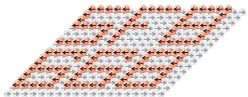
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG



MAGic Sky

Funded by the Horizon2020 Framework Programme of the European Union

Tuning non-collinear magnetic states by hydrogenation

Aurore Finco, Pin-Jui Hsu, Kirsten von Bergmann and Roland Wiesendanger

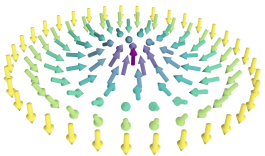
University of Hamburg

A. Finco *et al.* *Phys. Rev. B* 99 (2019), 064436

Slides available at https://magimag.eu

Motivation: tuning the properties of ultrathin magnetic films

- Non-collinear magnetic structures: domain walls, skyrmions, etc.
- In ultrathin films, promising for spintronics
  → need to stabilize and study them
  → need to **control the properties** of the films



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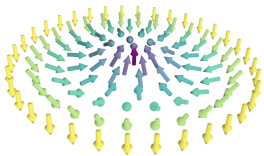

Composition	→ Choice of materials (film, substrate)
Interfaces	→ Strength and sign of the Dzyaloshinskii-Moriya interaction
Thickness	→ Tuning the anisotropy, the strength of the dipolar fields, the Curie temperature, etc.
Environment	→ Temperature, magnetic field, electric field, etc.
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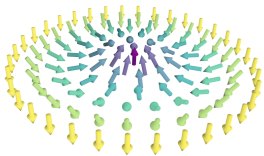

Composition	→ Choice of materials (film, substrate)
	→ **Hydrogenation**: change of the properties of a given material
Interfaces	→ Strength and sign of the Dzyaloshinskii-Moriya interaction
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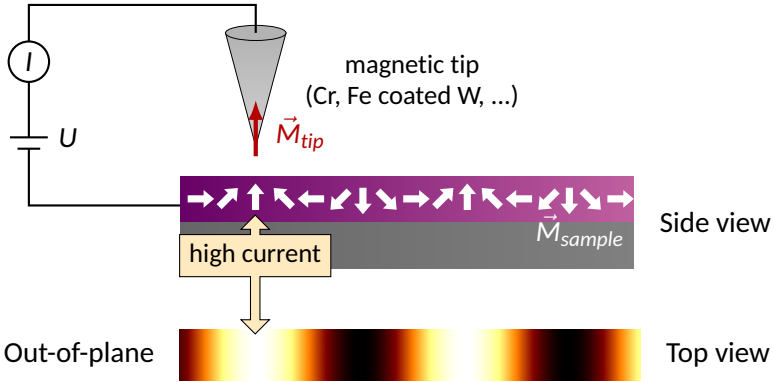
Spin-polarized Scanning Tunneling Microscopy (SP-STM)



$$I = I_0 \left(1 + P_{sample} P_{tip} \cos\left(\vec{M}_{sample}, \vec{M}_{tip}\right)\right)$$

R. Wiesendanger. *Rev. Mod. Phys.* 81 (2009), 1495–1550

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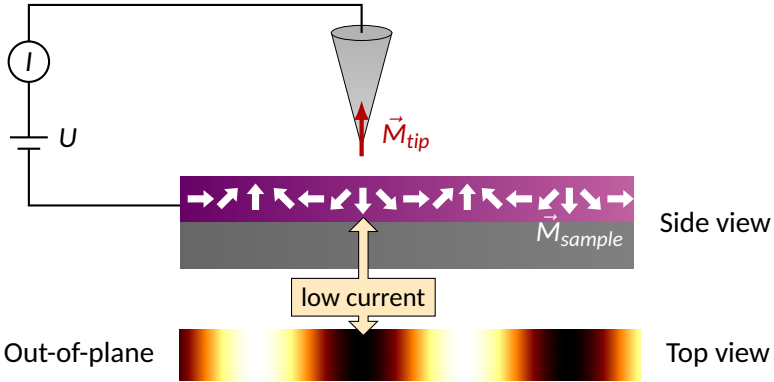

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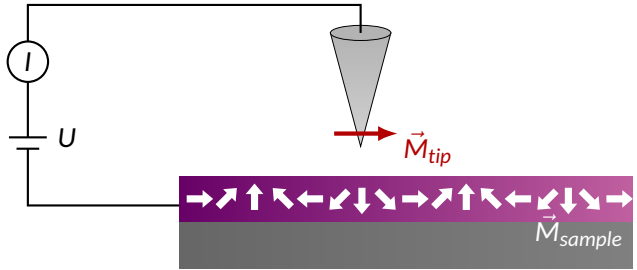


