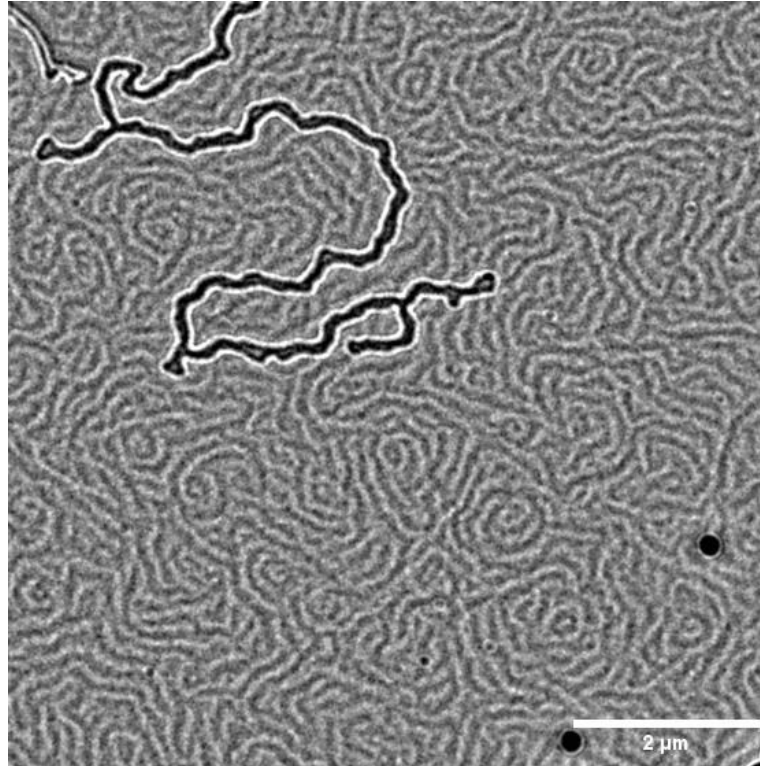


Resolving the interplay of dynamics and disorder at the nanoscale

— *Illustrating the relevance of advanced microscopy* —

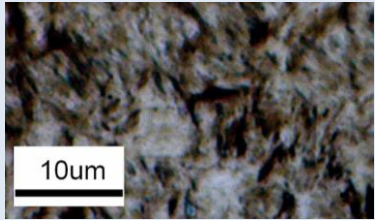


Felix Büttner

University of Augsburg and Helmholtz-Zentrum Berlin
Group MaXRay: Magnetism and Coherent X-Ray Imaging

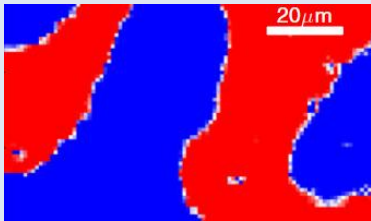
Relevance of this research

Steel



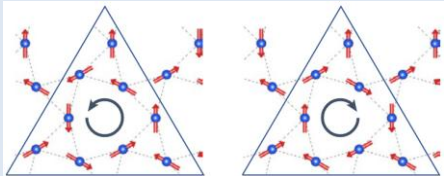
Wikipedia

Magnetic Weyl semimetals



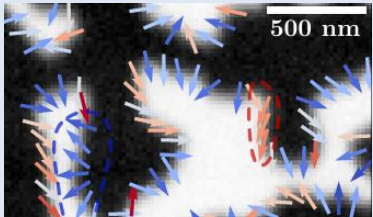
Lee, *et al.*, Nature Comm. (2022)

Spin ice materials



Khan, *et al.*, Nature Physics (2024)

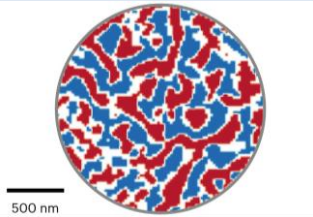
Chiral magnets



Metternich, FB, *et al.*, in preparation

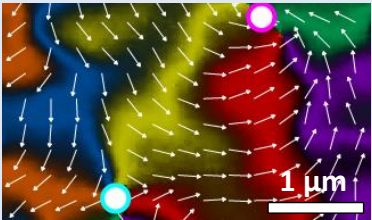
- Textures are ubiquitous
- They determine macroscopic behavior that makes materials functional
- They oftentimes can be changed...
- ...along disorder-shaped pathways

Metal-insulator transitions



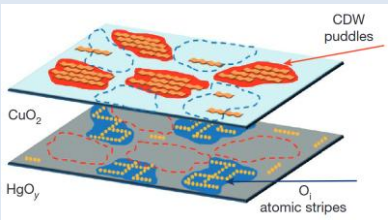
Johnson, *et al.*, Nature Physics (2023)

Antiferromagnets



Amin, *et al.*, Nature (2024)

Type-II superconductors

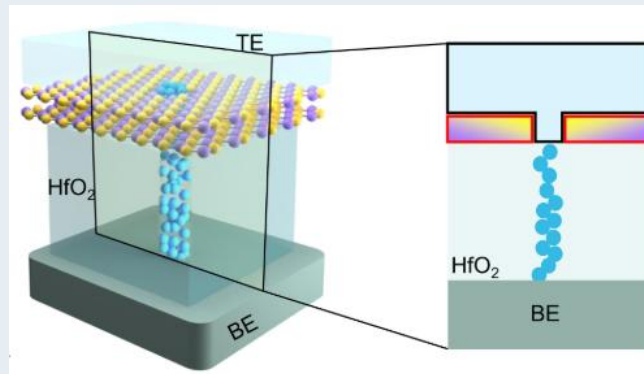


Campi, *et al.*, Nature (2015)

Examples of texture dynamics

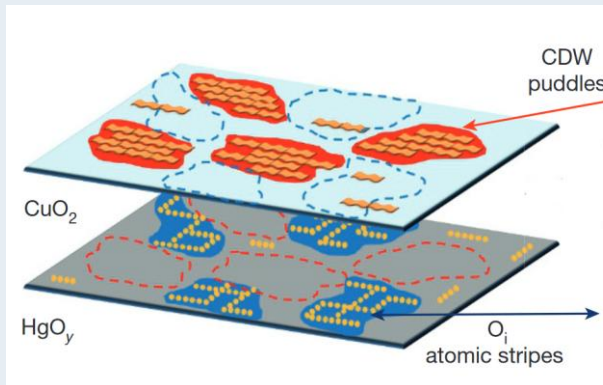
From fundamentals to applications

Formation dynamics / Phase trans. ("Morphogenesis")



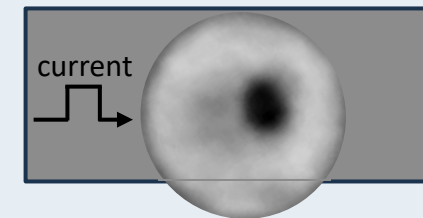
Conductive channels / Memristors
Science Advances **11**, eadu3309 (2025)

Persistent dynamics (Fluctuations)



Fluctuating CDWs in type-II superconductors
Nature **525**, 359 (2015)

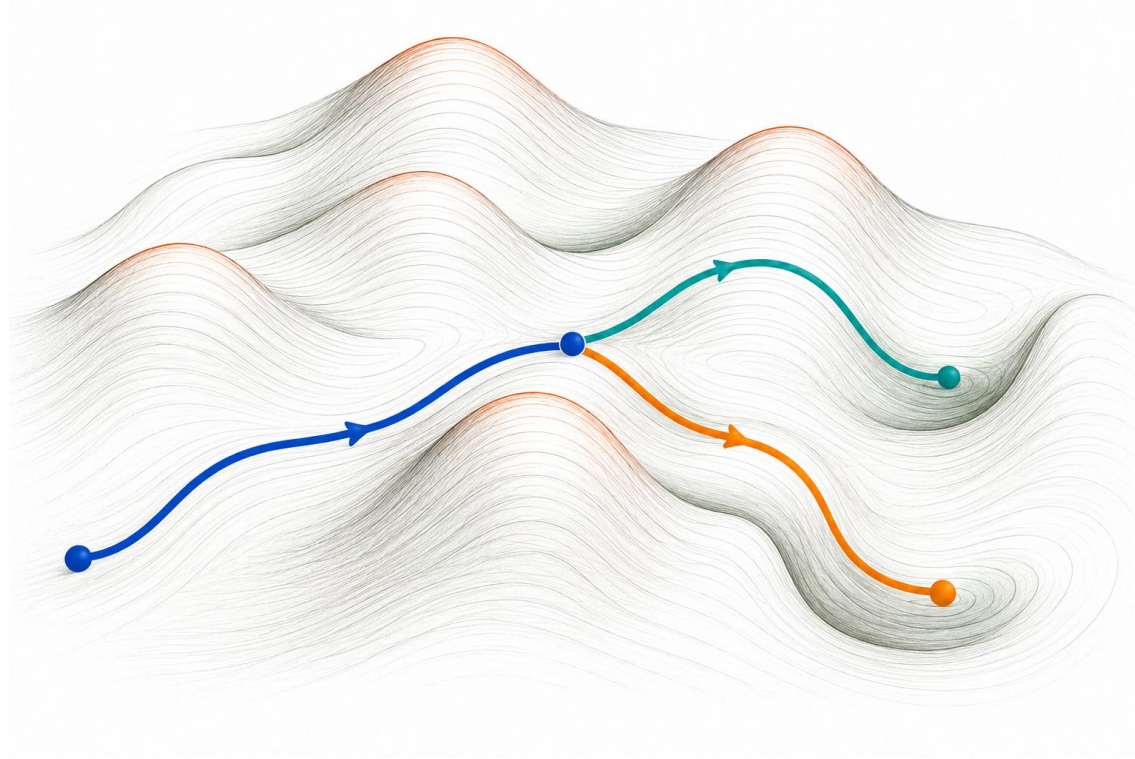
Driven dynamics / Switching (Operations)



Motion / coercivity
Nature Nanotechnology **12**, 1040 (2017)

How can we measure energy landscapes?

