Current induced nucleation and motion of skyrmion in symmetric multilayers

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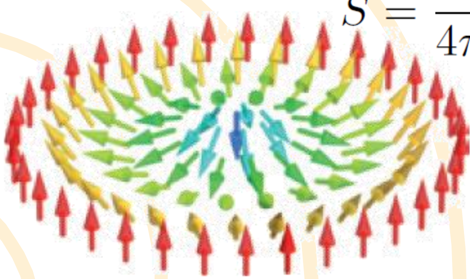
Beyond domain walls ? => skyrmions

Skyrmions are small, stable, less sensitive to defects

•*Toward a skyrmion race track memory : Fert et al. Nature Nano (2013)*

Skyrmion number

$$S = \frac{1}{4\pi} \int \vec{m} \left(\frac{\partial \vec{m}}{\partial x} \times \frac{\partial \vec{m}}{\partial y} \right) d^2 r = 1$$

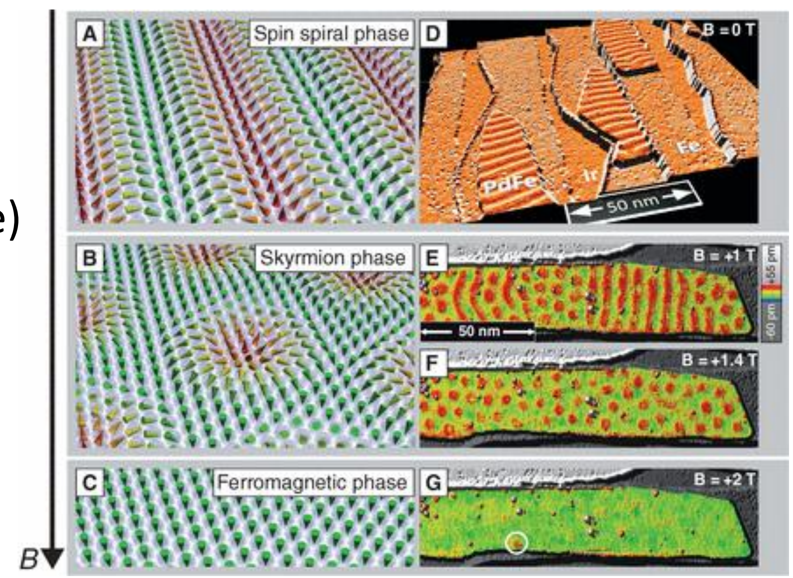


Interface DMI stabilized skyrmion

B20 structure (volume) DMI stabilized skyrmion

First description:
Bogdanov et al. SovPhys JETP (1989)
JMMM (1994)
Rössler et al. Nature (2006)

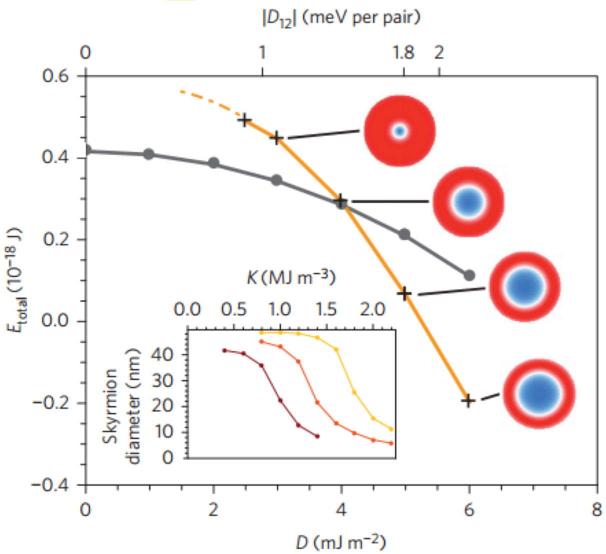
Skyrmions generally need magnetic field
Most experiments are on arrays of skyrmions



[N. Romming et al. Science (2013)]

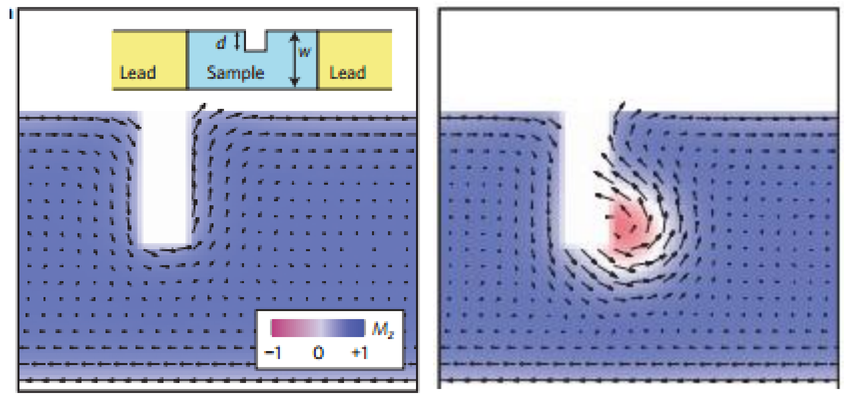
Duty list for skyrmion applications

Skyrmion stabilization in low field and at room temperature



Sampaio et al., Nature Nano 8 839 (2015)

Controlled nucleation



Iwasaki et al., Nature Nano 8 742 (2015)

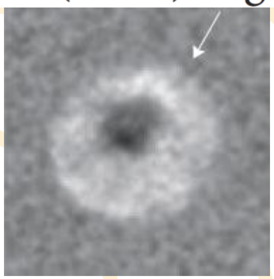
Efficient skyrmion motion

Sampaio et al., Nature Nano 8 839 (2015)

Duty list for skyrmion application

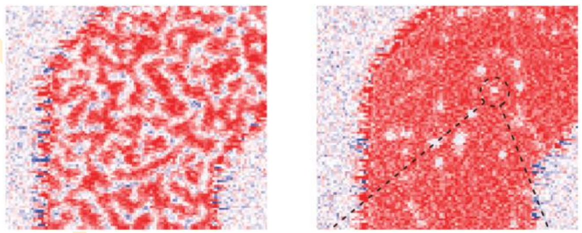
Skyrmion stabilization in low field and at room temperature

Pt/Co(1 nm)/MgO



Boulle et al., Nat. Nano (2016)

$Pt10|Co0.6|Pt1|(Ir1|Co0.6|Pt1)_{10}$

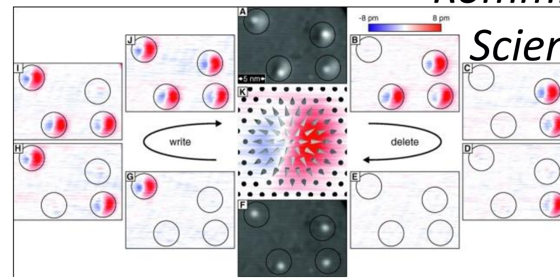


M.-L. et al., Nat. Nano (2016)

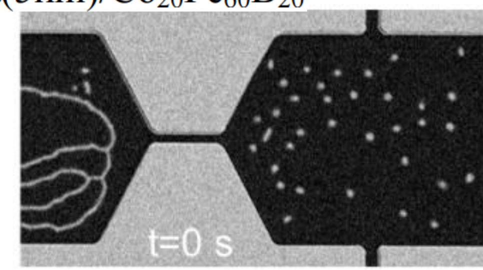
Controlled nucleation

Pd/Fe/Ir(111)

Romming et al., Science (2013)



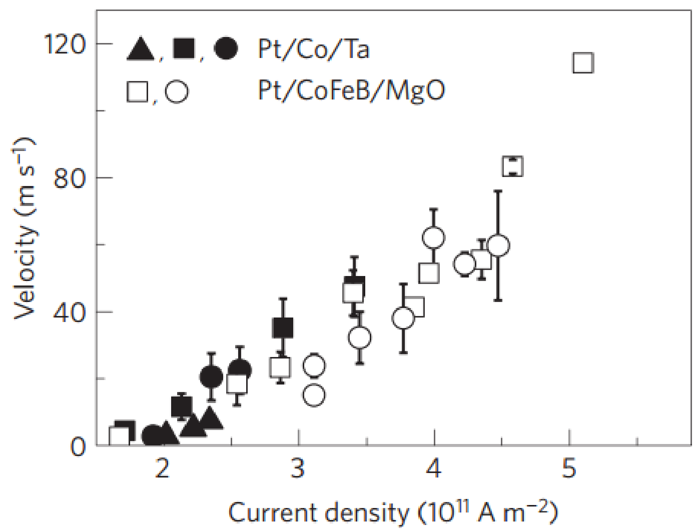
$Ta(5nm)/Co_{20}Fe_{60}B_{20}$



Jiang et al., Science (2015)

