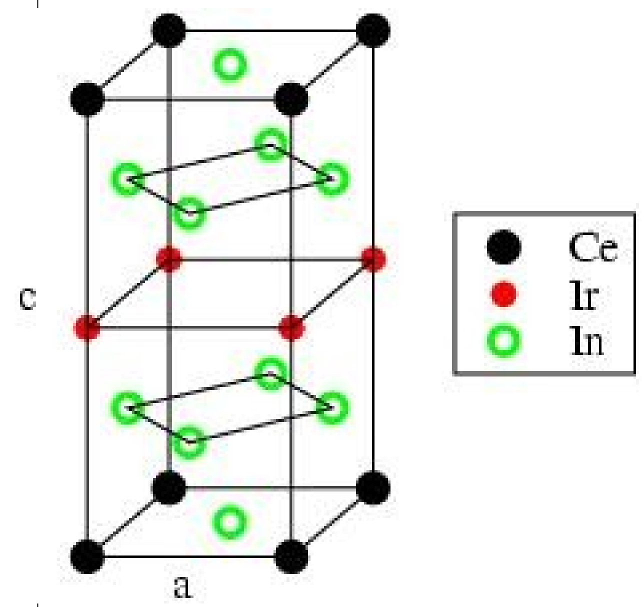
$$\frac{\partial T_c}{\partial P_c} = -89 \text{ mK/kbar}$$

Oechsler et al., PRL 91, 076402 (2003)

$CeMIn_5$

(M=Co, Ir, Rh)





[after Pagliuso et al., *Physica B* **131-132**, 129 (2001)]

To change c/a, use uniaxial pressure (NOT hydrostatic).

Lattice Constants and Superconductivity

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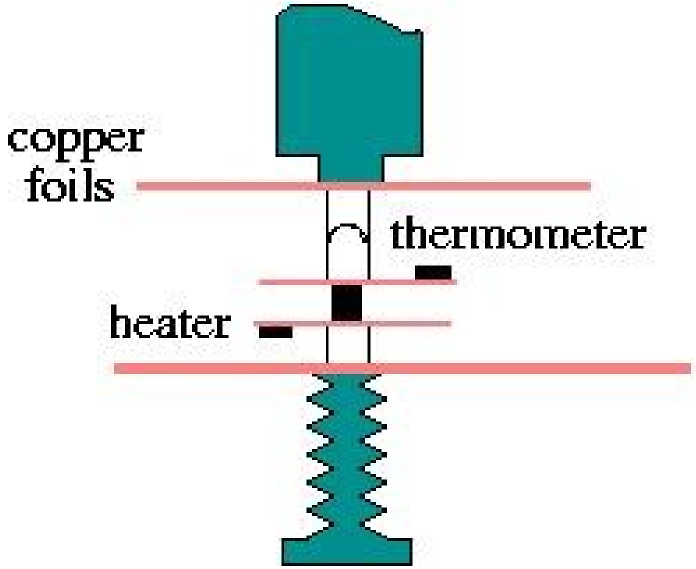
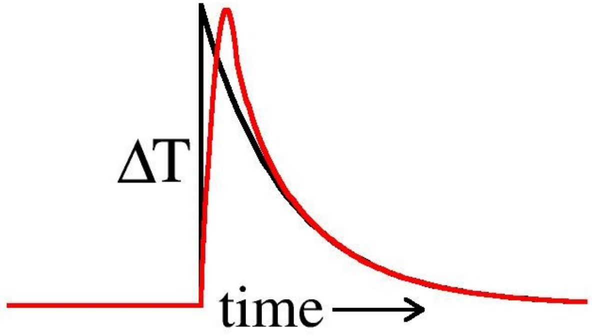


