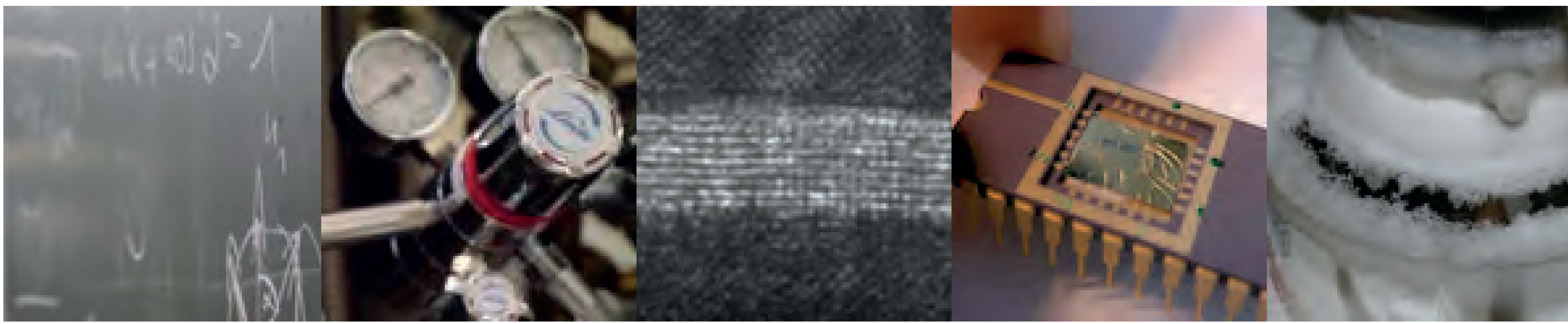
Anomalous Hall and Nernst effect in the magnetic Weyl semimetal $Co_3Sn_2S_2$

Kevin Geishendorf, IFW Dresden, Institute for Metallic Materials



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P. Vir
C. Shekhar
C. Felser

Berry curvature and anomalous velocity

- correction to Bloch electron group velocity:

$$\dot{x}_c = \frac{\partial \epsilon}{\hbar \partial \vec{k}} + \boxed{\frac{e}{\hbar}\vec{E} \times \vec{\Omega}} \longrightarrow \text{anomalous velocity}$$

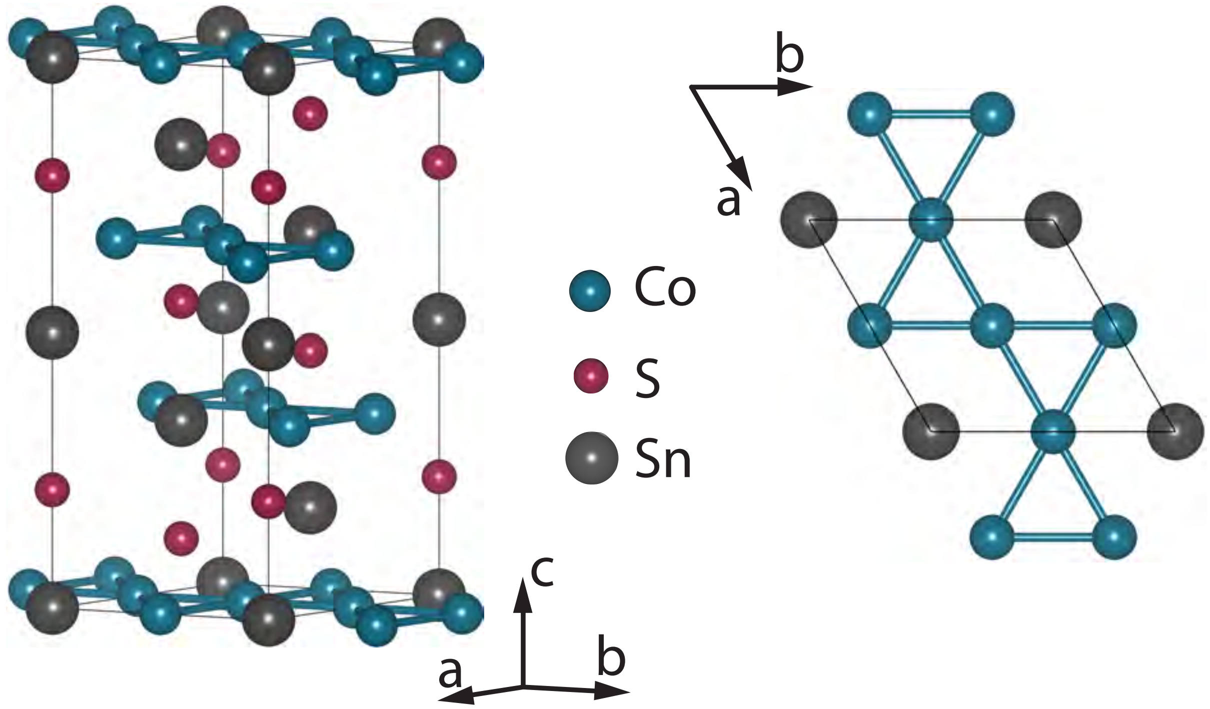
- anomalous Hall conductivity :

$$\sigma_{\mathrm{AH}}^{\mathrm{int}} = -\frac{e^2}{\hbar} \sum_n \int \frac{d\vec{k}}{(2\pi)^3} f_{n,\vec{k}} \boxed{\Omega_z(n,\vec{k})} \longrightarrow \text{Berry curvature contribution}$$

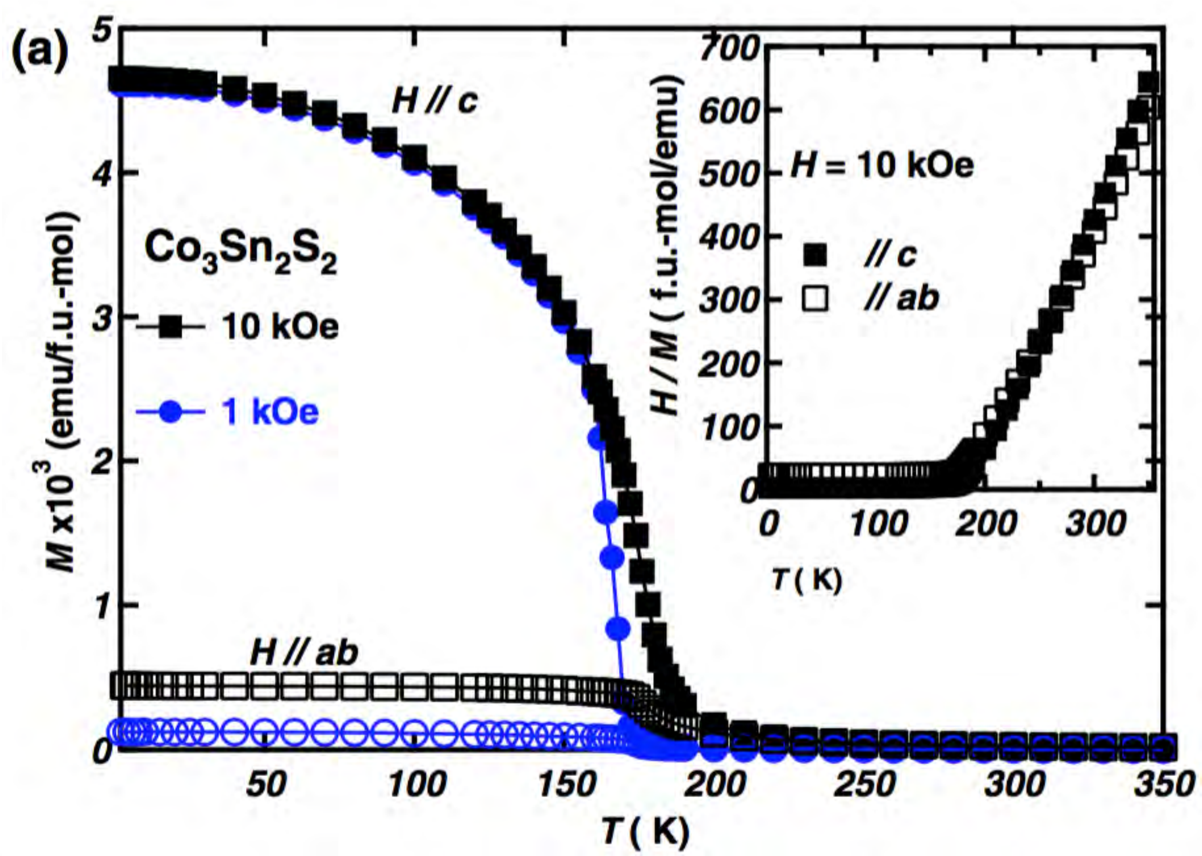
- Weyl points and nodal lines are accompanied by large Berry curvature

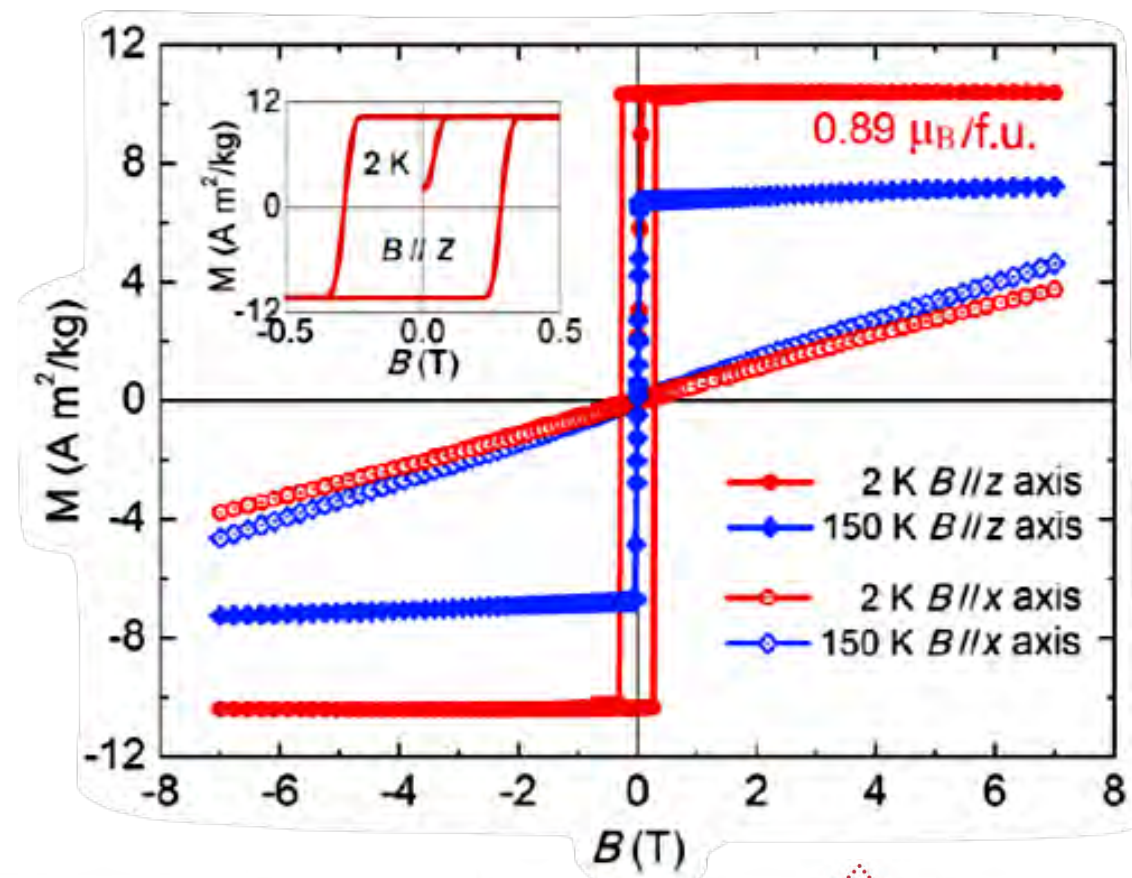
G. Sundaram and Q. Niu, (1999) *Physical Review B 59* (14)

