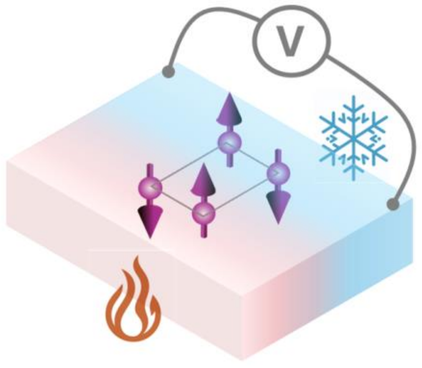
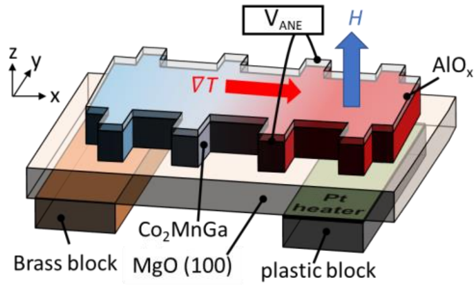
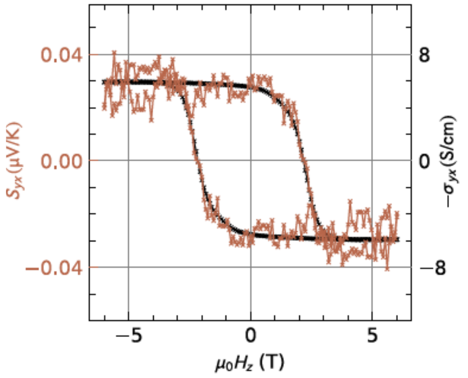
Anomalous Nernst effect:
Brief overview of experimental efforts

Helena Reichlova

Institute of Physics, Czech Academy of Sciences







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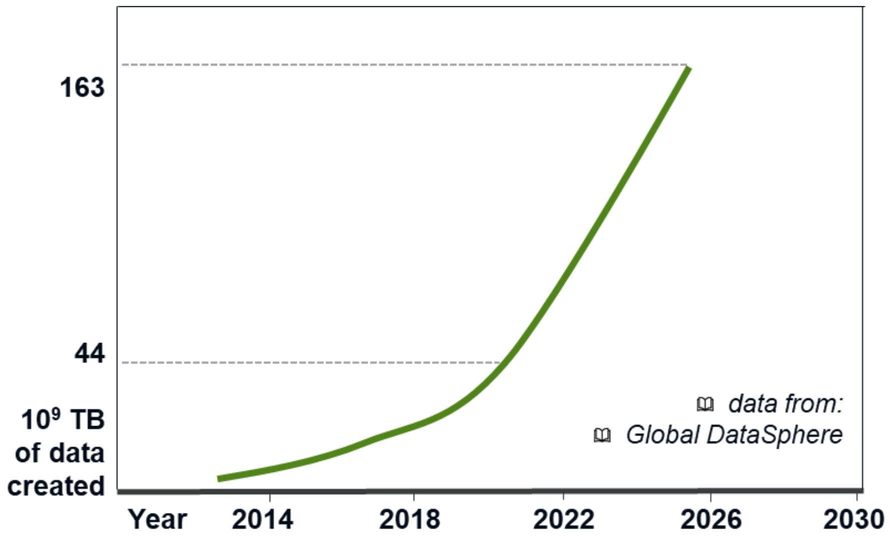
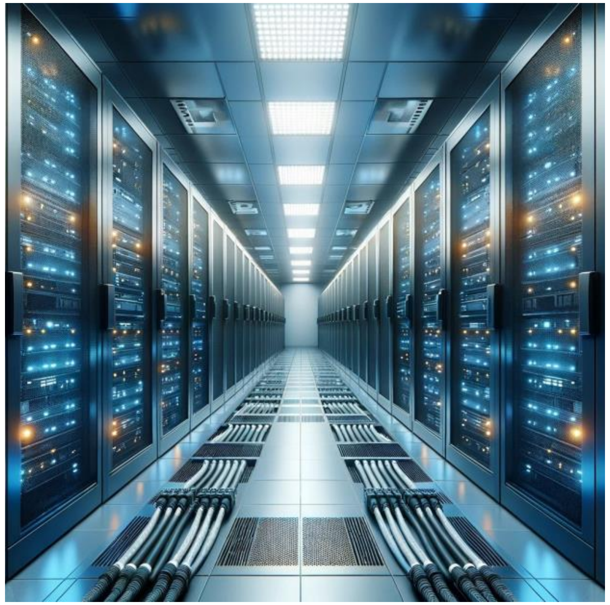
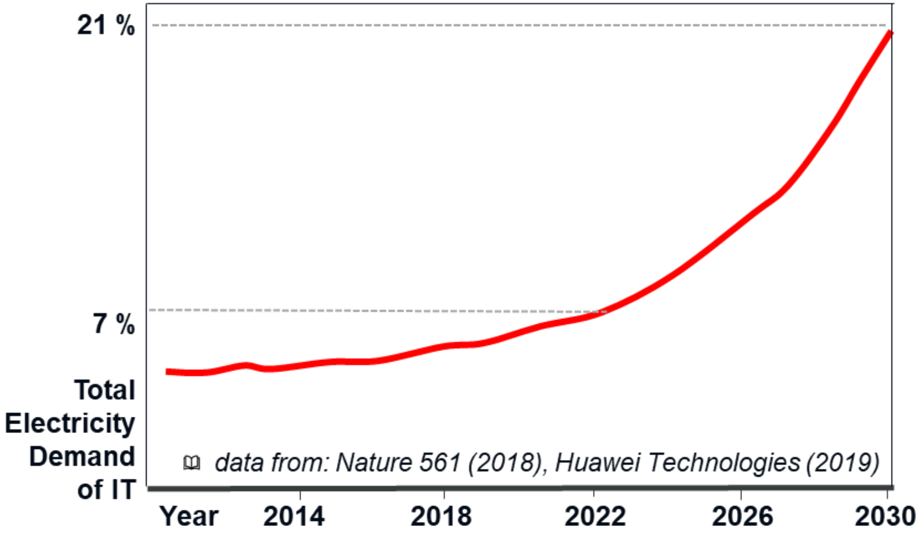
CENTRE FOR SPINCALORITRONICS AND MAGNONICS

