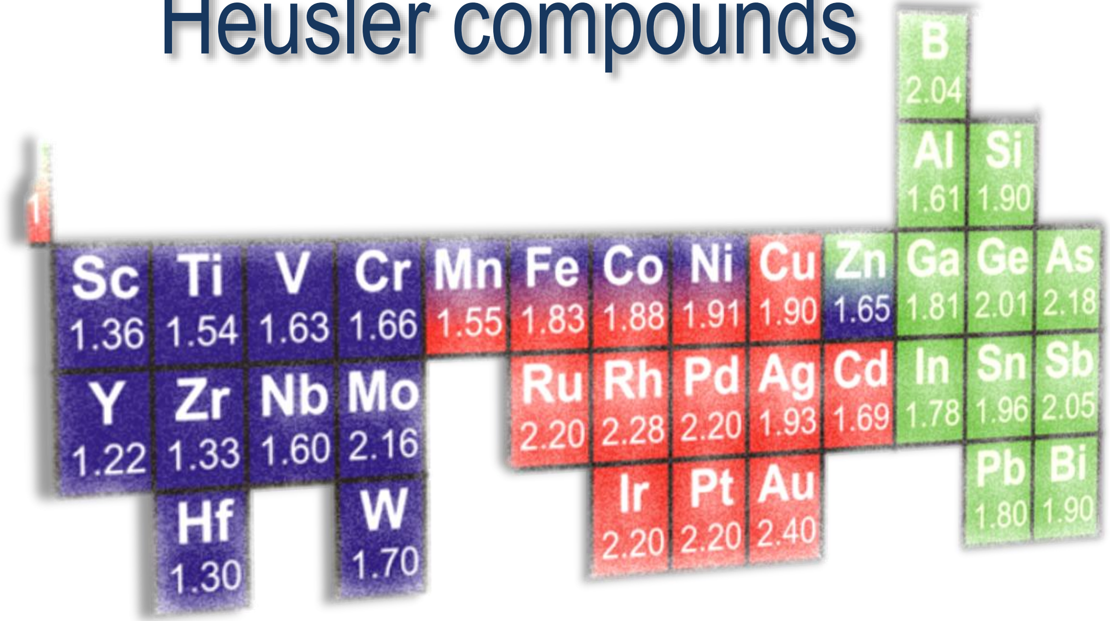
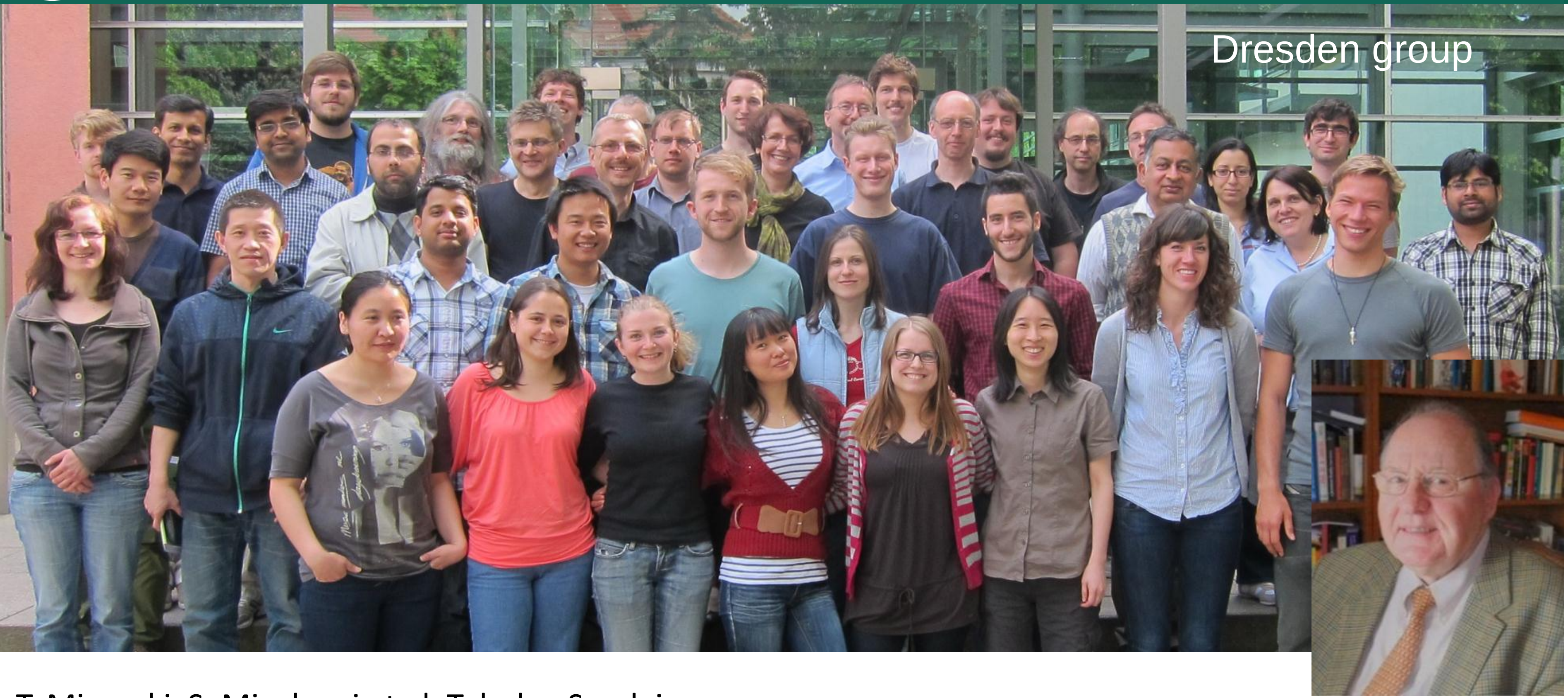
Magnetism in Mn-rich Heusler compounds



Claudia FELSER, Ajaya K. NAYAK, Daniel EBKE, Gerhard H. FECHER, Lukas WOLLMANN, Jürgen KÜBLER, Olga MESHCHERIAKOVA, Stas CHADOV

www.superconductivity.de

Co-workers in Dresden and elsewhere



T. Miyazaki, S. Mizukami et al. Tohoku, Sendai

G. Reiss et al. Bielefeld, G. Jakob, M. Jourdan Mainz

S. S. P. Parkin et al. IBM Almaden, MPI Halle

M. Coey, Dublin

ASPIMATT

Deutsche Forschungsgemeinschaft DFG

erc

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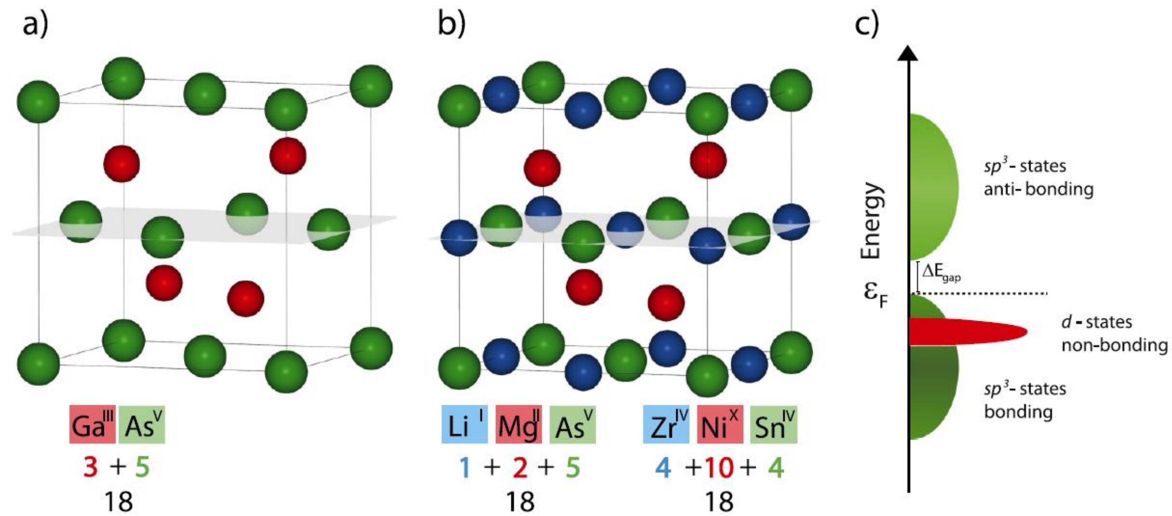
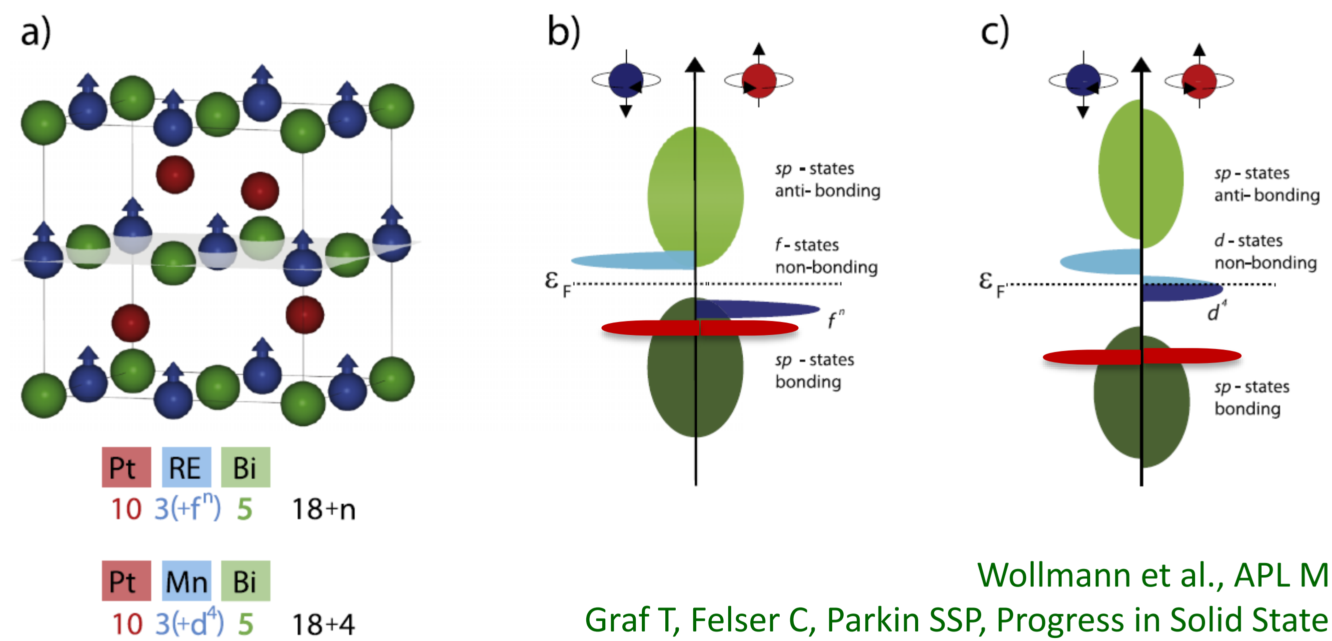
JST Japan Science and Technology Agency

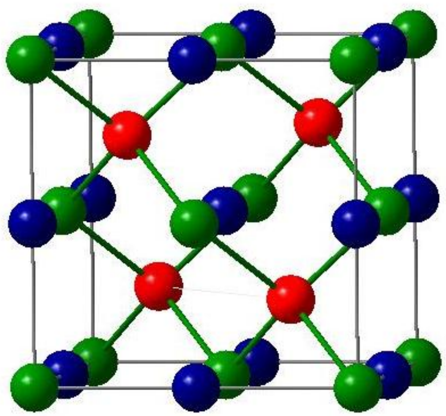
Half metallic Ferromagnets

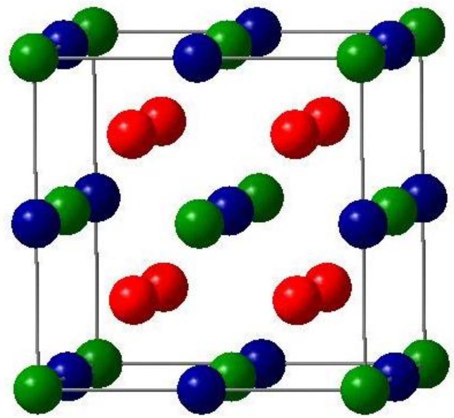




Wollmann et al., APL Mat. 3 (2015) 041518
Graf T, Felser C, Parkin SSP, Progress in Solid State Chemistry (2011) 1
Kandpal *et al.*, CF J. Phys. D **39** (2006) 776

Ternary Semiconductors ...





Ga As

13 + 5 = 18

Co Ti Sb

9 + 4 + 5 = 18

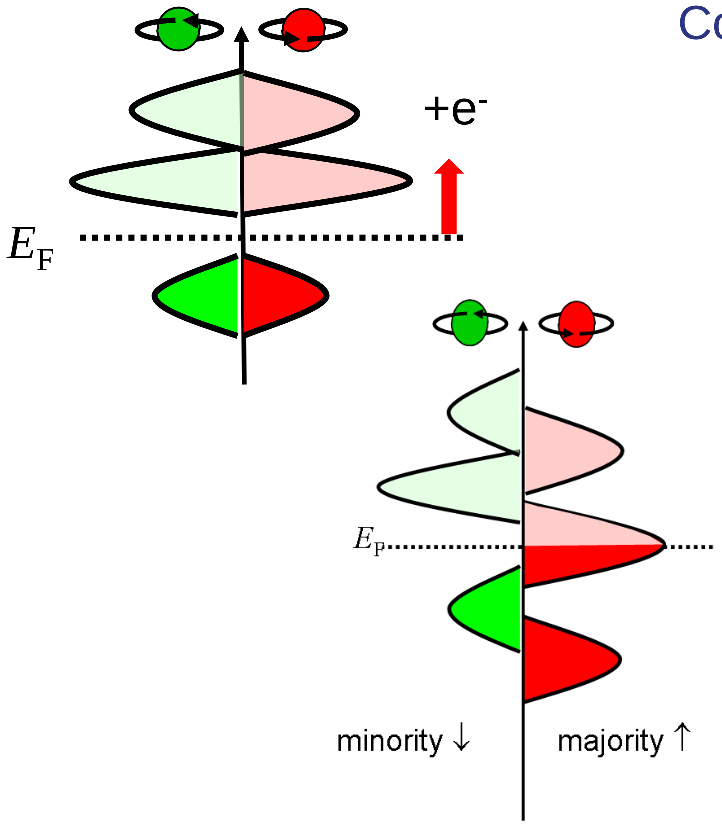
Fe_2 Ti Sn

2*8 + 4 + 4 = 24

additional t_2-levels

Materials: … to half metallic ferromagnets

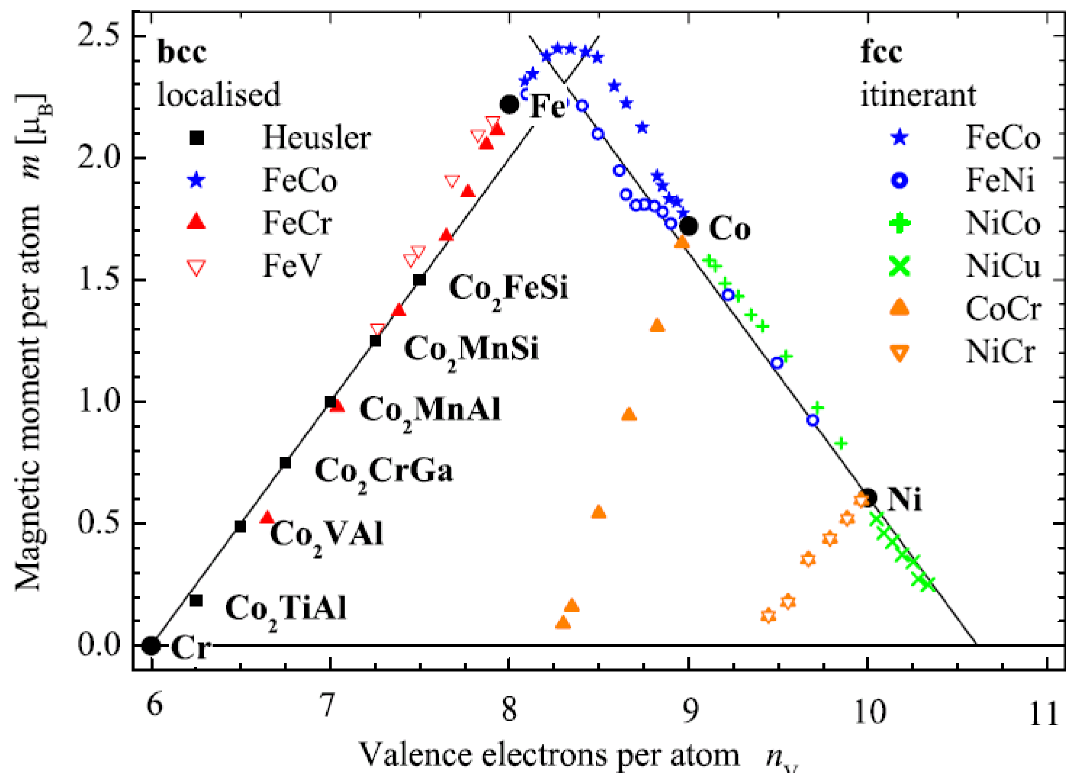
X_2YZ



Example: Co_2MnSi

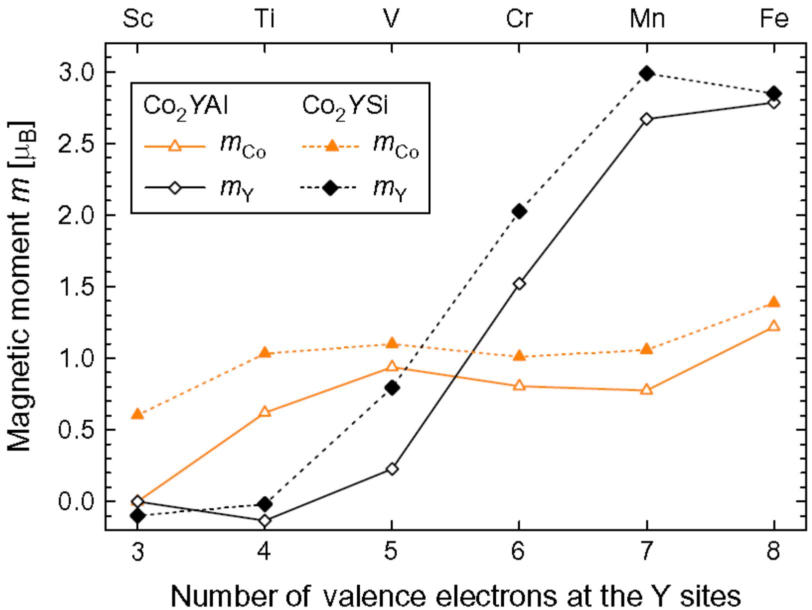
- magic valence electron number: 24
- valence electrons = 24 + magnetic moments

