Scale-invariant magnetic anisotropy in $RuCl_3$

Kimberly Modic
Institute of Science and Technology Austria

IST AUSTRIA
Institute of Science and Technology

In collaboration with...
Maja Bachmann
Marcus Schmidt
Philip Moll
Brad Ramshaw
Ross McDonald
Arkady Shekhter

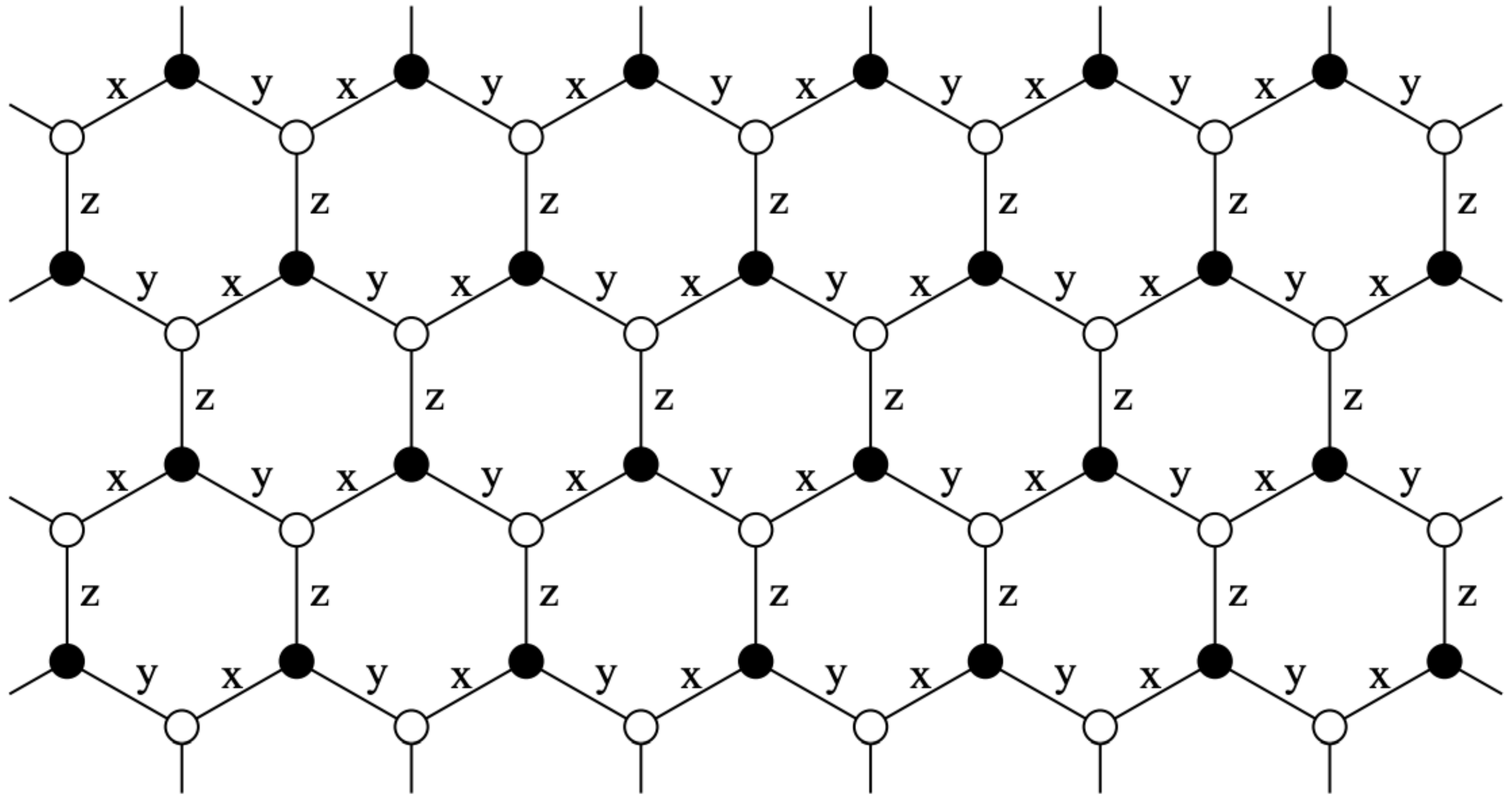
MAX-PLANCK-GESELLSCHAFT

NATIONAL HIGH MAGNETIC FIELD LABORATORY

CORNELL UNIVERSITY FOUNDED A.D. 1865

Mainz, 2019

Kitaev's model - anisotropic exchange interactions on a honeycomb lattice



$$H = -J_x \sum_{x\text{-links}} \sigma_j^x \sigma_k^x - J_y \sum_{y\text{-links}} \sigma_j^y \sigma_k^y - J_z \sum_{z\text{-links}} \sigma_j^z \sigma_k^z$$

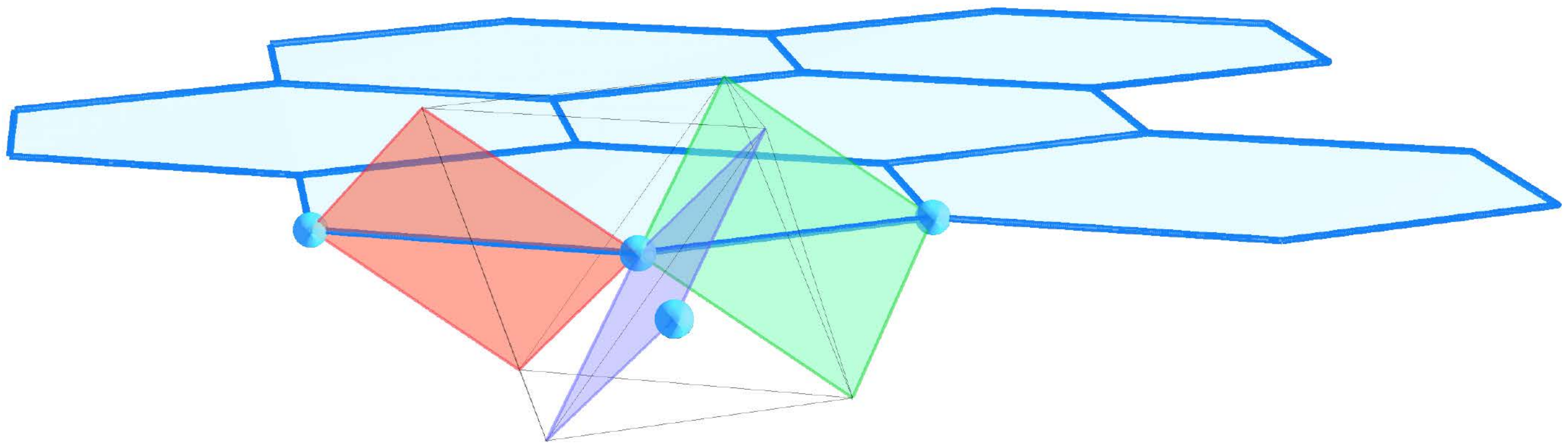
➡Spin liquid ground state!

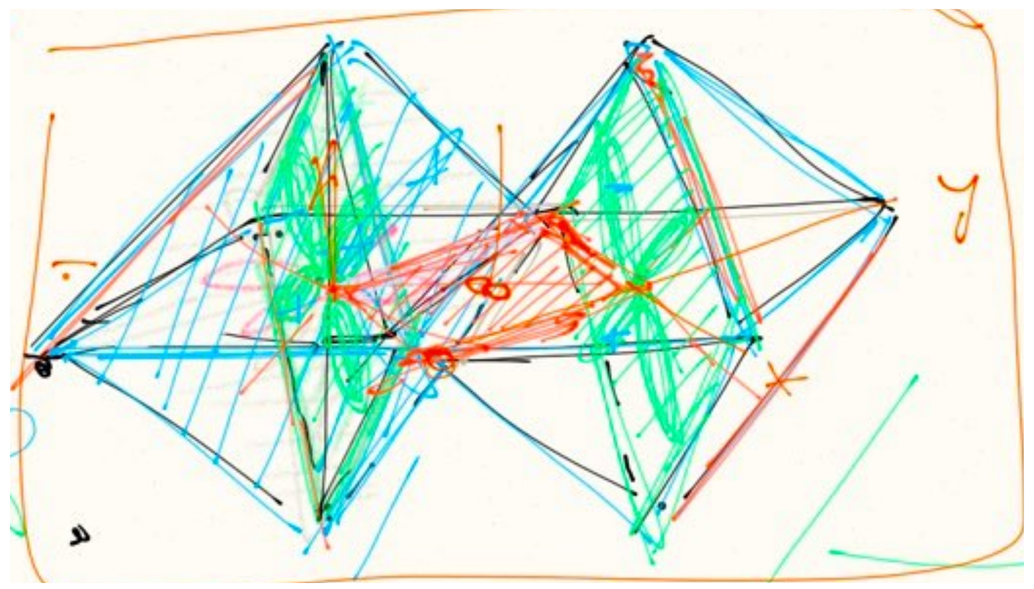
➡High-energy states are pulled down to zero energy by strong correlations

➡Real materials that emulate this model exist

Kitaev, A. *Ann. Phys.* (2006)

Realization of Kitaev's model

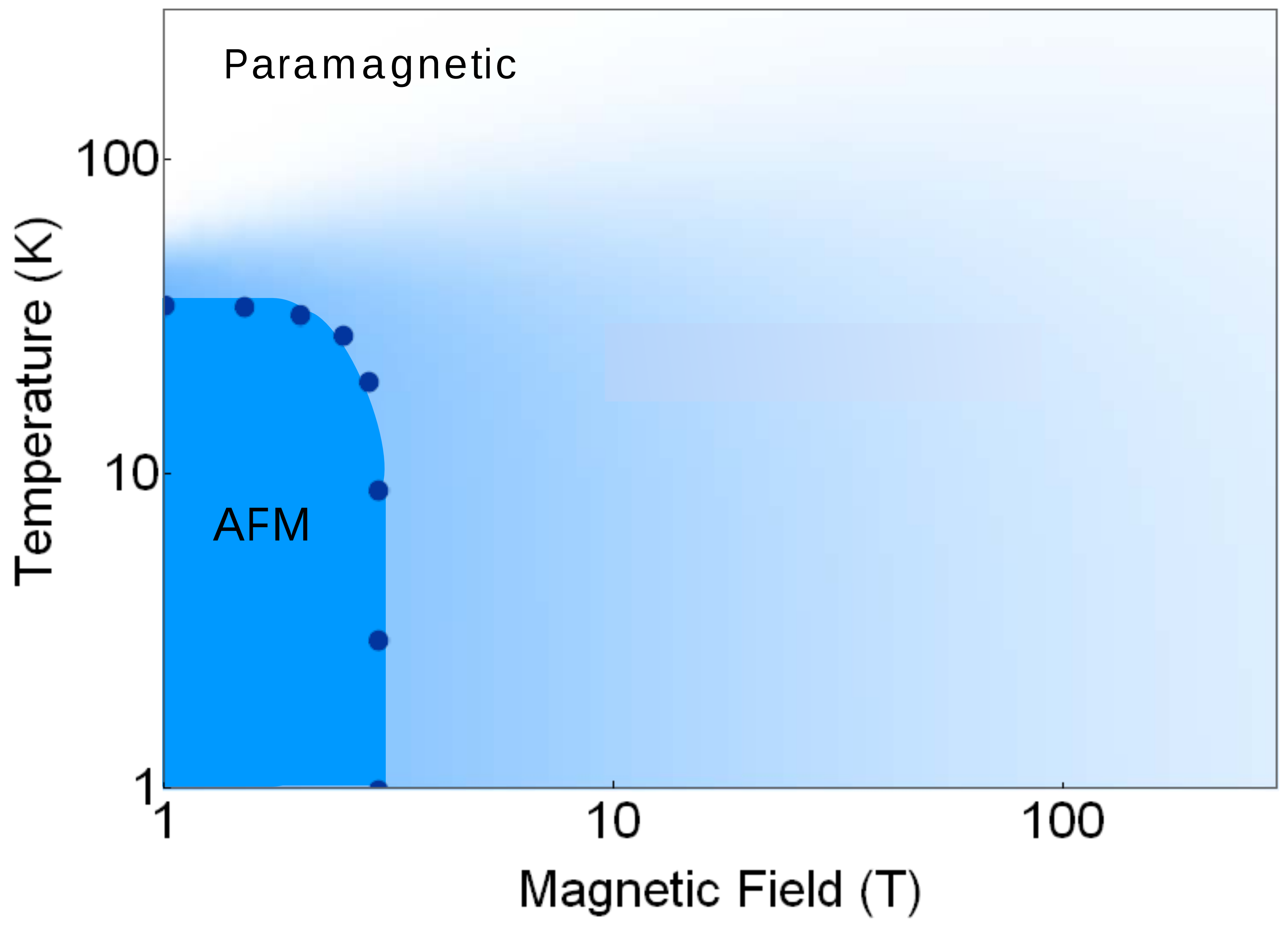




- ➡The honeycomb iridates (Li_2IrO_3 and Na_2IrO_3) and $RuCl_3$ are examples
- ➡Exchange is mediated by the surrounding oxygen or chlorine
- ➡Undistorted and edge-shared octahedral environment is key

Jackeli, G. *Phys. Rev. Lett.* (2009)
Modic, K.A. *Nat. Comm.* (2014)

