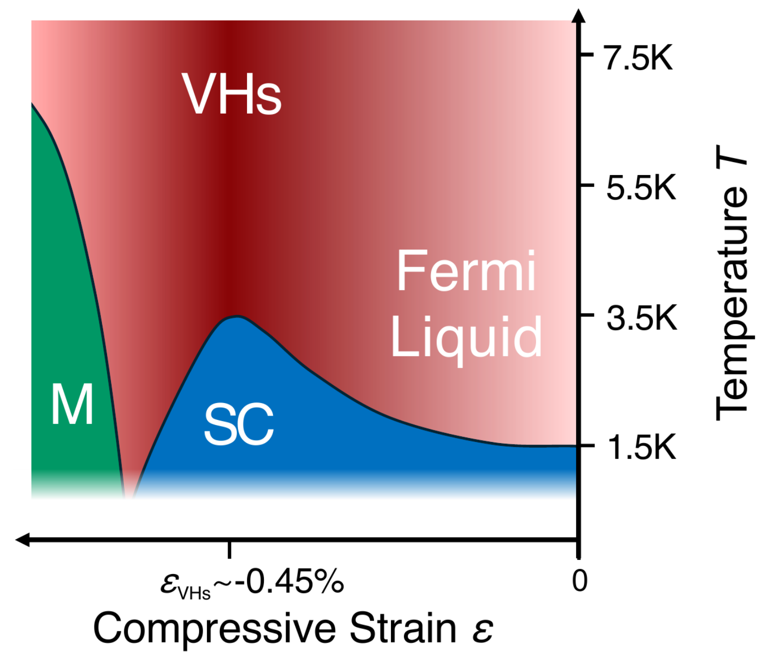
Towards fully quantitative entropy mapping using the elastocaloric effect in Sr_2RuO_4



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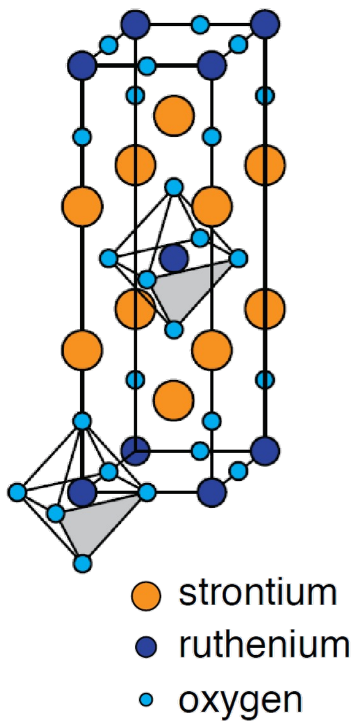
Brief overview of Sr_2RuO_4



