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Chiral domain walls and their current driven dynamics

Reunión del Club Español de Magnetismo

Eduardo Martínez

11 November 2016

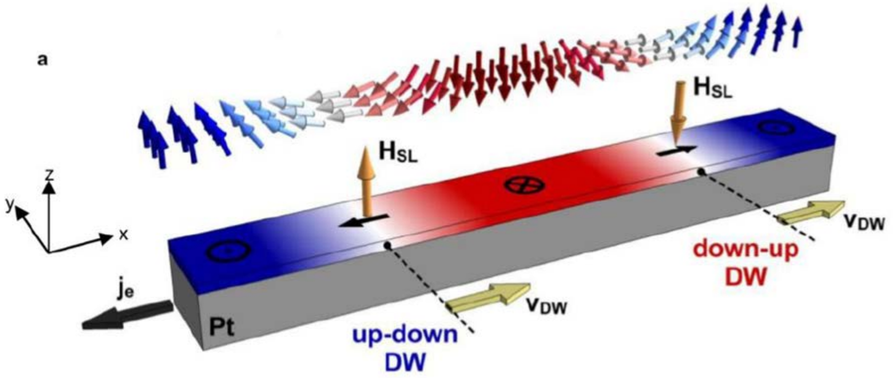
Outline: “***Chiral*** *domain walls and their* ***current-driven dynamics***”

- Current-driven DW motion by **Spin Transfer Torques** (STTs) - Gradient Torques
- Strips with high Perpendicular Magnetocristalline Anisotropy (PMA)

10 min

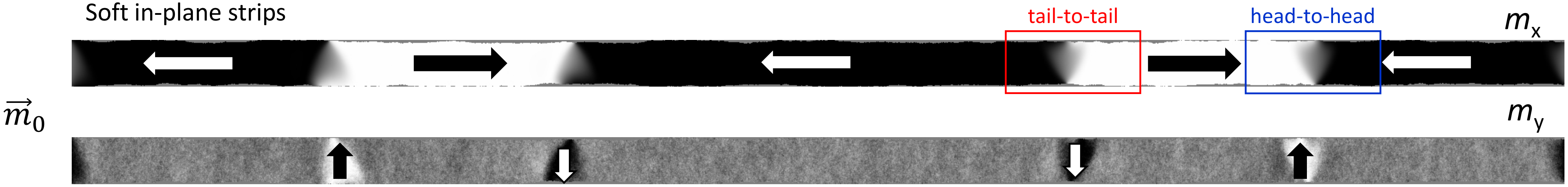
- Review of experimental results for high PMA systems: from “STT” to “DMI + SHE”
  - ♠ The driving forces responsables for the current-driven DW motion
  - ♠ Revisiting the exchange interaction: The chirality

30 min



Current-driven DW motion along in-plane strips

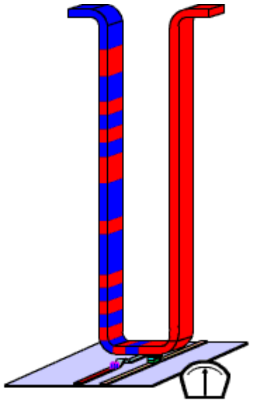
Soft in-plane strips

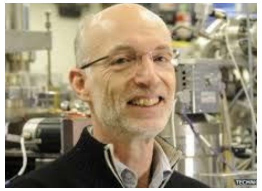


Permalloy; Lenght: ~ 10 um; Cross section: 320 x 5 nm^2

2 consecutive current pulses

- Current pulses drive adjacent DWs along the same direction, **without annihilation**.
- DWs in soft in-plane strips **move along the current flow** (against the current).
- Current-driven DW motion is potentially useful for applications





S. Parkin

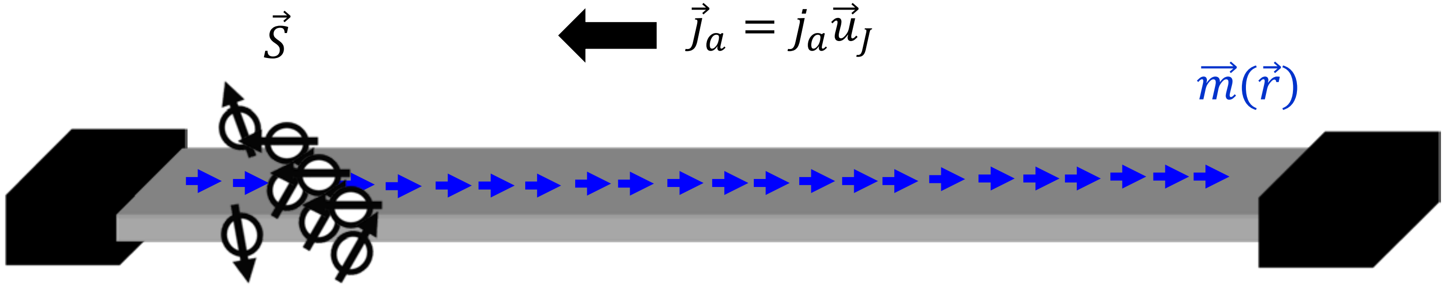
But, why the current can drive DWs (and other textures)?

L. Berger J. Slonczewski

L. Berger. JAP . **55**, 1954 (1984)

J. C. Slonczewski. JMMM. **159**, L1-L7 (1996).

- Ferromagnetic (FM) material are typically good conductors: **electrical current** ($\vec{j}_a$) can go throught it.
- The spin of the conduction electrons ($\vec{S}$) interacts (exchange) with the local magnetic moments ($\vec{m}(\vec{r})$).

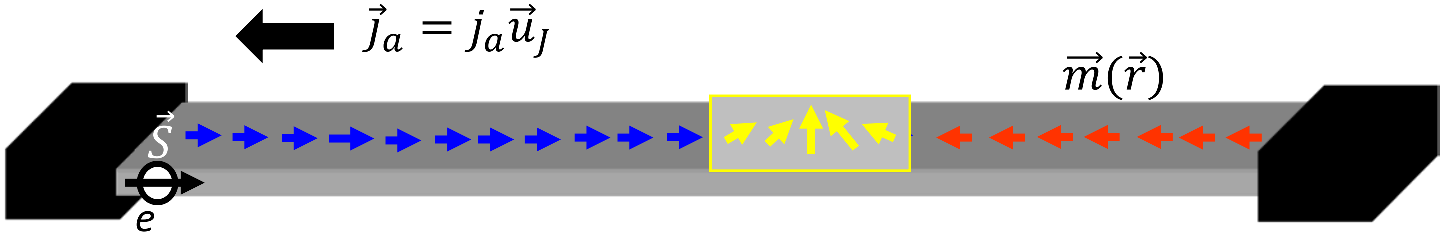


- The result is a **spin polarized current** ($\vec{j}_s$).
- A **spin polarized current** $\vec{j}_s$ **interacts with a magnetic pattern such as DW**.

But, why the current can drive DWs (and other textures)?

LLG eq. + Spin Transfer Torques (STT): $\frac{\partial \vec{m}}{\partial t} = -\gamma_0 \vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t} + \vec{\tau}_{STT}$ $\xrightarrow{\text{STTs:}}$ $\vec{\tau}_{STT} = \vec{\tau}_A + \vec{\tau}_{NA}$

Adiabatic STT



Transmitted *e* transfer spin angular momentum to DW: $\vec{\tau}_A = b_J (\vec{u}_J \cdot \nabla) \vec{m}$

$$b_J = \frac{\mu_B P}{e\, M_s} J_a$$

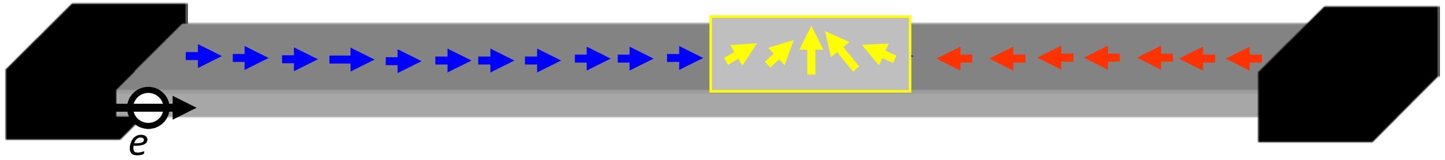
P: Polarization factor

S. Zhang and Z. Li, PRL, 93, 127204 (2004)
A. Thiaville et al. Europhys. Lett. 69, 990 (2005).

L. Berger

A. Thiaville

Non-Adiabatic STT

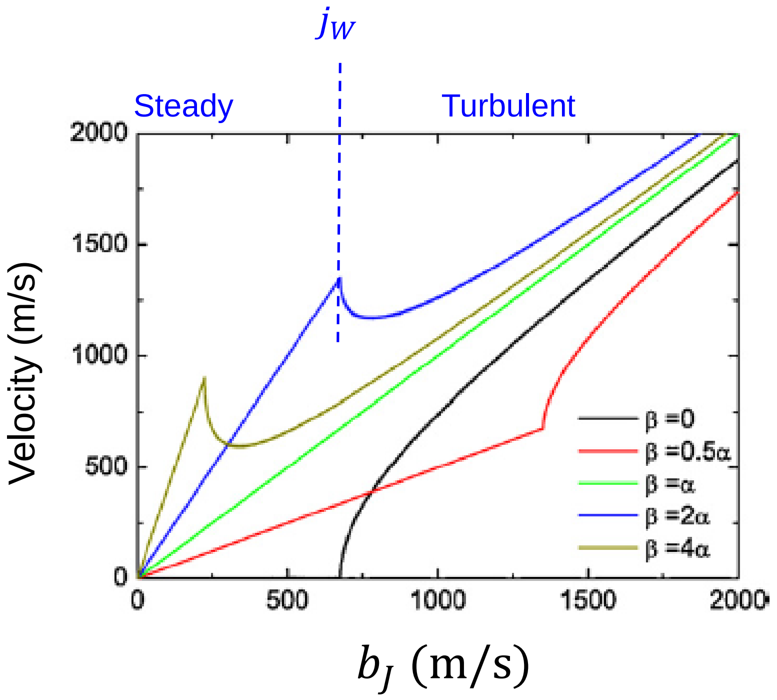


Reflected *e* transfer linear momentum to the DW: $\vec{\tau}_{NA} = -\beta b_J \vec{m} \times (\vec{u}_J \cdot \nabla) \vec{m}$

β: non-adiabatic parameter

G. Tatara et al, PRL, 92, 086601 (2004)
Y. Tserkovnyak et al. PRB, 74, 144405 (2006).
X. Waintal et al. Europhys. Lett. 65, 427 (2004).