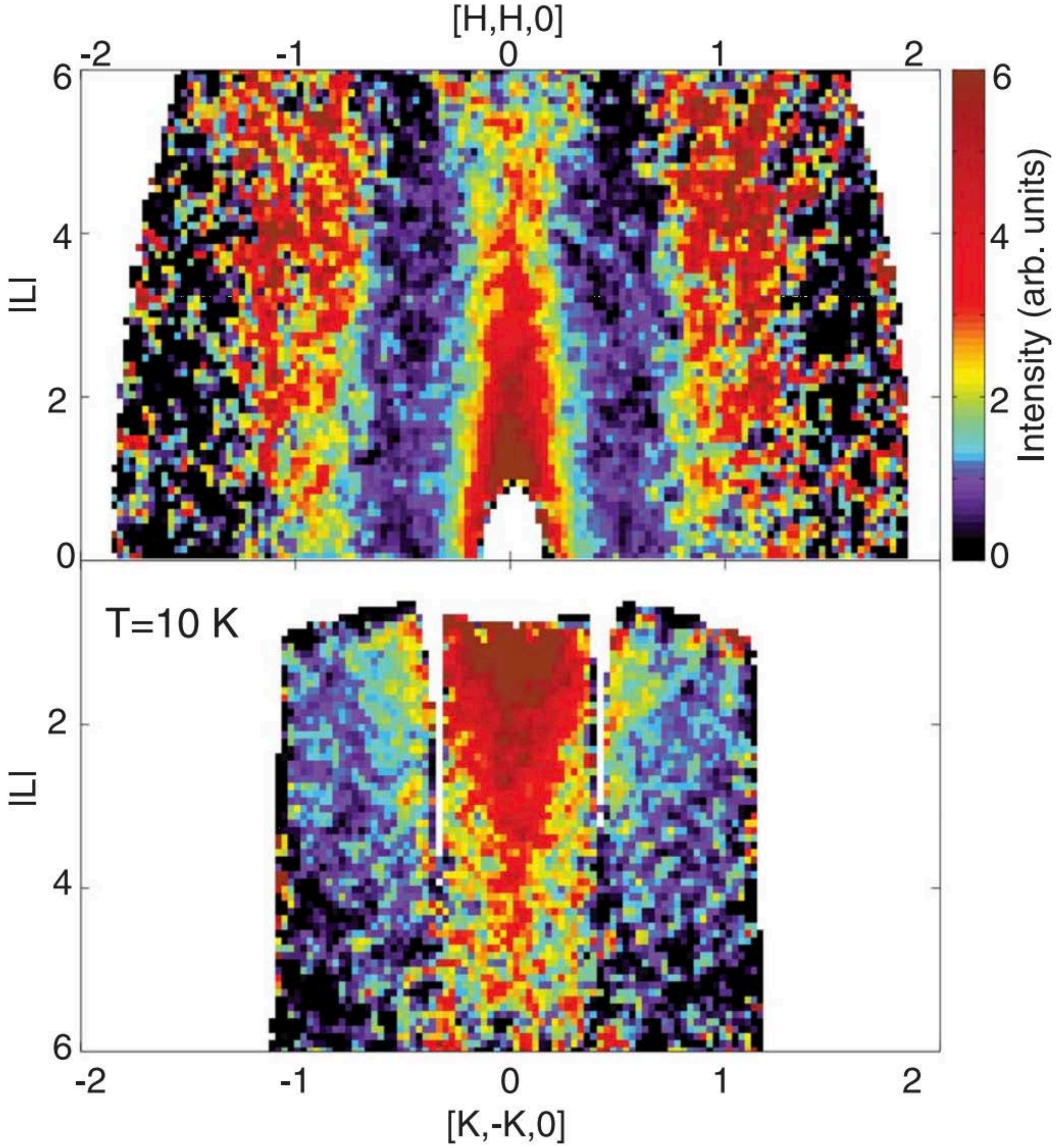
Is it a spin liquid?

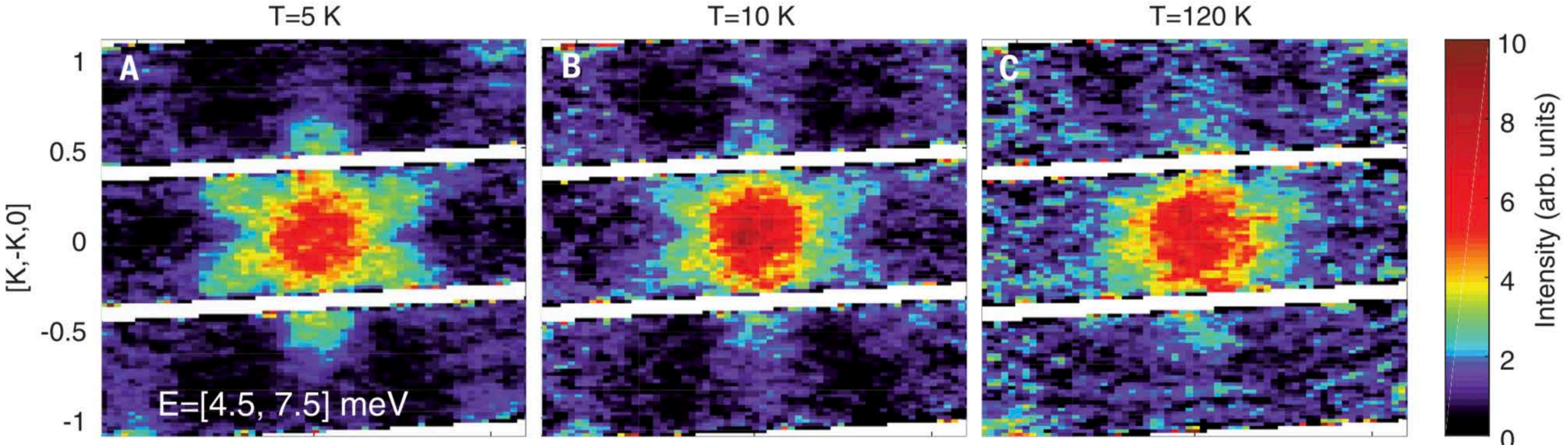


➡Unconventional antiferromagnetic ground state
➡Exchange is spin-anisotropic (Kitaev-like)

Modic, K.A. *Nat. Comm.* (2017)
Chun, Sae Hwan, *Nat. Phys.* (2015)

Non-spin-wave dynamics

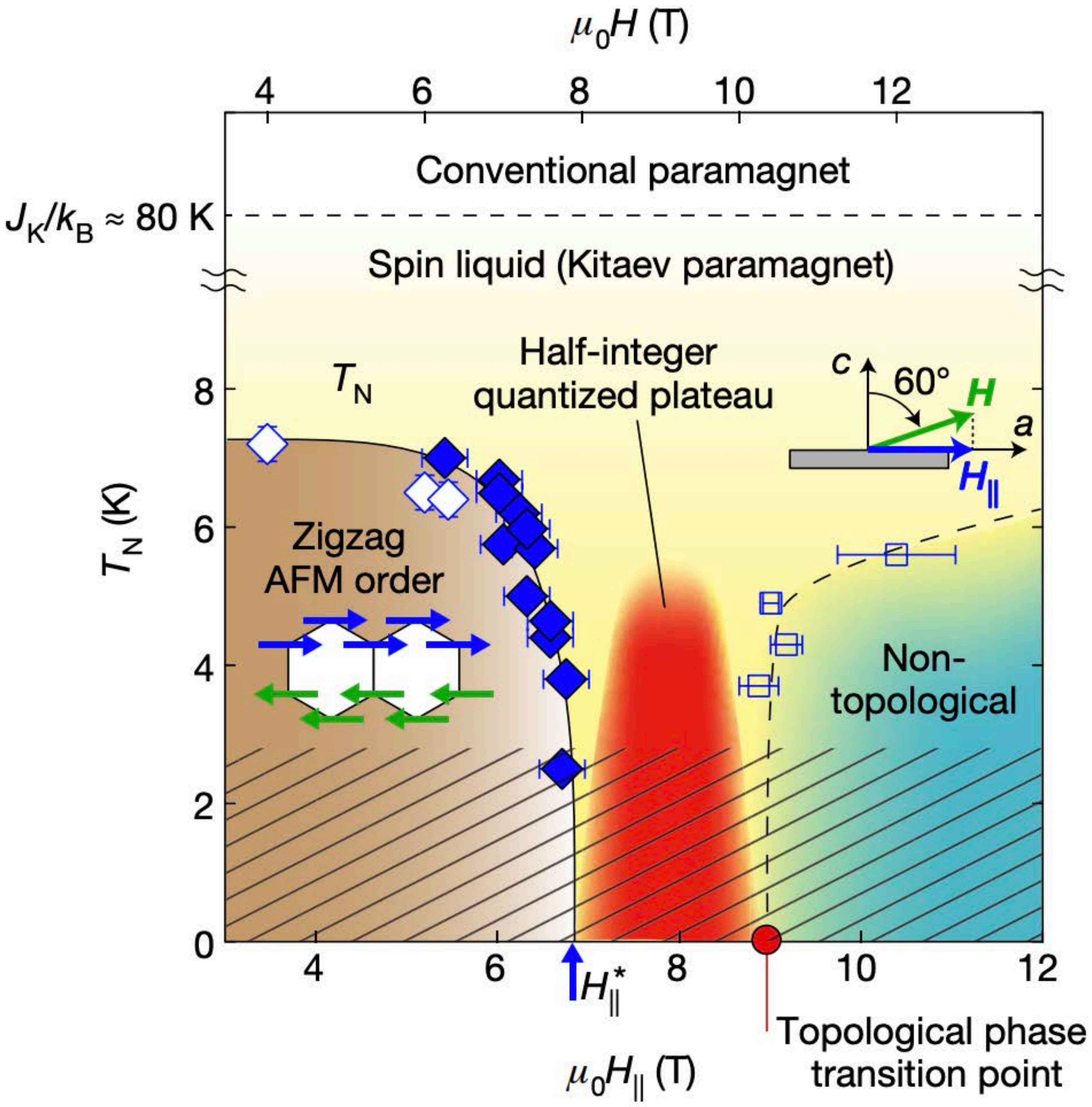




➡Continuum of excitations persists to at least 120K

Banerjee, A. *Science* (2017)

The spectrum is fractionalized!



➡Half-integer quantization from chiral edge currents

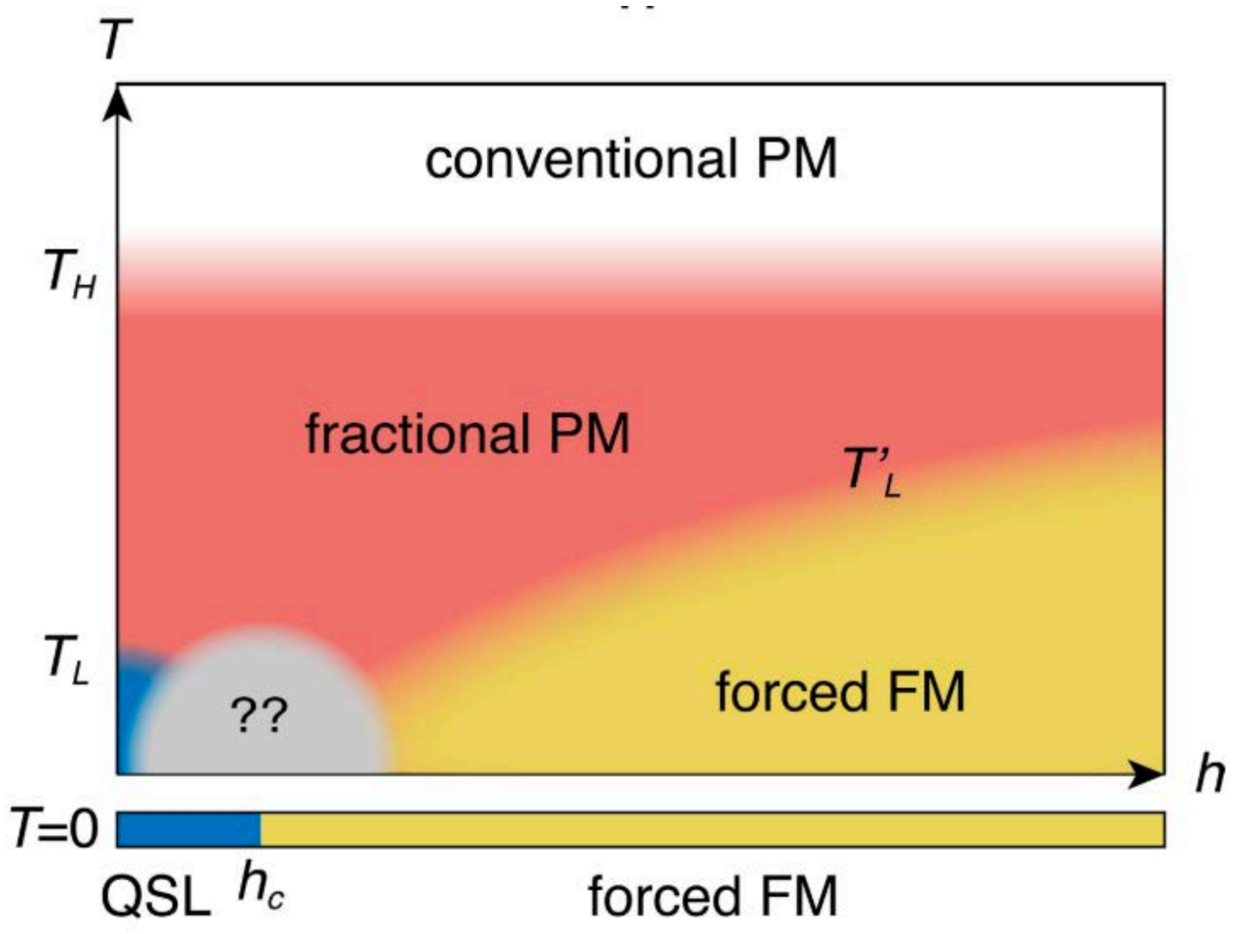
➡Spin dissociates into Majorana fermions and fluxes

