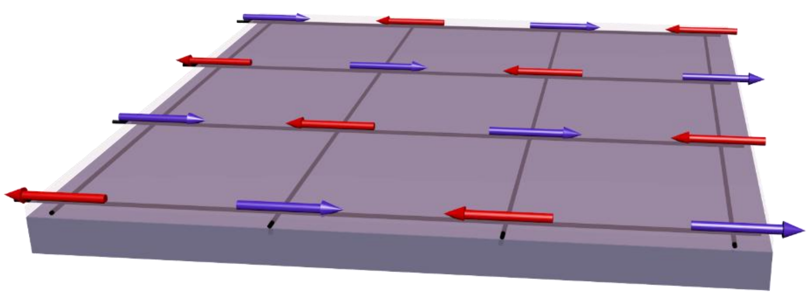
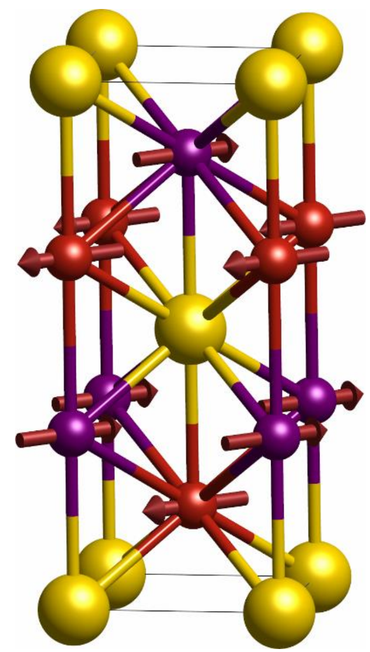
Method for manipulation of spin-axis in antiferromagnets by electrical current

J. Zelezny, H. Gao, K. Vyborny, J. Zemen, J. Masek, A. Manchon,

J. Wunderlich, J. Sinova, T. Jungwirth

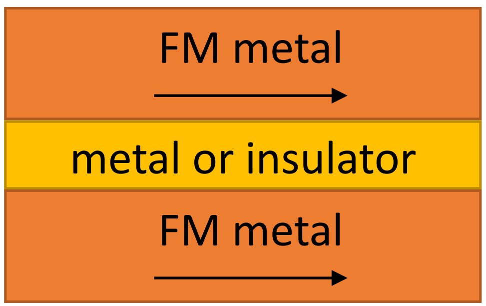




AFM spintronics

Ferromagnets

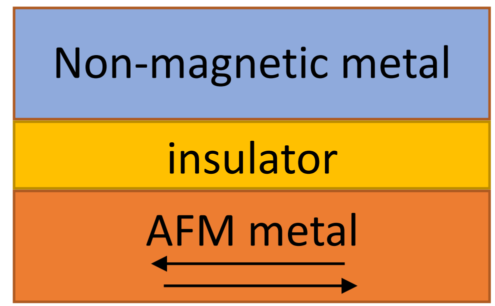
- ✓ Manipulation and detection possible by magnetic fields
- ✓ Magnetoresistance effects



- ✗ Sensitive to external magnetic fields
- ✗ Slow dynamics ~ ns
- ✗ Not many FM semiconductors

Antiferromagnets

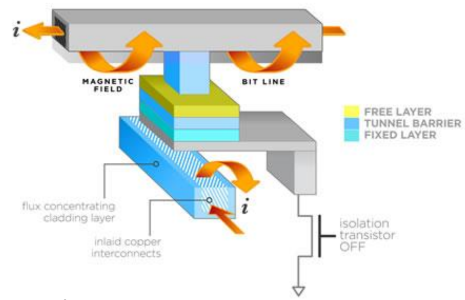
- ✗ Hard to detect and to manipulate
- ✓ TAMR



- ✓ Not sensitive to external magnetic fields
- ✓ Fast dynamics ~ ps
- ✓ AFM semiconductors are more common

