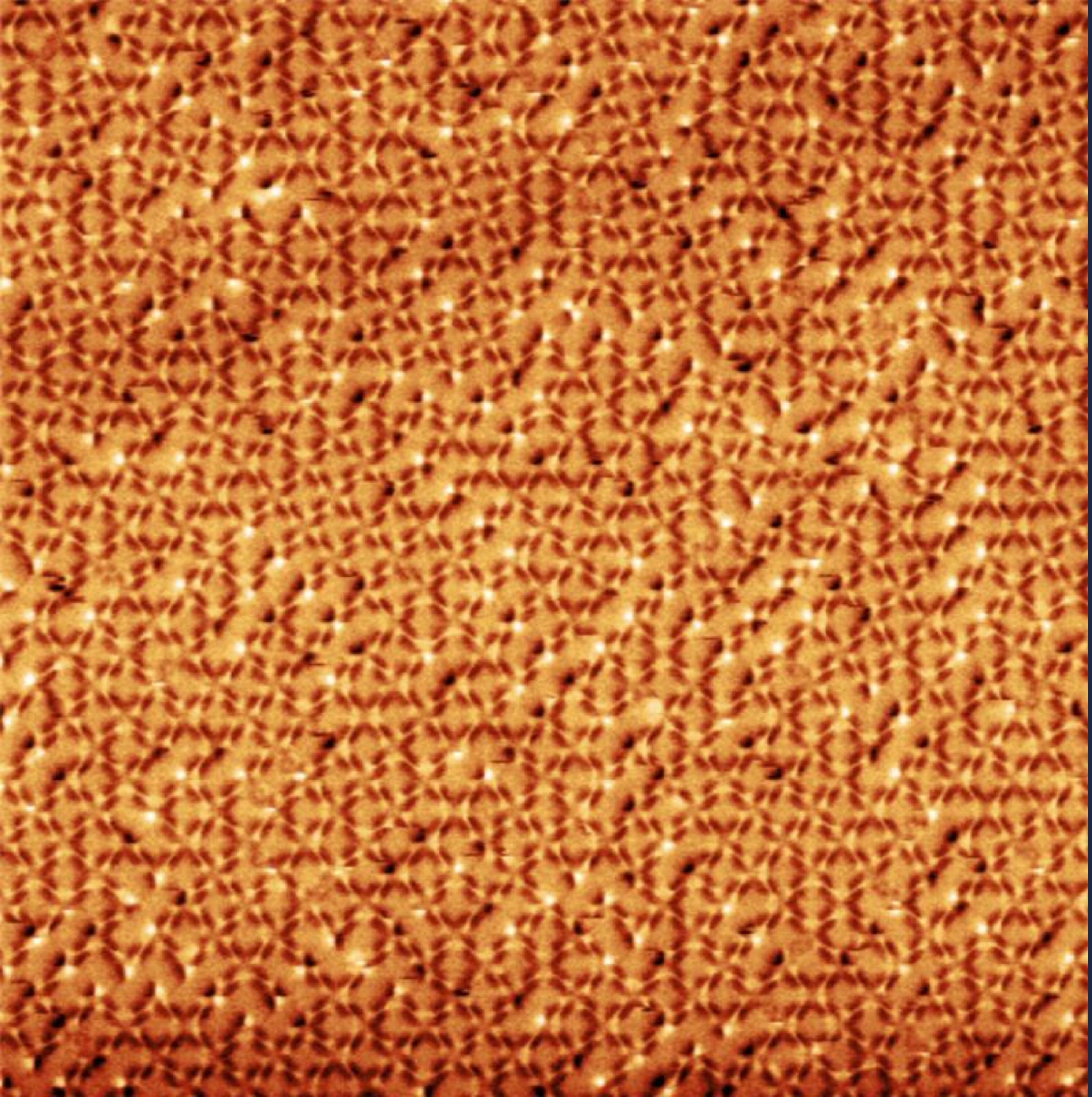

Reconfigurable Training and Reservoir Computing via Spin-Wave Fingerprinting in an Artificial Spin-Vortex Ice

Jack C. Gartside

Kilian D. Stenning, Alex Vanstone, Troy Dion, Holly H. Holder, Francesco Caravelli, Daan M. Arroo, Hidekazu Kurebayashi, Will R. Branford

Imperial College London, UCL, Los Alamos National Lab

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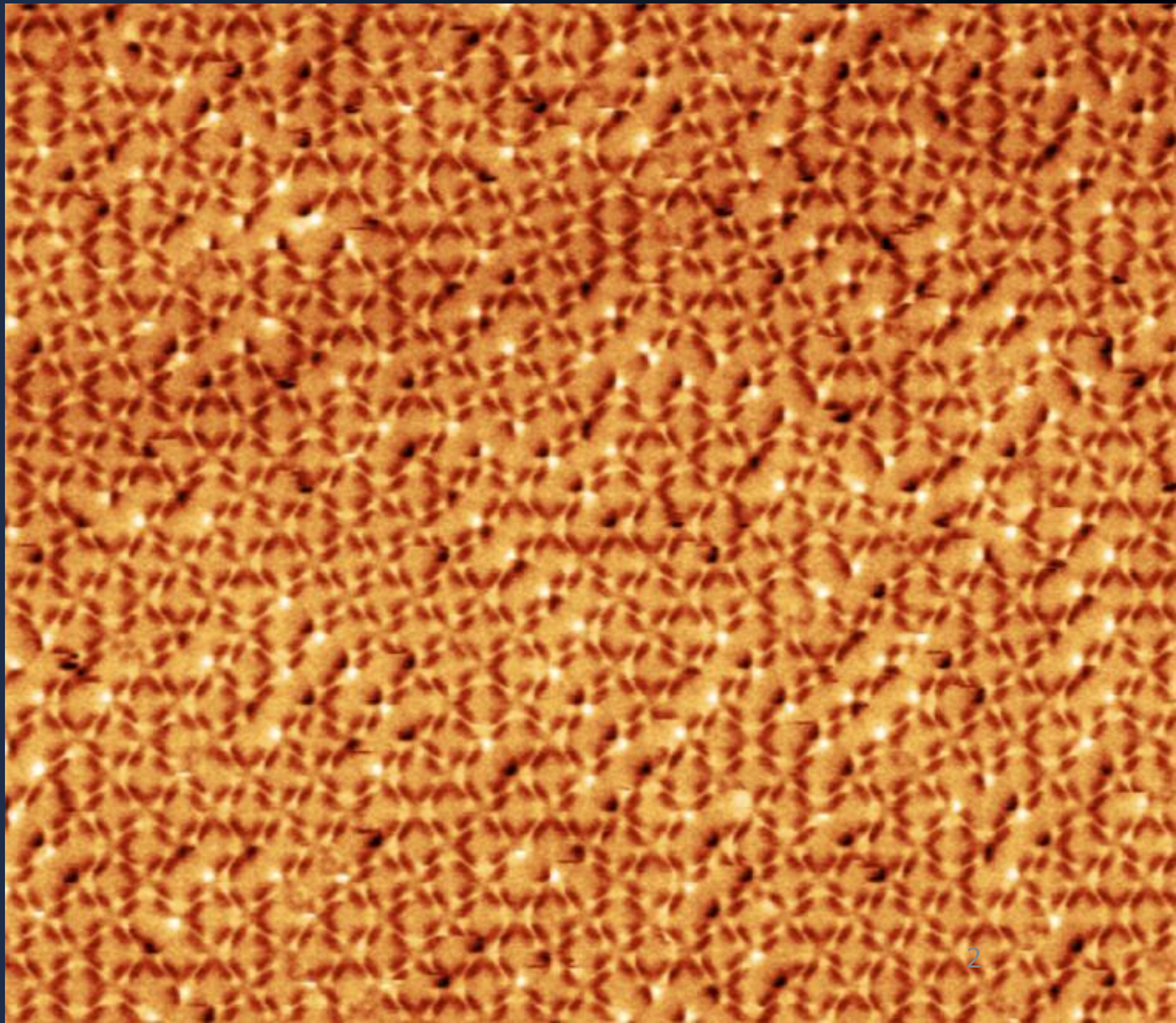
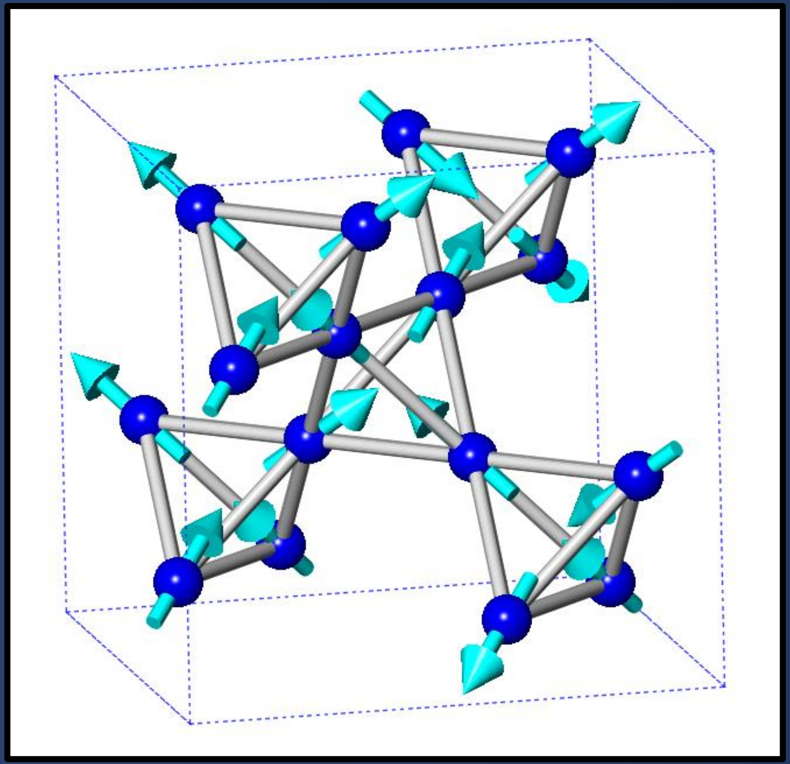
- Introduction to Artificial Spin Systems
- Microstate control
- ASVI - Artificial Spin System engineered for Vortex/Macrospin bistability
- Ratchet-like Macrospin to Vortex conversion
- FMR signatures of Vortex & Macrospin modes
- Long-term training up to 60 field loops
- Targeted vortex writing via MFM tip
- Reservoir computation scheme
  - Waveform transformations
  - Chaotic time-series prediction

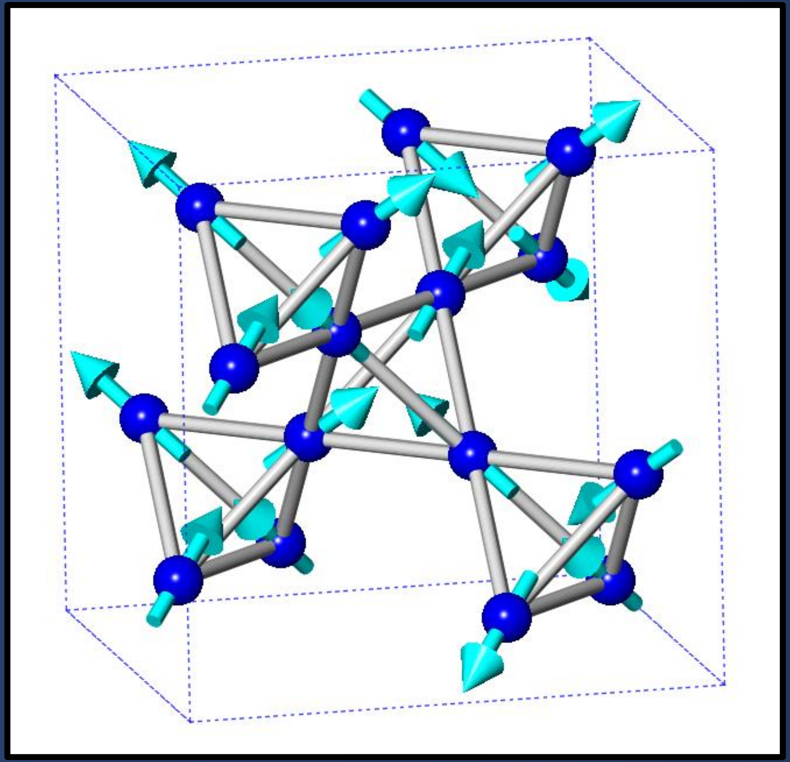


What is an artificial spin system?



Dysprosium titanate

What is an artificial spin system?



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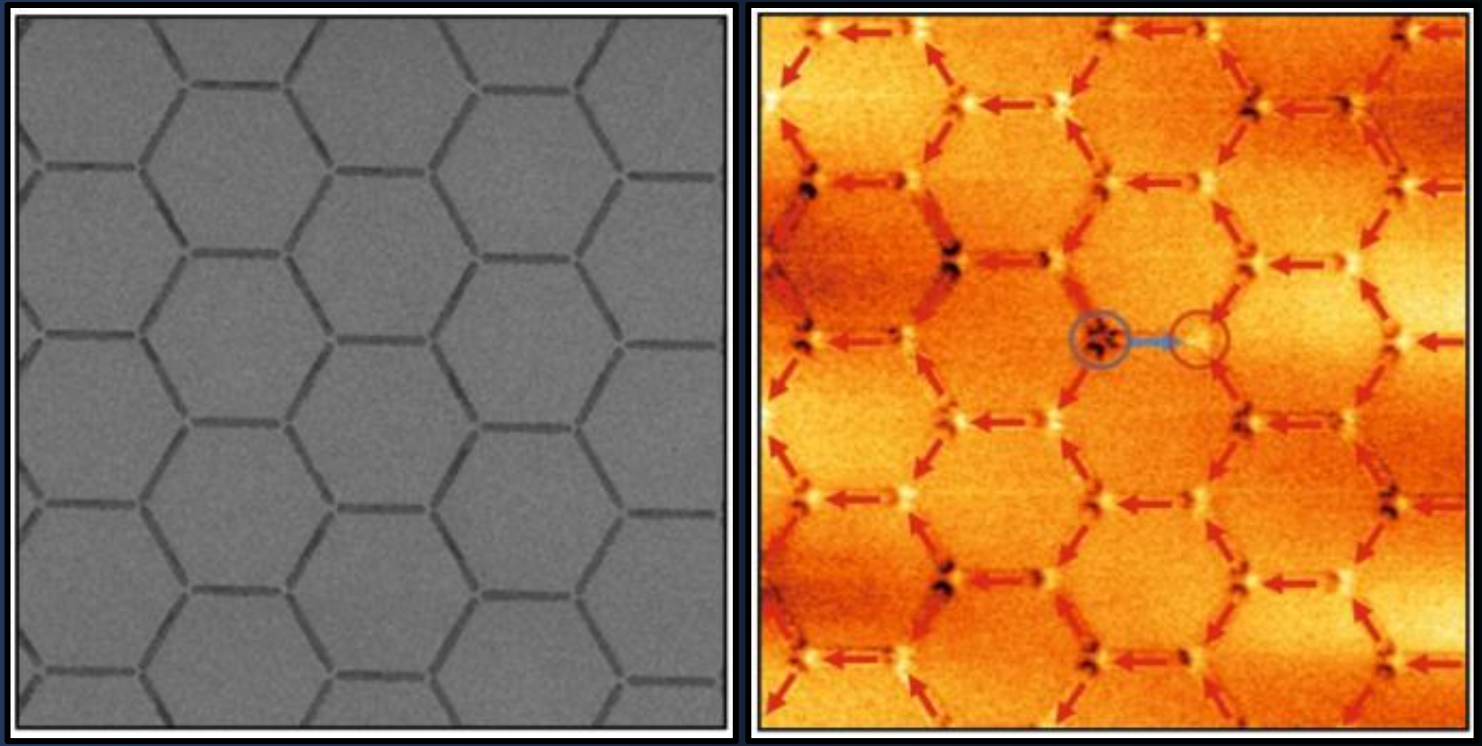
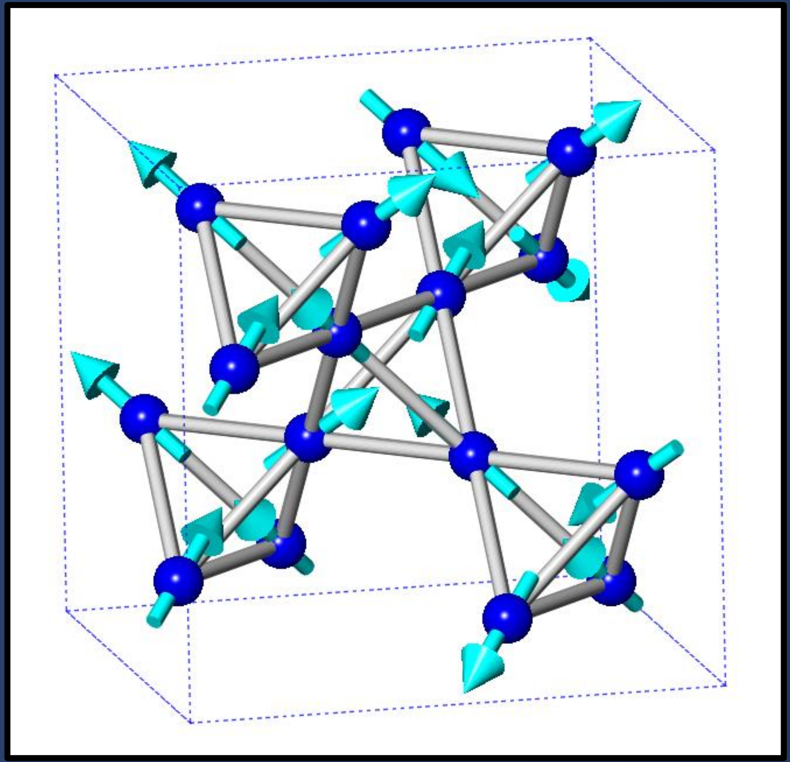


Artificial Spin Ice – Nanopatterned analogue

Gartside et al – *Nature Nanotechnology* (2018)

What is an artificial spin system?



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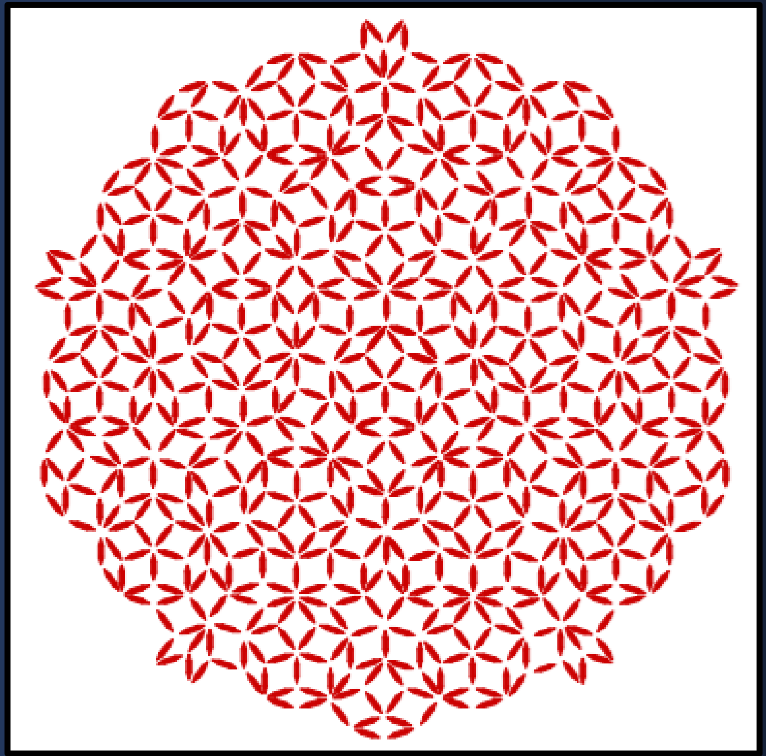
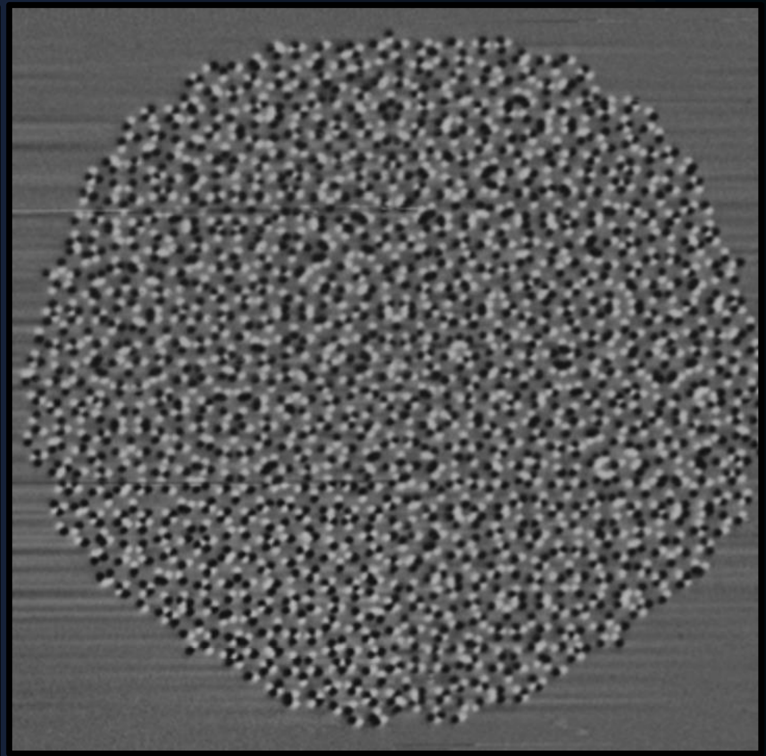


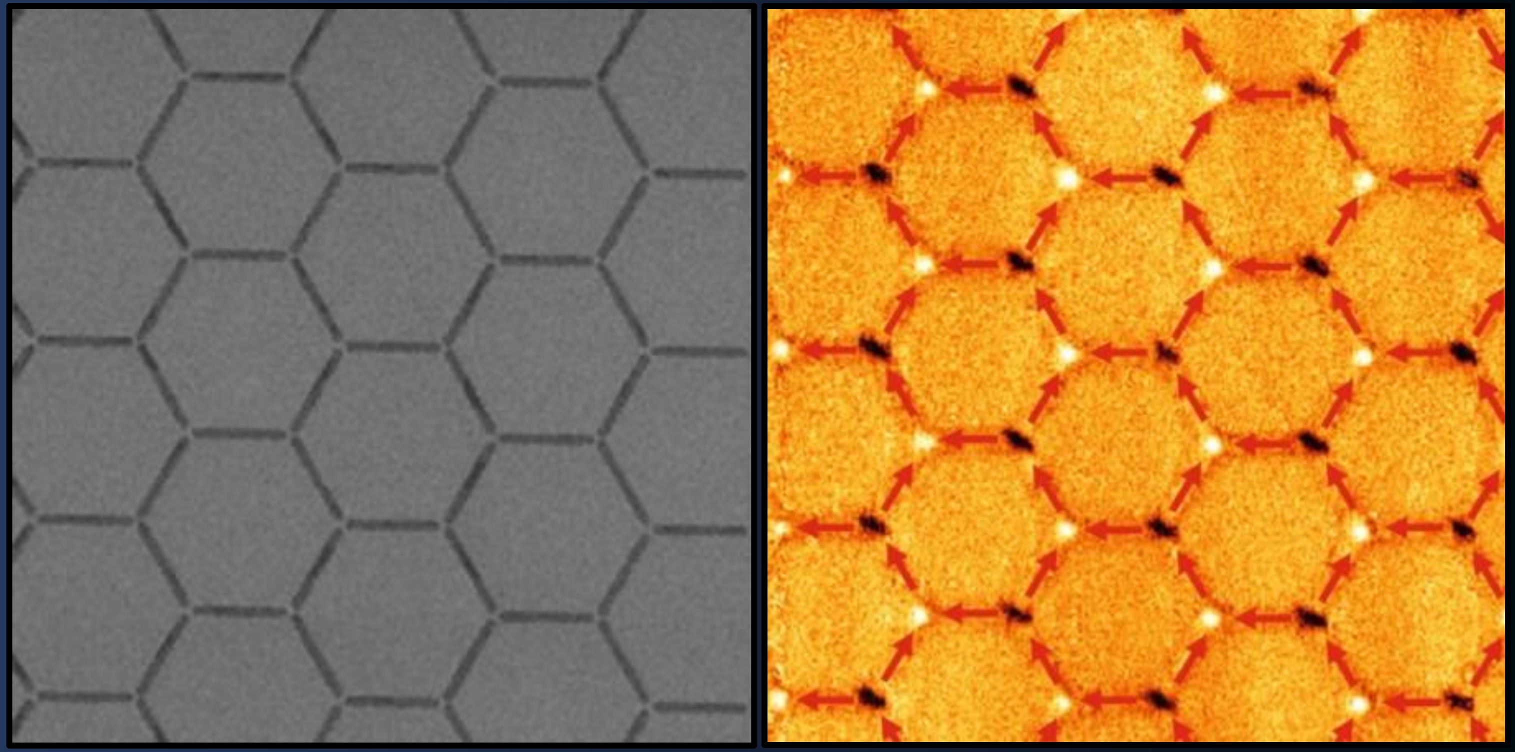


Artificial Spin Ice – Nanopatterned analogue

Shi et al – *Nature Physics* (2018)