Efficient skyrmion motion

Woo et al., Nat. Materials (2016)

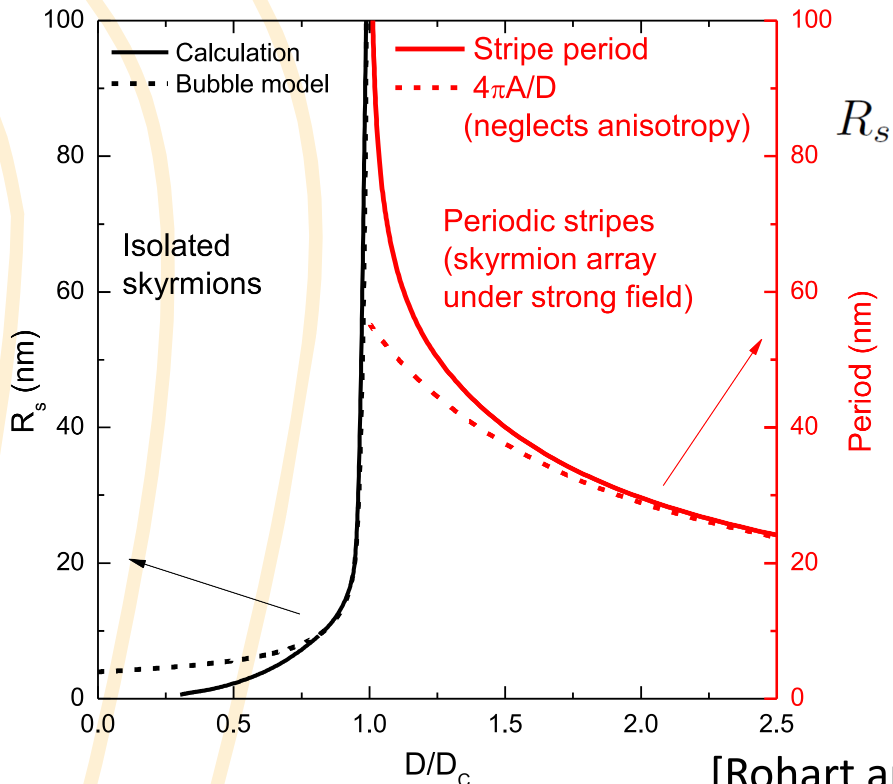


Isolated skyrmion in small magnetic field

Need control of domain wall chirality of spin orbite torque
Need low domain wall energy

Use Dzyaloshinskii-Moriya interaction in asymmetric films

$$\sigma = \sigma_0 - \pi D$$



$$R_s \approx \frac{\Delta}{\sqrt{2(1 - D/D_c)}}$$

D must be close to Dc
=> Control with thickness :

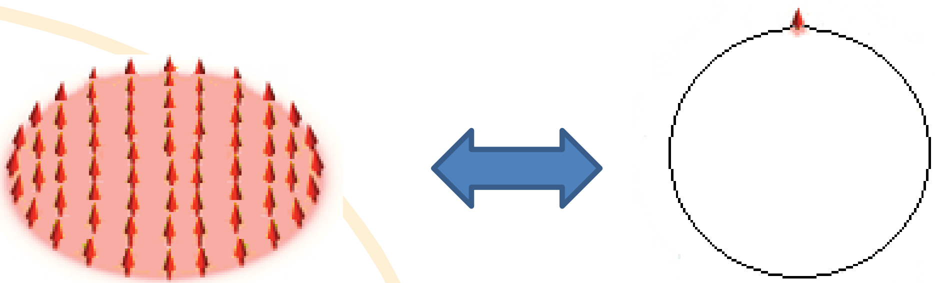
$$K = \frac{K_S}{t} - \tfrac{1}{2}\mu_0 M_S^2$$

$$D = \frac{D_S}{t}$$

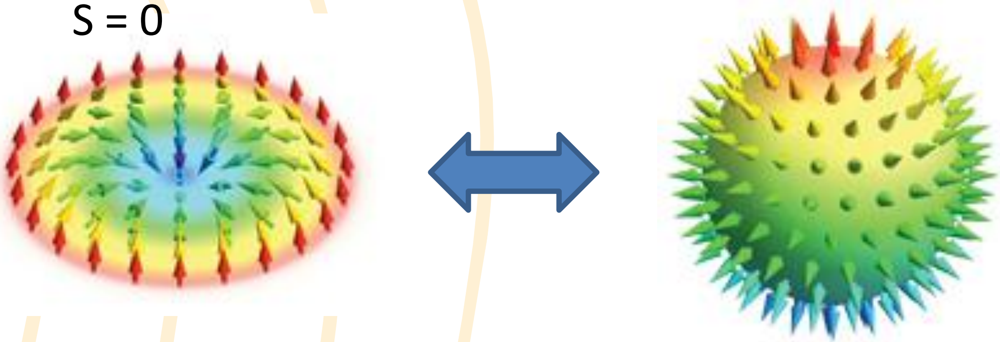
[Rohart and Thiaville Phys. Rev. B 88 184422 (2013)]

Skyrmion stability (1)

Transition toward the uniform state looks impossibe



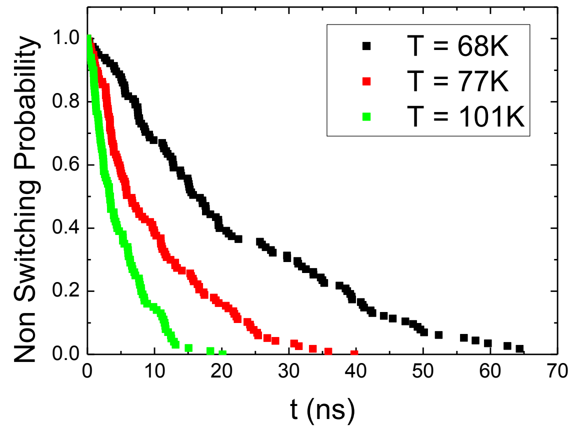
The uniform state points at the north pole
S = 0



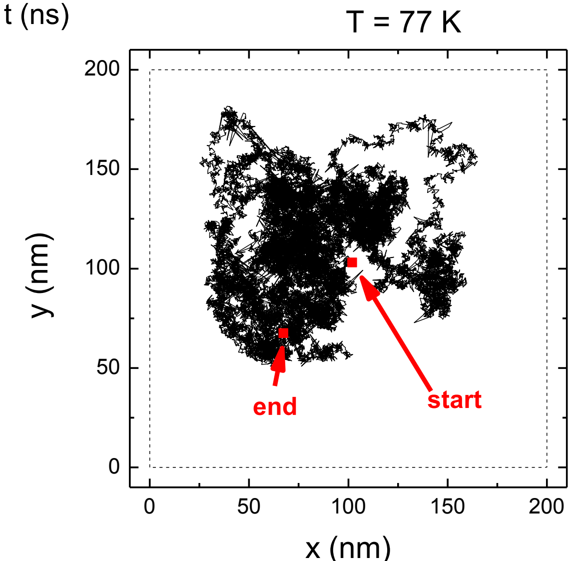
The skyrmion wraps all the unit sphere
S = 1

Topological stability ???