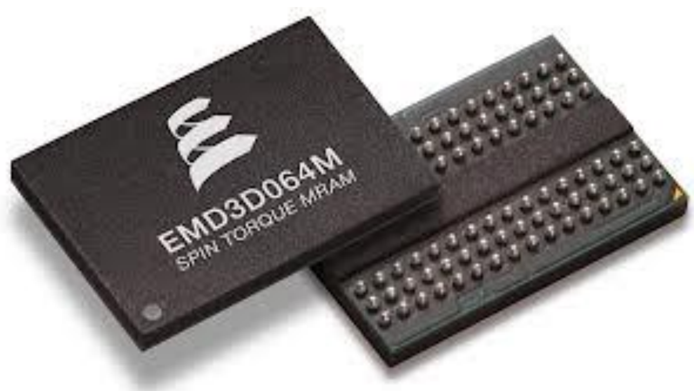
How to manipulate FM

1. Magnetic field

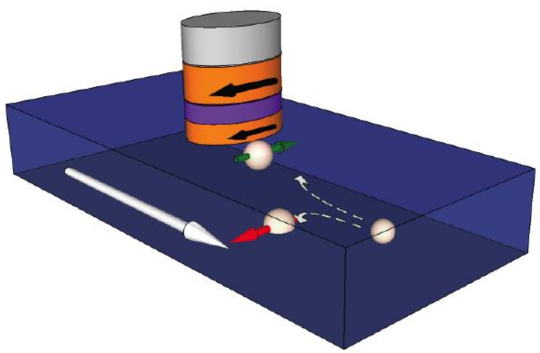


Toggle MRAM Everspin.com

2. Spin-transfer torque

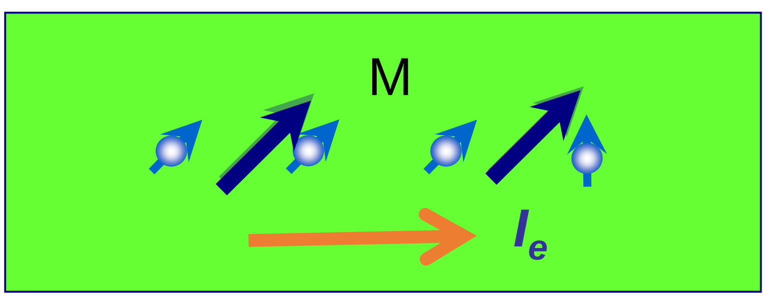


Spin Hall effect



Liu, Ralph, Buhrman,et al. 2012

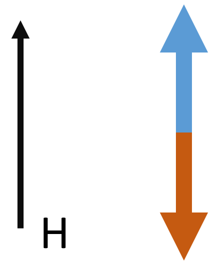
3. Spin-orbit torque



Due to spin-orbit coupling and broken inversion symmetry

How to manipulate AFM

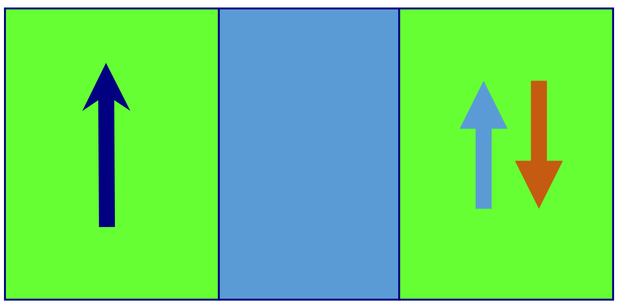
1. Magnetic field



$$H > \sqrt{2H_E H_A}$$

A Néel-order field is needed
for effective switching

2. Spin-transfer torque

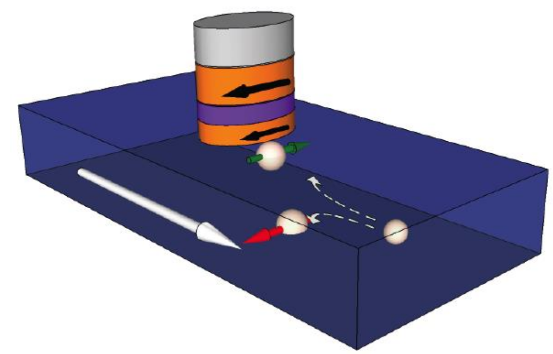


Antidamping STT

$$H_{eff} \sim M \times \mathrm{p}_{\mathrm{curr}}$$

Gomonay, Loktev, PRB 2010

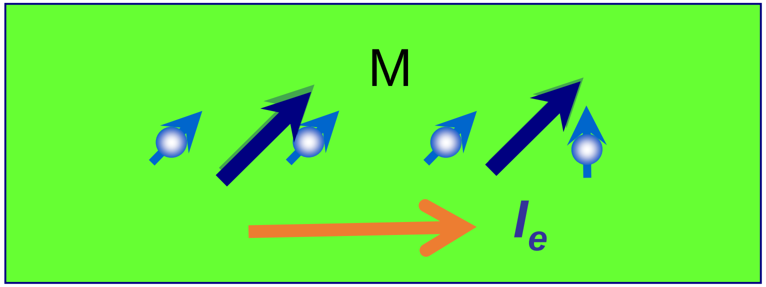
Spin Hall effect



3. Spin-orbit torque

?

How to calculate SOT



$$\mathbf{T} = \mathbf{M} \times \mathbf{B}_{eff}$$

$$\mathbf{B}_{eff} = J\frac{\delta \mathbf{s}}{\mathbf{M}}$$

Projection on a sublattice

$$\delta \mathbf{s}^A = \frac{1}{2\pi} \mathrm{Re} \sum_{\mathbf{k},n,m} < n\mathbf{k}|\mathbf{s}^A|m\mathbf{k} > < m\mathbf{k}|\mathbf{v}\cdot\mathbf{E}|n\mathbf{k} > (G^R_{\mathbf{k},n}G^A_{\mathbf{k},m} - G^R_{\mathbf{k},n}G^R_{\mathbf{k},m})$$

$n = m$

Intraband term

$n \neq m$

Interband term

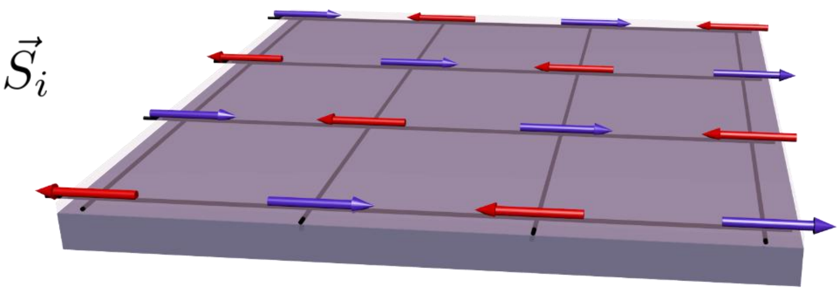
In 2D FM with Rashba SOC

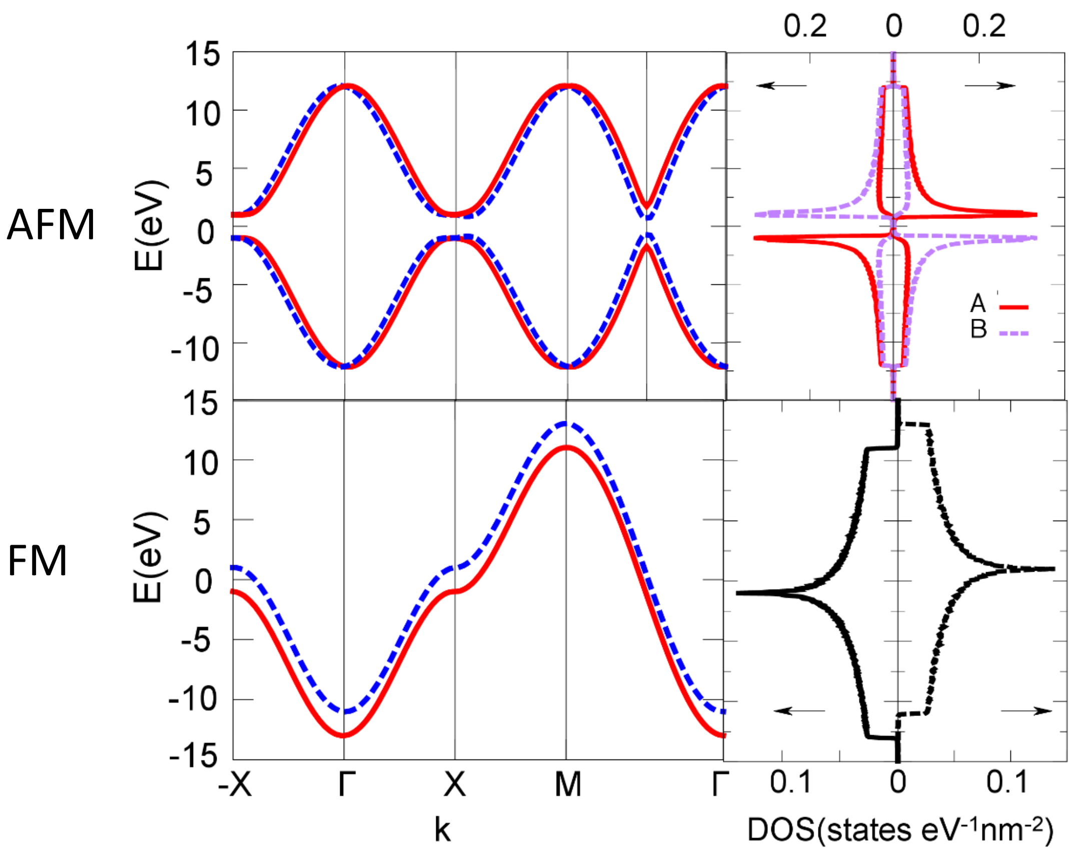
Field-like: $B_{eff} \sim \alpha(z \times J)$

