SPICE Workshop Mainz, Germany October 9, 2019

Large Spintronic Responses in Weyl Antiferromagnets

Correlation, Topology, Kagome, Spintronics

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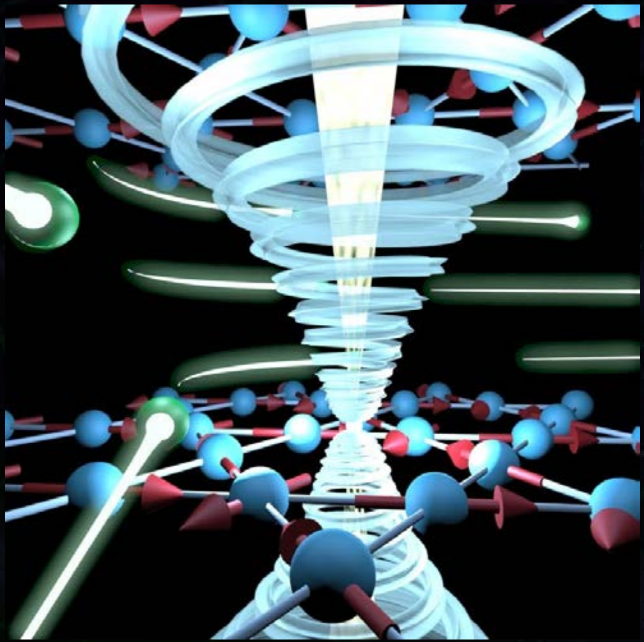


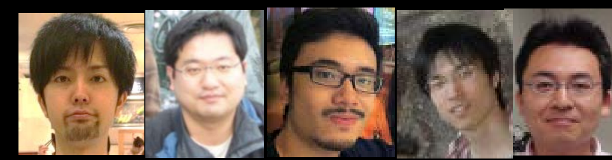
Overview

- Functional Magnets
  - Topological Weyl Semimetals,
  - Luttinger Semimetals
- Functional Antiferromagnets Mn_3X
  - *Topology and Multipoles*
  - *Novel Functions, Spintronics*
- Energy Harvesting

Collaborators

ISSP, U-Tokyo

T. Higo, T. Tomita, M. Ikhlas, A. Sakai, T. Ohtsuki



K. Kuroda, T. Kondo, S. Shin

M. Kimata, K. Kondo, Y. Otani

UC Berkley Liang Wu, J. Orenstein

NIST D. Gopman, R. D. Shull

Naval Res. Lab. O. van 't Erve

RIKEN

R. Arita, M-T. Suzuki, T. Koretsune

Colorado State Univ., UT Austin,

Hua Chen, A. MacDonald,

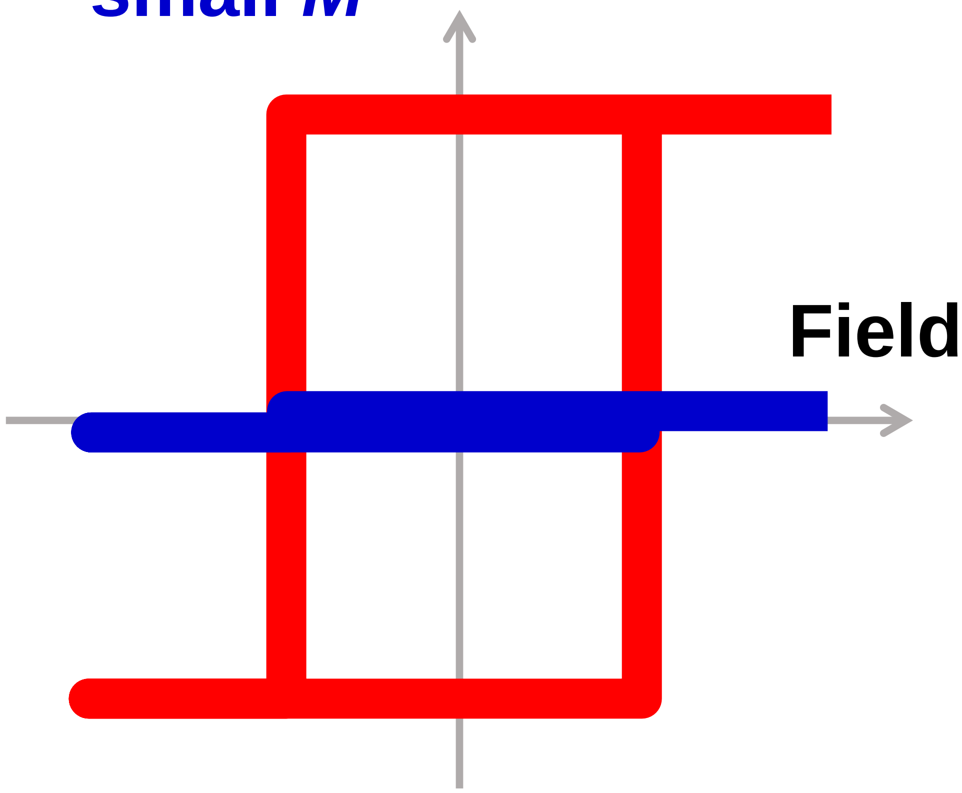
Northwestern Univ.

Pallab Goswami

Functional Antiferromagnet

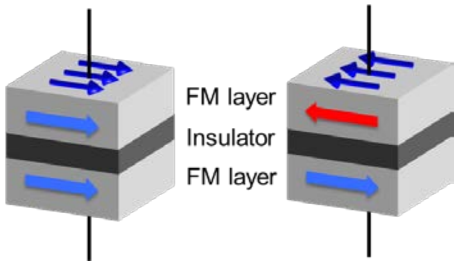
Large Response as in FMs

Vanishingly small *M*

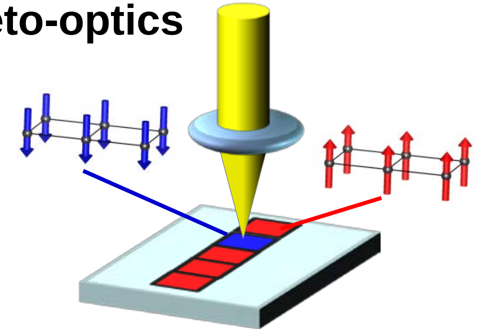


Dynamics ~THz

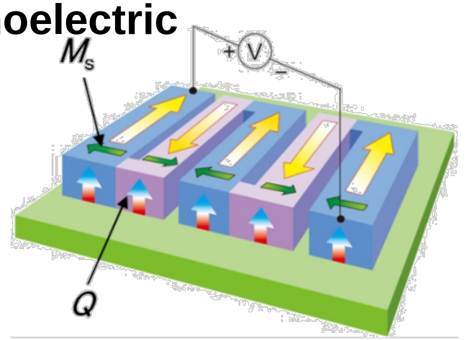
① **Nonvolatile Memory**



② **Magneto-optics**



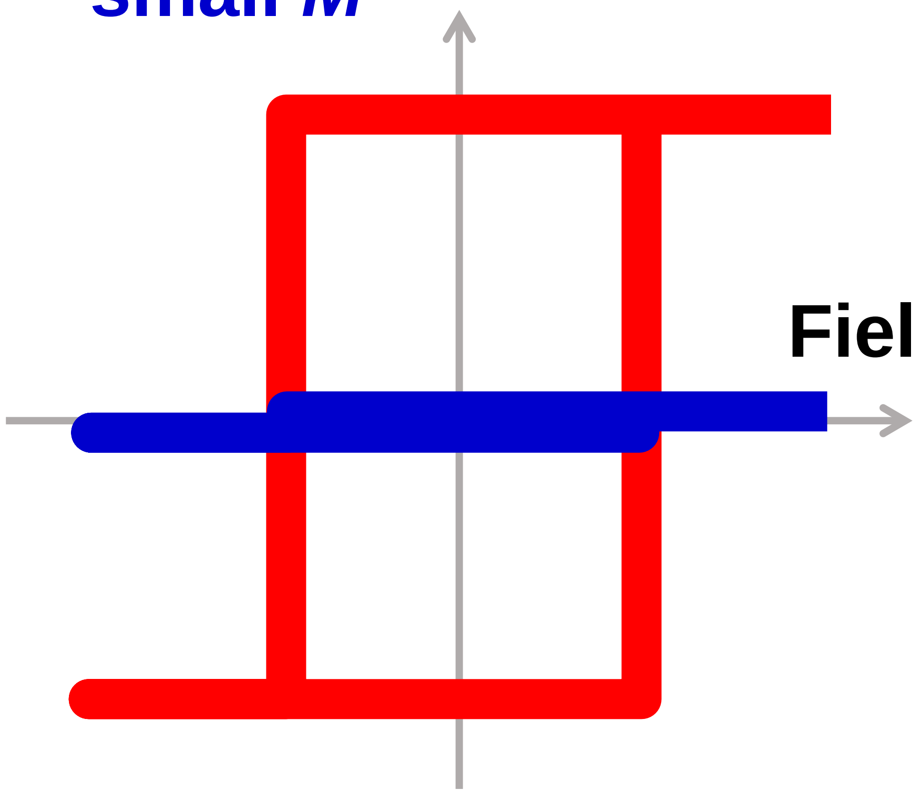
③ **Thermoelectric**



Novel Functional Magnet Mn_3X

Large Response as in FMs

Vanishingly small *M*



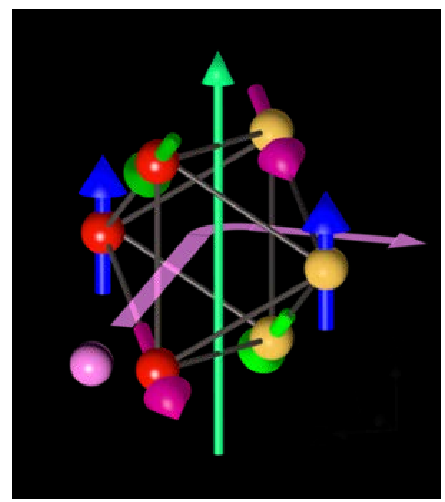
Field

Dynamics ~THz

Topological Weyl AFM

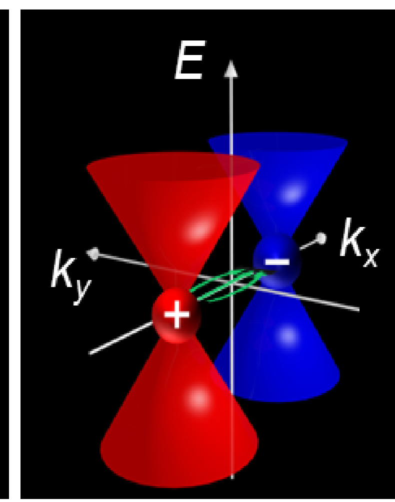
Mn_3Sn

Multipole



Real Space

Weyl Points

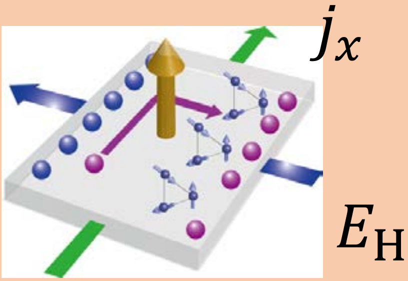


Momentum Space

Novel Functions in Antiferromagnet

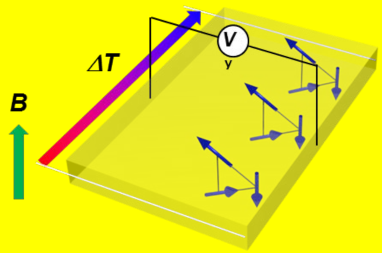
Large Fictitious Field in Momentum Space

Current



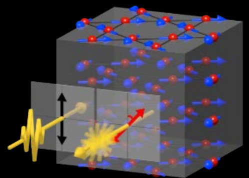
Anomalous Hall Effect

Heat



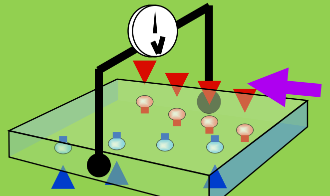
Anomalous Nernst Effect

Light



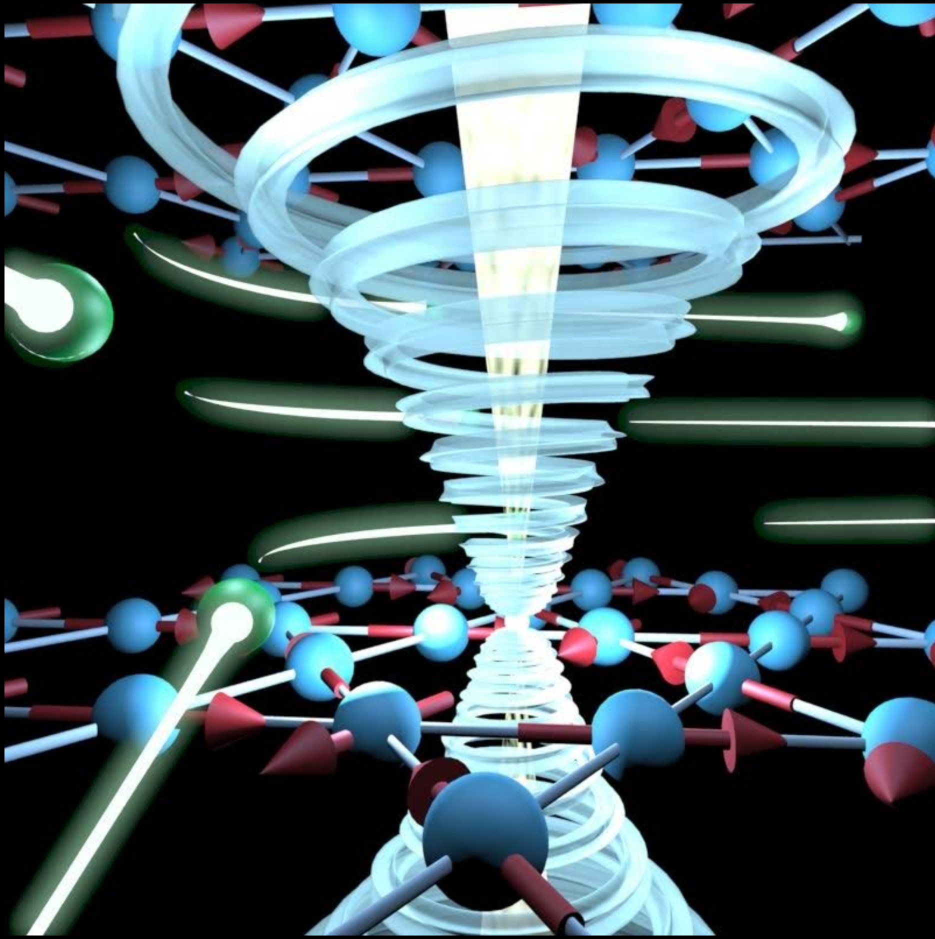
Magneto Optical Effect

Spin Current



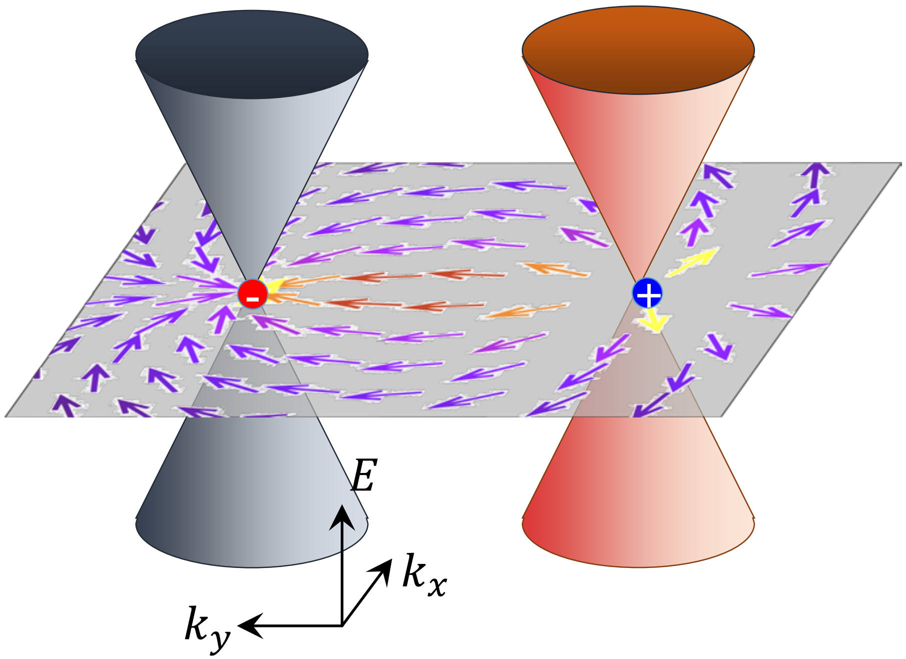
Magnetic Spin Hall Effect

Topological Weyl Magnets



Weyl Semimetal State

X. Wan, A. M. Turner, A. Vishwanath, and S. Y. Savrasov, 2011



Topological Metal with broken spatial inversion/ time reversal symmetry.

Pair of Linearly dispersive excitation Similar to Graphene, but in 3D.

Weyl Eq. $\mathcal{H} = \sum_{i=1}^{3} \mathbf{v}_i \cdot \mathbf{k}\ \sigma_i$

Robust against Symm. Breaking perturbation

Crossing points:

Magnetic Monopoles

Source and sink of Berry curvature/ Fictitious Field

- **Layered Quantum Hall Effect**
- **Chiral Anomaly**

Topological Aspect of AHE

Berry Phase Description e.g. Nagaosa, Sinova, Onoda, MacDonald, Ong., Rev. Mod. Phys. (2010).

Anomalous Hall current

$$\mathbf{J}_{\mathrm{H}} = 2e^2\,\mathbf{E} \times \sum_{\mathbf{k}} f_{\mathbf{k}}^{0}\,\mathbf{\Omega}_{\mathbf{k}}$$

Berry curvature
"Fictitious Field"

Anomalous Hall conductivity

$$\sigma_{xy} = n\frac{e^2}{\hbar}\langle\Omega\rangle$$

Independent of lifetime τ

Material Class for AHE at B = 0

- ✓ Ferromagnets — normally Berry curvature $\mathbf{\Omega} \sim M$
- ✓ Spin Liquids?
- ✓ Antiferromagnets?