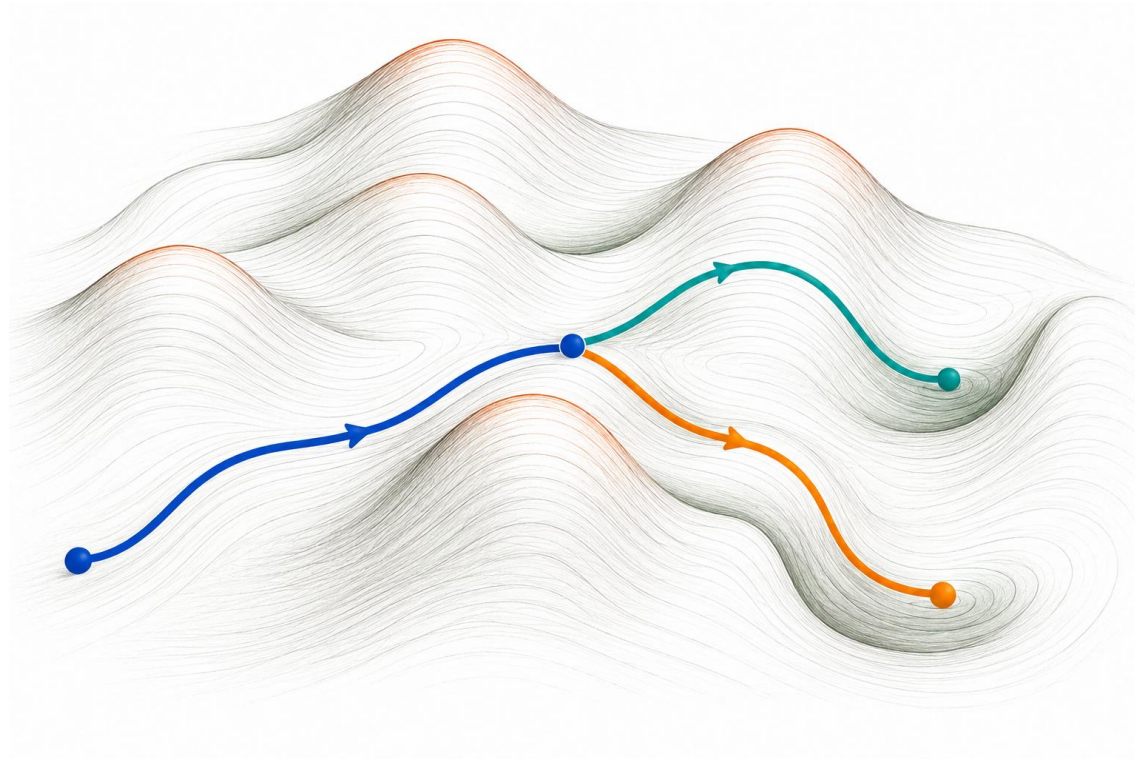
How can we observe the dynamic pathways?



Observation → Understanding → Control → Technology

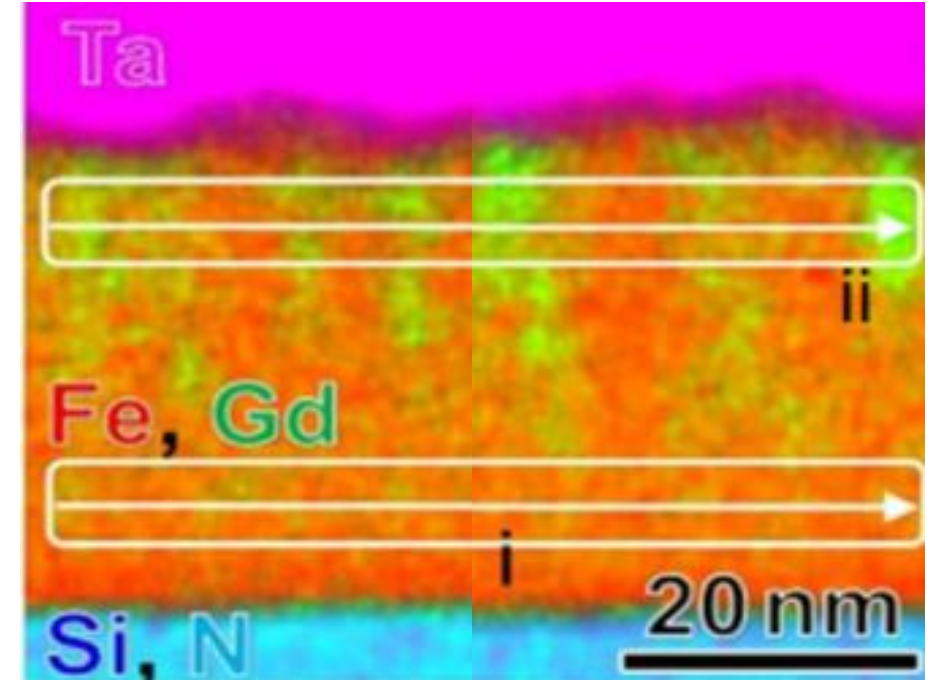
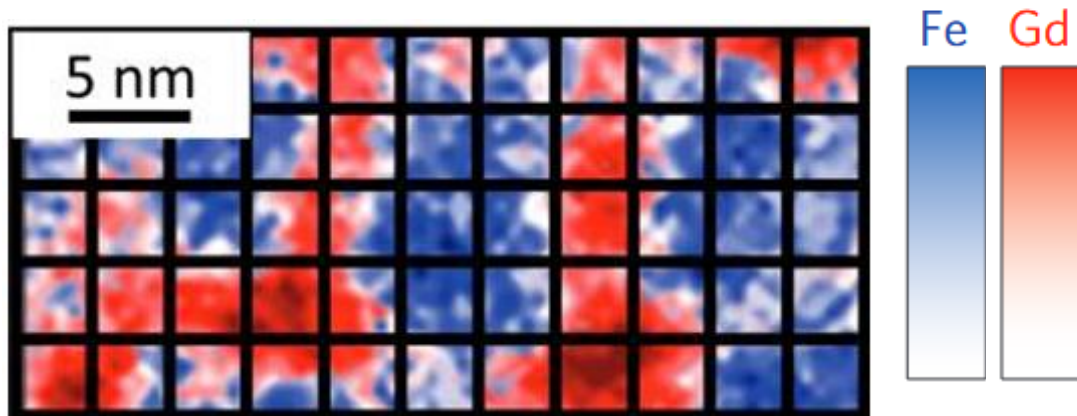
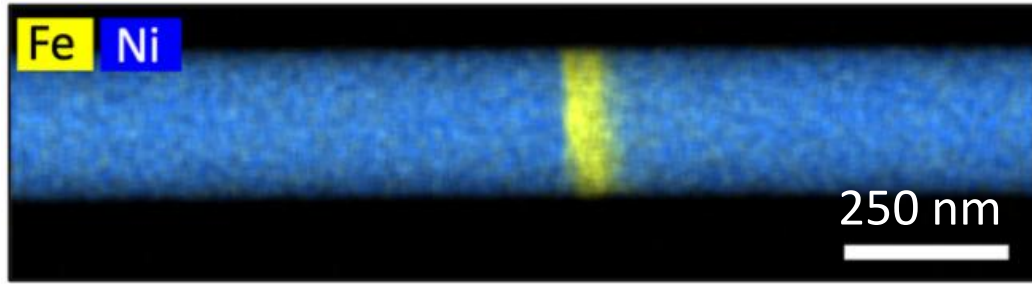
How can we measure energy landscapes?

How can we observe the dynamic pathways?