What is an artificial spin system? Microstate control

- Great promise of huge microstate space
- Problem: How to access?
- Few states possible:
- Typically all macrospins aligned by field
- Randomised/AC demagnetised
- Thermally annealed



Artificial Spin Ice – Nanopatterned analogue

Gartside et al – *Nature Nanotechnology* (2018)

What is an artificial spin system?
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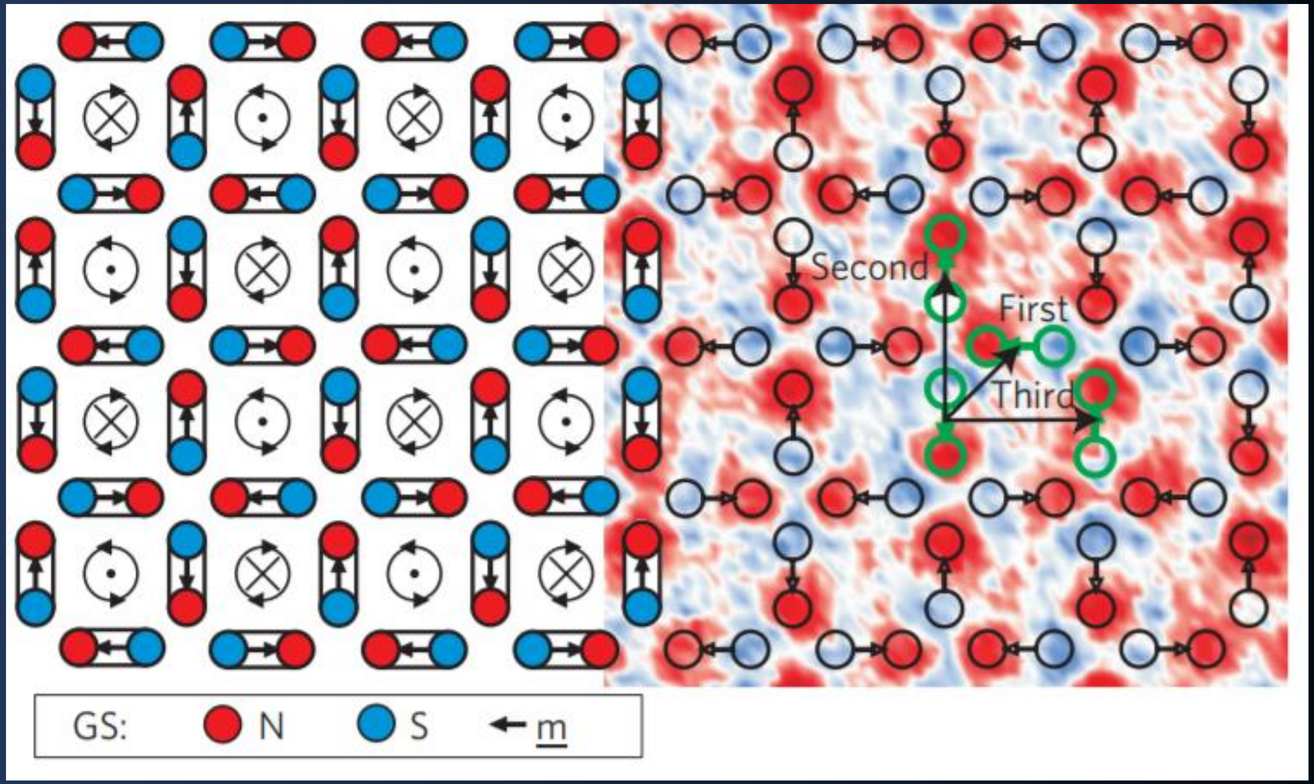
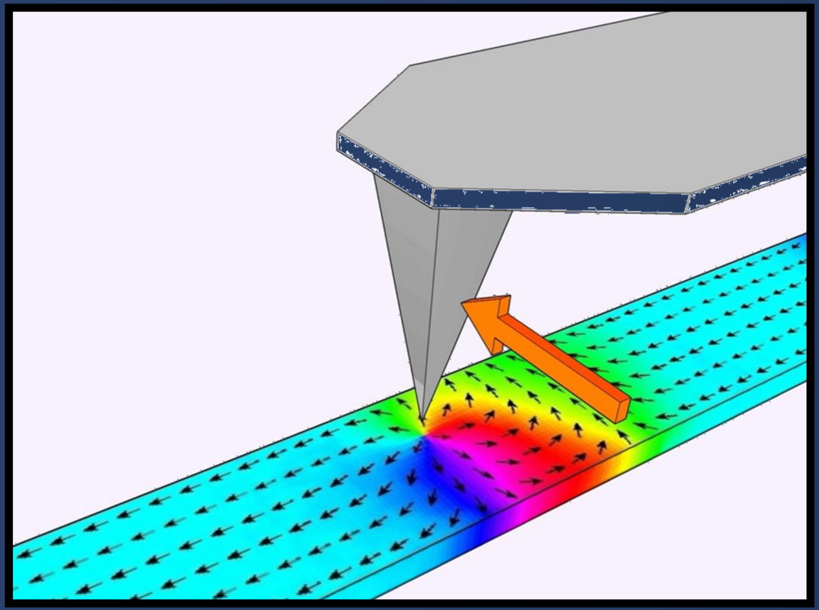
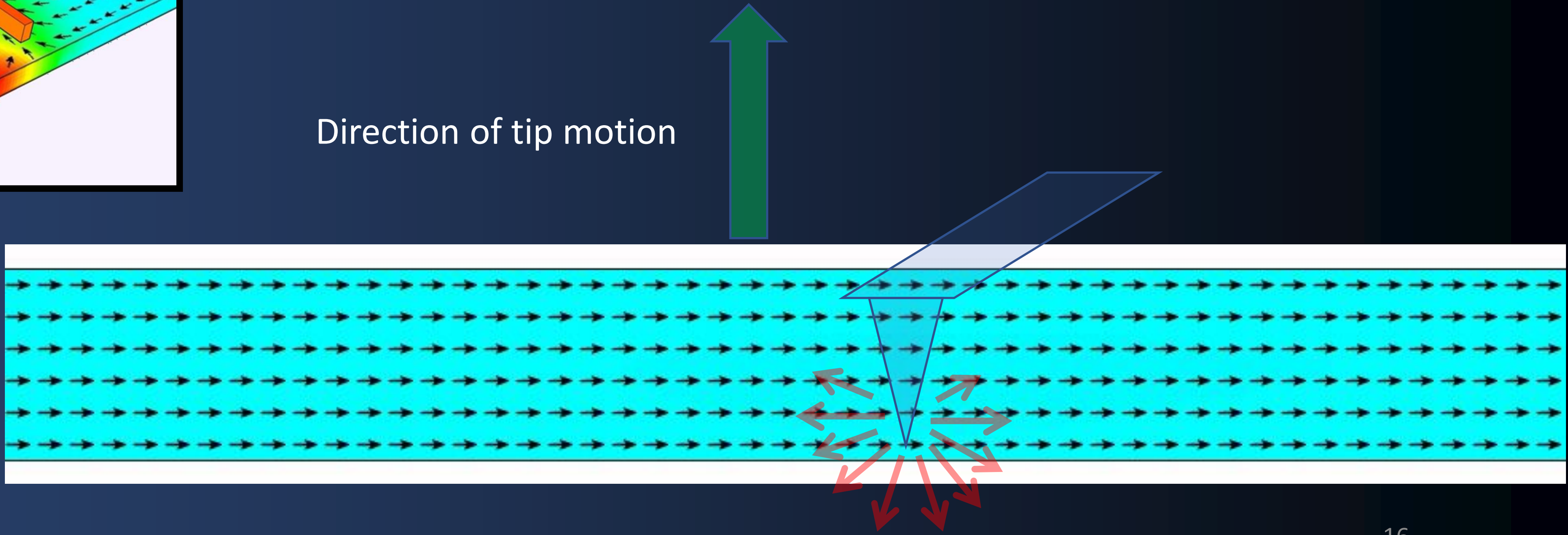


Artificial Spin Ice – Thermally-annealed ground state

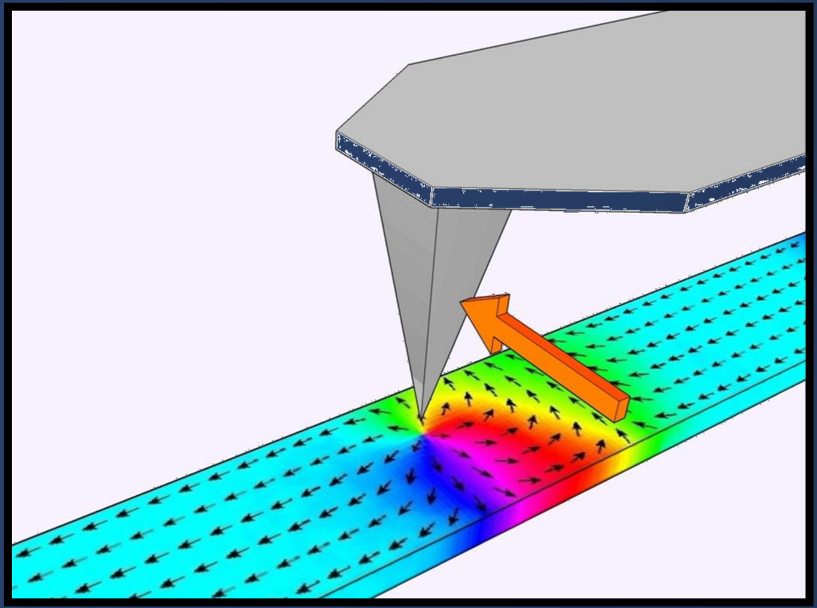
Morgan et al – *Nature Physics* (2010)

Microstate control
Developing a tip-based approach

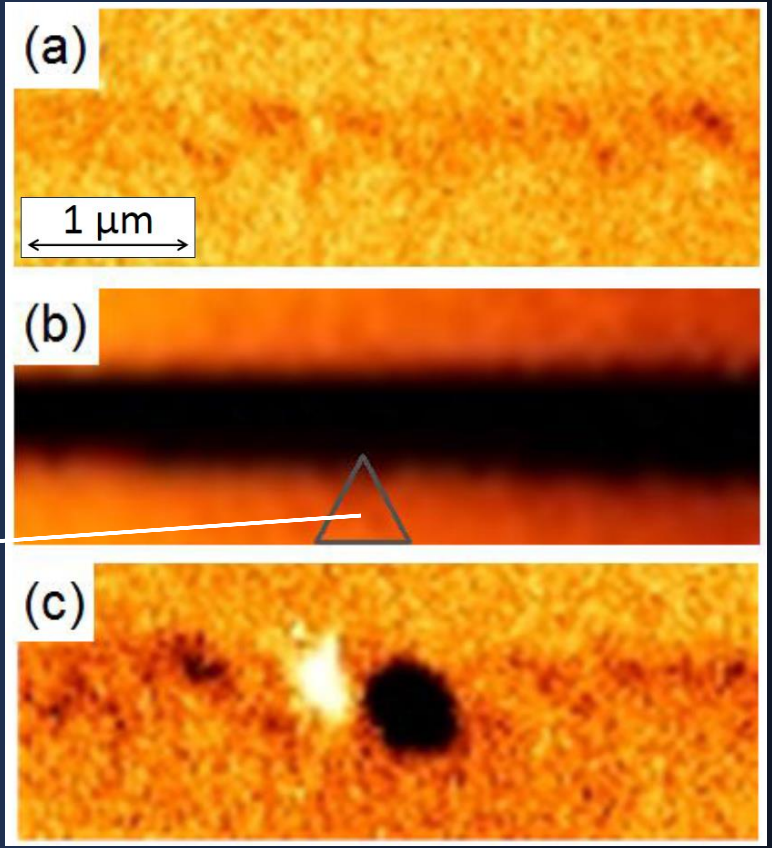




Microstate control
Developing a tip-based approach



MFM data



Low-moment tip

(0.3e-13 emu, 320 Oe)

High-moment tip

(3e-13 emu, 690 Oe)

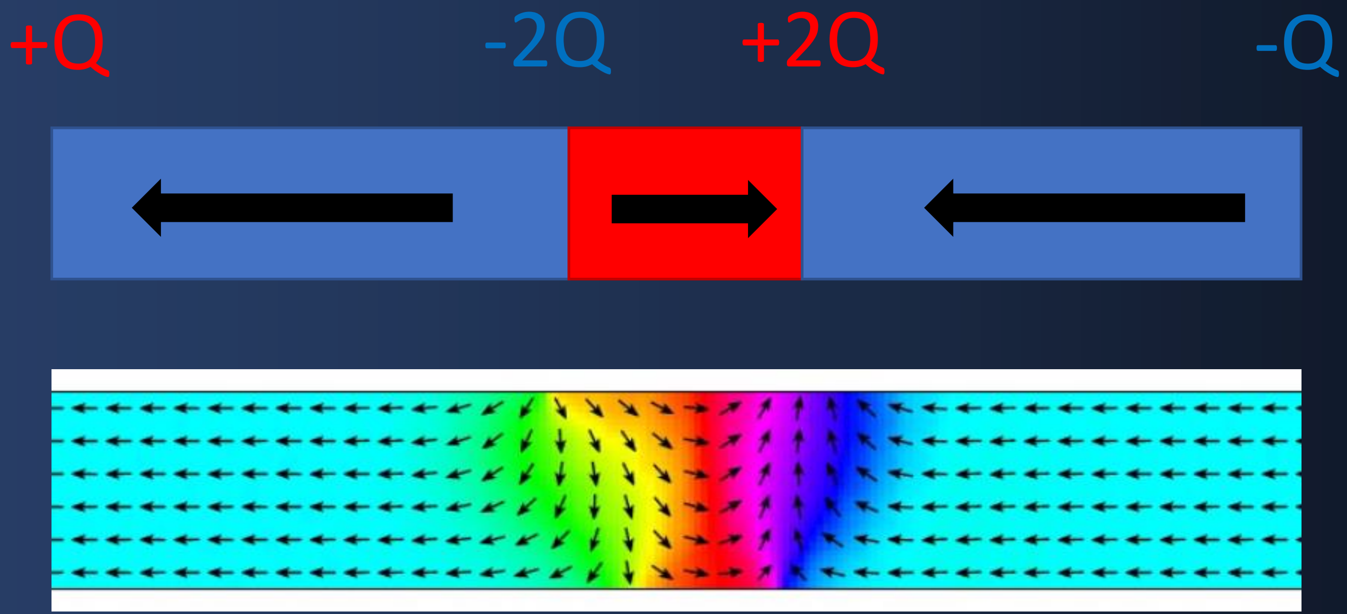
Tip-retraction point

Low-moment tip

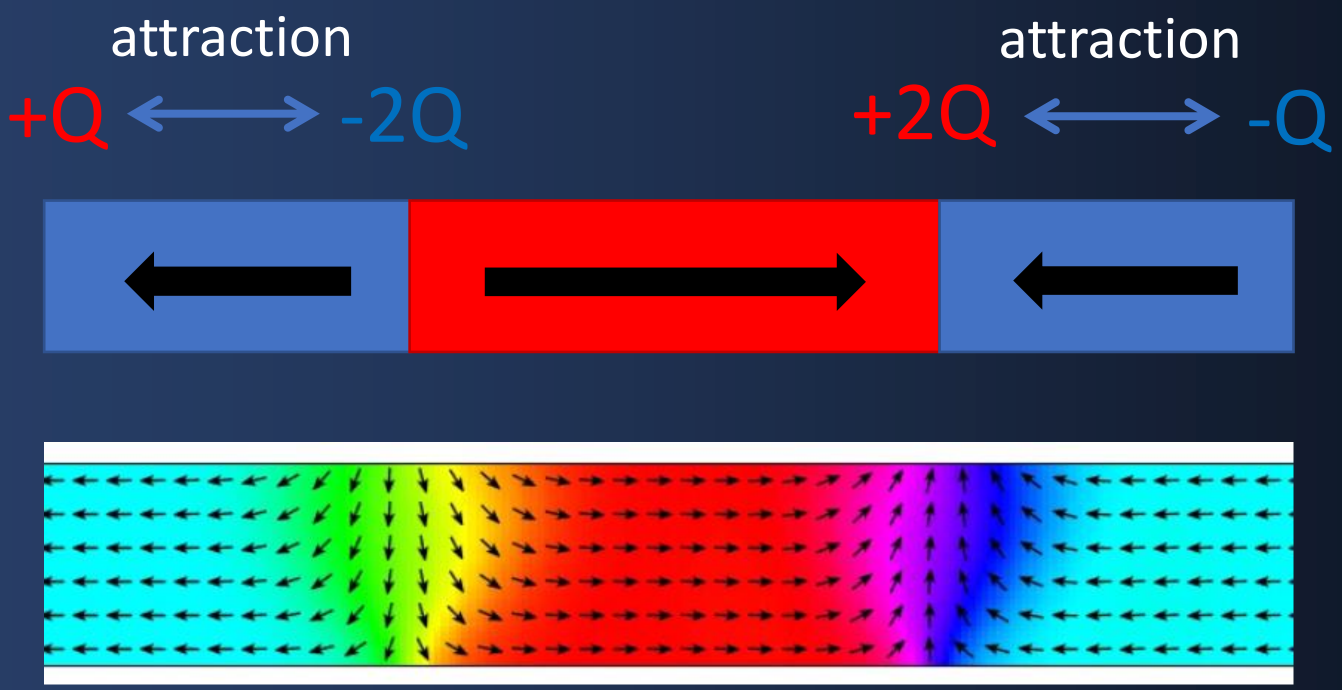
(0.3e-13 emu, 320 Oe)

Gartside et al *Scientific Reports* (2016)

Microstate control
Developing a tip-based approach



Microstate control
Developing a tip-based approach



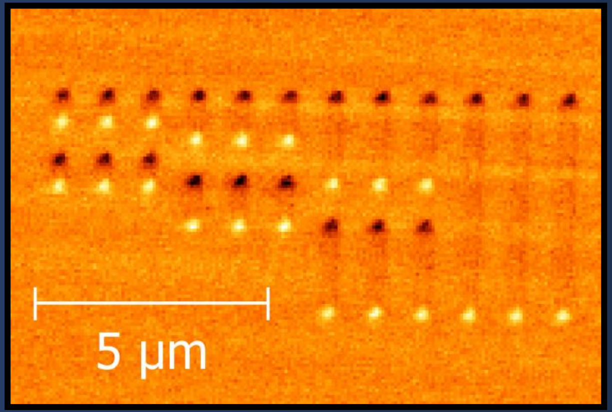
Microstate control
Developing a tip-based approach

Microstate control
Developing a tip-based approach

MFM Data

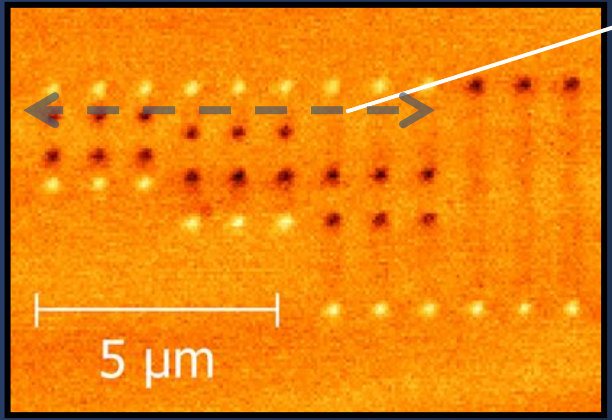
Schematic

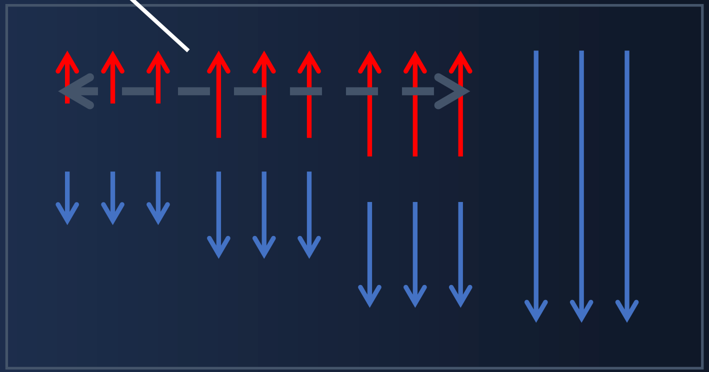
Before
HM scan



Injection scan

After
HM scan





Microstate control
Developing a tip-based approach

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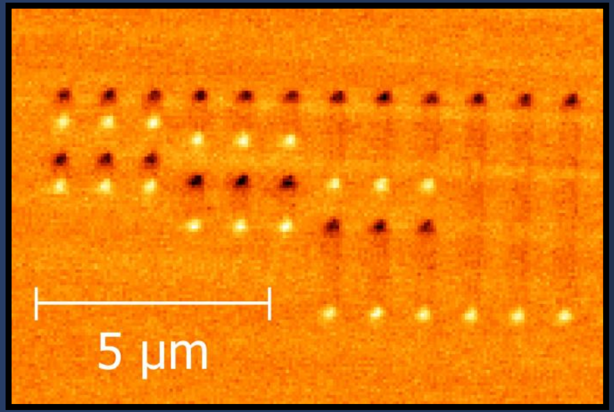
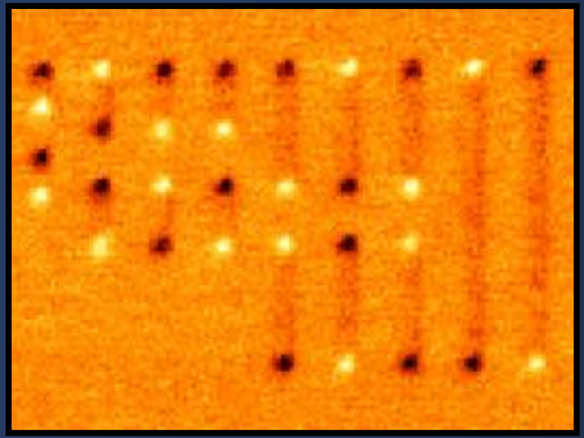
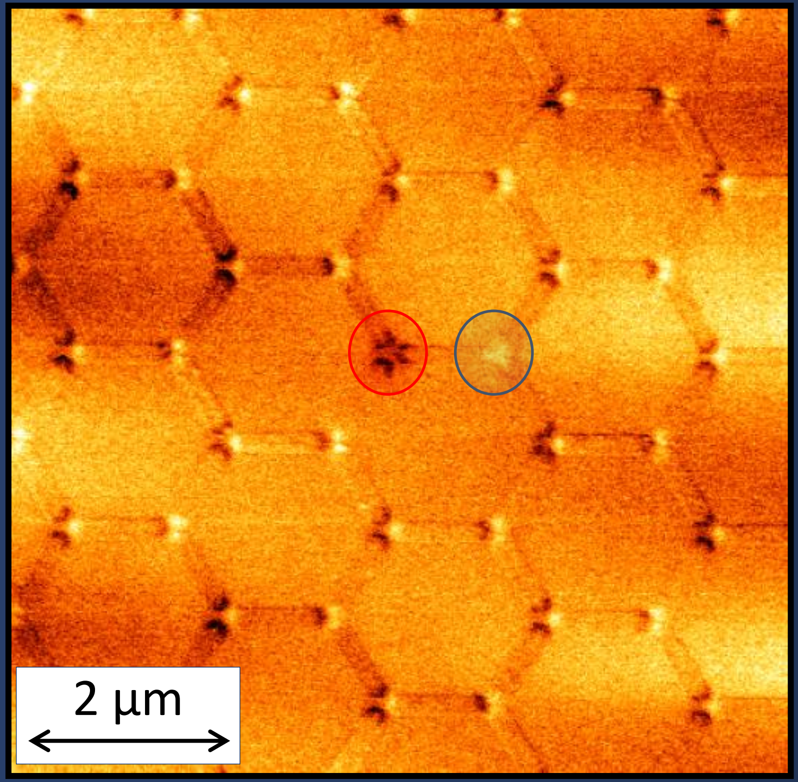


