Naëmi Leo

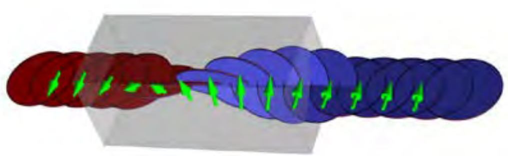
Multiferroic domains: Bulk and Boundaries

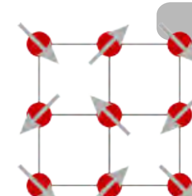
“Topology matters”, July 25th-28th 2017, Mainz

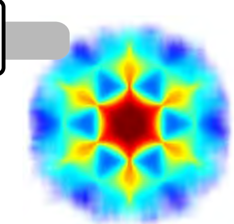
universitätbonn

ETH Zürich

PAUL SCHERRER INSTITUT PSI







Multiferroics: Bulk and Boundaries

1 – Ferroics and Multiferroic Materials

2 – Multiferroics: The Mesoscopic Scale

3 – Domain Coupling in Mn_2GeO_4

4 – Multiferroic Boundaries in $Co_{0.05}Mn_{0.95}WO_4$

5 – Next directions

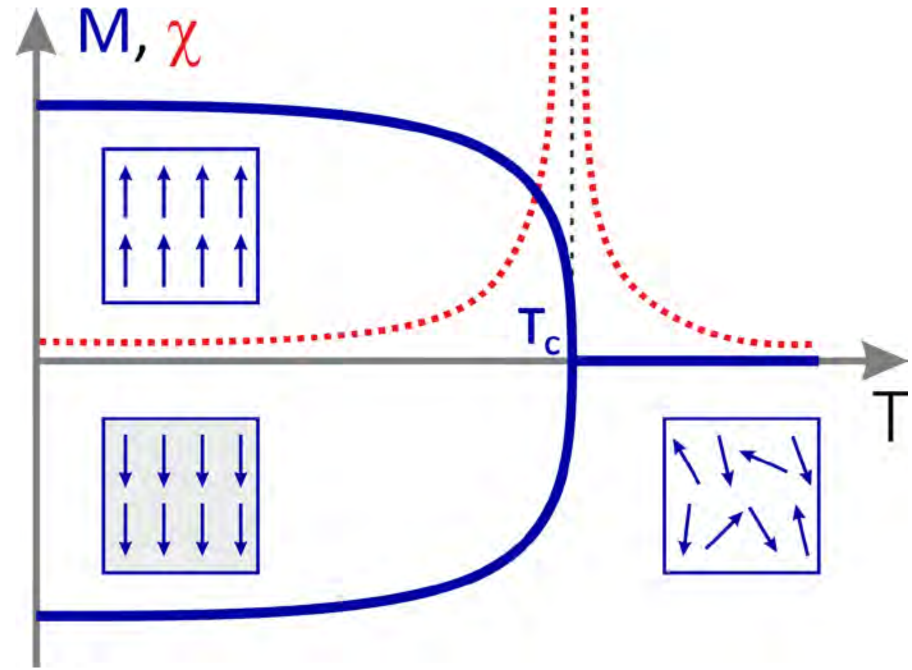
1 – Ferroic and Multiferroic Materials

Ferroic Phase Transitions

