

Complex Ordering Phenomena in Multifunctional Oxides at the Peter Grünberg Institute

Manuel Angst

Peter Grünberg Institut PGI and Jülich Centre for Neutron Science JCNS,
JARA-FIT, Forschungszentrum Jülich GmbH

5th Georgian-German School and Workshop in Basic Science, Tbilisi, Aug 10, 2012

- Information Technology and the Peter Grünberg Institute
- Complex Ordering Phenomena in Multifunctional Oxides

- **Information Technology and the Peter Grünberg Institute**
- Complex Ordering Phenomena in Multifunctional Oxides

„Moore“ ...



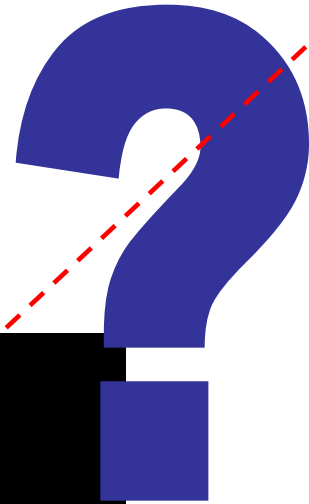
Transistors
/ Chip

Transistors / €

Computing speed

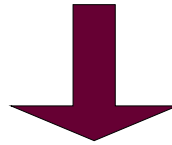
Memory capacity

Moore's Law:
doubling of
transistor density
every two years

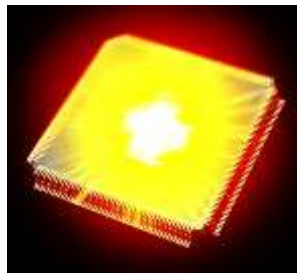


„Moore“ ?

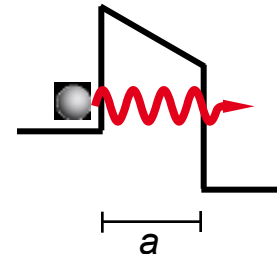
~ 2020-2030 : Structures over only few atoms



Fundamental limit reached



Waste-heat removal



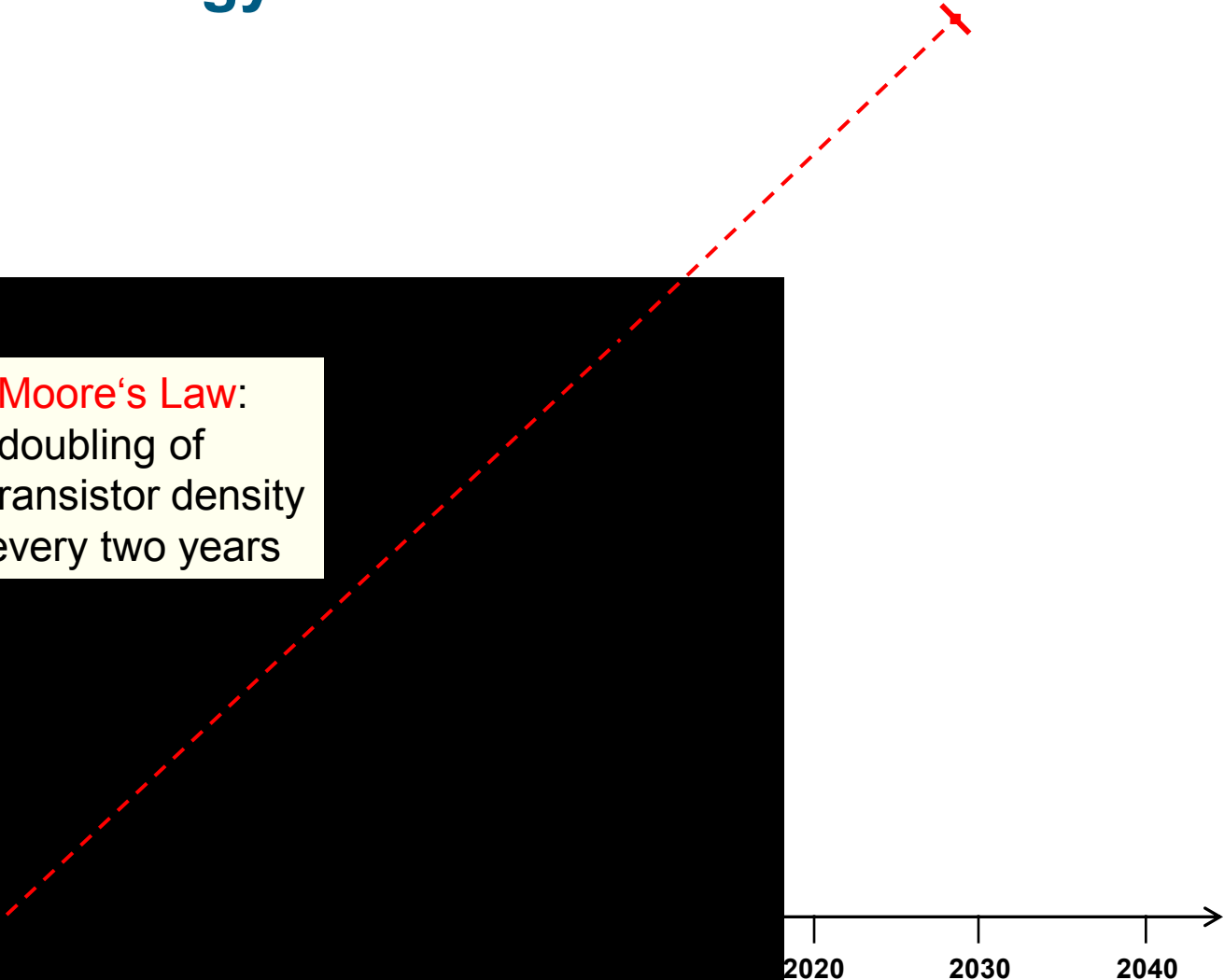
**Quantum mechanics
(tunneling)**

„Moore“ ?

Continuing „Moore“ will require completely new technology !

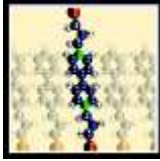
Transistoren / Chip

Moore's Law:
doubling of
transistor density
every two years

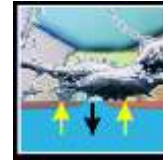


2020 2030 2040

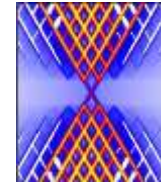
What after ?



**Single-molecule
junctions**



Bioelectronics



Quantum dots



**Phase-change
memories**



Spintronics



**Molecular
magnets**

Etc .. Etc..

Completely unclear which concepts will succeed

Peter Grünberg Institute

Mission: Fundamental research for future information technologies
novel physical concepts, emerging materials

Created 2011 out of divisions from
the former IFF (Institut für Festkörperforschung – solid state physics)
and from the former Institute of Bio- and Nanosystems IBN

Quantum Theory of Materials – S. Blügel

(Computational Physics-1)

– D. DiVincenzo

(Computational Physics-3)

Surfaces – S. Tautz

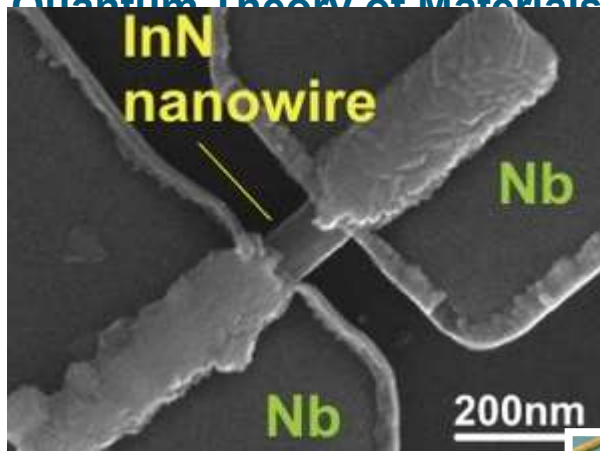
Electronics

(Computational Physics-2)

