MSE Day 18.11.2022

Correlative Characterisation of Magnetic Nanostructures using Transmission Electron Microscopy

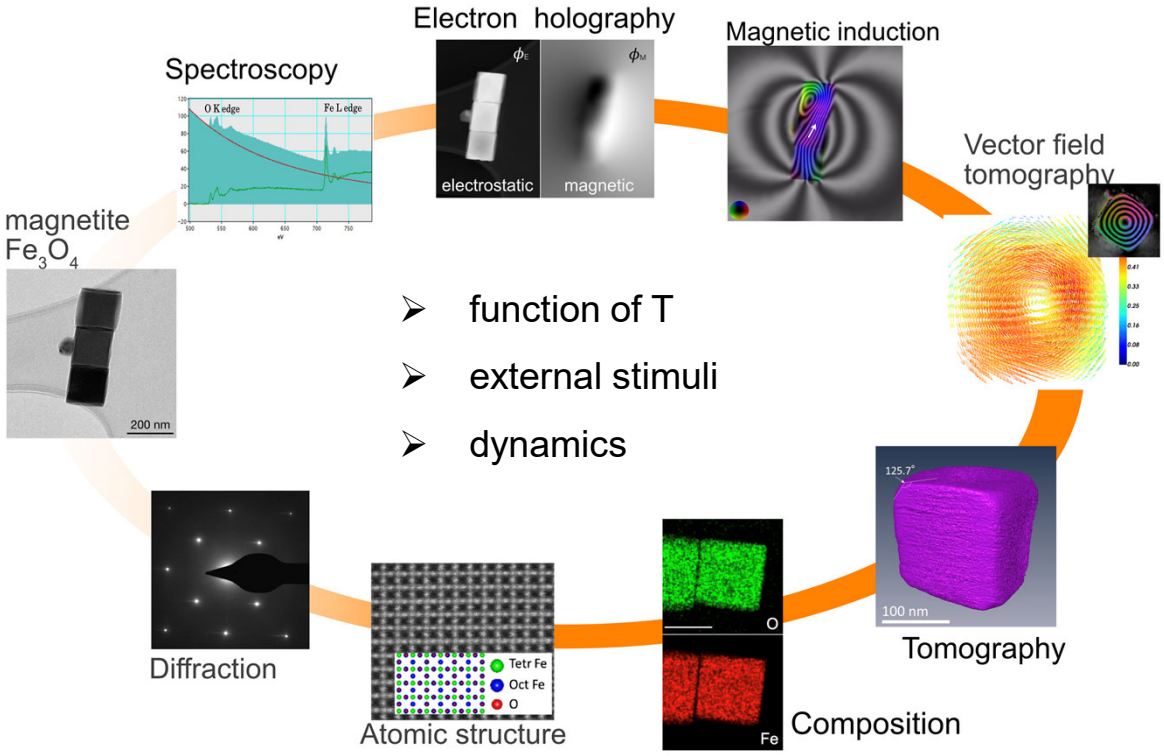
András Kovács

HELMHOLTZ

Advanced electron microscopy @ Ernst Ruska-Centre

fz-juelich.de/er-c

ThermoFisher Scientific



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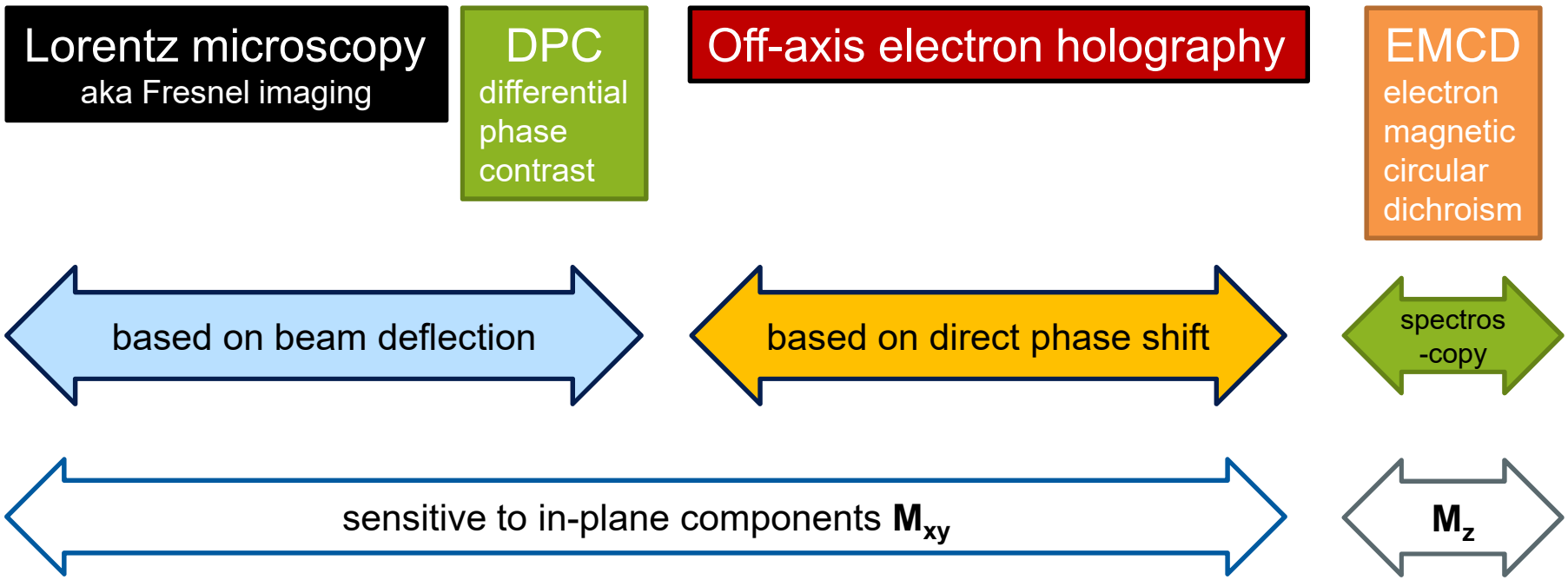
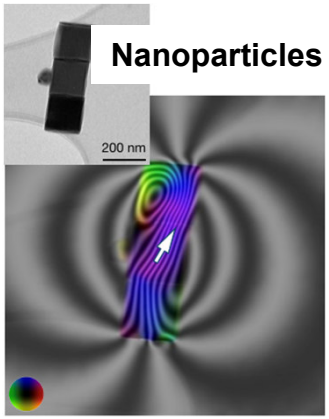
Methods for magnetic imaging in TEM

