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Update on the physics of Sr_2RuO_4

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Update on the physics of Sr_2RuO_4 – and news about multi-component superconductivity in $CeRh_2As_2$

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1. Current issues regarding superconductivity in Sr_2RuO_4
2. New field dependent Knight shift measurements from UCLA
3. The elasto-caloric effect and the phase diagram of Sr_2RuO_4
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Summary of Sr_2RuO_4

Very recent, fuller review talk on Sr_2RuO_4 can be found by clicking appropriate link at
https://sites.google.com/umn.edu/cm-weekly-seminar/home

In Twitter mode:

Sr_2RuO_4 is: a hugely studied, highly disorder-sensitive unconventional superconductor

a well-understood Fermi liquid metal for $T < 30$ K

a benchmark material for testing correlated electron theory

Sr_2RuO_4 is not: the answer to anyone's dreams of non-abelian quantum computation

*Pustogow et al., Nature **574**, 72 (2019)*

Sr_2RuO_4 may be: an odd parity superconductor with an in–plane **d**-vector

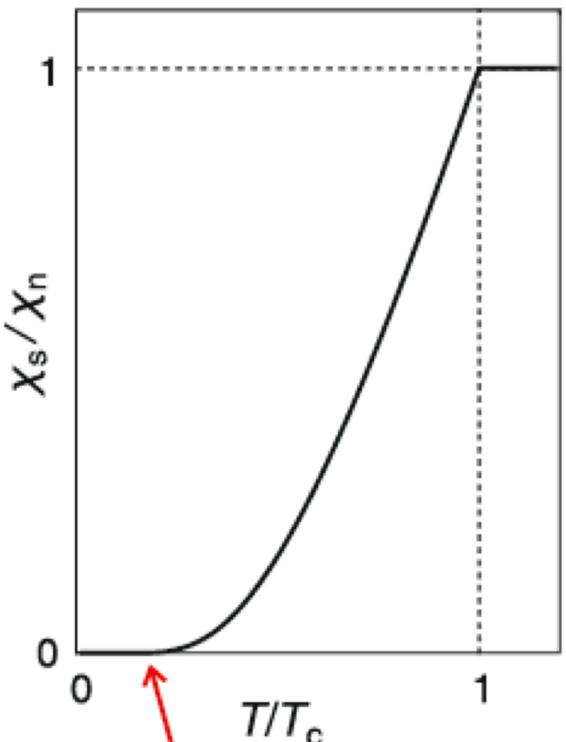
an even parity superconductor with a two-component order parameter that also breaks time reversal symmetry

an example of exotic interorbital or interplane pairing

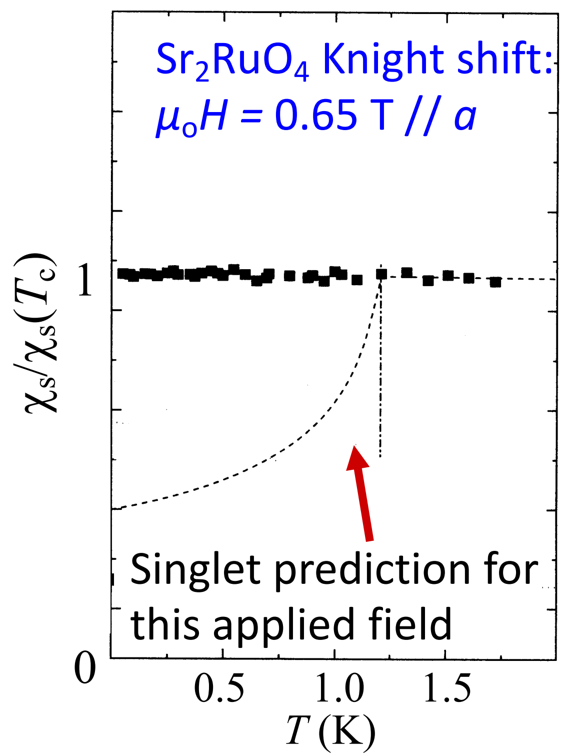
an example of an exotic mixed even- odd parity order parameter

Spin polarization and condensate formation: a fundamental struggle in almost all superconductors

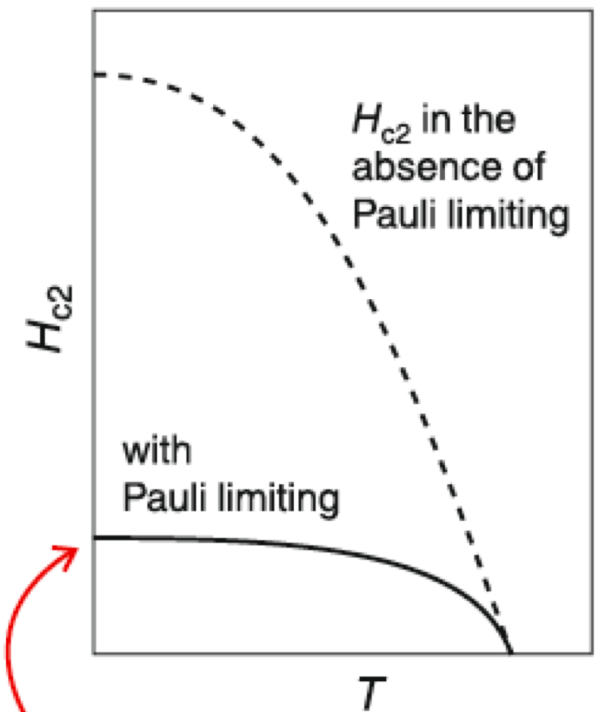
APM, T. Scaffidi, C.W. Hicks and Y. Maeno, npj Quantum Materials ***2****, 40 (2017)*



Superconducting condensation energy dominates at low applied field and spin susceptibility χ_s drops to zero at low temperatures.

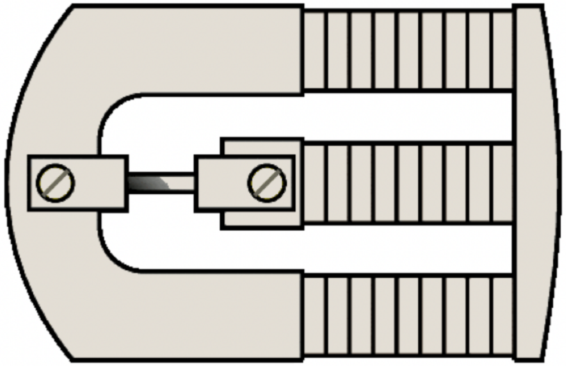


K. Ishida et al., Nature ***396*** *658 (1998)*



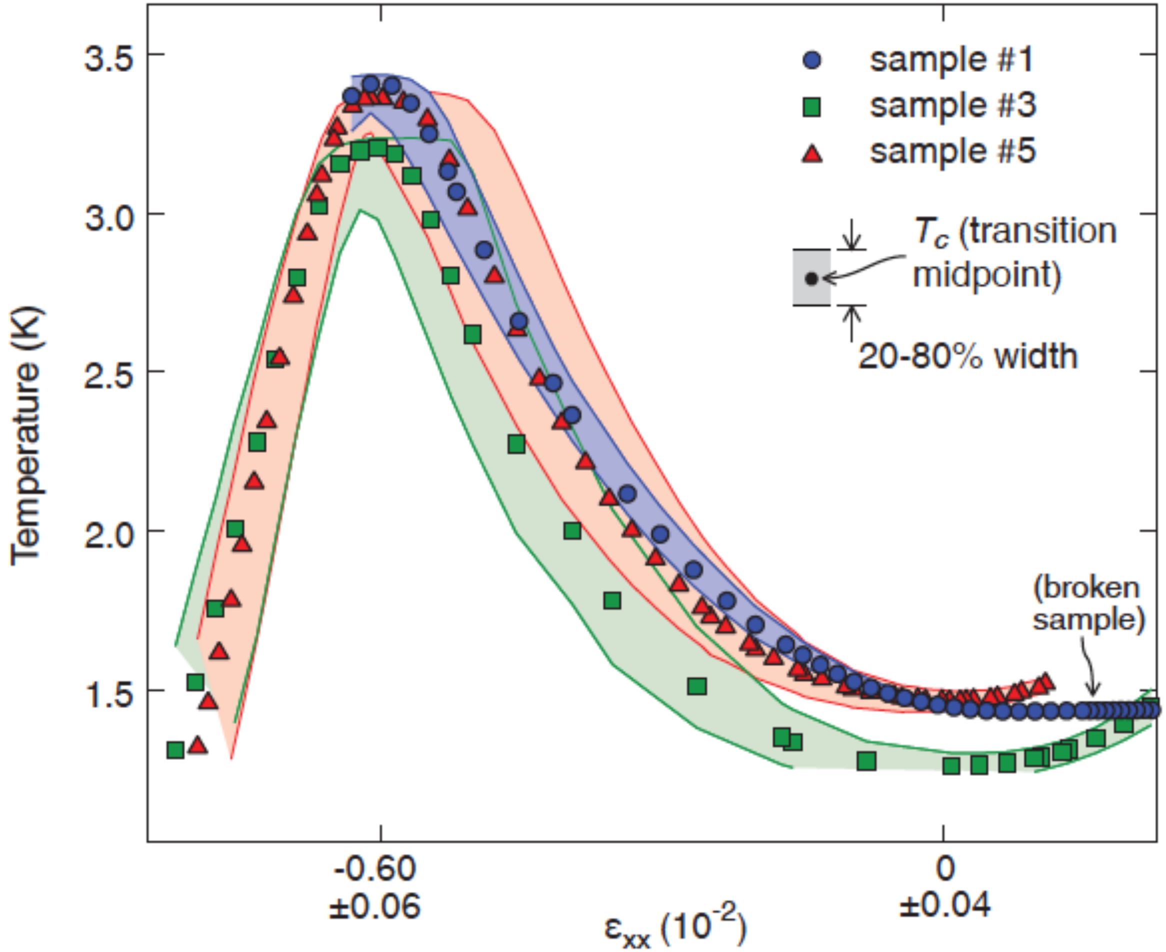
At sufficiently high applied fields the spin-derived magnetic energy dominates, and for strongly type II superconductors can be the limiting factor in destroying the superconductivity.