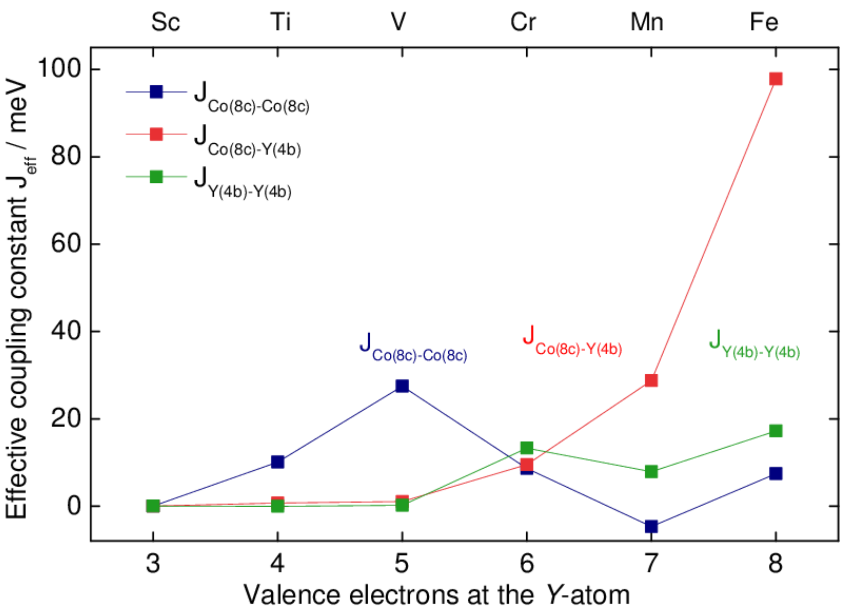
Co_2MnSi: $2\times9 + 7 + 4 = 29$ Ms = $5\mu_B$



Kübler *et al.*, PRB **28**, 1745 (1983)
Galanakis *et al.*, PRB **66**, 012406 (2002)

Tunability Co_2YZ

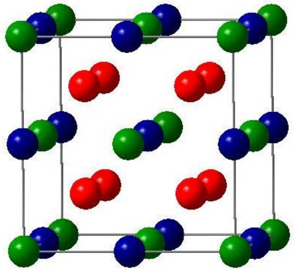


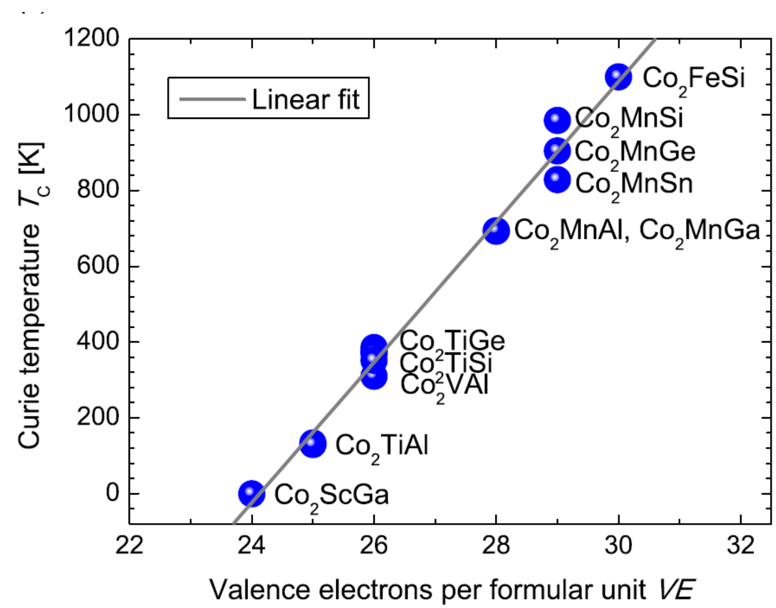


m (Co) ~ 1μ_B

m (Mn) ~ 3μ_B

Exchange coupling: ferro



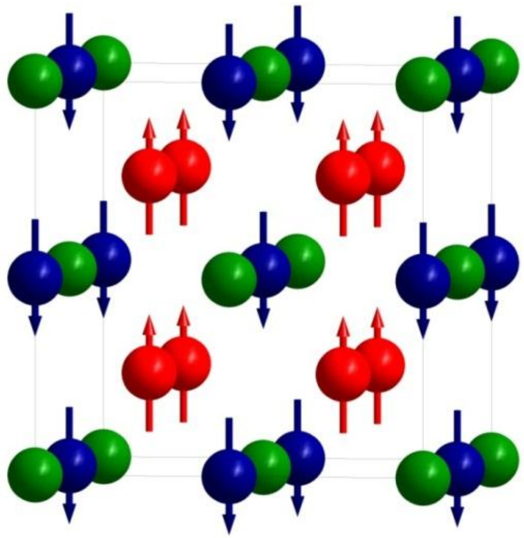


Kandpal et al., J. Phys. **D 40** (2007) 1507.

Balke *et al.* Solid State Com. **150** (2010) 529

Kübler *et al.*, Phys. Rev. B **76** (2007) 024414

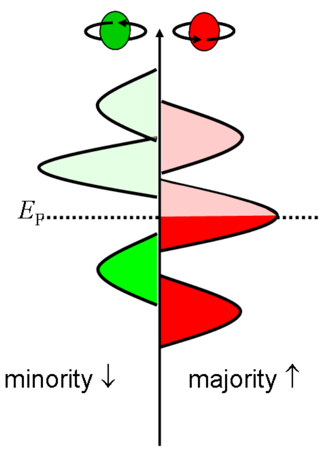
Ferrimagnetic Heusler compounds

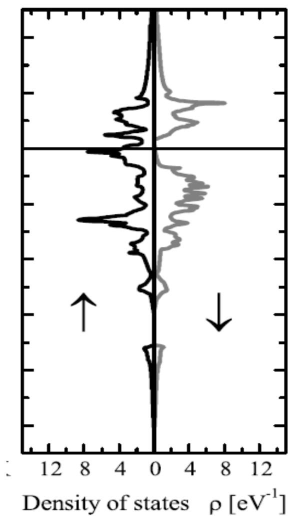


Kübler's Rule
Slater Pauling Rule

X_2MnGa

Two magnetic sublattices
24 Valence electrons – 0 μ_B
Mn^{3+} at octahedral site – 4 μ_B
Mn compensates





Mn_2MnGa

$3*7 + 3 = 24$

⇒ Compensated ferrimagnet

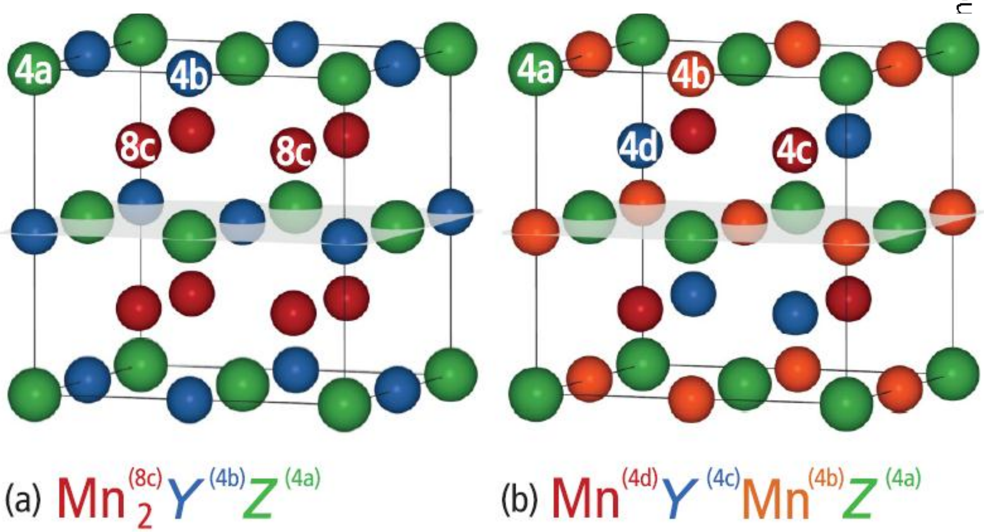
Wurmehl, *et al.*, J. Phys. Cond. Mat. **18** (2006) 6171
Balke *et al*. CF, APL **90** (2007) 152504

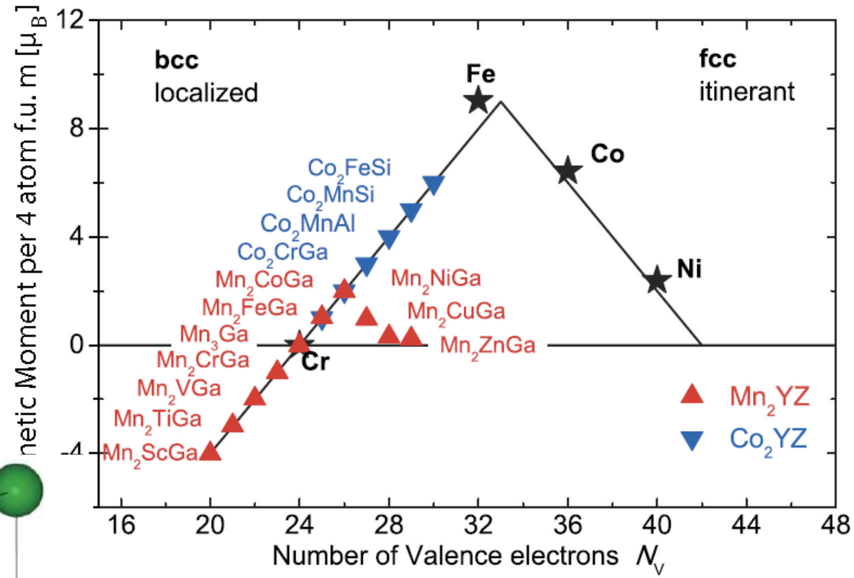
Kübler et al., Phys. Rev. **B** (1983)

Mn_2-Heusler compounds

V | Cr | Mn | Fe | Co | Ni

regular Heusler structure ← Y — **MnYMn Z** — Y → inverse Heusler structure





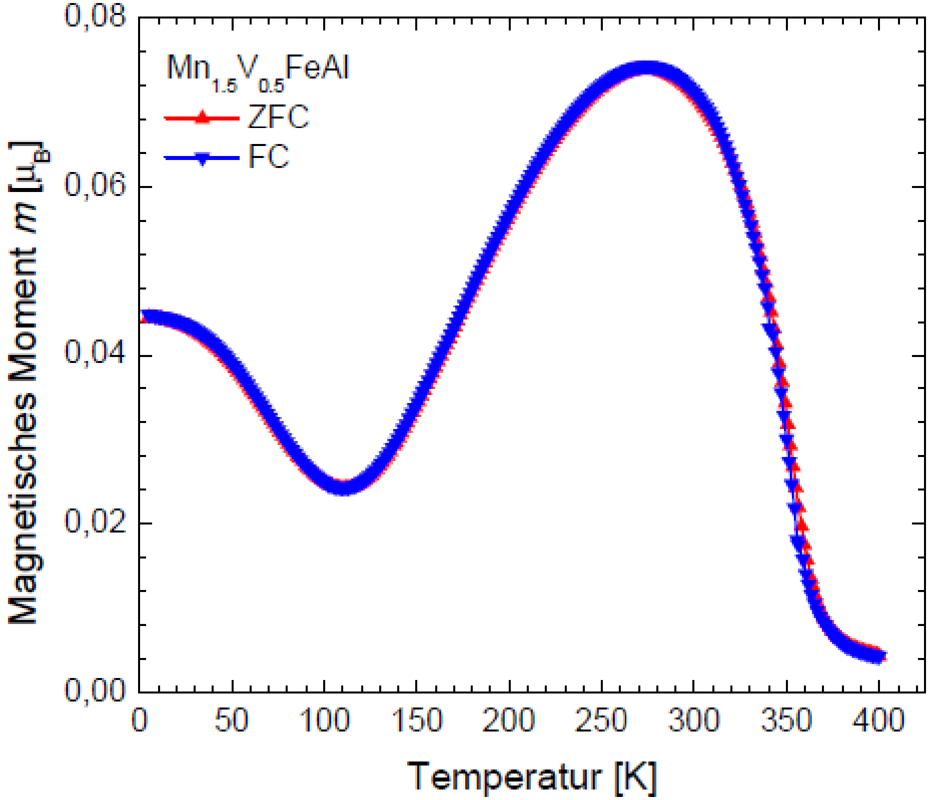
Mn_2VGa + Fe_2MnGa = compensated

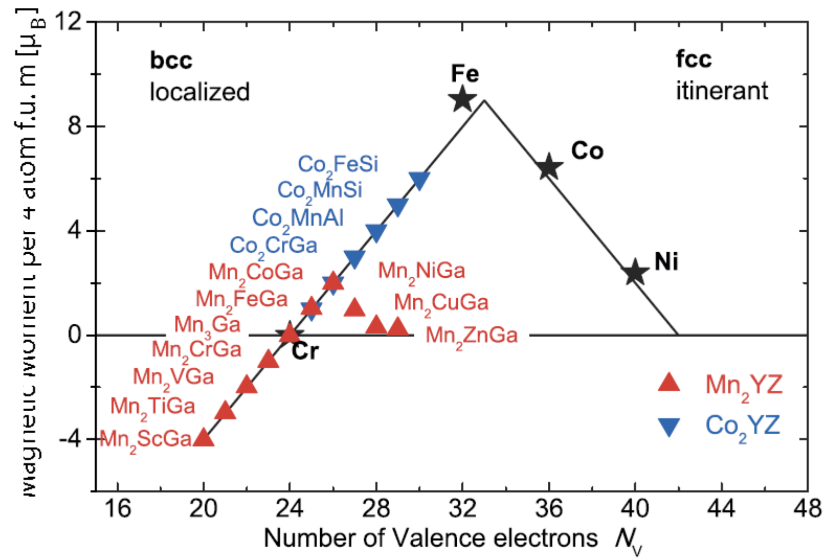
Wollmann et al., APL Mat. 3 (2015) 041518

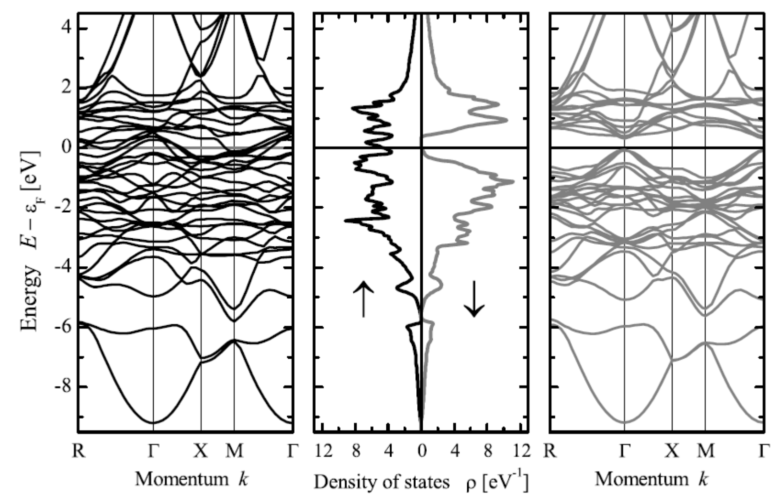
Graf T, Felser C, Parkin SSP, Progress in Solid State Chemistry (2011),