Thermometer – RuO_2 film

Heater – 50:50 Au:Cr alloy

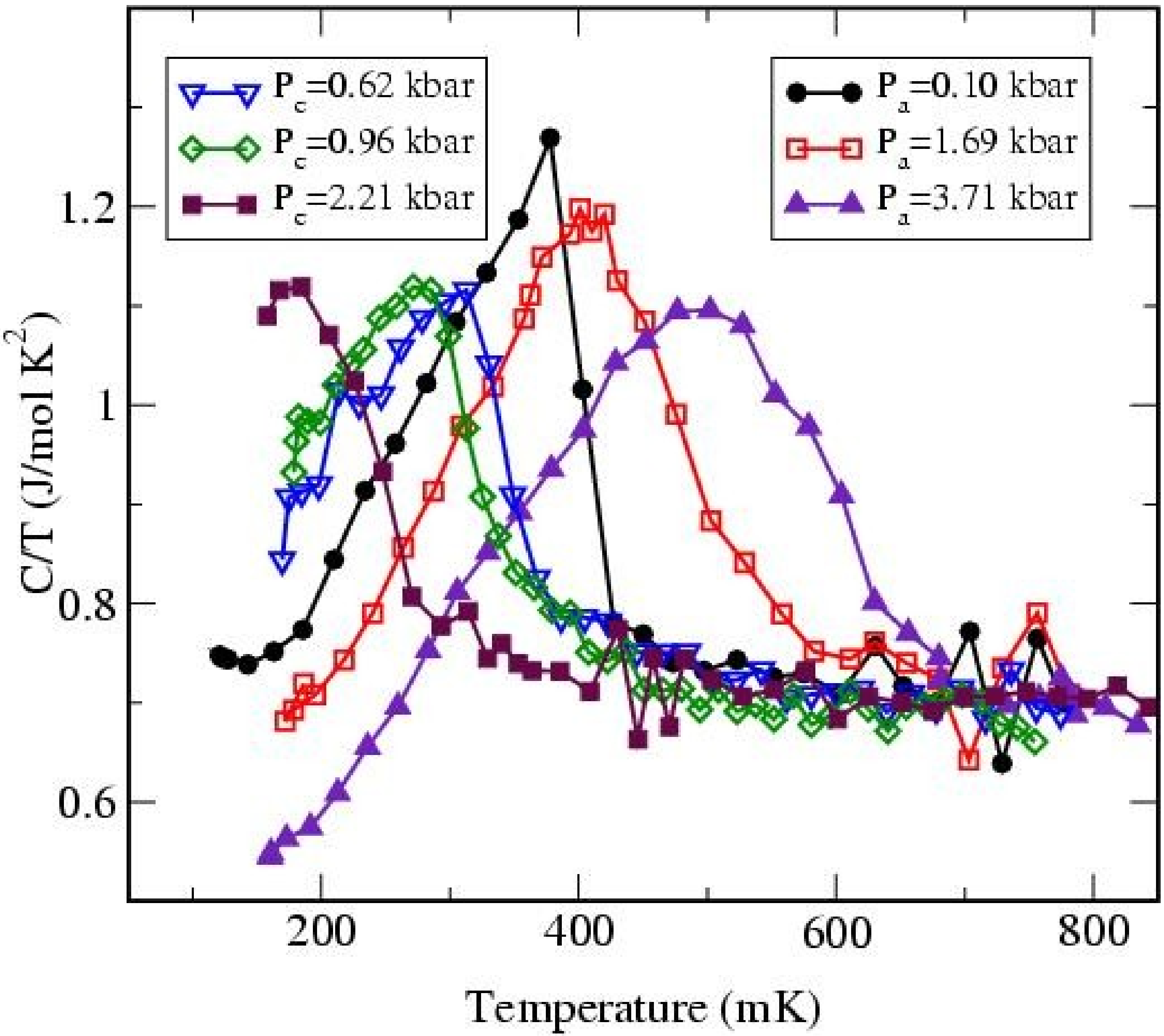


Use short heat pulse followed by exponential decay.

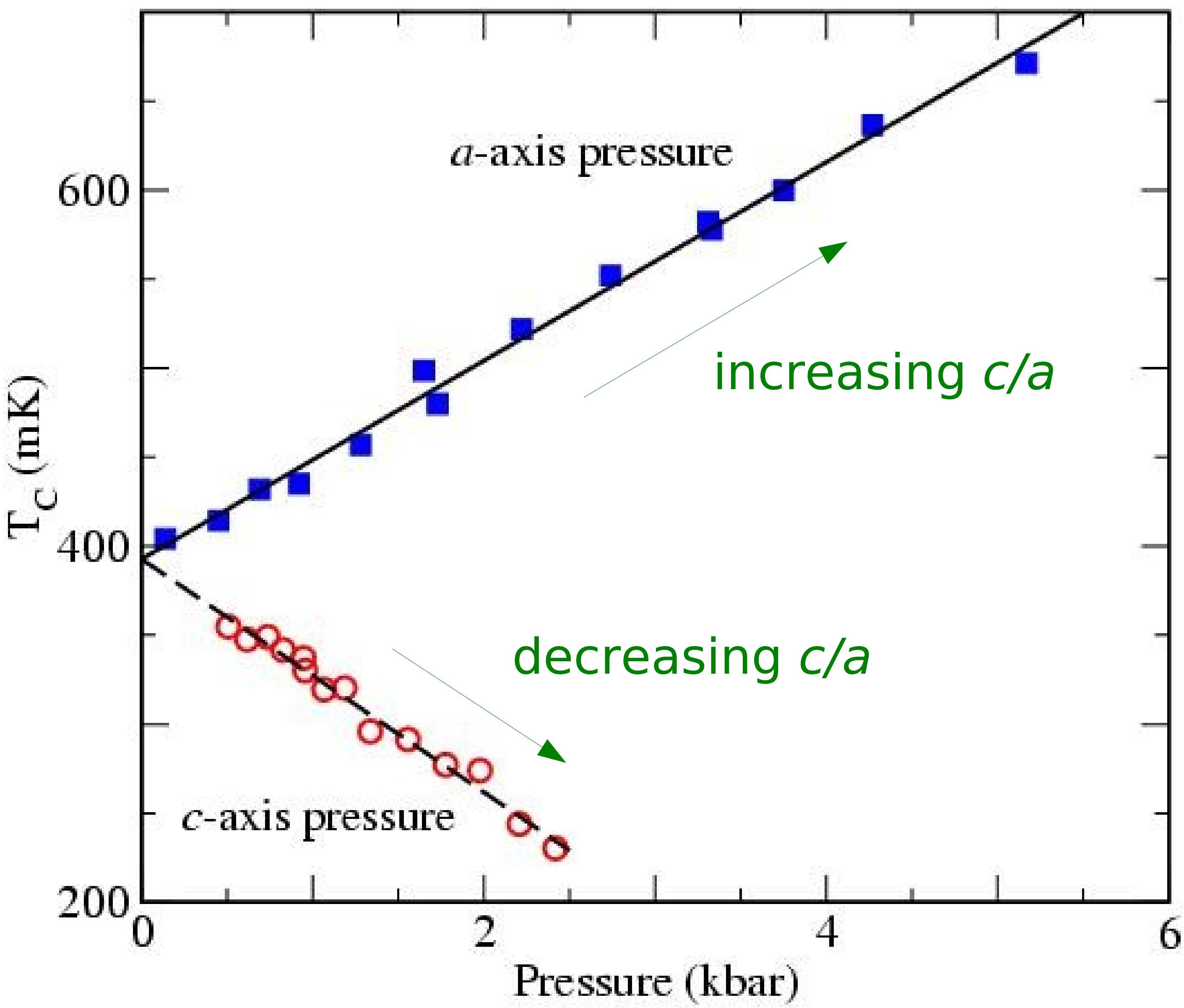
Time constant proportional to sample size.

Place sample between heater and thermometer to reduce initial spike, but still have large background.

