SPICE-SPIN+X (2022.03.16)

Ferrimagnetic Spintronics

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Outline

- Introduction

Compensated ferrimagnets @ angular momentum compensation point T_A

(1) Net angular momentum ~ 0 ➔ antiferromagnet-like

(2) Net magnetic moment ≠ 0 ➔ ferromagnet-like

- Fast ferrimagnetic domain wall (DW) motion
- Enhanced nonadiabaticity of spin current for DW motion
- Vanishing skyrmion Hall effect
- Relativistic kinematics of a magnetic DW
- Enhanced magnon-photon coupling in ferrimagnets

- Summary

Antiferromagnetic spintronics

nature physics

« Previous Issue | Volume 14 | Next Issue »

Volume 14 Issue 3, March 2018

Comment

Comment | 02 March 2018

The multiple directions of antiferromagnetic spintronics

New developments in spintronics based on antiferromagnetic materials show promise for improved fundamental understanding and applications in technology.

T. Jungwirth, J. Sinova [...] & C. Felser

Antiferromagnetic spintronics

V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono, and Y. Tserkovnyak
Rev. Mod. Phys. **90**, 015005 – Published 15 February 2018

Perspectives

Perspective | 02 March 2018

Antiferromagnetic spin textures and dynamics

As part of a Focus on antiferromagnetic spintronics, this Perspective looks at the complex and often faster dynamics of antiferromagnetic spin textures.

O. Gomonay, V. Baltz [...] & Y. Tserkovnyak

Focus: Antiferromagnetic spintronics

Perspective | 02 March 2018

Synthetic antiferromagnetic spintronics

As part of a Focus on antiferromagnetic spintronics, this Perspective examines the opportunities afforded by synthetic, as opposed to crystalline, antiferromagnets.

R. A. Duine, Kyung-Jin Lee [...] & M. D. Stiles

Focus: Antiferromagnetic spintronics

Review Articles

Review Article | 02 March 2018

Spin transport and spin torque in antiferromagnetic devices

As part of a focus on antiferromagnetic spintronics, this Review considers the role of spin transport and spin torque in potential antiferromagnetic memory devices.

J. Železný, P. Wadley [...] & H. Ohno

Focus: Antiferromagnetic spintronics

Review Article | 02 March 2018

Antiferromagnetic opto-spintronics

An overview of how electromagnetic radiation can be used for probing and modification of the magnetic order in antiferromagnets, and possible future research directions.

P. Němec, M. Fiebig [...] & A. V. Kimel

Focus: Antiferromagnetic spintronics

Review Article | 02 March 2018

Topological antiferromagnetic spintronics

Topological states of various kinds may find application in spintronic devices. The authors review recent progress in this area.

Rare-earth (RE)–transition metal (TM) Ferrimagnet

$\boldsymbol{S}$ = Angular momentum

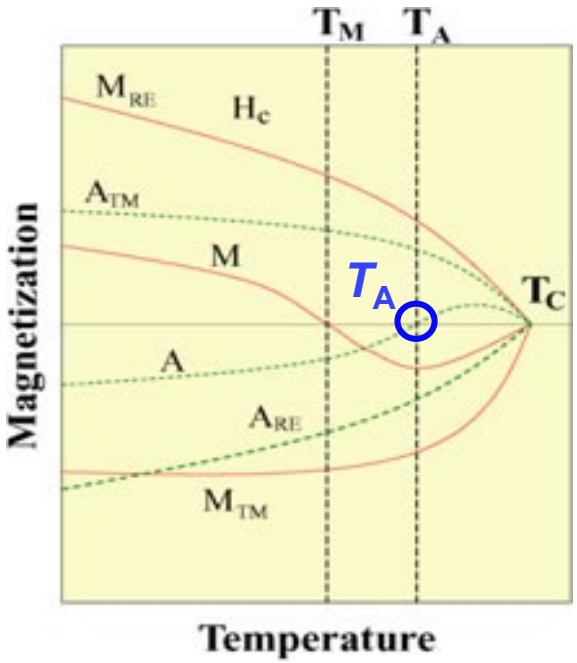
$\boldsymbol{M}$ = Magnetic moment

γ = Gyromagnetic ratio

$$\boldsymbol{S} = -\frac{\boldsymbol{M}}{\gamma} = -\frac{\hbar}{g_L \mu_B}\boldsymbol{M}$$

- Lande-g factor (g_L)

  ➔ 2.2 for Co, 2.0 for Gd



For RE-TM ferrimagnets, T_M ($\mathbf{M}_{tot}$ = 0 but $\mathbf{S}_{tot} \neq 0$) is different from $\mathbf{T_A}$ ($\mathbf{S}_{tot}$ = 0 but $\mathbf{M}_{tot} \neq 0$)

T_M: Magnetic moment compensation point

T_A: Angular moment compensation point ➔ Spin dynamics is antiferromagnetic at $\mathbf{T_A}$ + finite Zeeman coupling

Antiferromagnet vs Ferrimagnet

$$\frac{d\boldsymbol{S}}{dt} = \frac{1}{i\hbar}[\boldsymbol{S}, \mathcal{H}] \xrightarrow{\mathbf{M} = \gamma \mathbf{S}} \frac{d\mathbf{M}}{dt} = -\gamma \mathbf{M} \times \mathbf{B}$$

Time evolution of the state of a magnet is governed by the commutation relation of the angular momentum **S**, not of the magnetic moment **M**.

At $\mathbf{T_A}$ ($\mathbf{S}_{tot}$ = 0 but $\mathbf{M}_{tot} \neq 0$), the spin dynamics of ferrimagnets is antiferromagnetic, but a magnetic field works

Field-driven ferrimagnetic DW motion: Theory

Equations of Motion with two collective coordinates:

DW position X and DW angle ϕ

$$M\ddot{X} + G\dot{\phi} + \frac{M}{\tau}\dot{X} = F$$

$$I\ddot{\phi} - G\dot{X} + \frac{I}{\tau}\dot{\phi} = -\kappa \sin\phi \cos\phi$$

M : Mass

I : the moment of inertia

G : Gyrotropic coeff

τ : relaxation time

F : Force (external field)

κ : DW hard-axis anisotropy

- G = $2(S_1 - S_2)$ x Area
- At T = T_A ➔ $S_1 - S_2 = \delta_s = 0$ ➔ G = 0

➔ X and ϕ are decoupled

Field-driven ferrimagnetic DW motion: Theory (2)

In the precessional regime

DW speed $$v_{DW} = \frac{\alpha s}{(\alpha s)^2 + \delta_s^2}(M_1 - M_2)\lambda H$$

Walker breakdown field $$H_{WB} = \frac{K_d \alpha s}{2\delta_s (M_1 - M_2)\lambda}$$

- At $T = T_M$ ➔ $M_1 - M_2 = 0$

  ➔ $v_{DW} = 0$

& DW motion changes its direction at T_M

- **At $T = T_A$ ➔ $\delta_s = 0$ & $M_1 - M_2 \neq 0$**

  ➔ v_{DW} = maximum & $H_{WB} \rightarrow \infty$

$$\alpha S = \alpha_1 S_1 + \alpha_2 S_2$$

α : damping constant

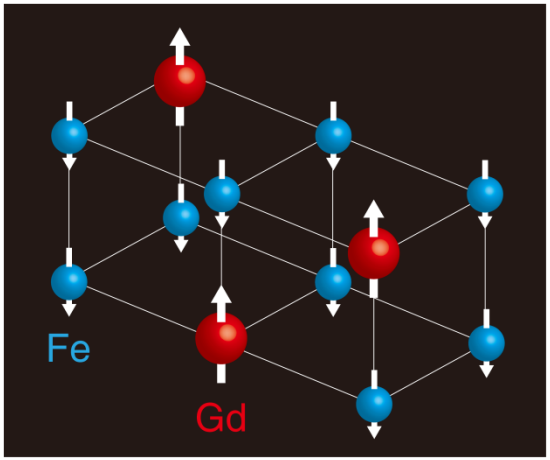
λ : DW width

H : external field

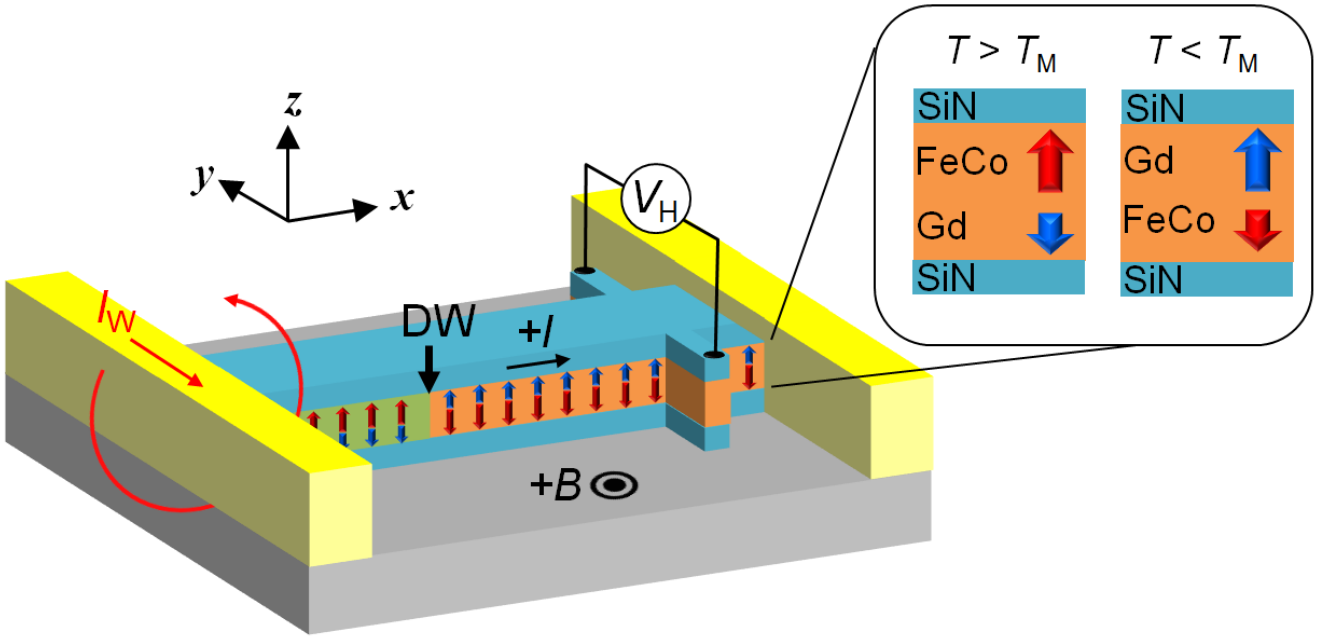
K_d : DW hard-axis anisotropy

Field-driven DW Experiment: FeCoGd

Kim et al., Nat. Mater. 16, 1187 (2017)

