Skyrmion dynamics in nanostructures

Oscillators and propagation in disordered systems

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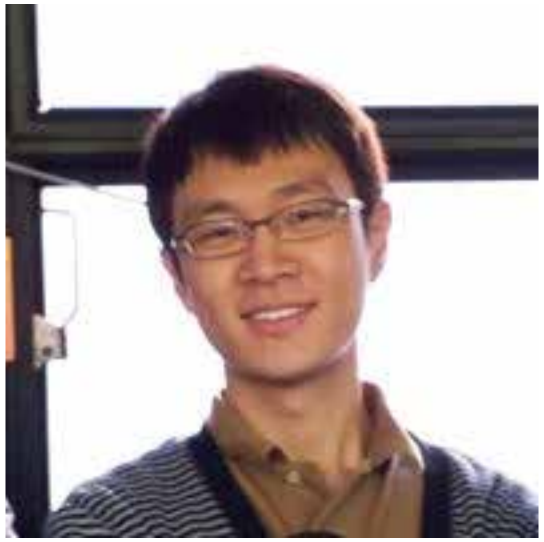
PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

MAGicSky

Funded by the Horizon2020 Framework Programme of the European Union

Acknowledgements



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Centre for Nanoscience and Nanotechnology (C2N)

Merger between the *Institut d'Electronique Fondamentale* (Orsay) and the *Laboratoire de Photonique et de Nanostructures* (Marcoussis), 1 June 2016

Saclay plateau end of 2017

- > 400 personnel, 18 000 m^2 with 2 800 m^2 of clean room
- Photonics | Materials | Nanoelectronics | Microsystems & Nanobiofluidics

« Mariage pluvieux, mariage heureux ? »

The Orsay campus on 1 June 2016 …

Emmanuelle Louis
@E_LouisUPSud

Inondations campus d'Orsay - vallée @u_psud -

RETWEETS 15
LIKES 4

9:13 AM - 1 Jun 2016

The new building at
the start of 2017 …

Outline

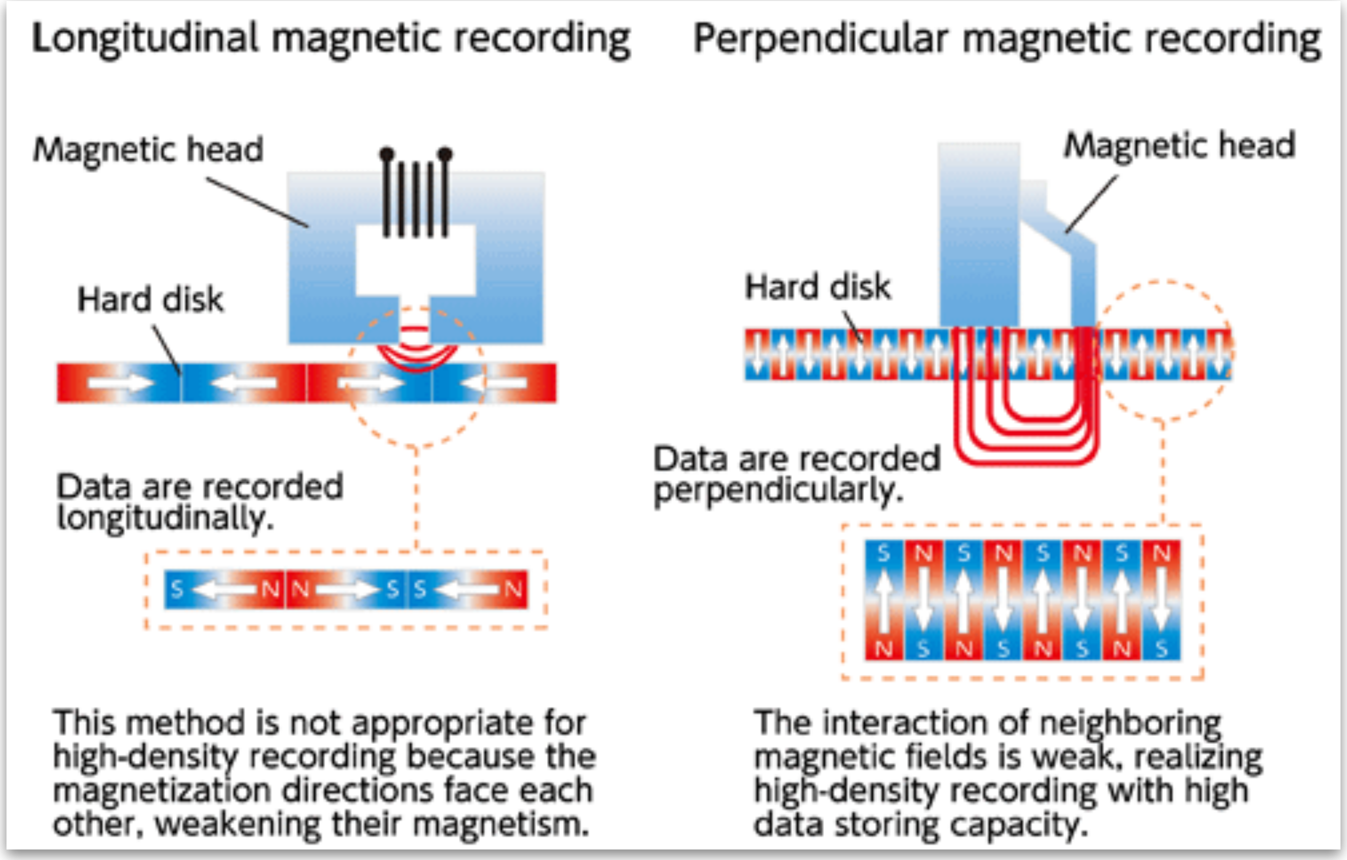
- Brief overview of skyrmions in ultrathin ferromagnets
- Skyrmion oscillators
- Current-driven motion in disordered systems
- Summary and outlook

Ultrathin metallic ferromagnets

- Ultrathin metallic ferromagnets, such as Co and its alloys, are interesting for spintronics applications
  - Strong ferromagnet, even above room temperature
  - Strong perpendicular magnetic anisotropy (PMA)

Narrower domain walls = higher information storage density

Larger energy barriers = higher thermal stability

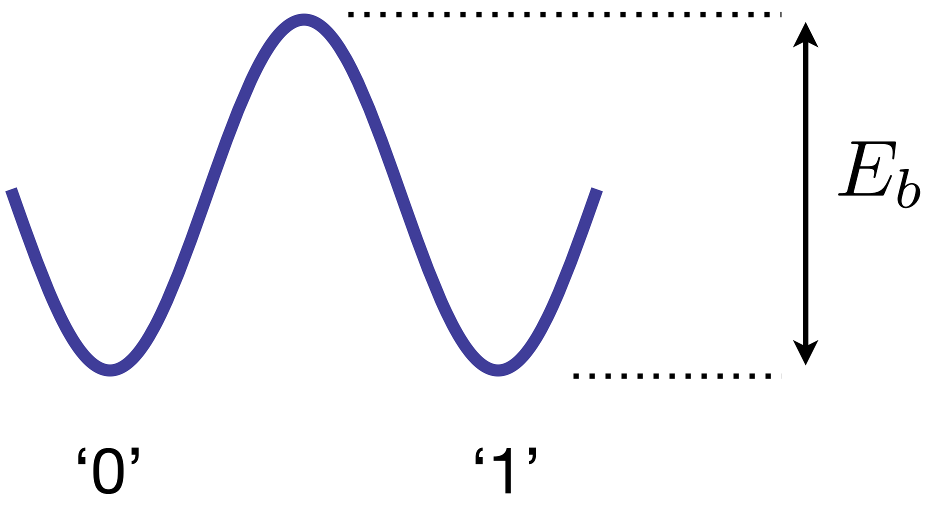


Data are recorded longitudinally.

Data are recorded perpendicularly.

This method is not appropriate for high-density recording because the magnetization directions face each other, weakening their magnetism.

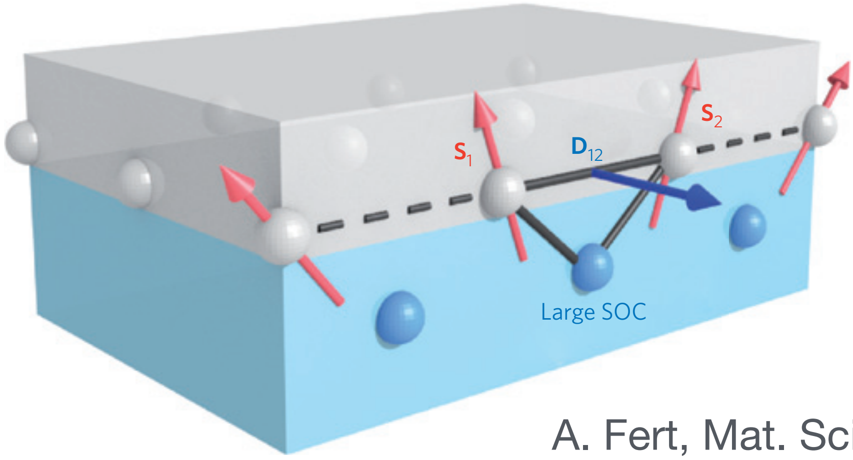
The interaction of neighboring magnetic fields is weak, realizing high-density recording with high data storing capacity.



Interface-driven chiral interactions

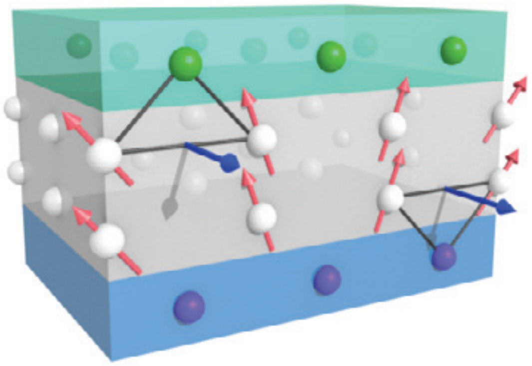
- Strong spin-orbit coupling at interfaces induces chiral (Dzyaloshinkii-Moriya) interactions

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



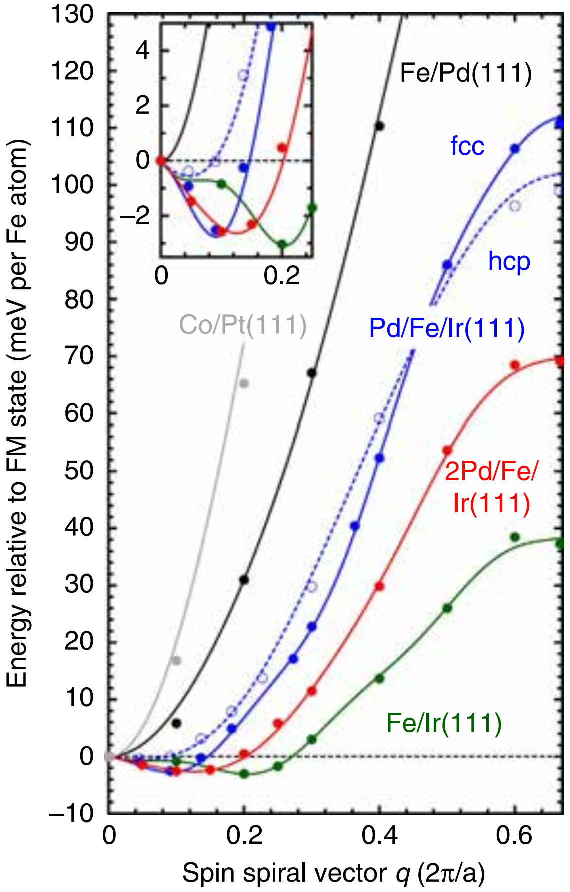
A. Fert, Mat. Sci. Forum (1990)
A. Fert and P. M. Levy, PRL (1980)

- DMI can be tailored through choice of multilayer configuration and materials



Pt/Co/Ir …

C. Moreau-Luchaire *et al*.,
Nat. Nanotechnol. (2016)



B. Dupé *et al*.,
Nat. Commun. (2014)

Chiral magnetic states in ultrathin ferromagnets

nature physics | ARTICLES

PUBLISHED ONLINE: 31 JULY 2011 | DOI: 10.1038/NPHYS2045

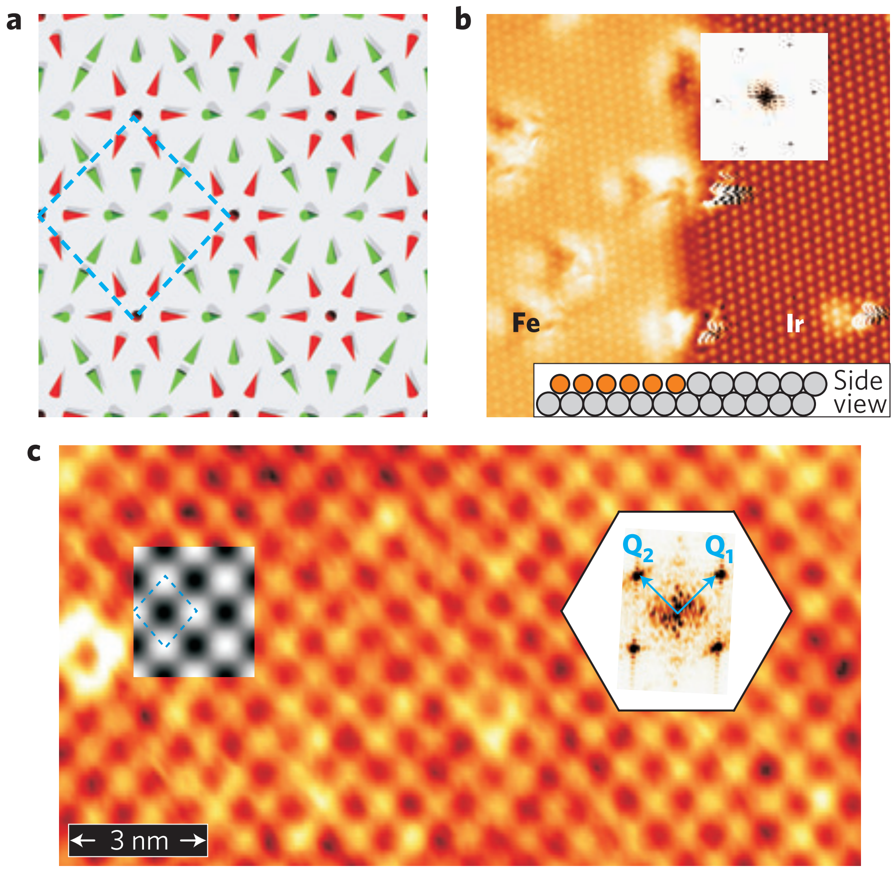
Spontaneous atomic-scale magnetic skyrmion lattice in two dimensions

Stefan Heinze[1*†], Kirsten von Bergmann[2*†], Matthias Menzel[2†], Jens Brede[2], André Kubetzka[2], Roland Wiesendanger[2], Gustav Bihlmayer[3†] and Stefan Blügel[3]

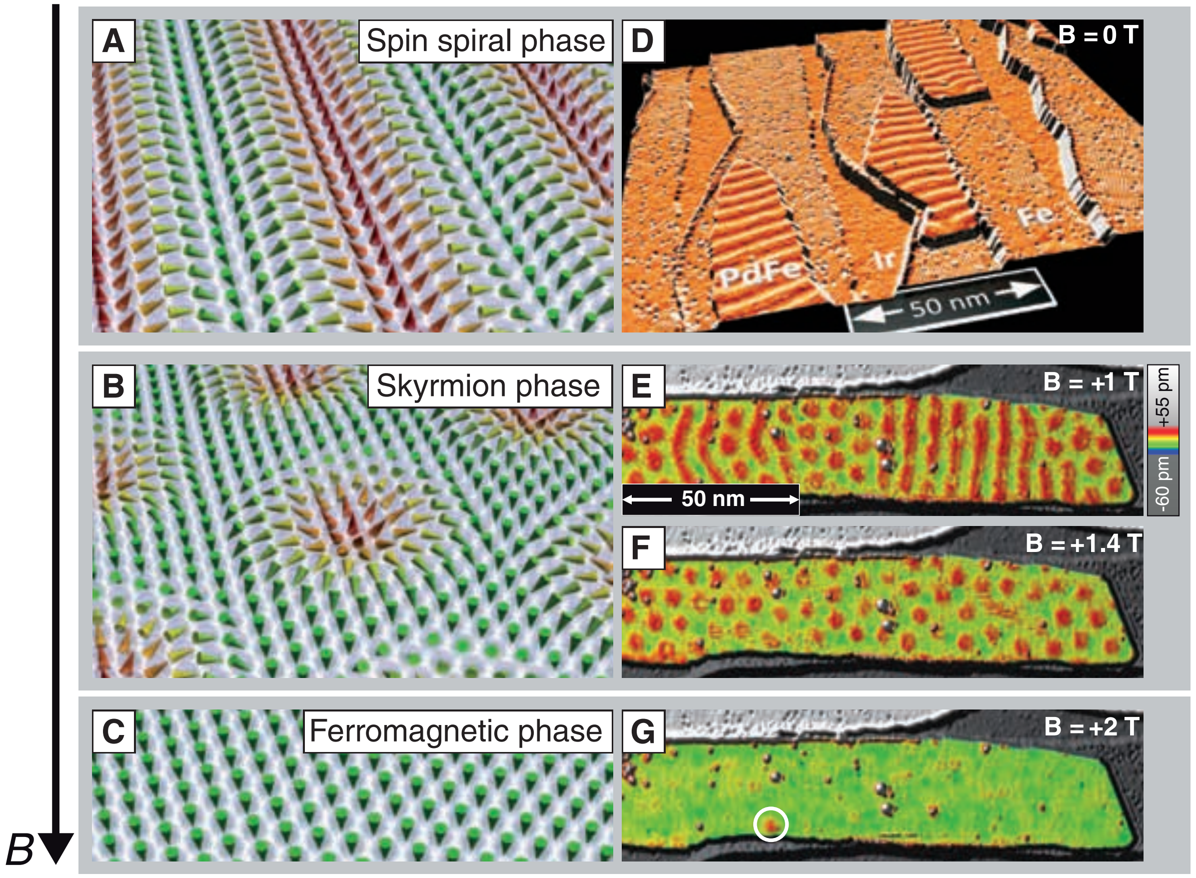
636 9 AUGUST 2013 VOL 341 **SCIENCE**

Writing and Deleting Single Magnetic Skyrmions

Niklas Romming, Christian Hanneken, Matthias Menzel, Jessica E. Bickel,* Boris Wolter, Kirsten von Bergmann,† André Kubetzka,† Roland Wiesendanger



Nano-skyrmion lattice in monolayer Fe/Ir(111)

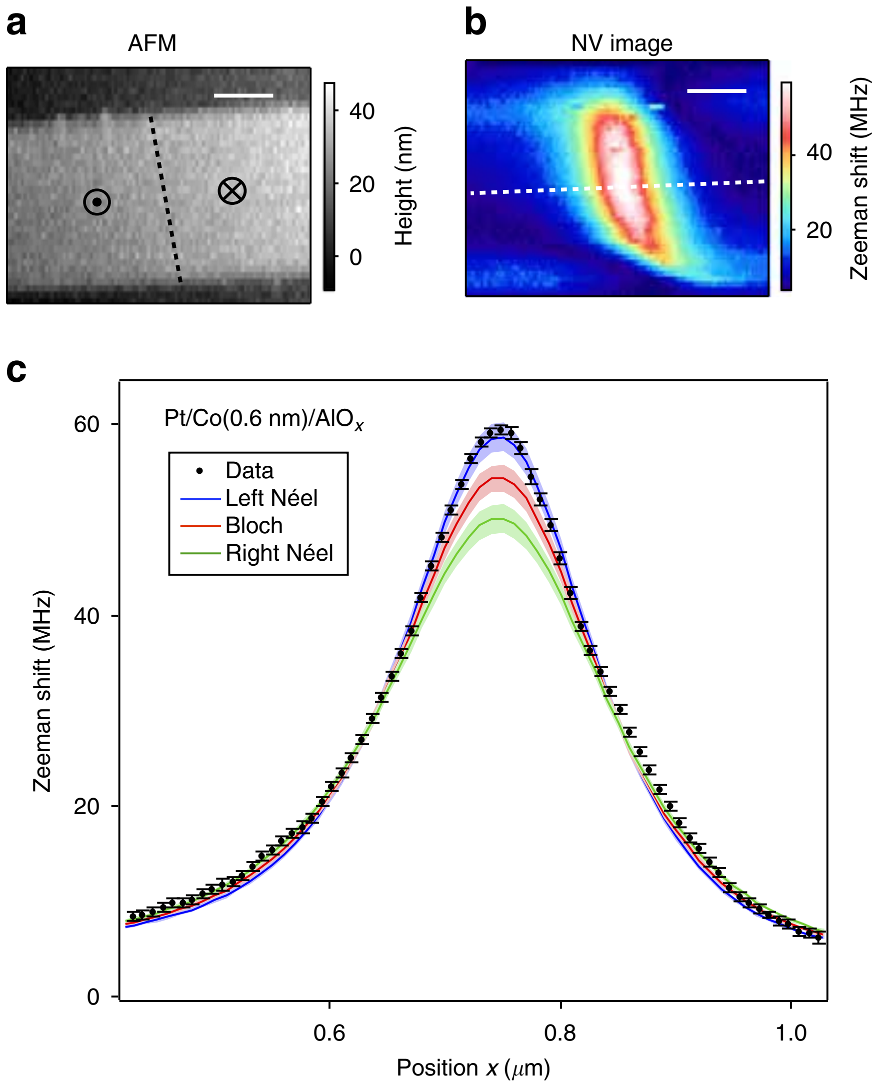


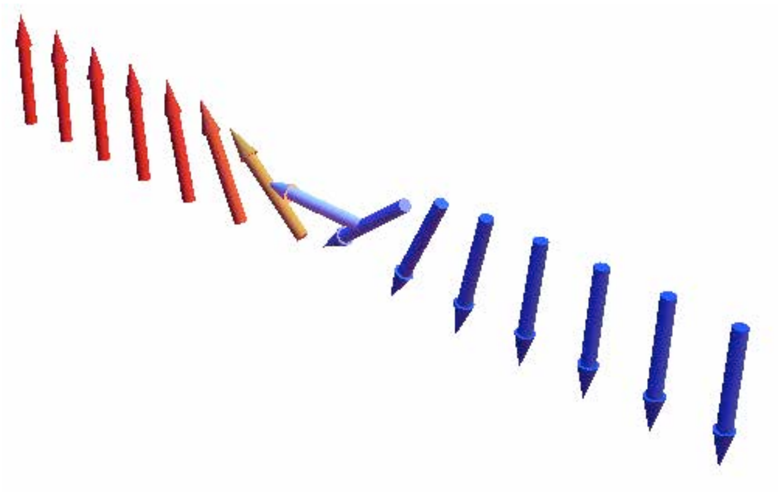
Pd/Fe/Ir(111)

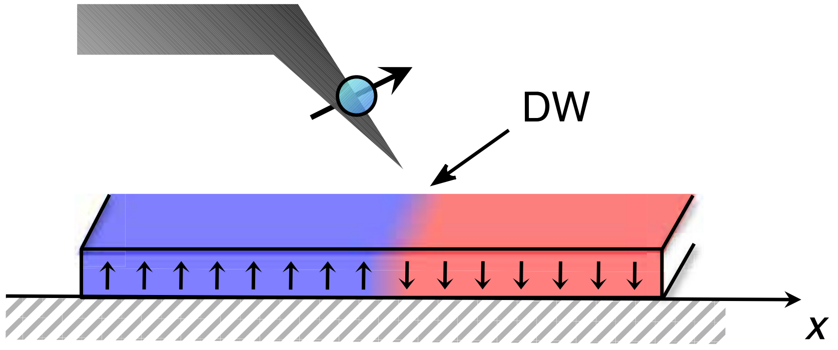
Chiral magnetic states in ultrathin ferromagnets

- Perpendicular anisotropy systems with interfacial DMI can support **Néel domain walls and skyrmions**