After
HM scan

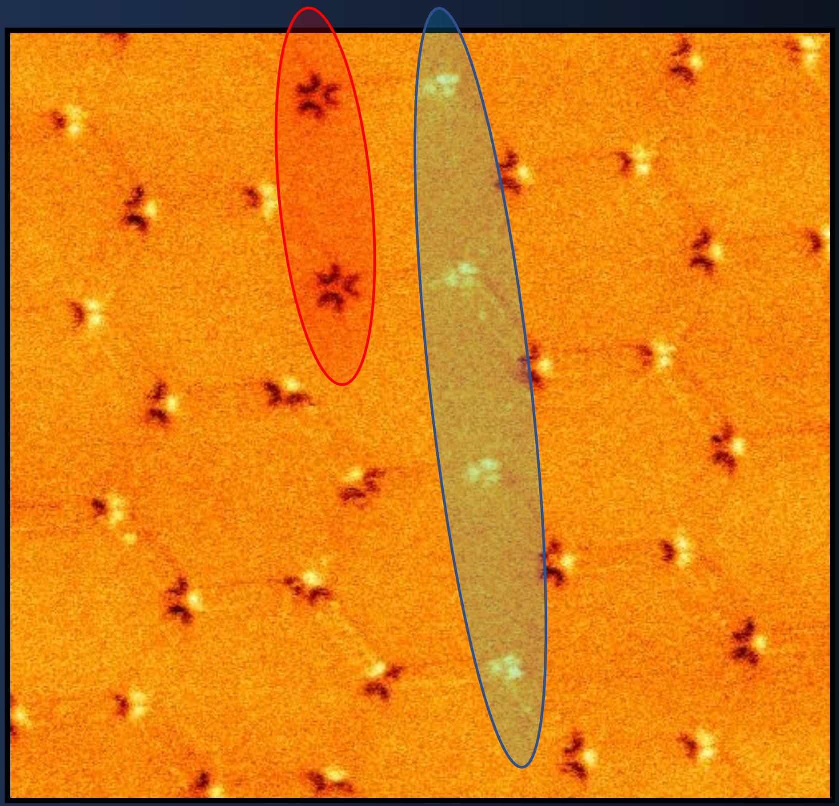


Microstate control
Developing a tip-based approach

Single 'monopole' defects



'monopole' chains



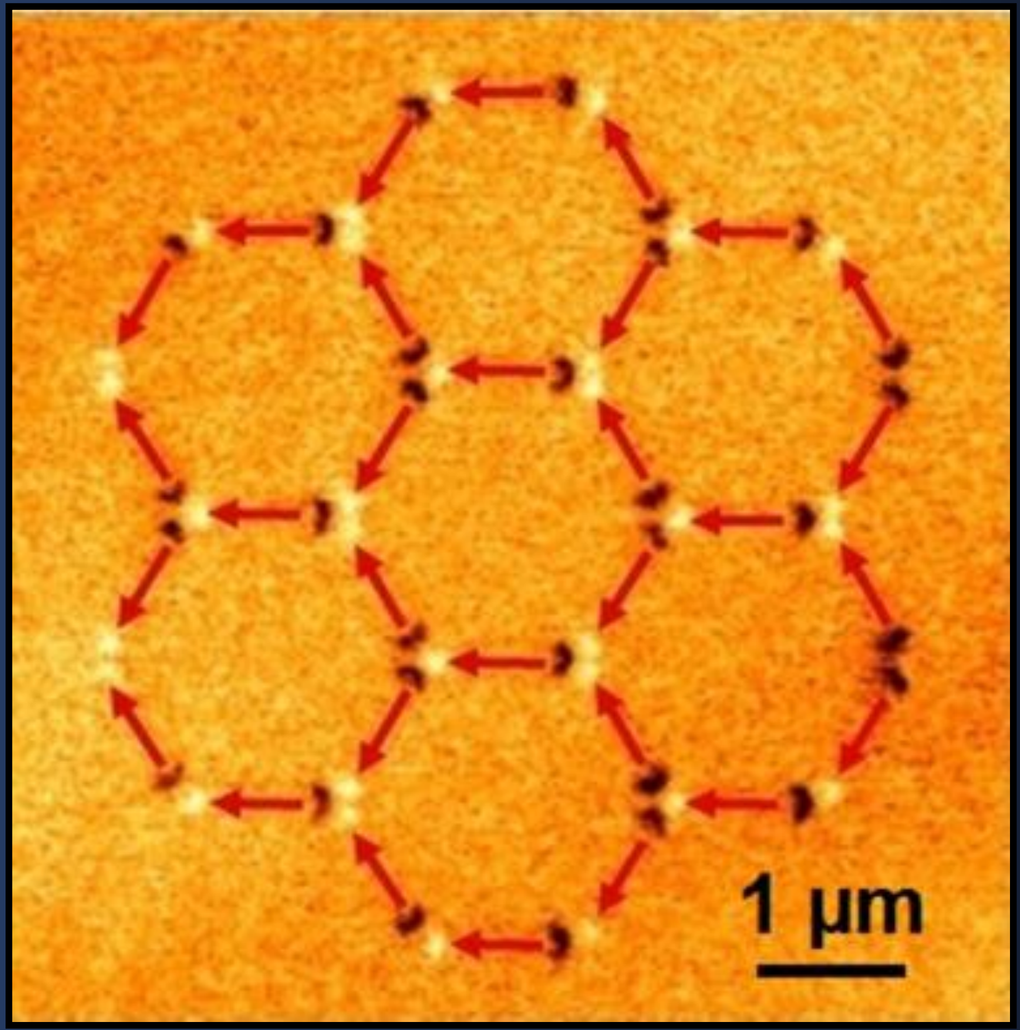
Gartside et al – *Nature Nanotechnology* (2018)

Microstate control

Developing a tip-based approach

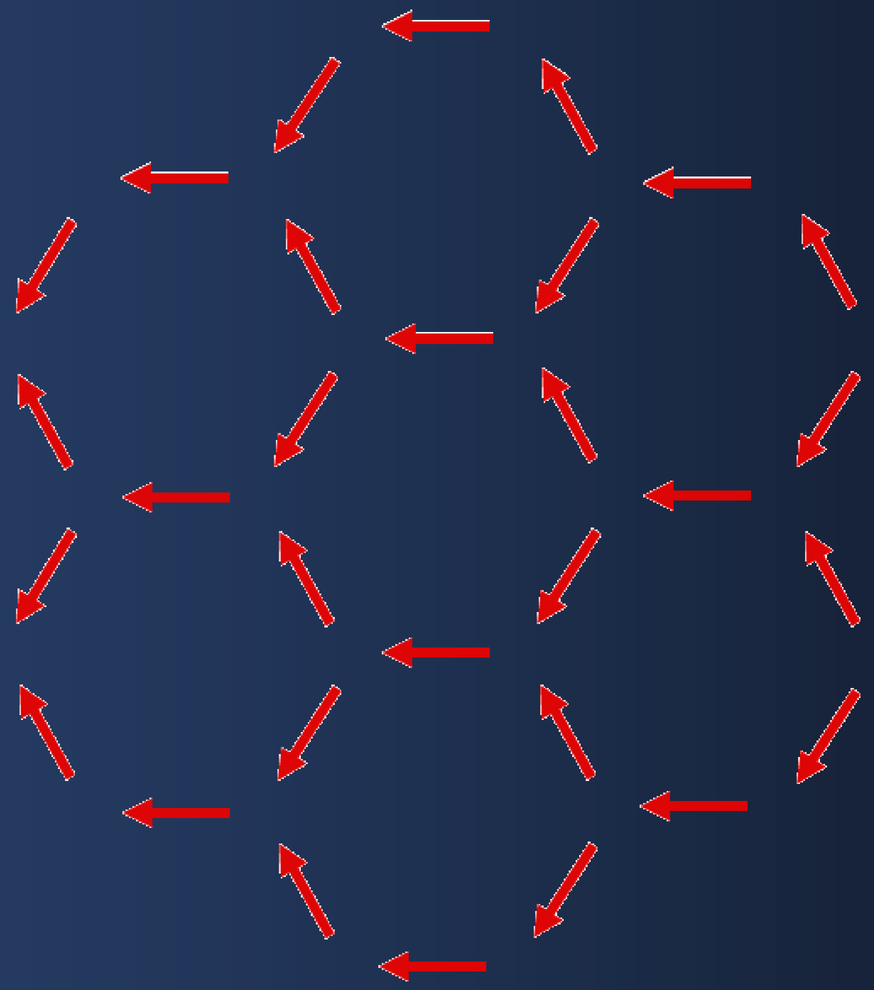
Ground state of kagome ASI

H_{Sat}



Microstate control
Developing a tip-based approach

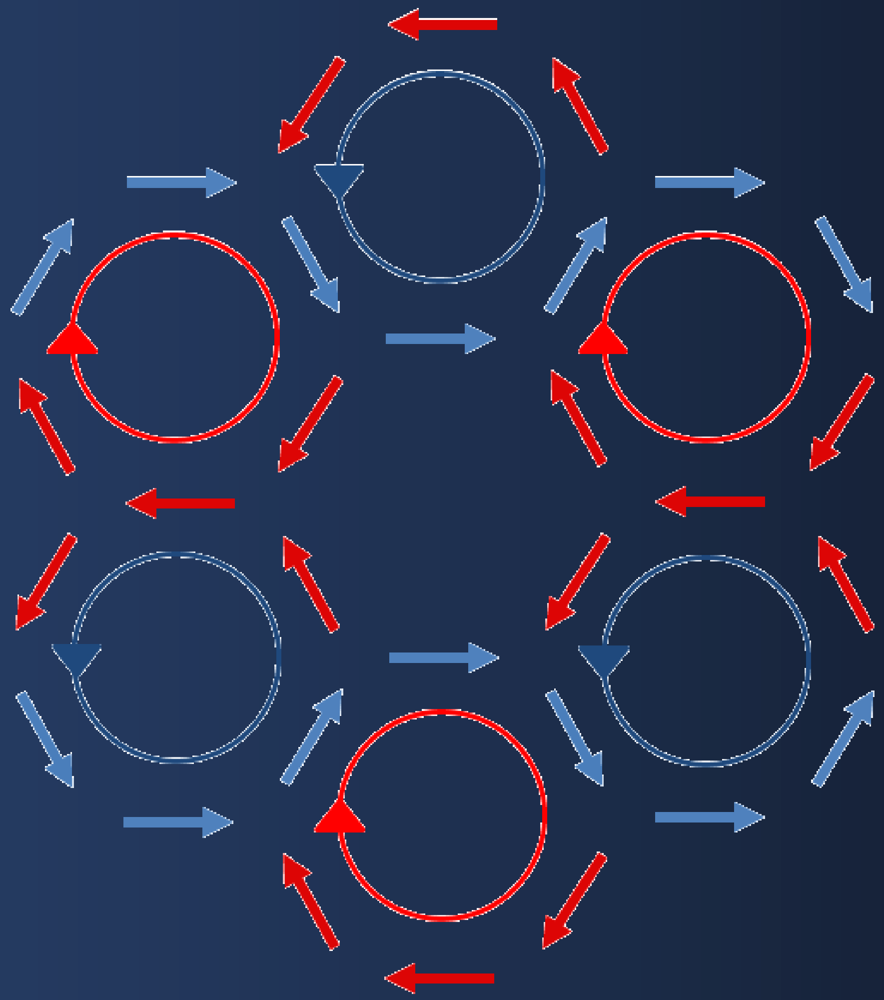
Ground state of kagome ASI



Microstate control
Developing a tip-based approach

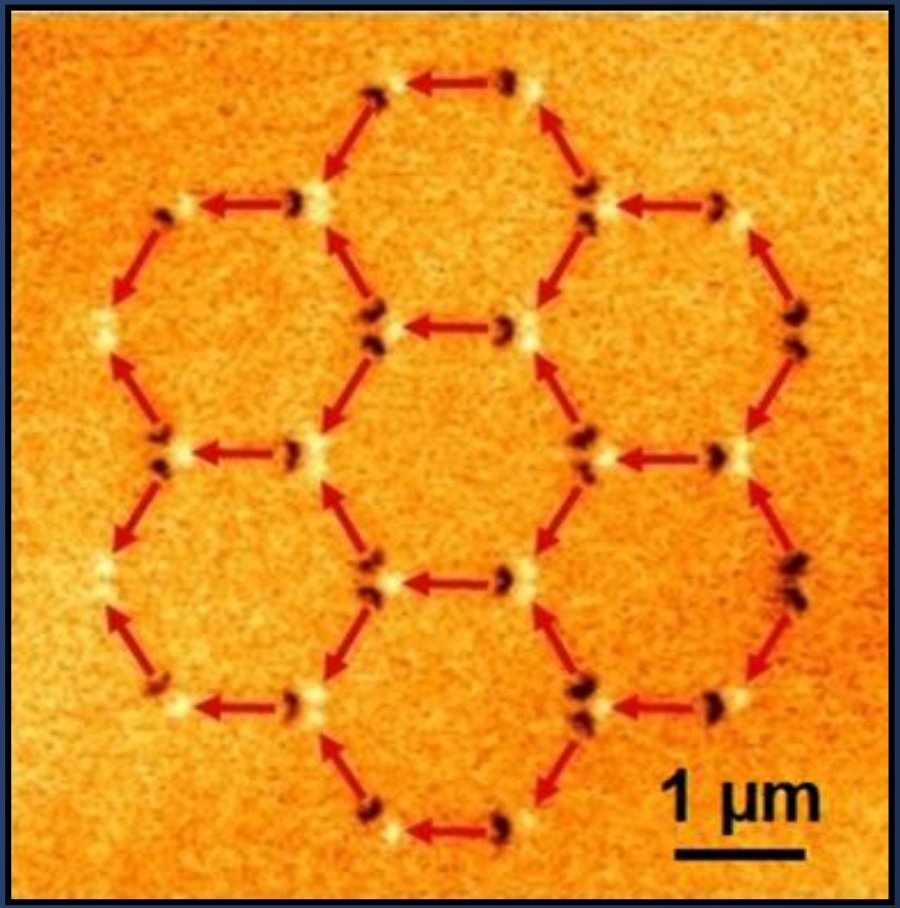
Ground state of kagome ASI

Flux-closure loops lower system energy

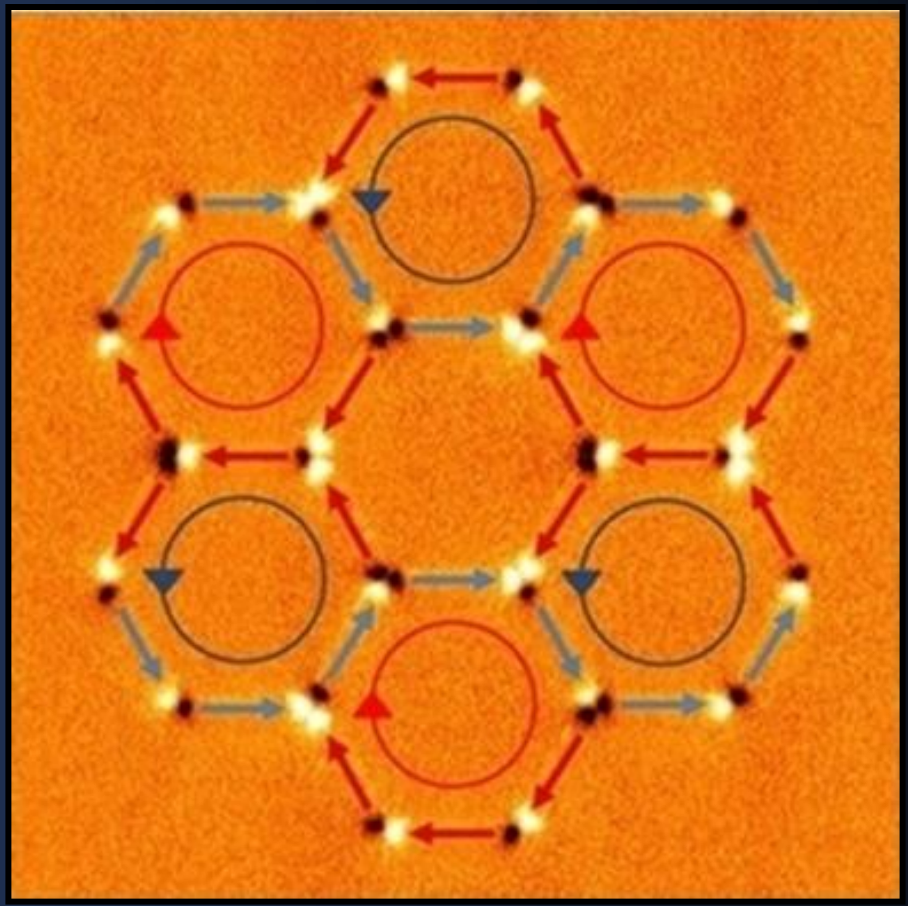


Microstate control
Developing a tip-based approach

Before

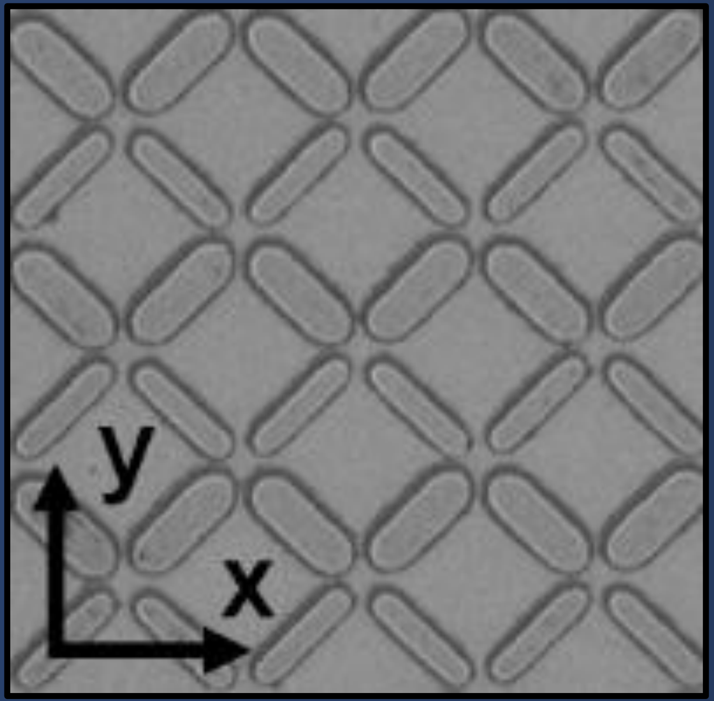


After

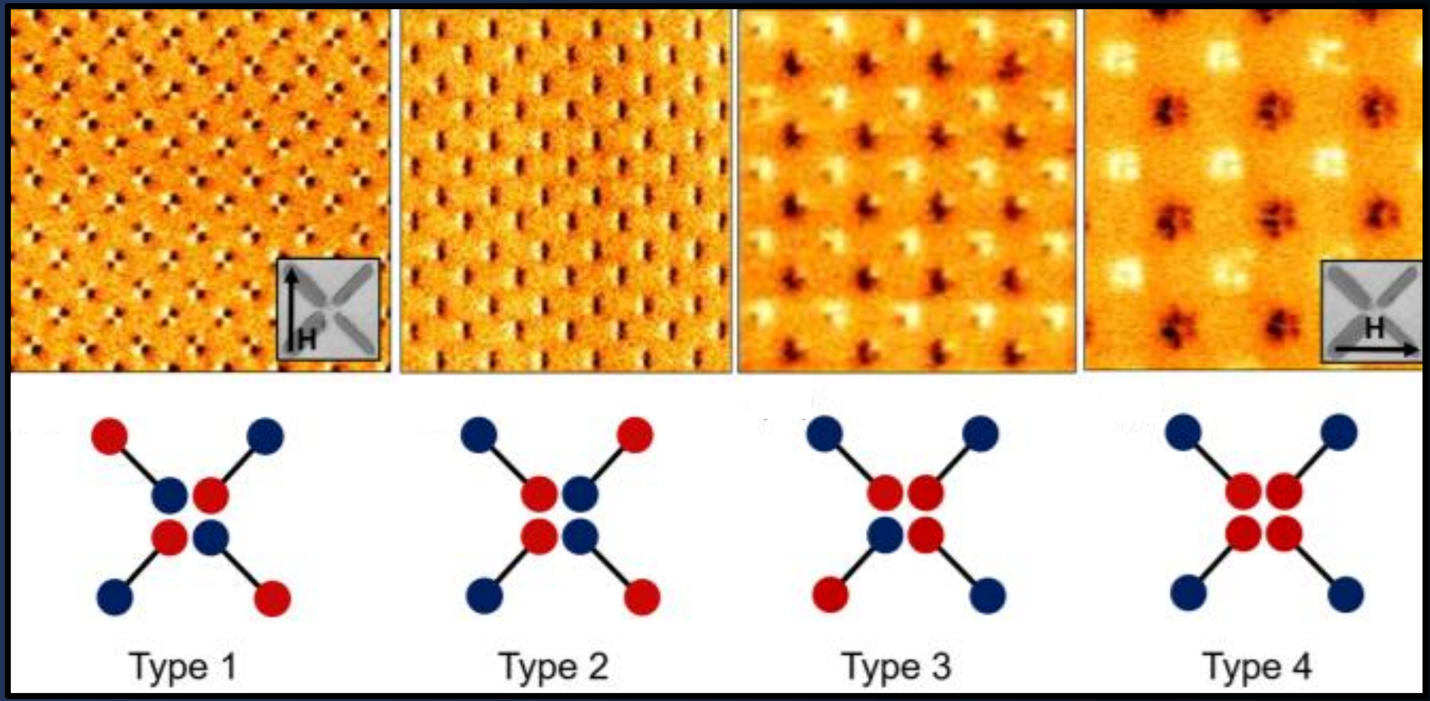


Gartside et al – *Nature Nanotechnology* (2018)