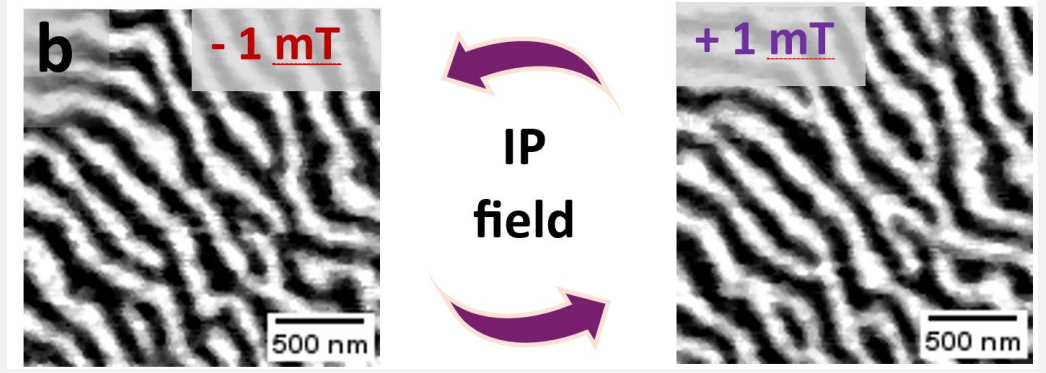
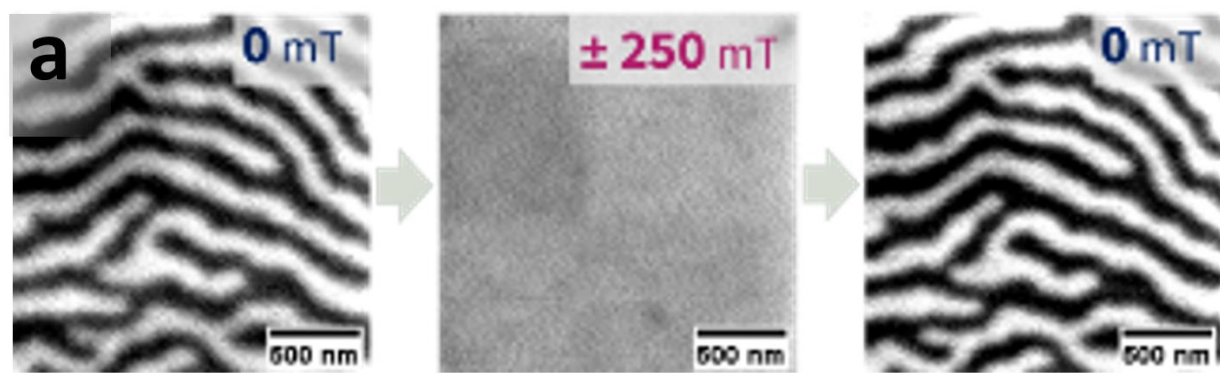
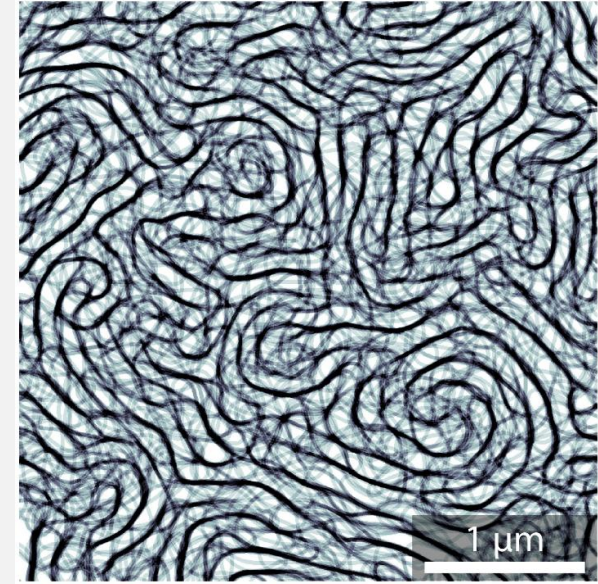
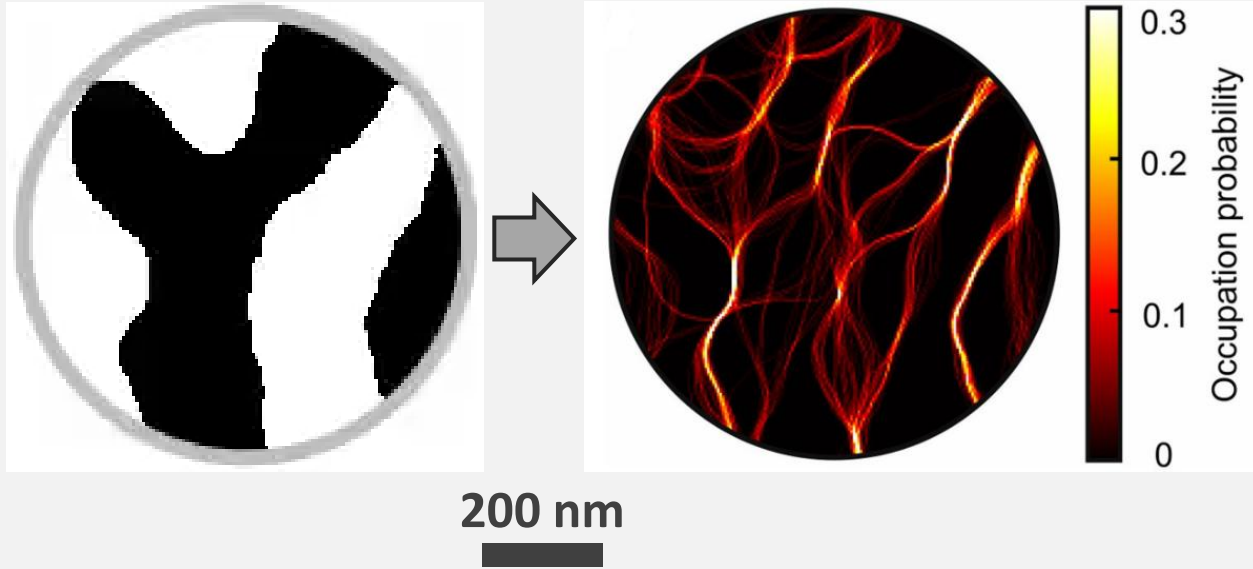