However theoretically, $|\mathbf{\Omega}| > 0$ even when B = 0 and M = 0

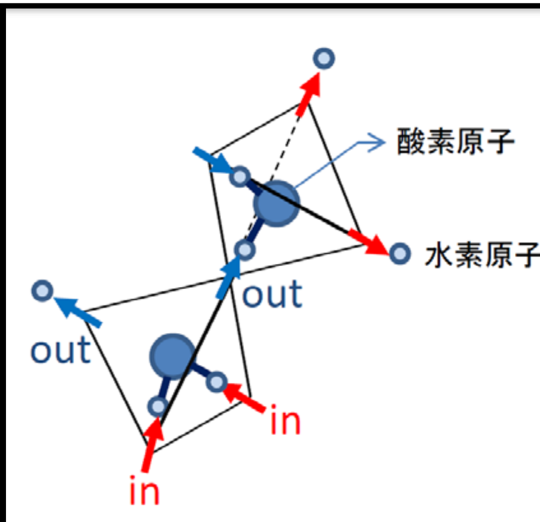
Shindou, Nagaosa (2001). Bruno (2006). Batista, Martin (2008). Chen et al., (2014)…

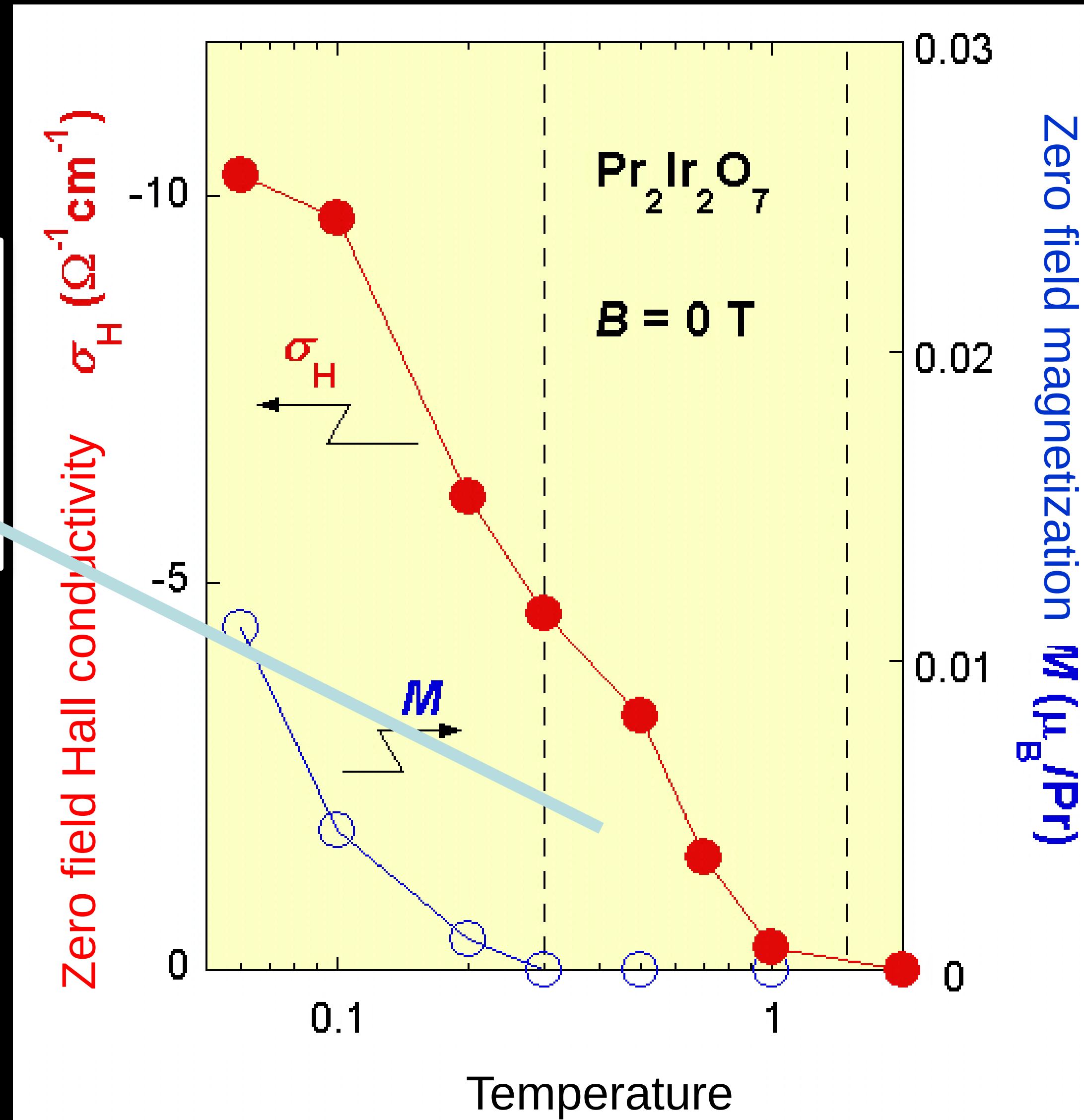
Spin liquids and AFM with large AHE: Nontrivial Topological Phases

Spontaneous Hall Effect in Spin Liquid

AHE w.
***B* = 0**
***M* =0**

***T* < 2*J* ~ 1.5 K Spin Ice:**
Quantum Fluctuations in the Spin Ice State
c.f. $Pr_2Zr_2O_7$, $Pr_2Hf_2O_7$



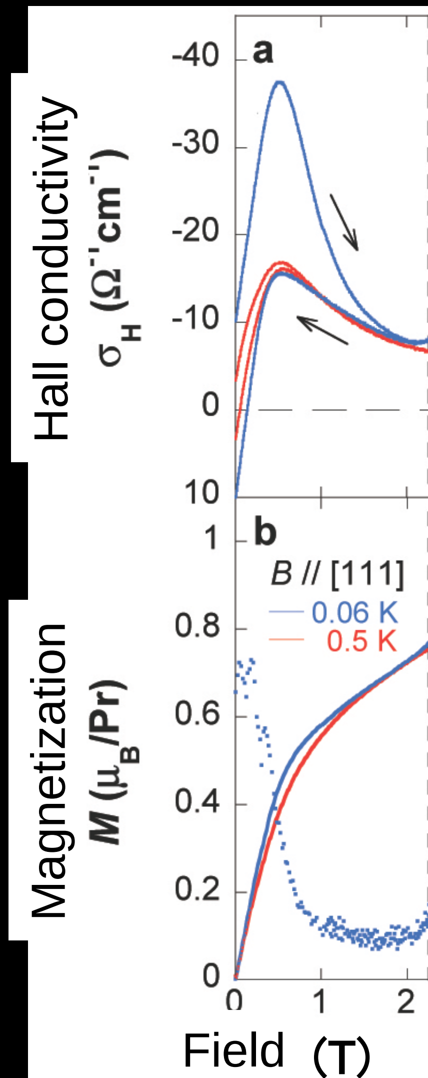


Machida et al., Nature (2009), Balicas et al., Phys. Rev. Lett.(2011).

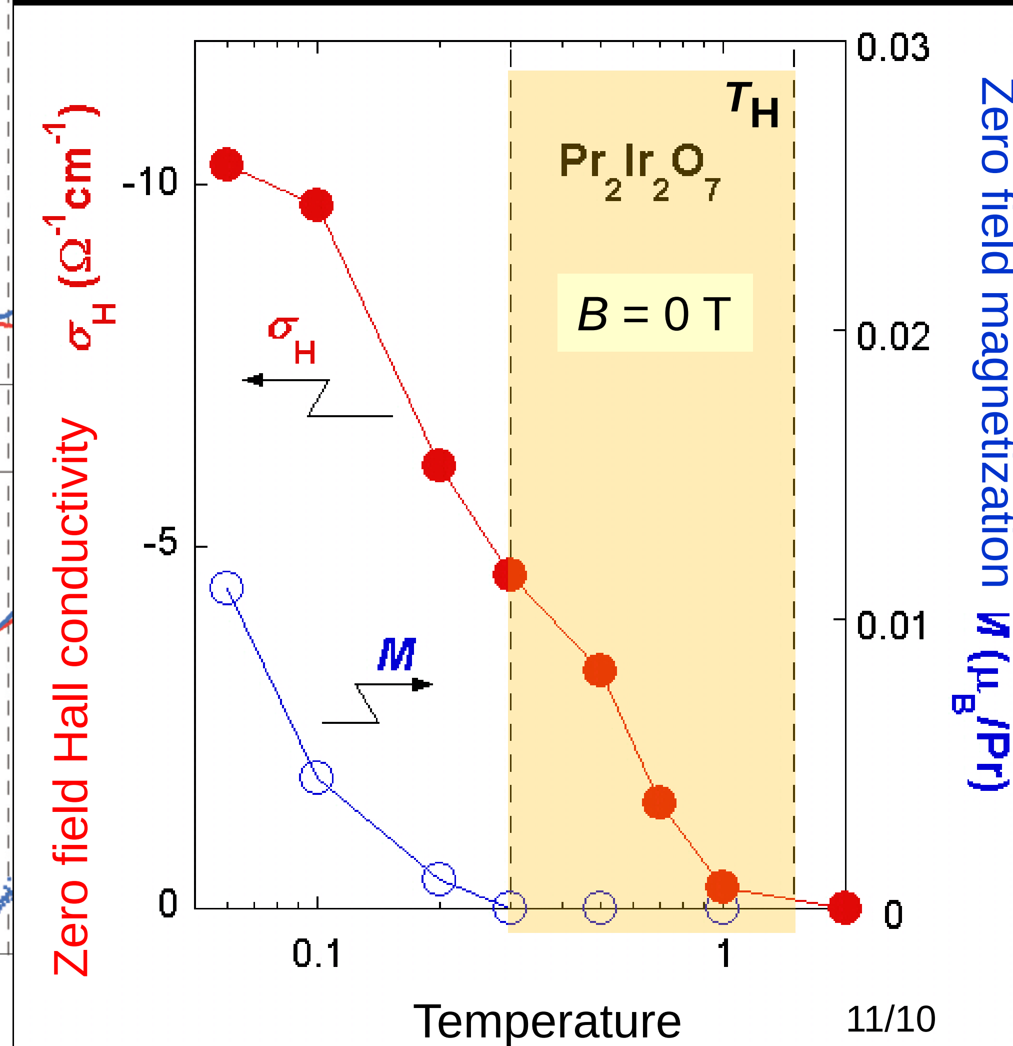
Spontaneous Hall Effect in Spin Liquid

Large Berry Curvature in *k*-Space

No Hysteresis in Magnetization



Large Hysteresis in Hall Effect

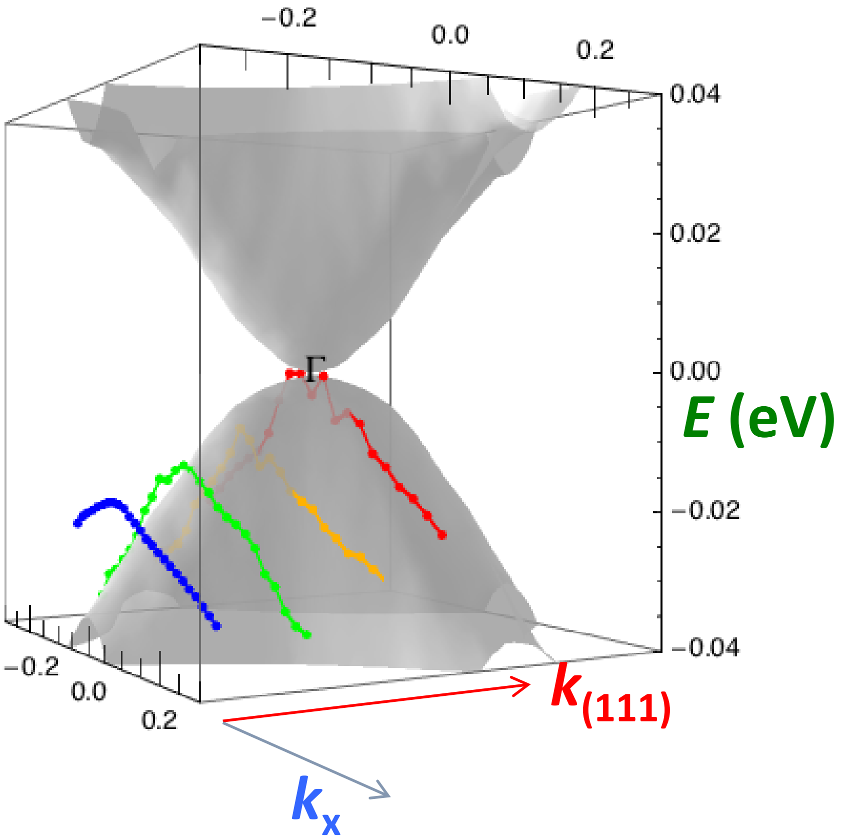


Machida et al., Nature (2009), Balicas et al., Phys. Rev. Lett.(2011).

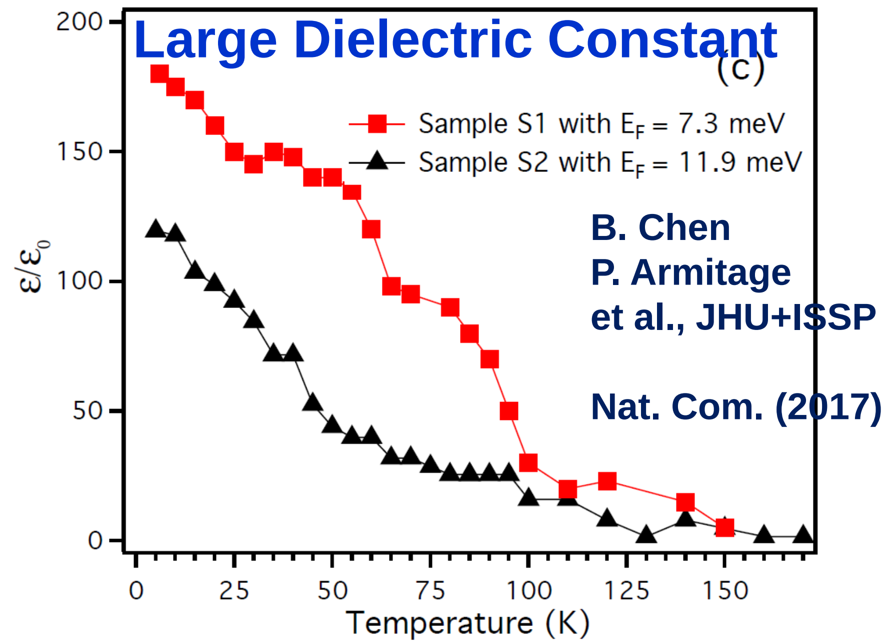
Fermi Node at Quadratic Band Touching

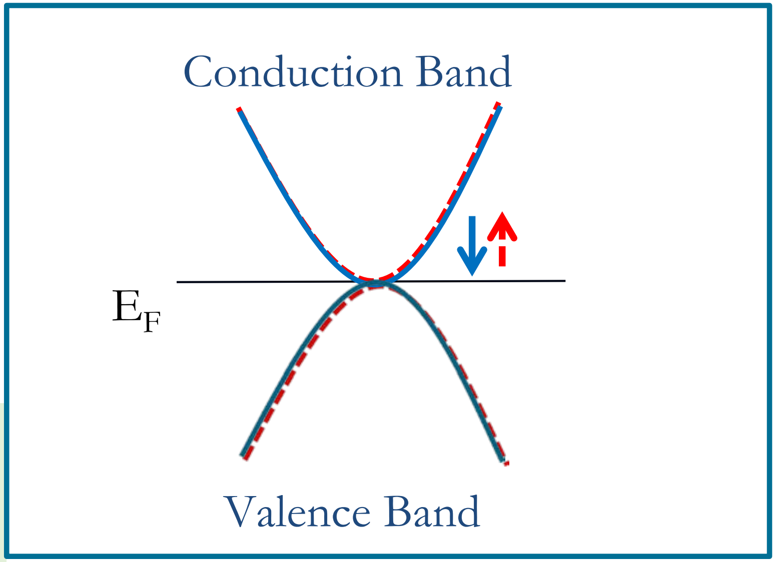
Luttinger Semimetal

Kondo & Shin, ISSP Nature Com. (2015)



Band Calc. by R. Chen, L. Balents



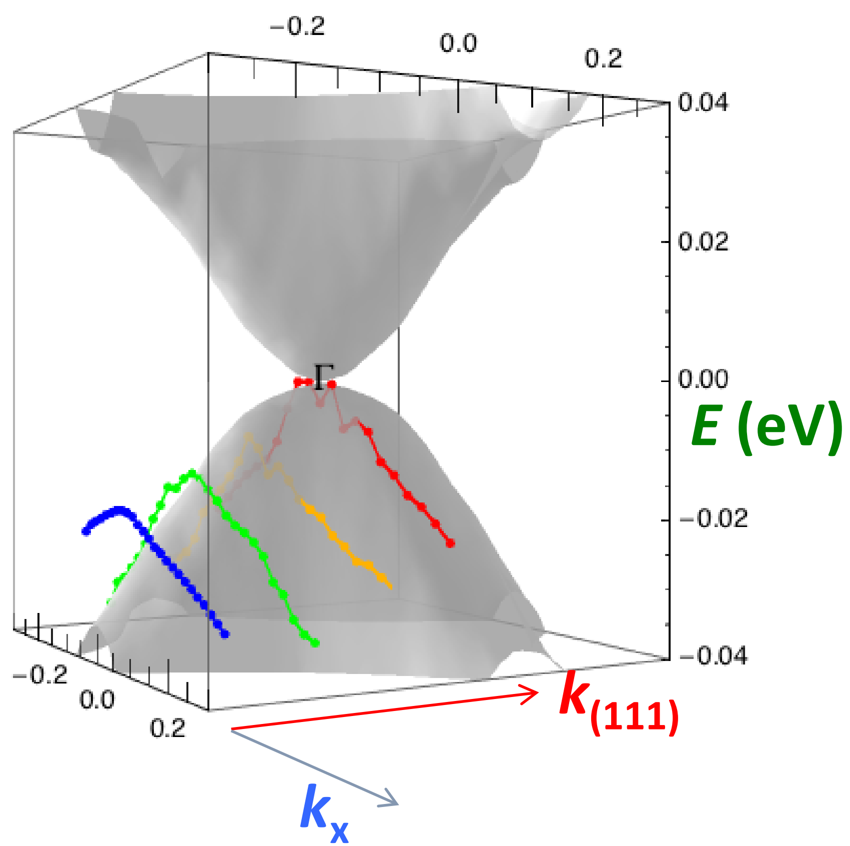


Correlated Version ($m^* \sim 6m_0$) of
Topological Insulator HgTe ($m^* \sim 0.03m_0$)