Microstate control
A global-field approach



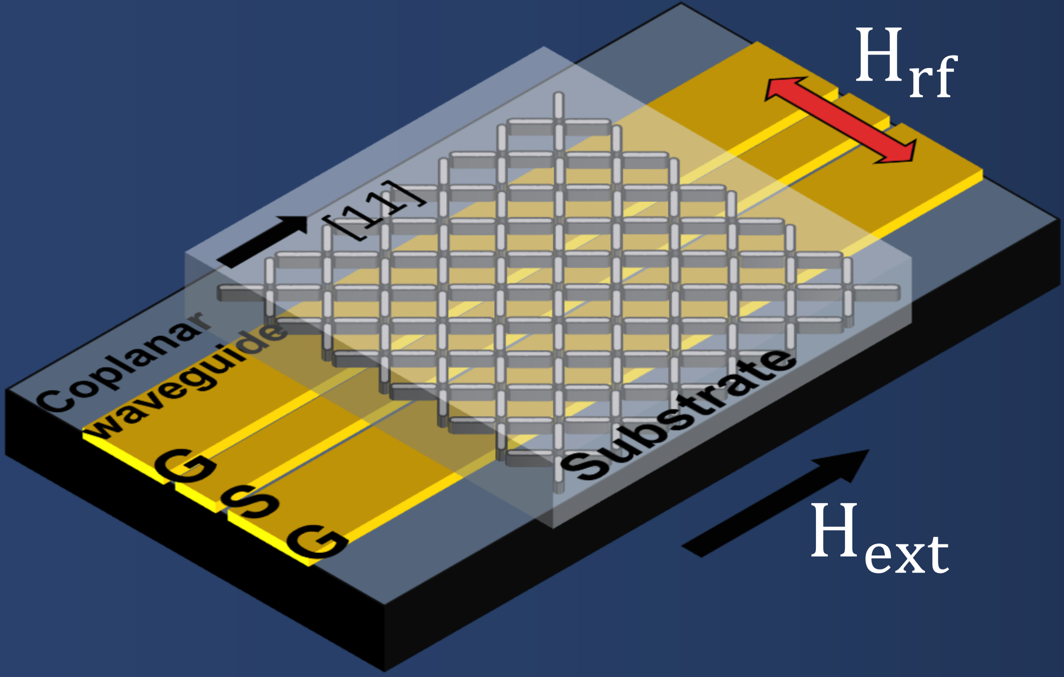
Break nanoelement symmetry

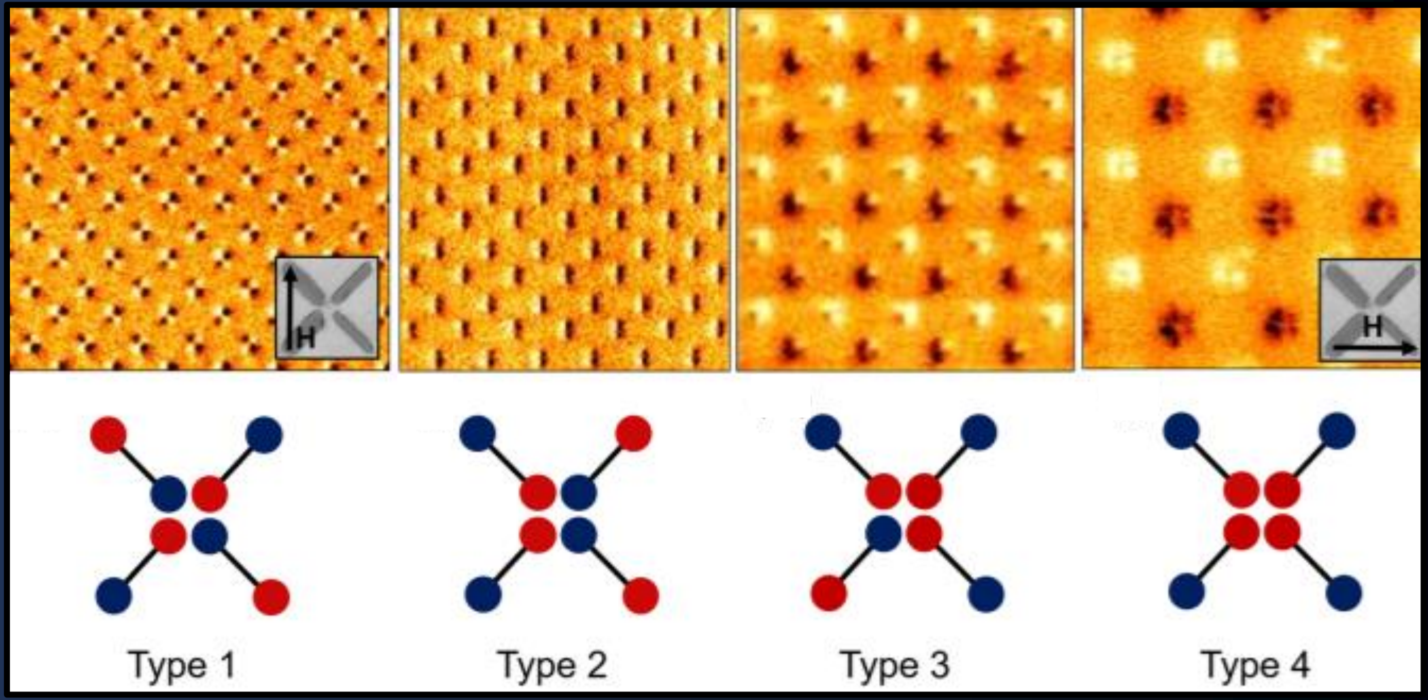


Allows access to otherwise elusive states

Gartside et al – *Nature Communications* (2021)

Microstate control
A global-field approach





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Gartside et al – *Nature Communications* (2021)

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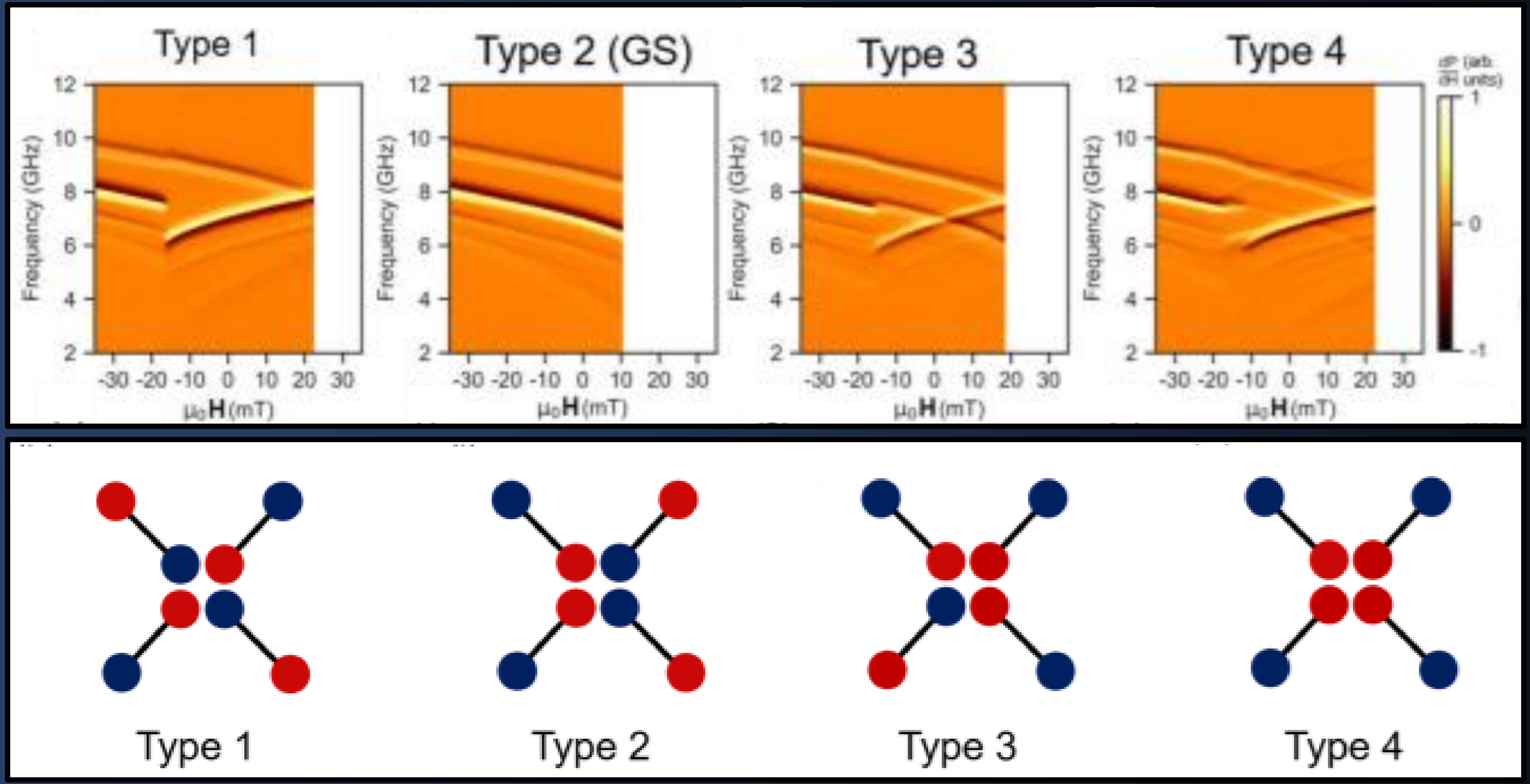
A global-field approach

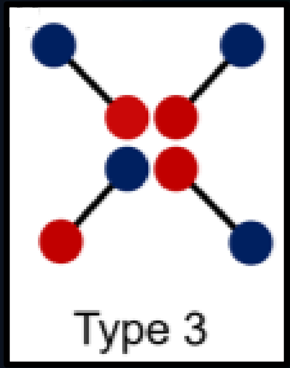


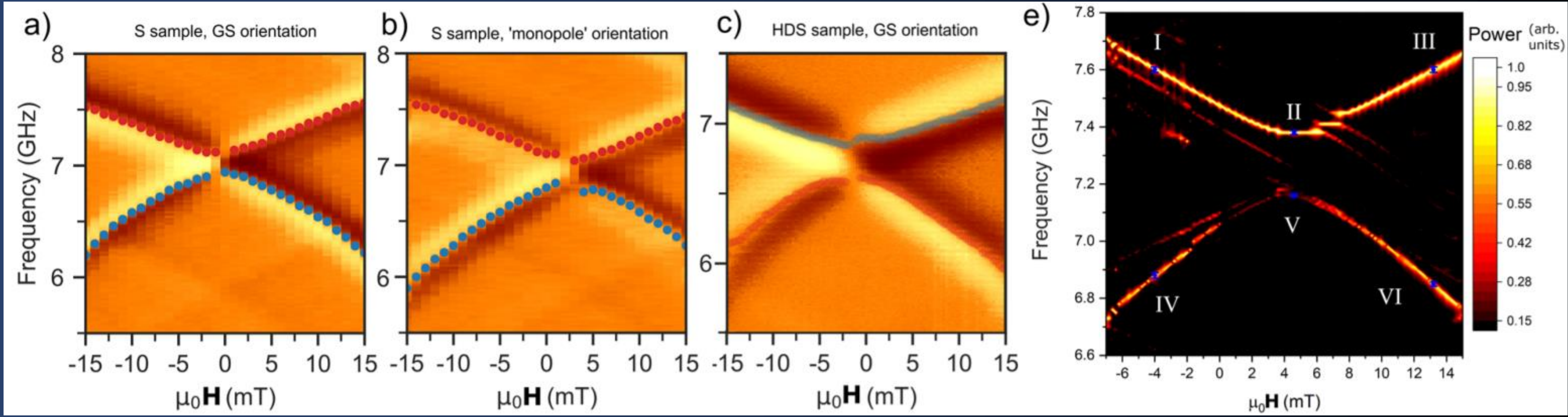
Explore magnonic properties of diverse states

Gartside et al – *Nature Communications* (2021)

Microstate control
A global-field approach

Use elusive 'Type 3' ASI state to observe dipolar coupling induced spin-wave mode anti-crossing



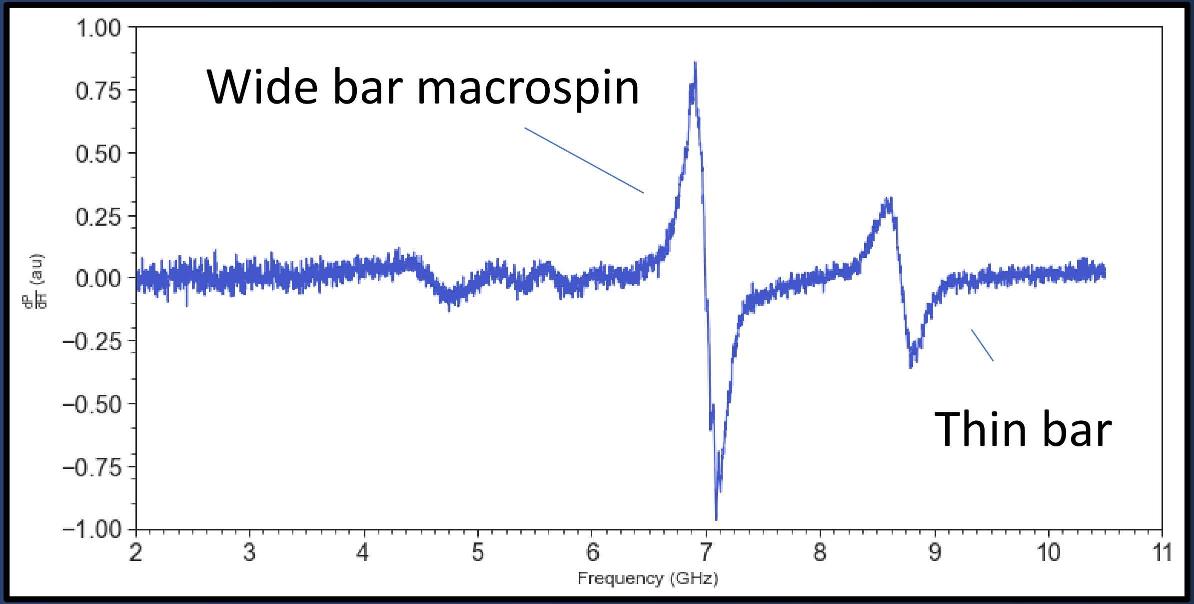


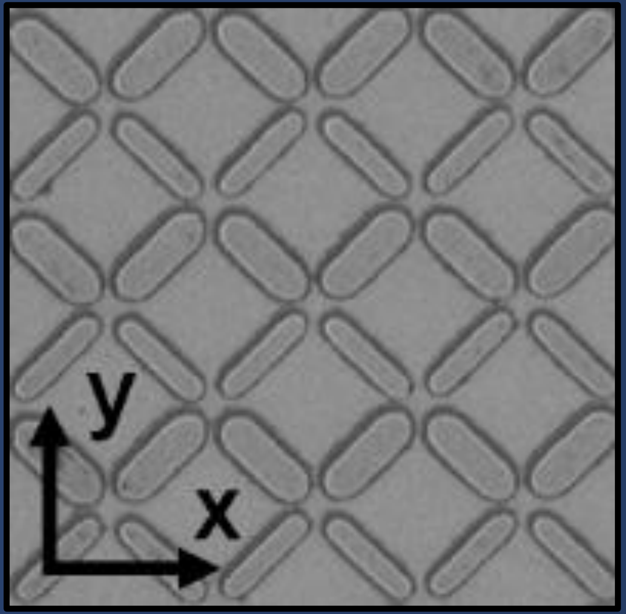
FMR experiment

Simulation

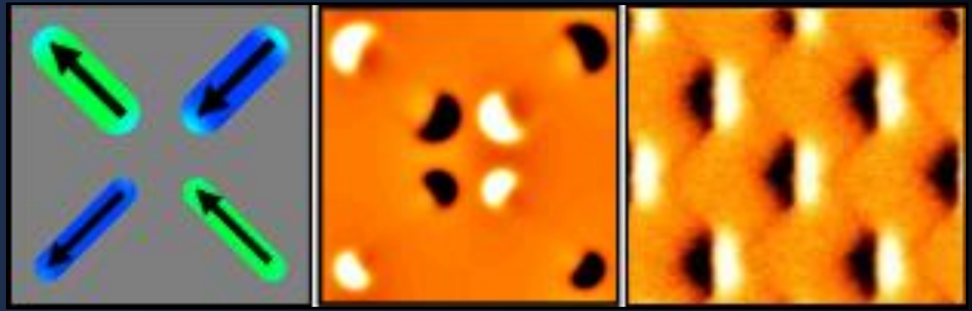
Gartside et al – *Nature Communications* (2021)

Microstate control – Beyond a single texture





Normal saturated ASI spectra

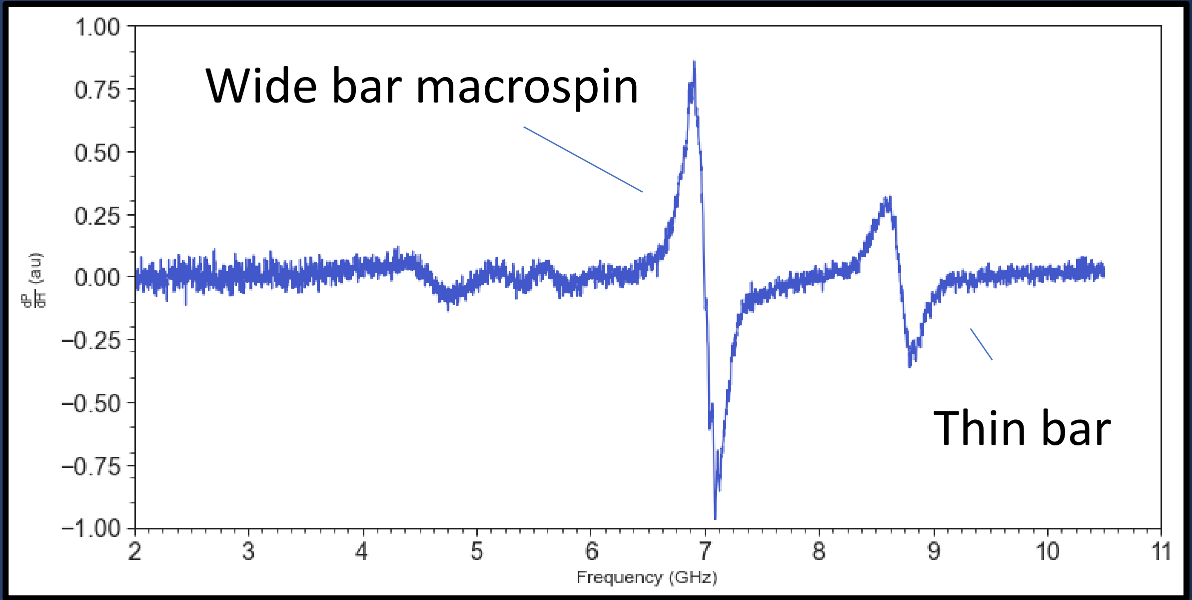


Magnetisation

Simulated MFM

Experimental MFM

Microstate control – Beyond a single texture



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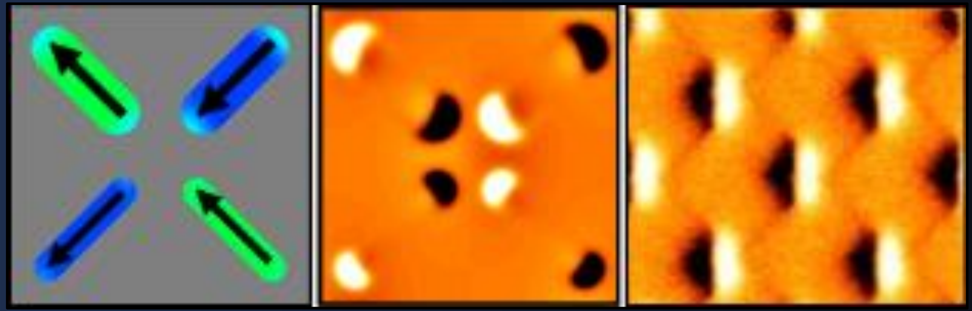

Magnetisation

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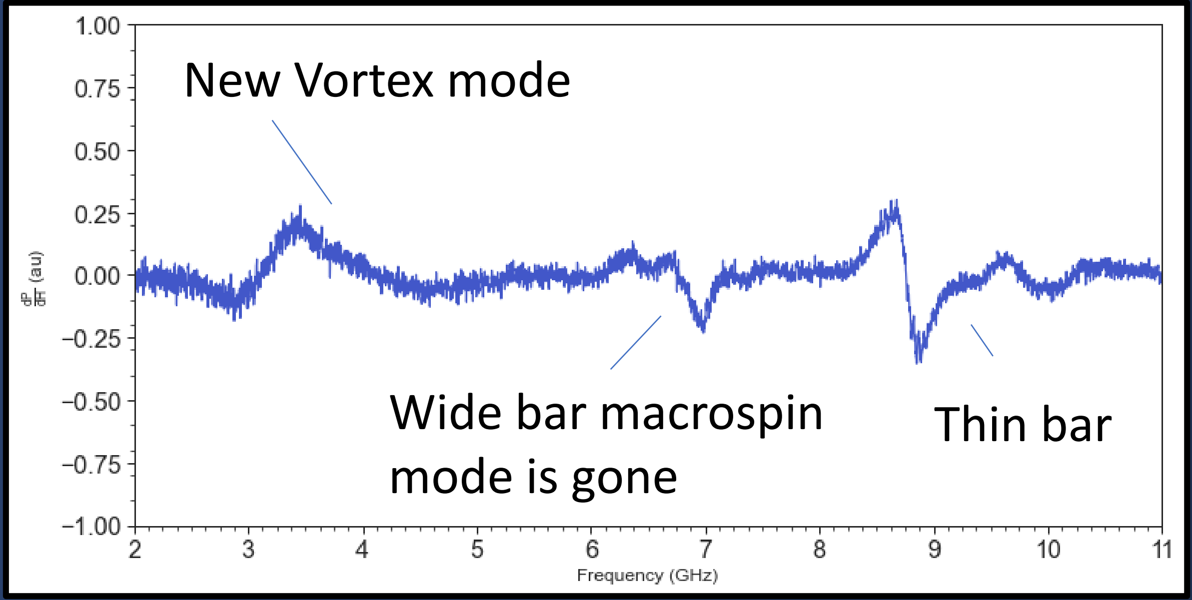
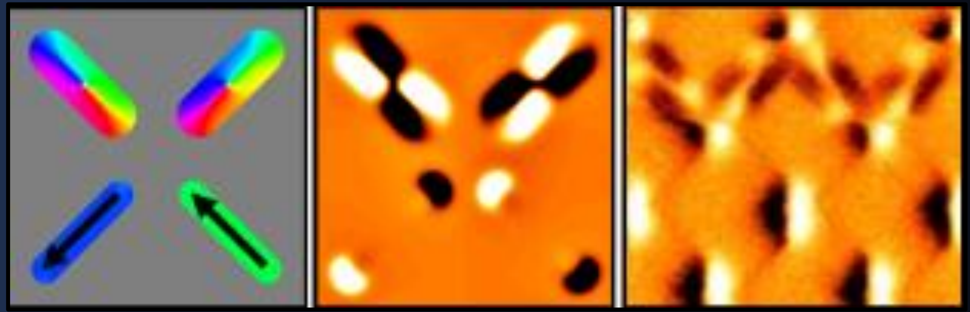
Experimental MFM