Antidamping-like: $B_{eff} \sim \alpha M \times (z \times J)$

2D AFM model

$$H = \sum_{<ij>} J_{dd}\vec{S}_i \cdot \vec{S}_j + H^{tb} + H_R + \sum_i J_{sd}\vec{s} \cdot \vec{S}_i$$



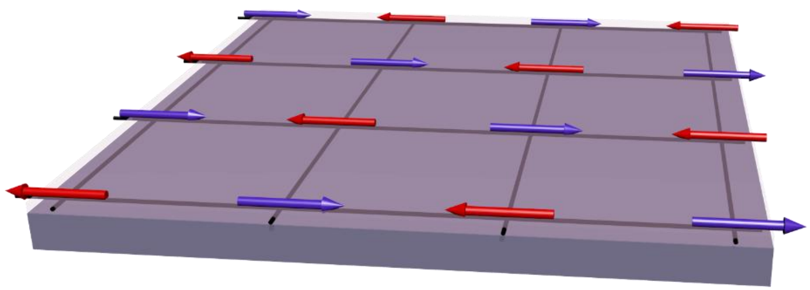


2D AFM model results

Intraband:

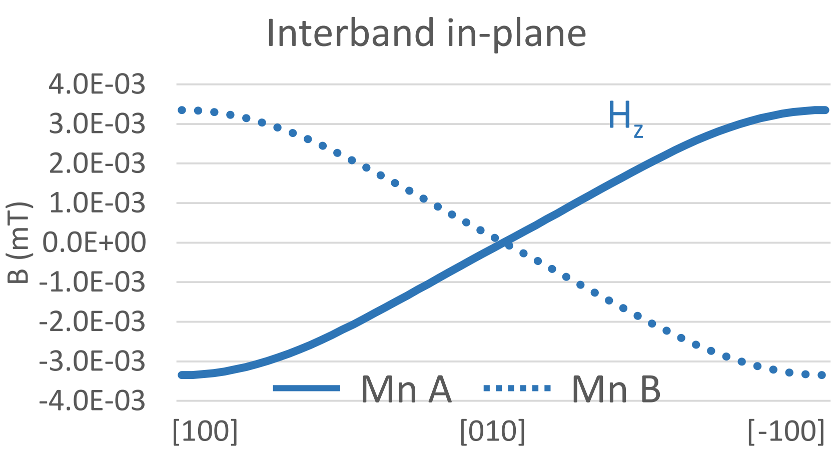
Field-like: $B_{eff} \sim (z \times J)$

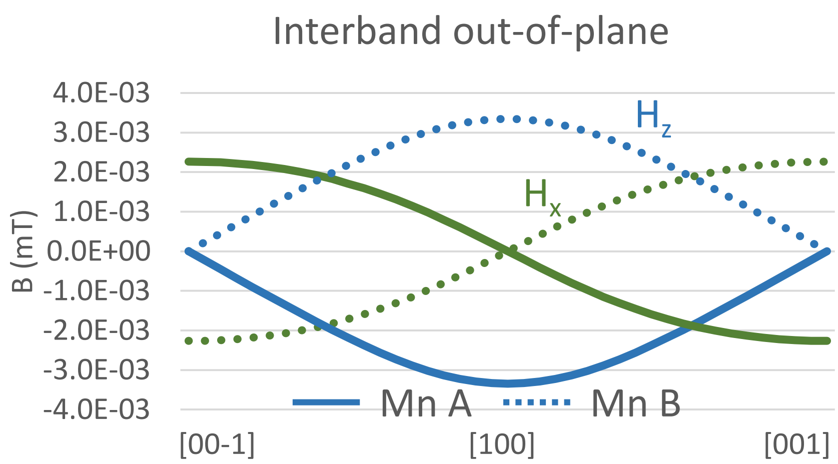
Same on both sublattices



Interband:

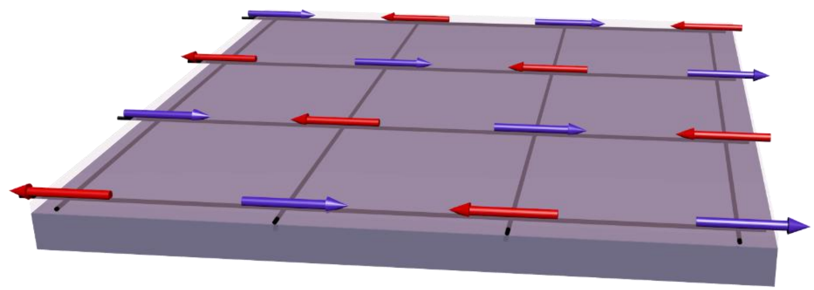
Antidamping-like: $B_{eff} \sim M \times (z \times J)$