Neutron/X-ray Scattering – Dunin-Borkowski

Theory

Neutron/x-ray



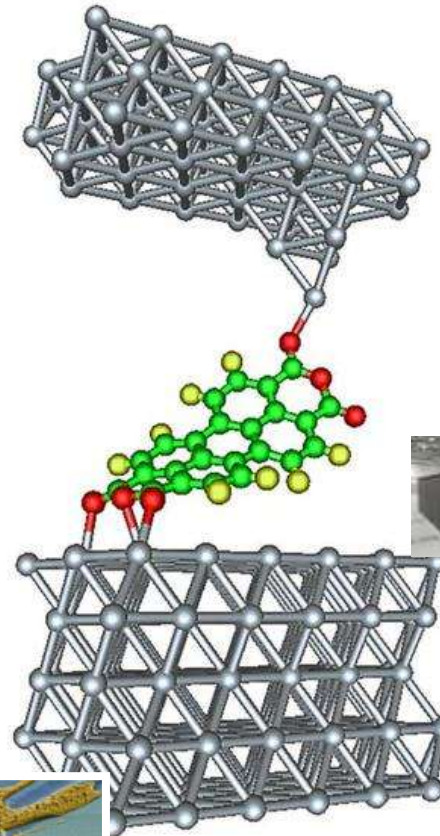
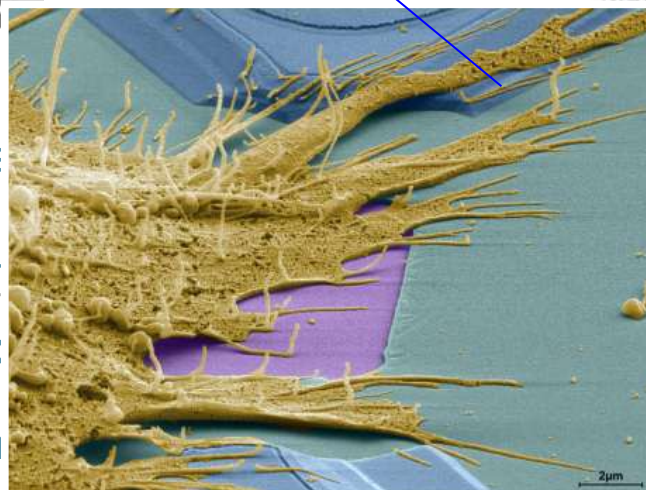
Electronic Properties – C. M. Schneider (PGI-6)

Electronic Materials – R. W. Fechner (PGI-7)

Bioelectronics – A. Offenhäuser (PGI-8 / Institute for Complex Systems)

Semiconductor Nanoelectronics (PGI-9)

Technical Services and Administration (PGI/JCNS-TA)



beyond

history



Ernst Ruska-Centre

Mission: Fundamental research for future information technology and beyond
novel physical concepts, emerging materials, ...

Created 2011 out of divisions from
the former IFF (Institut für Festkörperforschung – solid state research) with 40 years history
and from the former Institute of Bio- and Nanosystems.

Named after Peter Grünberg

Giant-Magnetoresistance „GMR“ – basis of spintronics



Photo: The Nobel Foundation 2007, Hans Mehlin



discovered 1988

Peter Grünberg



Albert Fert



Nobel price 2007

Mission: Fundamental research for future information technology and beyond
novel physical concepts, emerging materials, ...

Created 2011 out of divisions from
the former IFF (Institut für Festkörperforschung – solid state research) with 40 years history
and from the former Institute of Bio- and Nanosystems.

Named after Peter Grünberg

Close collaboration with RWTH Aachen in the **Jülich-Aachen Research Alliance JARA**

JARA|FIT

**Excellence University
RWTH Aachen**

Fundamentals of Future
Information Technology



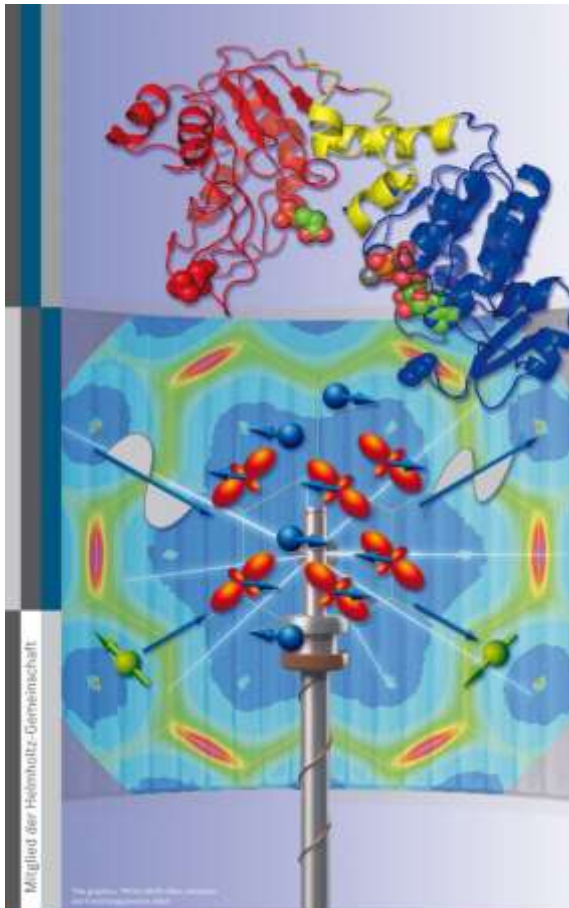
Distance: 35 km



JARA foundation: 06.08.2007

se
ys
from
tkö
f E
er
ac
IF

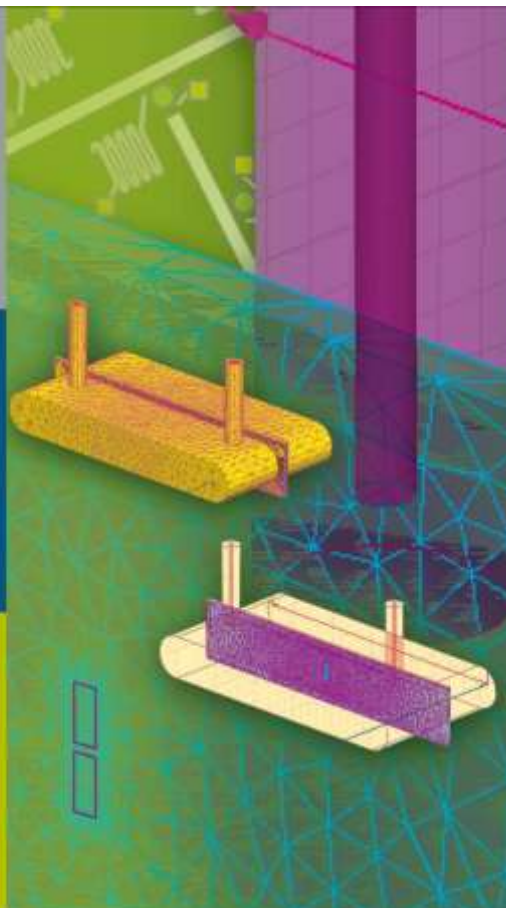
in technology and beyond
materials, ...



Scattering Methods for Condensed Matter Research: Towards Novel Applications at Future Sources

43rd IFF Spring School 2012

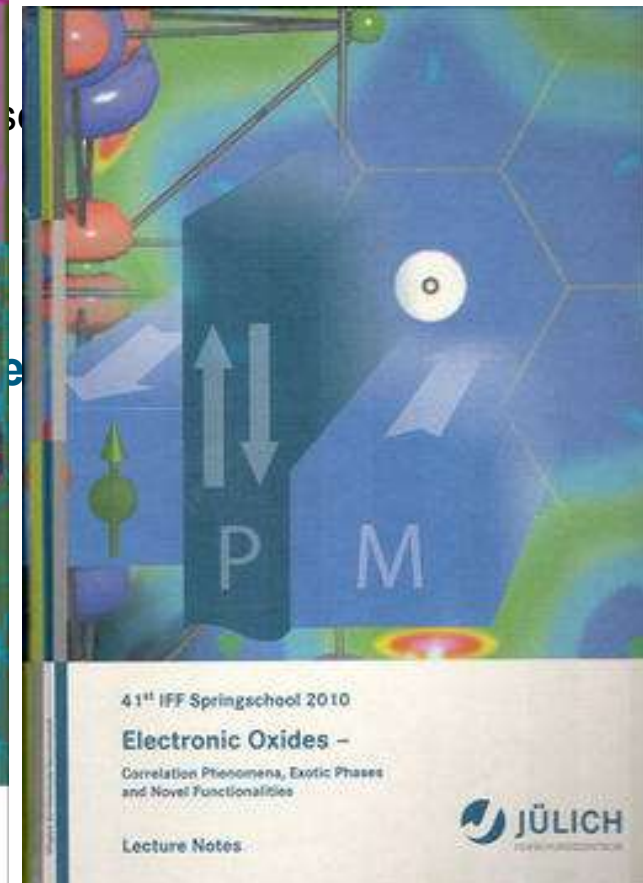
March 5 – 16, 2012
Jülich, Germany



Quantum Information Processing

44th IFF Spring School 2013

February 25 – March 8, 2013 in Jülich, Germany



41st IFF Spring School 2010

Electronic Oxides –

Correlation Phenomena, Exotic Phases
and Novel Functionalities

Lecture Notes



Topic 1
**Frontiers of
charge based
electronics**

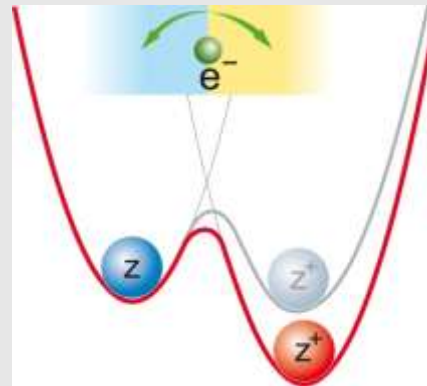


Topic 2
Spin
and
info

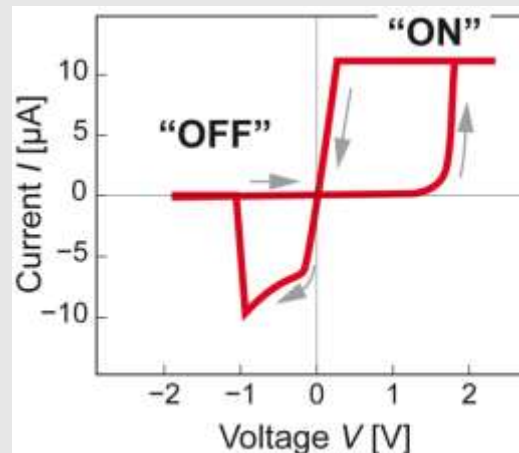


Peter
Grünberg
Centre

■ **State variable =
redox-active ions**



■ **Bipolar switching**



Topic 4
Laboratory
experiments and
phenomena

Each Topic

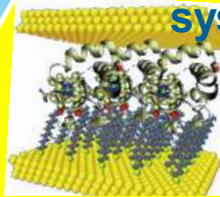
Topic 1
**Frontiers of
charge based
electronics**



