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Room temperature chiral skyrmions and skyrmion dynamics in nanostructures

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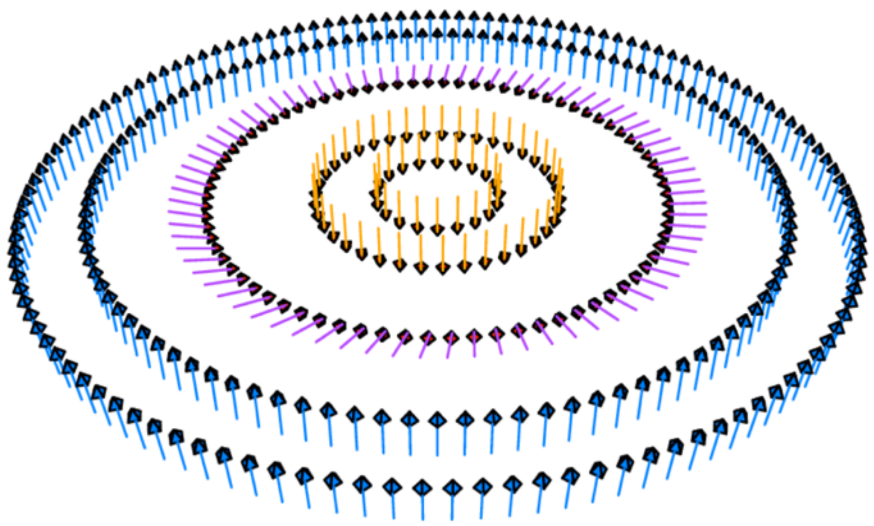

Saturday July 2016, 10:30
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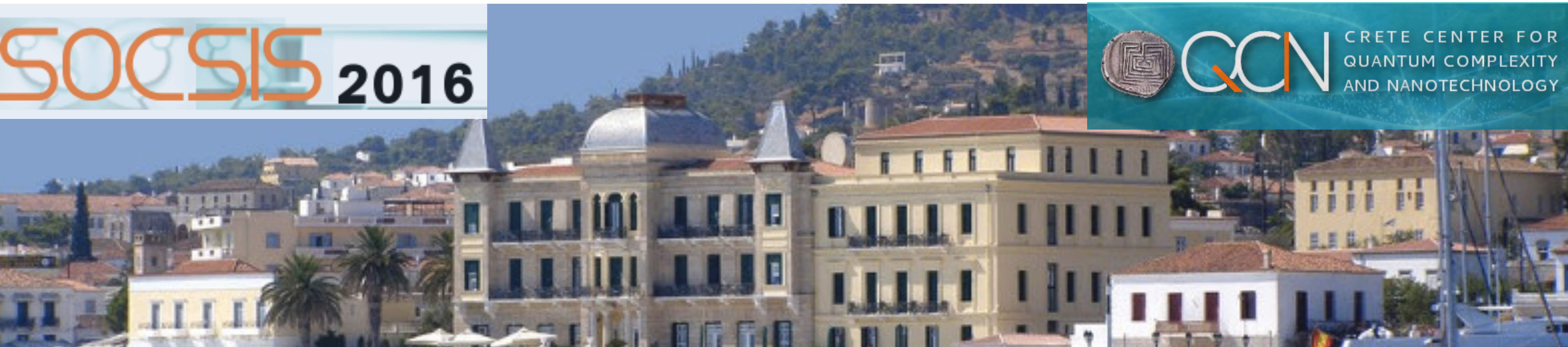
https://skyrmionics.wordpress.com/



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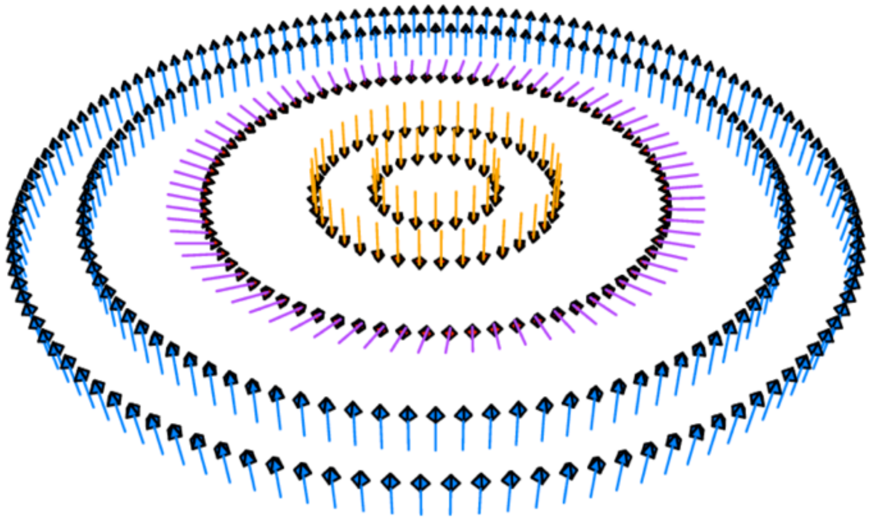
Room temperature chiral skyrmions and skyrmion dynamics in nanostructures

- Dr. J. Raabe, Swiss Light Source, Paul Scherrer Institute.
- Dr. R. Lavrisjen, Prof. H. J. M. Swagten lab, Technical University Eindhoven, Netherlands.
- Prof. M. Kläui lab, Institute of Physics, Johannes Gutenberg-University Mainz, Germany.
- Prof. S. Eisebitt, Institut für Optik und Atomare Physik, TU Berlin, Germany & Helmholtz Zentrum Berlin, Germany.
- Dr. M. Weigand, BESSY, HZB, Germany.
- Dr. V. Cros and Prof. A. Fert lab, CNRS/Thales, France.



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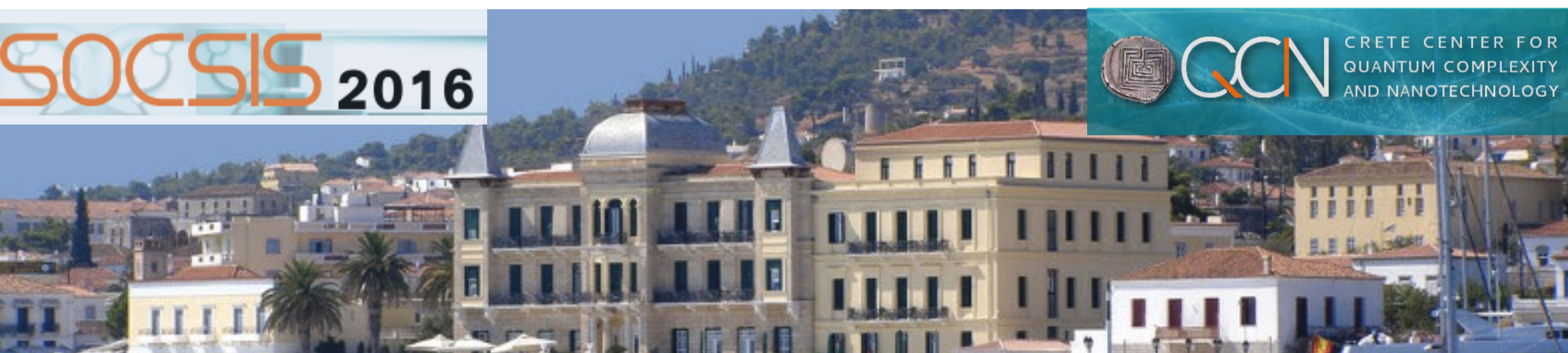
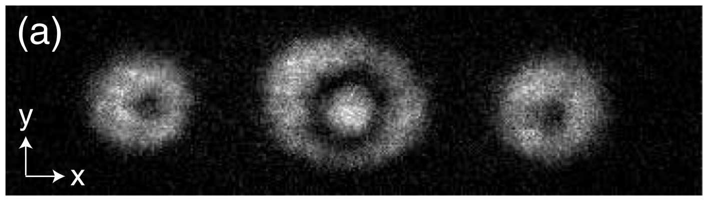
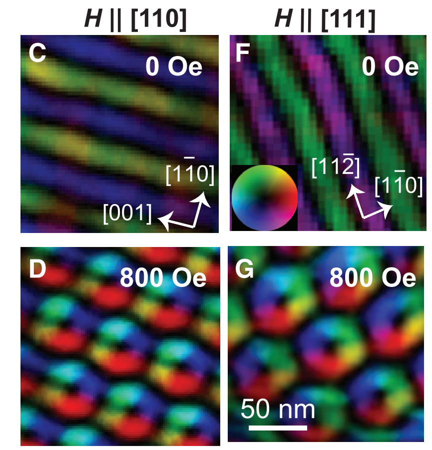


The Omnipresent Skyrmion



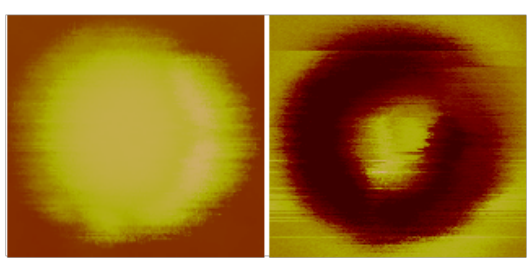
AF Spinor Bose-Einstein condensates
J. Choi et al., Phys. Rev. Lett. 108, 035301 (2012)



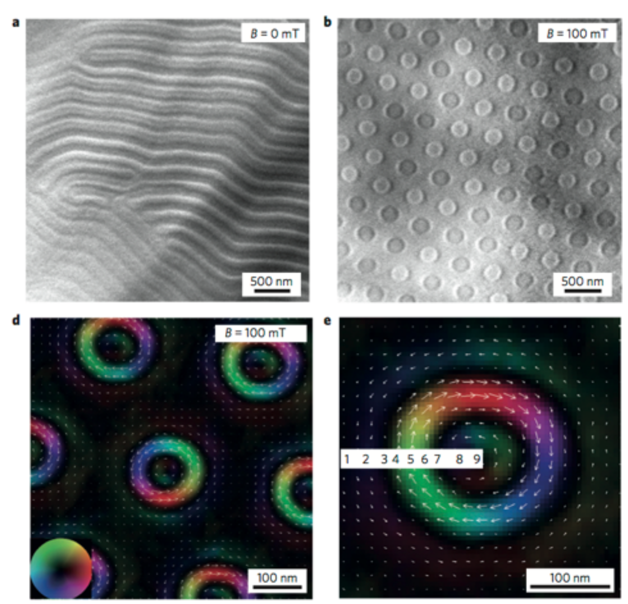
Multiferroics
(Cu_2OSeO_3)
S. Seki, et al.,
Science 336,
198 (2012)

Skyrmions in Ferromagnets

Dipolar-stabilised Skyrmions

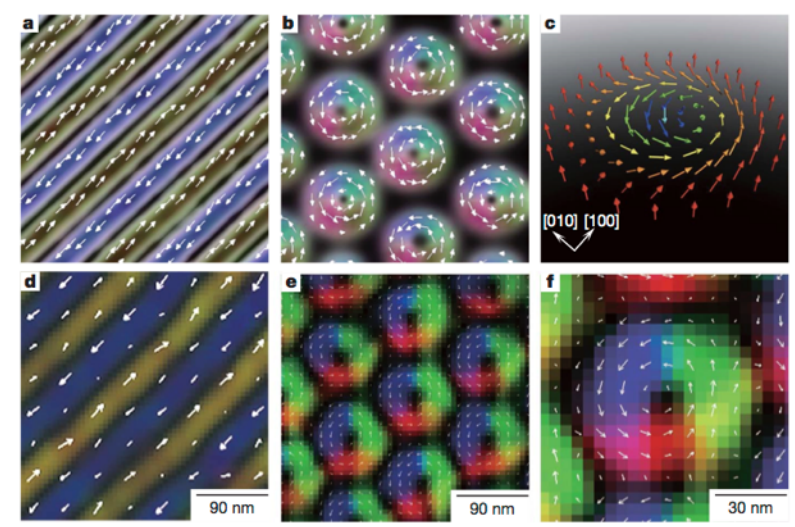


C. Moutafis, et al.
Phys. Rev. B 76, 104426 (2007)



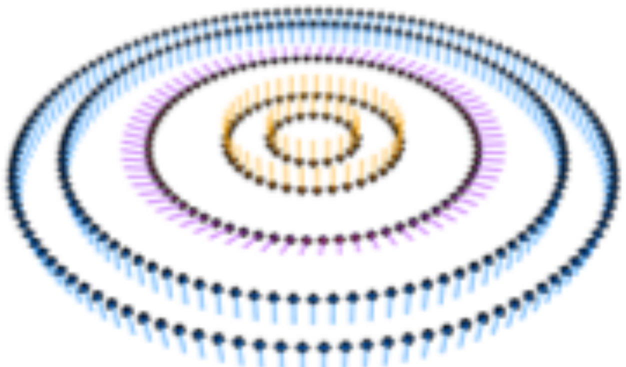
Sc-doped hexagonal barium ferrite
X. Yu, et al. PNAS 109, 8856 (2012)

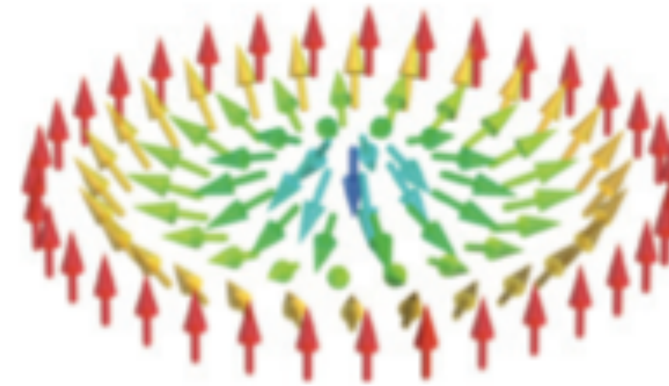
Dzyaloshinskii–Moriya (DMi) stabilised Skyrmions: chiral Magnets

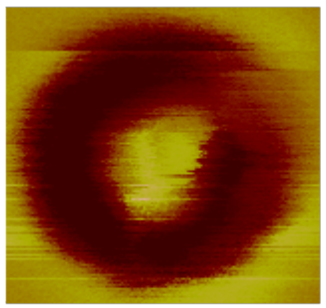


Helical Magnet, $Fe_{0.5}Co_{0.5}Si$
X. Yu, et al., Nature 465, 901 (2010)

The Skyrmion Topology







Skyrmion bubble

chiral Skyrmions

- "Skyrmion": topology of the mapping between real space and the unit sphere [1,2]
- Various energy mechanisms for skyrmions, e.g. : i) dipolar, ii) DMi [2]
- Skyrmion number unity **|N|=1** -> **Skyrmion Topology**
- Instances of Topological Solitons in PMA magnets: **topologically protected**

Magnetisation Dynamics is directly linked to Topology [1]

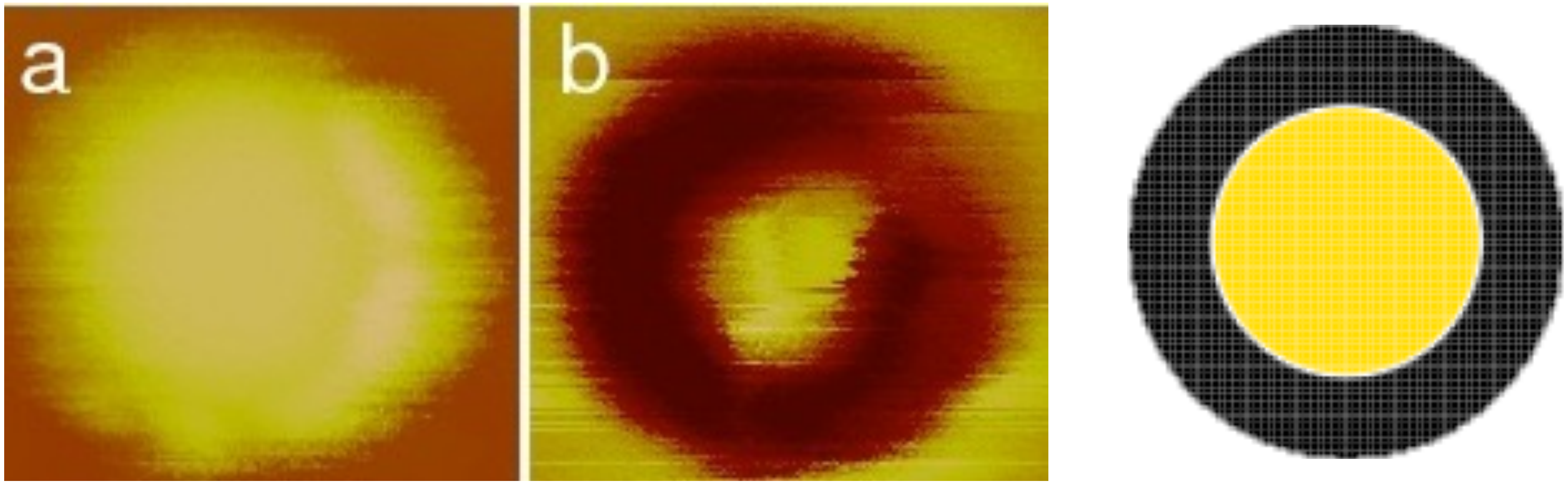
[1] R. Rajaraman, Solitons and instantons **(Elsevier, 1982)**

[2] N. Nagaosa, Y. Tokura, Topological properties and dynamics of magnetic skyrmions, **Nat. Nanotech. 8, 899 (2013)**

[3] A. Fert, et al. **Nature Nanotech. 8, 152 (2013)**

Isolated Bubbles in Confined Geometries

AFM MFM Simulation



a) 500nm FePt dot b) Magnetic Force Microscopy c) Monobubble state schematic

- Monobubble state: <u>nanoscale</u> bubble in the center of the dot [3]
- **Stable** at **remanence**; no bias-field

[1] A. P. Malozemoff and J. C. Slonczewski, Magnetic Domain Walls in Bubble Materials, **Academic Press (1979)**