Straining through the van Hove singularity gives a large peak in T_c



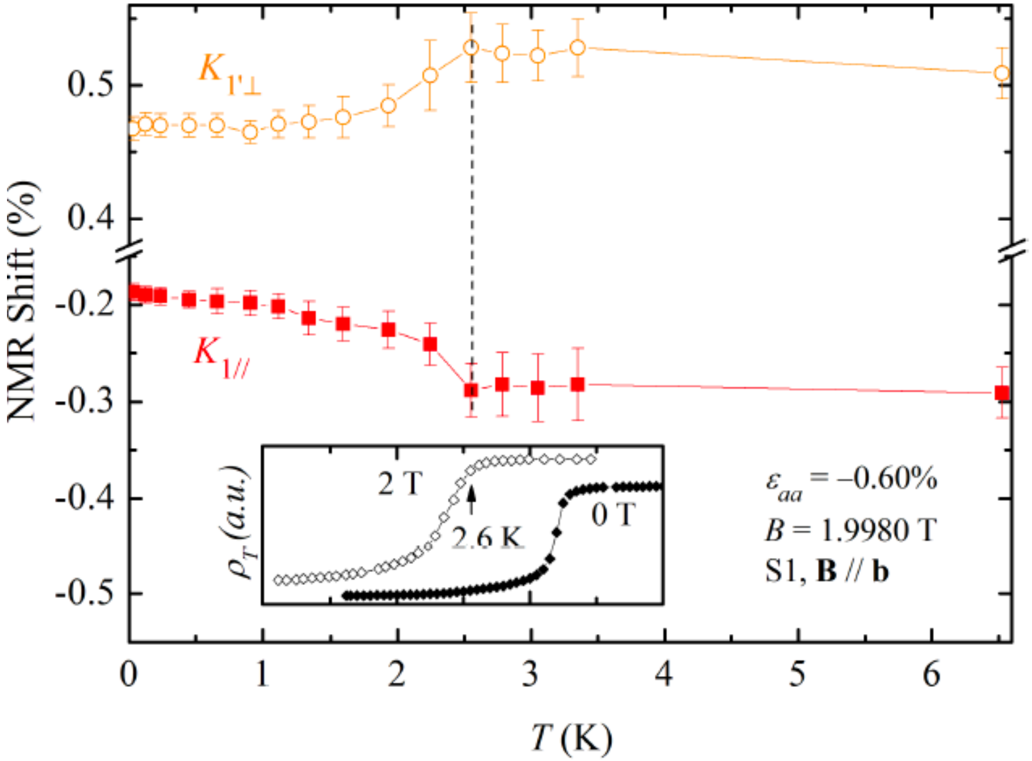
Basic principle of operation: a piezo-controlled vice.

C.W. Hicks, M.E. Barber, S.D. Edkins, D.O. Brodsky and APM, Rev. Sci. Inst. ***65****, 65003 (2014).*



A. Steppke, L. Zhao, M.E. Barber, T. Scaffidi, F. Jerzembeck, H. Rosner, A.S. Gibbs, Y. Maeno, S.H. Simon, APM and C.W. Hicks, Science ***355****, aaf9398 (2017)*

Revisit the classic experiments on strained material: NMR Knight shift



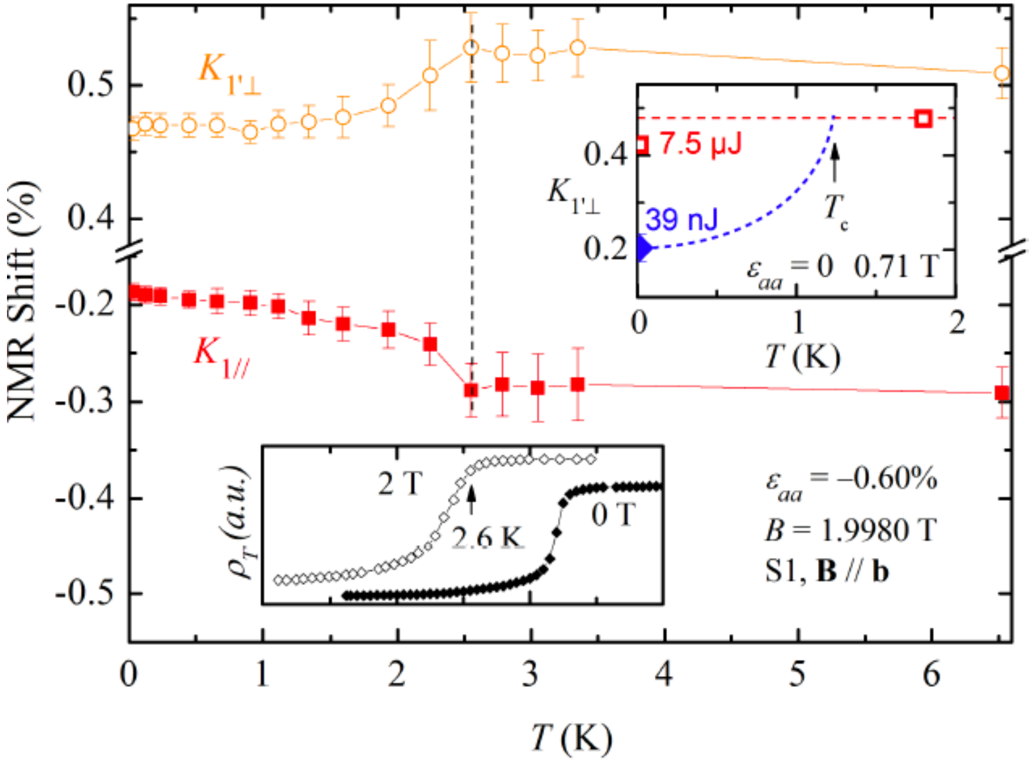
^{17}O NMR on highest T_c material indicates a pronounced drop of the spin susceptibility on entry to the superconducting state.

Is there a transition between two different superconducting states at some finite strain?

*A. Pustogow, Y. Luo, Y.-S. Su, A. Chronister, D. Sokolov, F. Jerzembeck, A.P. Mackenzie, C.W. Hicks, N. Kikugawa, S. Raghu, E.D. Bauer and S.E. Brown, Nature **574**, 72 (2019)*

Analysis of NMR in strained Sr_2RuO_4: *A.W. Lindquist & H.-Y. Kee, arXiv:1912.02215*

Revisit the classic experiments on strained material: NMR Knight shift



^{17}O NMR on highest T_c material indicates a pronounced drop of the spin susceptibility on entry to the superconducting state.

Is there a transition between two different superconducting states at some finite strain?

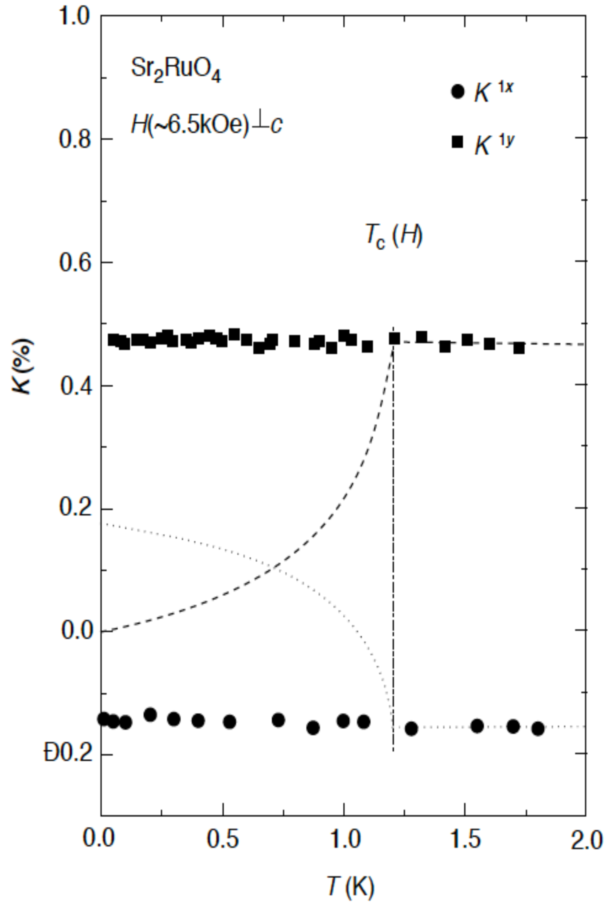
No – at zero strain there was a pronounced dependence on pulse energy.

*A. Pustogow, Y. Luo, Y.-S. Su, A. Chronister, D. Sokolov, F. Jerzembeck, A.P. Mackenzie, C.W. Hicks, N. Kikugawa, S. Raghu, E.D. Bauer and S.E. Brown, Nature **574**, 72 (2019)*

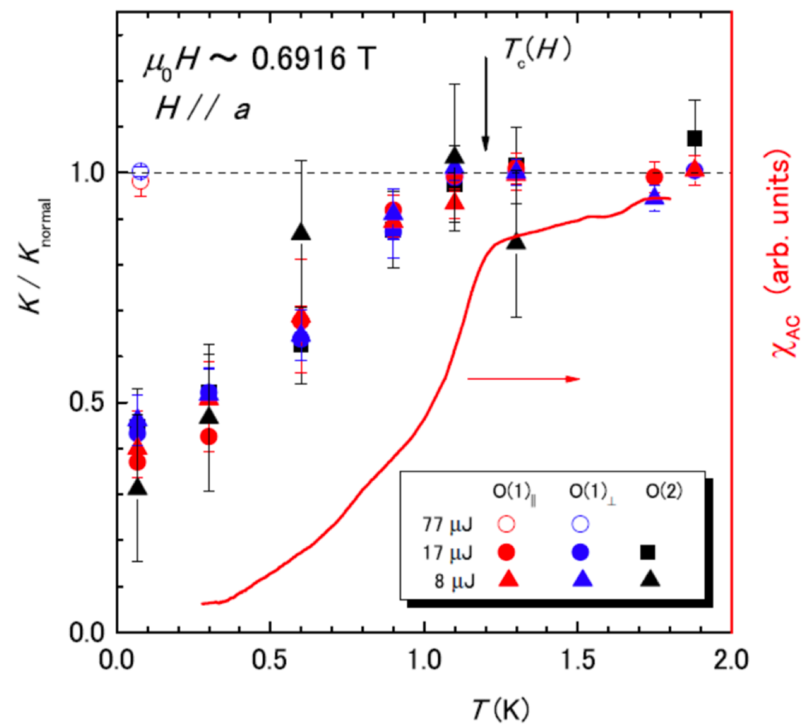
Analysis of NMR in strained Sr_2RuO_4: *A.W. Lindquist & H.-Y. Kee, arXiv:1912.02215*

Ishida: straight repeat of the 1998 experiment at reduced power

1998 data



2019 data on same sample



K. Ishida et al., JPSJ ***89****, 034712 (2020)*

Revised paradigm: Sr_2RuO_4 *cannot* have a *k*-independent **d**-vector order parameter.

Open question: how much of the remaining Knight shift is due to the condensate?