Néel walls in Pt/Co (0.6 nm)/AlOx

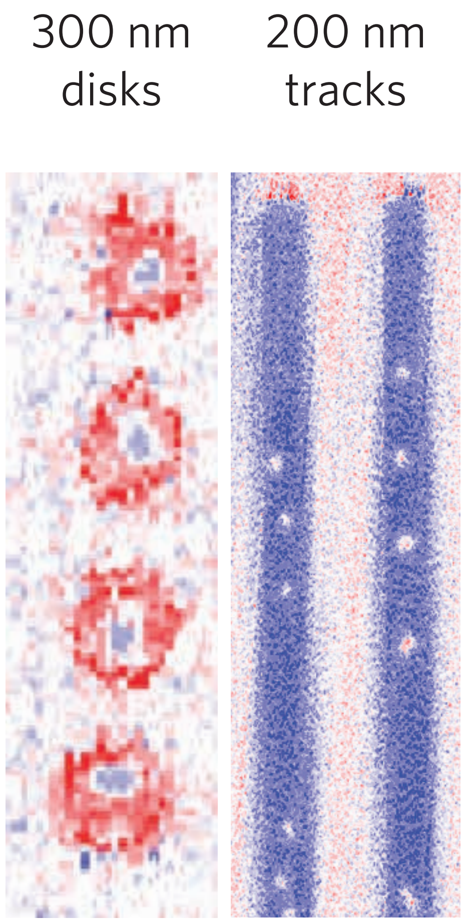






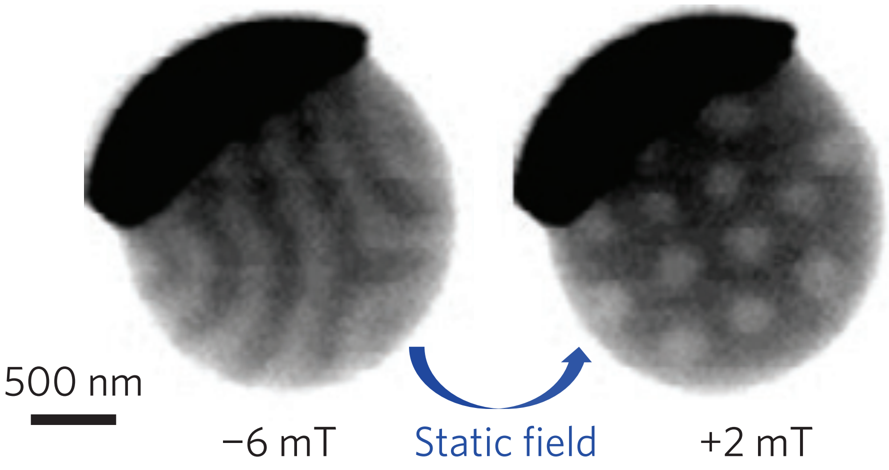
J.-P. Tétienne *et al.*, Nat. Commun. (2015)

Skyrmions in [Ir/Co (0.6 nm)/Pt]$_n$



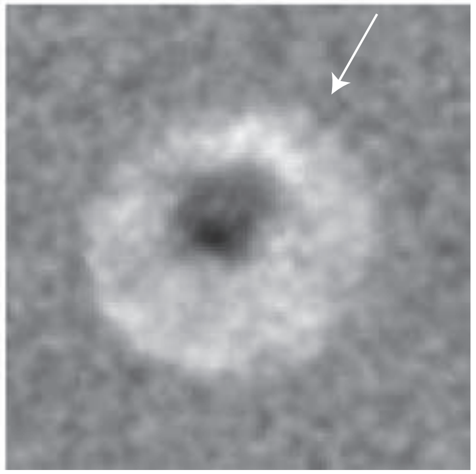
C. Moreau-Luchaire *et al*., Nat. Nanotechnol. (2016)

Skyrmions in Pt/Co (0.9 nm)/Ta



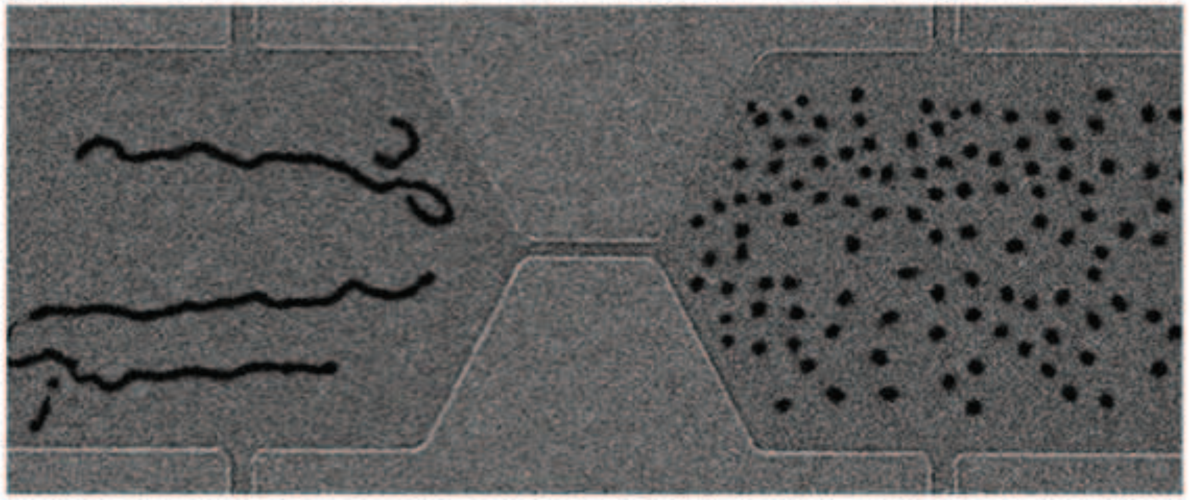
S. Woo *et al*., Nat. Mater. (2016)

Skyrmions in Pt/Co (1 nm)/MgO



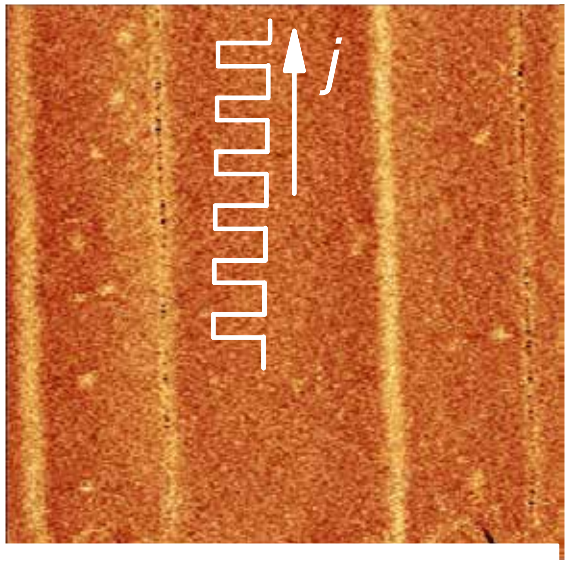
O. Boulle *et al*., Nat. Mater. (2016)

Skyrmionic bubbles in Ta/CoFeB (1.1 nm)/TaOx



W. Jiang *et al*., Science (2015)

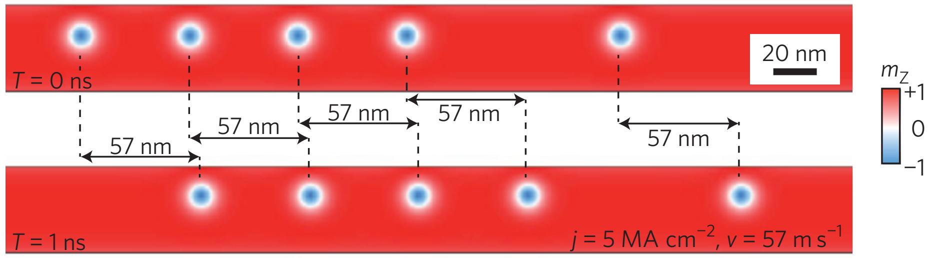
Skyrmions in Pt/(Ni/Co/Ni)/Au/(Ni/Co/Ni)/Pt



A. Hrabec *et al*., arXiv:1611.00647

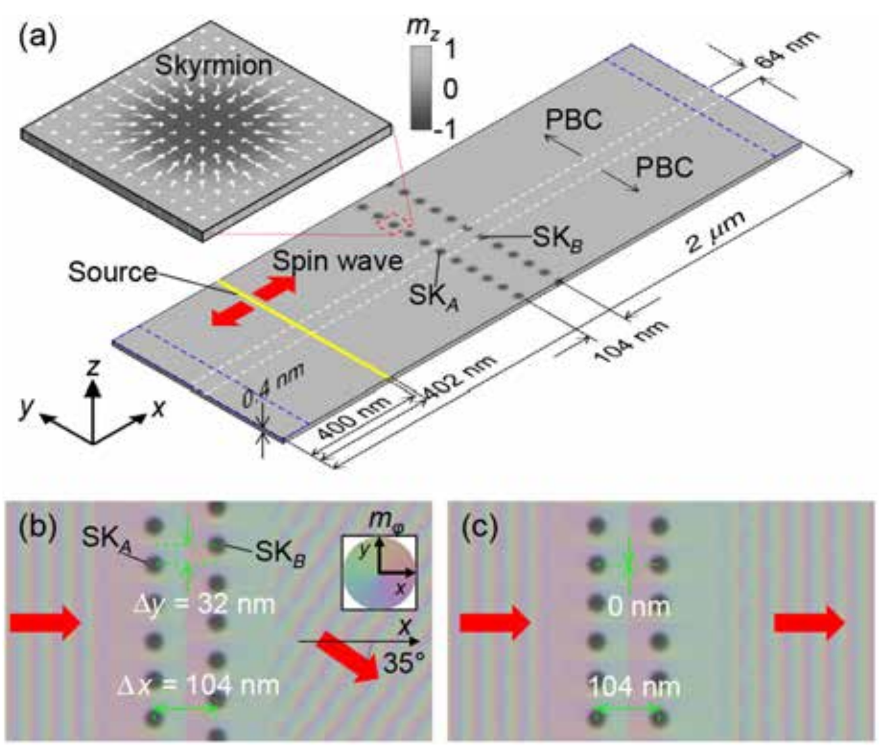
Potential applications of skyrmions

Racetrack memory



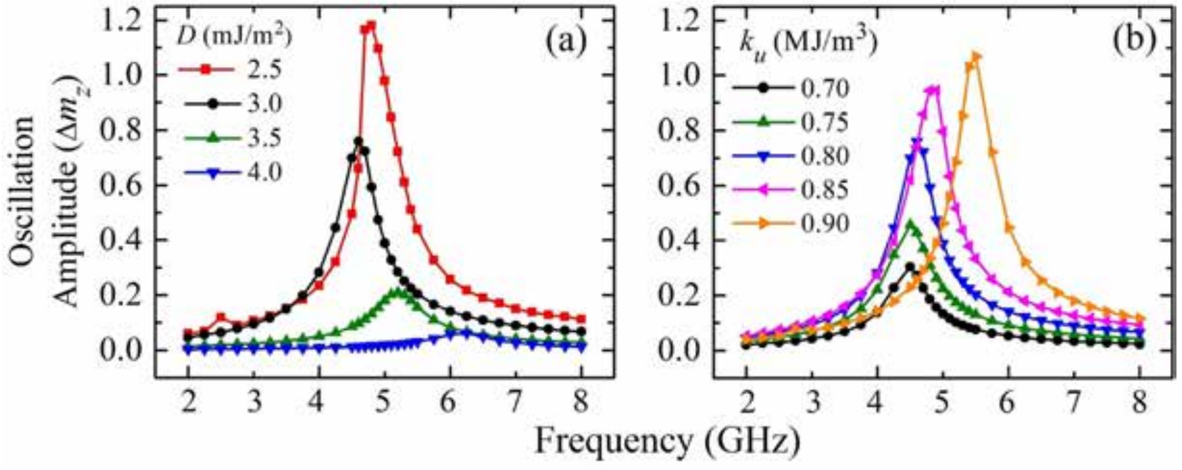
J. Sampaio *et al*., Nat. Nanotechnol. (2013)

Spin wave refraction



K.-W. Moon *et al*., Phys. Rev. Applied (2016)

Microwave detection and energy harvesting



G. Finocchio *et al*., Appl. Phys. Lett. (2015)

Oscillators, logic gates, …

Exploit linear and/or gyrotropic motion in one way or another

Outline

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- Skyrmion oscillators
- Current-driven motion in disordered systems
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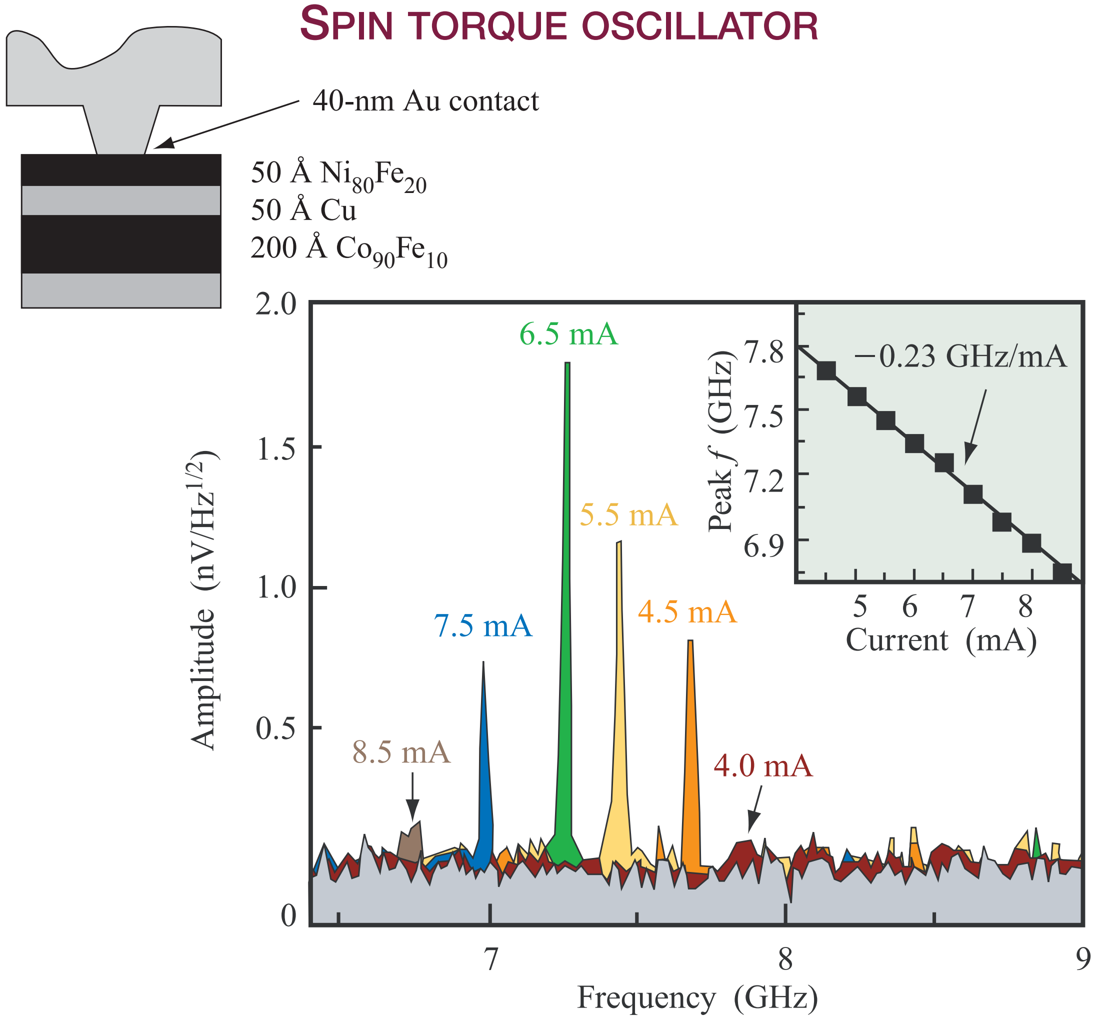
Spin-torque nano-oscillators (STNO)

Current-induced spin torques allow for nonlinear dynamical phenomena not accessible with magnetic fields alone

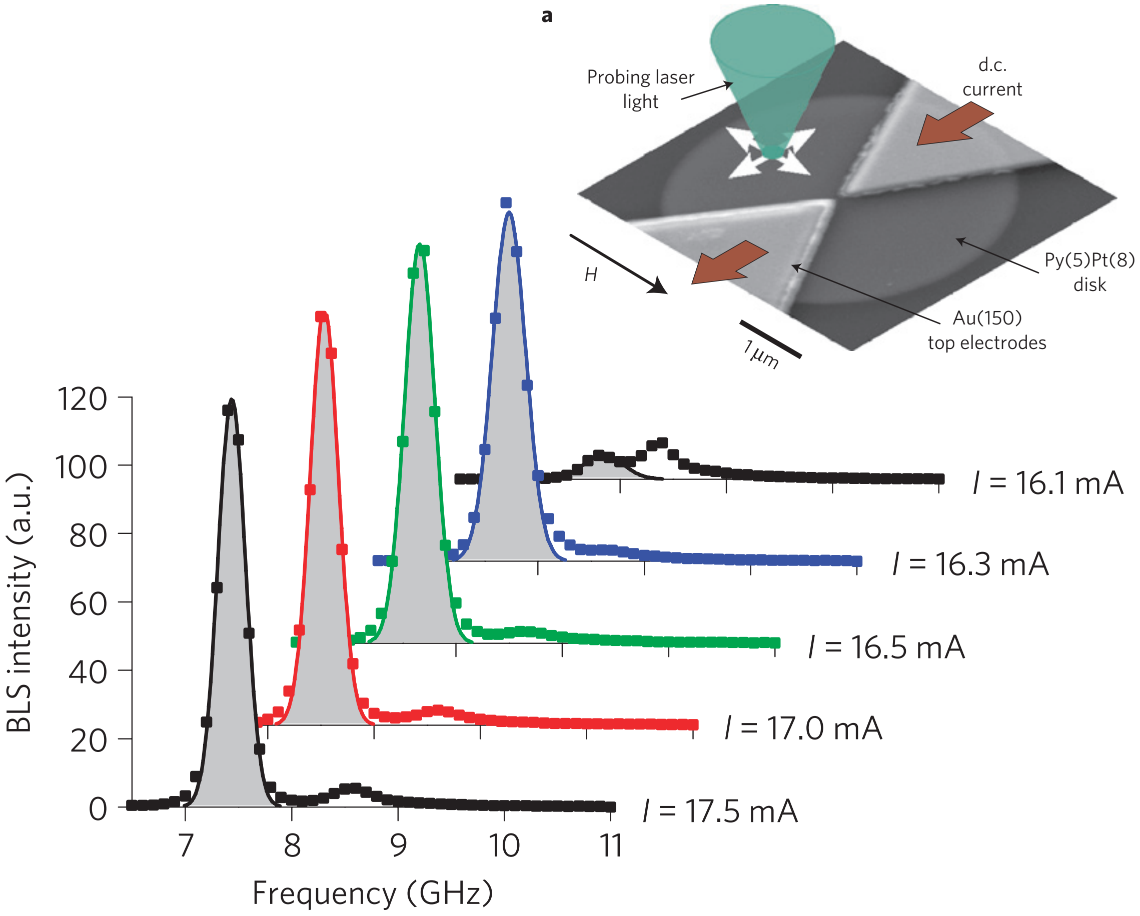
Example: *self-sustained magnetization oscillations*

SPIN TORQUE OSCILLATOR



W. Rippard *et al*., Phys. Rev. Lett. (2004)

SPIN HALL OSCILLATOR

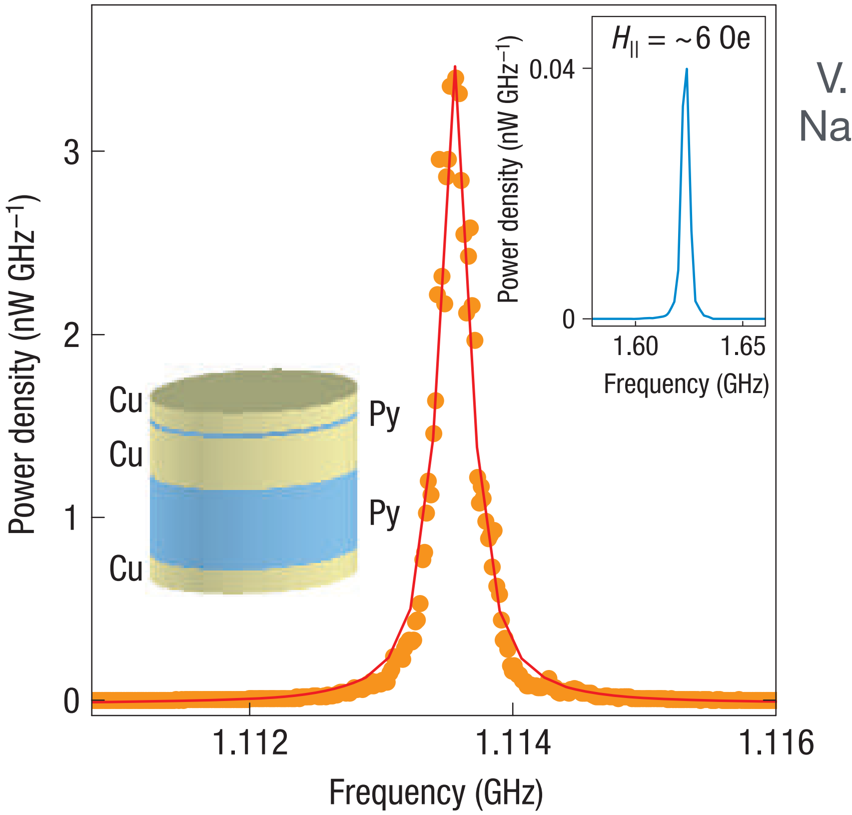


V. Demidov *et al*., Nat. Mater. (2011)

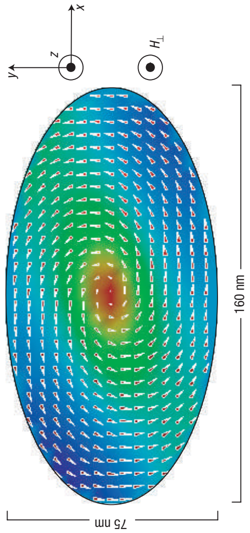
Vortex-based STNOs

In STNOs based on solitons such as vortices, the magnetostatic or Zeeman energy defines a *confinement* potential, i.e. gyration/oscillation frequencies.