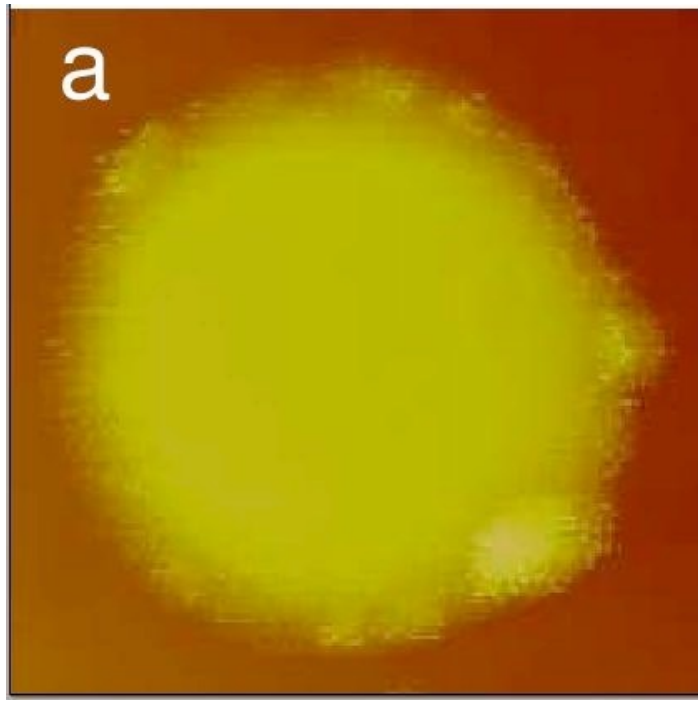
[2] M. Hehn et al., Nanoscale Magnetic Domains in Mesoscopic Magnets, **Science (1996)**

[3] <u>C. Moutafis</u>, S. Komineas, et al., Magnetic bubbles in FePt nanodots with perp. anis., **Phys. Rev. B 76, 104426 (2007)**

The Three-Ring state

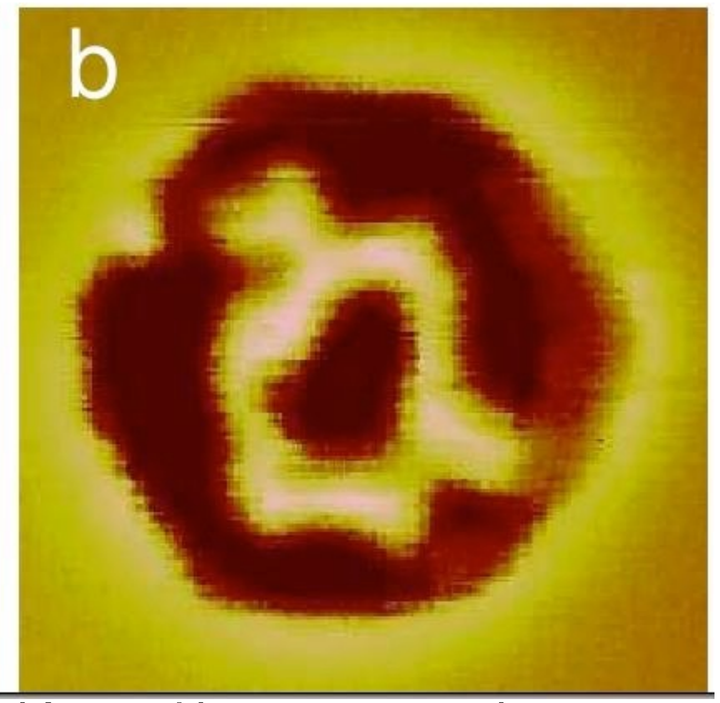
D = 1 μm

AFM



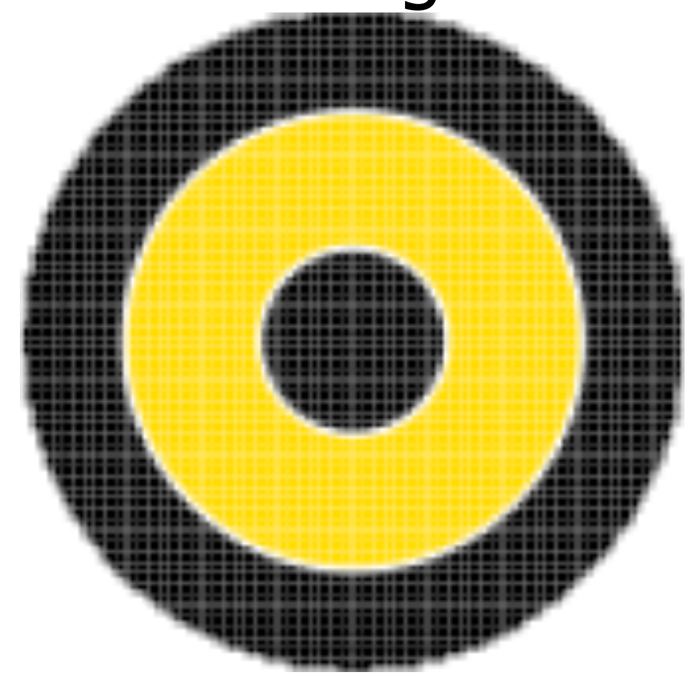
a) Topography of a dot

MFM



b)Ring-like structure: domains of alternating magnetisation

Three-ring state



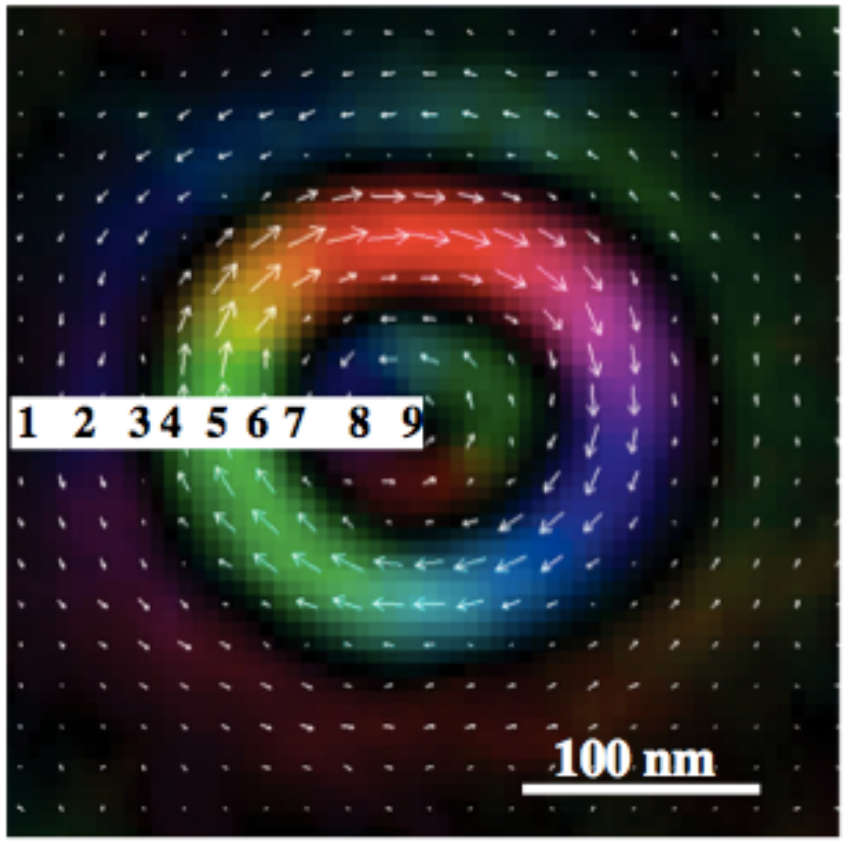
c) Schematic of the three-ring state

- Symmetric-like domain structures possible;tridomain ring structures observed
- **Stable** at **remanence**; no bias-field
- These can be interpreted as higher order bubble states

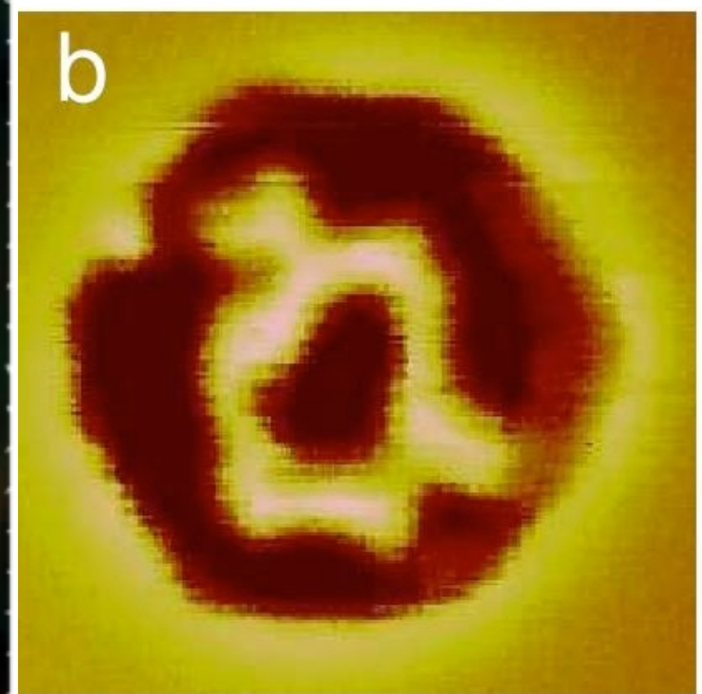
[1] **C. Moutafis,** et al., Magnetic bubbles in FePt nanodots with perpendicular anisotropy, **Phys. Rev. B 76, 104426 (2007)**

The Three-Ring state

D = 1 μm

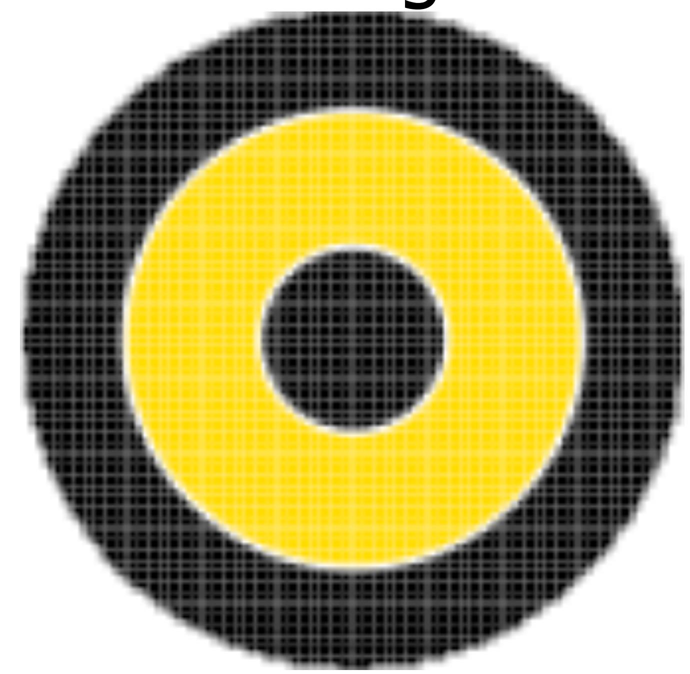


MFM



b)Ring-like structure: domains of alternating magnetisation

Three-ring state



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- Symmetric-like domain structures possible;tridomain ring structures observed
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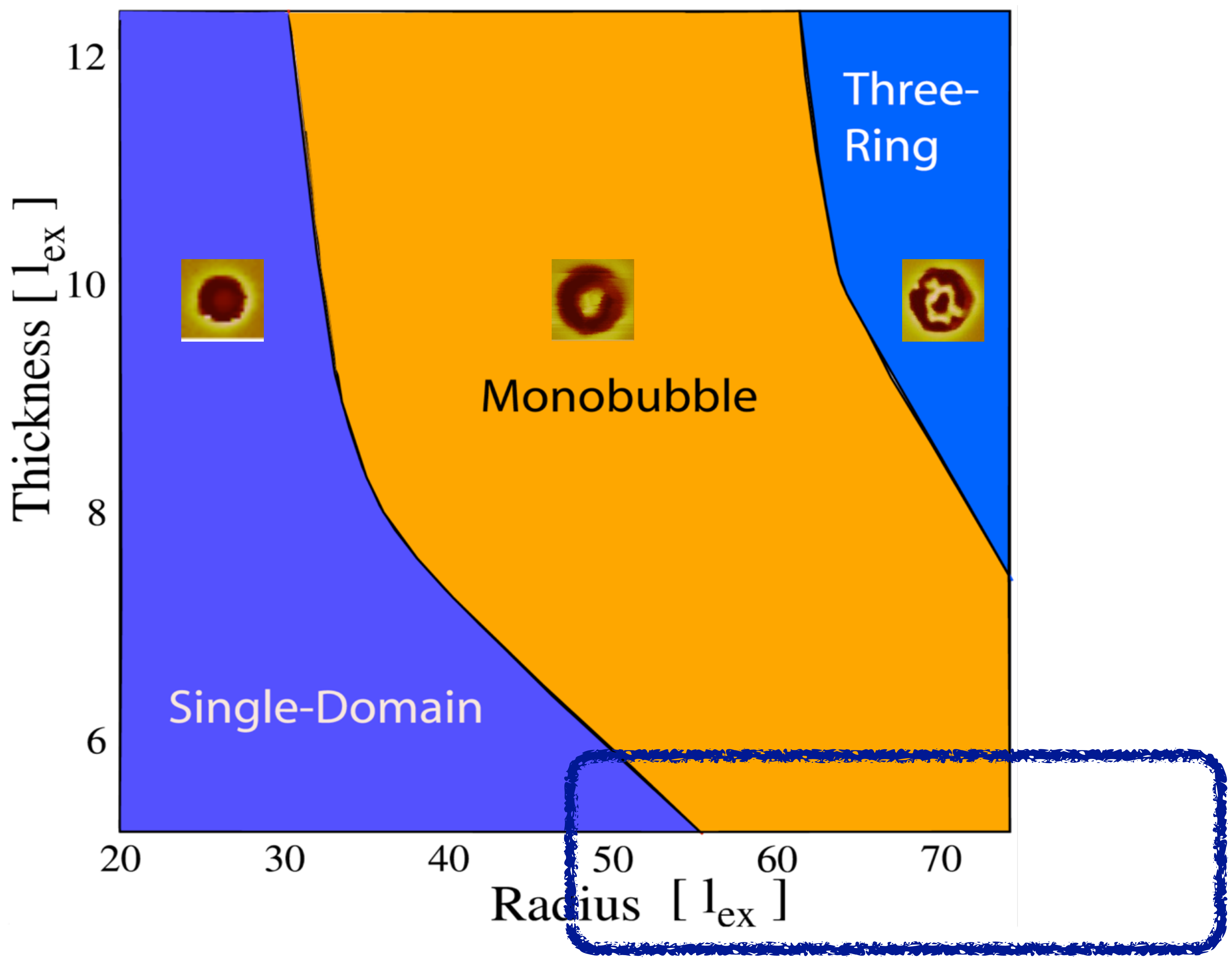
[1] X. Yu, et al., Magnetic stripes and skyrmions with helicity reversals, **PNAS 109, 8856–8860 (2012)**

Phase diagram in parameter-space

We explore numerically the effects of thickness in dots of varying diameters

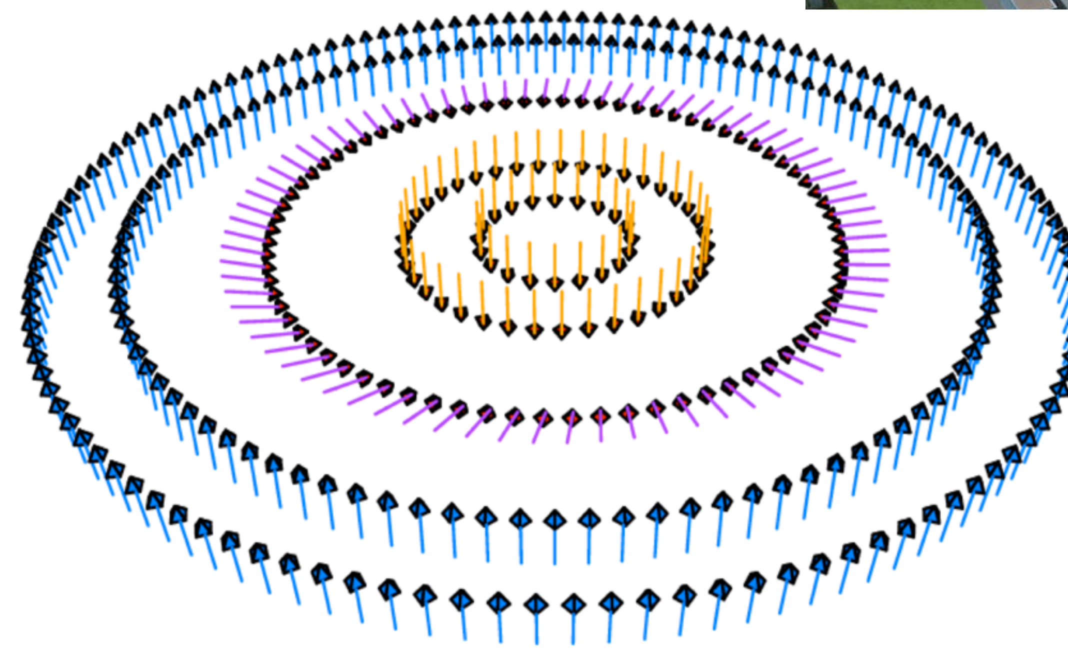


- The lines correspond to radii $\mathbf{R_{c1}}$ and $\mathbf{R_{c2}}$ as a function of thickness

The critical radius depends strongly on thickness, especially for ultrathin films

Topological considerations

Complexity of multidomain states can be quantified by a topological invariant [1,2].



Skyrmion number (∝Thiele's Gyrovector)

$$\mathcal{N} = \frac{1}{4\pi}\int n\, d^2x, \qquad n = \frac{1}{2}\epsilon_{\mu\nu}\left(\partial_\nu \boldsymbol{m} \times \partial_\mu \boldsymbol{m}\right)\cdot \boldsymbol{m}$$

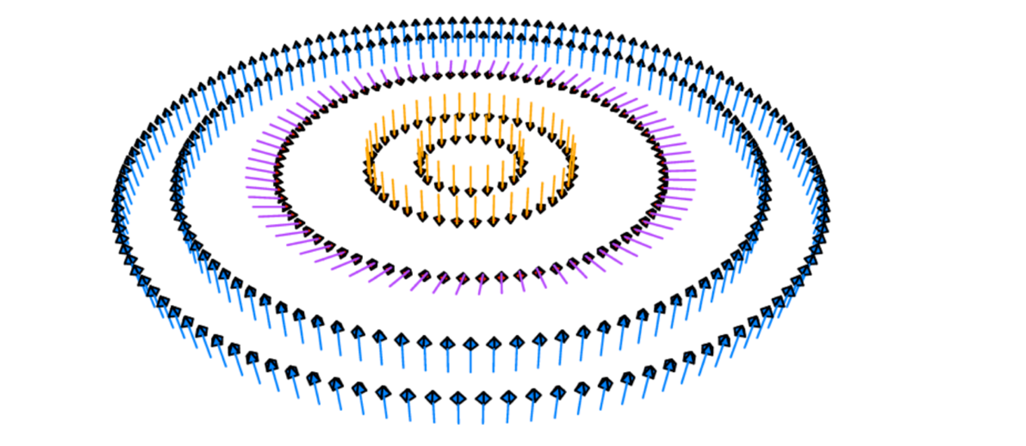
- **Monobubble** state has Skyrmion number (topological charge) N=±1
- Manifestations of Skyrmions in the ferromagnet: Skyrmion bubble.