Dioscuri Centre for Spincaloritronics and Magnonics

- Address exponentially increasing energy demands of IT







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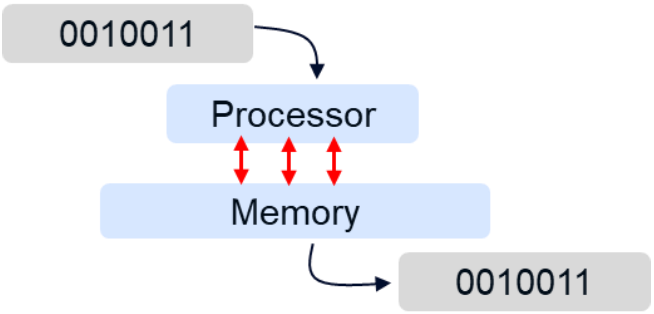
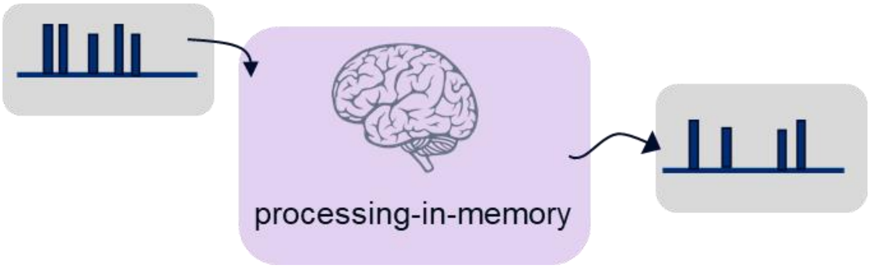
- Address exponentially increasing energy demands of IT
- Many ideas how to safe energy …
  - ➢ Inspiration by human brain





Numbers	Human brain	Von Neumann computer (a.d. 2005)
# elements	10^{10} - 10^{12} neurons	10^{7} - 10^{8} transistors
# connections / element	10^{4}	10
switching frequency	10^{3} Hz	10^{9} - 10^{10} Hz
energy / operation	10^{-16} Joule	10^{-6} Joule
power consumption	10 Watt	100 - 500 Watt
reliability of elements	low	reasonable

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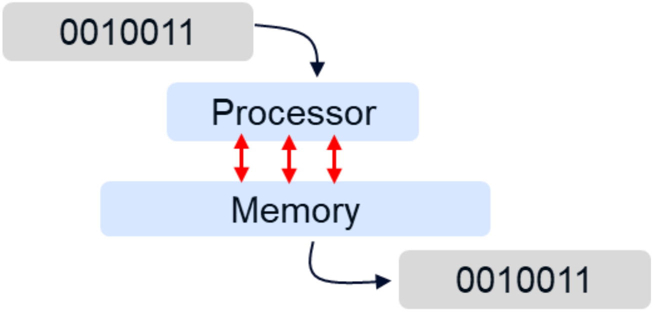
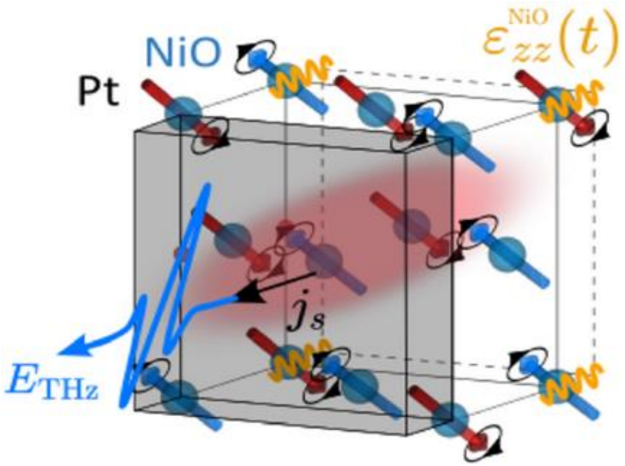
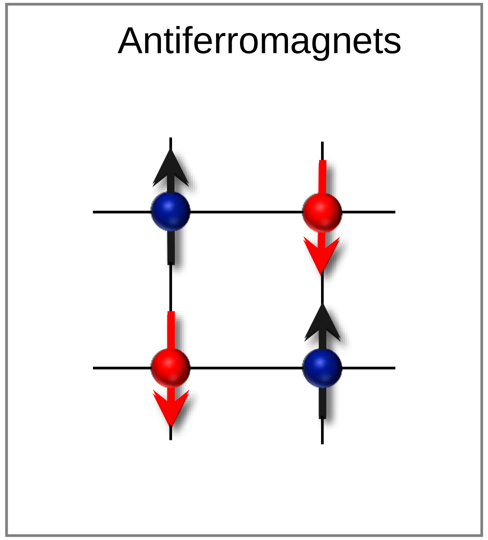
  - ➢ More energy efficient memory writing and reading





Rongione et al. Nat. Comm. 1818 (2023)



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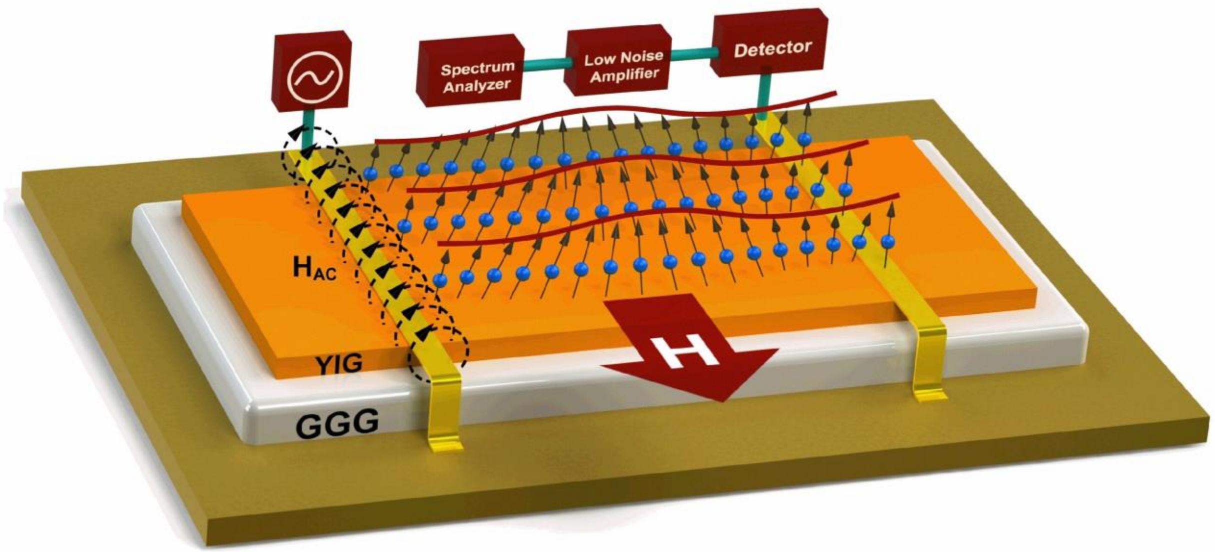
    - ➢ Reduce the Joule heating by magnonics



🕮 Rumyantsev et al. Appl. Phys. Lett. 114, 090601 (2019)