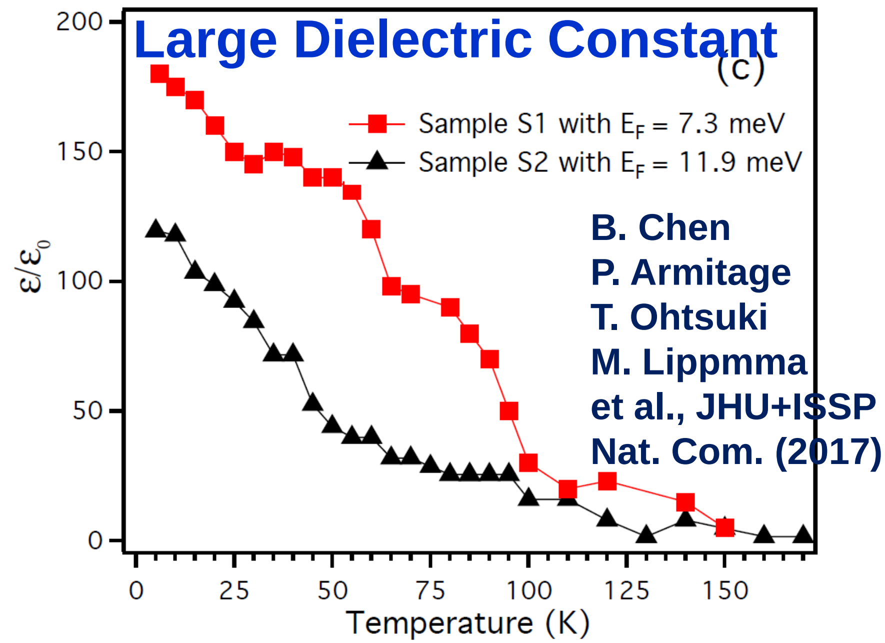
Fermi Node at Quadratic Band Touching

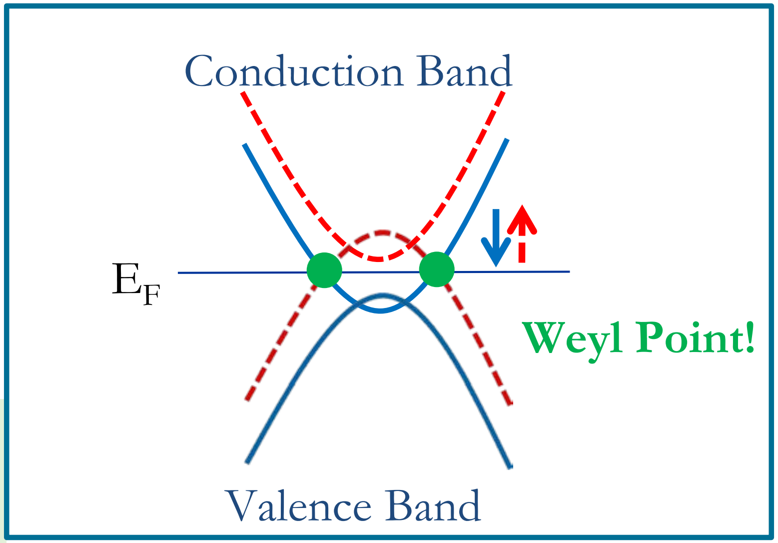
Luttinger Semimetal

Kondo & Shin, ISSP Nature Com. (2015)



Band Calc. by R. Chen, L. Balents



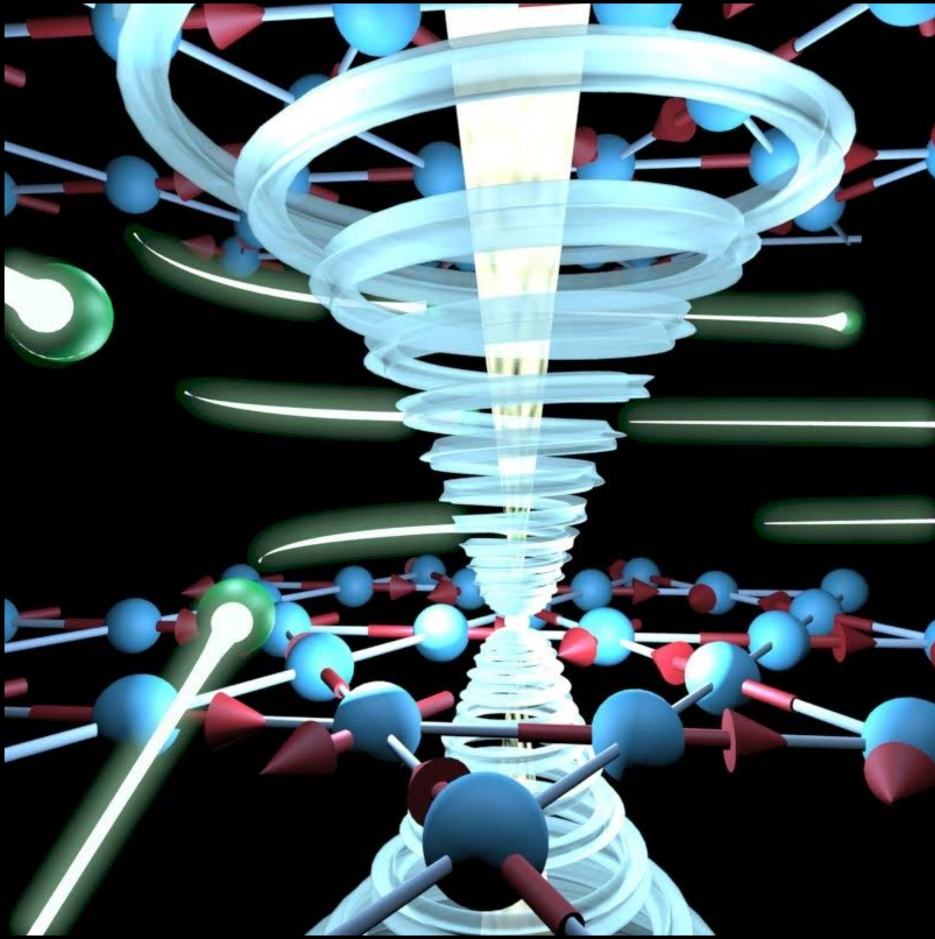


Correlated Version ($m^* \sim 6m_0$) of Topological Insulator HgTe ($m^* \sim 0.03m_0$)

Large Anomalous Hall Effect in Antiferromagnets

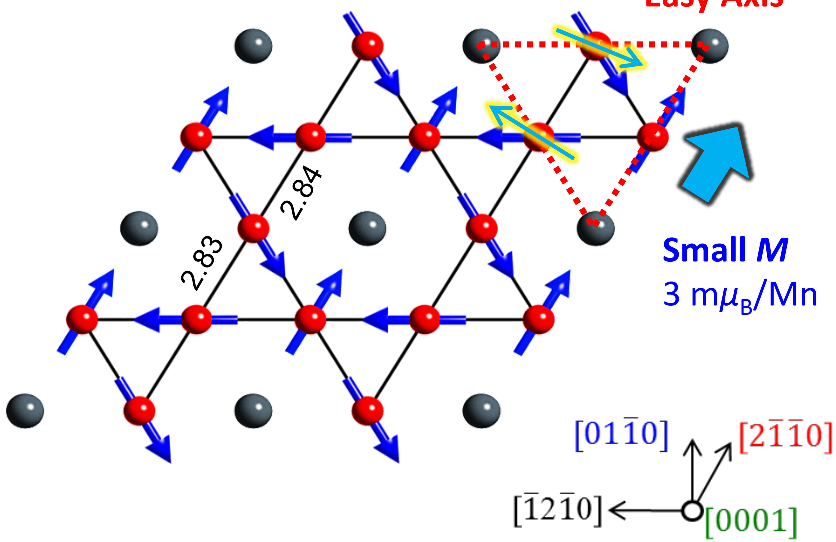
Antiferromagnets:

- ✓ Naturally abundant
- ✓ Higher Energy Scale than Spin Liquids



Kagome Metal AFM Mn_3Sn

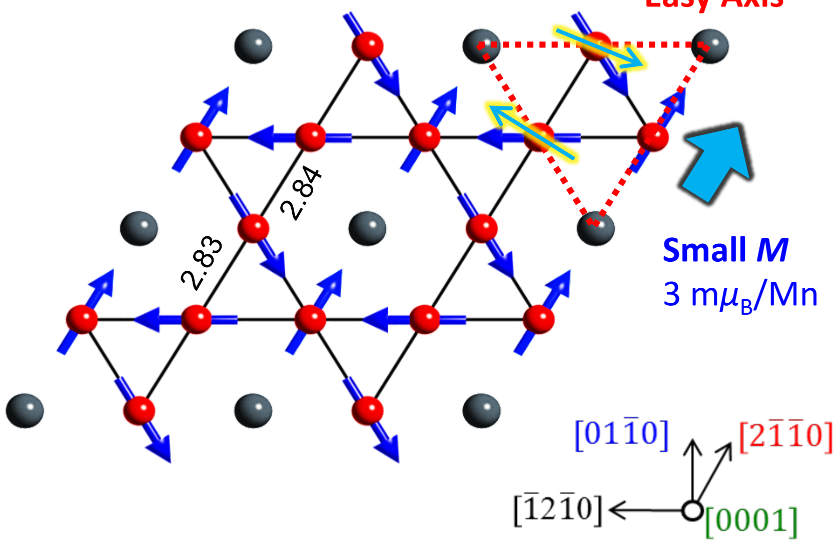
NonCollinear AFM T_N = 430 K

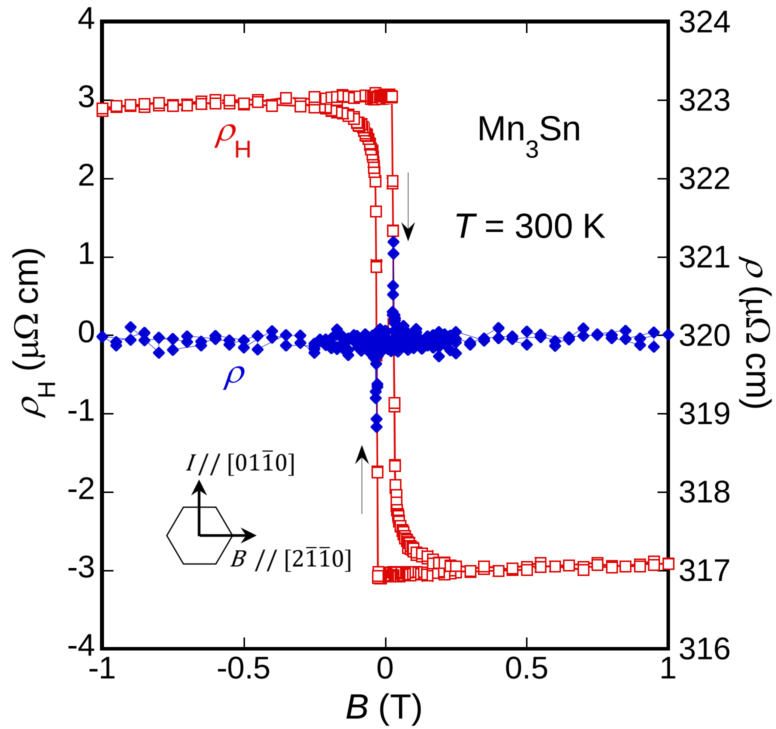


$$\rho_H = \underbrace{R_0 B + R_S \mu_0 M}_{\sim 0.01\ \mu\Omega\text{cm}}$$

Large AHE in AFM Mn_3Sn at R.T.

NonCollinear AFM T_N = 430 K





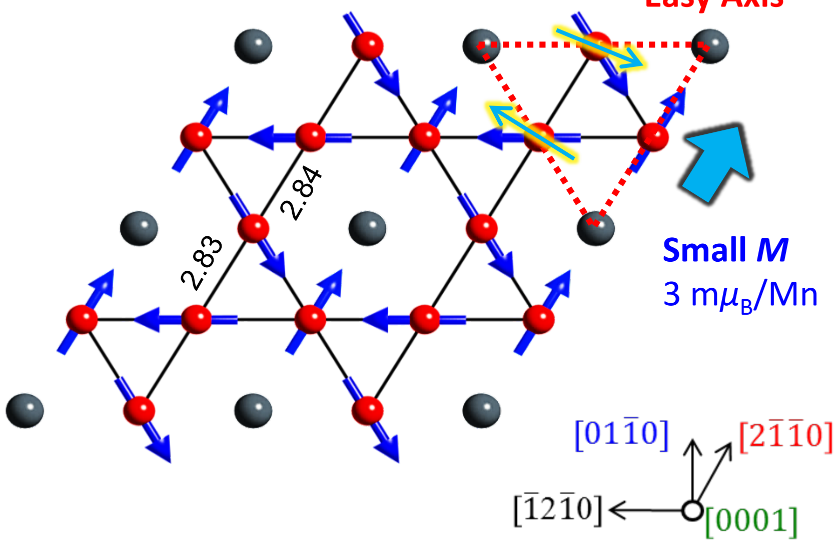
$$\rho_H = \underbrace{R_0 B}_{\sim 0.01\ \mu\Omega\text{cm}} + R_S \mu_0 M$$

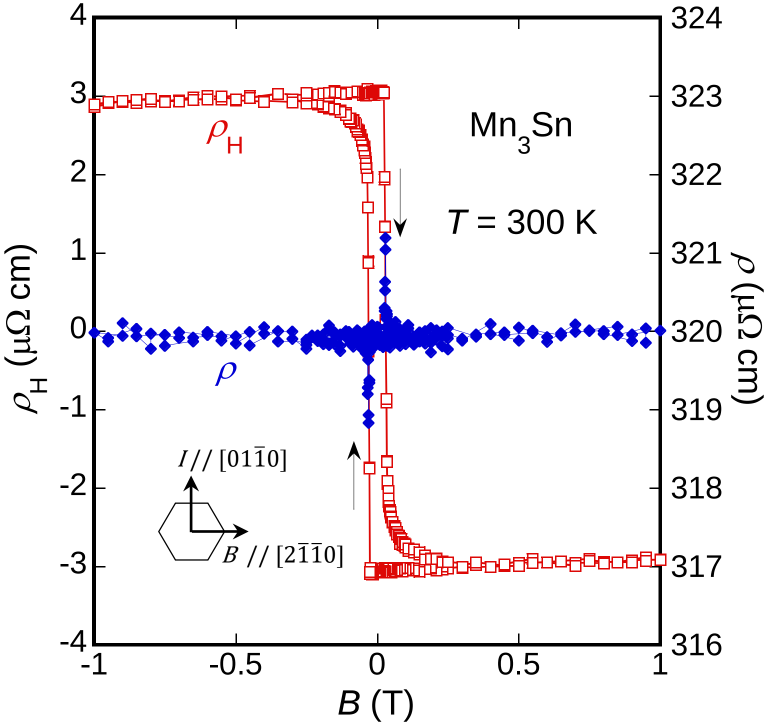
~ 3 μΩcm

Nature **527** 212 (2015).

Large AHE in AFM Mn_3Sn at R.T.

NonCollinear AFM T_N = 430 K





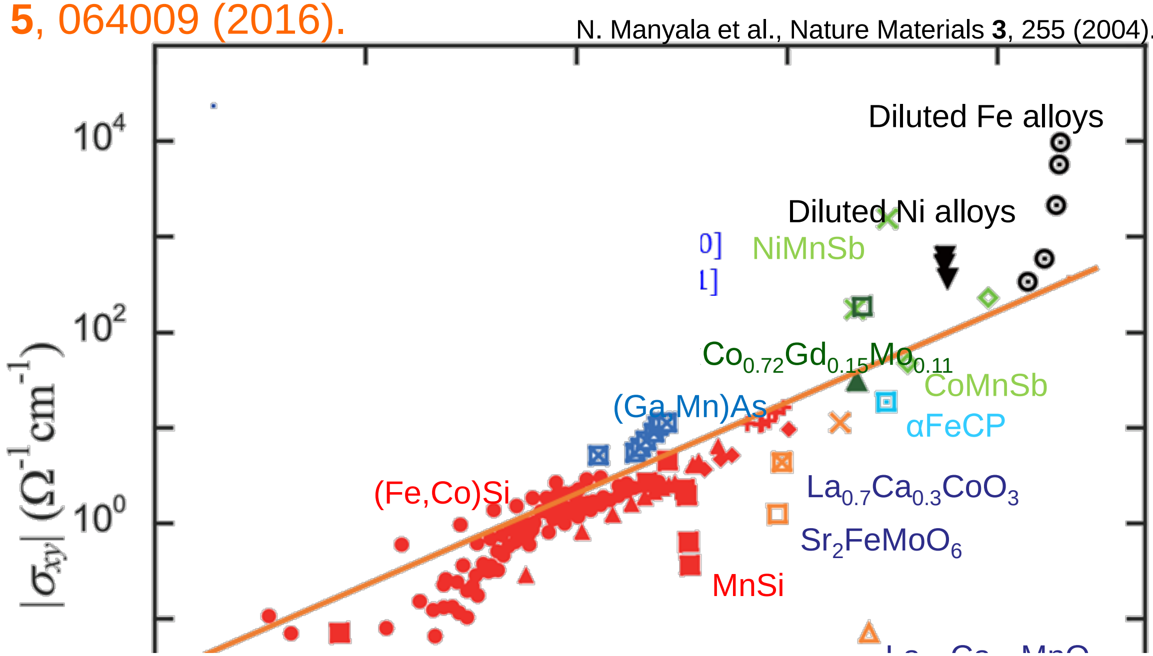
$$\rho_H = \underbrace{R_0 B + R_S \mu_0 M}_{\sim 0.01\ \mu\Omega\text{cm}} + \rho_H^{AF} \sim 3\ \mu\Omega\text{cm}$$

Nature **527** 212 (2015).