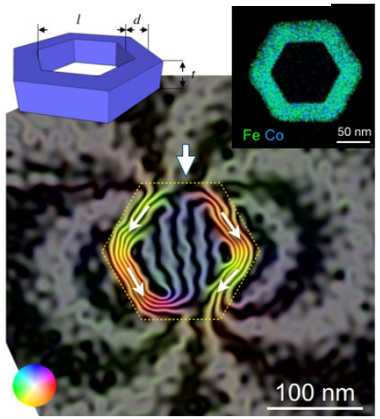


Applications

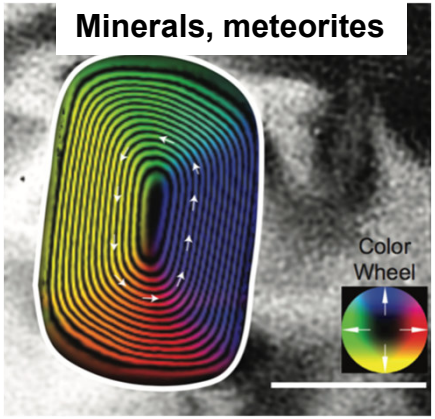
Nanostructures

Nanoparticles

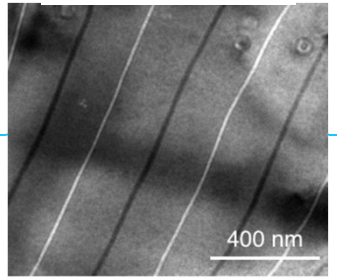


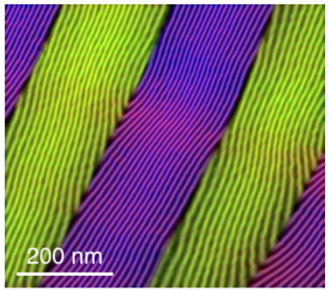


Minerals, meteorites

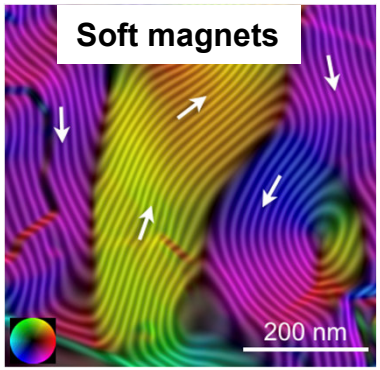


Hard magnets

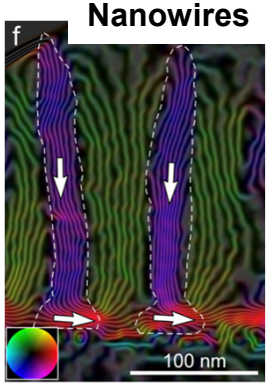




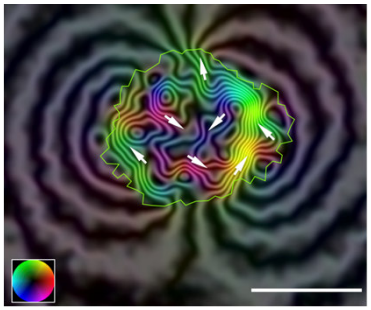
Soft magnets



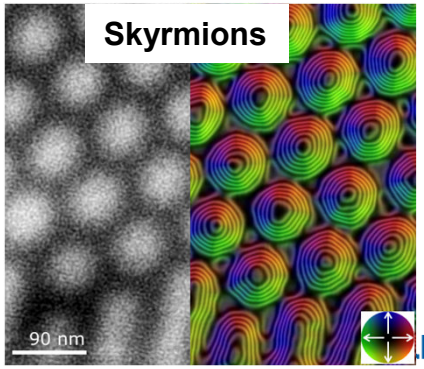
Nanowires



3D frustrated magnets



Skyrmions



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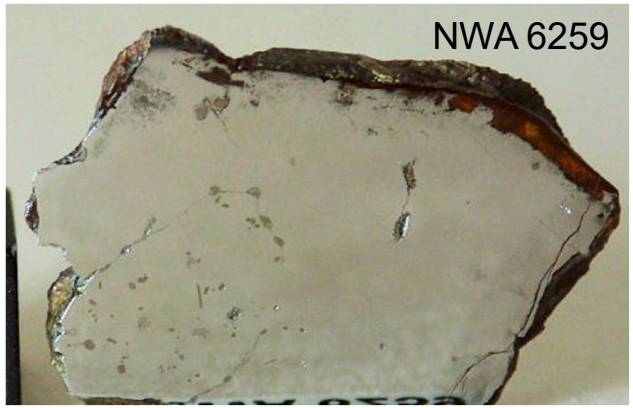
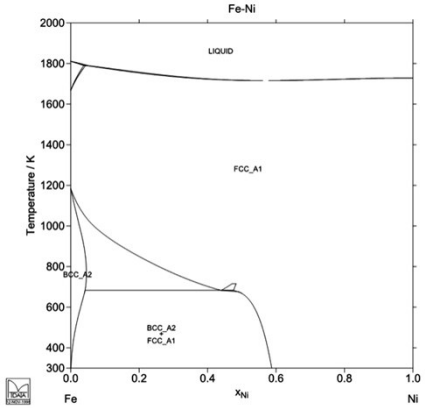