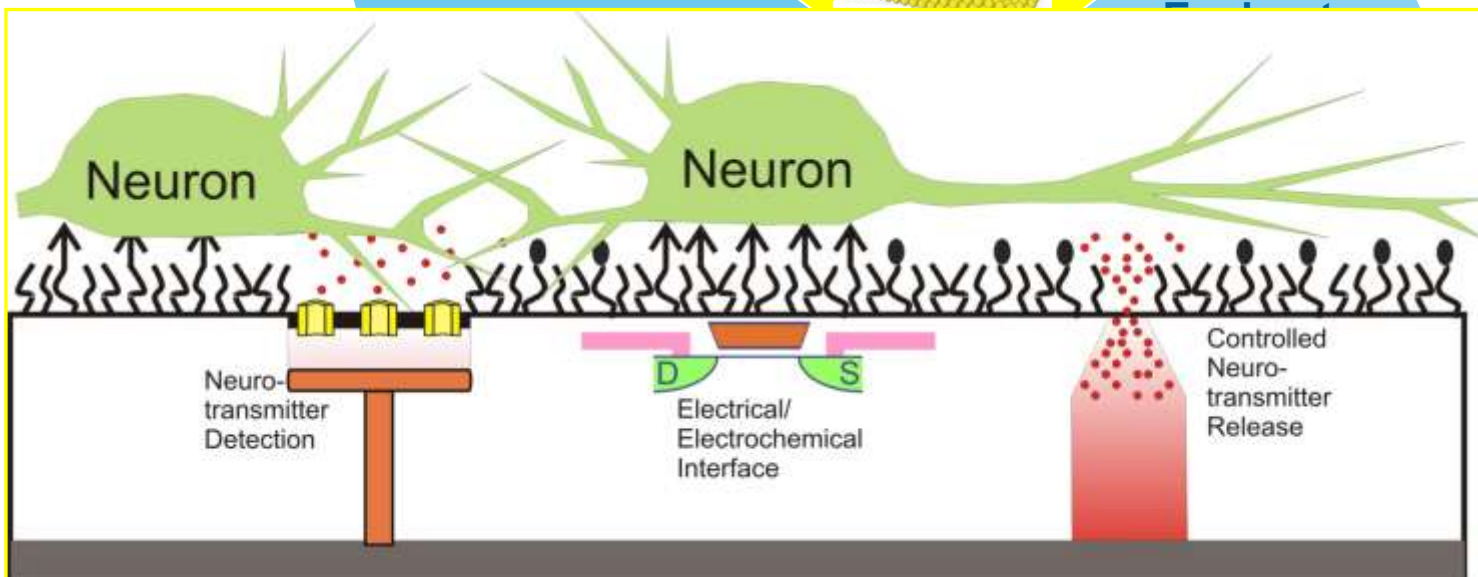
Topic 2
**Spin-based
and quantum
information**

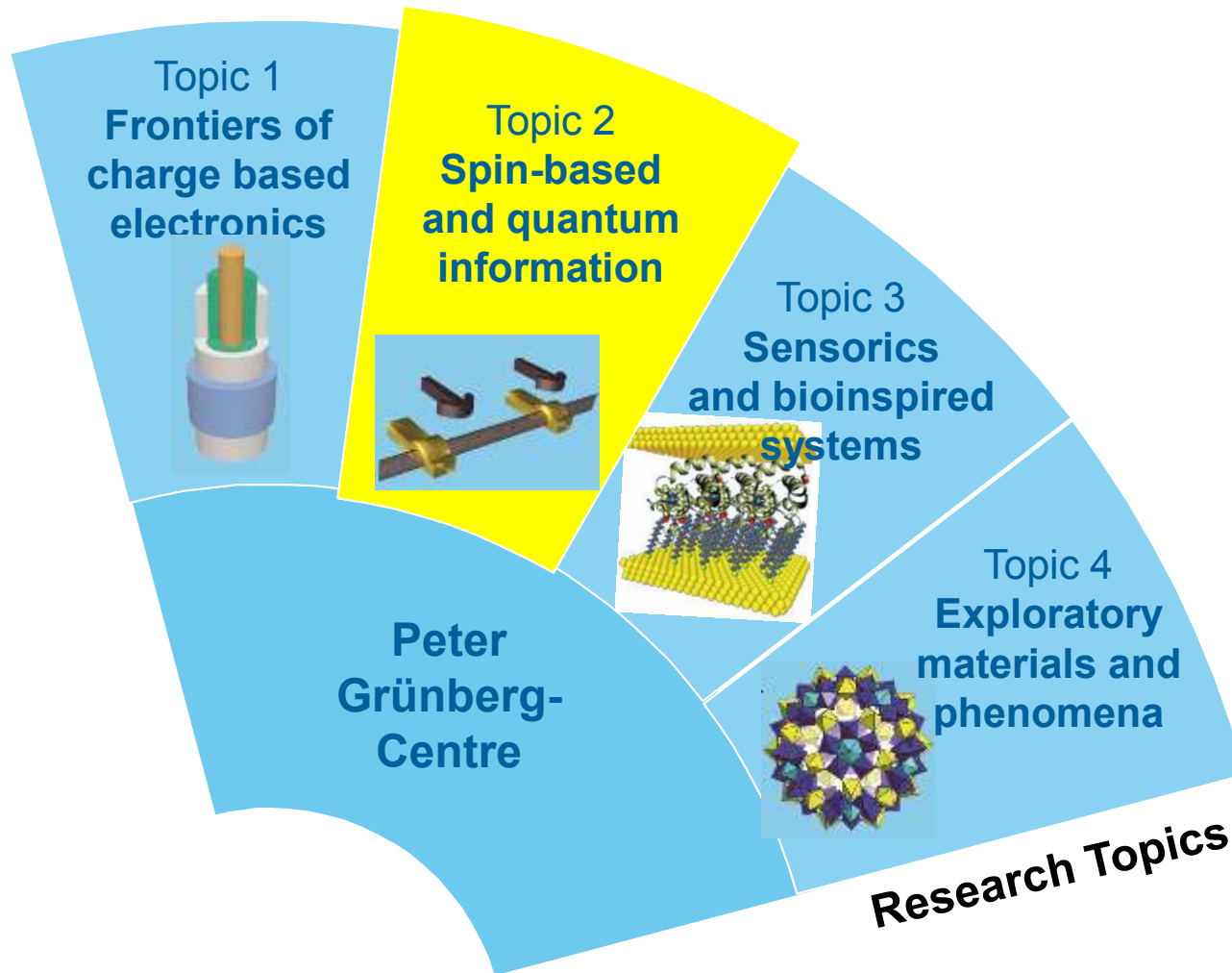


Topic 3
**Sensorics
and bioinspired
systems**



Topic 4





- Information Technology and the Peter Grünberg Institute
- **Complex Ordering Phenomena in Multifunctional Oxides**

Complex ordering phenomena in multi-functional oxides

Young-Investigators-Group funded by Helmholtz association,
part of the institute of scattering methods PGI-4 & JCNS-2 (director Th. Brückel)



Manuel Angst
Group leader



Joost de Groot
PhD student



Shilpa Adiga
PhD student



Pankaj Thakuria
PhD student

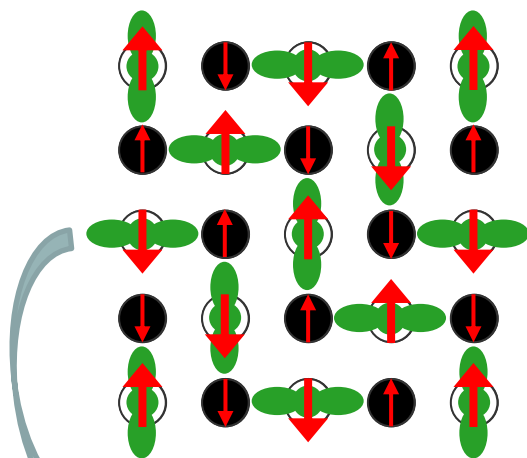


Thomas Müller
Diploma student



Hailey Williamson
Master student

Partner-University



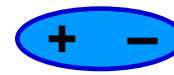
Scattering methods

E.g.



\vec{M}

&



\vec{P}

...