Observation → Understanding → Control → Technology

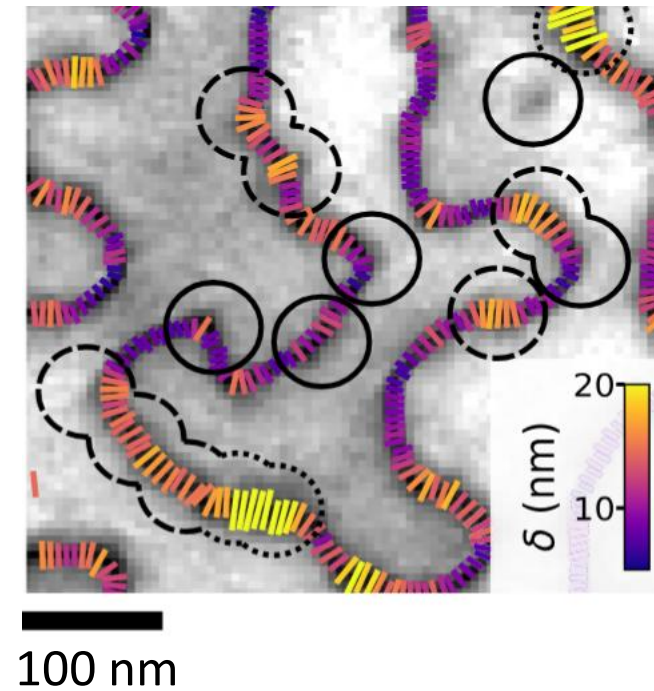
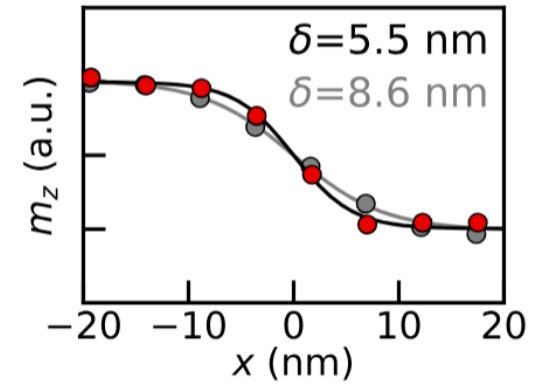
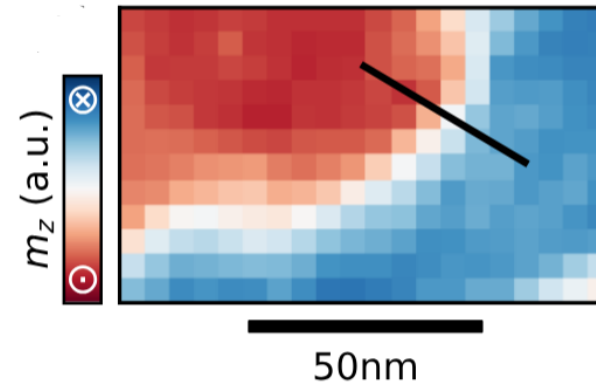
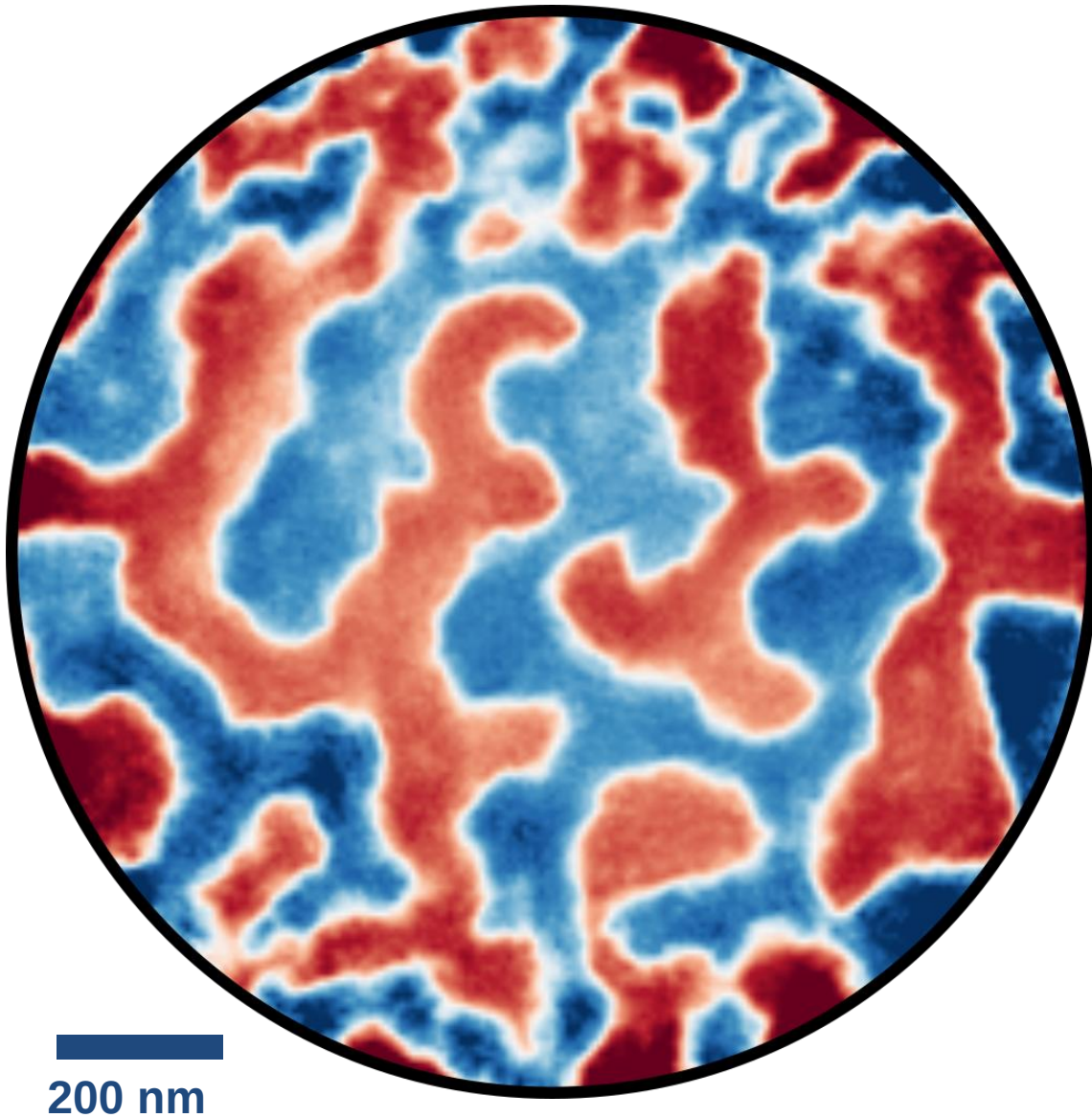
0th approach: Structural characterization



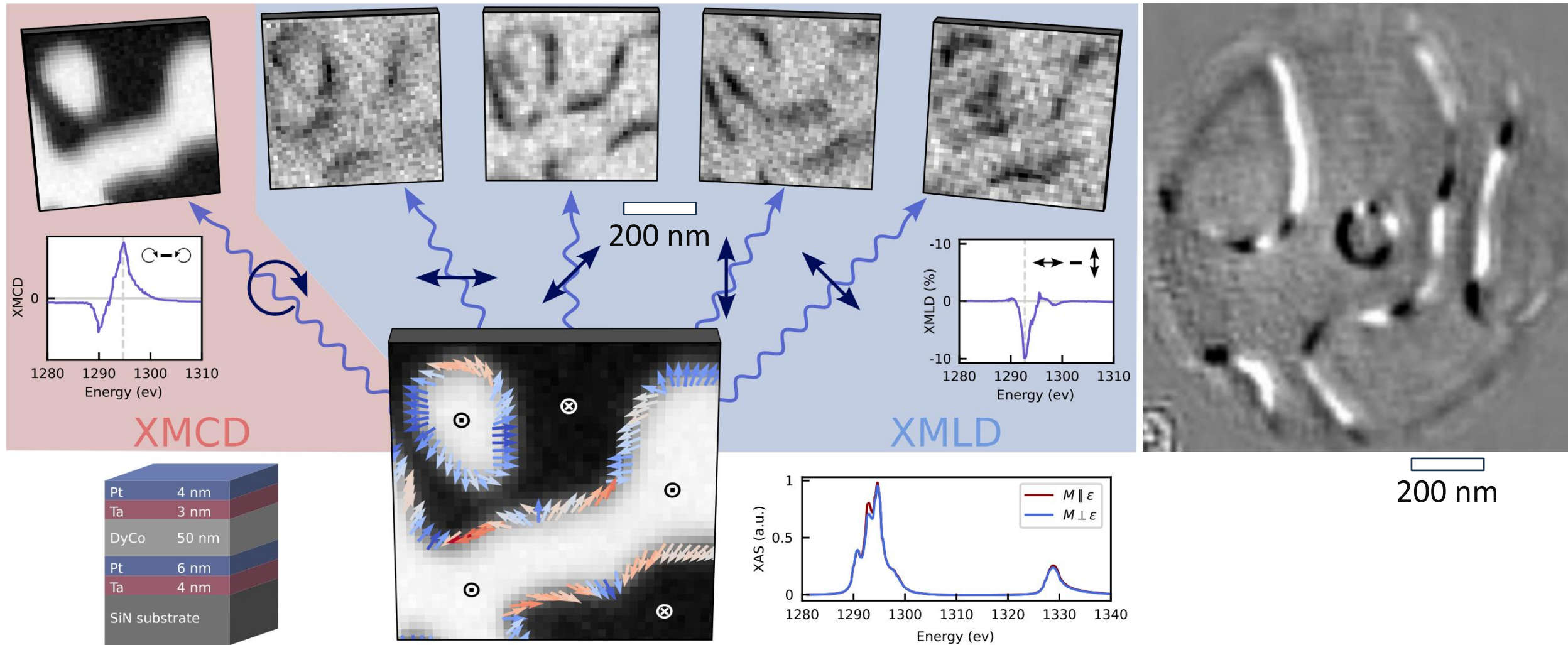
1st approach: Statistical studies of pinning



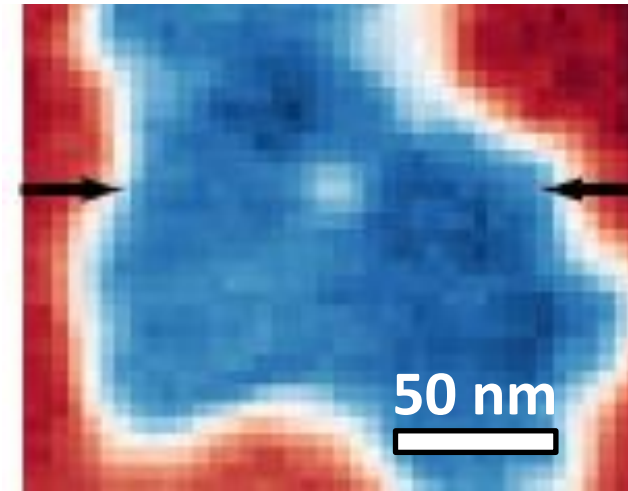
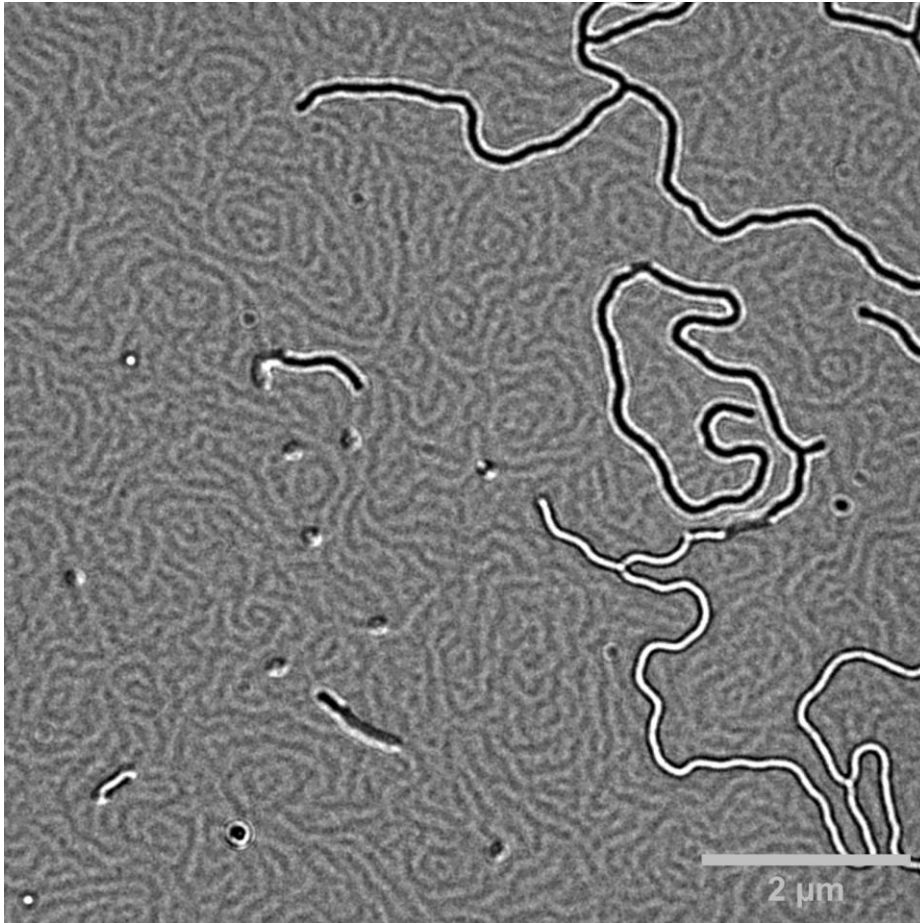
2nd approach: Local texture details