Symmetry-breaking spontaneous long-range order

$\Rightarrow$ Emergent tensor properties

$\Rightarrow$ Formation of domains

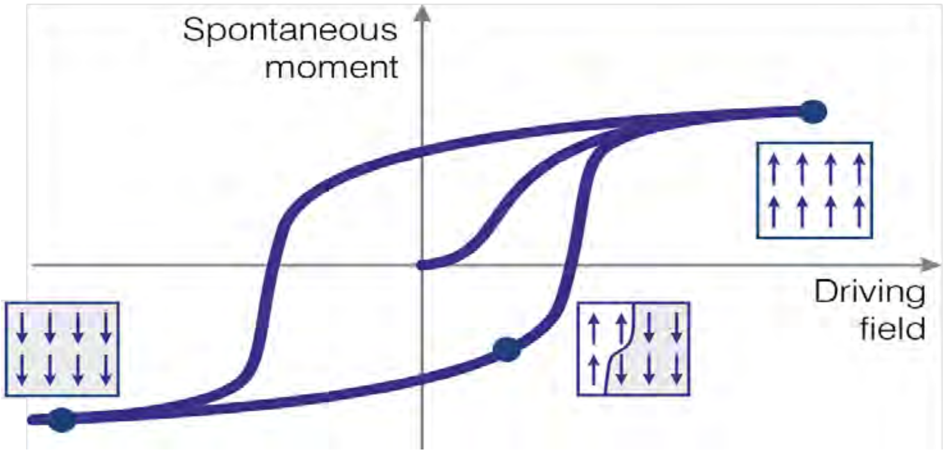


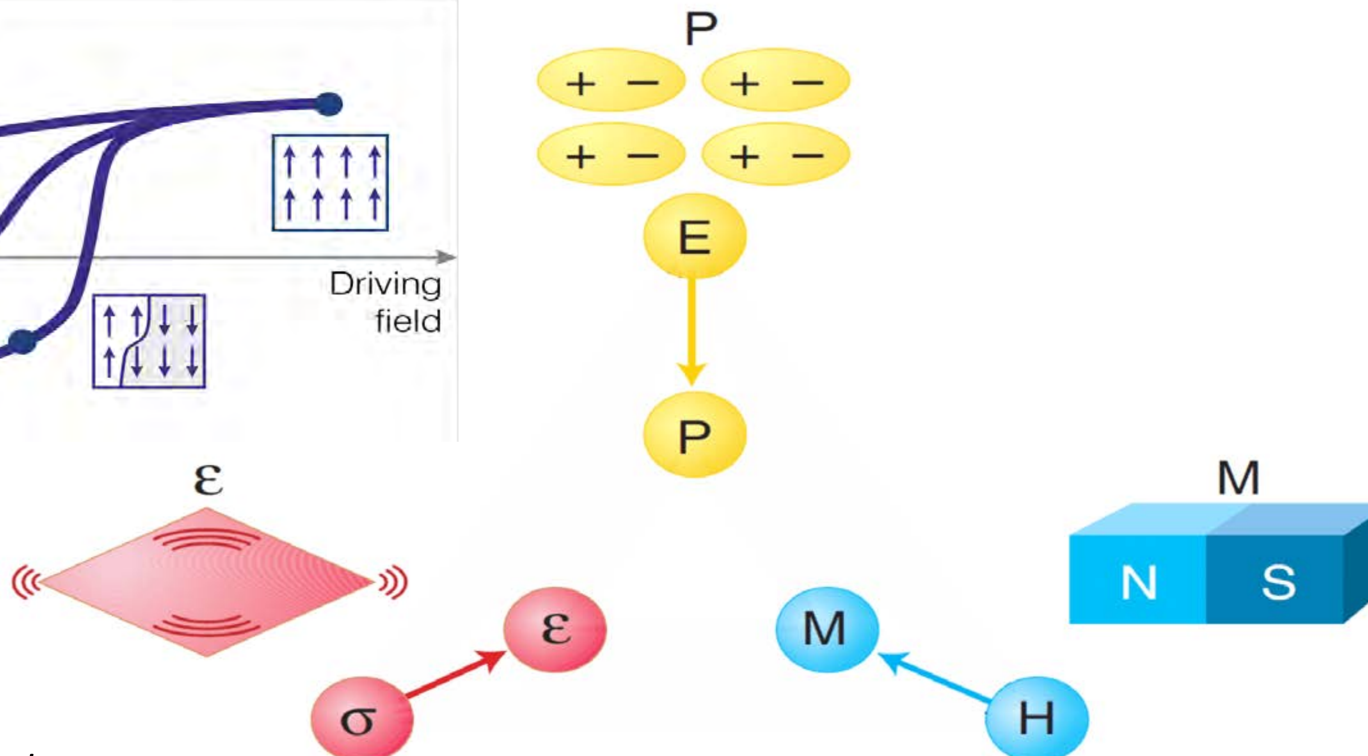
V. Wadhawan, *Introduction to Ferroic Materials*, CRC Press (2000)

H. Schmid, J. Phys. Cond. Mat. **20** 434201 (2008)

N. Spaldin & M. Fiebig, Science **309** 391 (2005)

Primary Ferroics and Ferroic Domain Switching





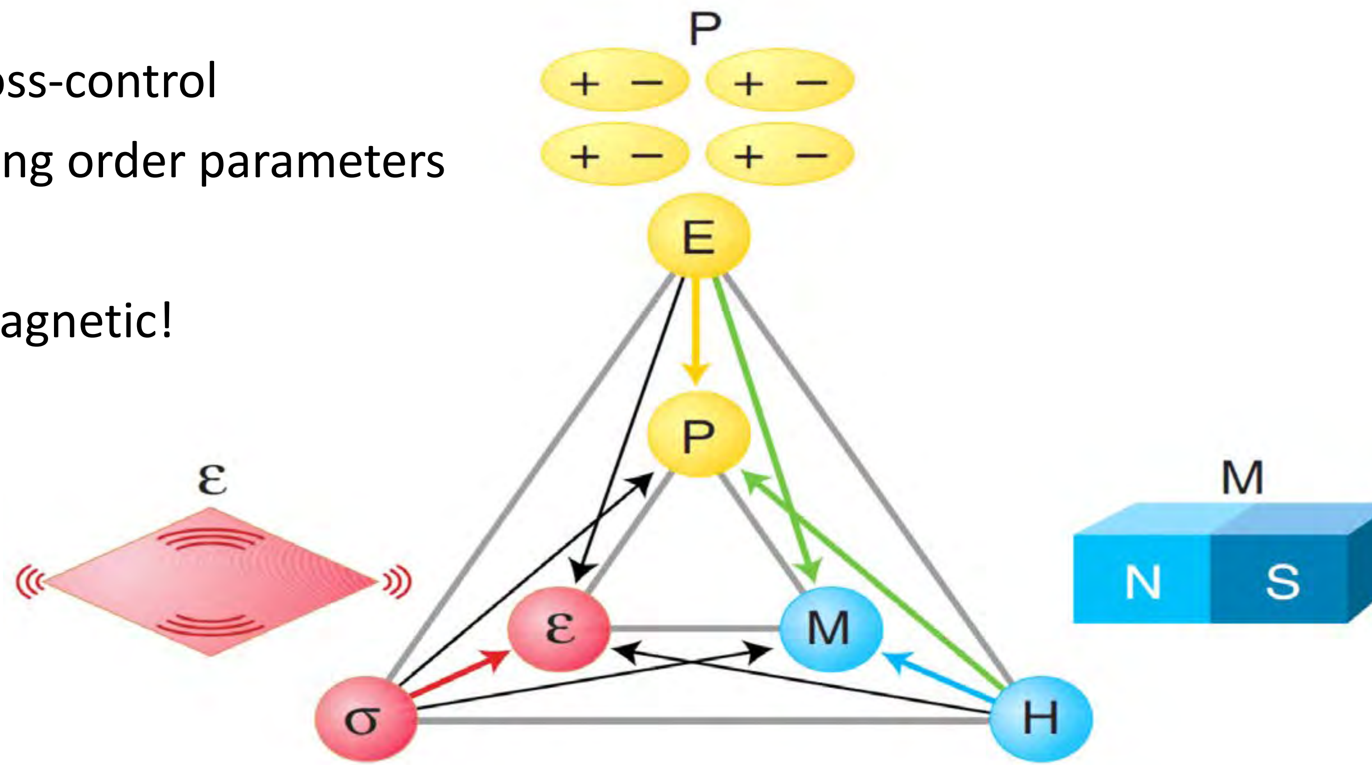
V. Wadhawan, *Introduction to Ferroic Materials*, CRC Press (2000)
H. Schmid, J. Phys. Cond. Mat. **20** 434201 (2008)
N. Spaldin & M. Fiebig, Science **309** 391 (2005)