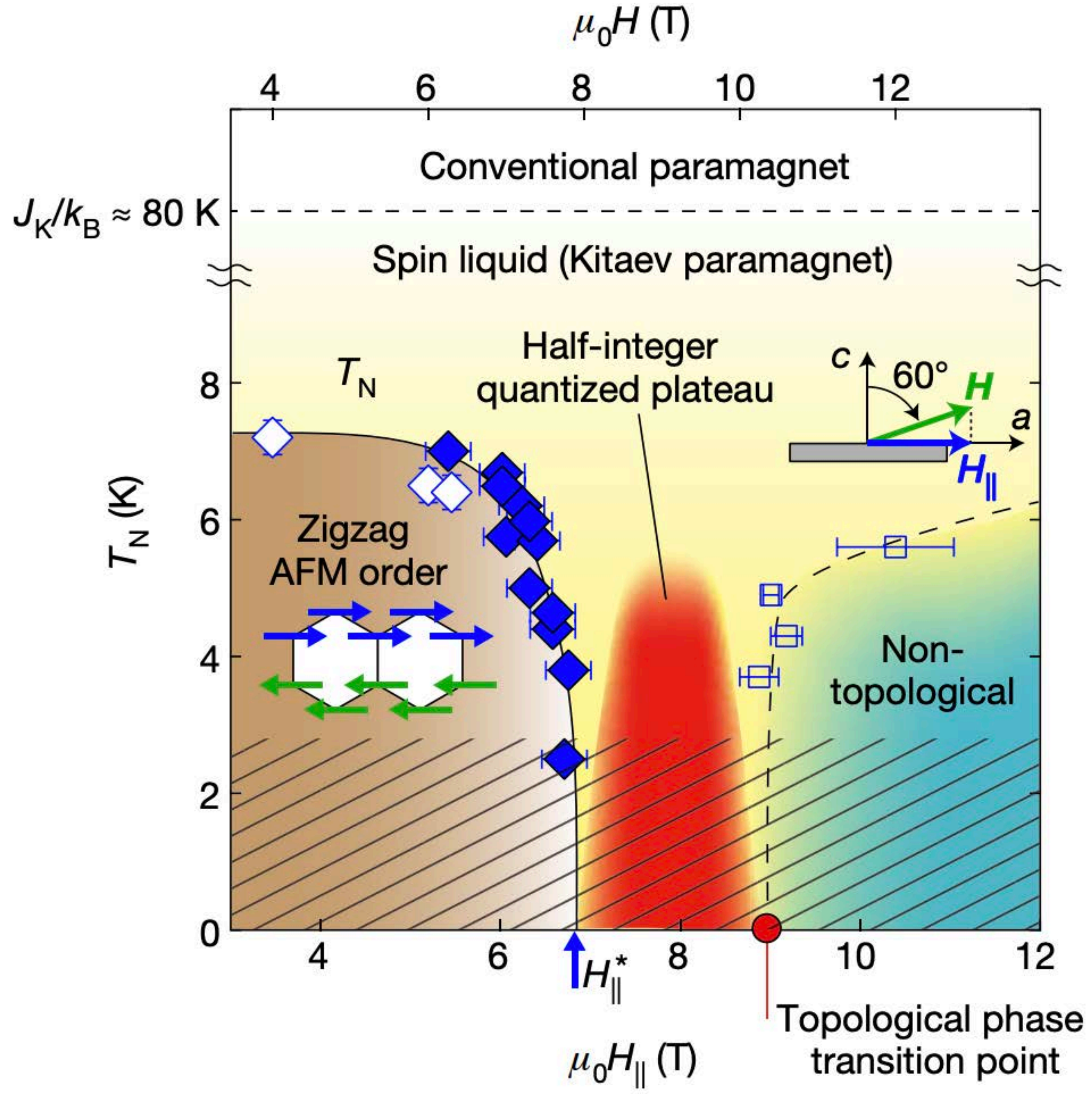
Kasahara, Y. *Nature* (2018)

Kasahara, Y. *Nature* (2018)
Yoshitake, J. *ArXiv:1907.07299v1* (2019)

There are still a lot of questions to be answered…

➡What other exchange interactions are at play?
➡Reliable theory for Kitaev model in a magnetic field at finite temperature?
➡Second phase transition?
➡High quality single crystals are small - what can we do?
➡Are there (what are the) thermodynamic signatures of a spin liquid??

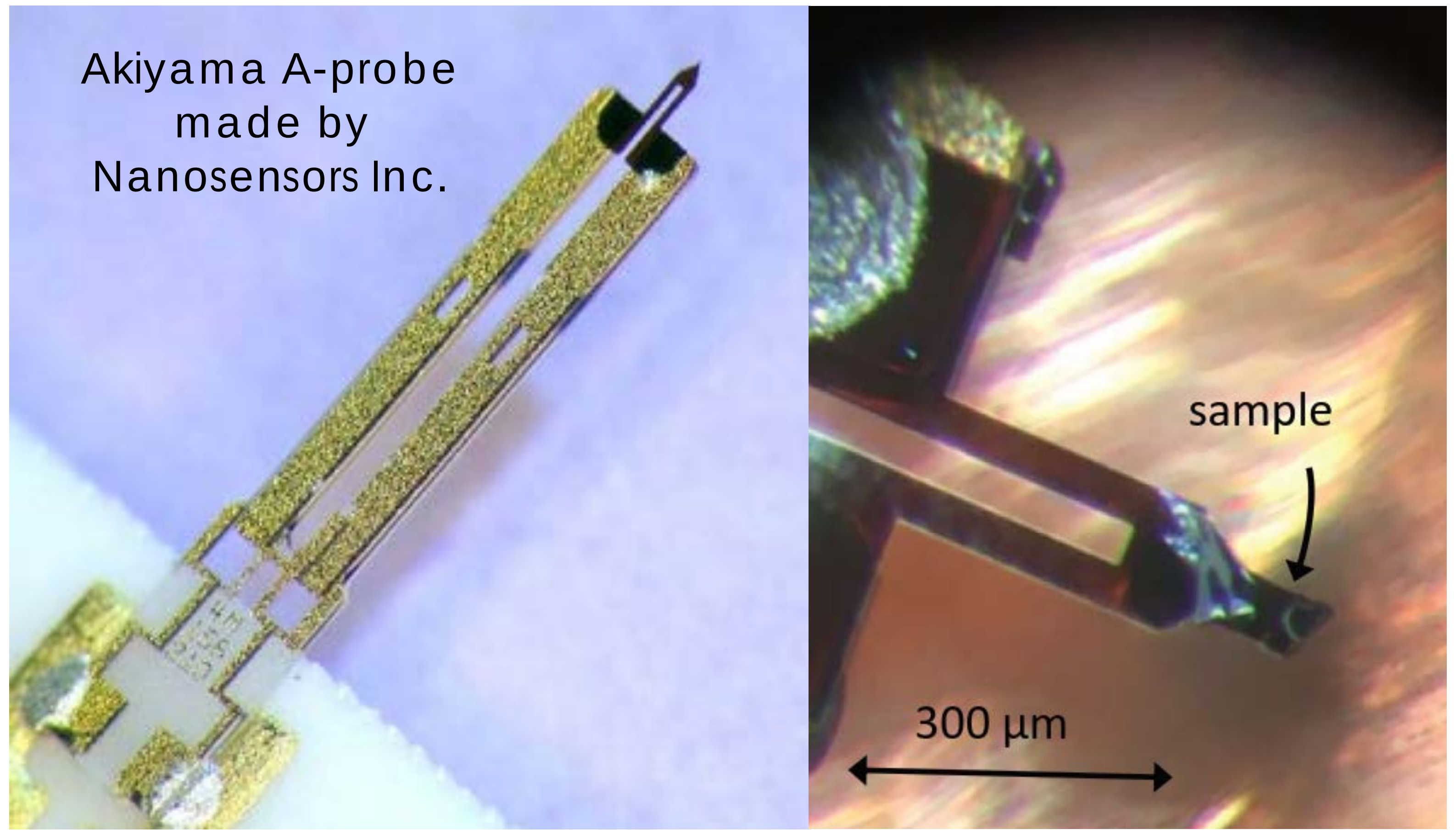


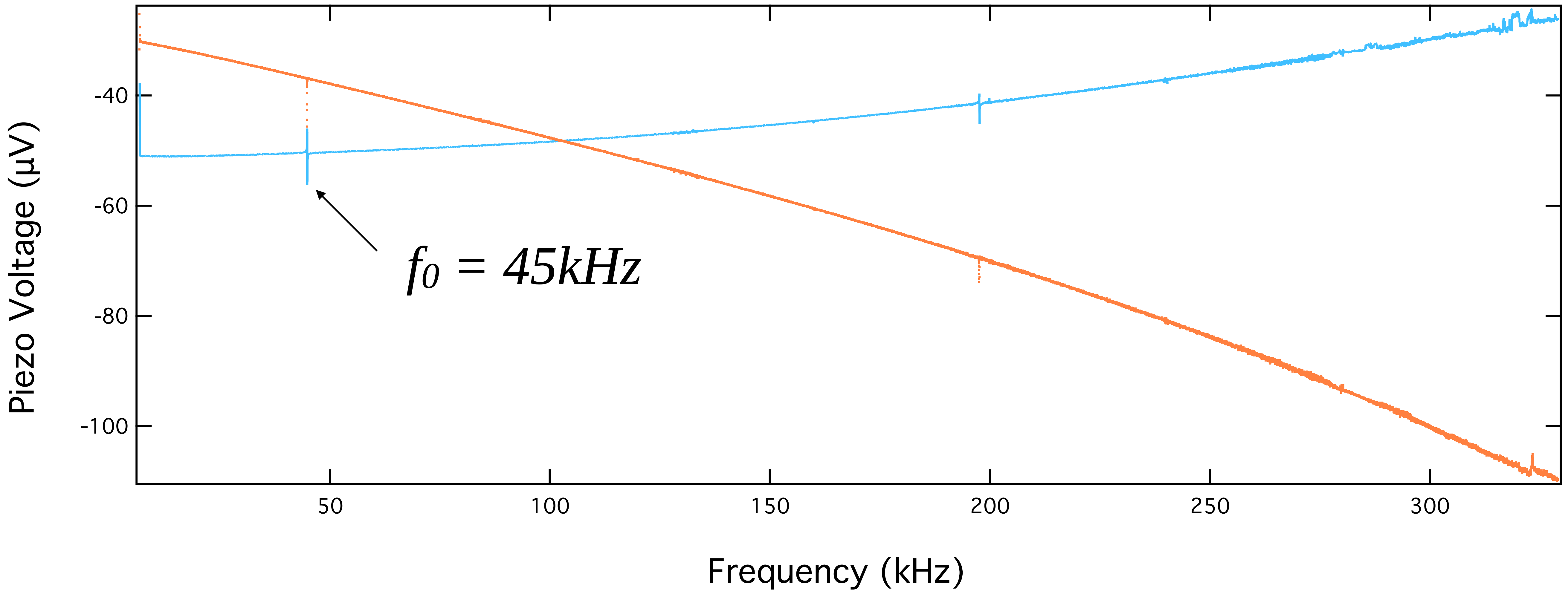


Resonant torsion magnetometry

Bare quartz tuning forks:
$f_0 = 32{,}768 = 2^{15}$ Hz

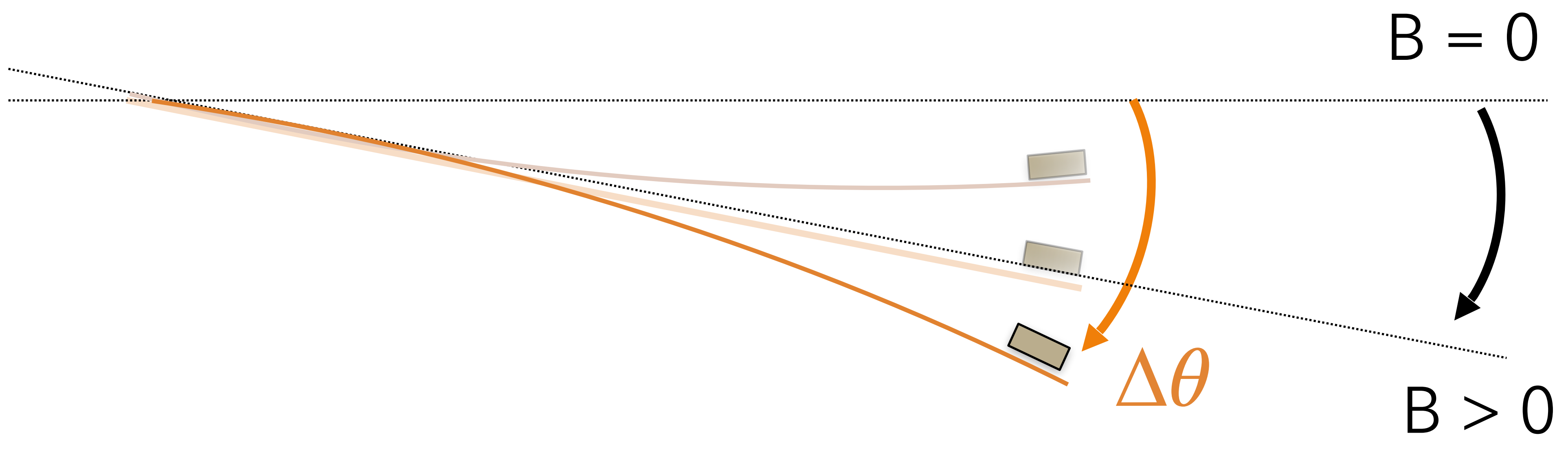
With silicon cantilever
and sample attached:
$f_0 \sim 40\text{-}50$ kHz