Wurmehl, *et al.*, J. Phys. Cond. Mat. **18** (2006) 6171

Compensated ferrimagnet



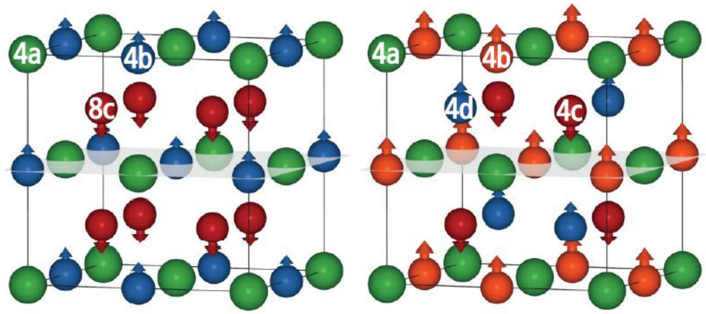




$Mn_2VGa + Fe_2MnGa$ = compensated

Wurmehl, *et al.*, J. Phys. Cond. Mat. **18** (2006) 6171

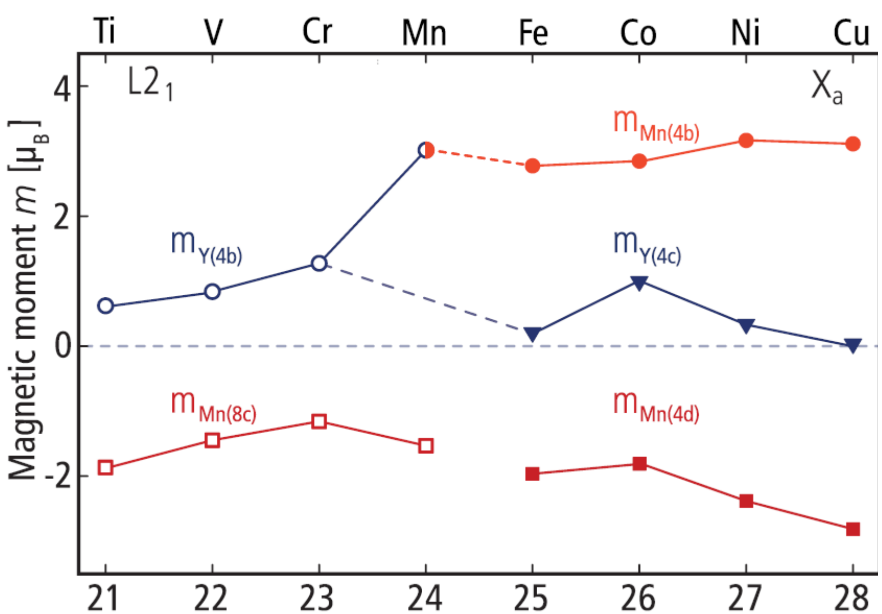
Tunability Mn_2YZ

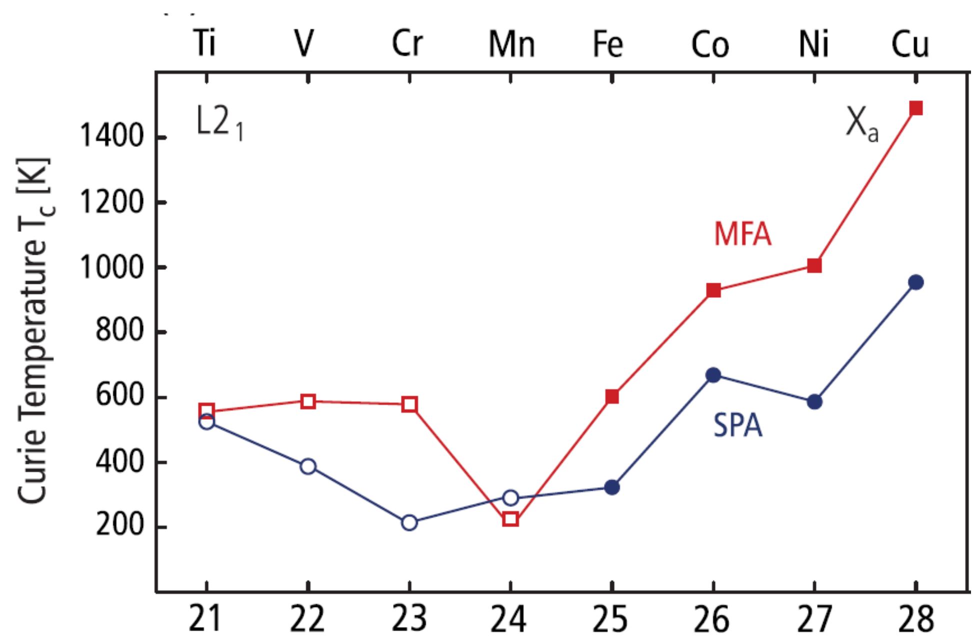


(a) $Mn_2^{(8c)}Y^{(4b)}Z^{(4a)}$ (b) $Mn^{(4d)}Y^{(4c)}Mn^{(4b)}Z^{(4a)}$

m (Mn) ~ 3μ_B
m (Mn) ~ 2μ_B

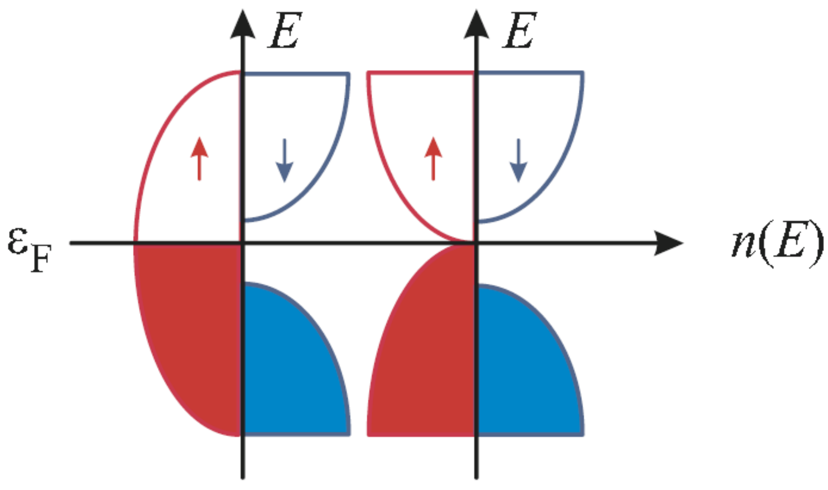
Exchange coupling: ferri

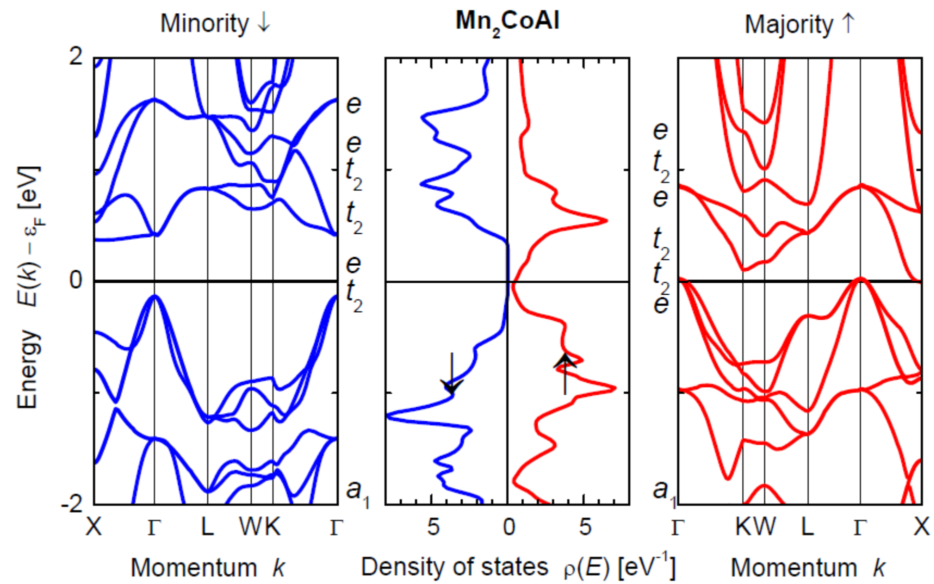


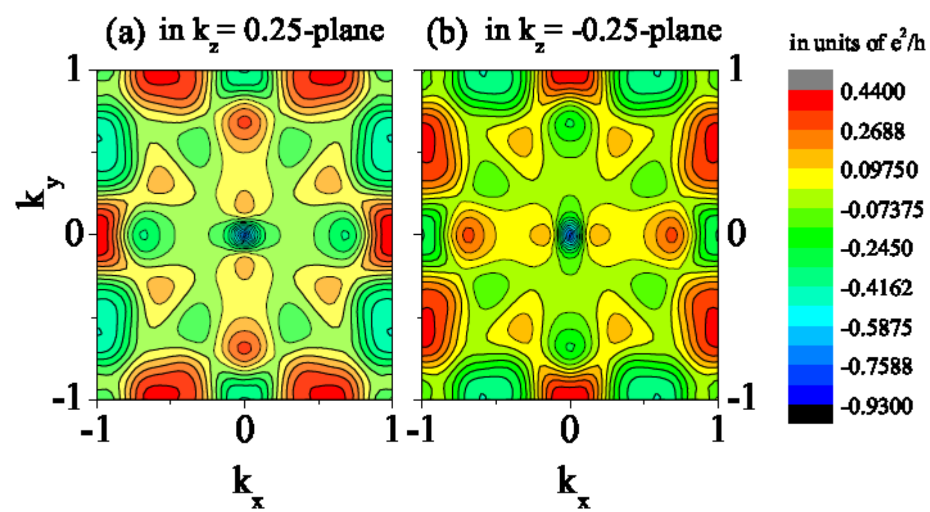


Wollmann et al., Phys. Rev. B 90 (2014) 214420 preprint arXiv:1409.6532

Spin gapless semiconductor Mn_2CoAl







Expected properties

100% spin polarisation

Properties sensitive to pressure

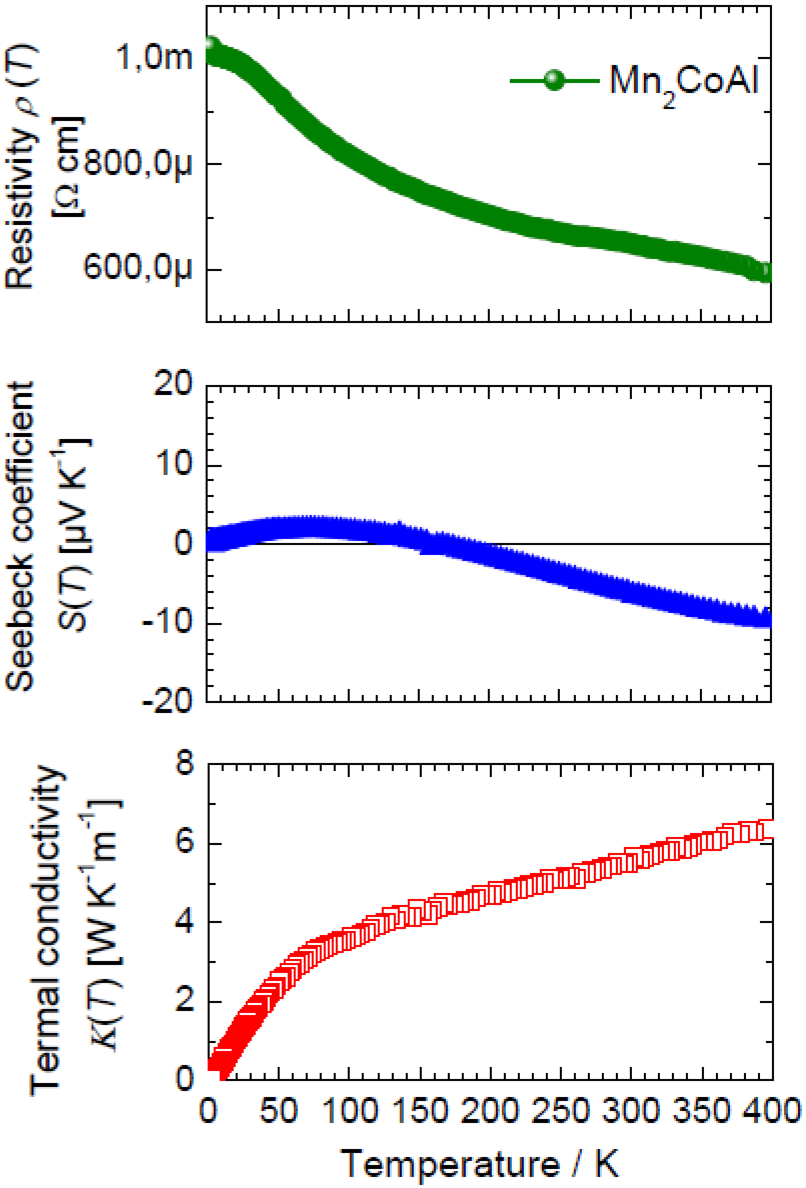
… gating … electrolyte gating

➔ new devices

Wang PRL **100,** 156404 (2008)

Ouardi et al., PRL 110 (2013) 100401

Mn_2CoAl a semiconducting ferromagnet

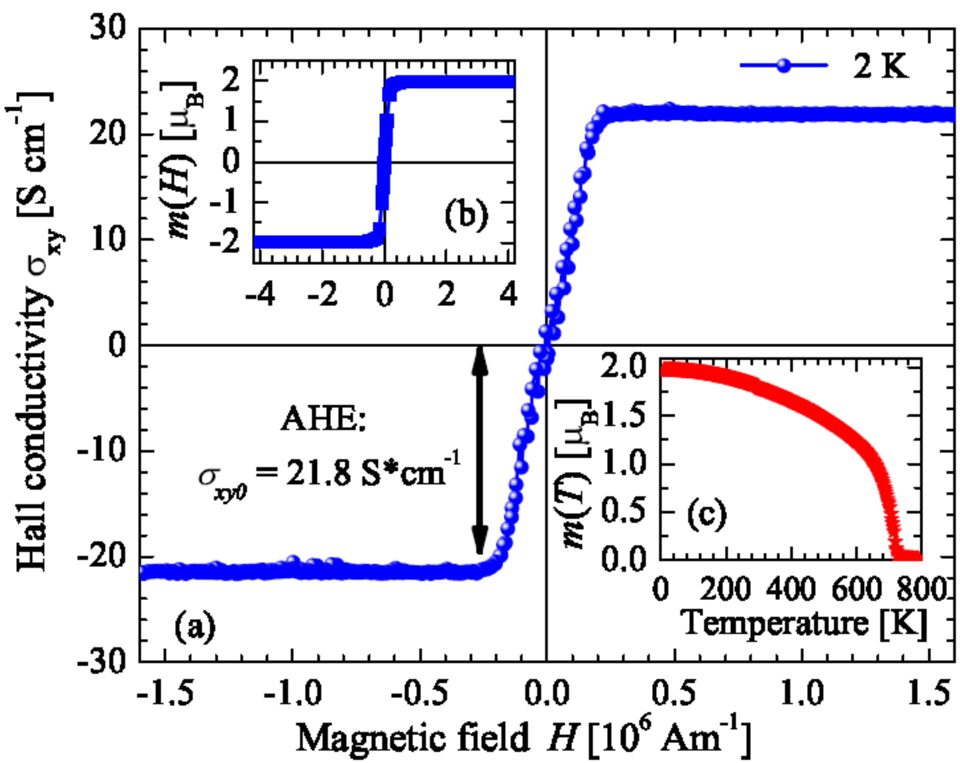


2*7 + 9 +3 = 26

m = 2 μ_B

T_C = 800 K

Charge carrier ~ 10^{17}cm^{-3}

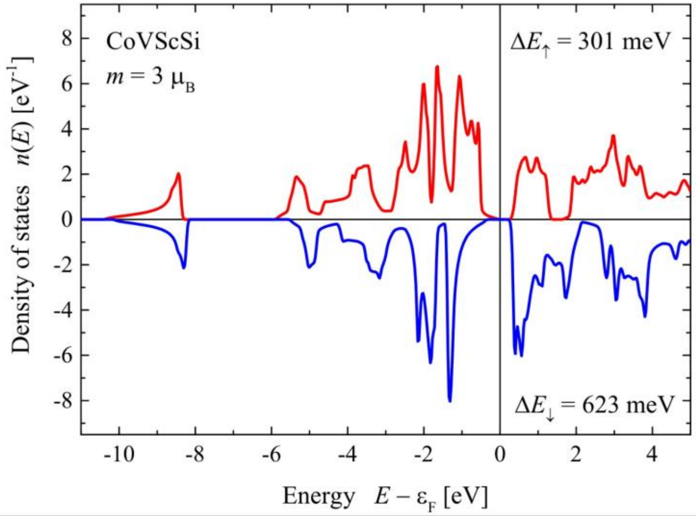


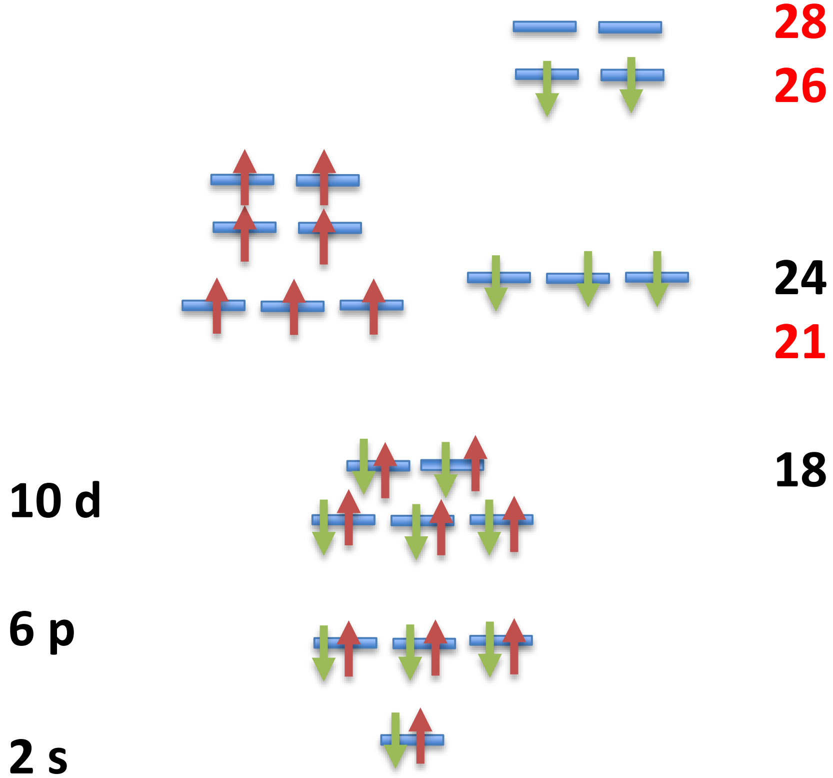
Ouardi et al., Phys. Rev. Lett. 110 (2013) 100401

More semiconductors

26	21
Mn_2CoAl	FeVTiSi
CoFeCrAl	CoVScSi
CoMnCrSi	FeCrScSi
CoFeVSi	FeVTiSi
FeMnCrSb	FeMnScAl

18	28
V_3Al	CoFeMnSi





Özdogan et al., JAP 113, 193903 (2013)

Fecher et al.unpublished

$$J \approx \frac{e}{\hbar g} \alpha M_s H_U d$$

J.C. Slonczewski:"Current-driven excitation of magnetic multilayers(1996)", Journal of Magnetism and Magnetic Materials Volume 159 (1996) L1-L7

Spin torque devices

- **High Spin polarization**
- **Materials with High T_C**
- **High perpendicular anisotropy**
- **Low magnetic damping**
- **Low saturation magnetization**

Problems:

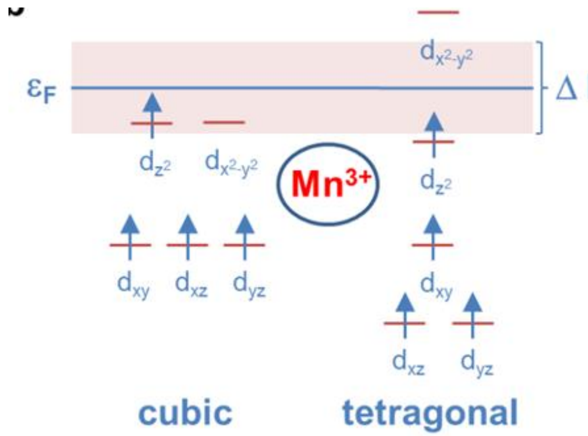
- **Better lattice match new Mn2-Heuslers**
- **Higher spinpolarization**
- **Resonant tunneling**
- **interface engineering - smooth**
  - **atomic structure - disorder**
  - **magnetic structure – non collinear**

Mn_3Ga tetragonal distortion

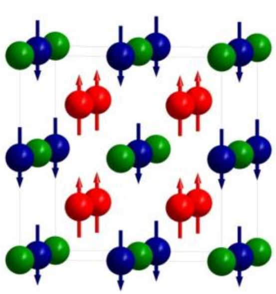
Designed Materials

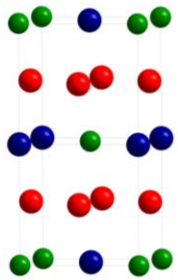
- **Materials with low magnetic damping**
- **Materials with low magnetic moments**
- **Materials with high perpendicular anisotrop**

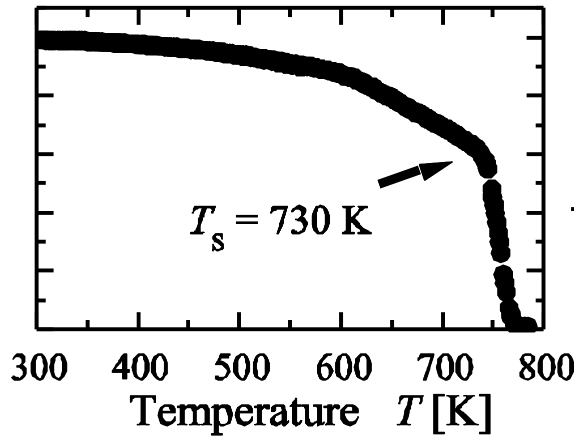
Tetragonal Heusler compounds: Mn_3Ga, $FeMn_2Ga$ …