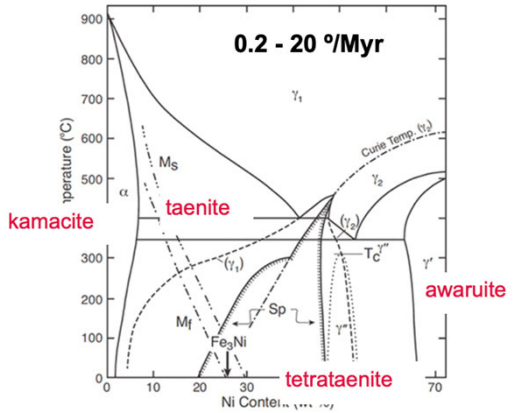
Billion years of materials science through an Fe-Ni meteorite

Michalis Charilaou (U Lousiana, USA), Laura H. Lewis (Northeastern U, USA), Dierk Raabe (MPIE Düsseldorf), A Schwedt (RWTH)

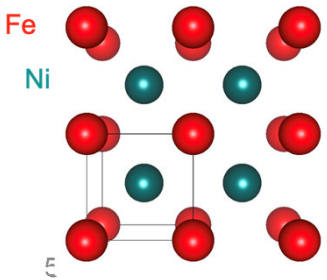


ataxite, 41.6 at% Ni, 1805 g





Goldstein, *2017*



Tetrataenite, δ'', $L1_0$-FeNi, P4mmm, a=0.253 c=0.358 nm

- 20 billion Euro - market share of permanent magnets in 2020
- 200-400 kA/m coercivity of Nd-Fe-B, Sm-Co (+Dy, Tb, Y, etc)
- 90-300 kA/m of $L1_0$-FeNi
- $L1_0$-FeNi can't be produced in laboratory conditions