Magnetisation dynamics is directly linked to topology [1].
Different **dynamics** is expected
for states with different Skyrmion number (e.g. N=0 and N=1)

[1] A.A. Thiele, Steady-state motion of magnetic domains, Phys. Rev. Lett. 30, 230 (1973)
[2] N. Nagaosa, Y. Tokura, Topological properties and dynamics of magnetic skyrmions, Nature Nanotech. 8, 899 (2013)

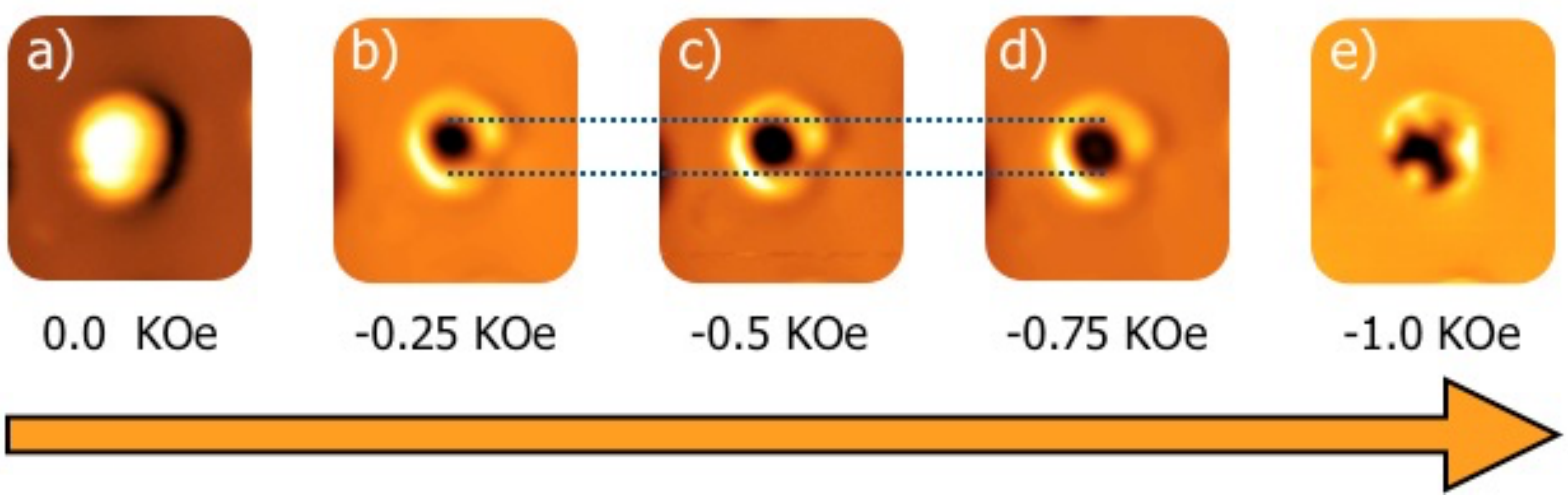
Dynamics

Interested in the dynamic response of such skyrmionic structures in a finite geometry:



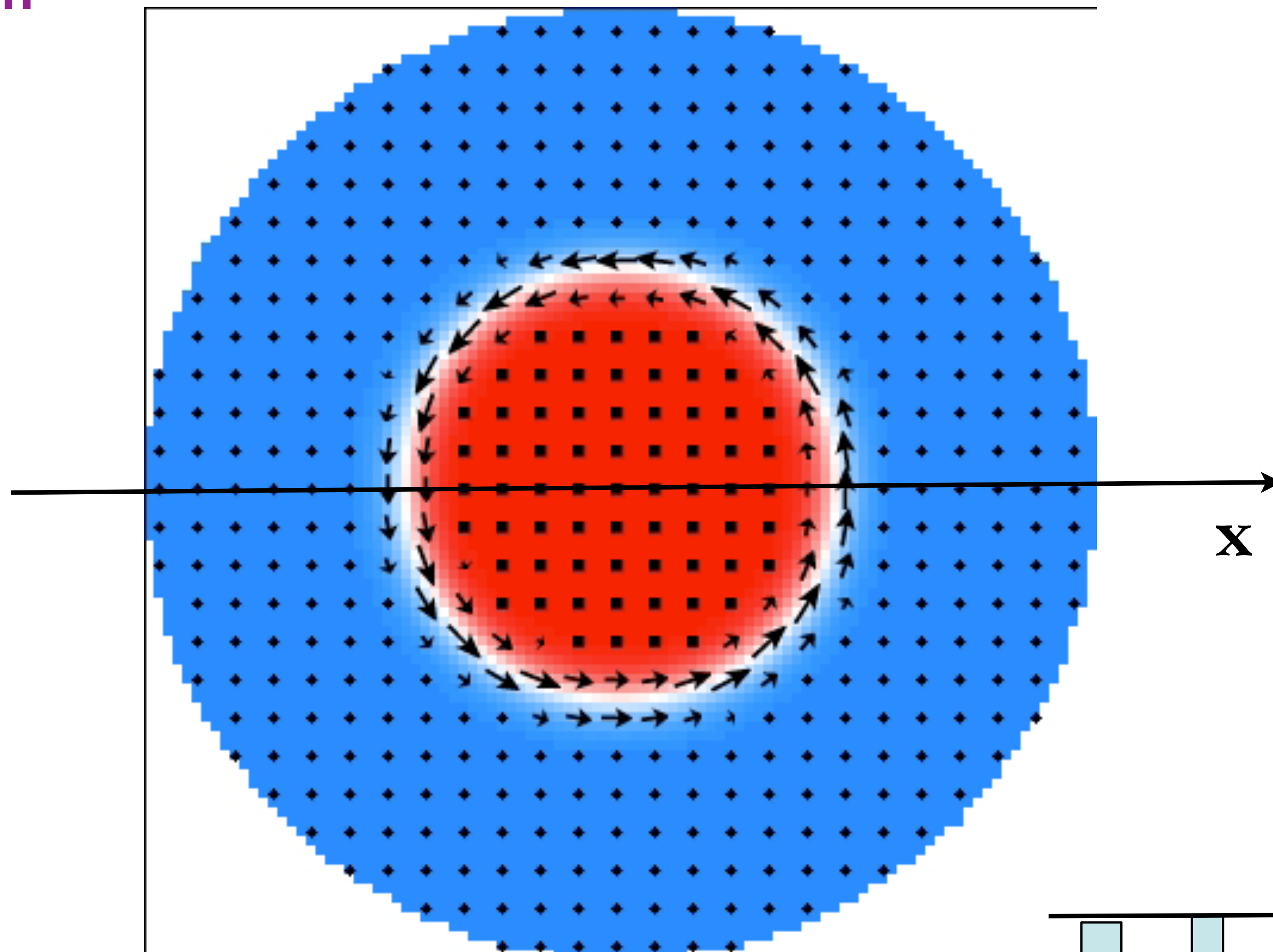
Field Pulse

?

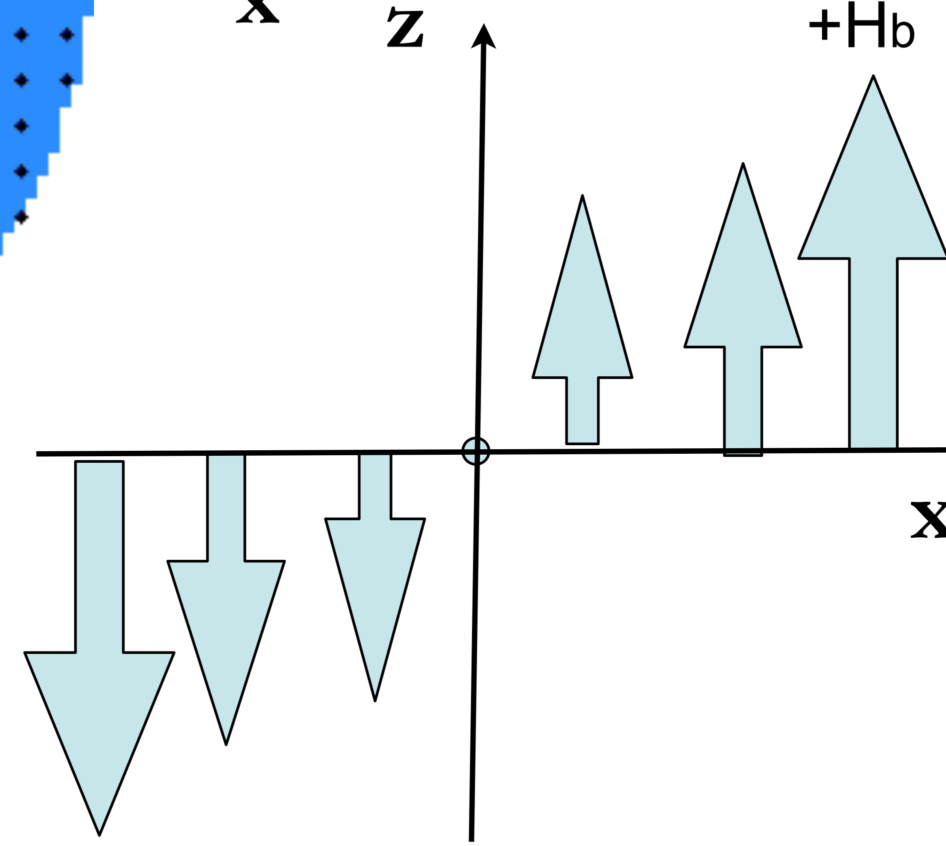


Gyrotropic Motion

Simulation



Period:~1ns
f=1Ghz



$H_{ext} = [-0.05M_s, 0.05M_s]$
Field strength g=-0.0025
$t = 44.5\tau_0\ (200\ ps)$

Note details of DW do **not** change considerably. Bubble size changes.

[1] C. Moutafis, S. Komineas, J. A. C. Bland, Phys. Rev. B vol. 79, 224429 (2009).
[2] DMi: M. Mochizuki, Phys. Rev. Lett. (2012): Simulations of CW & CCW modes in a DMi system.
[3] DMi: Y. Onose, et al., Y. Tokura, Phys. Rev. Lett. 109, 037603 (2012). Observation of CCW mode.

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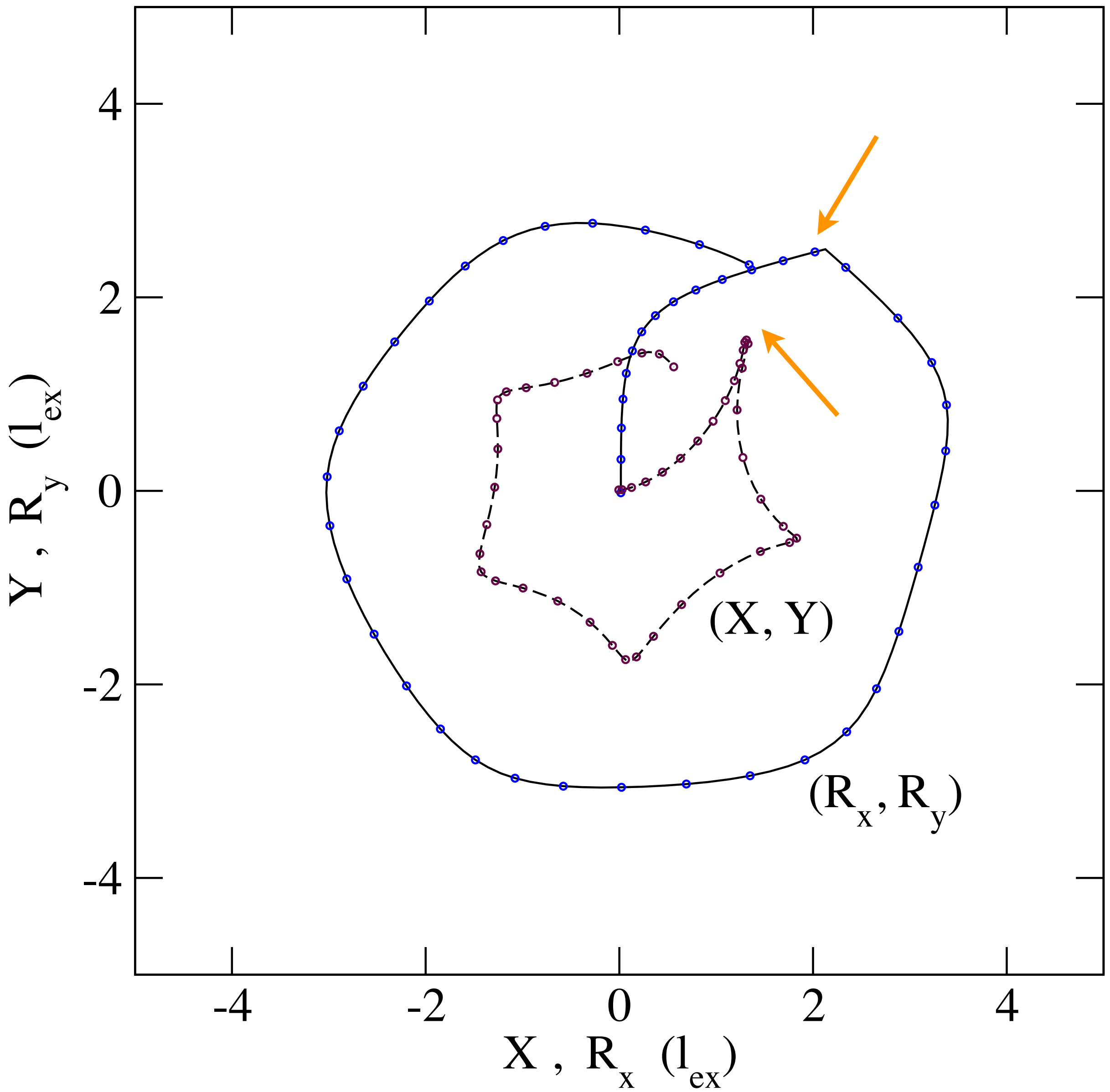
Measures of Bubble Position

In order to show the bubble’s orbit and measure the effect of the field:

Moments of the magnetization	$X = \frac{\int x\,(M_z - 1)\,dV}{\int (M_z - 1)\,dV}, \qquad Y = \frac{\int y\,(M_z - 1)\,dV}{\int (M_z - 1)\,dV}$
Moments of the topological density	$R_x = \frac{\int x\,n\,dV}{\int n\,dV}, \qquad R_y = \frac{\int y\,n\,dV}{\int n\,dV}$ where n is the topological density $n = \frac{1}{2}\,\epsilon_{\mu\nu}\,(\partial_\nu m \times \partial_\mu m)\cdot m$

[1] N. Papanicolaou and T. N. Tomaras, Nucl. Phys. B 360, 425 (1991)

N=1 Bubble's Gyrotropic Motion



Period:~1ns
f=1Ghz

- (X, Y) the guiding center of the center of magnetisation
- (Rx, Ry) the guiding center of the associated topological moments [1]
- N different to unity would exhibit non-regular trajectory

[1] N. Papanicolaou and T. N. Tomaras, Nucl. Phys. B 360, 425, 1991

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Dynamics: bubble under field gradient
Topological switching