Modic, K.A. *Nat. Comm.* (2018)

The magnetotropic coefficient (k)



$$\theta_\tau = \frac{\tau}{K + k}$$

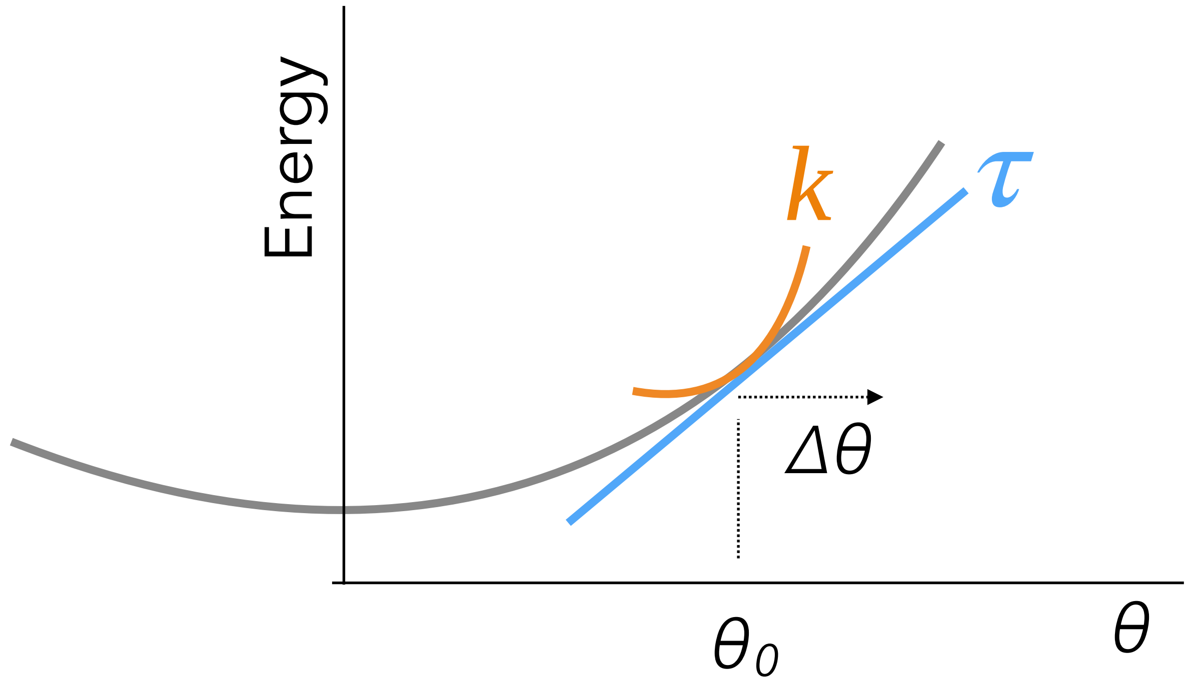
$$E = \frac{I}{2}\left(\frac{d\Delta\theta}{dt}\right)^2 + \frac{1}{2}\left[K + \frac{d^2F(\theta)}{d\theta^2}\right](\Delta\theta)^2 + \frac{dF(\theta)}{d\theta}\Delta\theta$$

magnetic torque

elastic energy of lever

curvature of the sample's energy
(magnetotropic coefficient)

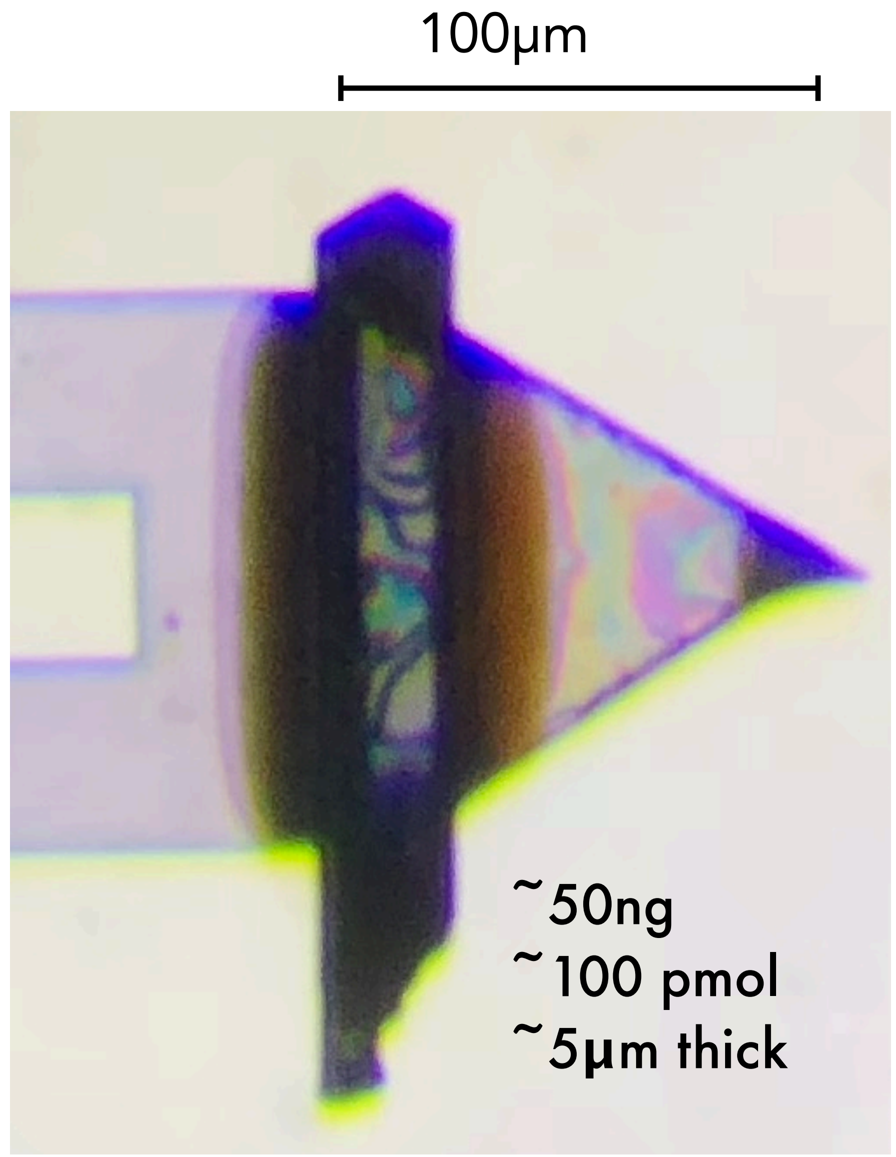
- ➡Greek word tropic = "to turn"
- ➡Thermodynamic coefficient: $\partial^2F/\partial\ldots^2$
- ➡For small frequency shifts: $\frac{\Delta\omega}{\omega_o} \approx \frac{k}{2K}$



Modic, K.A. *Nat. Comm.* (2018)

Unraveling spin-liquid physics in $RuCl_3$ - why the magnetotropic coefficient?

- ➡Detects magnetic anisotropy
- ➡Sharp jump at phase boundaries
- ➡Sensitively detect frequency changes, even in high magnetic fields
- ➡Measure small crystals!

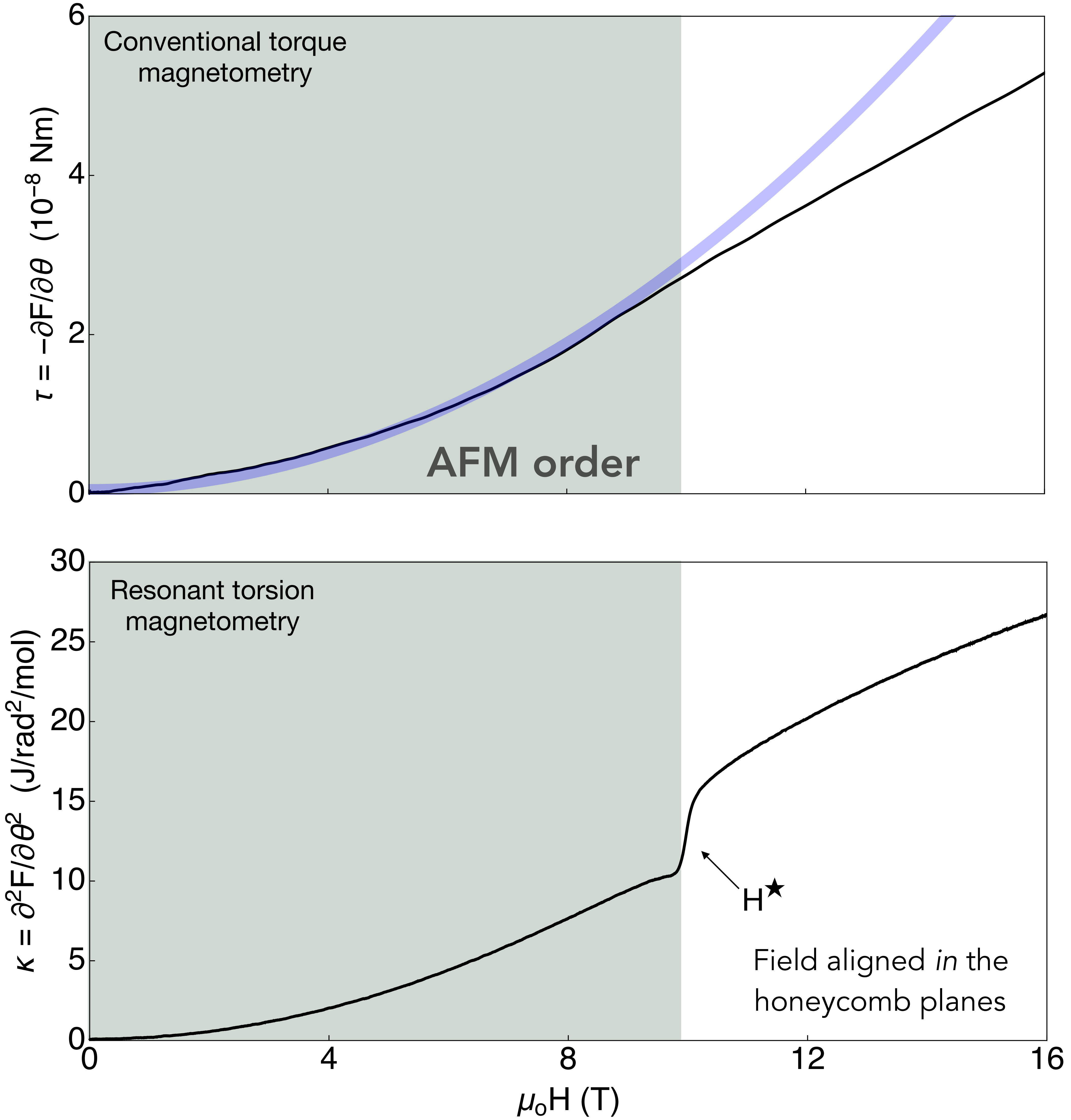


Ehrenfest relation:

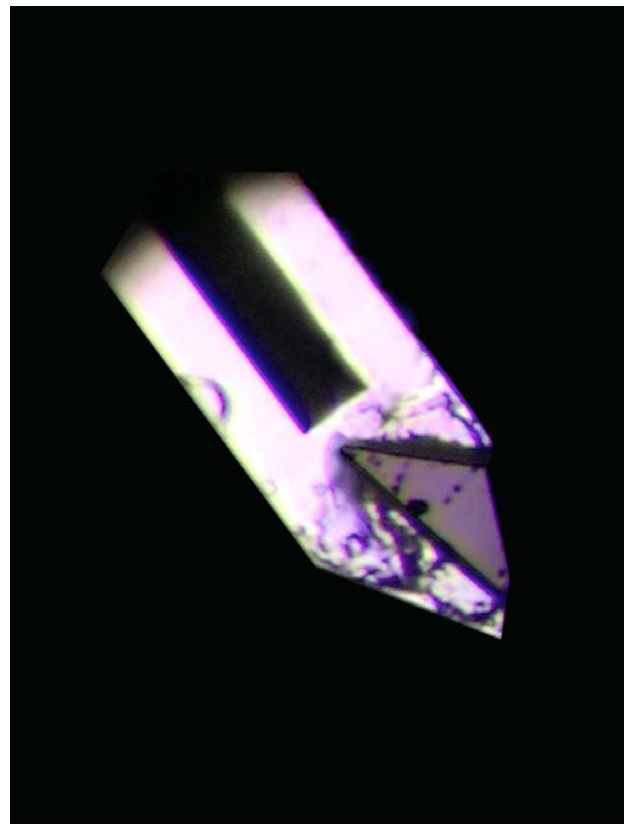
$$\Delta k = -\frac{\Delta C}{T_C}(\partial T_C/\partial\theta)^2$$