Kagome (ferro)magnet $Co_3Sn_2S_2$



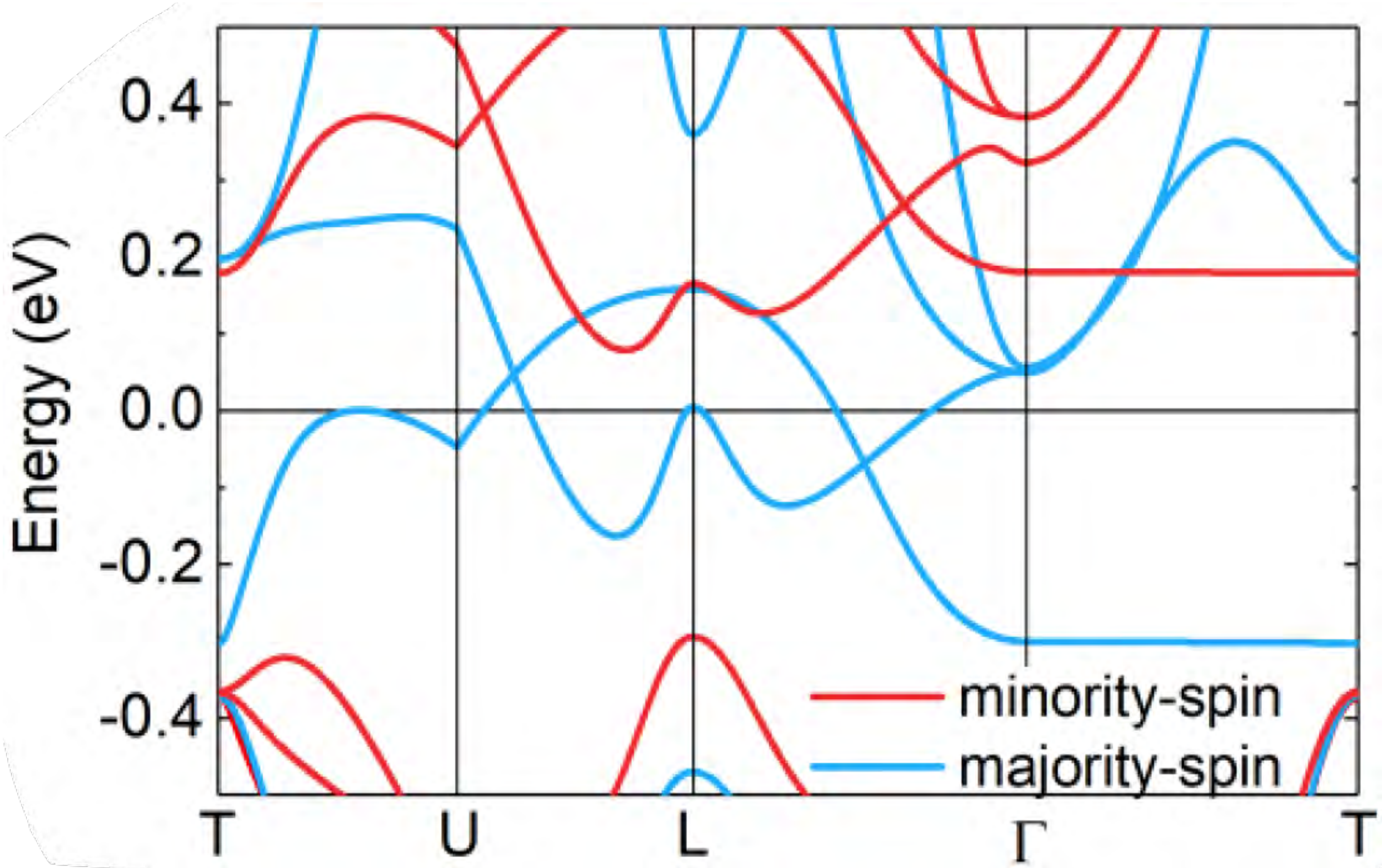
- Co - Kagome lattices stacked along *c*-direction
- Magnetic ordering at 175 K
- Easy axis along *c*-direction

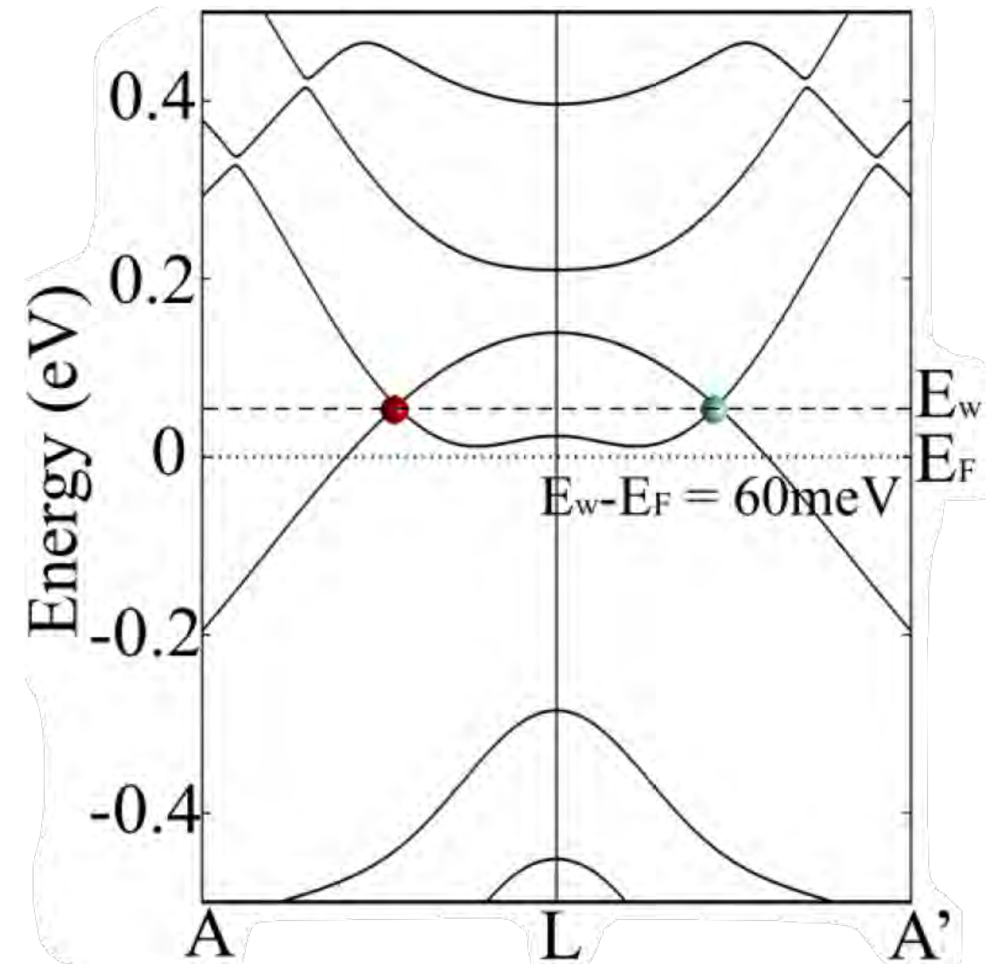




Kassem, M. A. et al. (2016). *Journal of the Physical Society of Japan, 85* (6), 064706–7.
Liu, E. et al. (2018). *Nature Physics, 14* (11),

Band structure of $Co_3Sn_2S_2$

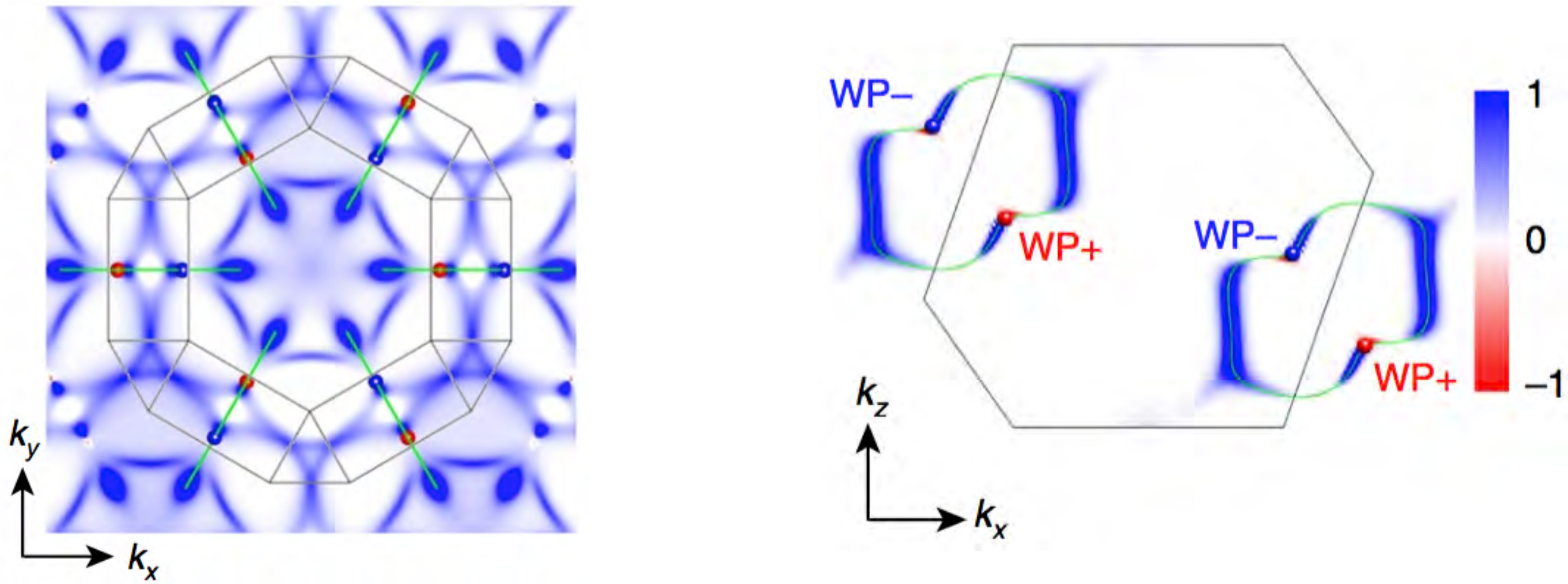




- majority-spin bands cross Fermi energy
- minority-spin bands are gaped with 0.35eV
- two band crossings between U - L and L - Γ
- SOC opens gap ⟶ splitting of nodal line

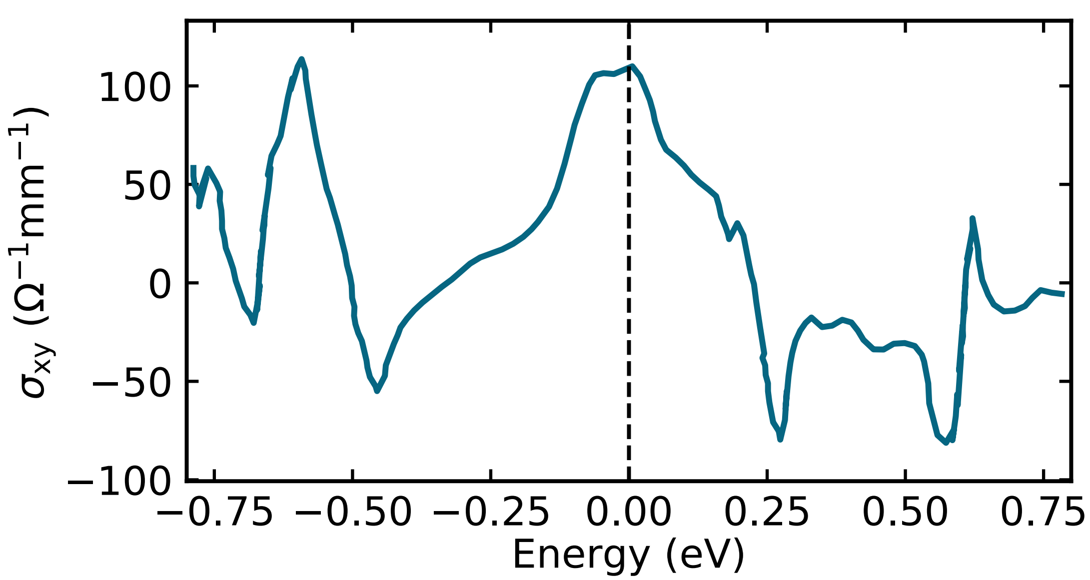
Xu, Q. et al. (2018). *Physical Review B*, *97* (8)

Berry curvature distribution in $Co_3Sn_2S_2$



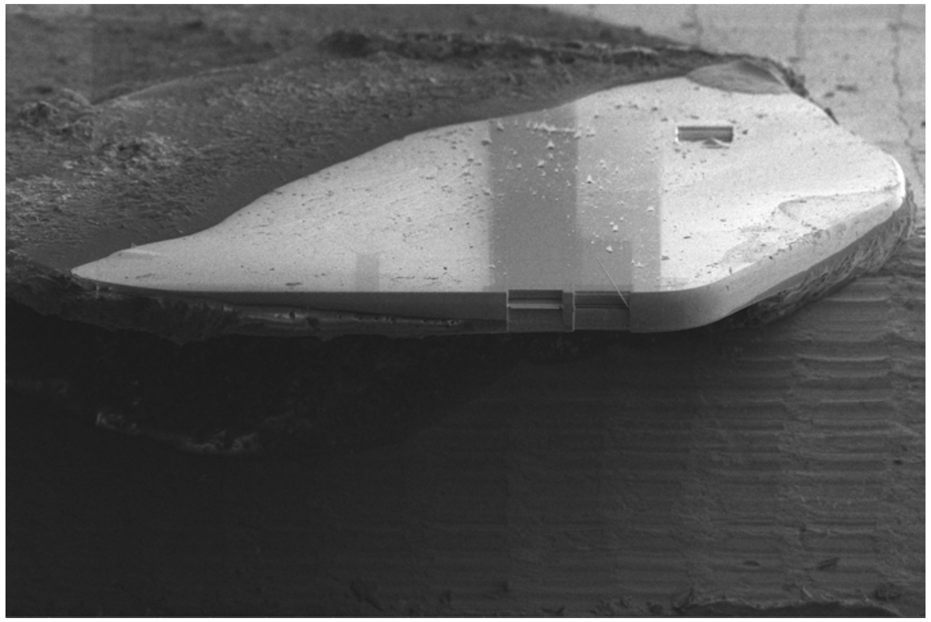
$$\sigma_{\mathrm{AH}}^{\mathrm{int}} = -\frac{e^2}{\hbar} \sum_n \int \frac{d\vec{k}}{(2\pi)^3} f_{n,\vec{k}}\ \Omega_z(n,\vec{k})$$