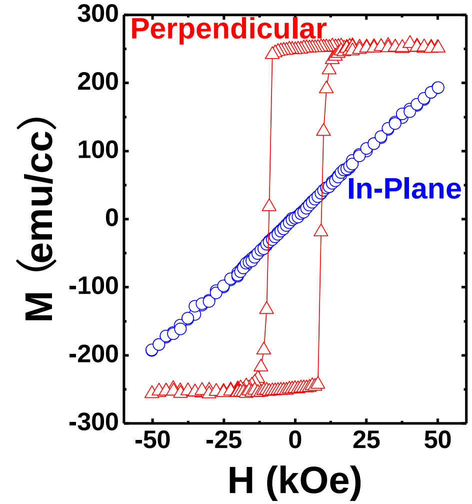


theory → **bulk material** → **thin film and devices**









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Balke *et al*. CF, APL **92**, 152504 (2007)

F. Wu *et al*., APL **94**, 122503 (2009)

$$J \approx \frac{e}{\hbar g} \alpha M_s H_U d$$

J.C. Slonczewski:"Current-driven excitation of magnetic multilayers(1996)", Journal of Magnetism and Magnetic Materials Volume 159 (1996) L1-L7

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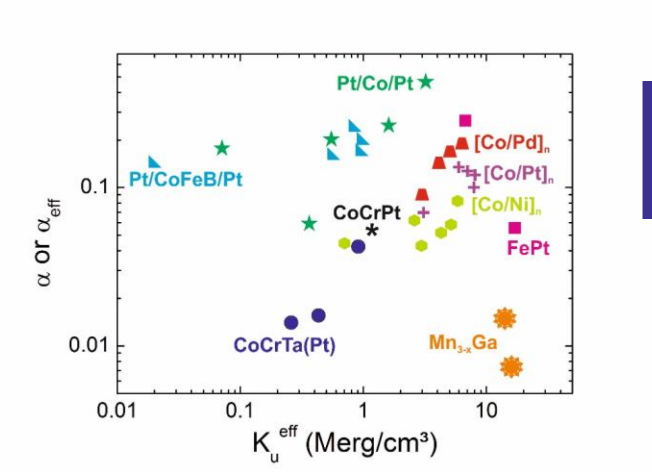
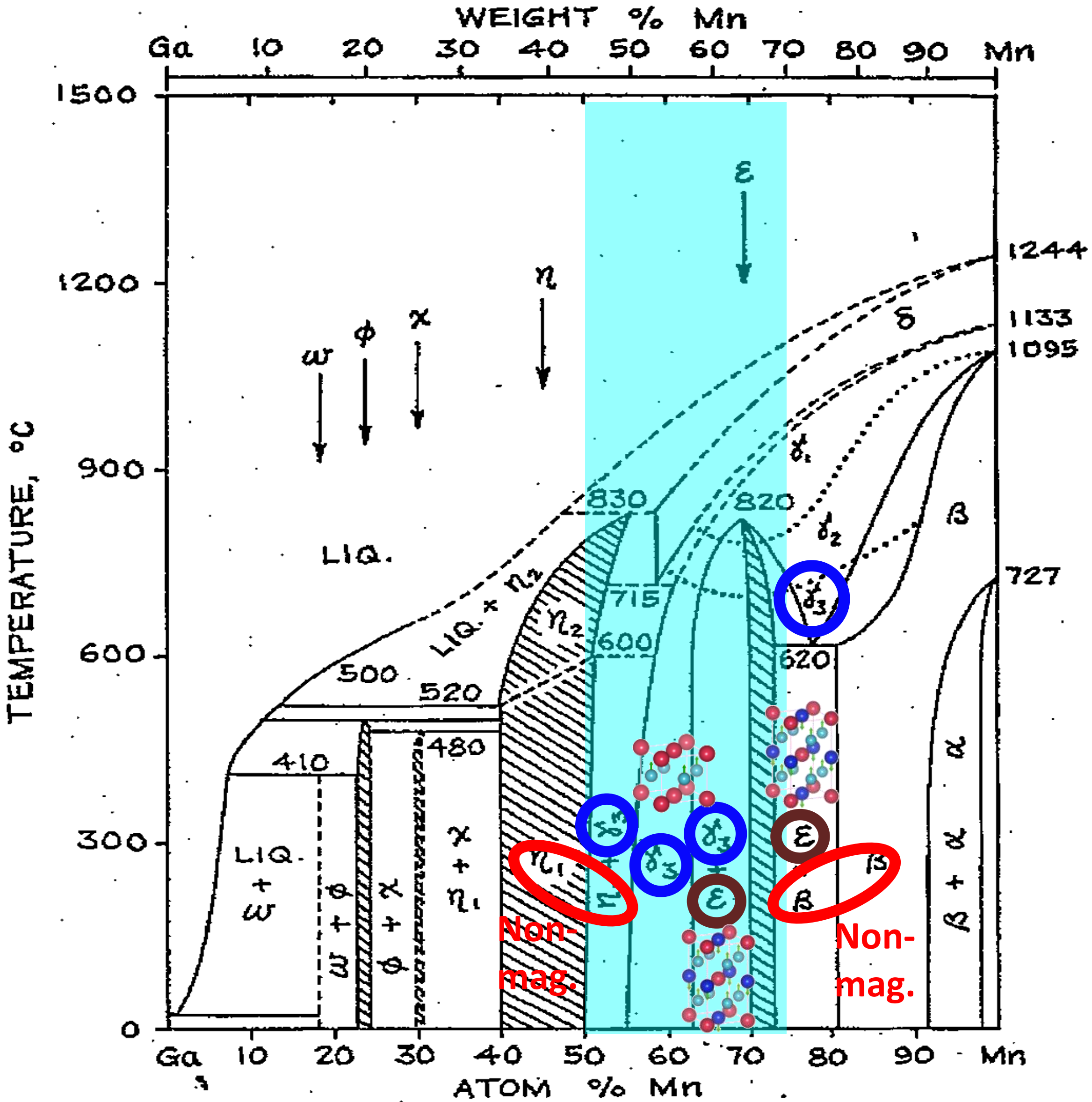
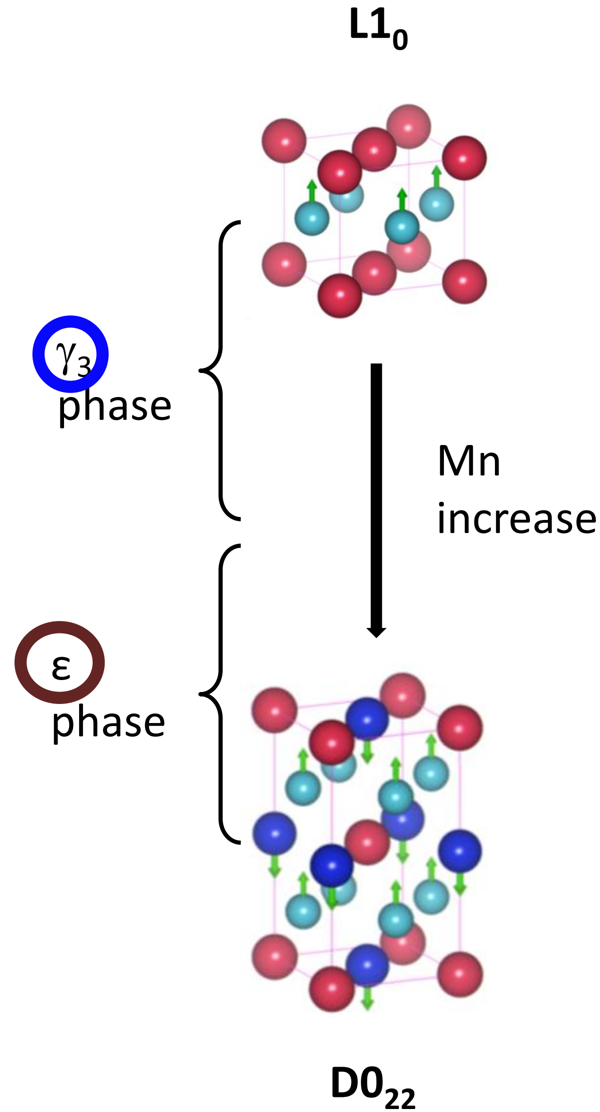
- Resonant tunneling
- interface engineering - smooth
  - atomic structure - disorder
  - magnetic structure – non collinear

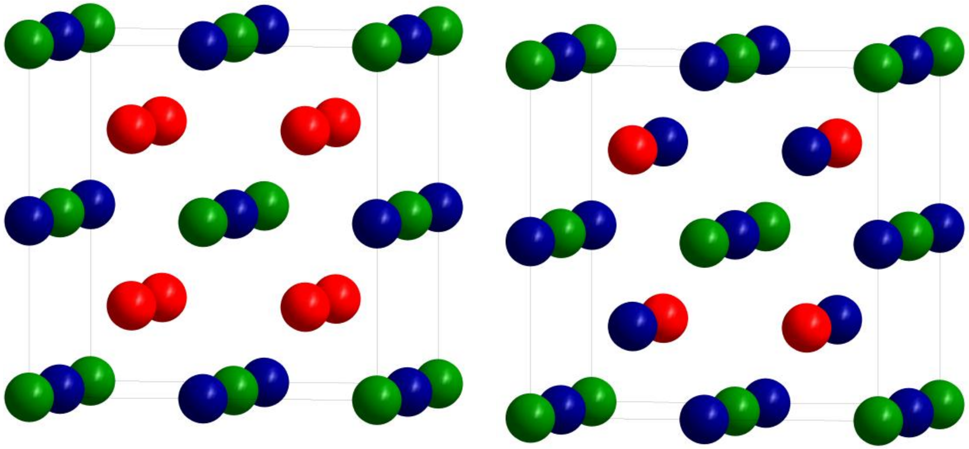


the Handbook of Binary Phase Diagrams (W.G.Moffatt ed.)

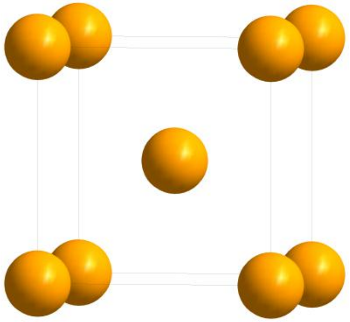




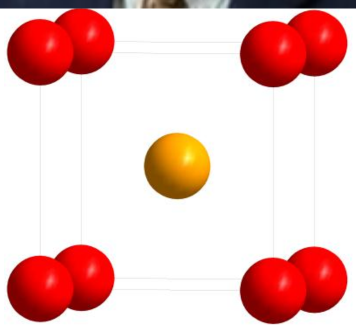
Disorder and Design recipe



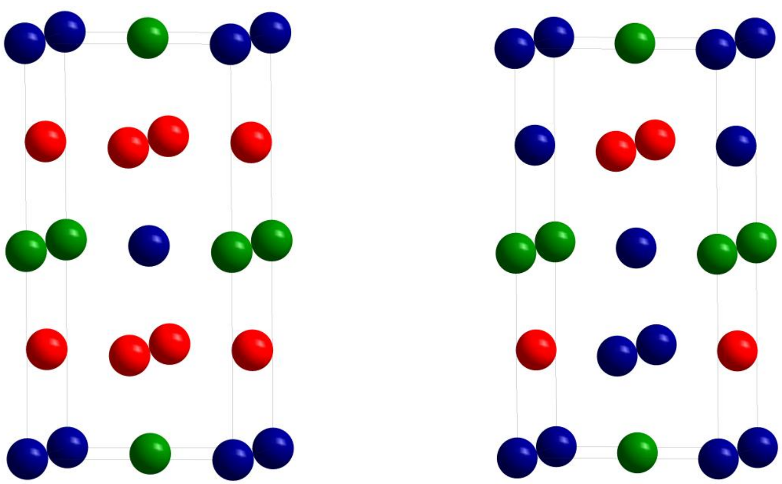
$L2_1$ structure



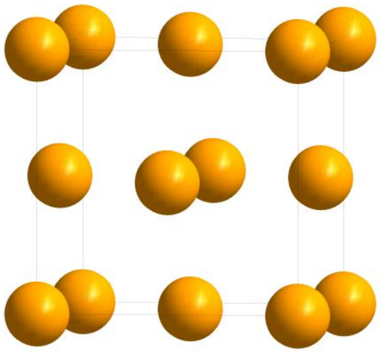
A2 structure



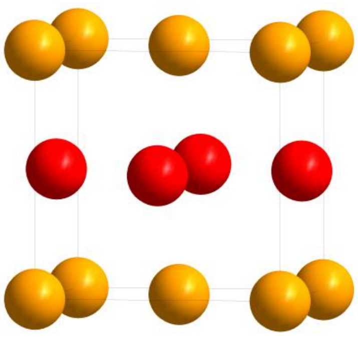
B2 structure



DO_{22} structure

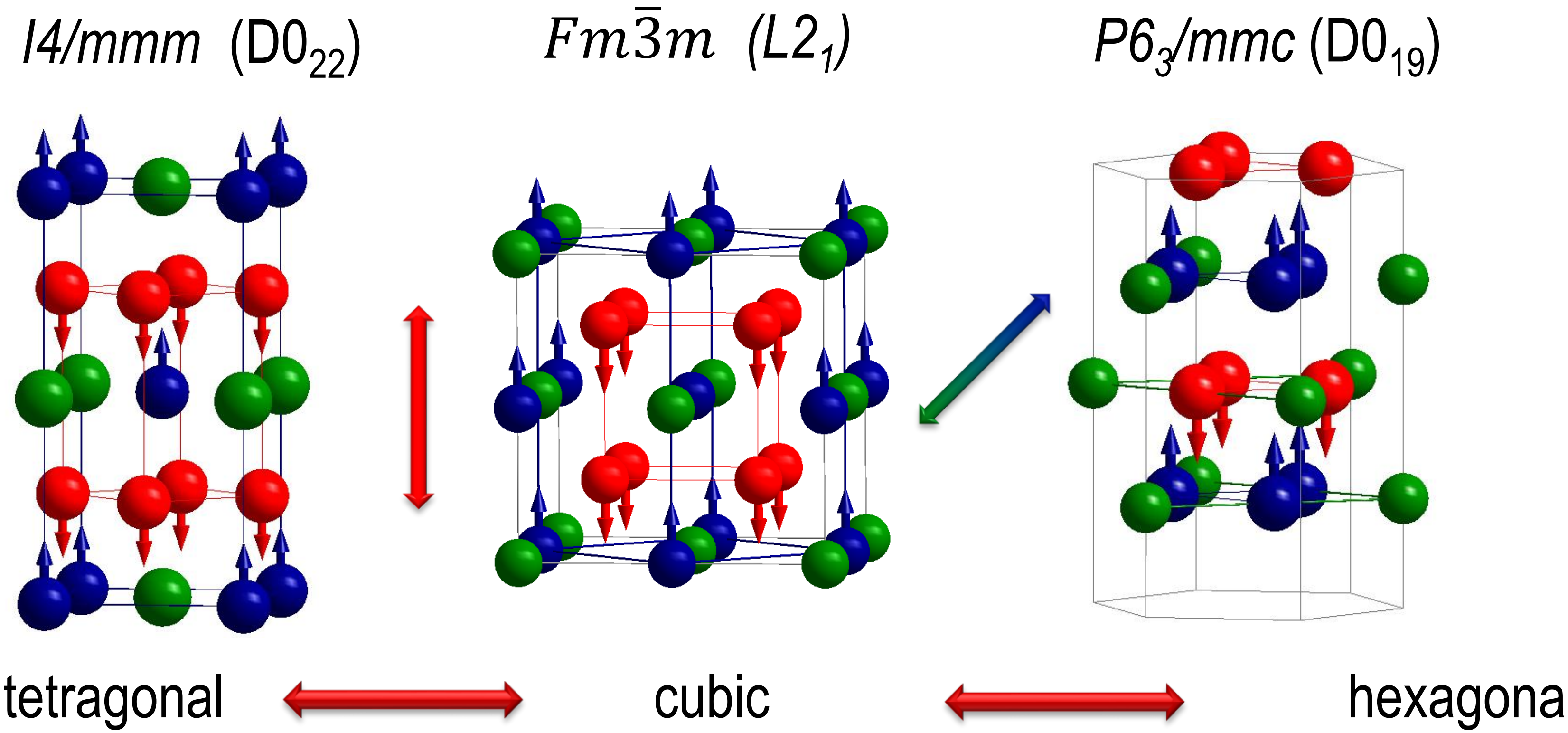


A1 structure



$L1_0$ structure

Structural distortion



STT-RAM with out of plane
Compensated ferrimagnets
Permament magnets
Non-collinear magnetism
Topological Hall effect
Skyrmions

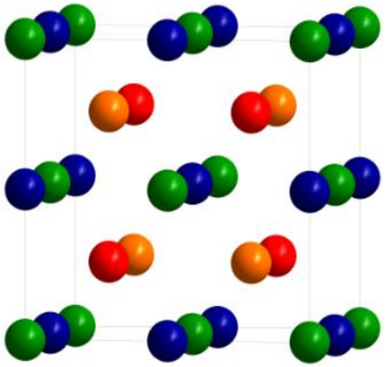
Half metallic ferro/i
Spin gapless
mag. semiconductors
compensated ferrim.
QAH

mag. shape memory
Magnetocalorics – CDW?

Out of plane magnets
Antiferromagnets: Mn_3Ge
Ferromagnets: Fe_3Sn
Anomalous Hall effect
Spin reorientation transition?