2nd approach: Local texture details

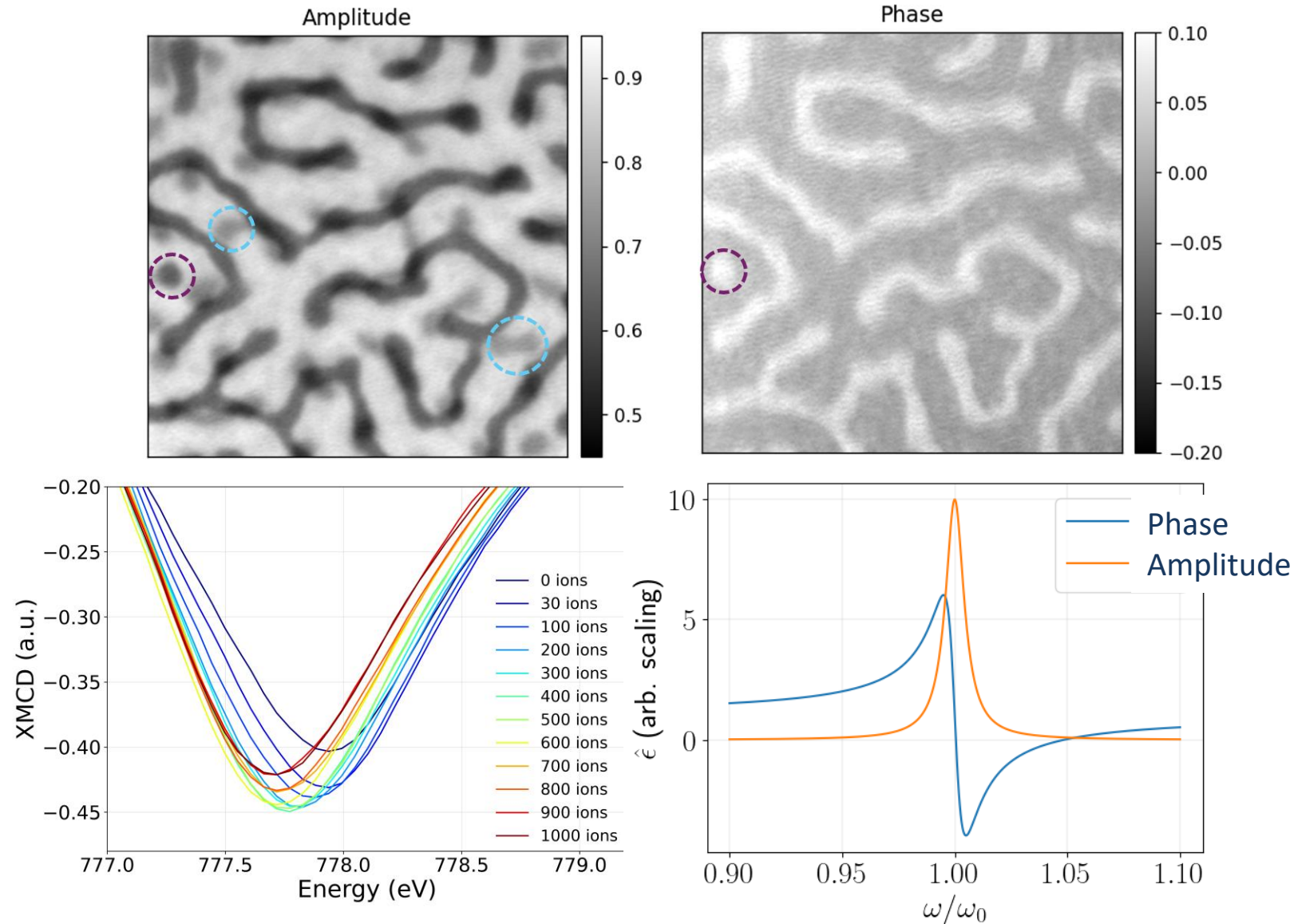
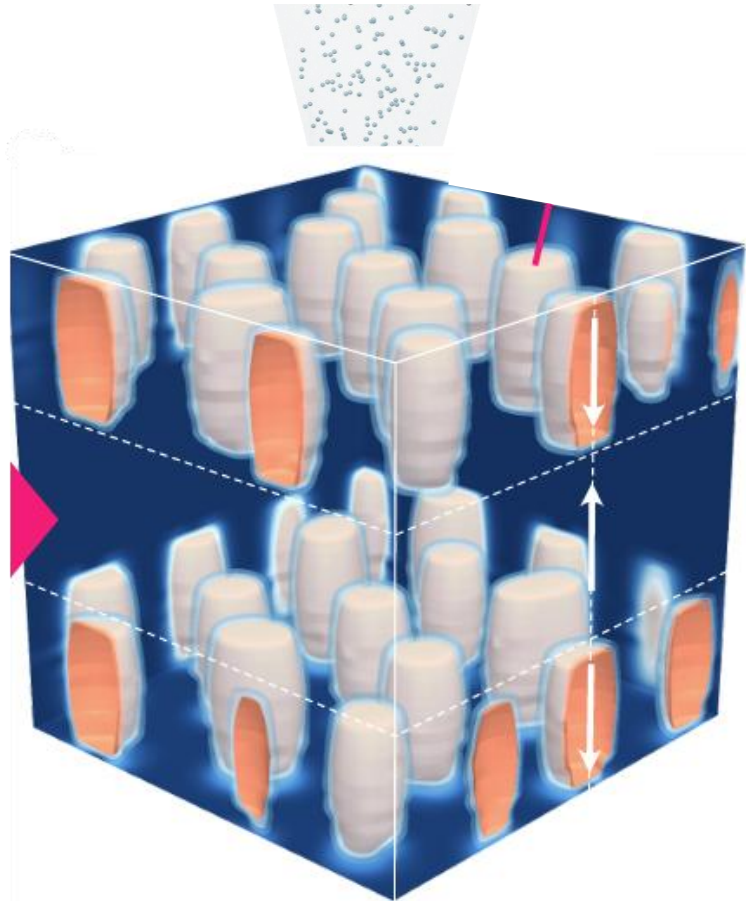