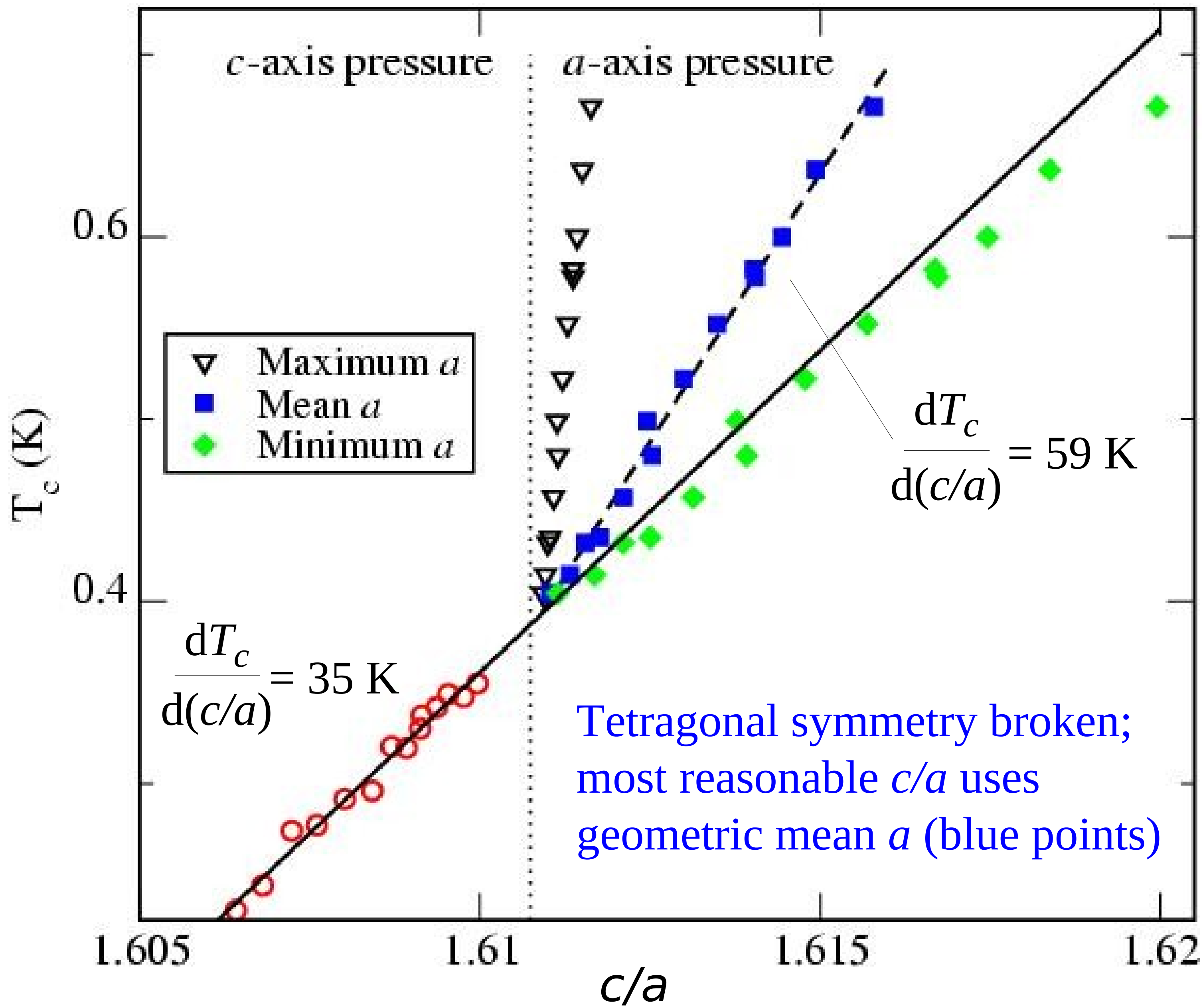
$CeIrIn_5$



P_c=0.62 kbar
P_c=0.96 kbar
P_c=2.21 kbar
P_a=0.10 kbar
P_a=1.69 kbar
P_a=3.71 kbar
C/T (J/mol K^2)
1.2
1
0.8
0.6
200
400
600
800
Temperature (mK)



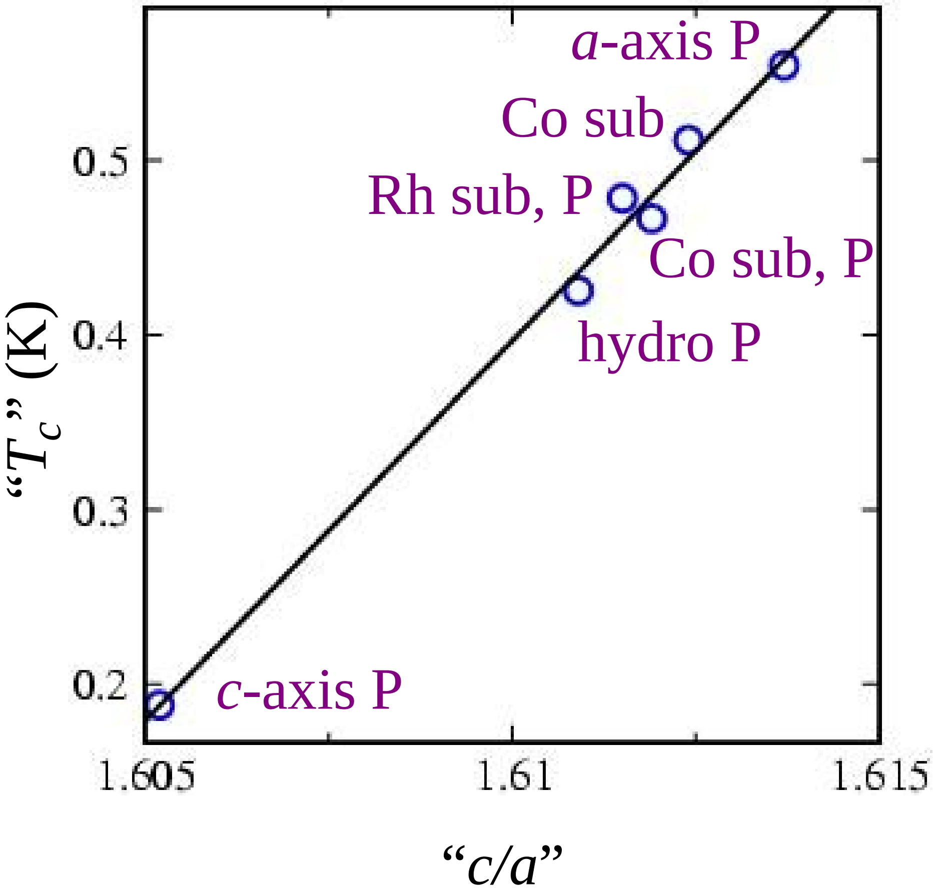
Linear change of T_c with pressure for both directions



Kink at zero pressure may indicate influence of hybridization

Calculate c/a and T_c if control parameters were scaled so all achieved the same hybridization

Uniaxial work important: gives extreme points



With hybridization variations removed, the resulting linear relationship shows the influence of dimensionality:

$$\frac{\partial T_c}{\partial (c/a)} = 44 \text{ K}$$

Further thermal expansion predictions

$CeIrIn_5$

$$\frac{\partial T_c}{\partial P_a} = 54 \text{ mK/kbar}$$

$$\frac{\partial T_c}{\partial P_c} = -89 \text{ mK/kbar}$$

$CeCoIn_5$

$$\frac{\partial T_c}{\partial P_a} = 29 \text{ mK/kbar}$$

$$\frac{\partial T_c}{\partial P_c} = -7.5 \text{ mK/kbar}$$

Why so small??