Today :

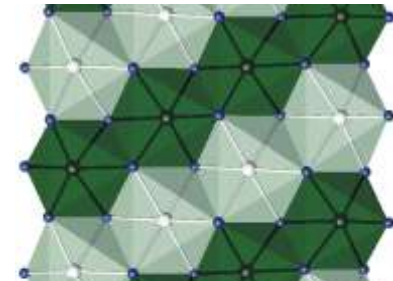
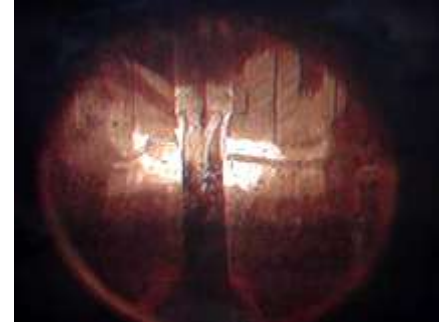
Silicon

Tomorrow :

Oxides ?

Modus Operandi

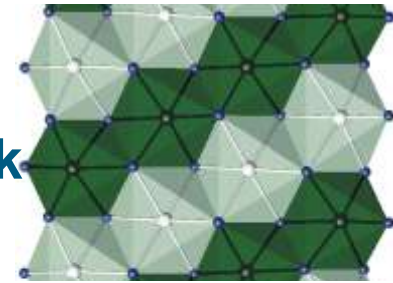
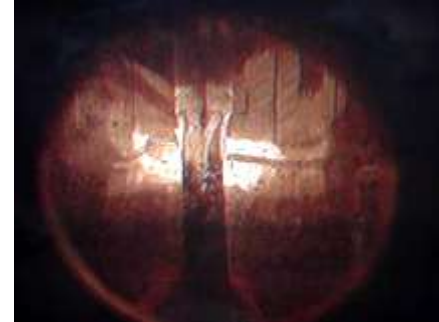
- **Exploratory synthesis** and crystal growth.
- Target **model materials** to understand fundamental processes behind functions.
- **In-house characterization**
(Diffraction, Macroscopic Properties).
- Discern detailed electronic ordering and excitations at remote **neutron/synchrotron** facilities
- Pursue **collaborations** for further in-depth studies, e.g. spectroscopy.



Modus Operandi

- **Exploratory synthesis** and crystal growth.
- Target **model materials** to understand fundamental processes behind functions.
- **In-house characterization**
(Diffraction, Macroscopic Properties).
- Discern detailed electronic ordering and excitations at remote **neutron/synchrotron** facilities
- Pursue **collaborations** for further in-depth studies, e.g. spectroscopy.

