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Nematicity and quantum criticality in $CeRhIn_5$ probed by dilatometry

Priscila F. S. Rosa
Los Alamos National Laboratory

LDRD Program

Outline

$CeRhIn_5$ in high fields: putative XY nematic. PFSR *et al,* Phys. Rev. Lett. 122, 016402 (2019).

$CeRhIn_5$ at high pressures: superconductivity around an unconventional QCP

CNLS conference
Santa Fe, May 3rd

Collaborators

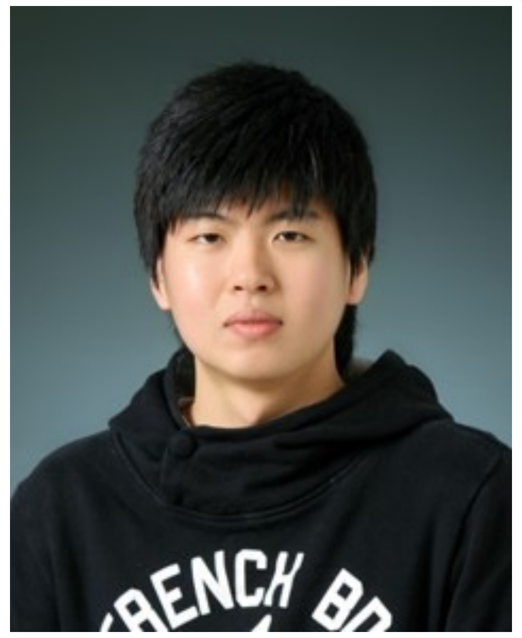
LANL's SCES Team

Joe Thompson

Eric Bauer

Filip Ronning

Sean Thomas



Soonbeom Seo

NHMFL PFF

Marcelo Jaime

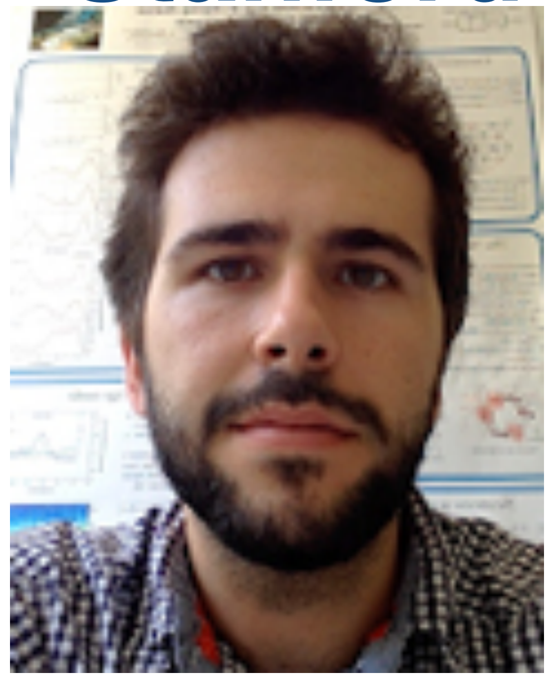
Fedor Balakirev

Jon Betts

UMN

Rafael Fernandes

Stanford



Nicolas Gauthier

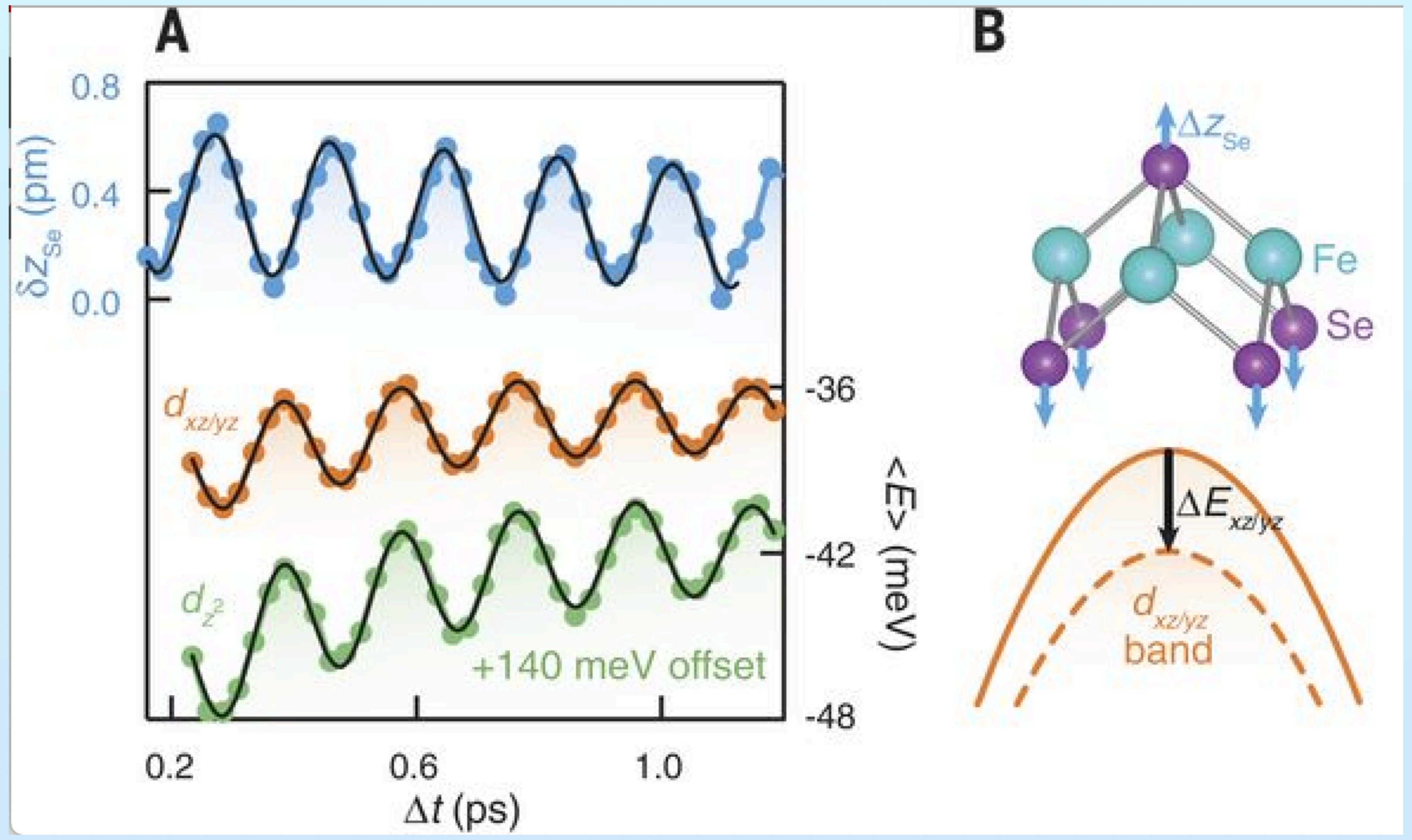
Max Planck

Andrea Severing

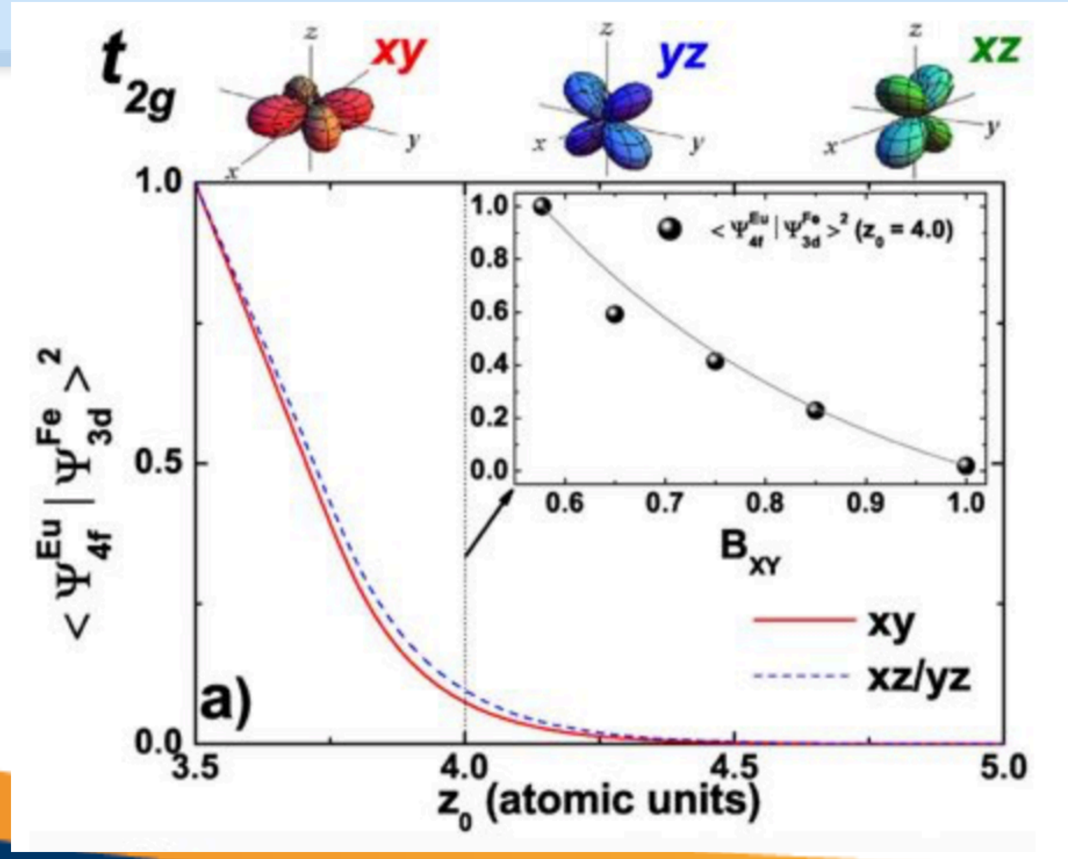
Underlying theme this week: local physics

Monday & Tuesday

Tom Deveraux, Ming Yi, …



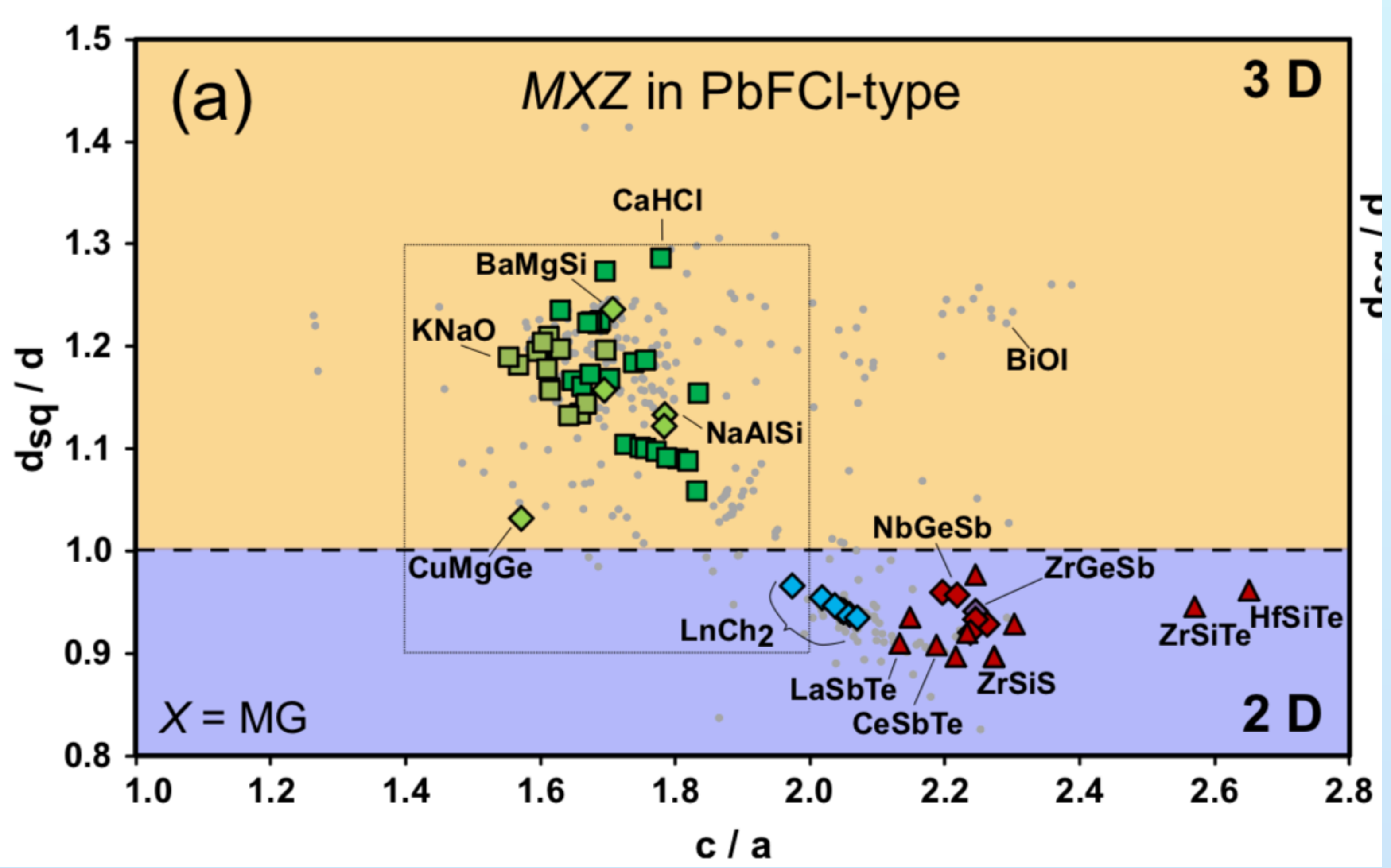
Gerber *et al*, Science (2017)



Electron spin resonance
PFSR *et al*, Sci. Rep. 4, 6543 (2014)

Wednesday

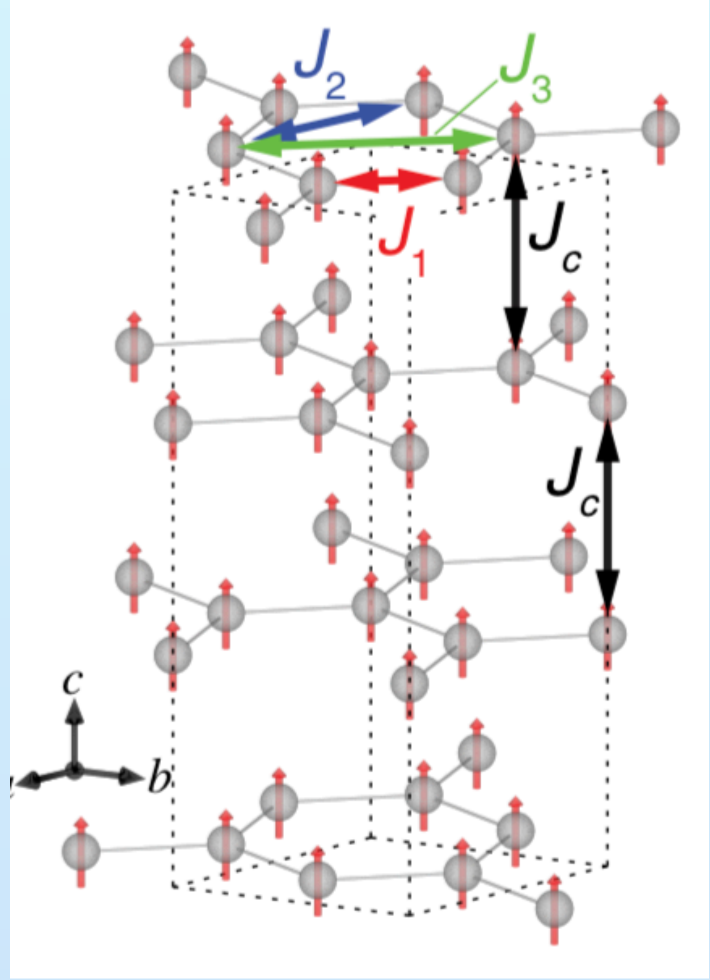
Leslie Schoop,
Yong Baek Kim,…



S Klemenz *et al*, Annual Review of Materials Research (2019)

Thursday

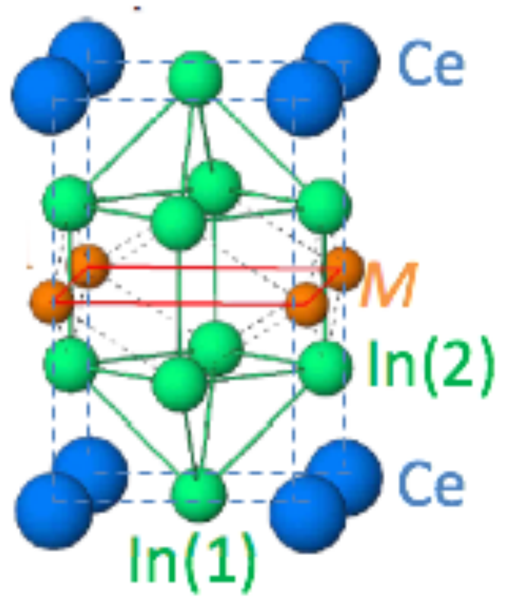
Pencheng Dai,
Kate Ross…



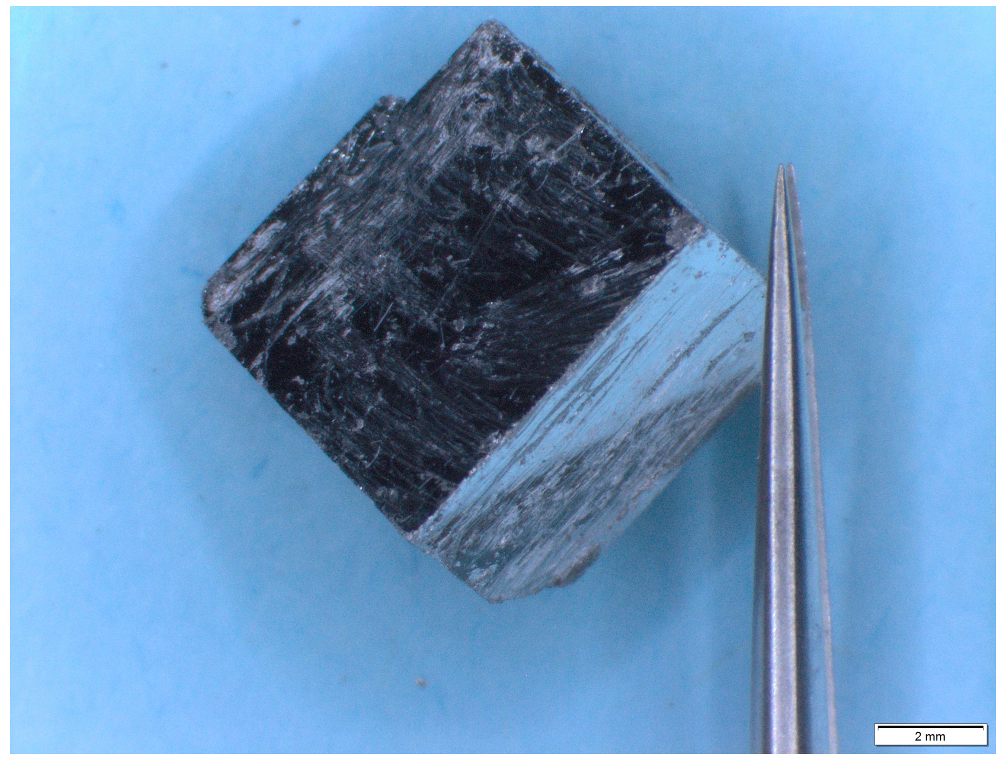
Chen *et al*, Phys Rev X 8, 041028 (2018).

