Elastocaloric probing and tuning of multipolar order in the altermagnet MnF_2

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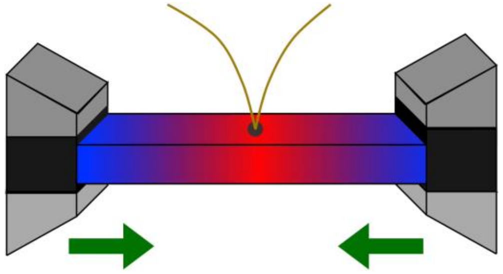
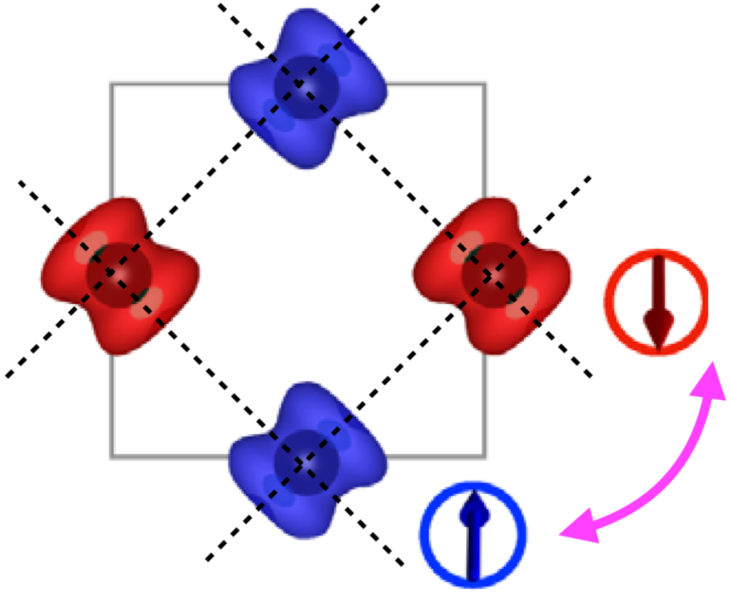
01.09.2026

Goal of the Talk



$$\eta = \left(\frac{\partial T}{\partial \epsilon}\right)_s$$

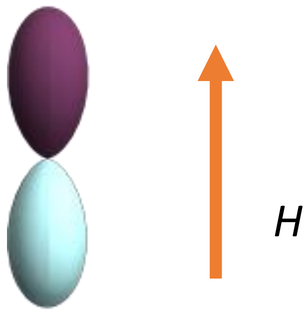


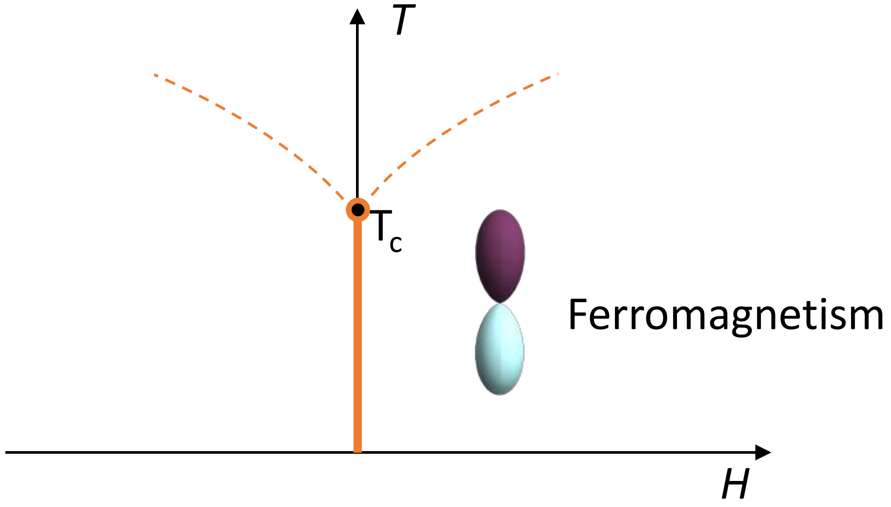
Elastocaloric Effect

Altermagnetism

Thermodynamic Probe ⟷ Symmetry

How does thermodynamics reveal altermagnetic symmetries?

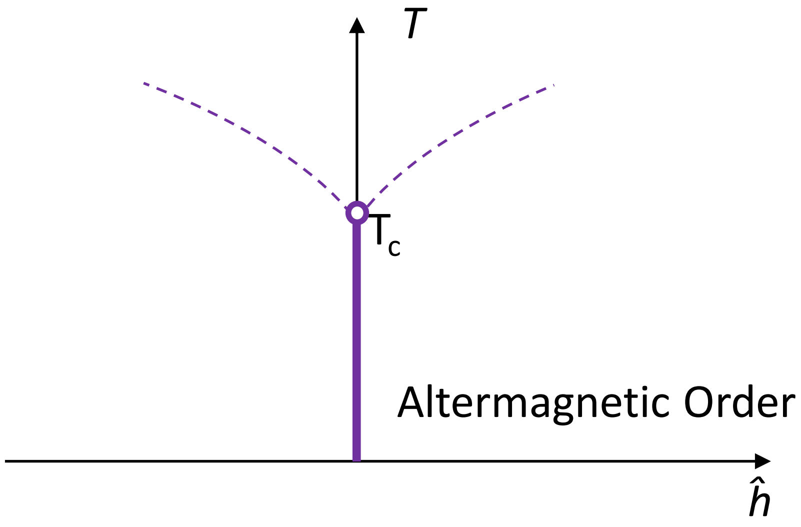




$$T^* - T_c \propto \hat{h}^{\frac{1}{\beta\delta}}$$

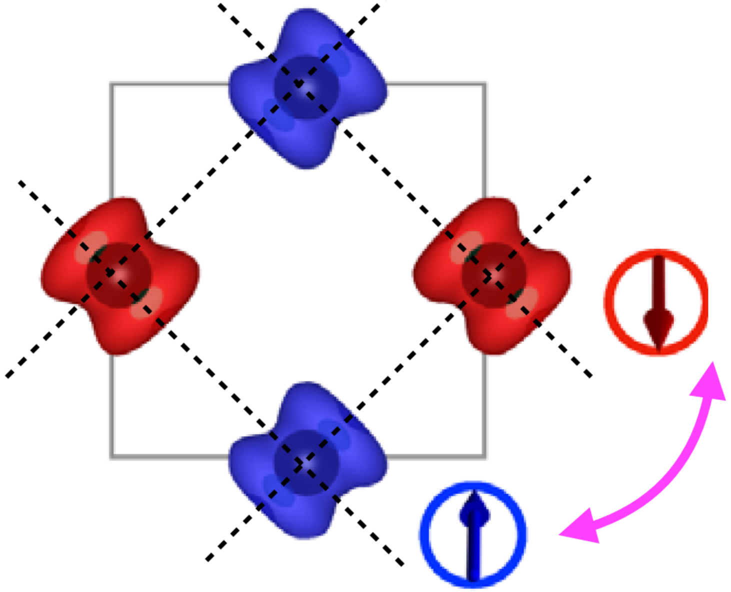
$\hat{h}$: conjugate field to order parameter
β,δ: critical exponents

? ?



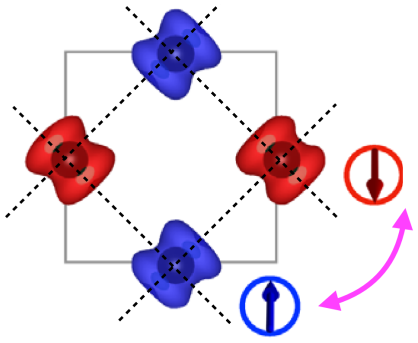
- What is the order parameter of an altermagnet?
- What is the corresponding conjugated field?

What is the order parameter of an altermagnet?

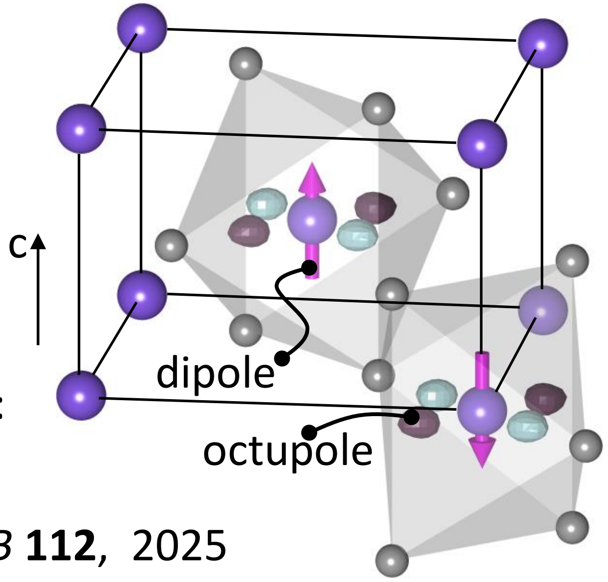


From: Smejkal *et al.*, *Phys. Rev. X* **12**, 2022

What is the order parameter of an altermagnet?



Rutile structure:



Buiarelli *et al.*, *Phys. Rev. B* **112**, 2025

$$\varepsilon_{int} = -\int \vec{\mu}(\vec{r}) \cdot \vec{H}(\vec{r})\, \mathrm{d}^3 r$$

$$= \cancel{-\int \mu_i(\vec{r}) H_i(0)\, \mathrm{d}^3 r} \; \cancel{- \int r_i \mu_j(\vec{r}) \partial_i H_j(0)\, \mathrm{d}^3 r}$$

Dipolar term

Quadrupolar term

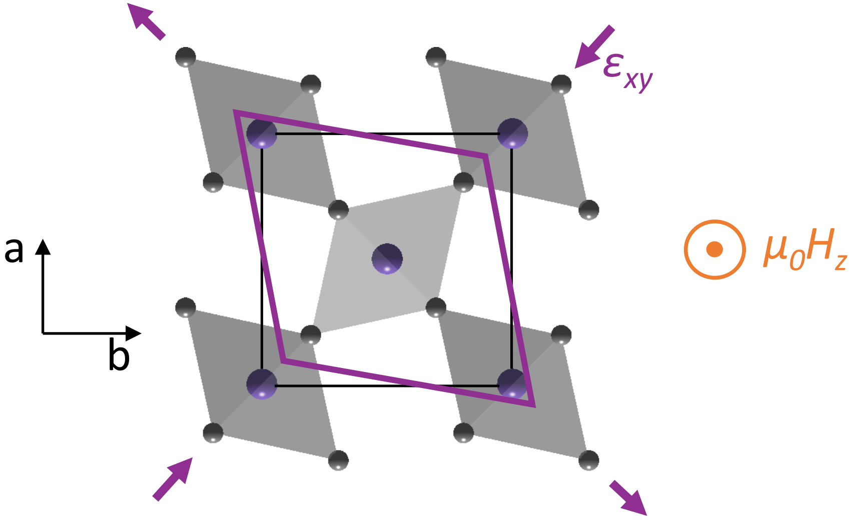
$$- \int \boxed{r_i\, r_j} \boxed{\mu_k} (\vec{r}) \partial_i \partial_j H_k(0) d^3 r + \ \ldots$$

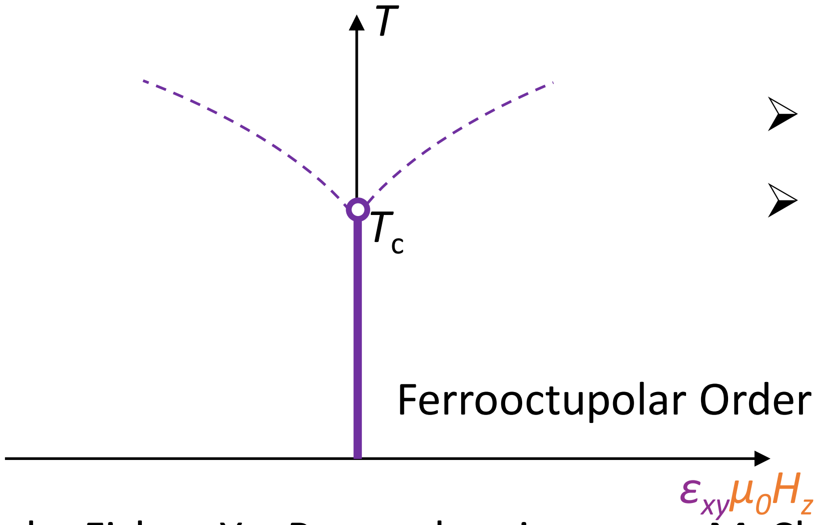
Octupolar term

From: Bhowal *et al.*, *Phys. Rev. X* **14**, 2024

Order parameter: Magnetic Octupole ✓

Conjugate field: $\hat{h}=\varepsilon_{xy}\mu_0 H_z$ ✓



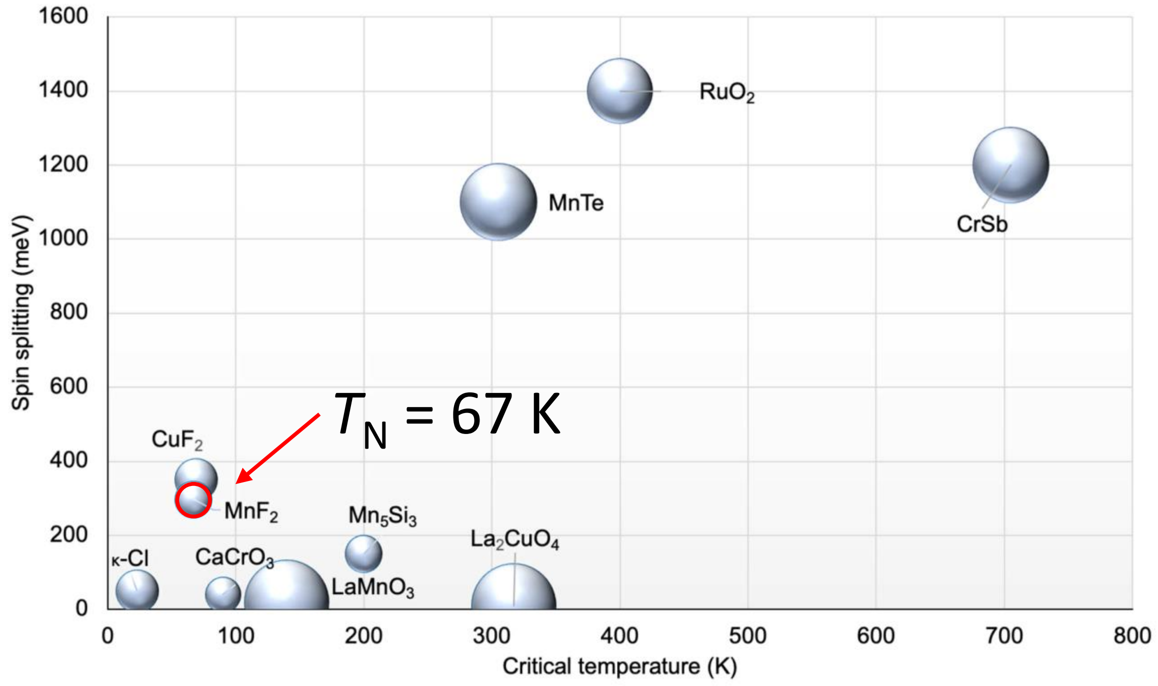


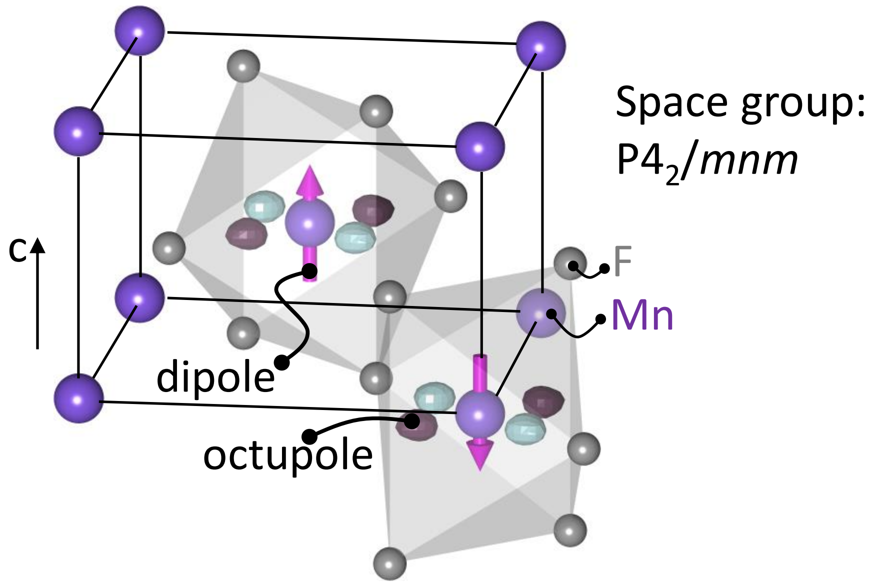
- Altermagnetic Material Candidate
- Thermodynamic Probe

Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026 c. f. works by Fisher, Ye, Paramekanti

McClarty *et al.*, *Phys. Rev. Lett* **132**, 2024

Altermagnetic Candidates

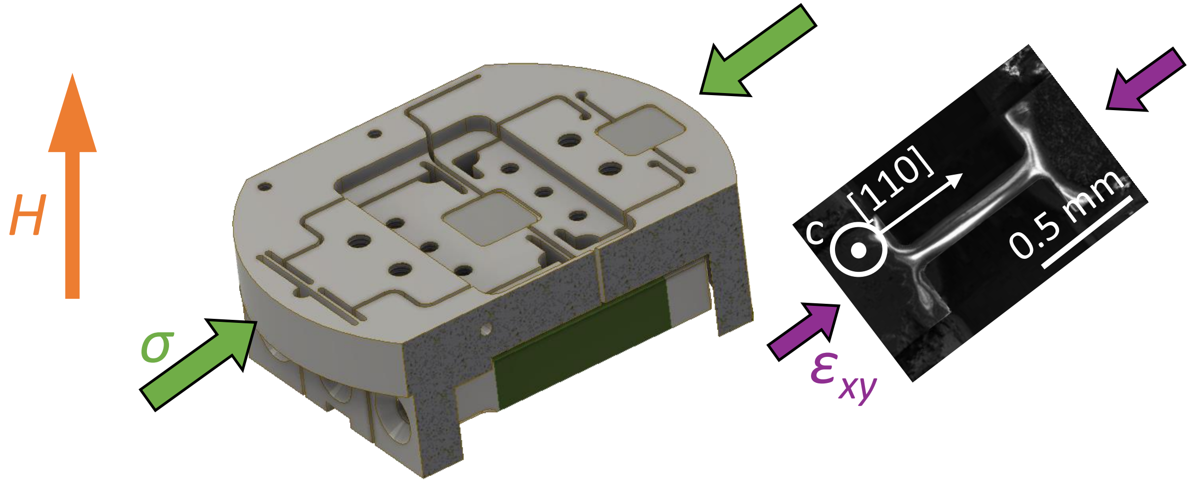




From: Smejkal *et al.*, *Phys. Rev. X* **12**, 2022

Experimental Methods

High-precision strain tuning:



Hicks *et al.*, *Science* **344**, 2014

Thermodynamic probe:

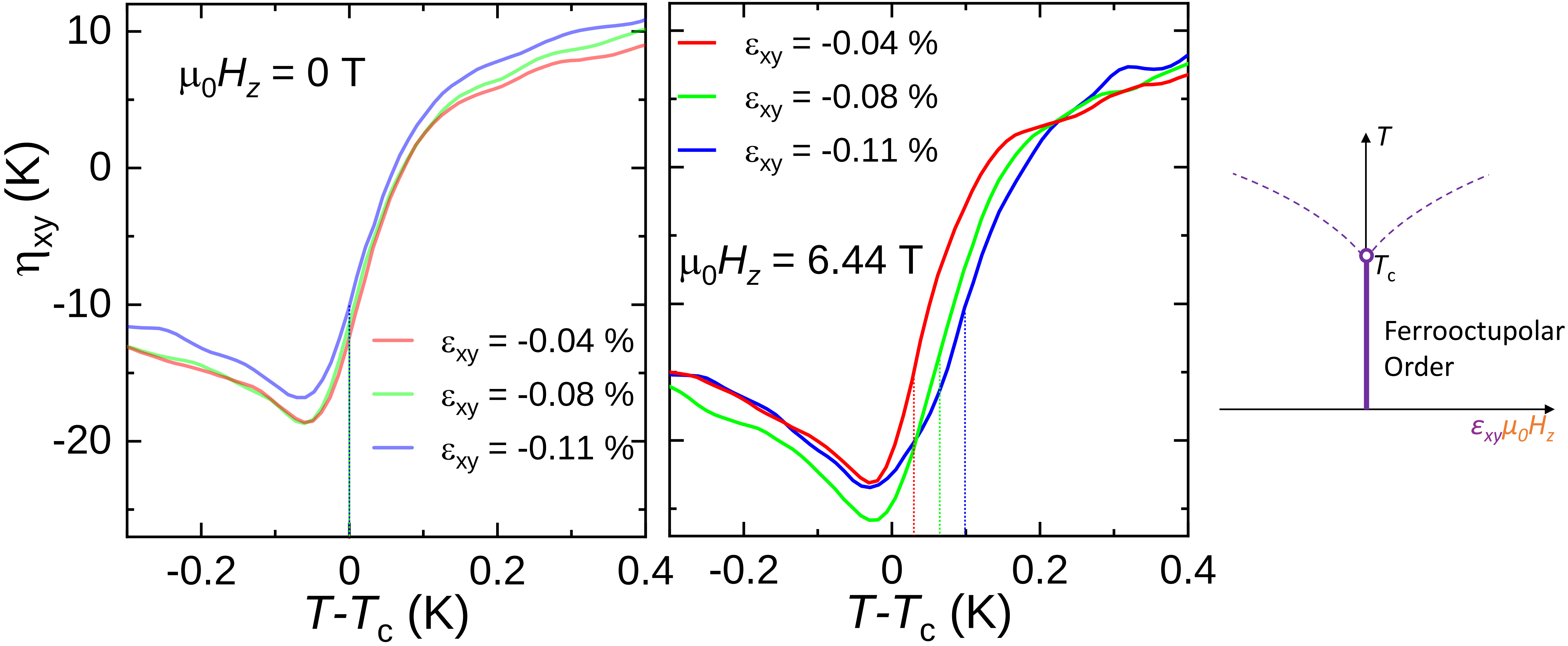
Elastocaloric Effect:

$$\eta = \left(\frac{\partial T}{\partial \epsilon}\right)_S = -\frac{T}{C_\epsilon}\left(\frac{\partial S}{\partial \epsilon}\right) \Rightarrow F(\epsilon, T, H)$$

Free energy

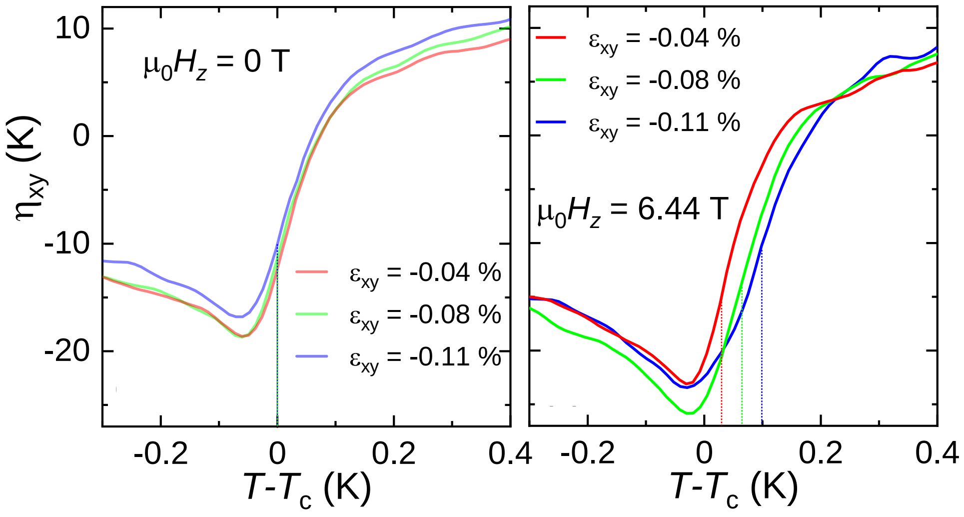
Ikeda *et al.*, *Rev. Sci. Instrum.* **90**, 2019

Altermagnetic signatures in MnF_2

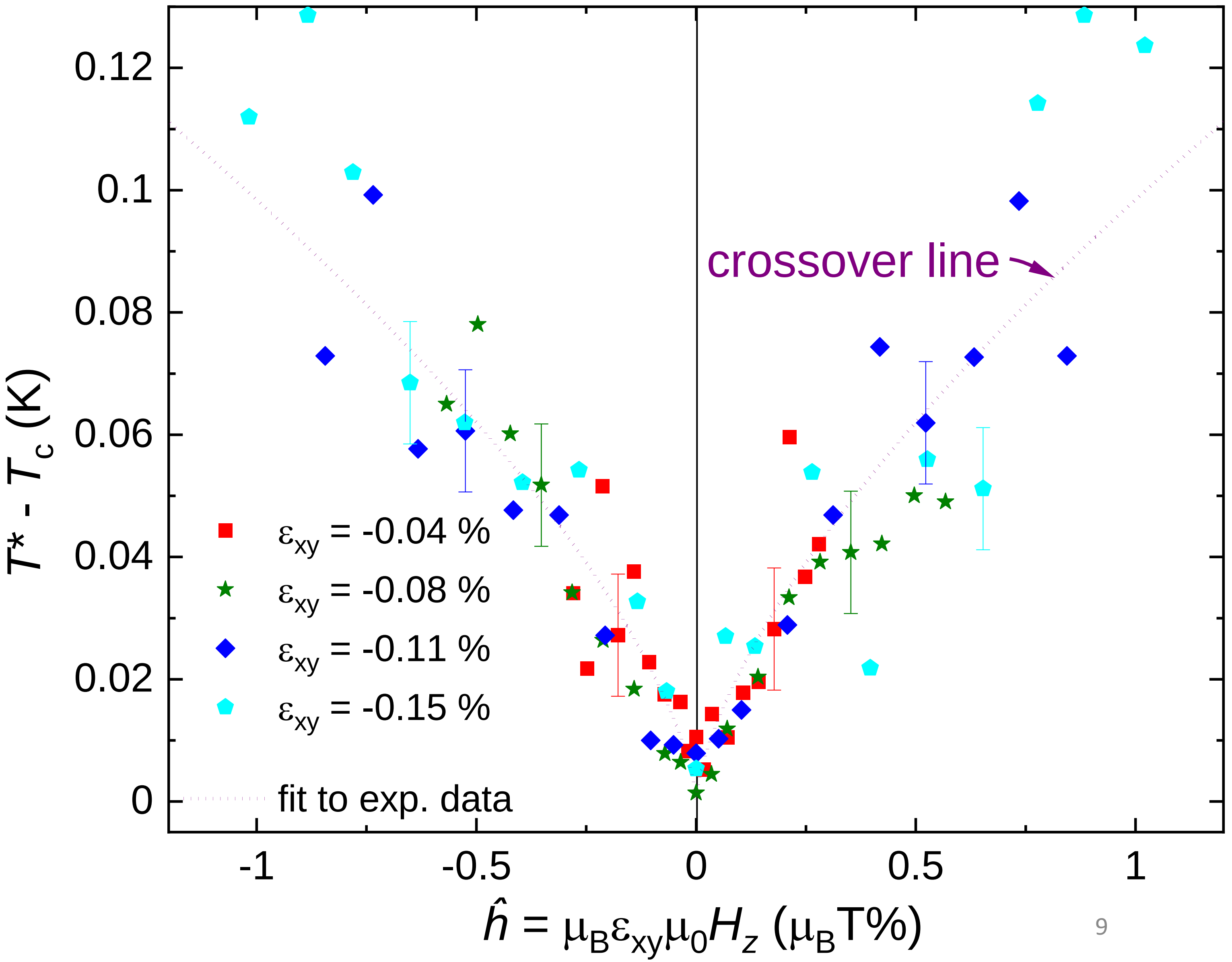


Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

Altermagnetic signatures in MnF_2

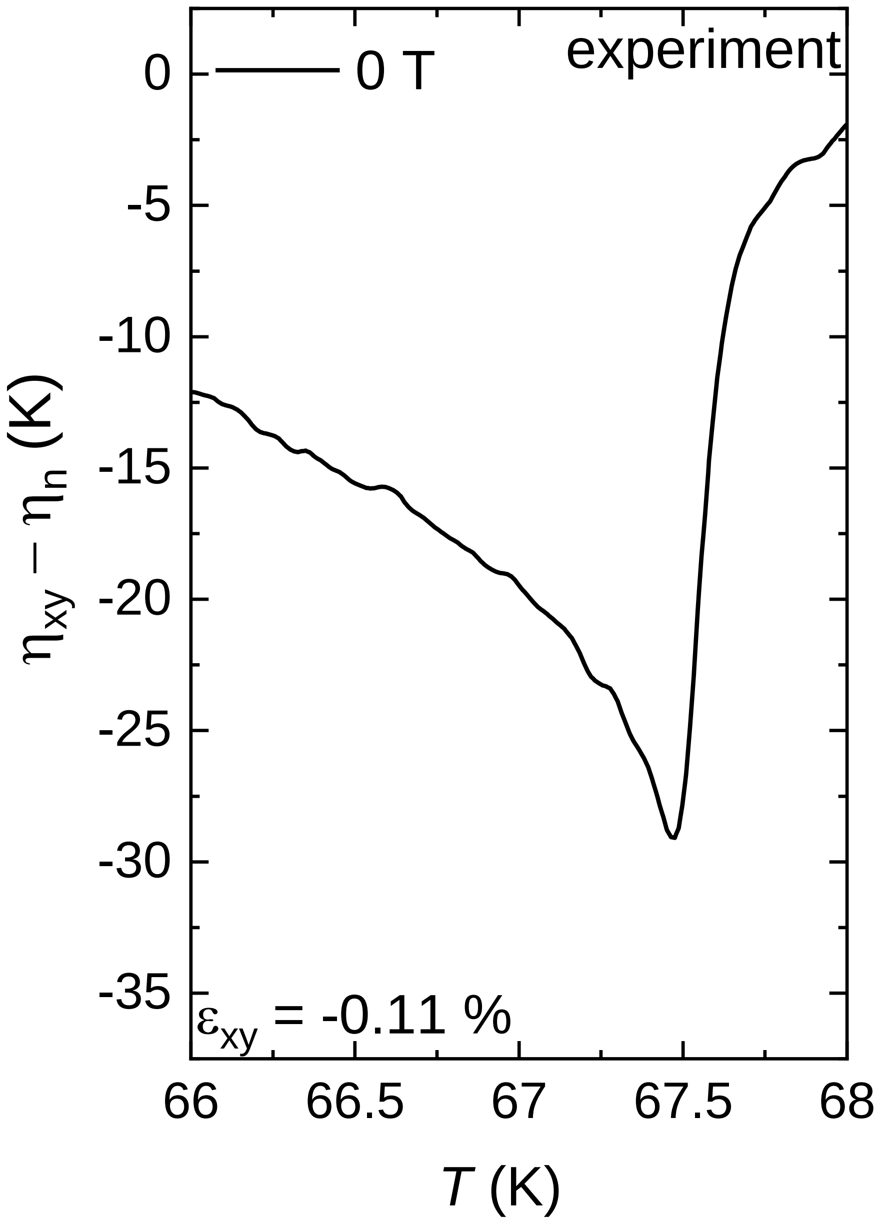


$$T^* - T_c = \left(\frac{\lambda \mu_B}{k_B} \epsilon_{xy} \mu_0 H_z\right)^{\frac{2}{3}} T_c^{\frac{1}{3}}$$



Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

Altermagnetic Signatures in the Magnitude of the ECE



Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

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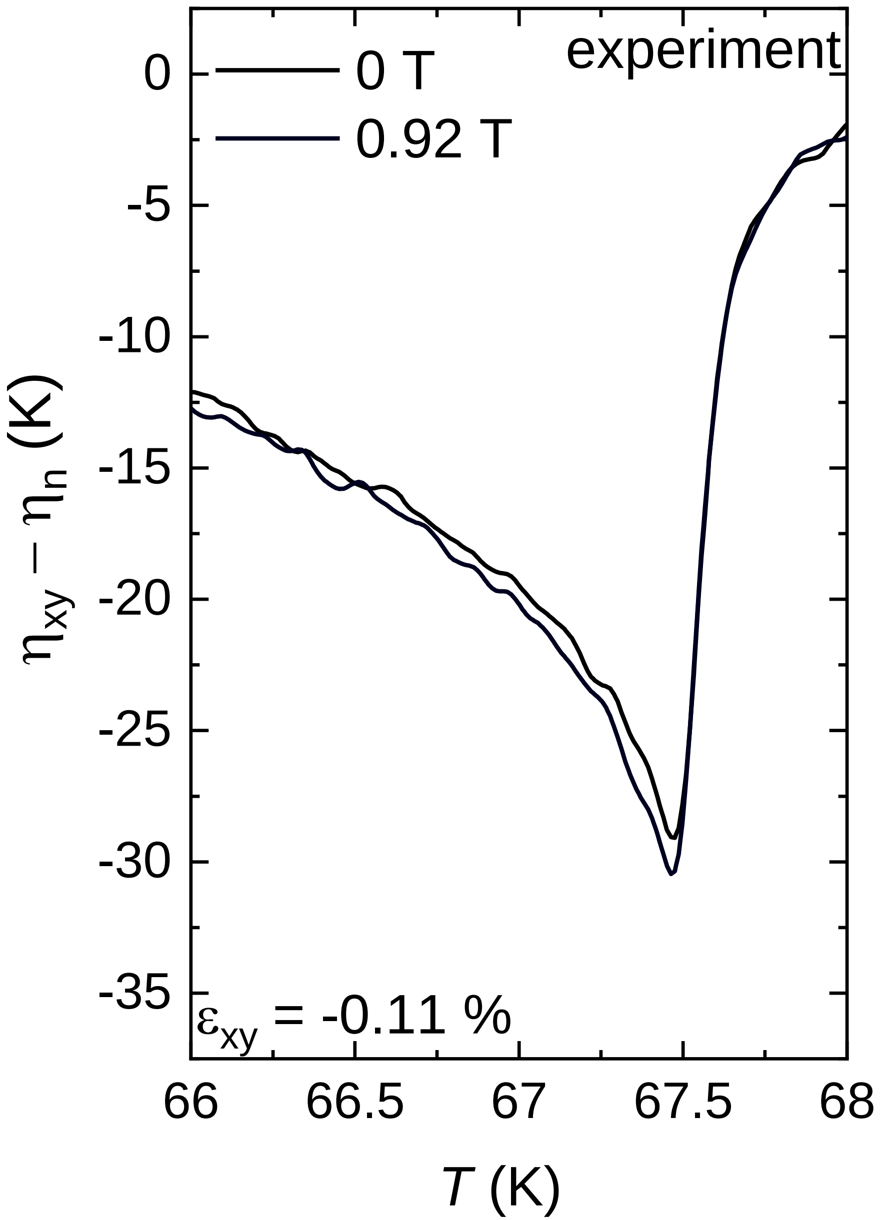

Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

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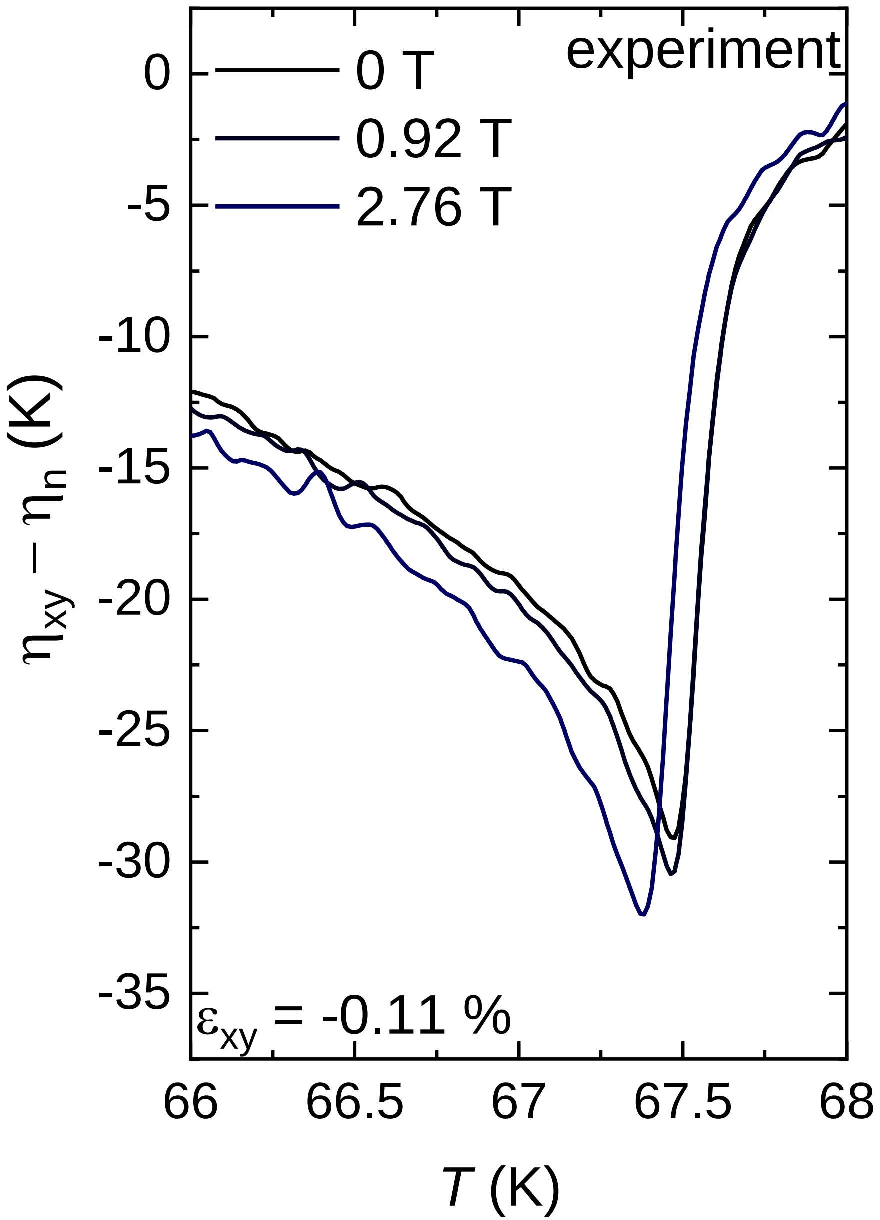

Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

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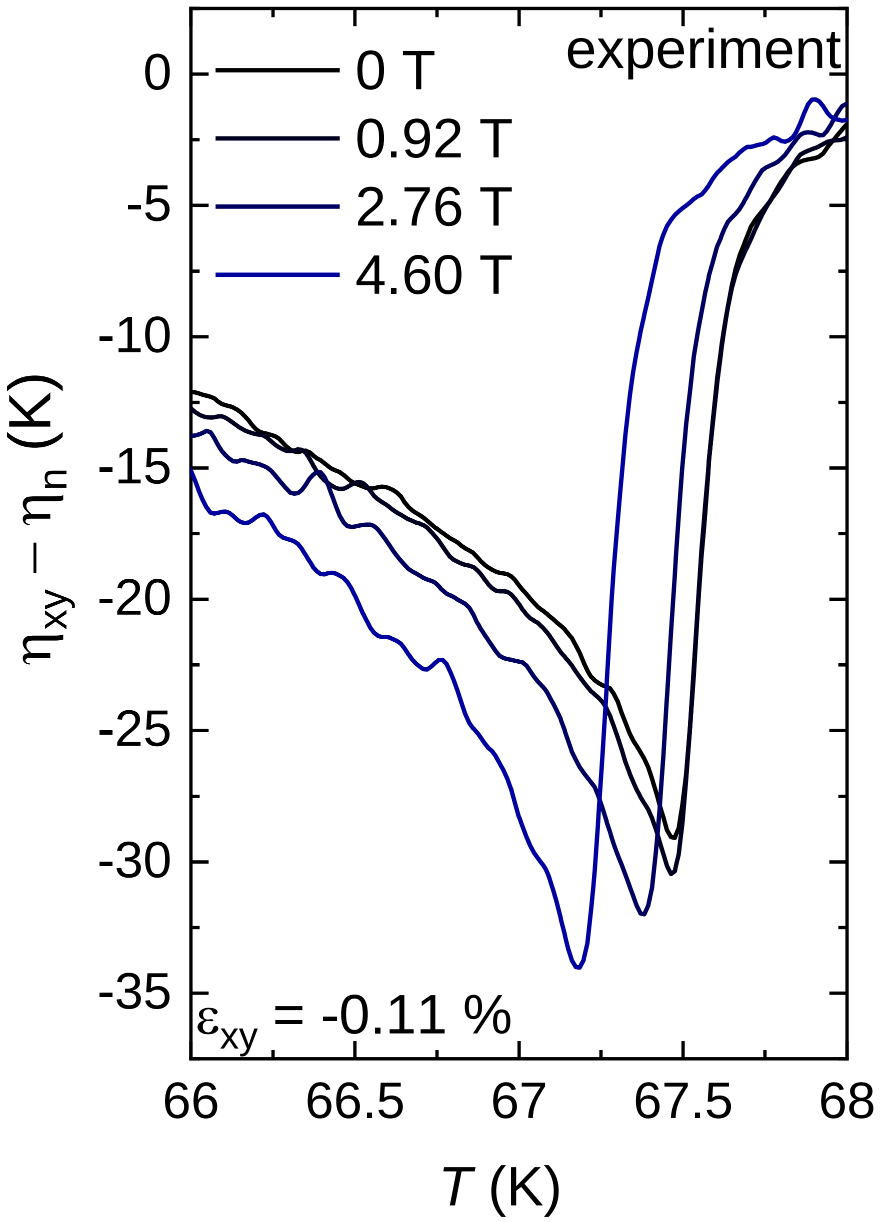

Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

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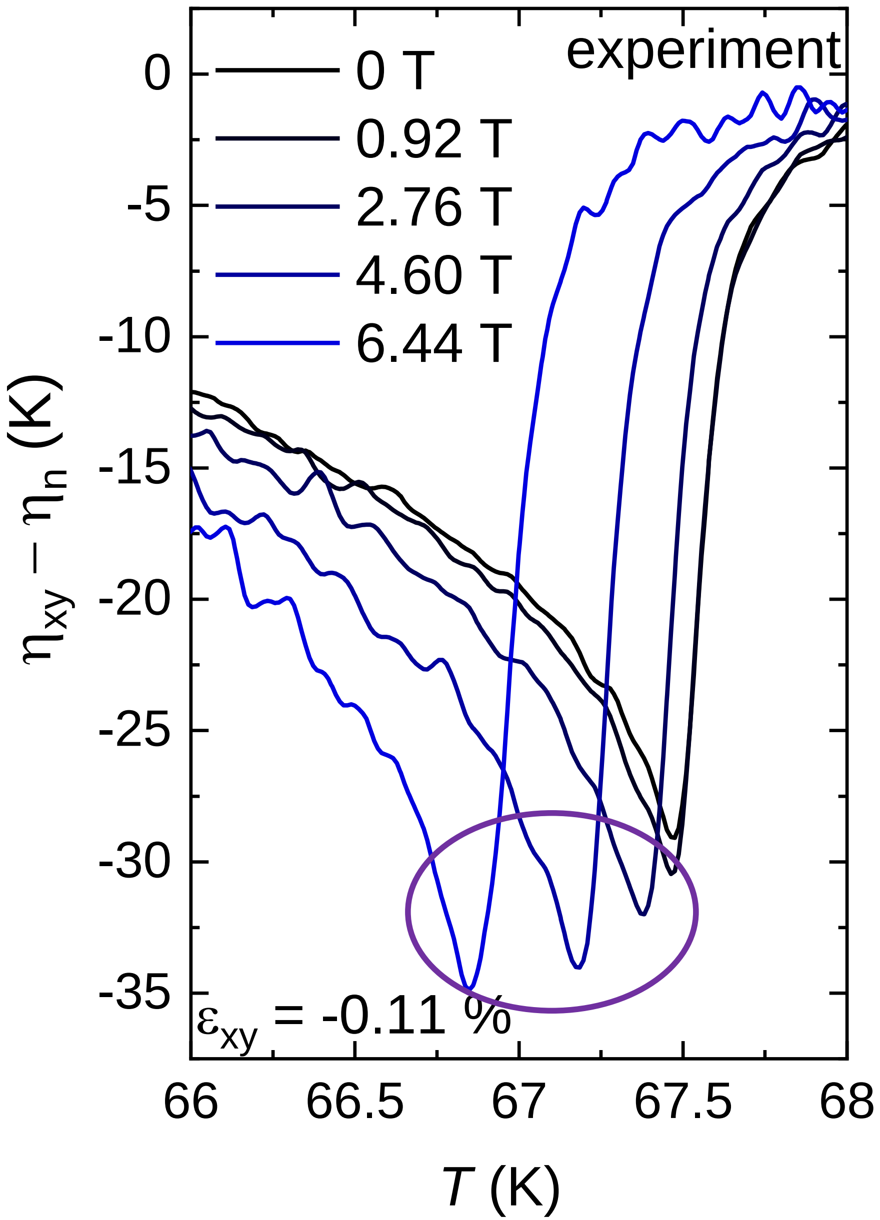
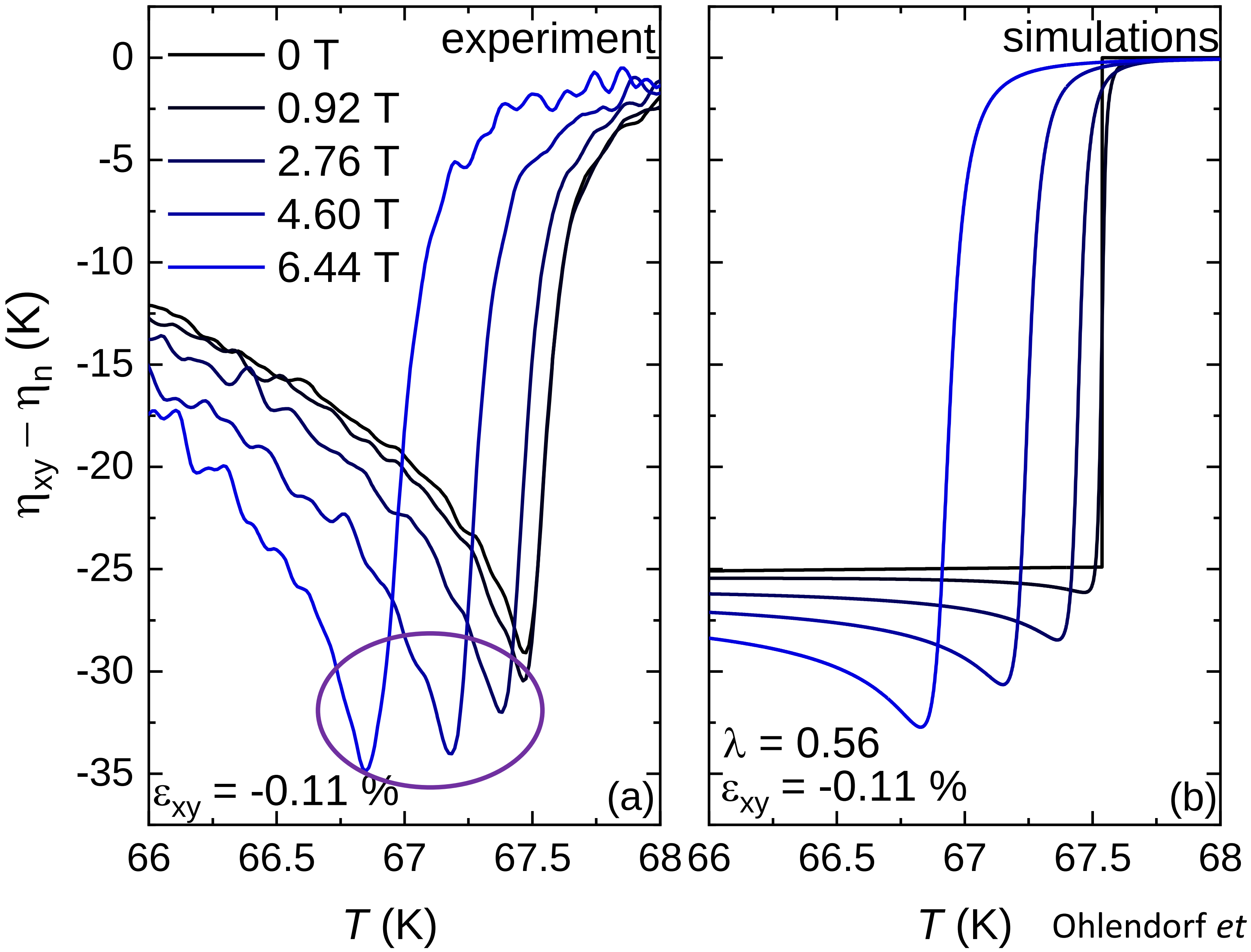


Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

Altermagnetic Signatures in the Magnitude of the ECE

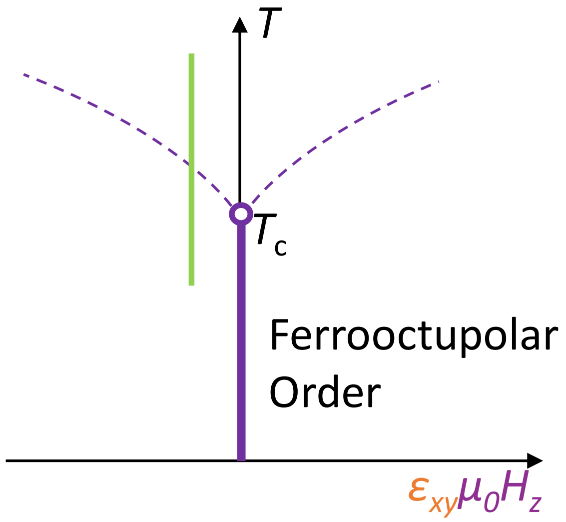


Coupling term: $\lambda\varepsilon_{xy}\mu_B\mu_0 H z$

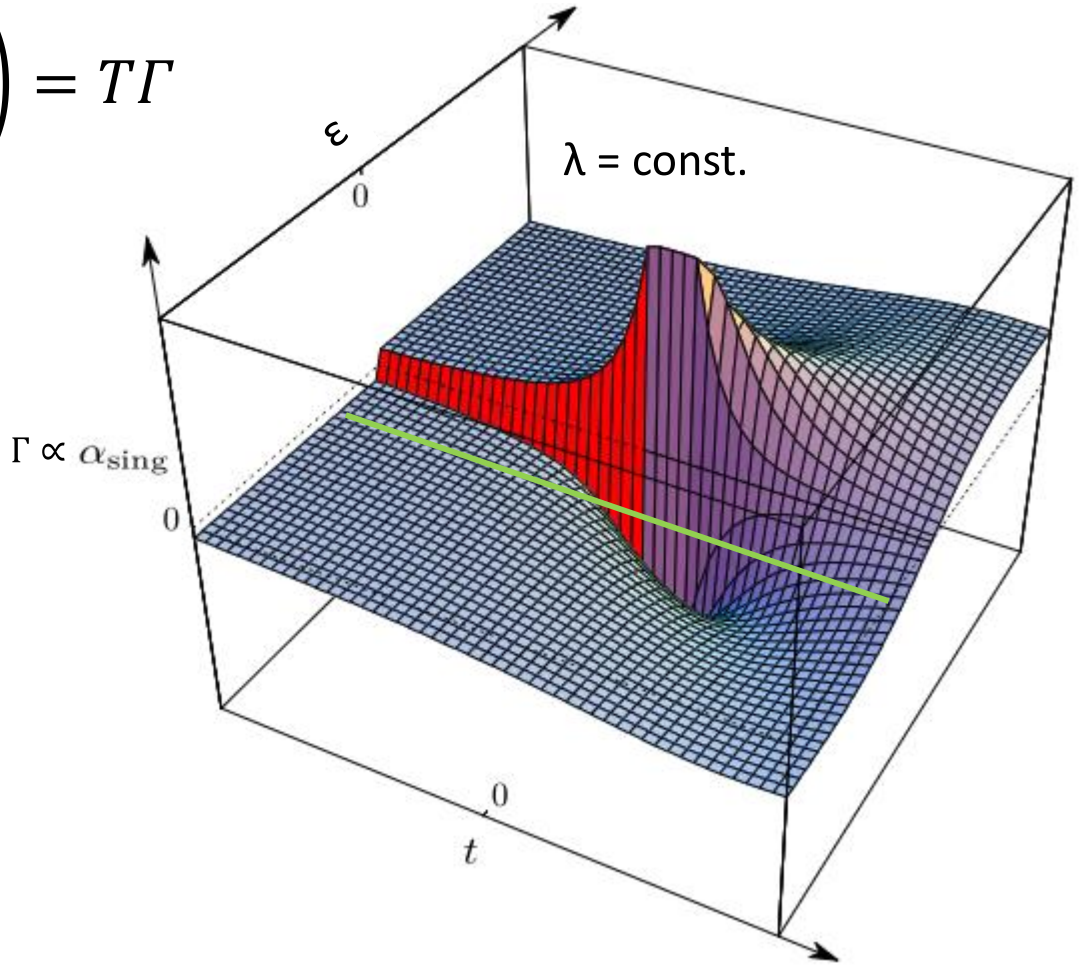
Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

Enhanced Grüneisen parameter at the altermagnetic finite temperature critical point

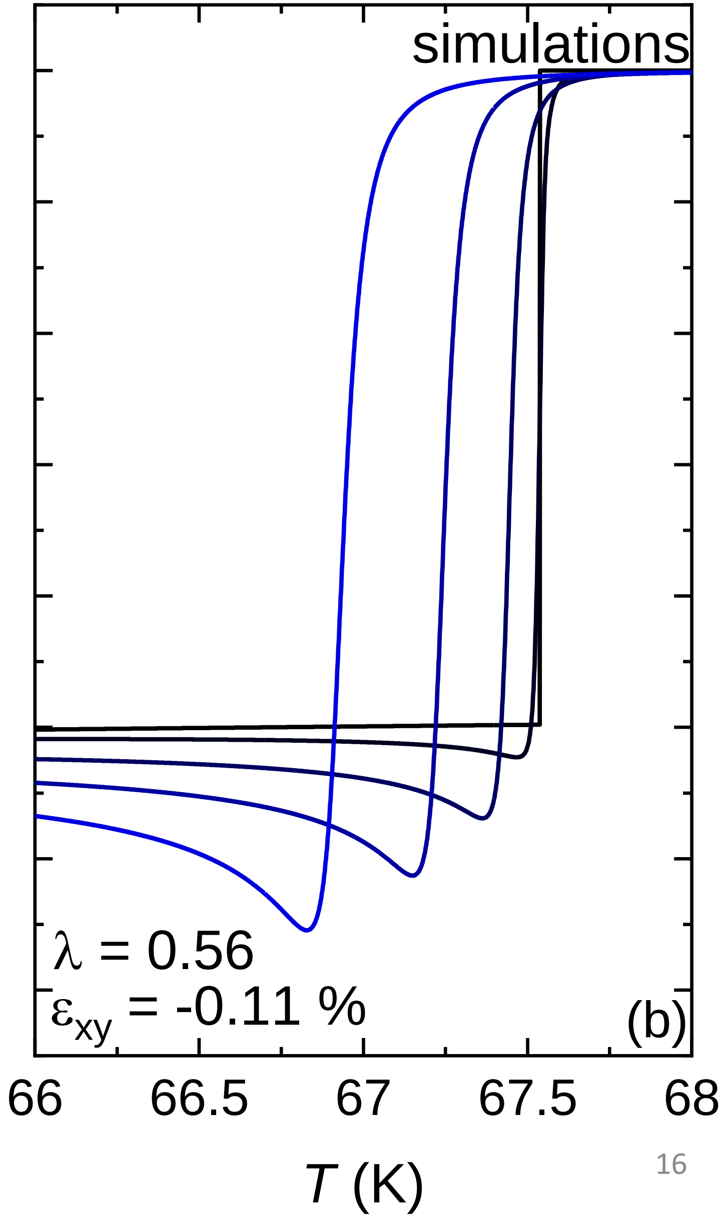
$$\eta = \left(\frac{\partial T}{\partial \epsilon}\right)_S = -\frac{T}{C_\epsilon}\left(\frac{\partial S}{\partial \epsilon}\right) = T\Gamma$$