Current-driven DW motion by STTs



$$b_J = \frac{\mu_B P}{e M_s} j_a \qquad e < 0$$

Mobility: $m_j \equiv \dfrac{\Delta v}{\Delta j_a}$

$\beta = 2\alpha$: $j_a < j_W$: Steady regime with high mobility.

$j_a > j_W$: Turbulent DW motion

$\beta = \alpha$: Rigid motion with constant mobility $m_R \equiv \dfrac{\beta}{\alpha}\dfrac{\mu_B P}{e M_s}$

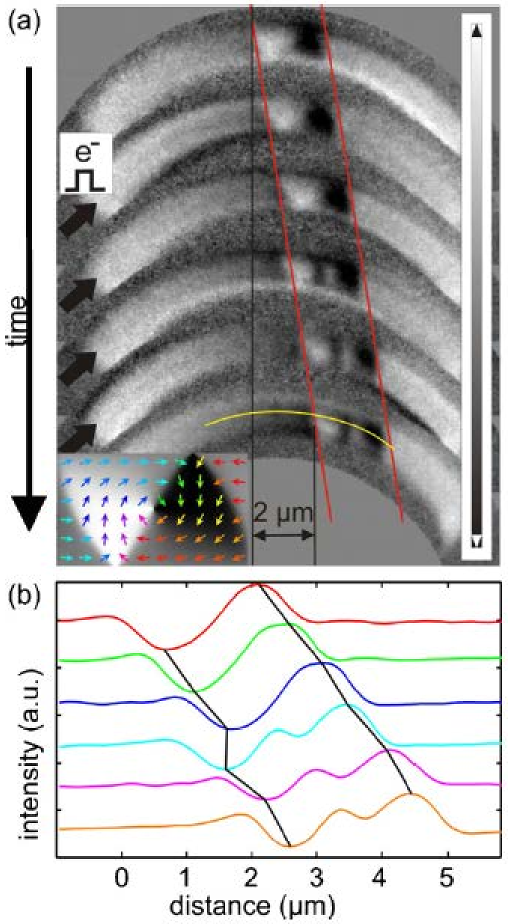
$\beta = 0$: $j_a < j_{th}$: No DW motion.

$j_a > j_{th}$: Turbulent DW motion $m_T \equiv \left(\dfrac{1+\alpha\beta}{1+\alpha^2}\right)\dfrac{\mu_B P}{e M_s}$

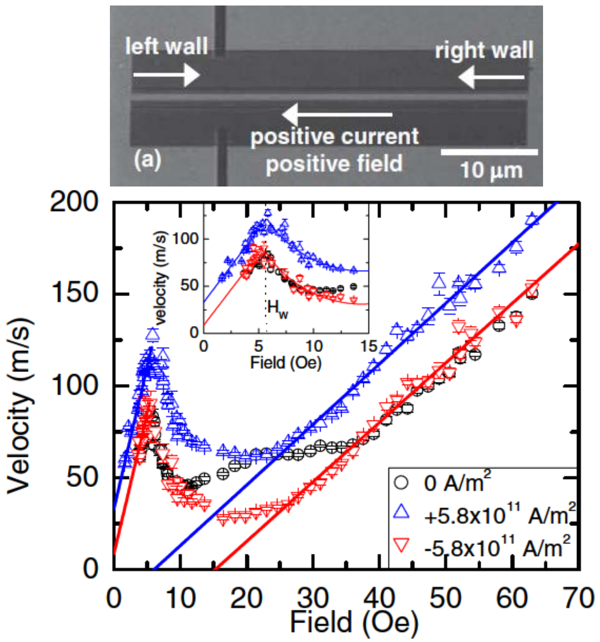
- ♣ DWM along the electron flow ($P > 0$, $\beta > 0$).
- ♣ In the rigid regime the mobility (m_R) scales with β.
- ♣ For very high currents the mobility m_T does not depend on β.

Current-driven DW motion by STTs: some examples

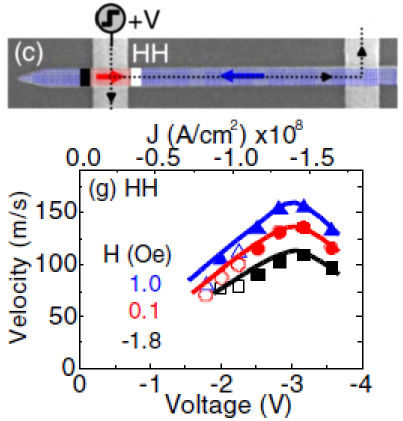
C.-Y. You et al. APL. **89**, 222513 (2006)



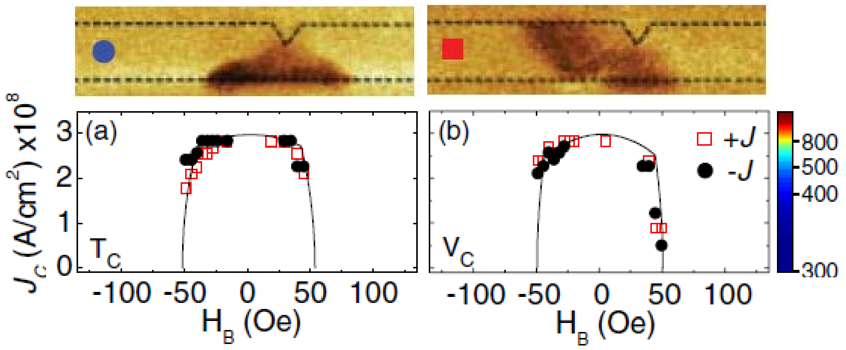
G. S. Beach et al. PRL **97,** 057203 (2006)



M. Hayashi et al. PRL **98,** 037204 (2007)



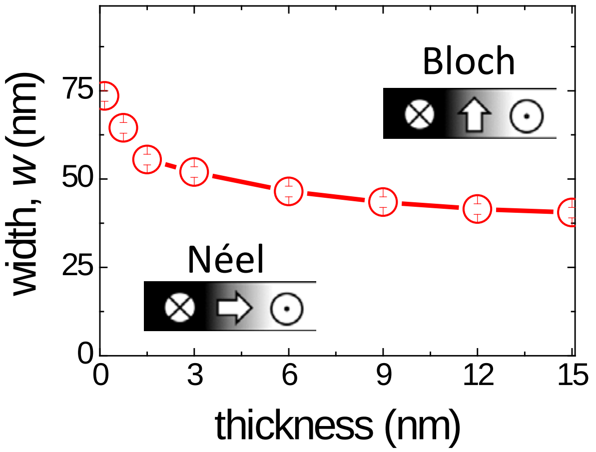
M. Hayashi et al. PRL **97,** 207205 (2006)



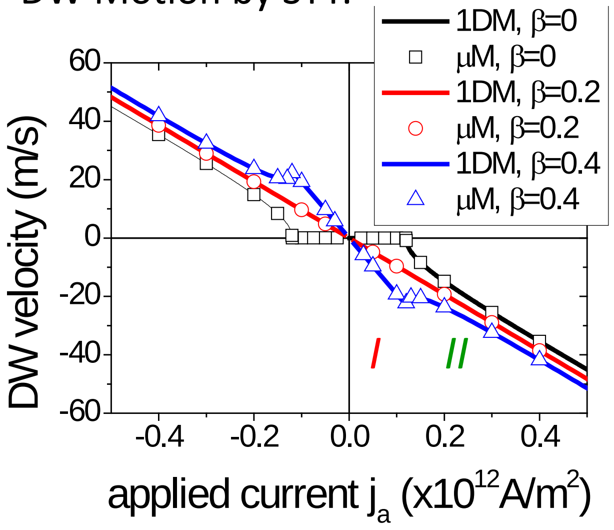
Still open questions !!

High PMA strips

DW at rest:



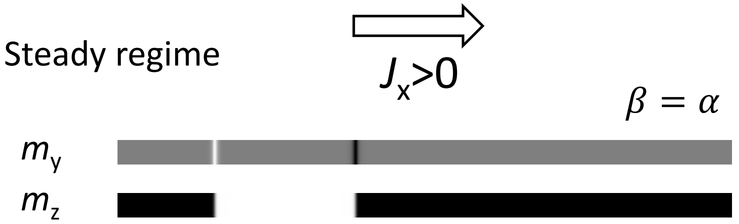
DW Motion by STT:



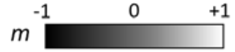
CoPtCr; *w* = 120nm, *t* = 3nm

- DWM along the electron flow ($P > 0, \beta > 0$).
- DWM independenlty of the internal DW state.