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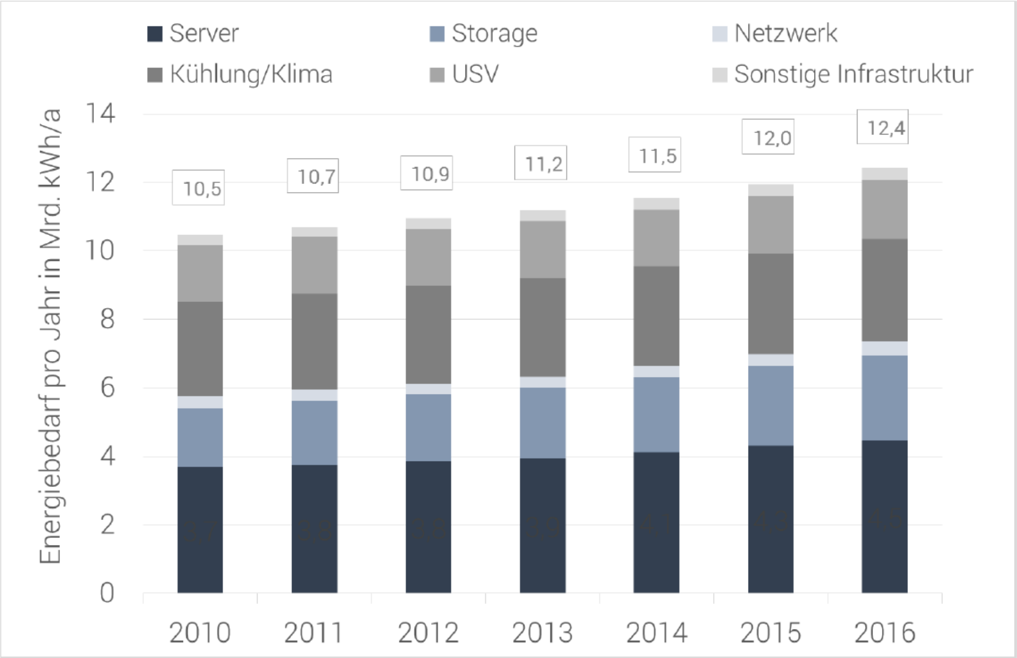
- Address exponentially increasing energy demands of IT
- Many ideas how to safe energy …
  - Inspiration by human brain
  - More energy efficient memory writing and reading
  - Reduce the Joule heating by magnonics
  - Recycle the waste heat

Abbildung 5: Entwicklung des Energiebedarfs der Server und Rechenzentren in Deutschland in den Jahren 2010 bis 2016



Quelle: Borderstep (Hintemann, 2017)

techspot.com

Dioscuri Centre for Spincaloritronics and Magnonics

- Address exponentially increasing energy demands of IT
- Many ideas how to safe energy …
  - ➢ Inspiration by human brain
  - ➢ More energy efficient memory writing and reading
  - ➢ Reduce the Joule heating by magnonics
  - ➢ Recycle the waste heat
    - ▪ Heat a nearby swimming pool
    - ▪ Convert back to electricity
    - ▪ Perform functionality

🕮 techspot.com

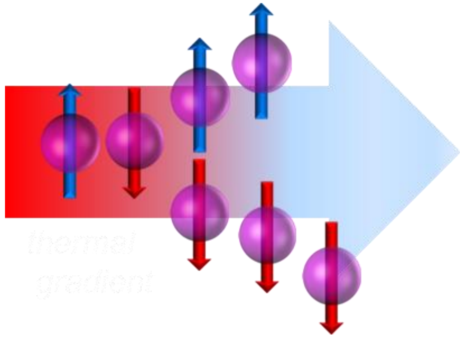
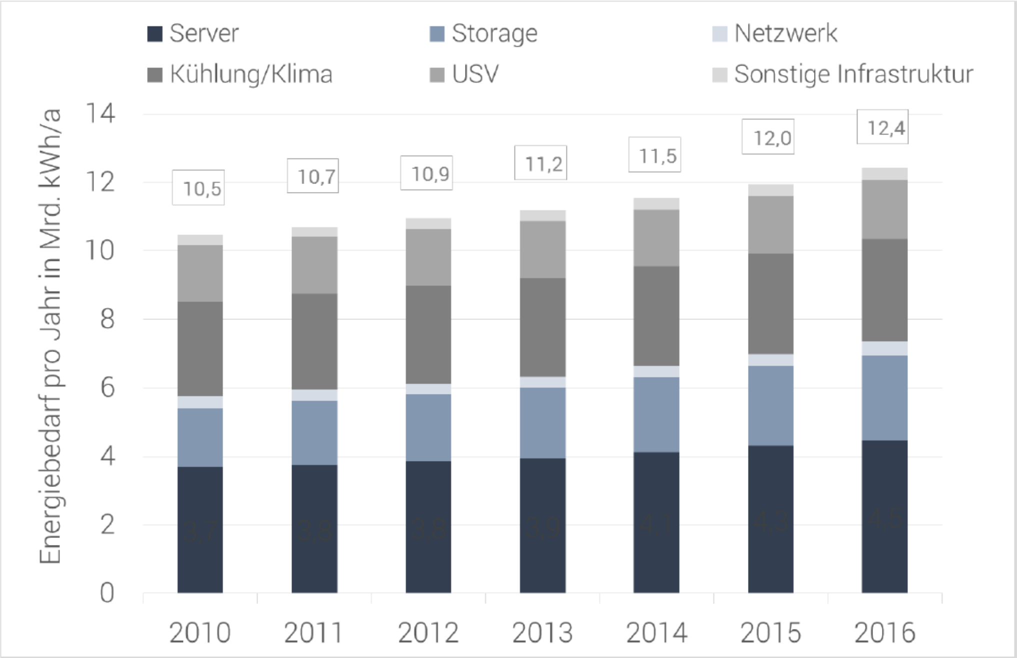


Abbildung 5: Entwicklung des Energiebedarfs der Server und Rechenzentren in Deutschland in den Jahren 2010 bis 2016



Quelle: Borderstep (Hintemann, 2017)