NANOPILLARS: MAGNETOSTATICS



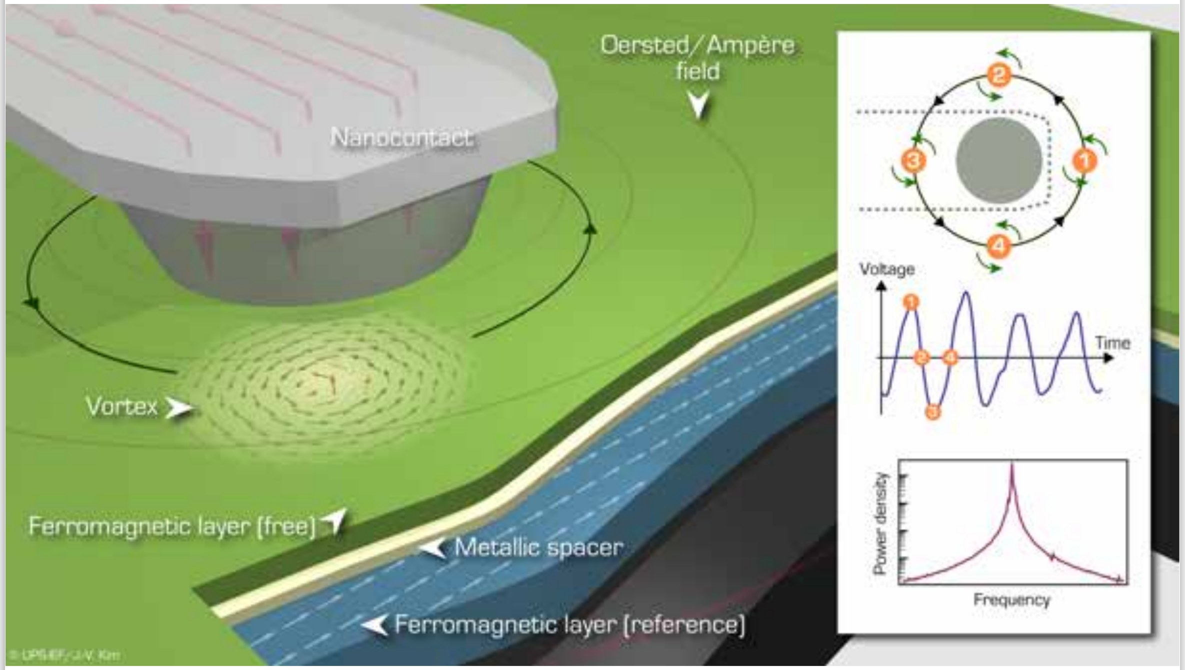
V. Pribiag *et al.*, Nat. Phys. (2007)



$$U(\|\vec{X}\|) = \frac{1}{2}\kappa\|\vec{X}\|^2 + \dots$$

B. Ivanov & C. E. Zaspel, Phys. Rev. Lett. (2007)

NANOCONTACTS: OERSTED FIELDS



$$U(\|\vec{X}\|) = \kappa\|\vec{X}\| + \dots$$

Q. Mistral, JVK *et al.*, Phys. Rev. Lett. (2008)

Thiele equation

- Magnetization dynamics governed by Landau-Lifshitz equation

$$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m} \times \mathbf{H}_{\mathrm{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} + \mathbf{\Gamma}_{\mathrm{ST}}$$

Precession **Damping** **Spin torques**

- By assuming profile for vortex/skyrmion core, can integrate out degrees of freedom and describe dynamics in terms of core position

$$\mathbf{G} \times \dot{\mathbf{X}}_0 + \alpha \cancel{D \mathbf{X}_0} = -\frac{\partial U}{\partial \mathbf{X}_0} + \cancel{\mathbf{F}_{\mathrm{ST}}}$$

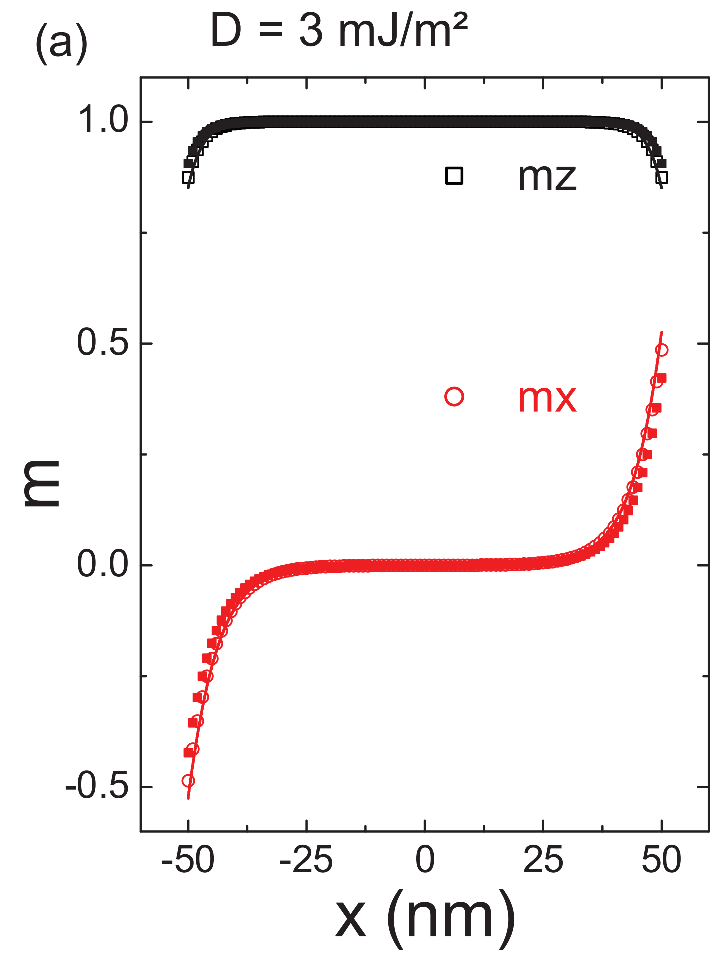
Gyrotropic **Damping** **Potential force** **Spin torques**

- When spin torques compensate damping, self-sustained gyration occurs → *spin-torque oscillator*

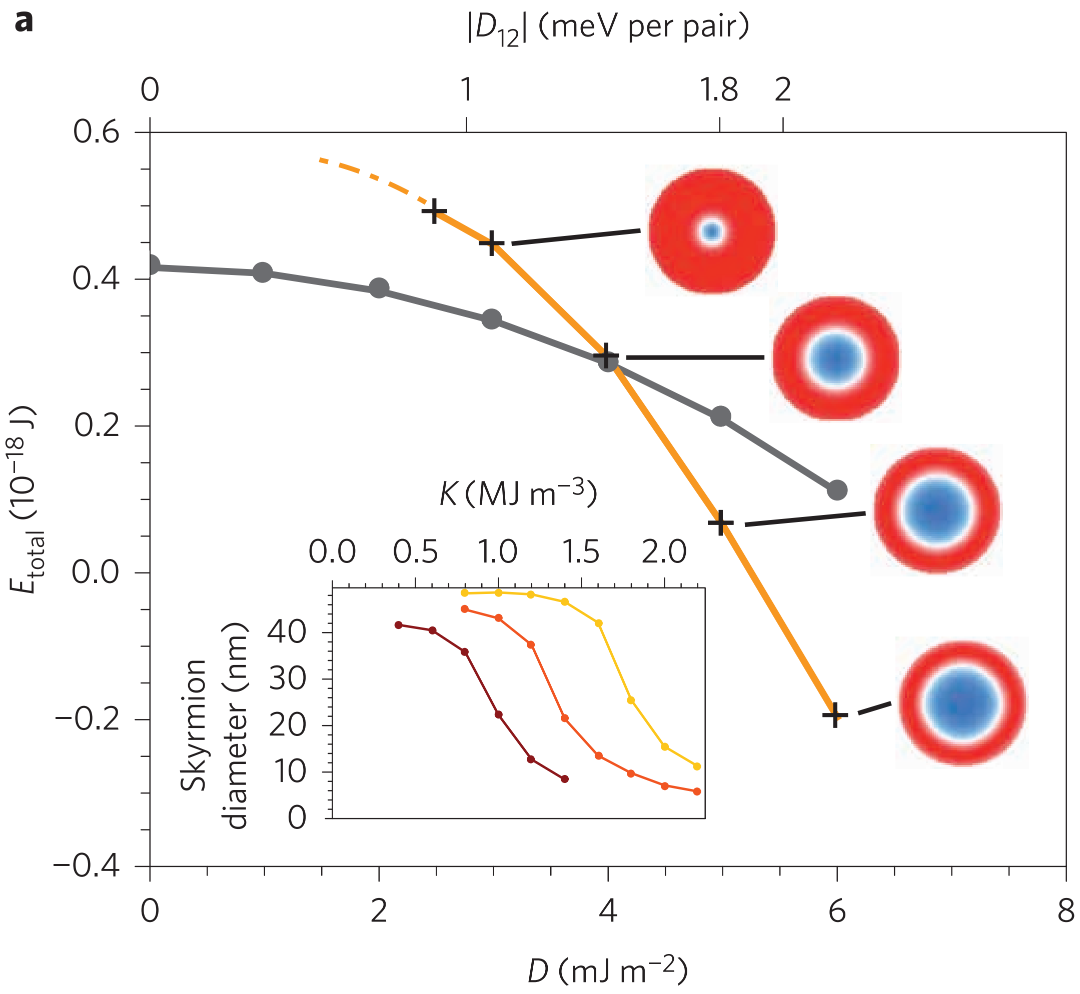
Skyrmion oscillators?

Is there a confinement potential for skyrmions?

Yes! Boundaries provide natural confinement due to repulsion with *partial walls* at edges.



S. Rohart & A. Thiaville, Phys. Rev. B (2013)

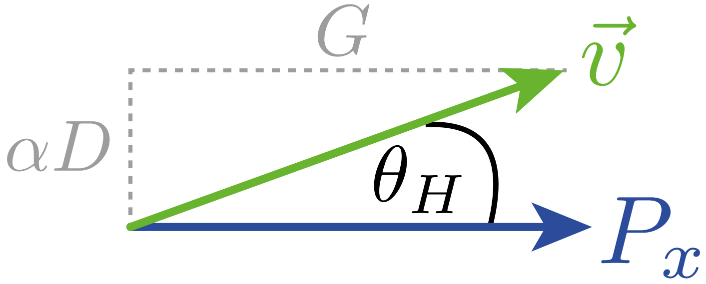


A. Fert *et al.*, Nat. Nanotech. (2013)
J. Sampaio *et al.*, Nat. Nanotech. (2013)

CPP torques with inhomogeneous polarizer

- Under CPP Slonczewski torques (~ SHE), skyrmion motion is not collinear with spin polarization vector *P*

e.g.

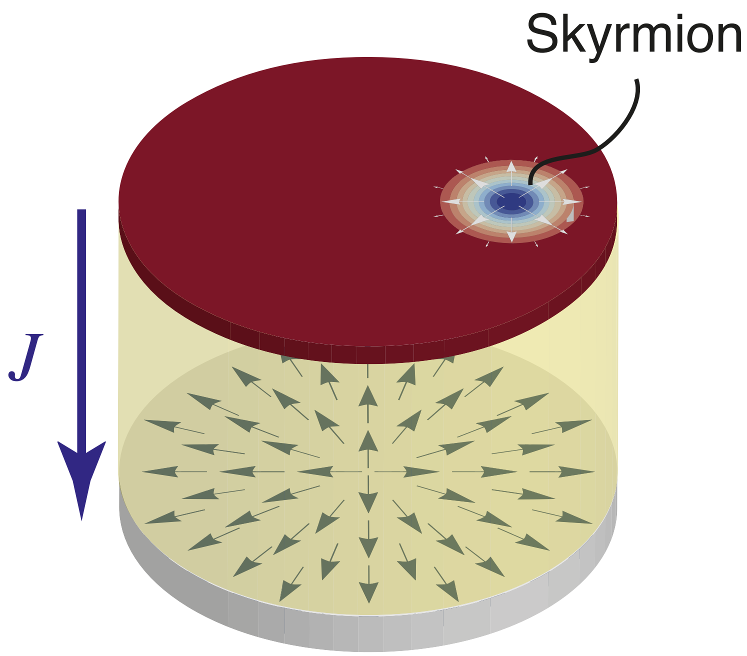


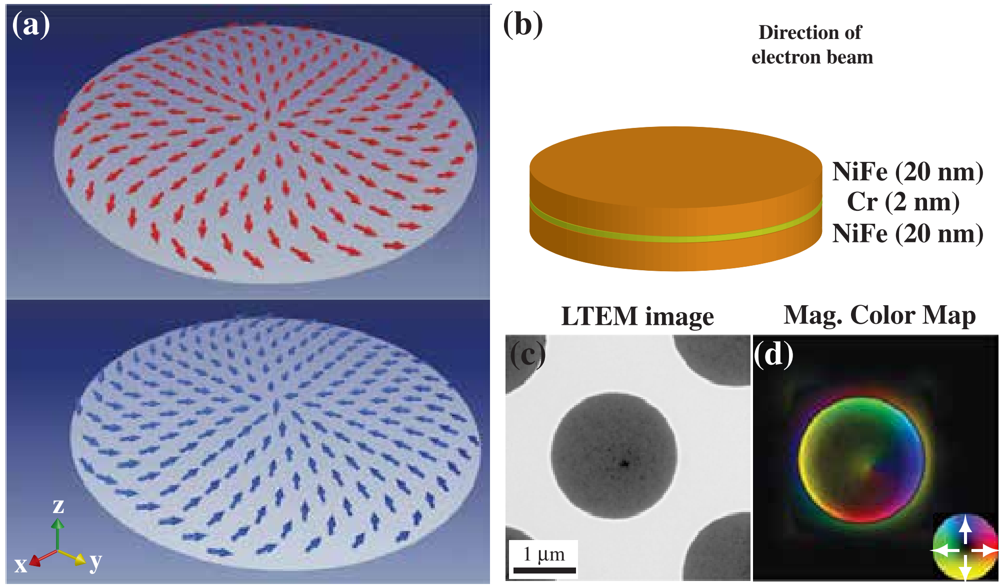
$$\tan\theta_H = \frac{\alpha D}{G}$$

Deflection analogous to Hall effect

- Could a vortex-like polarizer, combined with edge confinement, lead to skyrmion oscillations?

e.g.



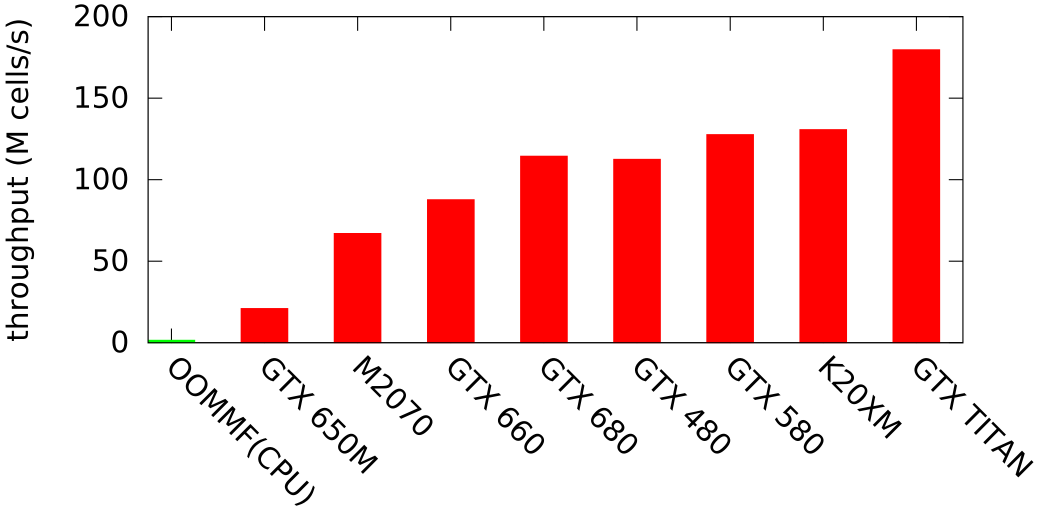


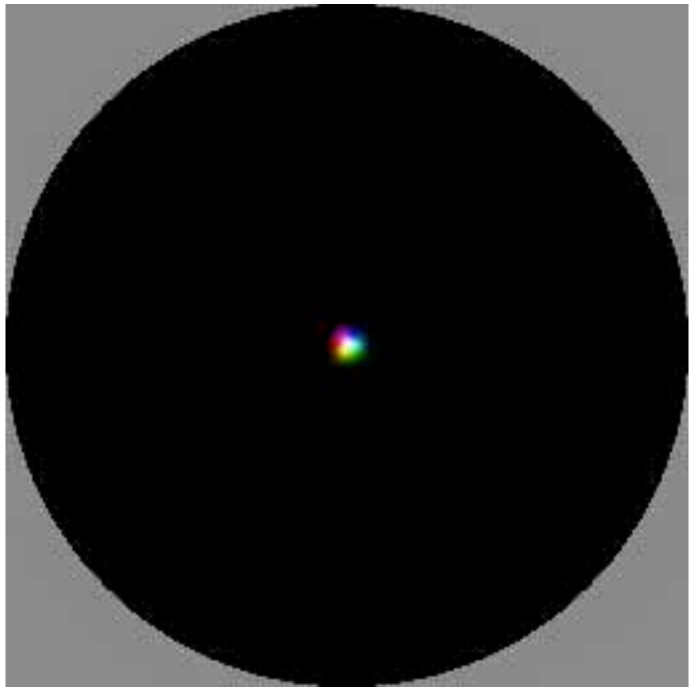
C. Phatak *et al.*, Phys. Rev. Lett. (2012)

Micromagnetics simulations

- Performed micromagnetics simulations using MuMax3 code
  - Solves Landau-Lifshitz-Gilbert + spin torques using finite difference method
  - Graphics processing units (GPUs) for fast computation of dipole-dipole interaction
  - Standard energy terms: exchange, anisotropy, dipole-dipole, DMI, Zeeman

$$\frac{d\mathbf{m}}{dt} = -\gamma_0 \mathbf{m} \times \mathbf{H}_{\mathrm{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} + \mathbf{\Gamma}_{\mathrm{ST}}$$



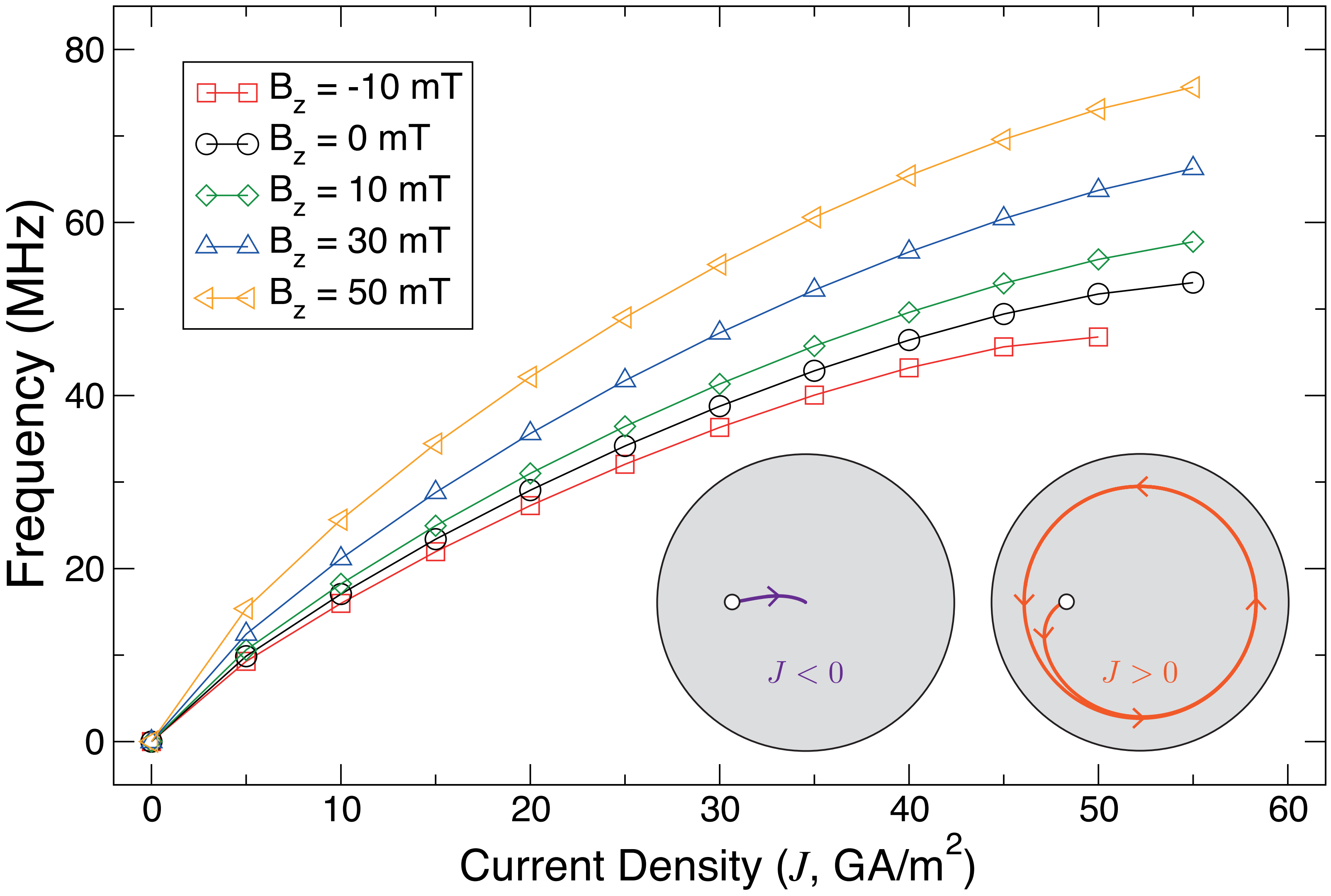


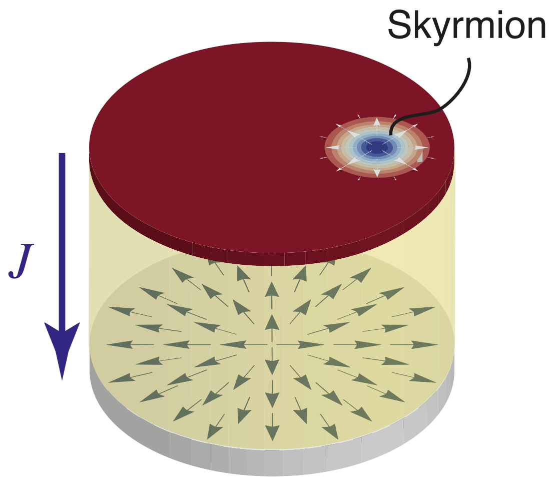
A. Vansteenkiste *et al*., AIP Adv. (2014)

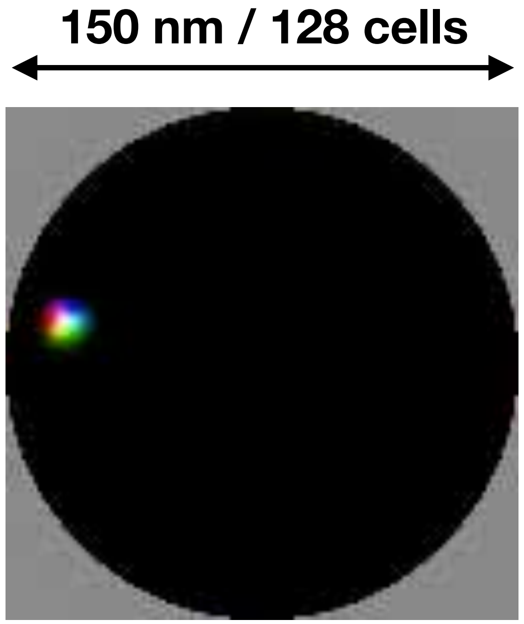
Radial polarizer – MuMax simulations

F. Garcia-Sanchez *et al.*, New J. Phys. (2016)

Oscillations occur for only one current polarity
("outward" motion)







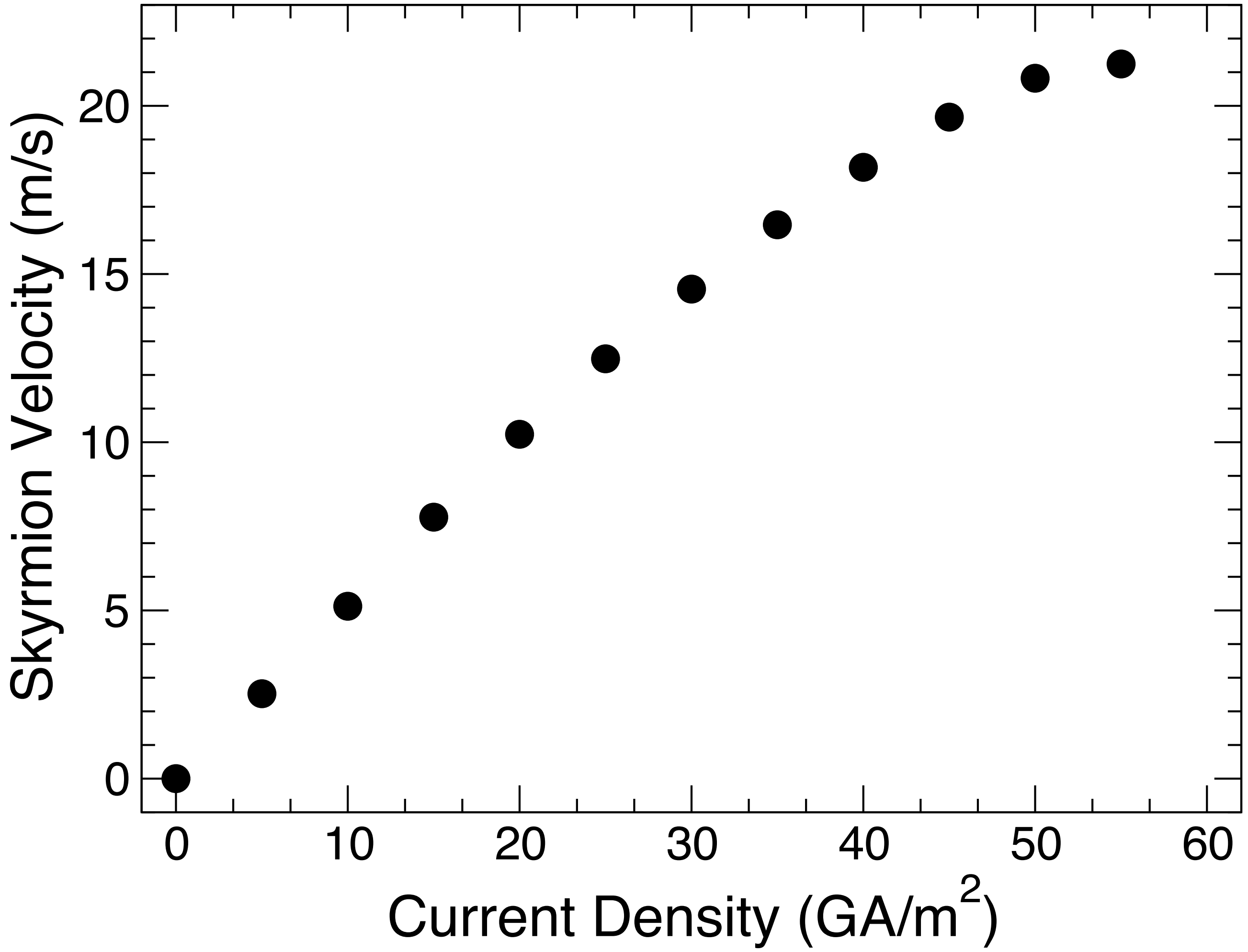
Parameters based on
Pt/Co (0.6 nm)/AlOx
[M. Belmeguenai *et al.*, PRB 2015]

$$\alpha = 0.3, \theta_H \approx 20^\circ$$

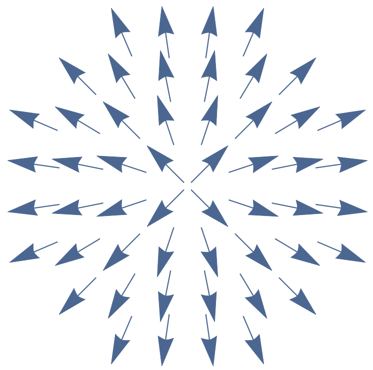
Estimating frequency from edge velocities