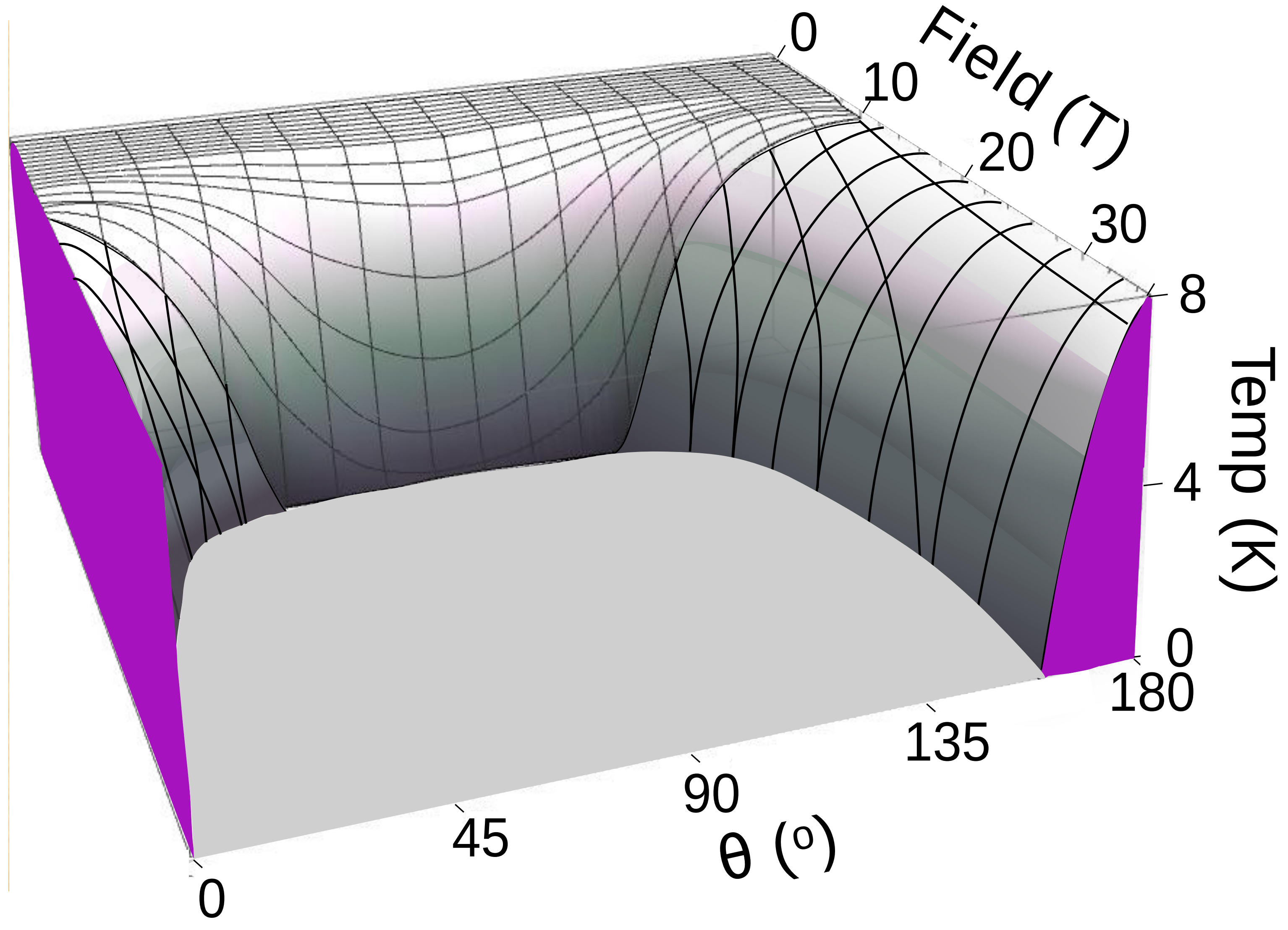
Modic, K.A. *Nat. Comm.* (2018)

Modic, K.A. *arXiv:1901.09245* (2019)

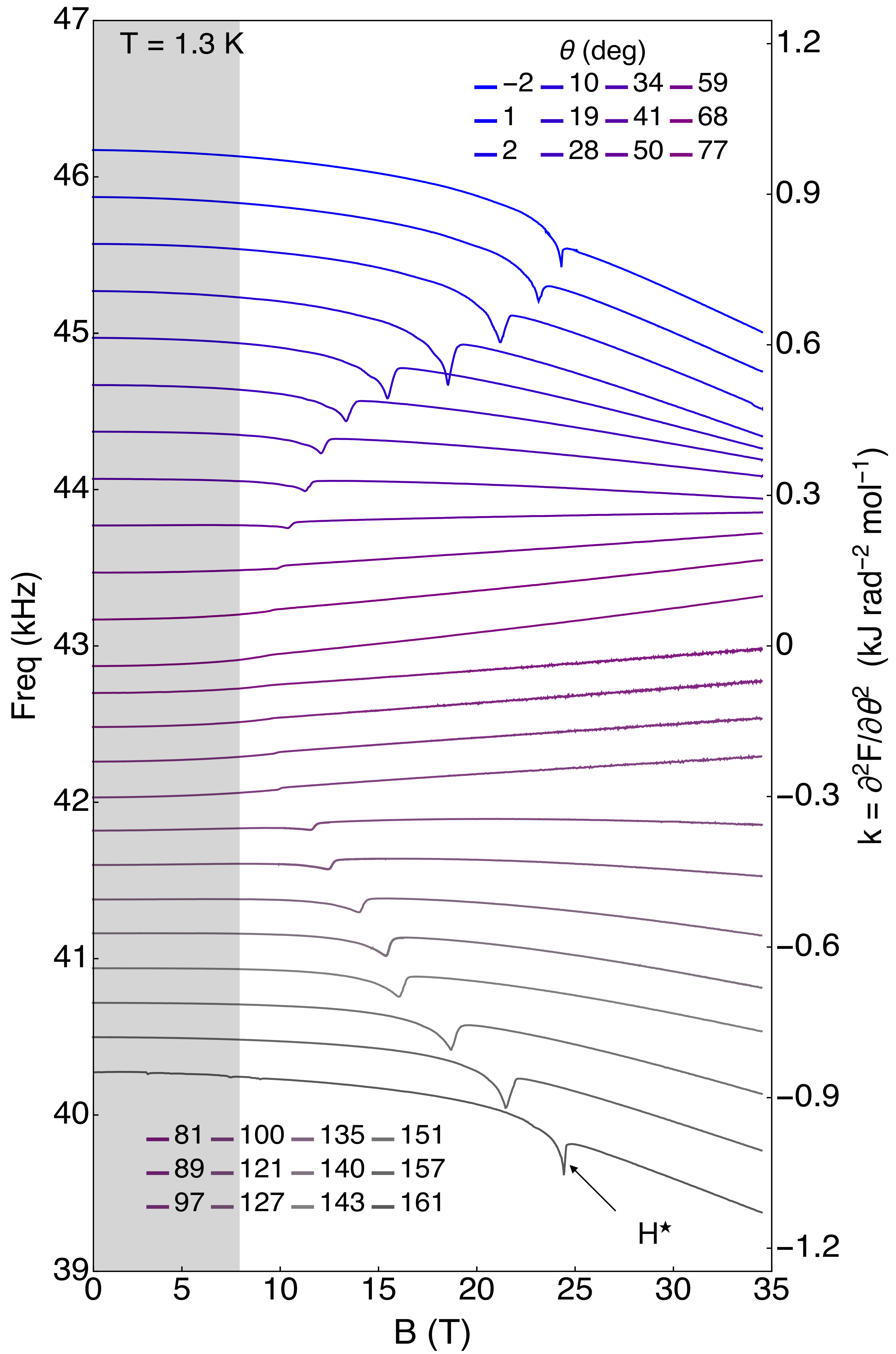


Anisotropic AFM phase boundary

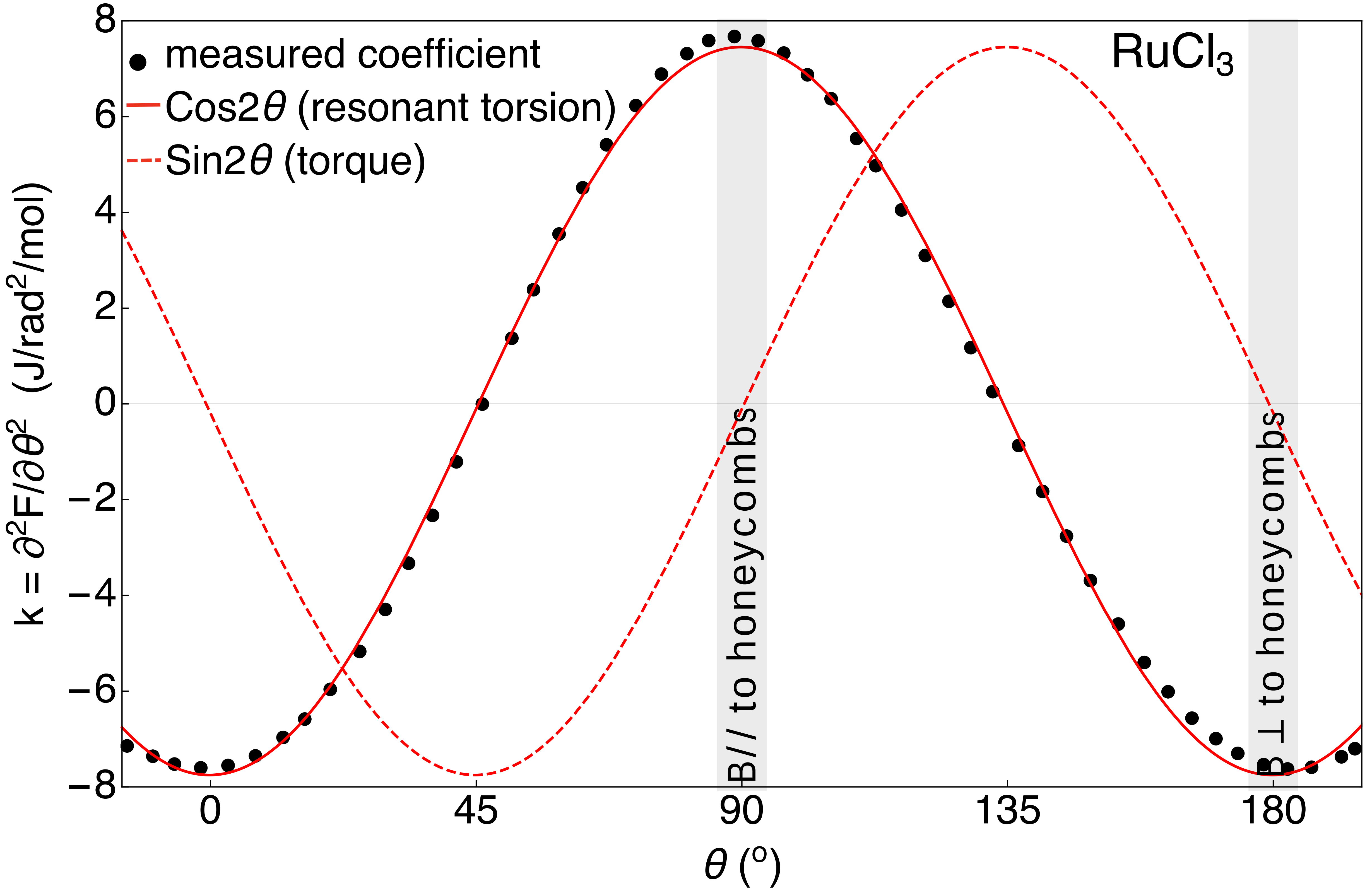




Modic, K.A. *arXiv:1901.09245* (2019)



Linear response regime $M_i = \chi_{ij} H_j$



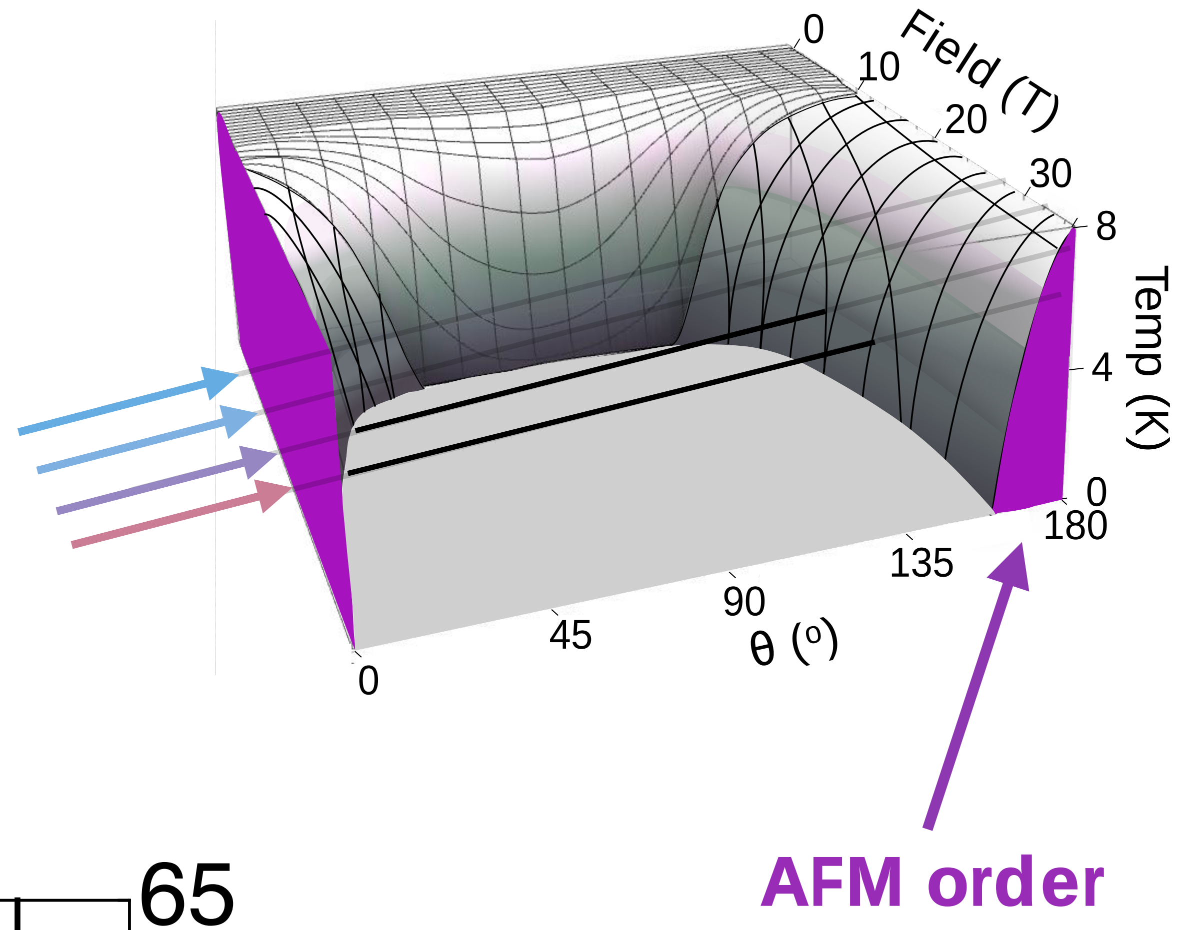
$$F = \frac{1}{4}B^2(\chi_\perp - \chi_\parallel)\cos 2\theta$$