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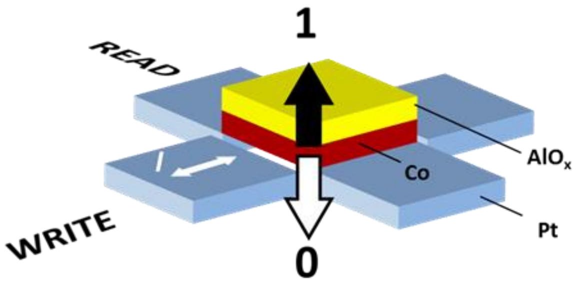
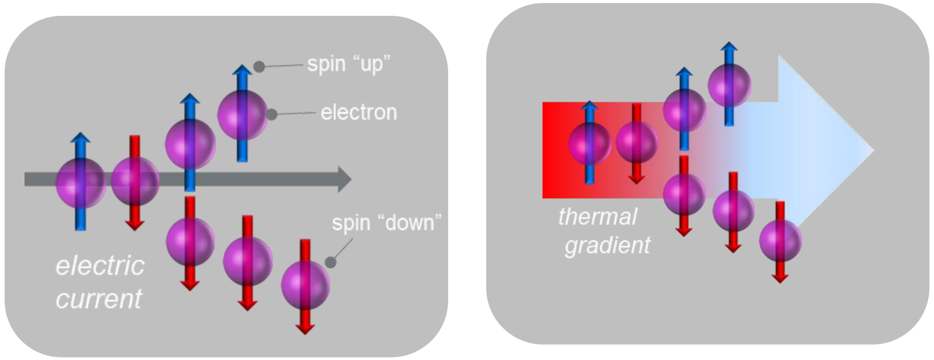
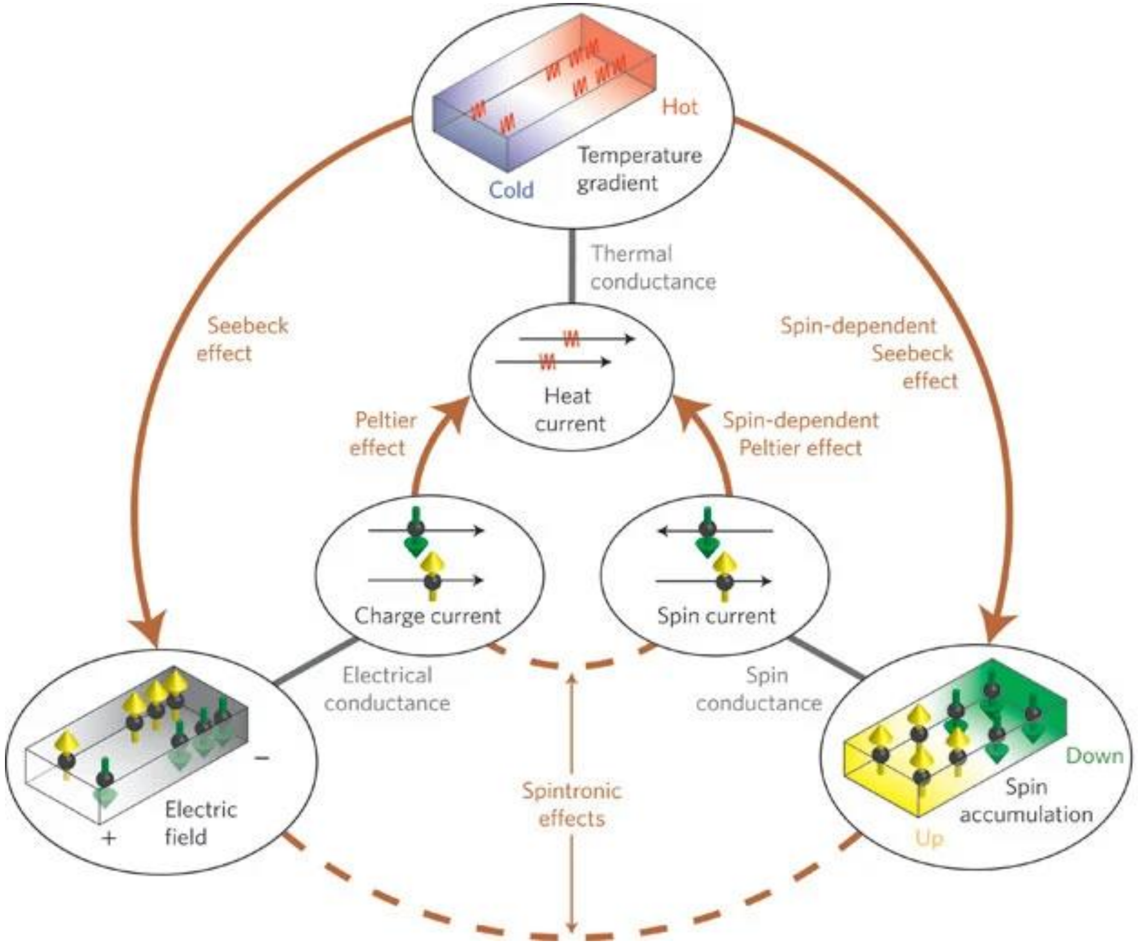
Spincaloritronics

- Functionalise the coupling of spin & heat
- Heat driven writing or reading?



Miron et al. Nature 476, 189 (2011)



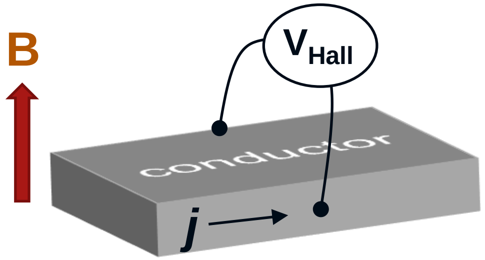


Goennenwein and Bauer, Nature Nanotechnology 7 (2012)

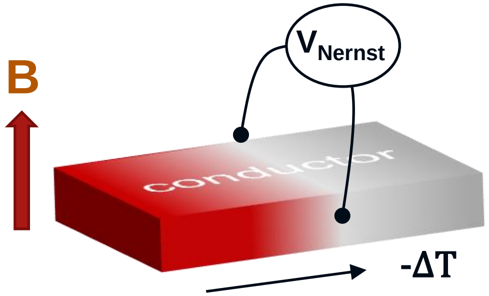
Spincaloritronics: Anomalous Nernst Effect

Breaking $\mathcal{T}$ symmetry in the band structure:

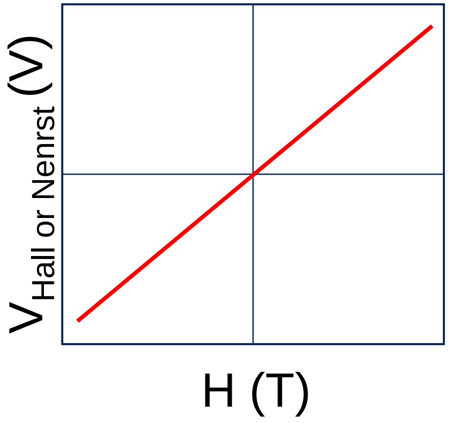
– by external magnetic field: **ordinary effects**