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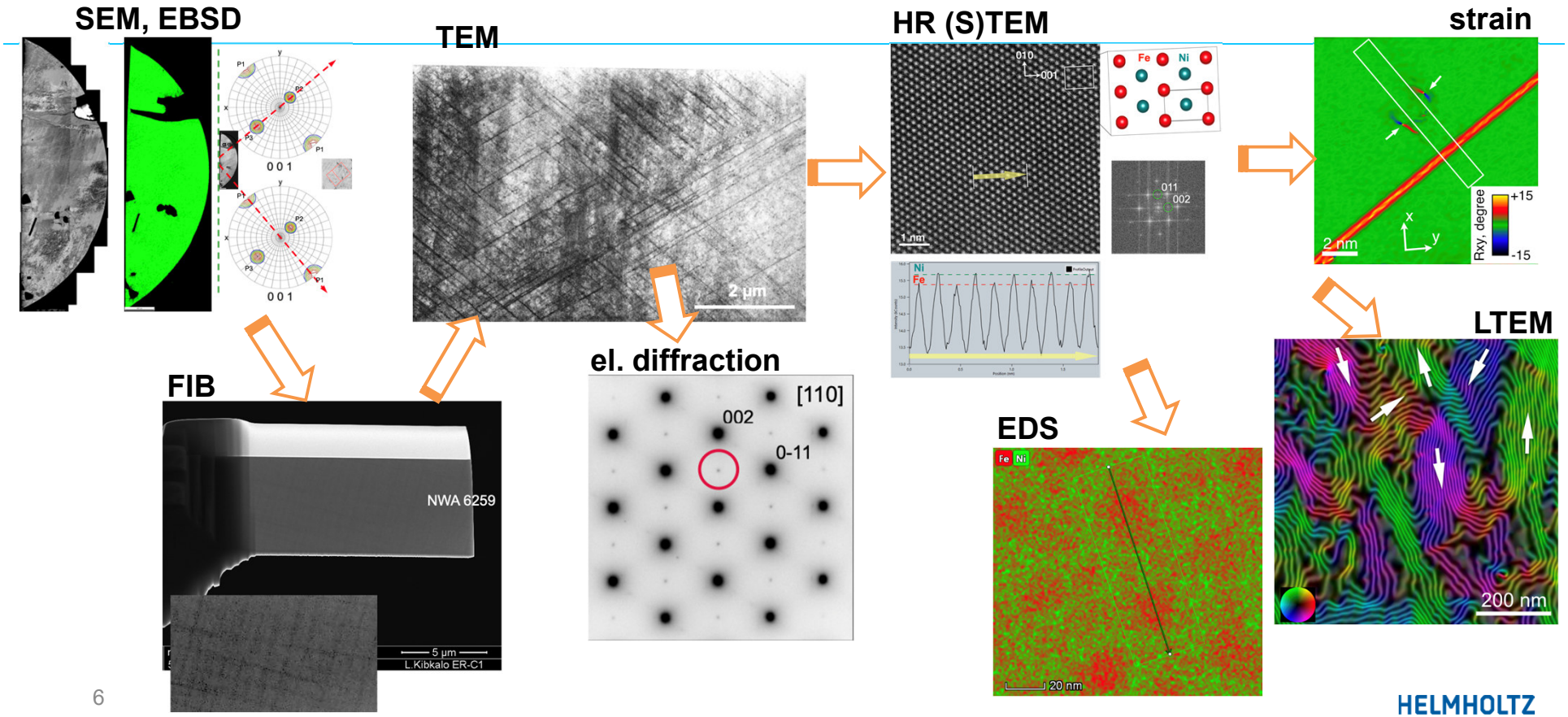
Measurement sequence using electron microscopy



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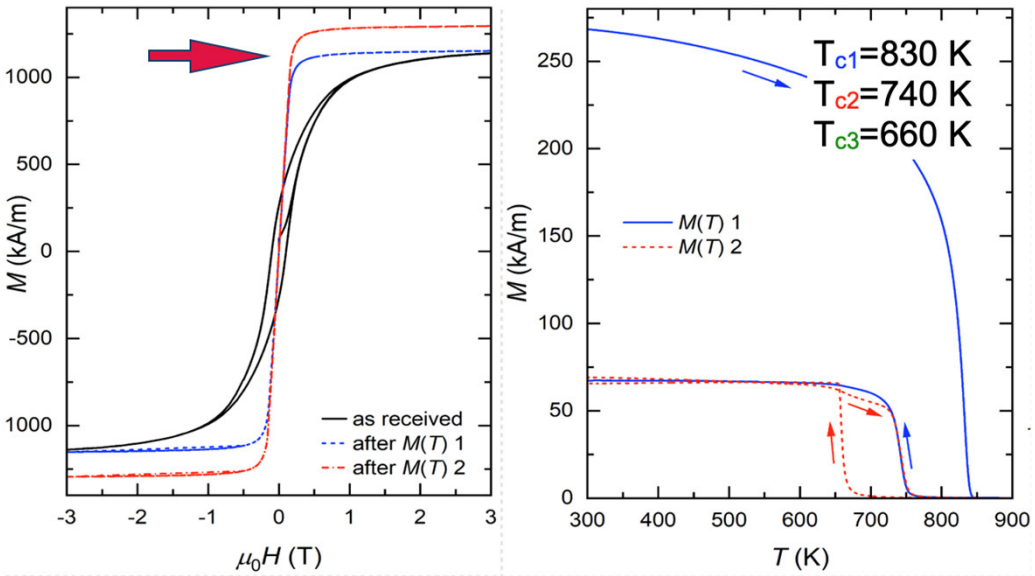
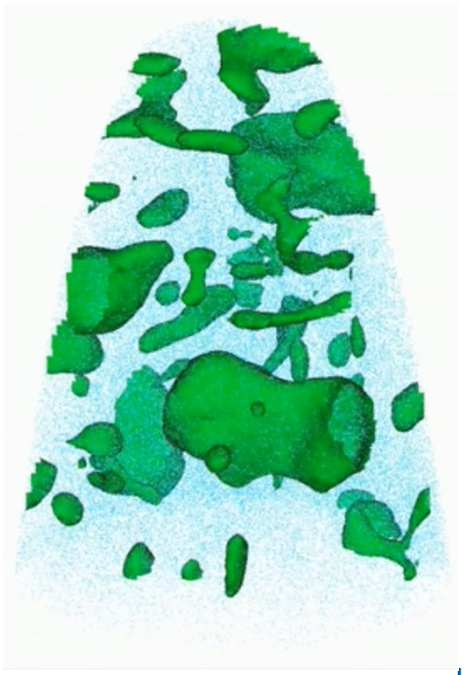
Correlative measurements of structure and magnetic properties