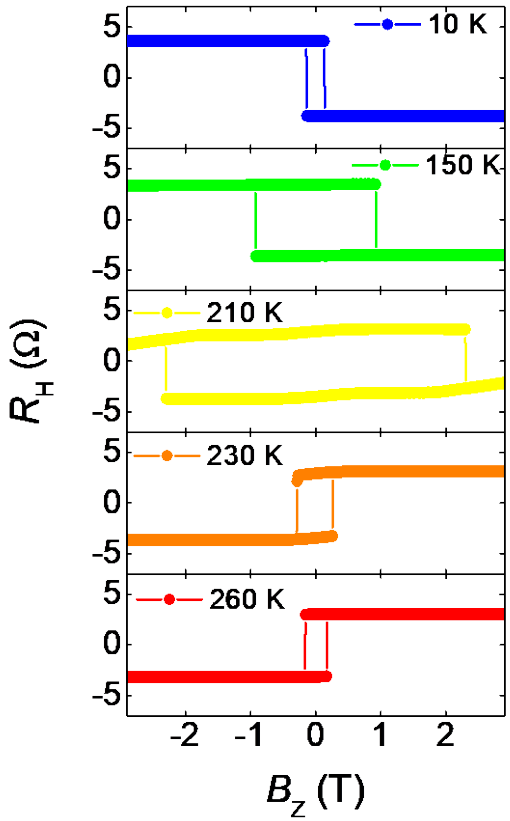


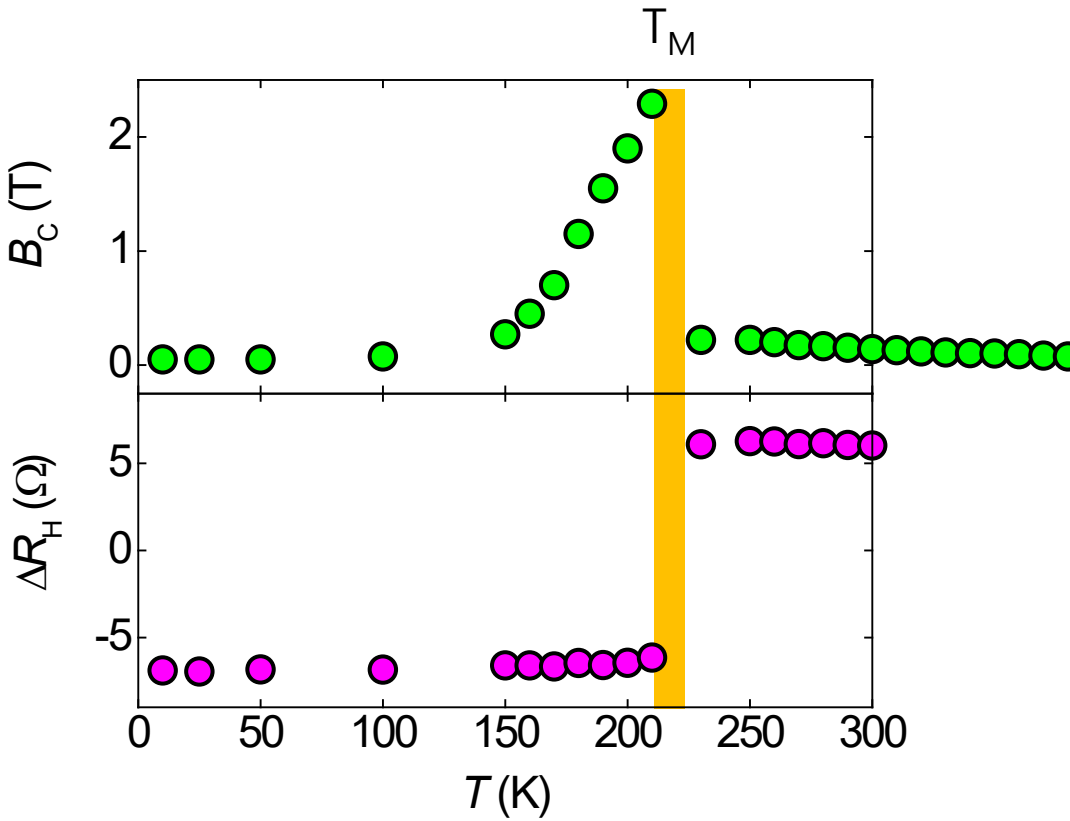
Done by T. Ono's group



Determination of T_M

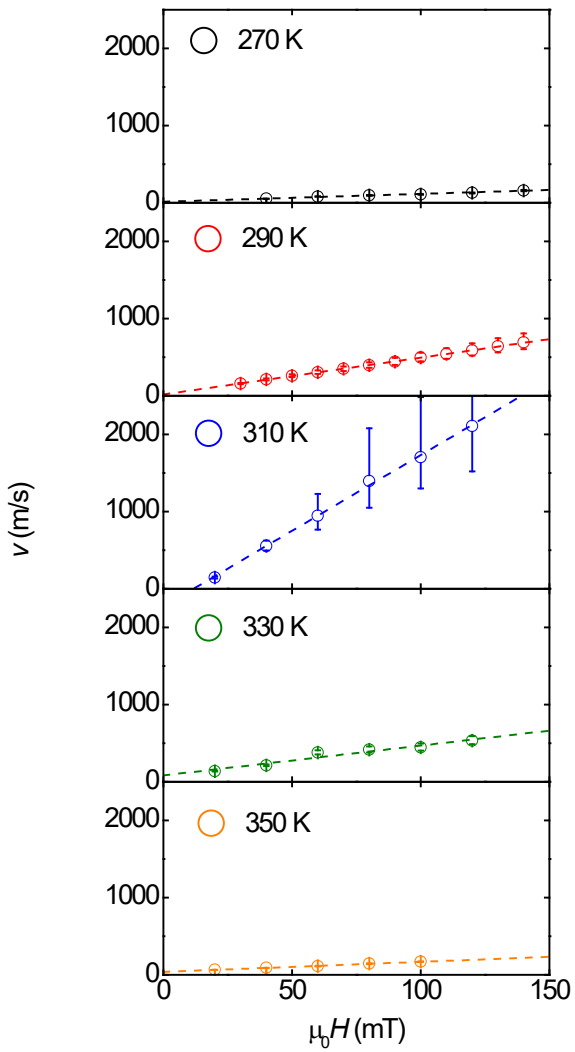
T_M : Magnetization compensation temperature