→ large intrinsic anomalous Hall conductivity for $Co_3Sn_2S_2$ expected ($100\ \Omega^{-1}mm^{-1}$)



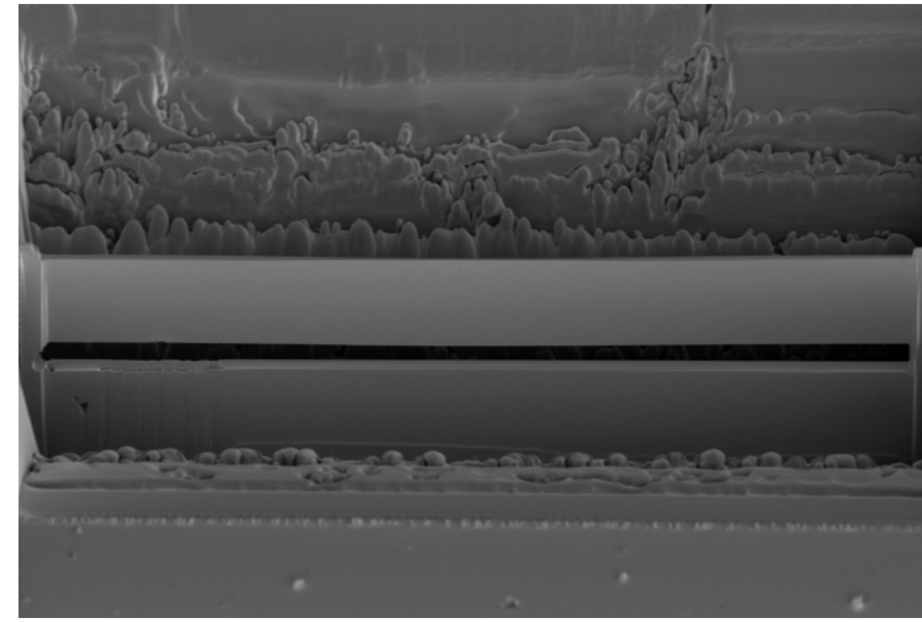
$Co_3Sn_2S_2$ microstructures

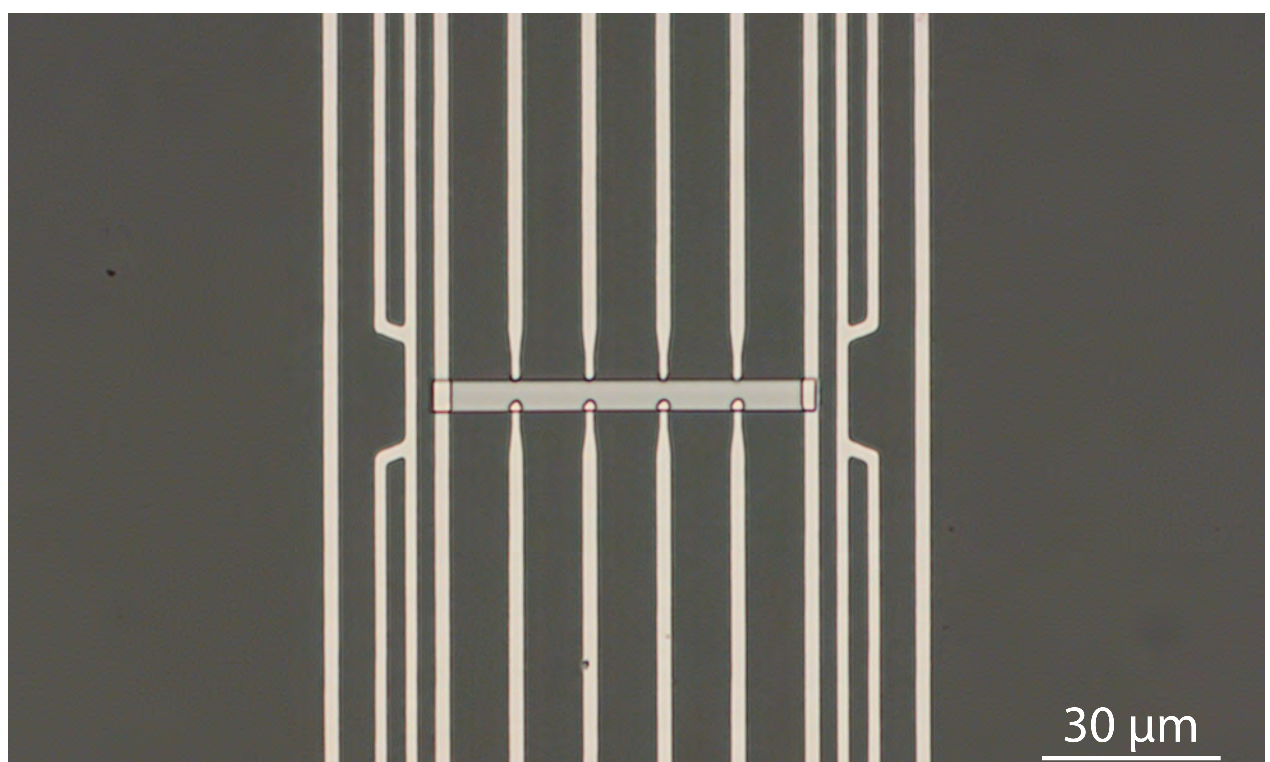
single crystal



focussed ion beam cutting

micro ribbon

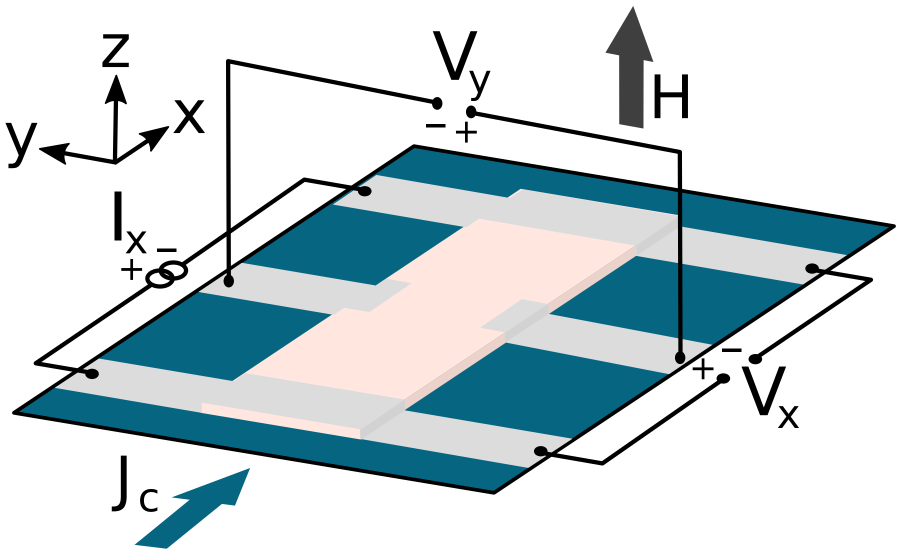




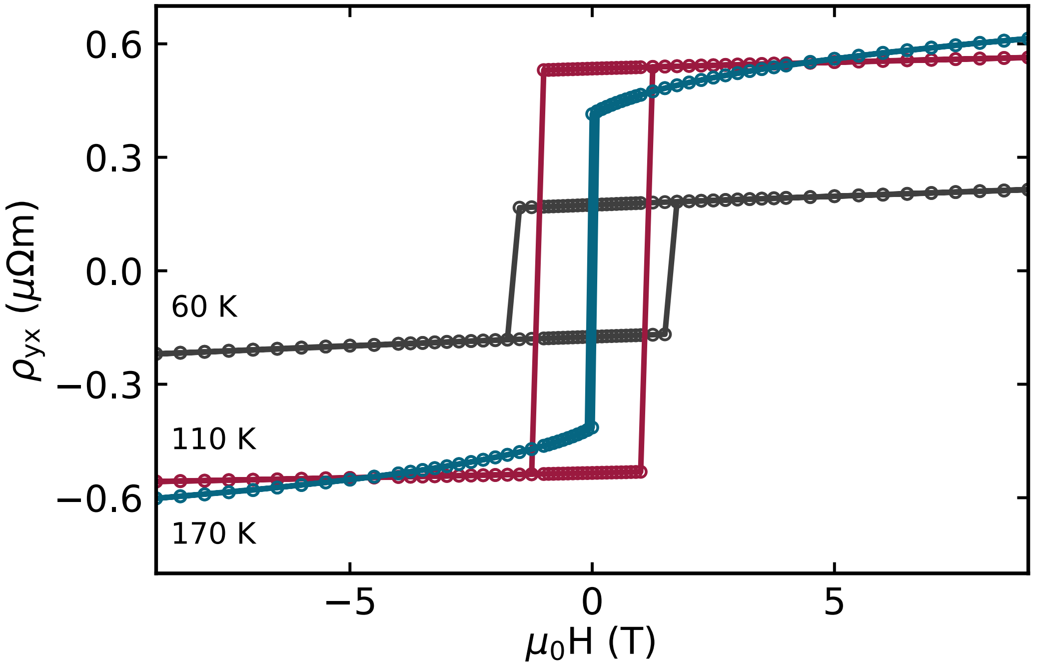
(*c*-axis out of plane)

optical lithography
+ lift-off process

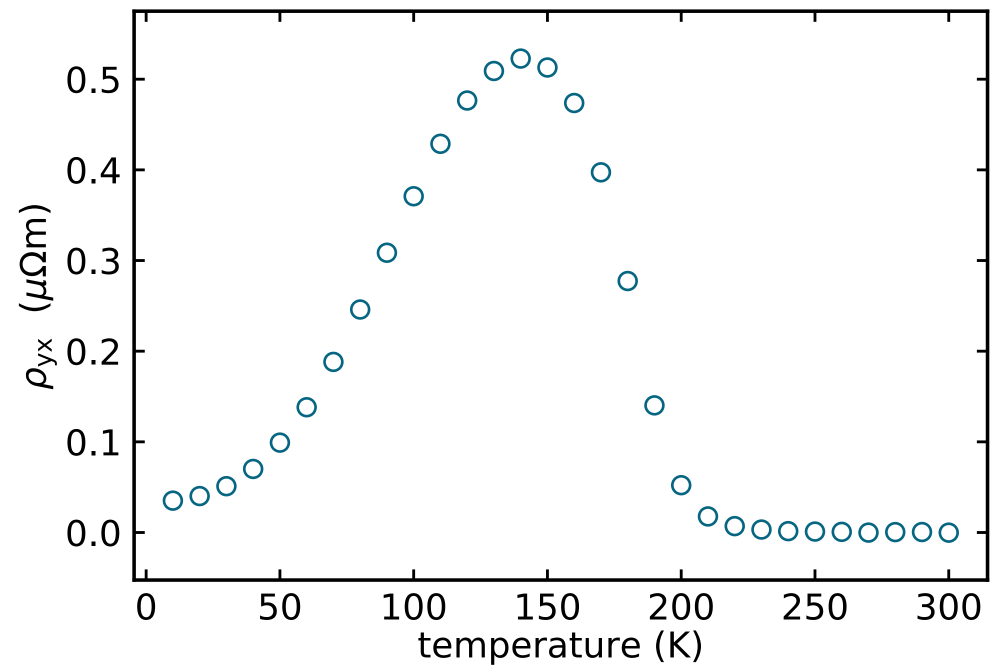
Anomalous Hall effect



Hall sweeps:



extracted anomalous Hall resistivity:



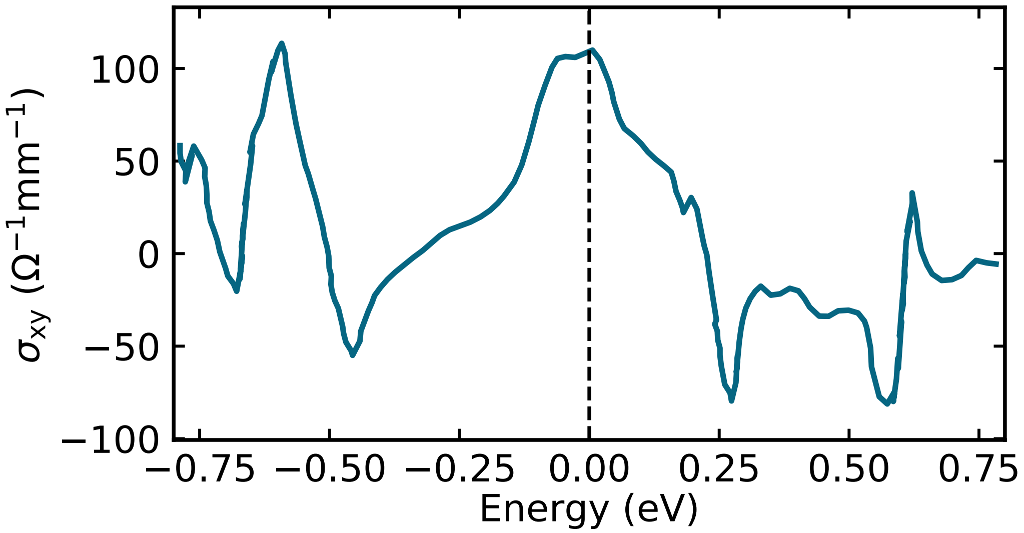
- linear extrapolation to extract anomalous contribution
- anomalous Hall odd with external magnetic field:

$$\rho^{\mathrm{A}}_{\mathrm{yx}} = \frac{\rho^{\mathrm{A}}_{\mathrm{yx}}(B) - \rho^{\mathrm{A}}_{\mathrm{yx}}(-B)}{2}$$