Side view

Out-of-plane

Top view

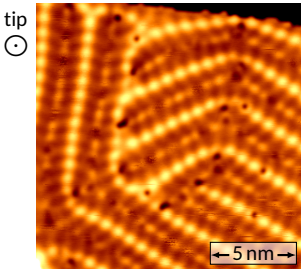
In-plane

Top view

R. Wiesendanger. *Rev. Mod. Phys.* 81 (2009), 1495–1550

Hydrogenation of the atomic Fe bilayer on Ir(111)

Pristine layer



Constant current map
200 mV, 1 nA, 5 K, 4 T, Fe on W tip

- Dislocation lines
- Spin spirals, period about 1.5 nm
- No change in magnetic field up to 9 T

P.-J. Hsu *et al.* *Phys. Rev. Lett.* 116 (2016), 017201

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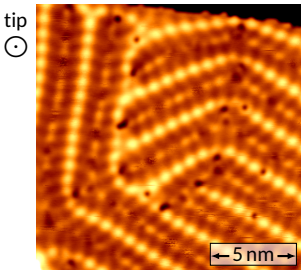

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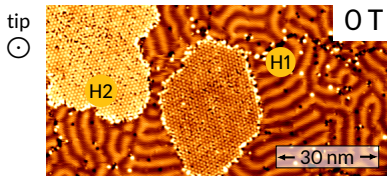
Hydrogenated layer

- Two phases with hexagonal superstructures
- H1: spin spirals, H2: FM state



Constant current map, −700 mV, 1 nA, 4 K, Cr bulk tip

Spiral period about 3.5 nm

P.-J. Hsu *et al.* *Nat. Commun.* 9 (2018), 1571

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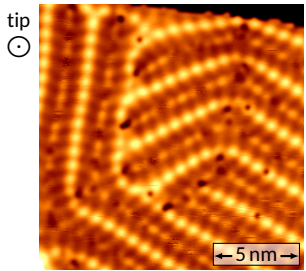

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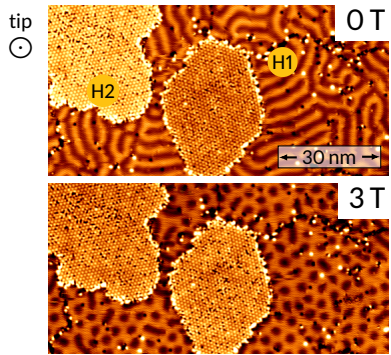


Spiral period about 3.5 nm

Skyrmions in magnetic field

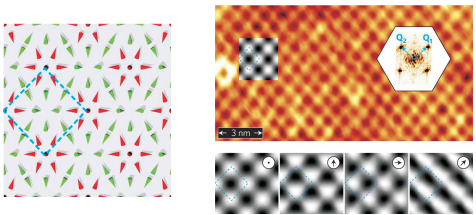
Constant current map, −700 mV, 1 nA, 4 K, Cr bulk tip

P.-J. Hsu *et al.* *Nat. Commun.* 9 (2018), 1571

The pristine Fe monolayer on Ir(111)

- Complex magnetic states: nanoskyrmion lattices, with a period about 1 nm
- Stabilized by the competition between exchange, anisotropy, DMI, and also higher order interactions

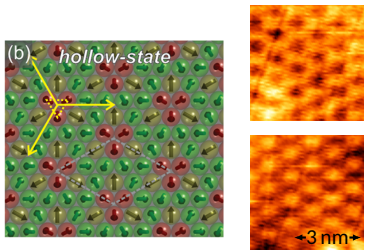
fcc stacking



Square incommensurate
nanoskyrmion lattice

S. Heinze *et al.* *Nat. Phys.* 7 (2011), 713–718

hcp stacking

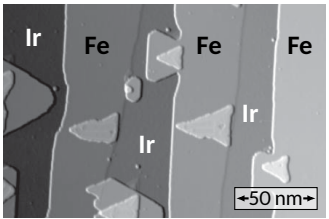


Hexagonal commensurate
nanoskyrmion lattice

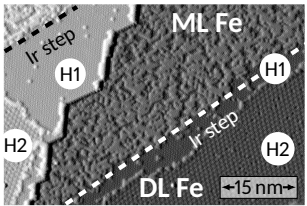
K. von Bergmann *et al.* *Nano Letters* 15 (2015), 3280–3285