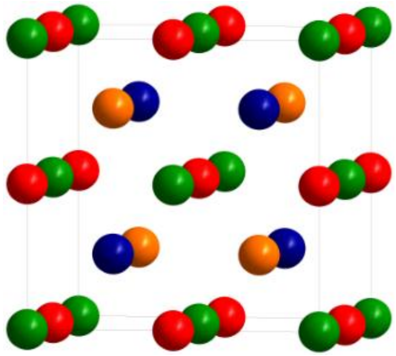
J. F. Qian, et al., J. Phys. Cond. Mat. 47 (2014)
J. Kübler and C. Felser EPL 108 (2014) 67001

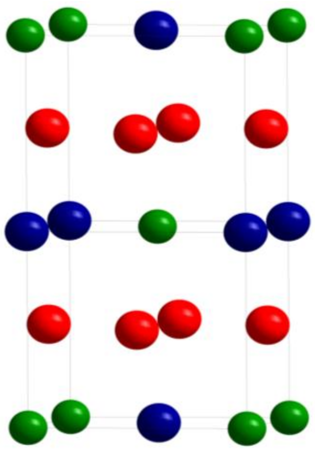
The tetragonal structure



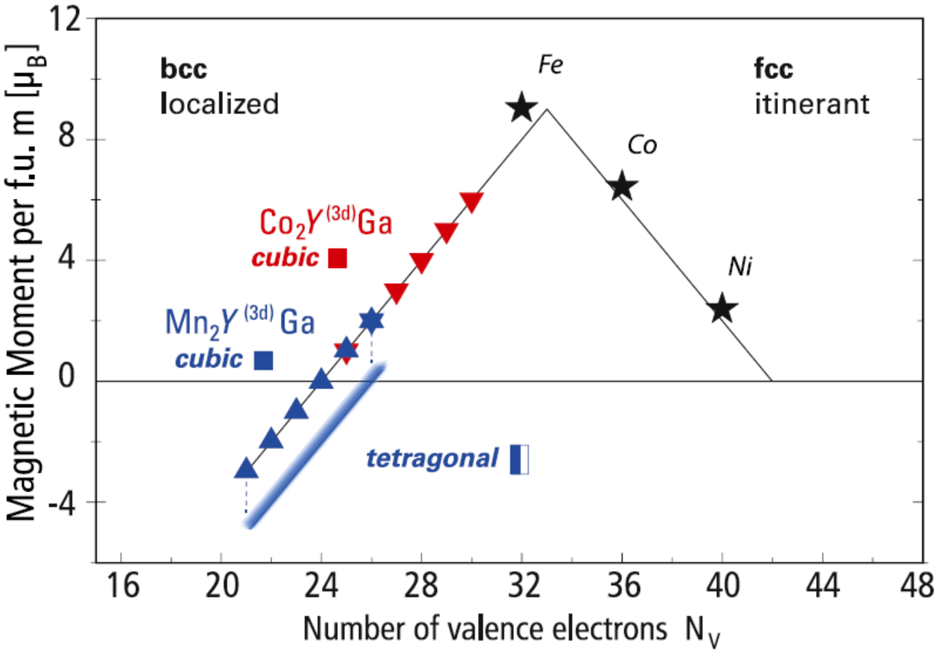
regular
Heusler
structure

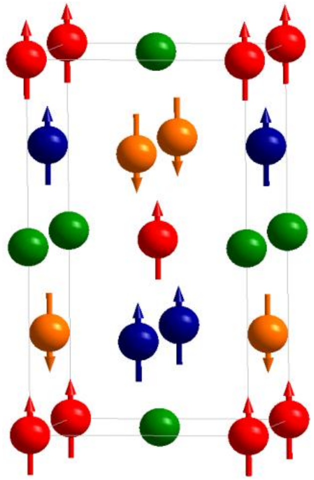
inverse
Heusler
structure





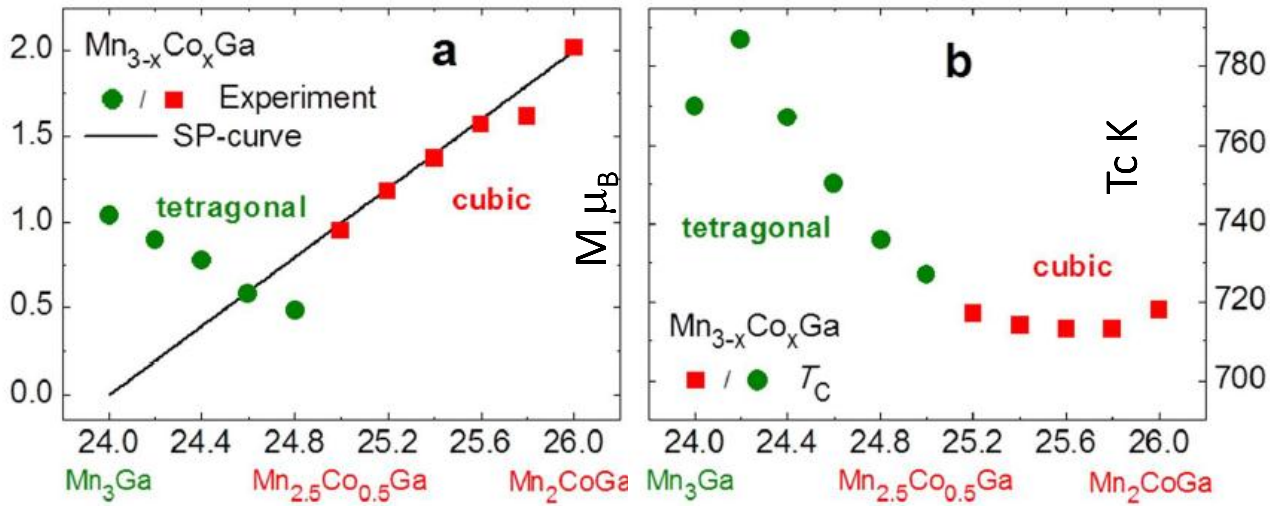
e) Slater - Pauling Curve

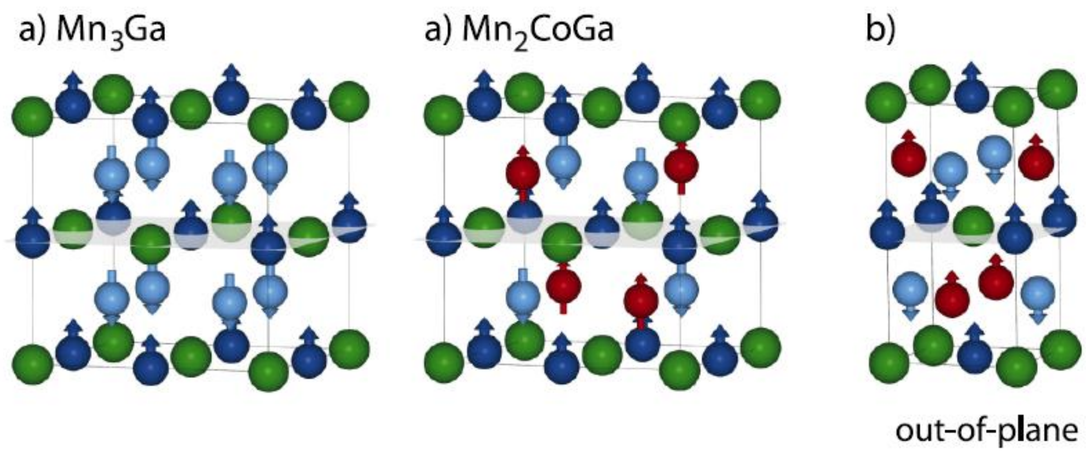


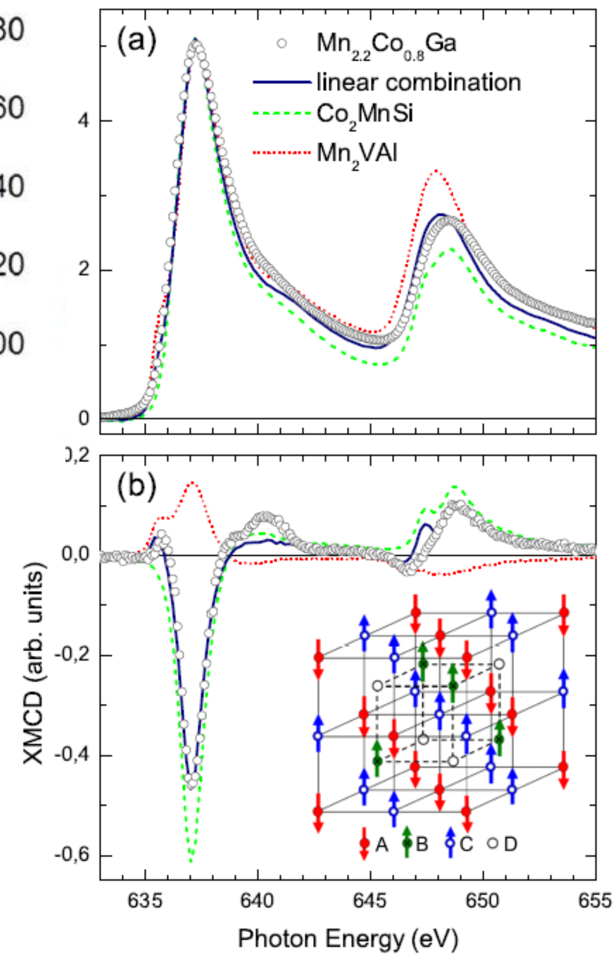


Wollmann et al., APL Mat. 3 (2015) 041518
Wollmann et al. Phys. Rev. B accepted arXiv:1506.03735

Mn_2CoGa – Mn_3Ga







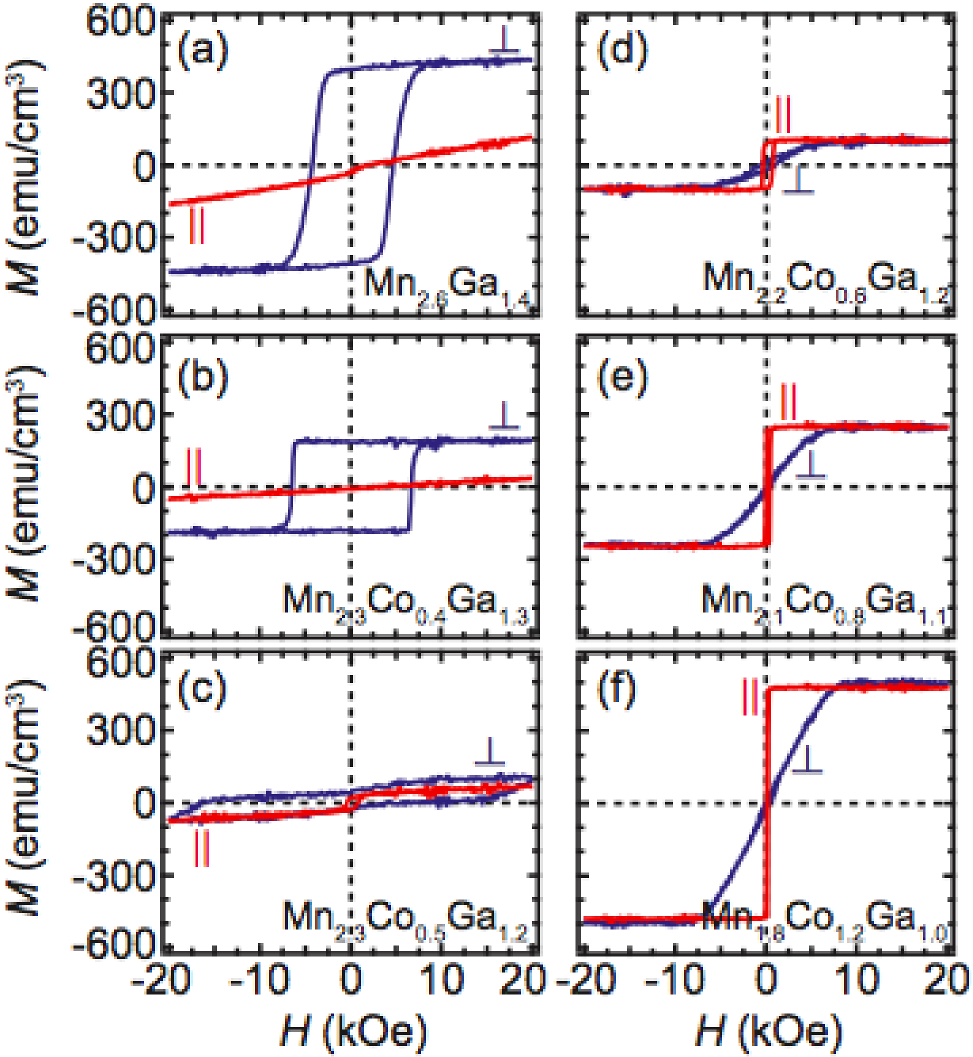
Winterlik, J et al, Advanced Materials 24 (2012) 6283

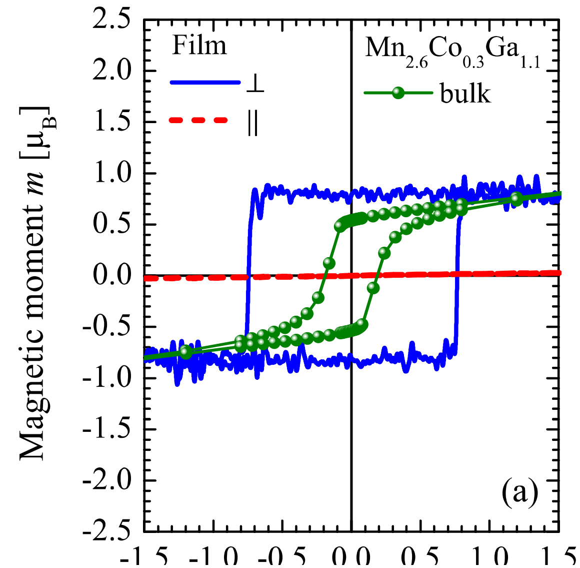
Klaer et al. Appl. Phys. Lett. 98 (2011) 212510.

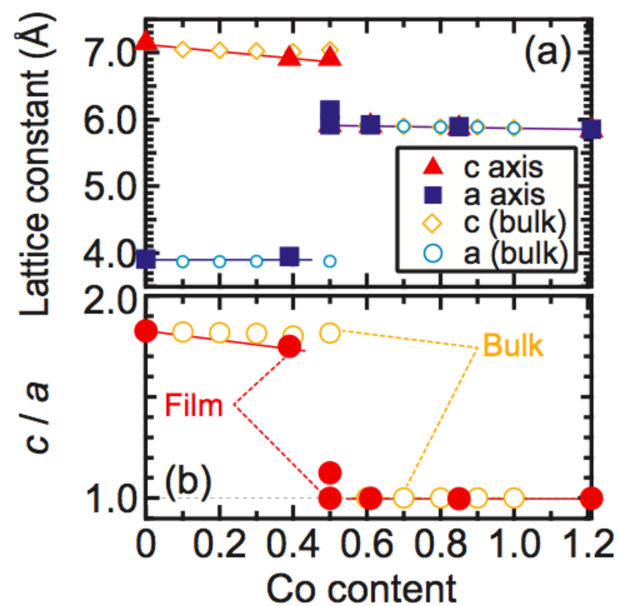
Graf T, Felser C, Parkin SSP, IEEE TRANSACTIONS ON MAGNETICS 47 (2011) 367

Graf T, Felser C, Parkin SSP, Progress in Solid State Chemistry (2011), doi:10.1016/j.progsolidstchem.2011.02.001