Large AHE is induced not by external or internal field, but the fictitious field.

Hall Conductivity vs. Magnetization

Nature **527** 212 (2015).
Phys. Rev. Appl. **5**, 064009 (2016).



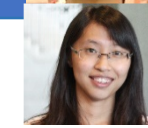
Q: How much field is needed for Ordinary HE to reach AHE?

■Hall Conductivity：

100～1000 times more than FMs

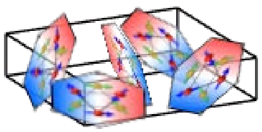
Large Berry Curvature ~ a few 100 T

Mn_3Sn Thin Film on Si substrate

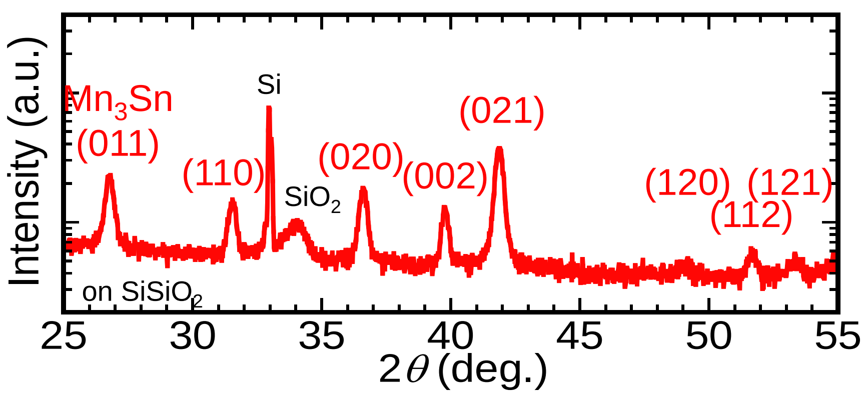


DC Sputtering Method

Mn_3Sn-target, Si/SiO_2/$Mn_{3+x}Sn_{1-x}$

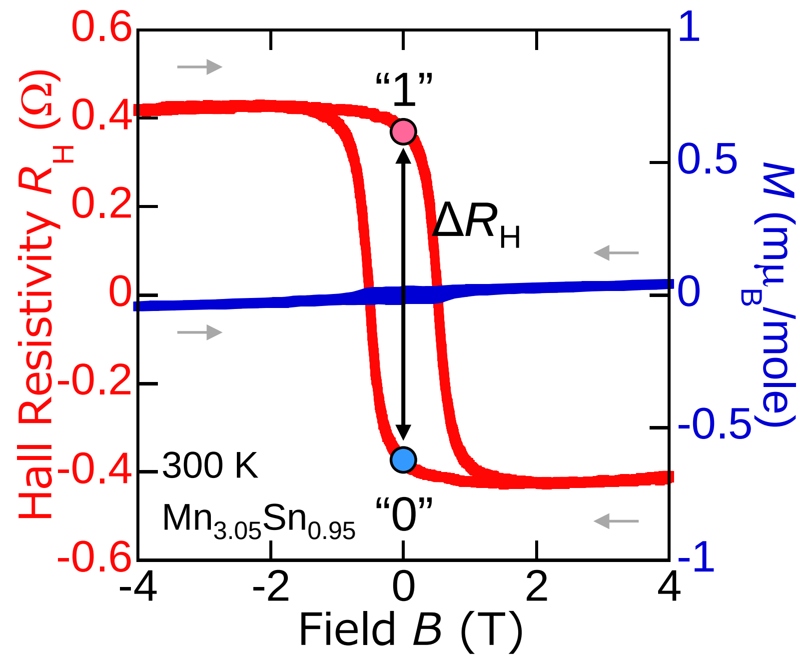


$Mn_{3.05}Sn_{0.95}$ thin film



a = 5.67 Å, c = 4.52 Å ≒ bulk results

Large Anomalous Hall Effect as Bulk



$\Delta R_H \sim 1\ \Omega$ >> AF-AMR ~ 0.01 Ω

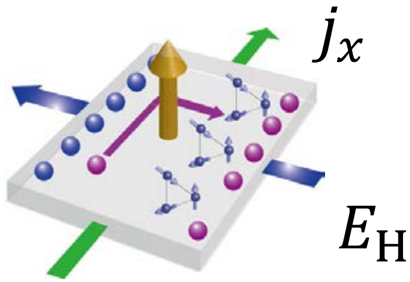
T. Higo et al., Applied Phys. Lett. (2018).

"featured articles"

Topological Spintronics using AFMs

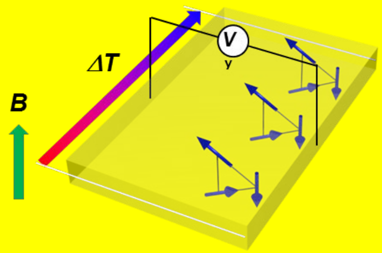
Fictitious Field e.q. a few 100 T in Momentum Space

Current



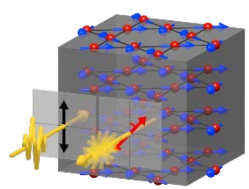
Anomalous Hall Effect

Heat



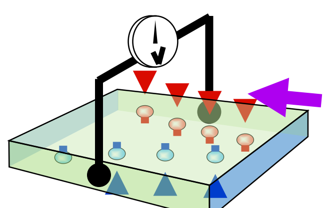
Anomalous Nernst Effect

Light



Magneto Optical Effect

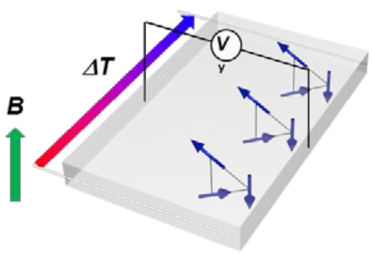
Spin Current

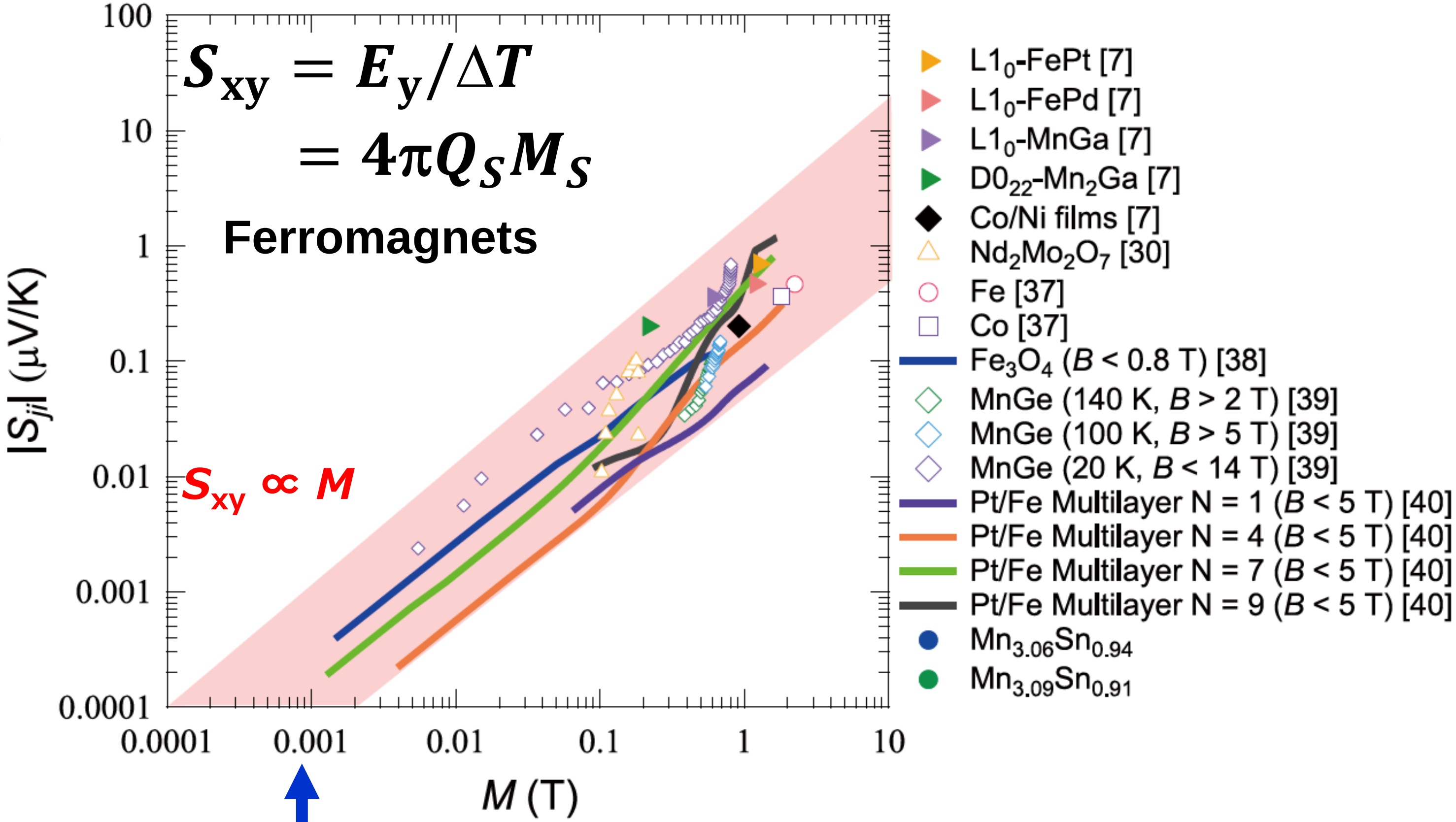


Magnetic Spin Hall Effect

Nernst Effect vs. Magnetization

Nat. Phys. 2017

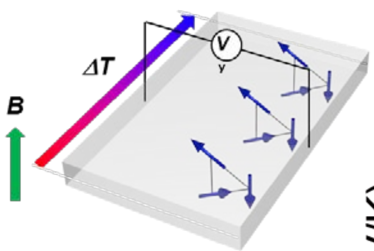




AFM Mn_3Sn

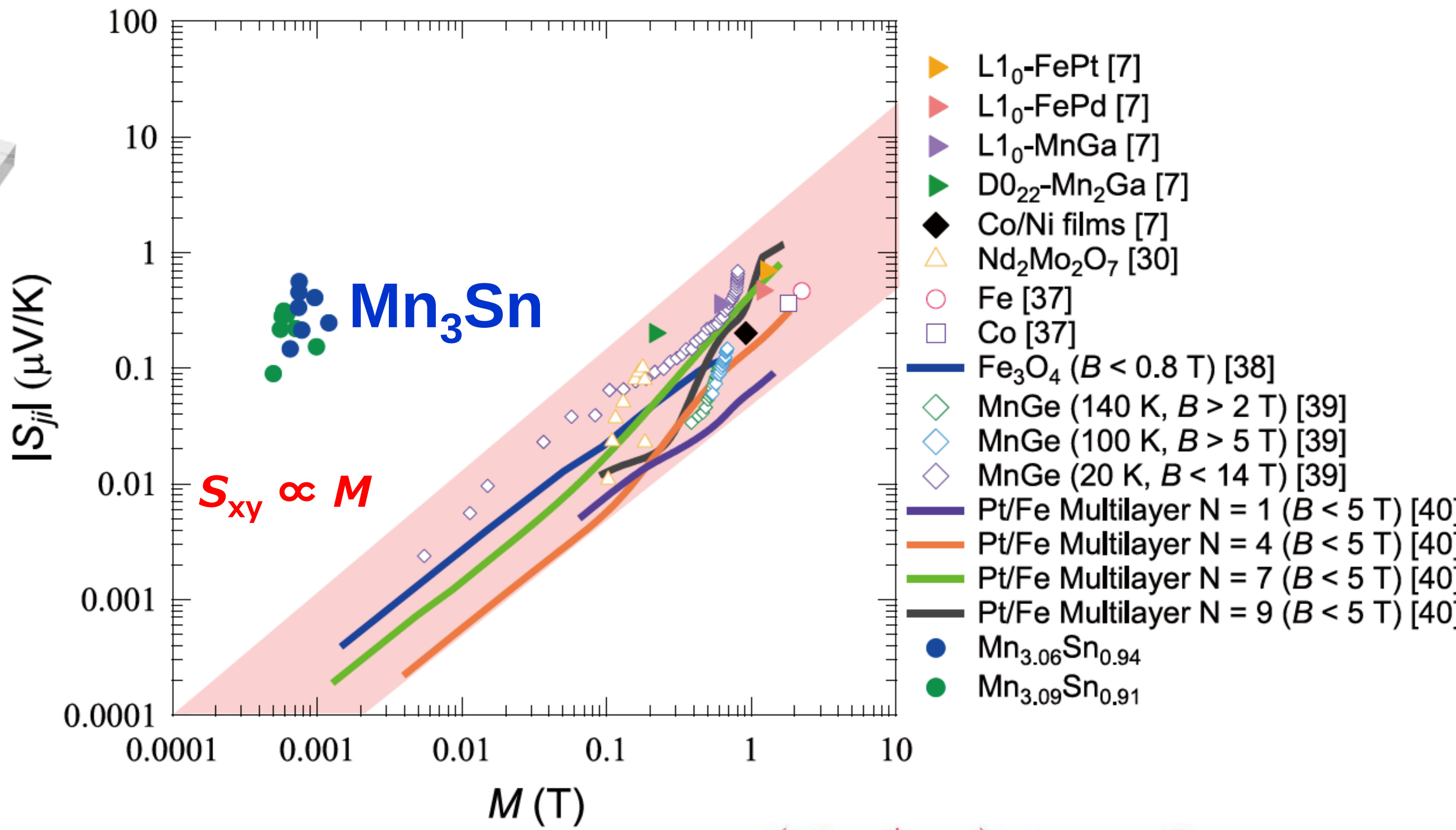
Nernst Effect vs. Magnetization

Nat. Phys. 2017



Ikhlas, Tomita et al., Nature Phys. (2017).

X. Li et al PRL **119**, 056601 (2017).



Transverse Thermoelectric Conductivity $\alpha_{zx} = (S_{zx}/\rho_{zz}) + \sigma_{zx} S_{xx}$

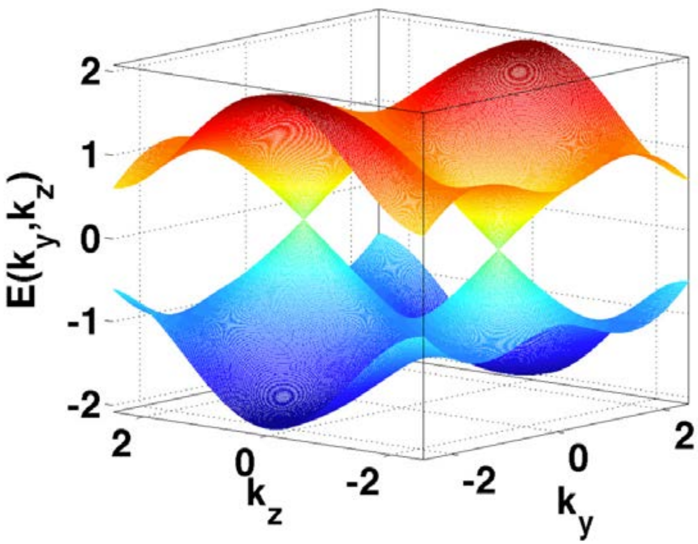
$$\alpha_{zx} = -\frac{e}{T\hbar} \int \frac{d\boldsymbol{k}}{(2\pi)^3} \Omega_{n,y}(\boldsymbol{k}) \left\{ (\varepsilon_{n\boldsymbol{k}} - \mu) f_{n\boldsymbol{k}} + k_{\mathrm{B}} T \ln \left[1 + e^{-\beta(\varepsilon_{n\boldsymbol{k}} - \mu)} \right] \right\}$$

■Nernst Effect：~Berry curvature at Fermi Energy

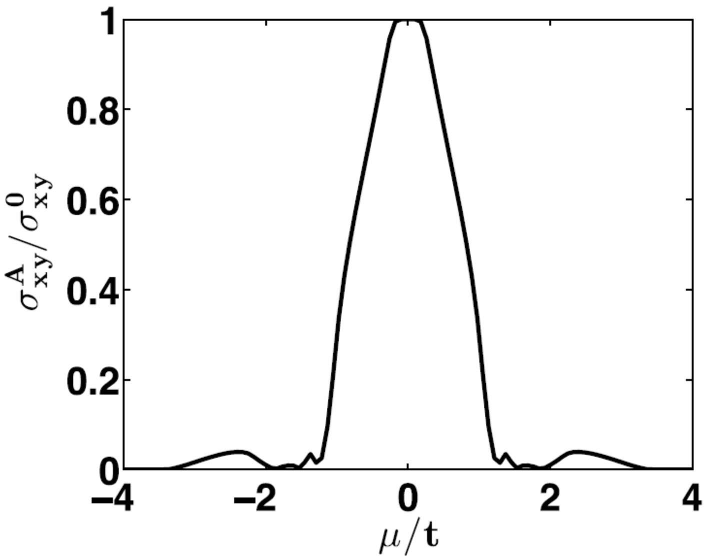
100～1000 times more than ferromagnets

Large Berry Curvature near E_F

Magnetic Weyl Semimetal: Toy Model

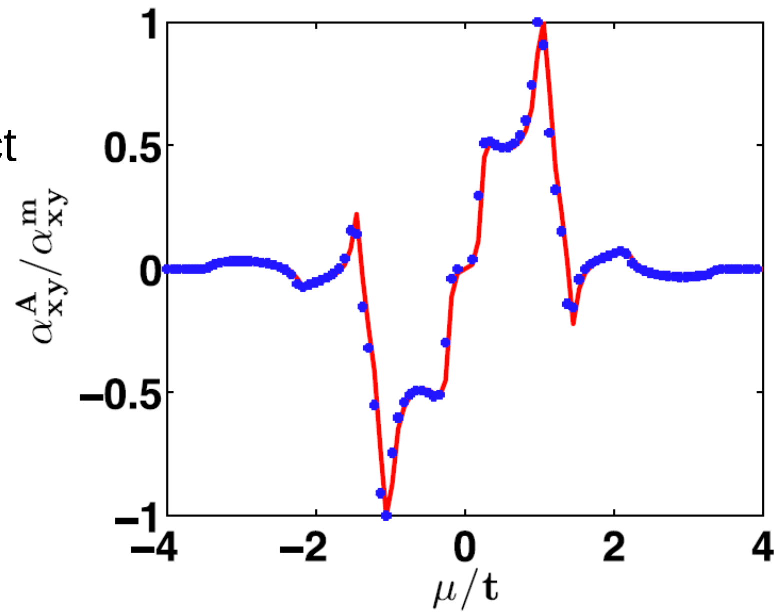


Anomalous
Hall Effect



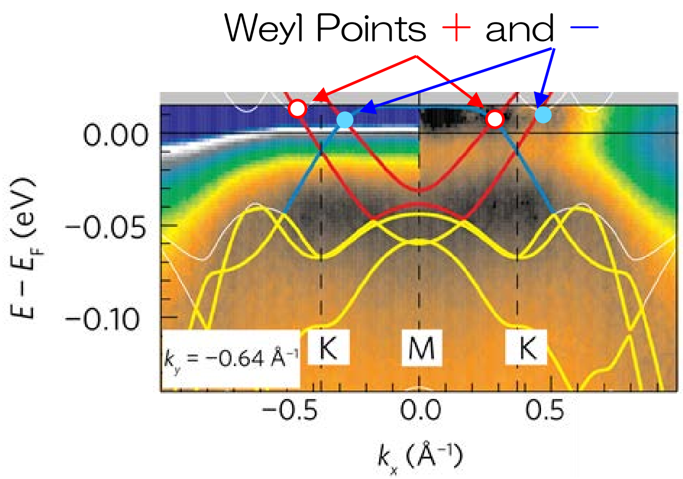
$$\alpha_{xy}{}^{\mathrm{AF}} \propto \left(\frac{\partial \sigma_{xy}}{\partial E} \right)_{E_F}$$