3rd approach: Residual modulations in the saturated state



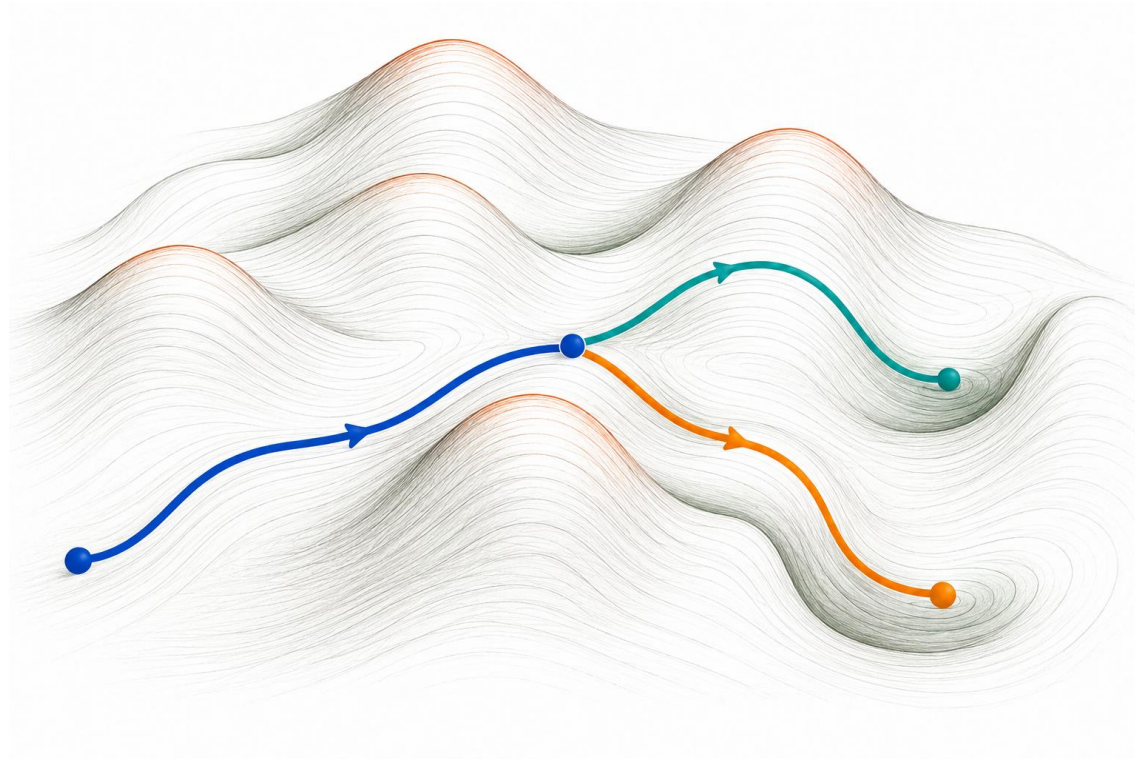
5 nm resolution:
Visibility of a magnetic pinning site.

4th approach: Local spectroscopy / Spectro-imaging



How can we measure energy landscapes?

How can we observe the dynamic pathways?



Observation → Understanding → Control → Technology

Current approach of dynamic imaging: Stroboscopic pump-probe



Only works if the dynamics is exactly periodic!

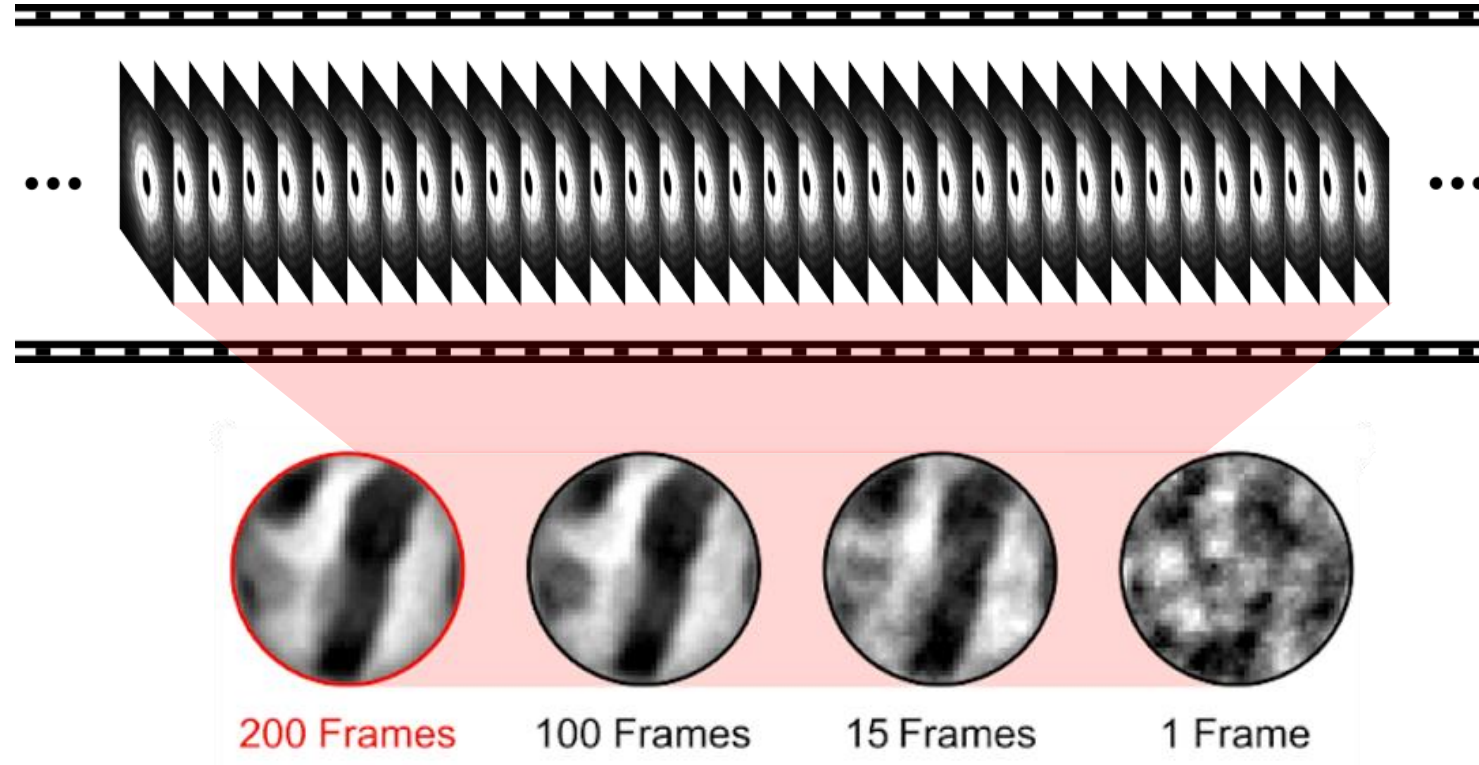
Typically requires 100,000,000 repetitions.

Dilemma of real-time imaging: Temporal vs. spatial resolution

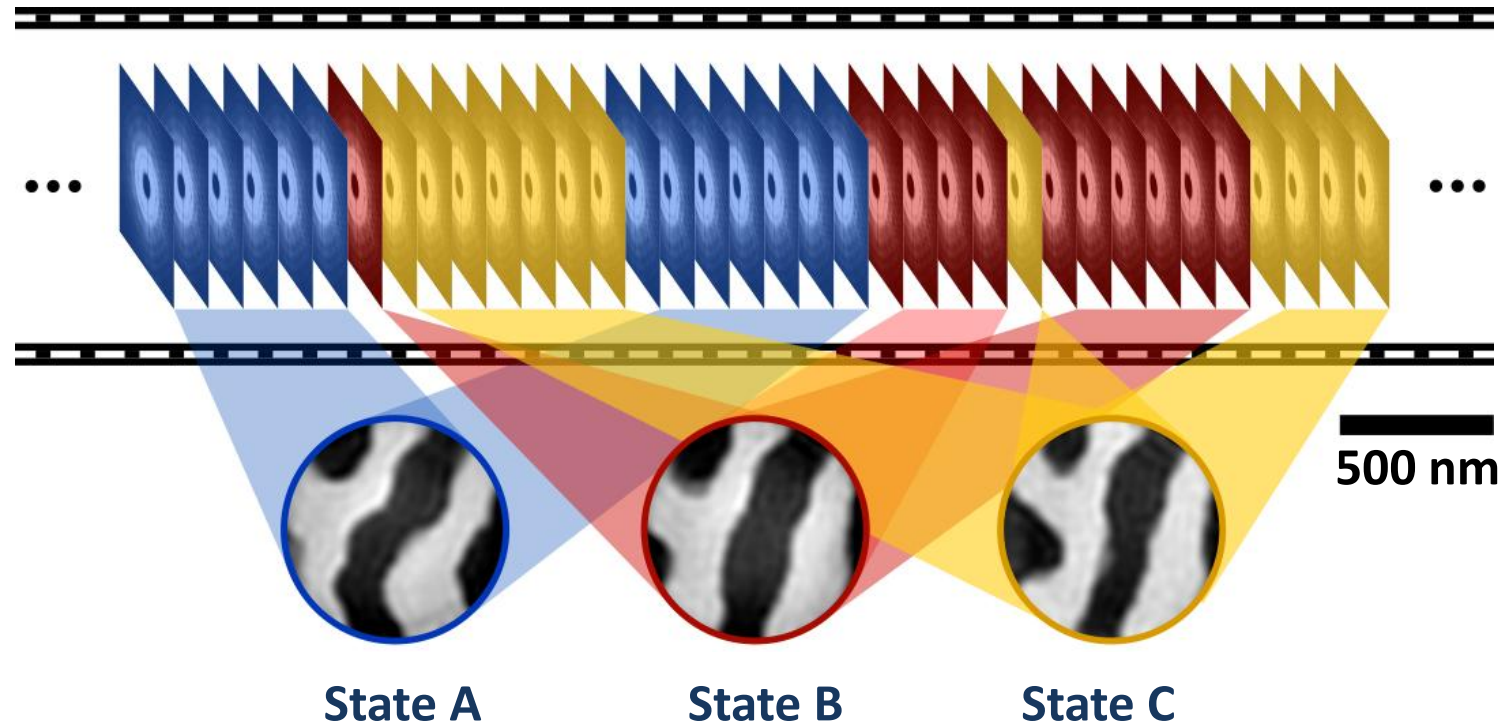


Cannot resolve individual cars (too fast, too dim).