Coupling term: $\lambda\mu_0 H_z \mu_B \varepsilon_{xy}$

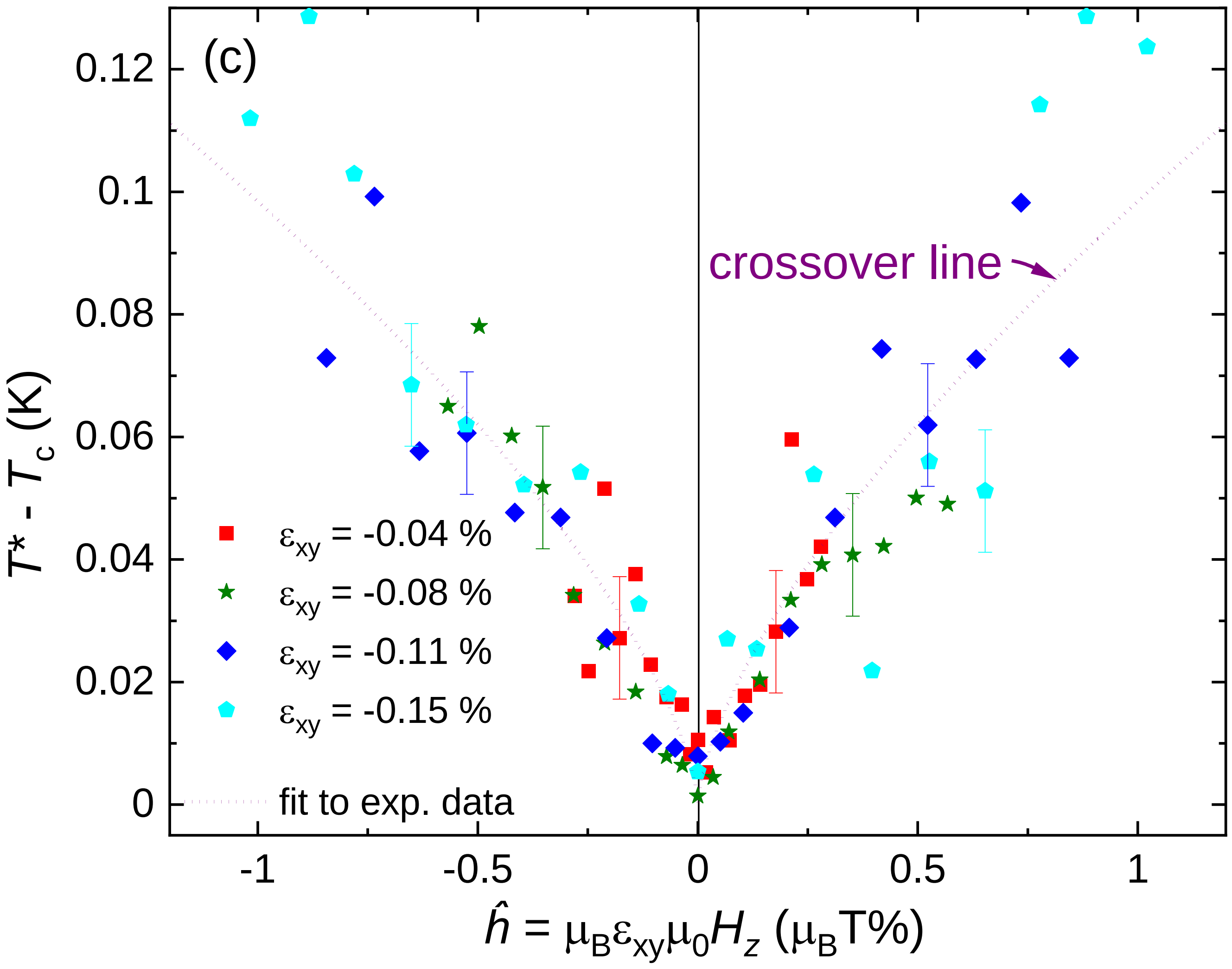


L. Bartosch et al., *Phys. Rev. L* **104**, 2010



C. Steward et al., *Phys. Rev. B* **112**, 2025

Outlook and Summary

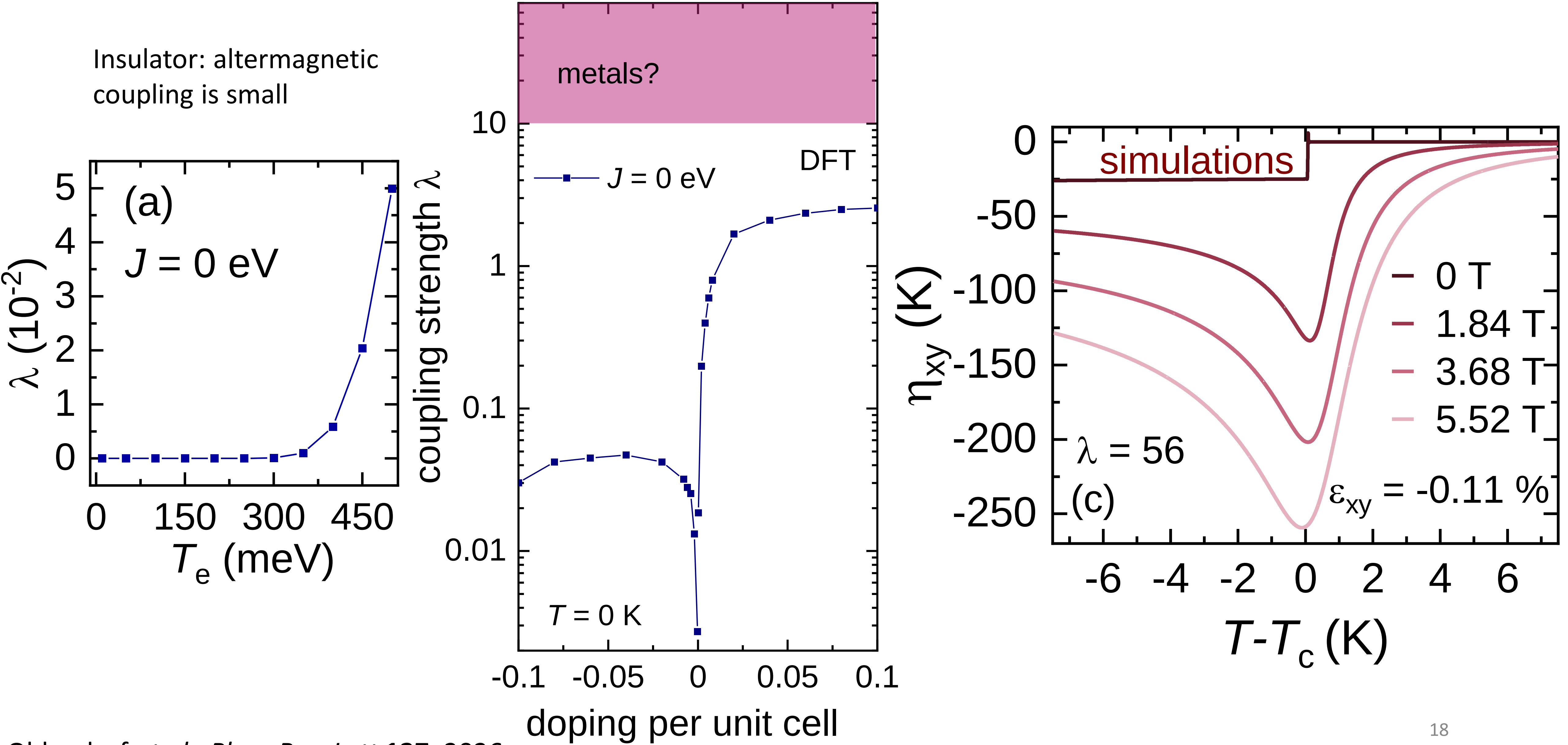


- Strain and magnetic field are key parameters to investigate octupoles/altermagnets
- The elastocaloric effect is a suitable thermodynamic probe:
  - Observation of characteristic crossover behavior
  - Enhanced elastocaloric signatures close to crossover due to quasi divergence of Grüneisen parameter at finite temperature critical end point
- More pronounced signatures expected in metals
  - In progress: Elastocaloric signals in metallic Ce_4Sb_3

Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

DFT Analysis of MnF_2

Insulator: altermagnetic coupling is small

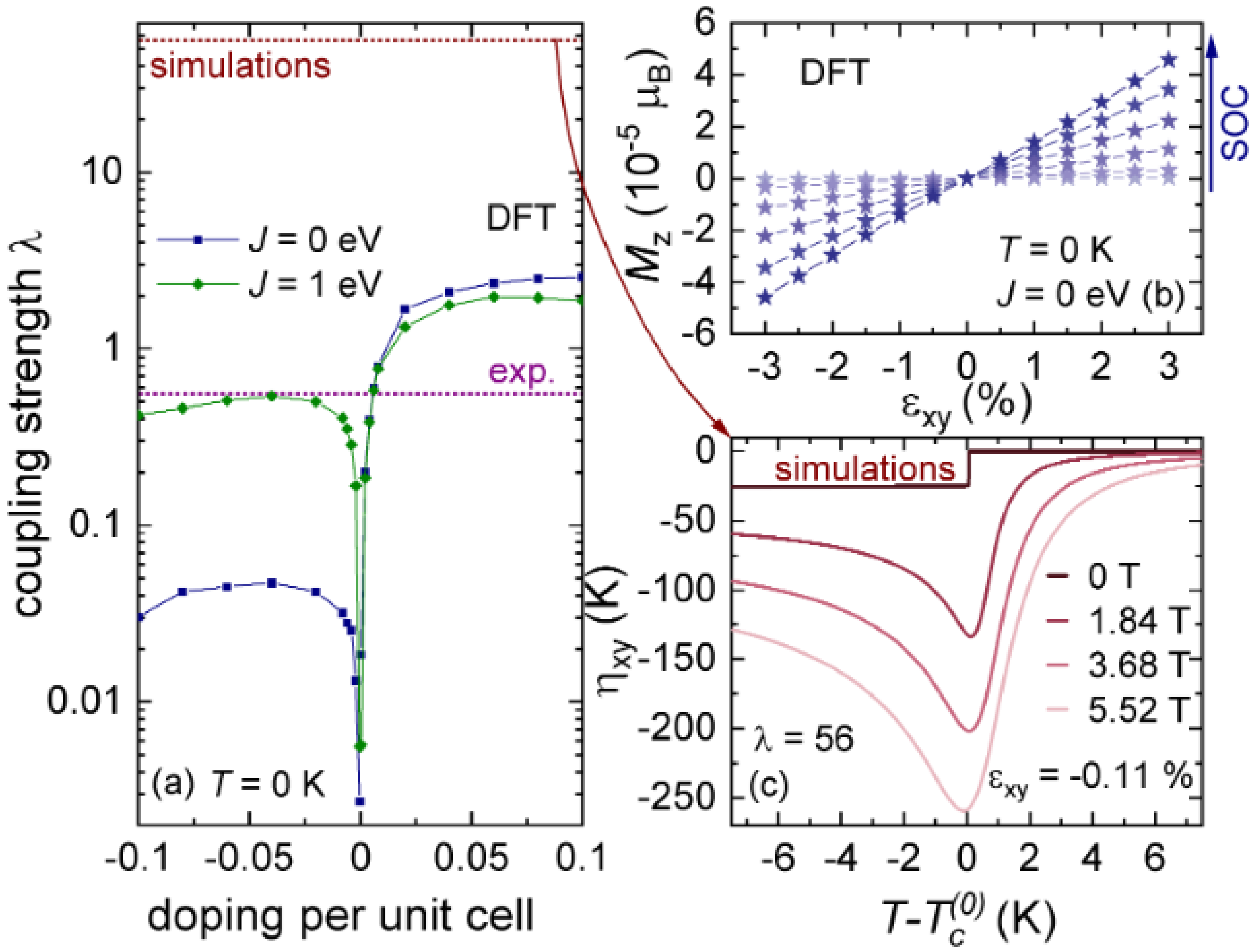


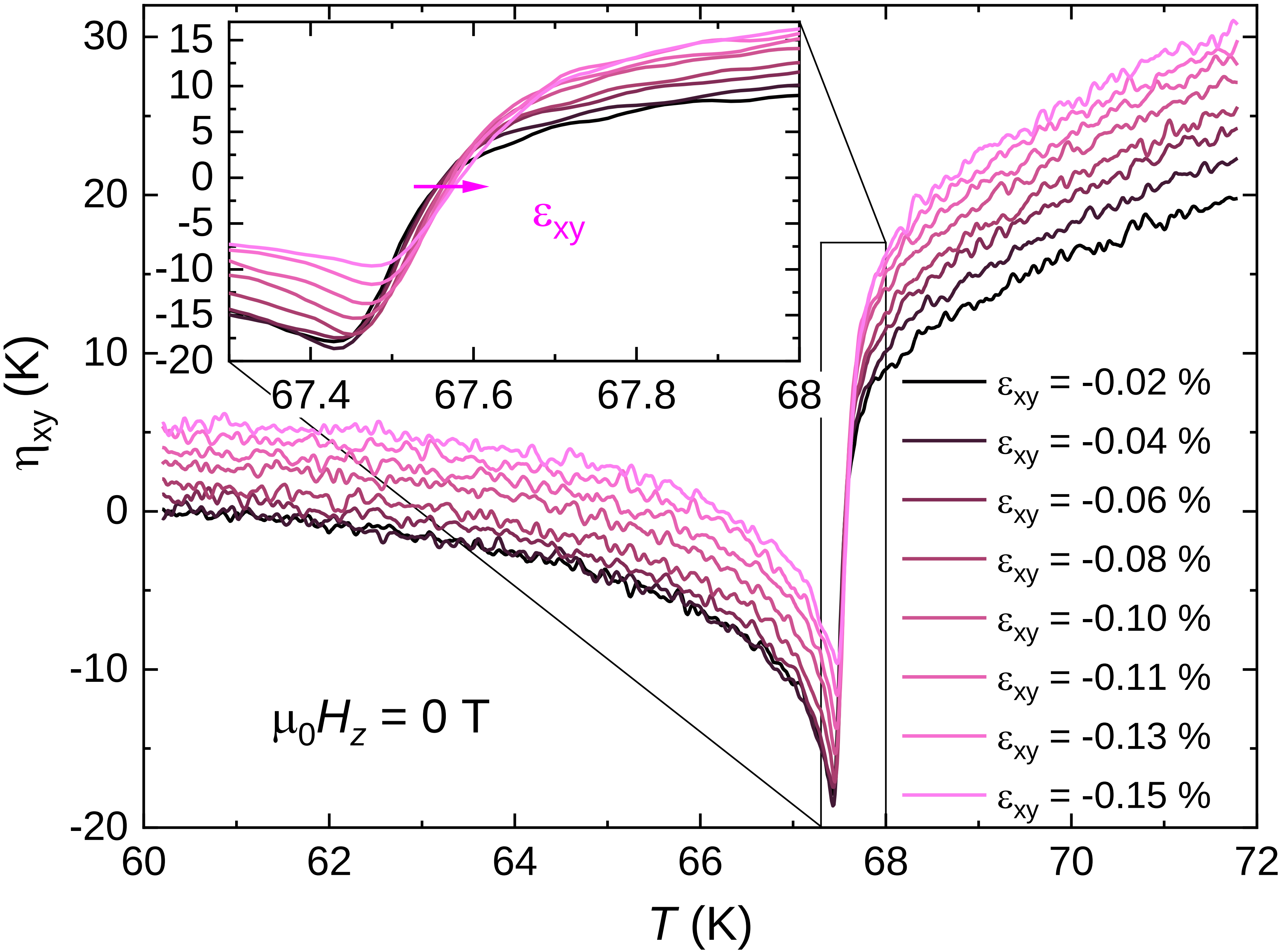
Ohlendorf *et al.*, *Phys. Rev. Lett* **137**, 2026

Relation between altermagnetic coupling constant and piezomagnetism

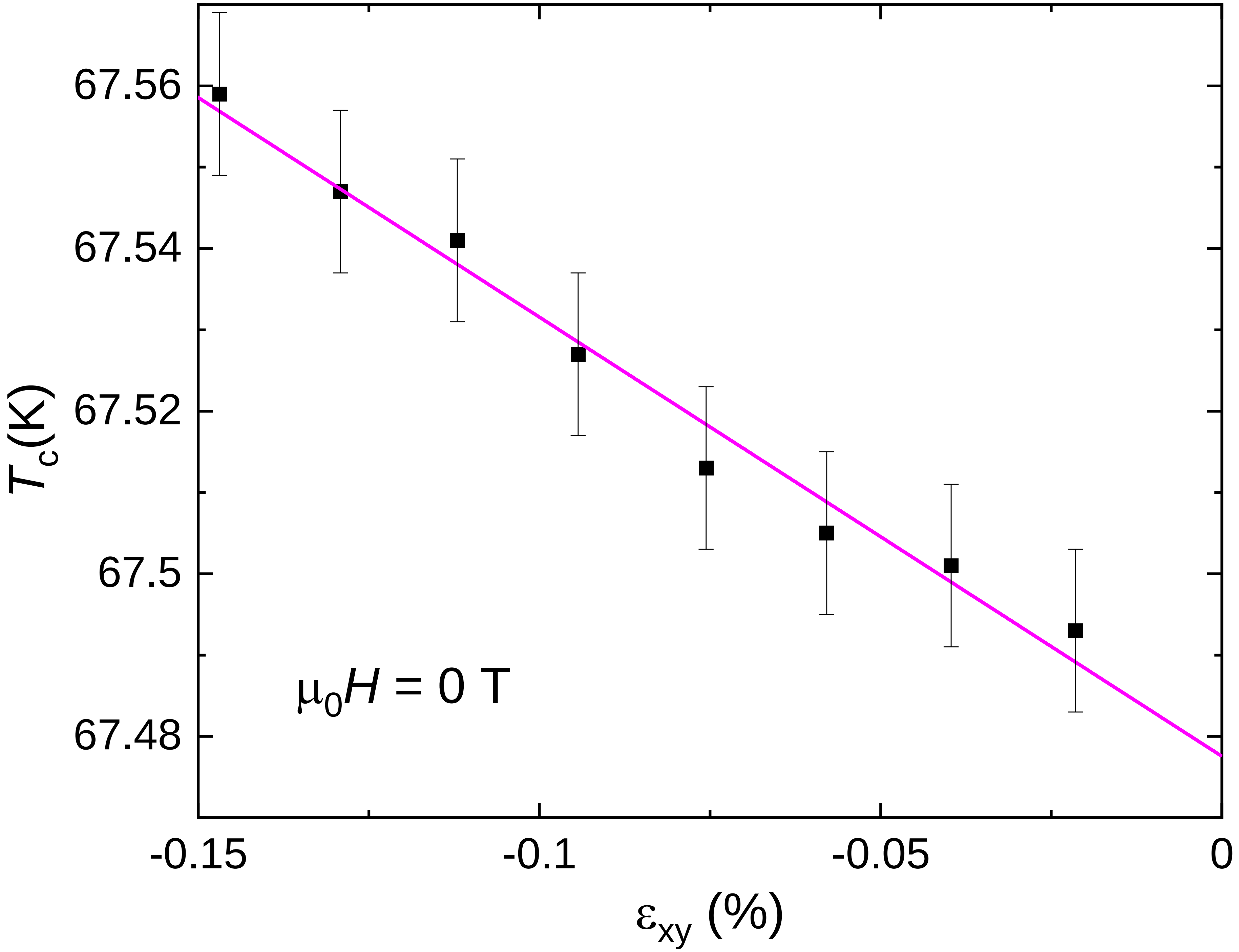
- $M_z = \Lambda_{zxy}\sigma_{xy}$
- $M_z = \Lambda_{zxy}C\epsilon_{xy}$ with C: Young's modulus
- $H = -J\sum_{\langle ij\rangle}\phi_i^z\phi_j^z - \lambda\epsilon\mu_B B\sum_i\phi_i^z$
- $M = -\frac{\partial f}{\partial B} = \lambda\epsilon\mu_B\Phi$
- $\lambda \approx \Lambda C/\mu_B$