Incorporation of H atoms in the Fe film

Pristine Fe/Ir(111), fcc



more H



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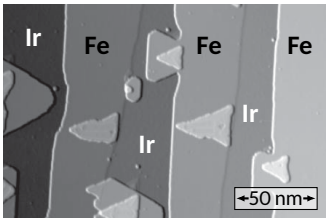

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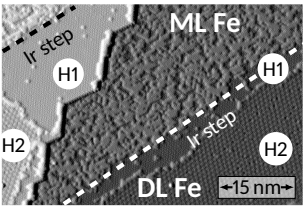

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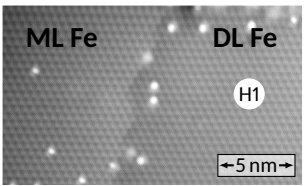

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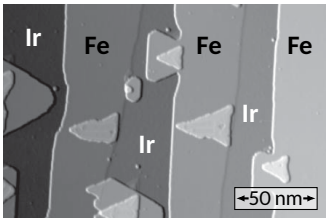

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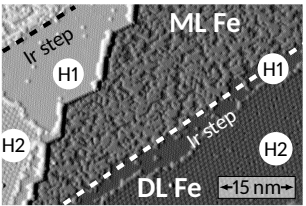

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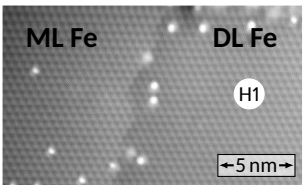

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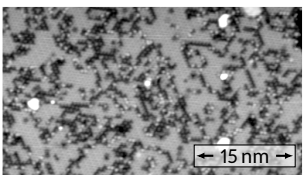

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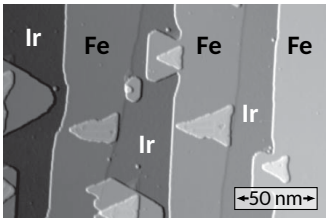

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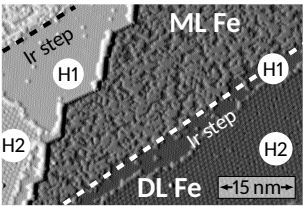

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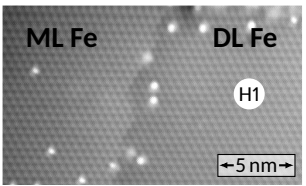

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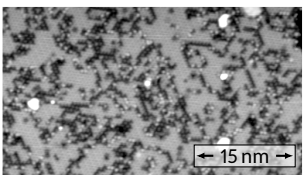

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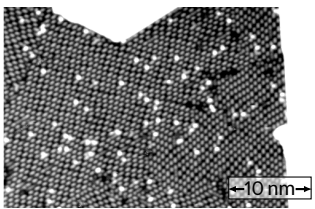

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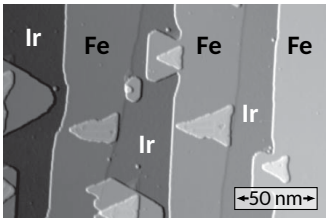

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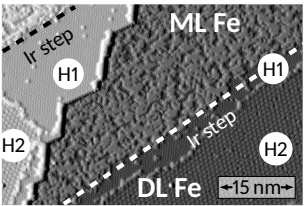

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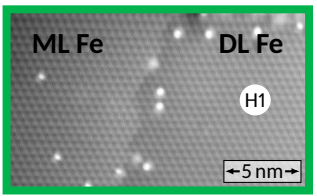

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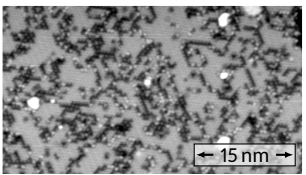

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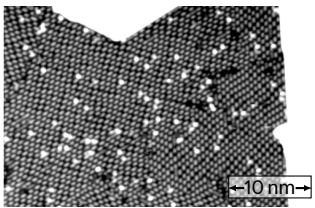
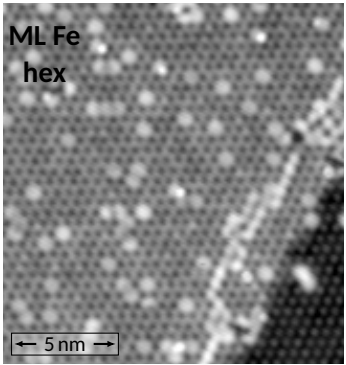