Layered superconductor

tetragonal 214 structure

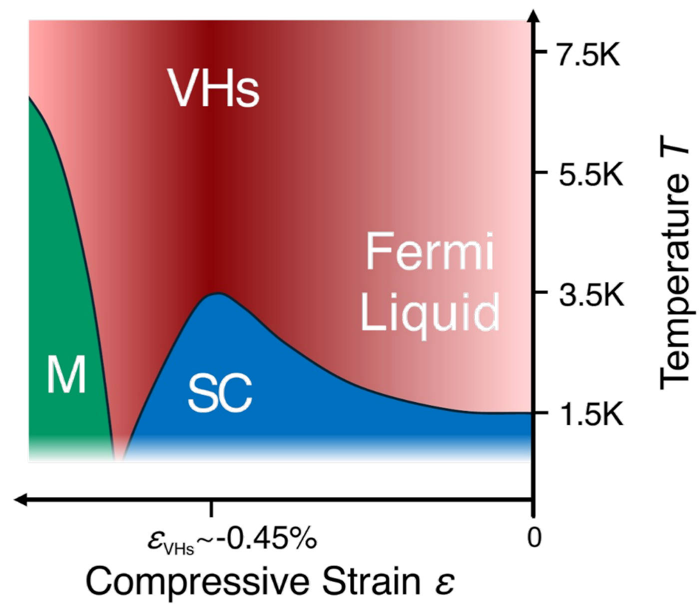
ambient SC $T_c = 1.5$ K

Unconventional pairing

the canonical chiral p-wave state is disfavored

Strong uniaxial strain response

T_c:$1.5 \rightarrow 3.5$K · VHs crossing · magnetic phase



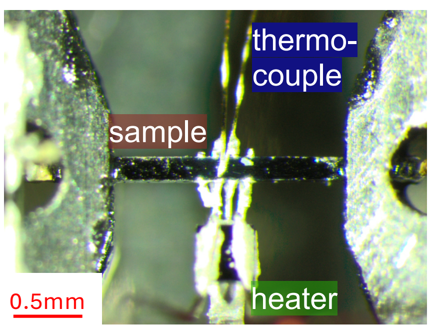
ECE in Sr_2RuO_4

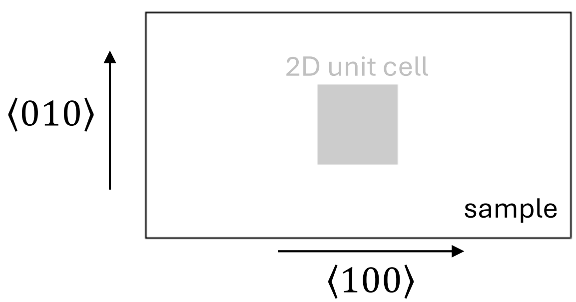
- ECE probes the strain derivative of entropy:

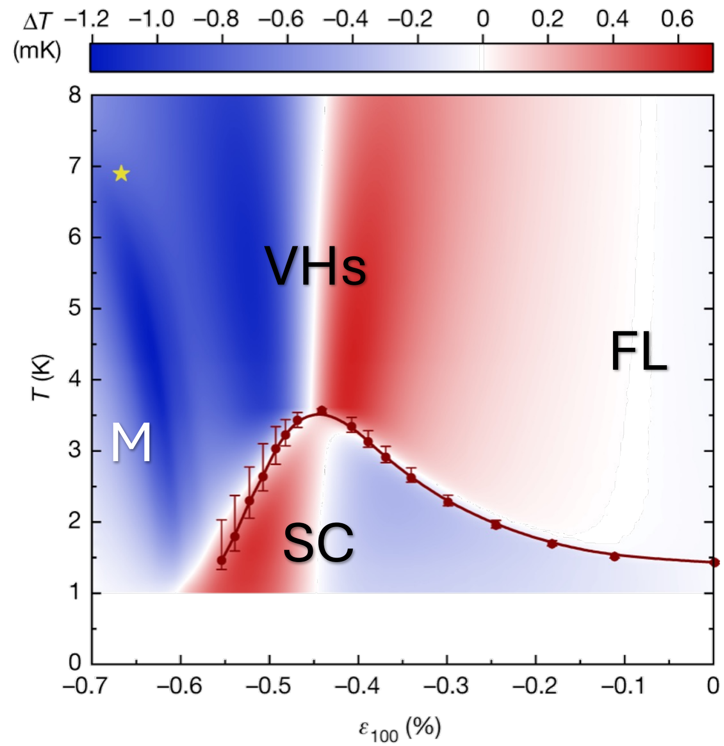
$$\tilde{T}_s = -\frac{T_s}{c_s}\left(\frac{\partial s_{strain}}{\partial \varepsilon}\right)_T \tilde{\varepsilon}$$

  under ideal (quasi-)adiabatic condition.

- Key signatures:
  - **SC**: sharp anomaly in ΔT
  - **VHs:** entropy extremum
  - **Magnetic order:** high-strain anomaly