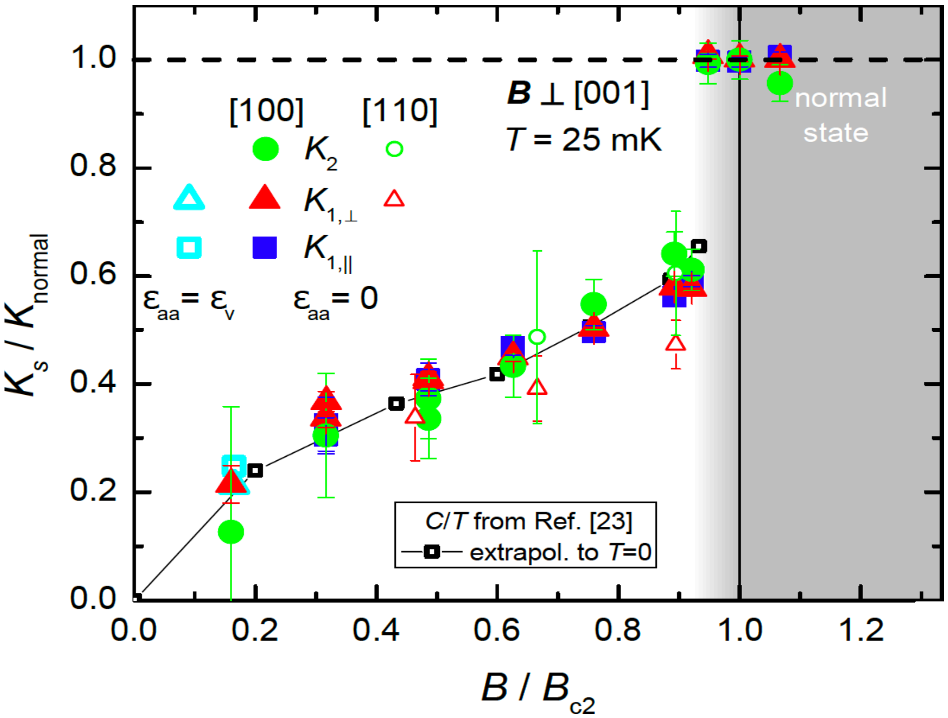
New UCLA experiments: detailed measurement of the *field dependence* of the spin susceptibility at 25 mK

Aaron Chronister

Andrej Pustogow

Stuart Brown

A. Chronister, A. Pustogow, N. Kikugawa, D.A. Sokolov, F. Jerzembeck, C.W. Hicks, APM, E.D. Bauer and S.E. Brown, arXiv:2007.13730



Field dependence identical within experimental error for [100] and [110] directions

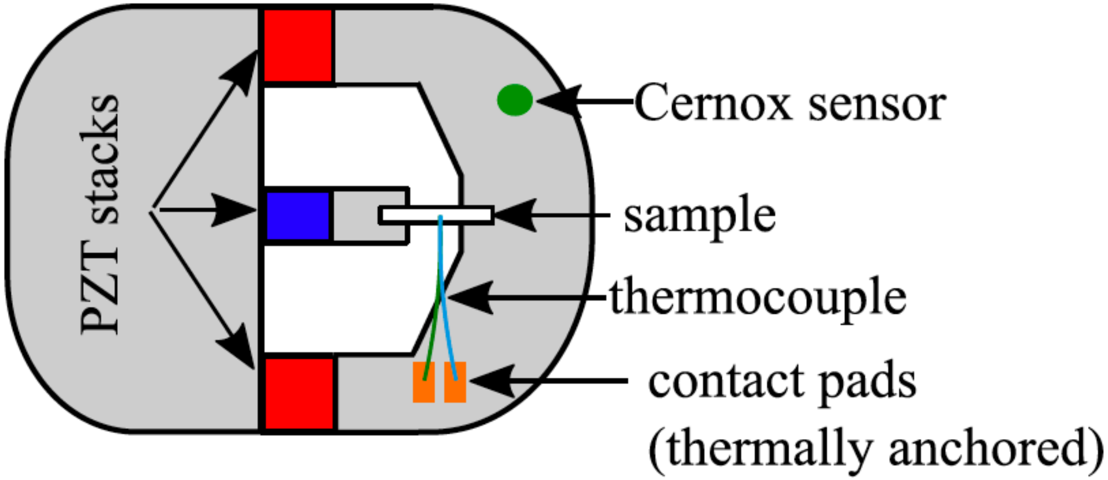
Normalised Knight shift identical within experimental uncertainty to normalised electronic specific heat from *S. NishiZaki et al., J. Phys. Soc. Jpn.* ***69****, 572 (2000)*

Condensate contribution to spin susceptibility is zero within (experimental + analysis) uncertainty of ~ 10%

Another very promising research avenue: the *elastocaloric effect*

Matthias Ikeda

Ian Fisher



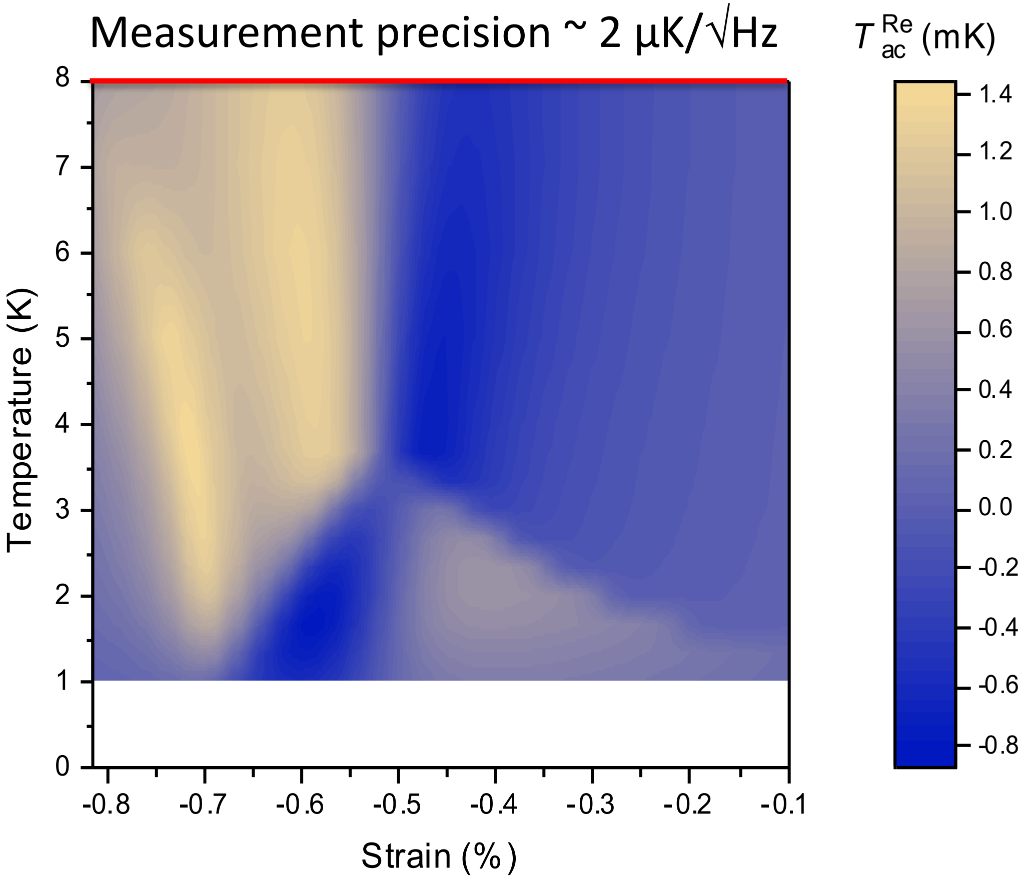
Close analogy with the magneto-caloric effect:

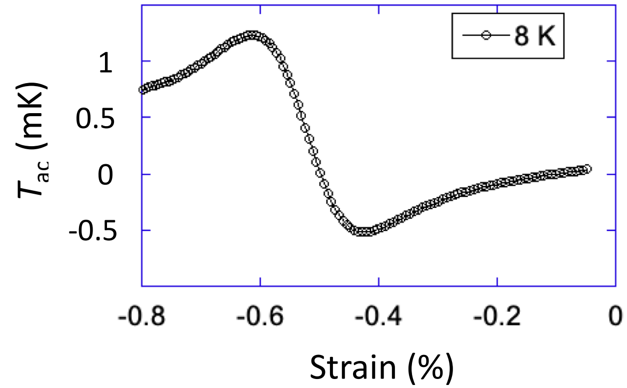
$$\left(\frac{\Delta T}{\Delta B}\right) \cong -\frac{T}{C}\left(\frac{\partial S}{\partial B}\right)$$

$$\left(\frac{\Delta T}{\Delta \varepsilon}\right) \cong -\frac{T}{C}\left(\frac{\partial S}{\partial \varepsilon}\right)$$

M. Ikeda, J.A.W. Straquadine, A.T. Hristov, T. Worasaran, J.C. Palmstrom, M. Sorensen, P. Walmsley and I. R. Fisher, Rev. Sci. Inst. ***90****, 083902 (2019)*

First elastocaloric effect data from Sr_2RuO_4





Minor disclaimer: temperatures > 4 K are from a generic curve, not a direct calibration

__Y.-S. Li__, M. Nicklas, C.W. Hicks, N. Kikugawa, D.A. Sokolov, M. Ikeda, I.R. Fisher, M. Garst, J. Schmalian and APM, unpublished