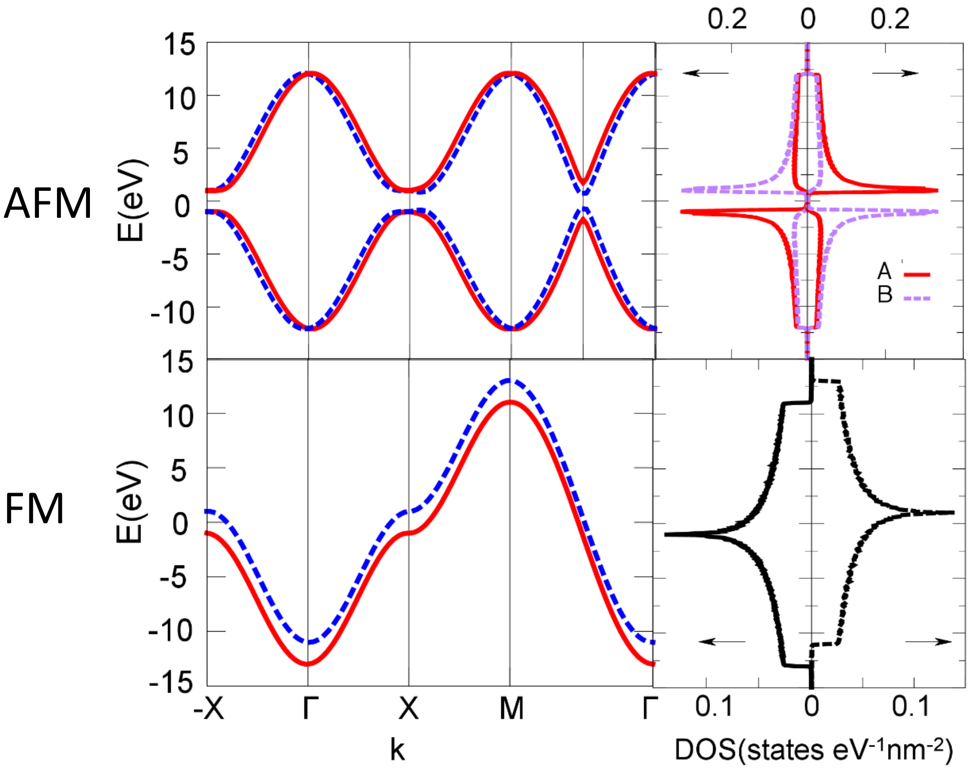


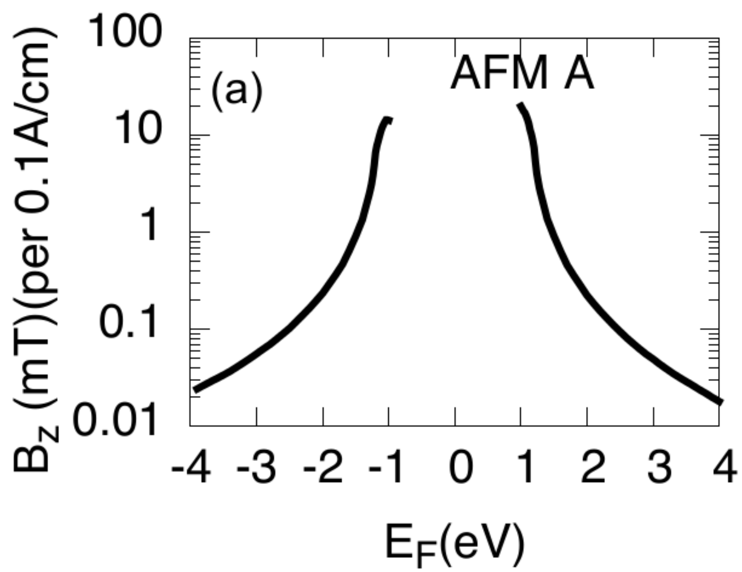


Opposite on A and B

2D AFM model results



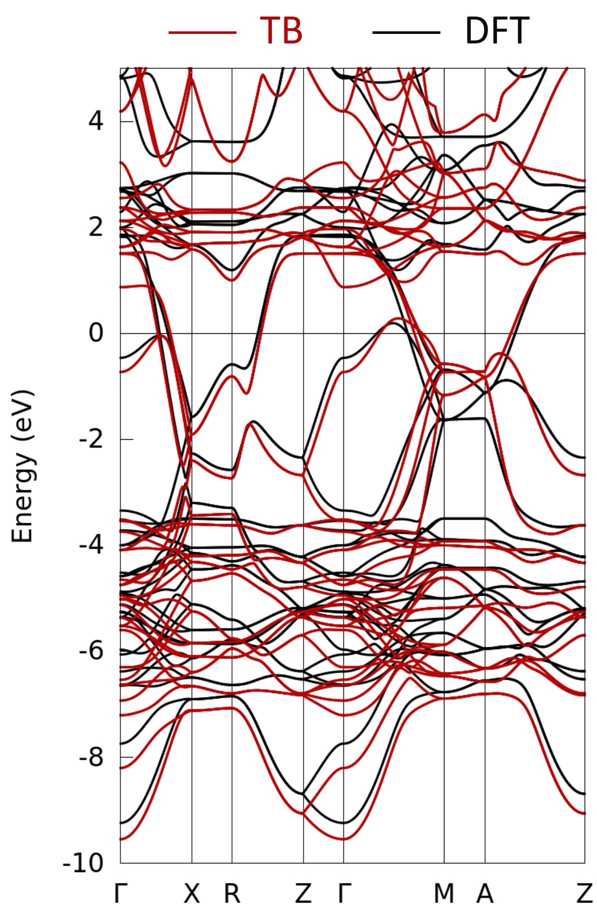


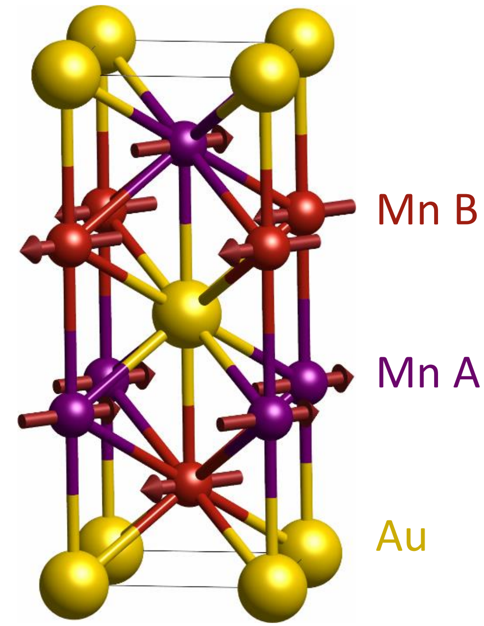


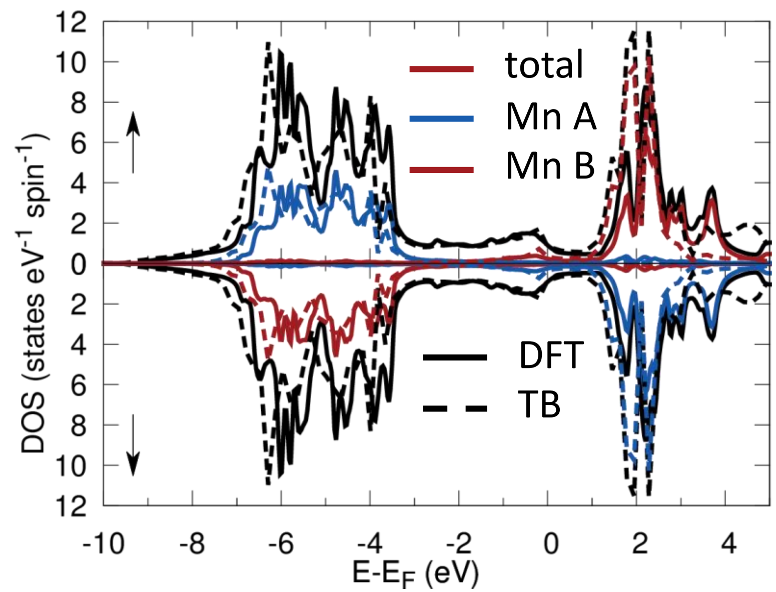
Mn2Au

Described by a multi-orbital tight-binding model

Zemen et al. JMMM ’03