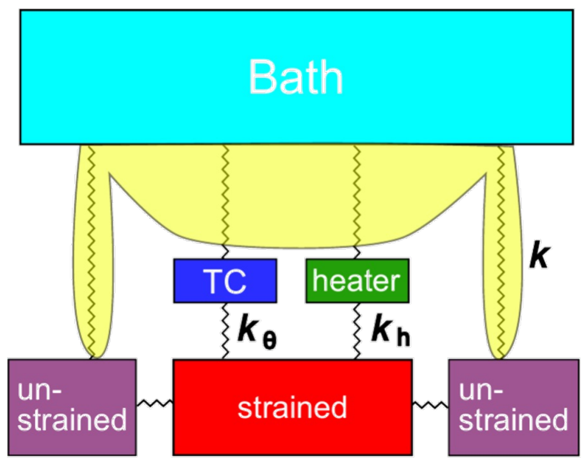






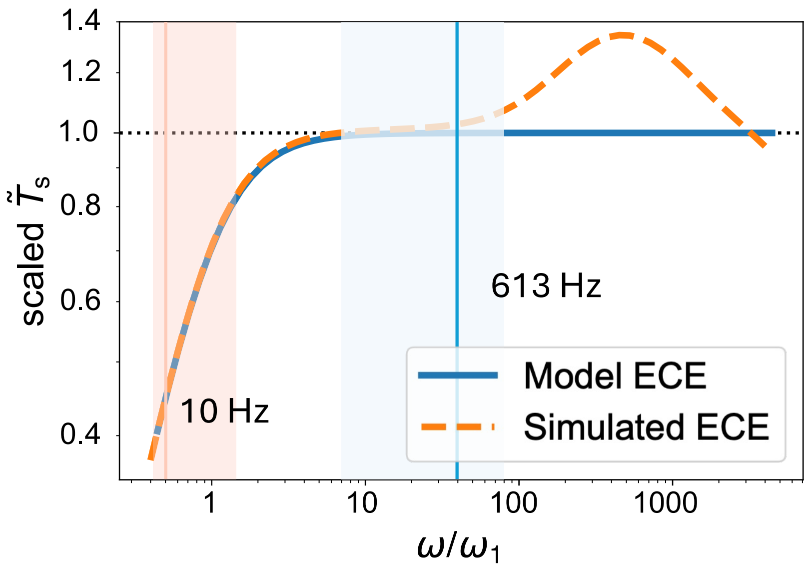
Reproduced from Li et al., *Nature* 607, 276–280, (2022).

AC ECE: Strong-coupling regime



State-dependent thermal properties
Heat capacity and thermal conductance of the sample changes across phase transitions

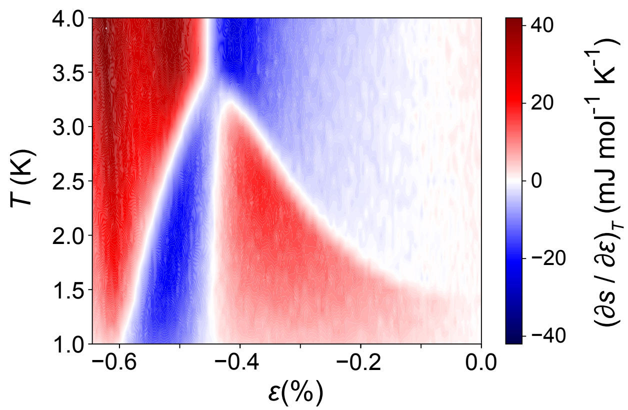
Volume mixing
Unstrained regions dilute the response



Strong-Coupling Low-frequency	Quasi-Adiabatic High-frequency
$\lvert\tilde{T}_s\rvert = \omega\times\frac{T_0}{k}\left\lvert\left(\frac{\partial S_{strain}}{\partial\varepsilon}\right)_T\tilde{\varepsilon}\right\rvert$	$\lvert\tilde{T}_s\rvert = \frac{T_0}{C_s}\left\lvert\left(\frac{\partial S_{strain}}{\partial\varepsilon}\right)_T\tilde{\varepsilon}\right\rvert$
Absolute scale correction: ~30%	**Absolute scale correction in FL phase: ~300%**

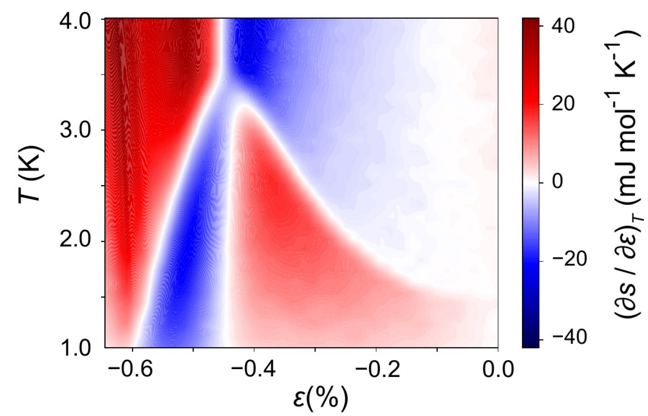
Multi-frequency fusion and quantitative entropy gradient