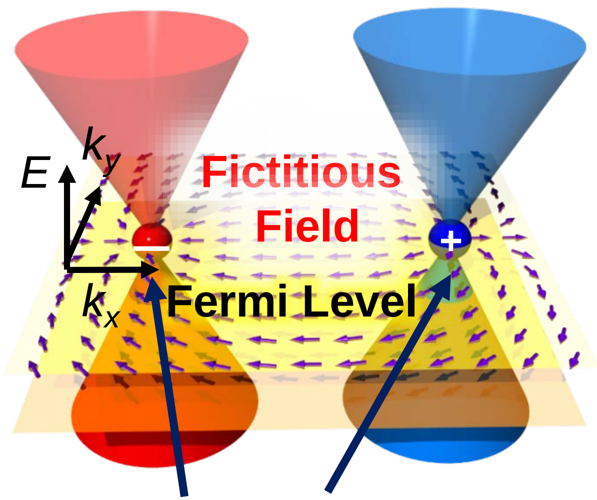
Anomalous
Nernst Effect



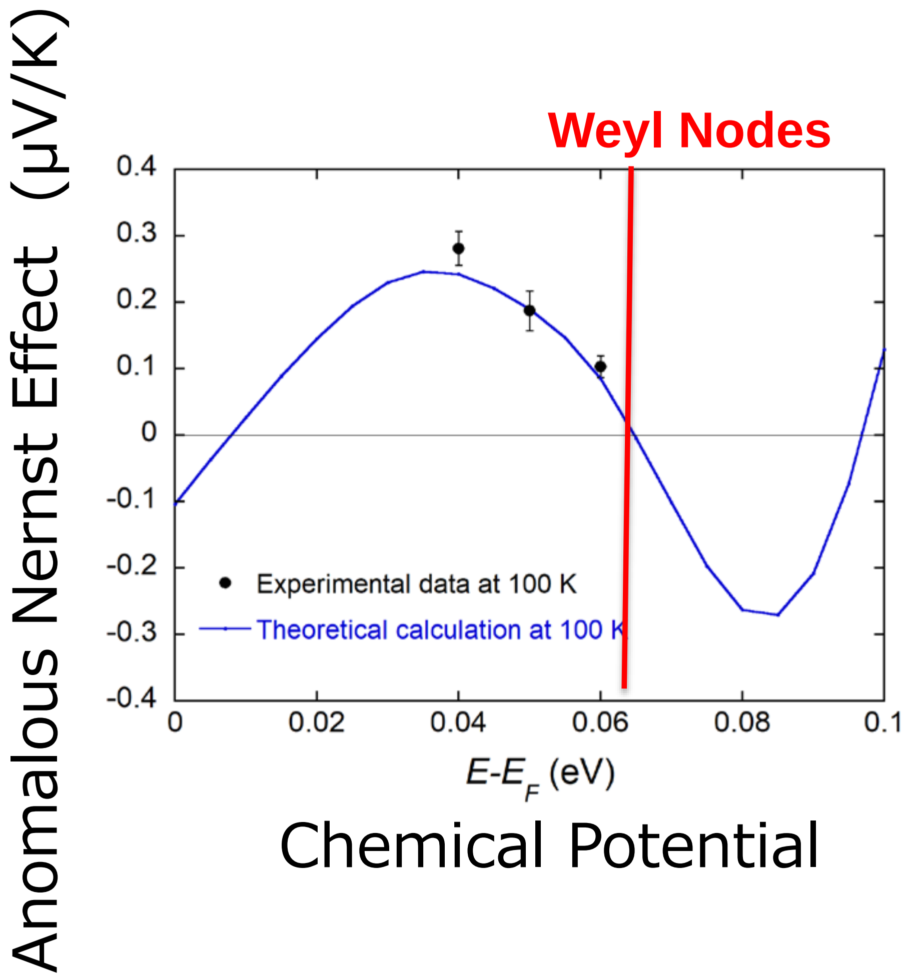
Sharma, Goswami, Tewari Phys. Rev. B 93 035116 (2016).

Magnetic Weyl Fermions



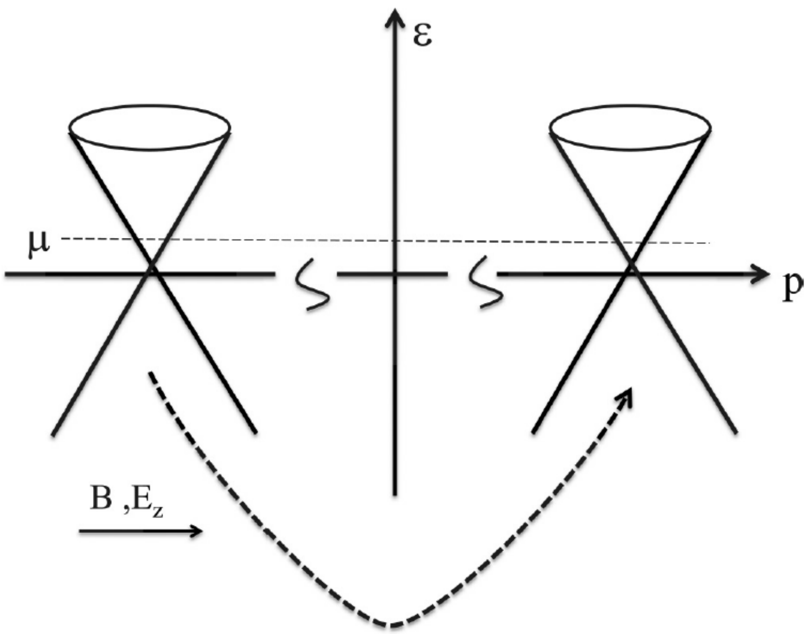


Berry Curvature from Weyl nodes near E_F



Kuroda, Tomita, SN et. al., Nature Materials (2017).
Ikhlas, Tomita, SN et. al., Nature Physics (2017).

Chiral Anomaly: Mag. Weyl Fermions



$$\sigma_{zz} = \frac{e^2}{4\pi^2\hbar c}\frac{v}{c}\frac{(eB)^2 v^2}{\mu^2}\tau.$$

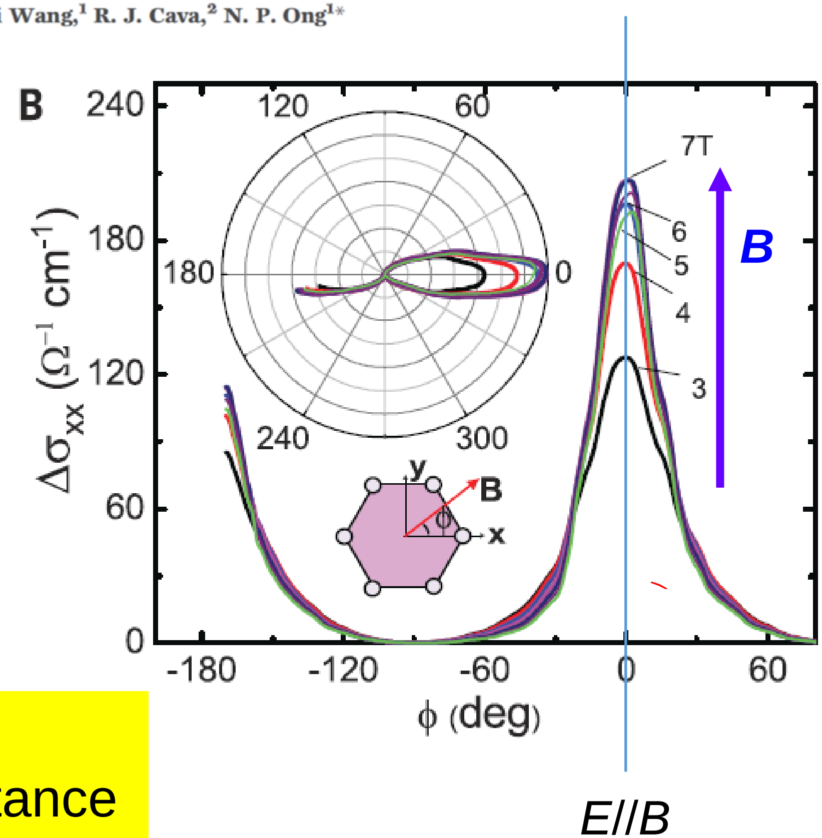
RESEARCH | REPORTS

Science 2015

TOPOLOGICAL MATTER

Evidence for the chiral anomaly in the Dirac semimetal Na_3Bi

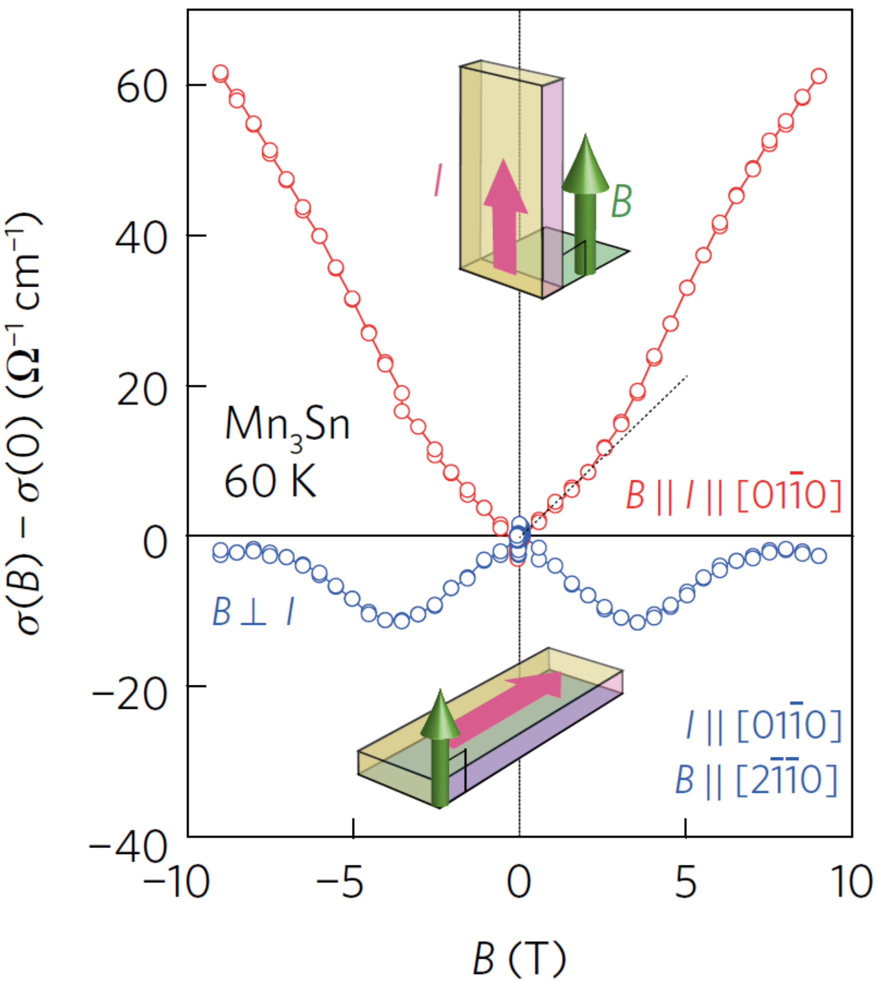
Jun Xiong,[1] Satya K. Kushwaha,[2] Tian Liang,[1] Jason W. Krizan,[2] Max Hirschberger,[1] Wudi Wang,[1] R. J. Cava,[2] N. P. Ong[1*]

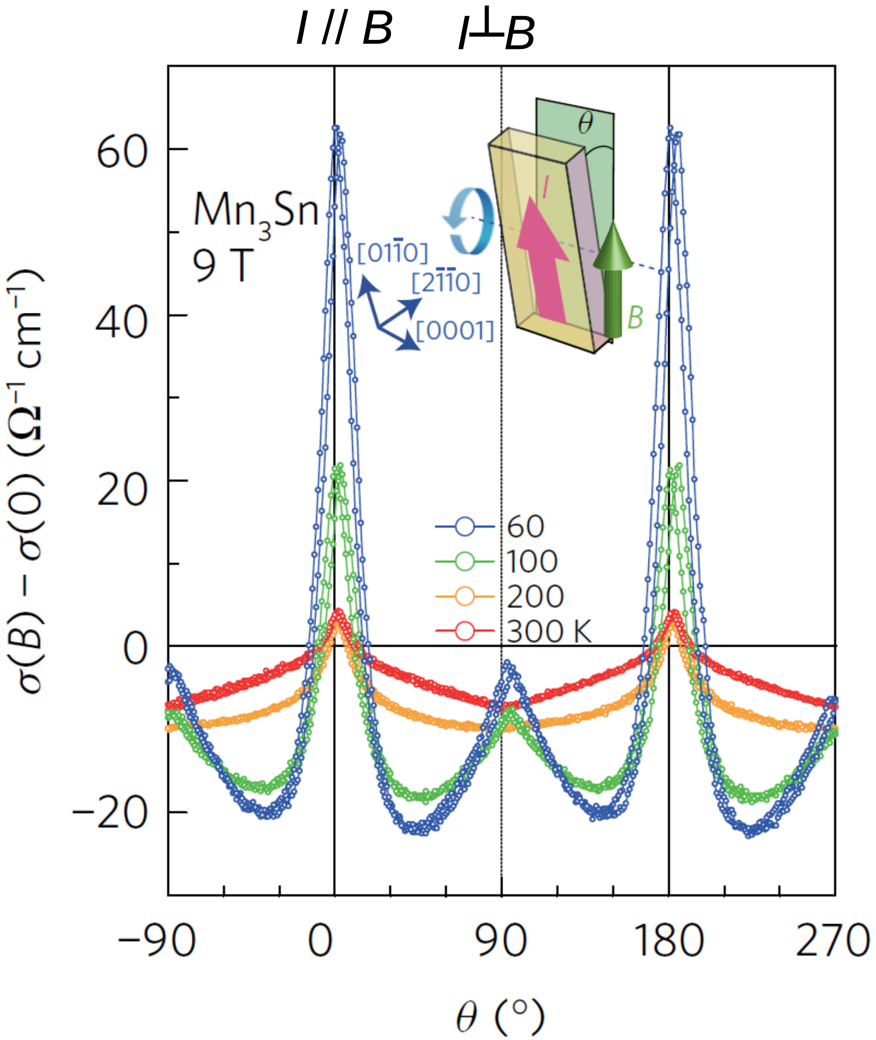


Strongly Anisotropic Magnetoconductance
Only when *E//B*, Positive Magenetoconductance

D. T. Son and B. Z. Spivak, Phys. Rev. B **88**, 104412 (2013).

Chiral Anomaly: Mag. Weyl Fermions

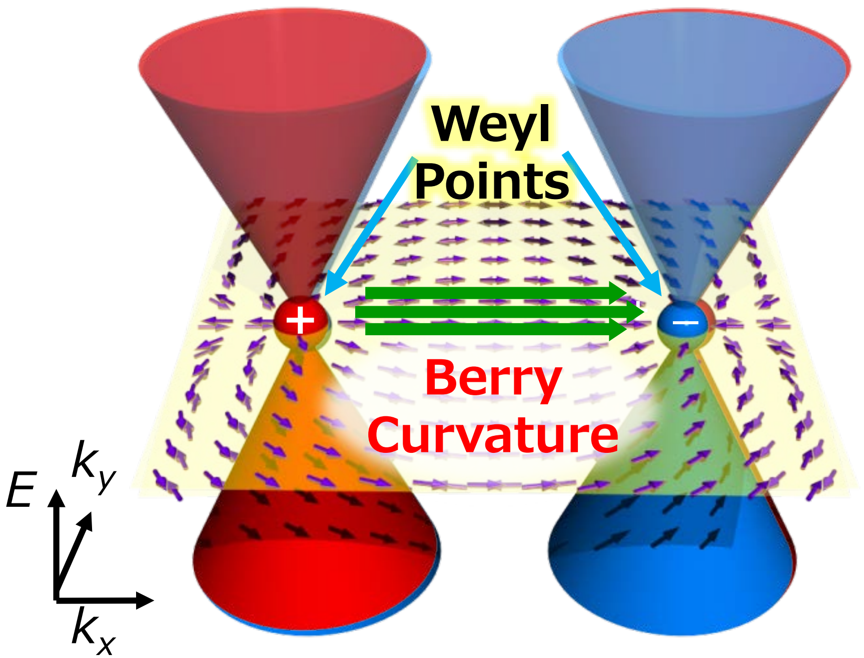




Nature Materials (2017).