I: Steady regime



Same dynamics for $\beta > 0$ and $j < j_{th}$



$$m_R \equiv \frac{\beta}{\alpha} \frac{\mu_B P}{e M_s}$$

II: Turbulent regime

$\beta = 2\alpha$

Same dynamics for $\beta \neq \alpha$ and $j > j_{th}$

Part II

- Review of experimental results for high PMA systems: from “STT” to “DMI + SHE”
  - ♠ The driving forces responsables for the current-driven DW motion
  - ♠ Revisiting the exchange interaction: The chirality

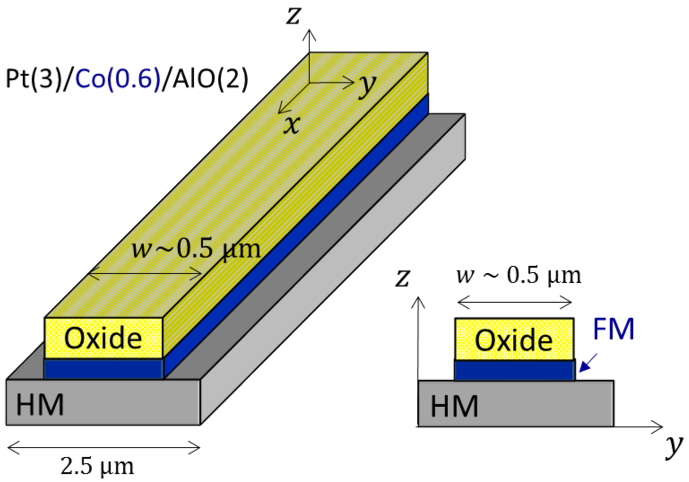
Experiment #1

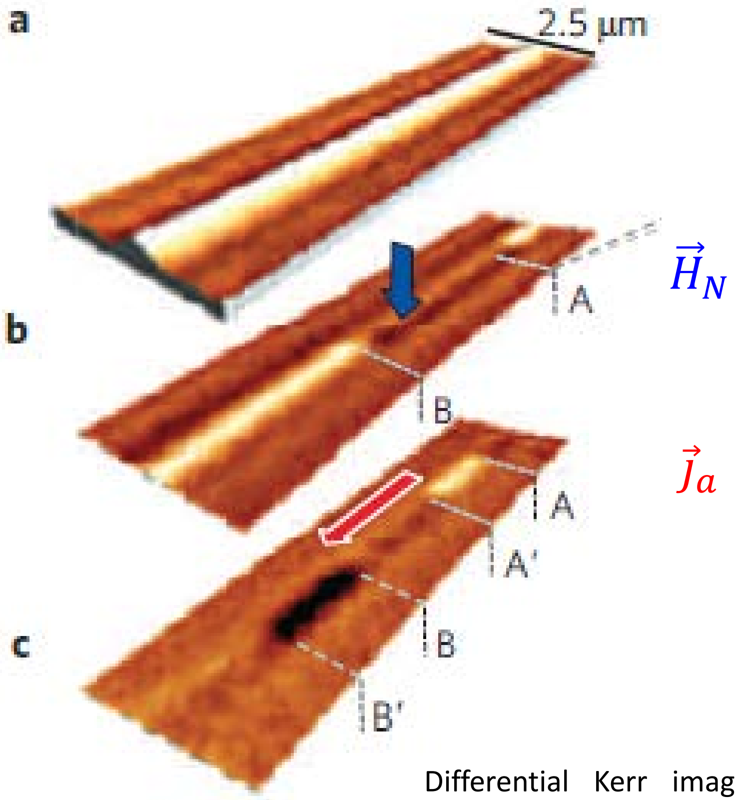
M. Miron

O. Boulle

G. Gaudin

I. M. Miron et al. Nat. Mat. **10**, 6 419 (2011)

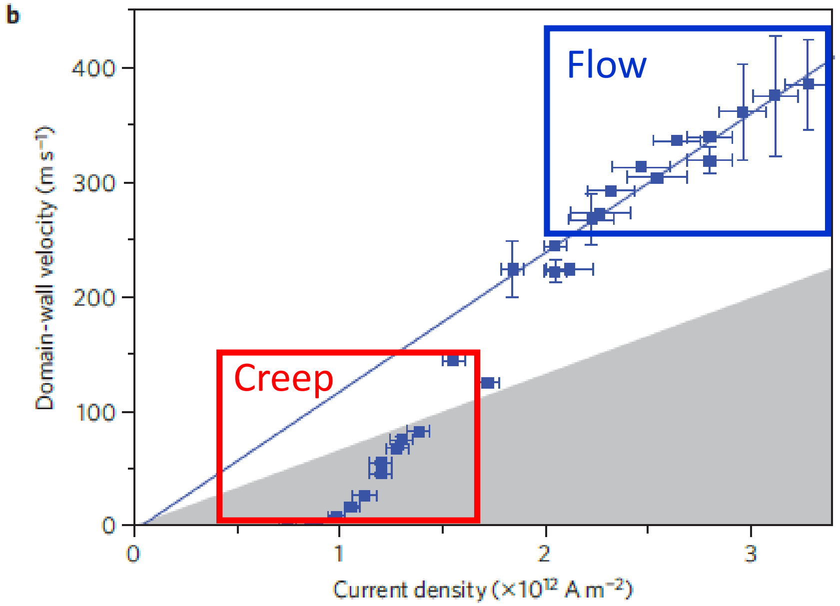




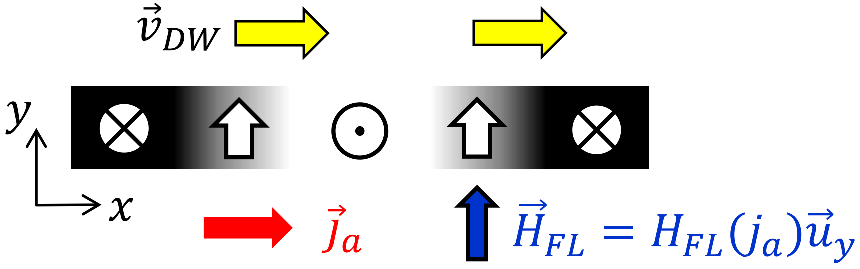
Differential Kerr image of the current-driven DW displacement under current pulses

Experiment #1: results & interpretation

I. M. Miron et al. Nat. Mat. **10**, 6 419 (2011)



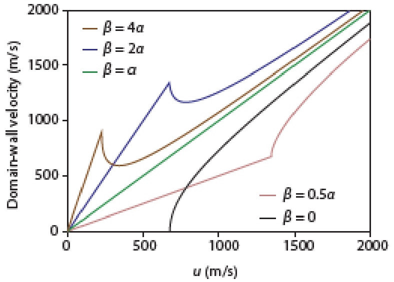
- ➢ DWs should be of **Bloch** type ($w \times t_{FM}$: $0.5\ \mu\text{m}^2 \times 0.6\ \text{nm}$).
- ➢ DWs move with **high mobility in the flow regime**.
- ➢ The **non-adiabatic STT must be very high**: ($\beta \sim 1$).
- ➢ The current ($\vec{j}_a$) must also induce a transverse effective field $\vec{H}_{FL}$.



$\vec{H}_{FL}$ supports Bloch configuration against WB

Remember that:

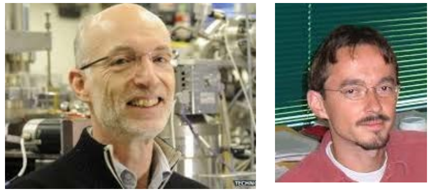
Rigid mobility: $m_R \equiv \dfrac{\beta}{\alpha}\dfrac{\mu_B P}{e\, M_s}$



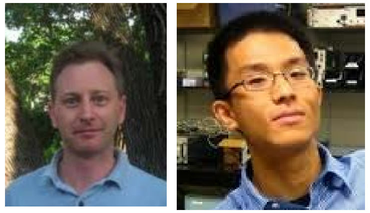
- ➢ BUT, the DWs move along the current !!!: $P < 0$ or $\beta < 0$!!!

Other people started to think about it

S. Parkin L. Thomas



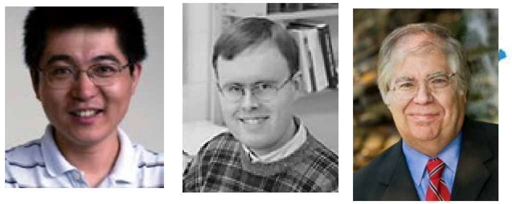
G. S. Beach S. Emori



A. Thiaville S. Rohart A. Fert

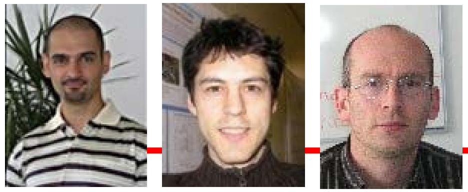
P. Haazen H. Swagten B. Koopmans

L. Liu D. C. Ralph R. A. Burhman



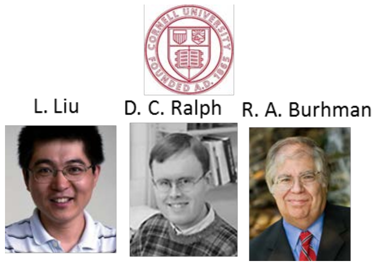
M. Hayashi J. Torrejon

M. Miron O. Boulle G. Gaudin

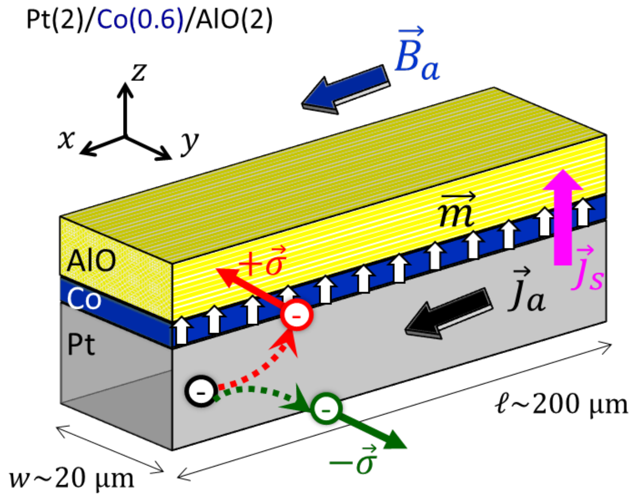


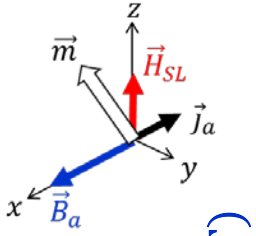
… and surely many others (sorry for the omission)