Entropy gradient measured@10 Hz



Combine
- high-accuracy strong-coupling regime
- high-resolution quasi-adiabatic regime

Entropy gradient recovered by 'dataset fusion'



Entropy extrema

Zero contour near ε_{VHs}

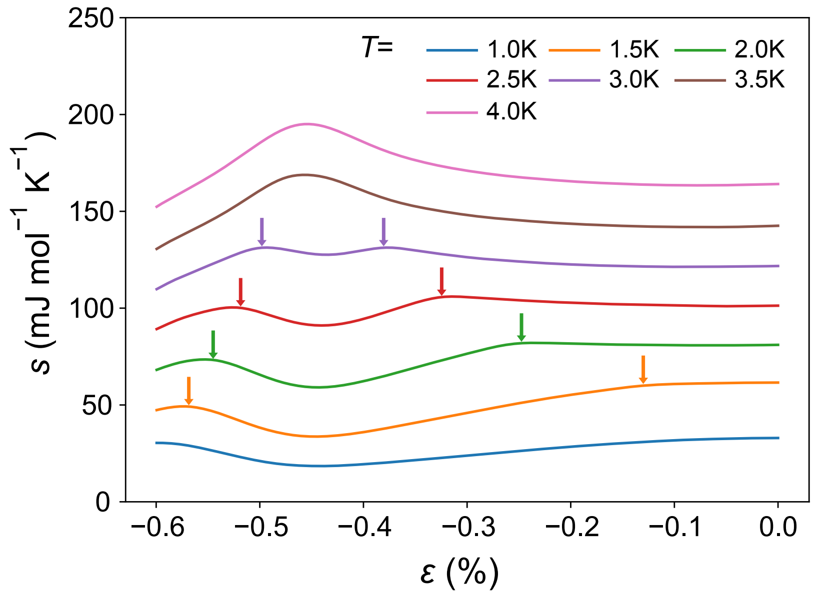
Offset in optimal strains

The maxima of T_c and normal-state entropy differ by $\approx 0.01\%$ strain: multi-band effect

Magnetic–SC boundary

The kink near -0.6% the magnetic and superconducting transitions coincide;

Absolute entropy



Arrows indicate the superconducting boundaries.

❖ **Absolute surface**

The calibrated entropy derivative is integrated and anchored by the zero-strain heat capacity.

$$s(\varepsilon,T) = s(0,T) + \int_0^{\varepsilon} (\partial s/\partial \varepsilon')_T \, d\varepsilon'$$

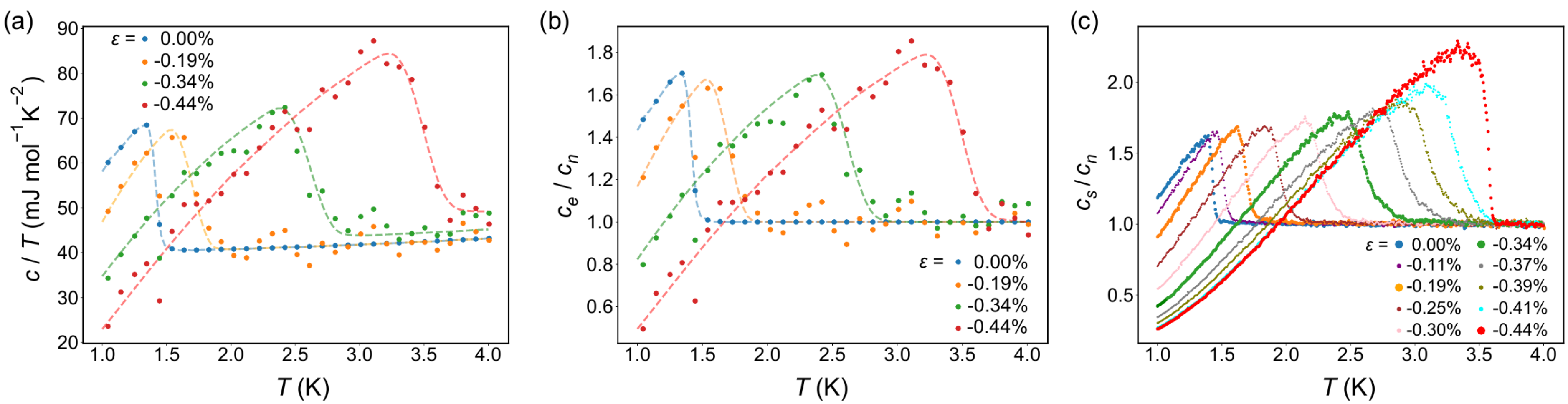
independent specific heat measurement

❖ **Superconductivity**

Entropy maxima in normal state is strongly quenched by SC state near the VH strain

Palle et al., *Phys. Rev. B* 108, 94516, (2023).