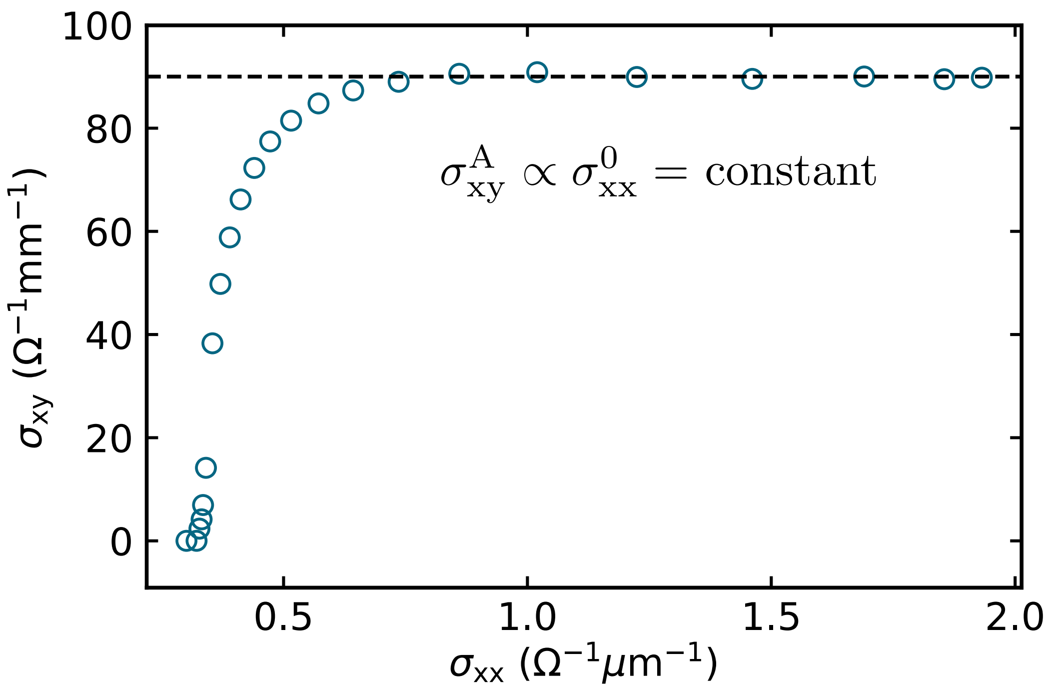
Geishendorf, K. et al. (2019). *Applied Physics Letters*, *114* (9), 092403–6.

Anomalous Hall conductivity

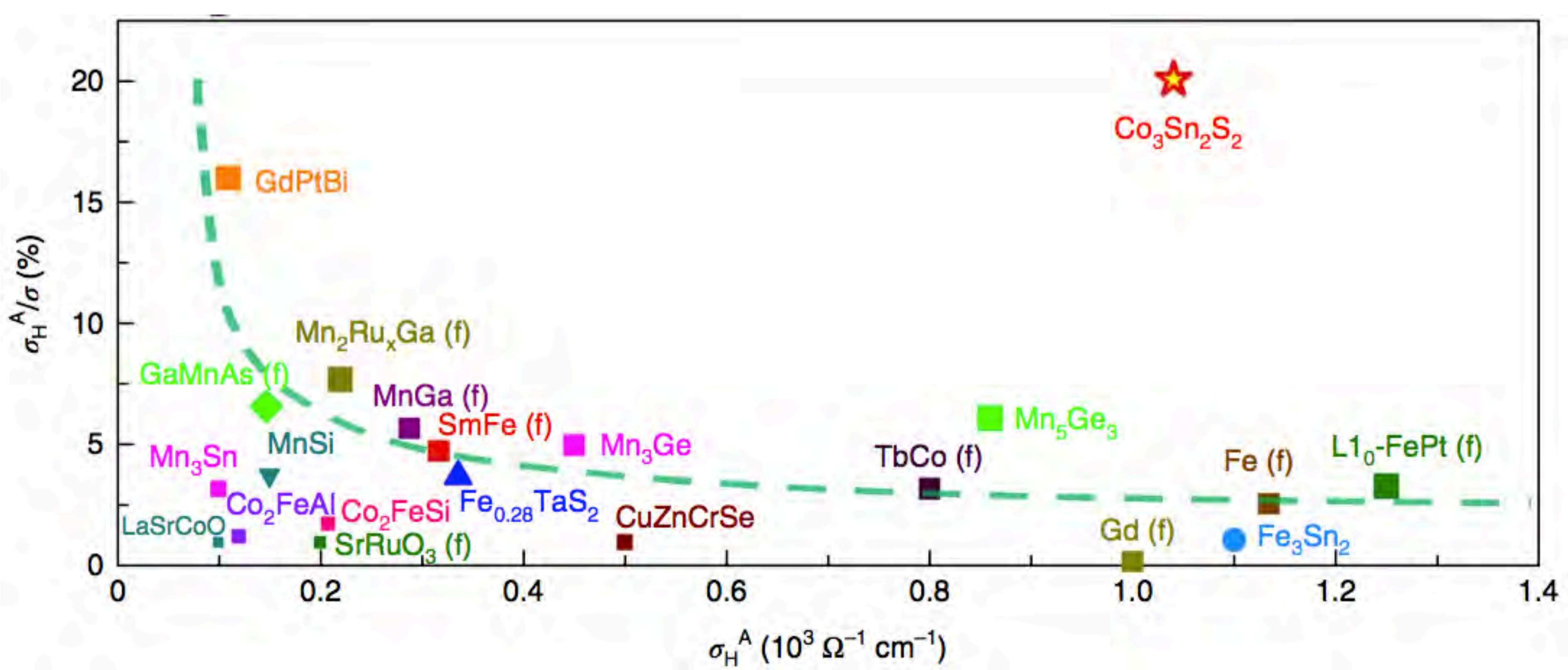
$$\vec{J} = \boldsymbol{\sigma}\vec{E} \Longleftrightarrow \vec{E} = \boldsymbol{\rho}\vec{J}$$



anomalous Hall conductivity:

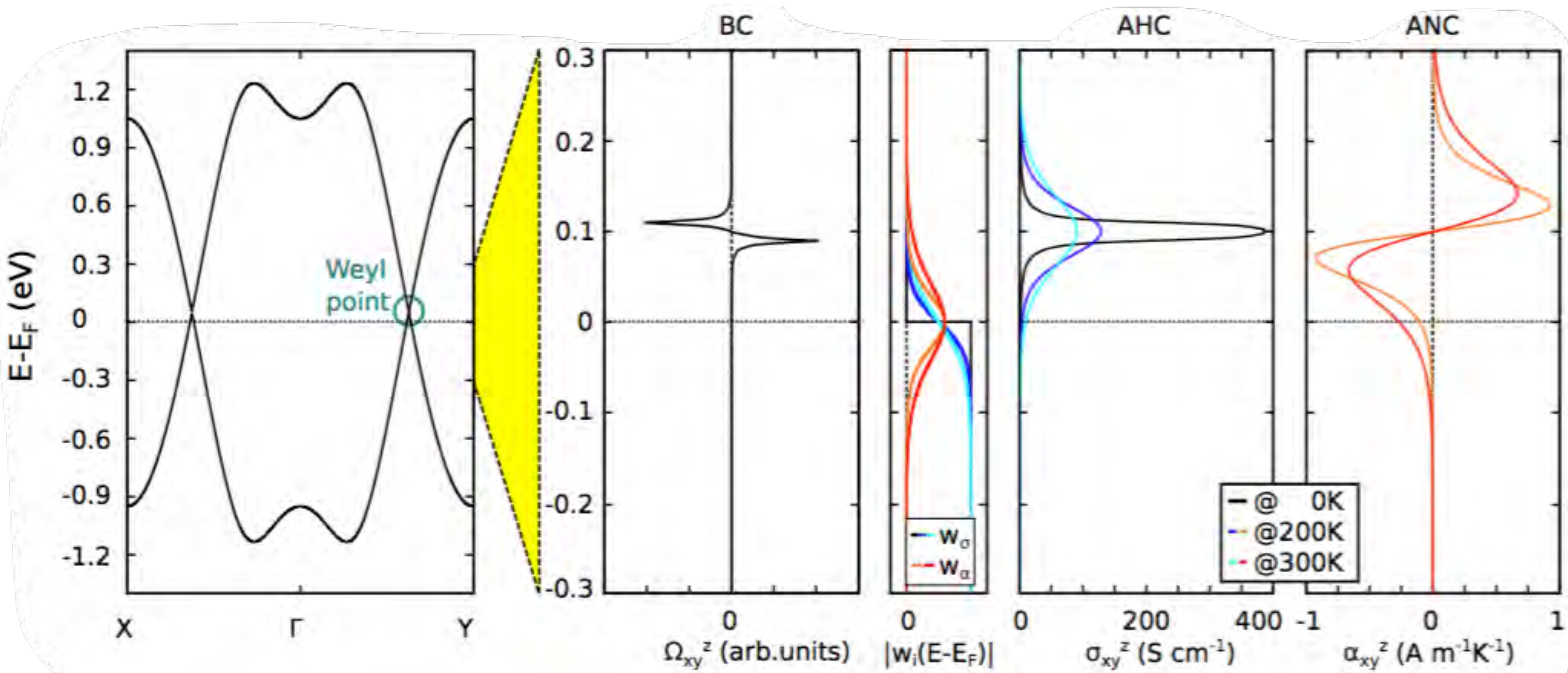


Anomalous Hall angle in $Co_3Sn_2S_2$:



Geishendorf, K. et al. (2019). *Applied Physics Letters*, *114* (9), 092403–6.
Liu, E. et al. (2018). *Nature Physics, 14* (11),

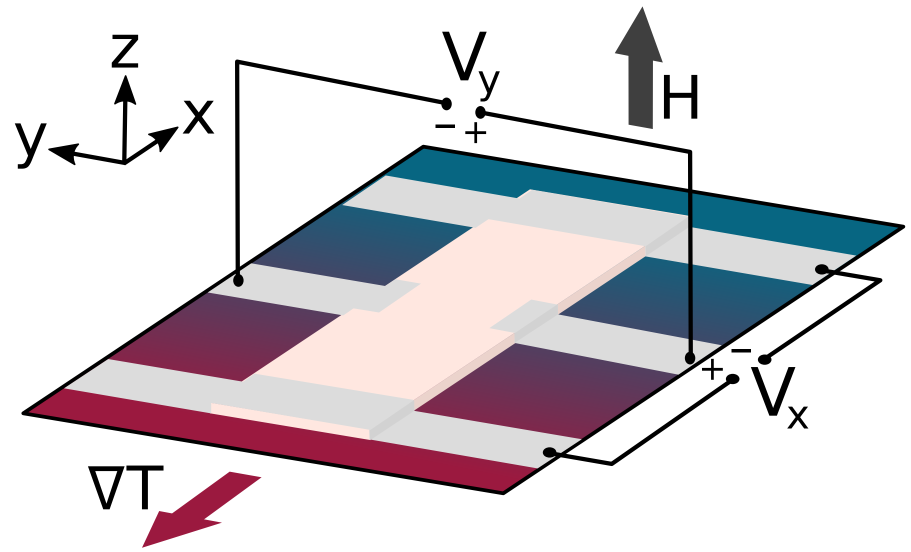
Anomalous Hall and Nernst effect



different weighing functions w_i for AHC and ANC:

⟶ different states visible in AHC and ANC measurements

Thermomagnetic transport



- non isothermal conditions:

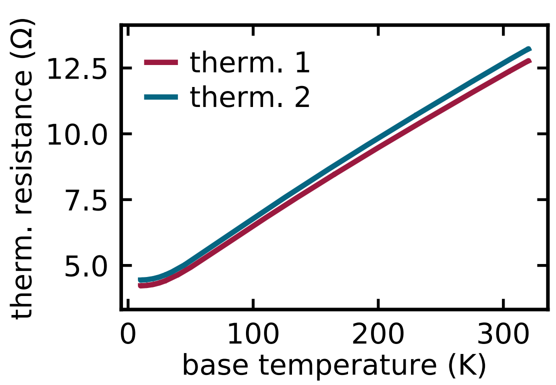
$$\vec{J} = \boldsymbol{\sigma}\vec{E} + \boldsymbol{\alpha}(-\nabla\vec{T})$$