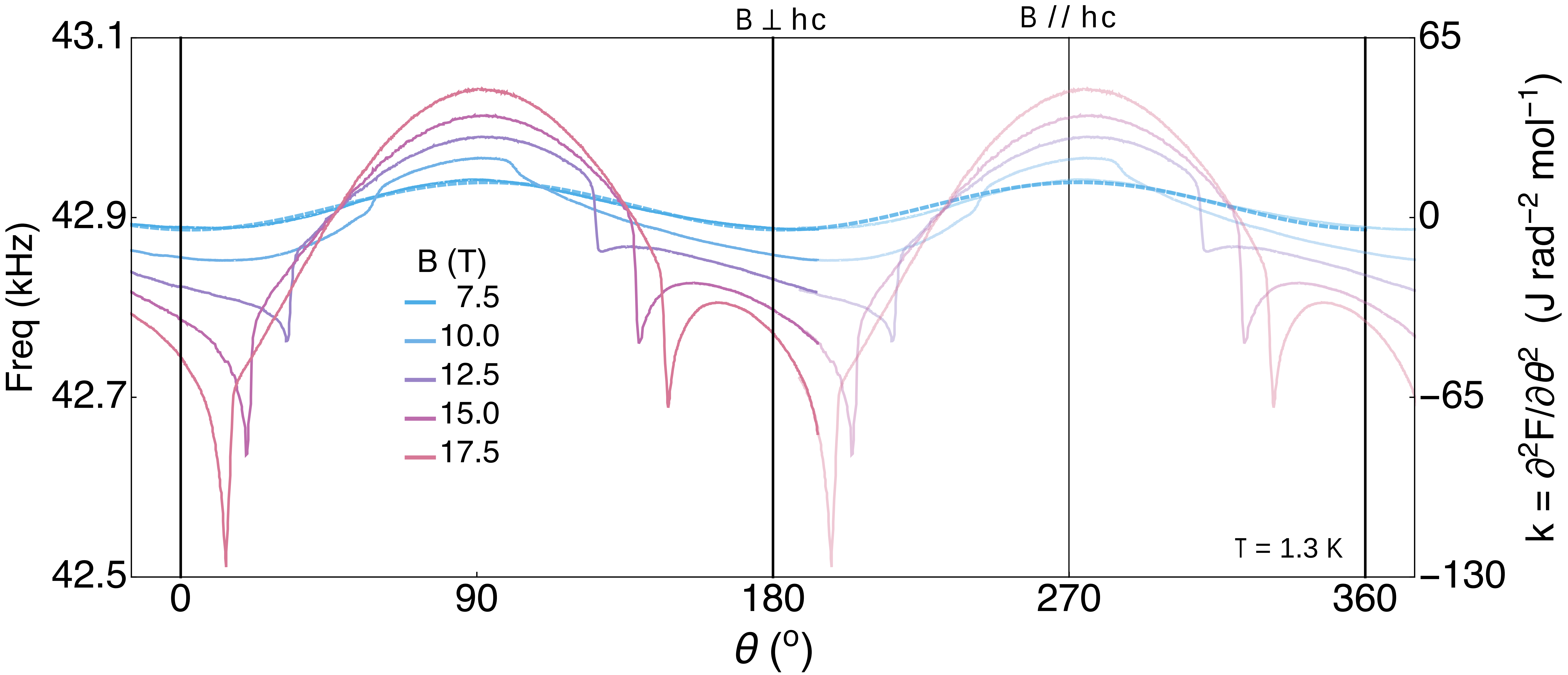
$$\tau = \frac{1}{2}B^2(\chi_\perp - \chi_\parallel)\sin 2\theta \qquad (\tau = \partial F/\partial\theta)$$

$$k = B^2(\chi_\perp - \chi_\parallel)\cos 2\theta \qquad (k = \partial^2 F/\partial\theta^2)$$

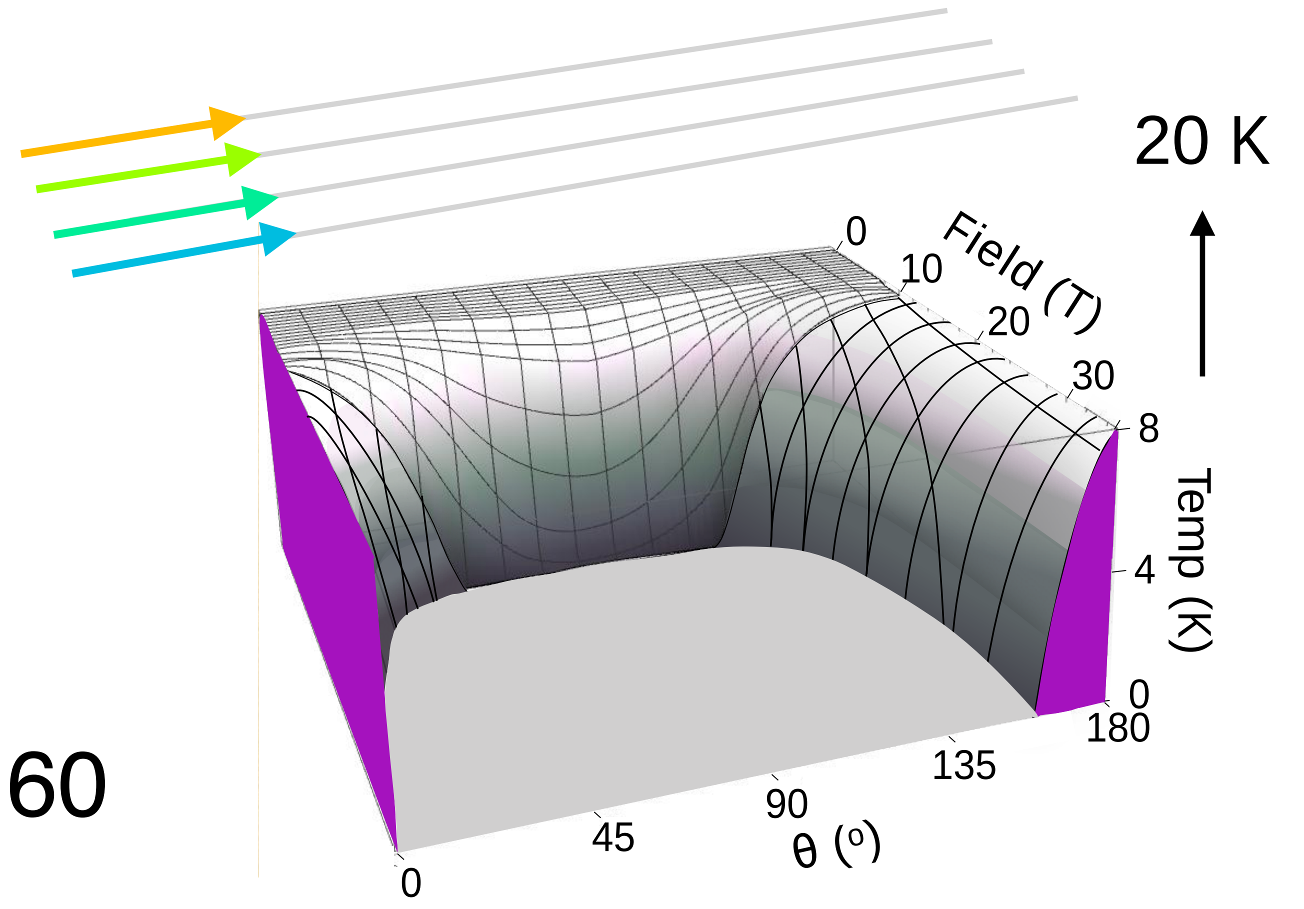
Modic, K.A. *Nat. Comm.* (2018)