Spectra after 30 training cycles at 18 mT (wide bar Hc = 16 mT)



Magnetisation

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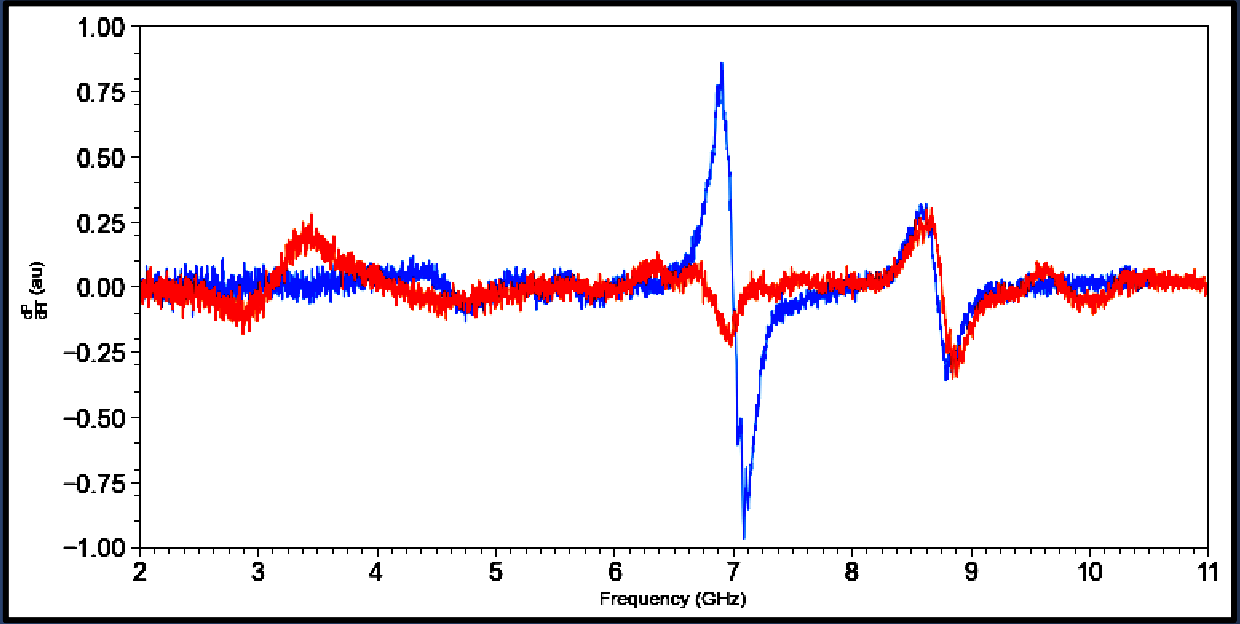
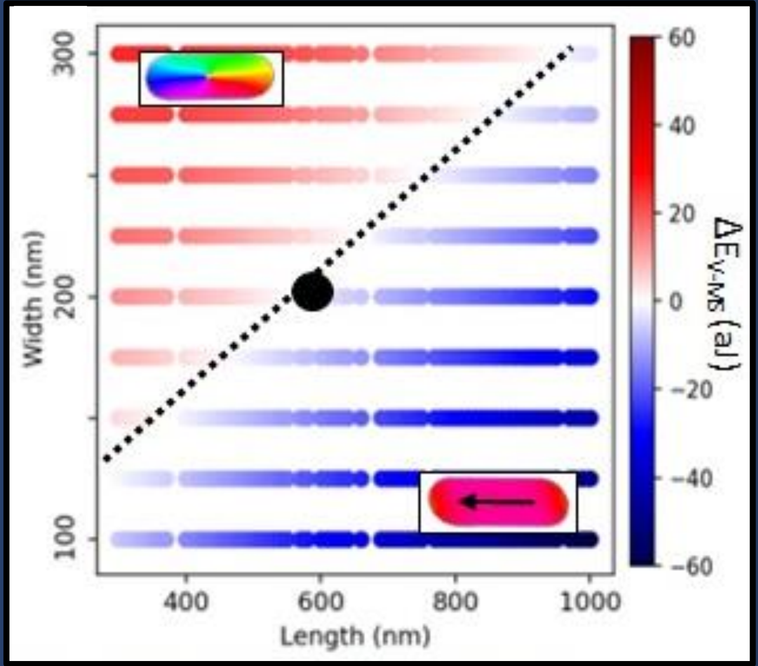
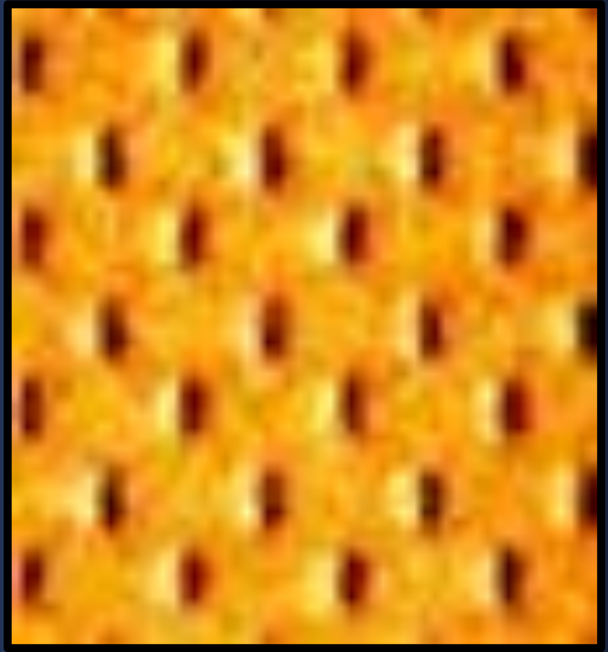
Experimental MFM



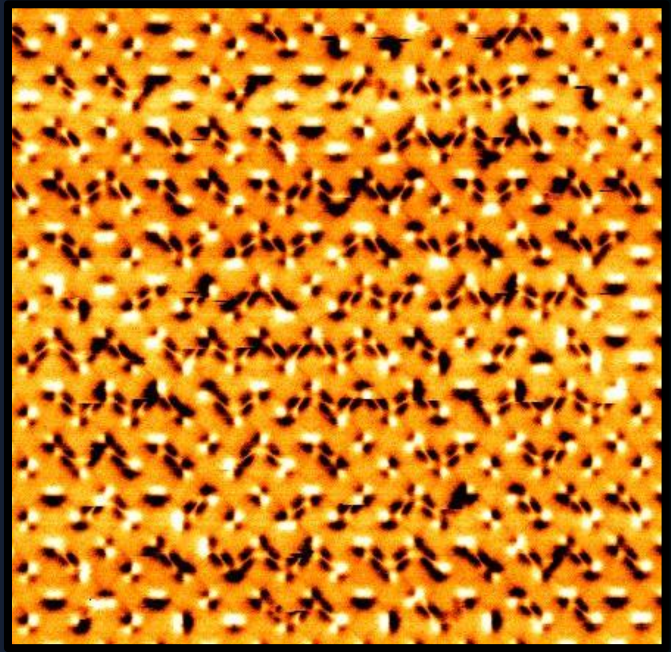
Blue = Initial -200 mT saturated
Red = After 30x 18 mT training loops



Vortex/Macrospin Energy

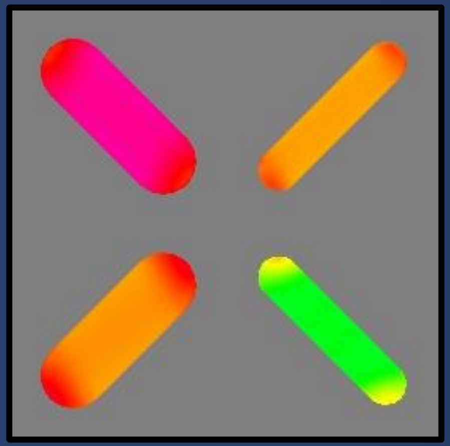


Saturated initial state

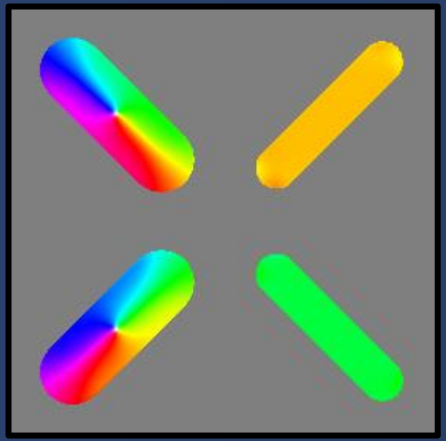


Field-Trained state

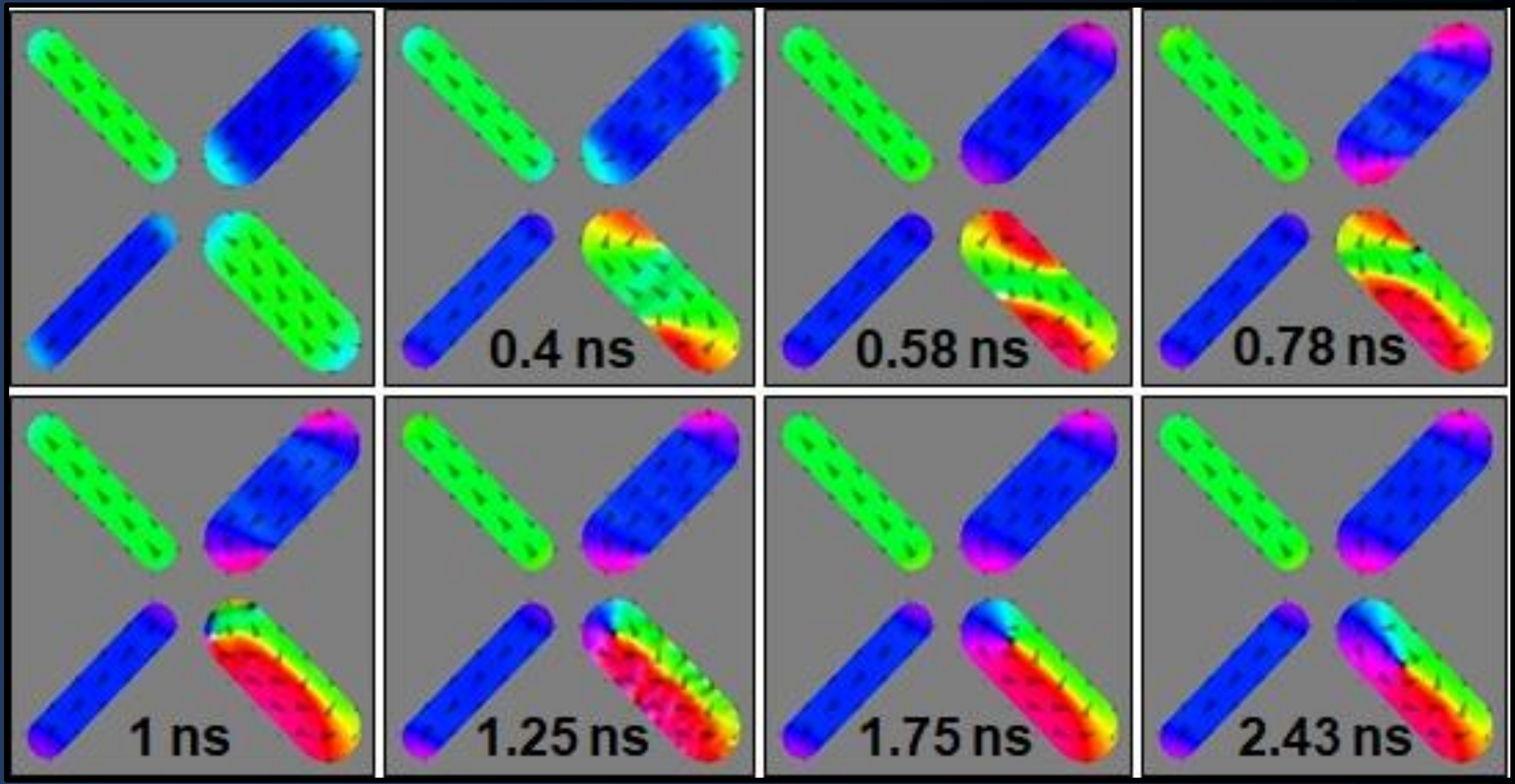
Simulating vortex formation



Saturated

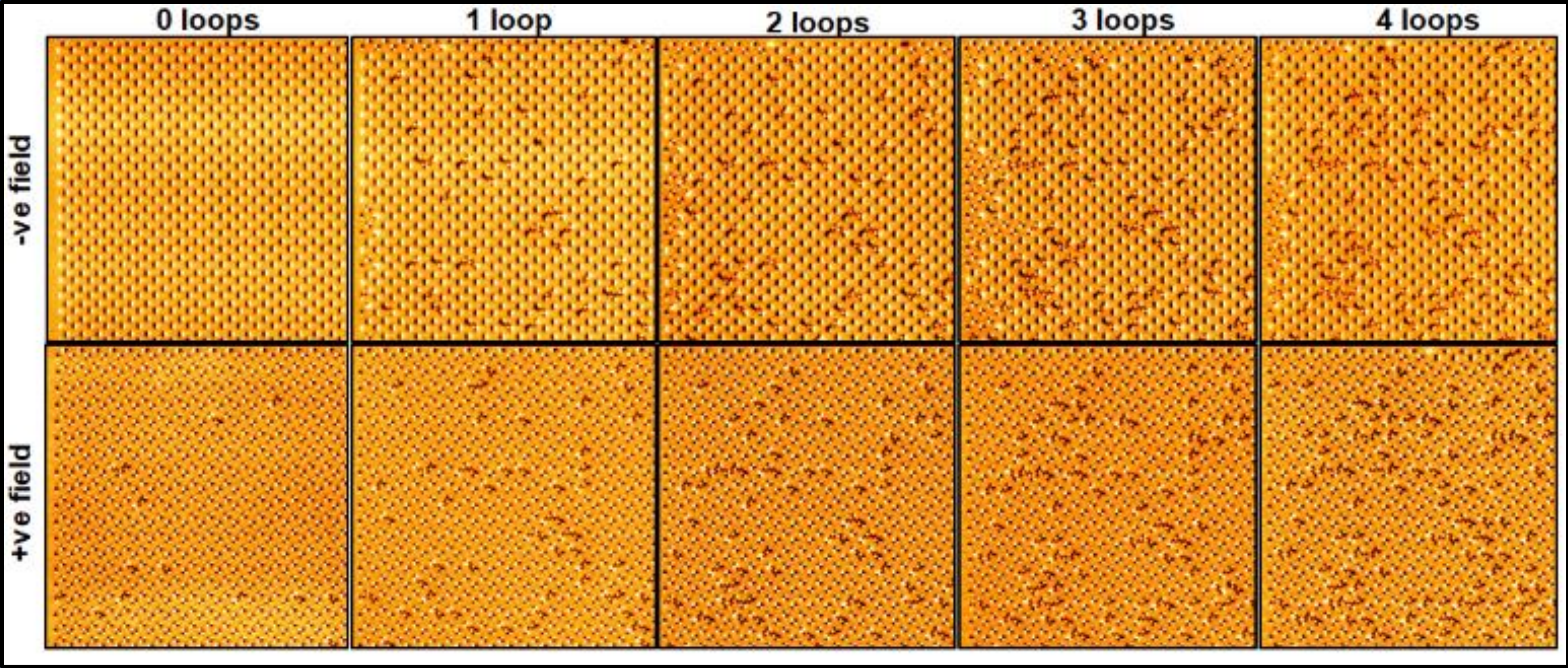


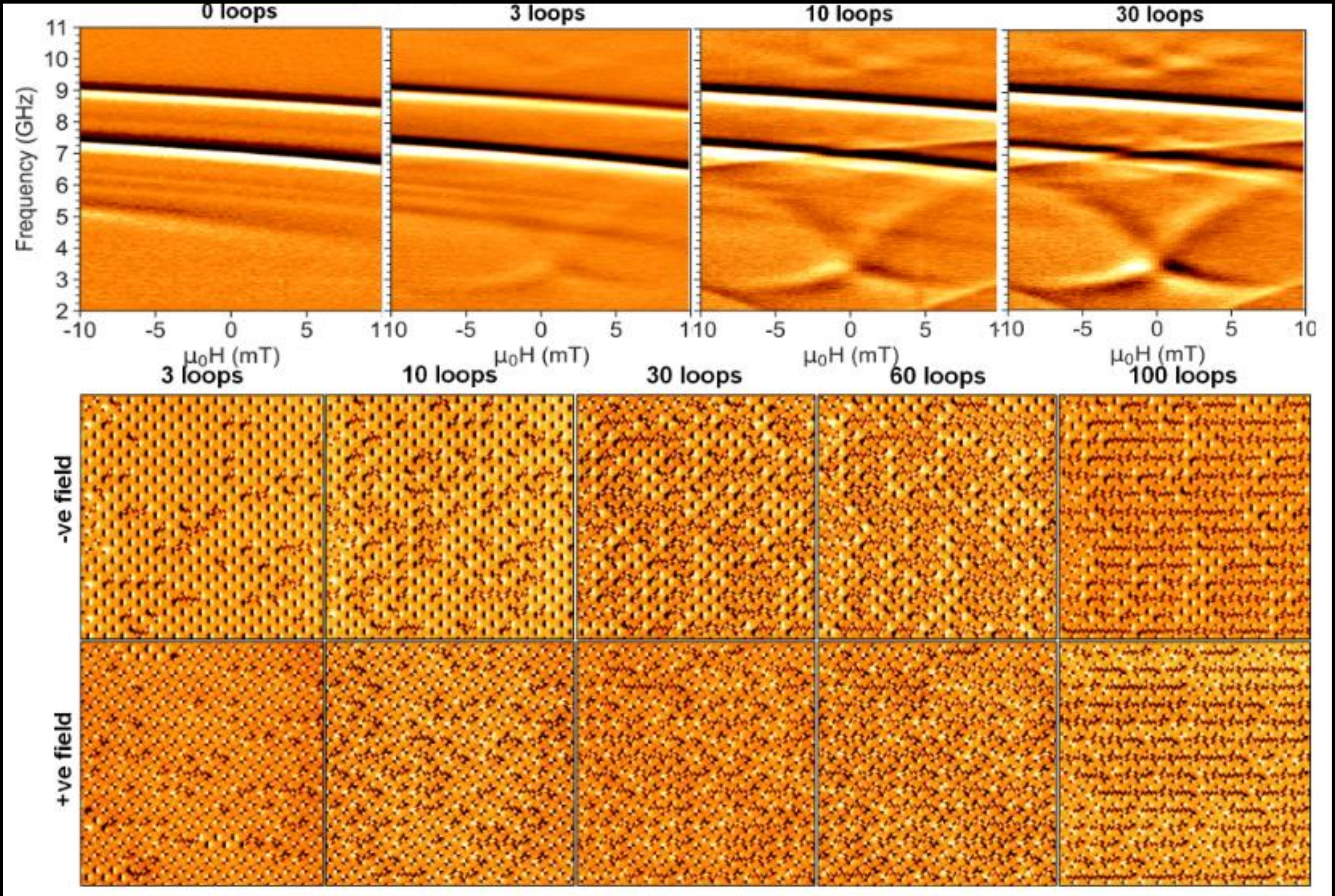
Trained – Vortices in wide bars



Vortex formation time-series – MuMax3

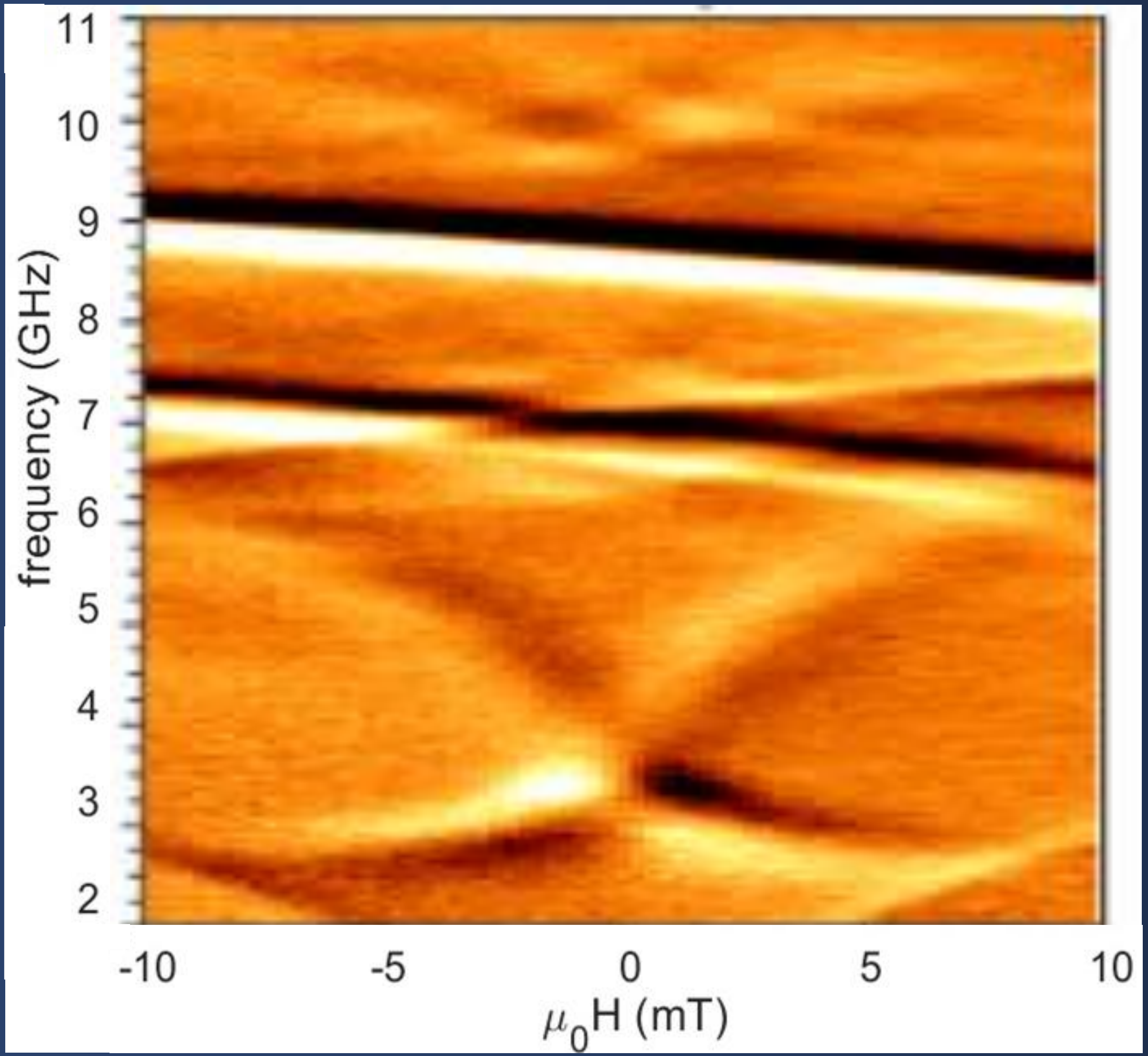
MFM Imaging of Vortex Training



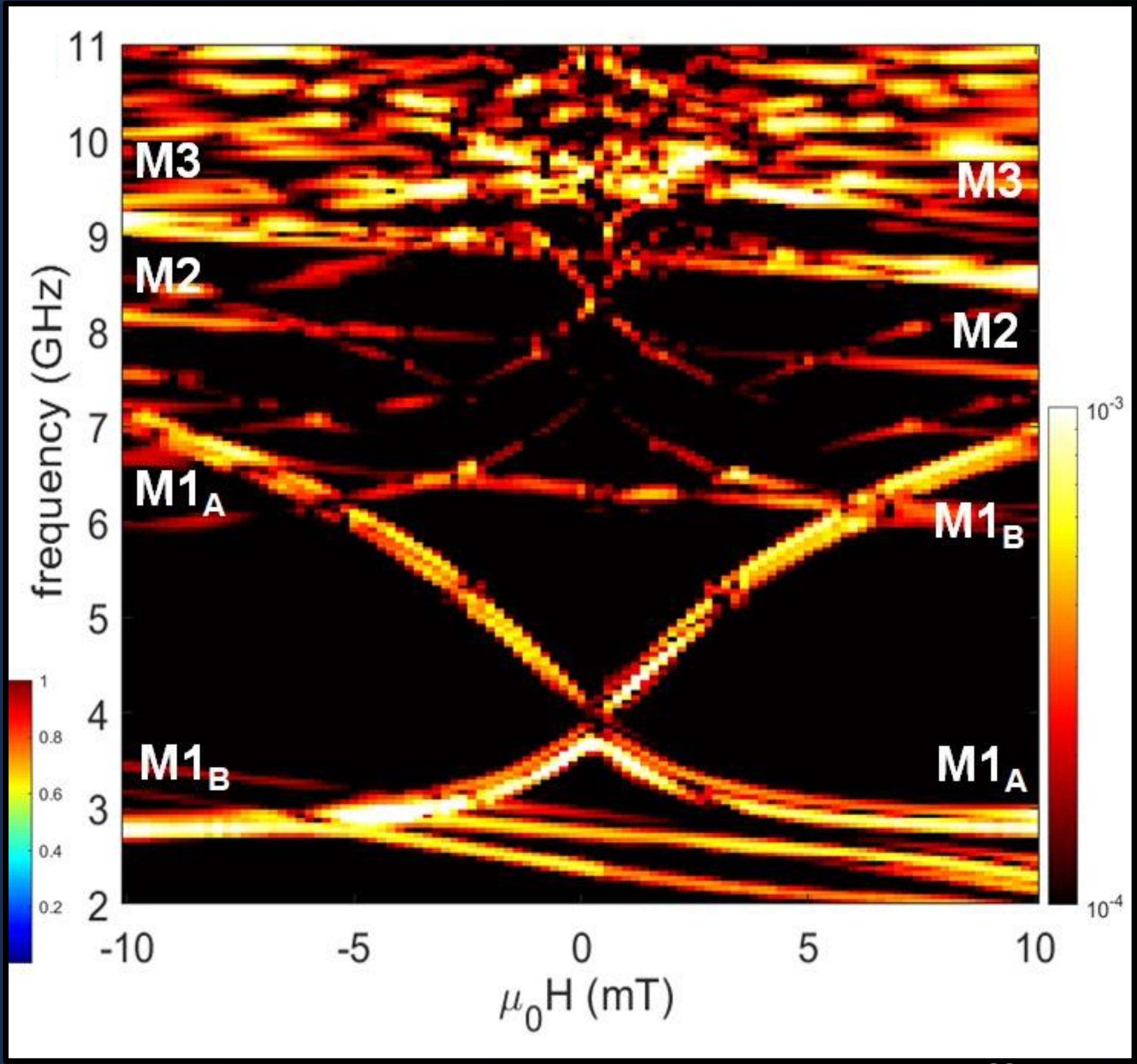

0 loops
3 loops
10 loops
30 loops
Frequency (GHz)
μ0H (mT)
μ0H (mT)
μ0H (mT)
μ0H (mT)
3 loops
10 loops
30 loops
60 loops
100 loops
-ve field
+ve field