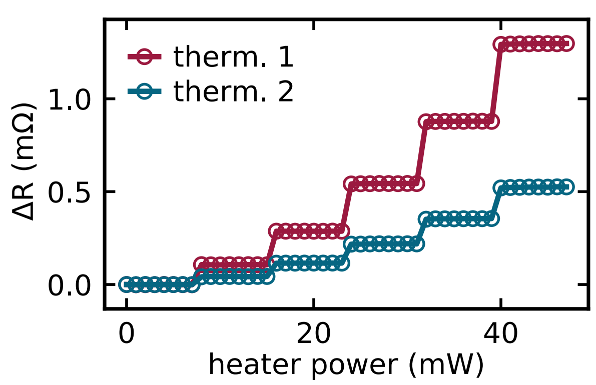
- open circuit:

$$\vec{E} = \boldsymbol{\sigma}^{-1}\boldsymbol{\alpha}(\nabla\vec{T})$$

- Seebeck tensor: $\boldsymbol{S} = \boldsymbol{\sigma}^{-1}\boldsymbol{\alpha}$

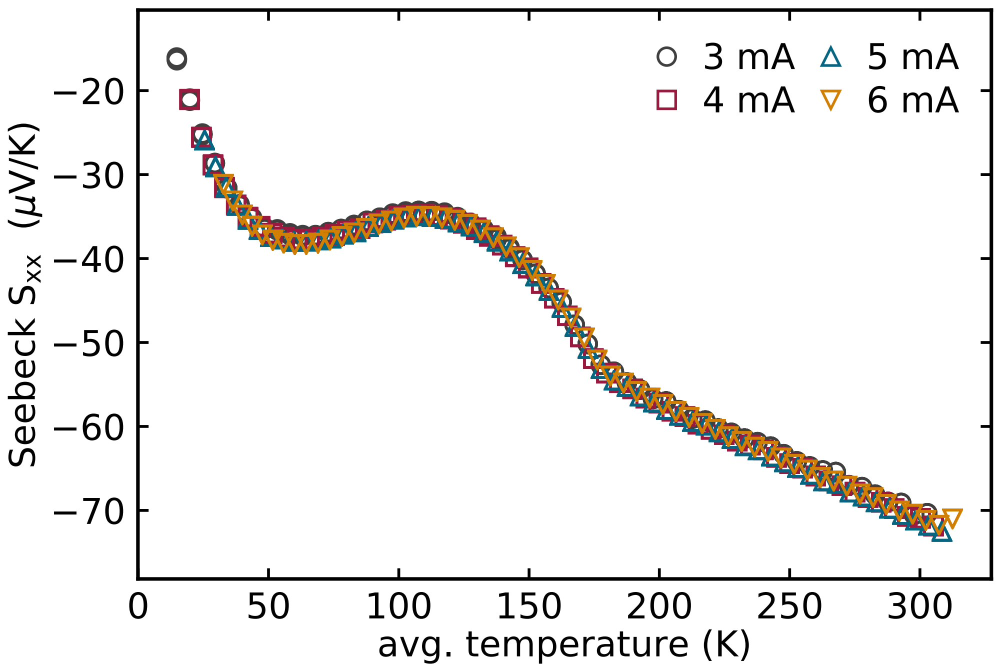
temperature gradient evaluation:





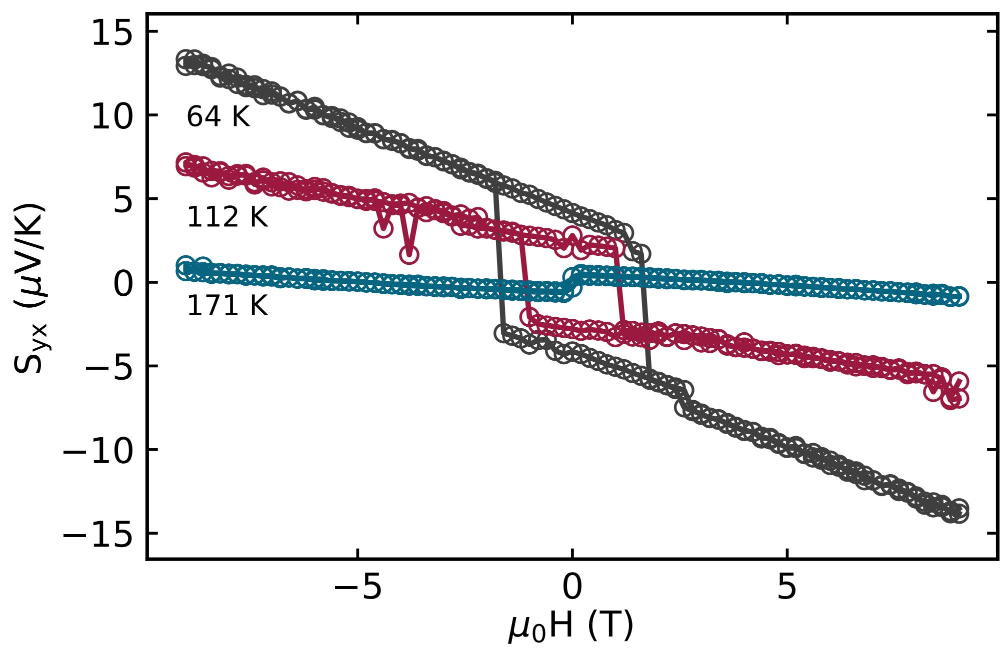
$$\nabla T_{\mathrm{x}} = (T_1 - T_2)/l_{\mathrm{T}}$$

longitudinal Seebeck coefficient

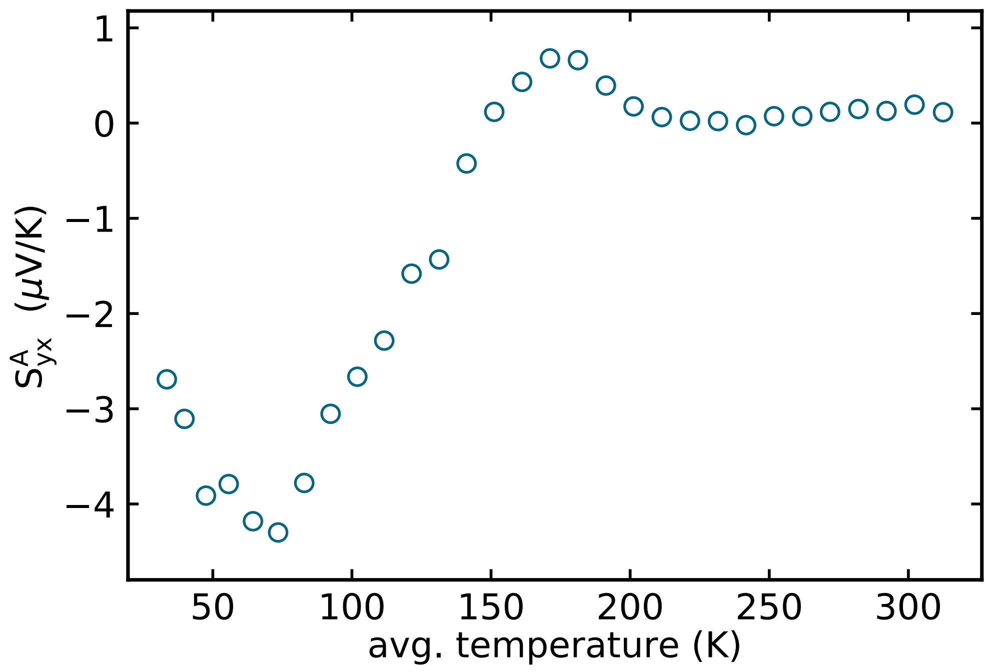


Anomalous Nernst effect

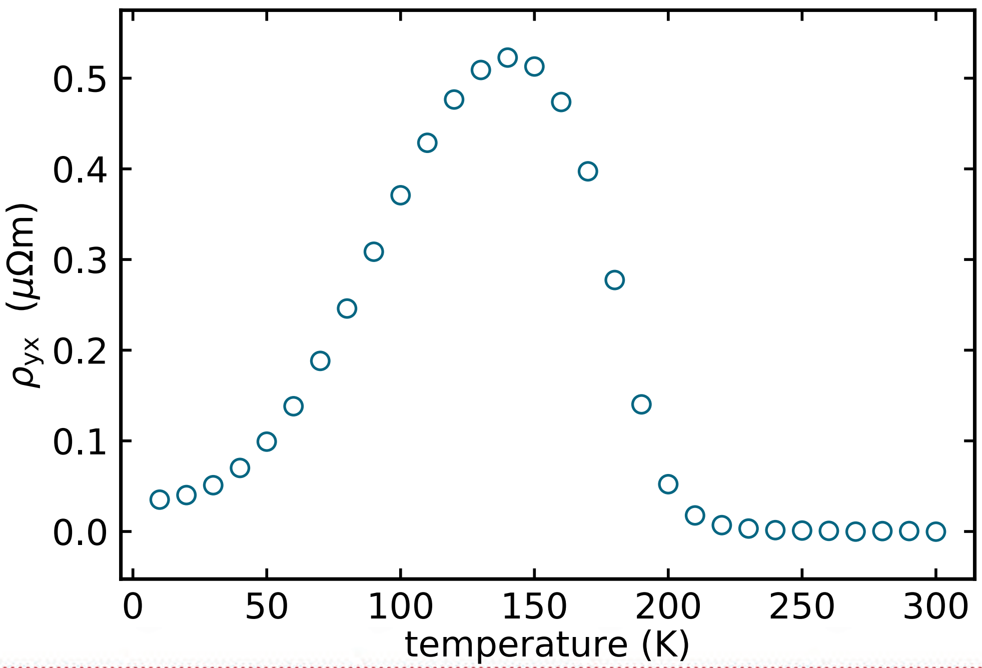
anomalous Nernst sweeps:



anomalous Nernst coefficient



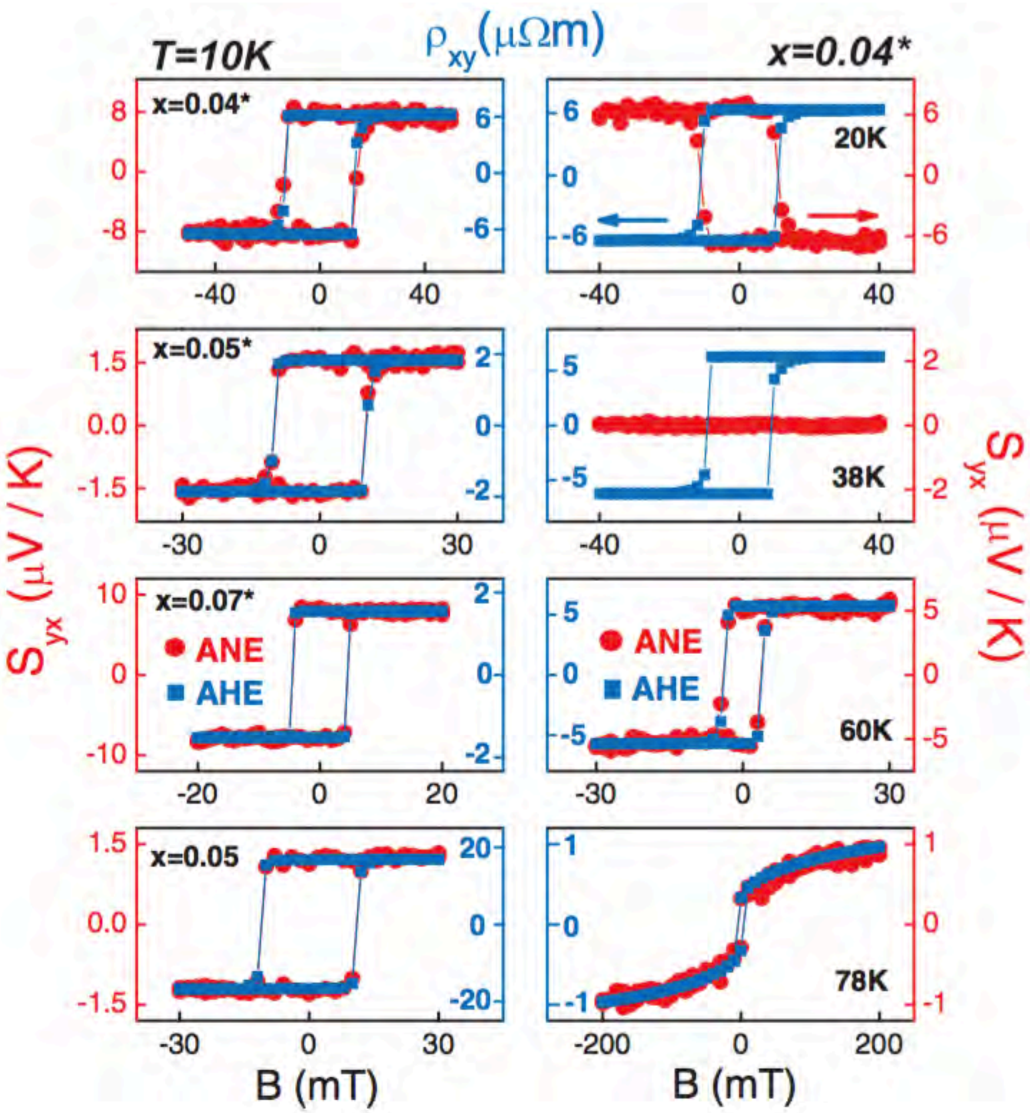
extracted anomalous Hall resistivity:



→ Significantly different temperature dependence?