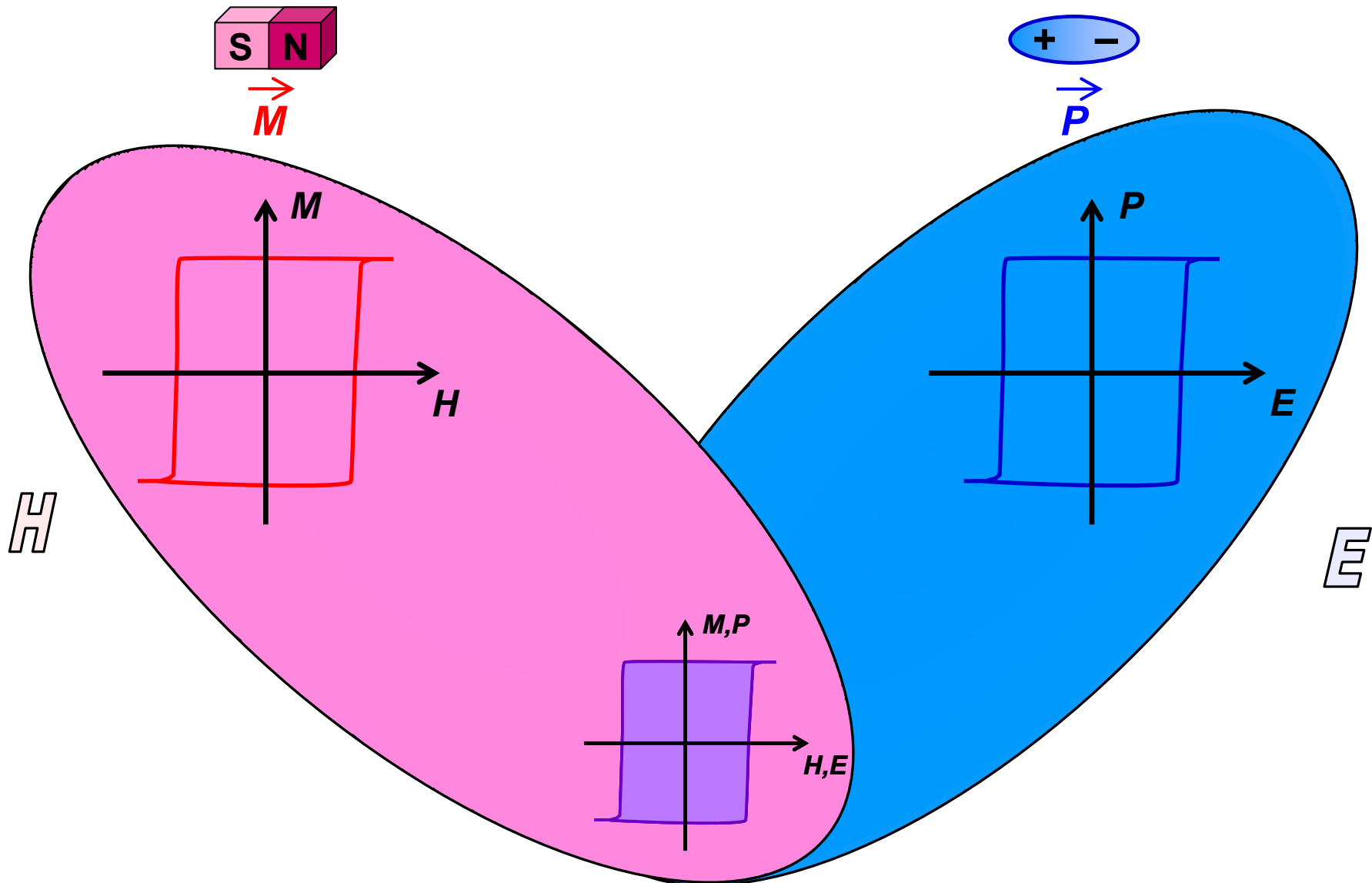
Feedback



Multiferroics

Magnetism: **Spins**

Ferroelectricity: **Charge (Dipoles)**

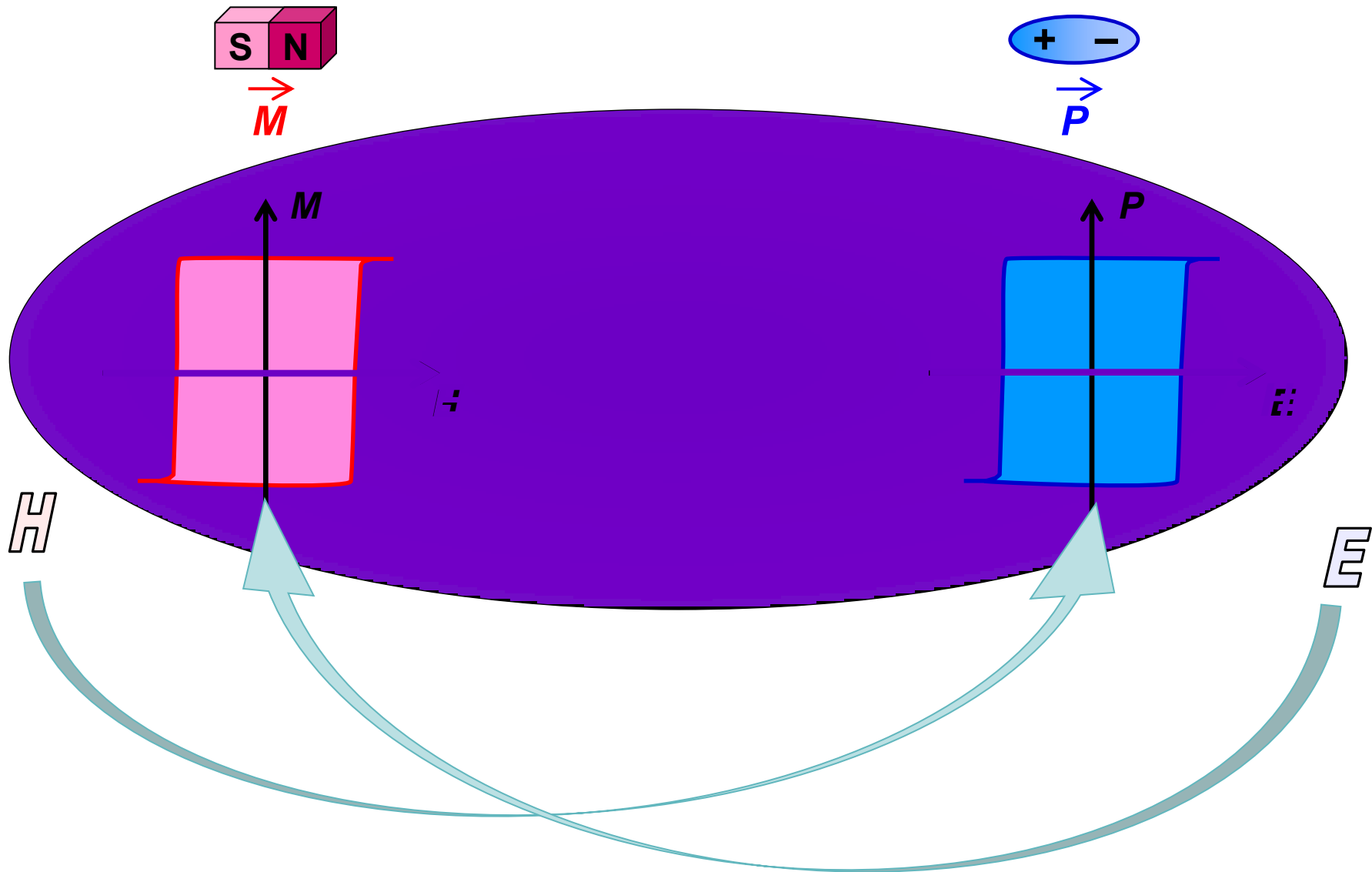


Multiferroicity: **Spins and Dipoles**

Multiferroics : Cross-coupling

Magnetism: **Spins**

Ferroelectricity: **Charge (Dipoles)**

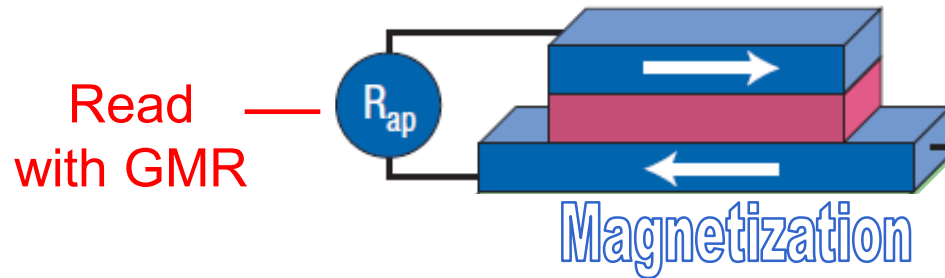


Multiferroicity: **Spins and Dipoles**

MRAM



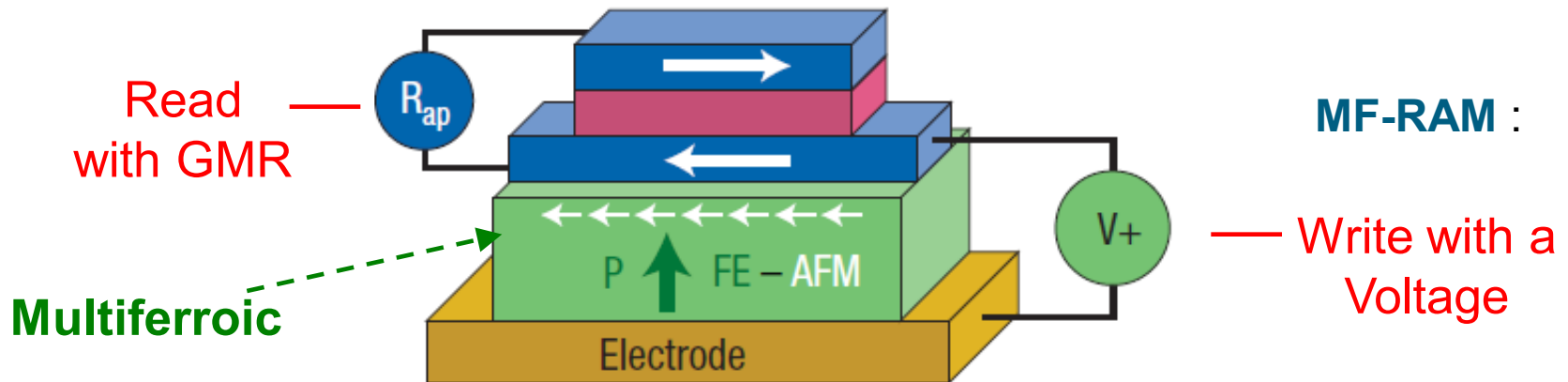
Write : requires remagnetization – high currents
(slow, high power consumption)



MRAM



Write : requires remagnetization – high currents
(slow, high power consumption)

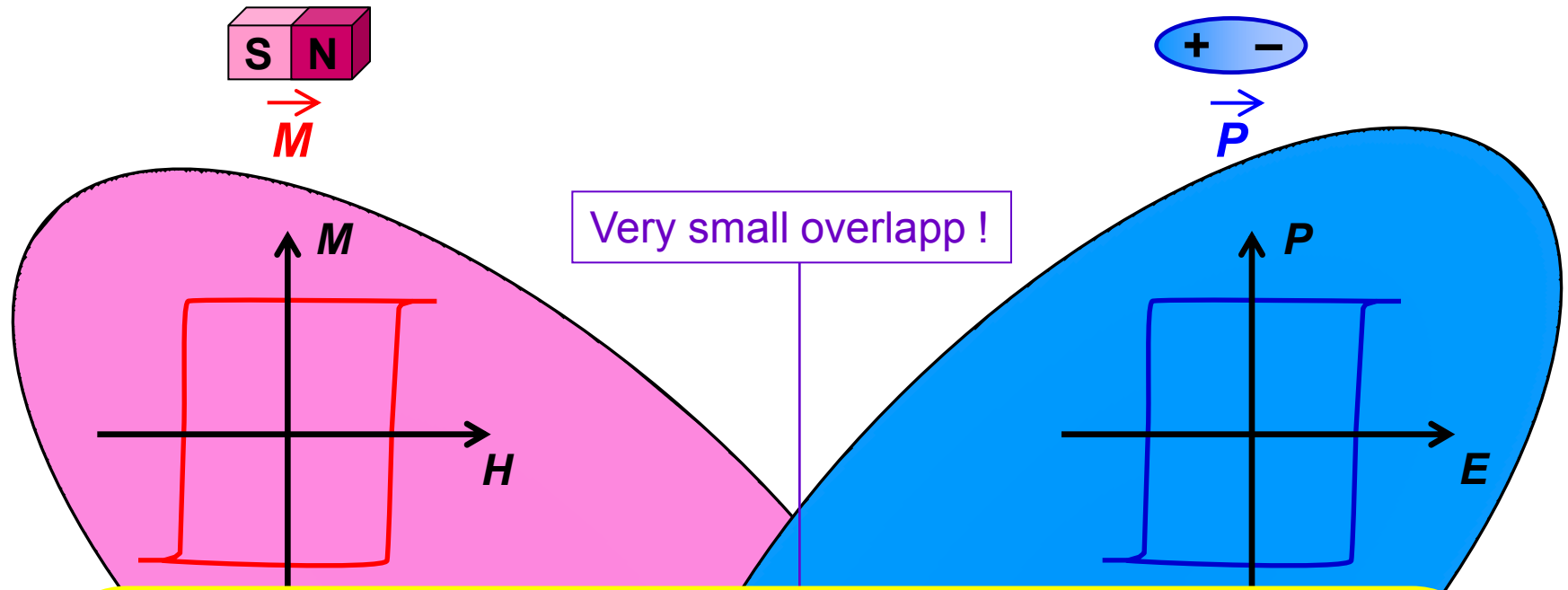


[M. Bibes and A. Barthélémy, Nat. Mater. 7, 425 (2008)]

Multiferroics : only few materials

Magnetism: **Spins**

Ferroelectricity: **Charge (Dipoles)**



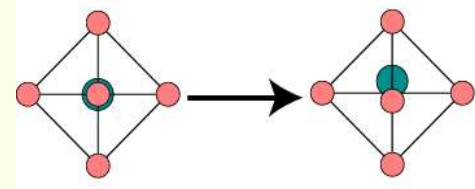
Magnetism



requires partially filled *d*-shell


Contra-indicated

**Ferroelectricity
(traditional mechanism)**

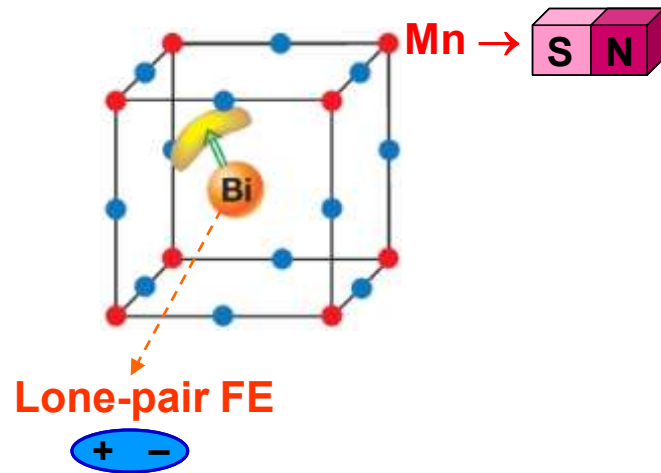


requires empty *d*-shell

Different routes to multiferroicity

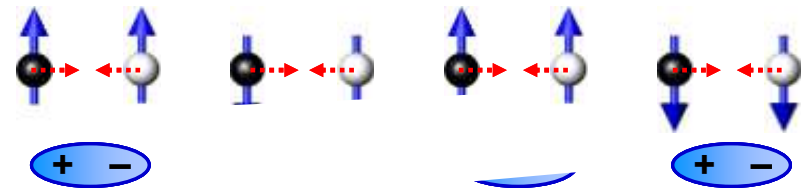
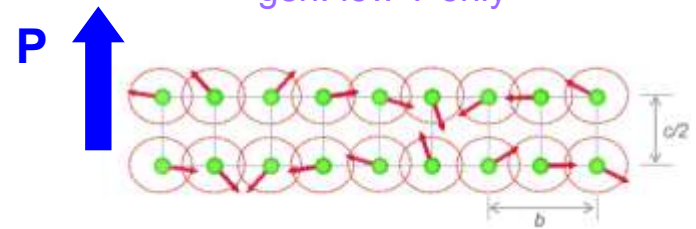
independent subsystems