Outstanding questions

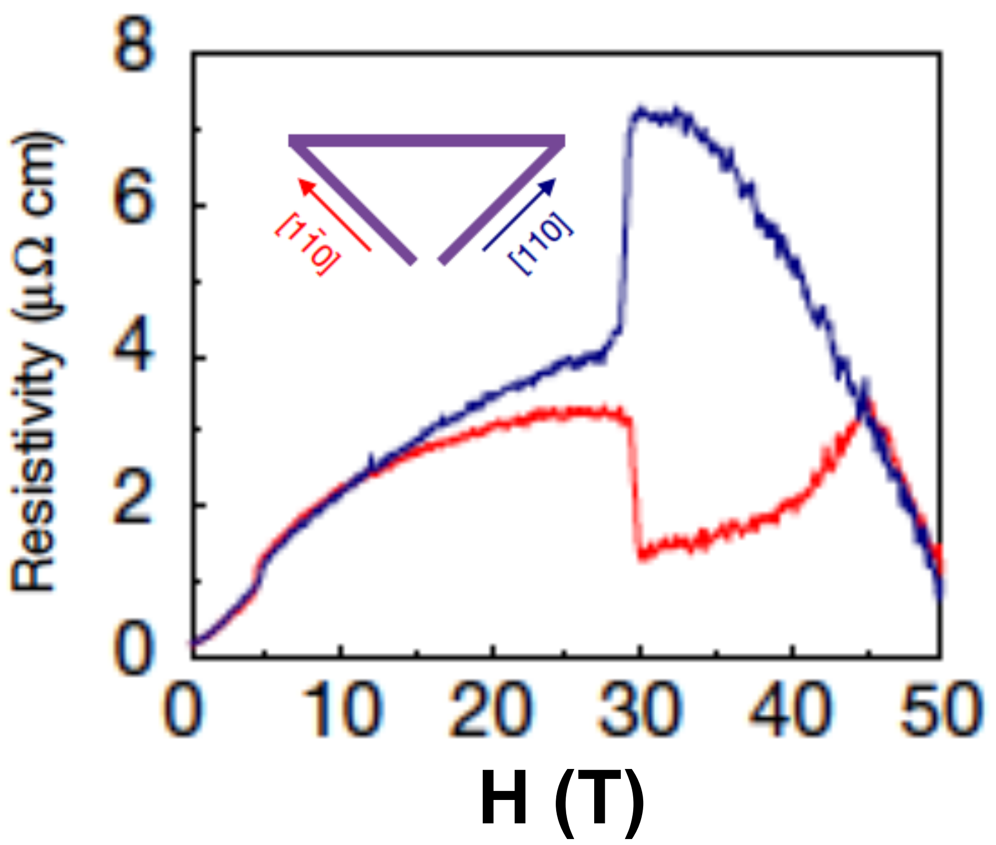
$CeRhIn_5$: an unconventional superconductor with a putative XY nematic state



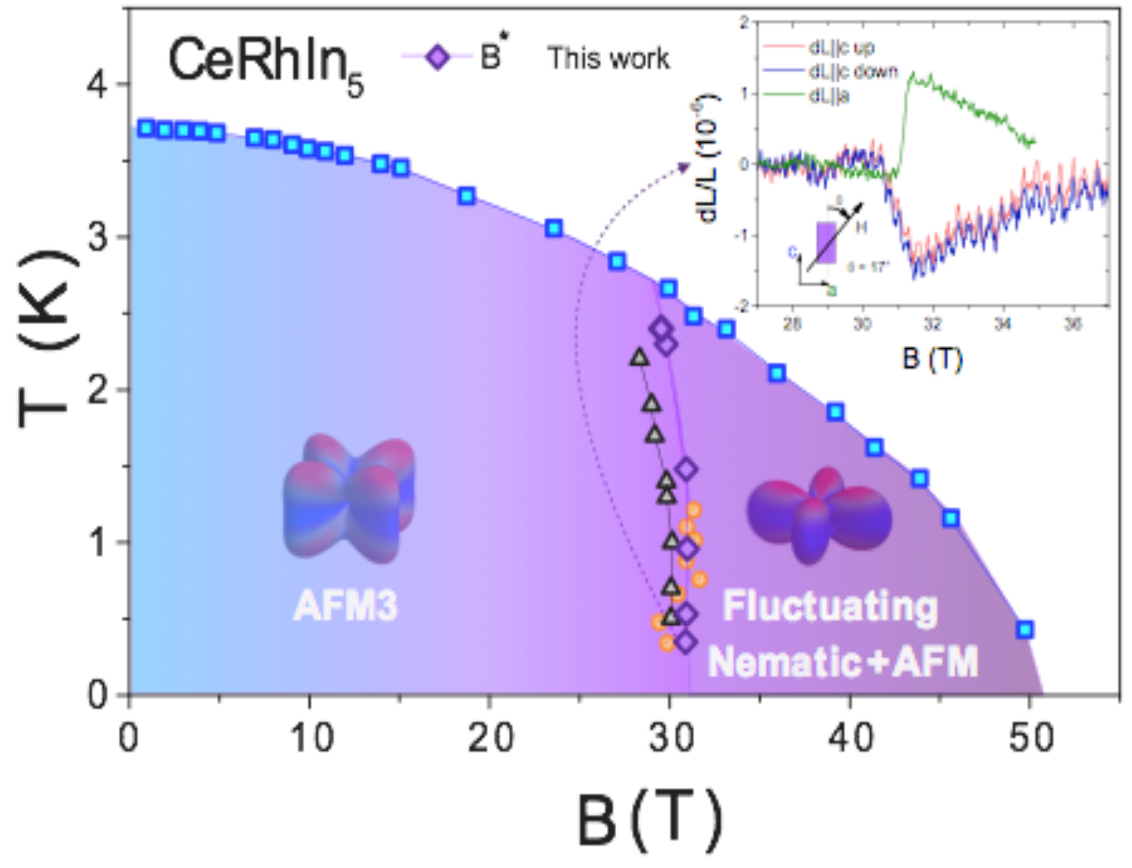
Ce*M*In_5
M=Co, Rh, Ir



Q1: What is the origin of the putative heavy-fermion nematic phase in $CeRhIn_5$?

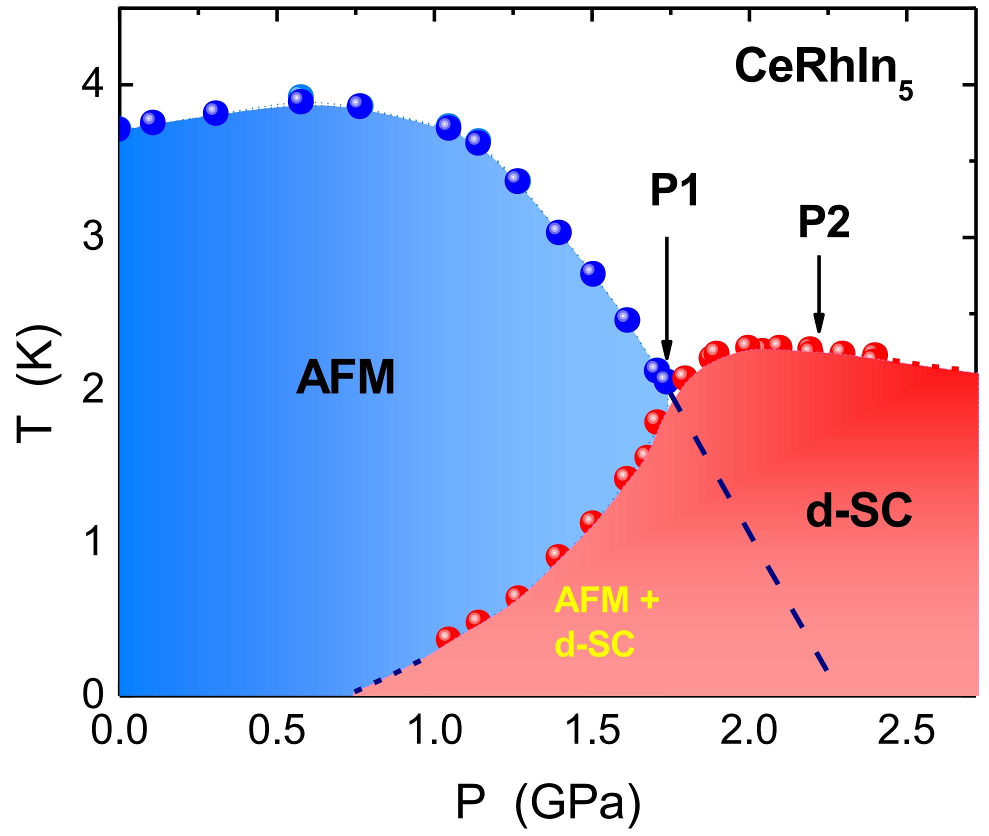


F. Ronning *et al*, Nature **548**, 313 (2017).



P. F. S. Rosa *et al*, Phys. Rev. Lett. **122**, 016402 (2019).

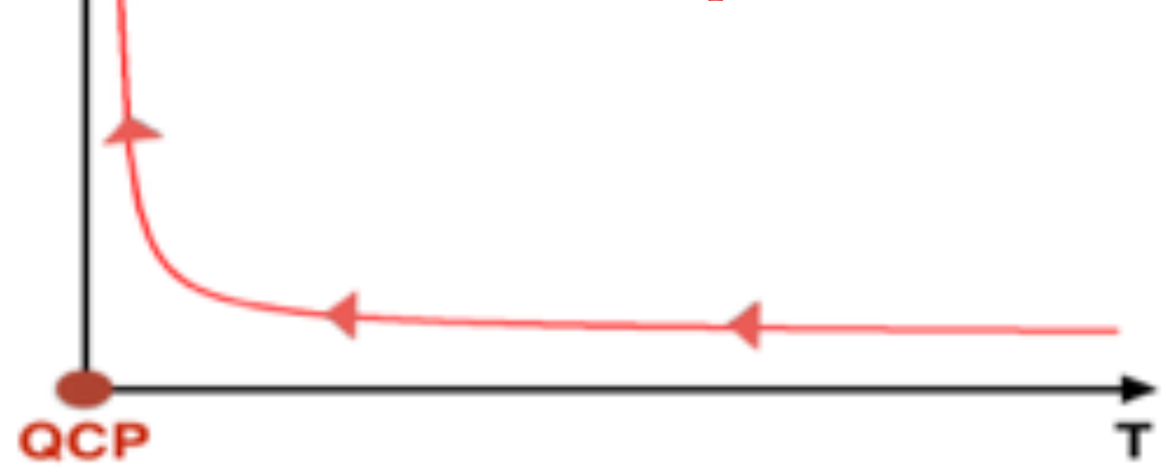
Q2: What is the universality class of the unconventional QCP in $CeRhIn_5$?



Hegger et al, Phys. Rev. Lett. **84**, 4986(2000);
T. Park et al, Nature **440**, 65 (2006).

Grüneisen ratio

$$\Gamma_{cr} = \frac{\alpha}{C_p} \sim -T^{-\epsilon}$$



L.. Zhu et al, Phys. Rev. Lett. **91**, 066404 (2003)

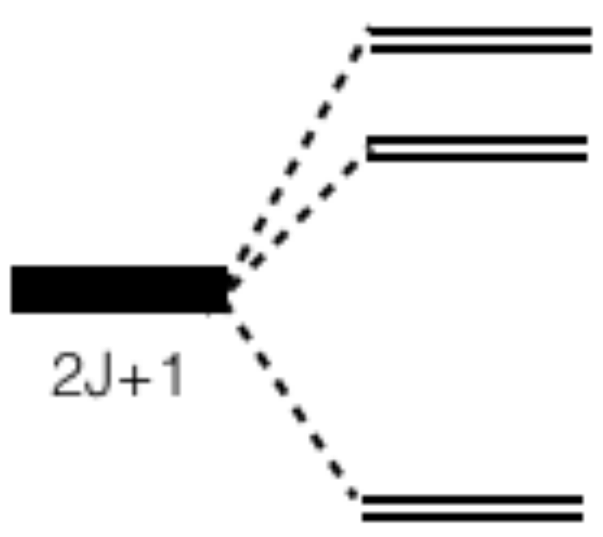
One-slide refresher on *f*-electron physics: crystal fields + RKKY + Kondo