Magnetoelectric Multiferroics

Magnetoelectric: Cross-control

Multiferroic: Coexisting order parameters

Often are antiferromagnetic!



N.A. Hill, J. Phys. Chem. B **104** 6694 (2000)

M. Fiebig, J. Phys. D **38** R123 (2005)

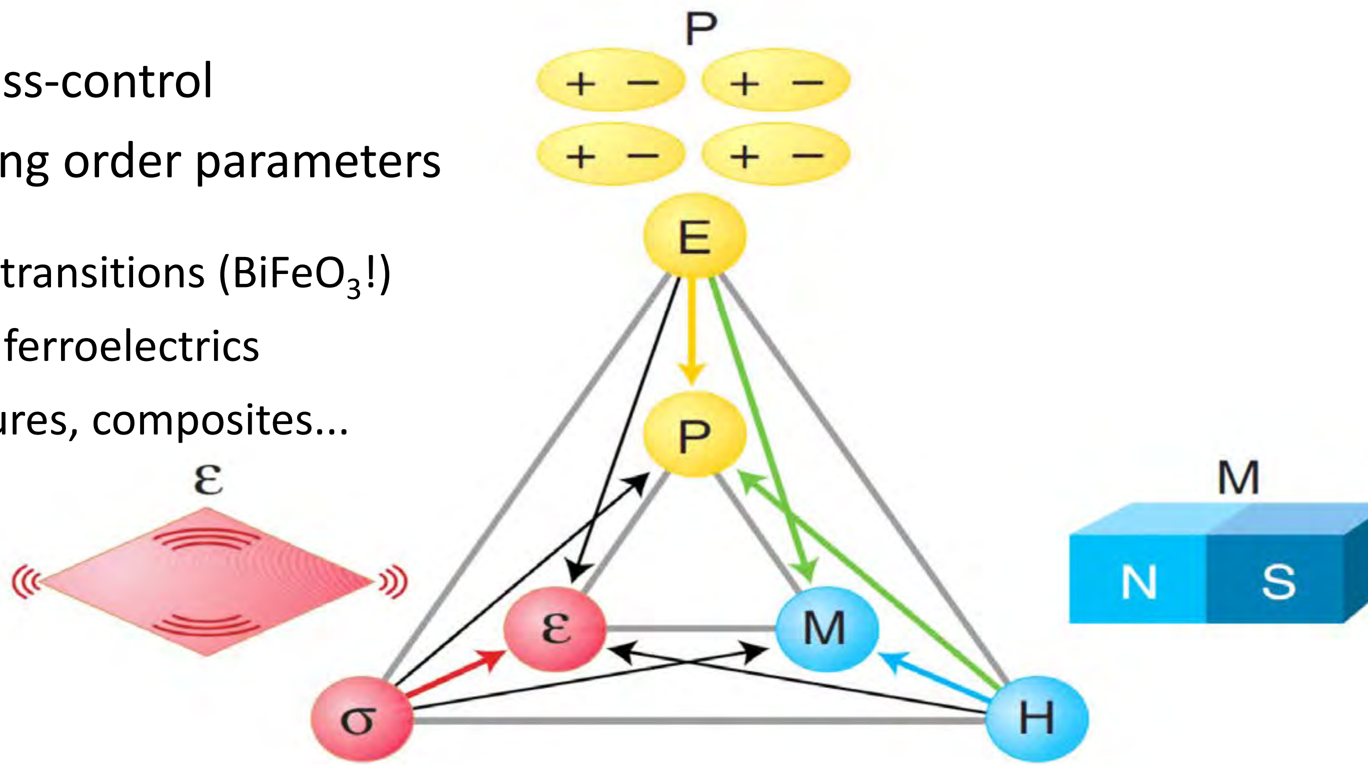
N. Spaldin & M. Fiebig, Science **309** 391 (2005)

Magnetoelectric Multiferroics

Magnetoelectric: Cross-control

Multiferroic: Coexisting order parameters

Type I	Independent transitions ($BiFeO_3$!)
Type II	Spin-induced ferroelectrics
Artificial	Heterostructures, composites...