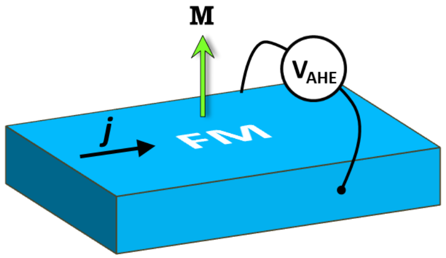
Hall effect



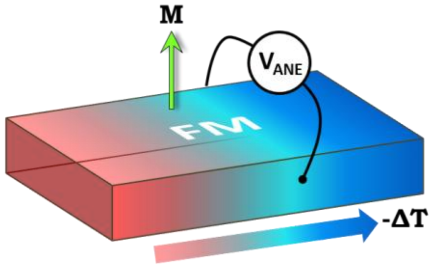
Nernst effect



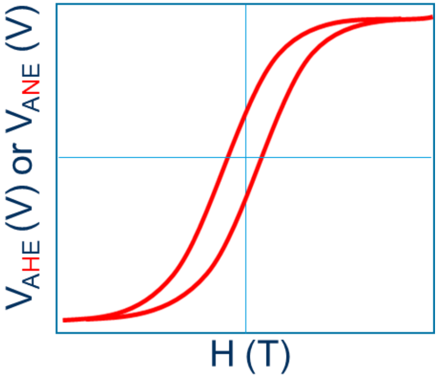
- by internal magnetic ordering: **anomalous effects**



anomalous Hall effect



anomalous Nernst effect



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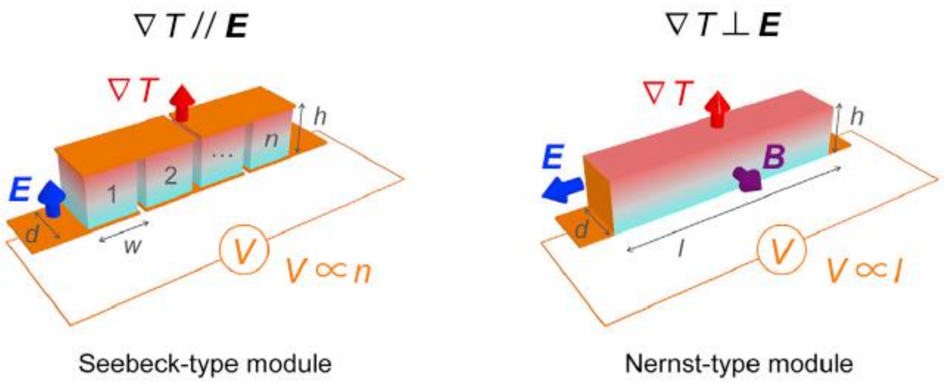
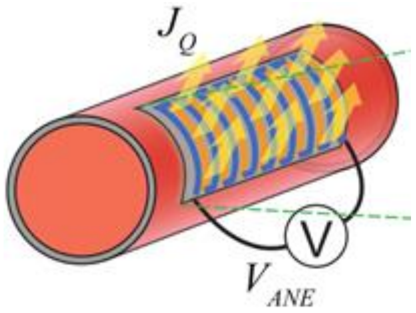
Spincaloritronics: Anomalous Nernst Effect

- **Direct conversion of heat in single material layer**



$$E_{Nernst} \sim N.\nabla T \times B$$

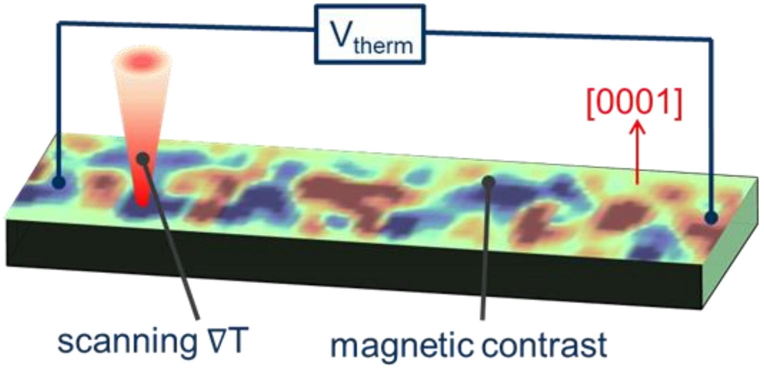
- more simple
- dissipation less
- more flexible, scalable
- more efficient



🕮 Murata et al. iScience 101967 (2021)
🕮 Zhou et al. APE 043001 (2020)
🕮 Uchida et al. APL (2021)

- **Magnetic microscopy**

🕮 Reichlova et al. Nat Comm (2019)
🕮 Weiler et al., PRL (2012)



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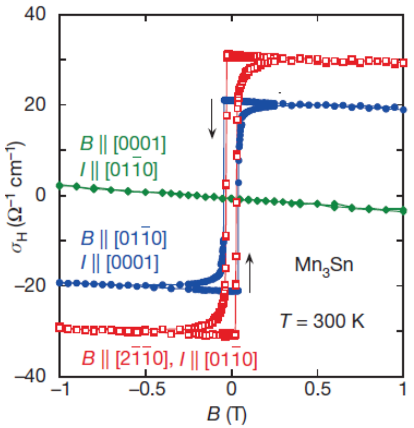
Anomalous Nernst Effect

Following developments anomalous Hall effect

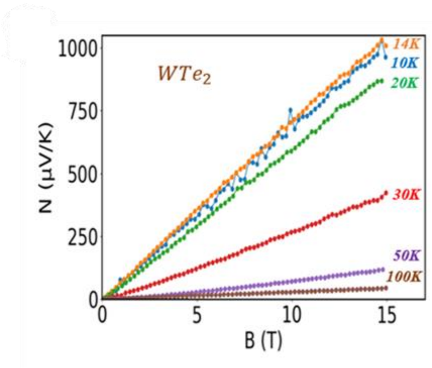
~ 1890: empirical relation $\rho_H \sim R_S M_z$
~ 1960: separate various scattering contributions
~ 2004: extrinsic (scattering) + **intrinsic part**
~ 2010: AHE unrelated to magnetization



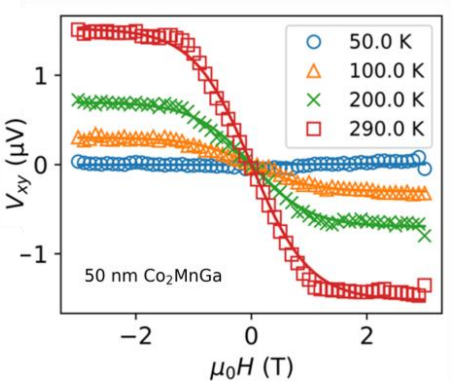
🕮 Nagaosa et al., Rev. Mod. Phys. (2010)
🕮 Chen et al., PRL (2014)
🕮 Nakatsuji et al., Nature (2015)
🕮 Nayak et al., Science Adv. (2015)