F. Garcia-Sanchez *et al.*, New J. Phys. (2016)

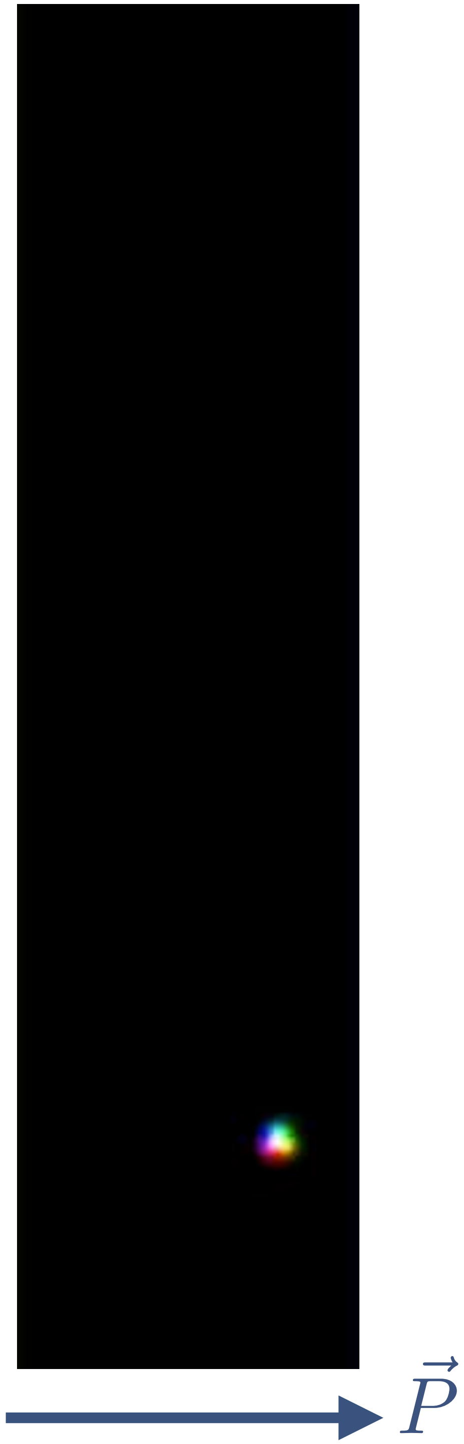
Use the skyrmion velocity along a straight edge (uniform polarizer) to predict oscillation frequency



$\vec{P} \parallel \hat{r}$

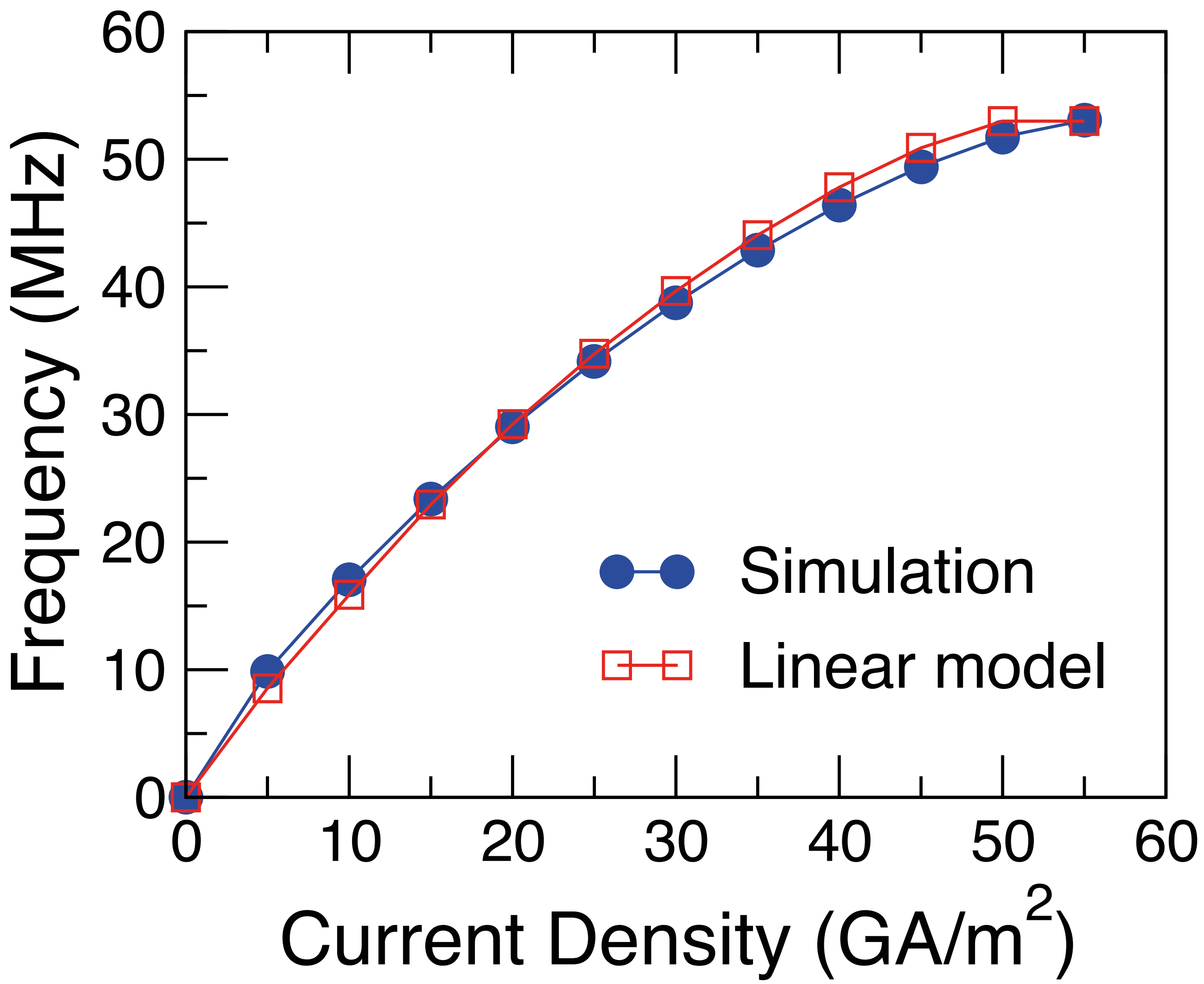


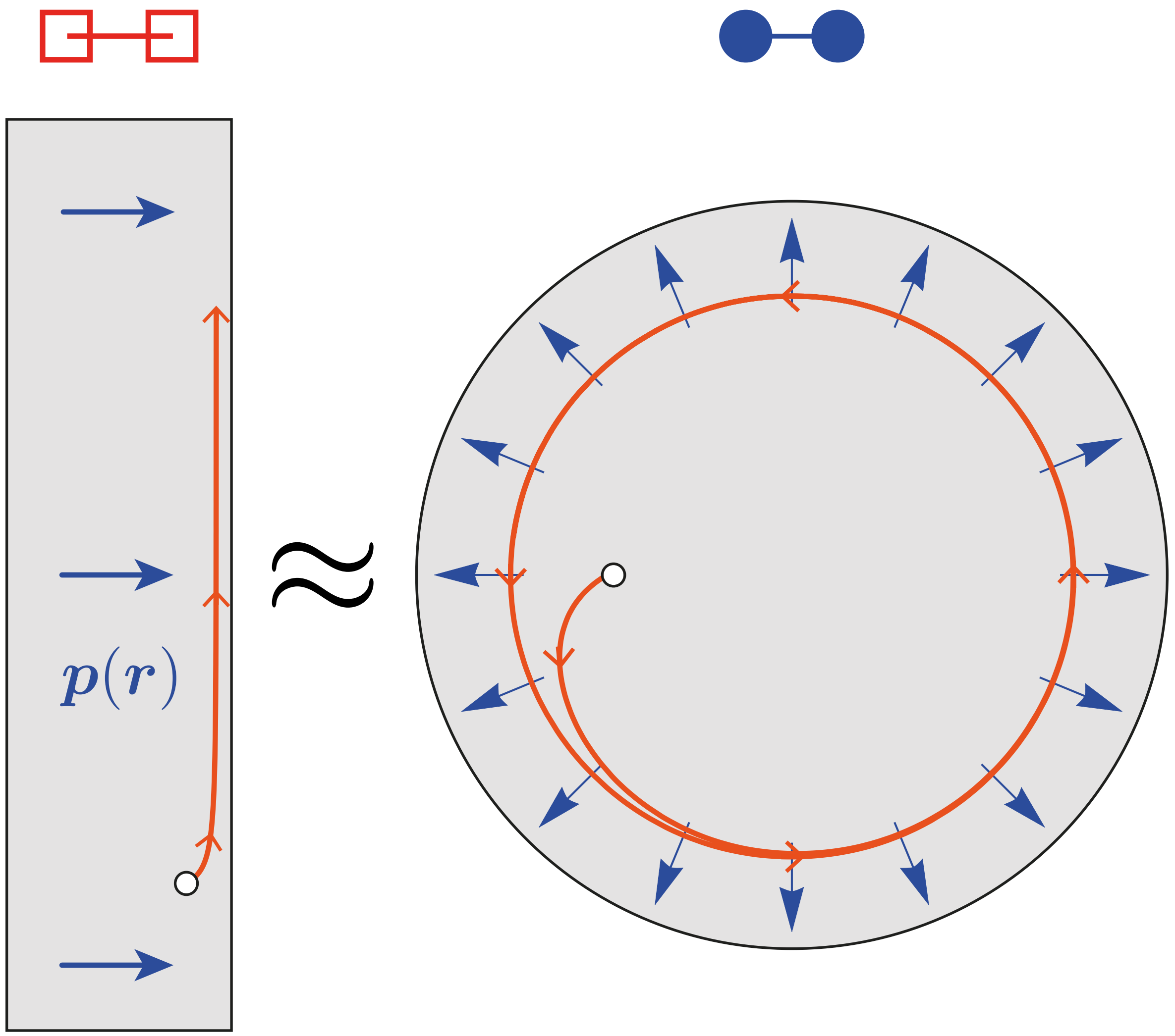
J_0 = 50 GA/m²



$$f = \frac{1}{2\pi}\frac{v}{r}$$

Estimate frequency from edge velocity and distance from edge

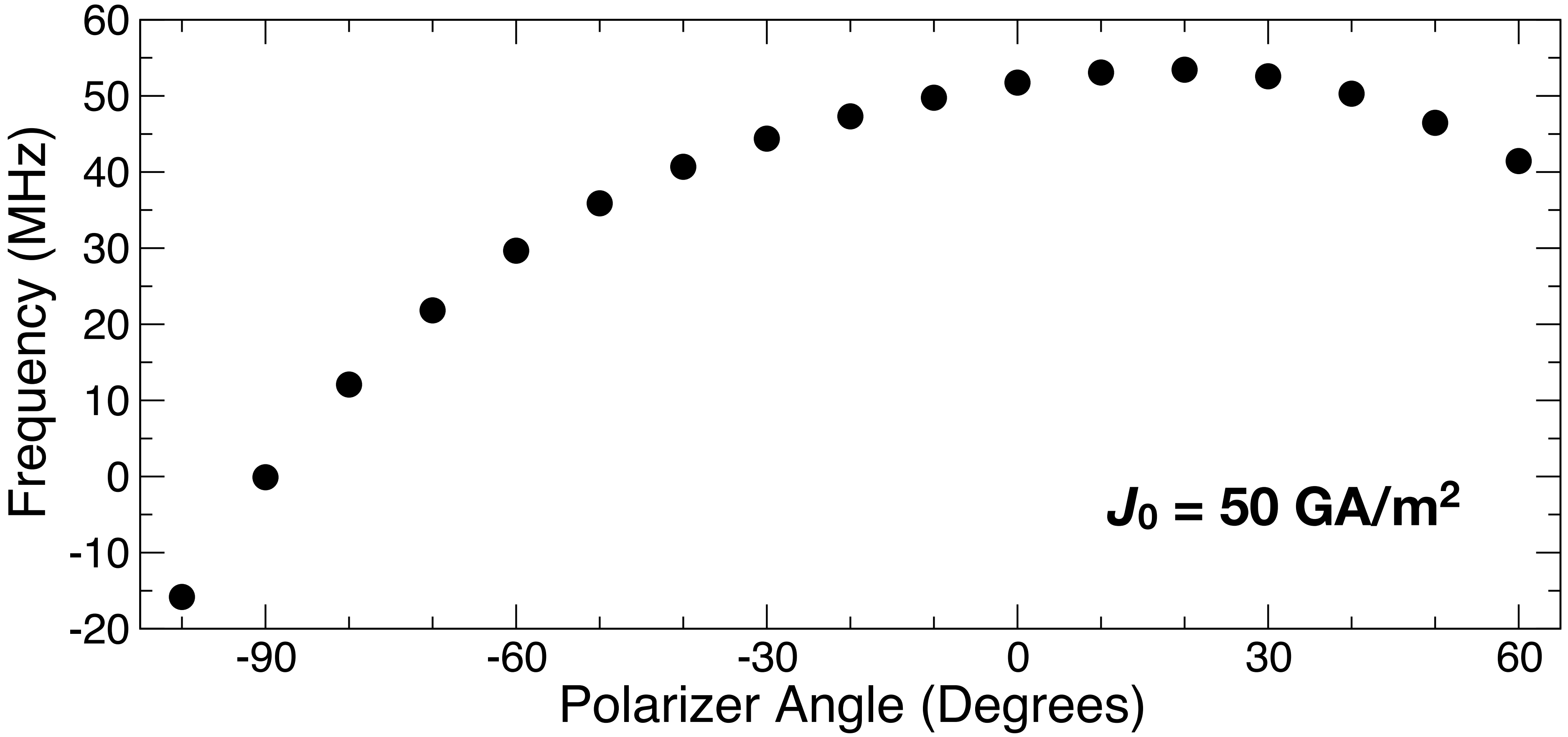


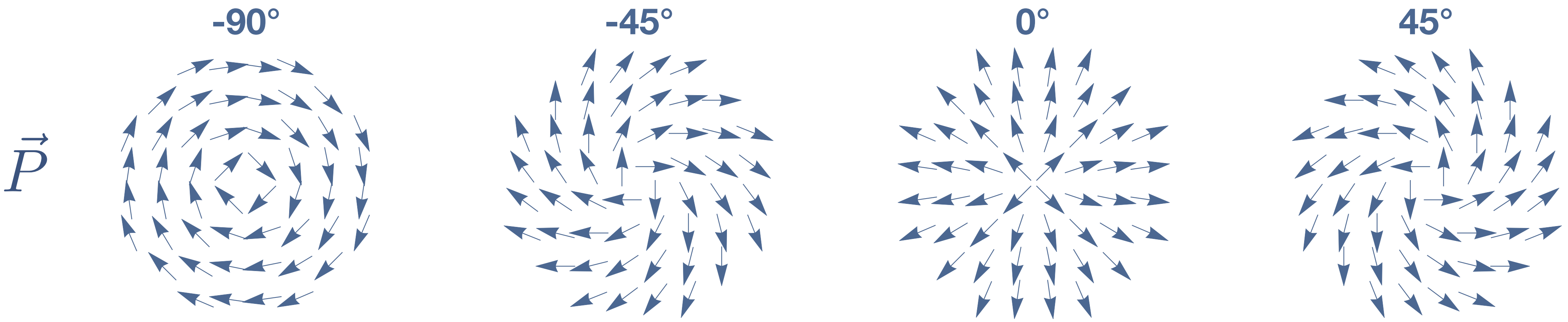


Generalized vortex polarizers

F. Garcia-Sanchez *et al.*, New J. Phys. (2016)

Similar oscillations are observed for different vortex polarizer configurations

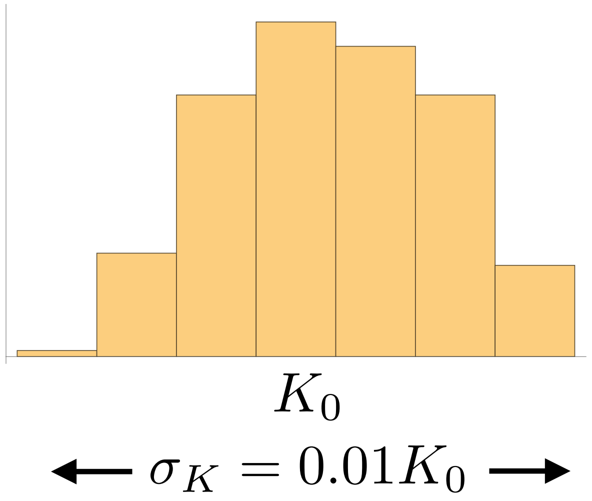


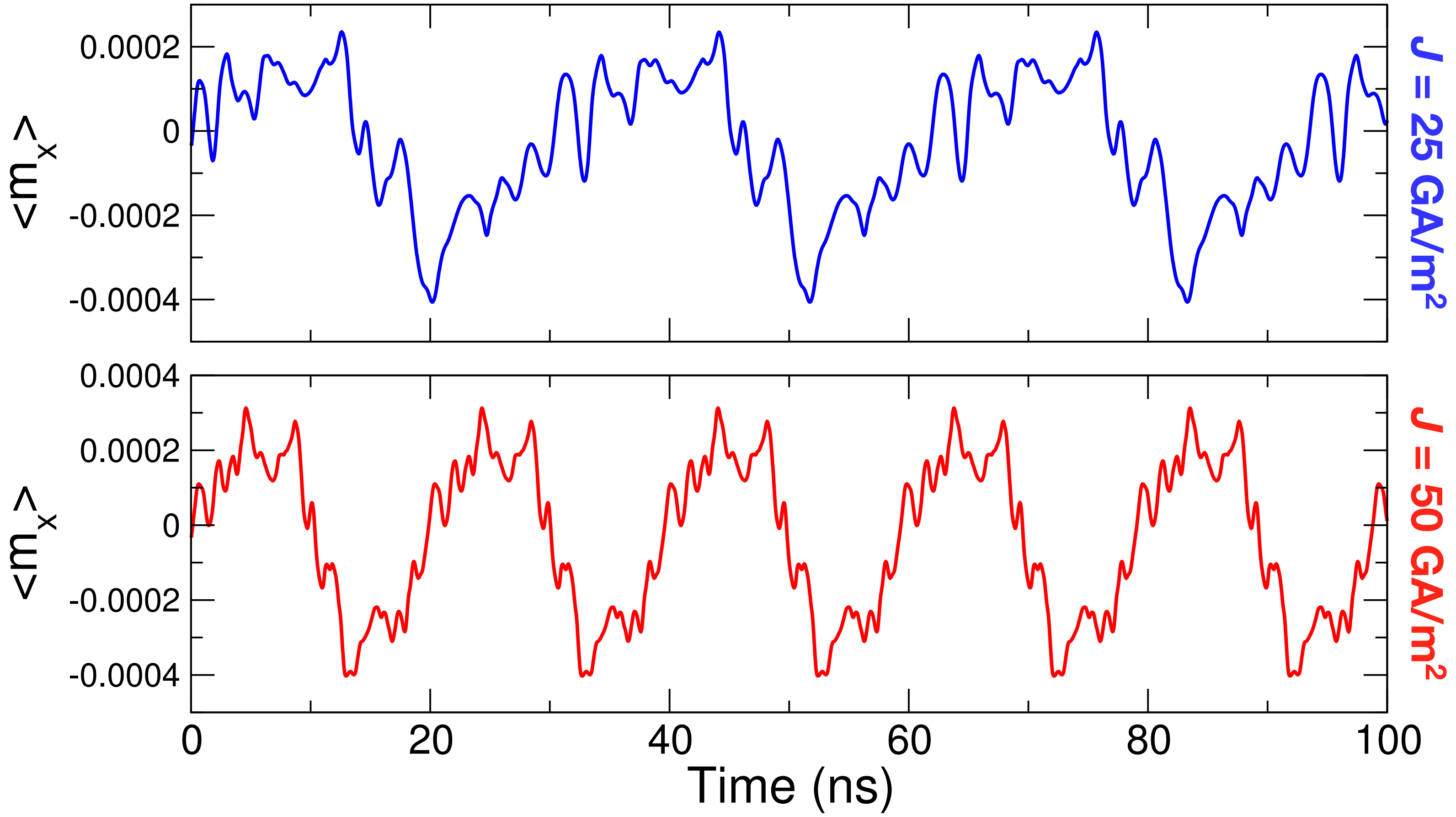


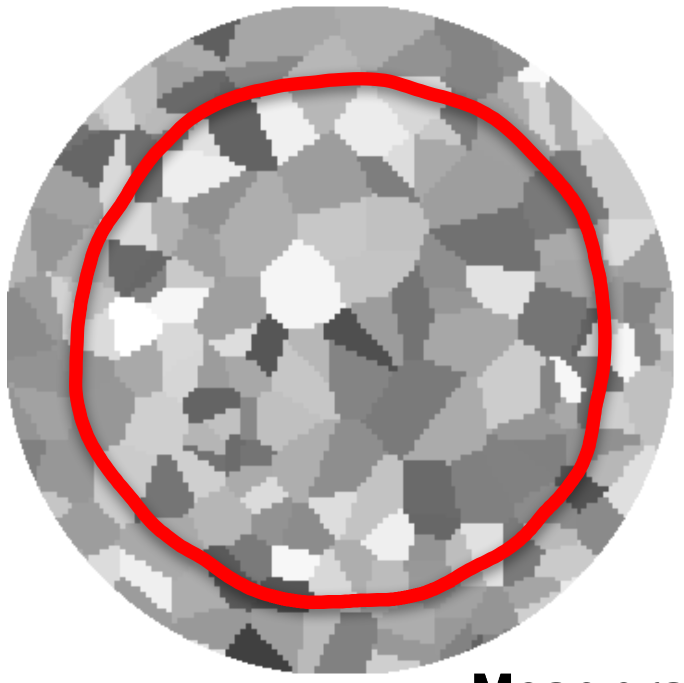
Role of grains and anisotropy distributions

F. Garcia-Sanchez *et al.*, New J. Phys. (2016)

- Modeled defects with distribution of grains with different anisotropies (Gaussian)
- Distorted trajectories with no evidence of athermal spectral line broadening