Oechsler et al., PRL 91, 076402 (2003)

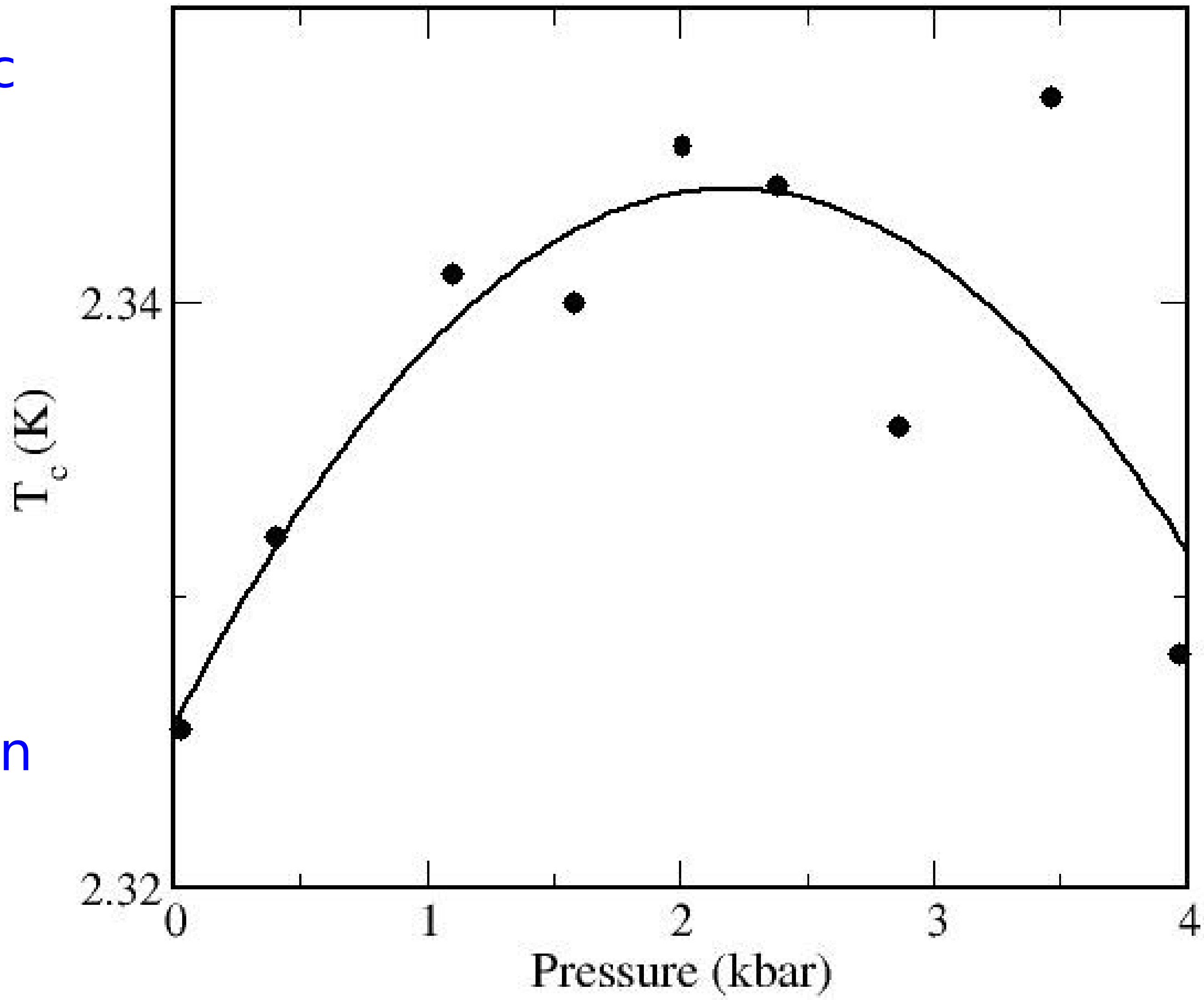
$CeCoIn_5$

Measure magnetic susceptibility

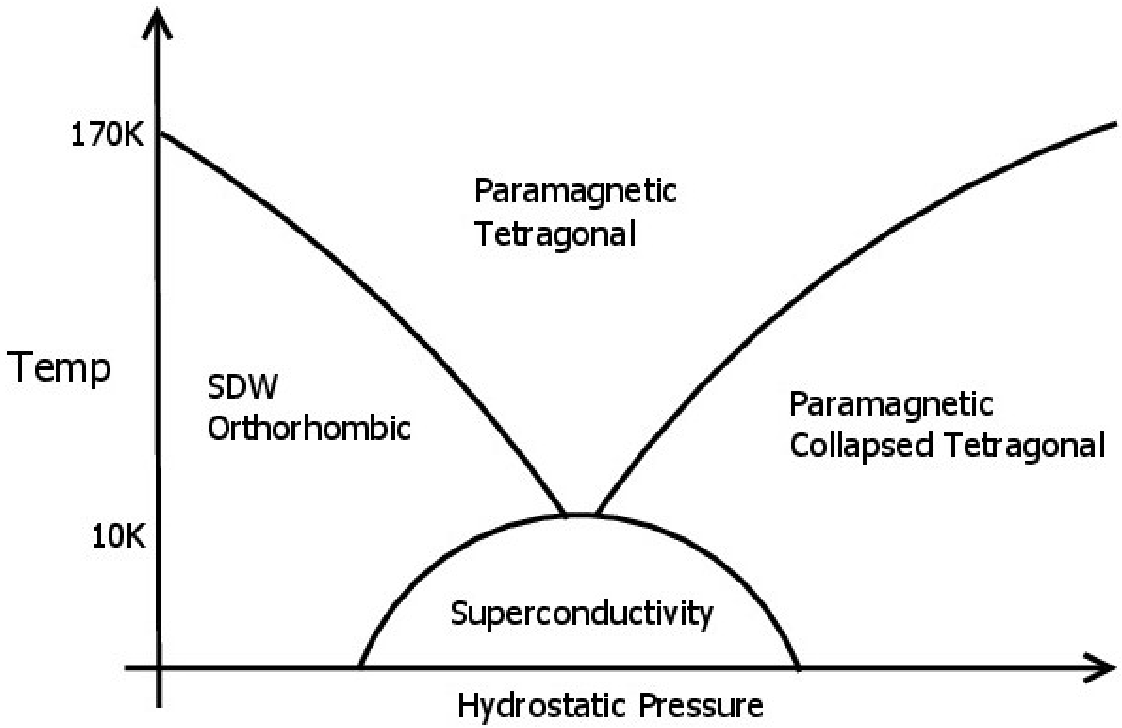
Very little P-dep (20 mK rather than 200 mK)