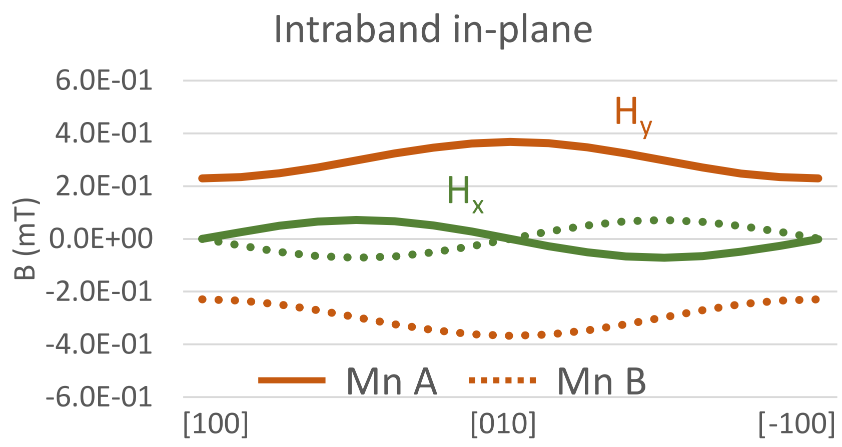


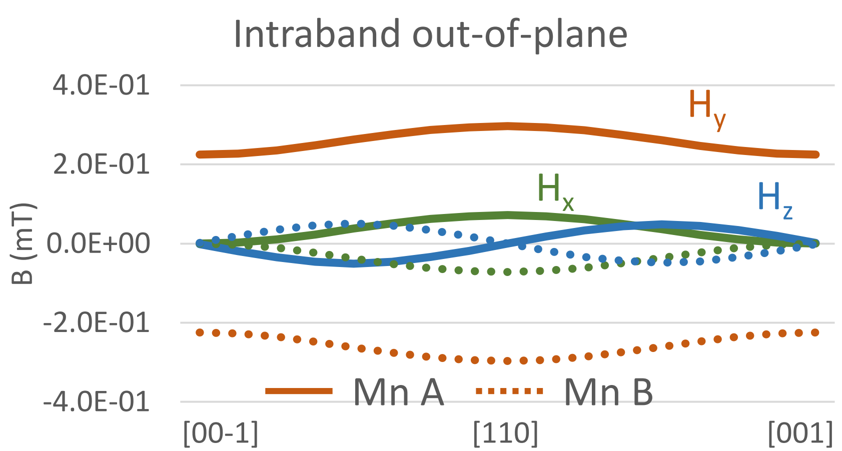


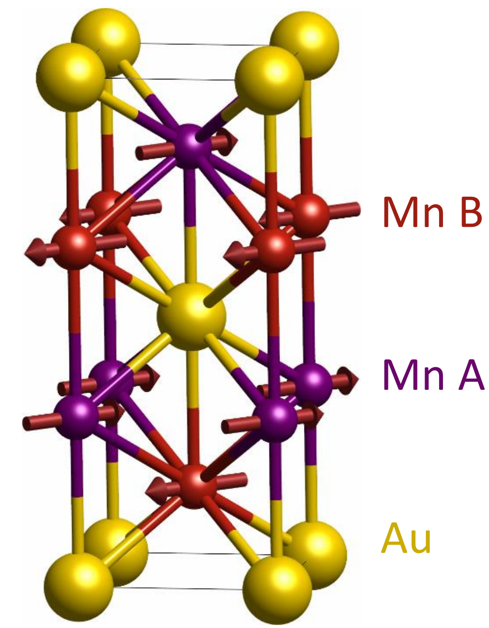
Comparison to DFT calculation

Mn2Au intraband

J along x







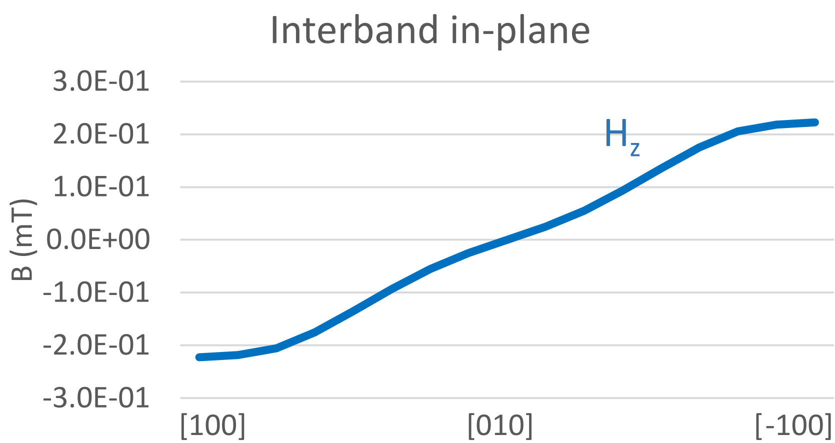
Field-like: $B_{eff} \sim (z \times J)$

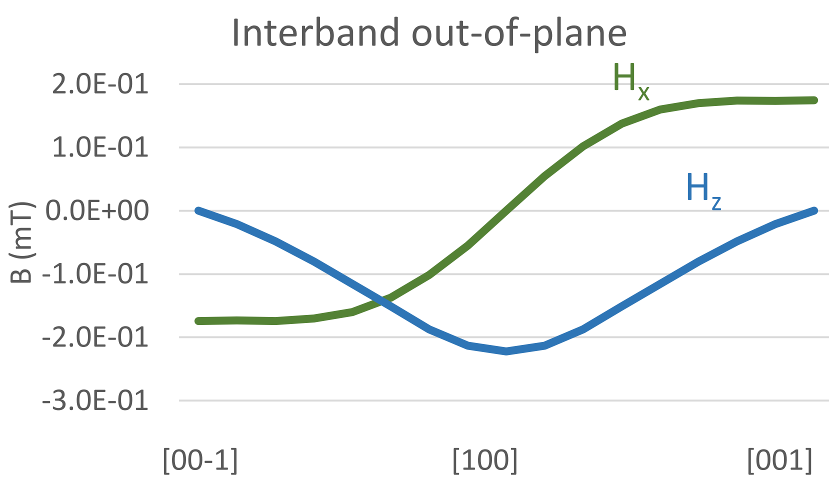
Current needed for switching:
$J \sim 10^9$ Acm $^{-2}$