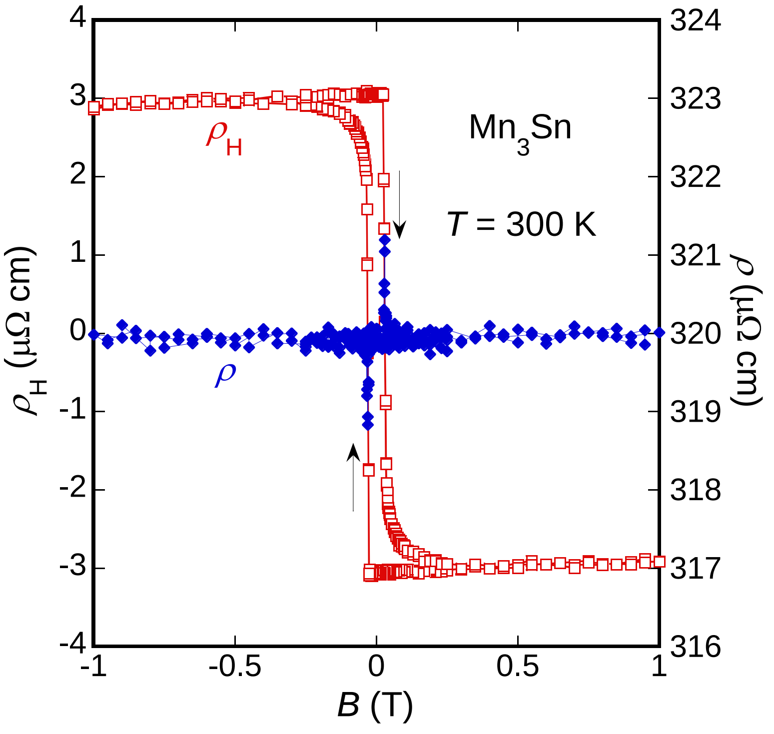
Mn_3Sn, Weyl Magnet

Control of Fictitious Field of a few 100 T by External Magnetic Field of 100 G.



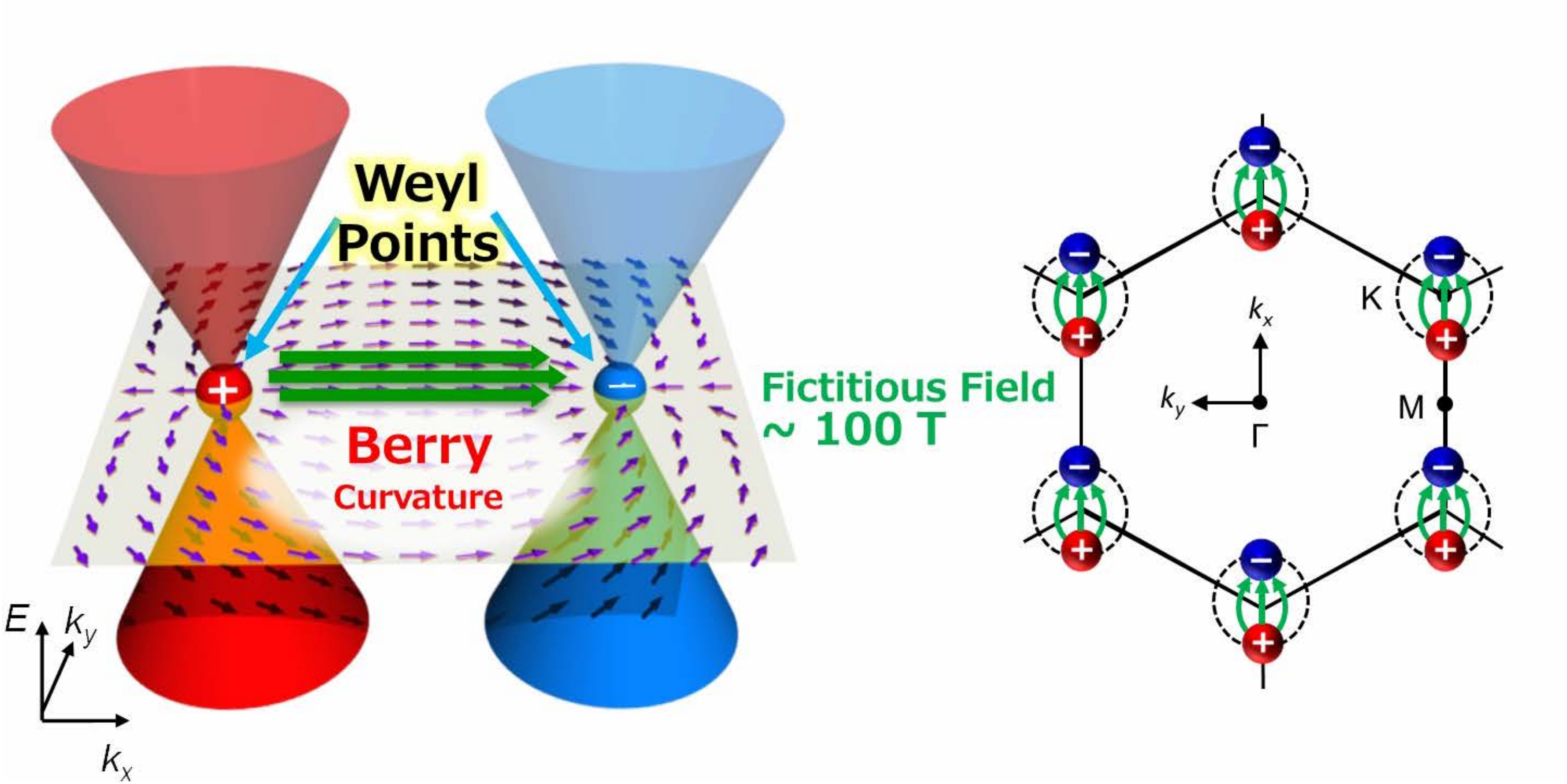
Nature Materials (2017).

$$\sigma_{xy} = n\frac{e^2}{\hbar}\langle\Omega\rangle$$



Control of Weyl Points

Control of Fictitious Field of a few 100 T by External Magnetic Field of 100 G.

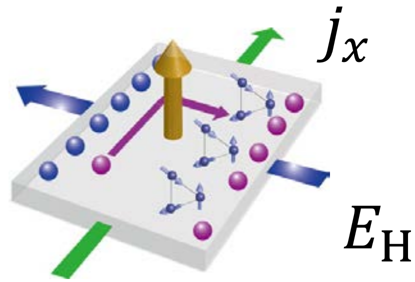


Nature Materials (2017).

Topological Spintronics using AFMs

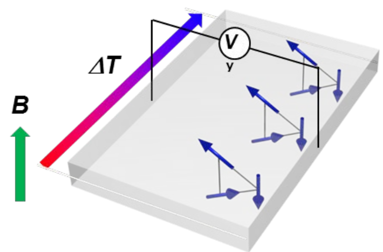
Fictitious Field e.q. a few 100 T in Momentum Space

Current



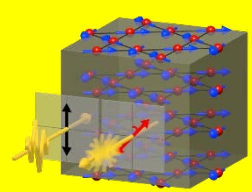
Anomalous Hall Effect

Heat



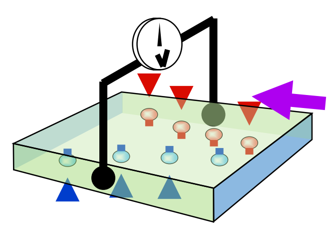
Anomalous Nernst Effect

Light



Magneto Optical Effect

Spin Current

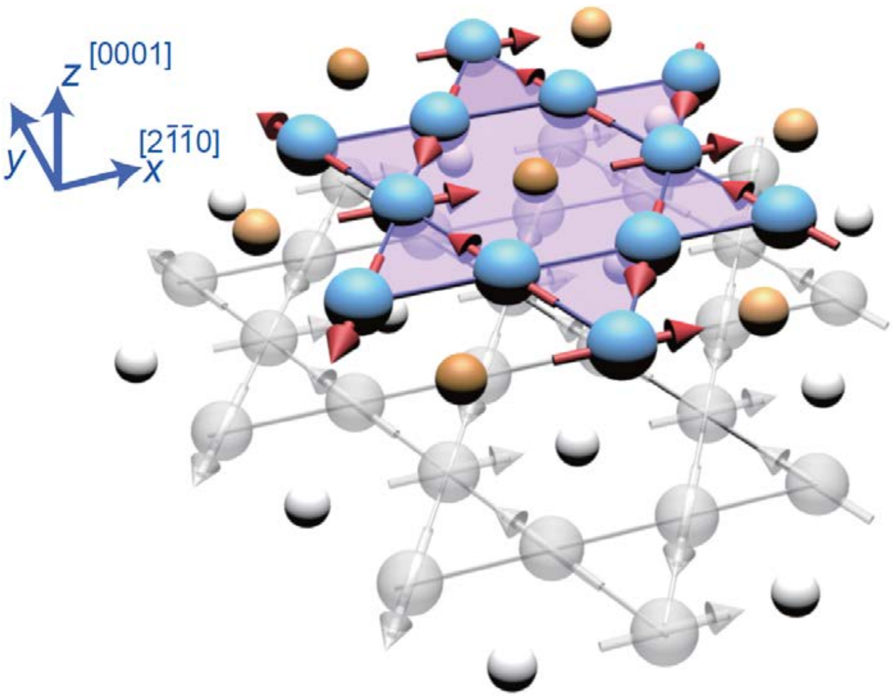


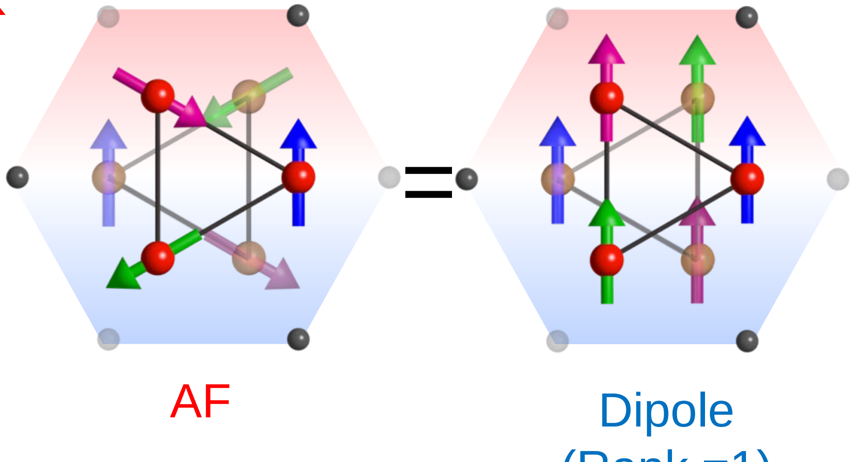
Magnetic Spin Hall Effect

Magnetic Multipole

Suzuki, Arita et al., PRB 094406(2017).

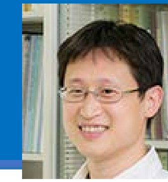
NonCollinear AFM T_N = 430 K





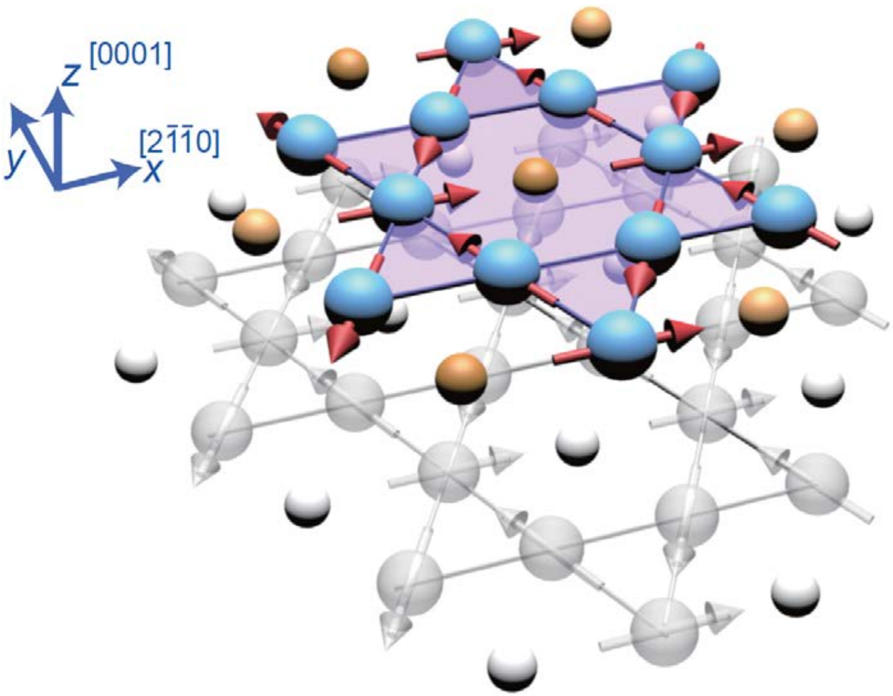
The Same Mag. Space Group
Breaking Time Reversal Symm.

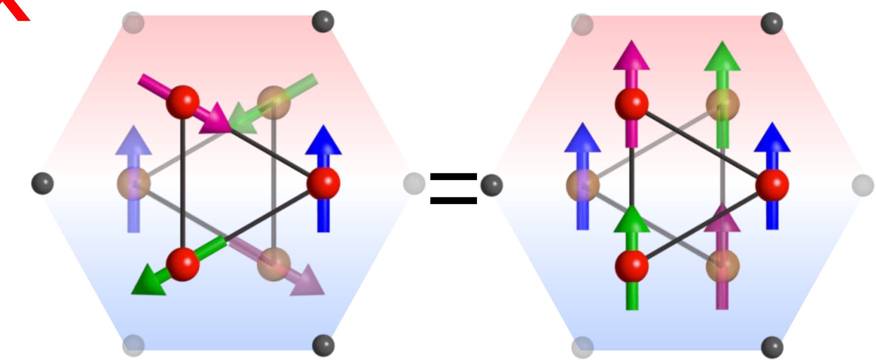
Magnetic Octupole



Suzuki, Arita et al., PRB 094406(2017).

NonCollinear AFM T_N = 430 K





Magnetic Octupole
(Rank = 3)

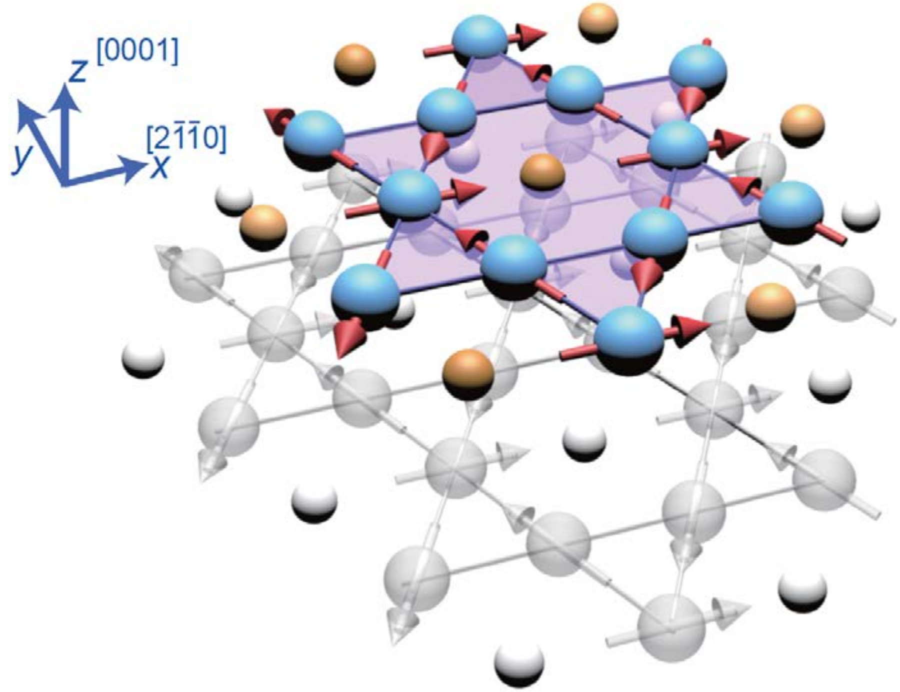
Dipole
(Rank =1)

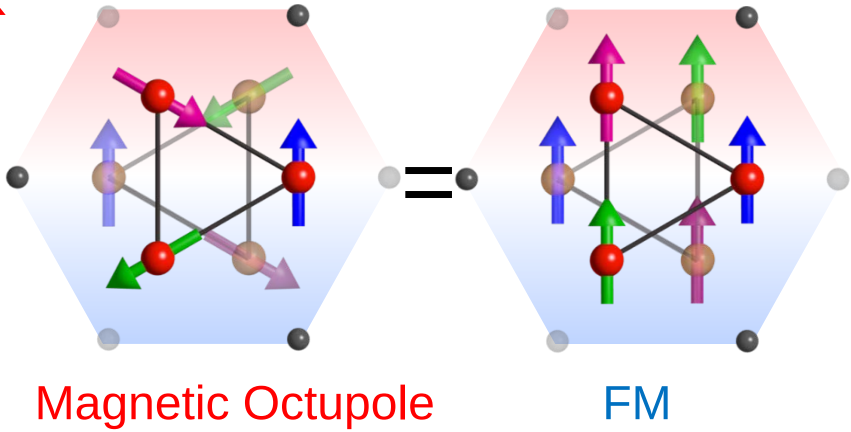
The Same Mag. Space Group
Breaking Time Reversal Symm.