Magnetometry (SQUID)



Atom probe tomography



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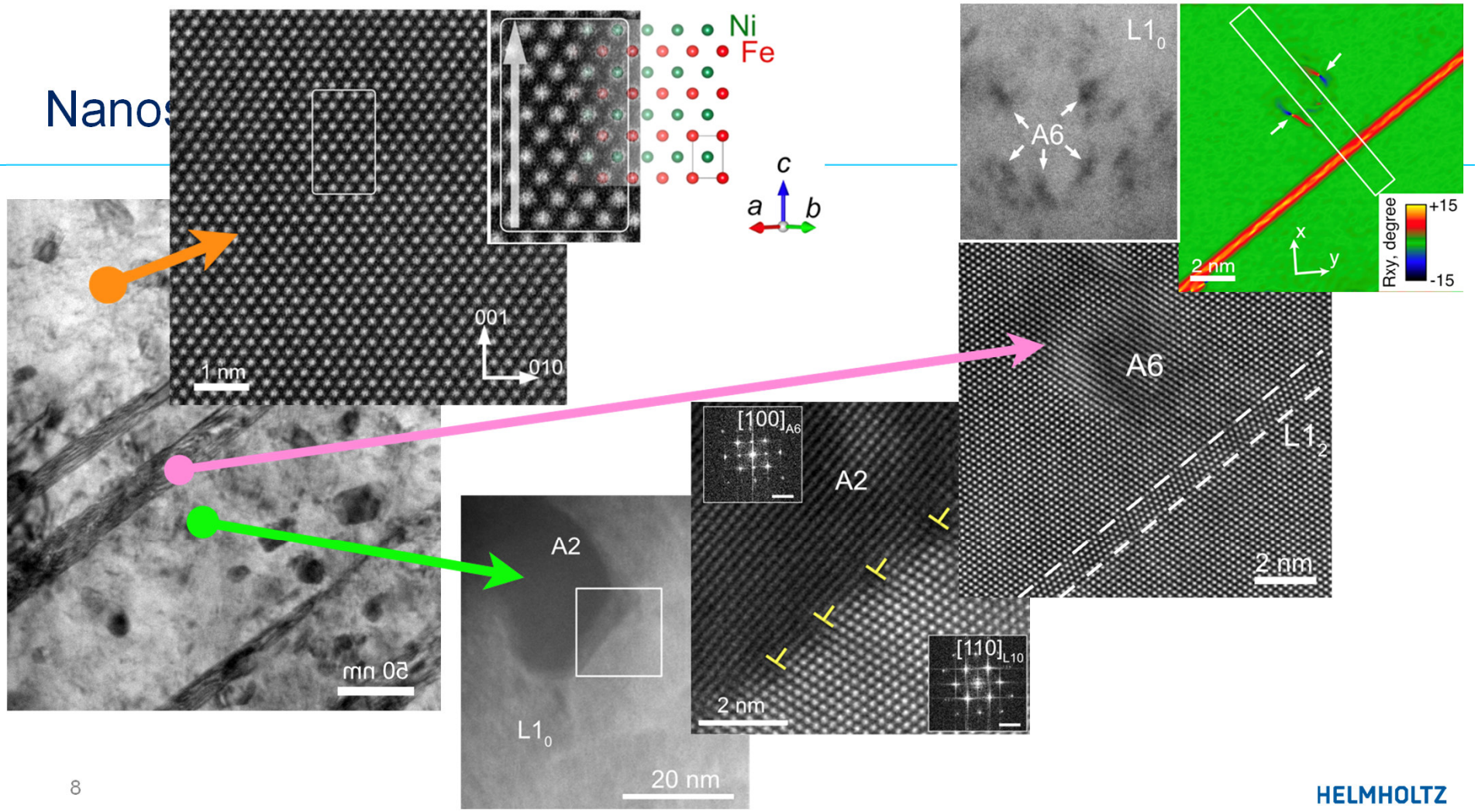
Nanos