Ce^{3+} $4f^1$ L = 3 S = 1/2

6-fold degenerate ground state

J = L - S = 3 - 1/2 = 5/2

In tetragonal symmetry…

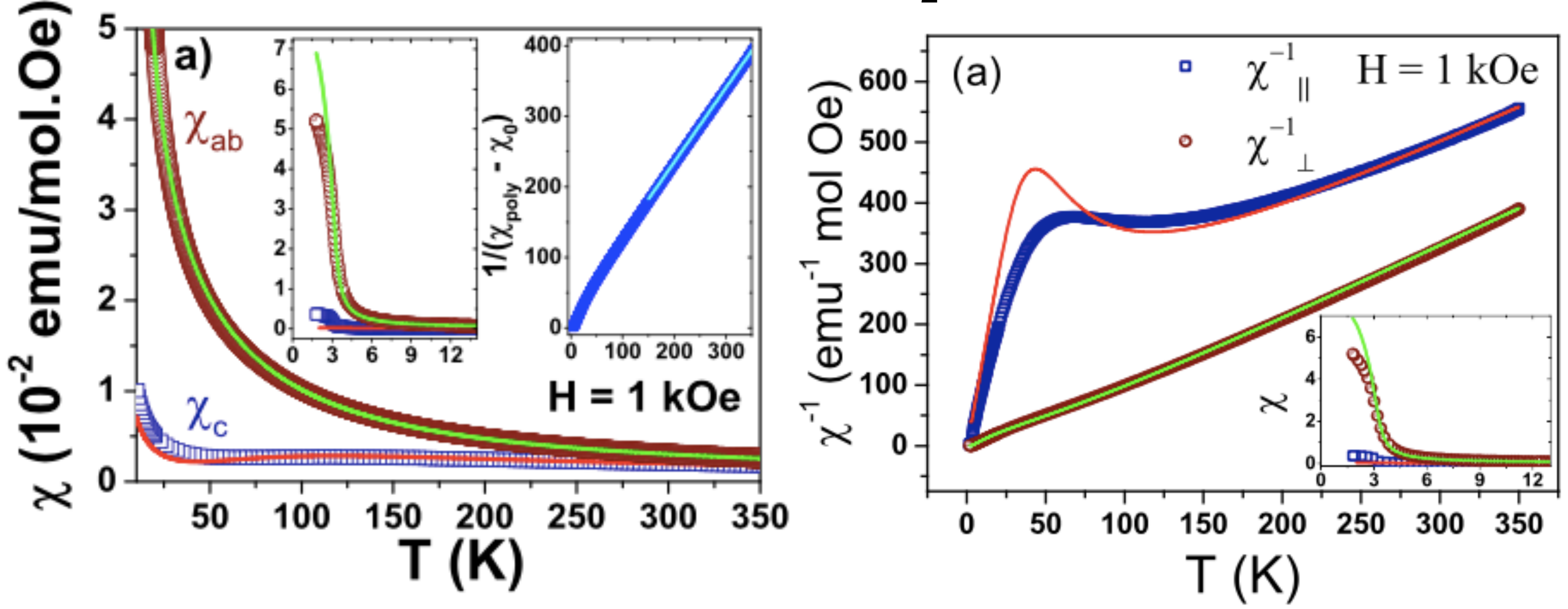


$$|2\rangle = \Gamma_6 = |\pm 1/2\rangle$$

$$|1\rangle = \Gamma_7^+ = \beta|\pm 5/2\rangle + |\alpha||\pm 3/2\rangle$$

$$|0\rangle = \Gamma_7^- = |\alpha||\pm 5/2\rangle - \beta|\pm 3/2\rangle$$

CeCdSb2

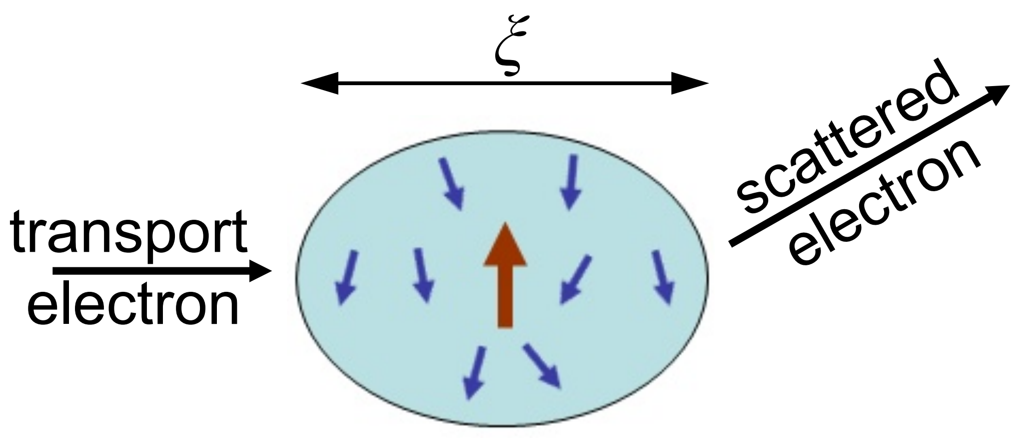


P. F. S. Rosa *et al*, Phys. Rev. B **92**, 134421 (2015).

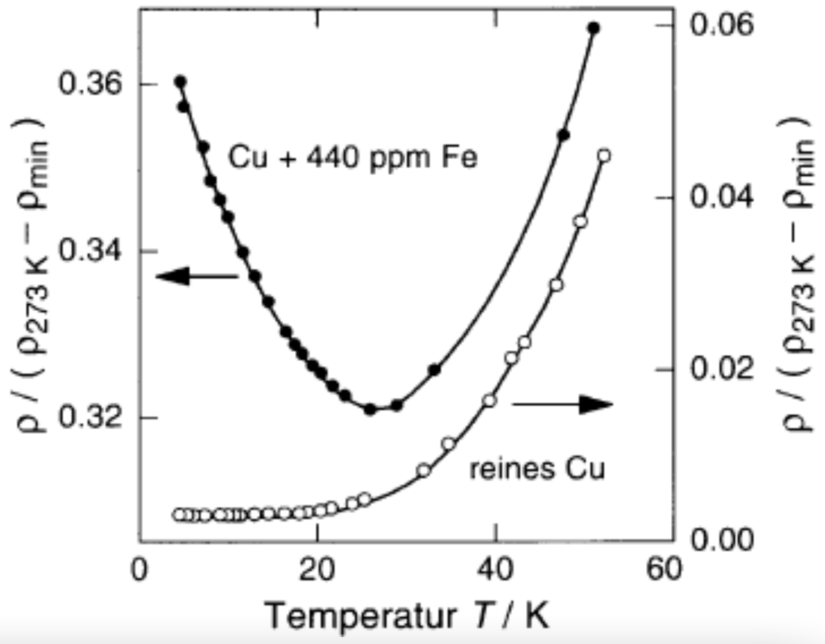
Local magnetic moments

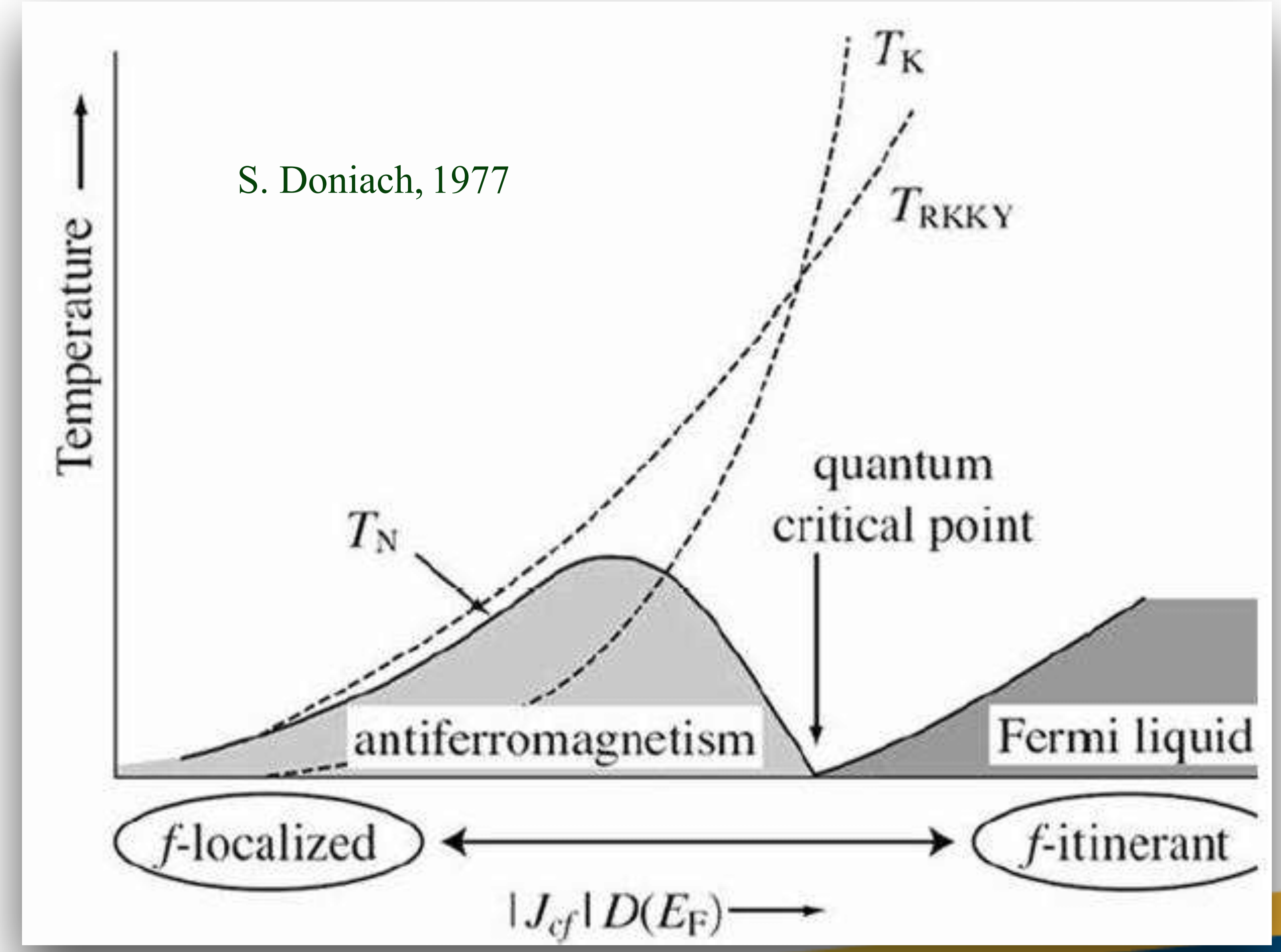
\+

conduction electrons



Jun Kondo '63

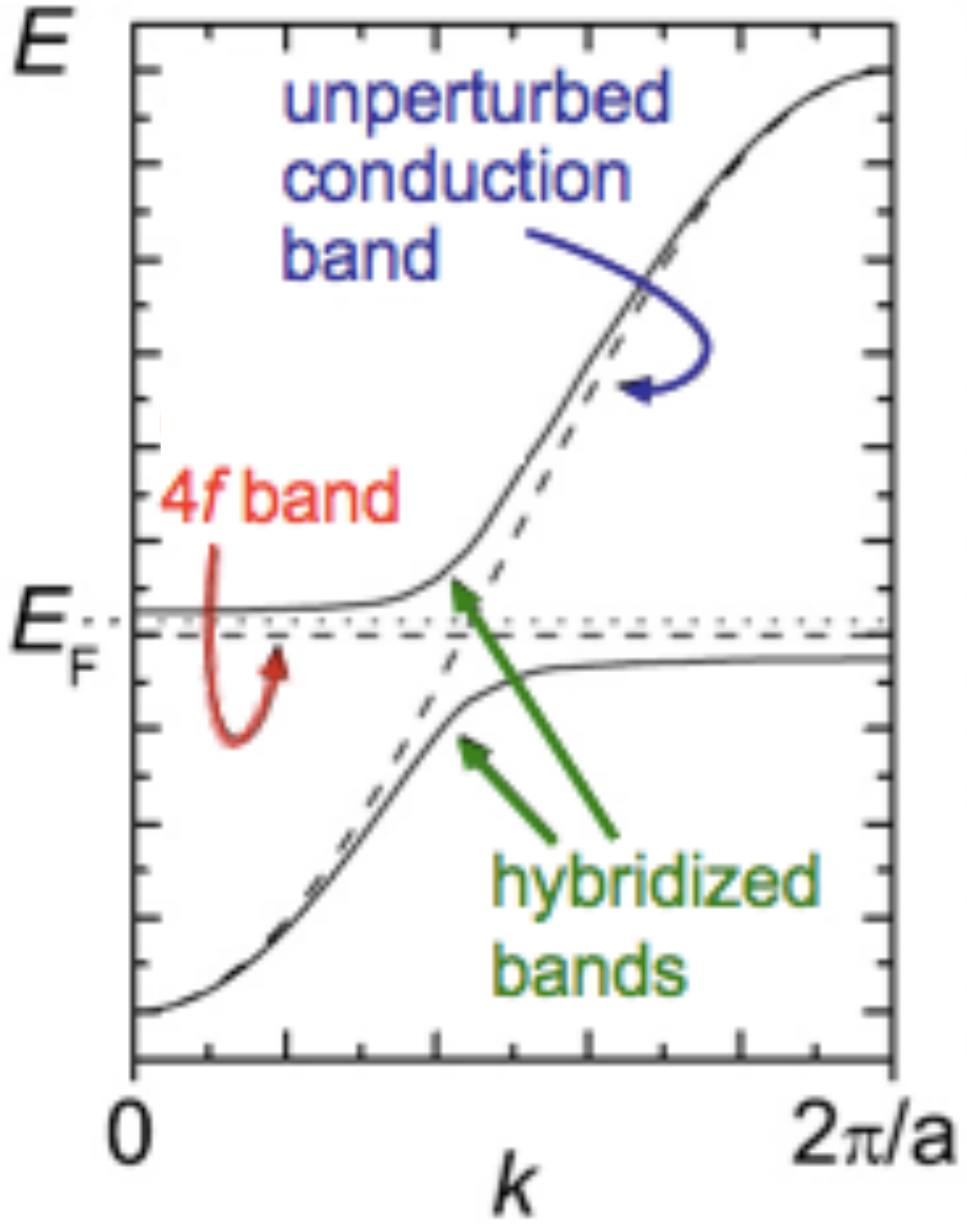




Kondo lattice

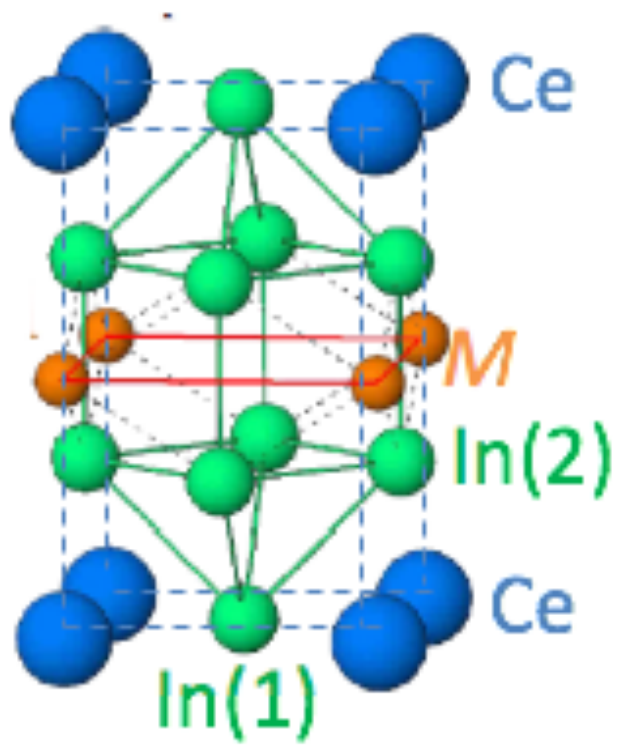
$$H_A = H_c + H_f + H_{hyb}$$

$$\hat{H}_{\text{hyb}} = \sum_{ij}\sum_{a\sigma\alpha}\left(V_{ia\sigma,j\alpha}\hat{c}^{\dagger}_{i,a\sigma}\hat{f}_{j\alpha} + V_{i\alpha,ja\sigma}\hat{f}^{\dagger}_{i\alpha}\hat{c}_{j,a\sigma}\right)$$

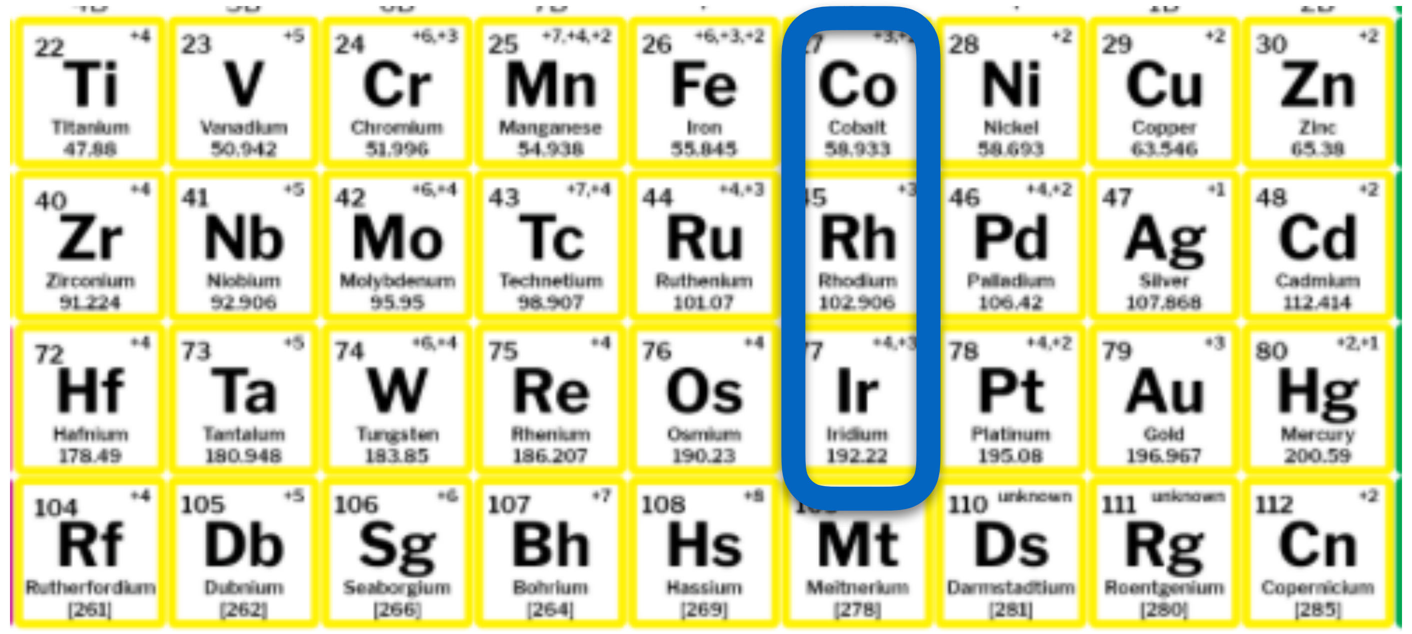


P. Coleman, Many-Body Physics: From Kondo to Hubbard (2015)

$CeMIn_5$ (M = Co, Rh, Ir): crystal fields and hybridization



$CeMIn_5$
M=Co, Rh, Ir



Co: T_c = 2.3 K

Rh: T_N = 3.8 K

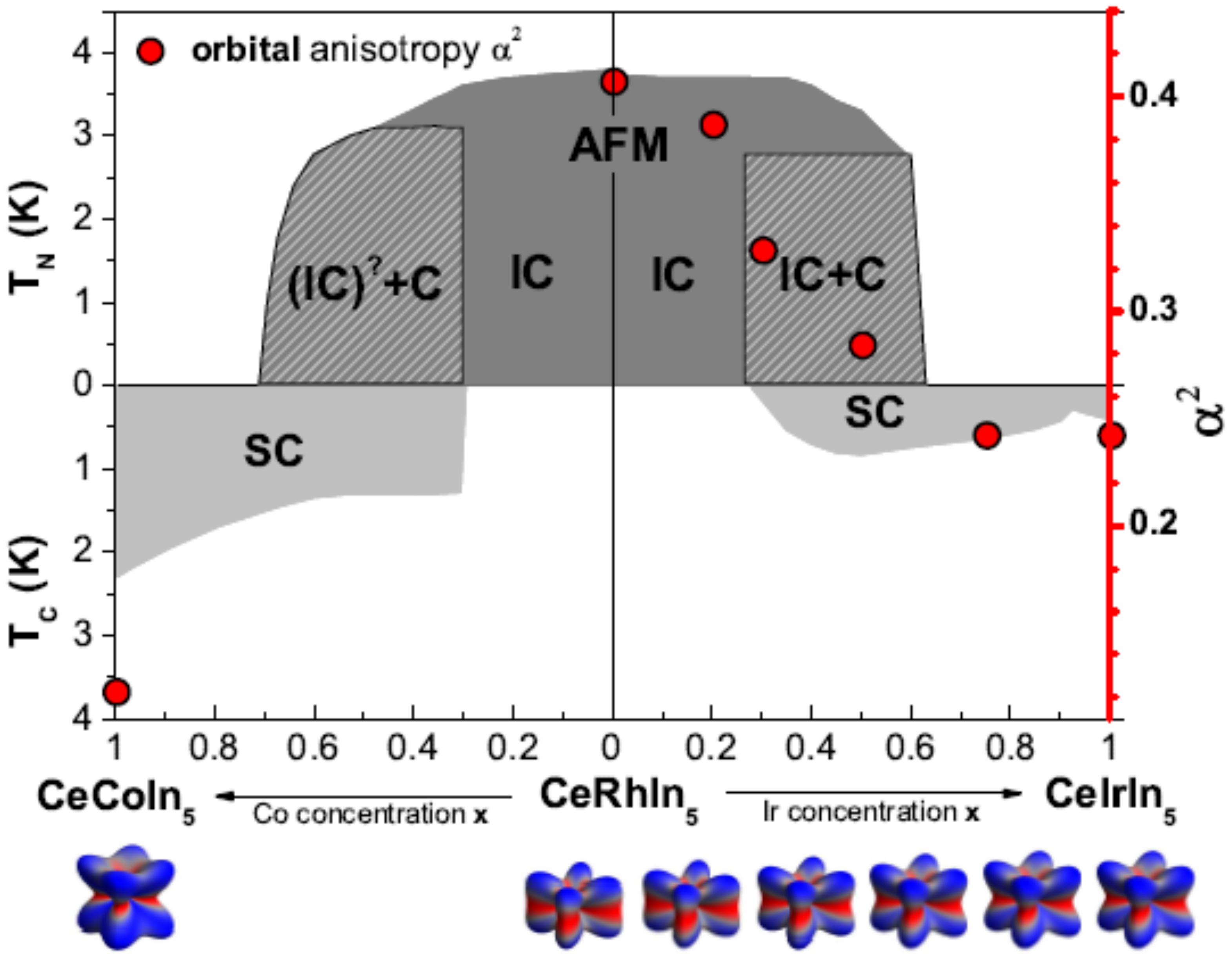
Ir: T_c = 0.4 K

$$|0\rangle = \Gamma_7^{\pm} = |\alpha||\pm 5/2\rangle \pm \beta|\pm 3/2\rangle$$

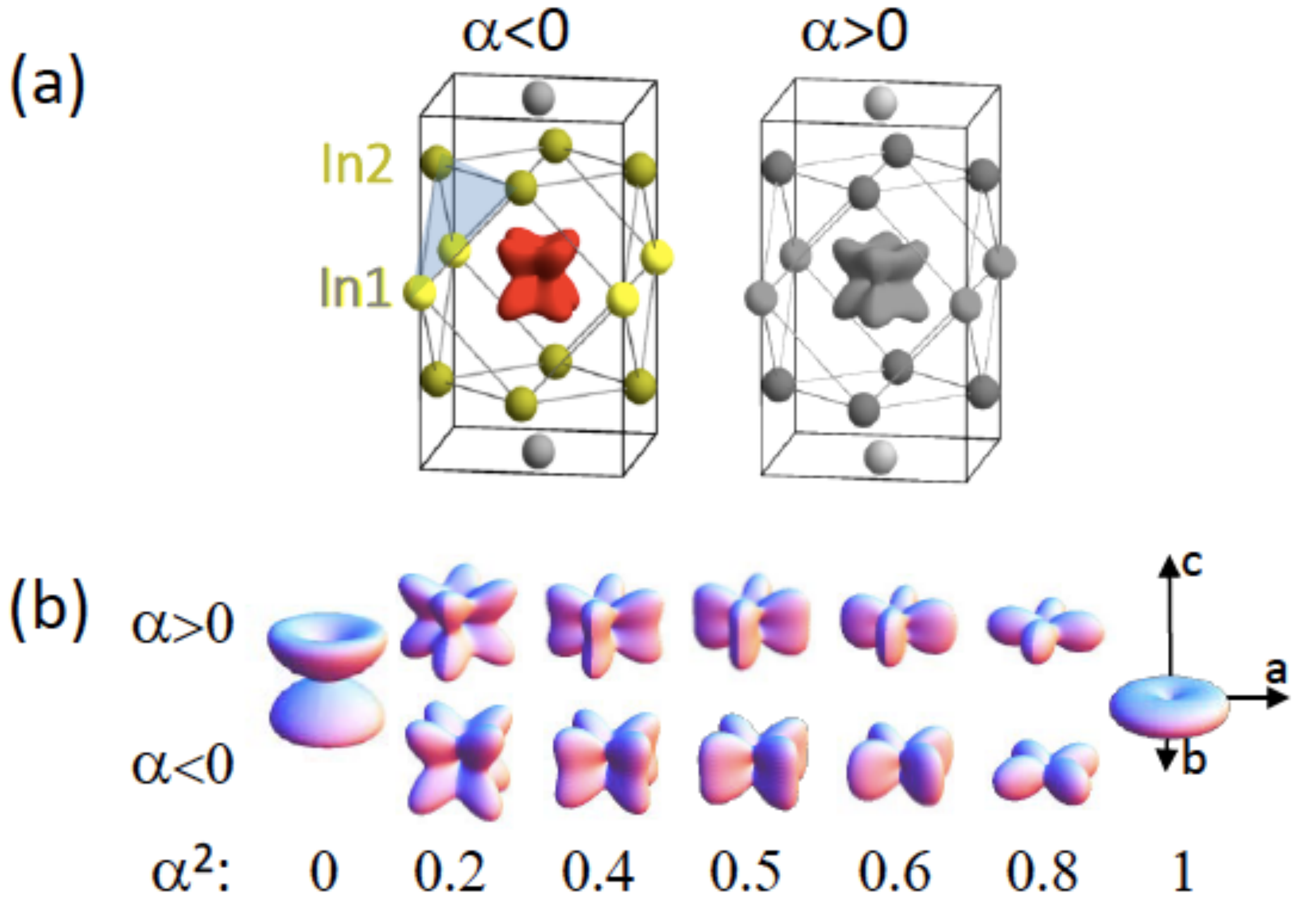
P. G. Pagliuso et al, Physica B **312**, 129 (2002).

J. H. Shim, K. Haule, G. Kotliar, Science **318**, 1615 (2007).
K. Haule, C.-H. See, and K. Kim. Phys. Rev. B, **81**, 195107 (2010).