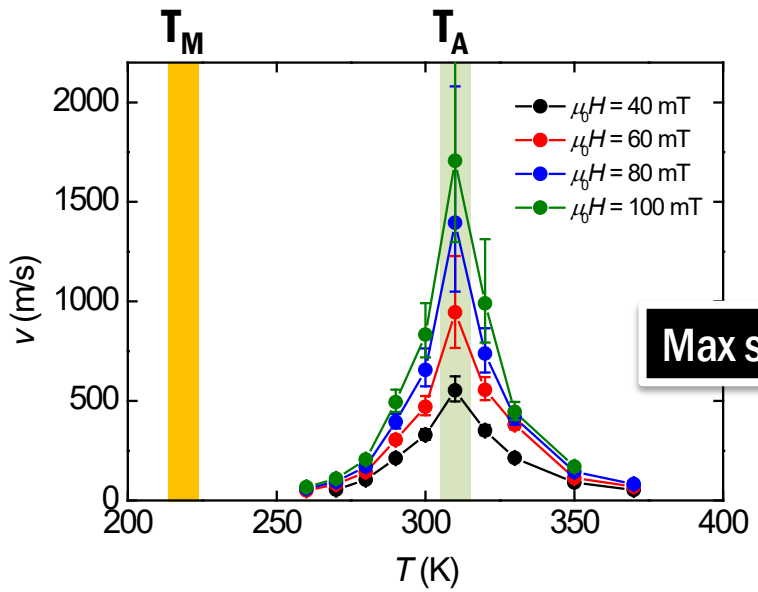




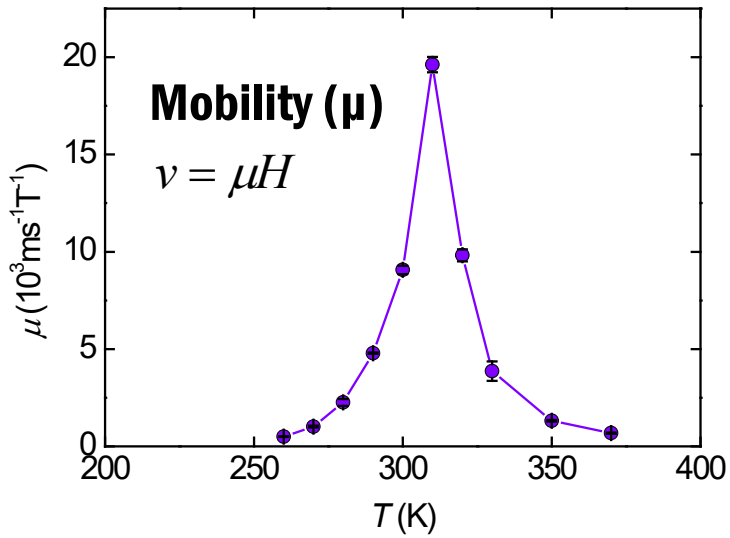
T_M is found to be 220 K

DW velocity: Experiment





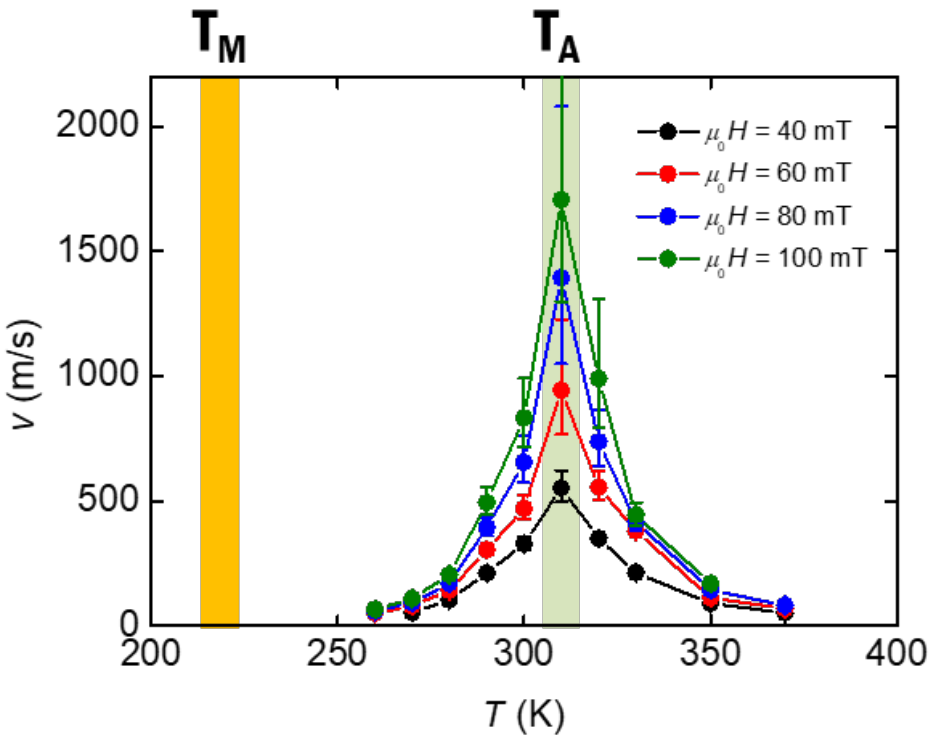
Max speed: 1.7 km/s



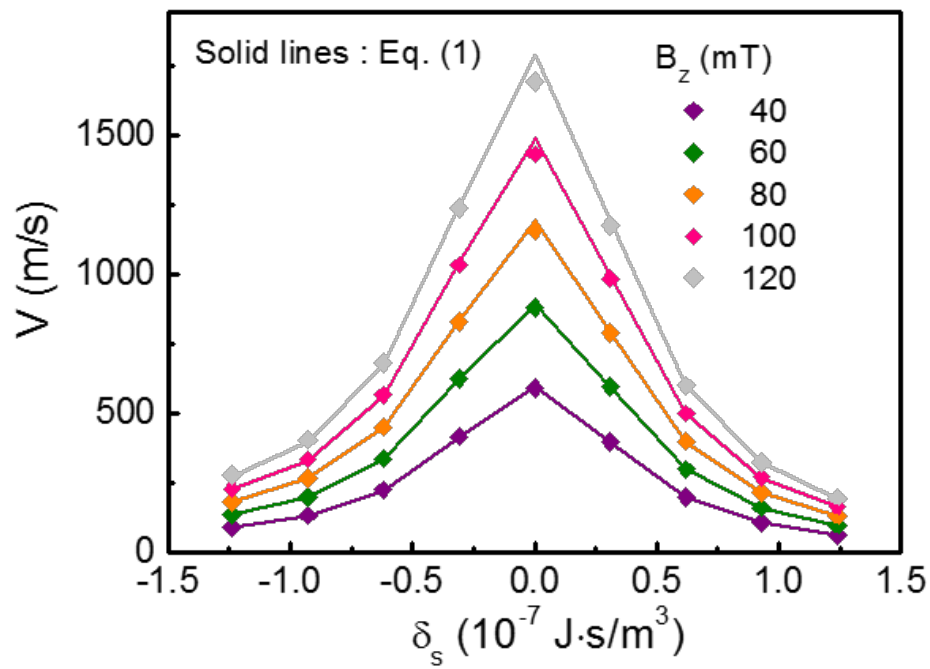
Field-driven DW Experiment: FeCoGd

Kim et al., Nat. Mater. 16, 1187 (2017)

Experiment (T. Ono group)



Theory/Modeling

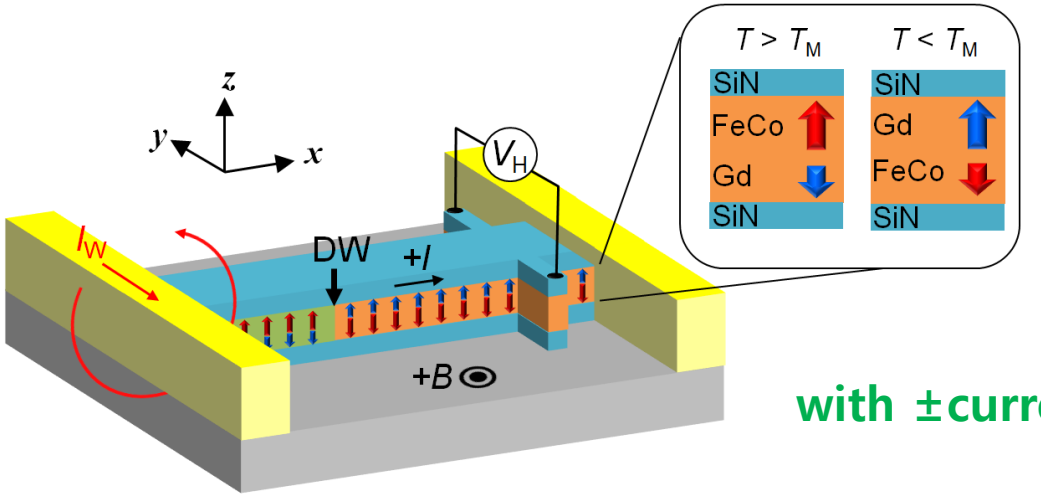


- Solid lines : $$v_{DW} = \frac{\alpha s}{(\alpha s)^2 + \delta_s^2}(M_1 - M_2)\lambda H$$

- T_A ➔ $\delta_s = 0$

Field-driven DW motion assisted by ±current J

T. Okuno et al. Nat. Electron. 2, 389 (2019)



with ±current injection

$$v_H = \frac{v(H,+J)+v(H,-J)}{2} = \frac{\alpha s(M_1 - M_2)}{\delta_s^2 + (\alpha s)^2}\lambda H$$

➔ Equivalent with the previous work

$$v_{STT} = \frac{v(H,+J)-v(H,-J)}{2} = -\frac{\delta_s}{\delta_s^2 + (\alpha s)^2}PJ - \frac{\alpha\beta s}{\delta_s^2 + (\alpha s)^2}PJ$$

$v_{A\text{-}STT}$: adiabatic STT

$v_{N\text{-}STT}$: non-adiabatic STT

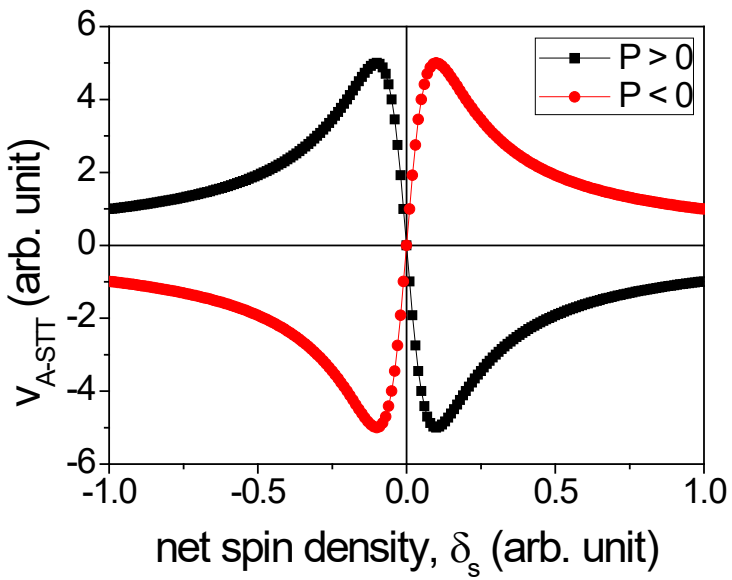
P = spin polarization, α = damping, β = non-adiabaticity

Expected v_{STT} as a function of temperature (or δ_s)

The signs of P and β do not change at T_A (i.e., spin transport is dominated by TM elements)

Adiabatic STT

$$v_{A-STT} = -\frac{\delta_s}{\delta_s^2 + (\alpha s)^2} PJ$$

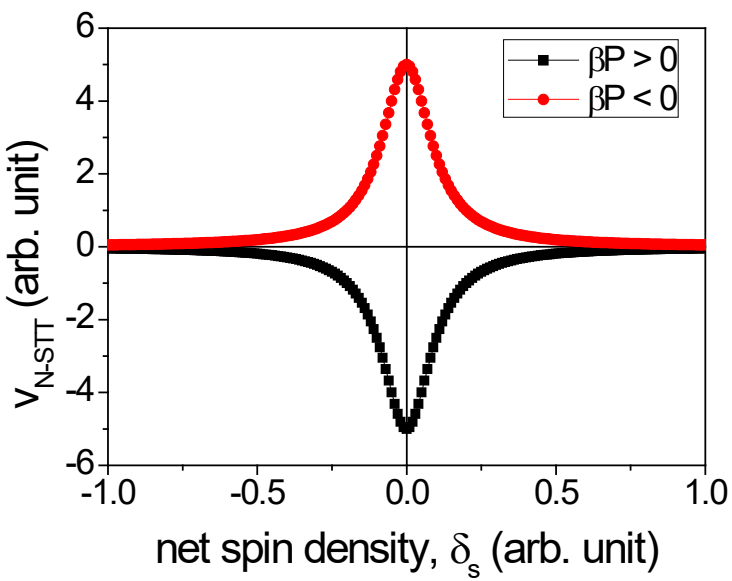


Anti-symmetric & $v_{A\text{-}STT}$ = 0 @ T_A

➔ No DW tilting ➔ No adiabatic contribution

Non-adiabatic STT

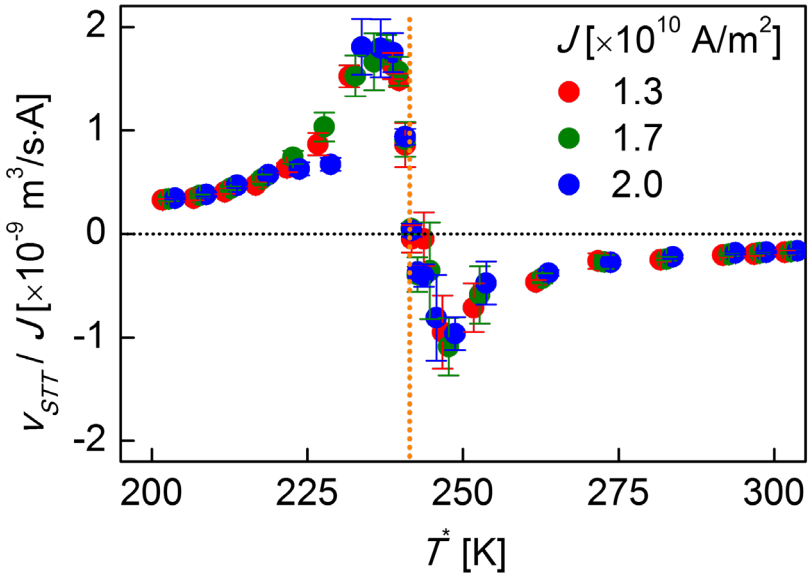
$$v_{N-STT} = -\frac{\alpha\beta s}{\delta_s^2 + (\alpha s)^2} PJ$$