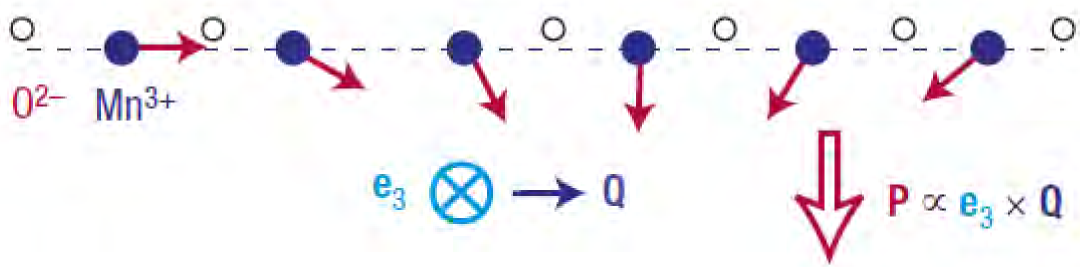
K. Wang *et al.*, Adv. Phys. **58** 321 (2009)

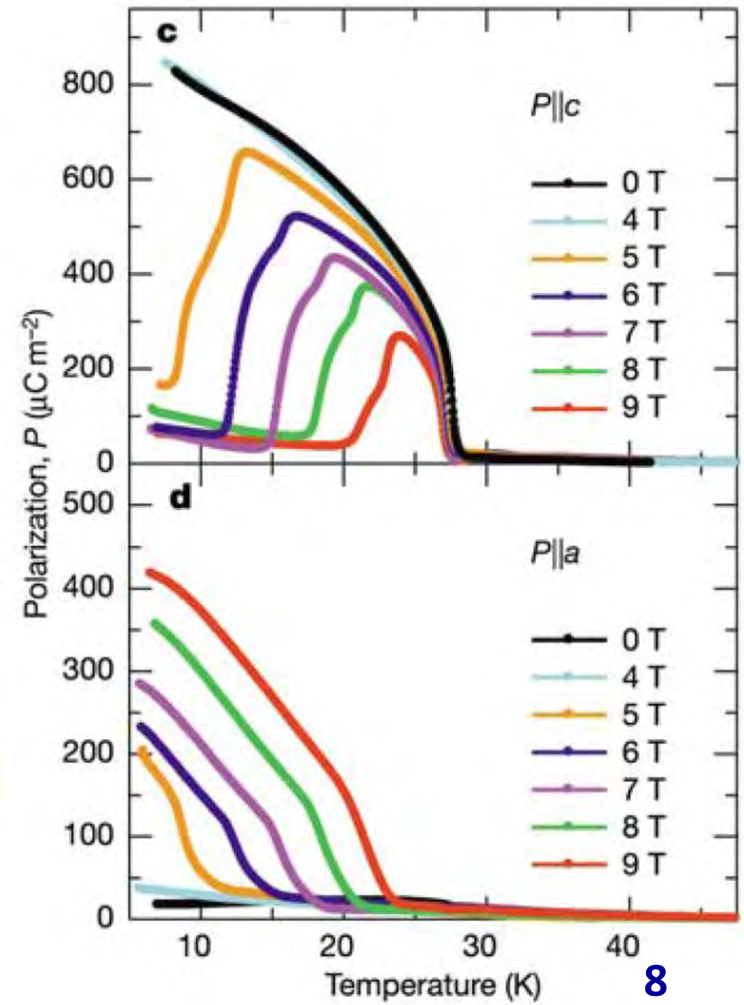
M. Fiebig *et al.*, Nature Rev. Mater. **1** 16046 (2016)

Type II Multiferroics: Spin-Induced Ferroelectrics

$TbMnO_3$: T_N = 42 K, $T_{C,P}$ = 27 K, H_{flop} ~ 4.5 T
With cycloidal spin-spiral order

Allows for spin-induced
spontaneous ferroelectric polarisation



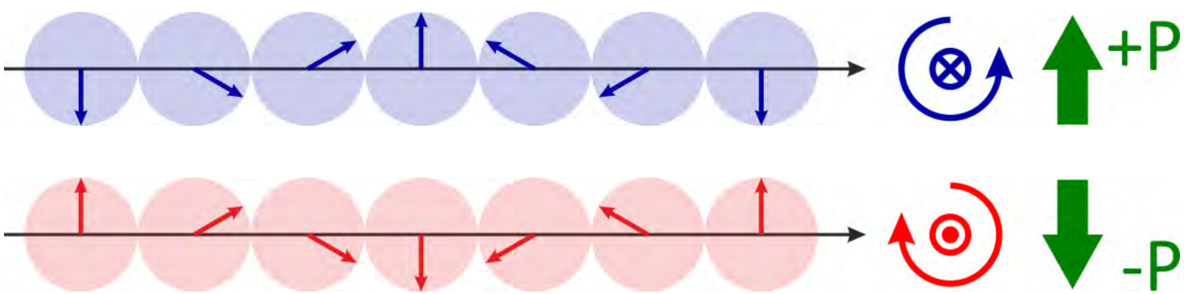


T. Kimura *et al.*, Nature **426**, 55 (2003)

Microscopic View: Spin-Induced Polarisation

Frustrated antiferromagnets (3*d*):
Modulated spin order breaks inversion symmetry