Absolute specific heat



Panel (c) reproduced from Li et al., *Proc. Natl. Acad. Sci.* 118, 1–2, (2021).

$$c(\varepsilon,T)/T = \left(\frac{\partial}{\partial T}\right)_{\varepsilon}\left(s(0,T) + \int_0^{\varepsilon}(\partial s/\partial\varepsilon')_T \mathrm{d}\varepsilon'\right)$$

AC calorimetry:

- ❖ locally inferred, not directly measured.

Entropy mapping through AC ECE:

- ❖ absolute specific heat free from state-dependent calibration factor

Take-away:
The enhancement of specific heat jump ratio is less significant, which is consistent with previous results after accounting for the transition width.

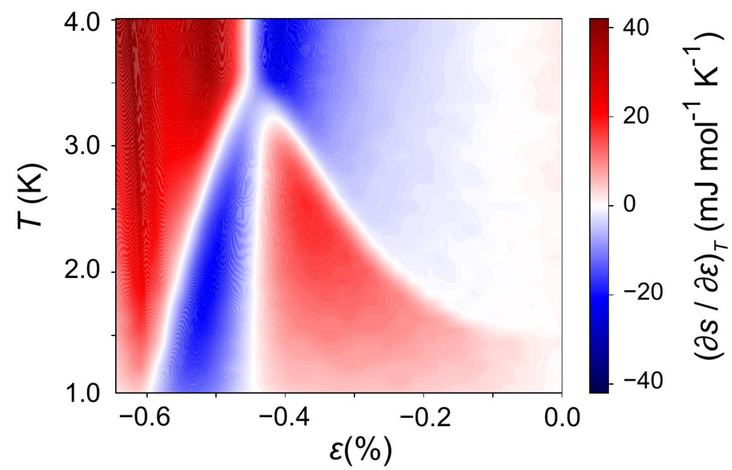
Summary

ECE in strong-coupling regime

- Absolute entropy and specific heat are reconstructed across the strain-temperature phase diagram.

- Maximum T_c and maximum normal-state entropy differ by $\simeq 0.01\%$ strain; superconducting entropy suppression is strongest near the VHs.

- $\Delta c/T$ increases near the VHs, but much less than previously inferred.

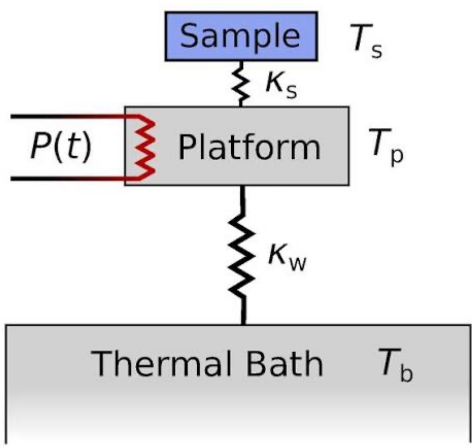


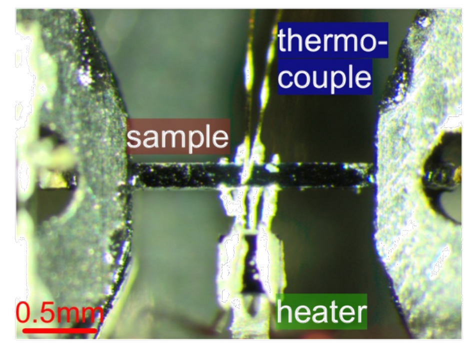
Thank you for your attention!