Micromagnetic simulation of FMR response

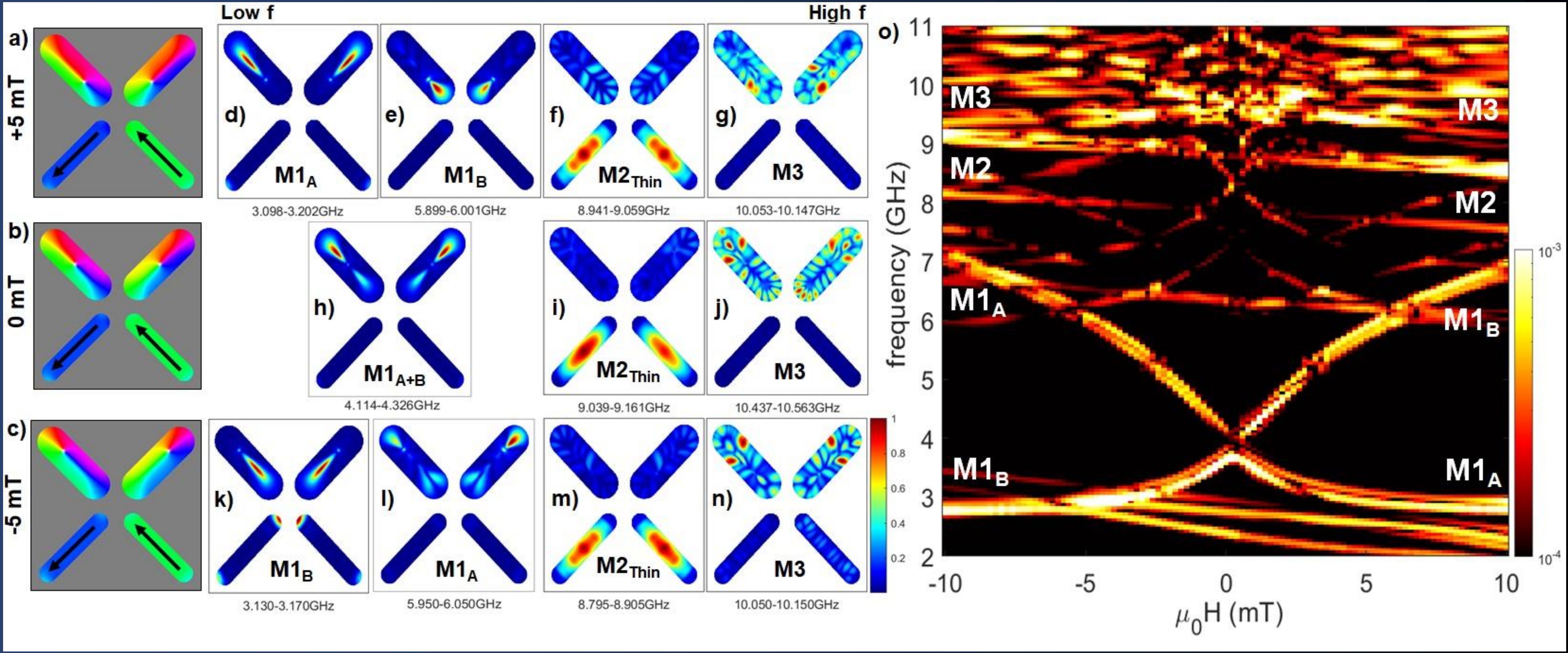
Experiment

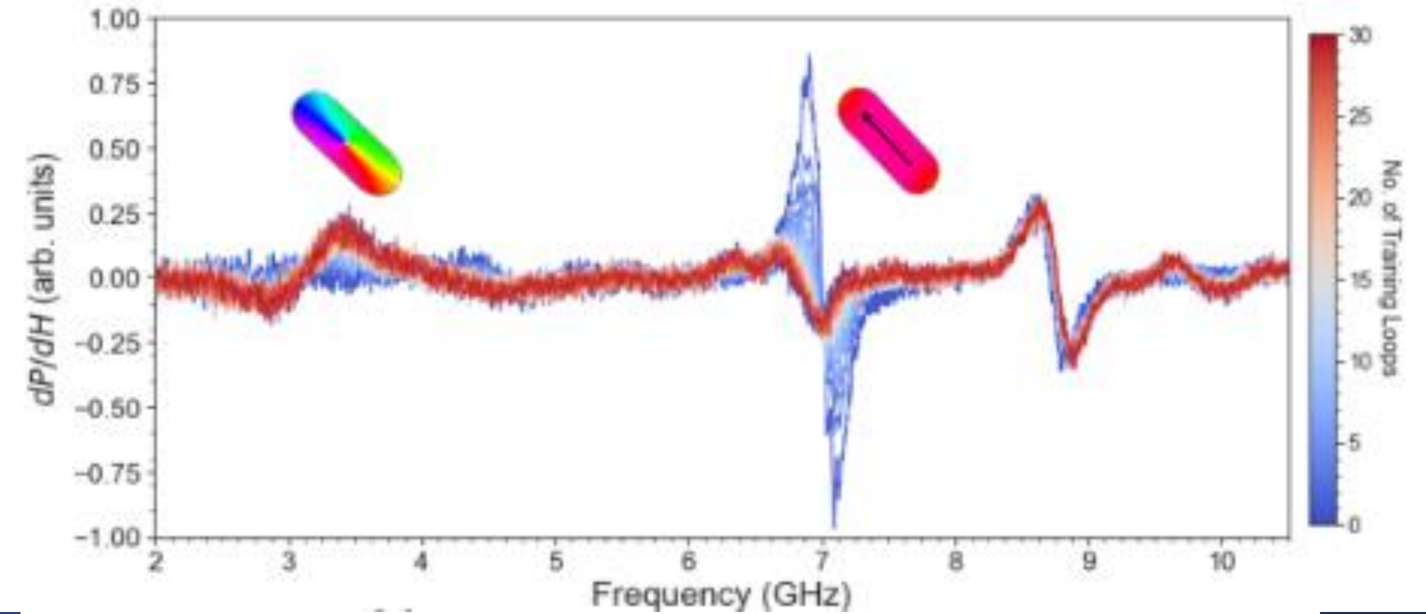


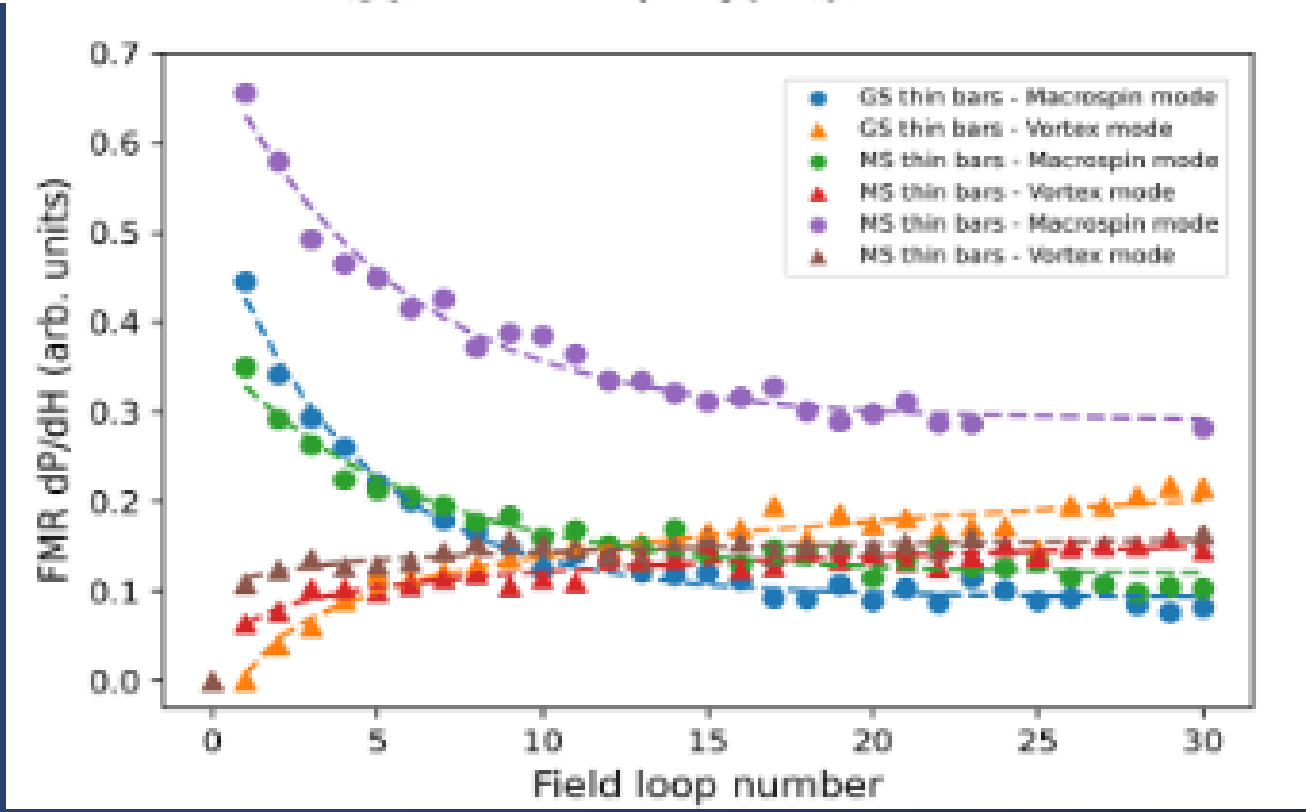
Simulation



Micromagnetic simulation of FMR response

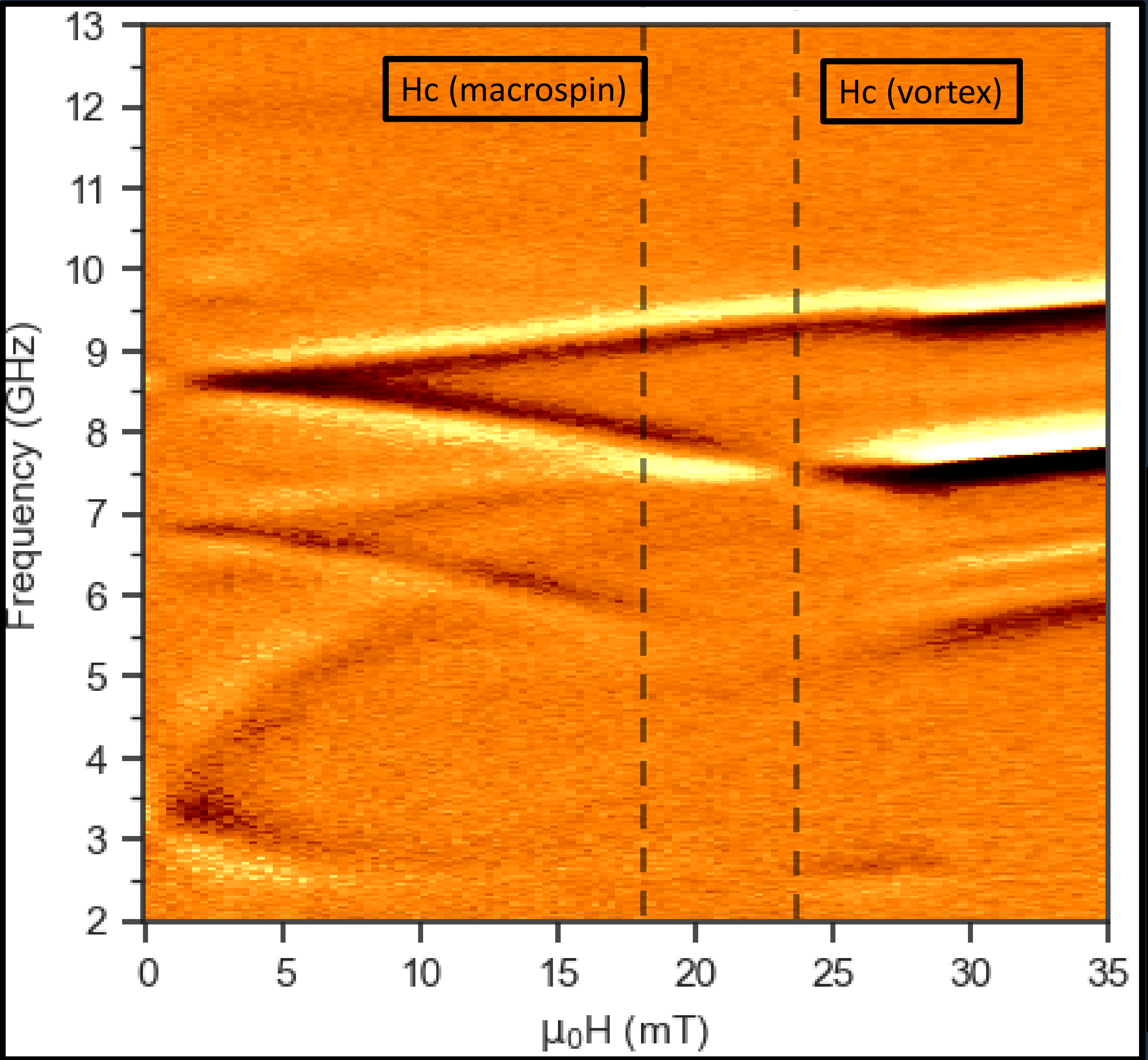






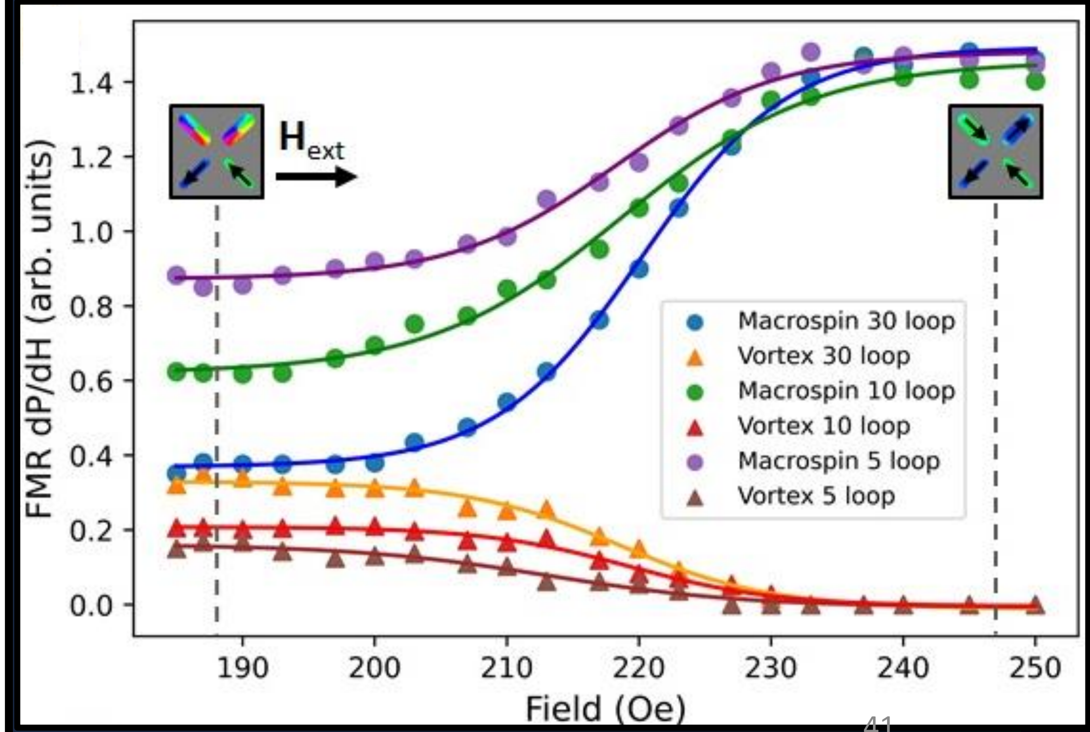
Waterfall spectra taken after each training field loop

Macrospin & vortex mode amplitudes throughout training for different thin-bar biasing



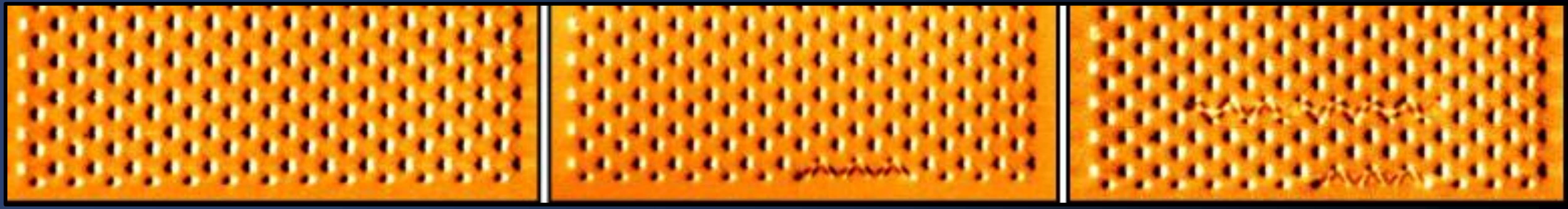
Vortex to Macrospin Conversion

- Initial high-vortex state
- Sweep **H** 0-35 mT
- Reach saturated macrospin state at 27 mT
- Thin bar biasing controls saturation field



Vortex Writing via MFM Tip

Top Frames (1-3): Tip-written vortices



Vortex Writing via MFM Tip

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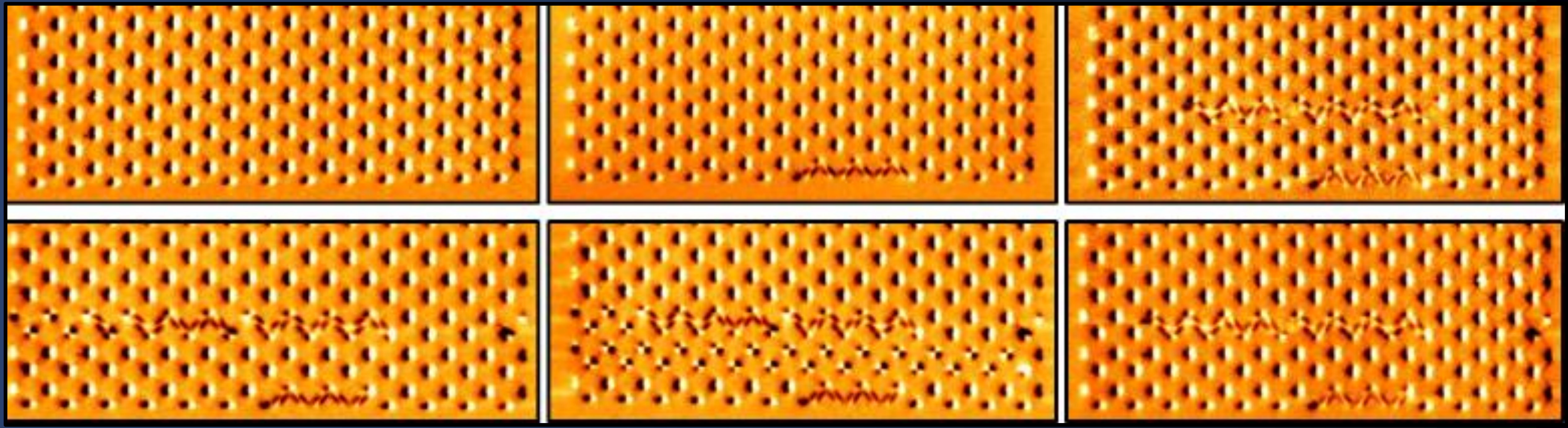
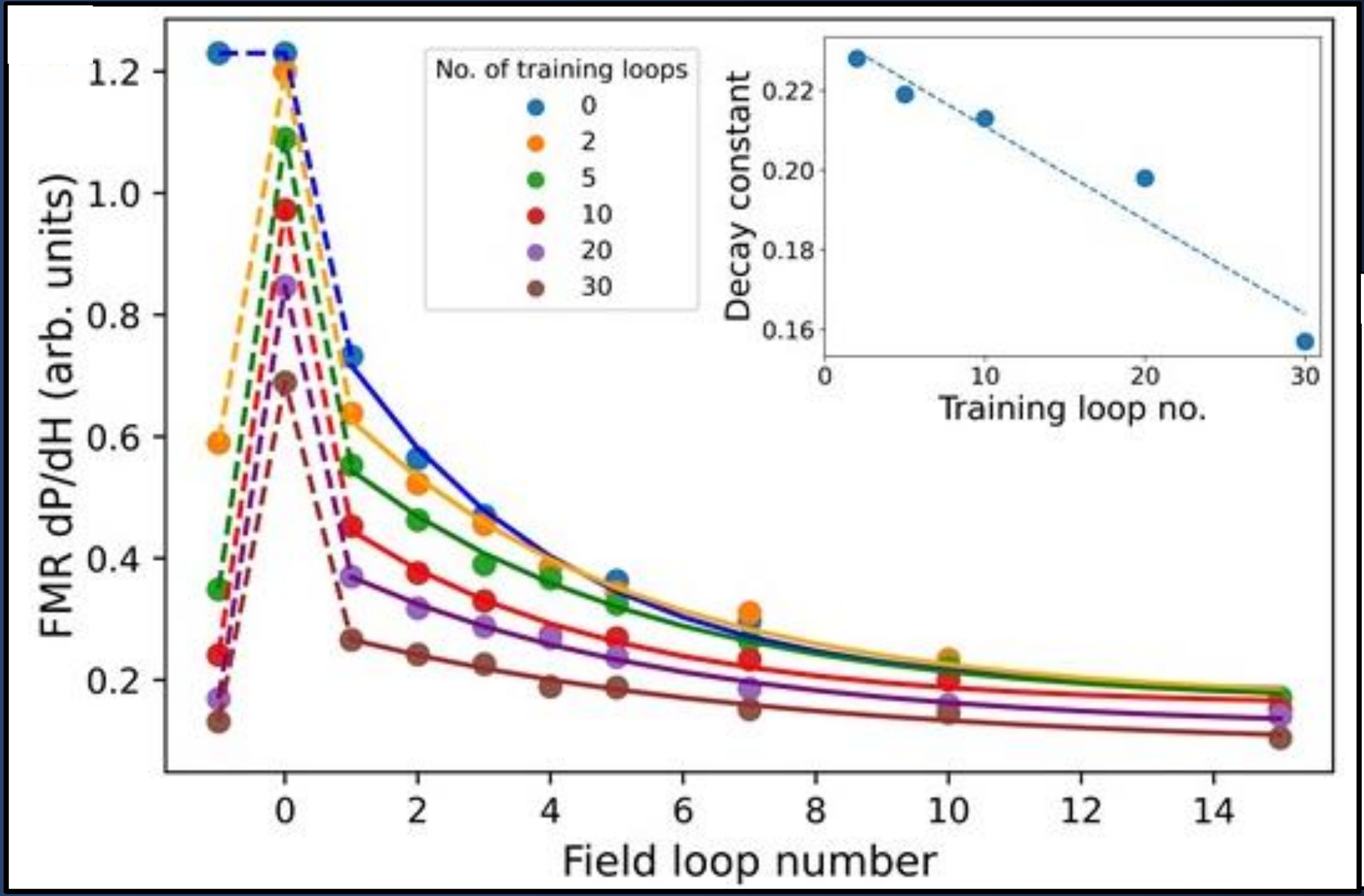