Asymmetry develops near the *c*-axis in high fields

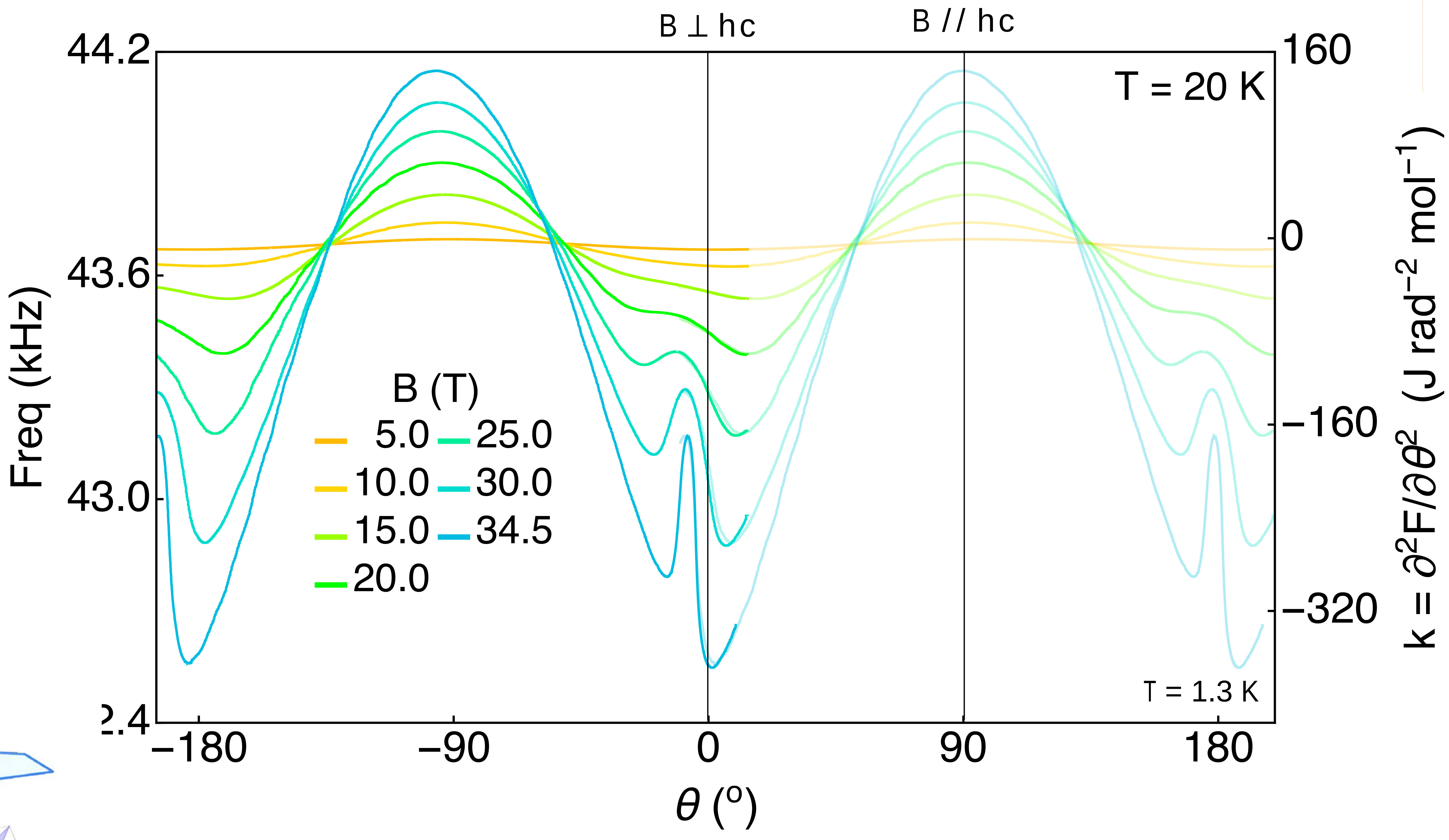


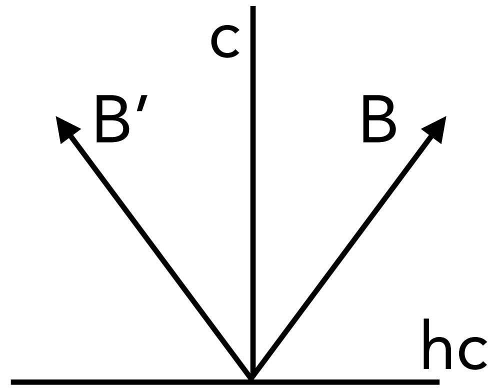


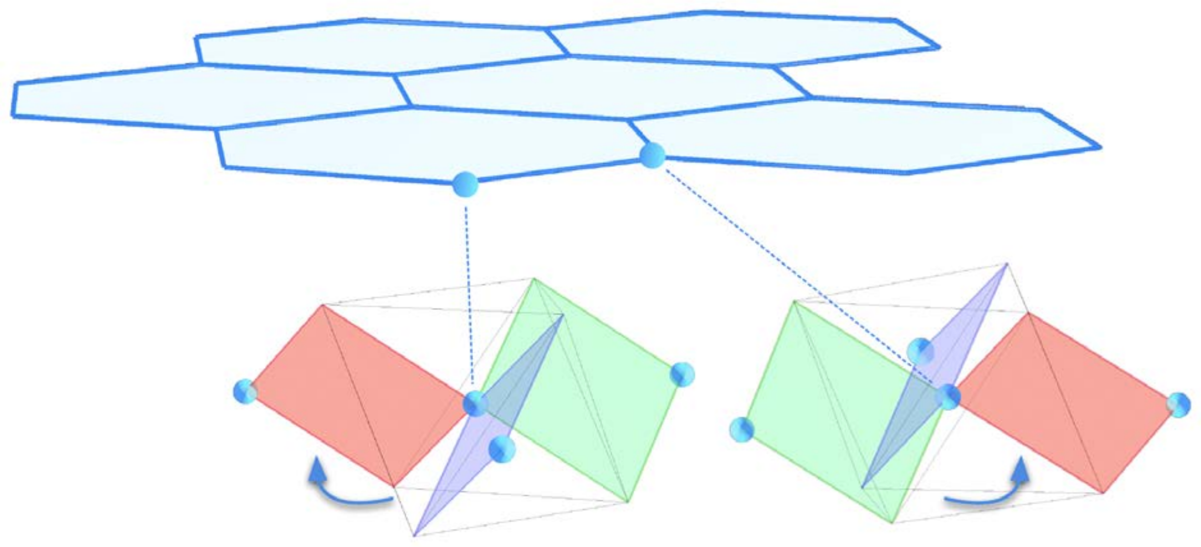
Modic, K.A. *arXiv:1901.09245* (2019)



Asymmetry develops near the *c*-axis in high fields

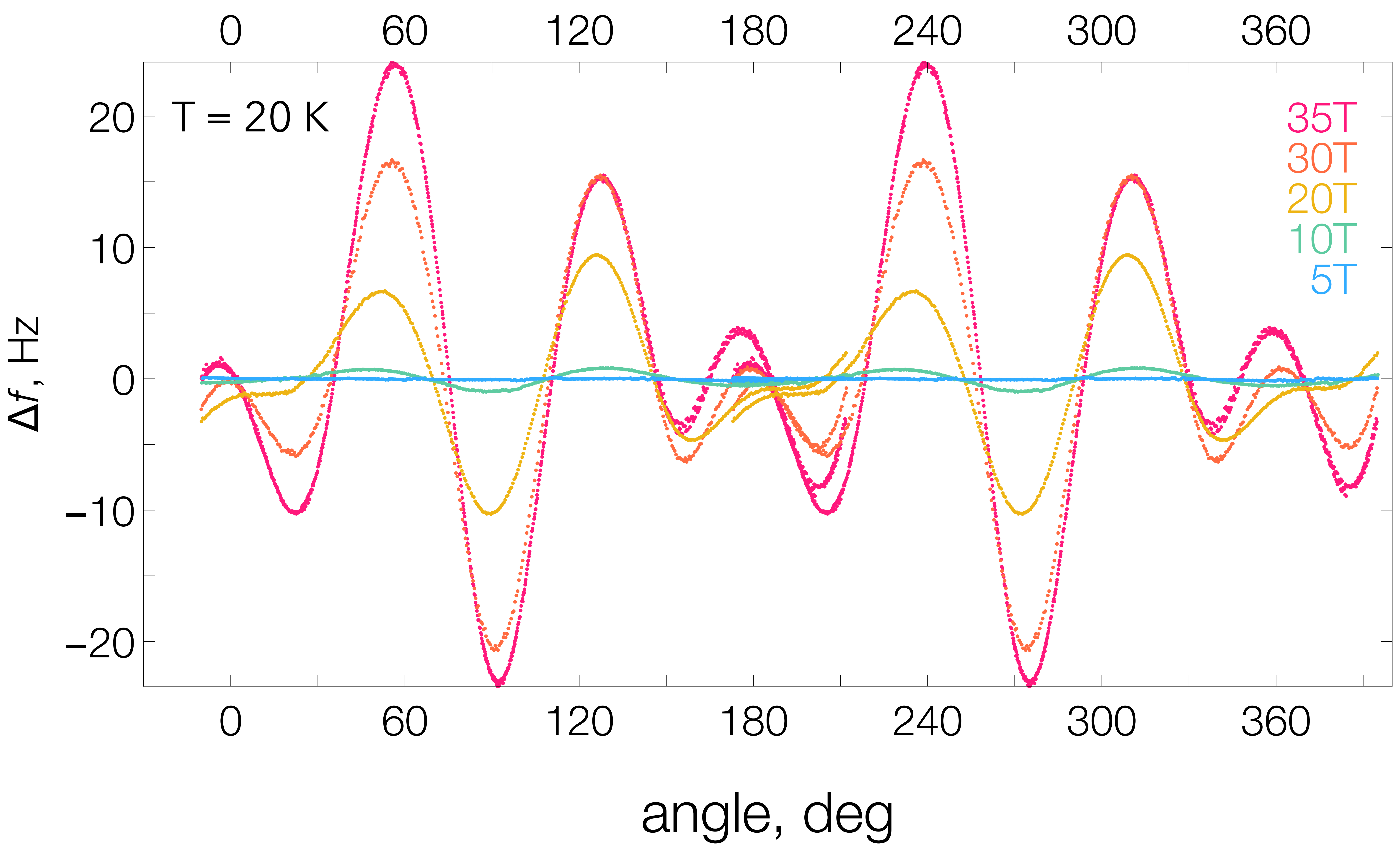


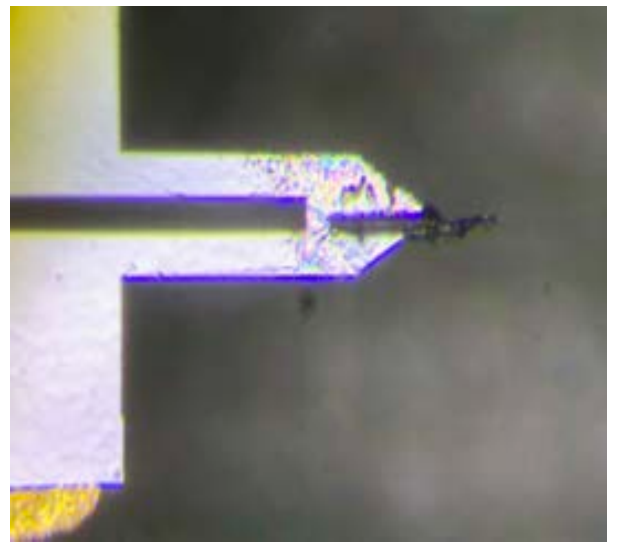




Modic, K.A. *arXiv:1901.09245* (2019)

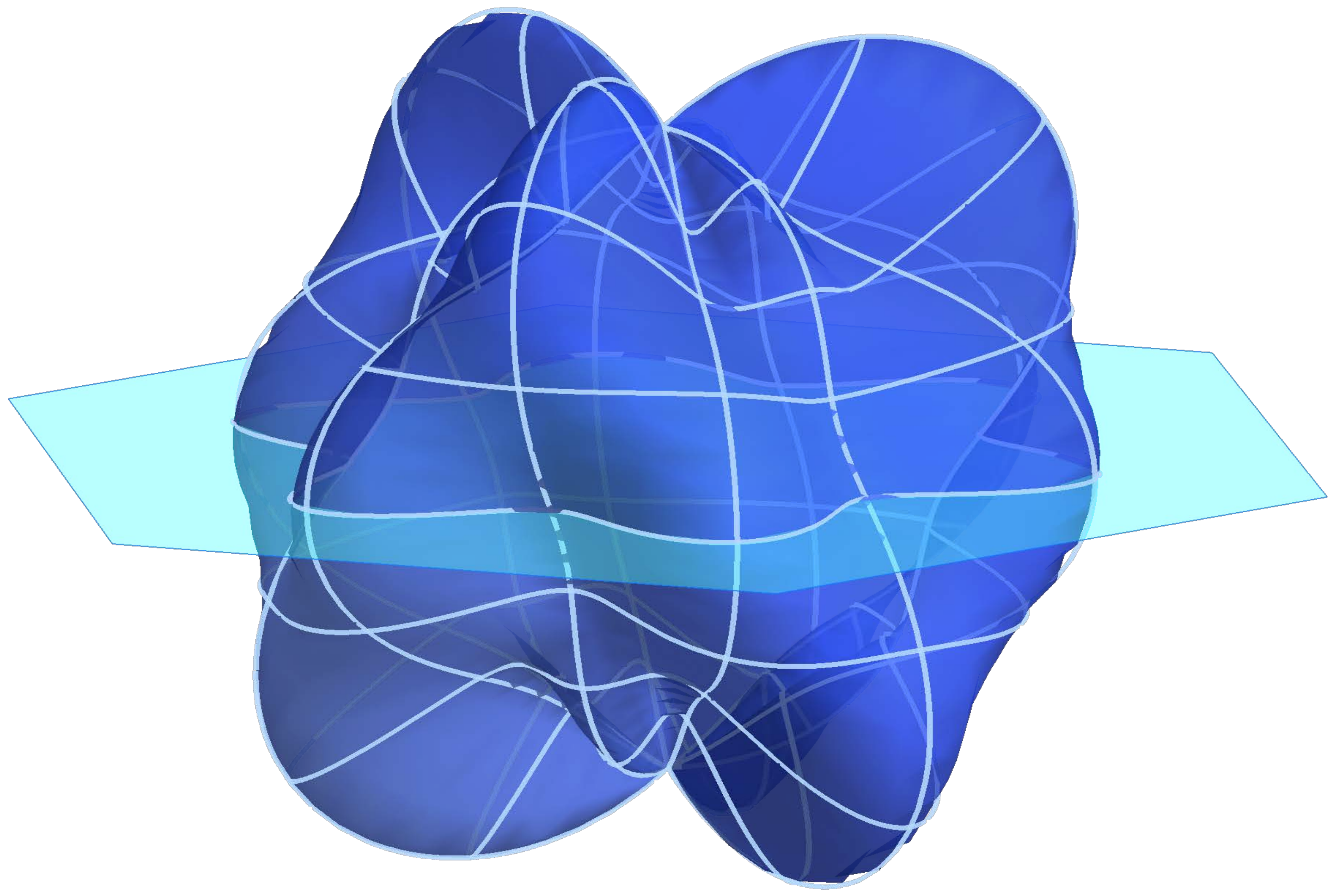
6-fold symmetry in the honeycomb plane

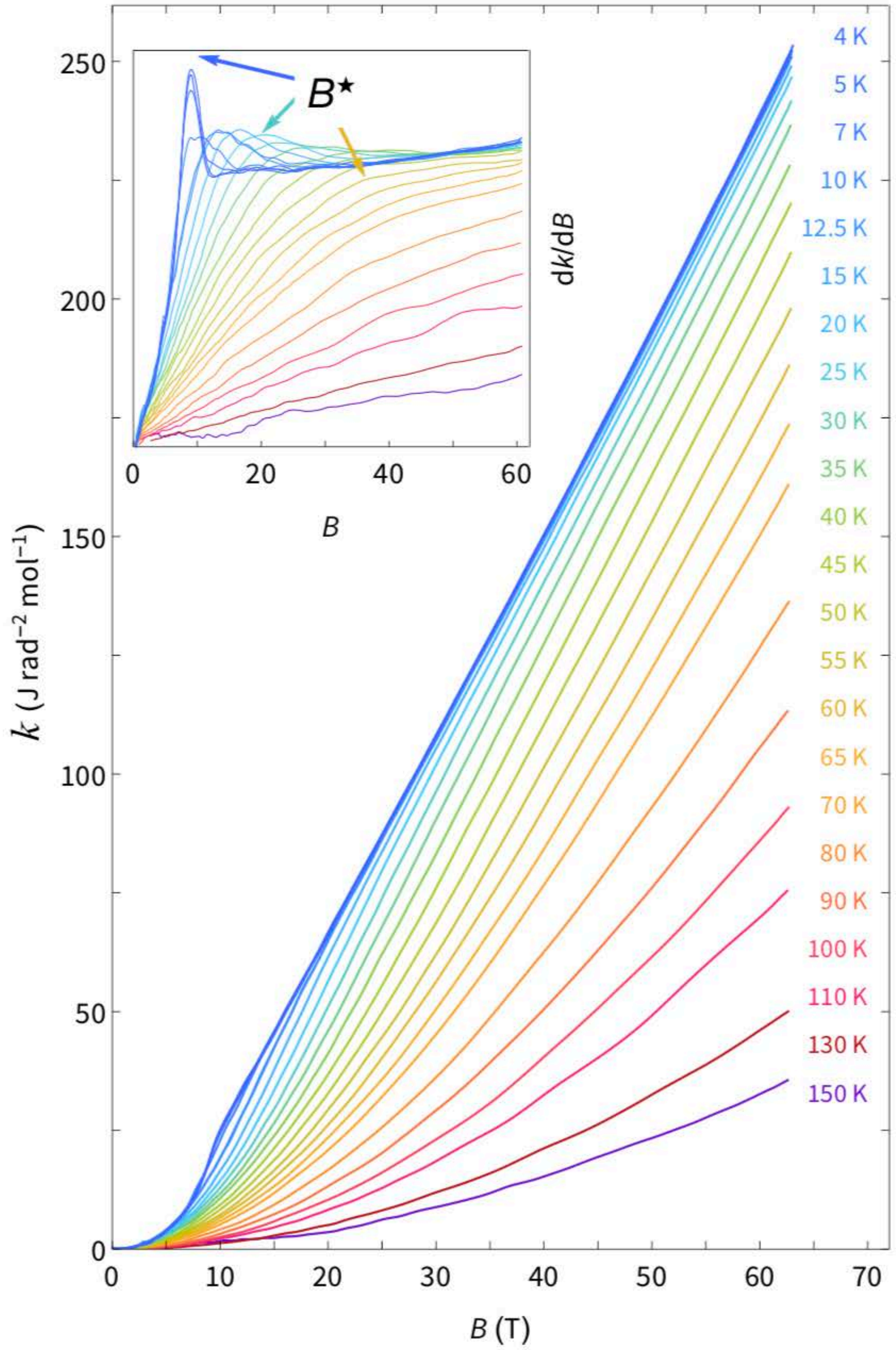




Modic, K.A. *arXiv:1901.09245* (2019)