gen. weak electromagnetic coupling

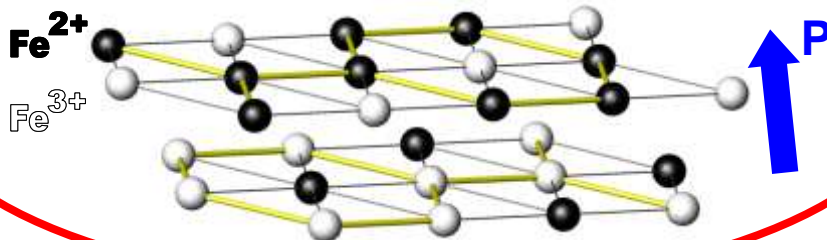


spin-spiral ferroelectricity

small polarization
gen. low T only

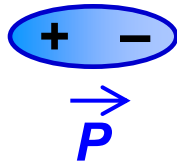


(symmetric) exchange striction



Charge-order-based

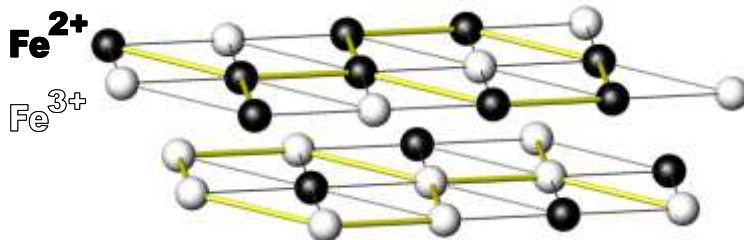
Ferroelectricity: **Charge (Dipoles)**



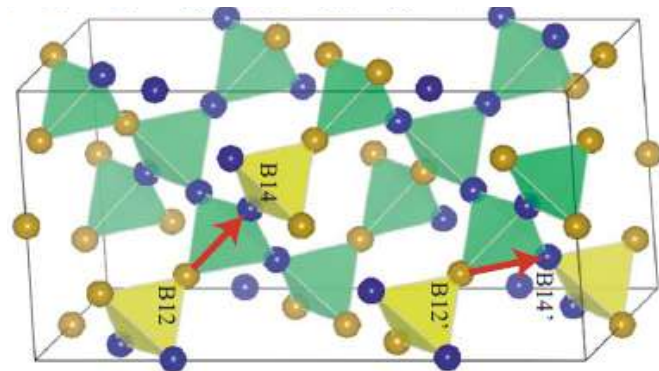
Any charge order breaking inversion-symmetry may be expected to be polar.

- Can in principle lead to very **large polarizations**
- Spins are for free !
- same electrons/sites involved in charge and spin order
→ **sizeable magnetoelectric coupling** possible

Examples ???



LuFe_2O_4

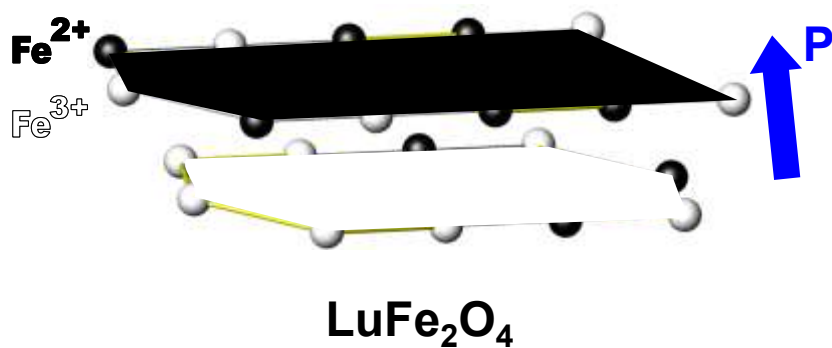


classical magnetite

LETTERS

in the
charge-frustrated system LuFe_2O_4

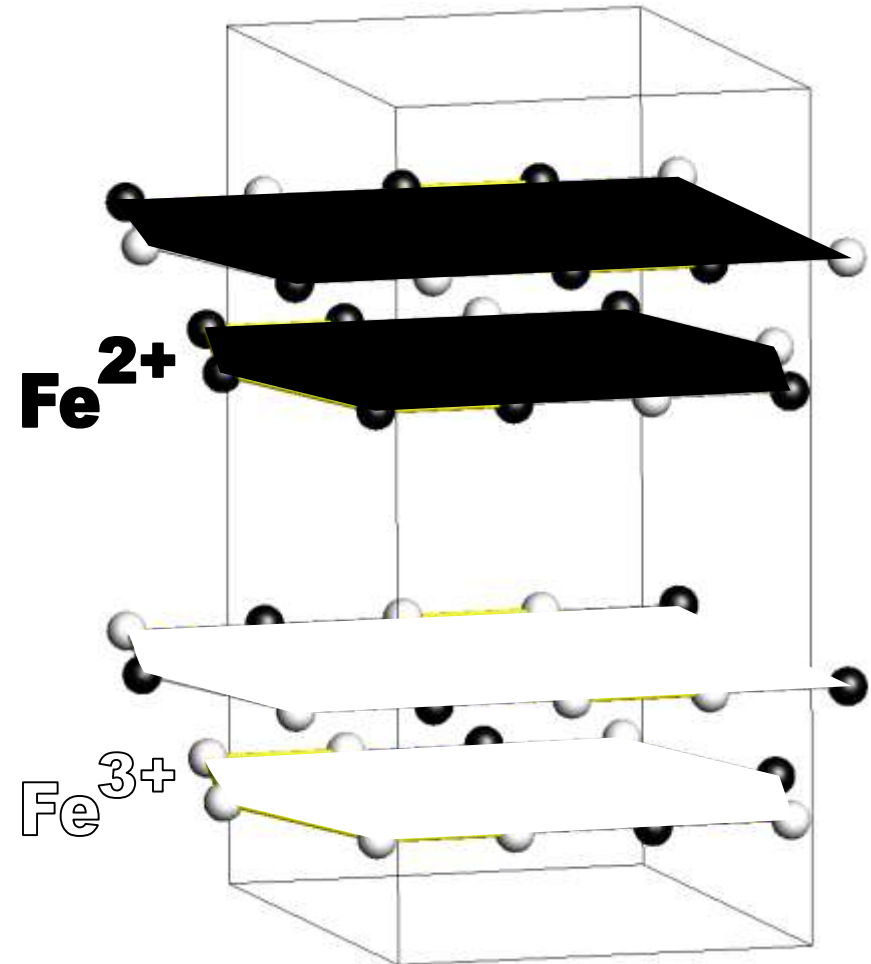
Naoshi Ikeda¹, Hiroyuki Ohsumi¹, Kenji Ohwada², Kenji Ishii², Toshiya Inami², Kazuhisa Kakurai³,
Youichi Murakami⁴, Kenji Yoshii², Shigeo Mori⁵, Yoichi Horibe⁵ & Hijiri Kitô⁶



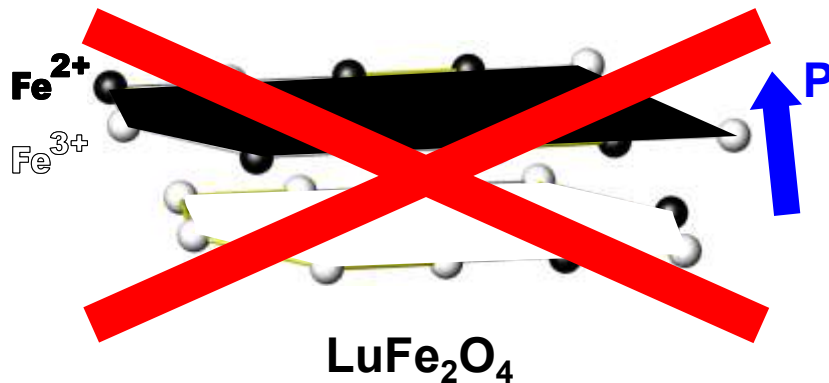
LETTERS

in the
charge-frustrated system LuFe_2O_4

Naoshi Ikeda¹, Hiroyuki Ohsumi¹, Kenji Ohwada², Kenji Ishii², Tosh
Youichi Murakami⁴, Kenji Yoshii², Shigeo Mori⁵, Yoichi Horibe⁵ & H