Simulation

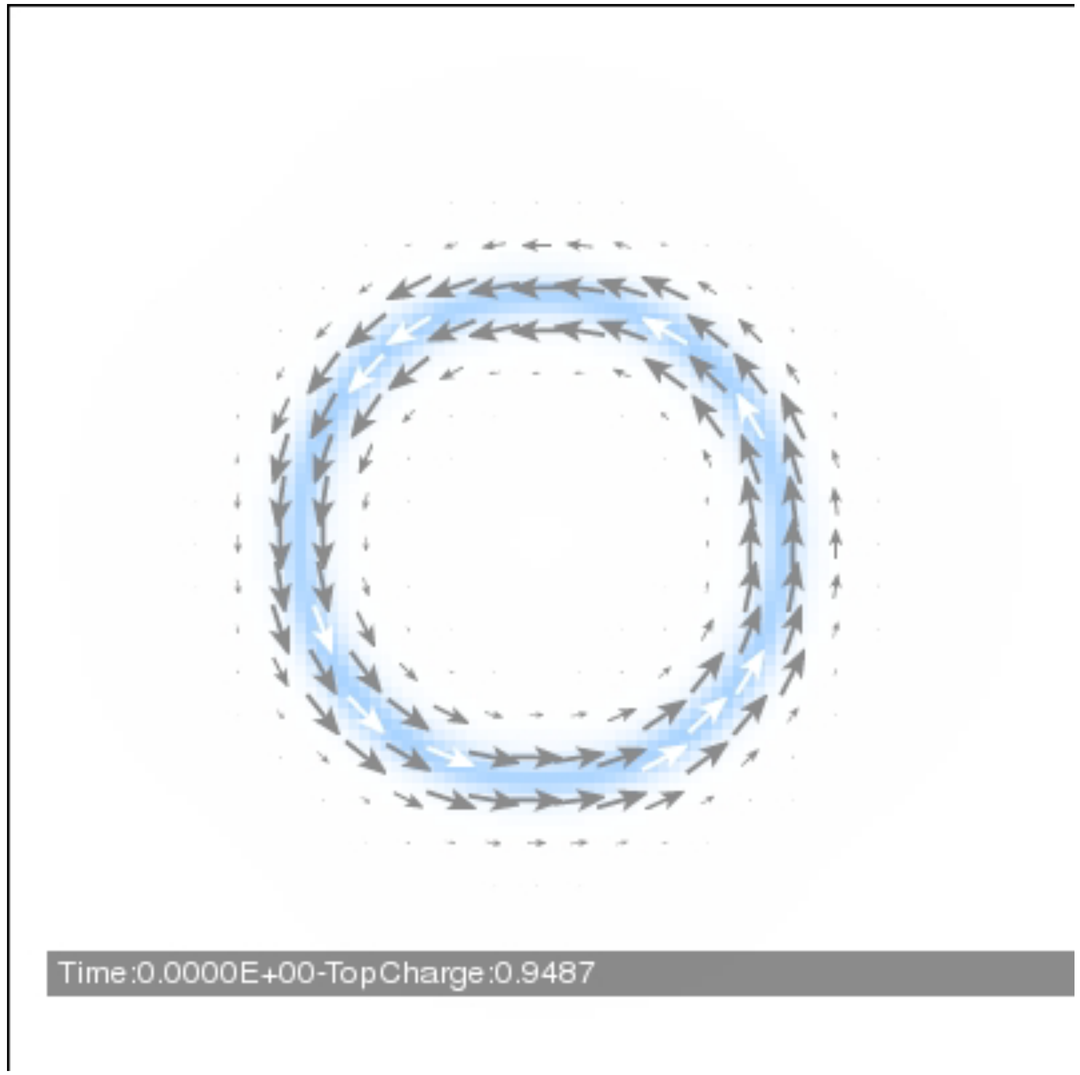
From: N=1

↓

To: N=0

↓

To: N=1



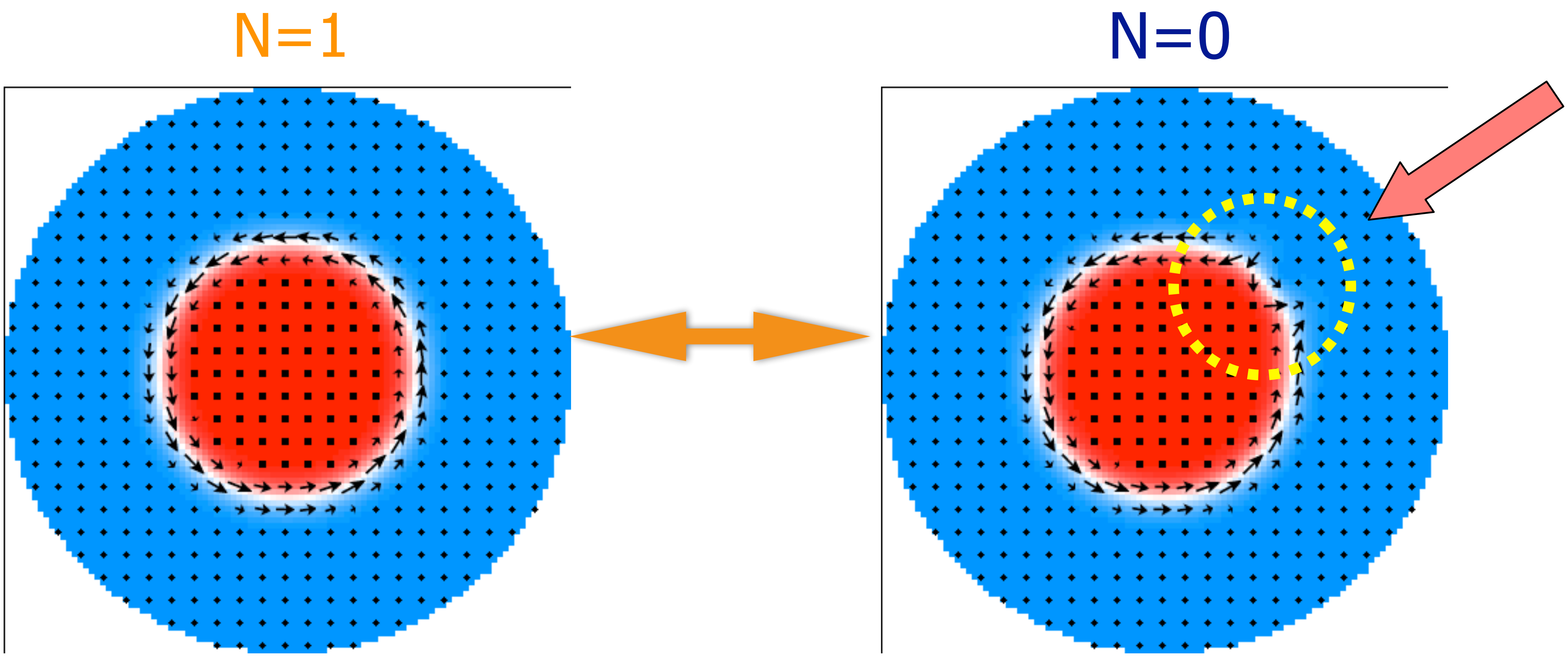
Different dynamics

- Larger field gradient (τ=45 ps)
- Switch off and allow the system to evolve freely
- Large gradients of magnetisation along the domain wall

At t = 385 ps, a burst of spin waves -> the Skyrmion number changes!
It switches to a "bubble" with different topological charge in less than 1 nanosecond

[1] **C. Moutafis**, S. Komineas, J. A. C. Bland, **Phys. Rev. B vol. 79, 224429 (2009)**

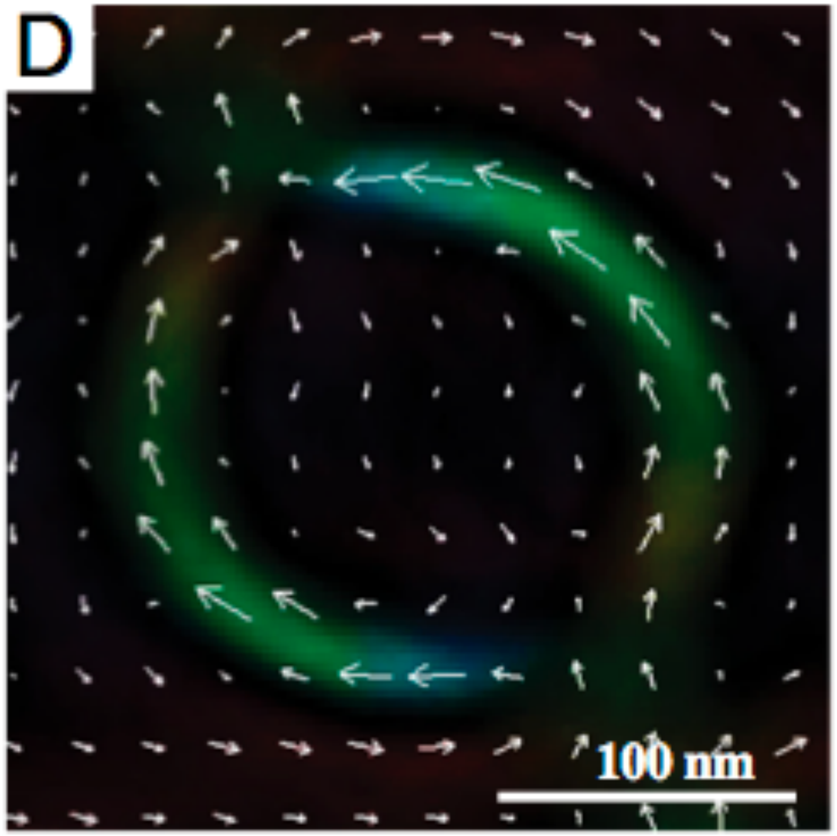
Topological Switching



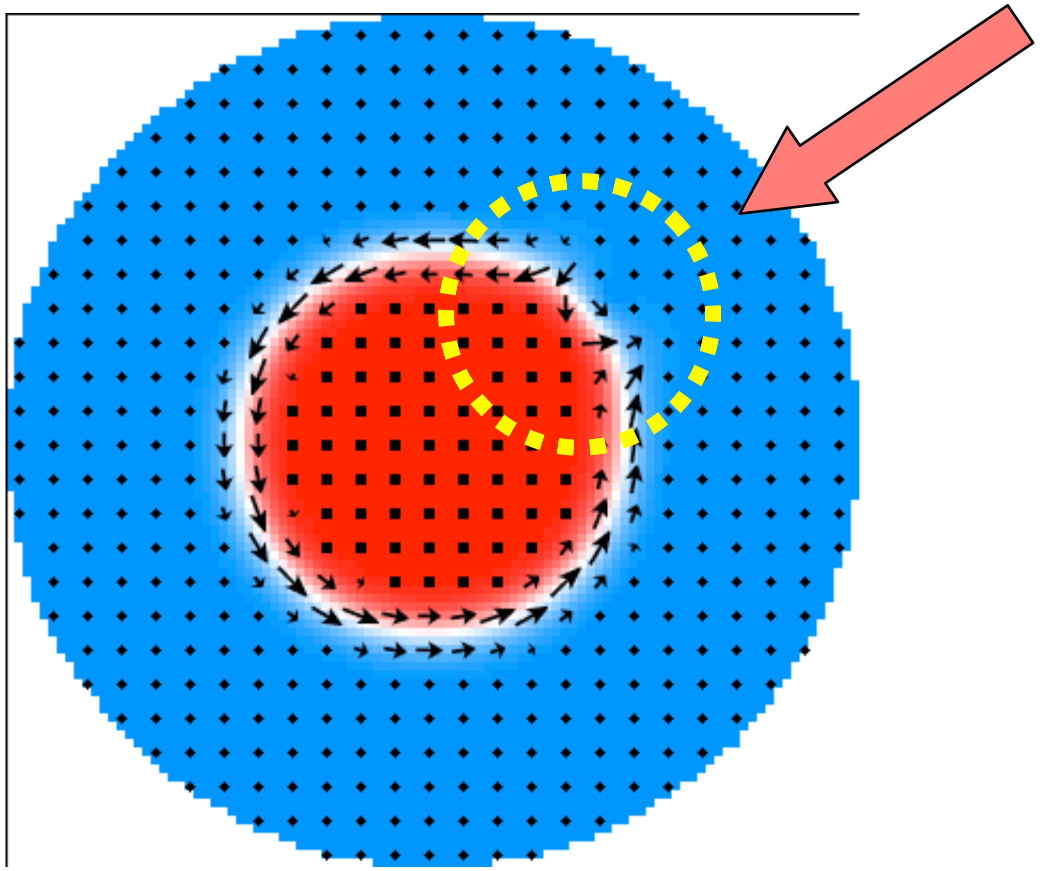
- Fast switching to a topologically trivial state. And back.
- Nucleation of a pair of VBLs
- Isolated states of various topological complexities can be stable/metastable

[1] **C. Moutafis**, et al. Dynamics & switching processes for magnetic bubbles in nanoelements, Phys. Rev. B 79, 224429 (2009)
[2] DMi: J. Sampaio, V. Cros, S. Rohart, A. Thiaville and A. Fert, Nat Nanotechnol vol. 8, 839-844, (2013)

Topological Switching



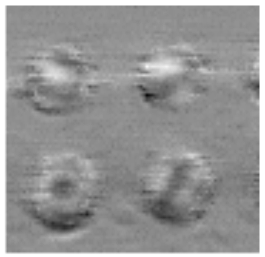
N=0

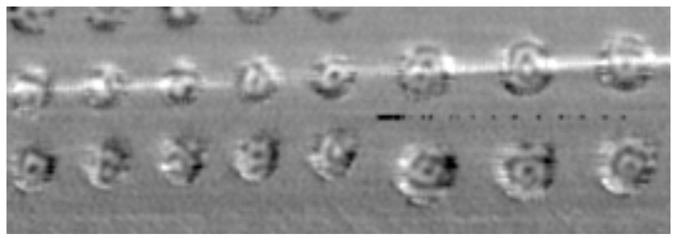


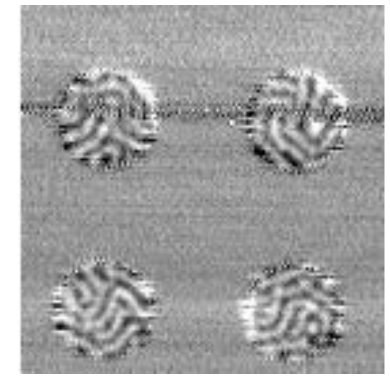
- Fast switching to a topologically trivial state. And back.
- Nucleation of a pair of VBLs
- Isolated states of various topological complexities can be stable/metastable
- Different dynamics

[1] **C. Moutafis**, et al. Dynamics & switching processes for magnetic bubbles in nanoelements, Phys. Rev. B 79, 224429 (2009)
[2] Yu, X. et al. Magnetic stripes and skyrmions with helicity reversals, PNAS 109, 8856–8860 (2012).

CoB/Pt Phase diagram: getting the desired states







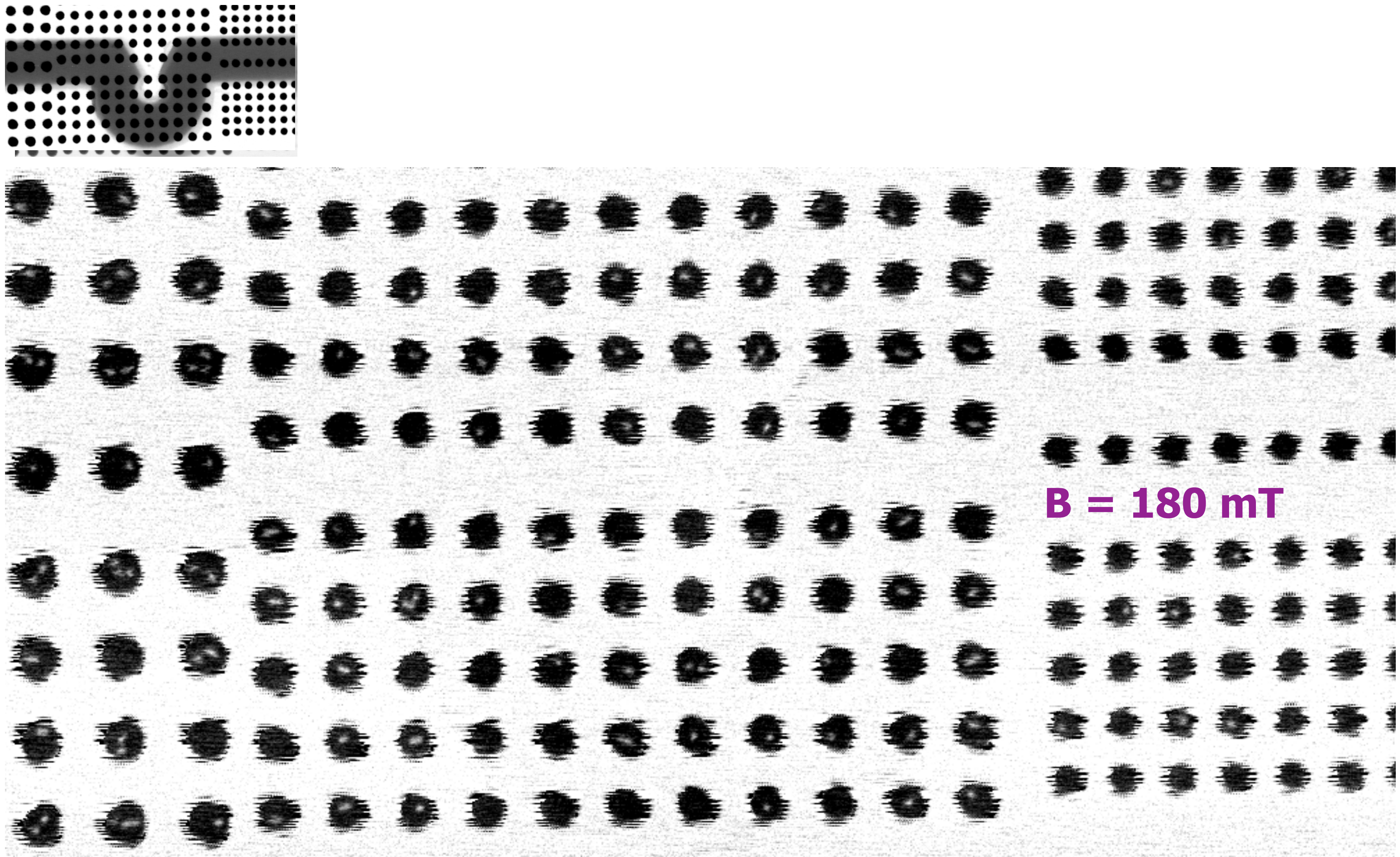
100 nm 200 nm 300 nm 400 nm 500 nm 600 nm 700 nm

- **X-rays (XMCD)** magnetic imaging
- Pump-and-probe **STXM** & **Soft X-ray Holography** (PolLux, SLS, UE46-MAXYMUS & UE52SGM, BESSY)
- Dots of amorphous **CoB/Pt** multilayers (Pt(2)/[CoB(0.4)/Pt(0.7)]x29/CoB(0.4)/Pt(2))
- From single domain, to **bubbles**, to **concentric ring** domains to film-like multidomains.

[1] "Magnetic states in low-pinning high-anisotropy material nanostructures suitable for dynamic imaging" F. Büttner, **C. Moutafis**, et al., **Phys. Rev. B 87, 134422 (2013).**

[2] "Reduced domain wall pinning in ultra thin Pt/Co100−xBx/Pt with perpendicular magnetic anisotropy" R. Lavrijsen, et al. , **Appl. Phys. Lett. 96, 022501 (2010).**

CoB/Pt Phase diagram:
Stripes, Bubbles, Skyrmions



- **X-rays (XMCD)** magnetic imaging
- Dots of amorphous **CoB/Pt** multilayers (Pt(2)/[CoB(0.4)/Pt(0.7)]x29/CoB(0.4)/Pt(2))
- "Symmetric" multilayer?