Allows for spin-induced
spontaneous ferroelectric polarisation



Bond angles

Bond length

Orbital
redistribution

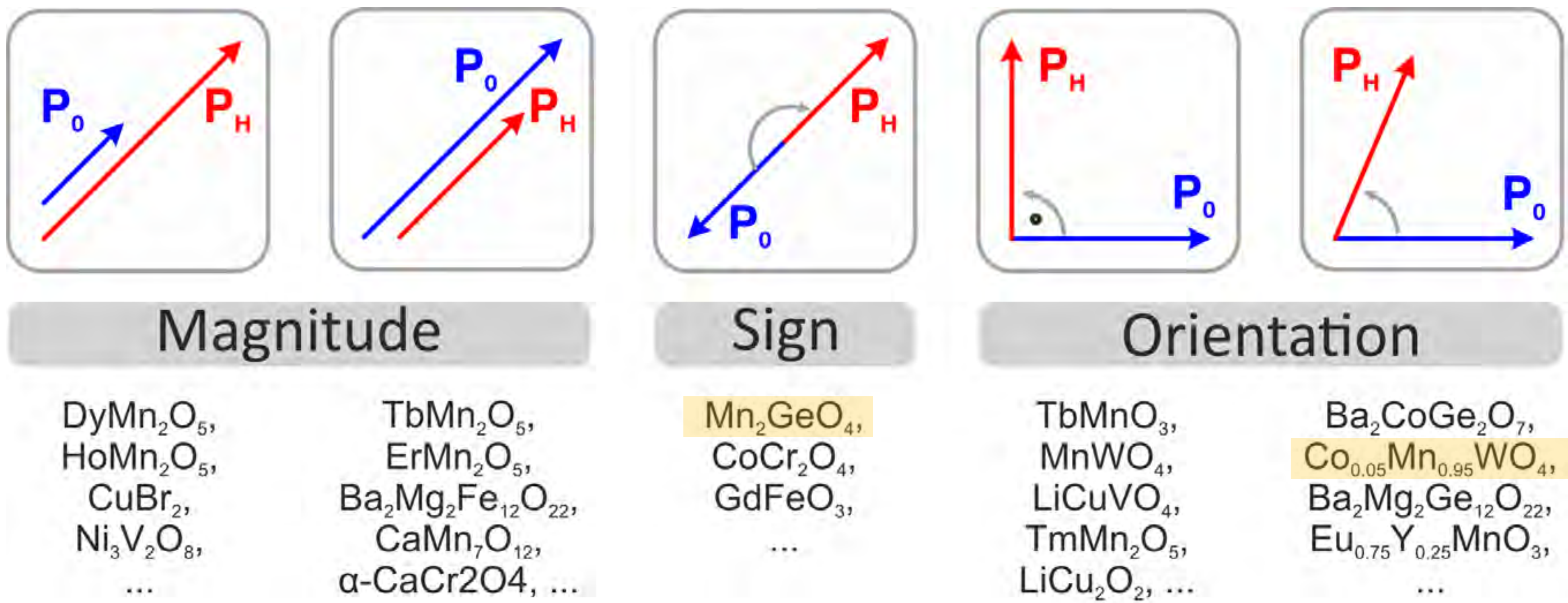
S.-W. Cheong and M. Mostovoy, Nat. Mater. **6** 13 (2007)

T. Kimura, Annu. Rev. Mater. Res. **37** 387 (2007)

Y. Tokura, S. Seki & N. Nagaosa, Rep. Prog. Phys. **77** 076501 (2014)

M. Fiebig *et al.*, Nature Rev. Mater. **1** 16046 (2016)

Macroscopic View: Magnetic Polarisation Control

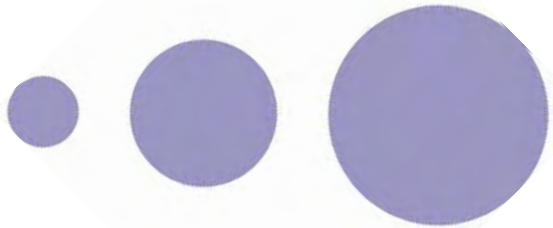


2 – Ferroics and Multiferroics:
The Mesoscopic Scale

Domains and Domain Walls

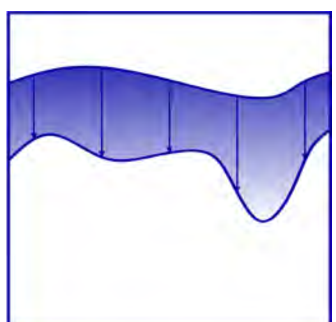
Bulk: Ferroic Domains

Domain size:

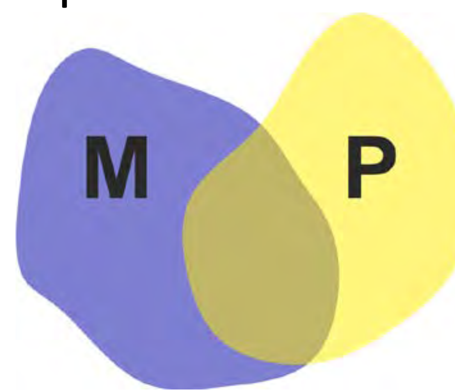


Domain morphology:

Domain dynamics:



Coupling of order parameters:



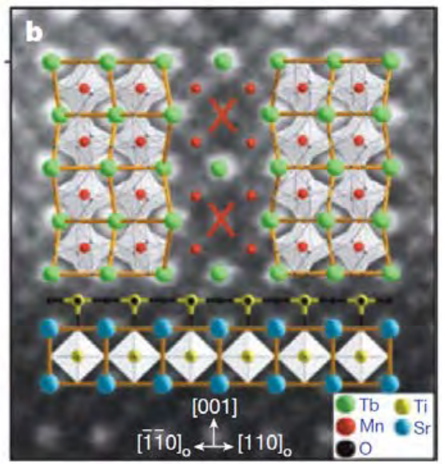
A. Hubert & R. Schäfer, *Magnetic Domains*, Springer (2009)

A. K. Tagantsev *et al.*, *Domains in ferroic crystals and thin films*, Springer (2010)

Boundaries: Ferroics domain walls

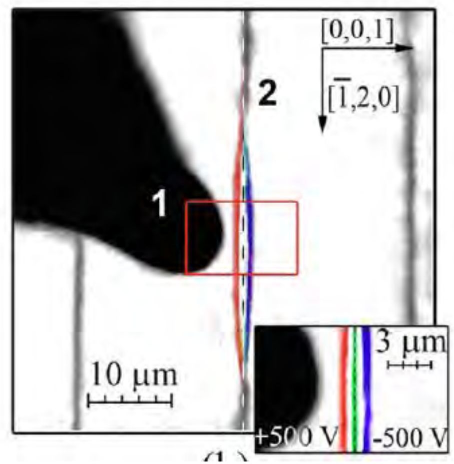
Domain walls: Localised, movable environments with novel properties

chemical



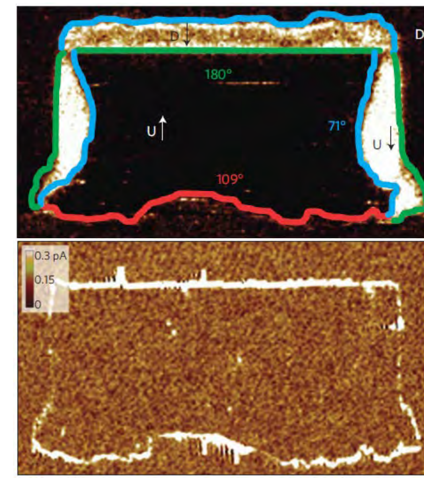
S. Farokhipoor *et al.*,
Nature **515** 379 (2014)