DFT Calculations

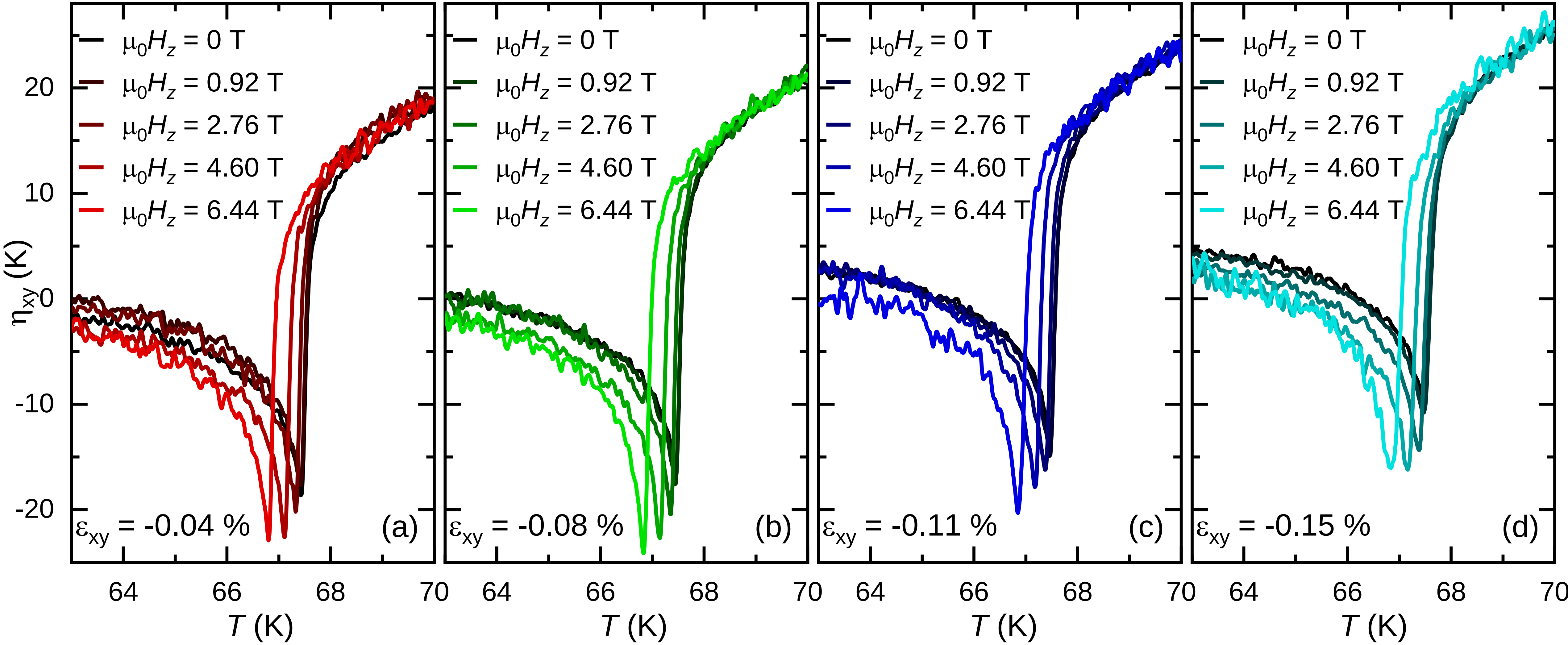




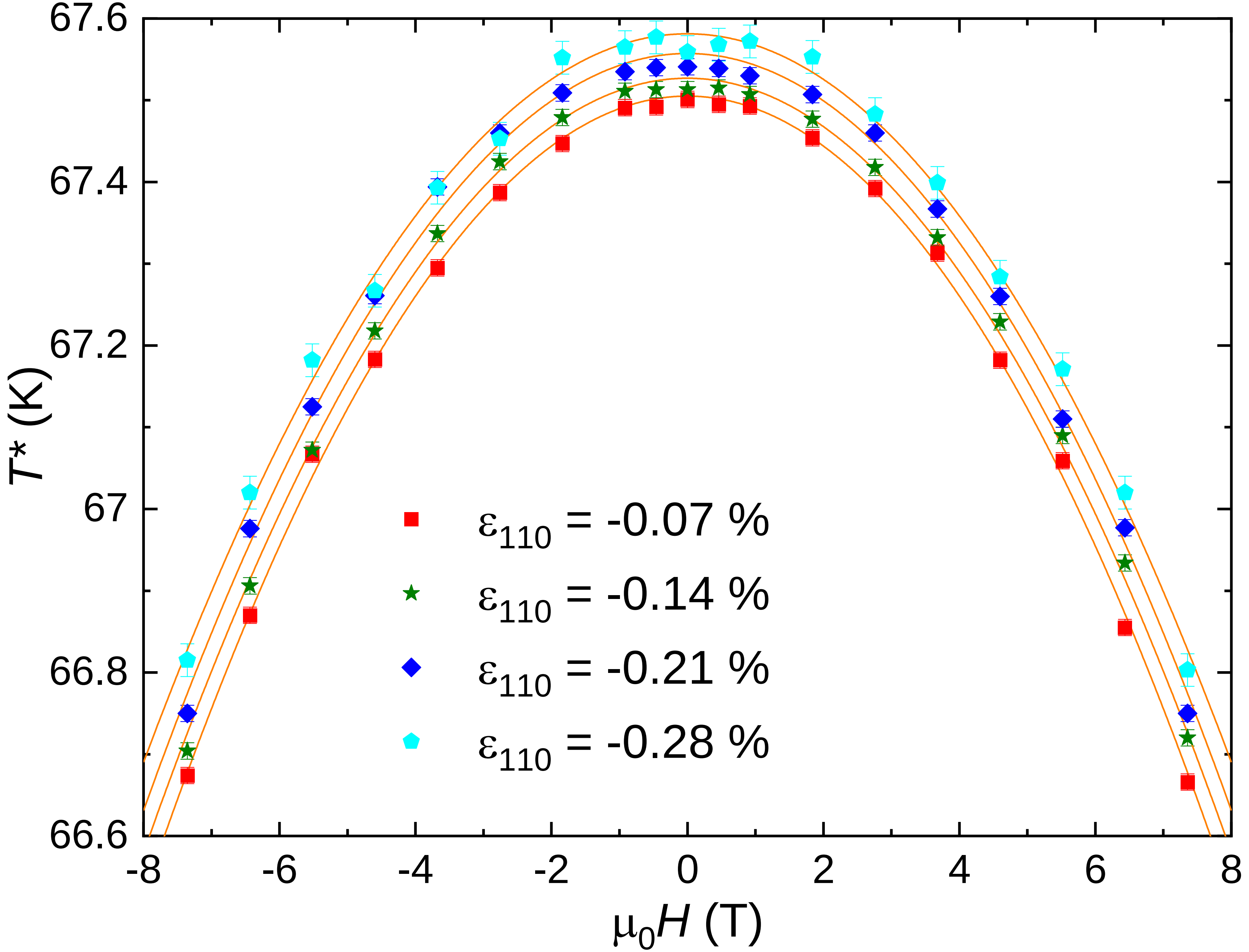
η_{xy} (K)
T (K)
$\mu_0 H_z$ = 0 T
ε_{xy}
ε_{xy} = -0.02 %
ε_{xy} = -0.04 %
ε_{xy} = -0.06 %
ε_{xy} = -0.08 %
ε_{xy} = -0.10 %
ε_{xy} = -0.11 %
ε_{xy} = -0.13 %
ε_{xy} = -0.15 %
30
20
10
0
-10
-20
60
62
64
66
68
70
72
15
10
5
0
-5
-10
-15
-20
67.4
67.6
67.8
68



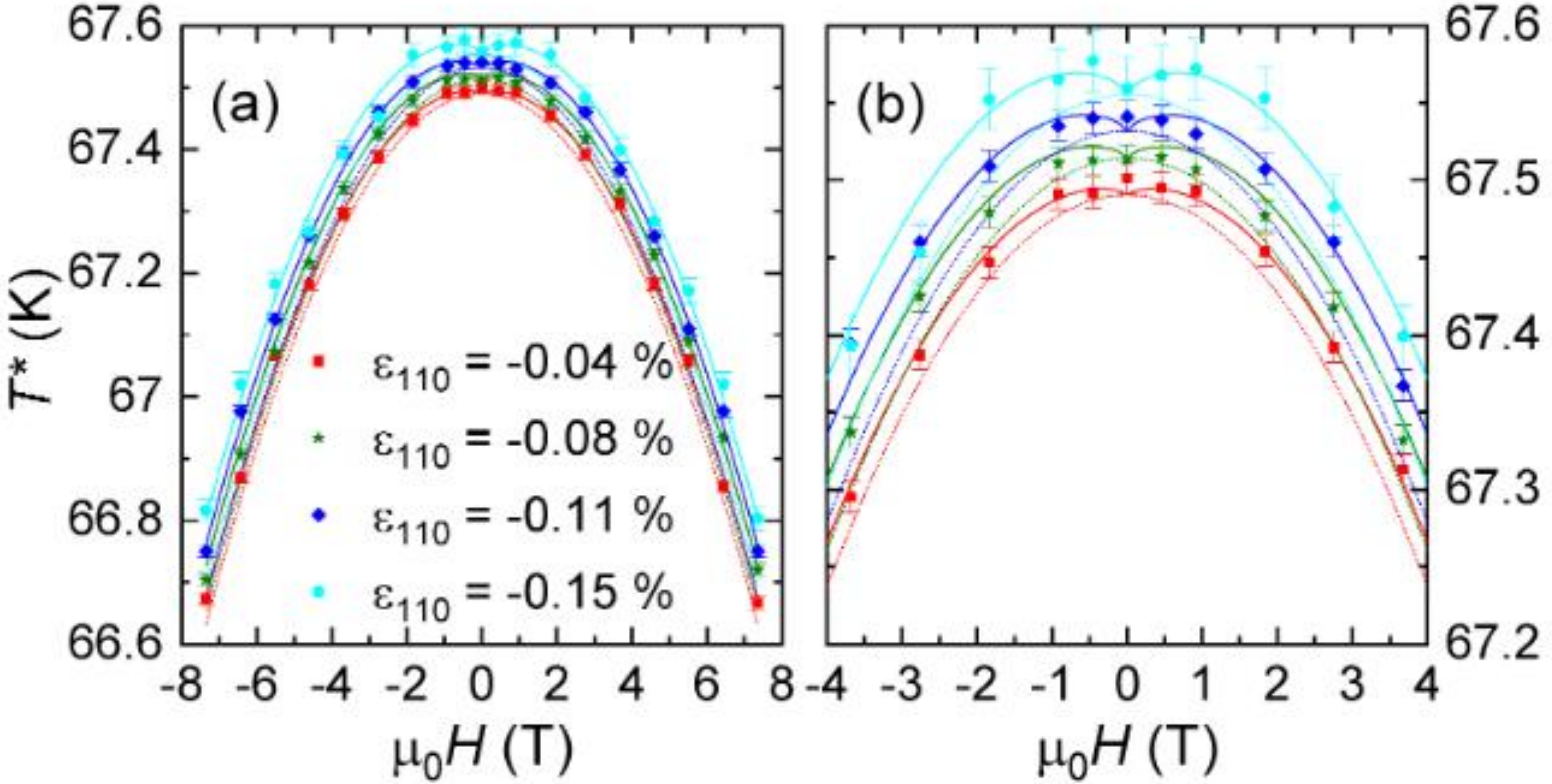
67.56
67.54
67.52
67.5
67.48
T_c(K)
$\mu_0 H$ = 0 T
-0.15
-0.1
-0.05
0
ε_{xy} (%)

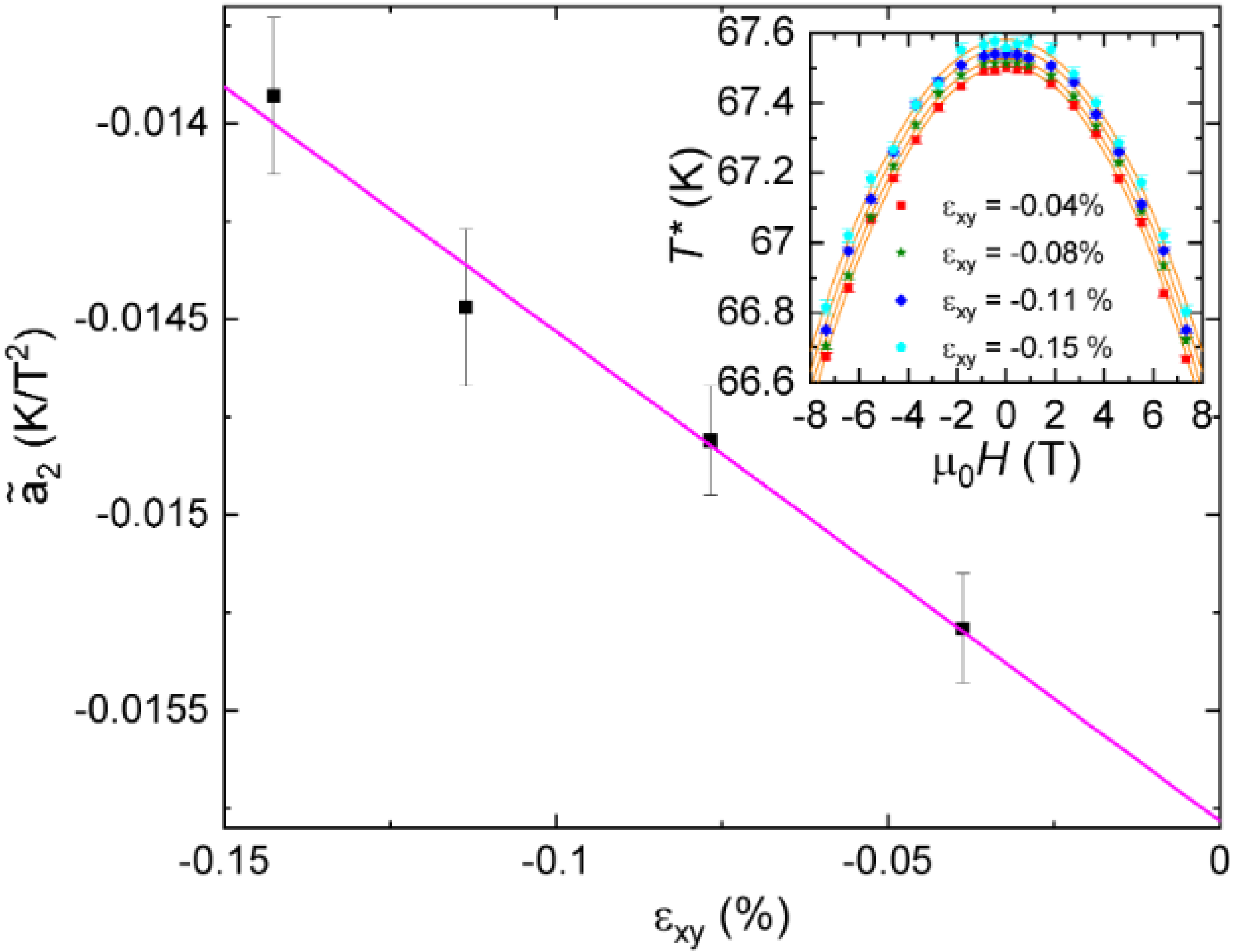


$\mu_0 H_z$ = 0 T
$\mu_0 H_z$ = 0.92 T
$\mu_0 H_z$ = 2.76 T
$\mu_0 H_z$ = 4.60 T
$\mu_0 H_z$ = 6.44 T
η_{xy} (K)
T (K)
ε_{xy} = -0.04 %
(a)
ε_{xy} = -0.08 %
(b)
ε_{xy} = -0.11 %
(c)
ε_{xy} = -0.15 %
(d)