Compensated ferrimagnet





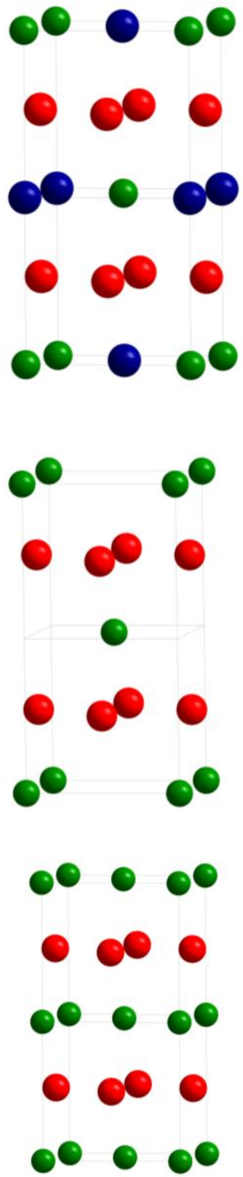


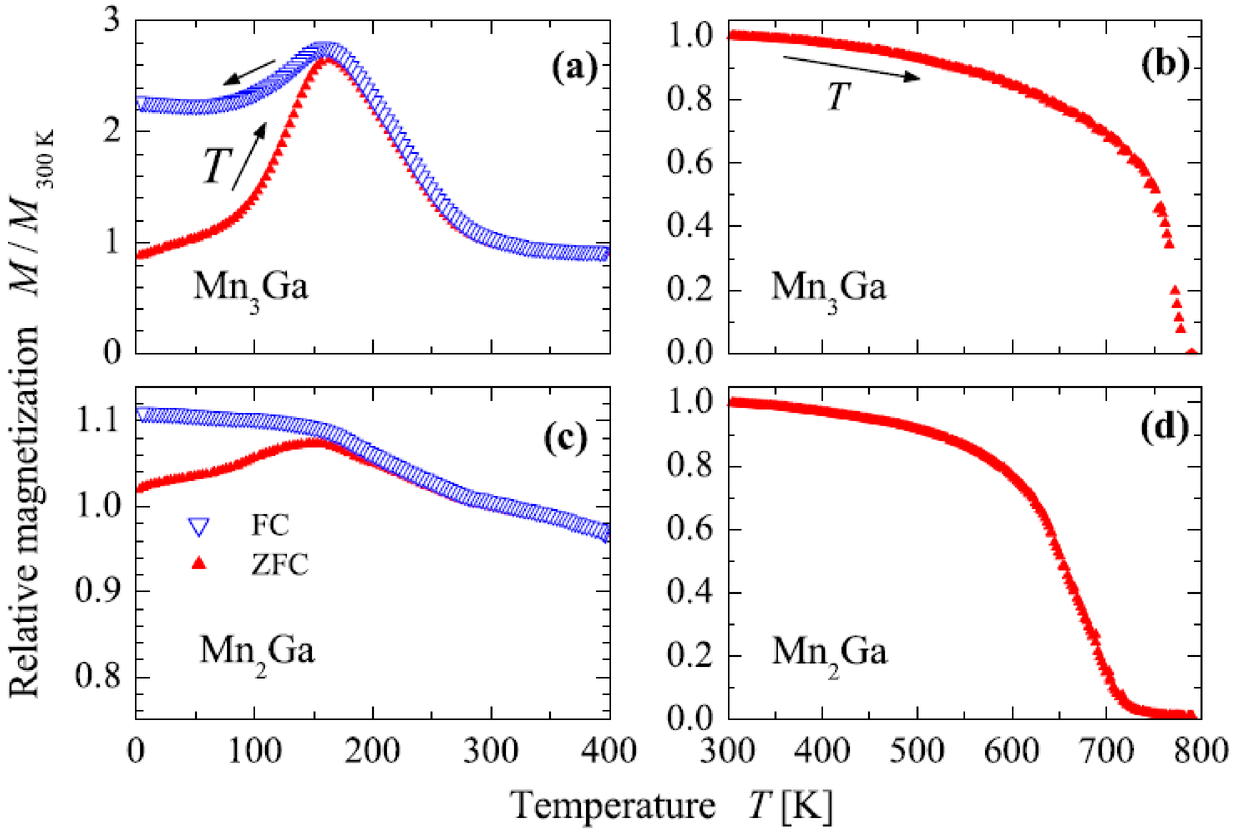
prepared in Mizukami lab

S. Ouardi, et. al , APL 101 (2012) 242406 arXiv:1211.2440

T. Kubota, S. Ouardi, arXiv:1211.2524

$Mn_{3-x}Ga$: Tunability

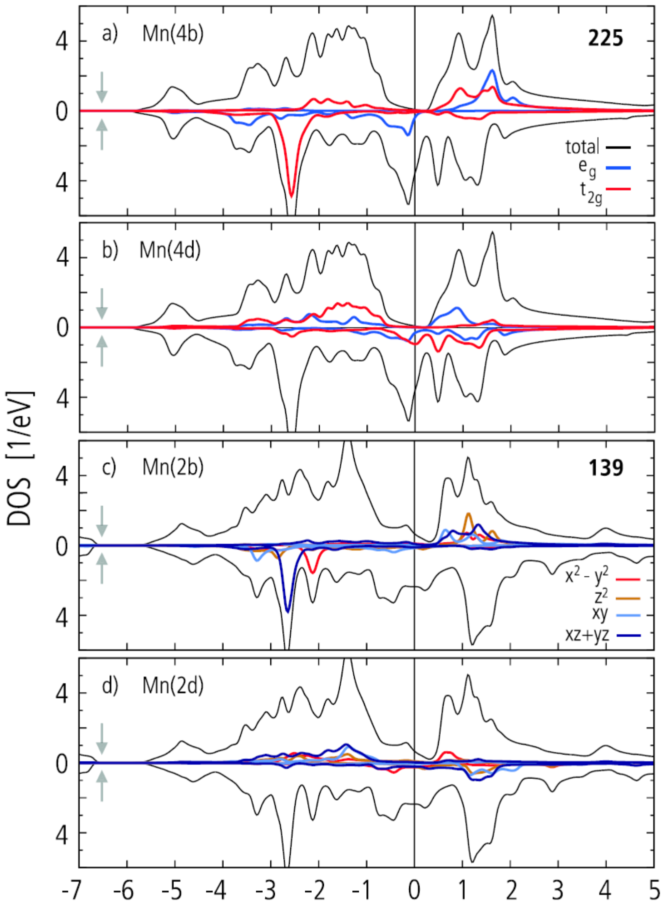


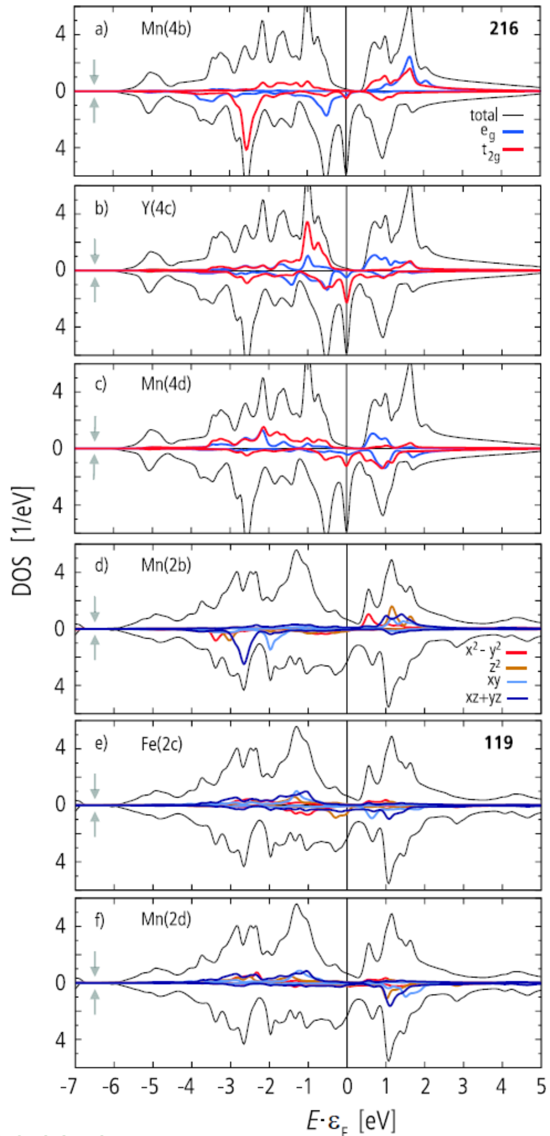


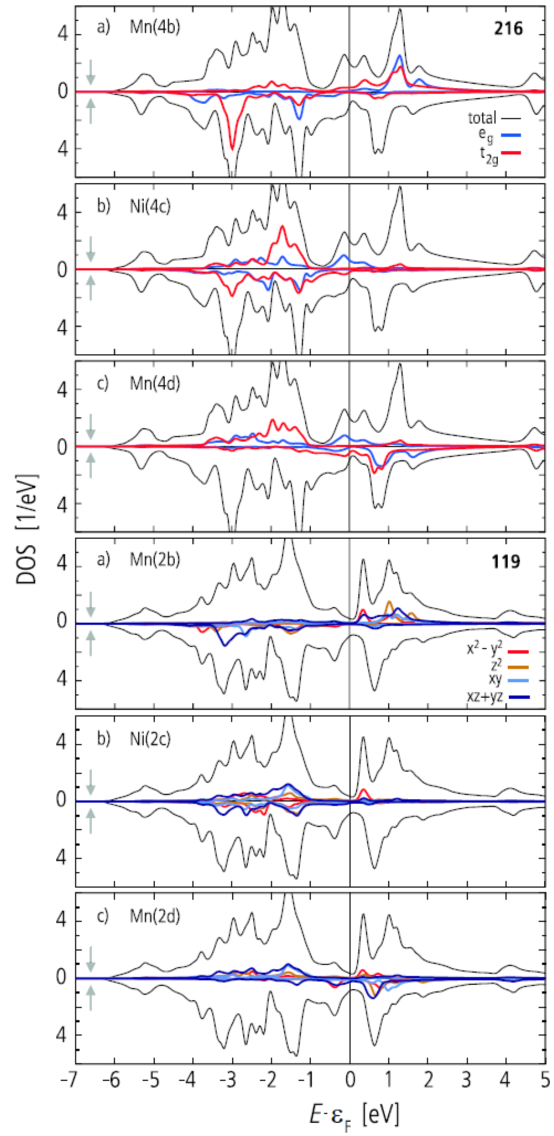
More complex magnetism at low T
Removing one sort of Mn (octahedral) leads to ferromagnetism

Winterlik *et al.* Phys. Rev. B **77** (2008) 054406

Tetragonal Heusler

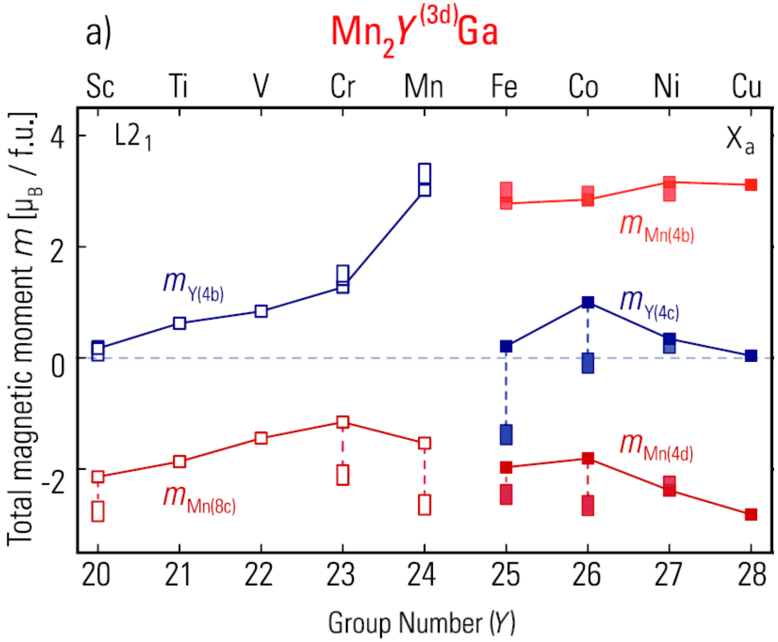


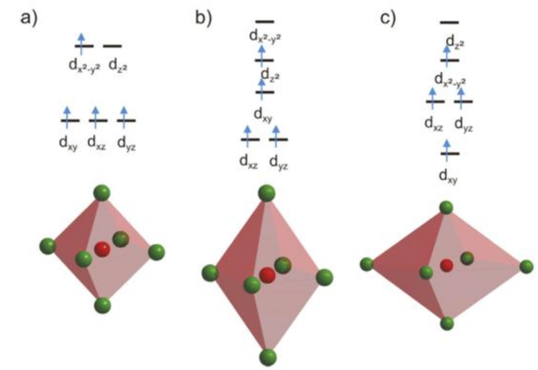


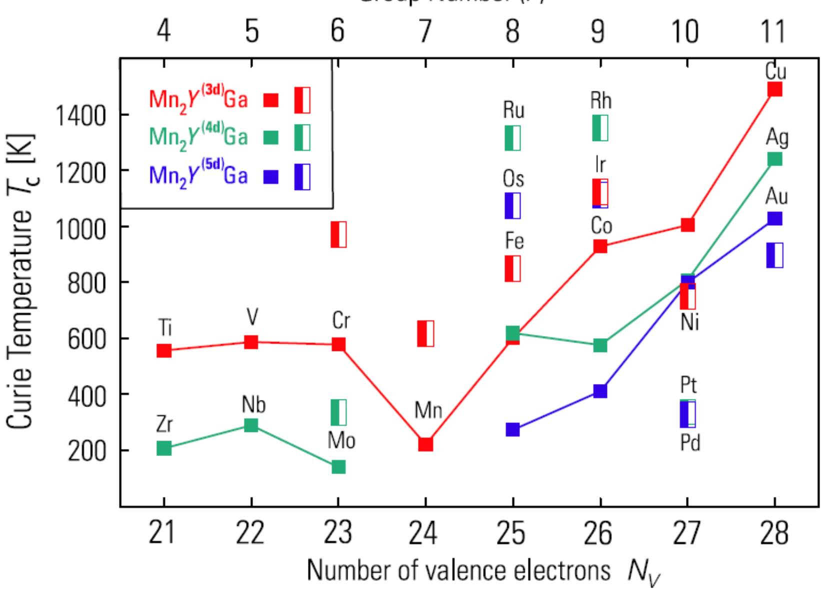


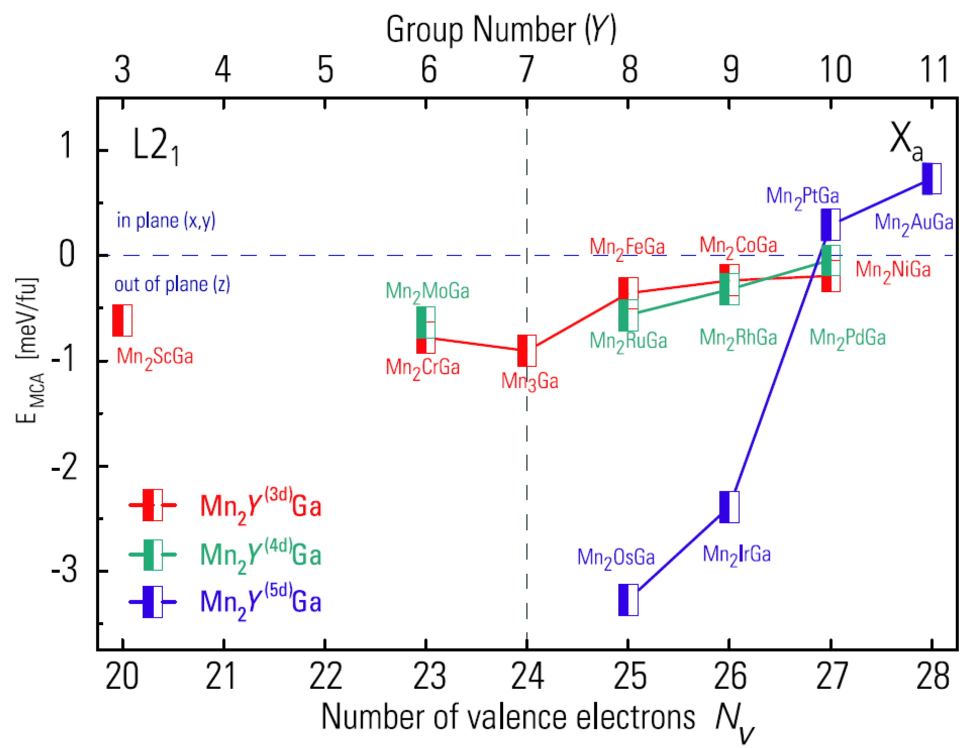
Wollmann et al. Phys. Rev. B accepted arXiv:1506.03735

Magnetocrystalline Anisotropy



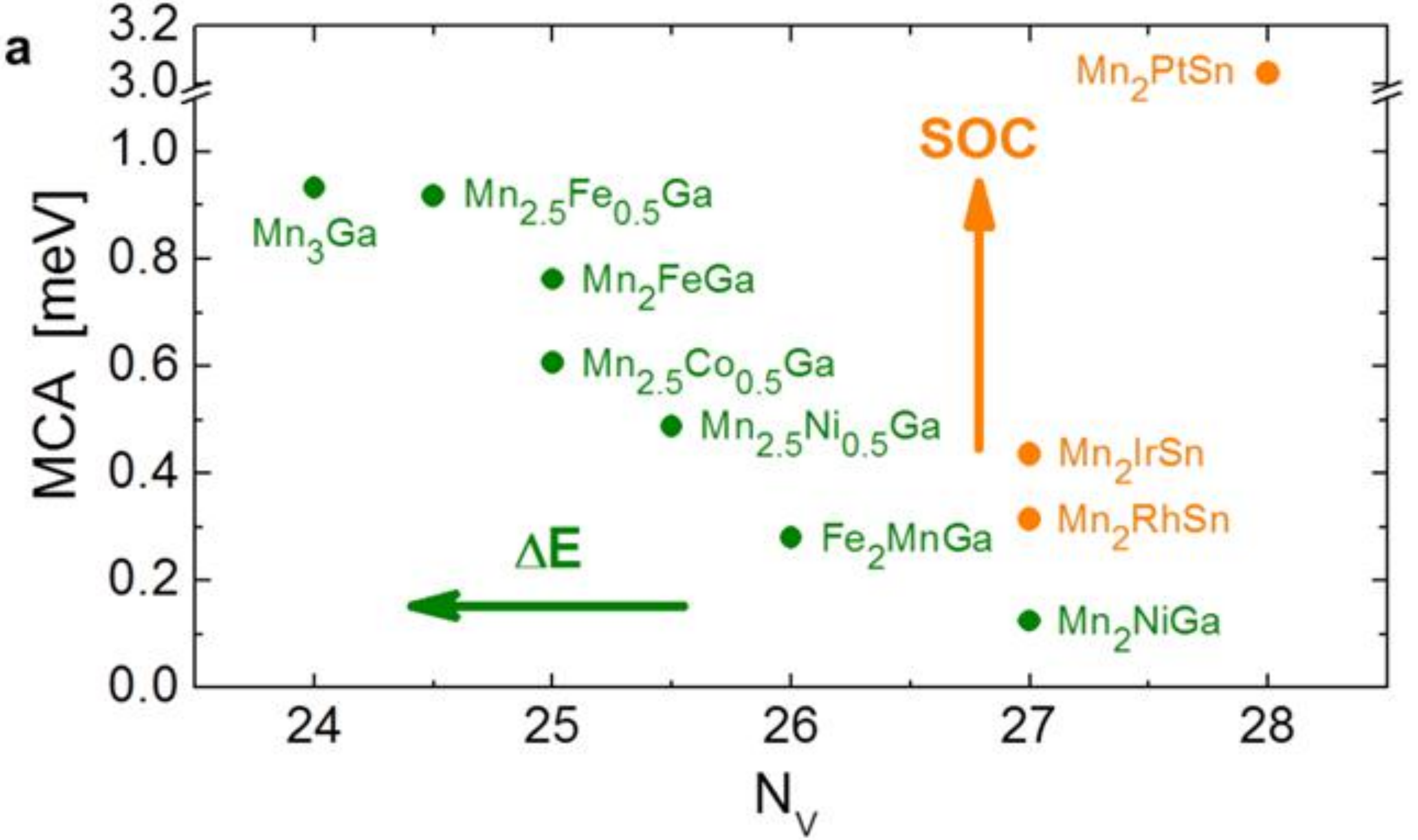






Wollmann et al. Phys. Rev. B accepted arXiv:1506.03735

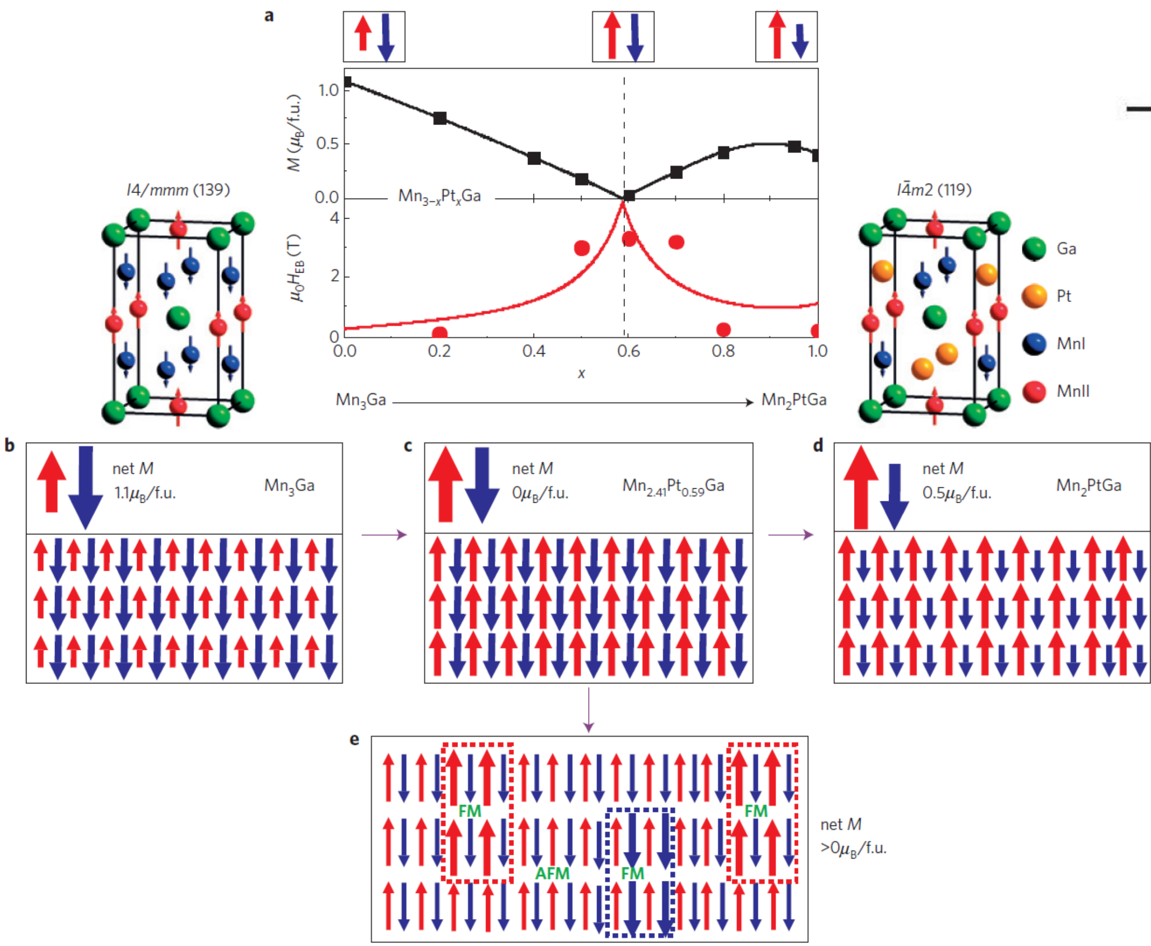
Heuslers with SOC – DM interaction

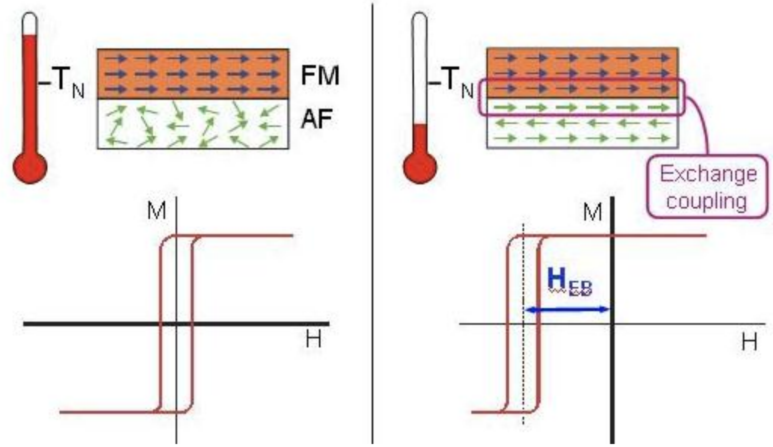


Winterlik et al. Advanced Materials 24 (2012) 6283

Design of compensated ferrimagnetic Heusler alloys for giant tunable exchange bias