Magnetic anisotropy is scale-invariant at high fields

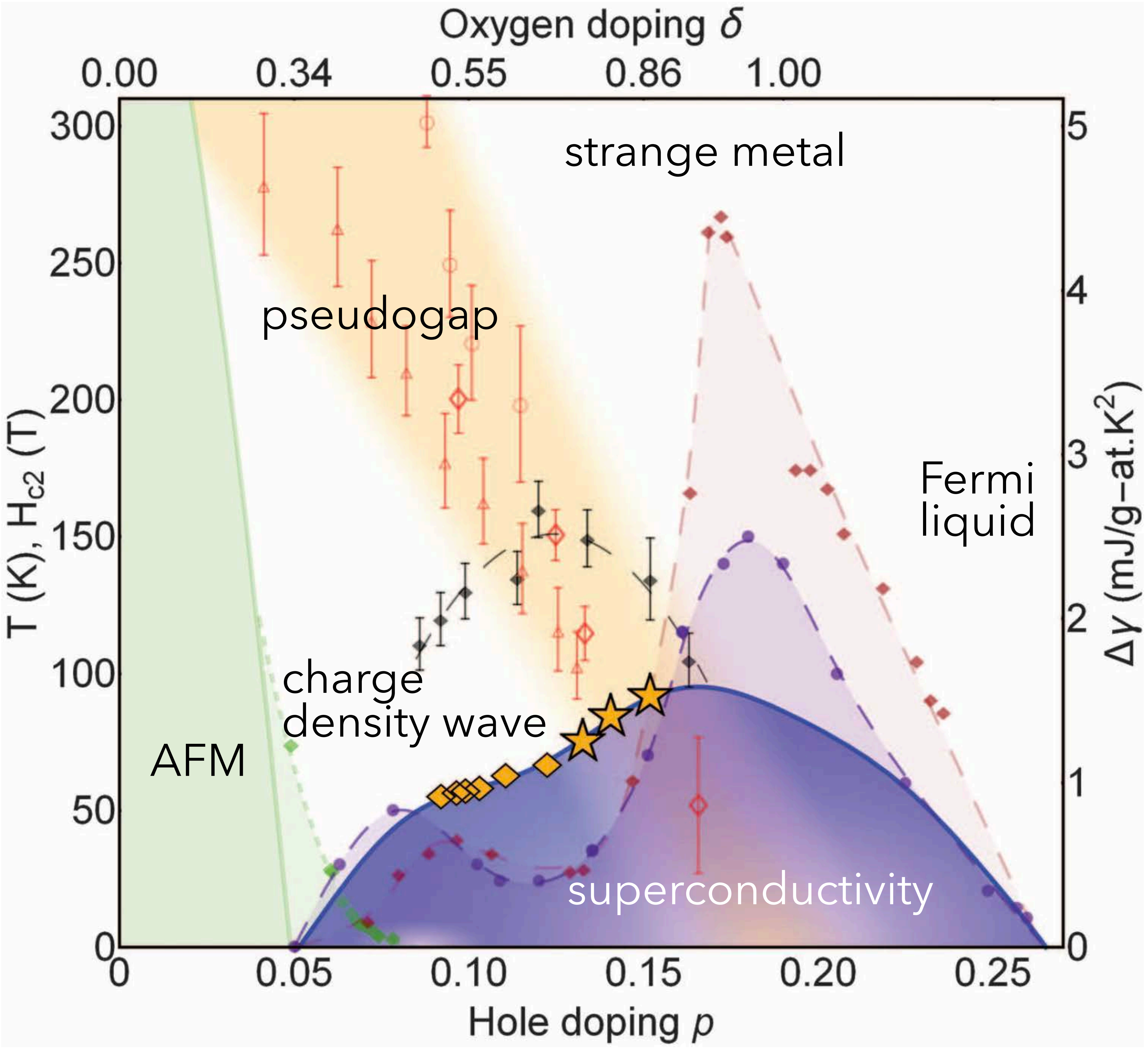


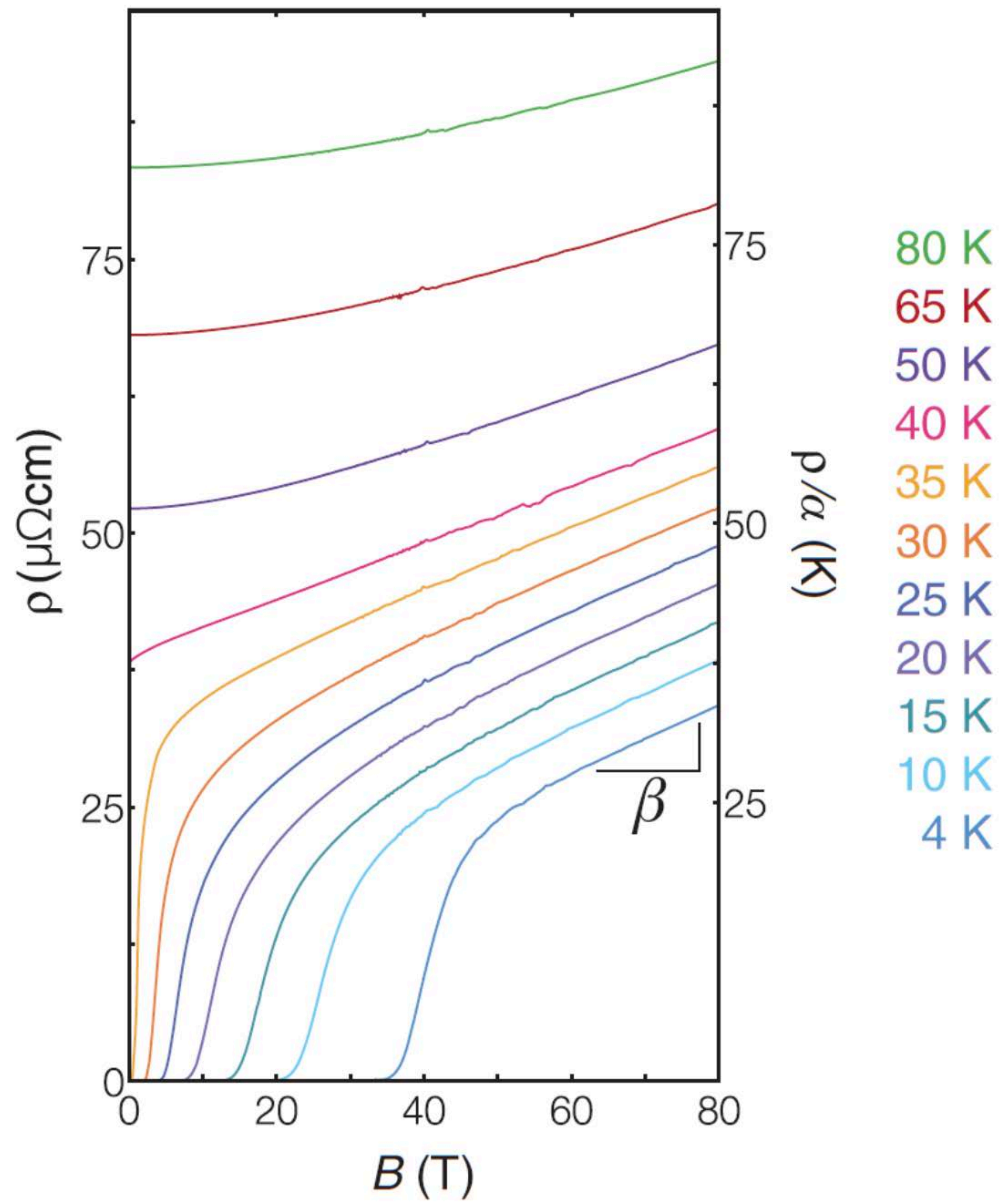


➡Magnetic anisotropy saturates at the AFM transition
➡Singularity in the free energy at the north and south poles
➡Curvature of the free energy is robust to temperature and magnetic field

Modic, K.A. *arXiv:1901.09245* (2019)

What does the lack of an intrinsic energy scale tell us?



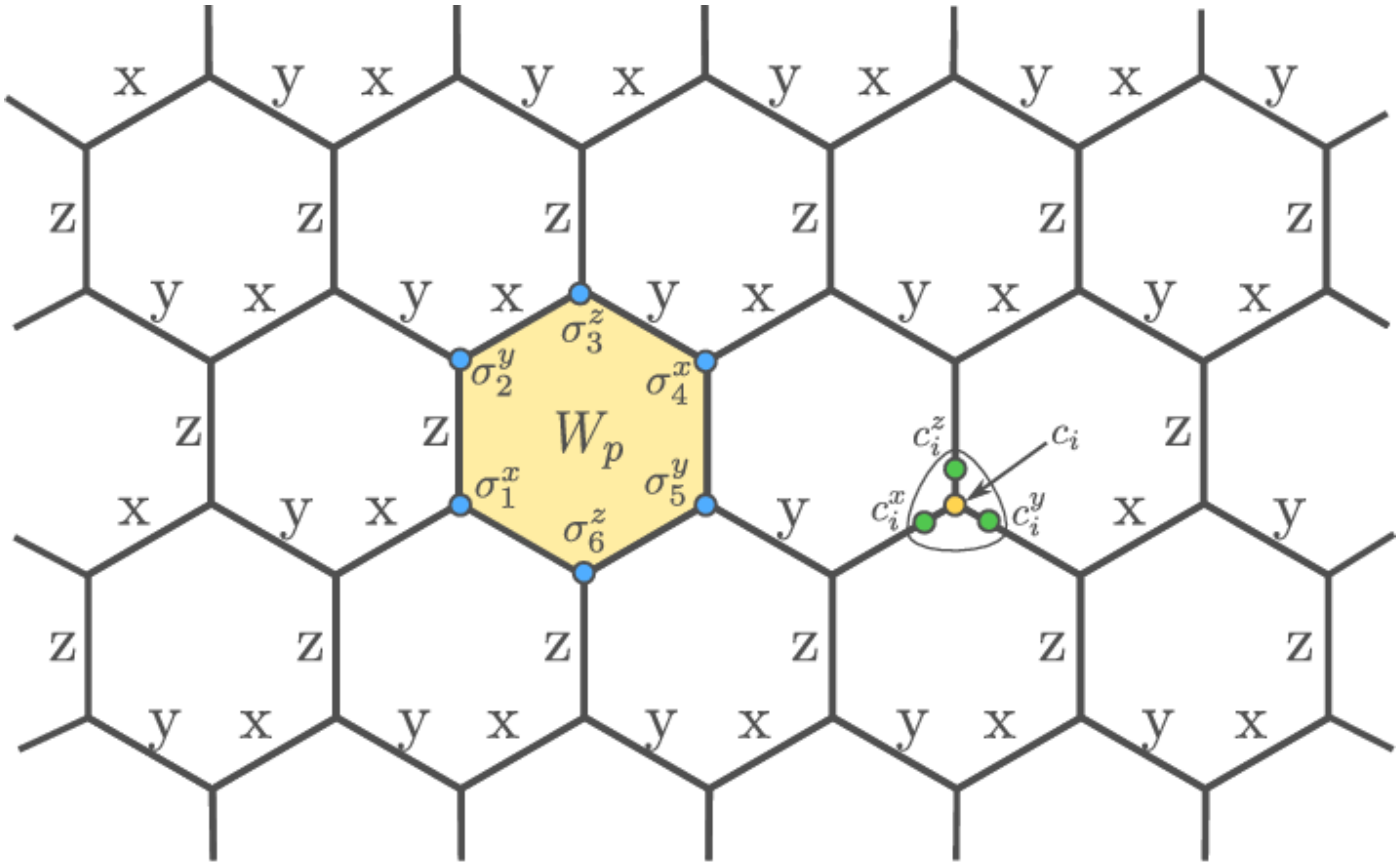


Ramshaw, B.J. *Science* (2015)

Giraldo-Gallo, P. *Science* (2018)

Conclusions:

- ➡Scale-invariant behavior in a spin system
- ➡Magnetic field introduces interactions between the low-energy excitations of the Kitaev model?



Kitaev, A. *Ann. Phys.* (2006)
Savary, L. *Rep. Prog. Phys.* (2017)

Thank you for your attention!

Mia
June 1st, 2019