Using atomic description, skyrmion have a finite lifetime



Co monolayer on Pt(111)

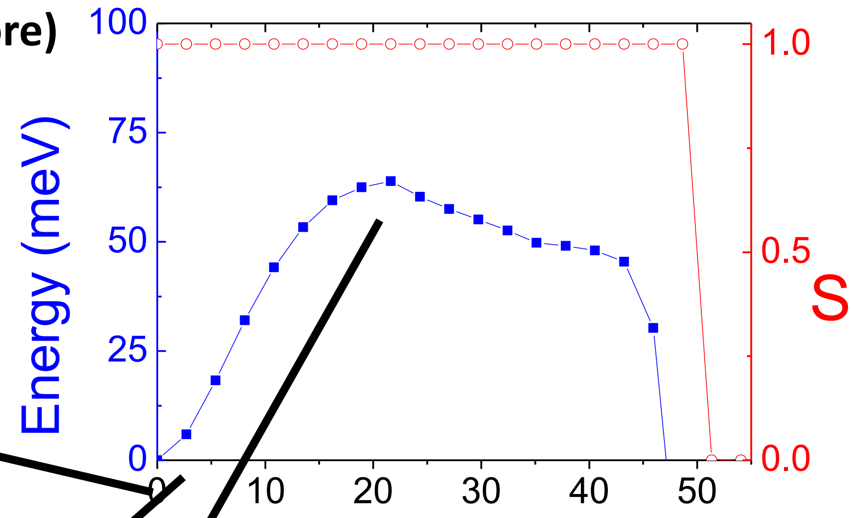


-diffusion of the skyrmion
-Skyrmion collapse
-Low lifetime

Skyrmion stability (2)

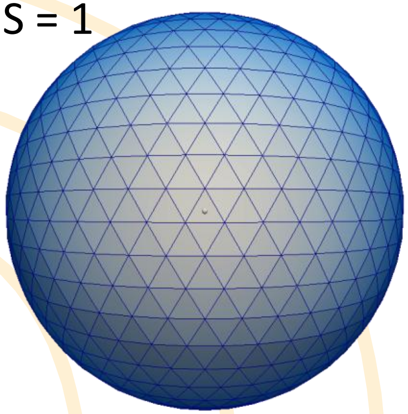
Representation of colapse on the unit sphere

Seens from z axis, noth pole (skyrmion core)



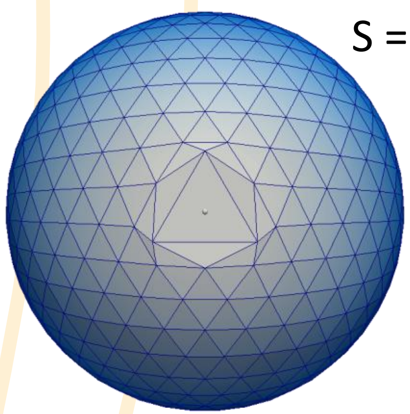
Initial state (skyrmion)

S = 1



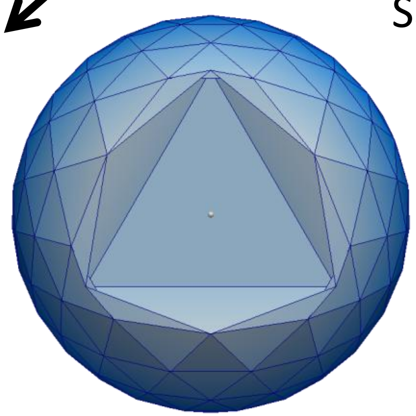
First step

S = 1



Saddle point

S = 1

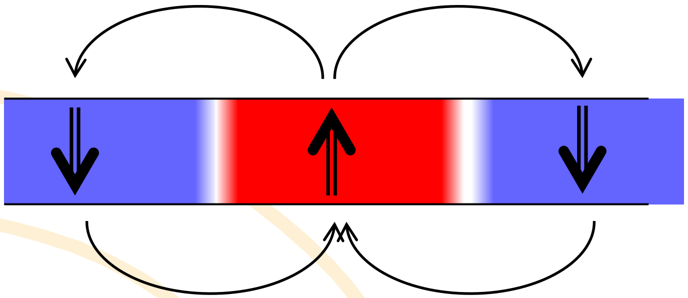


Stability is not connected to topology

Destabilization occurs before topology change

[Rohart et al. Phys. Rev. B 93 214412 (2016)]

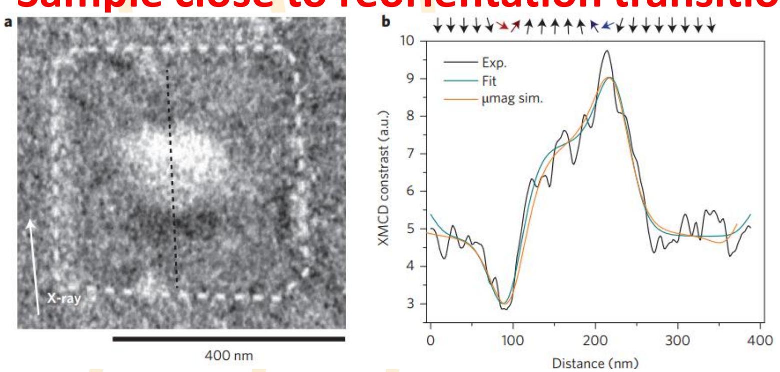
Role of dipolar coupling for stabilitzation



Provide another source of stabilization
Enlarge the skyrmions

Efficient dipolar coupling require thickness larger than $\frac{\sigma}{\mu_0 M_S}$ [Kooy and Enz Philips Res Rep 15 181 (1960)]

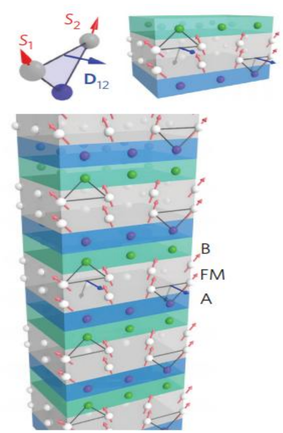
Sample close to reorientation transition



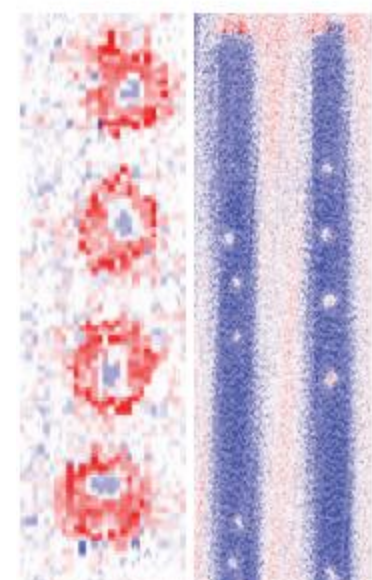
[Boulle et al. Nature Nano 11 449 (2016)]

Requires fine tunning of thickness

Multilayers



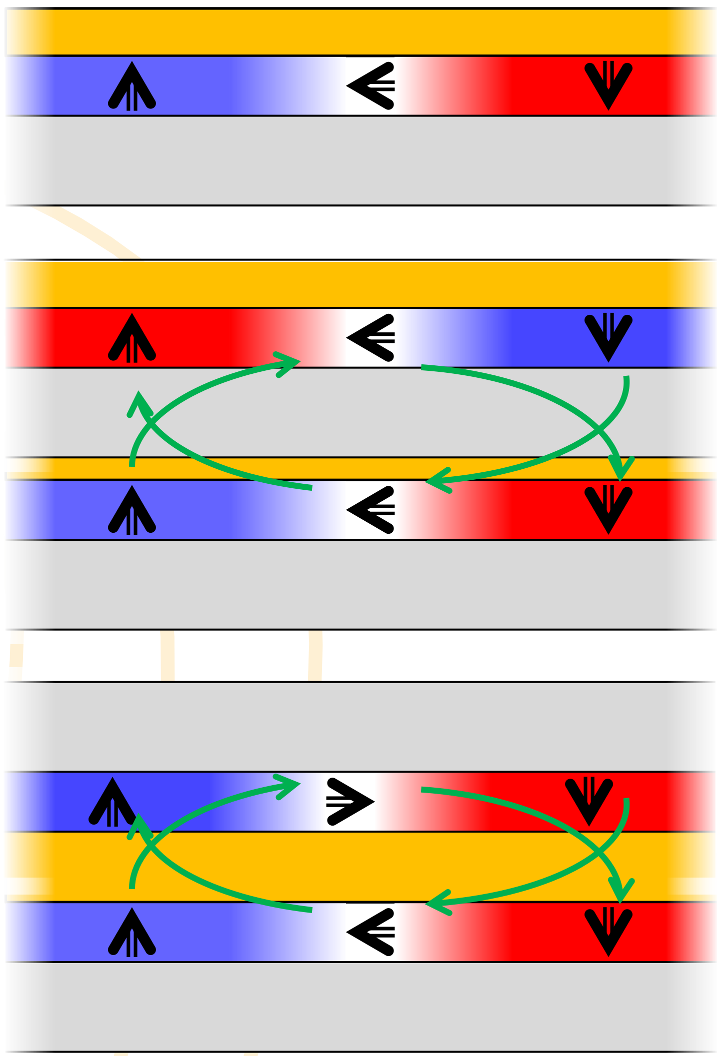
300 nm disks | 200 nm tracks



[Moreau-Luchaire et al. Nature Nano 11 444 (2016)]
[Woo et al. Nature Mat. 15 501 (2016)]