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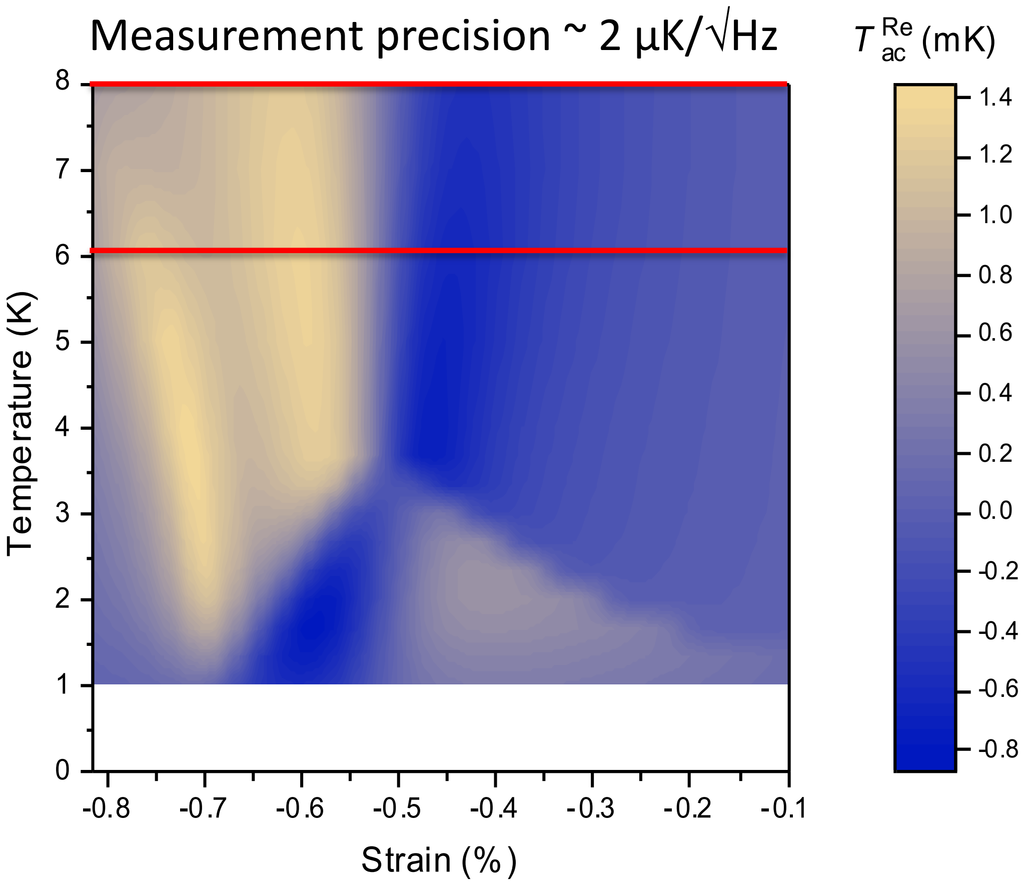

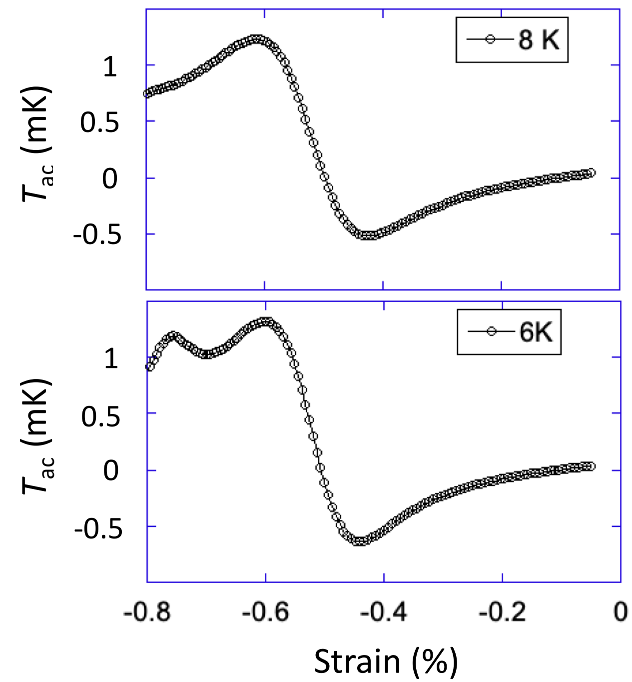

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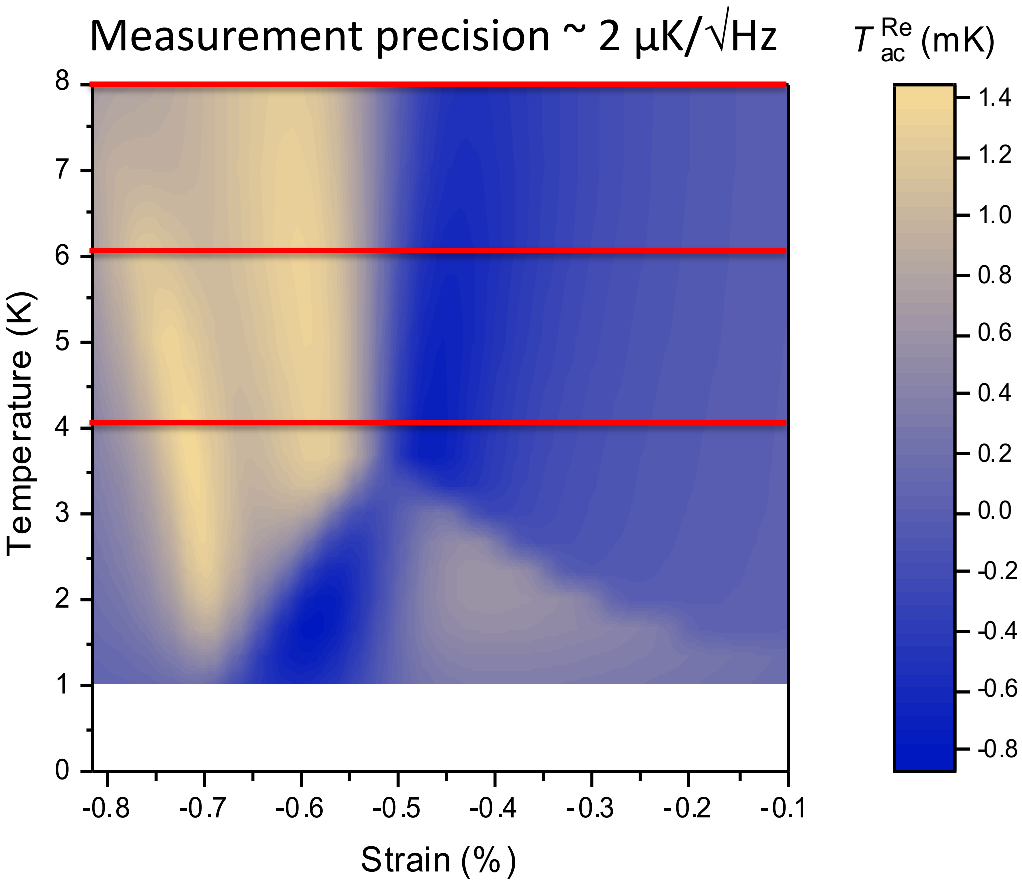

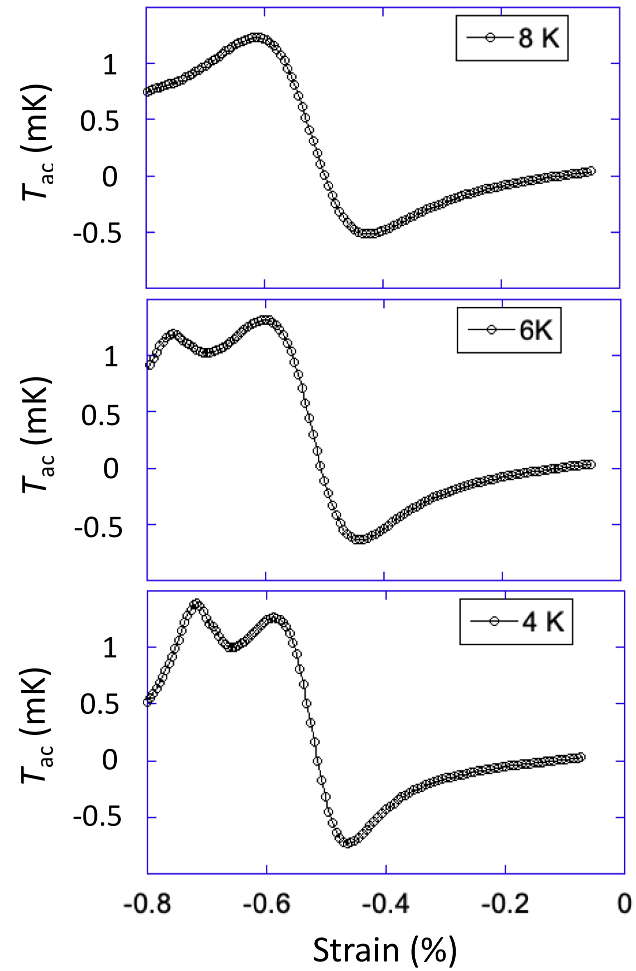

***Y.-S. Li**, M. Nicklas, C.W. Hicks, N. Kikugawa, D.A. Sokolov, M. Ikeda, I.R. Fisher, M. Garst, J. Schmalian and APM, unpublished*