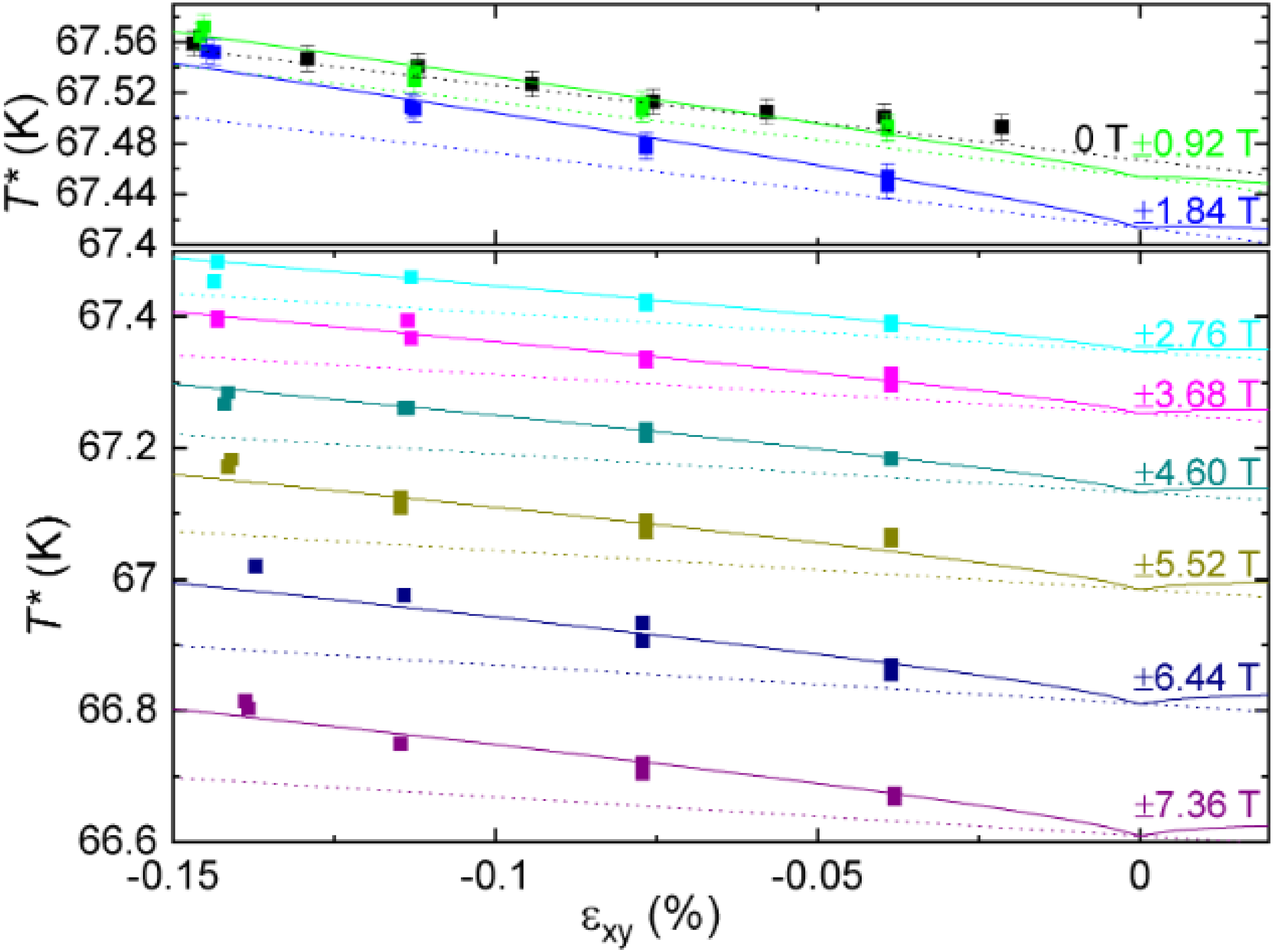


67.6
67.4
67.2
67
66.8
66.6
T^* (K)
-8
-6
-4
-2
0
2
4
6
8
$\mu_0 H$ (T)
ε_{110} = -0.07 %
ε_{110} = -0.14 %
ε_{110} = -0.21 %
ε_{110} = -0.28 %

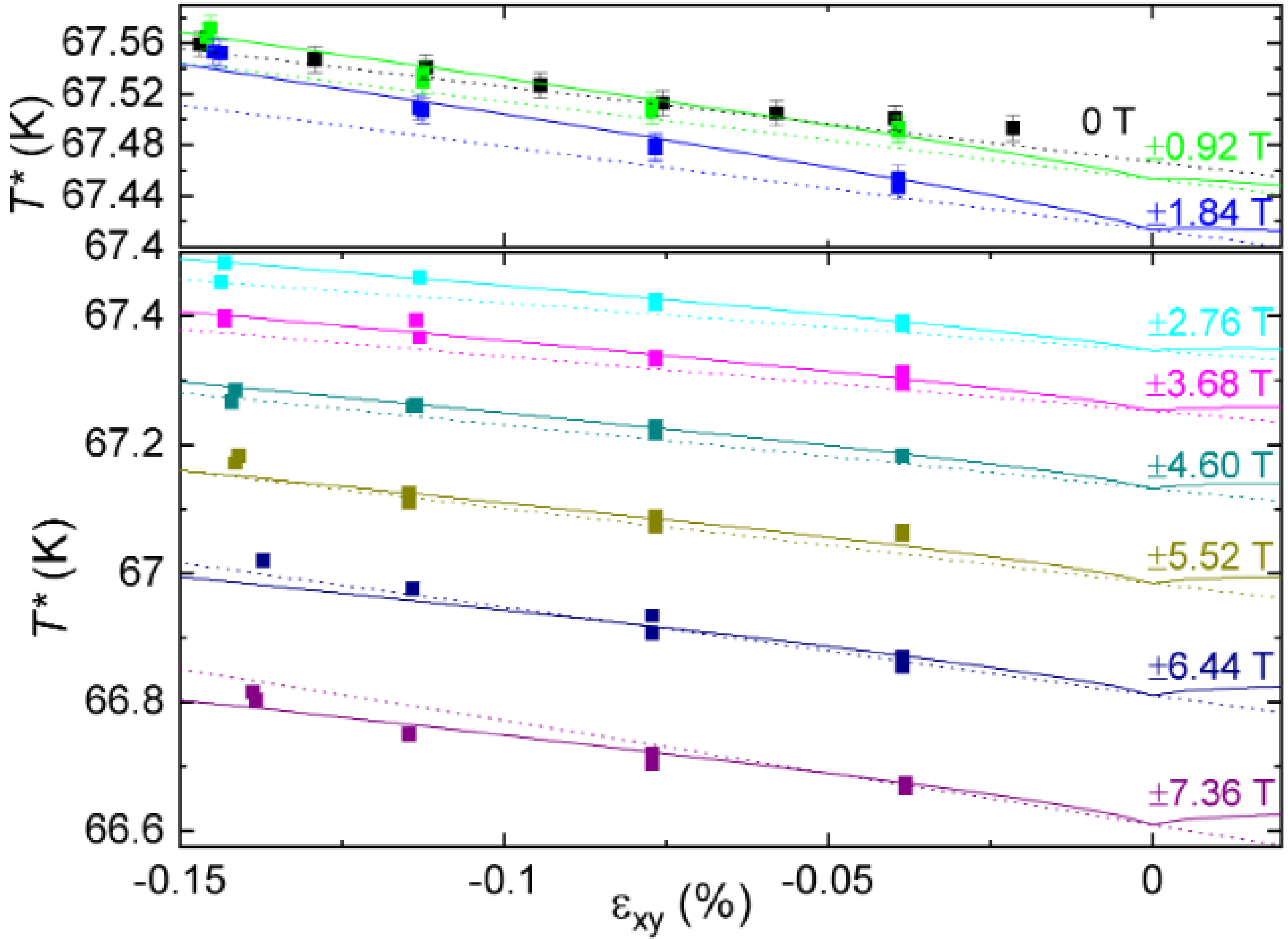

(a)
(b)
T^* (K)
$\mu_0 H$ (T)
$\mu_0 H$ (T)
ε_{110} = -0.04 %
ε_{110} = -0.08 %
ε_{110} = -0.11 %
ε_{110} = -0.15 %
67.6
67.4
67.2
67
66.8
66.6
-8 -6 -4 -2 0 2 4 6 8
-4 -3 -2 -1 0 1 2 3 4
67.6
67.5
67.4
67.3
67.2



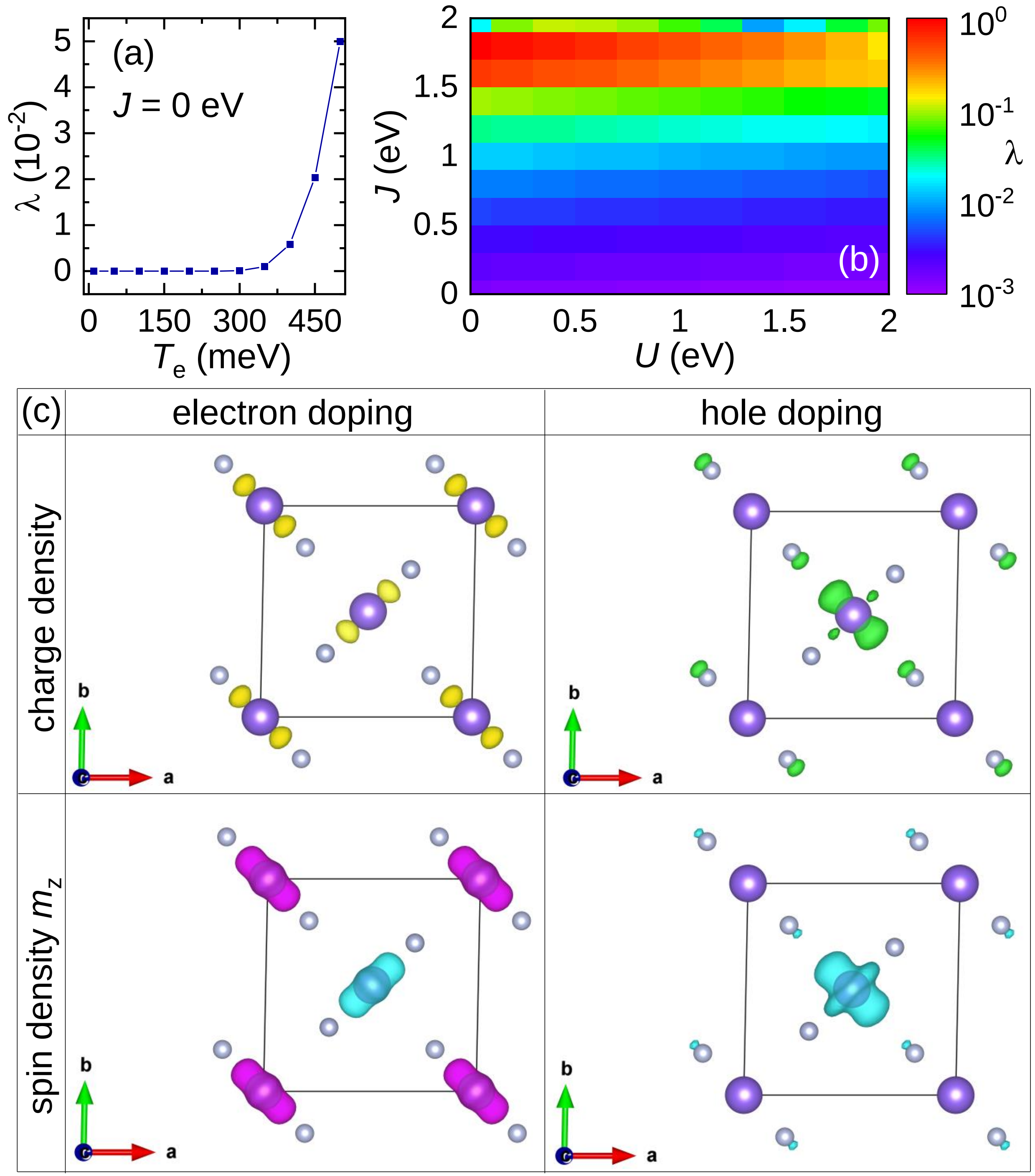
-0.014
-0.0145
-0.015
-0.0155
-0.15
-0.1
-0.05
0
$\tilde{a}_2$ (K/T^2)
ε_{xy} (%)
67.6
67.4
67.2
67
66.8
66.6
T^* (K)
-8 -6 -4 -2 0 2 4 6 8
$\mu_0 H$ (T)
ε_{xy} = -0.04%
ε_{xy} = -0.08%
ε_{xy} = -0.11 %
ε_{xy} = -0.15 %

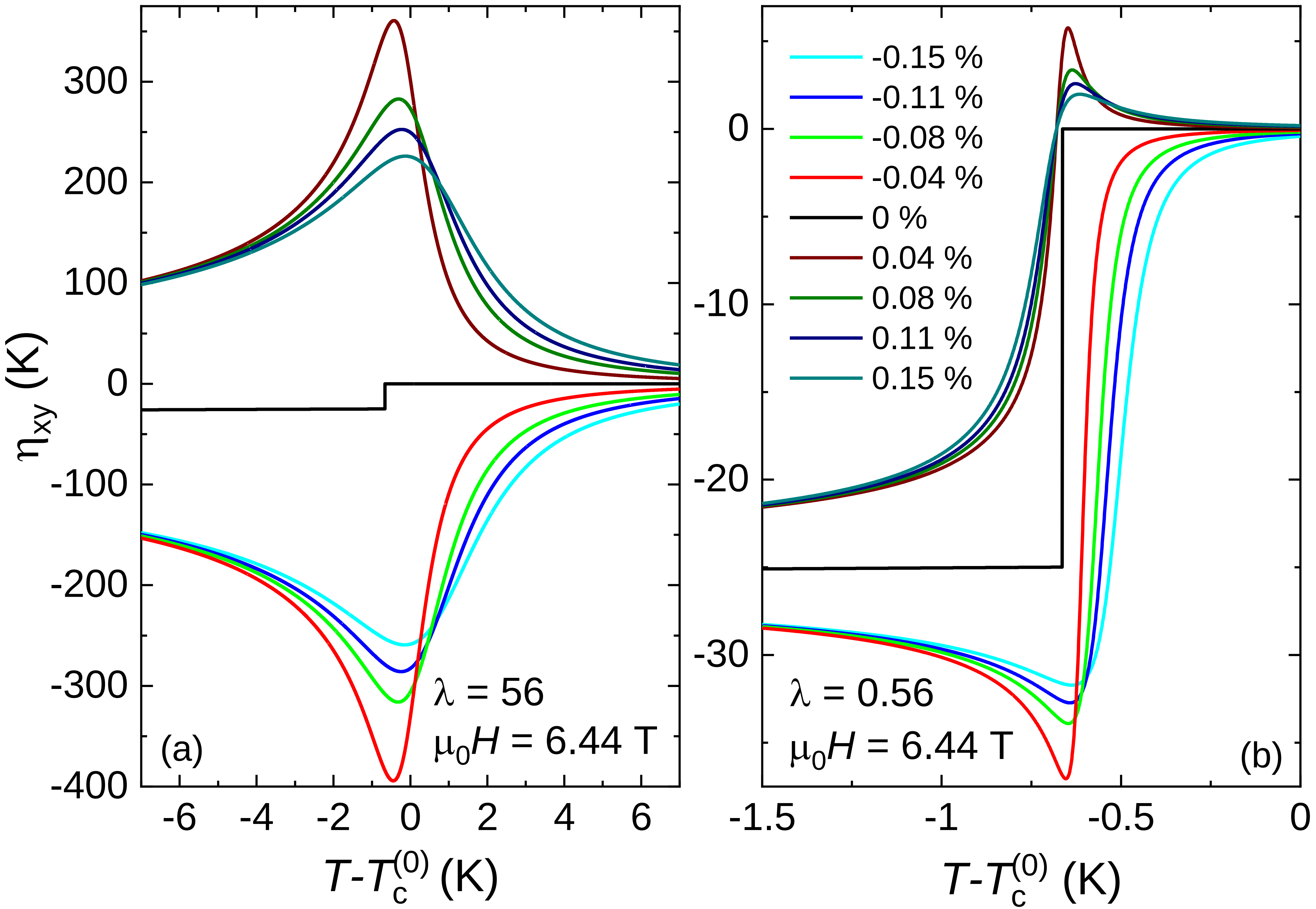


67.56
67.52
67.48
67.44
67.4
T^* (K)
0 T
±0.92 T
±1.84 T
67.4
67.2
67
66.8
66.6
T^* (K)
±2.76 T
±3.68 T
±4.60 T
±5.52 T
±6.44 T
±7.36 T
-0.15
-0.1
-0.05
0
ε_{xy} (%)