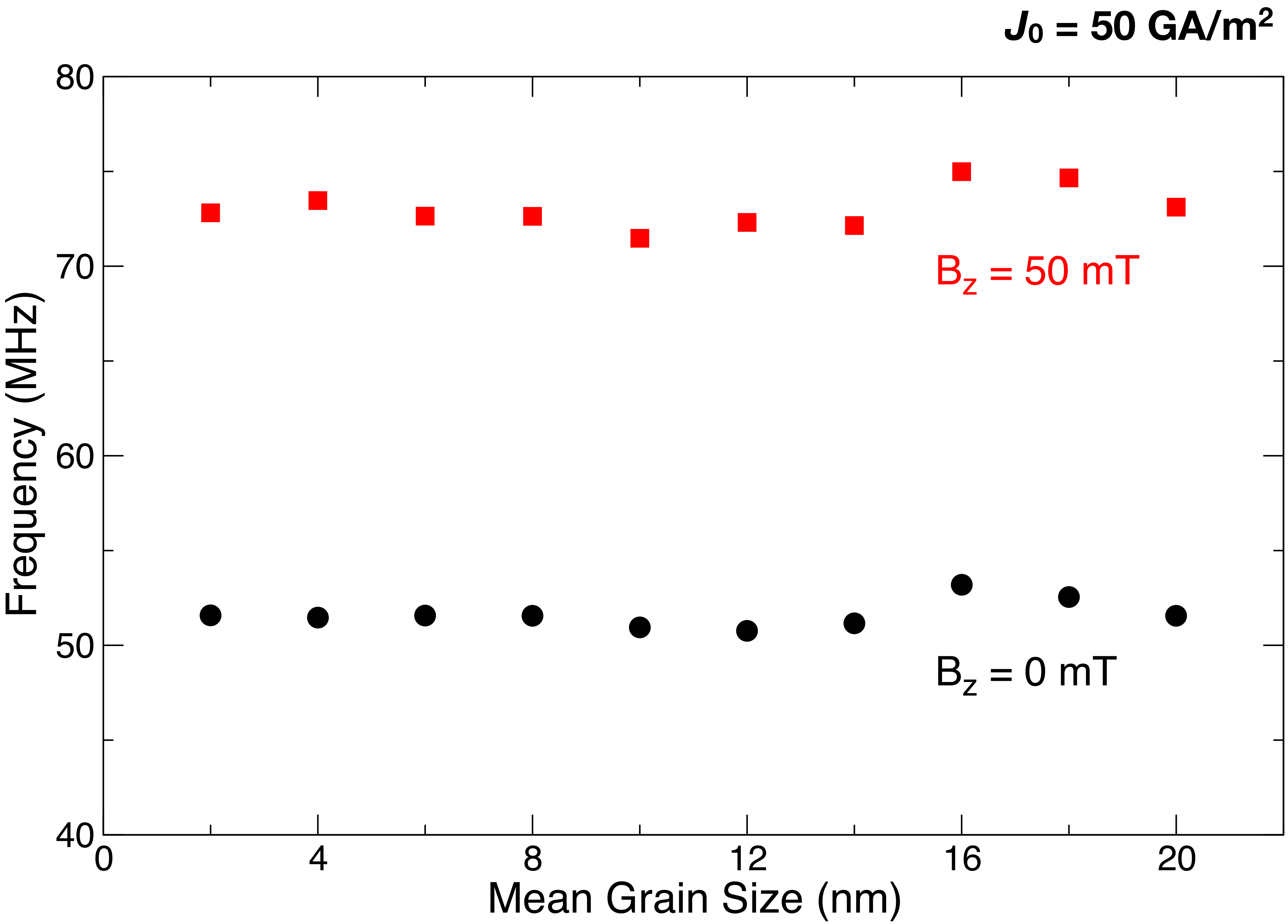






Mean grain size = 10 nm

- Frequencies largely independent of grain size



Outline

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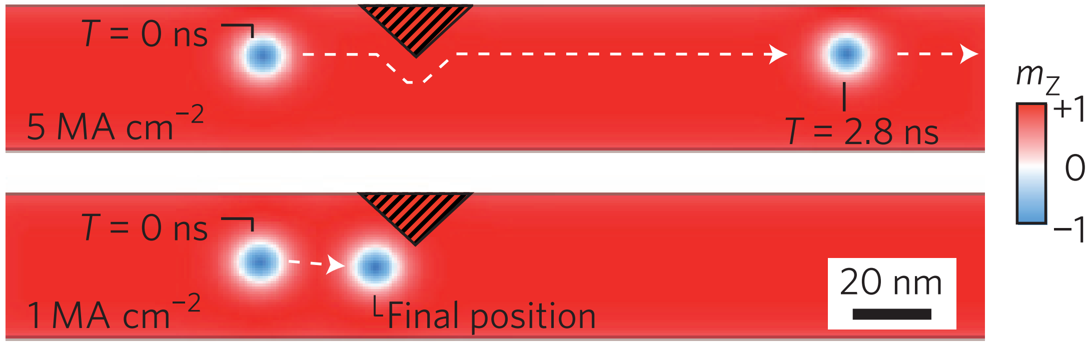
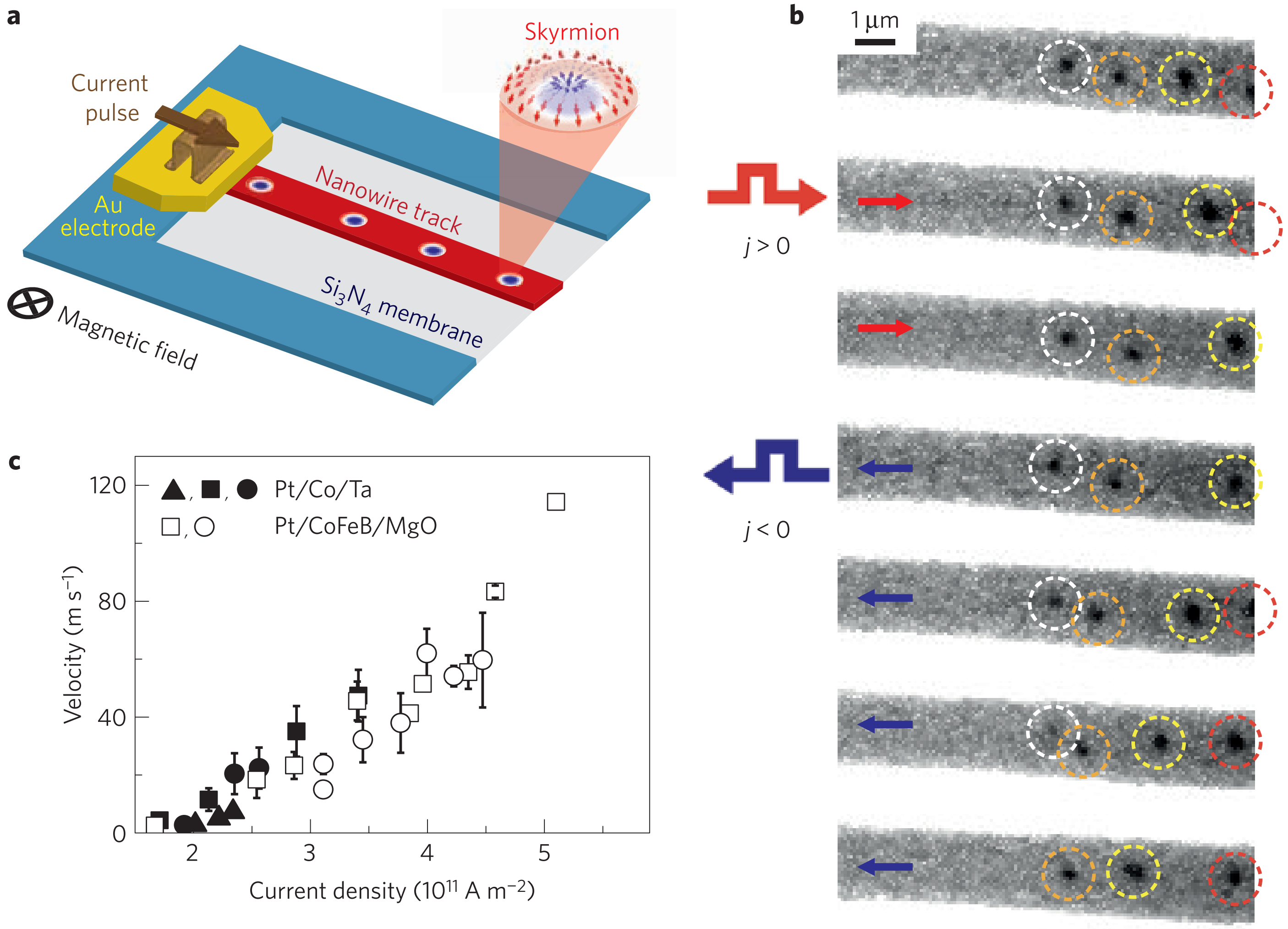
Role of disorder in current-driven skyrmion motion

- **Q**: What is the role of (anisotropy) defects in current-driven skyrmion motion?
- **Q**: Is “topological protection” relevant, or do skyrmions just get pinned like *domain walls*?



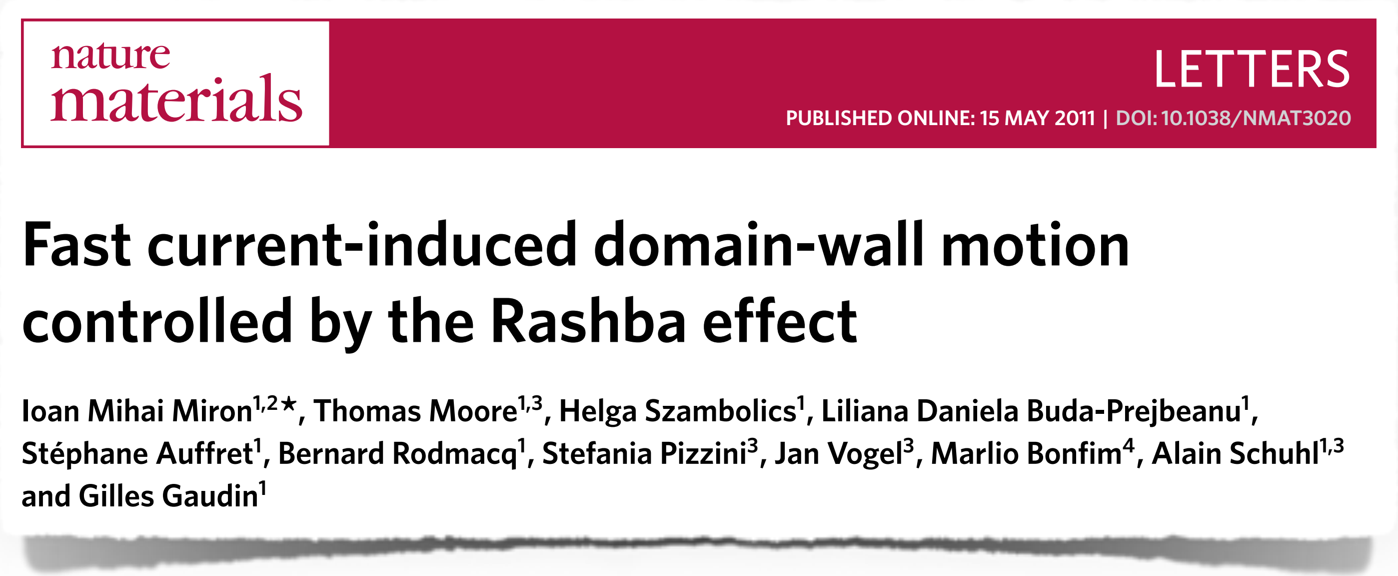
J. Sampaio *et al*., Nat. Nanotech. 2013



S. Woo *et al*., Nat. Mater. 2016

What can domain wall dynamics teach us?

- In PMA materials, domain wall pinning is an important issue and remains key roadblock for racetrack-type applications
- Pinning leads to <u>finite threshold</u> field or current for propagation



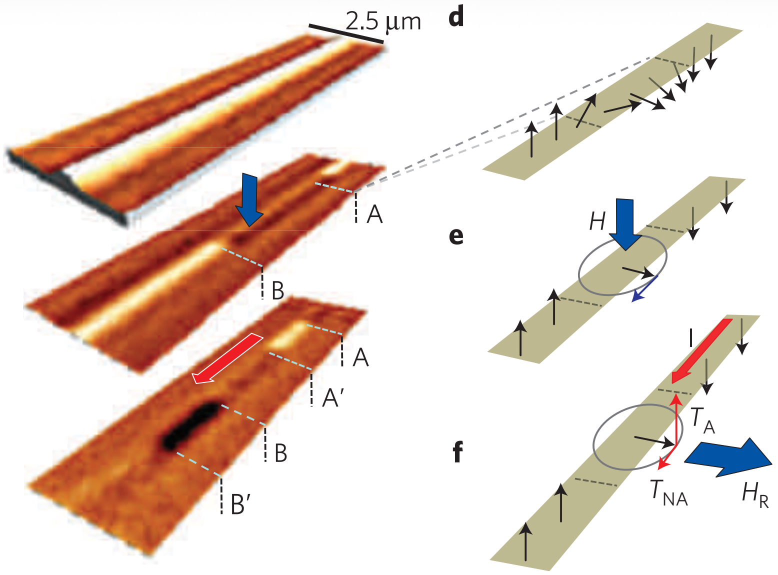
nature materials

LETTERS

PUBLISHED ONLINE: 15 MAY 2011 | DOI: 10.1038/NMAT3020

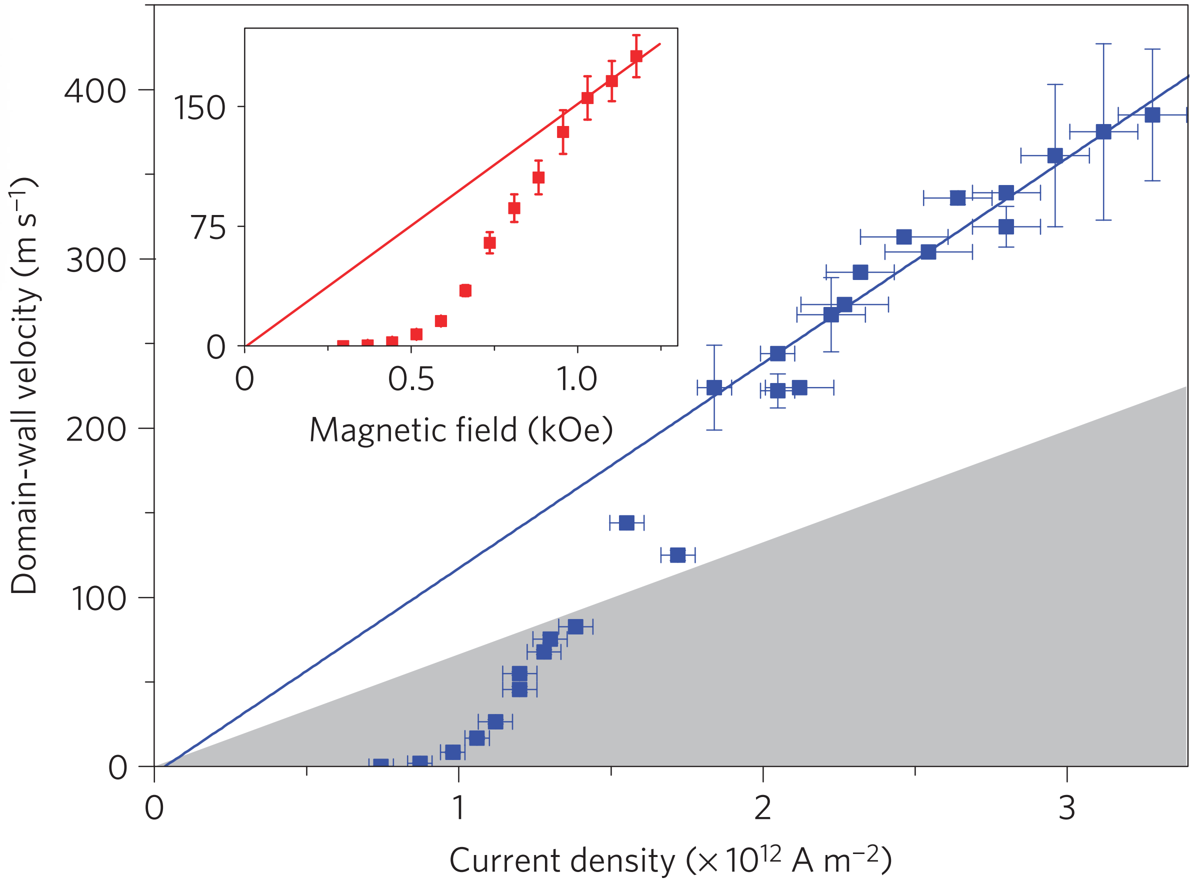
Fast current-induced domain-wall motion controlled by the Rashba effect

Ioan Mihai Miron[1,2]★, Thomas Moore[1,3], Helga Szambolics[1], Liliana Daniela Buda-Prejbeanu[1], Stéphane Auffret[1], Bernard Rodmacq[1], Stefania Pizzini[3], Jan Vogel[3], Marlio Bonfim[4], Alain Schuhl[1,3] and Gilles Gaudin[1]

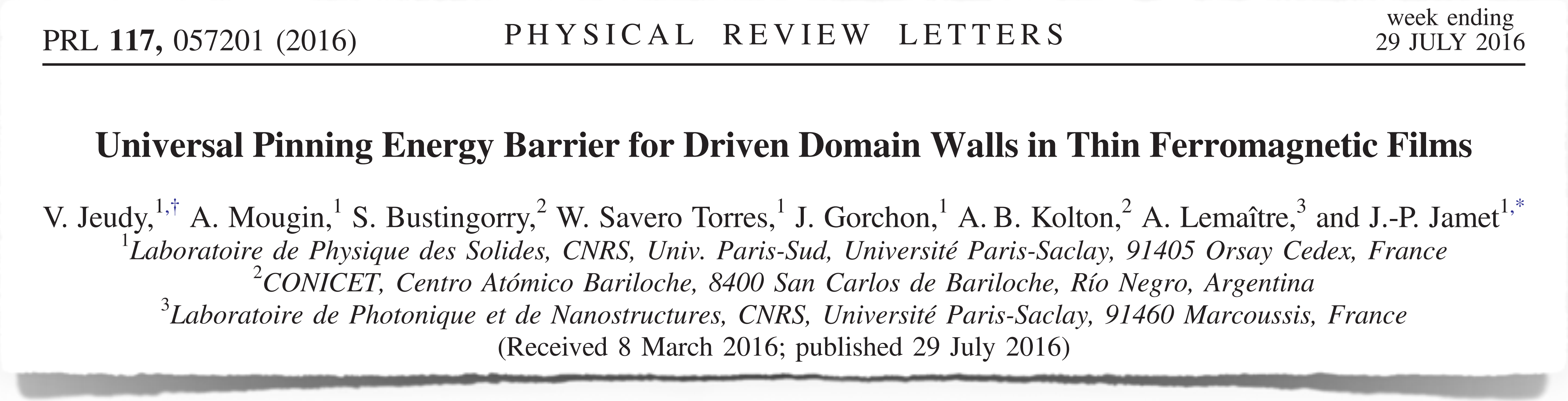


Pt/Co (0.6 nm)/AlOx

Néel wall (DMI) + spin Hall effect



- For field-driven dynamics, motion at low fields occurs in *creep regime*



PRL **117,** 057201 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

Universal Pinning Energy Barrier for Driven Domain Walls in Thin Ferromagnetic Films

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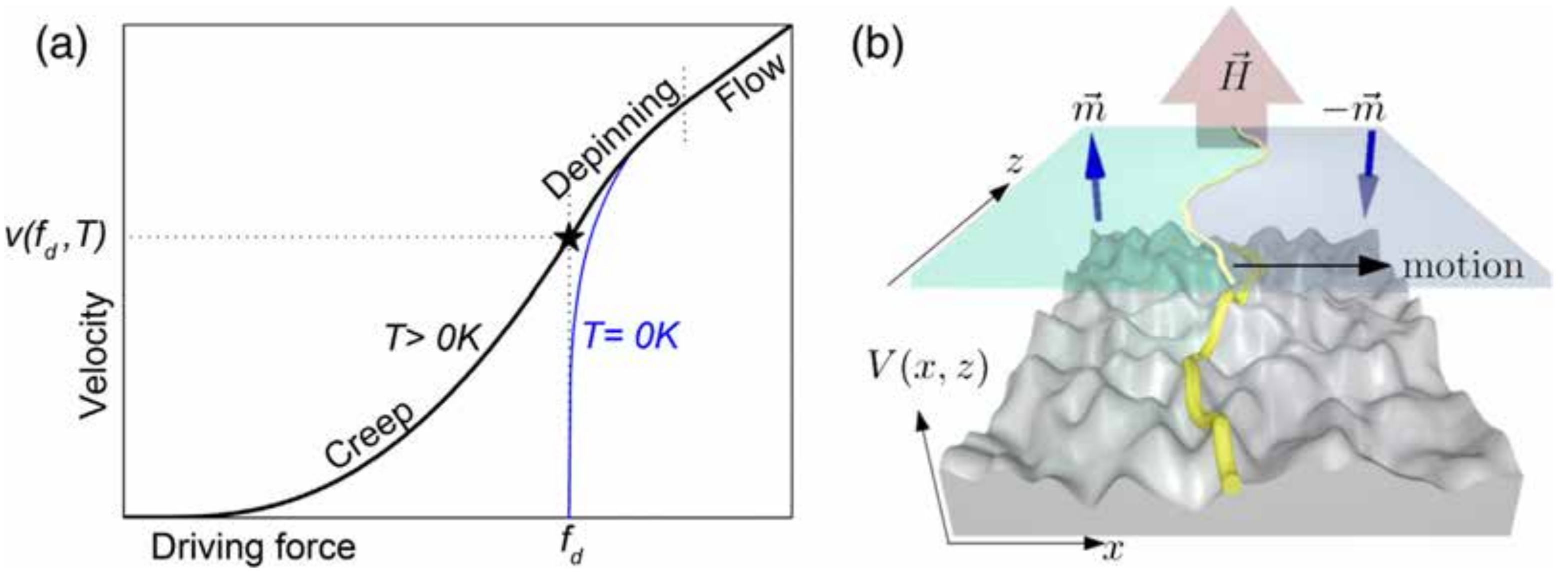
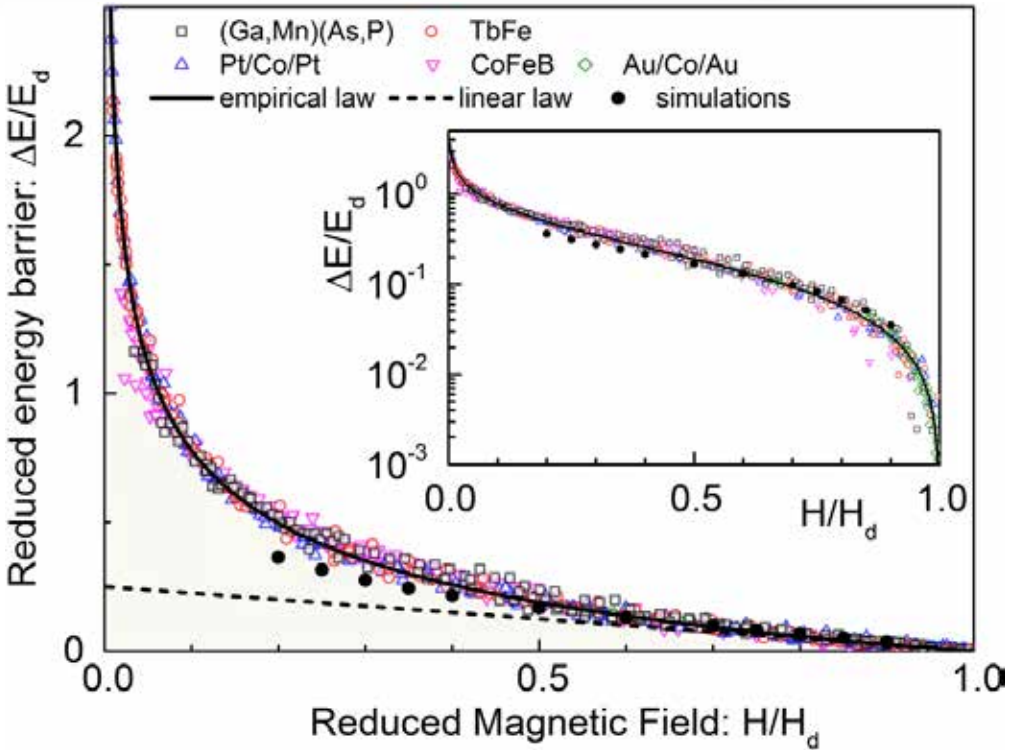
(Received 8 March 2016; published 29 July 2016)





$$v = v_0 \exp\left(-\beta_d\left[\left(\frac{H}{H_d}\right)^{-1/4} - 1\right]\right)$$

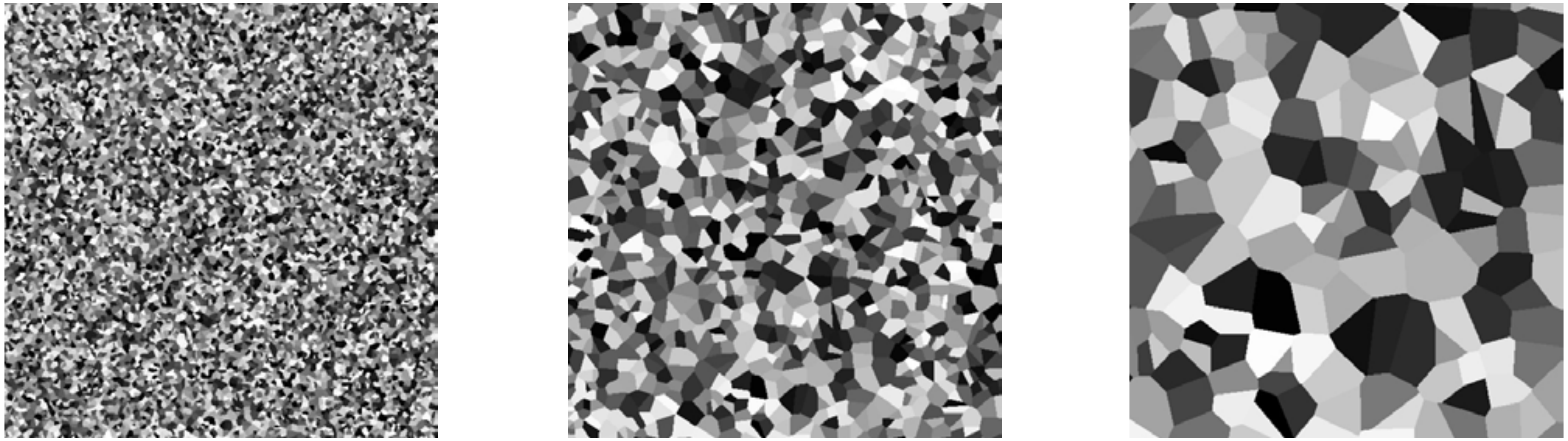
- Proposal: Depinning field, H_d, is a useful material parameter for characterizing disorder (even for skyrmion dynamics)

$$v = v_0 \exp\left(-\beta_d\left[\left(\frac{H}{H_d}\right)^{-1/4} - 1\right]\right)$$