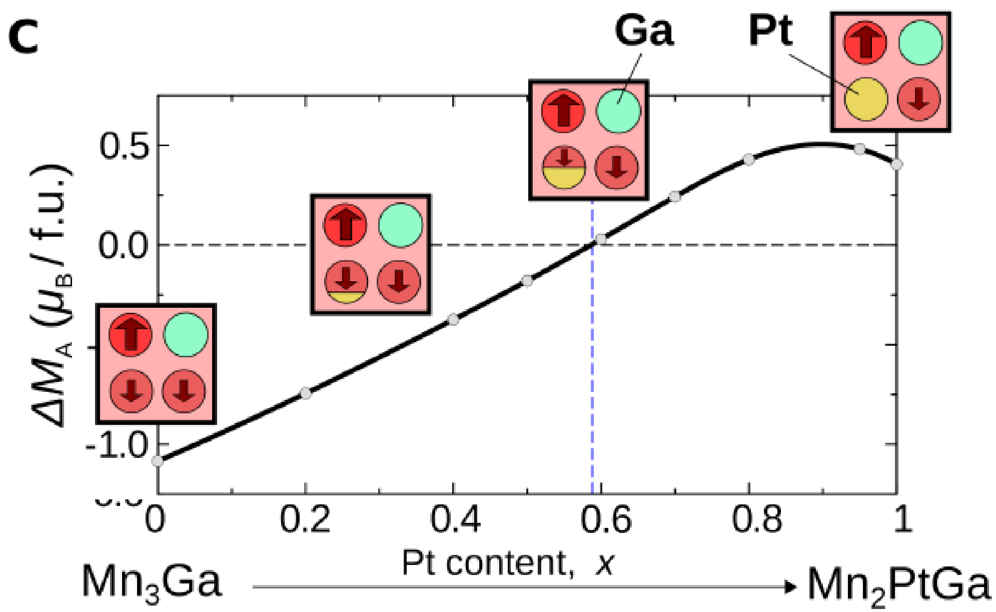
Ajaya K. Nayak[1]*, Michael Nicklas[1], Stanislav Chadov[1], Panchanana Khuntia[1], Chandra Shekhar[1], Adel Kalache[1], Michael Baenitz[1], Yurii Skourski[2], Veerendra K. Guduru[3], Alessandro Puri[3], Uli Zeitler[3], J. M. D. Coey[4] and Claudia Felser[1]*

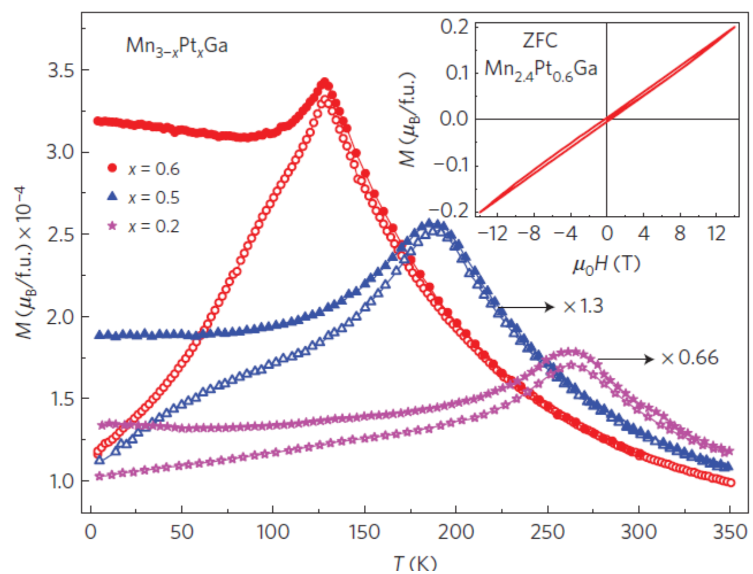


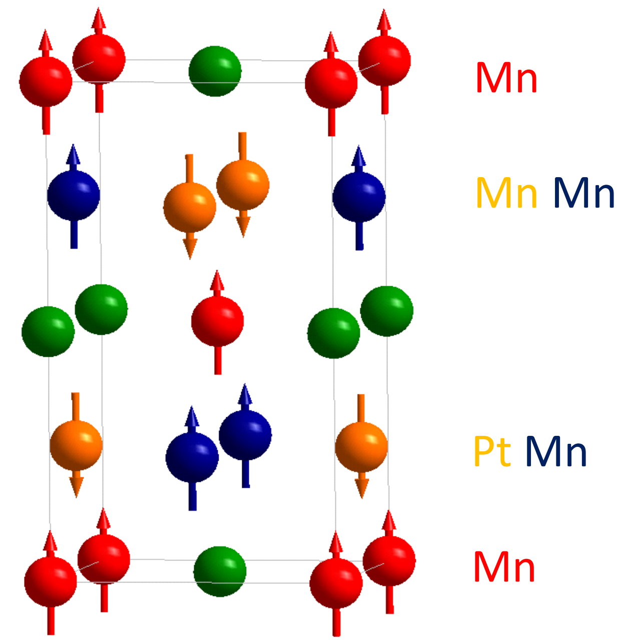


Ajaya K. Nayak, et. al, Nature Materials (2015) doi:10.1038/nmat4248

Artificial AFM or compensated ferrimagnet



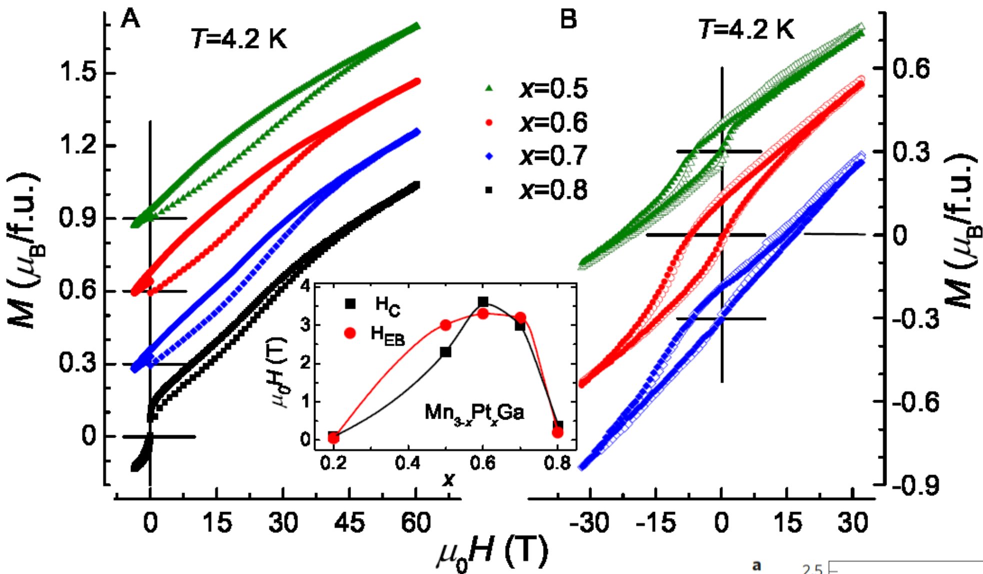


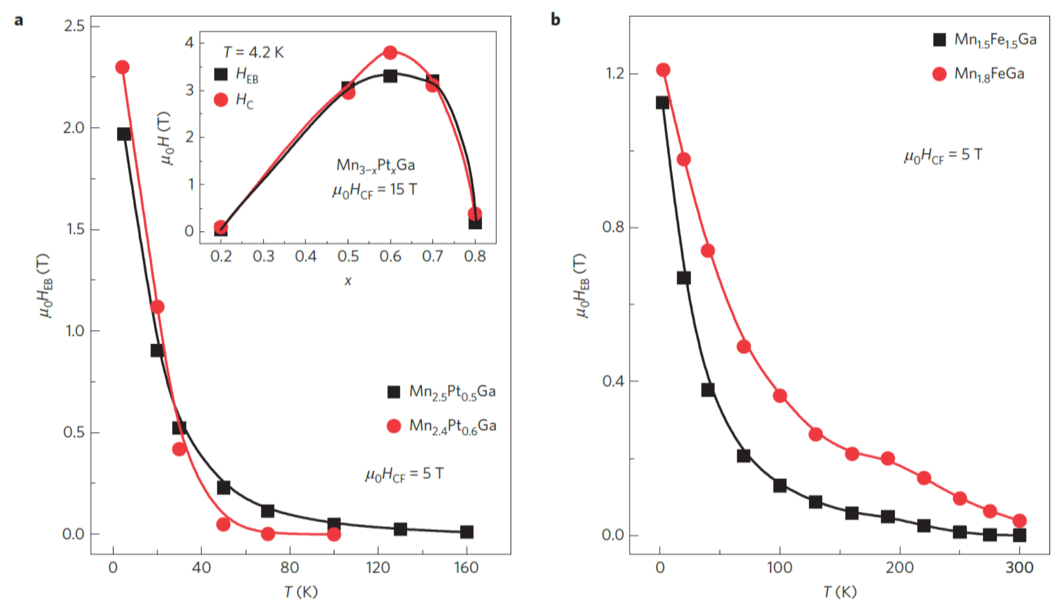


Ajaya K. Nayak, et al PRL 110 (2013) 127204

ıya K. Nayak, et Nature Materials (2015) doi:10.1038/nmat4248

Artificial AFM or compensated ferrimagnet



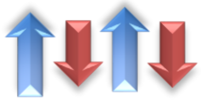


Ajaya K. Nayak, et. al, Nature Materials (2015) doi:10.1038/nmat4248

Magnetic orderings in Heusler compounds

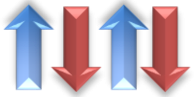
Half-metallic ferromagnetism: **Co_2MnZ...**

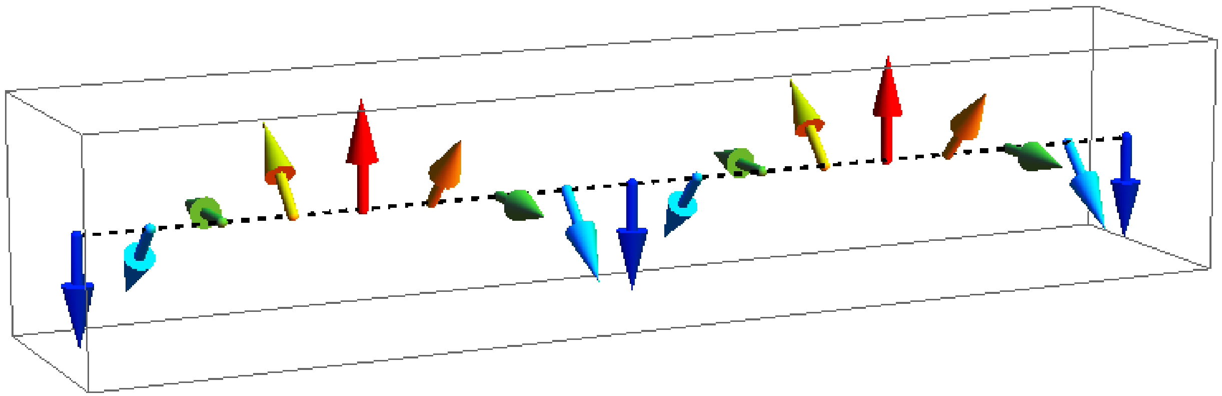
Half-metallic ferrimagnetic: **Mn_2YZ**

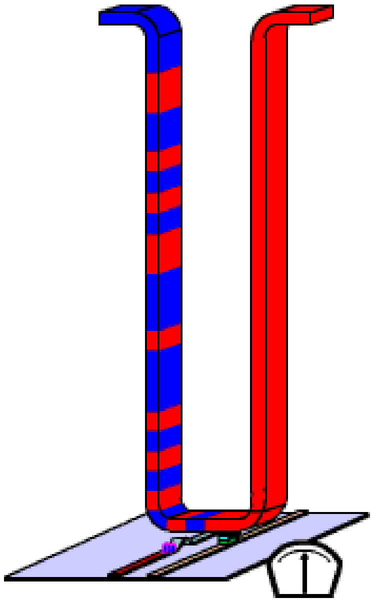


Antiferromagnetic: **Mn_3Si, Fe_2VSi, Ru_2MnGe,**

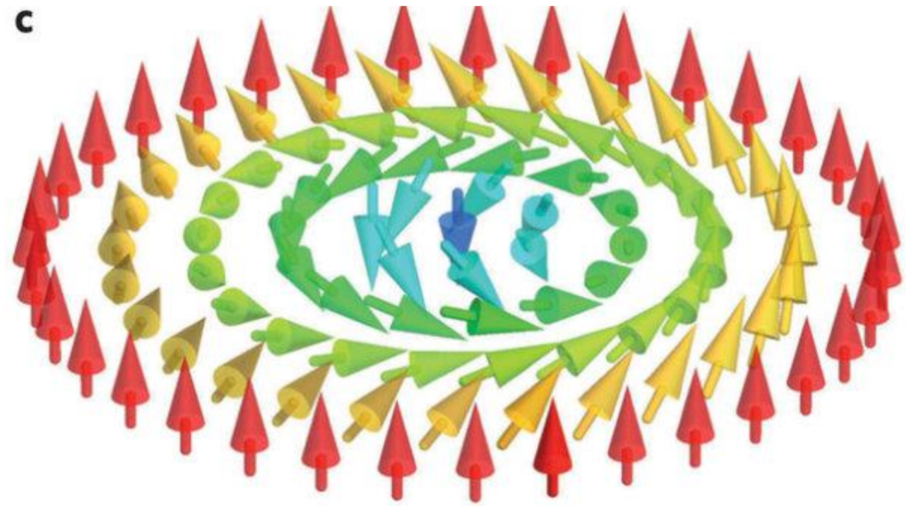
Compensated ferrimagnetic: **Mn-Pt-Ga, Mn-Co-Ga**







Stuart S. P. Parkin, et al.: *Magnetic Domain-Wall Racetrack Memory*, *Science* 320 (2008) 190–194



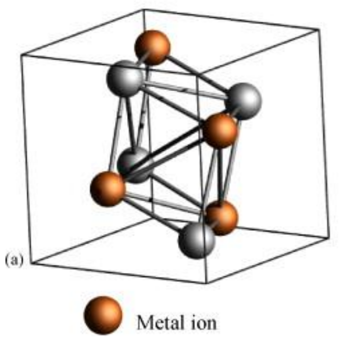
Skyrmions on the track

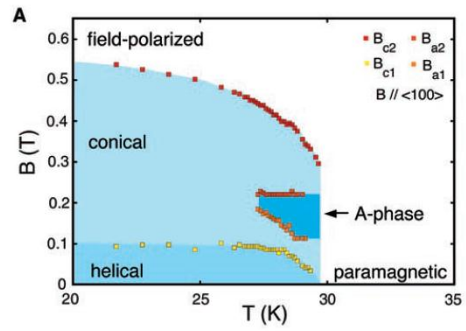
Albert Fert, Vincent Cros and João Sampaio

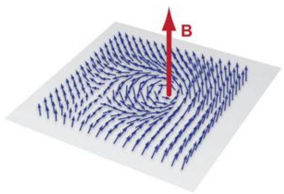
Magnetic skyrmions are nanoscale spin configurations that hold promise as information carriers in ultradense memory and logic devices owing to the extremely low spin-polarized currents needed to move them.