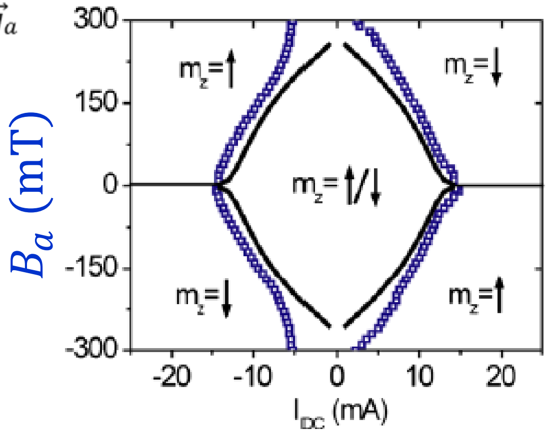
Experiment #2: current-driven switching

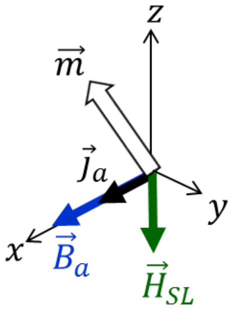


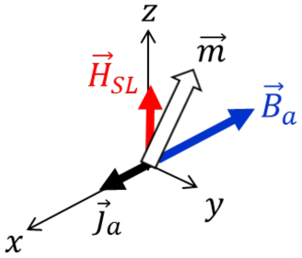
L. Liu et al. PRL. **109**, 096602 (2012)











$\vec{J}_a$: electrical current in the HM: $\vec{J}_a = J_a \vec{u}_J$ $\quad J_a \gtrless 0$

$\vec{\sigma}$: spin current polarization: $\vec{\sigma} = \vec{u}_z \times \vec{u}_J$

$\vec{J}_s$: spin polarized current: $\vec{J}_s = J_s \vec{u}_z$ $\quad J_s = \theta_{SH} J_a$ $\quad \theta_{SH} \gtrless 0$

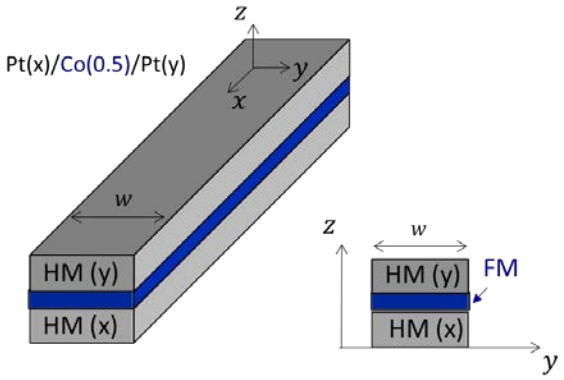
◆ SL effective field: $\vec{H}_{SL} = \dfrac{\hbar \theta_{SH} J_a}{2e\mu_0 M_s t_{FM}} (\vec{m} \times \vec{\sigma})$ $\quad (e < 0)$

$\vec{\sigma} = +\vec{u}_y$

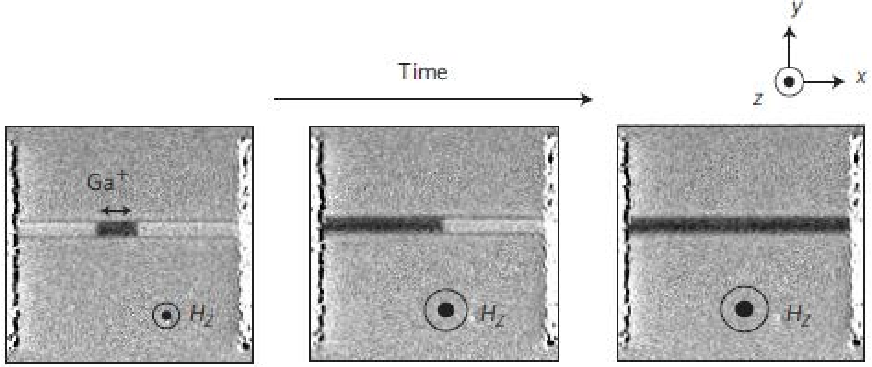
$\theta_{SH}(Pt) > 0$ $\qquad H^0_{SL}(J_a > 0) < 0$

Experiment #3

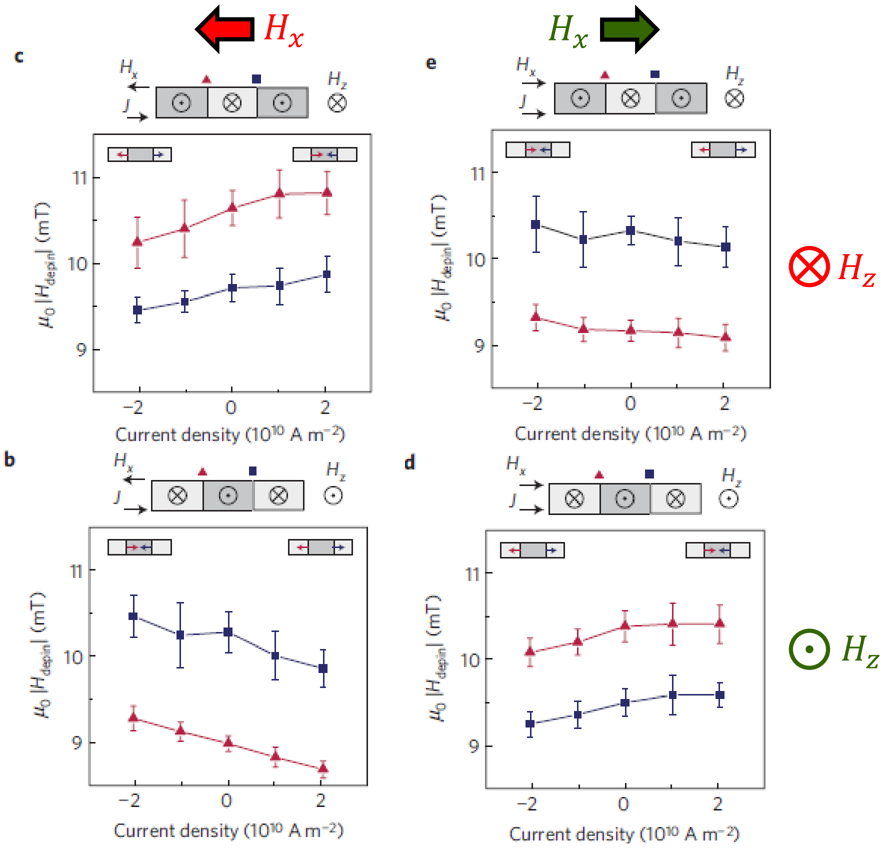
P. P. J. Haazen et al. Nat. Mat. **12**, 299 (2013)



Current-driven depinning experiments under both H_z and H_x.

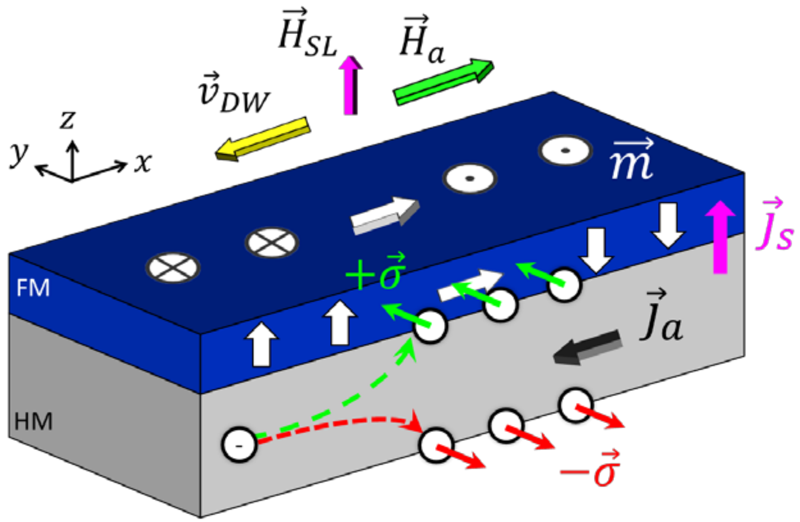


Pt(4)/Co(0.5)/Pt(2) $\mu_0 H_x = \pm 15\ \mathrm{mT}$ ⇨ j_a



Spin Hall effect (SHE) – DW motion

SL-SOT: Slonczewski-like spin-orbit torque



$\vec{J}_a$: electrical current in the HM: $\vec{J}_a = J_a \vec{u}_J$ $\quad J_a \gtrless 0$

$\vec{\sigma}$: spin current polarization: $\vec{\sigma} = \vec{u}_z \times \vec{u}_J$

$\vec{J}_s$: spin polarized current: $\vec{J}_s = J_s \vec{u}_z$ $\quad J_s = \theta_{SH} J_a$ $\quad \theta_{SH} \gtrless 0$

$$\frac{\partial \vec{m}}{\partial t} = -\gamma_0 \vec{m} \times \vec{H}_{eff} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t} + \vec{\tau}_{STT} + \vec{\tau}_{SL}$$

- SL-SOT: $\vec{\tau}_{SL} = -\gamma_0 H_{SL}^0 \vec{m} \times (\vec{m} \times \vec{\sigma})$
- SL effective field: $\vec{H}_{SL} = H_{SL}^0 (\vec{m} \times \vec{\sigma})$ $\quad H_{SL}^0 = \dfrac{\hbar \theta_{SH} J_a}{2e\mu_0 M_s t_{FM}}$ $\quad (e < 0)$