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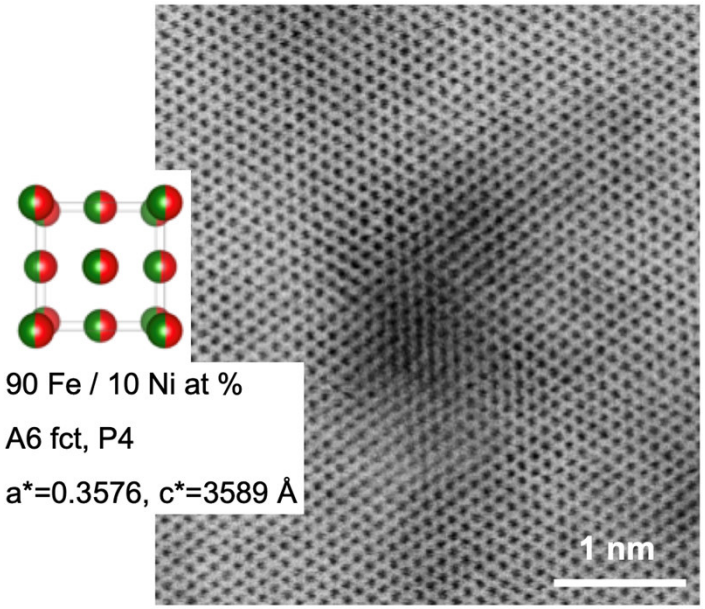
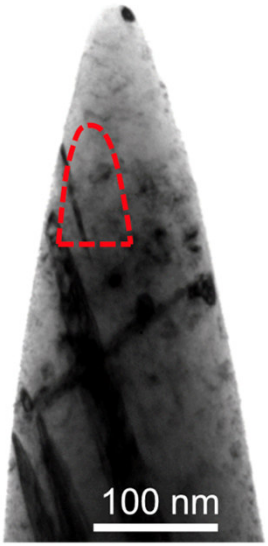
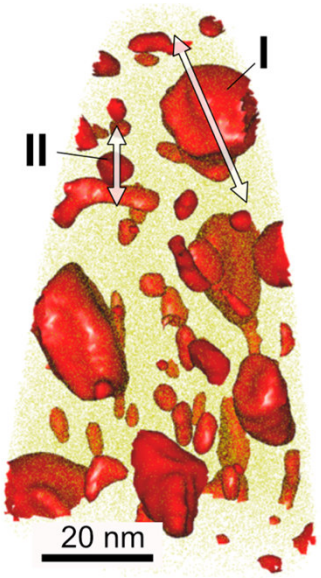
Nanometre scale phase decomposition

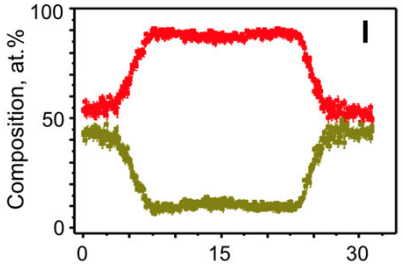
HR STEM



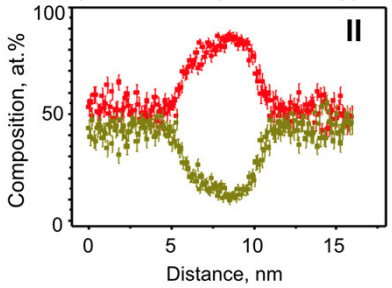
APT







A2-$Fe_{90}Ni_{10}$, kamacite



A6-$Fe_{90}Ni_{10}$, ???

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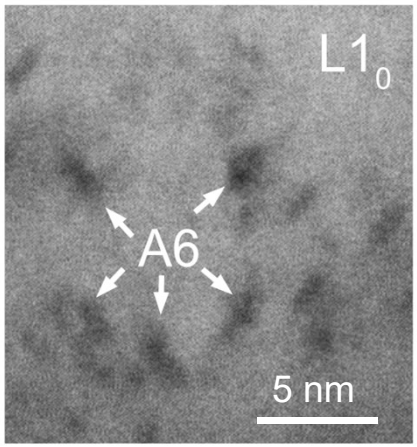
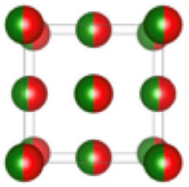
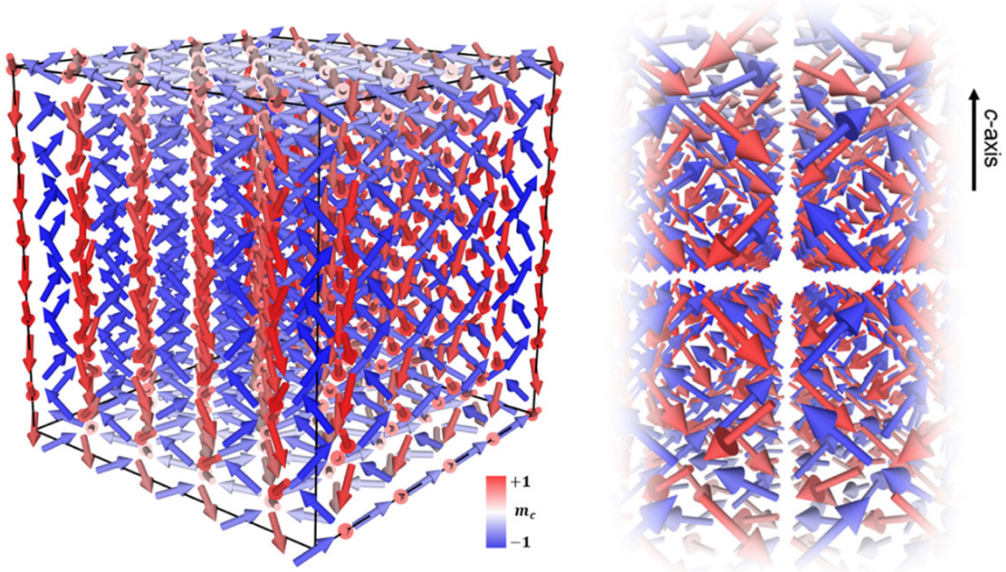
What kind of magnet is the new Fe-Ni phase?