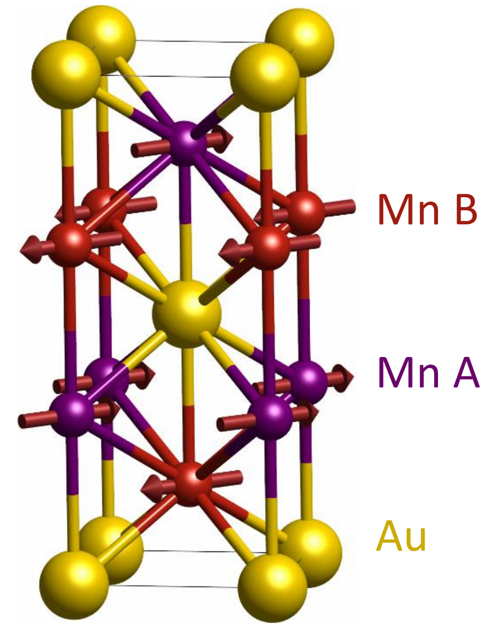
Fields are opposite for A and B

Mn2Au interband

J along x





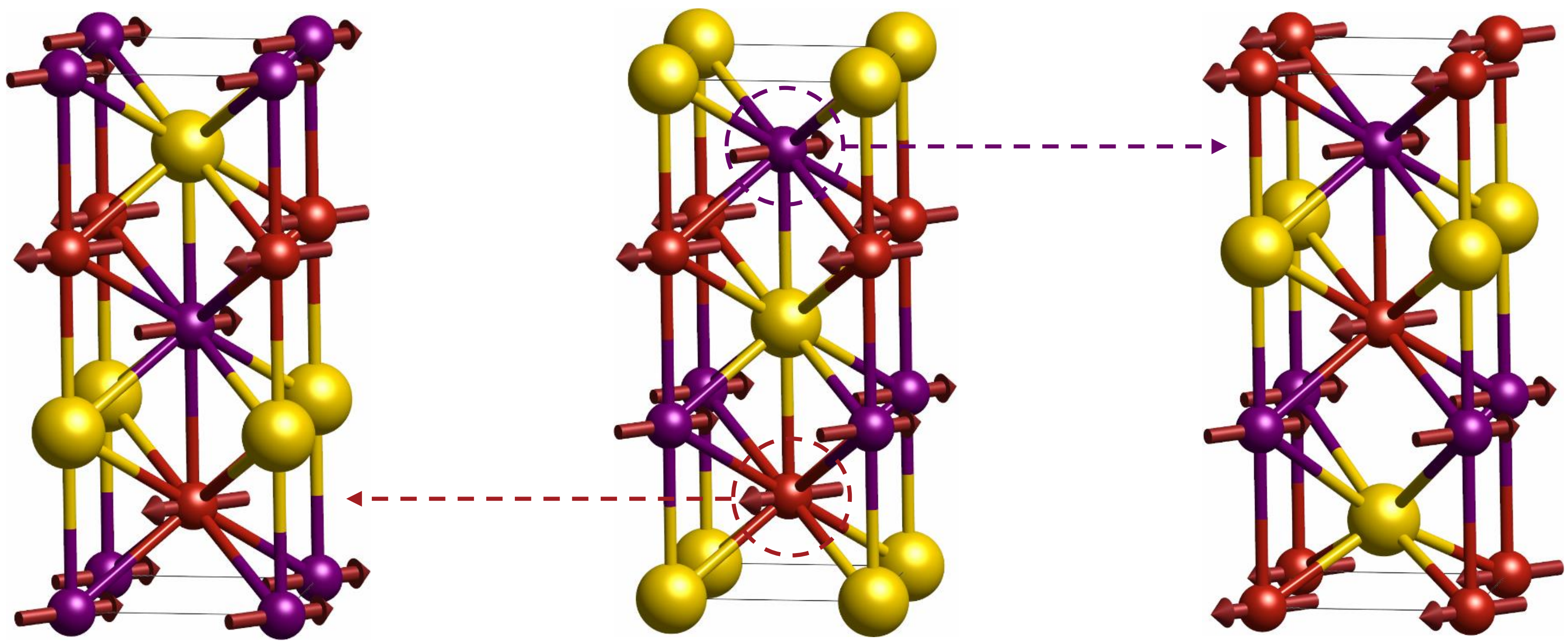


Antidamping-like: $B_{eff} \sim M \times (z \times J)$

Fields are the same for A and B

Symmetry

		2D system	Mn2Au
Intraband	$\mathrm{B}_{eff} \sim (z \times J)$	Same on A and B	Opposite on A and B
Interband	$B_{eff} \sim M \times (z \times J)$	Opposite on A and B	Same on A and B