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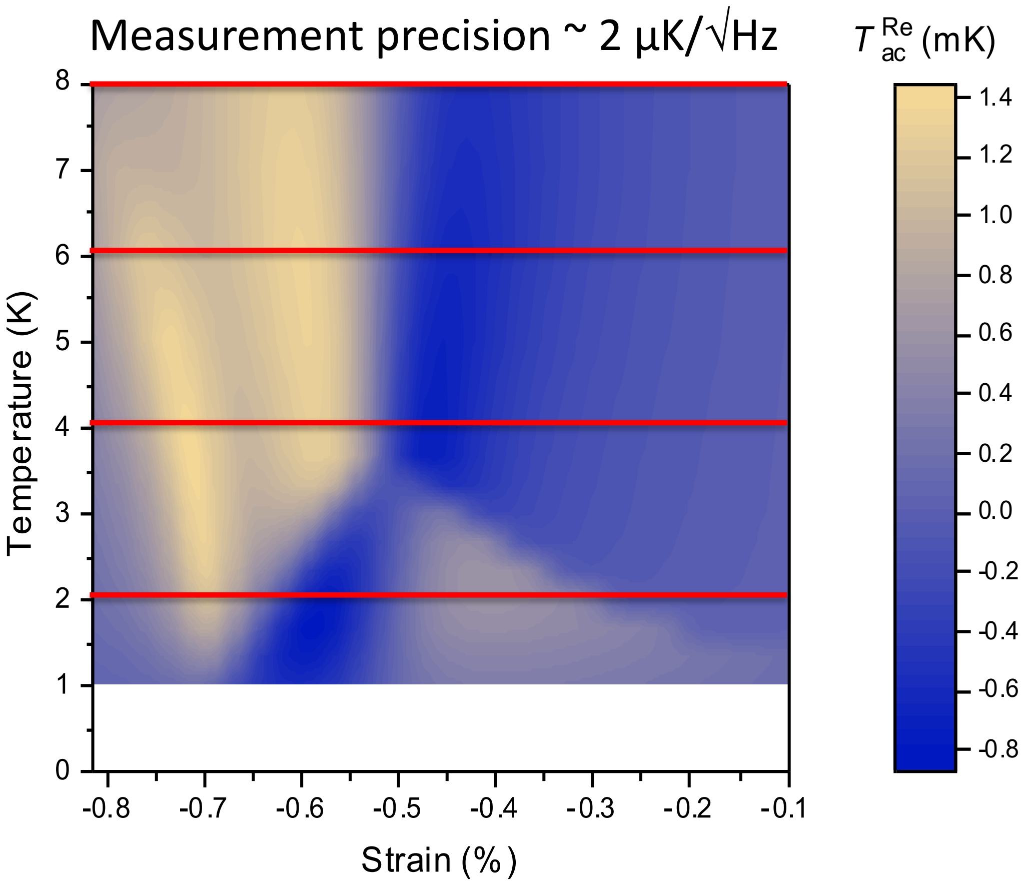
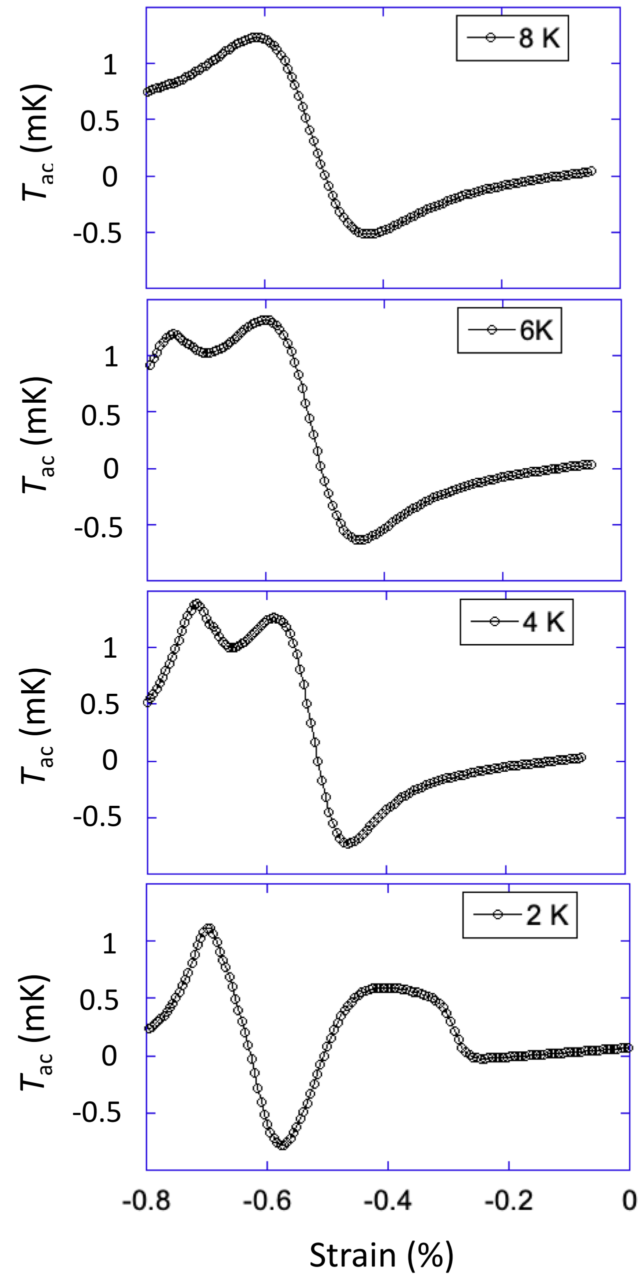
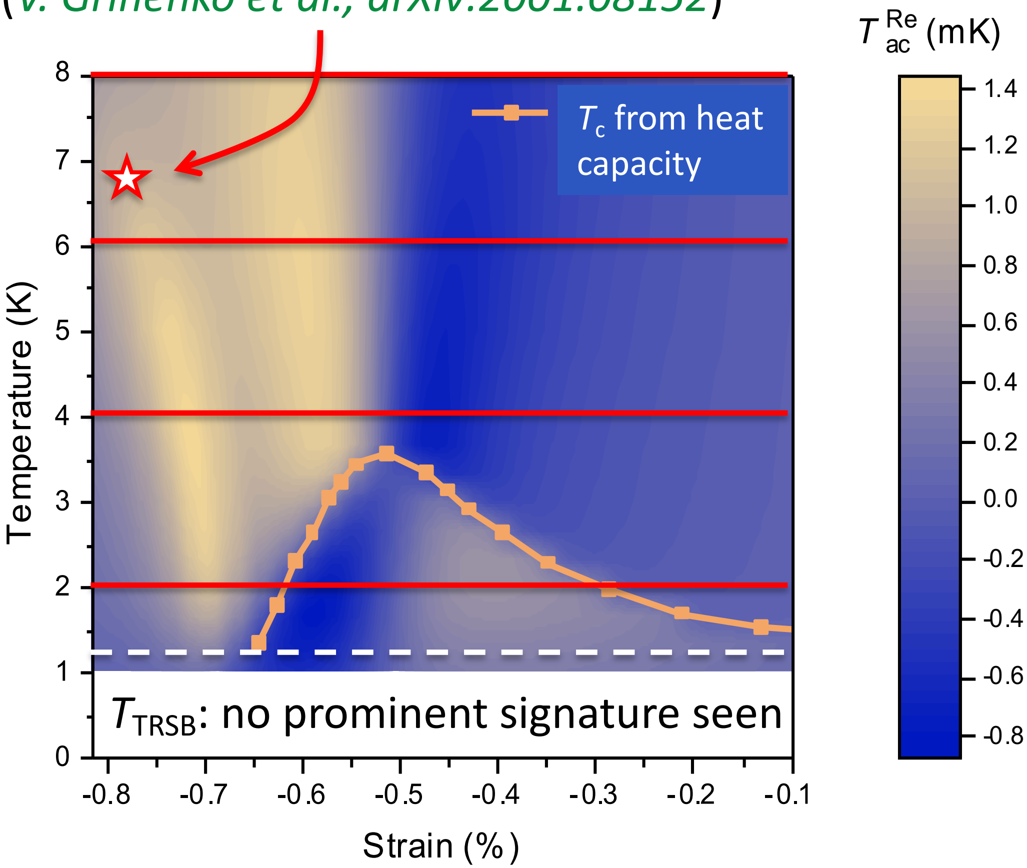


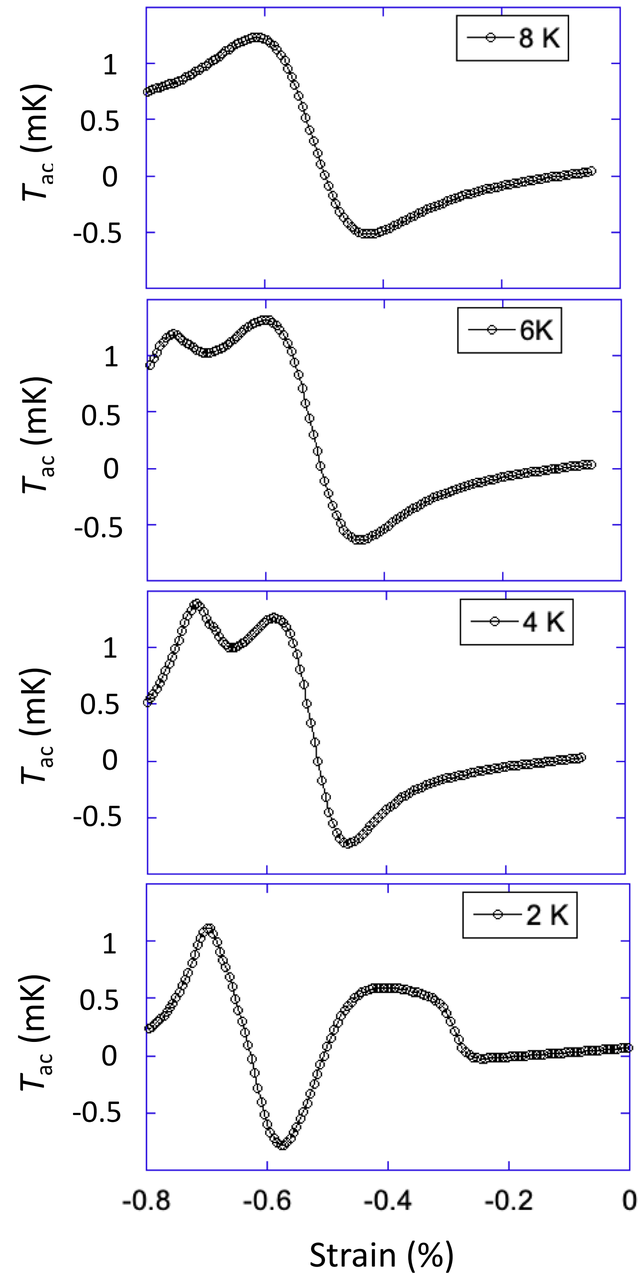


__Y.-S. Li__, M. Nicklas, C.W. Hicks, N. Kikugawa, D.A. Sokolov, M. Ikeda, I.R. Fisher, M. Garst, J. Schmalian and APM, unpublished

First elastocaloric effect data from Sr_2RuO_4

Onset of magnetic order identified by μSR
(*V. Grinenko et al., arXiv:2001.08152*)



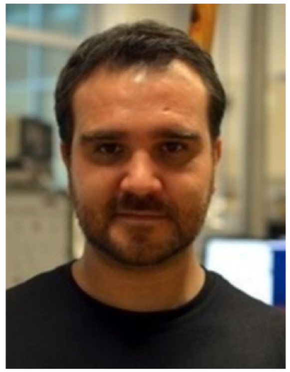


***Y.-S. Li**, M. Nicklas, C.W. Hicks, N. Kikugawa, D.A. Sokolov, M. Ikeda, I.R. Fisher, M. Garst, J. Schmalian and APM, unpublished*

Change of tack – discovery of multi-phase Rashba superconductivity in $CeRh_2As_2$

Experiment

Seunghyun Khim



Javier Landaeta

Elena Hassinger

Christoph Geibel

Manuel Brando

Daniel Hafner

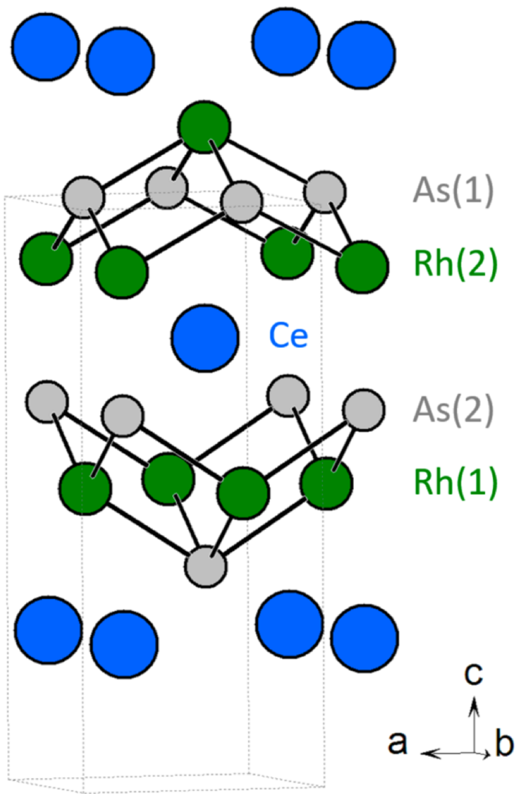
Theory

Daniel Agterberg (U Wisconsin)