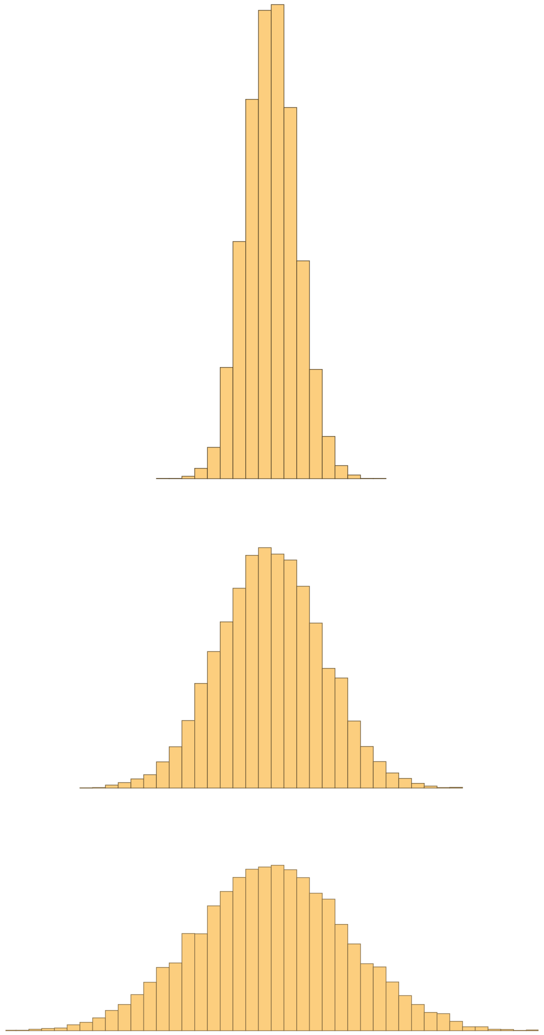
Material	Thick. (nm)	$T(K)$	$T_d(K)$	$H_d(mT)$	$v(H_d)(m/s)$
(Ga,Mn)(As,P)	12	10	616(10)	6.2(0.1)	1.8(0.1)
		30	1440(20)	5.8(0.1)	1.8(0.1)
		50	1140(20)	5.6(0.1)	2.0(0.2)
		65	815(10)	5.5(0.1)	2.3(0.1)
TbFe	5×1.8	271	5750(50)	295(5)	1.4(0.1)
		289	4200(50)	225(5)	1.8(0.1)
		304	3050(50)	130(5)	1.7(0.1)
		310	2600(50)	100(5)	1.7(0.1)
		315	2200(50)	80(5)	1.8(0.1)
Pt/Co/Pt	0.5	293	2558(10)	28.5(2)	5.7(0.2)
	0.6		4145(25)	56(1)	10.6(1.0)
	0.7		6490(30)	76(1)	16.6(1.0)
	0.8		9720(45)	72(1)	18.4(1.0)
irradiated	0.5		2260(50)	15(1)	7.5(1.0)

V. Jeudy *et al.*, Phys. Rev. Lett. 2016 (Supplementary)

Simulating disorder with micromagnetics

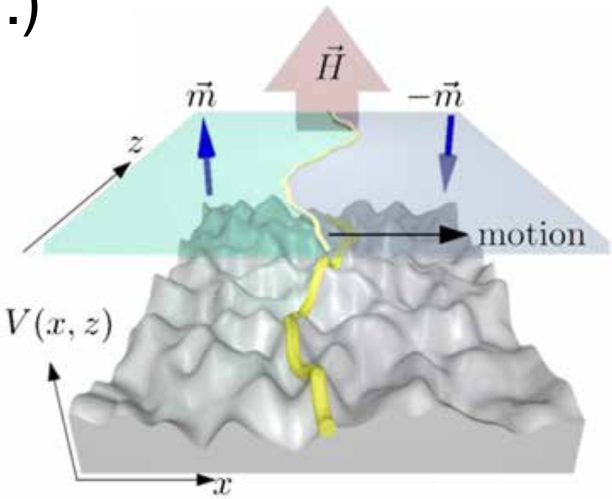


vary average grain size



vary spread in (Gaussian) distribution of K_u

- Simulate disorder using random grain distribution with different anisotropies
- Anisotropy variation leads to random potential for domain walls (and skyrmions …)

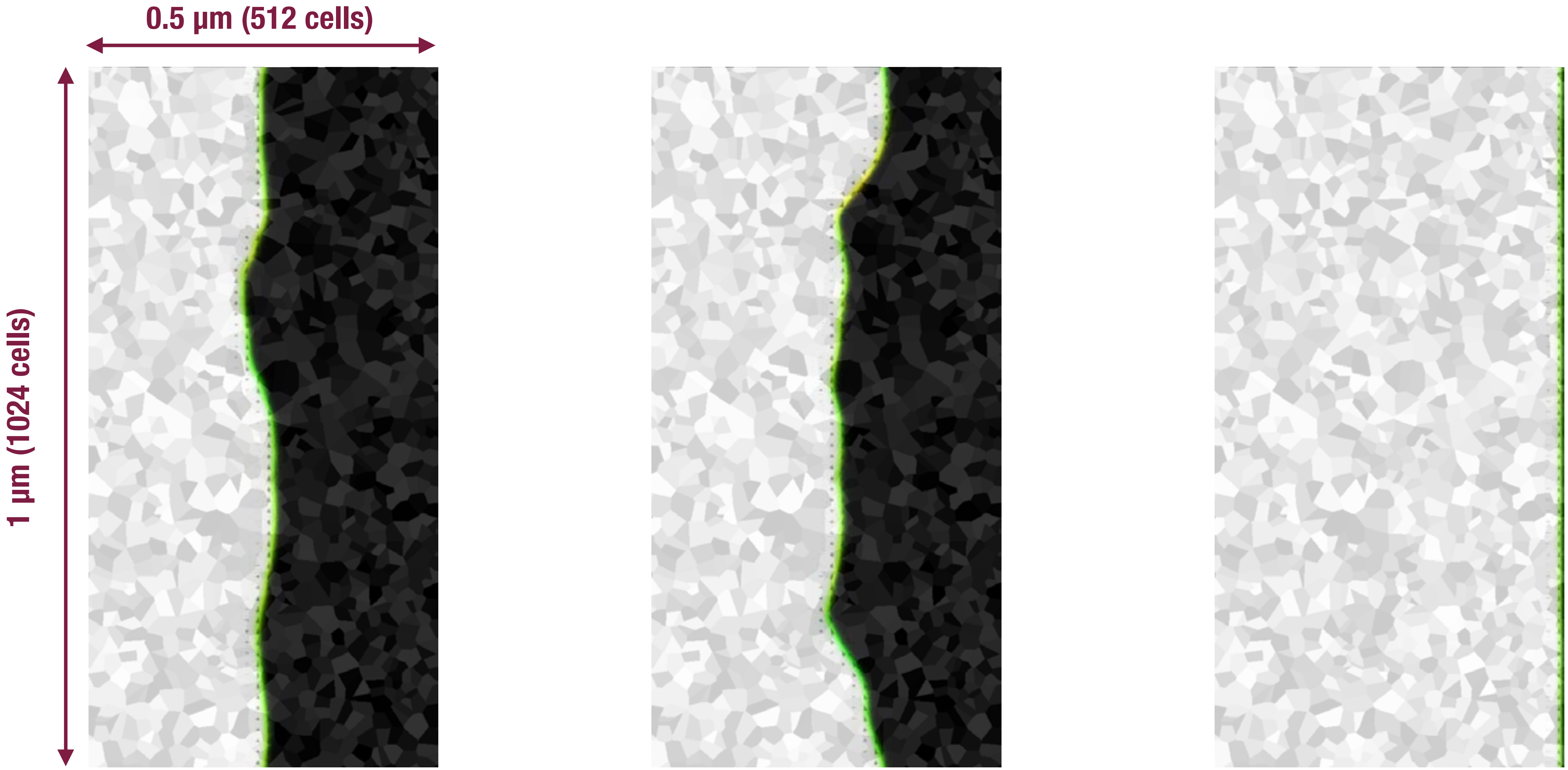


Simulating domain wall depinning

- Minimize energy at each field step

avg. grain size = 20 nm

10% variation in K_u



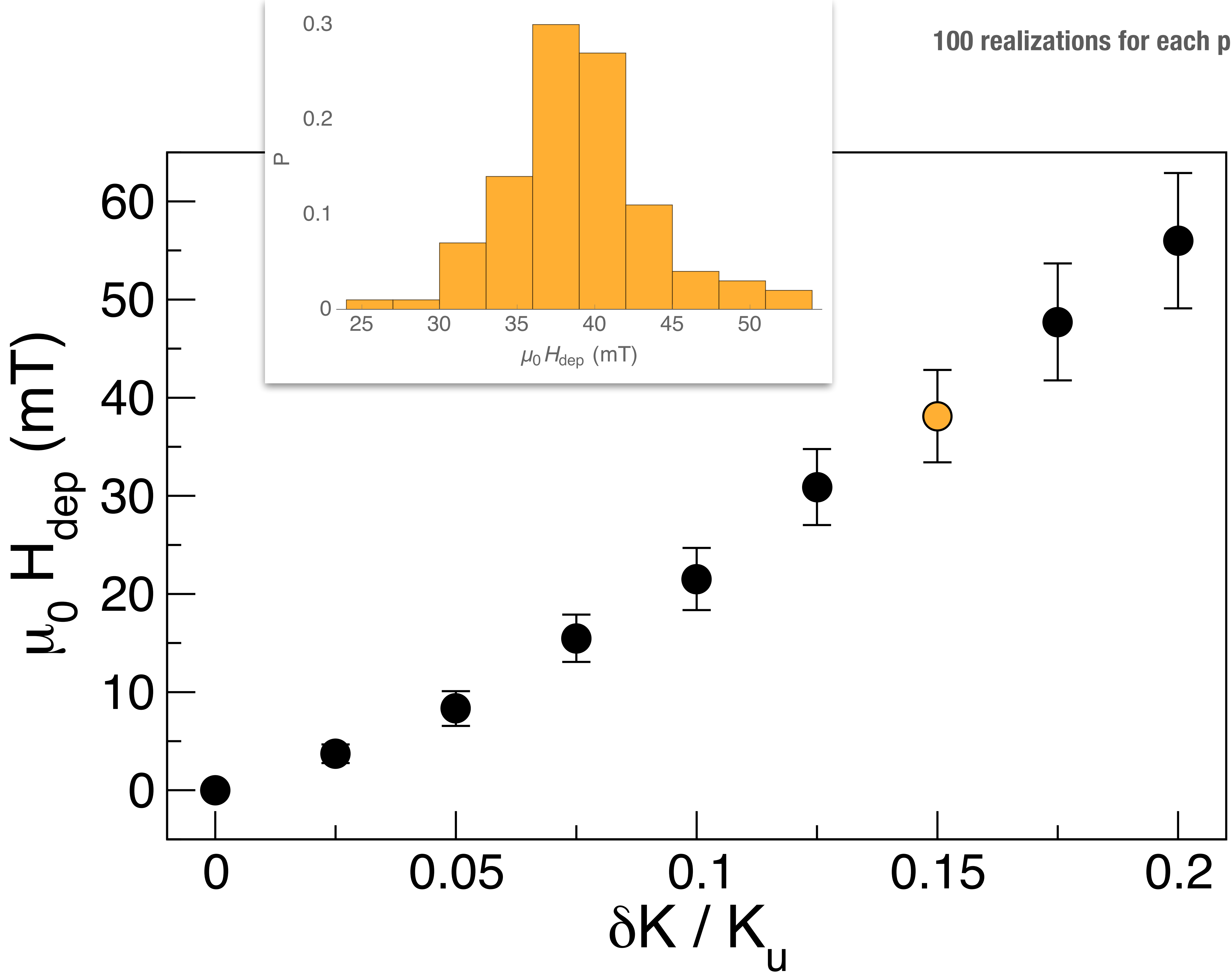
$H = 0$

$H < H_{dep}$

$H > H_{dep}$

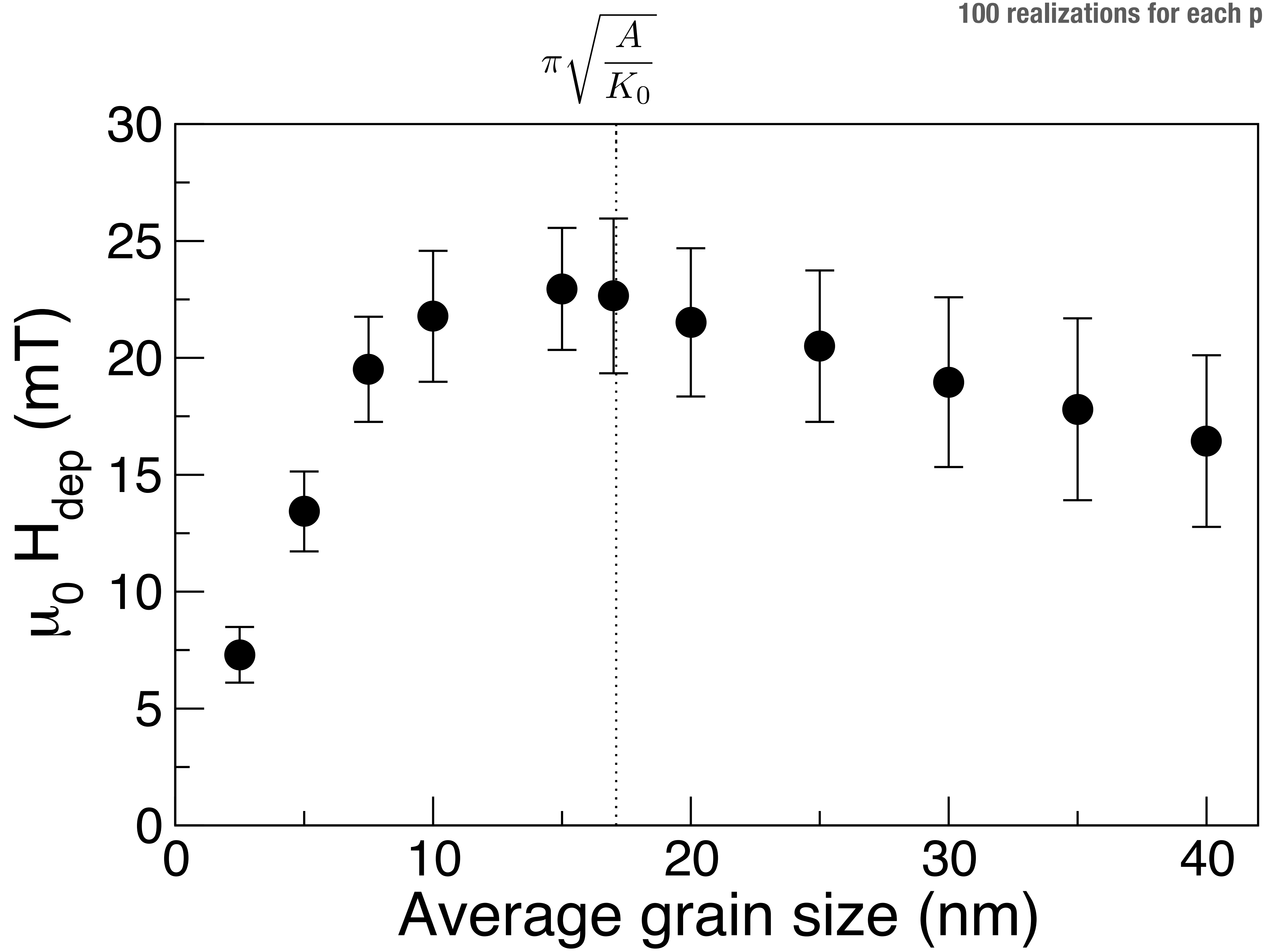
avg. grain size = 20 nm

100 realizations for each point



10% anisotropy variation

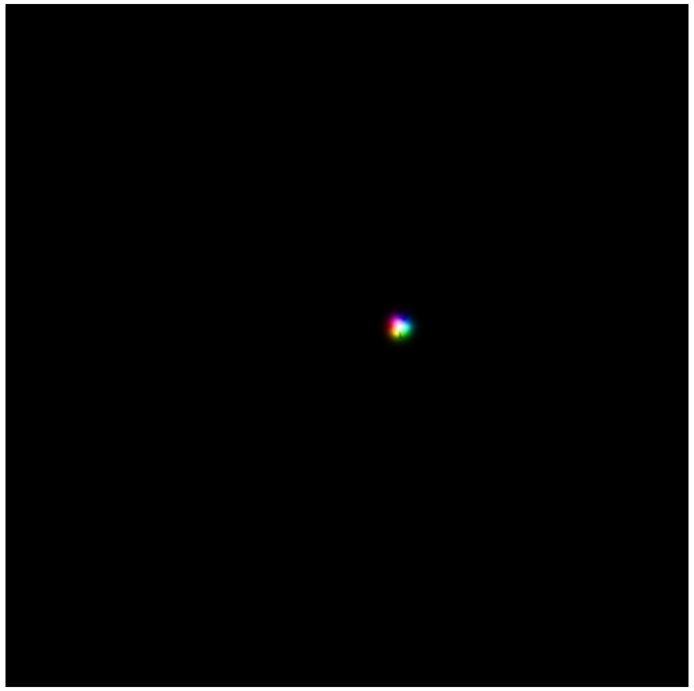
100 realizations for each point



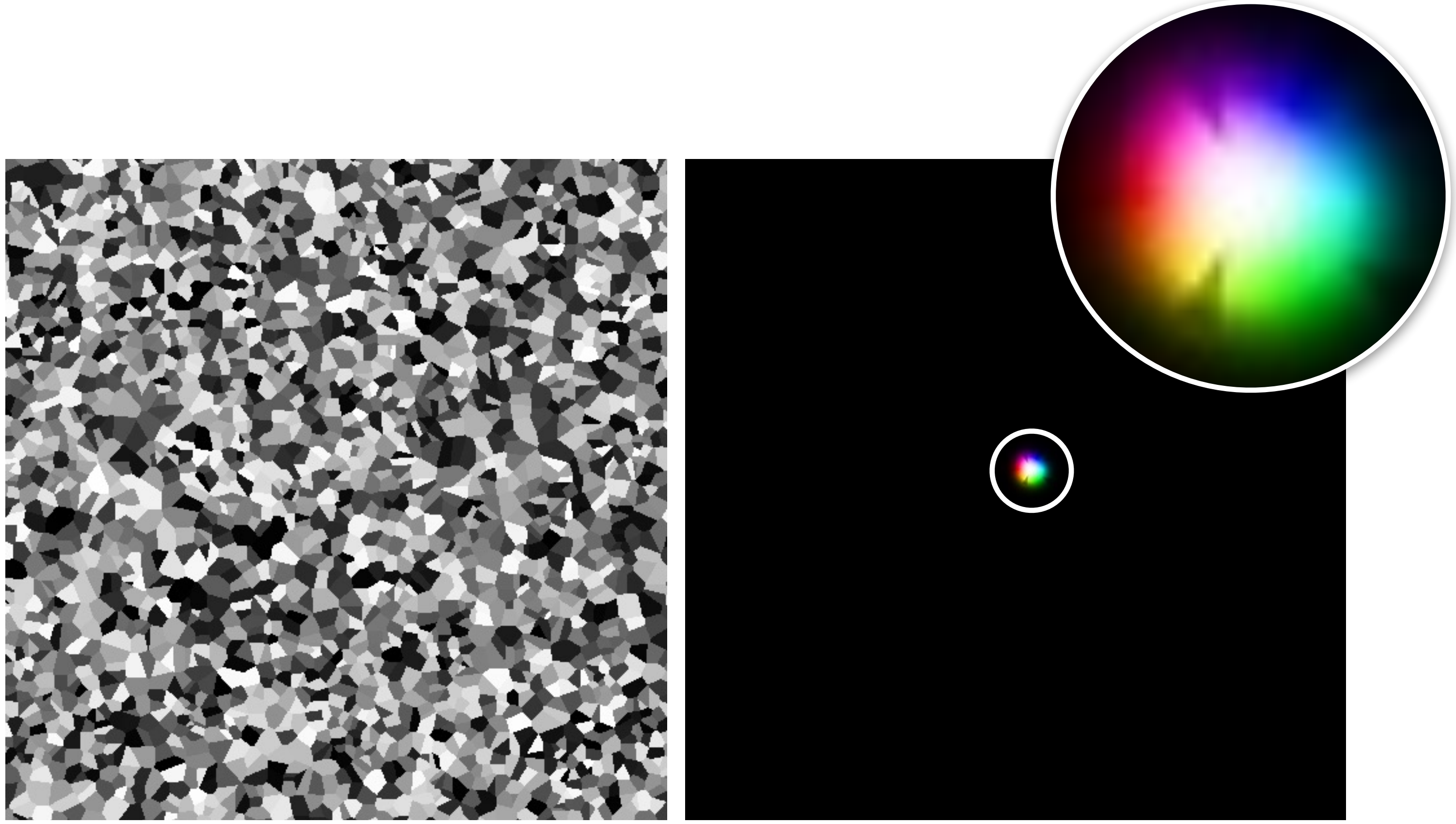
Simulating current-driven skyrmion motion (T = 0 K)

J.-V. Kim *et al.*, arXiv:1701.08357

0.5 µm (512 cells), PBC



clean system



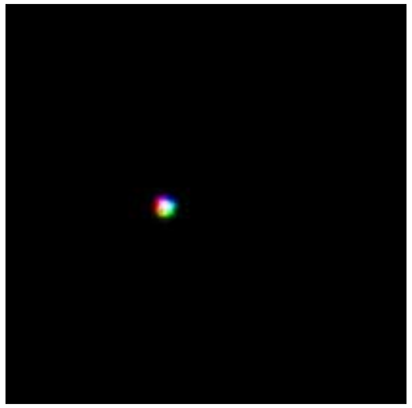
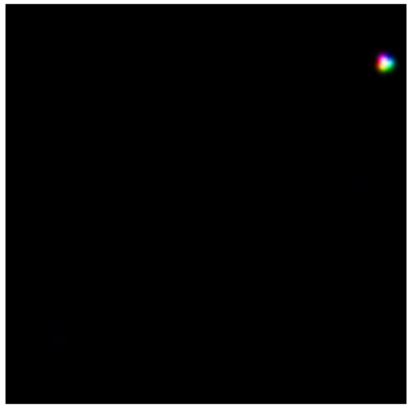
disordered system

- For each current density, considered 50 different realizations of disorder
- For each realization, applied current during 10 ns (*)
- Velocity for each current density averaged over the 50 realizations

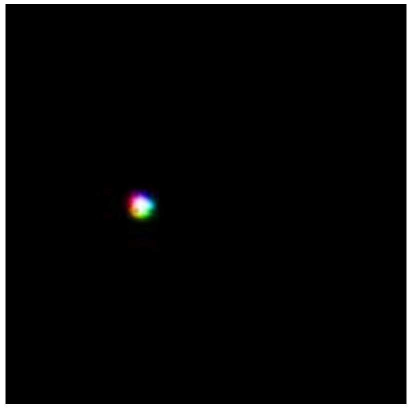
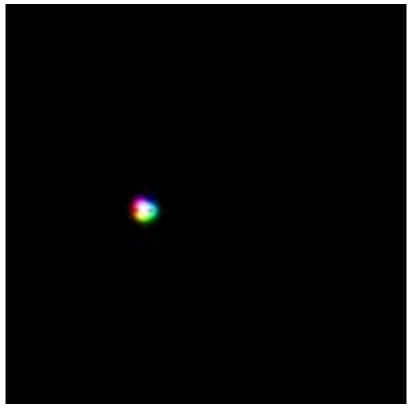
Possible scenarios

$t = 0$ $t = t_{\text{final}}$

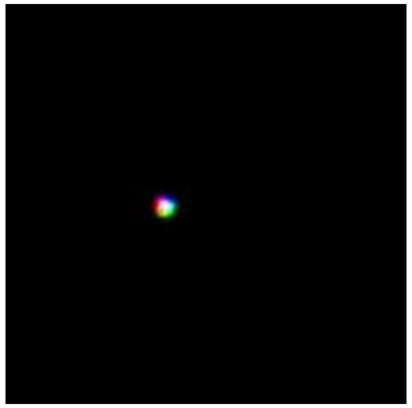
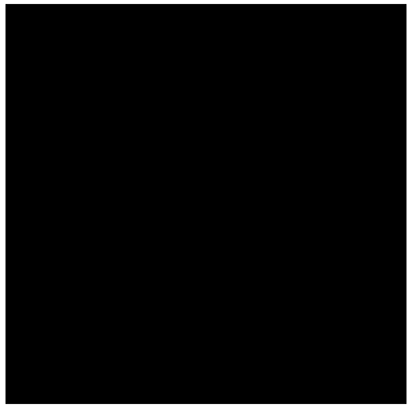
1. Propagation