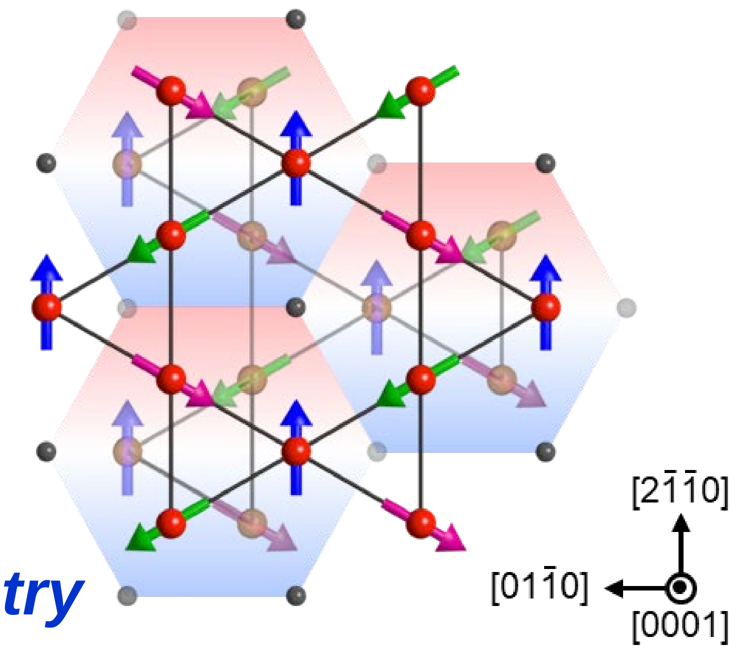
Magnetic Octupole

Suzuki, Arita et al., PRB 094406(2017).

NonCollinear AFM T_N = 430 K



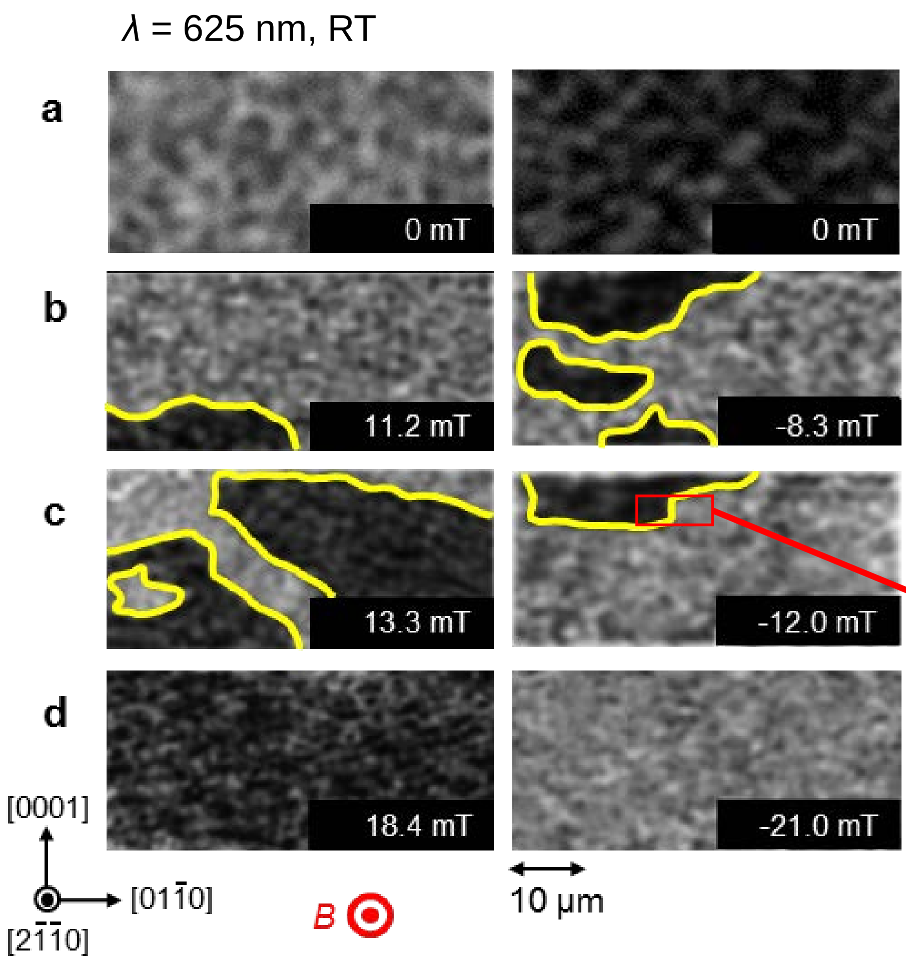


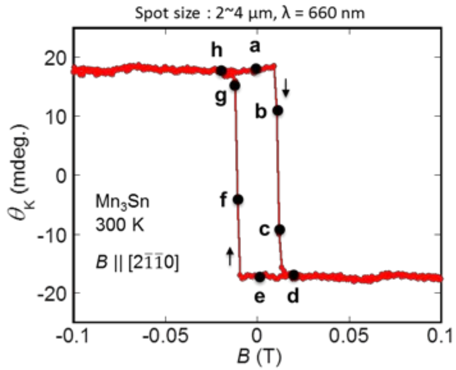


Ferroic Order of Magnetic Octupole

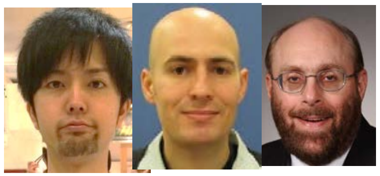
Breaking Time Reversal Symmetry

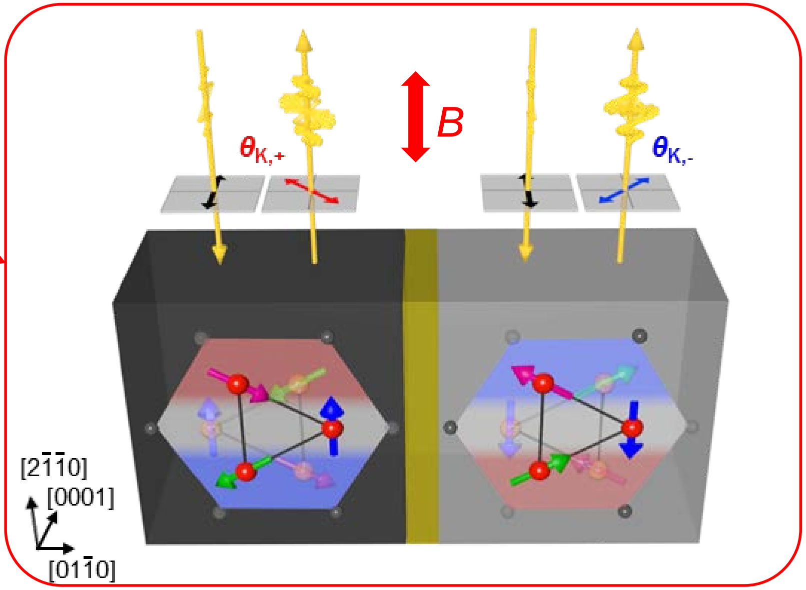
MOKE imaging of AF domains





Higo et al. Nature Photon. (2018).





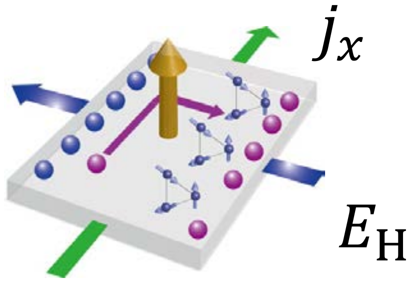
■ domain nucleation and domain wall propagation were observed

The first observation of the domain reversal in an AF metal by the MOKE microscopy

Topological Spintronics using AFMs

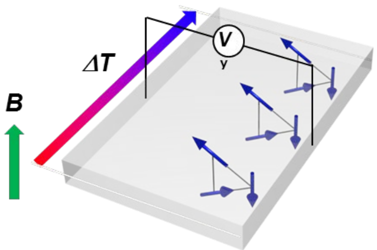
Fictitious Field e.q. a few 100 T in Momentum Space

Current



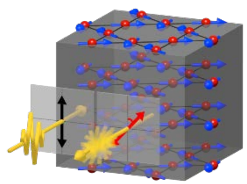
Anomalous Hall Effect

Heat



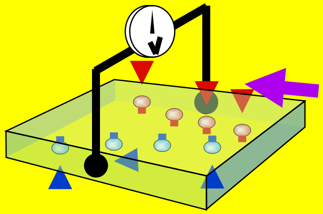
Anomalous Nernst Effect

Light



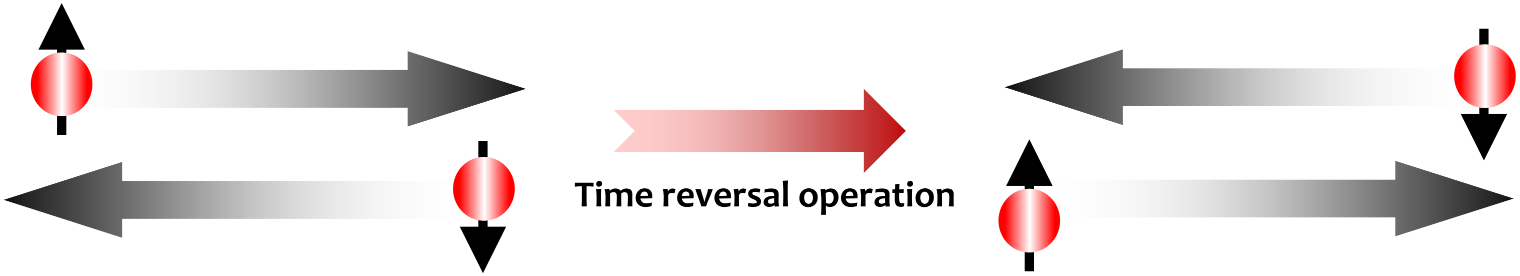
Magneto Optical Effect

Spin Current



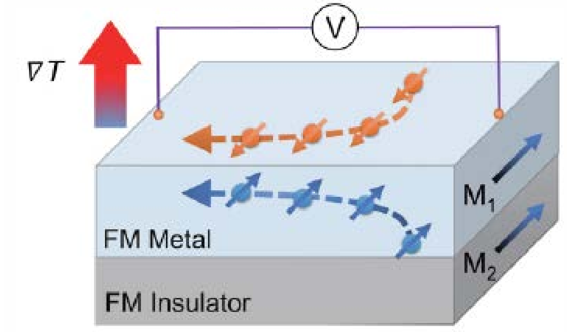
Magnetic Spin Hall Effect

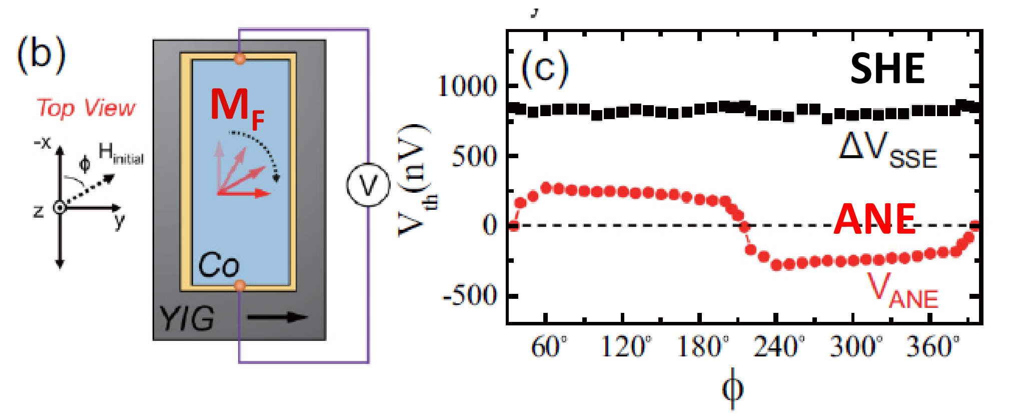
Spin Current



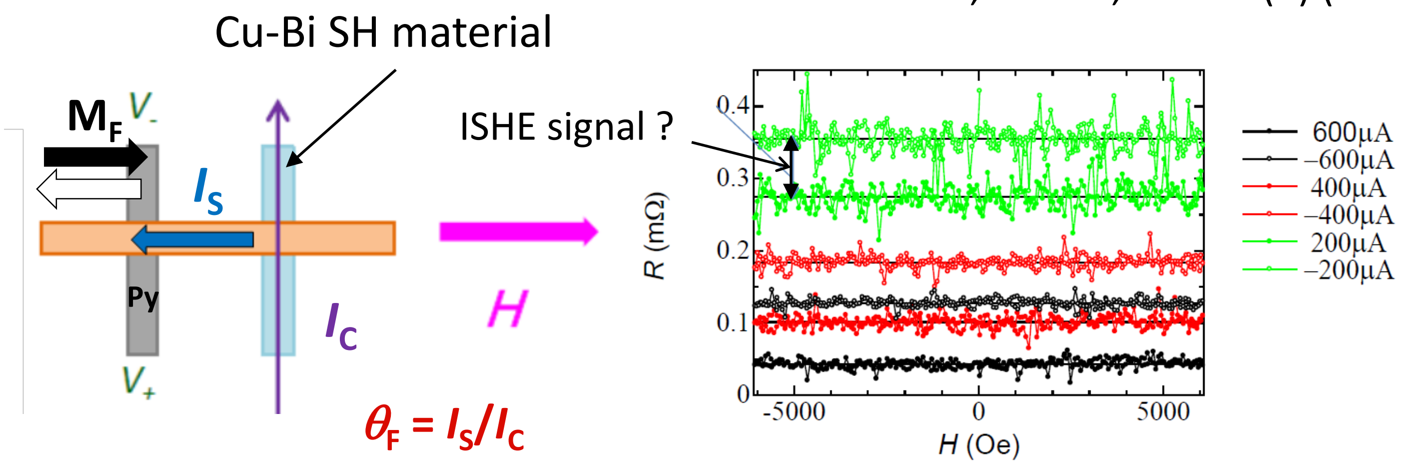
Spin current is time reversal even.
Likewise, spin Hall effect is the case.

FM: Spin Hall Effect



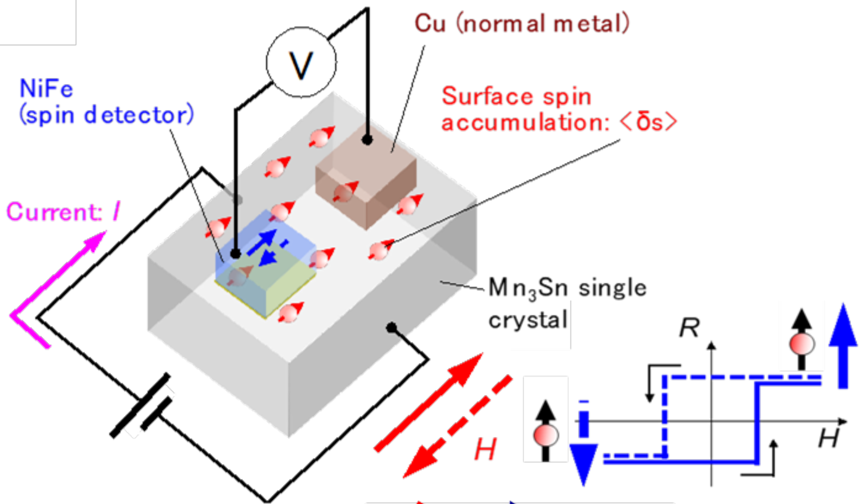


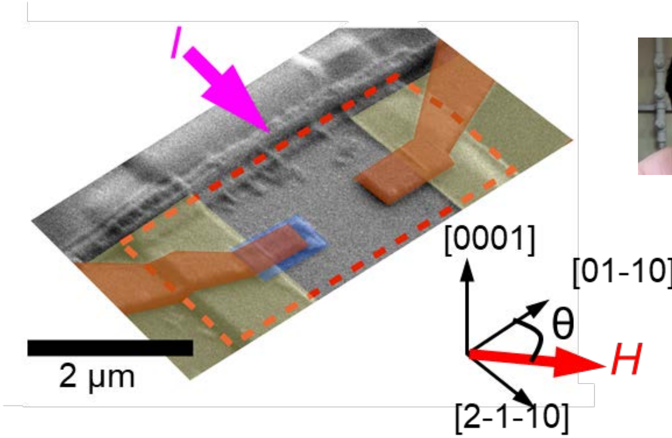
D. Tian et al., PRB **94**, 020403(R) (2016).