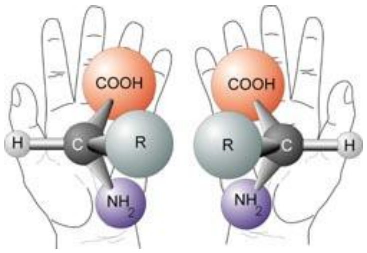
Recipe

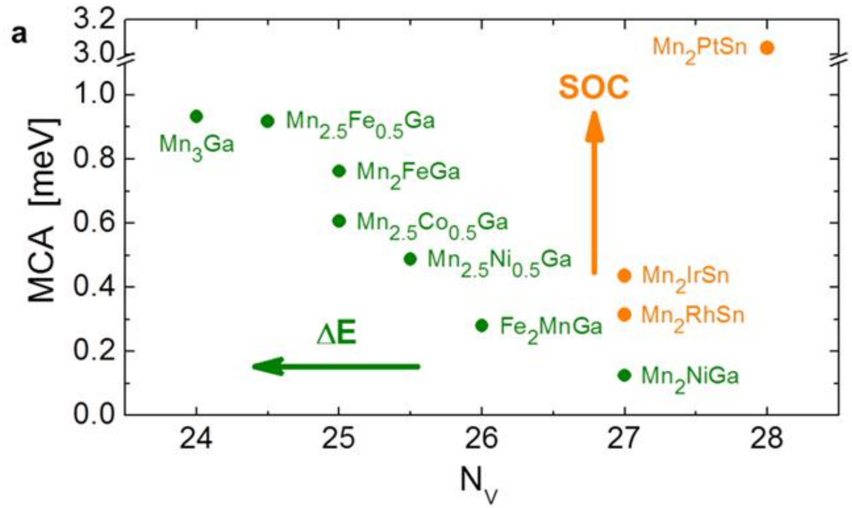
- Large spin orbit coupling
- Dzyaloshinsky–Moriya interaction
  - Non centro symmetric structure
  - Helical magnetism
- Topology: Berry phase in real space
- RT Skyrmions – high T_C
- Skyrmion in zero field via high magneto crystalline anisotropy
- For data storage: bulk materials





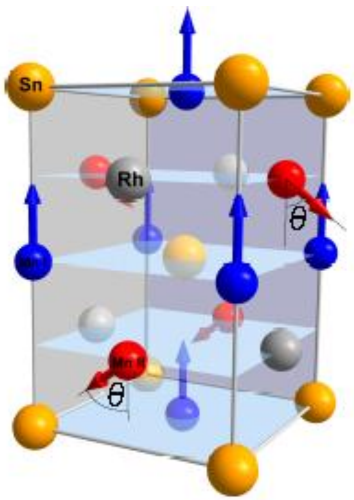


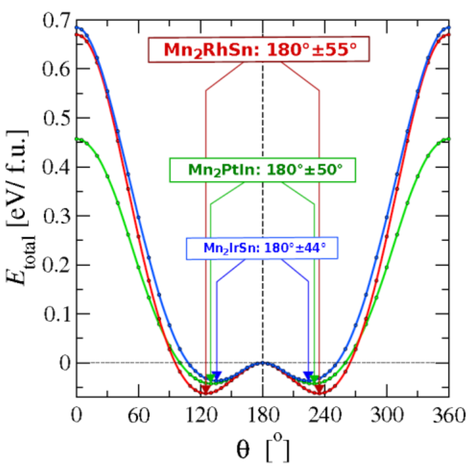


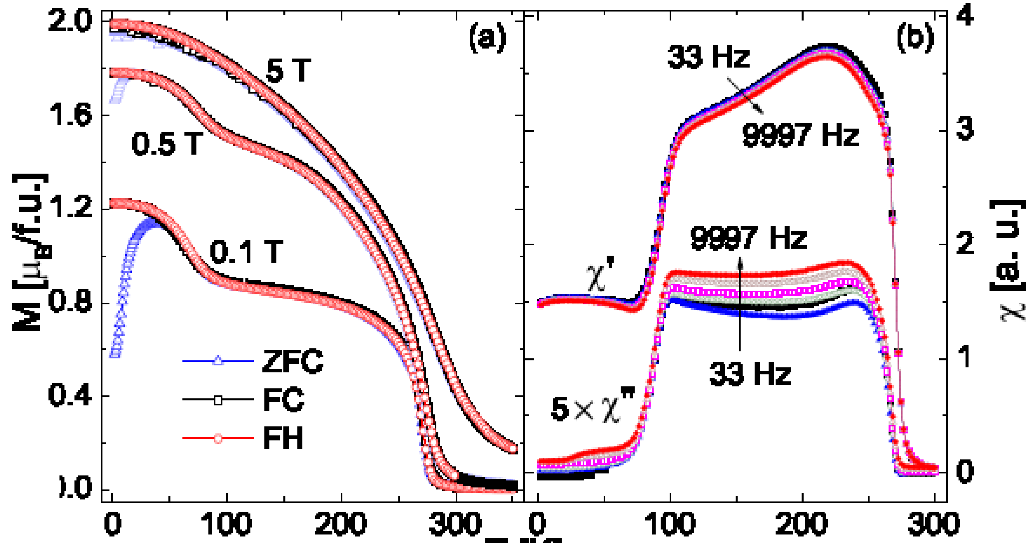


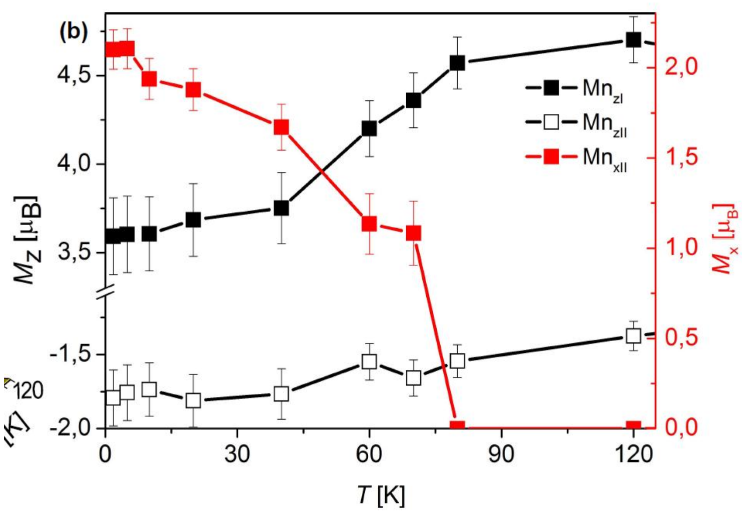
Skyrmions, C. Felser, Angewandte Chemie 125 (2013) 1673, Int. Ed. 52 (2013) 1631

Mn_2RhSn – non collinear magnet



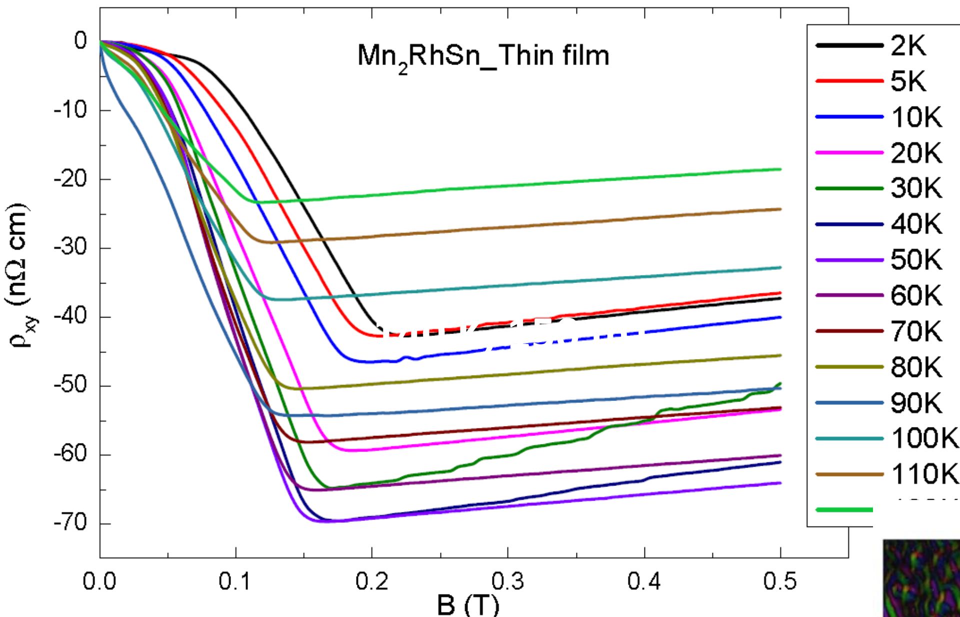


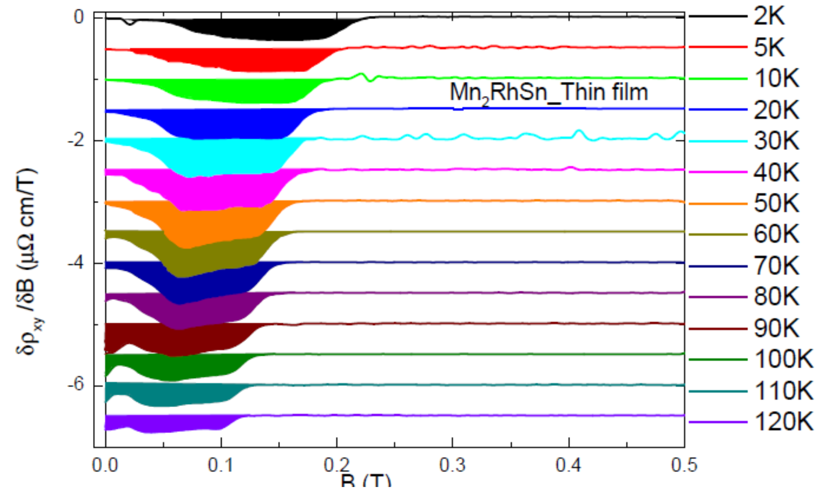


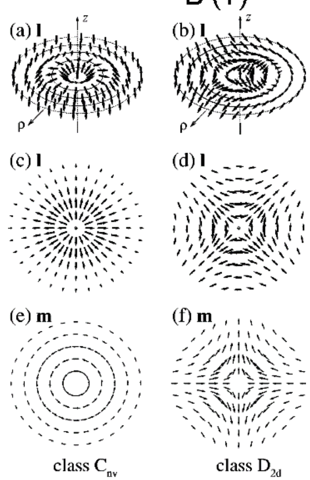


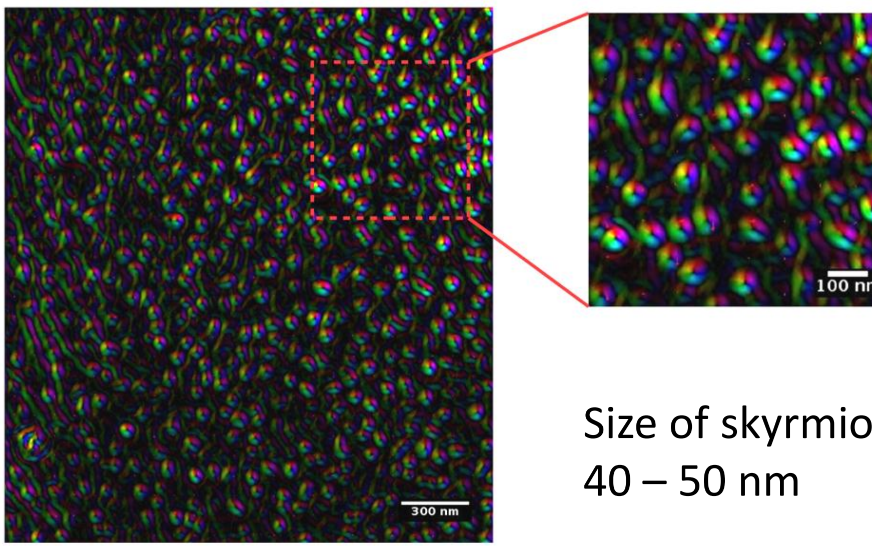
O. Meshcheriakova et al. Phys.Rev.Lett. 113 (2014) 087203, preprint arxiv:1404.4581

Skyrmions







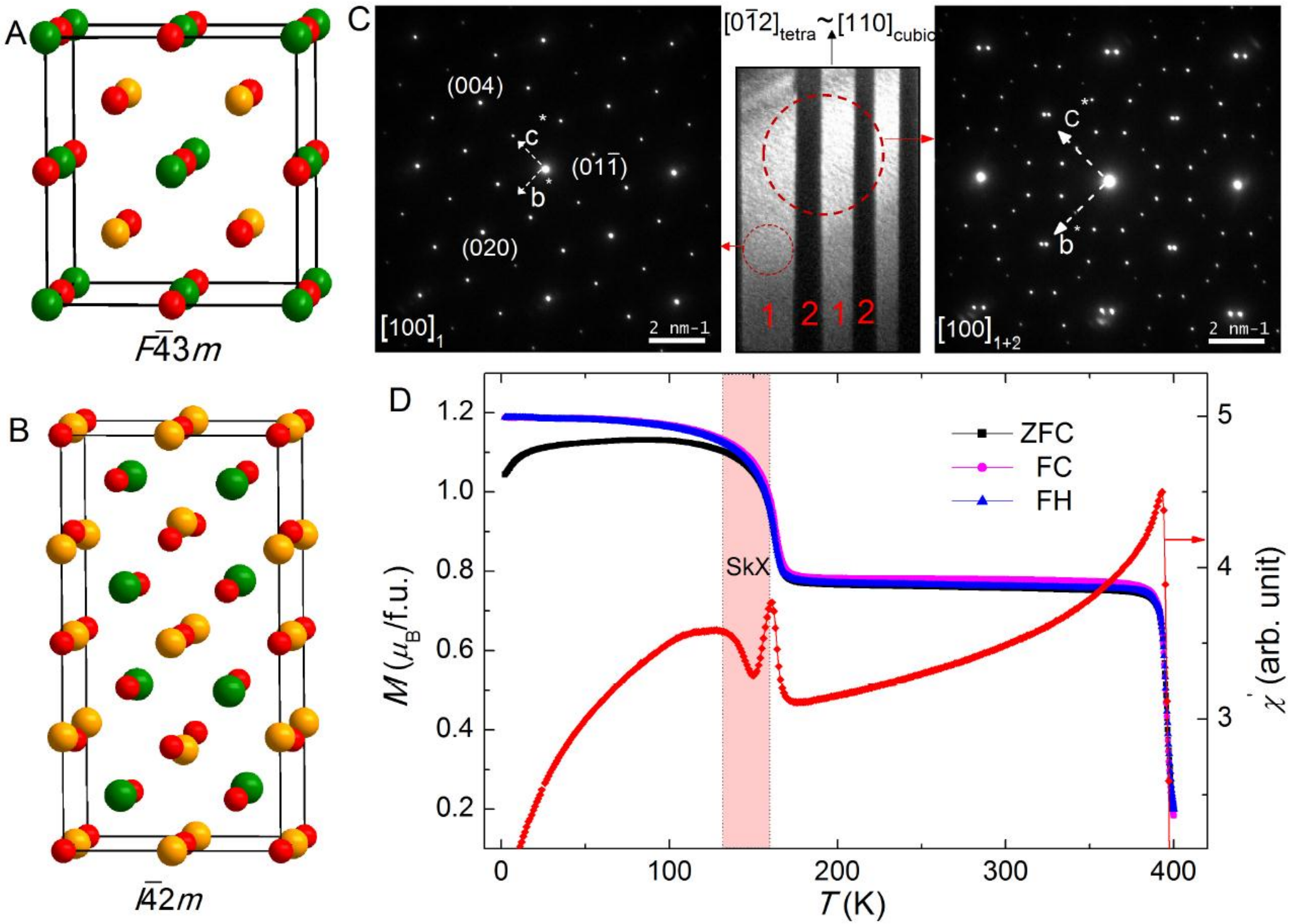


Size of skyrmion ~ 40 – 50 nm

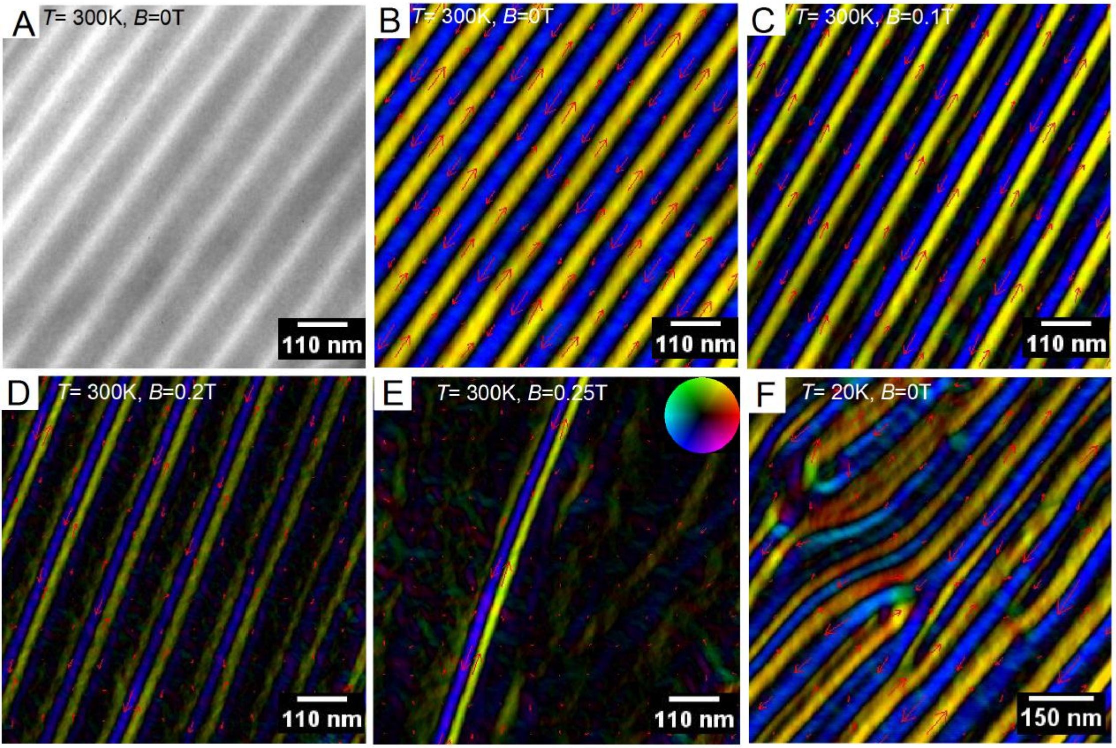
Bogdanov et al PRB **66**, 214410 (2002)

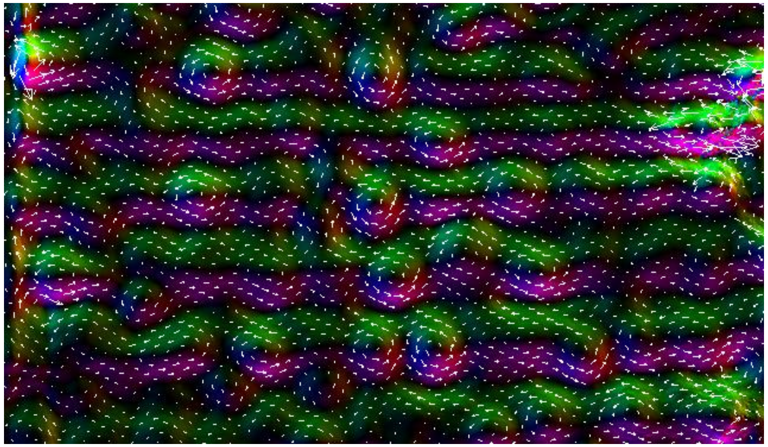
Ajaya K. Nayak and O. Meshcheriakova et al. unpublished (2015)

Mn-Pt-Sn – Skyrmions



Ajaya K. Nayak et al. under review (2015)





- The infocus Lorentz TEM image shows the structural microstructure (martensitic like plates).
- The stripes in the out of focus images correspond to the helical magnetic structure.
- They disappear completely for fields > 0.3 T.
- The helix propagates along [110].

Graf, Felser, Parkin, IEEE TRANSACTIONS ON MAGNETICS 47 (2011) 367
Graf, Felser, Parkin, Progress in Solid State Chemistry 39 (2011) 1