Relation of AHE and ANE signal

AHE and ANE in $Ga_{1-x}Mn_xAs$

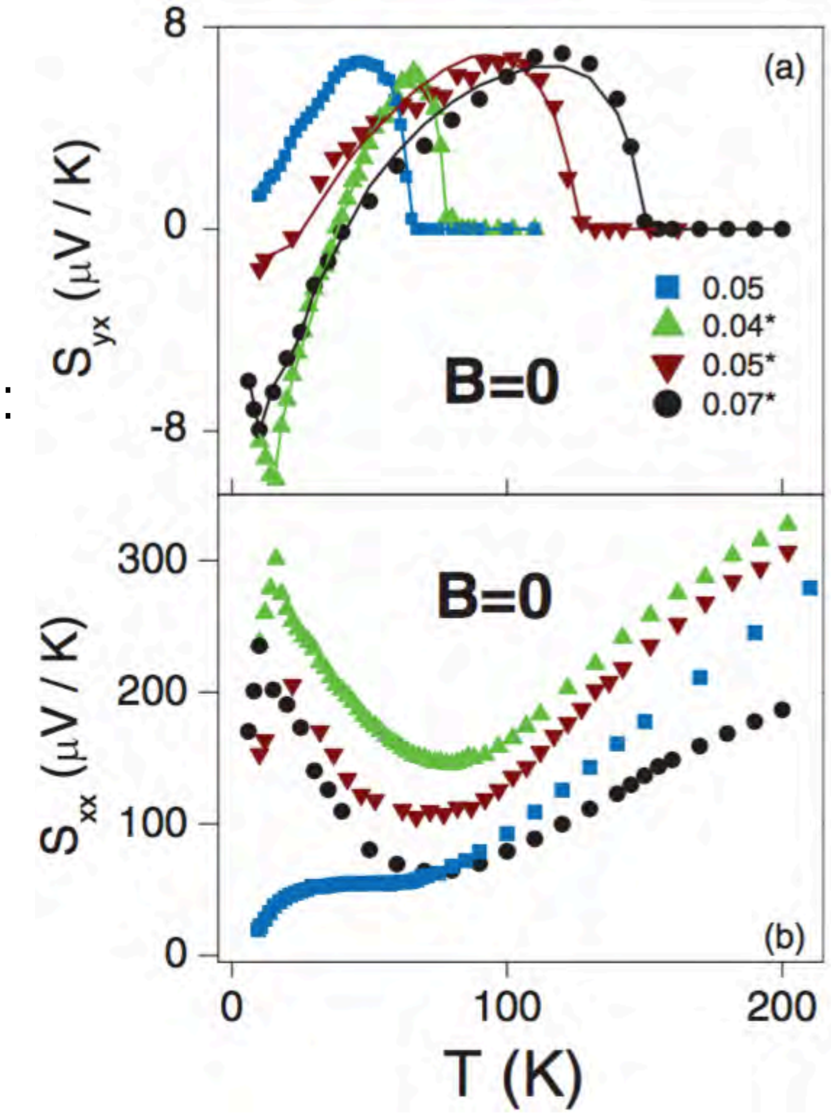


Mott relation:

$$\alpha_{yx} = \frac{\pi^2 k_B^2 T}{3e} \times \left(\frac{\partial \sigma_{yx}}{\partial E}\right)_{E_F}$$

and power law approach:

$$\rho_{xy}^{A} = \lambda M_z \rho_{xx}^{n}$$

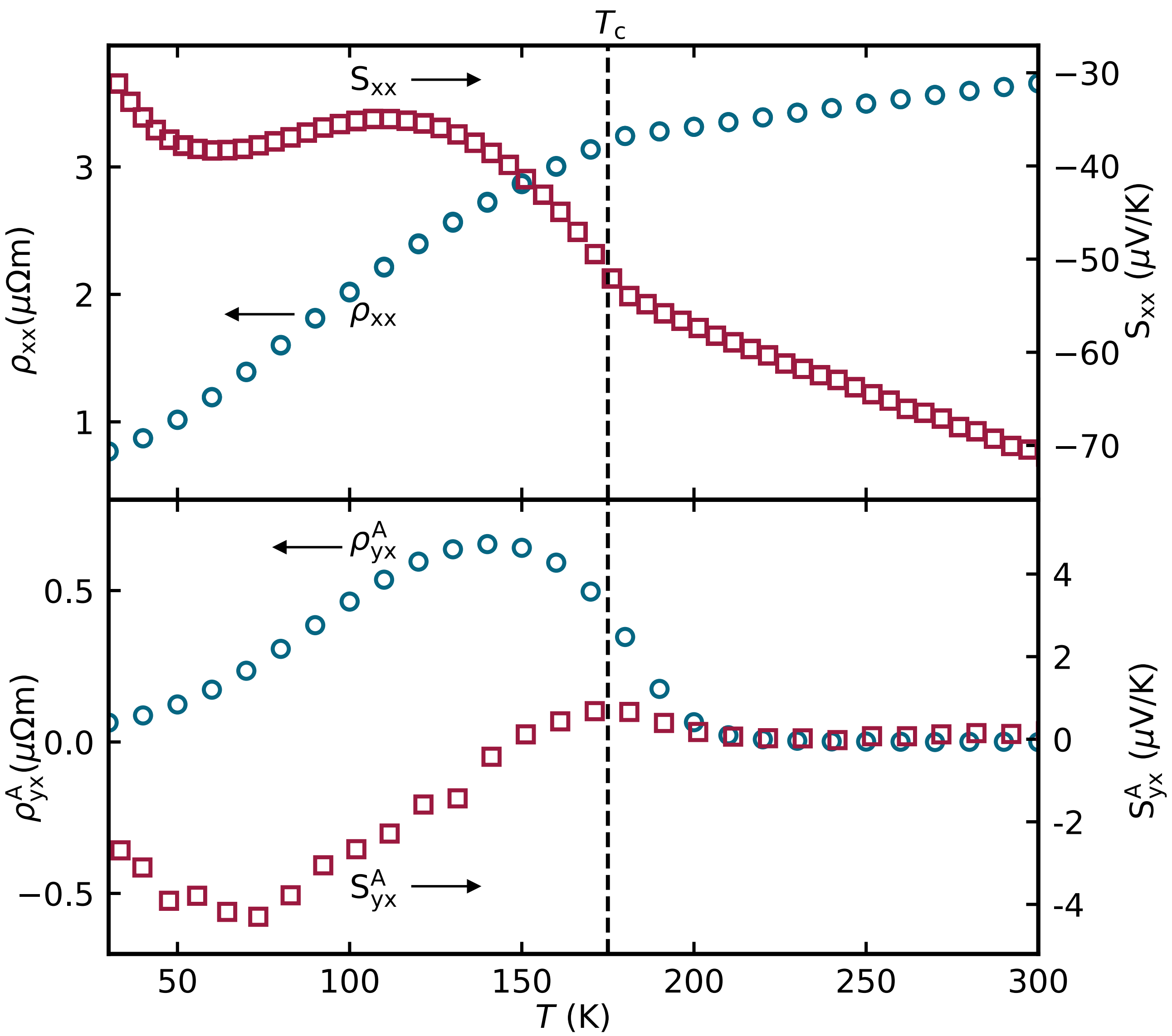


Relate 4 thermomagnetic transport coefficients
with 2 parameters

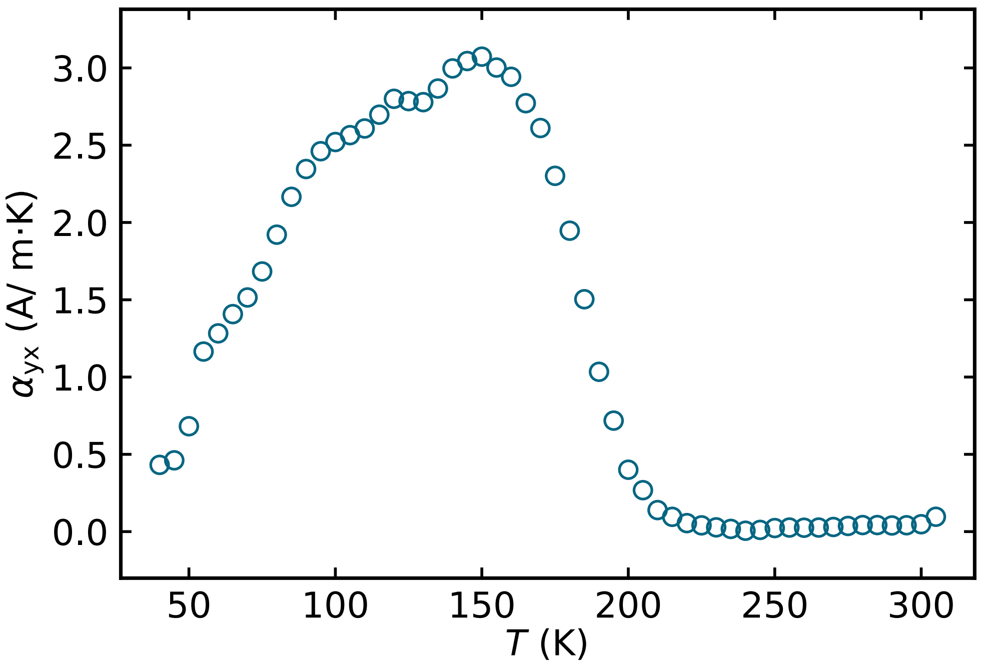
$$S_{yx} = \frac{\rho_{xy}}{\rho_{xx}}\left(T\frac{\pi^2 k_B^2}{3e}\frac{\lambda'}{\lambda} - (n-1)S_{xx}\right)$$

Pu, Y. et al. (2008). *Physical Review Letters*, *101* (11), 117208–4.

Anomalous Nernst Conductivity

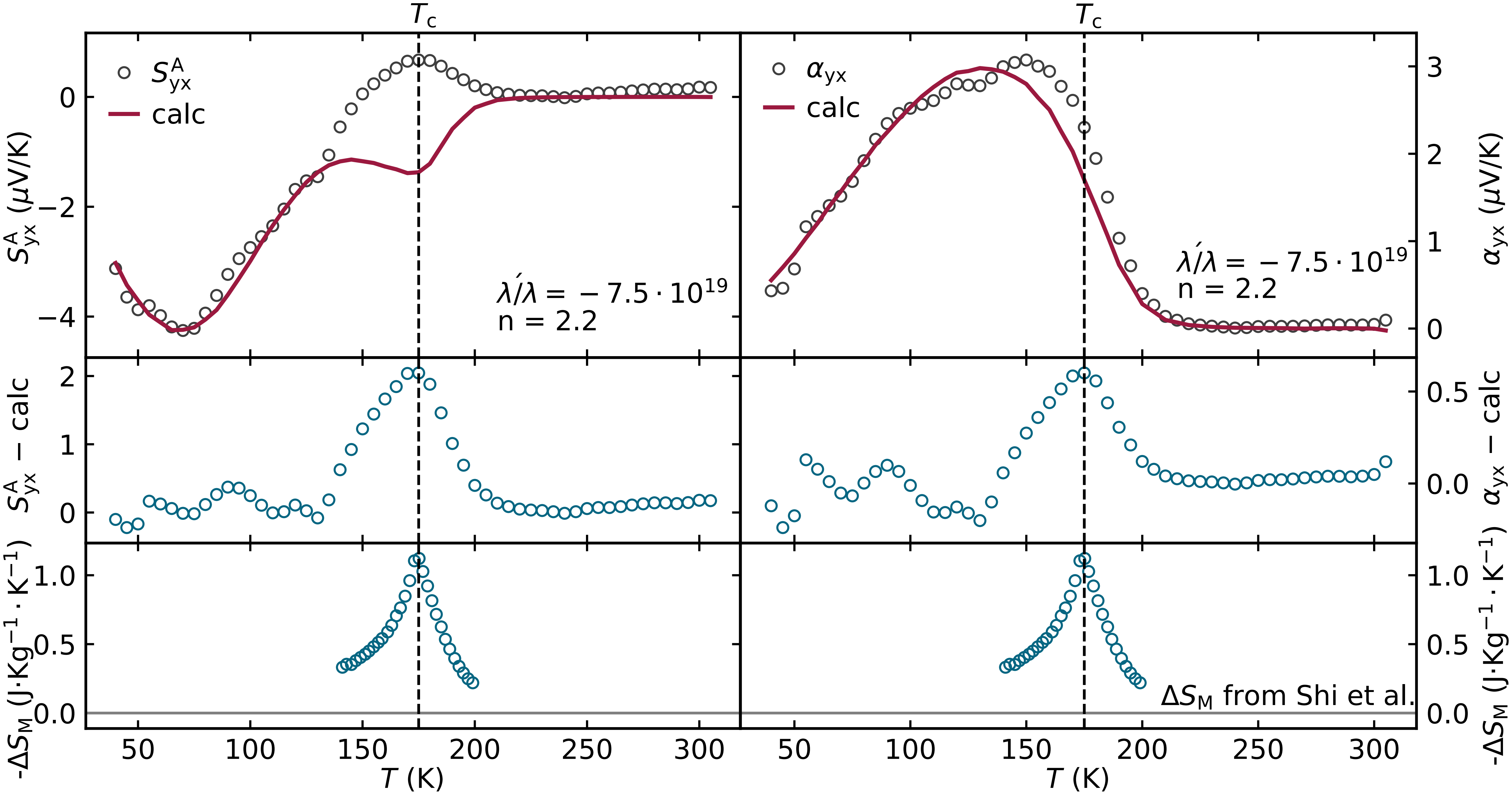


$$\alpha_{yx} = \frac{S_{yx}\rho_{xx} - S_{xx}\rho_{yx}}{\rho_{xx}^2 + \rho_{yx}^2}$$