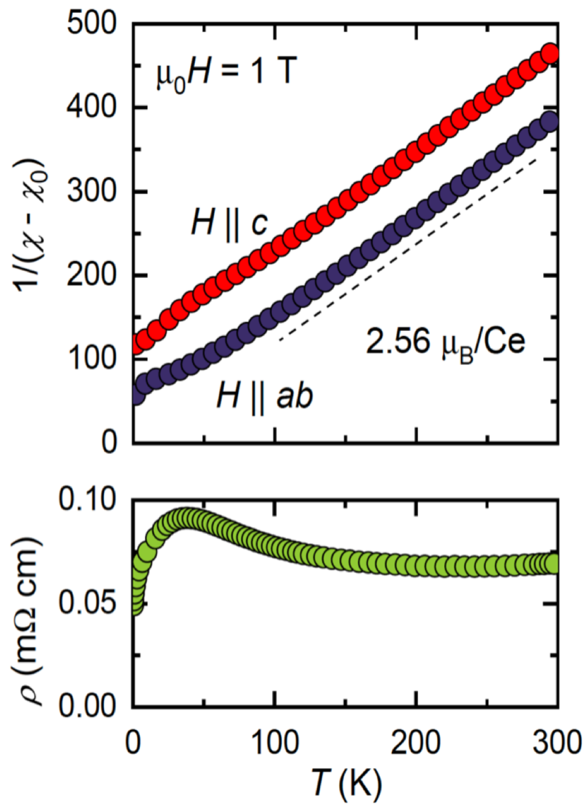
Helge Rosner

Philip Brydon (U Otago)

$CeRh_2As_2$: basic properties

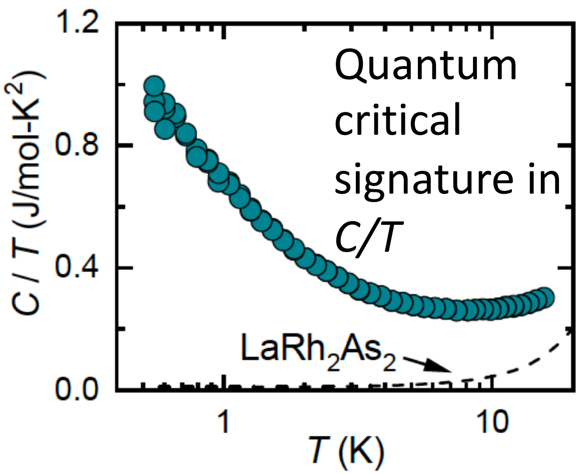


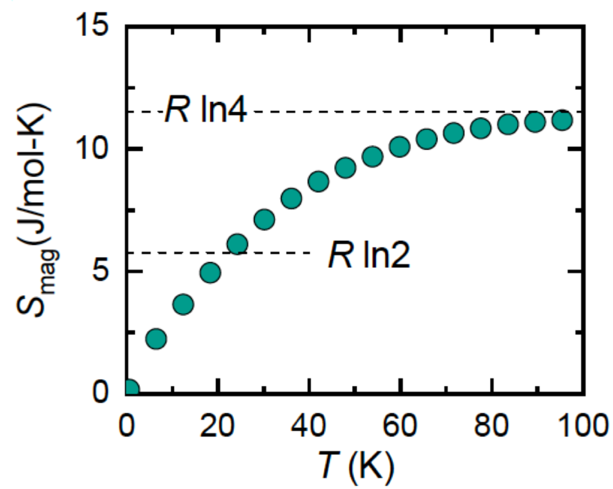
Very interesting Ce environment: local C_{4v} point group

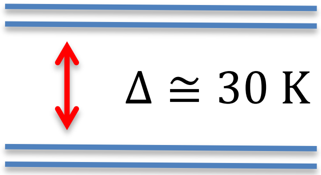


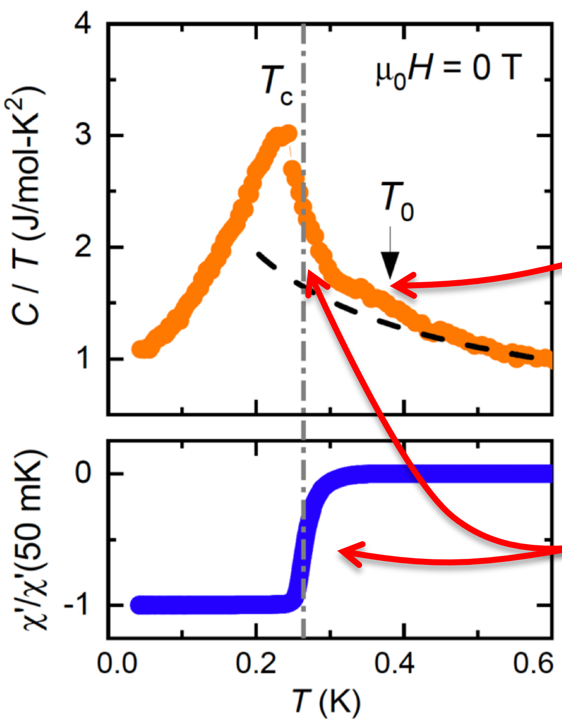
Kondo lattice system $T_K \sim 40$ K

$CeRh_2As_2$: proximity to quantum critical point and superconductivity







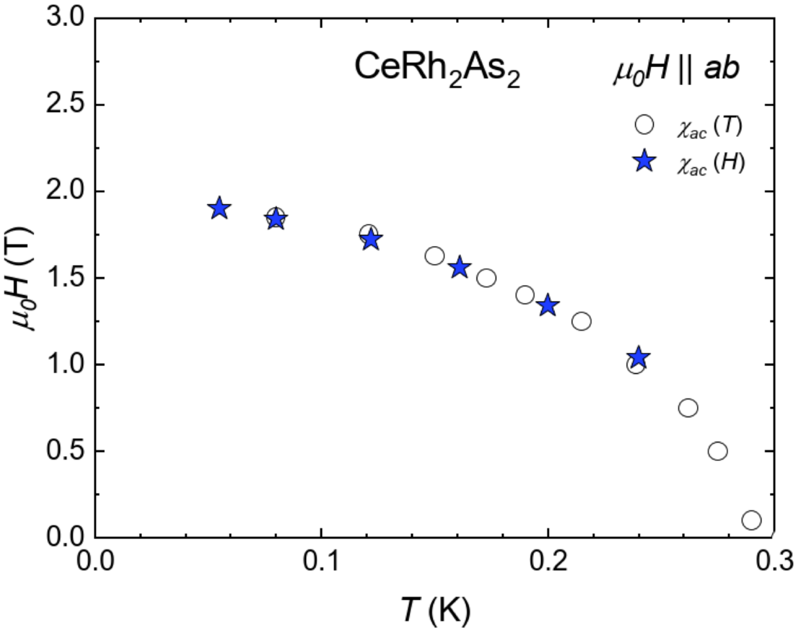


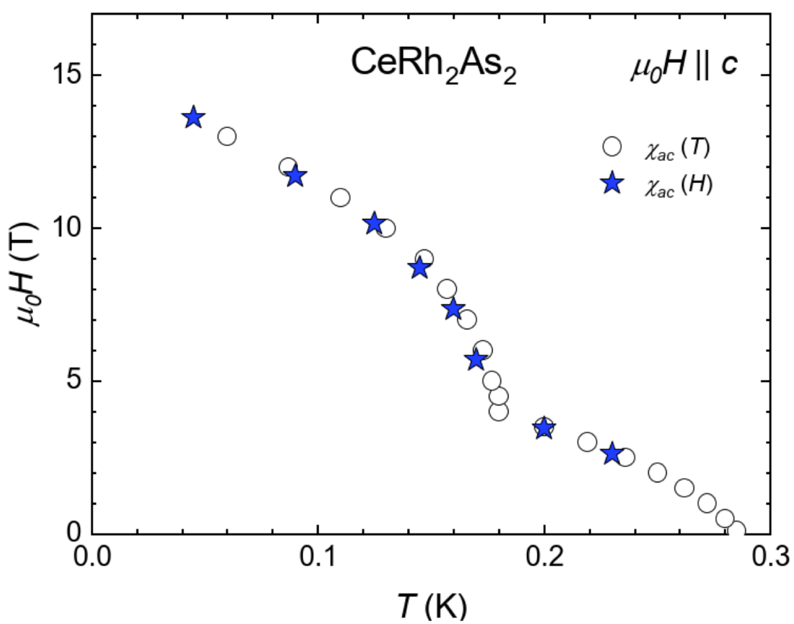
Two lowest-lying crystal field doublets only ~ 30 K apart

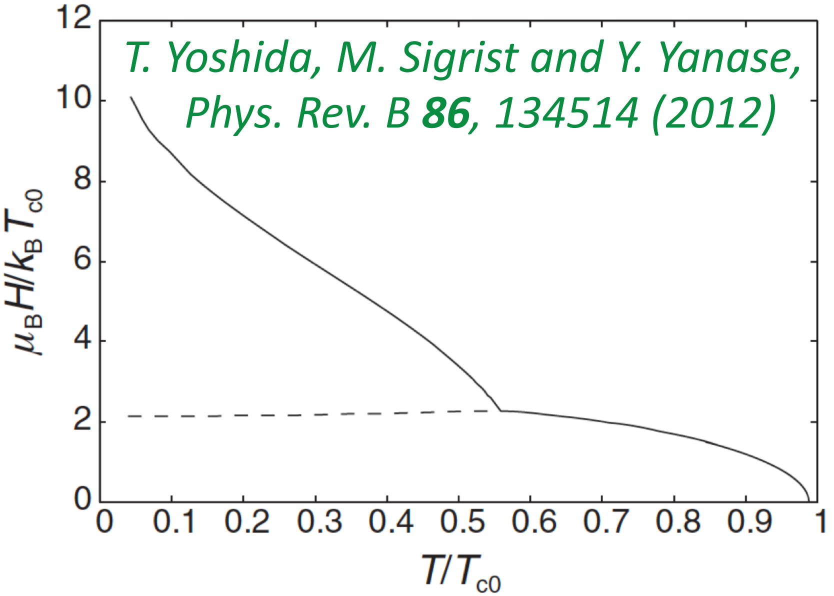
Second small but clearly resolvable heat capacity feature that has no associated signature in magnetism. Multipolar?