Hexagonal phase

The hexagonal phase



Constant current map, 50 mV, 1 nA, 8 K

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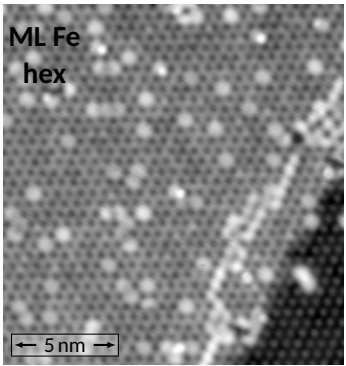

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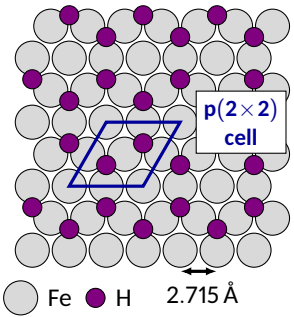
DL Fe
H1

Hydrogenated Fe DL
Model of the H1 phase
Top view



P.-J. Hsu *et al.* *Nat. Commun.* 9 (2018), 1571

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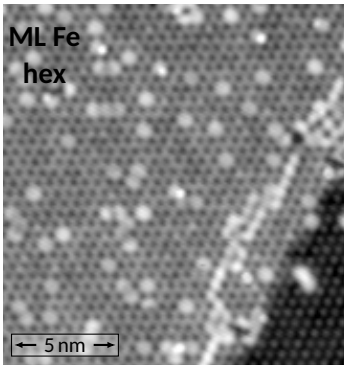

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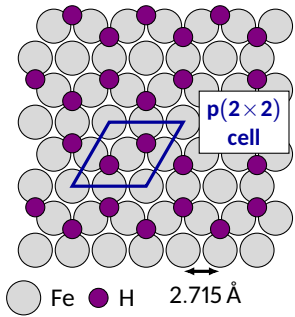
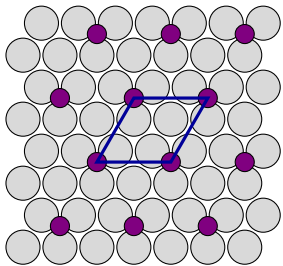


Hydrogenated Fe ML
Model of the hexagonal phase
Top view



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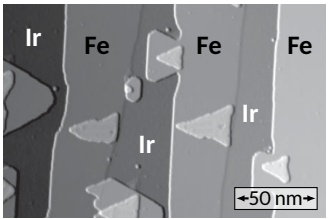

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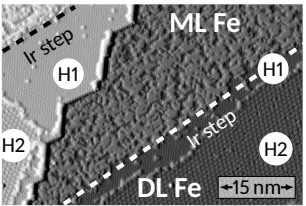

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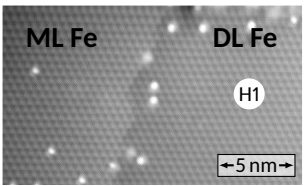

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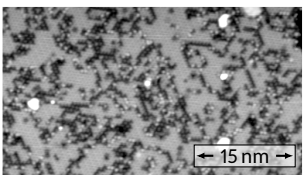
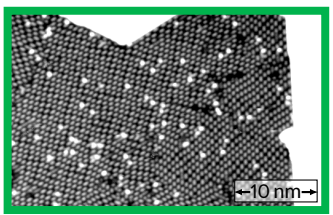