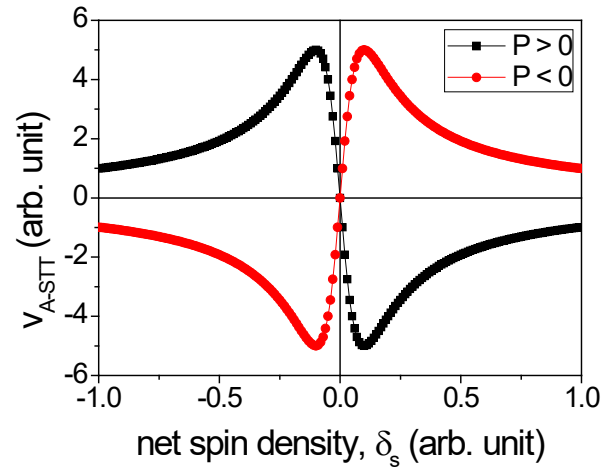


Symmetric & $|v_{N\text{-}STT}|$ = max @ T_A

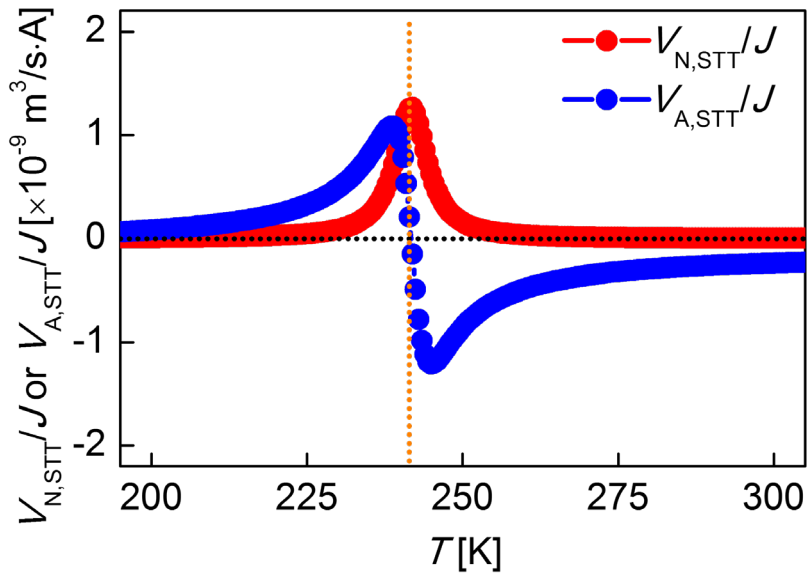
➔ Equivalent with a magnetic field

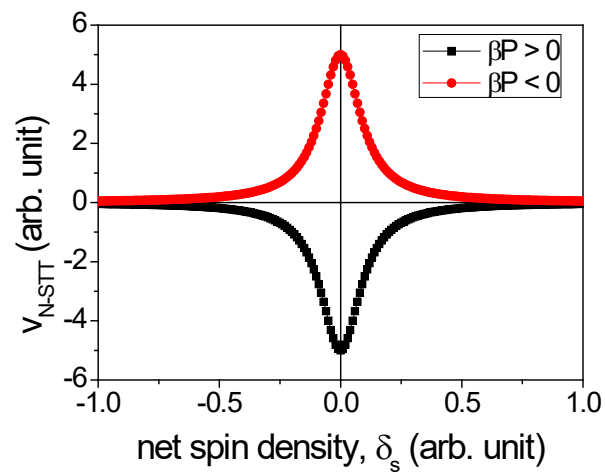
Field-driven DW motion assisted by ±current J





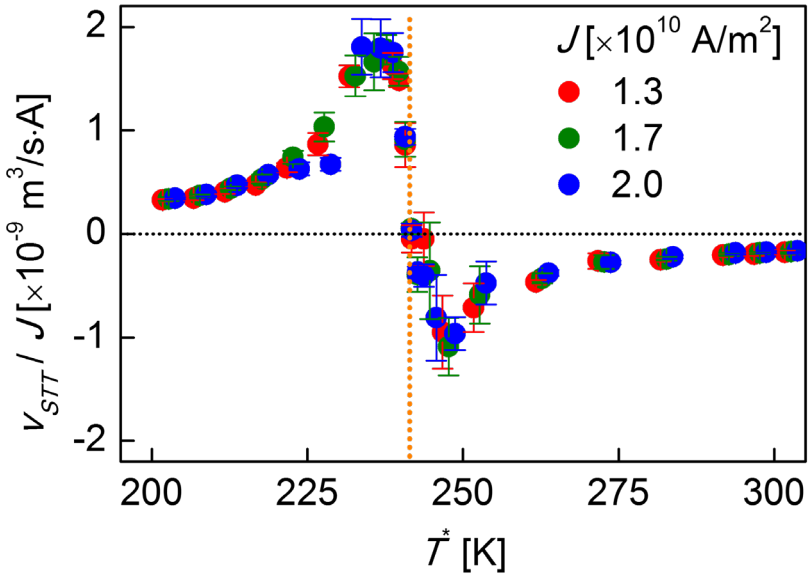
P > 0

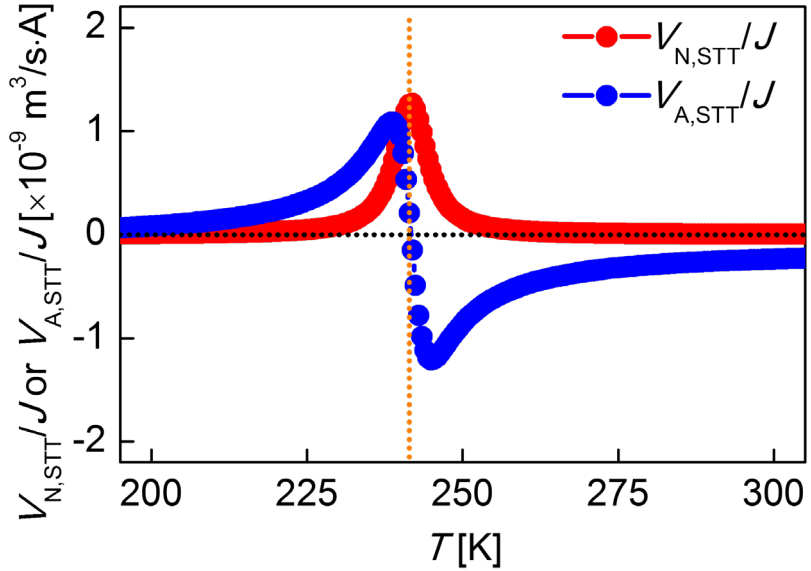




βP < 0 ➔ β < 0

Fitting results





Fitting Parameters

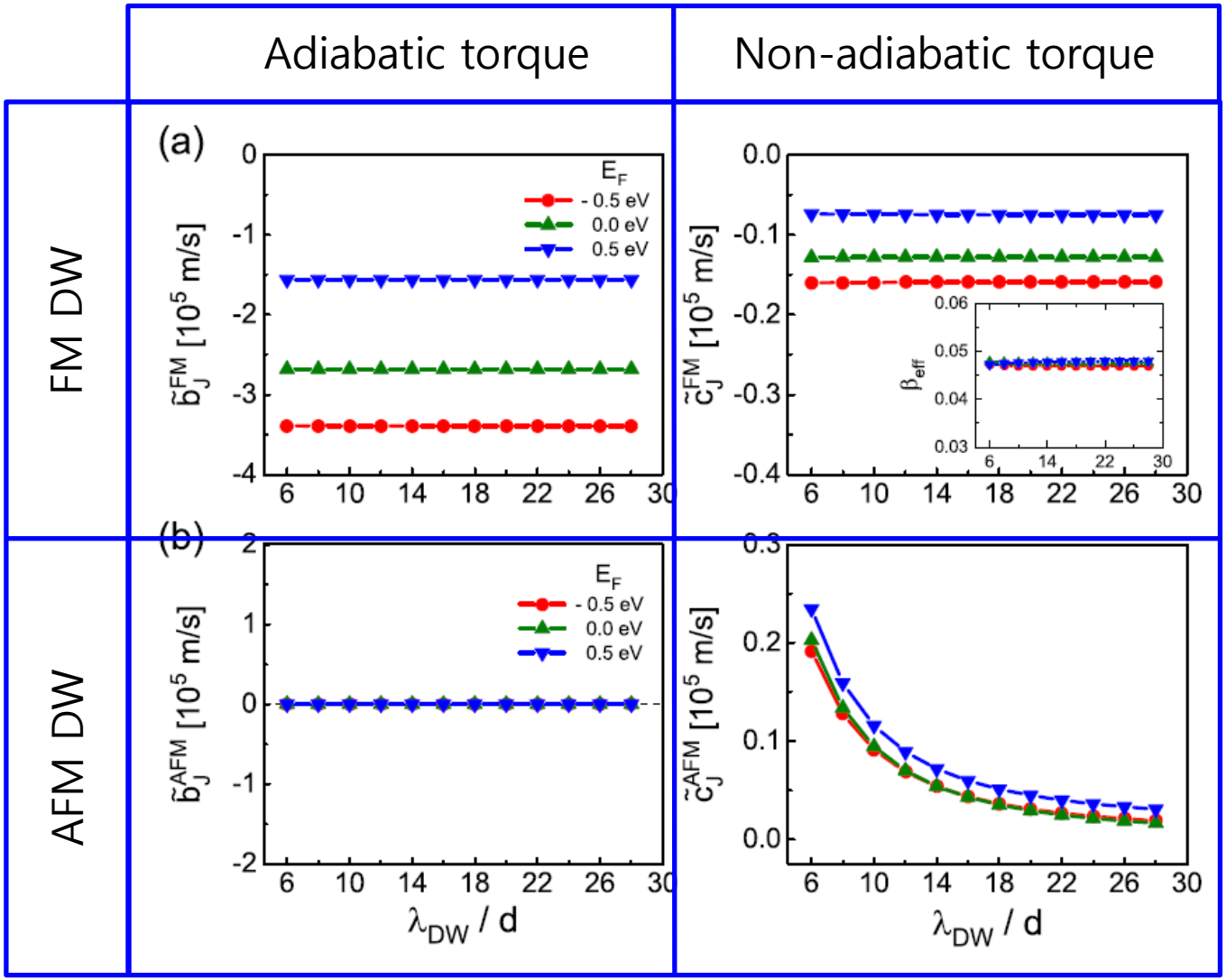
$$\alpha = 0.00317 \pm 0.00009$$
$$\beta = -0.529 \pm 0.016$$
$$P = 0.092 \pm 0.001$$

- Small damping ➔ also observed in another set of experiment (**PRL 122, 127203 (2019)**)
- Negative β ➔ Garate et al. PRB 79, 104416 (2009); β can be negative in systems with both holelike and electronlike carriers.
- Large |β| & small P ➔ possibly due to antiferromagnetic coupling

Enhanced non-adiabaticity for AF-DWs

H.-J. Park et al. Phys. Rev. B 101, 144431 (2020)

- Linear response theory in a tight-binding model

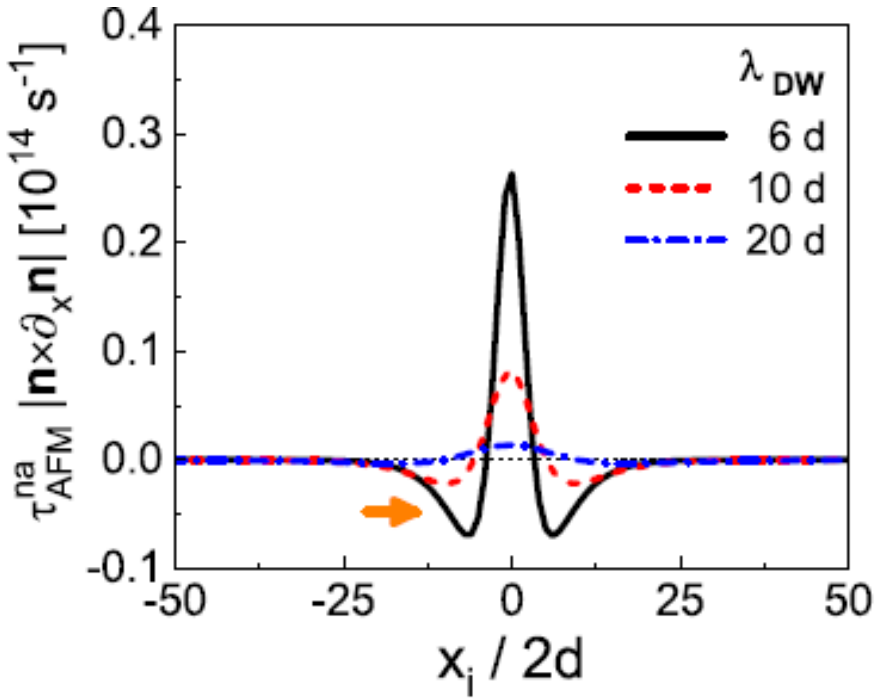


Larger non-adiabatic torque at shorter AF-DW

Enhanced non-adiabaticity for AF-DWs

H.-J. Park et al. Phys. Rev. B 101, 144431 (2020)