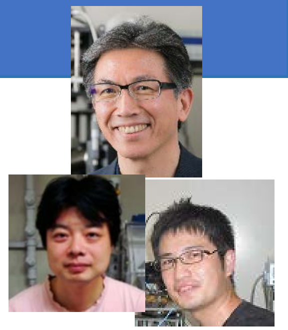


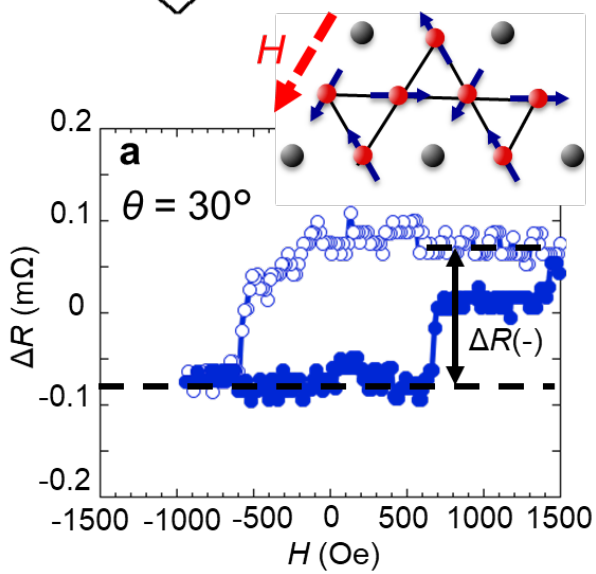
➢ **The SH angle $\theta_S = I_S/I_C$ for FM (or NM) DOES NOT change its sign**

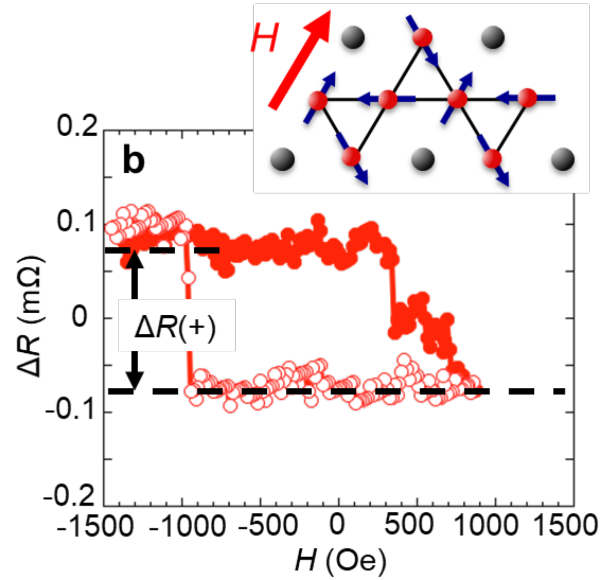
Spin Accumulation











➢ **Spin Hall Effect is time reversal odd; controllable by *M***

Nature (2019)


Magnetic Spin Hall Effect

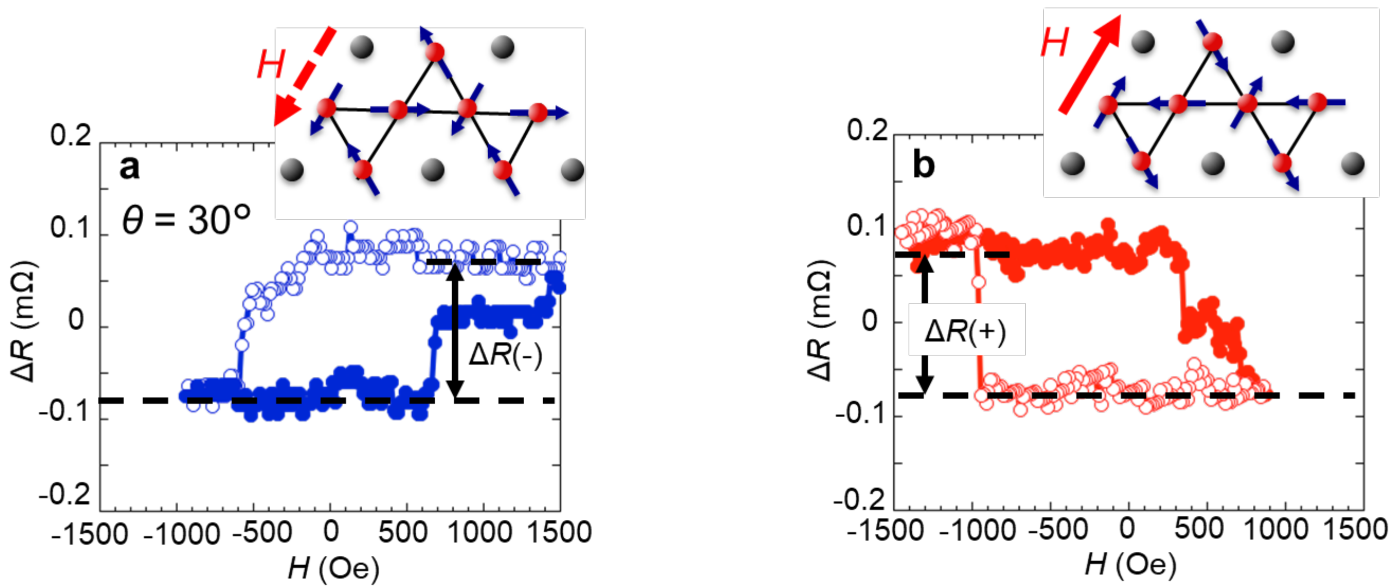
Kimata et al., Nature (2019)

- ◆ **Off-diagonal inter-band element of spin density**

$$\langle s^{\alpha}\rangle_{od} = -\frac{e\hbar}{2}E_{\beta}\sum_{m\neq n}\int [d\mathbf{k}](f_m - f_n)\mathrm{Im}\left[\frac{v^{\beta}_{mn}\sigma^{\alpha}_{nm}}{(\epsilon_m-\epsilon_n)^2}\right]$$

MSHE

- ➢ **No dependence on disorder in the relaxation time approximation**
- ➢ **Intrinsic effect like AHE, determined by the electronic structure**

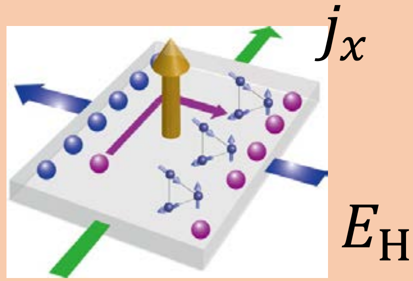


➢ **Spin Hall Effect is time reversal odd; controllable by *M***

Topological Spintronics using AFMs

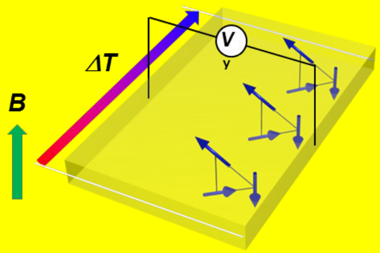
Large Fictitious Field in Momentum Space

Current



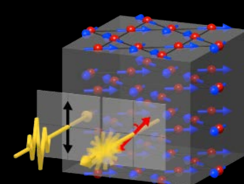
Anomalous Hall Effect

Heat



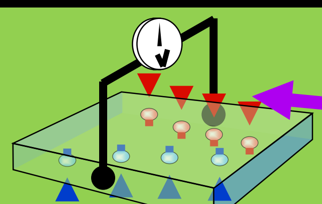
Anomalous Nernst Effect

Light



Magneto Optical Effect

Spin Current



Magnetic Spin Hall Effect

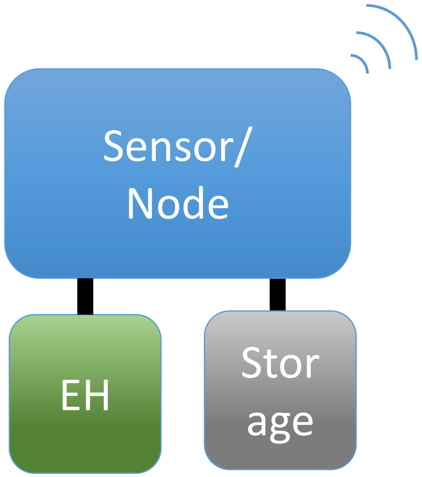
Weyl Magnet: Energy Harvesting

✓IoT: Trillions of Sensors

✓Maintenance free power source

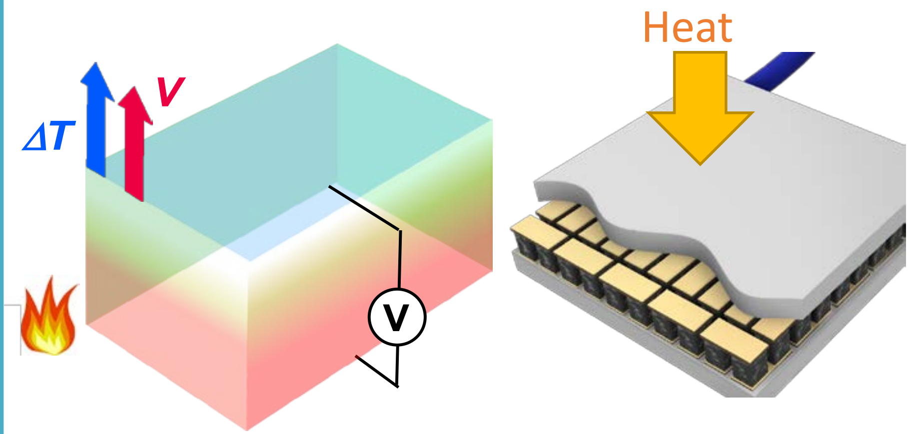
✓µW~mW is enough to operate sensors and nodes

✓ Thermoelectric power generation



Anomalous Nernst effect for Harvesting?

Seebeck effect



A) *E* ∥ Heat current

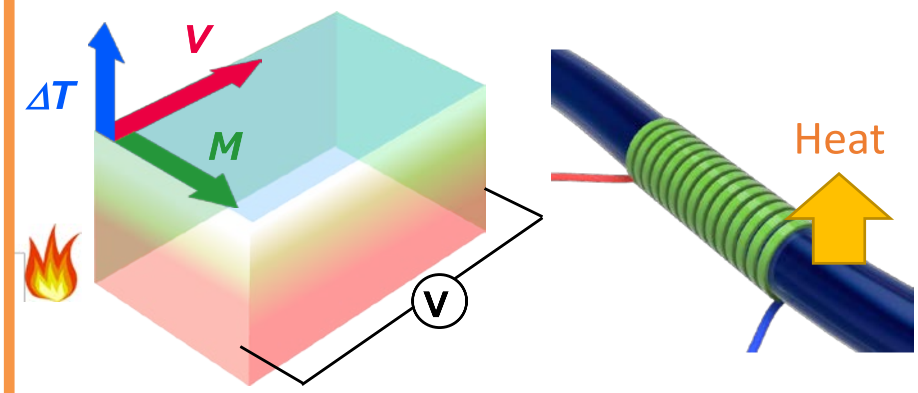
B) Pillar structure device

C) High Production Cost

D) Toxic, precious (Bi,Te,Pb)

E) Large output ~ 100 μV

Anomalous Nernst effect



A) *E* ⊥ Heat current

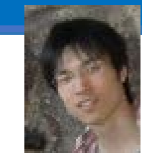
B) Simpler device (film)

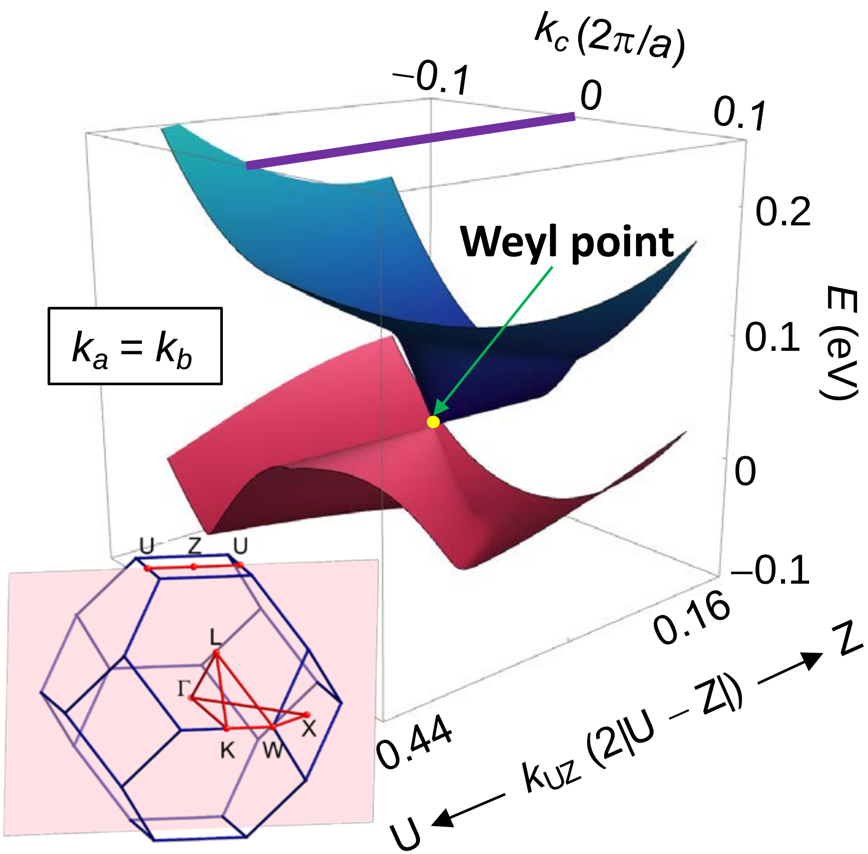
C) Low Production Cost

D) Safe, naturally abundant

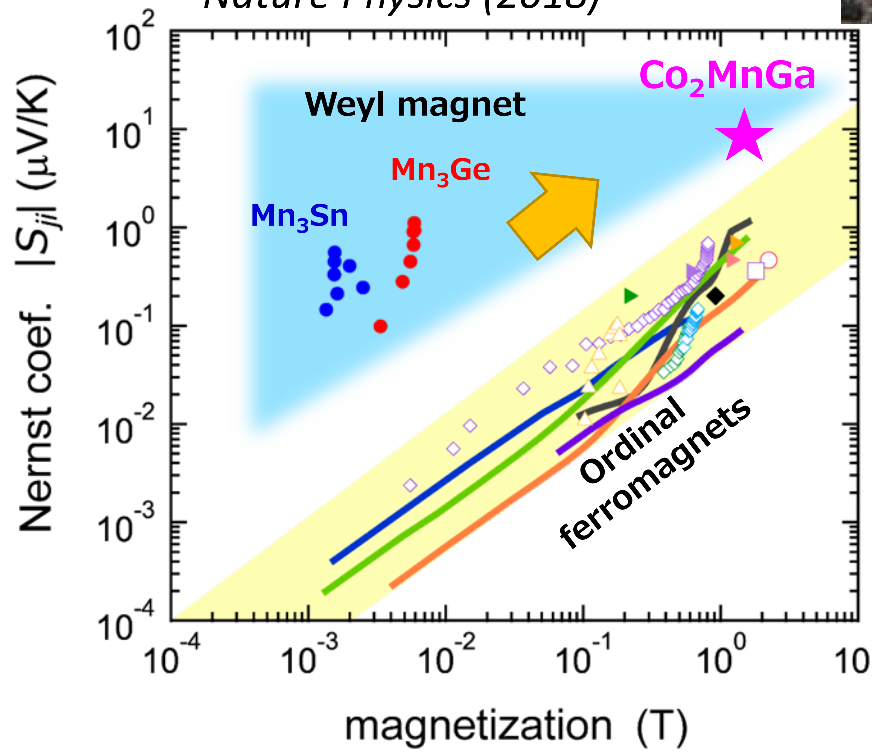
E) small output ~ 0.1 μV

Giant anomalous Nernst effect in Co_2MnGa





A. Sakai et al., arxiv:1807.04761
Nature Physics (2018)

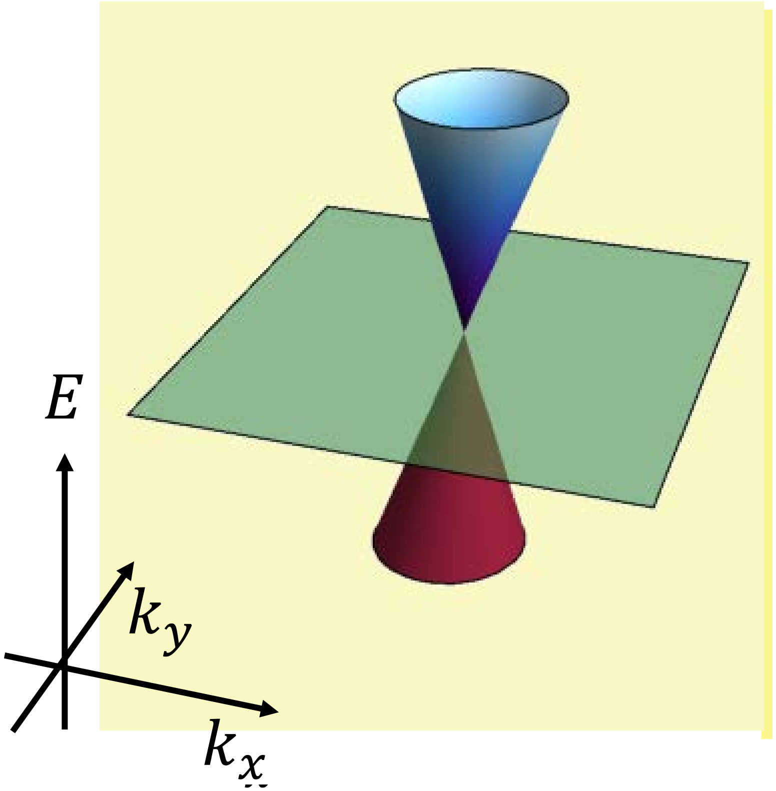


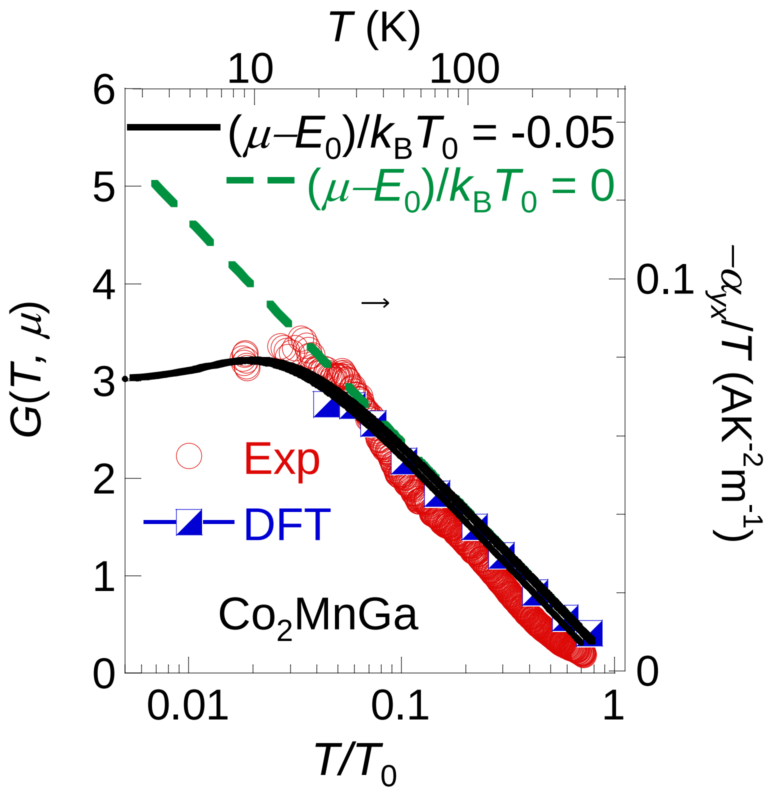
- Co_2MnGa: Magetic Weyl Semimetal
- S_{yx} ~ 6 μV/K at 300 K, ~ 8 μV/K at 400 K.
- One order magnitude higher than previous reports

Z. Wang et al., PRL (2016).
J. Kübler & C. Felser EPL (2016).

See also: Y. Sakuraba *et al.*,arXiv:1807.02209
S. N. Guin *et al.*, arXiv:1806.06753

Proximity to the Quantum Lifshitz Transition





Weyl Magnet: Energy Harvesting

Summary and Perspective