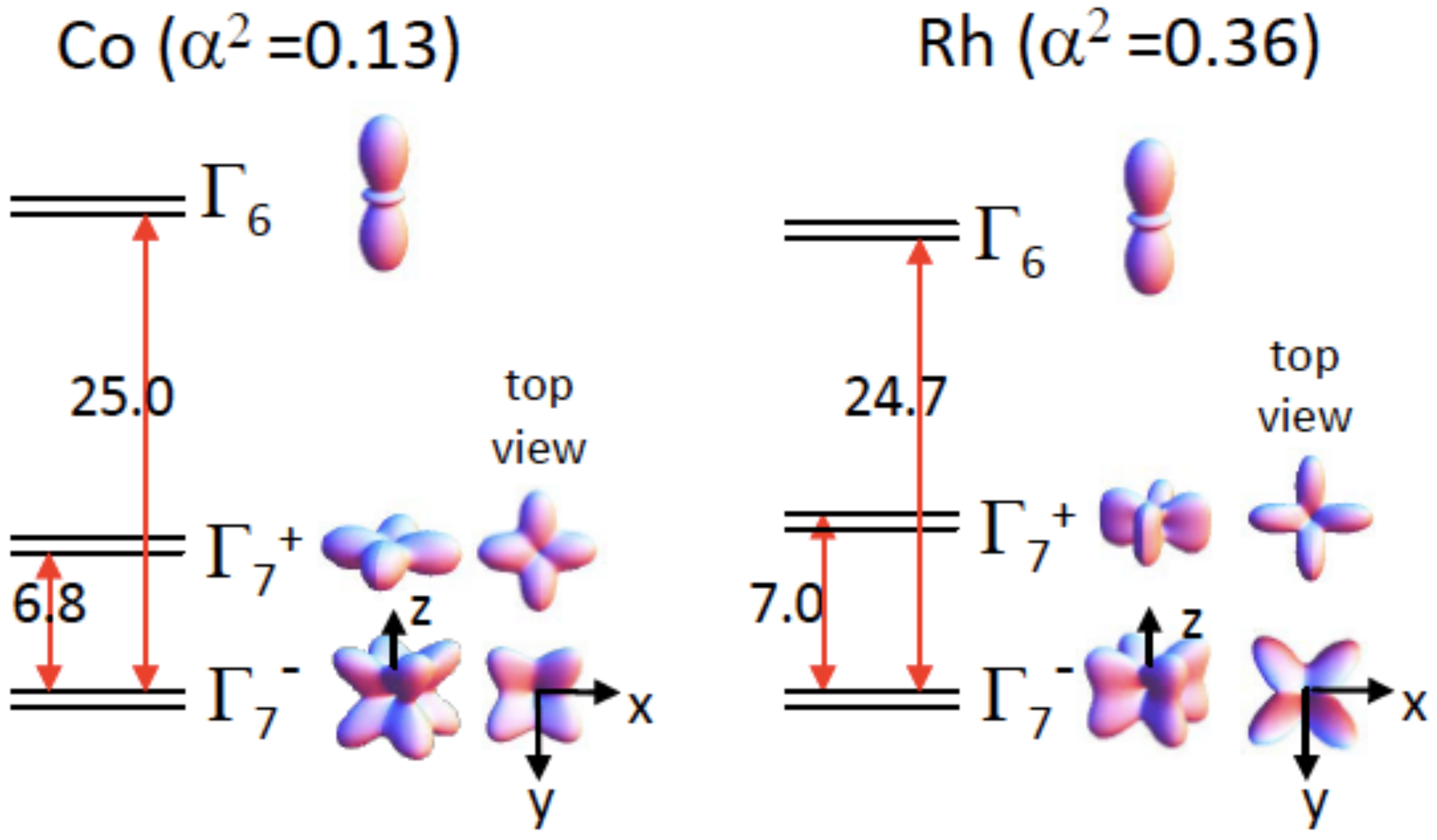
Linearly polarized x-ray absorption spectroscopy



T. Willers et al., PNAS **112**, 2384 (2015).



M. Sundermann *et al*, arXiv:1902.06726 (2019).

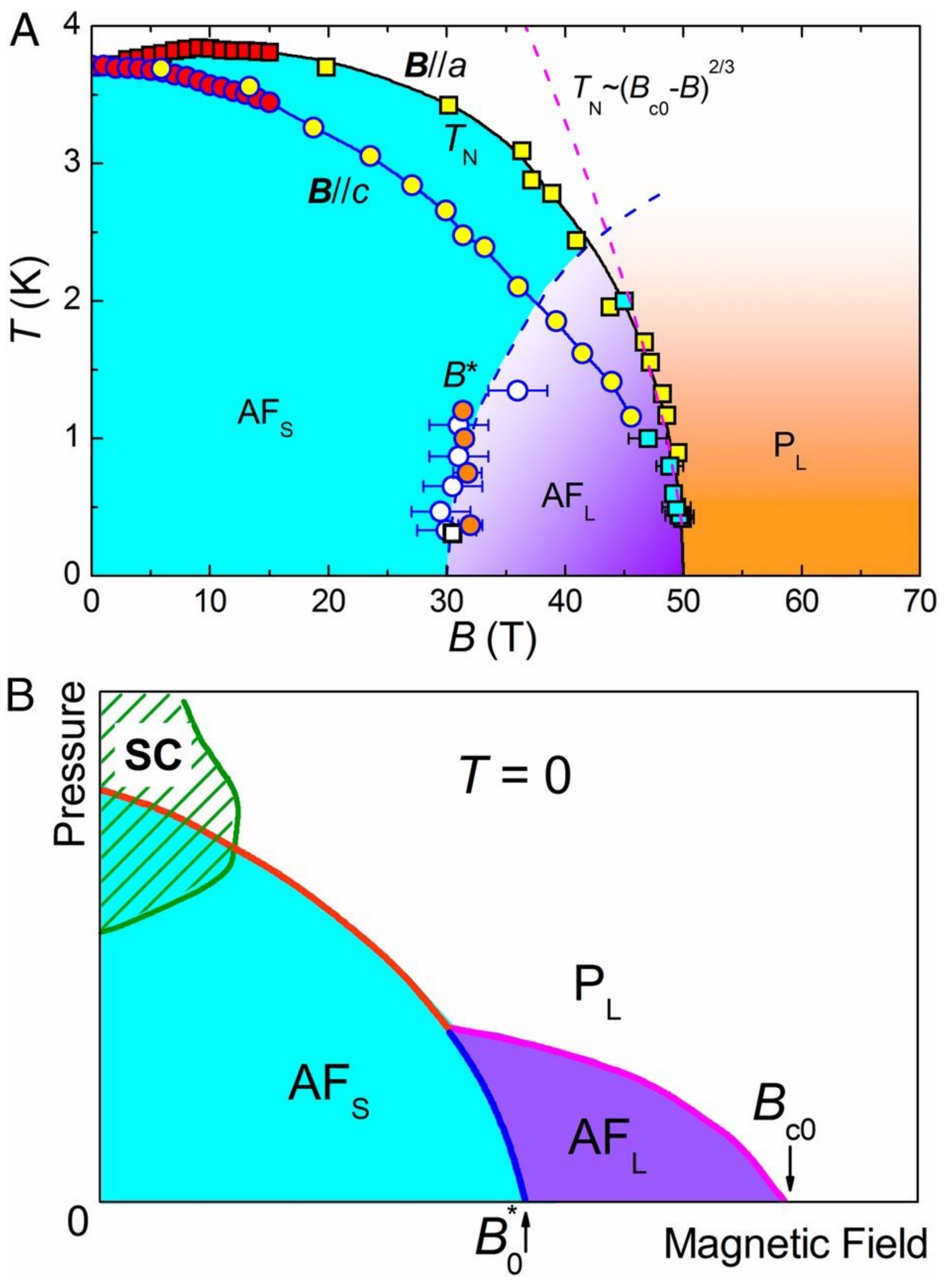


Larger α^2 ⇨ weaker *4f* - In(2) hybridization

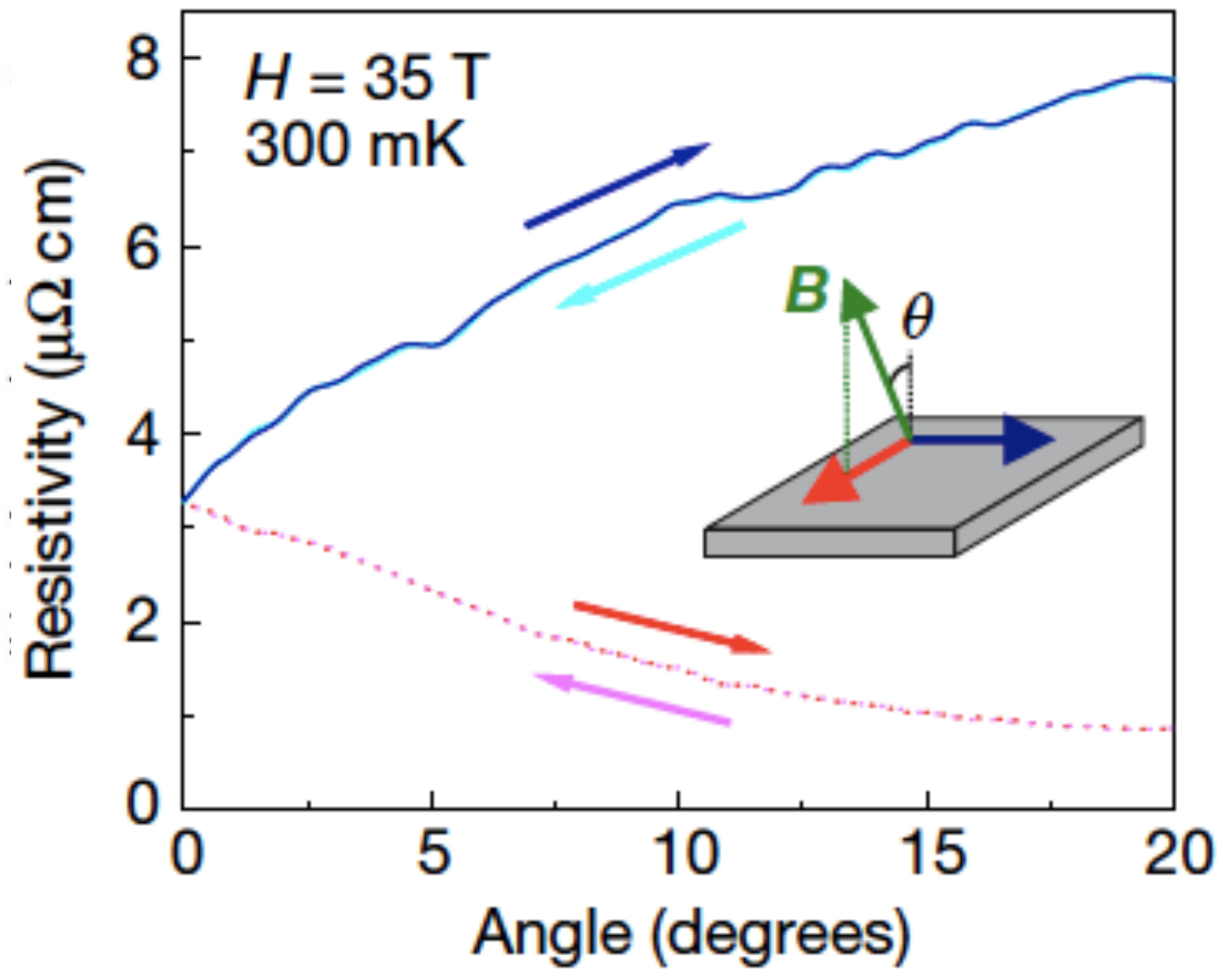
CeRhIn$_5$ in high magnetic fields

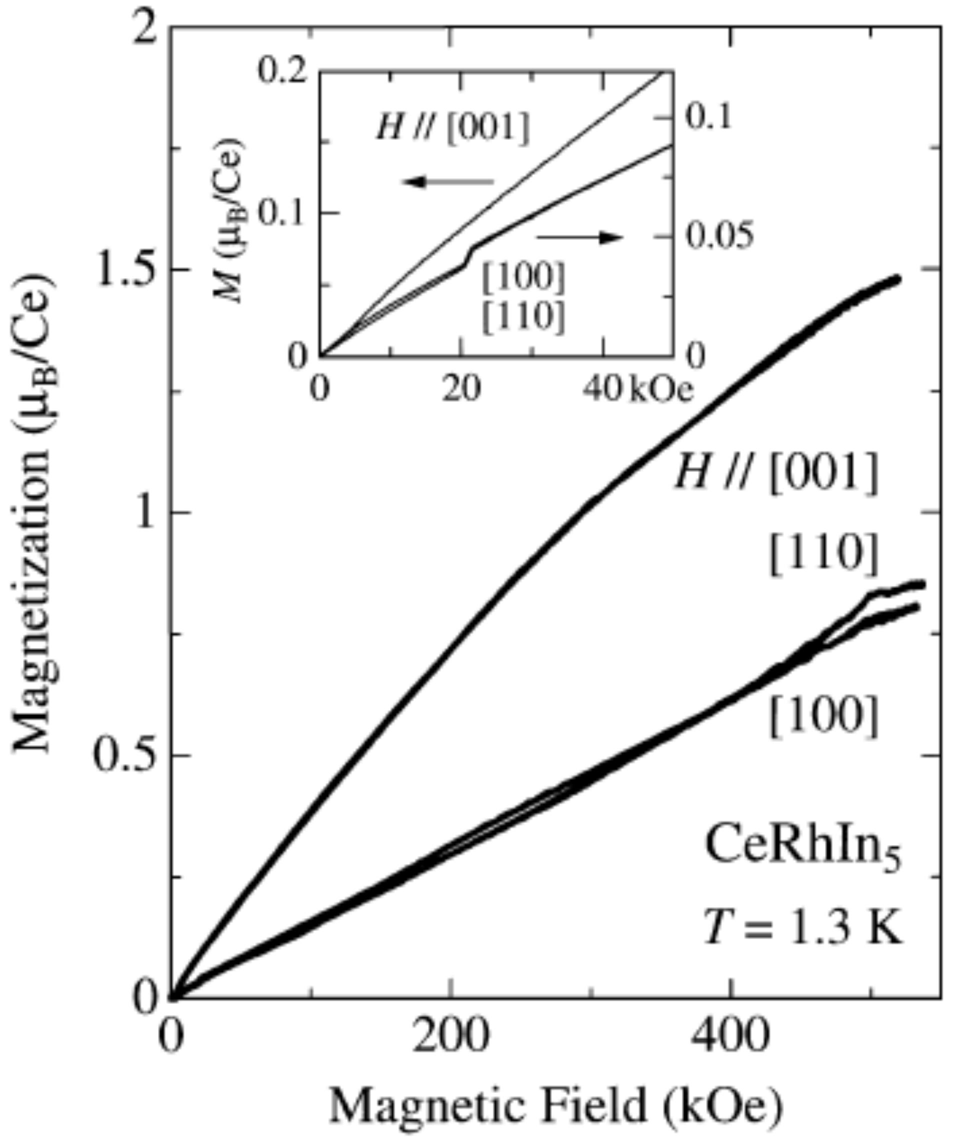
What else do we know?

- Magnetic fields also destabilize T_N;
- At B* ~ 30 T, the Fermi surface changes;



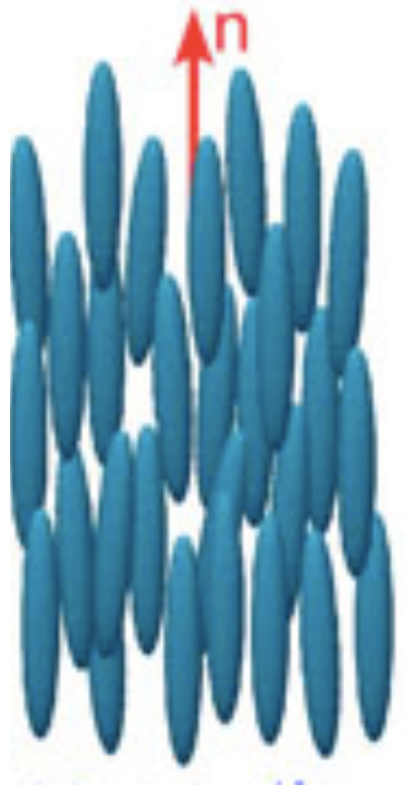
L. Jiao et al., PNAS **112**, 673 (2015).

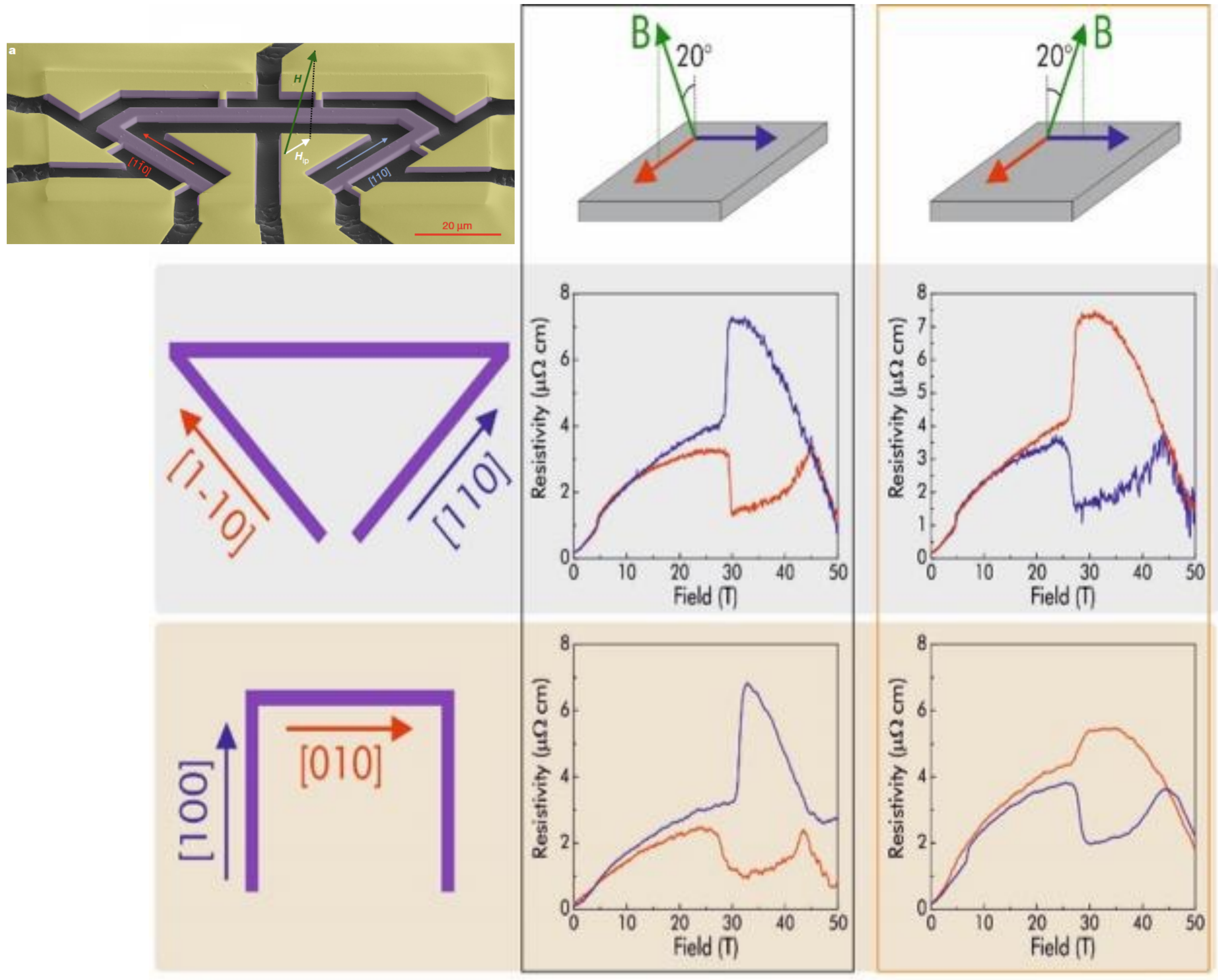




Takeuchi et al., JPSJ **70**, 877 (2000).

- At B* ~ 30 T, a large in-plane anisotropy emerges in transport;
- XY nematic scenario: lower symmetry of the electronic system compared to the lattice.