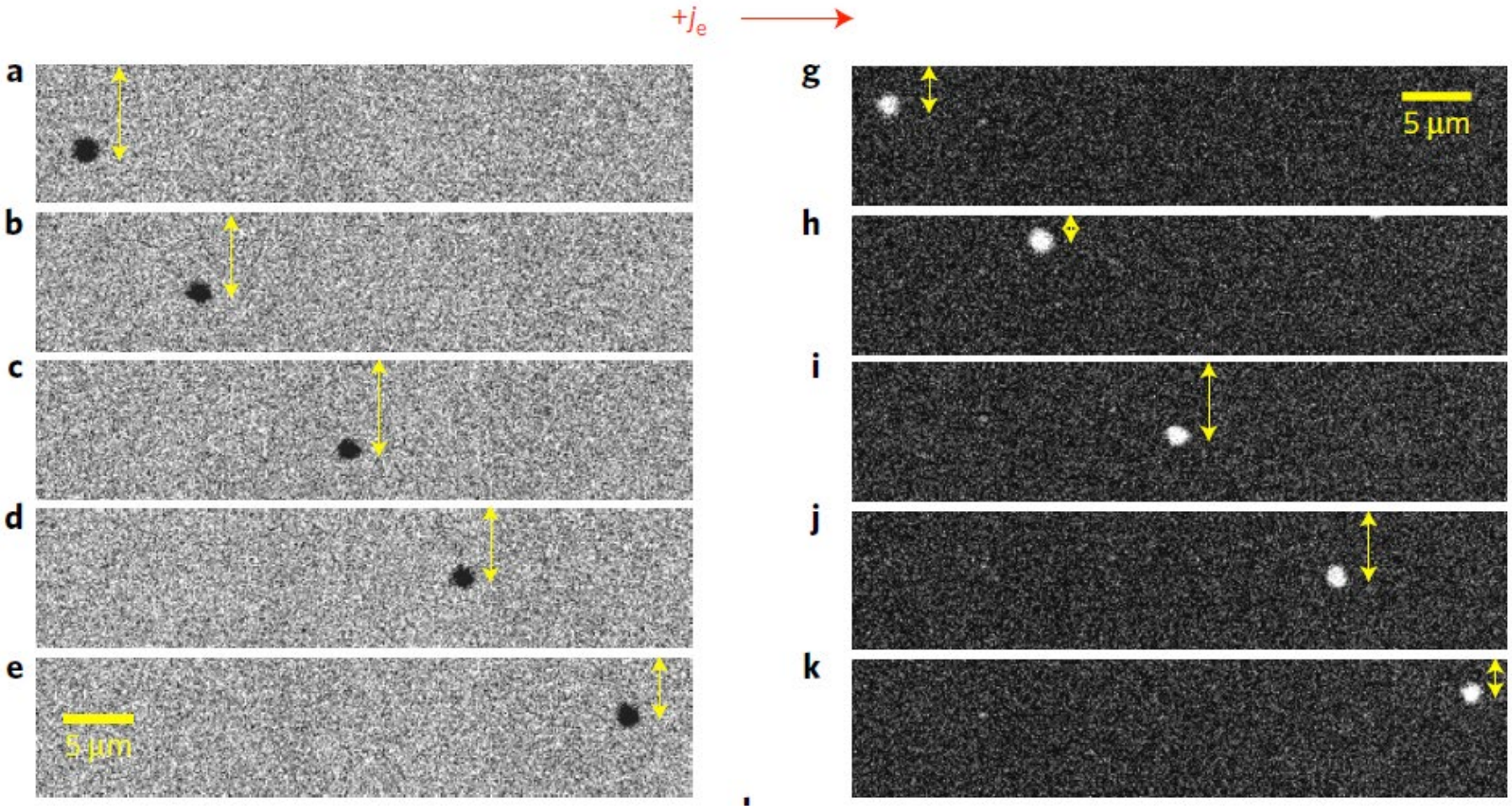
- Spatial profile of non-adiabatic torque for AF-DW



- Oscillatory behavior ➔ Enhanced non-adiabaticity due to spin mistracking [J. Xiao et al. PRB **73**, 054428 (2006); K.-J. Lee et al. Phys. Rep. **531**, 89 (2013)]
- Similar conclusion for SOT on single domain ferrimagnet [Yu et al., Nat. Mater. 18, 29 (2019)]

Skyrmion Hall effect

W. Jiang et al., Nat. Phys. (2017); K. Litzius et al., Nat. Phys. (2017)



- **Transverse deflection of skyrmion ~ the Hall effect**

Charge Hall effect vs Skyrmion Hall effect

Charge Hall effect

Elementary charge

External magnetic field

Lorentz force: $Q\dot{\boldsymbol{R}} \times \boldsymbol{B}$

Topological charge

Fictitious magnetic field

$$Q \equiv \int dxdy\boldsymbol{n} \cdot \left(\partial_x \boldsymbol{n} \times \partial_y \boldsymbol{n}\right)/4\pi$$

$$\boldsymbol{B} = -4\pi \boxed{s_{\mathrm{net}}}\hat{\boldsymbol{z}}$$

Net spin density

Skyrmion Hall effect

Vanishing skyrmion Hall effect for antiferromagnet (s_{net} = δ_s= 0)

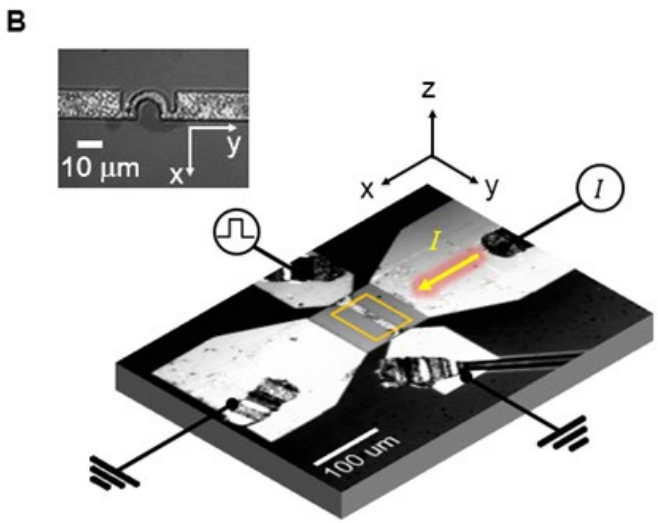
Barker & Tretiakov, PRL **116**, 147203; Zhang, Zhou, & Ezawa, NCOMM **7**, 10293 (16)

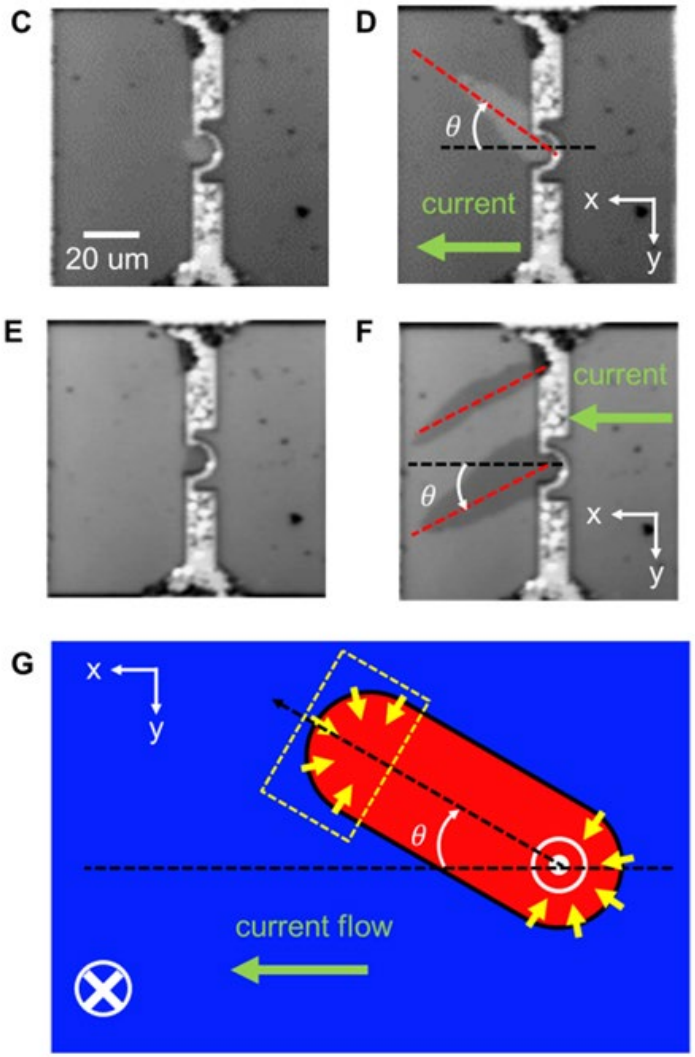
Current-driven bubble elongation in GdFeCo/Pt

Hirata et al., Nat. Nanotechnol. 14, 232 (2019)