Need large spacers to enable SOT

Chiral domain wall in symmetric samples



Single layer :

$$\sigma = \sigma_0 - \pi D$$

ASymmetric bilayer

$$\sigma = \sigma_0 - \pi D$$

Dipolar coupling not satisfied

Requires large spacer for spin-orbite torque

Symmetric bilayer

$$\sigma = \sigma_0 - \pi D \boxed{- \delta\sigma_{D-DW}}$$

Dipolar coupling satisfied

Not constrain on spacer thickness

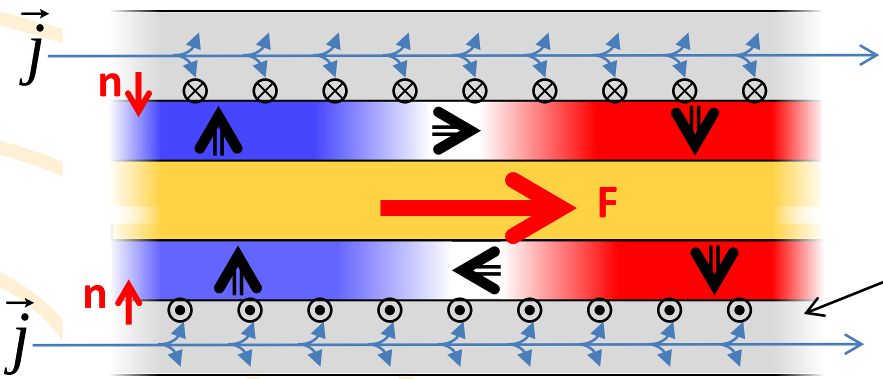
Dipolar coupling reenforces the chirality

[Bellec et al. Europhys. Lett. 91 17009 (2010)]

⇒Both layer have opposite stacking

⇒Both domain wall have opposite chirality

Spin orbite torque in symmetric samples



Single layer

Spin accumulation due to spin Hall effect

$$\vec{e}_p = \mathrm{sgn}[\theta_H](\vec{n} \times \vec{j})$$

Interface normal
From SO to ferro layers

Force on domain wall

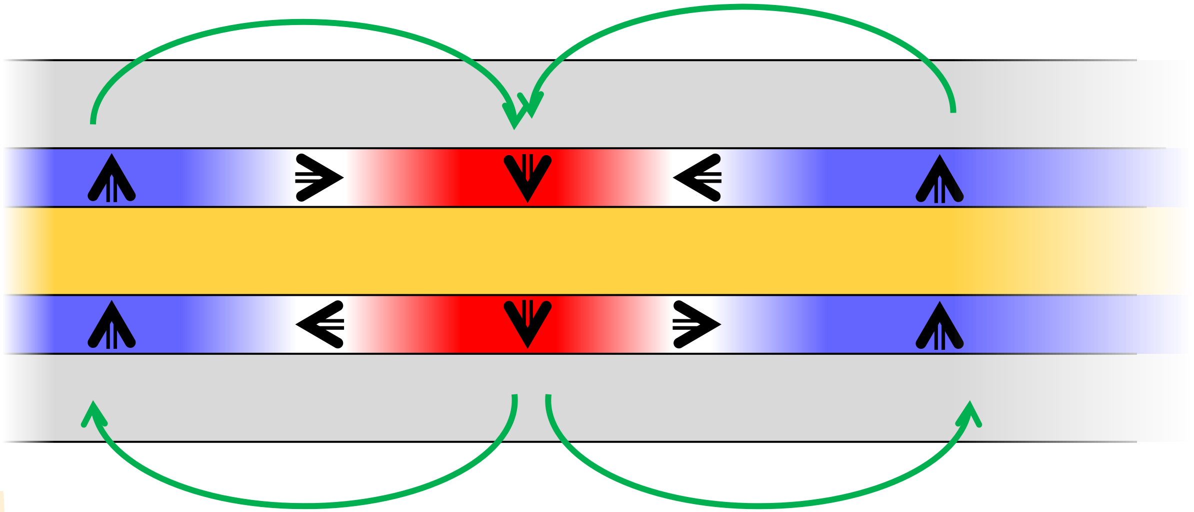
$$\vec{F} \propto c(\vec{e}_z \times \vec{e}_p)$$

chirality

Symmetric bilayer

$\vec{n}$ and c with opposite sign
=> Force acting on domain wall with the same direction

Skyrmion in symmetric bilayers



Study of pair of skyrmions with opposite chirality
Strong coupling through dipolar field
Naturally ready for spin-orbite torques

Single layer characterization

Base stack :