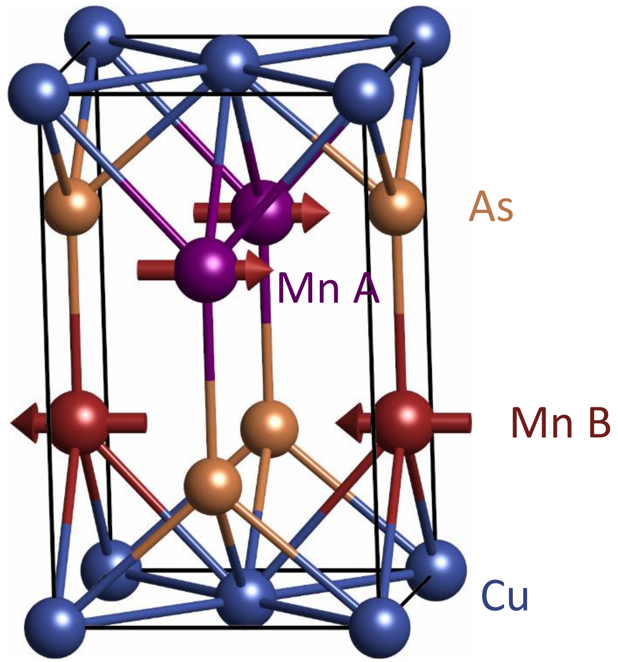


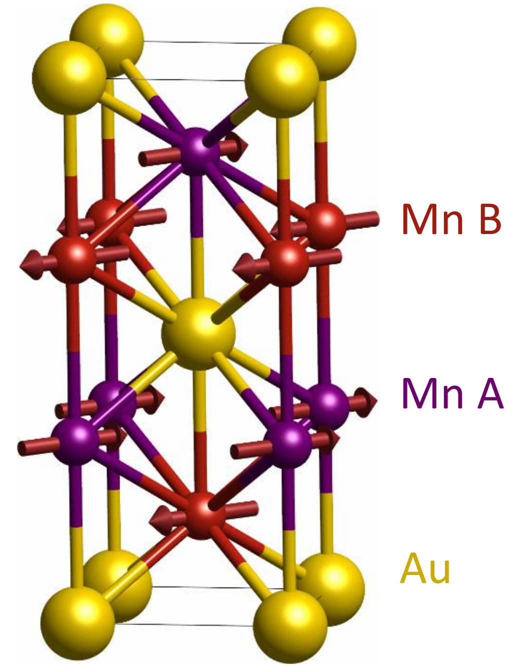
Inversion around Mn A

Inversion around Mn B

Zhang, Liu, Luo et al. Nat. Phys. 2014

CuMnAs



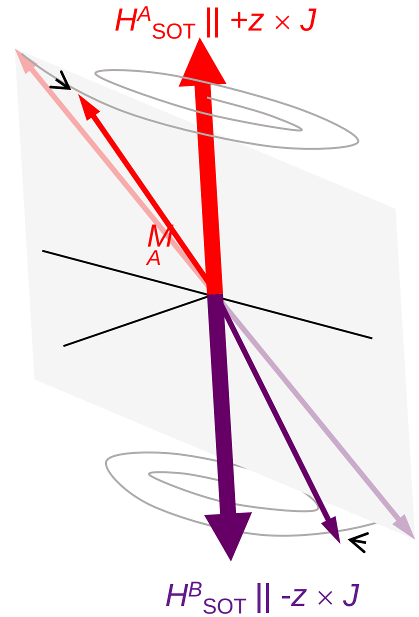


Same symmetry as Mn2Au

$$\mathbf{B}_{eff}^{A} \approx (\mathbf{z} \times \mathbf{J})$$
$$\mathbf{B}_{eff}^{B} \approx -(\mathbf{z} \times \mathbf{J})$$

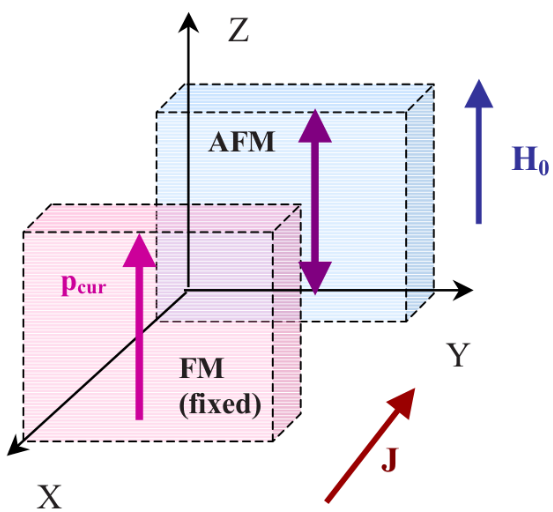
Dynamics

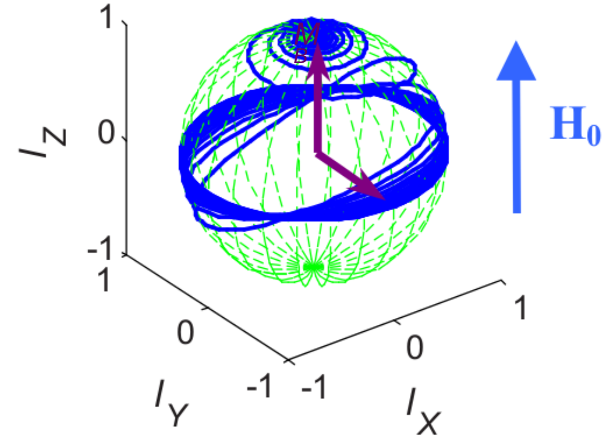
Field-like: $B_{eff} \sim (z \times J)$



Keffer, Kittel, Phys. Rev. 1952

Antidamping-like: $B_{eff} \sim M \times (z \times J)$





Gomonay, Loktev, PRB 2010

Summary

1. Current can produce Néel-order effective field in AFM

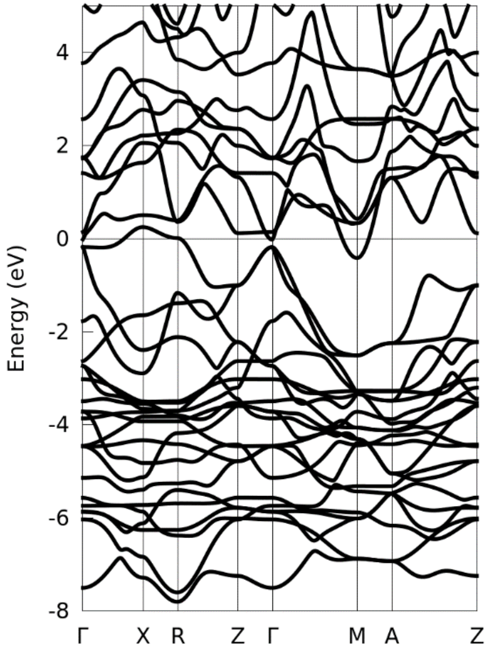
2. Breaking of inversion symmetry is probably necessary, but it does not have to be global -> SOT should be present in many systems

3. Switching by such torques can be very fast

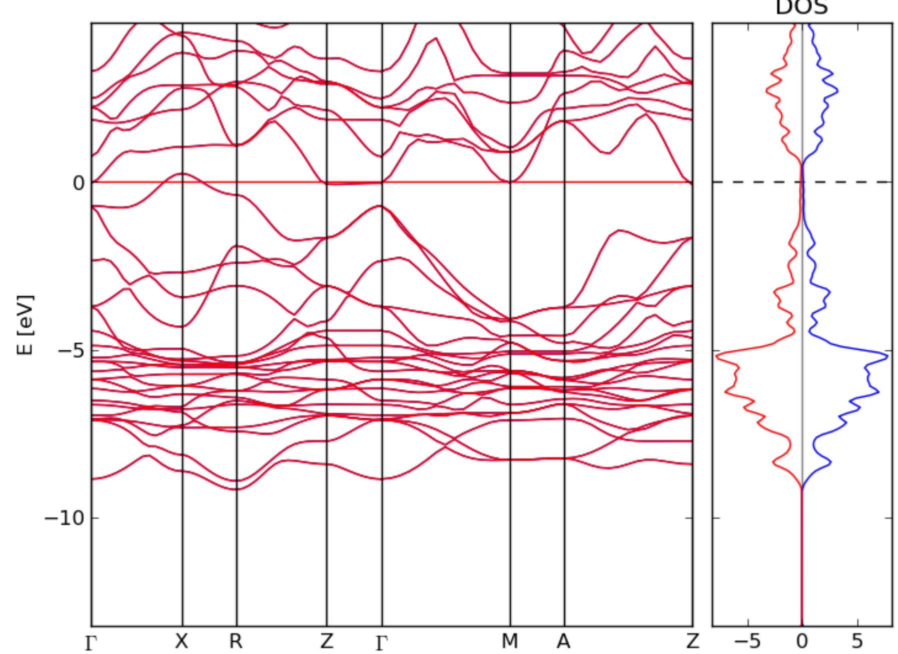
4. Both field-like and antidamping-like torques are possible -> different dynamics