DMI field = 63 mT >> DW hard-axis anisotropy field = 0.9 mT

➔ Well-defined topological charge Q

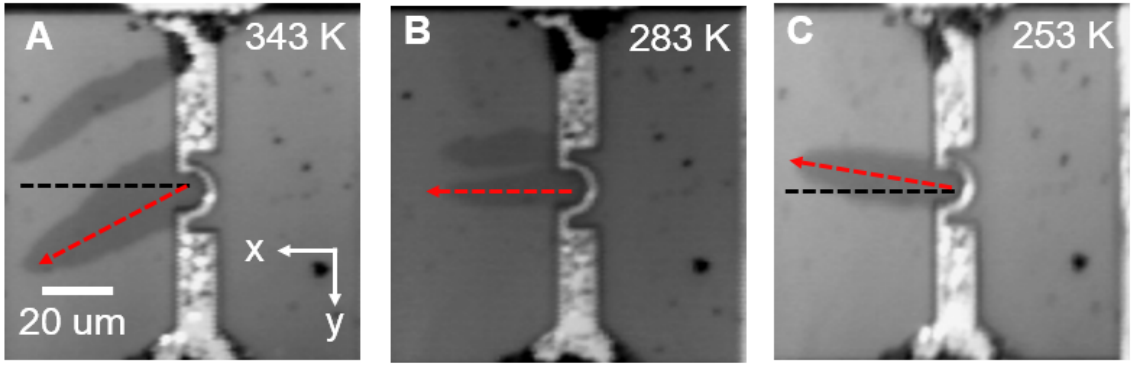




Bubble elongation ~ half skyrmion motion

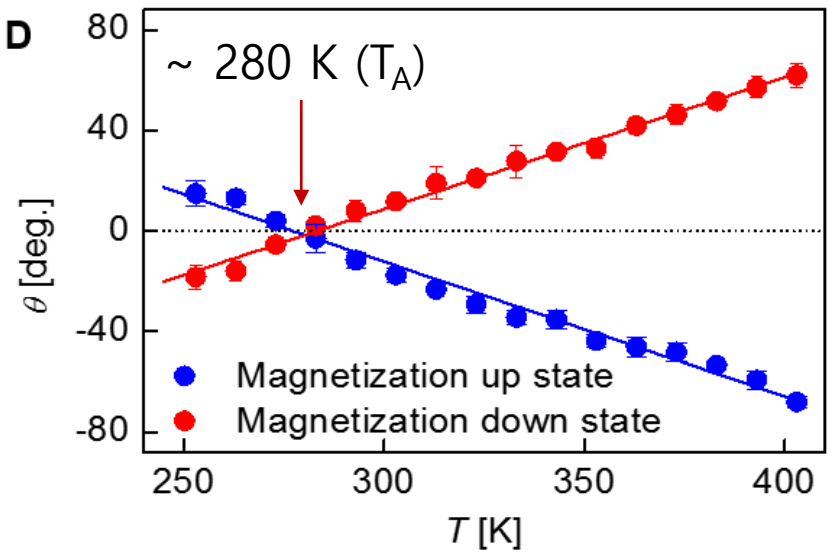
Current-driven bubble elongation in GdFeCo/Pt

Hirata et al., Nat. Nanotechnol. 14, 232 (2019)



Experiment:

T. Ono group



$$Q \equiv \int dxdy\boldsymbol{n} \cdot (\partial_x \boldsymbol{n} \times \partial_y \boldsymbol{n})/4\pi$$

$$\theta_{\mathrm{SkH}} \approx \tan^{-1}\left(\frac{2s_{\mathrm{net}}Q\lambda}{\alpha s_{\mathrm{total}} r}\right),$$

Elongation angle ≈ 0 at T_A ➔ Vanishing skyrmion Hall effect for s_{net} = 0

AF-DW motion by spin-orbit torque

Shiino et al. PRL 117, 087203 (2016)

$$v_{\mathrm{DW}} = v_{\mathrm{AF}} = -\pi\gamma\lambda B_D/2\alpha,$$

Shiino et al. PRL '16

$$v_{\mathrm{F}} = \frac{\gamma\pi D}{2m_s\sqrt{1+(\alpha D/B_D m_s\lambda)^2}}.$$

Thiaville et al. EPL '12

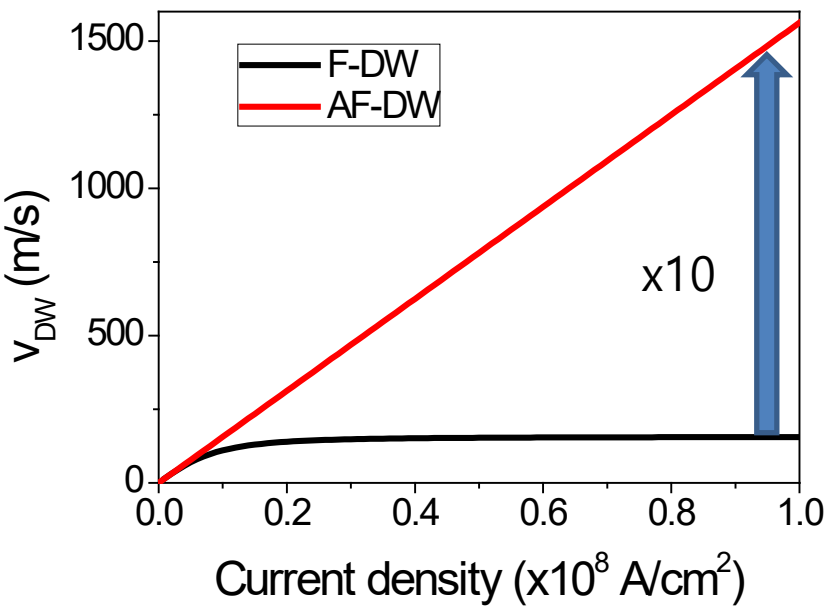
α : damping constant

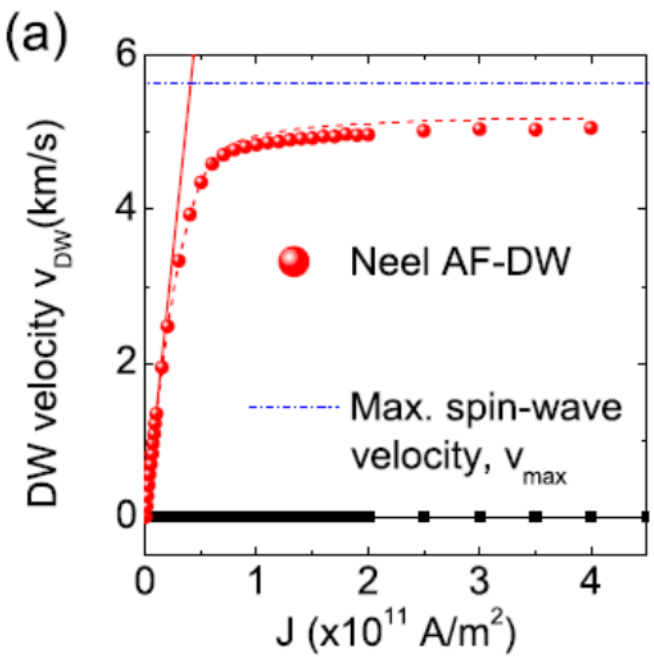
λ : DW width

D : DMI

M_S : Saturation magnetization

B_D : Damping-like SOT ~ J





See also Gomonay, Jungwirth, Sinova, PRL 117, 017202 (2016)

Antiferromagnetic spin-wave dynamics

Shiino et al. PRL 117, 087203 (2016)

$$\frac{\partial^2 n_x}{\partial t^2} = a\gamma^2 \tilde{A} \frac{\partial^2 n_x}{\partial x^2} - a\gamma^2 K n_x$$

n = Neel order parameter

a = homogeneous exchange

A = inhomogeneous exchange

K = magnetic anisotropy

From Maxwell's equations, the wave equations:

$$\nabla^2 \phi - \frac{\partial^2 \phi}{\partial t^2} = -4\pi\rho$$

$$\nabla^2 \mathbf{A} - \frac{\partial^2 \mathbf{A}}{\partial t^2} = -4\pi \mathbf{J}\,.$$

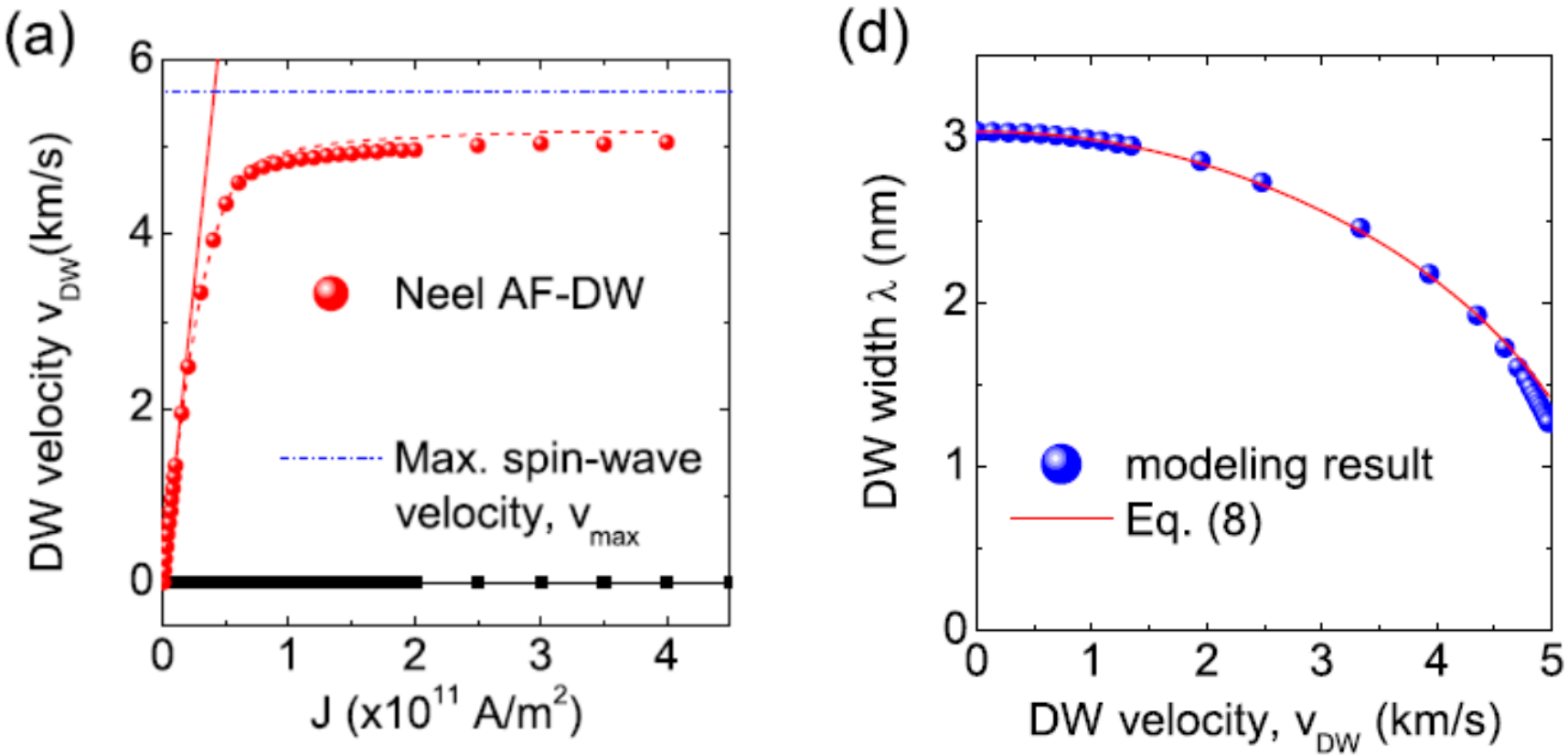
Lorentz invariance

No particle can exceed the speed of light (special relativity)