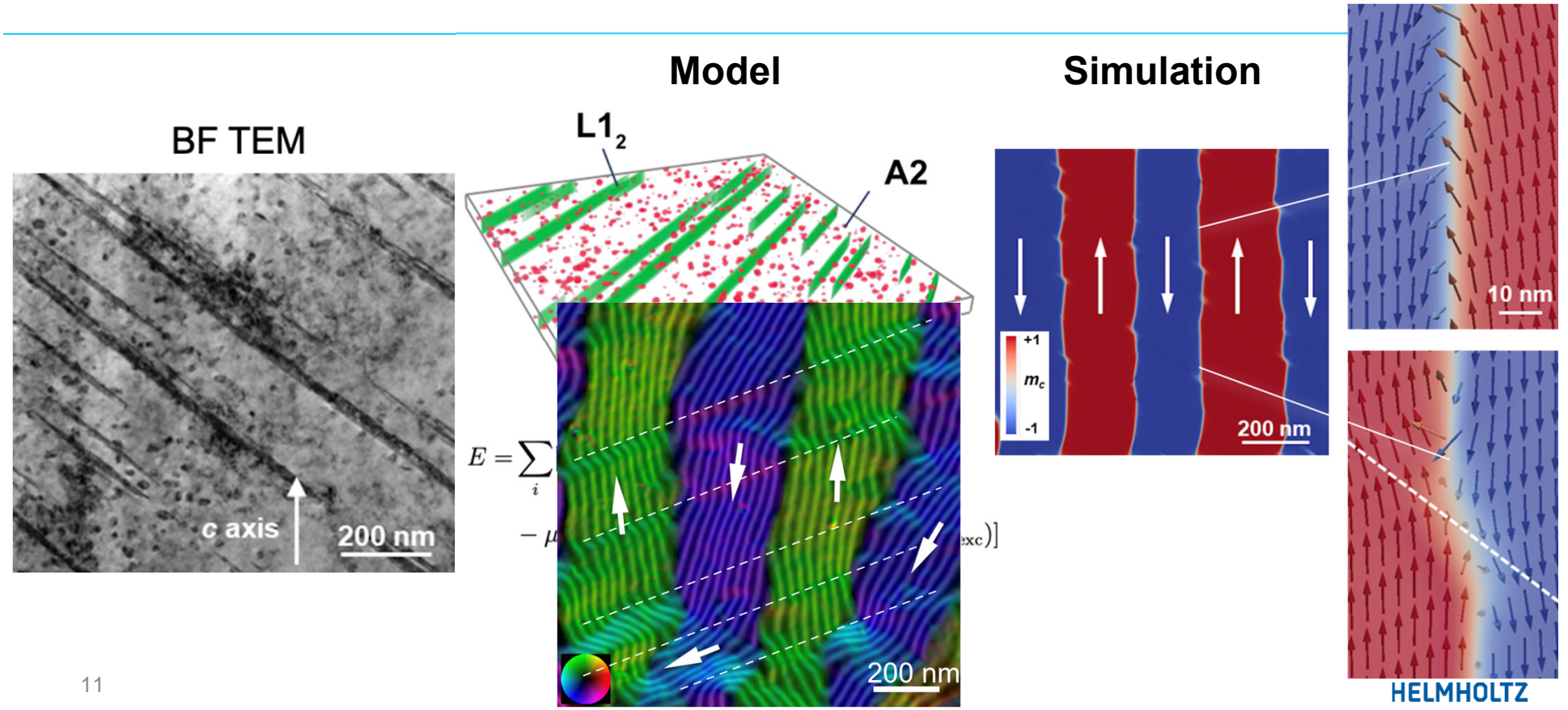
90 Fe / 10 Ni at %
A6 fct, P4
a*=0.3576, c*=3589 Å

Atomistic simulations



Non-collinear antiferromagnetic ground state

Micromagnetic simulation



NANO LETTERS

pubs.acs.org/NanoLett Letter

Discovery and Implications of Hidden Atomic-Scale Structure in a Metallic Meteorite

András Kovács,* Laura H. Lewis, Dhanalaksmi Palanisamy, Thibaud Denneulin, Alexander Schwedt, Edward R.D. Scott, Baptiste Gault, Dierk Raabe, Rafal E. Dunin-Borkowski, and Michalis Charilaou*