Heavy fermion superconductivity at T_c = 270 mK

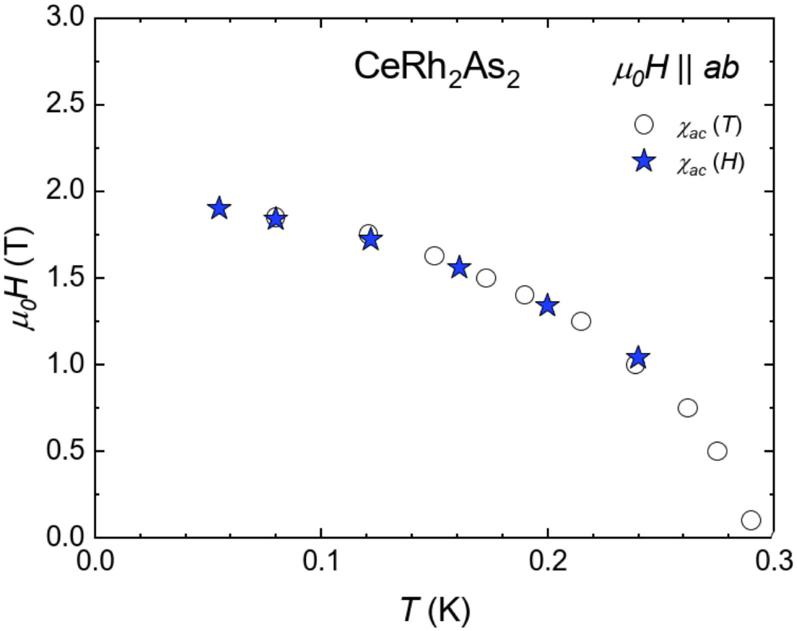
$CeRh_2As_2$: critical fields

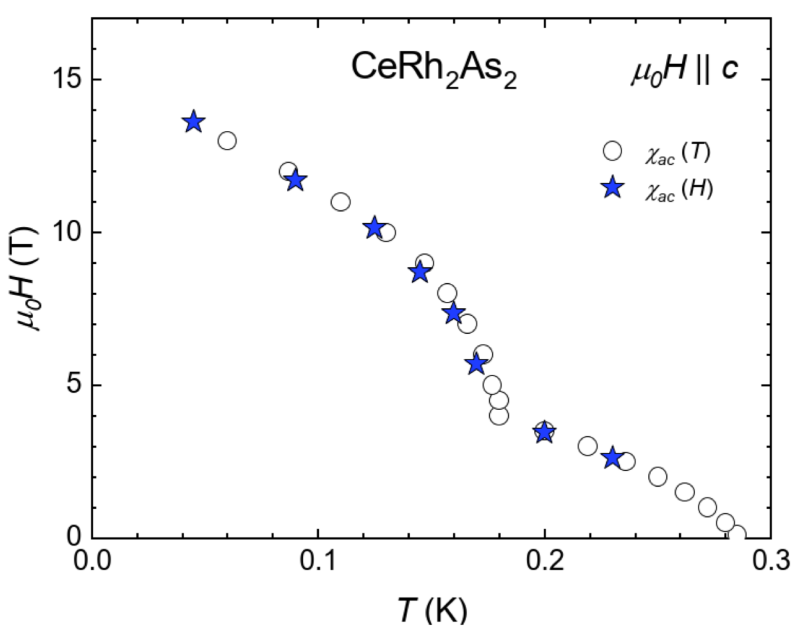


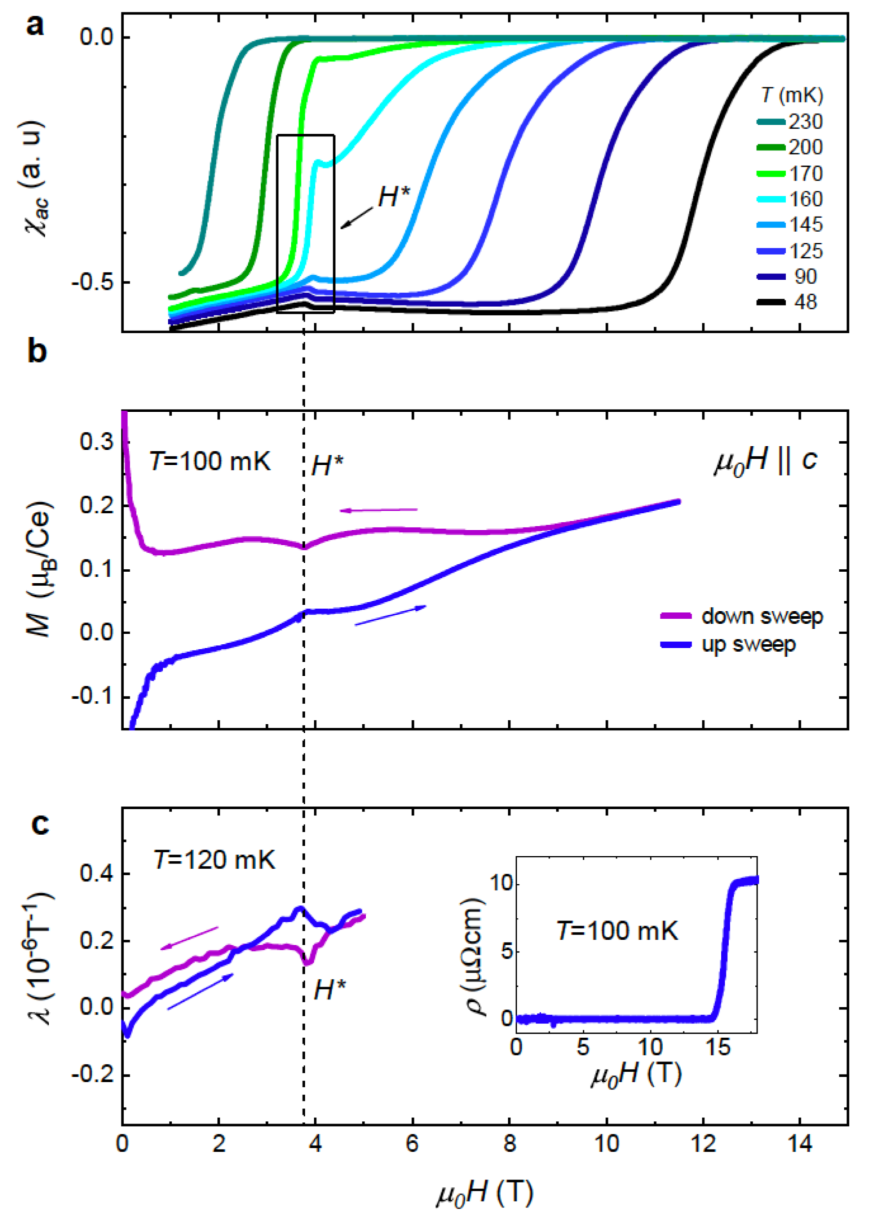




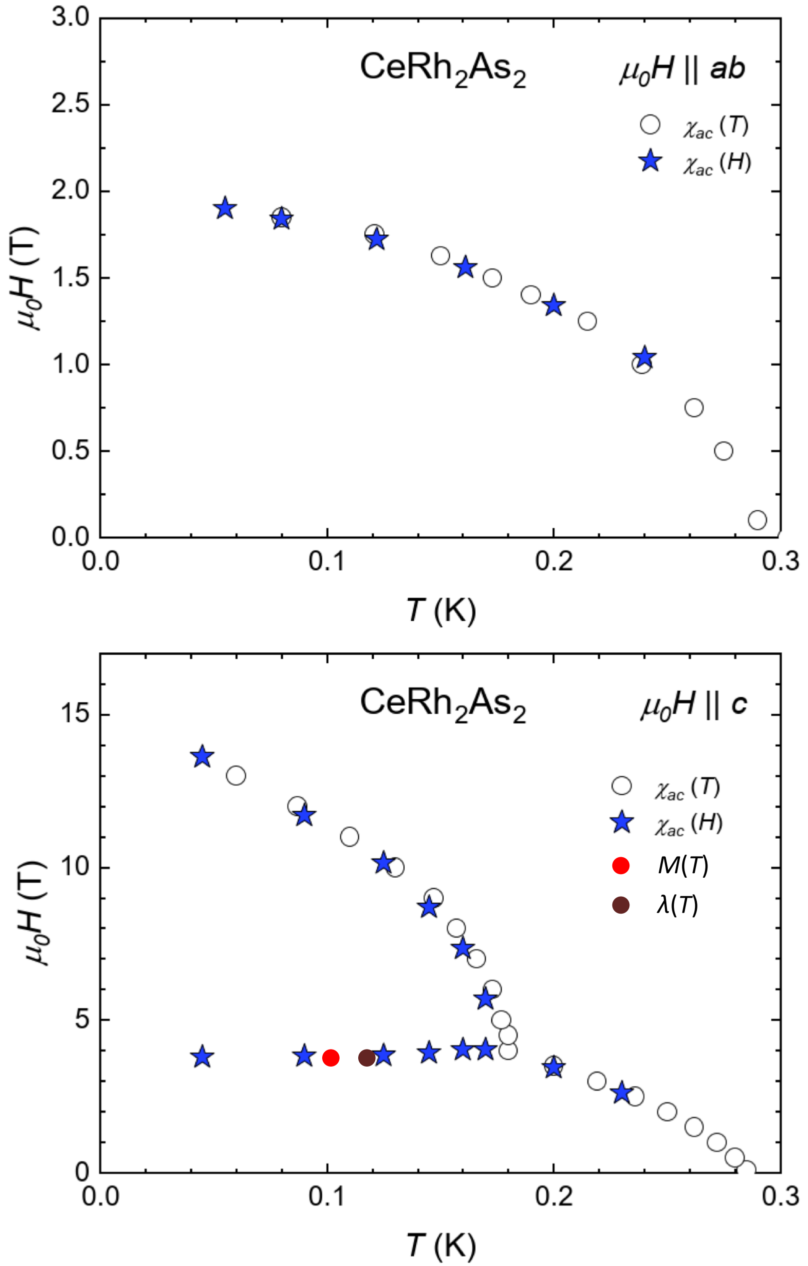
$CeRh_2As_2$: phase boundary in superconducting state