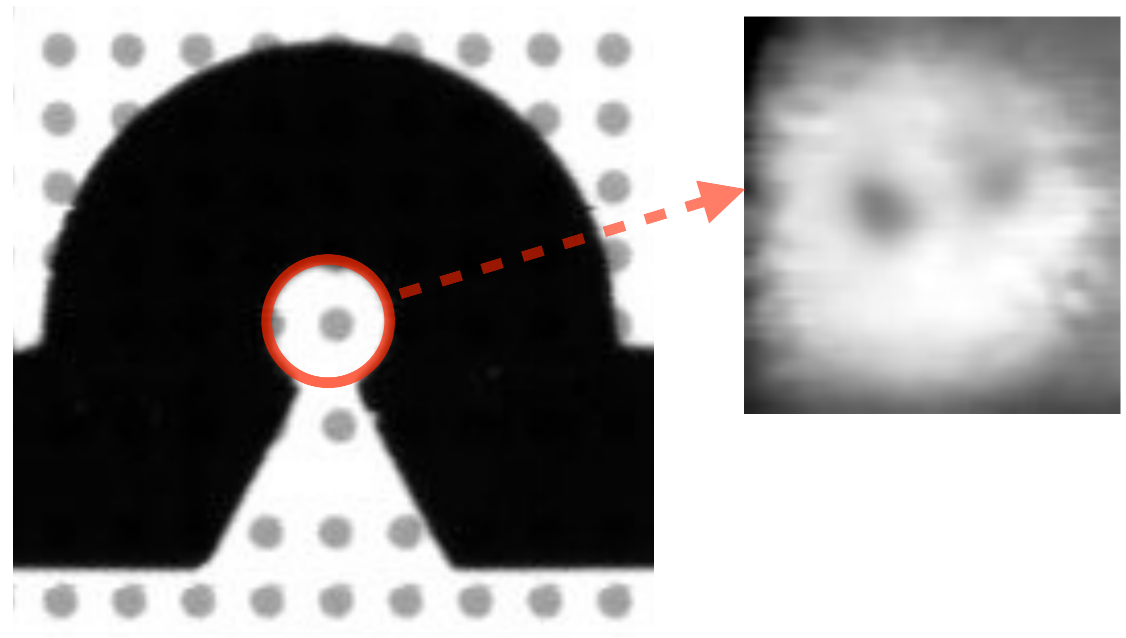
[1] "Magnetic states in low-pinning high-anisotropy material nanostructures suitable for dynamic imaging"
F. Büttner, **C. Moutafis**, et al., **Phys. Rev. B 87, 134422 (2013).**

[2] "Dynamics & inertia of skyrmionic spin structures",
F. Büttner, **C. Moutafis**, et al., **Nature Physics 11, 225–228 (2015).**

Dynamics: Excitations / Set-up

500 nm CoB/Pt dot in a microcoil

MicroMagnum

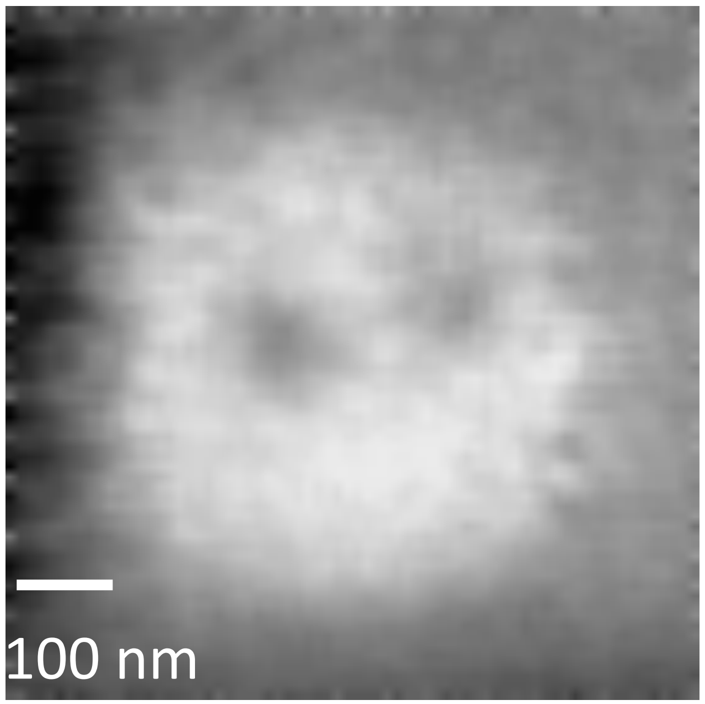


- 500 nm diameter dot [Ta(2)/Pt(2)/[CoB(0.35)/Pt(0.7)]x39/CoB(0.35)/Pt(2)].
- 90 mT in-situ magnetic field results in two confined bubbles.
- We pass a 3 ns bi-polar current pulse (1.5 ns in each polarity).
- Dynamical imaging of the bubbles' response, during the pulse, imaged every 125 ps.

Expansion and Shrinking of two bubbles on the pulse

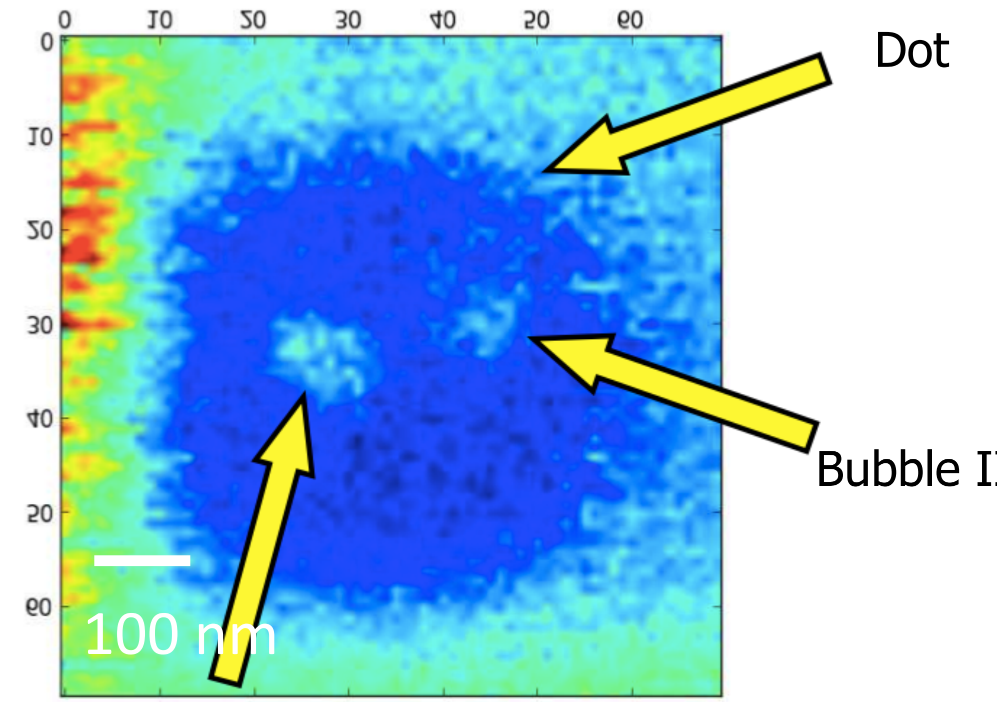
X-ray imaging (STXM)

a)



STXM

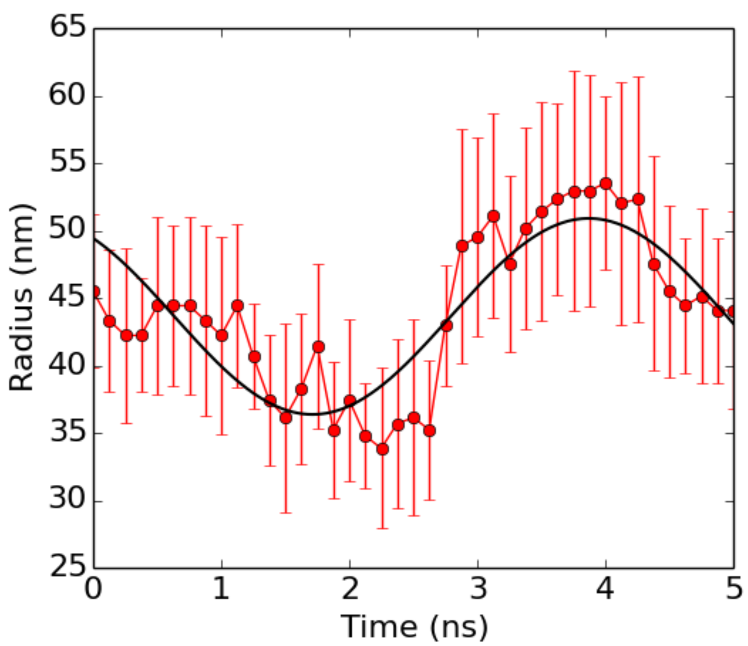
b)



Bubble I

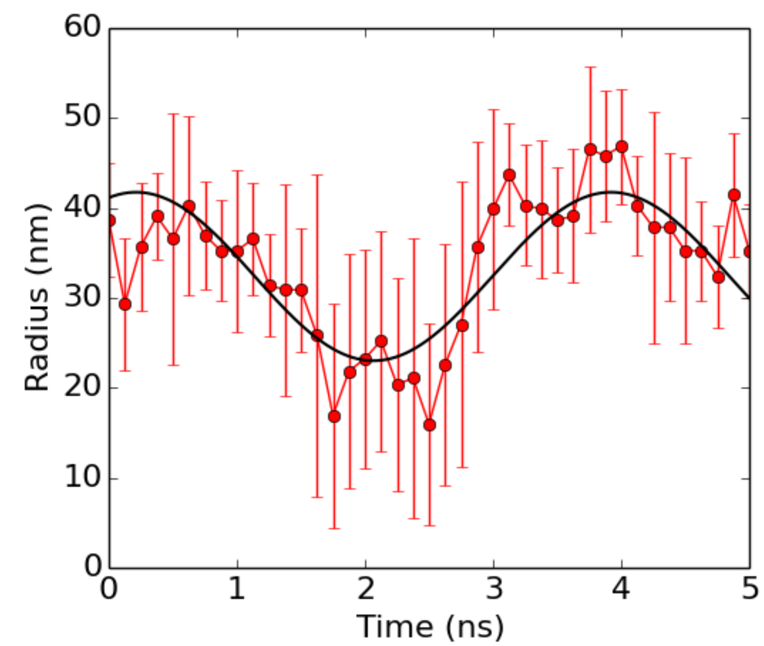
Evolution over time

c)



Bubble I

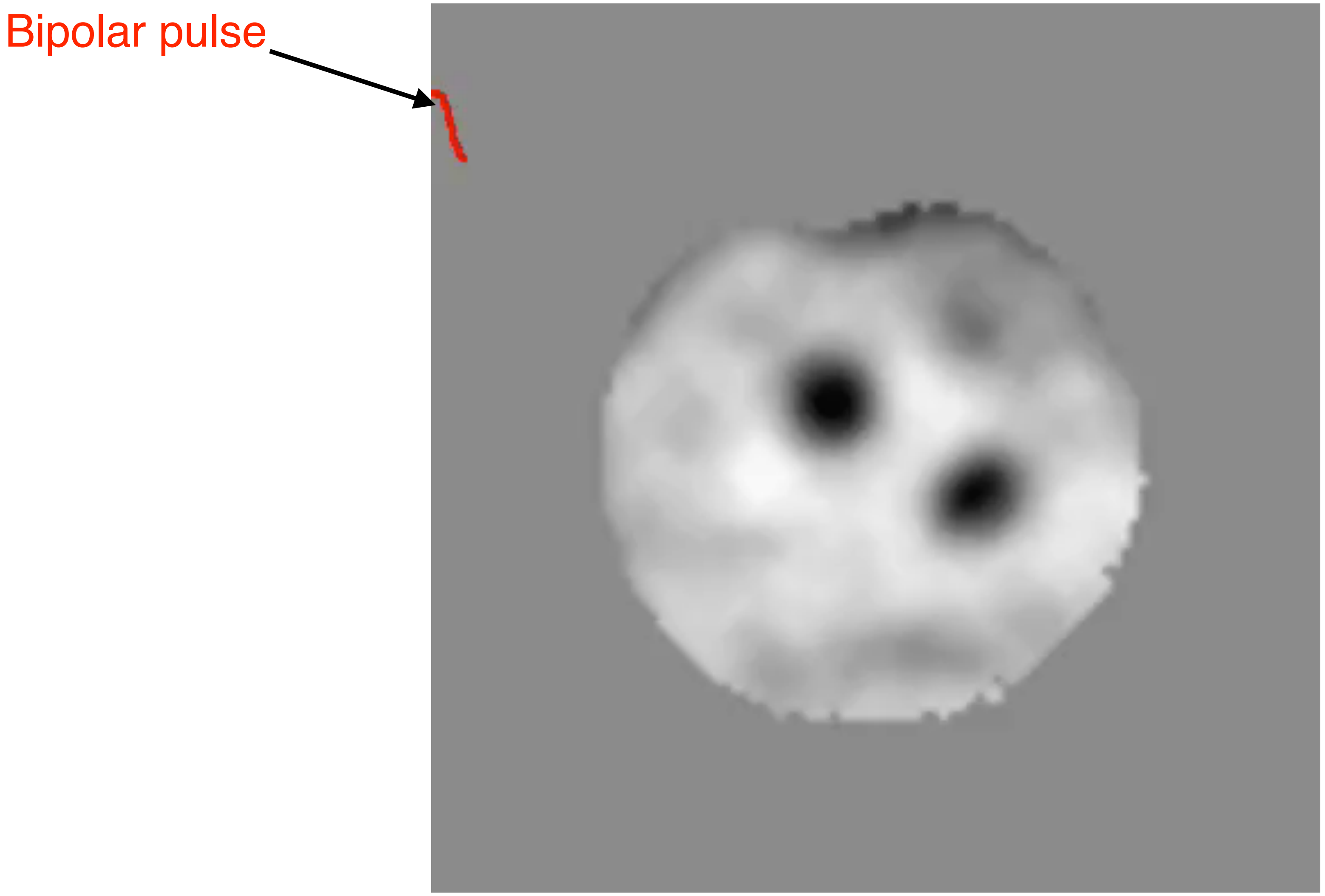
d)



Bubble II

Bubble Gyrotropic motion?

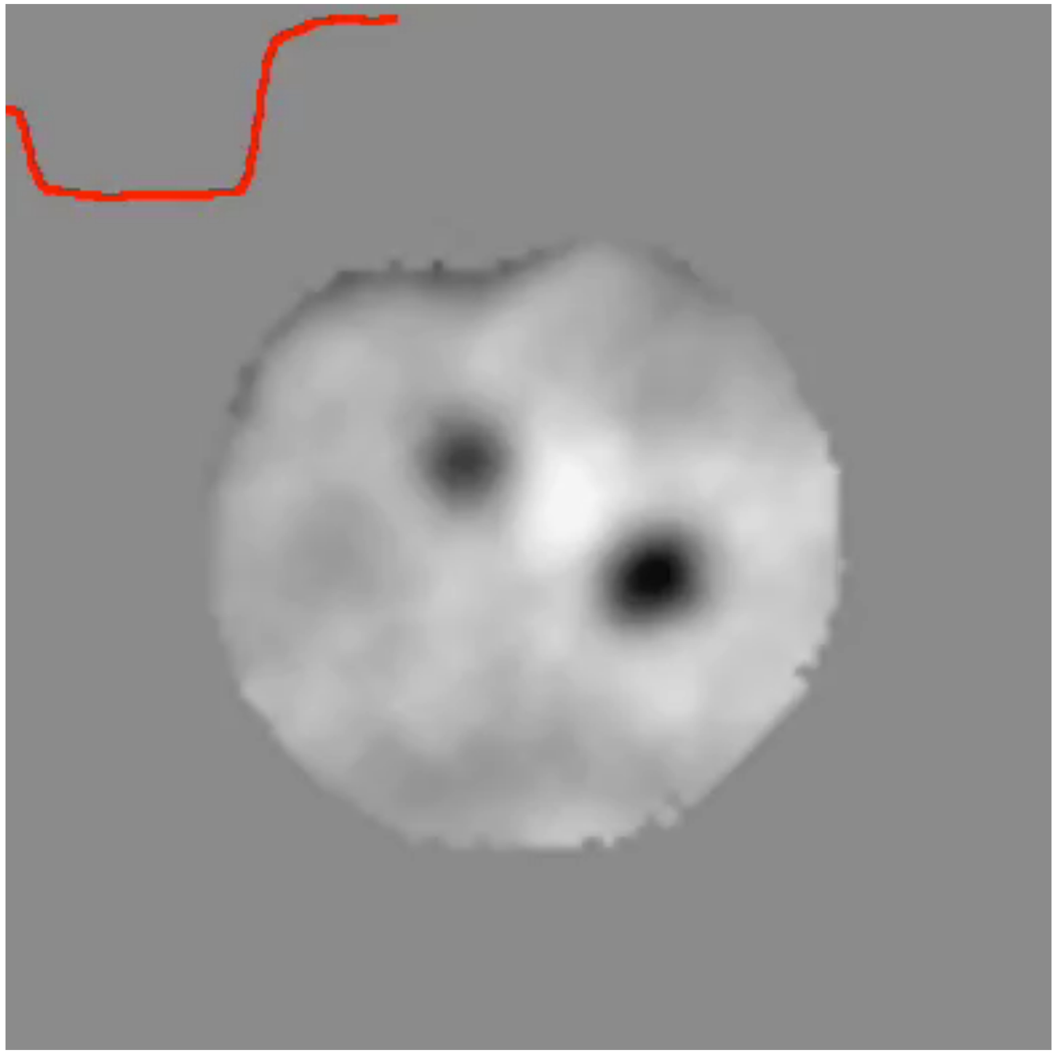
X-ray imaging (Holography)



- 550 nm diameter dot (Pt(2)/[CoB(0.4)/Pt(0.7)]x29/CoB(0.4)/Pt(2))
- External bias field (120 mT) sustains the magnetic configuration
- We pass a 6 ns bi-polar current pulse (3 ns in each polarity)

[1] "Dynamics & inertia of skyrmionic spin structures", F. Büttner, **C. Moutafis**, et al., **Nature Physics 11, 225–228 (2015)**