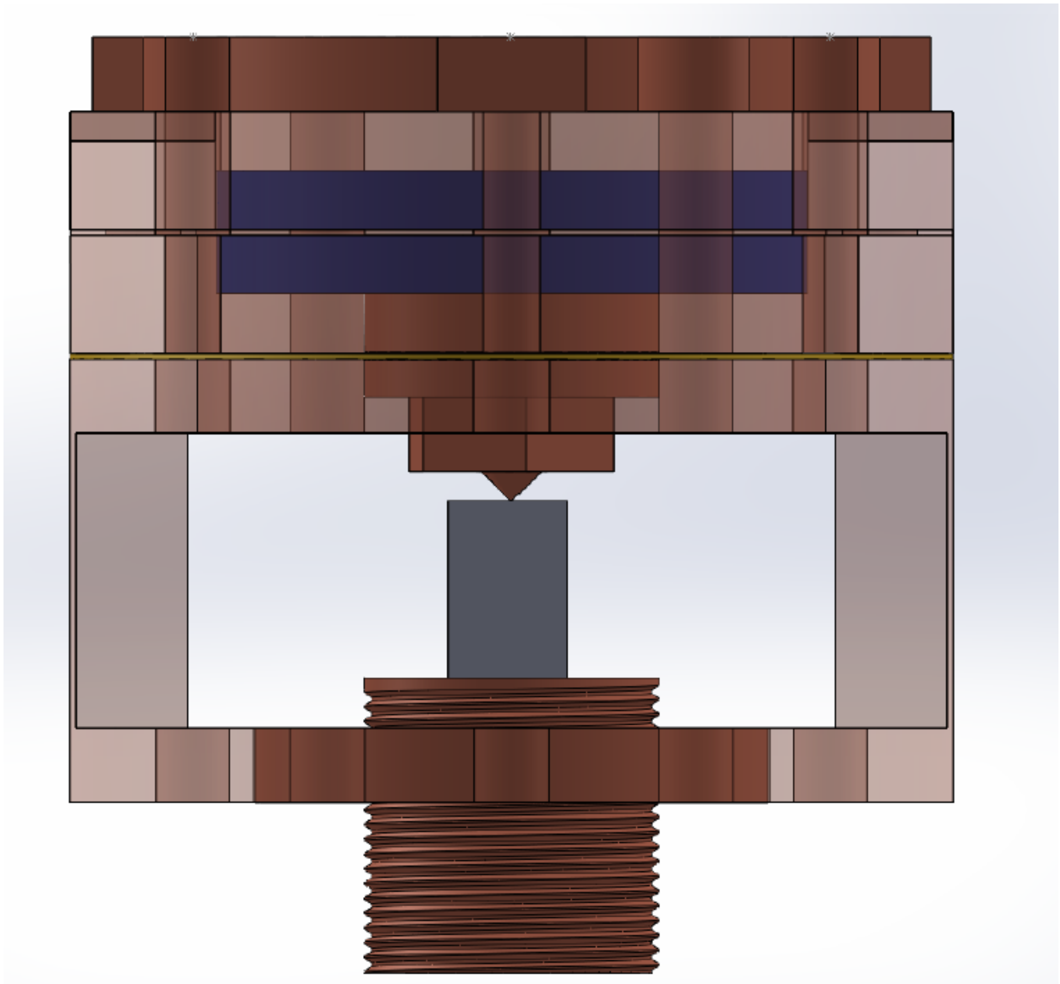


F. Ronning *et al*, Nature **548**, 313 (2017).

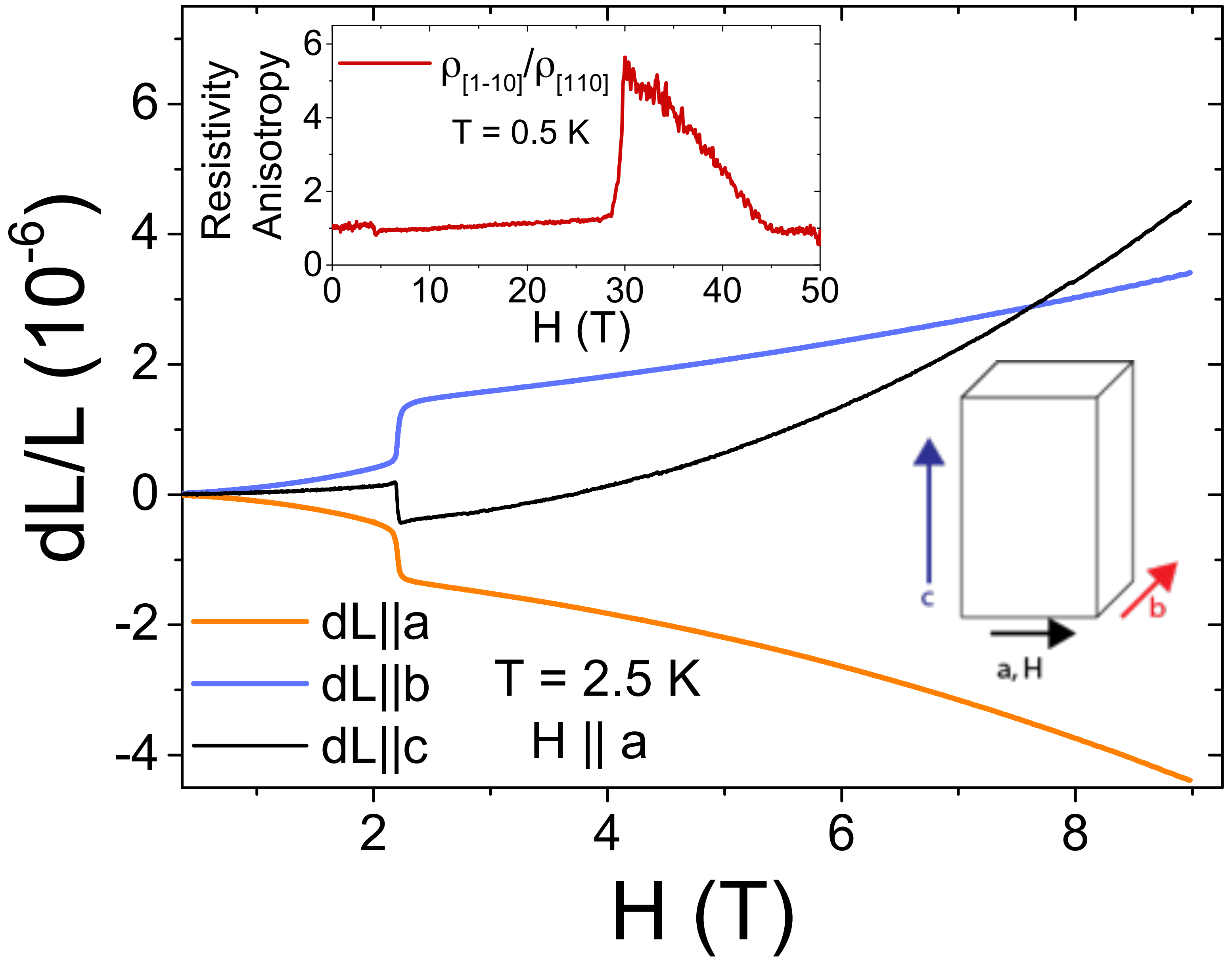
But what is the cause of B*?

Dilatometry at low fields

Capacitance Dilatometer



G. M. Schmiedeschoff et al, Rev. Sci. Inst. **77**, 123907 (2006).



Ginzburg-Landau's Magneto-elastic free energy

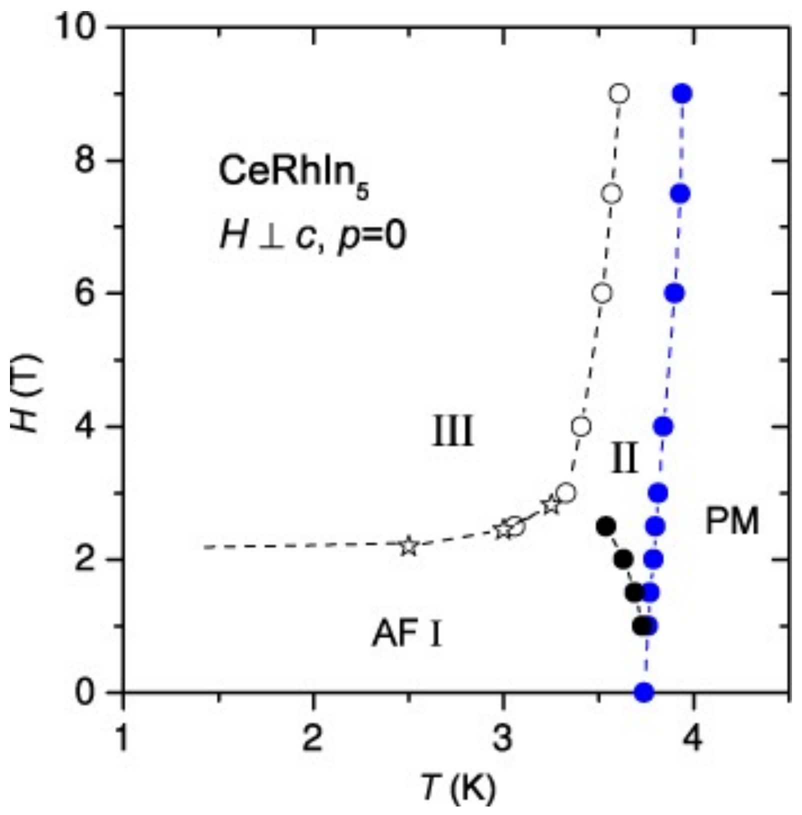
$$F = -\lambda\delta(H_a^2 - H_b^2) + (\alpha/2)\delta^2$$

$\delta = (a-b)/b$ orthorhombic distortion

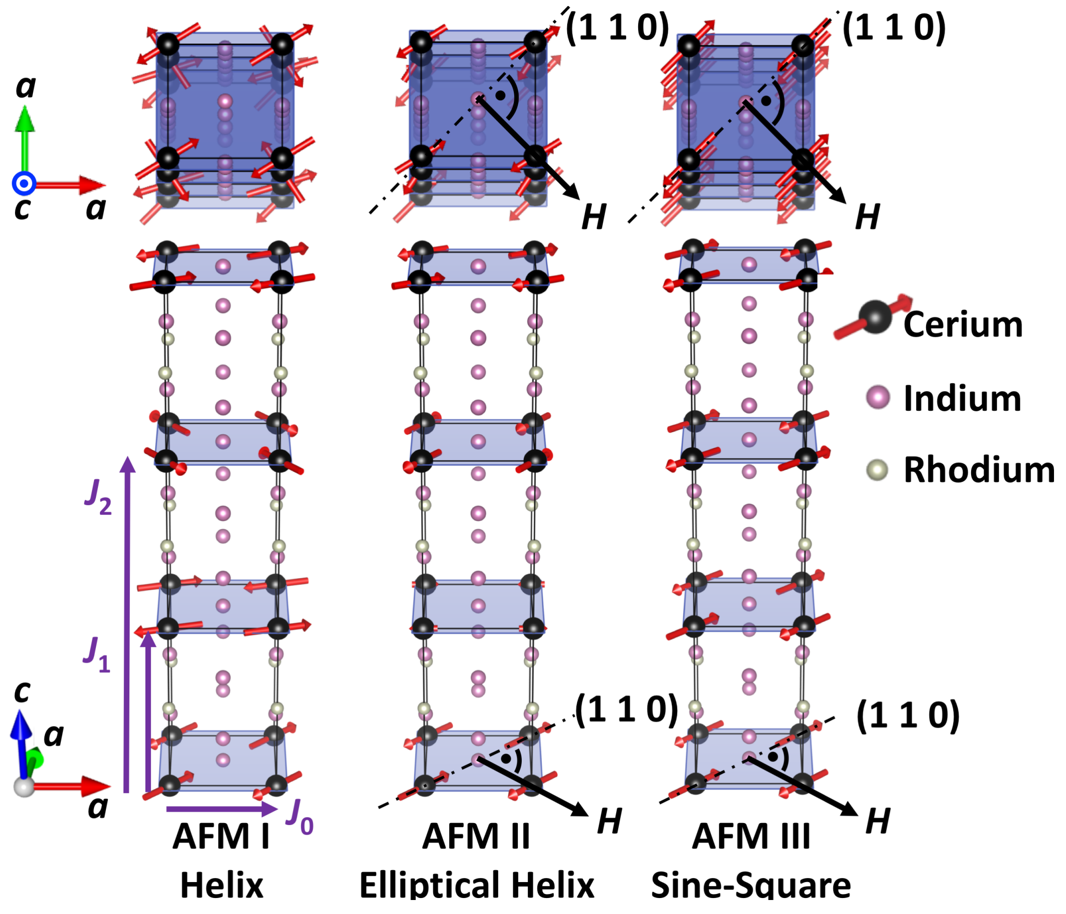
α elastic constant

$$\chi_{\rm nem} \propto \partial\Delta/\partial H_a^2$$

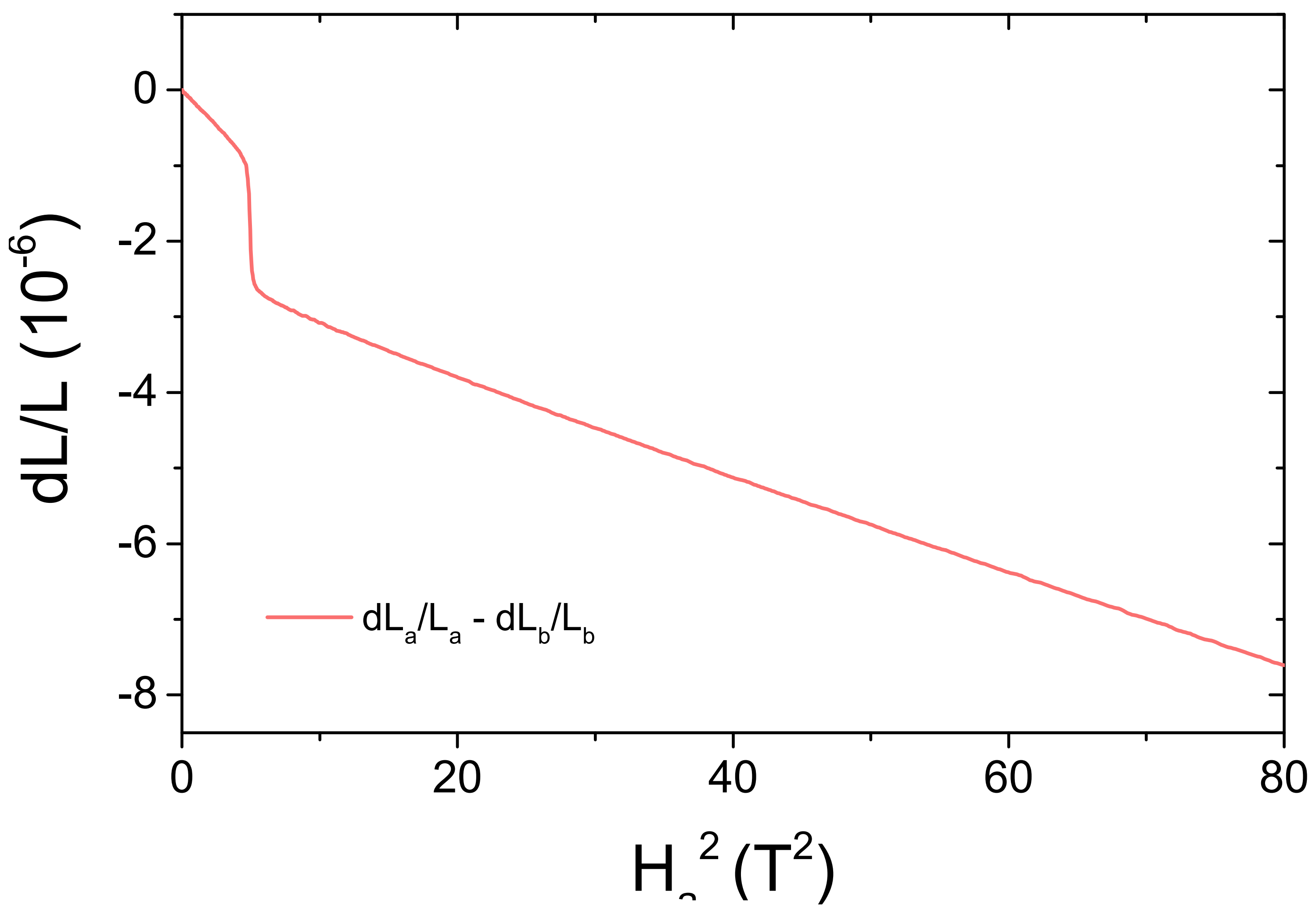
$$\Delta = dL_a/L_a - dL_b/L_b$$



S Raymond *et al*, J. Phys.: Condens. Matter **19,** 242204 (2007).