Mott relation

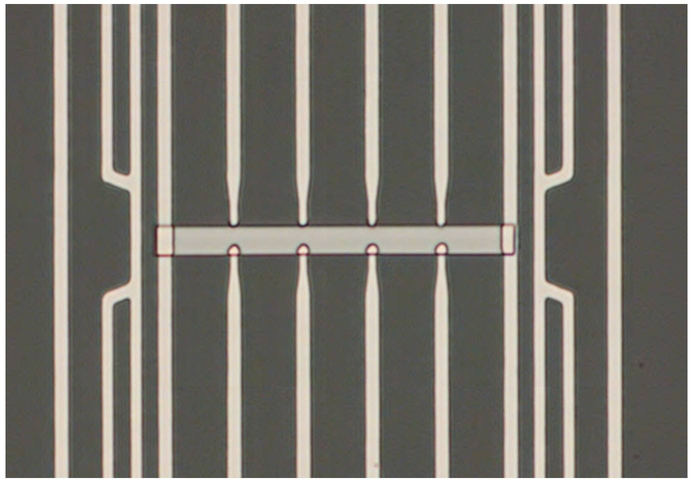
$$S_{\mathrm{yx}} = \frac{\rho_{\mathrm{xy}}}{\rho_{\mathrm{xx}}}\left(T\frac{\pi^2 k_B^2}{3e}\frac{\lambda'}{\lambda} - (n-1)S_{\mathrm{xx}}\right) \qquad \alpha_{\mathrm{yx}} = \frac{\rho_{\mathrm{xy}}}{\rho_{\mathrm{xx}}^2}\left(T\frac{\pi^2 k_B^2}{3e}\frac{\lambda'}{\lambda} - (n-2)S_{\mathrm{xx}}\right)$$

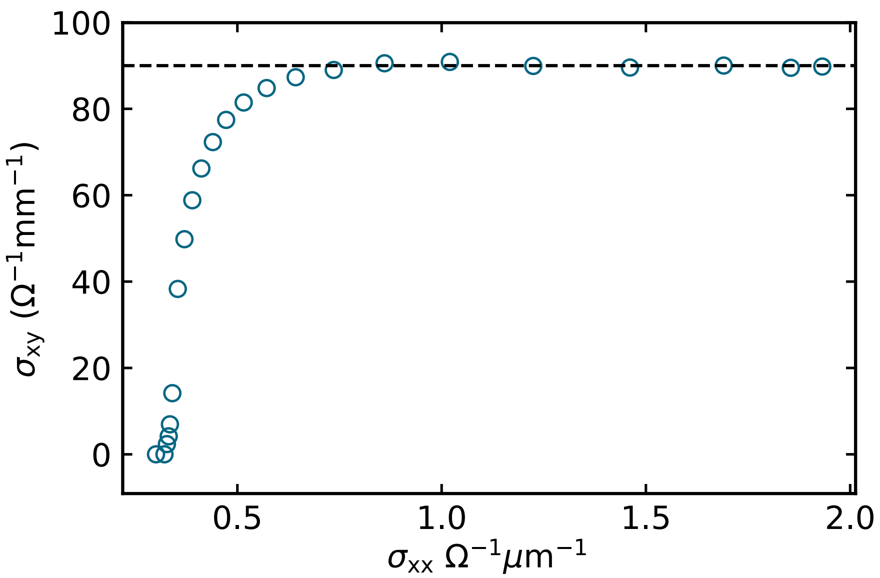


Pu, Y. et al. (2008). *Physical Review Letters, 101* (11), 117208–4.
Shi, Q. et al. (2018). *Results in Physics, 11*, 1004–1007.

Summary $Co_3Sn_2S_2$

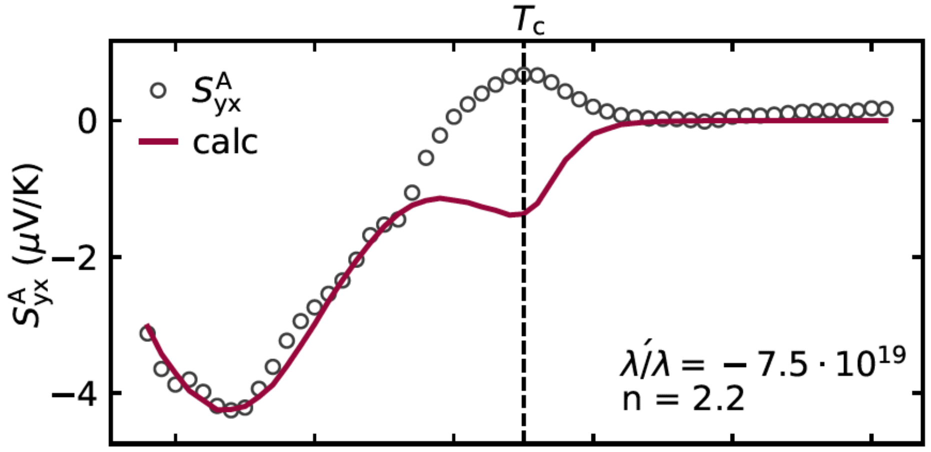
- successful fabrication of single crystalline microstructures of $Co_3Sn_2S_2$
- access to galvano- and thermomagnetic transport coefficients





- experimental observation of large AHC governed by Berry curvature contribution

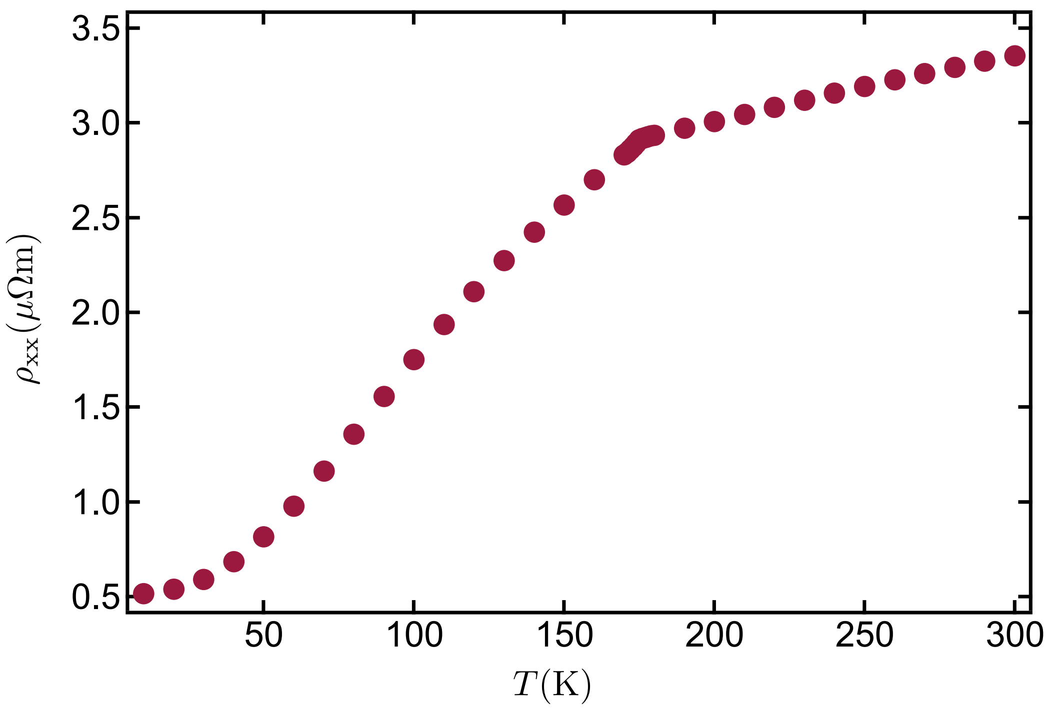
- additional contribution to anomalous Nernst effect possibly by magnetic fluctuations near T_c



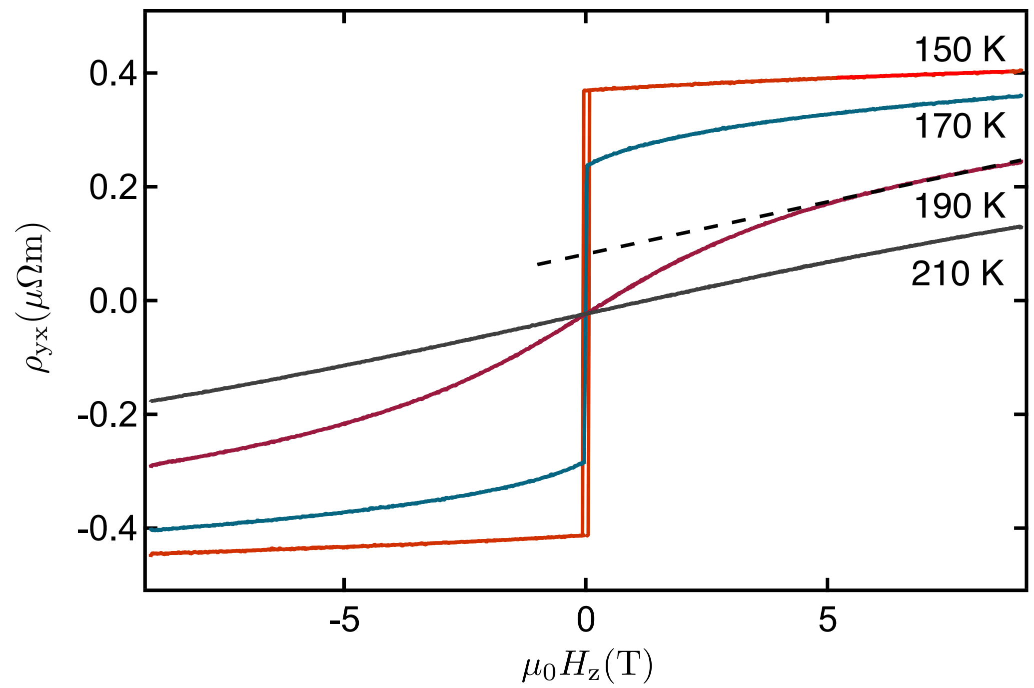
Thank you for your attention

Supplementary Information $Co_3Sn_2S_2$ I

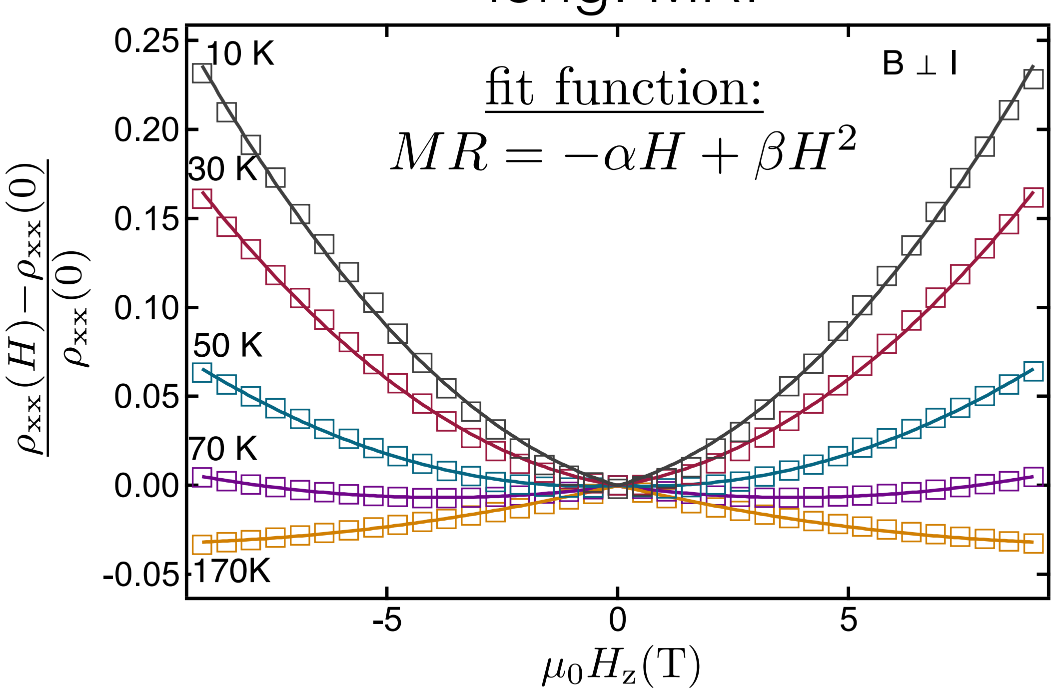
R vs. T:



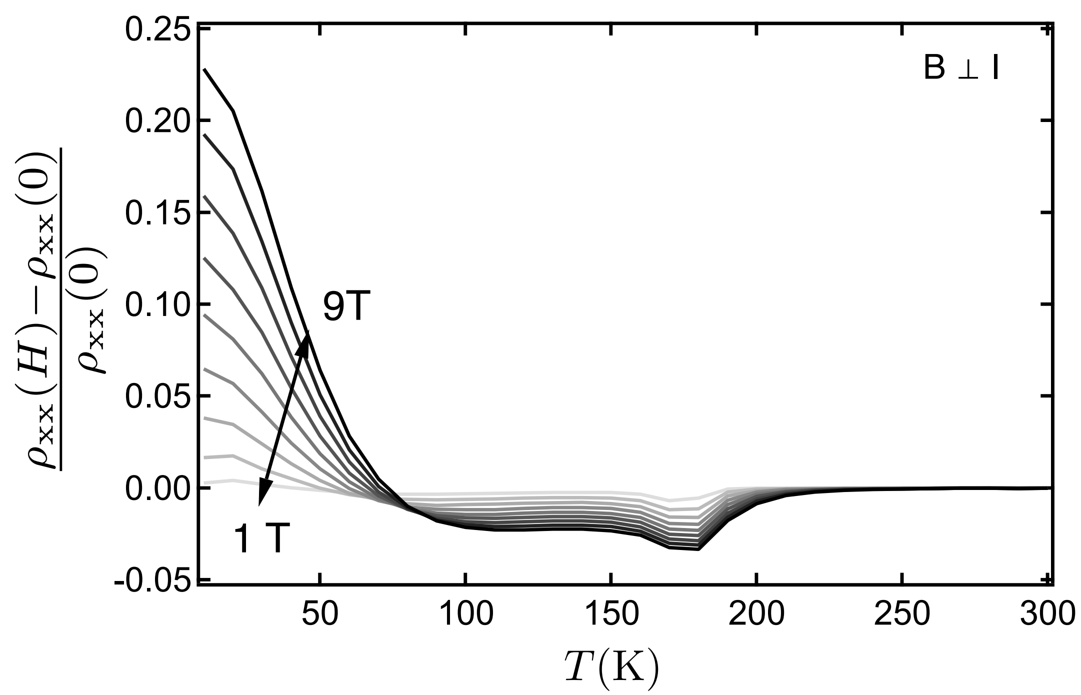
Hall extrapolation:



long. MR:



long. MR vs. T:

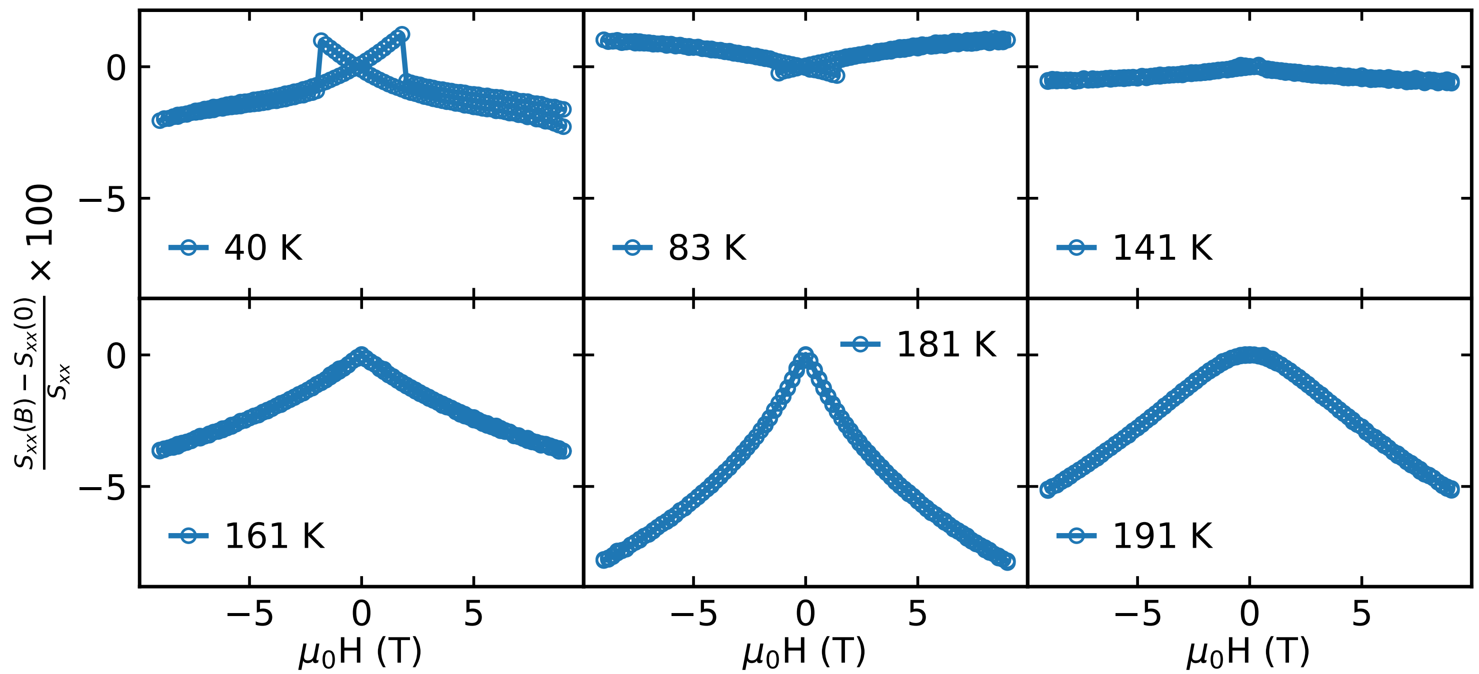


Supplementary Information $Co_3Sn_2S_2$ II

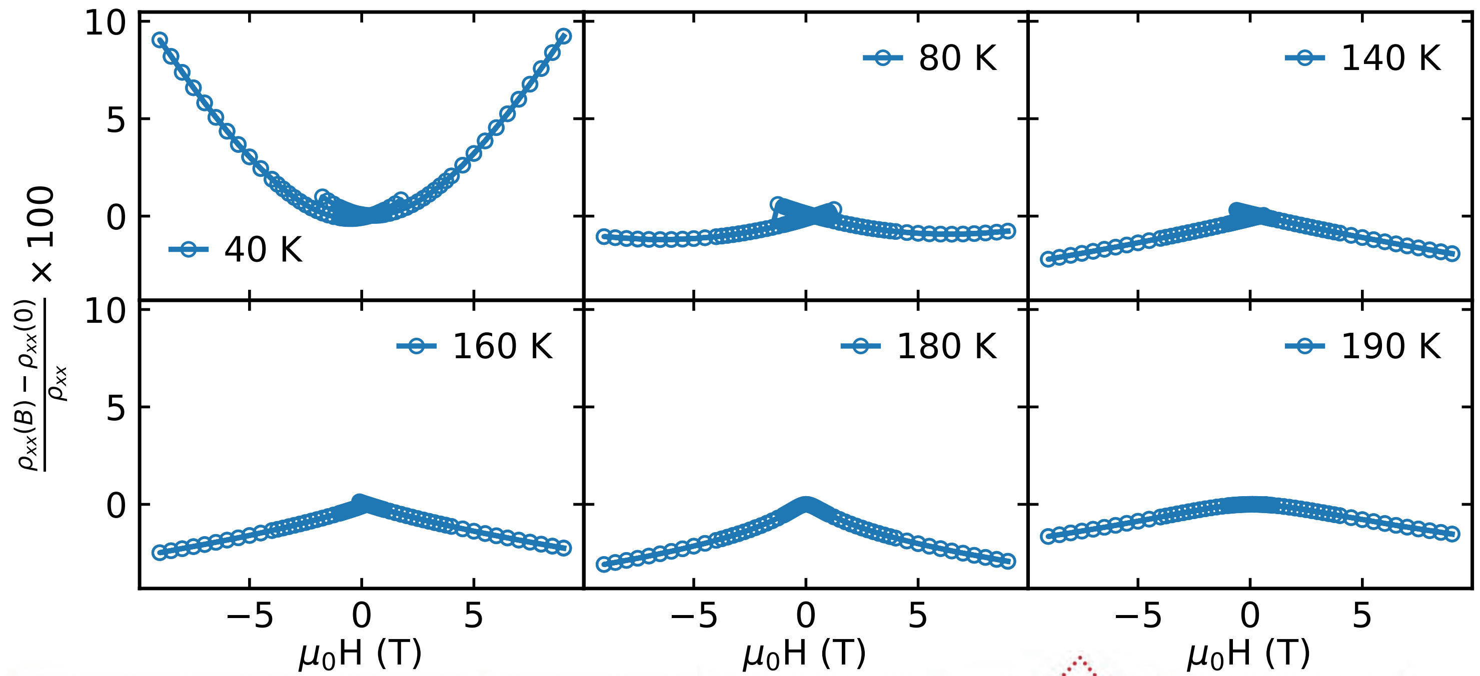
300 K > T > 140 K:
- larger magnitude of MS
- similar curve shape

140 K > T > 10 K:
- sign change to positive MS & MR
- second sign change to negative MS at low temperatures

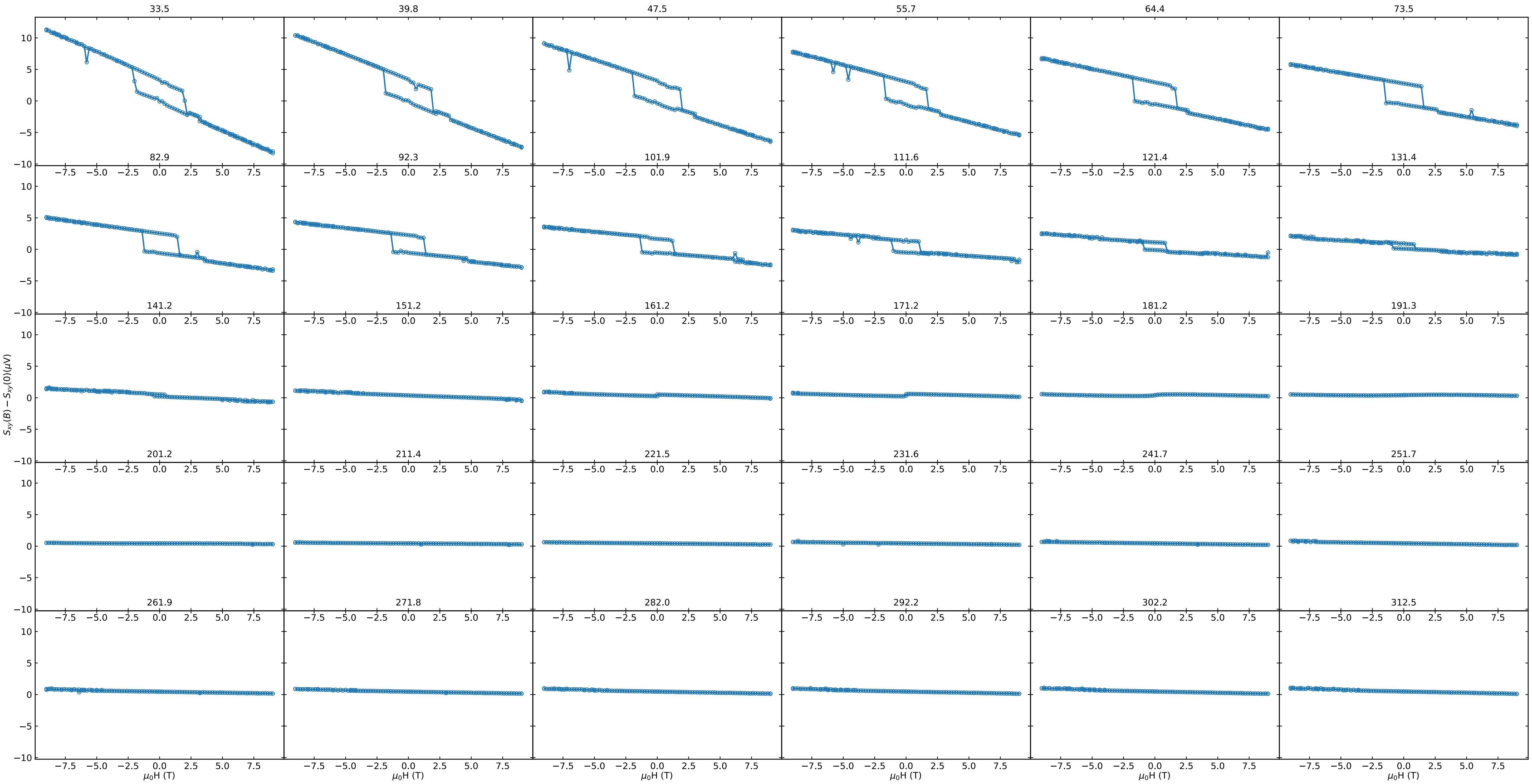
magnetoseebeck (MS):



magnetoresistance (MR) at similar temperatures:



Supplementary Information $Co_3Sn_2S_2$ III



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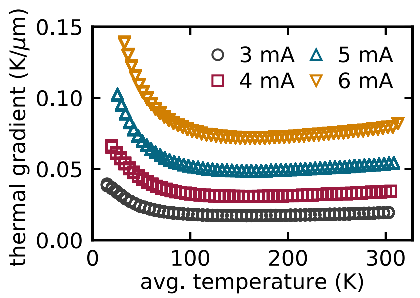

$$\rho_{\mathrm{yx}}^{\mathrm{A}} = \frac{\rho_{\mathrm{yx}}^{\mathrm{A}}(B) - \rho_{\mathrm{yx}}^{\mathrm{A}}(-B)}{2}$$

$$\sigma_{\mathrm{xx}} = \frac{\rho_{\mathrm{xx}}}{\rho_{\mathrm{xx}}^2 + \rho_{\mathrm{yx}}^2}$$

$$\sigma_{\mathrm{xy}}^{\mathrm{A}} \propto \sigma_{\mathrm{xx}}^{0} = \mathrm{constant}$$

$$\sigma_{\mathrm{xy}} = \frac{\rho_{\mathrm{yx}}}{\rho_{\mathrm{xx}}^2 + \rho_{\mathrm{yx}}^2}$$