Example (HM=Pt): $\theta_{SH} > 0; \quad J_a < 0$

$\vec{m}_{DW} = +\vec{u}_x \qquad \vec{H}_{SL} \sim +\vec{u}_z$

$\vec{v}_{DW} \sim -\vec{u}_x \parallel \vec{J}_a$

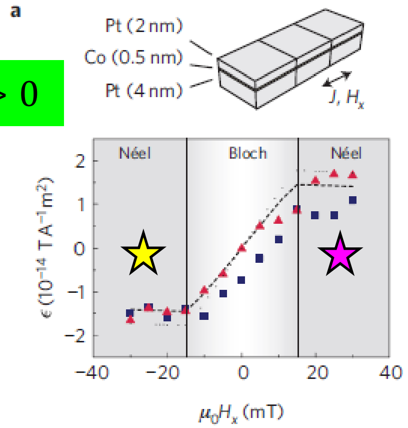
The DW moves along the current

Experiment #3: Interpretation

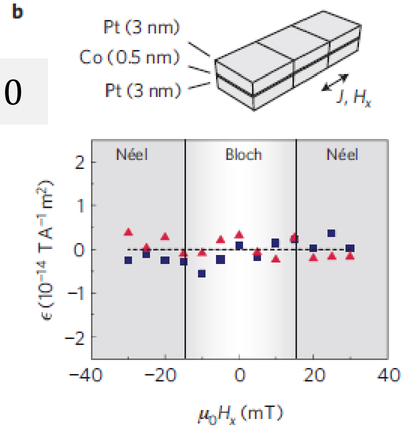
$$\epsilon \equiv \mu_0 \frac{\Delta H_d}{J_a}$$

P. P. J. Haazen et al. Nat. Mat. **12**, 299 (2013)

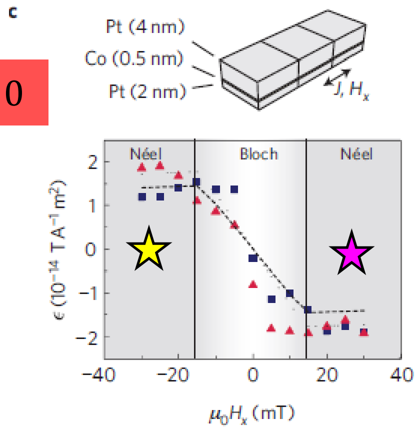
$\theta_{SH}^{net} > 0$

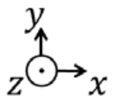


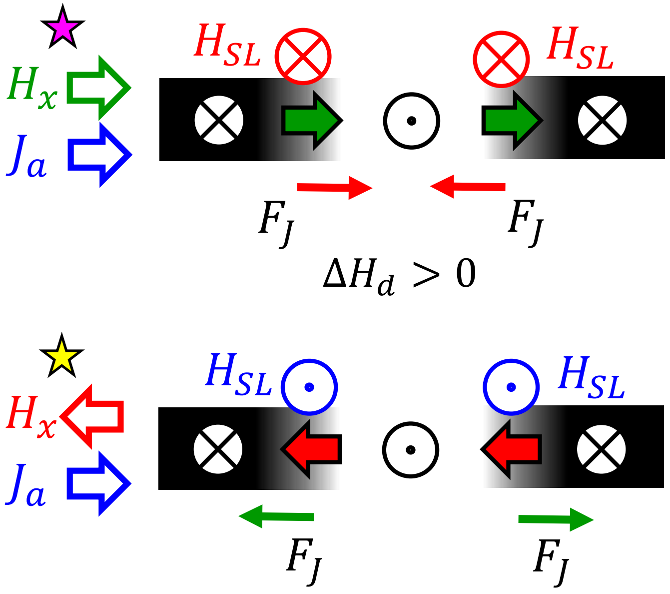
$\theta_{SH}^{net} = 0$



$\theta_{SH}^{net} < 0$

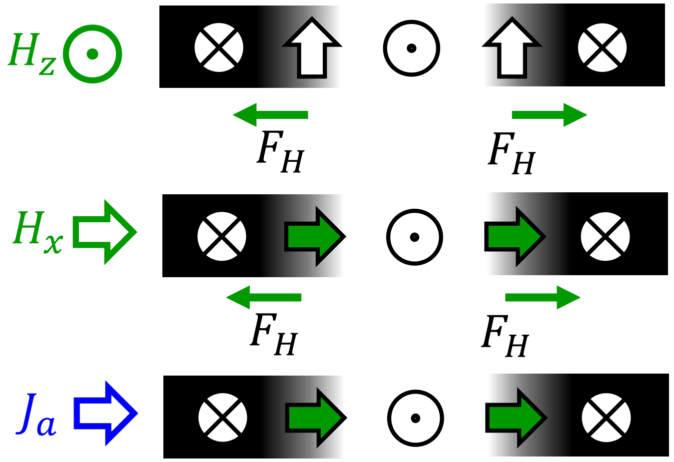




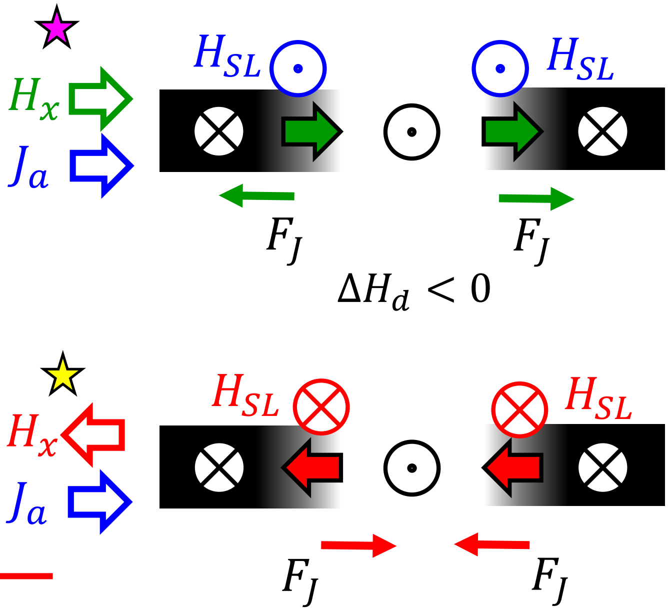


$\Delta H_d > 0$

$\Delta H_d < 0$



$F_J = 0$

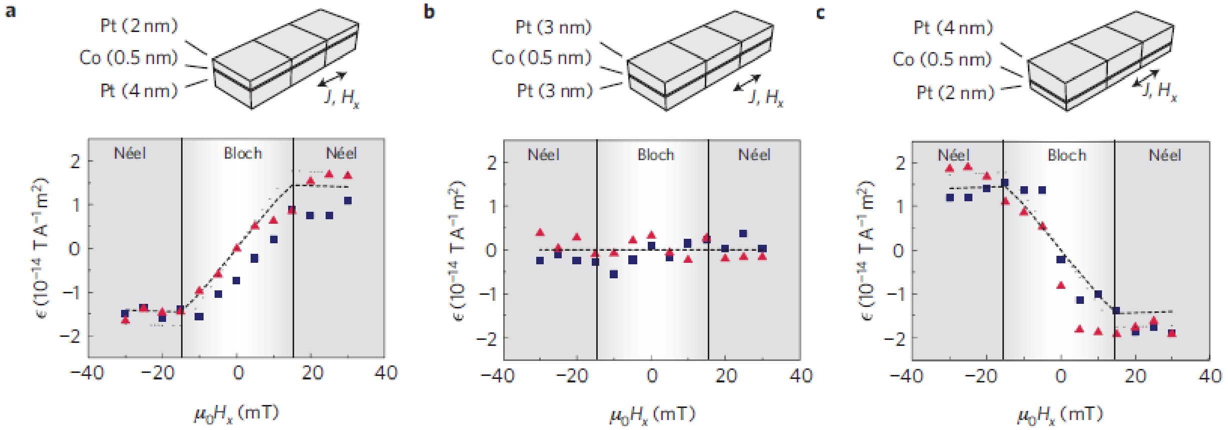


$\Delta H_d < 0$

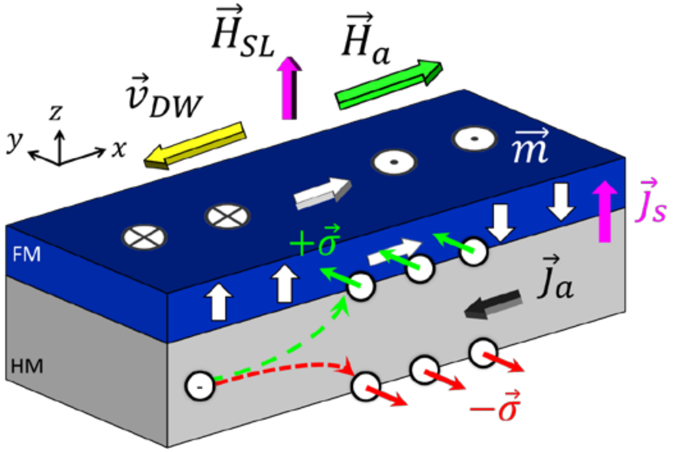
$\Delta H_d > 0$

Experiment #3: Interpretation

P. P. J. Haazen et al. Nat. Mat. **12**, 299 (2013)



Depinnig efficiency: $\epsilon \equiv \mu_0 \dfrac{\Delta H_d}{\Delta J}$



- ➢ Conventional STT is unrelevant.
- ➢ DWs are of **Bloch** type for $H_x = 0$.
- ➢ In-plane field H_x promotes Néel DWs.
- ➢ Néel DWs are driven by the **Spin Hall effect (SHE)**.
- ➢ BUT, Miron's exp. show DW motion for $H_x = 0$!!