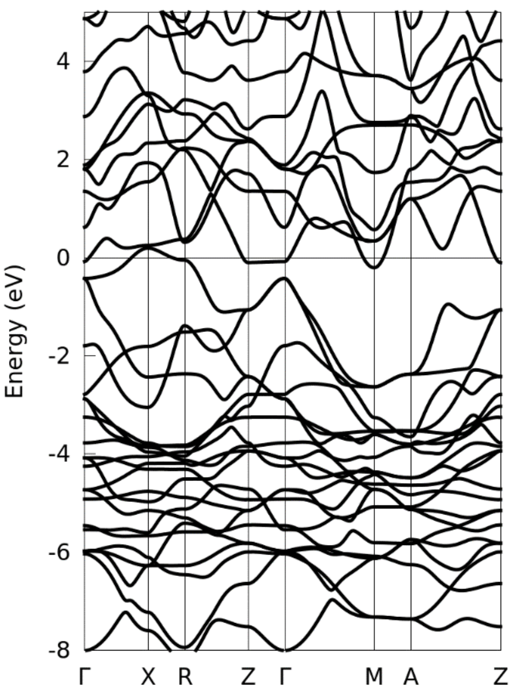
I(b)-Mn-V compounds overview

	CuMnAs	CuMnP	CuMnN	AgMnAs	AgMnP	AgMnN	NaMnAs	CuMnSb
I charge	0.041	0.168	0.208	-0.033	0.029	0.140	0.804	-0.435
Mn charge	0.94	1.017	1.206	0.962	1.027	-1.178	0.746	0.896
V charge	-0.96	-1.172	-1.405	-0.919	-1.047	-1.314	-1.534	-0.459
FM-AFM (ev)	0.216	0.296	0.329	0.142	0.244	0.316	0.488	0.006
Str. stab. (eV)	1.377	1.525	1.877	0.442	0.330	-0.788	0.116	

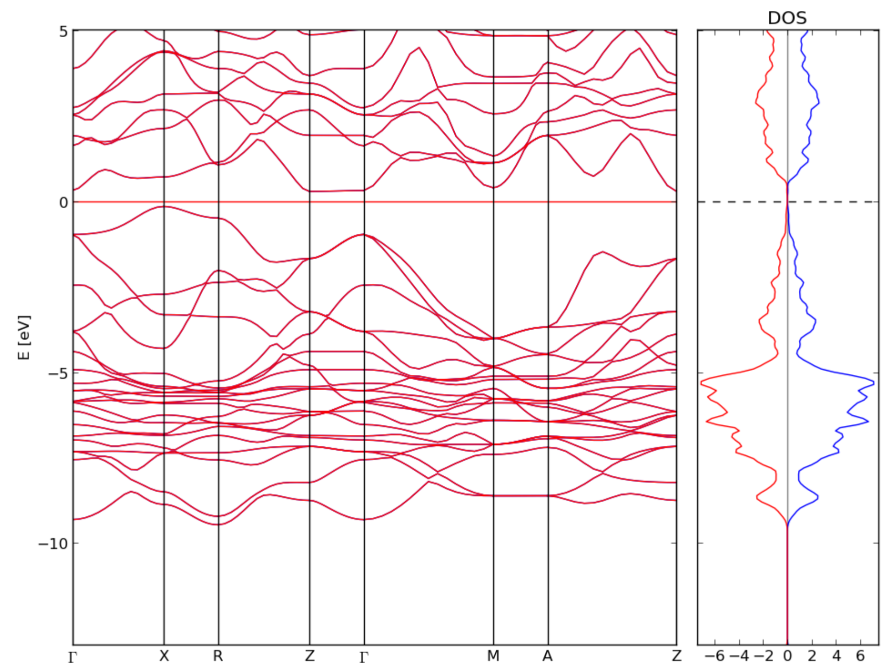


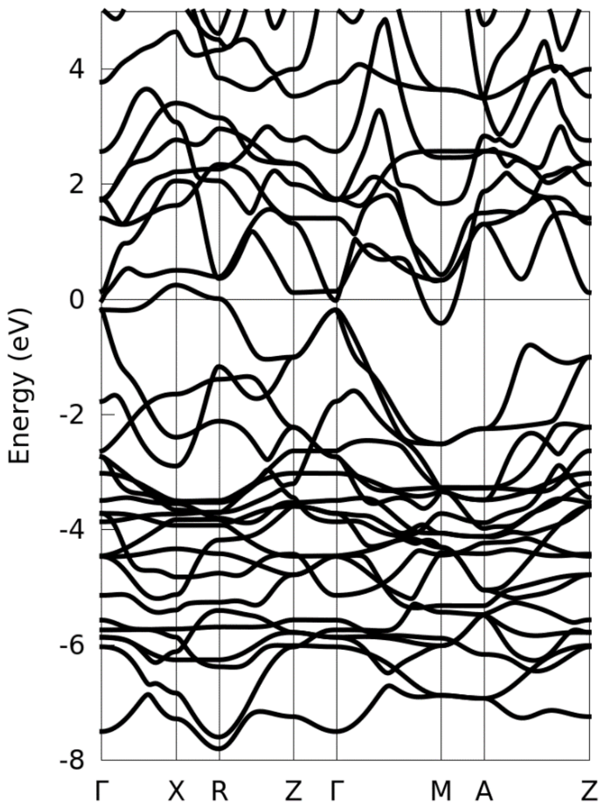
CuMnAs



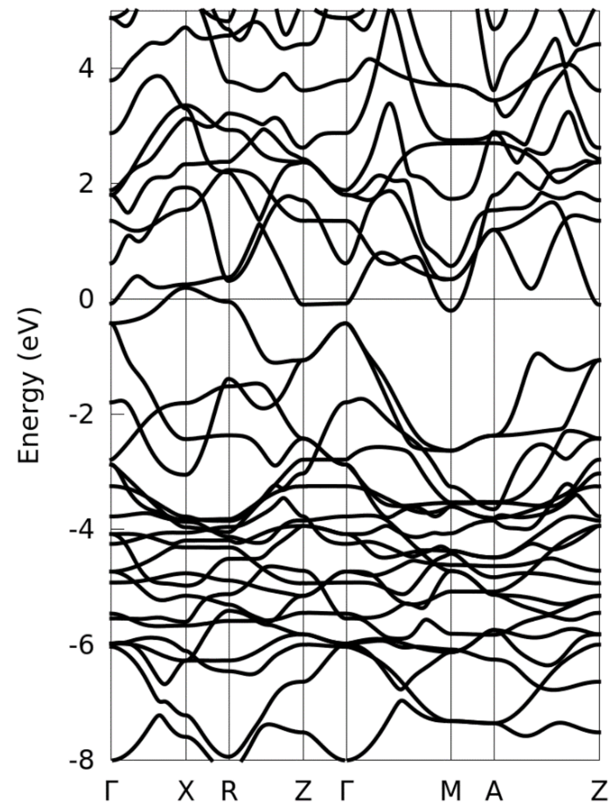


CuMnP





CuMnAs



CuMnP

GGA+U