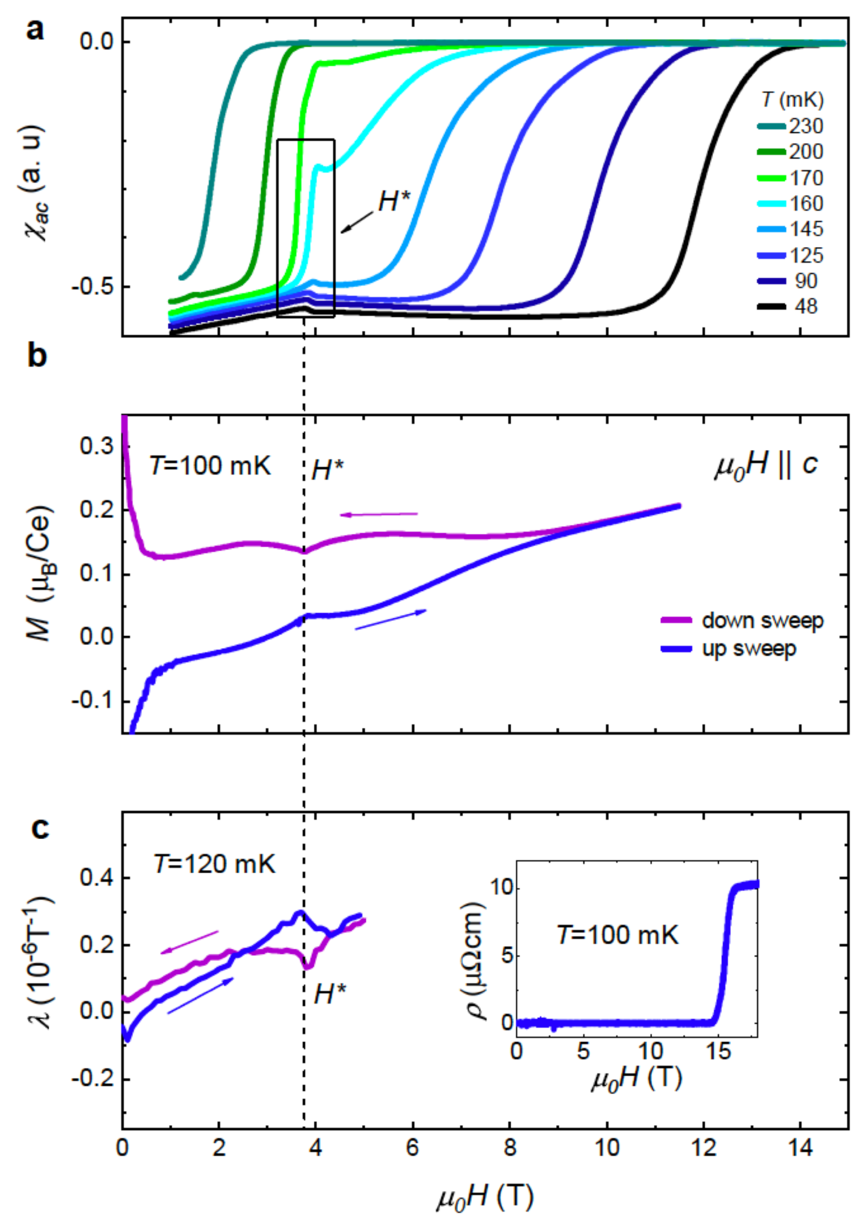




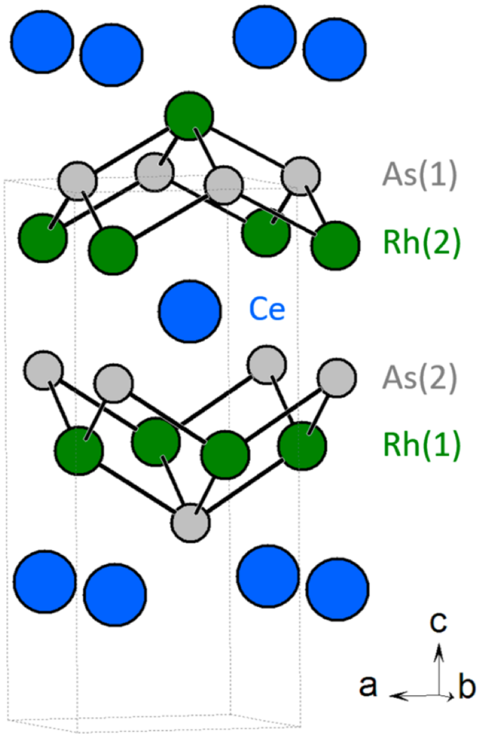


$CeRh_2As_2$: phase boundary in superconducting state

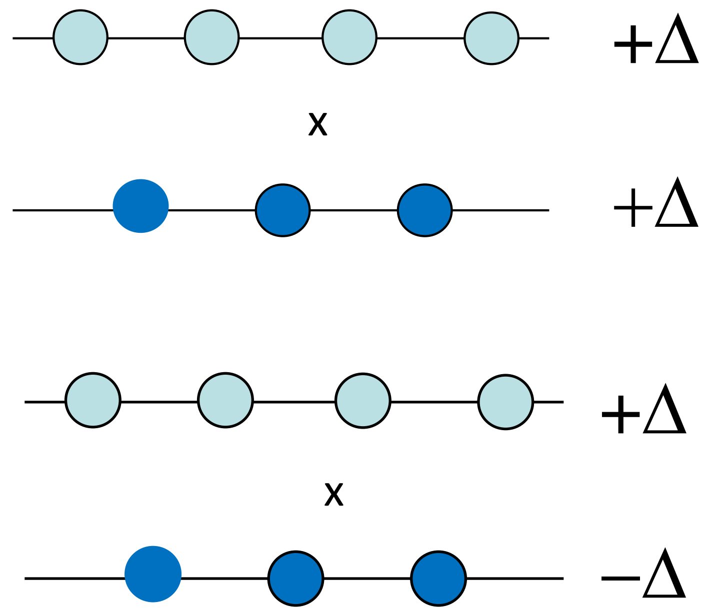




$CeRh_2As_2$: theoretical considerations



$$H = \varepsilon(k) + \alpha_R \tau_z (\sigma_y \sin k_x - \sigma_x \sin k_y) + t_c(k) \tau_x$$



t_c term favours even parity state

α_R term favours odd parity state

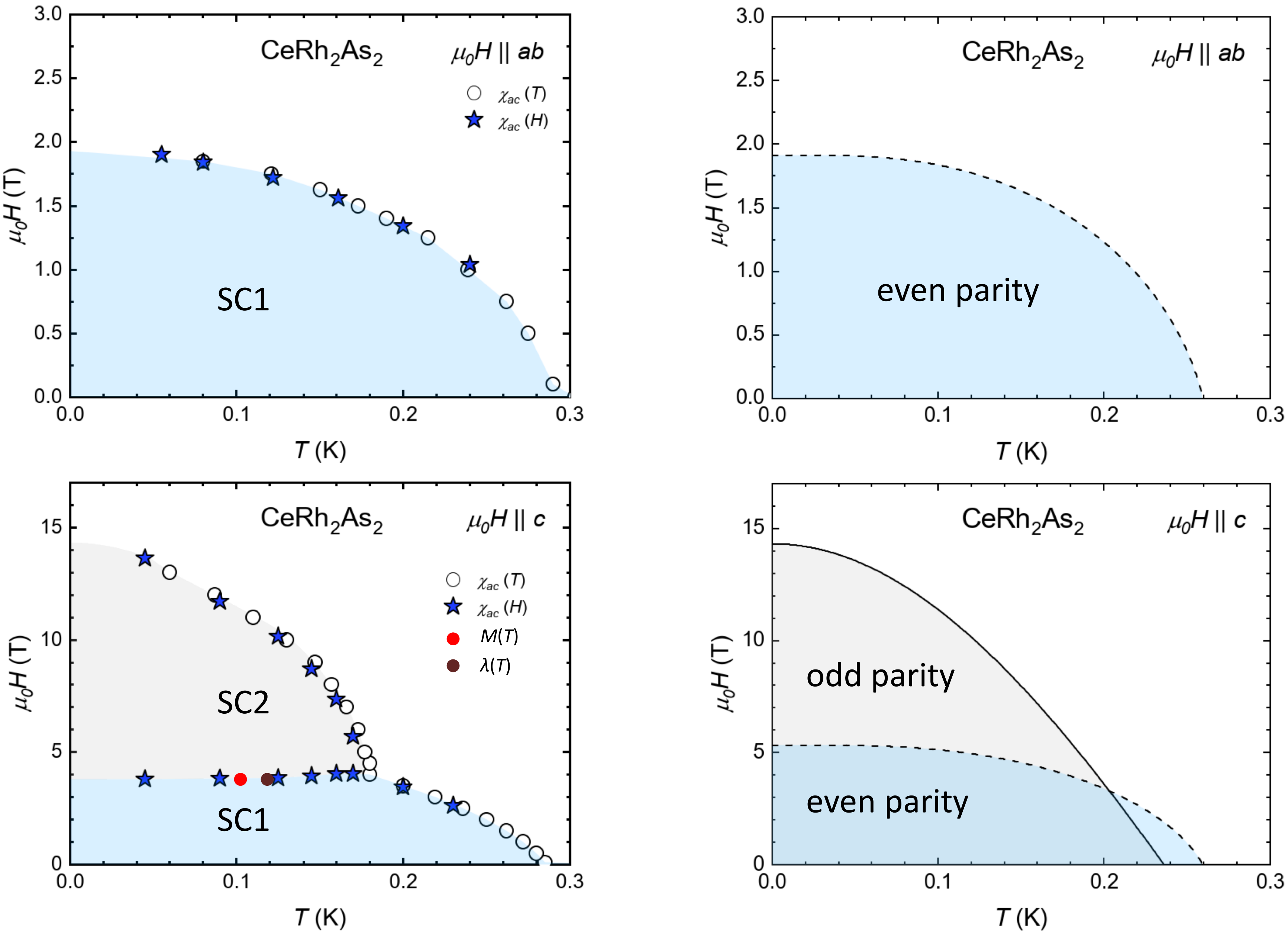
Local inversion (Ce with respect to Rh and As) is broken.

Global inversion (Ce with respect to Ce) is preserved.

Even parity state has higher T_c but is suppressed by c-axis field.

In $CeRh_2As_2$ at low T, $\alpha_R \cong 2t_c$ and the theory becomes similar to the idealised model of *T. Yoshida, M. Sigrist and Y. Yanase, J. Phys. Soc. Jpn.* ***83****, 013703 (2014)*

$CeRh_2As_2$: comparison of theory and experiment



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Summary

1. New NMR results constrain the condensate contrbution to the spin susceptibility of Sr_2RuO_4 to less than 10% of the normal state value
2. The elastocaloric effect provides detailed information on the phase diagram of Sr_2RuO_4
3. The new Rashba superconductor $CeRh_2As_2$ shows proven multiphase superconductivity

Future

4. Hopefully, the end-game in the quest to fully understand superconductivity of Sr_2RuO_4
5. Widespread incorporation of the elastocaloric effect in strain tuning experiments
6. Quest for a full understanding of the phase diagram and superconducting mechanism in $CeRh_2As_2$ as a benchmark material for Rashba superconductivity and possible multipolar order.