D. M. Fobes *et al*, Nat. Phys. 14, 456 (2018).



AF I

$$\lambda\chi_{\rm nem} = -2\times10^{-9}$$

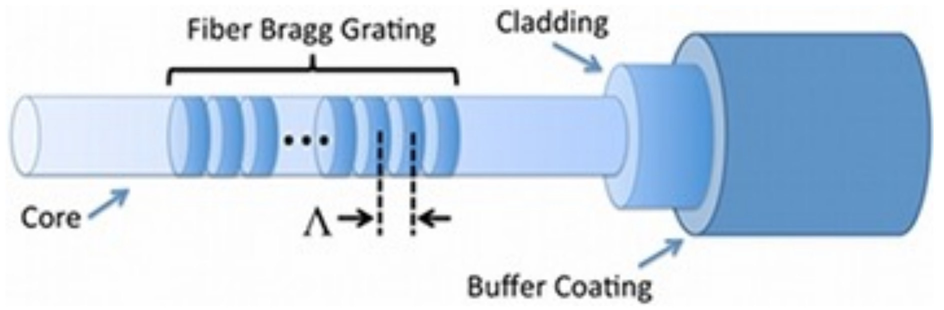
AF III

$$\lambda\chi_{\rm nem} = -6\times10^{-10}$$

Dilatometry at high fields

Optical dilatometry

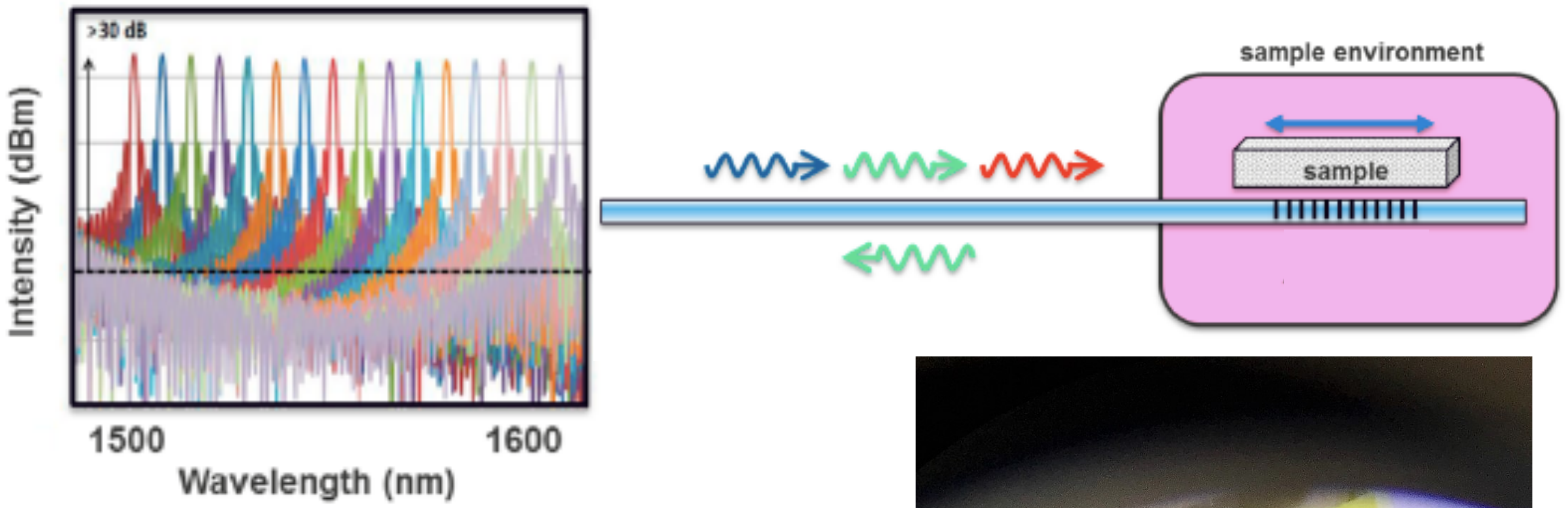
* Fiber Bragg grating sensors



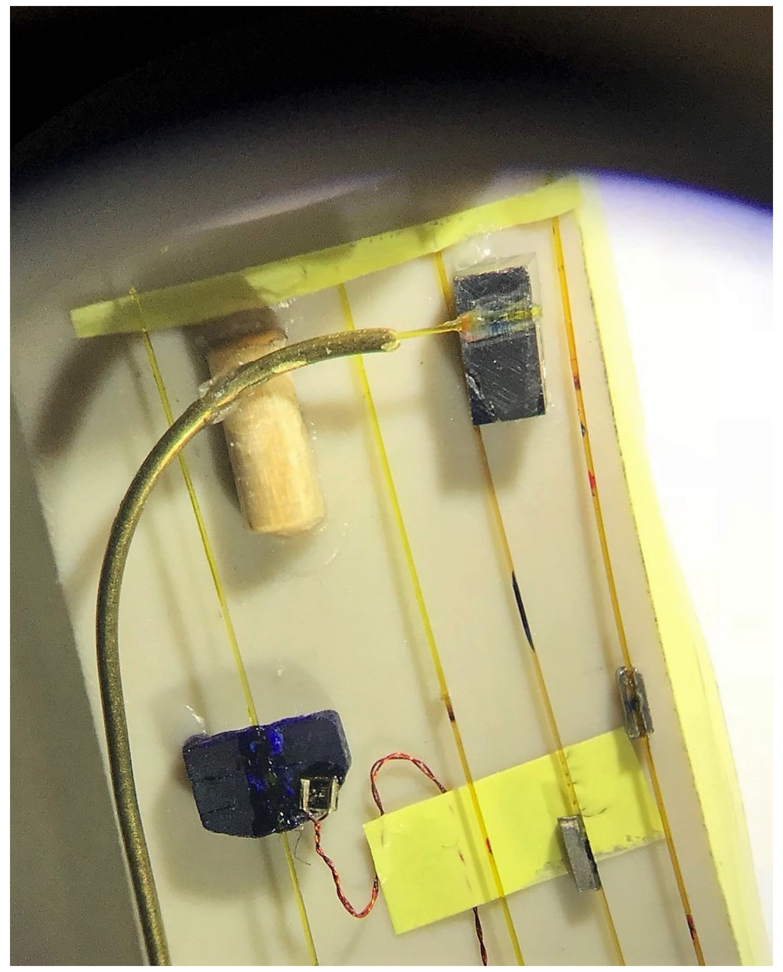
$$\lambda_B = 2n_{eff}\Lambda$$

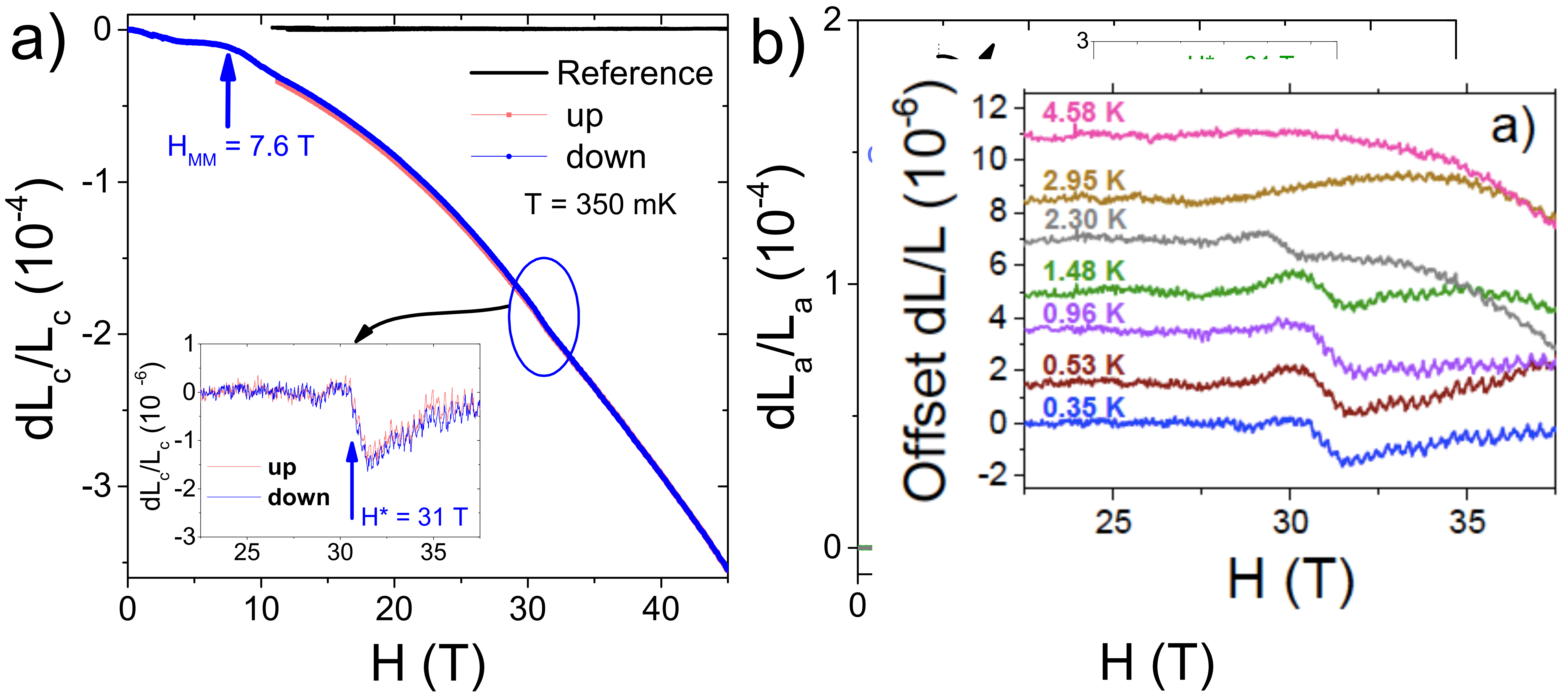
* Swept-wavelength lasers interrogate FBGs at 1kHz

R. Daou *et al*, *Rev. Sci. Instrum.* **81**, 033909 (2010);
M. Jaime et al, *Sensors* **17**, 2572 (2017).



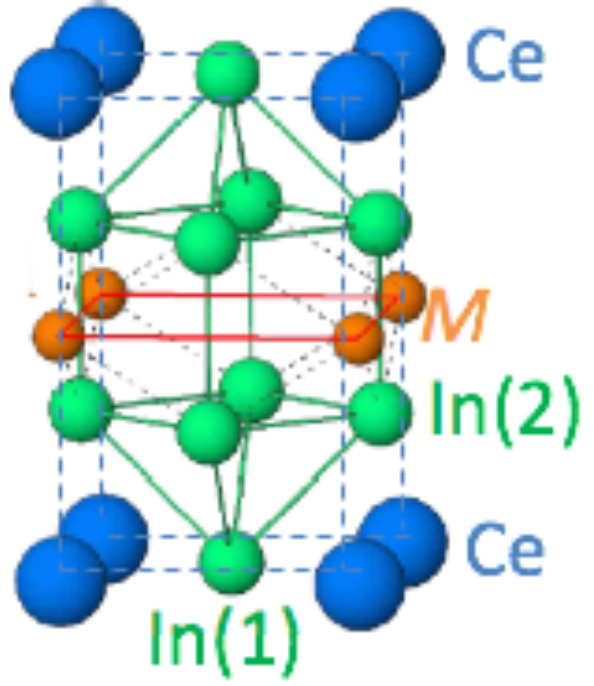
$$\frac{dL}{L} \propto \frac{d\lambda}{\lambda}$$



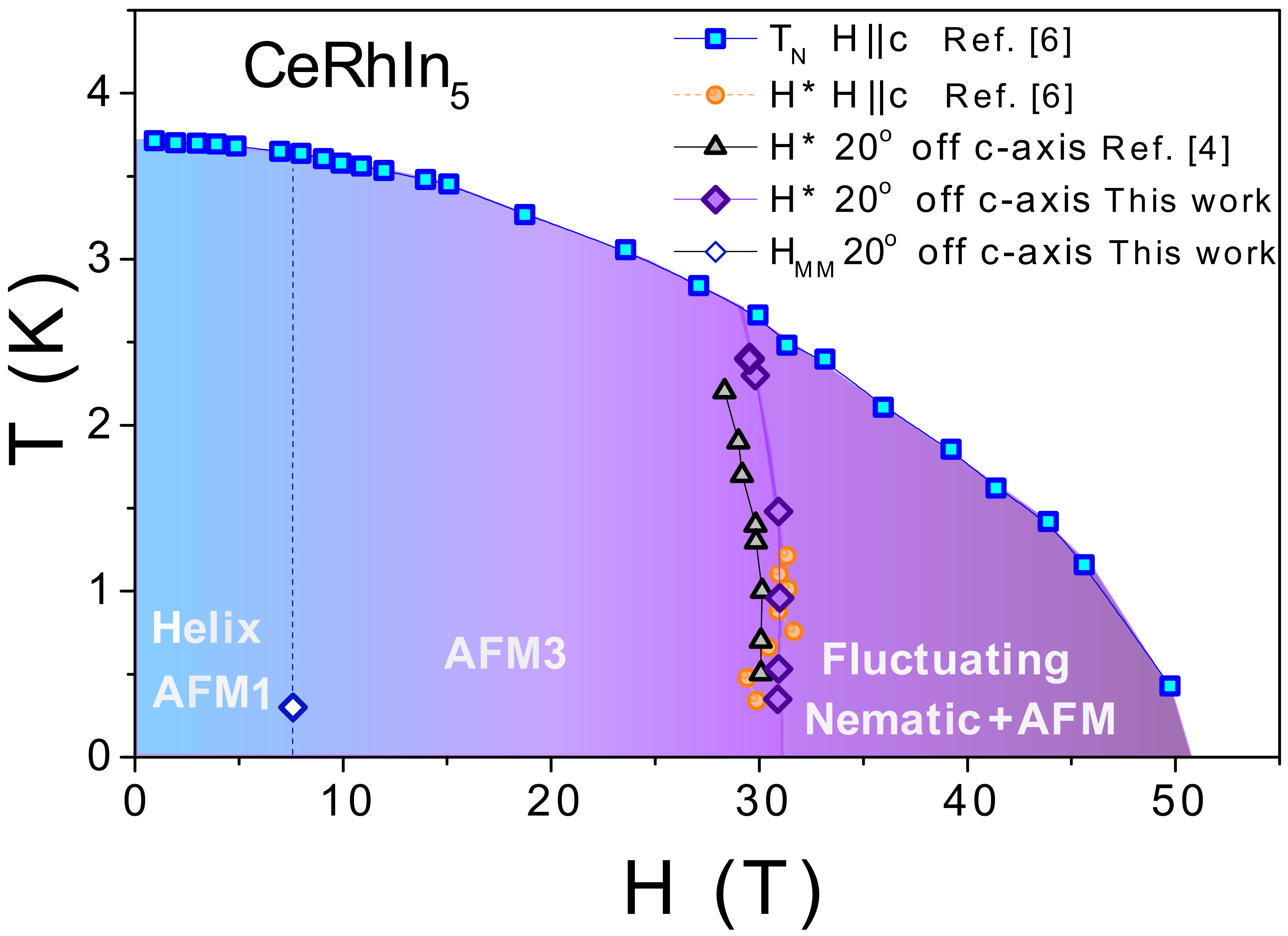


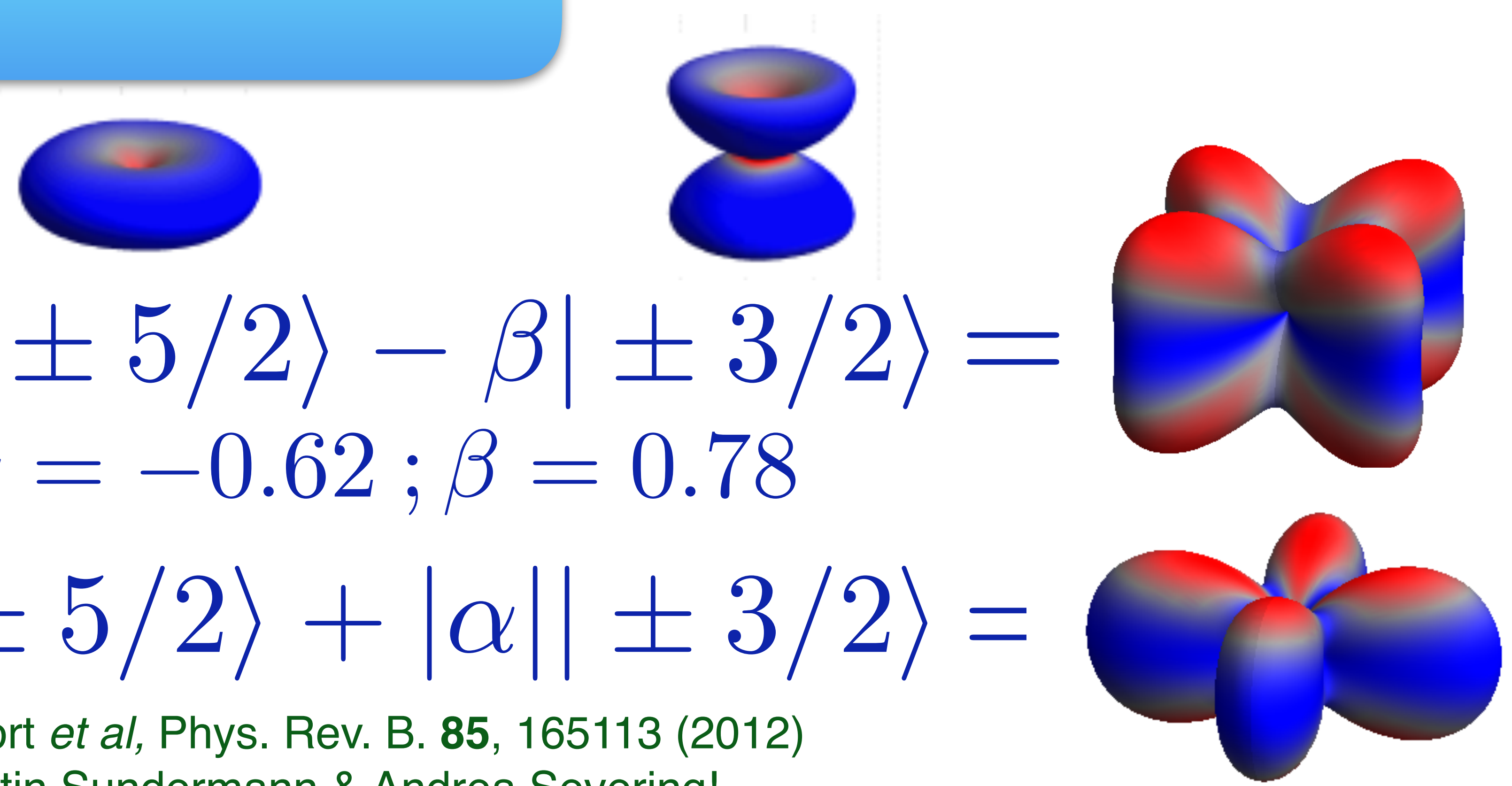
* Small a-axis expansion and small c-axis contraction at H*
* No hysteresis is found
* Magnetostriction quantum oscillations
* B* is a (nematic) crossover

Ground state evolution in field



CeMIn$_5$
M=Co, Rh, Ir





$$|0\rangle = \Gamma_7^- = |\alpha||\pm 5/2\rangle - \beta|\pm 3/2\rangle =$$

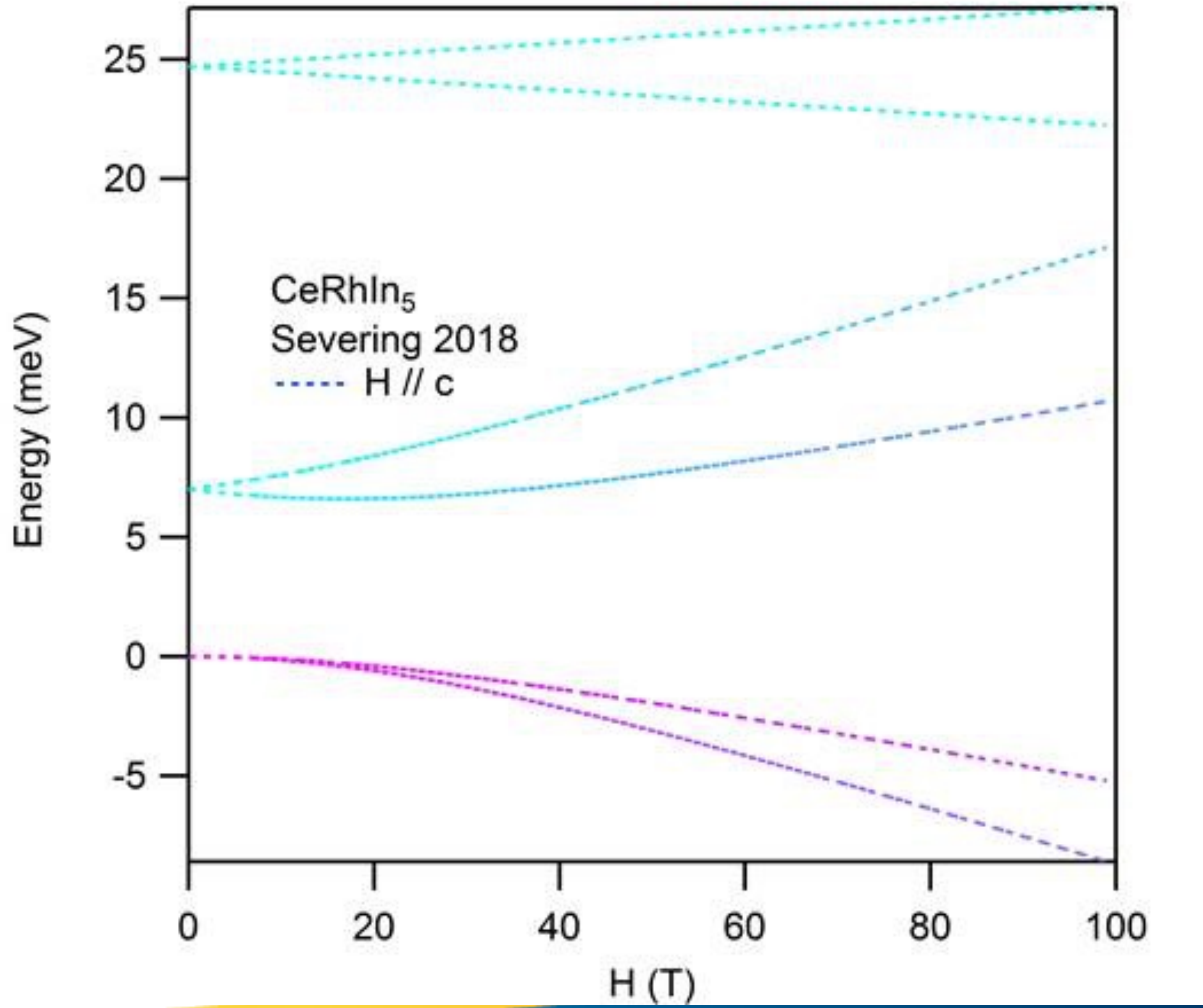
$$\alpha = -0.62\,;\, \beta = 0.78$$

$$|1\rangle = \Gamma_7^+ = \beta|\pm 5/2\rangle + |\alpha||\pm 3/2\rangle =$$

M. W. Haverkort *et al,* Phys. Rev. B. **85**, 165113 (2012)
Thanks to Martin Sundermann & Andrea Severing!

$$\mathcal{H} = \mathcal{H}_{CEF} + \mathcal{H}_{Zeeman}$$

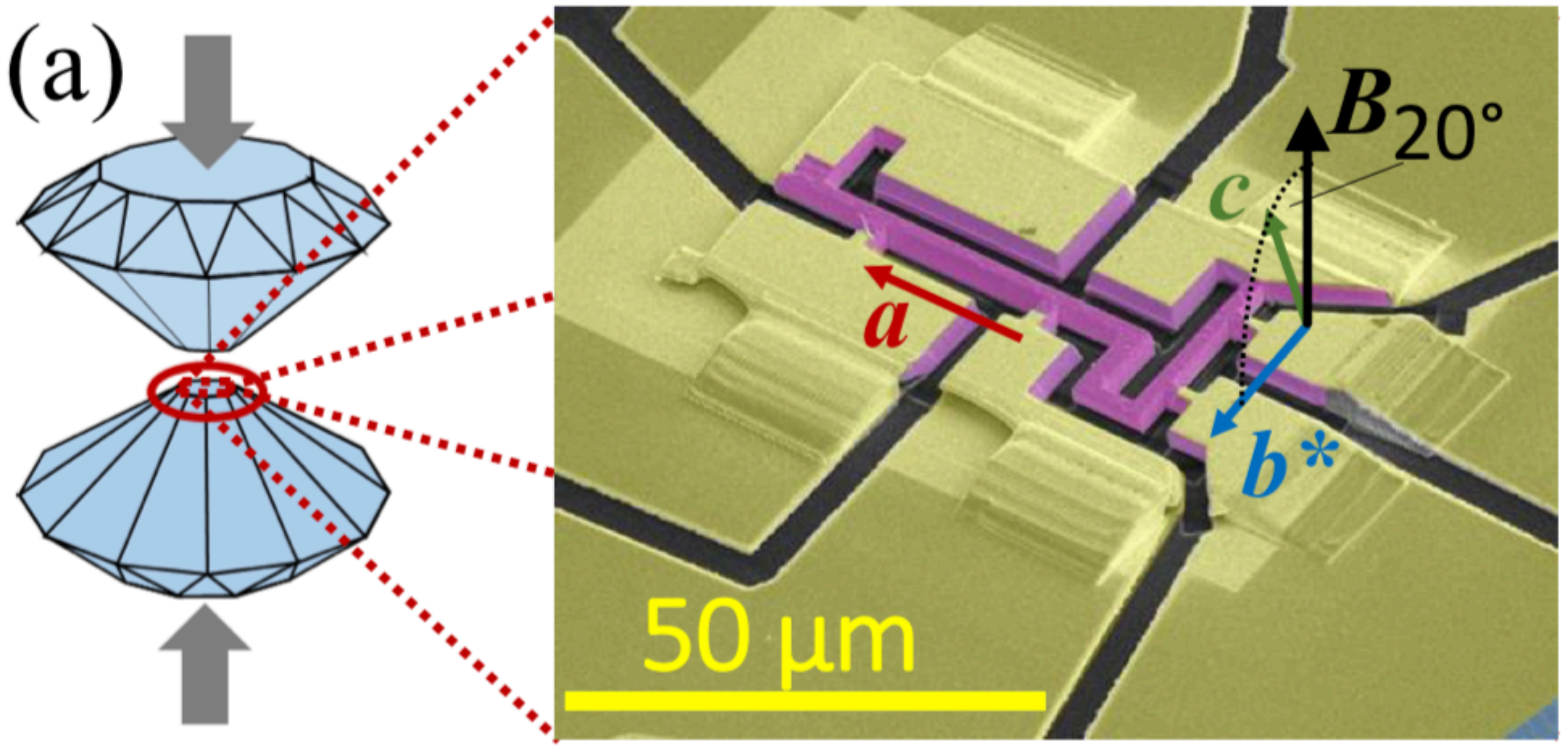
$$\mathcal{H}_{\text{CEF}} = \sum B_{20}O^0_{2,i} + B_{40}O^0_{4,i} + B_{44}O^4_{4,i}$$