Dzyaloshinskii-Moriya interaction (DMI)

A. Fert et al. Nat. Nano. **8**, 152 (2013)

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A. Fert

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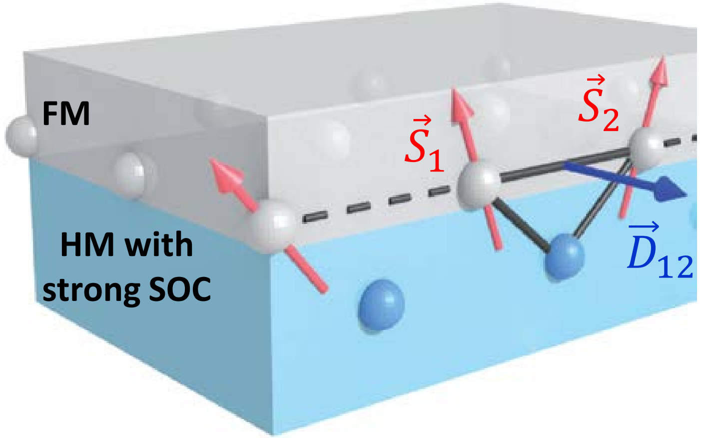
Spin-orbit interactions originating from relativistic effects that occur due to the **lack of inversion symmetry of the atomic structure**.

I. Dzyaloshinsky, J. Phys. Chem. Solids 4, 241 (1958).
T. Moriya, Phys. Rev. 120, 91 (1960).



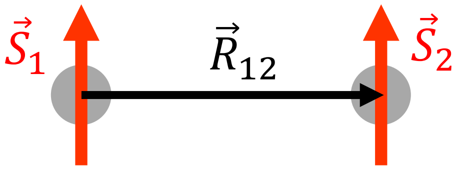
DMI hamiltonian: $\mathcal{H}_{DM} = -\vec{D}_{12}\cdot\left(\vec{S}_1 \times \vec{S}_2\right)$

3-site indirect exchange mechanism between two atomic spins $\vec{S}_1$ and $\vec{S}_2$ with a neighbouring atom with large SOC

Ferromagnetic state

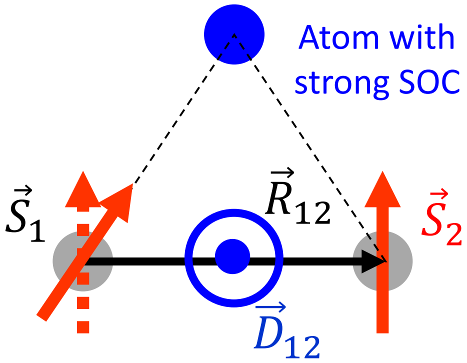
(parallel spins)

$$\mathcal{H}_{exc} = -J_{12}\,\vec{S}_1\cdot\vec{S}_2$$



Chiral magnetic state

(rotated spins)



♦ Starting from the parallel ferromagnetic state, the DMI rotates $\vec{S}_1$ with respect to $\vec{S}_2$ around $\vec{D}_{12}$.

♦ The magnitude of the interfacial DMI can be very large, ~ 10-30% of Exchange.

Theoretical prediction: continuous DMI *vs* shape Anistropy

A. Thiaville

S. Rohart

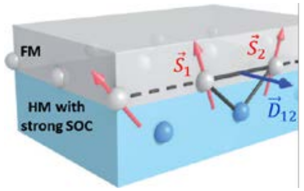
A. Fert

A. Thiaville et al. EPL. 100, 5, (2012)

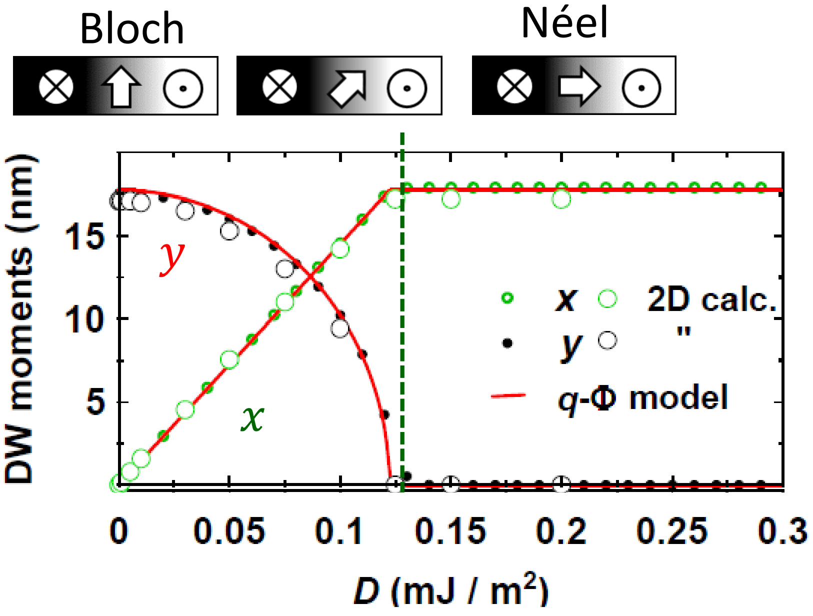
exchange anisotropy magnetostatic Zeeman

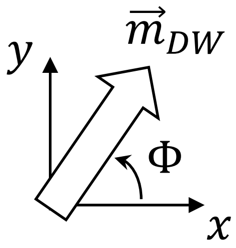
$$\varepsilon = A(\nabla\vec{m})^2 + K_u\left(1-(\vec{m}\cdot\vec{u}_k)^2\right) - \frac{1}{2}\mu_0 M_s\vec{m}\cdot\vec{H}_d - \mu_0 M_s\vec{m}\cdot\vec{H}_a$$

Intefacial Dzyaloshinskii-Moriya (DMI): $\varepsilon_{DM} = D[m_z\nabla\vec{m} - (\vec{m}\cdot\nabla)m_z]$



DW energy density (1D): $\sigma_{DW} = 2\Delta K_d\cos^2\Phi - \pi D\cos\Phi + C^{st}$





$$\Delta = \sqrt{\frac{A}{K_{eff}}}$$

DW width

$$K_{eff} = K_u - \frac{1}{2}\mu_0 M_s^2$$

Effective ⊥ anisotropy

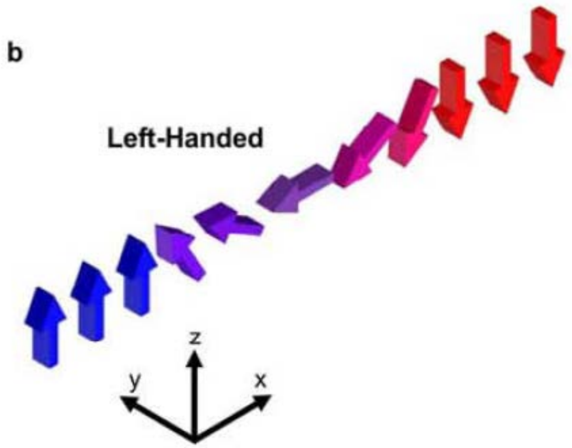
$$K_d = N_x\frac{1}{2}\mu_0 M_s^2$$

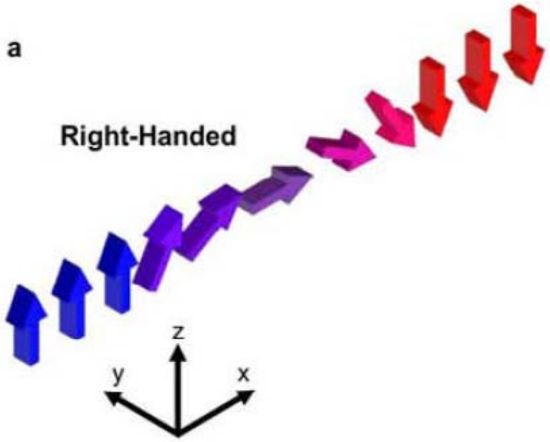
Shape anisotropy

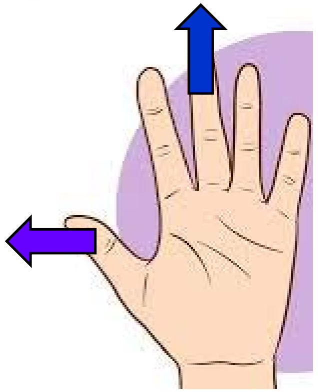
$$\cos\Phi_{\mathrm{eq}} = \begin{cases} \dfrac{\pi D}{4\Delta K_d}; & \pi|D| < 4\Delta K_d \\ sign\,(D); & \pi|D| > 4\Delta K_d \end{cases}$$

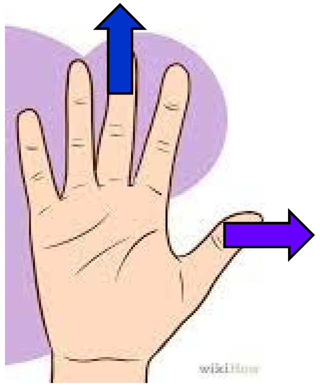
Néel DW if: $|D| > D_c = \dfrac{4\Delta K_d}{\pi}$

Chirality (imposed by the DMI)