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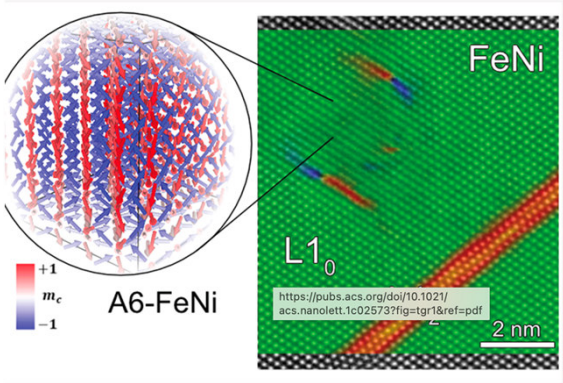
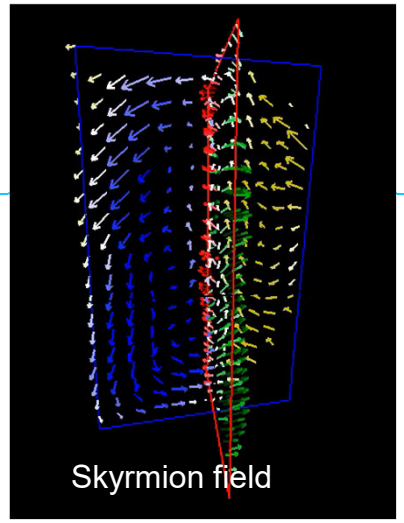
- We still don't know how to grow tetrataenite
- Correlative APT and TEM methods reveal the constituent phases in a metallic meteorite those responsible for the striking magnetic properties
- Micromagnetic (or atomistic) simulations are essential
- A new antiferromagnetic Fe-Ni phase observed



Summary

- Materials science and technology investigations require multiple combinations of different experimental and theoretical techniques
- Electron microscopy is a unique tool that provides wide range of methoodologies
- Multiple level and various data acquisition and processing is a challenge



Acknowledgement

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Rafal Dunin-Borkowski, Lidia Kibkalo, Thibaud Denneulin, Amir Tavabi, Penghan Lu, Fengshan Zheng, René Borowski

Skyrmion tomo
A Lubk, D Wolf, S Schneider, B Rellinghaus

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Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons ER-C

erc

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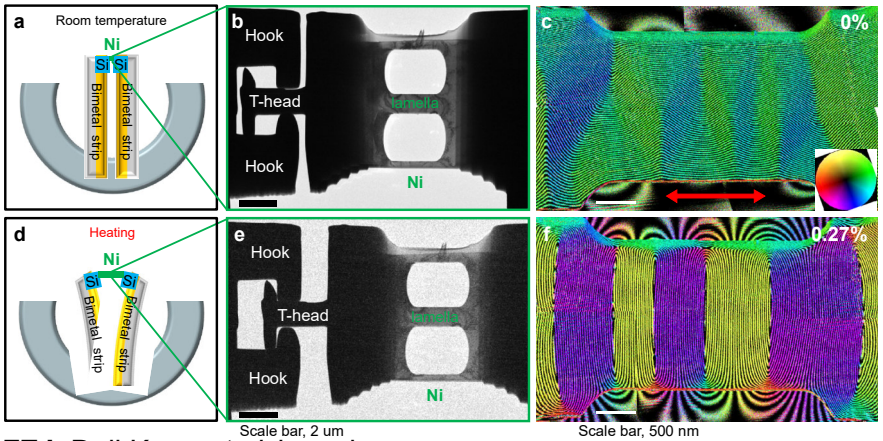
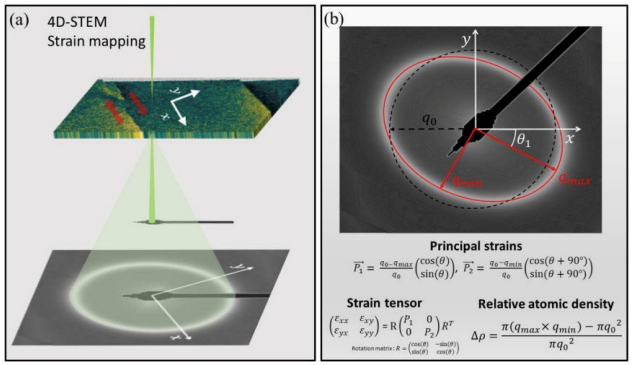
In situ 4D-STEM of strain-engineered nanomagnetism

Collaboration FZJ – KIT within the Joint Lab MDMC

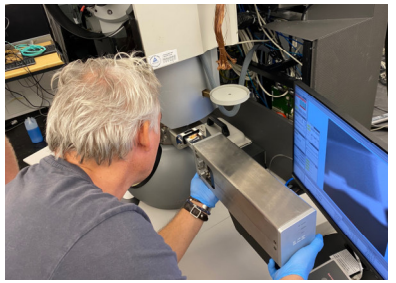
Measure nanoscale strain and magnetic contrast simultaneously during *in situ* tensile straining using ultrafast event-driven detector augmented by high-throughput live data processing



FZJ: Deli Kong *et al.* in review



KIT: S. J. Kang *et al.* in review



New event-driven detector installed at ER-C, FZJ, allowing for MHz 4D-STEM!

FZJ: Penghan Lu, Deli Kong, András Kovács, Dieter Weber, Alexander Clausen, Rafal E Dunin-Borkowski
KIT: Xiaoke Mu, Lucas Brauch, Maximilian Töllner, Christian Kübel