symmetry



A. Logginov et al.,
Appl. Phys. Lett. **93** 182510 (2008)

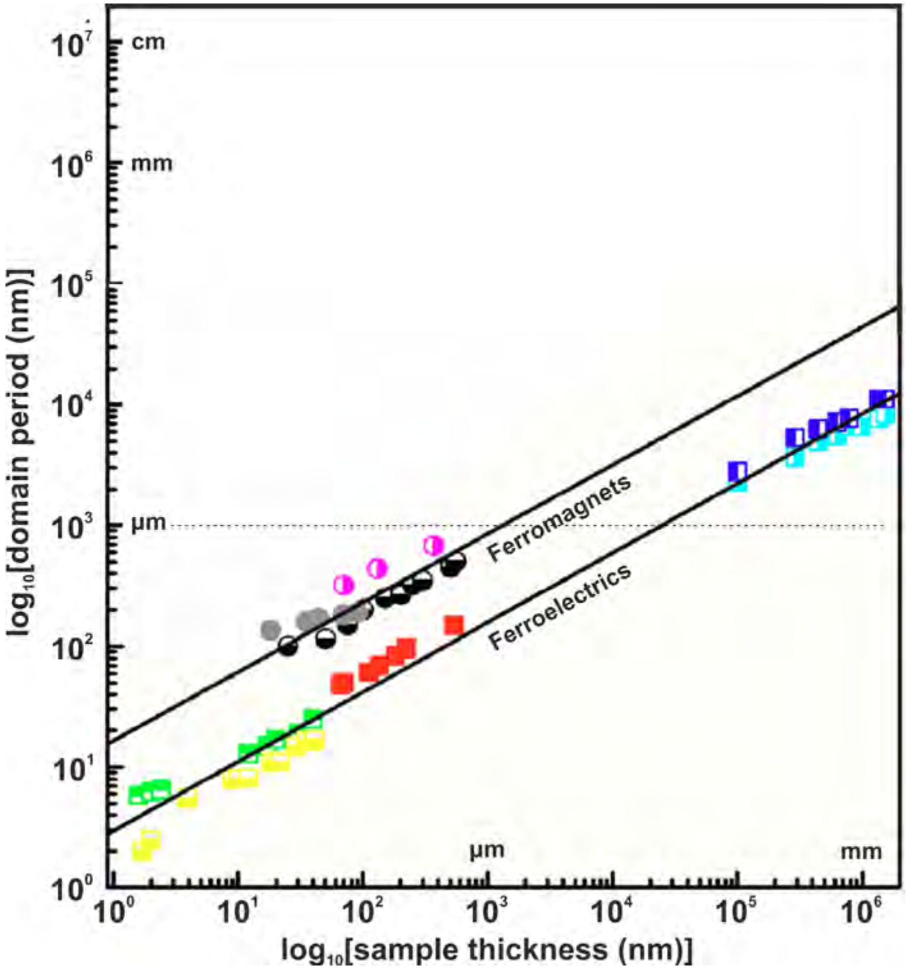
electronic



J. Seidel *at al.*,
Nature Mater. **8** 229 (2009)

G. Catalan *et al.*, Rev. Mod. Phys. **84** 119 (2012)
E. Salje & H. Zhang, Phase Trans. **82** 452 (2009)

Kittel Law: Domain Size vs. Sample Thickness



Kittel law:

domain size ~ (sample thickness)$^{\alpha}$
with α ~ 0.5

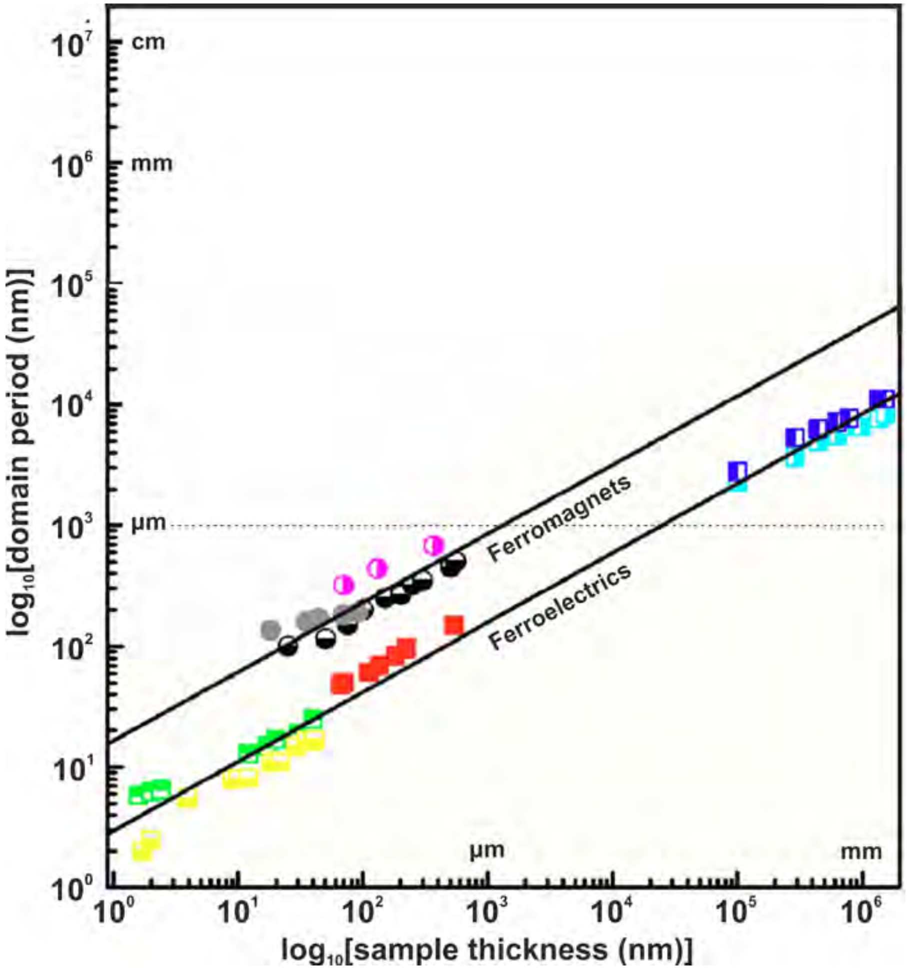
C. Kittel. Rev. Mod. Phys. **21**, 541 (1949)

M. Seul & D. Andelman, Science **267** 476 (1995)

Figure adapted from

A.Schilling *et al.*, Phys. Rev. B **74**, 024115 (2006)

Kittel Law: Domain Size vs. Sample Thickness



Kittel law:

domain size ~ (sample thickness)$^{\alpha}$

with α ~ 0.5

Antiferromagnetic domains?