Not linear! Sample "tuned" unusually well

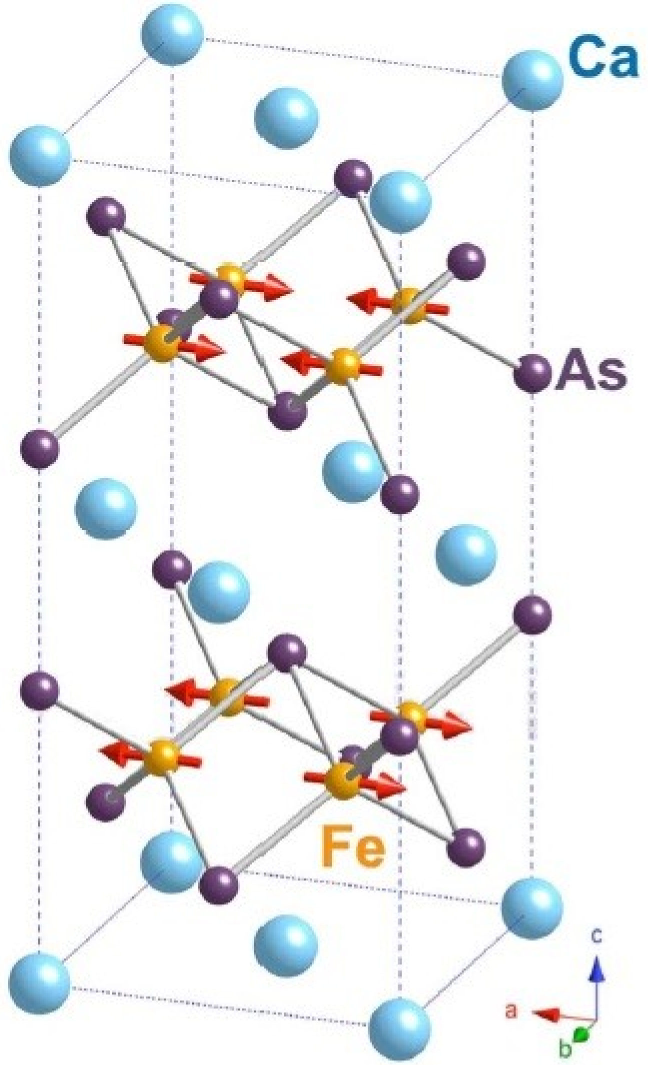
Thermal expansion only gives info on P=0 slope.



$CaFe_2As_2$

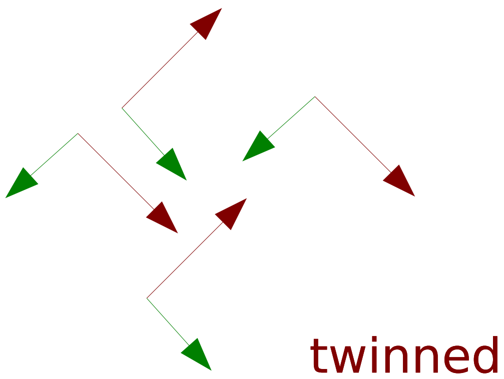


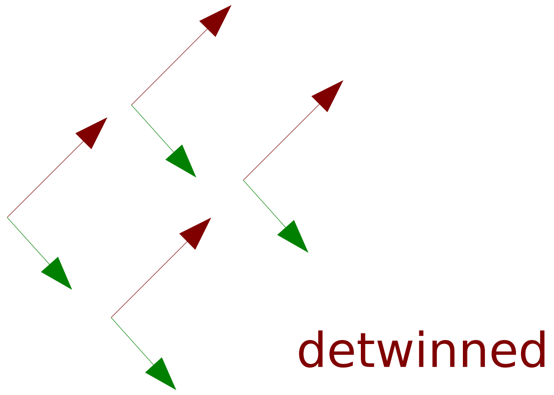
170K
10K
Temp
Paramagnetic
Tetragonal
SDW
Orthorhombic
Paramagnetic
Collapsed Tetragonal
Superconductivity
Hydrostatic Pressure