🕮 Behnami, HR et al., in preparation
🕮 Reichlova et al. APL 212405 (2018)
🕮 Ikhlas et al., Nat.Phys. (2015)
🕮 Schlitz, HR et al., Nano Lett. (2019)

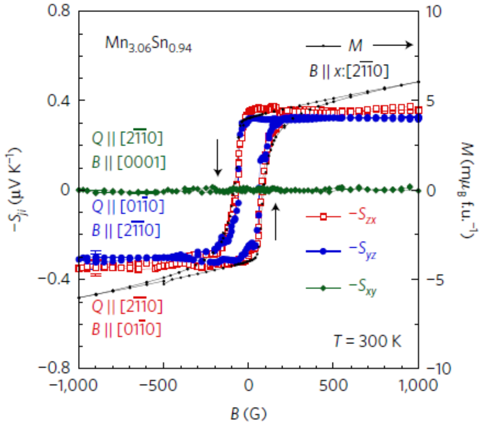
Nernst ~ ordinary ($\mathbf{B_{ext}}$) + anomalous (**M**) + anomalous (not dependent **M**) + topological +…



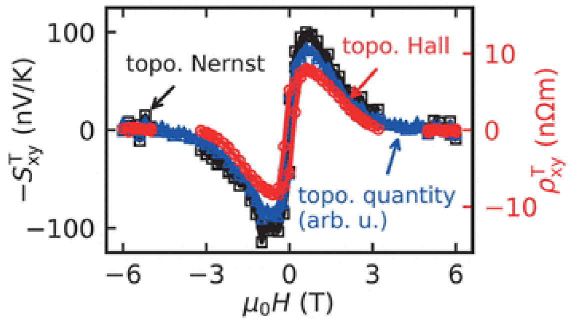
non-magnetic WTe_2



ferromagnetic Co_2MnGa



antiferromagnetic Mn_3Sn



skyrmion hosting $Mn_{1.8}PtSn$

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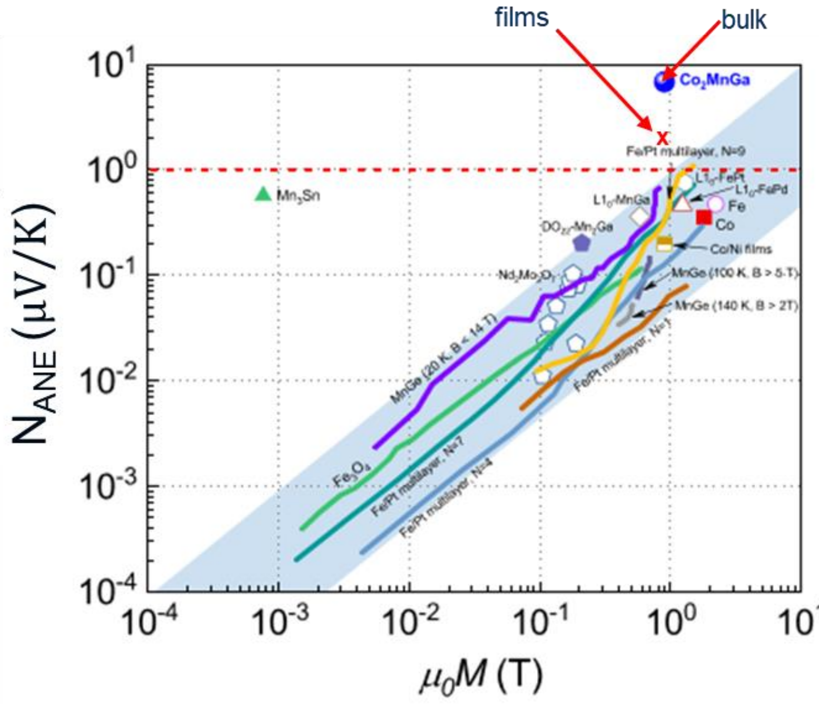
Anomalous Nernst Effect

- Intrinsic contribution - renaissance of studies
- Observed in many compensated systems
- Connection to AHE

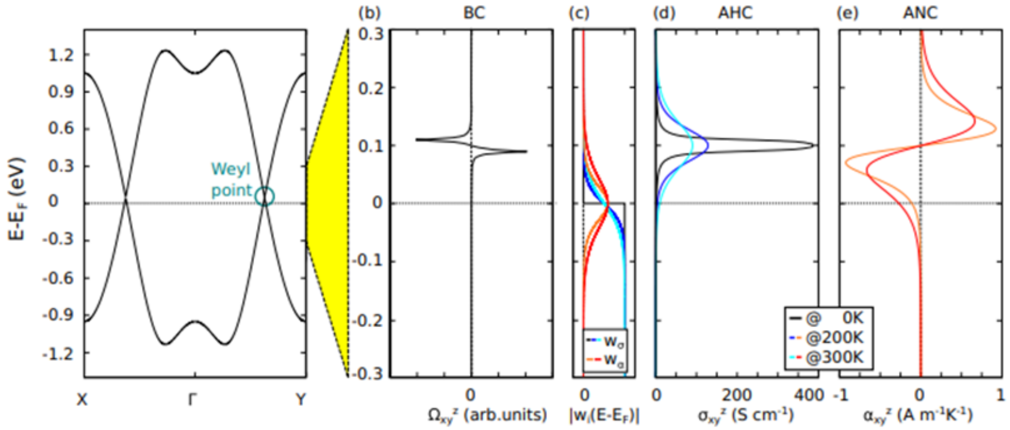
$$\begin{pmatrix} \boldsymbol{j} \\ \boldsymbol{j}_{heat} \end{pmatrix} = \begin{pmatrix} \boldsymbol{\sigma} & \boldsymbol{\alpha} \\ \boldsymbol{\alpha'} & \boldsymbol{\kappa} \end{pmatrix} \begin{pmatrix} e\boldsymbol{E} \\ -\boldsymbol{\nabla T}/T \end{pmatrix}$$

$$\alpha_{xy} = \left(\frac{\pi^2 k_B^2}{3e}\right) T \frac{d}{d\epsilon}[\sigma_{xy}(\epsilon)]_\mu$$

- higher sensitivity to states at the μ position

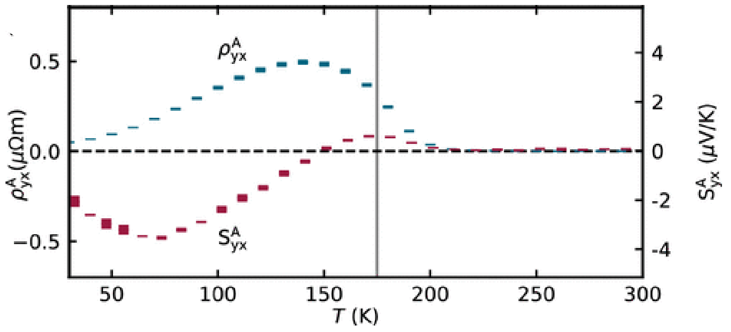


- Ikhlas et al. Nat. Phys. (2017)
- Reichlova et al. APL (2018)
- Guin et al. NPG Asia (2019)
- Reichlova et al. Nat Comm (2019)
- Pan et al. Nat. Mat.(2022)
- Beckert, HR et al. PRB (2023)
- …