Pt/ [Ni(4)/Co(8)/Ni(4)] /Au

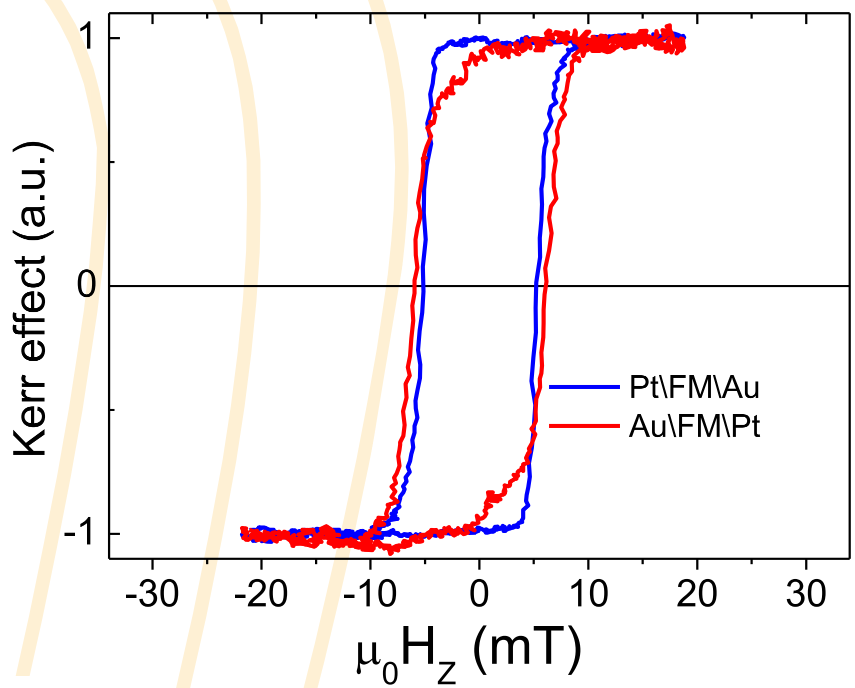
Large spin orbite
Large SHE

Tunable
anisotropy

Neutral

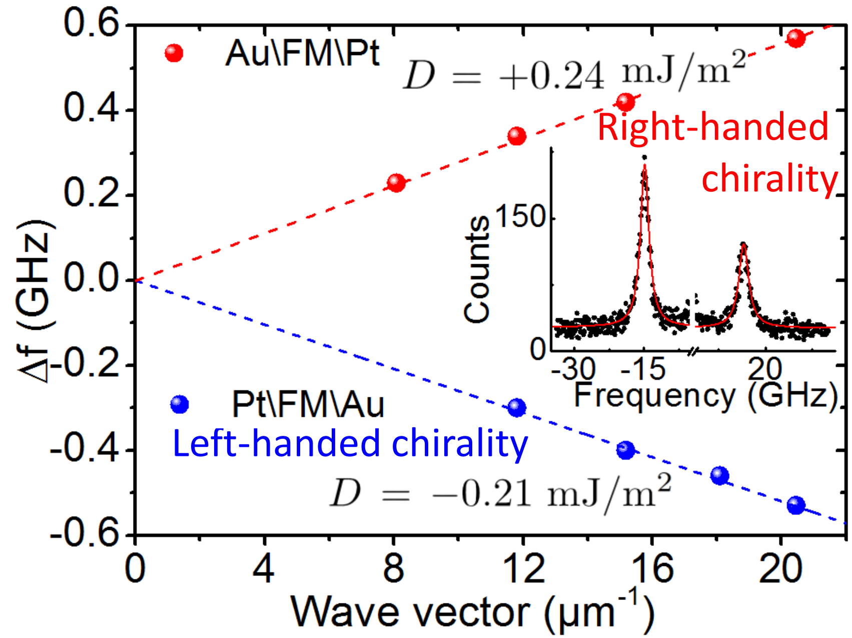
Magnetometry

Single layers have PMA, square loop



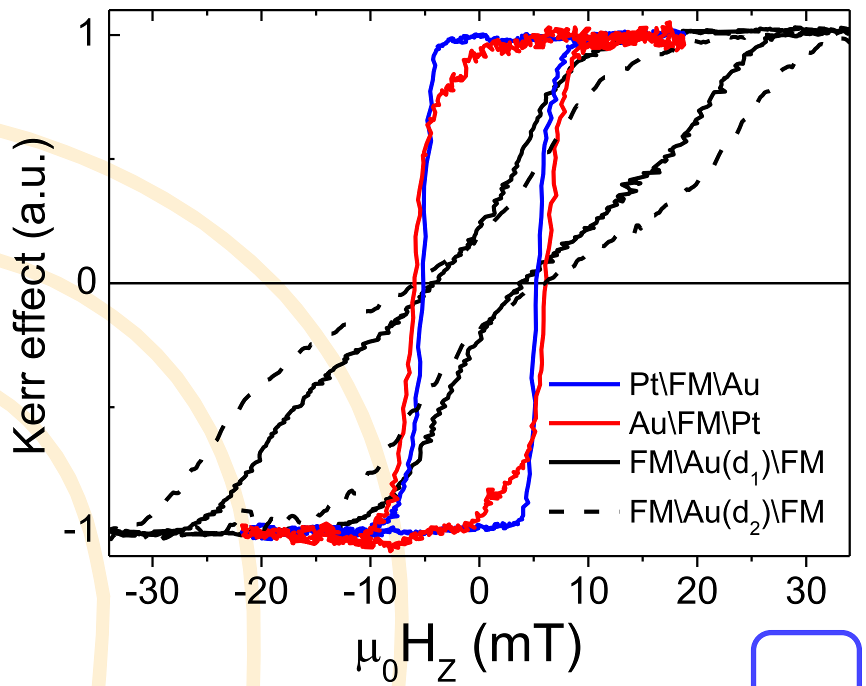
Brillouin light scattering characterization of DMI

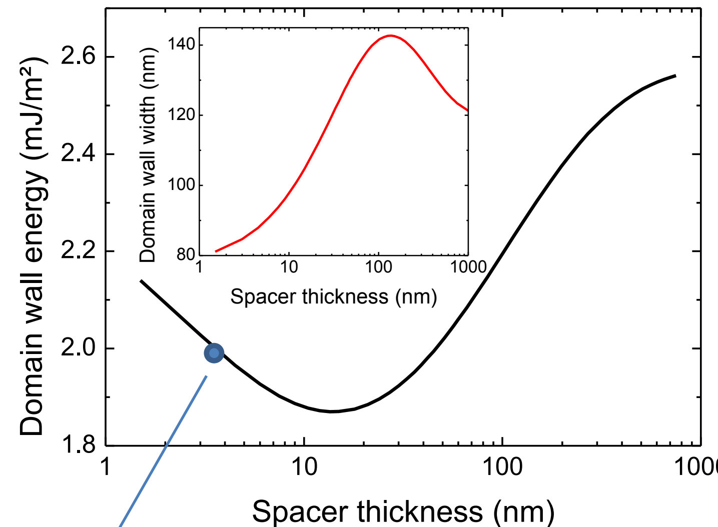
$$\Delta f = f_S - f_{AS} = 2\gamma k_x D / \pi M_s$$



- Layers are similar but with oposite DMI and DW chirality
- DW energy is positive

Bilayer characterization





$$\sigma = \sigma_0 - \pi D - \delta\sigma_{D-DW}$$

3.25 mJ/m²

D = 0.2 mJ/m²
πD = 0.63

0.6 mJ/m²

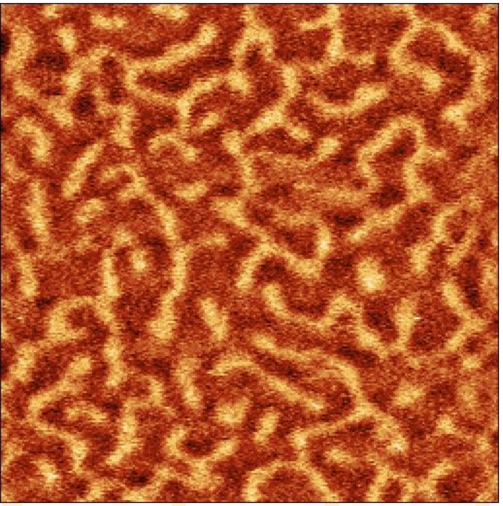
Domain wall energy remains positive

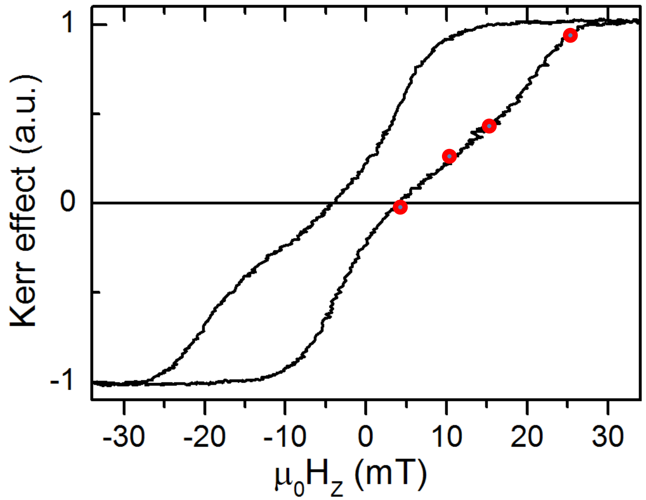
Demagnetization due to dipolar coupling

thanks to thickness larger than $\sigma / \mu_0 M_S = 2.2\text{nm}$

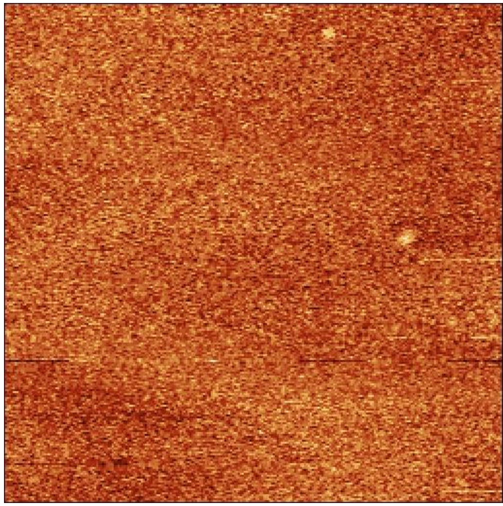
MFM imaging : from stripe phase to skyrmions