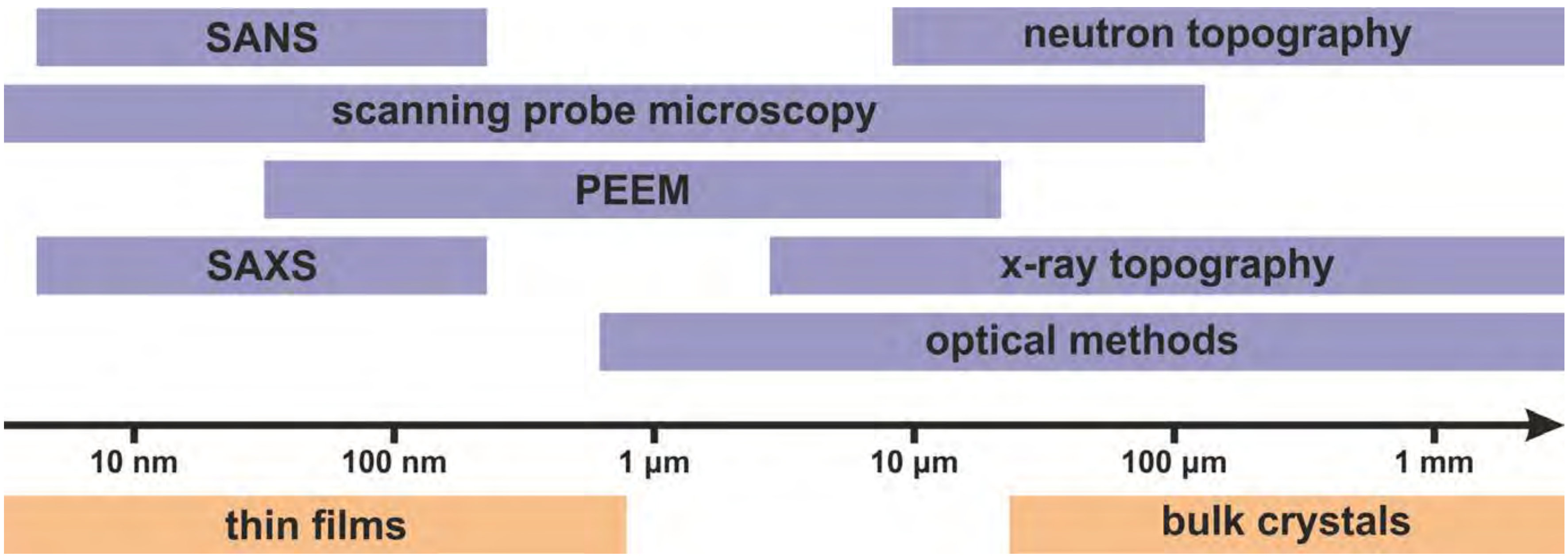
- 180° domains (time reversal)
- Configurational domains (**q**)
- Orientational domains (**S**)
- Chirality domains
- Secondary order parameters

Figure adapted from

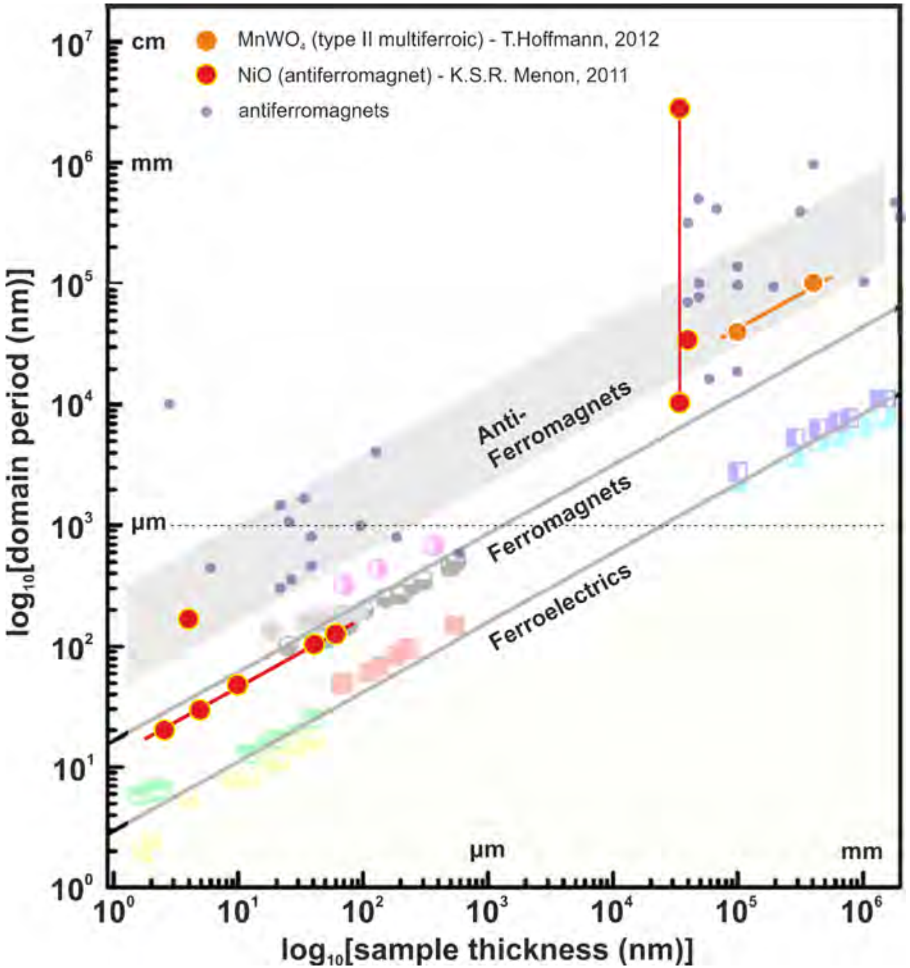
A.Schilling *et al.*, Phys. Rev. B **74**, 024115 (2006)

Measuring Antiferromagnetic Domains

Incomplete list of experimental methods to detect antiferromagnetic domains:



Kittel Law: Domain Size vs. Sample Thickness



Kittel law:

domain size ~ (sample thickness)$^{\alpha}$
with α ~ 0.5

Antiferromagnetic domains are larger...

Figure adapted from
A.Schilling *et al.*, Phys. Rev. B **74**, 024115 (2006)