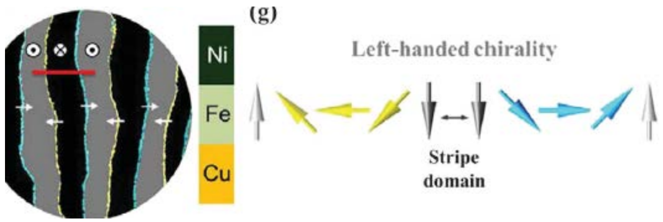


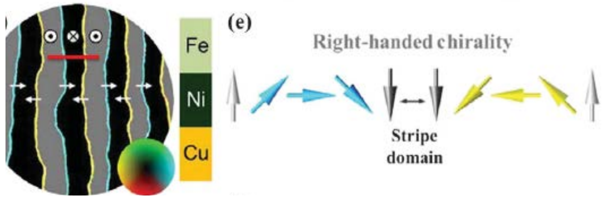






G. Chen et al. PRL, 110, 177204 (2013)



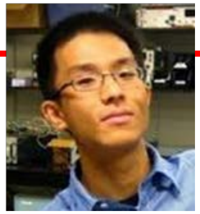


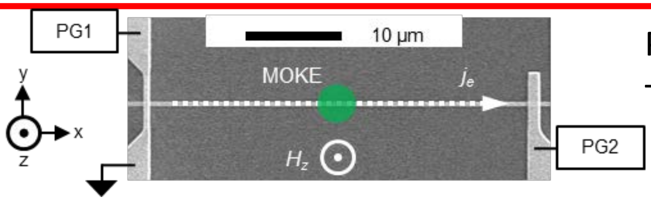
Experiments 4

S. Emori et al. Nat. Mat. **12**, 6117 (2013)
S. Emori et al. PRB **90**, 184427 (2014)

G. S. Beach

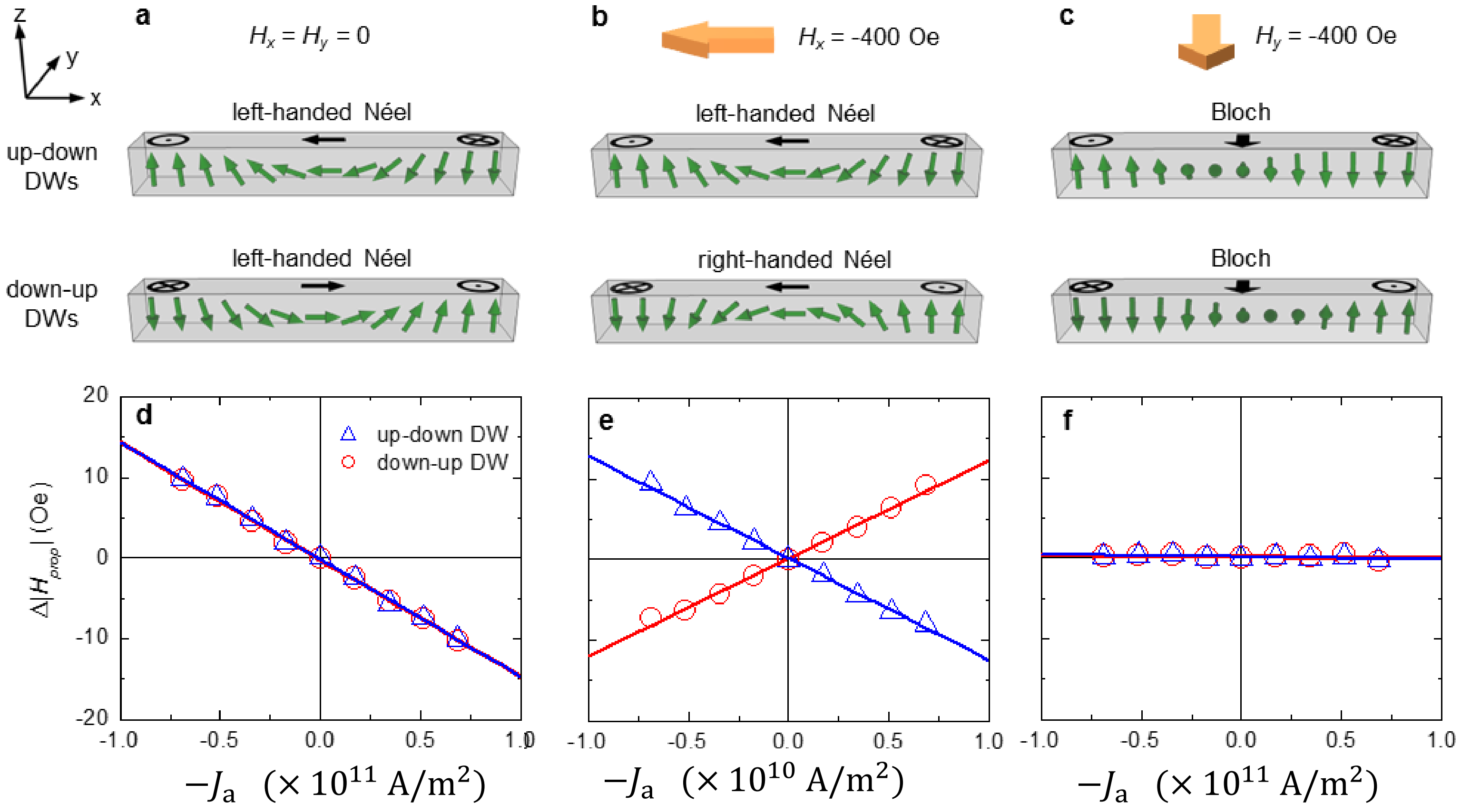
S. Emori



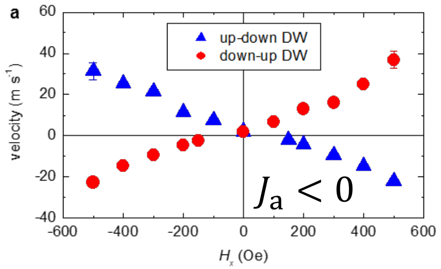


Pt(3)/CoFe(0.6)/MgO(1.8)
Ta(5)/CoFe(0.6)/MgO(1.8)

Ta(5)/CoFe(0.6)/MgO(1.8)



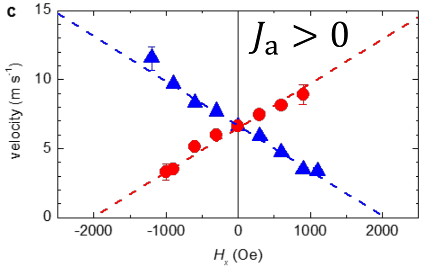
Ta(5)/CoFe(0.6)/MgO(1.8)



$$D = -0.05\ \mathrm{mJ\ m^{-2}}$$

$$\theta_{SH} = -0.11$$

Pt(3)/CoFe(0.6)/MgO(1.8)



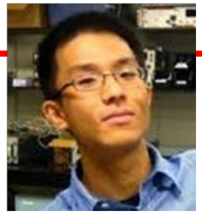
$$D = -1.2\ \mathrm{mJ\ m^{-2}}$$

$$\theta_{SH} = +0.07$$

Experiments 4 & 5

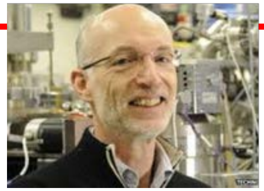
G. S. Beach

S. Emori



S. Emori et al. Nat. Mat. **12**, 6117 (2013)

S. Parkin

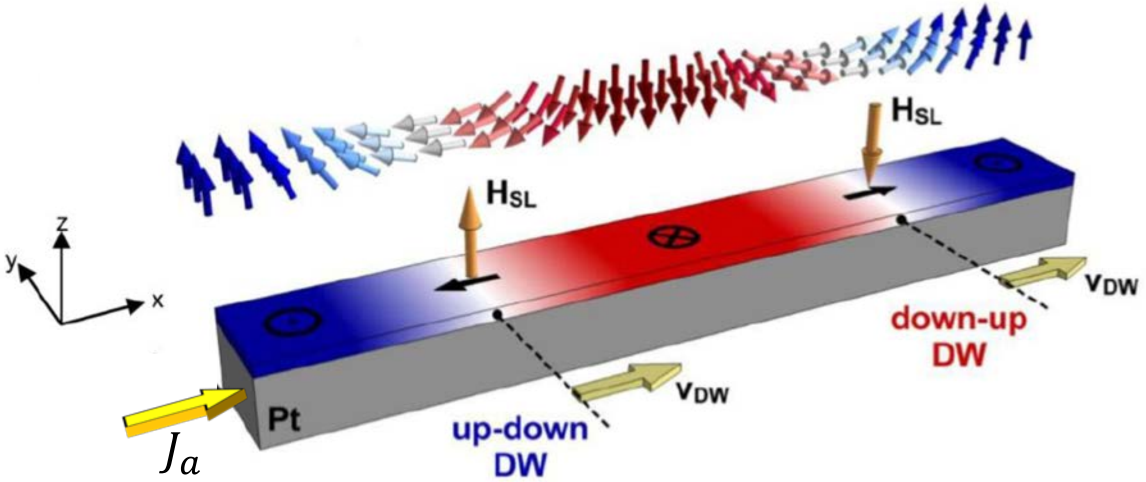


L. Thomas

K.-S. Ryu et al. Nat. Nano. **8**, 527 (2013)

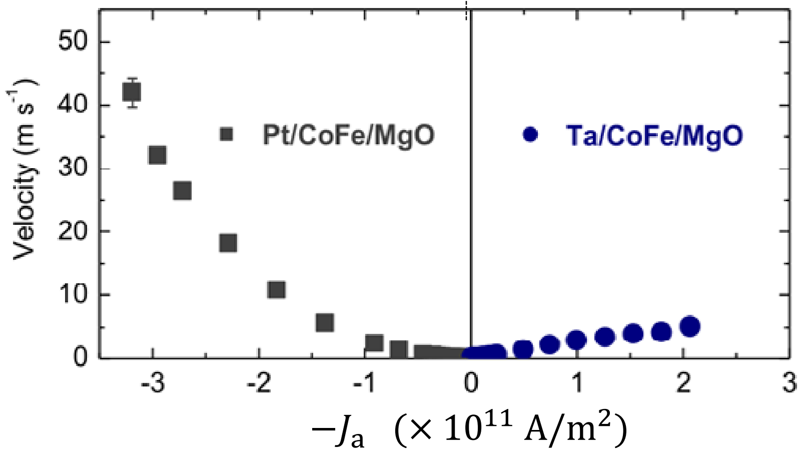
$$\vec{H}_{SL} = H_{SL}^{0}(\vec{m} \times \vec{\sigma})$$

$$H_{SL}^{0} = \frac{\hbar \theta_{SH} J_a}{2e\mu_0 M_s t_{FM}}; \quad (e < 0)$$



$\theta_{SH}(\mathrm{Pt}) = +0.06$ along J_a

$\theta_{SH}(\mathrm{Ta}) = -0.25$ against J_a



♠ **Dyzaloshkii-Moriya Interaction** (DMI): Stabilizes **chiral Néel DW**.