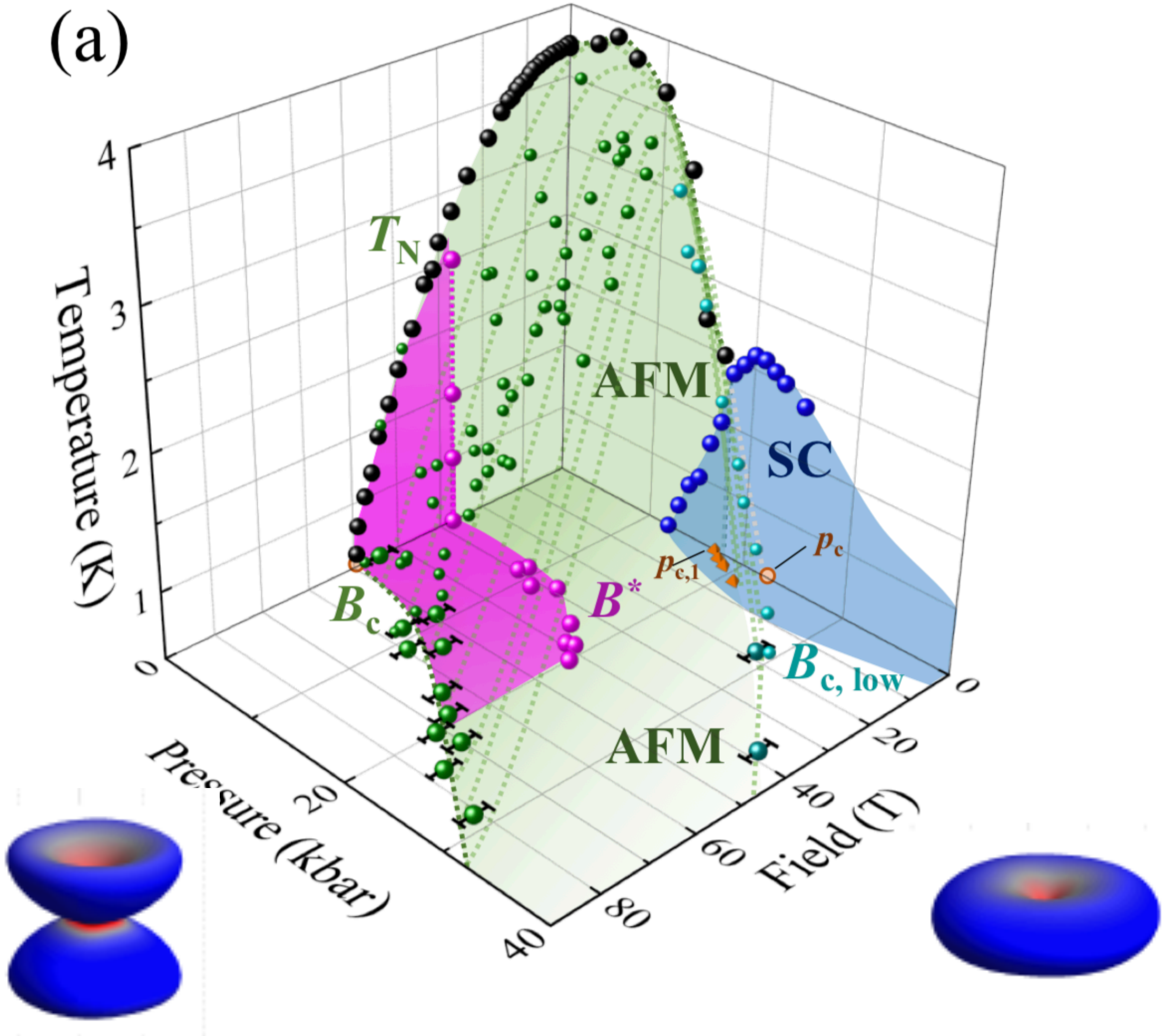


- Enhancement of the in-plane hybridization
- Similar to Sn-doped CeRhIn$_5$
  K. Chen *et al,* Phys. Rev. B. **97**, 045134 (2018)
- Intuitively related to the large Fermi surface above H*
- Nematic behavior is of electronic origin, but is driven by anisotropic hybridization between *4f* and conduction electrons
- In agreement with recent NMR measurements too!

G.G Lesseux, H. Sakai, … P. G. Pagliuso, and R. R. Urbano,
submitted to PNAS

Ground state evolution in field + pressure

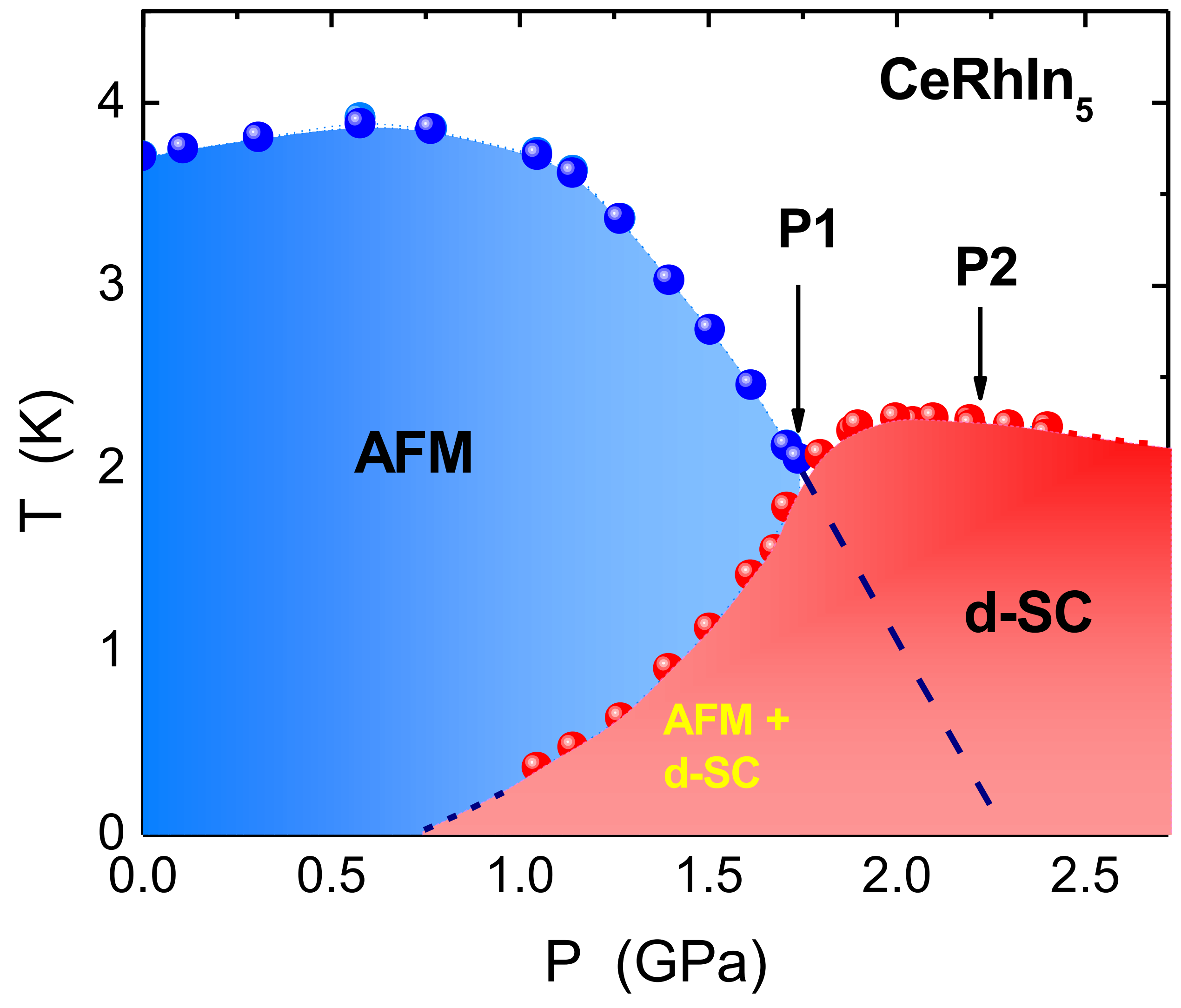


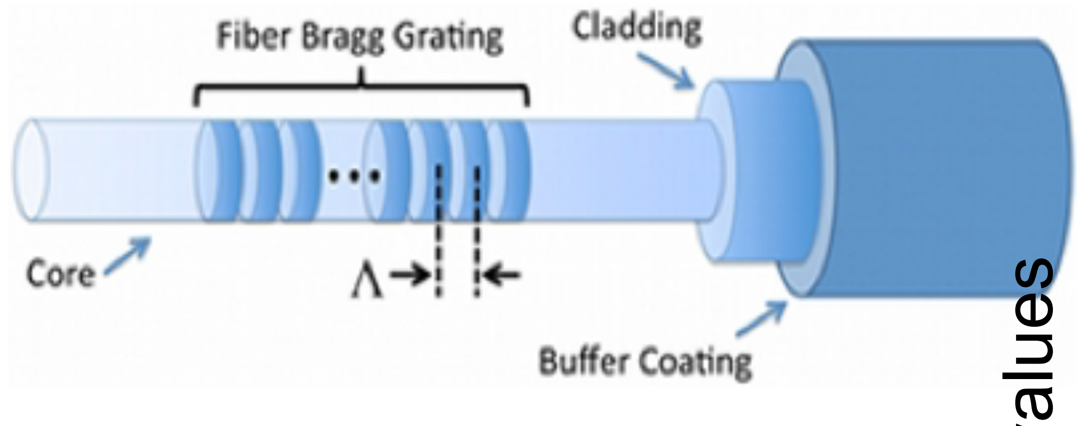


T. Helm et al, arXiv:1902.00970 (2019)

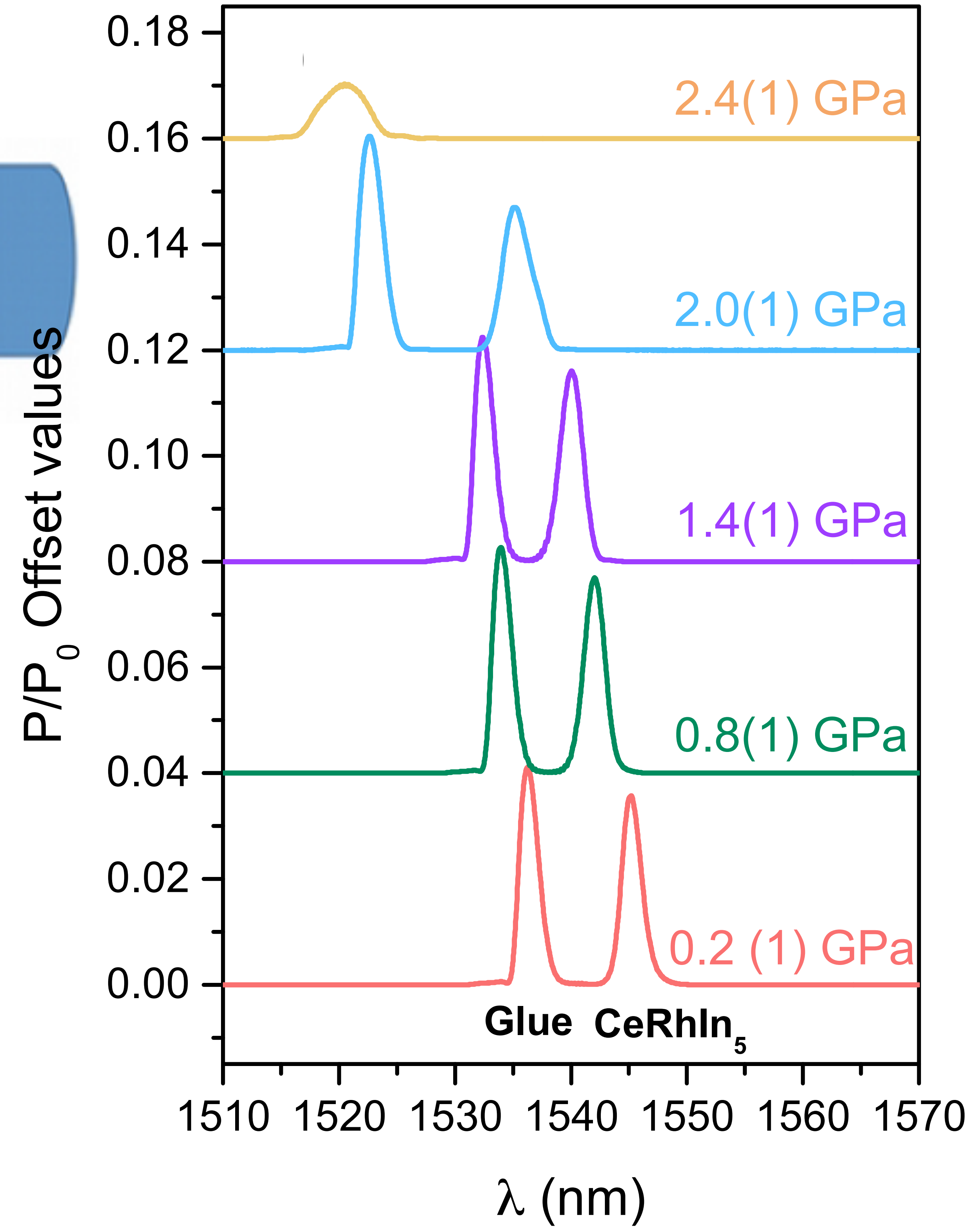
Q2: $CeRhIn_5$ at high pressures

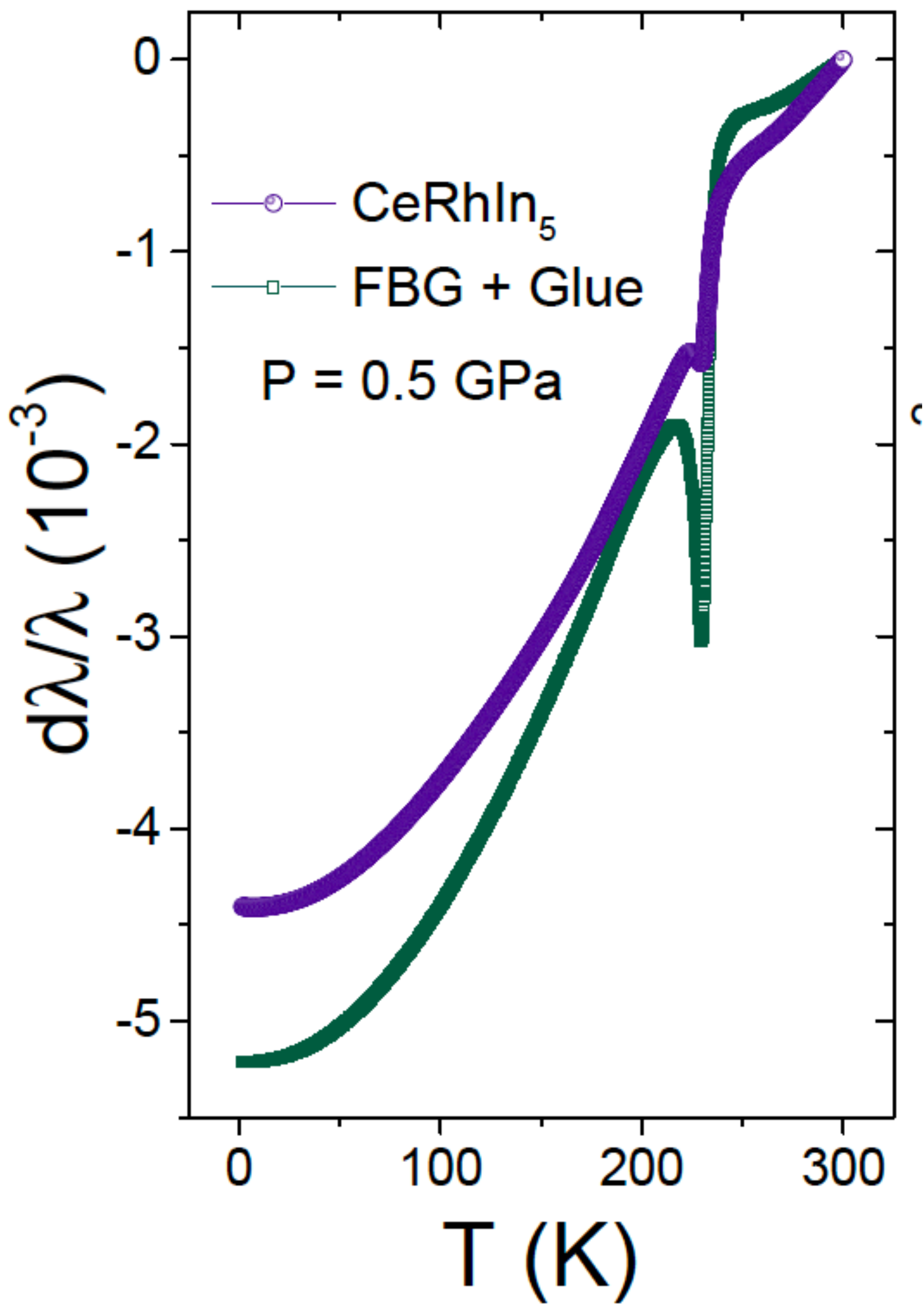
P. F. S. Rosa et al, Sensors **17**, 2543 (2017).