2 mT

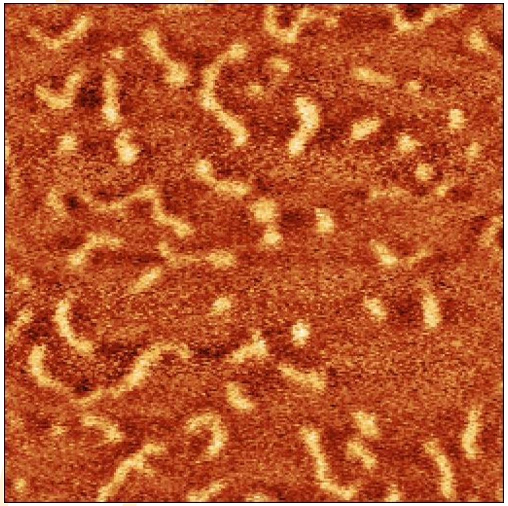




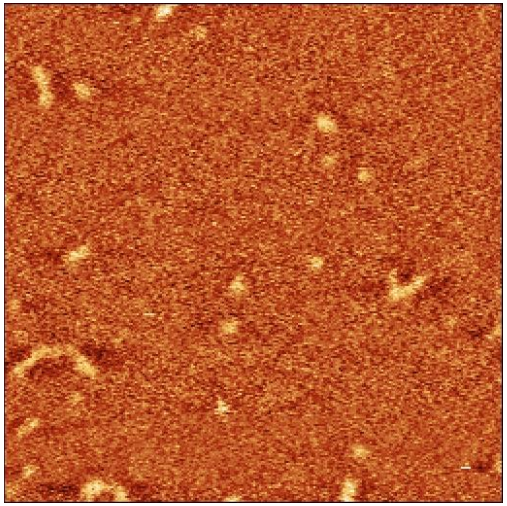
25 mT



10 mT



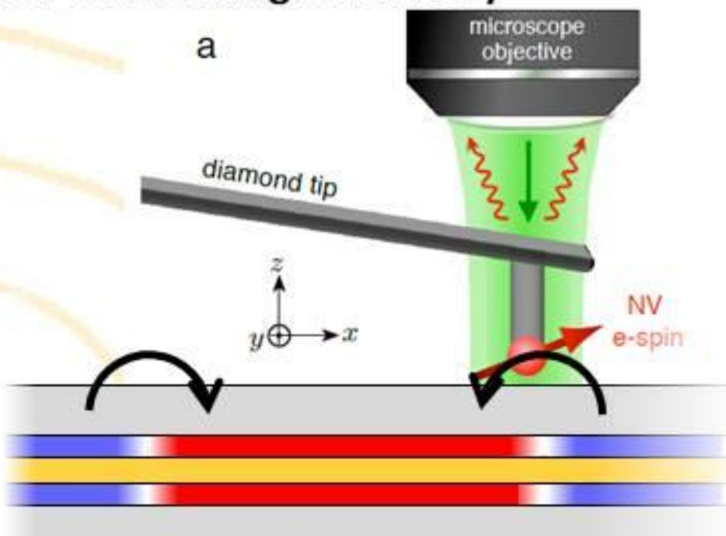
14 mT



Isolated skyrmion

Skyrmion size

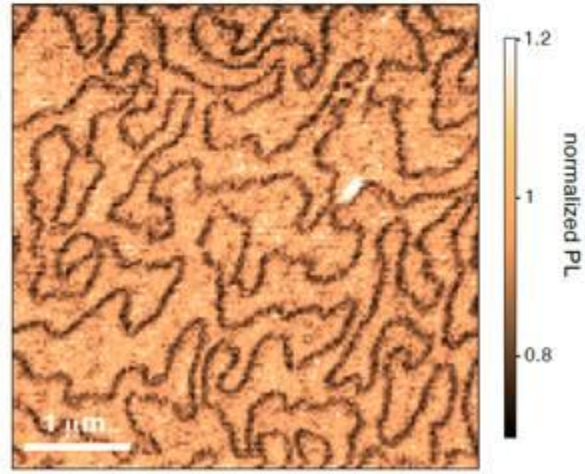
Perturbation free measurment using NV-center magnetometry

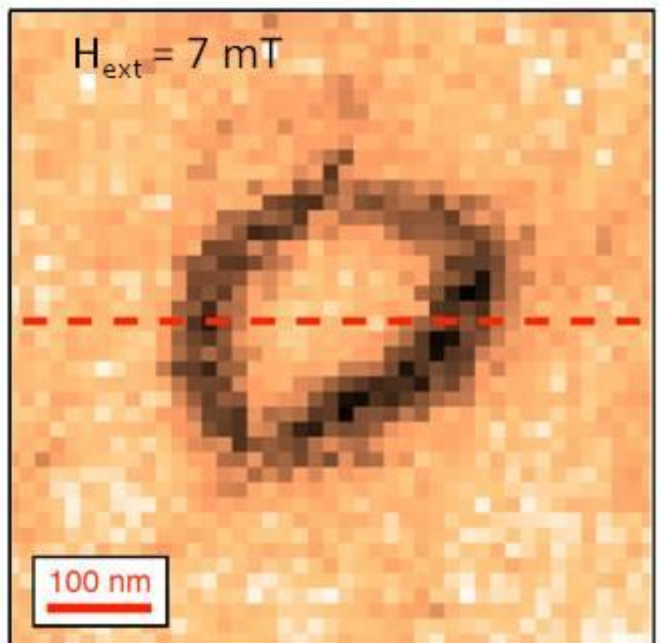


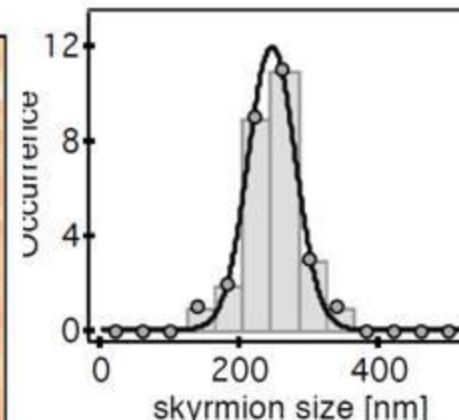
Quenching mode: measure of the luminescence rate depending on the magnetic field

For the technique see :
Rondin et al. Appl. Phys. Lett. 100 153118 (2012)
Tetienne et al. Science 344 1366 (2014);
Nature Com. 6 6733 (2015)]

$H_{ext} = 0$





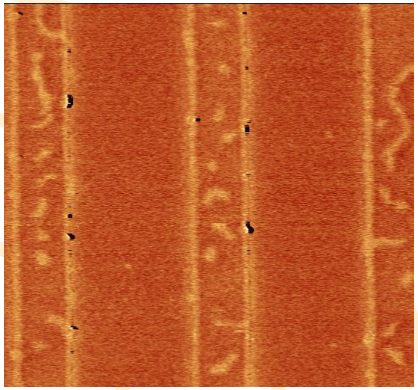


Average size : 250 nm

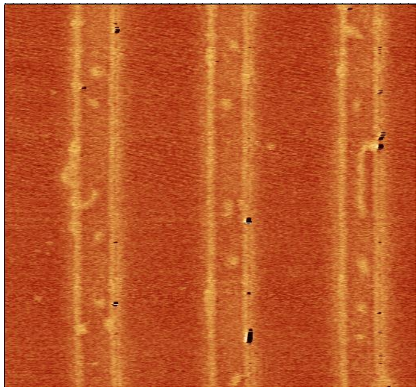
Toward a functional device

Skyrmions in nanowires

2.5 mT



W = 500 nm

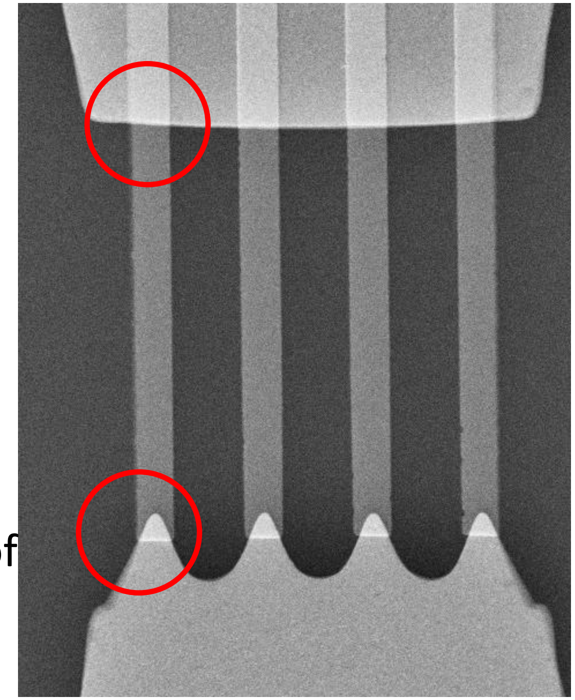


W = 300 nm

Skyrmion isolation at lower field
(modified dipolar energy ?)
Saturated state at 6 mT
=> try nucleation experiments

Asymetric device

Flat electrode
-> homogeneous current lines
used for skyrmion motion

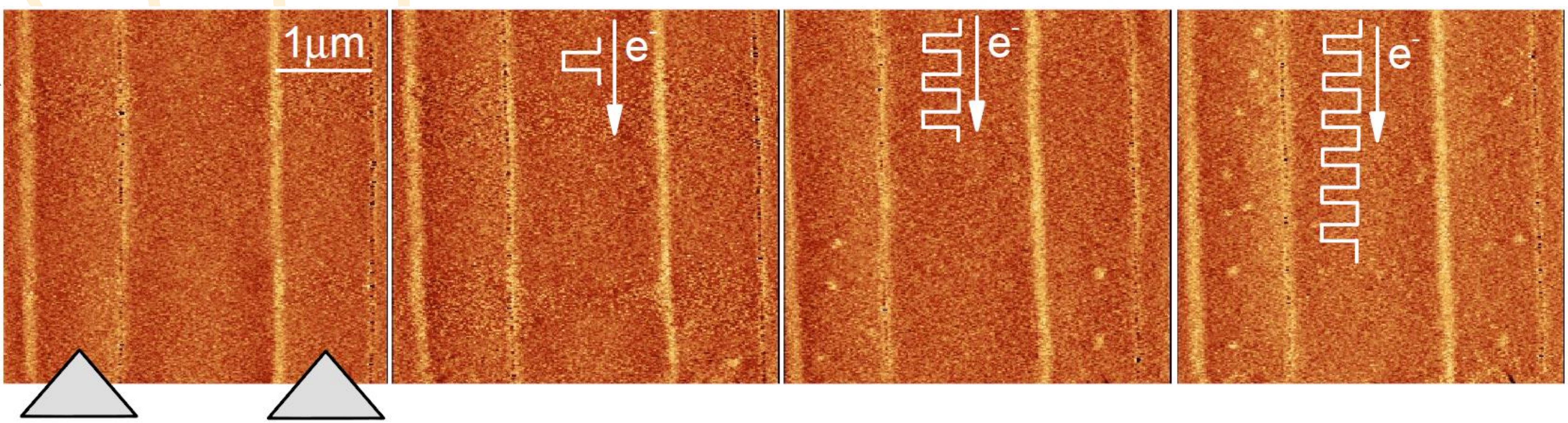


Sharp electrode
-> larger current density, divergence of current lines
used for skyrmion nucleation