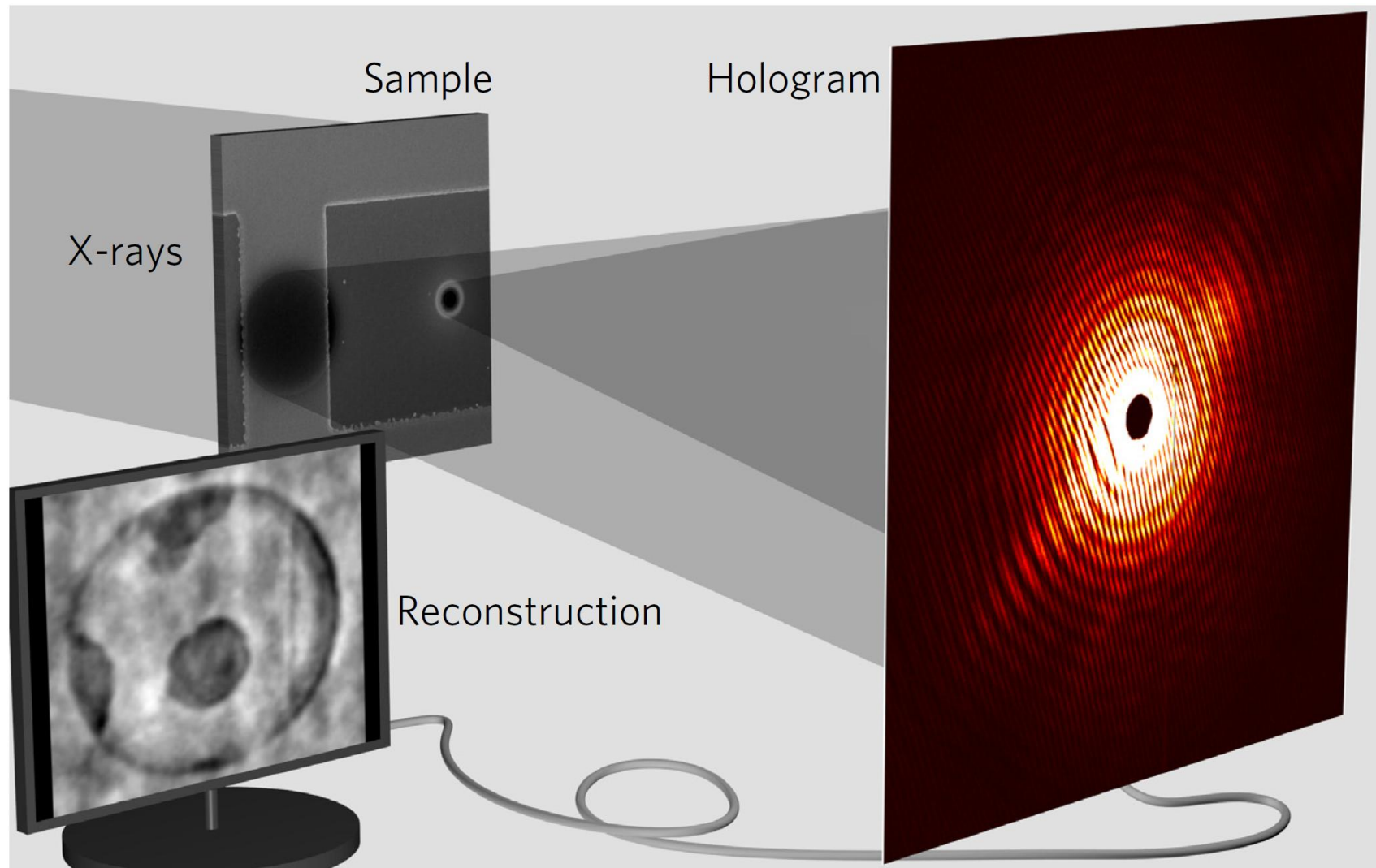
What is the problem with averaging? The indiscriminate process!