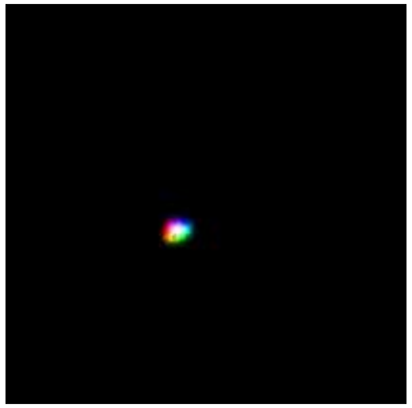
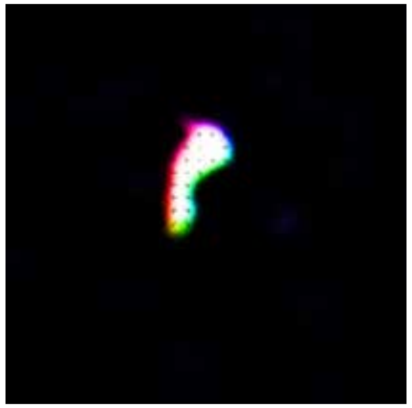
2. Pinned

3. Annihilation

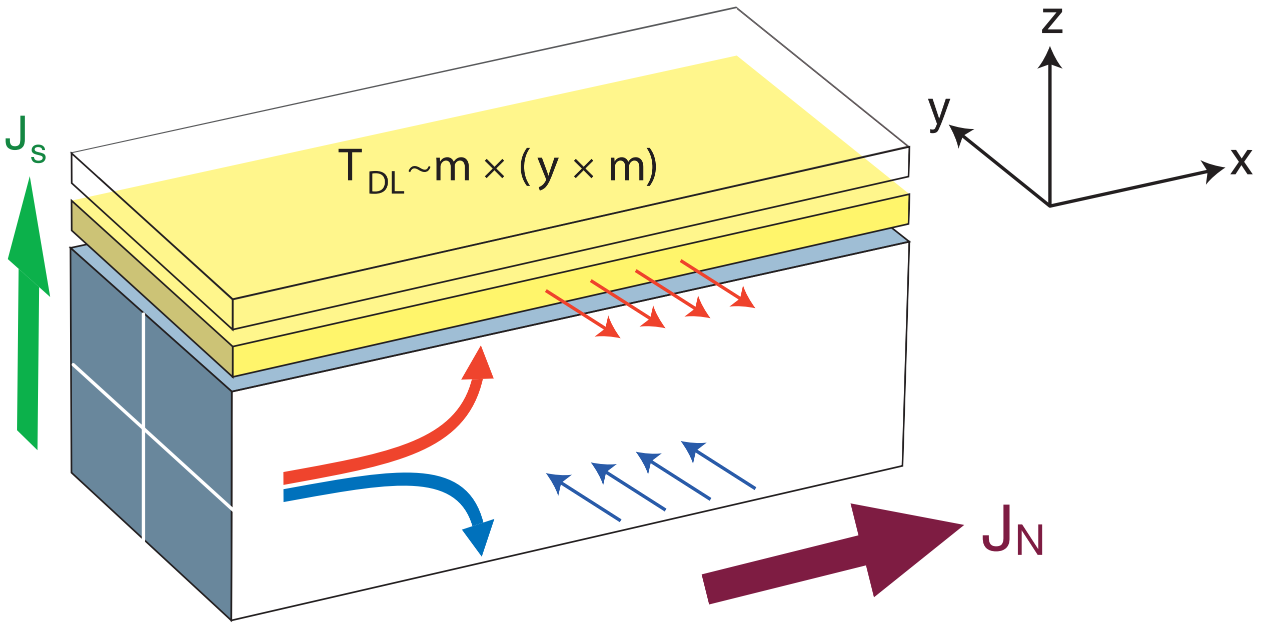
4. Explosion (SHE)

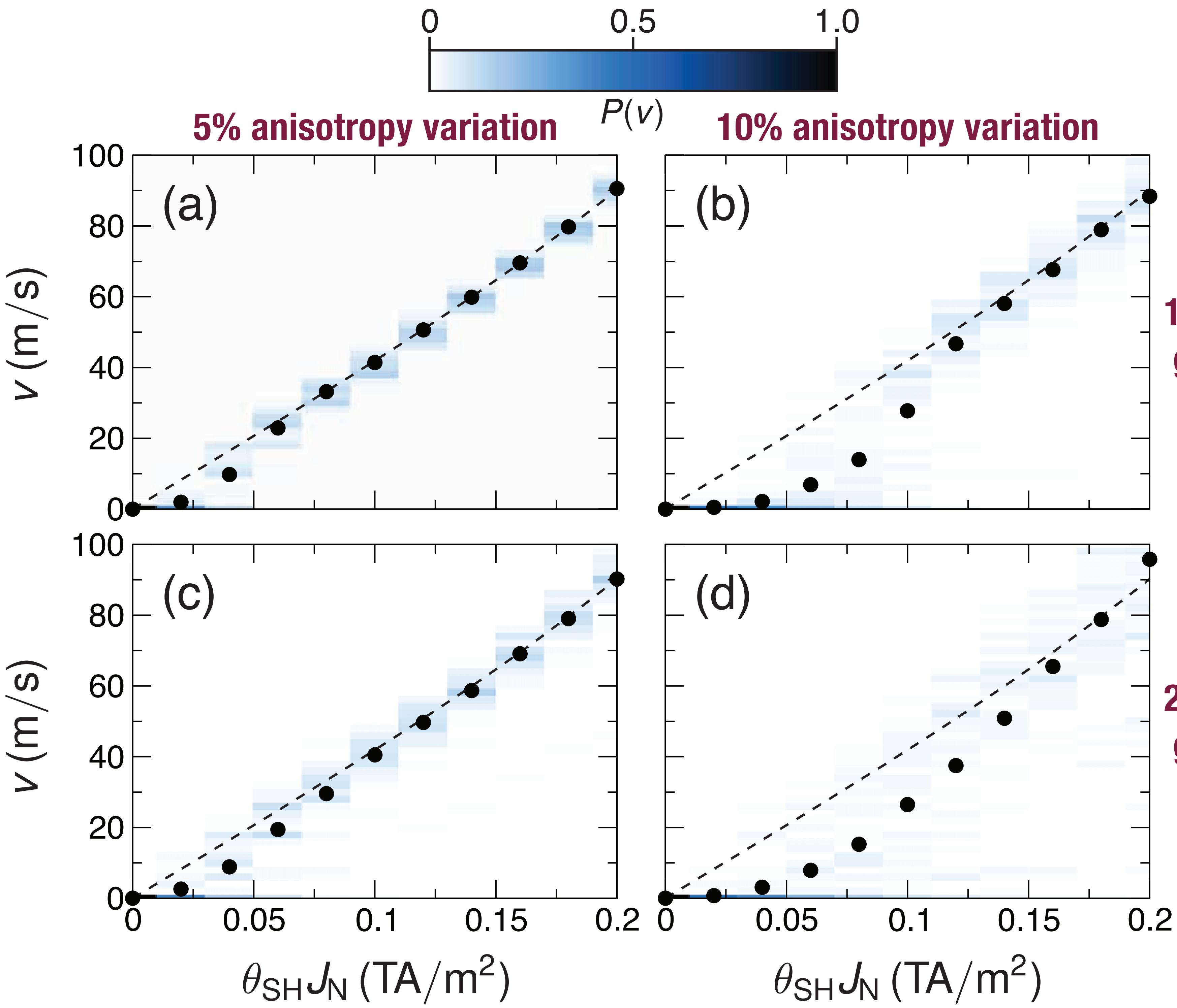
Motion due to the spin Hall effect

J.-V. Kim *et al*., arXiv:1701.08357

- Considered spin torques due to the spin Hall effect
- Implicit assumption: Current density J_N flows through a heavy-metal under layer along *x* (e.g., Pt, W, …), which leads to spin current polarized along *y* that flows in the *z* direction.
- Caveat: currents must be below switching current at which magnetization is aligned // *y*.

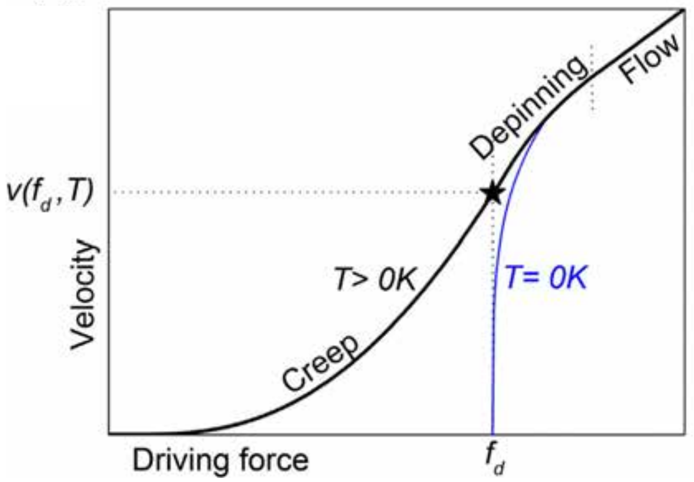


$$\frac{d\mathbf{m}}{dt} = -|\gamma|\mu_0 \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} + \frac{\hbar\gamma}{2eM_s d}\theta_{\text{SH}} J_{\text{N}}\, \mathbf{m} \times (\mathbf{m} \times \hat{\mathbf{y}})$$



10 nm avg. grain size

20 nm avg. grain size



- Pinning observed at low currents, disorder-free regime attained as current is increased.

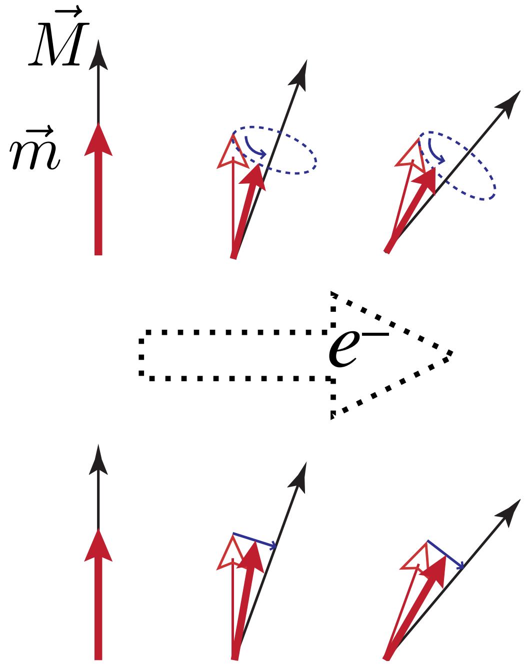
Motion due to CIP currents

J.-V. Kim *et al.*, arXiv:1701.08357

- Also considered spin torques due to current flow through ferromagnet

- Implicit assumption: Uniform current density J_F leads to torques that depend on magnetization gradients (Zhang-Li model)

- Caveat: currents must be below instability threshold for uniform magnetization state



$$\frac{1}{\tau_{\rm ex}} \sim \gamma_0 H_{sd}$$

Adiabatic: spin precession

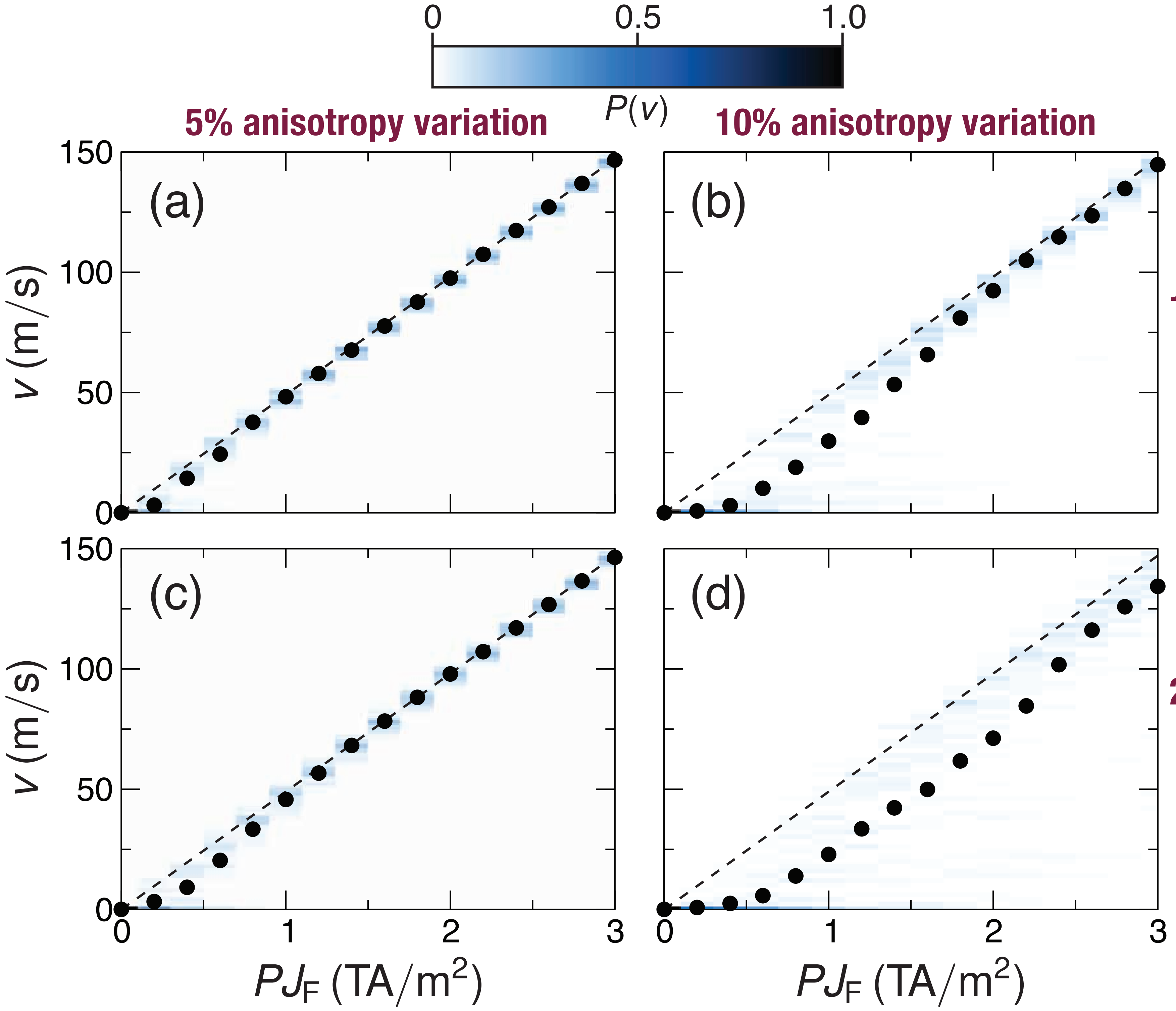
$$-\frac{\delta m}{\tau_{\rm sf}}$$

Nonadiabatic: spin relaxation

$$\mathbf{u} = (\hbar\gamma/2eM_s)P\,\mathbf{J}_{\rm F}$$

Effective spin current drift velocity

$$\frac{d\mathbf{m}}{dt} = -|\gamma|\mu_0 \mathbf{m} \times \mathbf{H}_{\rm eff} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} \underbrace{- \mathbf{u}\cdot\nabla\mathbf{m}}_{\text{adiabatic}} + \underbrace{\beta\, \mathbf{m} \times (\mathbf{u}\cdot\nabla\mathbf{m})}_{\text{nonadiabatic}}$$

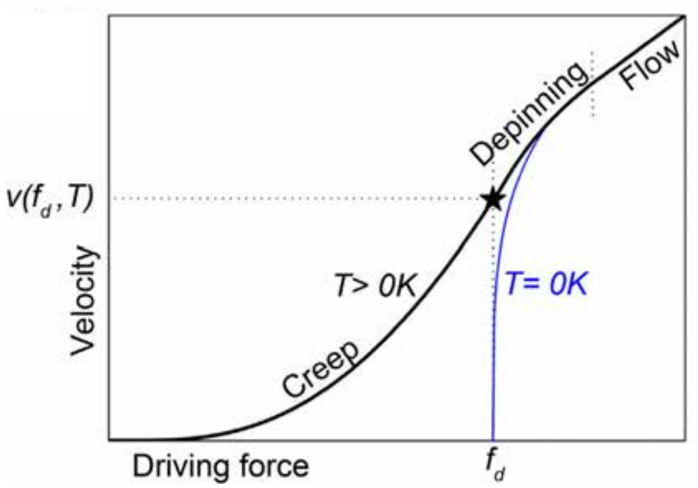


5% anisotropy variation

10% anisotropy variation

10 nm avg. grain size

20 nm avg. grain size



- Similar pinning behavior observed as for SHE-driven motion

Extrinsic skyrmion Hall effect

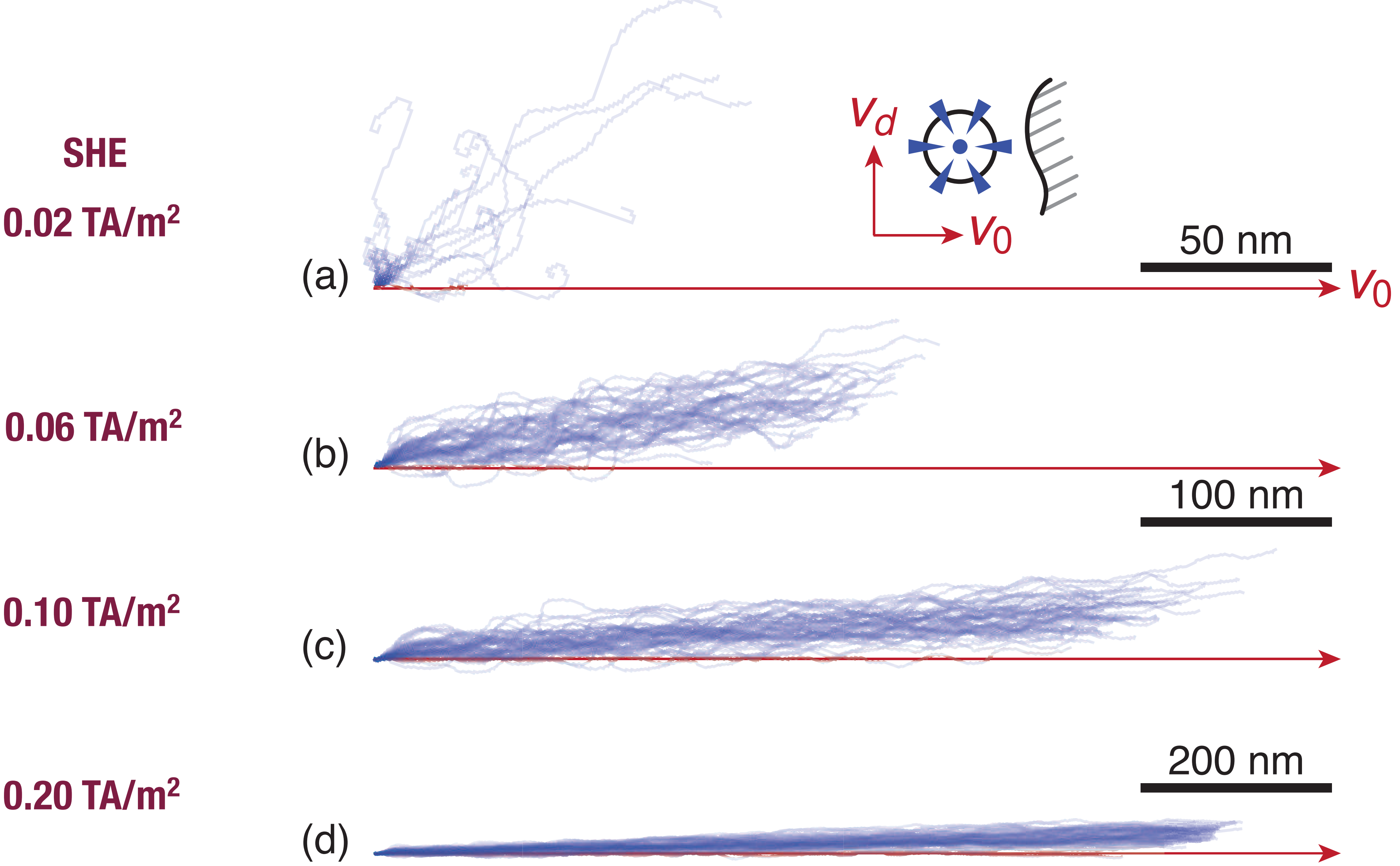
J.-V. Kim *et al*., arXiv:1701.08357

- Disorder-induced local fields lead to jagged motion of skyrmion
- Pinning forces (cf. boundary edges) give rise to additional Hall effect

SHE

5% anisotropy variation

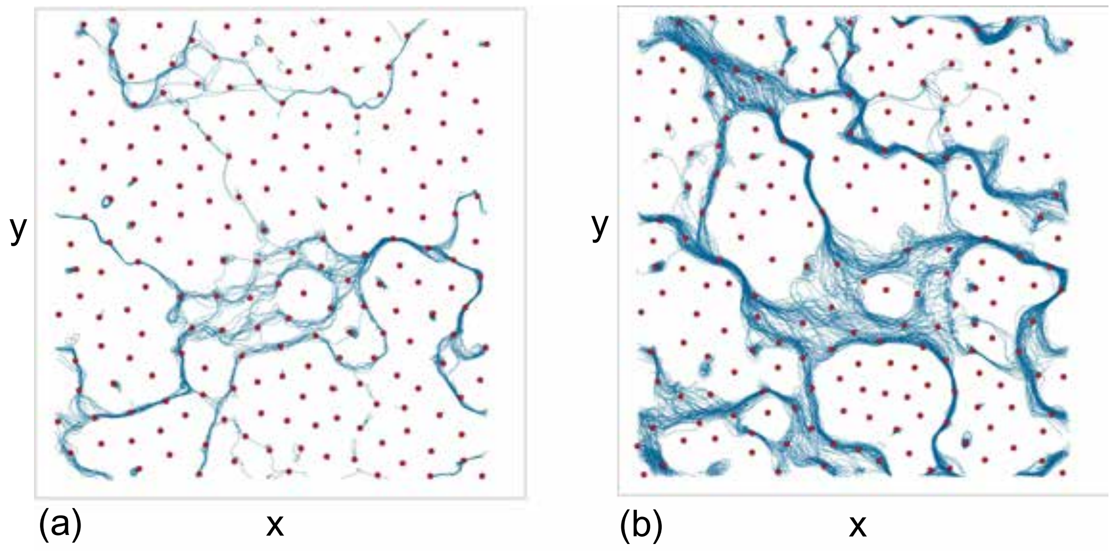
10 nm avg. grain size

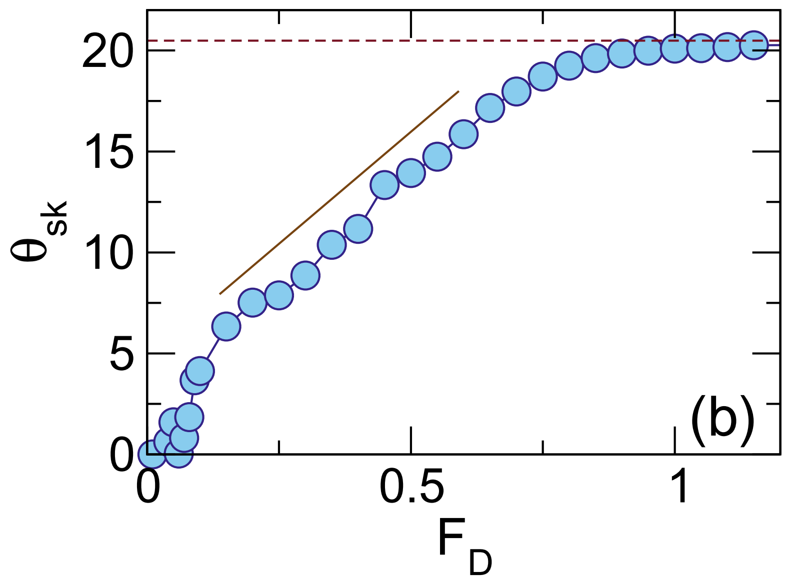


- Behavior consistent with molecular dynamics simulations (hard cores) and recent experimental results