Lorentz contraction: $\sqrt{1-(v/c\,)^2}$

Lorentz contraction of antiferromagnetic DW

Shiino et al. PRL 117, 087203 (2016)



$$\lambda = \lambda_{eq}\sqrt{1-(v_{DW}/v_{max})^2}, \qquad (8)$$

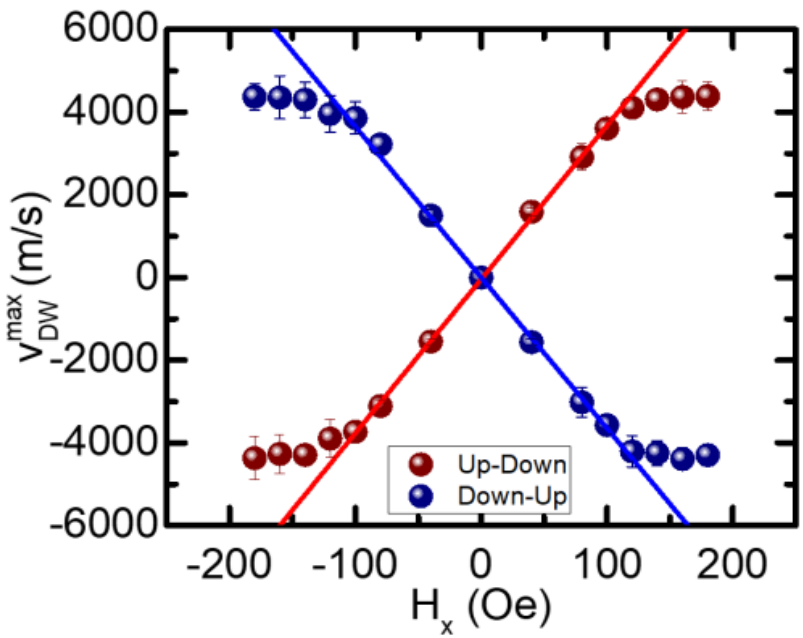
v_{max} = maximum spin-wave velocity

Experiment on relativistic kinematics of AF DW

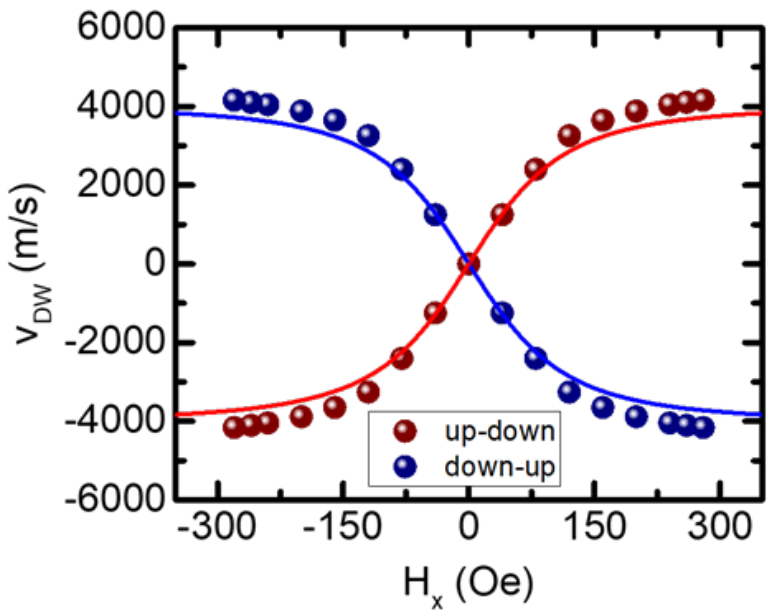
Caretta et al. Science 370, 1438 (2020)

Bi-YIG/Pt (almost compensated and very small damping)

Experiment (G. S. D. Beach group)



Theory/Modeling



Lines (non-relativistic)

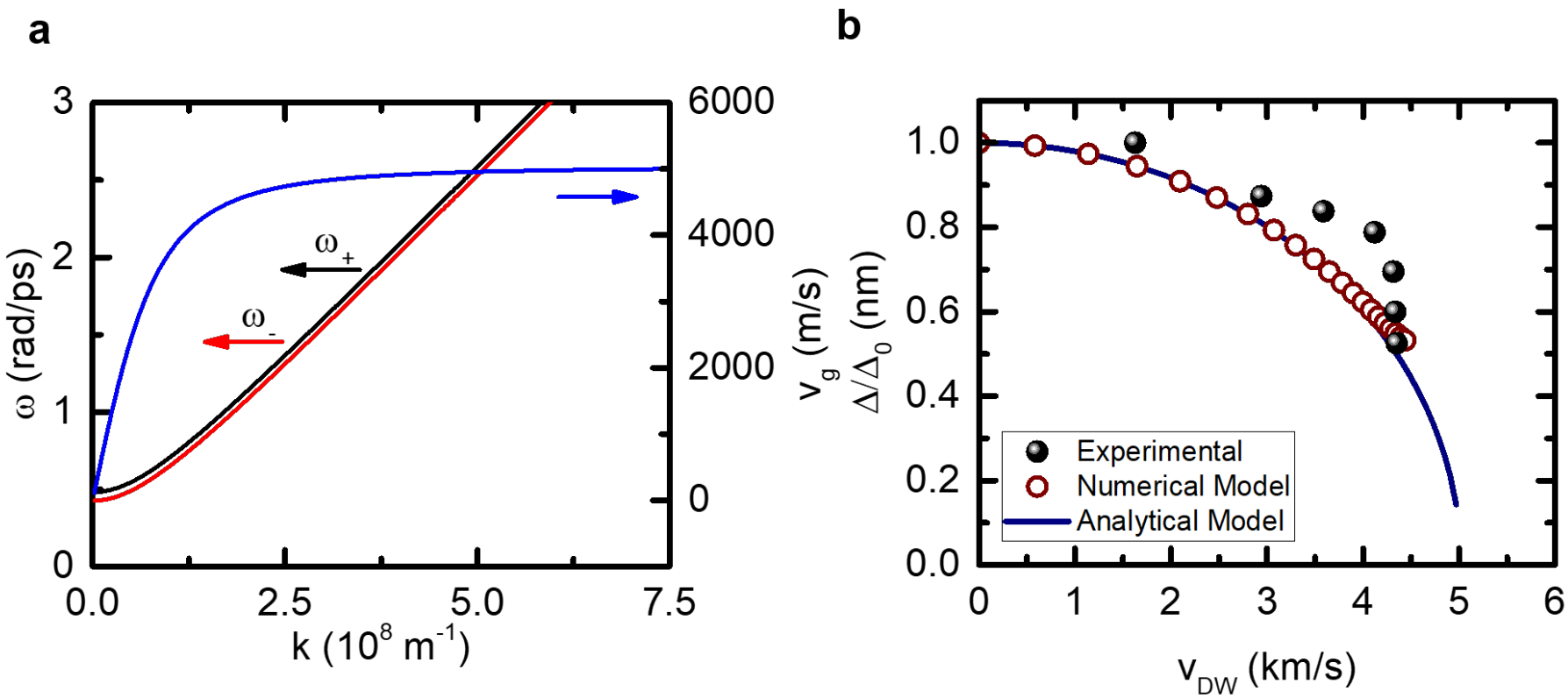
$$v_0 = \frac{\pi}{2}\gamma\Delta\mu_0 H_x$$

Curves (Relativistic)

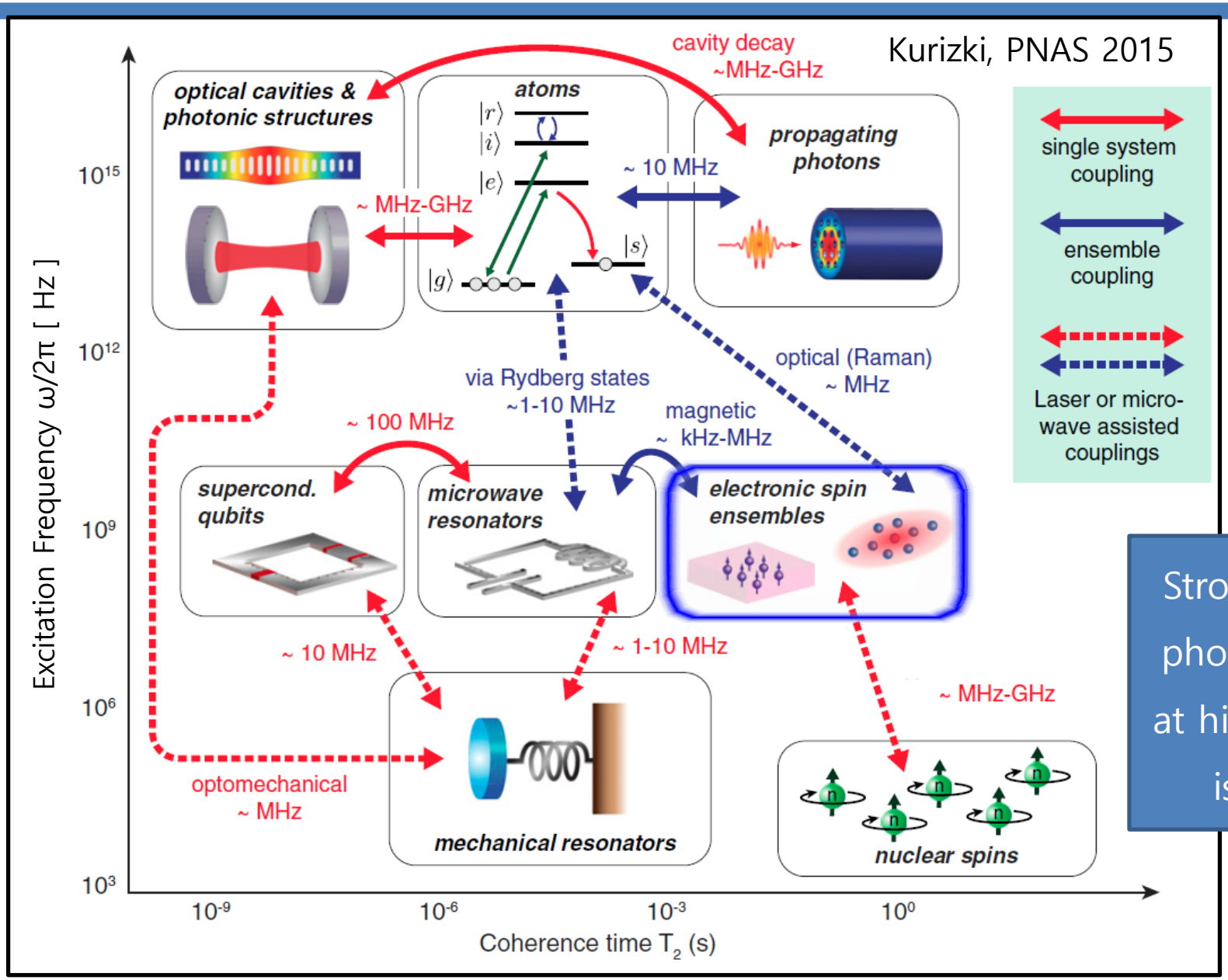
$$v = v_g^{max} / \sqrt{1 + \left(v_g^{max}/v_0\right)^2}$$

Experiment on relativistic kinematics of AF DW

Caretta et al. Science 370, 1438 (2020)