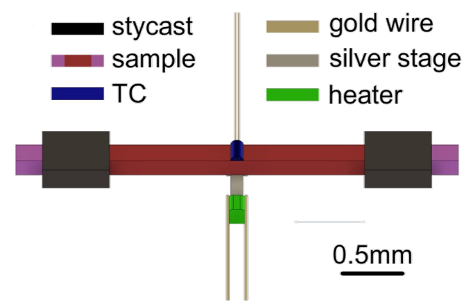
Supplementary

Why strain cells frustrate calorimetry

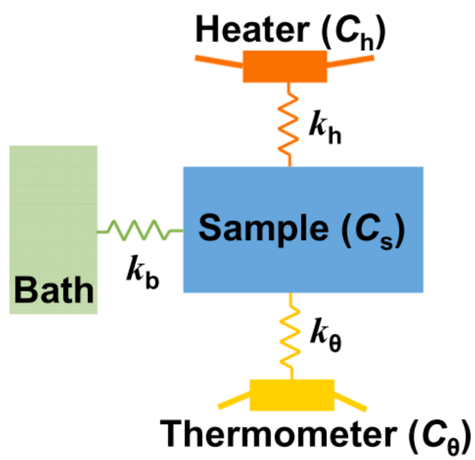
- Adiabatic measurement
  - $Q = C\Delta T$
- Pulse measurement

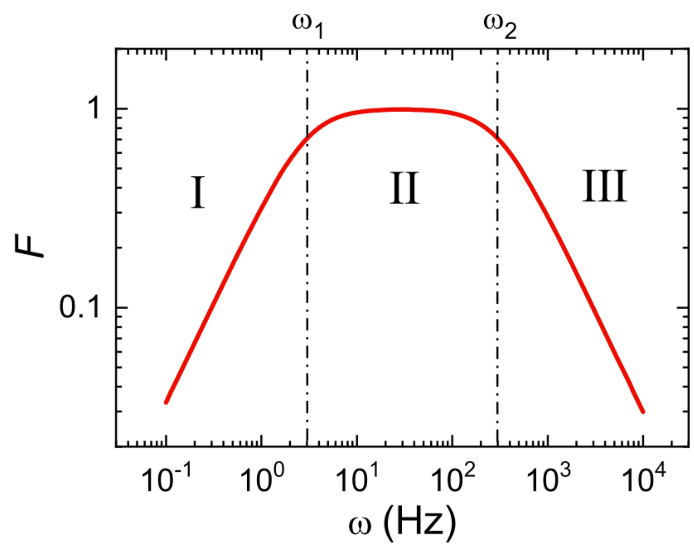






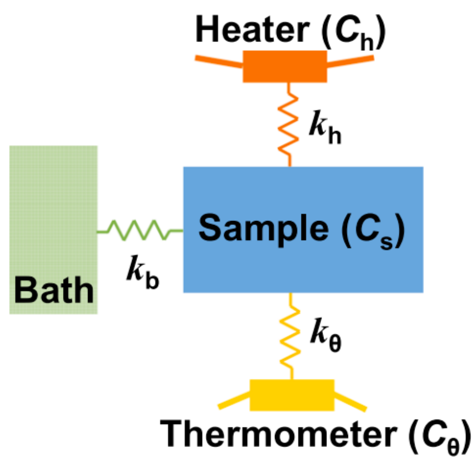
AC calorimetry

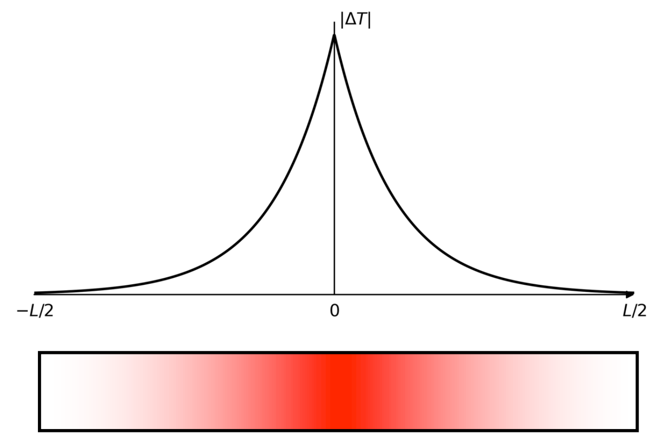




Adapted from Li et al., *Review of Scientific Instruments* 91, (2020).