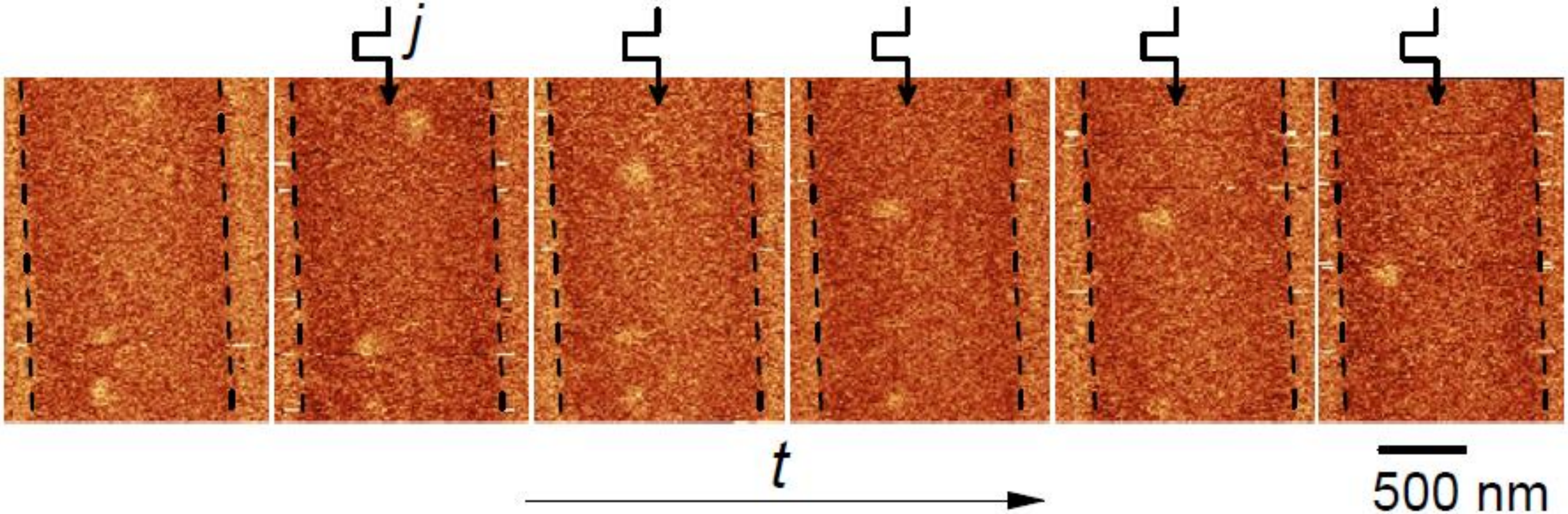
Skyrmion nucleation using sharp electrode

Skyrmion nucleate at the sharp electrode
for $J > 2.6 \times 10^{11}$ A/m²
Skyrmion are pushed along J

Reversing the current : no nucleation at any electrode



Skyrmion motion



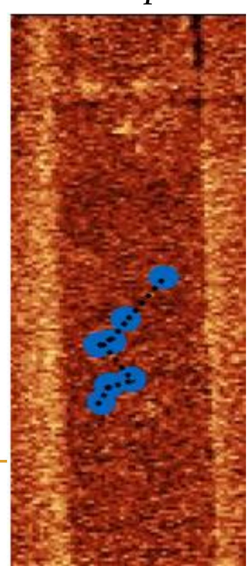
Skyrmion move along J => spin Orbite torque

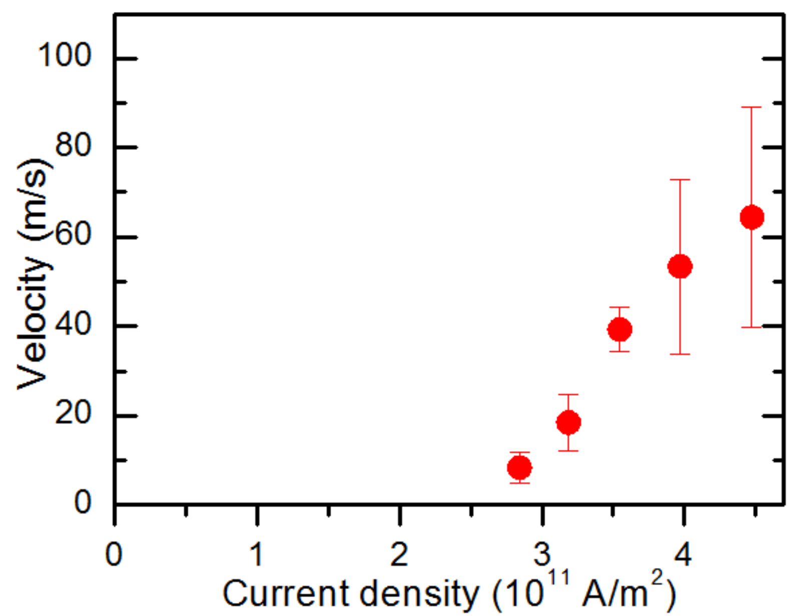
$$\vec{F}_{sky} = \frac{\hbar}{2e}\pi j\theta_H (\pi R_{sky})\, \vec{e}_Z \times \vec{e}_p$$

Velocity expected : $\vec{v} = \frac{\vec{F}_{sky}}{\alpha D}$

> 300 m/s at J = 0.44 TA/m²

<u>Important role of defects</u>





Topological motion of skyrmions

A topological particle should display a transverse motion

Thiele Equation for Skyrmion motion:

$$\vec{F}_{SOT} + \vec{G}\times\vec{v} + \alpha \,\overset{=}{D}\,\vec{v} = 0$$

Damping $D = \frac{M_s t}{\gamma}\int\left(\frac{\partial \vec{m}}{\partial x}\right)^2 d^2 r \approx \frac{M_s t}{\gamma}\frac{2\pi R}{\Delta}$

Spin orbite torque

Topology inside

Gyrovector : $\vec{G} = \frac{M_s t}{\gamma}\int \vec{m}\left(\frac{\partial \vec{m}}{\partial x}\times\frac{\partial \vec{m}}{\partial y}\right) d^2 r\ \hat{z} \equiv \frac{4\pi S M_s t}{\gamma}$

Steady state velocity :

$$v_{//} = -\frac{F_{SOT}}{G}\frac{\alpha D/G}{1+\left(\alpha D/G\right)^2} \approx -\frac{\alpha F_{SOT} D}{G^2}$$

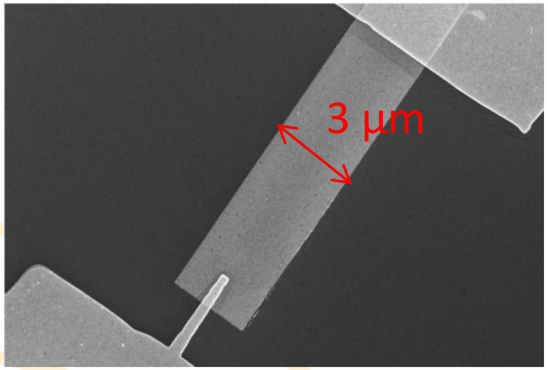
$$v_{\perp} = \frac{F_{SOT}}{G}\frac{1}{1+\left(\alpha D/G\right)^2} \approx \frac{F_{SOT}}{G}$$

Deflection angle

$$\chi = \mathrm{atan}\left[\frac{G}{\alpha D}\right] \approx S\,\mathrm{atan}\left[\frac{2\Delta}{\alpha R}\right]$$