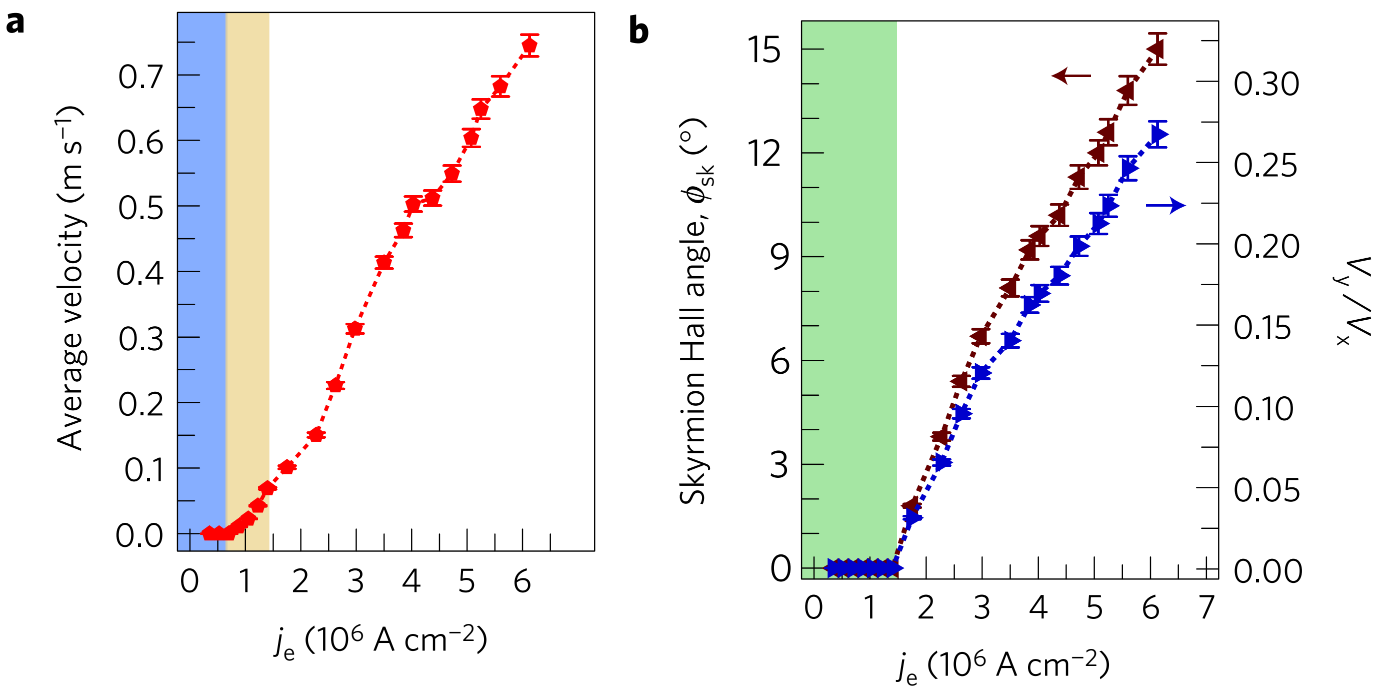
Molecular dynamics

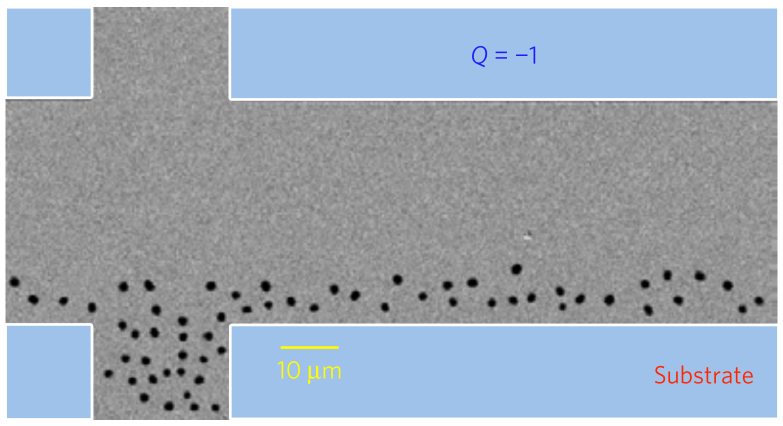
Experiments on Ta/CoFeB/TaOx





C. Reichhardt *et al*., New J. Phys. 2016





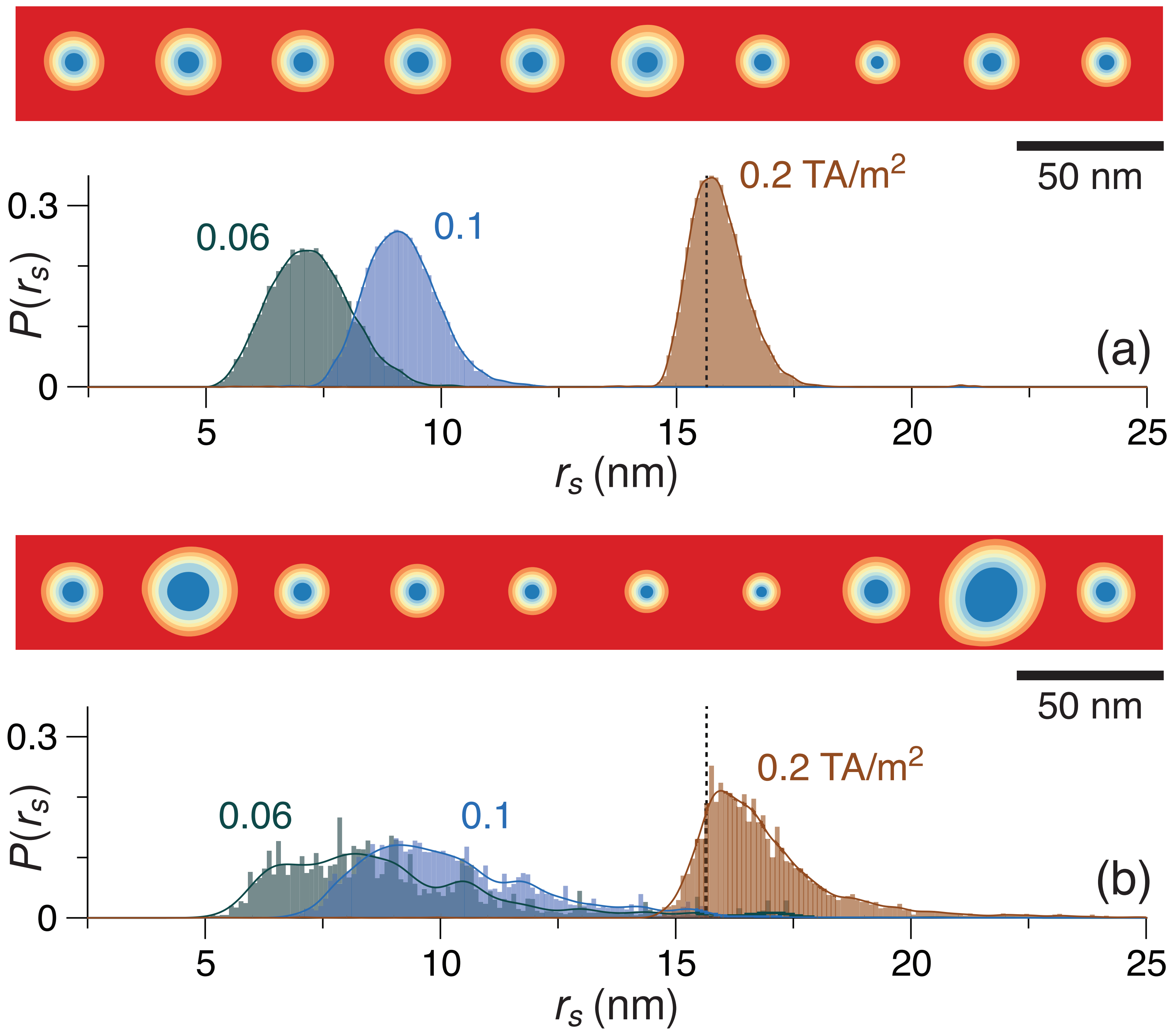
W. Jiang *et al*., Nat. Phys. 2017

Fluctuations of core size

J.-V. Kim *et al.*, arXiv:1701.08357

20 nm avg. grain size

Large variations in core size seen as skyrmion propagates through disordered film

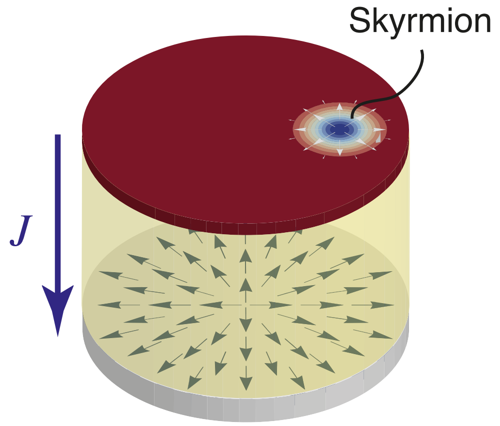


5% anisotropy variation

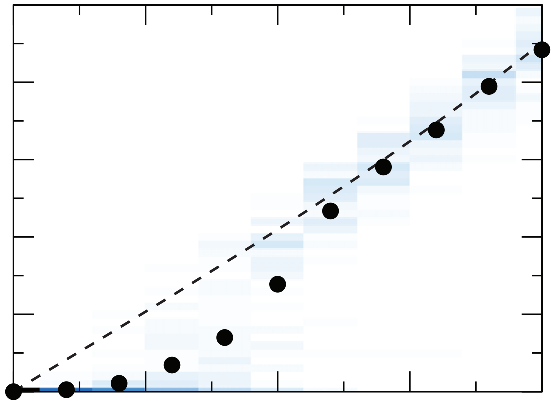
10% anisotropy variation

Summary and outlook

- Examined boundary edge and disorder-induced confinement effects in ultrathin ferromagnets with perpendicular anisotropy:
  - *Skyrmion oscillators with inhomogeneous polarizers* [1]
  - *Current-induced motion in disordered films* [2]



- Disorder can result in strong pinning, finite threshold currents, stochastic motion in realistic films
  - *Undesired effects for information storage applications, possibly no advantages compared with domain walls*



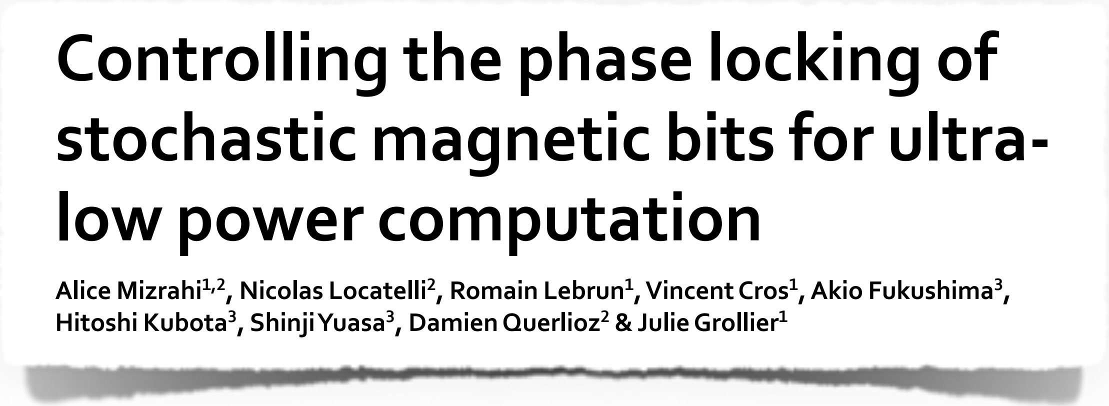
- Besides their fundamental interest, can skyrmions actually be used for applications?

[1] F. Garcia-Sanchez *et al*., New J. Phys. (2016)
[2] J.-V. Kim *et al*., arXiv:1701.08357

Exploiting the stochastic nature of skyrmion dynamics?

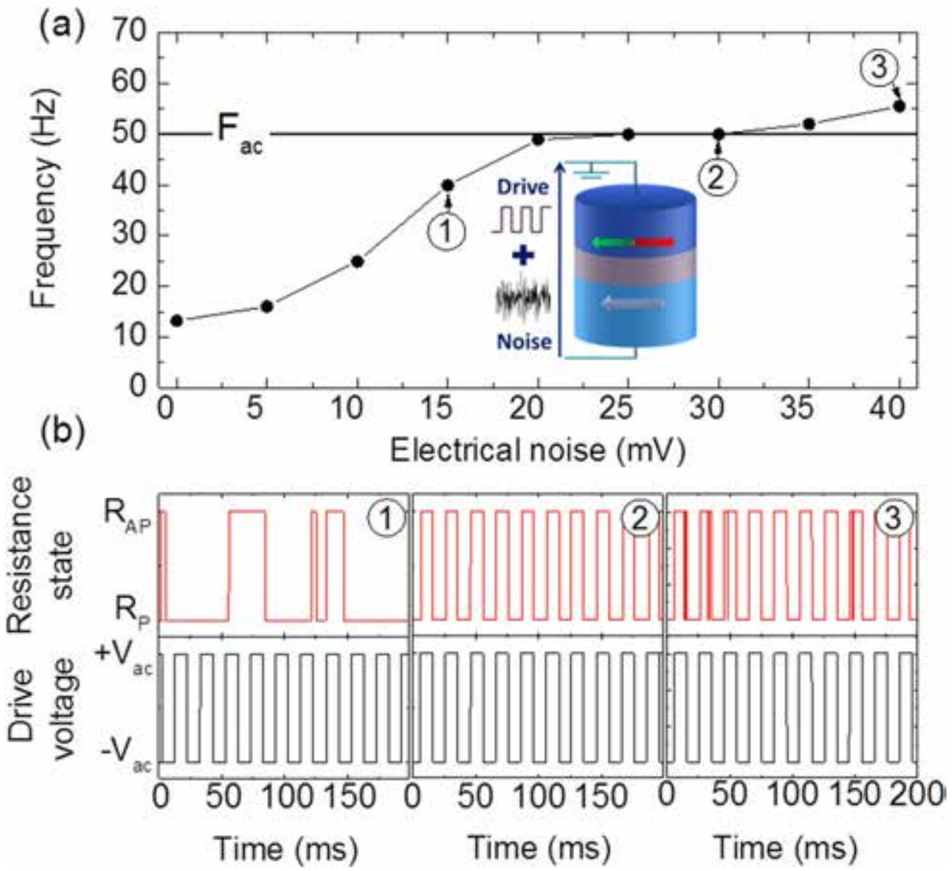
- Idea: Instead of exploiting the deterministic nature (hard), why not use the stochastic nature (easier) instead for applications?

arXiv:1701.07750

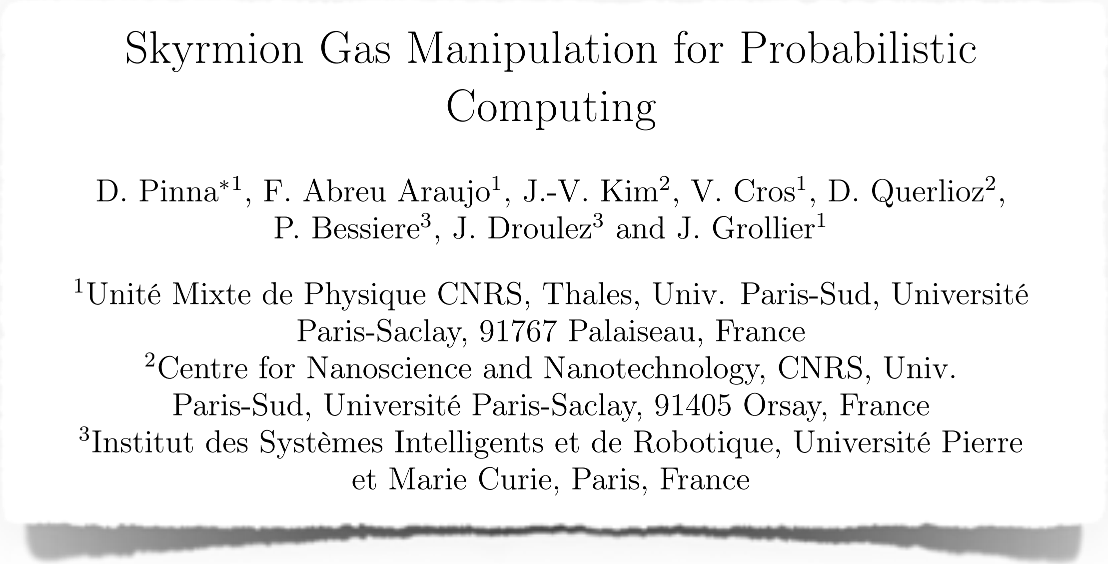


Controlling the phase locking of stochastic magnetic bits for ultra-low power computation

Alice Mizrahi[1,2], Nicolas Locatelli[2], Romain Lebrun[1], Vincent Cros[1], Akio Fukushima[3], Hitoshi Kubota[3], Shinji Yuasa[3], Damien Querlioz[2] & Julie Grollier[1]



Sci. Rep. 2016



Skyrmion Gas Manipulation for Probabilistic Computing

D. Pinna*[1], F. Abreu Araujo[1], J.-V. Kim[2], V. Cros[1], D. Querlioz[2],
P. Bessiere[3], J. Droulez[3] and J. Grollier[1]

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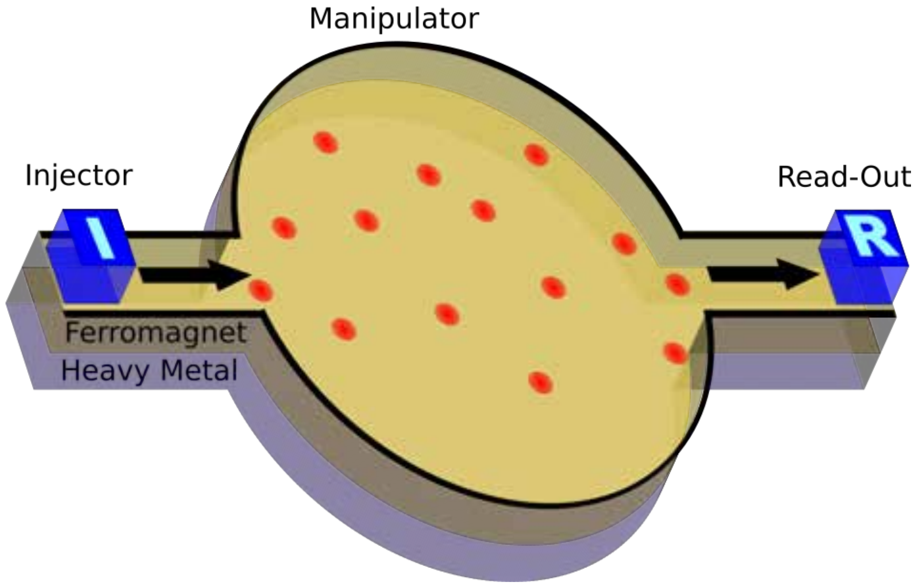
[3]Institut des Systèmes Intelligents et de Robotique, Université Pierre et Marie Curie, Paris, France



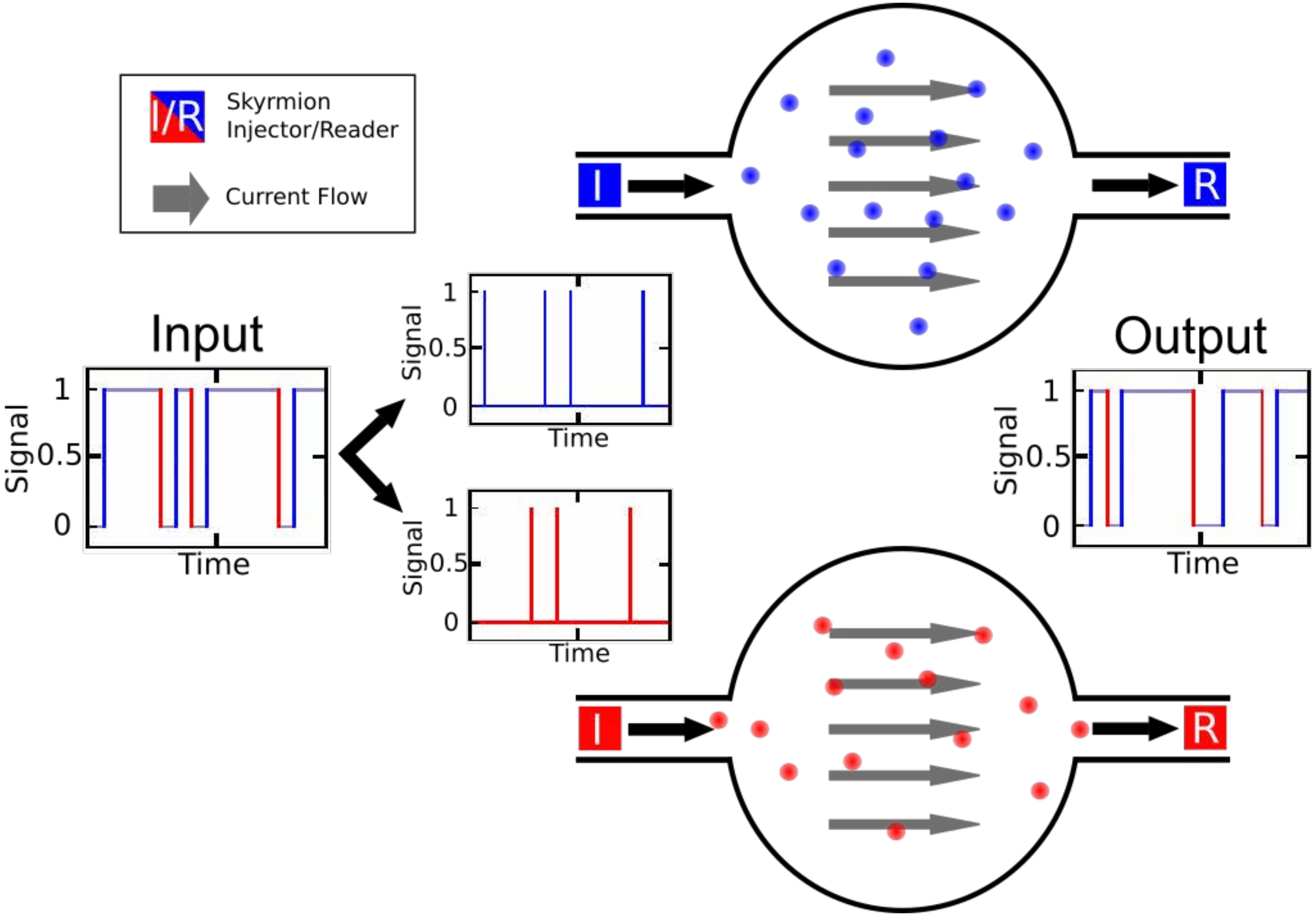
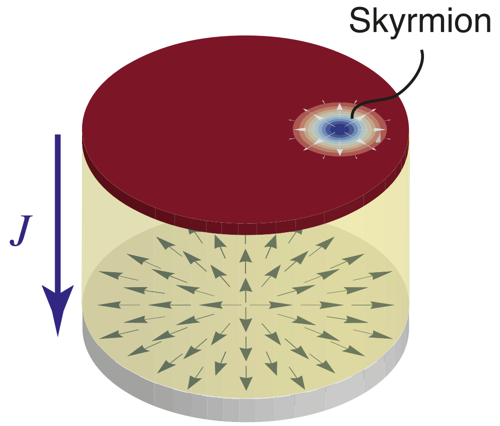


Figure 9: The proposed device consists of two magnetic chambers into which skyrmions are injected depending on the state of an input telegraph noise signal. The net drift of the skyrmion particles due to a constant current flow along with the thermal diffusion in the chambers leads to an exit order that can be significantly different from that of entry. This is employed to reconstruct a new outgoing signal with the same statistical properties as the first as well as being uncorrelated from it.

Skyrmion reshuffler device

Summary and outlook

- Examined boundary edge and disorder-induced confinement effects in ultrathin ferromagnets with perpendicular anisotropy:
  - *Skyrmion oscillators with inhomogeneous polarizers*
  - *Current-induced motion in disordered films*



- Disorder can result in strong pinning, finite threshold currents, stochastic motion in realistic films
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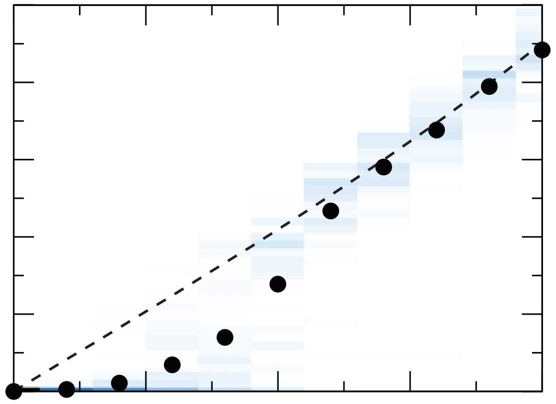

- Besides their fundamental interest, can skyrmions actually be used for applications?
  - *Stochastic-based paradigms for computing*