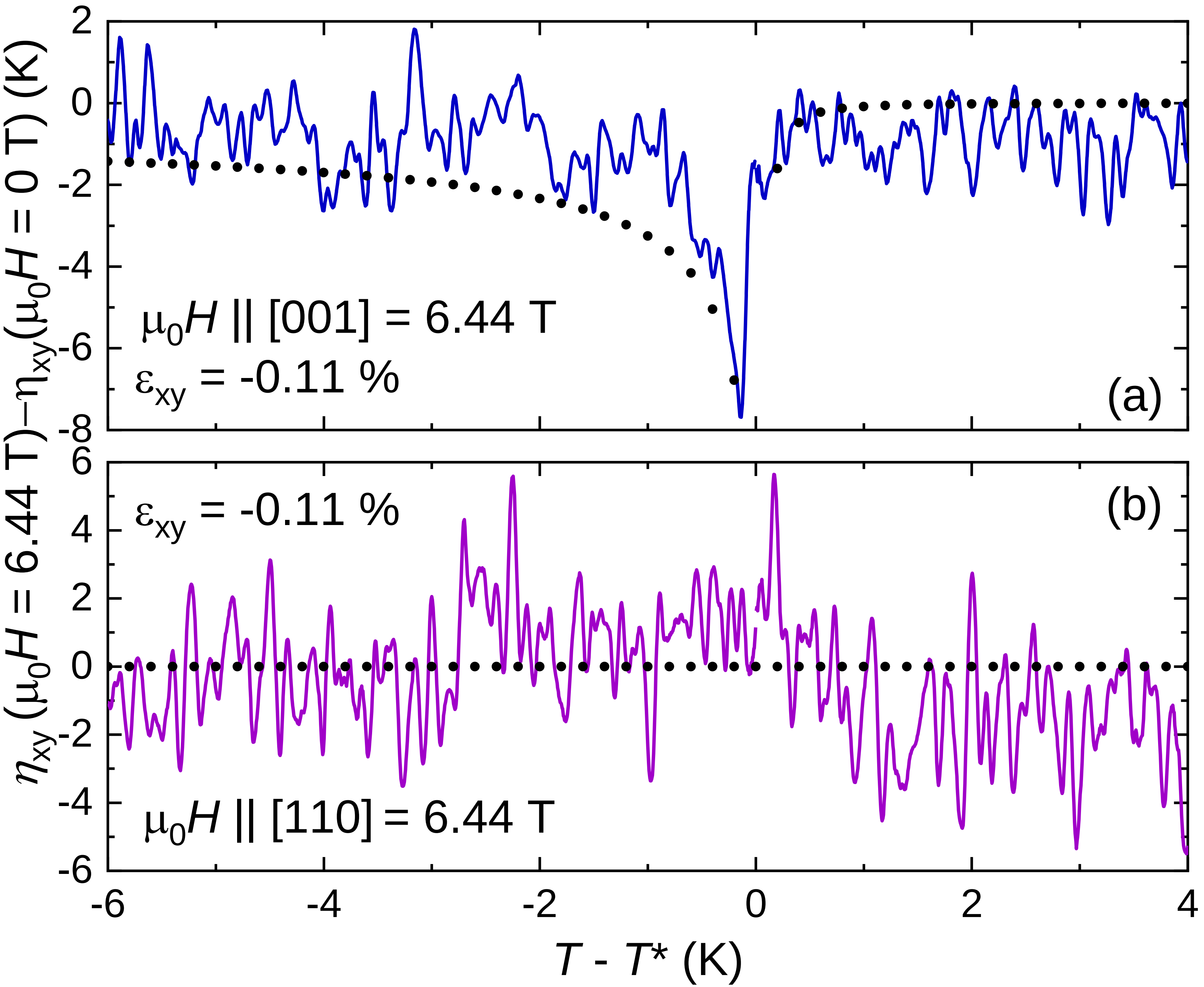


67.56
67.52
67.48
67.44
67.4
T^* (K)
0 T
±0.92 T
±1.84 T
67.4
67.2
67
66.8
66.6
T^* (K)
±2.76 T
±3.68 T
±4.60 T
±5.52 T
±6.44 T
±7.36 T
-0.15
-0.1
-0.05
0
ε_{xy} (%)

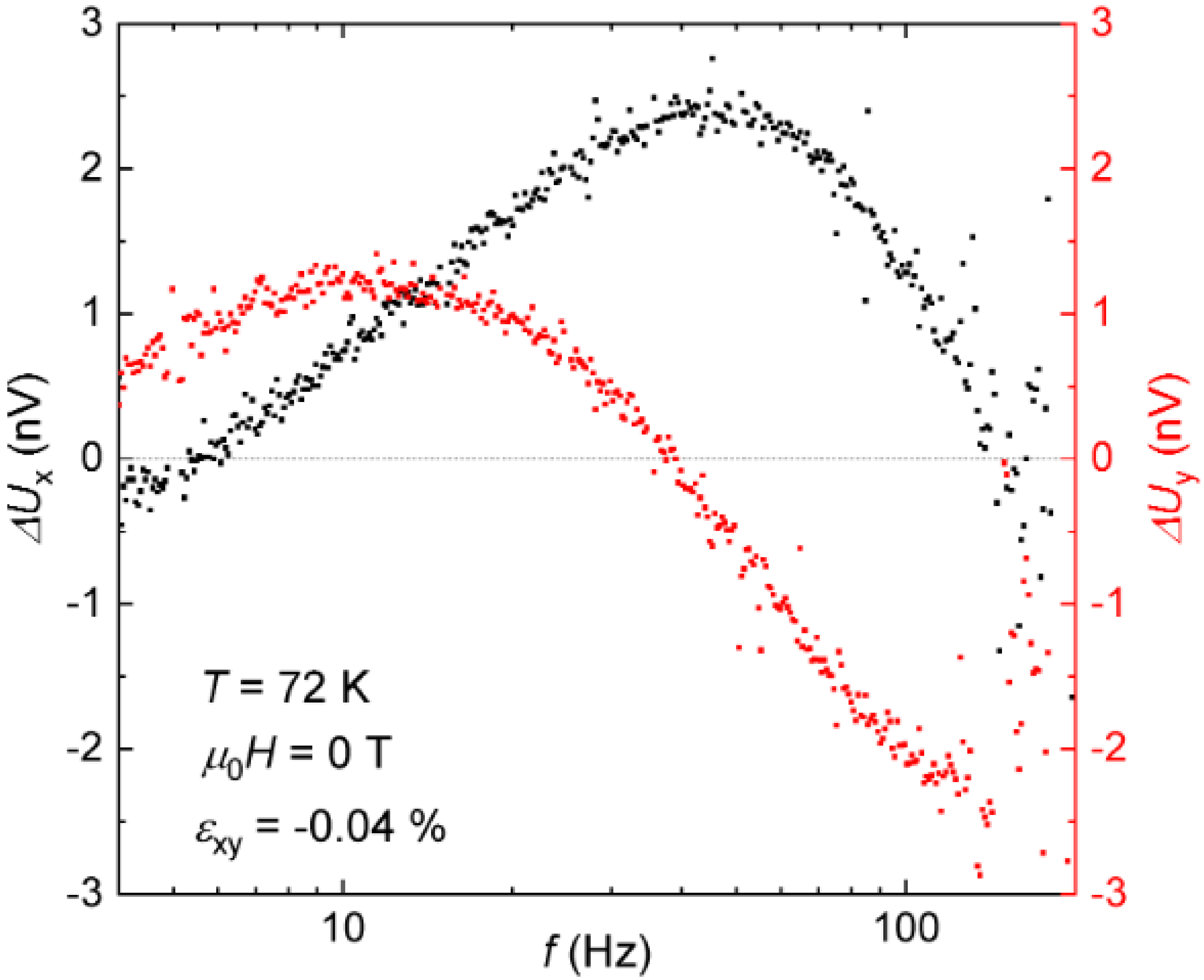

(a)
J = 0 eV
λ (10^-2)
T_e (meV)
(b)
J (eV)
U (eV)
λ
(c)
electron doping
hole doping
charge density
spin density m_z
b
a
c



η_{xy} (K)
300
200
100
0
-100
-200
-300
-400
-6 -4 -2 0 2 4 6
T-$T_c^{(0)}$ (K)
λ = 56
$\mu_0 H$ = 6.44 T
(a)
0
-10
-20
-30
-1.5 -1 -0.5 0
T-$T_c^{(0)}$ (K)
-0.15 %
-0.11 %
-0.08 %
-0.04 %
0 %
0.04 %
0.08 %
0.11 %
0.15 %
λ = 0.56
$\mu_0 H$ = 6.44 T
(b)



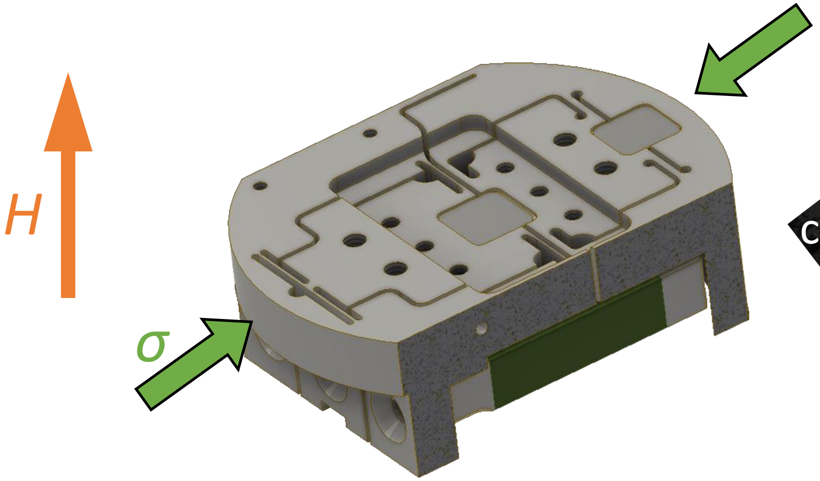
$\eta_{xy}(\mu_0 H = 6.44$ T$) - \eta_{xy}(\mu_0 H = 0$ T$)$ (K)
$\mu_0 H \parallel [001] = 6.44$ T
$\varepsilon_{xy} = -0.11$ %
(a)
$\eta_{xy}(\mu_0 H = 6.44$ T$)$
$\varepsilon_{xy} = -0.11$ %
(b)
$\mu_0 H \parallel [110] = 6.44$ T
$T - T^*$ (K)
2
0
-2
-4
-6
-8
6
4
2
0
-2
-4
-6
-6
-4
-2
0
2
4

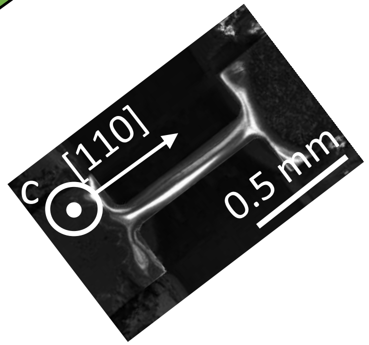


3
2
1
0
-1
-2
-3
ΔU_x (nV)
ΔU_y (nV)
10
100
f (Hz)
T = 72 K
$\mu_0 H$ = 0 T
ε_{xy} = -0.04 %

Experimental Methods

High-precision strain tuning:





Hicks *et al.*, Science **344**, 2014

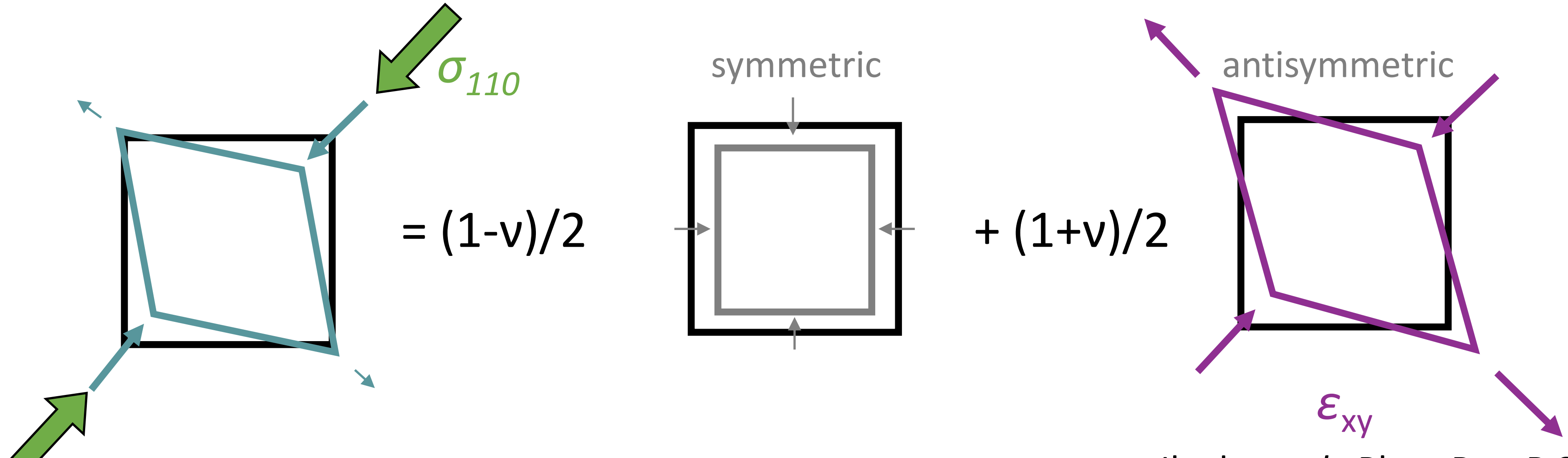
Thermodynamic probe:

Elastocaloric Effect:

$$\left(\frac{\partial T}{\partial \epsilon}\right)_S = -\frac{T}{C_\epsilon}\left(\frac{\partial S}{\partial \epsilon}\right) \quad \Rightarrow F(\epsilon, T, H)$$

Free energy

Ikeda *et al.*, Rev. Sci. Instrum. **90**, 2019



Ikeda *et al.*, Phys. Rev. B **98**, 2018