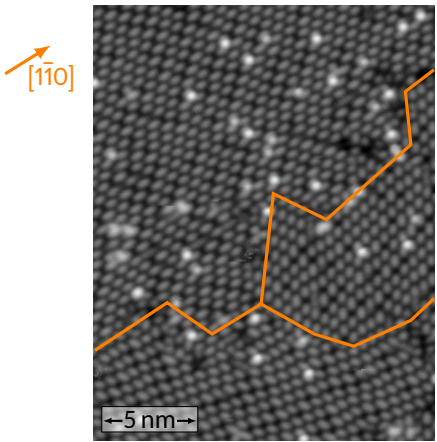
more H

Roughly square phase



The roughly square phase

3 rotational domains



Constant current map, 800 mV, 1 nA, 4 K

The roughly square phase

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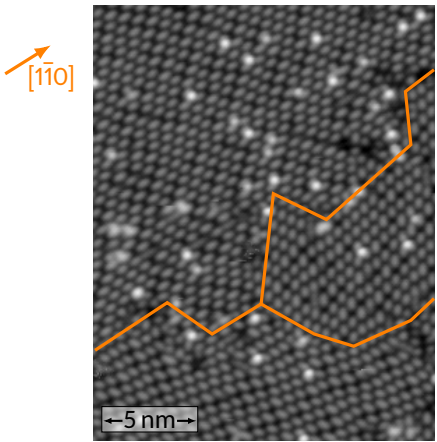

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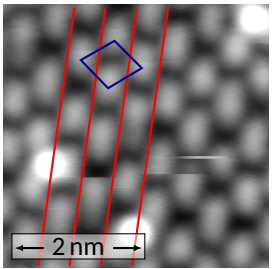
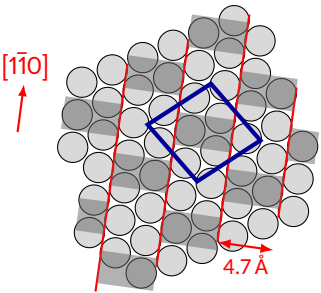
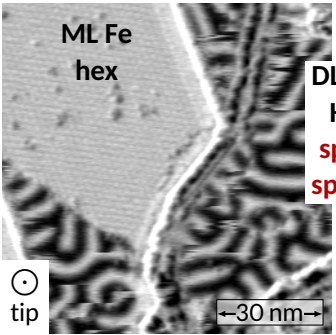


Constant current map
500 mV, 1 nA, 4 K

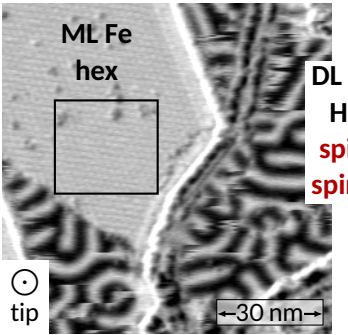


Magnetic state of the hexagonal phase: a p(4×4) structure



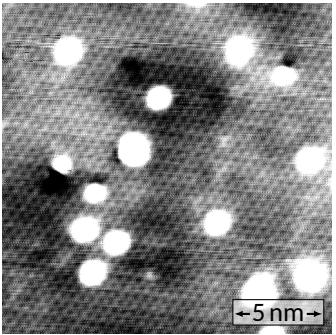
Differential conductance map
−1 V, 1 nA, 4 K, Cr bulk tip

Magnetic state of the hexagonal phase: a p(4×4) structure



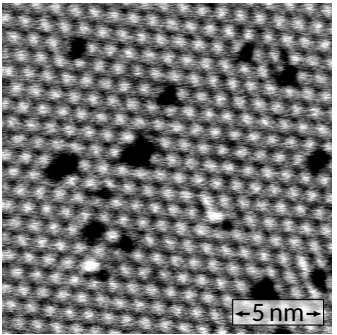
Differential conductance map
−1 V, 1 nA, 4 K, Cr bulk tip