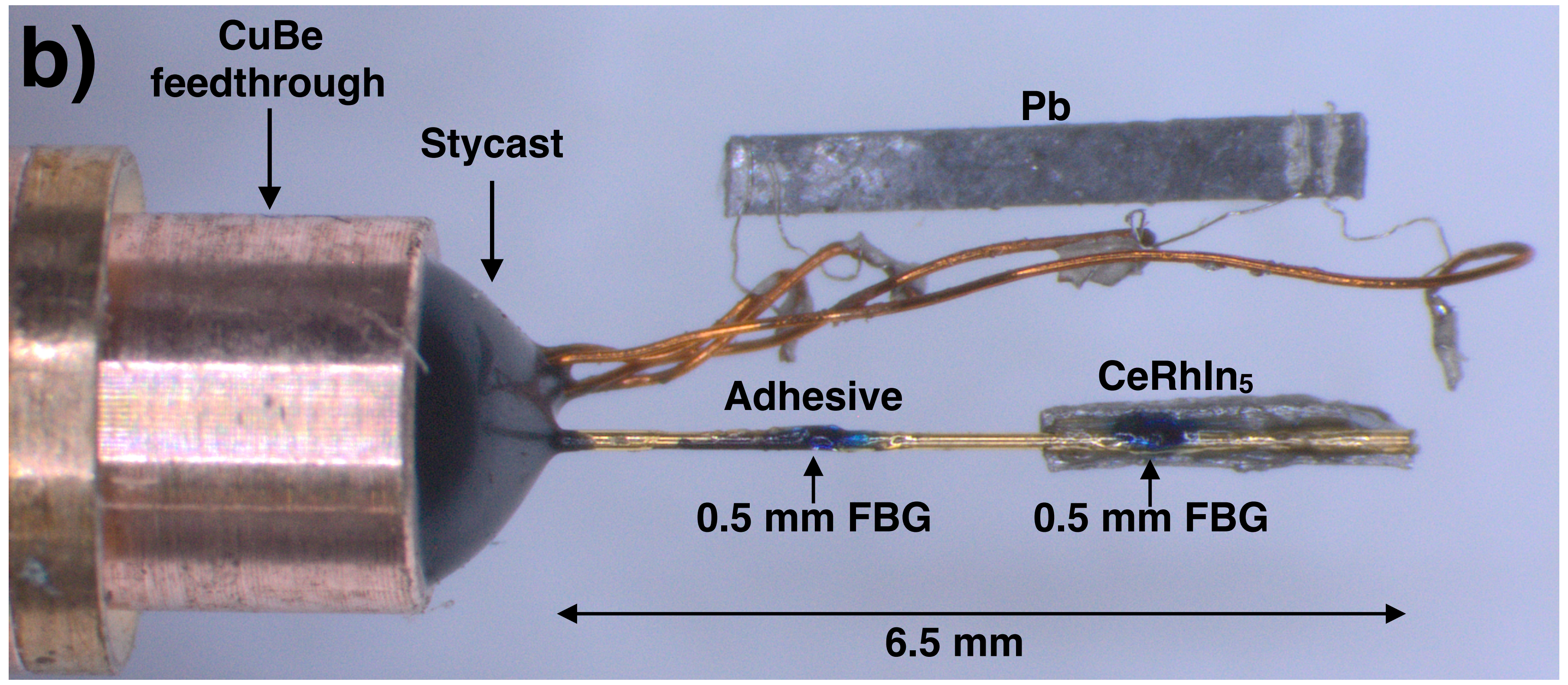




$$\lambda_B = 2n_{eff}\Lambda$$

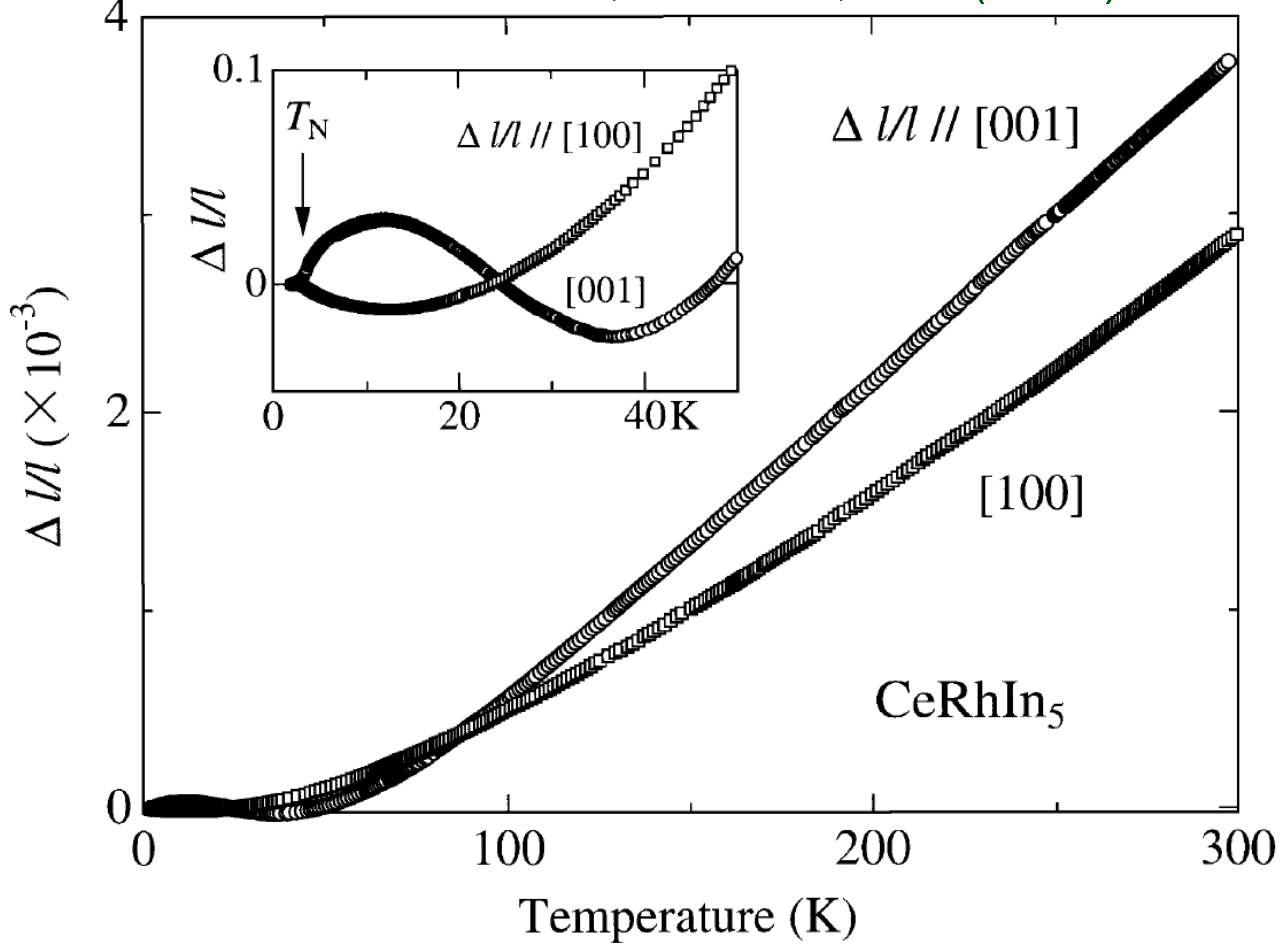


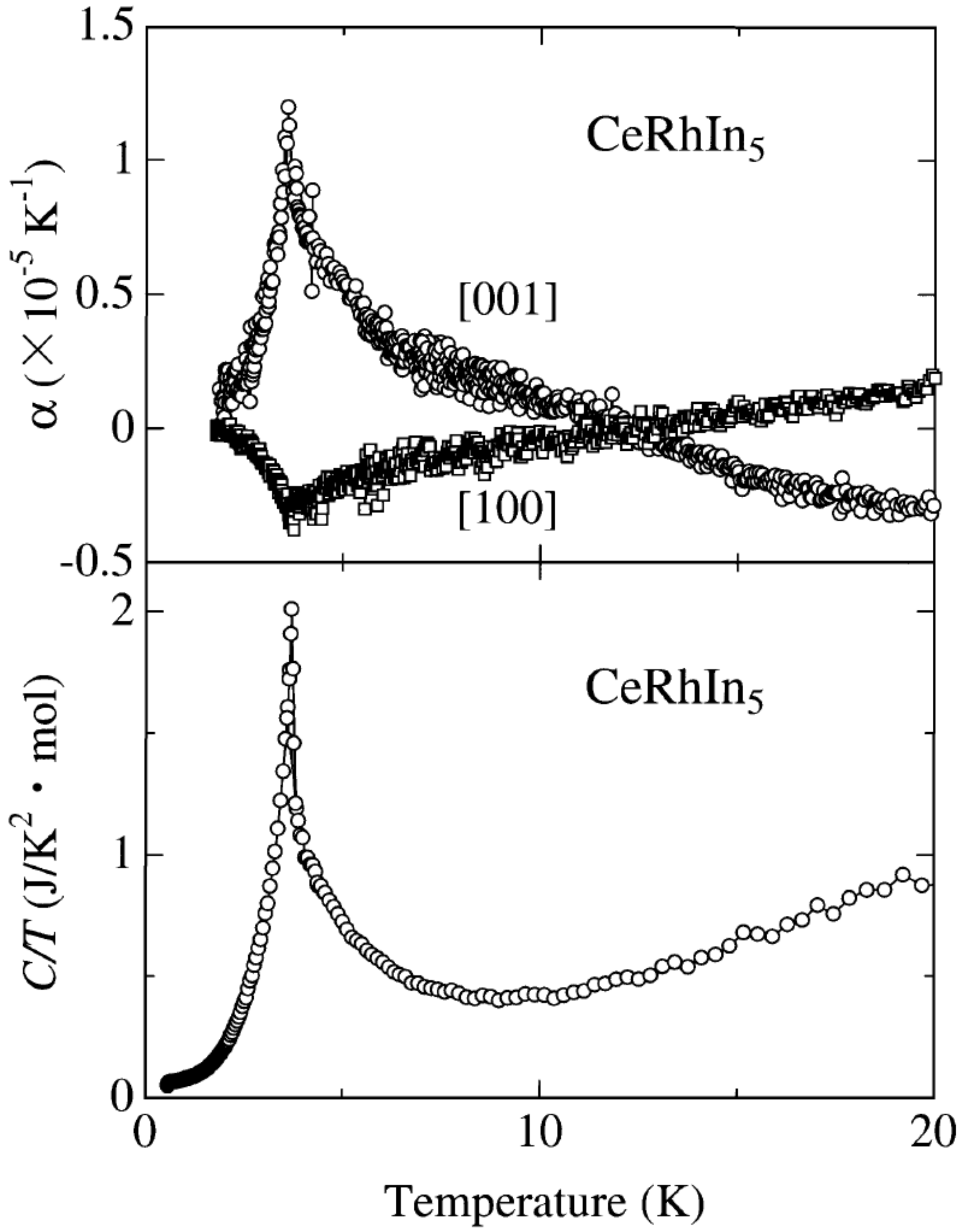


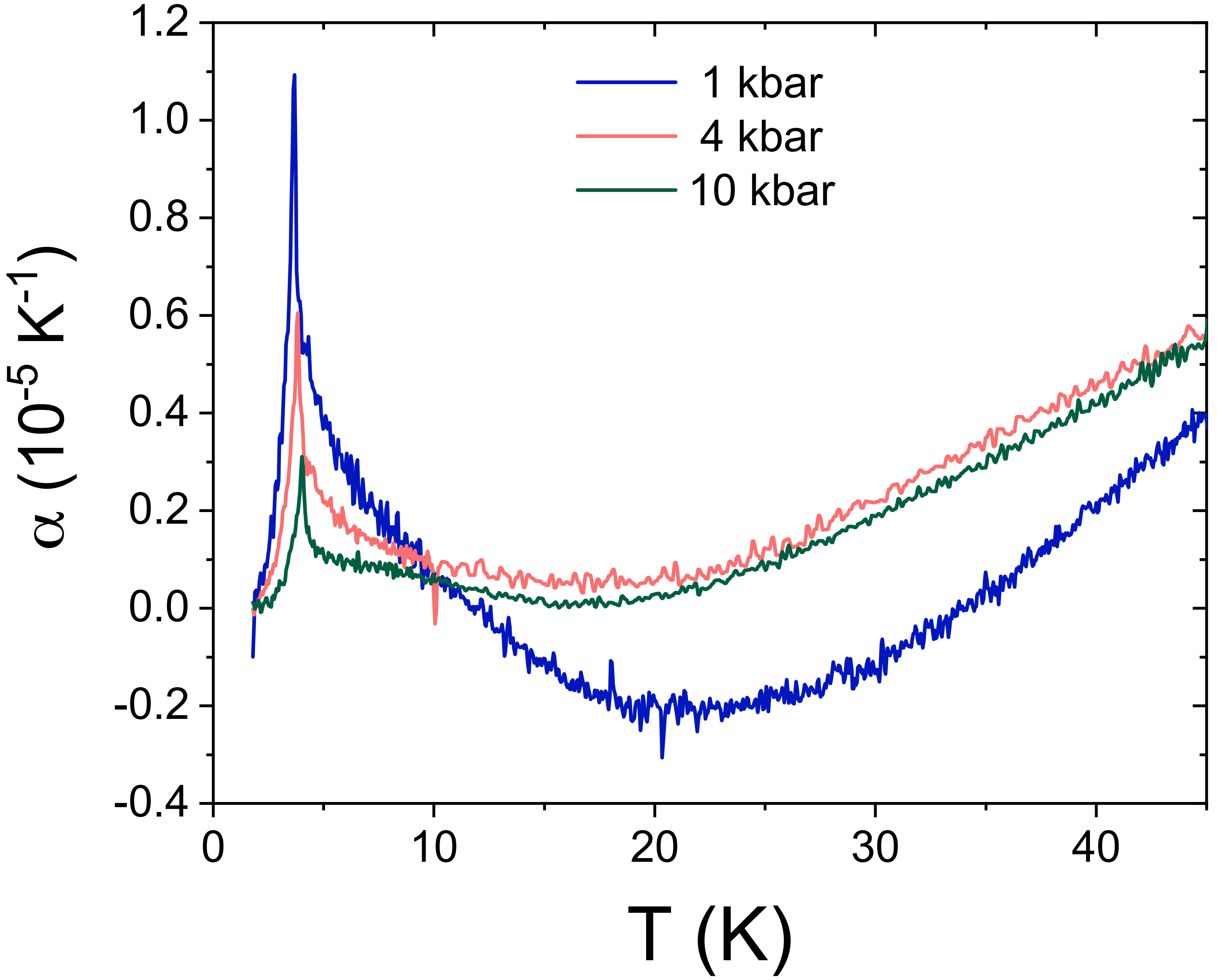


Q2: $CeRhIn_5$ at high pressures

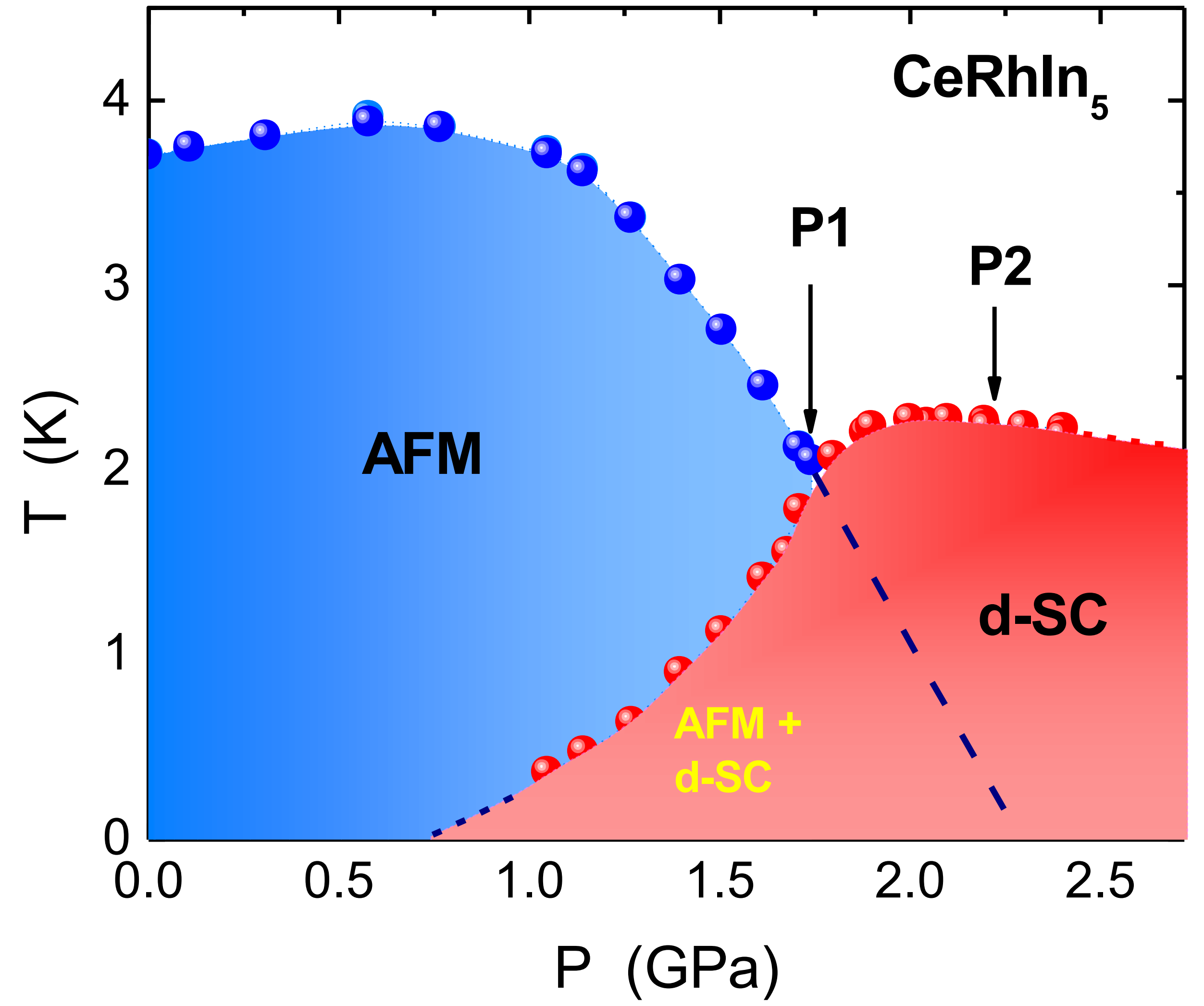
Takeuchi et al., JPSJ **70**, 877 (2000).

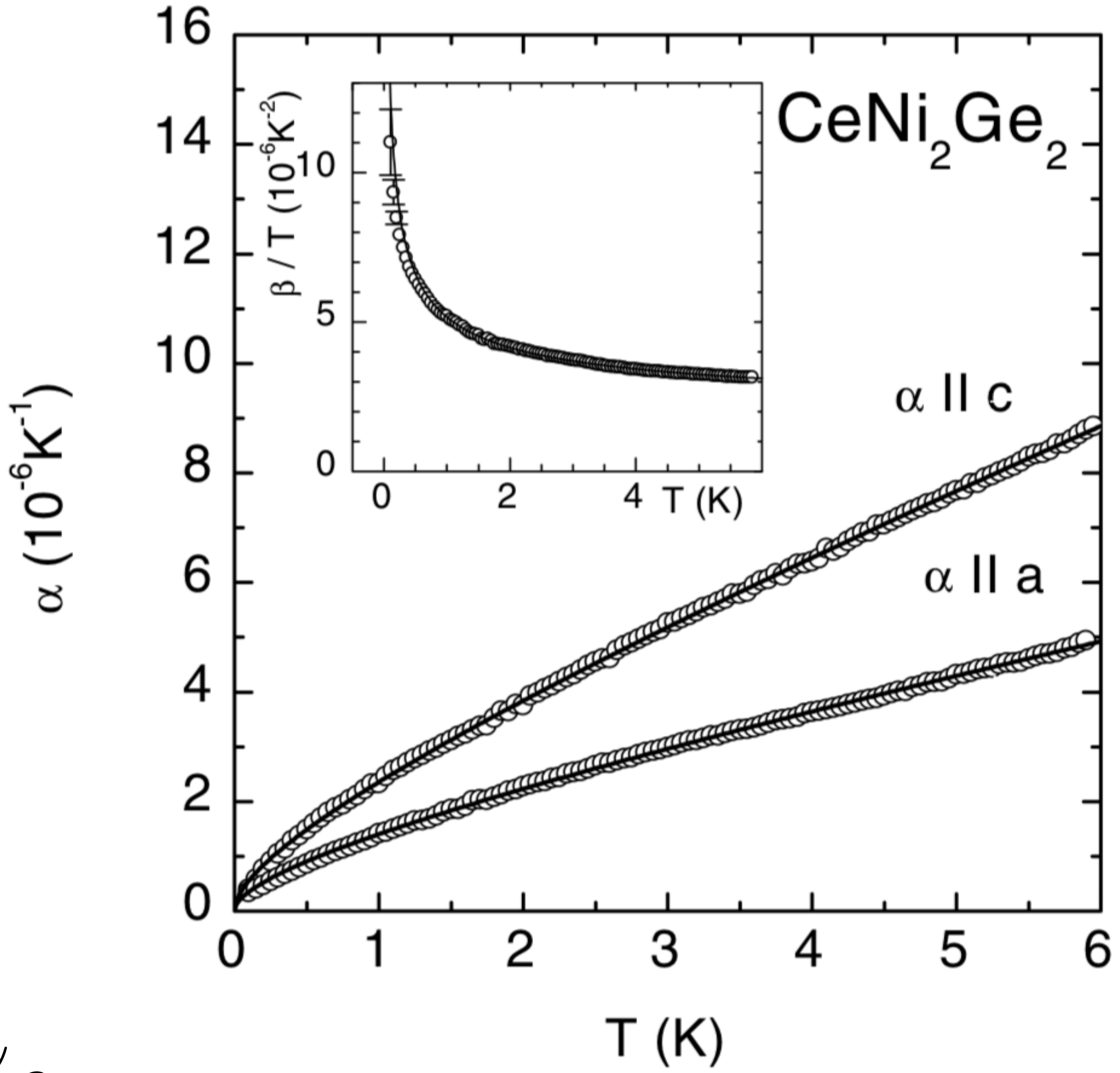






$$\frac{dT_N}{dP} = V_m T_N \frac{\Delta\beta}{\Delta C_p}, \quad \Delta\beta = 2\Delta\alpha_a + \Delta\alpha_c$$

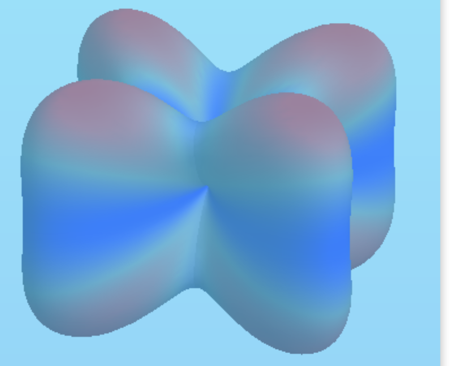




Kuchler et al., PRL **91**, 66405 (2003).

Take-home messages

Crystal-field wavefunctions (local physics) can tell you a lot about a correlated system



Nematicity in *f*-based materials is driven by magnetic fluctuations, similar to iron-based superconductors and cuprates

Los Alamos NATIONAL LABORATORY EST. 1943

The Strongly Correlated Electron Team is (always) looking for postdocs!

pfsrosa@lanl.gov

Thank you for your attention!