Ca
As
Fe
c
a
b

$CaFe_2As_2$



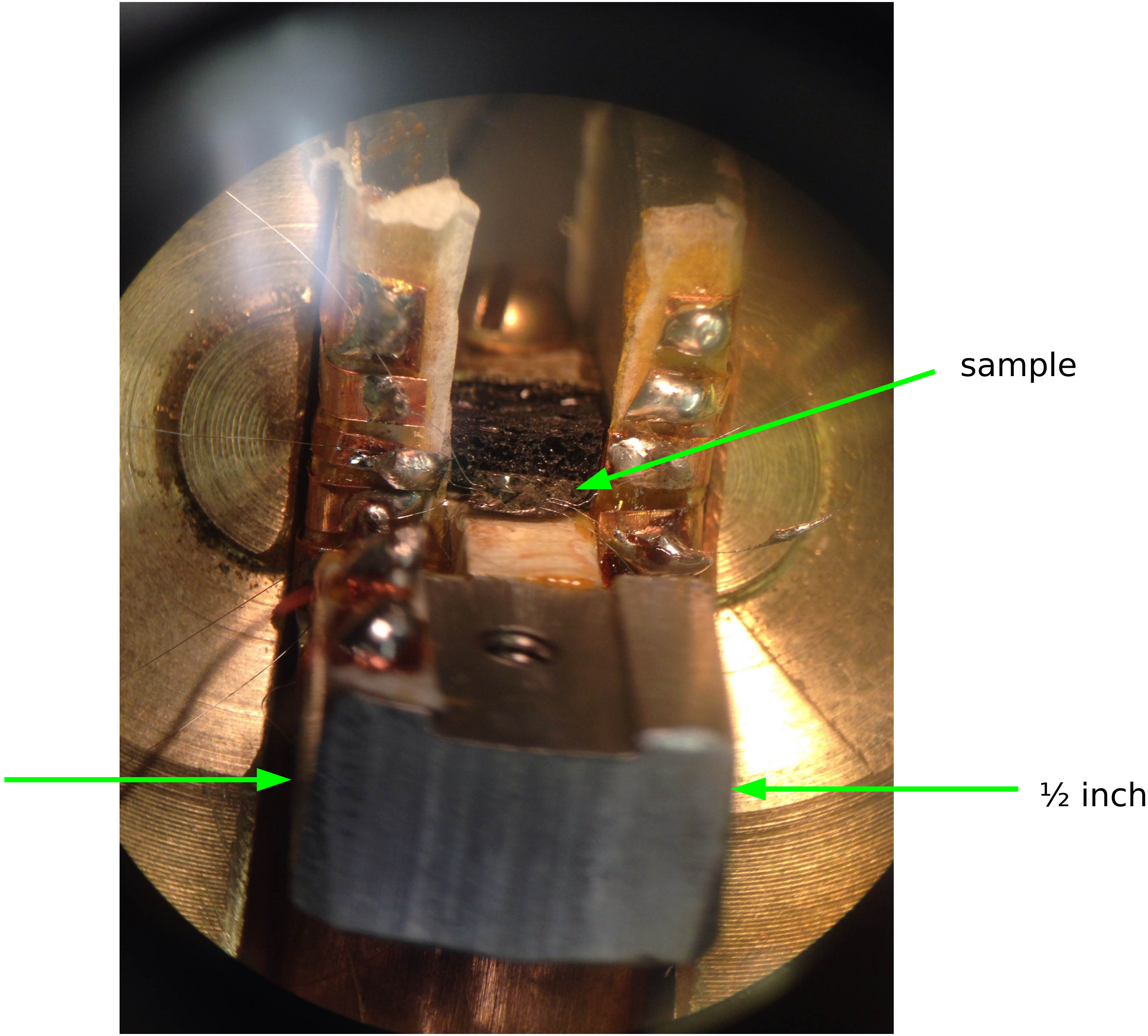


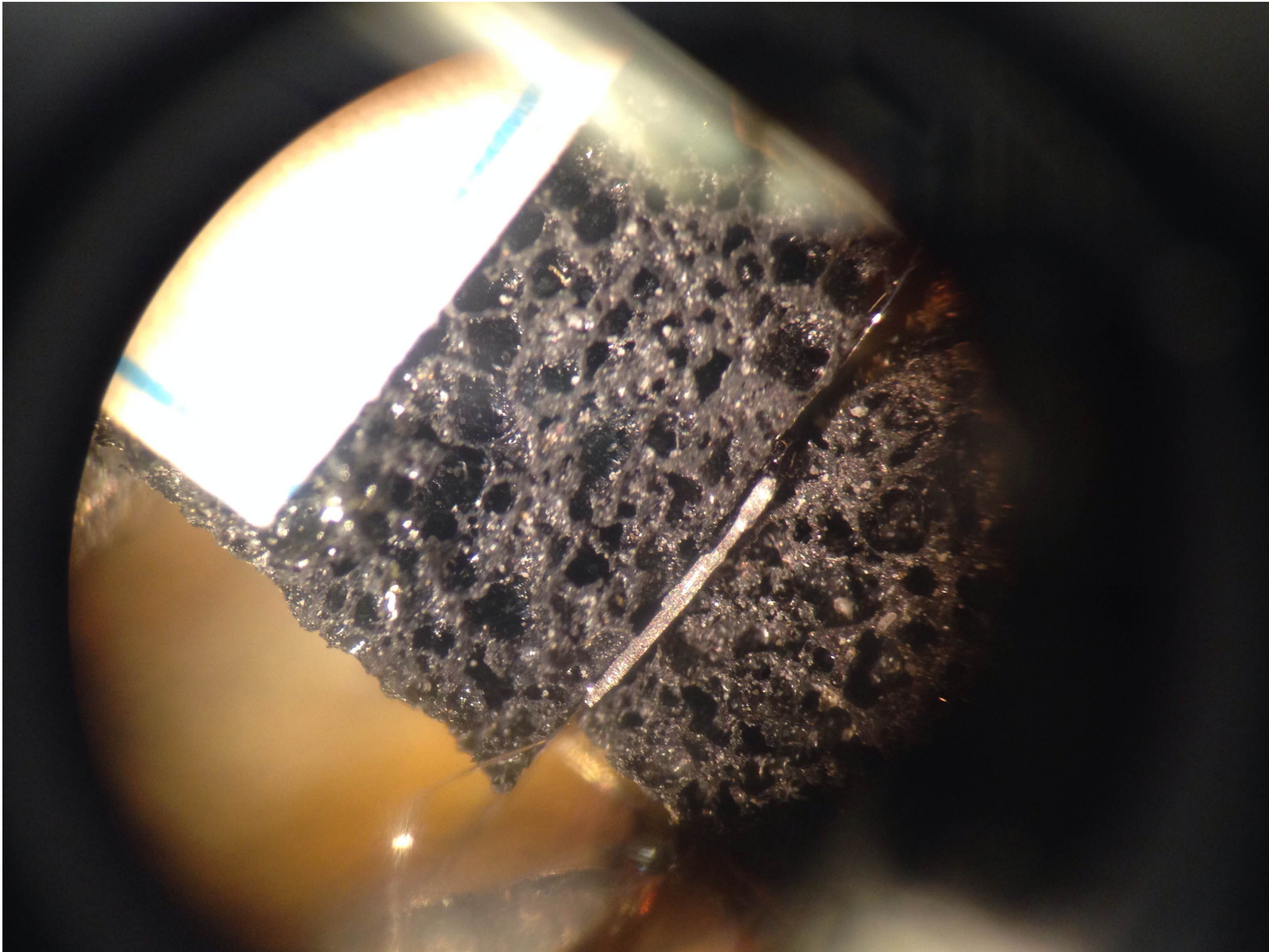
In orthorhombic phase, detwinned crystals have different $\rho(T)$ along the *a* and *b* axes.