Bottom Frames (4-6):

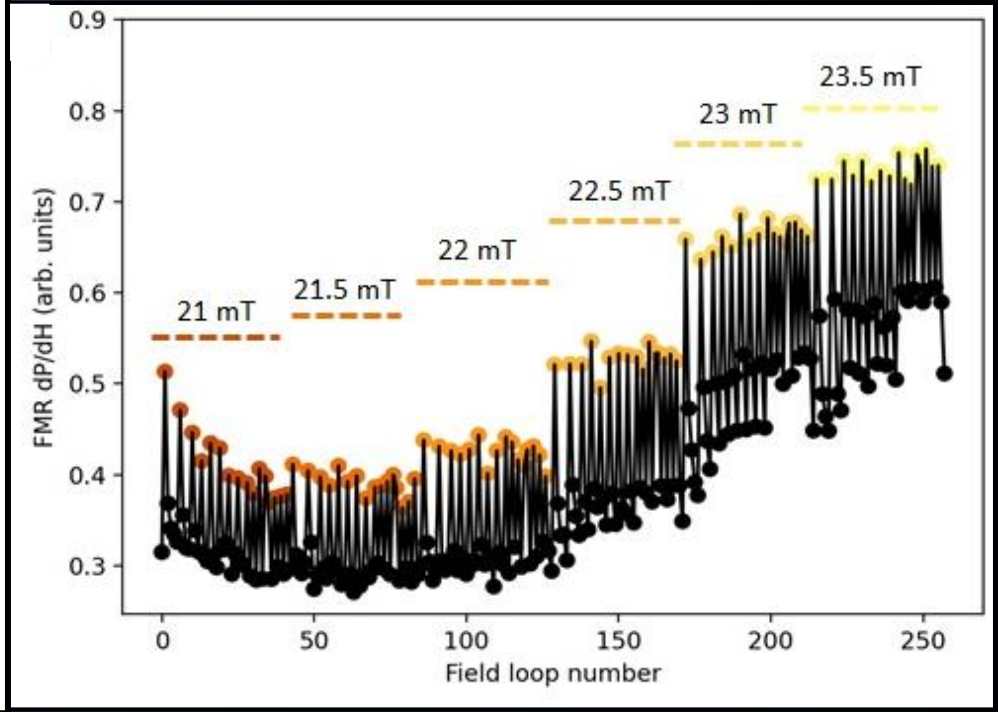
Field looping of vortex line states at 13 mT (Hc = 16-17 mT)

Training ASVI

Higher field application after different training lengths



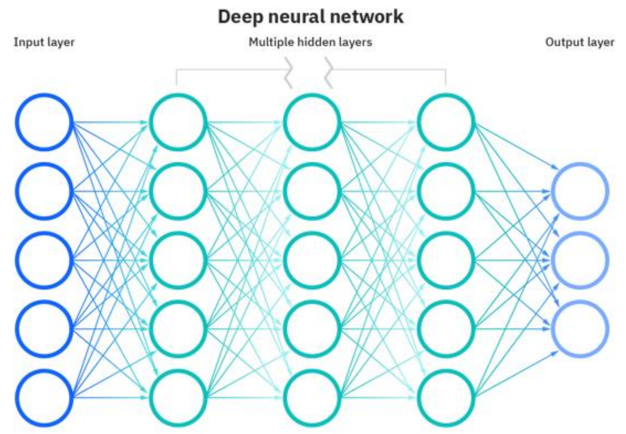
Echo-state property:
System converges from different initial states when driven through same input sequence



Reservoir Computation

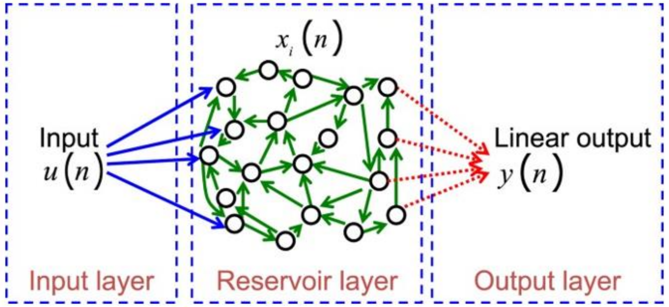
- **Aim:** To map complex problems onto linearly-solveable ones
- Reservoir has huge number of strongly-interacting hidden connections
- Only need to train small number of outputs
- Strengths are temporal data prediction, transformation and classification
- Huge energy savings possible vs. deep neural networks as only train small subset of weights
- Energy cost of global Machine Learning doubling every 3.5 months (!) *OpenAI white paper (2019)*

Neural network



Train all of the weights
Costs time and energy

Reservoir computing

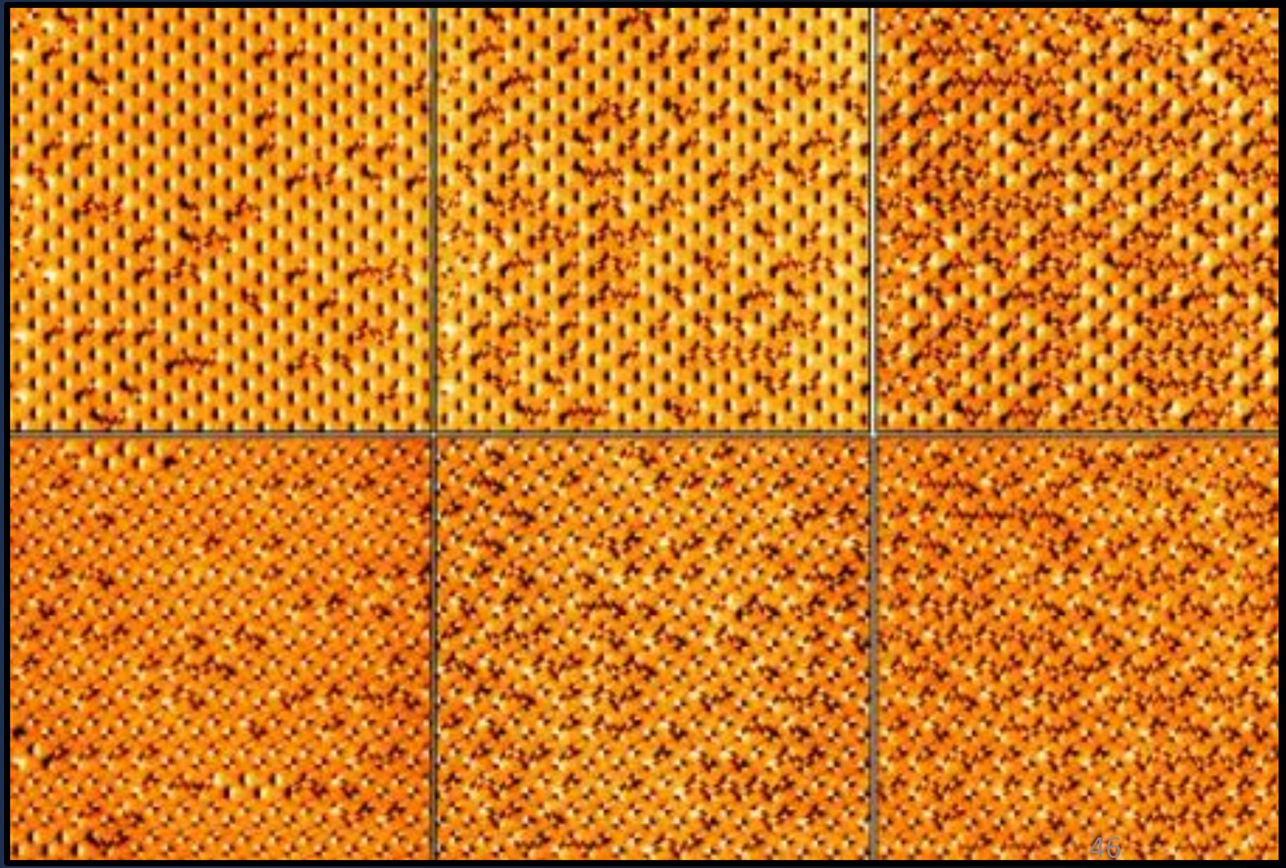


Only train output weights
Much simpler and still competitive

Reservoir Computation

Prerequisites for good reservoir computation:

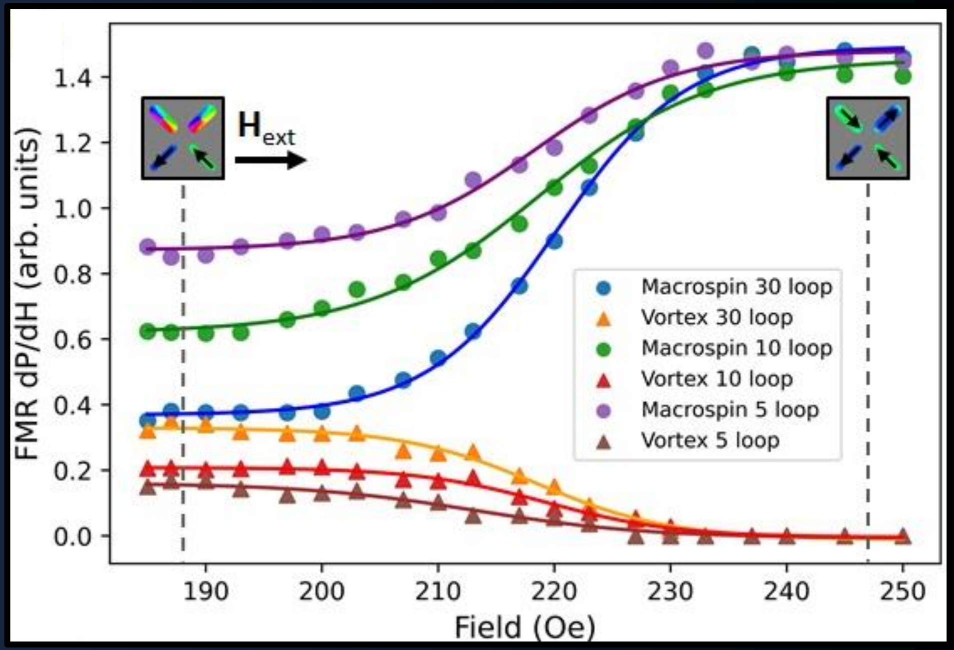
✓Wide range of distinguishable states

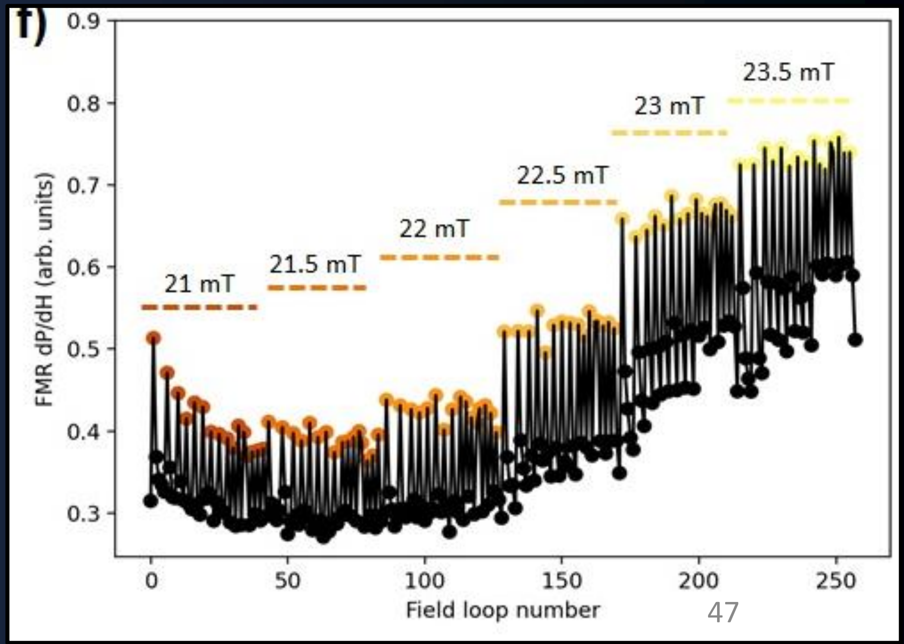


Reservoir Computation

Prerequisites for good reservoir computation:

✓Wide range of distinguishable states
✓Highly-nonlinear response to input

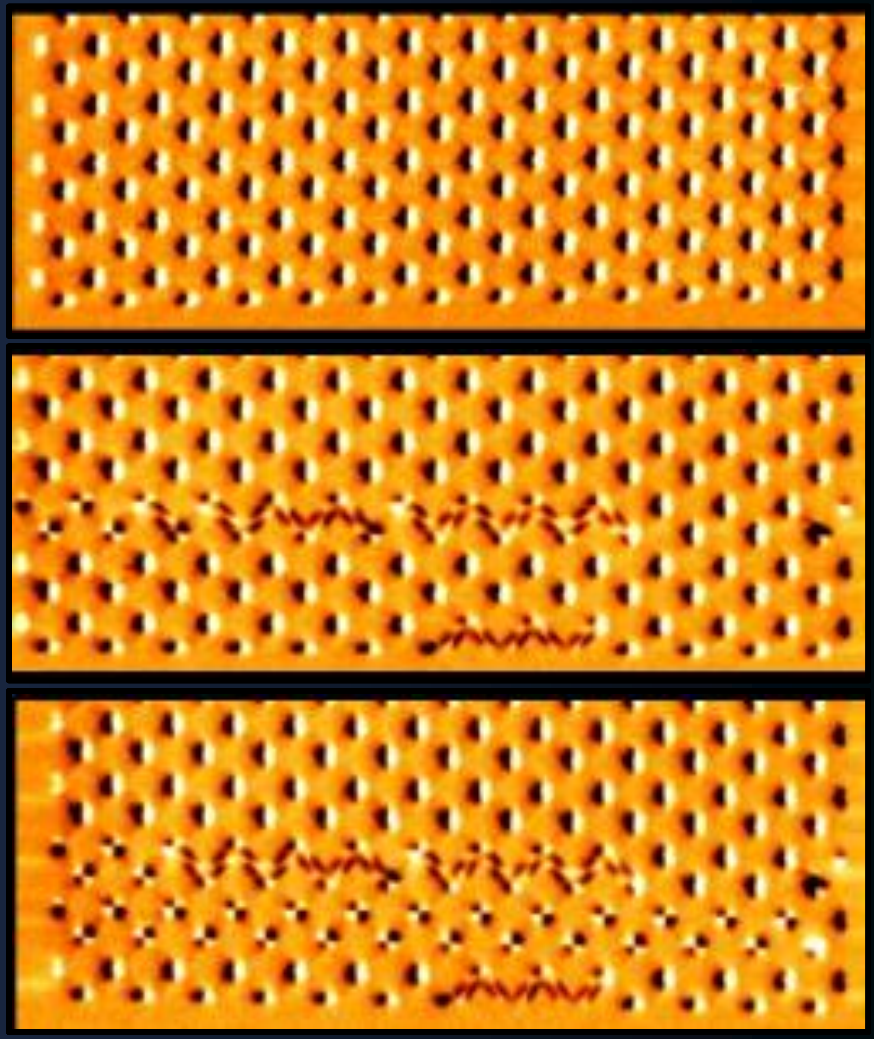




Reservoir Computation

Prerequisites for good reservoir computation:

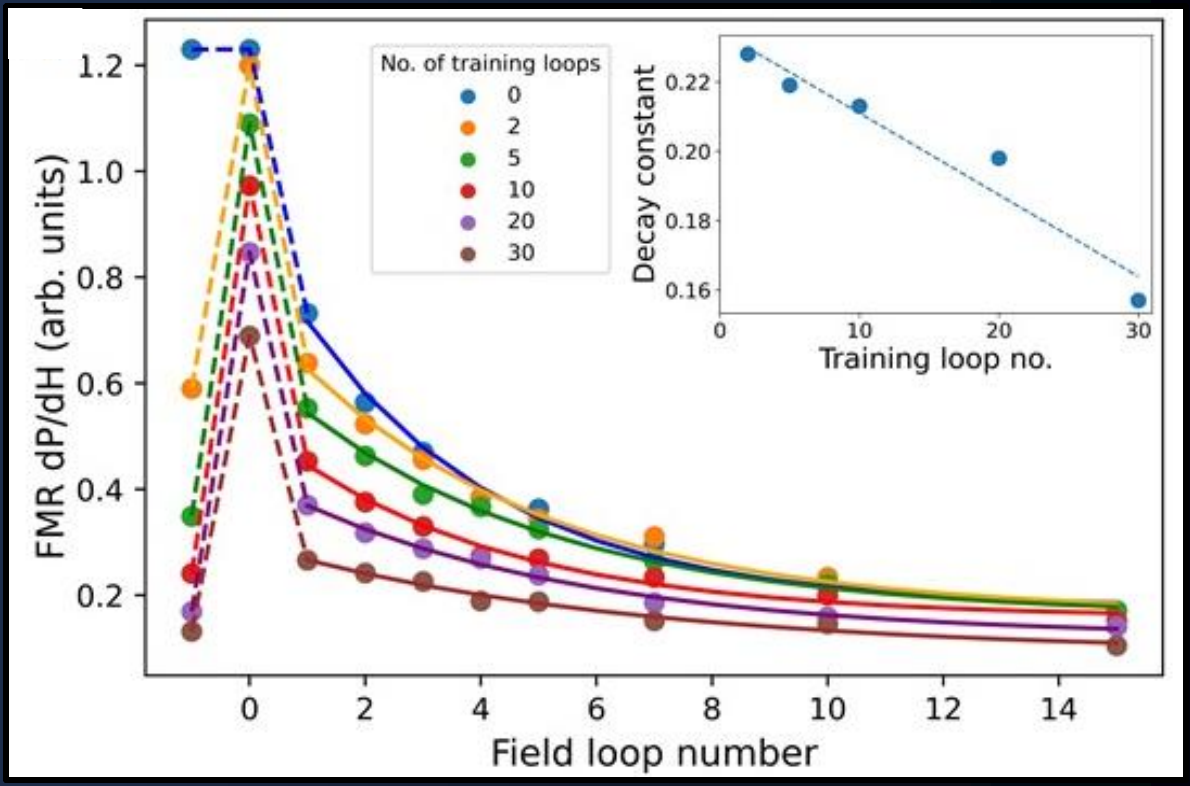
✓Wide range of distinguishable states
✓Highly-nonlinear response to input
✓Strong inter-element coupling



Reservoir Computation

Prerequisites for good reservoir computation:

- ✓Wide range of distinguishable states
- ✓Highly-nonlinear response to input
- ✓Strong inter-element coupling
- ✓Short-term memory of input sequences
- ✓Ability to gradually 'forget' – Echo-state property