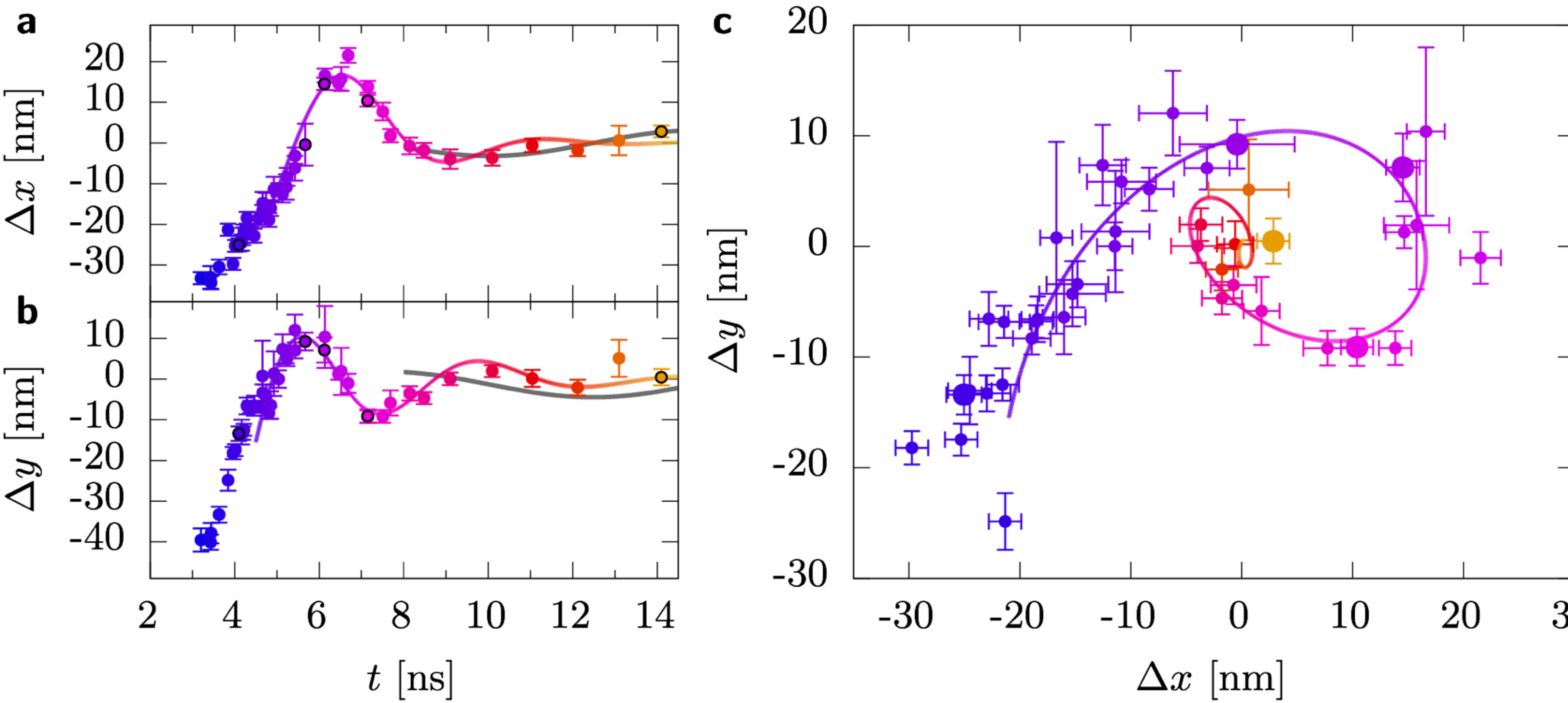
Bubble Gyrotropic motion



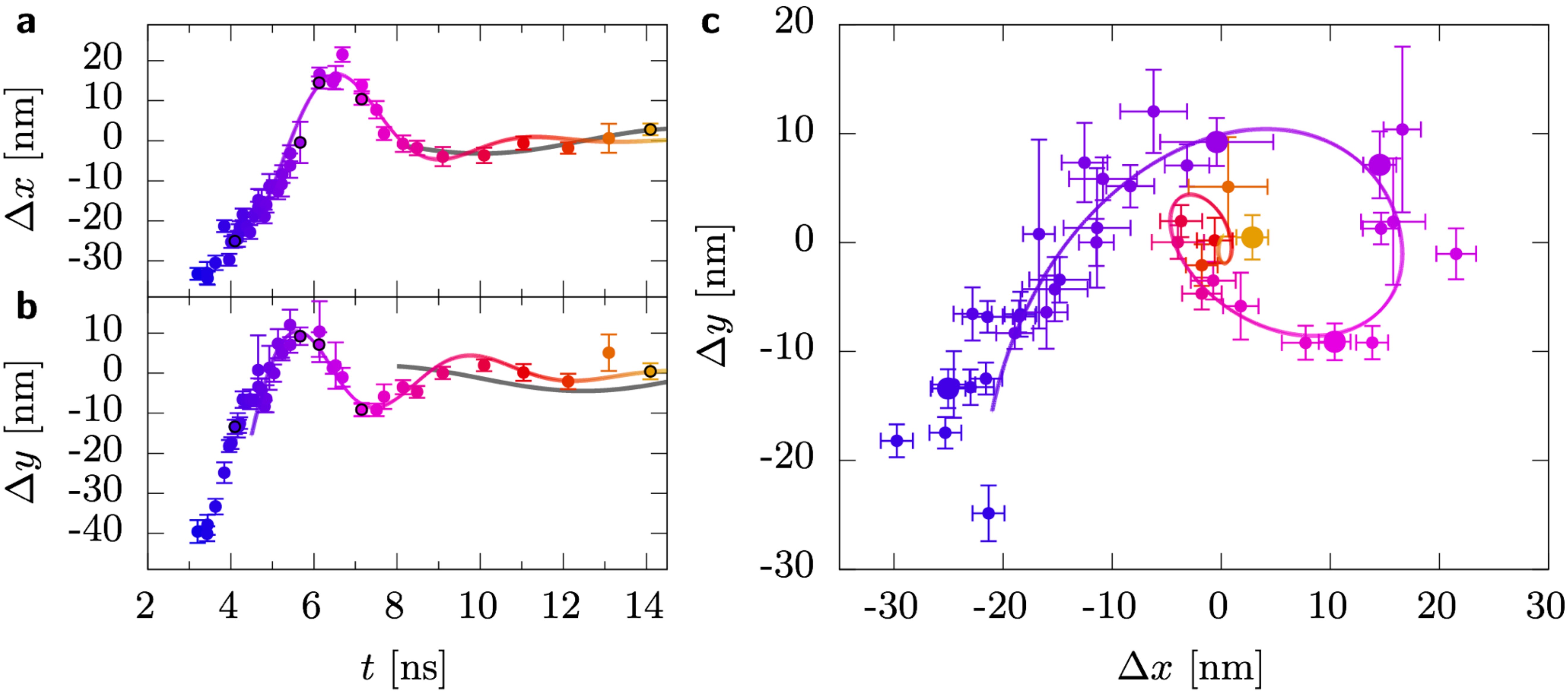
- Pulse finishes, relaxation process, center of bubble's magnetisation back to original point

[1] "Dynamics and inertia of skyrmionic spin structures", F. Büttner, **C. Moutafis**, et al., Nature Physics 11, 225–228 (2015)

Gyrotropic motion



Gyrotropic motion

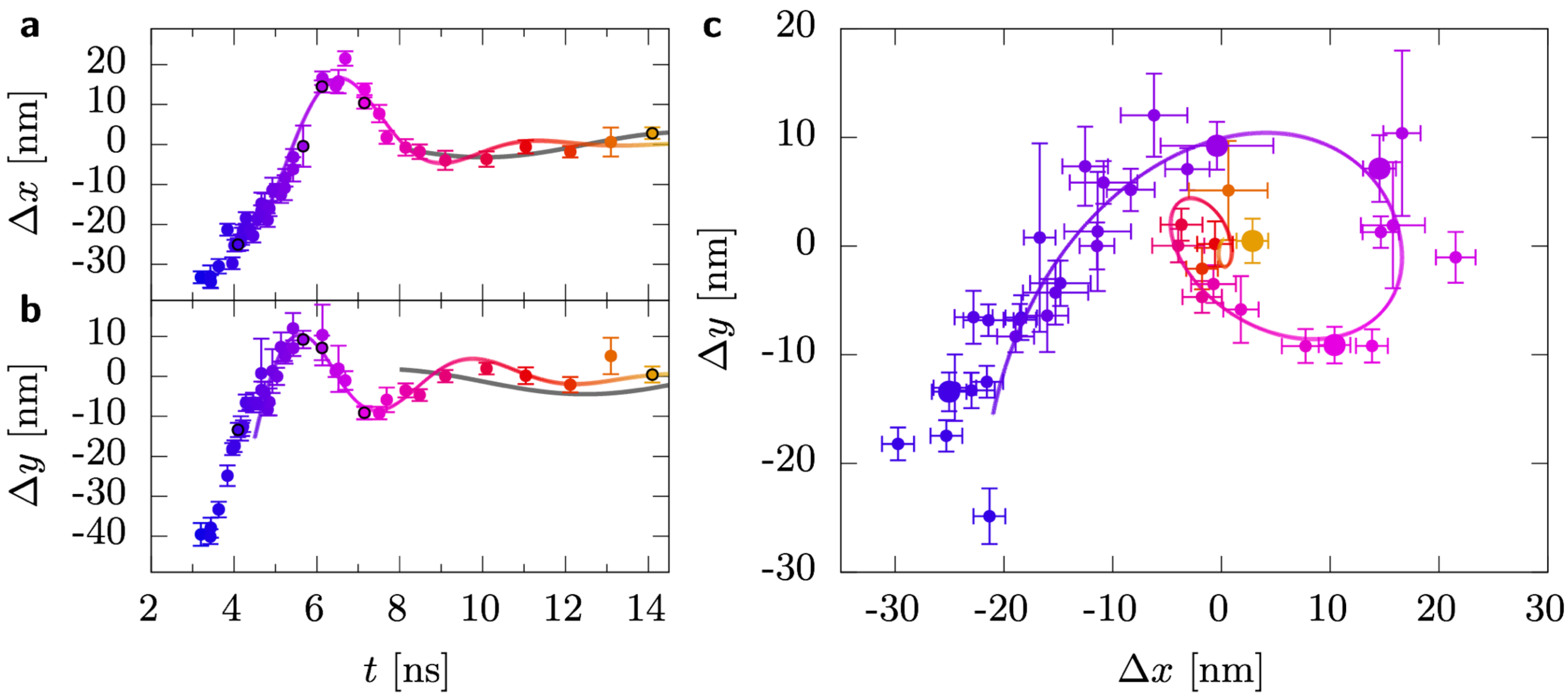


- Damped gyrotropic motion (GHz regime), in line with predictions [1]
- We can conclude it is the N=1 bubble [1,2]
- First direct experimental observation of gigahertz dynamics of a skyrmionic spin structure

[1] "Dynamics & switching processes for magnetic bubbles in nanoelements",
C. Moutafis, et al., **Phys. Rev. B vol. 79, 224429 (2009)**

[2] "Dynamics & inertia of skyrmionic spin structures",
F. Büttner, C. Moutafis, et al., **Nature Physics 11, 225–228 (2015)**

Inertia



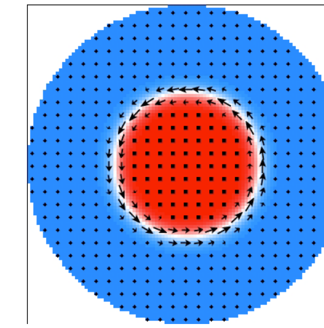
$$-M\ddot{\boldsymbol{R}} + \boldsymbol{G} \times \dot{\boldsymbol{R}} + \boldsymbol{D} \cdot \dot{\boldsymbol{R}} - \partial_{\boldsymbol{R}} U = 0$$

- Fit from model accurately described observed trajectory [1,2].
- Model implies a **mass** for the N=1 bubble.
- M > 8 x 10^{-22} Kg / Areal mass density of 2.0 x 10-7 Kg m^{-2}. Governs the displacement [3].
- Reflects its extended size and deformability.

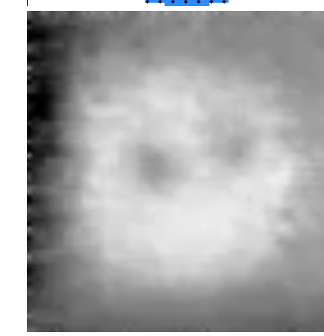
[1] "Dynamics & switching processes…", C. Moutafis, S. Komineas, J. A. C. Bland, Phys. Rev. B vol. 79, 224429 (2009)
[2] I. Makhfudz, B. Krüger, and O. Tchernyshyov, Phys. Rev. Lett. 109, 217201 (2012)
[3] "Dynamics and inertia of skyrmionic spin structures", F. Büttner, C. Moutafis, et al., Nature Physics 11, 225–228 (2015)

Conclusions

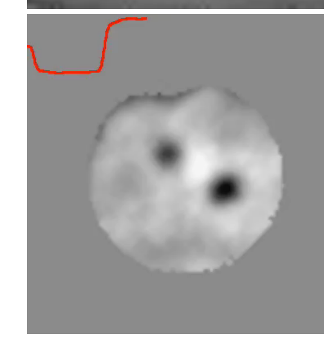
- Bubbles a laboratory to study link between Topology & Dynamics



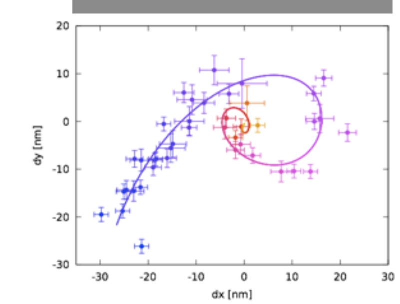
- Nanostructures laboratories of topological states
- Isolated/Single skyrmion bubble GHz dynamics observed



- The Gyrotropic & breathing-like motion demonstrated
- Skyrmion bubble exhibits inertia



- Infer topological complexity (Skyrmion number N) from dynamical behaviour -> Skyrmion topology



Next step...?

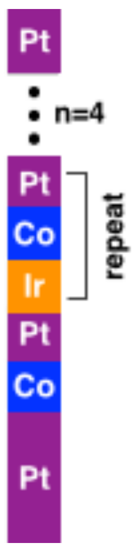
Interfacial DMI in asymmetric magnetic multilayers

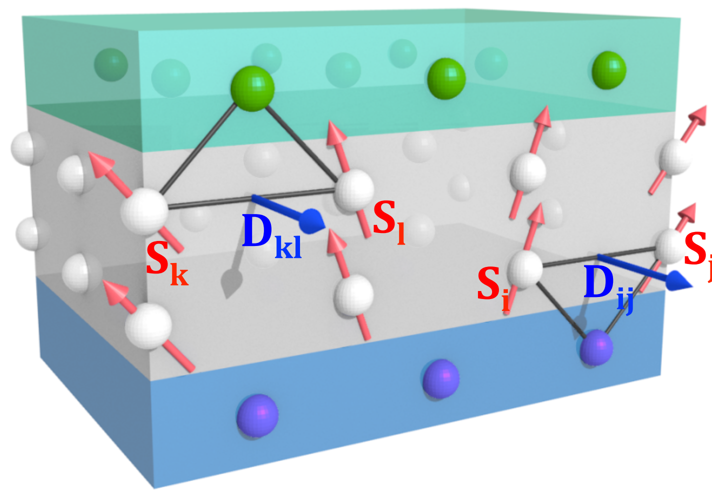
DMi System: Engineer films with Dzyaloshinskii-Moriya interaction

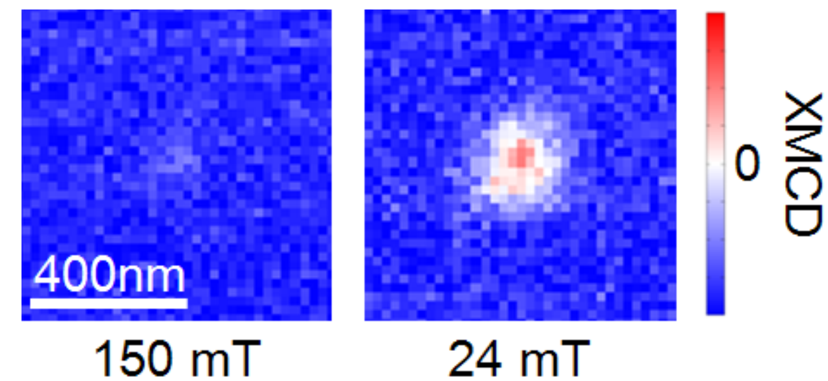
Collaboration between PSI/Manchester and **CNRS/Thales V. Cros & A. Fert**

European Union MAGicSky No. FET-Open-665095

http://magicsky-fet.prod.lamp.cnrs.fr/







[1] N. Nagaosa, Y. Tokura, Topological properties and dynamics of magnetic skyrmions, Nature Nanotech. 8, 899 (2013)

[2] Fixed Chirality: e.g. G. Chen, et al., "Tailoring the chirality of DWs by interface engineering." Nat. Comm. 4: 2671. (2013), G. Chen, et al., Appl. Phys. Lett. 106, 242404 (2015).

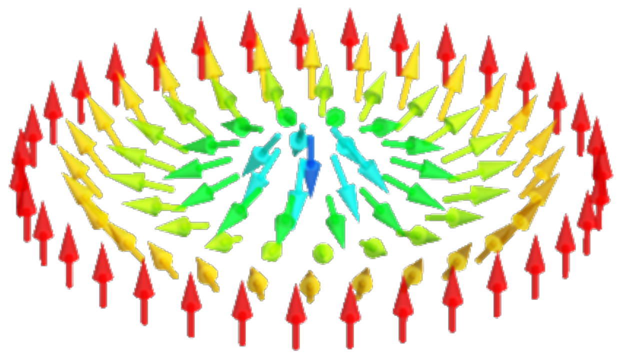
Recent publications, e.g.: [A] "Room temperature chiral magnetic skyrmion in ultra thin magnetic nanostructures", O. Boulle, …, G. Gaudin, Nature Nanotechnology, 25 Jan. 2016, doi:10.1038/nnano.2015.315

[B] 'Observation of room temperature magnetic skyrmions and their current-driven dynamics in ultrathin Co films', S. Woo,…, G. Beach Nature Materials, Published online 29 February 2016 doi:10.1038/nmat4593

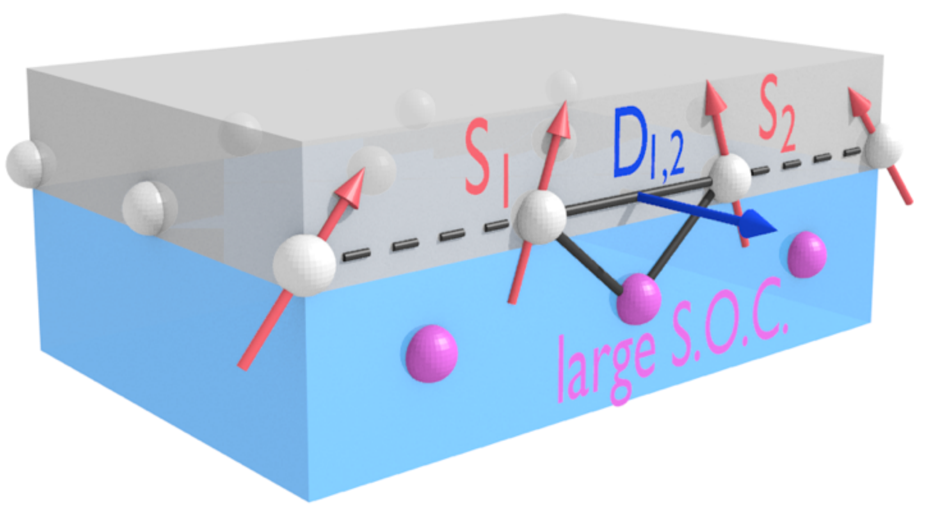
[C] "Additive interfacial chiral interaction in multilayers for stabilisation of small individual skyrmions at room temperature", C. M.-Luchaire, C. Moutafis, …, V. Cros, A. Fert, Nat. Nanotechnology, 18 Jan. 2016, doi:10.1038/nnano.2015.313