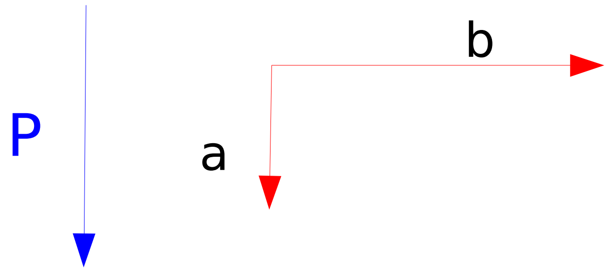
In-plane pressure can accentuate the *a*-*b* difference.

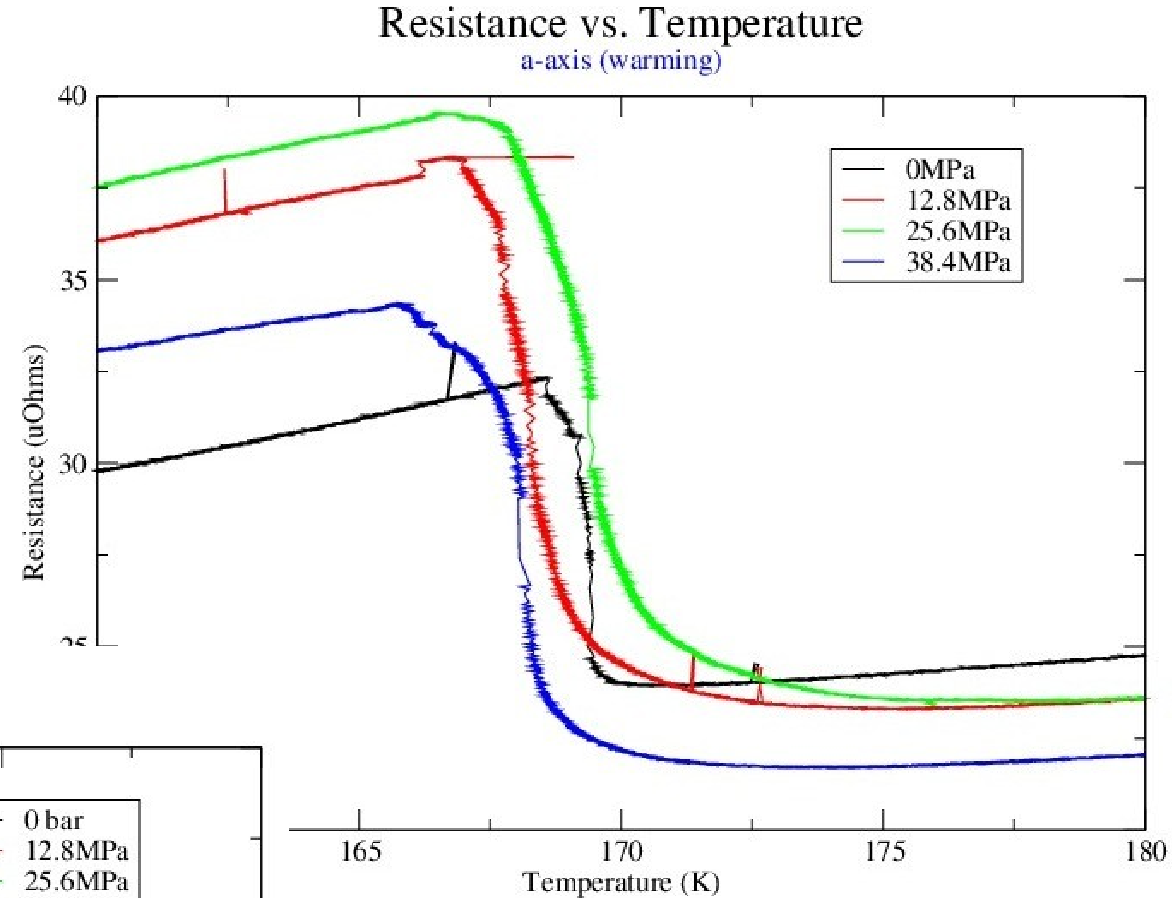
A technical challenge: platelet samples! (Unfortunately common among materials with layered crystal structures.)

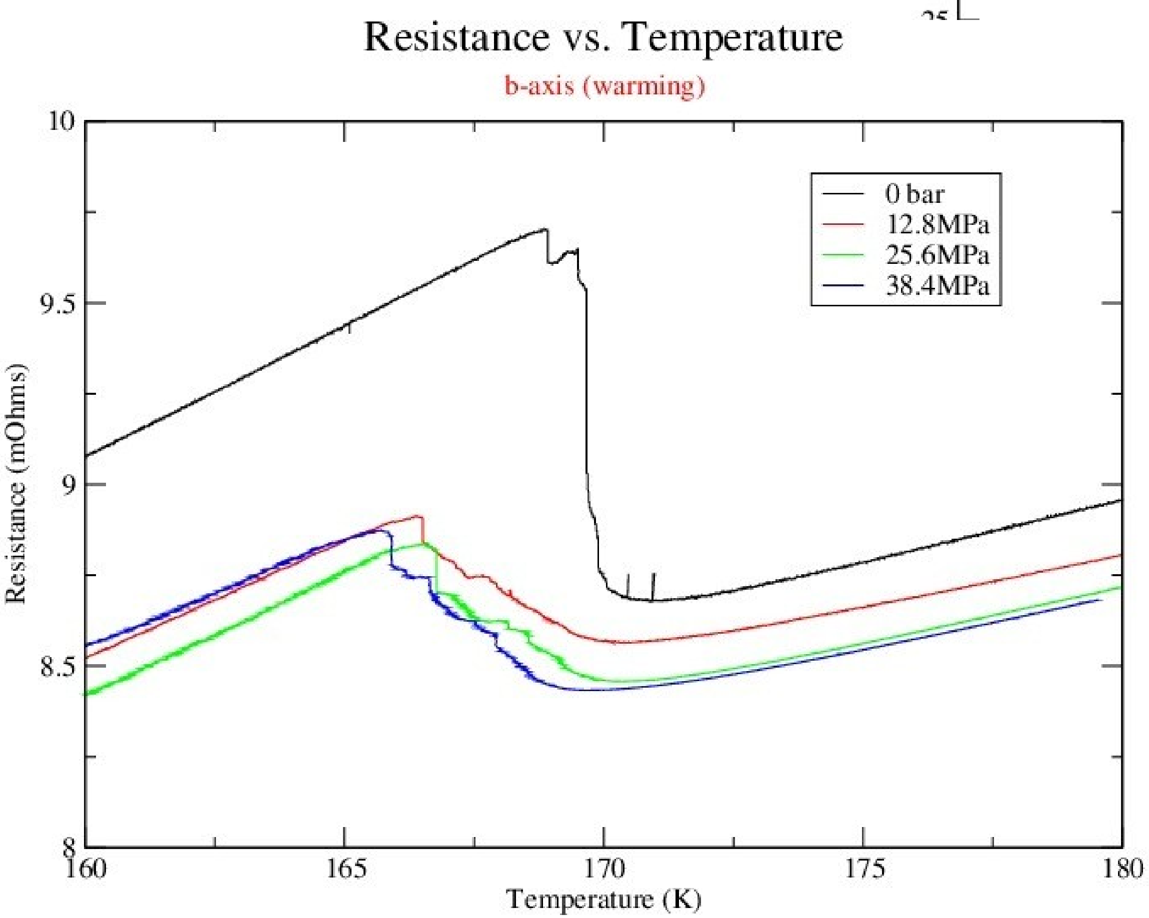
Use foam to keep alignment.