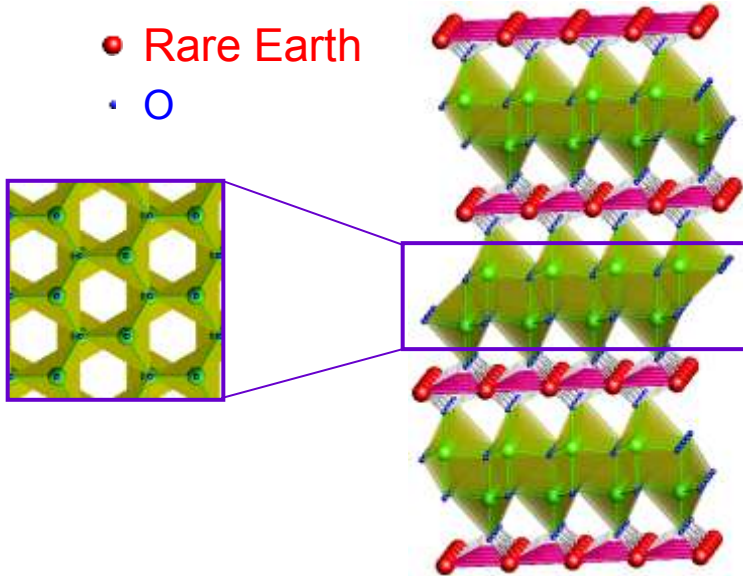
[de Groot *et al.*, and MA, PRL **108**, 187601 (2012)]



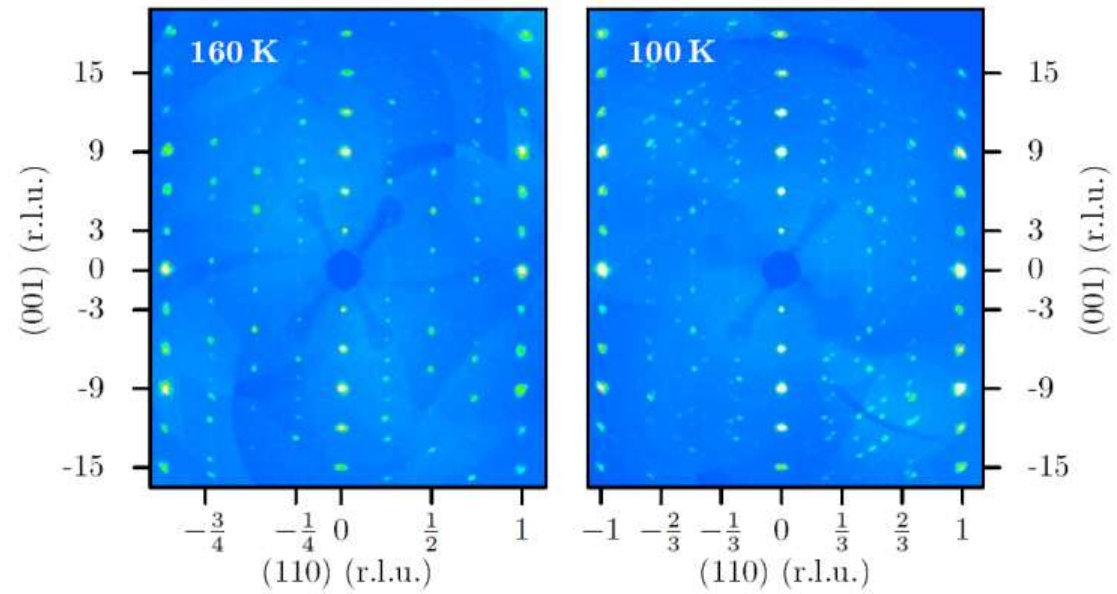
Tuning ...

Can a ferroelectric CO be stabilized ?

- Fe
- Rare Earth
- O

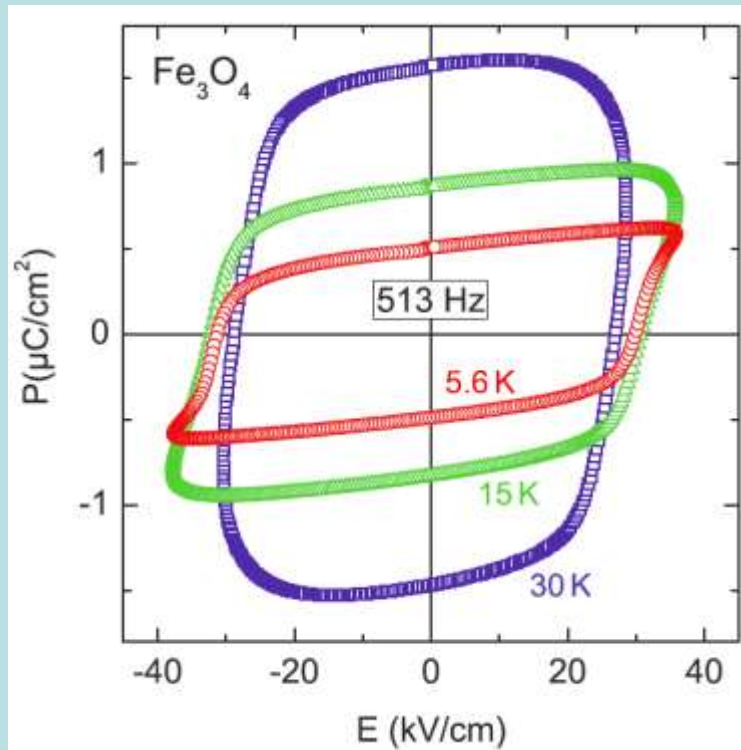


Lu \rightarrow Y substitution
(synthesis optimized)



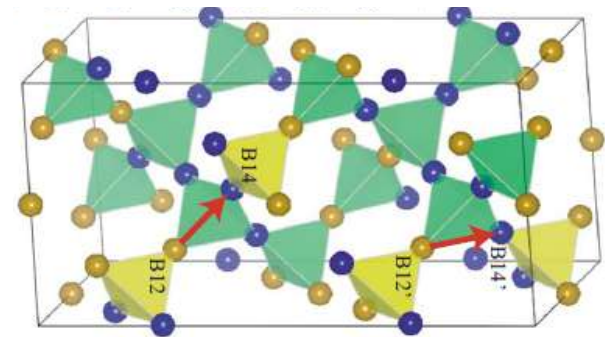
Classical magnetite: a (relaxor) ferroelectric from charge order?

Charge order structure: complex, polar according to recent refinement [Senn *et al.*, Nature 481, 173 (2012)]



Recent proposal of relaxor-like FE
[Schrettle *et al.*, PRB **83**, 195109 (2011)]

Time-resolved in-situ diffraction
with ac electric field applied for
microscopic proof
(beamtime PETRAIII P09 next week)

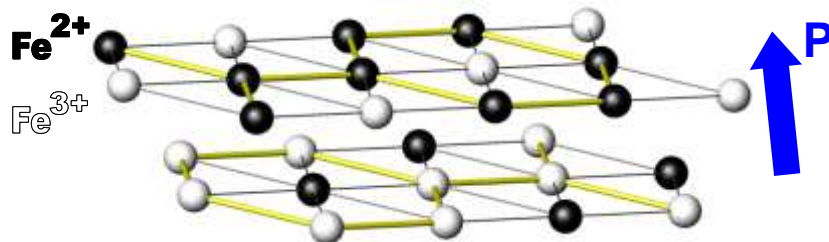
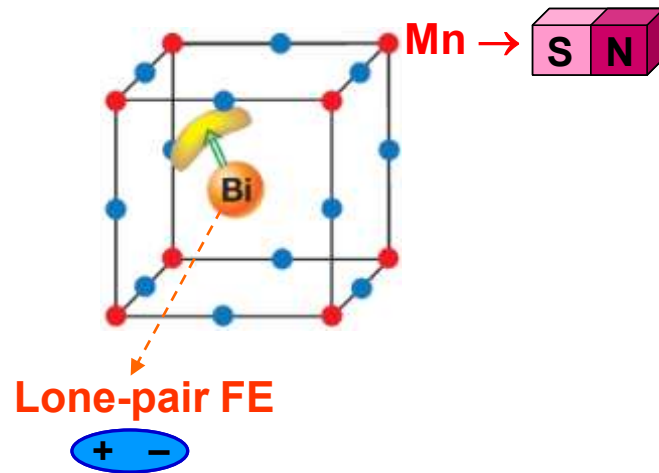