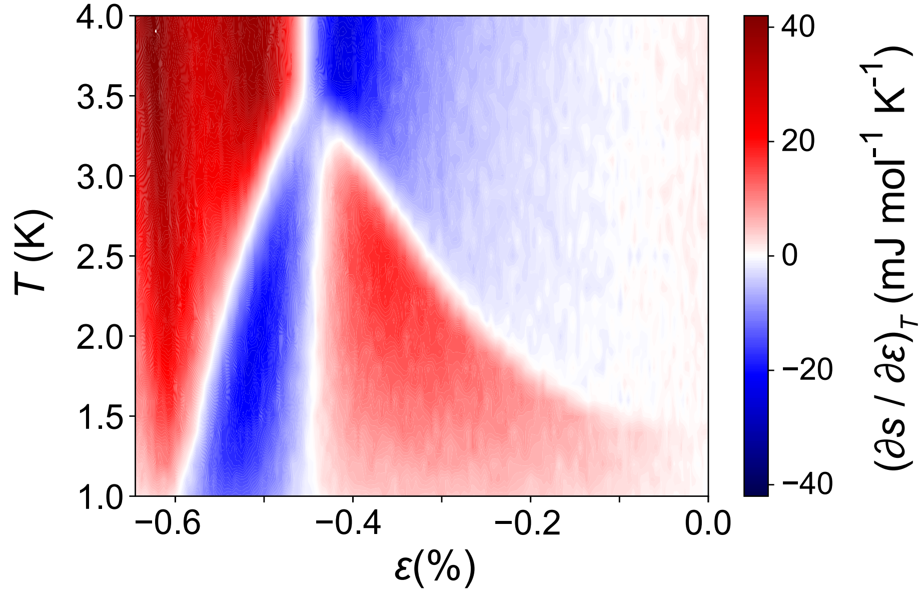
AC calorimetry





Adapted from Li et al., *Review of Scientific Instruments* 91, (2020).

10 Hz anchors the absolute scale



Thermal link

The epoxy-dominated conductance k is nearly independent of strain.

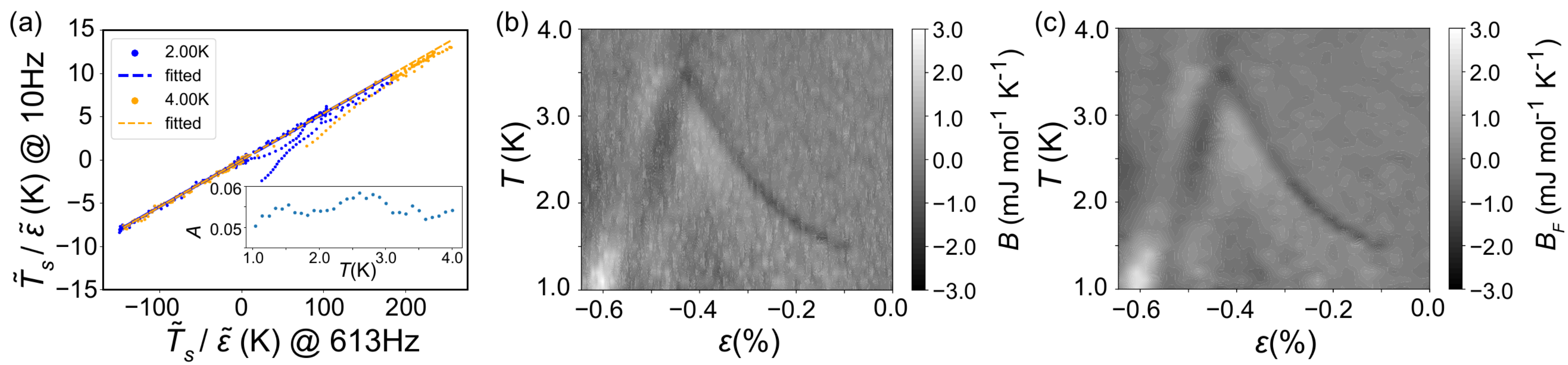
Strained volume

A two-dimensional fit gives $n = 0.76 \pm 0.10$ µmol.

Absolute accuracy

The remaining scale uncertainty is about 30%, dominated by the strained volume **without calibration**.

A linear map transfers high-frequency precision



$$\widetilde{T}_{LF}(\varepsilon, T) = A(T) \cdot T_{HF}(\varepsilon, T) + B(\varepsilon, T)$$

A(T) sets the scale; a shape-preserving residual captures the phase-boundary structure.