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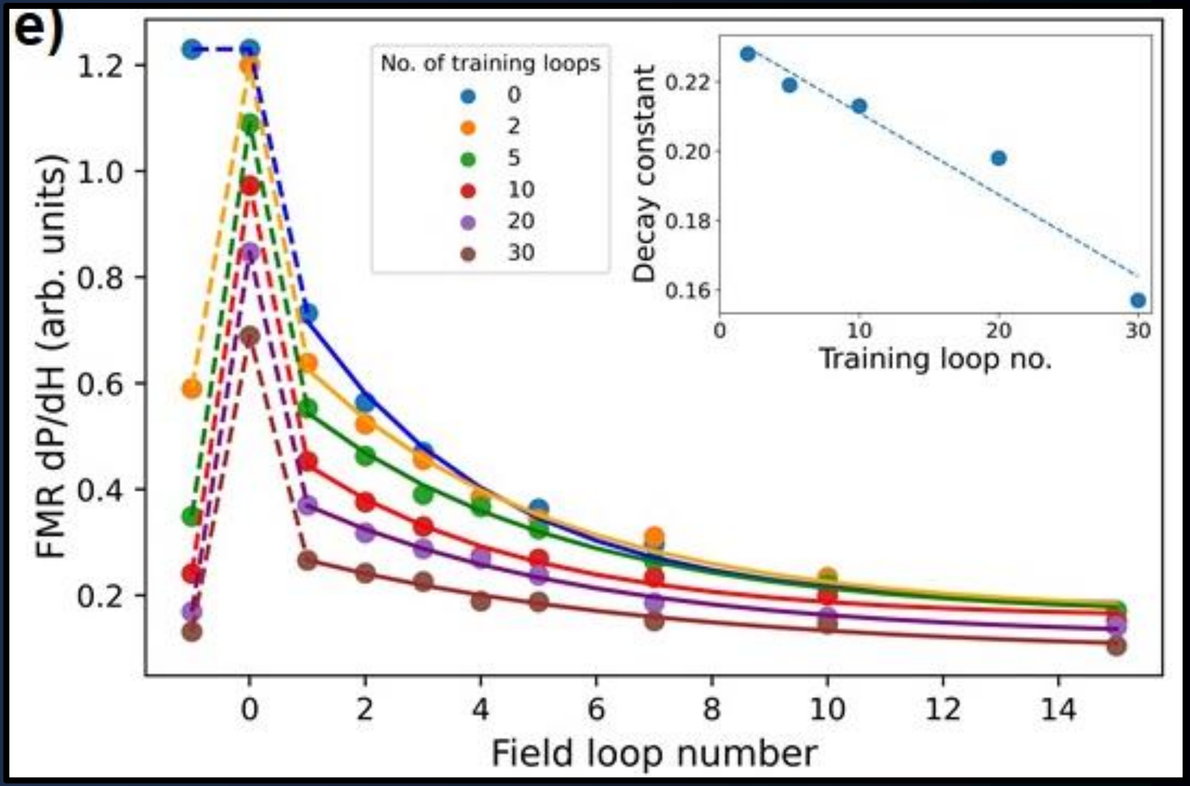
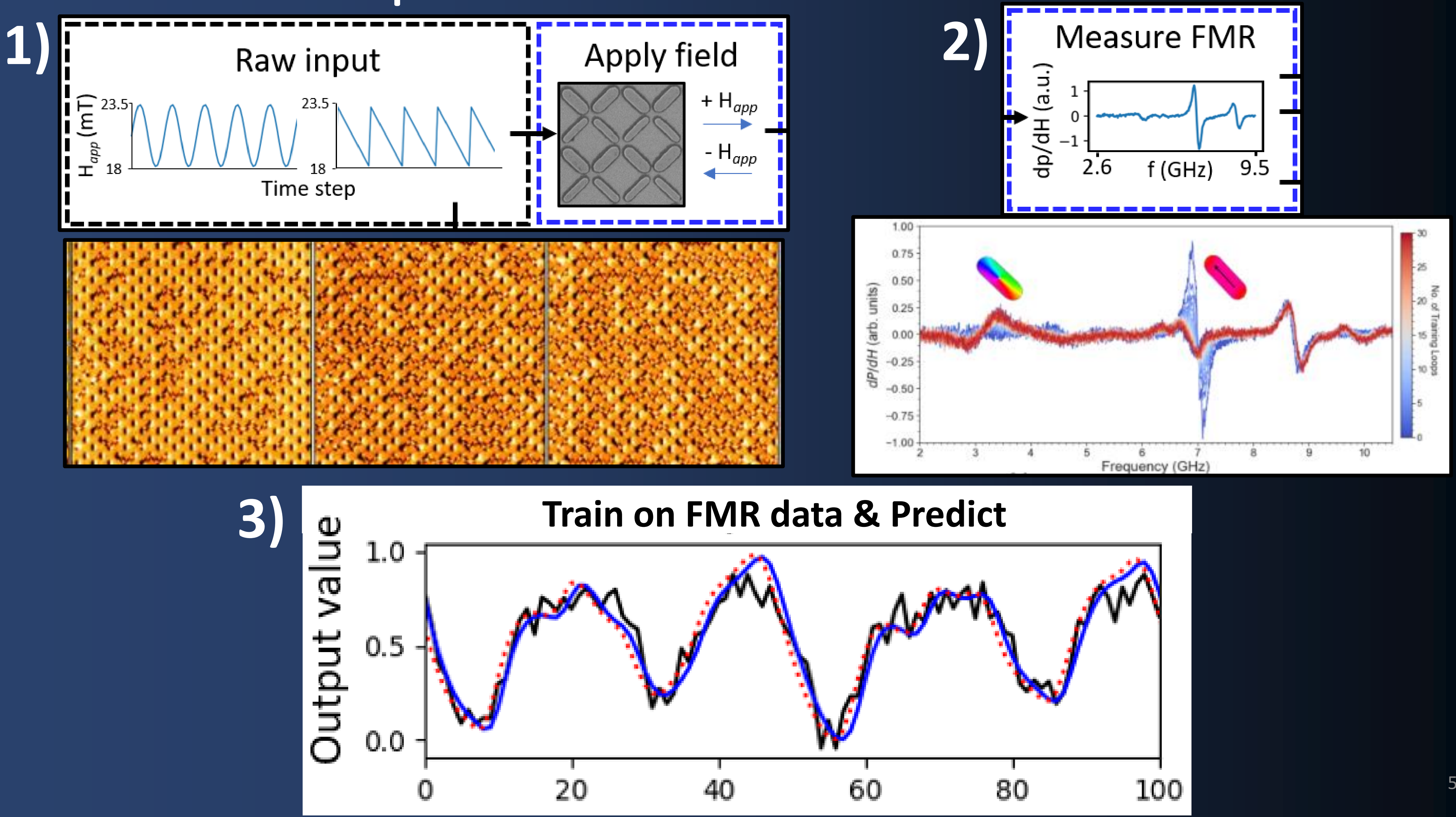


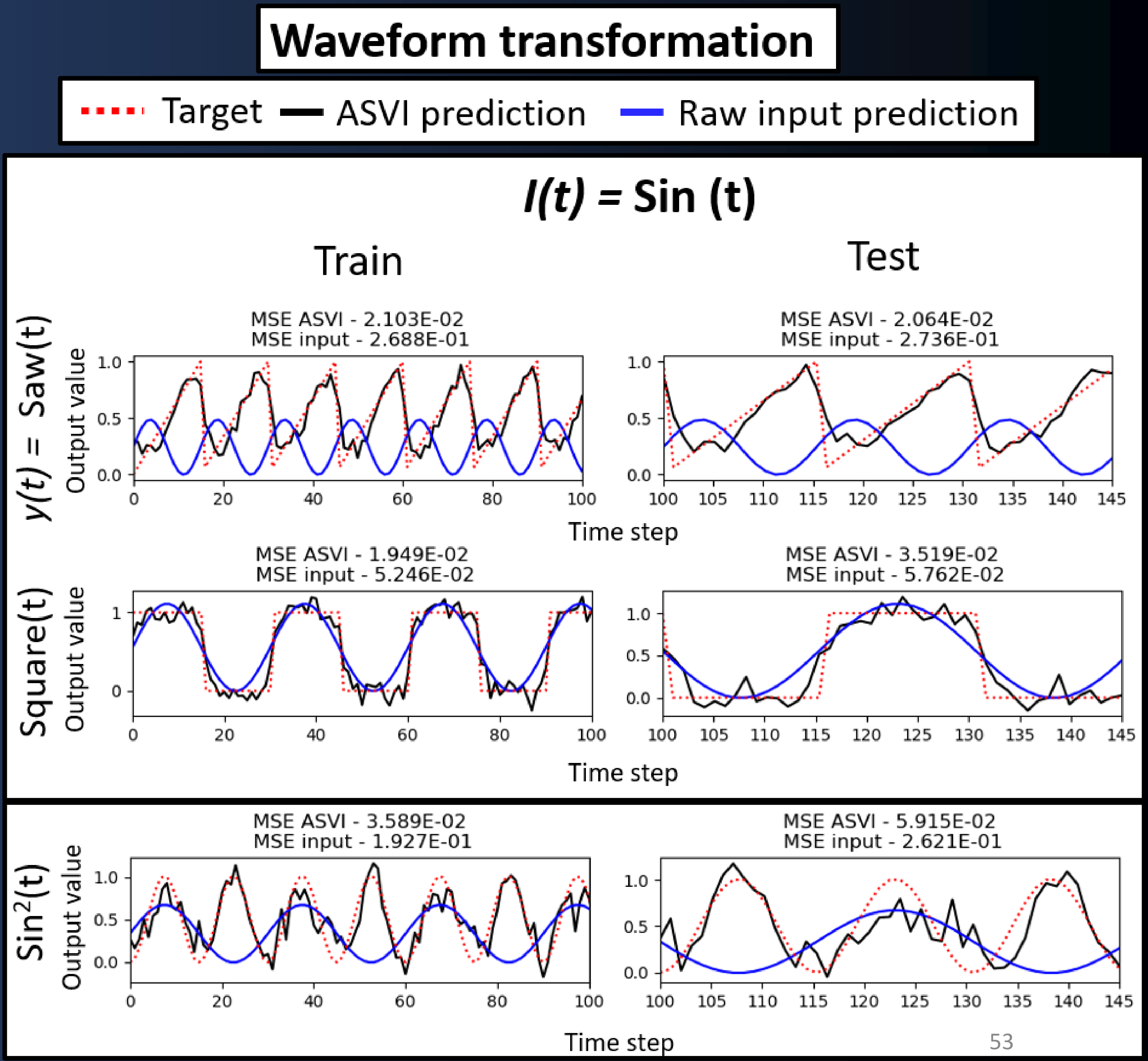
ASVI appears to tick boxes well – Implement ASVI reservoir!
PhD student Kilian Stenning lead our implementation

Reservoir Computation with ASVI



Waveform transformation

- Input I(t) dataset as field-sequence
- Transform output data to desired waveform y(t) via Ridge-Regression
- Unknown transformation relation, challenging benchmarking task
- Short 100 datapoint training to reflect real-world embedded device use cases



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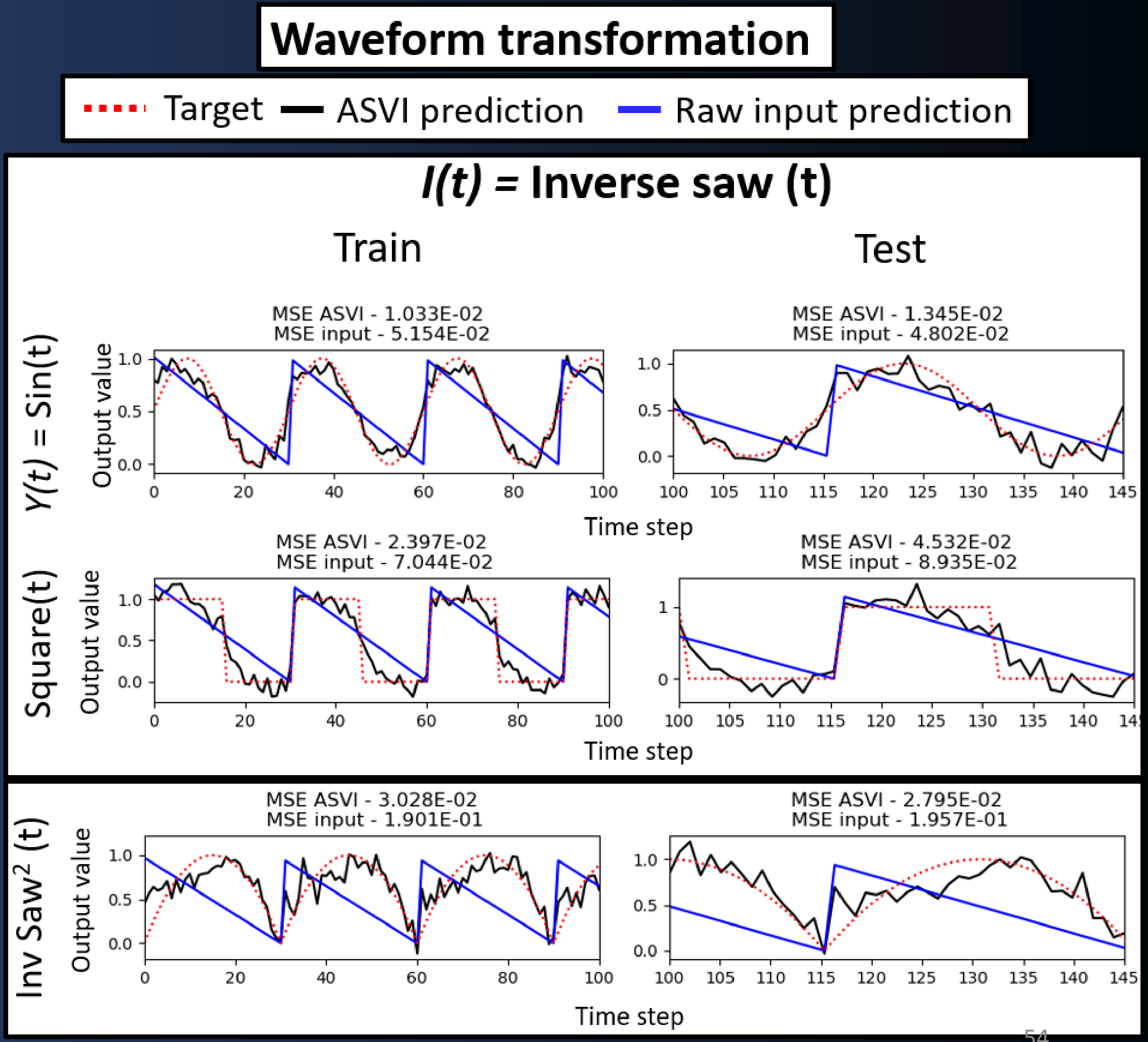
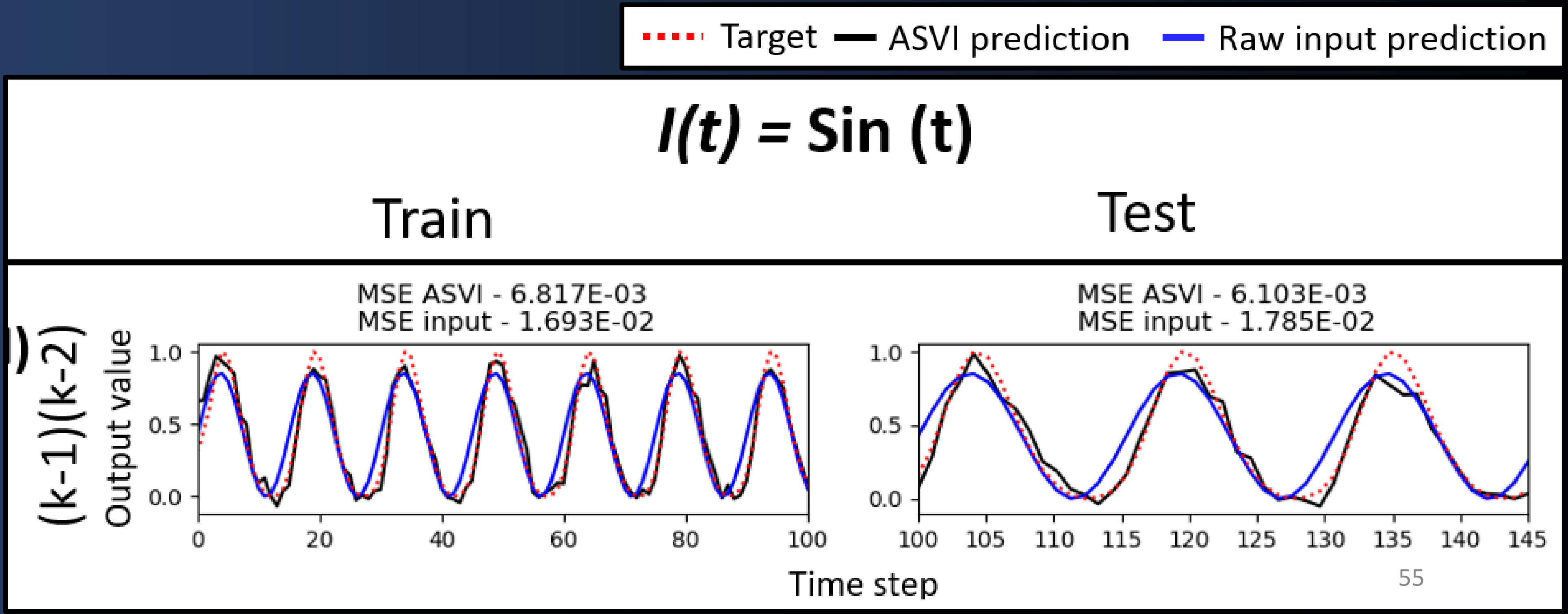


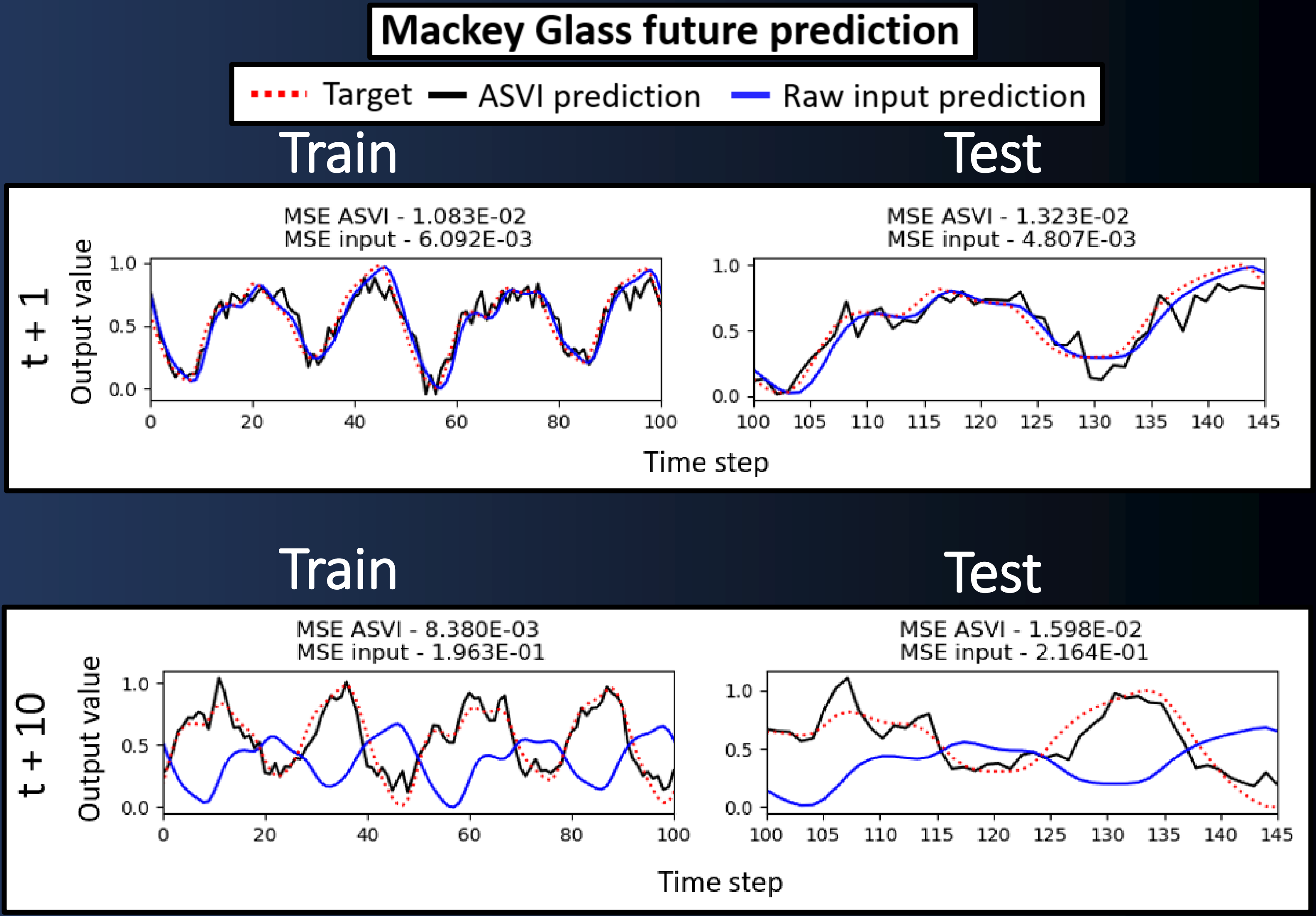
Waveform transformation

- Hysteretic Non-Linear Transformation task
- $y(t) = 0.4y(t-1)+0.4y(t-1)y(t-2)+0.613(t)$
- Challenge of training to prior steps in addition to higher-order
- Function after Du et al, *Nat Comms* (2017)



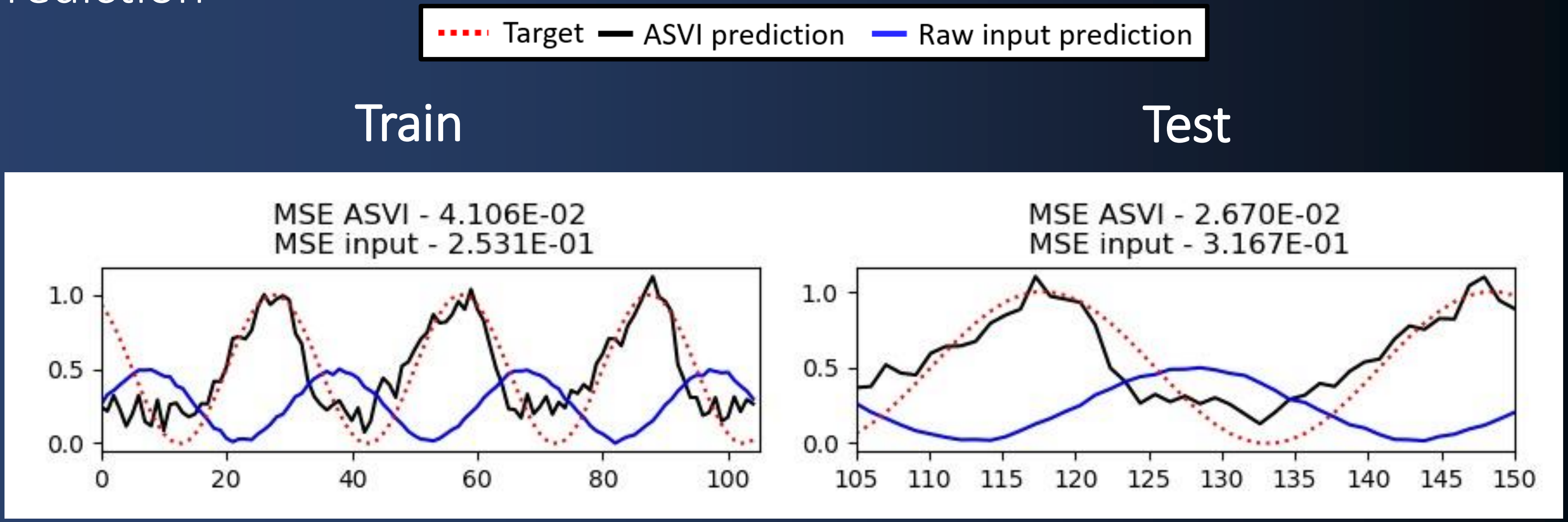
Time-Series Prediction

- Input training waveform as field-sequence
- Train on FMR output to predict future behaviour
- Employ chaotic oscillatory 'Mackey-Glass' time series
- ASVI performs increasingly well vs. no reservoir case as prediction moves further into future



Time-Series Prediction – Noise Tolerance

- Inject white noise to input signal
- ASVI retains good future prediction



Sin(t) future prediction, t+10

Conclusions & Future Work

- Designed & tested a new artificial spin system with controllable bistabile magnetic textures
- Exhibits ratchet-like macrospin-to-vortex training & emergent physical memory behaviour
- Rich spin-wave spectra with analogue-style mode amplitude tuning via training
- Tip-written vortices allow local control of training behaviour
- Potential as a new versatile platform for reconfigurable magnonics & neuromorphic computation
- Leverage Vortex-writing for directed reservoir computation
- Multiple nanoscale FMR pickups for reservoir scheme

Thanks & Acknowledgements

- Thanks to Prof. Karin Everschor-Sitte & Jake Love for reservoir discussions
- Thanks again to all co-authors and collaborators:
- Kilian D. Stenning, Alex Vanstone, Troy Dion, Holly H. Holder, Francesco Caravelli, Daan M. Arroo, Hidekazu Kurebayashi, Will R. Branford
- In particular
  - Kilian Stenning – Reservoir scheme design & implementation
  - Alex Vanstone – Establishing FMR readout of microstates
  - Troy Dion – Simulation of spin-wave modes & spatial profiles