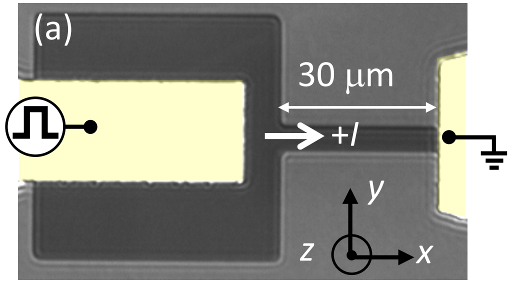
♠ **Spin Hall effect** (SHE): Drives the Néel DWM.

♠ **Left-handed chirality** for Pt/CoFe & Ta/CoFe given by the sign of DMI.

A lot of experiments have confirmed the DMI+SHE scenario

J. Torrejon et al. Nat. Comm. **5**, 4655 (2014)

W(3)/CoFeB(1)/MgO(2)

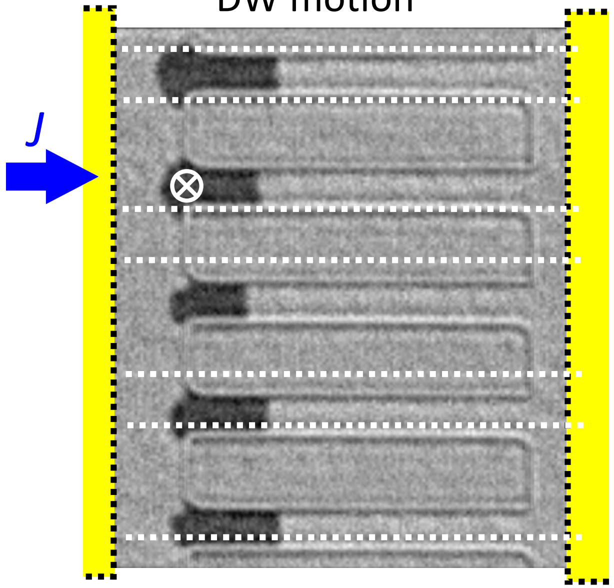


- $\theta_{SH}(\mathrm{W}) = -0.33$
- **Right-handed** chirality

$$\vec{H}_{SL} = H_{SL}^0(\vec{m} \times \vec{\sigma})$$

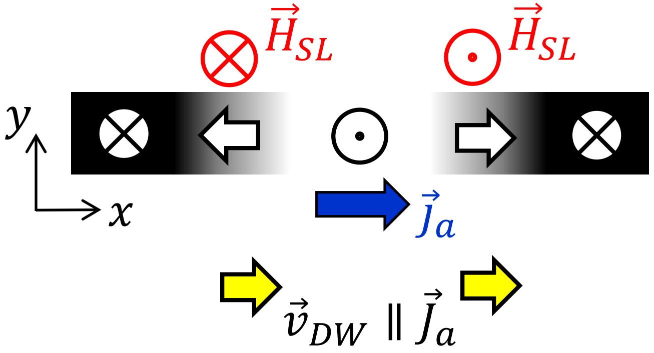
$$H_{SL}^0 = \frac{\hbar\theta_{SH}J_a}{2e\mu_0 M_s t_{FM}}; \qquad (e < 0)$$

DW motion



M. Hayashi

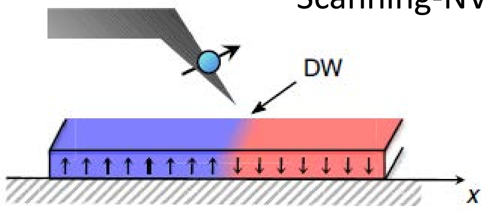
J. Torrejon

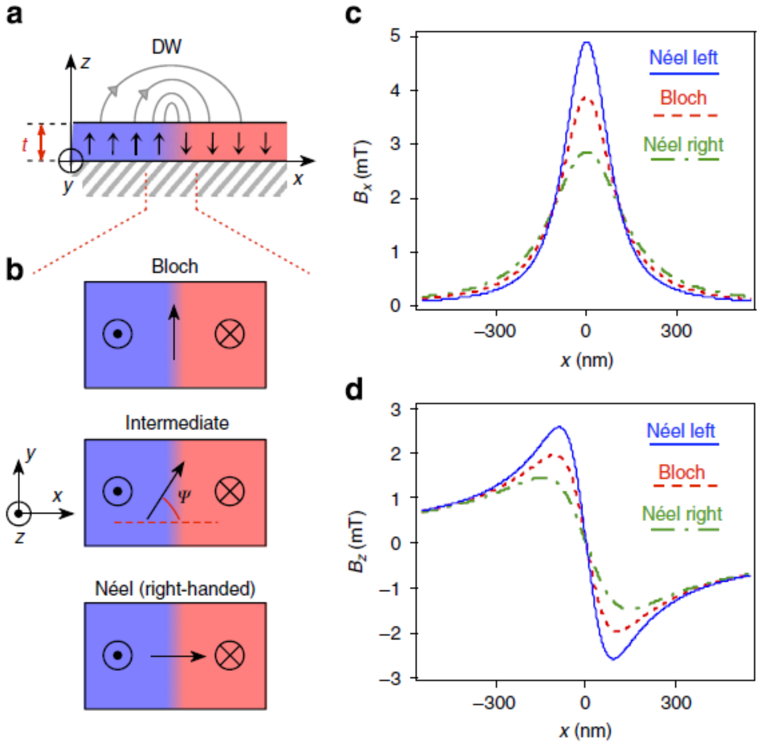


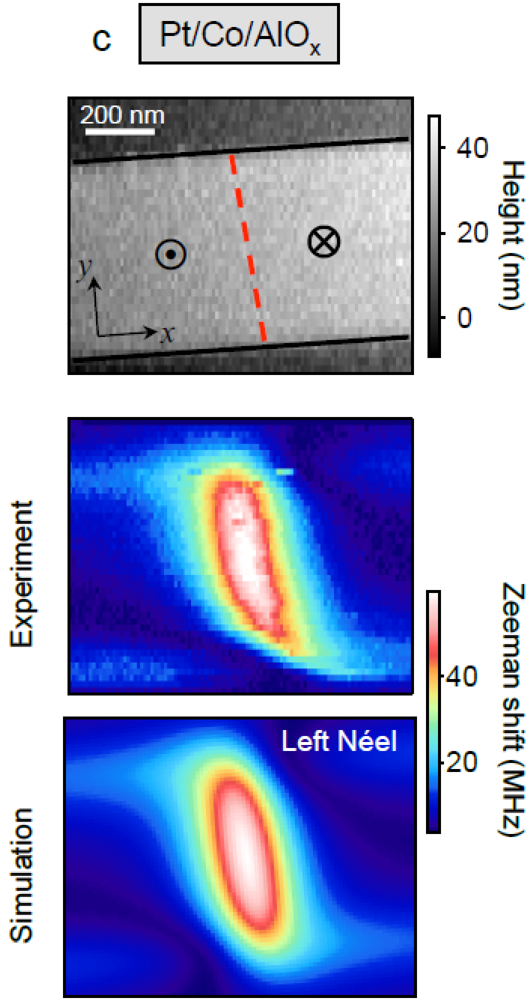
Direct evidence of Left-handed chirality in Pt/Co/AlO

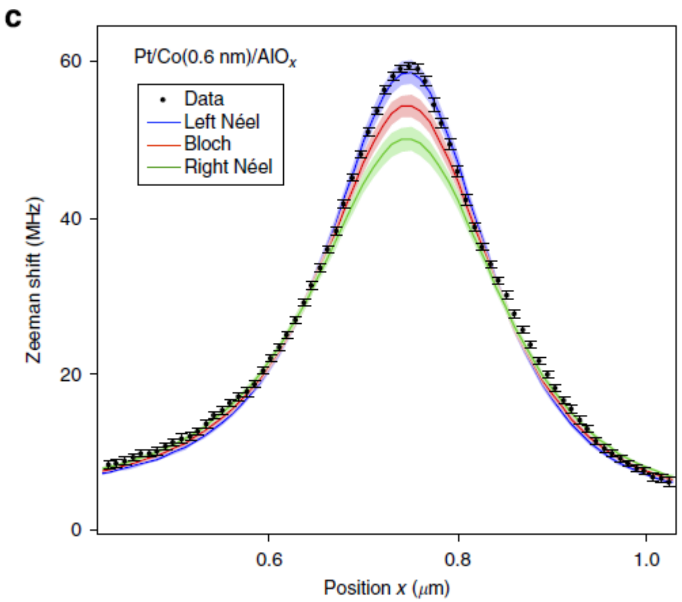
J.-P. Tetienne et al. Nat. Comm. **6**, 6733 (2015)

Scanning-NV magnetometry









Conclusions

- Chiral magnetic patterns and their current-driven dynamics are interesting for fundamental and technologycal reasons.
- Several advances in the understanding on the physics behind these systems have been achieved in the last years.
- But, surely several others are still to come...

Thanks for your attention