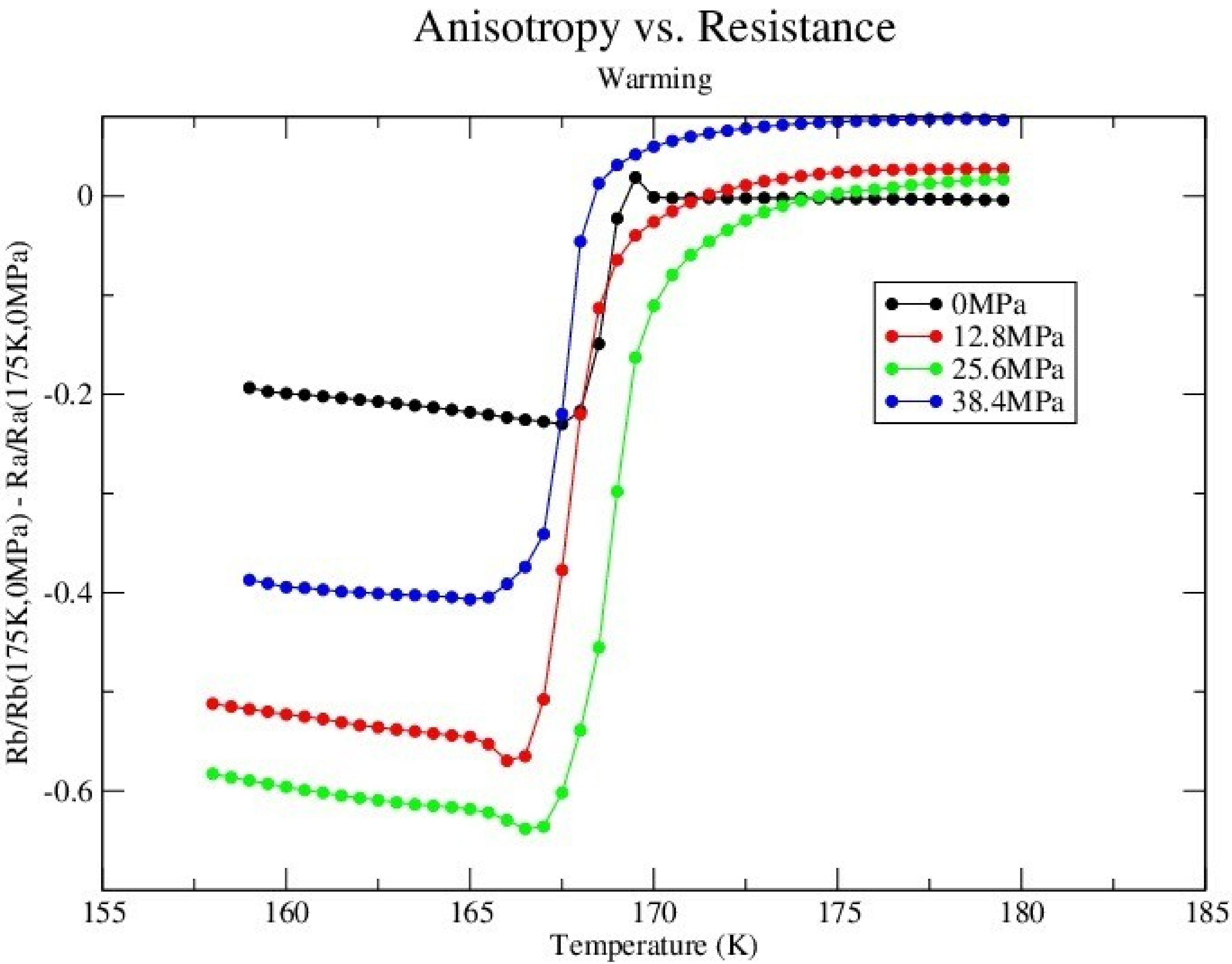

sample
½ inch




P
b
a


Resistance vs. Temperature
a-axis (warming)
Resistance (uOhms)
Temperature (K)
0MPa
12.8MPa
25.6MPa
38.4MPa
40
35
30
165
170
175
180


Resistance vs. Temperature
b-axis (warming)
Resistance (mOhms)
Temperature (K)
0 bar
12.8MPa
25.6MPa
38.4MPa
10
9.5
9
8.5
8
160
165
170
175
180



Anisotropy vs. Resistance
Warming
Rb/Rb(175K,0MPa) - Ra/Ra(175K,0MPa)
Temperature (K)
0
-0.2
-0.4
-0.6
155
160
165
170
175
180
185
0MPa
12.8MPa
25.6MPa
38.4MPa

Conclusions

- Uniaxial pressure provides a unique probe of strongly correlated systems.

- Our setup runs from below 100 mK to over 200 K, and to pressures of 1 GPa. At low temperature a magnetic field can also be applied along the pressure axis.

- We observe how dimensionality favors superconductivity in 115 materials and measure anisotropy from in-plane symmetry breaking in iron pnictides.