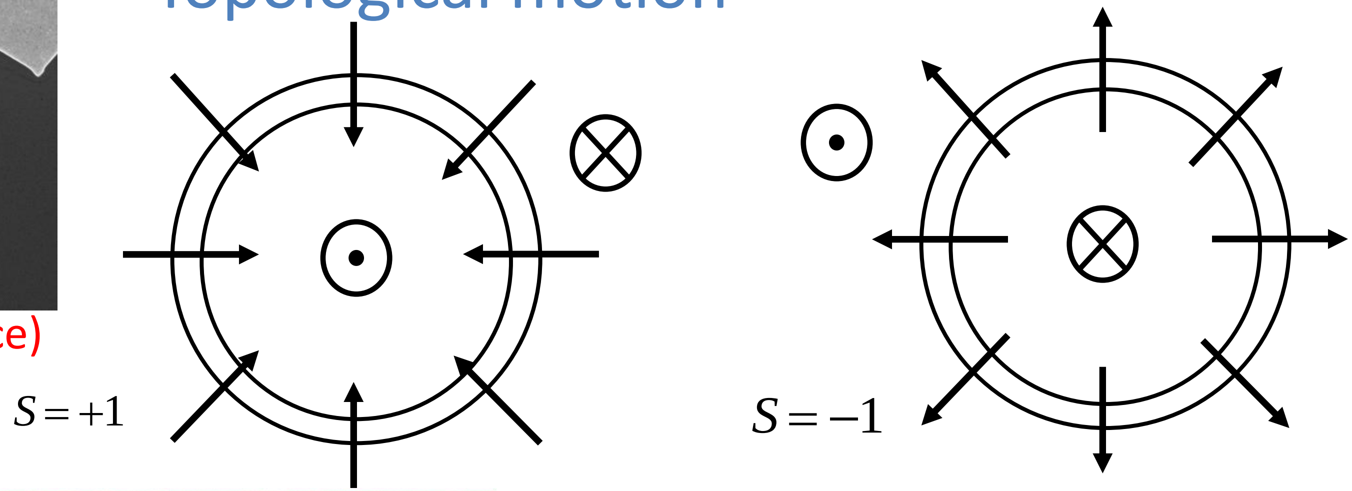
Skyrmion should move at an angle with the current flow

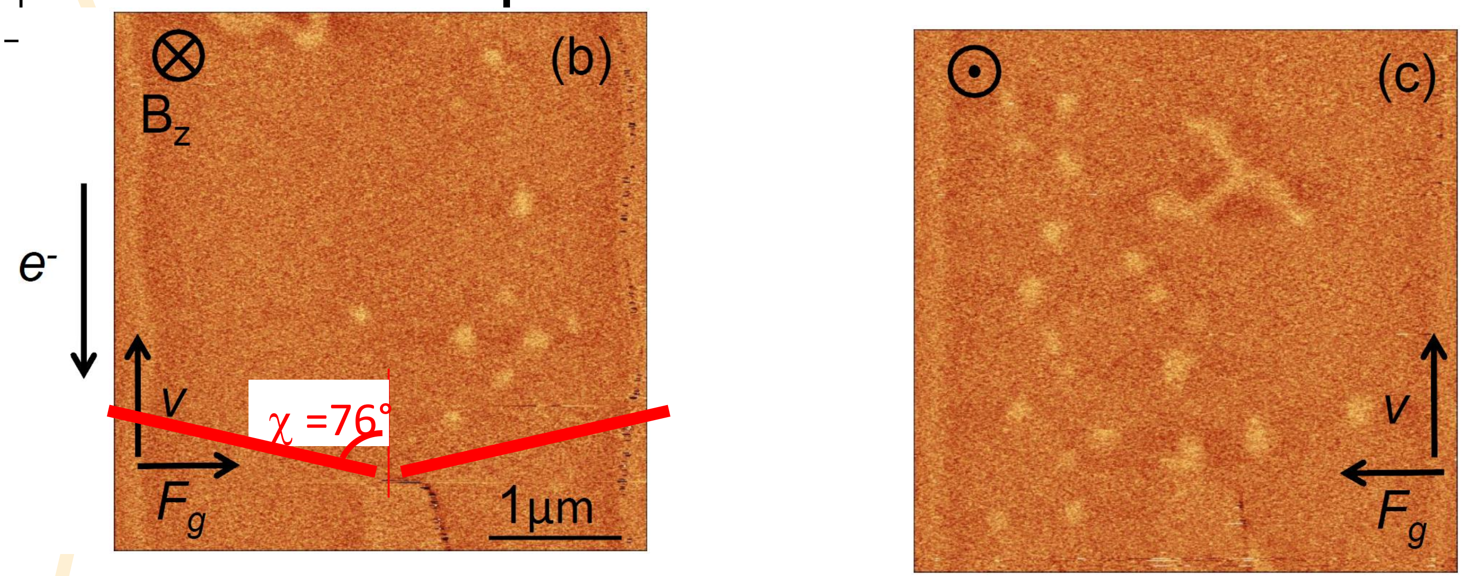
Topological motion



(larger device)

$$\chi \approx S\, \mathrm{atan}\left[\frac{2\Delta}{\alpha R}\right]$$

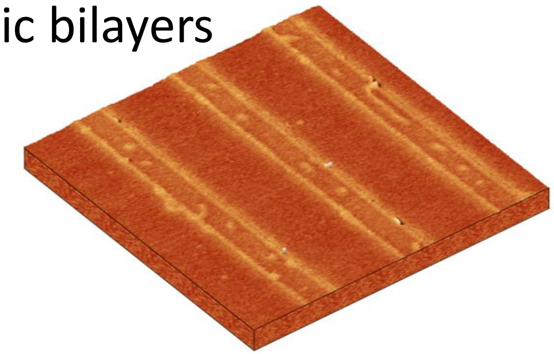




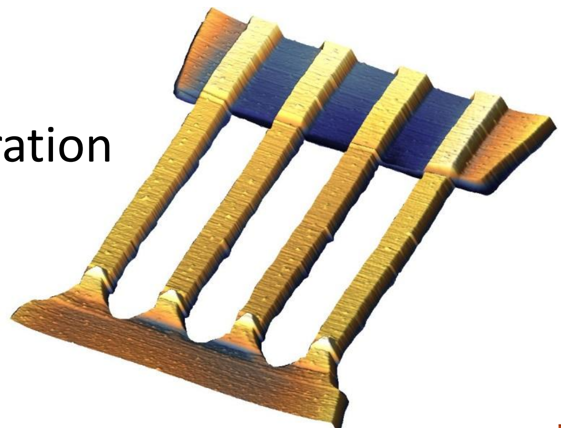
Topologic is confirmed
Gyrotropic force is strong
Topological motion is suppressed at the edges

Conclusion

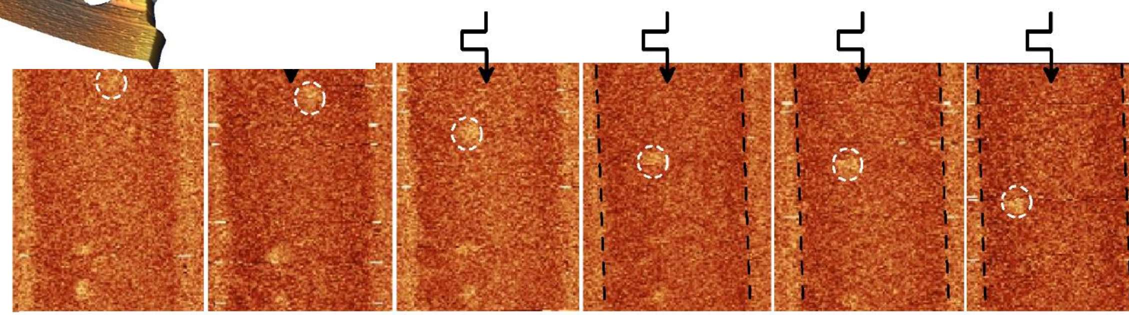
- Developing of a new system with symmetric bilayers for isolated skyrmions phase



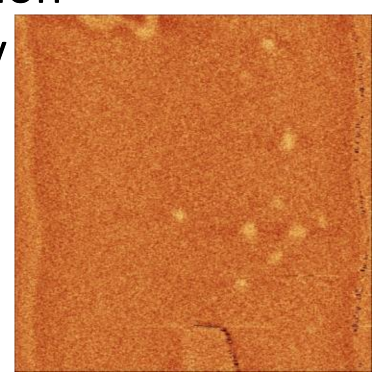
- Skyrmion generation



- Skyrmion displacement



- Skyrmion deflection demonstration
  => proof of skyrmion topology



Current-induced skyrmion generation and dynamics in symmetric bilayers
A. Hrabec et al. arXiv:1611.00647