- strain induced enhancement
- sensitive to topological features
- enhancement by spin fluctuations

- Noky et al., PRB 241106 (2018)
- Geishendorf et al. NanoLetters (2020)



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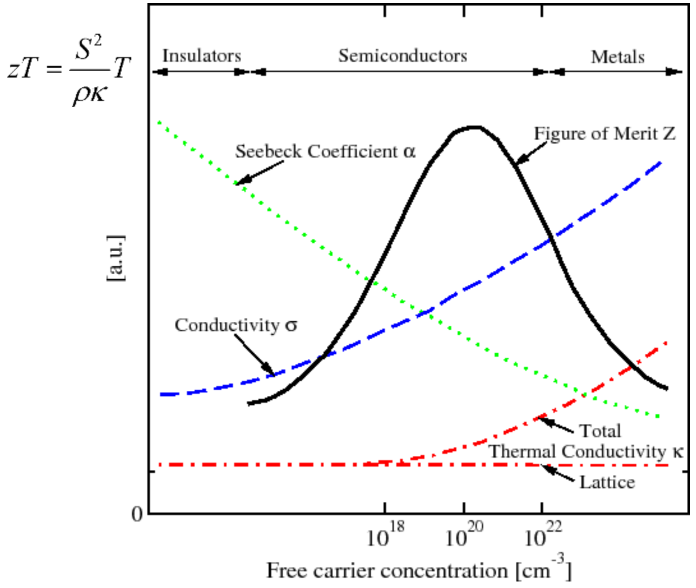
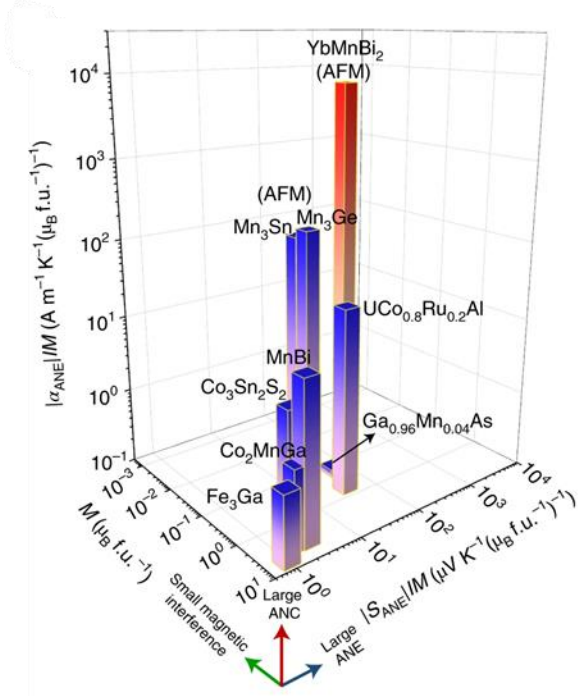
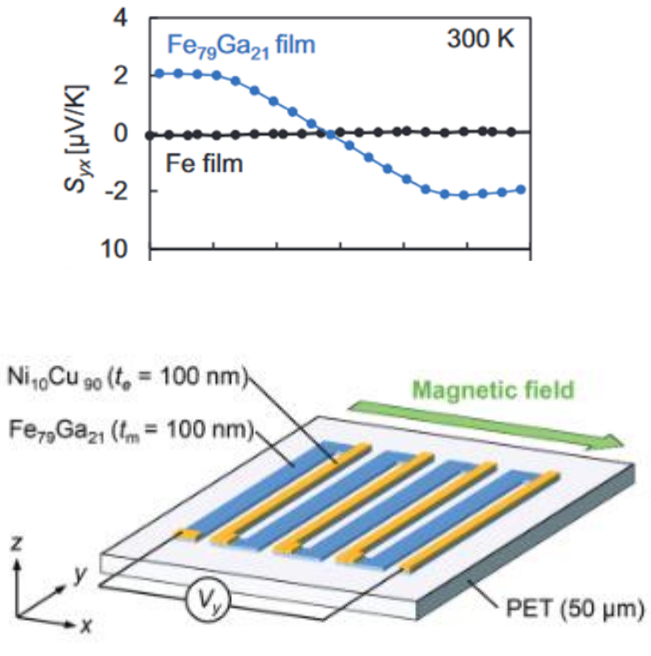
Anomalous Nernst Effect & Efficiency

- semimetal character for optimal figure of merit
- large ANE in non-collinear antiferromagnets
- large ANE in compounds with heavy elements
- application: need of controllable spontaneous ANE





Pan et al. Nat. Mat.(2022)



Tanaka et al. Advanced Materials (2023)

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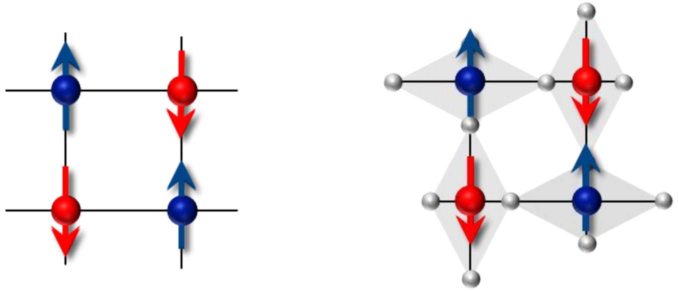
Anomalous Nernst effect in collinear compensated magnets

- Collinear antiferromagnets: does not exist
- Altermagnets: predicted to exist
  - ✓ altermagnetic $\mathcal{T}$ breaking
  - ✓ no need of heavy elements



🕮 Zhou et al. PRL (2024)

Altermagnetic Mn_5Si_3 films

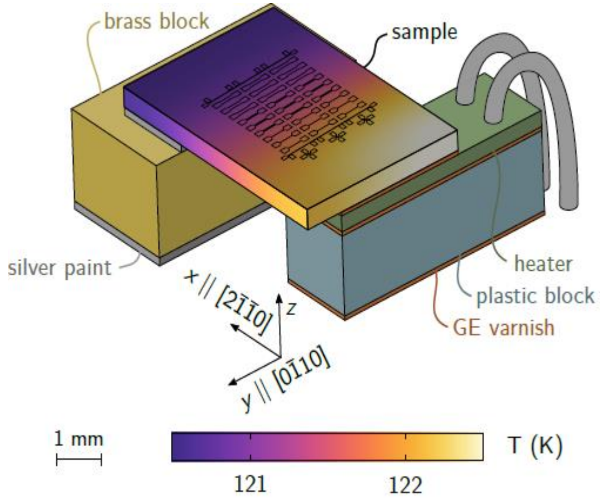
🕮 Reichlova et al. Nat. Comm. 4961 (2024)