H superstructure



Constant current map
−1 V, 1 nA, 4 K, Cr bulk tip

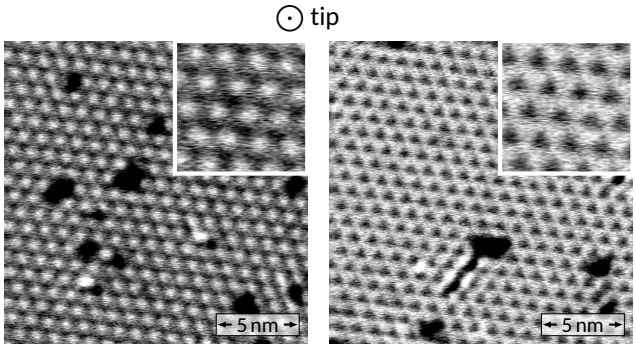
Magnetic state



Differential conductance map
−1 V, 1 nA, 4 K, Cr bulk tip

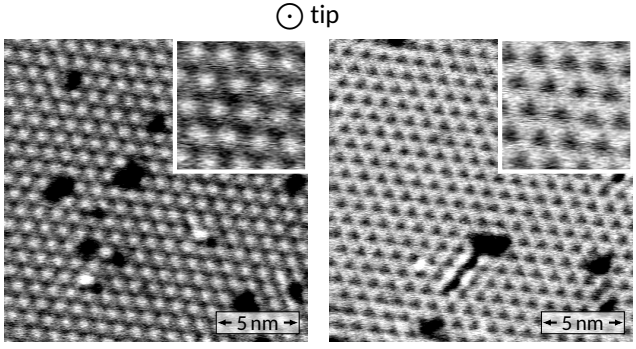
The magnetic unit cell is 4 times larger $p(4 \times 4)$ than the unit cell of the H superstructure $p(2 \times 2)$

Opposite magnetic domains



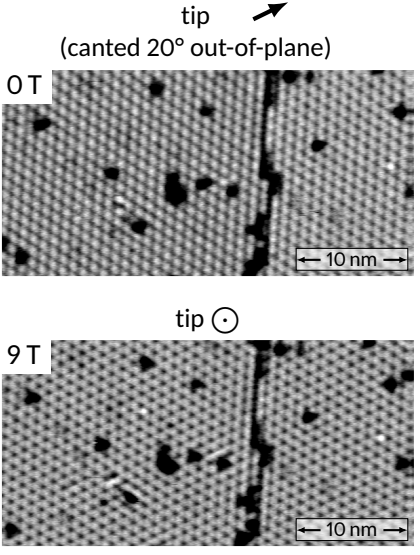
Differential conductance maps, −1 V, 1 nA, 4 K, 0 T, Cr bulk tip

Opposite magnetic domains



Differential conductance maps, −1 V, 1 nA, 4 K, 0 T, Cr bulk tip

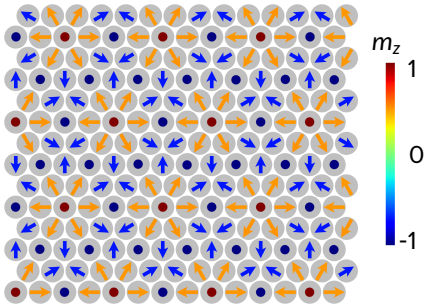
Switching of the domains with out-of-plane magnetic field!



Differential conductance maps
−700 mV, 1 nA, 4 K, Cr bulk tip

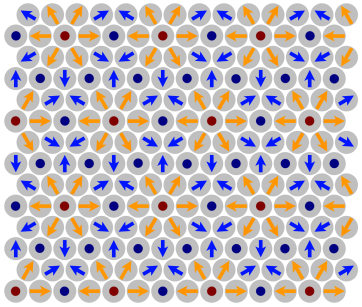
An hexagonal nanoskyrmion lattice

Superposition of 3 cycloidal spirals

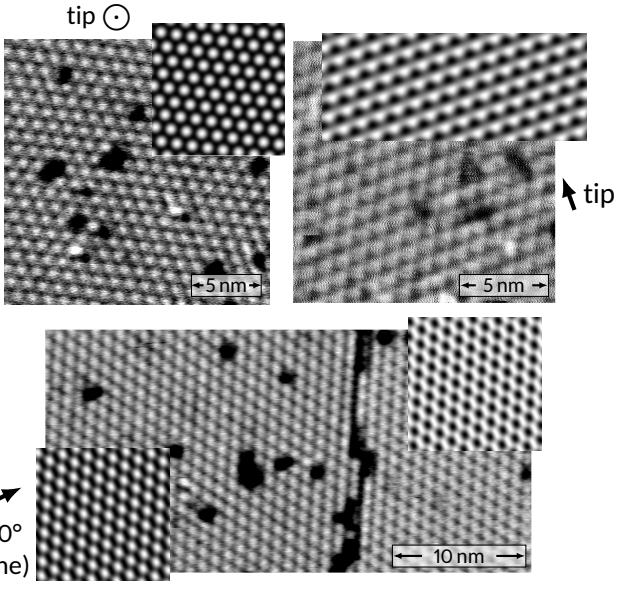


An hexagonal nanoskyrmion lattice

Superposition of 3 cycloidal spirals



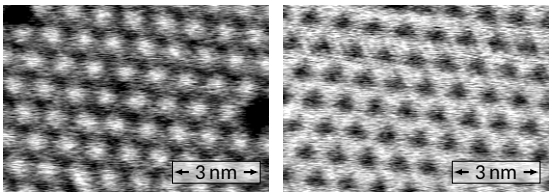
Good agreement between simulations and experiments!