classical magnetite

Different routes to multiferroicity

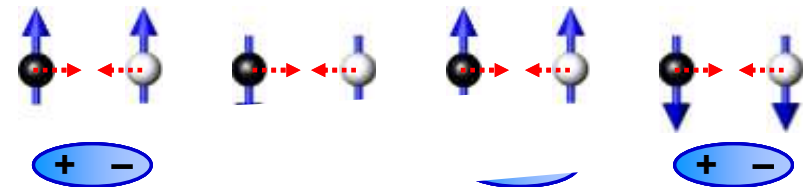
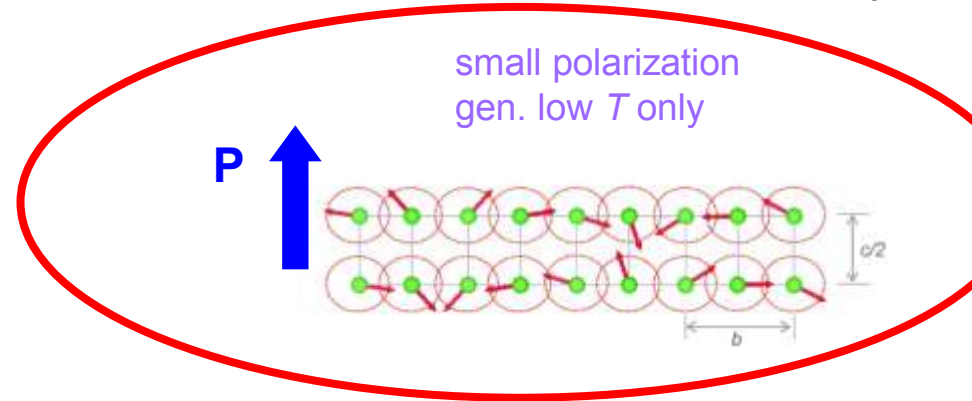
independent subsystems

gen. weak electromagnetic coupling



Charge-order-based

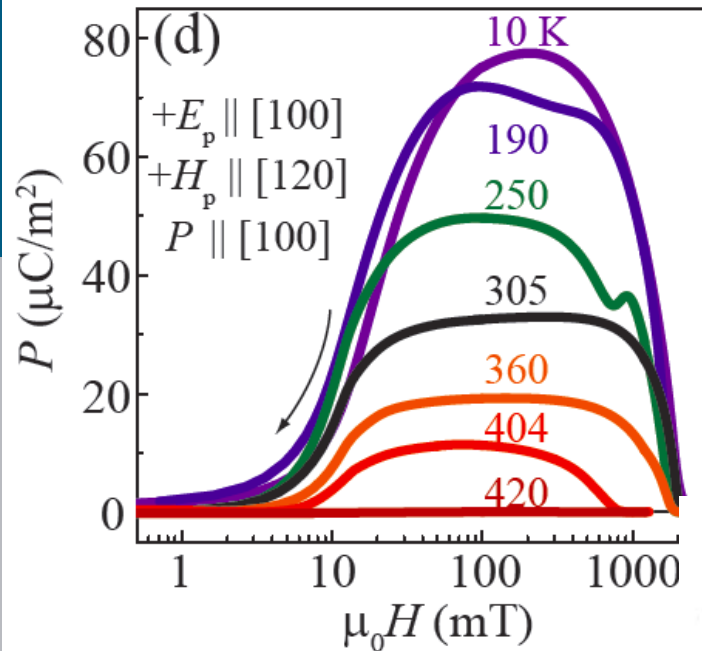
spin-spiral ferroelectricity



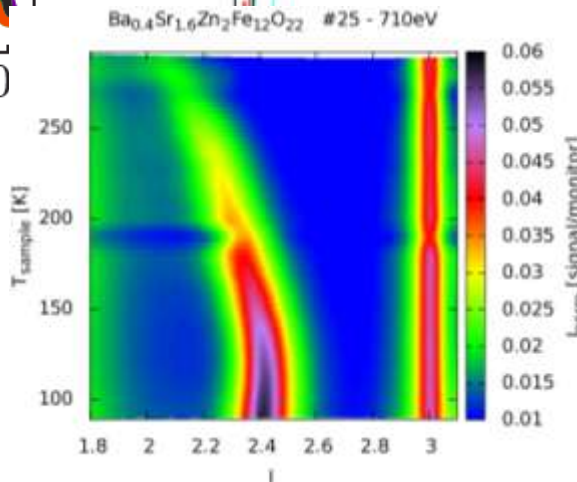
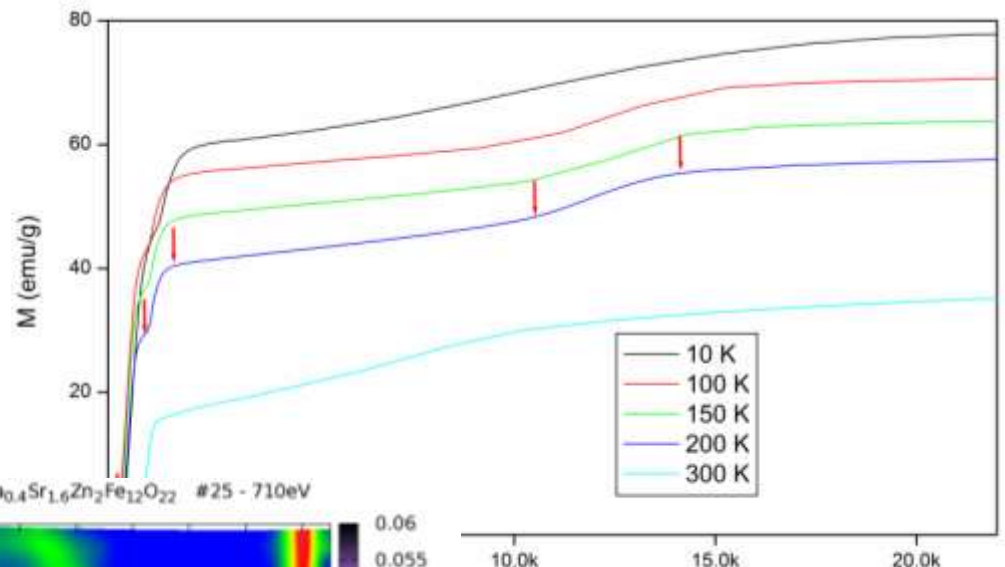
(symmetric) exchange striction

Spin spiral FE at room temperature: JÜLICH FORSCHUNGSZENTRUM

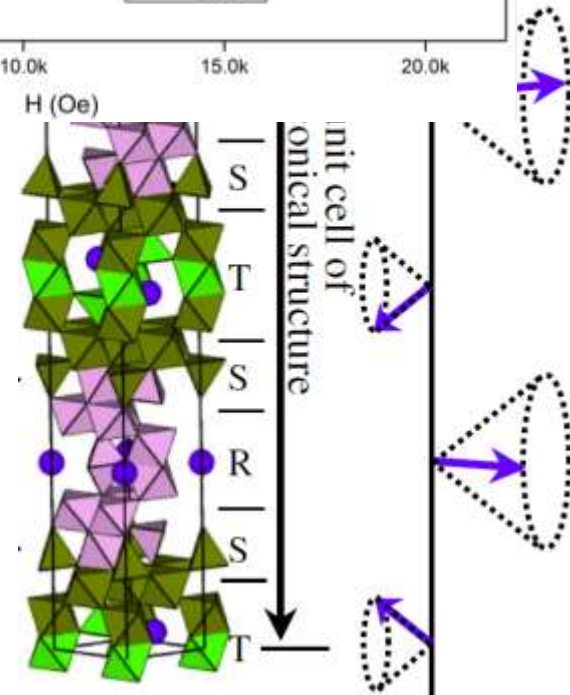
hexaferrite $(\text{Ba,Sr})_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$



Chun *et al.*, arXiv:1111.3224



Proposed magnetic structure
(to be verified by scattering)



Complex ordering phenomena in multi-functional oxides

Young-Investigators-Group funded by Helmholtz association,
part of the institute of scattering methods JCNS-2 & PGI-4 (director Th. Brückel)



Manuel Angst
Group leader



Joost de Groot
PhD student
(LuFe_2O_4)



Shilpa Adiga
PhD student
(magnetite)



Pankaj Thakuria
PhD student
(hexaferrites)



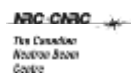
Thomas Müller
Diploma student
(YFe_2O_4)



Hailey Williamson
Master student
(YbFe_2O_4)

Recent collaborators

Karin Schmalzl
Werner Schweika,
Yixi Su, , Wouter Borghols
Raphael P. Hermann,
Ilya Sergueev, Dimitrios Bessas
Marjana Lezaic



Andy D. Christianson,
Mark D. Lumsden,
Karol Marty, Steve E. Nagler,
David Mandrus, Brian C. Sales,
Michael McGuire, Athena S. Sefat

Zahra Yamani



Ana Akrap,
Laszlo Forro



Stew R. Bland,
Tom A.W. Beale
Peter D. Hatton



Racquel de Souza,
Urs Staub



Daniel Niermann,
Florian Washkowski
Joachim Hemberger



Jörg Stremper



M.H. Phan,
Nathalie Frey, Hari Srikanth



Xiaoshan Xu,
Jan L. Musfeldt



Tae-Hwan Kim, Ronying Jin,
E. Ward Plummer



Jong-Woo Kim,
Phil Ryan, Zahir Islam,
Douglas Robinson
Richard A. Rosenberg,
David J. Keavney



Ulrich Peltzer, Rudolf Ruffer,
F. Yakhov



S. S. Dhesi



Semen Gorfman