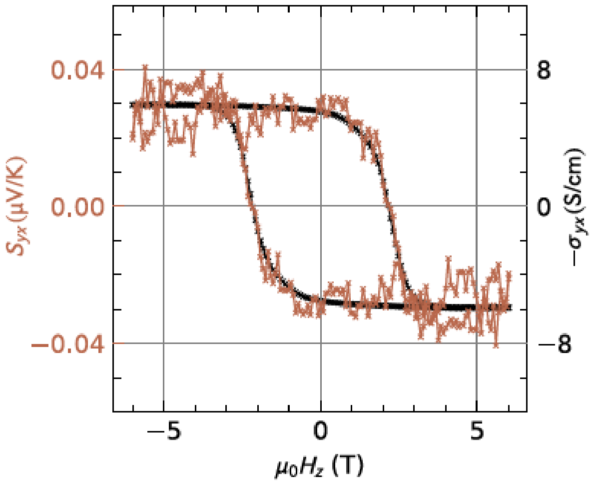
- collinear compensated order
- abundant light elements
- silicon compatible

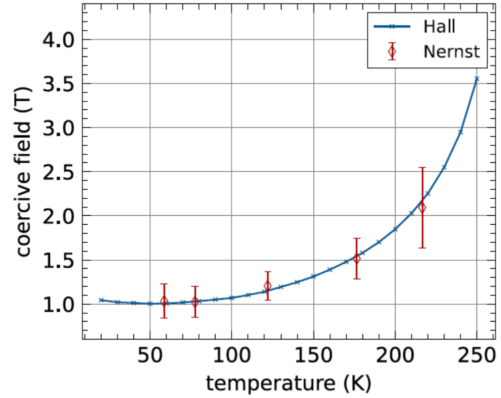
Anomalous Nernst in Mn_5Si_3 films

🕮 Badura et al. *in review*

- robust spontaneous ANE
- anisotropy as AHE
- in agreement with theory







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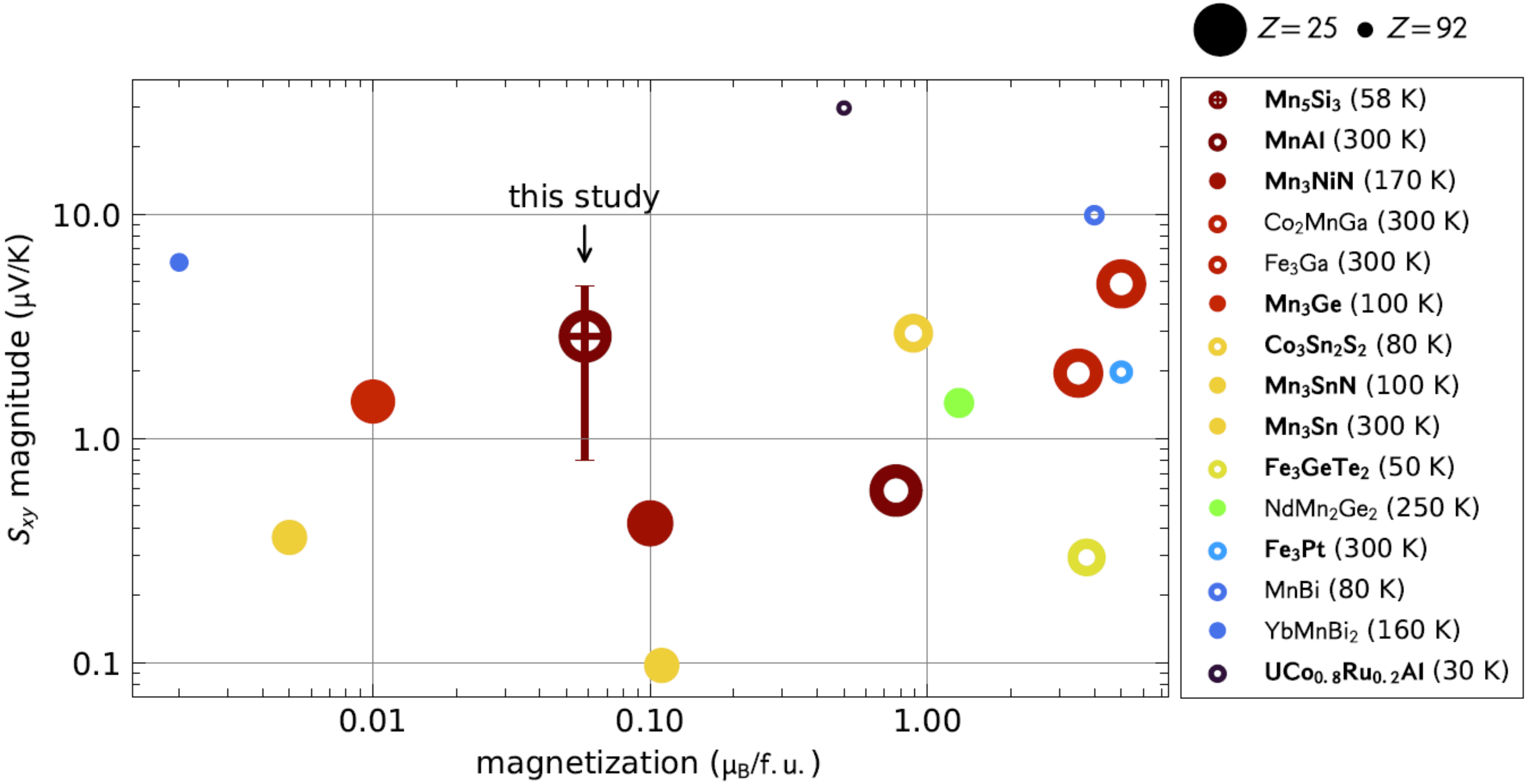
Anomalous Nernst Effect in Mn5Si3

- first ANE in collinear compensated magnet
- comparable magnitude to other materials
- Si compatible film, vanishing magnetization, metallic

📖 Badura et al. arXiv:2403.12929
📖 Han et al. arXiv:2403.13427



Summary

- Approaches to reduce energy costs of IT sector
- Spincaloritronics: harvesting and functionalizing waste heat
- Various contributions to the anomalous Nernst effect
- Highest ANE efficiency in heavy & toxic compounds
- First ANE in altermagnets
- ANE next steps: strain control, magnetic imaging, figure of merit