Where are the H atoms?

What is the position of the H superstructure with respect to the magnetic lattice?

Experiments



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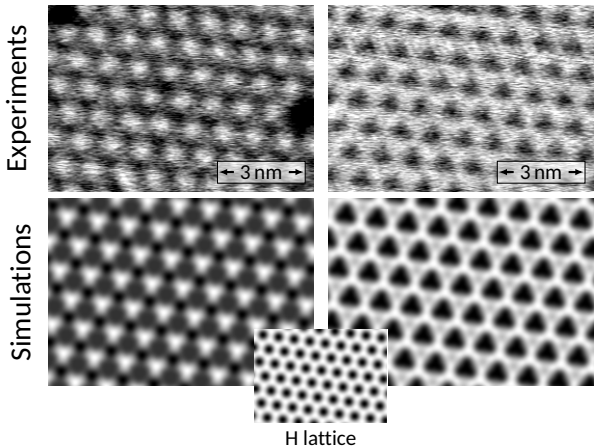

Where are the H atoms?

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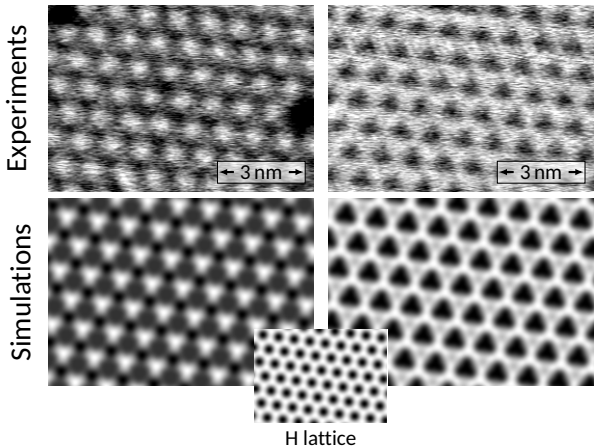
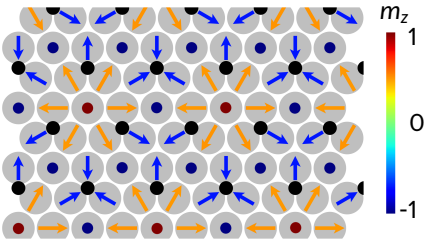
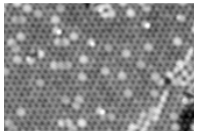
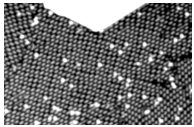




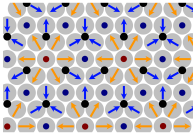
Summary

- The incorporation of H atoms in the Fe monolayer on Ir(111) induces the formation of a $p(2 \times 2)$ superstructure. With more H atoms, an irregular roughly square structure appears.





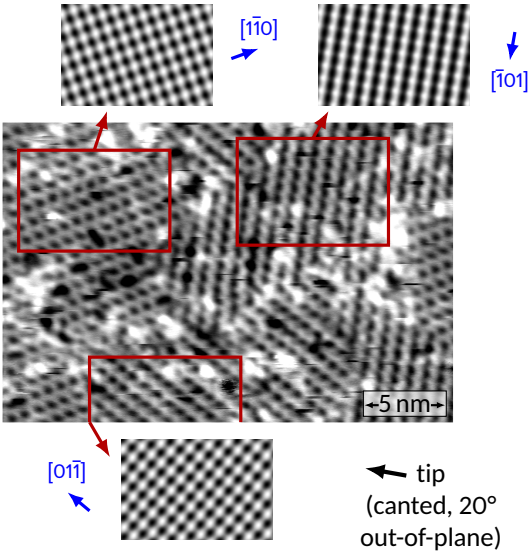
- These structural changes influence the nanoskyrmion lattice, its symmetry follows the H superstructure.



→ Demonstration of the possibility to tune the symmetry of the magnetic lattice without changing the symmetry of the substrate.

A. Finco *et al*. *Phys. Rev. B* 99 (2019), 064436

Magnetic state of the roughly square phase



- Superposition of two cycloidal spirals
- Unit cell size about 1 nm
- No net magnetic moment