Interfacial Dzyaloshinskii-Moriya Interaction in films

- Break of the inversion symmetry at **the interface**
- Large spin - orbit coupling in the normal metal
  (i.e. large Dzyaloshinskii-Moriya interaction DMi)



Hedgehog skyrmion



In case of interfacial DMi :

A. Fert, Mater. Sci. Forum 59, 439 (1990)

$$H_{DM} = -D_{1,2} \cdot (S_1 \times S_2)$$

→ Opportunities to tune various parameters : DMi (dilution with thickness), magnetic anisotropy, number of active interfaces etc…

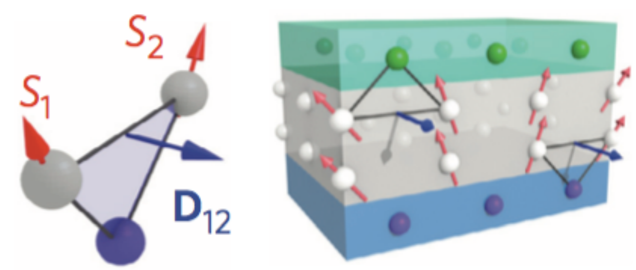
Main advantages : multiple possible associations of magnetic thin films and metals with large SO coupling (Pt, W, Ir , etc…) in bilayers or multilayers

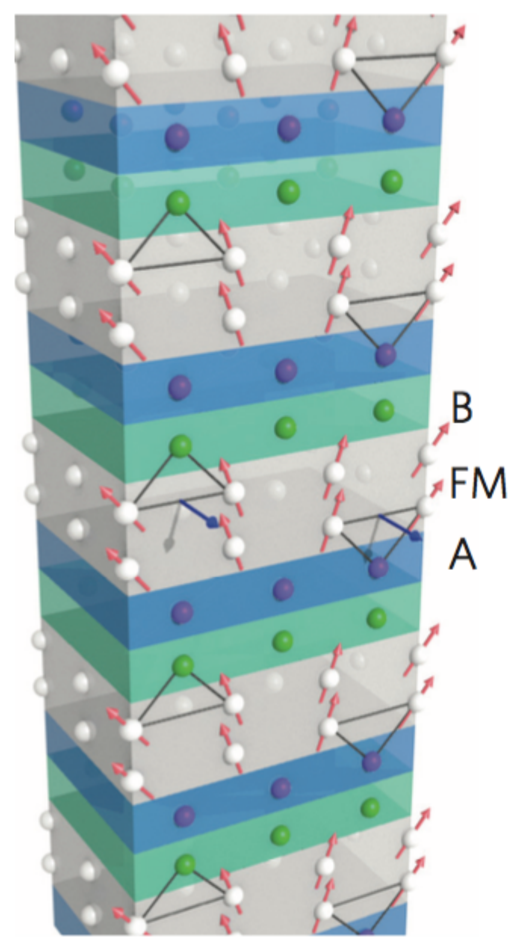
[1] N. Nagaosa, Y. Tokura, Topological properties and dynamics of magnetic skyrmions, Nature Nanotech. 8, 899 (2013)
[2] **Fixed Chirality:** G. Chen, et al., "Tailoring the chirality of DWs by interface engineering." Nat. Comm. 4: 2671. (2013)

Interfacial DMI in asymmetric magnetic multilayers

The DMI for two magnetic atoms (grey spheres) close to an atom with a large spin–orbit coupling (blue sphere) in the Fert–Levy picture[1].

A single trilayer composed of a magnetic layer (FM, grey) sandwiched between two different heavy metals A (blue) and B (green) that induce the same chirality (same orientation of D) when A is below and B above the magnetic layer.



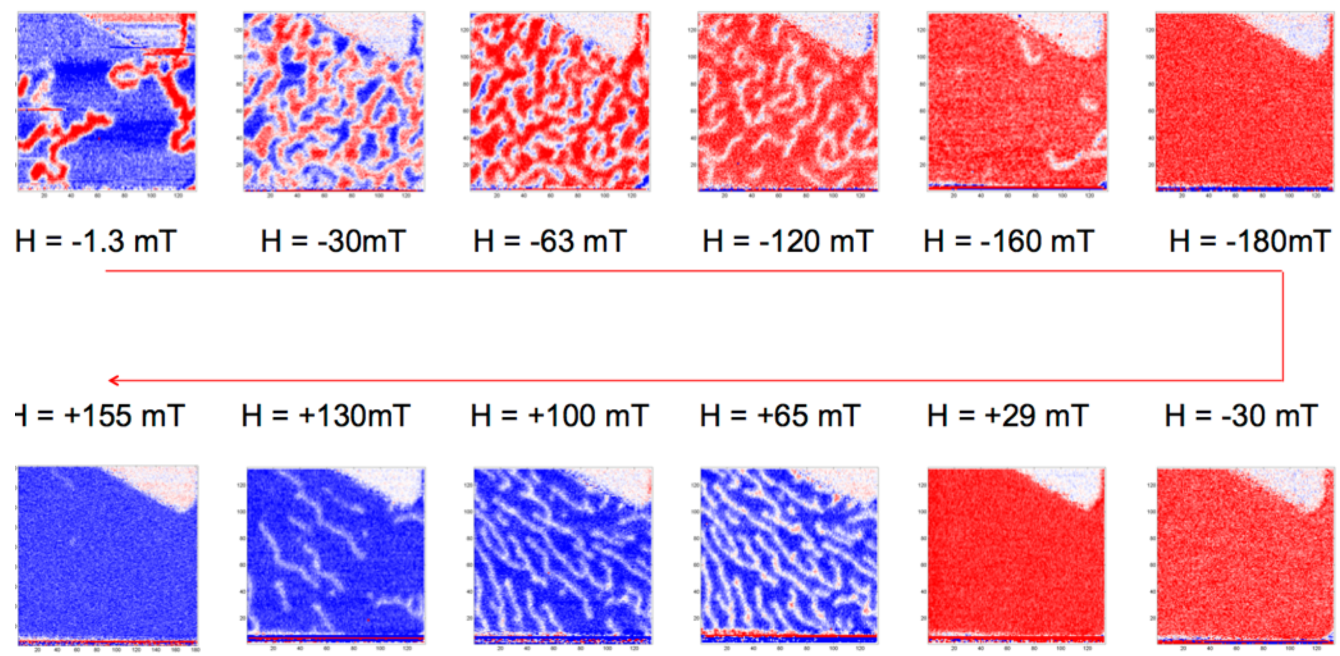


Asymmetric multilayer made of several repetitions of the trilayer. Additive chiral interactions.

[1] Fert, A. & Levy, P. M. Role of anisotropic exchange interactions in determining the properties of spin-glasses. Phys. Rev. Lett. 44, 1538–1541 (1980).

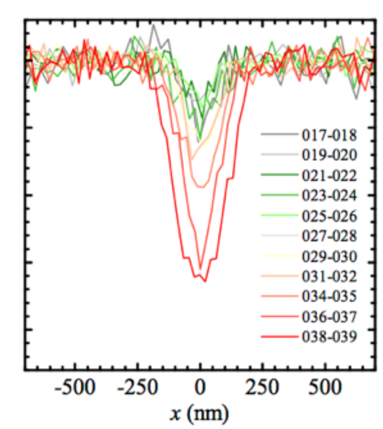
Domain size with perpendicular field cycles

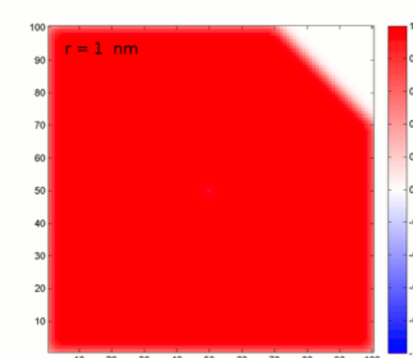
(Pt|Co)x10



- Magnetic field cycle and image (Pt/Co/Pt and Ir/Co/Pt). Experimentally determine domain and bubble size.
- Simulate domain/bubble size during field cycle and fit DMi value to obtain experimental domain/bubble size.

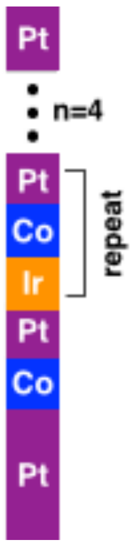
[1] "Skyrmions at room temperature : From magnetic thin films to magnetic multilayers" C. M.-Luchaire, C. Moutafis, et al., arxiv.org/abs/1502.07853.
or
[2] "Additive interfacial chiral interaction in multilayers for stabilisation of small individual skyrmions at room temperature"
C. M.-Luchaire, C. Moutafis, …, V. Cros, A. Fert, online 18th of January, **Nature Nanotechnology 11, 444–448 (2016)**.

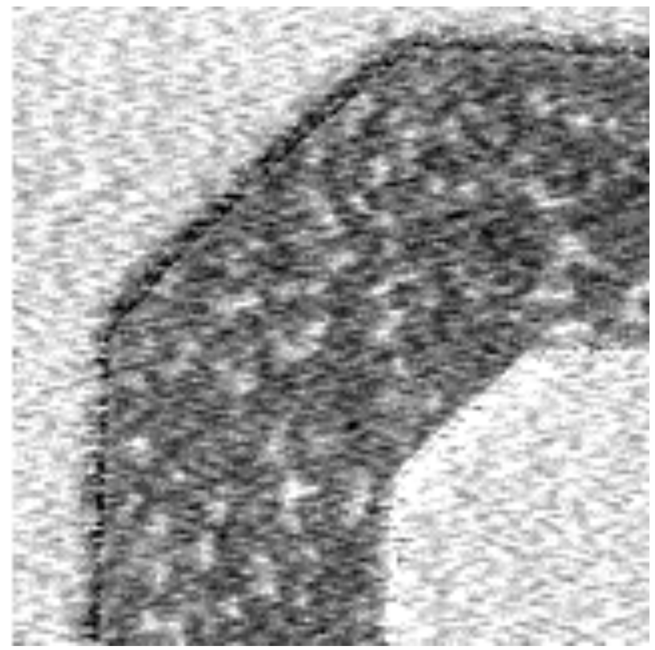




Domain size with perpendicular field cycles

(Ir|Pt|Co)x10





[1] "Skyrmions at room temperature : From magnetic thin films to magnetic multilayers" C. M.-Luchaire, C. Moutafis, et al., arxiv.org/abs/1502.07853.
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[2] "Additive interfacial chiral interaction in multilayers for stabilisation of small individual skyrmions at room temperature"
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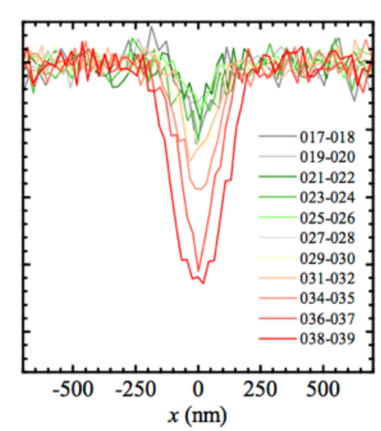
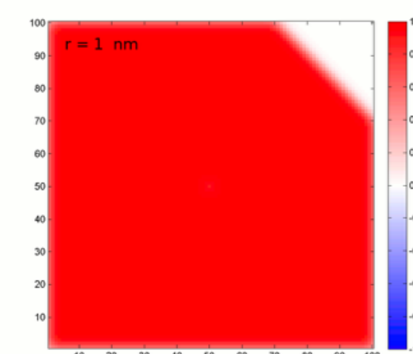
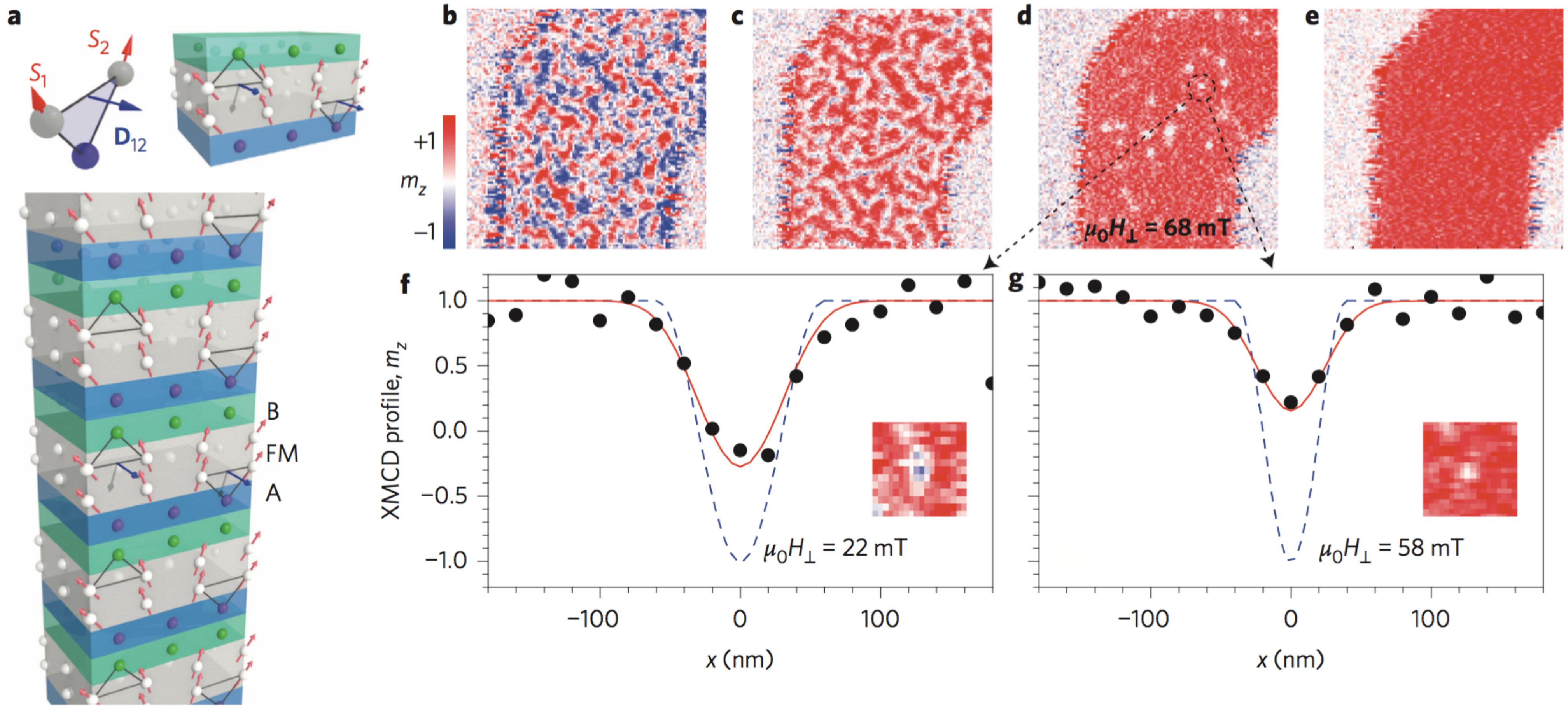


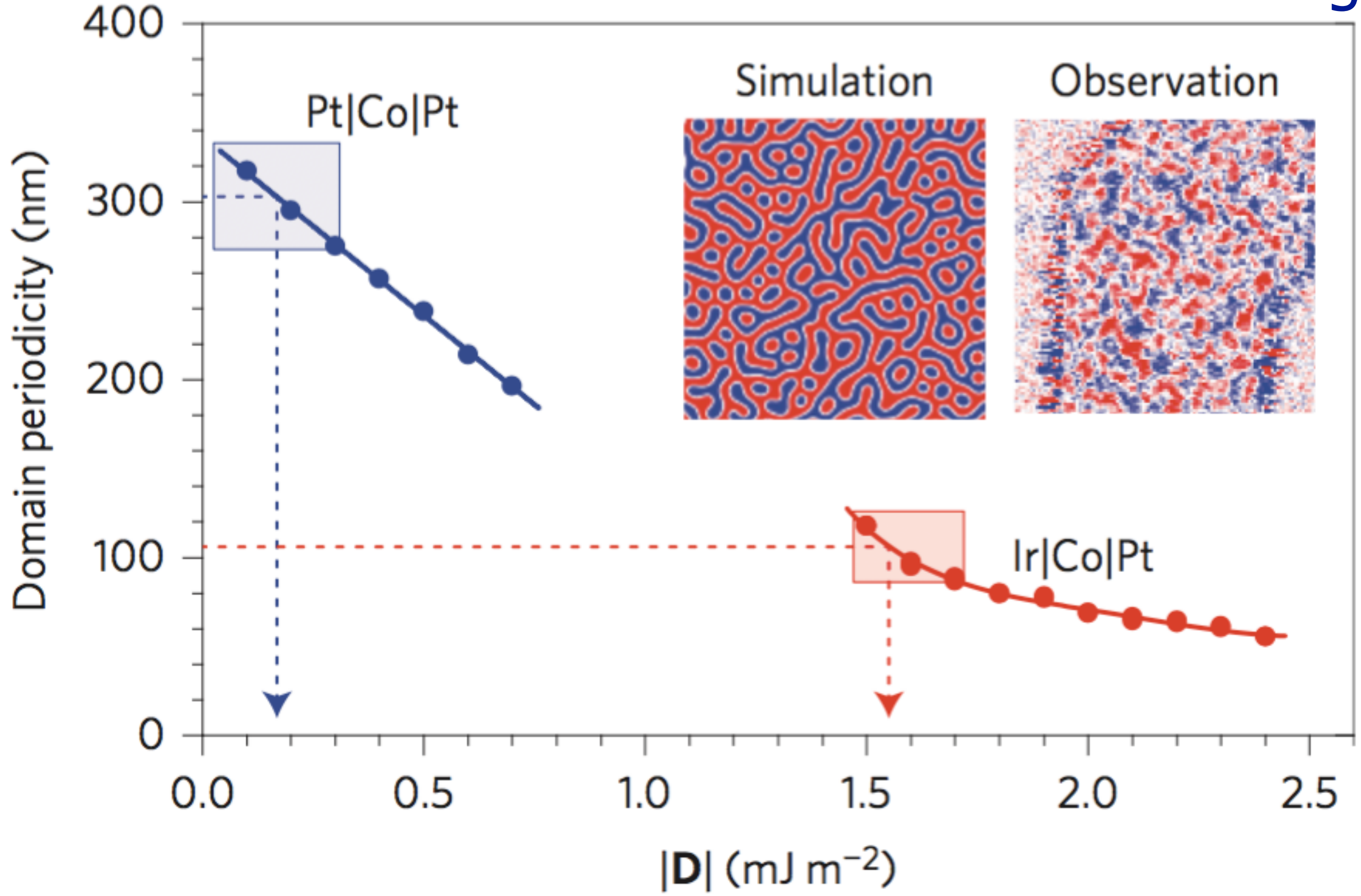


Interfacial DMI in asymmetric magnetic multilayers



- Asymmetric multilayer made of several repetitions of the trilayer.
- A 1.5 × 1.5 μm^2 out-of-plane magnetization (m_z) map (STXM) on a (Ir|Co|Pt)$_{10}$ multilayer at R.T. for applied out-of-plane magnetic fields of 8 (b), 38 (c), 68 (d) and 83 (e) mT.
- f) XMCD signal through a magnetic circular domain (skyrmion) as observed at 22 mT (black dots). The blue dashed curve is the magnetization profile of an ideal 60-nm-diameter skyrmion.
- g) Same type of data at 58 mT and the corresponding simulation of a 40-nm-diameter skyrmion. The images and data of f and g result from the same skyrmion evolution in the field. The actual image size of the insets is 360 nm.