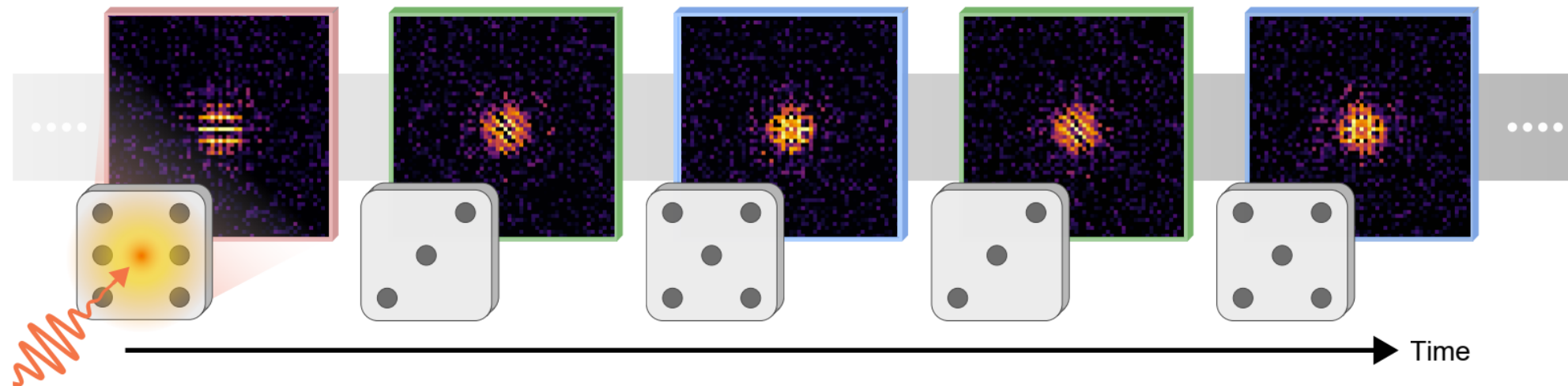
Conceptual idea: Informed averaging



Key ingredient: Coherent imaging

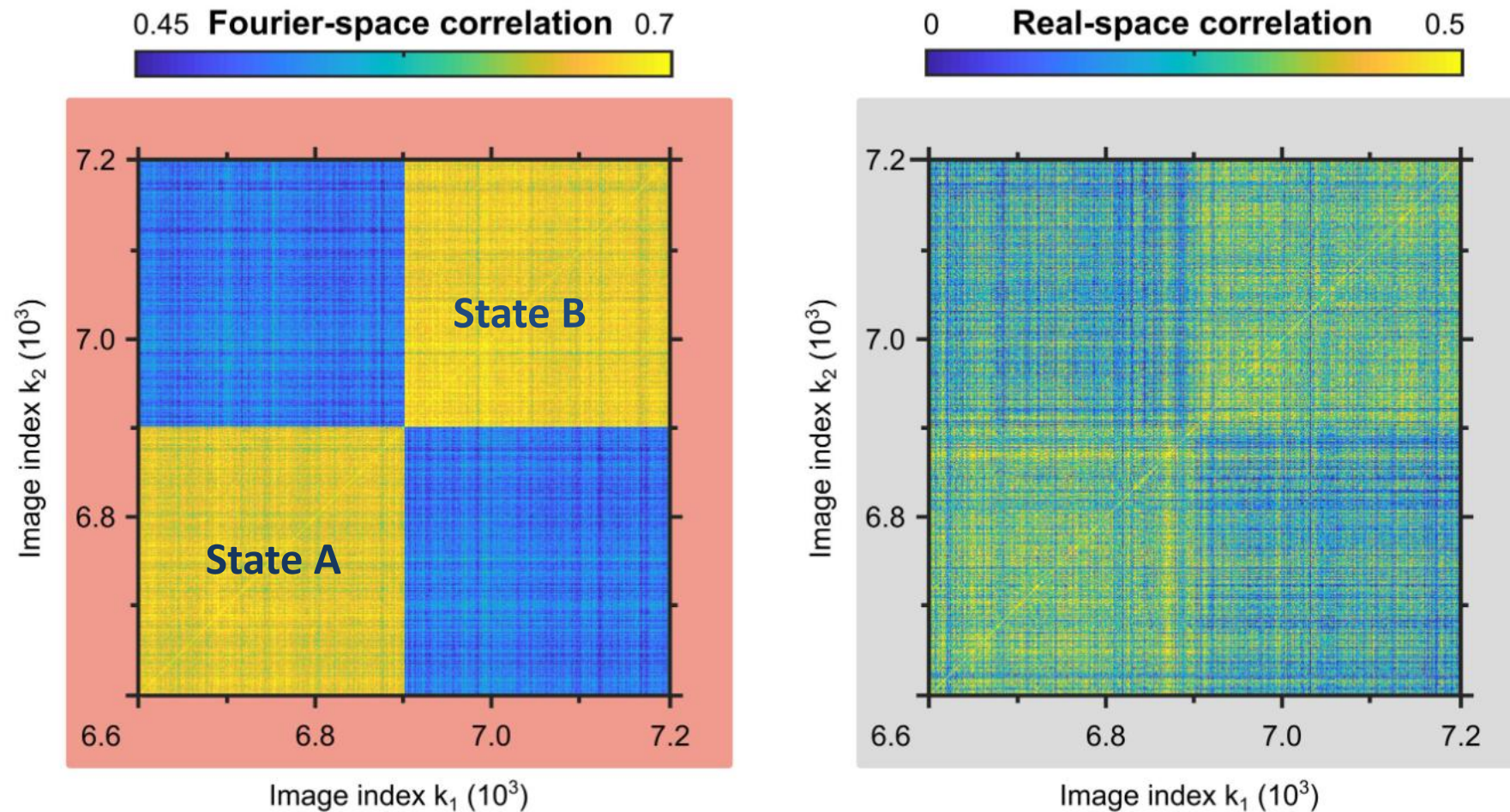


Time-resolved coherent imaging



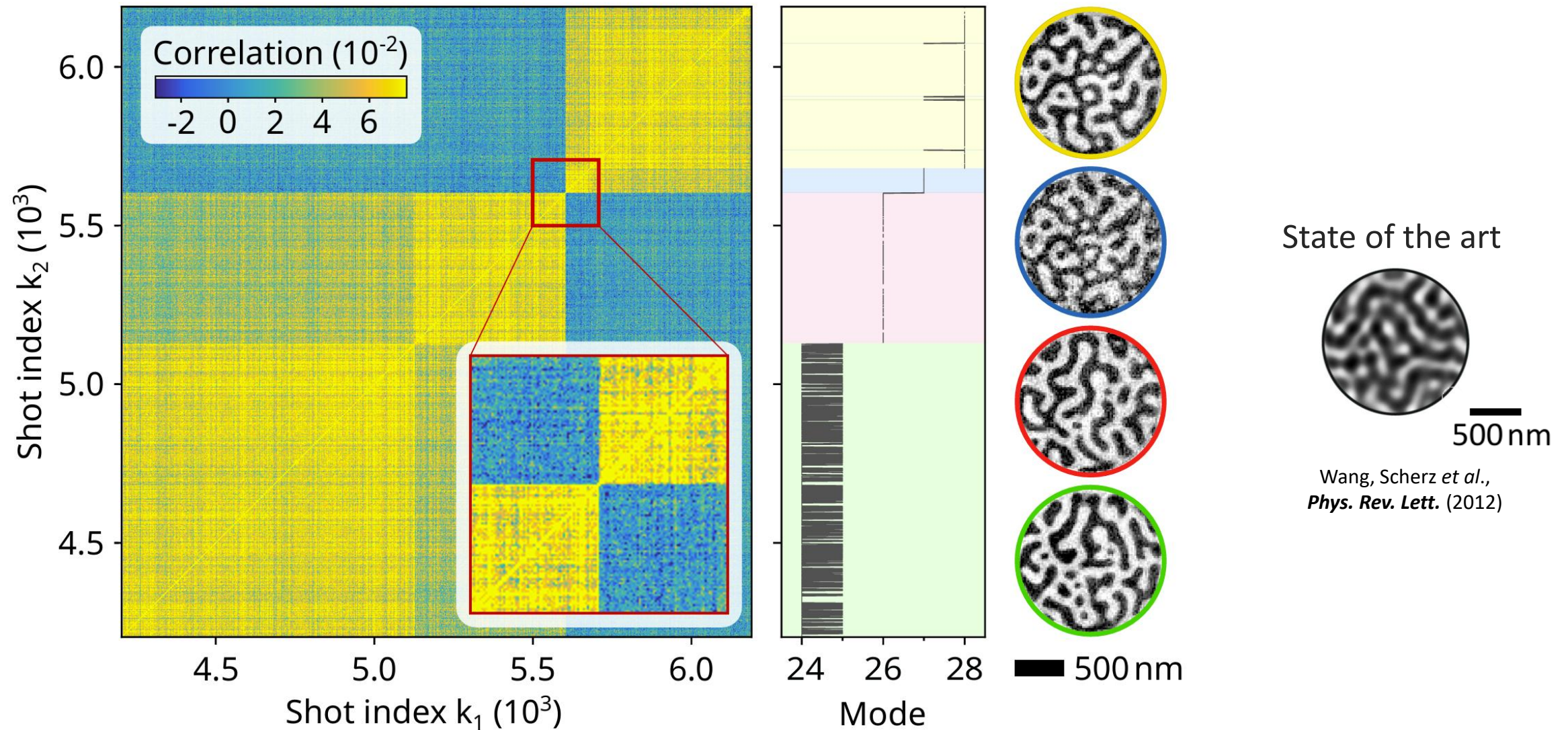
3 photons can be enough to identify the state of the system!
(Compared to **100 million photons** for an image)

How to identify same-state frames? By a correlation analysis.



Fourier-space: 100x better statistics

Works down to fs pulses and with millions of images



Acknowledgements



C. Klose



R. Battistelli



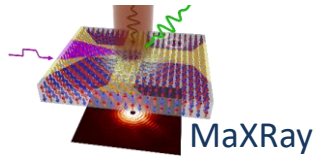
D. Metternich



K. Puzhekadavil Joy



T. Karaman



***K. Litzius, S. Wittrock,
M. Patra, ...***



***M. Valvidares, P.
Gargiani, D.P. Salinas***



***B. Pfau, M. Schneider, L.-
M. Kern, K. Gerlinger, D.
Engel, S. Eisebitt, ...***



***A.-O. Mandru, E.
Darwin, ..., H. J. Hug***



***W. Hu, C. Mazzoli,
S. Wilkins, A. Barbour***



***S. Zayko,
C. Ropers***

Funding:

HELMHOLTZ RESEARCH FOR
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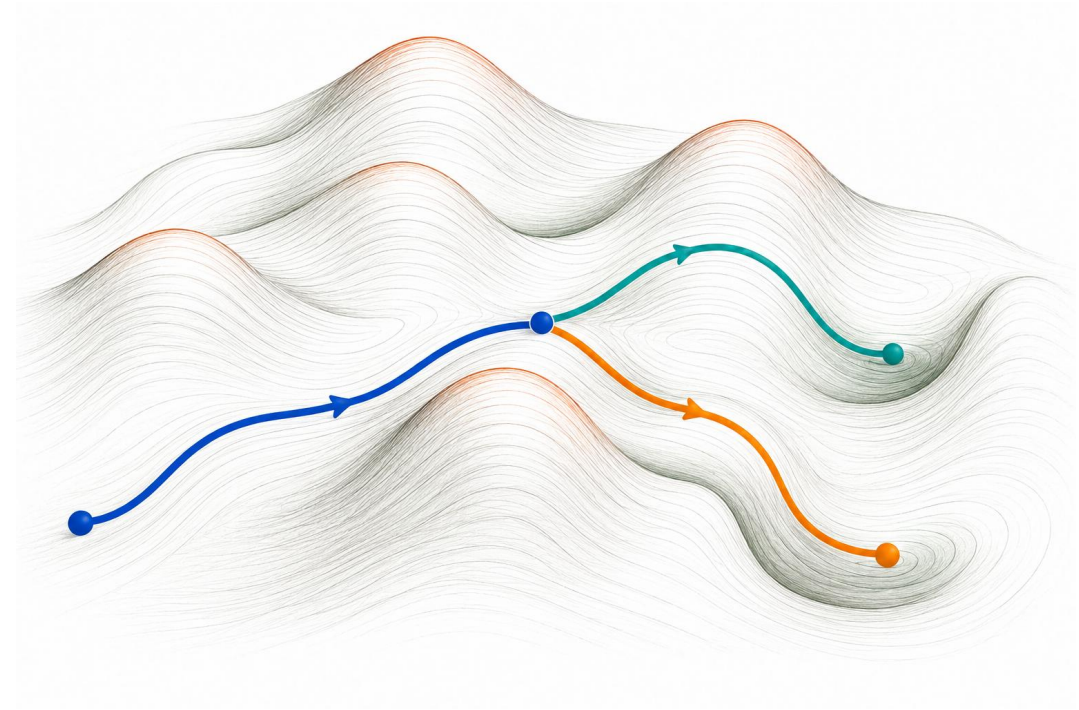
Bundesministerium
für Forschung, Technologie
und Raumfahrt

Summary and outlook

Dynamics-disorder relations are rich, relevant and underexplored

Quantitative, not-averaging microscopy is key

Next-gen synchrotrons, with connected labs, can provide this key



Further reading:

- [1] Battistelli, FB, Zayko, *et al.*, **Optica** **11**, 234 (2024)
- [2] Klose, FB, Hu, Mazzoli, Pfau, *et al.*, **Nature** **614**, 256 (2023)

- [3] Metternich, FB, *et al.*, *in preparation*
- [4] Karaman, FB, *et al.*, *in preparation*

- [5] Klose, Sorokin, Pfau, FB, *et al.*, *in preparation*
- [6] K.P. Joy, FB, *et al.*, *in preparation*

Backup