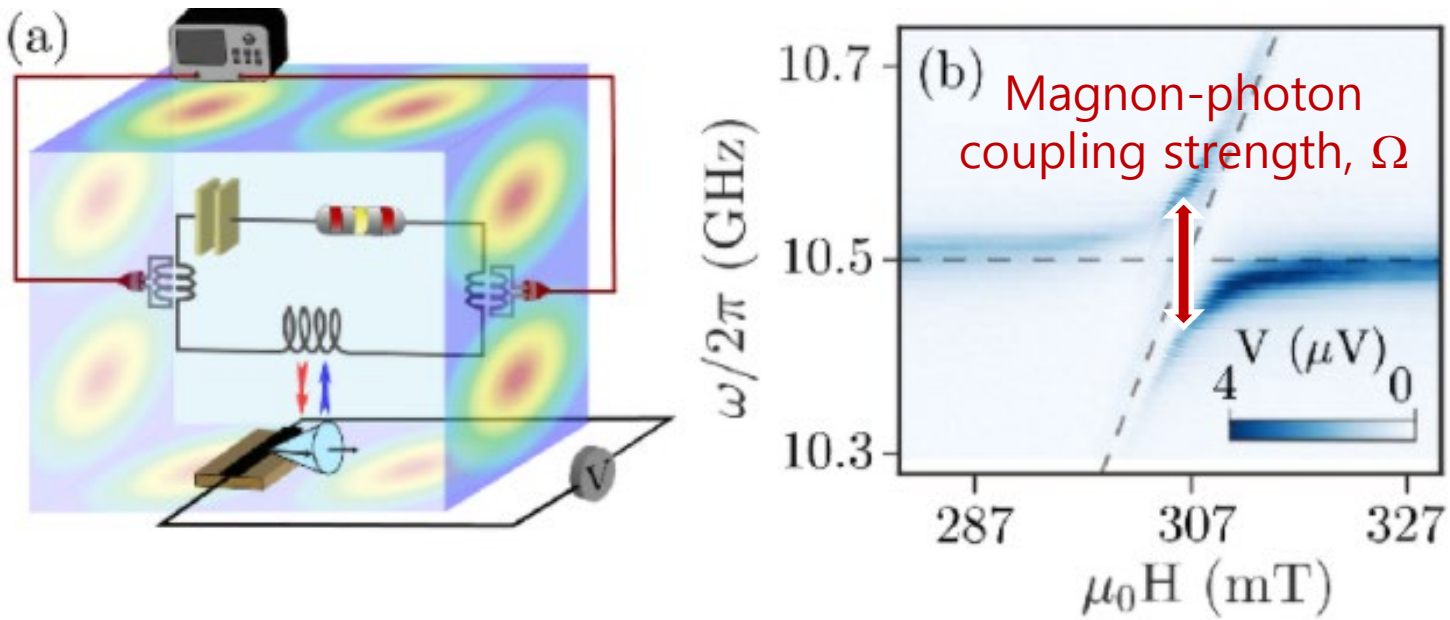
Quantum storage and transduction



Strong magnon-photon coupling at high frequency is required

Cavity spintronics

Harder and Hu, Solid State Phys. 69, 47 (2018)



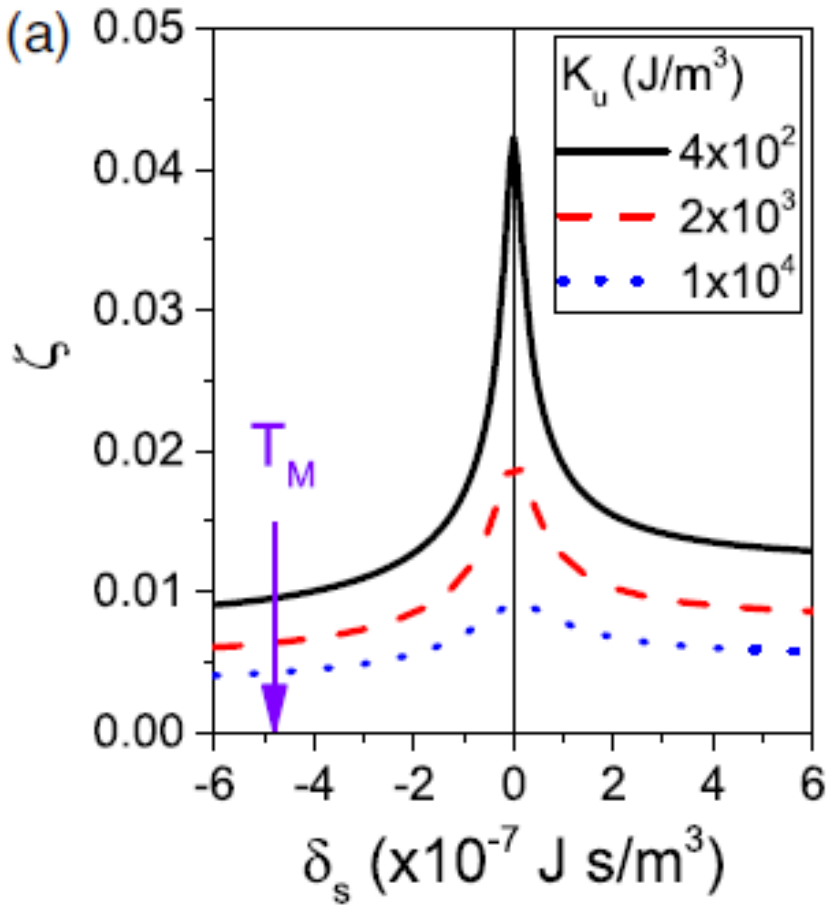
- Coupling between microwaves and magnons in a cavity
- In quantum information processing, photons in a cavity mediate qubits from one physical constituent to another.
- Spin ensemble for storage and transduction of qubits
- Coupling strength $\Omega \propto \sqrt{(\#\ of\ spins)}$ ➔ Ferromagnet
- How about ferrimagnets?

Enhanced magnon-photon coupling at T_A

J. Shim et al., Phys. Rev. Lett. 125, 027205 (2020)

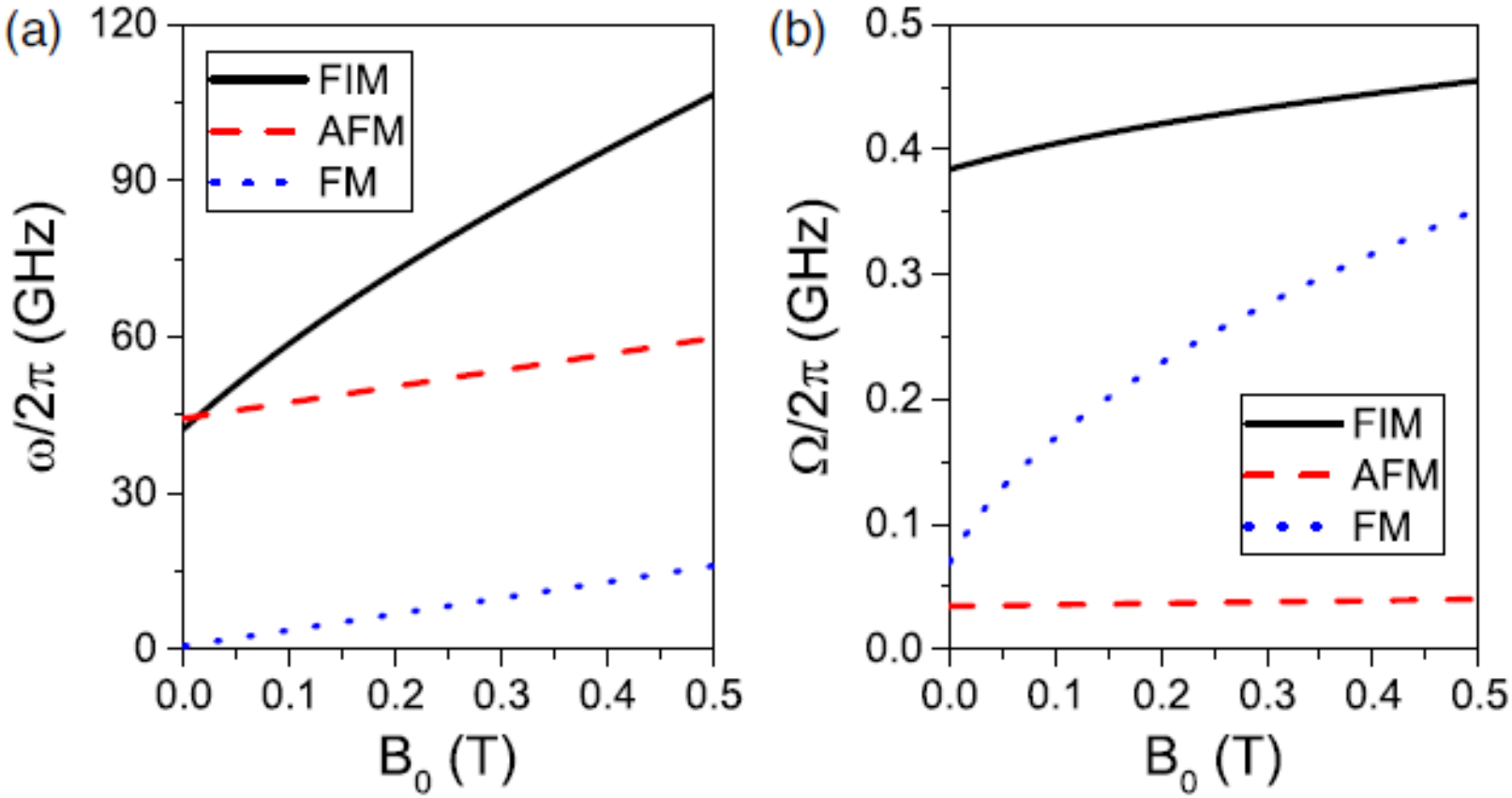
Coupling efficiency = $\Omega/\omega = \zeta \approx K\sqrt{\mu_0 M_l^2}\left[\frac{s^2}{K_u(a\delta_s^2 + K_u s^2)}\right]^{1/4}$.

where M_l = net moment, s = total spin density, and δ_s = net spin density



- At T_A ($\delta_s = 0$), the magnon-photon coupling is enhanced by a concerted action between the antiferromagnetic dynamics and finite Zeeman coupling

Enhanced magnon-photon coupling at T_A



- Comparison of excitation frequency (ω) and coupling strength (Ω) among ferrimagnet (FIM), antiferromagnet (AFM), and ferromagnet (FM)
- Strong coupling at high excitation frequency is realized at T_A

Summary

Antiferromagnetic spin dynamics at the angular momentum compensation point (T_A) in a ferrimagnet

1. Maximum field-driven DW speed ➔ Zeeman energy is used only fo
2. N g
3. R ion of fe
4. Skyrmion Hall effect ➔ No rotational motion at T_A due to zero net spin density ➔ Skyrmion Hall effect vanishes at T_A
5. Enhanced magnon-photon coupling at high frequency at T_A
6. Change of spin-wave handedness at T_A [Nat. Mater. **19**, 980 (2020)]

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nature materials

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