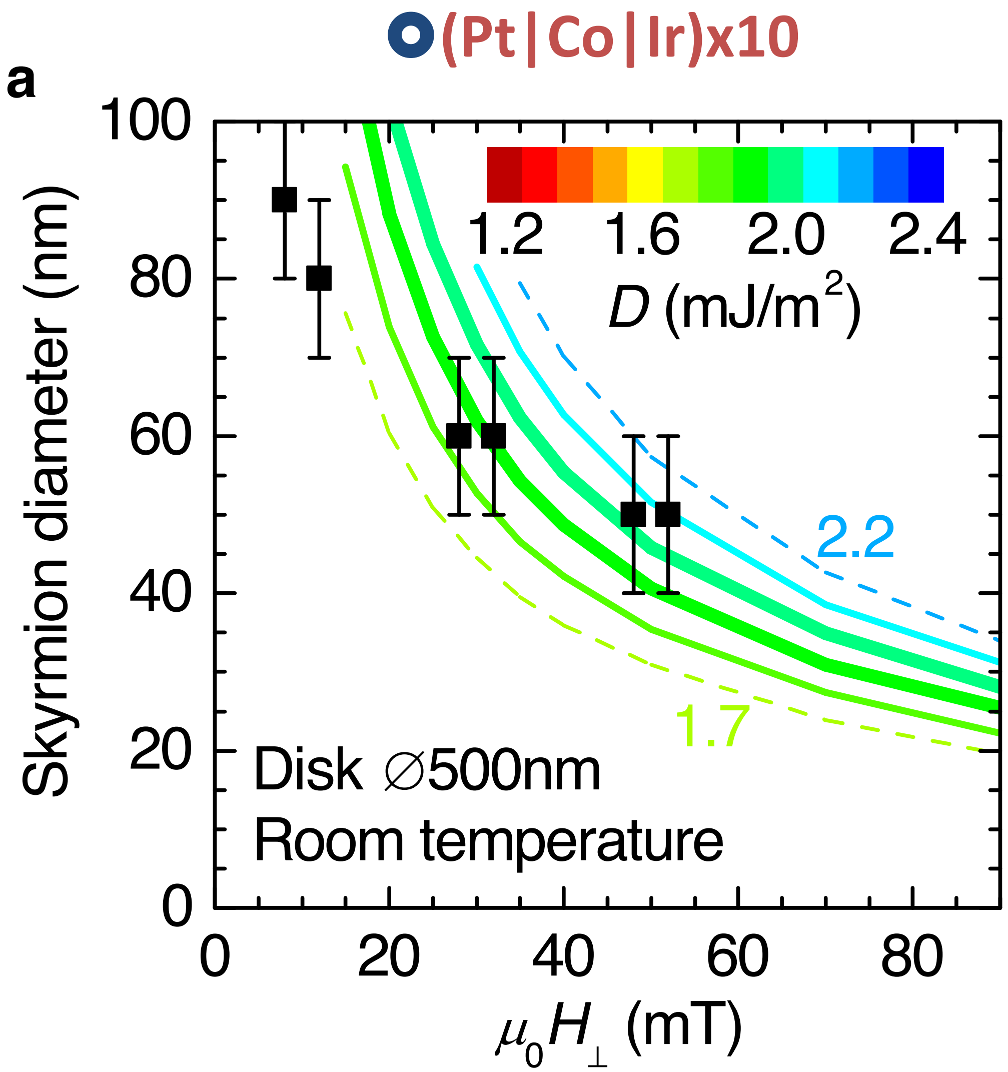
Micromagnetic simulations & experimental measurements of mean domain-width evolution with DMI after demagnetization



- Comparing the simulations with the experimental domain-width value (dotted horizontal line) allows us to estimate |D|(Ir|Co|Pt) = 1.6 ± 0.2 mJ m^{-2} and |D|(Pt|Co|Pt) = 0.2 ± 0.2 mJ m^{-2}.
- The box height represents the error margins on the experimental domain-size evaluation; its width gives the resulting error on |D| for the used simulation parameters.
- The inset shows a simulated worm pattern for |D| = 1.6 mJ m^{-2} in Ir|Co|Pt (1.5 × 1.5 μm^2) and a corresponding experimental observation at the same scale (using the same colour code as in Fig. 1).

Evolution of the skyrmion size in patterned nanoscale disks and tracks

DMi ~1.5 - 2 mJ m^{-2}



- Isolated nanoscale skyrmions, at R.T. in nanodiscs and nanowires / racetracks
- a) field dependence of the diameter of circular domain in a 500-nm-diameter disk, compared with micromagnetic simulations.
- We need large DM values of at least 1.5 mJ m–2 to stabilize any bubble-like domain in nanodiscs.

[1] "Additive interfacial chiral interaction in multilayers for stabilisation of small individual skyrmions at room temperature", C. M.-Luchaire, C. Moutafis, …, V. Cros, A. Fert, **online 18 Jan. 2016, Nature Nanotechnology 11, 444–448 (2016)**.

Evolution of the skyrmion size in patterned nanoscale disks and tracks

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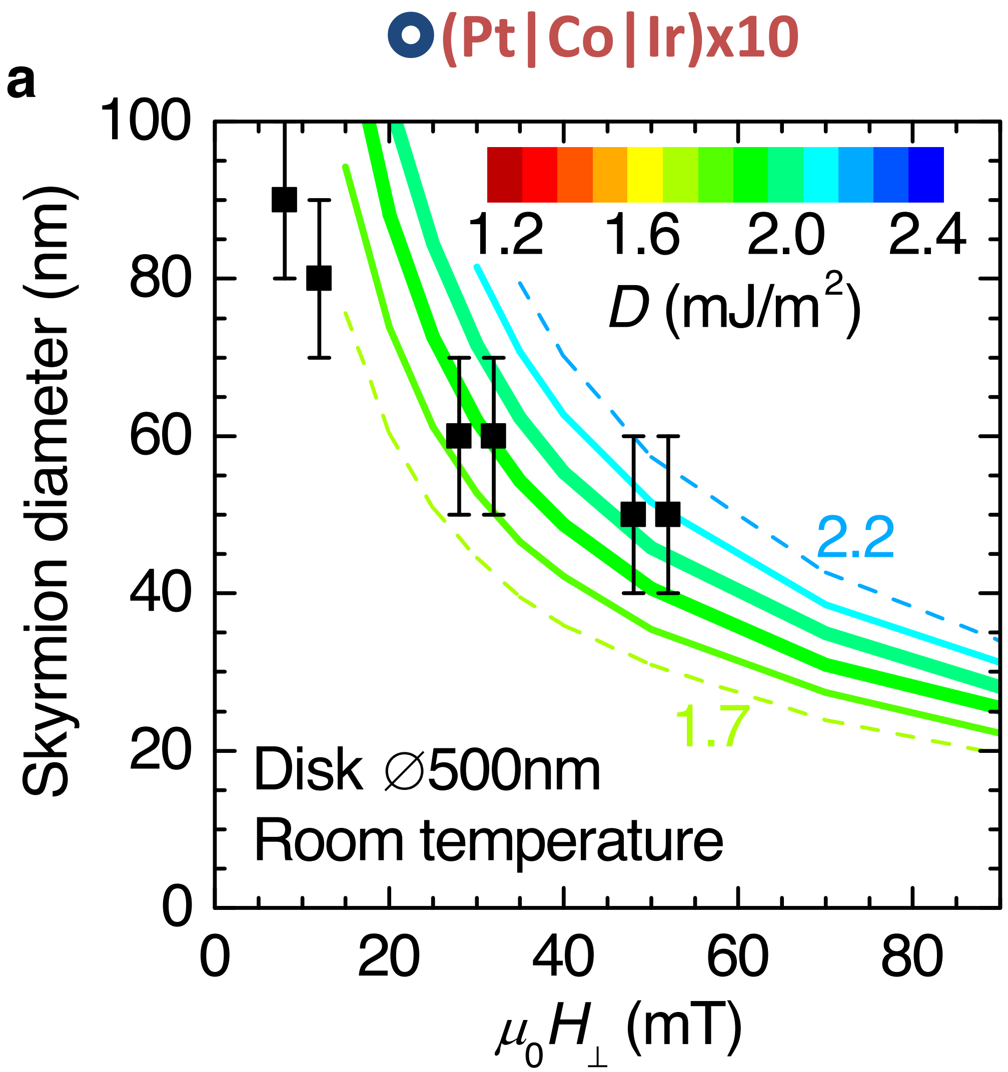
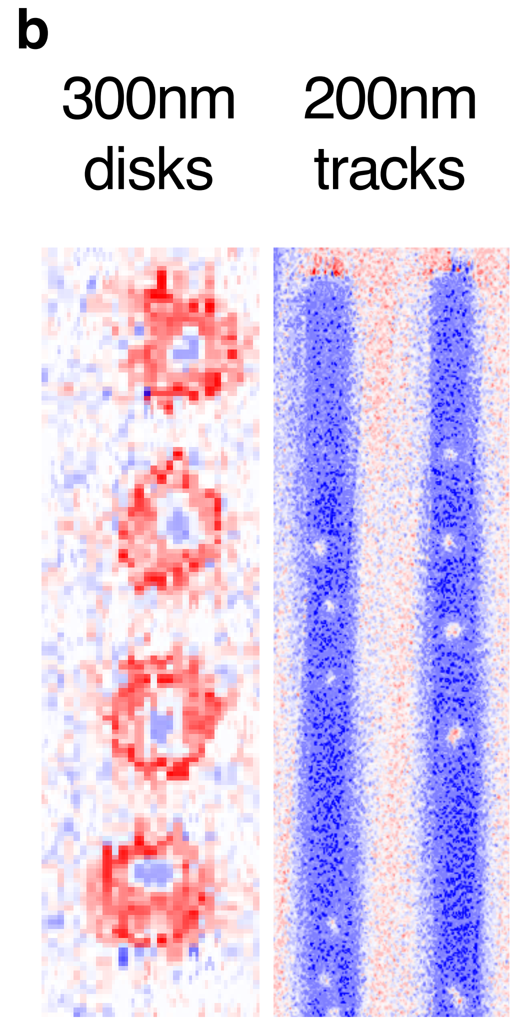


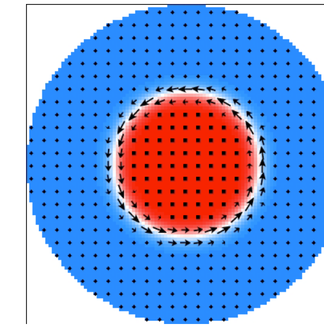


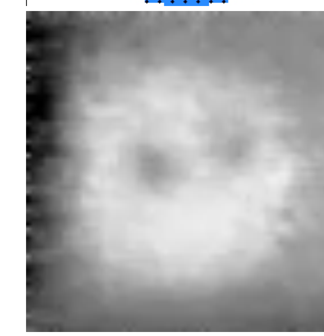
- Isolated nanoscale skyrmions, at R.T. in nanodiscs and nanowires / racetracks
- a) field dependence of the diameter of circular domain in a 500-nm-diameter disk, compared with micromagnetic simulations.
- We need large DM values of at least 1.5 mJ m–2 to stabilize any bubble-like domain in nanodiscs.
- b) 300 nm disks and tracks 200 nm wide with nanoscale skyrmions, stable down to very small fields (~8 mT) of dimensions that range from 90 nm close to a zero field to 50 nm in an applied field.

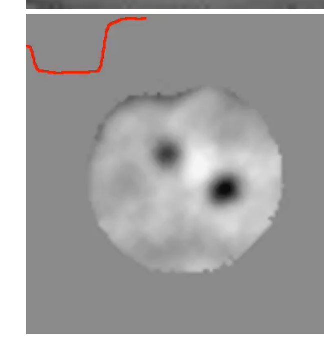
[1] "Additive interfacial chiral interaction in multilayers for stabilisation of small individual skyrmions at room temperature", C. M.-Luchaire, C. Moutafis, …, V. Cros, A. Fert, **online 18 Jan. 2016, Nature Nanotechnology 11, 444–448 (2016)**.

Conclusions

- Isolated/Single skyrmion bubble GHz dynamics observed
- The Gyrotropic & breathing-like motion demonstrated
- Infer topological complexity (Skyrmion number N) from dynamical behaviour -> Skyrmion Bubble
- Inertia/mass
- Nanoscale Room Temperature Chiral Skyrmions

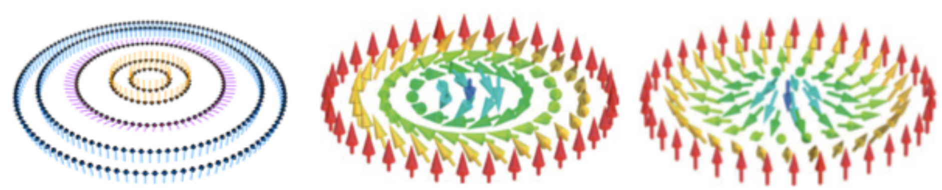


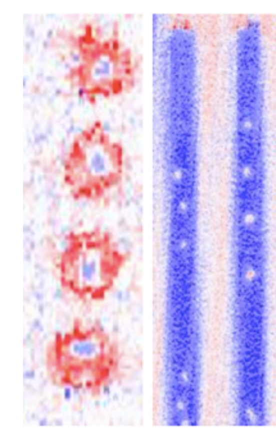


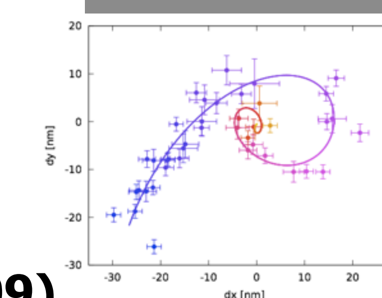


Ongoing…

- Topologically equivalent systems -> Similar behaviour?





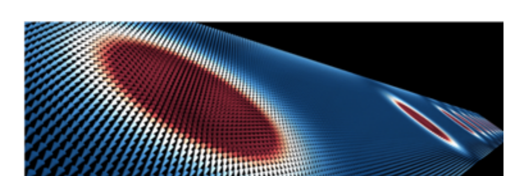


[1] C. Moutafis, et al., **Phys. Rev. B 76 (10), 104426 (2007); Phys. Rev. B vol. 79, 224429 (2009)**

& F. Büttner, C. Moutafis, et al., **Nature Physics 11, 225–228 (2015)**

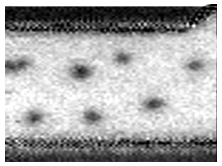
[2] C. M.-Luchaire, C. Moutafis, …, **V. Cros**, **A. Fert**, **Nature Nanotechnology 11, 444–448 (2016)**

Acknowledgements for recent work [2]: Univ. Manchester set-up grant &
European Union MAGicSky No. FET-Open-665095:
http://magicsky-fet.prod.lamp.cnrs.fr/

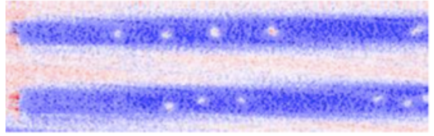


The story continues…

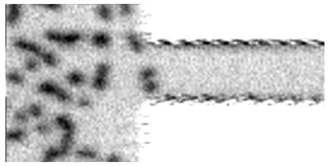
- Cooling Skyrmions



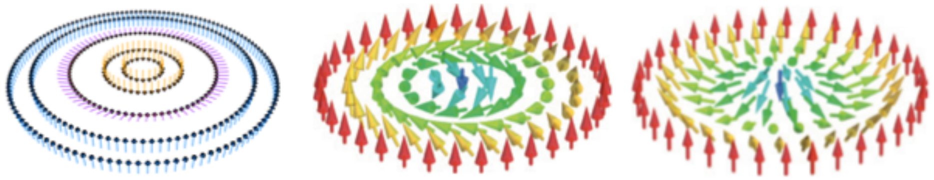
- Moving Skyrmions

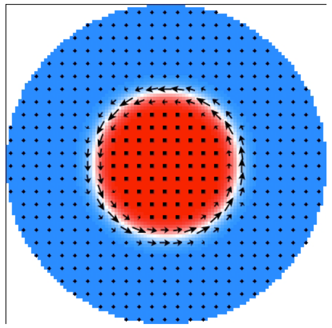


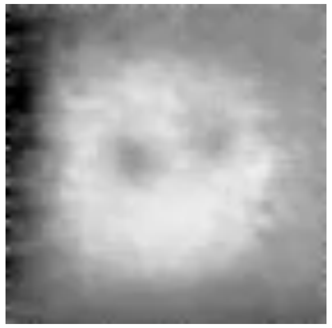
- Writing/Deleting Skyrmions

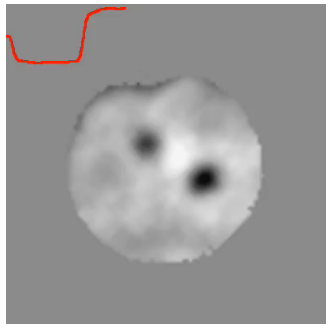


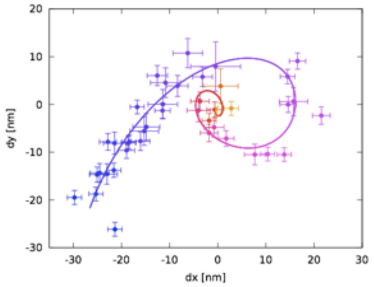
- Topology & Dynamics











ACK for recent work [B]: Univ. Manchester set-up grant & EU MAGicSky No. FET-Open-665095:
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